Beyond the Standard Model: Dark Matter in the Early Universe and Today

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CERN
The Standard Cosmology:
Hot Big Bang Model

Friedmann-Lemaitre-Robertson-Walker

Gravity = General Relativity
Space: Homogeneous & Isotropic

- Expanding Universe
  \( t \approx 14 \text{ Gyr}; T \approx 10^{-4} \text{ eV} \)

- Cosmic Microwave Background (CMB)
  \( t \approx 400,000 \text{ yr}; T \approx 1 \text{ eV} \)

- Big-Bang Nucleosynthesis (BBN)
  \( t \approx 1 \text{ sec}; T \approx 1 \text{ MeV} \)

- Dark Matter

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Freedman et al. 2001
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Follow weak and nuclear reactions in expanding, cooling Universe

Dramatis Personae

Radiation dominates! \(\gamma, e^\pm, 3\nu\bar{\nu}\)

Matter: nuclear building blocks = “baryons” \(p, n\)

tiny baryon-to-photon ratio

\(\eta \equiv n_B/n_\gamma \sim 10^{-9}\)
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Initial Conditions: $T >> 1$ MeV, $t << 1$ sec

n-p weak equilibrium:

$pe^- \leftrightarrow n\nu_e$

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neutron-to-proton ratio:

$n/p = e^{-(m_n-m_p)c^2/kT}$
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Weak Freezeout: $T \sim 1$ MeV, $t\sim 1$ sec

$\tau_{\text{weak}}(n \leftrightarrow p) > t_{\text{universe}}$

$$\left(\frac{n}{p}\right)_{\text{freeze}} \approx e^{-\Delta m/T_{\text{freeze}}} \sim \frac{1}{7}$$
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Light Elements Born: $T \sim 0.07 \text{ MeV}, t \sim 3 \text{ min}$
reaction flow $\rightarrow$ most stable

BBN Network

$\rightarrow$ key reactions

All reactions measured in lab at relevant energies
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essentially all $n\rightarrow^4\text{He}, \sim 24\% \text{ by mass}$

also: traces of $^3\text{He}, \, ^7\text{Li}$

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Curve Widths: Theoretical uncertainty on nuclear cross sections

Cyburt, BDF, Olive 08
Cyburt 04
Coq et al 04
Serpico et al 05
Cyburt, BDF, Olive 01
Krauss & Romanelli 88
Smith, Kawano, Malaney 93
Hata et al 1995
Copi, Schramm, Turner 1995
Nollett & Burles 2000
CMB is exquisite “baryometer”

WMAP baryon density very precise

\[ \Omega_B h^2_{100} = 0.0226 \pm 0.008 \]

\[ \eta = (6.14 \pm 0.25) \times 10^{-10} \]

i.e., a 4% measurement!

New strategy to test BBN:

✓ use WMAP as BBN input
✓ predict all lite elements
  with appropriate error propagation
✓ compare with observations
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Battle of the Baryons
New World Order
Cyburt, BDF, Olive 2003

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Battle of the Baryons: II
A Closer Look
Cyburt, BDF, Olive 2003

Cayrel talk

Heil talk

PANIC 20I
Battle of the Baryons: II
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Predict:

BBN theory: abundances vs $\eta$

$\eta_{\text{cmb}} \rightarrow$ BBN+CMB abundances (blue)

Compare with Observations (yellow)
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- $^7\text{Li}$ discrepant: “Lithium Problem”
  - systematic errors in obs? Cayrel talk
  - nuclear uncertainties? …no!
  - new physics? primordial $^6\text{Li}$? Heil talk
Dark Matter

$$\Omega_B = 0.044 \pm 0.004$$
$$\frac{\Omega_M}{\Omega_B} = \frac{\text{matter}}{\text{baryons}} = 5.9 \pm 0.3$$
Dark Matter

Pre-CMB Anisotropies:

BBN $\rightarrow$ Dark Matter

WMAP finds:

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two kinds!
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Baryonic Dark Matter: \( \Omega_B \gg \Omega_{\text{lum}} \sim 0.007 \)

→ warm-hot IGM, Ly-alpha, X-ray gas
  Fukugita, Hogan, Peebles; Cen & Ostriker; Dave et al
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Non-Baryonic Dark Matter: $\Omega_B \ll \Omega_M$

⇒ most of cosmic matter!

