Transcriptional regulatory control of mammalian nephron progenitors revealed by multi-factor cistromic analysis and genetic studies

Lori L. O'Brien¹, Qiuyu Guo¹,², Emad Bahrami-Samani², Joo-Soop Park², Sean M. Hasso¹, Young-Jin Lee¹,², Alan Fang³, Albert D. Kim¹, Jinjin Guo¹, Trudy M. Hong⁵, Kevin A. Peterson⁶, Scott Lozanoff⁵, Ramya Raviram⁷, Bing Ren¹, Ben Fogelgren⁵, Andrew D. Smith⁸, Anton Valouev², Andrew P. McMahon¹*  

¹ Department of Stem Cell Biology and Regenerative Medicine, Broad-CIRM Center, Keck School of Medicine, University of Southern California, Los Angeles, California, United States of America, 2 Department of Preventative Medicine, Division of Bioinformatics, Keck School of Medicine, University of Southern California, Los Angeles, California, United States of America, 3 Department of Molecular and Computational Biology, University of Southern California, Los Angeles, California, United States of America, 4 Division of Pediatric Urology and Division of Developmental Biology, Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio, United States of America, 5 Department of Anatomy, Biochemistry, and Physiology, University of Hawaii at Manoa, Honolulu, Hawaii, United States of America, 6 The Jackson Laboratory, Bar Harbor, Maine, United States of America, 7 Ludwig Institute for Cancer Research, Department of Cellular and Molecular Medicine, Institute of Genomic Medicine, Moores Cancer Center, University of California San Diego La Jolla, California, United States of America

* These authors contributed equally to this work.

A Current address: Department of Cell Biology and Physiology, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, United States of America
b Current address: Cancer Genetics Incorporated, Morrisville, North Carolina, United States of America
¢ Current address: iDream Research Center, Mizmedi Women’s Hospital, Seoul, Republic of Korea

© Copyright: © 2018 O’Brien et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper and its Supporting Information files except sequencing data. All sequencing files are available from the GEO database, accession number GSE90017.

Funding: This work was supported by grants from the National Institutes of Health (https://www.nih.gov/) to APM (DK054364, DK094526), LLO (DK085959), JSP (DK100315), ADS (HG006015), and BF (DK087852, DK100738, GM103457-8293).

Abstract

Nephron progenitor number determines nephron endowment; a reduced nephron count is linked to the onset of kidney disease. Several transcriptional regulators including Six2, Wt1, Osr1, Sall1, Eya1, Pax2, and Hox11 paralogues are required for specification and/or maintenance of nephron progenitors. However, little is known about the regulatory intersection of these players. Here, we have mapped nephron progenitor-specific transcriptional networks of Six2, Hoxd11, Osr1, and Wt1. We identified 373 multi-factor associated ‘regulatory hot-spots’ around genes closely associated with progenitor programs. To examine their functional significance, we deleted ‘hotspot’ enhancer elements for Six2 and Wnt4. Removal of the distal enhancer for Six2 leads to a ~40% reduction in Six2 expression. When combined with a Six2 null allele, progeny display a premature depletion of nephron progenitors. Loss of the Wnt4 enhancer led to a significant reduction of Wnt4 expression in renal vesicles and a mildly hypoplastic kidney, a phenotype also enhanced in combination with a Wnt4 null mutation. To explore the regulatory landscape that supports proper target gene expression, we performed CTCF ChIP-seq to identify insulator-boundary regions. One such putative boundary lies between the Six2 and Six3 loci. Evidence for the functional significance of this
boundary was obtained by deep sequencing of the radiation-induced Brachyrrhine (Br) mutant allele. We identified an inversion of the Six2/Six3 locus around the CTCF-bound boundary, removing Six2 from its distal enhancer regulation, but placed next to Six3 enhancer elements which support ectopic Six2 expression in the lens where Six3 is normally expressed. Six3 is now predicted to fall under control of the Six2 distal enhancer. Consistent with this view, we observed ectopic Six3 in nephron progenitors. 4C-seq supports the model for Six2 distal enhancer interactions in wild-type and Br/+ mouse kidneys. Together, these data expand our view of the regulatory genome and regulatory landscape underpinning mammalian nephrogenesis.

Author summary

Nephrons, the filtering units of the kidney, derive from nephron progenitors. Deficiencies in nephron number increases the risk of kidney disease. An understanding of the regulatory programs governing progenitor actions has important translational potential. Several transcription factors regulate the nephron progenitor population. However, their target interactions are largely unknown. Here, we mapped and intersected the genome-wide binding sites for four such factors in mouse nephron progenitor cells in the developing kidney: Six2, Hoxd11, Osr1, and Wt1. The intersectional data highlight a high-value set of putative enhancer elements linked to genes regulating nephron progenitor properties. We validate the function of two such enhancer elements regulating the levels of Six2, a key transcriptional regulatory factor in nephron progenitor maintenance, and Wnt4, a critical signaling factor controlling the mesenchyme to epithelial transition of induced nephron progenitors. Further characterization of the Six2 regulatory landscape identified higher order regulatory interactions that ensure appropriate enhancer-promoter specificity. CTCF-bound sites between Six2 and the adjacent Six3 locus likely act as boundary elements to define topological interactions domains separating enhancer elements thereby providing distinct tissue specificity to each gene’s expression. An inversion of this region in the Brachyrrhine (Br) mutant mouse reverses Six2 and Six3 expression domains, placing Six3 under control of the Six2 enhancer element above resulting in kidney-specific expression, while Six2 expression shifts to the lens, a normal expression domain for Six3. Together, these data expand our view of the regulatory genome and regulatory landscape underpinning mammalian nephrogenesis.

Introduction

The mammalian metanephric kidney maintains fluid homeostasis. The number of individuals afflicted with kidney disease is on the rise, and reduced nephron number has been associated with disease outcome [1]. In the mouse, genetic studies have demonstrated that nephrons are generated from a Six2+ progenitor pool in a regulatory process requiring the transcriptional action of Six2 for progenitor maintenance [2]. Human SIX2 shows an expression and activity similar to its murine counterpart suggesting that mouse Six2 and human SIX2 likely have similar functions [3]. Consistent with this view, human mutations in SIX2 are associated with renal hypoplasia and the malignant transformation of progenitor cells in Wilms’ tumor, a pediatric nephroblastoma [4–6]. There is an increasing interest in the relationship between nephron progenitors, their output, and congenital and acquired kidney disease [1, 7]. Further, new
approaches to modulate nephron progenitor outputs to generate kidney structures in vitro call for a better understanding of regulatory processes at play in vivo [8–10]. Nephron progenitor specification and nephron progenitor maintenance are dependent on a number of additional transcriptional regulatory factors including Hoxa/c/d11, Osr1, Wt1, Sall1, Eya1, Pax2, and Six1. Previous studies of mouse mutants in these genes suggest complex hierarchical interactions amongst these factors [11–27]. Identification of their genomic targets and target regulatory mechanisms are essential to determine the nephrogenic regulatory network.

Direct nephron progenitor ChIP-seq studies have identified a broad range of potential transcriptional targets of Six2/SIX2 action in the mouse and human kidney, respectively, and verified predicted enhancer modules for several of these targets [3, 28, 29]. Six2 interacts at cis-regulatory modules of genes expressed both in the nephron progenitors and their committed nephron-forming descendants through enhancers co-engaged by differentiation-inducing transcriptional complexes formed in response to canonical Wnt signaling [28, 29]. Interestingly, a potential role for Hox11 paralogs within Six2-predicted cis-regulatory modules is suggested by the strong enrichment of AT-rich homeobox motifs in Six2 ChIP-seq peaks [28]. The genomic targets of Wt1 have also been analyzed by ChIP experiments of embryonic mouse kidneys [30–32]. Though the approach was not specific to nephron progenitors, these studies revealed the interplay with many genes expressed in, and critical for, nephron progenitors, including Fgf and Bmp family members [30–32]. Sall1 ChIP-seq has also shed light on its active roles in nephron progenitors and repressive actions on development of nascent nephrons, respectively [29]. Interestingly, a subset of Six2- and Sall1-bound regions overlap suggesting these factors co-associate and target analysis predicts genes regulating the nephron progenitor population [29].

With a working model that multi-factor binding will highlight key regulatory nodes of the nephron progenitor pathway [33–37], we utilized ChIP-seq analysis to identify a subset of putative regulatory elements associated with multiple transcription factors. gRNA/Cas9-mediated ablation of ‘regulatory hotspots’ adjacent to Six2 and Wnt4 highlight the significance of these enhancer elements in regulating target gene expression. Additional analyses of the regulatory landscape surrounding Six2 identified insulator-bound elements which constrain enhancer function. In support of this finding, deep sequencing of the Br mutant mouse identified an inversion of Six2 and Six3 loci altering enhancer specificity. These studies highlight the critical role of multi-factor input and proper enhancer context for directing appropriate target gene expression.

Results
Identification of nephron progenitor-specific transcription factor interaction sites using a novel transgenic strategy

To extend our understanding of the transcriptional regulatory networks operating within mouse nephron progenitors, we developed a transgenic approach to overcome the limited availability and inconsistency of working antibodies for key transcriptional components, and complications that arise from the diverse expression of regulatory factors elsewhere in the kidney. In this transgenic strategy, an epitope-tagged transcription factor-of-interest is expressed exclusively within the nephron progenitor compartment using a Six2 distal enhancer (DE) previously shown to recapitulate Six2-like, nephron progenitor restricted expression (Fig 1A [28]). This approach obviates the need to enrich for the progenitor population in whole kidney samples simplifying ChIP procedures and avoiding potential artifacts introduced by tissue dissociation and fluorescence-activated cell sorting (FACS). We also took advantage of established tagging methods which have been utilized to successfully isolate protein:DNA
complexes. Each transcription factor-of-interest is appended with a BioTag-FLAG (BF) epitope at the C-terminus of the target protein. Co-production of an EGFP-BirA enzyme on the transgene through an IRES element also allows both ready visualization of transgenic kidneys and biotinylation of the biotin-recognition motif (BioTag) enabling an additional
mode of isolation of factor-associated DNA or protein complexes through streptavidin affinity purification (Fig 1A). Though the biotin tagging strategy proved successful (S1C Fig) and provided a secondary purification option, we did not utilize it for any ChIP experiments as anti-FLAG antibodies were sufficient for all of the studies presented here.

To rigorously assess the efficacy of this strategy and to develop a protocol for whole kidney ChIP, we first generated Six2-BF$^{tg}$ mice to determine whether Six2 ChIP-seq generated with the transgenic line (Six2-BF) replicates Six2 ChIP-seq using a Six2-specific antibody (Six2-ab) [3]. Six2-BF was restricted to the Six2+ nephron progenitors as indicated by specific detection of the anti-FLAG epitope (Fig 1C). FLAG ChIP-seq from Six2-BF+ kidneys identified 6808 Six2-associated regions in the Six2-BF data, with 90% of these peaks overlapping with Six2-ab peaks (Fig 1B). The two datasets were relatively correlated ($R^2 = 0.69$) and, as expected, overlapping peaks were ranked higher than Six2-BF unique peaks indicating the variability in the data reflects marginal peak calls (S1A Fig). The most enriched motif discovered from the top 1000 peaks in the Six2-BF ChIP-seq dataset (‘TCANGTTTCA’, 47%, p-value = 10$^{-1190}$, Fig 1D) matched and agreed with the identified Six2 motif from our previous ChIP studies (S1B Fig; [3, 28, 29]). The motif was relatively centered within the peaks suggesting direct binding of Six2 to the motif (Fig 1D). Additionally, electrophoretic mobility shift assays (EMSA) utilizing recombinant Six2 and a Six2 motif identified within the Six2-DE showed a strong interaction of Six2 protein with its DNA target (S2A Fig). Mutational analysis on this Six2-binding site demonstrated that the most conserved bases in the consensus (1T, 6T and 9C) were critical individually for effective protein-DNA interaction (S2A Fig). Wt1 and bHLH recognition motifs were also significantly enriched in Six2 binding regions (S1F Fig) consistent with an expected role for Wt1 within the progenitor compartment [31, 42], and an unidentified role for a bHLH factor. To interrogate the regulatory functions of Six2-BF, we performed GREAT Gene Ontology (GO) analysis [43] on Six2-BF peaks. Six2-BF peaks were highly enriched near genes associated with kidney development as reflected by the top GO term ‘ureteric bud development’ (Fig 1E).

In summary, the FLAG transgenic strategy robustly reproduced Six2-ab ChIP-seq data generated from wild-type kidneys identifying expected Six2 target and gene associations. These whole kidney-derived datasets significantly extend the depth of Six2 ChIP-seq peaks identified from earlier reports ([28]: 3907 peaks, [29]: 4306 peaks). While our transgenic strategy is useful for targets for which there are no working antibodies or when a progenitor-specific ChIP is desired, expression levels of the tagged protein or affinities of the FLAG antibody versus protein-specific antibodies (if one exists) may affect the number of relevant peaks discovered.

Interestingly, although peaks identified uniquely with the Six2-ab showed lower levels of enrichment, these peaks still enriched for the Six2 motif at a similar level (46%) and were linked to kidney development GO terms suggesting a biological relevance to the interactions (S1A Fig). As nearly all Six2-BF peaks are contained within the larger Six2-ab dataset (~90%, Fig 1B), for a more complete analysis of Six2 bound target regions we used the latter dataset for subsequent analyses.

Having validated the transgenic strategy for generation of nephron progenitor specific ChIP-seq data, we established additional transgenic mouse lines to identify regulatory interactions mediated by other transcriptional regulators in nephron progenitors. Viable and phenotypically normal founders were generated for Hoxd11 (Hoxd11-BF$^{tg}$) and Osr1 (Osr1-BF$^{tg}$). Immunostaining with anti-FLAG antibodies confirmed the restriction of Hoxd11-BF and Osr1-BF to Six2+ nephron progenitors and validated the use of both transgenic lines for ChIP-seq analyses (Fig 1C). We also attempted to generate transgenic lines for Wt1, Hoxa11, Pax2, Sall1, and Eya1 but were unsuccessful in producing any founder animals. Further, we were not able to obtain transgenic progeny which survived past birth from the original Hoxd11-BF
founder. These observations suggest transgene and/or transgenic line dependent lethality (see Discussion).

To map Hoxd11- and Osr1-associated genomic regions within nephron progenitors, we performed FLAG ChIP-seq on E16.5 Hoxd11-BF+/+ and Osr1-BF+/+ kidneys identifying 7776 Hoxd11-BF and 5032 Osr1-BF associated regions (Fig 1D). Osr1-BF protein levels were markedly lower and this may account for the lower number of target sites identified (Fig 1C). Both Hoxd11-BF and Osr1-BF peaks showed typical enhancer features: similar to the Six2-BF dataset the majority of the peaks were located >5kb from the transcription start site (TSS) within intronic (Six2-BF:46.6%, Hoxd11-BF: 46.2%, Osr1-BF: 44.7%) or intergenic regions (Six2-BF: 46.5%, Hoxd11-BF: 48.7%, Osr1-BF: 43.6%) (S1D and S1E Fig). GREAT analysis identified an enrichment for both factors near genes associated with processes related to metanephric kidney development (Fig 1E).

