ASTRO AND PARTICLE CONNECTIONS

Theoretical Advanced Studies Institute (TASI)  
University of Colorado, Boulder

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UC Irvine  
20-22 June 2011
TASI 2011: THE DARK SECRETS OF THE TERASCALE

• This TASI anticipates the coming revolution in terascale particle physics

• We are living through a period of scientific revolution in the closely allied field of cosmology

• These 3 lectures are devoted to explaining how the terascale and cosmology might be related
# TASI 2011: The Dark Secrets of the Terascale

## Week 1: June 6-10

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ESSENTIAL COSMOLOGY

• For the first time in history, we now have a complete picture of the Universe

• How did this come about?

• Here review the standard model of cosmology and some of the key observational evidence leading to it

• Little knowledge of cosmology assumed; focus on heuristic derivations, order-of-magnitude estimates, intuitive arguments
COSMOLOGY BASICS

• The evolution of the Universe is dominated by gravity, described by the Einstein equations
  \[ R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu} \]

• The (flat, k=0) Friedmann-Lemaitre-Robertson-Walker metric is
  \[ ds^2 = dt^2 - a^2(t) \left[ dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right] \]

• The stress-energy tensor is \( T^\mu_{\nu} = \text{diag} [\rho(t), -p(t), -p(t), -p(t)] \)
  We may parameterize various materials by \( w \), where \( p = w\rho \)

• Stress-energy conservation \( T^{\mu \nu ; \nu} = 0 \rightarrow \rho \sim a^{-3(1+w)} \)

• The Einstein equations imply the Friedmann equation
  \[ H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho \]

  MD: \( \rho \propto a^{-3} \Rightarrow \dot{a} \propto \frac{1}{a} \Rightarrow a \propto t^{2/3} \)

  RD: \( \rho \propto a^{-4} \Rightarrow \dot{a} \propto \frac{1}{a^2} \Rightarrow a \propto t^{1/2} \)

  VD: \( \rho \propto a^0 \Rightarrow \dot{a} \propto a^2 \Rightarrow a \propto e^{\alpha t} \)
ROTATION CURVES OF GALAXIES

Rubin, Ford (1970); Bosma (1978)

- Rotational velocity $v_c$ as function of distance from center $r$
  - $v_c \sim O(300) \text{ km/s} \sim O(10^{-3}) \text{ c}$
  - $r \sim \text{few kpc} \ (\text{pc} = 3.26 \ \text{ly})$

- Expect $v_c \sim r^{-1/2}$ beyond luminous region

$$\frac{mv_c^2}{r} = G_N \frac{mM}{r^2}$$

Instead find $v_c \sim \text{constant}$

- The discrepancy may be resolved by missing mass and is classic (but not the first) evidence for dark matter
AN EXAMPLE: NGC 2403

- $v_c$ from HI line
- Fit mass-to-light ratio, dark halo model; this tells us about $\rho(r)$
- For Milky Way, get $\rho \sim 0.2-0.5$ GeV/cm$^3$
MISSING MASS IN CLUSTERS OF GALAXIES

• ~10-1000 galaxies, the largest gravitationally-bound structures;

• Intracluster gas mass, total mass constrained by X-rays from bremsstrahlung, lensing, etc.

• Gas mass fraction $f_{\text{gas}}$ as function of distance from center
  - $f_{\text{gas}} = \rho_B / \rho_M$
  - $r_{2500} \sim \text{Mpc}$

• Extrapolating from clusters to the whole Universe, this constrains $\Omega_M = \Omega_B \rho_M / \rho_B$, where $\Omega = \rho / \rho_c$ is energy density in units of the critical density and $\Omega_B$ is determined independently

Zwicky (1933)
RECESSIONAL VELOCITIES

• The original evidence that the universe is expanding

• Now carried out to far larger distances with supernovae

• Constrains the acceleration of expansion:

  \[ \Omega_\Lambda - \Omega_M \]

  “Attractive matter vs. repulsive dark dark energy”
COSMIC MICROWAVE BACKGROUND

• $\delta T/T << 1$: The universe is isotropic and homogeneous on large scales

• Constrains the geometry of the universe:

  $\Omega_\Lambda + \Omega_M$

  “total energy density”
BIG BANG NUCLEOSYNTHESIS

• At $T \sim 1$ MeV, the universe cooled enough for light elements to start forming

• The abundance of each light species is fixed by $\eta$, the baryon-to-photon ratio

• These determinations are consistent* and constrain (with the CMB) the density in baryons: $\Omega_B$
SYNTHESIS

• Remarkable agreement
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  [vs: 0.2% for $\Sigma m = 0.1$ eV]

• Remarkable precision (~10%)

• Remarkable results
STANDARD COSMOLOGICAL HISTORY

• For many applications, temperature is a better clock than time. We would like to find the time-temperature correspondence.

• For radiation, $\rho \propto a^{-4}$

• But by dimensional analysis, $\rho \propto T^4 \Rightarrow T \propto \frac{1}{a}$

• The relations in the matter- and radiation-dominated eras are therefore

\[
\text{MD : } T \propto t^{-2/3} \\
\text{RD : } T \propto t^{-1/2}
\]
WHAT DOMINATES WHEN?

• We know $\Omega_\Lambda \approx 0.73$, $\Omega_M \approx 0.27$. We can also determine

$$\Omega_{\text{CMB}} \equiv \frac{\rho_{\text{CMB}}}{\rho_c} \sim \frac{T_{\text{CMB}}^4}{\frac{3H^2}{8\pi G}} \sim \frac{(2.7 \text{ K})^4(14 \text{ Gyr})^2}{(10^{19} \text{ GeV})^2}$$

$$\sim \frac{(10^{-4} \text{ eV})^4(14\pi \times 10^{16} \text{ s})^2}{(10^{-16} \text{ eV s})^2(10^{28} \text{ eV})^2} \sim 10^{-4}$$

• Matter-radiation equality
  – $T \sim 10^4 \ T_0 \sim \text{eV}$
  – $t \sim 10^{-6} \ t_0 \sim 10^{12} \text{ s}$

• Vacuum-matter equality
  – yesterday (roughly)
THERMAL HISTORY OF THE UNIVERSE
DECOUPLING

• Decoupling of particle species is an essential concept for particle cosmology. It is described by the Boltzmann equation

\[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right] \]

Dilution from expansion

\[ XX \rightarrow f\bar{f} \quad f\bar{f} \rightarrow XX \]

• Particles decouple (or freeze out) when \( n_{eq}\langle \sigma v \rangle \sim H \)

• An example: neutrino decoupling. By dimensional analysis,

\[ n_{eq} \sim T^3 \quad \langle \sigma v \rangle \sim G_F^2 T^2 \quad H \sim T^2 / M_{Pl} \]

\[ T^3 \sim M_W^4 / M_{Pl} \Rightarrow T \sim \text{MeV} \]
A useful mnemonic: most things happened at only two times.
PROBLEMS

The standard model of cosmology answers many questions, but also highlights many others:

- What is dark matter?
- What is the distribution of dark matter?
- How did structure form?
- What is dark energy?
- Why is the cosmological constant so small?
- Why matter and no anti-matter?
- Why are all energy densities roughly comparable now?
- How did the universe begin?
- ...

Particle physics is required to answer these, not least because it is required to understand the hot early Universe.
DARK ENERGY

• $\Omega_\Lambda \approx 0.73 \Rightarrow \rho_\Lambda \sim (\text{meV})^4$: tiny, but all fields contribute

• Quantum mechanics:
  \[ \pm \frac{1}{2} \hbar \omega, \quad \omega^2 = k^2 + m^2 \]

• Quantum field theory:
  \[ \pm \frac{1}{2} \int^E d^3k \hbar \omega \sim \pm E^4, \]
  where $E$ is the energy scale where the theory breaks down

