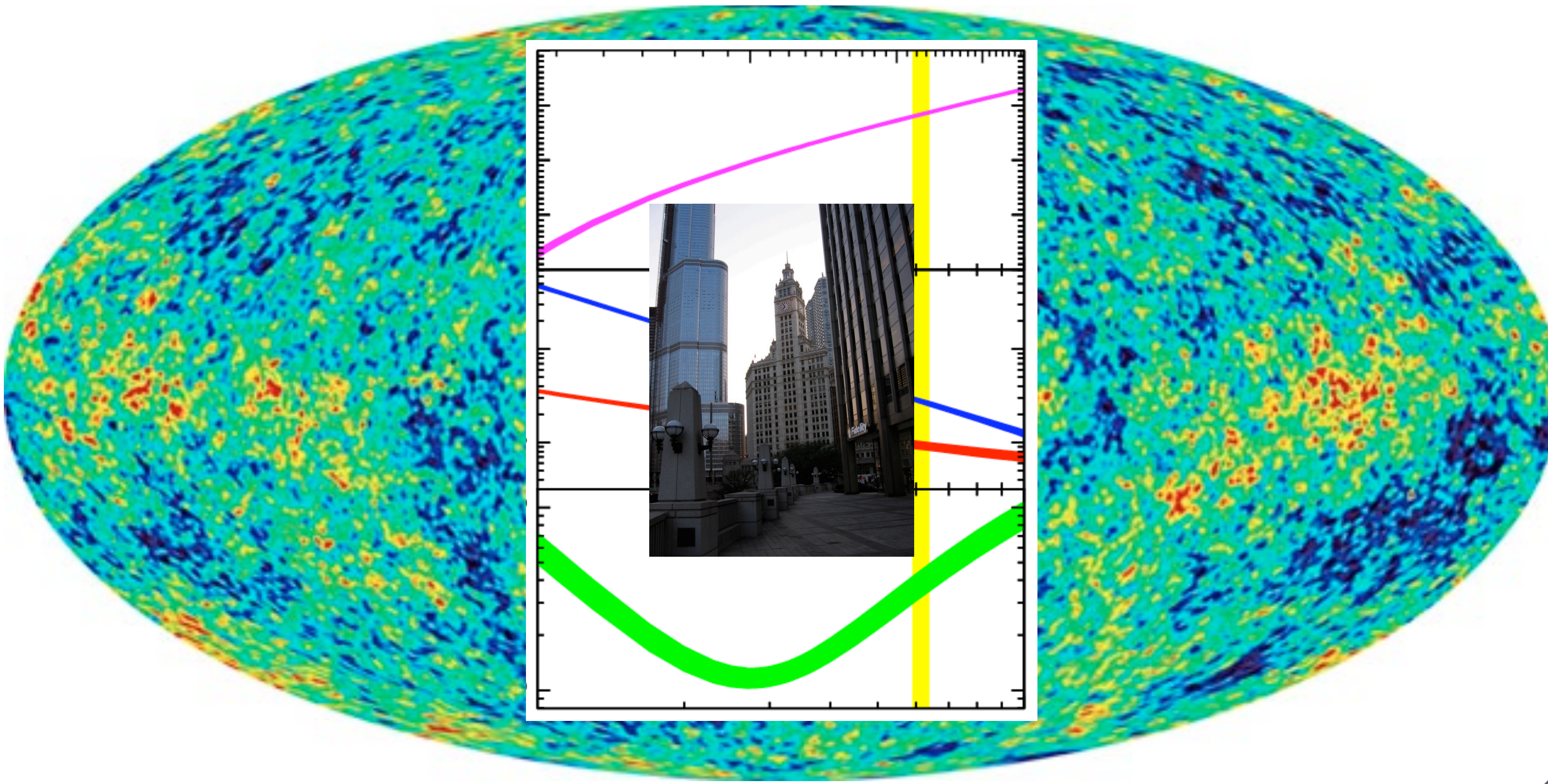
Big Bang Nucleosynthesis

in the

New Cosmology



Brian Fields

University of Illinois

NIC School, Argonne

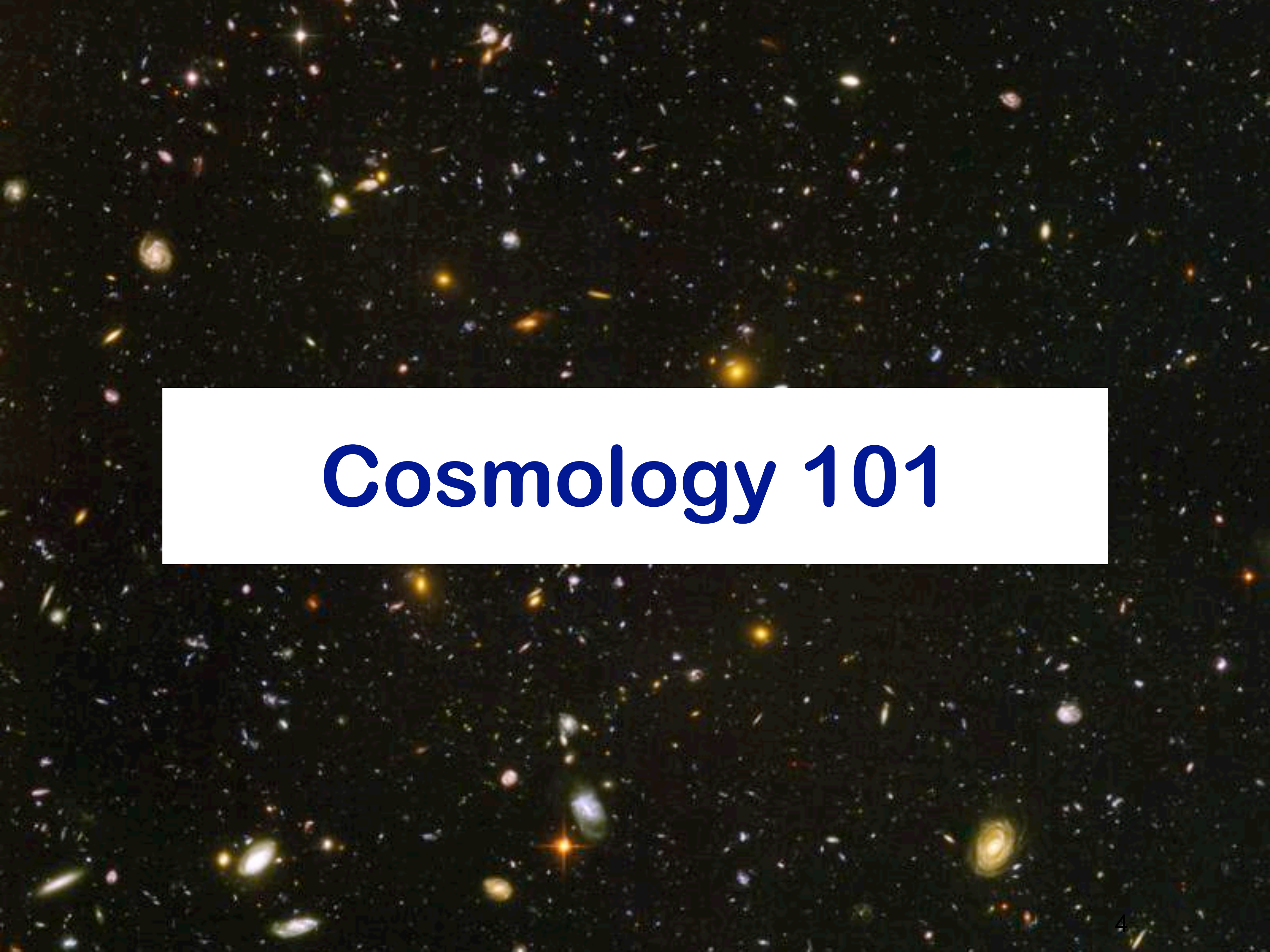
July 23, 2008

Collaborators

Richard Cyburt	Michigan State U.
Tijana Prodanovic	U. Novi Sad
Vassilis Spanos	
Keith Olive, Evan Skillman	U. Minnesota
John Ellis	CERN

Syllabus

- ★ **Cosmology Primer**
  - life in an expanding universe
- ★ **Nuclear Physics in the Early Universe**
  - Big bang nuke (BBN) theory
  - Light element observations and cosmic baryons
- ★ **Battle of the Baryons**
  - Cosmic microwave background (CMB): a new baryometer
  - BBN vs CMB: tests cosmology
- ★ **Implications**
  - dark matter: two kinds!
  - BBN+CMB: probe particle physics, astrophysics



Cosmology 101

Cosmology

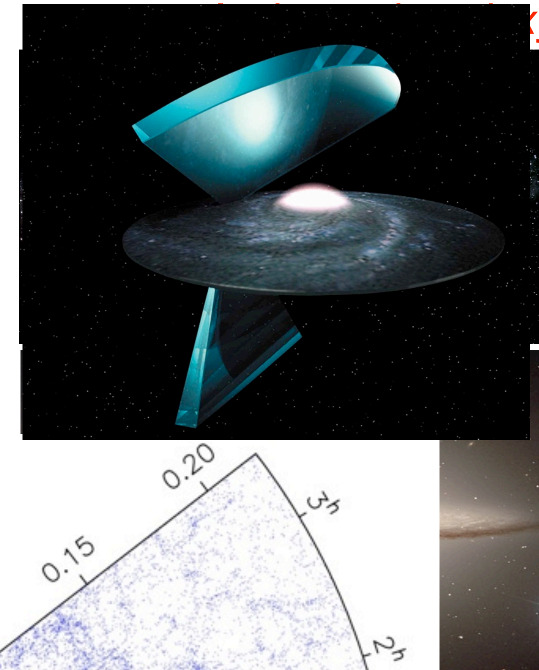
- Structure, Origin, Evolution of the Universe
  - today: stars organized into galaxies
  - ex: Solar Sytem is part of Milky Way
- Typical galaxy: 100 billion stars

