SPIE Proceedings: Two decades of Exoplanetary Science with Adaptive Optics

Chauvin G., a, b

a Unidad Mixta Internacional Franco-Chilena de Astronomía, CNRS/INSU UMI 3386 and Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
b Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France

ABSTRACT

As astronomers, we are living an exciting time for what concerns the search for other worlds. Recent discoveries have already deeply impacted our vision of planetary formation and architectures. Future bio-signature discoveries will probably deeply impact our scientific and philosophical understanding of life formation and evolution. In that unique perspective, the role of observation is crucial to extend our understanding of the formation and physics of giant planets shaping planetary systems. With the development of high contrast imaging techniques and instruments over more than two decades, vast efforts have been devoted to detect and characterize lighter, cooler and closer companions to nearby stars, and ultimately image new planetary systems. Complementary to other planet-hunting techniques, this approach has opened a new astrophysical window to study the physical properties and the formation mechanisms of brown dwarfs and planets. I will briefly review the different observing techniques and strategies used, the main samples of targeted stars, the key discoveries and surveys, to finally address the main results obtained so far about the physics and the mechanisms of formation and evolution of young giant planets and planetary system architectures.

Keywords: Adaptive Optics - Direct Imaging - Exoplanets - Formation - Architecture - Physical Properties

1. INTRODUCTION

Today’s heritage in direct imaging (DI) of exoplanets is intimately connected to the pioneer work in the late 80’s and early 90’s for the development of Adaptive Optics (AO) system, infrared (IR) detectors, and coronographic techniques for the instrumentation of ground-based telescopes. The COME-ON AO prototype (that will later become the ESO3.6m/ADONIS instrument), the Johns Hopkins University AO Coronagraph, or the CFHT CIRCUS coronographic camera at CFHT, were precursor instruments that soon motivated the research and development of more sophisticated AO high-contrast imagers on 10m-class telescopes (PALAO-PHARO at Palomar, CIAO at Subaru, NIRC2 at Keck, NaCo at VLT, and NRI and NICI at Gemini), confirming that ground-based instrumentation had demonstrated performances that could compete with space and HST. Already at that time, following the discovery of the first brown dwarf GD 165 B, the power of combining high-angular resolution and high-contrast techniques was well envisioned for the discovery and characterization of substellar companions, including exoplanets, and protoplanetary and debris disks. The emblematic discoveries and images of Gl 229 B and β Pictoris shown in Fig. 1 simply supported it, and motivated it even more. Later-on, with the dawn of exoplanet discoveries in radial velocity in 1995, DI started to routinely exploit 10m-class telescopes in the early 2000s to slowly joined the small family of planet hunting techniques known nowadays with radial velocity, transit, µ-lensing and astrometry. Nowadays, DI currently brings a unique opportunity to explore the outer part of exoplanetary systems at more than 5-10 au to complete our view of planetary architectures, and to explore the properties of relatively cool giant planets. The exoplanet’s photons can indeed be spatially resolved and dispersed to probe the atmospheric properties of exoplanets (and brown dwarf companions). As today’s imaged exoplanets are young (because they are hotter, brighter, thus easier to detect than their older counterparts), their atmospheres show low-gravity features, as well as the presence of clouds, and non-equilibrium chemistry processes. These physical conditions are very different and complementary to the ones observed in

Further author information: E-mail: gael.chauvin@univ-grenoble-alpes.fr
the atmospheres of field brown dwarfs or irradiated inflated Hot Jupiters (studied in spectroscopy or with transit techniques like transmission and secondary-eclipse, respectively). Finally, DI enables to directly probe the presence of planets in their birth environment. Planet characteristics and disk spatial structures can then be linked to study the planet–disk interactions and the planetary system’s formation, evolution, and stability, which is a fundamental and inevitable path to understand the formation of smaller telluric planets with suitable conditions to host life.

2. TELESCOPE, INSTRUMENT, TECHNIQUES AND OBSERVING STRATEGIES

The success of DI relies on a sophisticated instrumentation designed to detect faint planetary signals angularly close to a bright star. A Jupiter-like planet (orbiting at 5 au) around a typical young, nearby star at 50 pc would lie at an angular separation of 100 mas setting the order of angular separation we aim at. The typical planet–star contrast are about $10^{-6}$ for a young Jupiter (today’s performances) and $10^{-8}$ for a mature Jupiter observed in emitted light. It goes down $10^{-9}$ for a super-Earth in reflected-light. From the recent discoveries of young, massive self-luminous giant planets like β Pic b (H-band contrast of $10^{-4}$ at 200-400 mas) with the first generation of planet imagers at Palomar, Subaru, Keck, VLT, and Gemini to the first images of an Exo-Earth with maybe an Extremely-Large Telescope (ELT), several orders of magnitudes in contrast and separation must be covered. Therefore, innovant technological developments are required to meet the ultimate goal of imaging Exo-Earths (including the construction of extremely large telescope and the ability of achieving high-quality wavefront control combined with ultimate coronographic and differential techniques). In that perspective, the second generation of planet imagers, like the Spectro-Polarimetric High-Contrast Exoplanet Resarch instrument (SPHERE), the Gemini Planet Imager (GPI), and the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument, aim at pushing high-contrast performances down to $10^{-6} - 10^{-7}$ at typical separation of 200 mas. They validate a dedicated instrumentation based on a 3-stages implementation design with: i) high angular resolution access, ii) stellar light attenuation using coronography, iii) speckle subtraction using differential imaging techniques. A fourth step can be added with the recent development of powerful post-processing tools (iv/) to optimize the stellar signal suppression. These instruments will undoubtedly serve as references and demonstrators for future telluric planet imagers of the ELTs, including the proposed PFI instrument for the TMT or EPICS for the European ELT.

From the ground, the atmosphere turbulence affects the light propagation and prevents large telescopes from reaching a spatial resolution at the diffraction limit. Current Extreme-Adaptive Optics (XAO) systems enable to compensate for atmospheric, but also telescope and common path defects to routinely reach nowadays Strehl\(^*\) correction of 90% in H-band on bright ($V \leq 10$ mag) targets. The evolution of the AO-systems performances

\(^*\)The Strehl ratio can be defined as the ratio between the peak of the AO corrected PSF and the one of the ideal diffraction-limited Airy pattern.
over the past decades is remarkable as illustrated in Fig. 2. Current XAO-instruments like SPHERE, GPI, and SCExAO rely on high-order deformable mirror, fast-temporal sampling frequency at more than 1.0 kHz, spatial filtering of the wavefront before sensing, tuned calibrations of the instrumental defects and enhanced stability to limit low-order wavefront errors and alignment drift. The main specifications are driven by the need to get i/ optimal spatial sampling of the wavefront given the turbulence coherence length (sampling better than $D/r_0^2$; $r_0 \sim 20$ cm at Paranal) and ii/ optimal temporal sampling to beat the turbulence speed (coherence time $\tau_0$; 2-5 ms at Paranal) to minimize the errors of wavefront reconstruction and command. The correction stability in terms of Strehl-correction, control of low-order aberrations and pointing stability are essential to avoid any leakage or PSF deformation during the observation that would significantly degrade the planet detection performances.

With a stable and diffraction-limited Point-Spread Function (PSF), the motivation for coronography is relatively intuitive as it consists in blocking the light from the central star to search for fainter objects in the close stellar environment. Simple occcluding masks or classical Lyot coronographs (CLC) have been massively used in the past years on high-contrast imagers (see Table 2) to essentially: i/ reduce by a typical factor of $\sim 100$ the intensity of the central star diffracted-limited core and avoid any saturation effects, ii/ reduce the intensity of the PSF wings without canceling the off-axis planetary signal, iii/ improve the observing efficiency by reducing overheads, and iv/ reduce the total read-out noise. Classical and more recent apodized version of the Lyot coronagraph are typically limited to $3-4\lambda/D$ inner working angle (IWA)†, mostly because they rely on amplitude manipulation to attenuate starlight diffraction, covering a large area of the PSF at the coronagraph plane. With the improvement of instrumental stability achieved with the new generation of planet imagers, new concepts have emerged, particularly to access smaller inner working angles down to $\lambda/D$ (see apodized vortex and phase-induced amplitude coronographs). Pushing the instrumental limitation to access smaller IWA down to $\lambda/D$ or $2\lambda/D$ (40 to 80 mas for the VLT at $H$-band) can make a significant scientific breakthrough as the bulk of the giant planet population around young, nearby stars is predicted to be located beyond the ice-line at $\sim 3$ au (i.e. 100 mas for a star at 30 pc). Various concepts have been proposed and can be grouped in three main families: i/ phase masks (four-quadrant phase mask and vortex coronographs), ii/ phase/amplitude pupil apodization (phase-induced amplitude apodization and apodizing phase plates) + focal plane masks (phase and/or amplitude), and iii/ interferometers. Common to all these concepts is some sort of phase manipulation, either in the focal plane or in the pupil plane, or both. There is also a need to find a trade-off to mitigate effects of chromaticity, throughput, sensitivity to low-order aberrations considering ultimate contrast performances of each concept.

As shown in Fig. 3, boiling atmospheric speckles and instrumental quasi-statics speckles still remain an important source of limitation in the XAO coronographic PSF. Differential imaging techniques are nowadays a

---

†The IWA is universally defined as the 50% off-axis throughput point of a coronagraphic system
Figure 3. High angular resolution and high contrast implementation steps for AO imaging of exoplanets. Post-processing comes as a fourth step in the process for optimized PSF subtraction. NCPA refers to non-common path aberrations.
Table 1. List of first and second planet imagers on 10-m class telescopes. FQPM/8QPM: four-quadrant phase mask, 8 octant phase mask. OVC: optical vortex coronagraph. PIAAC: phase induced amplitude apodization. APP: apodizing phase plate.

| Telescope     | AO/Instruments        | 1st Light | λ (µm) | Coronographs | Diff. techniques |
|---------------|-----------------------|-----------|--------|--------------|-----------------|
| Palomar      | PALAO/PHARO           | 2000      | 1.1–2.5 | CLC/4QPM/OVC | ADI             |
| Subaru       | CIAO                  | 2000      | 0.9–5.0 | CLC          | ADI             |
| Keck         | NIRC2-OSIRIS-NIRSPEC  | 2001      | 0.9–5.0 | CLC/OVC      | ADI             |
| VLT          | NACO                  | 2002      | 1.0–5.0 | CLC/FQPM/APP/OVC | SDI/PDI/ADI |
| Gemini-N     | ALTAIR/NIRI           | 2003      | 1.1–2.5 | CLC          | ADI             |
| VLT          | MACAO/SINFONI         | 2004      | 1.0–2.5 |              | IFS             |
| Gemini-S     | NICI                  | 2007      | 1.1–5.0 | CLC          | SDI/ADI         |
| Subaru       | AO188/HiCIAO          | 2008      | 1.1–2.5 | CLC/PIAA/8QPM | SDI/PDI/ADI    |
| Palomar      | PALAO/PHARO-P1640     | 2009      | 1.1–1.7 | APLC/OVC     | IFS/ADI         |
| LBT          | FLAO/LMIRCAM          | 2012      | 1.0–5.0 | CLC/OVC      | ADI             |
| Magellan     | MagAO/VisAO-CLIO      | 2012      | 0.6–5.0 | CLC          | ADI             |
| Gemini-S     | GPI                   | 2013      | 1.1–2.3 | CLC/ALC      | IFS/ADI/PDI    |
| VLT          | SPHERE                | 2014      | 0.5–2.3 | CLC/ALC/4QPM | IFS/ADI/PDI    |
| Subaru       | SCExAO/HiCIAO-CHARIS  | 2016      | 0.5–2.2 | PIAA         | IFS/ADI/PDI    |

must-have for any high-contrast instruments to address that issue. I will detail below the techniques commonly used in the field of DI of exoplanets without considering Polarimetric Differential Imaging (PDI) or a promising approach like Coherent Differential imaging \cite{15} (CDI) barely exploited for exoplanets for the moment.