• We expect
  \[ (M_{\text{Planck}})^4 \sim 10^{120} \rho_\Lambda \]
  \[ (M_{\text{GUT}})^4 \sim 10^{108} \rho_\Lambda \]
  \[ (M_{\text{SUSY}})^4 \sim 10^{60} - 10^{90} \rho_\Lambda \]
  \[ (M_{\text{weak}})^4 \sim 10^{60} \rho_\Lambda \]
ONE APPROACH

• Small numbers ↔ broken symmetry

\[ \rho_\Lambda \sim M_{Pl}^4 \]

\[ \rho_\Lambda \sim m_v^4, \quad (M_W^2/M_{Pl})^4, \ldots \]

\[ \rho_\Lambda = 0 \]
ANOTHER APPROACH

\[ \rho_\Lambda \sim M_{\text{Pl}}^4 \]

Many densely-spaced vacua (string landscape, eternal inflation, etc.)

Anthropic principle:
\[-1 < \Omega_\Lambda < 100\]

Weinberg (1989)
DARK ENERGY PROSPECTS

• These approaches are very different. Their only similarity is that the more you think about either one, the more you think the other one must be more promising.

• Terascale prospects:
  – Worst case imaginable: we discover only the minimal Higgs boson
  – Best case imaginable: we discover the minimal Higgs boson. At least we'll know that fundamental scalars exist!

• Challenge: identify a concrete scenario in which the LHC will shed light on dark energy (crazy is ok)
DARK MATTER

Known DM properties

• Gravitationally interacting
• Not short-lived
• Not hot
• Not baryonic

Unambiguous evidence for new particles
DARK MATTER CANDIDATES

- There are many
- Masses and interaction strengths span many, many orders of magnitude, but the gauge hierarchy problem especially motivates Terascale masses

HEPAP/AAAC DMSAG Subpanel (2007)
FREEZE OUT: QUALITATIVE

(1) Assume a new heavy particle $X$ is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{qq}$$

(2) Universe cools:

$$XX \rightarrow \bar{qq}$$

(3) Universe expands:

$$XX \not\leftrightarrow \bar{qq}$$

Zeldovich et al. (1960s)
FREEZE OUT: MORE QUANTITATIVE

• The Boltzmann equation:

\[
\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right]
\]

Dilution from expansion

\[\chi \chi \rightarrow f \bar{f} \quad f \bar{f} \rightarrow \chi \chi\]

• \(n \approx n_{eq}\) until interaction rate drops below expansion rate:

\[
n_{eq} \langle \sigma v \rangle \sim H
\]

\[
(mT)^{3/2} e^{-m/T}, m^{-2}T^2/M_{Pl}
\]

• Might expect freeze out at \(T \sim m\), but the universe expands slowly! First guess: \(m/T \sim \ln (M_{Pl}/m_W) \sim 40\)
The relation between $\Omega_X$ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter.
STABILITY

- This all assumes the WIMP is stable

- How natural is this?
LEP’S COSMOLOGICAL LEGACY

- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable:
  
  \[ \text{LEP constraints} \leftrightarrow \text{Discrete Symmetry} \leftrightarrow \text{Stability} \]

  Cheng, Low (2003); Wudka (2003)

- The result: dark matter is easier to explain than no dark matter, and the WIMP paradigm is more natural than ever before, leading to a proliferation of candidates.
WIMP EXAMPLES

- Weakly-interacting massive particles: many examples, broadly similar, but different in detail

- The prototypical WIMP: neutralinos in supersymmetry
  
  Goldberg (1983)

- KK B¹ (“KK photons”) in universal extra dimensions
  
  Servant, Tait (2002); Cheng, Feng, Matchev (2002)
NEUTRAL SUSY PARTICLES

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<td>Neutralinos: ${\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4}$</td>
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$G$ graviton
$\tilde{G}$ gravitino
R-PARITY AND STABLE LSPS

• One problem: proton decay

Forbid this with R-parity conservation: $R_p = (-1)^{(B-L)+2S}$
- SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
- Require $\prod R_p = 1$ at all vertices

• Consequence: the lightest SUSY particle (LSP) is stable!
WHAT’S THE LSP?