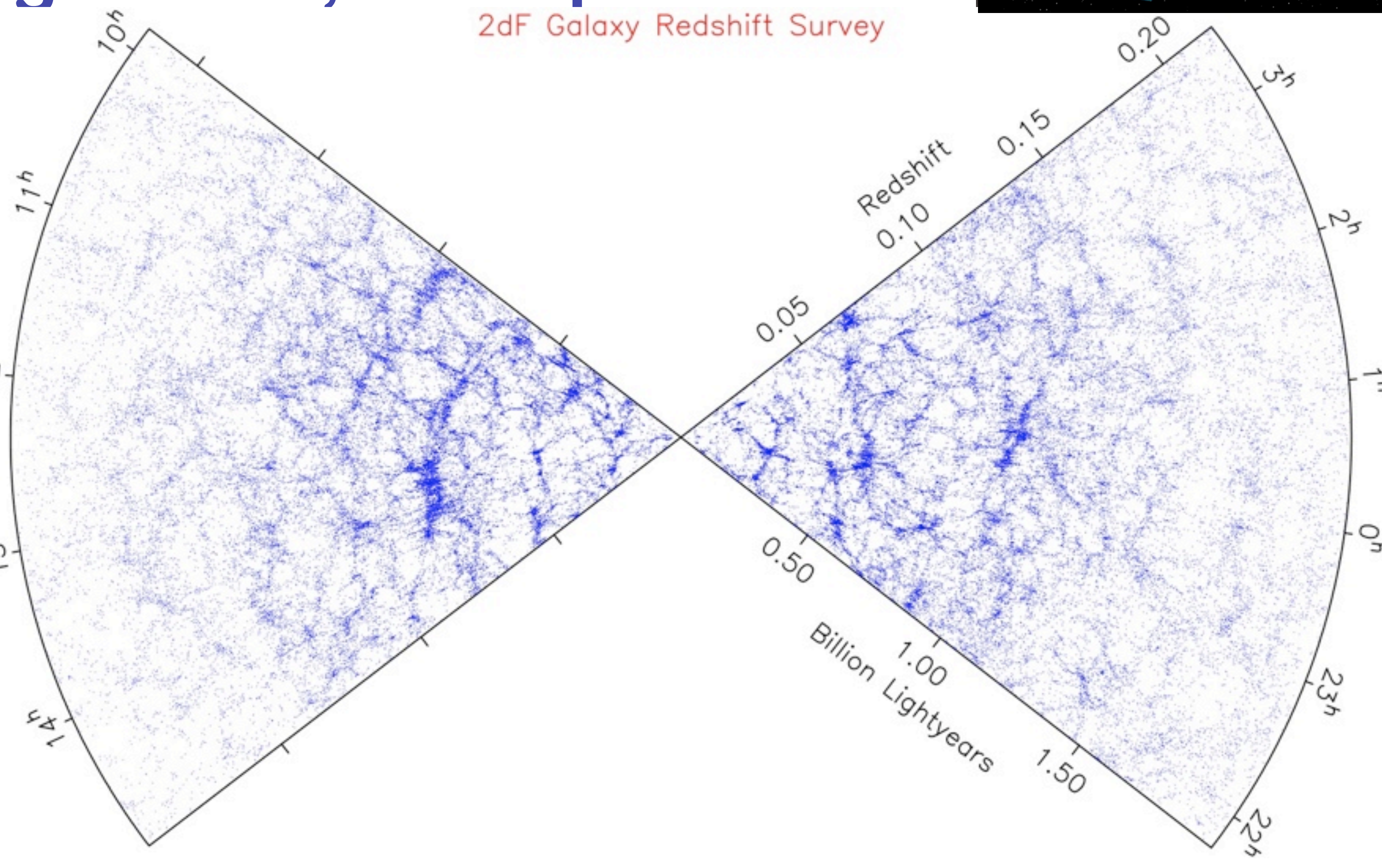
Think big!

galaxies are building blocks

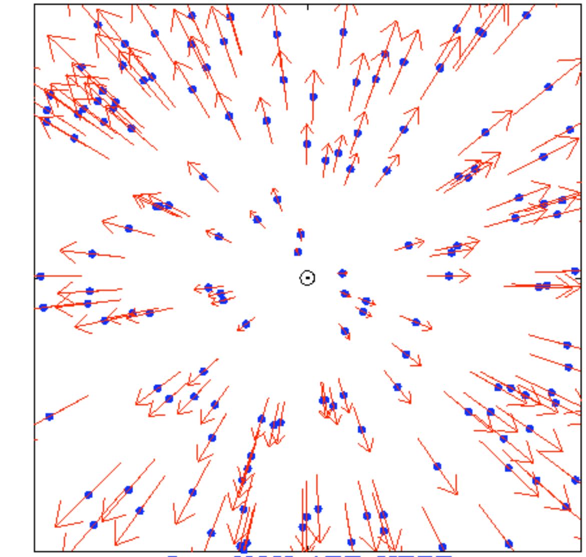
smoothly fill universe:

homogeneous, isotropic





Hubble's Law and Its Meaning



Edwin Hubble (1929):

- measured galaxy motions, distances
- galaxies moving away from us
- farther ⇨ faster
- that is, $\vec{v} = H \ \vec{r}$

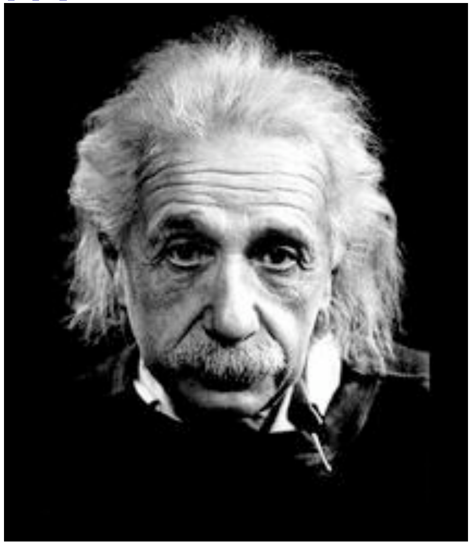
Interpretation: *What does it mean?*

➢ Egoist view:

We are at center of Universe

➢ Einstein view

Universe is expanding! No center!



Cosmology 101: Kinematics

expanding U: write interparticle distances as

$$\vec{r}(t) = a(t)\, \vec{r}_{\rm today}$$

separate into

space-indep universal scale factor

and time-indep "rubber sheet" comoving coord

expansion speed:

$$\vec{v}(t) = \dot{\vec{r}}$$

recover Hubble's law! with Hubble "constant"

$$H(t) = \frac{\dot{a}}{a}$$

Cosmology 101: Dynamics

Newtonian Cosmodynamics:

consider arbitrary point, in homogeneous U of density ρ

test particle at r sees enclosed mass $M = \frac{4\pi}{3} r^3 \rho$

Homework: show that Newtonian gravity gives

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho - \frac{K}{a^2}$$

General Relativity: for Euclidean ("flat") geometry,

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho$$

Lessons:

expansion rate of the universe depends on what's in it

density evolves with expansion: $\rho = \rho_{\mathrm{matter}} + \rho_{\mathrm{radiation}} + \rho_{\mathrm{dark\ energy}}$

today: $\rho_{\mathrm{today}} \gg \rho_{\mathrm{radiation}} \propto T_{\mathrm{CMB}}^4$ ⇨ CMB dynamically unimportant

but in early U: T_{CMB} high

$\rho_{\mathrm{early\ univ}} \approx \rho_{\mathrm{radiation}}$ "radiation domination"

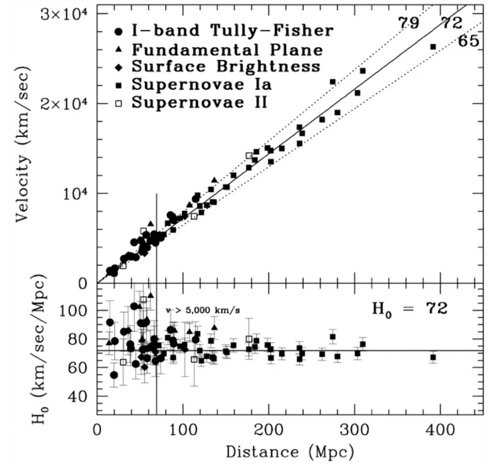
The Standard Cosmology:

Hot Big Bang Model

Friedmann-Lemaitre-Robertson-Walker

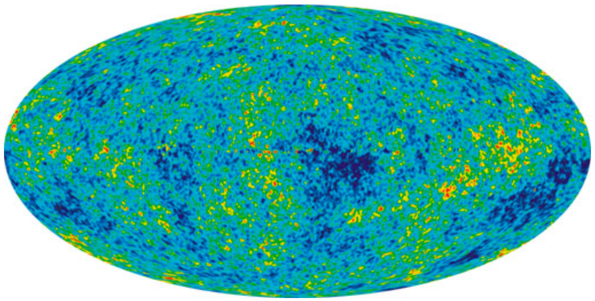
Gravity = General Relativity
Space: Homogeneous & Isotropic

- **Expanding Universe**
  t~14 Gyr; T~10^{-4} eV



Freedman et al 2001

- **Cosmic Microwave Background (CMB)**
  t~400,000 yr; T~1 eV



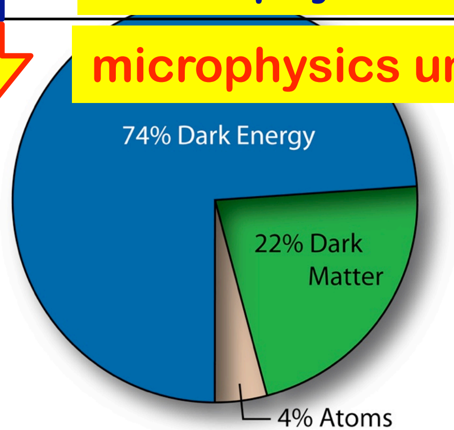
WMAP 2005

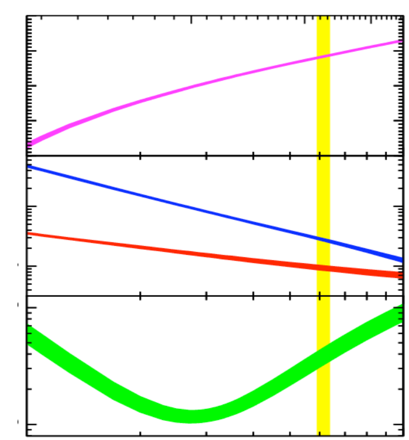
- **Big-Bang Nucleosynthesis (BBN)**
  t~1 sec, T Me