A classical approach widely used since the 90’s for disk science with \textit{HST} is to register an additional single star for reference differential imaging (RDI). This technique has been successfully applied to the case of $\beta$ Pictoris system and enabled the detection of the $\beta$ Pic b planet with NaCo at VLT \cite{16}. From the ground and with AO-instruments, the reference must be well chosen to: i/ match magnitude and colors of the science star to preserve the same AO setting and the similar NIR flux, and ii/ match the parallactic angle variation to keep a similar pupil configuration (for observations with alt-az telescopes). With an increased stability of the telescope+instrument and a duty cycle of a few minutes, high degree of correlation may in addition persist between the science star and the reference to significantly gain in contrast. This promising technique of star hopping still needs to be validated in terms of performances with the second generation of planet imagers if (pointing, AO setting) overheads can be reduced.

An alternative differential technique makes use of the planet spectral properties. Giant planet atmospheres are composed of chemical elements (water, methane, amonia, carbon monoxide and/or dioxide), not present in the stellar atmospheres. Signatures of planetary accretion in emitting lines like H$\alpha$ can also be used \cite{17}. These differential spectral signatures between the planet and the star can be optimally used to suppress part of the stellar light and to reveal broad molecular absorptions or accretion lines in the planet spectrum. The spectral differential imaging technique (SDI) \cite{18,19} relies on the simultaneous observations of the star+planet at well defined wavelengths (on/off defined molecular absorptions quoted above). Although it efficiently tackles the subtraction of residual atmospheric speckles, SDI remains: i/ sensitive to differential aberrations between the different imaging paths and ii/ optimized for the detection of cool or accreting, and spectrally contrasted planets. An extension of this approach makes use of integral field spectrographs offering a broader spectral range. Optimized subtraction of the PSF simultaneously observed at different wavelengths considering the complete star/planet NIR spectral properties enables a significant gain in terms of detection performances. Two SPHERE instruments, the IRDIS Dual-Band image and the IFS Integral Field Spectrograph have been designed to exploit that concept, as the GPI and SCExAO/CHARIS planet imagers which have for unique instrument an integral field spectrograph.
Finally, a last and complementary technique exploits the field and pupil rotation of alt-az Telescope. This
is the so-called angular differential imaging technique\textsuperscript{20} (ADI). It enables to discriminate quasi-statics speckles
(over the duration of the observations) and fixed instrumental aberrations (frozen when the pupil is stabilized)
from astrophysical sources like exoplanets rotating with the field. The efficiency of that technique highly depends
on the parallactic angle variation rate (therefore the target coordinates and observing time) and the companion
separation given the resolving power of the telescope. ADI can be optimally applied after SDI to remove
differential aberrations between the SDI paths. The SPHERE and GPI imagers actually combine both techniques
to boost their detection performances, however care must be taken as they affect the planetary (astrometric and
spectro-photometric) signal.

With these various stages of instrumental complexity (XAO, low order aberration control, coronography and
differential techniques), important progress in the past years has been made to develop innovative algorithms to
optimally calibrate the PSF, spatially, temporally and spectrally in order to suppress the stellar contribution and
recover faint planetary signals as close as possible to the star. These algorithms make heavy use of the known
modulation of the signal imprinted by the observing strategy. They deploy various degrees of complexity for
example in the context of ADI with: i/ classical ADI (cADI) using the median of the ADI cube as a reference
PSF, ii/ smart ADI (sADI) with a reference PSF selection criteria for each science image considering frames
that have rotated by more than \( \alpha \times \text{FWHM} \) (\( \alpha \) being a resolution criteria used as input), iii/ radial ADI (rADI)
following the reference PSF selection criteria of sADI, but repeated for various separations, iv/ locally optimized
combination of images\textsuperscript{21} (LOCI) with the definition of optimization zone (larger than the subtraction zone)
where the coefficients for the linear optimization are computed by minimizing the sum of the squared residuals of
the subtraction using various set of parameters (criteria of separation, size of optimization zone, radial width and
ratio of the radial-to-azimuthal widths of subtraction zones) and v/ principal component analysis\textsuperscript{22,23} (PCA) that
uses an orthogonal basis of eigenimages, on which the science target is projected to create the PSF reference.
Spectrally, whereas simple spatial and flux rescaling are used in SDI, more elaborated approach like spectral
deconvolution,\textsuperscript{24} spectral LOCI and PCA,\textsuperscript{25,26} forward modeling for specific characterization\textsuperscript{27} or more recently
combined high or even medium-resolution dispersed spectroscopy with molecular mapping\textsuperscript{28} can also be applied
to optimize the PSF subtraction and minimize the planetary signal cancellation using Integral Field Spectrograph
to exploit the spectral diversity.

Whereas the flux subtraction in ADI processing is purely geometric and related to the planet position and
parallactic angle variation during the observation, the situation is much more complex for SDI. The SDI signature
of any point-source depends on the separation, luminosity, but also on the spectral properties of the object. Self-
subtraction cannot be reduced to a simple geometric effect. As a consequence, the detection performances of
SDI observations (and more generally high and medium-resolution dispersed spectroscopy coupled to AO) cannot
be expressed as a contrast in magnitude relative the central star without an a-priori knowledge of the spectral
properties of the searched companions.\textsuperscript{20} Consequently, although the characterization of detected planets can
be individually and locally treated using injection of fake planets in the data in ADI, SDI or ASDI (combination
of ADI and SDI), the determination of accurate detection limits requires further a priory assumptions on the
spectral properties of the hunted planets.

3. TARGETING YOUNG, NEARBY STARS
Young (\( \leq 500 \text{ Myr} \)), nearby (\( \leq 100 \text{ pc} \)) stars have been prime targets for DI of exoplanets for more than a decade
now. The identification of these comoving groups of young stars started from an anomaly observed three decades
ago. The TW Hya T Tauri star was discovered isolated from any dark cloud nor birth place regions.\textsuperscript{30} A few
years later, IRAS excesses combined with H\( \alpha \) and Lithium depletion measurements enabled the identification a
handful of young stars in the vicinity of TW Hya. Their origin, runaway stars from some cloud or formed in situ
from a lowmass cloud, their age and their distance remained unclear for years. X-ray data finally confirmed that
they were members of the first identified young, nearby association, i.e. the nearest known region of recent star
formation, the so-called TW Hydrae association\textsuperscript{31} (TWA). Over the next decade, the number of TWA members
dramatically increased to more than 30 members, with age and mean distance estimates converging towards 10 Myr
and 50 pc, respectively. Immediately after the confirmation of the existence of TWA, several research groups
became specifically interested in identifying new young, nearby associations in the vicinity of the Sun.\textsuperscript{32,33}
In most current studies, the identification relies on two main pillars:

- **Galactic kinematics studies** (space velocity analyses). Techniques have become increasingly sophisticated using for instance Bayesian analysis to derive membership probability considering combined photometric and kinematics catalogs,

- **Youth diagnostics determination**. Various diagnostics can be used depending on the stellar age and spectral type like color-magnitude diagram, rotation, Lithium depletion, H\(_\alpha\) emission, Ca H&K, Coronal X-rays and chromospheric UV activity, or the presence of IR excess to inter-compare and refine stellar ages.

Since the discovery of TW Hydrae, more than 500 young, nearby (<100 pc) stars were identified, mostly F, G, K and M dwarfs. Recent systematic studies are now pushing the horizon down to very low-masses with the discovery of a large population of M-, L- and even T-type members. These young, nearby stars are gathered in several groups (TW Hydrae, β Pictoris, Tucana-Horologium, η Cha, AB Dor, Columba, Carinae...), sharing common kinematics, photometric and spectroscopic properties. They are also more recently completed by stars with intermediate-age or located at larger distance like in the so-called Sco-Cen complex. Their main properties are reported in Table ??.

With typical contrast of 10–15 magnitudes for separations beyond 1.0–2.0″ (50–100 au for a star at 50 pc) achieved with the first generation of planet imagers, planetary mass companions down to 1–2 Jupiter masses became potentially detectable. Therefore, without surprise, a significant amount of telescope time in the early-2000’s was dedicated to deep imaging surveys of young, nearby stars to search for exoplanets, brown companions and disks leading to the first discoveries of planetary mass companions in DI.

### 4. DISCOVERIES AND SURVEYS

In the course of a DI survey, the discovery of a serious planetary candidate is usually indicated by a combination of small separation, high contrast and cool atmosphere features. Very red near-IR colors or specific spectral features such as a peaked H-band spectrum are indicative of young L dwarfs atmospheres. Methane absorption detected in SDI indicates a probable young and cool T dwarf. These diagnostics enable the observers to rapidly estimate the predicted mass, effective temperature and physical separation of the candidate using evolutionary model predictions. It highlights one key limitation of DI which is the dependency on luminosity-mass predictions from uncalibrated formation and evolutionary models detailed here after.
Table 2. Non-exhaustive, but illustrative list of substellar/planetary-mass companions and/or exoplanets discovered by DI around young, nearby \( \ast \)ars in the last two decades.

| Primary Companion | Name | Asso. | Age (Myr) | d (pc) | SpT | \( \varphi \) | \( \Delta \) (AU) | \( \Delta H \) (mag) | Mass\( ^{a} \) | SpT | Date |
|------------------|------|-------|-----------|-------|-----|--------|--------|--------|--------|-------|-----|
| Gl 229 B | Field | \( \sim 500 \) | 5.8 | M1V | 7.8 | 45 | 10.0 | 35 | T6.5 | 1995 |
| TWA 5 B | TWA | 10 | 50 | M3 | 2.0 | 100 | 4.9 | 20 | M9 | 1999 |
| HR 7329 B | \( \beta \) Pic | 20 | 48 | A0 | 4.0 | 200 | 6.9 | 20 | M8 | 2000 |
| GSC 08047 B | Tac-Hor | 40 | 85 | K1 | 3.2 | 250 | 6.9 | 25 | M8 | 2003 |
| 2M1207 b | TWA | 10 | 53 | M8 | 0.78 | 41 | 5.7 | 3 | L3 | 2004 |
| AB Pic b | Tac-Hor | 40 | 45 | K1 | 5.5 | 248 | 7.6 | 12 | L1 | 2005 |
| GQ Lup b | Lupus | 1 | 140 | K1 | 0.7 | 100 | 6.0 | 12 | M8 | 2005 |
| DH Tau b | Tau | 2 | 140 | M7 | 2.3 | 330 | 6.2 | 15 | M8 | 2005 |
| CHXR 73 b | Cha | 2 | 160 | M | 1.3 | 210 | 5.2 | 12 | M8 | 2006 |
| CT Cha b | Cha | 2 | 165 | M | 2.7 | 440 | 5.5 | 15 | M8 | 2008 |
| RXJ1609 b | Upp Sco | 5 | 150 | K7 | 2.2 | 330 | 7.8 | 8 | L4 | 2008 |
| HR 8799 (b) | Col | 30 | 39.4 | A5 | 1.72 | 68 | 12.5 | 7 | L/T | 2008 |
| (c) | - | - | - | - | 0.94 | 37 | 11.6 | 10 | L/T | 2008 |
| (d) | - | - | - | - | 0.66 | 26 | 11.6 | 10 | L7 | 2008 |
| (e) | - | - | - | - | 0.39 | 15 | 11.5 | 10 | L7 | 2010 |
| \( \beta \) Pic b | \( \beta \) Pic | 23 | 19.3 | A6 | 0.4 | 9 | 10.0 | 8 | L1 | 2008 |
| Fomalhaut b | Field | 200-400 | 7.7 | A4 | 15.5 | 115 | - | \( \leq 3 \) | ? | 2008 |
| \( \kappa \) And b | Col? | 10-150 | 51.6 | B9 | 1.1 | 55 | 10.6 | 13 | L5 | 2013 |
| HD 95086 b | LCC | 17 | 90.3 | A8 | 0.6 | 61 | 13.1 | 5 | L7 | 2013 |
| GJ 504 b | Field | 120 | 17.5 | G0 | 2.5 | 44 | 16.3 | 4 | T | 2013 |
| GU Psc b | AB Dor | 140 | 48 | M3 | 42 | 2000 | 8.1 | 11 | T3.5 | 2014 |
| 51 Eri b | \( \beta \) Pic | 23 | 29.4 | F0 | 0.55 | 13 | 14.4 | 2 | T3 | 2015 |
| HIP 65426 b | LCC | 17 | 83.9 | A2 | 0.83 | 92 | 11 | 9 | L5 | 2017 |
| PDS 70 b | UCL | 3 | 113.4 | K7 | 0.19 | 9.3 | 29 | 5 | mid-L | 2018 |

