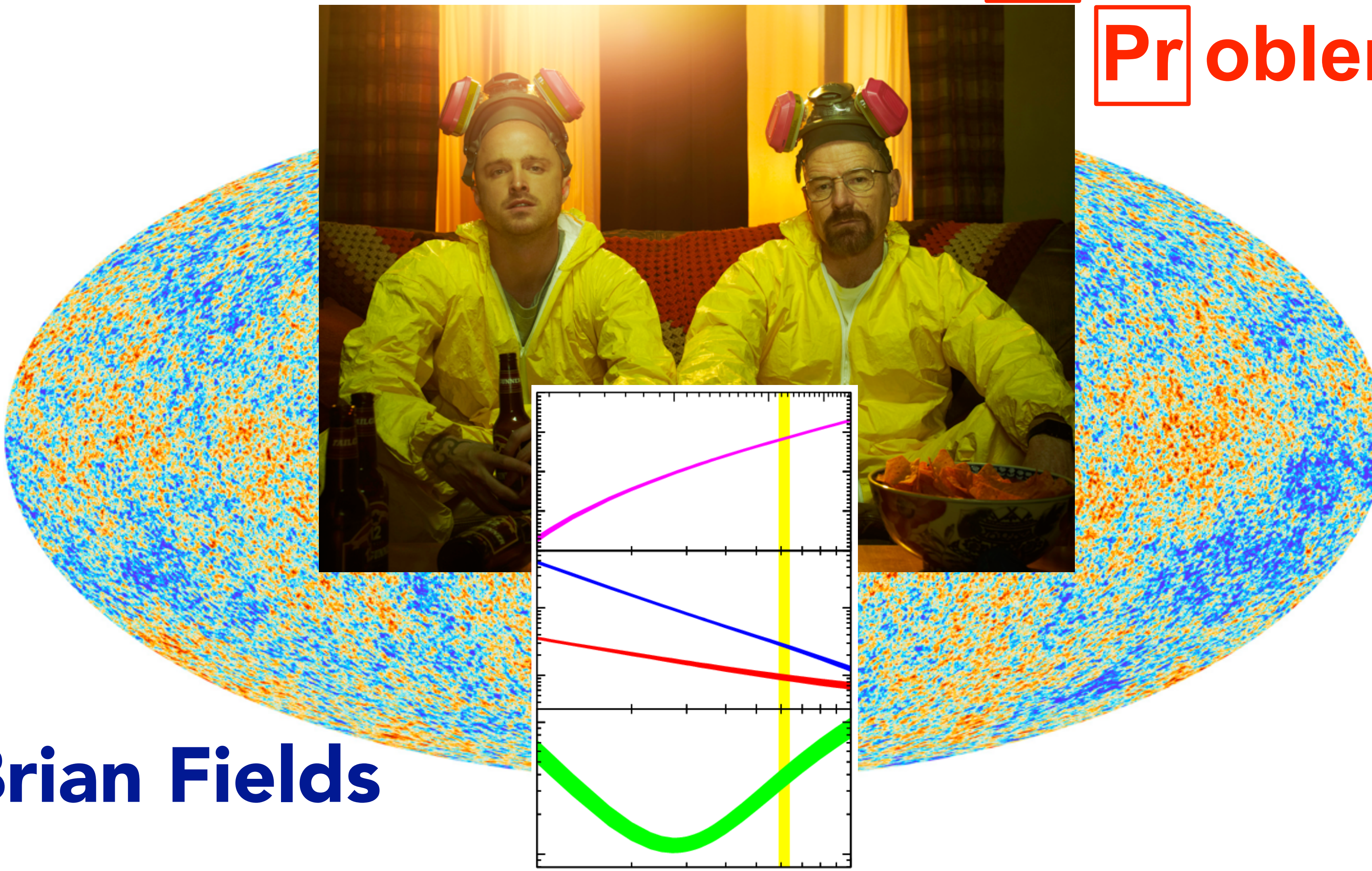
# A Bitter Pill:

# The Primordial Lithium Problem




**Brian Fields**

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KeithFest | Minneapolis | May 17, 2017

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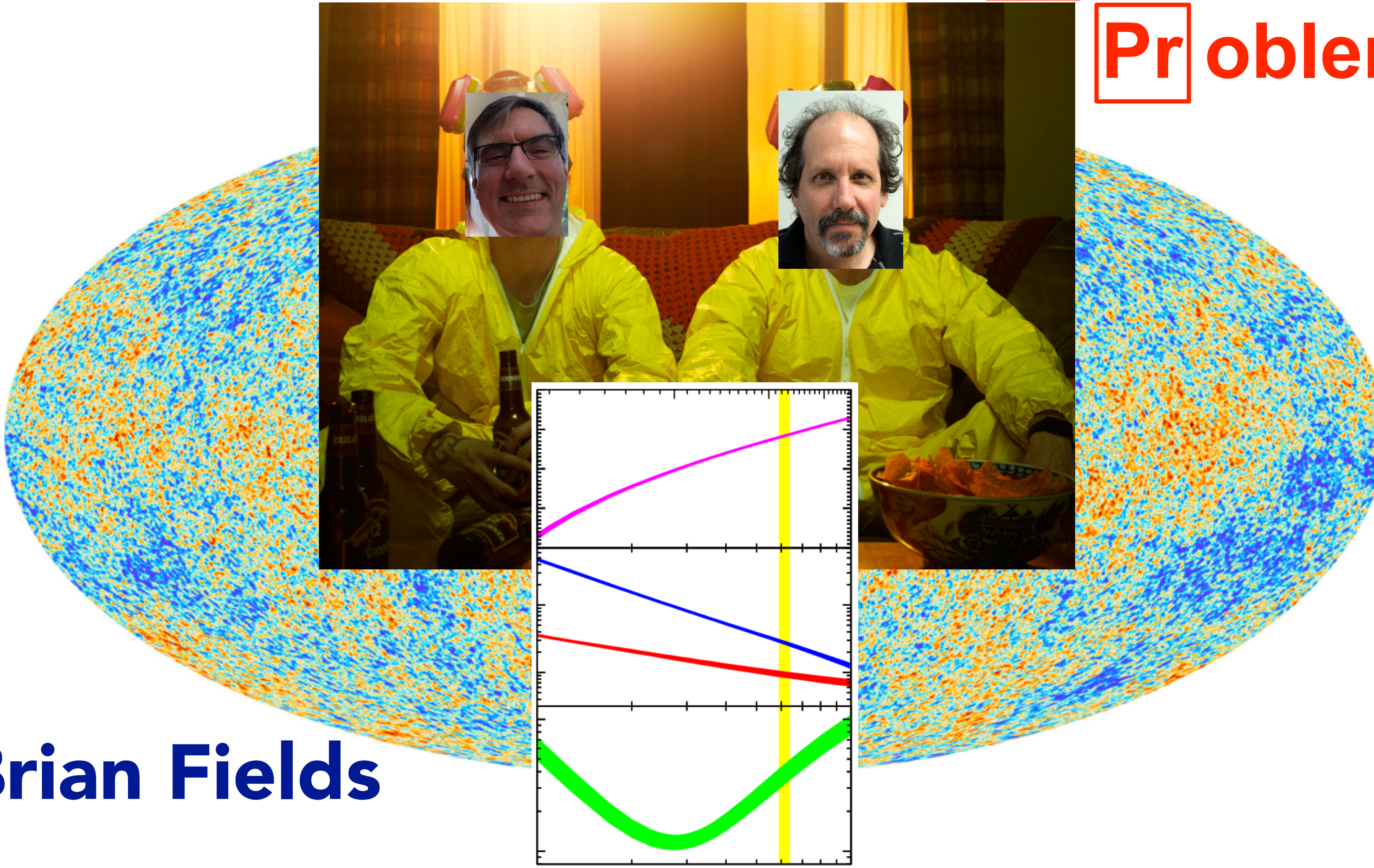


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# Keith's Greatest Hits:  BBN Edition

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# PHYSICAL REVIEW LETTERS

VOLUME 43 | 23 JULY 1979 | NUMBER 4

## Cosmological Constraints on Superweak Particles

G. Steigman

*Bartol Research Foundation of the Franklin Institute, University of Delaware, Newwark, Delaware 19711,*[a] *and Institute for Plasma Research, Stanford University, Stanford, California 94305*[b]

and

K. A. Olive and D. N. Schramm

*Department of Physics and The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*[c]

(Received 29 May 1979)

Previous work has used the primordial abundance of $^4$He to infer limits on the number of neutrinos with full-strength neutral-current weak interactions. By accounting for the quark-gluon constituents of hadrons, we extend the analysis to earlier times and higher temperatures and densities and, therefore, to considerably weaker interactions. The maximum number of new, superweakly interacting, light ($\lesssim$ MeV) particles is between ~1 and ~20.

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Bart...

# 38 years of KAO+BBN:
# 99+ refereed papers
# 8500+ citations

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# A Bitter Pill:
# The Primordial Lithium Problem

## ★ Nuke and Particle 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: particle dark dark matter beyond Standard Model

## ★ The Lithium Problem

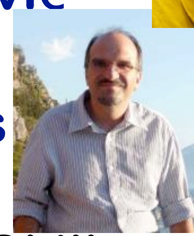
- $^7Li+^7Be$ disagreement: WMAP vs astro observations
- new nuclear physics? Hoyle's revenge in $^{10}C$?
- new particle physics? SUSY decays?

# Collaborators

Richard Cyburt — NSCL/Michigan State U.

Nachiketa Chakraborty — MPIK Heidelberg

Tijana Prodanović — U. Novi Sad



Vassilis Spanos — U. Patras

Keith Olive, Evan Skillman — U. Minnesota

John Ellis, Feng Luo — King’s College

Chris Howk, Nicolas Lehner — Notre Dame

Tsung-Han Yeh (葉宗翰) — U. of Illinois

Lloyd Knox, Marius Millea — UC Davis

# Big Bang Nucleosynthesis:

## A Symphony of Fundamental Forces

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- **BBN: unique arena**
  - **all four fundamental forces participate**


# 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
- Dark Matter and Dark Energy
  - Present (presumably) but non-interacting

Homogeneous U. ⇒ $\eta \equiv \frac{n_{\rm baryon}}{n_\gamma}$ Spatially const

- Expansion adiabatic

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

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

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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!) $\eta \equiv n_{\rm B}/n_\gamma \sim 10^{-9}$

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n-p weak equilibrium:

$$pe^- \leftrightarrow n\nu_e$$

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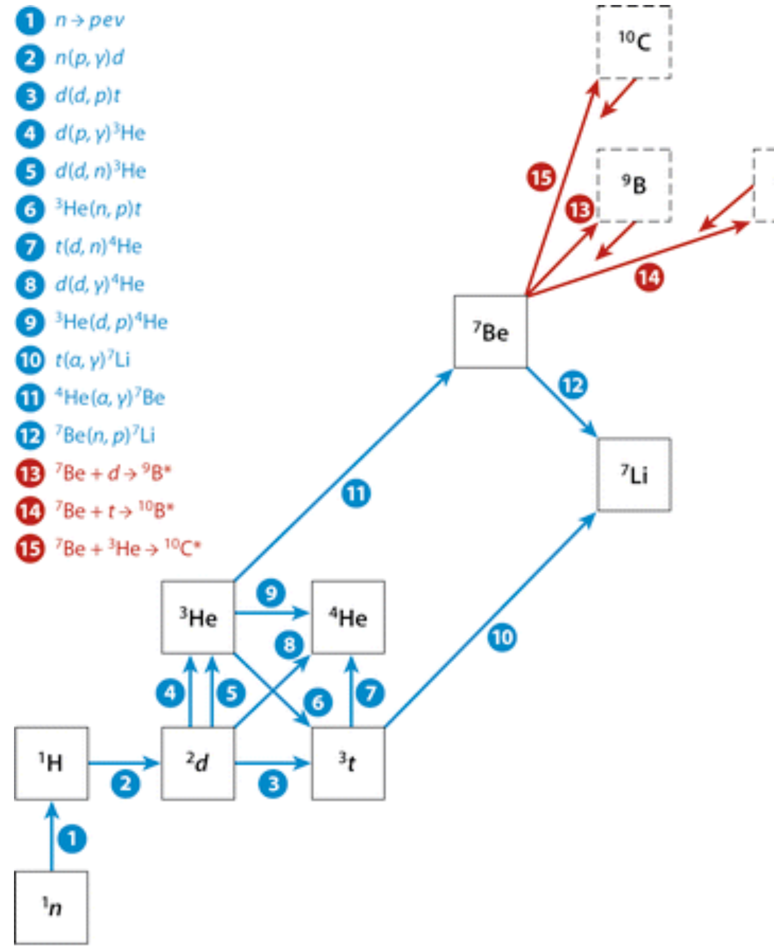
**Light Elements Born: T~0.07 MeV, t~3 min**

reaction flow ⇨ most stable light nucleus

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

also: traces of D, $^3$He, $^7$Li




Fields BD. 2011.
Annu Rev. Nucl. Part. Sci. 61:47–68

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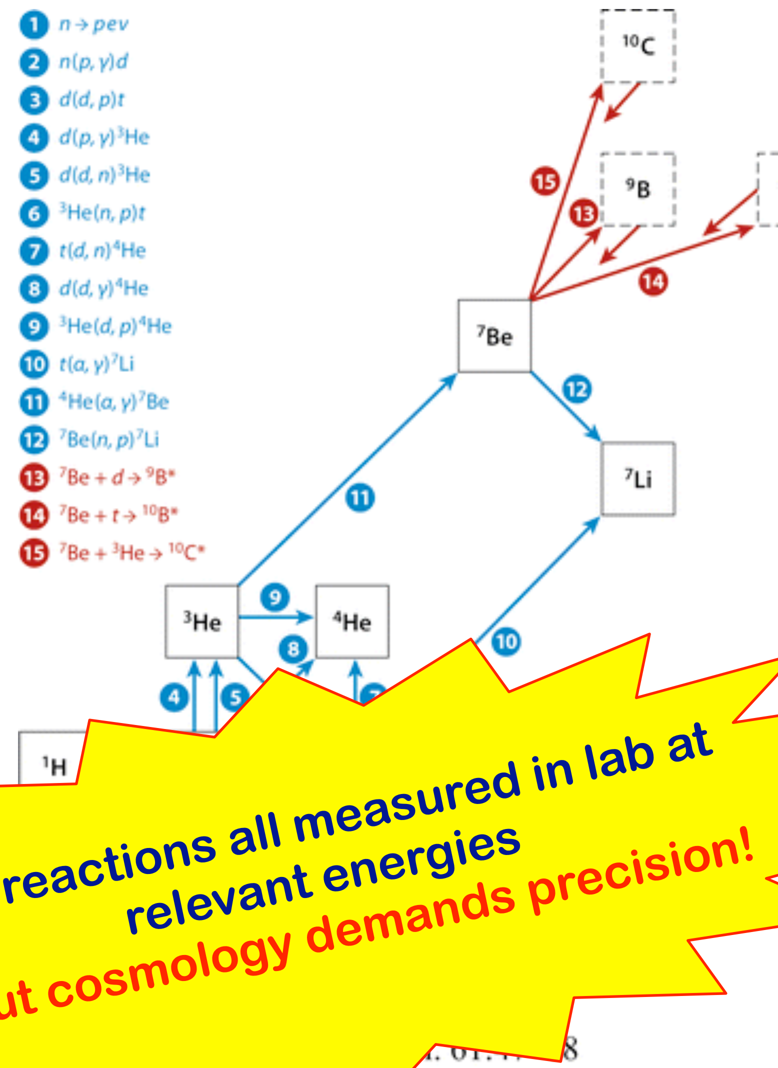
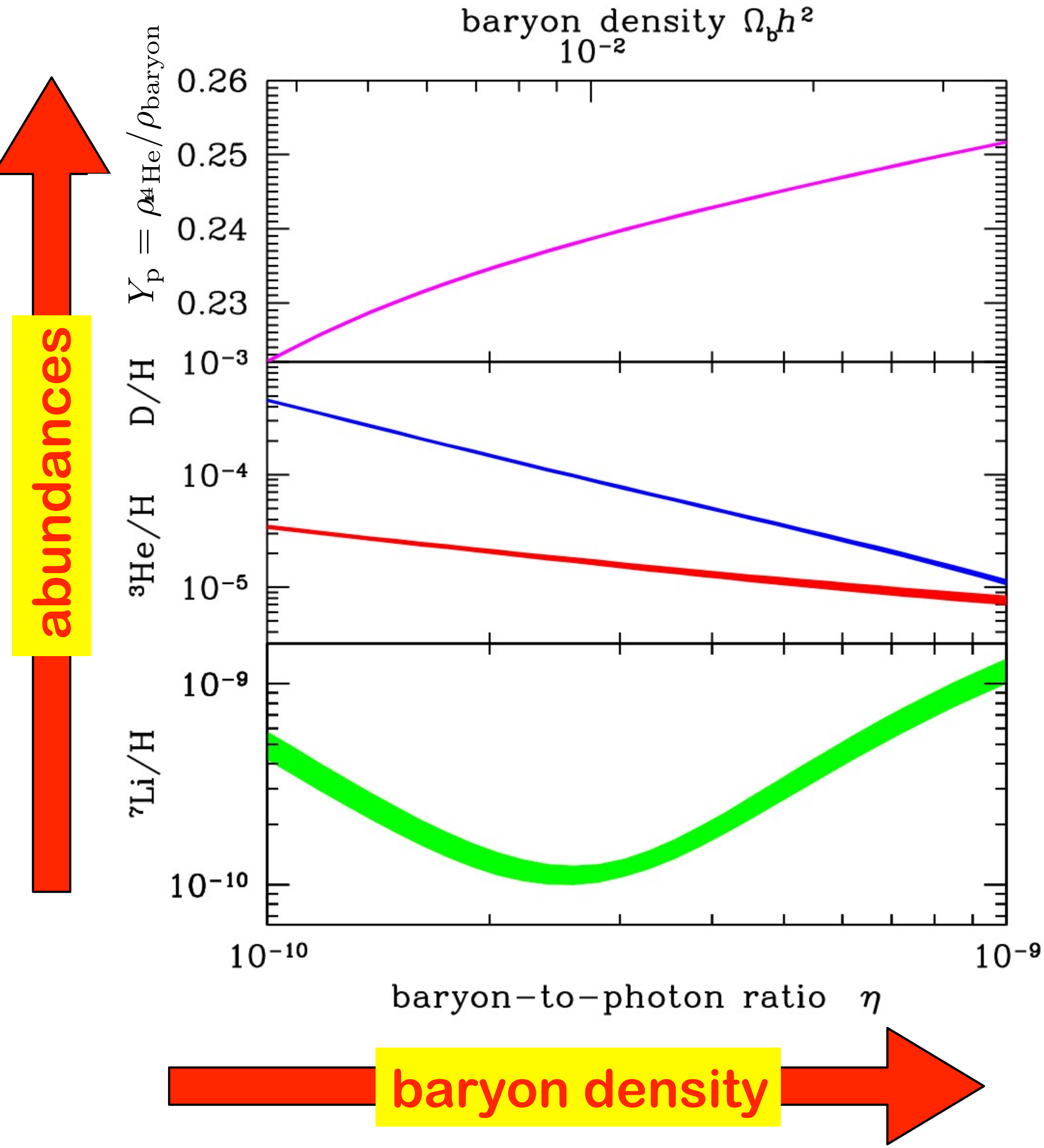



key reactions all measured in lab at relevant energies

…but cosmology demands precision!




# 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

# Light Elements:  Sites

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## Deuterium

- QSO absorbers
- z~3, metals~0.01 solar
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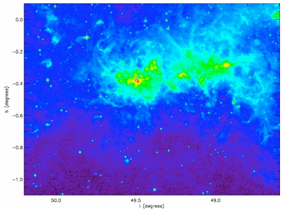
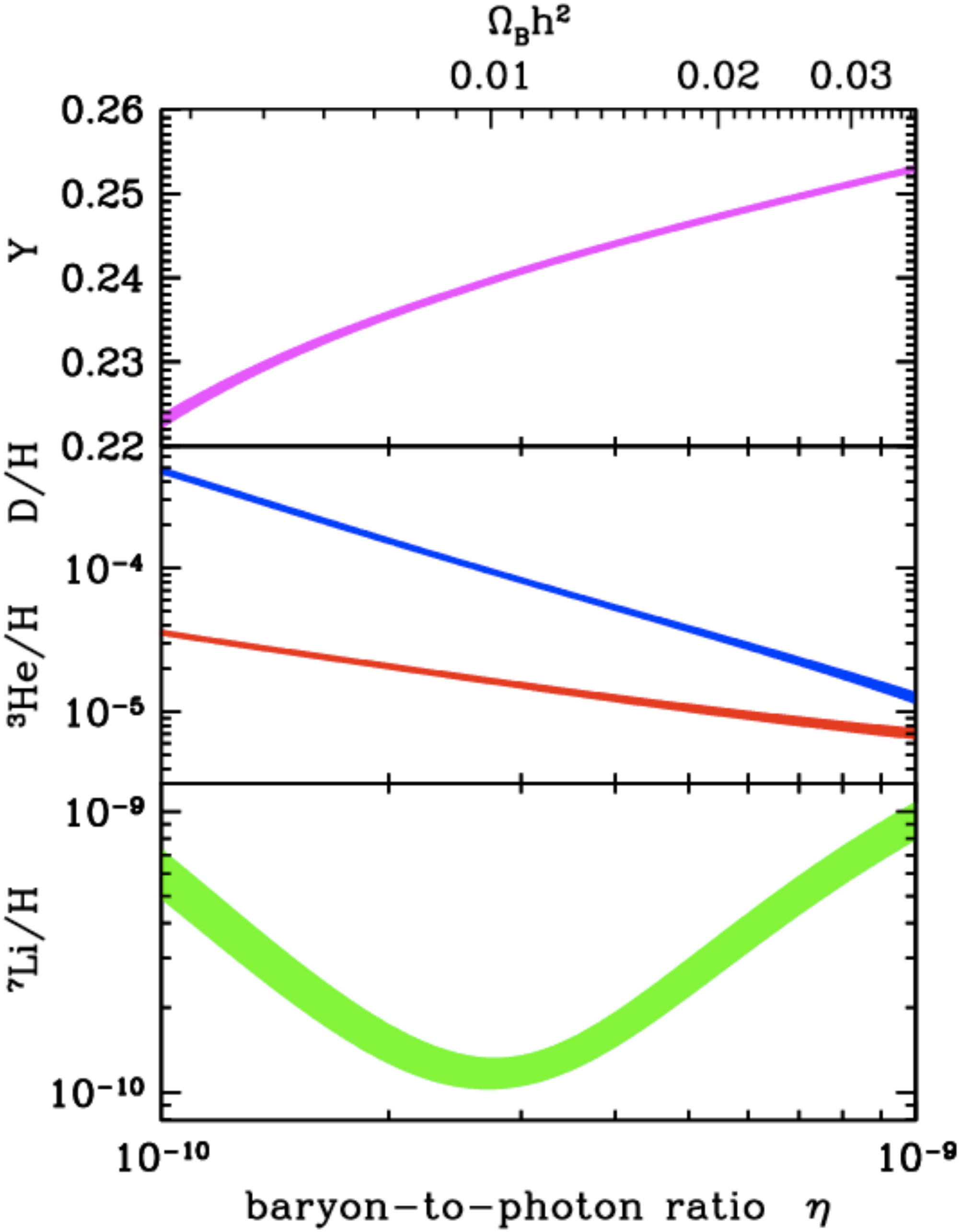


**$^3$He**

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

# Testing BBN:



$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
$10^{-4}$
$^3$He/H
$10^{-5}$
$10^{-9}$
$^7$Li/H
$10^{-10}$
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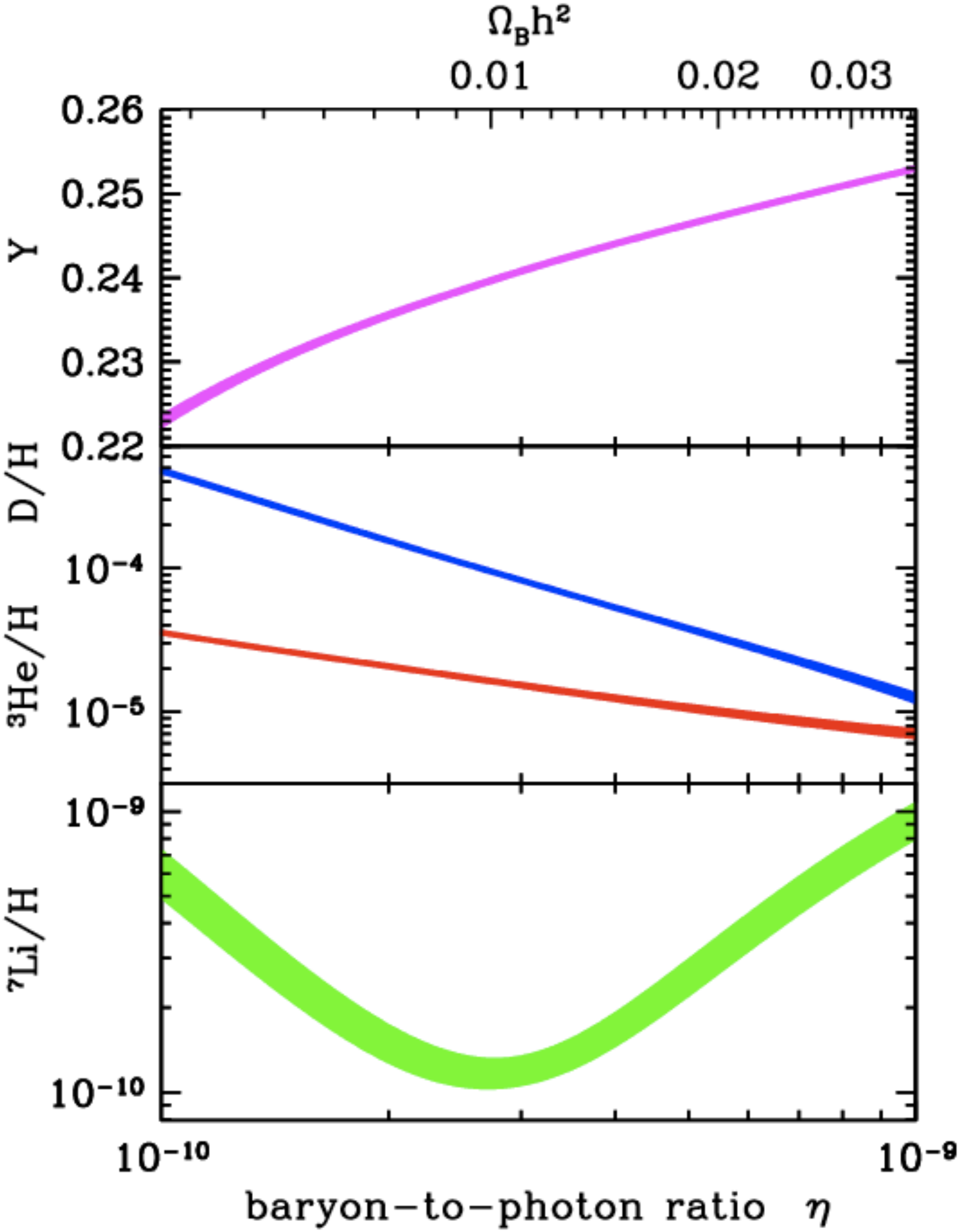
$10^{-9}$
baryon−to−photon ratio η