microphysics known

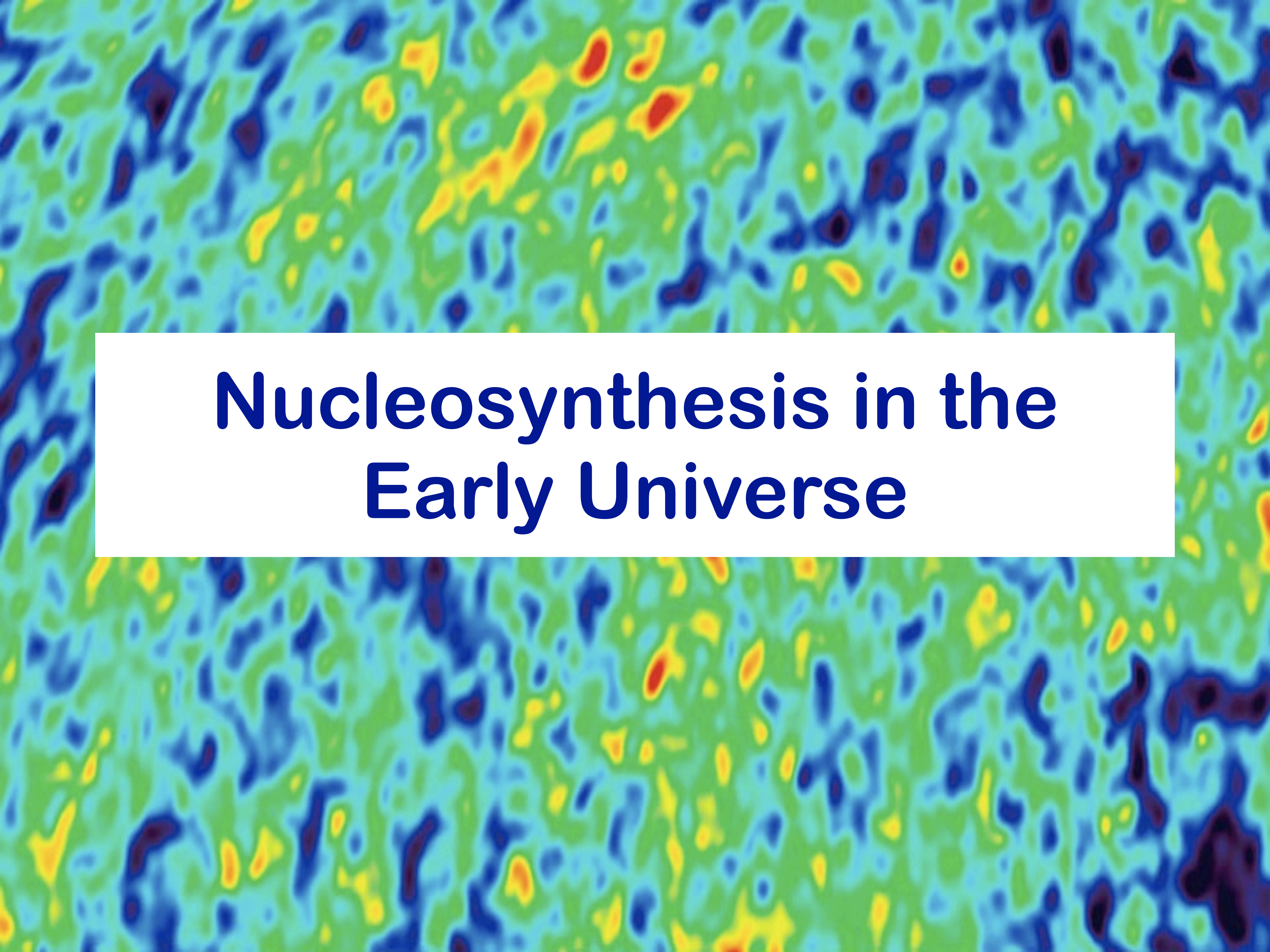
microphysics unknown

- Dark Matter
- Dark Energy
- Inflation





Cyburt, BDF, Olive 2003



Nucleosynthesis in the Early Universe

Standard BBN

- 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. ⇒ $\eta \equiv \frac{n_{\text{baryon}}}{n_\gamma}$ Spatially const

- Expansion adiabatic

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

- gives baryon density $\eta \propto \rho_{\text{B,today}} \propto \Omega_{\text{B}}$

Big Bang Nucleosynthesis

Follow weak and nuclear reactions
in expanding, cooling Universe

Dramatis Personae

Radiation dominates! $\gamma, \; e^{\pm}, \; 3\nu\bar{\nu}$

Matter p, n

tiny baryon-to-photon ratio
(the only free parameter!) $\eta \equiv n_{\rm B}/n_\gamma \sim 10^{-9}$

Initial Conditions: T >> 1 MeV, t<< 1 sec

n-p weak equilibrium: $pe^- \leftrightarrow n\nu_e$

$$ne^+ \leftrightarrow p\bar{\nu}_e$$

neutron-to-proton ratio:

$$n/p = e^{-(m_n - m_p)c^2/kT}$$

Weak Freezeout: T ~ 1 MeV, t~1 sec

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

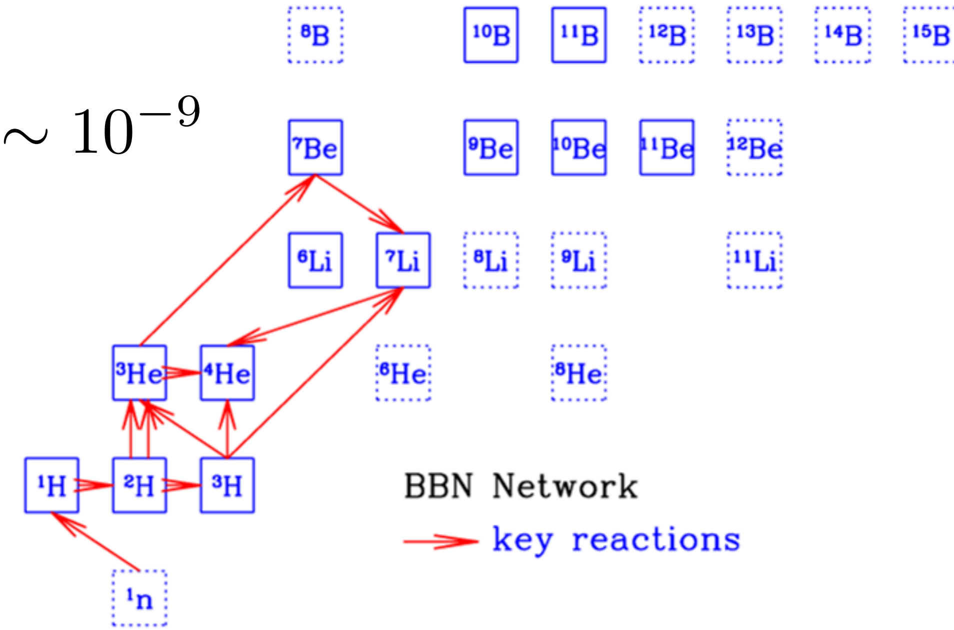
fix $\left(\frac{n}{p}\right)_{\rm freeze} \approx e^{-\Delta m/T_{\rm freeze}} \sim \frac{1}{7}$

Light Elements Born: T~0.07 MeV, t~3 min

reaction flow ⇨ most stable light nucleus

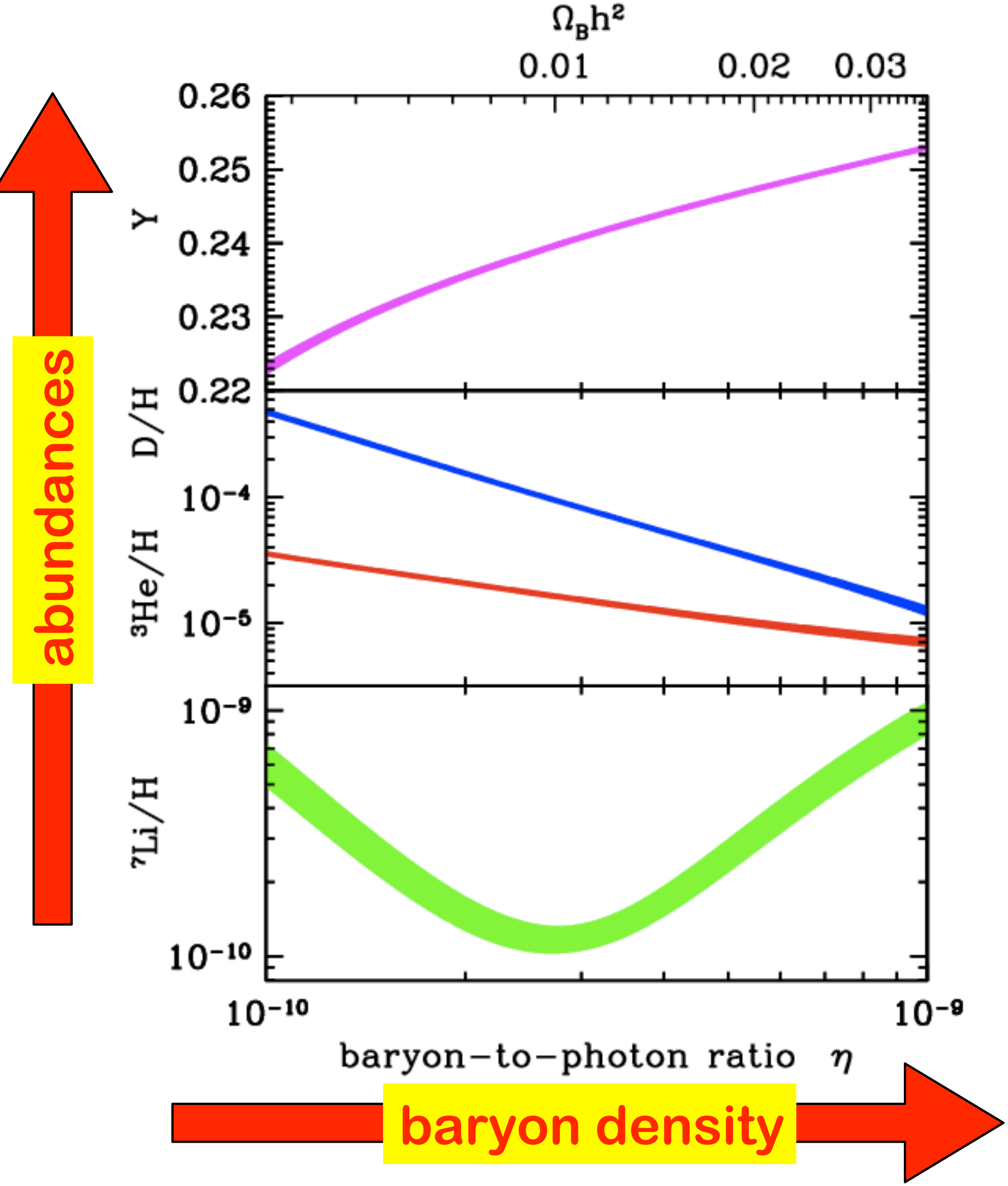
essentially all n ⇨ ^{4}He, ~24% by mass

also: traces of D, ^{3}He, ^{7}Li



All reactions measured in lab at relevant energies

BBN Predictions



Curve Widths:
Theoretical uncertainty
nuclear cross sections

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

BBN Observations:
Light Element Abundances

Where and *when* do predicted BBN abundances apply?

Where and *when* can light elements be observed?

What problems might complicate comparing theory and observation?

How might these problems be overcome?