Using the same workflow adopted above for analysis of Six2 interactions, we identified the top DNA motif enriched in Hoxd11-BF (‘TTTATGG’, 38%, p-value = 10^{-1033}, Fig 1D) and Osr1-BF datasets (‘GCTNCTG’, 45%, p-value = 10^{-1438}, Fig 1D). Both motifs were well-centered within each peak dataset (Fig 1D). Multiple Hox factors are expressed in nephron progenitors and each may exhibit distinct binding preferences. While the predicted Hoxd11 motif has a prominent AT-rich Hox factor consensus feature, the motif differs from that identified through protein-DNA binding microarray (PBM) studies in vitro (‘TTTACGA’, [44], S2B Fig). EMSA analysis confirmed Hoxd11 binding and the relative importance of the bases 2T and 4A which are conserved in both the PBM and ChIP-seq based predictions, while the 1T and the 5T/C positions, which differed between the two predicted motifs, were not important for binding in vitro (S2B Fig). The Osr1 motif identified from our ChIP-seq data closely resembled that predicted from PBM studies (‘GCTACTG’, [44]) though no strong preference for the 4th nucleotide position was seen in the in vivo motif. EMSA demonstrated Osr1 bound to the predicted Osr1 binding site within the Six2-DE (GCTGCTG). Interestingly, substituting an A in the 4G position to more closely reflect the PBM motif enhanced the Osr1 interaction (S2C Fig). These findings suggest that in vivo regulatory processes may prefer weaker binding, potentially adding greater flexibility to transcriptional interactions. Wt1 and bHLH motifs were also enriched in each peak dataset, as was observed for Six2-BF peaks (S1F Fig).

**Six2, Hoxd11, Osr1 and Wt1 co-bound sites predict key enhancers and targets of the nephron progenitors**

A Wt1-like binding motif was predicted within all three datasets suggesting Wt1 co-regulation within Six2, Hoxd11 and Osr1 transcriptional networks. Other groups have published Wt1 ChIP from the whole embryonic kidney or glomerulus [30–32] but no nephron progenitor-specific Wt1 data has been generated. We attempted to generate a viable Wt1-BF transgenic line but failed, so we adopted a recently developed protocol for enriching nephron progenitors by magnetic-activated cell sorting (MACS) [45], and performed ChIP-seq with a Wt1-specific antibody on E16.5 nephron progenitors (Wt1-NP, S3A Fig).

Compared to a Wt1 ChIP from the whole kidney (Wt1-kidney) which we generated from the same stage (S3A Fig), the recovered motif from the Wt1-NP dataset, ‘CCTCCCCNC’, closely matches the motif identified in our own whole kidney dataset, and published non-nephron progenitor-restricted Wt1 kidney ChIP data (S3B Fig, [30–32]). The motif also matched the predicted Wt1 motif that was highly enriched in the earlier Six2, Osr1, and Hoxd11 datasets (S1F Fig). The motif was centered in the ChIP peak dataset supporting direct DNA binding (S3B Fig). The nephron progenitor-specific Wt1 ChIP shared >50% of peaks with our whole kidney dataset. Shared target genes with roles in kidney development were
focused on genes involved nephron progenitor maintenance and differentiation, while those unique to the whole kidney also targeted genes associated with podocytes (S3F Fig). This suggests that our Wt1-NP ChIP is representative of regulatory functions for Wt1 within nephron progenitors. The majority of peaks showed an intergenic (35%) and intronic (33%) distribution (S3D Fig). However, Wt1 showed significant enrichment near promoters within 5kb of the TSS (25%, S3C and S3D Fig), significantly more promoter enrichment than observed with the other factors (between 3.1 and 5.3%, S1E Fig), potentially reflecting Wt1’s binding preference to a cytosine-rich motif and GC enrichment at promoters. This result is in contrast to the Wt1 ChIP-seq performed by Motamedi et al., who found peaks to be enriched more distally [31]. However, if we performed GREAT analysis with the ‘basal plus extension’ parameter which includes larger regulatory domains compared to the more restricted ‘single nearest gene’ parameter which was utilized in all of our analyses, we observe a greater enrichment for Wt1-NP peaks 50-500kb from the TSS (S3C Fig). Importantly, the GREAT parameters recovered ‘ureteric bud development’ and ‘metanephric nephron morphogenesis’ terms which are consistent with Wt1 kidney functions (S3E Fig).

To investigate potential co-operative actions of Six2, Hoxd11, Osr1, and Wt1 in nephron progenitors, we analyzed all pairwise overlaps of transcription factor binding sites, and evaluated the statistical significance of such two-factor overlap. Not all genome fractions are accessible to transcription factor binding, and binding of many transcription factors correlates with open chromatin [46]. For simplicity, our statistical analysis is built on the assumption that only open chromatin, identified by utilizing the Assay for Transposase Accessible Chromatin with high-throughput sequencing (ATAC-seq) within nephron progenitors (see Methods for details of the approach and access to data), is accessible to any of the DNA binding factors analyzed in the current study. We found that the greatest significance of co-binding is observed between Six2 and Hoxd11 (-log_{10}p = 320 at all Six2 sites where Hoxd11 is bound and -log_{10}p = 361 at all Hoxd11 sites where Six2 is bound), and Six2 and Wt1 (-log_{10}p = 106 at all Six2 sites where Wt1 is bound and -log_{10}p = 123 at all Wt1 sites where Six2 is bound) interacting regions. The weakest co-association is between Wt1 and Hoxd11 (-log_{10}p = 6 for each pairwise association), although still significant (Fig 2A). Potential target genes for each factor (based on GREAT analysis, [43]) were also subjected to pairwise comparisons. Hoxd11, Osr1, and Wt1 share the majority of their target genes with Six2 (ratio greater than 0.60 or 60%, Fig 2A and 2B). Hoxd11 shows the greatest overlap with Six2 (0.80 or 80%), although all pairwise overlaps showed that nearly half of the comparators target genes are shared with any one factor. These results suggest that these factors likely cooperate in regulatory actions within nephron progenitors.

Next, we overlapped all four datasets to identify sites where all factors converge in the potential regulation of target genes. We recovered 373 putative cis-regulatory modules where Six2, Hoxd11, Osr1, and Wt1 associated within 1kb of each other (Fig 2B, S1 Table). Regions co-bound by all four factors displayed the strongest Six2 binding. In addition, Six2 peaks bound by any three-factor combination were on average stronger than two-factor combinations, while Six2 peaks bound by any factor in combination with Six2 were stronger than Six2-only peaks (S1H Fig).

We refer to regions co-bound by all four factors as ‘regulatory hotspots’ hypothesizing that these may play a key role in nephron progenitor programming. Consistent with this view, regulatory hotspots were enriched around genes annotated to developmental processes such as ‘ureteric bud development’ (Fig 2C). Further, two regulatory hotspots are known from published studies to drive transgenic reporters with expression profiles reflecting the putative target genes: a region ~60kb upstream of Six2 which corresponds to the Six2-DE used in our transgenic strategy and the Wnt4-DE 50kb upstream of Wnt4 (Fig 2D, [28]). Sall1 is also
Fig 2. Regulatory hotspots in nephron progenitors defined by co-binding of Six2, Hoxd11, Osr1 and Wt1. (A) Heatmap shows significance of pairwise overlap between transcription factor binding sites (left, represented by binomial -log10 p-value) or between assigned target genes (right, represented by ratio). TFBS = transcription factor binding site. (B) Venn diagram shows the overlap of Six2, Hoxd11, Osr1, and Wt1 binding sites (left) and target genes (right). The 4-way overlapping sites were defined as the ‘regulatory hotspots’. The 4-way overlapping target genes were defined as ‘core targets’. (C) Barplots show result of gene ontology (GO) analysis on the ‘regulatory hotspots’ (left). Examples of ‘core targets’ known to have roles in the nephron progenitors and their differentiation are listed (right). (D) Genome browser view of Six2, Hoxd11, Osr1, and Wt1 ChIP-seq signals at the ‘regulatory hotspots’ (shadow area) near Six2 and Wnt4. (E) Six2 immunoprecipitation from E16.5 kidney nuclear extracts. Western blot was probed with antibodies to Six2, Hoxd11, and Wt1 to identify protein complexes.

https://doi.org/10.1371/journal.pgen.1007181.g002
bound at the Six2 distal enhancer but not at the Wnt4 enhancer site [29]. Six2 is largely restricted to the nephron progenitors while Wnt4 expression is absent from nephron progenitors but activated on progenitor induction in the formation of differentiating renal vesicles [2, 47]. Thus, engagement of the four factors can occur on target genes for nephron progenitors or genes activated shortly after the onset of nephrogenesis. Other putative targets of regulatory hotspots include Fgf9 which is expressed by nephron progenitors and is involved in regulating their maintenance [48], and Pax8 which regulates nephron progenitor differentiation [49] (S1 Table). Tsc22d1 and Mgat5 also represent putative targets and knockouts of these genes are reported to generate kidney phenotypes [50, 51] (S1 Table).

Regulatory information may also converge on a common target through alternative enhancer usage. To examine this possibility, we intersected the predicted target gene sets for each factor and identified 1744 genes sharing Six2, Hoxd11, Osr1, and Wt1 associated peaks (Fig 2B, S2 Table). The set of genes identified as having all four factors co-associated at one putative cis-regulatory module or dispersed through multiple interactions sites are predicted to define a set of genes with a significant role in nephron progenitors or their derivatives; we termed this group ‘core targets’ (Fig 2C, S2 Table). This set includes genes expressed in nephron progenitors and implicated in progenitor maintenance and self-renewal including Six2, Pax2, Sall1, Sox4, and Gas1 [2, 19, 52–54]. However, the ‘core targets’ also included genes normally activated downstream in the induced/developing nephron such as Wnt4, Lhx1, Pax8, Hes1, and Irx1/2 [47, 49, 55–57].

To determine whether interactions amongst these transcription factors exist in vivo, we performed immunoprecipitations with Six2 antibodies from E16.5 kidney nuclear lysates. Six2 was able to co-immunoprecipitate Hoxd11 and Wt1 (Fig 2E); however, the absence of a working Osr1 antibody precluded analysis of this factor although recent studies show Six2 and Osr1 complex in vitro [17]. Six2 is also purported to complex with Sall1 [29] though we could not replicate this interaction with available antibodies in our assay. Taken together, these data provide evidence for endogenous, multi-protein complexes among three of the four factors.

Transcription factor co-binding is preferentially associated with genes active in differentiating structures and reveals novel targets

We sought to identify whether Six2, Hoxd11, Osr1, and Wt1 are each involved in activating or repressing gene expression in nephron progenitors. First, we generated RNA-seq expression profiles of E16.5 Six2TGCtg/+ kidney cortex preparations FAC-sorted for GFP+(Six2+) or GFP-(Six2-) cells. Six2+ cells would represent the nephron progenitor population (both self-renewing and recently induced) and Six2- cells would largely represent stromal cells as well as ureteric bud tip cells and endothelial cells. Genes with a TPM (Transcripts Per Kilobase Million) value >5 and a fold difference >3 between the two cell types were identified: 246 genes were enriched in the Six2+ fraction and 545 genes were enriched in the Six2- cortex fraction (Fig 3A, S3 Table). We asked whether ChIP-seq peaks of any of the transcription factors or the regulatory hotspots are preferentially located adjacent to differentially expressed genes. The results show that peaks from all ChIP-seq datasets occur significantly more often around genes enriched in the Six2+ cells (Fig 3C) consistent with a specific role in regulating the nephron progenitor cell versus other cell types of the kidney cortex. However, regulatory hotspots near Foxd1, a marker of self-renewing stromal progenitors [58], and Wnt11, a ureteric tip marker required for normal kidney development [59] (S1 Table), raises the possibility that the four factors may also work together to repress these genes within nephron progenitors.

Nephron progenitor cells can be divided into Cited1+/Six2+ self-renewing progenitors and Cited1-/Six2+ differentiating progenitor cells [60]. To address the relationship between
Multi-factor cistromic analysis of nephron progenitor regulatory networks

A

Six2+ specific genes (n=246)
Six2- specific genes (n=545)

B

Genes enriched in self-renewing NP (n=137)
Genes enriched in differentiating NP (n=227)

C

Six2 TFBS (n=12488)
Six2+ specific genes
Six2- specific genes
Genes specific to self-renewing NP
Genes enriched in differentiating NP

Hoxd11 TFBS (n=7776)
Six2+ specific genes
Six2- specific genes
Genes enriched in self-renewing NP
Genes enriched in differentiating NP

Osr1 TFBS (n=5032)
Six2+ specific genes
Six2- specific genes
Genes enriched in self-renewing NP
Genes enriched in differentiating NP

WT1 TFBS (n=5425)
Six2+ specific genes
Six2- specific genes
Genes enriched in self-renewing NP
Genes enriched in differentiating NP

Regulatory hotspots (n=373)
Six2+ specific genes
Six2- specific genes
Genes enriched in self-renewing NP
Genes enriched in differentiating NP

D

% of genes within group

Genome-wide average
0 factor targeting
1 factor targeting
2 factors targeting
3 factors targeting
4 factors targeting
NP-enriched genes
Self-renewing NP-enriched genes
Differentiating NP-enriched genes
regulatory hotspots and programs of progenitor maintenance or commitment, we performed RNA-seq analysis to identify progenitor-specific and early induction gene sets. For the former, a transcriptional profile was generated for E16.5 Cited1+; RFP+ cells from Cited1-mut-TagRFP-Tg/+ kidneys while Six2+; GFP+ cells from Six2TGCr/+ P2 kidneys were used to generate the latter dataset (S4 Table). As expected, Cited1 levels were appreciably lower in the P2 Six2+ cells (200.9 TPM in E16.5 Cited1+ cells vs. 3.8 TPM in P2 Six2+ cells) while Wnt4 transcripts were markedly increased (9.0 TPM in E16.5 Cited1+ cells vs. 219.1 TPM in P2 Six2 + cells) supporting our classification of these datasets (S4 Table).

As expected, a comparison of the genes with a TPM >5 and a fold difference >3 between the two cell types showed self-renewing nephron progenitor-specific genes such as Cited1 and Osr1 enriched in the E16.5 Cited1+ cell dataset whereas genes involved in progenitor differentiation such as Pax8 and Wnt4 were enriched in the P2 Six2+ cell dataset (Fig 3B, S4 Table). Six2 and Hoxd11 displayed similar enrichment near genes up-regulated in either self-renewing nephron progenitors or in differentiating progenitors (1.4–1.5 fold; Fig 3C) consistent with roles in promoting the progenitor state, and either preventing or priming nephron forming programs. Osr1 and Wt1 interactions were slightly enriched near genes associated with self-renewing nephron progenitors (1.4-fold vs 1.0-fold for Osr1, 1.2-fold vs 1.0-fold for Wt1; Fig 3C). Interestingly, the regulatory hotspot associated gene lists showed a higher enrichment around genes upregulated in differentiating cells versus self-renewing progenitors (1.6-fold vs. 1.3-fold; Fig 3C).