- High-scale $\rightarrow$ weak scale through RGEs.
- Gauge couplings increase masses; Yukawa couplings decrease masses
- “typical” LSPs: $\chi$, $\tilde{\tau}_R$

Particle physics alone $\rightarrow$ neutral, stable, cold dark matter
RELIC DENSITY

• Neutralinos annihilate through many processes. [➔]
  But there are typically two dominant classes:

  \[ \chi \rightarrow f \bar{f} \]

  • \( \chi \) are Majorana fermions, so Pauli exclusion \( \Rightarrow \) \( S_{_{in}} = 0, L \) conservation \( \Rightarrow \)
    – \( P \)-wave suppression: \( \sigma v \sim \sigma_0 + \sigma_1 v^2, \)
      \( mv^2/2 = 3T/2 \Rightarrow v^2 \sim 3T/m \sim 0.1 \)
    – \( m_f/m_W \) suppression

  \[ \chi \rightarrow W^- \bar{\chi}^+ \]

  • Gauge boson diagrams suppressed for \( \chi \approx \) Bino

Bottom line: annihilation is typically suppressed, \( \Omega_{_{DM}}h^2 \) is typically high
NEUTRALINO ANNIHILATION

Jungman, Kamionkowski, Griest (1995)
COSMOLOGICALLY PREFERRED SUPERSYMMETRY

Typically get too much DM, but there are mechanisms for reducing it

Excluded: Stau LSP

Yellow: pre-WMAP
Red: post-WMAP

Stau and χ degenerate to within roughly T ~ m/25

Excluded: Stau LSP

Typically get too much DM, but there are mechanisms for reducing it
KK DARK MATTER

- Consider 1 extra spatial dimensions curled up in a small circle
- Particles moving in extra dimensions appear as a set of copies of normal particles.
• A problem: many extra 4D fields; some with mass $n/R$, but some are massless! E.g., 5D gauge field:

$$V_{\mu}(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu) \cos(ny/R) + \sum_m V_\mu^m(x^\mu) \sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu) \cos(ny/R) + \sum_m V_5^m(x^\mu) \sin(my/R)$$

• A solution…
• Compactify on $S^1/Z_2$ instead (orbifold); require

$$y \to -y : \quad V_\mu \to V_\mu \quad V_5 \to -V_5$$

• Unwanted scalar is projected out:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V^n_\mu(x^\mu) \cos(ny/R) + \sum_m V^m_\mu(x^\mu) \sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V^n_5(x^\mu) \cos(ny/R) + \sum_m V^m_5(x^\mu) \sin(my/R)$$

• Similar projection on fermions $\to$ chiral 4D theory, ...

Appelquist, Cheng, Dobrescu (2001)
KK-PARITY

• A consequence: KK-parity $(-1)^{KK}$ conserved: interactions require an even number of odd KK modes

• 1\textsuperscript{st} KK modes must be pair-produced at colliders

• LKP (lightest KK particle) is stable – dark matter!

Appelquist, Cheng, Dobrescu (2001)
Macesanu, McMullen, Nandi (2002)
B¹ ANNIHILATION

• The level-1 KK hypercharge gauge boson B¹ is often the LKP, is neutral, and so is a natural DM candidate

• It’s a massive gauge boson, annihilates through S-wave processes, so preferred masses are larger than in SUSY
MORE B\(^1\) ANNIHILATION

- Minimal UED has a compressed spectrum, so co-annihilation is natural. In contrast to SUSY, these typically add to the relic density

- Level-2 KK resonances

Servant, Tait (2002); Burnell, Kribs (2005)
Kong, Matchev (2005); Kakizaki, Matsumoto, Sato, Senami (2005)
Prediction for $\Omega_{B(1)} h^2$ The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the case $\Delta = 0.01$ and the red curves (lower of each pair) $\Delta = 0.05$. 

Servant, Tait (2002)
LECTURE 1 SUMMARY

• The revolution in cosmology has produced remarkable progress and highlights remarkable problems

• Cosmology and particle physics both point to the Terascale for new particles, with viable WIMP candidates from SUSY, UED, etc.

• Next time: what are the implications for dark matter searches?