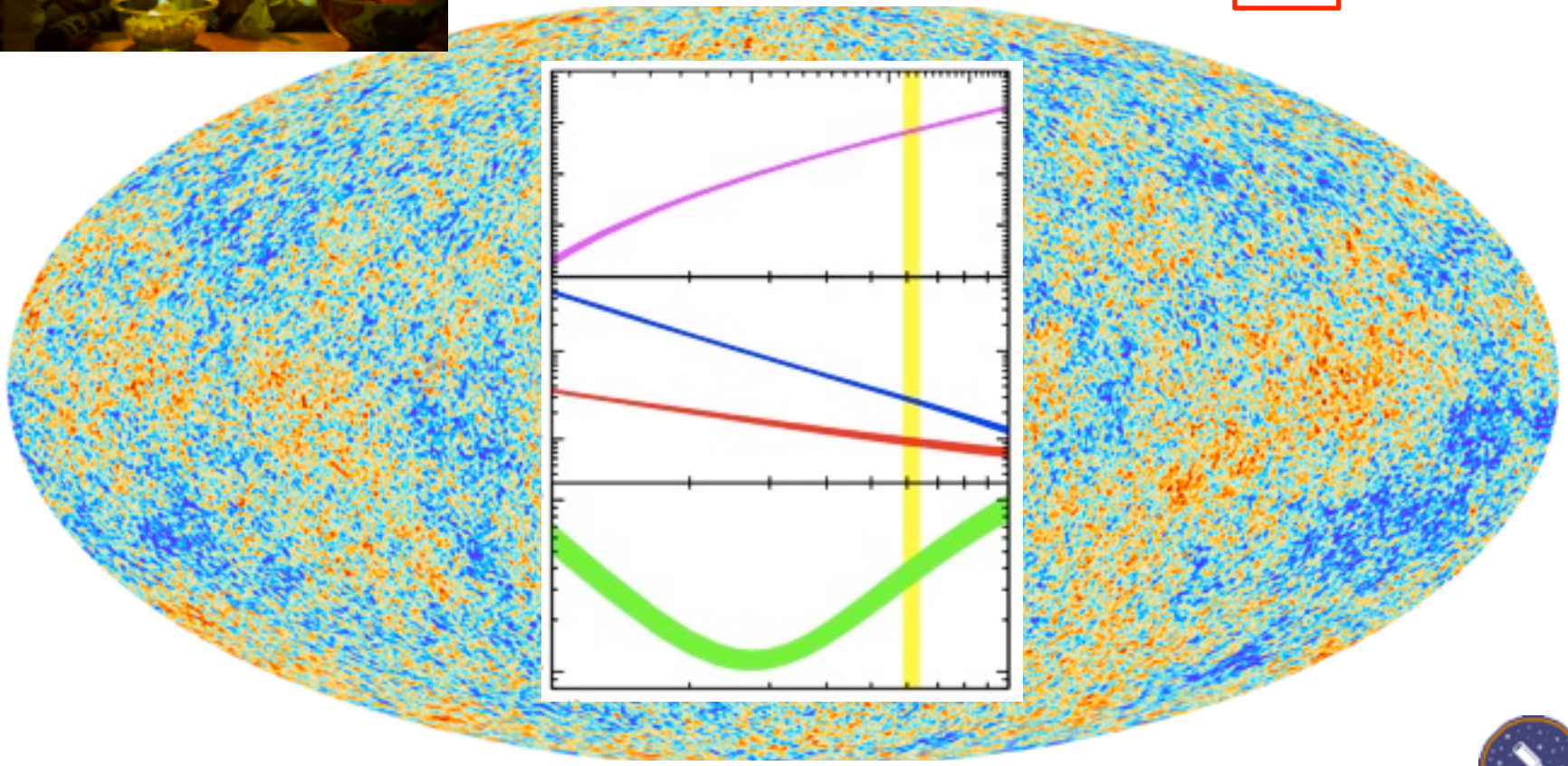
A Bitter Pill:
The Primordial Li thium Pr oblem



Brian Fields

University of Illinois

TALENT School in Nuclear Astrophysics

MSU/JINA | June 3, 2014

An Egregiously Short Intro to

Dark Matter

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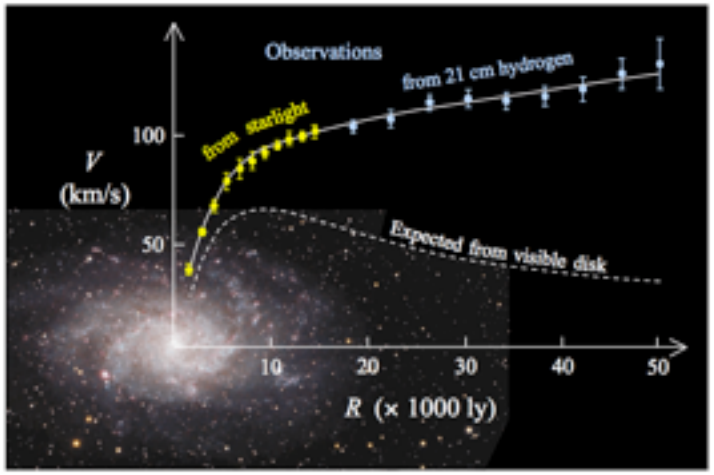
measure circular speed vs radius: **"rotation curve"**

results: rapid rise to "flat" $v(r) \rightarrow v_c = const$



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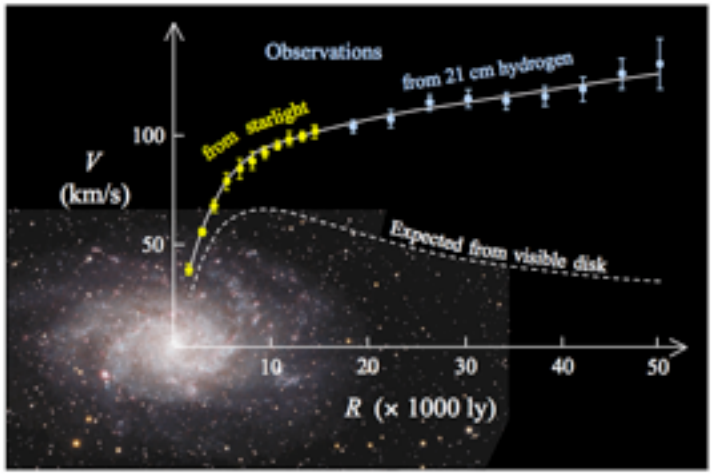

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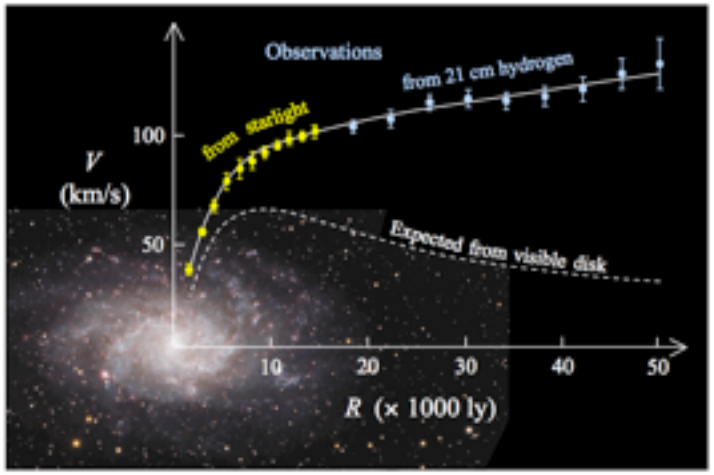

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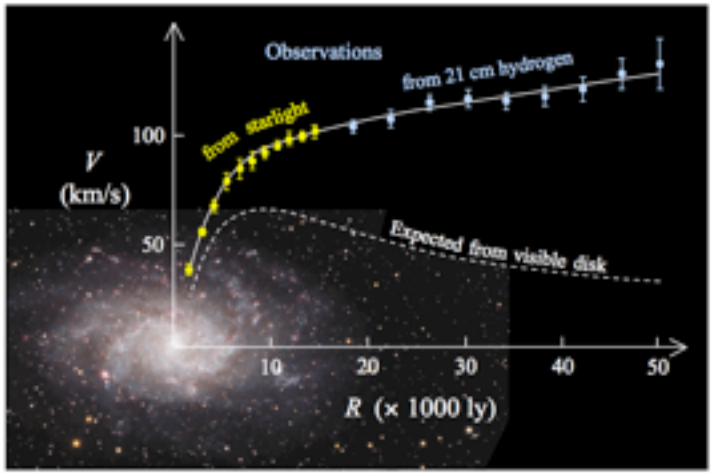

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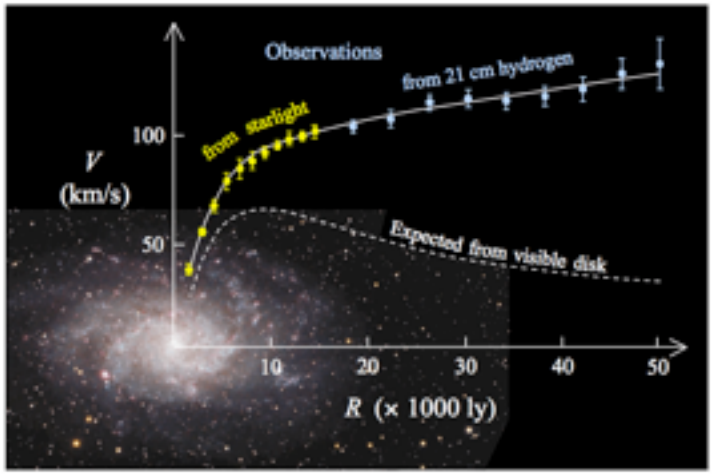

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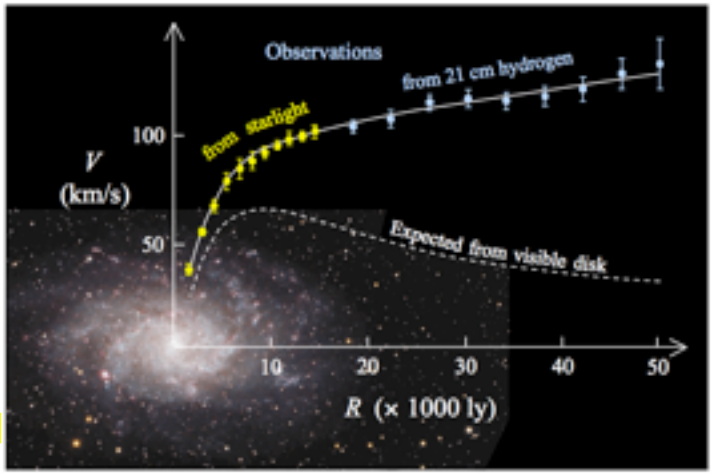

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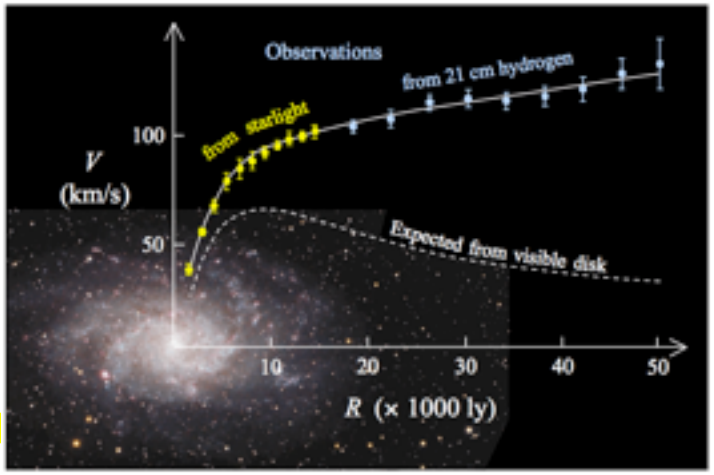

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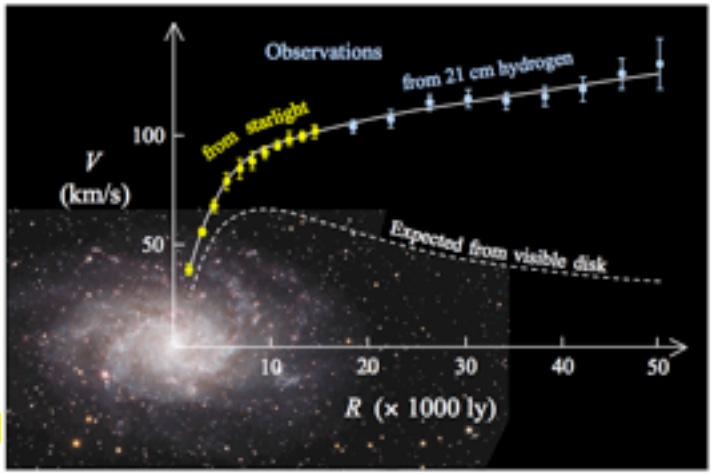

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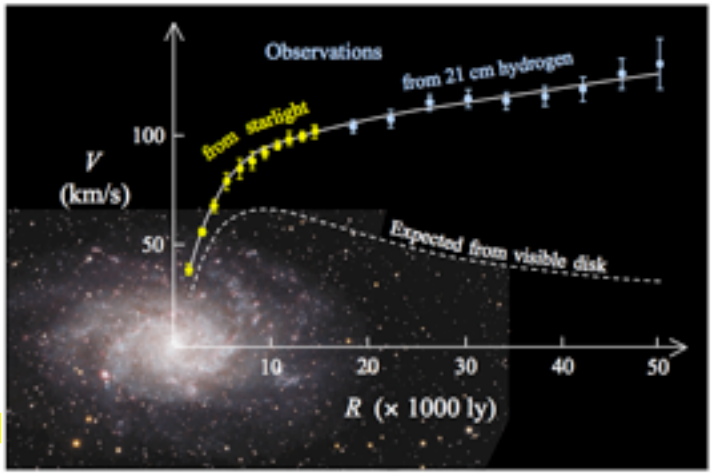

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Q: differences between dark matter and dark energy?

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Who Ordered That?

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neutrinos known to exist! and have mass! …but not nearly enough!

mass density of cosmic neutrinos < baryons << dark matter

relic exotic particles from early Universe

Margaret & Geoffrey Burbidge, Willy Fowler, Fred Hoyle

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Synthesis of the Elements in Stars*

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Elements	Mode of production	Total mass in galaxy ($M_\odot$ as unit)	Astrophysical origin	Total mass of all material ejected over lifetime of galaxy ($M_\odot$ as unit)	Required efficiency
He	H burning	8.1×10^{9}	Emission from red giants and supergiants	2×10^{10}	0.4
D	x process?	7.5×10^{6}?	Stellar atmospheres? Supernovae?	?	?
Li, Be, B	x process	8.5×10^{2}	Stellar atmospheres	?	?
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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

Athol Kemball, Doug Friedel — U. of Illinois

A Bitter Pill: The Primordial Lithium Problem

★ Nuclear Physics in the Early Universe

- Big bang nuke (BBN) theory
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★ The Lithium Problem

- ^{7}Li disagreement: CMB vs astro observations
- new observational probes of Li
- new nuclear physics?
- new particle physics?

The Standard Cosmology:

Hot Big Bang Model

Friedmann-Lemaitre-Robertson-Walker

Gravity = General Relativity
Space: Homogeneous & Isotropic

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- **Cosmic Microwave Background (CMB)**
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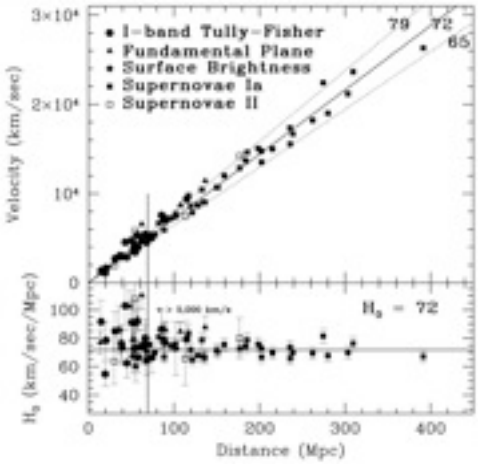

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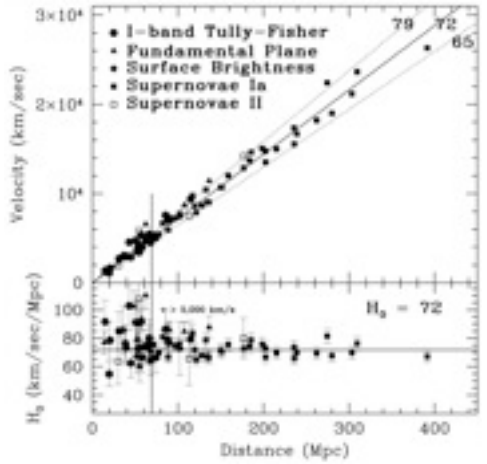

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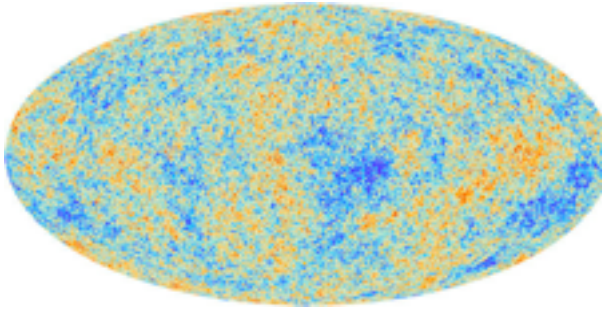

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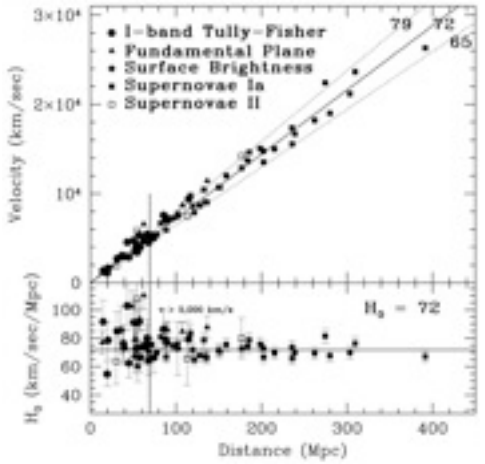

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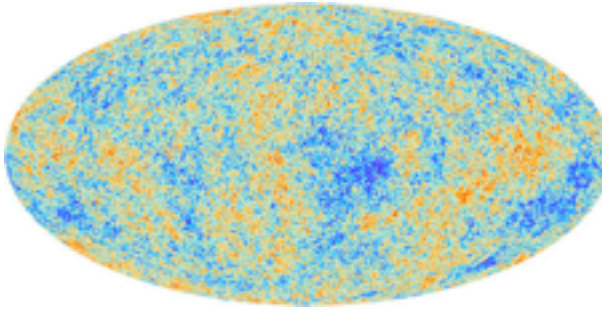

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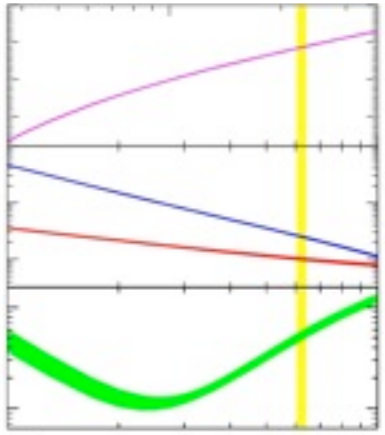

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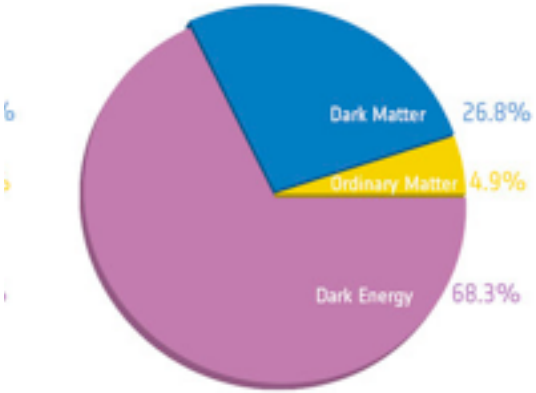

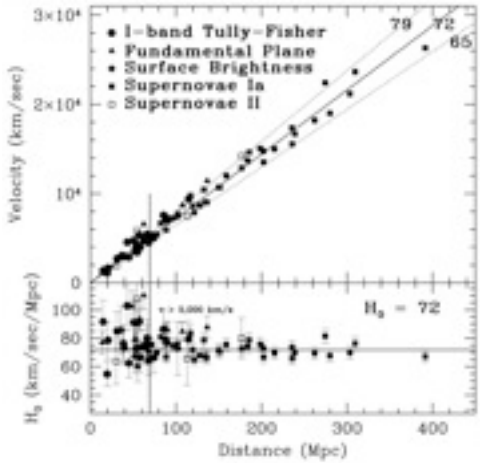

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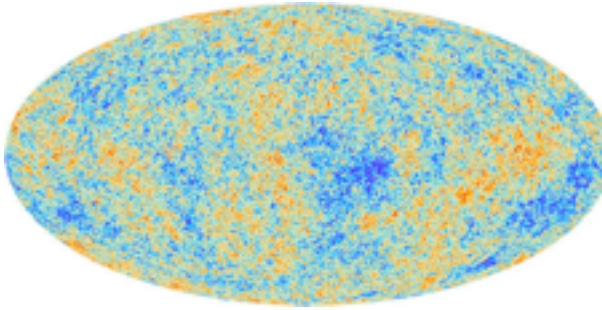

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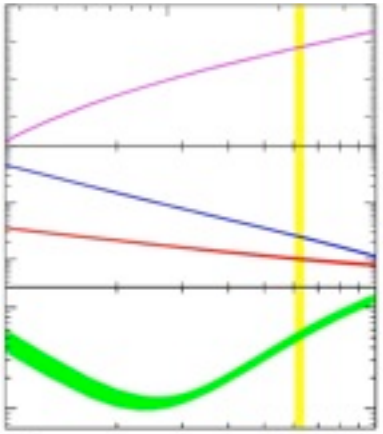

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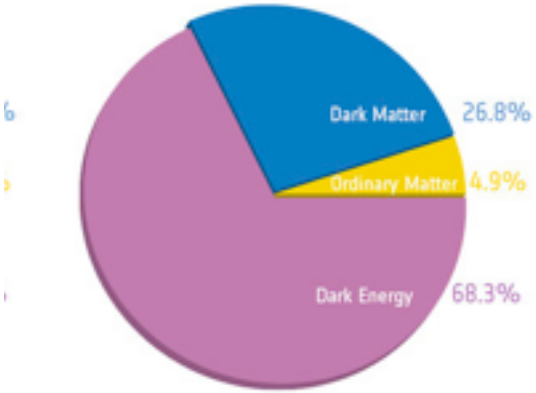

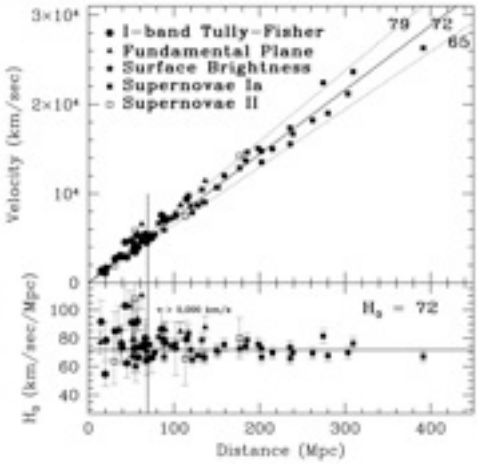

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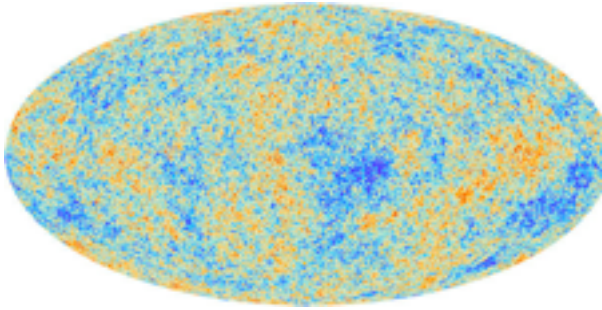

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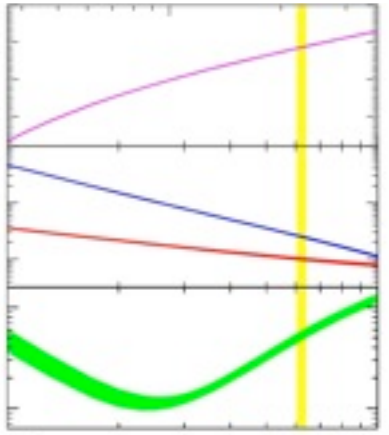

Cyburt, BDF, Olive 2008

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
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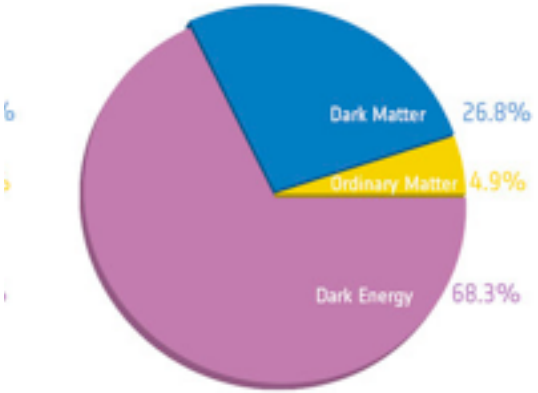
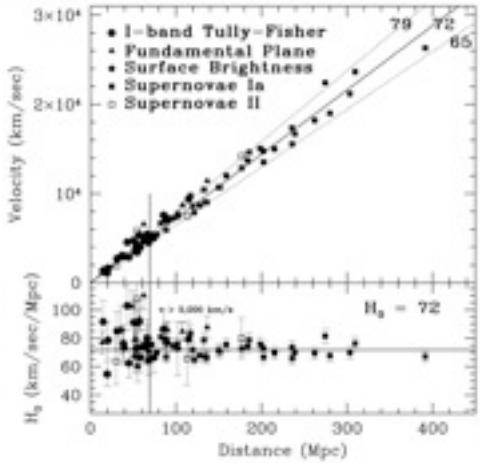
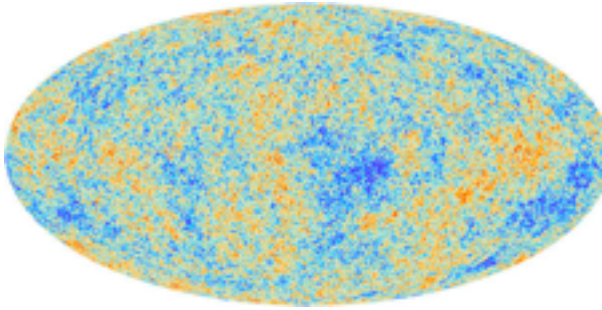




Freedman et al 2001



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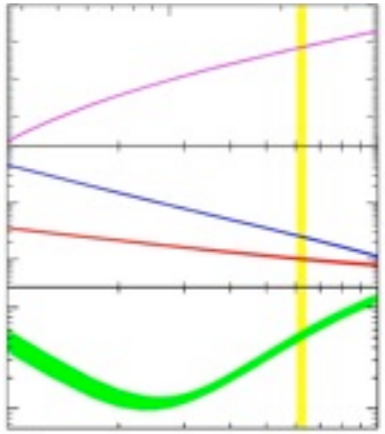

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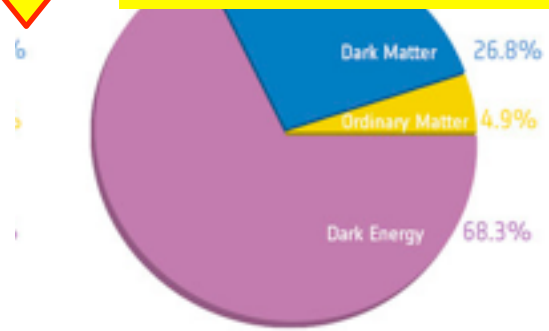

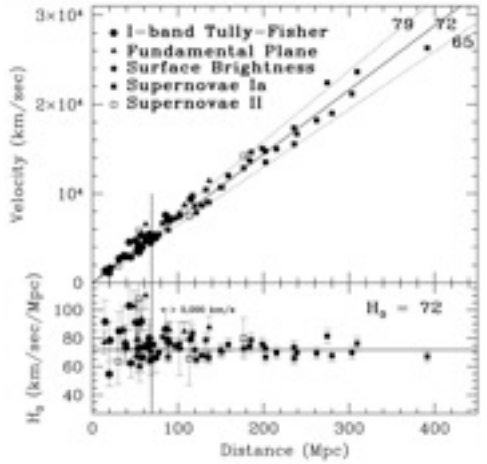

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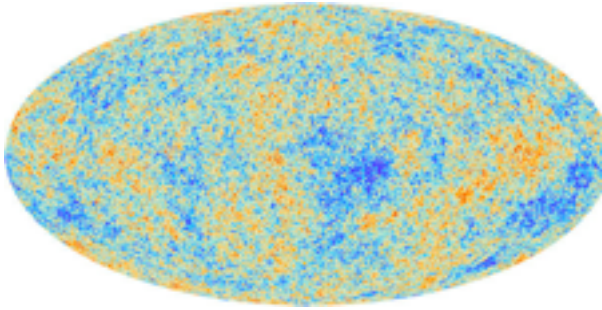

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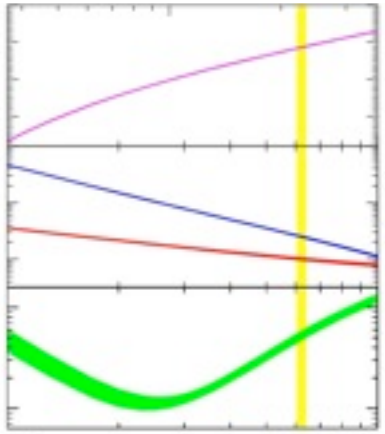

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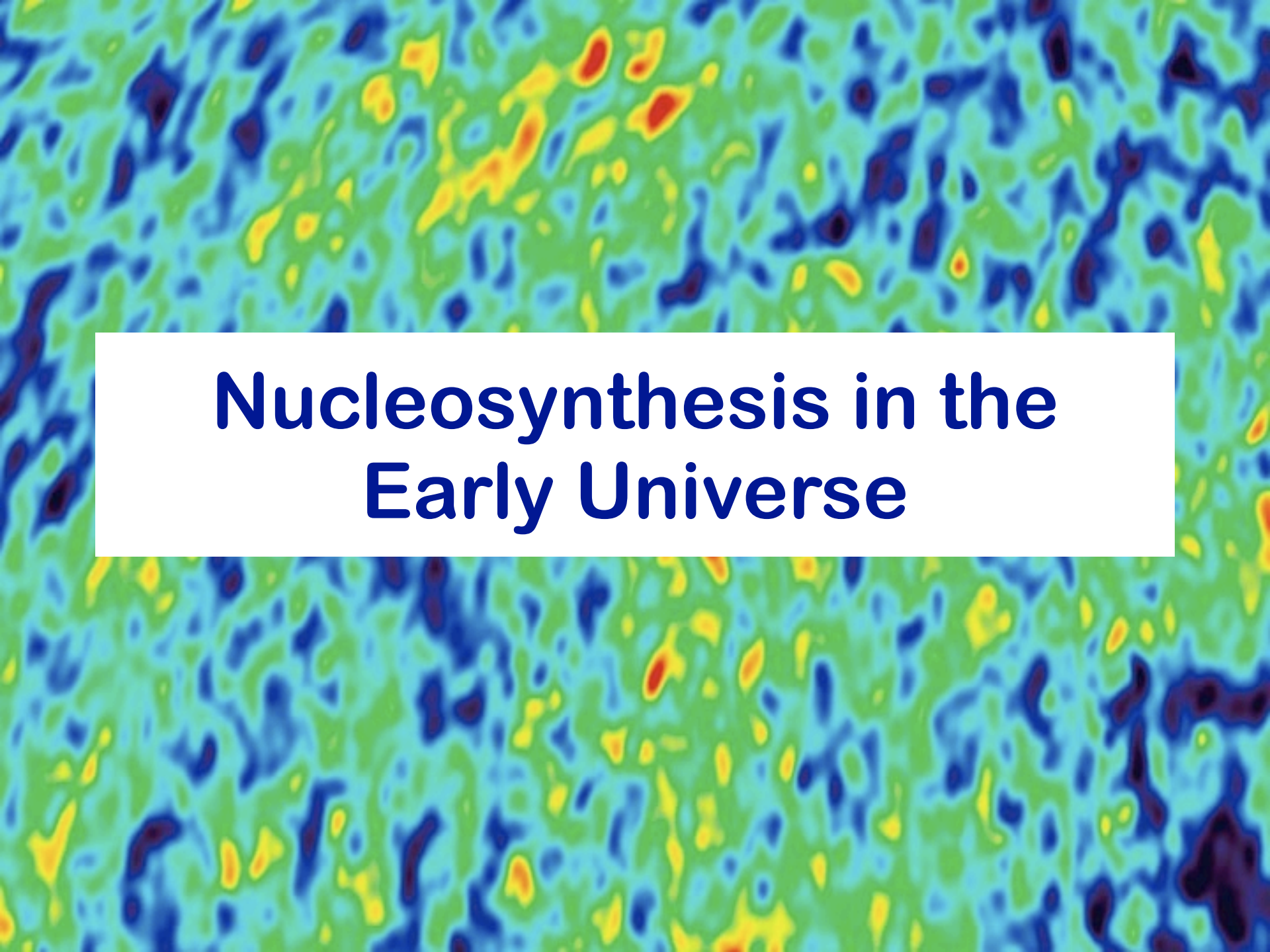
  - compare: nuclear physics sets $\rho_{\rm H} \sim \rho_{\rm He}$



Nucleosynthesis in the Early Universe

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A Symphony of Fundamental Forces

- **BBN: unique arena**
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- **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. ⇒ $\eta \equiv \dfrac{n_{\rm baryon}}{n_\gamma}$ Spatially const

- Expansion adiabatic

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

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

Big Bang Nucleosynthesis

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
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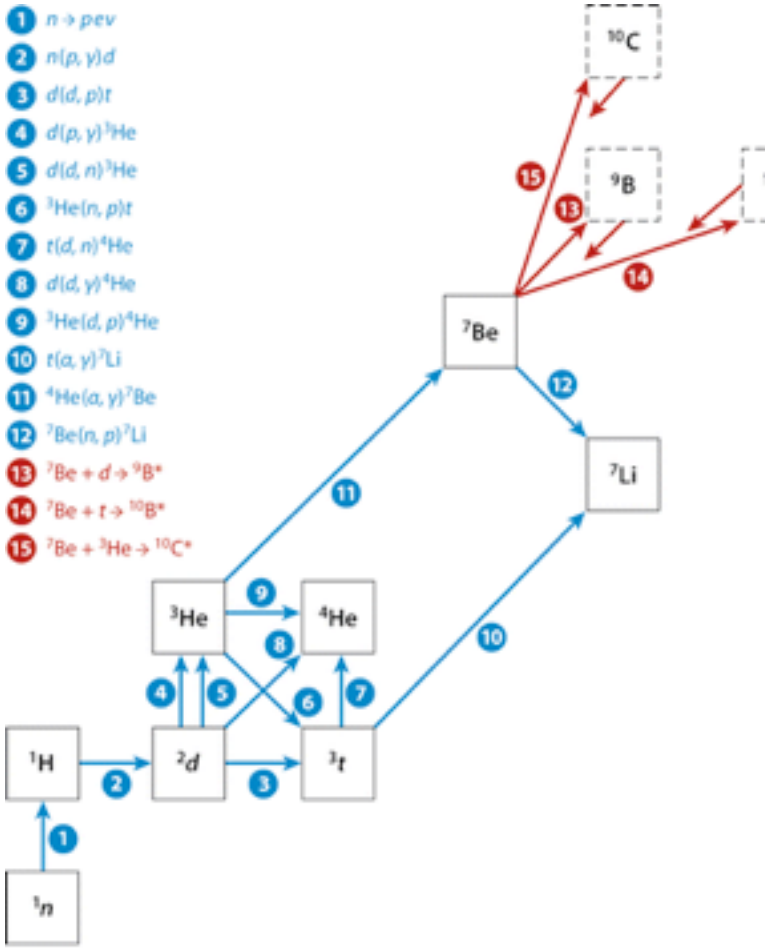
reaction flow ⇨ most stable light nucleus

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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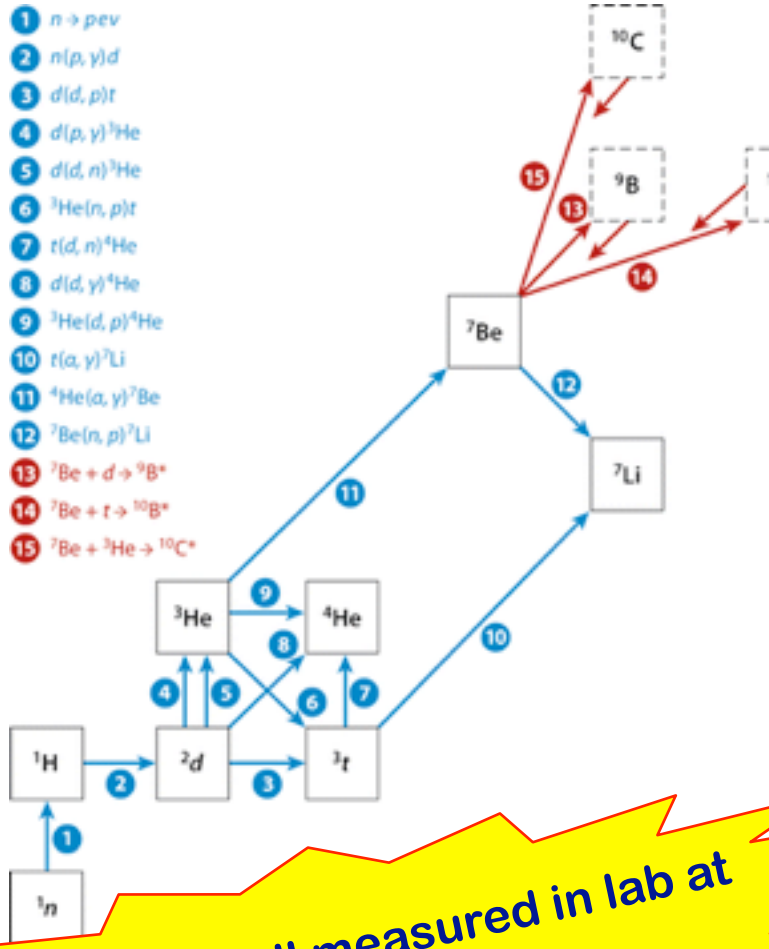
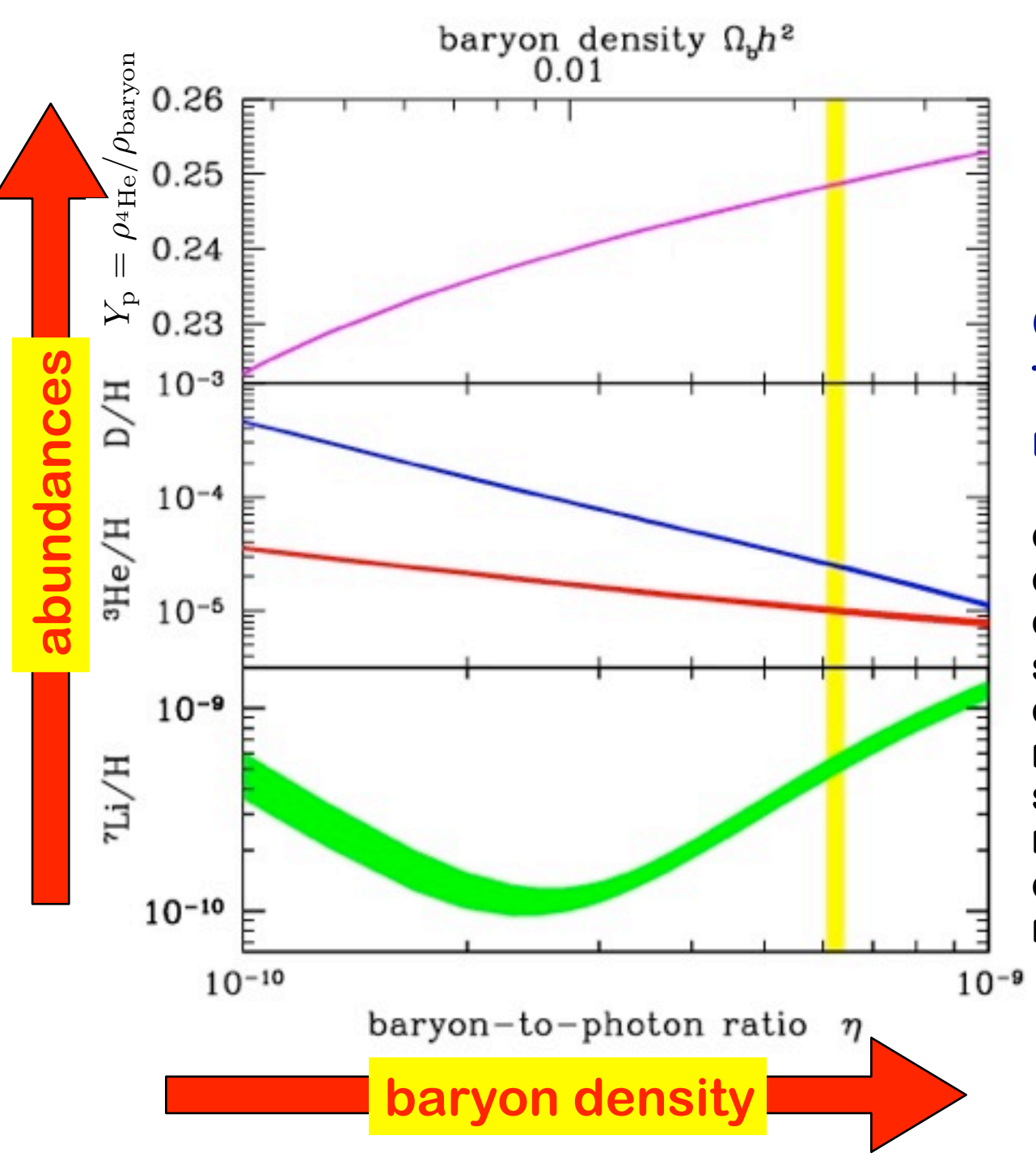


key reactions all measured in lab at relevant energies



BBN Predictions

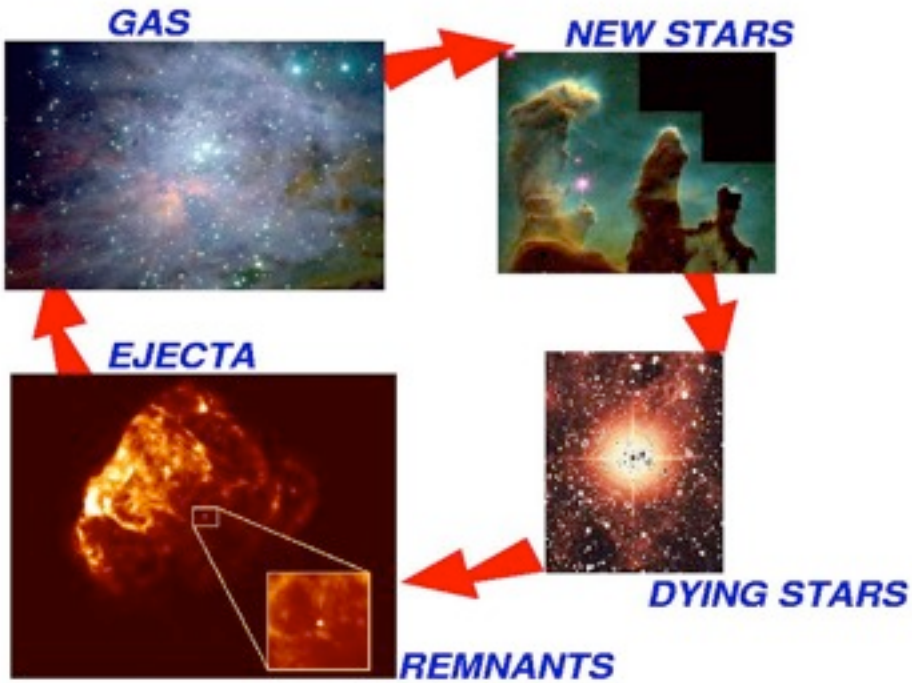
Curve Widths: Theoretical uncertainty nuclear cross sections

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*
- But... Galactic nuke changes abundances



The Solution

- measure & correct for post-BBN processing:

Metals $\Leftrightarrow$ stars $\geq 10 M_\odot$ $\Leftrightarrow$ "time"

Light Elements: Sites

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Deuterium

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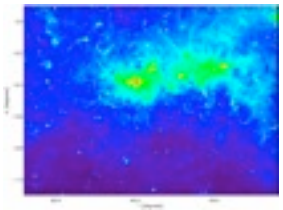
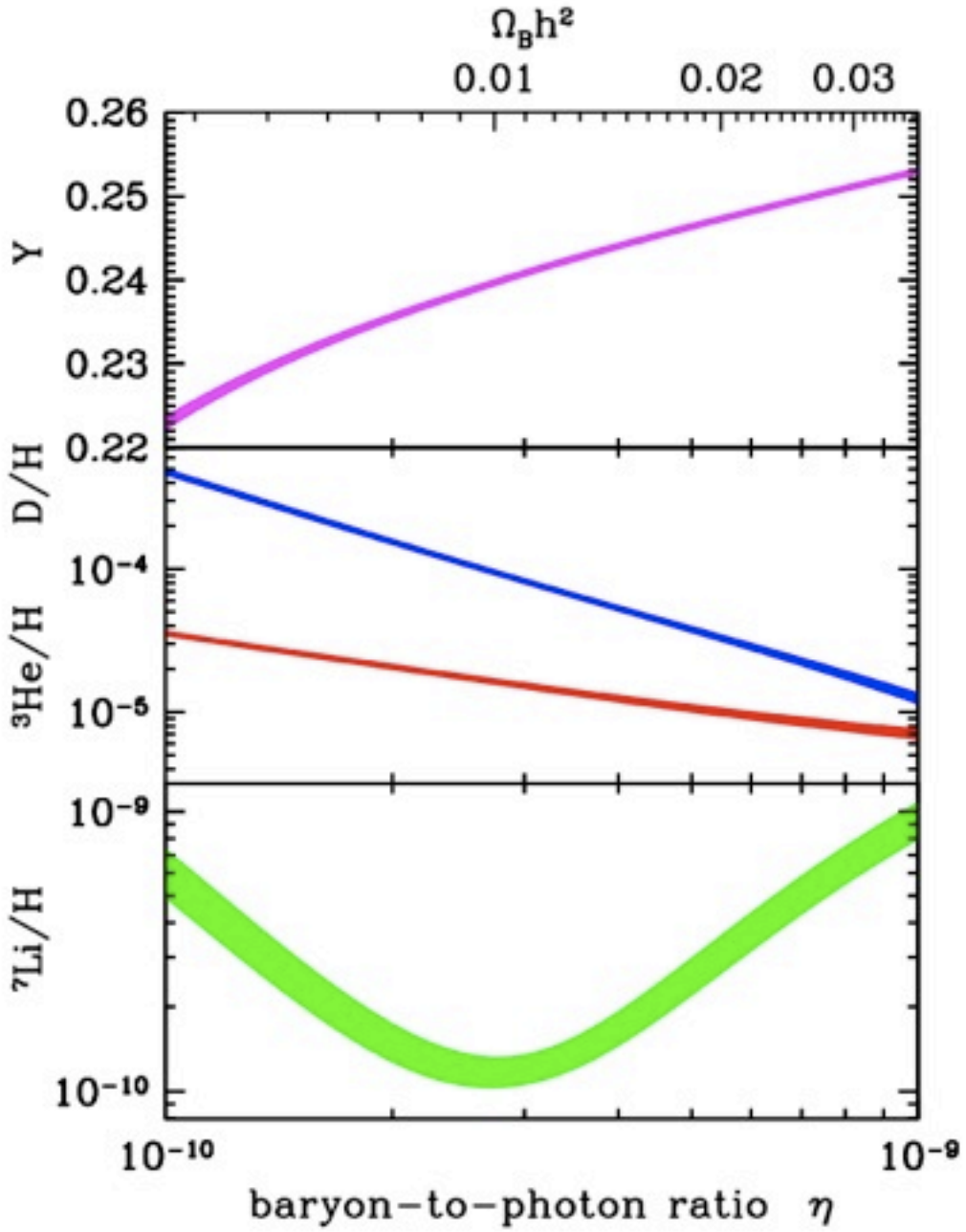