In the case of the 2M1207 b planetary mass companion, the very red near-IR colors \((K - L' = 1.65 \pm 0.20 \text{ mag})\) were indicative of a very dusty atmosphere. DUSTY models were predicting a mass of \(3-5 \text{ M}_J\).\(^{35}\) Firmed confirmation in DI then came with follow-up test at different epochs to verify that the candidate was actually co-moving with the central star. Orbital motion can be resolved to unambiguously confirm that both objects are physically bound. Depending on the parallactic and proper motion of the central source as well as the astrometric precision of the planet imager, up to one year interval between both epochs could be necessary for final confirmation as illustrated in the case of 2M1207 \((\mu_\alpha = -78 \pm 11 \text{ mas/yr}, \mu_\delta = -24 \pm 9 \text{ mas/yr}; d = 53.2 \text{ pc}; \text{typical NaCo astrometric precision } \sim 10 \text{ mas})\). With GPI, SPHERE, SCExAO reaching an astrometric precision down to 1-2 mas, a few weeks to a few months are now sufficient, which shows the gain of enhanced instrumental performances. After the discovery of the first brown dwarf companion Gl 229 B\(^{7}\) in 1994 that benefited from the combined technological innovation of high contrast techniques, the ones of the first young brown dwarf companions (TWA5 B\(^{36}\) and HR 7329 B\(^{37}\)) in young, nearby associations that exploited the HST/NICMOS stability, the first generation of planet imagers on 10m-class telescopes at Palomar, Subaru, Keck, VLT, Gemini, and later-on LBT and Magellan enabled systematics survey of large sample of young, nearby stars. They rapidly led to the discovery of the first planetary mass companions in the early 2000’s. The first companions were detected at large distances \((\geq 100 \text{ au})\) and/or with small mass ratio with their primaries, indicating a probable formation via gravo-turbulent fragmentation\(^{38}\) or gravitational disk instability as already addressed early-on in the discovery papers.\(^{39,40}\) The implementation of differential techniques, starting in 2005–2006, enabled the breakthrough discoveries of closer and/or lighter planetary mass companions like HR 8799 bcde\(^{41,42}\)
Table 3. Deep imaging surveys of young (< 100 Myr) and intermediate-old to old (0.1 – 5 Gyr), nearby (< 100 pc) stars dedicated to the search for planetary mass companions. We have indicated the telescope and the instrument, the imaging mode (I: standard imaging; Sat-I: saturated imaging; Cor-I: coronagraphic imaging; SDI: simultaneous differential imaging; ADI: angular differential imaging; ASDI: angular and spectral differential imaging), the filters, the field of view (FoV), the number of stars observed (#), their spectral types (SpT) and ages (Age).

| Reference       | Telescope   | Instr. | Mode   | Filter | FoV (as) | #   | SpT   | Age (Myr) |
|-----------------|-------------|--------|--------|--------|---------|-----|-------|-----------|
| Nakajima+94     | Palomar     | AOC    | Cor-I  | I      | 60      | 24  | G-M   | ⩽ 50     |
| Chauvin+03      | ESO3.6m     | ADONIS | Cor-I  | H,K    | 13      | 29  | G–M   | ⩽ 50     |
| Neuhäuser+03    | NTT         | Sharp/Sofi | Sat-I | K/H    | 20      | 33  | A–M   | ⩽ 50     |
| Lowrance+05     | HST         | NICMOS | Cor-I  | H      | 19      | 45  | A–M   | 10 – 600 |
| Masciiadri+05   | VLT         | NaCo   | Sat-I  | H,K    | 14      | 28  | KM    | ⩽ 200    |
| Biller+07       | VLT/MMT     | NaCo/ARIES | SDI   | H      | 5       | 45  | G–M   | ⩾ 300    |
| Kasper+07       | VLT         | NaCo   | Sat-I  | L'     | 28      | 22  | G–M   | ⩽ 50     |
| Lafrenière+07   | Gemini-N    | NRI    | Sat-ADI | H    | 22      | 85  | F–K   | 10-5000  |
| Apai+08         | VLT         | NaCo   | SDI    | H      | 3       | 8   | FG    | 12-500   |
| Chauvin+10      | VLT         | NaCo   | Cor-I  | H,K    | 28      | 88  | B–M   | ⩽ 100    |
| Heinz+10ab      | MMT         | Clio   | Sat-ADI | L',M  | 15.5    | 54  | F–K   | 100-5000 |
| Janson+11       | Gemini-N    | NRI    | Sat-ADI | H,K    | 22      | 15  | BA    | 20-700   |
| Vigan+12        | Gemini-N/VLT | NRI  | Sat-ADI | H,K    | 22/14   | 42  | AF    | 10-400   |
| Delorme+12      | VLT         | NaCo   | Sat-ADI | L'    | 28      | 16  | M     | ⩽ 200    |
| Rameau+13c      | VLT         | NaCo   | Sat-ADI | L'    | 28      | 59  | AF    | ⩽ 200    |
| Yamamoto+13     | Subaru      | HiCIAO | Sat-ADI | H,K    | 20      | 20  | FG    | 125 ± 8  |
| Biller+13       | Gemini-S    | NICI   | Cor-ASDI | H    | 18      | 80  | B–M   | ⩽ 200    |
| Nielsen+13      | Gemini-S    | NICI   | Cor-ASDI | H    | 18      | 70  | BA    | 50-500   |
| Wahhaj+13       | Gemini-S    | NICI   | Cor-ASDI | H    | 18      | 57  | A–M   | ~ 100    |
| Janson+13       | Subaru      | HiCIAO | Sat-ADI | H     | 20      | 50  | A–M   | ⩽ 1000   |
| Brandt+14       | Subaru      | HiCIAO | Sat-ADI | H     | 20      | 63  | A–M   | ⩽ 500    |
| Chauvin+15      | VLT         | NaCo   | Sat-ADI | H     | 14      | 86  | F–K   | 200      |
| Meshkat+15ab    | VLT         | NaCo   | APP-ADI | L'    | 28      | 20  | AF    | 200      |
| Bowler+15       | Keck/Subaru | NIRC2/HiCIAO | Cor-ADI | H    | 10/20   | 78  | M     | ⩽ 200    |
| Galicher+16     | Keck        | NIRC2  | Cor-ADI | H,K   | 10      | 229 | A–M   | ⩽ 200    |
| Durkan+16       | Spitzer     | IRAC   | I      | 4.5 µm | 312     | 73  | A–M   | ⩽ 200    |

(10, 10, 10 and 7 M\(_{Jup}\) at resp. 14, 24, 38 and 68 au), \(\beta\) Pictoris\(b\)\(^{16}\) (8 M\(_{Jup}\) at 8 au), Fomalhaut\(b\)\(^{43}\) (< 1 M\(_{Jup}\) at 177 au; still debated), \(\kappa\) And\(b^{14}\) (14\(^{+25}_{−2}\) M\(_{Jup}\) at 55 au), HD95086\(b^{45}\) (4 – 5 M\(_{Jup}\) at 56 au), GJ5041\(b^{46}\) (4\(^{+4.5}\) M\(_{Jup}\) at 43.5 au), 51 Eri\(b^{17}\) (2 M\(_{Jup}\) at 13 au), HIP65426\(b^{48}\) (9 M\(_{Jup}\) at 92 au), and more recently PDS\(70\)\(b\) (9 M\(_{Jup}\) at 29 au, Keppler et al. 2018, accepted). They indicate that we are just initiating the characterization of the giant planet population at wide orbits, between typically 5 – 100 au. Fig. 4 and Table 4 show and summarize the non-exhaustive, but illustrative family portrait of young very low mass brown dwarf companions and/or planets discovered in DI in the past two decades.

The dozens of discoveries obtained in DI so far has been possible thanks to large surveys of young stars that mostly identified background contaminants (see Table 4). Various motivations were followed for the target selection of these surveys: i/ complete census of given associations, ii/ selection of young, intermediate-mass stars, iii/ or very low-mass stars, or iv/ application of figure of merit considering detection rate with toy models of planet population. The near-infrared wavelengths (\(H\) and \(K_s\)) have been used intensively. They are a good compromise between low-background noise, angular resolution and good Strehl correction. However, thermal imaging has been very competitive in terms of detection performances as the planet-star contrast and the Strehl correction are more favorable in those wavelengths despite an increased thermal background. For instance,
SPHERE is less performant than NaCo for the detection of giant planets around young, nearby M dwarfs at typical separation larger than 500-1000 mas. The low-rate of planet detection in DI considering the large number of stars observed has motivated the approach of new systematic and very large scale surveys (as conducted in radial velocity for instance). The Gemini GPIES survey and the VLT/SPHERE SHINE\textsuperscript{49} (The SpHere INfrared survey for Exoplanets) will observe both 600 stars over four to five years. With enhanced detection performances, the objective is to significantly increase the number of imaged planets to characterize, but also to provide better statistical constraints on the occurrence and the characteristics of exoplanets at wide orbits ($\geq 5$ au). This will give us a more global picture of planetary systems architecture at all orbits to improve our understanding of planetary formation and evolution mechanisms. Early-results already confirm the gain in terms of detection performances compared with the first generation of planet imagers.

5. KEY ASTROPHYSICAL RESULTS

5.1 Mass & accretion history

As previously mentioned, DI gives access to the photometry, the luminosity and the spectral energy distribution of exoplanets, but not directly to the mass. In this context, we have to rely on evolutionary model predictions that are not well calibrated at young ages. In addition to the system age uncertainty, the predictions highly depend on the formation mechanisms and the gas-accretion phase that will form the exoplanetary atmosphere. The way the accretion shock will behave (sub or super-critical) on the surface of the young accreting proto-planets during the phase of gas runaway accretion will drive the planet initial entropy or internal energy, hence its initial physical properties (luminosity, effective temperature, surface gravity and radius) and their evolution with time. These different physical states are described by the so-called hot-start (sub-critical shock), cold-start (super-critical shock), and warm-start (intermediate cases) models. They predict luminosities that are spread over several order of magnitudes for young, massive giant planets. This is illustrated by Fig. 5 based on the BEX models\textsuperscript{50} where predictions in terms of luminosity are reported for different planet masses as a function of time and for the cold-start and hot-start cases. The higher is the mass, the larger is the spread and the time duration for the models to converge. Nowadays, most masses reported in the literature or in table 4 for imaged planets are the ones predicted by hot-start models and may under-estimate the planet masses.

The consequence is that much remain to be understood about the formation of giant planet and of their atmospheres from the theoretical point of view. The observations of proto-planets in their birth environment
and the direct measurement of mass accretion rate using Hα differential imaging would add interesting constraints on the way gas is accreted on young forming planets (see for instance the pioneer case of HD142527 B detected using MagAO\textsuperscript{17}). Several interesting candidates in transition disks will maybe shed some light on this terra incognita in terms of mass and accretion rate regime (see Fig. 6). One exciting solution comes from the combination of DI and radial velocity and/or astrometry to derive the dynamical mass of imaged planets with their luminosity in order to explore the possible states of initial entropies that are consistent with observations. Future systematic and combined characterization will enable to populate a mass/luminosity space as a function of time to calibrate models of planetary formation and evolution. This will soon come using the synergy between observing techniques, such as radial velocity, astrometry with GAIA and DI that will overlap with the new generation of planet imagers SPHERE and GPI or more likely the ones that will be offered on the ELTs.

