Warped Kaluza-Klein Dark Matter

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Warped KK Dark Matter

Dark Matter

KK DM

Decays

Discussion
Outline

1. Review of Dark Matter
2. Kaluza-Klein Dark Matter from String Theory
3. Decay Rates
4. Discussion and Future Directions
Concordance Cosmology
Agreement of many observations
- Few percent normal matter
- 5-6× as much dark matter: Invisible except gravitationally
- Mostly dark energy

We review
- Evidence
- Usual particle physics
- Decay rates
Concordance Cosmology
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(NASA/WMAP Science Team)
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Review of Dark Matter

Evidence

Velocities

Stars in galaxies:
- Kepler: speeds should drop
- Instead increase!

Clusters of galaxies:
- Galaxy speeds
- Temperature of gas

Much more mass than what’s visible

(Sheffield Univ, PPPA group)  
(Hubble, Chandra, VLA)
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Review of Dark Matter
Evidence

Gravitational Lensing
- Background images distorted
- Map mass from lensing
- Mass not aligned with light

(Hubble, Chandra, Magellan)

(NASA, ESA, Jee & Ford)
Review of Dark Matter
Evidence

Structure Formation
- Regular matter feels pressure
- Can’t clump as soon
- Observations match prediction for dark matter of same amount

(WMAP)
What Do We Know About Dark Matter?

- Nonrelativistic since early times
- Interactions with atoms must be weak
- Stable on cosmological time scales
- Self-interactions must be weak
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  *Expect new particles at masses near TeV*

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May naturally occur in string theory
Review of Dark Matter
Weakly Interacting Massive Particle

Why TeV Scale Assumed?
- Thermal particle production
- Expansion cools universe
  Particles are more spread out
- Particles not energetic enough
  \[ n_{DM} \propto \exp\left(-\frac{M c^2}{k T}\right) \]
- Too dilute to annihilate
  Stable so relic population
- Density \( n_{DM} \propto \frac{1}{\sigma_{ann}} \)
  Right for TeV masses
  Assume for our candidates
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(E. Kolb)
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Review of Dark Matter
Bounds on Decay Rate

Constraining Dark Matter Lifetime

- At least age of universe
- Recent experiments find excess of high-energy $e^\pm$
- Perhaps decaying dark matter
- Fits lifetime $\tau \sim 10^{26}$ s
- Constraint: for TeV mass
  Lifetime no less than $10^{26}$ s

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- DM annihilation?
- Other signals?
- Exciting time phenomenologically
**Review of Dark Matter**

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Motivations

- Theory-driven modeling
  How does dark matter fit in?
- Broad landscape of string vacua
  Few constraints available
- DM is simple probe
  Survey class of compactifications
- Related to troublesome relics
  (from brane inflation)

Kaluza-Klein Dark Matter

- Review compactifications
- Warped throats
- Dark matter candidates
- Angular excitations of throats
Kaluza-Klein Dark Matter from String Theory

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Review of Compactifications

Well-Understood Class

- Based on Calabi-Yau space
  - Supersymmetric
  - Geometry well-studied
- Extra stringy ingredients:
  - Higher-dimensional flux
  - D3- and D7-branes
  - Orientifold planes
- External & internal warping
  \[ ds^2 = e^{2A(y)} dx^\mu dx_\mu + e^{-2A(y)} d\tilde{s}^2 \]
  Warped throats near singularities
- Some quantum understanding
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Review of Compactifications

Moduli Stabilization
- Free parameters in metric
- Massless scalars (moduli) in 4D
  - Kähler moduli like volume
  - Complex structure
- Phenomenologically problematic
- Need to generate masses
- Flux stabilizes complex structure
- Kähler moduli classically massless
- Stabilized quantum mechanically

Light Fields
- Graviton, possibly moduli
- SM fields (from D-branes)
Kaluza-Klein Dark Matter from String Theory
Warping and Throats

**Beyond Product Spaces**

\[ ds^2 = e^{2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} \tilde{g}_{mn} dy^m dy^n \]

- Large space depends on compact
- Small warping leads to long distance
- Warp factor acts like potential
- Mass falls to low potential
  becomes lighter \( m \rightarrow e^A m \)

**Randall-Sundrum Models**

- 1 extra dimension: line segment
- Exponential warping \( A = -kz \)
- \( AdS_5 \) spacetime
- Hierarchy for SM
Kaluza-Klein Dark Matter from String Theory
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Klebanov-Strassler: A Prototype Throat