BBN Observations:
Light Element Abundances

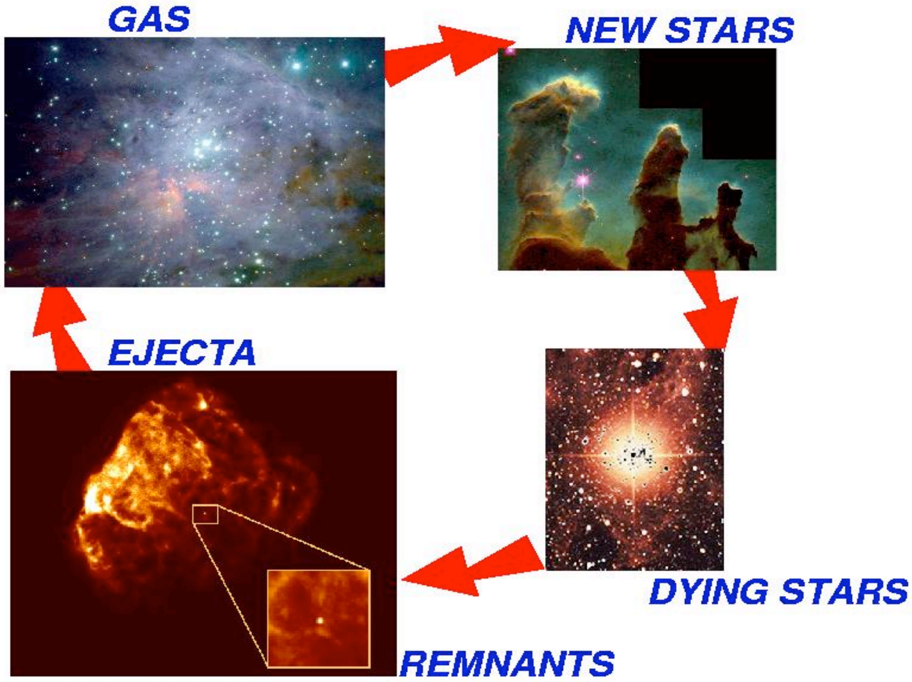
The Problem

- Theoretical predictions: *there and then*
- Observations: *here and now*
- But... Galactic nuke changes abundances

The Solution

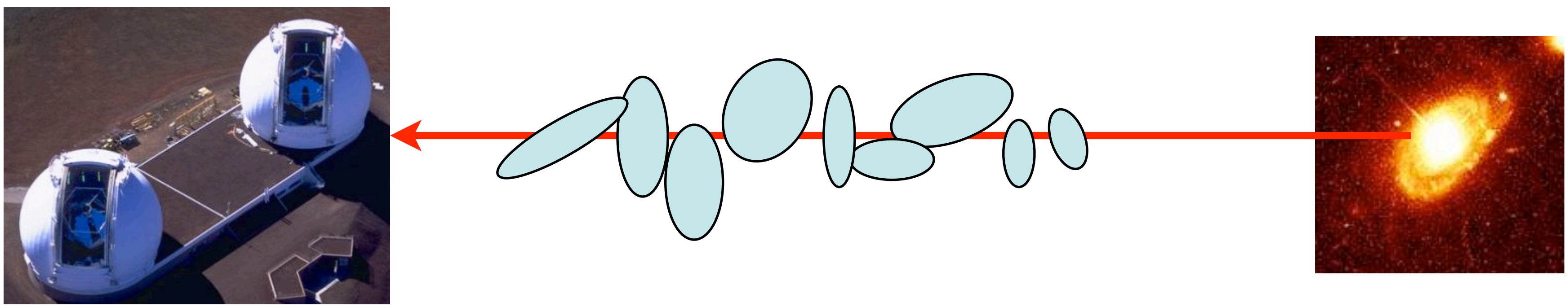
- measure & correct for post-BBN processing:

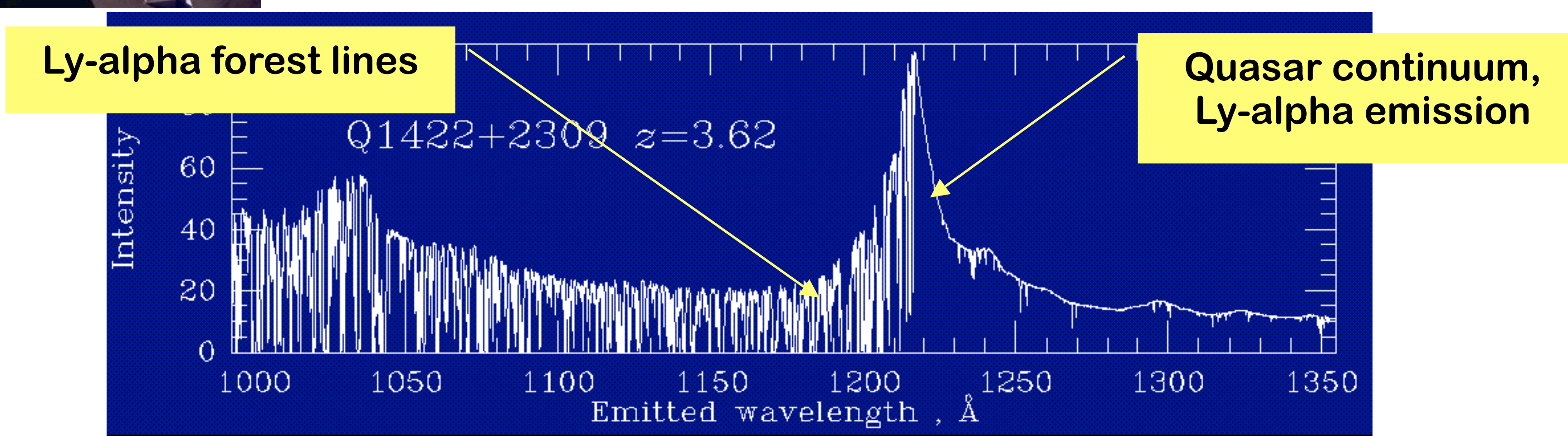
Metals $\Leftrightarrow$ $\text{stars} \geq 10 M_{\odot}$ $\Leftrightarrow$ "time"



BBN Observations: Case Study
Primordial Deuterium

- High-redshift quasar=light bulb
- Intervening H gas absorbs at $\mathrm{Ly}\alpha(n=1 \rightarrow n=2)$
- Observed spectrum: Ly-alpha "forest"





Deuterium Data

Deuterium Ly-alpha shifted from H:

$$E_{\mathrm{Ly}\alpha} = \frac{1}{2}\alpha^2\mu_{\mathrm{reduced}}$$

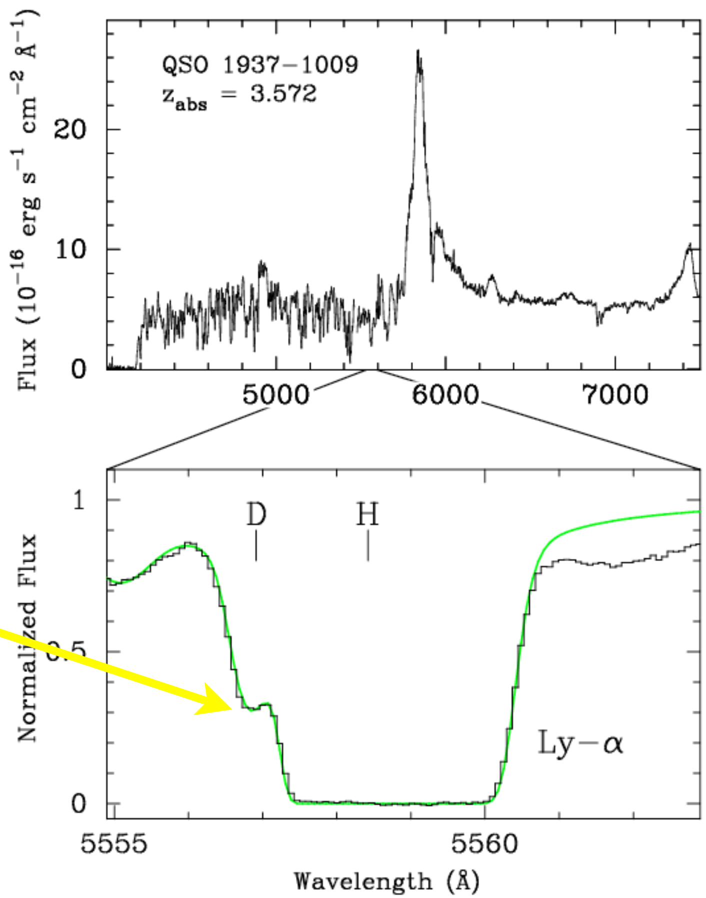
$$\frac{\delta\lambda_{\mathrm{D}}}{\lambda_{\mathrm{D}}} = -\frac{\delta\mu_{\mathrm{D}}}{\mu_{\mathrm{D}}} = -\frac{m_e}{2m_p}$$

$$c\delta z = 82\ \mathrm{km/s}$$

Get D directly at high-z!

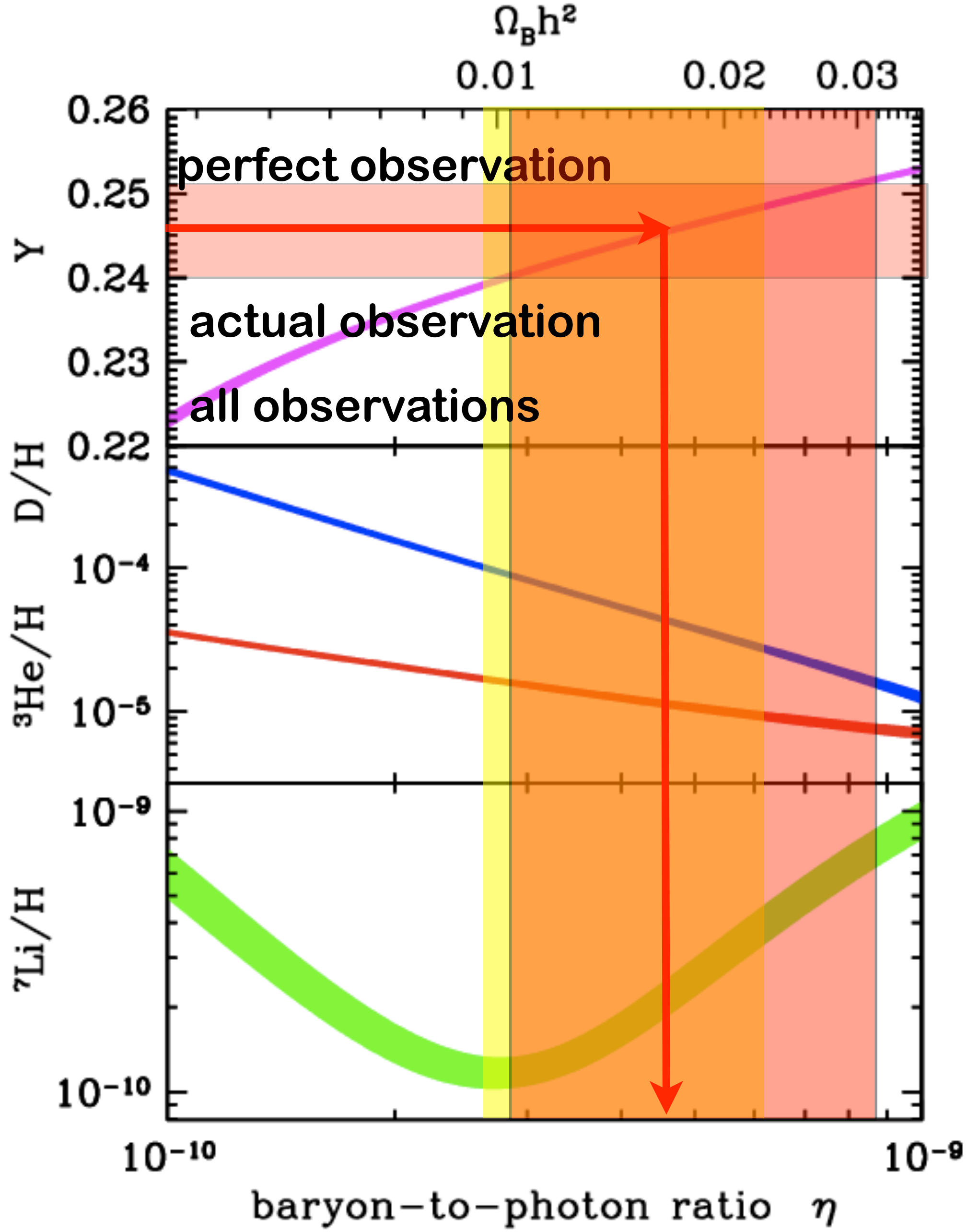
But:

- **Hard to find good systems**
- **Don't resolve clouds**
- **Dispersion/systematics?**



Tytler & Burles

Testing BBN: Light Element Observations



Theory:

- **1** free parameter predicts
- **4** nuclides: D, ^{3}He, ^{4}He, ^{7}Li

Observations:

- **3** nuclides with precision: D, ^{4}He, ^{7}Li

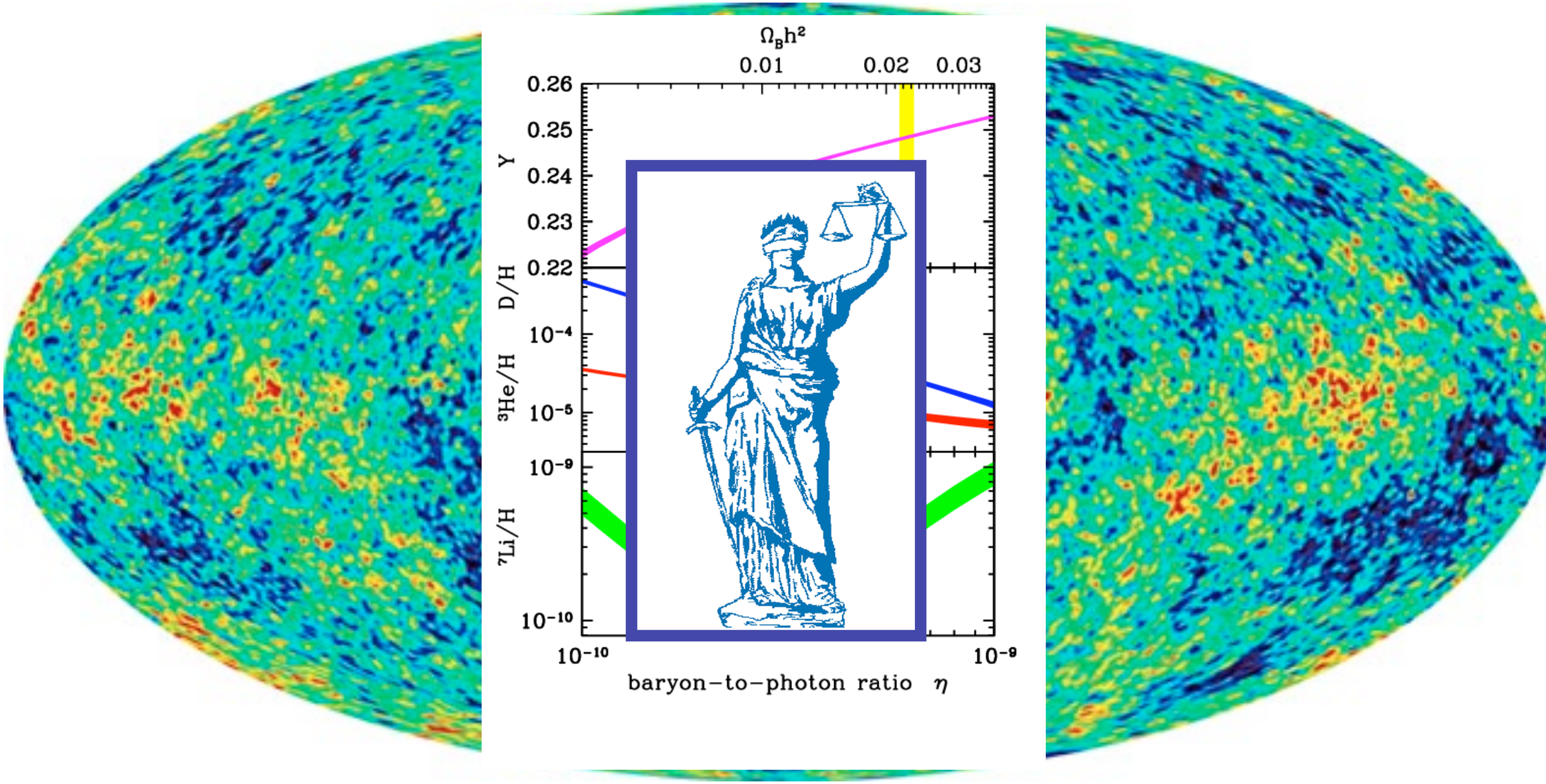
Comparison:

★each nuclide selects baryon density
★overconstrained--nontrivial test!

Result:

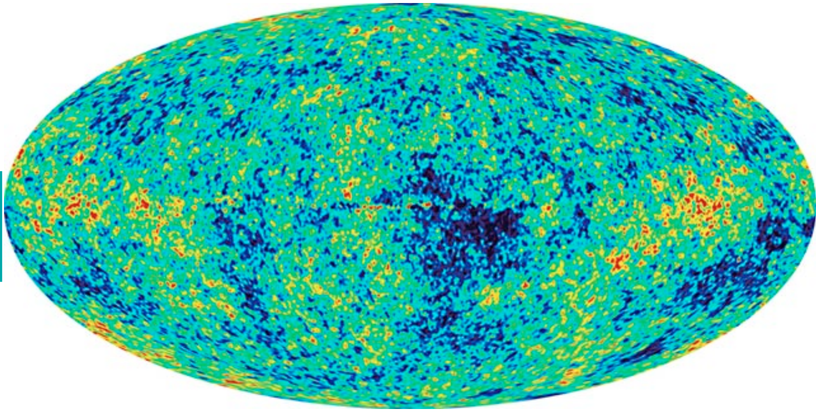
★rough concordance!
★cosmological confidence at t~1 sec
measures baryon content of Universe

Battle of the Baryons:



The CMB: A Powerful New Baryometer

CMB ΔT_ℓ independent measure of Ω_B

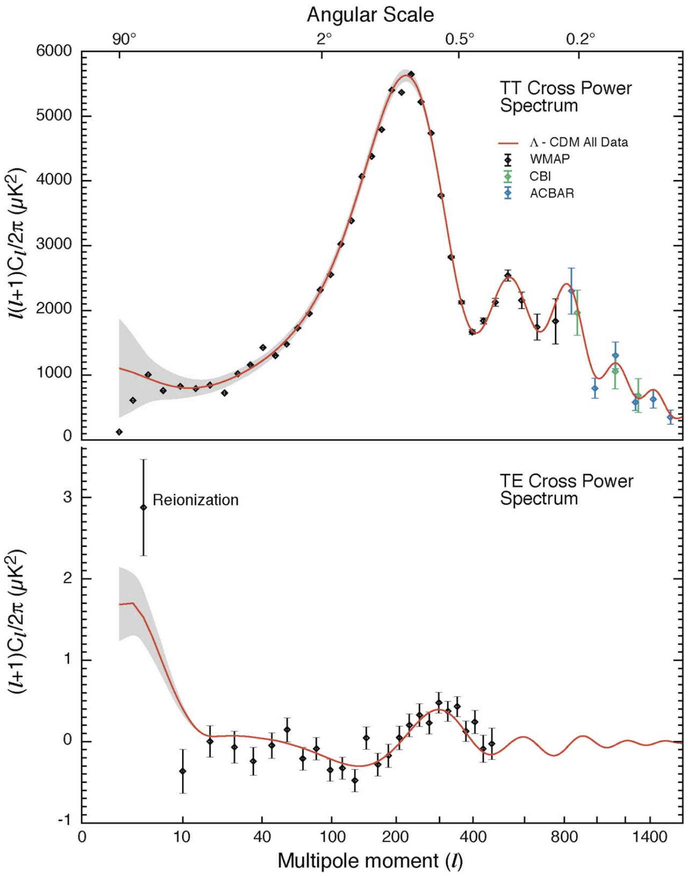


Power spectrum features < 1°
set by acoustic oscillation

Detailed peak posns, heights:

- sensitive to cosmological parameters
- first peak: curvature of U.
- second, third peaks/first peak: Ω_B

BBN vs CMB: fundamental test of cosmology



Wilkinson Microwave Anisotropy Probe WMAP
"Best-Fit":

$$\Omega_B h_{100}^2 = 0.0226 \pm 0.008$$
$$\eta = (6.14 \pm 0.25) \times 10^{-10}$$

Battle of the Baryons: I
The Big Picture

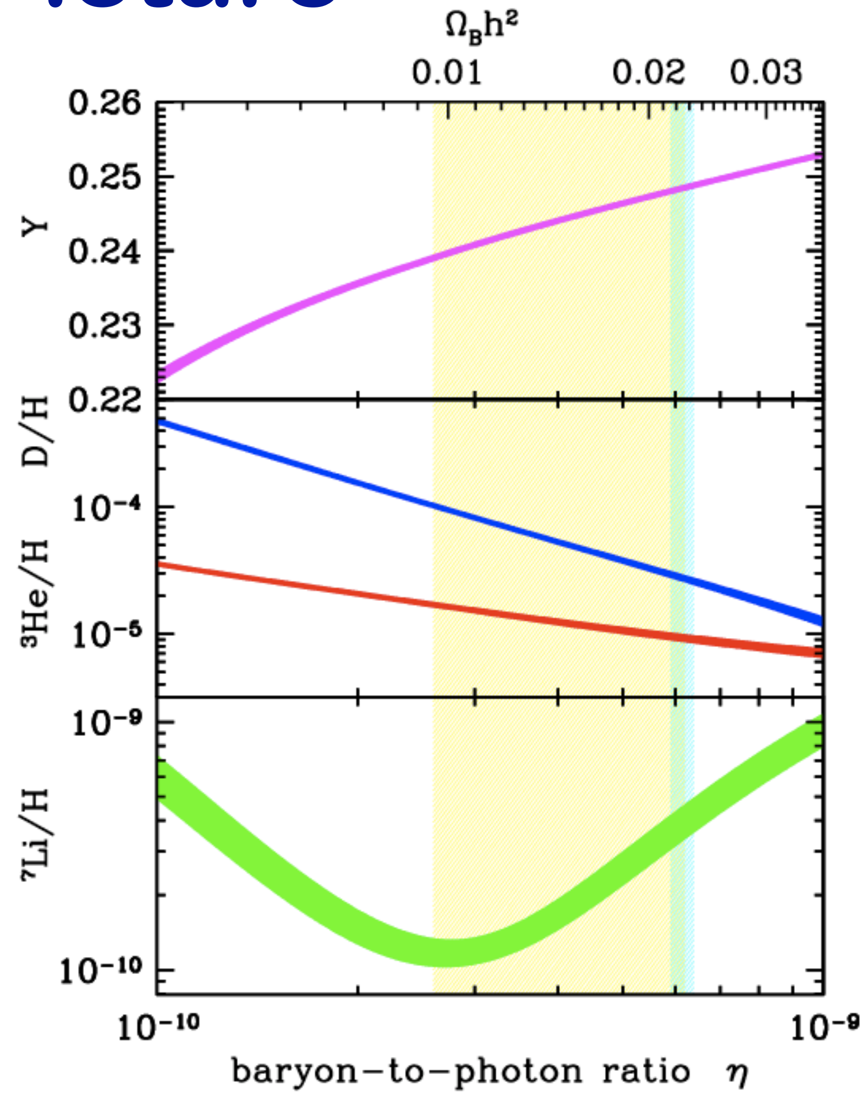
Compare:

$\eta_{\rm bbn}$ versus $\eta_{\rm cmb}$

independent baryometers

Consistency check for big bang model

⇨ Rough agreement cosmological success!