^{3}He

- 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}
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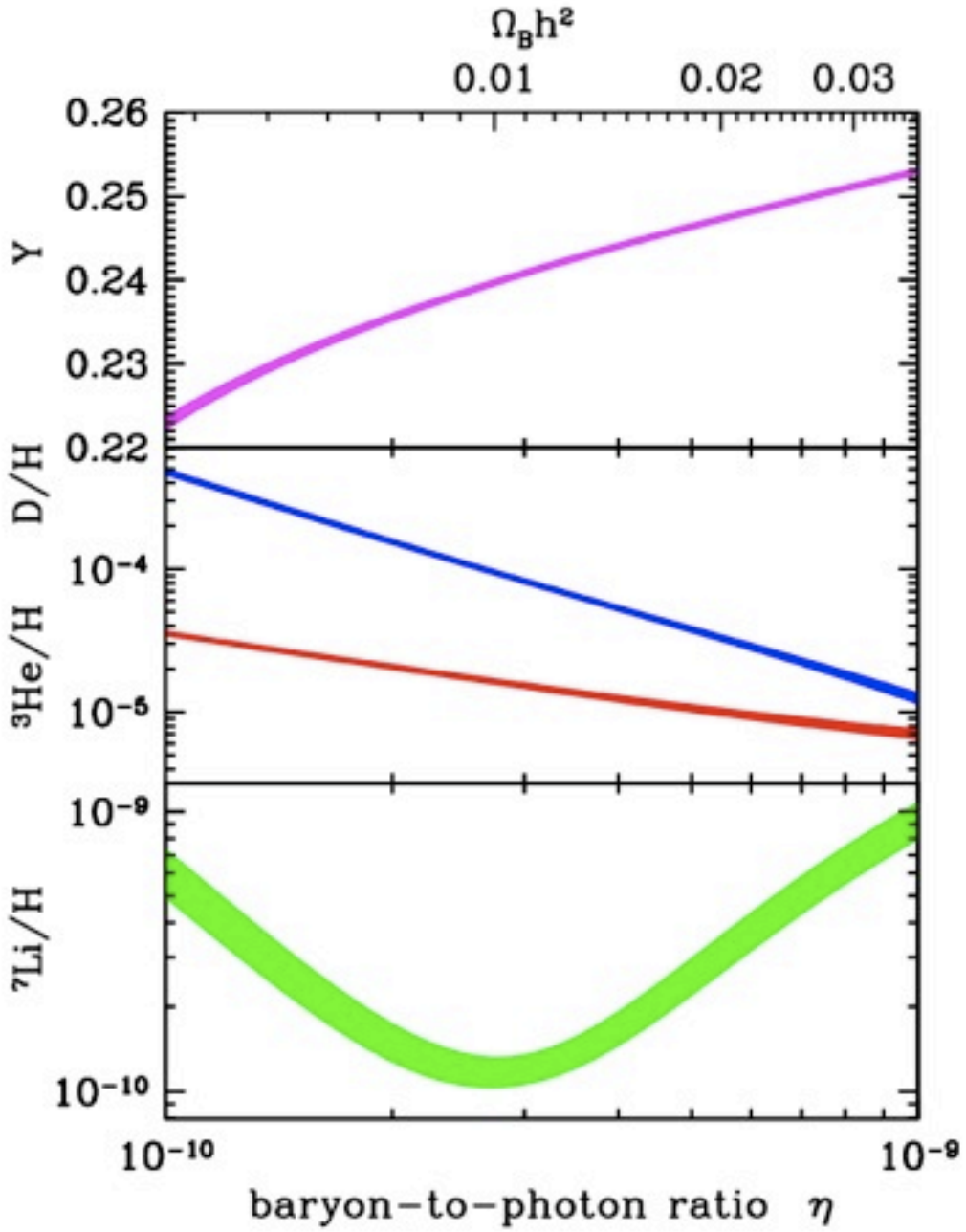

Testing BBN: Light Element Observations

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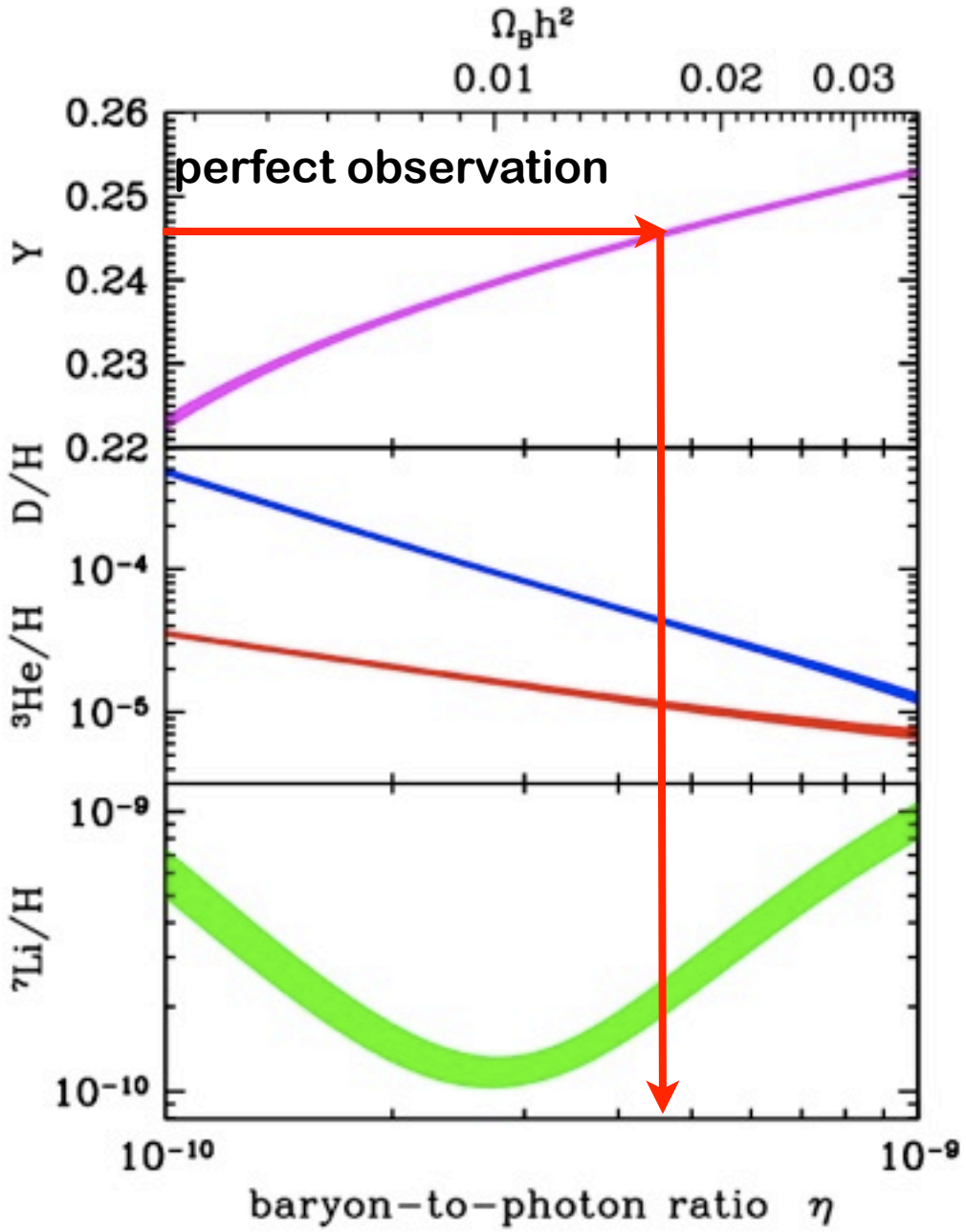

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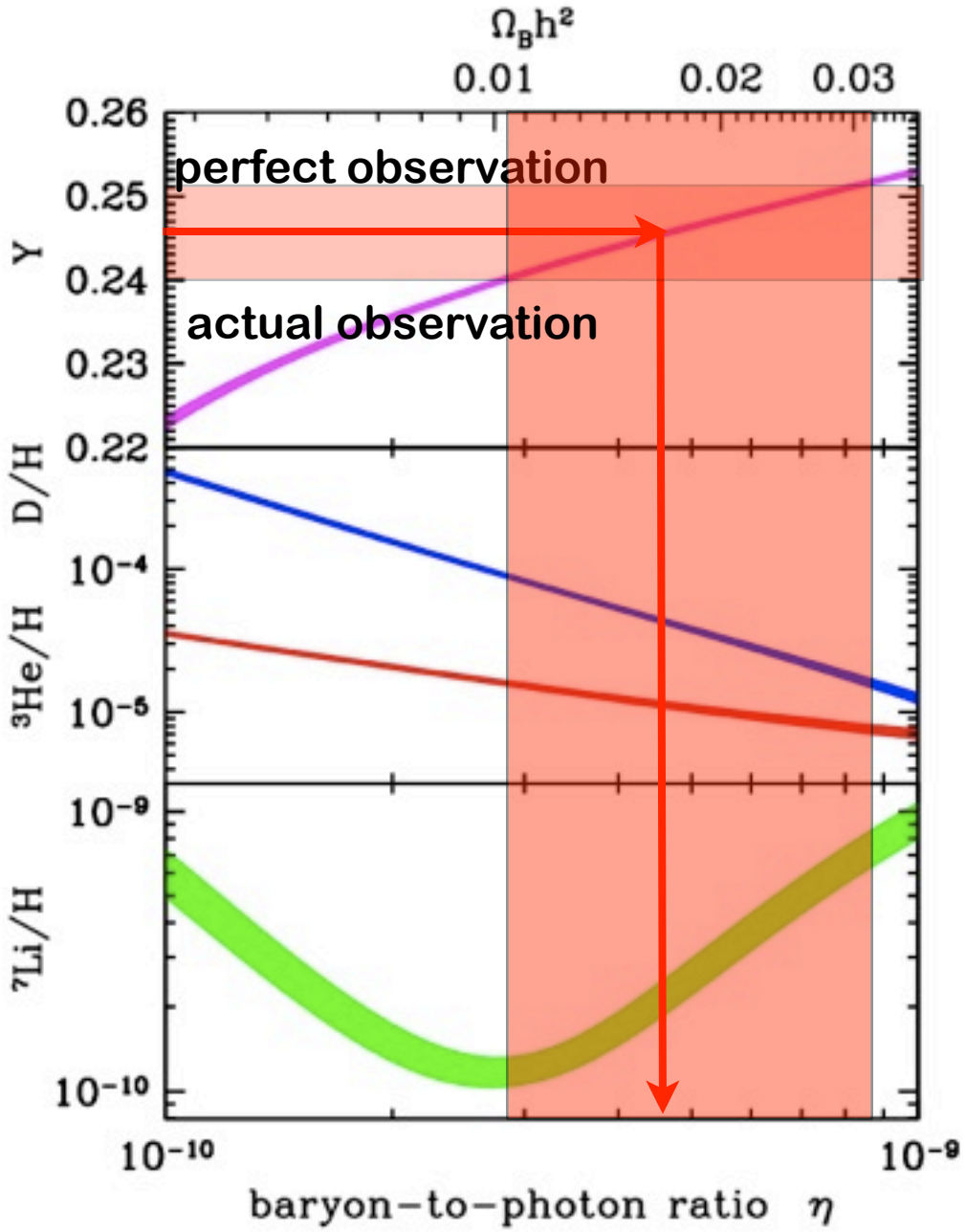

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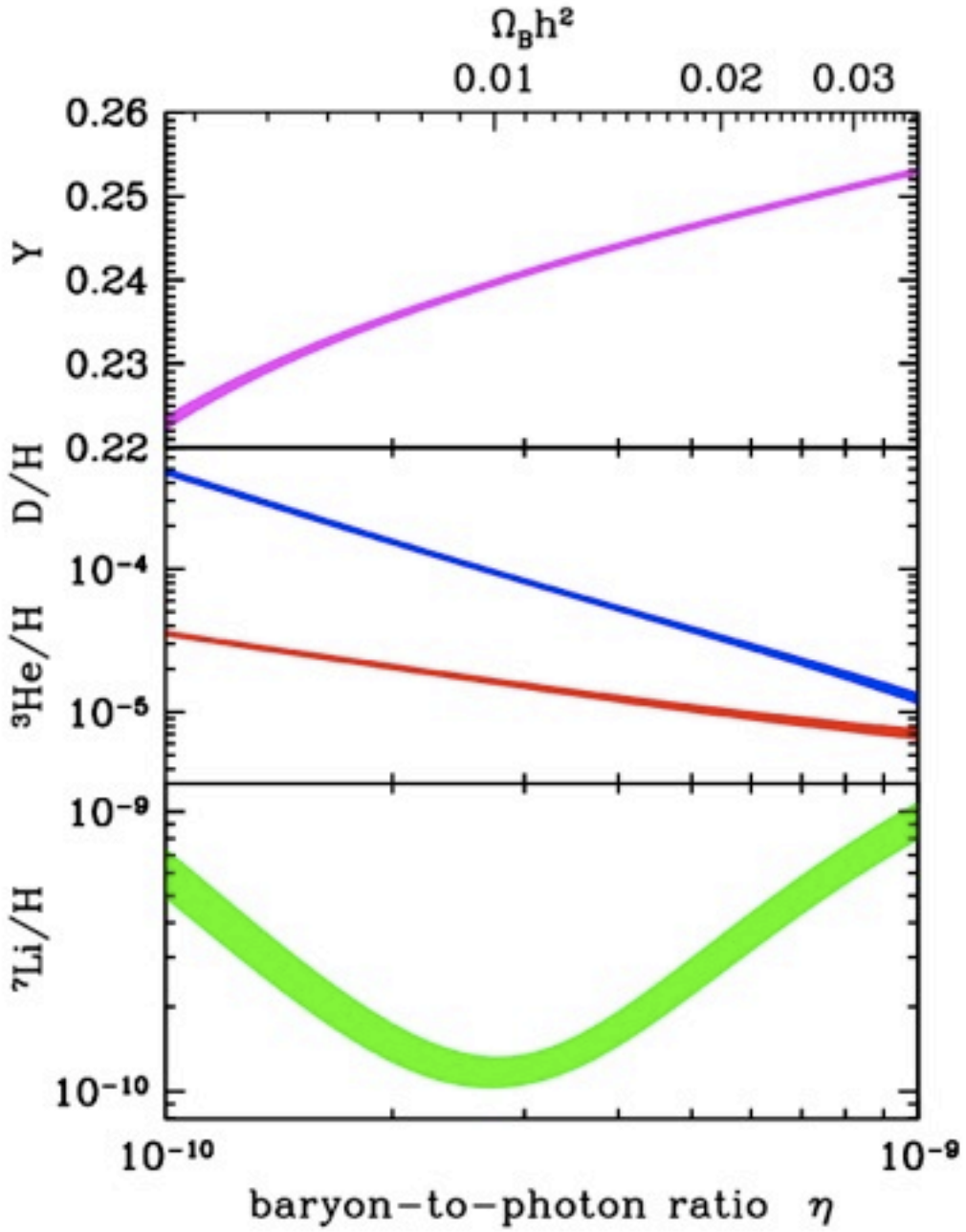

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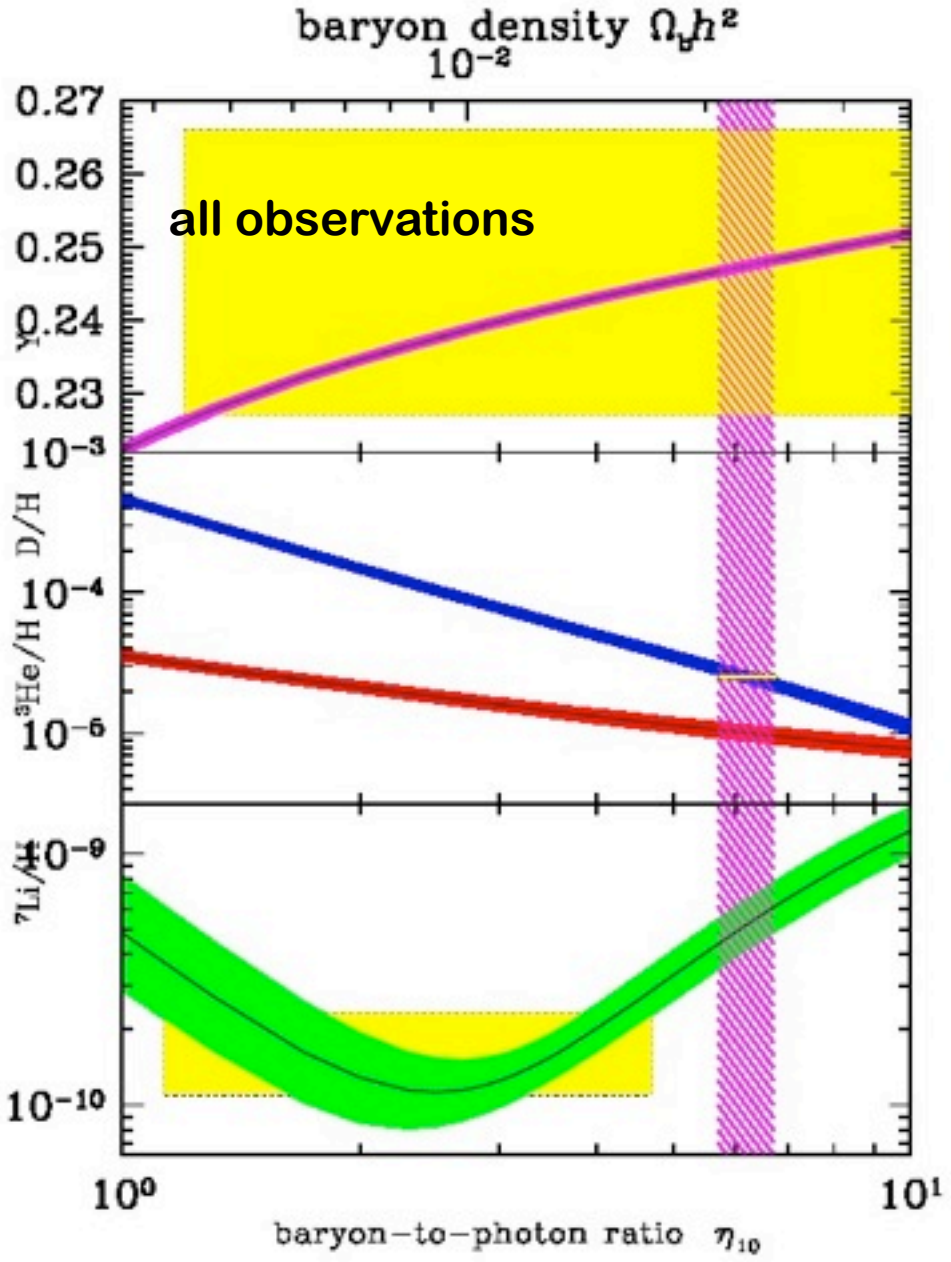

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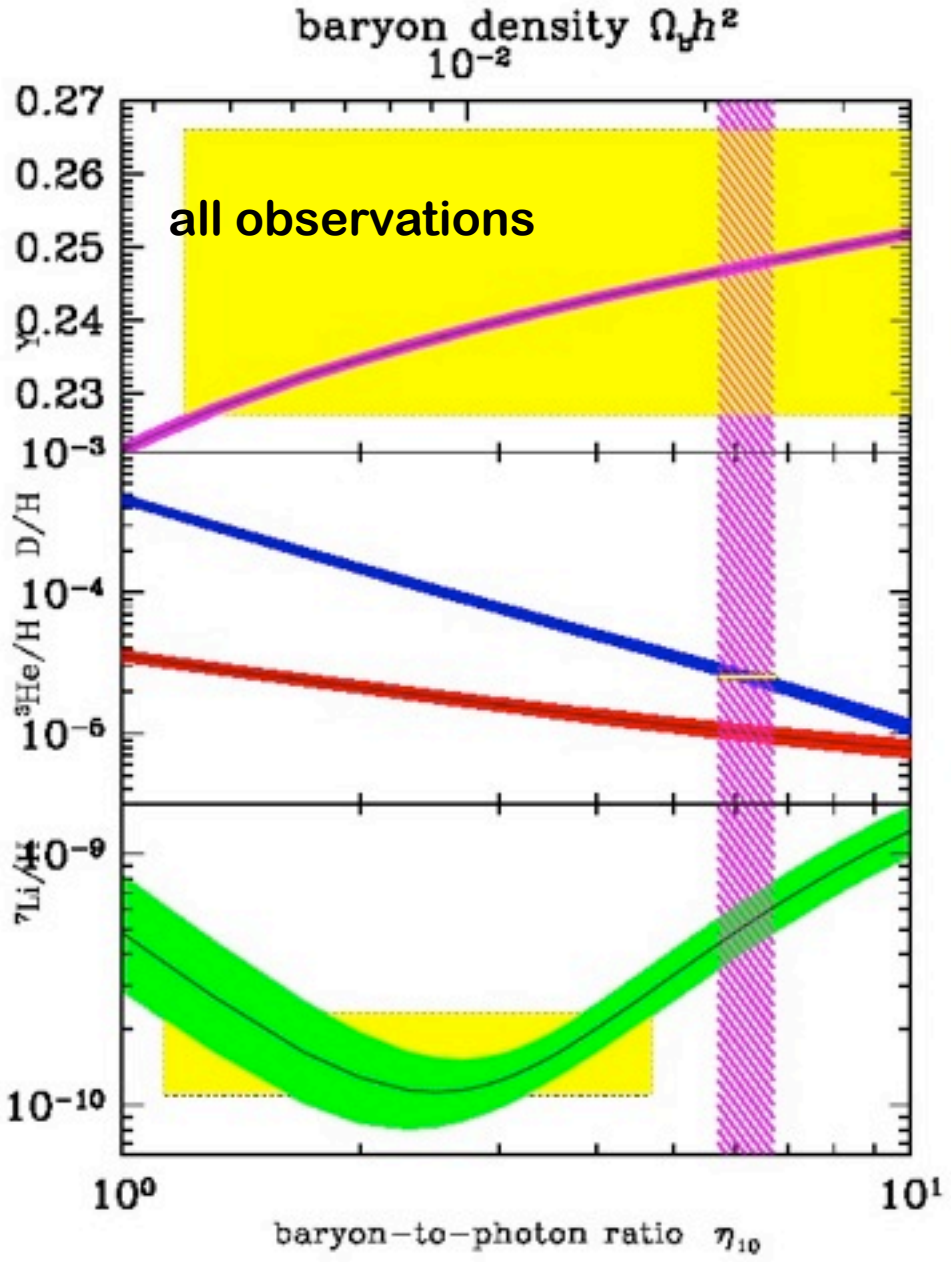

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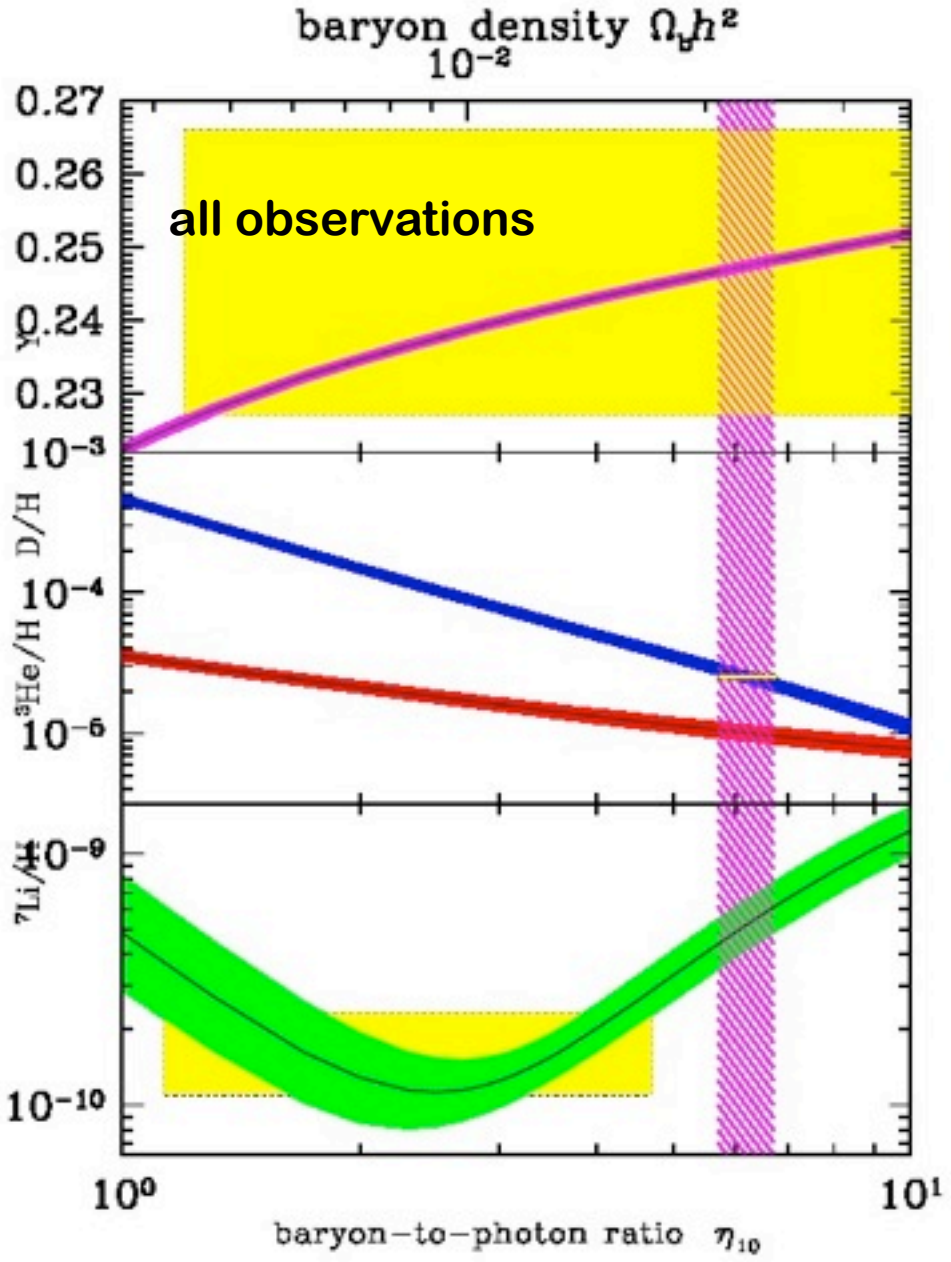

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⇨ need a tiebreaker

A Bitter Pill: The Primordial Lithium Problem

★ Nuclear Physics in the Early Universe

- Big bang nuke (BBN) theory
- Light element observations and cosmic baryons

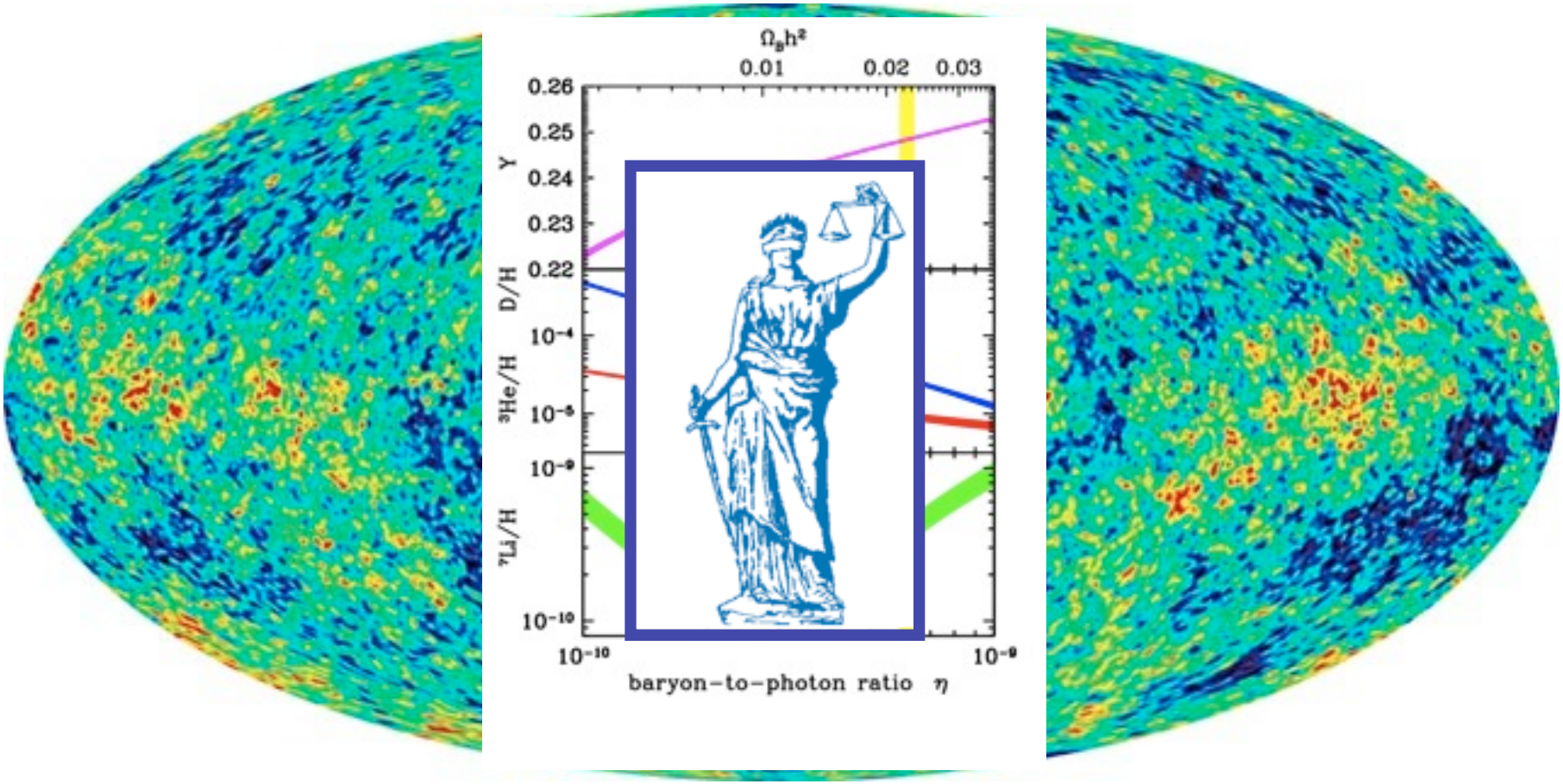
★ Battle of the Baryons

- Cosmic microwave background (CMB): a new baryometer

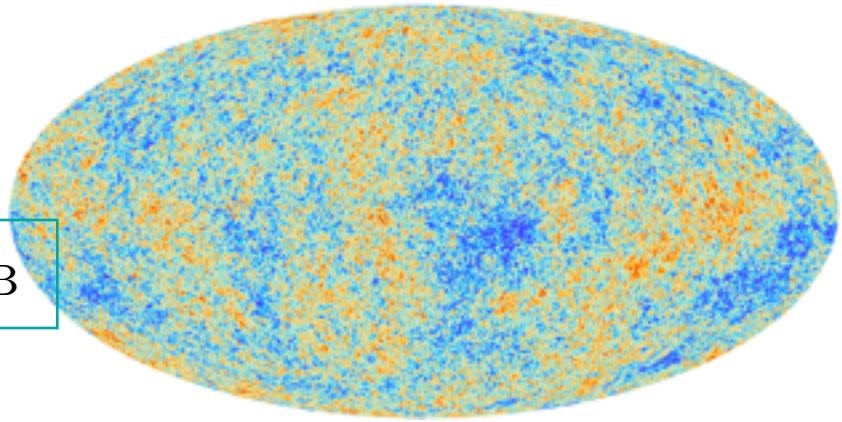
★ The Lithium Problem

- ^{7}Li disagreement: CMB vs astro observations
- new observational probes of Li
- new nuclear physics?
- new particle physics?

Battle of the Baryons:



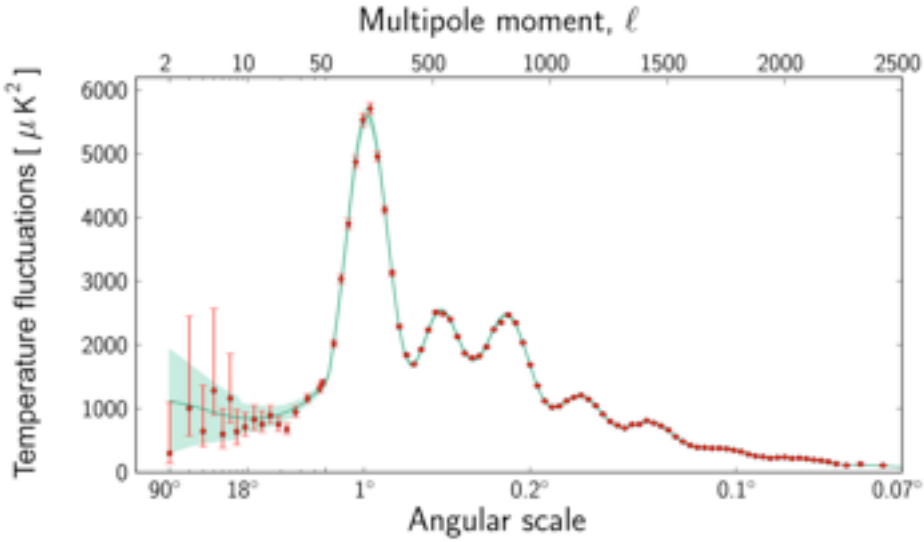
The CMB: A Powerful New Baryometer



CMB ΔT_ℓ independent measure of $\Omega_{\rm B}$

Power spectrum features < 1°

set by acoustic oscillation cf helioseismology



Detailed peak posns, heights:

- sensitive to cosmological parameters
- first peak: curvature of U.
- second, third peaks/first peak: $\Omega_{\rm B}$

BBN vs CMB: fundamental test of cosmology

Planck Explorer:

$$\Omega_{\rm B}\ h^2_{100} = 0.02218 \pm 0.00026$$

$$\eta = (6.078 \pm 0.071) \times 10^{-10}$$

Battle of the Baryons: I
The Big Picture

Compare:

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

independent

baryometers

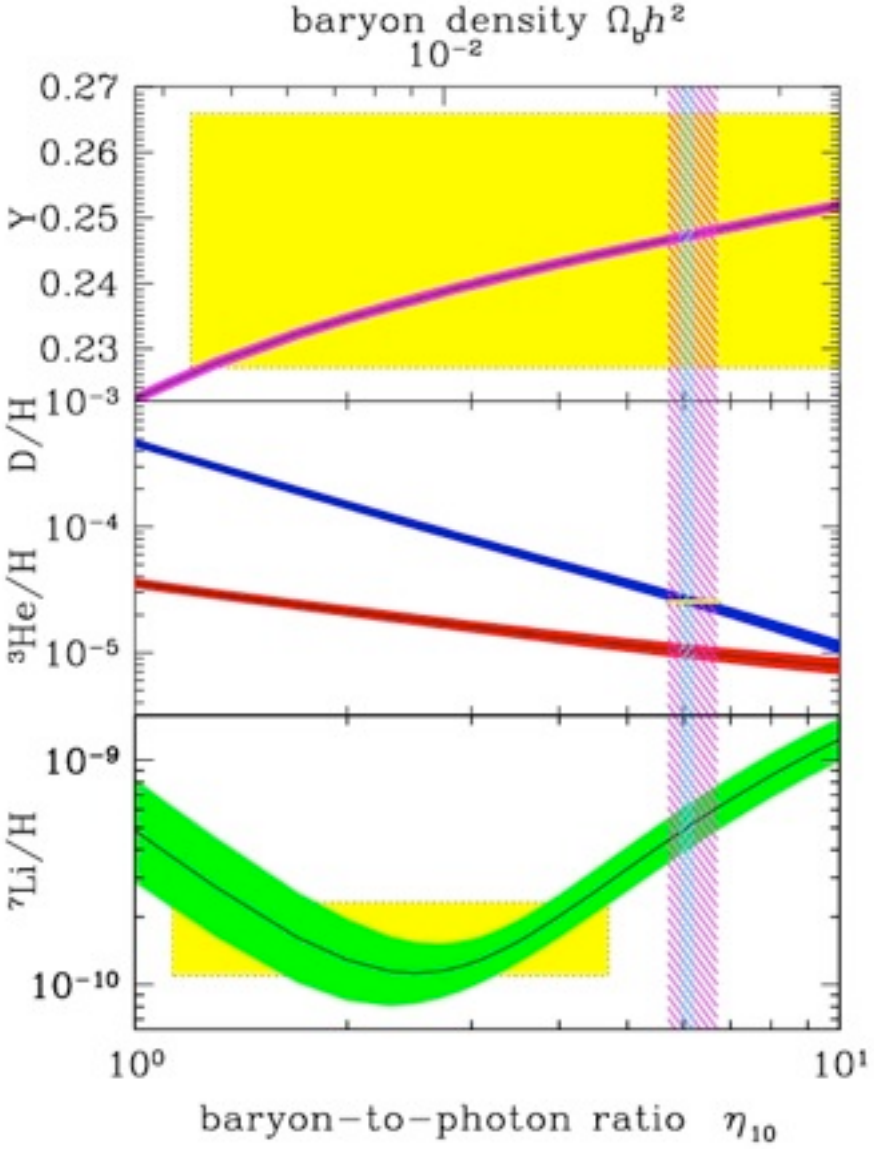
Consistency check

for big bang model

Rough agreement

cosmological success!

Tiebreaker favors D/H



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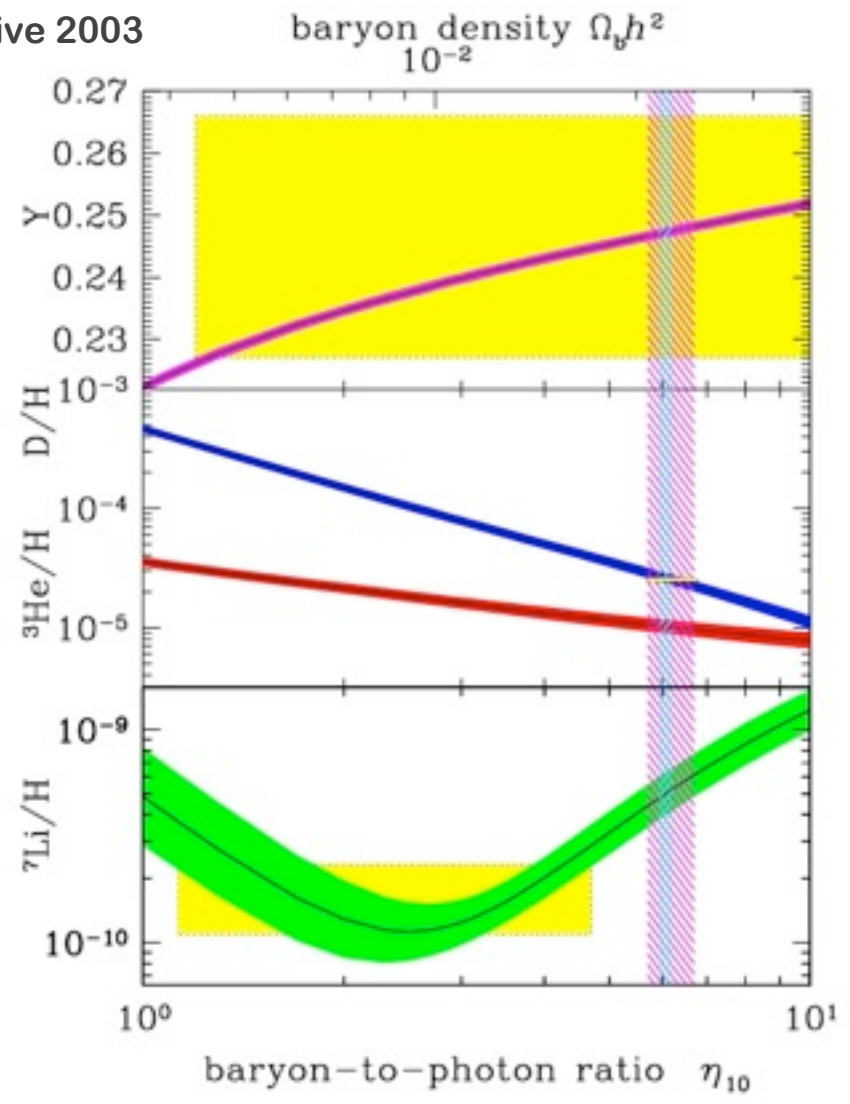

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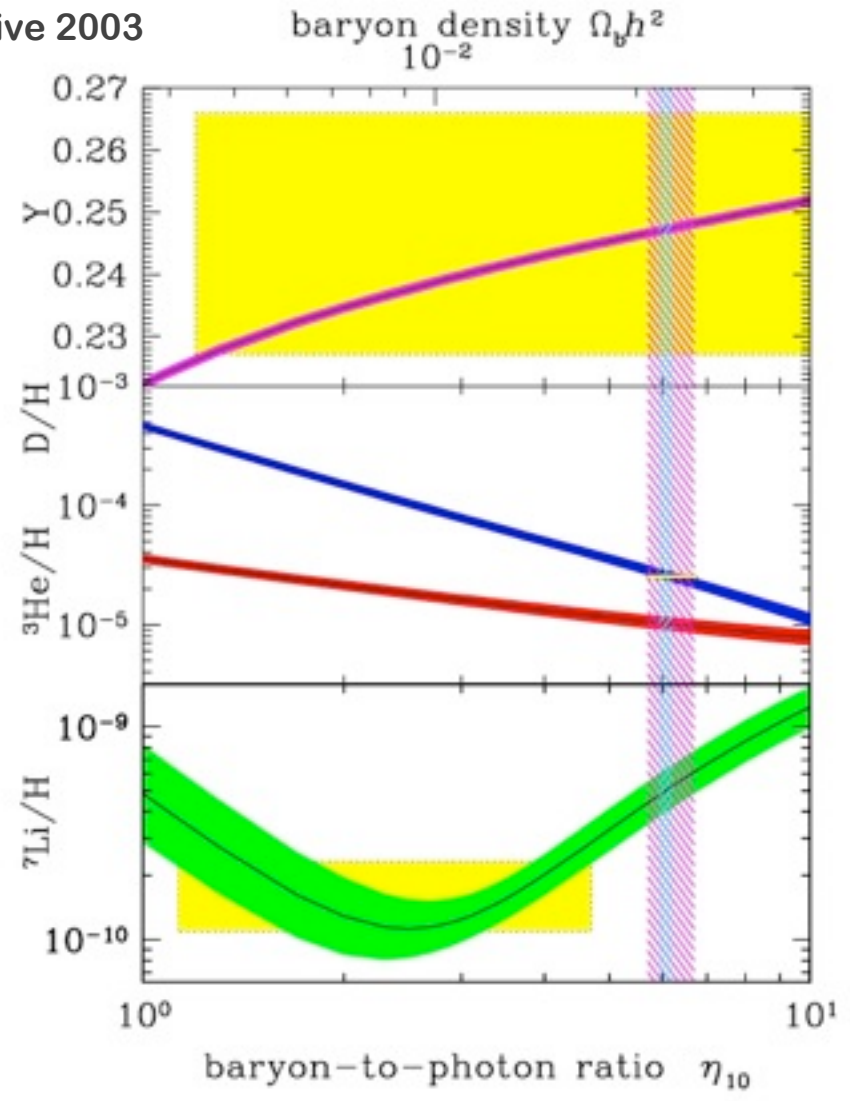

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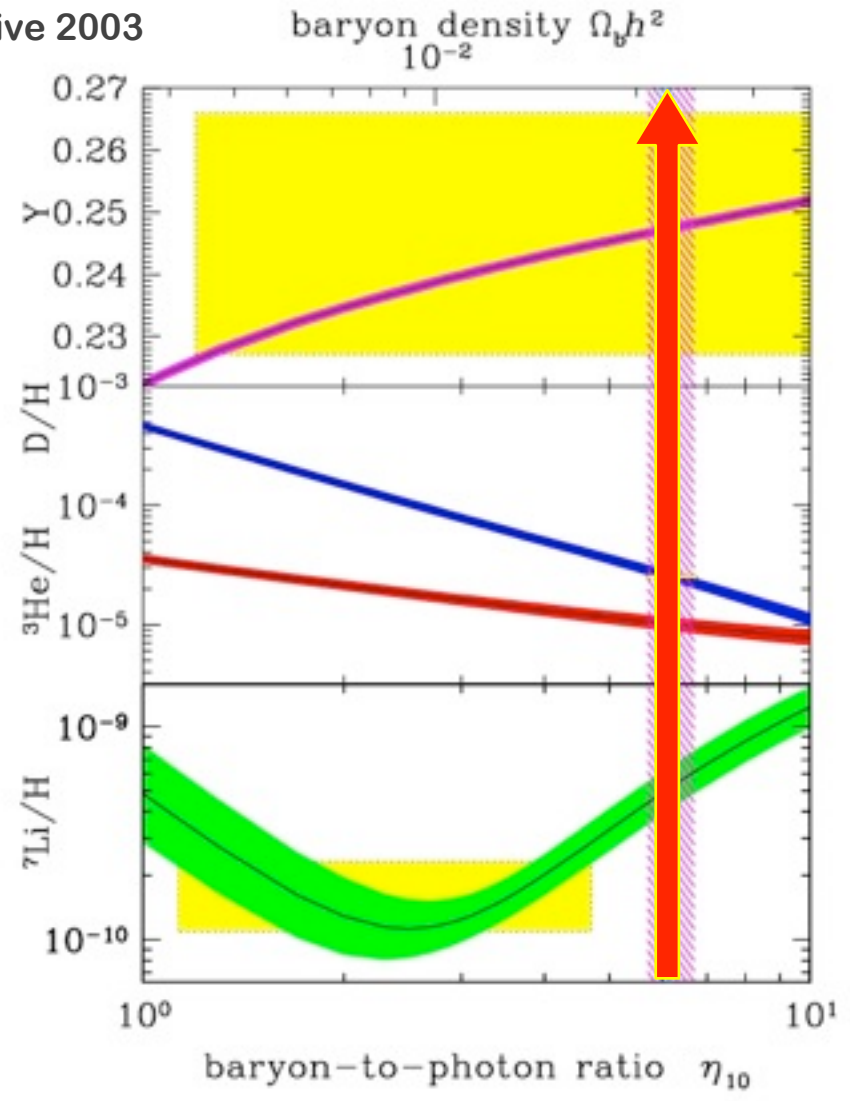
✓ use Planck $\eta_{\rm cmb}$ as BBN input



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New World Order

Cyburt, BDF, Olive 2003

Planck baryon density very precise

$$\Omega_{\rm B}\ h^2_{100} = 0.02218 \pm 0.00026$$
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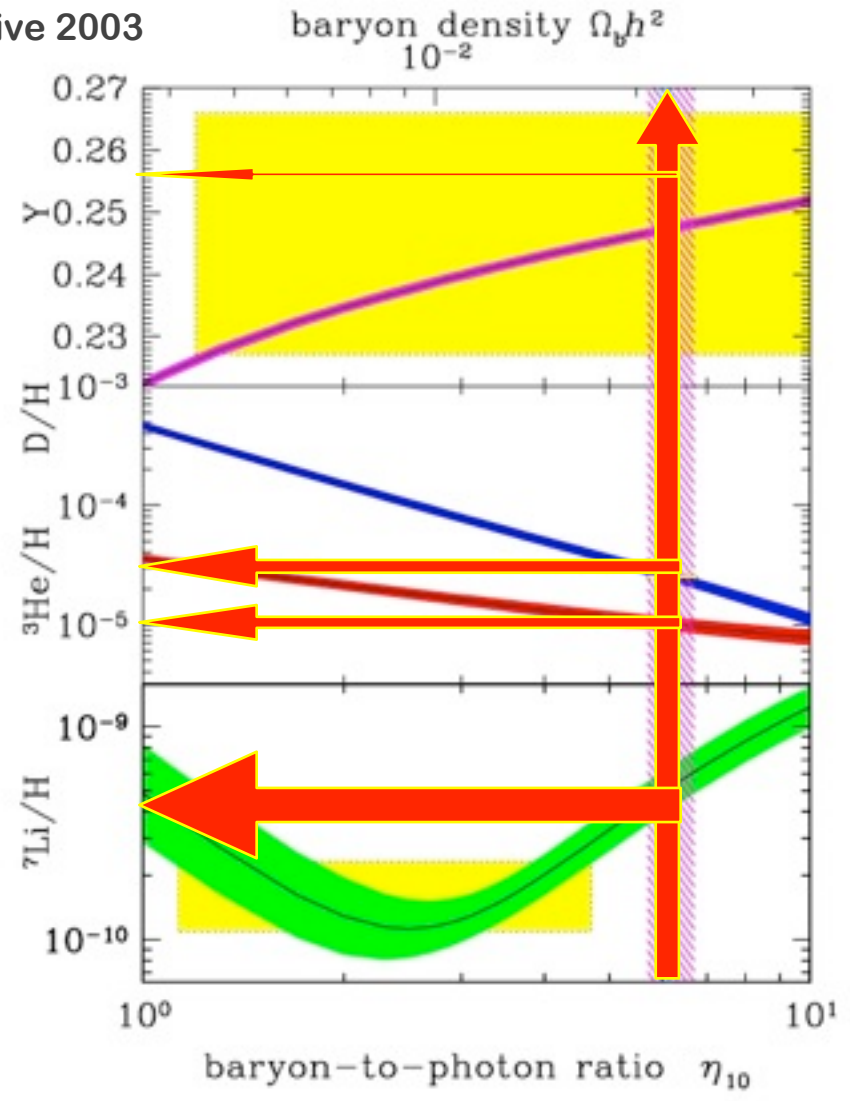

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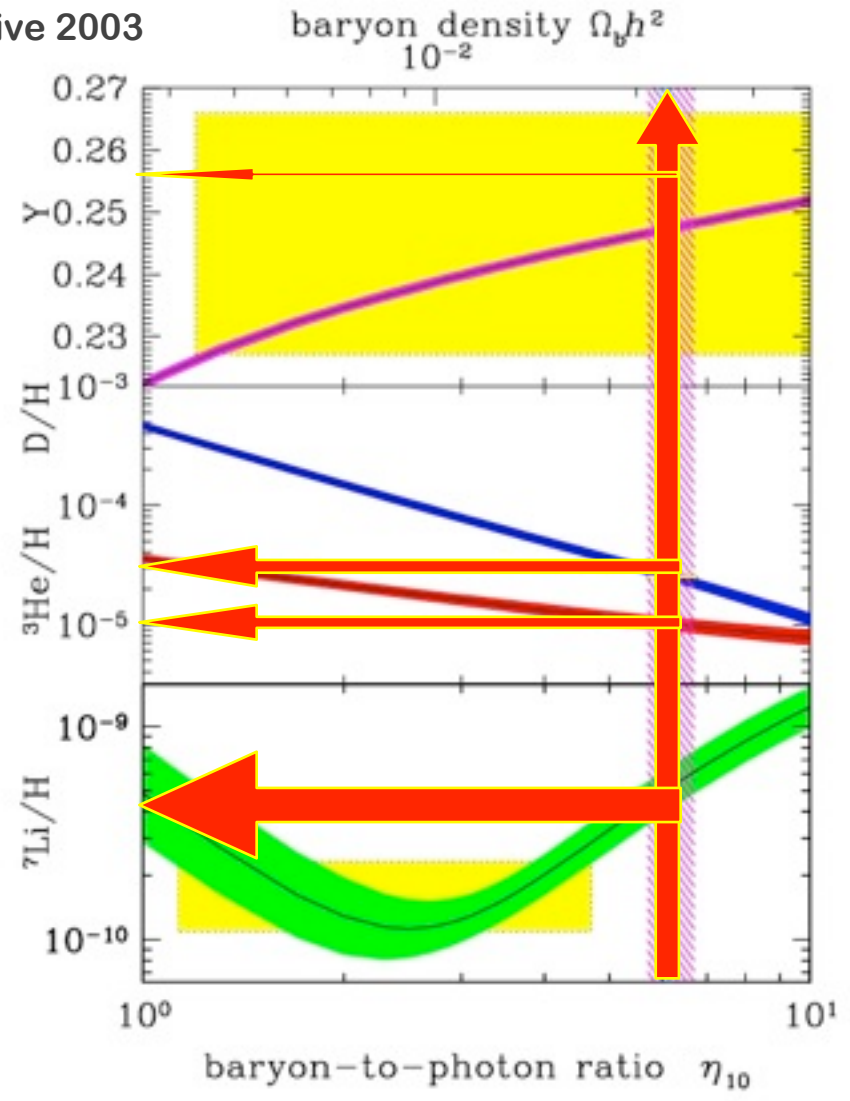