Intergalactic gas absorbs QSO backlight
Fang, Canizares, & Yao 07

Bullet Cluster
optical, X-rays=baryons (red), lensing=gravity (blue)
Non-Baryonic Dark Matter

Particle Candidates

the vast majority of dark matter is non-baryonic

but oscillation data show: not neutrinos!

exhausts known particle candidates!

Dark matter demands physics beyond particle Standard Model!
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Good news: particle Standard Model experimentally triumphant
but conceptually incomplete: cries out for a deeper theory!

~All such theories provide dark matter candidates

inner space/outer space link
early Universe as poor man’s accelerator
contrast with dark energy--no good theories “off the shelf”
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lightest spartner stable excellent DM candidate
Supersymmetric Dark Matter & Big-Bang Nucleosynthesis

Supersymmetry scorecard:

• very predictive: precision calculations of laboratory processes, DM abundances
• but large parameter space for models
• experiments/cosmology have begun to rule out some

Currently favored scenarios

lightest SUSY particle (LSP) is dark matter...
...but next-lightest particle long-lived: \( \tau_{\text{nlp}} \sim 1 \times 10^6 \text{sec} \)
can decay during or after BBN!
Could Lithium Be SUSY-licious?

If
✓ the world is supersymmetric
✓ and nonbaryonic dark matter is the lightest SUSY particle

Then
‣ In Early U: SUSY cascade
‣ next-to-lightest particle can be long-lived
‣ hadrononic decays can erode $^7$Li, and make $^6$Li

Jedamzik, Pospelov, Cyburt et al, Khori et al

A SUSY solution to lithium problems?

In any case: illustrates tight links among nucleo-cosmo-astro-particle physics
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OUTLOOK

Convergence of Particle Physics and Cosmology

- successes of both point to larger, deeper picture
- theoretical & experimental progress linked

BBN & CMB: Gates to the Early Universe

- concordance: big bang working to $t \sim 1$ sec
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- must arise in physics beyond the Standard Model of particle physics

The Dark Matter Discovery Trifecta
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Answers (& new surprises?) in <10 years!
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Future exciting--stay tuned!
Non-Baryonic Dark Matter

Early Universe History

Birth

in hot early Universe $kT \gg m_\chi c^2$
dark matter particles $\chi$, antiparticles $\bar{\chi}$ produced thermally
creation, annihilation rates balance

Midlife

universe cools until $kT < m_\chi c^2$ production stops
dark matter annihilates, abundance drops

Fossilization

annihilations freeze out
relic abundance fixed
weaker particles earlier freezeout larger relic abundance
$\Omega_\chi \sim \frac{1}{\sigma_{\text{weak}}}$ Weak (& SUSY) scale gives right amount of DM!
explains why DM = weakly interacting massive particles: WIMPs!
Dark Matter Discovery

Direct Detection

Earth and Sun move through “wind” of Galactic dark matter

If DM interactions ~ weak scale, detectable

Techniques similar to neutrino hunting

- small signal < 1 event/day
- need low background underground

Detectors: cryogenic crystals

Interaction: elastic scattering

Signals: crystal response to nuclear recoil

- vibration: phonons
- scintillation: photons
- heating: T rise and/or phase transition
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Dark Matter Discovery
Laboratory Creation

Accelerators can create dark matter pairs in collisions with

**Fermilab**: running now

**CERN (Geneva)**:
- Large Hadronic Collider
- coming online this Spring
- can probe most of Supersymmetry model space
- discover or rule out SUSY dark matter

If discover:
- can predict cosmic abundance, direct detection signature
Dark Matter Discovery

Gamma-Ray Observations

In many dark matter models: WIMPs & anti-WIMPS in equal numbers

Frozen out: annihilations too slow in average universe

but in high-density peaks, can find each other and annihilate

look for Gamma-ray signal from

✓ Galactic Center
✓ other galaxies
✓ nearby dark matter clumps
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If detect dark matter signature:

gamma signature probes WIMP mass

\[ E_\gamma \leq m_\chi c^2 \]
The Standard Model of Particle Physics: Impressionist’s View

Inspiration: quantum E&M. Charged particles interact via photon exchange and generalize to other forces.

Structure: matter composed of fermions (spin-1/2) and force carriers (bosons, spin-1).

Predictive Power & Empirical Success. Organizes a mountain of data. E.g., ~130 observed $qqq$ are baryonic states.

Of which 2 are stable: $uud$ is $p$ and $udd$ is $n$.

Quantitatively explains observed properties. E.g., production/decay/scattering rates, daughter properties.