Battle of the Baryons: II
New World Order

Cyburt, BDF, Olive 2003

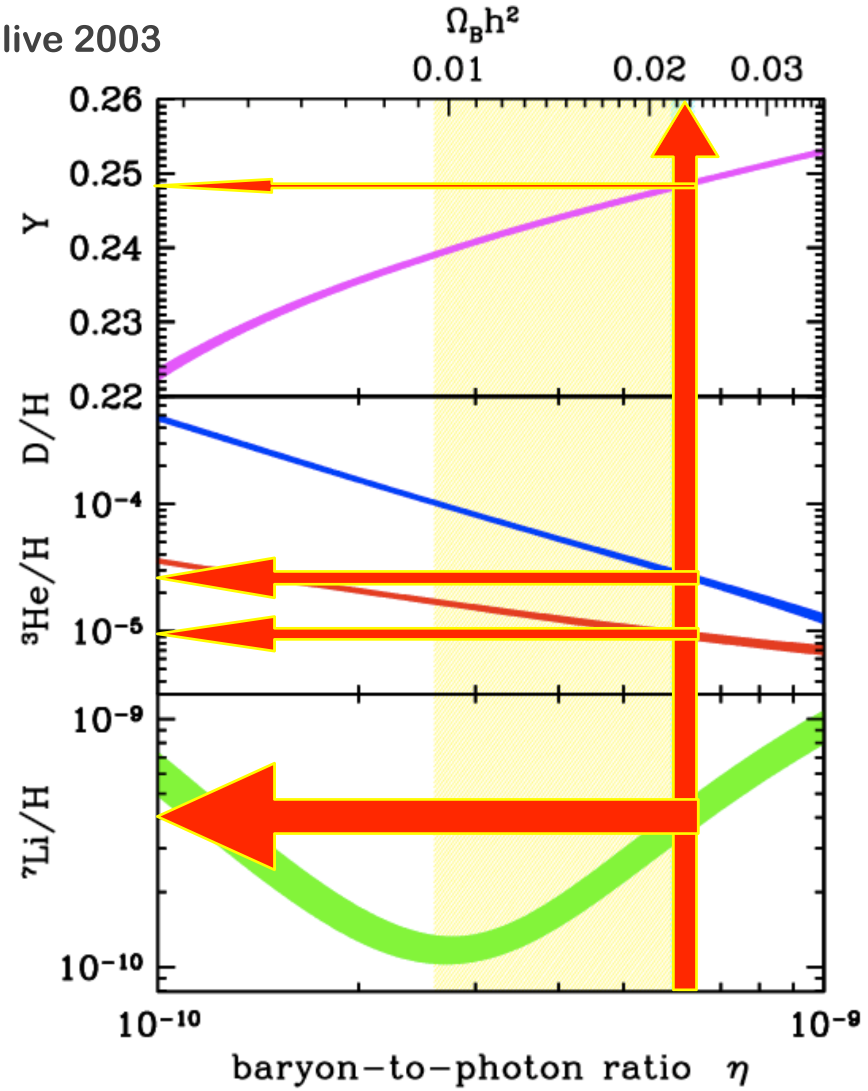
WMAP baryon density very precise

$$\Omega_{\rm B} h^2_{100} = 0.0226 \pm 0.008$$
$$\eta = (6.14 \pm 0.25) \times 10^{-10}$$

i.e., a 4% measurement!

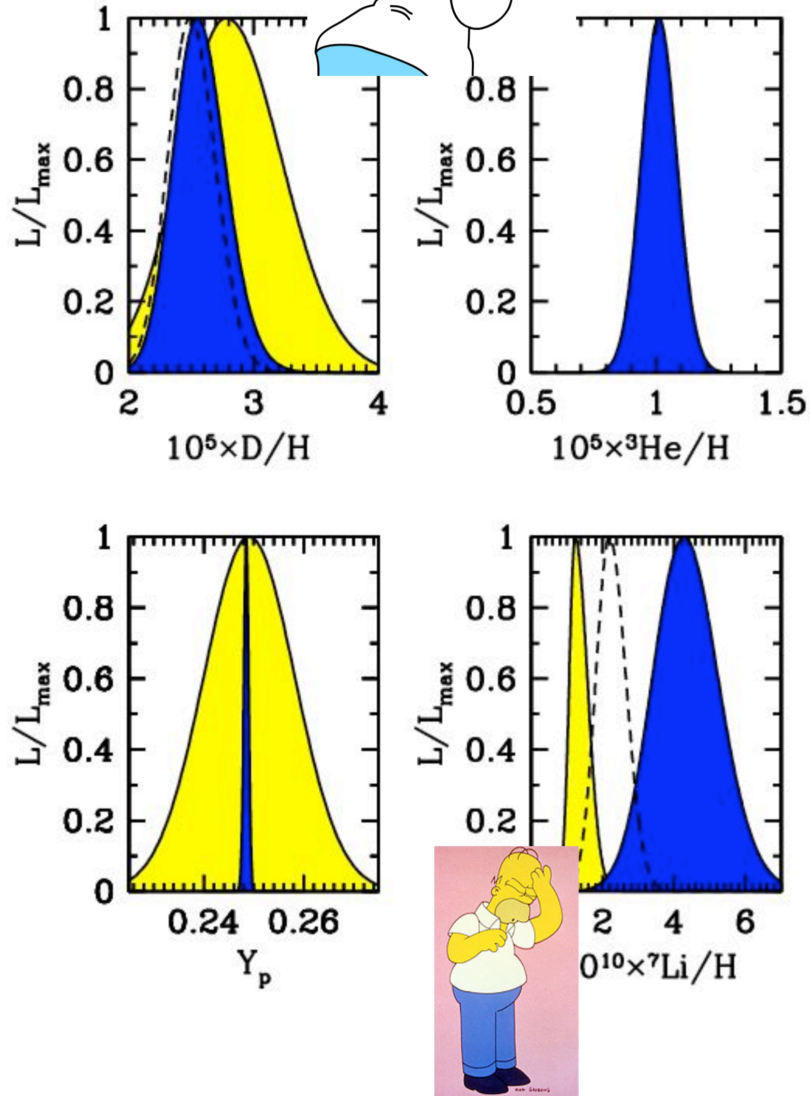
New strategy to test BBN:

- ✓ use WMAP $\eta_{\rm cmb}$ as BBN input
- ✓ predict all lite elements
  - with appropriate error propagation
- ✓ compare with observations



Battle of the Baryons: II
A Closer Look

Cyburt, BDF, Olive 2003



Predict:

BBN theory: abundances vs η

WMAP $\eta_{\rm cmb}$ ⇨ BBN+CMB abundances (blue)

Compare with Observations (yellow)

Results:

- D agreement excellent: woo hoo!
- ^{7}Li not so good
  - systematic errors in obs?
  - theory?
  - new physics?

Dark Matter

Pre-CMB Anisotropies:

BBN ⇨ Dark Matter

WMAP finds:

★ $\Omega_B = 0.044 \pm 0.004$

★ $\frac{\Omega_M}{\Omega_B} = \frac{\text{matter}}{\text{baryons}} = 5.9 \pm 0.3$

Optical galaxy surveys ⇨ luminous matter

★ $\Omega_{lum} \sim 0.007$

Confirms & sharpens case for dark matter: two kinds!

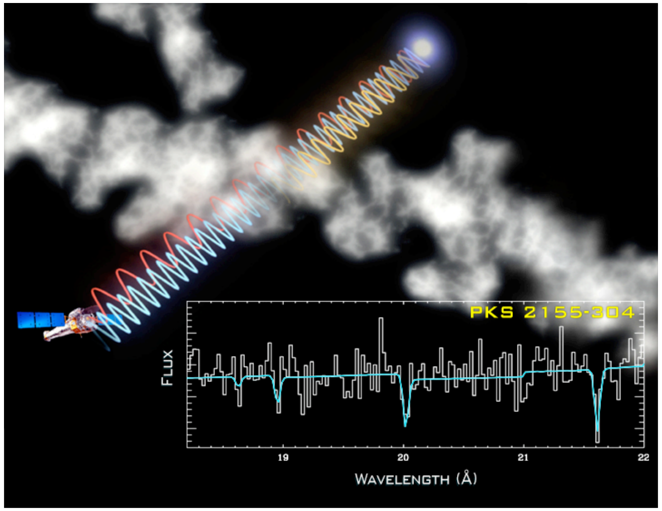
Baryonic Dark Matter: $\Omega_B \gg \Omega_{lum}$

➡ **warm-hot IGM, Ly-alpha, X-ray gas**

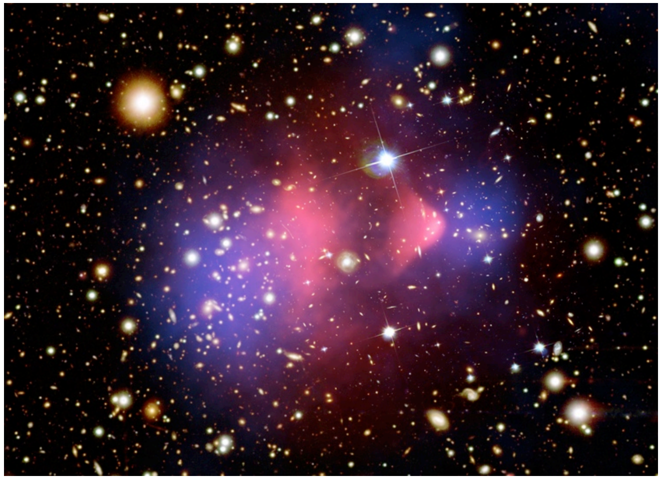
Fukugita, Hogan, Peebles; Cen & Ostriker; Dave etal

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)