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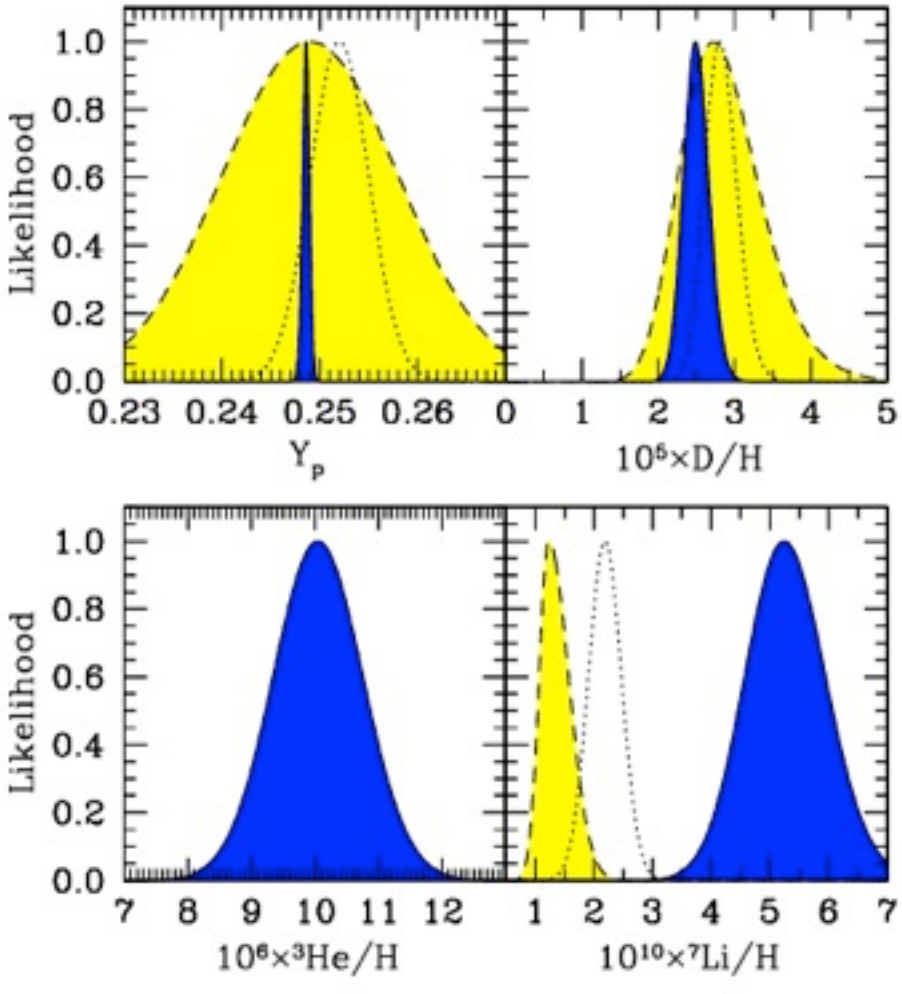

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Predict:

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

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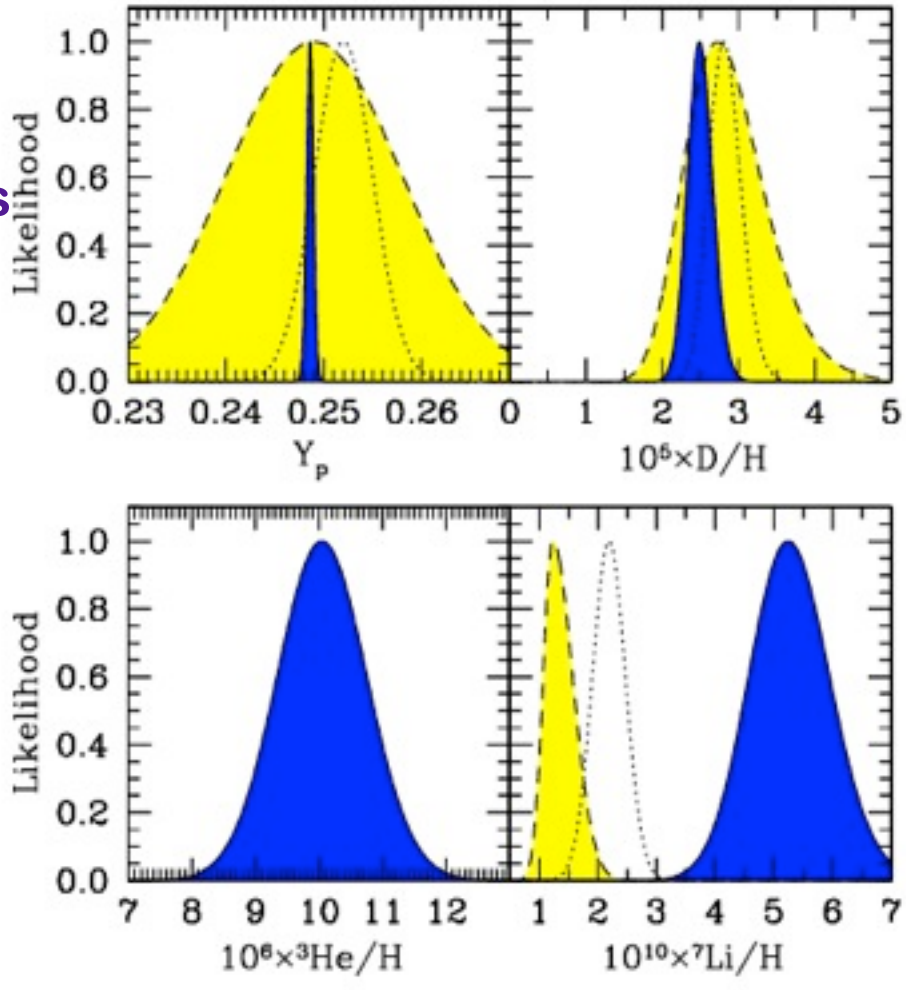

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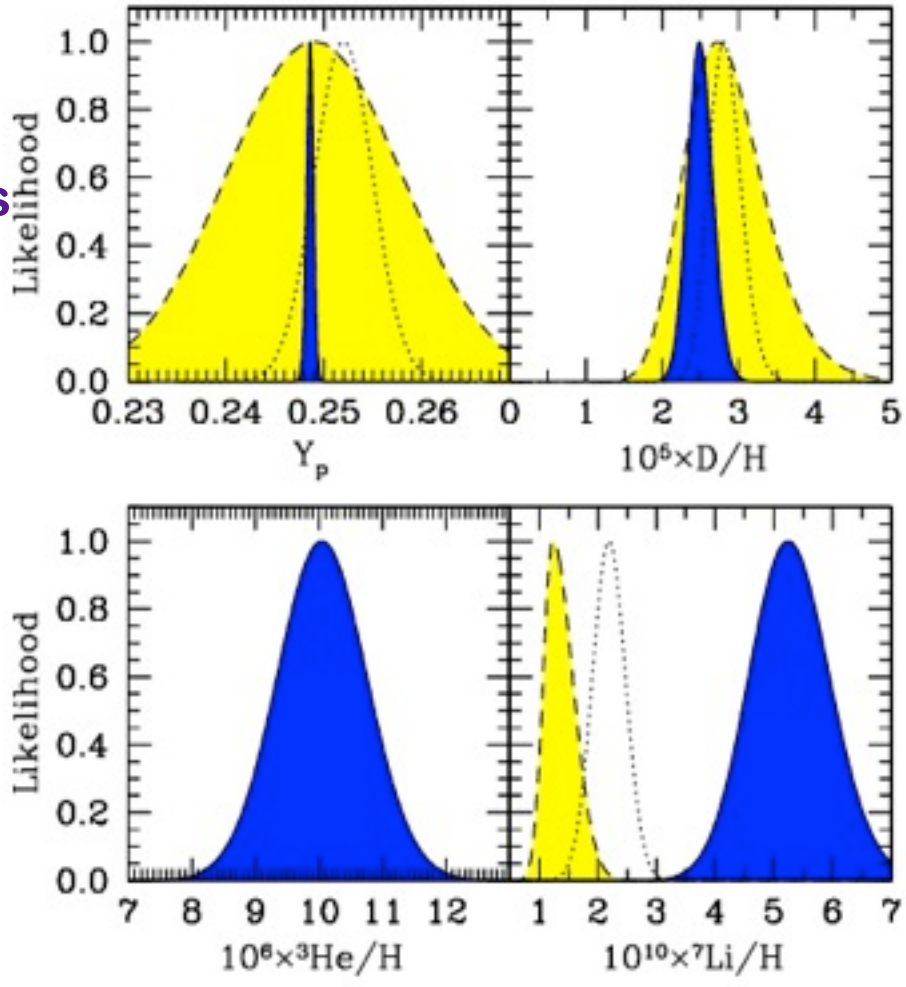

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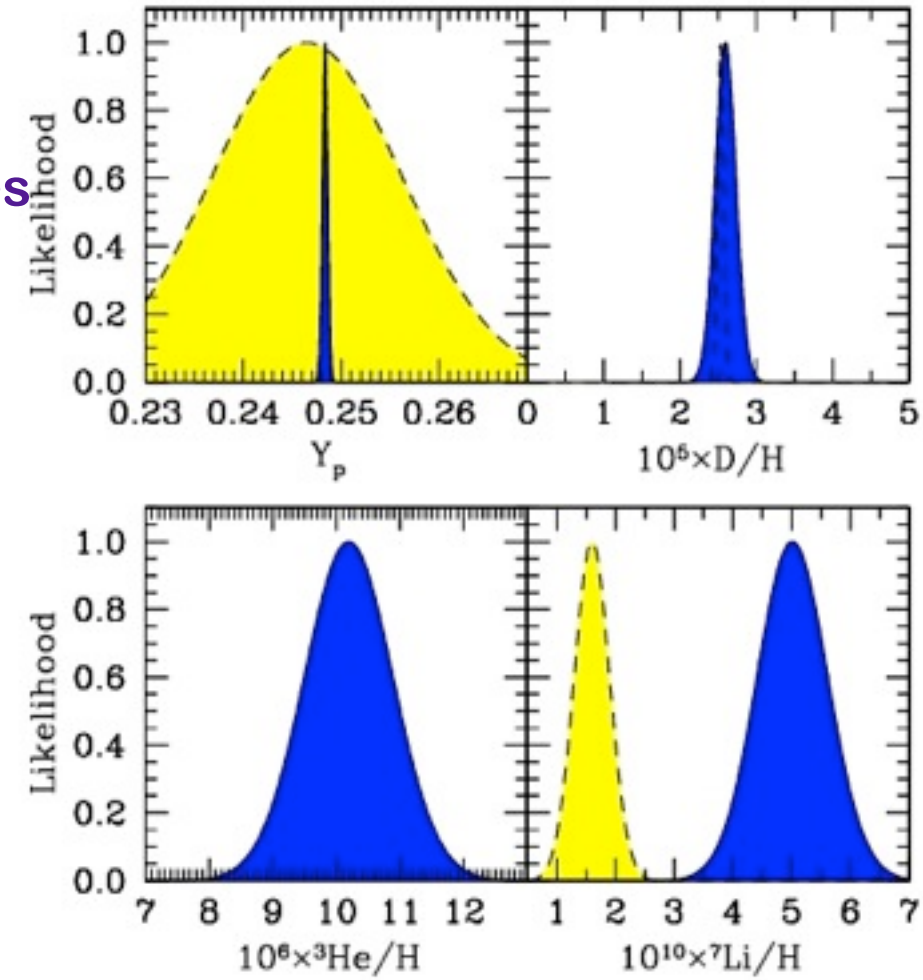

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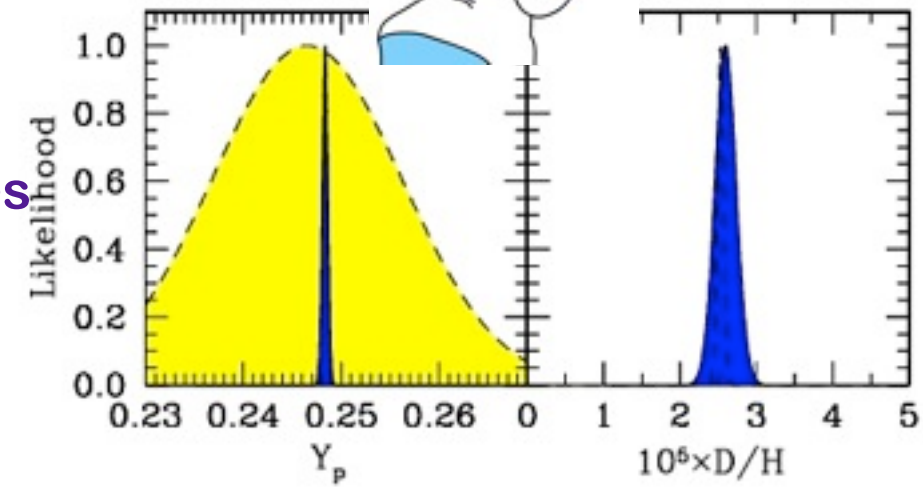

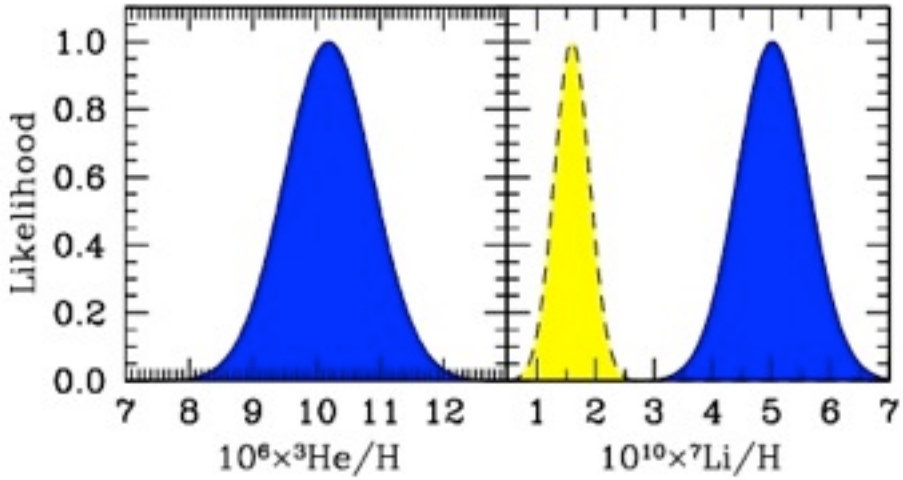

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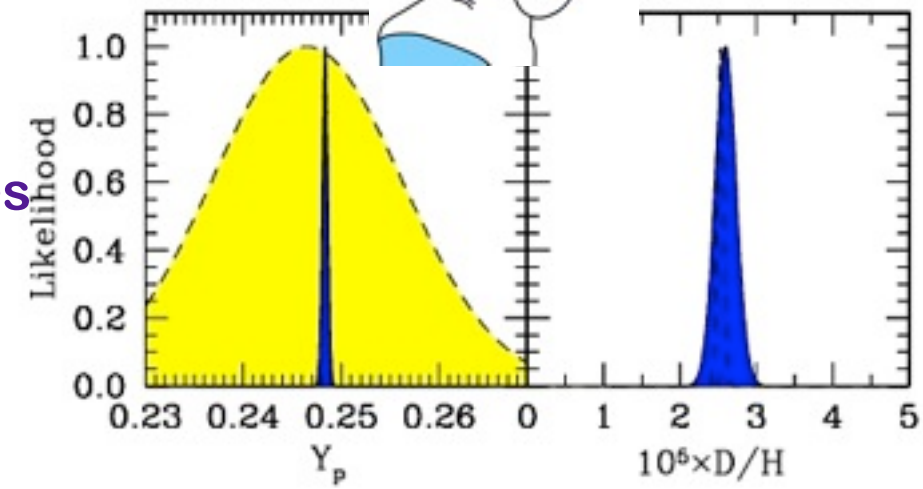

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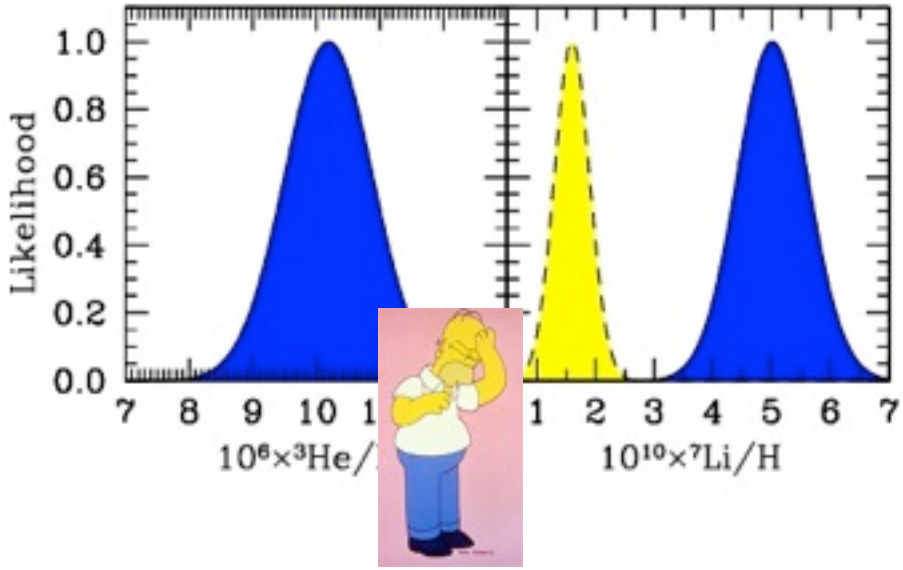

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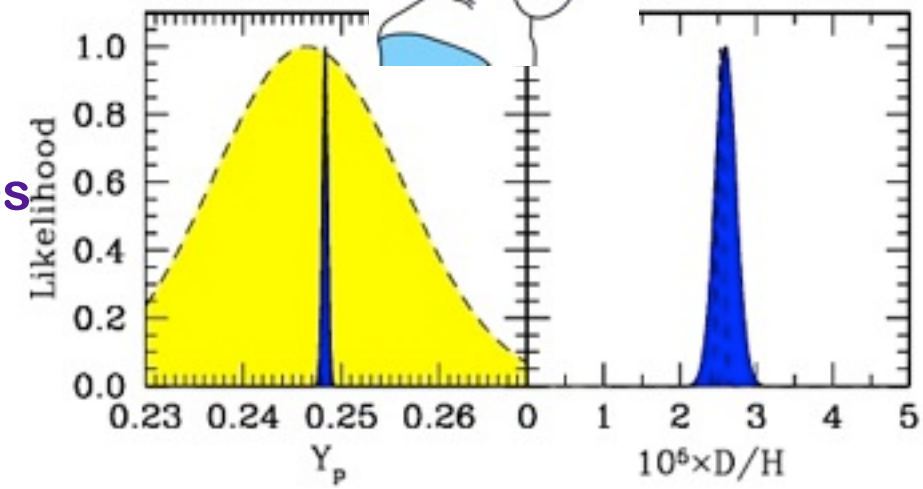

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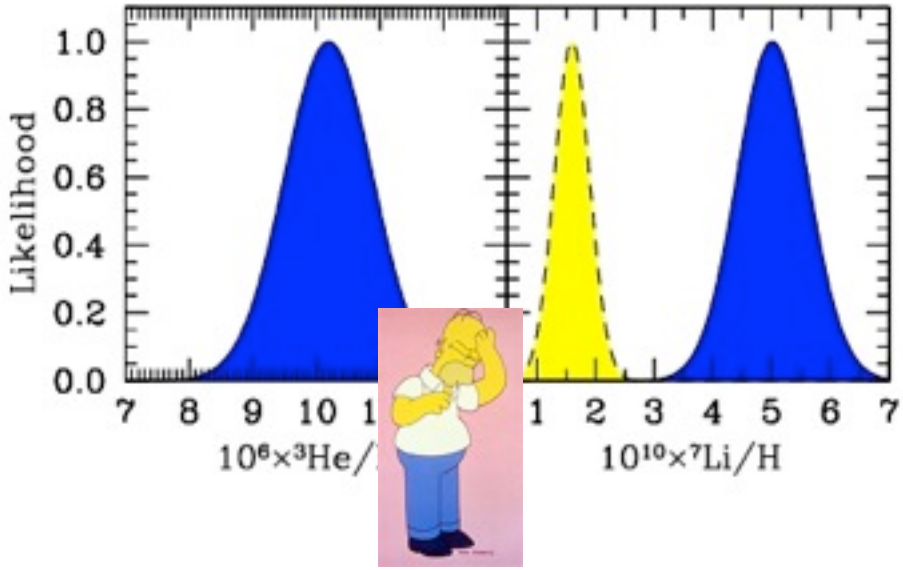

Lithium Strategy I:
No Worries
Two out of three ain't bad

Dark Matter

Pre-CMB Anisotropies:

BBN ⇨ Dark Matter

WMAP finds:

- ★ $\Omega_{\rm B} = 0.044 \pm 0.004$
- ★ $\dfrac{\Omega_{\rm M}}{\Omega_{\rm B}} = \dfrac{\rm matter}{\rm baryons} = 5.9 \pm 0.3$

Optical galaxy surveys ⇨ luminous matter

$$\Omega_{\rm lum} \sim 0.007$$

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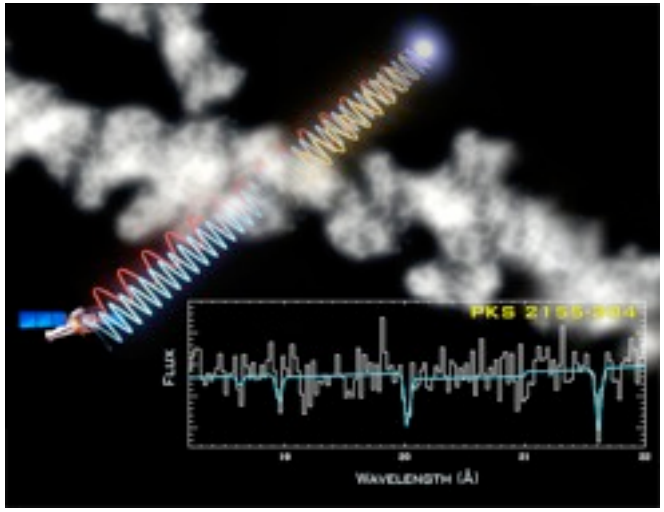
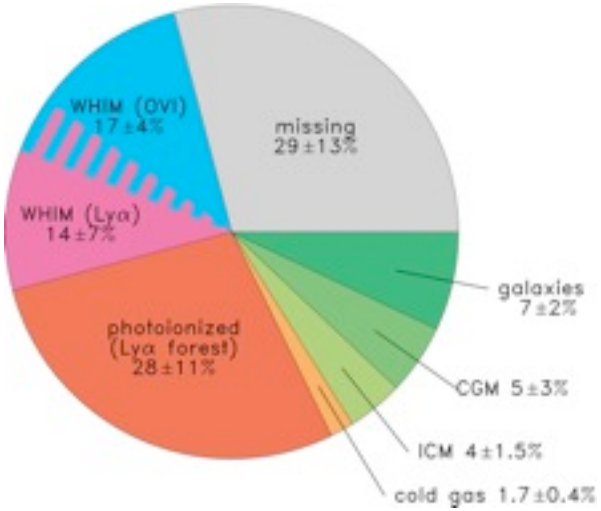
Baryonic Dark Matter: $\Omega_{\rm B} \gg \Omega_{\rm lum}$

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

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



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



Shull, Smith, Danforth 2012

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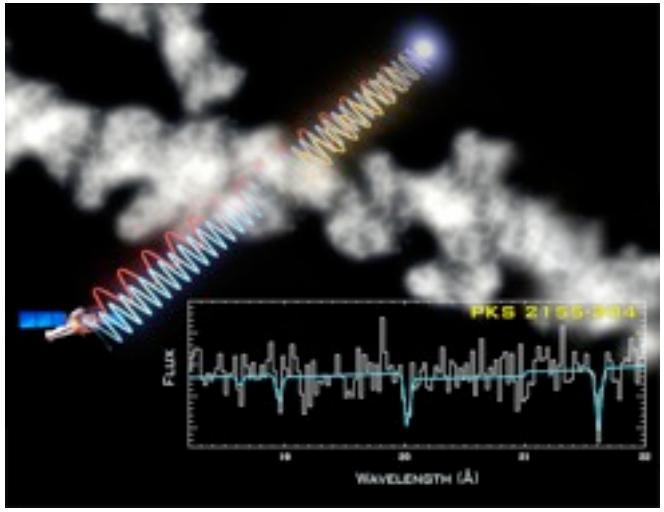

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Non-Baryonic Dark Matter: $\Omega_{\rm B} \ll \Omega_{\rm M}$

➡ **most of cosmic matter!**

Bullet Cluster
optical, X-rays=baryons (red), lensing=gravity (blue)

Dark Matter

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[illegible]r: Dave etal

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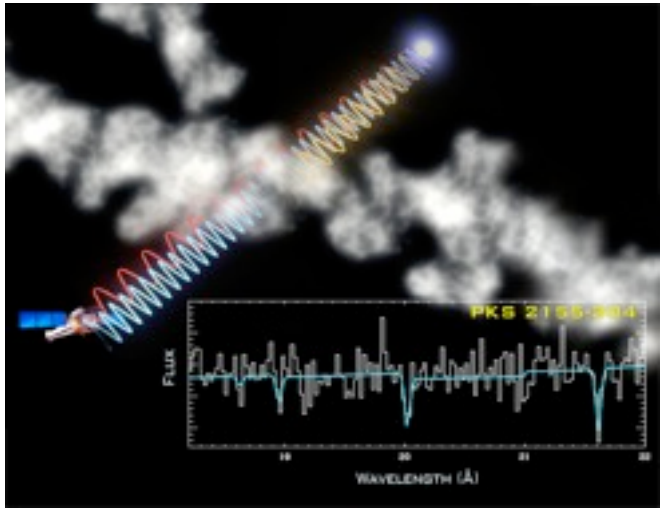
Non-baryonic dark matter demands physics beyond the Standard Model!



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Big Bang Nuke Lessons Thus Far

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Standard Cosmology in Great Shape

- expanding world model fits mountain of data
- hot, early Universe confirmed by CMB: atomic age
- earliest current probe: big bang nuke: t~1 sec
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Big Bang Nucleosynthesis

- theory simple, precise: relies on solid physics
- observations: light elements -- challenging
- Planck $\eta_{\rm cmb}$ 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!

A Bitter Pill: The Primordial Lithium Problem

★ 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

★ The Lithium Problem

- ^{7}Li disagreement: CMB vs astro observations
- new observational probes of Li
- new nuclear physics?
- new particle physics?

Lithium Strategy II:
Worry

Lithium: Observables

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

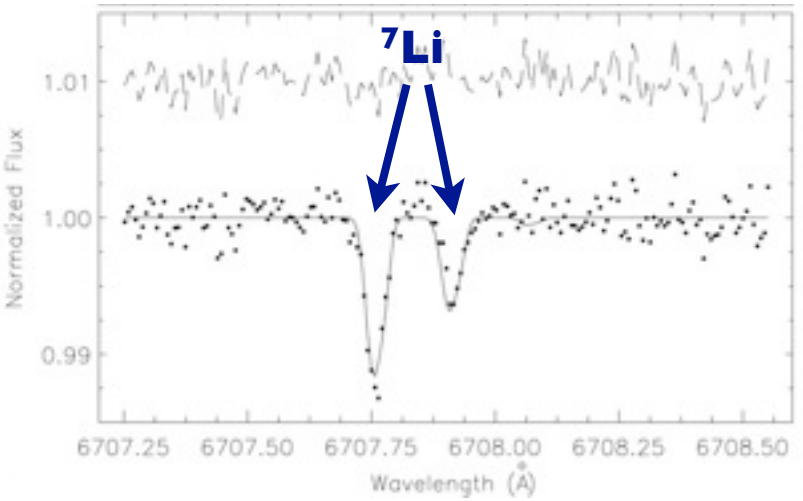
Lithium: Observables

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



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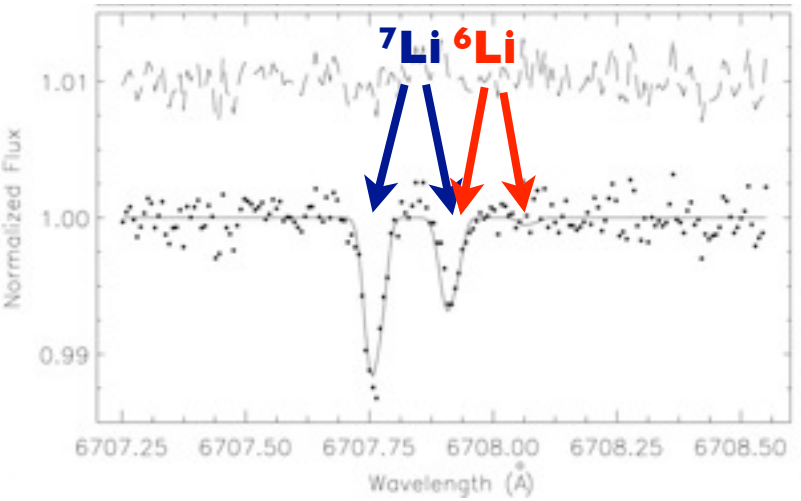

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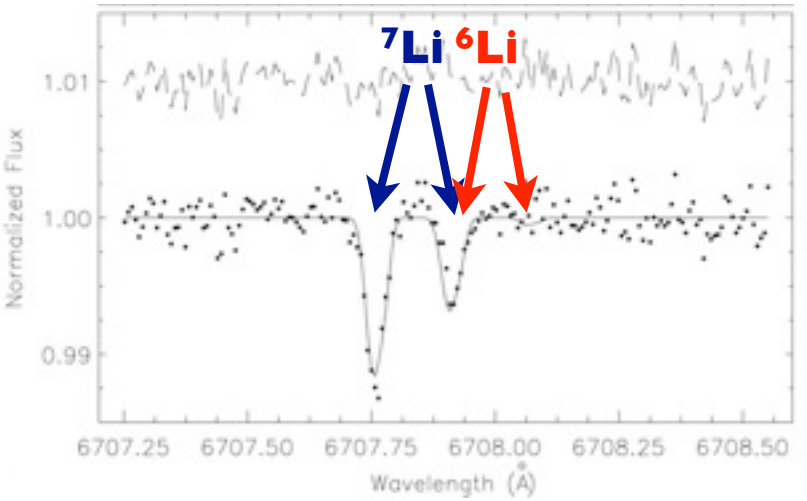

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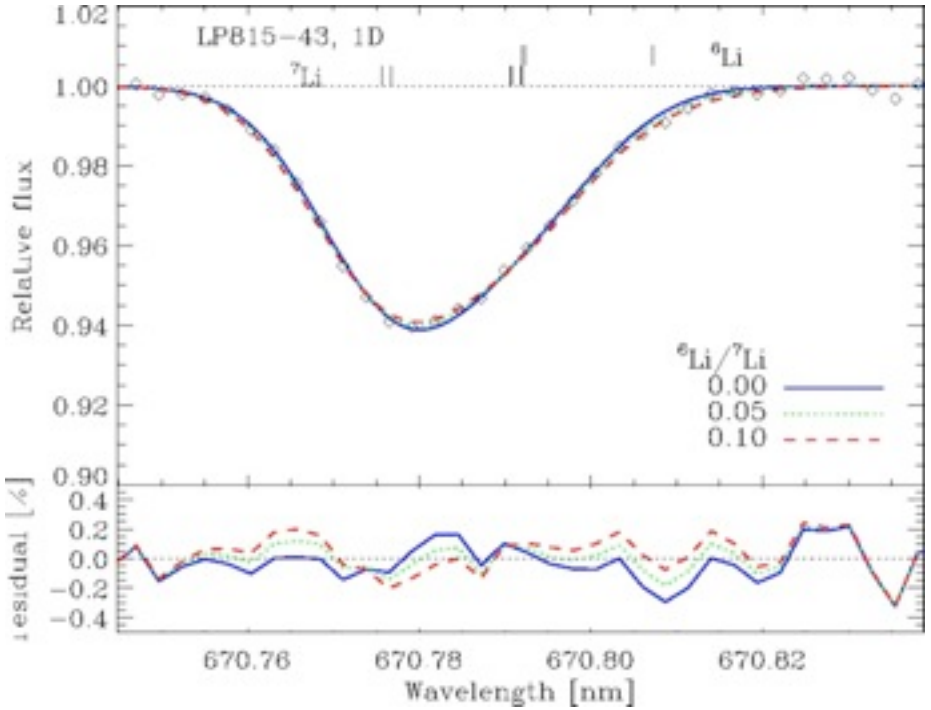

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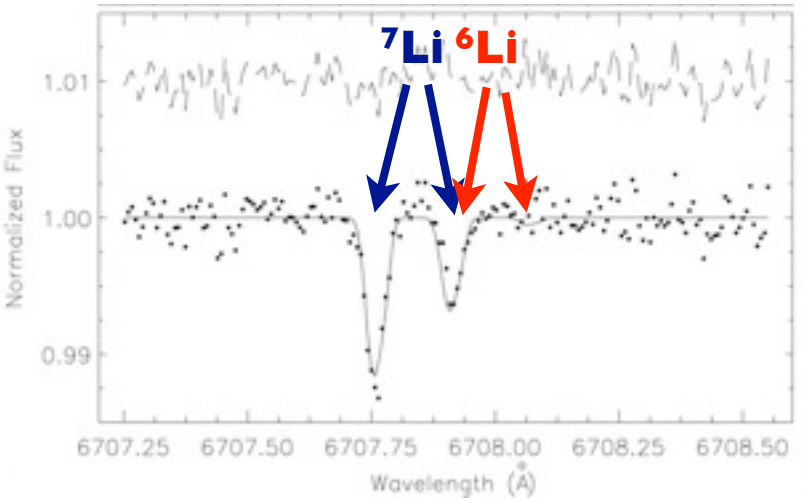

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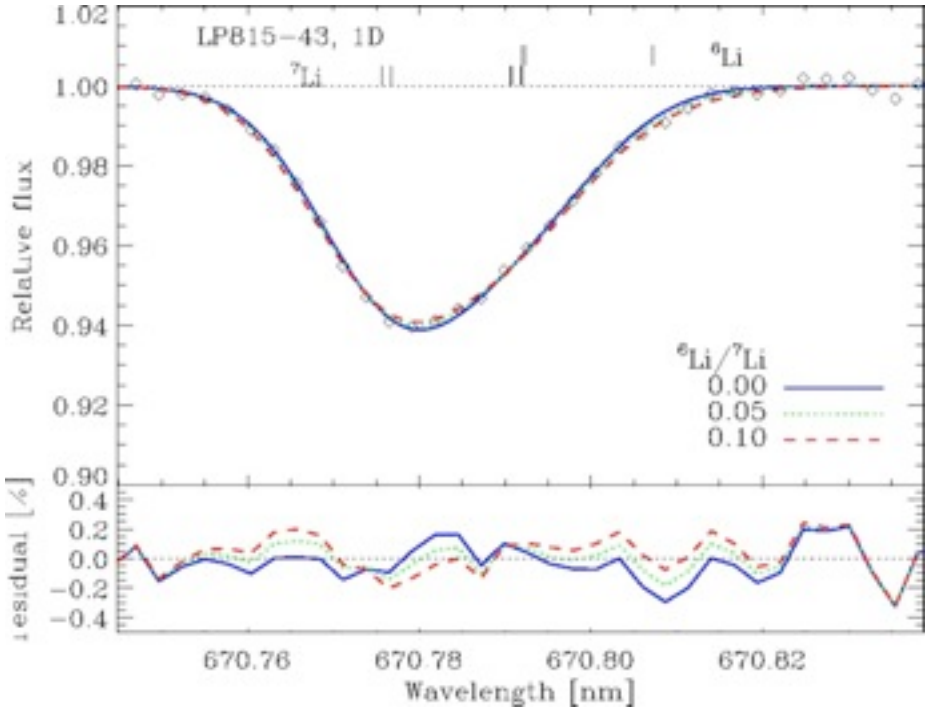

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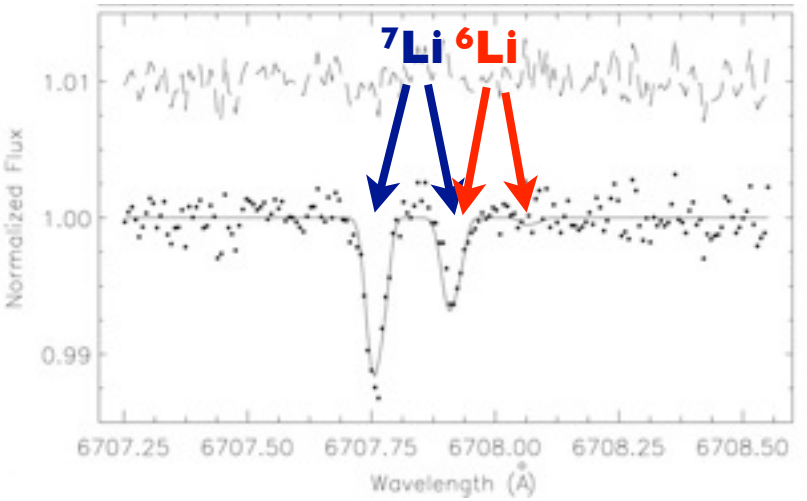

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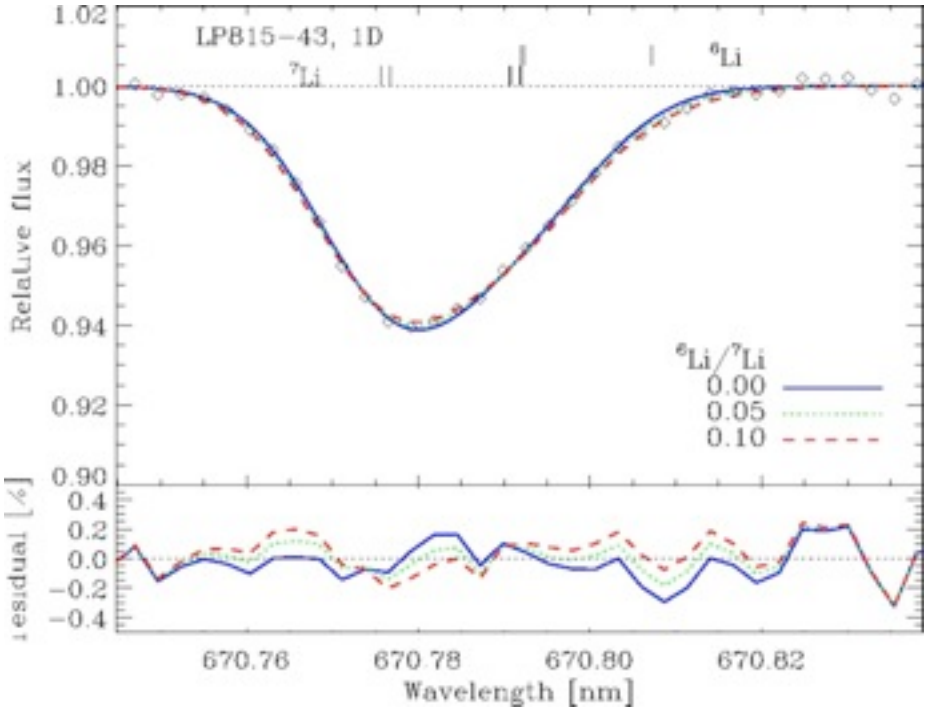
lineshape gives isotopic ratio ^{6}Li/^{7}Li



Primordial Lithium

Observe in primitive (Pop II) stars

Li-Fe ⇨ evolution

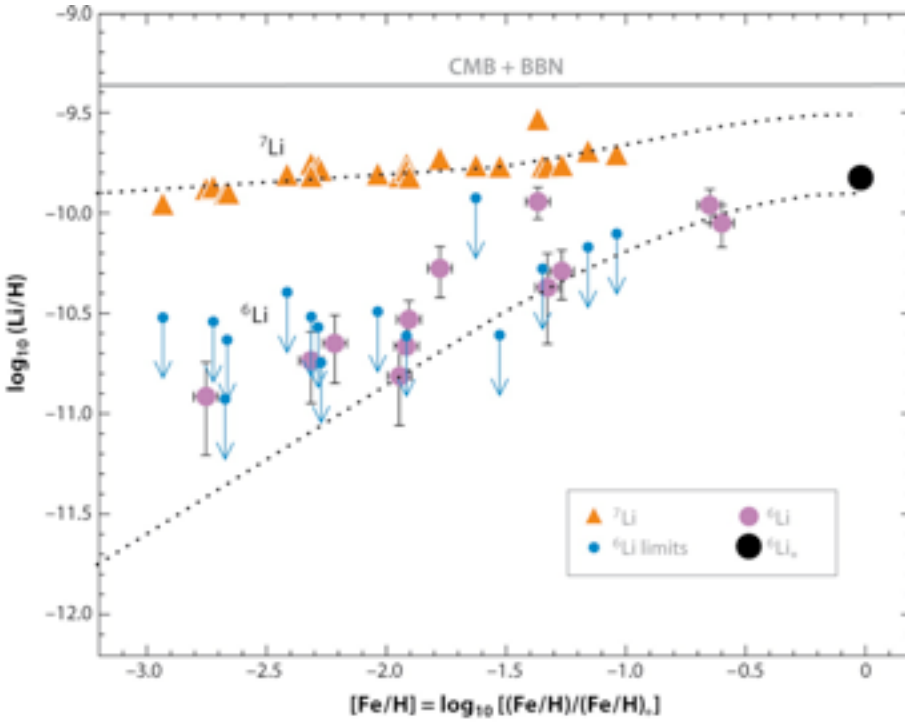
Plateau at low Fe Spite & Spite 82

★ down to [Fe/H]~-2.75

★ const. abundance at early epochs

★ Li is primordial

lithium abundances



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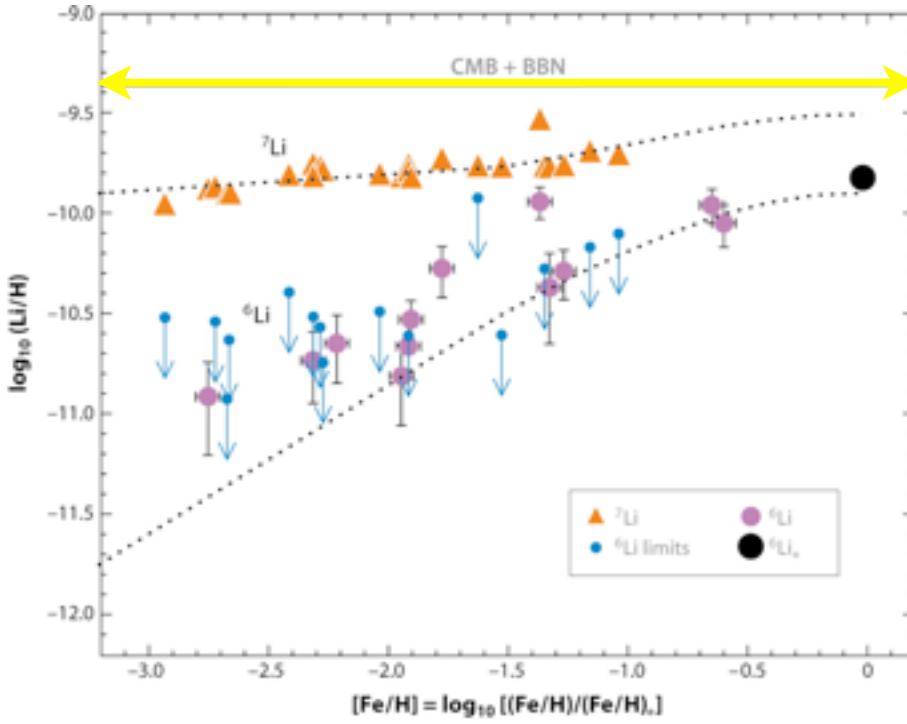

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Also: Recent hints of Asplund et al 2006 primordial $^6Li >> {}^6Li_{SBBN}$?!

lithium abundances

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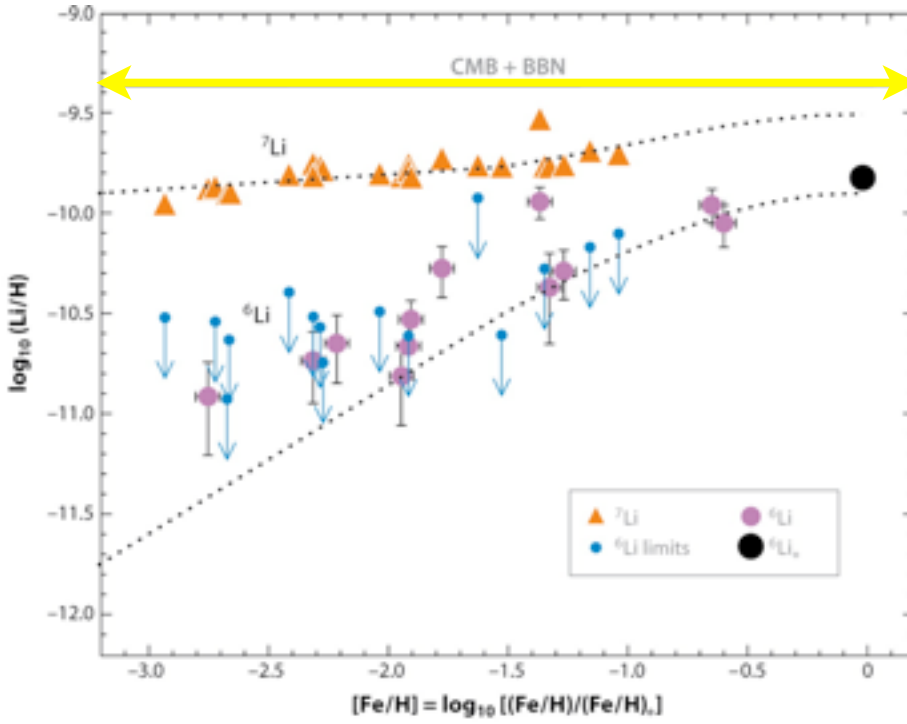

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Astrophysical Systematics

Scenario:

- data & theory correct,
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- but not of initial Li/H

stellar depletion over ~10^{10} yr

if Li burned: correct Li_p upward!