Crowning jewel: e magnetic moment to ~1 ppb. No known disagreement with experiment!
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[Diagram of elementary particles and quark generations]
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  • of which 2 are stable: \( uud=\text{p} \) & \( udd=\text{n} \)
  quantitatively explains observed properties
  • e.g., production/decay/scattering rates, daughter properties
  • crowning jewel: e magnetic moment to ~1 ppb
  no known disagreement with experiment!

PANIC 2008
If it ain’t broke why fix it?

➡️ Standard Model can’t be the final theory
➡️ Open questions remain

  SM has ~29 independent (?) parameters
  • what sets them? are they related?

  Why families? How many?

  Neutrinos: number of species? Masses?
  Boson/fermion dichotomy?
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➡ All new models predict new particles relevant to cosmology!
Cosmic Job Security: Precision Ignorance

What is the dark matter?
- how is it produced?
- how does it interact?
- what was its role in the early universe?

What is the dark energy?
- is it related to dark matter?
- does it evolve with time?
- what was its role in the early universe?

What sets \( \Omega_{\text{baryon}} \sim \Omega_{\text{matter}} \sim \Omega_{\Lambda} \) today?
- compare: nuclear physics sets \( \Omega_{\text{H}} \sim \Omega_{\text{He}} \)
Big Bang Nucleosynthesis
& Particle Dark Matter

- The State of the Art
  - Standard Model of Particle Physics
  - Standard Cosmology

- Big Bang Nucleosynthesis
  & non-baryonic dark matter

- Particle Dark Matter
  candidates & interplay with BBN

- Dark Matter Discovery Scenarios
  accelerators, direct detection, gamma rays
Big Bang Nucleosynthesis
Standard BBN

Marriage of Standard Model and Standard Cosmology

- Gravity = General Relativity
- Microphysics: Standard Model of Particle Physics
  - $N_\nu = 3$ neutrino species
  - $m_\nu \ll 1 \text{ MeV}$
  - left-handed neutrino couplings only
- Dark Matter and Dark Energy
  - Present (presumably) but non-interacting
- Homogeneous U. spatially const
- Expansion adiabatic

$$\eta \equiv \frac{n_{\text{baryon}}}{n_\gamma}$$

$$\left( \frac{n_B}{n_\gamma} \right)_{\text{BBN}} = \left( \frac{n_B}{n_\gamma} \right)_{\text{CMB}} = \left( \frac{n_B}{n_\gamma} \right)_{\text{today}}$$

- gives baryon density $\eta \propto \rho_{B,\text{today}} \propto \Omega_B$
BBN Observations: Case Study
Primordial Deuterium

Q1422+2309 $z=3.62$
BBN Observations: Case Study

Primordial Deuterium

- High-redshift quasar=light bulb
BBN Observations: Case Study
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- High-redshift quasar = light bulb
- Intervening H gas absorbs at $\text{Ly}\alpha (n = 1 \rightarrow n = 2)$
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BBN Observations: Case Study
Primordial Deuterium

- High-redshift quasar = light bulb
- Intervening H gas absorbs at $Ly\alpha (n = 1 \rightarrow n = 2)$
- Observed spectrum: Ly-alpha “forest”
Deuterium Data

Deuterium Ly-alpha shifted from H:

\[ E_{\text{Ly}\alpha} = \frac{1}{2} \alpha^2 \mu_{\text{reduced}} \]
\[ \frac{\delta \lambda_D}{\lambda_D} = -\frac{\delta \mu_D}{\mu_D} = -\frac{m_e}{2m_p} \]
\[ c\delta z = 82 \text{ km/s} \]

Get D directly at high-z!

Tytler & Burles
Testing BBN: Light Element Observations

Theory:
- 1 free parameter predicts
- 4 nuclides: D, $^3$He, $^4$He, $^7$Li
Testing BBN:
Light Element Observations

Theory:
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Observations:
- 3 nuclides with precision: $^2$D, $^4$He, $^7$Li
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Light Element Observations

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Comparison:
- ★ each nuclide selects baryon density
Testing BBN: Light Element Observations

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Comparison:
- Each nuclide selects baryon density
- Overconstrained--nontrivial test!