5.2 Physics of imaged planets

Today, most imaged exoplanets are young, late-M, L to early T-types exoplanets with dusty atmospheres (see Table 4). The majority occupies a slightly distinct space compared to field brown dwarfs in near-IR color-magnitude diagrams. They are redder than field brown dwarfs, their older counterparts. For some cases like 2M1207 b, HR8799 b and VHS 1256 b, they are also underluminous (see Fig. 7, Left). The most plausible explanation is the presence of unusual thick clouds due to low surface gravity conditions in these young planetary atmospheres. Modification of the cloud thickness and distribution is corroborated by recent variability studies that show higher-amplitude variability in young L dwarfs than old ones.\textsuperscript{52} In that perspective, future high-precision photometric monitoring are very promising to probe time-variability in the planet’s flux and/or spectra and explore the physical and dynamical processes at play in young exoplanetary atmospheres. To further characterize the physical properties of imaged planets (luminosity, effective temperature, surface gravity, radius and ultimately the mass), a logical approach is to use multi-wavelength photometry to constrain the exoplanet’s spectral energy distribution (SED). All imaged planets have good parallaxes measurements thanks to the primary star. Planetary SEDs of current imaged planets peak between 1.2 to 5.0 μm for $T_{\text{eff}} = 2400$ K to $T_{\text{eff}} = 600$ K, respectively. The use of bolometric correction calibrated with observations of field brown dwarfs is rather risky as small variation in the cloud and dust properties may actually affect the flux re-distribution over the SED and therefore biases the luminosity determination. The challenge is now to extend the spectral coverage to lift degeneracies in the fitting of the physical and atmospheric properties, and JWST will be very precious in that sense. For SED characterization, the case of β Pic b is nowadays the most favorable one as the planet is the brightest one imaged to date with an apparent magnitude of $H = 13.5 \pm 0.2$ mag (HR 8799 bcde have $H$-band magnitudes of 17.7,
16.8, 16.8, 16.7 mag, respectively). Based on a combination of MagAO, NaCo, NICI observations from 0.9 to 5.0 μm, accurate bolometric luminosity of $\log(L/L_\odot) = 3.78 \pm 0.03$ could be derived. For an age of $23 \pm 3$ Myr, it corresponds to predicted hot-start physical parameters of $T_{\text{eff}} = 1708 \pm 23$ K, radius of $R = 1.45 \pm 0.02 \, R_{\text{Jup}}$, and mass of $M = 12.7 \pm 0.3 \, M_{\text{Jup}}$, compatible with previous atmosphere model fitting in near-IR and current radial velocity constraints for the planet dynamical mass.

For further insight on the atmospheric properties of the direct imaged planets, spectroscopic observational at higher spectral resolution are particularly interesting to study the atmosphere composition through the various atomic and molecular lines, to explore the impact of low-gravity conditions, to confirm the existence of clouds and constrain their micro-physics (grain size distribution and composition), finally to test the effect of alternative non-equilibrium processes at play. As proxies, the use of young brown dwarfs as exoplanets analogs has proven to be extremely useful to test the reliability of atmospheric models as we cannot currently distinguish both classes of objects. It enabled to confirm for instance that low-gravity conditions are responsible for the temperature shift by $200 - 500$ K observed in the classical $T_{\text{eff}} - \text{SpT}$ classification between young and field dwarf, the inhibition of the formation of methane at the L/T transition that probably occurs at lower effective temperatures or the enhanced production of dust forming thick clouds and potentially responsible for increased photometric variabilities. These results can directly be compared to the building sequence of low-resolution spectra of imaged exoplanets, now regularly acquired with the new generation of planet imagers, to further understand the physics of their atmospheres and the influence of effective temperature, low-gravity conditions or clouds in shaping their spectral morphology (see Fig. 7, Right). With the increased of $(R_\lambda > 2000)$ spectral resolution, the measurement of molecular abundances such as water, carbon-dioxide and monoxide or methane becomes possible as done for HR 8799 b. It may give a first estimation of the carbon-to-oxygen ratio in the planet atmosphere (0.6-0.7 for HR 8799 b). When compared to the stellar C/O ratio, it can indicate some enrichment by heavy elements as for the giant planets of our Solar systems relative to our Sun ($\sim 4$ for Jupiter, $\sim 7$ for Saturn and $\sim 45$ for Uranus and Neptune). However, despite non-negligible errors in the determination of C/O ratio using that technique, a direct link between C/O ratio and formation mechanisms by core accretion or gravitational instability is not trivial as additional physical processes might also enrich the planetary envelope after the giant planet formation.
5.3 Orbits & planetary architectures

Among the known imaged planets which are mostly located at wide orbits (\(\geq 10\) au), orbital motion has been resolved for a very few cases. It actually concerns the case of \(\beta\) Pic b, Fomalhaut b, HR 8799 b, HD 95086 b, 51 Eri b, and GJ 504 b and \(\kappa\) And b. Vast efforts have been devoted to monitor the two emblematic cases \(\beta\) Pic and HR 8799 for more than a decade now. Since the first epoch discovery of \(\beta\) Pic b in November 2003 with NaCo at VLT, various ground-based instruments have been used and enabled to follow more than half of the orbit around its stellar host. For the four planets around HR 8799, the longest baseline has been achieved for the b planet thanks to the re-analysis of archived \(HST/NICMOS\) data from 1998. Although accurate astrometric monitoring with deep imagers is often a meticulous task to achieve due to the relatively small field of view of these instruments that could lead to astrometric calibration systematics, we see now that the 1-2 mas astrometric precision achieved by current planet imagers with adequate calibration strategy allows to study, in addition to the planet’s orbit, the global system architecture including the planet-planet and planet-disk interactions and the system stability. The orbital monitoring of \(\beta\) Pic b enabled for instance to witness the planet’s revolution around its star, passing behind the star from a North-East location to South-West, reaching quadrature in Summer 2013 and then coming back toward us for a possible transit in mid-2017 or early-2018 to be confirmed as soon as the planet is recovered on the North-East location. In that specific case, sophisticated statistical approaches using the Markov-chain Monte Carlo (MCMC) Bayesian analysis technique have been used as they offer the advantage to be less sensitive to the initial conditions assumed to derive and systematically explore the parameter space of orbital parameters. In the case of \(\beta\) Pic b, the results indicate a semi-major axis distribution peaking at \(8-10\) au with most eccentricities by \(e \leq 0.20\), and extremely concentrated inclined solutions.\(^{64, 65}\) Similar studies have been conducted for 51 Eri b and the young solar analogs HR 8799 b c d e planets, and HD 95086 b.\(^{69, 70}\) An interesting question addressed by DI in the context of the multiple planetary system HR 8799 is connected to the system’s dynamical stability. The long-term astrometric monitoring actually enabled to characterize the planet orbits, to check for coplanarity, and ultimately to test the dynamical stability of the whole system. The derived orbital properties of each planet showed that all planets evolve on coplanar and circular orbits except HR 8799 d which seems to be misaligned by 15–20 degrees and significantly more eccentric (\(\sim 0.3\)). This configuration likely suggests remaining imprints of dynamical interactions between the planets in this system. The system seems however stable as indicated by the existence of several mean motion resonances: a period ratio between 5:2 or 3:1 between b-c, 2:1 between c-d, and 3:2 or 2:1 between d-e. Even if HR 8799 d most likely does not orbit in the same plane as HR 8799 c and e, the period ratios involving these planets do not rule out a 1e:2c:4d Laplace resonance.\(^{96}\)

Regarding the global architecture and the circumstellar environment, scattered-light observations bring additional constraints and accurately map the morphology of the proto-planetary or debris disk generally discovered before the planet discoveries. For \(\beta\) Pic, the disk observations revealed mainly a nearly edge-on system composed of a main disk observed beyond 80 au with a position angle of \(\sim 209.0^\circ\), and an inner warped component (at less than 80 au), inclined by \(2 - 5^\circ\) with respect to the main disk position angle (i.e with a position angle of \(\sim 211.0 - 214.0^\circ\)). Dynamical simulations\(^{9, 72, 73}\) demonstrated that the presence of a planet orbiting the star at 10 au, misaligned with the main disk, could actually form and sustain the \(\beta\) Pic inner warped disk. The current distribution of longitude of ascending node \(\Omega\) found for \(\beta\) Pic b, when compared with the main disk and the warp orientations, supports an orbital plane for \(\beta\) Pic b that does not coincide with the main disk midplane, but more probably with the warp component. The orbital solutions therefore confirm that the planet is the perturber that excites the disk of planetesimals, forcing them to precess about its misaligned orbit. Simultaneous observations of the planet and disk position unambiguously confirm this conclusion.\(^{74}\) Similar studies have been conducted for the young solar analogs HR 8799\(^{66, 67}\) and HD 95086.\(^{69, 70}\) Here again, the planet location(s) can be compared to the dust spatial distribution and architecture. At ages \(\geq 10\) Myr, the gas is expected to have dispersed, giant planets to have formed and the dynamics of planetesimals to be influenced by the presence of giant planets. For both cases, the orbital properties of the imaged planets suggest that the planets are shepherded by an inner warm belt and an outer cold belt revealed by a two-temperature component model fitting their observed spectral energy distributions. This configuration is very similar to the one of our solar system with the asteroid and the Kuiper belts separated by giant planets. Their origin remains unclear. We could be witnessing two independent belts undergoing normal collisional evolution.\(^{75}\) The inner components may also be linked to the outer belt via inward scattering of material by intervening planets.\(^{76}\) The second generation of planet imagers, by discovering
new exoplanetary systems, should significantly extend this list in the coming years to study the orbital diversity of theses systems. It already started with the GPI and SPHERE discoveries around 51 Eri, HIP 65426 and more recently PDS 70 b, but also of the interesting young brown dwarf companions around HR 2562 and HIP 64892. Further discoveries of exoplanetary systems in DI and in combination with other techniques should enable to more systematically study the diversity of the planetary architectures at young ages. Young, nearby associations with ages spanning from a few Myrs to a hundred offer an ideal laboratory to explore various stages of evolution of planetary systems from the giant planet formation phase to more catastrophic events like the heavy bombardment of our Solar system caused by Jupiter and Saturn migration.

5.4 Occurrence & formation

With the manna of exoplanet discoveries since the 51 Peg b announcement, the diversity of systems found (Hot Jupiters, irradiated and evaporating planets, misaligned planets with stellar spin, circumstellar and circumbinary planets in binaries, telluric planets in habitable zone, discovery of Mars-size planet...), the theories of planetary formation have drastically evolved to digest these observing constraints. However, we are still missing the full picture and some key fundamental questions still lack answers like: the physical processes at play to pass the km-size barrier to form planetary cores, the physics of accretion to form planetary atmospheres, the formation mechanisms to explain the existence of giant planets at wide orbits, the physical properties of young Jupiters, the impact of planet-planet and planet-disk interaction in the final planetary system architecture, the influence of the stellar mass and stellar environment in the planetary formation processes. Neither core accretion plus gas capture nor disk fragmentation driven by gravitational instabilities can globally explain all current observable from planet hunting techniques. Alternative mechanisms are then proposed, such as pebbles accretion to enable CA to operate at wide orbits, inward/outward migration or planet-planet or simply the possibility to have several mechanisms forming giant planets operating in concert. A stellar-like mechanism like gravo-turbulent fragmentation could be also an alternative solution to form massive planetary mass companions at wider separations (≥ 5−10 au) in the earliest phase of the disk’s lifetime. In this context, one final key element addressed by DI surveys concerns the occurrence of giant planets beyond 5−10 au to actually test these theories. The rate of discovery in DI is currently low despite the large number of stars observed. These non-detection can however be used to actually derive the survey completeness and the frequency of the giant planet population.