Next, for each single factor or combination of factors we compared the percent of target genes in distinct transcriptional categories: nephron progenitor enriched (E16.5 Six2+ cells), self-renewing nephron progenitor enriched (E16.5 Cited1+ cells), or differentiating nephron progenitor enriched (P2 Six2+ cells) relative to the whole transcriptome. Target genes unique to any single factor were not enriched in any of these categories (≤1.6% for each) compared to the whole transcriptome (≤1.6% for each) suggesting that single factor input has no particular relevance to nephron progenitor function. Similar observations hold when Hoxd11 co-targeting is examined with Osr1 and Wt1, (≤1.8%). but not with a Six2 binary combination (≥2.5%) suggesting that Hoxd11 has a strong preference for co-regulation of target genes with Six2 (Fig 3D). Generally, the greatest enrichments are observed when all four factors are bound near the target gene in any category (2.4–7.2%) consistent with co-regulatory input by multiple factors impacting target gene regulation to the greatest extent. In agreement with our earlier analyses, the four-factor overlap has a preference for genes expressed upon differentiation rather than in self-renewing progenitors (5.9% compared to 2.4%; Fig 3D).

While we have described target genes with known functions in kidney development, we wanted to identify potentially novel candidate genes which are targets of co-regulation either by one cis-regulatory module or dispersed through multiple interactions sites. Target genes of interest include Shisa2 and Shisa3 which are enriched in self-renewing nephron progenitors.
(S2 Table). *Shisa2* is a modulator of Wnt and Fgf signaling, specifically attenuating such signals. The majority of mutant mice exhibit dwarfism and half die postnatally. *Shisa3* is a related family member although no overt phenotype was observed for the null allele [62]. *Pdgfc* and *Pdgfa* are enriched in the self-renewing and differentiating progenitors, respectively (S2 Table). Their conserved expression in these cell populations of developing mouse and human kidneys have been reported [63–65]. *Pdgfc* and *Pdgfa* double mutants have a reported deficiency in cortical renal mesenchyme, however, the mutant kidney phenotype was not analyzed in detail [66].

*Ccnd1* (cyclin D1) is a putative target that shows a nearly 7-fold increase in expression in P2 Six2+ cells versus E16.5 Cited1+ cells (S2 Table). In situ hybridization confirms strong *Ccnd1* in E15.5 pretubular aggregates and early differentiating nephrons (www.gudmap.org, [67, 68]). This suggests that the regulatory networks may directly modulate cell cycle dynamics and balance progenitor proliferation or alternatively may prime putative enhancers of *Ccnd1* for rapid activation upon nephron progenitor induction.

*Sema5a* and *Epha4* are predicted targets with a similar ~6-7-fold increase in expression in differentiating progenitors confirmed by in situ studies (S2 Table; www.gudmap.org, [67, 68]) suggesting factor regulation of targets genes controlling local cell interactions.

**Deletion of the Six2 and Wnt4 distal enhancers reveals their roles in modulating target gene expression**

To examine the functional significance of "regulatory hotspots", we focused on *Six2-DE* (chr17: 85747271–85749534; Fig 4A) and *Wnt4-DE* (chr4:137216986–137217756; Fig 5A) elements previously verified in transgenic reporter assays [28]. To examine the requirement for each enhancer, we used CRISPR/Cas9 gene editing technology to delete each enhancer in B6SJLF1/J mice. The *Six2-DE* deletion and *Wnt4-DE* deletion were confirmed in founder lines by PCR and Sanger sequencing of products (*Six2* ΔDE: chr17:85747284–85749542; *Wnt4* ΔDE: chr4:137216991–137217771). For the *Six2-DE* knockout, we examined kidneys at E16.5 and observed no obvious difference in the size of wildtype, *Six2* ΔDE/+ and *Six2* ΔDE/ΔDE kidneys (Fig 4B). *Six2*+ and Wt1+ nephron progenitors were present in *Six2* ΔDE/ΔDE kidneys though *Six2* levels appear reduced relative to wild-type embryos (Fig 4C and 4D). Nephron structures were formed as reflected by the presence of podocytes and proximal tubules, labeled by Wt1 and LTL (*Lotus tetragonolobus* lectin), respectively (Fig 4C). The *Six2* ΔDE/ΔDE mice were viable; no phenotype was observed.

To more accurately assess the effect of the distal enhancer deletion on *Six2* expression, we used qPCR to measure relative *Six2* levels in nephron progenitors of E16.5 kidneys. A 40% reduction of *Six2* mRNA was measured in *Six2* ΔDE/ΔDE nephron progenitors compared to wildtype (Fig 4E, p-value = 0.006); higher levels than in mice heterozygous for a *Six2* null allele (*Six2* CE/+ [69]) where *Six2* transcripts were reduced approximately 50% relative to wild-type as expected (Fig 4E). The levels of *Pax2* mRNA, which is not dependent on *Six2* [2], were relatively similar across all genotypes showing a *Six2*-specificity for the *Six2-DE* deletion. Strikingly, when *Six2* levels were further reduced by combining a *Six2* ΔDE allele with a *Six2* null allele (either *Six2* CE/+ or *Six2* GCE/+ [69]), the resultant *Six2* ΔDE/GCE embryos exhibited severely hypoplastic kidneys at E16.5, with a complete absence of *Six2*+ nephron progenitors, mirroring the phenotype of complete removal of *Six2* activity (Fig 4B and 4D, [2]) where only a few glomeruli (Wt1+) and tubules (LTL+) have formed by E18.5 (S4 Fig). As early as E11.5, at the outset of active kidney morphogenesis, *Six2* ΔDE/GCE kidneys were devoid of *Six2*+ nephron progenitor cells but filled with Pax8+ differentiating nephron progenitors as in *Six2* protein null mutant kidneys (Fig 4G, [2]). Taken together these results demonstrate that *Six2-DE* accounted for approximately 40% of *Six2* expression and by combining one *Six2-DE* allele
Fig 4. Deletion of the Six2 distal enhancer leads to reduction in Six2 levels and concomitant loss of a Six2 allele results in severe renal hypoplasia. (A) Schematic of the Six2 locus showing the location of the proximal (PE) and distal (DE) enhancer elements. The DE was targeted for deletion using CRISPR/
Cas9 and the resulting Cas9-mediated deletion of the Six2-DE is shown. (B) Brightfield images of whole urogenital systems from E16.5 embryos resulting from Six2<sup>ΔDE/+</sup> matings or Six2<sup>x2/+</sup> x Six2<sup>ΔDE/+</sup> crosses. (C) Immunostaining for Wt1 to identify nephron progenitors and podocytes, LTL (Lotus tetragonolobus lectin) to mark proximal tubules, and Cdh1 to show the collecting duct network of kidneys associated with (B). (D) Immunostaining for Six2 to identify nephron progenitors in kidneys associated with (B). (E) Box plots showing results of qPCR for Six2 and Pax2 (normalized to GAPDH) from nephron progenitors (NP) and nephron progenitor-depleted cortex. Genotypes and number of samples analyzed are shown. (F) Samples from Six2<sup>ΔDE/GCE</sup> were compared to Six2<sup>ΔDE/GCE</sup> collected at early stages of kidney development and immunostained with Six2 to mark the nephron progenitors, Pax2 to identify differentiating structures (Pax8 antibody appears to cross react with Pax2 as seen by expression in Ecad+ collecting duct), and Ecad to mark epithelial structures.

https://doi.org/10.1371/journal.pgen.1007181.g004

with a Six2 null allele, the remaining Six2 mRNA levels (predicted to be 30% of wild-type levels) were insufficient for Six2-mediated maintenance of the nephron progenitor state.

Next, we investigated a ‘regulatory hotspot’ predicted to function in progenitor differentiation. Deletion of the Wnt4 distal enhancer resulted in mutant kidneys that are ~25% smaller than those from wildtype animals (p = 0.2e-4; Fig 5B and 5C). Nephrons developed in Wnt4<sup>ΔDE/ΔDE</sup> kidneys as reflected by presence of both LTL+ proximal tubules and Wt1+ podocytes (Fig 5D) and Wnt4<sup>ΔDE/ΔDE</sup> mice are viable. Interestingly, in situ hybridization revealed that expression of Wnt4 is significantly reduced in renal vesicles but remained largely unaltered in the renal medulla of Wnt4<sup>ΔDE/ΔDE</sup> kidneys consistent with an overall reduction of Wnt4 mRNA levels in Wnt4<sup>ΔDE/ΔDE</sup> kidneys measured by qPCR (Fig 5E). Thus, the Wnt4-DE plays a functional role in regulating Wnt4 mRNA levels in forming nephrons (Fig 5E). The Wnt4<sup>ΔDE/ΔDE</sup> phenotype was less severe than Wnt4 protein null mutants where the severely hypoplastic kidney lacks nephron tubules and glomeruli [47]; indeed, low levels of Wnt4 RNA were detected in Wnt4<sup>ΔDE/ΔDE</sup> kidneys (Fig 5D; arrows in Fig 5E). When the Wnt4<sup>ΔDE</sup> allele was combined with a Wnt4<sup>GCE</sup> protein null allele [69], Wnt4<sup>ΔDE/GCE</sup> kidney size and nephron structures were further reduced, though kidneys were still larger than Wnt4 null kidneys (Fig 5B–5D) and Wnt4 mRNA levels were markedly reduced in whole kidney PCR (Fig 5E and 5F).

Taken together these results indicate a dose-dependent reduction in kidney size through reduced nephrogenesis upon decreasing Wnt4 activity. Further, residual levels of Wnt4 activity in Wnt4<sup>ΔDE/GCE</sup> kidneys were sufficient to drive low levels of nephrogenesis. Clearly, the Wnt4-DE plays a role in maintaining appropriate levels of Wnt4 transcripts in the nephrogenic program to ensure a normal program of kidney development.

The Br mouse is the result of an inversion altering the Six2 regulatory landscape

Six3 lies ~60 kb from a related family member Six3, although significant Six3 expression is not observed in the self-renewing nephron progenitors (S4 Table) indicating a specificity in Six2-DE interactions. Topologically associating domain (TAD) boundaries have been described as CTCF-enriched sites which serve as insulators and prevent promiscuous enhancer activity [70]. We performed CTCF ChIP-seq using E16.5 purified nephron progenitors to identify CTCF-bound regions of the genome (Fig 6B and S3G and S3H Fig). We identified strongly bound CTCF sites between the Six2 and Six3 locus, most of which are consistent with ENCODE data analyzing whole P0 kidney samples (S5B Fig, ENCODE experiment ENCSR143WOK, submitted by Richard Myers, HAIB, [71]) and predictions from Hi-C on mouse ES cells (TAD: chr17:85640660–85680660, S5A Fig, [70]). We hypothesize that this region serves as a TAD boundary to prevent the Six2-DE from engaging the Six3 promoter. Consistent with this view, there is a marked bias in the engagement of regulatory factors in nephron progenitors to the Six2 side of this putative boundary, 5′ to the Six2 transcriptional start site (Fig 6B).
With these insights into regulation of Six2, our attention was drawn to the *Brachyrrhine* (*Br*) mouse, an X-irradiation induced mutant that displays kidney hypoplasia and frontonasal
Fig 6. The Six2 regulatory landscape is altered in the Br mouse leading to reduced Six2 expression and ectopic Six3 expression in the kidney. (A) Schematic showing the X-irradiation induced breakpoints and subsequent deletion with inversion that resulted in the Br allele.
dysplasia, and maps to the Six2 region of chromosome 17 [72]. Though Br mutants have significantly reduced Six2 expression in the kidney and craniofacial tissues, no mutation has been found in the Six2 transcription unit or within 1.8 kb upstream of the start codon which includes the Six2-PE elements [72]. Interestingly, Six2 is ectopically expressed in the developing lens of Br heterozygous and homozygous animals, a normal site of Six3 expression [72].

Given that irradiation induces large-scale genomic rearrangements, we speculated that the Br mutation led to a chromosomal rearrangement that removed Six2 from enhancer(s) directing normal regulatory input to the nephron progenitor population, placing Six2 under the control of Six3 regulatory elements normally inaccessible the other side of a CTCF-dependent boundary element.

Next generation sequencing and sequence alignment identified the underlying sequence change in the Br mutant (S1 Supplemental Material and Methods). The main feature was a large inversion of 324,596bp including both the Six2 and Six3 loci. The inversion moves Six3 ~206kb from the Six2-DE, actually further than in the wild-type organization, but importantly the inversion removes the intervening TAD boundary (Fig 6B). In contrast, Six2 is repositioned on the other side of this boundary element within Six3's unchartered regulatory territory (Fig 6B). In addition to the inversion, two small deletions were detected: a 4,630bp deletion (chr17:85414584–85419213) 5' to the Six3 TSS in the intron of Camkmt, and a 5bp deletion between the Six2-PE and Six2-DE (chr17:85743809–85743813, Fig 6A and 6B). The results from the sequencing and computational analysis were confirmed by allele-specific diagnostic PCR assays (SSC and S5D Fig). The inversion also separates the last 4 exons of Camkmt from the rest of the transcription unit. However, Camkmt has a TPM of only 2.26 in the E16.5 Cited1+ nephron progenitor cells and homozygous mutant mice are viable (International Mouse Phenotyping Consortium, http://www.mousephenotype.org/, Release 5.0 [73]), so Camkmt is unlikely to contribute to the kidney phenotype. The rearrangement predicts: i) ectopic Six2 expression in Six3's normal expression domain, the lens, as Six3 enhancers can now target Six2, and ii) an abnormal interaction between the Six2-DE and Six3 promoter resulting in ectopic Six3 expression in nephron progenitors.

To directly examine interaction of Six2-DE with Six2 and Six3 promoters, we performed 4C-seq [74] using Six2-DE as the view point. As expected, in wildtype kidneys Six2-DE interacts with a broad region that includes Six2 transcription start site (TSS) (Fig 6B), with the local maxima 7.2 kb upstream of Six2 TSS. Noticeably, Six2-DE interaction was restricted by the TAD boundary between Six2 and Six3 (Fig 6B and S5B Fig) and no interaction was observed around the Six3 TSS. In kidneys from Br/+ embryos, strong Six2-DE contacts were now observed in the segment of the inverted region that was repositioned between the Six2-DE and CTCF-bound TAD boundary element (Fig 6B and S5B Fig). As expected, with the loss of one wildtype allele in Br/+ embryos, Six2-DE interactions with Six2 TSS, and in general with the region on Six2 side of the TAD boundary, were significantly reduced. A relatively strong, de novo interaction of the Six2-DE was observed ~15 kb upstream of Six3 TSS (Fig 6B and S5B Fig) consistent with the model of Six3 expression driven, at least in part, by the Six2-DE in the Br allele. Importantly, the predicted Six2-DE/Six3 upstream contact in the Br allele occurs over...
a distance of 200 kb from the Six2-DE to the Six3 TSS, a longer interval than the ~130 kb that separates these non-interacting elements in the wild-type allele (S5B Fig). Therefore, the differential interaction of Six2-DE with Six2 TSS and Six3 TSS between wildtype and Br/+ cannot be attributed to shortened distance from Six2-DE to Six3 TSS. Rather, this data supports specific regulation by Six2-DE to Six2 and Six3 that is defined by the TAD boundary.