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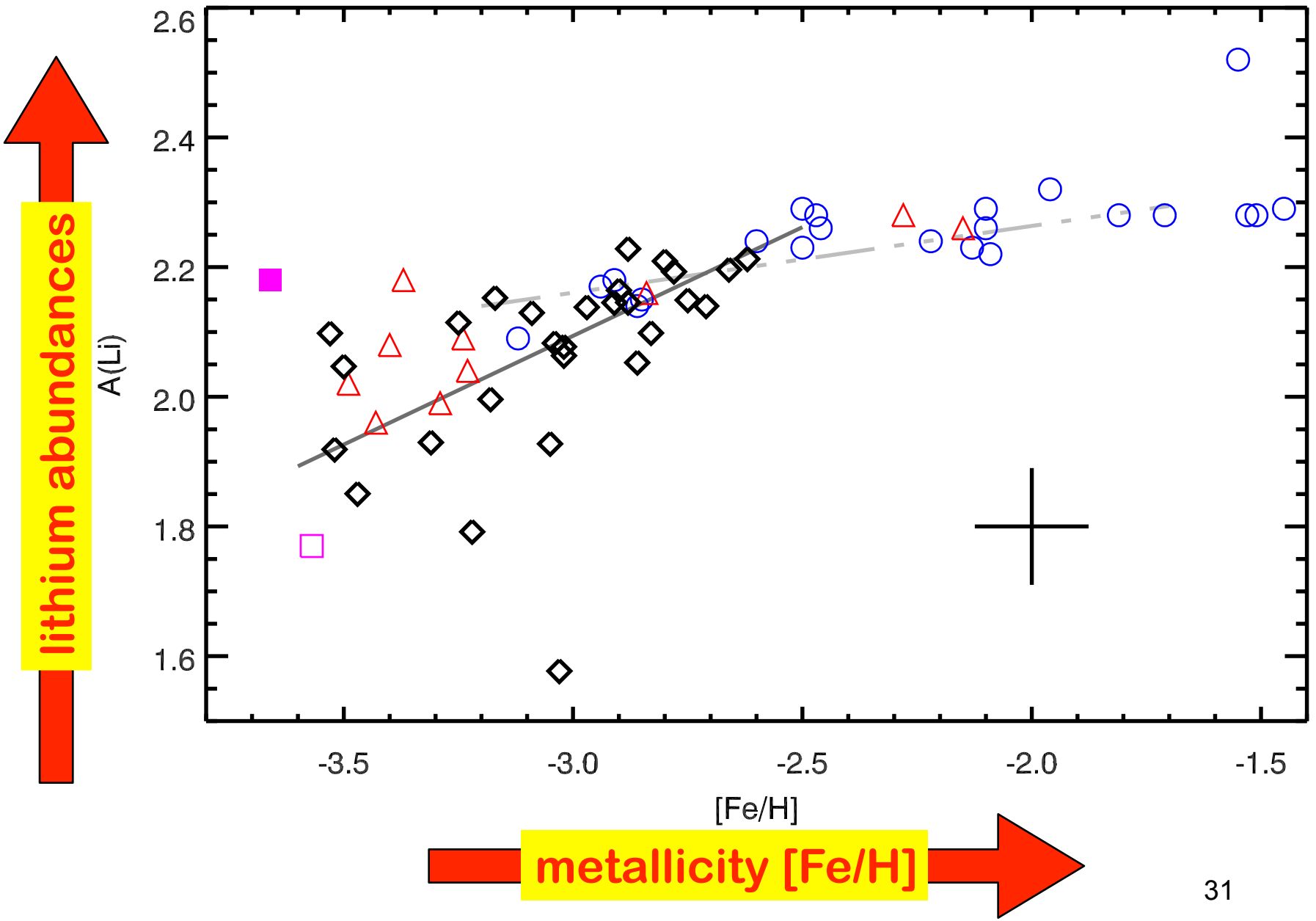
★**no stars seen close to BBN value**

New! Very Low Metallicities

Sbordone et al 2010



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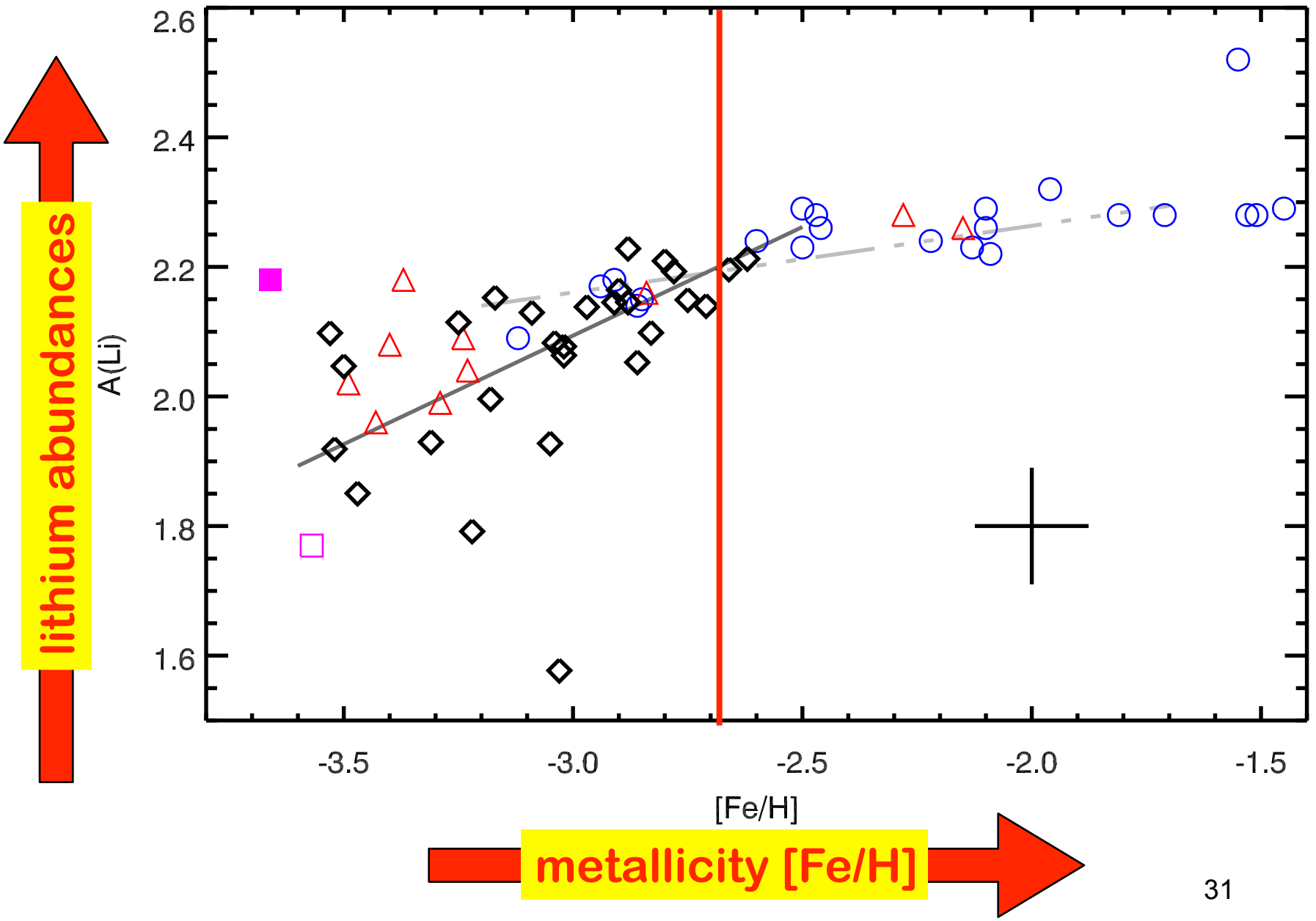

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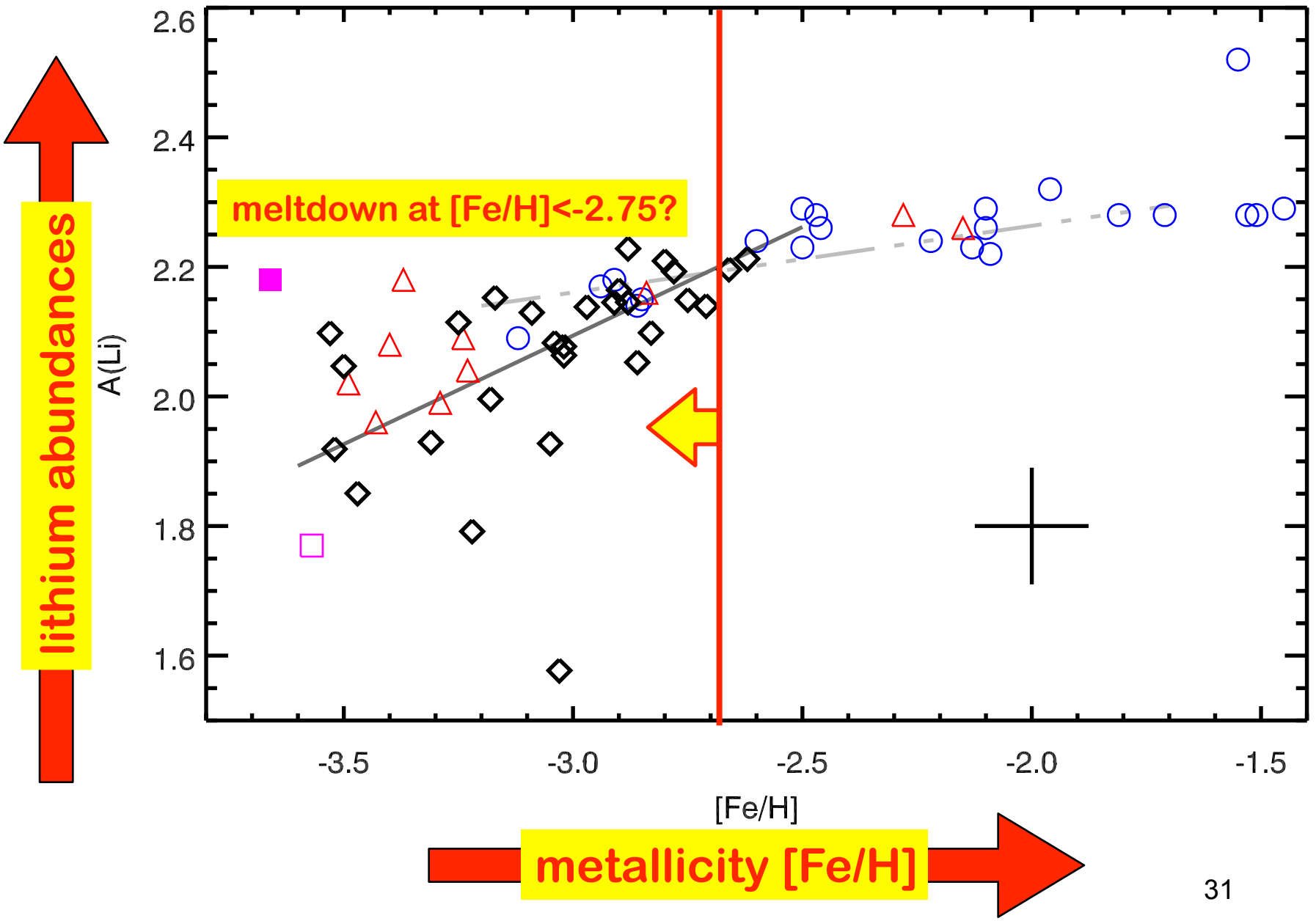

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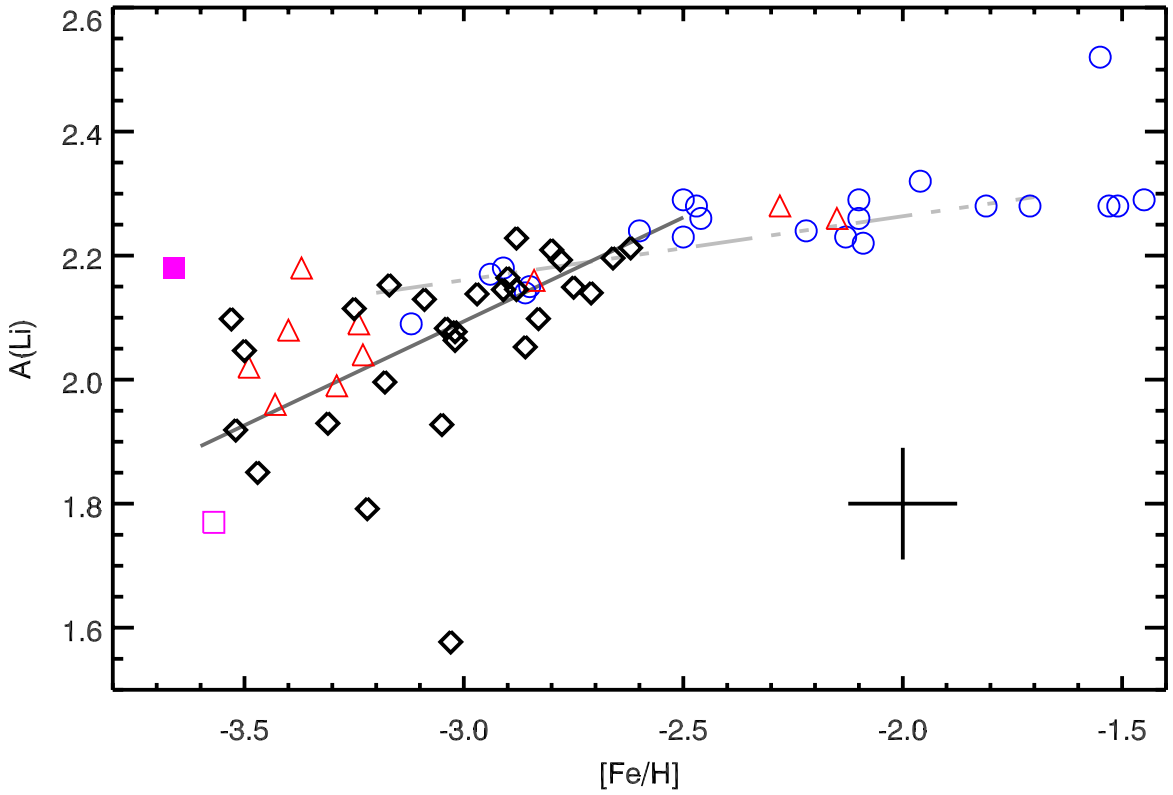

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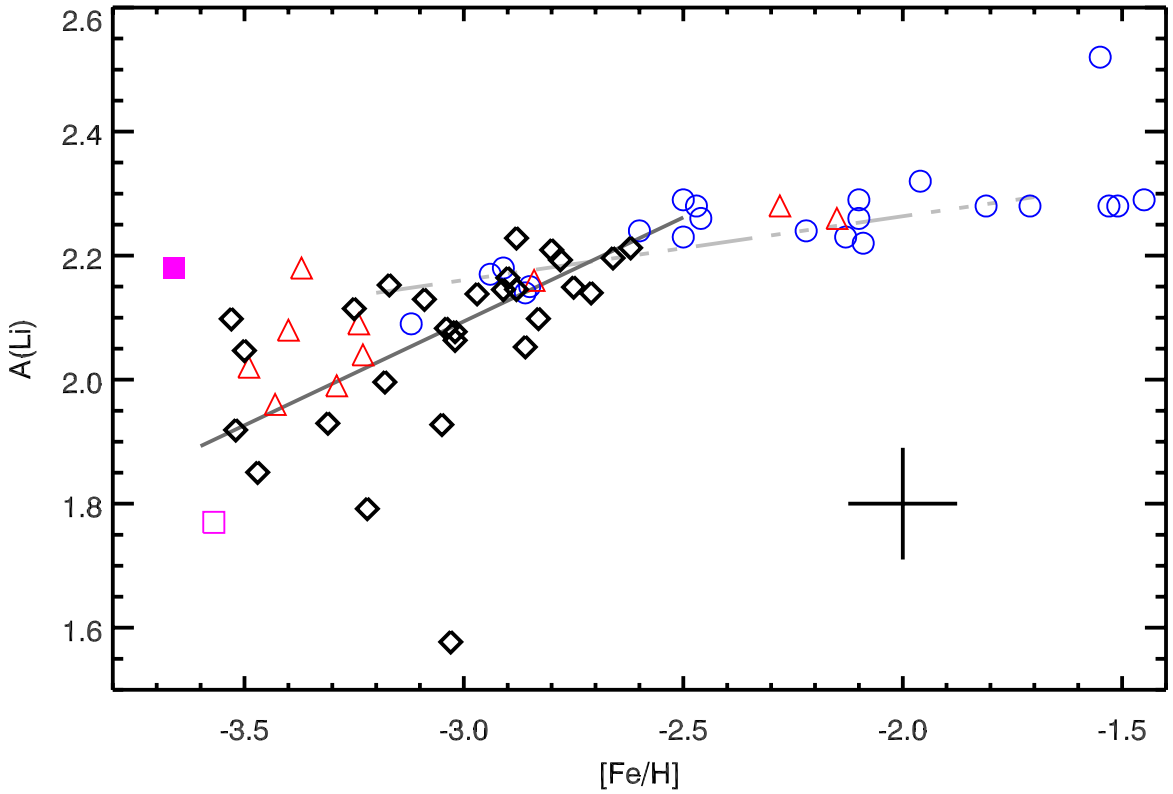
- huge increase in scatter at low [Fe/H]



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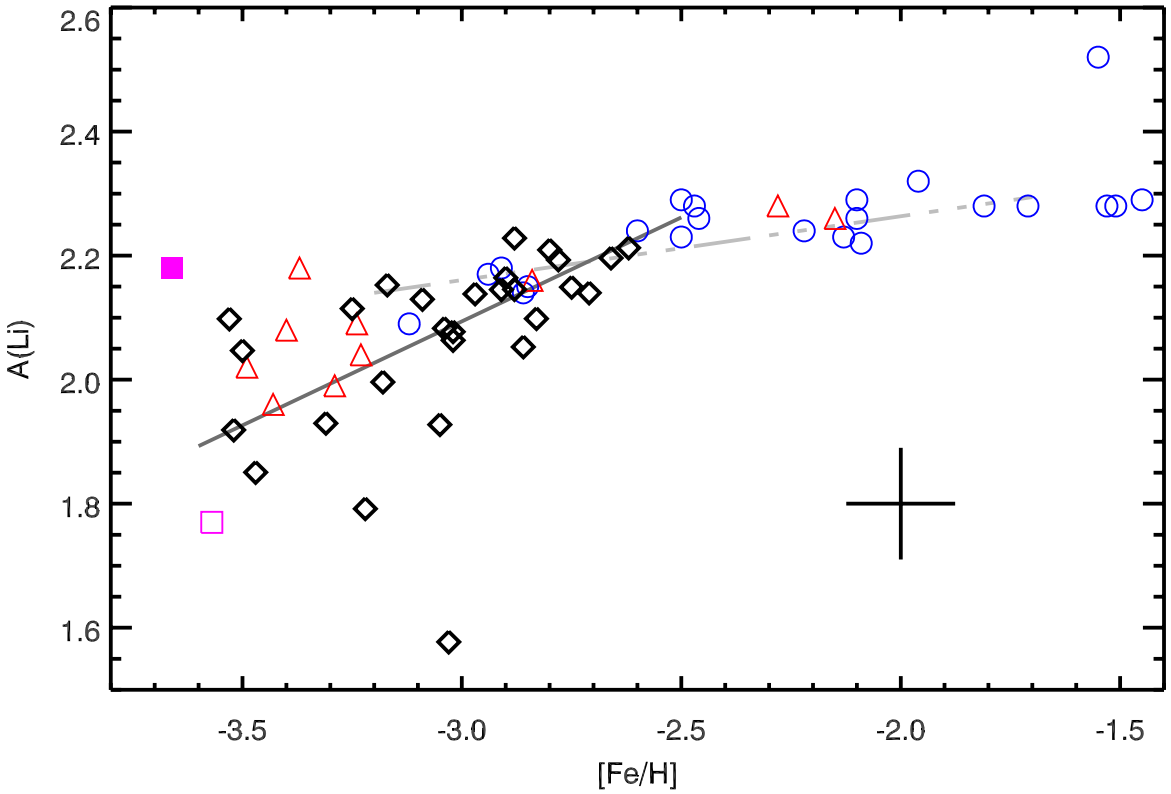

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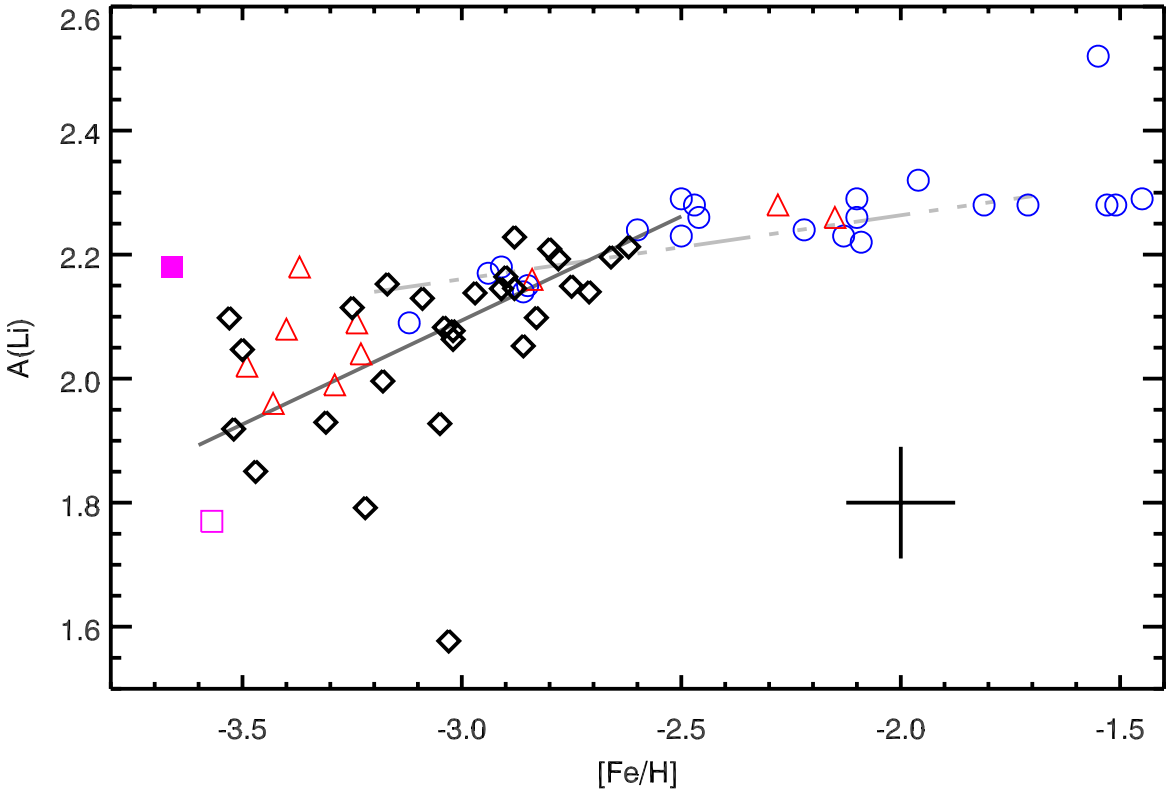

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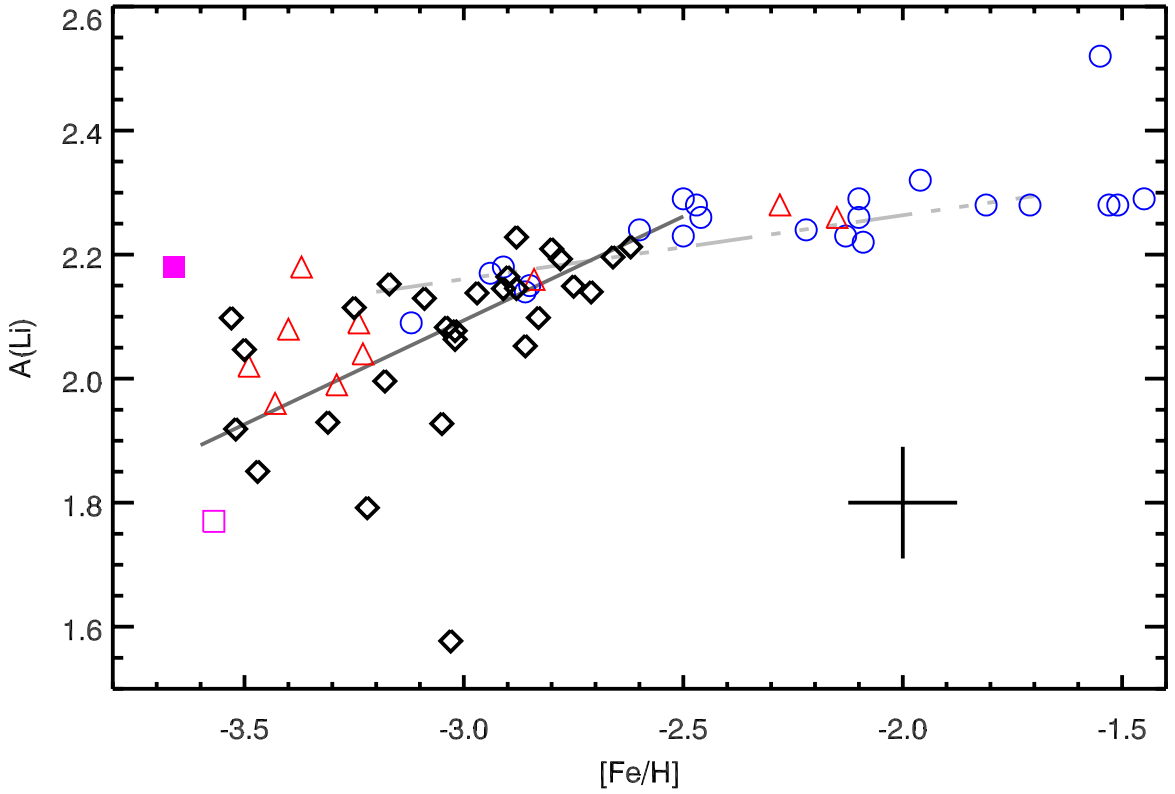

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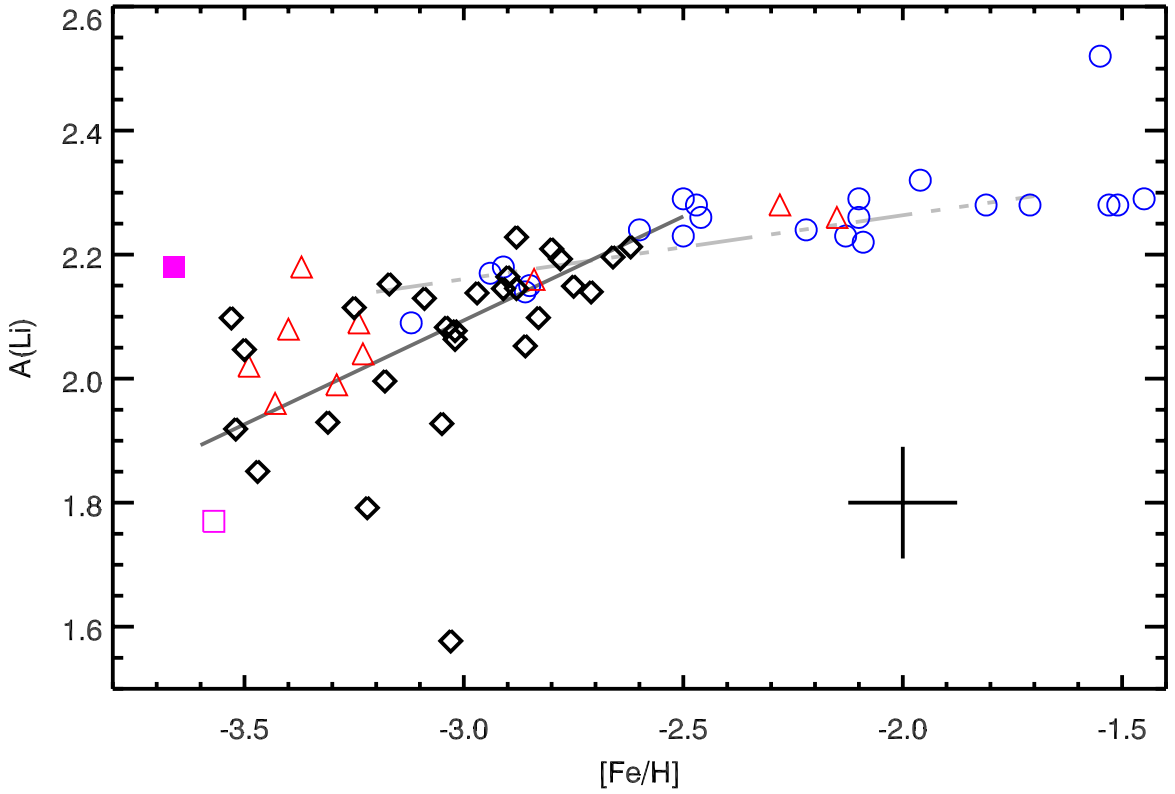

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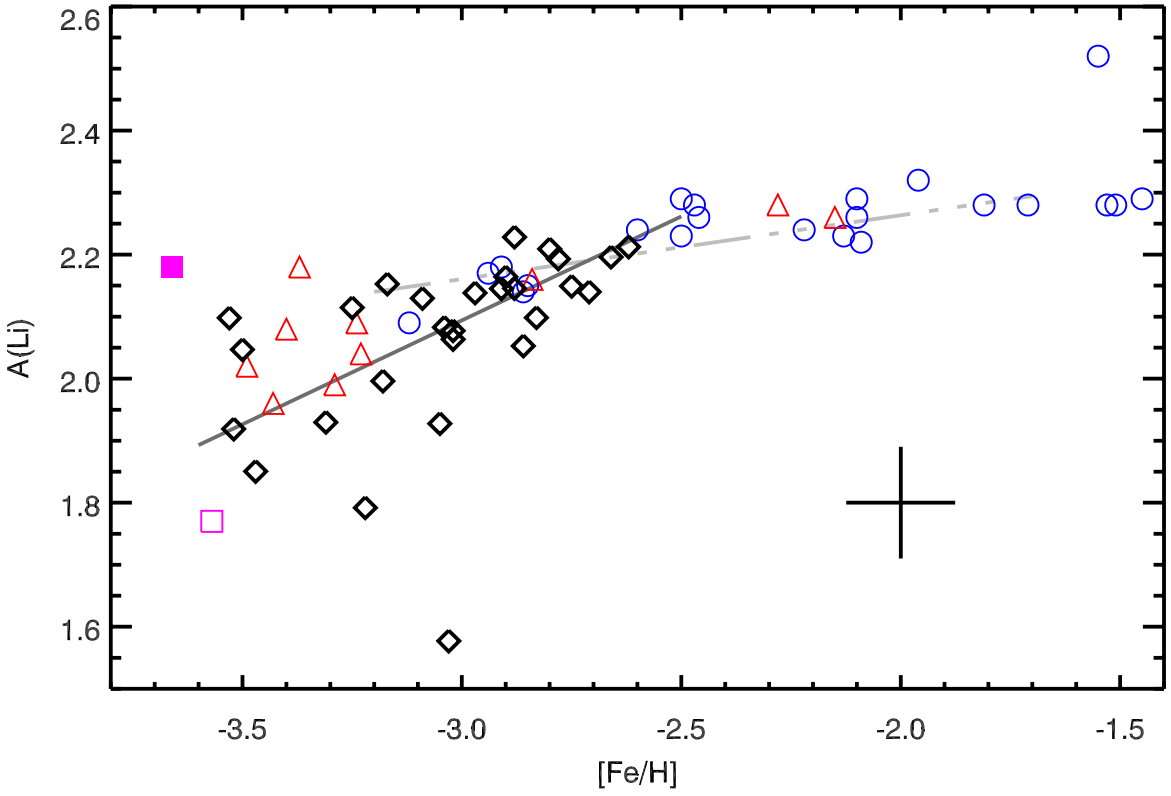

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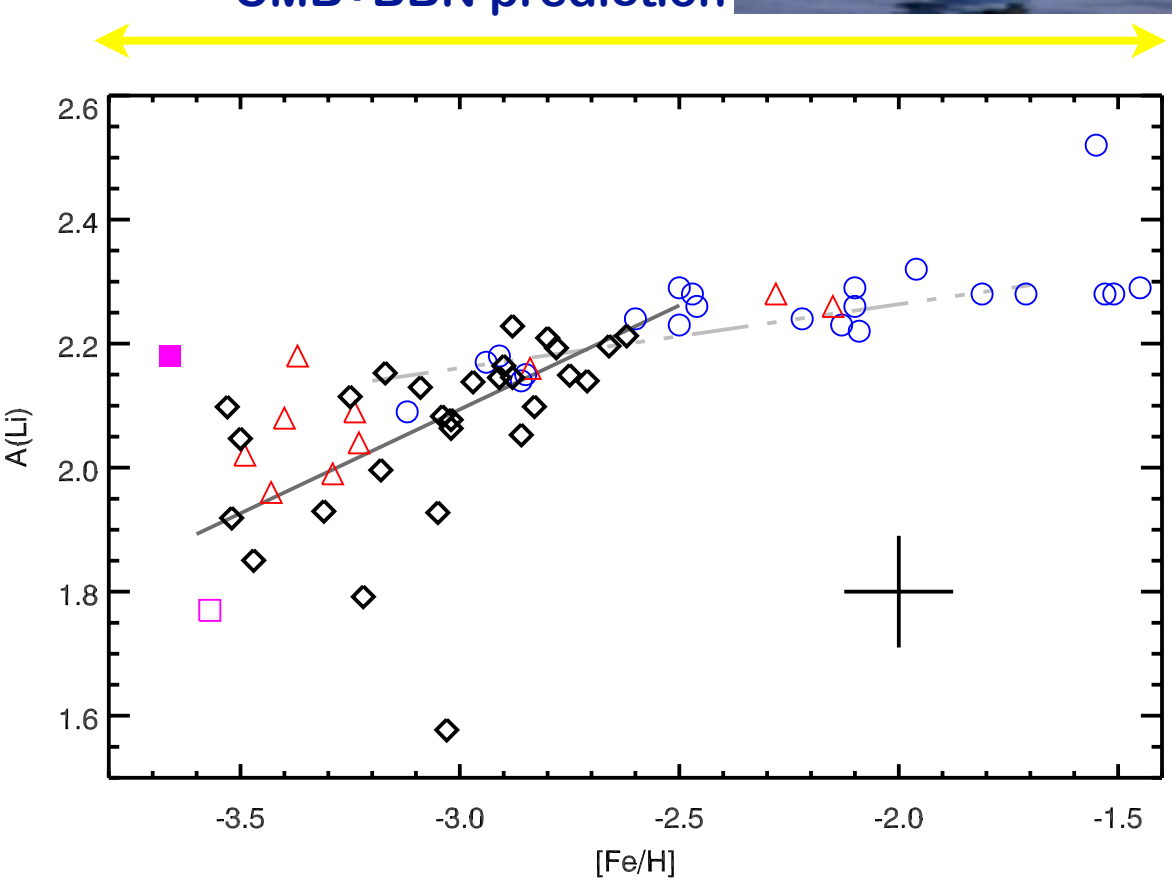

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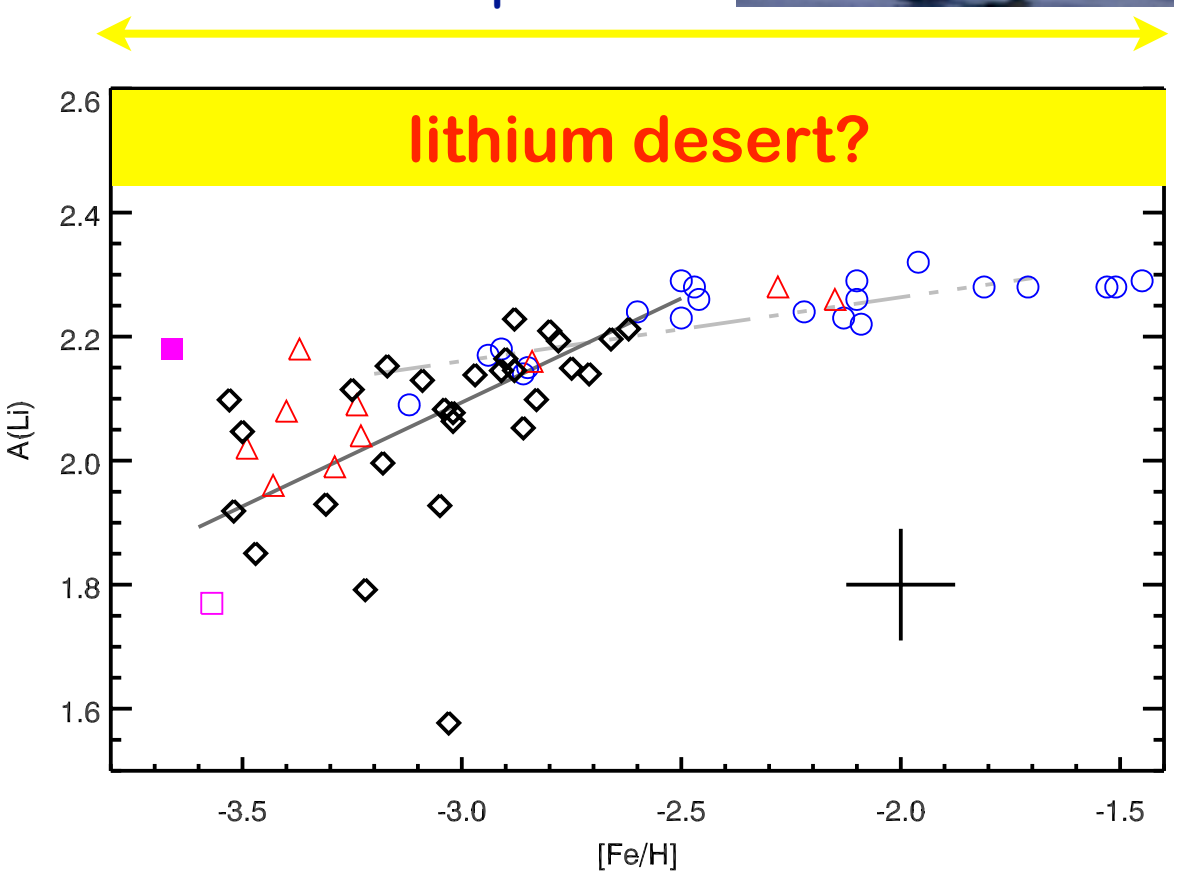

A New Lampost:
Interstellar Lithium

- stellar lithium: measuring air quality outside factory

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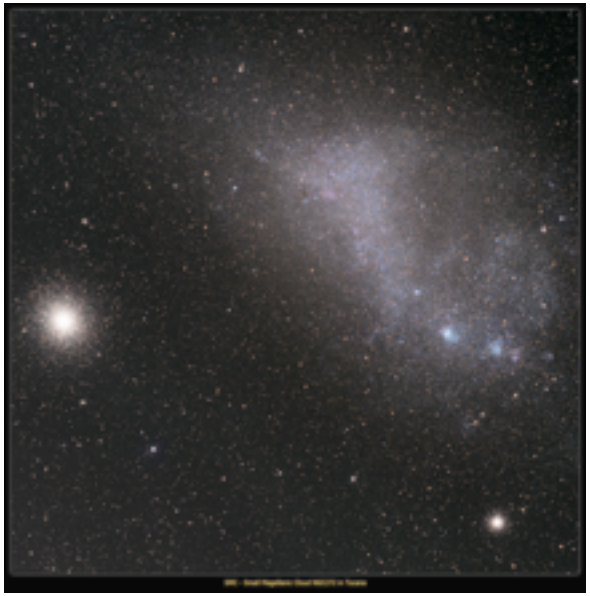

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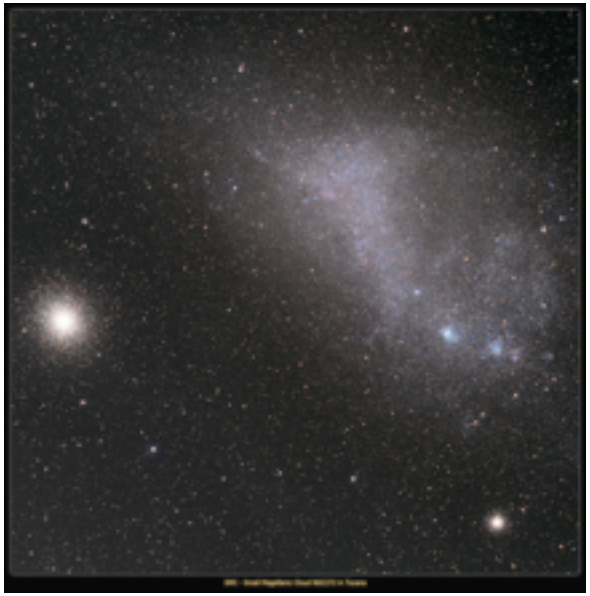

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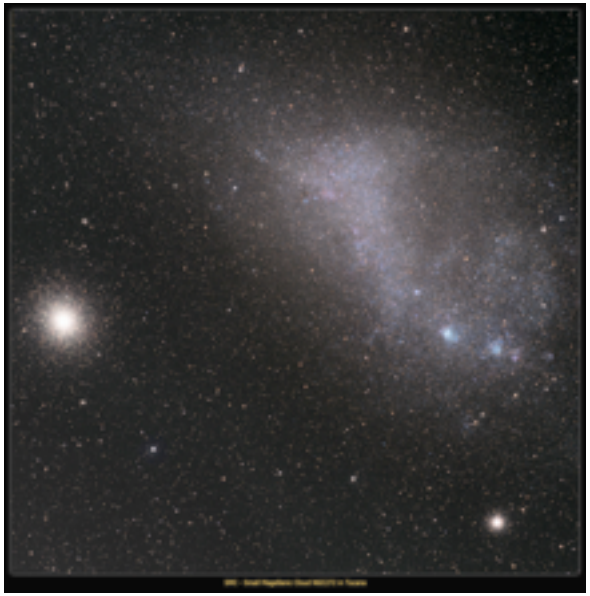

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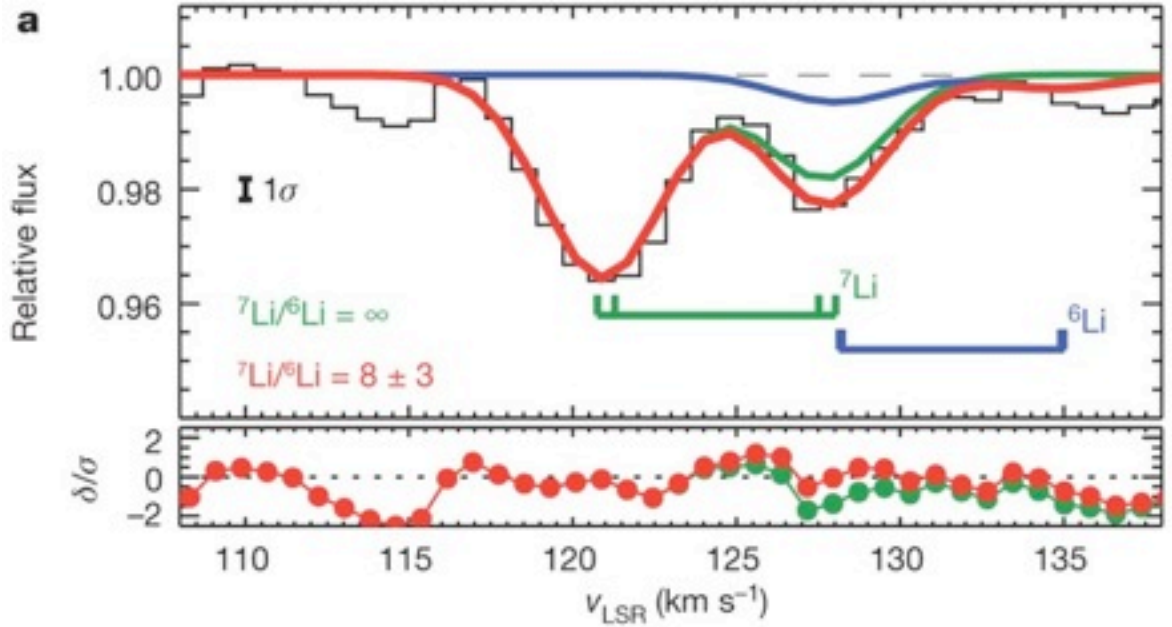

Howk, Lehner, BDF, & Mathews 2013

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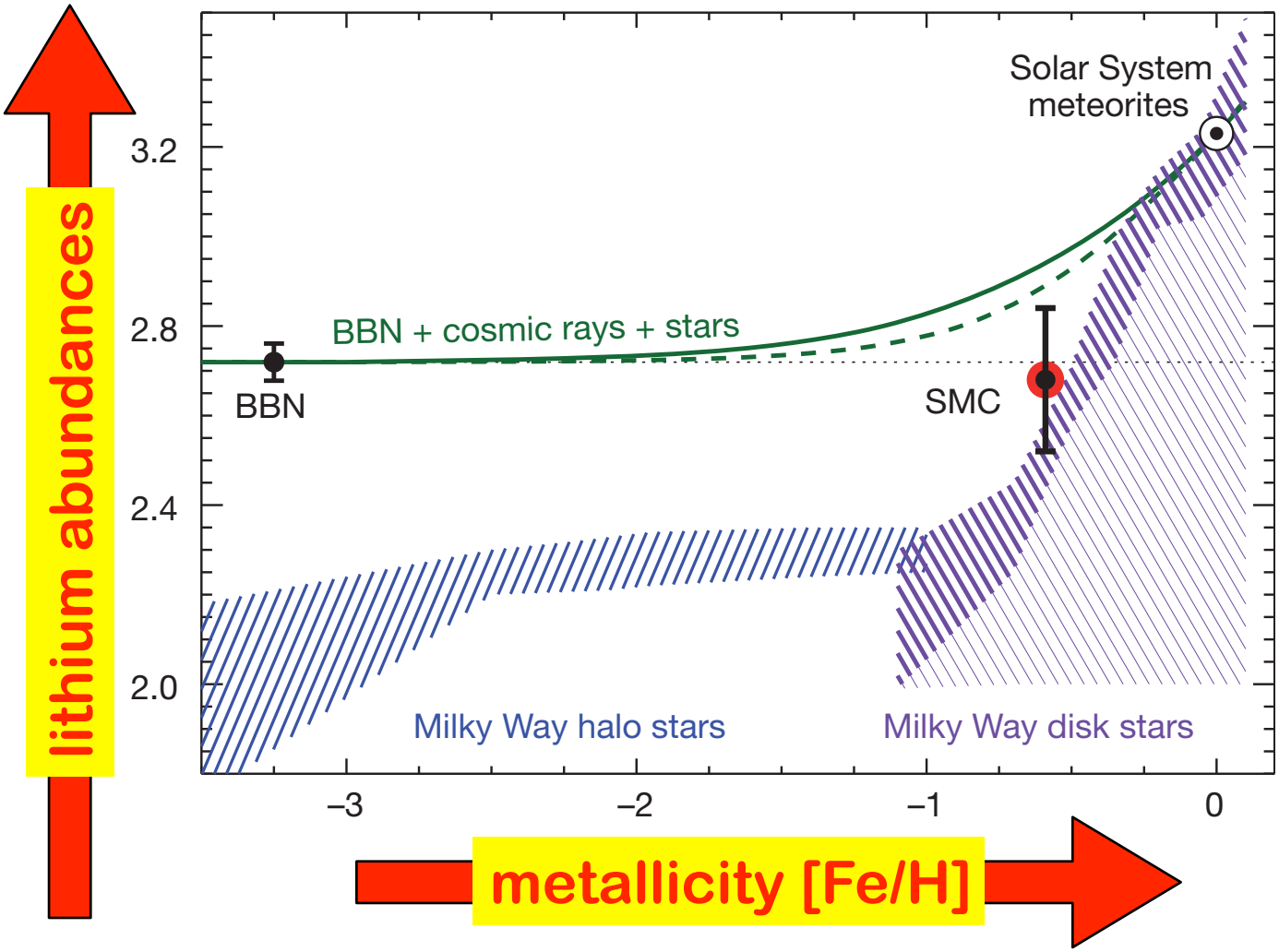

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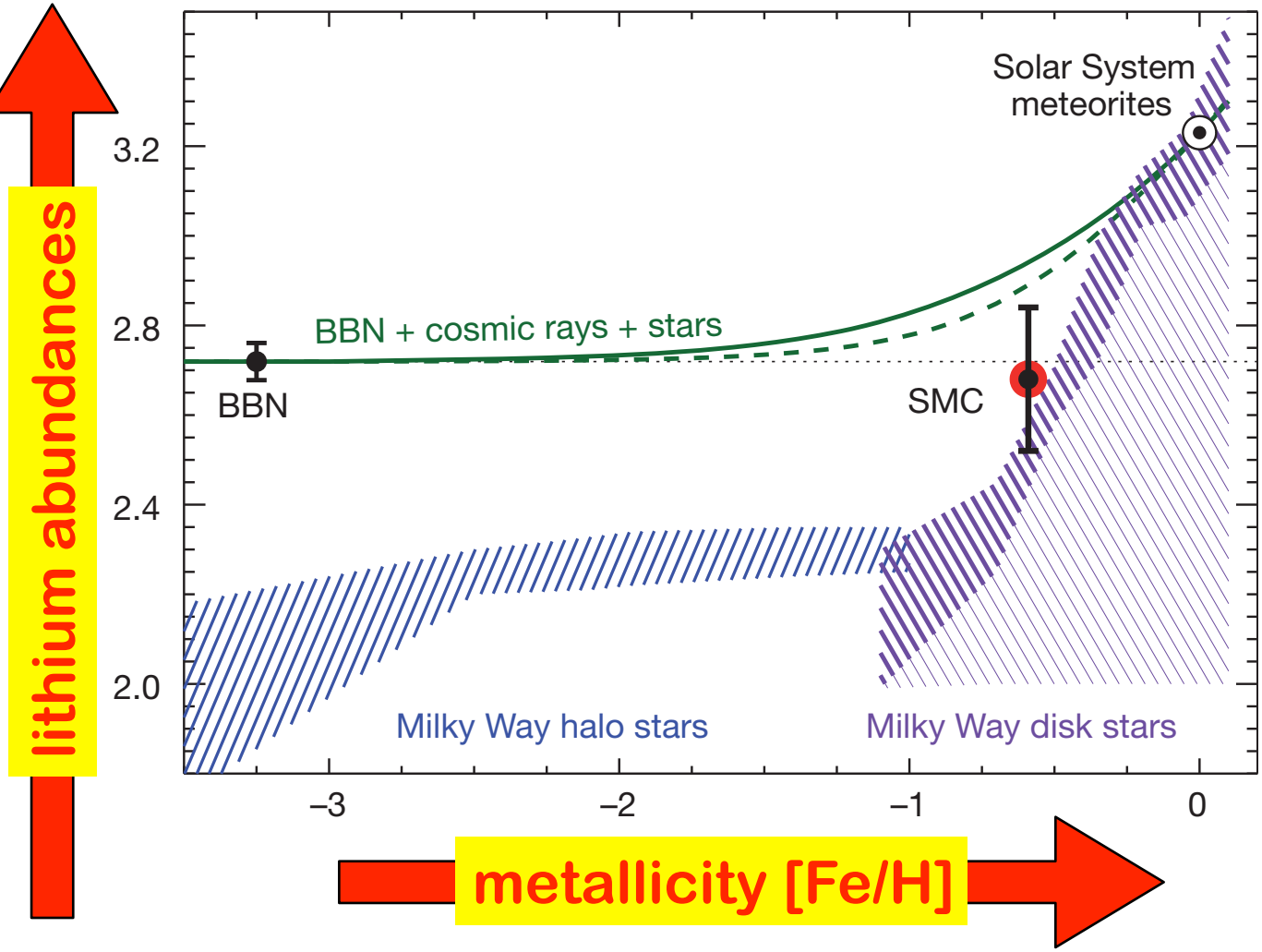

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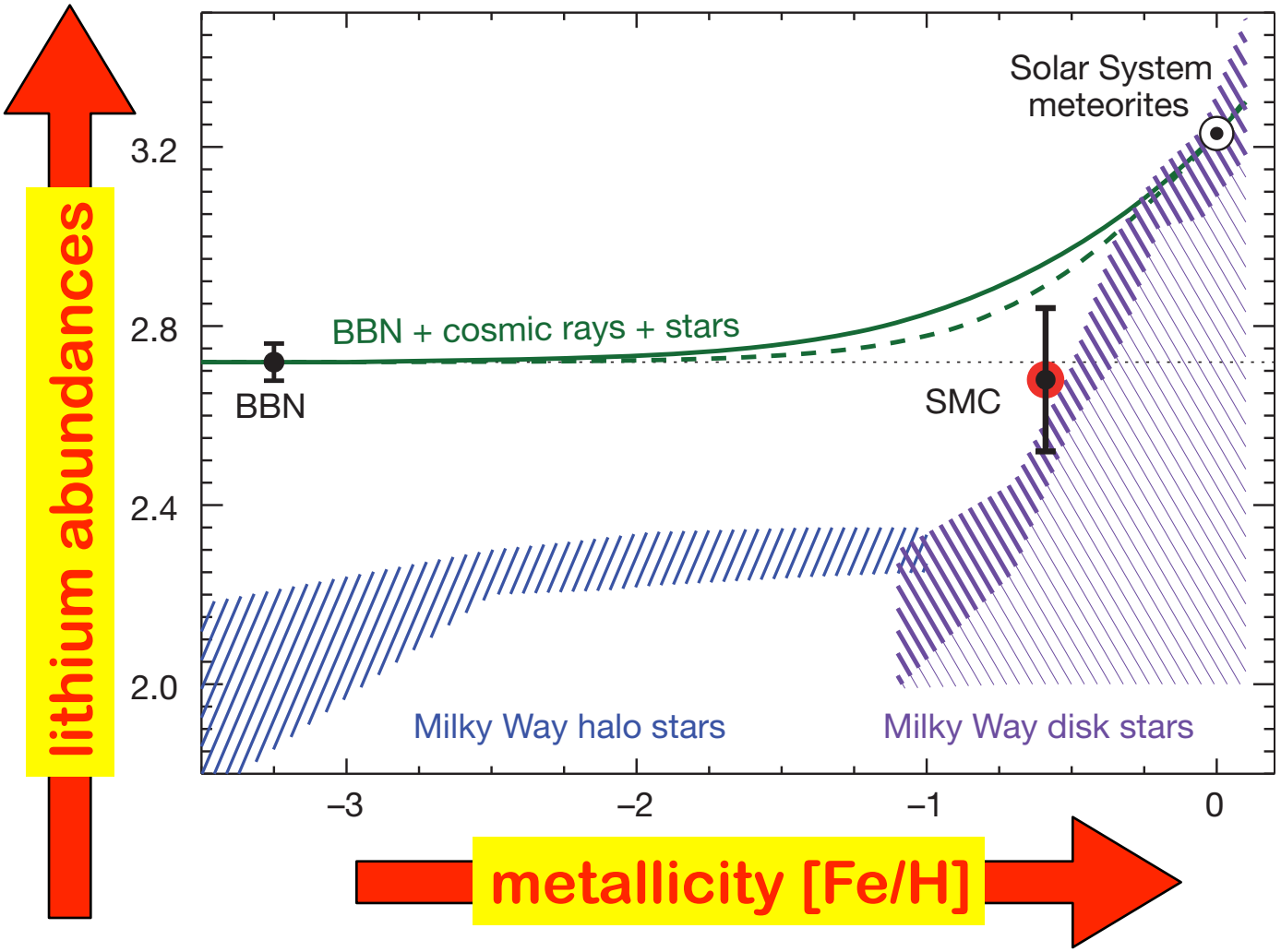

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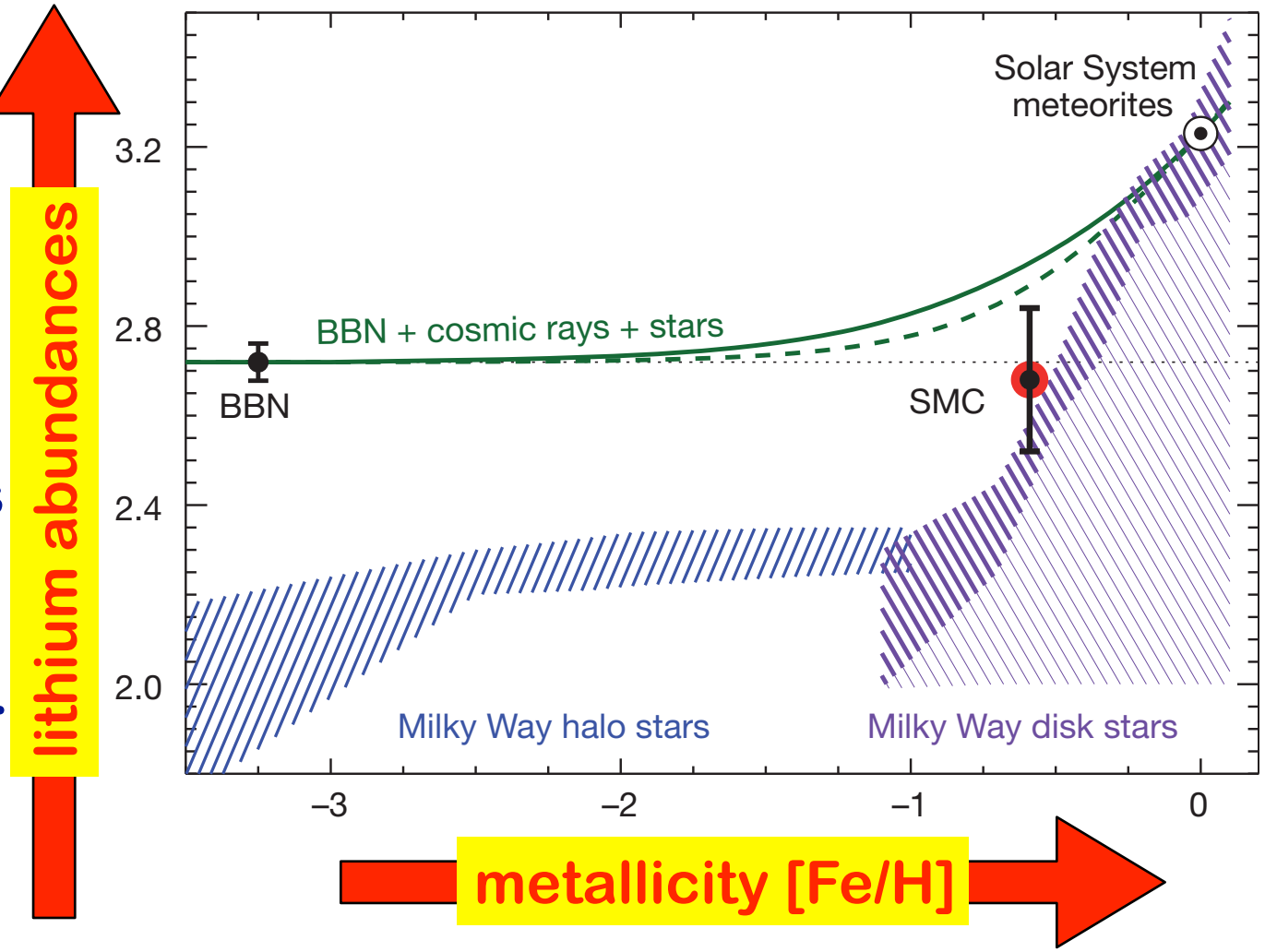
- stellar effects must "turn on" at lower metallicities...