Early studies have developed statistical analysis tools to exploit the complete deep imaging performances and derive the detection probabilities of their surveys by simulating synthetic planet population described
by various sets of (mass, eccentricity, semi-major axes) parametric distributions confronted to the survey detection limits. They show that the first generation of surveys were mostly sensitive to giant planets more massive than $5 \, M_{\text{Jup}}$ for semi-major axis between typically 30 to 300 au (see Fig. 9, Left). Pushing that logic, the recent large meta-analysis of 384 unique and single young (5–300 Myr) stars spanning stellar masses between 0.1 and 3.0 $M_\odot$ and combining several DI surveys illustrates that the current overall occurrence rate of $5 - 13 \, M_{\text{Jup}}$ companions at orbital distances of 30–300 au is $0.6^{+0.7}_{-0.5}$% (assuming hot-start evolutionary models). Splitting the analysis for separate bins of masses containing BA stars (110 targets), FGK stars (155 targets), and M dwarfs (119 targets), it shows that the frequency of planets orbiting BA, FGK, and M stars is $2.8^{+3.7}_{-2.3}$%, < 4.1%, and < 3.9%, respectively (see Fig. 9, Right). Although there are hints of a higher occurrence rate of giant planet around massive stars analogous to the well-established correlation at small separations, the trend is not yet statistically significant at wide orbital distances. It will require larger sample sizes in each stellar mass bin to unambiguously test this correlation, which is supporting the need for systematic DI surveys like the ones currently carried out by the GPI and SPHERE large programs of more than 600 young, nearby stars of various masses and ages.

In addition to the determination of the occurrence of giant planets at wide orbits, a further step in such a statistical exploitation of the survey completeness is a direct comparison with the predictions of planetary formation models. Here again, Monte-Carlo simulations can be used to compare the sensitivity of DI surveys with the state-of-the-art population synthesis models. This is actually illustrated with Fig. 10 that shows two populations of giant planets predicted by the CA scenario and the GI one. Both models include scattering effects between planetary embryos. They are compared with the completeness of the NaCo-LP survey of about 200 young, nearby solar-type stars published together with the Direct Imaging Virtual Archive. This comparison highlights the fact that the first generation of DI surveys marginally explored the bulk of giant planets predicted by CA, that planets formed by GI are rare considering that they should be easily detectable in most current DI surveys, finally that, although GI is not common, it predicts a mass distribution of wide-orbit massive companions closer to what is observed compared to current CA predictions. In a near future, the synergy of all observing techniques will be very precious to constrain the occurrence rate of giant planets at all separations, but more importantly the properties of their underlying mass, separation, and eccentricity distributions to shed more light on the formation and evolution mechanisms of giant planets.

‡DIVA, http://cesam.lam.fr/diva/
Figure 10. Density plots representing scattered populations based on GI\(^{86}\) and CA\(^{87}\) compared to the detections in our sample and to the mean detection probabilities of the observations (contour lines are at 5%, 25%, 50%, 90%, and 95%).\(^{88}\) Density colors go from dark blue (low occurrence) to cyan (high occurrence) for the CA population, and from red (low occurrence) to yellow (high occurrence) for the GI population. The histograms on top and on the right represent the relative frequency in each bin of semi-major axis and planetary mass respectively. The histograms take into account the whole population, including the planets that are outside of the visibility window of the main plot. The semi-major axis and mass of the known companions are represented with dashed lines in the histograms.

6. CONCLUSIONS & PERSPECTIVES

Today’s success of DI relies on a sophisticated instrumentation designed to detect a faint planetary signal, angularly close to a bright host star. It also relies on a fine target selection of young, nearby stars sharing common kinematics, photometric and spectroscopic properties. This combination enabled the discovery of the first exoplanets and/or planetary mass companions at large physical separations (> 100 au) or with small mass ratio with their primaries. This success was followed by breakthrough discoveries of closer and/or lighter exoplanets. Each one of these discoveries has proven to be rich in terms of scientific exploitation and characterization to directly probe the presence of planets in their birth environment, to explore the orbital, physical and spectral characterization of young Jupiters, or more globally explore the young planetary system architectures. Vast efforts are now devoted to systematic searches of exoplanets in DI with an increasing number of large scale surveys. With bigger samples and enhanced detection performances, new large surveys of 100+ nights with the second generation of planet finders will offer unprecedented statistical constraints on the occurrence of giant planets at wide orbits. With the rich perspective of new/upgraded instruments from the ground (VLT/ESPRESSO, CFHT/SPYROU, ESO3.6/NIRPS, LBT/iLocater, SCExAO/CHARIS, Keck/KPIC, VLT/ERIS, LBT/SHARK(S), MagAO-X, Gemini/GPI+, VLT/SHERE+...) and space missions (GAIA, TESS, CHEOPS, JWST, PLATO, WFIRST, ARIEL...), devoted to the study of exoplanets, we can hope to obtain a complete census of nearby planetary systems within a decade from now. This will end the era of exoplanet surveys and will open a characterization phase for the extremely large telescopes (ELT, TMT, GMT) or the dedicated space missions from space (LUVOIR, HABEX...) that might exploit the synergy of various planet hunting techniques including DI with the ultimate objective to detect and characterize the first bio-signatures at the horizon 2030–2040.

ACKNOWLEDGMENTS

This review is the fruit of the successful work of the large direct imaging community over the years. For the preparation of this review, I would like to particularly thank D. Mouillet, M. Bonnefoy, L. Close, C. Mordasini, M. Booth, P. Kern, L. Pueyo, J. Rameau and A. Vigan for their help.
REFERENCES

[1] Kern, P., Lena, P., Gigan, P., Fontanella, J.-C., Rousset, G., Merkle, F., and Gaffard, J. P., “COME-ON - an adaptive optics prototype dedicated to infrared astronomy,” in [Active telescope systems], Roddier, F. J., ed., SPIE 1114, 54–64 (Sept. 1989).

[2] Rousset, G., Fontanella, J. C., Kern, P., Gigan, P., and Rigaut, F., “First diffraction-limited astronomical images with adaptive optics,” A&A 230, L29–L32 (Apr. 1990).

[3] Beuzit, J. L. and Hubin, N., “ADONIS - a user friendly adaptive optics system for the 3.6-m telescope,” ESO Messenger 71, 52–53 (Mar. 1993).

[4] Golimowski, D. A., Clampin, M., Durrance, S. T., and Barkhouser, R. H., “High-resolution ground-based coronagraphy using image-motion compensation,” ApOpt 31, 4405–4416 (Aug. 1992).

[5] Beuzit, J.-L., Lacombe, F., Mariotti, J.-M., Perrier, C., and Rouan, D., “A search for substellar objects with a coronographic near infrared camera,” in [Astronomical Society of the Pacific Conference Series], Elston, R., ed., Astronomical Society of the Pacific Conference Series 14, 316–318 (1991).

[6] Zuckerman, B. and Becklin, E. E., “Companions to white dwarfs: very low-mass stars and the brown dwarf candidate GD 165B,” ApJ 386, 260–264 (Feb. 1992).

[7] Nakajima, T., “Planet detectability by an adaptive optics stellar coronagraph,” ApJ 425, 348–357 (Apr. 1994).

[8] Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., and Durrance, S. T., “Discovery of a cool brown dwarf,” Nature 378, 463–465 (Nov. 1995).

[9] Mouillet, D., Larwood, J. D., Papaloizou, J. C. B., and Lagrange, A. M., “A planet on an inclined orbit as an explanation of the warp in the Beta Pictoris disc,” MNRAS 292, 896 (Dec. 1997).

[10] Beuzit, J.-L., Feldt, M., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Abe, L., Antichi, J., Baruffolo, A., Baudou, P., Boccaletti, A., Cariblet, M., Charton, J., Claudi, R., Downing, M., Fabron, C., Feautrier, P., Fedrigo, E., Fusco, T., Gach, J.-L., Gratton, R., Henning, T., Hubin, N., Joos, F., Kasper, M., Langlois, M., Lenzen, R., Moutou, C., Pavlov, A., Petit, C., Pragt, J., Rabou, P., Rigal, F., Roelfsema, R., Rousset, G., Saisse, M., Schmid, H.-M., Staadle, E., Thalmann, C., Utartu, M., Udny, S., Vakili, F., and Waters, R., “SPHERE: a ‘Planet Finder’ instrument for the VLT,” in [Ground-based and Airborne Instrumentation for Astronomy II], Proc. SPIE 7014, 701418 (July 2008).

[11] Macintosh, B. A., Graham, J. R., Palmer, D. W., Doyon, R., Dunn, J., Gavel, D. T., Larkin, J., Oppenheimer, B., Saddlemeyer, L., Siavaramakrishnan, A., Wallace, J. K., Bauman, B., Erickson, D. A., Marois, C., Poyneer, L. A., and Soummer, R., “The Gemini Planet Imager: from science to design to construction,” Proc. SPIE 7015, 701518 (July 2008).

[12] Macintosh, B., Troy, M., Doyon, R., Graham, J., Baker, K., Bauman, B., Marois, C., Palmer, D., Phillion, D., Poyneer, L., Crossfield, I., Dumont, P., Levine, B. M., Shao, M., Serabyn, G., Shelton, C., Vasisht, G., Wallace, J. K., Lavigne, J.-F., Valee, P., Rowlands, N., Tam, K., and Hackett, D., “Extreme adaptive optics for the Thirty Meter Telescope,” in [Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series], SPIE 6272, 62720N (June 2006).

[13] Kasper, M. E., Beuzit, J.-L., Verinaud, C., Yaitskova, N., Baudou, P., Boccaletti, A., Gratton, R. G., Hubin, N., Kerber, F., Roelfsema, R., Schmid, H. M., Thatte, N. A., Dohlen, K., Feldt, M., Venema, L., and Wolf, S., “EPICS: the exoplanet imager for the E-ELT,” in [Adaptive Optics Systems], SPIE 7015, 70151S (July 2008).

[14] Mawet, D., Pueyo, L., Lawson, P., Mugnier, L., Traub, W., Boccaletti, A., Trager, J. T., Gladysz, S., Serabyn, E., Milli, J., Belikov, R., Kasper, M., Baudou, P., Macintosh, B., Marois, C., Oppenheimer, B., Barrett, H., Beuzit, J.-L., Devany, N., Girard, J., Guyon, O., Krist, J., Mennesson, B., Mouillet, D., Murakami, N., Poyneer, L., Savransky, D., Vérinaud, C., and Wallace, J. K., “Review of small-angle coronagraphic techniques in the wake of ground-based second-generation adaptive optics systems,” Proc. SPIE 8442, 844204 (Sept. 2012).

[15] Baudou, P., Mazoyer, J., Mas, M., Galicher, R., and Rousset, G., “Dark hole and planet detection: laboratory results using the self-coherent camera,” Proc. SPIE 8446, 84468C (Sept. 2012).
[16] Lagrange, A.-M., Gratadour, D., Chauvin, G., Fusco, T., Ehrenreich, D., Mouillet, D., Rouan, D., Allard, F., Gendron, É., Charton, J., Mugnier, L., Rabou, P., Montri, J., and Lacombe, F., “A probable giant planet imaged in the β Pictoris disk. VLT/NaCo deep L’-band imaging,” A&A 493, L21–L25 (Jan. 2009).

[17] Close, L. M., Follette, K. B., Males, J. R., Puglisi, A., Xompero, M., Apai, D., Najita, J., Weinberger, A. J., Morzinski, K., Rodigas, T. J., Hinz, P., Bailey, V., and Briguglio, R., “Discovery of Hα Emission from the Close Companion inside the Gap of Transitional Disk HD 142527,” ApJL 781, L30 (Feb. 2014).

[18] Racine, R., Walker, G. A. H., Nadeau, D., Doyon, R., and Marois, C., “Speckle Noise and the Detection of Faint Companions,” PASP 111, 587–594 (May 1999).