As a result of the altered chromatin architecture introduced by the genomic inversion, ectopic Six2 expression has been reported in the lens of Br/Br mutants [72], and Six3 expression was reduced in this structure (S5E Fig). Quantitative PCR detected Six3 expression in the kidneys of Br/+ mice at E13.5 (Fig 6C) and Six3 protein was detected in Six2+ nephron progenitors (Fig 6D). Br/Br mutants resemble Six2 null mutants and have no nephron progenitors at this stage [2] (Fig 6C and 6D). When Br/Br mutants were examined at E11.5, they showed a similar loss and premature differentiation of nephron progenitors as in Six2 null mutants but interestingly low-levels of Six3 were detected in differentiating progenitors (S5F Fig). Taken together, these data lend additional weight to the importance of the Six2-DE in directing Six2 expression and reveal higher order principles of topological organization acting in conjunction with this enhancer to provide target gene specificity to the regulatory landscape.

Discussion

In this study, we utilized novel transgenic mouse strains to map the nephron progenitor-specific interactions of Six2, Hoxd11, and Osr1, and incorporated nephron progenitor-specific ChIP-seq profiling of Wt1, to identify the regulatory genome controlled by these four factors in the developing mouse kidney. Our data identifies a subset of binding sites, or ‘regulatory hotspots’ where the engagement of all four factors occurs in close proximity. The putative target genes of their combinatorial action are largely associated with kidney function. Deletion of two of these hotspots for Six2 and Wnt4 highlight their roles in target gene regulation and their significance to kidney development. These data suggest that ‘hotspots’ with multi-factor input play significant roles in target gene regulation. Our analysis on the Br mutant demonstrated that re-arrangement of the regulatory scenario of Six2 and Six3 genes can cause dramatic, predictable effects on their expression and the resulting developmental phenotypes highlighting the importance of appropriate regulatory context to proper gene regulation and biological function.

Transcriptional hierarchy of nephron progenitors

Our ChIP studies reveal a complex regulatory architecture of the nephron progenitors. Examining co-binding of the four factors suggests each of these genes is itself a target of their combined actions through auto and cross-regulatory inputs, as are a number of other transcriptional regulatory components important for kidney development and nephron progenitor maintenance such as Sall1 and Pax2 (S2 Table). By combining our data with insight from previous studies, a hierarchical network starts to emerge. For example, mutational analyses have demonstrated a requirement for the Hox11 paralogues to activate Six2 expression in metanephric mesenchyme [12]. Hox11 members complex with Pax2 and Eya1 binding to an enhancer that lies within ~1kb of the Six2 TSS, in the Six2-PE [75]. Hox11 acts as an activator of Six2 activity and mutations in Hox motifs results in loss of reporter activity in transgenic assays [76]. We have also shown that the Hox motif within the Six2-DE is required for reporter activity [28]. Consistent with this data, Hoxd11 is bound at the Six2-DE (Fig 2D). However, we did not observe a significant Hoxd11 association to the Six2-PE as reported [76]. This
discrepancy may result from preferential enhancer usage at different developmental stages. Two previous studies assayed reporter activity of the ~1kb Six2-PE at E11.5 [75, 76] while our studies assayed Six2-DE activity at E15.5 [28]. Hox11 may be required at the Six2-PE to help initiate Six2 expression, but maintenance of expression may then rely, at least partially, with the Six2-DE where Hoxd11 is engaged at E15.5. Additionally, Osr1 and Wt1 are enriched at the Six2-DE compared to the PE (Fig 2D), as is Sall1 [29], supporting multifactor input at the DE as an important mechanism of Six2 regulation. However, Six2 is bound at both the PE and DE, though PE association is weaker (Fig 2D), suggesting both may contribute at some level to the maintenance and autoregulation by Six2 itself. Unfortunately, technical difficulties preclude detailed temporal analysis of engagement in the small numbers of cells that are the foundation of the nephron progenitor pool.

When assessing the targets unique to any transcription factor combination, the greatest enrichment for genes with expression within the nephron progenitors, either in self-renewing or differentiating cells, generally occurred when they were complexed with Six2 (Fig 3D). Hoxd11 showed the lowest levels of enrichment for these targets when engaged with Osr1 or Wt1 in the absence of Six2, suggesting that its primary regulatory functions rely on engaging with Six2. Taken together, these data suggest Six2 acts as a master regulator: co-engagement with Six2 predicts a higher probability of regulatory functions within nephron progenitors.

**Transcriptional factors: Activator, repressor and enabling interactions**

Osr1 has been described as a transcriptional repressor in vertebrate kidney development [77]. Xu et al. showed that Osr1 works with the Groucho family members and represses activation of a Wnt4 enhancer specifically in Six2+ nephron progenitors [17]. Consistent with this result, Osr1 associates with the Wnt4 enhancer in our ChIP assay (Fig 2D). Additionally, other genes that are not present in the nephron progenitors but rather in differentiating structures such as Pax8 and Lhx1 are also bound by Osr1 suggestive of a repressive role (Fig 3C, S2 Table, [49, 56]). However, Osr1 is also bound near genes actively expressed in nephron progenitors such as Six2 and Osr1 itself (Fig 3C, S2 Table, [2, 16, 69]). Therefore, our data suggest a more complex relationship than Osr1 simply repressing transcription at all engaged targets. Further, our previous ChIP studies supported dual roles for Six2 in activating transcription within nephron progenitors but also engaging at targets silent in progenitors but activated as progenitors differentiate towards nephrons [3, 28]. Similarly, Hox11 has been characterized as an activator, specifically of Six2 expression [76]. Consistent with this view, Hoxd11, is bound near nephron progenitor-specific genes but like Six2 binding is also prominent around differentiation targets (Fig 3C, S3 Table). Similarly, these observations extend to Wt1 nephron progenitor targets. Engagement most likely reflects dual activator and repressor actions of these complexes and which activity could be dependent on currently unidentified co-bound factors. Conversely, factor engagement at differentiation-specific gene targets may facilitate or enable subsequent activation of enhancers for differentiation-associated genes following the induction of nephron progenitors. In this scenario, multi-factor engagement may be necessary but not sufficient for target activation for differentiation associated genes. Additional factors or modification of existing transcriptional components following progenitor commitment may modify the action of these regulatory complexes.

**Genomic co-localization of transcription factors in nephron progenitor cells**

We observed a highly significant overlap of transcription factor binding in nephron progenitors. Motif analysis of each ChIP dataset showed de novo, factor-specific motifs were the most
enriched (Fig 1D), supporting direct protein-DNA binding. Additionally, our EMSA assays confirmed factor binding to each motif (S2 Fig). On the other hand, previous studies have shown that Six2 can complex with a number of transcription factors, including Hoxa11 [28] and Osr1 [17] in vitro, and Eya1 and Sall1 both in vitro and in vivo [29, 78, 79]. Osr1 has also been shown to interact with Wt1 in vitro [80]. These studies support protein-protein interactions amongst these factors and may account, in part, for the multi-factor co-localization on specific genomic targets. Additionally, our kidney immunoprecipitation data suggests that Six2 can interact with Wt1 and Hoxd11 (Fig 2E), confirming such complexes exist in vivo. However, without confirming the co-association of these factors on any genomic loci at the same time and in the same cell, we can only suggest their combined function. The association of each factor with its own DNA target and co-association with each other adds to the difficulty of predicting the actions of the regulatory circuit. Further, it is likely that there are significant components yet to be discovered. For example, all of the ChIP datasets recovered a bHLH motif amongst the most-significantly enriched motifs (S1F Fig). Whereas Myc is a bHLH transcription factor that has been shown to complex with Eya1 and Six2 in the kidney [79], and loss of function Myc mutants argue for a role in kidney development [81], the recovered motif is distinct from the conventional Myc-Max target site [44], suggesting a role for another, unidentified family member.

**Target gene functions in nephron progenitors**

In addition to identifying target genes with known function during kidney development, we also uncovered novel putative targets of the four factors (see S2 Table for list of all target genes). Bmpr1 is a secreted protein that interacts with Bmp proteins and inhibits their function [82]. Inactivation of Bmpr1 in the kidney leads to mild hypoplasia [83]; Bmp signaling plays important roles in the progenitor self-renewal and differentiation [84]. Six2 and the other factors may help fine-tune the level of Bmp signaling through activation of Bmpr1. Rspo1 is a secreted protein that binds to G protein-coupled receptors that activate Wnt signaling and its function has been implicated in multiple developmental systems [85]. Rspo1 could have a role in modulating Wnt signaling in the nephron progenitor niche although Rspo1 mutants have no obvious kidney phenotype, these mutants have not been analyzed in depth [85]. We also identified other modulators of Wnt signaling within our data. Shisa2 is reported to attenuate Wnt and Fgf signaling during development [62]. Shisa2 is expressed in the nephron progenitors along with its related family member Shisa3 (S2 Table). Other targets like Tsc22d1 and Mgat5 are reported to display kidney phenotypes. Mgat5 is expressed in differentiating structures including podocytes (S2 Table, Eurexpress, [86]) and shows a glomerular phenotype [51]. Tsc22d1 is expressed in the nephron progenitors (S2 Table) and mutants have small kidneys [50]. Given the current associations of known targets with kidney development and disease, it is likely that functional analysis of new targets predicted here will identify additional regulators of mammalian kidney development.

From our analyses, the majority of significant targets fall under the control of all four factors. These genes fall into multiple functional categories from transcriptional regulators like Six2, Sall1, and Pax2 to signaling factors like Fgf9 and Wnt4 to cell cycle regulators such as Ccnd1 and matrix proteins such as Lamb1 (S2 Table). This suggests that these transcription factors control many different aspects of progenitor cell biology. Fewer targets with known kidney functions emerge from the interaction maps where one of more the factors was not bound at the putative regulatory region (S5 Table). However, Eya1, Wt1, and Bcam lacked an Osr1 association in combined factor interaction analysis (S6 Table) but are well known for their early roles in the kidney program [18, 21]. Bcam, encodes a surface receptor which binds
laminin and is expressed at increasing levels in differentiating progenitors (S6 Table). Knockouts display glomerular abnormalities suggesting important functions in the kidney [87]. Phgdh, a Six2-independent target with highest expression in nephron progenitors (S6 Table) participates in L-serine synthesis and knockouts are embryonic lethal [88].

Deletion of regulatory hotspots
Enhancers directing Six2-like and Wnt4-like reporter gene expression [28], identified as ‘regulatory hotspots’ co-bound by Six2, Hoxd11, Osr1, and Wt1 in the data here, were shown to play roles in regulating activity of both gene targets. Kidney phenotypes were observed in embryos homozygous for the enhancer deletion (Wnt4-DE) or when combined with protein null mutations (Six2-DE and Wnt4-DE). While the study identified functional enhancer regions, neither works alone in regulating normal transcript levels in the target cell type. An alternative proximal enhancer has been documented for Six2 [76, 89]. This proximal enhancer lies a few hundred base pairs upstream of Six2's transcriptional start site and strongly binds Six2, but not the other regulatory factors analyzed here. Alternative enhancers have not been functionally demonstrated for Wnt4. In summary, our studies provide evidence to support a focus on multifactor input to prioritize functional analysis of large datasets emerging from ChIP-seq studies. CRISPR/Cas9 deletion of an enhancer region >100kb from the TSS for Sox2 that is co-bound by multiple transcription factors regulating pluripotency (Oct4, Sox2, Nanog, and Klf4 [90, 91]) provides another example of this strategy to identify strong, bone-fide components of the regulatory genome.

Topological rearrangements in the Br mutant and cis regulation of Six2
Individual enhancer action depends on the larger context of the chromosomal landscape. Our demonstration that the inversion in Br mutant strain, repositions Six2 and Six3 in a new regulatory landscape modifying enhancer interactions that likely contribute to altered features of each gene’s regulation. Each gene exists in a distinct TAD that is likely enforced by the action of a CTCF-dependent boundary element between the two genes. In Br heterozygous and mutant alleles, Six3 is ectopically expressed in nephron progenitors: the boundary element no longer separates the Six3 promoter from the Six2-DE. We hypothesize that this enhancer, and potentially undefined regulatory information 5’ to this enhancer, dominate over other regulatory information that might be present within the Six3 flanking region. As a result, the Six2-DE drives Six3 expression in nephron progenitor cells while Six3 expression is lost from its normal lens expression domain. Even though Six3 was detected in nephron progenitors in Br/+ mutants, Six3 is a member of a functionally divergent sub-group of Six factors [92]. Consequently, Six3 activity failed to compensate for loss of Six2 and Br/Br mutants resemble Six2 null mutants [72].

Interestingly, even though there is no alteration in Six2-PE position relative the Six2 gene, the Six2-PE is not sufficient to drive levels of Six2 which maintain nephron progenitor development in the context of the inversion. Thus, if the Six2-PE were capable of sustaining normal Six2 levels, the inversion may prevent Six2-PE engagement with regulatory factors necessary for its activation. Alternatively, there may be distinct enhancers other than the Six2-PE that are required for Six2’s expression. Six2-bound putative regulatory regions lie upstream of Six2-DE (S8 Table, Fig 6B) and these would be predicted to disengage from Six2 regulation in the Br inversion.

Topological domains are highly conserved between cell types and across mammalian species [70]. Recent studies have shown that alterations in TADs and CTCF site orientation can affect chromosome architecture and result in altered gene expression [93, 94]. Specifically,
several limb malformations in the human were attributed to the rearrangement of TADs and disrupted boundaries. When genetically modeled in the mouse, altered gene expression suggests a mechanism for driving the limb malformations [93]. The type of topological rearrangements described here could play a role in a subset of the congenital anomalies of the kidney and urinary tract (CAKUT) syndrome. Importantly, these micro-rearrangements would not be detected in traditional exome screens. Even whole genome sequencing approaches required tailored alignment algorithms to uncover the junction fragments for the rearrangements as performed here. Together, these studies highlight the importance of non-coding DNA and chromatin architecture to the appropriate regulation of gene expression and the resulting phenotypic consequences incurred by rearranging the regulatory landscape.

Limitations of the transgenic approach
In addition to Six2, Hoxd11, and Osr1, we attempted to generate transgenic lines for other important regulatory factors including Wt1, Hoxa11, Pax2, Sall1, and Eya1. Our goal was to build an extensive regulatory network for the nephron progenitor population and more precisely identify the targets and combinatorial actions of these major players in vivo. However, despite considerable efforts, we were unable to establish correctly expressing founder lines for these factors. The Six2-DE is not only active in the kidney but Six2 is expressed in the developing brain, ear, tendons, and smooth muscle [95] and we observed transgene expression in the brain and ear. Some transgenic lines showed a circling behavior, consistent with inner ear defects, along with insufficient kidney expression and thus were not utilized. The ectopic action of a sub-set of factors in these other sites of Six2-DE activity may have resulted in severe defects and subsequent lethality. Alternatively, there could be dominant effects within the kidney itself from elevating levels of that factor in the normal nephron progenitor context, though this seems less likely given the absence of a kidney phenotype in Six2, Hoxd11, or Osr1 transgenic strains, a Six2-BF binding profile that was comparable to the native Six2 protein, and the levels of Six2-DE activity.