# Testing BBN: Light Element Observations

**Theory:**

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

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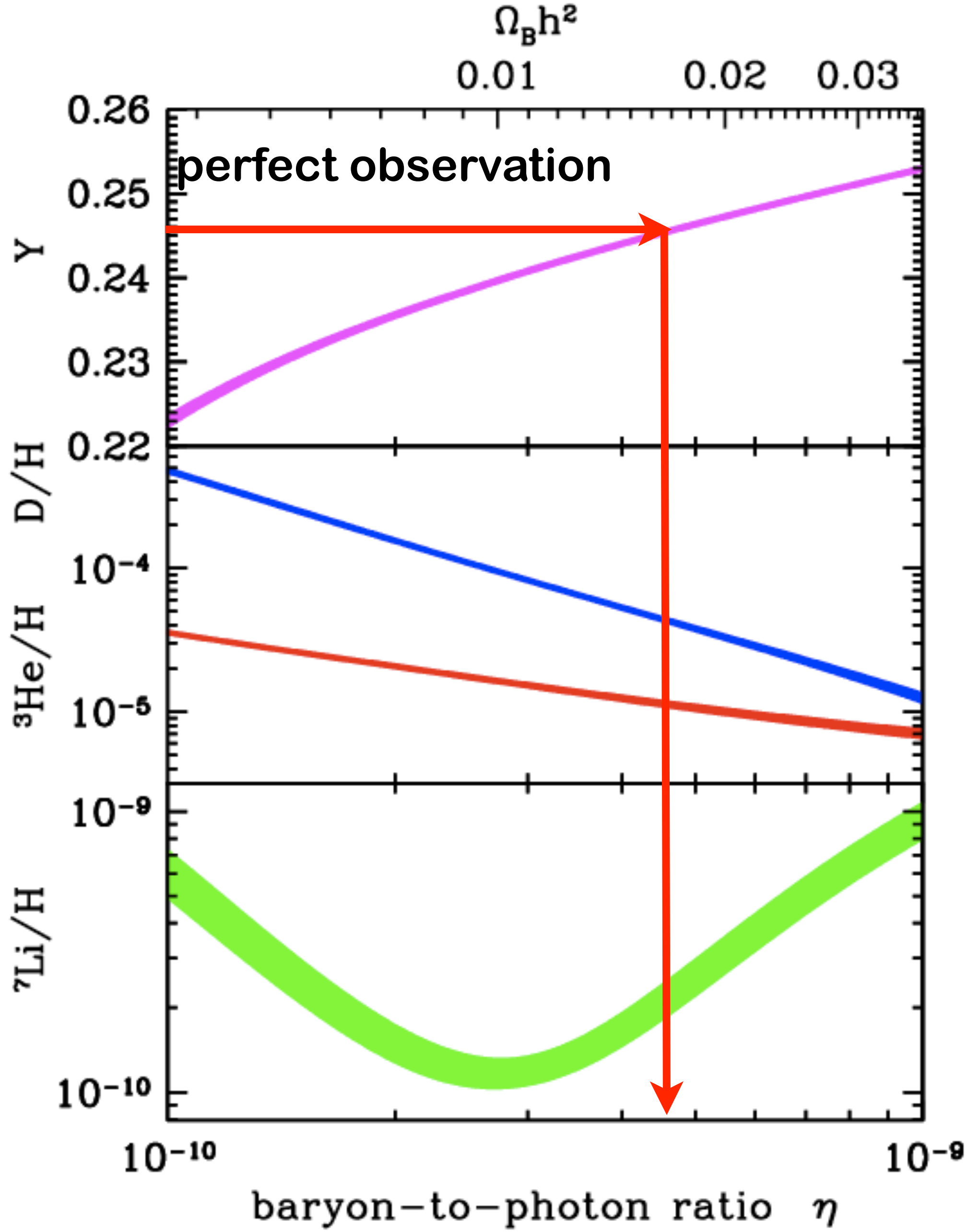


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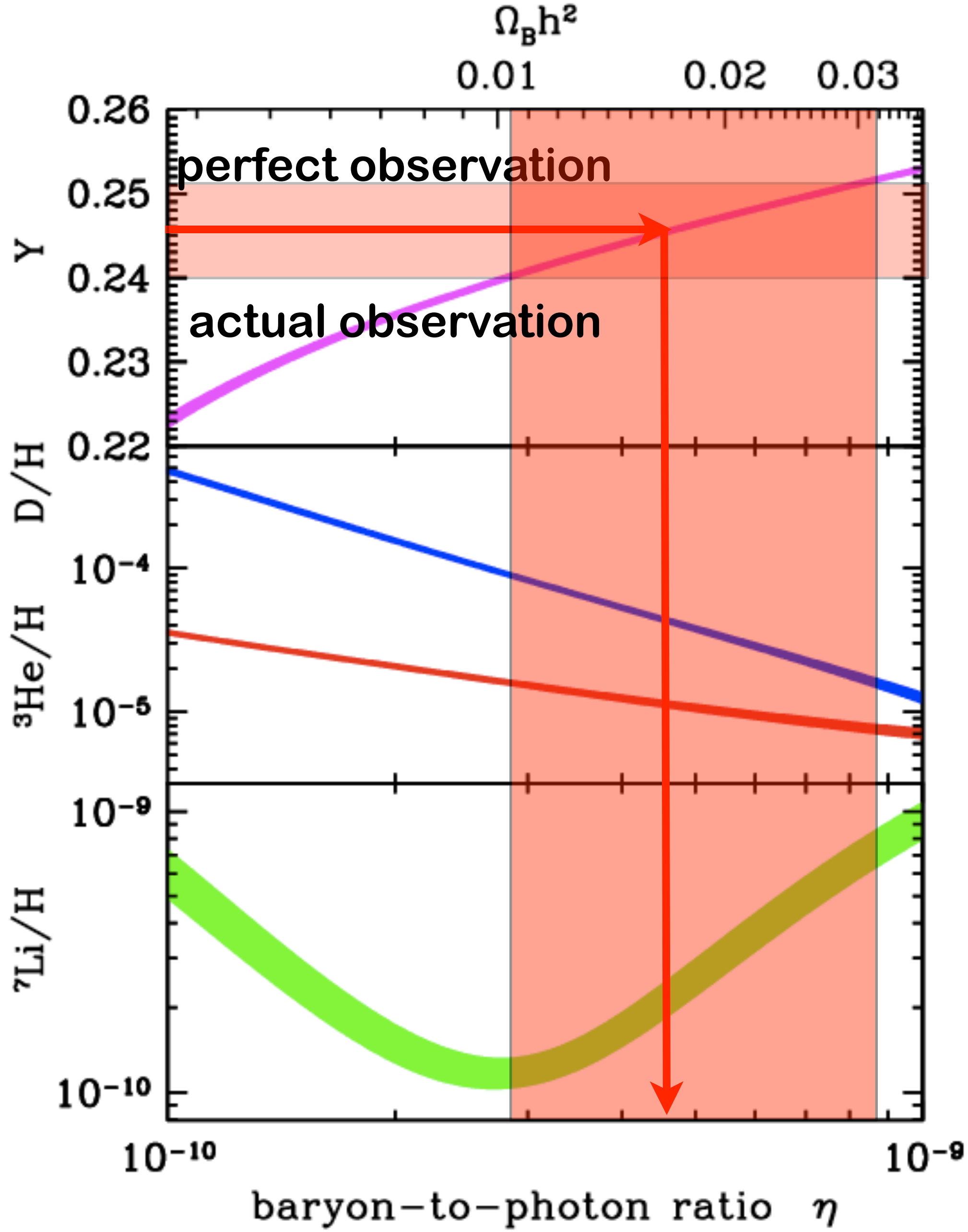


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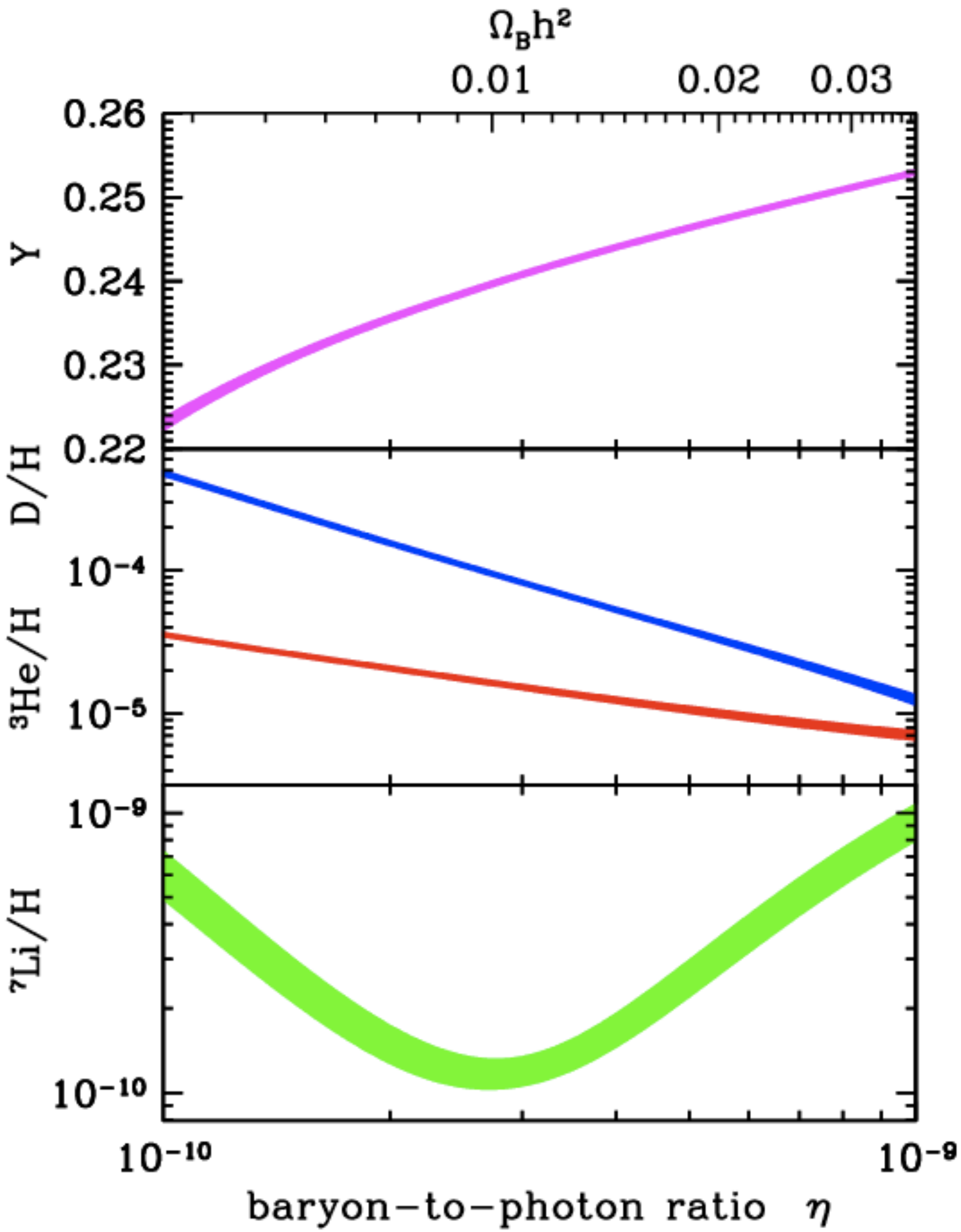


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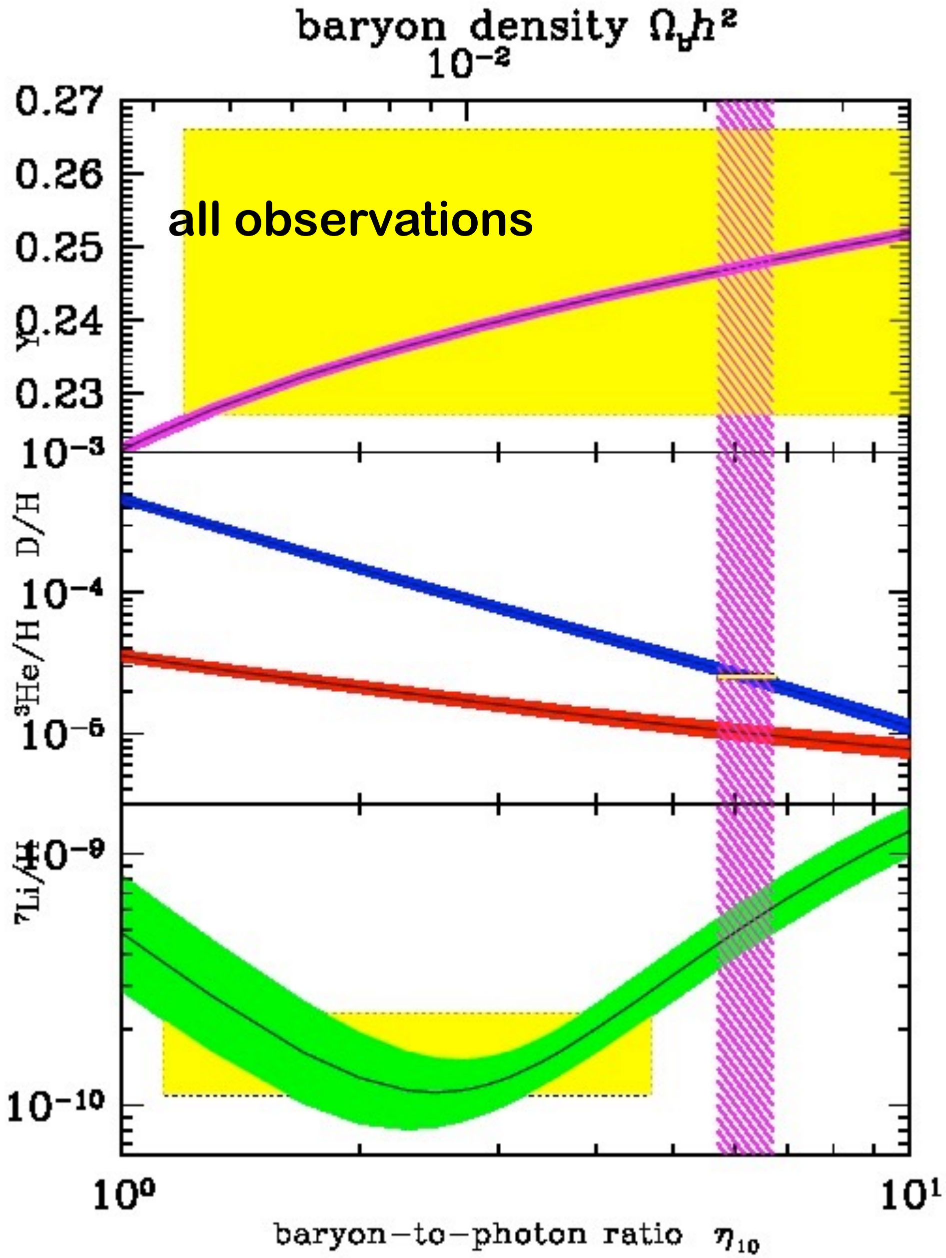


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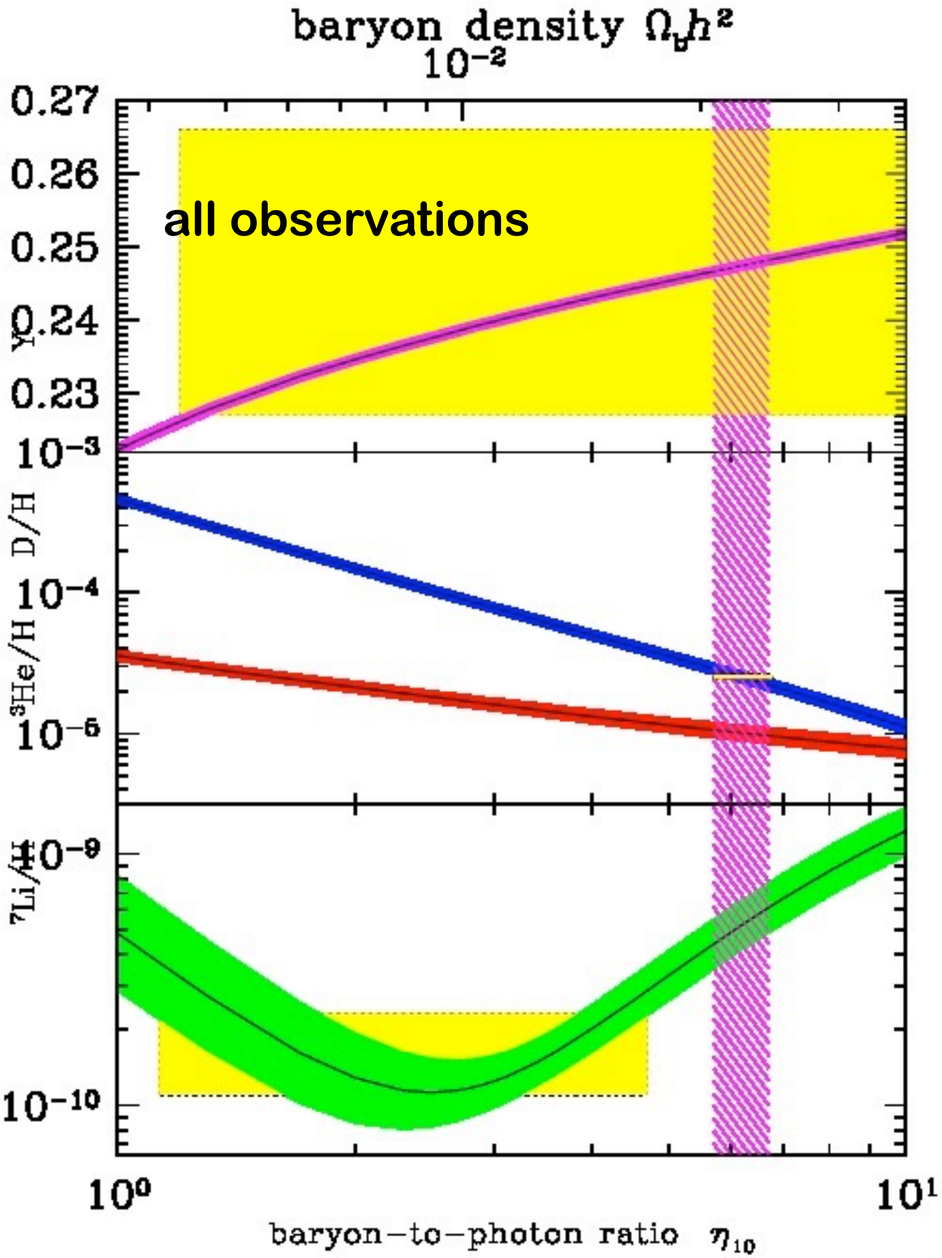


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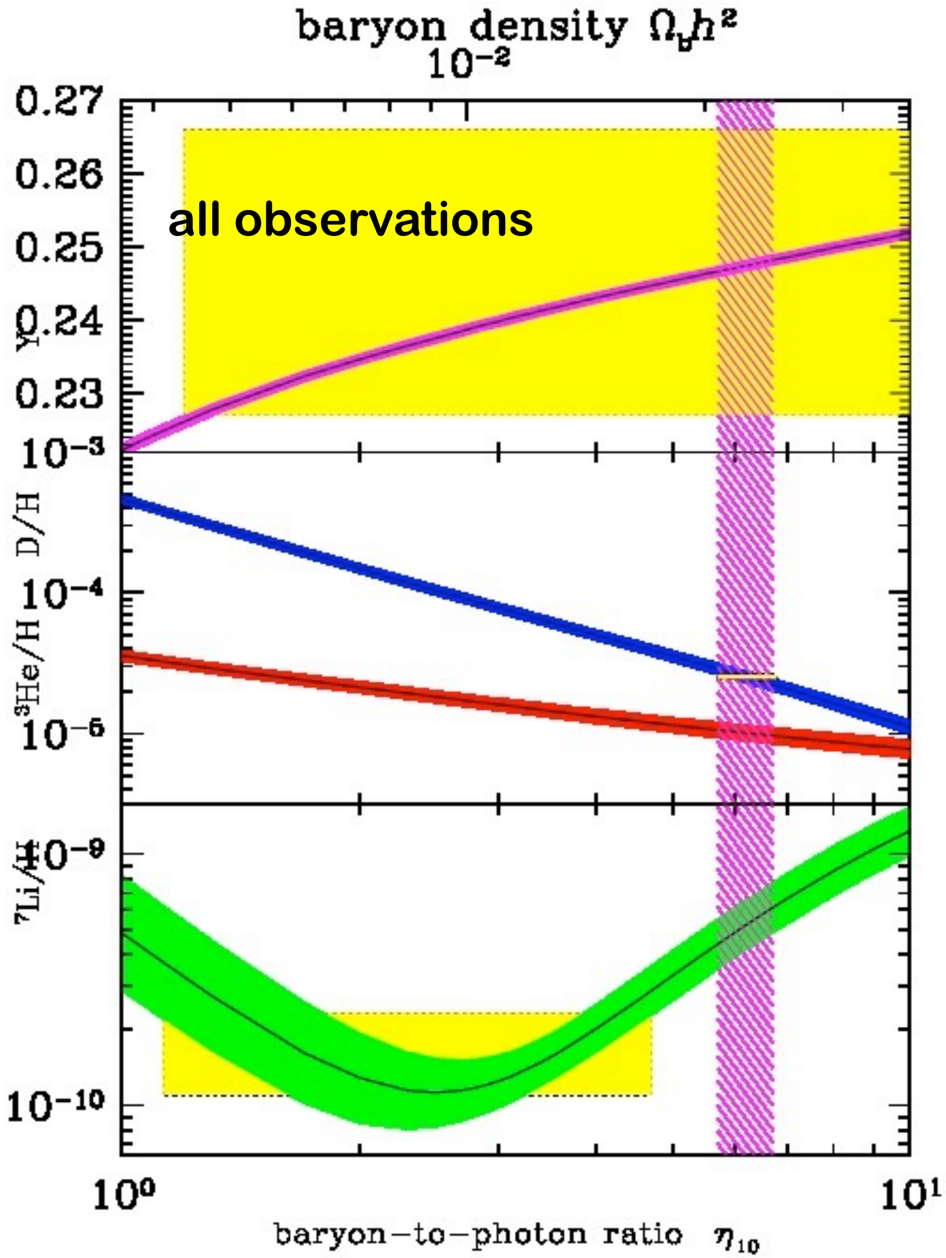


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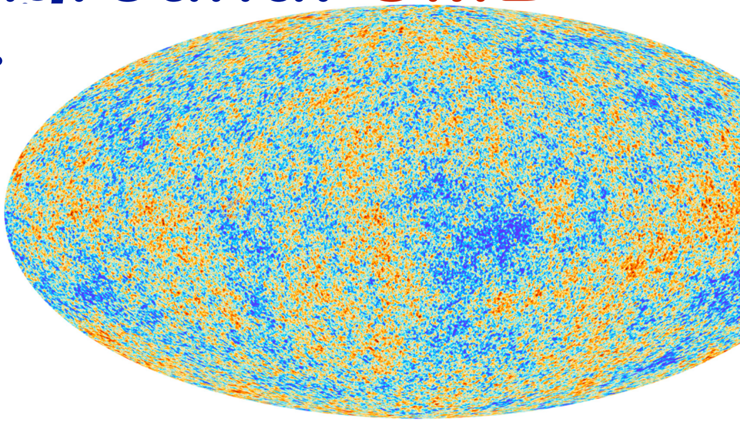
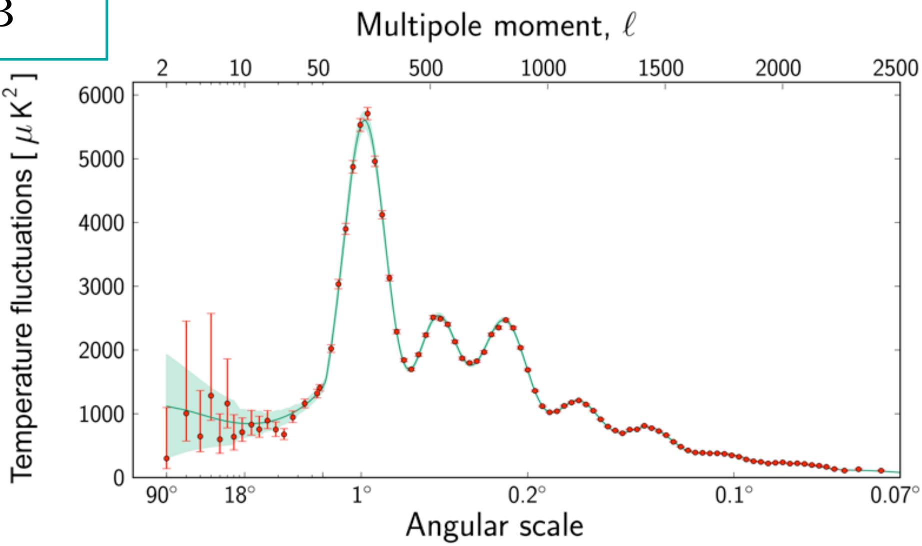
⇨ need a tiebreaker

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



CMB $\Delta T_\ell$ independent measure of $\Omega_B$

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

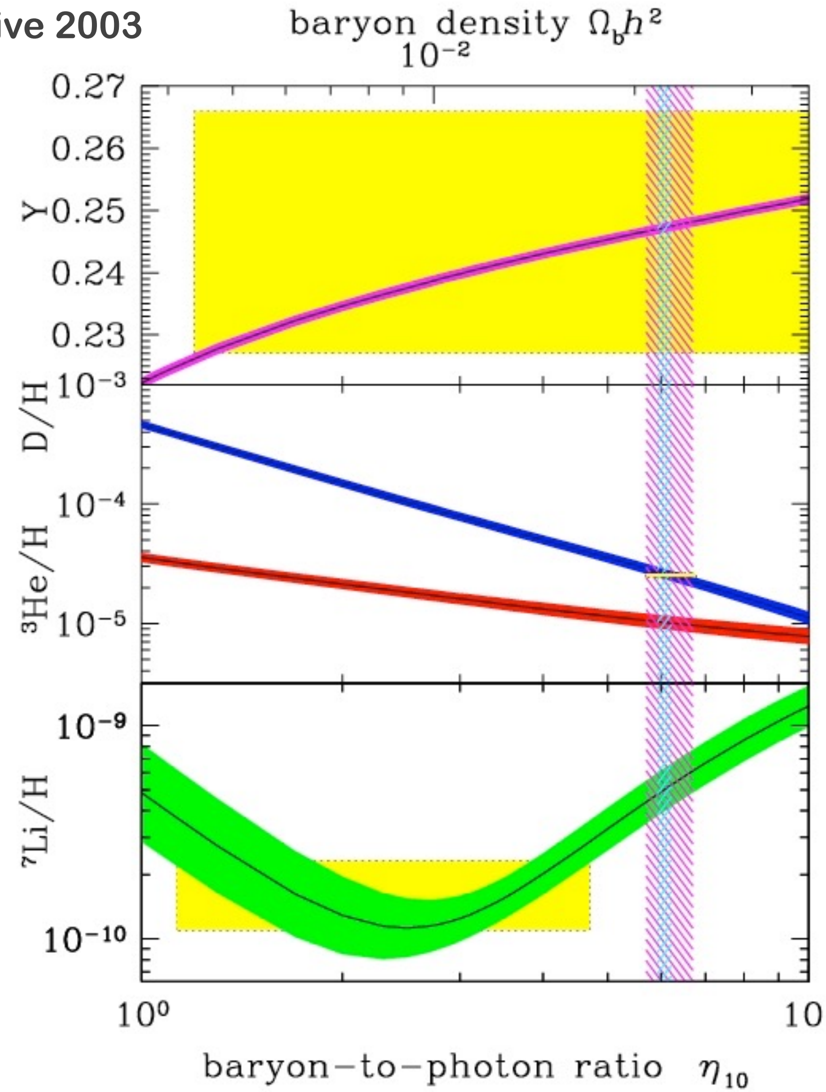



**Planck Explorer:**

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

# Battle of the Baryons: II
# New World Order

Cyburt, BDF, Olive 2003

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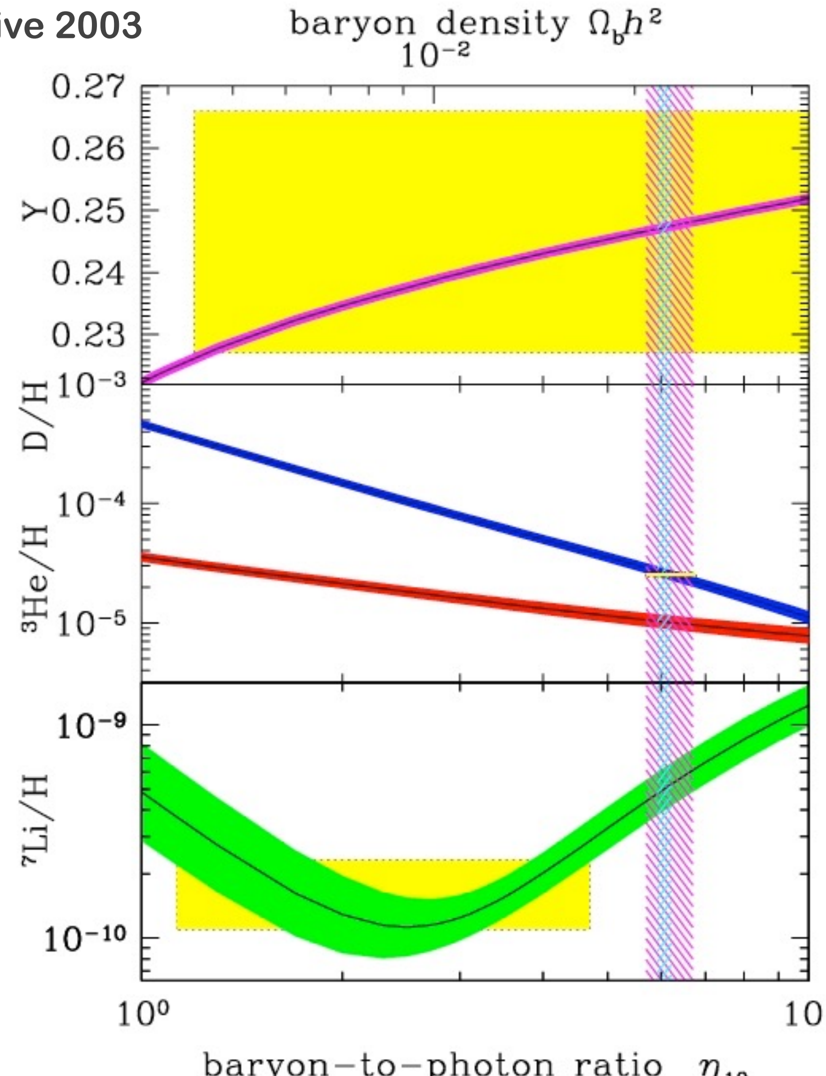


