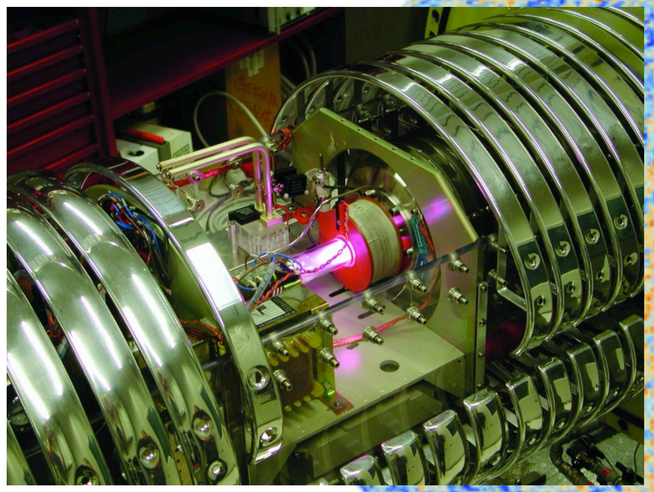
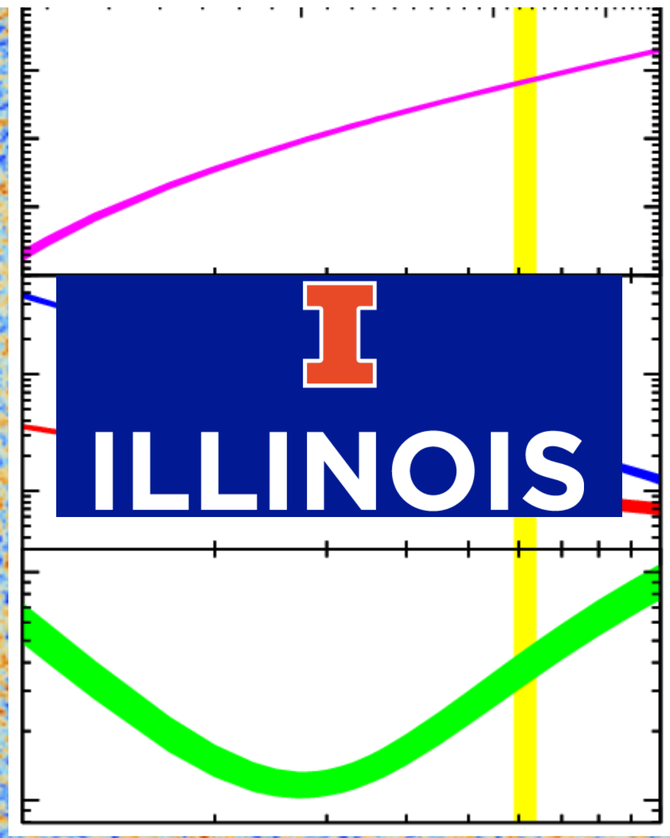
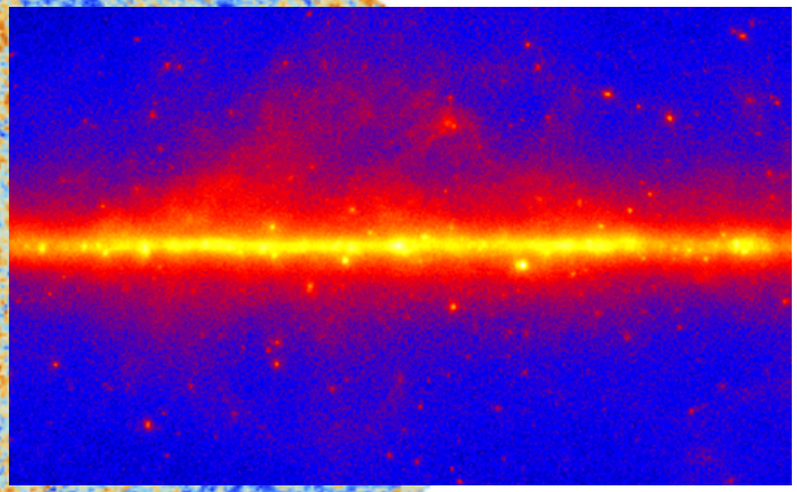
Big-Bang Nucleosynthesis

New Developments and a Bright Future





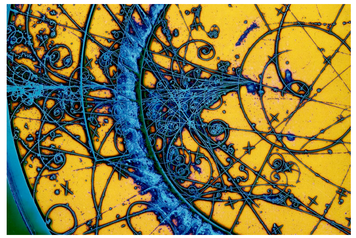


Brian Fields

ChETEC-INFRA General Assembly

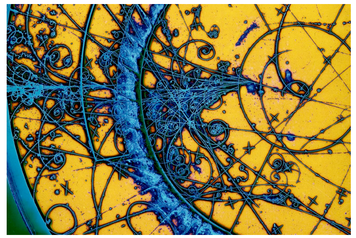
Padova & Online: May 31, 2022

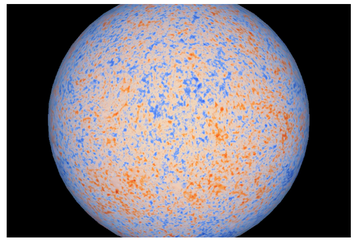
Big-Bang Nucleosynthesis



★ **Nuclear Physics in the Early Universe**

Big-Bang Nucleosynthesis





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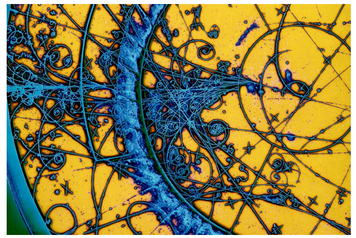

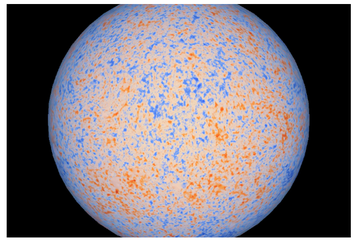

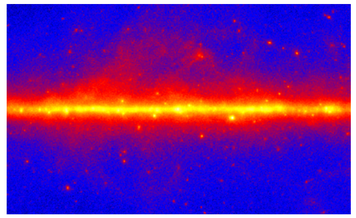

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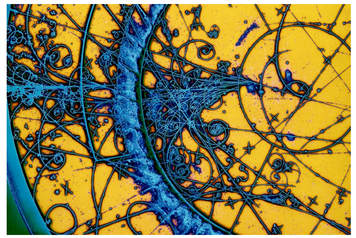

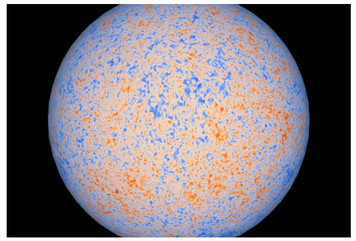

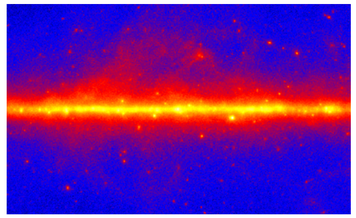

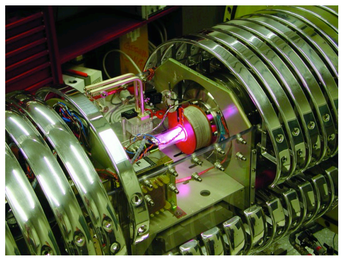

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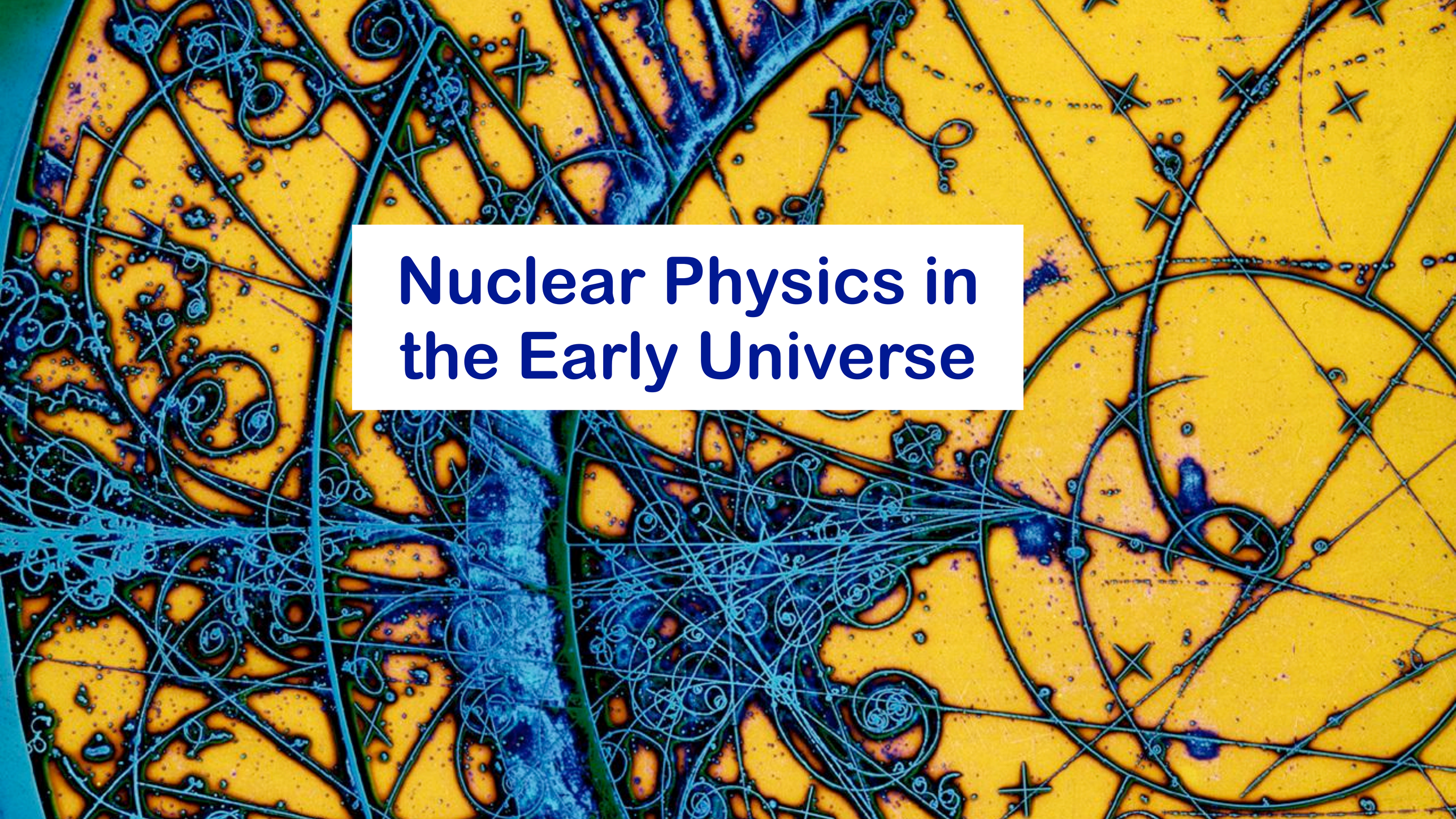
★ The Future: Nuclear Reactions Take Center Stage



Nuclear Physics in the Early Universe

Big Bang Nucleosynthesis

Big Bang Nucleosynthesis

Follow weak and nuclear reactions
in expanding, cooling Universe

Dramatis Personae

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

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

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3: $d(d,p)t$
4: $d(p,\gamma)^3\mathrm{He}$
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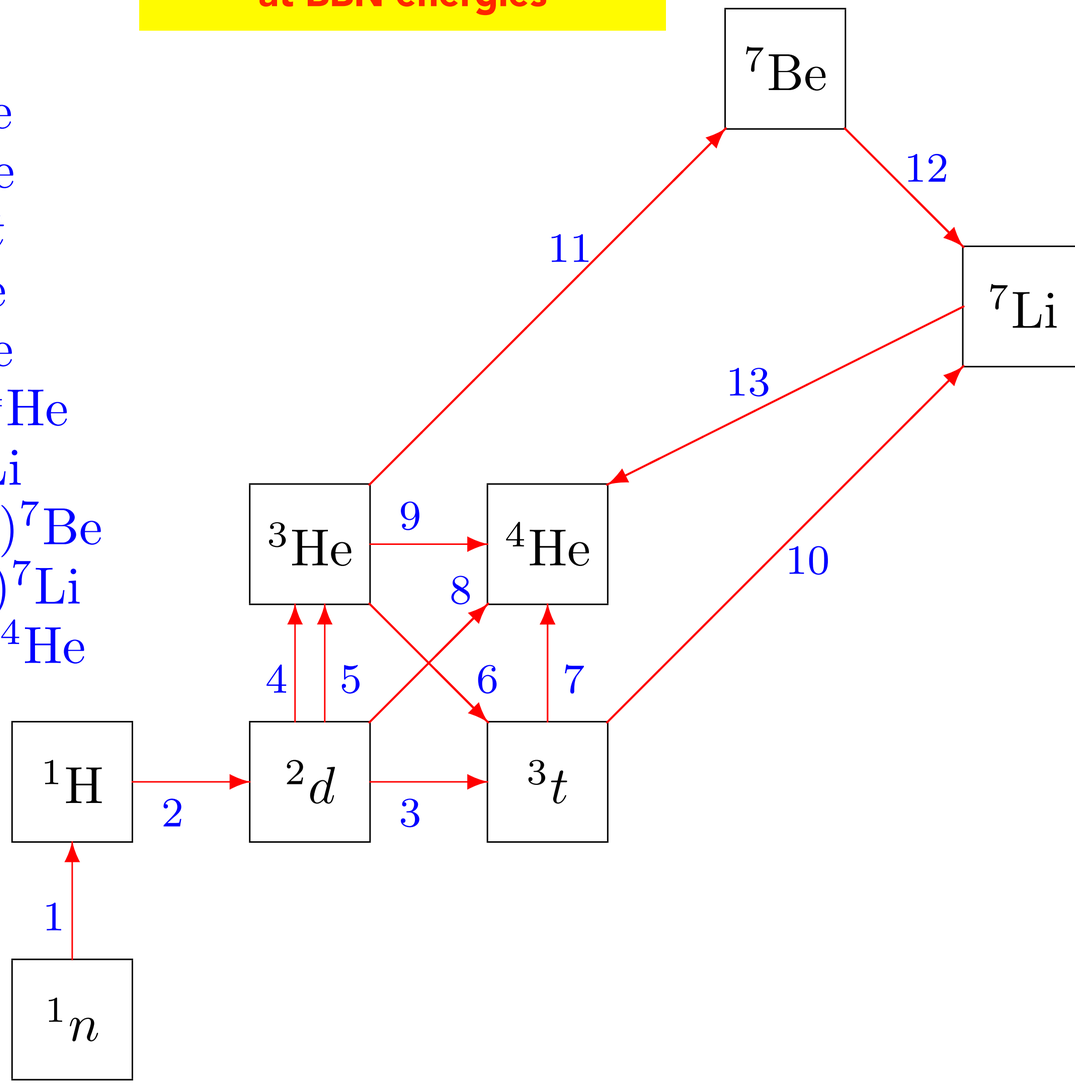
all reactions measured in lab at BBN energies



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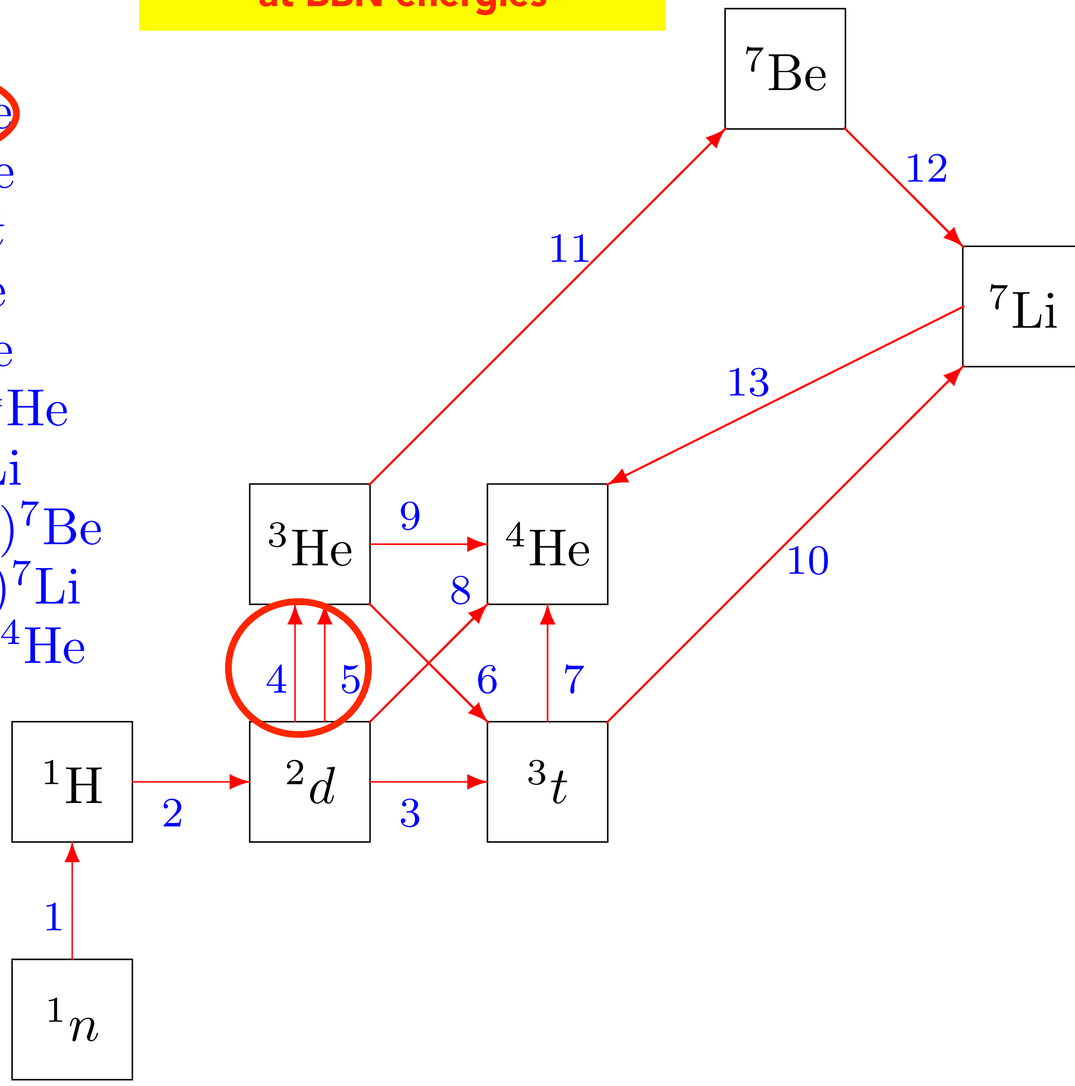

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Light Elements Born: T~0.07 MeV, t~3 min

- **reaction flow ⇨ most stable light nucleus**
- **essentially all n ⇨ ^{4}He, ~25% by mass**
- **also: traces of D, ^{3}He, ^{7}Li**

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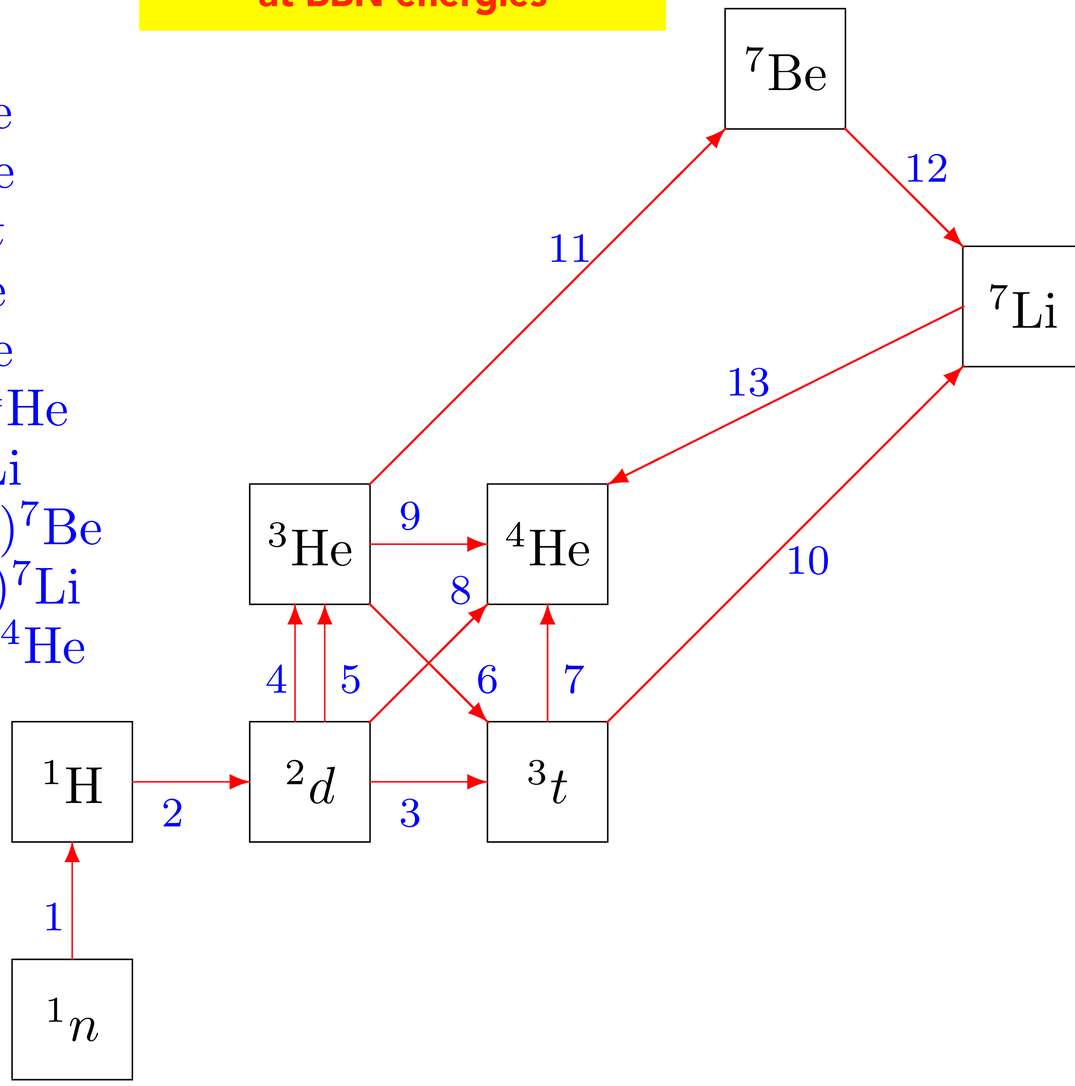

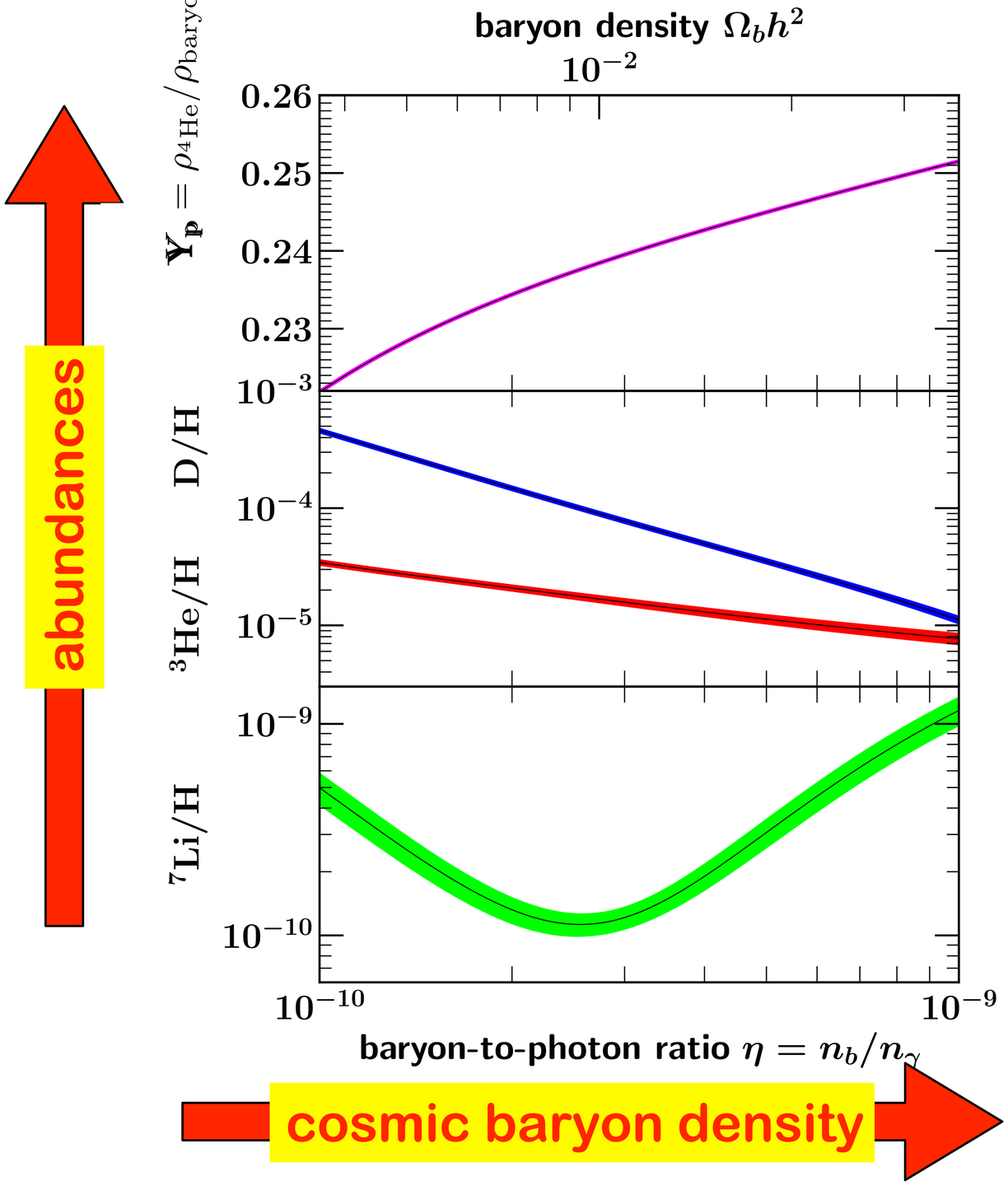

Stanard BBN Predictions

Curve Widths: Theoretical uncertainty nuclear cross sections

BDF, Olive, Yeh, Young 2020
Pitrou+ 2018
Cyburt, BDF, Olive, Yeh 2015
Descouvement poster
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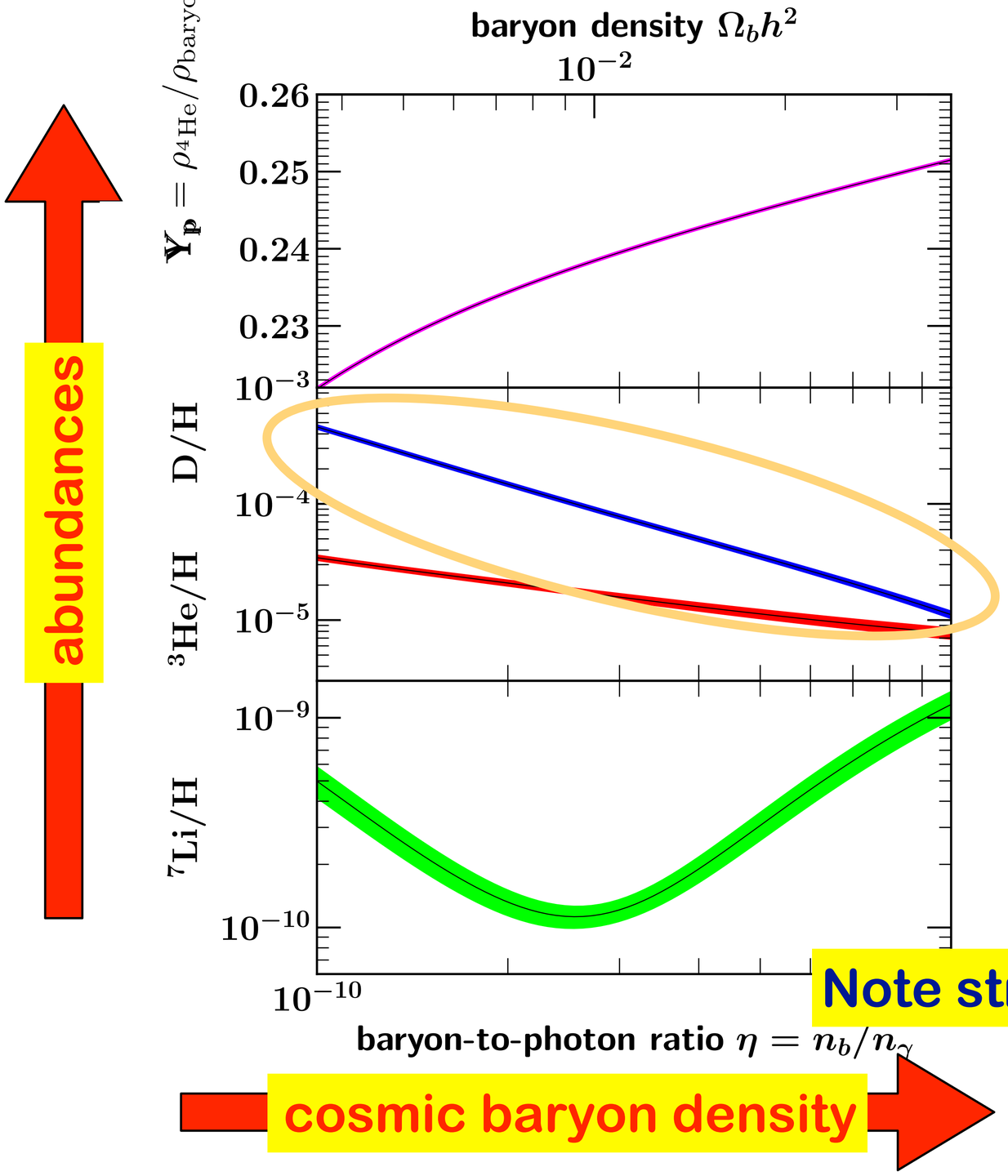

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Note strong D sensitivity to density

Light Elements: Sites

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Deuterium

- in z~3 galaxies backlit by quasars
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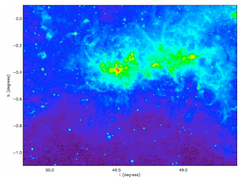
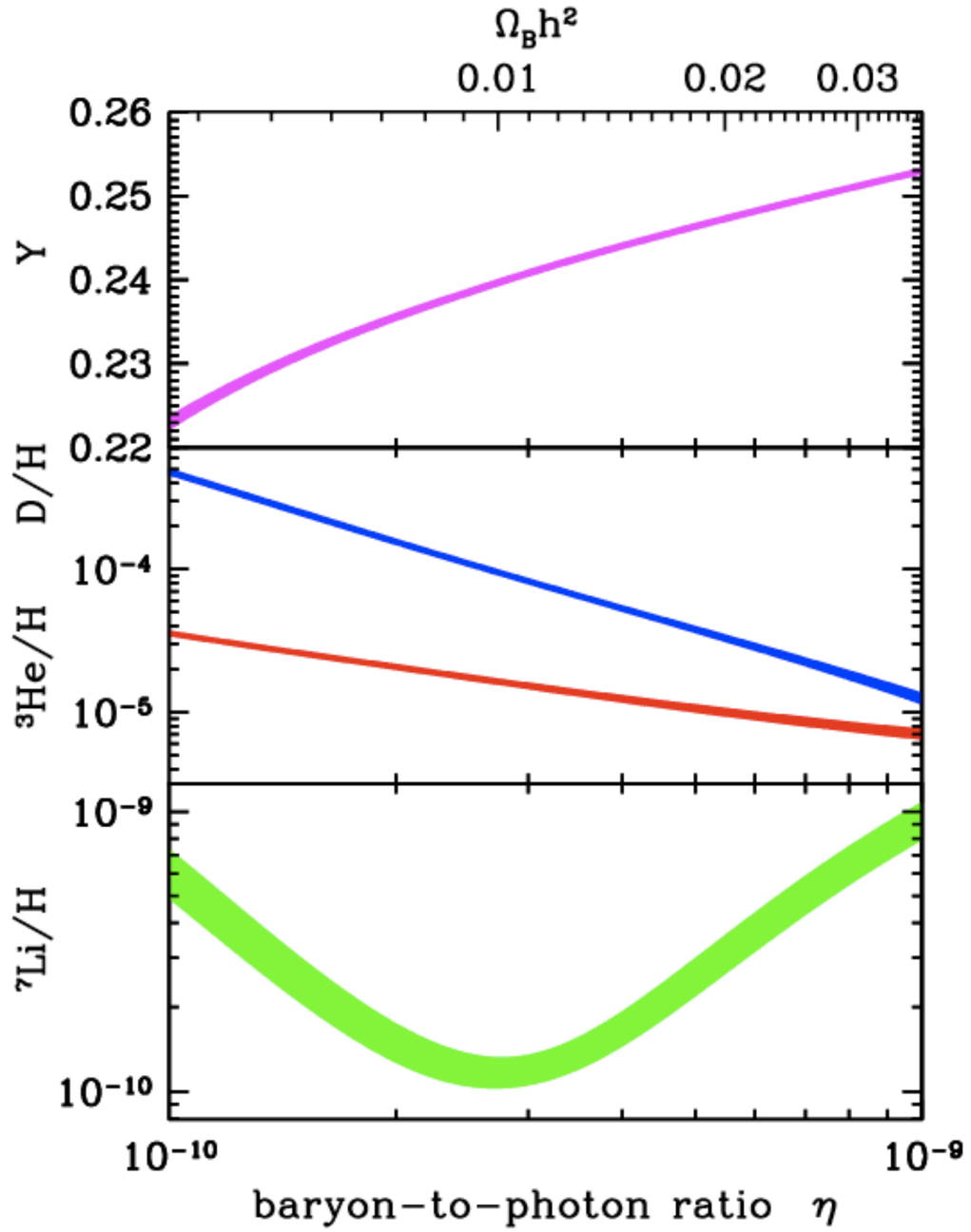


^{3}He

- 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
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^{3}He/H
10^{-4}
10^{-5}
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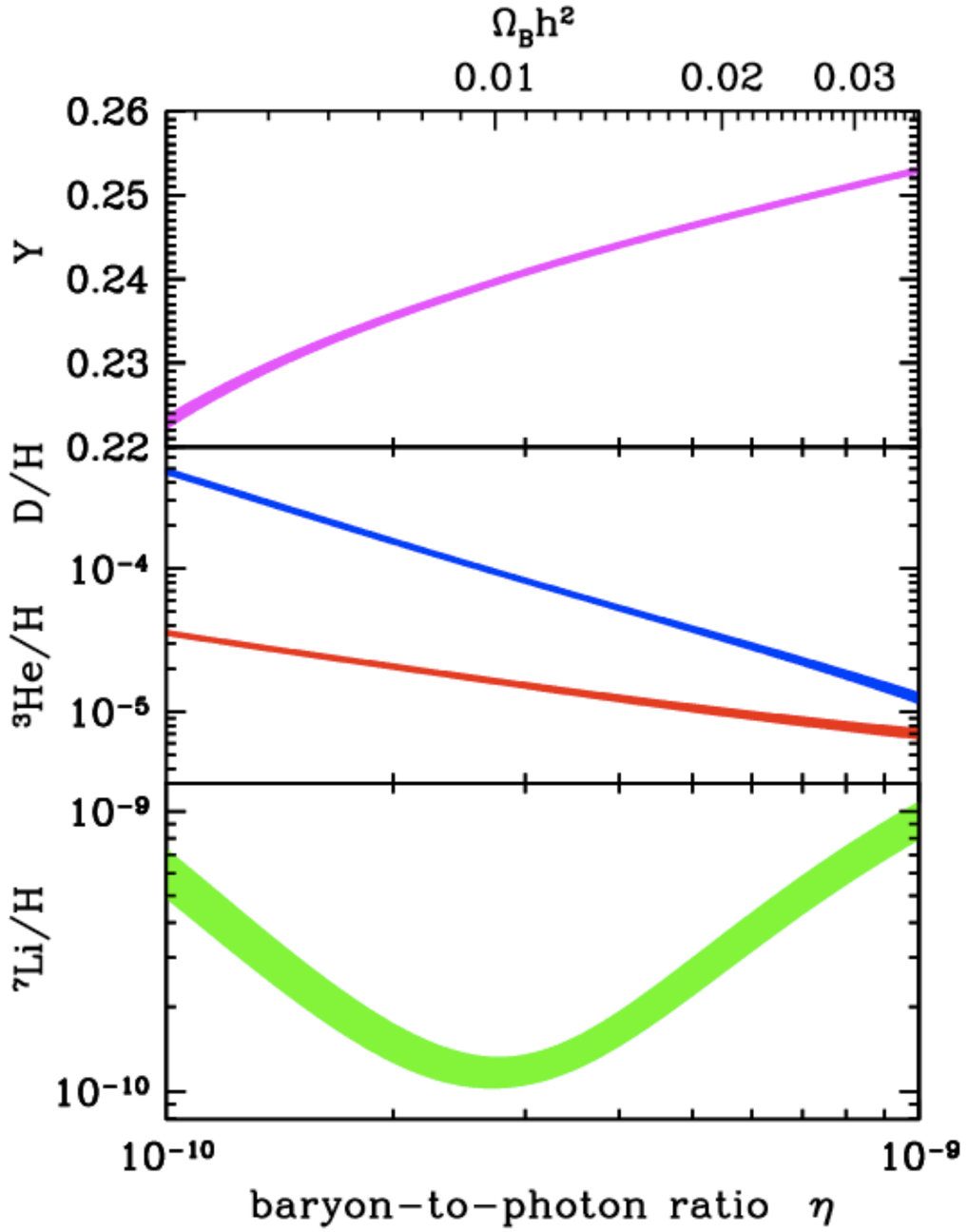
baryon−to−photon ratio η



Testing BBN: Light Element Observations

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Observations:

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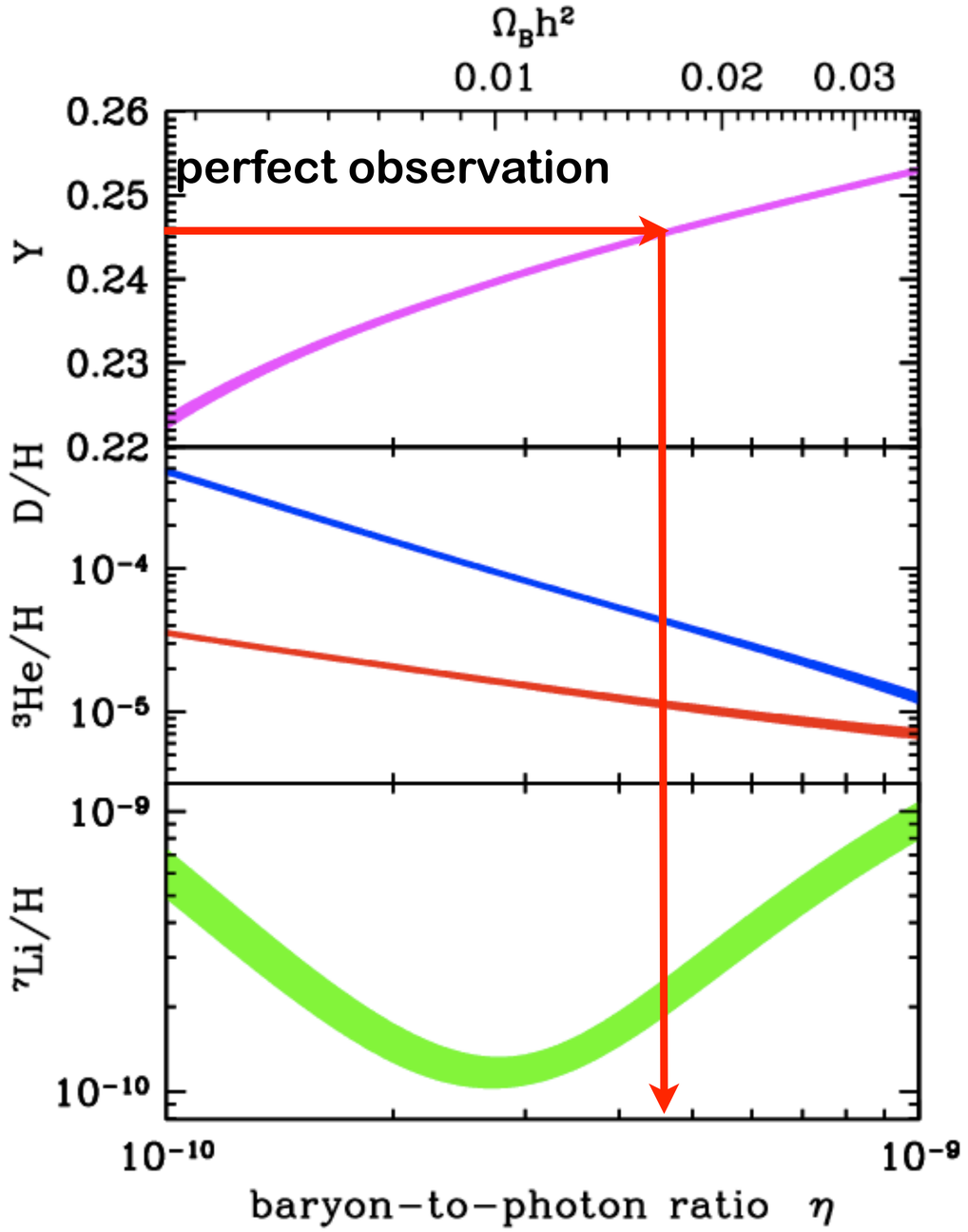

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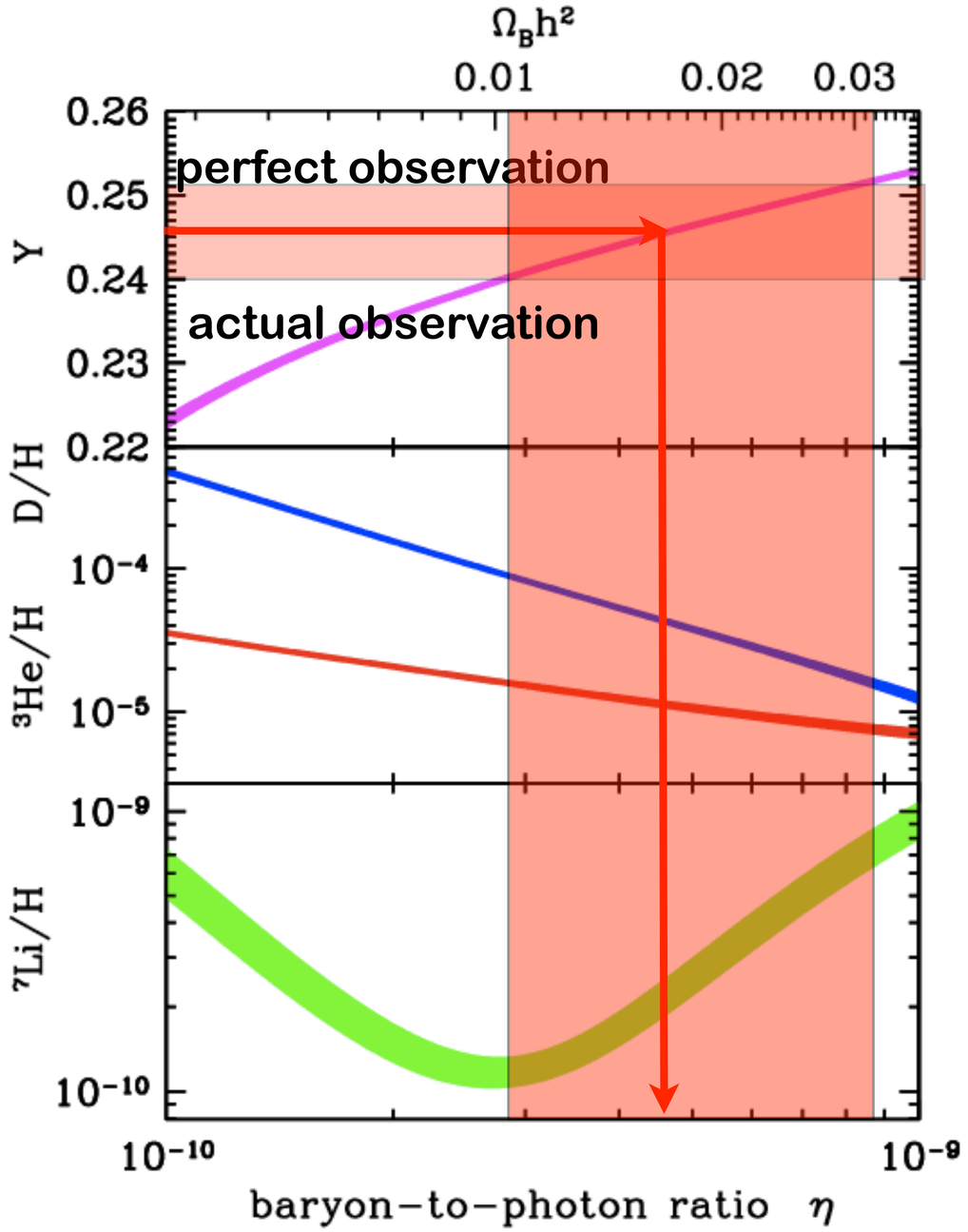
★each nuclide selects baryon density



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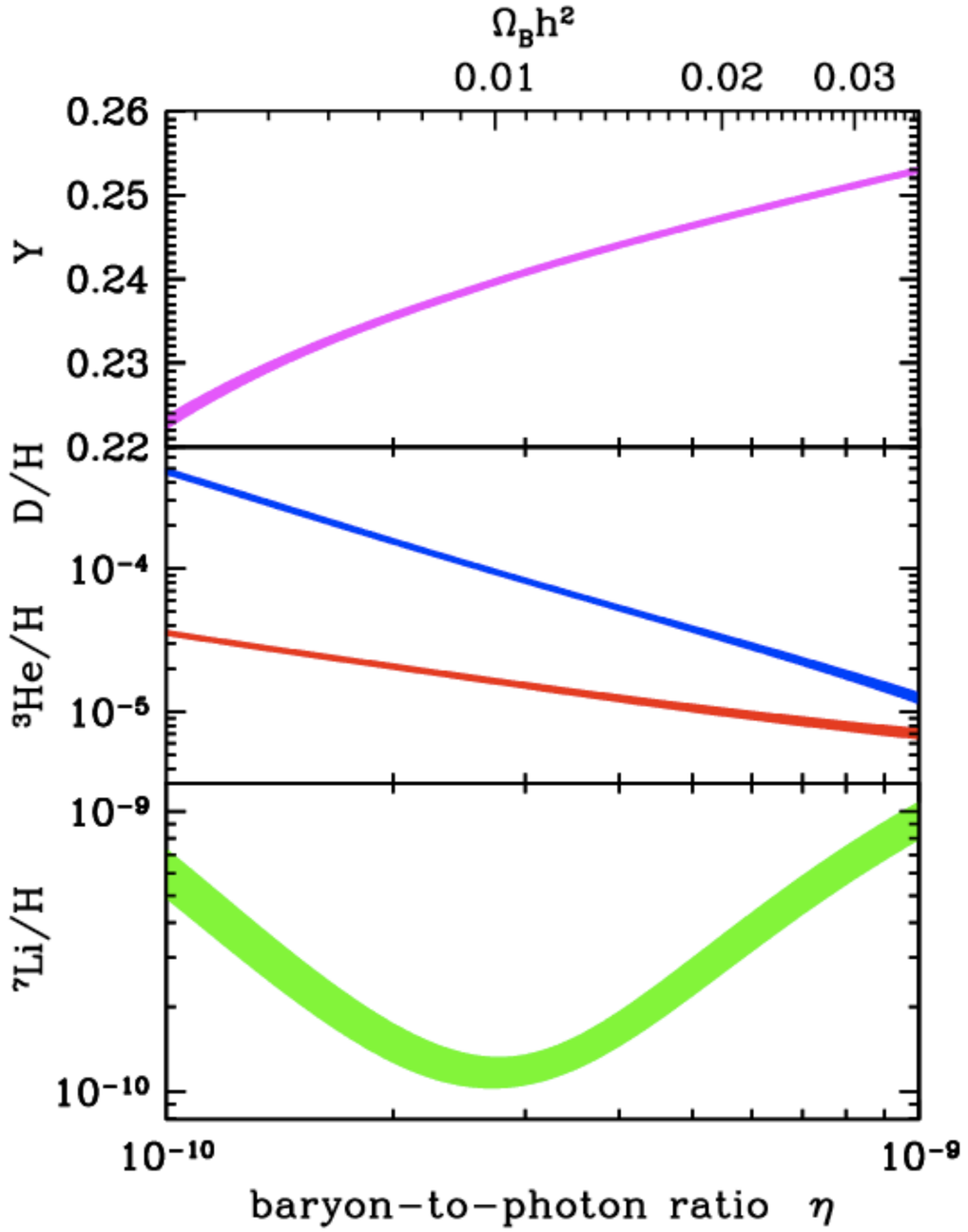

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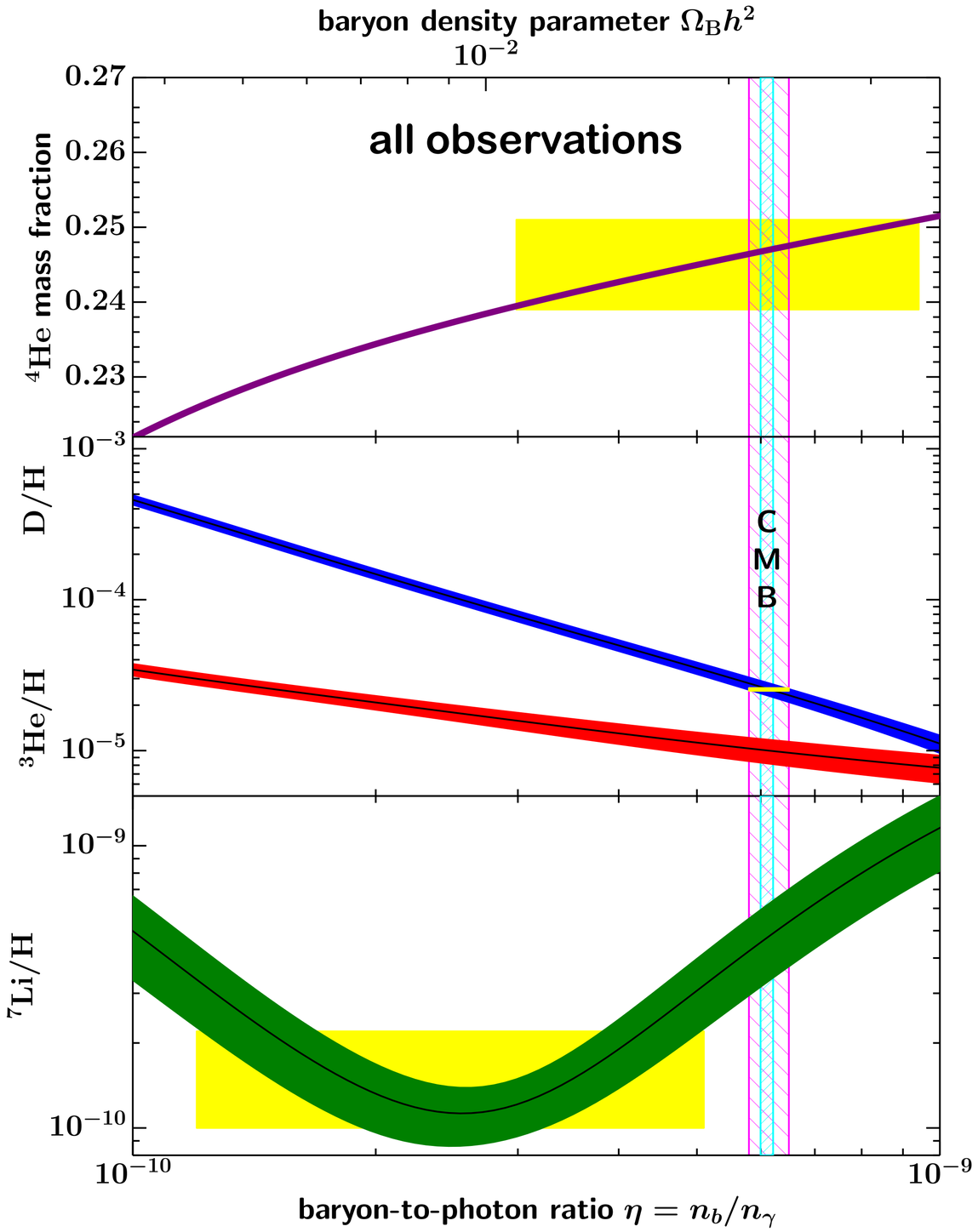

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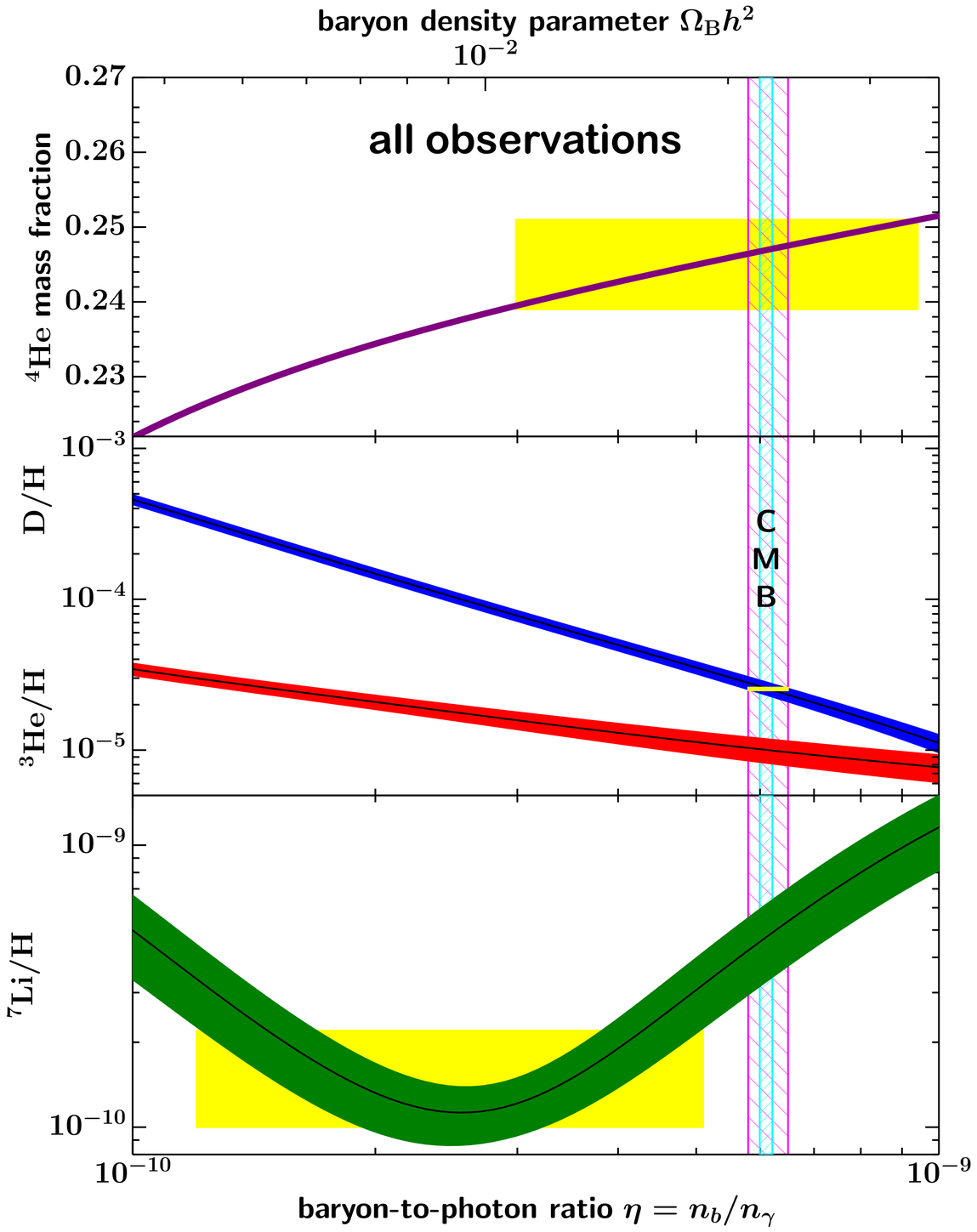

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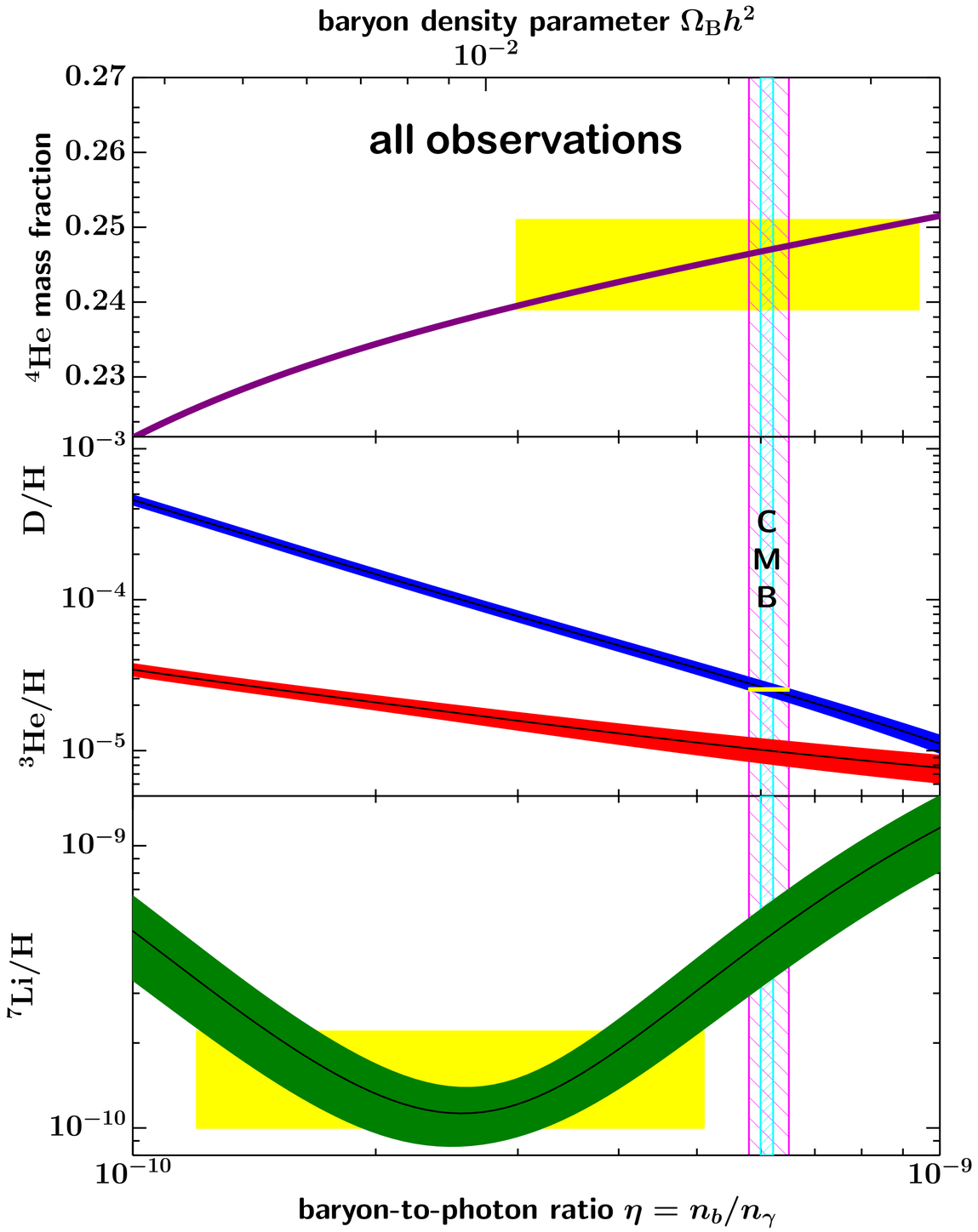

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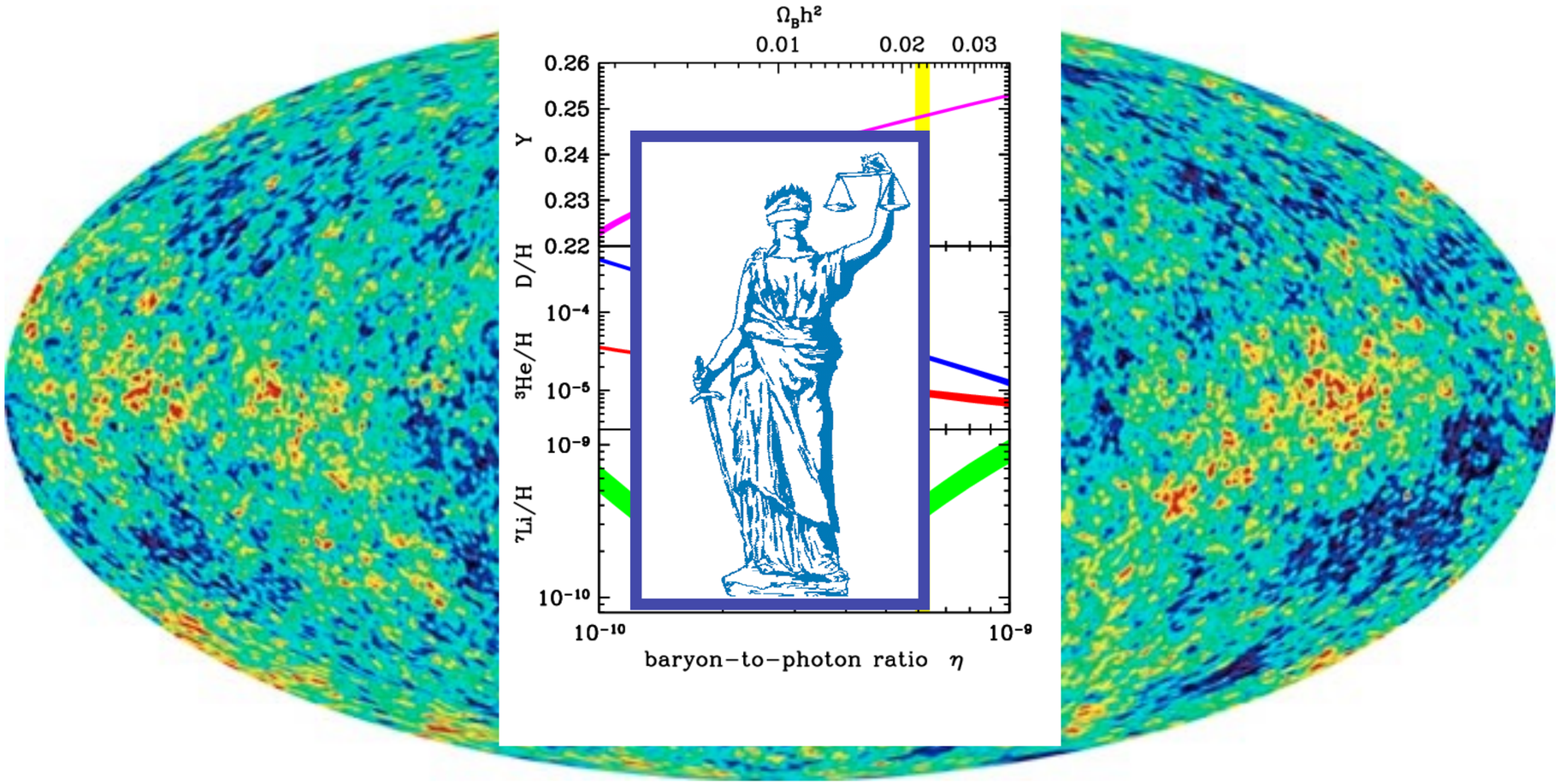
⇨ need a tiebreaker

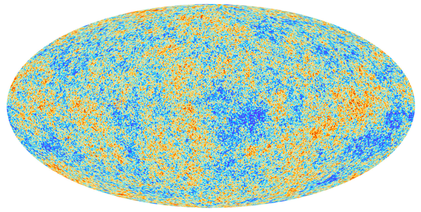
COSMIC BARYONS
and the
MICROWAVE BACKGROUND



Battle of the Baryons: II

CMB New World Order

Cyburt, BDF, Olive 2003, …, Yeh, Olive, BDF 2021

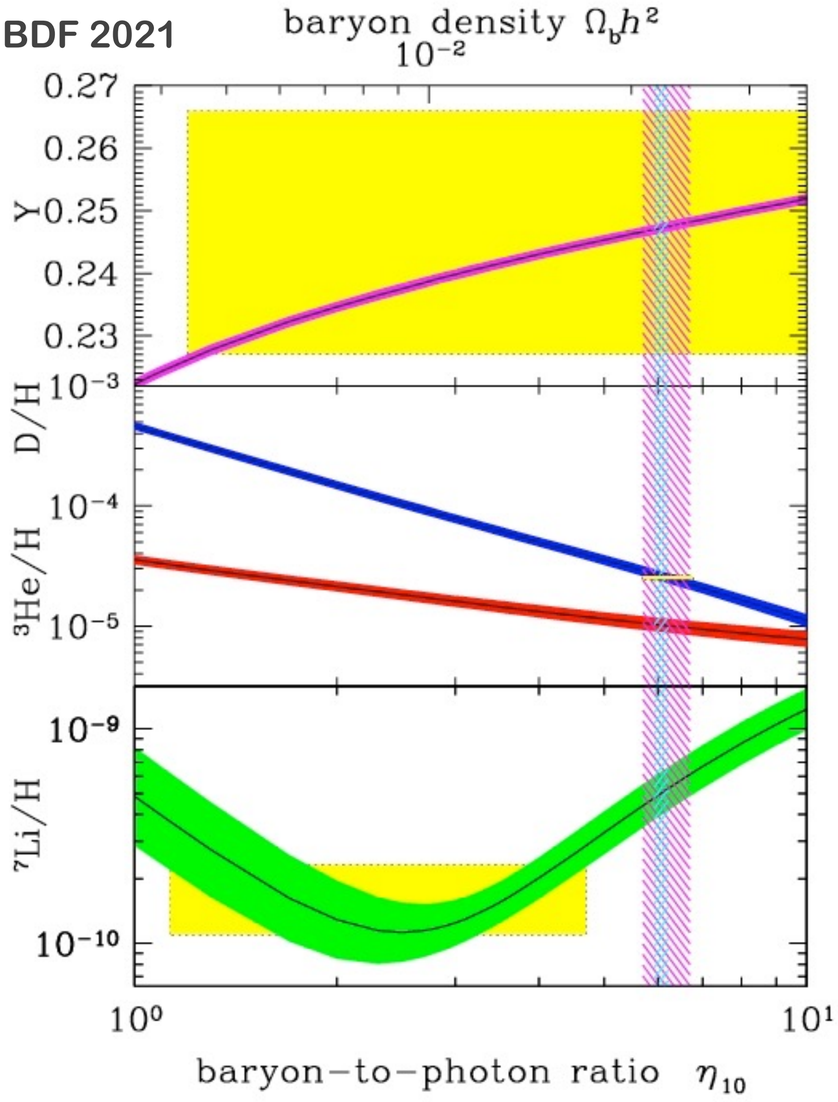


Planck baryon density very precise

$$\Omega_{\rm B}\, h^2 = 0.022298 \pm 0.000020$$

$$\eta = (6.104 \pm 0.058) \times 10^{-10}$$

i.e., a sub-1% measurement!



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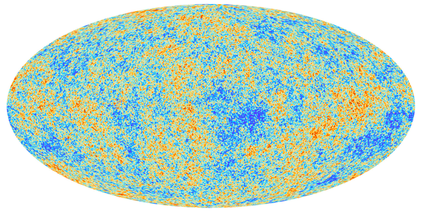

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$$\eta = (6.104 \pm 0.058) \times 10^{-10}$$

i.e., a sub-1% measurement!

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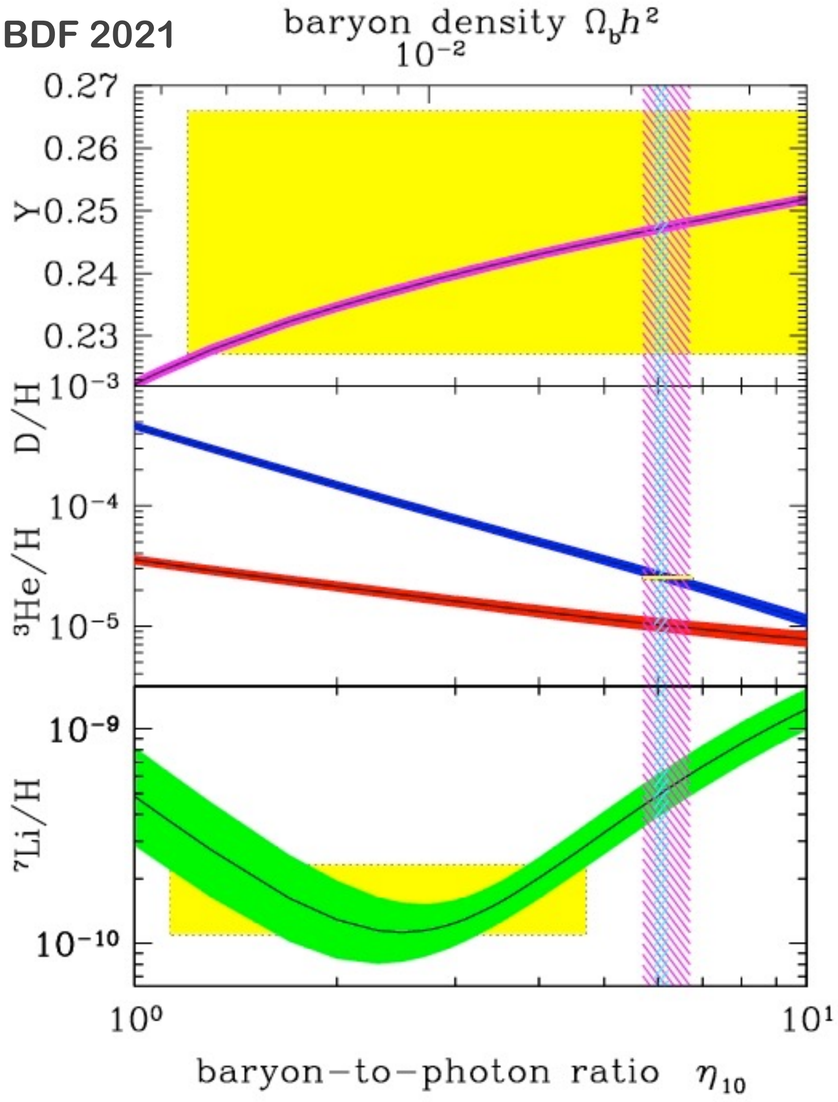
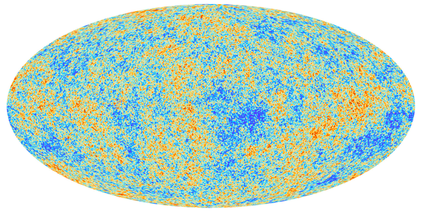


Battle of the Baryons: II

CMB New World Order

Cyburt, BDF, Olive 2003, …, Yeh, Olive, BDF 2021



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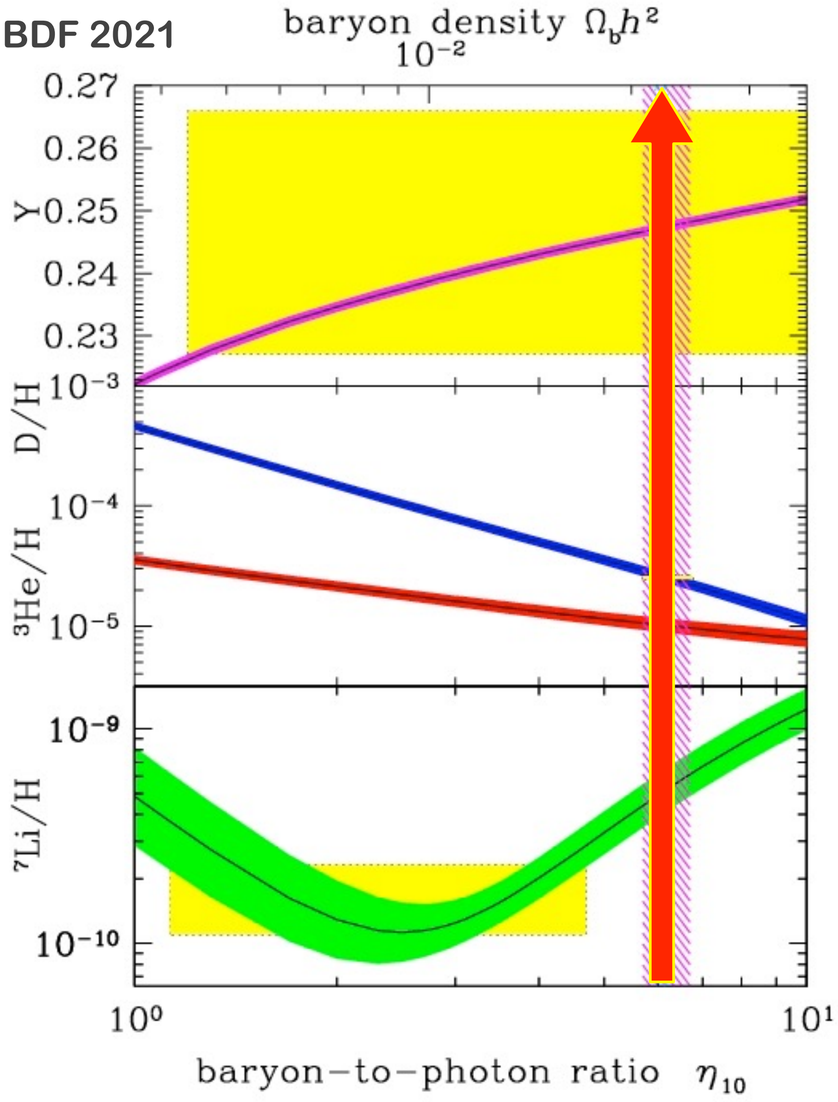

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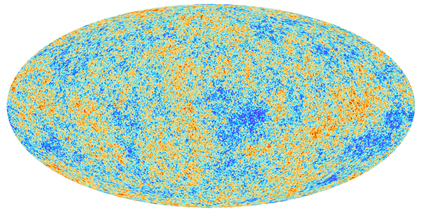

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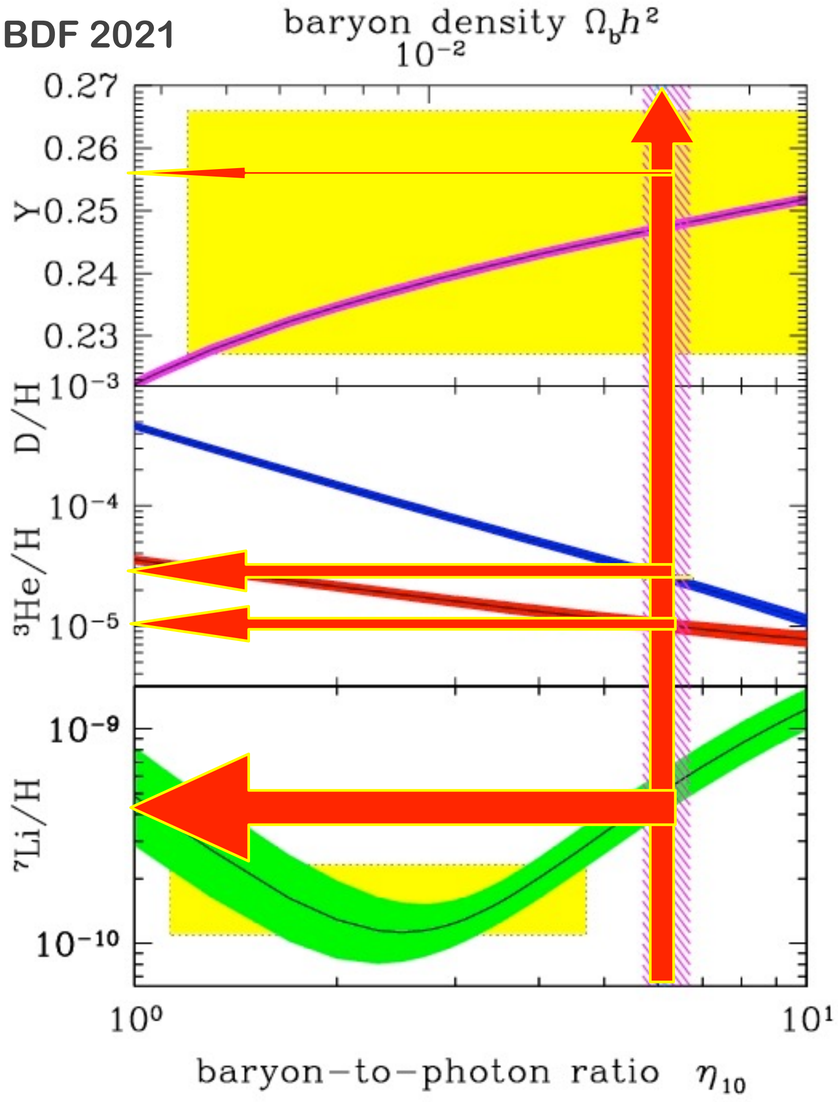