Despite these technical limitations, we were able to generate a core transcriptional network of four factors important for kidney development. Overlap with additional factors may not add much greater insight; comparison with Sall1 and β-catenin targets reveals many of the same nephron progenitor-specific target genes and a lack of nephron progenitor relevant independent regulation by these factors (S1, S5 and S6 Tables). Therefore, the data presented here is likely to highlight some of the most critical regulatory elements and target genes which modulate nephron progenitor programs.

Materials and methods
Mouse strains
All surgical procedures, mouse handling, and husbandry were performed according to guidelines issued by the Institutional Animal Care and Use Committees (IACUC) at the University of Southern California and after approval from the institutional IACUC committee. The transgenic construct utilized by Park et al. [28] to test Six2-DE enhancer activity was modified to insert PacI and SwaI sites for cloning downstream of the Hsp68 minimal promoter followed by an IRES-NLS-GFP-BirA cassette. However, the IRES-NLS-GFP-BirA cassette was not included in the generation of the Six2-BF line. Each transcription factor of interest (Six2, Hoxd11, and Osr1) was amplified from E15.5 kidney cDNA with a BioTag-3XFLAG sequence on the 3’ C-terminus and inserted into the transgenic vector using PacI and SwaI sites. Transgenes were purified and injected as previously described [28]. F0 animals were genotyped and transgenic animals bred to confirm germline transmission. Embryonic offspring were also analyzed for correct expression patterns of the transgene in the developing kidney.
Cas9-mediated removal of the Six2-DE (chr17:85747271–85749534) was performed by identifying optimal gRNAs flanking the enhancer utilizing the CRISPR Design Tool (crispr.mit.edu; 5’ gRNA: gttaccatctacggtgatgc, chr17: 85747271–85747290; 3’ gRNA: gatatgattctccggagctt, chr17: 85749515–85749537). The gRNAs were cloned into the pX330-U6-Chimeric_BB-hSpCas9 plasmid (Addgene) as described (‘One-page Protocol for Cloning Using CRISPR Cas9 Backbone Plasmids’ found at http://www.genome-engineering.org/crispr/; [96]). Pronuclear injection of 2.5ng/μl of each construct into B6SJLF1/J x B6SJLF1/J zygotes (The Jackson Laboratory) with transfer to Swiss Webster (The Jackson Laboratory) pseudopregnant females was performed in house. A similar strategy was used to create the Wnt4-ΔDE mouse (chr4:137216986–137217756). The CRISPR Design Tool (crispr.mit.edu) was utilized to identify optimal gRNAs flanking the enhancer (5’ gRNA: aggctgacaagcgaagttac, chr4:137216986–137217008; 3’ gRNA: atgtcggttgattaataatc, chr4: 137217756–137217778). The following primers were used to generate complexes for in vitro transcription of the gRNAs using the MEGAshortscript T7 Transcription Kit (Ambion):

Six2-DE 5’ gRNA F: AATAATACGACTCACTATAA GGCTGACAAGCGAAGTTACGTT
TTAGAGC TAGAAATAGC,
Six2-DE 3’ gRNA F: AATAATACGACTCACTATAATGTCGGTTGATTAATAATCGTT
TTAGAGCTA GAAATAGC,
Wnt4-DE 5’ gRNA F:AATAATACGACTCACTATAAGGCTGACAAGCGAAGTTACG
TTTTAGAGC TAGAAATAGC,
Wnt4-DE 3’ gRNA F: AATAATACGACTCACTATAAGGCTGACAAGCGAAGTTACG
TTTTAGAGCTA GAAATAGC,

Common R: AAAAGCACCGACTCAGGTGCCCCACTTTTTCAAGTTGATAACCGACTAG
CTTTATTTAATCTGTCTTCTAGCTCTAAAC.

Cytoplasmic injection of 100ng of each gRNA and 50ng of Cas9 mRNA (TriLink Biotech) into B6SJLF1/J x B6SJLF1/J zygotes with transfer to Swiss Webster pseudopregnant females was performed in house. To establish lines, F0 animals were born and genotyped to confirm presence of the deletion. One animal carrying a deletion from chr17:85747284–85749542 for the Six2-DE and a deletion of chr4:137216991–137217771 for the Wnt4-DE (each confirmed by Sanger sequencing of PCR product) was mated to C57BL/6J (The Jackson Laboratories) to establish the line. Genotyping primers:

Six2-DE flank F: GCAGAATGAGATTCTGACA GCCCAG
Six2-DE flank R: CAAGGATGTCTTTTGTTGTCCTTAGTGAG
Six2-DE internal F: GAGGCCCATAAATAGAAGCTGGGACG
Six2-DE internal R: CTCCAGTGCAGCATACACTCTTTACTG
Wnt4-DE flank F: AAGCCATGAGGAATAAGAGAAGGGTT
Wnt4-DE flank R: TTCTCAACCCCAAACCAACC
Wnt4-DE internal F: AGTGTGAGGACCTGTGTAGC
Wnt4-DE internal R: GTGGATGCTGCTTTATGGGGT
Six2TGCTg or Cited1-nuc-TagRFP-Tg lines utilized for FACS were previously described [69] (http://www.gudmap.org/index.html). Six2GCE, Six2CE, and Wnt4GCE mice were previously described [69]. The Br mutant mouse and mapping are previously described [97] and experimental protocols were approved by the University of Hawaii Institutional Animal Care and Use Committee.

ChIP-seq

Wildtype or transgenic kidneys were utilized for ChIP. Hoxd11-BFg/+ and Osr1-BFg/+ kidneys were sorted out prior to ChIP by visualizing GFP+ kidneys. ChIP from E16.5 whole kidneys
was carried out as previously described [3]. Nephron progenitor purification by MACS prior to ChIP was carried out is described in Brown et al., 2015 [45].

4C-seq

Briefly, E16.5 mice kidney cortex cells were dissociated with collagenase/pancreatin as described in Brown et al., 2015 [45], fixed with 1% formaldehyde for 10 min in room temperature in AutoMACS running buffer. The fixed cells were then processed following published protocols [74] to generate 4C libraries. Dpn II and NlaIII were used in the first and second restriction enzyme digests, respectively. In order to create a view point from Six2-DE, the primers used in 4C-PCR:

Six2DE DpnII reading F: tccctacagctttccgatctGTTCGAAAGAGCCGTTGATAGGGA
Six2DE NlaIII noReading R: gtgactgagttcagacgtgtgtcttcgatcGGGGCCCATAAATCGTGATTCAAC

The capitalized letters indicate the complimentary sequences to the genomic view point and the remainder illumina adaptor sequences. The 4C-libraries were then indexed by PCR and sequenced by NextSeq500. 4C-seq data were analyzed following the workflow provided by 4C-ker [98]. Briefly, the data was mapped to a reduced genome containing 25 bp regions from DpnII sites genome-wide and were subsequently quantified in 3 kb windows to show enrichment. The 4C-seq data is deposited on GEO (GSE90017).

ChIP-seq data analysis

All ChIP-seq sequences were mapped to the mouse reference genome (mm10) using Novoalign software (Novocraft; parameters: single-end reads trimming 10 bp, polyclonal read filter: 7,10 0.4,2, maximum alignment score acceptable: 120). Mapped ChIP-seq and input data were analyzed using QuEST 2.4 software [99] using a “transcription factor” setting. The false discovery rate (FDR) for detecting the bound regions was evaluated by allocating the same number of mapped reads from a separate mouse input library and performing QuEST analysis using the same parameters. We generated multiple replicates for each ChIP-seq experiment (except Hoxd11 due to technical issues), and used the replicate containing the most peaks using the same peak calling parameters for downstream analyses (see S1G and S3A Figs, G for peak overlap between replicates. The smaller replicates all had >50% overlap with the larger replicate). To account for the innate differences between transcription factors in binding to the genome, we used different parameters in calling peaks of different transcription factors. We used high ratio of peaks with motif and low variability of motif-peak distances as our standard in determining the validity of a data set. See S7 Table for ChIP-seq data information and parameters in peak calling.

In this paper, overlapping sites are defined as those with ChIP-seq peak center distance <150 bp from each other unless otherwise specified. To evaluate the statistical significance of two sets of peaks overlapping each other (Fig 2A), we performed binomial test with the null hypothesis that peaks fall randomly into open chromatin regions in nephron progenitors. To determine the open chromatin regions in nephron progenitor, we performed ATAC-seq [100] in MACS-purified nephron progenitors [45]. We called ATAC-seq peaks with QuEST using the ‘transcription factor’ setting following threshold of fold enrichment > 10. Then we extended the ATAC-seq peak coordinates by 150 bp to both sides, resulting in a total size of accessible chromatin as 21856500 bp. This process is modeled as following:

\[ N_{A,B} \sim Binom(N_A, p_B) \]
where \( N_{A,B} \) is the number of peaks in set A that overlap with set B, and \( p_B \) is the probability of a randomly located peak overlapping with set B. Information on all ChIP-seq samples presented in the paper can be found in S7 Table. The ChIP-seq and ATAC-seq data is accessible from GEO (GSE90017).

### DNA sequence motif analysis

All de novo motif discovery work was carried out using MEME (Multiple Em for Motif Elicitation, [101]). To find the most enriched motifs for each transcription factor, MEME was run on a pool of 100 bp sequences around the predicted peak center for the top 1000 ChIP-seq peaks called from each data set (or all peaks if number of the total peaks is less than 1000). The locations of motif within 300 bp of peaks are found by FIMO (Find Individual Motif Occurrences, [102]) with data set-specific p-value threshold setting (Six2 motif: 2e-4; Hoxd11 motif: 2e-4; Osr1 motif: 2e-4; Wt1 motif: 2e-5; bHLH motif: 2e-5). We model the appearance of a motif near a set of peaks as following:

\[
N_{A,m} \sim Binom(N_A, p_m)
\]

\[
p_m = \frac{N_m}{300 \cdot N_A}
\]

where \( N_{A,m} \) is the number of motif \( m \) found in +/-150 bp of the peak set \( A \); \( p_m \) is the probability of finding such motif near a matched random set with the same number of peaks in \( A \). Since promoter regions of genes are GC-rich, resulting higher rate of discovering GC-rich motif (Wt1, Osr1 and bHLH) than TA-rich motif (Six2, Hoxd11) in promoter regions. To address this bias, we created the matched random set of peaks by picking genomic coordinates with the same distances to the nearest TSS as the observed peaks set, but with permuted nearest genes. We then screen the matched random peaks for the same motif to obtain \( N_m \).

### Genomic Regions Enrichment of Annotations Tool (GREAT) analysis

GREAT GO analysis was performed utilizing the online GREAT program, version 2.0 [43]. Gene regulatory domains utilized for region annotation were defined as minimum 5.0 kb upstream and 1.0 kb downstream of the TSS, and extended up to 500.0 kb to the nearest gene’s minimal regulatory domain (‘single nearest gene’ option). GO Biological Processes annotations were assessed for each peak category.

### Region-based enrichment analysis

To infer the statistical significance of a set of ChIP-seq peaks found near a set of genes (Fig 3), we performed the following analysis. We assigned +/-500 kb from TSS of a gene as its ‘regulatory domain’. We then calculated the probability of a selected set of ChIP-seq peaks falling into the merged regulatory domains of a list of selected genes. This is modeled by a binomial process with the null hypothesis that each peak falls uniformly throughout the genome.

\[
N_{A,s} \sim Binom(N_A, p_s)
\]
\[ p_x = \frac{1}{\text{Genome Size}} \sum_{i=1}^{\text{Size}(RR_i)} \]

\( N_{A,x} \) is the number of peaks in set \( A \) that fall into the regulatory domains defined by the gene list \( G_x \). \( p_x \) is the probability of a peak falling into regulatory domains defined by the gene list \( G_x \), assuming the peak randomly falling on any position in the genome. \( \text{Size}(RR_i) \) is size of a regulatory region after resolving the overlap with any nearby regulatory regions.

We found that each observed set of peaks fall into any random sets of regulatory domains more often than expected, which is not observed when doing the same experiment using random sets of genomic coordinates. To control this background over-representation, we obtained a background enrichment ratio over random sets of regulatory domains by

\[ r_{A,x} = \frac{1}{n} \sum_{i=1}^{n} N_{A,xr_i} / \left( N_{A} p_{x r_i} \right) \]

where \( r_{A,x} \) is the normalizing factor for a specific set of peaks \( A \). \( N_{A,xr_i} \) is the number of peaks from set \( A \) that fall into a the regulatory domain defined by a random list of genes \( G_x \) which contains the same number of genes as \( G_x \). Therefore, the final binomial model we used in the analysis is

\[ N_{A,x} \sim \text{Binom}(N_{A}, p_x r_{A,x}) \]

**Fluorescence-activated cell sorting**

Cortical tissues of E16.5 or P2 kidneys from \( \text{Six2TGC}^{tg/+} \) or E16.5 \( \text{Cited1-nuc-TagRFP-T}^{tg/+} \) embryos were dissociated as described in Brown et al., 2015 [45]. The dissociated cells were resuspended in autoMACS buffer (Miltenyi Biotec) and passed through a 40 μm nylon filter to obtain single cells. The respective GFP+, GFP−, or RFP+ cells were then isolated with the BD FACS Aria II.

