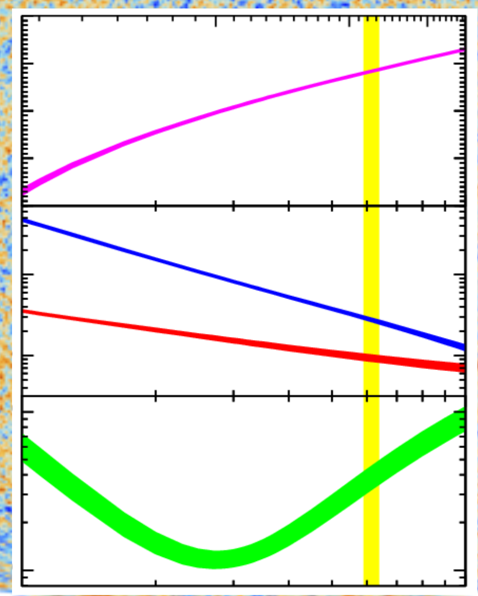
# Primordial Nucleosynthesis after Planck: The Lithium Problem and Dark Matter



**Brian Fields**

Indirect Methods in Nuclear Astrophysics

ECT* Trento, Nov 5 2018

# Collaborators


Richard Cyburt


Nachiketa Chakraborty


Vasilis Spanos


Tiajana Prodanovic


Tsung-Han Yeh 葉宗翰


Charlie Young


Keith Olive


Chris Howk


John Ellis

# Big Bang Nuke After Planck

## ★ Nuclear Physics in the Early Universe

- Cosmology
- 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: particle dark dark matter beyond Standard Model

## ★ The Lithium Problem

- $^{7}$Li+$^{7}$Be disagreement: CMB vs astro observations
- new nuclear physics? new particle physics?

# The Standard Cosmology:

## Hot Big Bang Model

Friedmann-Lemaitre-Robertson-Walker

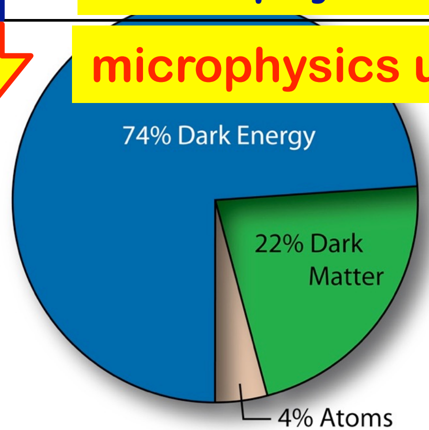
**Gravity = General Relativity**
**Space: Homogeneous & Isotropic**

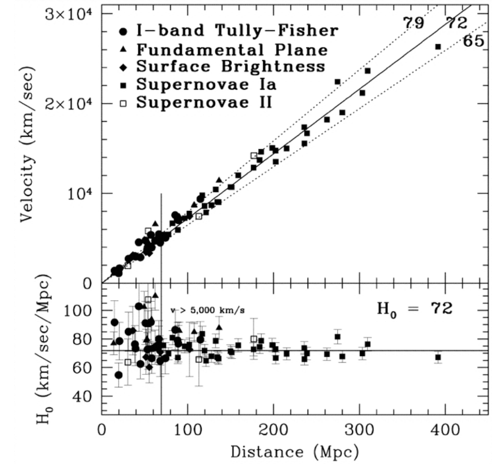
- Expanding Universe
  - t~14 Gyr; T~$10^{-4}$ eV
- Cosmic Microwave Background (CMB)
  - t~400,000 yr; T~1 eV   atomic physics
- Big-Bang Nucleosynthesis (BBN)
  - t~1 sec, T Me

microphysics known

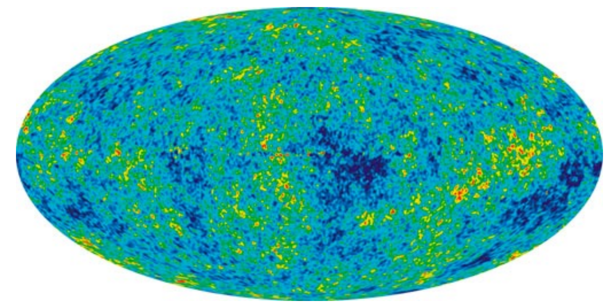
microphysics unknown

- Dark Matter
- Dark Energy
- Inflation

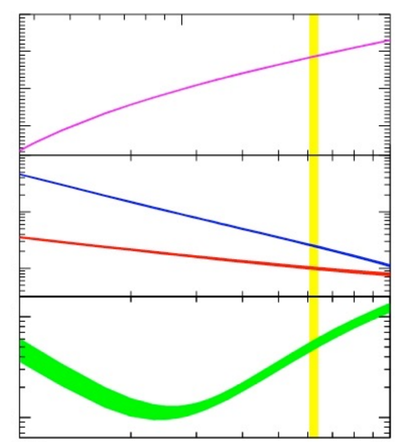



Freedman et al 2001



WMAP 2005



Cyburt, BDF, Olive 2008

# Cosmic Job Security:
# Precision Ignorance

- **Why does the dark matter weigh?** apologies to Feynman
  - what is it?
  - how is it produced?
  - how does it interact?
  - what was its role in the early universe?
- **Dark energy—who ordered that?** apologies to Rabi
  - is it related to dark matter?
  - does it evolve with time?
  - what was its role in the early universe?
- **What sets $\rho_{\rm baryon} \sim \rho_{\rm matter} \sim \rho_\Lambda$ today?**
  - compare: nuclear physics sets $\rho_{\rm H} \sim \rho_{\rm He}$

# Big Bang Nucleosynthesis:
## A Symphony of Fundamental Forces

- **BBN: unique arena**
  - all four fundamental forces participate
- **BBN: unique testbed**
  - probes all fundamental interactions


# Standard BBN

- Gravity = General Relativity
- Microphysics: Standard Model of Particle Physics
  - $N_\nu = 3$ neutrino species
  - $m_\nu \ll 1\ \mathrm{MeV}$
  - Left handed neutrino couplings only
  - neutrinos non-degenerate: $L \approx B$ and n
- Kinetic equilibrium: Maxwell-Bo
- Dark Matter and Dark Energ
  - Present (presumably) b

Non-Standard BBN models
relax these assumptions
test new physics

Homogeneous U.

➢ Expansion adiabatic

$$\left(\frac{n_{\rm B}}{n_\gamma}\right)_{\rm BBN}$$

• gives baryon density

$$\eta \propto \rho_{\rm B,today} \propto \Omega_{\rm B} h^2 \propto \left(\frac{\rm entropy}{\rm baryon}\right)^{-1}$$

# Big Bang Nucleosynthesis

**Follow weak and nuclear reactions in expanding, cooling Universe**

**Dramatis Personae**

- Radiation dominates! $\gamma,\ e^{\pm},\ 3\nu\bar{\nu}$
- Baryons $p, n$
- 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:

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

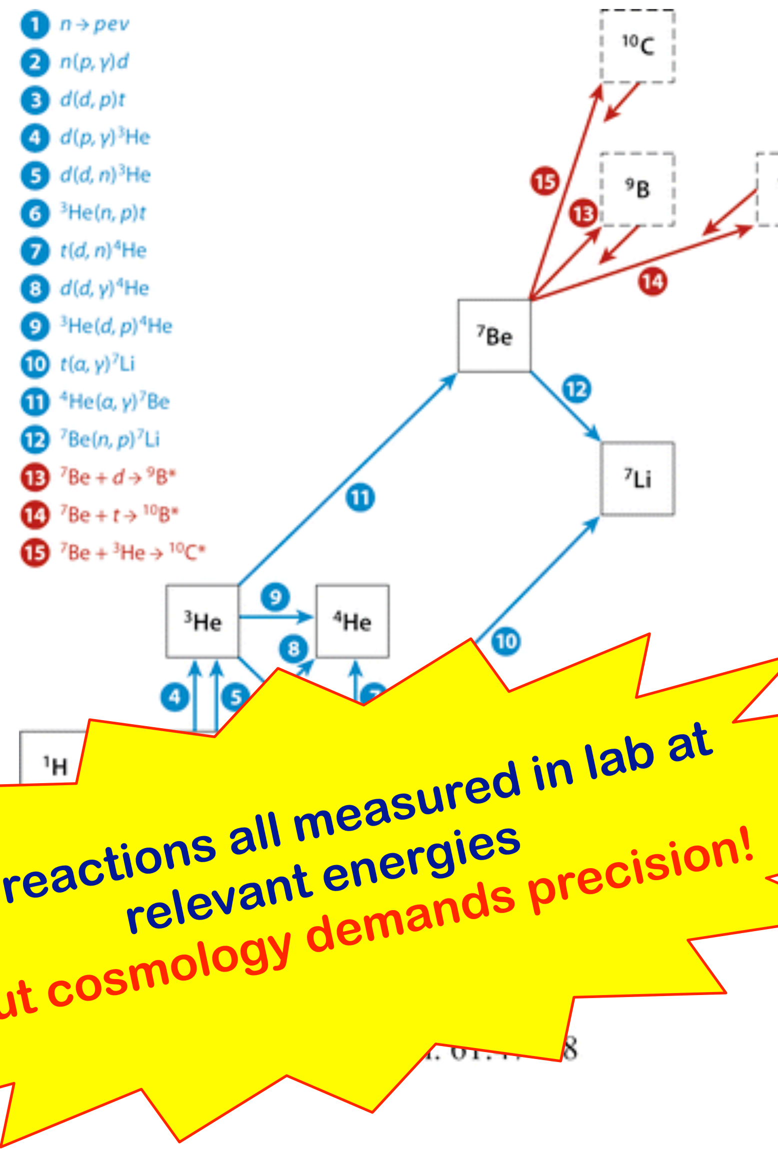
**Weak Freezeout: T ~ 1 MeV, t~1 sec**

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

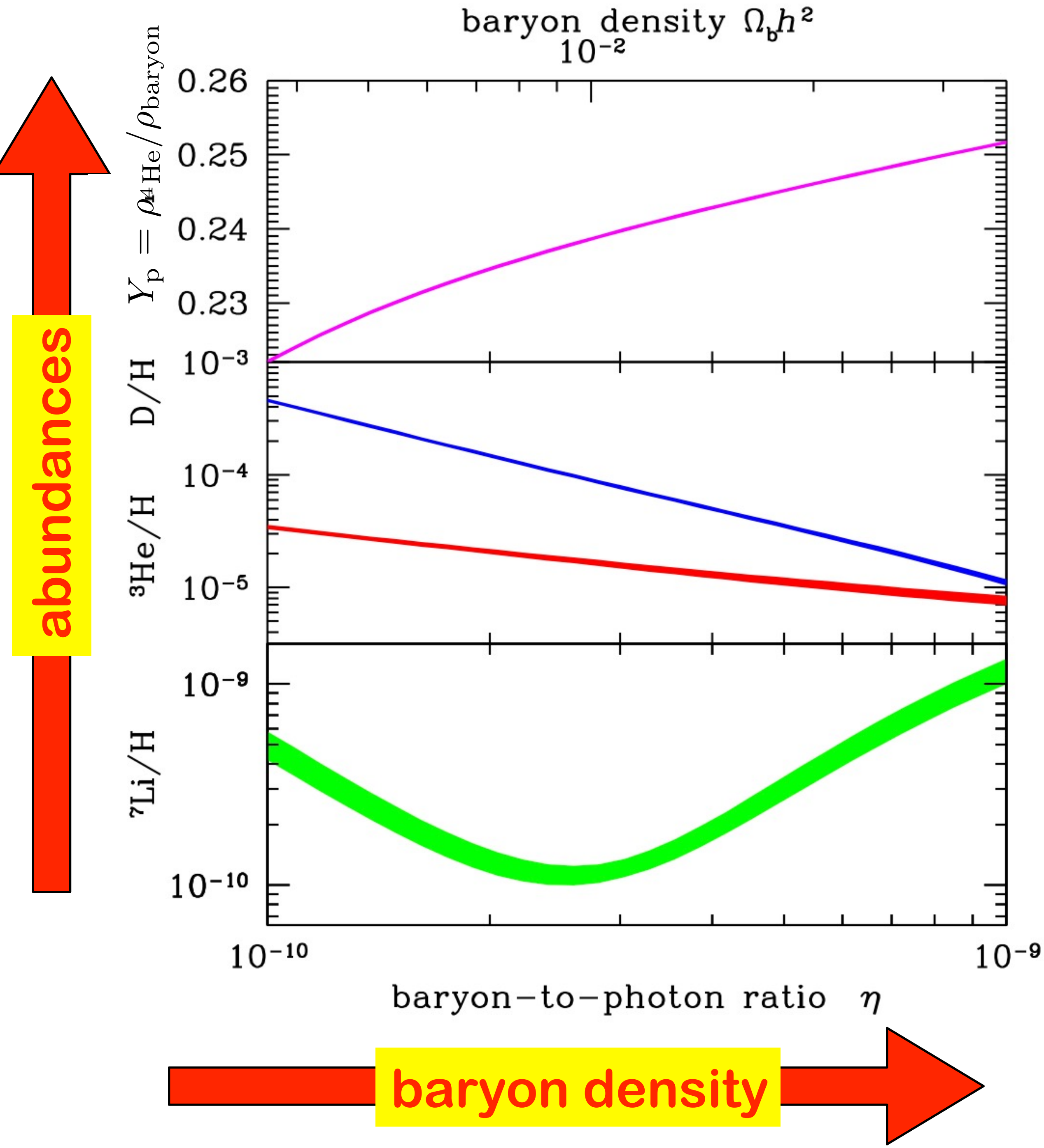
fix $\left(\frac{n}{p}\right)_{\rm freeze} \approx e^{-\Delta m/T_{\rm freeze}} \sim \frac{1}{7}$