- Locally conifold geometry
  \[ d\tilde{s}^2 = e^{-2kz} \left[ dz^2 + \frac{d\hat{s}^2}{k^2} \right] \]
- \( d\hat{s}^2 \) is \( T^{1,1} \sim S^3 \times S^2 \)
- \( \mathbb{R}^{3,1} \times z \) form \( AdS_5 \): \( A = -kz \)
  Same as Randall-Sundrum
- Product \( AdS_5 \times T^{1,1} \)
- Smooth tip with finite \( S^3 \) at \( z_0 \)
- Angular symmetry \( SU(2)^2/U(1) \)
  Slightly broken by compactification
Kaluza-Klein Dark Matter from String Theory
Dark Matter Candidates

**Kaluza-Klein Modes**
- Massive from compact motion
  - Momentum quantized \( m \sim n/R \)
- Warping pulls wavefunction to tip
  - Localized in throat & approximately exponential
  - Warped KK scale: \( m \sim wk \)
    - Use TeV as example
- Labeled by angular charge
  - \( (j, l, r = j_3 - l_3) \)
  - \( j_3 + l_3 \) constrained
  - Also some light modes
- Model-dependence in \( m \) from moduli stabilization

\[ w \equiv e^{-kz_0} \]
Proxy Dark Matter Candidate

- Approximately conserved charge: Lightest charged state is DM candidate
- Masses depend on moduli stabilization
  Consider only KK masses as proxy
- Charged $T^{1,1}$ breathing mode
  Lowest mass for $(1, 0, 0)$ or $(0, 1, 0)$
- Simple structure but couples generally
- Graviton modes much heavier
- Wavefunction (also for uncharged)

$$\gamma^* \propto w^{1+\nu_\ast} e^{(2+\nu_\ast)kz} Y_{(1,0,0)}(\theta)$$

$$\nu_\ast^2 = 4 + \frac{m_5^2}{k^2}$$
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Symmetry Breaking and Decays

- Simple model has exact symmetry
  - Dark matter candidates stable
- Full theory breaks symmetry
  - Dark matter can decay
- Broken by brane positions
  - Decay on brane
- Or deformations of background
  - Lose charge then decay
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Dominant Background Deformation
Should grow at large $z$ to overlap $\gamma^*$

- $T^{1,1}$ breathing has relevant deformations
  Charge $(1, 0, 0)$, $(0, 1, 0)$, or $(1/2, 1/2, \pm 1)$
- Not allowed in classical compactification
  Related to known quantum effects
- Leading behavior protected by symmetry
- Overall behavior: $\Delta \Gamma \approx w^4 e^{2kz}$
- Other deformations allowed
  - Classical and quantum
  - Can tabulate rules to modify decay rates
**Dominant Background Deformation**

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Symmetry Breaking Mixes Charged & Uncharged

- Scan for $\gamma^* \Delta \Gamma \gamma$ terms in potential

$$U \propto \int d^6 y \sqrt{\tilde{g}} \tilde{R} - \frac{g_s}{12} \int d^6 y \sqrt{\tilde{g}} e^{4A} G_{mnp} \left( \bar{G} - i \tilde{\gamma}_6 \bar{G} \right)^{\bar{mnp}}$$

- Throat magnetic field about constant $G_{z\theta\phi} \sim k G_{\theta\phi\psi}$

- Finally $U \approx k^2 w^4 \gamma^*(x) \gamma(x)$ mixing
  Encodes scattering off deformation and losing charge

- Similar mixing with moduli: for volume modulus

$$U \approx (M_s^4 / k M_p) w^{5+\nu_\star} u(x) \gamma^*(x) , \nu_\star < 4$$
Decay Rates

Surveying Models
- Checking for long-lived relics
  Either dark matter or from reheating
- Decay from deformation or directly
- Compare different SM embeddings
- Uncharged KK mode decays similar
- Adapts to include tunneling
- Parameters: \( w \sim 10^{-13}, k \sim M_s \sim 10^{16} \text{ GeV} \)

Decay Channels
- Supergravity modes: Moduli and gravitons
- D3-brane SM fields
- D7-brane SM fields
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Decays to Supergravity Modes