**RNA-seq analysis**

RNA was isolated from FACS isolated cells using the QIAGEN RNasy Micro Kit. RNA was submitted to the USC Epigenome Center for library preparation and sequencing on the Illumina HiSeq 2000. All RNA-seq reads were aligned to the mouse reference genome (mm10) using the TopHat2 [103]. Sequences have been deposited in GEO, accession number GSE90017. Quantification of RNA-seq reads to generate RPKM was performed by Partek Genomics Suite software, version 6.6 (St. Louis, MO, USA). TPM was calculated by dividing the RPKM by the mapping ratio of the library to exon regions of the genome. To identify genes differentially expressed in a cell type, we select those with a fold difference > 3, TPM > 5 and \( p \)-value < 0.05. Sample information can be found in S7 Table. A complete list of all annotated genes and their coordinating RNA-seq data can be found in S3 and S4 Tables, and coordinating ChIP-seq data can be found in S8 Table. Gene ontology analysis of gene lists was carried out by PANTHER [104]. For the gene set analysis in Fig 3D, we selected the enriched gene lists using the following metrics: nephron progenitor-enriched (TPM > 10 in E16.5 Six2GFP+ cells and fold change > 2 in E16.5 Six2GFP+ vs. Six2GFP− cells), self-renewing nephron progenitor-enriched (TPM > 10 in E16.5 Cited1RFP+ cells and fold change > 2 in E16.5 Cited1RFP+ vs. P2 Six2GFP+ cells) and differentiating nephron progenitor-enriched (TPM > 10 in P2 Six2GFP+ cells and fold change > 2 in P2 Six2GFP+ vs. E16.5 Cited1RFP+ cells). S5 and S6 Tables are pre-filtered to show the nephron progenitor-enriched genes only, but entire lists can be viewed by releasing the filter.
qPCR

qPCR reaction was performed with Luna Universal qPCR Master Mix Protocol (New England Biolabs) on a Roche LightCycler 96 System. The primers used in this paper includes:

- GAPDH F: AGGTCGGTGTGAACGGATTTG
- GAPDH R: TGTAGACCATGTAGTTGAGGTA
- Six2 F: CACCTCCACAAGAATGAAAGCG
- Six2 R: CTCCGCTCAGTGTAGTG
- Pax2 F: AAGCGCGAGTGATTG
- Pax2 R: CAGCCGAACATAGTGGGC
- Wnt4 F: AGACGTGCGAGAACTCAAAG
- Wnt4 R: GGAACTGTTATTCGACTCCT

**In situ hybridization**

In situ hybridizations were performed on frozen sections as previously described (https://www.gudmap.org/Research/Protocols/McMahon.html). The primer sequences used to generate Wnt4 probe template are:

- F: GAGAAACTCAAAGCGCTGATC
- R: TAATACGACTCACATAGGGGCTTTAGATGTCTTG

**Electrophoretic mobility shift assay (EMSA)**

EMSA was carried out using Glutathione S-transferase (GST)-tagged recombinant proteins purified from bacterial lysates. To produce the protein, bacterial expression constructs (pDEST15 backbone) were prepared using the Gateway system. BL21-AI One Shot (Life Technology) chemically competent cells were transformed and grown to OD600 = 0.6 before induction with 0.2% L- (+)-arabinose (Sigma) for 3 hrs at 37 °C. The bacteria pellets were resuspended in lysis buffer (20 mM Tris-HCl, 150 mM NaCl, 1% TritonX-100, 1x protease inhibitor, 5 mM DTT) and incubated with 1 mg/mL lysozyme (Sigma). The lysates were sonicated with Branson digital sonifier at 50% amplitude for 90 s. After sonication, supernatant of the lysates were incubated with 5mL glutathione-agarose beads (Sigma) per 1 L bacteria culture for 1 hr at 4°C. The beads were washed with 1% TritonX-100/PBS and eluted with elution buffer (20 mM Tris-HCl, 150 mM NaCl, 15 mg/mL (50 mM) reduced glutathione, 1x protease inhibitor). The eluted protein was concentrated to at least 10 mg/mL using Amicon Centrifugal Filter Unit with the right filter size. The concentrated protein was diluted with PBS and concentrated again to exchange buffer. To perform the EMSA experiments, the recombinant protein was incubated with biotinylated DNA probe for 30 min at room temperature, then the mixture was run through a native TBE gel. The gel was transferred to a nitrocellulose membrane, which was then illuminated using the LightShift Chemiluminescent EMSA Kit (Pierce). The sequences of DNA probes can be found in S2 Fig.

**Immunoprecipitations**

Nuclear lysates were prepared from E16.5 whole kidneys using the Nuclear Complex Co-IP Kit (Active Motif). Normal rabbit IgG or Six2 (Proteintech, 11562-1-AP) antibodies were crosslinked with dimethyl pimelimidate to Dynabeads Protein G (Thermo Fisher Scientific) using the Protein A/G SpinTrap Buffer Kit (GE Healthcare). Nuclear extracts were incubated overnight with beads at 4°C. Samples were washed 5x with TBS+0.1% Triton X-100, and proteins subsequently eluted with 0.1M Glycine-HCl, pH 2.9. Samples were run on a 10% SDS-PAGE gel, transferred to nitrocellulose, and subjected to standard Western blotting.
protocols using Six2 (Proteintech), Hoxd11 (Abcam, ab60715), or Wt1 (Santa Cruz, sc-192) antibodies.

**Immunofluorescence**

Kidneys were isolated at the appropriate stage and fixed in 4% PFA for 1 hour. Cryosections were immunostained as previously described [28]. Antibodies used include Six2 (Proteintech, 11562-1-AP), FLAG (Sigma, F1804), Wt1 (Abcam, ab89901), pan-cytokeratin (Sigma, C2931), Pax8 (Abcam, ab13611), Ecad (Sigma, U3254), Six3 (Rockland, 200-201-A26S), and LTL-FITC (Vector Labs, FL-1321). Images were acquired on a Nikon Eclipse 90i epi-fluorescent microscope or Zeiss LSM 780 inverted confocal microscope.

**Br sequencing and mapping**

Purified genomic DNA from one wildtype and two Br/Br animals was sequenced on the Illumina Hi-seq 2000 and mapped to the mm10 genome using Bowtie2. Specific details of the mapping and allele characterization are described further in S1 Supporting Information. Sequences have been deposited in GEO, accession number GSE90017.

**Supporting information**

S1 Fig. Additional statistics of Six2, Hoxd11, and Osr1 ChIP-seq data. (A) (Top left) Box-plot shows distribution of QuEST scores of Six2-BF peaks overlapping with Six2-ab peaks and the peaks unique to Six2-BF. (Top right) Scatter plot shows correlation of ChIP-seq reads within 150 bp window of Six2-ab and Six2-BF ChIP-seq peaks. (Middle) Enrichment of the Six2 motif in shared versus Six2-ab unique peaks. (Bottom) GREAT gene ontology analysis of shared peaks and peaks unique to the Six2-ab ChIP-seq. (B) The most enriched motif identified from top Six2-FACS or Six2-ab peaks, its enrichment, and distribution. (C) Immunostaining of E15.5 kidneys for Streptavadin 568 on Hoxd11-BF kidneys to highlight the biotinylation of the BioTag component of the BioTagFLAG (BF). (D) Histograms shows distribution of Six2-BF (top), Hoxd11-BF (middle) and Osr1-BF (bottom) peaks’ distance to the nearest TSS. (E) Pie charts show distribution of Six2-BF (top), Hoxd11-BF (middle) and Osr1-BF (bottom) peaks in the genome. (F) Wt1 and bHLH motifs identified from Six2-BF, Hoxd11-BF or Osr1-BF peaks with MEME. Coverage and p-values were calculated with FIMO results. Smoothened histogram indicates distribution of motif-peak distance. (G) Venn diagrams show overlap of peaks identified from Six2-ab and Osr1-BF replicates ChIP-seq data sets. (EPS)

S2 Fig. Validation of ChIP-seq identified binding motifs by EMSA. (A) (1) Weblogo of Six2 motif and probe sequences, with red bases indicating mutation made in the corresponding probes. WT = Wildtype, M = mutant (2) EMSA result shows binding of recombinant GST-tagged Six2 protein (Six2) or GST control (G) to the indicated probes. (3) EMSA result shows effect of the GST or Six2 antibodies on Six2 protein binding to probes. (4) EMSA result shows binding of Six2 to the WT probe in the presence of the indicated competitor probe. (B) (1) Weblogo of Hoxd11 motif and probe sequences, with red bases indicating mutation made in the corresponding probes. (2) EMSA result shows binding of recombinant GST-tagged Hoxd11 protein (Hoxd11) or GST (G) to the indicated probes and effect of antibody on the binding. (3) EMSA result shows effect of competitors on Hoxd11 protein binding to the probe. (4) Weblogo of published PBM Hoxd11 motif. (C) (1) Weblogo of Osr1 motif and probe sequences, with red bases indicating mutation made in the corresponding probes. UP = UniProbe (PBM) motif, O2 = Osr2 motif [S1]. (2) EMSA result shows binding of recombinant

PLOS Genetics | https://doi.org/10.1371/journal.pgen.1007181 January 29, 2018 28 / 37
GST-tagged Osr1 protein (O) or GST control (G) to the indicated probes. W = water control. (3) EMSA result shows effect of antibody on protein binding to the indicated probe. (4) EMSA result shows effect of competitors on Osr1 binding to the indicated probe. (5) The published Osr1 motif.

EPS

S3 Fig. ChIP-seq reveals Wt1-mediated regulatory programs in the developing kidney. (A) Venn diagrams show overlap of (left) Wt1-kidney (whole kidney) replicate ChIP-seq peaks, (right) Wt1-NP (nephron progenitor) replicate peaks. (B) From left to right: the number of peaks from Wt1-kidney (top) or Wt1-NP (bottom) ChIP-seq, the most enriched motif identified from the top 1,000 peaks with MEME (using +/- 50 bp window), coverage, p-value, predicted transcription factor (TF) bound, and histogram showing distribution of motif relative to the peak center (Gaussian kernel smoothening was applied to reveal the trend, green curve). (C) Histograms show distribution of Wt1-NP peaks’ distance to the nearest TSS using both the ‘single nearest gene’ and ‘basal plus extension’ parameters in GREAT. (D) Pie chart shows distribution of Wt1-NP peaks in the genome. (E) Functional annotation of Wt1-NP peaks using GREAT. (F) From left to right: Venn diagram shows overlap of Wt1-kidney and Wt1-NP peaks, Venn diagram shows overlap target genes of Wt1-kidney-unique or shared peaks with Wt1-NP that are associated with the Gene Ontology term ‘nephron development’, selected genes from the indicated part of the diagram. (G) Venn diagram show overlap of the CTCF-NP replicate peaks. (H) Similar as (B), the motif information of the CTCF-NP ChIP-seq dataset.

EPS

S4 Fig. E18.5 phenotypes of Six2^{ΔDE/GCE} compared to Six2^{GCE/GCE} mutants. (A) Brightfield images of E18.5 kidneys from Six2^{GCE/GCE} mutants and compound heterozygous Six2^{ΔDE/GCE} compared to wildtype and single heterozygous littermates. (B) Samples from Six2^{GCE/GCE} were compared to Six2^{ΔDE/GCE} collected at E18.5 and stained for Wt1, LTL, and cytokeratin (CK).

EPS

S5 Fig. Localization of the predicted topologically associating domains around Six2 and Six3 and further characterization of the Br allele. (A) Hi-C heatmap from Dixon et al. showing the chromatin interactions and predicted topologically associating domains (TADs) surrounding the Six2 and Six3 loci, which are boxed in [70]. (B) Genomic view of the inverted region in Br allele, with Six2 ChIP-seq, CTCF-NP ChIP-seq, and 4C-seq data tracks. Pink highlighted region is the inverted region. The dashed square indicates predicted TAD boundary from Dixon et al. [70]. Green arrows point to the 4C-seq peak near the Six2 TSS which is reduced in the Br/+ kidneys and the 4C-seq peak near the Six3 TSS which is gained in Br/+ kidneys. Gray boxes represent the zoomed views of these regions to the right. (C) Schematic of the wildtype (WT) and Br alleles with red boxes to indicate primer loci used for PCR. (D) PCR results confirming the appropriate wildtype and mutant Br products for each of 3 wildtype and 2 Br/Br samples. (-) = No DNA control. (E) Wholemount in situ hybridization for Six3 on E11.5 embryos of the indicated Br genotypes. Arrows highlight the lens expression of Six3 and its loss in the Br mutant. (F) Immunostaining for Six2 and Six3 in the E14.5 cranial base of wild type and Br mutants. DAPI (nuclei) is shown in red.

EPS

S1 Table. Regulatory hotspots in nephron progenitors. Genomic coordinates of regulatory hotspots as identified by co-binding of Six2, Hoxd11, Osr1, and Wt1. Coordinates are listed for each transcription factor bound peak.

(XLSX)
S2 Table. Core targets and gene expression in the developing kidney. Gene expression of core targets and listing of all target-associated peaks.
(XLSX)

S3 Table. Expression of genes in Six2+ and Six2- fractions of the kidney cortex. Results from RNA-seq of E16.5Six2+ (GFP+) vs E16.5Six2- (GFP-) FAC-sorted cells of the kidney cortex.
(XLSX)

S4 Table. Expression of genes enriched in E16.5 Cited1+ and P2 Six2+ cells of the kidney. Results from RNA-seq of uncommitted (E16.5 Cited1+, RFP+) vs differentiating (P2 Six2+, GFP+) FAC-sorted nephron progenitors.
(XLSX)

S5 Table. Putative targets of two and three factor unique regulation. Targets, their RNA-seq expression, and associated peaks. Individual sheets are labeled for each two or three factor combination. Combinations of interest were identified from Fig 3D where they showed an enrichment over the whole transcriptome for nephron progenitor specific targets.
(XLSX)

S6 Table. Putative targets of single factor unique regulation. Targets, their RNA-seq expression, and associated peaks. Individual sheets are labeled for each unique factor. Targets unique to Six2, or any of the other factors independent of Six2.
(XLSX)

S7 Table. Sample information for ChIP-seq and RNA-seq data.
(XLSX)

S8 Table. All annotated genes and their associated RNA-seq and ChIP-seq data.
(XLSX)

S1 Supporting Information. Supplemental materials and methods and references.
(DOCX)

Acknowledgments
We would like to thank Dr. Zoia Stoytcheva at the University of Hawaii for technical assistance with the Br mice. We would also like to thank Tristin Liu at University of California, San Diego for technical guidance and discussion of generating 4C-seq data. We thank all members of the McMahon Lab for helpful discussions.

Author Contributions
Conceptualization: Lori L. O’Brien, Qiuyu Guo, Anton Valouev, Andrew P. McMahon.
Data curation: Qiuyu Guo.
Formal analysis: Lori L. O’Brien, Qiuyu Guo, Emad Bahrami-Samani, Kevin A. Peterson, Ramya Raviram, Bing Ren, Andrew D. Smith, Anton Valouev, Andrew P. McMahon.
Funding acquisition: Andrew P. McMahon.
Investigation: Lori L. O’Brien, Qiuyu Guo, Joo-Seop Park, Sean M. Hasso, Young-Jin Lee, Alan Fang, Albert D. Kim, Jinjin Guo.
Resources: Trudy M. Hong, Scott Lozanoff, Ben Fogelgren.
Software: Qiuyu Guo, Emad Bahrami-Samani, Anton Valouev.
Supervision: Lori L. O’Brien, Andrew P. McMahon.
Validation: Lori L. O’Brien.
Visualization: Lori L. O’Brien, Qiuyu Guo, Emad Bahrami-Samani, Anton Valouev.
Writing – original draft: Lori L. O’Brien, Qiuyu Guo, Andrew P. McMahon.
Writing – review & editing: Lori L. O’Brien, Qiuyu Guo, Andrew P. McMahon.

References
1. Bertram JF, Douglas-Denton RN, Diouf B, Hughson MD, Hoy WE. Human nephron number: implications for health and disease. Pediatr Nephrol. 2011; 26(9):1529–33. Epub 2011/05/24. https://doi.org/10.1007/s00467-011-1843-8 PMID: 21604189.

2. Self M, Lagutin OV, Bowling B, Hendrix J, Cai Y, Dressler GR, et al. Six2 is required for suppression of nephrogenesis and progenitor renewal in the developing kidney. Embo j. 2006; 25(21):5214–28. Epub 2006/10/13. https://doi.org/10.1038/sj.emboj.7601381 PMID: 17036046; PubMed Central PMCID: PMC3669216.

3. O’Brien LL, Guo Q, Lee Y, Tran T, Benazet JD, Whitney PH, et al. Differential regulation of mouse and human nephron progenitors by the Six family of transcriptional regulators. Development. 2016; 143 (4):595–608. Epub 2016/02/12. https://doi.org/10.1242/dev.127175 PMID: 26884396; PubMed Central PMCID: PMC4676318.

