Dark Matter and Dark Energy

Rocky I: Evidence for dark matter and dark energy
Rocky II: Dark matter candidates
Rocky III: Dark energy reloaded

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Rocky Kolb, Fermilab & The University of Chicago
Microlensing limits

- Excluded at 95% CL by EROS (solid line) or by MACHO (dotted line).
- Permitted by MACHO at 95% CL.
Dark matter?

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars
  - brown    red    white
- Black holes
- Nonbaryonic particle dark matter
**Epicycle II – Dark matter**

*What is dark matter?*

“In questions like this, truth is only to be had by laying together many variations of error.”

-- Virginia Wolf

*A Room of Ones Own*
Collisionless damping of HDM

\[ P(k) \text{ [ } h^{-3} \text{ Mpc}^3 \text{]} \]

\[ \Omega_{CDM} = 0.7; \quad \Omega_{HDM} = 0.3 \]

\[ \Omega_{HDM} = 1 \]

\[ \Omega_{CDM} = 1 \]

CDM

HDM
$\Omega_\nu h^2 < 0.0076$

$m_\nu < 0.23 \text{eV}$
Nonbaryonic dark matter

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
**Sterile neutrinos & gravitinos**

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity
- “warm”
- satellite & cusp problem?

Particle models with sterile neutrinos or gravitinos in desired mass range are “unfashionable.”

**Warm Dark Matter**
Nonbaryonic dark matter

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, …) (cold dark matter)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, Screw-balls….)
- supermassive relics

<table>
<thead>
<tr>
<th>Mass range</th>
<th>Interaction strength range</th>
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<tbody>
<tr>
<td>$10^{-6}$ eV $(10^{-40}$ g) axions</td>
<td>Noninteracting: wimpzillas</td>
</tr>
<tr>
<td>$10^{-8}$ $M_\odot$ $(10^{25}$ g) axion clusters</td>
<td>Strongly interacting: B balls</td>
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Particle Dark Matter Candidates

Other Scales:

- $M_{\text{EWK}}$
- $M_{\text{STERILE}}$
- $M_{\text{STRING}}$
- $M_{\text{TECHNICOLOR}}$
- $M_{\text{EXTRA DIMENSIONS}}$

- $\Lambda_{\text{QCD}}$
- $f_{\text{PQ}}$
- $H_1$
- $M_{\text{GUTS}}$
- $M_{\text{PLANCK}}$

$\sigma_{\text{WIMP}}$
Cold thermal relics

$\Omega_X \propto \sigma^{-1}_A$ (independent of mass)
Cold thermal relics

\[ \Omega_X h^2 \sim \left( \langle \sigma_A n \rangle \right)^{-1} \]

\[ \sigma_A \Leftrightarrow \Omega_X \]

\[ \sigma_A \Leftrightarrow \sigma_S \]

\[ X + \bar{X} \rightarrow q + \bar{q} \]

\[ X + q \rightarrow X + q \]

Goodman & Witten
Cold thermal relics

Not quite so clean:

- s-wave or p-wave?
- annihilation or scattering cross section?
- co-annihilation?
- sub-leading dependence on mass, $g^*$, etc.
- targets are nuclei (spin-dependence)
**SUSY**

**MSSM:** The minimal supersymmetric standard model  
18 + 106 parameters

**MSUGRA:** Minimal SUGRA  
18 + 5 parameters $A_0, m_0, m_{1/2}, \tan \beta, \text{sign} \mu$

**PhenoMSSM:** Simplified weak-scale MSSM  
18 + 7 parameters $A_b, A_t, M_2, m_A, \tilde{m}, \tan \beta, \mu$

**Lightest neutralino:**  
$\tilde{\chi} = a \tilde{\gamma} + b \tilde{Z} + c \tilde{H}_1 + d \tilde{H}_2$

- often lightest R-odd particle
- weakly interacting
- massive ($M \geq 30 \text{ GeV}$)
SUSY

- Neutralino dark matter
- Direct detection
- Indirect detection
- Role of halo substructure
$\tan \beta = 50$

wide resonance in neutralino annihilation
\[ \tan \beta = 30, \mu < 0, A_0 = 0 \]

Isolevel curves for \( \Omega h^2 \); from the top:

\[ \Omega h^2 = 0.3, 0.25, 0.2, 0.15, 0.1, 0.075, 0.05, 0.025 \]
\[ \tan \beta = 50 \quad A_0 = 0 \]
Ellis, Olive, Santoso
Cold thermal relics
**Indirect detection**

- Neutrinos from the sun or Earth
- Anomalous cosmic rays and $\gamma$ rays from galactic halo (S)
- Neutrinos, $g$ rays, radio waves from our galactic center
- Role of halo substructure (Avishai Deckel)
  \[ \text{rate} \propto (\text{density})^2 \]
  Galactic center: spike cusp, ???
  Black hole in the galactic center
Muons from the sun
Ghez et al.
Orbits near the galactic center

S2: \(15M_\odot; 7R_\odot\)

Pericenter passage: \(100\text{AU} = 2000R_s; 11 \times 10^6 \text{ mph}\)