[19] Marois, C., Doyon, R., Racine, R., and Nadeau, D., “Efficient Speckle Noise Attenuation in Faint Companion Imaging,” PASP 112, 91–96 (Jan. 2000).

[20] Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., and Nadeau, D., “Angular Differential Imaging: A Powerful High-Contrast Imaging Technique,” ApJ 641, 556–564 (Apr. 2006).

[21] Soummer, R., Pueyo, L., and Larkin, J., “Detection and Characterization of Exoplanets and Disks Using Projections on Karhunen-Loève Eigenimages,” ApJL 755, L28 (Aug. 2012).

[22] Amara, A. and Quanz, S. P., “PYNPOINT: an image processing package for finding exoplanets,” MNRAS 427, 948–955 (Dec. 2012).

[23] Sparks, W. B. and Ford, H. C., “Imaging Spectroscopy for Extrasolar Planet Detection,” ApJ 578, 543–564 (Oct. 2002).

[24] Mesa, D., Gratton, R., Zurlo, A., Vigan, A., Claudi, R. U., Alberi, M., Antichi, J., Baruffolo, A., Beuzit, J.-L., Boccaletti, A., Bonnefoy, M., Costille, A., Desidera, S., Dohlen, K., Fantinel, D., Feldt, M., Fusco, T., Giro, E., Henning, T., Kasper, M., Langlois, M., Maire, A.-L., Martin, P., Moeller-Nilsson, O., Mouillet, D., Moutou, C., Pavlov, A., Puget, P., Salasnich, B., Sauvage, J.-F., Sissa, E., Turatto, M., Udry, S., Vakili, F., Waters, R., and Wildi, F., “Performance of the VLT Planet Finder SPHERE. II. Data analysis and results for IFS in laboratory,” A&A 576, A121 (Apr. 2015).

[25] Hoeijmakers, H. J., Schwarz, H., Snellen, I. A. G., de Kok, R. J., Bonnefoy, M., Chauvin, G., Lagrange, A. M., and Girard, J. H., “Medium-resolution integral-field spectroscopy for high-contrast exoplanet imaging: Molecule maps of the β Pictoris system with SINFONI,” ArXiv e-prints (Feb. 2018).

[26] Kastner, J. H., Zuckerman, B., Weintraub, D. A., and Forveille, T., “X-ray and molecular emission from the nearest region of recent star formation,” Science 277, 67–71 (1997).
[32] Zuckerman, B. and Song, I., “Young Stars Near the Sun,” *ARAA* **42**, 685–721 (Sept. 2004).

[33] Torres, C. A. O., Quast, G. R., Melo, C. H. F., and Sterzik, M. F., “Young Nearby Loose Associations,” (Dec. 2008).

[34] Gagné, J., Lafrenière, D., Doyon, R., Malo, L., and Artigau, É., “BANYAN. V. A Systematic All-sky Survey for New Very Late-type Low-mass Stars and Brown Dwarfs in Nearby Young Moving Groups,” *ApJ* **798**, 73 (Jan. 2015).

[35] Chabrier, G., Baraffe, I., Allard, F., and Hauschildt, P., “Evolutionary Models for Very Low-Mass Stars and Brown Dwarfs with Dusty Atmospheres,” *ApJ* **542**, 464–472 (Oct. 2000).

[36] Lowrance, P. J., McCarthy, C., Becklin, E. E., Zuckerman, B., Schneider, G., Webb, R. A., Hines, D. C., Kirkpatrick, J. D., Koerner, D. W., Low, F., Meier, R., Rieke, M., Smith, B. A., Terrile, R. J., and Thompson, R. I., “A Candidate Substellar Companion to CD -337795 (TWA 5),” *ApJ* **512**, L69–L72 (Feb. 1999).

[37] Lowrance, P. J., Schneider, G., Kirkpatrick, J. D., Becklin, E. E., Weinberger, A. J., Zuckerman, B., Plait, P., Malmuth, E. M., Heap, S. R., Schultz, A., Smith, B. A., Terrile, R. J., and Hines, D. C., “A Candidate Substellar Companion to HR 7329,” *ApJ* **541**, 390–395 (Sept. 2000).

[38] Hennebelle, P. and Chabrier, G., “Analytical Star Formation Rate from Gravitoturbulent Fragmentation,” *ApJL* **743**, L29 (Dec. 2011).

[39] Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckerman, B., Mouillet, D., Song, I., Beuzit, J.-L., and Lowrance, P., “Giant planet companion to 2MASSW J1207334-393254,” *A&A* **438**, L25–L28 (Aug. 2005).

[40] Lafrenière, D., Jayawardhana, R., and van Kerkwijk, M. H., “Direct Imaging and Spectroscopy of a Planetary-Mass Candidate Companion to a Young Solar Analog,” *ApJL* **689**, L153 (Dec. 2008).

[41] Marois, C., Macintosh, B., Barman, T., Zuckerman, B., Song, I., Patience, J., Lafrenière, D., and Doyon, R., “Direct Imaging of Multiple Planets Orbiting the Star HR 8799,” *Science* **322**, 1348 (Nov. 2008).

[42] Marois, C., Zuckerman, B., Konopacky, Q. M., Macintosh, B., and Barman, T., “Images of a fourth planet orbiting HR 8799,” *Nature* **468**, 1080–1083 (Dec. 2010).

[43] Kalas, P., Graham, J. R., Chiang, E., Fitzgerald, M. P., Clampin, M., Kite, E. S., Stape1feldt, K., Marois, C., and Krist, J., “Optical Images of an Exosolar Planet 25 Light-Years from Earth,” *Science* **322**, 1345 (Nov. 2008).

[44] Carson, J., Thalmann, C., Janson, M., Kozakis, T., Bonnefoy, M., Biller, B., Schlieder, J., Currie, T., McElwain, M., Goto, M., Henning, T., Brandner, W., Feldt, M., Kandori, R., Kuzuhara, M., Stevens, L., Wong, P., Gainey, K., Fukagawa, M., Kuvada, Y., Brandt, T., Kwon, J., Abe, L., Egner, S., Grady, C., Guyon, O., Hashimoto, J., Hayano, Y., Hayashi, M., Hayashi, S., Hodapp, K., Ishii, M., Iye, M., Knapp, G., Kudo, T., Kusakabe, N., Matsuo, T., Miyama, S., Morino, J., Moro-Martín, A., Nishimura, T., Pyo, T., Serabyn, E., Suto, H., Suzuki, R., Takami, R., Takato, N., Terada, H., Tomono, D., Turner, E., Watanabe, M., Wisniewski, J., Yamada, T., Takami, H., Usuda, T., and Tamura, M., “Direct Imaging Discovery of a "Super-Jupiter" around the Late B-type Star κ And,” *ApJL* **763**, L32 (Feb. 2013).

[45] Rameau, J., Chauvin, G., Lagrange, A.-M., Boccaletti, A., Quanz, S. P., Bonnefoy, M., Girard, J. H., Delorme, P., Desidera, S., Klahr, H., Mordasini, C., Dumas, C., and Bonavita, M., “Discovery of a Probable 4-5 Jupiter-mass Exoplanet to HD 95086 through Direct Imaging,” *ApJL* **772**, L15 (Aug. 2013).

[46] Kuzuhara, M., Tamura, M., Kudo, T., Janson, M., Kandori, R., Brandt, T. D., Thalmann, C., Spiegel, D., Biller, B., Carson, J., Hori, Y., Suzuki, R., Burrows, A., Henning, T., Turner, E. L., McElwain, M. W., Moro-Martín, A., Sunagawa, T., Takahashi, Y. H., Kwon, J., Lucas, P., Abe, L., Brandner, W., Egner, S., Feldt, M., Fujiwara, H., Goto, M., Grady, C. A., Guyon, O., Hashimoto, J., Hayano, Y., Hayashi, M., Hayashi, S. S., Hodapp, K., Ishii, M., Iye, M., Knapp, G. R., Matsuo, T., Mayama, S., Miyama, S., Morino, J.-I., Nishikawa, J., Nishimura, T., Kotani, T., Kusakabe, N., Pyo, T.-S., Serabyn, E., Suto, H., Takami, M., Takato, N., Terada, H., Tomono, D., Watanabe, M., Wisniewski, J. P., Yamada, T., Takami, H., and Usuda, T., “Direct Imaging of a Cold Jovian Exoplanet in Orbit around the Sun-like Star GJ 504,” *ApJ* **774**, 11 (Sept. 2013).
Macintosh, B., Graham, J. R., Barman, T., De Rosa, R. J., Konopacky, Q., Marley, M. S., Marois, C., Nielsen, E. L., Pueyo, L., Rajan, A., Rameau, J., Saumon, D., Wang, J. J., Patience, J., Ammons, M., Arriaga, P., Artigau, E., Beckwith, S., Brewster, J., Bruzzone, S., Bulger, J., Burningham, B., Burrows, A. S., Chen, C., Chiang, E., Chilcote, J. K., Dawson, R. I., Dong, R., Doyon, R., Draper, Z. H., Duchêne, G., Esposito, T. M., Fabrycky, D., Fitzgerald, M. P., Follette, K. B., Fortney, J. J., Gerard, B., Goodsell, S., Greenbaum, A. Z., Hibon, P., Hinkley, S., Cotten, T. H., Hung, L.-W., Ingraham, P., Johnson-Groh, M., Kalas, P., Lafrenière, D., Larkin, J. E., Lee, J., Line, M., Long, D., Maire, J., Marchis, F., Matthews, B. C., Max, C. E., Metchev, S., Millar-Blanchaer, M. A., Mittal, T., Morley, C. V., Morzinski, K. M., Murray-Clay, R., Oppenheimer, R., Palmer, D. W., Petal, R., Perrin, M. D., Peyne, L. A., Rafikov, R. R., Rantakyrö, F. T., Rice, E. L., Rojo, P., Rudy, A. R., Ruffio, J.-B., Ruiz, M. T., Sadakuni, N., Saddlemeyer, L., Salama, M., Savransky, D., Schneider, A. C., Sivaramakrishnan, A., Song, I., Soummer, R., Thomas, S., Vasisht, G., Wallace, J. K., Ward-Duong, K., Wiktorowicz, S. J., Wolff, S. G., and Zuckerman, B., “Discovery and spectroscopy of the young jovian planet 51 Eri b with the Gemini Planet Imager,” *Science* **350**, 64–67 (Oct. 2015).

Chauvin, G., Desidera, S., Lagrange, A.-M., Vigan, A., Gratton, R., Langlois, M., Bonnefoy, M., Beuzit, J.-L., Feldt, M., Mousliet, D., Meyer, M., Cheetham, A., Biller, B., Boccaletti, A., D’Orazi, V., Galicher, R., Hagelberg, J., Maire, A.-L., Mesa, D., Olofsson, J., Samland, M., Schmidt, T. O. B., Sissa, E., Bonavita, M., Charnay, B., Cudel, M., Daemgen, S., Delorme, P., Janin-Potiron, P., Janson, M., Kepler, M., Le Coroller, H., Ligi, R., Marleau, G. D., Messina, S., Mollière, P., Mordasini, C., Müller, A., Peretti, S., Perrot, C., Rodet, L., Rouan, D., Turatto, M., Udry, S., Vakili, F., Abe, L., Antichi, J., Baruffolo, A., Baudouz, P., Brandner, J., Blanchard, P., Bazzon, A., Buey, T., Carbillet, M., Carle, M., Charton, J., Cascone, E., Claudi, R., Coudé, A., De Caprio, V., Dohlen, K., Fantinel, D., Feautrier, P., Fusco, T., Gigan, P., Gisler, D., Gluck, L., Hugot, E., Jaquet, M., Kasper, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Llored, M., Moulin, T., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rigal, R., Rochat, S., Roelfsema, R., Rouset, G., Roux, A., Salasnich, B., Sauvage, J.-F., Sevin, A., Soenke, C., Stadle, E., Suarez, M., Weber, L., Wildi, F., Antoniucci, S., Augereau, J.-C., Baudino, J.-L., Brandner, W., Engler, N., Girard, J., Gry, C., Kral, Q., Kopytova, T., Lagadec, E., Milli, J., Moutou, C., Schlieder, J., Szulágyi, J., Thalmann, C., and Wahhaj, Z., “Discovery of a warm, dusty giant planet around HIP 65426,” *A&A* **605**, L9 (Sept. 2017).