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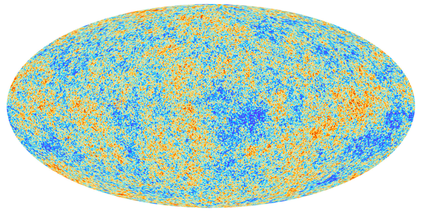

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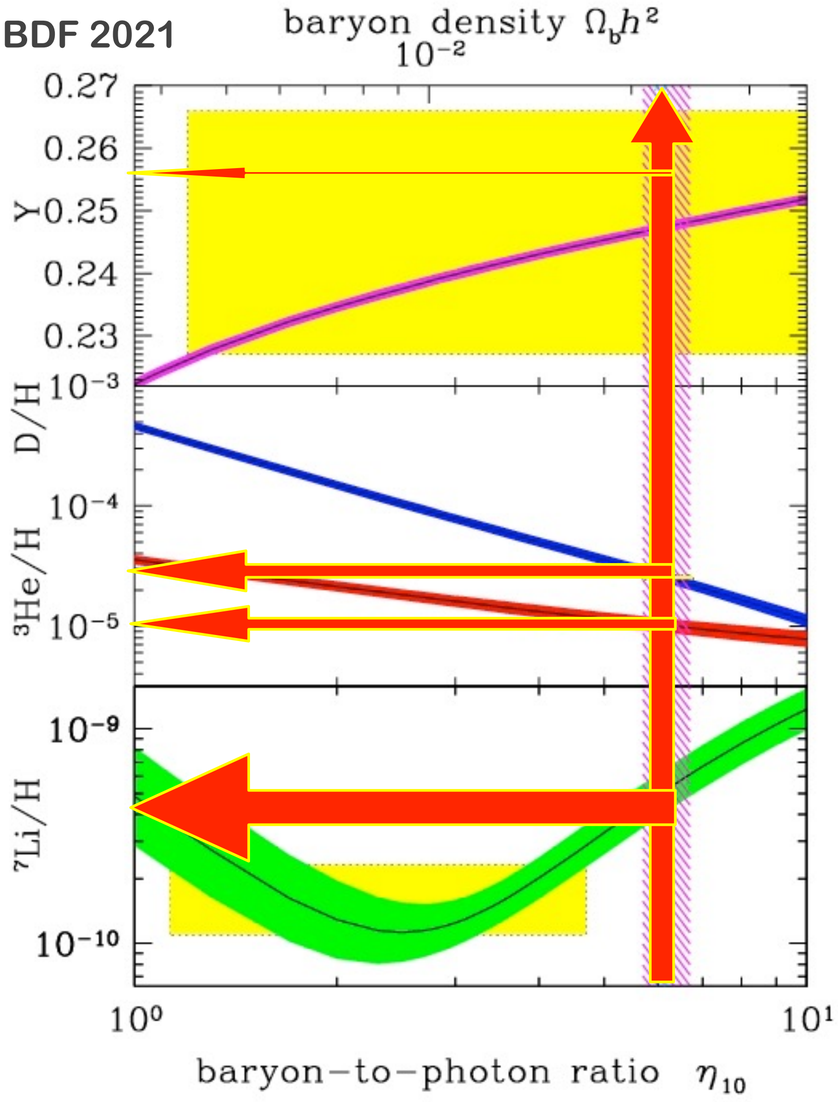

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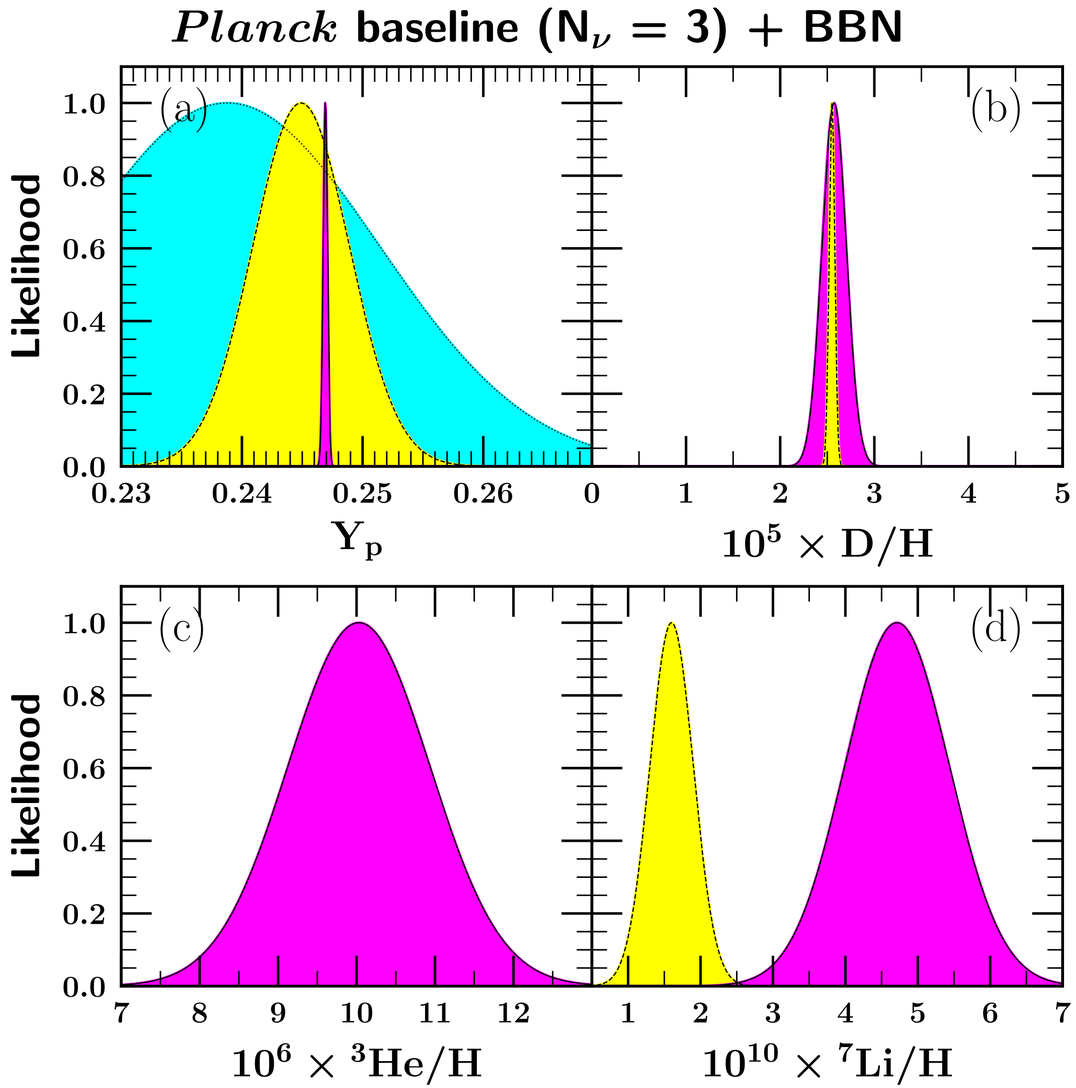
Battle of the Baryons: II
A Closer Look

Cyburt, BDF, Olive 2003, 2008, 2015; BDF, Olive, Yeh, Young 2020



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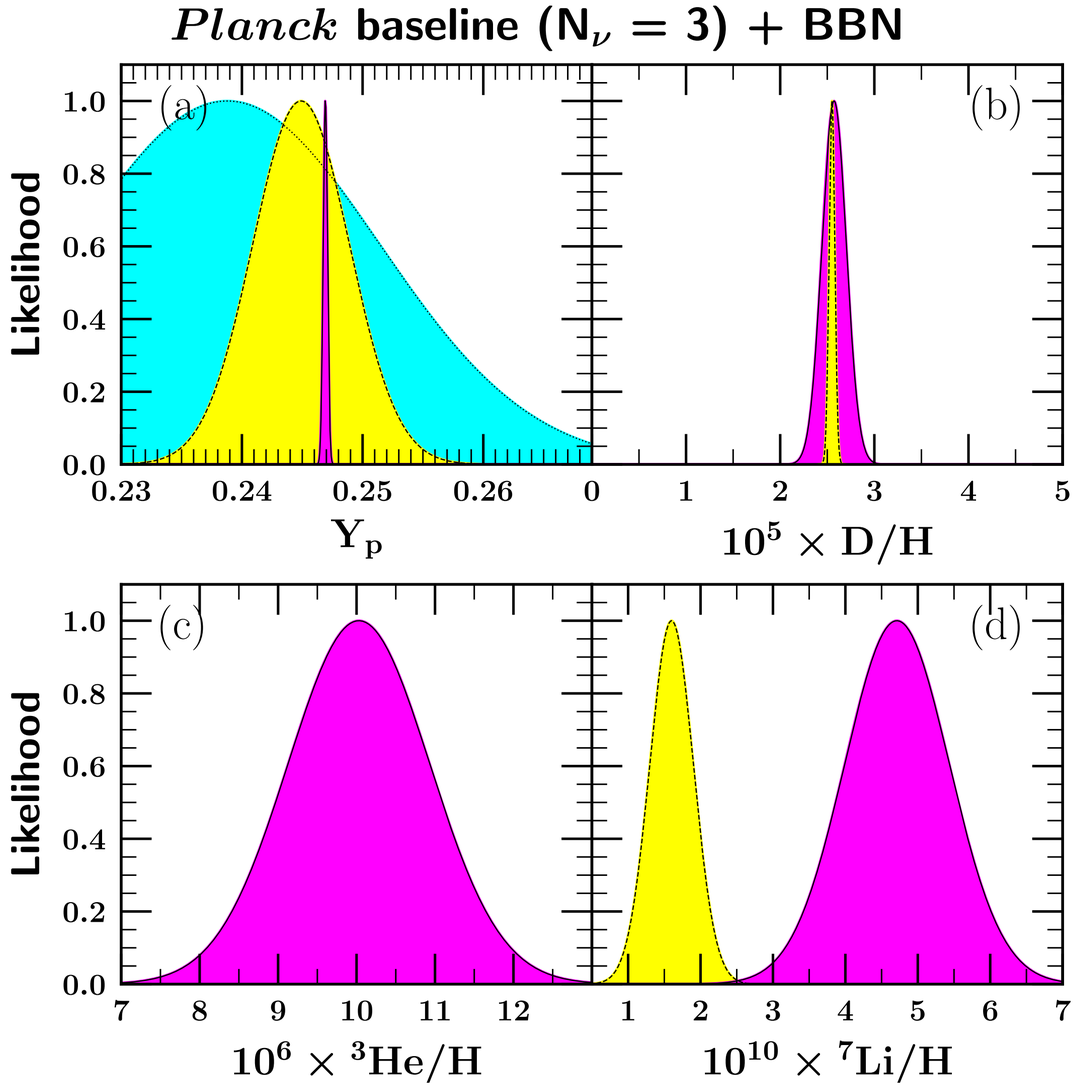
Likelihoods

purple: BBN+CMB predictions

yellow: observations



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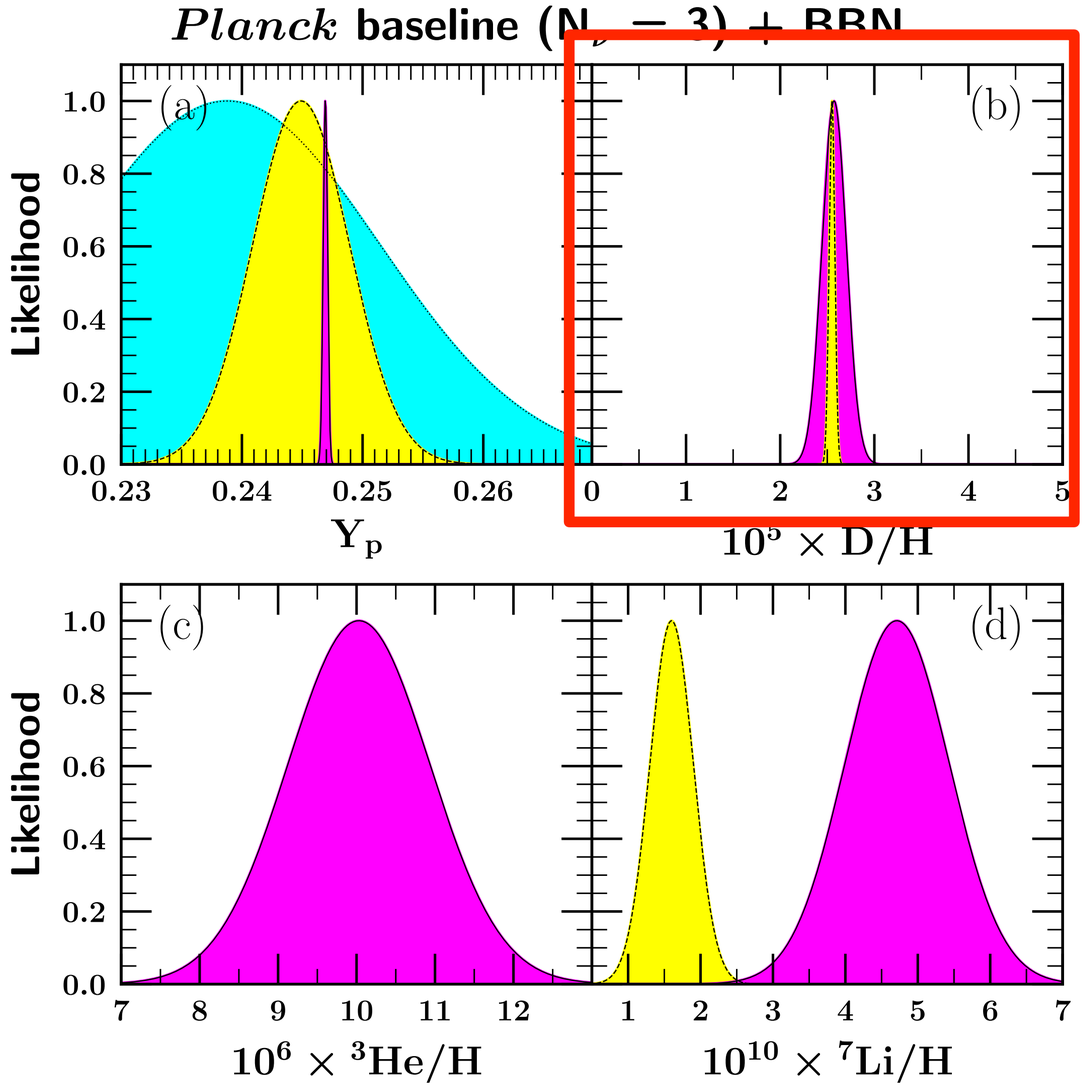

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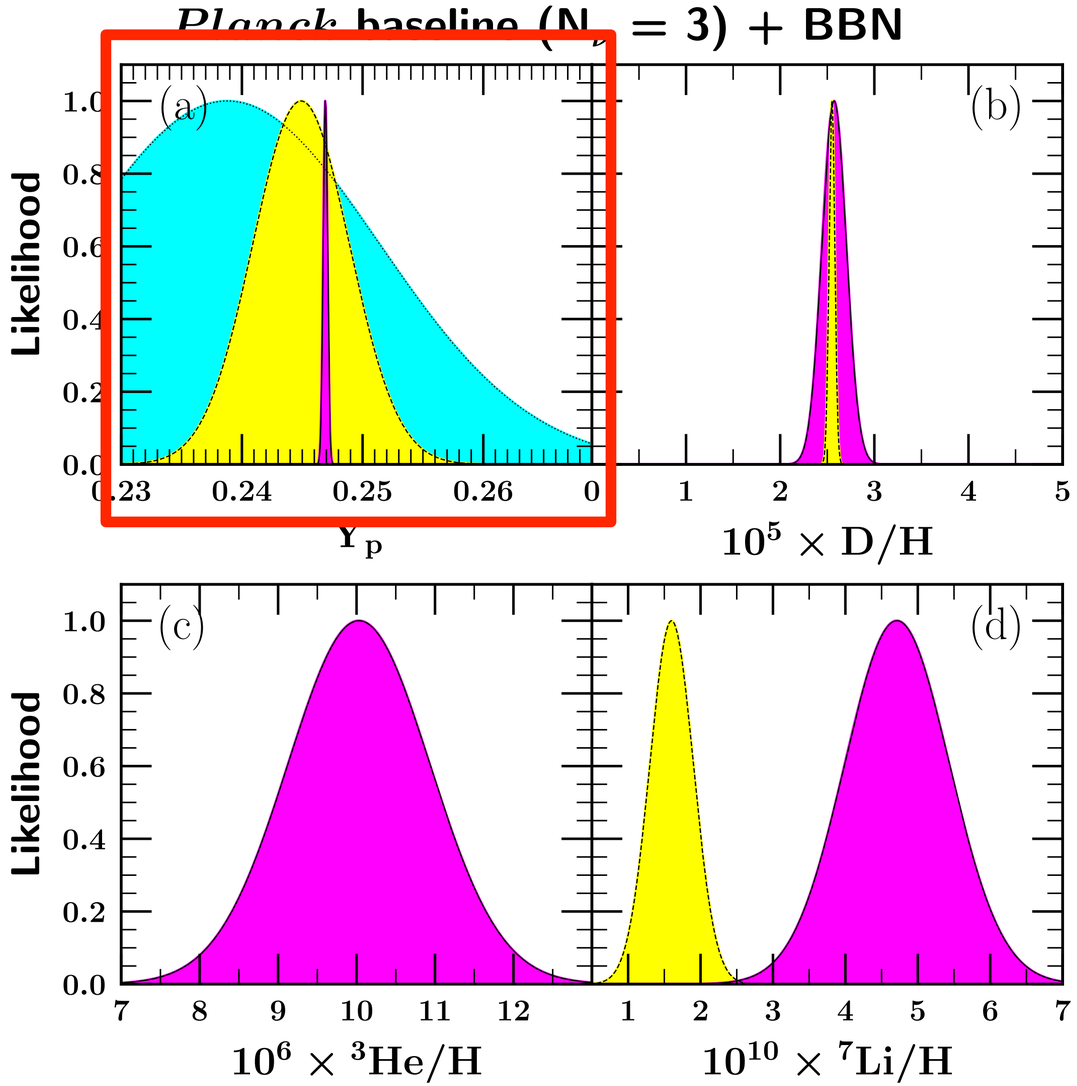

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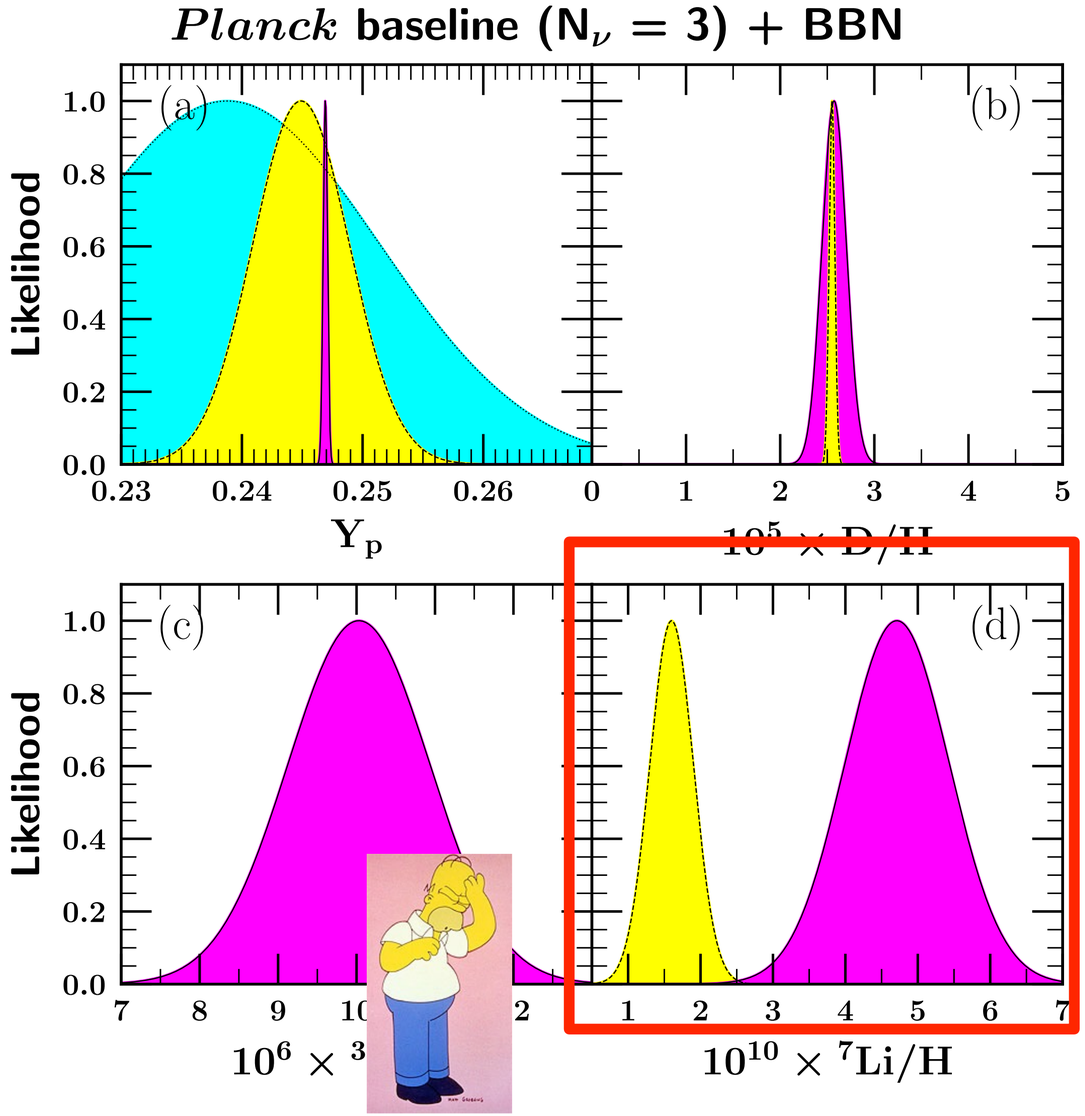

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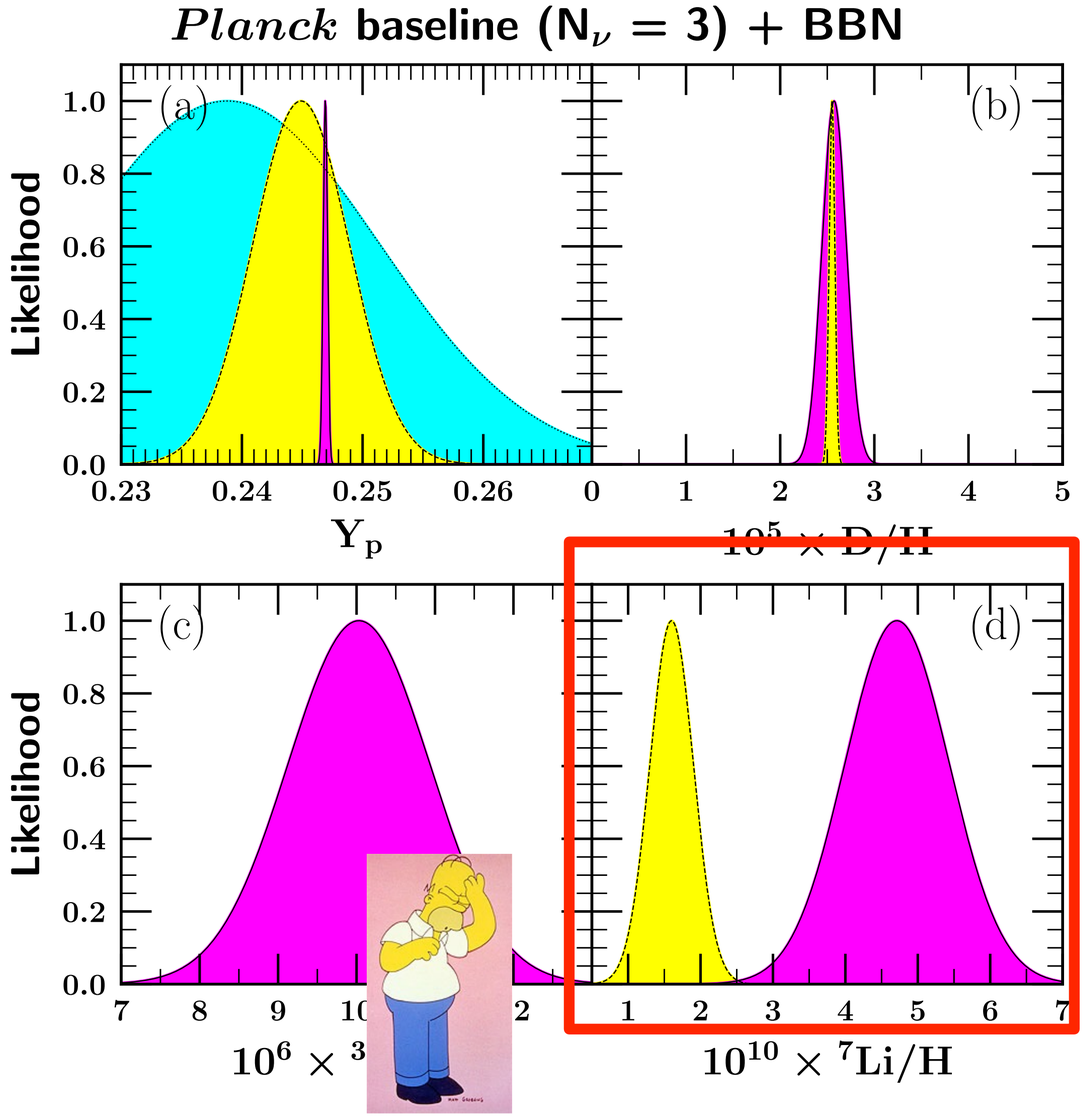

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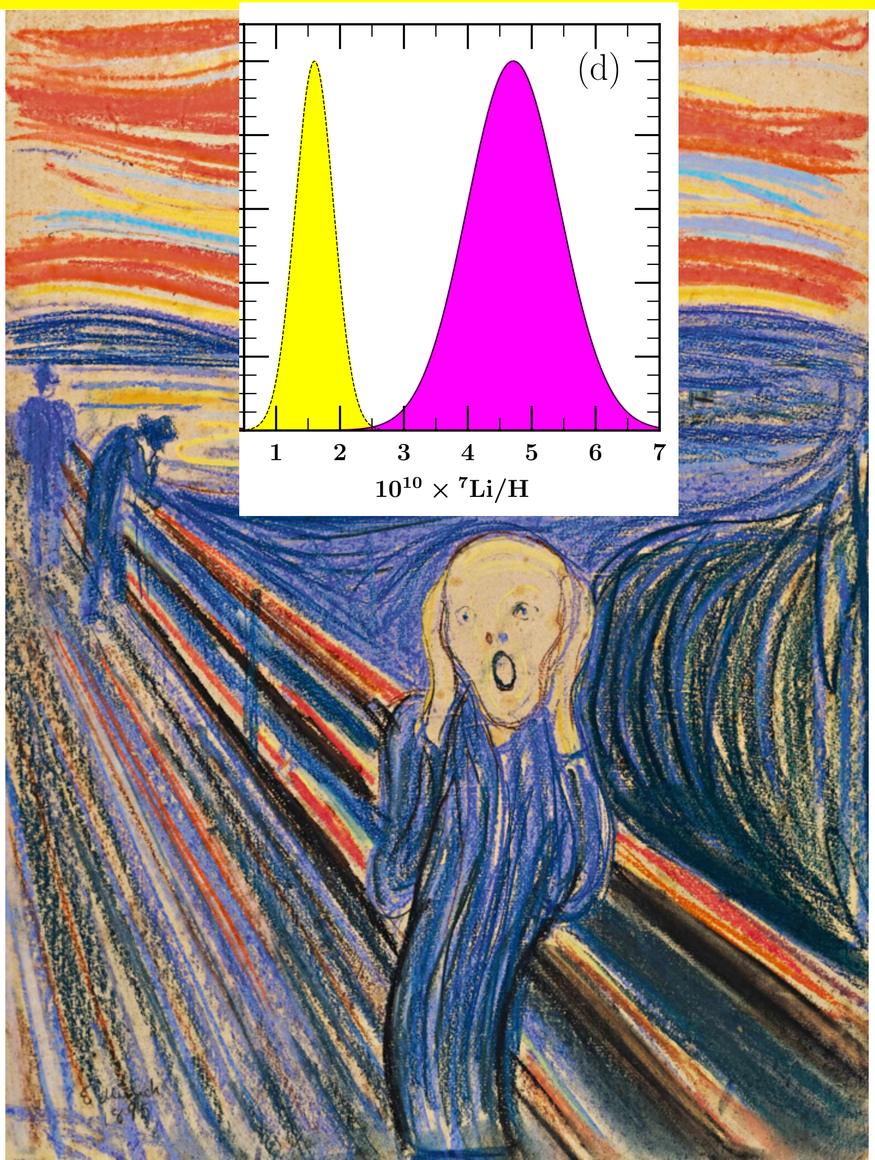

Lithium Problem Overview

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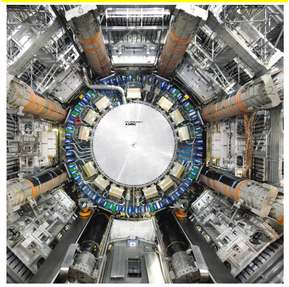
standard particle physics



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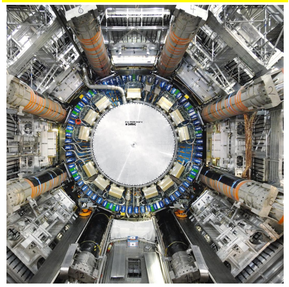

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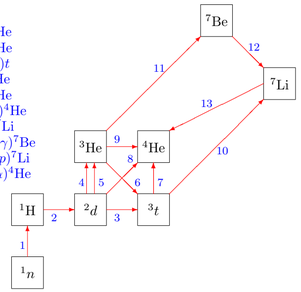

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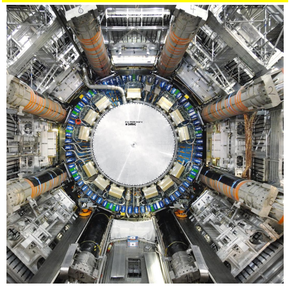

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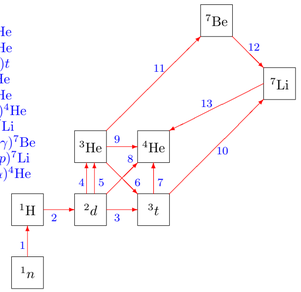

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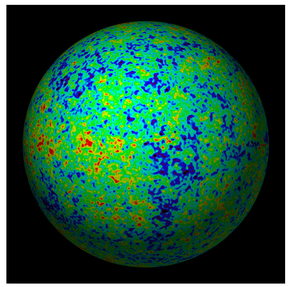

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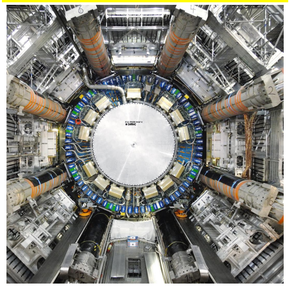

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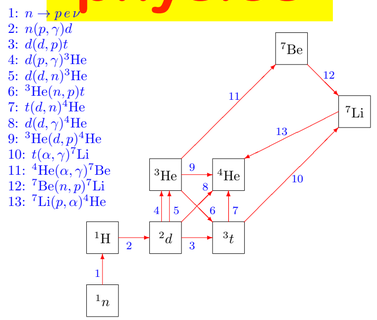

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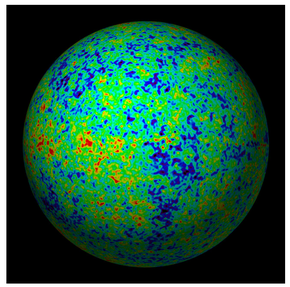

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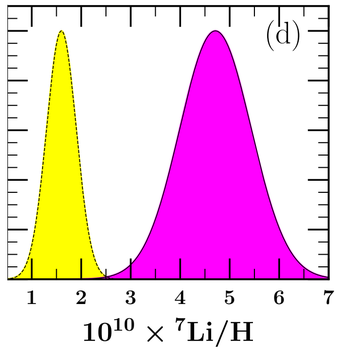

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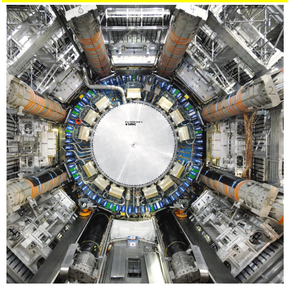

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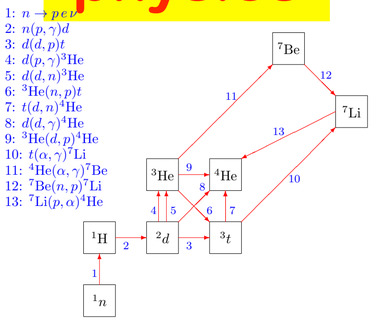

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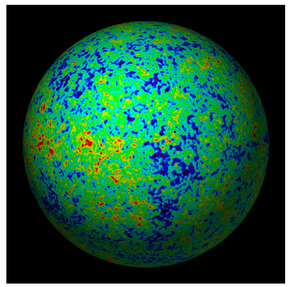

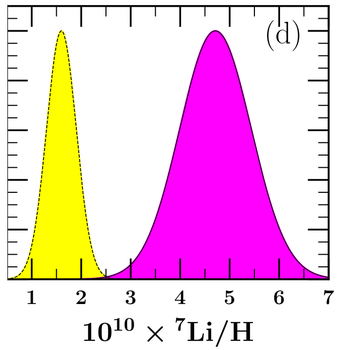

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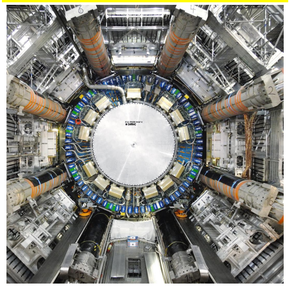

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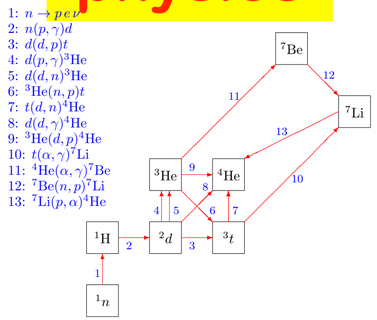

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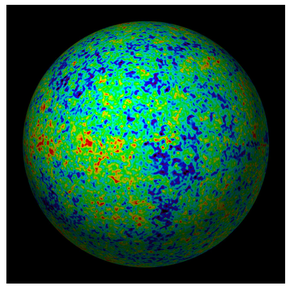
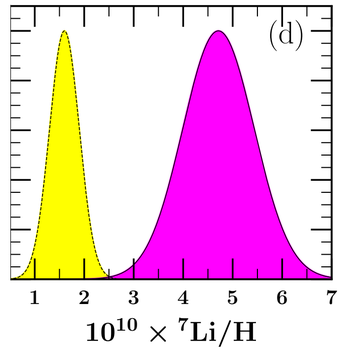
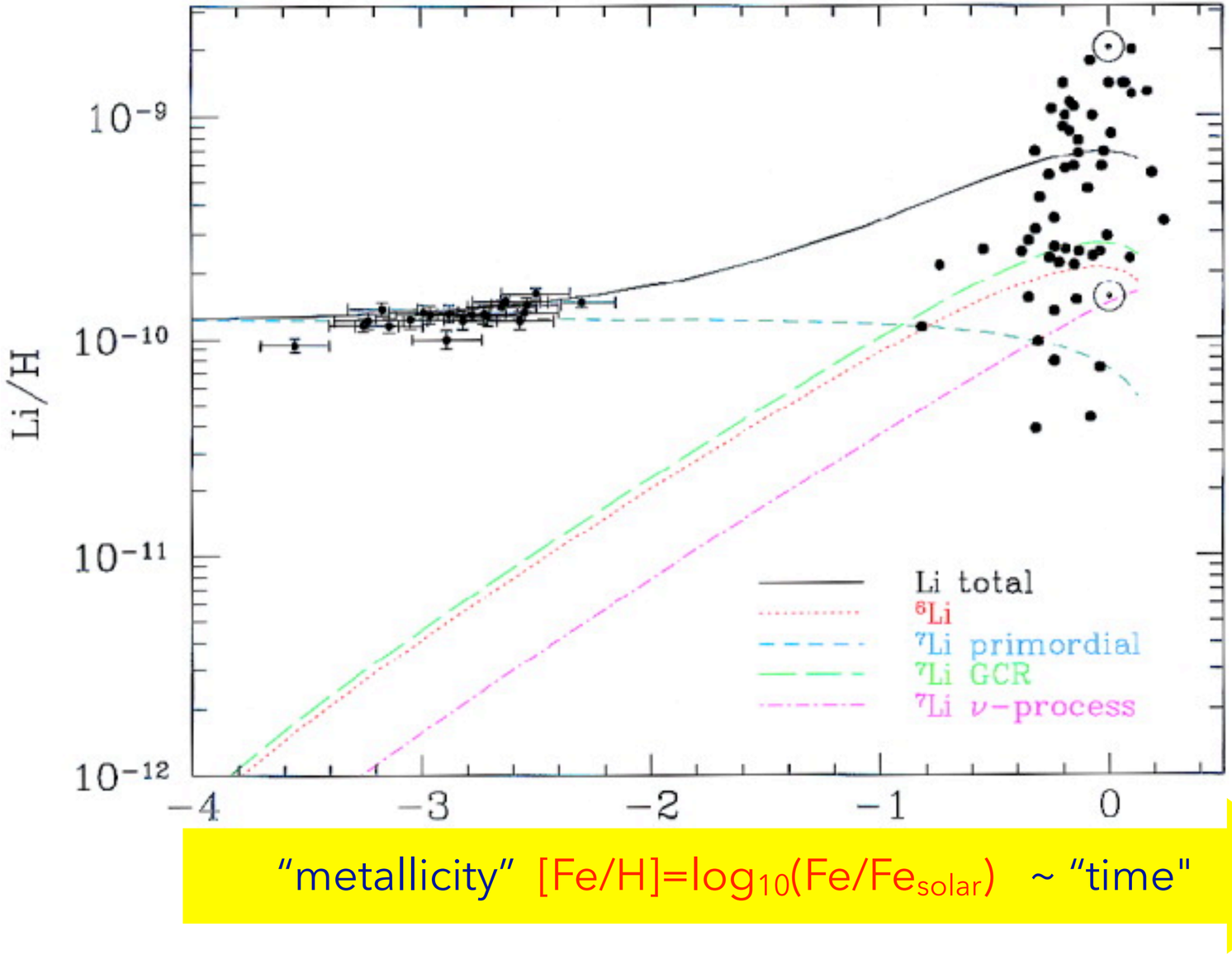