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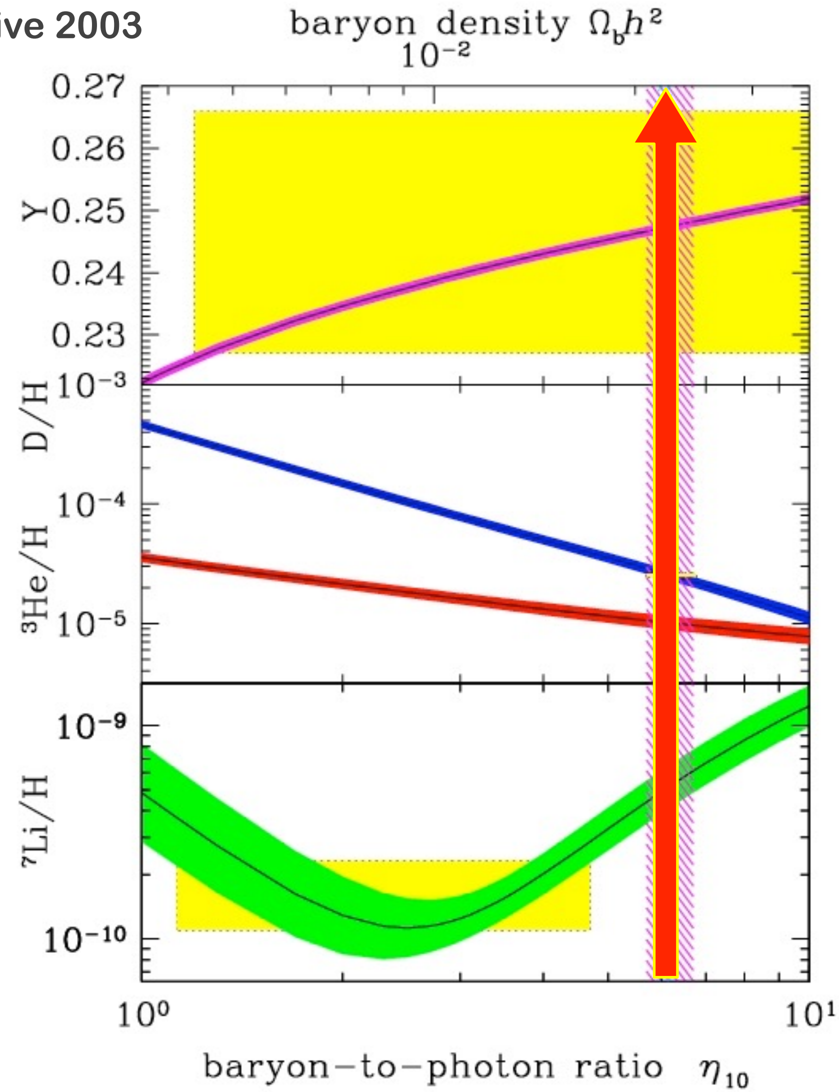


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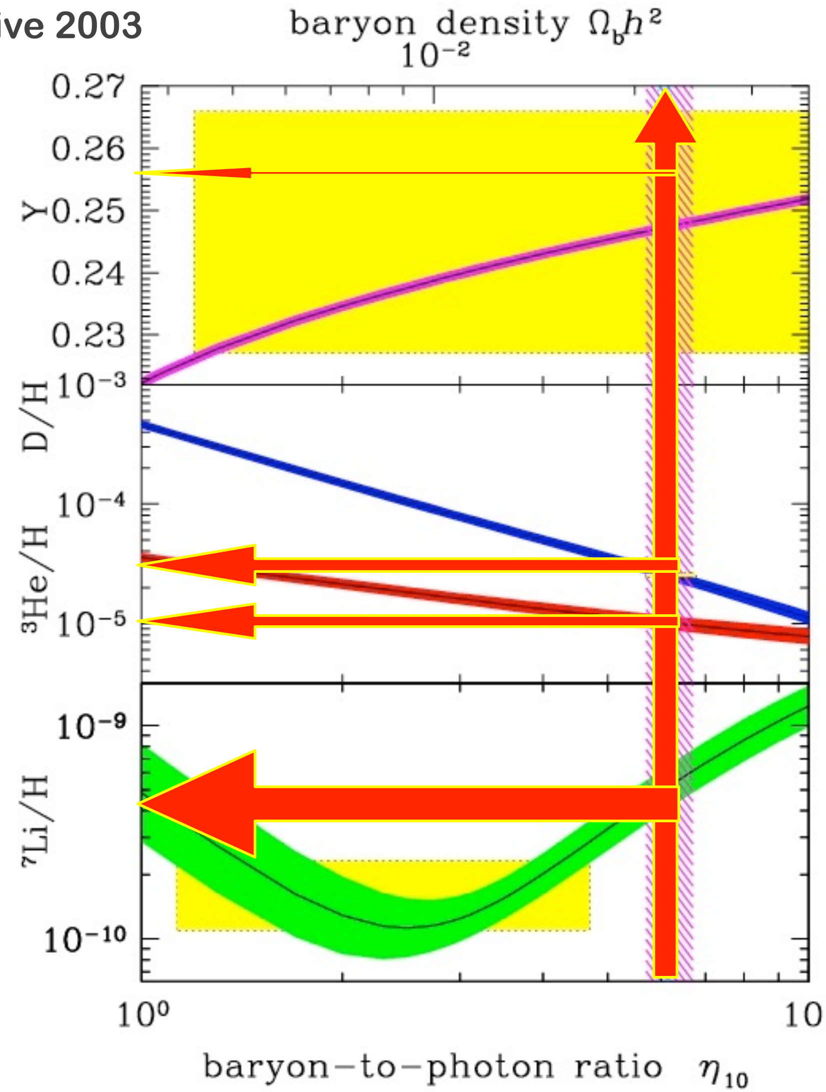


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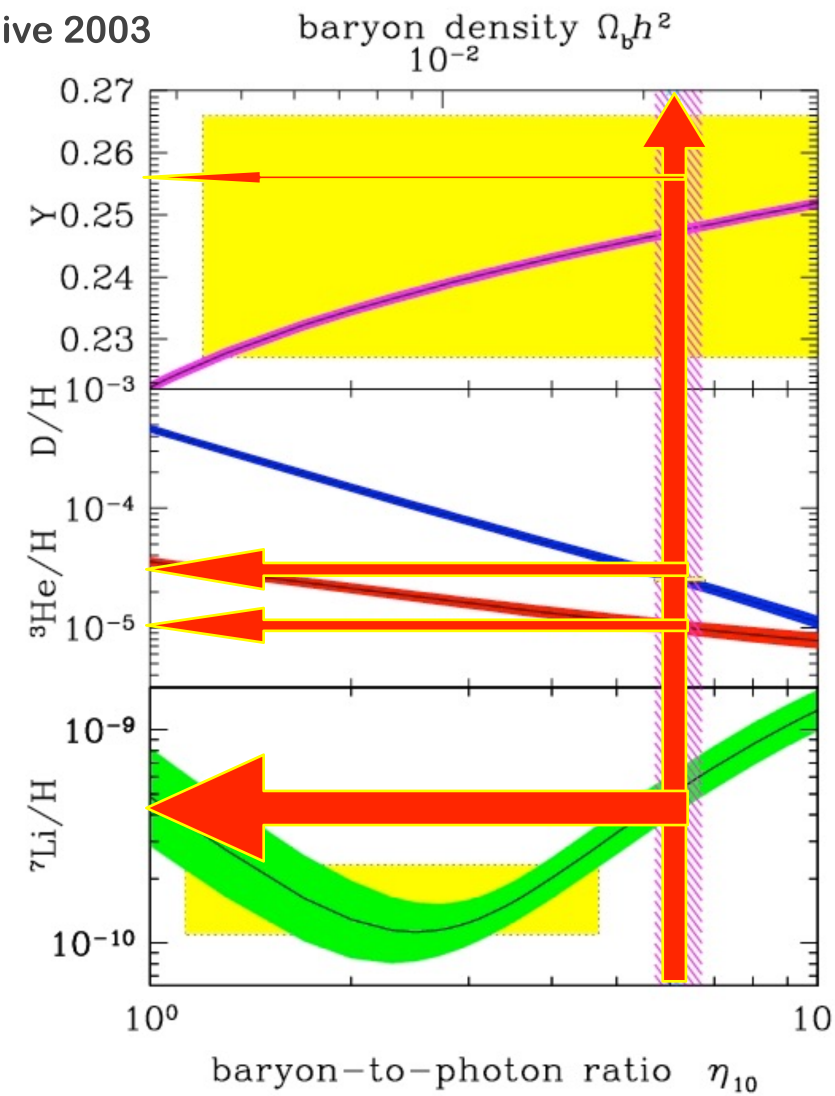
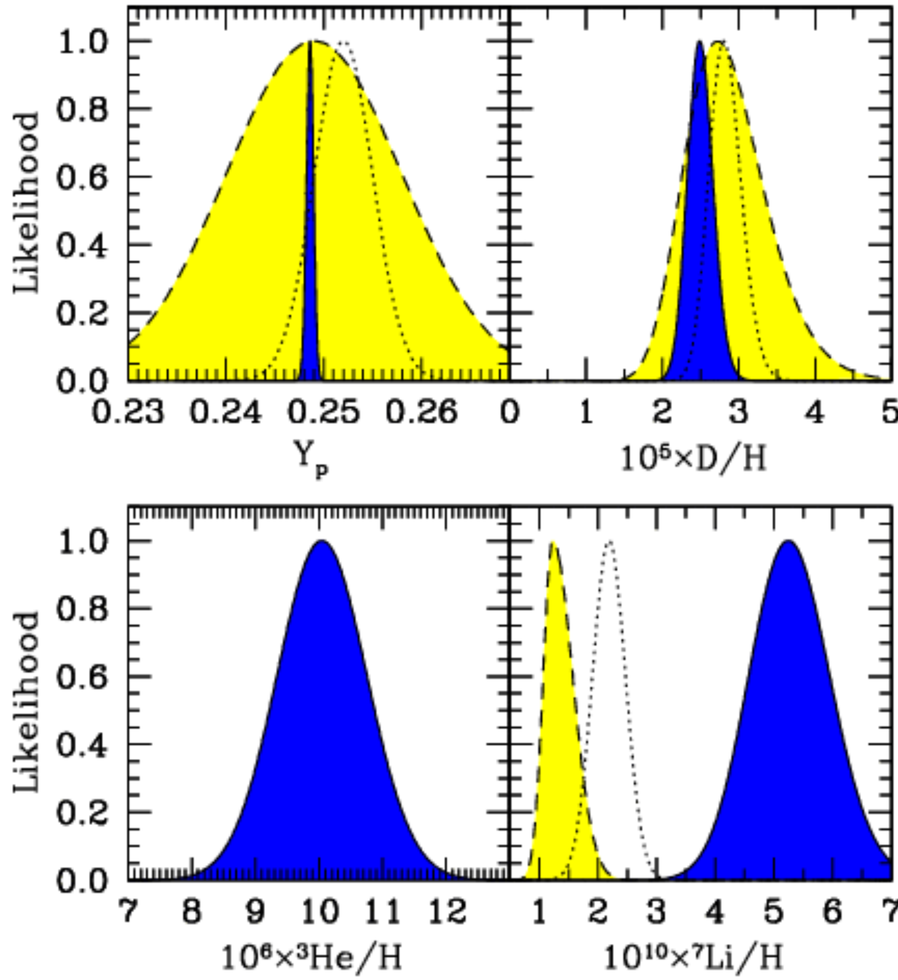


# Battle of the Baryons: II
# A Closer Look

Cyburt, BDF, Olive 2003, 2008, 2015



# Battle of the Baryons: II
# A Closer Look

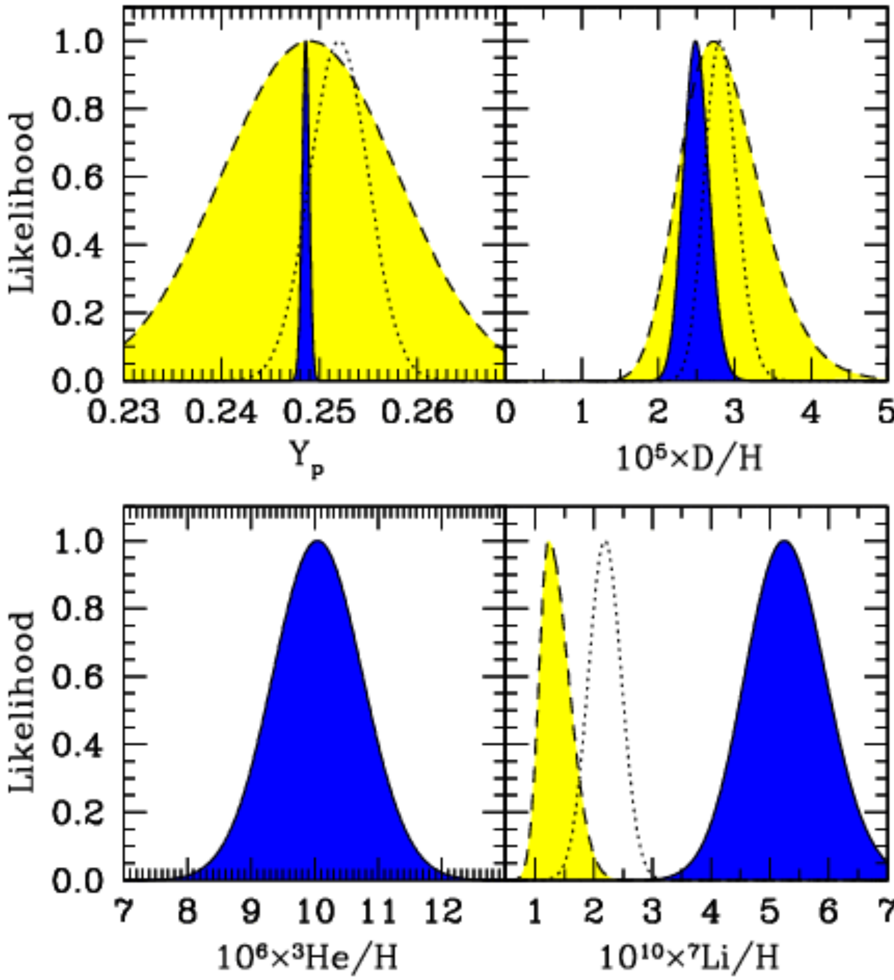
Cyburt, BDF, Olive 2003, 2008, 2015

**Predict:**

**BBN theory: abundances vs $\eta$**

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

**Compare with Observations (yellow)**



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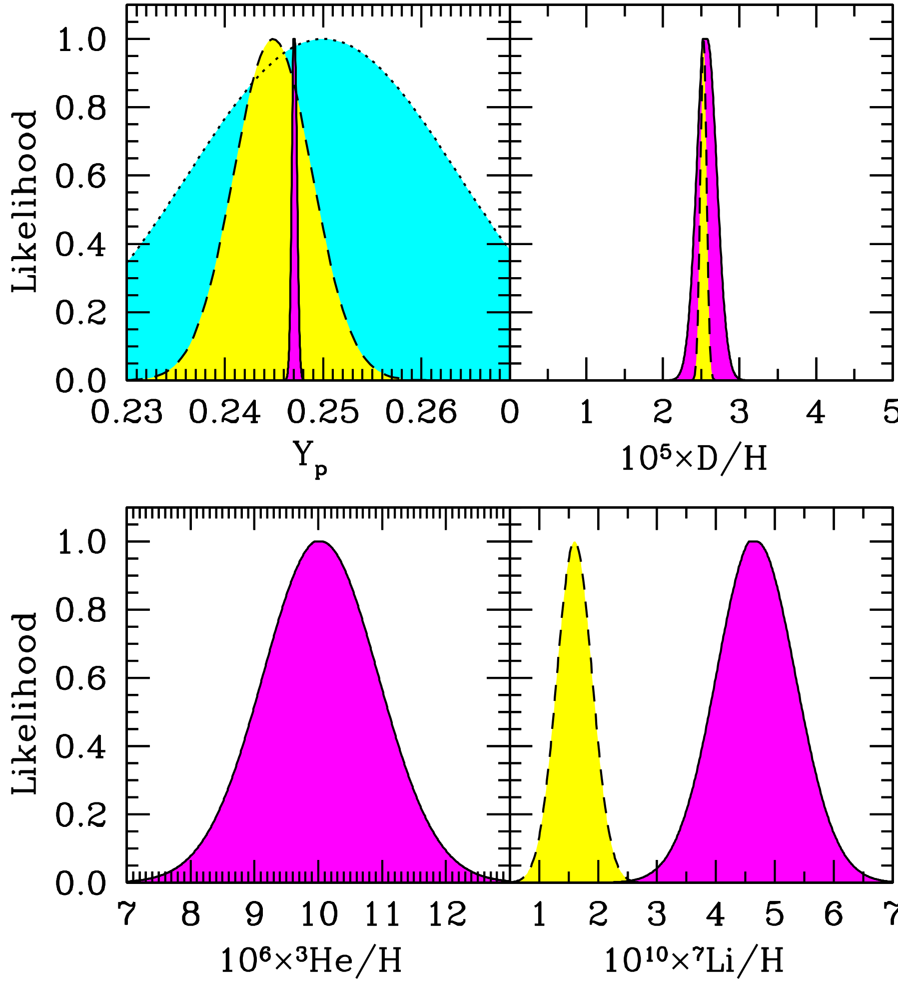

New! Improved!
Planck baryons
QSO D/H

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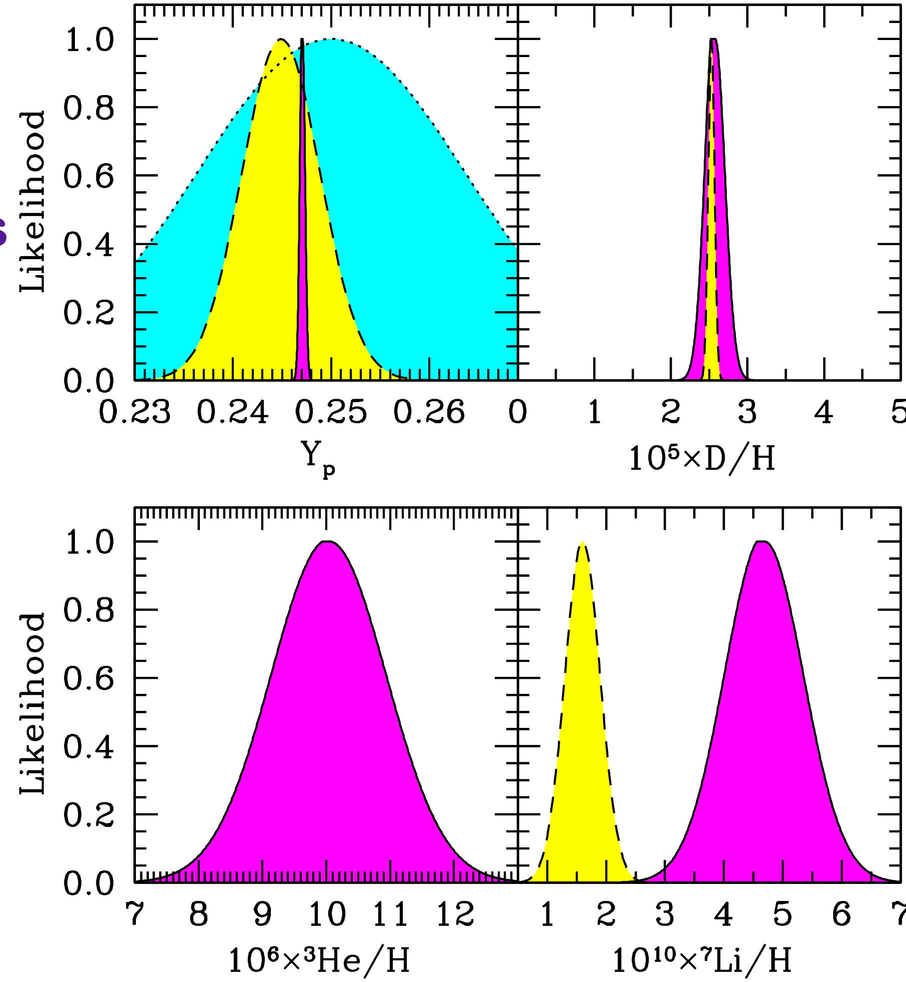


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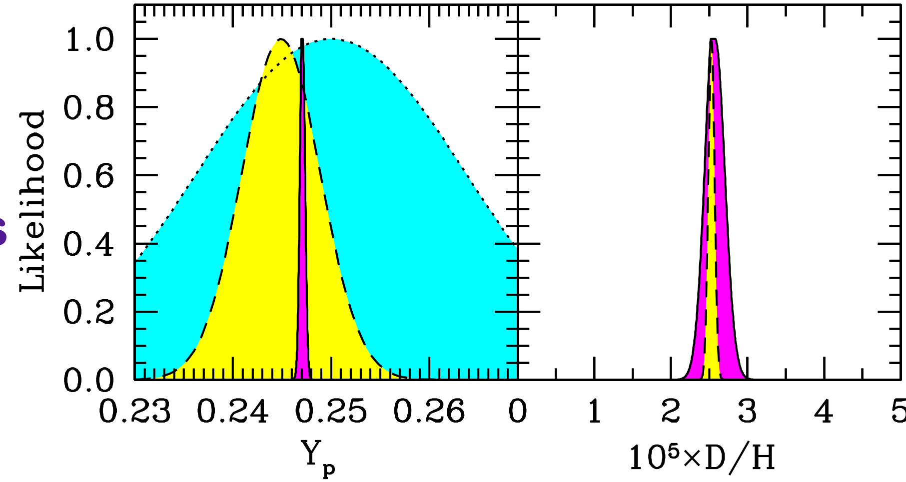


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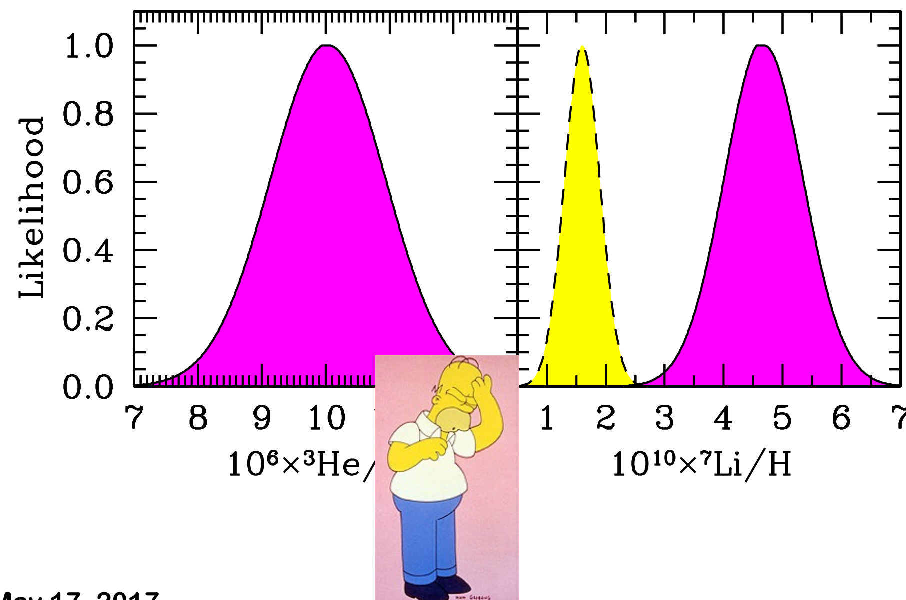

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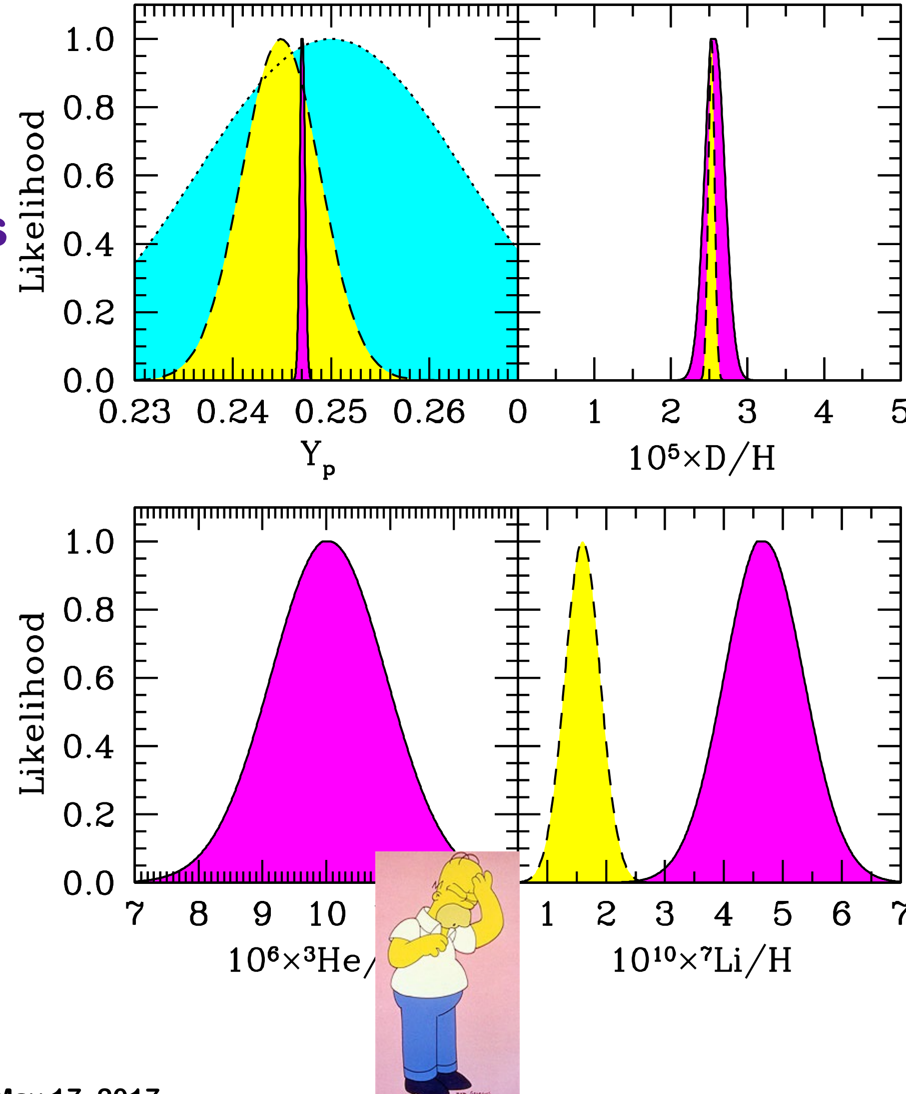