Enclosed mass

\[ M = 2.6 \times 10^6 \ M_\odot \]
Nonbaryonic dark matter

Familiar candidate: a neutralino

“a simple, elegant, compelling explanation for a complex physical phenomenon”

“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”

- Tommy Gold
Kaluza-Klein Particles

Quantized Kaluza-Klein excitations

\[ E^2 = \vec{p}^2 + p_5^2 \]
\[ = \vec{p}^2 + M_n^2 \]
\[ p_5^2 = n^2 / R^2 \]
\[ M_n^2 = n^2 / R^2 \]

Conservation of momentum \(\rightarrow\) conservation of KK mode number

First excited mode \((n=1)\) stable, mass \(R^{-1}\)

need chiral fermions

KK quantum number \(\rightarrow\) KK parity

First excited mode \((n=1)\) stable, mass \(R^{-1}\)
Kaluza-Klein Particles

\[ R^{-1} = 500 \text{ GeV} \]

- LKP = KK photon
  Cheng, Matchev & Schmaltz
- Looks like SUSY
  Cheng, Matchev & Schmaltz
- Beware KK graviton
  Kolb, Servant & Tait
- Direct detection
  Servant & Tait
  Cheng, Feng & Matchev
- Indirect detection
  Bertrone, Servant, Sigl
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Axion dark matter

... about to be ruled out or closing in on detection

- Pseudo-Nambu-Goldstone boson

- Axion mass: $m_a = \frac{\Lambda_{QCD}^2}{f_{PQ}} = 1 \text{ eV} \frac{10^7 \text{ GeV}}{f_{PQ}}$

- Pseudoscalar

- Couples to two photons through the anomaly

- Very weakly interacting with matter

- Origin of axions
  - phase transition
  - decay of axion strings

Fischler et al.
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**Cold thermal relics**

**Unitarity limit:**
- largest cross section: \( \sigma_A \leq \frac{8\pi}{M^2} \)
- \( M \leq 300 \text{ TeV} \)
• **Q-balls (non-topological solitons):**

  Scalar field with conserved global charge “Q”

  $E \propto Q^{3/4}$: can’t decay to Q free particles

  Ground state is a Q-ball, lump of coherent scalar condensate

• **Q-ball production and evolution:**

  Solitogenesis

  Solitosynthesis

  Statistical fluctuations

  Condensate fragmentation
• Q-balls exist in MSSM scalars = squarks & sleptons

\[ M_B \sim (1 \text{ TeV}) \times B^{3/4} \quad \left( \text{stable for } B \geq 10^{12} \right) \]

Kusenko, Shapashnikov & Tinyakov

• Fragmentation of Affleck-Dine condensate

\[ M_B \sim 10^{-3} \text{ g} \quad \left( B \simeq 10^{24} \right) \]

Kusenko & Shapashnikov

• Relates \( \Omega_{\text{DM}} \) to \( \Omega_B \)

Affleck-Dine condensate

Baryon asymmetry

B-ball dark matter

related!
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  - 
  -
Supermassive relics
(Nonthermal dark matter)

Production Mechanisms:

• Reheating Chung, Kolb, Riotto

• Preheating Chung

• Bubble collisions Chung, Kolb, Riotto

• Gravitational Chung, Kolb, Riotto; Kuzmin & Tkachev
**Expanding universe ➔ particle creation**

Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Lukash, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel’dovich,…

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**It’s not a bug, it’s a feature!**

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**first application:**
- density perturbations from inflation
- gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

**new application:** dark matter

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)massive particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter
Scalar field $X$ of mass $M_X$

Fourier modes $[a(\tau) = \text{expansion scale factor}]$

$$X(\vec{x}, \tau) = \int \frac{d^3 x}{(2\pi)^{3/2} a(\tau)} \left[ a_k h_k(\tau) e^{i k \cdot \vec{x}} + a_k^\dagger h_k^*(\tau) e^{-i k \cdot \vec{x}} \right]$$

Mode equation ($\tau = \text{conformal time}$)

$$h''_k(\tau) + \left[ k^2 + M_X^2 a^2 + (6\xi - 1) a''/a \right] h_k(\tau) = 0$$

$$h''_k(\tau) + \omega^2_k(\tau) h_k(\tau) = 0$$

Particle creation in nonadiabatic region

measure of nonadiabaticity $\propto \frac{\omega'_k}{\omega_k}$ or $\frac{\dot{H}}{H^2}$
Particle production

\[ \Omega_X \approx 1 \quad \text{for} \quad \frac{M_X}{M_{\text{INFLATON}}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV} \]
Inflaton mass (in principle measurable from gravitational wave background, guess $10^{12}$ GeV), may signal a new mass scale in nature.

Other particles may exist with mass comparable to the inflaton mass.

Conserved quantum numbers may render the particle stable.
Gravitino production

Giudice, Riotto, Tkachev
Linde, Kallosh, Kofman, Van Proeyen
Nilles, Peloso, Sorbo
Nilles, Olive, Peloso

……

(perhaps it is a bug after all…)
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