Solutions: one of these is wrong

Primordial Lithium Observed: Halo Stars & the Spite Plateau

Monique & François Spite



Ryan, Olive, Beers, BDF, Norris 2000

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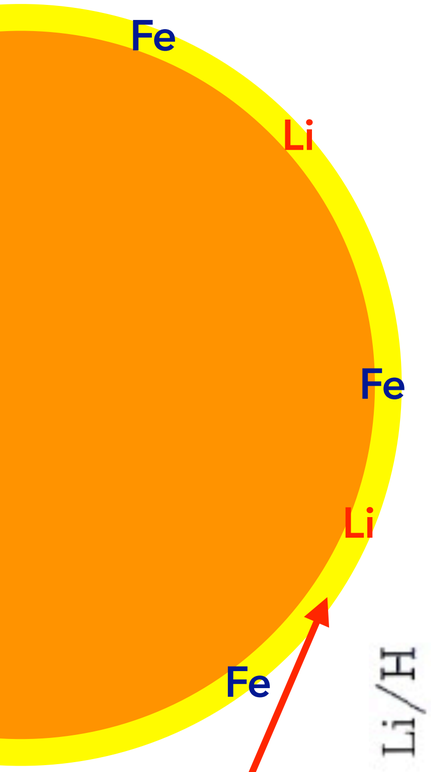
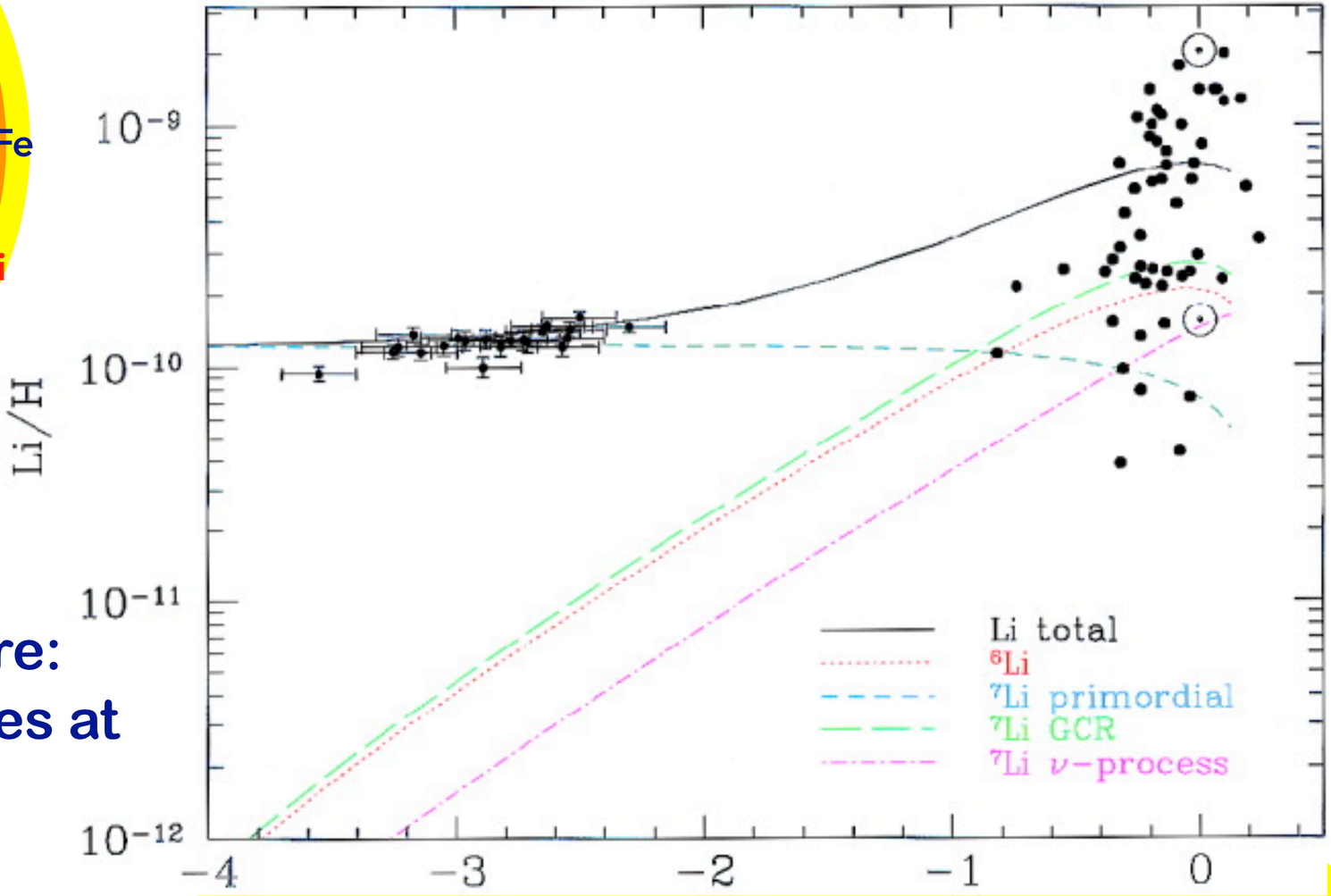


Observe atmosphere: abundances at star birth



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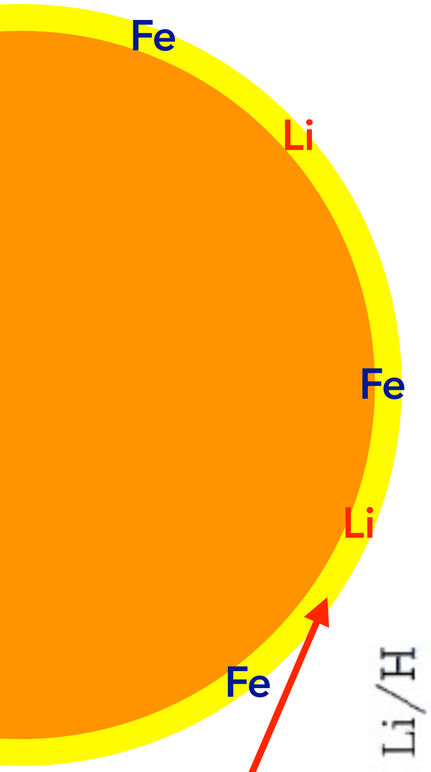

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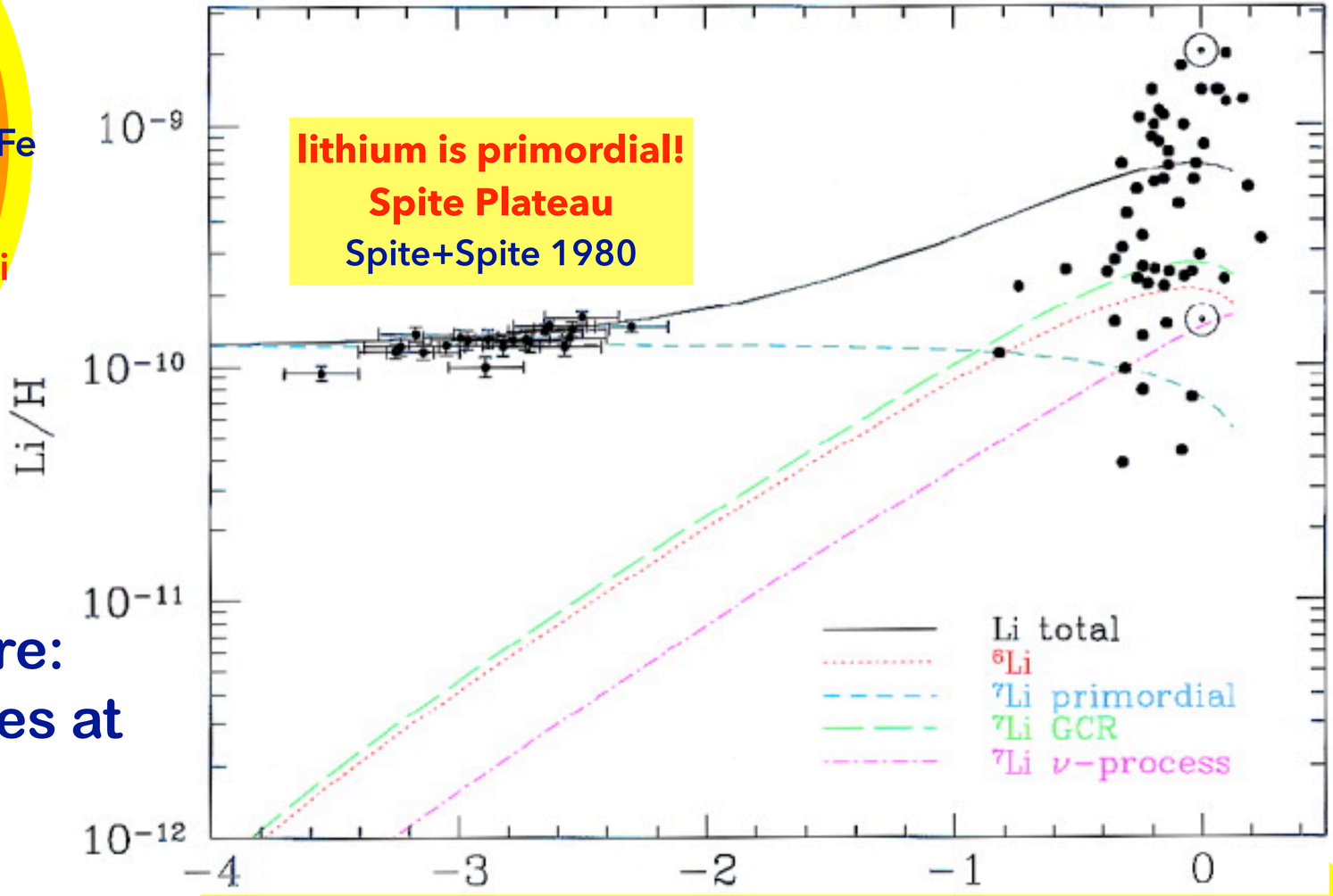

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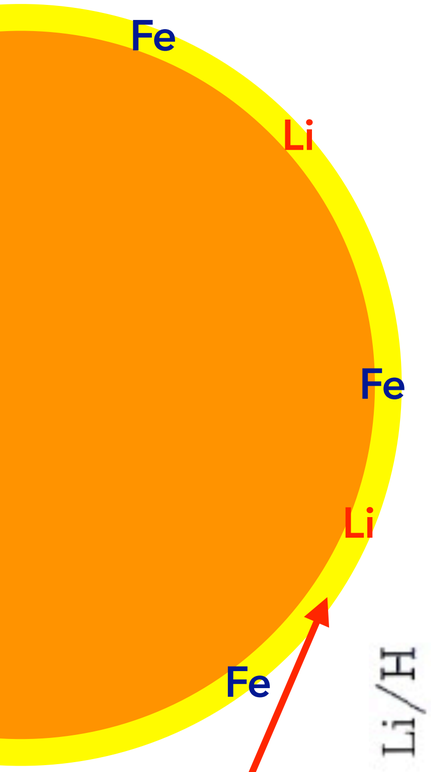

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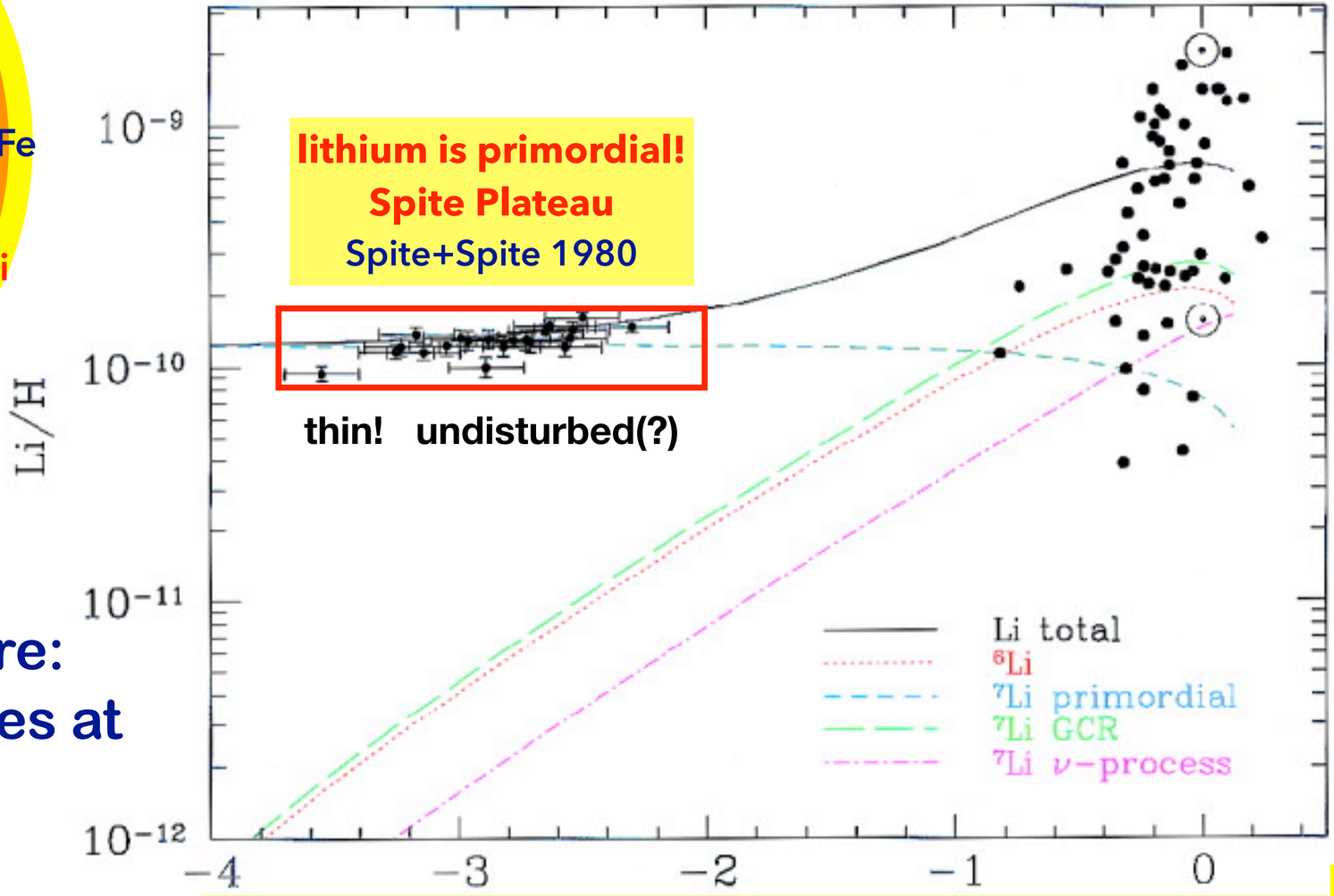

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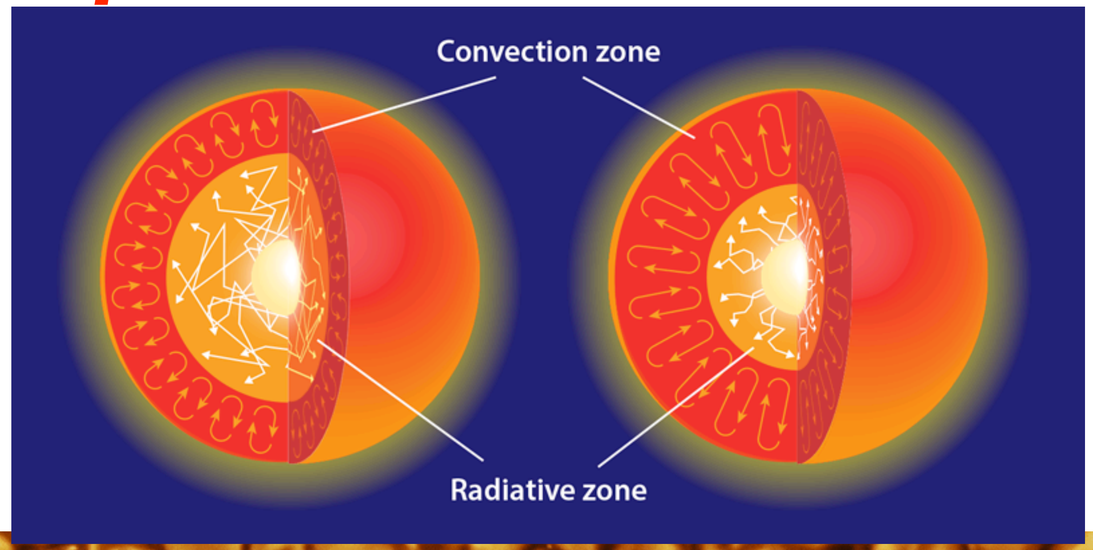
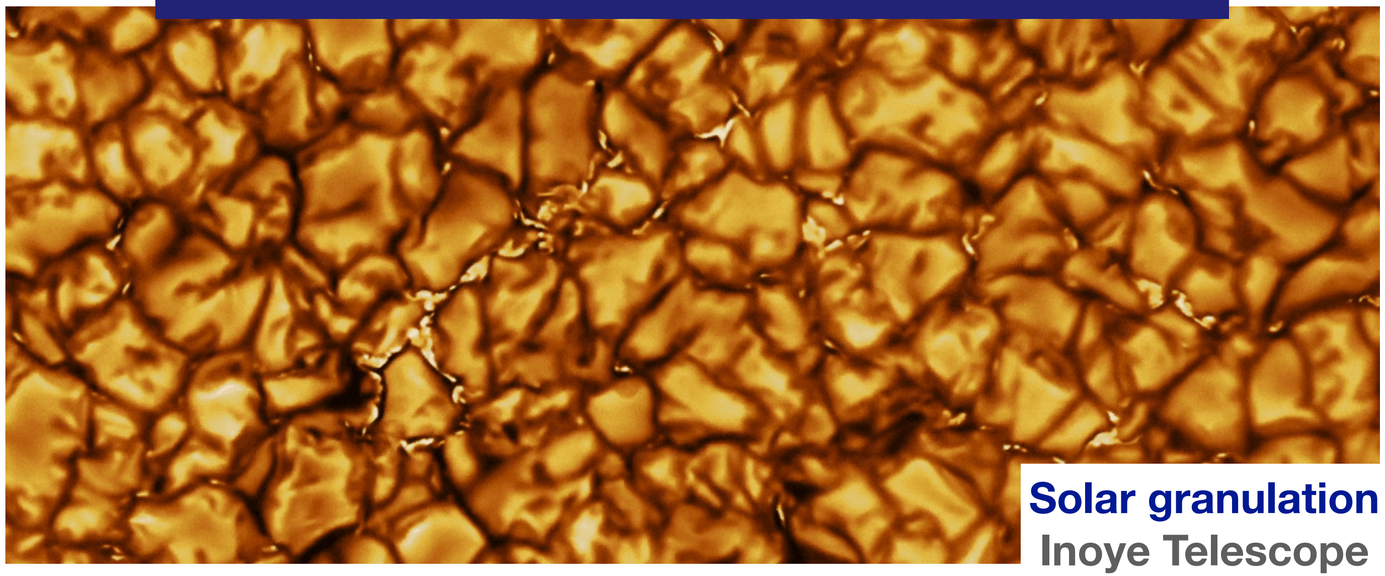
Lithium is Primordial

But is Spite Plateau the primordial value?

The Worry:

★**Convection** can lead to Li destruction





Solar granulation
Inoye Telescope

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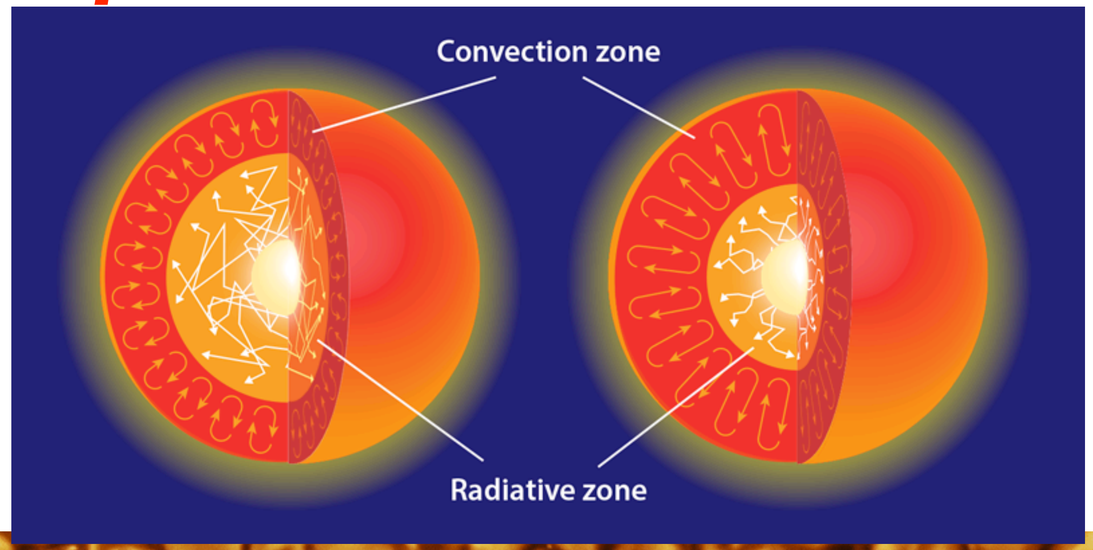

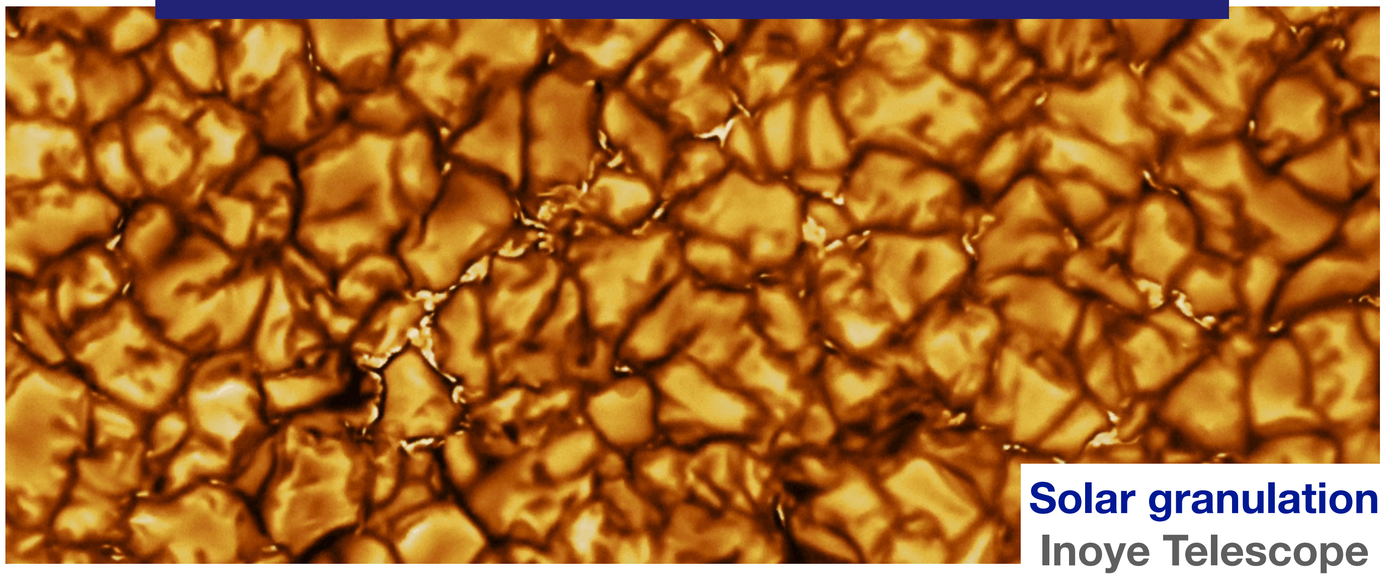

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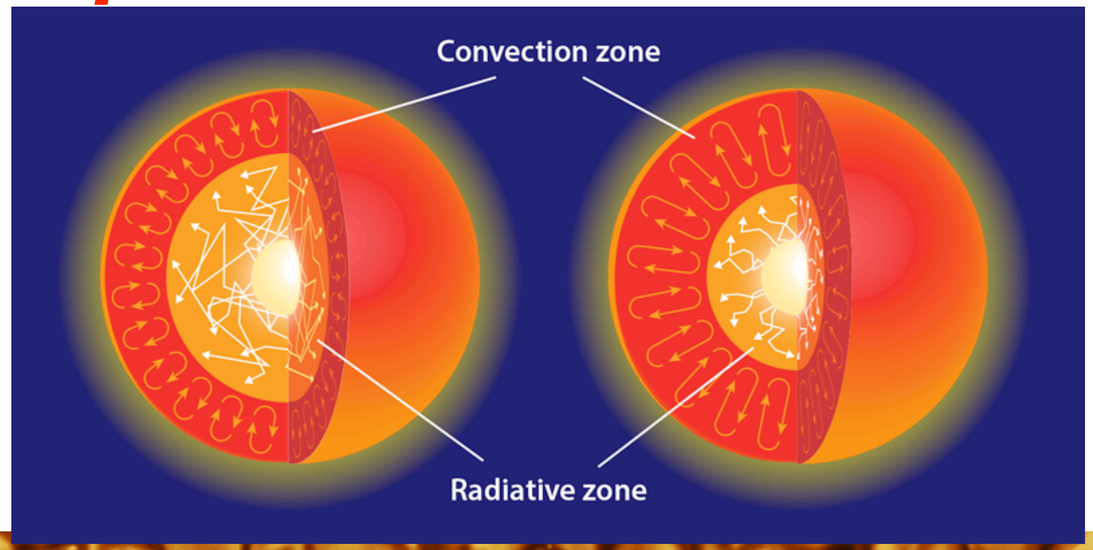
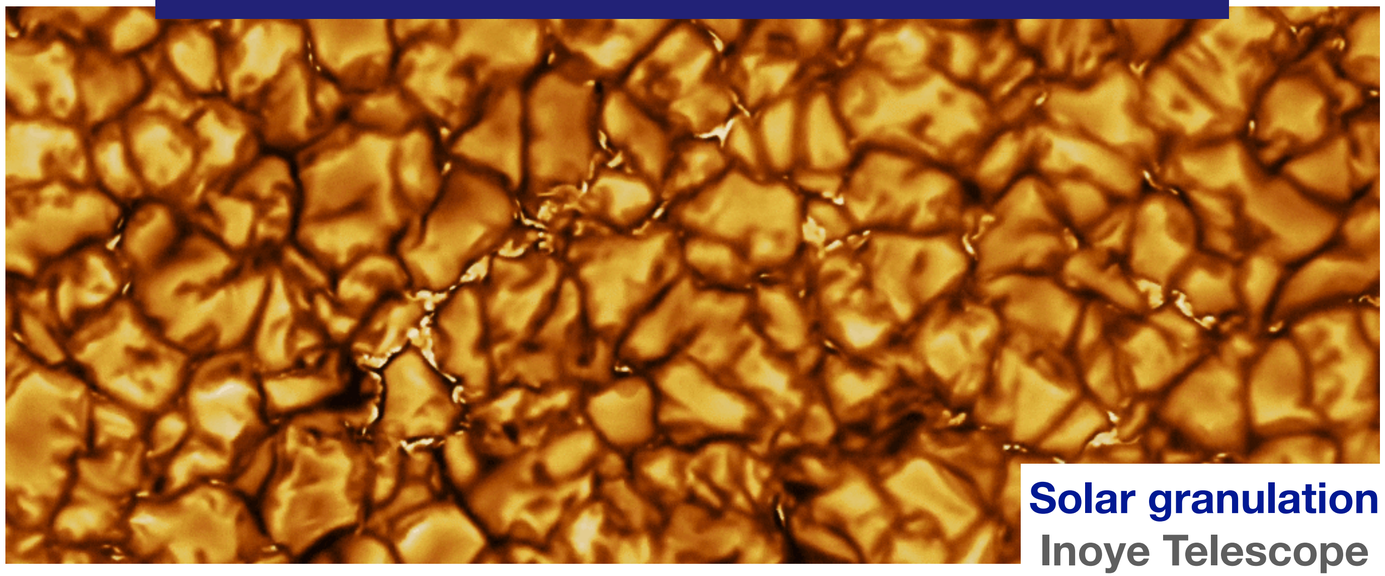


The Fix:

★select stars with thin convection zone



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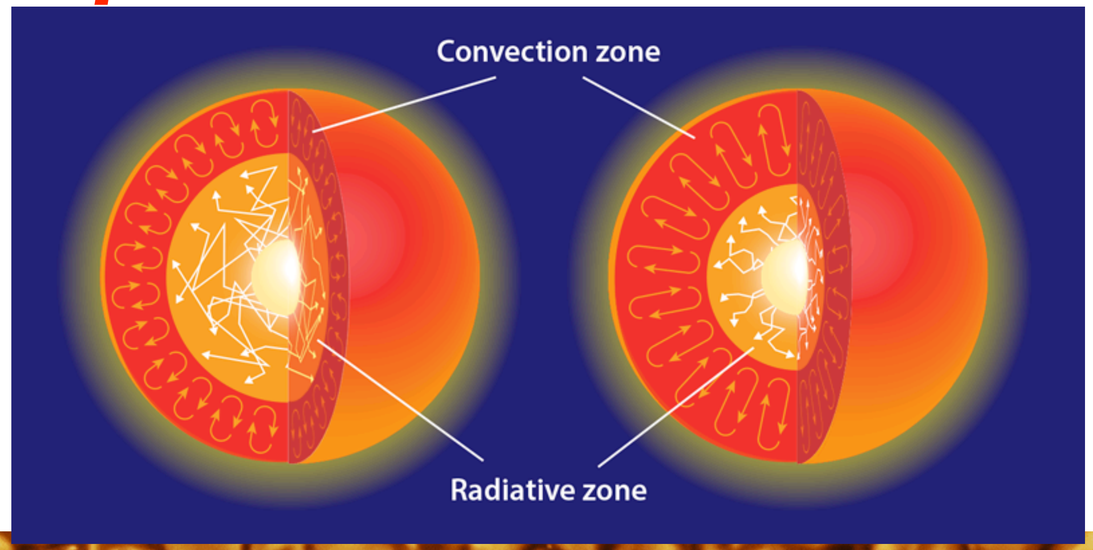

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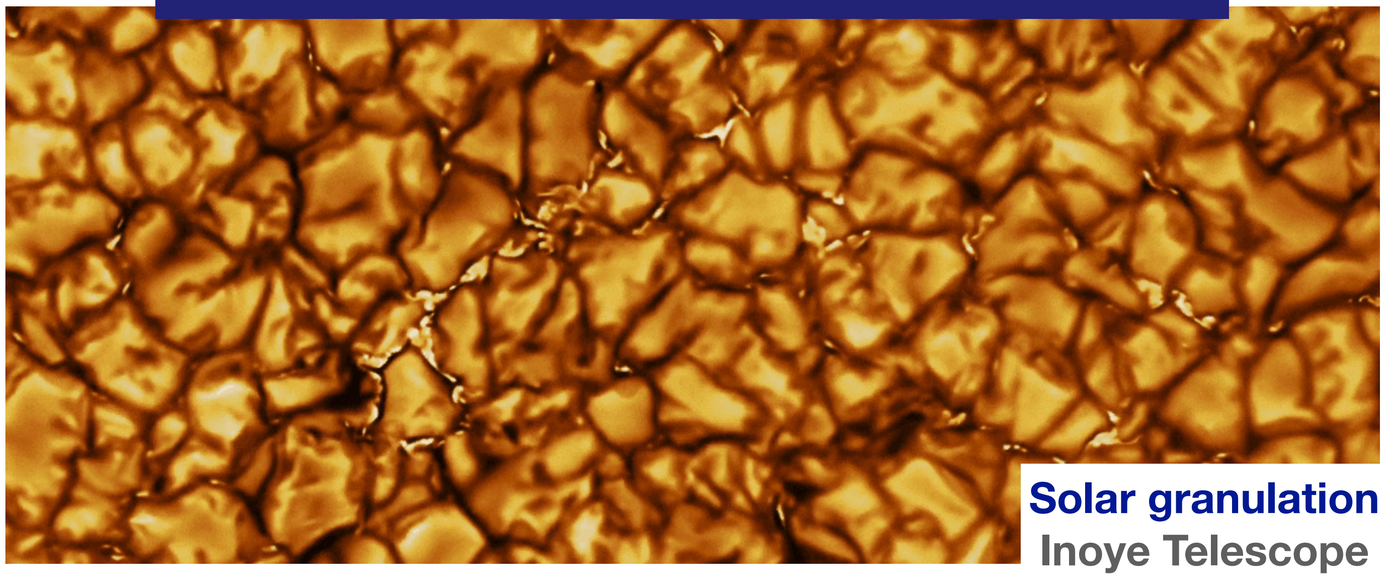
★select stars with thin convection zone

★empirically show small depletion



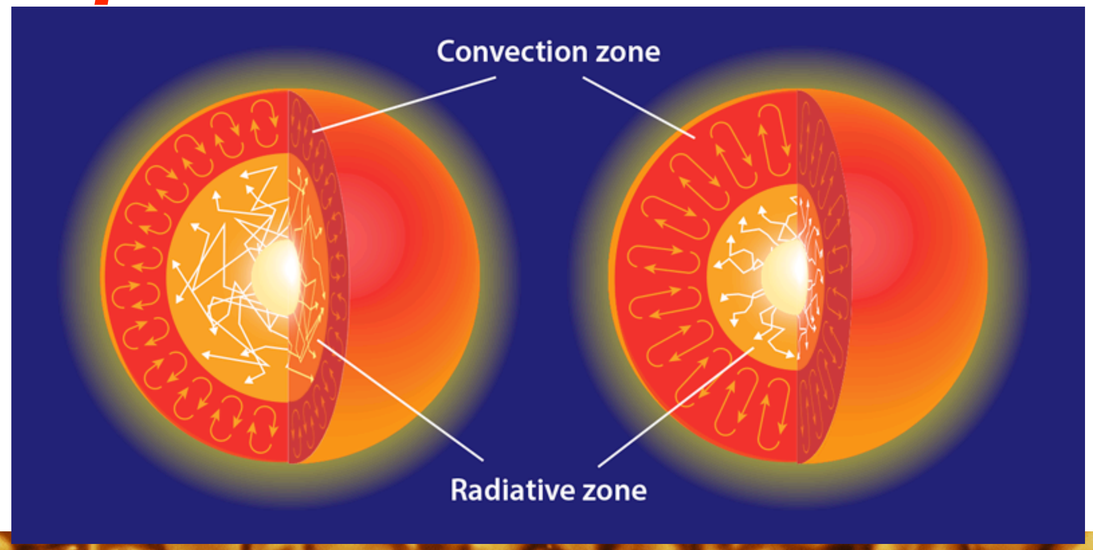
Solar granulation
Inoye Telescope

Lithium is Primordial

But is Spite Plateau the primordial value?