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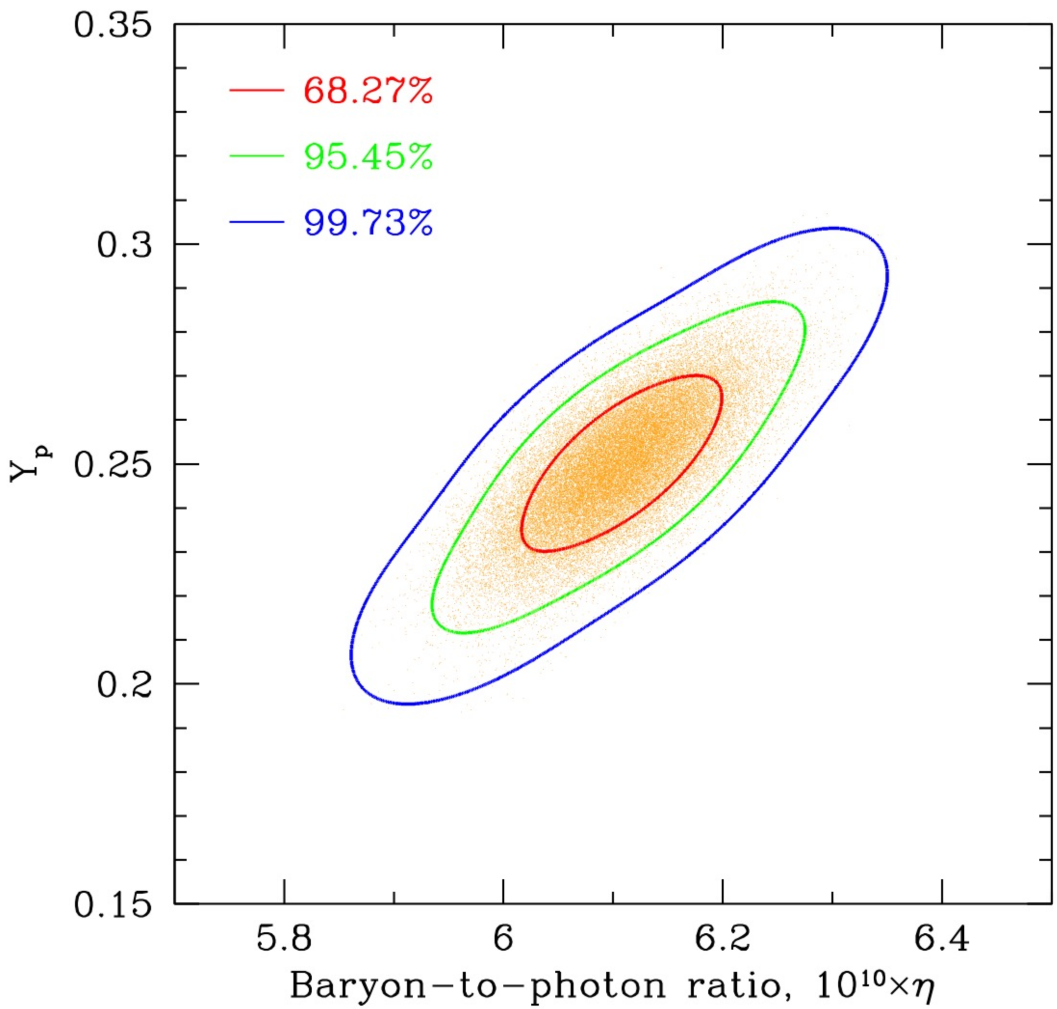

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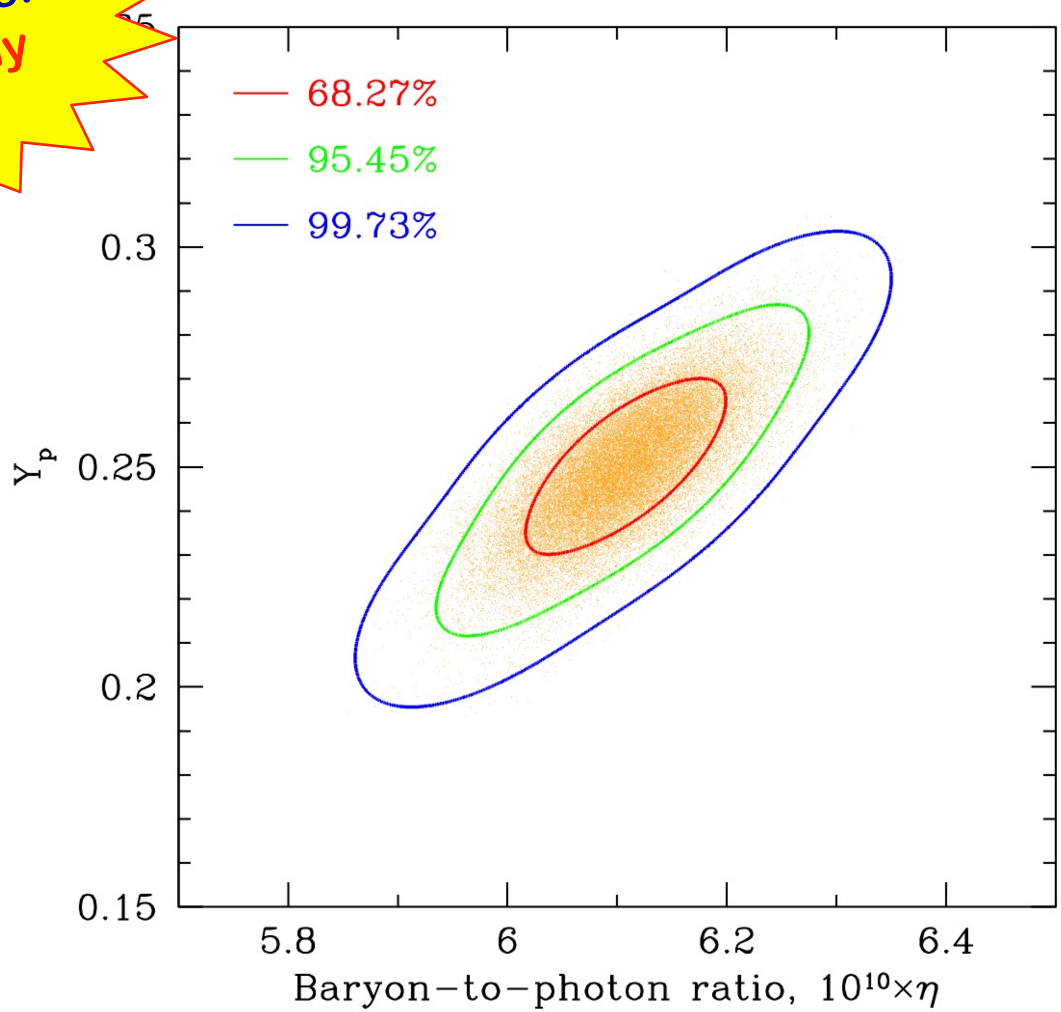

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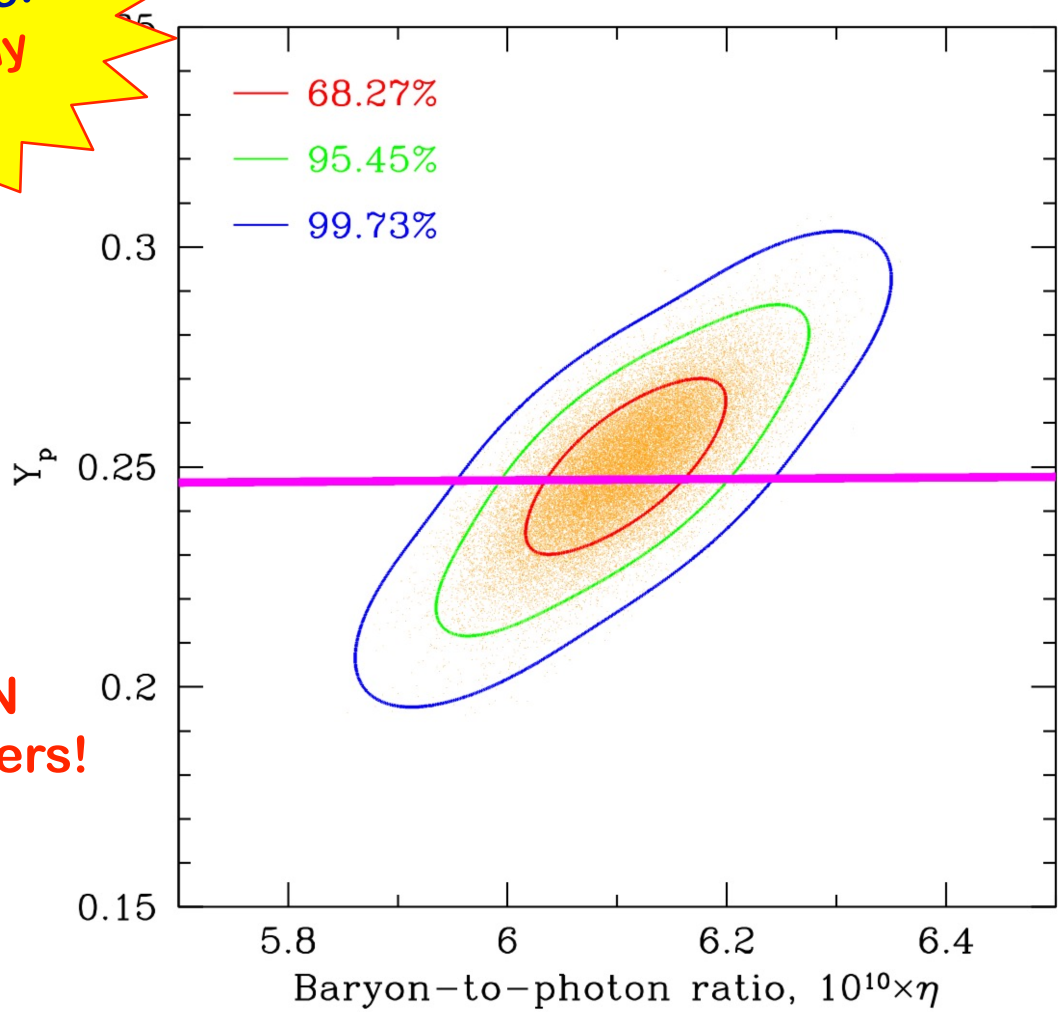


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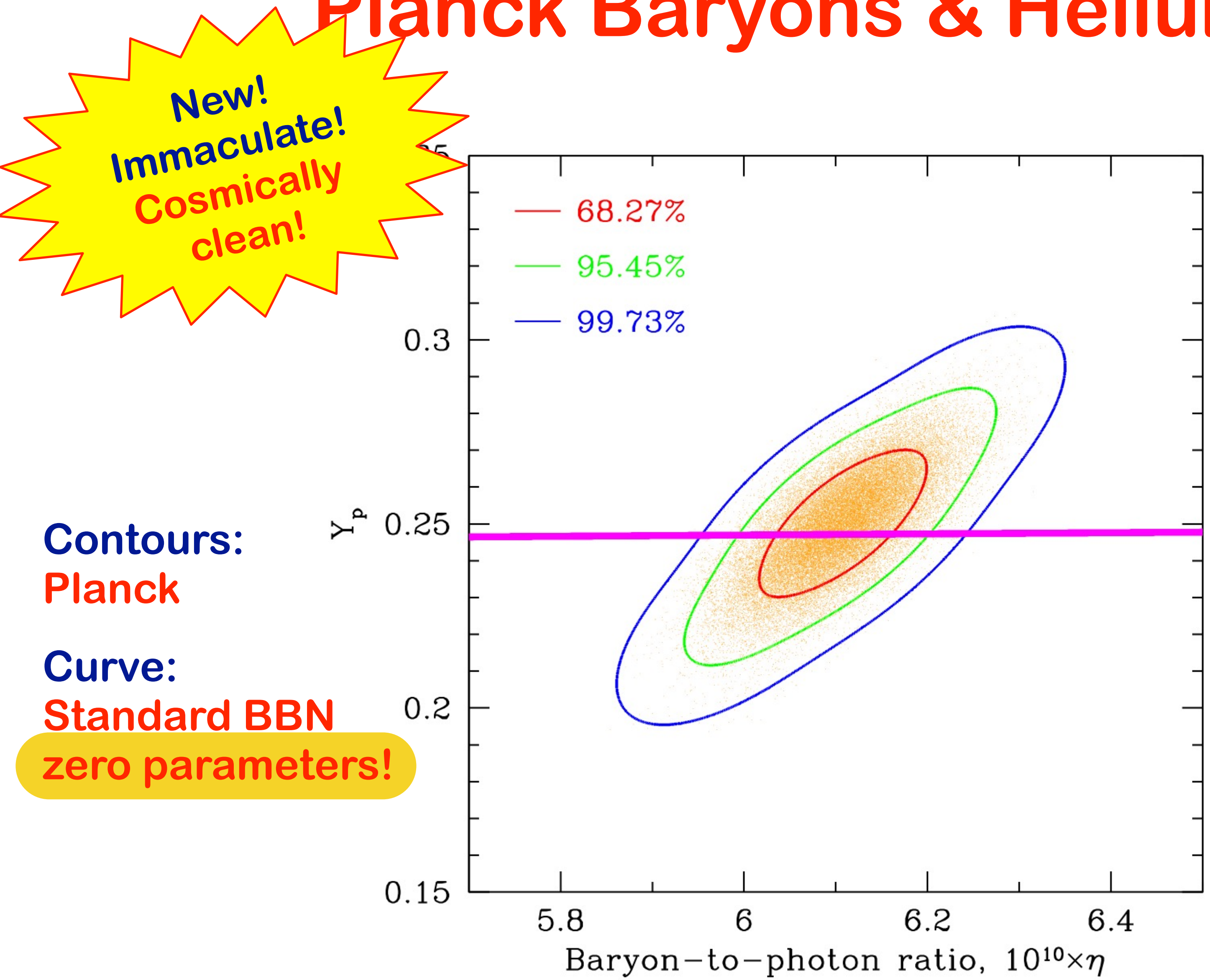


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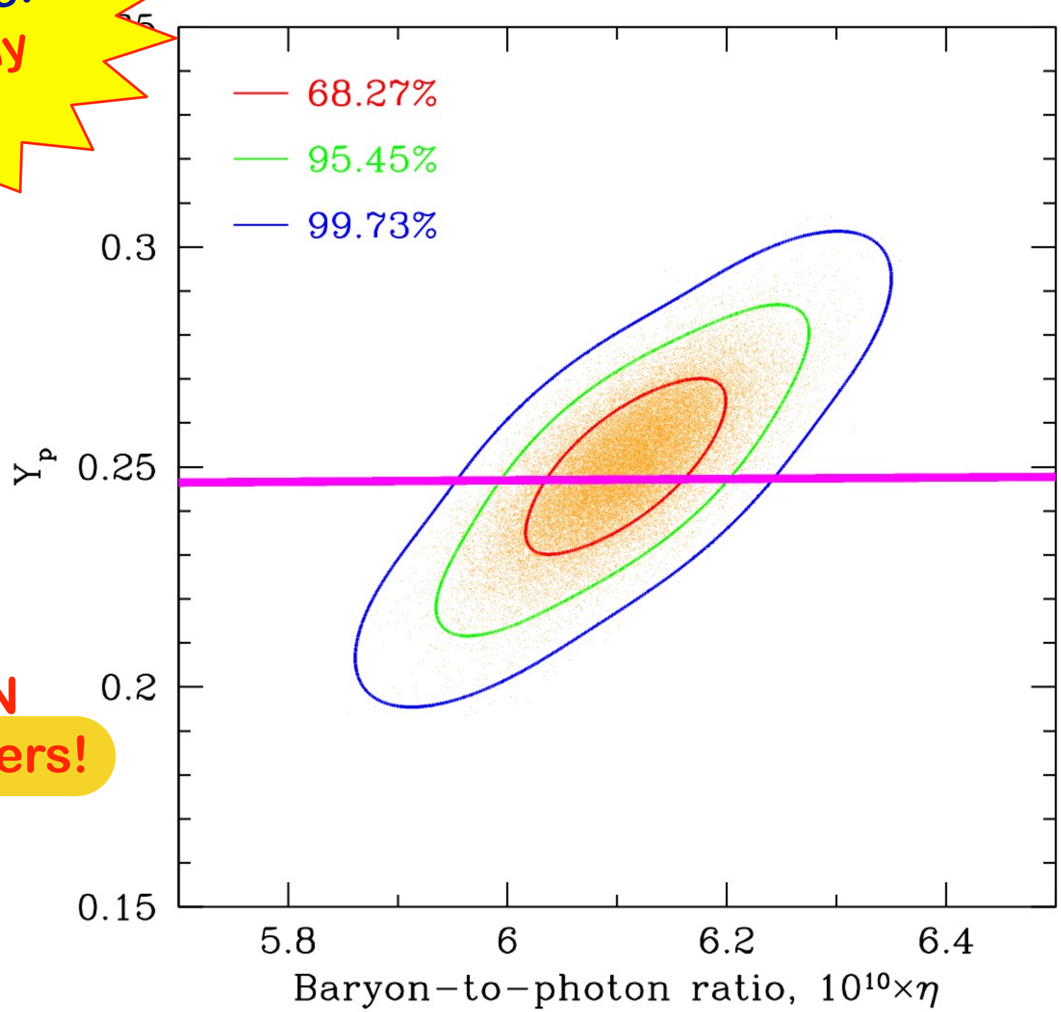


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# Lithium Strategy I:
# No Worries
## Two out of three ain't bad

# Dark Matter

**Pre-CMB Anisotropies:**

**BBN ⇨ Dark Matter**

**WMAP finds:**

$$\Omega_{\rm B} = 0.044 \pm 0.004$$

$$\frac{\Omega_{\rm M}}{\Omega_{\rm B}} = \frac{\rm matter}{\rm baryons} = 5.9 \pm 0.3$$

**Optical galaxy surveys ⇨ luminous matter**

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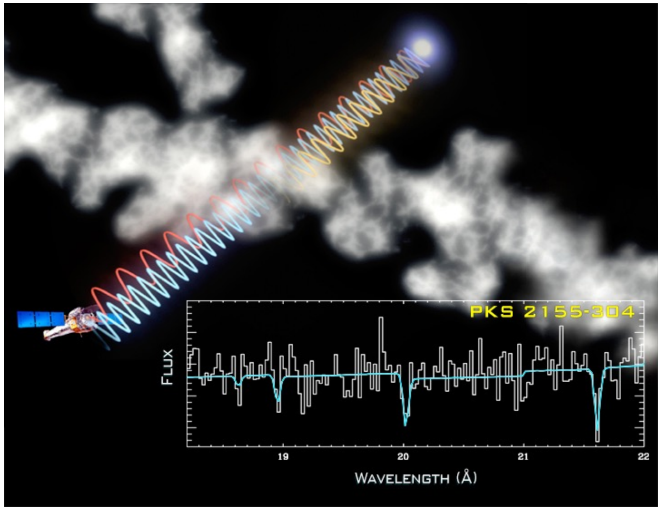
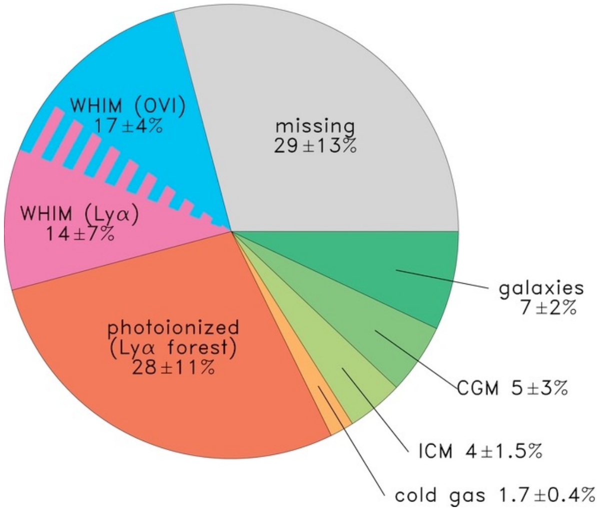



Intergalactic gas absorbs QSO backlight
Fang, Canizares, & Yao 07

**Baryonic Dark Matter:** $\Omega_{\rm B} \gg \Omega_{\rm lum}$

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

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




Shull, Smith, Danforth 2012

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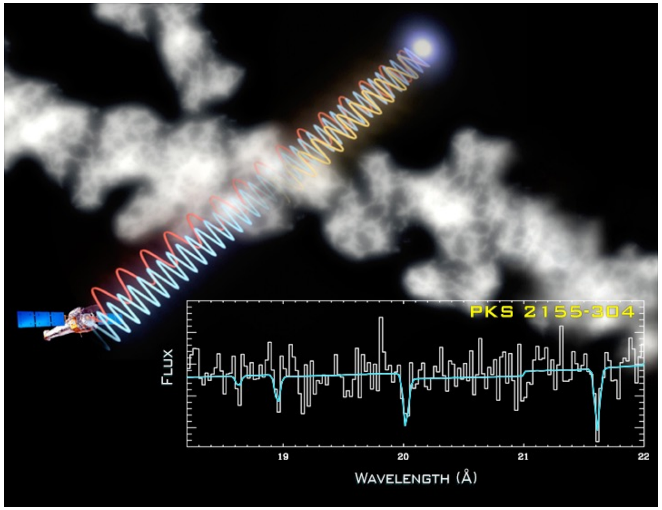
**Non-Baryonic Dark Matter:** $\Omega_B \ll \Omega_M$

➡ **most of cosmic matter!**

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

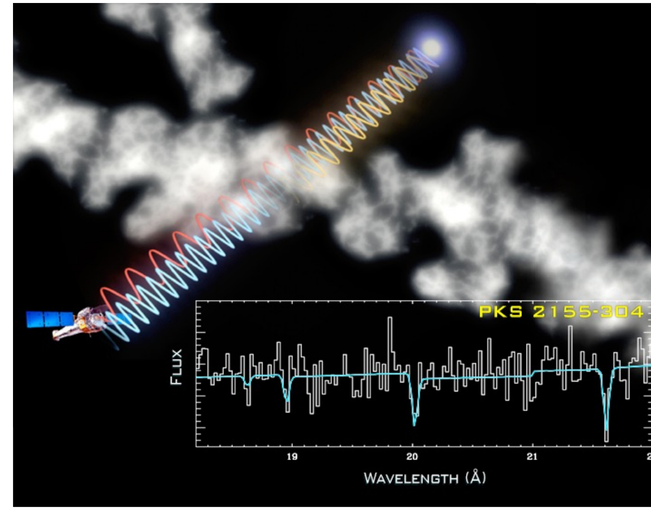
**Baryonic Da k M ... $\Omega_{\rm B} \gg \Omega_{\rm lum}$**

➡ **wa ... ay gas**

**...er: Dave etal**

$\Omega_{\rm B} \ll \Omega_{\rm M}$

**...ter!**

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# Lithium Strategy II:
# Worry

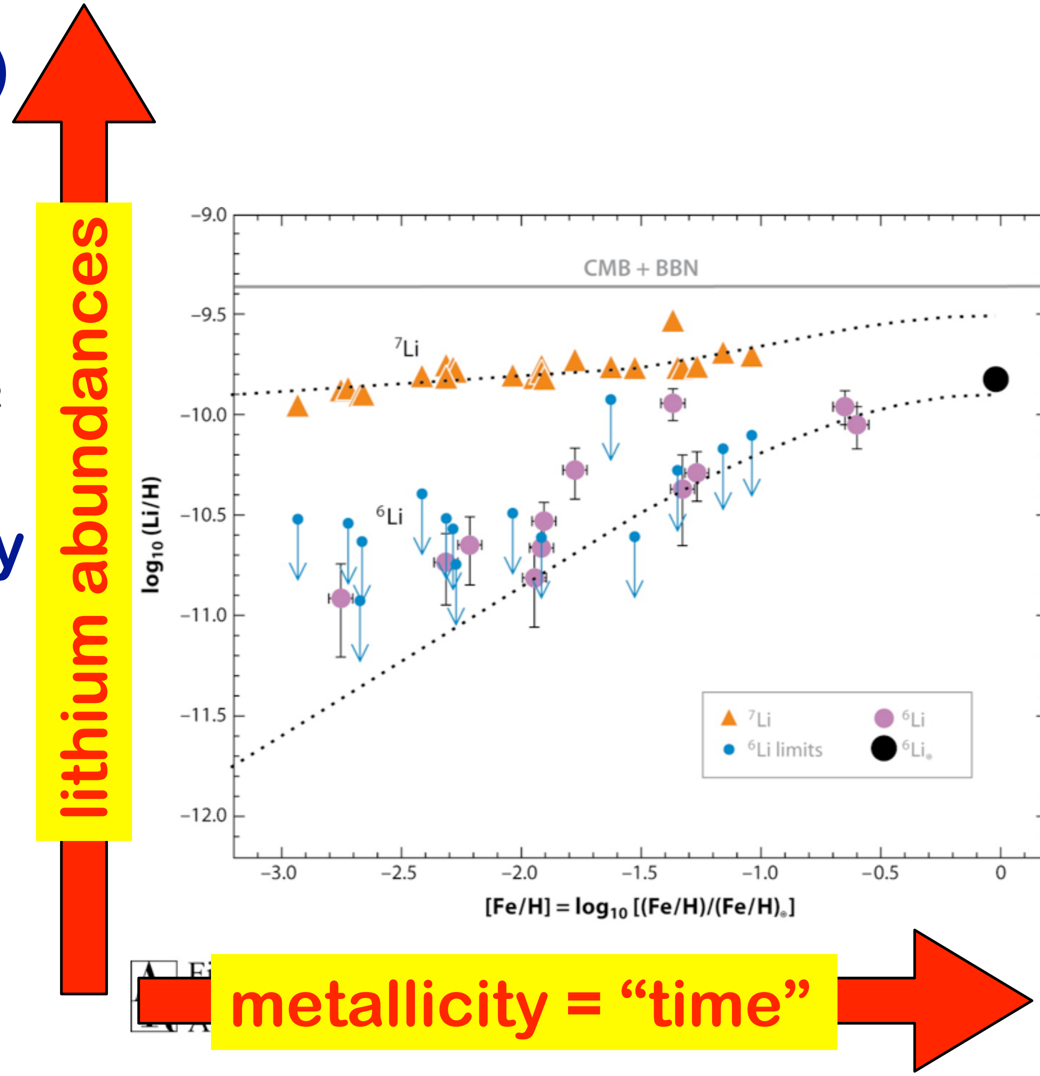
# Primordial Lithium

**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



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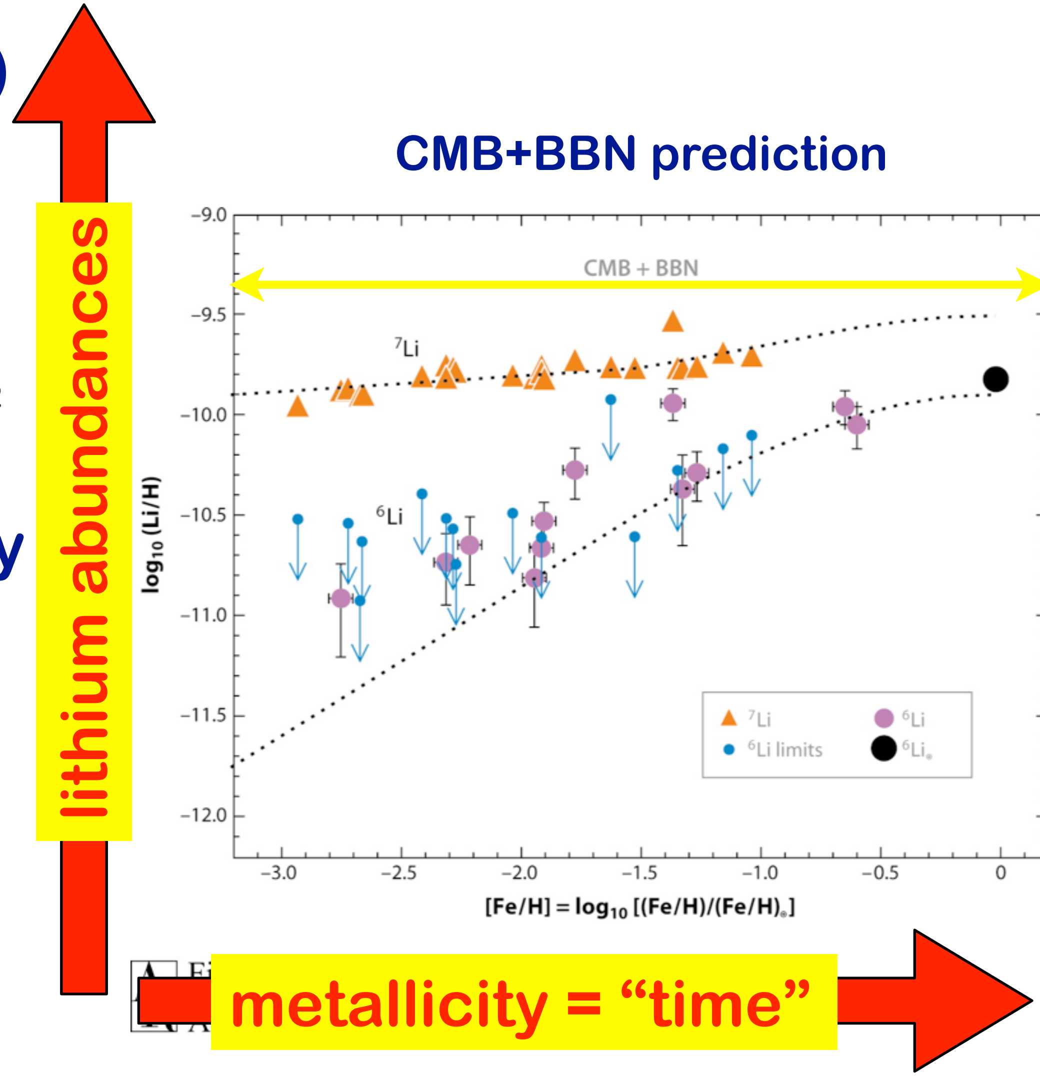
**But is the plateau at $Li_p$?**