Chauvin, G., Desidera, S., Lagrange, A.-M., Vigan, A., Gratton, R., Langlois, M., Bonnefoy, M., Beuzit, J.-L., Feldt, M., Mouliet, D., Meyer, M., Cheetham, A., Biller, B., Boccaletti, A., D’Orazi, V., Galicher, R., Hagelberg, J., Maire, A.-L., Mesa, D., Olofsson, J., Samland, M., Schmidt, T. O. B., Sissa, E., Bonavita, M., Charnay, B., Cudel, M., Daemgen, S., Delorme, P., Janin-Potiron, P., Janson, M., Kepler, M., Le Coroller, H., Ligi, R., Marleau, G. D., Messina, S., Mollière, P., Mordasini, C., Müller, A., Peretti, S., Perrot, C., Rodet, L., Rouan, D., Turatto, M., Udry, S., Vakili, F., Abe, L., Antichi, J., Baruffolo, A., Baudouz, P., Baudrand, J., Blanchard, P., Bazzon, A., Buey, T., Carbillet, M., Carle, M., Charton, J., Cascone, E., Claudi, R., Coudé, A., De Caprio, V., Dohlen, K., Fantinel, D., Feautrier, P., Fusco, T., Gigan, P., Gisler, D., Gluck, L., Hubin, N., Hugot, E., Jaquet, M., Kasper, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Llored, M., Moulin, T., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rigal, R., Rochat, S., Roelfsema, R., Rouset, G., Roux, A., Salasnich, B., Sauvage, J.-F., Sevin, A., Soenke, C., Stadle, E., Suarez, M., Weber, L., Wildi, F., Antoniucci, S., Augereau, J.-C., Baudino, J.-L., Brandner, W., Engler, N., Girard, J., Gry, C., Kral, Q., Kopytova, T., Lagadec, E., Milli, J., Moutou, C., Schlieder, J., Szulágyi, J., Thalmann, C., and Wahhaj, Z., “Discovery of a warm, dusty giant planet around HIP 65426,” *A&A* **605**, L9 (Sept. 2017).

Mordasini, C., “Luminosity of young Jupiters revisited. Massive cores make hot planets,” *A&A* **558**, A113 (Oct. 2013).

Sallum, S., Follette, K. B., Eisner, J. A., Close, L. M., Hinz, P., Kratter, K., Males, J., Skemer, A., Macintosh, B., Tuthill, P., Bailey, V., Defrère, D., Morzinski, K., Rodigas, T., Spalding, E., Vaz, A., and Weinberger, A. J., “Accreting protoplanets in the LkCa 15 transition disk,” *Nature* **527**, 342–344 (Nov. 2015).

Metchev, S. A., Heinze, A., Apai, D., Plavchan, P., and Goldman, B., “Weather on Other Worlds. II. Survey Results: Spots are Ubiquitous on L and T Dwarfs,” *ApJ* **799**, 154 (Feb. 2015).

Morzinski, K. M., Males, J. R., Skemer, A. J., Close, L. M., Hinz, P. M., Rodigas, T. J., Puglisi, A., Esposito, S., Riccardi, A., Pinna, E., Kompero, M., Briguglio, R., Bailey, V. P., Follette, K. B., Kopon, D., Weinberger, A. J., and Wu, Y.-L., “Magellan Adaptive Optics First-light Observations of the Exoplanet β Pic b. II. 3-5 μm Direct Imaging with MagAO+Clio, and the Empirical Bolometric Luminosity of a Self-luminous Giant Planet,” *ApJ* **815**, 108 (Dec. 2015).

Bonnefoy, M., Boccaletti, A., Lagrange, A.-M., Allard, F., Mordasini, C., Beust, H., Chauvin, G., Girard, J. H. V., Homeier, D., Apai, D., Lacour, S., and Rouan, D., “The near-infrared spectral energy distribution of β Pictoris b,” *A&A* **555**, A107 (July 2013).
[55] Lagrange, A.-M., De Bondt, K., Meunier, N., Sterzik, M., Beust, H., and Galland, F., “Constraints on planets around $\beta$ Pic with Harps radial velocity data,” *A&A* **542**, A18 (June 2012).

[56] Mesa, D., Vigan, A., D’Orazi, V., Ginski, C., Desidera, S., Bonnefoy, M., Gratton, R., Langlois, M., Marzari, F., Messina, S., Antichi, J., Biller, B., Bonavita, M., Cascone, E., Chauvin, G., Claudi, R. U., Curtis, I., Fantinel, D., Feldt, M., Garufi, A., Galicher, M., Henning, T., Incorvaia, S., Lagrange, A.-M., Millward, M., Perrot, C., Salasnich, B., Scuderi, S., Sissa, E., Wahhaj, Z., and Zurlö, A., “Characterizing HR 3549 B using SPHERE,” *A&A* **593**, A119 (Oct. 2016).

[57] Chilcote, J., Barman, T., FitzGerald, M. P., Graham, J. R., Larkin, J. E., Macintosh, B., Bauman, B., Burrows, A. S., Cardwell, A., De Rosa, R. J., Dillon, D., Doyon, R., Dunn, J., Erikson, D., Gavel, D., Goodsell, S. J., Hartung, M., Hibon, P., Ingraham, P., Kalas, P., Konopacky, Q., Maire, J., Marchis, F., Marley, M. S., Marois, C., Millar-Blanchaer, M., Morzinski, K., Norton, A., Oppenheimer, R., Palmer, D., Patience, J., Perrin, M., Poyneer, L., Pueyo, L., Rantakyrö, F. T., Sadakuni, N., Sadler, E. M., Savransky, D., Serio, A., Sivaramakrishnan, A., Song, I., Soummer, R., Thomas, S., Wallace, J. K., Wiktorowicz, S., and Wolff, S., “The First H-band Spectrum of the Giant Planet $\beta$ Pictoris b,” *ApJL* **798**, L3 (Jan. 2015).

[58] De Rosa, R. J., Rameau, J., Patience, J., Graham, J. R., Doyon, R., Lafrenière, D., Macintosh, B., Pueyo, L., Rajan, A., Wang, J. J., Ward-Duong, K., Hung, L.-W., Maire, J., Nielsen, E. L., Ammons, S. M., Bulger, J., Cardwell, A., Chilcote, J. K., Galvez, R. L., Gerard, B. L., Goodsell, S., Hartung, M., Hibon, P., Ingraham, P., Johnson-Groh, M., Kalas, P., Konopacky, Q. M., Marchis, F., Marois, C., Metchev, S., Morzinski, K. M., Oppenheimer, R., Perrin, M. D., Rantakyrö, F. T., Savransky, D., and Thomas, S., “Spectroscopic Characterization of HD 95086 b with the Gemini Planet Imager,” *ApJ* **824**, 121 (June 2016).

[59] Samland, M., Mollière, P., Bonnefoy, M., Maire, A.-L., Cantalloube, F., Cheetham, A. C., Mesa, D., Gratton, R., Biller, B. A., Wahhaj, Z., Bouwman, J., Brandner, W., Melnick, D., Carson, J., Janson, M., Henning, T., Homeier, D., Mordasini, C., Langlois, M., Quanz, S. P., van Boekel, R., Zurlö, A., Schlieder, J. E., Avenhaus, H., Beuzit, J.-L., Boccaletti, A., Bonavita, M., Chauvin, G., Claudi, R. U., Delorme, P., Farisato, G., Feldt, M., Giro, E., Hagelberg, J., Incorvaia, S., Lagrange, A.-M., Lazzoni, C., Lessio, L., Salasnich, B., Scuderi, S., Sissa, E., and Turatto, M., “New spectro-photometric characterization of the substellar object 51 Eridani b using VLT/SPHERE,” *A&A* **603**, A57 (July 2017).

[60] Mesa, D., Baudino, J.-L., Charnay, B., D’Orazi, V., Desidera, S., Boccaletti, A., Gratton, R., Bonnefoy, M., Delorme, P., Langlois, M., Vigan, A., Zurlø, A., Maire, A.-L., Janson, M., Antichi, J., Baruffolo, A., Bruno, P., Cascone, E., Chauvin, G., Claudi, R. U., De Caprio, V., Fantinel, D., Farisato, G., Feldt, M., Giro, E., Hagelberg, J., Incorvaia, S., Lagrange, A.-M., Lazzoni, C., Lessio, L., Salasnich, B., Scuderi, S., Sissa, E., and Turatto, M., “New spectro-photometric characterization of the substellar object HR 2562 B using SPHERE,” *A&A* **612**, A92 (May 2018).

[61] Cheetham, A., Bonnefoy, M., Desidera, S., Langlois, M., Vigan, A., Schmidt, T., Olofsson, J., Chauvin, G., Klahr, H., Gratton, R., D’Orazi, V., Henning, T., Janson, M., Biller, B., Peretti, S., Hagelberg, J., Ségransan, D., Udry, S., Mesa, D., Krul, Q., Schlieder, J., Maire, A.-L., Mordasini, C., Menard, F., Zurlö, A., Beuzit, J.-L., Feldt, M., Mouillet, D., Meyer, M., Lagrange, A.-M., Boccaletti, A., Kepller, M., Kopytova, T., Ligi, R., Rouan, D., Le Coroller, H., Dominik, C., Lagadec, E., Turatto, M., Abe, L., Antichi, J., Baruffolo, A., Baudouz, P., Blanchard, P., Buey, T., Carlibet, M., Carle, M., Cascone, E., Claudi, R., Costille, A., Delboulbé, A., De Caprio, V., Dohlen, K., Fantinel, D., Feautrier, P., Fusco, T., Giro, E., Gluck, L., Hubin, N., Hugot, E., Jaquet, M., Kasper, M., Llored, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Le Mignant, D., Möller-Nilsson, O., Moulin, T., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rigal, F., Rockah, S., Roelfsema, R., Roux, G., Roux, A., Salasnich, B., Sauvage, J.-F., Sevin, A., Soenke, C., Stadler, E., Suarez, M., Weber, L., and Wildi, F., “Discovery of a brown dwarf companion to the star HIP 64892,” *ArXiv e-prints* (Mar. 2018).

[62] Konopacky, Q. M., Marois, C., Macintosh, B. A., Galicher, R., Barman, T. S., Metchev, S. A., and Zuckerman, B., “Astrometric Monitoring of the HR 8799 Planets: Orbit Constraints from Self-consistent Measurements,” *AJ* **152**, 28 (Aug. 2016).

[63] Barman, T. S., Konopacky, Q. M., Macintosh, B., and Marois, C., “Simultaneous Detection of Water, Methane, and Carbon Monoxide in the Atmosphere of the Exoplanet HR8799b,” *ApJ* **804**, 61 (May 2015).
Chauvin, G., Lagrange, A.-M., Beust, H., Bonnefoy, M., Boccaletti, A., Apai, D., Allard, F., Ehrenreich, D., Girard, J. H. V., Mouillet, D., and Rouan, D., “Orbital characterization of the β Pictoris b giant planet,” A&A 542, A41 (June 2012).