4. Wegert J, Ishaque N, Vardapour R, Georg C, Gu Z, Bieg M, et al. Mutations in the SIX1/2 pathway and the DROSHA/DGCR8 miRNA microprocessor complex underlie high-risk blastemal type Wilms tumors. Cancer Cell. 2015; 27(2):298–311. Epub 2015/02/12. https://doi.org/10.1016/j.ccel.2015.01.002 PMID: 25670083.

5. Walz AL, Ooms A, Gadd S, Gerhard DS, Smith MA, Guidry Auvil JM, et al. Recurrent DGCR8, DROSHA, and SIX homeodomain mutations in favorable histology Wilms tumors. Cancer Cell. 2015; 27(2):286–97. Epub 2015/02/12. https://doi.org/10.1016/j.ccel.2015.01.003 PMID: 25670082; PubMed Central PMCID: PMC4800737.

6. Weber S, Taylor JC, Winyard P, Baker KF, Sullivan-Brown J, Schild R, et al. SIX2 and BMP4 mutations associate with anomalous kidney development. J Am Soc Nephrol. 2008; 19(5):891–903. Epub 2008/02/29. https://doi.org/10.1681/ASN.2006111282 PMID: 18305125; PubMed Central PMCID: PMC2386720.

7. Bertram JF, Goldstein SL, Pape L, Schaefer F, Shroff RC, Warady BA. Kidney disease in children: latest advances and remaining challenges. Nat Rev Nephrol. 2016; 12(3):182–91. Epub 2016/02/03. https://doi.org/10.1038/nrneph.2015.219 PMID: 26831913.

8. Takasato M, Er PX, Chiu HS, Maier B, Bailie GJ, Ferguson C, et al. Kidney organoids from human iPS cells contain multiple lineages and model human nephrogenesis. Nature. 2015. England2015. p. 564–8. https://doi.org/10.1038/nature15695 PMID: 26444236.

9. Taguchi A, Kaku Y, Ohmori T, Sharmin S, Ogawa M, Sasaki H, et al. Redefining the in vivo origin of metanephric nephron progenitors enables generation of complex kidney structures from pluripotent stem cells. Cell Stem Cell. 2014; 14(1):53–67. Epub 2013/12/18. https://doi.org/10.1016/j.stem.2013.11.010 PMID: 24332837.

10. Morizane R, Lam AQ, Freedman BS, Kishi S, Valerius MT, Bonventre JV. Nephron organoids derived from human pluripotent stem cells model kidney development and injury. Nat Biotechnol. 2015; 33 (11):1193–200. Epub 2015/10/13. https://doi.org/10.1038/nbt.3392 PMID: 26458176; PubMed Central PMCID: PMC4747656.

11. Patterson LT, Pembaur M, Potter SS. Hoxa11 and Hoxd11 regulate branching morphogenesis of the ureteric bud in the developing kidney. Development. 2001; 128(11):2153–61. Epub 2001/08/09. PMID: 11493536.

12. Wellik DM, Hawkes PJ, Capecchi MR. Hox11 paralogous genes are essential for metanephric kidney induction. Genes Dev. 2002; 16(11):1423–32. Epub 2002/06/07. https://doi.org/10.1101/gad.953702 PMID: 12051019; PubMed Central PMCID: PMC953702.

13. Mugford JW, Sipila P, Kobayashi A, Behringer RR, McMahon AP. Hoxd11 specifies a program of metanephric kidney development within the intermediate mesoderm of the mouse embryo. Dev Biol.
14. Wang Q, Lan Y, Cho ES, Maltby KM, Jiang R. Odd-skipped related 1 (Odd 1) is an essential regulator of heart and urogenital development. Dev Biol. 2005; 288(2):582–94. Epub 2005/10/15. https://doi.org/10.1016/j.ydbio.2005.09.024 PMID: 16223478; PubMed Central PMCID: PMCPMC3869089.

15. James RG, Kamei CN, Wang Q, Jiang R, Schultheiss TM. Odd-skipped related 1 is required for development of the metanephric kidney and regulates formation and differentiation of kidney precursor cells. Development. 2006; 133(15):2995–3004. Epub 2006/06/23. https://doi.org/10.1242/dev.02442 PMID: 16790474.

16. Mugford JW, Sipila P, McMahon JA, McMahon AP. Osr1 expression demarcates a multipotent population of intermediate mesoderm that undergoes progressive restriction to an Osr1-dependent nephron progenitor compartment within the mammalian kidney. Dev Biol. 2008; 324(1):88–98. Epub 2008/10/07. https://doi.org/10.1016/j.ydbio.2008.09.010 PMID: 18835385; PubMed Central PMCID: PMCPMC2642884.

17. Xu J, Liu H, Park JS, Lan Y, Jiang R. Osr1 acts downstream of and interacts synergistically with Six2 to maintain nephron progenitor cells during kidney organogenesis. Development. 2014; 141(7):1442–52. https://doi.org/10.1242/dev.113283 PMID: 24598167.

18. Kreidberg JA, Sariola H, Loring JM, Maeda M, Pelletier J, Houseman D, et al. WT-1 is required for early kidney development. Cell. 1993; 74(4):679–91. Epub 1993/08/27. PMID: 8395349.

19. Nishinakamura R, Matsumoto Y, Nakao K, Nakamura K, Sato A, Copeland NG, et al. Murine homolog of SALL1 is essential for ureteric bud invasion in kidney development. Development. 2001; 128(16):3105–15. Epub 2001/11/02. PMID: 11688560.

20. Ohmori T, Tanigawa S, Kaku Y, Fujimura S, Nishinakamura R. Sall1 in renal stromal progenitors non-cell autonomously restricts the excessive expansion of nephron progenitors. Sci Rep. 2015; 5:15676. Epub 2015/10/30. https://doi.org/10.1038/srep15676 PMID: 26511275; PubMed Central PMCID: PMCPMC4625151.

21. Xu PX, Adams J, Peters H, Brown MC, Heaney S, Maas R. Eya1-deficient mice lack ears and kidneys and show abnormal apoptosis of organ primordia. Nat Genet. 1999; 23(1):113–7. Epub 1999/09/02. https://doi.org/10.1038/12722 PMID: 10471511.

22. Sajithlal G, Zou D, Silvius D, Xu PX. Eya 1 acts as a critical regulator for specifying the metanephric mesenchyme. Dev Biol. 2005; 284(2):323–36. Epub 2005/07/16. https://doi.org/10.1016/j.ydbio.2005.05.029 PMID: 16018995; PubMed Central PMCID: PMCPMC3876995.

23. Torres M, Gomez-Pardo E, Dressier GR, Gruss P. Pax-2 controls multiple steps of urogenital development. Development. 1995; 121(12):4057–65. Epub 1995/12/01. PMID: 8575306.

24. Bouchard M, Souabni A, Mandler M, Neubuser A, Busslinger M. Nephric lineage specification by Pax2 and Pax8. Genes Dev. 2002; 16(22):2958–70. Epub 2002/11/19. https://doi.org/10.1101/gad.240102 PMID: 12435636; PubMed Central PMCID: PMCPMC187478.

25. Xu PX, Zheng W, Huang L, Maire P, Laclef C, Silvius D. Six1 is required for the early organogenesis of mammalian kidney. Development. 2003; 130(14):3085–94. Epub 2003/06/05. PMID: 12783782; PubMed Central PMCID: PMCPMC3872112.

26. Li X, Oghi KA, Zhang J, Krones A, Bush KT, Glass CK, et al. Eya protein phosphatase activity regulates Six1-Dach-Eya transcriptional effects in mammalian organogenesis. Nature. 2003; 426(6964):247–54. Epub 2003/11/29. https://doi.org/10.1038/nature02083 PMID: 14628042.

27. Xu J, Xu PX. Eya-six are necessary for survival of nephrogenic cord progenitors and inducing nephric duct development before ureteric bud formation. Dev Dyn. 2015; 244(7):866–73. Epub 2015/04/24. https://doi.org/10.1002/dvdy.24282 PMID: 25903664; PubMed Central PMCID: PMCPMC485534.
31. Motamedi FJ, Badro DA, Clarkson M, Lecca MR, Bradford ST, Buske FA, et al. WT1 controls antagonistic FGF and BMP-pSMAD pathways in early renal progenitors. Nat Commun. 2014; 5:4444. Epub 2014/07/18. https://doi.org/10.1038/ncomms5444 PMID: 25031030.

32. Kann M, Ettou S, Jung YL, Lenz MO, Taglimenti ME, Park PJ, et al. Genome-Wide Analysis of Wilms’ Tumor 1-Controlled Gene Expression in Podocytes Reveals Key Regulatory Mechanisms. J Am Soc Nephrol. 2015; 26(9):2097–104. Epub 2015/02/01. https://doi.org/10.1681/ASN.2014090940 PMID: 25636411; PubMed Central PMCID: PMC4552122.

33. Boyer LA, Lee TI, Cole MF, Johnstone SE, Levine SS, Zucker JP, et al. Core transcriptional regulatory circuitry in human embryonic stem cells. Cell. 2005; 122(6):947–56. Epub 2005/09/13. https://doi.org/10.1016/j.cell.2005.08.020 PMID: 16153702; PubMed Central PMCID: PMC3606442.

34. Mazzoni EO, Mahony S, Iacovino M, Morrison CA, Mountoufaris G, Closser M, et al. Embryonic stem cell-based mapping of developmental transcriptional programs. Nat Methods. 2011; 8(12):1056–8. https://doi.org/10.1038/nmeth.1775 PMID: 22081127; PubMed Central PMCID: PMC3228994.

35. Essafi A, Webb A, Berry RL, Slight J, Burn SF, Spraggon L, et al. A wt1-controlled chromatin switching machinery underpins tissue-specific wnt4 activation and repression. Dev Cell. 2011; 21(3):559–74. https://doi.org/10.1016/j.devcel.2011.04.002 PMID: 21734141.

36. Gerstein MB, Kundaje A, Hariharan M, Landt SG, Yan KK, Cheng C, et al. Architecture of the human regulatory network derived from ENCODE data. Nature. 2012; 489(7414):1–10. Epub 2012/09/08. https://doi.org/10.1038/nature11245 PMID: 22955619; PubMed Central PMCID: PMC4154057.

37. Balleseter B, Medina-Rivera A, Schmidt D, Gonzalez-Porta M, Carlucci M, Chen X, et al. Multi-species, multi-transcription factor binding highlights conserved control of tissue-specific biological pathways. Elife. 2014; 3:e02626. Epub 2014/10/04. https://doi.org/10.7554/eLife.02626 PMID: 25279814; PubMed Central PMCID: PMC4359374.

38. Wang J, Cantor AB, Orkin SH. Tandem affinity purification of protein complexes in mouse embryonic stem cells using in vivo biotinylation. Curr Protoc Stem Cell Biol. 2009; Chapter 1:Unit1B.5. Epub 2009/03/19. https://doi.org/10.1002/9780470151808.sc01b05s8 PMID: 19890324.

39. Zhang X, Peterson KA, Liu XS, McMahon AP, Ohba S. Gene regulatory networks mediating canonical Wnt signal-directed control of pluripotency and differentiation in embryonic stem cells. Stem Cells. 2013; 31(12):2667–79. https://doi.org/10.1002/stem.1371 PMID: 23505158.

40. Zinzen RP, Girardot C, Gagneur J, Braun M, Furlong EE. Combinatorial binding predicts spatio-temporal cis-regulatory activity. Nature. 2009; 462(7269):65–70. Epub 2009/11/06. https://doi.org/10.1038/nature08531 PMID: 19980324.

41. He A, Kong SW, Ma Q, Pu WT. Co-occupancy by multiple cardiac transcription factors identifies transcriptional enhancers active in heart. Proc Natl Acad Sci U S A. 2011; 108(14):5632–7. Epub 2011/03/19. https://doi.org/10.1073/pnas.1016959108 PMID: 21415370; PubMed Central PMCID: PMC3078411.

42. Hojo H, Ohba S, He X, Lai LP, McMahon AP. Sp7/Osterix Is Restricted to Bone-Forming Vertebrates where It Acts as a Dax Co-factor in Osteoblast Specification. Dev Cell. 2016; 37(3):238–53. https://doi.org/10.1016/j.devcel.2016.04.002 PMID: 27134141.

43. Boyer LA, Lee TI, Cole MF, Johnstone SE, Levine SS, Zucker JP, et al. Core transcriptional regulatory circuitry in human embryonic stem cells. Cell. 2005; 122(6):947–56. Epub 2005/09/13. https://doi.org/10.1016/j.cell.2005.08.020 PMID: 16153702; PubMed Central PMCID: PMC3604688.

44. McLean CY, Bristor D, Hillier M, Clarke SL, Schaar BT, Lowe CB, et al. GREAT improves functional interpretation of cis-regulatory regions. Nat Biotechnol. 2010; 28(5):495–501. Epub 2010/05/04. https://doi.org/10.1038/nbt.1630 PMID: 20436461; PubMed Central PMCID: PMC4840234.

45. Badis G, Berger MF, Philippakis AA, Talukder S, Gehlke AR, Jaeger SA, et al. Diversity and complexity in DNA recognition by transcription factors. Science. 2009; 324(5935):1720–3. Epub 2009/05/16. https://doi.org/10.1126/science.1162327 PMID: 19443739; PubMed Central PMCID: PMC2905877.

46. Brown AC, Muthukrishnan SD, Oxburgh L. A synthetic niche for nephron progenitor cells. Dev Cell. 2015; 34(2):229–41. Epub 2015/07/21. https://doi.org/10.1016/j.devcel.2015.06.021 PMID: 26190145; PubMed Central PMCID: PMC4519427.

47. Thurman RE, Rynes E, Humbert R, Vierstra J, Maurano MT, Haugen E, et al. The accessible chromatin landscape of the human genome. Nature. 2012; 489(7414):75–82. https://doi.org/10.1038/nature11232 PMID: 22955617.

48. Badis G, Berger MF, Philippakis AA, Talukder S, Gehlke AR, Jaeger SA, et al. Diversity and complexity in DNA recognition by transcription factors. Science. 2009; 324(5935):1720–3. Epub 2009/05/16. https://doi.org/10.1126/science.1162327 PMID: 19443739; PubMed Central PMCID: PMC2905877.
16. https://doi.org/10.1016/j.devcel.2012.04.018 PMID: 22698282; PubMed Central PMCID: PMCPMC3376351.

49. Narlis M, Grote D, Gaitan Y, Boualia SK, Bouchard M. Pax2 and pax8 regulate branching morphogenesis and nephron differentiation in the developing kidney. J Am Soc Nephrol. 2007; 18(4):1121–9. Epub 2007/02/23. https://doi.org/10.1681/ASN.2006070739 PMID: 17314325.

50. Yu J, Ershler M, Yu L, Wei M, Hackanson J, Yokohama A, et al. TSC-22 contributes to hematopoietic precursor cell proliferation and repopulation and is epigenetically silenced in large granular lymphocyte leukemia. Blood. 2009; 113(22):5558–67. https://doi.org/10.1182/blood-2009-02-205732 PMID: 19329776.

