PARTICLE PHYSICS AND COSMOLOGY

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OUTLINE

LECTURE 1
Essential Cosmology: Contents and History of the Universe

LECTURE 2
WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3
Inflation, Gravitinos, and Hidden Sectors
INTRODUCTION

• Why should HEP physicists care about cosmology?
  – We want to answer age-old questions about our Universe and our place in it
  – We are in a golden age of cosmology, and cosmology and particle physics have become inextricably intertwined
  – Many of the leading motivations for new particle physics come from cosmology: dark matter, dark energy, inflation, baryon asymmetry
  – Cosmology sets new interesting mass scales and can provide upper bounds on masses
  – Cosmology reaches the hard corners of parameter space (high masses, weak interactions)
  – HEP physicists and cosmologists have a lot to learn from each other
  – These topics capture the imagination of the public
ESSENTIAL COSMOLOGY

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

• How did this come about?

• We will first review the standard model of cosmology and some of the key observational evidence leading to it

• Little previous knowledge of cosmology is assumed; focus on heuristic derivations, order-of-magnitude estimates, intuitive arguments, and some aspects that (at present) seem to be most linked to particle physics, and particularly high-energy physics. This is a huge topic, many important topics will be neglected.
PARTICLE PHYSICS SCALES

• Natural units: \( h = c = k_B = 1 \)
  – \( h = c = 1 \) is standard
  – \( k_B = 1 \) \( \Rightarrow \) 1 K = 0.08 meV

• Some useful energy scales
  – \( 10^{19} \) GeV: Planck scale
  – \( 10^{16} \) GeV: GUT scale
  – TeV: weak scale
  – GeV: binding energy of quarks (\( \Lambda_{QCD} \))
  – MeV: binding energy of nuclei
  – eV: binding energy of atoms
  – 0.1 meV: CMB temperature now
ASTROPHYSICS SCALES

- 1 pc = 3.3 ly. Some useful length scales
  - $10^{-5}$ pc: distance to Sun (AU)
  - pc: distance to the next star (Alpha Centauri)
  - 10 kpc: distance to Milky Way center
ASTROPHYSICS SCALES

- Some useful length scales
  - $10^{-5}$ pc: distance to Sun
  - pc: distance to next-nearest star (Alpha Centauri)
  - 10 kpc: distance to Milky Way center
  - 10-100 kpc: distance to nearest dwarf galaxies
  - Mpc: distance to nearest big galaxy (Andromeda)
  - 10 Mpc: size of clusters of galaxies
  - 10 Gpc: size of the observable Universe
COSMOLOGY BASICS

• The evolution of the Universe is dominated by gravity. We must therefore begin with some basic general relativity.

• Let the spacetime metric $g_{\mu\nu}$ be a dynamical field. This specifies lengths through

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$$

• With a dynamical metric, our theory is specified by the Einstein-Hilbert action

$$S = \int d^4x \sqrt{-g} \left( \frac{R}{16\pi G} + \mathcal{L}_{SM} \right)$$

where $g = \text{det}(g_{\mu\nu})$, $G = M_{Pl}^{-2}$, and $R = R(g_{\mu\nu}, \partial g_{\mu\nu}, \partial^2 g_{\mu\nu})$ is the scalar curvature.

• Extremizing this action, we find the equations of motion

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu} \quad \text{where} \quad T_{\mu\nu} \equiv -2\frac{\delta \mathcal{L}_{SM}}{\delta g^{\mu\nu}} + g_{\mu\nu}\mathcal{L}_{SM}$$

These are the Einstein equations, where $R_{\mu\nu}$ is the Ricci curvature tensor, again a function of the metric, and $T_{\mu\nu}$ is the stress-energy tensor and contains all the particle physics.
COSMOLOGY BASICS

- The Einstein equations are complicated to solve, so we make some approximations, based on observations.

- The Universe appears to be homogeneous and isotropic on scales larger than \( \sim 10 \) Mpc.