**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



# BBN Predictions




**Curve Widths:**
**Theoretical uncertainty**
**nuclear cross sections**

Cyburt, BDF, Olive, Yeh 2015
Descouvement poster
Cyburt, BDF, Olive 2008
Cyburt 2004
Coq et al 2004
Serpico et al 2005
Cyburt, BDF, Olive 2001
Krauss & Romanelli 1988
Smith, Kawano, Malaney 1993
Hata et al 1995
Copi, Schramm, Turner 1995
Nollett & Burles 2000

# BBN Observations:
# *Light Element Abundances*

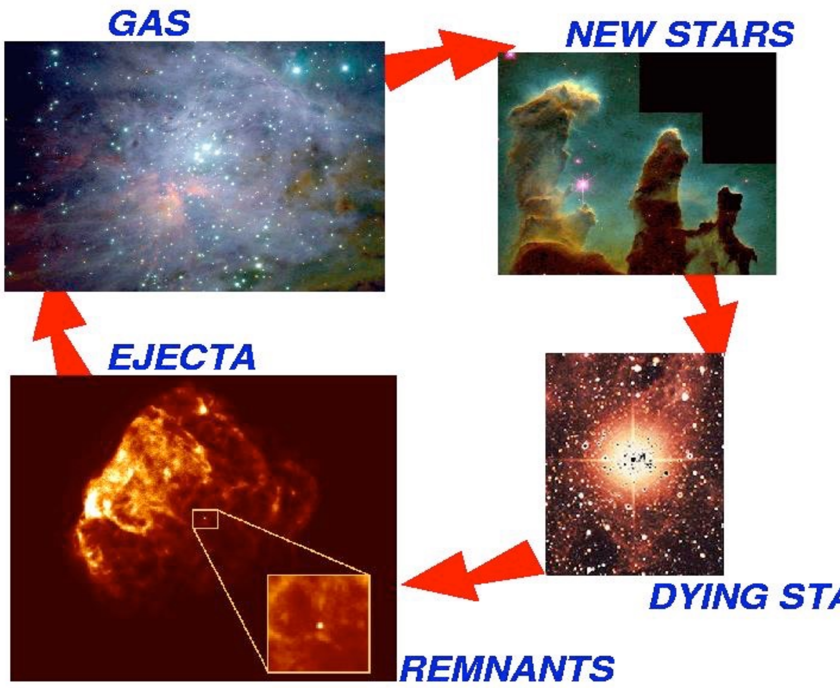
## The Problem

- Theoretical predictions: *there and then*
- Observations: *here and now*

## The Solution

- correct for post-BBN processing:

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



# Light Elements: Sites

**Deuterium**

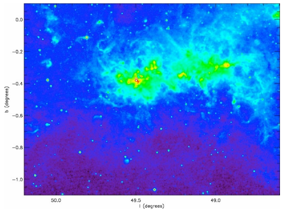
- QSO absorbers
- z~3, metals~0.01 solar
- New! leap in precision: Pettini+ 2013 Riemer-Sørensen+ poster

$^4$**He**

- ionized gas (HII regions) in metal-poor galaxies
- New! CMB damping tail: SPT 2011,2012; Planck 2013

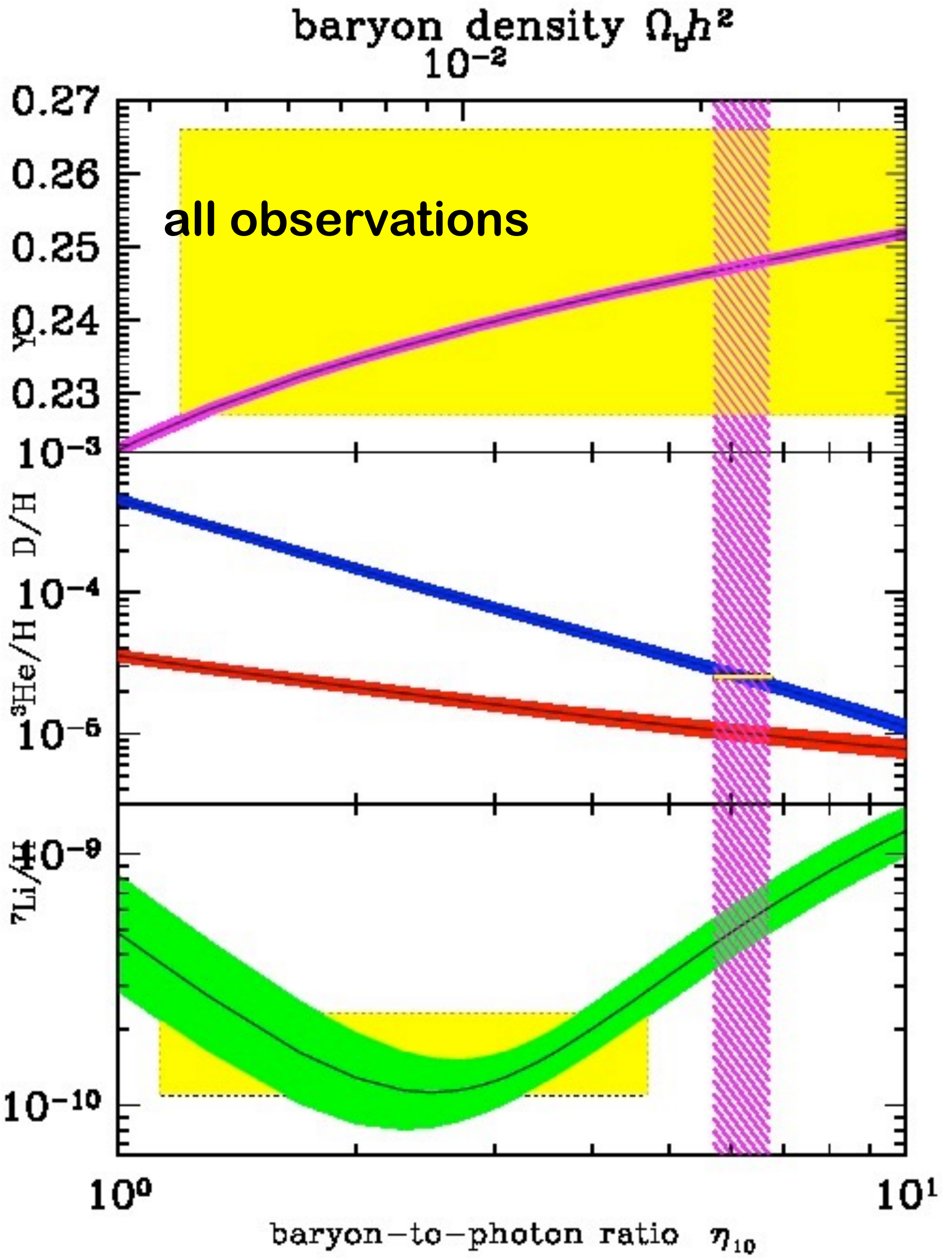

$^7$**Li**

- metal-poor halo stars in Milky Way
- New! now also extragalactic observations



$^3$**He**

- hyperfine in Milky Way HII regions Rood, Wilson, Bania+
- no low-metal data; not used for cosmology




# 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!

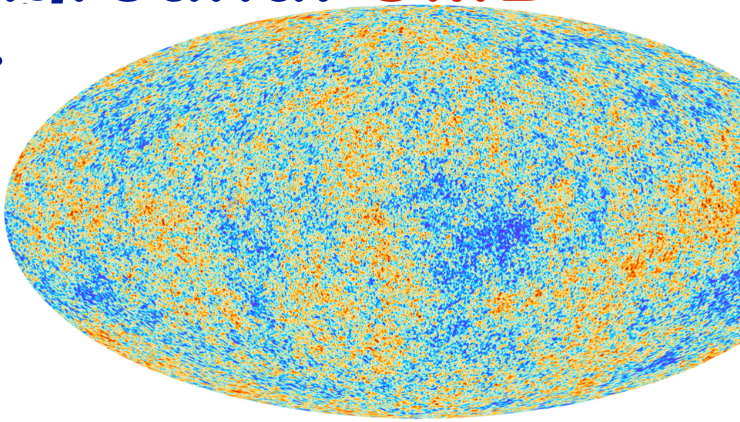
**Result:**

★ rough concordance!