Howk, Lehner, BDF, & Mathews 2013

Lithium: High Redshift

Friedel, Kemball, BDF 2011

- ★ B0218+357: QSO + lens
- ★ lens/absorber: galaxy z~0.658
- ★ look for LiH in absorption
- ★ Prospects:
  - first/only Li evidence outside Local Group
  - ^{7}Li and ^{6}Li isotopes cleanly separable
  - LiH as coolant for first stars

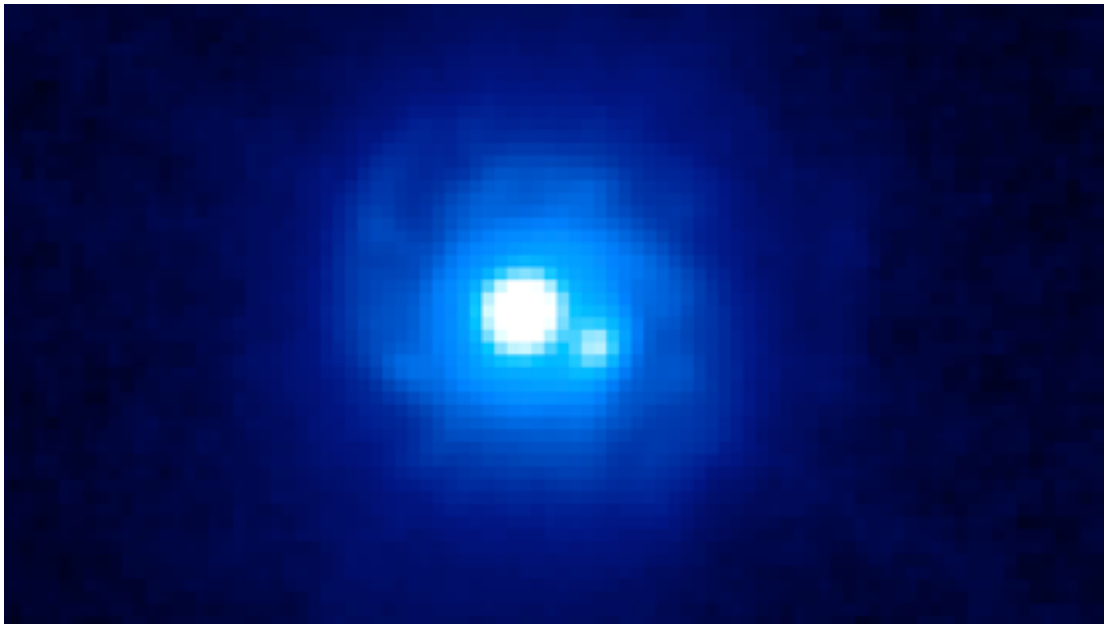


Image: Hubble Legacy

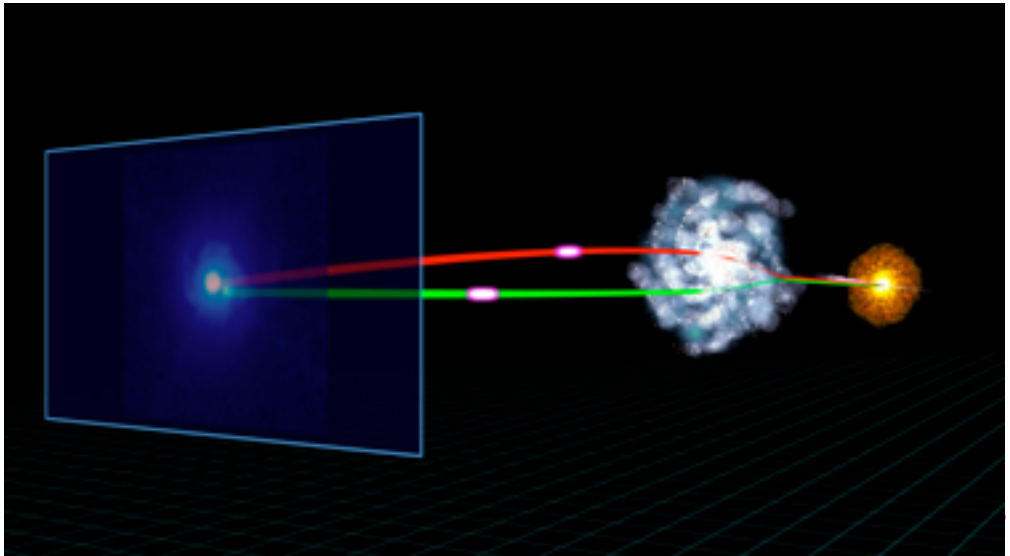


Image: NASA

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Combined Array for Research in Millimeter-Wave Astronomy

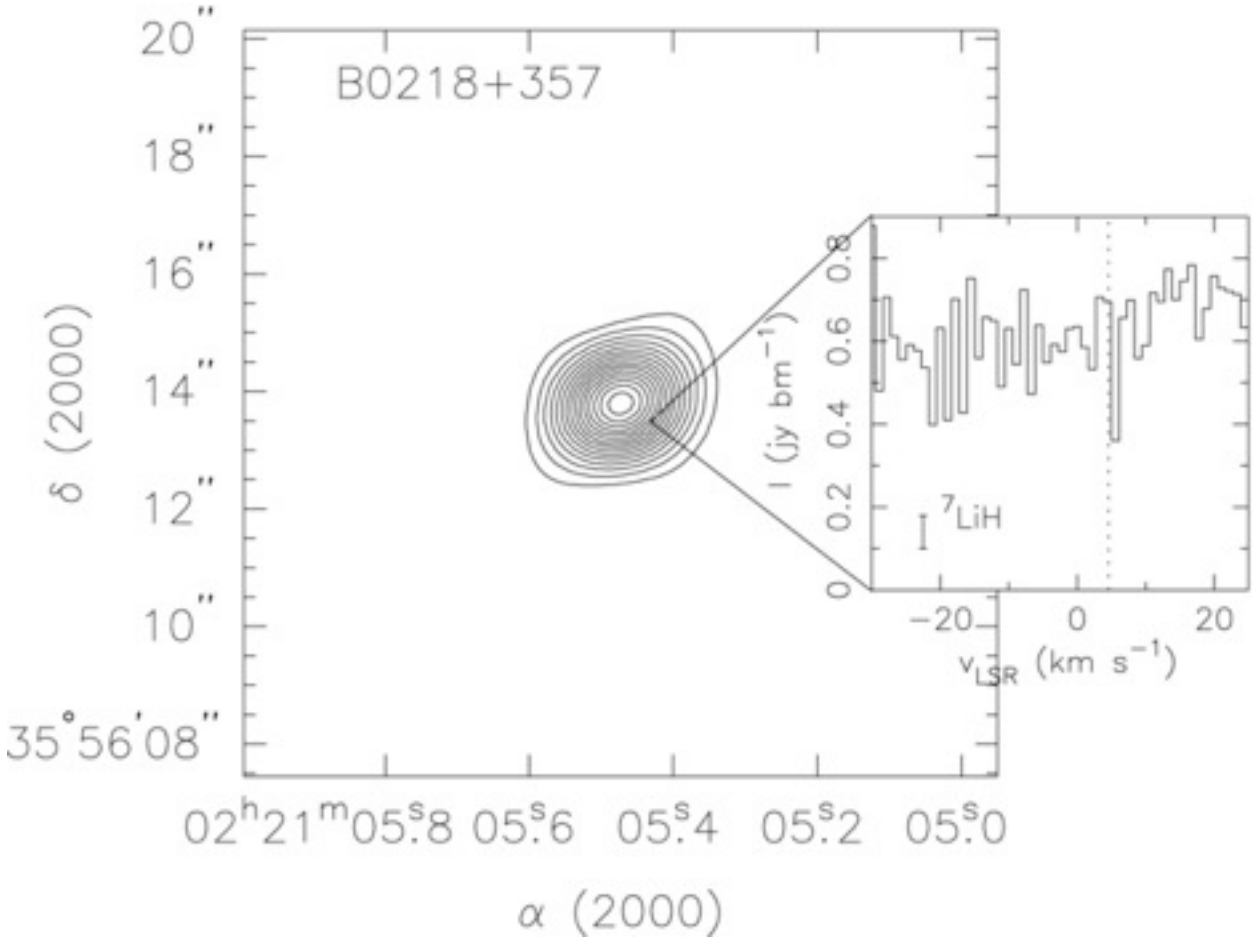
CARMA:

- ^{7}LiH feature ~2-3sigma
- no ^{6}LiH, ^{13}CO

with higher resolution:

isotopes

LiH abundance



Lithium Problem: Conventional Solutions

III: Nuclear Systematics

Scenario:

observed Li/H represents primordial value
Standard Model (particles & cosmo) correct
but nuclear physics treatment incomplete

^{7}Li has single dominant 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 Pena-Garay, Smirnov talks
- kills this "nuke fix" to Li problem Cyburt, BDF, Olive 04

Hoyle's Revenge?

Possible Resonant Solutions to the Lithium Problems

Cyburt & Pospelov 2009

- 11 dominant BBN reactions already well-studied
- no room for factor ~3 surprises
- but "sub-dominant" reactions important if narrow resonance missed

  cf Hoyle state in ^{12}C burning
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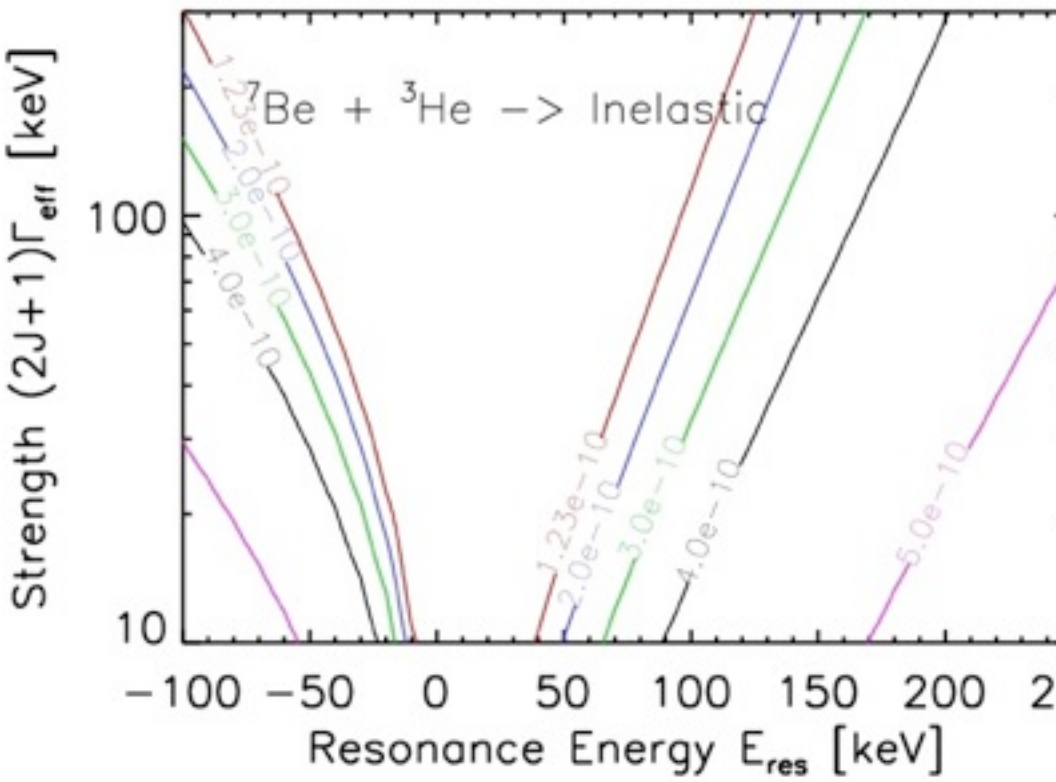

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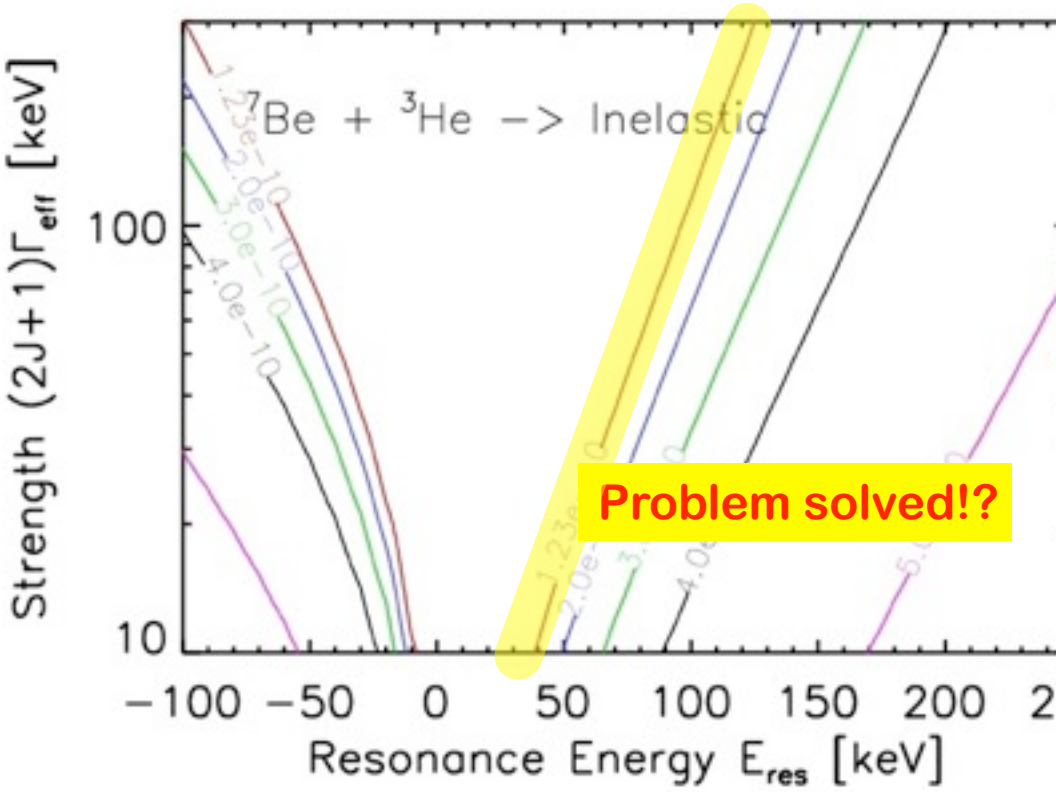

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Experiment Says:

Not there!

^{10}C*: Hammache+ 2013

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

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conventional solutions increasingly difficult

- though not yet ruled out

worthwhile to consider alternative:

- observations correct, nuclear physics correct
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Proposed New Physics Solutions

- ✓ changing fundamental constants (⇨ Coulomb barriers, nuke biniding)
- ✓ "Hubble Bubble" inhomogeneous baryon/photon ratio

Lithium and Dark Matter

Imagine a rich dark matter sector

- **"tower" of particle states created in early Universe**
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If decaying particle is charged:

bound states can form

Coulomb reduced, destruction enhanced

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If

- ✓ the world is supersymmetric
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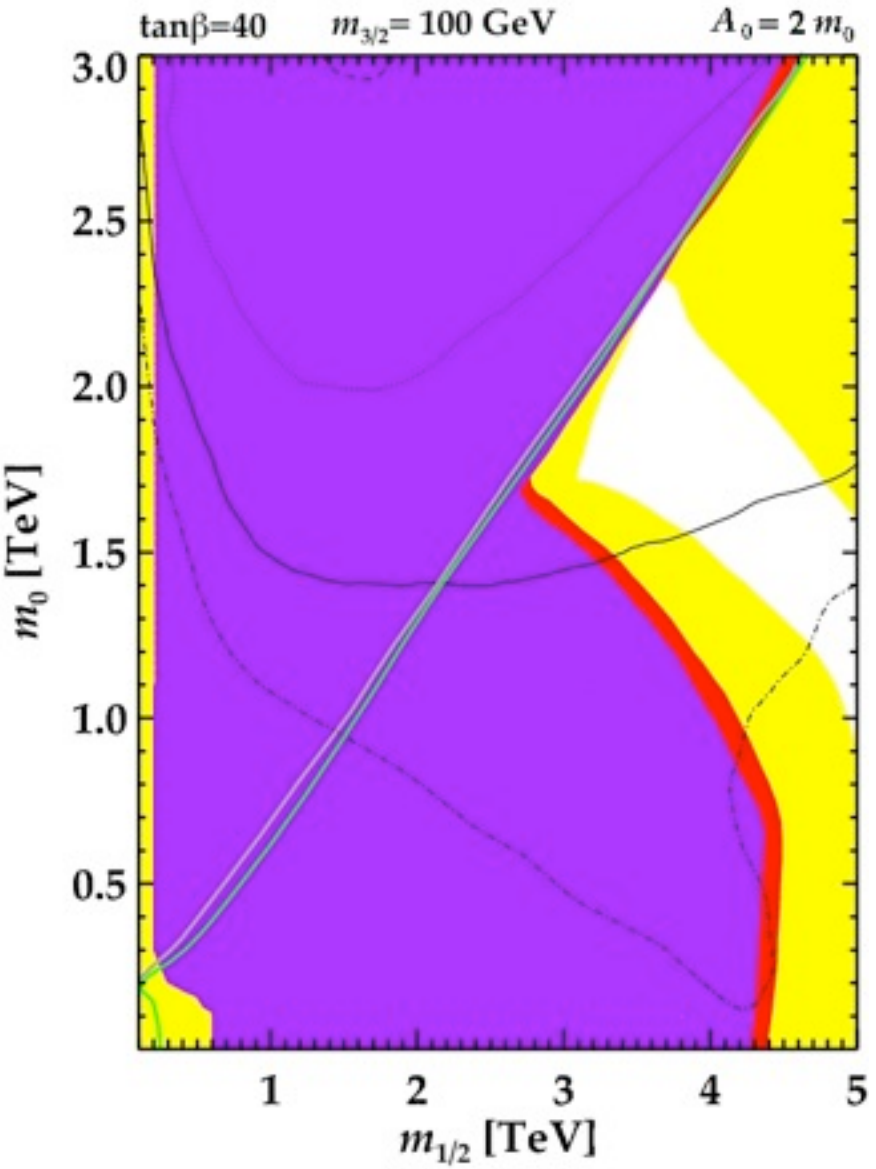

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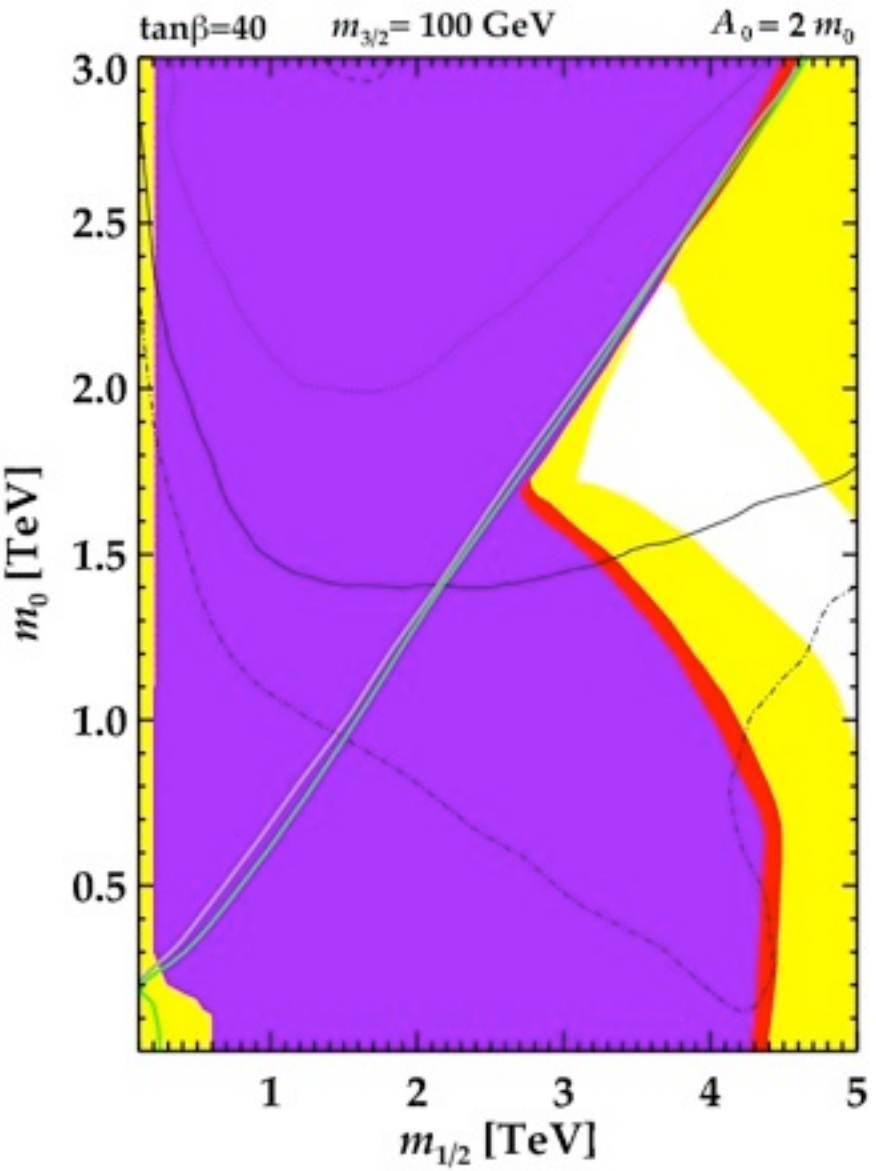

Cyburt, Ellis, BDF, Luo, Olive, Spanos 2012

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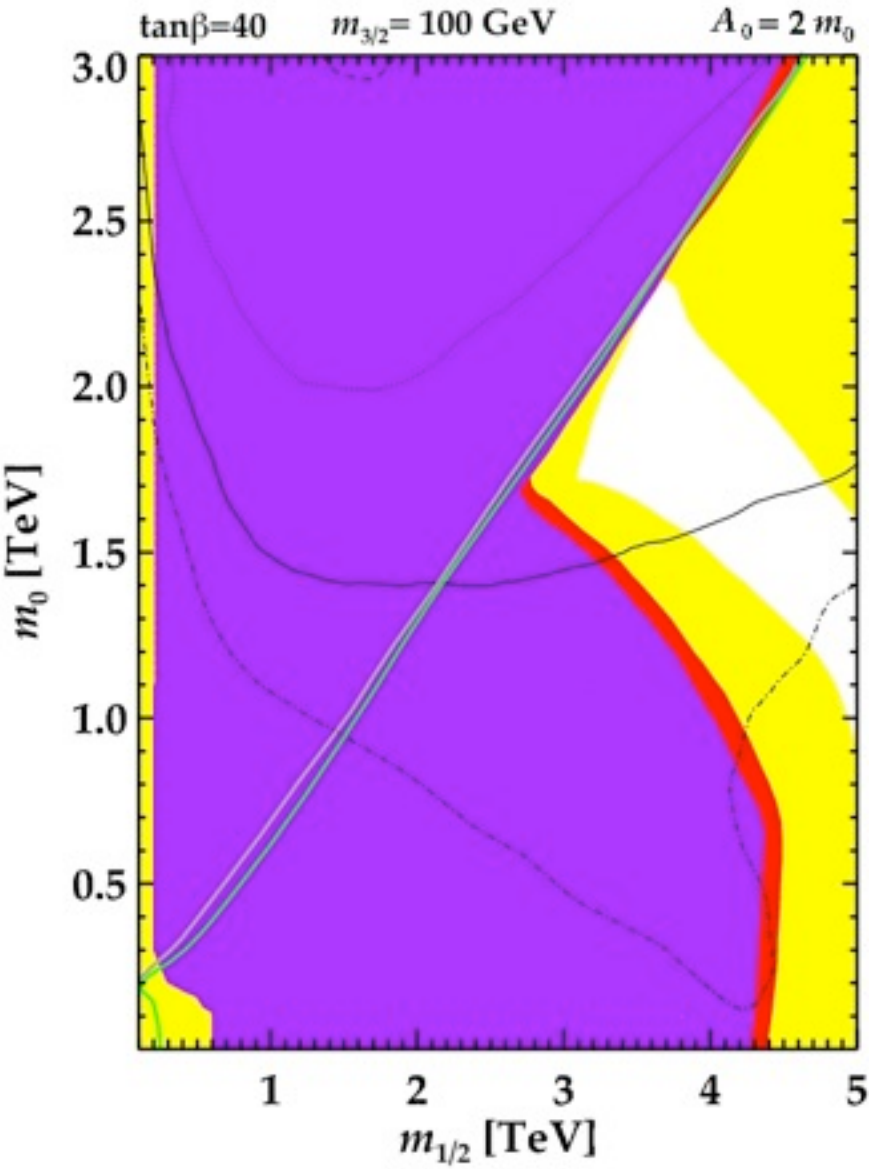

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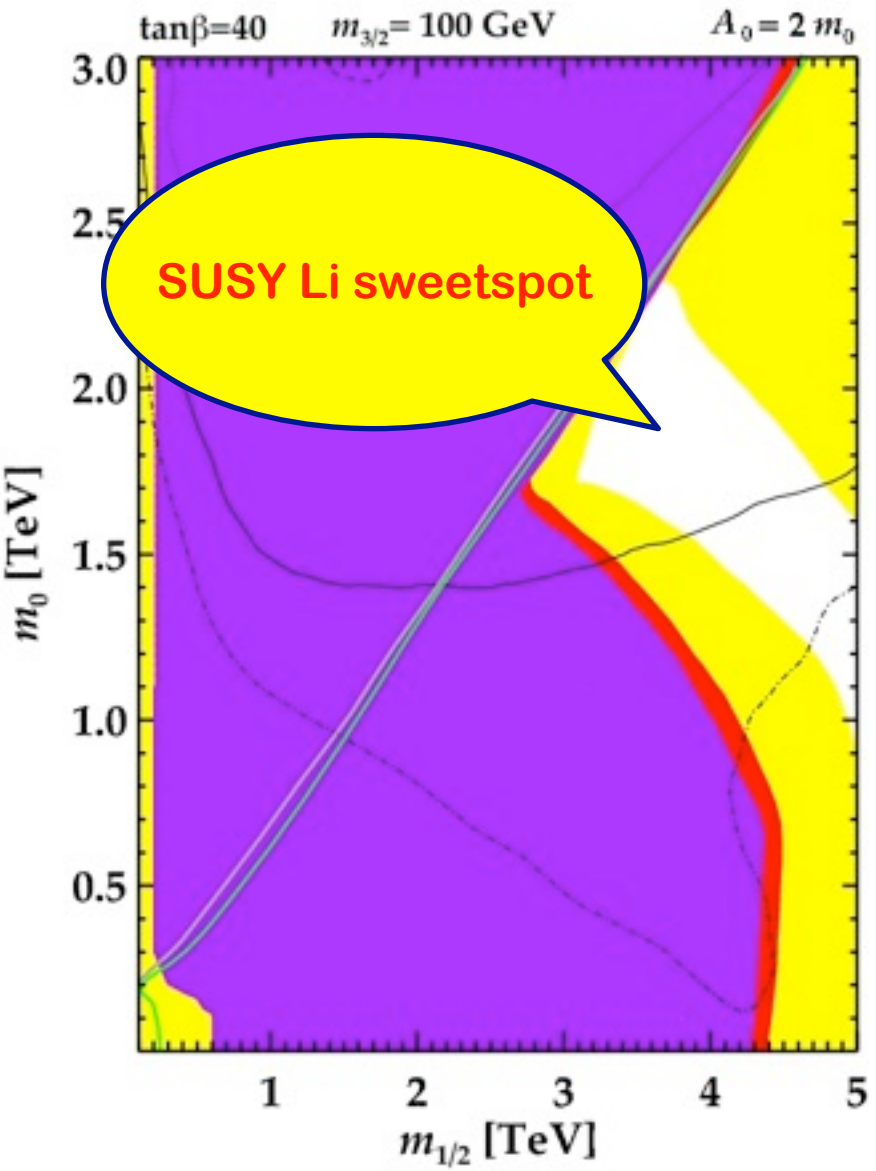

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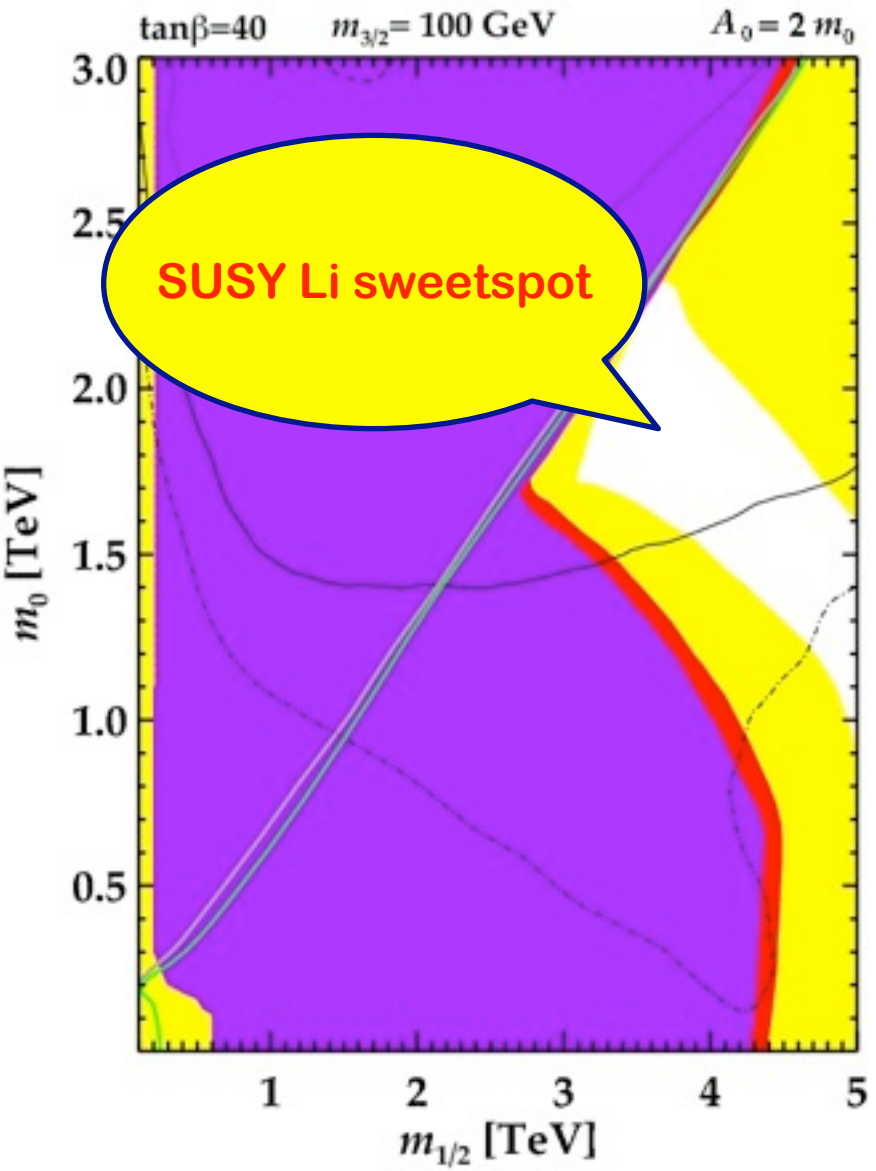

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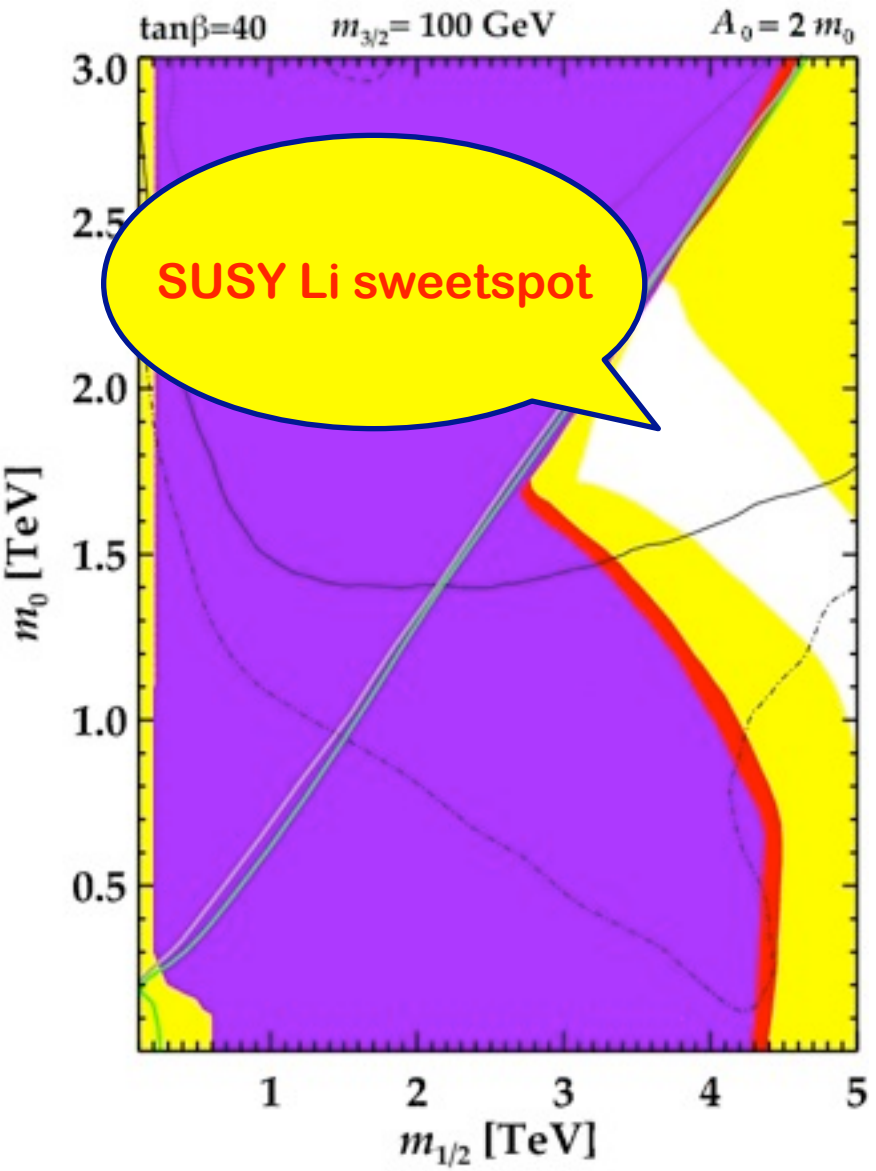

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New D/H removes much solution space

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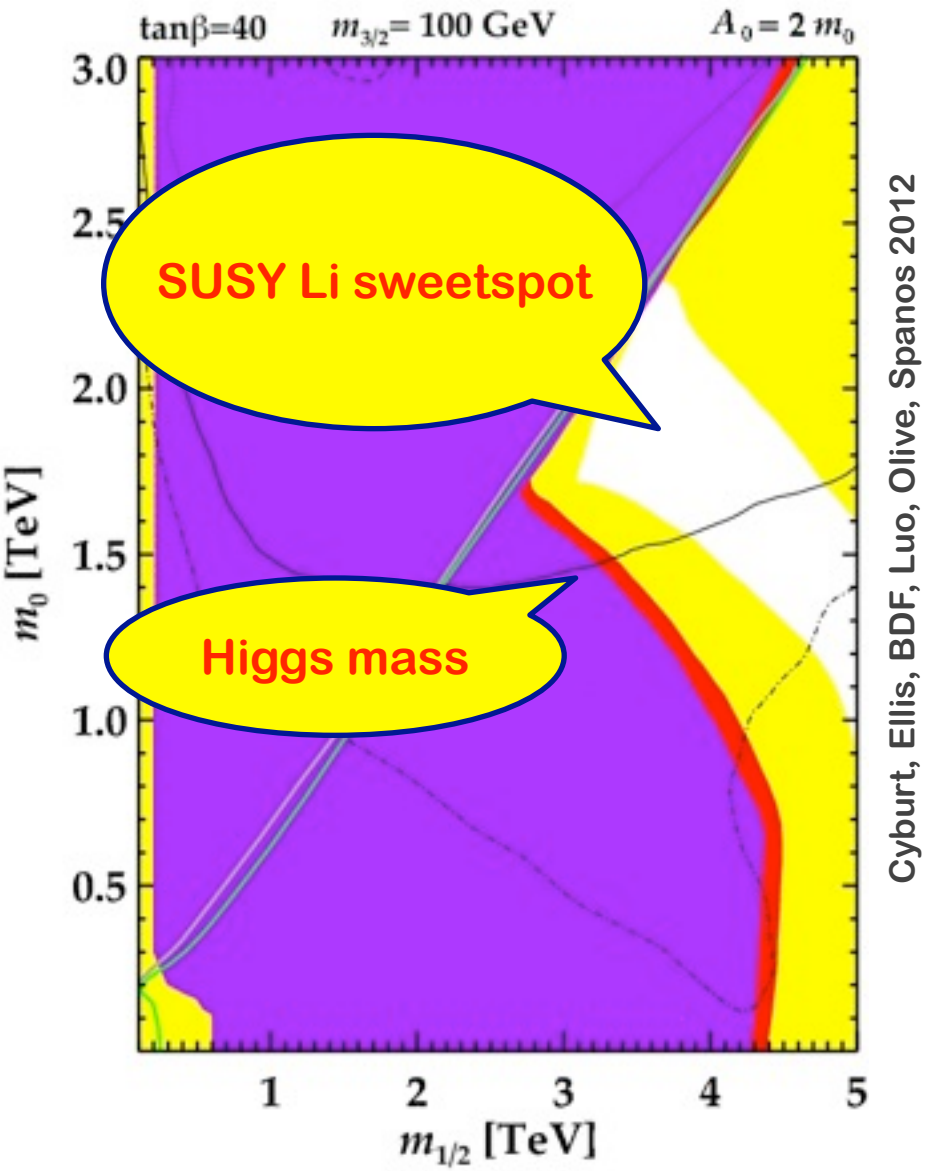
- ✓ rule out large regions of parameter space



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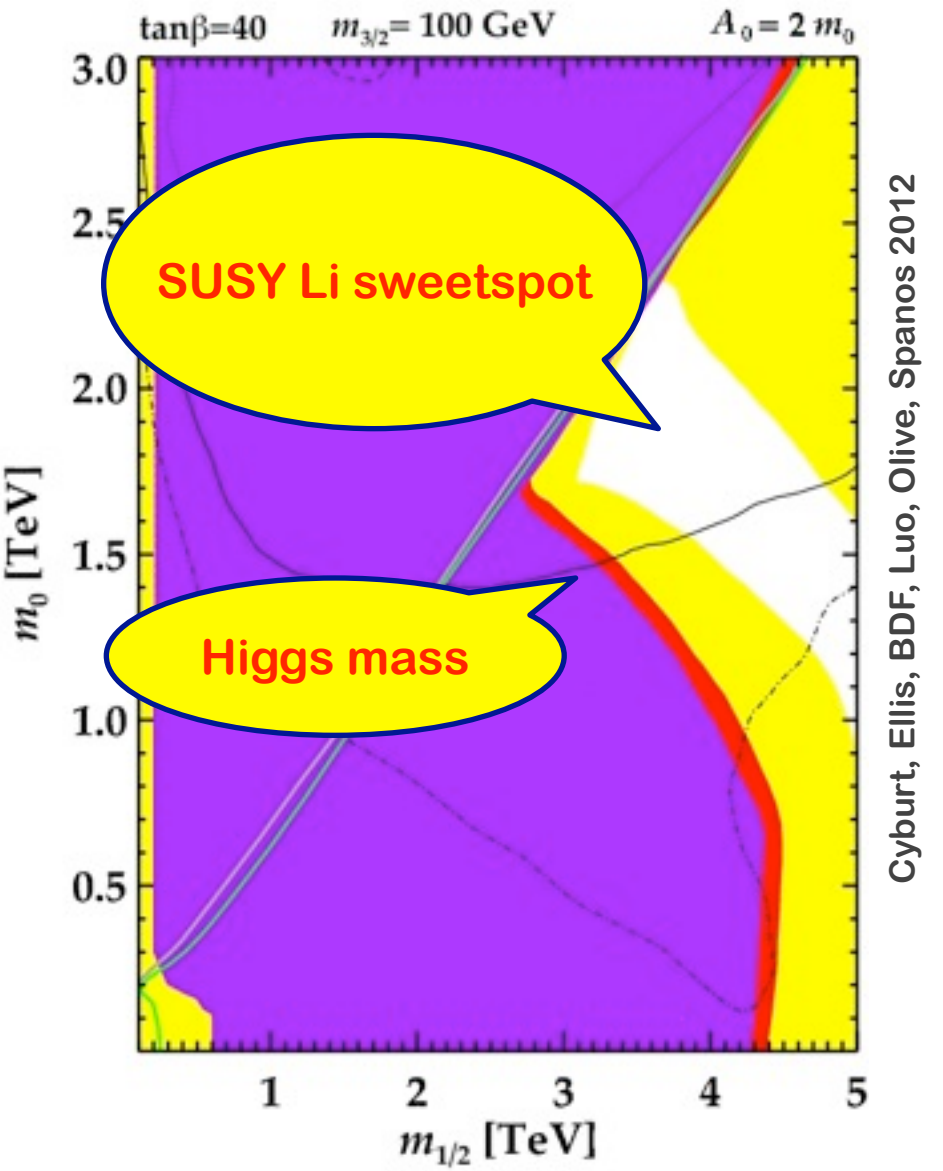