51. Granovs(150x699)y M, Fata J, Pawling J, Muller WJ, Khokha R. Suppression of tumor growth and metastasis in Mgt5-deficient mice. Nat Med. 2000; 6(3):306–12. Epub 2000/03/04. https://doi.org/10.1038/73163 PMID: 10700233.

52. Bouchard M, Pfeffer P, Busslinger M. Functional equivalence of the transcription factors Pax2 and Pax5 in mouse development. Development. 2000; 127(17):3703–13. Epub 2000/08/10. PMID: 10934015.

53. Huang J, Arsenault M, Kann M, Lopez-Mendez C, Saleh M, Wadowska D, et al. The transcription factor Sry-related HMG box-4 (SOX4) is required for normal renal development in vivo. Dev Dyn. 2013; 242(6):790–9. Epub 2013/04/06. https://doi.org/10.1002/dvdy.23971 PMID: 23595682.

54. Kann M, Bae E, Lenz MO, Li L, Trannguyen B, Schumacher VA, et al. WT1 targets Gas1 to maintain nephron progenitor cells by modulating FGF signals. Development. 2015; 142(7):1254–66. Epub 2015/03/26. https://doi.org/10.1242/dev.119735 PMID: 25804736; PubMed Central PMCID: PMCPMC4378252.

55. Piscione TD, Wu MY, Quaggin SE. Expression of Hairy/Enhancer of Split genes, Hes1 and Hes5, during murine nephron morphogenesis. Gene Expr Patterns. 2004; 4(6):707–11. Epub 2004/10/07. https://doi.org/10.1016/j.modgep.2004.04.007 PMID: 15465493.

56. Kobayashi A, Watanabe H, Sawada K, Nishikawa N, Nishimura H, et al. Identification of a multipotent self-renewing stromal progenitor population during mammalian kidney organogenesis. Stem Cell Reports. 2014; 3(6):1716–27. Epub 2014/11/02. https://doi.org/10.1016/j.stemcr.2014.08.008 PMID: 25358792; PubMed Central PMCID: PMCPMC4223698.

57. Majumdar A, Vainio S, Kispert A, McMahon J, McMahon AP. Wnt11 and Ret/Gdnf pathways cooperate in regulating ureteric branching during metanephric kidney development. Development. 2003; 130(14):3175–85. Epub 2003/06/05. PMID: 12783789.

58. Rumballe BA, Georgas KM, Combes AN, Ju AL, Gilbert T, Little MH. Nephron formation adopts a novel spatial topology at cessation of nephrogenesis. Dev Biol. 2011; 360(1):110–22. Epub 2011/10/04. https://doi.org/10.1016/j.ydbio.2011.09.011 PMID: 21963425.

59. Furushima K, Yamamoto A, Nagano T, Shibata M, Miyachi H, Abe T, et al. Mouse homologues of Shisa antagonistic to Wnt and Fgf signalings. Dev Biol. 306. United States2007. p. 480–92. https://doi.org/10.1016/j.ydbio.2007.03.028 PMID: 17481602.

60. Alpers CE, Hudkins KL, Ferguson M, Johnson RJ, Rutledge JC. Platelet-derived growth factor A-chain expression in developing and mature human kidneys and in Wilms’ tumour. Kidney Int. 48. United States1995. p. 146–54. PMID: 7564071.

61. Li X, Ponten A, Aase K, Karlsson L, Abramsson A, Uutela M, et al. PDGF-C expression in the developing and normal adult human kidney and in glomerular diseases. J Am Soc Nephrol. 2003; 14 (5):1145–53. Epub 2003/04/23. PMID: 12707365.

62. Eitner F, Ostendorf T, Kretzler M, Cohen CD, Eriksson U, Grone HJ, et al. PDGF-C expression in the developing and normal adult human kidney and in glomerular diseases. J Am Soc Nephrol. 2003; 14 (5):1145–53. Epub 2003/04/23. PMID: 12707365.

63. Alpers CE, Hudkins KL, Ferguson M, Johnson RJ, Rutledge JC. Platelet-derived growth factor A-chain expression in developing and mature human kidneys and in Wilms’ tumour. Kidney Int. 48. United States1995. p. 146–54. PMID: 7564071.
66. Ding H, Wu X, Bostrom H, Kim I, Wong N, Tsoi B, et al. A specific requirement for PDGF-C in palate formation and PDGFR-alpha signaling. Nat Genet. 2004;36(6):1111–6. https://doi.org/10.1038/ng1415 PMID: 15361870

67. Harding SD, Armit C, Armstrong J, Brennan J, Cheng Y, Haggraty B, et al. The GUDMAP database—an online resource for genitourinary research. Development. 2011;138(13):2845–53. Epub 2011/06/10. https://doi.org/10.1242/dev.063594 PMID: 21652655; PubMed Central PMCID: PMC318593.

68. McMahon AP, Aronow BJ, Davidson DR, Davies JA, Gaido KW, Grimmond S, et al. GUDMAP: the genitourinary developmental molecular anatomy project. J Am Soc Nephrol. 2008;19(3):667–71. https://doi.org/10.1681 ASN.2007101078 PMID: 18287559

69. Kobayashi A, Valerius MT, Mugford JW, Carroll TJ, Self M, Oliver G, et al. Six2 defines and regulates a multipotent self-renewing nephron progenitor population throughout mammalian kidney development. Cell Stem Cell. 2008;3(2):169–81. Epub 2008/08/07. https://doi.org/10.1016/j.stem.2008.05.020 PMID: 18682239; PubMed Central PMCID: PMCPMC2561900.

70. Dixon JR, Selvaraj S, Yue F, Kim A, Li Y, Shen Y, et al. Topological domains in mammalian genomes identified by analysis of chromatin interactions. Nature. 2012;485(7398):376–80. Epub 2012/04/13. https://doi.org/10.1038/nature11082 PMID: 22495300; PubMed Central PMCID: PMCPMC3356448.

71. van de Werken HJ, Landan G, Holwerda SJ, Hoichman M, Klous P, Chachik R, et al. Robust 4C-seq data analysis to screen for regulatory DNA interactions. Nat Methods. 2012;9(9):969–72. https://doi.org/10.1038/nmeth.2173 PMID: 22961246

72. Gong KQ, Yallowitz AR, Sun H, Dressler GR, Wellik DM. A Hox-Eya-Pax complex regulates early kidney developmental gene expression. Mol Cell Biol. 2007;27(21):7661–8. Epub 2007/09/06. https://doi.org/10.1128/MCB.00465-07 PMID: 17795448; PubMed Central PMCID: PMCPMC2169072.

73. Xu J, Liu H, Chai OH, Lan Y, Jiang R. Osr1 Interacts Synergistically with Wt1 to Regulate Kidney Organogenesis. PLoS One. 2016;11(7):e0159597. https://doi.org/10.1371/journal.pone.0159597 PMID: 27442016.

74. Couillard M, Trudel M. C-myc as a modulator of renal stem/progenitor cell population. Dev Dyn. 2009;238(2):505–14. Epub 2009/01/24. https://doi.org/10.1002/dvdy.21841 PMID: 19161241.

75. Moser M, Binder O, Wu Y, Altschbaomo J, Ren R, Bode C, et al. BMPER, a novel endothelial cell precursor-derived protein, antagonizes bone morphogenetic protein signaling and endothelial cell differentiation. Mol Cell Biol. 2003;23(16):5664–79. Epub 2003/08/05. https://doi.org/10.1128/MCB.23.16.5664-5679.2003 PMID: 12897139; PubMed Central PMCID: PMCPMC166349.

76. Ikeya M, Kawada M, Kiyonari H, Sasai N, Nakao K, Furuta Y, et al. Essential pro-Bmp roles of crossveinless 2 in mouse organogenesis. Development. 2006;133(22):4463–73. Epub 2006/10/13. https://doi.org/10.1242/dev.02647 PMID: 17035289.
84. Nishinakamura R, Sakaguchi M. BMP signaling and its modifiers in kidney development. Pediatr Nephrol. 2014; 29(4):681–6. Epub 2013/11/13. https://doi.org/10.1007/s00467-013-2671-9 PMID: 24217785.

85. Tomizuka K, Horkoshi K, Kitada R, Sugawara Y, Iba Y, Kojima A, et al. R-spondin1 plays an essential role in ovarian development through positively regulating Wnt-4 signaling. Hum Mol Genet. 2008; 17 (9):1278–91. Epub 2008/02/06. https://doi.org/10.1093/hmg/ddn036 PMID: 18250097.

86. Diez-Roux G, Banfi S, Sultan M, Geffers L, Anand S, Rozado D, et al. A high-resolution anatomical atlas of the transcriptome in the mouse embryo. PLoS Biol. 2011; 9(1):e1000582. https://doi.org/10.1371/journal.pbio.1000582 PMID: 21267068.

87. Rahuel C, Filipe A, Ritie L, El Nemer W, Patey-Mariaud N, Eladari D, et al. Genetic inactivation of the laminin alpha5 chain receptor Lu/BCAM leads to kidney and intestinal abnormalities in the mouse. Am J Physiol Renal Physiol. 2008. United States. p. F393–406. https://doi.org/10.1152/ajprenal.00315.2007 PMID: 18032551.

88. Yoshida K, Furuya S, Osuka S, Mitoma J, Shinoda Y, Watanabe M, et al. Targeted disruption of the mouse 3-phosphoglycerate dehydrogenase gene causes severe neurodevelopmental defects and results in embryonic lethality. J Biol Chem. 279. United States. 2004. p. 3573–7. https://doi.org/10.1074/jbc.C300507200 PMID: 14645240.

89. Brodbeck S, Besenbeck B, Englert C. The transcription factor Six2 activates expression of the Gdnf gene as well as its own promoter. Mech Dev. 2004; 121(10):1211–22. Epub 2004/08/26. https://doi.org/10.1016/j.mod.2004.05.019 PMID: 15327782.

90. Zhou HY, Katsman Y, Dhaliwal NK, Davidson S, Macpherson NN, Sakthidevi M, et al. A Sox2 distal enhancer cluster regulates embryonic stem cell differentiation potential. Genes Dev. 2014; 28 (24):2699–711. Epub 2014/12/17. https://doi.org/10.1101/gad.248526.114 PMID: 25512558; PubMed Central PMCID: PMCPMC4265674.

91. Li Y, Rivera CM, Ishii H, Jin F, Selvaraj S, Lee AY, et al. CRISPR reveals a distal super-enhancer required for Sox2 expression in mouse embryonic stem cells. PLoS One. 2014; 9(12):e114485. Epub 2014/12/09. https://doi.org/10.1371/journal.pone.0114485 PMID: 25486255; PubMed Central PMCID: PMCPMC4259346.

92. Kumar JP. The sine oculis homeobox (SIX) family of transcription factors as regulators of development and disease. Cell Mol Life Sci. 2009; 66(4):565–83. Epub 2008/11/08. https://doi.org/10.1007/s00018-008-8335-4 PMID: 18989625; PubMed Central PMCID: PMCPMC2716997.

93. Lupianez DG, Kraft K, Heinrich V, Krawlitz P, Brancati F, Klopacki E, et al. Disruptions of topological chromatin domains cause pathogenic rewiring of gene-enhancer interactions. Cell. 2015; 161 (5):1012–25. Epub 2015/05/12. https://doi.org/10.1016/j.cell.2015.04.004 PMID: 25959774; PubMed Central PMCID: PMCPMC4791538.

94. Guo Y, Xu Q, Canzio D, Shou J, Li J, Gorkin DU, et al. CRISPR Inversion of CTCF Sites Alters Genome Topology and Enhancer/Promoter Function. Cell. 2015; 162(4):900–10. Epub 2015/08/16. https://doi.org/10.1016/j.cell.2015.07.038 PMID: 26276636; PubMed Central PMCID: PMCPMC4642453.

95. Oliver G, Wehr R, Jenkins NA, Copeland NG, Cheyette BN, Hartenstein V, et al. Homeobox genes and connective tissue patterning. Development. 1995; 121(3):693–705. Epub 1995/03/01. PMID: 7720577.

96. Cong L, Ran FA, Cox D, Lin S, Barretto R, Habib N, et al. Multiplex genome engineering using CRISPR/Cas systems. Science. 2013; 339(6121):819–23. Epub 2013/01/05. https://doi.org/10.1126/science.1231143 PMID: 23287718; PubMed Central PMCID: PMCPMC2716997.

97. Ma W, Lozanoff S. External craniofacial features, body size, and renal morphology in prenatal brachyrhine mice. Teratology. 1993; 47(4):321–32. Epub 1993/04/01. https://doi.org/10.1002/tera.1420470409 PMID: 8322226.

98. Ravid R, Rocha PP, Muller CL, Miraldi ER, Badri S, Fu Y, et al. 4C-ker: A Method to Reproducibly Identify Genome-Wide Interactions Captured by 4C-Seq Experiments. PLoS Comput Biol. 2016; 12 (3):e1004780. https://doi.org/10.1371/journal.pcbi.1004780 PMID: 26938081.

99. Valouev A, Johnson DS, Sundquist A, Medina C, Anton E, Batzoglou S, et al. Genome-wide analysis of transcription factor binding sites based on ChIP-Seq data. Nat Methods. 2008; 5(9):829–34. Epub 2009/01/23. https://doi.org/10.1038/nmeth.1246 PMID: 19160518; PubMed Central PMCID: PMCPMC2917543.

100. Buenrostro JD, Giresi PG, Zaba LC, Chang HY, Greenleaf WJ. Transposition of native chromatin for fast and sensitive epigenomic profiling of open chromatin, DNA-binding proteins and nucleosome position. Nat Methods. 2013; 10(12):1213–8. Epub 2013/10/08. https://doi.org/10.1038/nmeth.2688 PubMed Central PMCID: PMCPMC3959825. PMID: 24097267.
101. Bailey TL, Williams N, Misleh C, Li WW. MEME: discovering and analyzing DNA and protein sequence motifs. Nucleic Acids Res. 2006; 34(Web Server issue):W369–73. Epub 2006/07/18. https://doi.org/10.1093/nar/gkl198 PMID: 16845028; PubMed Central PMCID: PMCPMC1538909.

102. Grant CE, Bailey TL, Noble WS. FIMO: scanning for occurrences of a given motif. Bioinformatics. 2011; 27(7):1017–8. Epub 2011/02/19. https://doi.org/10.1093/bioinformatics/btr064 PMID: 21330296; PubMed Central PMCID: PMCPMC3065696.

103. Trapnell C, Pachter L, Salzberg SL. TopHat: discovering splice junctions with RNA-Seq. Bioinformatics. 2009; 25(9):1105–11. https://doi.org/10.1093/bioinformatics/btp120 PMID: 19289445.

104. Mi H, Huang X, Muruganujan A, Tang H, Mills C, Kang D, et al. PANTHER version 11: expanded annotation data from Gene Ontology and Reactome pathways, and data analysis tool enhancements. Nucleic Acids Res. 2017; 45(D1):D183–d9. Epub 2016/12/03. https://doi.org/10.1093/nar/gkw1138 PMID: 27899595; PubMed Central PMCID: PMCPMC5210595.