- So we assume a Friedmann-Lemaître-Robertson-Walker metric

\[
ds^2 = dt^2 - a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right]
\]

and stress-energy tensor

\[
T_\mu^\nu = \text{diag} [\rho(t), -p(t), -p(t), -p(t)]
\]

Here \( a(t) \) is the scale factor and \( k \) is a constant that specifies the curvature (\( k = 0 \) implies a flat Universe);

\( \rho \) is energy density and \( p \) is pressure.
COSMOLOGY BASICS

• With these simplifications, the Einstein equations become quite manageable.

• The Einstein equations imply the Friedmann equation \( \left( \frac{\dot{a}}{a} \right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3} \rho \).

We define the Hubble parameter \( H \equiv \frac{\dot{a}}{a} \) and the critical density \( \rho_c \equiv \frac{3H^2}{8\pi G} \).

• We may parameterize various materials by \( w \), where \( p = w\rho \). If \( w \) is constant, stress-energy conservation \( T^\mu_\nu ;_\nu \equiv 0 \rightarrow \rho \sim a^{-3(1+w)} \)

• For example, we can consider 3 kinds of contributions to the energy density:

Matter: \( \rho \) is diluted by expansion (\( w = 0 \))
\[ \text{MD} : \rho \propto a^{-3} \Rightarrow \frac{\dot{a}^2}{a} \propto \frac{1}{a} \Rightarrow a \propto t^{2/3} \]

Radiation: \( \rho \) is diluted by expansion and redshifting (\( w = 1/3 \))
\[ \text{RD} : \rho \propto a^{-4} \Rightarrow \frac{\dot{a}^2}{a^2} \propto \frac{1}{a^2} \Rightarrow a \propto t^{1/2} \]

Vacuum energy: \( \rho \) is not diluted (\( w = -1 \))
\[ \text{VD} : \rho \propto a^0 \Rightarrow \frac{\dot{a}^2}{a^2} \propto a^2 \Rightarrow a \propto e^{ct} \]

• What do observations tell us about the contents of the Universe now?
Rotational velocity $v_c$ as function of distance from center $r$
- $v_c \sim \mathcal{O}(300) \text{ km/s} \sim \mathcal{O}(10^{-3}) \text{ c}$
- $r \sim \text{ few kpc} \ (\text{pc} = 3.26 \text{ ly})$

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

$$\frac{m v_c^2}{r} = G_N \frac{m M}{r^2}$$

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, halo model; this tells us about $\rho(r)$
MISSING MASS IN CLUSTERS OF GALAXIES

Zwicky (1933)

- ~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
DARK MATTER DISTRIBUTION

• Many other observations lead to the same conclusions: weak lensing, strong lensing, Bullet Cluster, …

• Simulations and observations lead to a consistent picture on large scales

• DM clumps, leads to structure formation, every galaxy is surrounded by a dark matter halo

• Local DM properties
  \[ \rho \sim 0.2 \text{ – } 0.5 \text{ GeV/cm}^3, \]
  \[ \text{overdense by factor of } \sim 10^5 \]
  \[ v \sim 10^{-3} c \] for many DM candidates, independent of mass (virial theorem)
EXPANSION OF THE UNIVERSE

• Galaxies that are far from us are receding from us, and the recessional velocity is roughly proportional to the distance

• This is Hubble’s Law, and the constant of proportionality is Hubble’s constant

\[ \nu = H d \]

• The current value of the Hubble parameter is

\[ H_0 = h \ 100 \ \text{km/s/Mpc} \]

\[ h = 0.705 \pm 0.015 \ (h^2 \approx \frac{1}{2}) \]

• This means that light from distant galaxies is redshifted

\[ \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = 1 + z \]
EXPANSION OF THE UNIVERSE

- The original evidence for the expanding universe has now been extended to far larger distances with Type Ia supernovae.
- Note the evolution of the measurement of $H_0$ -- a lesson in underestimated systematics!
- The universe’s expansion is currently accelerating!
- Measurement of this expansion history constrains the acceleration of expansion:

$$\Omega_\Lambda - \Omega_M$$

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

- The Universe is filled with an essentially perfect black body spectrum

- The temperature is 2.725 K in all directions, implying the Universe is highly isotropic on large scales
COSMIC MICROWAVE BACKGROUND

- There is, however, a tiny anisotropy of $\delta T/T \sim 10^{-5}$
- Dramatic improvements from COBE to WMAP to Planck
- Angular size of the hot and cold spots constrains the geometry:
  \[
  \Omega_\Lambda + \Omega_M
  \]
  "total energy density"
• At $T \sim 1 \text{ MeV}$, around the binding energy of nuclei, the universe cooled enough for light elements to start forming.