Decays to Moduli
- Relevant for very massive relics
- Two diagrams to moduli:
  - Cubic vertex $\gamma^* u^2$ with $\Delta \Gamma$ from flux
  - Mix with $u$, decay by $u(\partial u)^2$ term
- Decay rate:
  $$\Gamma \approx \frac{M_s^8}{M_p^4 k^3} w^{9+2\nu^*} \approx 10^{-89-26\nu^*} s^{-1}$$
- Incredibly slow decays but sensitive to $w$
- Also considered decays to axion partners
- Possibly charged moduli
  Direct decays $\gamma^* \rightarrow uu^*$ considerably faster
**Decay Rates**

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Decays to Supergravity Modes

Decays to Gravitons

- $\gamma^* hh$ couplings disallowed in Einstein gravity
  Proportional to equation of motion for $\gamma^*$

- Higher derivatives allow couplings
  Simplest $\sim \lambda \gamma^* \partial^4 h^2$ with $\lambda \lesssim 1/m_* M_p^2$

- KK decay rate:
  $$\Gamma \lesssim \frac{w^5 k^5}{M_p^4} \approx 10^{-37} s^{-1}$$

- Bound is faster than decays to moduli

- KK gravitons prohibited from decaying to gravitons at all
**Decay Rates**

**D3-brane Standard Model**

### Original Randall-Sundrum Model
- SM lives on D3-brane
- Sits at tip of throat
- Warping provides SM hierarchy
- Sits at one angle
  - Breaks some angular symmetry
- Some dark matter candidates decay directly on brane
- Other charge sector does not
Decay Rates
D3-brane Standard Model

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Brane Breaks Symmetry

- Direct coupling to scalar kinetic term
  \[ \frac{k^3}{M_s^4} w^{-1} p_1 \cdot p_2 \gamma^*(x) \phi(x)^2 \]

- Also interaction with brane fermions
  \[ w \bar{\Theta} \Gamma^{mnp} \Theta \text{Re} (iG - \bar{\chi}_6 G)_{mnp} \]

- Yukawa coupling
  \( (k/M_s)^4 \gamma^* \bar{\Theta} \Theta \)

- Either decay rate is extremely fast:
  \[ \Gamma \approx \frac{wk^9}{M_s^8} \approx 10^{27} s^{-1} \]
No Direct Coupling to Brane

- Brane doesn’t break enough symmetry
  Or centrifugal barrier blocks $\gamma^*$ from tip
- Scatters off background into uncharged KK
- Decays through couplings of uncharged KK
- Scalar and fermion estimates again the same

$$\Gamma \approx \frac{w^5 k^9}{M_8^8} \approx 10^{-25} s^{-1}$$

- Just around observational limit!
  Independent constraint on RS models
Decay Rates
D3-brane Standard Model

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Intermediate Scale SM

- SM lives on D7-brane
- Controlled setting for SM
- Extends to intermediate warping
- Supersymmetry provides hierarchy
- Fills some angular directions
- Possibly symmetric or not
- Related to F-theory model building

\[ w_1 = e^{-kz_1} \sim 10^{-4} \]
Brane Breaks Symmetry

- Angular integral of $\gamma^*$ nonvanishing
- Coupling in brane scalar kinetic term
- Decay rate to D7 scalar:

$$\Gamma \approx w^5 k \left( \frac{M_s}{M_p} \right)^{8/3} \left( \frac{w}{w_1} \right)^{2\nu_*} \approx 10^{-33-18\nu_*} \text{s}^{-1}$$

Brane Preserves Symmetry

- Coupling via uncharged KK or modulus
- Or direct integration against $\Delta\Gamma$
- Modulus couples outside throat
- All rates considerably slower
Decay Rates
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 Scalars vs Fermions

- Fermions also have flux-induced Yukawa with KK mode
  But form unknown with warping
- Estimate: multiply dim 5 coupling of scalars by cutoff $w_1 k$
- Consistent with D3-brane couplings
- No flux-induced Yukawa with volume modulus
  But possibly light complex structure
- Estimated decay rate for symmetry-breaking case:
  \[
  \Gamma \approx w^5 k \left( \frac{M_s}{M_p} \right)^{8/3} \left( \frac{w}{w_1} \right)^{-2 + 2 \nu_\ast} \approx 10^{-15 - 18 \nu_\ast} s^{-1}
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- Potentially in observable range
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- Potentially in observable range
Conclusions

- Found new dark matter candidates from top-down view
- Arise from motion in extra dimensions
- Appear for different Standard Model embeddings
- In some models, dark matter decays at observable rates
- Possibility of constraining extra dimensional models

Future Directions

- Return to D7-brane Standard Model
- Cosmic history of KK modes
- Start to constrain some stringy Standard Models
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