★ but not in detail! D and $^7$Li disagree

⇨ need a tiebreaker

# The Cosmic Microwave Background: CMB
# A Powerful New Baryometer

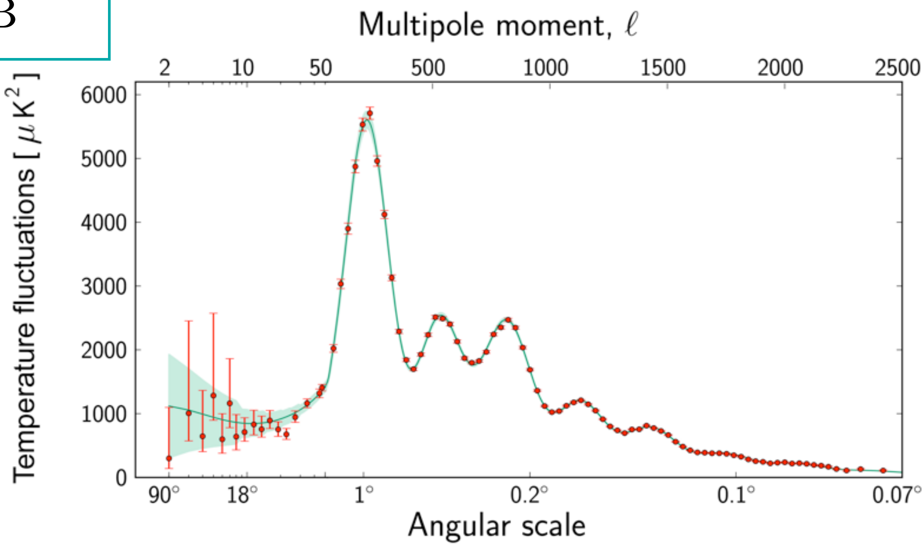


CMB $\Delta T_\ell$ independent measure of $\Omega_{\rm B}$

**BBN vs CMB: fundamental test of cosmology**

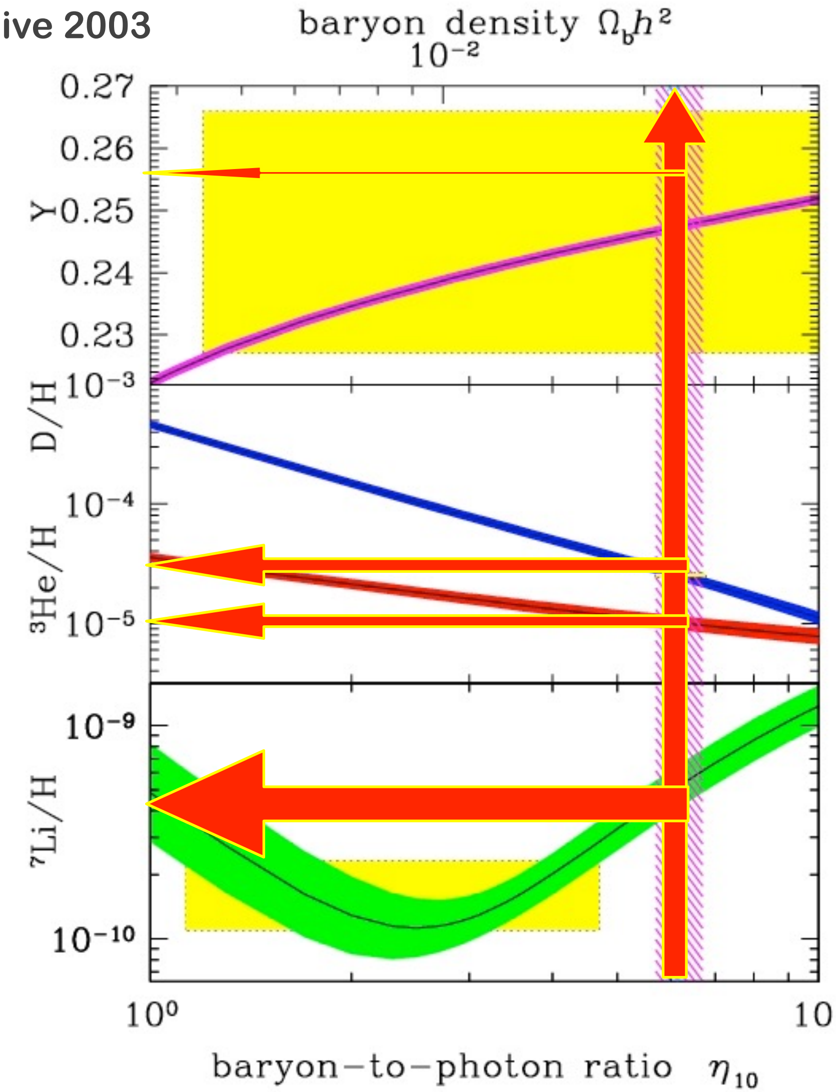
**Planck Explorer:**

$$\begin{aligned} \Omega_{\rm B}\ h^2_{100} &= 0.02218 \pm 0.00026 \\ \eta &= (6.078 \pm 0.071) \times 10^{-10} \end{aligned}$$



# Battle of the Baryons: II
# New World Order

Cyburt, BDF, Olive 2003




**Planck baryon density very precise**

$$\Omega_B \, h_{100}^2 = 0.02218 \pm 0.00026$$
$$\eta = (6.078 \pm 0.071) \times 10^{-10}$$

**i.e., a 1% measurement!**

**New strategy to test BBN:**

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

New! Improved!
Planck baryons
QSO D/H

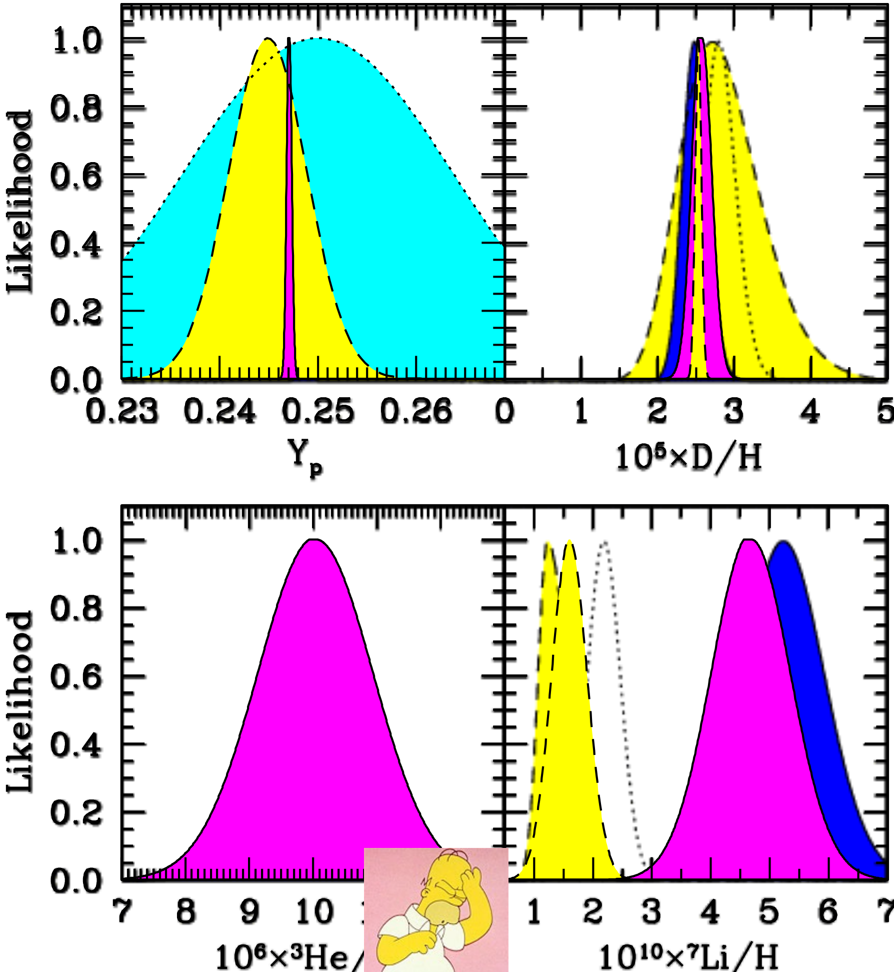
# of the Baryons: II
# Closer Look

Cyburt, BDF, Olive 2003, 2008, 2015

## Predict:

BBN theory: abundances vs $\eta$

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




Compare with Observations (yellow)

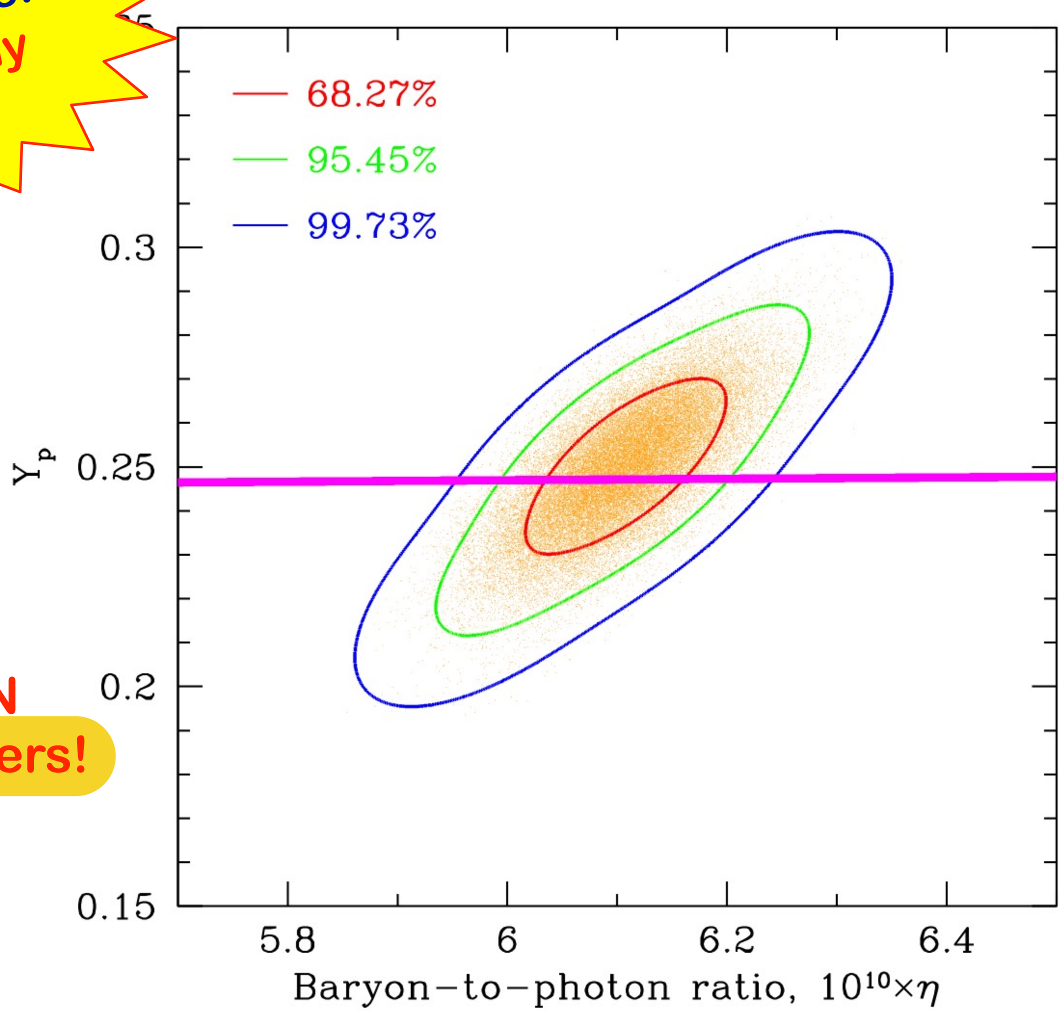
## Results:

- D agreement excellent: woo hoo!
- $^7$Li poor agreement:
  - observation ~ theory/4
  - 4-5 sigma discrepancy
  - Lithium Problem

# Standard BBN Tested With CMB Only

# Planck Baryons & Helium!

New!
Immaculate!
Cosmically clean!




**Contours:**
**Planck**

**Curve:**
**Standard BBN**
**zero parameters!**

# Lithium Strategy I:
# No Worries
## Two out of three ain't bad

# Dark Matter

**Pre-CMB Anisotropies:**

**BBN ⇨ Dark Matter**

**WMAP finds:**

★ $\Omega_B = 0.044 \pm 0.004$

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

**Optical galaxy surveys ⇨ luminous matter**

★ $\Omega_{\text{lum}} \sim 0.007$

**Confirms & sharpens case for dark matter: two kinds!**

**Baryonic Da... M... $\Omega_B \gg \Omega_{\text{lum}}$**

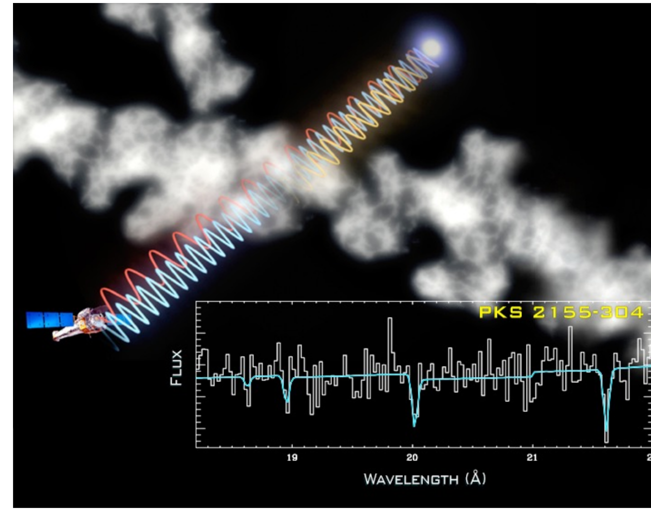
➡ wa... ...ay gas

...er: Dave etal

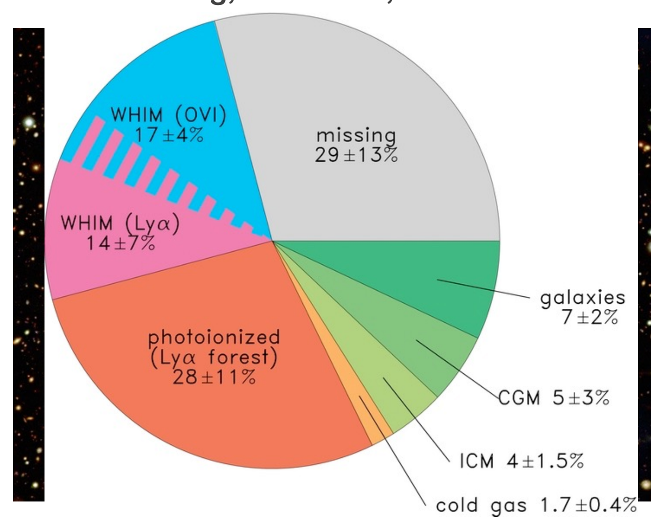
$\Omega_B \ll \Omega_M$

...ter!