The Worry:

★**Convection** can lead to Li destruction

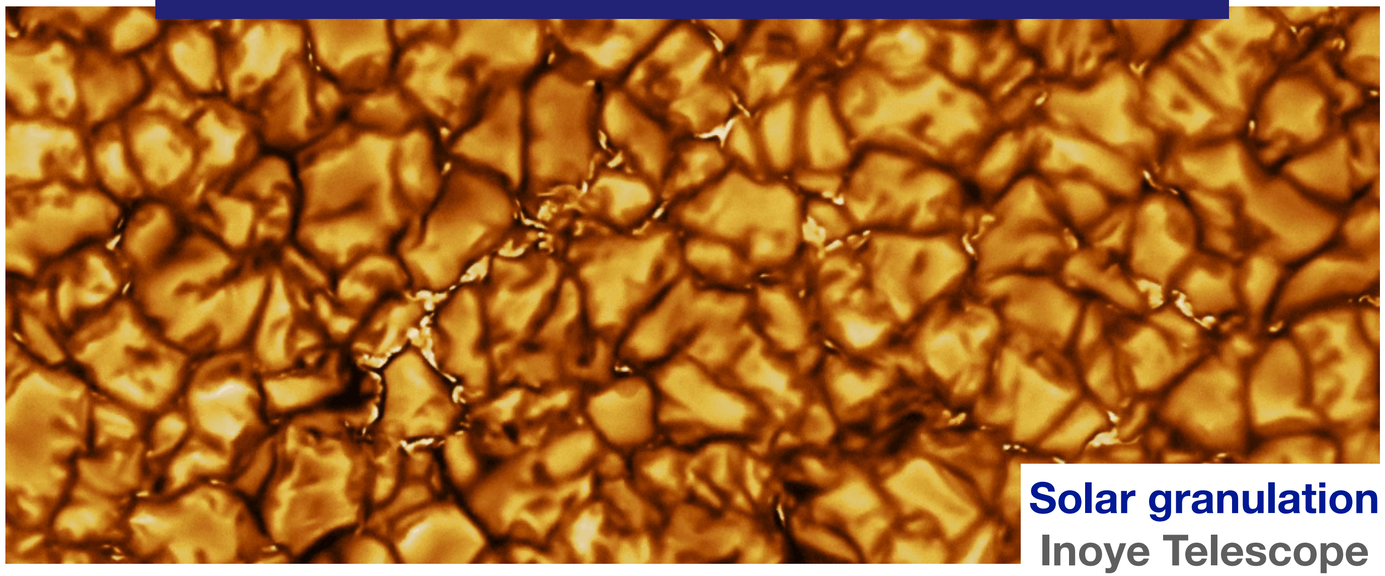


The Fix:

★select stars with thin convection zone

★empirically show small depletion

★consistent with thin Spite plateau



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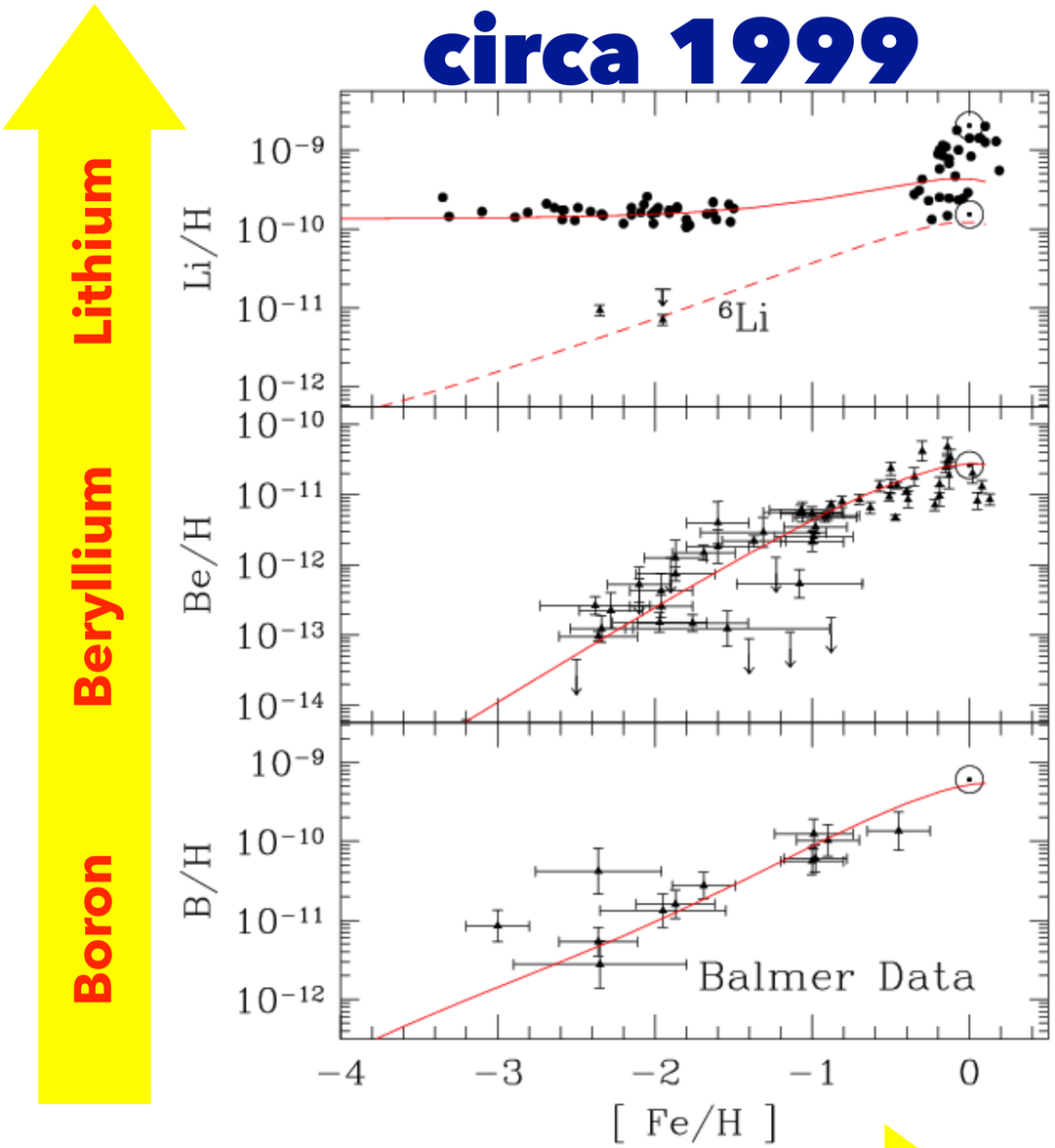
Context: ^{7}Li versus ^{6}Li, Be, and B circa 1999



BDF & Olive 99

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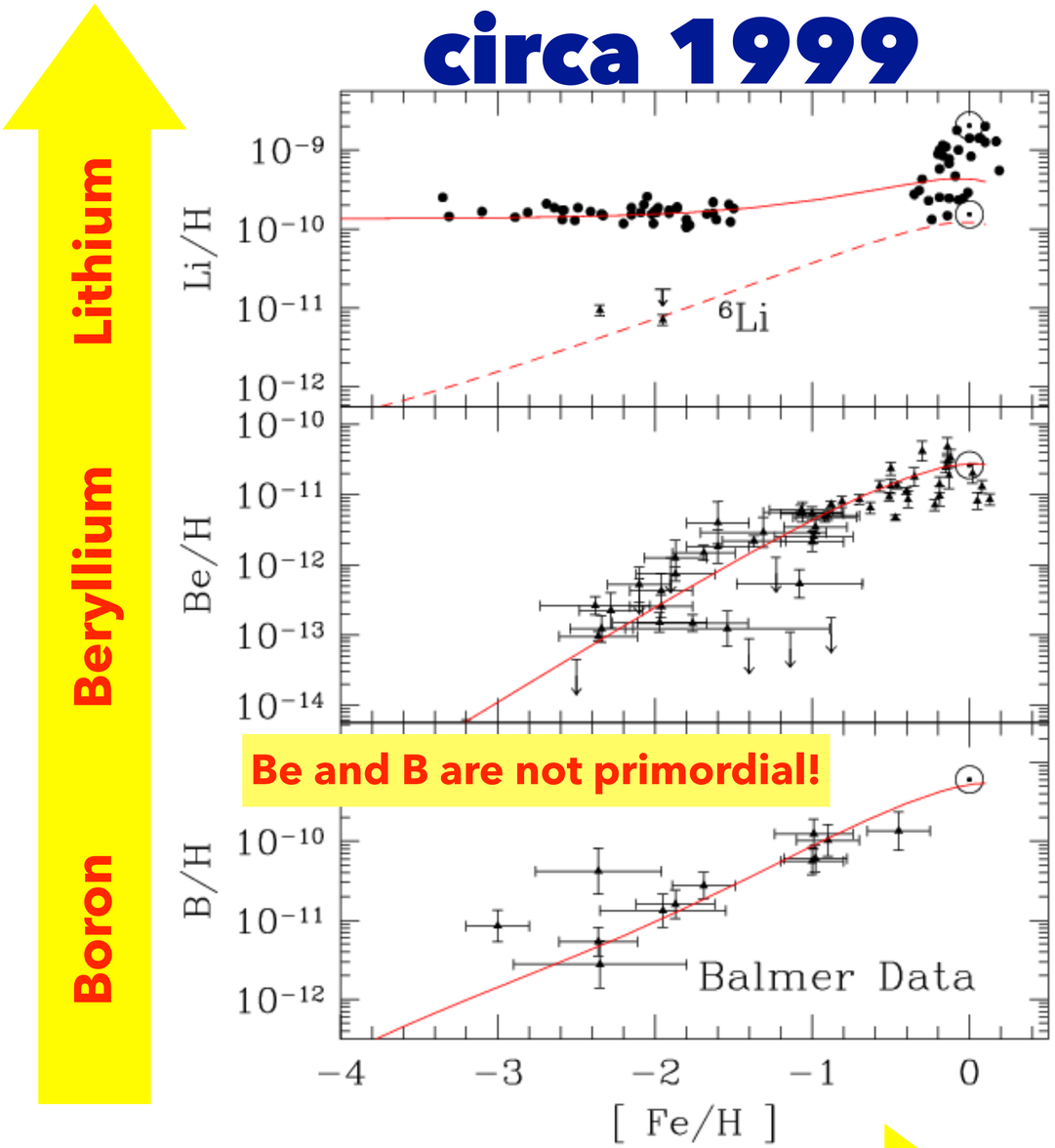

Be and B are not primordial!

[Fe/H]=$\log_{10}$(Fe/Fe$_{solar}$)

BDF & Olive 99

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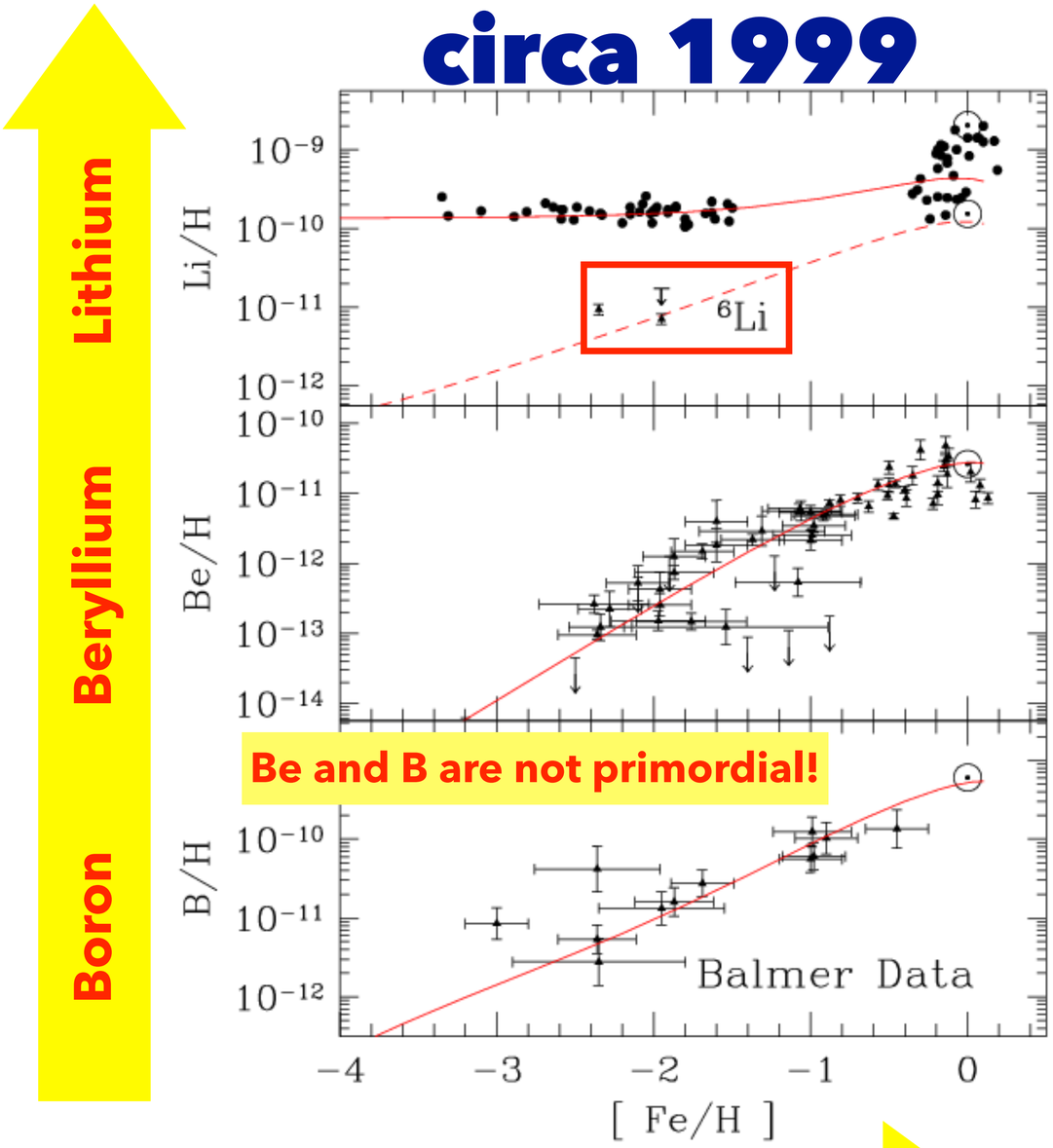

Be and B are not primordial!

^{6}Li found in two stars… then claimed in more

More fragile than ^{7}Li

^{6}Li survival means ^{7}Li depletion small

BDF & Olive 99

[Fe/H]=$\log_{10}$(Fe/Fe$_{solar}$)

Cosmic-Ray Nucleosynthesis of LiBeB

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**

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

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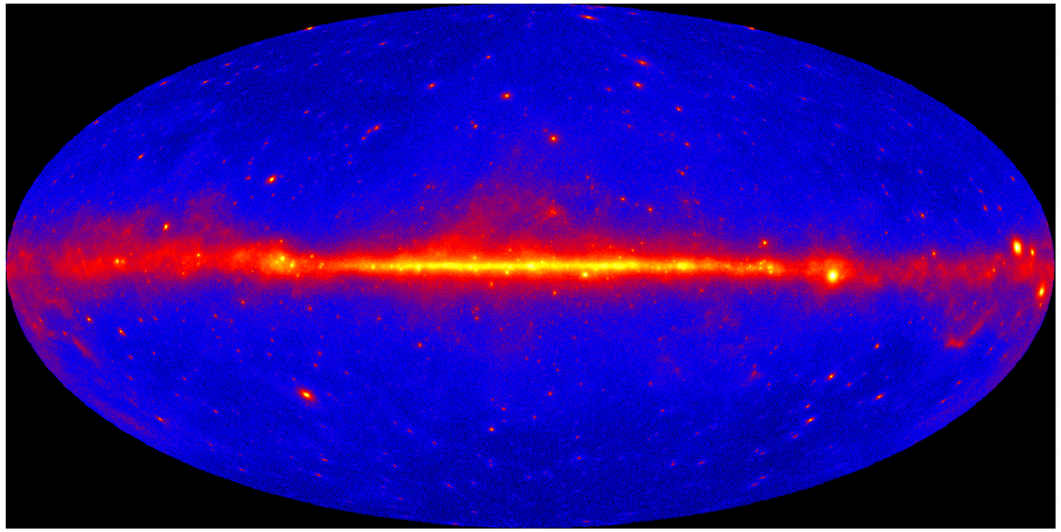

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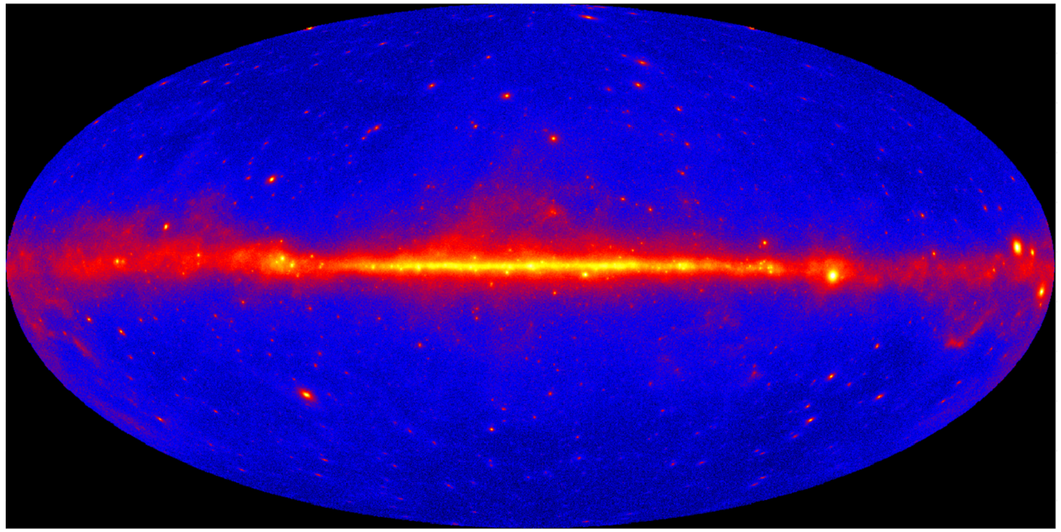

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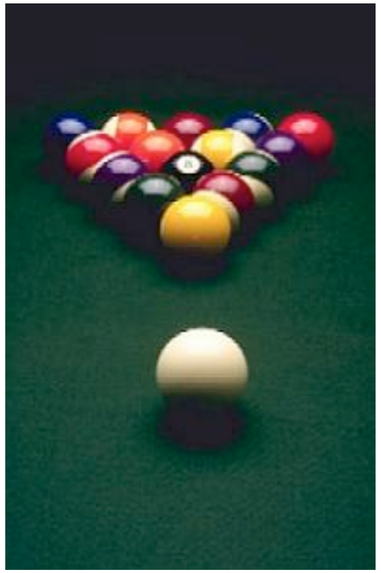

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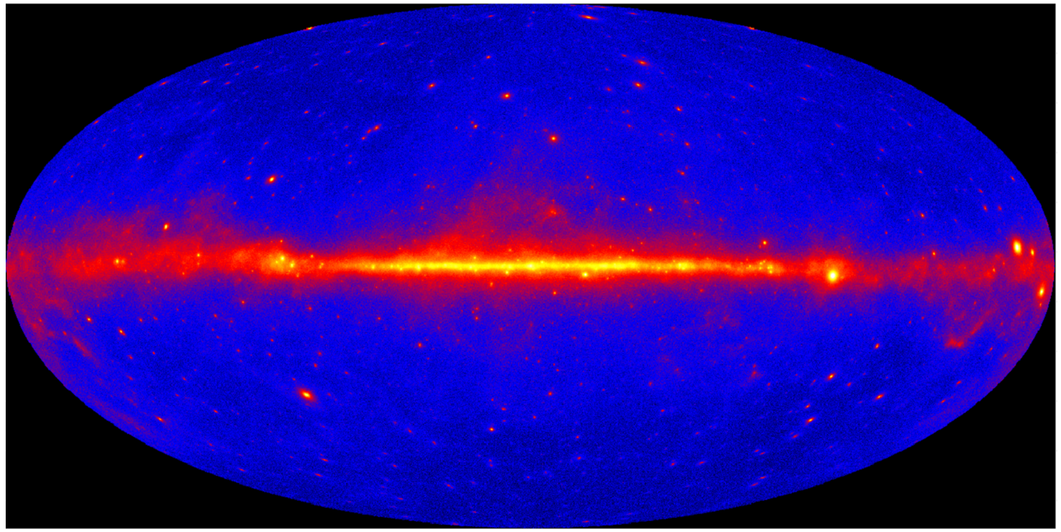

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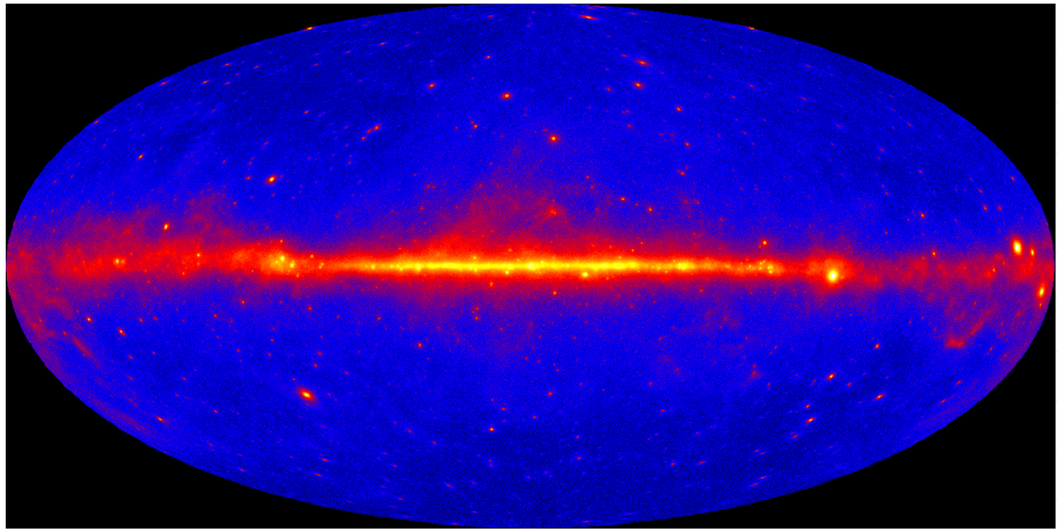

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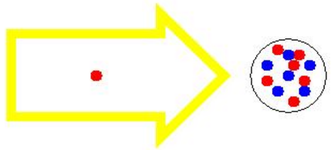
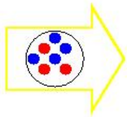


$p, \alpha + \mathrm{C, N, O}$



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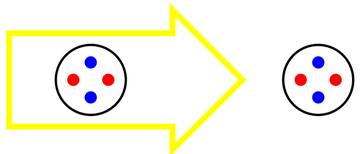
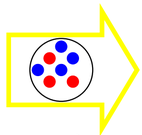
Fusion:



$\alpha + \alpha$



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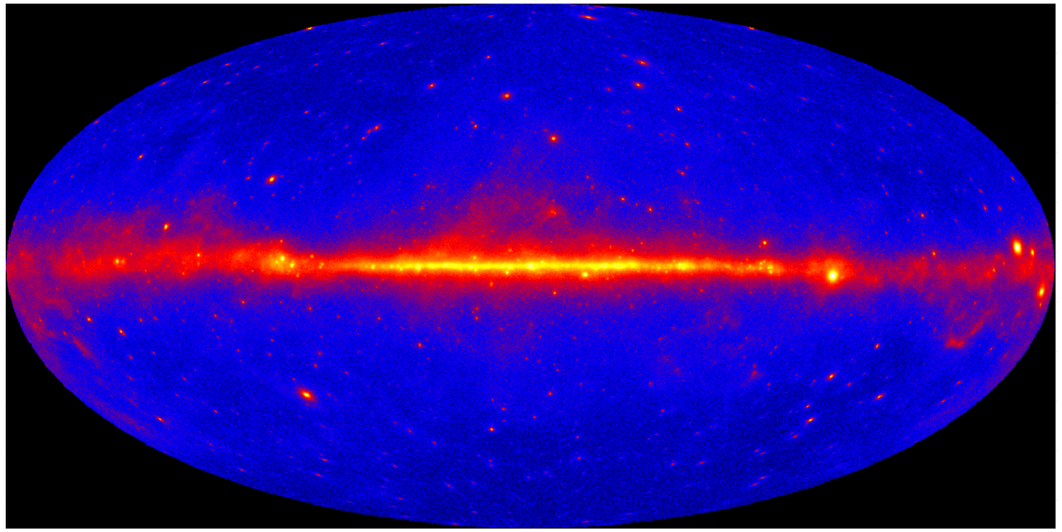

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Spallation: $p, \alpha + \mathrm{C, N, O}$ → all of Li,Be,B

need metals in projectiles or targets

Fusion: $\alpha + \alpha$ → ^{6}Li and ^{7}Li *only*

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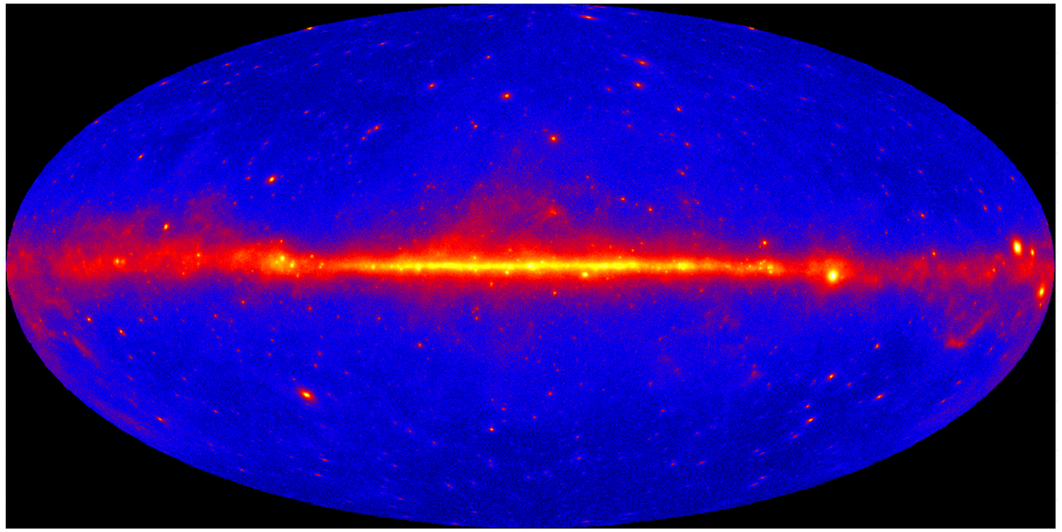

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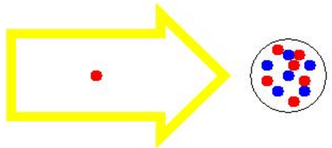

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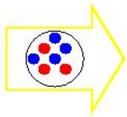

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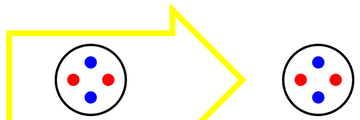

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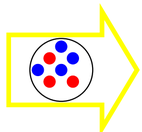


^{6}Li and ^{7}Li *only*

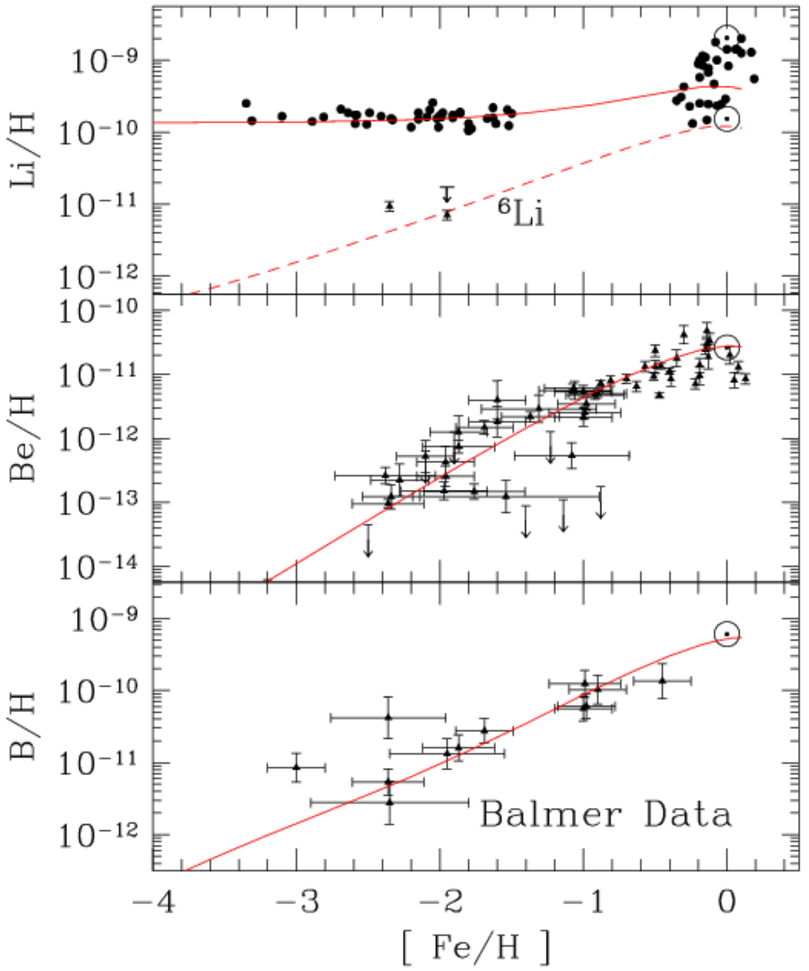
no metals required--helium is primordial

Galactic Cosmic Rays: Archaeology

Prantzos, Cassé, Vangioni-Flam 1993; Walker et al 1993; BDF Olive & Schramm 1994; Ramaty, Kozlovsky, & Lingenfelter 1996

LiBeB as Cosmic Ray Dosimeters

Solar LiBeB: cumulative irradiation at Sun birth



BDF & Olive 99

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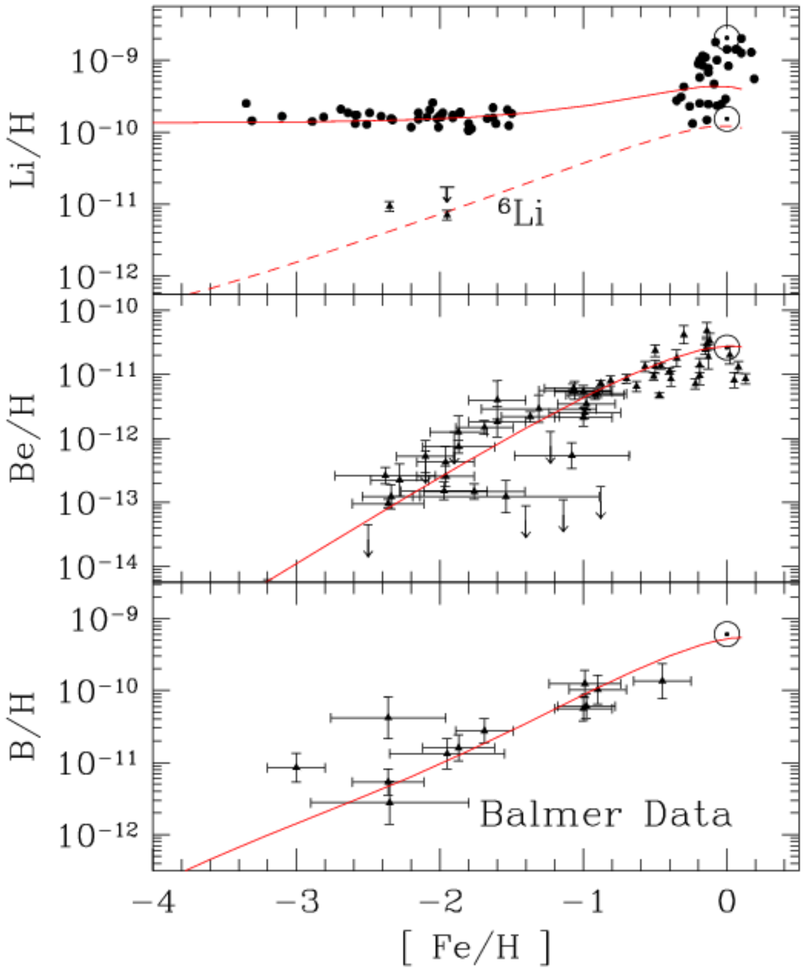

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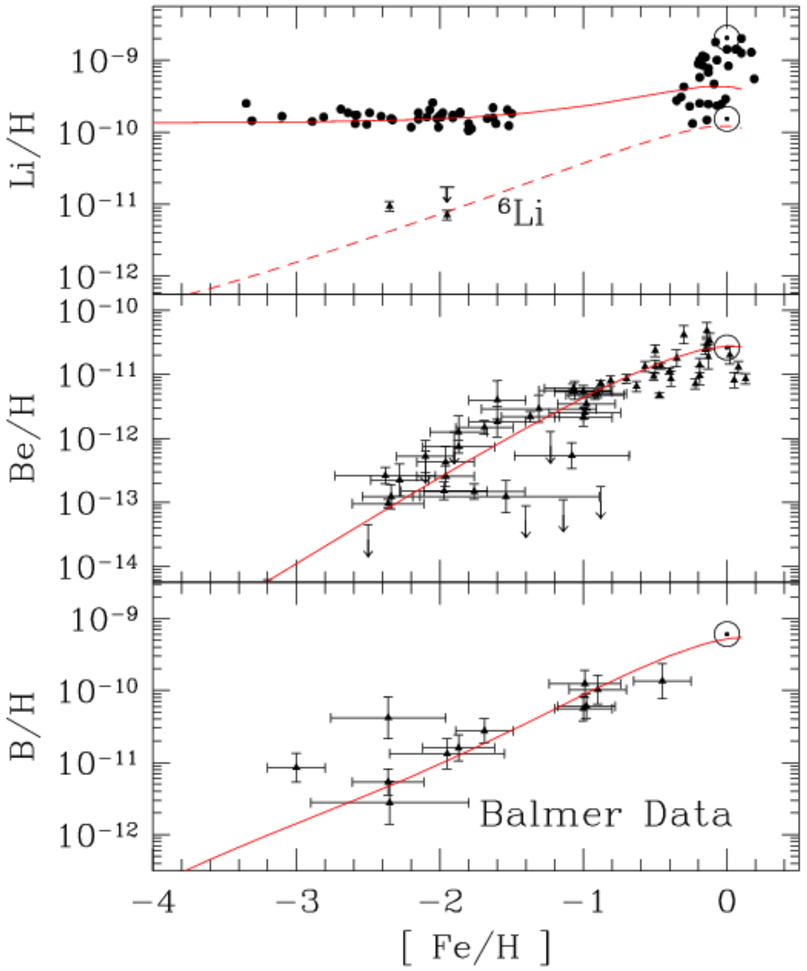

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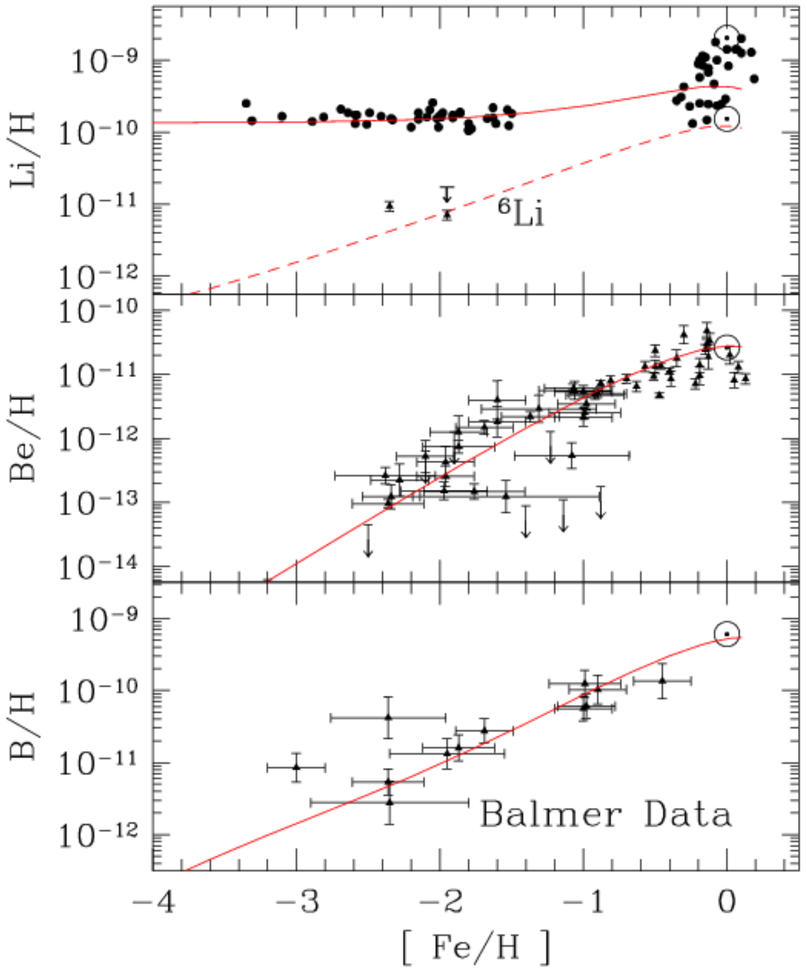
LiBeB in halo stars: cosmic-ray fossils

Cosmic rays present in early Galaxy!