Big Bang Nuke
Lessons Thus Far

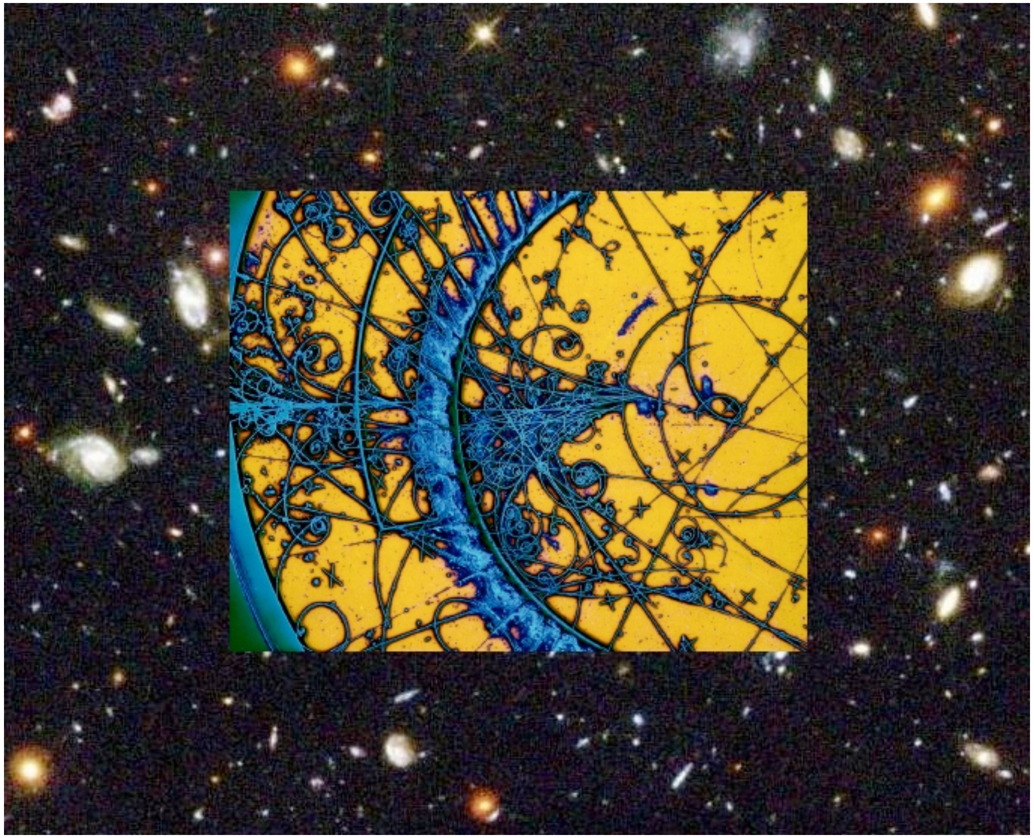
Standard Cosmology in Great Shape

- expanding world model fits mountian of data
- hot, early Universe confirmed by CMB: atomic age
- earliest current probe: big bang nuke: t~1 sec
- but outstanding questions: dark matter, energy

Big Bang Nucleosynthesis

- theory simple, precise: relies on solid physics
- observations: light elements challenging
- WMAP $\eta_{\rm cmb}$ removes only free parameter in standard BBN
- D, He concordance excellent
- points to dark matter: baryonic, non-baryonic
- but outstanding questions: lithium is a problem!
- **Stay tuned!**

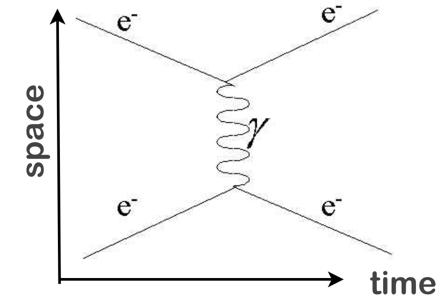
Big Bang Nucleosynthesis and Particle Dark Matter



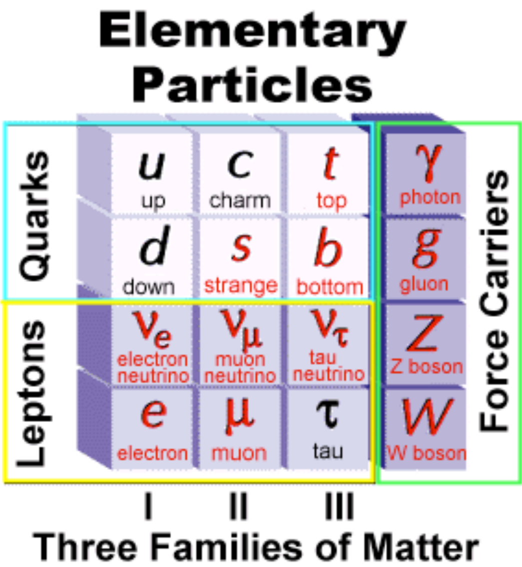
Illinois Astronomy Colloquium 29 Jan 2008

The Standard Model of Particle Physics: Impressionist's View

- **Inspiration: quantum E&M**
  - charged particles interact via photon exchange
  - generalize to other forces



- **Structure**
  - matter: fermions (spin-1/2)
  - force carriers: bosons (spin-1)



- **Predictive Power & Empirical Success**
  - organizes a mountain of data
    - e.g., ~130 observed *qqq*=baryonic states
    - of which 2 are stable: *uud*=p & *udd*=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!

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?
  - Unification of forces?
- The game: invent larger framework which
  - inherits all of SM successes
  - addresses some/all of these questions
  - doesn't violate existing data
  - predicts results of future experiments
- All new models predict new particles relevant to cosmology!

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: $\rho_{\text{tot,rel}} = \rho_{\text{EM}} + N_{\nu,\text{eff}}\ \rho_{\nu\bar{\nu}}$

Stiegman, Schramm, & Gunn 77

Pre-CMB:

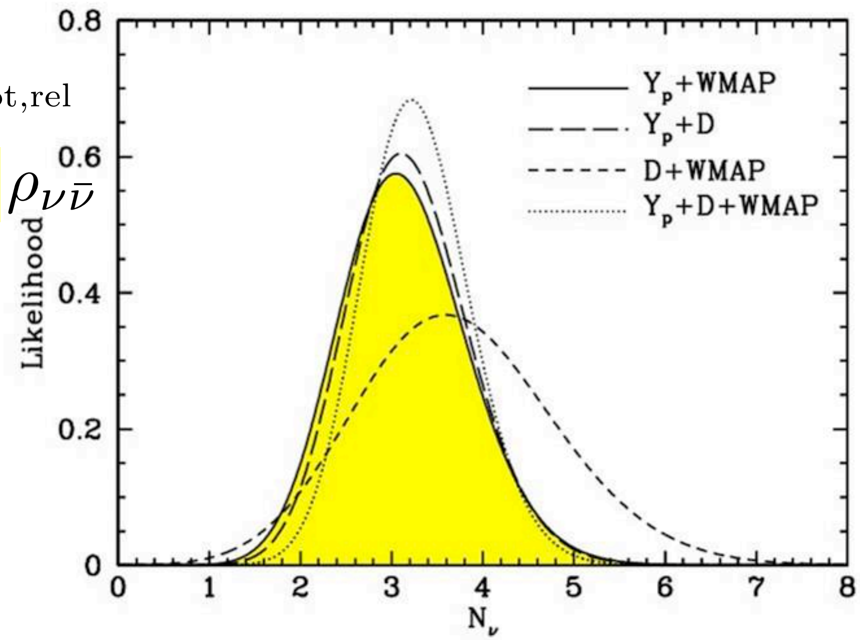
^{4}He as probe, other elements give baryon density

With η from CMB

- All abundances probe
- Now: 4He sharpest probe, but syst errors?
- Future: If get D/H to 3%
- Get best leverage on $N_{\nu,\text{eff}}$

Cyburt, BDF, & Oiive 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

Non-Baryonic Dark Matter: Neutrinos?

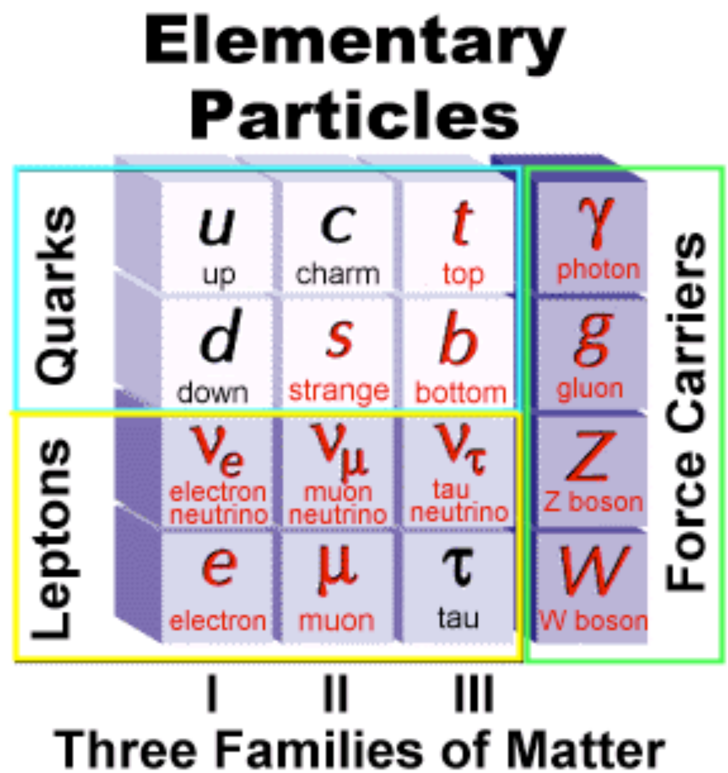
Required Dark Matter Properties

- dark → feeble interactions
- matter → has mass
- present at t~14 Gyr → stable
- inert @ BBN, recomb → non-baryonic
- abundant: $\Omega_{\rm m} \simeq 0.3$

Consult Standard Model

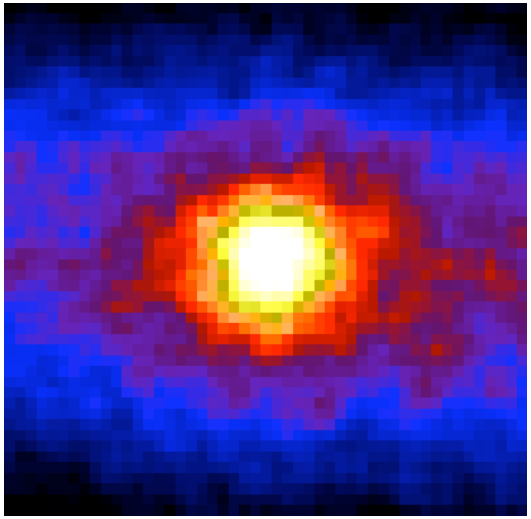
neutrinos very promising!

- ✓massive
- ✓stable
- ✓weakly interacting
- ✓not quarks → not baryons



Non-Baryonic Dark Matter:

Neutrinos?