**Non-baryonic dark matter demands physics beyond the Standard Model!**




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




Bullet Cluster
optical, X-rays=baryons (red), lensing=gravity (blue)
Shull, Smith, Danforth 2012

# BBN Beyond the Standard Model: Probing

**Predicted Lite elements sensitive to expansion history during BBN**

**Rate** $(\text{expansion})^2 = H^2 \sim G\rho_{\text{tot,rel}}$

**Controlled by**

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

**Observed Lite Elements Constrain**

**anything that**

- ✓ Couples to gravity
- ✓ Perturbs relativistic energy dens

Stiegman, Schramm, & Gunn 77

**All light elements sensitive to** $N_{\nu,\text{eff}}$

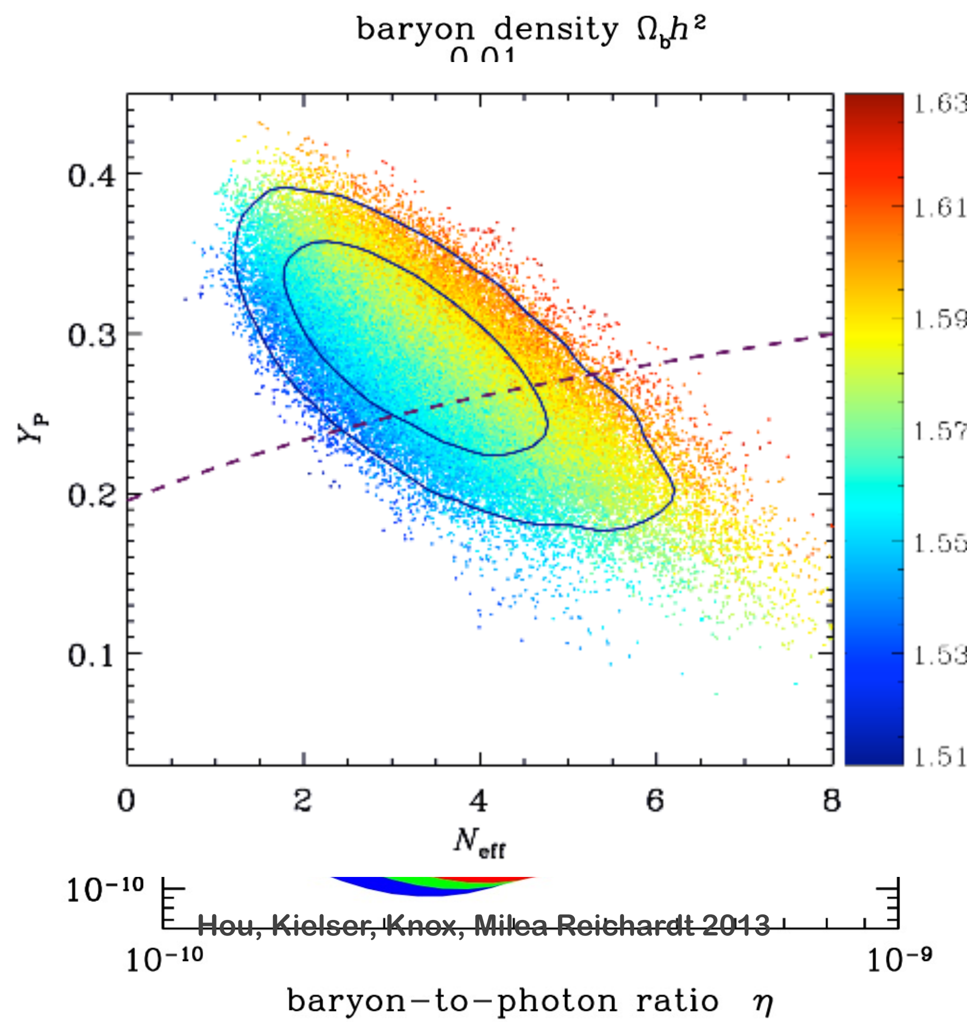
**New! D/H now an interesting probe**

**7Li shift right direction but small**

**New! CMB damping tail can probe al**

$\eta$ $N_{\nu,\text{eff}}$ $^4\text{He}$

**clean test of BBN**

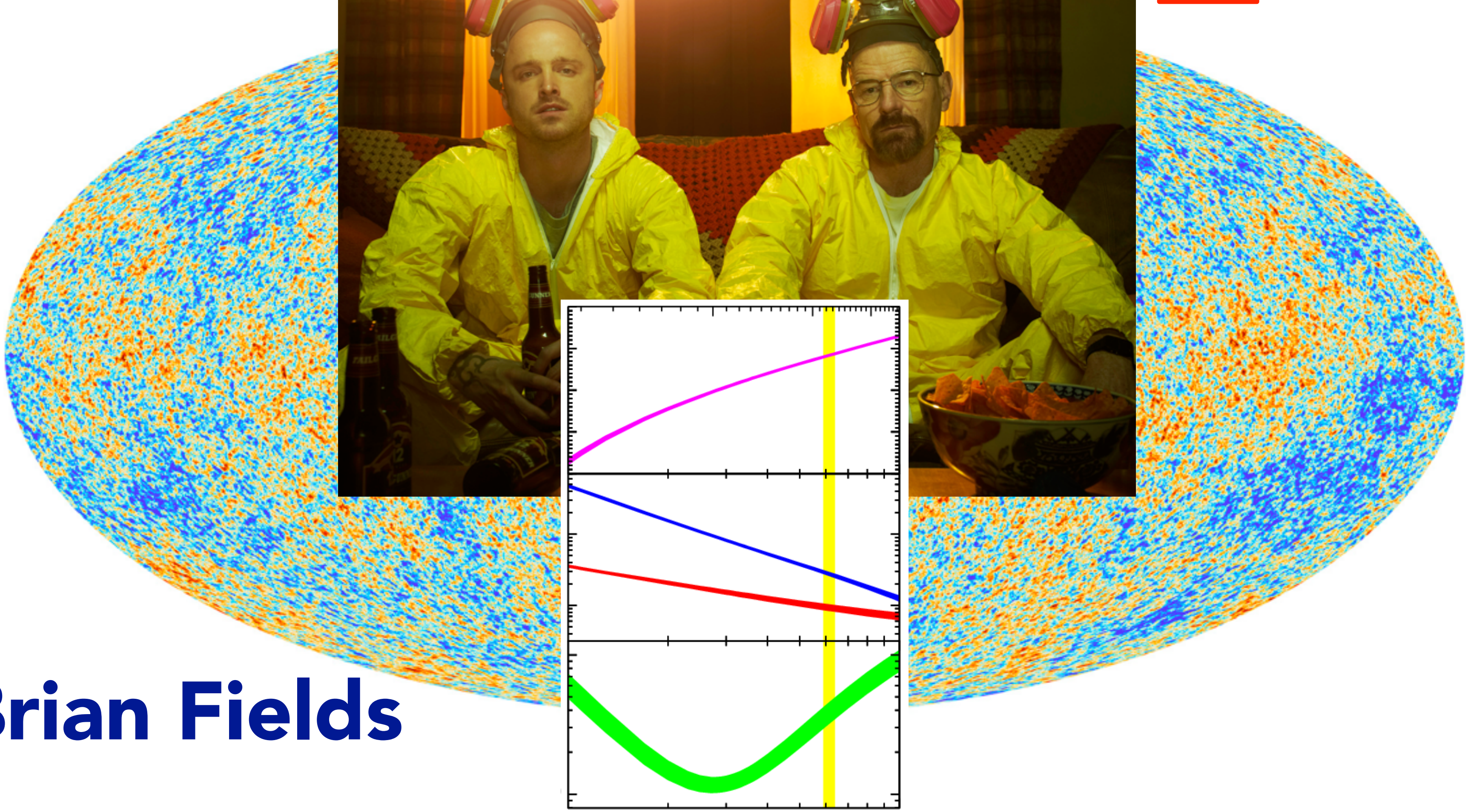



Cyburt, BDF, Olive, Yeh 2015

# Lithium Strategy II:
# Worry

# A Bitter Pill:

# The Primordial Lithium Problem



**Brian Fields**

University of Illinois

# Primordial Lithium

**Observe in primitive (Pop II) stars**

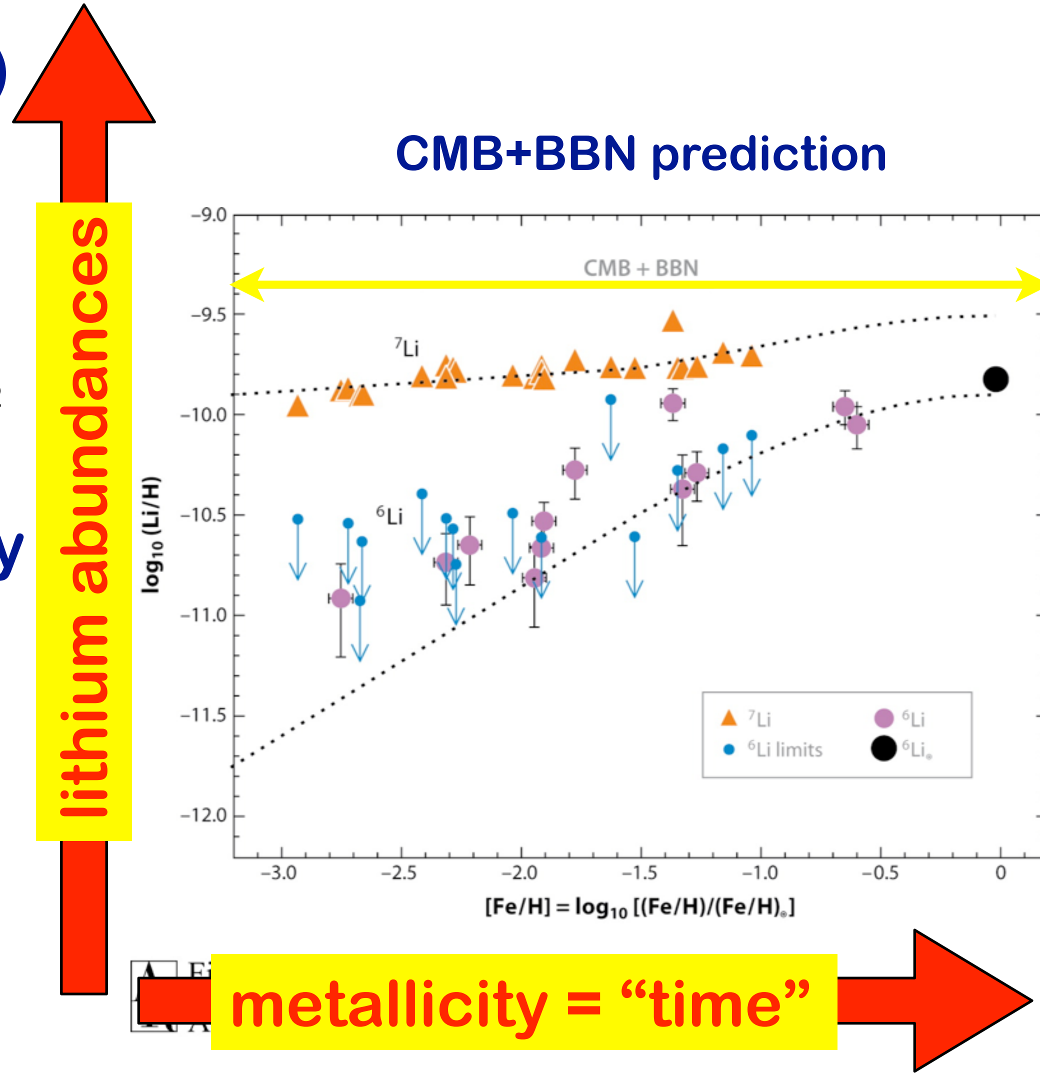
**Li-Fe ⇨ evolution**

**Plateau at low Fe** Spite & Spite 82

- ★ down to [Fe/H]~-2.75
- ★ const. abundance at early epochs
- ★ Li is primordial