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



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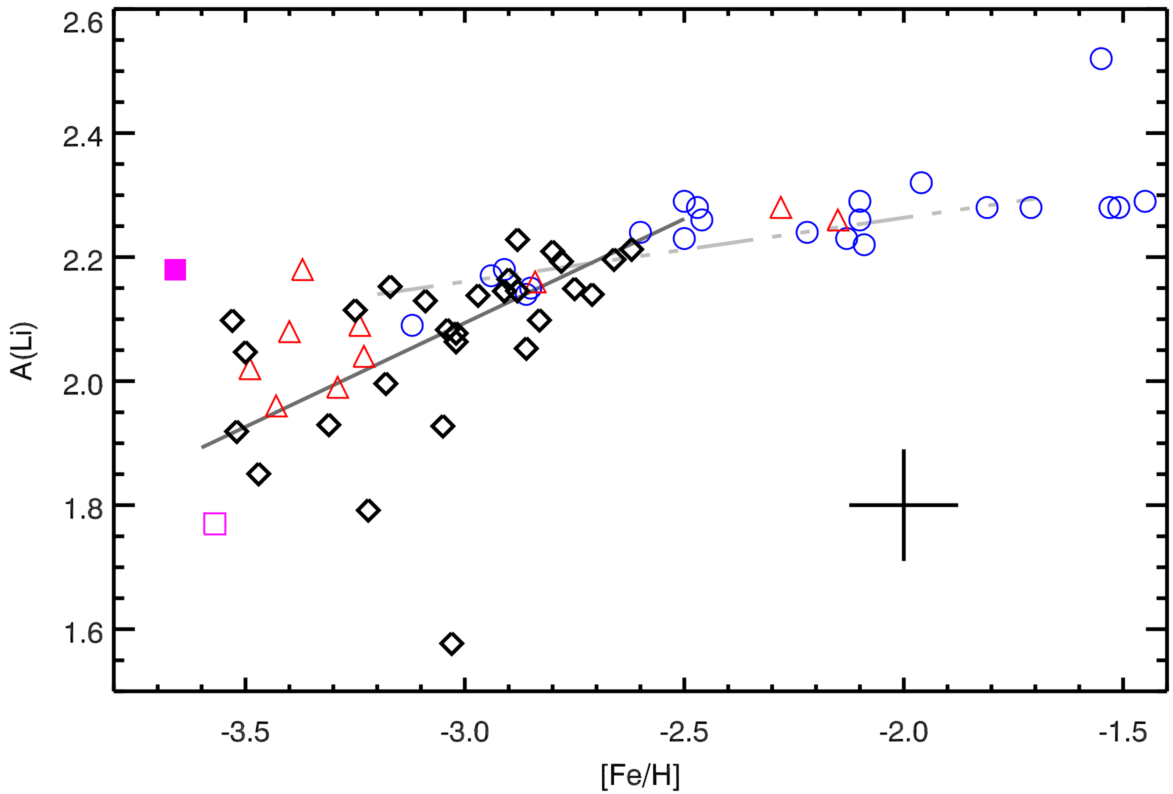
Sbordone+ 2010



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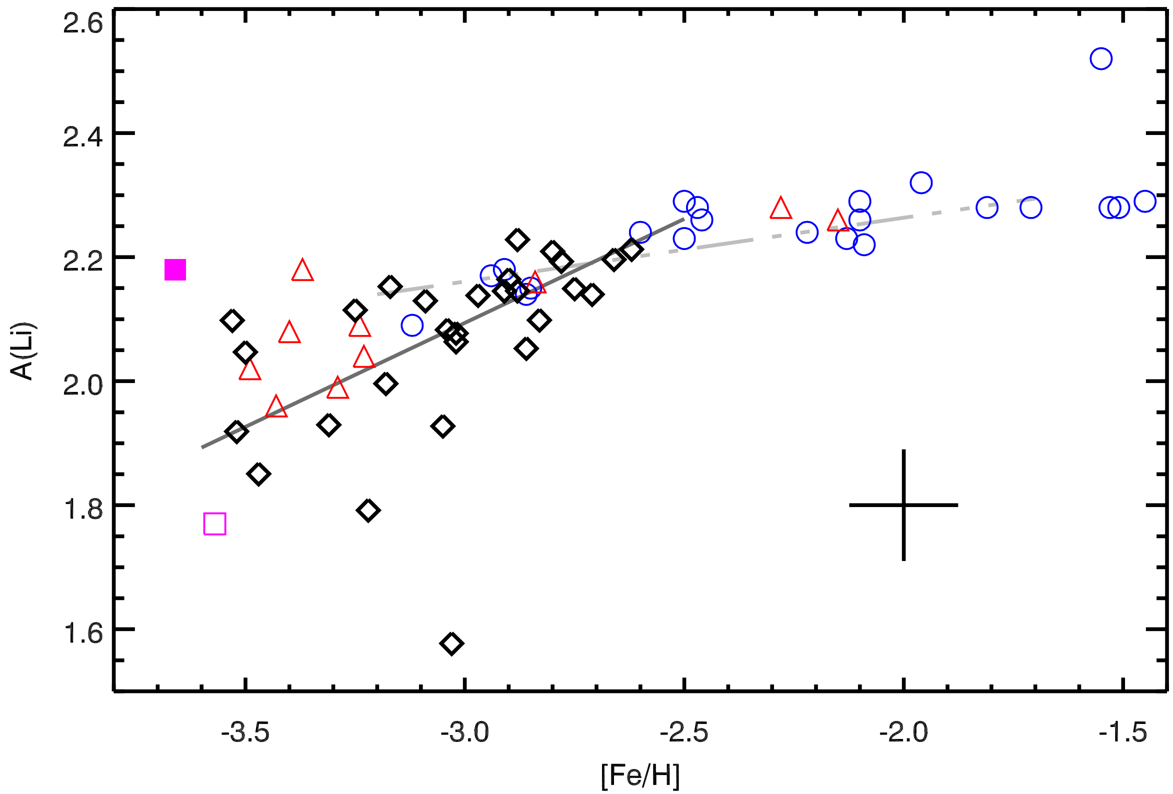

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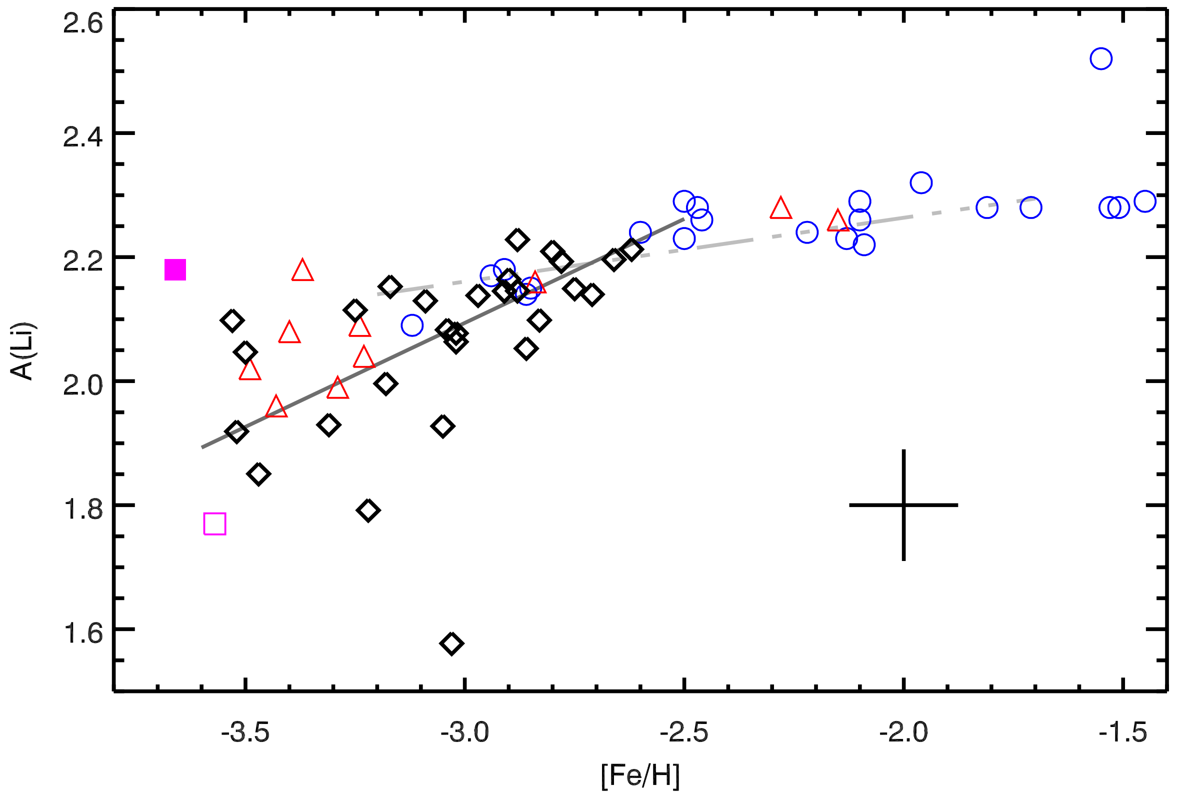

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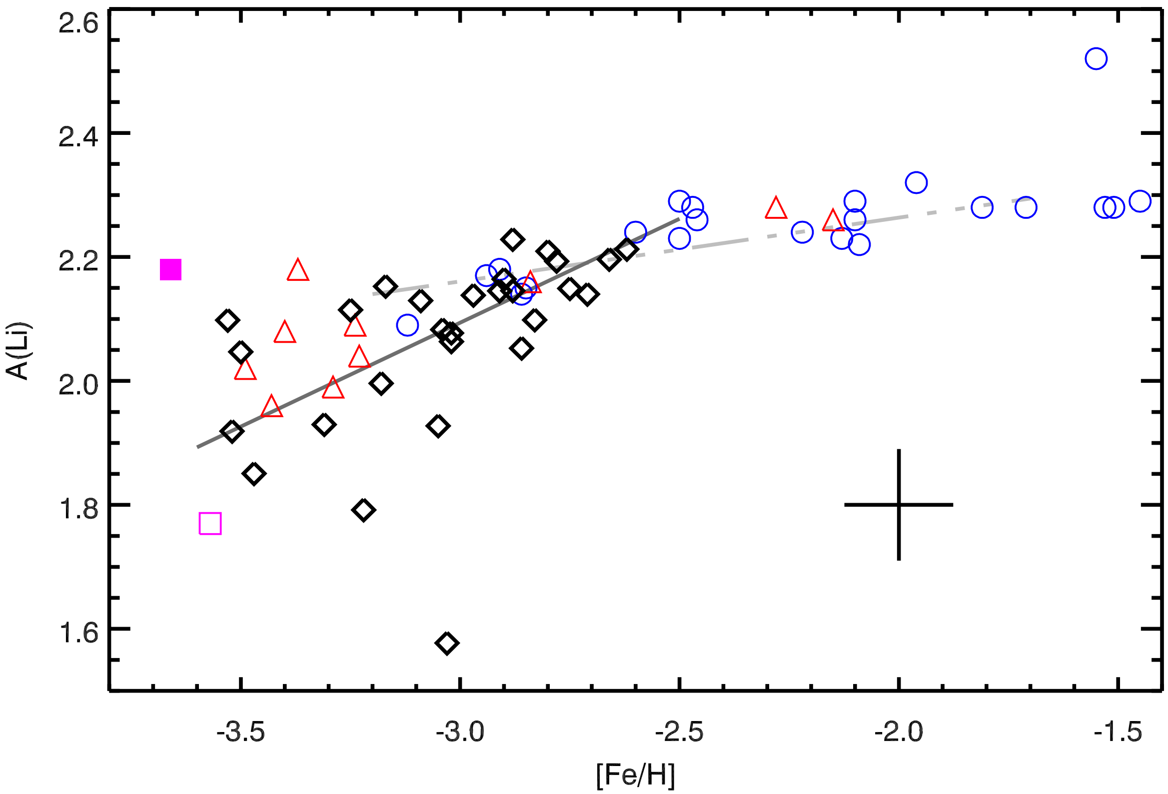

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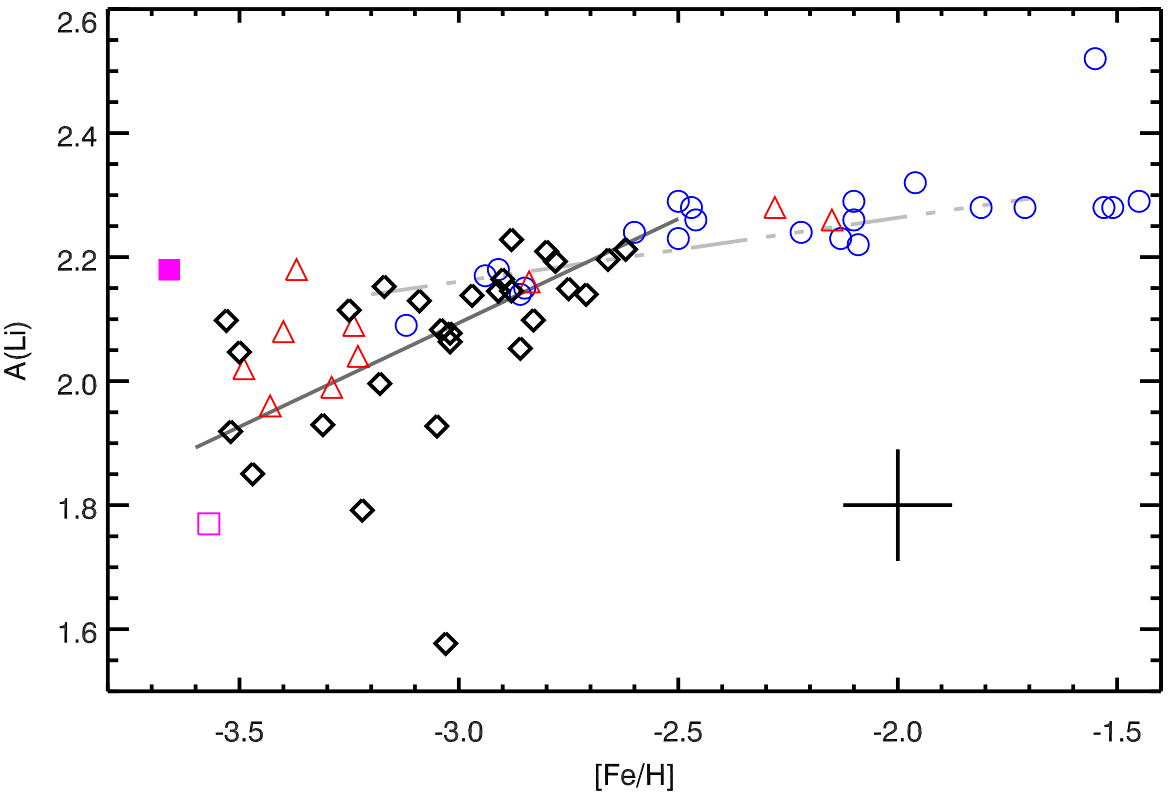

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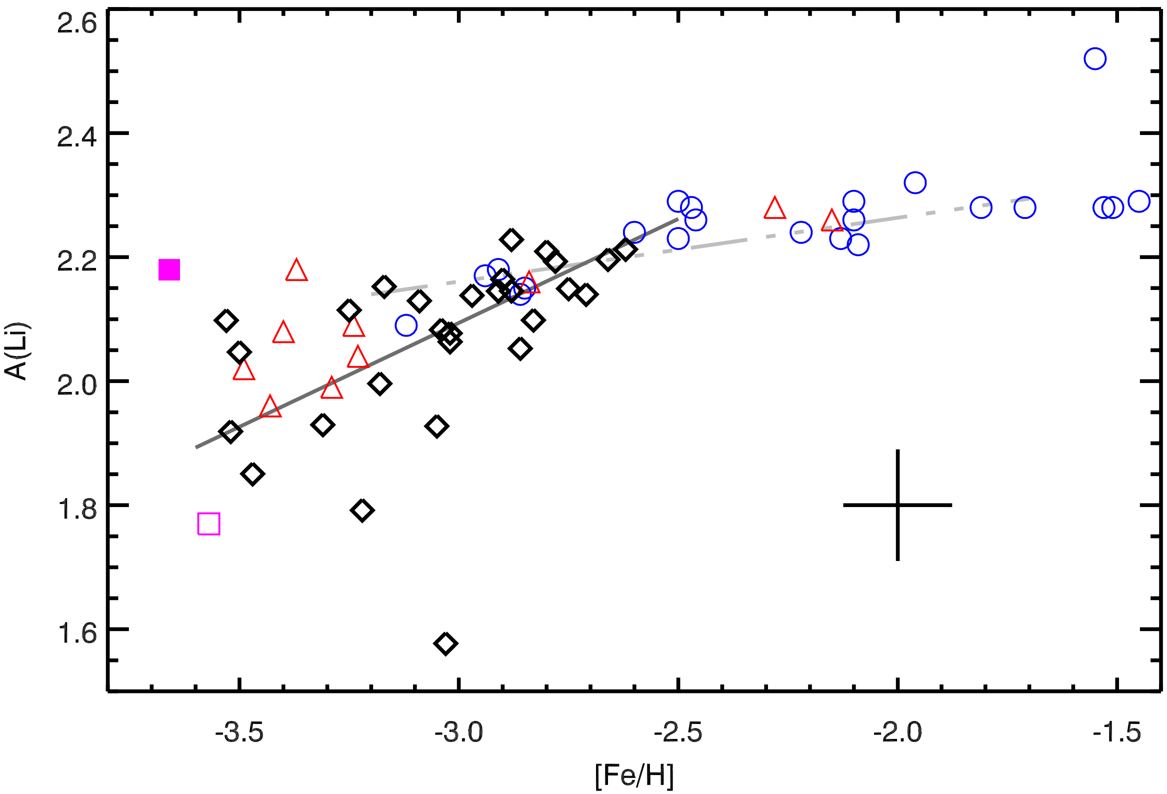

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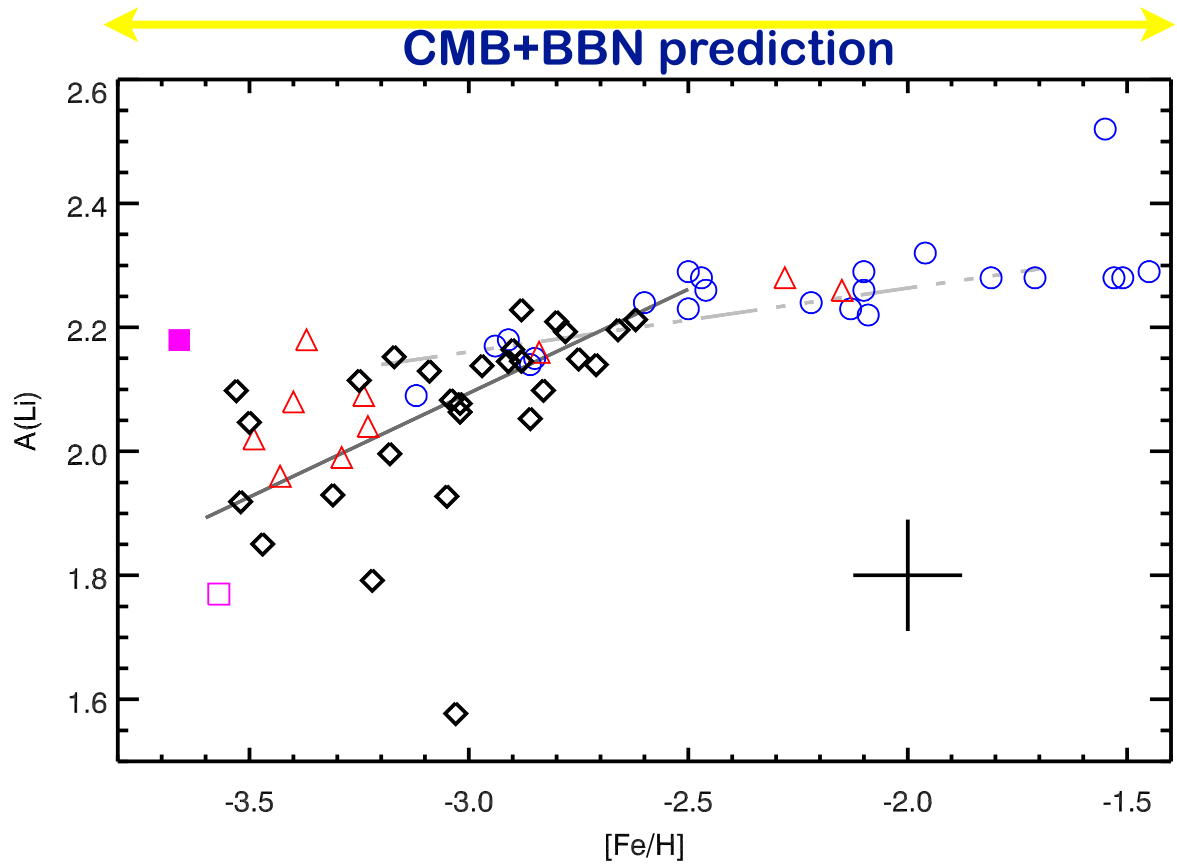

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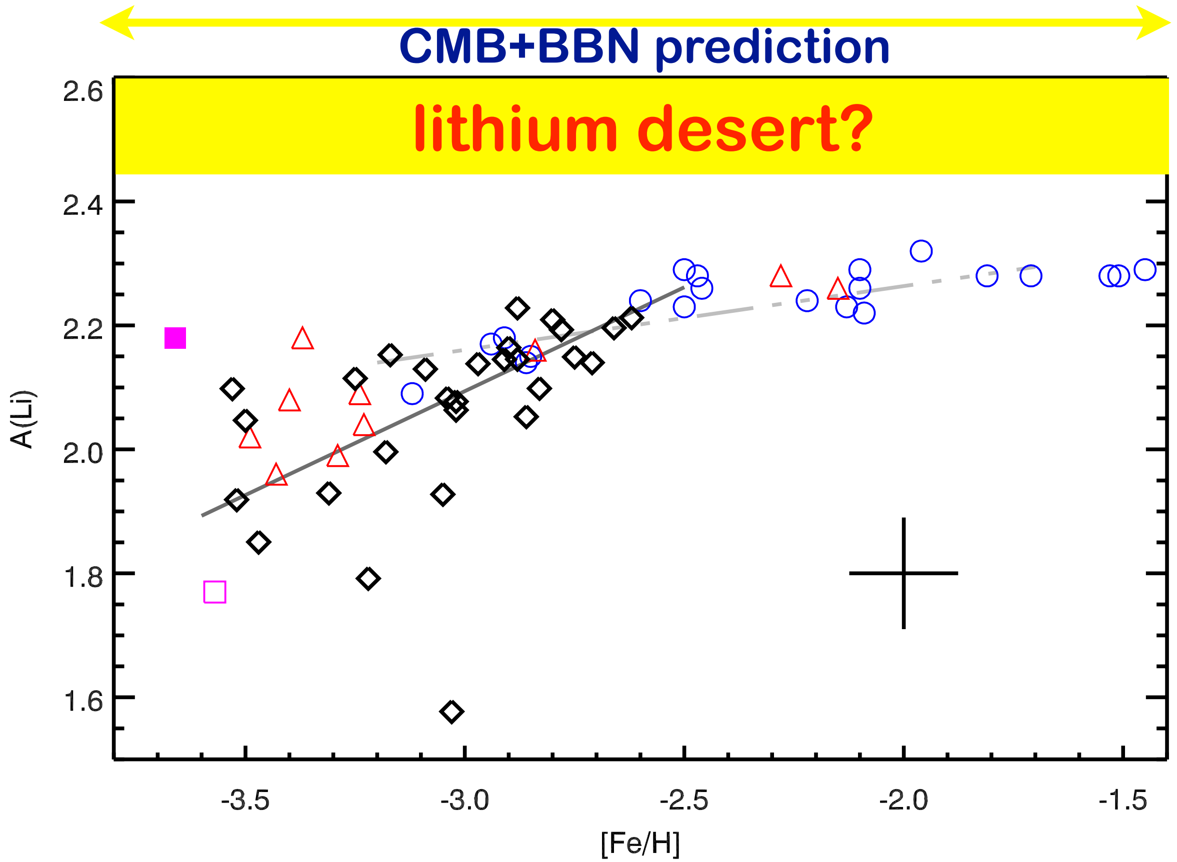

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## A Resonatingly Pretty Solution to Lithium?