Result:
Testing BBN:
Light Element Observations

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Observations:
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Comparison:
- Each nuclide selects baryon density
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Result:
- Broad concordance!
- Cosmological confidence at t~1 sec
- Measures baryon content of Universe
The CMB: A Powerful New Baryometer

\[ \text{CMB} \Delta T_\ell \text{ independent measure of } \Omega_B \]

BBN vs CMB: fundamental test of cosmology

Dodelson & Hu 2003
Non-Baryonic Dark Matter: Neutrinos?

Required Dark Matter Properties

dark \rightarrow \text{feeble interactions}

\text{matter} \rightarrow \text{has mass}

\text{present at } t \sim 14 \text{ Gyr} \rightarrow \text{stable}

\text{inert @ BBN, recomb} \rightarrow \text{non-baryonic}

\text{abundant: } \Omega_m \simeq 0.3
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Consult Standard Model
neutrinos very promising!

✓ massive
✓ stable
✓ weakly interacting
✓ not quarks $\rightarrow$ not baryons
Non-Baryonic Dark Matter: Neutrinos?

Neutrino densities today

- **number**: \( n_\nu = \frac{3}{11} N_\nu n_\gamma \approx 350 \) neutrinos cm\(^{-3}\)
- **mass**: \( \rho_\nu = \sum m_\nu n_\nu \)
- **cosmic contribution**: \( \Omega_\nu = \frac{\sum m_\nu}{46 \text{ eV}} \)

All hangs on neutrino masses
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Neutrinos are not the dark matter

\( \Omega_\nu = \sum m_\nu n_\nu \)

\( \rho_\nu = \frac{\sum m_\nu}{46 \text{ eV}} \)

The Sun, imaged in neutrinos
SuperKamiokande

KamLAND Reactor Neutrino Detector
BBN+CMB: A Shaper Probe of Particle Physics

Example: “Neutrino Counting"

Predicted Lite elements sensitive to expansion history during BBN

\[(\text{expansion})^2 = H^2 \sim G\rho_{\text{tot,rel}}\]

Observed Lite Elements Constrain Relativistic Energy Density: Stiegman, Schramm, & Gunn 77

\[\rho_{\text{tot,rel}} = \rho_{\text{EM}} + \left(\overline{N}_0,_{\text{eff}}\right)\rho_{\nu\bar{\nu}}\]

Pre-CMB:

$^4$He as probe, other elements give baryon density

With $\eta$ from CMB

- All abundances probe
  
  \[\delta N_{\nu,\text{bbn}} \equiv N_\nu - 3 < 1.6\]

- Now: $^4$He sharpest probe, but syst errors?

- Future: If get D/H to 3%Get best leverage Cyburt, BDF, & Olive 02; Cyburt et al 2006

- Observational errors dominate!

\[\delta N_{\nu,\text{bbn}} \equiv N_\nu - 3 < 1.6\]

WMAP+BBN+D/H limits

Cyburt, BDF, Olive, & Skillman 2004
The Lithium Problem
Primordial Lithium

Observe in primitive (Pop II) stars
Li-Fe → evolution

Plateau at low Fe
★ const. abundance at early epochs
★ Li is primordial

But is the plateau at Li_p?
• Li_{WMAP}/Li_{obs} \sim 3
• Why?

Also: Recent hints of primordial $^6$Li $>>$ $^6$Li_{SBBN}?!
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BBN vs WMAP

Can view WMAP as “tiebreaker”

- D and $^4$He in great shape
- Possible problems with $^7$Li

Sources of Discrepancy

1. Astrophysics: observational systematics?
2. Nuclear Physics: nuclear reaction systematics?
3. Nonstandard Physics: most intriguing, but last resort
Lithium Systematic Errors
Observational Systematics

Measure: $\text{Li I} = \text{Li}^0$ absorption line(s)
Infer: $\text{Li}/H$
$T_{\text{eff}}$ critical: mostly $\text{Li II} = \text{Li}^+\text{I}$
Needed error in $T$ scale $\sim 500 \text{ K}$: large!
But maybe possible: Melendez & Ramirez 04; BDF, Olive, Vangioni-Flam 05

Astrophysical Systematics

stellar depletion over $\sim 10^{10}$ yr
if Li burned: correct $\text{Li}_p$ upward!
But: no Li scatter, and $^6\text{Li}$ preserved... Ryan et al 2000

Nuclear Systematics

$^7\text{Li}$ production channel $^3\text{He}(\alpha, \gamma)^7\text{Be}$
Normalization error?
But: also key for Solar neutrinos
The Sun as reactor: SNO+Solar Model success
no “nuke fix” to Li problem Cyburt, BDF, Olive 04