**But is the plateau at $Li_p$?**

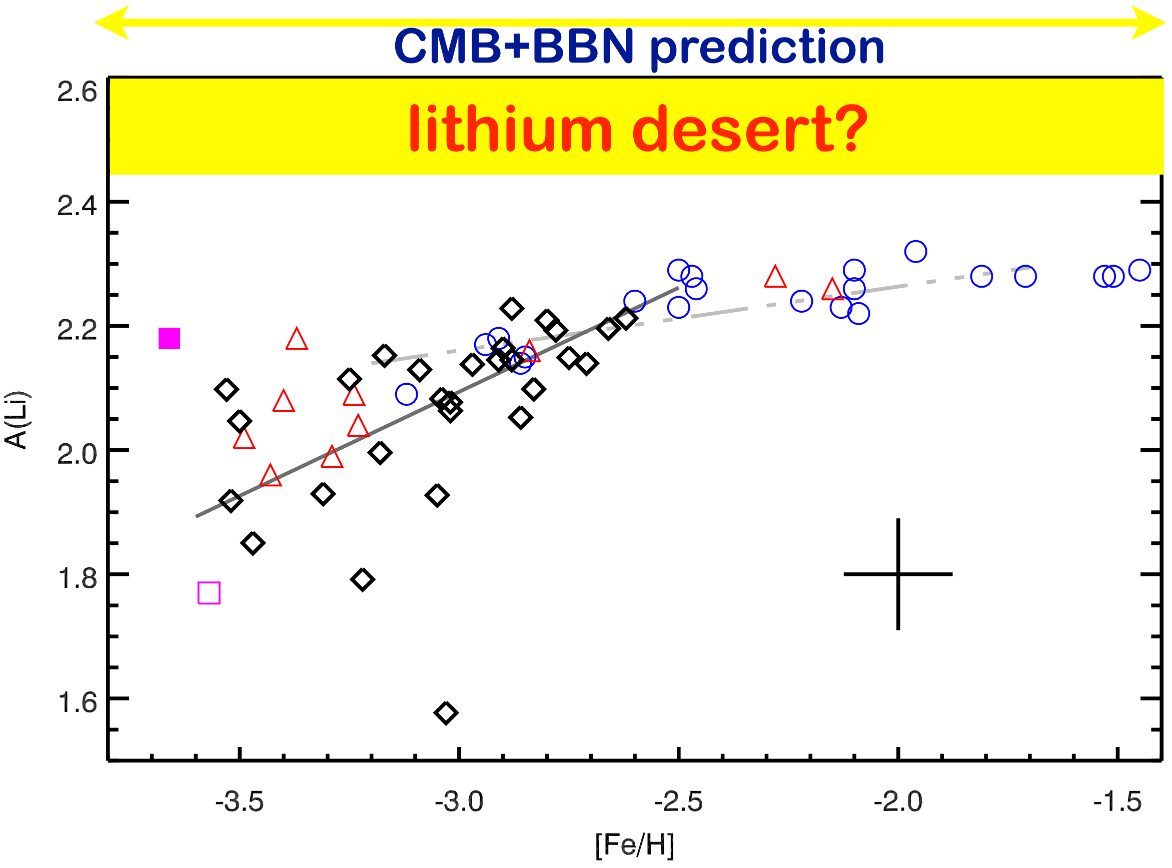
- $Li_{Planck}/Li_{obs} \sim 4$
- Why?



# New! Nuclear Meltdown

Sborodone+ 2010

- huge increase in scatter at low [Fe/H]
- at least some stars efficiently eat lithium
- why does meltdown “turn on”?
- no points scatter up to BBN+CMB abundance



# Hoyle's Revenge?

## A Resonatingly Pretty Solution to Lithium?

### Cyburt & Pospelov 20

- 11 dominant BBN reacti already w studied
- no room for
- but "sub-domina im missed
  cf Hoyle state in
- propo

### Chakraborty, B 2011

- systemati study of all A destruction rxns
  - ✓ confirms $^{7}Be$+d ⇨ $^{9}$
  - ✓ even better: $^{3}He$+$^{7}Be$ ⇨ $^{10}C^{*}$
    t+$^{7}Be$ ⇨ $^{10}B^{*}$

**Experiment Says:**

**Not there!**

$^{10}C^{*}$: Hammache+ 2013

$^{9}Be^{*}$: O'Malley+ 2011

# 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,

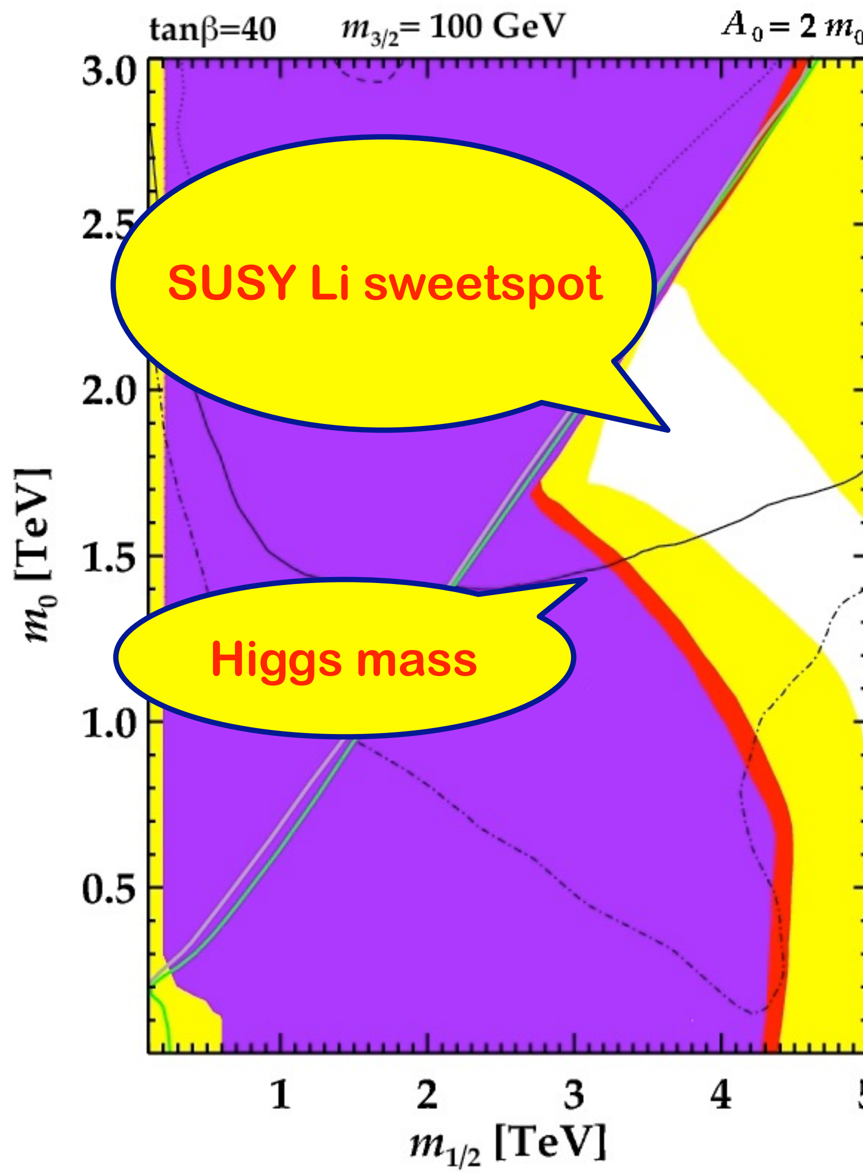
**A SUSY solution to lithium problems?**

New D/H removes much solution space

**Also: Light elements are a strong SUSY probe**

- ✓ rule out large regions of parameter space
- ✓ complementary to LHC

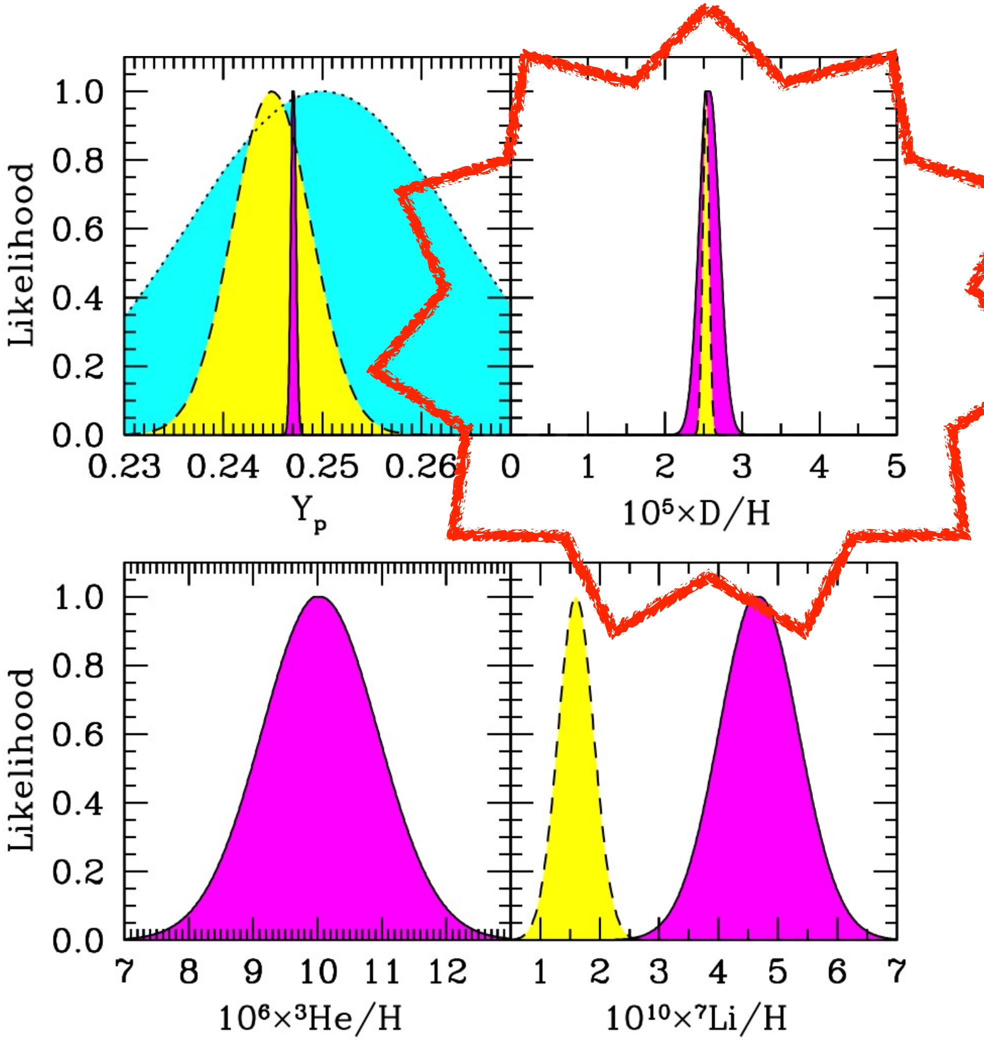
**Illustrates tight links among nucleo-cosmo-astro-particle physics**