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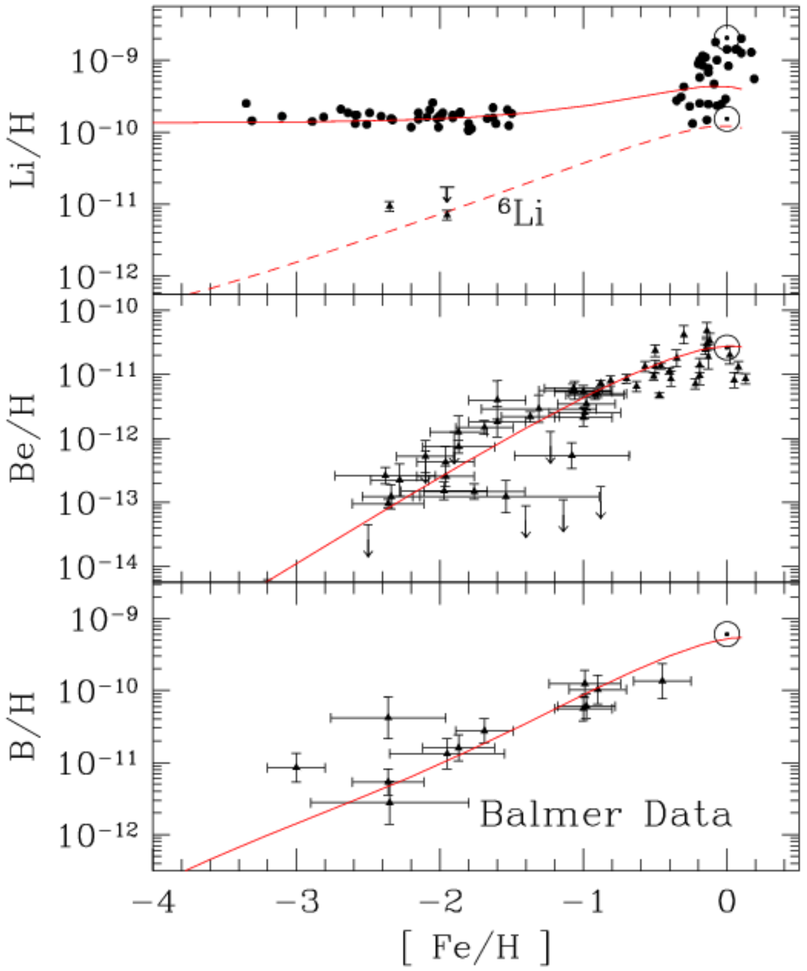
LiBeB probe cosmic-ray origin & history



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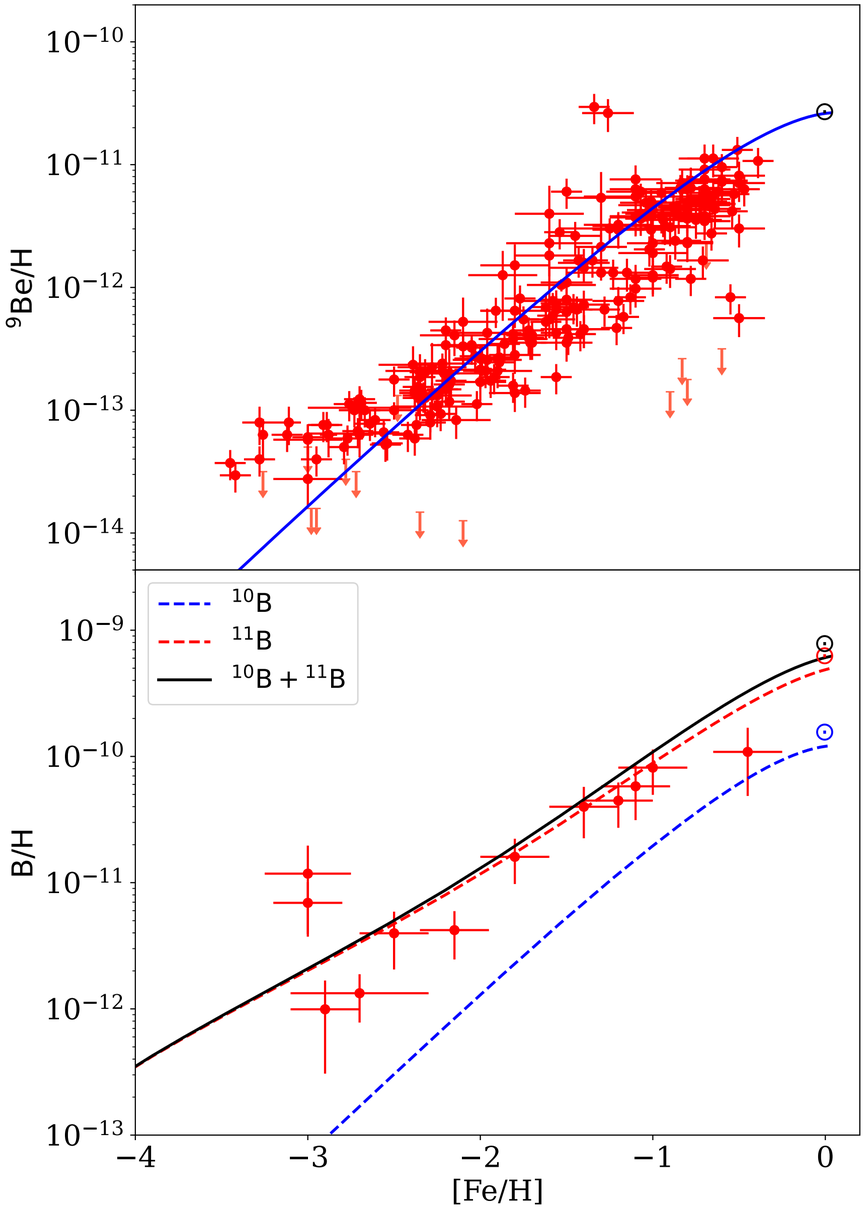
2022: A Possible Solution

Keith Olive

BDF & Olive 2022



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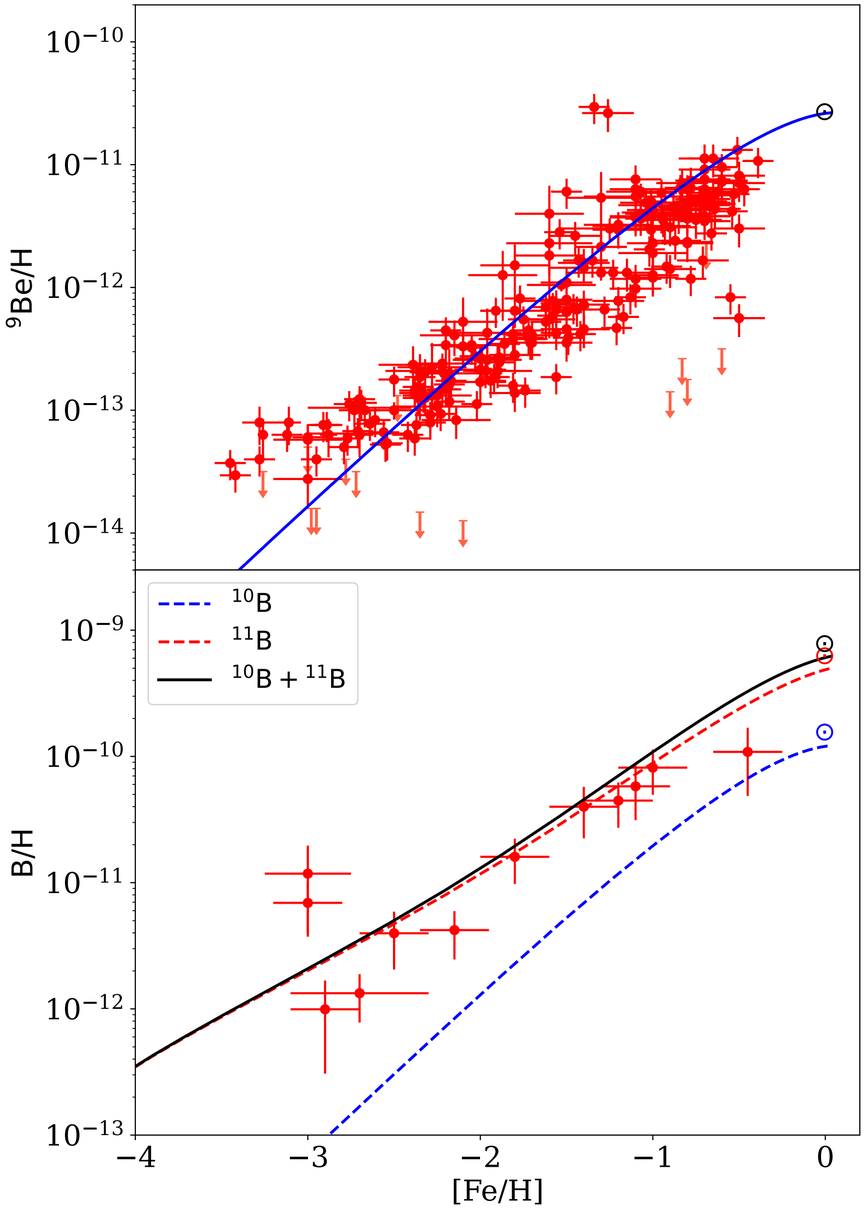
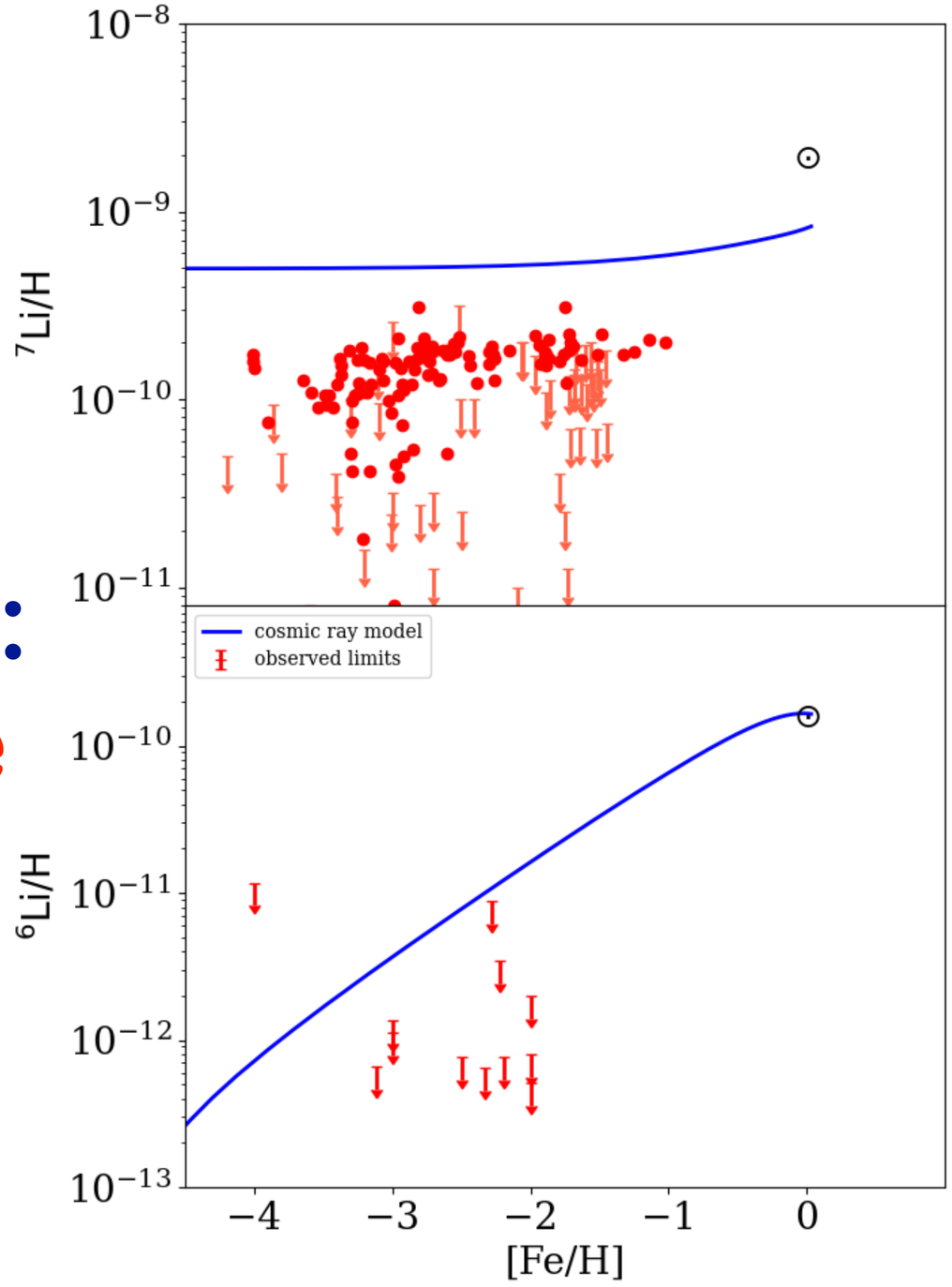


Same CR model

New data added

Still good fit, strong evidence for cosmic rays in early Galaxy

Lithium and Cosmic Rays: 2022 Update



BDF & Olive 2022

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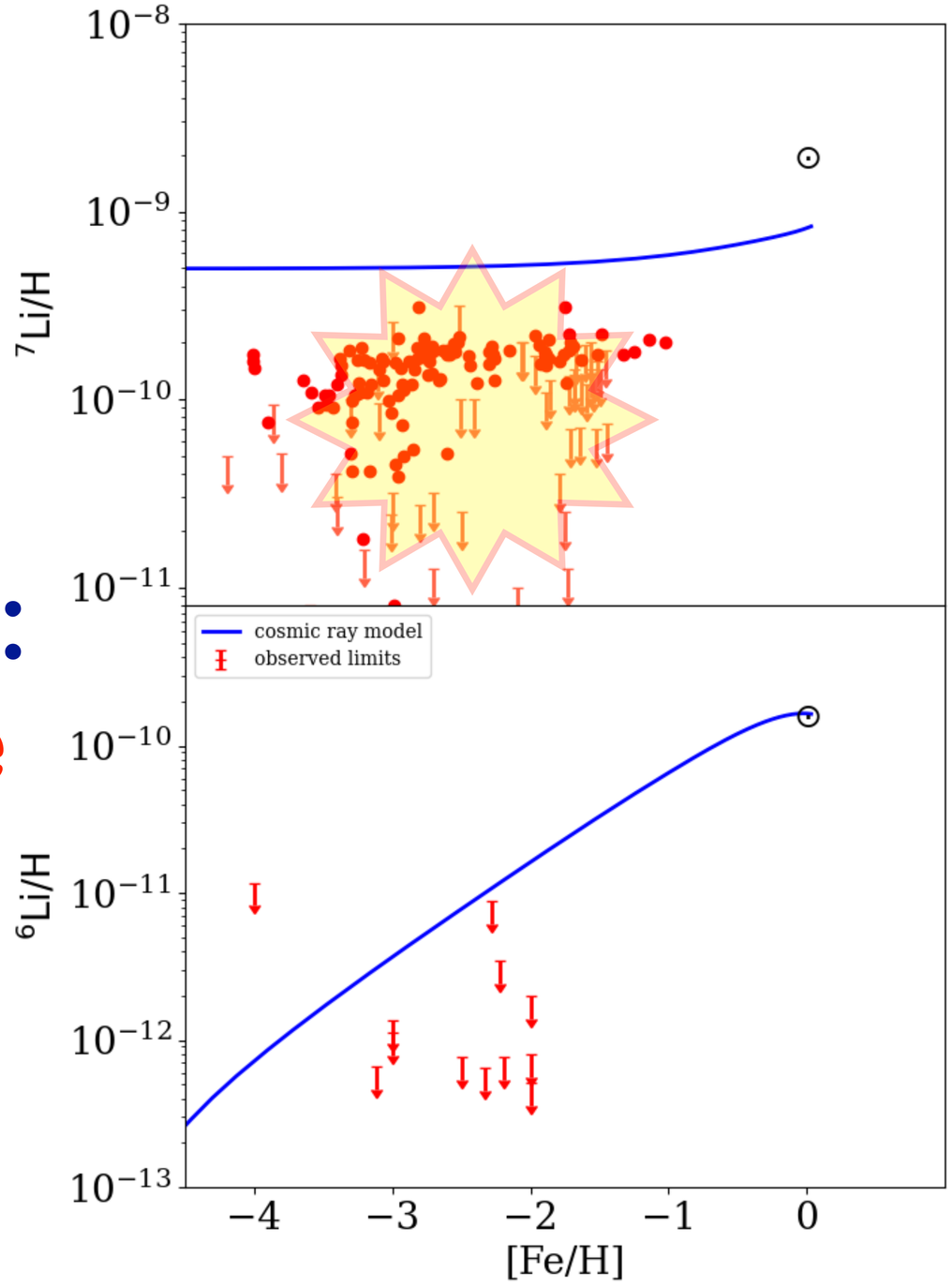

BDF & Olive 2022

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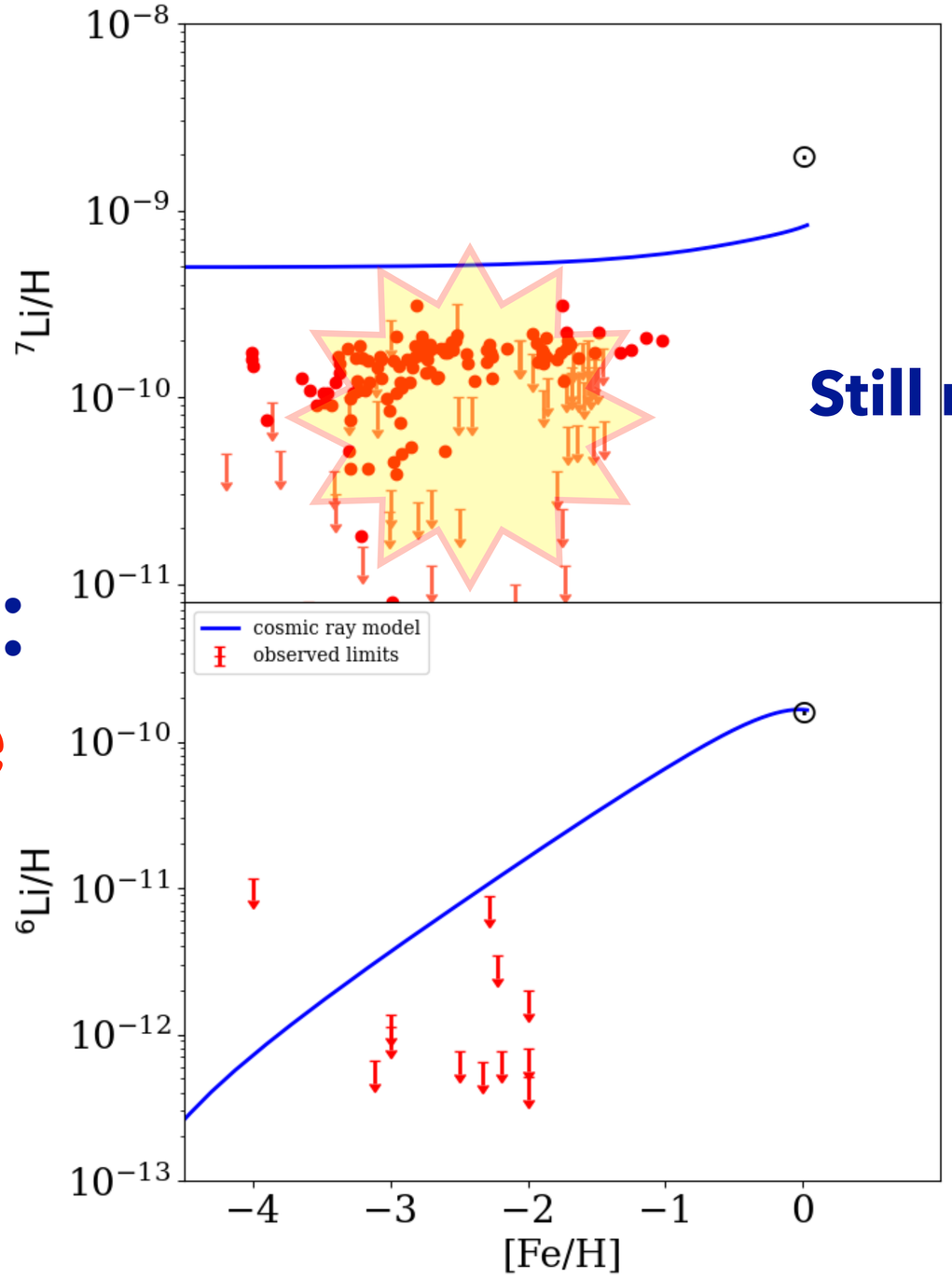

Newer Li data:

Large dispersion!

Still mostly a "lithium desert" below primordial

BDF & Olive 2022

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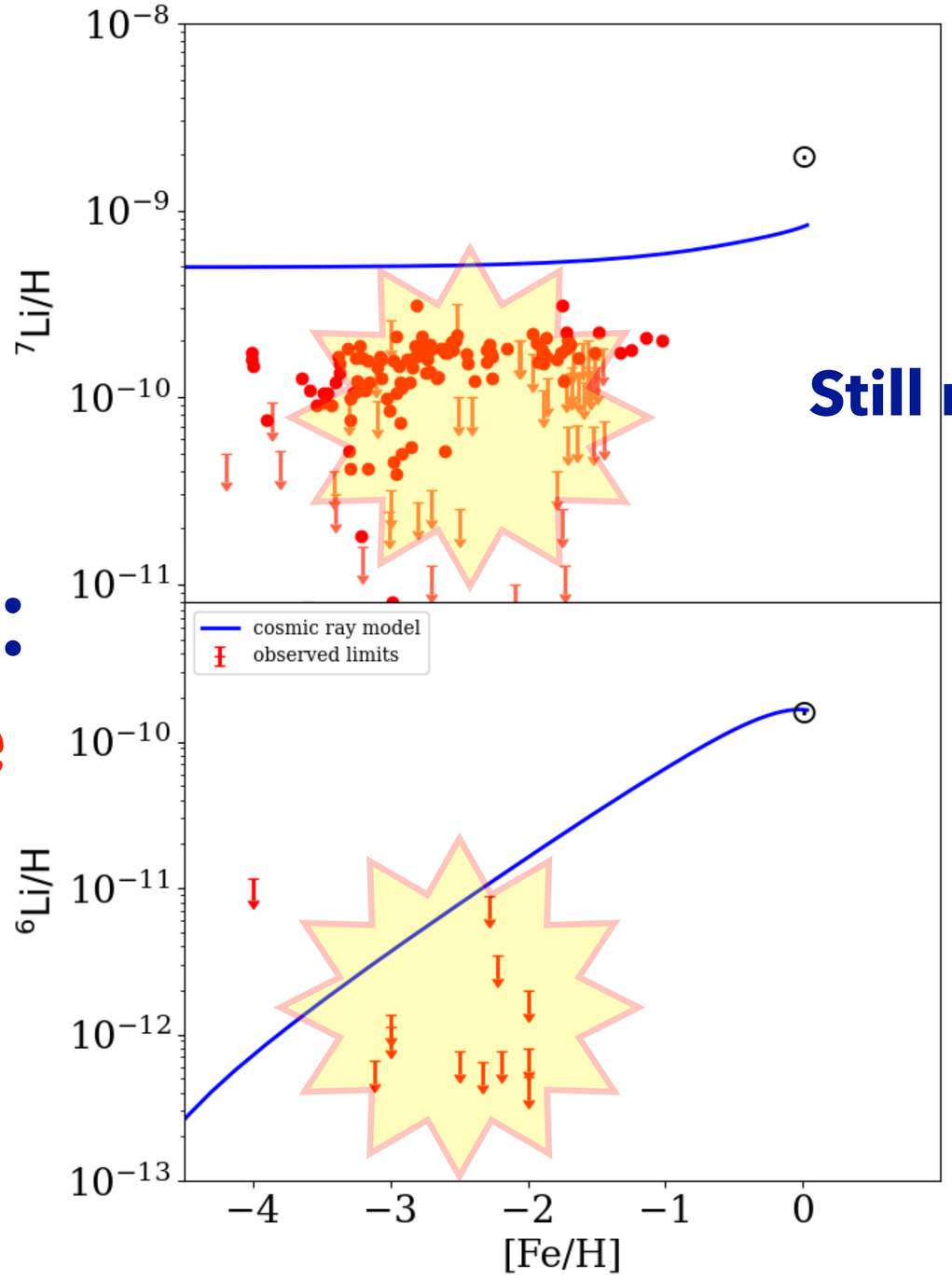

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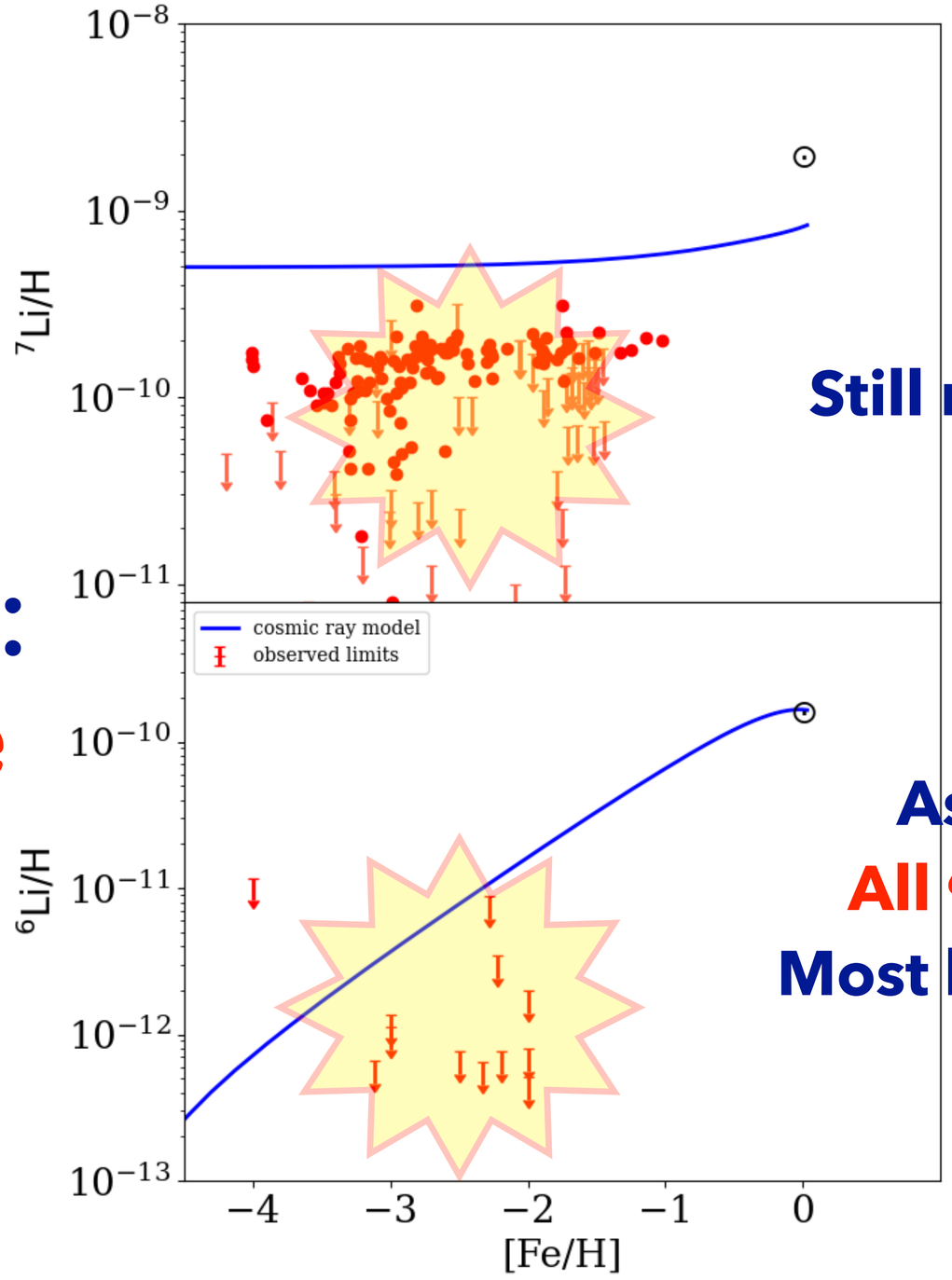

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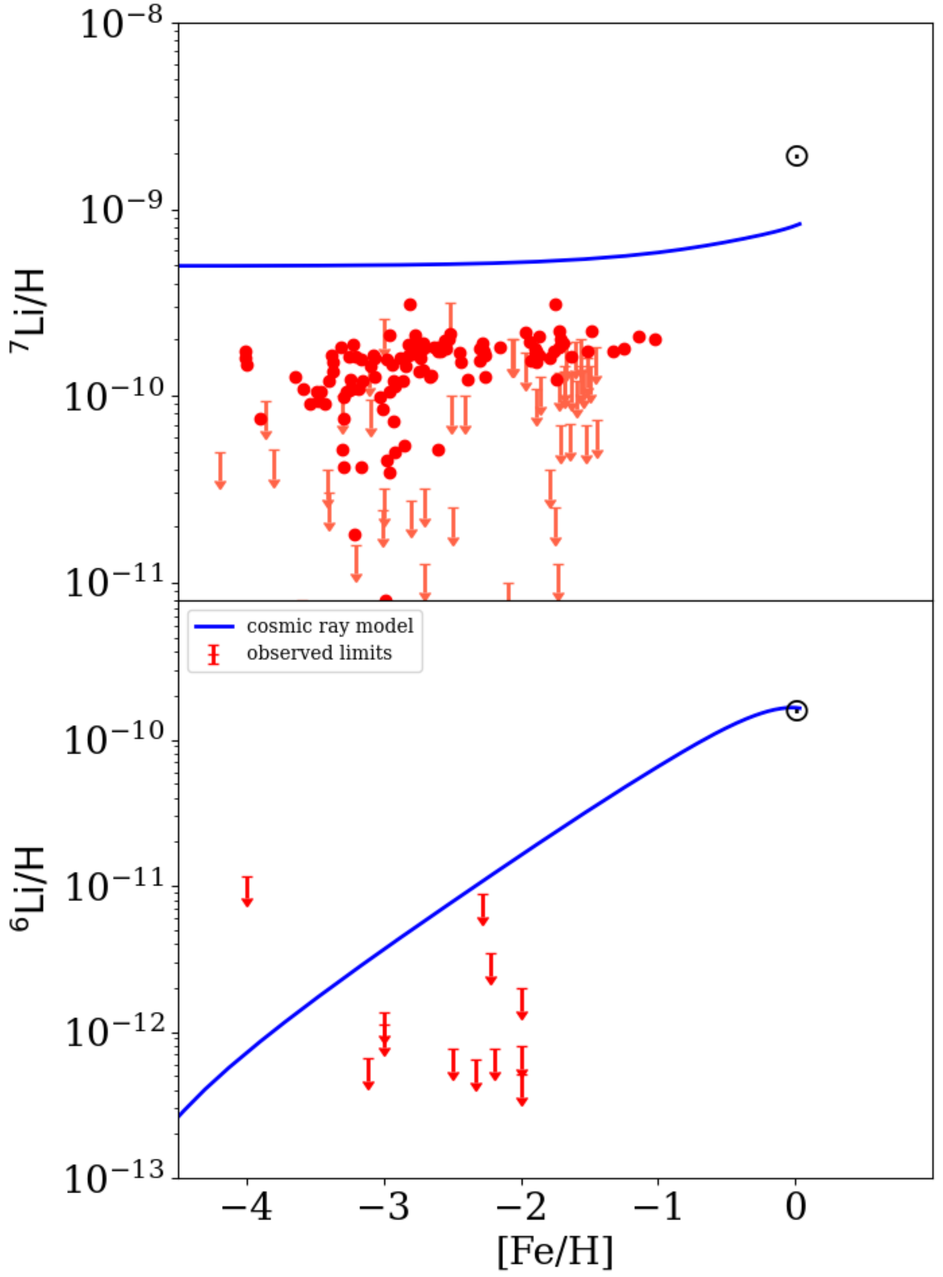
As of Autumn 2021:

All ^{6}Li detections gone!

Most limits far below model

BDF & Olive 2022



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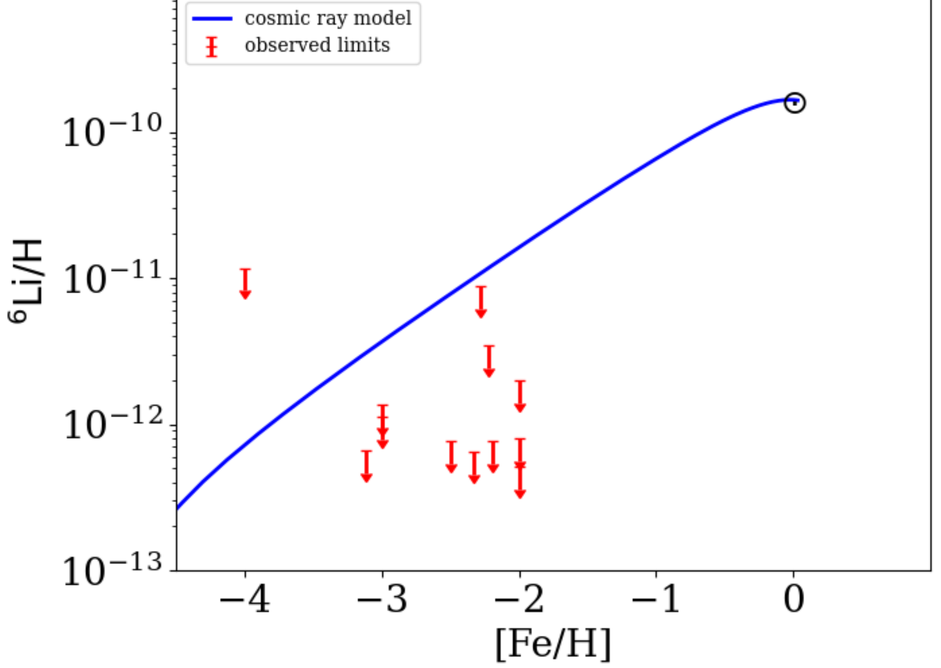

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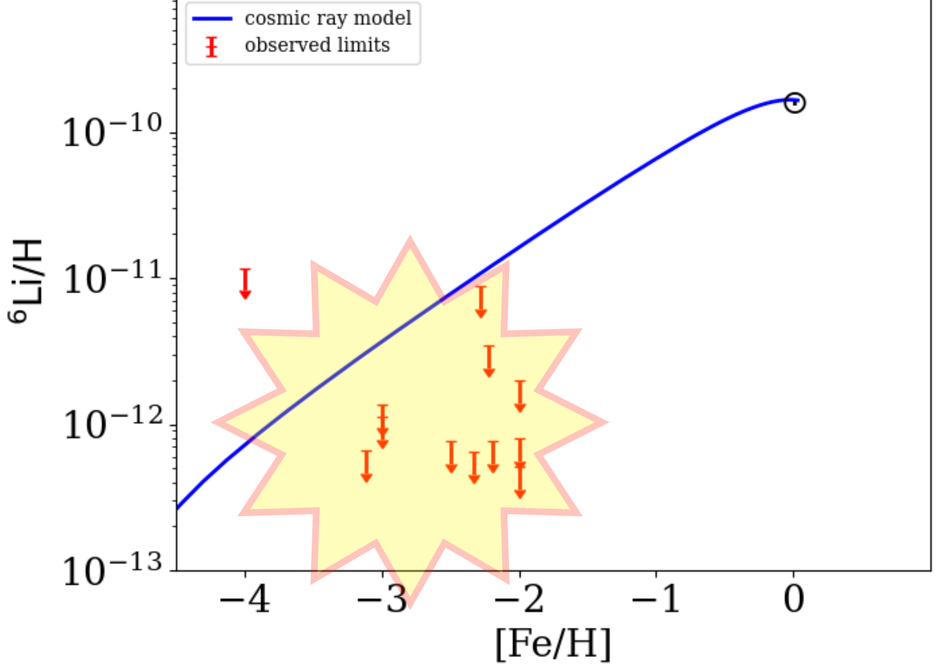

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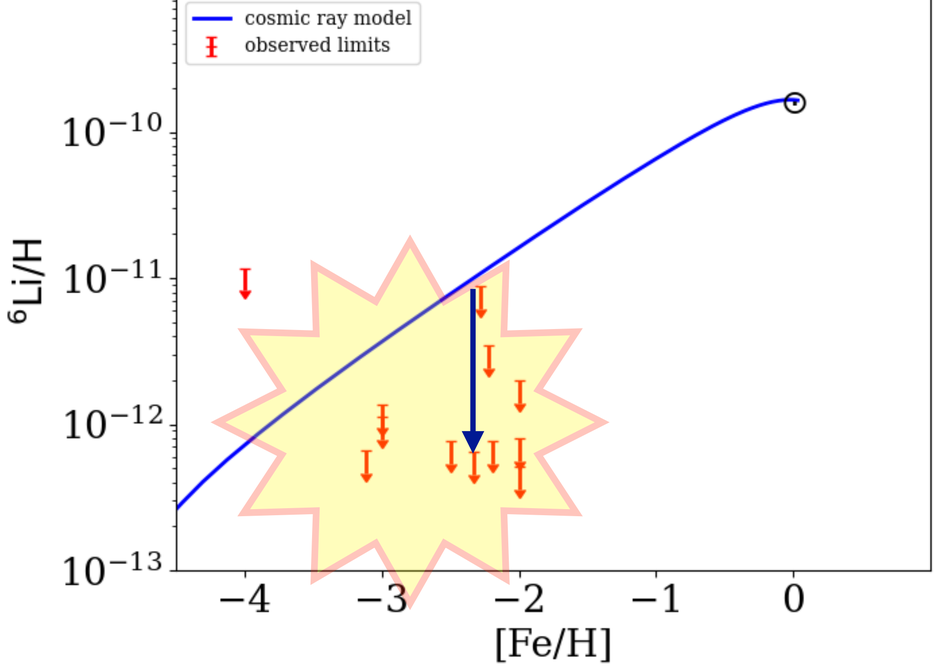
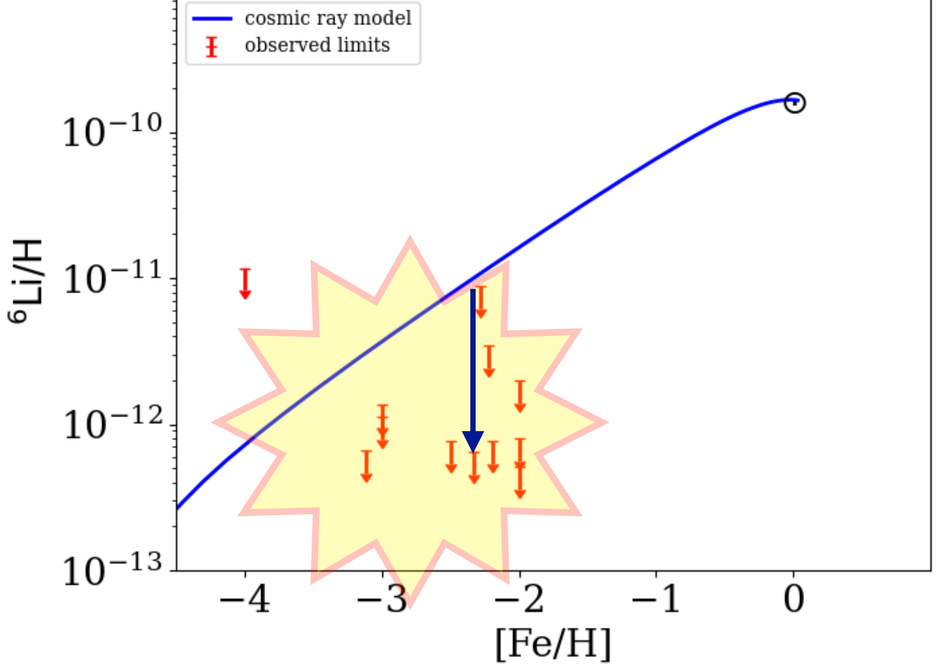


Find ^{6}Li depletion:

$$D_6 = \frac{^6\mathrm{Li}_{\mathrm{CR}}}{^6\mathrm{Li}_{\mathrm{obs}}} \geq 1$$

BDF & Olive 2022



If ^{7}Li depletion the same:

$$D_7 = D_6$$

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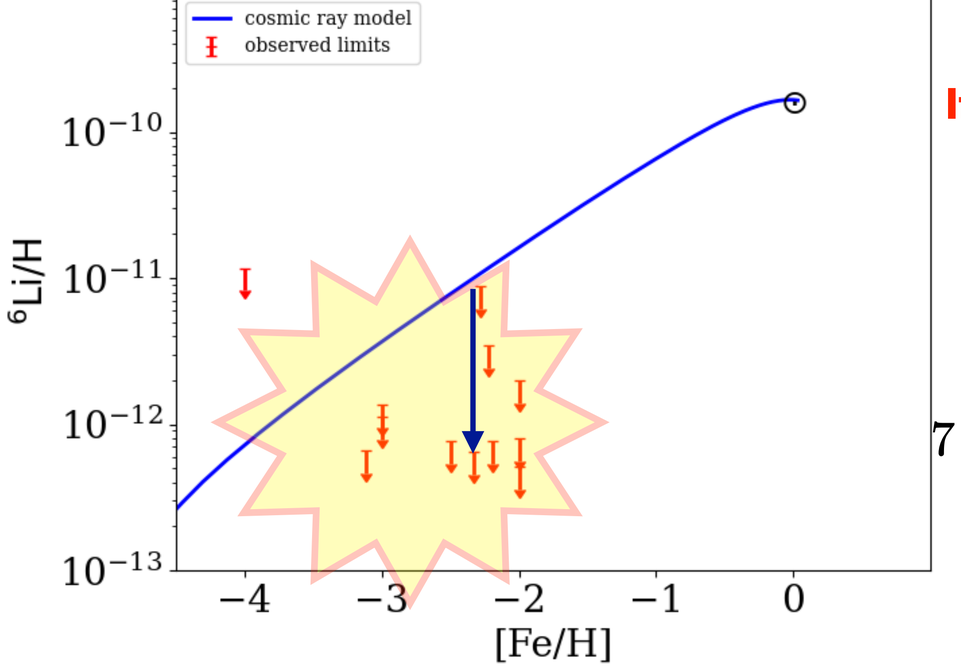
BDF & Olive 2022



If ^{7}Li depletion the same:

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Infer initial ^{7}Li

$$^7\mathrm{Li}_{\mathrm{init}} = D_7\ ^7\mathrm{Li}_{\mathrm{obs}}$$

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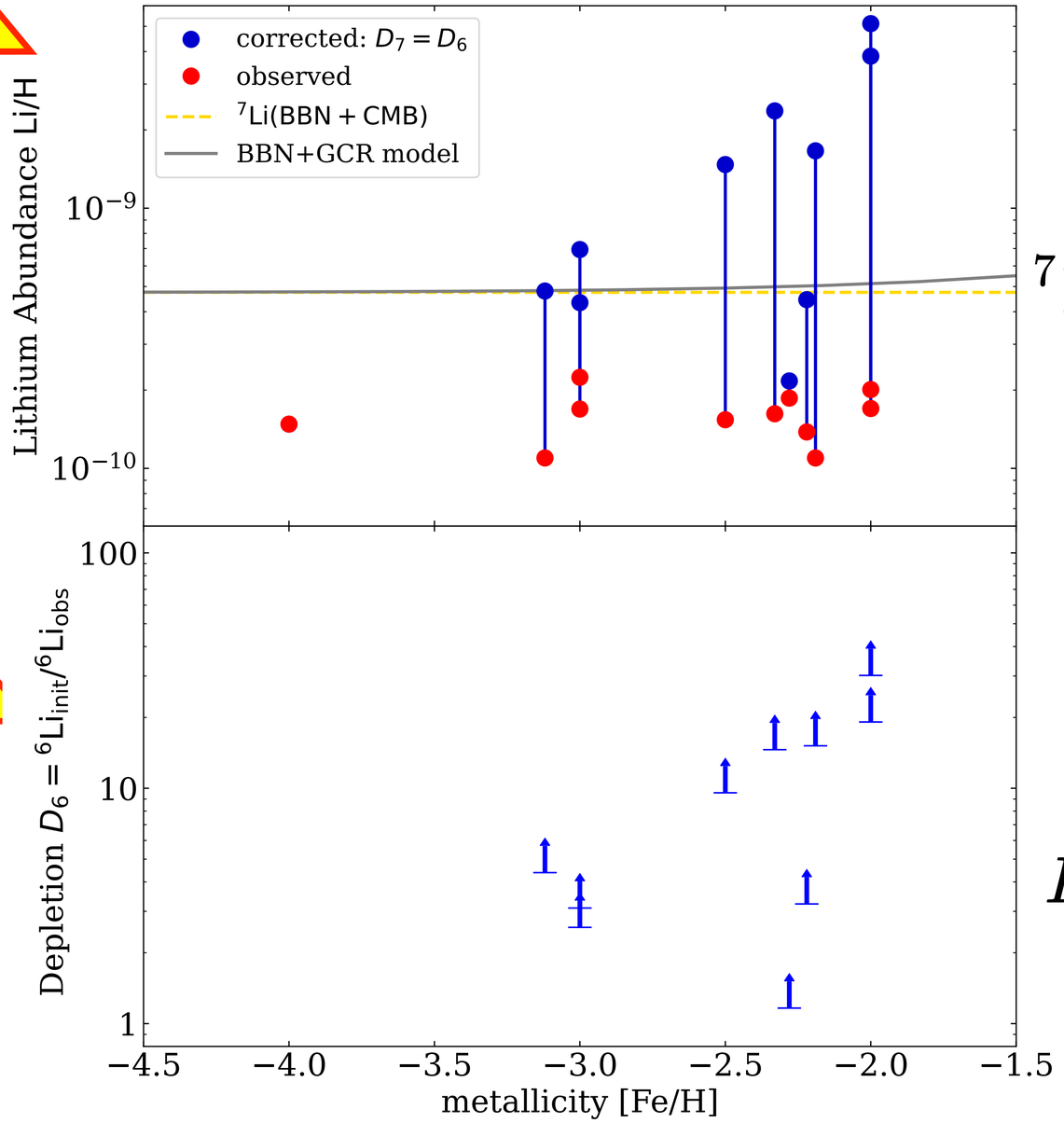
BDF & Olive 2022

Lithium-7

Depletion



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BDF & Olive 2022

Lithium-7

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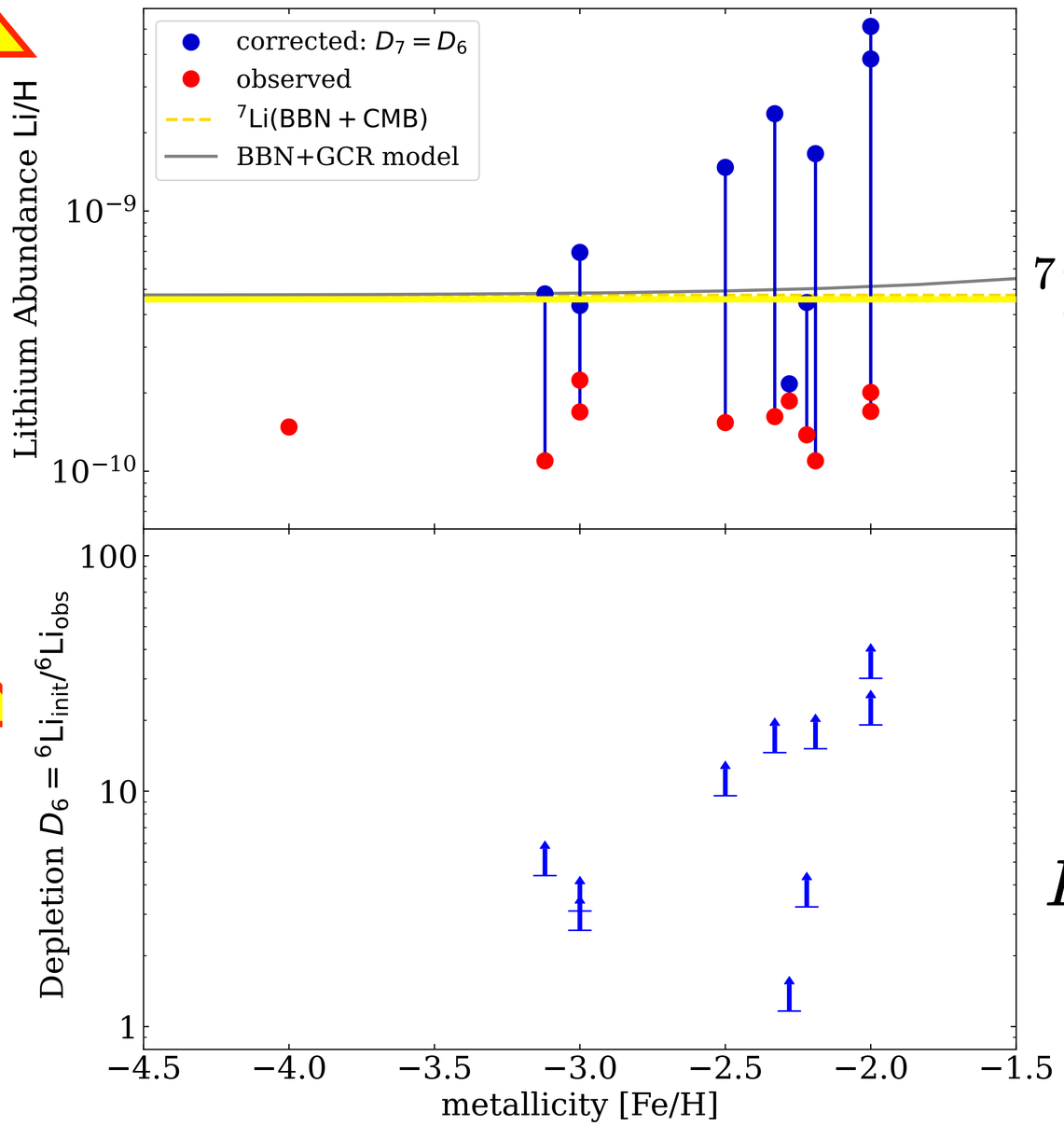

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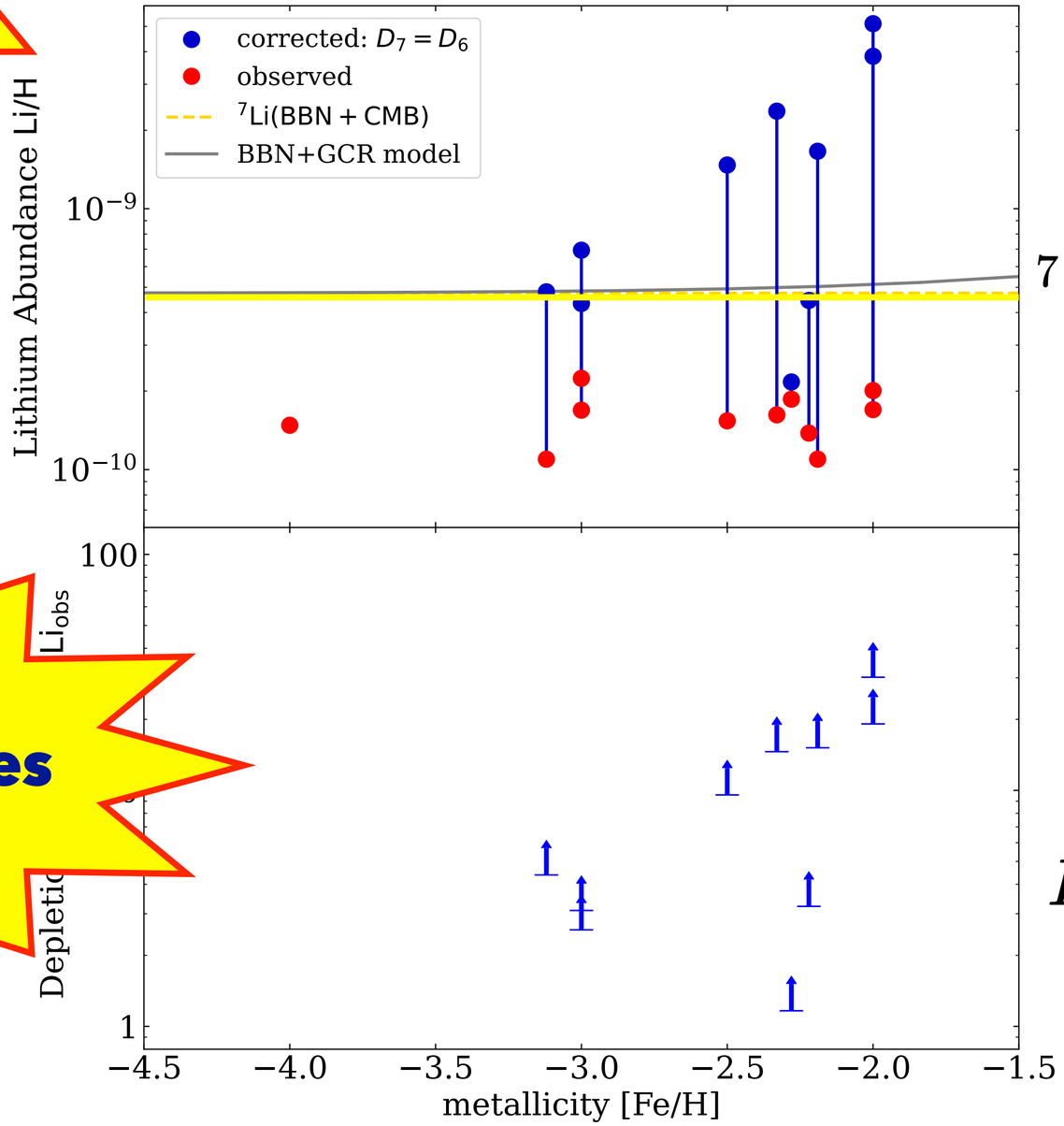
BDF & Olive 2022

Lithium-7



Dep

Easily accommodates BBN+CMB!

If ^{7}Li depletion the same:

$$D_7 = D_6$$

Infer initial ^{7}Li

$$^7\mathrm{Li}_{\mathrm{init}} = D_7\ ^7\mathrm{Li}_{\mathrm{obs}}$$

Find ^{6}Li depletion:

$$D_6 = \frac{^6\mathrm{Li}_{\mathrm{CR}}}{^6\mathrm{Li}_{\mathrm{obs}}} \geq 1$$

BDF & Olive 2022

Implications: Lithium Problem Solved?

Good news—without lithium problem…

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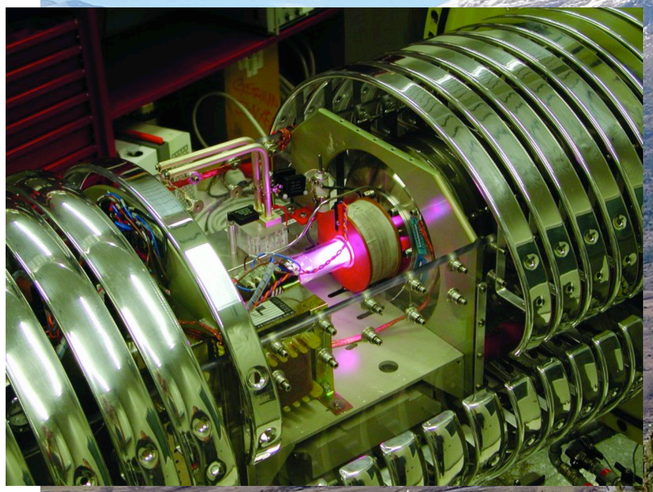
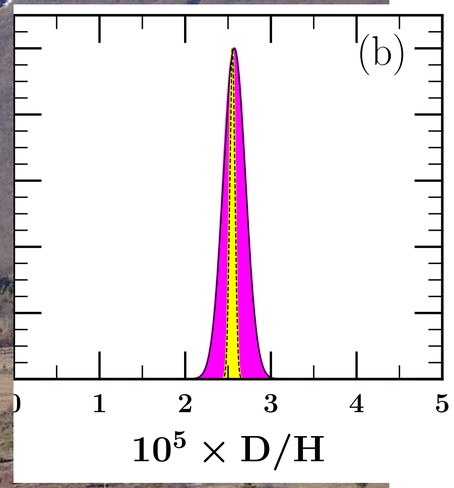
Bad news—Li unreliable for cosmo

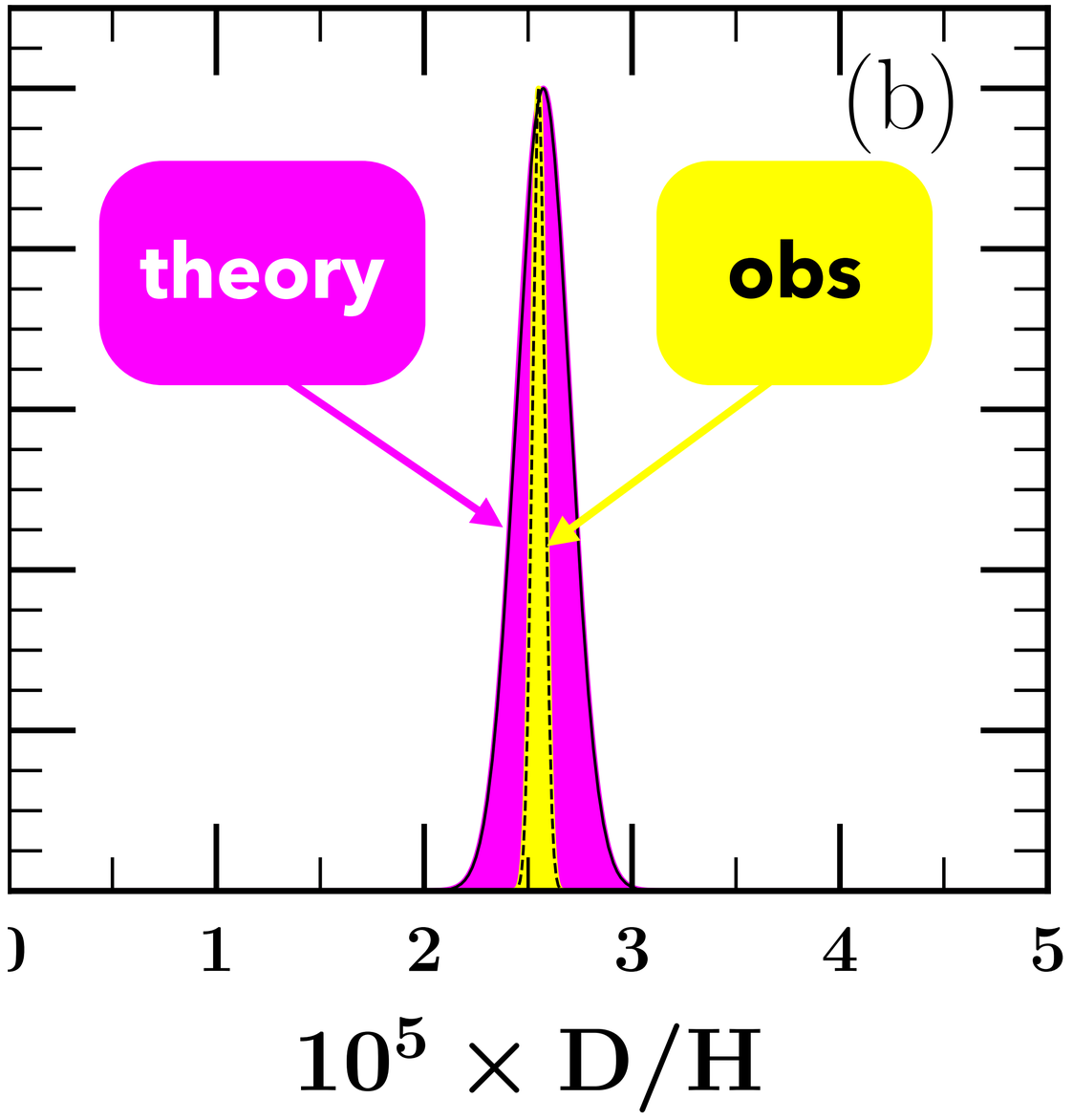
…for now. Clever ideas needed!

Nuclear Reactions take Center Stage





Nuclear Crisis for Deuterium



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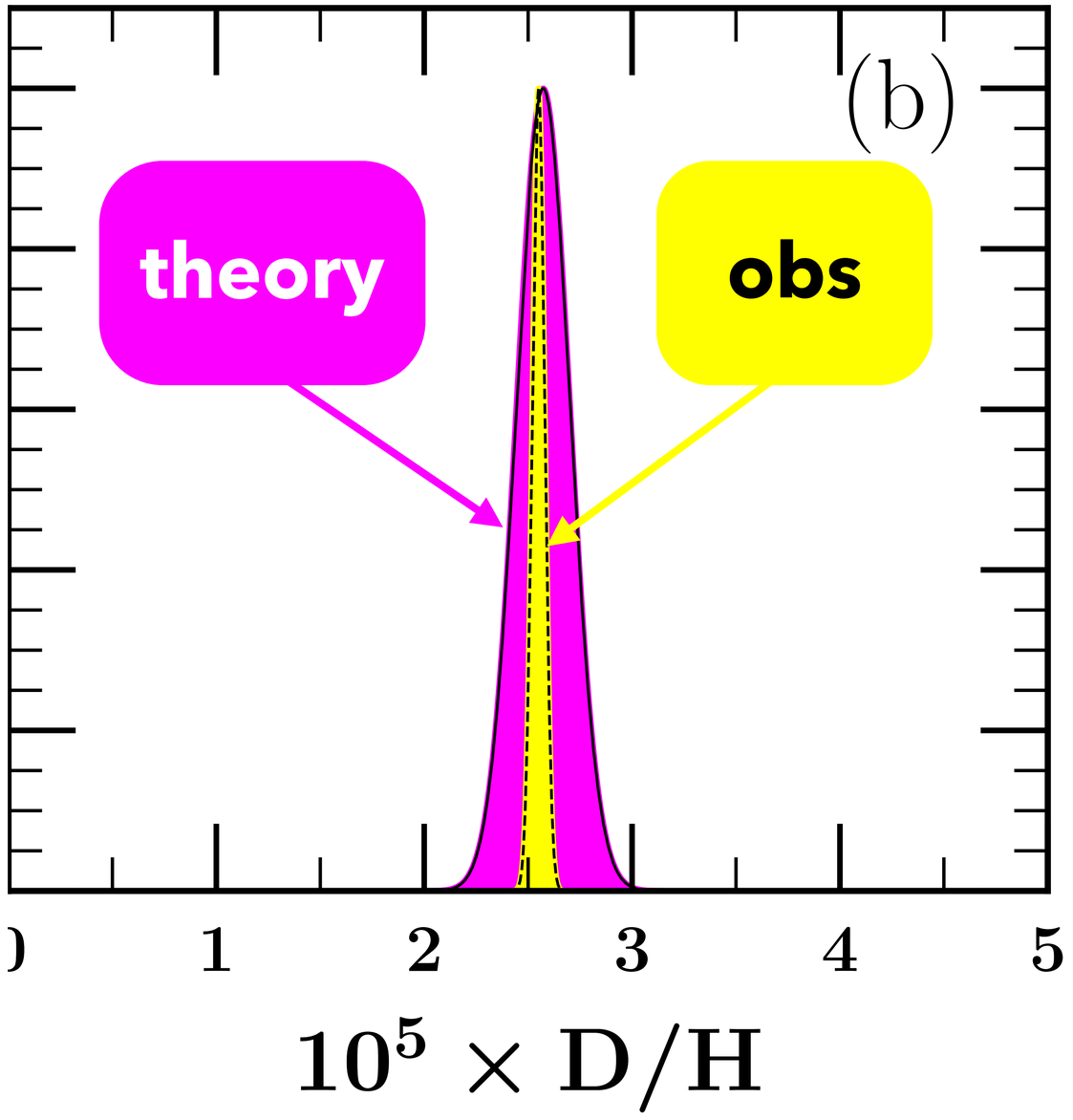

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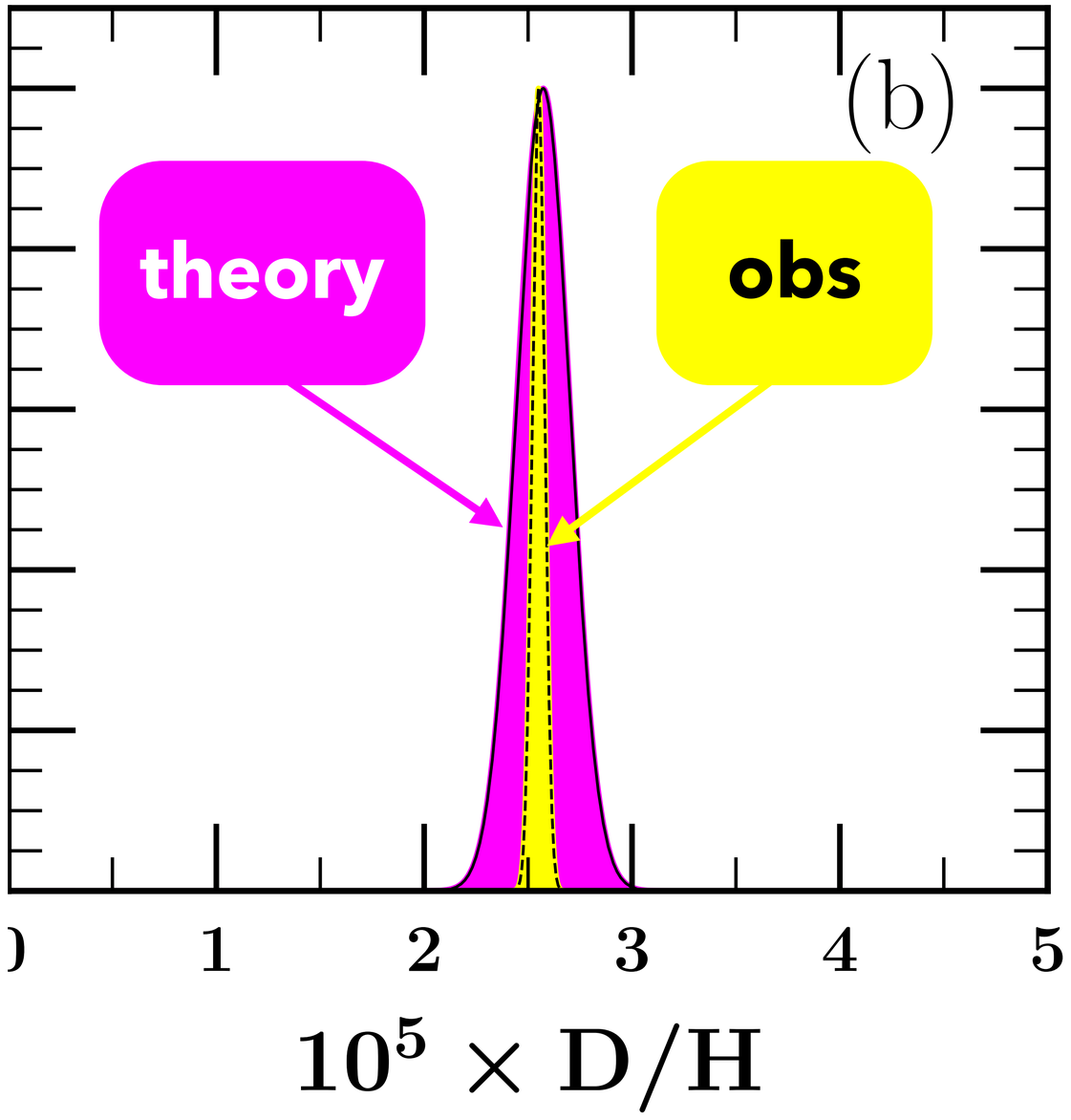

Nuclear Crisis for Deuterium

- Astro obs err < BBN+CMB theory!
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- Most Wanted circa 2020:

$$d(p,\gamma)^3\mathrm{He}$$

$$d(d,n)^3\mathrm{He}$$

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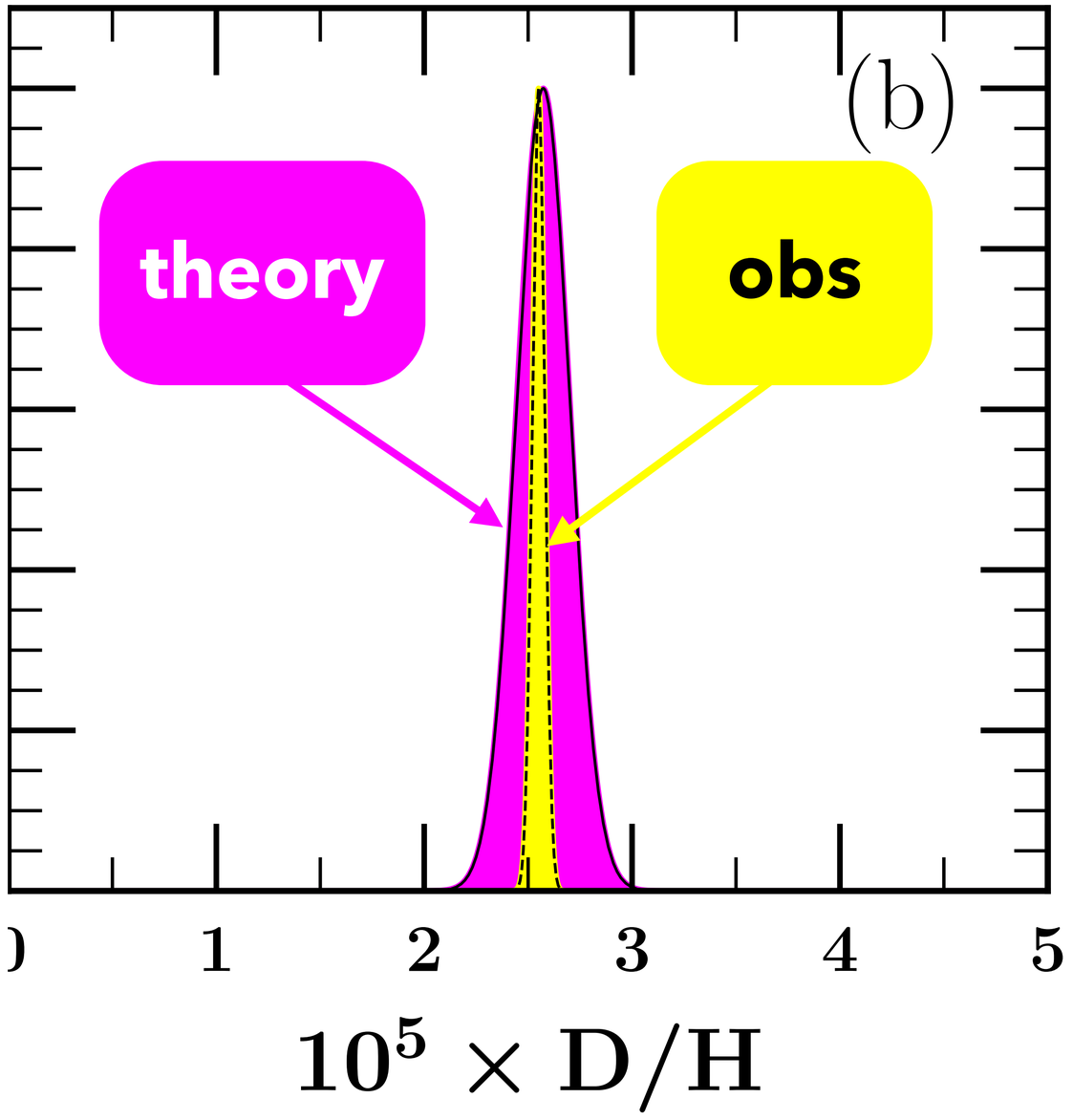

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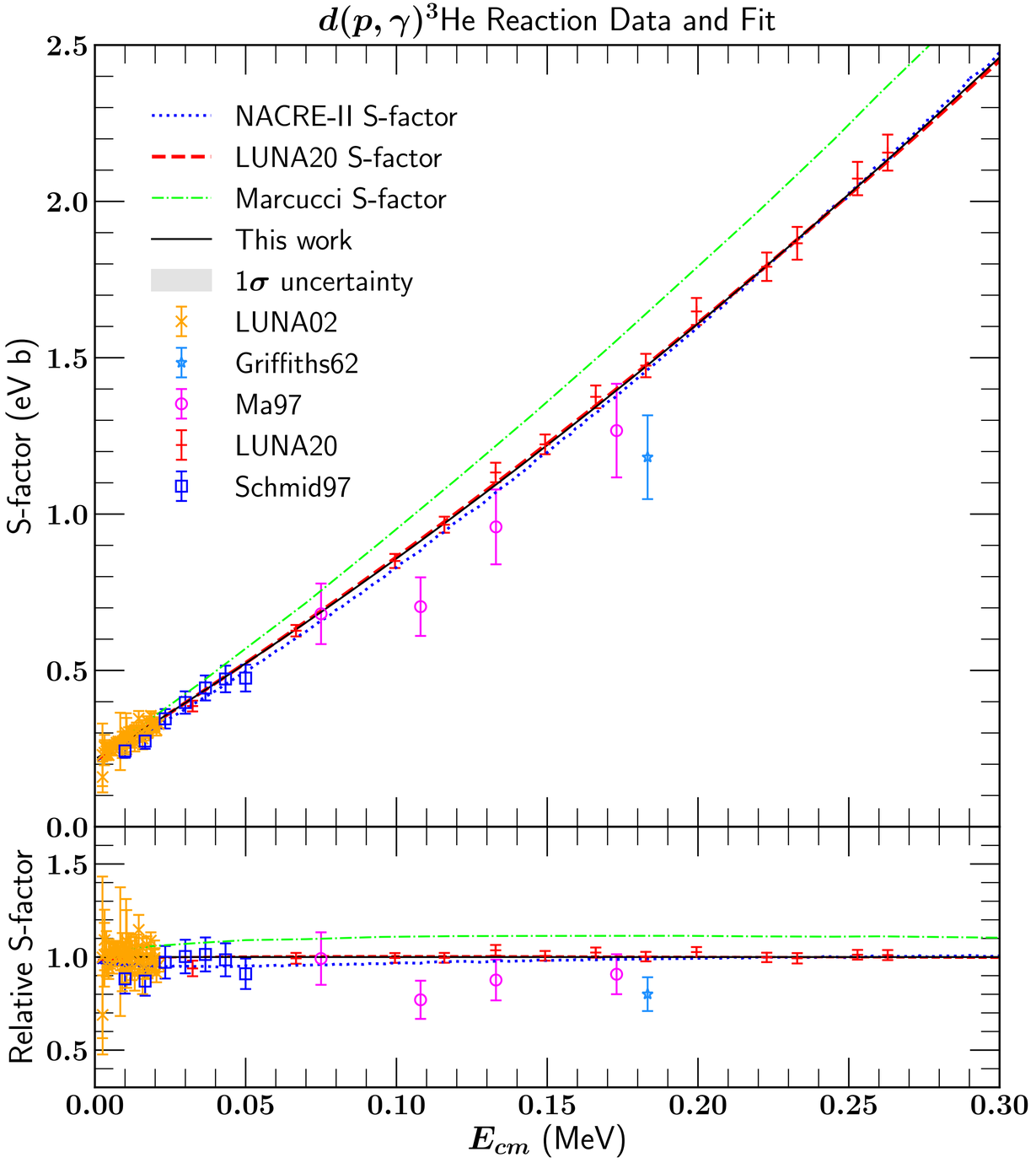

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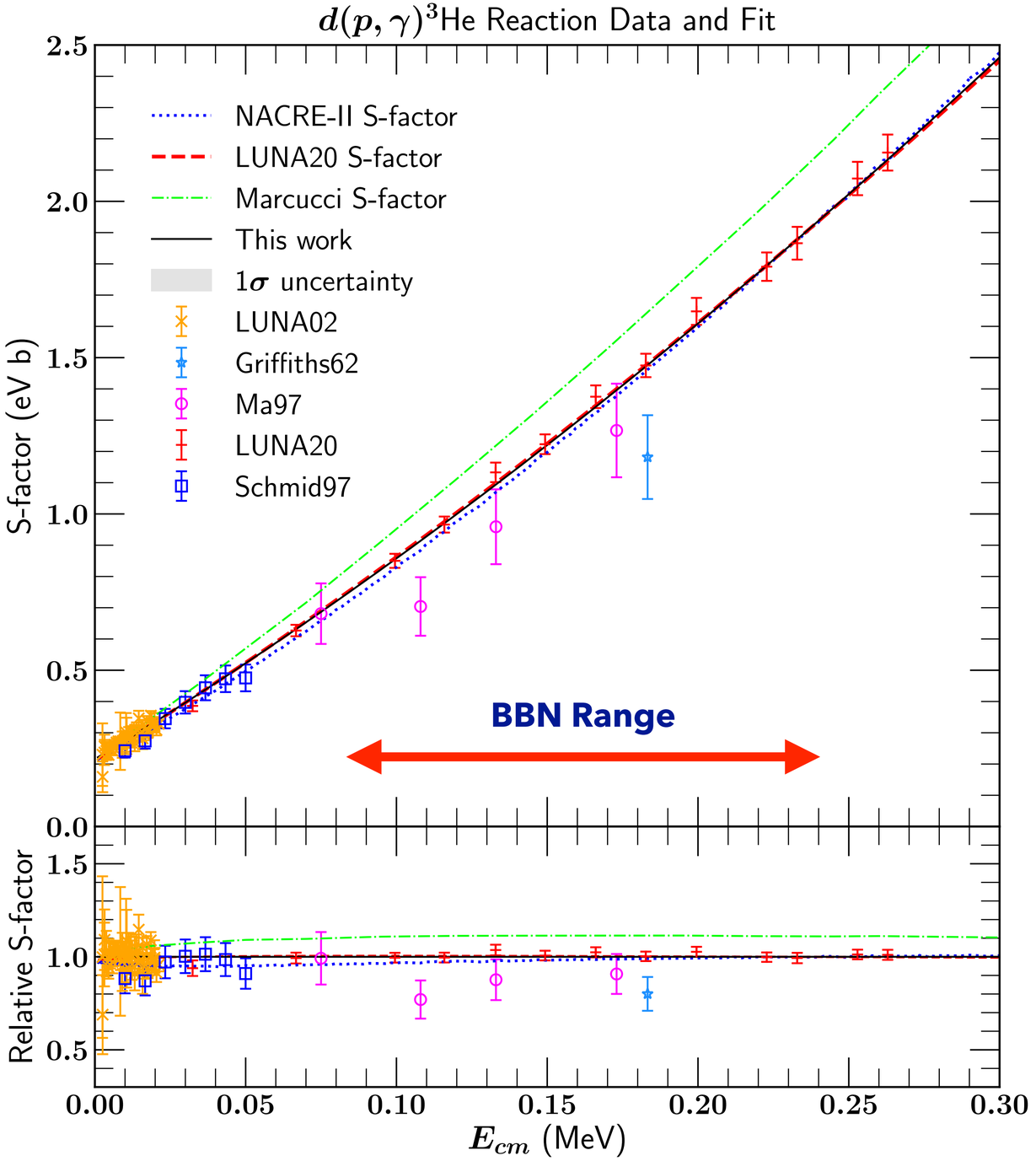

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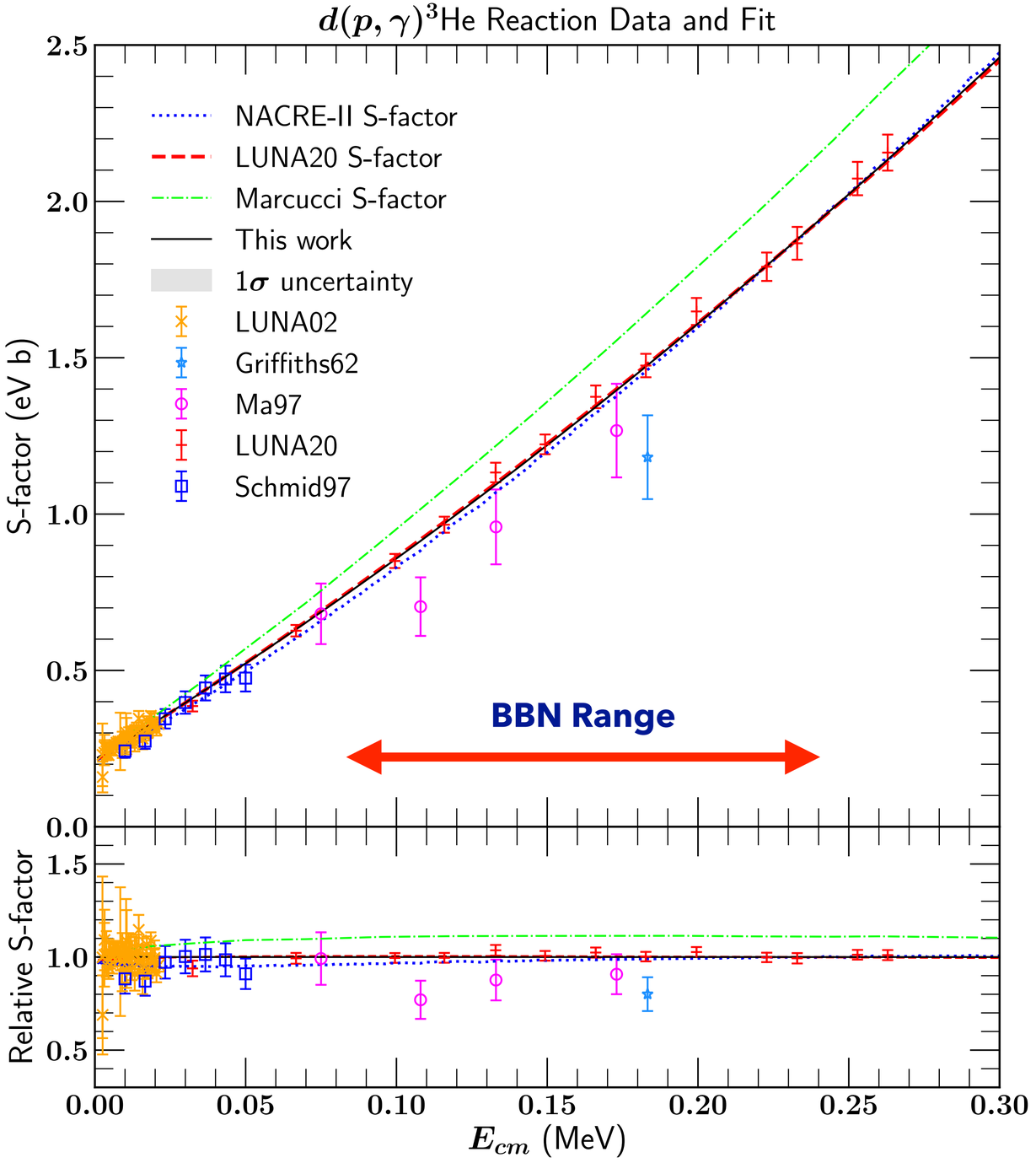