Wang, J. J., Graham, J. R., Pueyo, L., Kalas, P., Millar-Blanchaer, M. A., Ruffio, J.-B., De Rosa, R. J., Ammons, S. M., Arriaga, P., Bailey, V. P., Barman, T. S., Bulger, J., Burrows, A. S., Cardwell, A., Chen, C. H., Chilcote, J. K., Cotten, T., Fitzgerald, M. P., Follette, K. B., Doyon, R., Duchêne, G., Greenbaum, A. Z., Hibon, P., Hung, L.-W., Ingraham, P., Konopacky, Q. M., Larkin, J. E., Macintosh, B., Maire, J., Marchis, F., Marley, M. S., Marois, C., Metchev, S., Nielsen, E. L., Oppenheimer, R., Palmer, D. W., Patel, R., Patience, J., Perrin, M. D., Poyneer, L. A., Rajan, A., Rameau, J., Rantakyrö, F. T., Savransky, D., Sivaramakrishnan, A., Song, I., Soummer, R., Thomas, S., Vasisht, G., Vega, D., Wallace, J. K., Ward-Duong, K., Wiktorowicz, S. J., and Wolff, S. G., “The Orbit and Transit Prospects for β Pictoris b Constrained with One Milliarcsecond Astrometry,” AJ 152, 97 (Oct. 2016).

Pueyo, L., Soummer, R., Hoffmann, J., Oppenheimer, R., Graham, J. R., Zimmerman, N., Zhai, C., Wallace, J. K., Vescelus, F., Veicht, A., Vasisht, G., Truong, T., Sivaramakrishnan, A., Shao, M., Roberts, Jr., L. C., Roberts, J. E., Rice, E., Parry, I. R., Nilsson, R., Lockhart, T., Ligon, E. R., King, D., Hinkley, S., Hillenbrand, L., Hale, D., Dekany, R., Crepp, J. R., Cady, E., Burruss, R., Brenner, D., Beichman, C., and Baraneč, C., “ Reconnaissance of the HR 8799 Exosolar System. II. Astrometry and Orbital Motion,” ApJ 803, 31 (Apr. 2015).

Maire, A.-L., Skemer, A. J., Hinz, P. M., Desidera, S., Exposito, S., Gratton, R., Marzari, F., Skrutskie, M. F., Biller, B. A., Defrère, D., Bailey, V. P., Leisewid, J. M., Apai, D., Bonnefoy, M., Brandner, W., Buenzli, E., Claud, R. U., Close, L. M., Crepp, J. R., De Rosa, R. J., Eisner, J. A., Fortney, J. J., Henning, T., Hofmann, K.-H., Kopytova, T. G., Males, J. R., Mesa, D., Morzinski, K. M., Oza, A., Patience, J., Pinna, E., Rajan, A., Schertl, D., Schlindl, J. E., Su, K. Y. L., Vaz, A., Ward-Duong, K., Weigelt, G., and Woodward, C. E., “The LEECH Exoplanet Imaging Survey. Further constraints on the planet architecture of the HR 8799 exoplanetary system,” A&A 579, C2 (July 2015).

Zurlo, A., Vigan, A., Galicher, R., Maire, A.-L., Mesa, D., Gratton, R., Chauvin, G., Kasper, M., Moutou, C., Bonnefoy, M., Desidera, S., Aebi, L., Apai, D., Baruffolo, A., Baudouin, P., Baudrand, J., Beuzit, J.-L., Blancard, P., Boccaletti, A., Cantalloube, F., Carle, M., Cascone, E., Charton, J., Claud, R. U., Costille, A., de Caprio, V., Dohlen, K., Dominik, C., Fantinel, D., Feautrier, P., Feldt, M., Fusco, T., Gigan, P., Girard, J. H., Gisler, D., Gluck, L., Gry, C., Henning, T., Hugot, E., Janson, M., Jaquet, M., Lagrange, A.-M., Langlois, M., Llored, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Mawet, D., Meyer, M. R., Milli, J., Moelker-Nilsson, O., Moillet, D., Origné, A., Pavlov, A., Petit, C., Puget, P., Quanz, S. P., Rabou, P., Ramos, J., Rousseau, G., Roux, A., Salasnich, B., Salter, G., Sauvage, J.-F., Schmid, H. M., Soenke, C., Stadel, E., Suarez, M., Turatto, M., Udry, S., Vakili, F., Wahhaj, Z., Wildi, F., and Antichi, J., “First light of the VLT planet finder SPHERE. III. New spectrophotometry and astrometry of the HR 8799 exoplanetary system,” A&A 579, A57 (Mar. 2016).

Rameau, J., Nielsen, E. L., De Rosa, R. J., Blunt, S. C., Patience, J., Doyon, R., Graham, J. R., Lafrenière, D., Macintosh, B., Marchis, F., Bailey, V., Chilcote, J. K., Duchêne, G., Lépine, J.-R., Konopacky, Q. M., Maire, J., Marois, C., Metchev, S., Perrin, M. D., Pueyo, L., Rajan, A., Savransky, D., Wang, J. J., Ward-Duong, K., Wolf, S. G., Ammons, S. M., Hibon, P., Ingraham, P., Kalas, P., Morzinski, K. M., Oppenheimer, R., Rantakyrö, F. T., and Thomas, S., “ Constraints on the Architecture of the HD 95086 Planetary System with the Gemini Planet Imager,” ApJL 822, L29 (May 2016).

Chauvin, G., Gratton, R., Bonnefoy, M., Lagrange, A.-M., de Boer, J., Vigan, A., Beust, H., Lazennec, C., Boccaletti, A., Galicher, R., Desidera, S., Delorme, P., Keppler, M., Lannier, J., Maire, A.-L., Mesa, D., Mennier, N., Kral, Q., Henning, T., Menard, F., Moor, A., Avenhaus, H., Bazzon, A., Janson, M., Beuzit, J.-L., Blomnik, T., Bonavita, M., Borgniet, S., Brandner, W., Cieza, A., Cudel, M., Feldt, M., Fontanive, C., Ginski, C., Hagelberg, J., Janin-Potiron, P., Lagadec, E., Langlois, M., Le Coroller, H., Messina, S., Meyer, M., Mouillet, D., Perret, S., Perro, C., Rodet, L., Samland, M., Sissa, E., Olofsson, J., Salter, G., Schmidt, T., Zurlo, A., Milli, J., van Boekel, R., Quanz, S., Wilson, P. A., Feautrier, P., Le Mignant, D., Perret, D., Ramos, J., and Rochat, S., “Investigating the young Solar System analog HD95086,” A&A (Jan. 2018).
[71] Booth, M., Jordán, A., Casassus, S., Hales, A. S., Dent, W. R. F., Faramaz, V., Matrà, L., Barkats, D., Brahms, R., and Cuadra, J., “Resolving the planetesimal belt of HR 8799 with ALMA,” *MNRAS* **460**, L10–L14 (July 2016).

[72] Augereau, J. C., Nelson, R. P., Lagrange, A. M., Papaloizou, J. C. B., and Mouillet, D., “Dynamical modeling of large scale asymmetries in the beta Pictoris dust disk,” *A&A* **370**, 447–455 (May 2001).

[73] Dawson, R. I., Murray-Clay, R. A., and Fabrycky, D. C., “On the Misalignment of the Directly Imaged Planet β Pictoris b with the System’s Warped Inner Disk,” *ApJL* **743**, L17 (Dec. 2011).

[74] Lagrange, A.-M., Boccaletti, A., Milli, J., Chauvin, G., Bonnefoy, M., Mouillet, D., Augereau, J. C., Girard, J. H., Lacour, S., and Apai, D., “The position of β Pictoris b position relative to the debris disk,” *A&A* **542**, A40 (June 2012).

[75] Kennedy, G. M. and Wyatt, M. C., “Do two-temperature debris discs have multiple belts?,” *MNRAS* **444**, 3164–3182 (Nov. 2014).

[76] Bonsor, A. and Wyatt, M. C., “The scattering of small bodies in planetary systems: constraints on the possible orbits of cometary material,” *MNRAS* **420**, 2990–3002 (Mar. 2012).

[77] Mayor, M. and Queloz, D., “A Jupiter-mass companion to a solar-type star,” *Nature* **378**, 355–359 (Nov. 1995).

[78] Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., and Greenzweig, Y., “Formation of the Giant Planets by Concurrent Accretion of Solids and Gas,”

[79] Cameron, A. G. W., “Physics of the primitive solar accretion disk,” *Moon and Planets* **18**, 5–40 (Feb. 1978).

[80] Lambrechts, M. and Johansen, A., “Rapid growth of gas-giant cores by pebble accretion,” *A&A* **544**, A32 (Aug. 2012).

[81] Crida, A., Masset, F., and Morbidelli, A., “Long Range Outward Migration of Giant Planets, with Application to Fomalhaut b,” *ApJL* **705**, L148–L152 (Nov. 2009).

[82] Boley, A. C., “The Two Modes of Gas Giant Planet Formation,” *ApJL* **695**, L53–L57 (Apr. 2009).

[83] Bowler, B. P., “Imaging Extrasolar Giant Planets,” *PASP* **128**, 102001 (Oct. 2016).

[84] Nielsen, E. L., Close, L. M., Biller, B. A., Masciadri, E., and Lenzen, R., “Constraints on Extrasolar Planet Populations from VLT NACO/SDI and MMT SDI and Direct Adaptive Optics Imaging Surveys: Giant Planets are Rare at Large Separations,” *ApJL* **674**, 466–481 (Feb. 2008).

[85] Forgan, D., Parker, R. J., and Rice, K., “The dynamical fate of self-gravitating disc fragments after tidal downsizing,” *MNRAS* **447**, 836–845 (Feb. 2015).

[86] Ida, S., Lin, D. N. C., and Nagasawa, M., “Toward a Deterministic Model of Planetary Formation. VII. Eccentricity Distribution of Gas Giants,” *ApJ* **755**, 42 (Sept. 2013).

[87] Vigan, A., Bonavita, M., Biller, B., Forgan, D., Rice, K., Chauvin, G., Desidera, S., Meunier, J.-C., Delorme, P., Schlieder, J. E., Bonnefoy, M., Carson, J., Covino, E., Hagelberg, J., Henning, T., Janson, M., Lagrange, A.-M., Quanz, S. P., Zurlo, A., Beuzit, J.-L., Boccaletti, A., Buenzli, E., Feldt, M., Girard, J. H. V., Gratton, R., Kasper, M., Le Coroller, H., Mesa, D., Messina, S., Meyer, M., Montagnier, G., Mordasini, C., Mouillet, D., Moutou, C., Reggiani, M., Segransan, D., and Thalmann, C., “The VLT/NaCo large program to probe the occurrence of exoplanets and brown dwarfs at wide orbits. IV. Gravitational instability rarely forms wide, giant planets,” *A&A* **509**, A52 (Jan. 2010).

[88] Janson, M., Bonavita, M., Klahr, H., Lafrenière, D., Jayawardhana, R., and Zinnecker, H., “High-contrast Imaging Search for Planets and Brown Dwarfs around the Most Massive Stars in the Solar Neighborhood,” *ApJ* **736**, 89 (Aug. 2011).

[89] Rameau, J., Chauvin, G., Lagrange, A.-M., Klahr, H., Bonnefoy, M., Mordasini, C., Bonavita, M., Desidera, S., Dumas, C., and Girard, J. H., “A survey of young, nearby, and dusty stars conducted to understand the formation of wide-orbit giant planets. VLT/NaCo adaptive optics thermal and angular differential imaging,” *A&A* **553**, A60 (May 2013).
[91] Chauvin, G., Vigan, A., Bonnefoy, M., Desidera, S., Bonavita, M., Mesa, D., Boccaletti, A., Buenzli, E., Carson, J., Delorme, P., Hagelberg, J., Montagnier, G., Mordasini, C., Quanz, S. P., Segransan, D., Thalmann, C., Beuzit, J.-L., Biller, B., Covino, E., Feldt, M., Girard, J., Gratton, R., Henning, T., Kasper, M., Lagrange, A.-M., Messina, S., Meyer, M., Mouillet, D., Moutou, C., Reggiani, M., Schlieder, J. E., and Zurlo, A., “The VLT/NaCo large program to probe the occurrence of exoplanets and brown dwarfs at wide orbits. II. Survey description, results, and performances,” A&A 573, A127 (Jan. 2015).