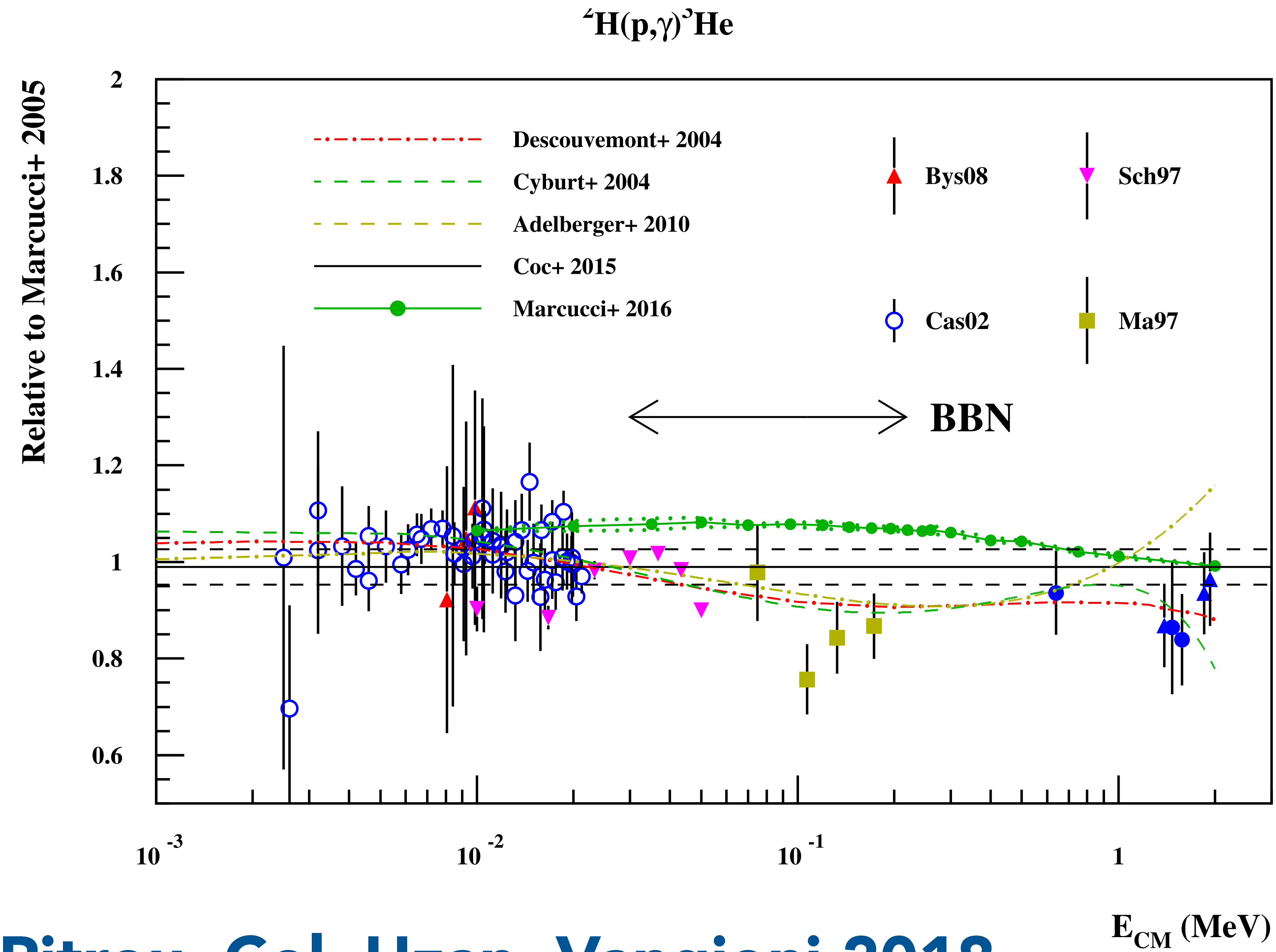



Cyburt, Ellis, BDF, Luo, Olive, Spanos 2012

# Precision Cosmology Demands Precision Cross Sections

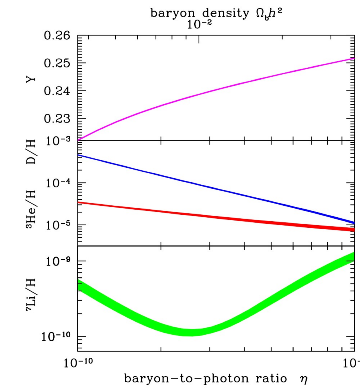
- D/H obs more precise than theory!
- Need ~1% absolute cross sections for
  - $d(p,g)^3He$
  - $d(d,p)t$
  - $d(d,n)^3He$






**Pitrou, Col, Uzan, Vangioni 2018**

# 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

- basic concordance: big bang working to t~1 sec
- CMB alone now independently tests BBN!
- BBN + CMB powerfully probe new physics: dark matter, early Universe

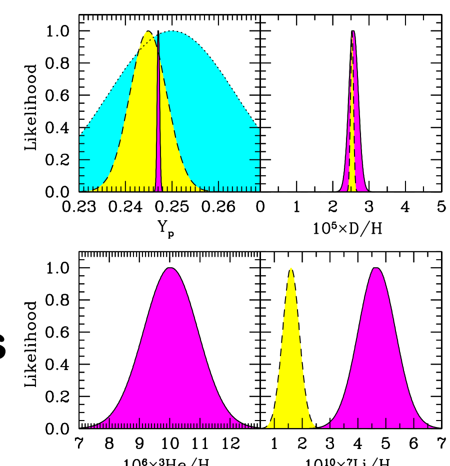
## The Lithium Problem: Planck+BBN >> $Li_{obs}$

- problem has worsened since WMAP 2003
- astrophysics solutions possible but highly constrained
- nuclear physics precision needed: d(p,gamma)3He; 7Be(n,p)7Li
- new physics: SUSY? non-WIMP dark matter?

## The Future:

- **Even better CMB measurements (S4)**
- **New light element measures**
- **Closer interplay with dark matter & accelerator physics**

**Stay Tuned!**



# Director’s Cut Extras

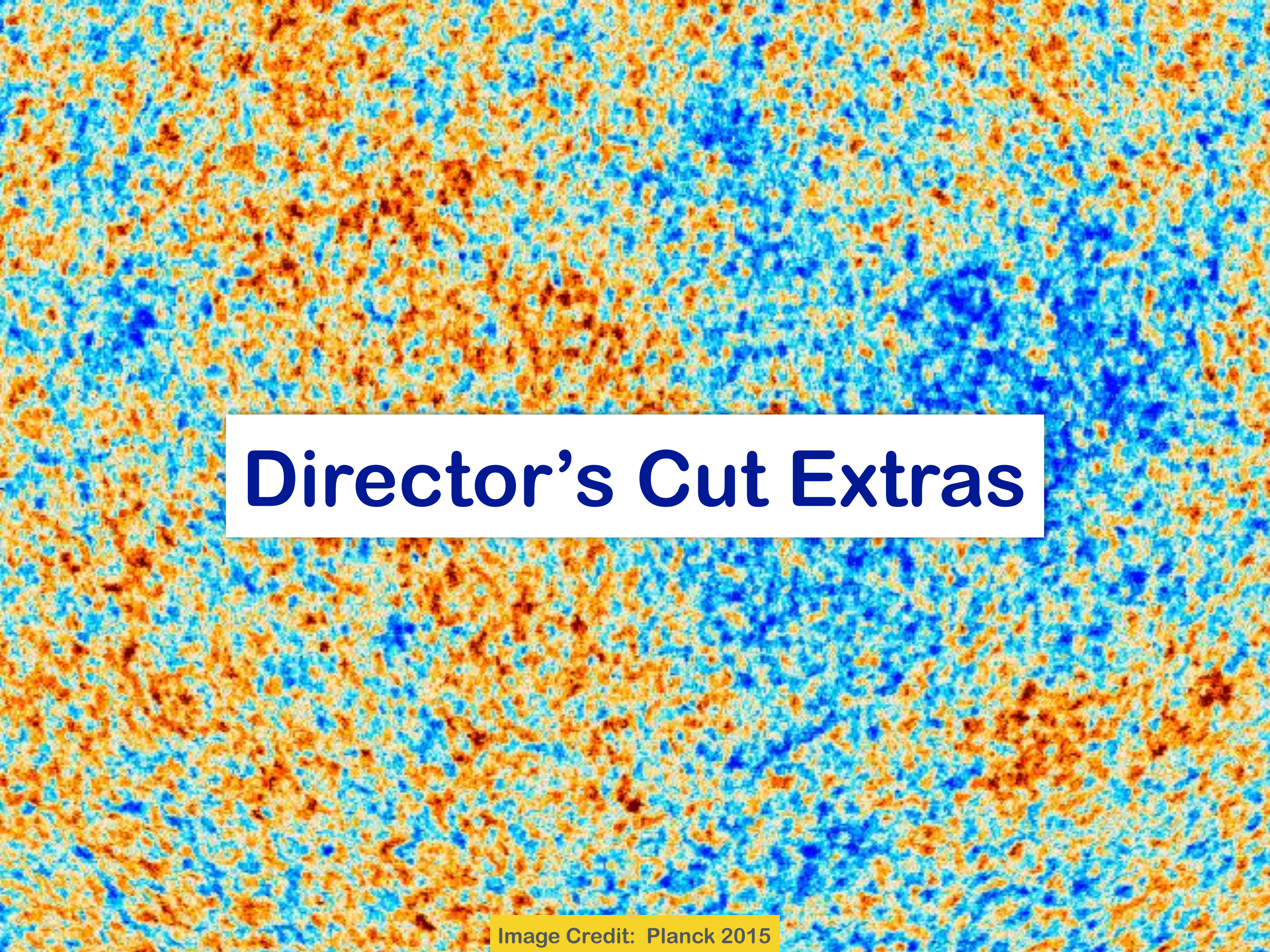


Image Credit: Planck 2015

# The Standard Cosmology

## Cosmodynamics

Space: Homogeneous & Isotropic
Think Big! Galaxies as building blocks

Edwin Hubble (1929): Cosmic dynamics

map velocity vs distance

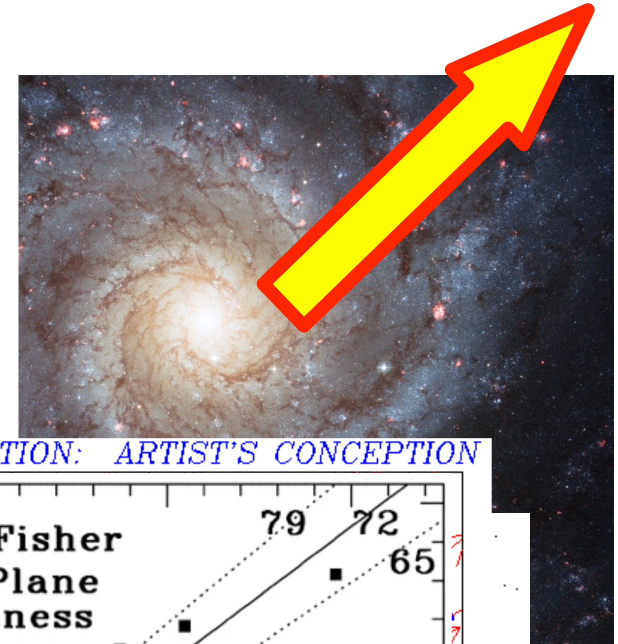
- result: ~all galaxies move away from us!
- highly organized pattern:

speed ∝ distance

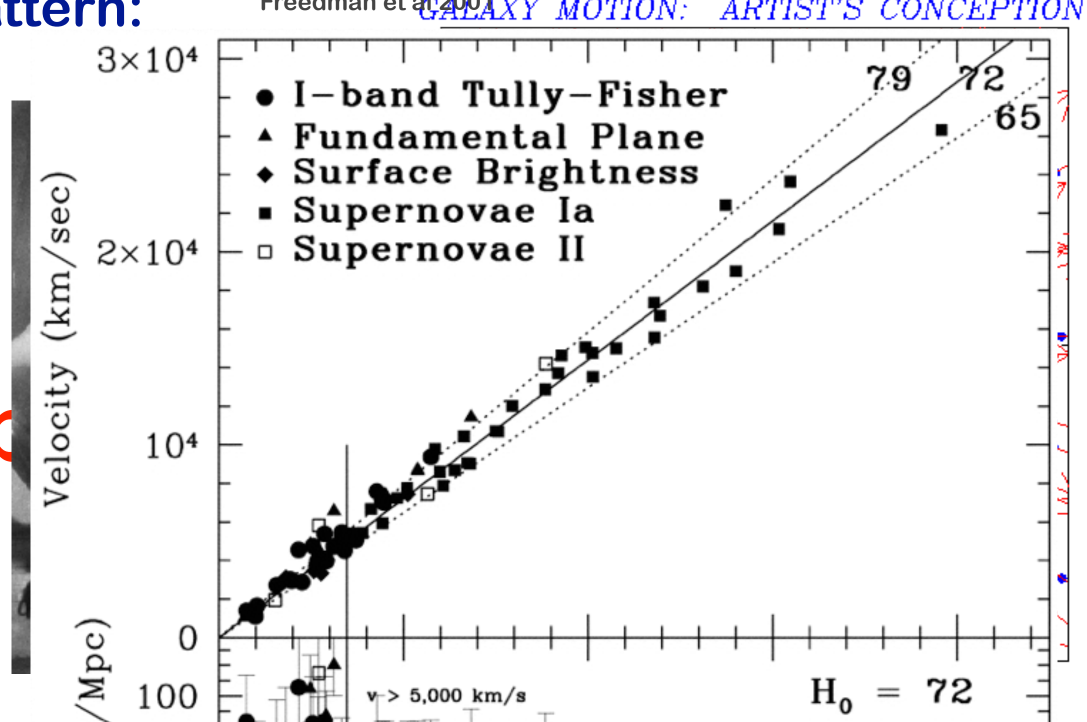
$\vec{v} = H\vec{r}$

- Interpretation:

Universe is Exp



Freedman et al 2001




Hubble 1929

# Lithium Problem: Conventional Solutions

## Astrophysical Systematics

**Scenario:**

- data & theory correct,
- Li/H accurate portrait of stars today
- but not of initial Li/H

**stellar depletion over ~$10^{10}$ yr**

**if Li burned: correct $Li_p$ upward!**

**But:**

★ **Li scatter small:**

- within observational errors for low metallicity
- possible increase in scatter at very lowest metallicity

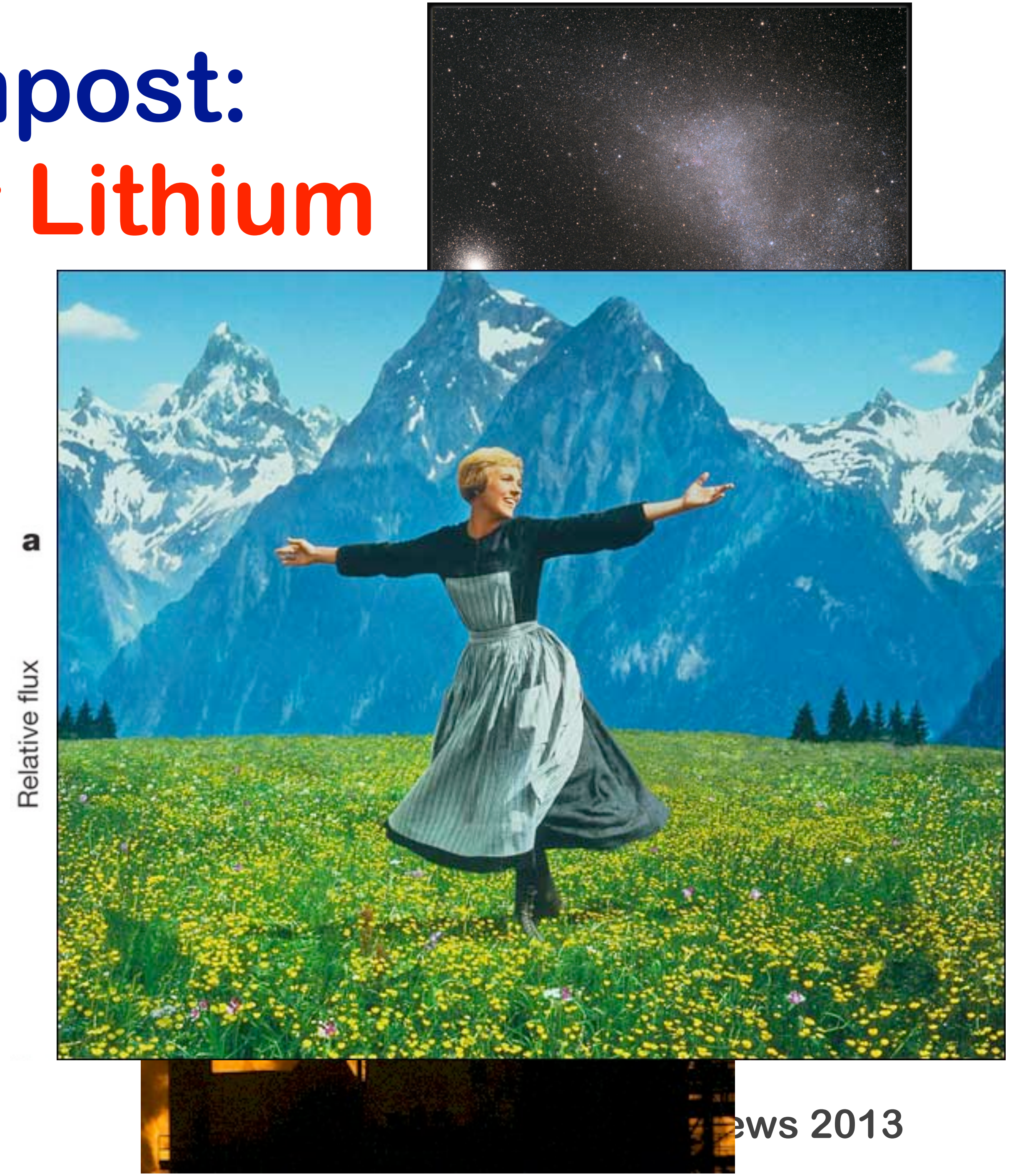
★ **$^6Li$ apparently preserved**

- despite weaker binding, exponentially stronger destruction Brown & Schramm 1988, Stiegman et al 1993

★ **no stars seen close to BBN value**

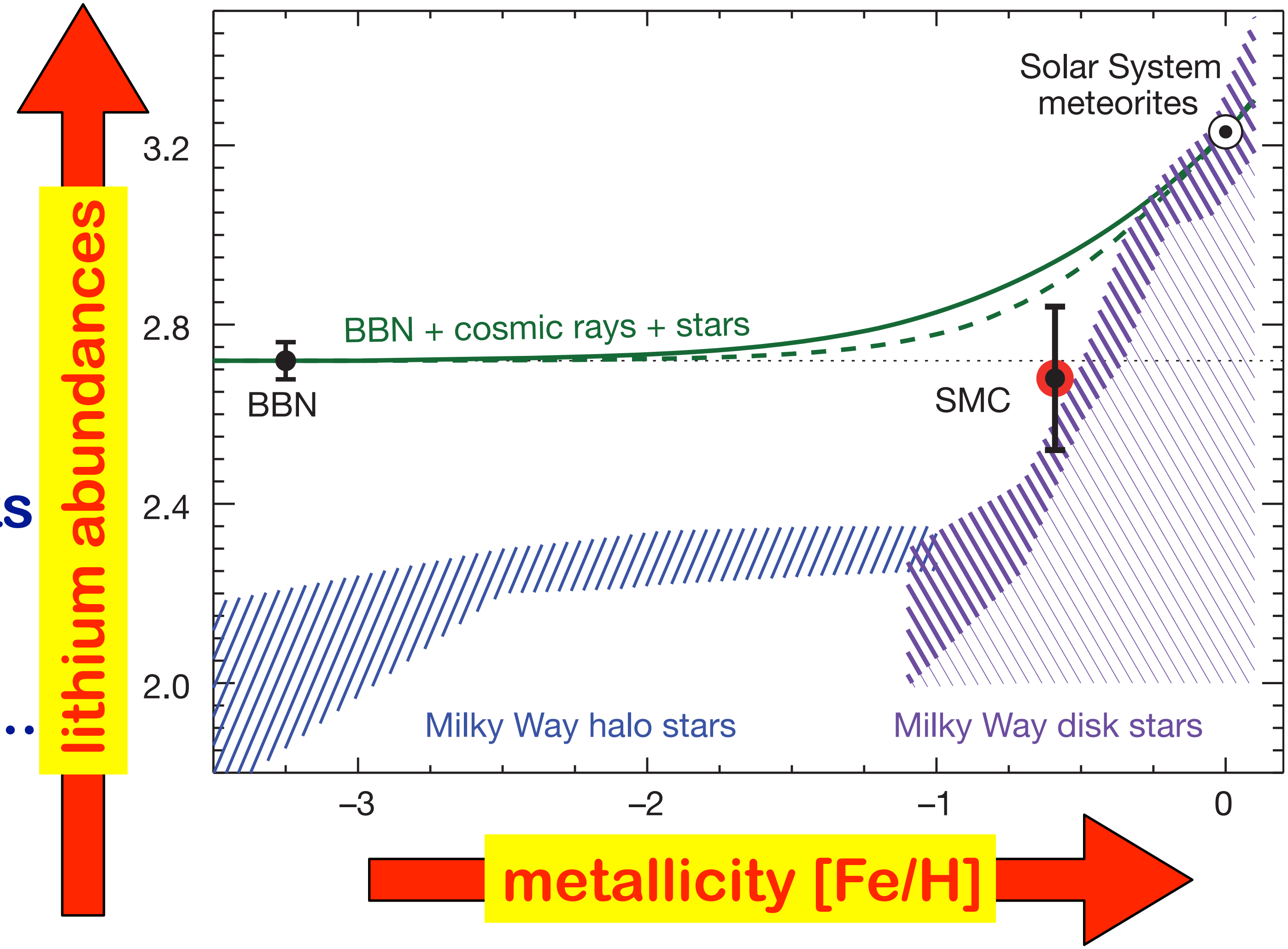
# A New Lampost: Interstellar Lithium

- stellar lithium: measuring air quality outside factory
- try going to countryside!
  - interstellar medium of low-metal galaxies
- proof of concept:
  - interstellar Li in SMC
  - metals ~ solar/4
  - VLT UVES



# A New Lampost:
# Interstellar Lithium

- SMC Li/H is at BBN level!
- but fits Milky Way stellar trend
- stellar effects must “turn on” at lower metallicities...




Howk, Lehner, BDF, & Mathews 2013

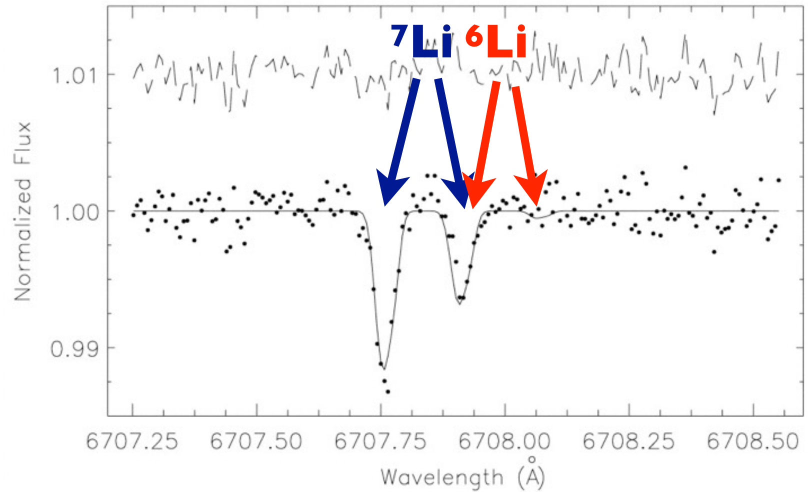
# Lithium: Observables

## Good News

both $^7$Li and $^6$Li observable

isotope shift $\lambda(^6\mathrm{Li}) > \lambda(^7\mathrm{Li})$

resolved in local interstellar medium (high-metallicity, cold gas) Knauth, Federman, Lambert 03




## Bad News

in stellar atmosphere: isotopes blend into one line $\delta\lambda_{\mathrm{thermal}} > \delta\lambda_{\mathrm{isotope}}$