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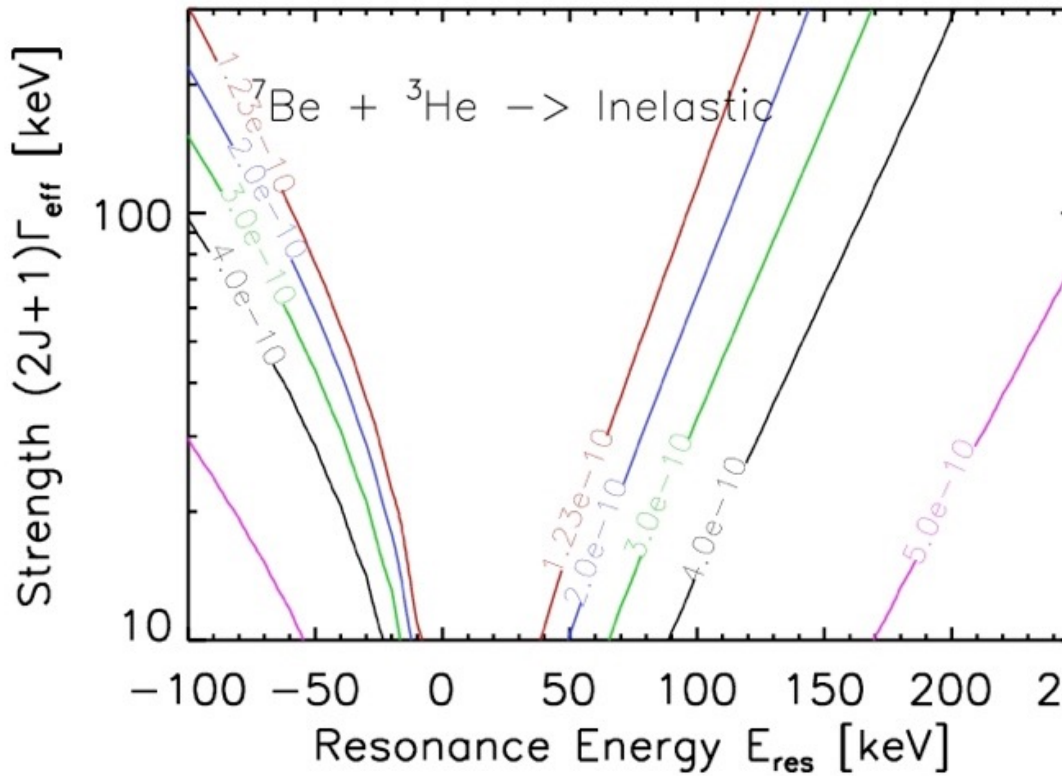

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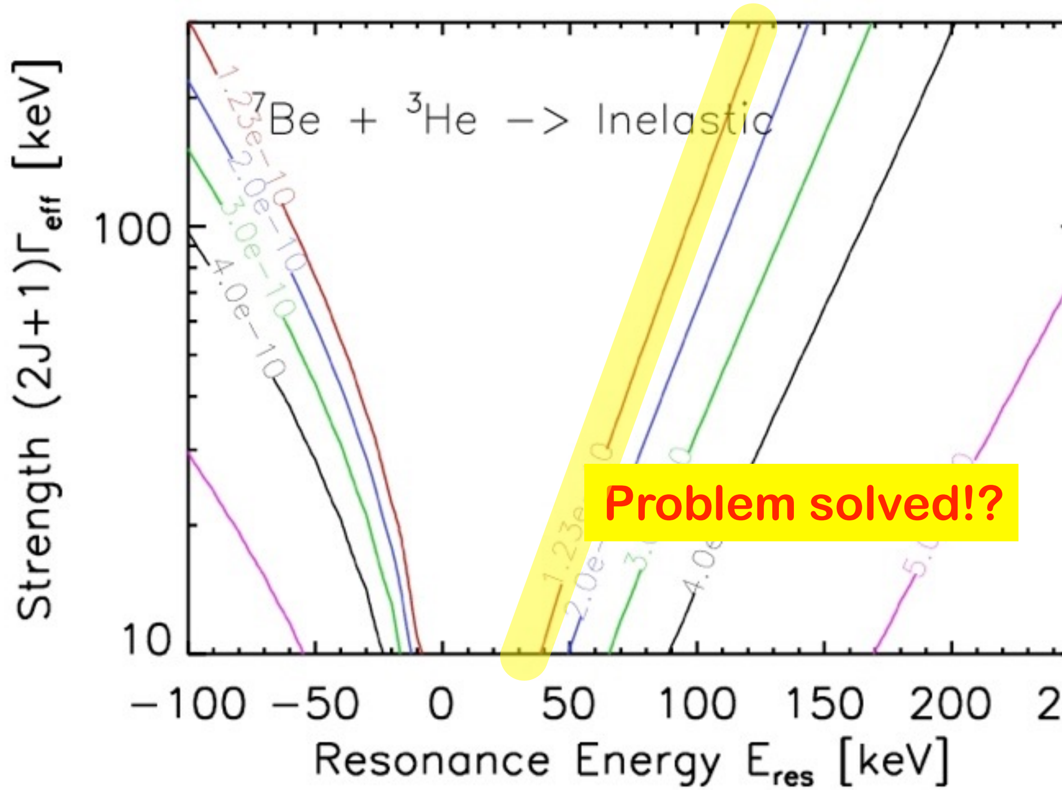

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**Experiment Says:**

**Not there!**

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

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

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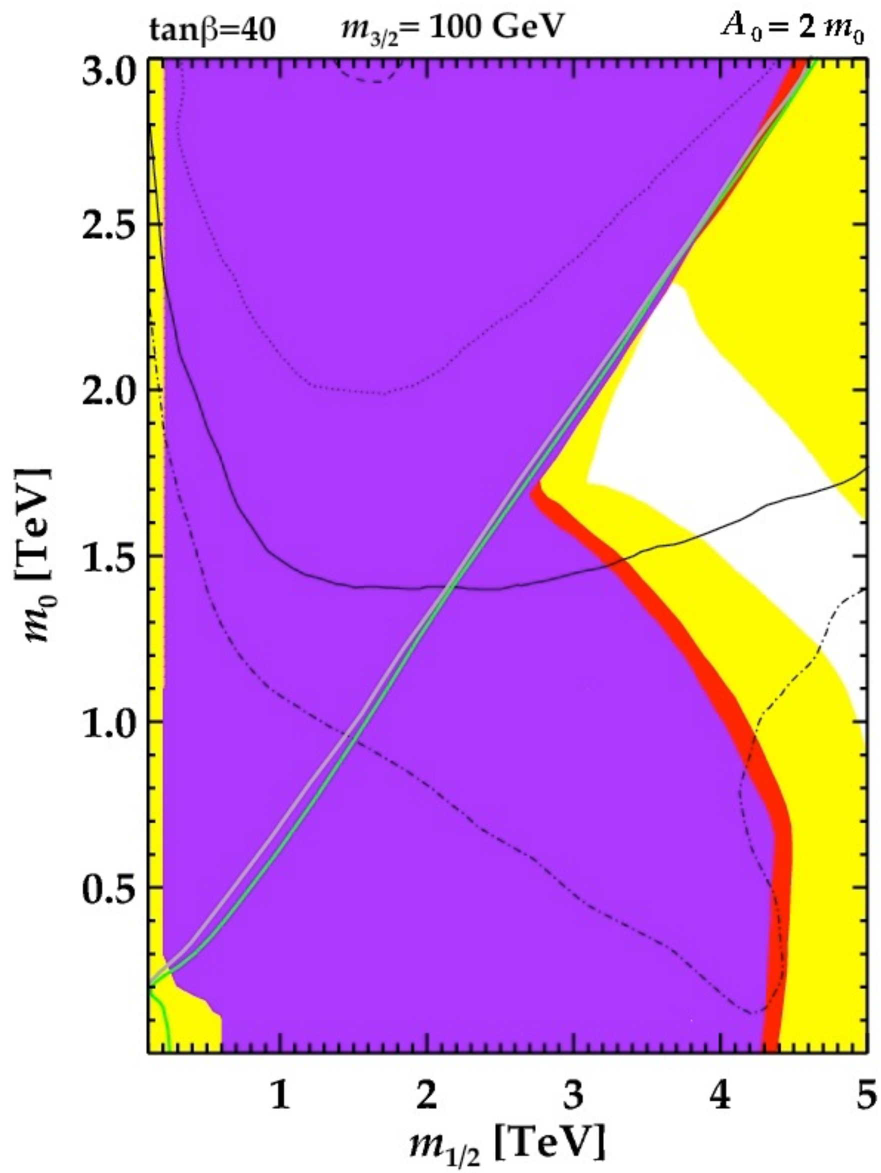
If

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

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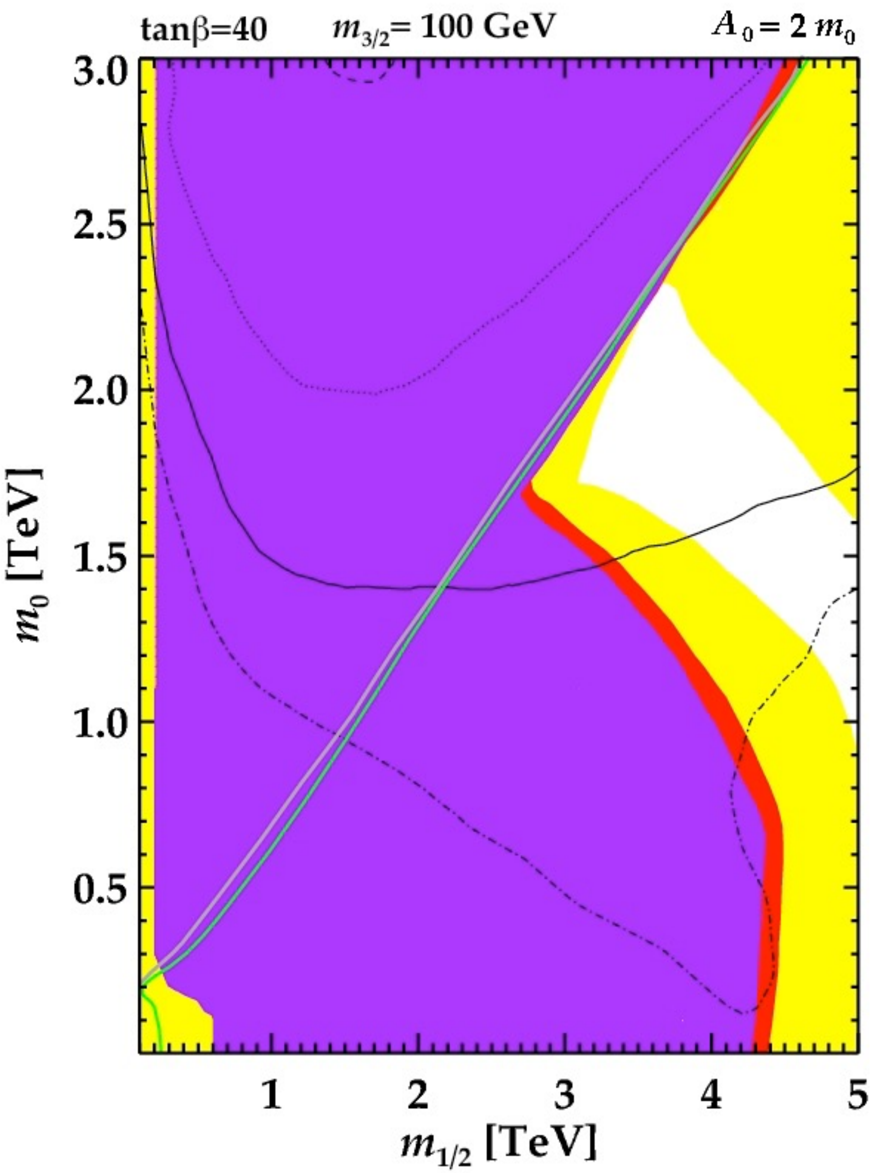


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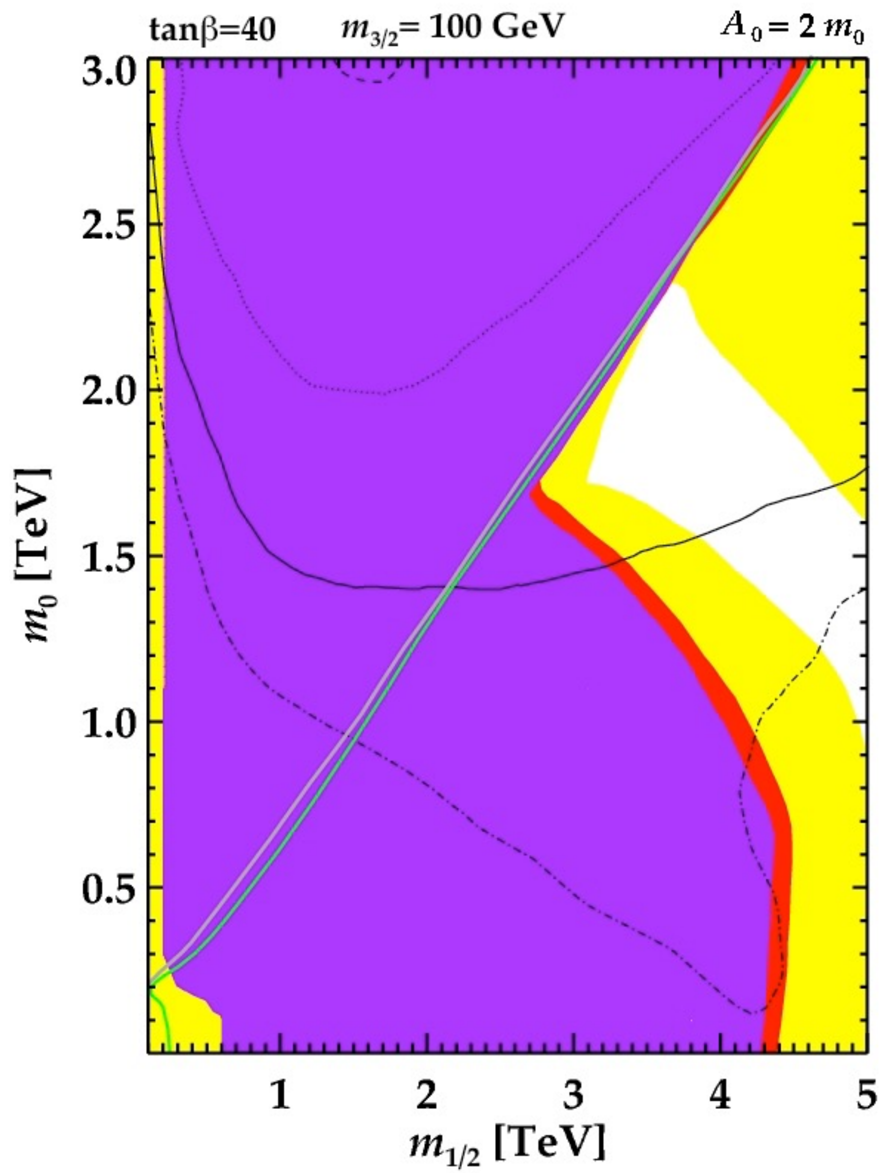


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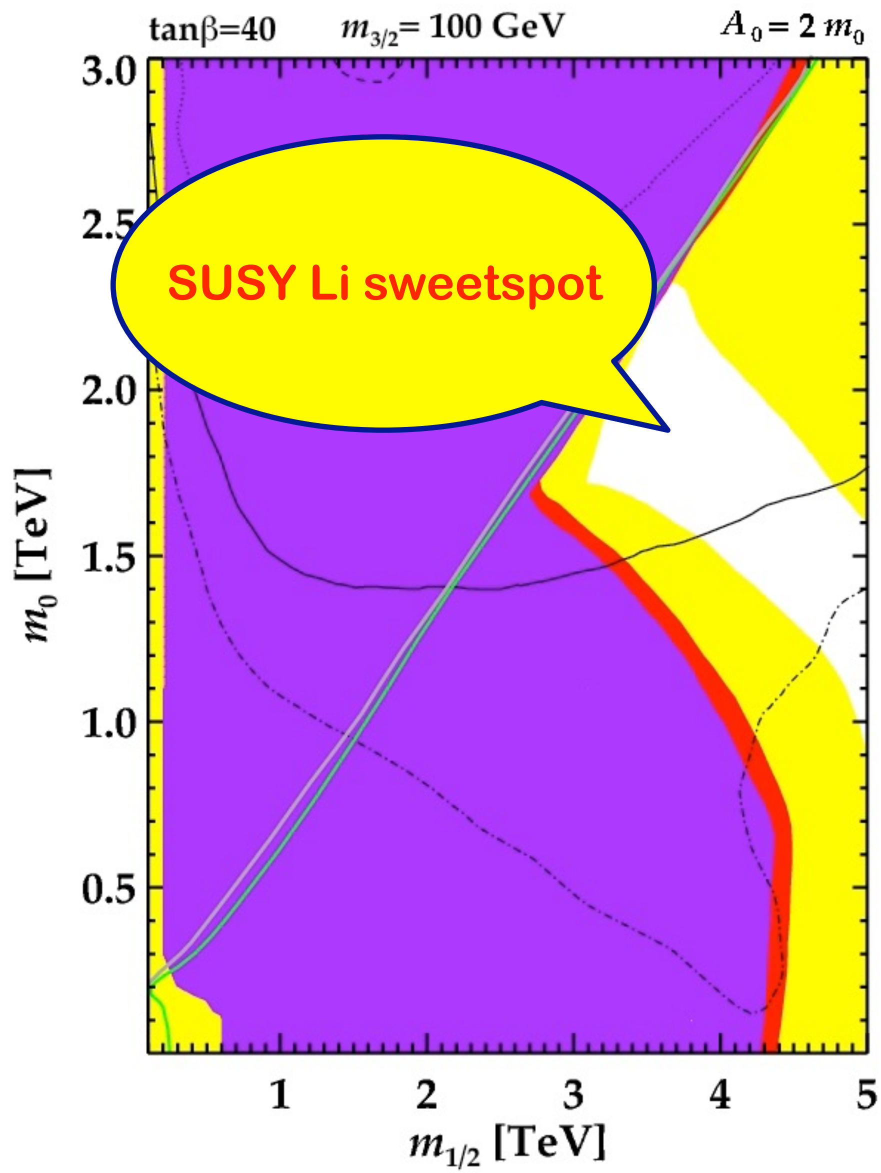


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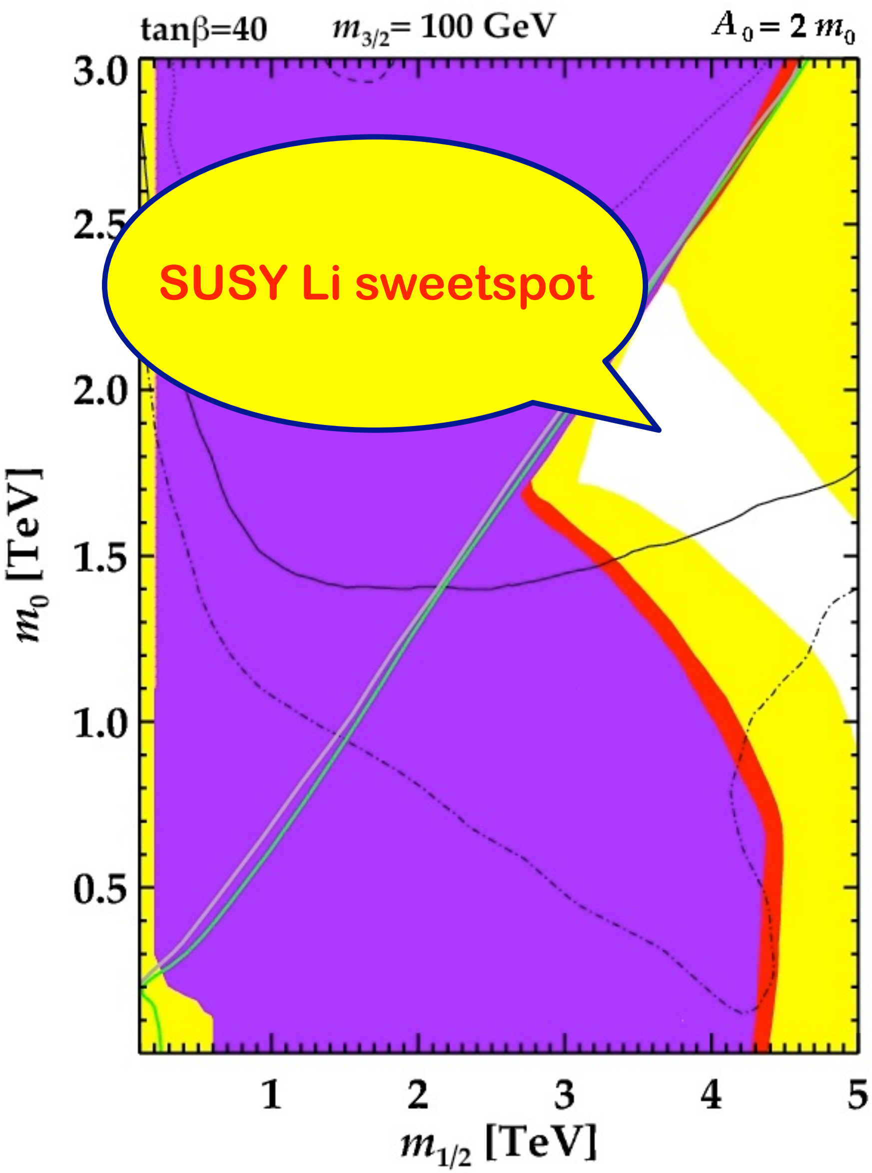


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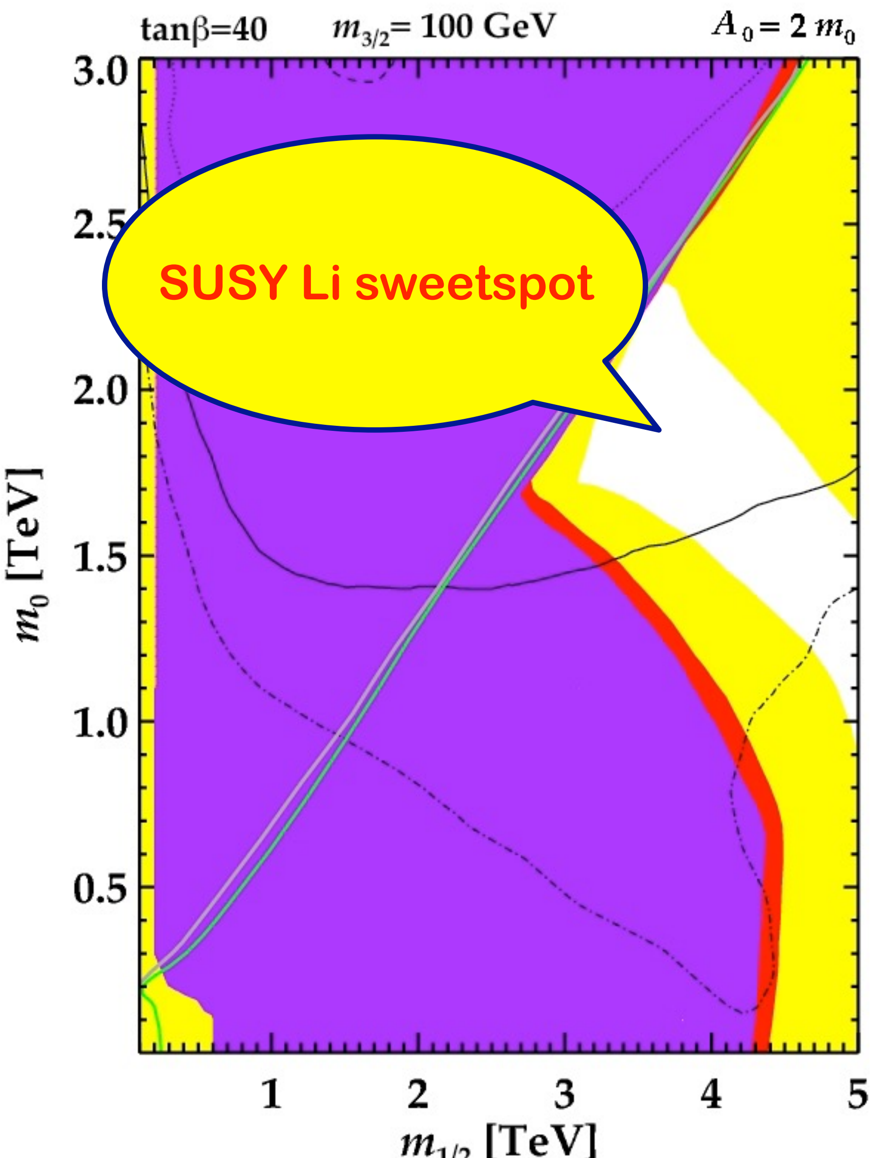


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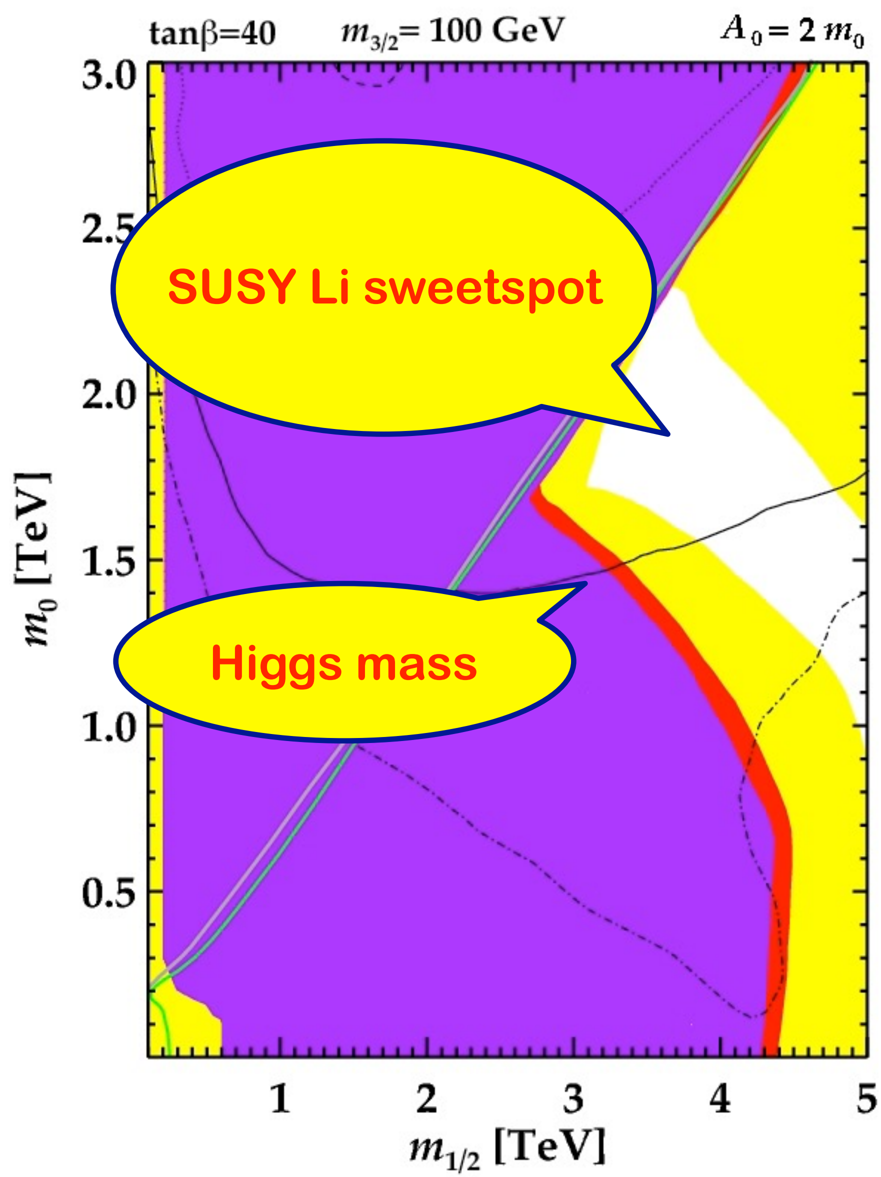
New D/H removes much solution space

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

- ✓ rule out large regions of parameter space

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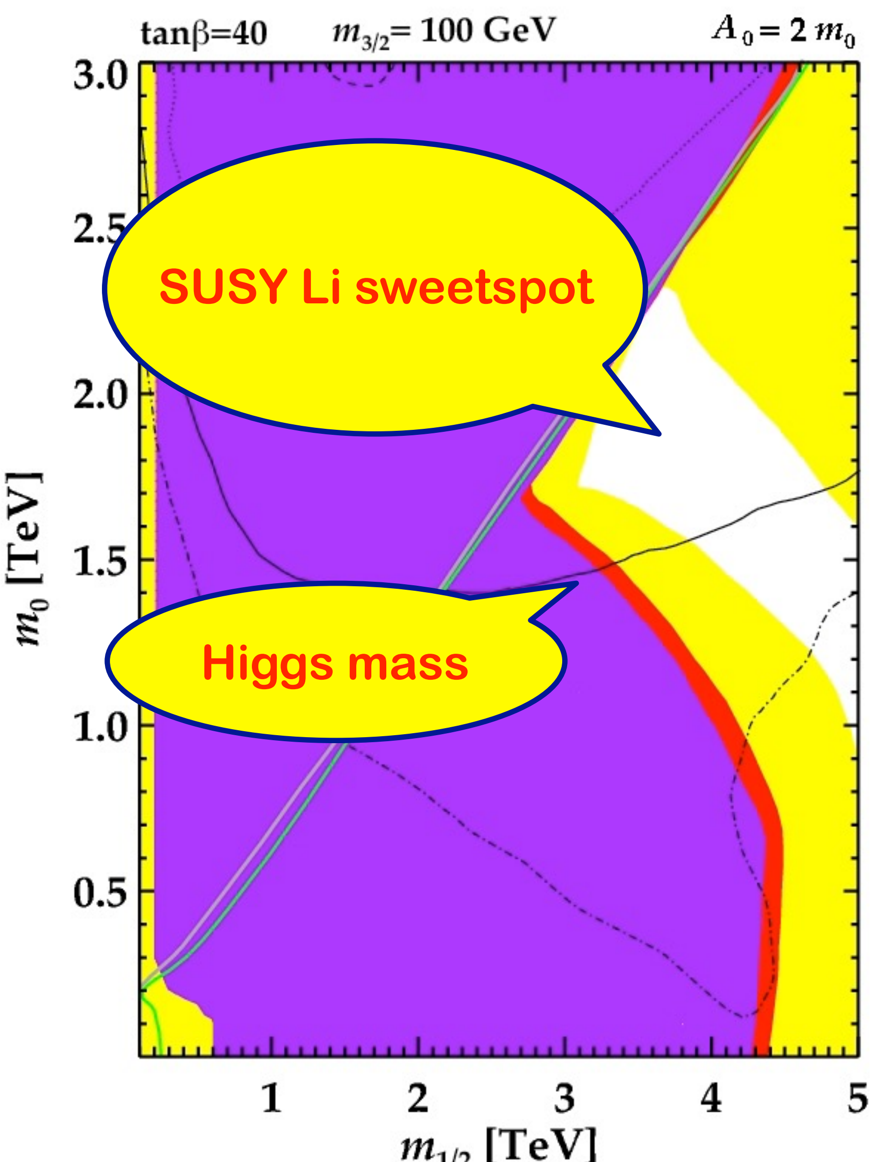