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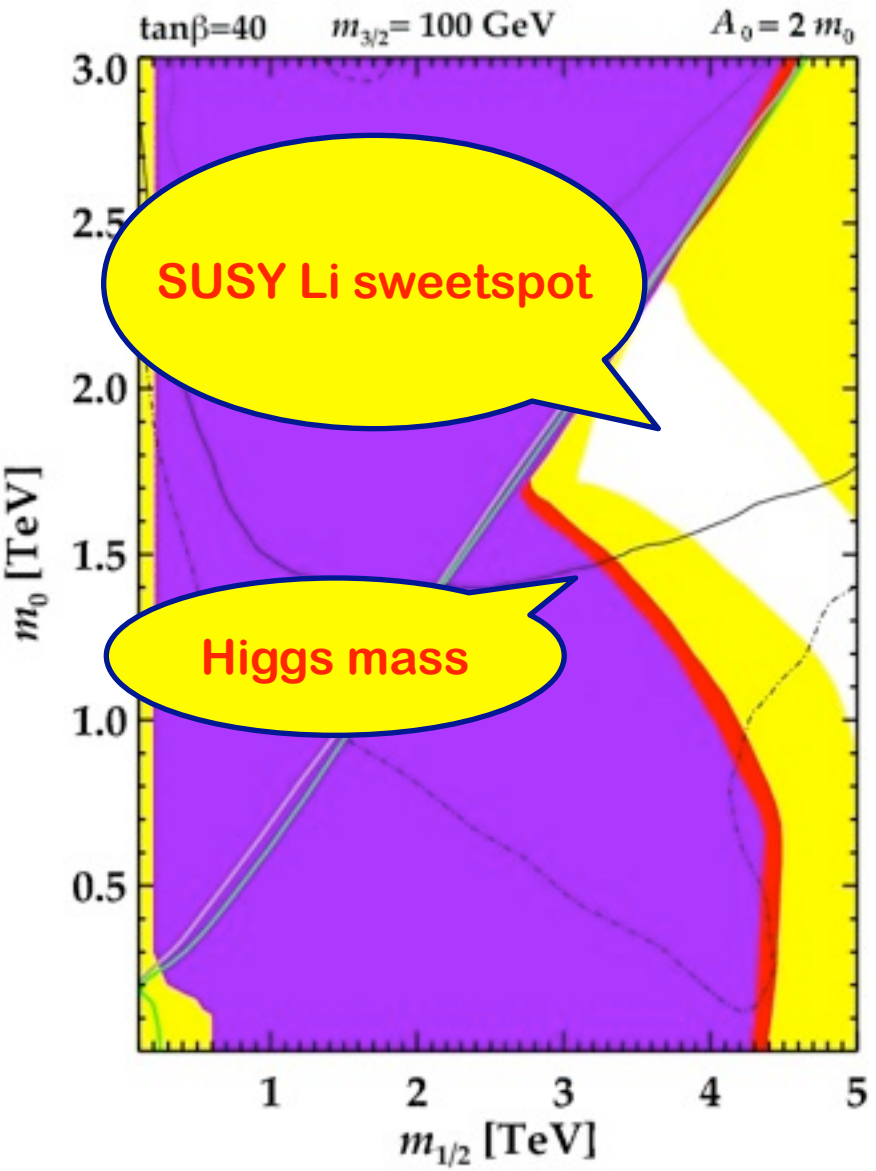
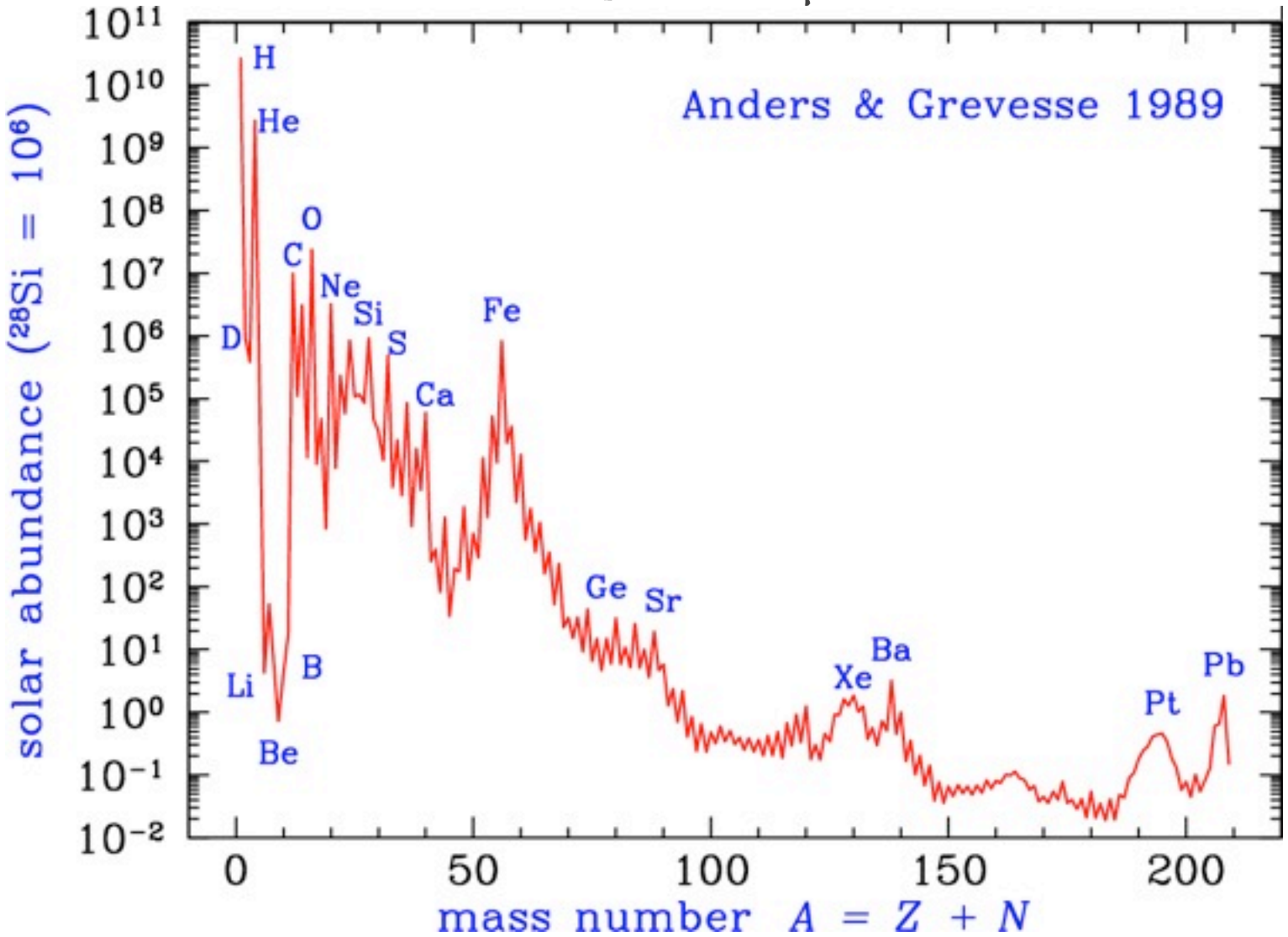
Illustrates tight links among nucleo-cosmo-astro-particle physics



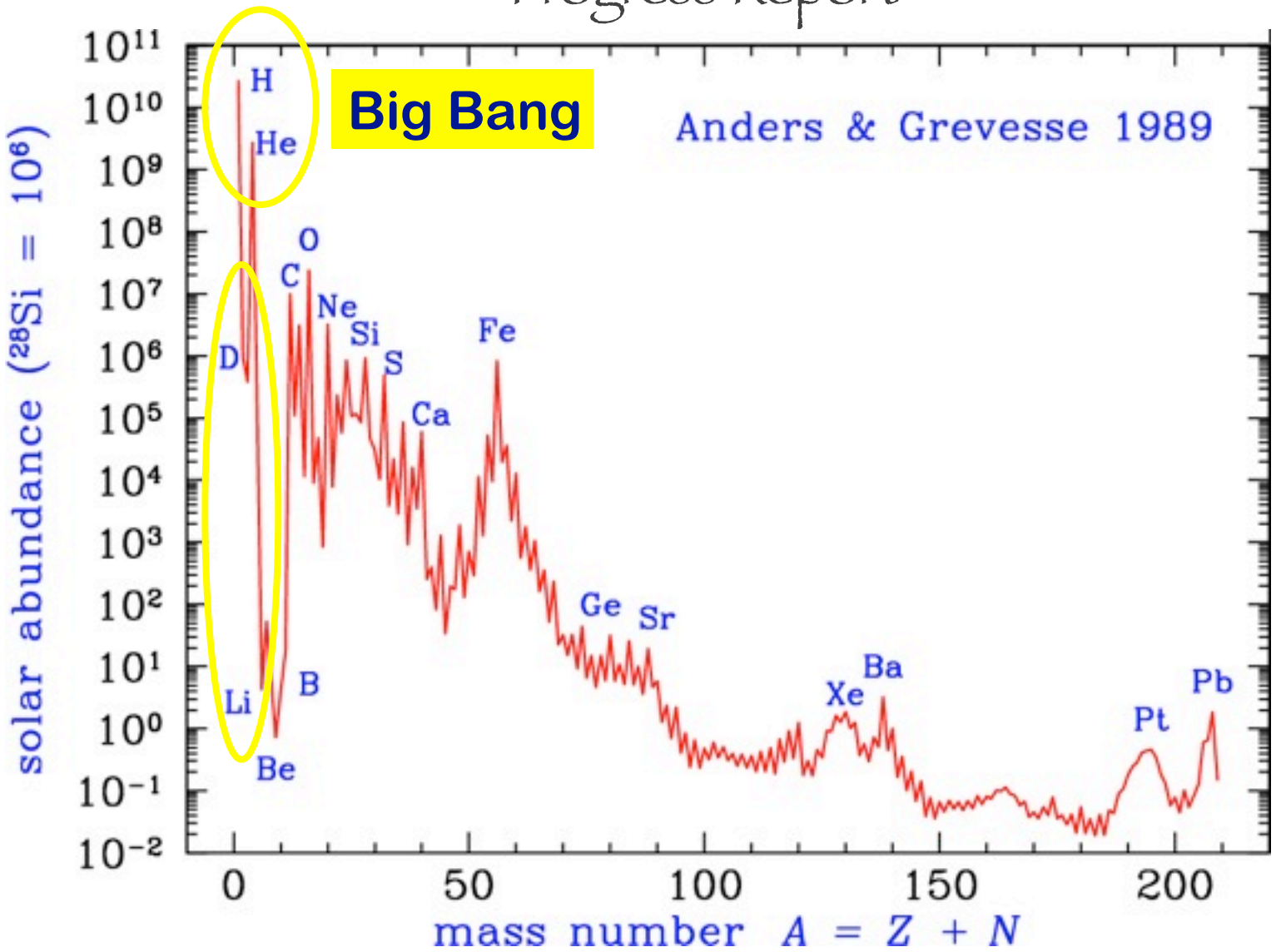
Solar System Abundances

Progress Report



Solar System Abundances

Progress Report



OUTLOOK

Convergence of Particle Physics and Cosmology

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

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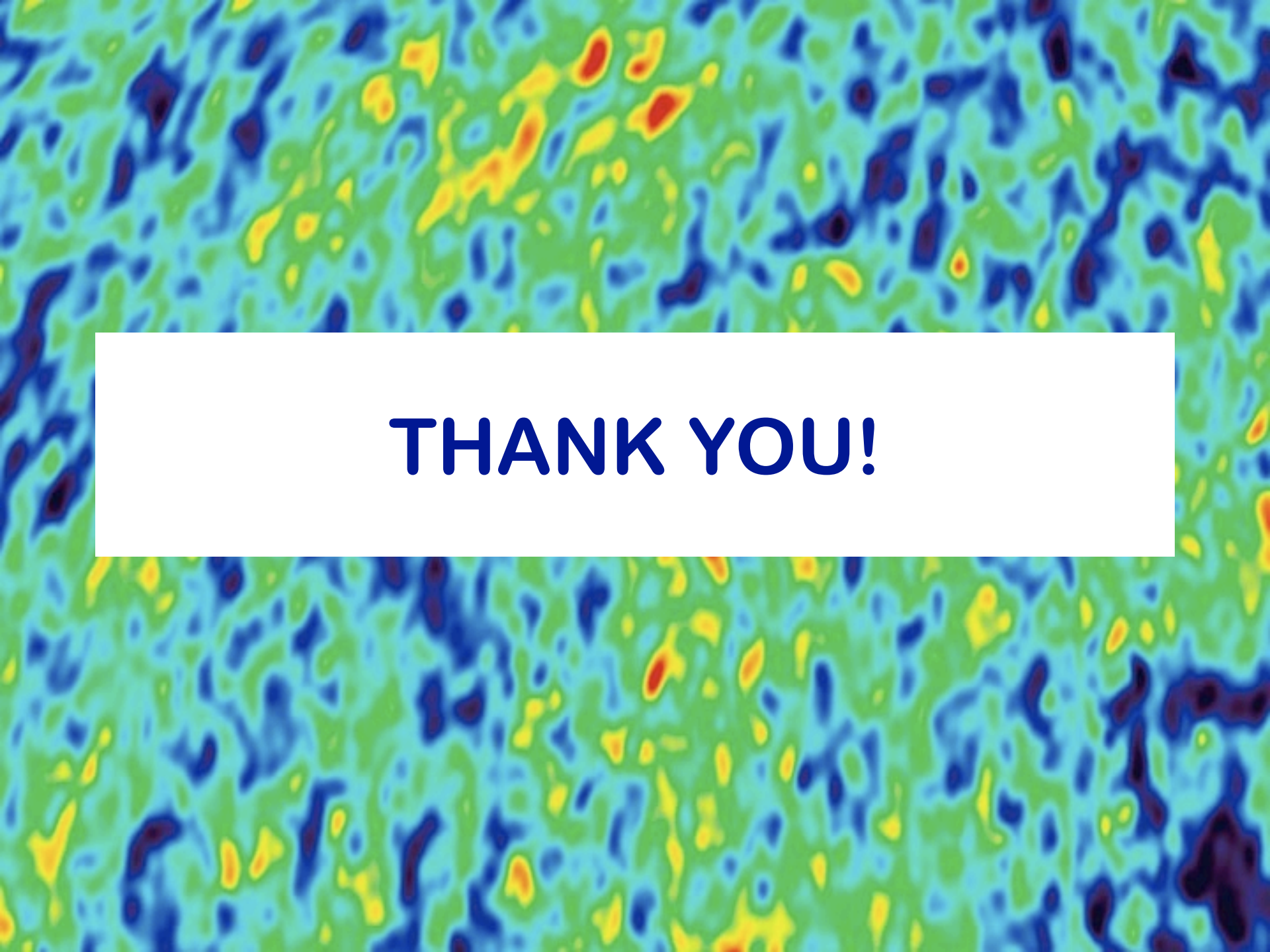
The Lithium Problem: WMAP+BBN >> Li_{obs}

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

The Truth is out there--stay tuned!


THANK YOU!

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

BBN Beyond the Standard Model: Probing Particle Physics

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 density**

Stiegman, Schramm, & Gunn 77

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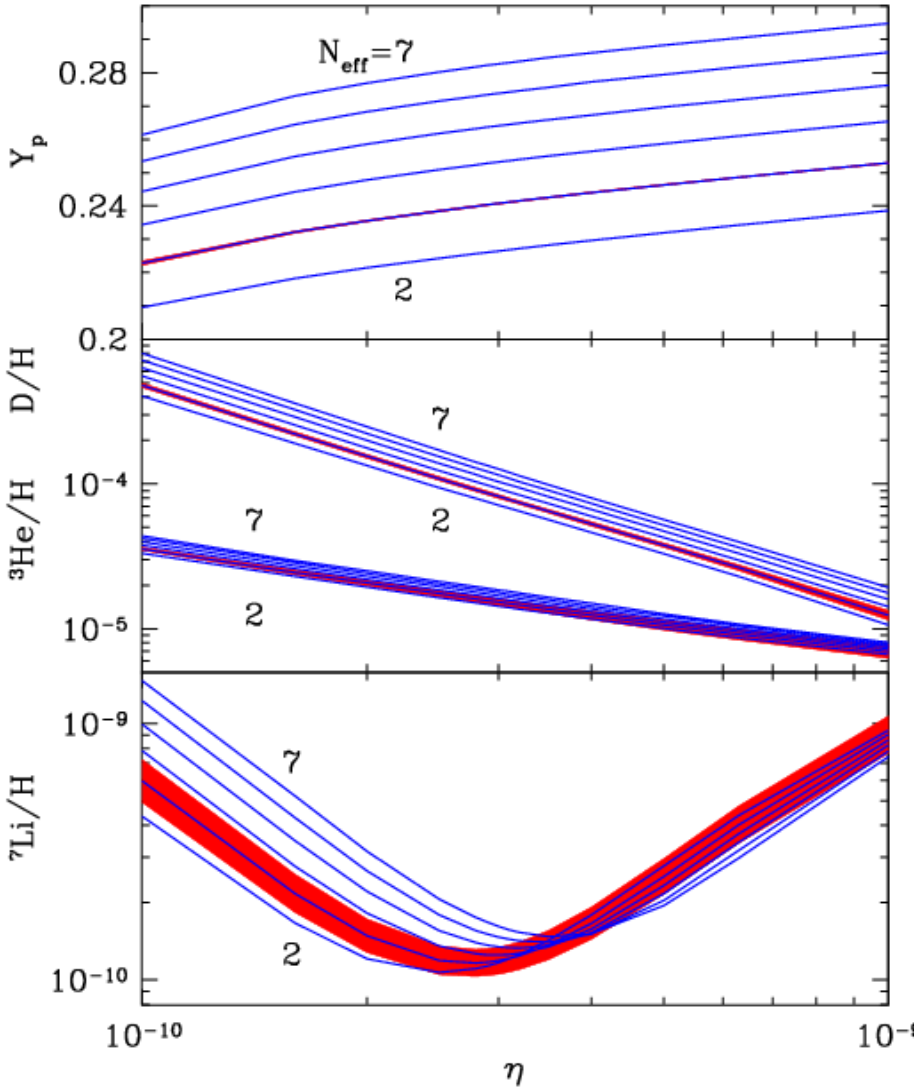
7Li shift right direction but small



Cyburt, BDF, Olive 2002

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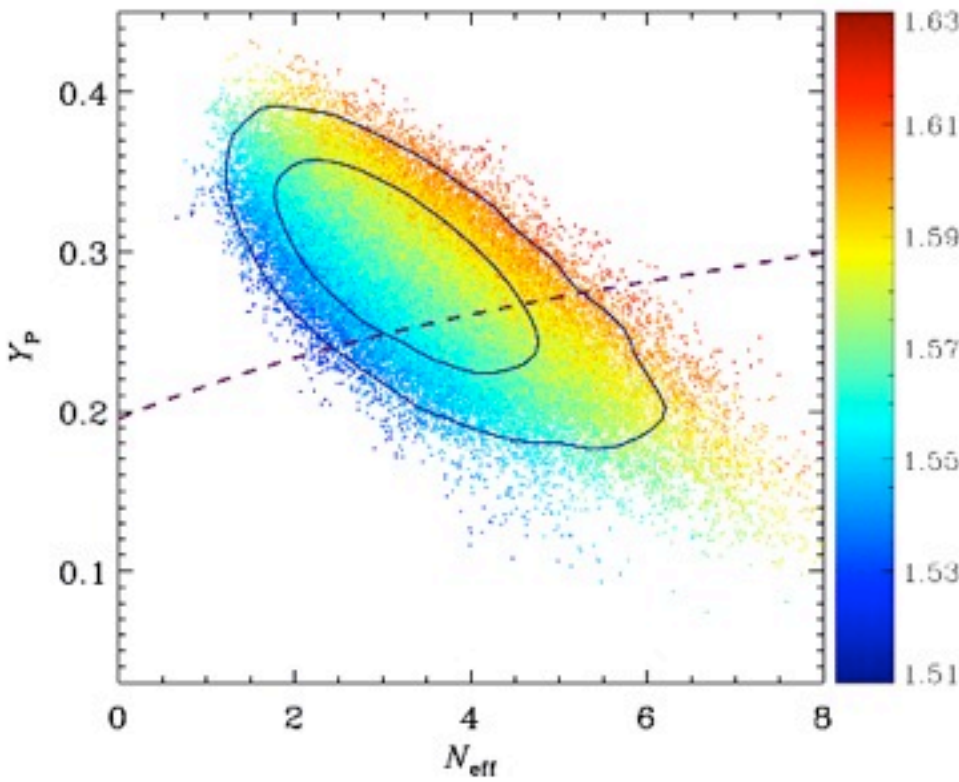
New! CMB damping tail can probe all of η $N_{\nu,\text{eff}}$ ^4He

clean test of BBN



Hou, Kielser, Knox, Milea Reichardt 2013

BBN Observations: Case Study
Primordial Deuterium

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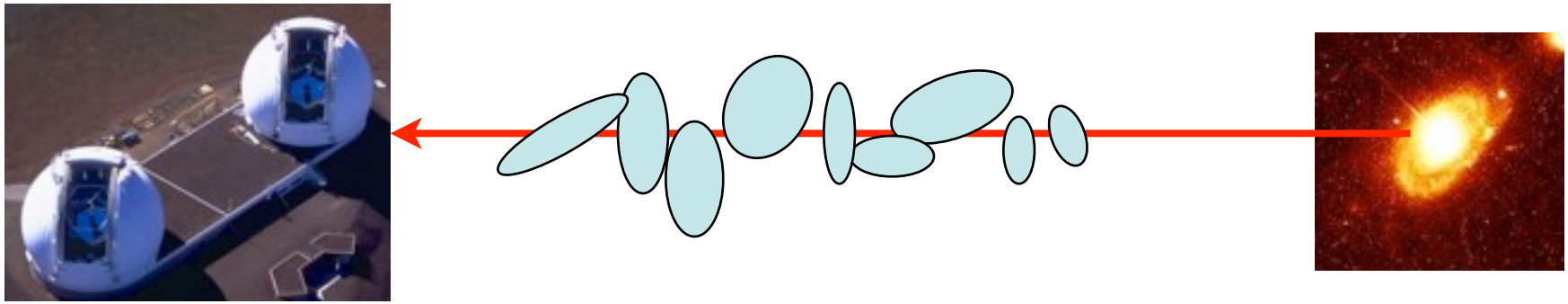
- **High-redshift quasar=light bulb**
- **Intervening H gas absorbs at** $\mathrm{Ly}\alpha(n = 1 \rightarrow n = 2)$



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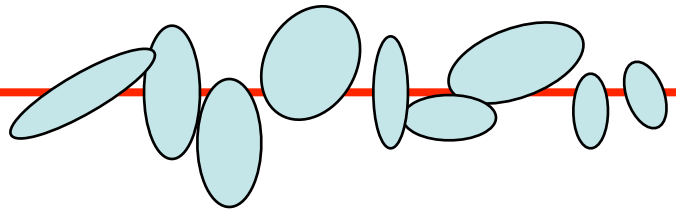
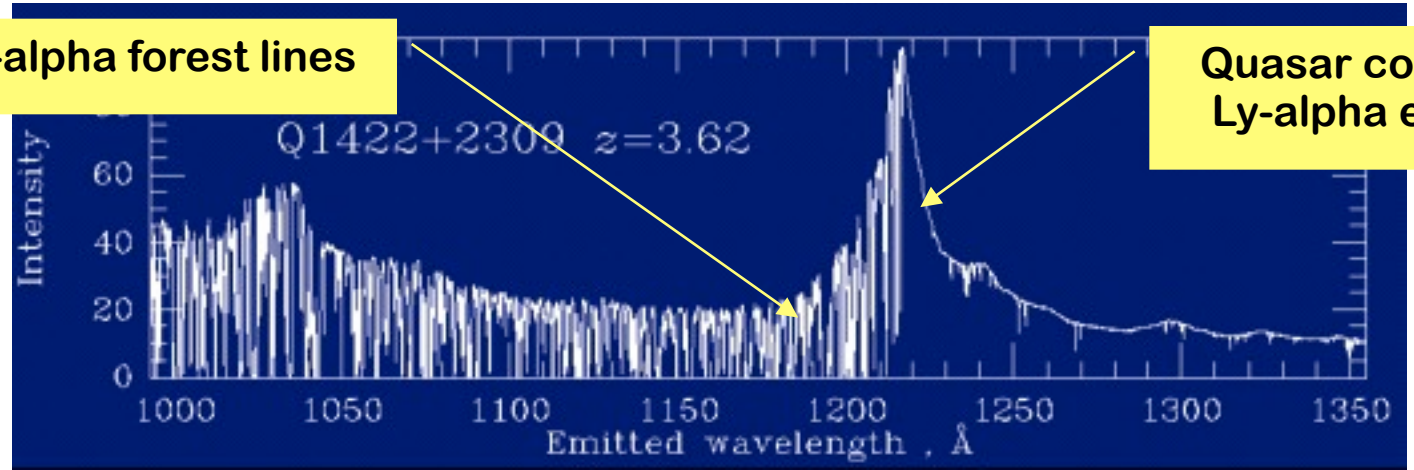
- **High-redshift quasar=light bulb**
- **Intervening H gas absorbs at** $\mathrm{Ly}\alpha(n = 1 \rightarrow n = 2)$
- **Observed spectrum: Ly-alpha "forest"**





Deuterium Data

Deuterium Ly-alpha shifted from H:

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

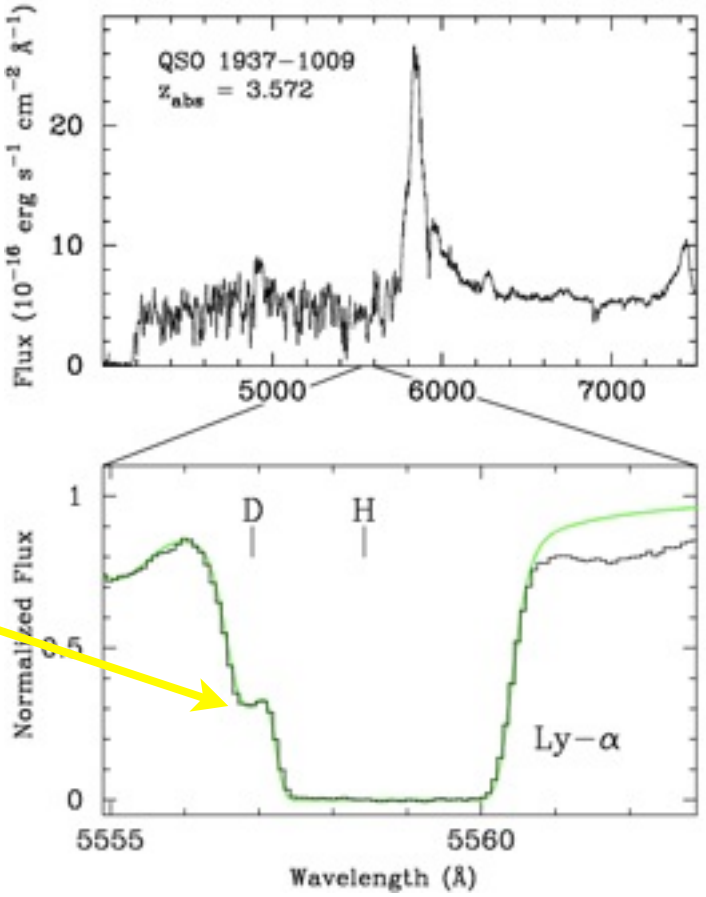
$$\frac{\delta\lambda_{\mathrm{D}}}{\lambda_{\mathrm{D}}} = -\frac{\delta\mu_{\mathrm{D}}}{\mu_{\mathrm{D}}} = -\frac{m_e}{2m_p}$$

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

Get D directly at high-z!

But:

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



Tytler & Burles

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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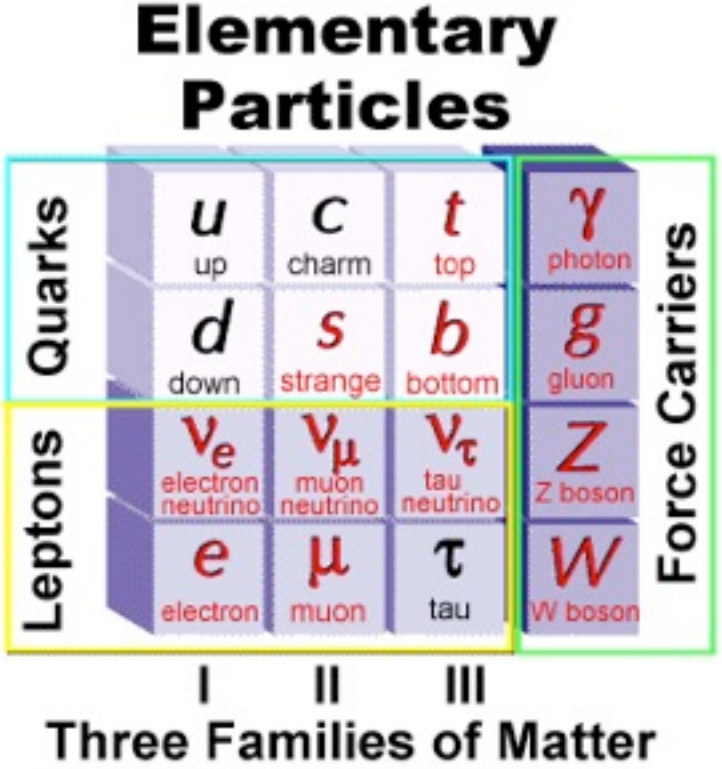
Consult Standard Model

neutrinos very promising!

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



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Neutrino densities today

- **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:** $\Omega_\nu = \frac{\sum m_\nu}{46 \text{ eV}}$

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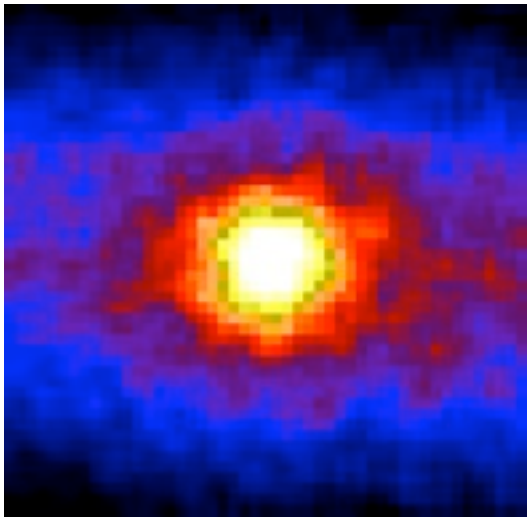
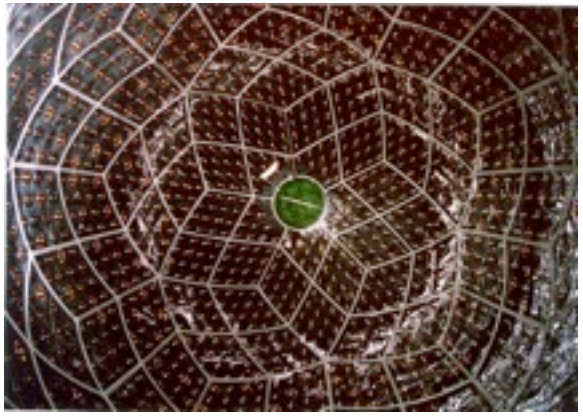
$\sum m_\nu \leq 2 \text{ eV}$ (from large-scale structure)



The Sun, imaged in neutrinos
SuperKamiokande



KamLAND Reactor Neutrino Detector

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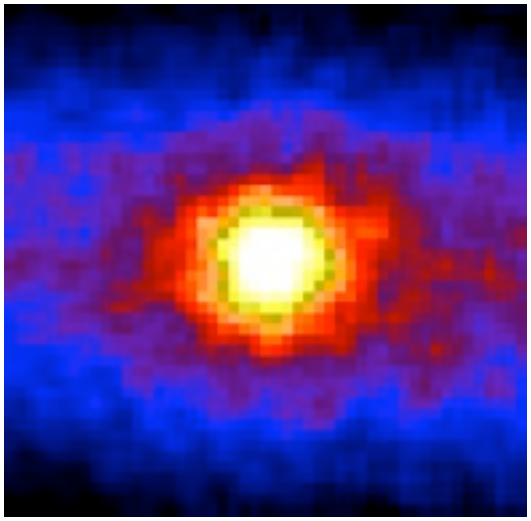

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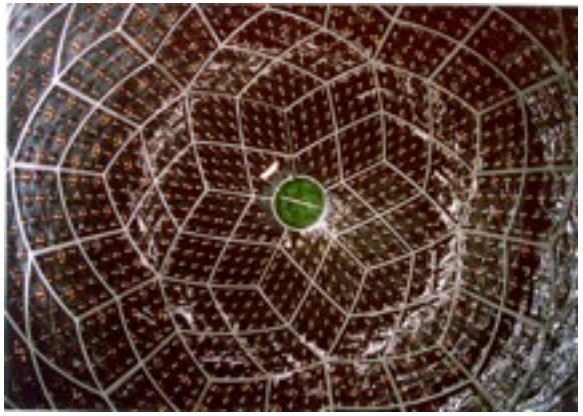

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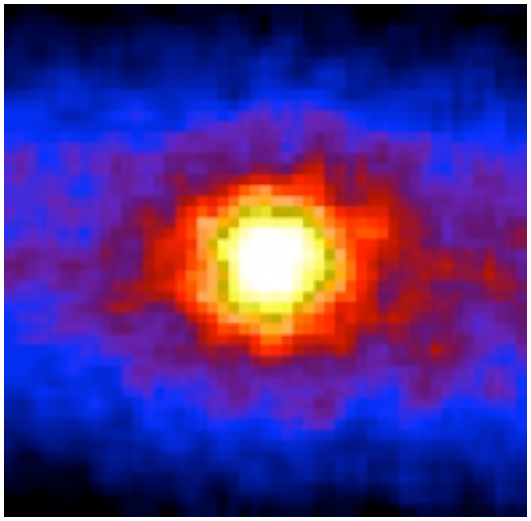
Neutrinos are **not** the dark matter



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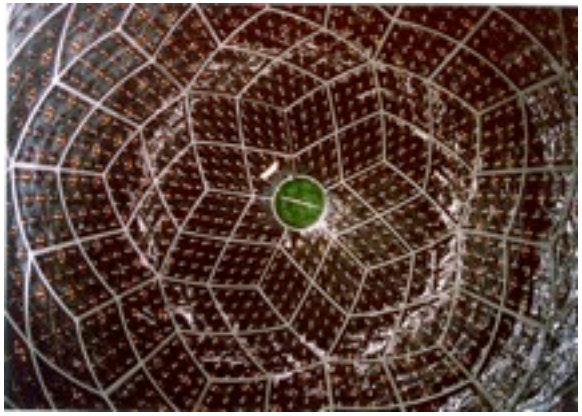

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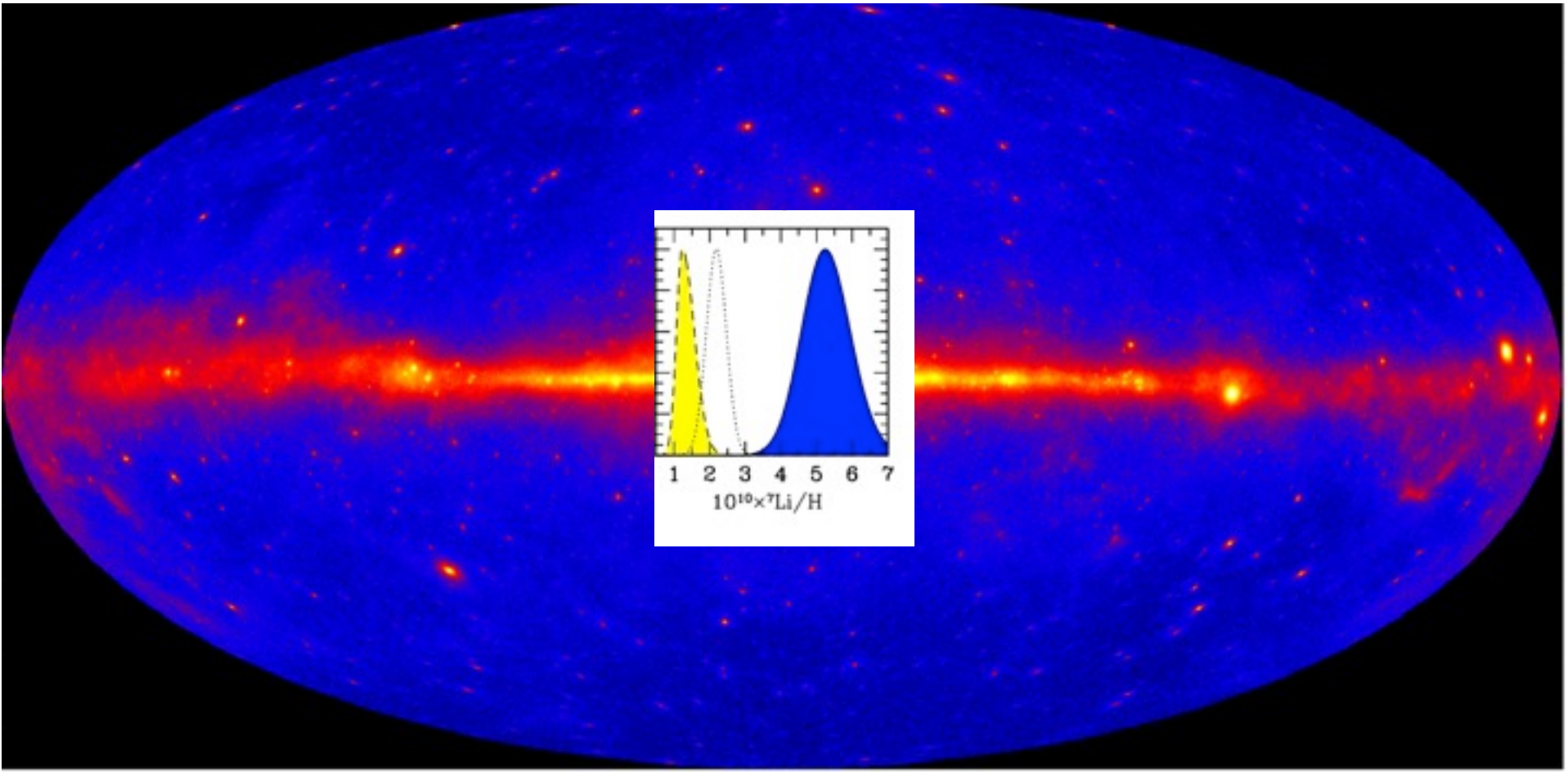
Orphans of Nucleosynthesis



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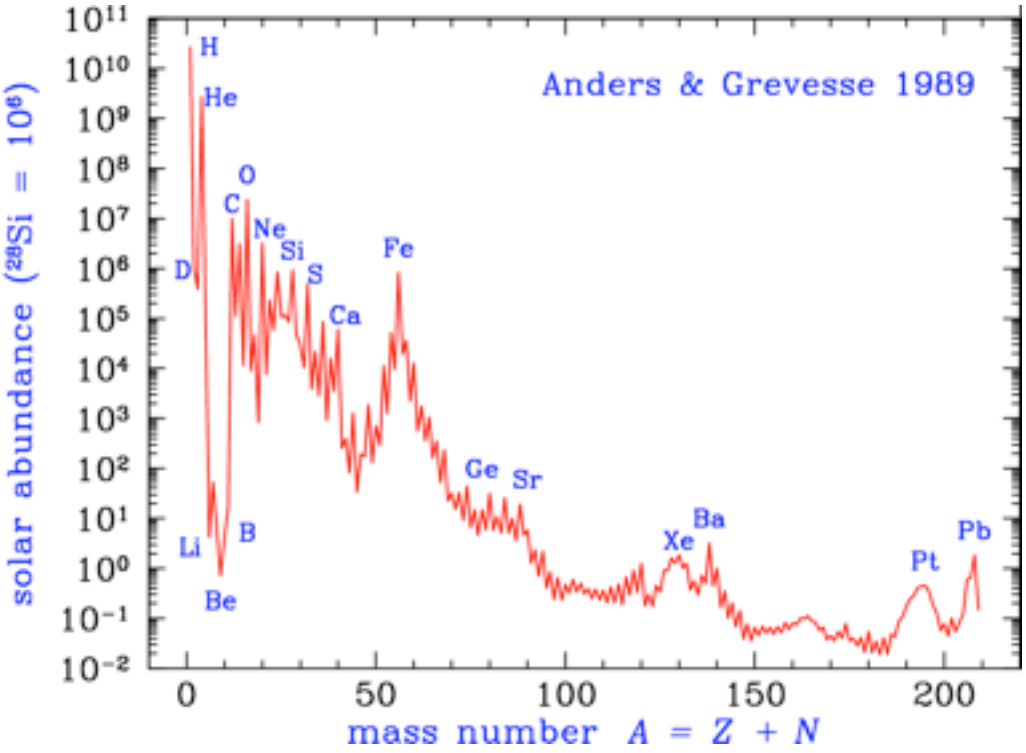
The Big Picture, circa 1967



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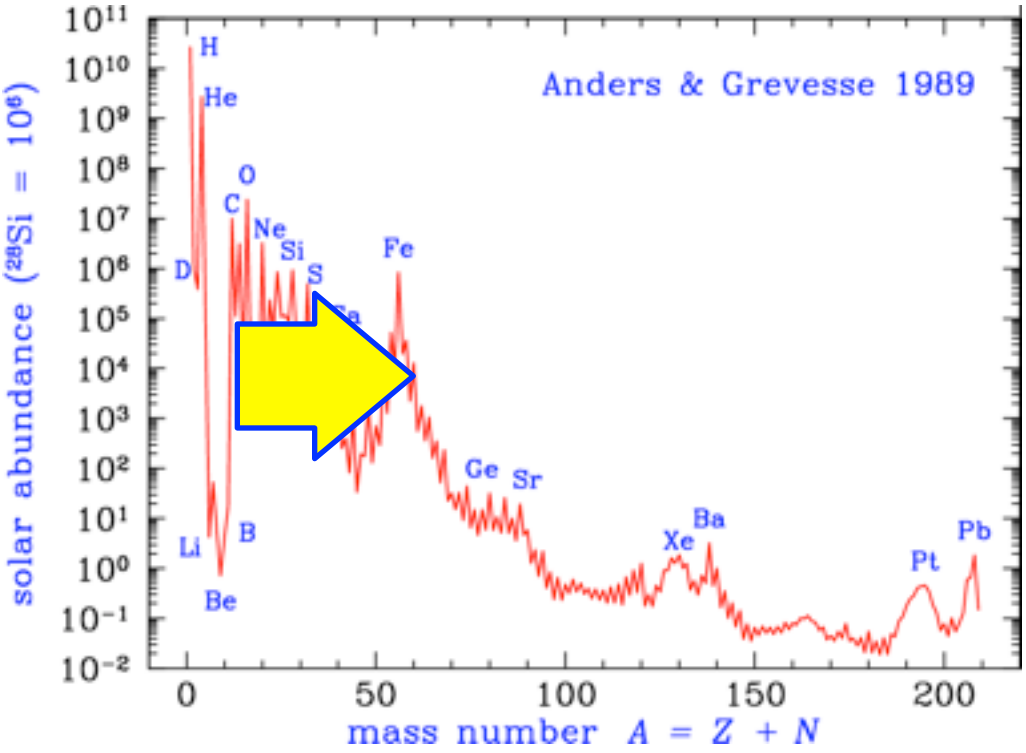

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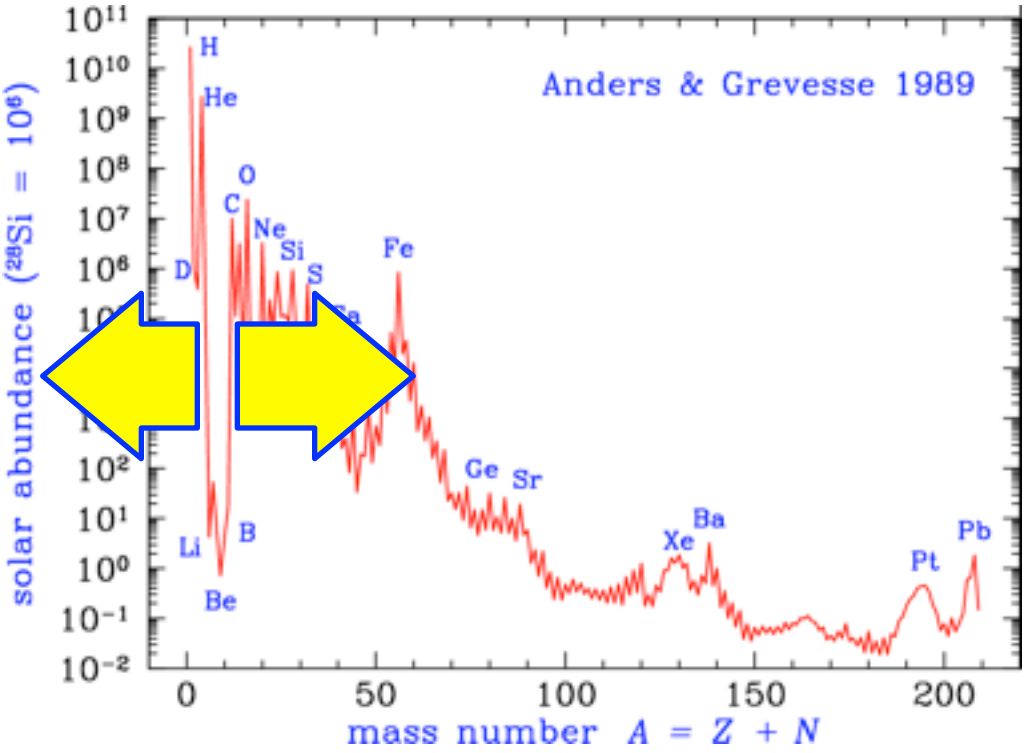

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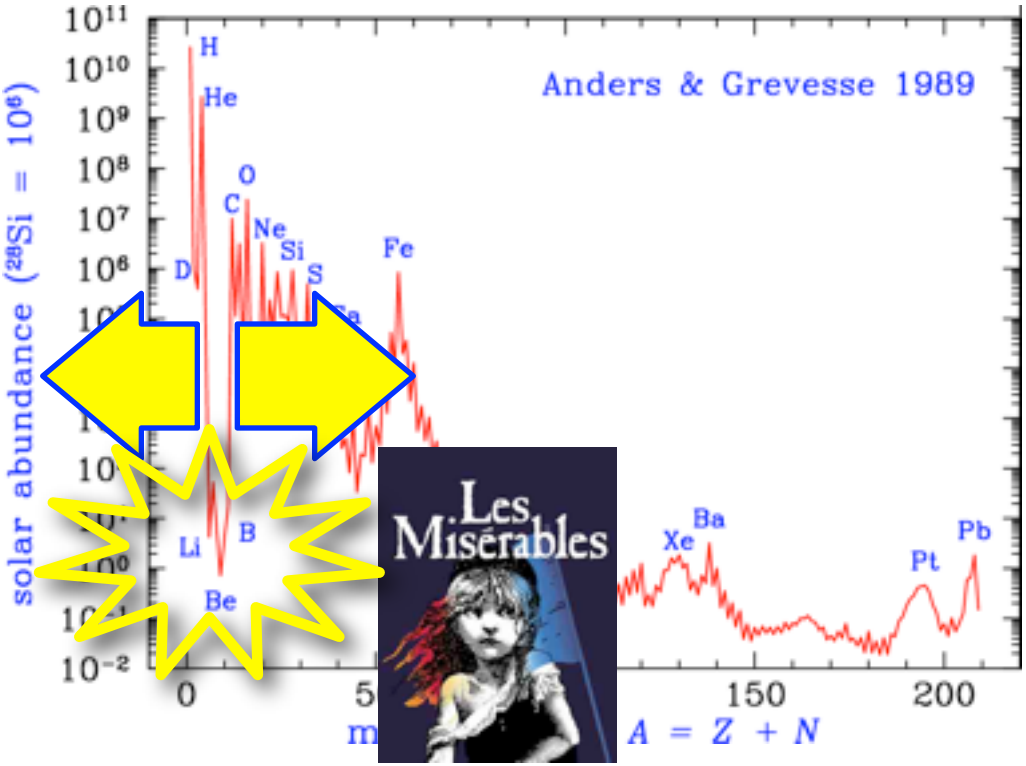

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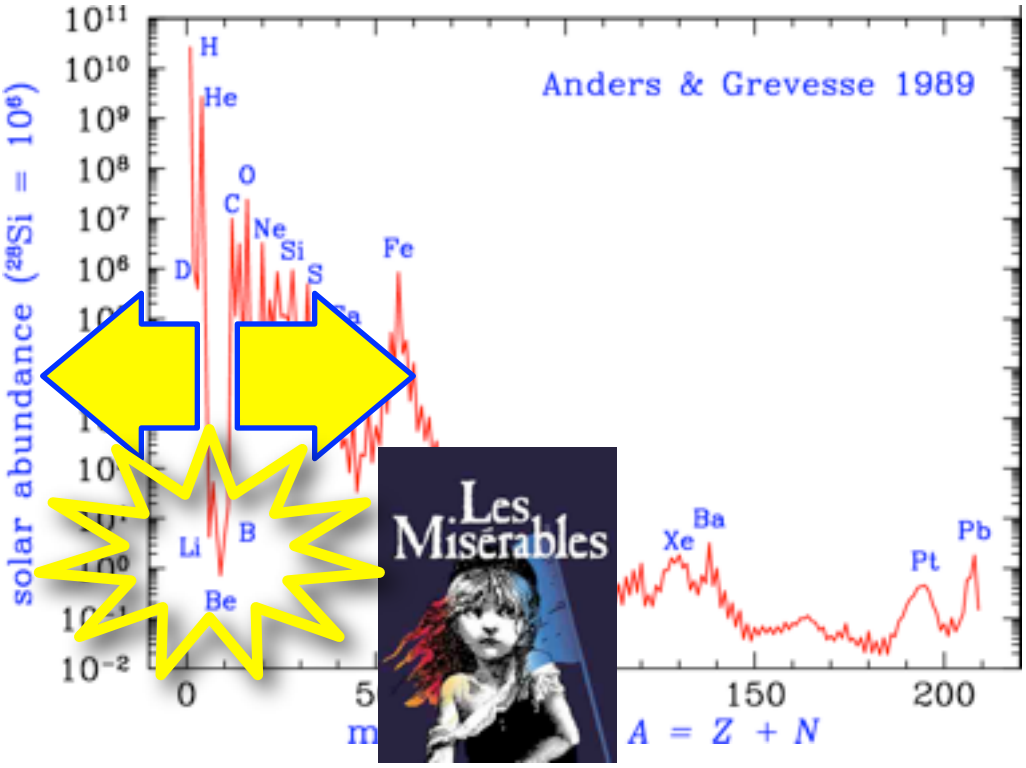
- lowest binding after D
- **stars destroy** at ~2.7 x 10^6 K

Need **non-thermal origin**



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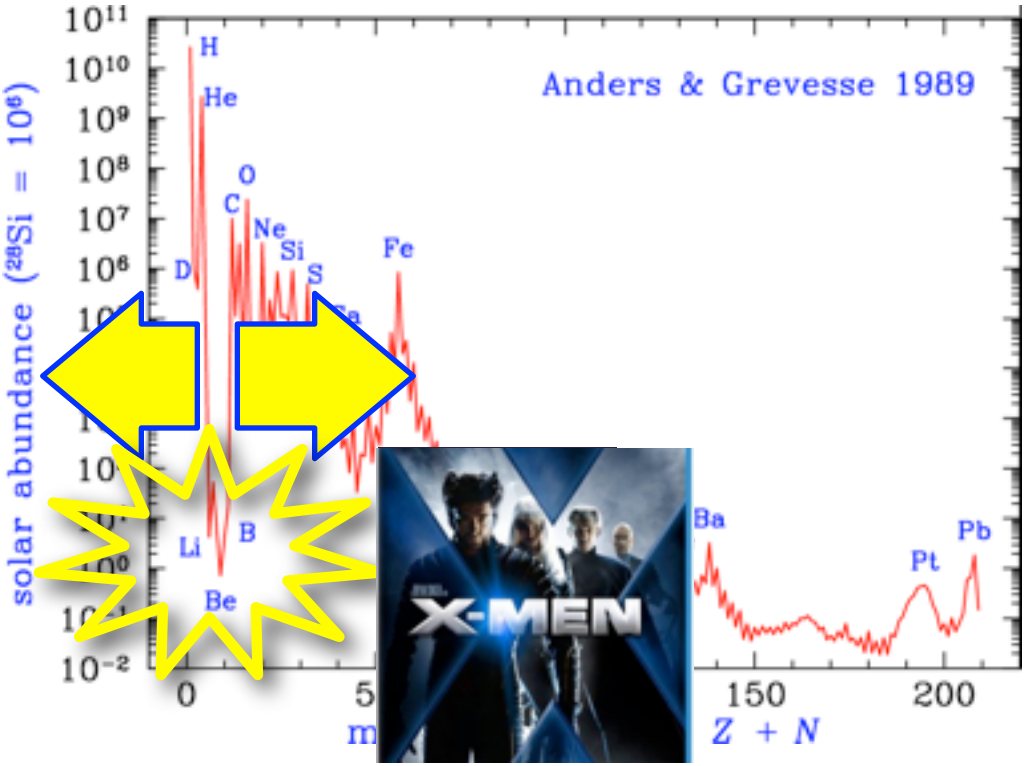

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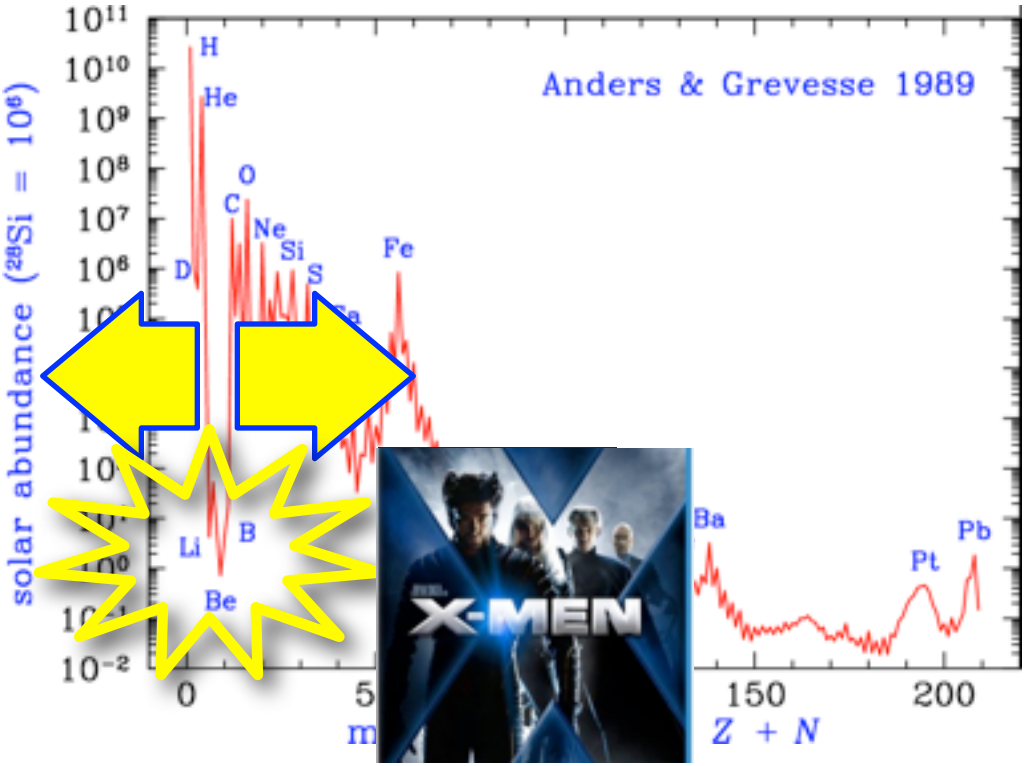
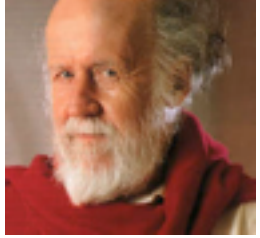
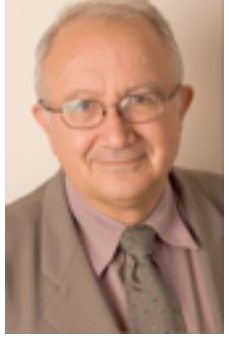




What about cosmic rays?