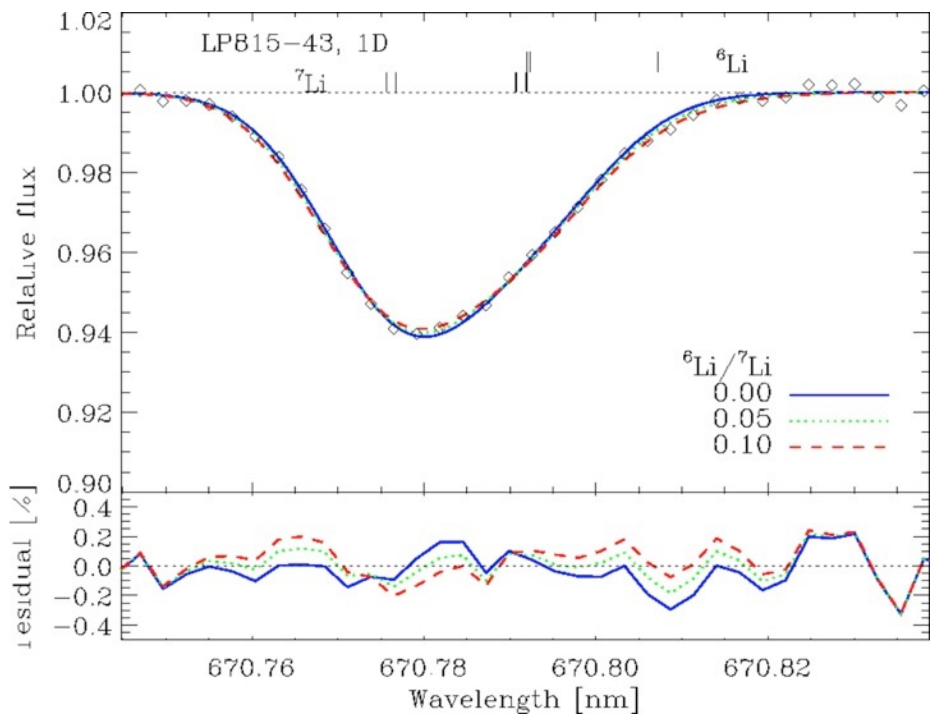
## Strategy

high resolution stellar spectra:

elemental abundance Li = $^7$Li + $^6$Li

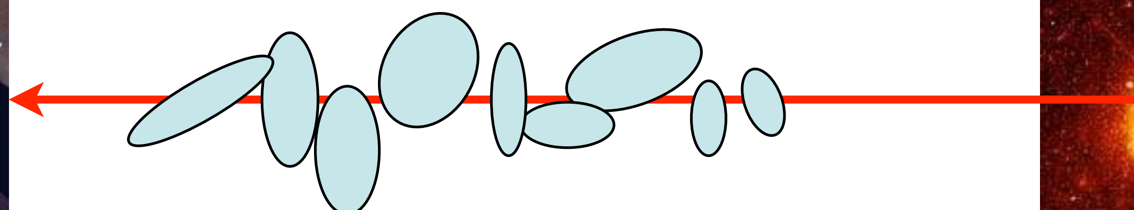
ultra-high resolution stellar spectra Smith Lambert Nissen; Asplund et al

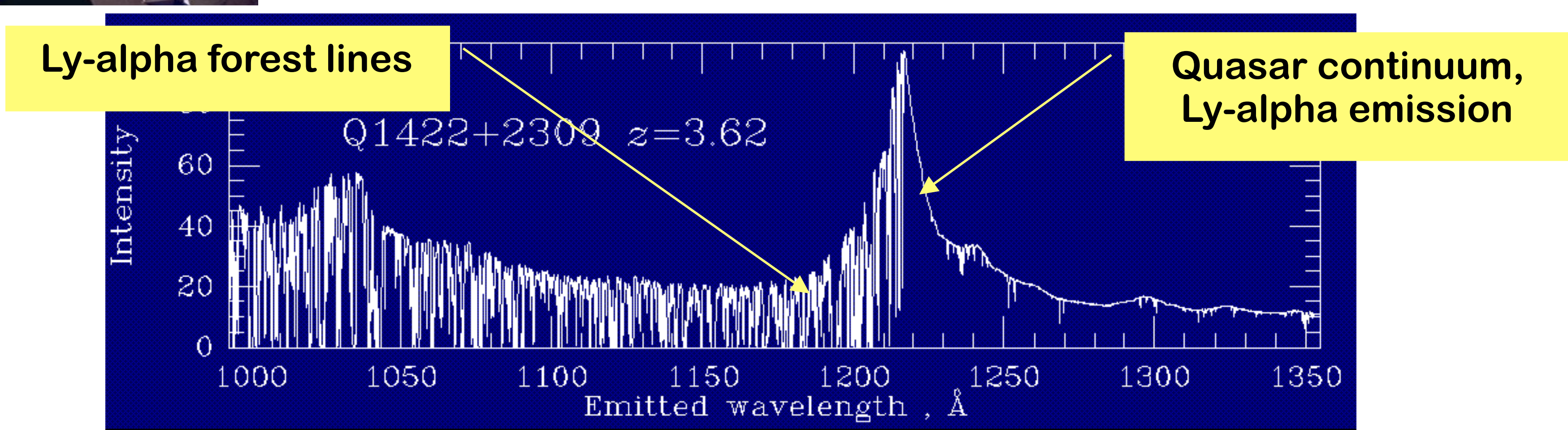
lineshape gives isotopic ratio $^6$Li/$^7$Li



# 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"





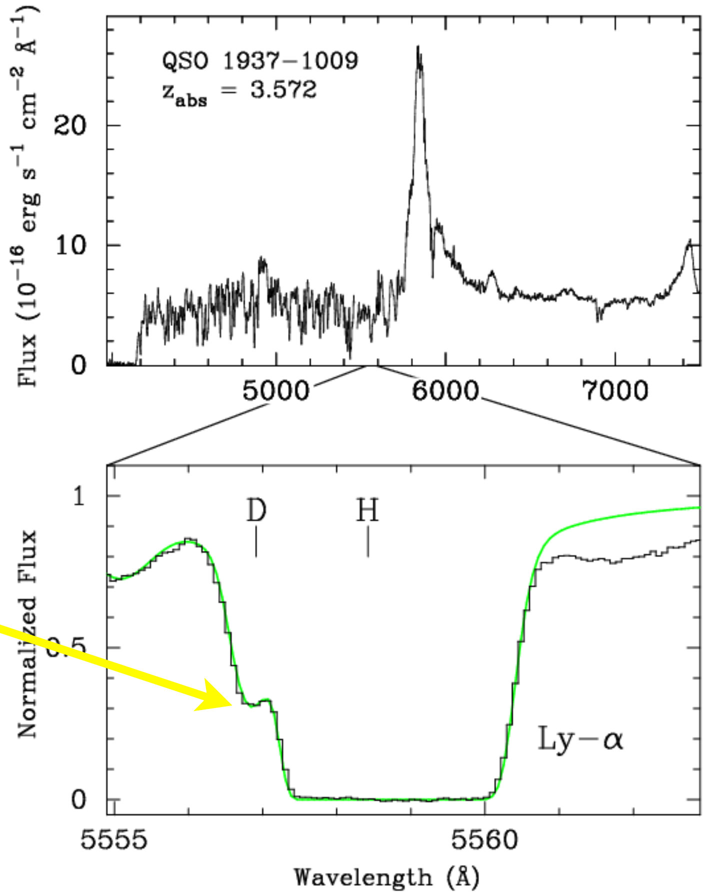
# Deuterium Data

Deuterium Ly-alpha shifted from H:

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

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

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




Tytler & Burles

Get D directly at high-z!

**But**:

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

# Non-Baryonic Dark Matter:
# Neutrinos?

## Required Dark Matter Properties

dark ⇨ feeble interactions

matter ⇨ has mass

present at t~14 Gyr ⇨ stable

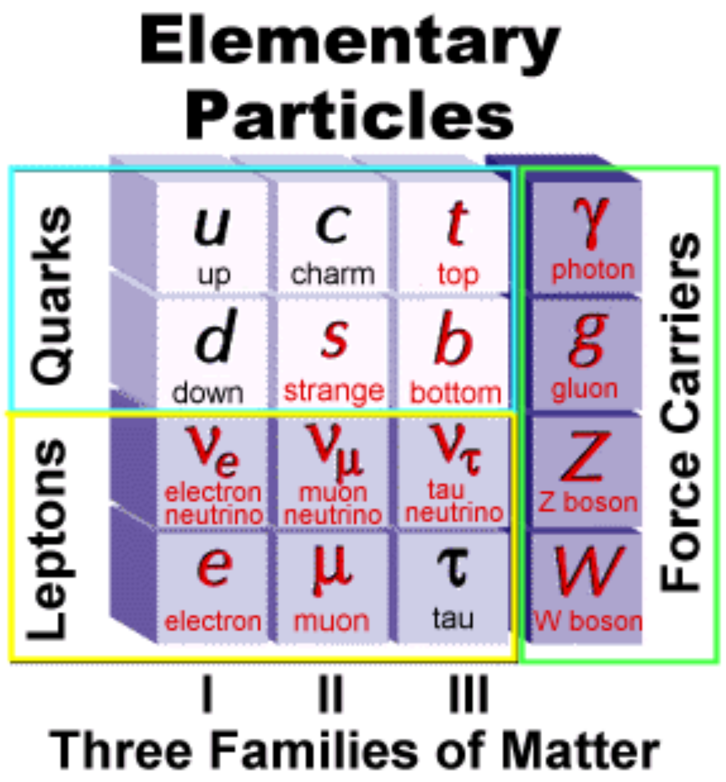
inert @ BBN, recomb ⇨ non-baryonic

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?

### 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:

Smirnov, Pena-Garay lectures

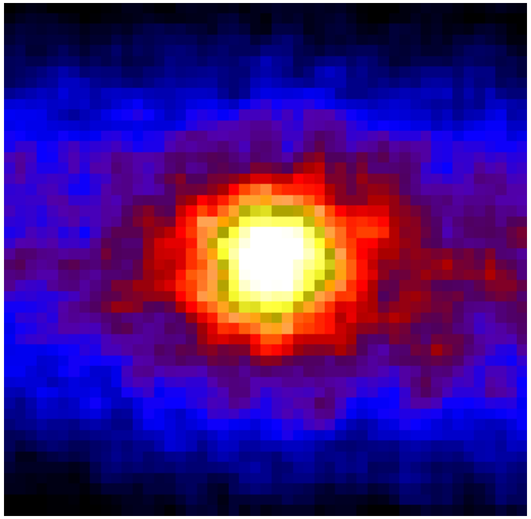
mass differences (from oscillations)

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

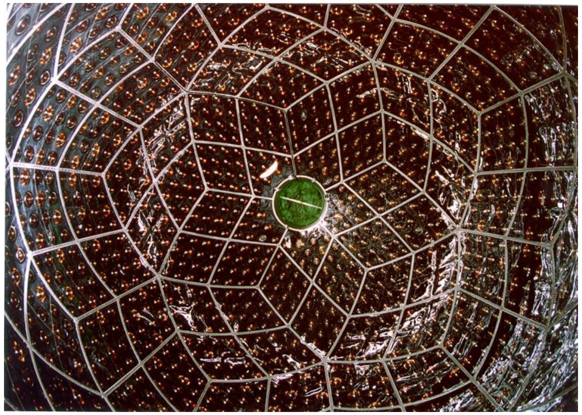
$\sum m_\nu \leq 2 \text{ eV}$ (from large-scale structure)

### Total density contribution: $\Omega_\nu \leq 0.1 \; \Omega_\mathrm{m}$

### Neutrinos are **not** the dark matter



The Sun, imaged in neutrinos
SuperKamiokande



KamLAND Reactor Neutrino Detector

# Lithium Problem: Conventional Solutions

## I: Observational Systematics

Scenaro: Data &Standard Model correct
inference of Li/H wrong

Measure: Li I =$Li^0$ absorption line
i.e., neutral Li atoms

But: in stellar atmospheres, mostly Li II =$Li^{+1}$

Infer: $$\frac{\mathrm{Li}}{\mathrm{H}} = \frac{\mathrm{Li}^0 + \mathrm{Li}^{+1}}{\mathrm{H}} = \frac{\mathrm{Li}^0 + \mathrm{Li}^{+1}}{\mathrm{Li}^0} \frac{\mathrm{Li}^0}{\mathrm{H}}$$

ionization correction $$\frac{\mathrm{Li}^0 + \mathrm{Li}^{+1}}{\mathrm{Li}^0} \sim e^{\Phi(\mathrm{Li}^+)/T_{\rm eff}}$$

exponentially sensitive to temperature
$T_{eff}$ critical!

Needed error in stellar T scale ~500 K: large!
maybe possible: Melendez & Ramirez 04; BDF, Olive, Vangioni-Flam 05
but maybe not: Hosford et al 2009