Cyburt, Ellis, BDF, Luo, Olive, Spanos 2012

# 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,

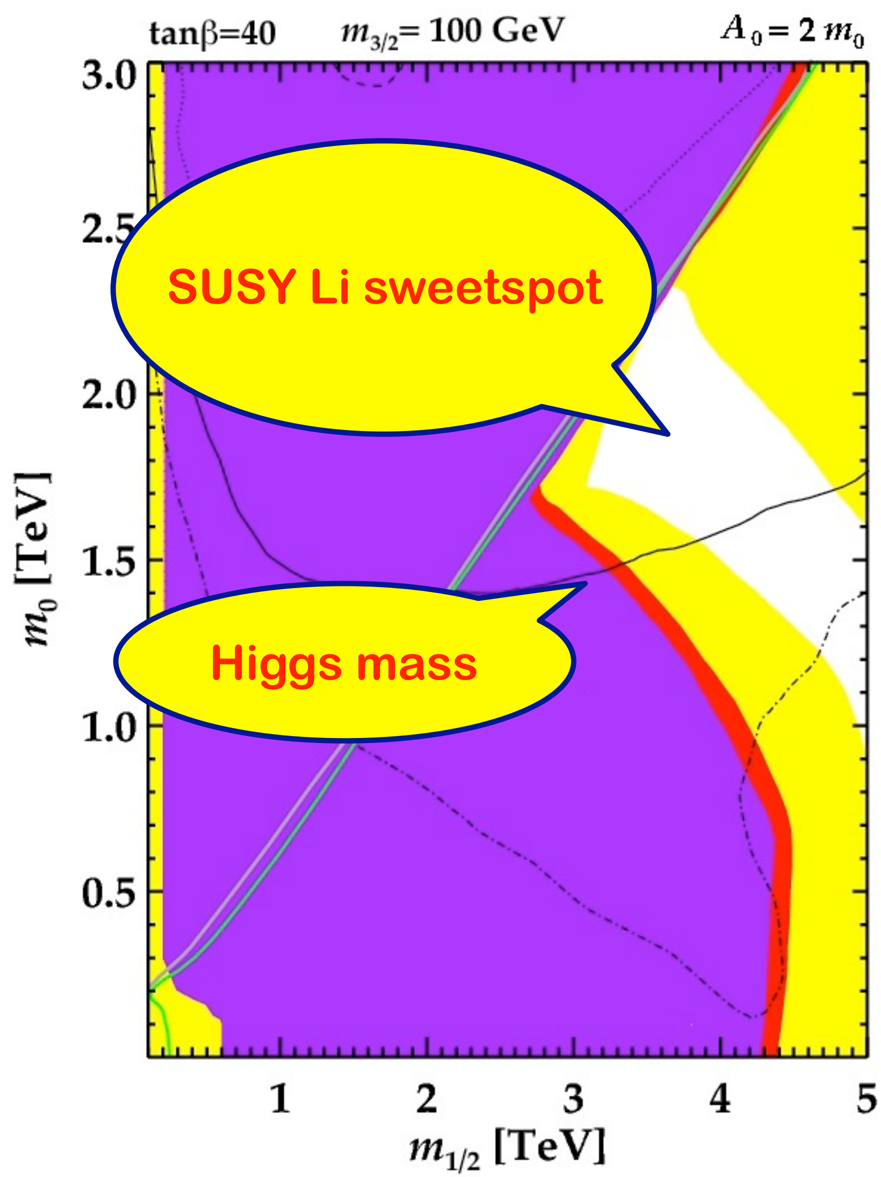
**A SUSY solution to lithium problems?**

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**

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## Convergence of Particle Physics and Cosmology

- successes of both point to larger, deeper picture
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## The Lithium Problem: Planck+BBN >> $Li_{obs}$

- problem has worsened since WMAP 2003
- astrophysics solutions possible but highly constrained
- interstellar lithium as a new way forward?
- nuclear physics solutions all but ruled out
- new physics: SUSY?

**The Truth is out there--stay tuned for KeithFest 2022!**

# Director’s Cut Extras

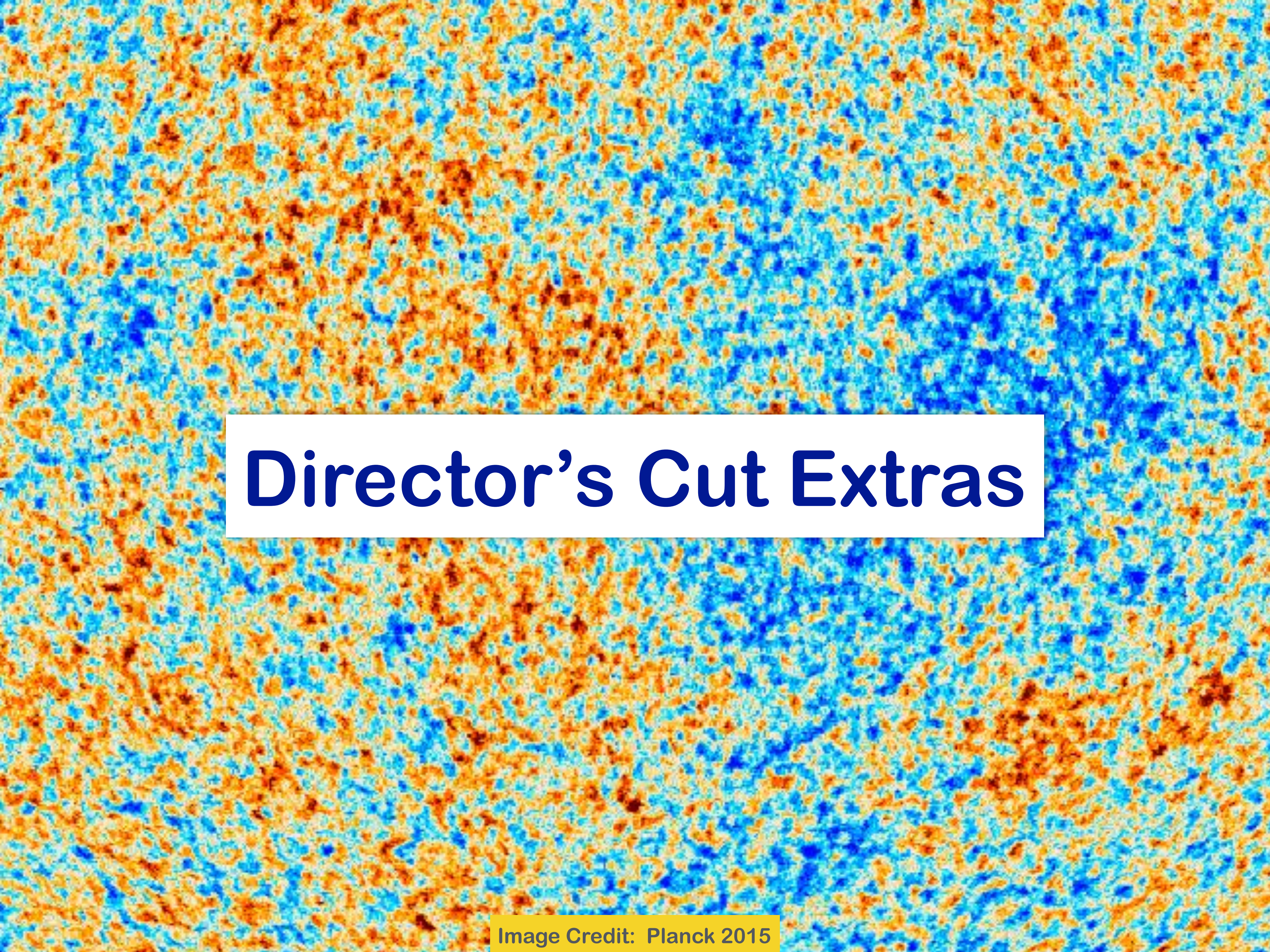

Image Credit: Planck 2015

# Lithium Problem: Conventional Solutions

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**Scenario:**

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

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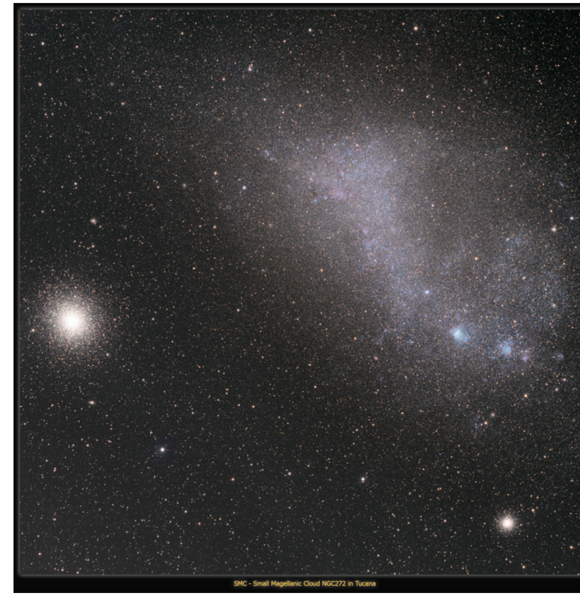


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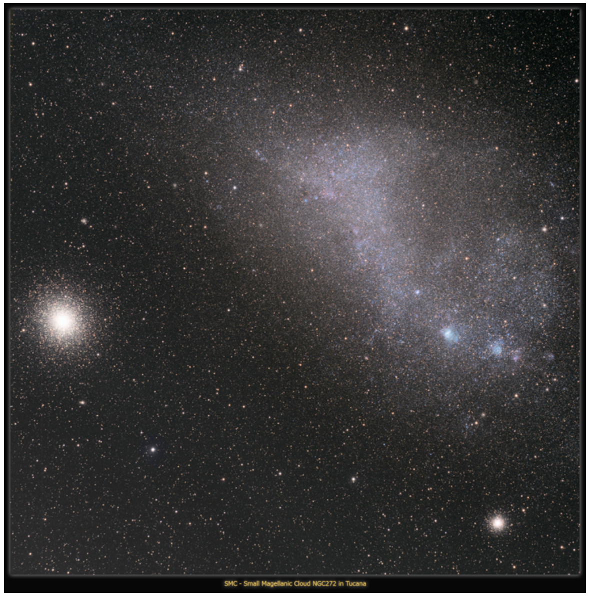


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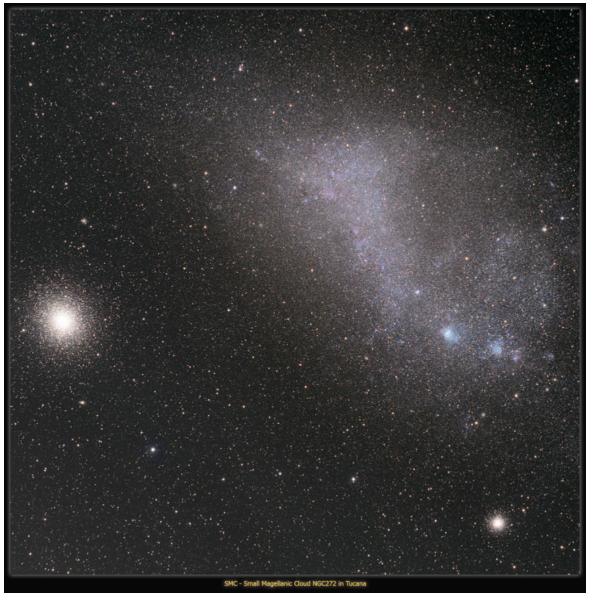


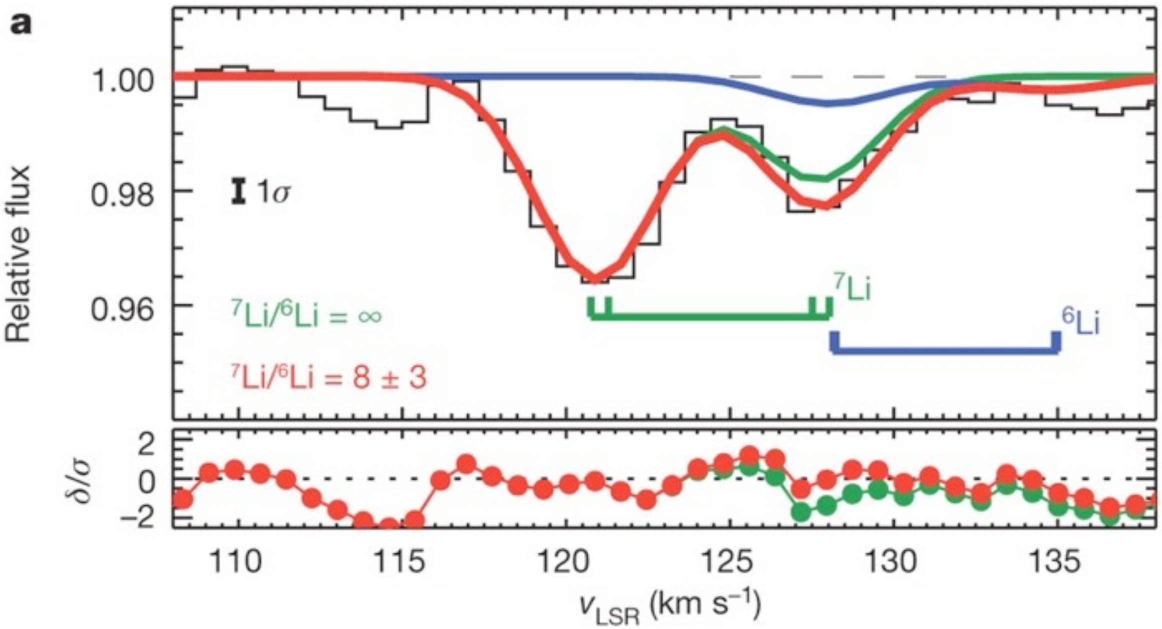


Howk, Lehner, BDF, & Mathews 2013

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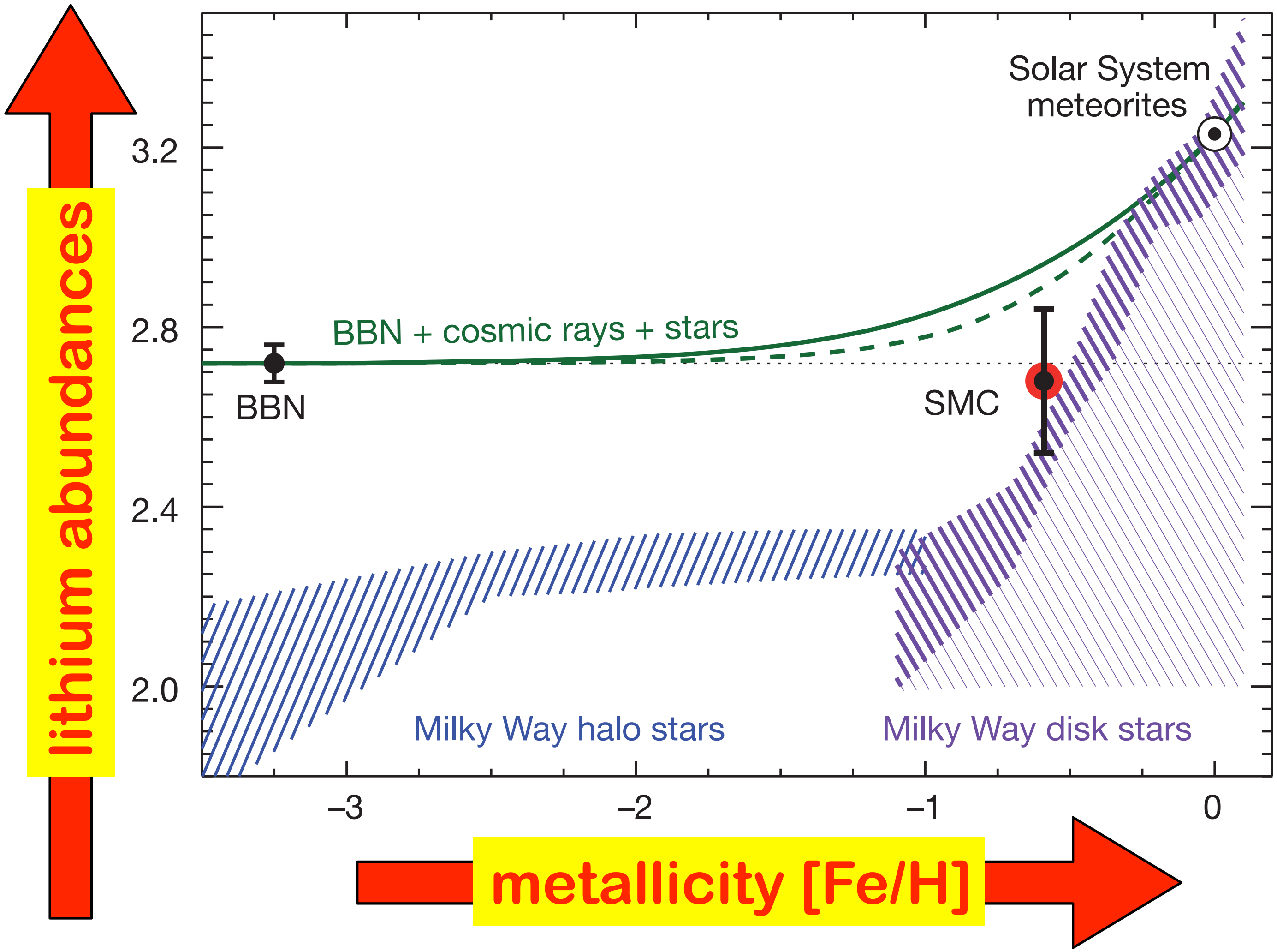


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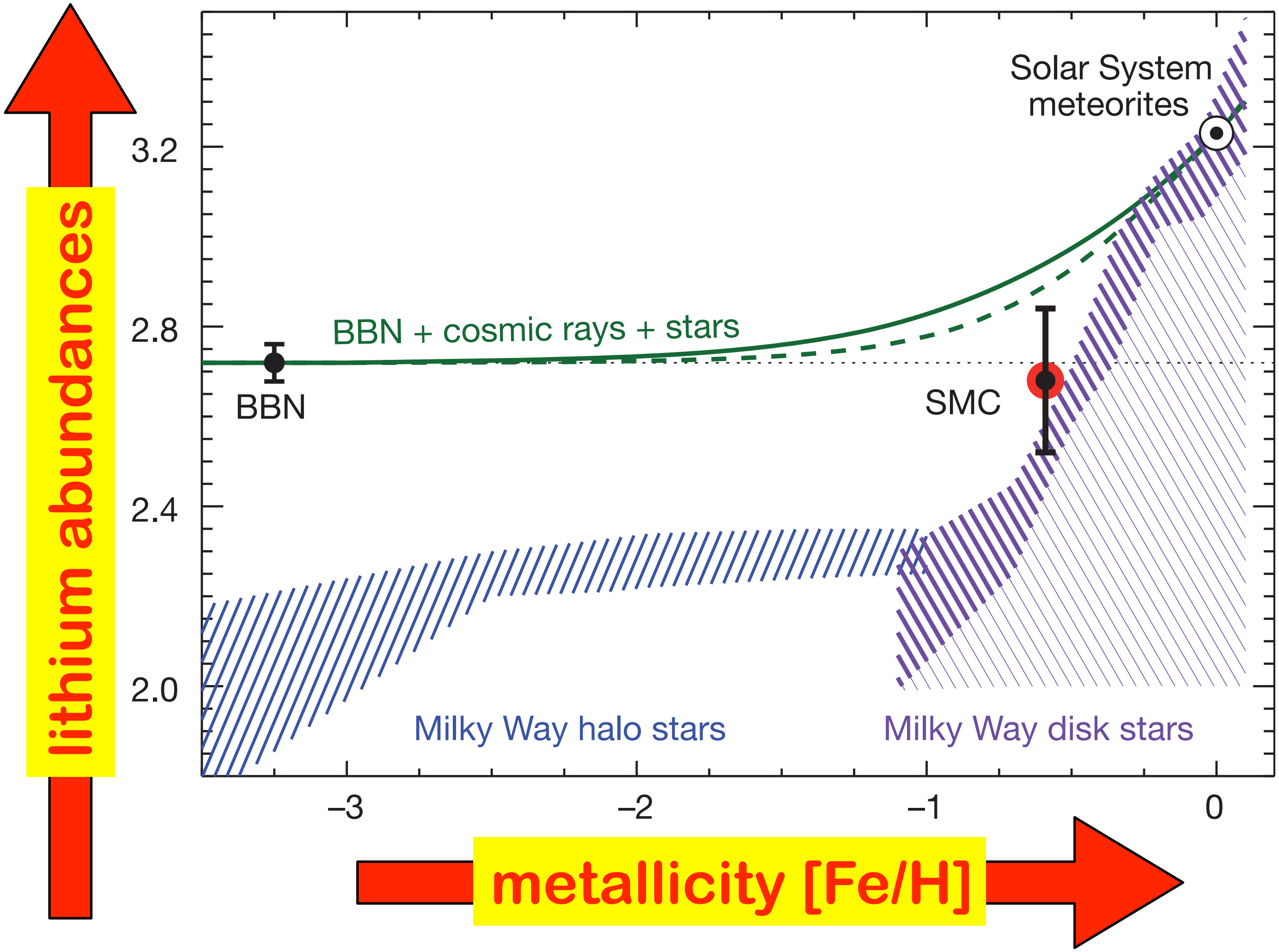


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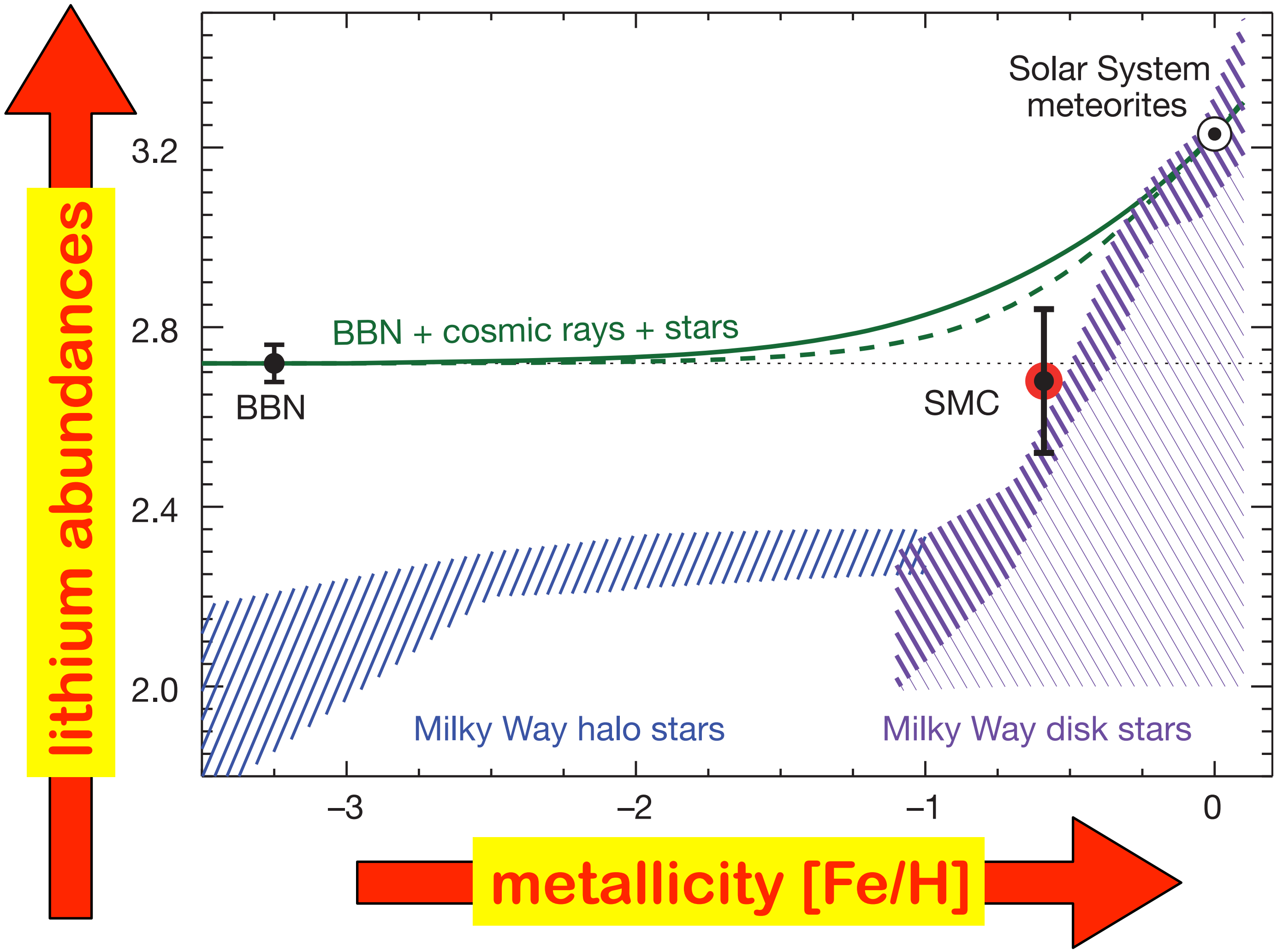


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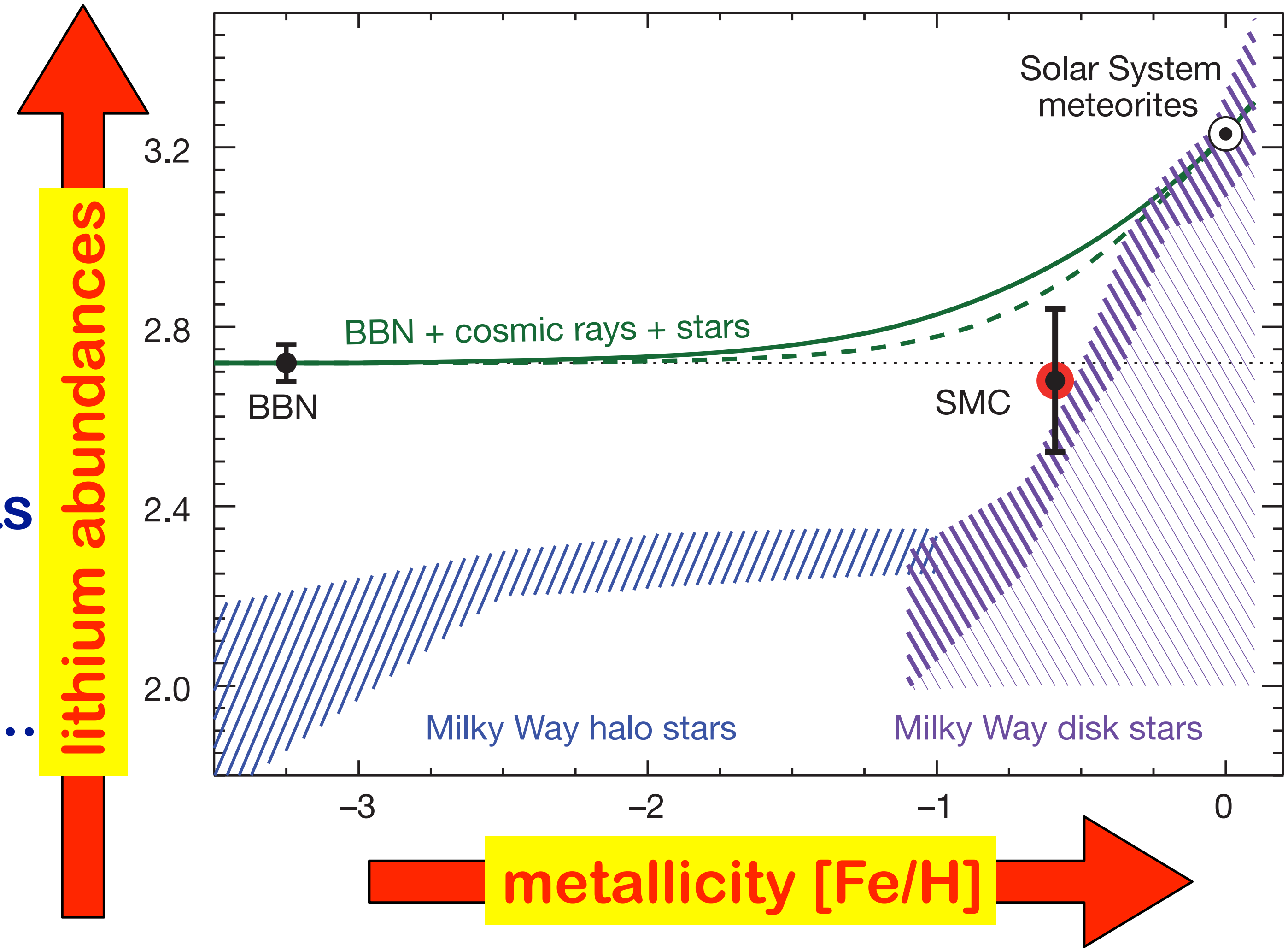