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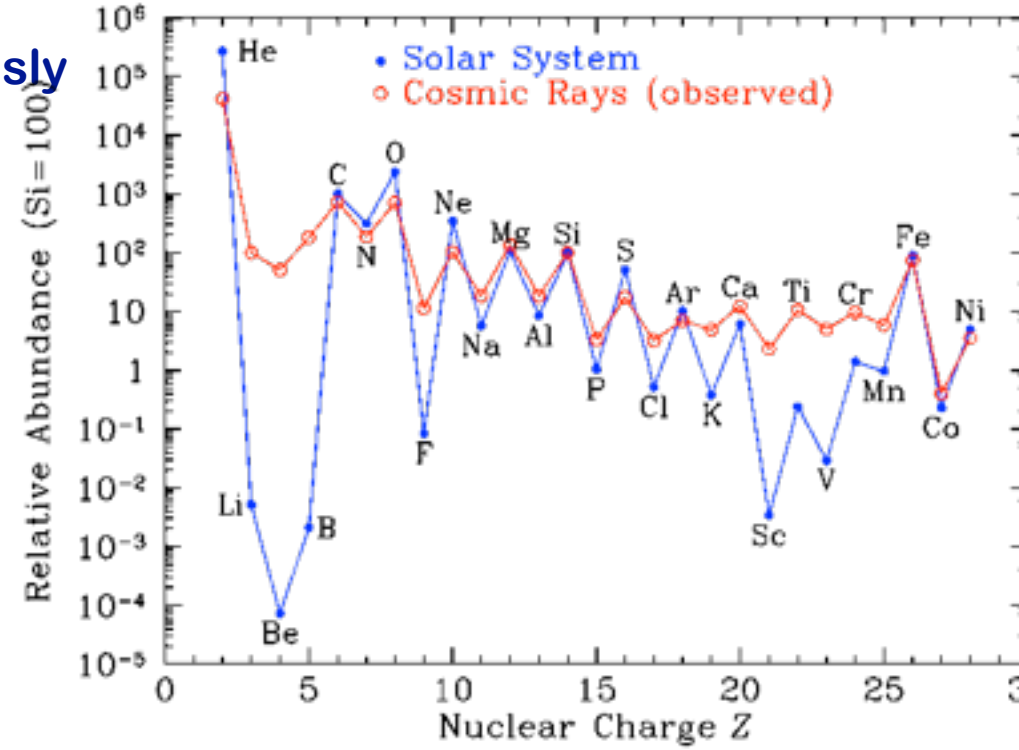
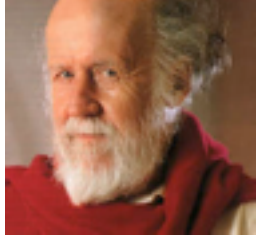
- Cosmic rays are nonthermal
- Could they do the job?

Key hint:

- LiBeB abundances anomalously high in cosmic rays

Why?





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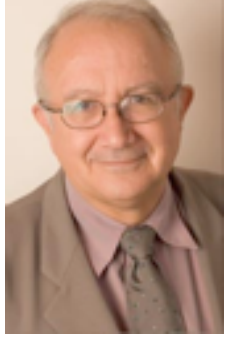

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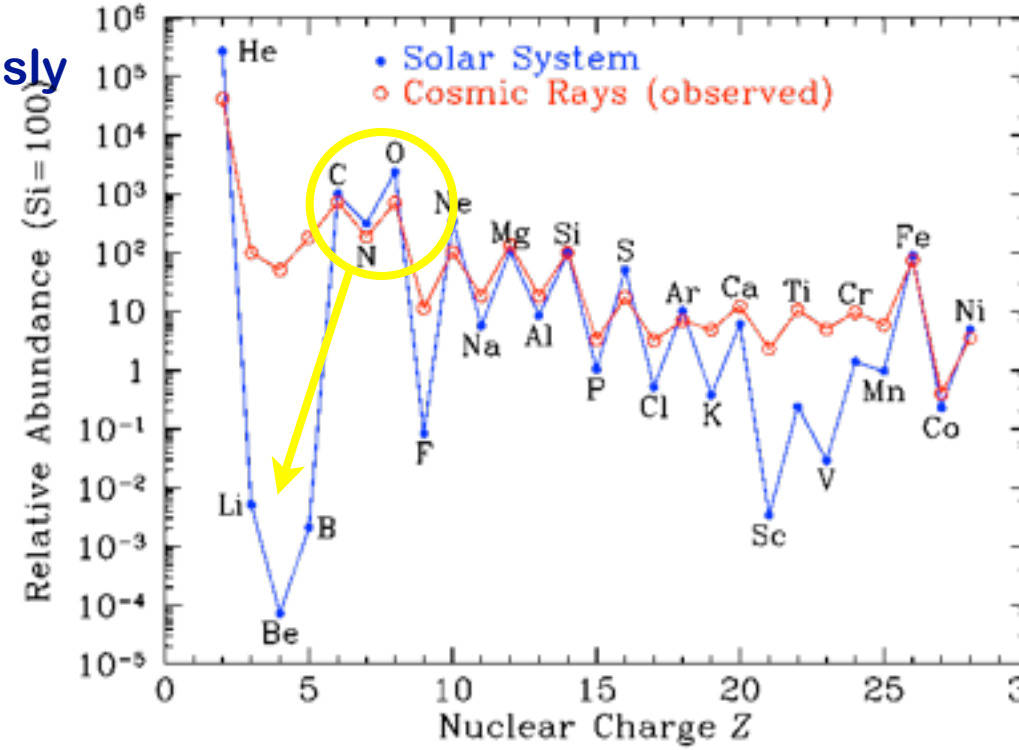
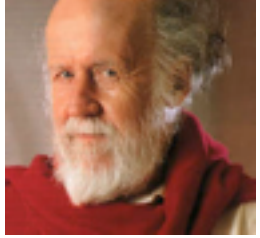
LiBeB that stop in ISM will accumulate!





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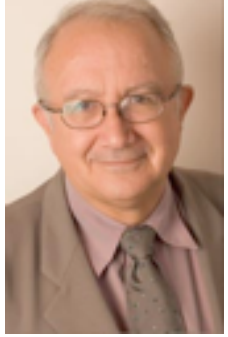

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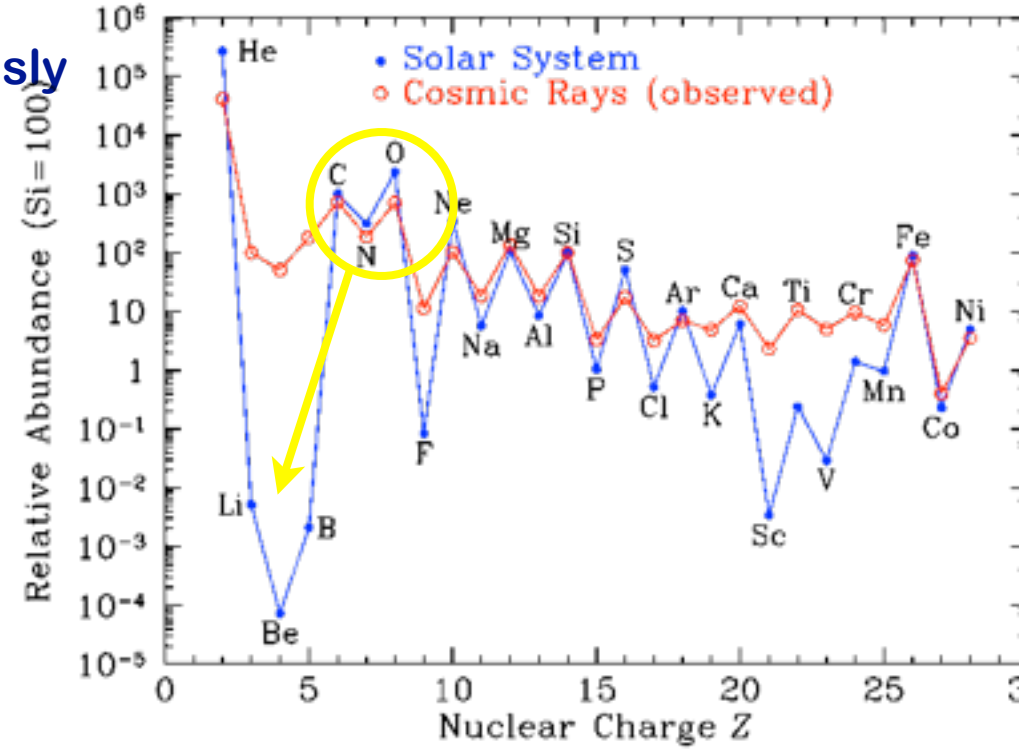

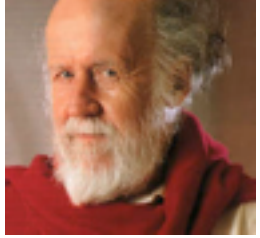

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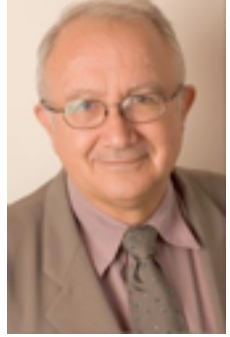

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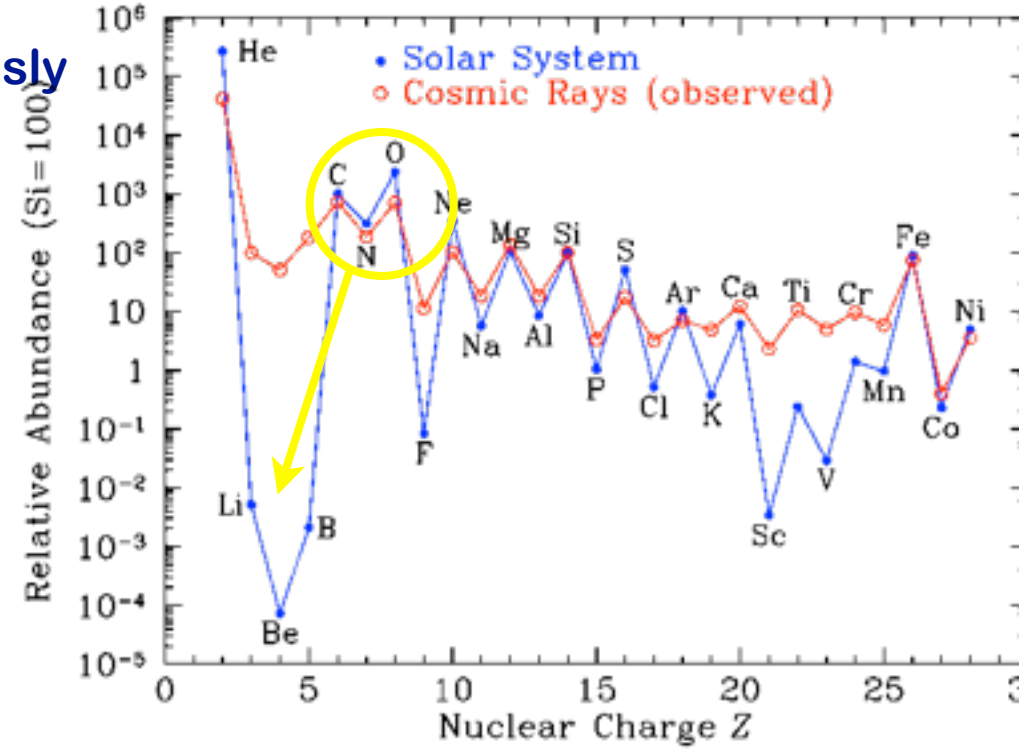
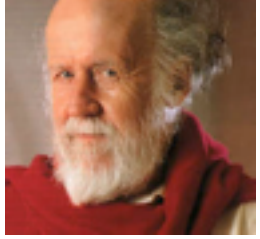
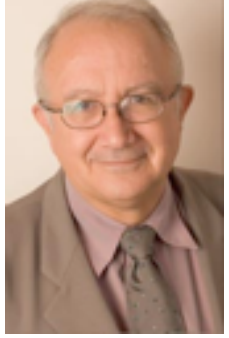




What about cosmic rays?



Reeves, Audouze et al (+Silk!):

- Cosmic rays are nonthermal
- Could they do the job?

Key hint:

- LiBeB abundances anomalously high in cosmic rays

Why?

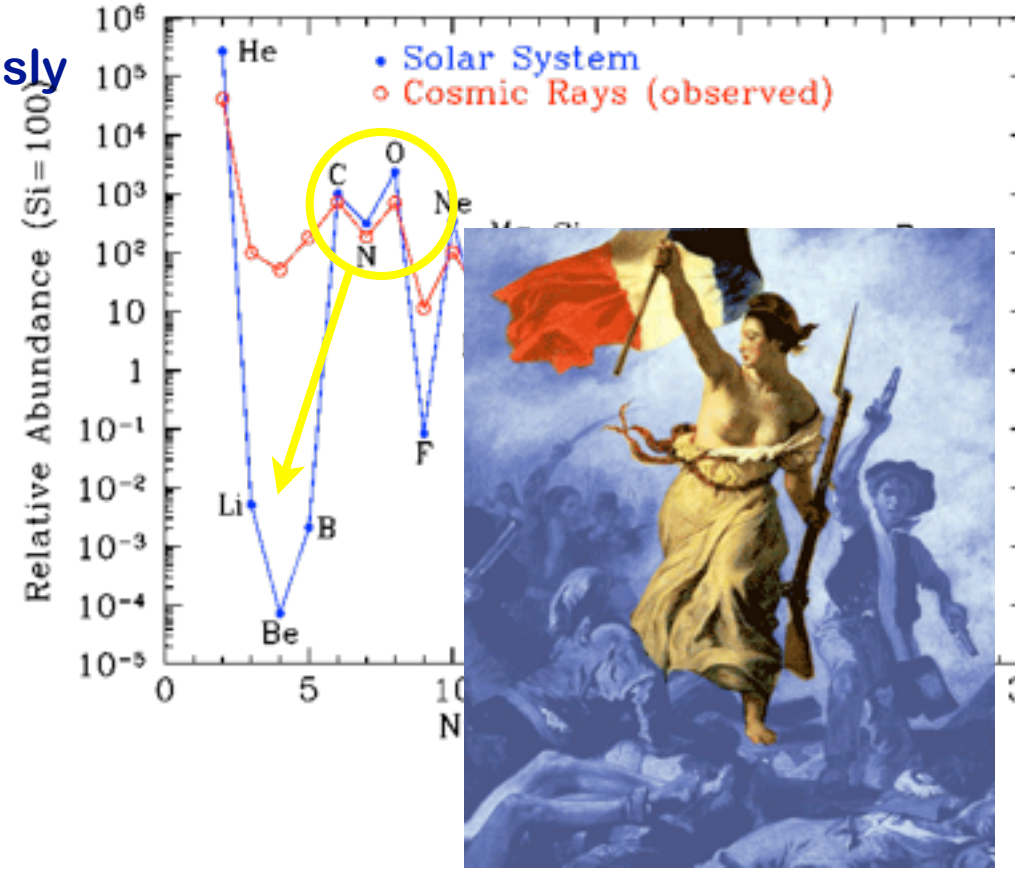
- produced in flight

LiBeB that stop in ISM will accumulate!

Quantitatively:

$$\Phi_{\rm cr}\ \sigma_{p{\rm O}\to{\rm Be}} \left(\frac{\rm O}{\rm H}\right)_\odot\ t_{\rm disk} \approx \left(\frac{\rm Be}{\rm H}\right)_\odot$$

- it works!



Cosmic-Ray Nucleosynthesis

Reeves, Fowler, Hoyle 1970; Meneguzzi, Audouze, Reeves 1971; Walker, Mathews, Viola

Cosmic Rays interact with ISM

Interstellar gas: beam dump

- **Observe in gamma-ray sky**

$$p_{\rm cr} + p_{\rm gas} \rightarrow pp\pi^0$$
$$\pi^0 \rightarrow \gamma\gamma$$

- **Stable debris created**

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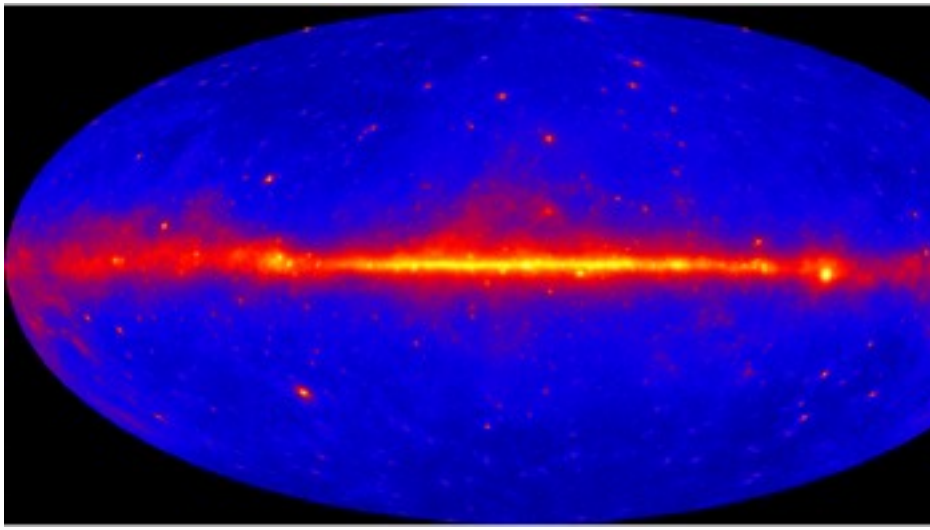

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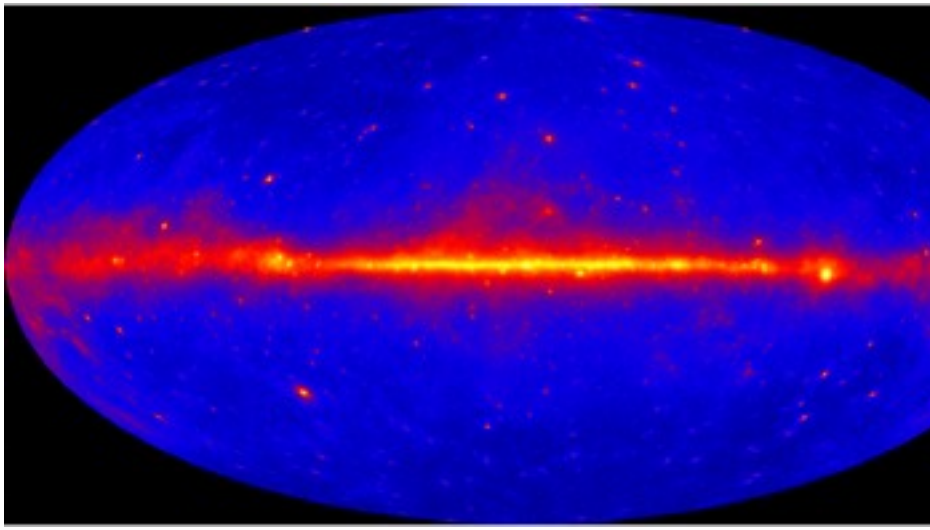

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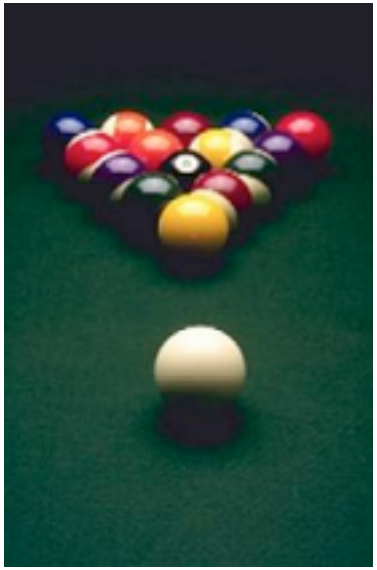

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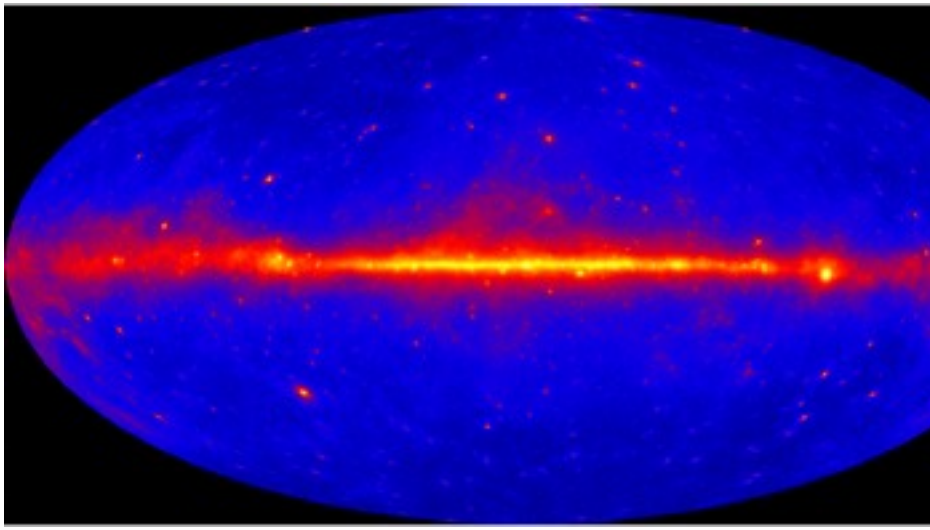

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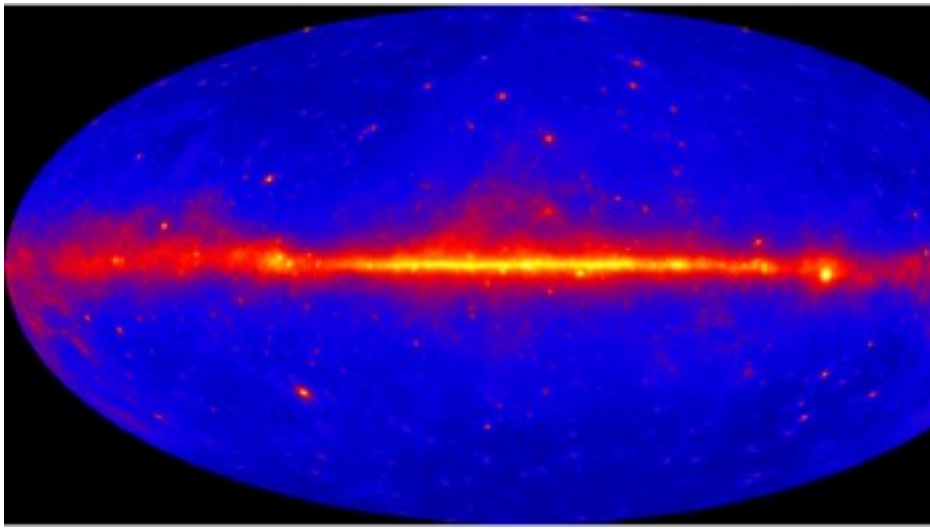

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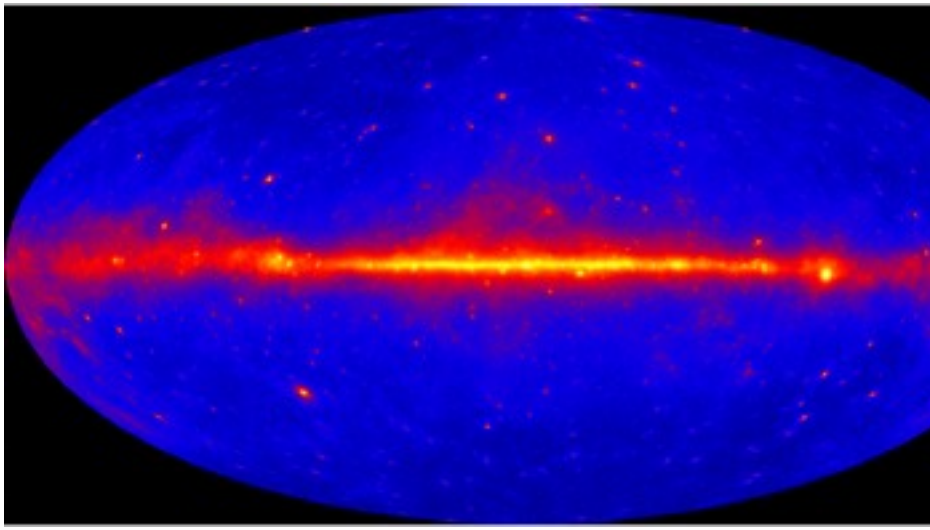

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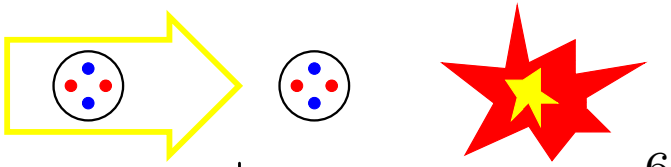

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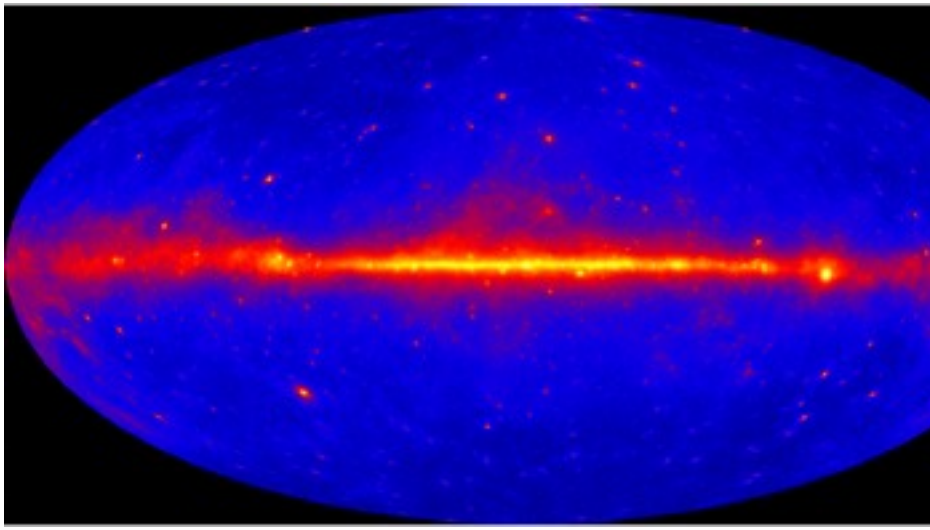

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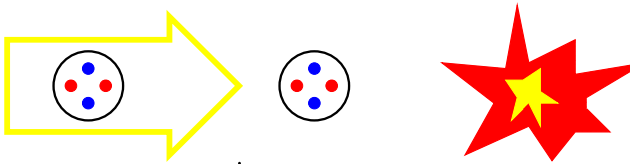

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no metals required--helium is primordial

Cosmic Ray Acceleration: Astrophysical Shocks

In magnetized collisionless shocks:

- ★ **shock deceleration**
  - ➡ **converging flows**
- ★ **charged particles scatter off magnetic inhomogeneities**
- ★ **repeatedly cross shock,**

  gain energy

  with some chance of escape
- ★ **result: power-law spectrum**

$$dN/dE \propto E^{-(2+4/\mathcal{M}^2)} \rightarrow E^{-2}$$

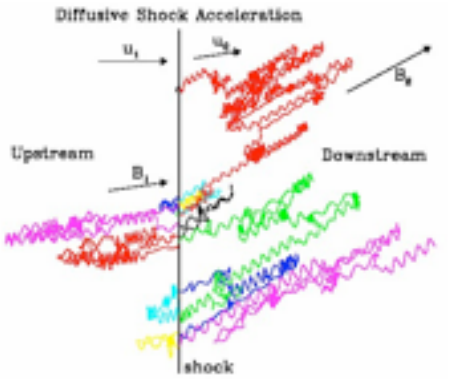
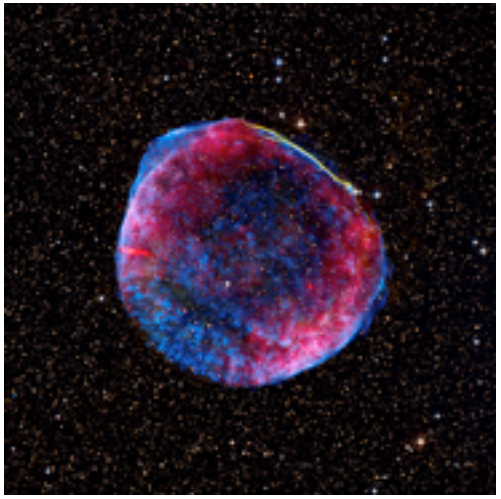


Image: Matthew Baring



SN 1006 X-ray/Radio/Optical

Galactic Cosmic Rays

composition: mostly protons

- heavier nuclei in roughly ISM proportions

spectrum: nonthermal

- power law with breaks

sources: Supernovae

- Galactic CR flux:

- SNe also sites of metal production:

Li production:

- rate
- abundance

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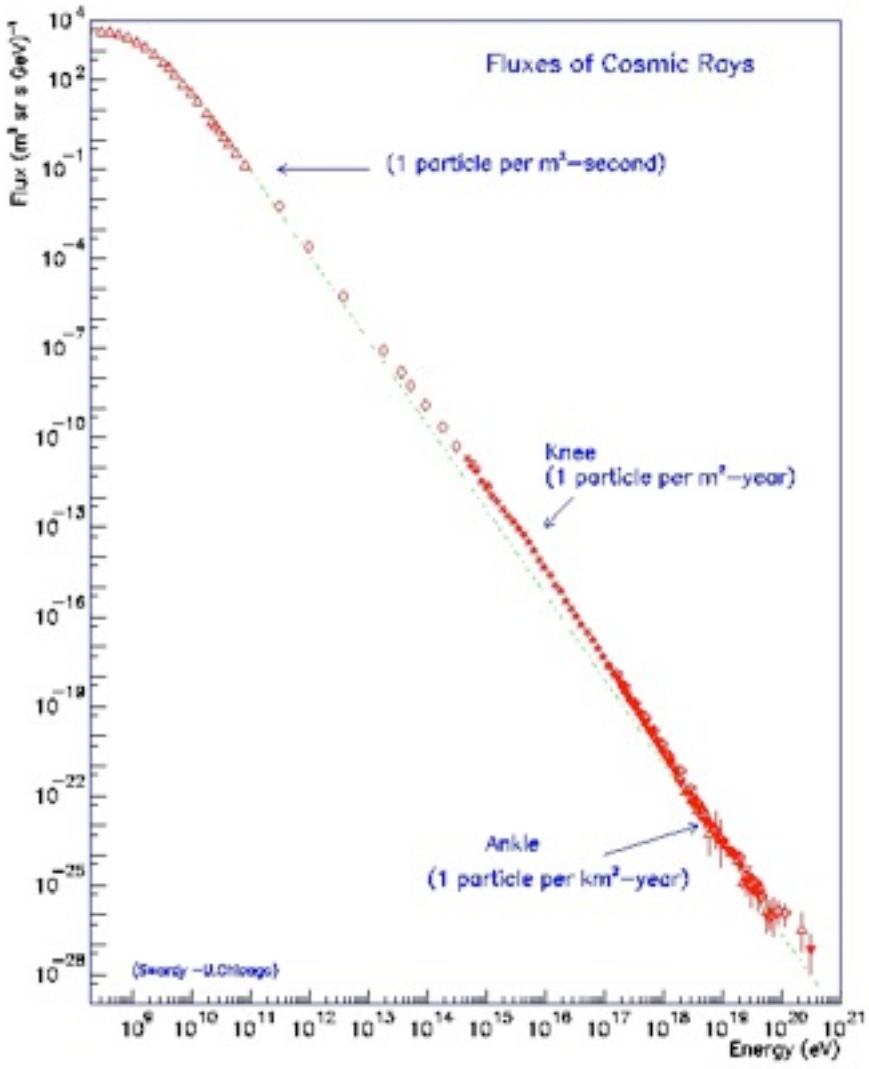

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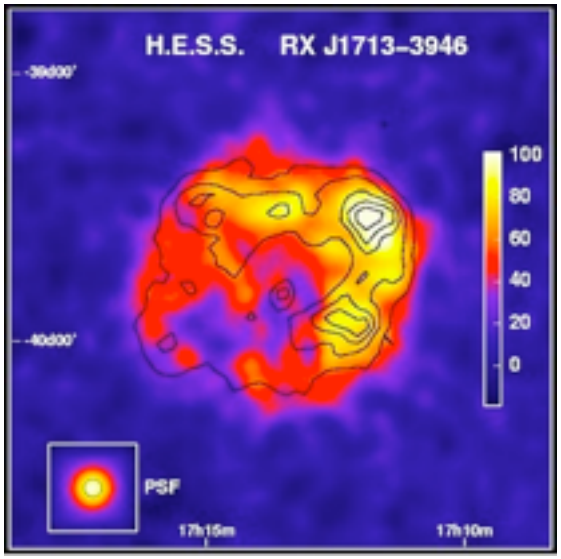

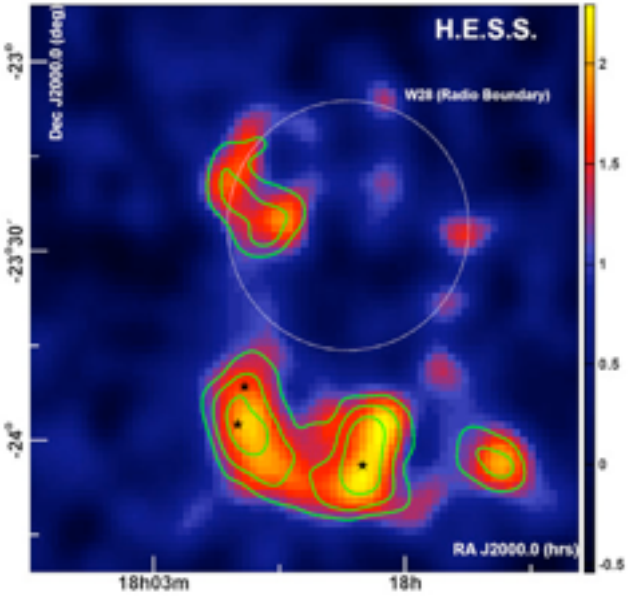

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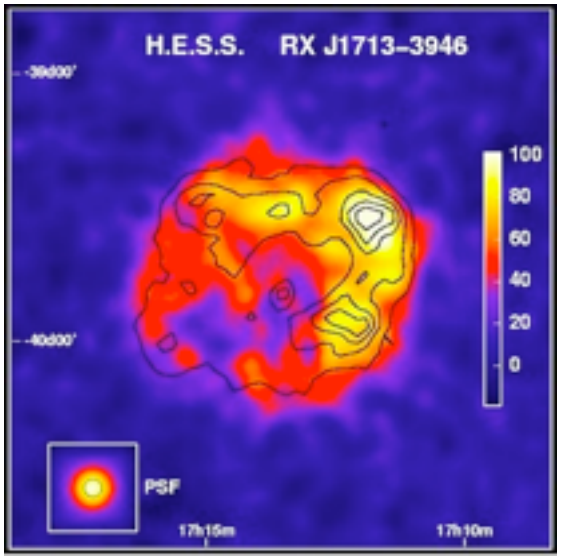
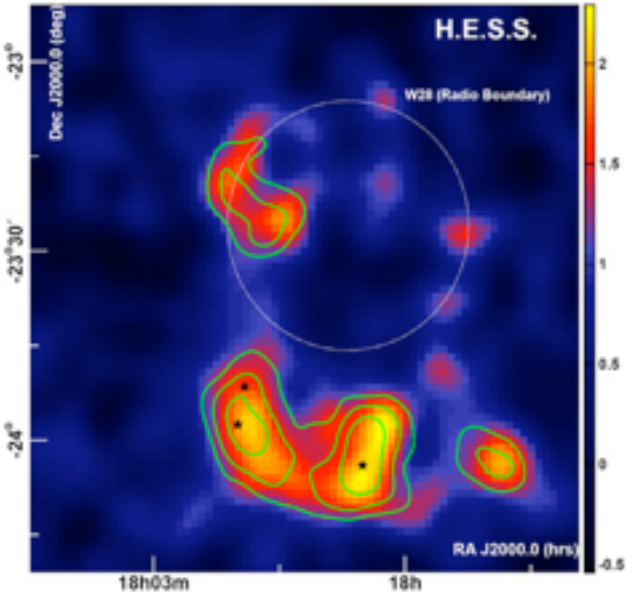
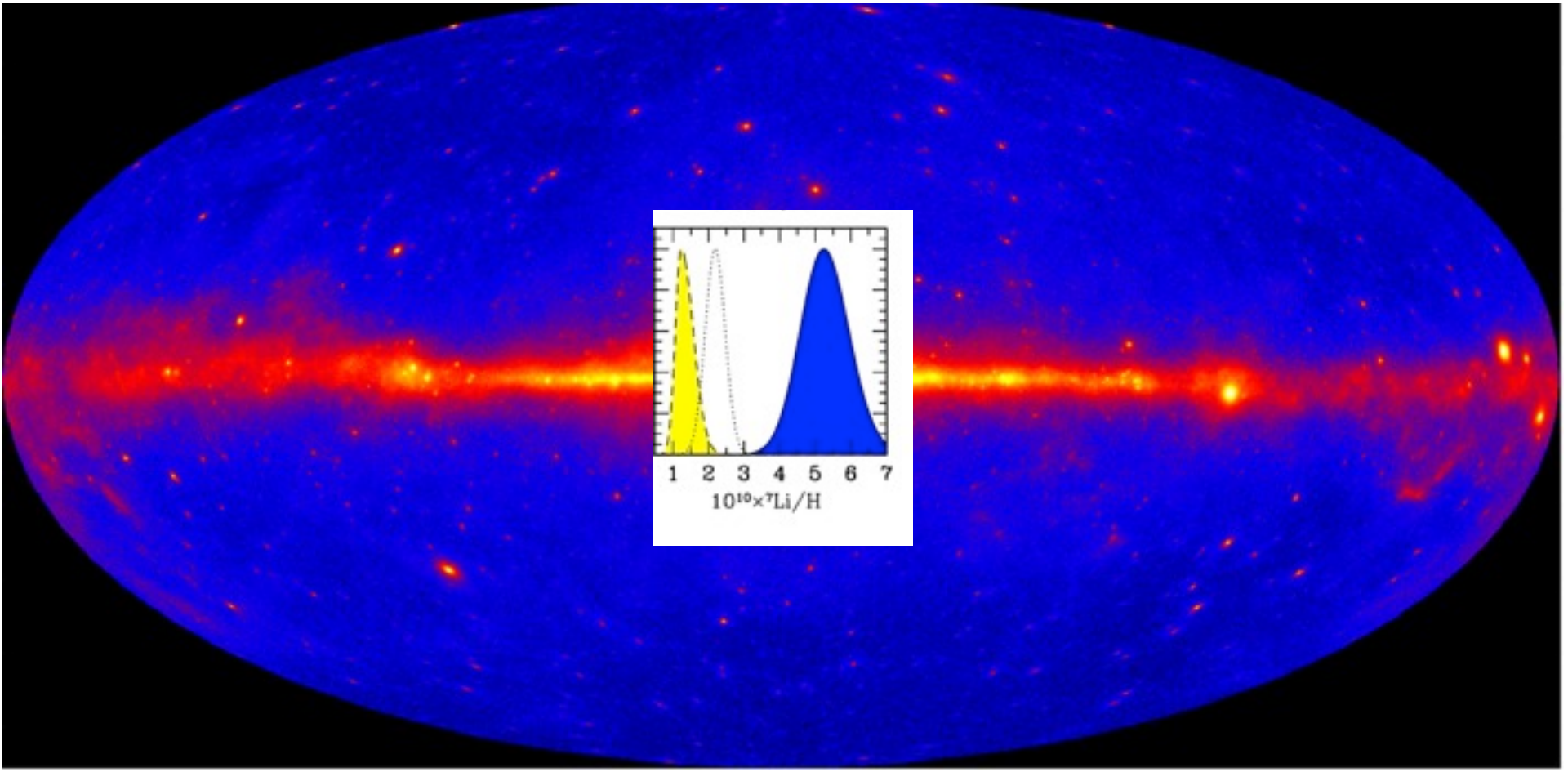
Li production: $\alpha\alpha \rightarrow {}^6\mathrm{Li} + \cdots$

- rate $\frac{d}{dt}\,\mathrm{Li}|_{\rm gcr} \sim \Phi_\alpha \sigma_{\alpha\alpha} \quad \propto \quad \frac{d}{dt} Z$
- abundance $\mathrm{Li}|_{\rm gcr} \propto Z$





Cosmic Rays and LiBeB Evolution



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LiBeB as Cosmic Ray Dosimeters

Solar LiBeB: cumulative irradiation at Sun birth

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LiBeB in halo stars: cosmic-ray fossils

Cosmic rays present in early Galaxy!