The Sun, imaged in neutrinos
SuperKamiokande

Neutrino densities today

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

All hangs on neutrino masses

...which we don't know

But we know enough:

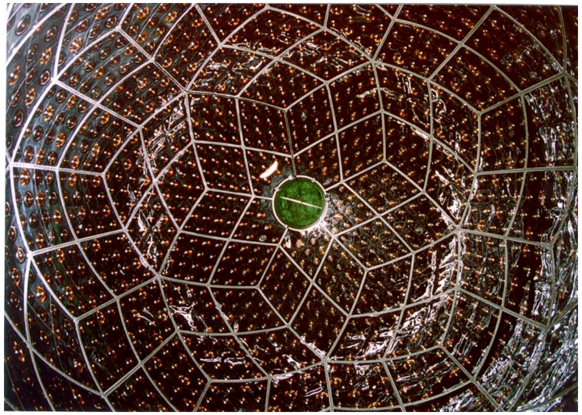
mass differences (from oscillations)

$m(\nu_e) \leq 2 \text{ eV}$ (from beta decays)

$\sum m_\nu \leq 2 \text{ eV}$ (from large-scale structure)

Total density contribution: $\Omega_\nu \leq 0.1\ \Omega_{\rm m}$

Neutrinos are not the dark matter



KamLAND Reactor Neutrino Detector

Non-Baryonic Dark Matter
Particle Candidates

the vast majority of dark matter is

- non-baryonic
- but not neutrinos

exhausts known particle candidates!

Dark matter demands physics beyond Standard Model!

But recall: Standard Model 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"

most popular (& most promising?) theory: Supersymmetry

- boson-fermion symmetry: super-partners to all SM members
- lightest spartner stable ⇨ excellent DM candidate

Non-Baryonic Dark Matter

Early Universe History

Birth

in hot early Universe $kT \gg m_\chi c^2$

dark matter particles χ, 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

$\Omega_\chi \sim \frac{1}{\sigma_{\mathrm{weak}}}$ Weak (& SUSY) scale gives right amount of DM!

explains why DM = weakly interacting massive particles: **WIMPs**!

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

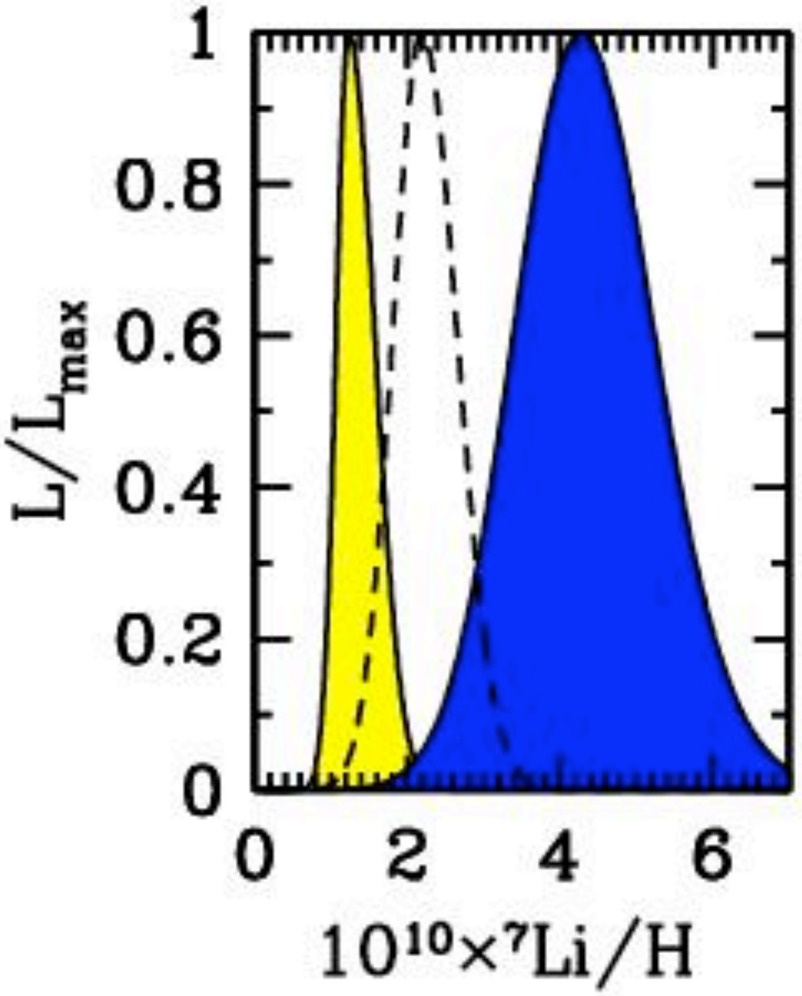
Currently favored scenarios

lightest SUSY particle (LSP) is dark matter...

...but next-lightest particle long-lived: $\tau_{\rm nlsp} \sim 1 - 10^6 {\rm sec}$

can decay during or after BBN!

The Lithium Problem



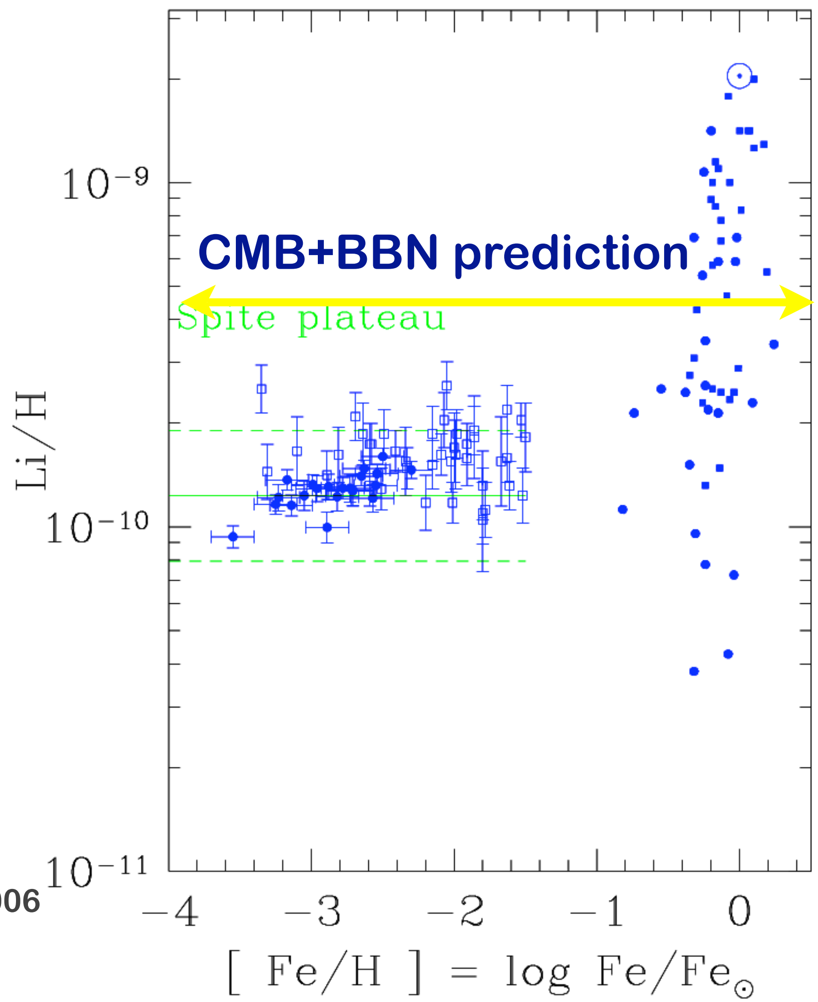
Primordial Lithium

Observe in primitive (Pop II) stars

Li-Fe ⇨ evolution

Plateau at low Fe Spite & Spite 82

- ★ 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 Asplund et al 2006 **primordial $^6Li >> ^6Li_{SBBN}$?!**

Lithium Problem: Conventional Solutions

Observational Systematics

Measure: Li I = Li^0 absorption line(s)

Infer: Li/H

T_{eff} critical: mostly Li II = Li^{+1}

Needed error in T scale ~500 K: large!

But maybe possible: Melendez & Ramirez 04; BDF, Olive, Vangioni-Flam 05

Astrophysical Systematics

stellar depletion over ~10^{10} yr

if Li burned: correct Li_p upward!

But: no Li scatter, and ^6Li preserved… Ryan et al 2000

Nuclear Systematics

^7Li production channel $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

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

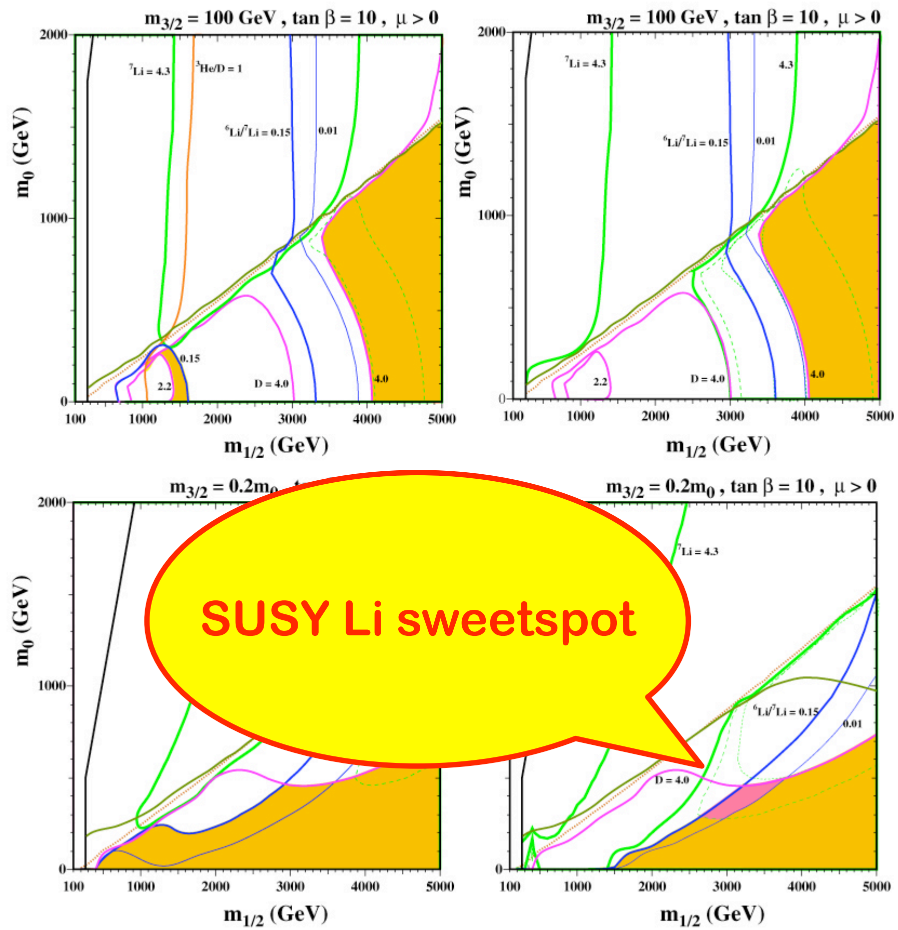
Could Lithium Be SUSY-licious?

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
- hadronic decays can erode ^{7}Li, and fix Li problem Jedamzik
- if next-to-lightest particle charged, additional effects (catalysis!) make ^{6}Li Pospelov, Cyburt etal,



A SUSY solution to lithium problems?

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

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~1 sec
- non-baryonic dark matter required
- must arise in physics beyond the Standard Model of particle physics

The Dark Matter Discovery Trifecta

- underground direct detection
- LHC@CERN: recreate dark matter and/or SUSY
- gamma-ray signature: GLAST--up and running!

Answers (& new surprises?) in <10 years!

Future exciting--stay tuned!