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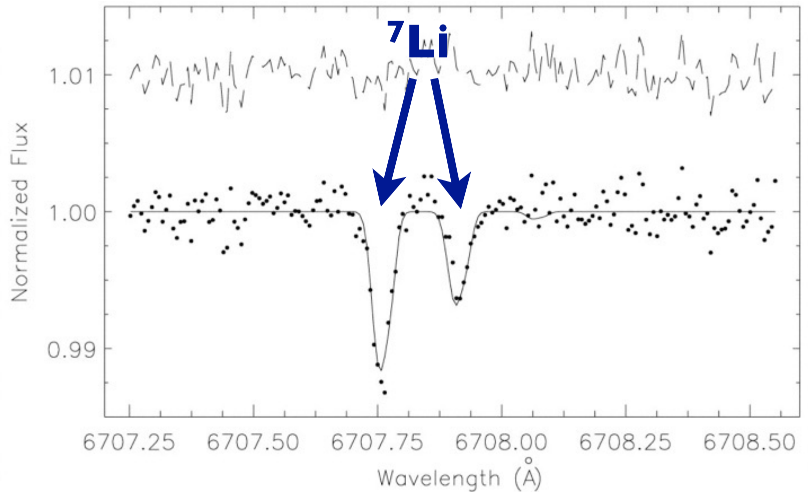

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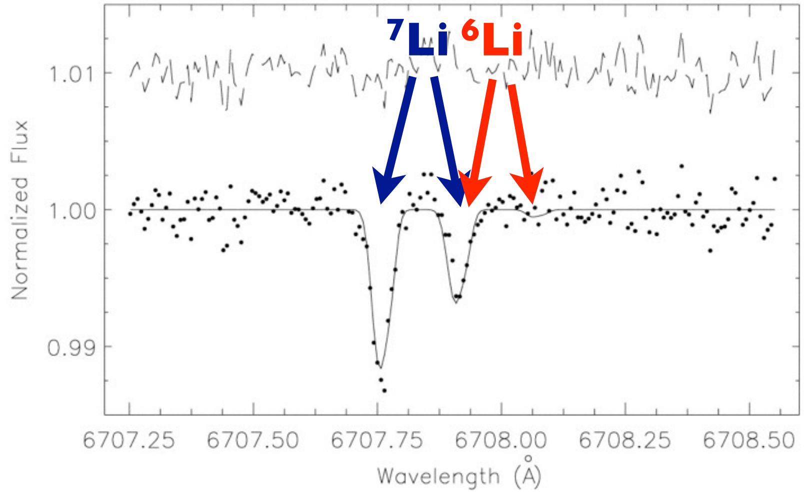

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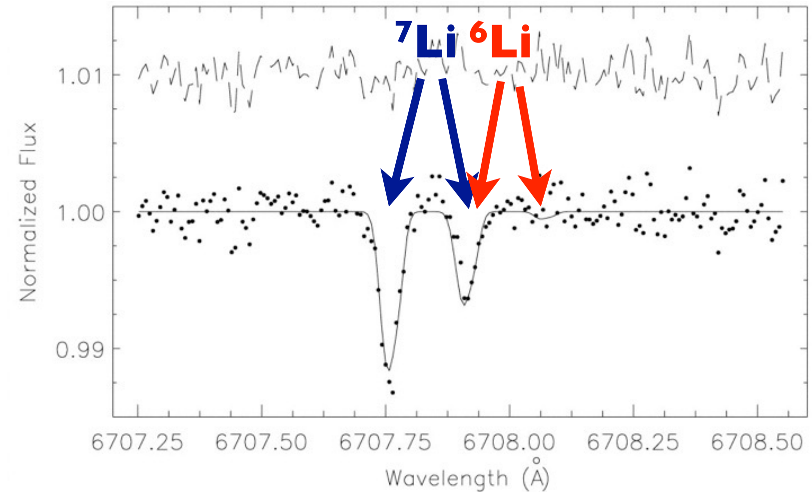


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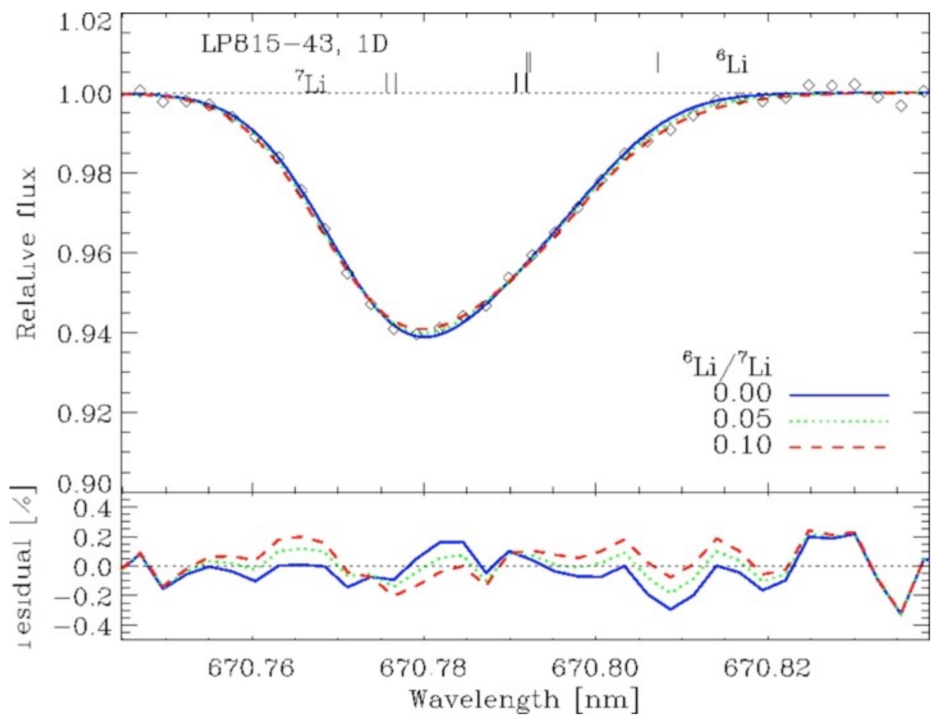

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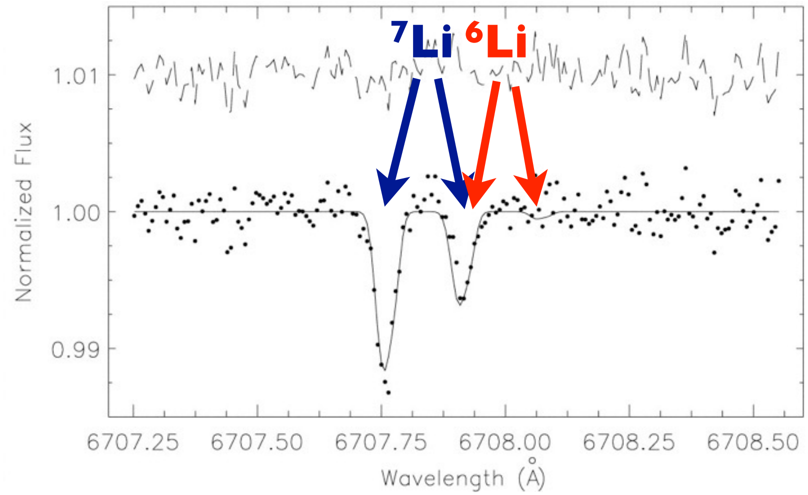


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high resolution stellar spectra:

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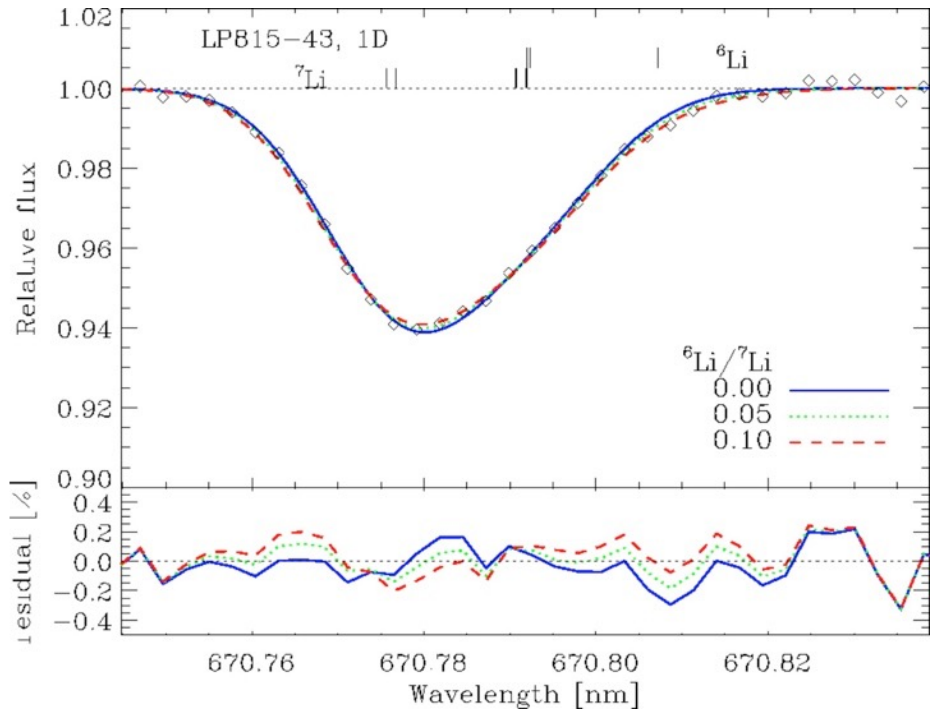

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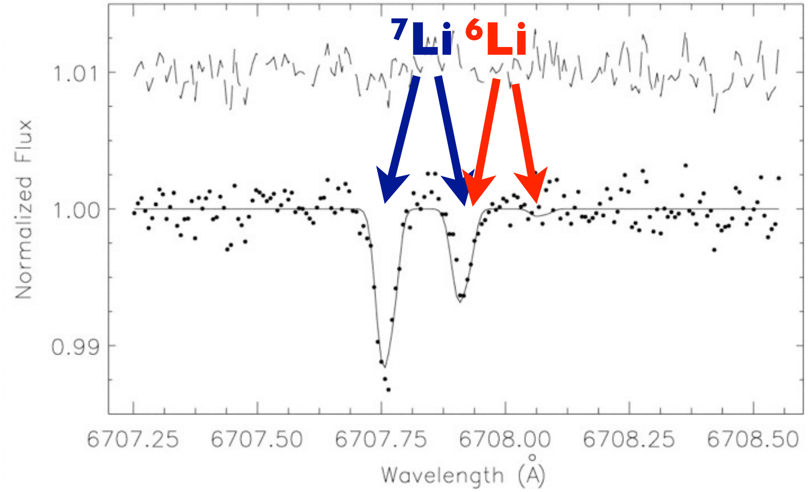


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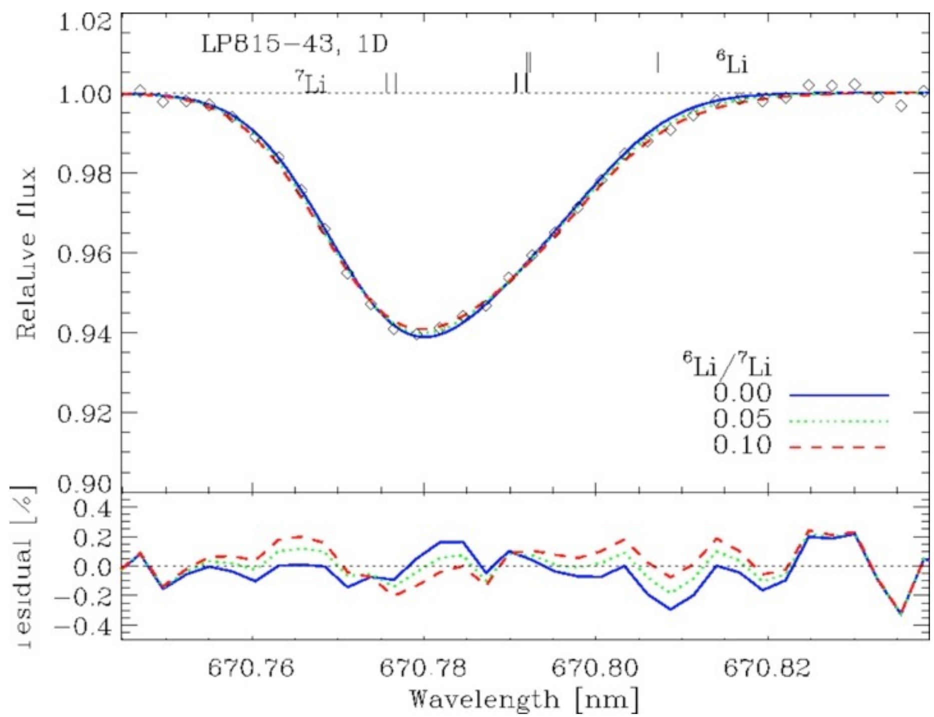
ultra-high resolution stellar spectra Smith Lambert Nissen; Asplund et al

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



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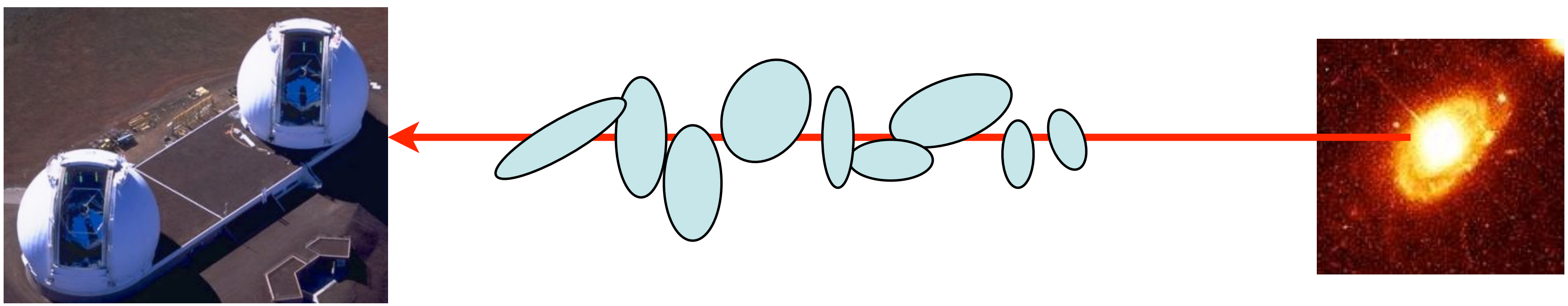

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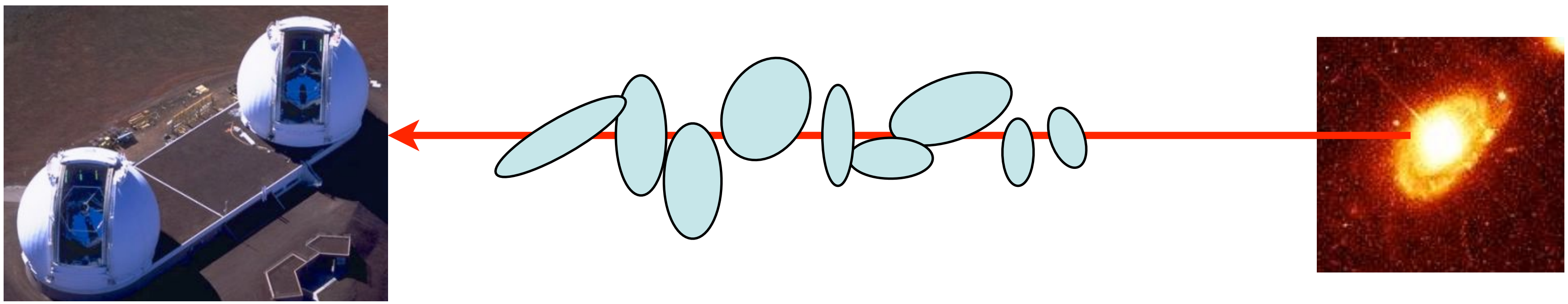
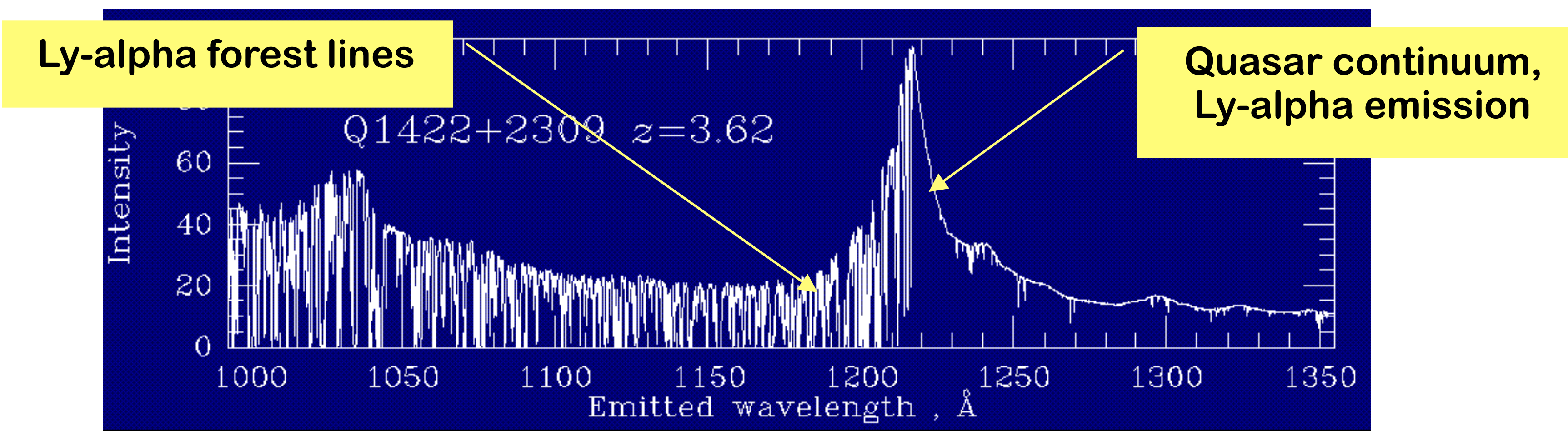
- Observed spectrum:  Ly-alpha "forest"





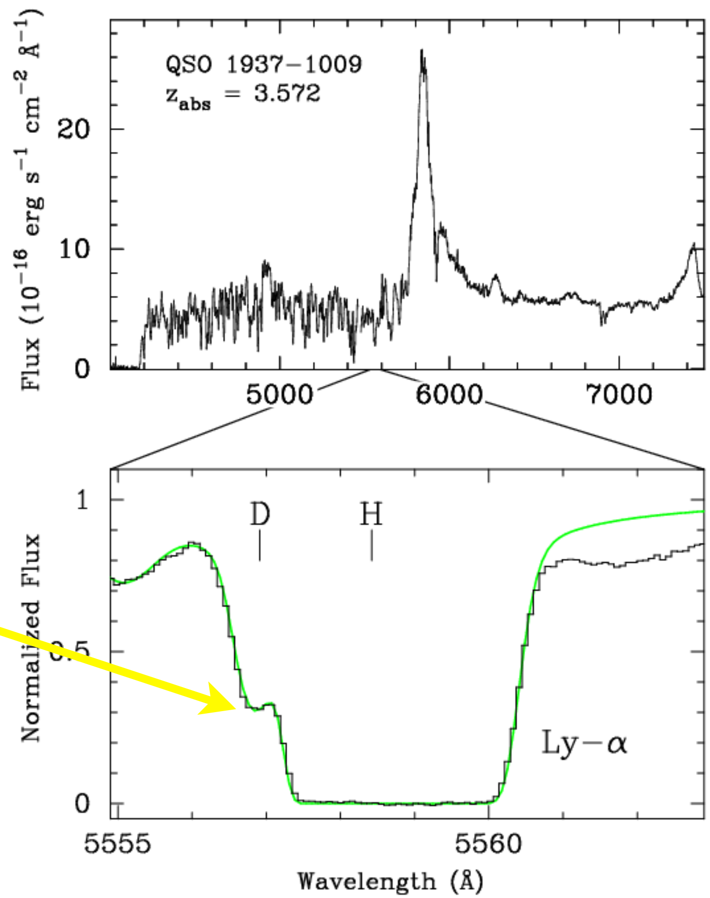
# Deuterium Data

**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: $\Omega_{\rm m} \simeq 0.3$

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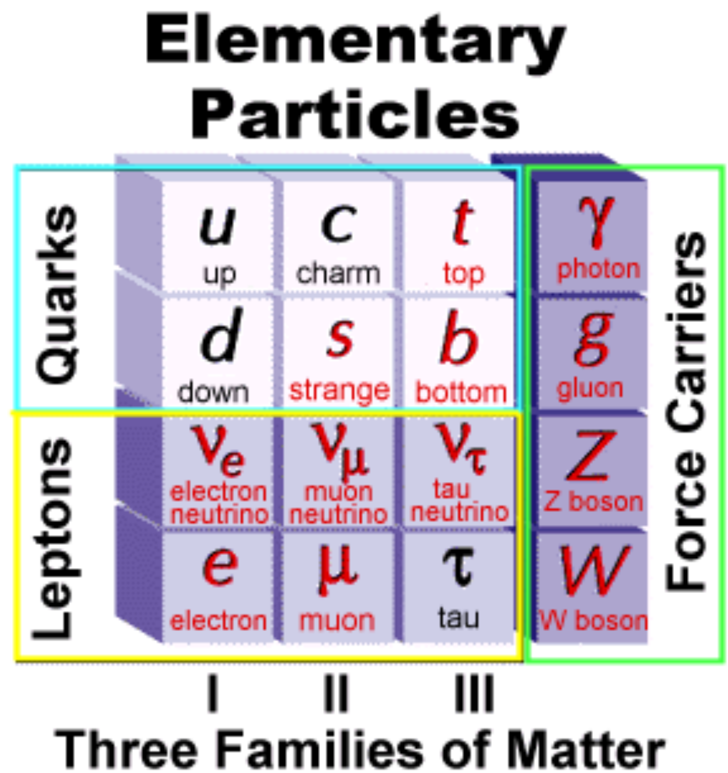
## Consult Standard Model

neutrinos very promising!

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



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**Neutrino densities today**

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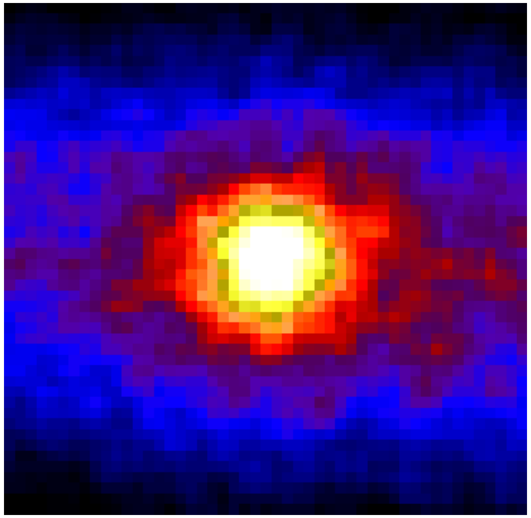

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SuperKamiokande

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mass differences (from oscillations)

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

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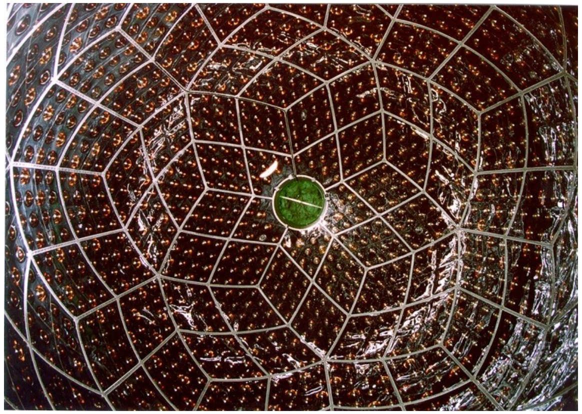

KamLAND Reactor Neutrino Detector

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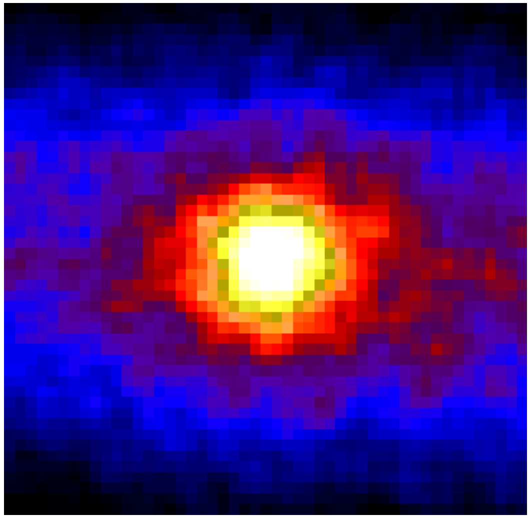
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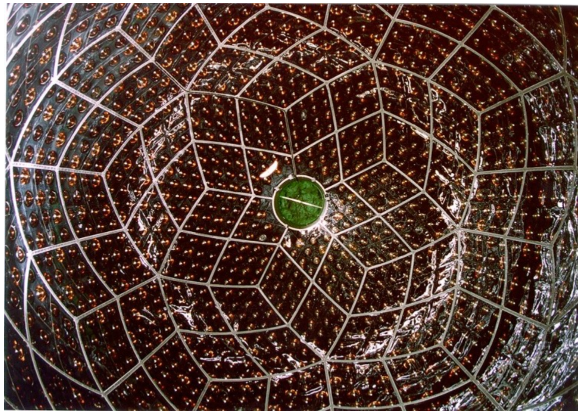
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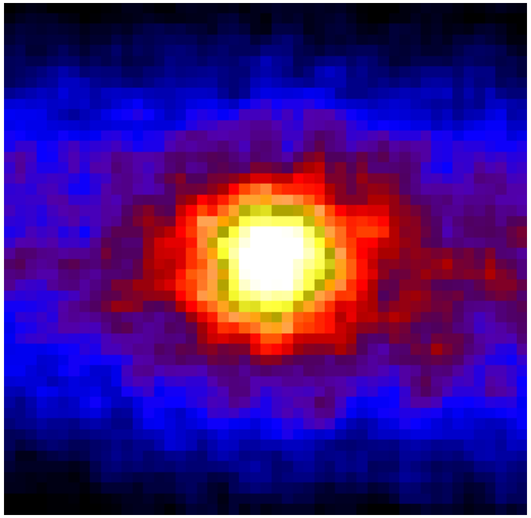

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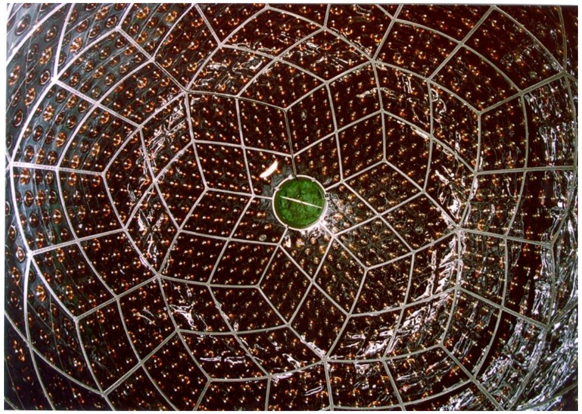
### Neutrinos are **not** the dark matter



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

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