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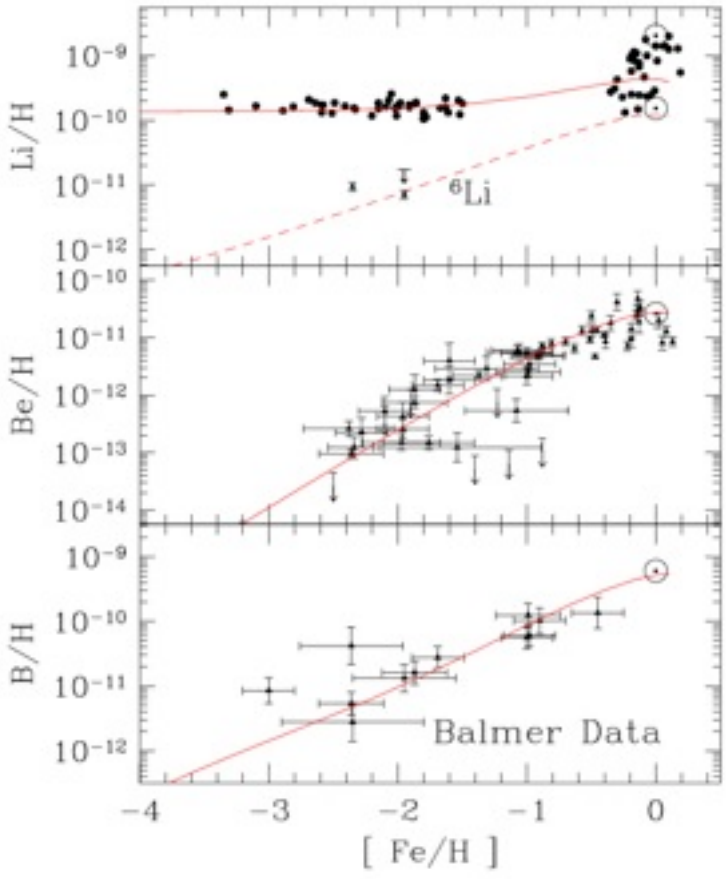

BDF & Olive 99

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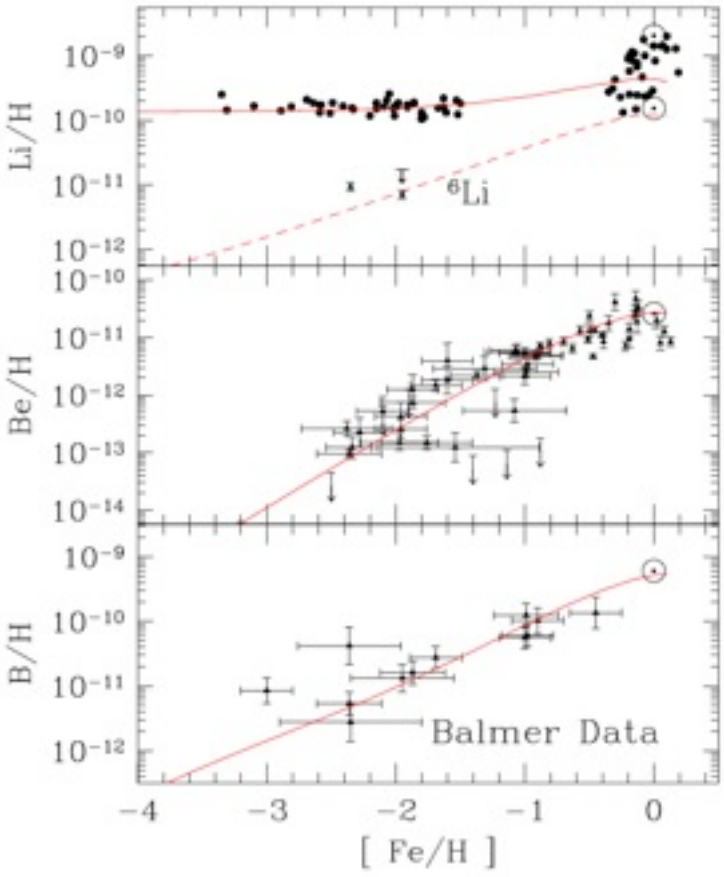

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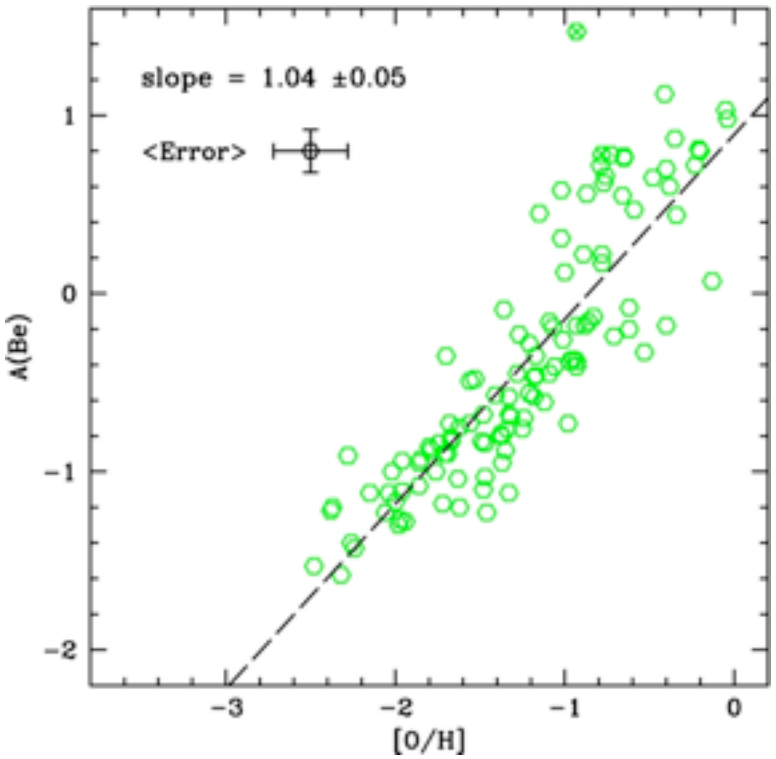

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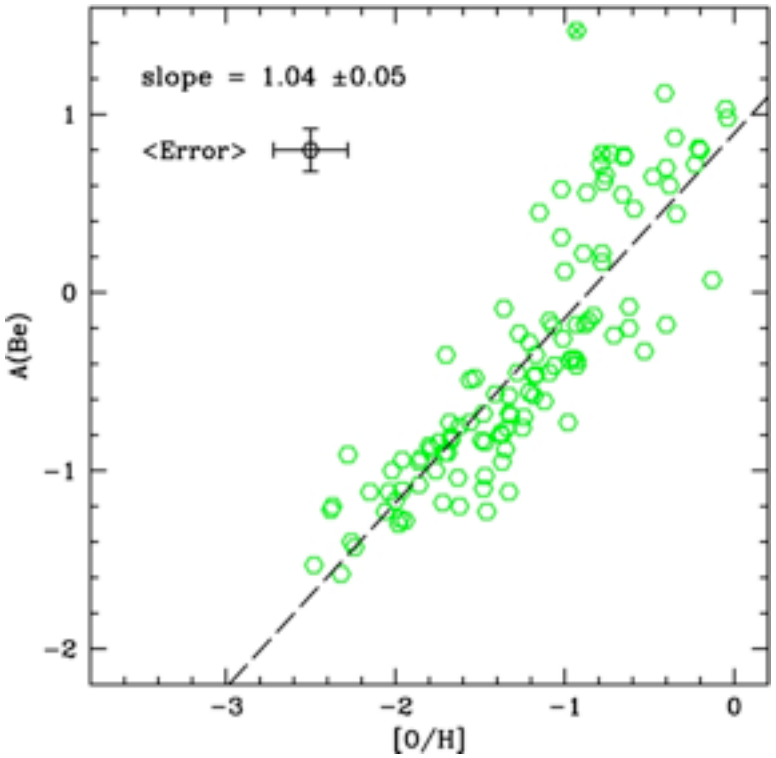

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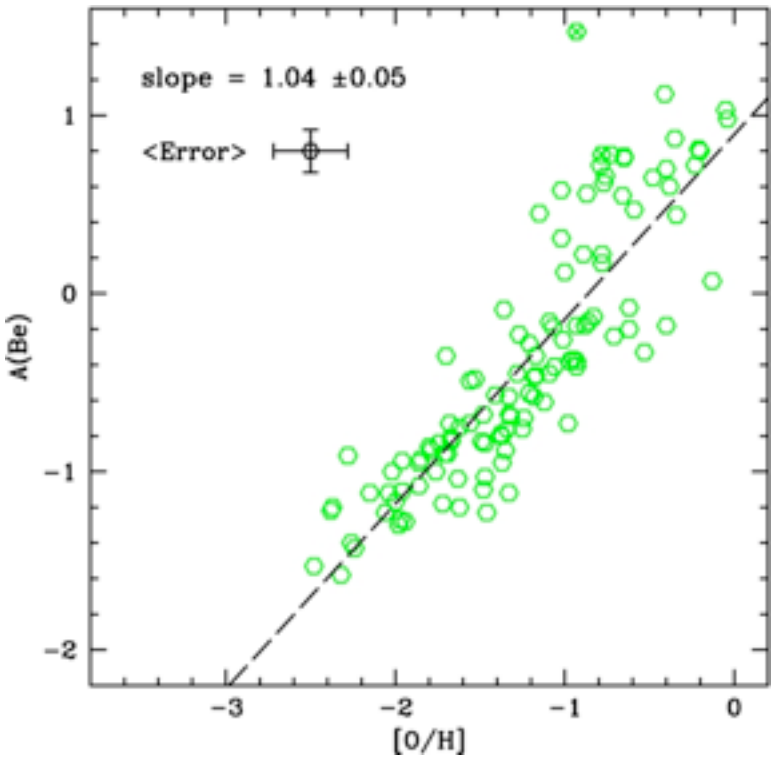

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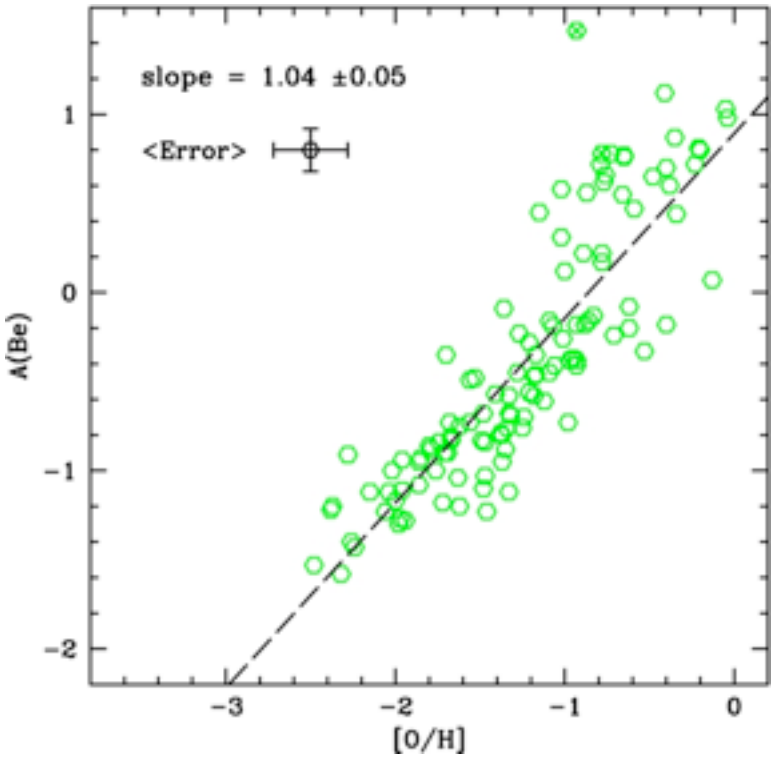

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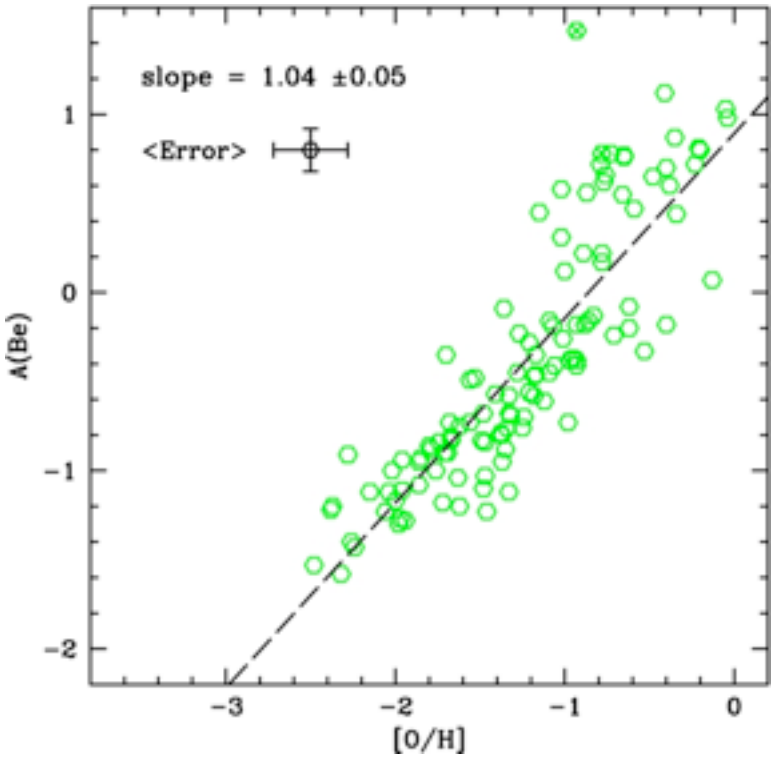

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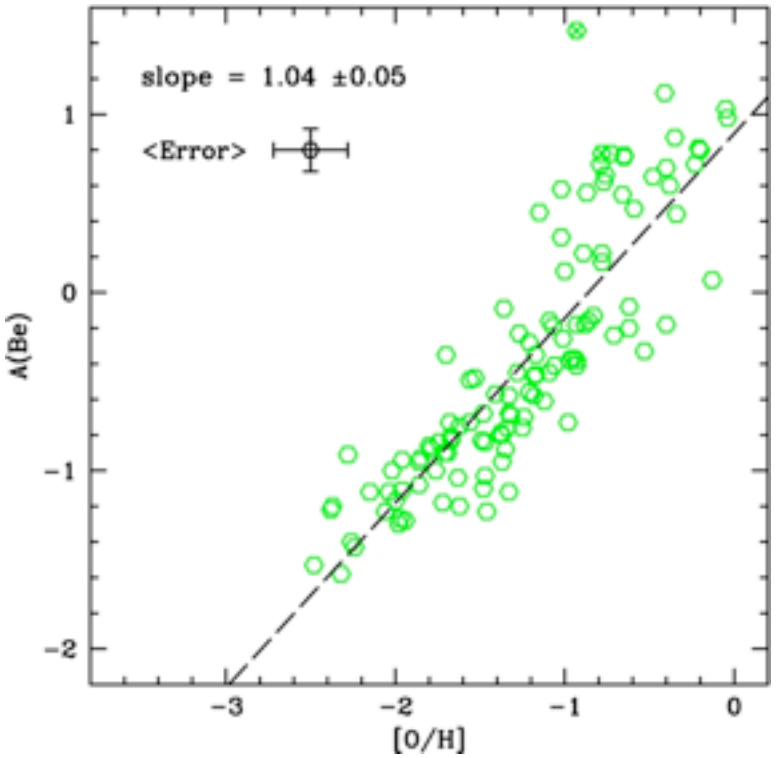

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Galactic Cosmic Rays and Halo Star Lithium

- Cosmic rays pollute primordial Li

  $^7Li_{observed} = {}^7Li_{CR} + {}^7Li_{BBN}$

  But $^6LiBeB_{GCR}$ ⇒ $^{6,7}Li_{GCR}$

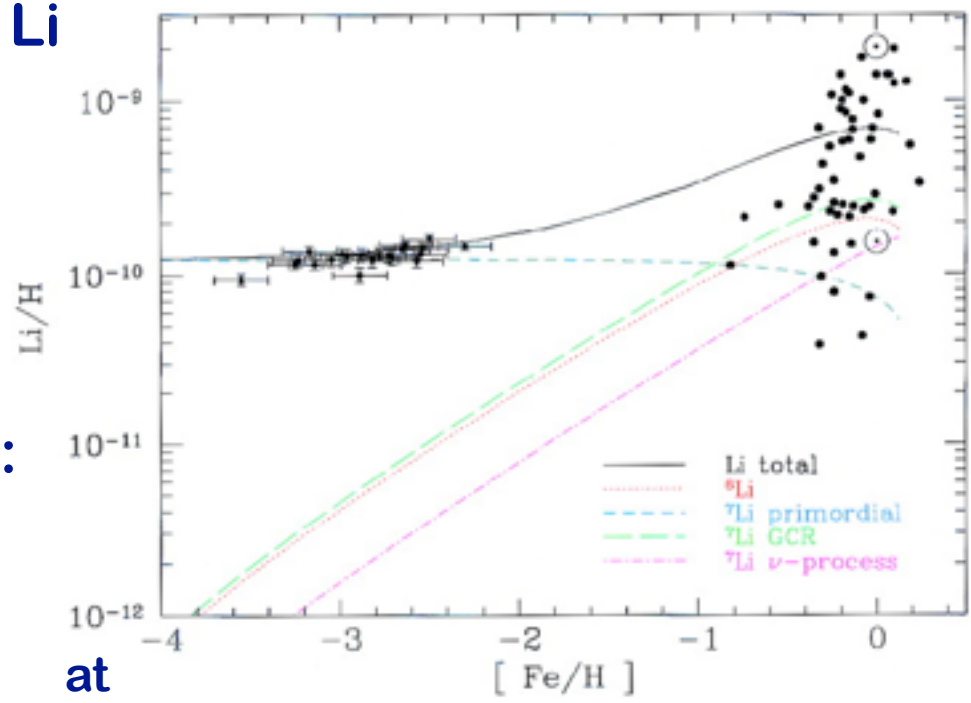
  Infer true $^7Li_{BBN}$!

- Consequences
  - predict small positive slope:

    $$\mathrm{Li} = \mathrm{Li}_{\mathrm{bbn}} + \left.\frac{d\mathrm{Li}}{d\mathrm{Fe}}\right|_{\mathrm{cr}} \mathrm{Fe}$$

  - makes ^{7}Li problem slightly worse!

    ~10% downwards correction at [Fe/H]=-3



Ryan, Olive, Beers, BDF, Norris 2000

^{6}Li and Cosmic Rays

Cosmic-Ray prediction:

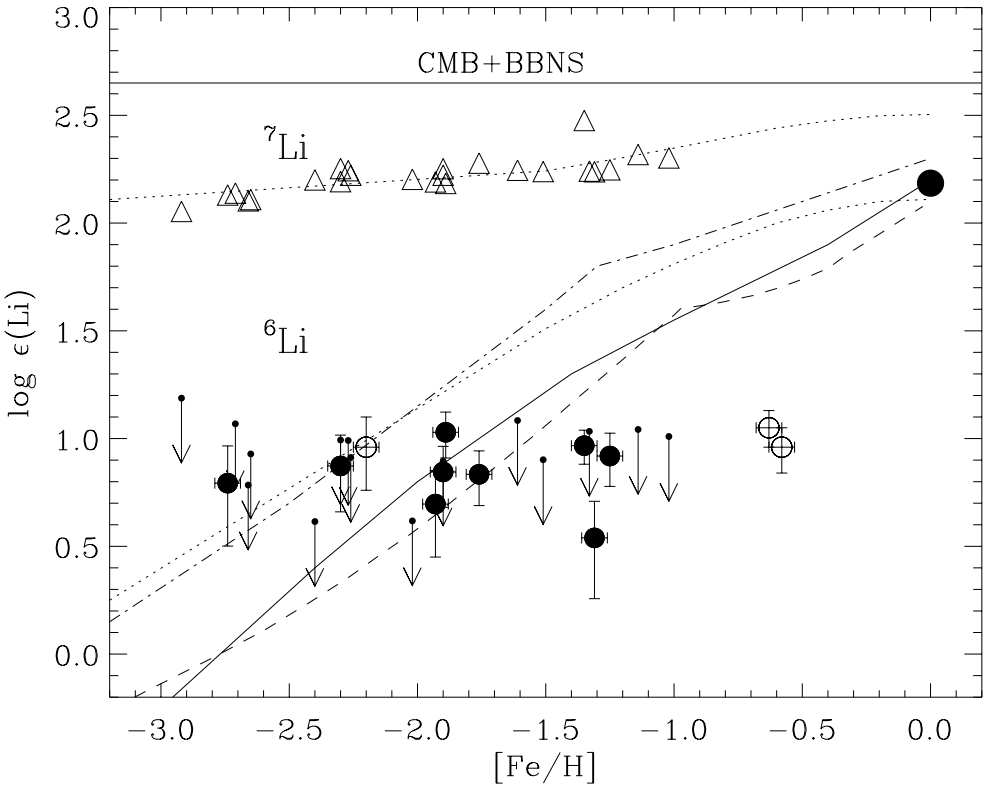
- **linear metal scaling**

$$^6\mathrm{Li} = \left.\frac{d^6\mathrm{Li}}{d\mathrm{Fe}}\right|_{\mathrm{cr}} \mathrm{Fe}$$

inconsistent with a ^{6}Li plateau!

because CR interactions unavoidable:

- **^{6}Li non-detection at [Fe/H]>-1.5 disagrees with CR prediction**
- **suggests depletion must operate at least in this regime**



Data: Asplund et al 2006

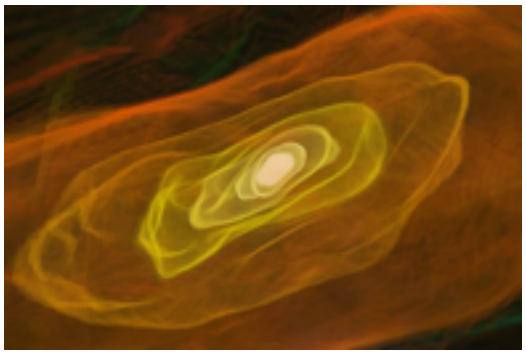
Pre-Galactic Cosmic Rays: Pop III Stars

First stars (PopIII)

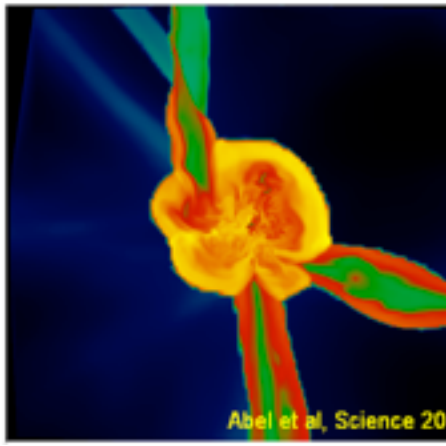
- Zero metallicity star formation
- thought to lead to ~few stars per halo
- massive to supermassive

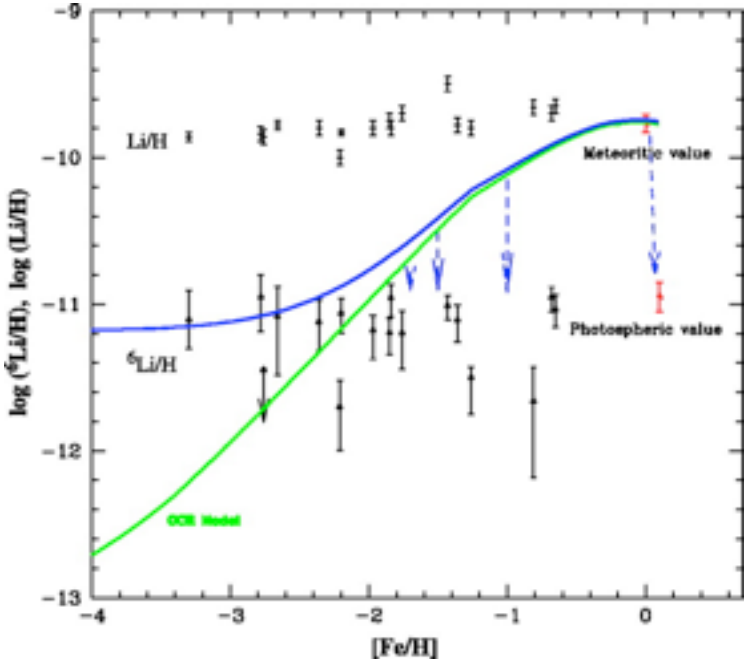
Explosions would be sources of cosmic rays Rollinde, Vangioni, Olive, Silk; Kusukabe

- once outside of birth remnant, produce lithium in metal-free environment
- can give ^{6}Li "plateau" without substantial disruption to ^{7}Li
- gamma-ray signal redshifted, small



Abel, Bryan, & Norman





Rollinde, Vangioni, & Olive 2006

Shock Power for Acceleration of Cosmological Cosmic Rays

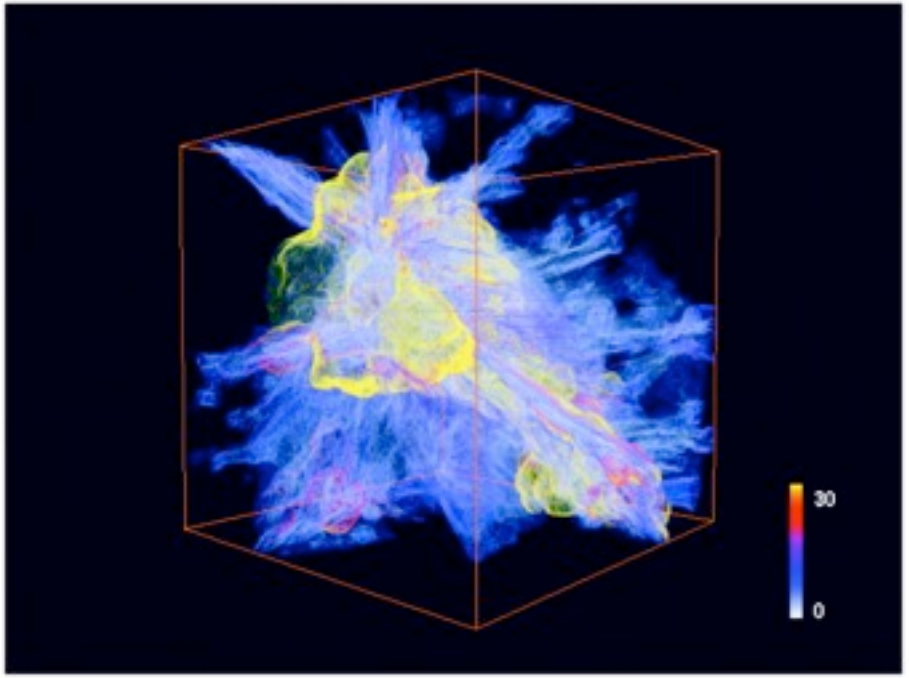
dark matter potentials drive baryon flows

If flow speed > sound speed: shocks

Cosmic accretion shocks:

- ✓ High Mach
- ✓ Long-lived
- ✓ Large power

Ideal sites for particle acceleration!



Ryu et al 2003

Shock surfaces, Mach colors

$(25\ h^{-1}\ \mathrm{Mpc})^3$ simulation

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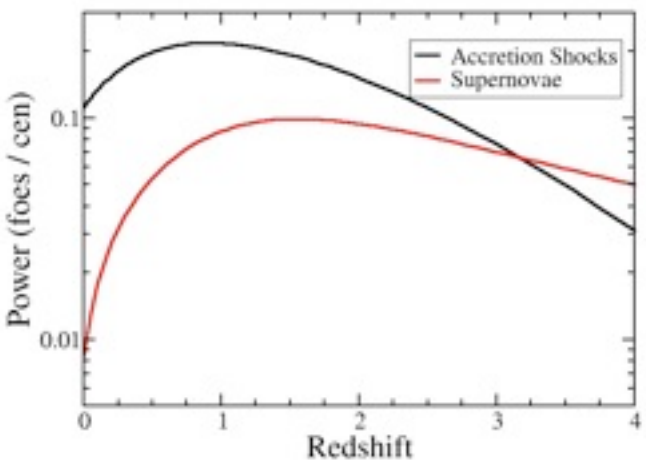
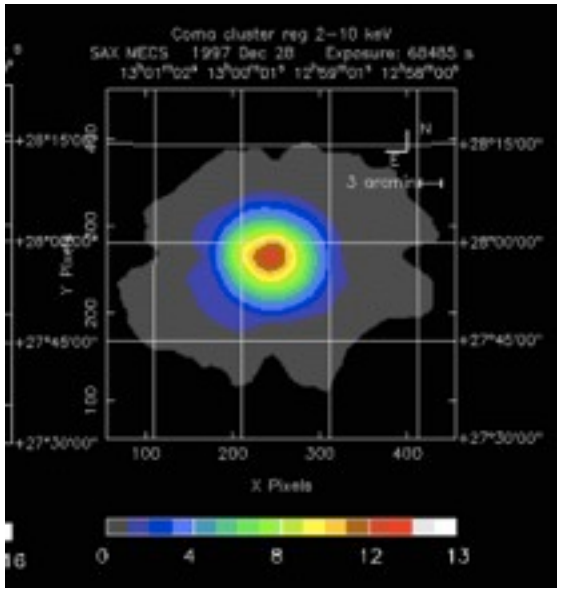


Pavlidou & BDF 2006

Structure Formation Cosmic Rays

- An inevitable fact of baryonic life?
- Acceleration begins before galaxy birth?
- Galaxy clusters:
  - nonthermal radio Fusco-Femiano et al 99
  - but no gamma rays Ackermann et al 2010



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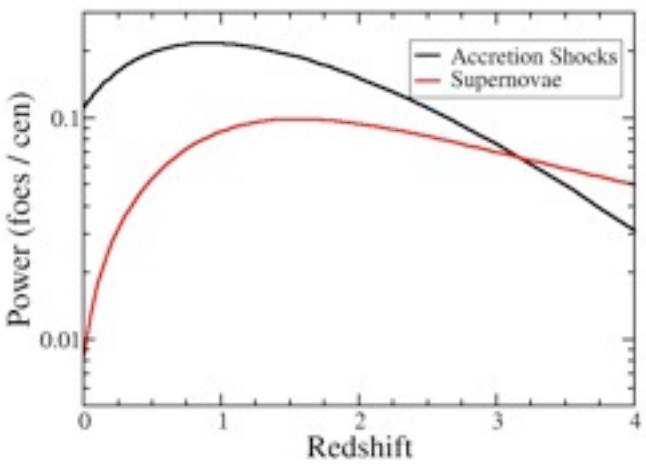

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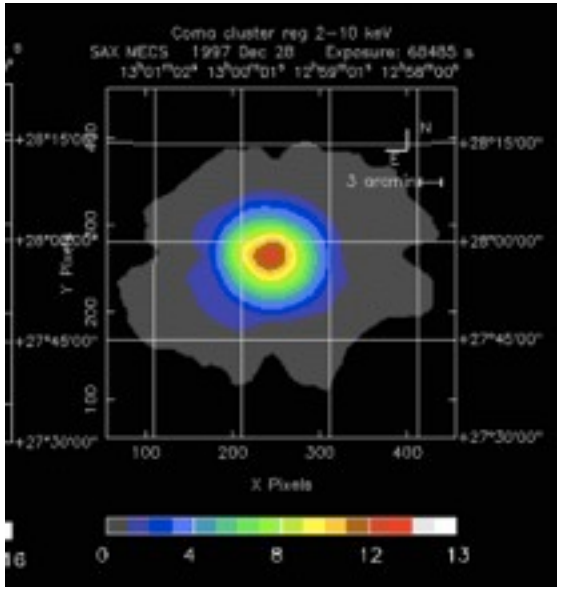

Structure Formation CR Nuke

Primordial beam, targets:

- ✓ produce ^{6}Li and ^{7}Li only,
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- ✓ no correlation with metals

Plateau candidate!

also see Prodanović poster

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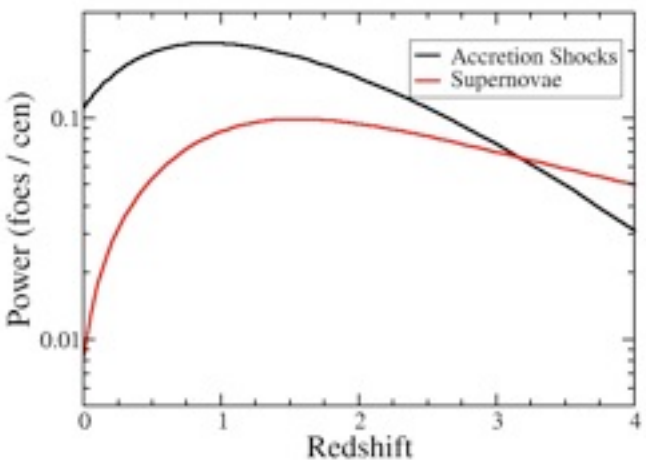

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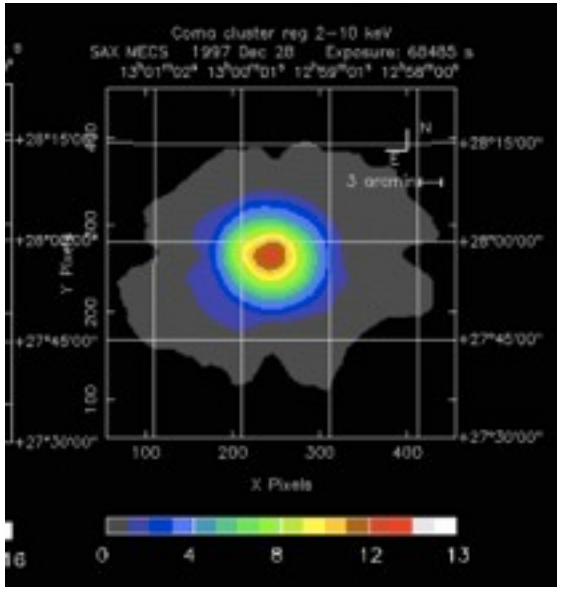
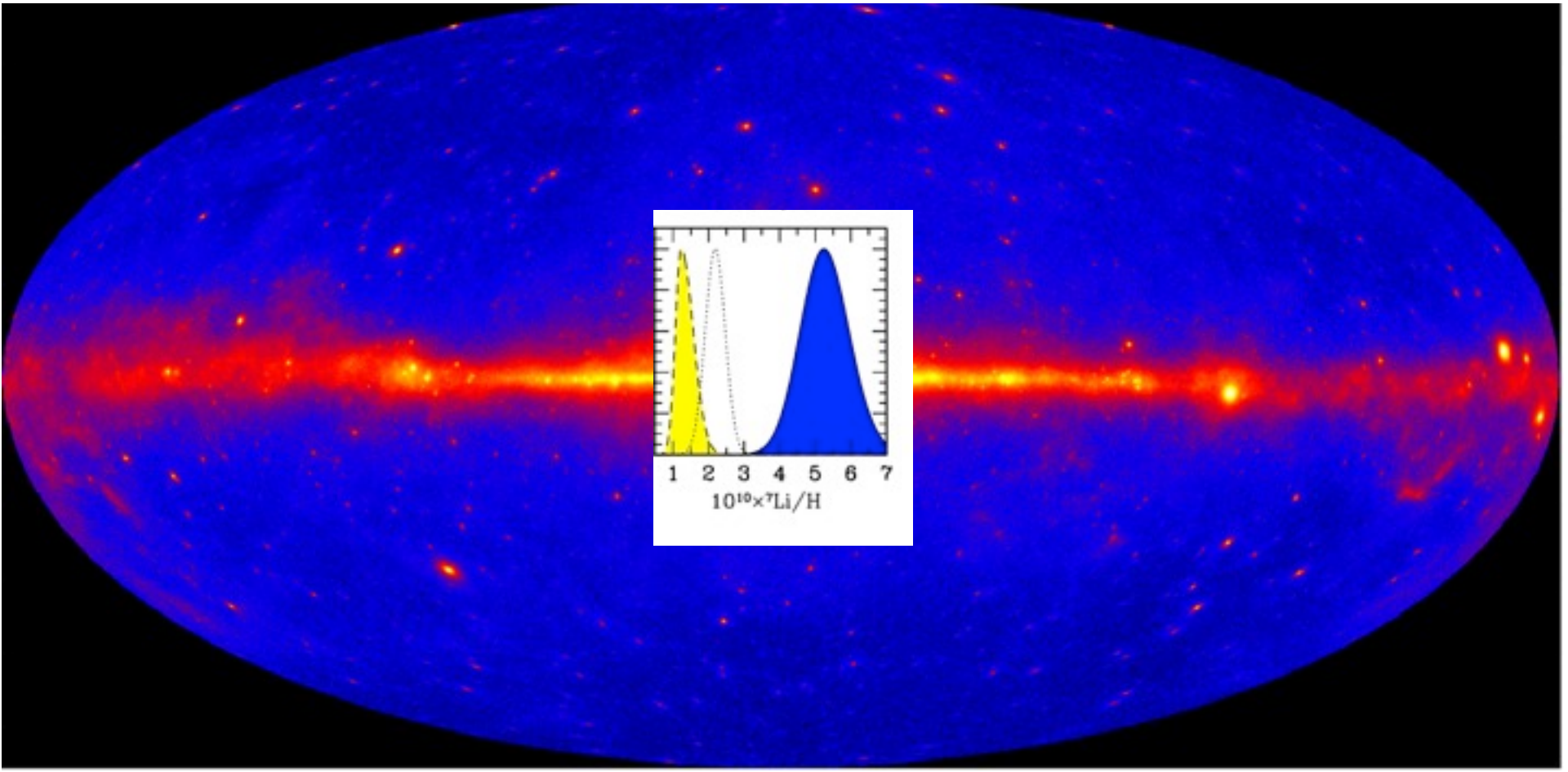
But how disentangle primordial Li?



The Fermí Era



Paleolithography:
Gamma-Ray Probes of Cosmic-Ray History

Prodanovic & BDF

Fermi

Hadronic gamma production
inevitably means ***lithium synthesis***

Observables

star-forming galaxies: new source class!

- probes global cosmic-ray/ISM interactions

gamma background: measure mean CR fluence across universe

lithium abundance: measures local CR fluence

Complementary:

use one to probe the other

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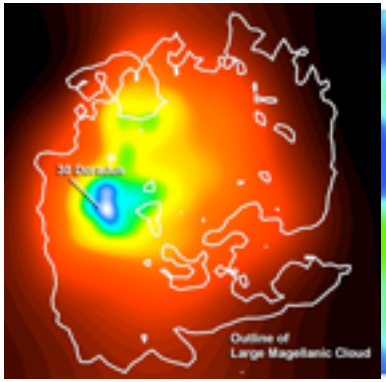
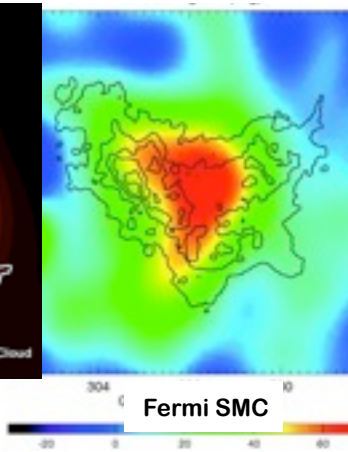


Fermi LMC



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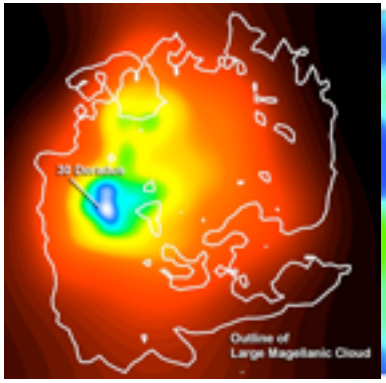

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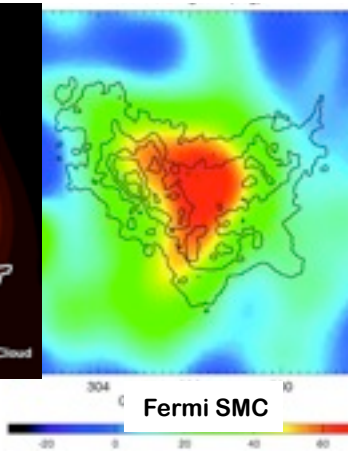

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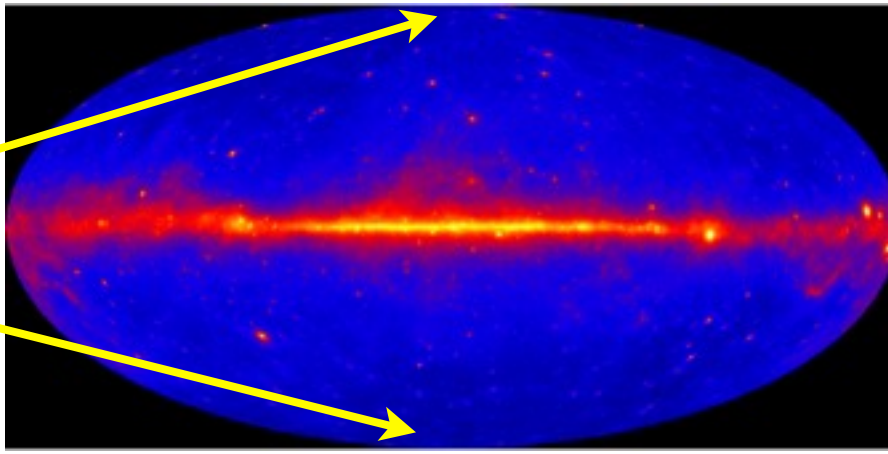

All-Sky, 2-years, >100 MeV
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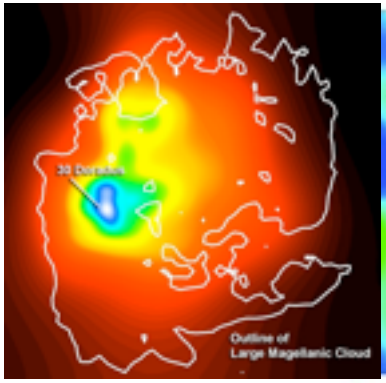

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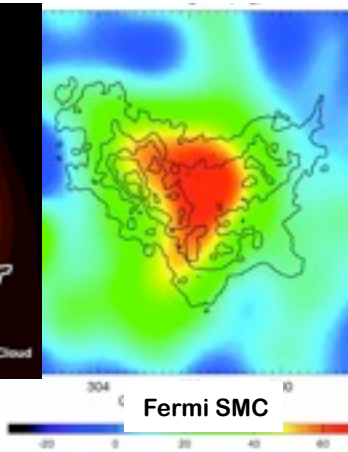

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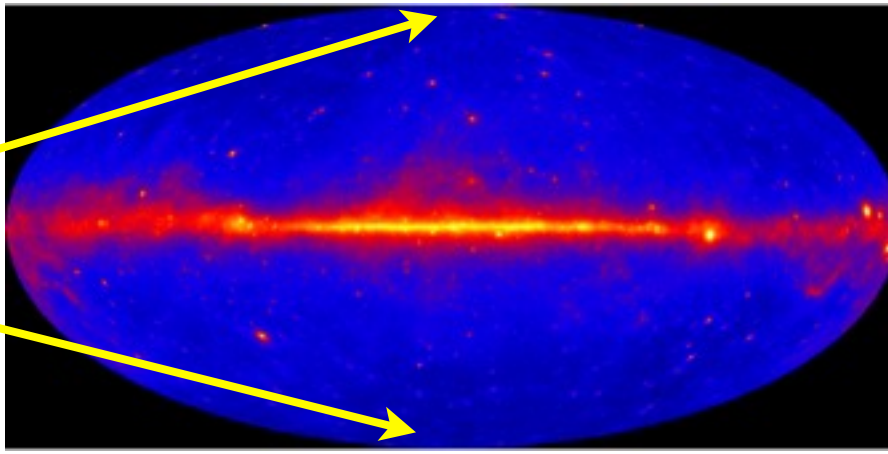

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Diffuse Gamma-Ray Background

Diffuse Gamma-Ray Background

Unresolved Normal Galaxies?

working hypothesis:
supernovae are engines of cosmic-ray acceleration

star formation ➤ SN ➤ cosmic rays

✓ gamma signal:

$$I \sim \int_{\rm los} (\text{cosmic star form}) \times (\text{ISM targets})$$

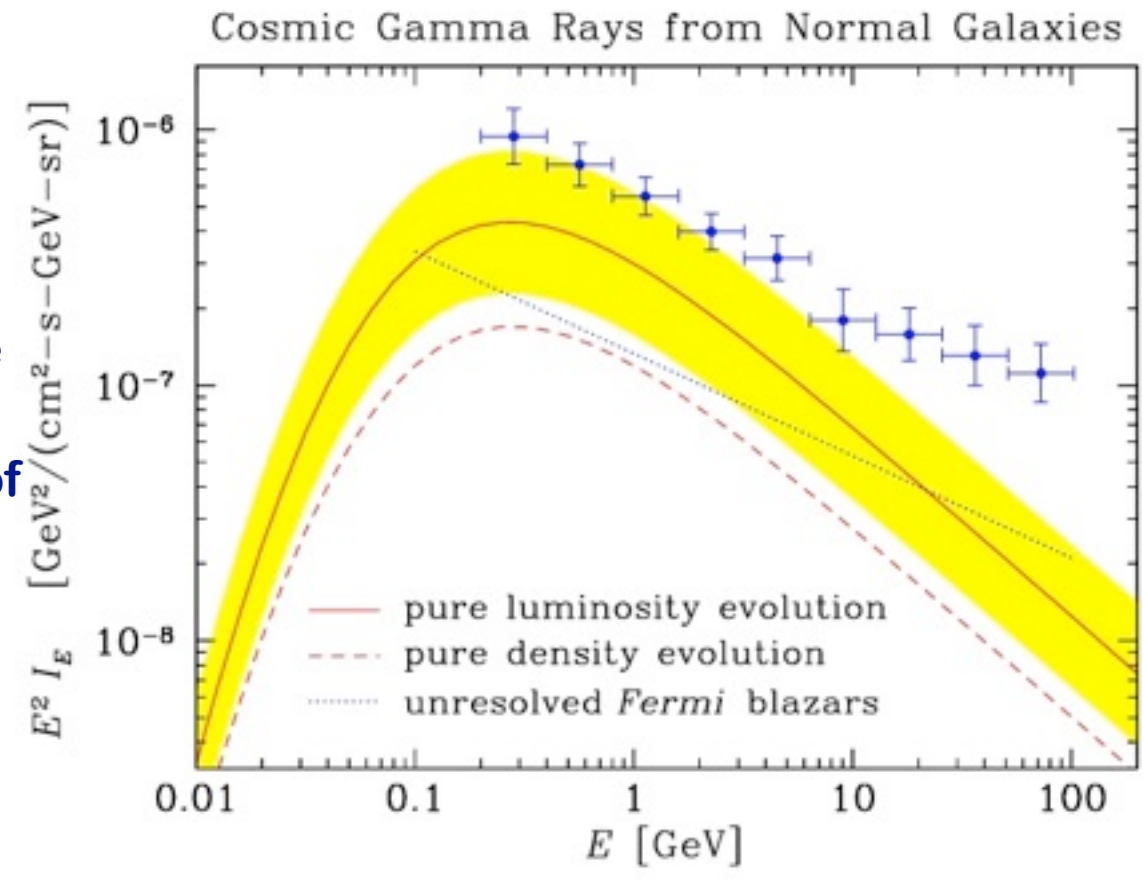
✓ shape: Galactic/pionic feature redshifted

✓ amplitude: substantial part of preliminary Fermi signal

✓ Fits! Can saturate but does not overproduce background

✓ consistent with solar lithium

✓ limits cosmic-ray activity not associated with star formation (e.g., structure form)



Curves: BDF, Pavlidou, Prodanovic 2010

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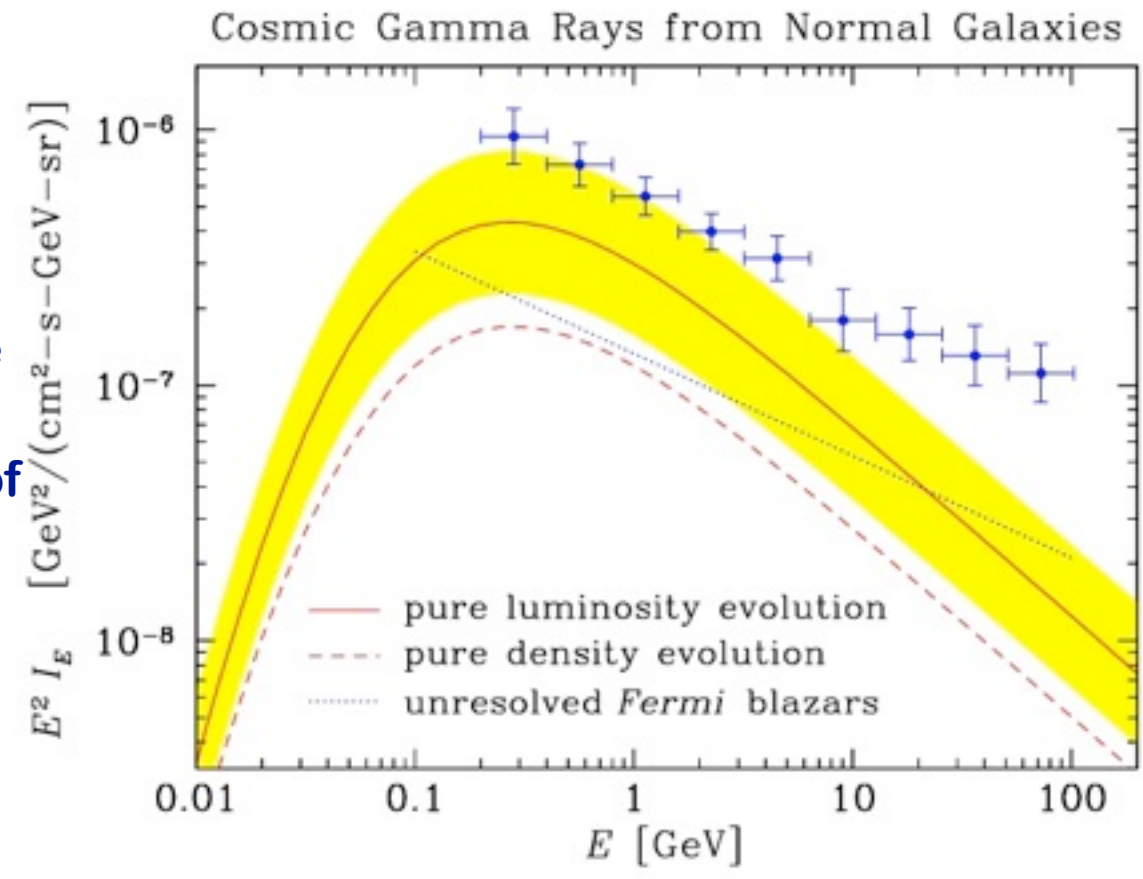
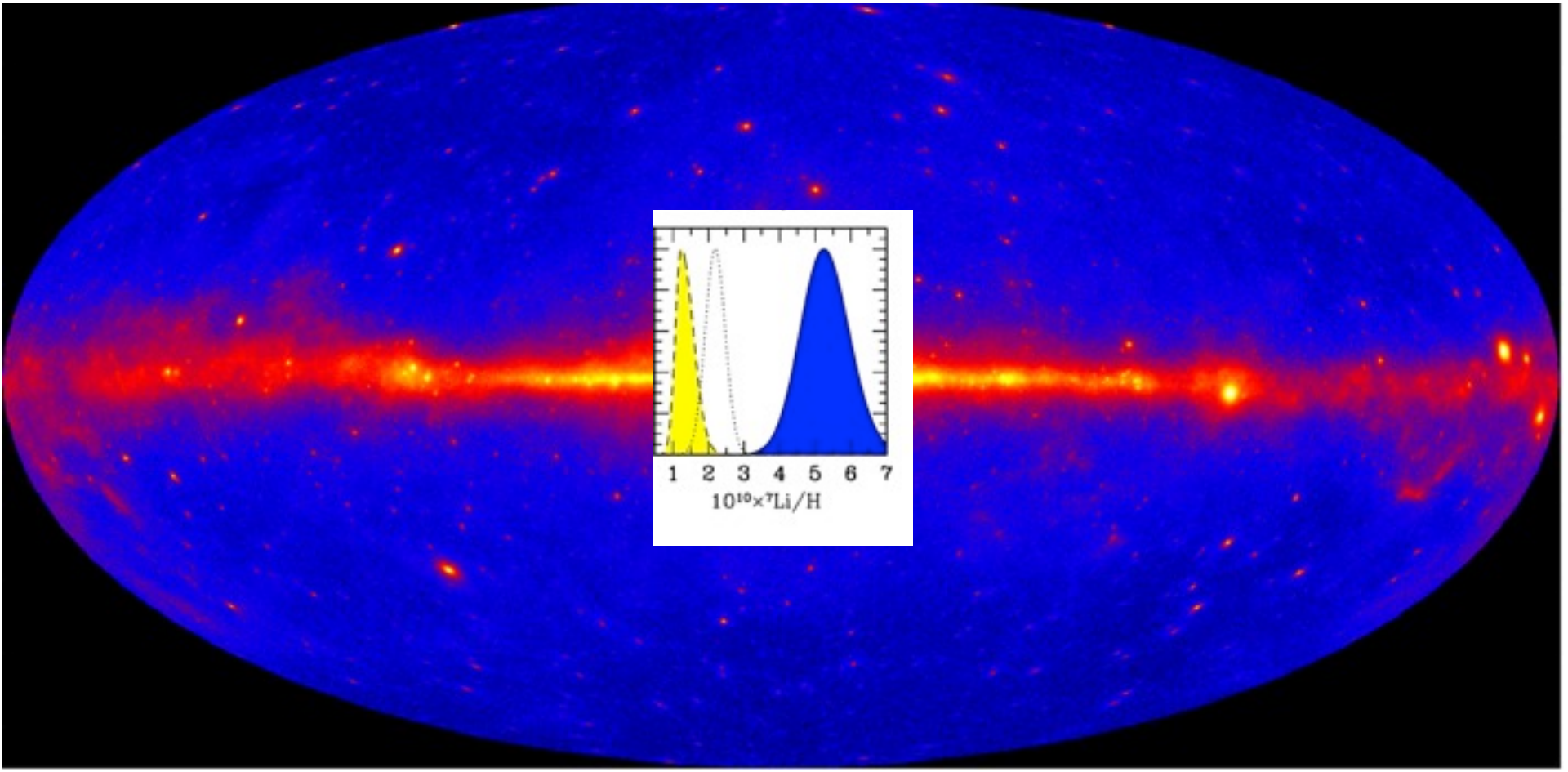
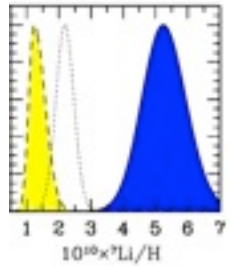


Curves: BDF, Pavlidou, Prodanovic 2010
Points: Fermi (Abdo et al 2010)

Implications and Outlook



Outlook



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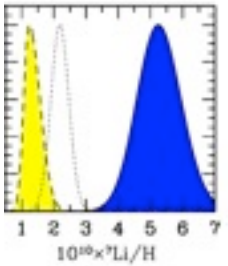
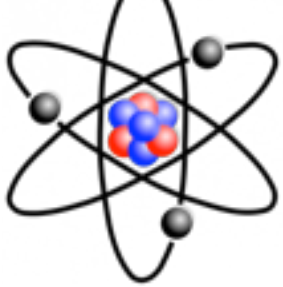


Cosmic-ray interactions with diffuse gas unavoidably produce lithium

- only conventional source of ^{6}Li, ^{9}Be, ^{10}B
- important source of ^{7}Li and ^{11}B
- nucleosynthesis of last resort



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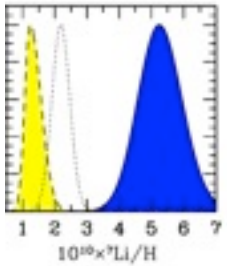

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^{6}LiBeB observed in halo stars

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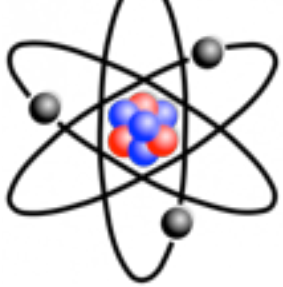
- abundance evolution traces cosmic-ray history



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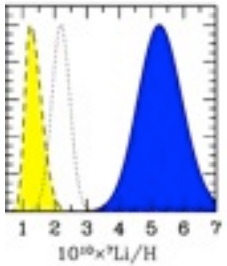

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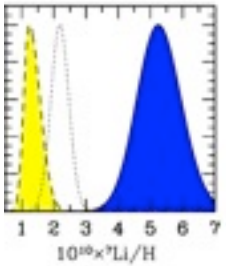
Cosmic-ray ^{6}Li and ^{7}Li adds to Spite plateau

- leads to small positive slope
- contaminates primordial signal
- worsens (slightly) the lithium problem -- a bitter pill

  but also makes problem more pressing and interesting

Outlook



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The Fermi Era

- Gamma-rays produced by same cosmic-ray interactions
- probe Galactic and pre-Galactic synthesis