• The abundance of each light species is a function of a single parameter, $\eta$, the baryon-to-photon ratio.

• BBN and CMB determinations are consistent (except possibly for Li) for a single choice of $\eta$ and constrain the density in baryons: $\Omega_B$. 

\[ \Omega_B h^2 \]

- FIG. 1. Determinations of $\Omega_B h^2$ from BBN (black) and CMB (blue) roughly agree over the region $0.26 < \Omega_B h^2 < 0.27$.
SYNTHESE

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

- Remarkable precision

- 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

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

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

• 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
  – very recent past
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 → f f̅  f̅ f → 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: many 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 (small-scale) 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 all of these, not least because it is required to understand the hot early Universe
DARK ENERGY

• The properties of dark energy are now investigated by many methods
  – Supernovae
  – CMB
  – Weak lensing
  – Baryon acoustic oscillations
  – Galaxy cluster abundance

• The results are consistent with a cosmological constant, vacuum energy with $w = -1$ constant throughout the Universe’s history

$$w(z) = w_0 + \frac{w_a}{1 + z}$$
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
  
  $\left( M_{\text{Planck}} \right)^4 \sim 10^{120} \rho_\Lambda$
  $\left( M_{\text{GUT}} \right)^4 \sim 10^{108} \rho_\Lambda$
  $\left( M_{\text{SUSY}} \right)^4 \sim 10^{60} - 10^{90} \rho_\Lambda$
  $\left( M_{\text{weak}} \right)^4 \sim 10^{60} \rho_\Lambda$
ONE APPROACH

- Small numbers ↔ broken symmetry

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

\[ \rho_\Lambda = 0 \]

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

• The discrepancy between the expected and measured values of $\Omega_\Lambda$ is the greatest hierarchy problem in particle physics, not just because it is numerically large, but because we think we understand meV-scale physics

• Ways forward
  – Constrain DE properties, see if it deviates from a cosmological constant or indicates a deviation from GR
  – Make a breakthrough in understanding quantum gravity
  – Learn something unexpected about fundamental scalars
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 particles with weak-scale masses
FREEZE OUT: QUALITATIVE

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

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

(2) Universe cools:

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

(3) Universe expands:

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

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:

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

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

• 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.
WIMP STABILITY

• The WIMP Miracle is very well appreciated, and it is a quantitative feature. But its success relies on some less well-advertised qualitative features.

• First, the WIMP must be stable.

• How natural is this? *A priori*, not very: the only stable particles we know about are very light.

\[\text{New Particle States} \quad \downarrow \quad \text{Stable} \quad \downarrow \quad \text{Standard Model Particles}\]
LEP’S COSMOLOGICAL LEGACY

In some cases, there are even stronger reasons to exclude these 4-particle interactions (e.g., proton decay in SUSY)

- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable:
  
  LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)
WIMP NEUTRALITY

• WIMPs must also be neutral

• How natural is this? Again, *a priori*, not very: what is the chance that the lightest new particle happens to be neutral?

• In fact, in many cases (SUSY, extra dims, …), masses are “proportional” to couplings, so neutral particles are the lightest

Bottom line: WIMPs, new particles that are *stable* and *neutral* with $\Omega \sim 0.1$, appear in many models of new particle physics
LECTURE 1 SUMMARY

• The revolution in cosmology has produced remarkable progress

• This progress also highlights puzzles that require particle physics answers

• Cosmology and particle physics both point to the weak scale for new particles

• Next time: what are the opportunities for probing the weak scale with dark matter searches?