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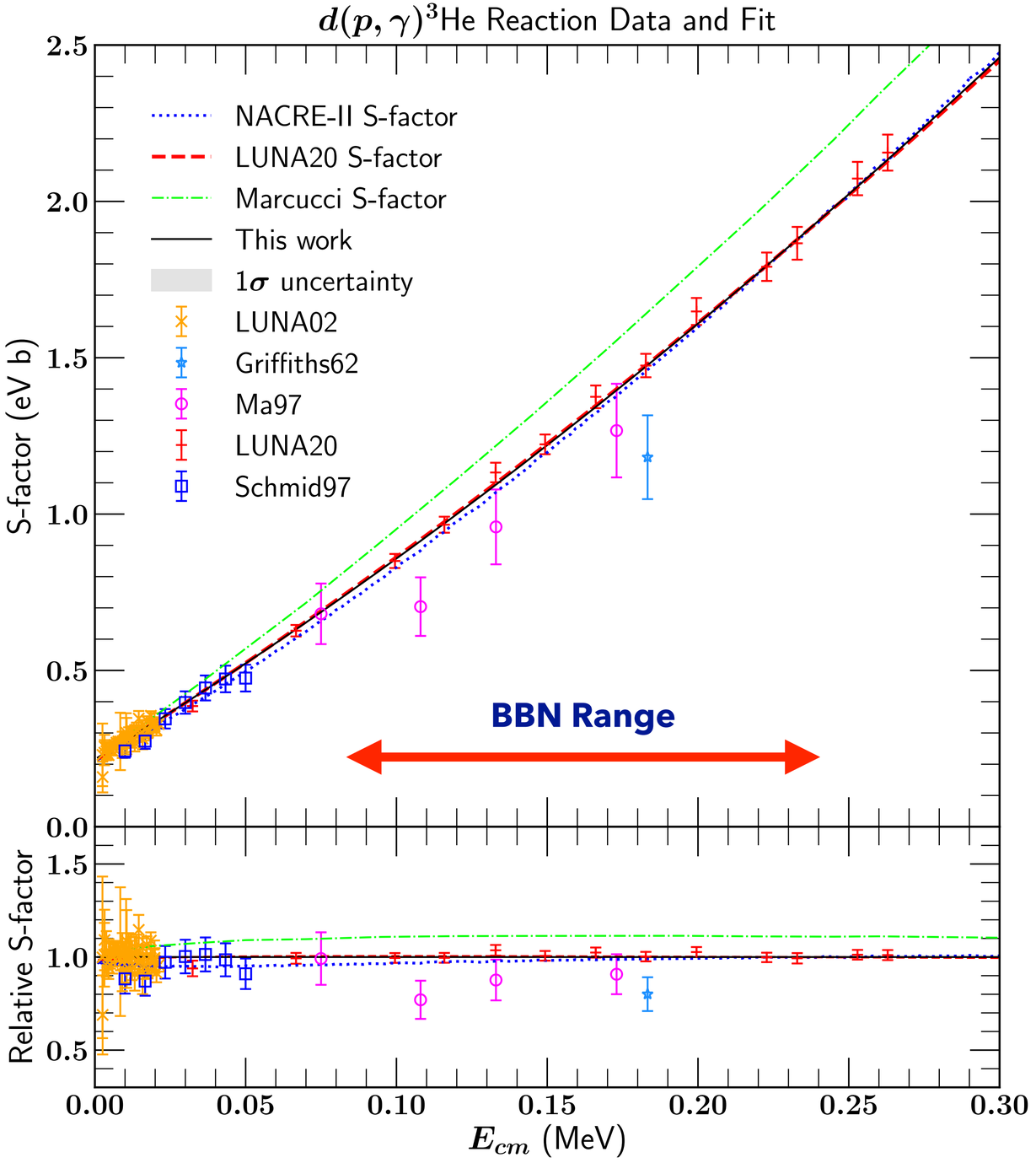

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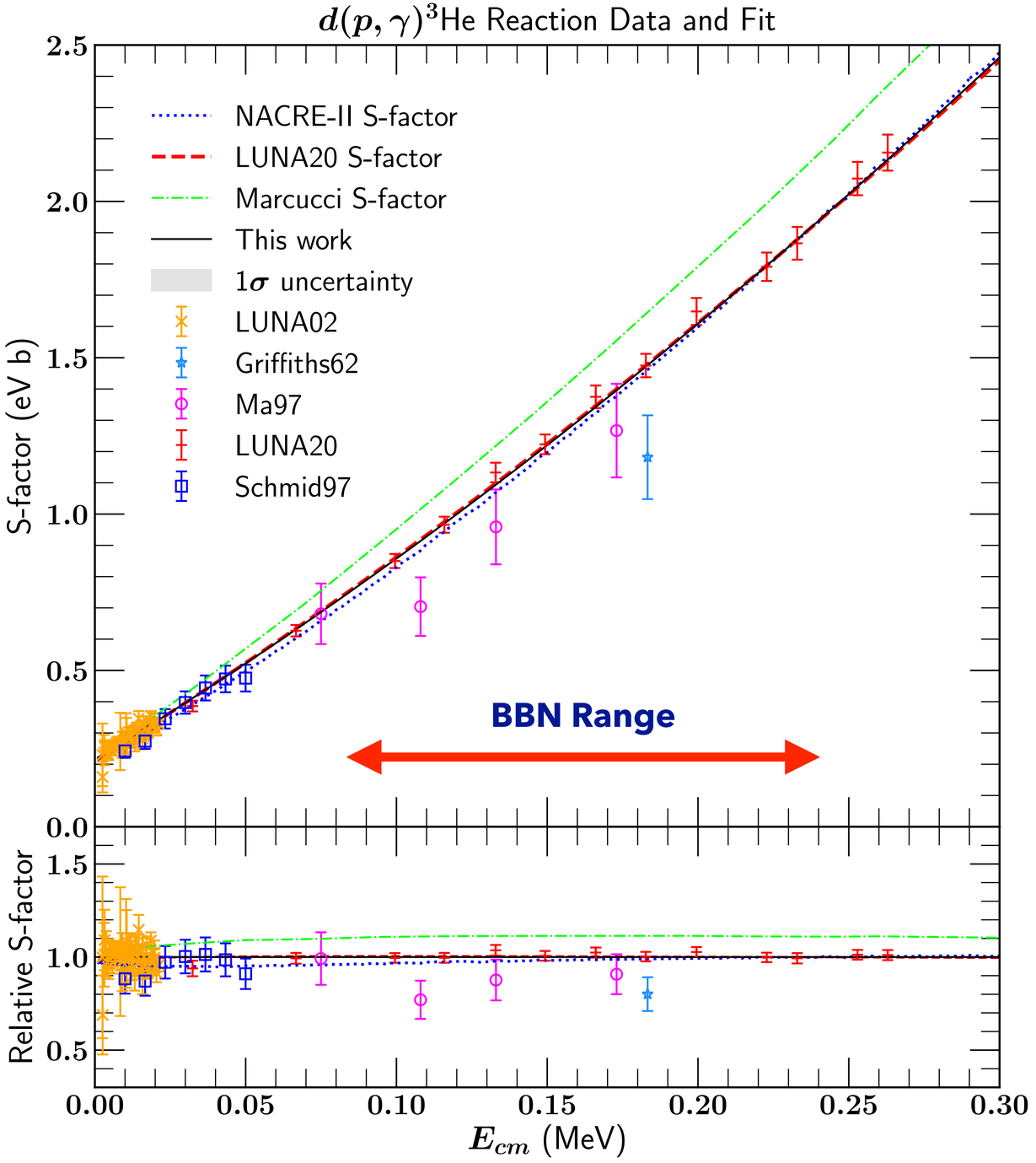

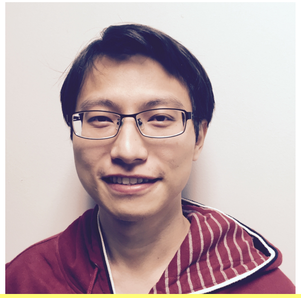

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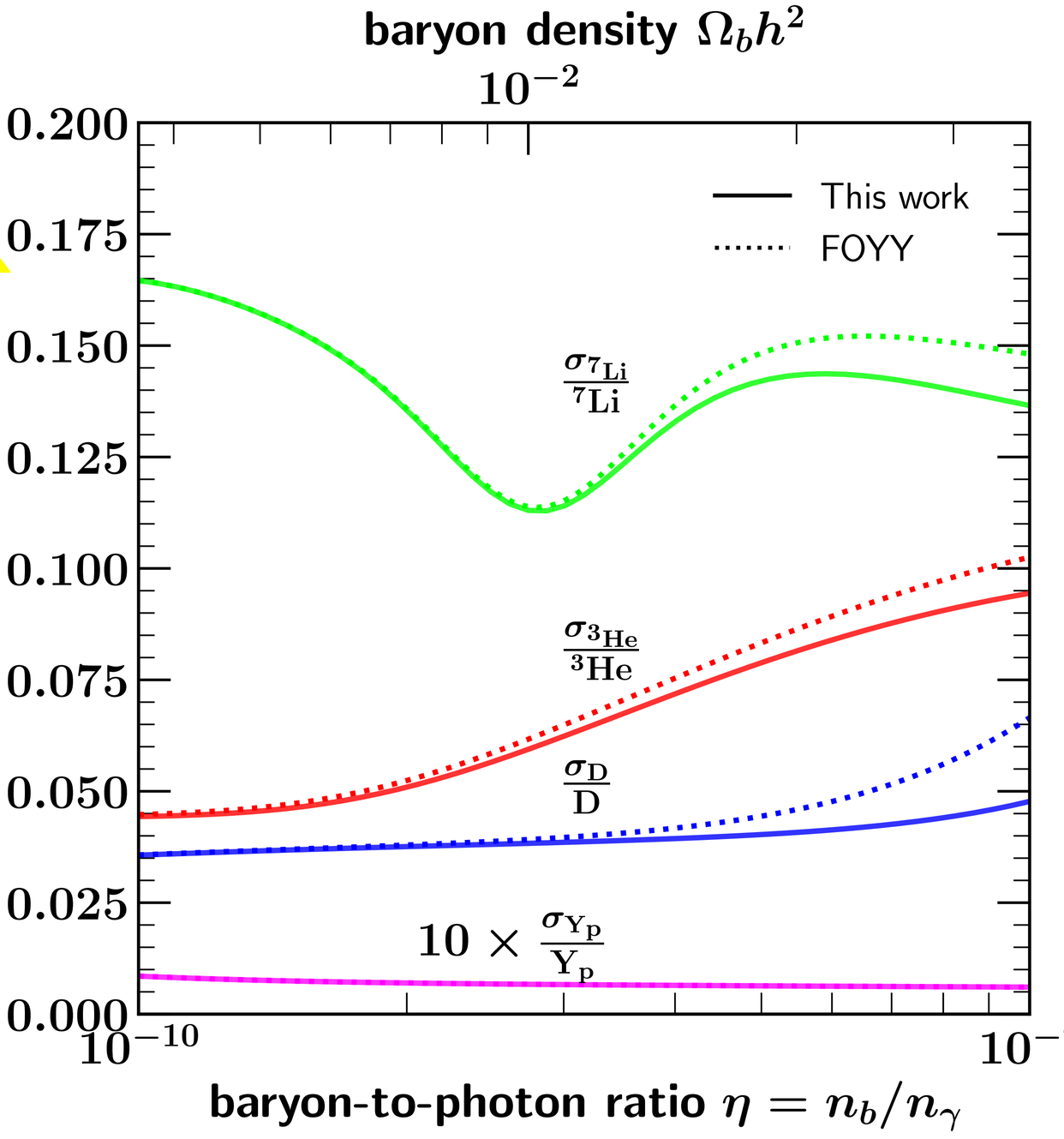
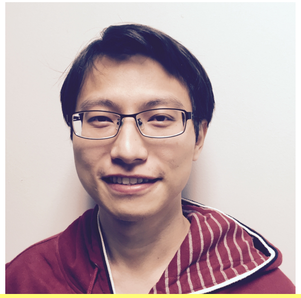
LUNA Impact on BBN Precision

Yeh, BDF, and Olive 2021

BBN Fractional Error





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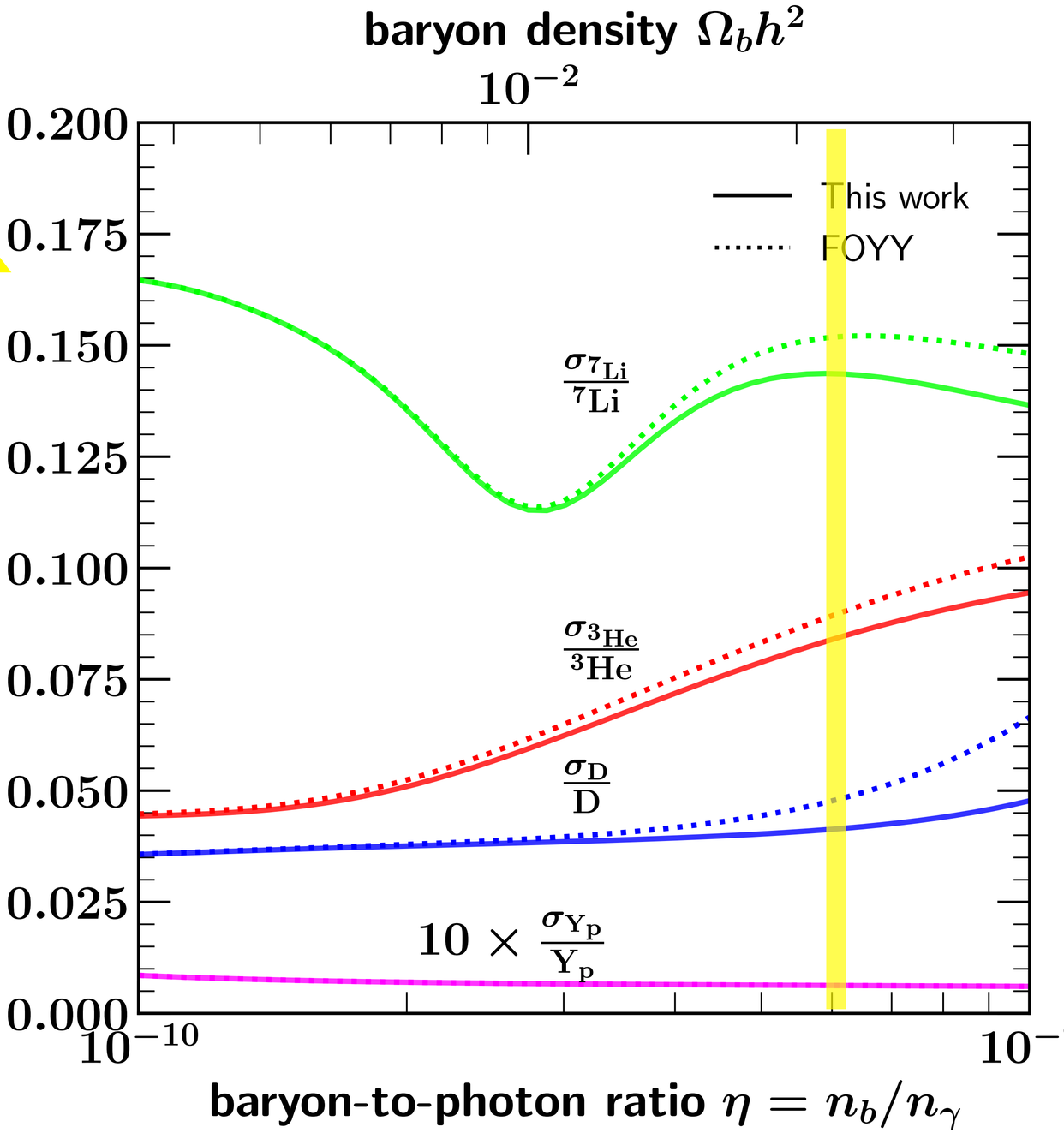

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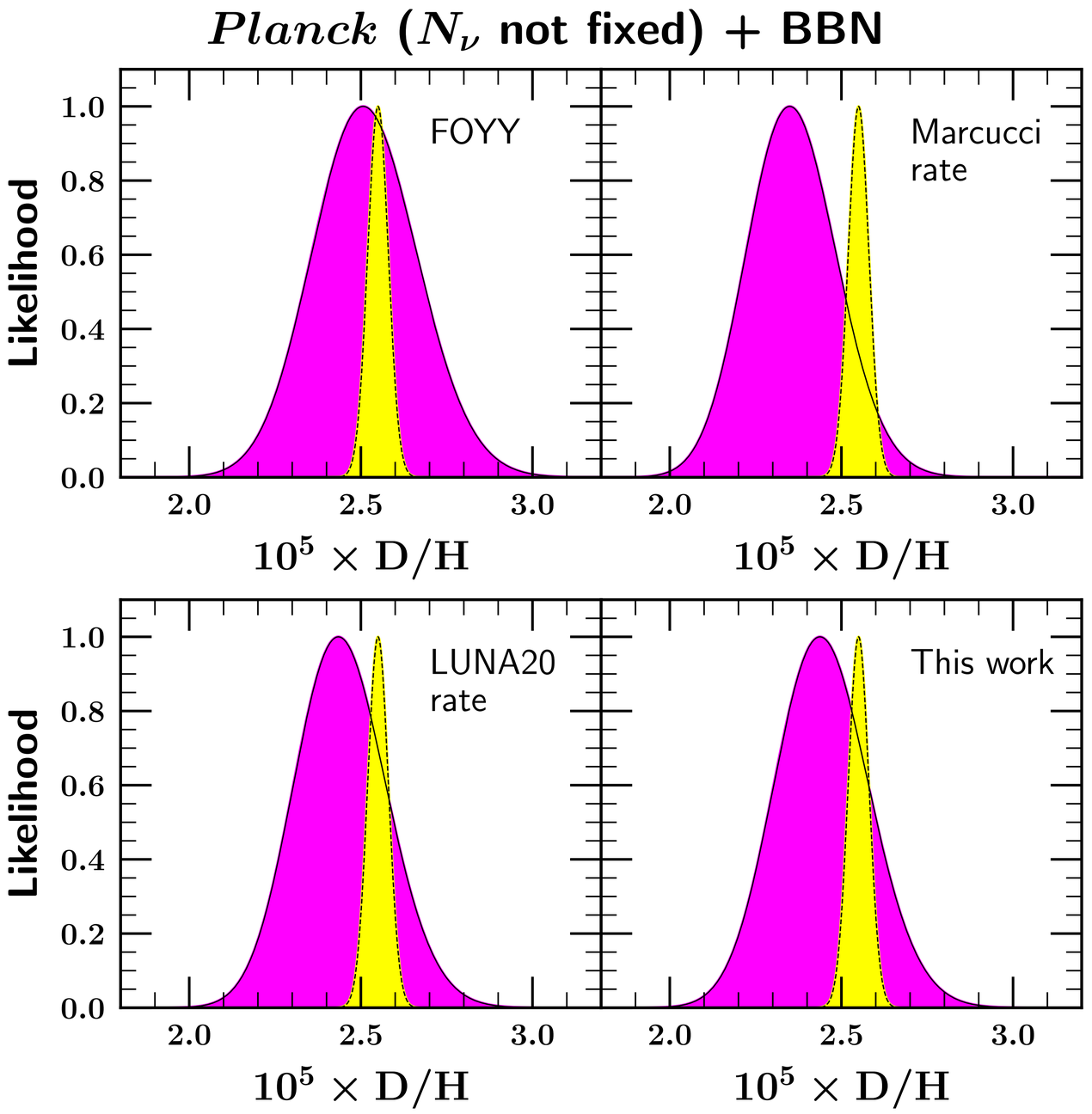

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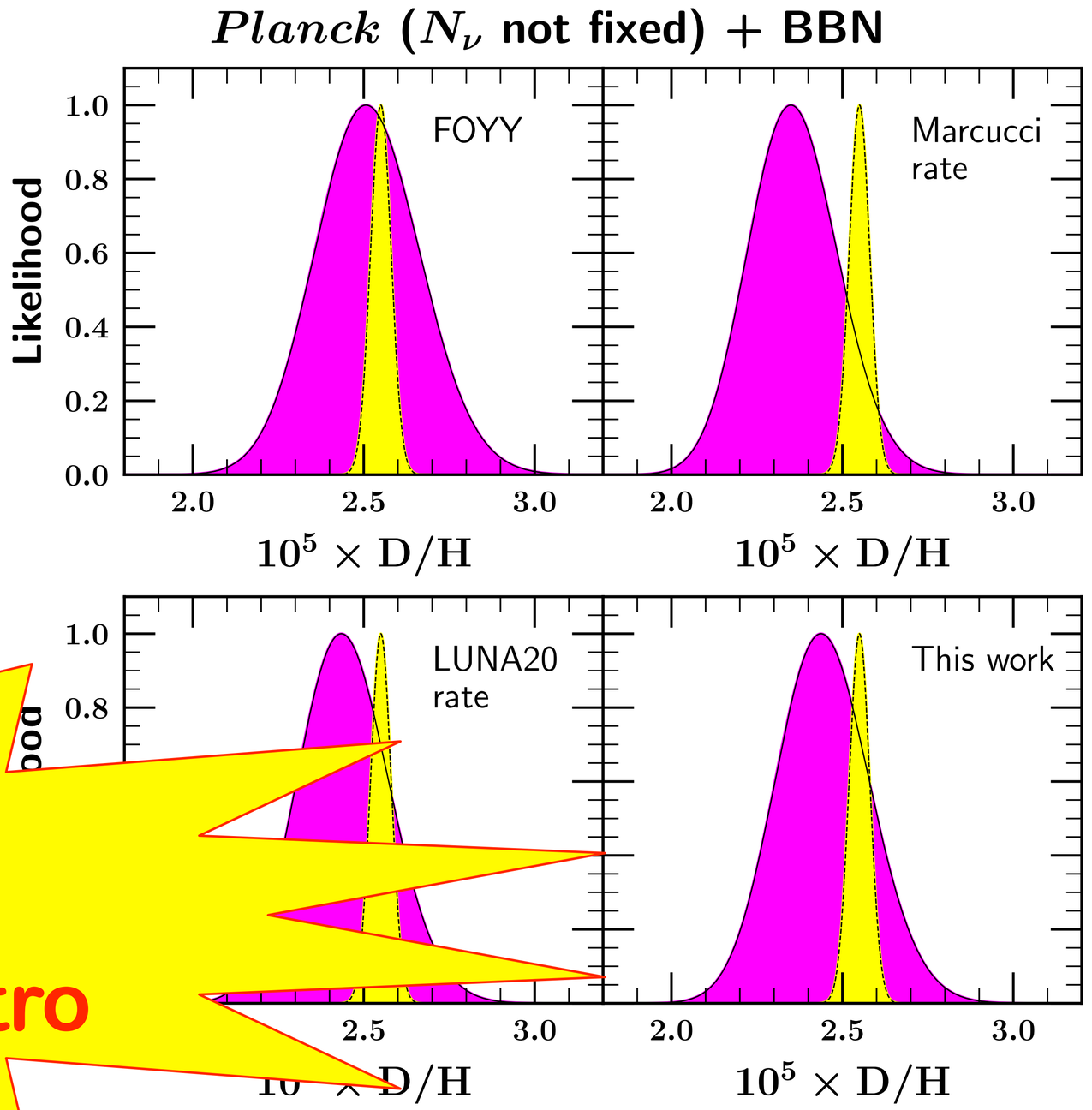

Excellent Agreement Remains!

…but nuke still trails astro

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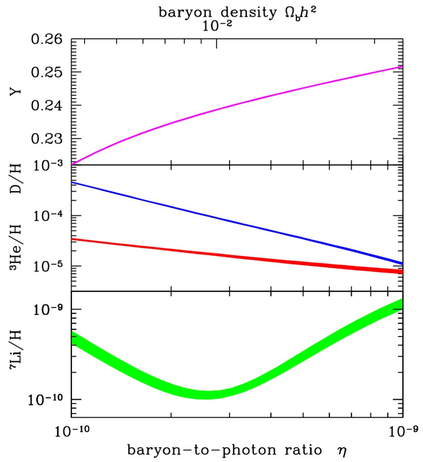

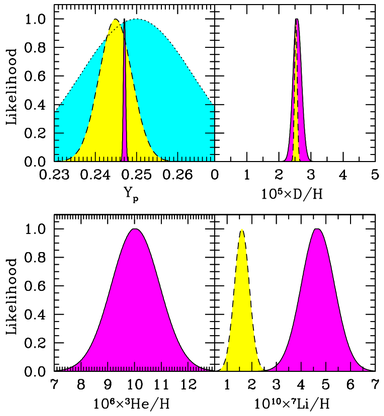

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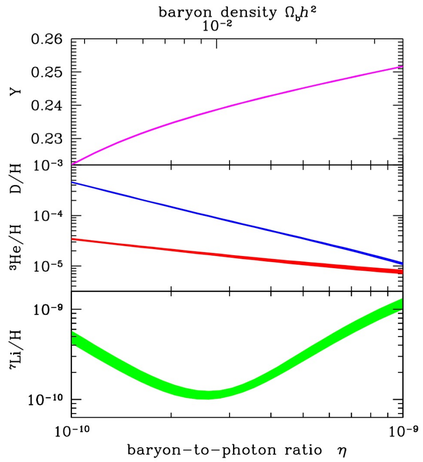

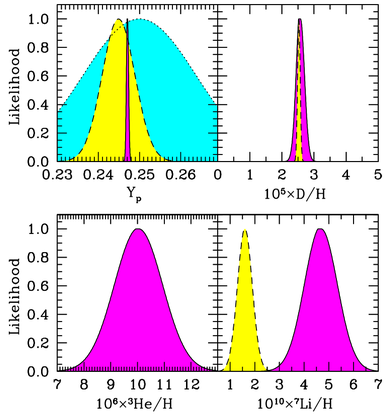

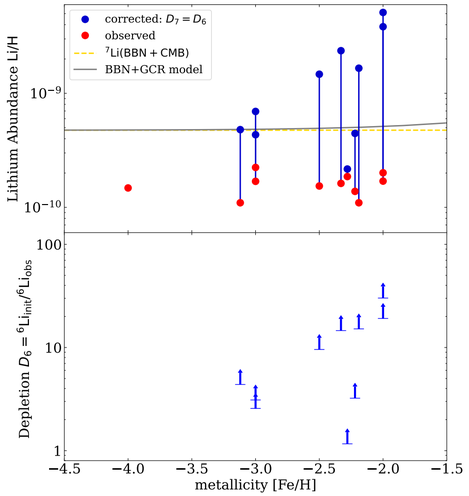

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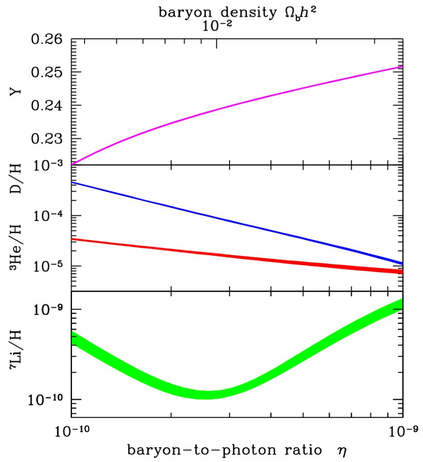

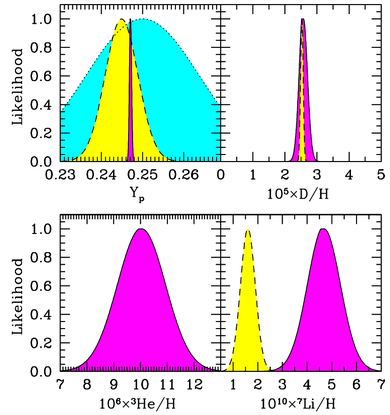

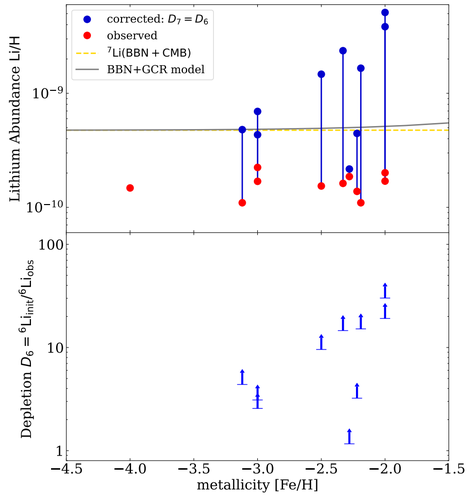

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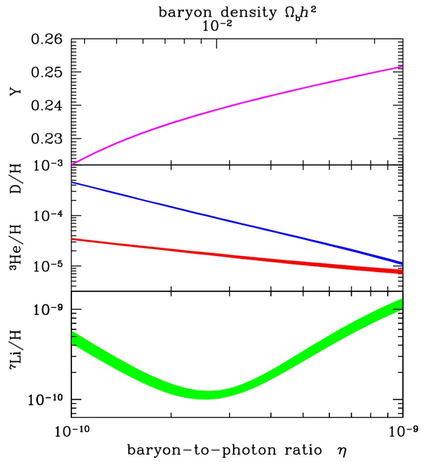

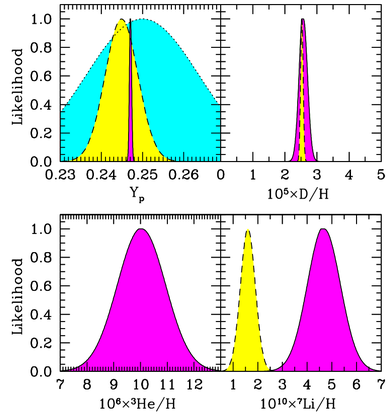

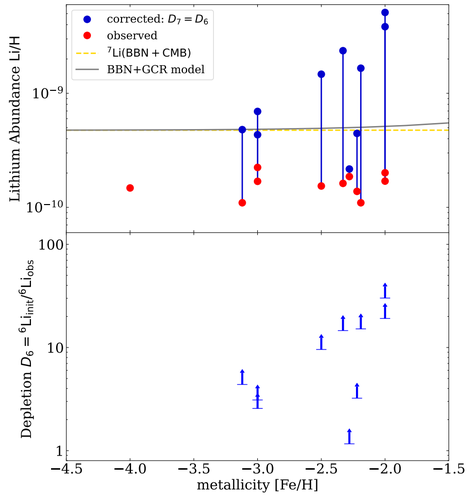

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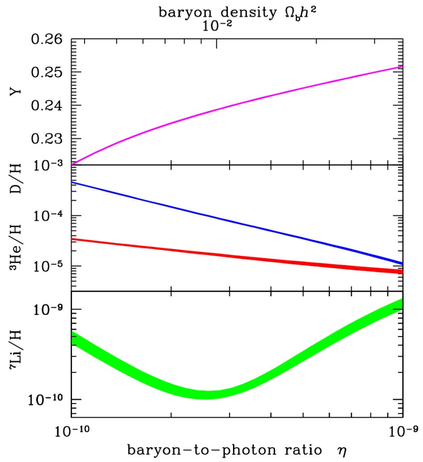

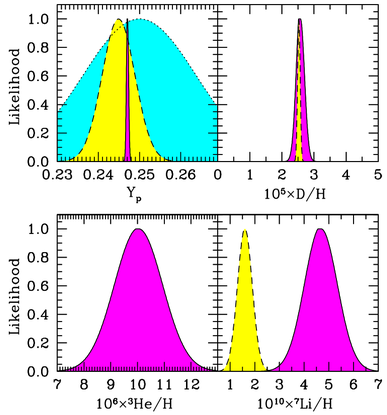

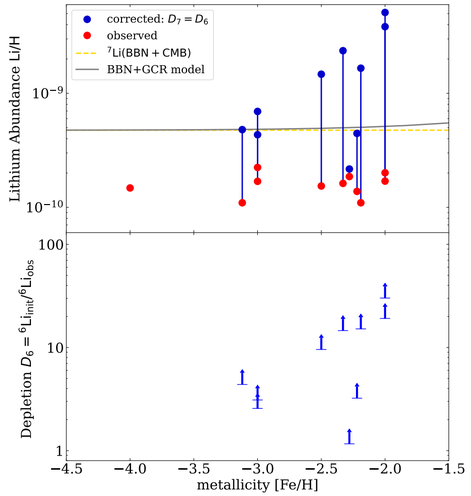

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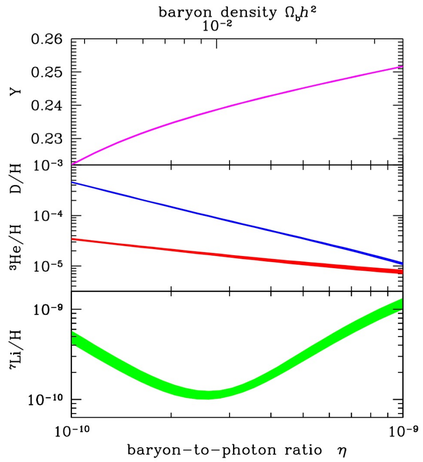

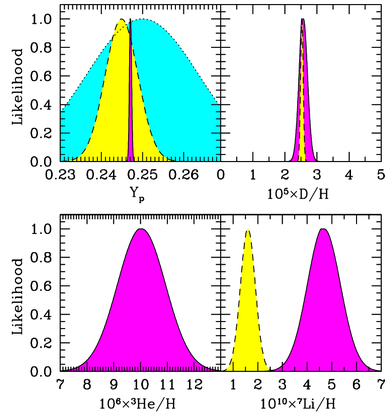

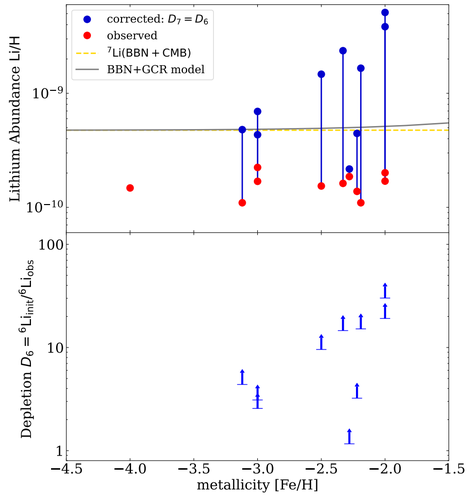

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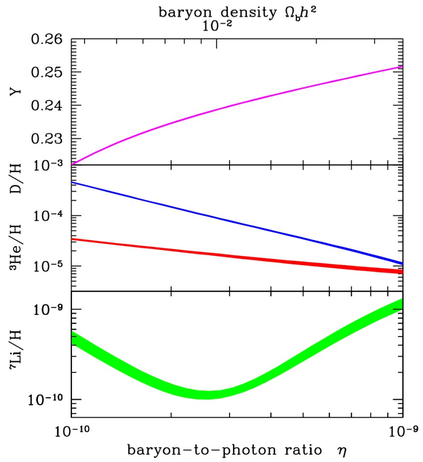

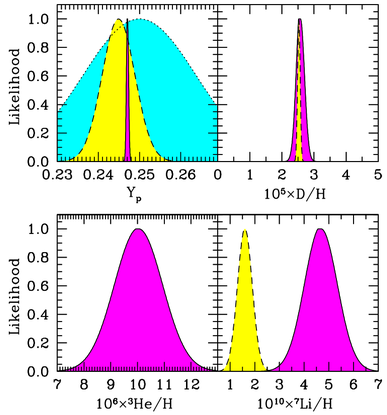

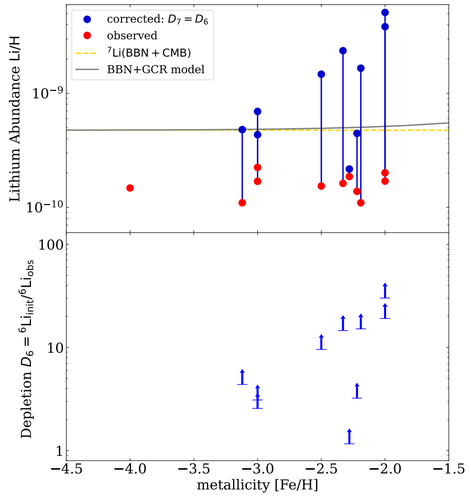

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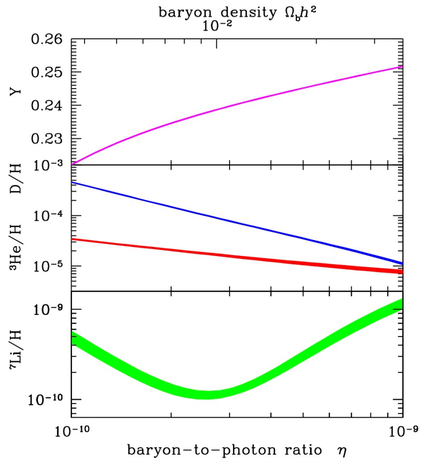

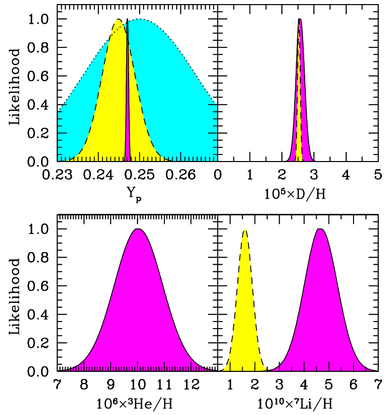

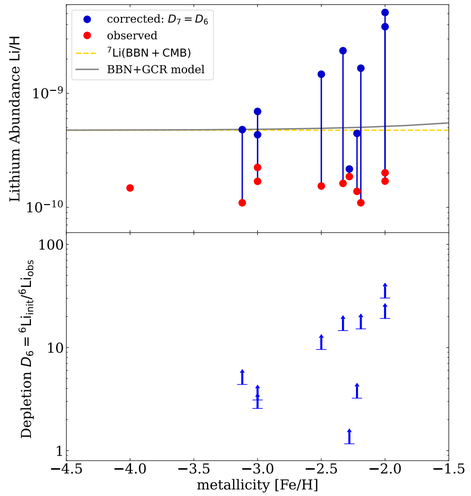

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Convergence of Nuclear/Particle Physics and Cosmology

- successes of both point to larger, deeper picture
- theory & experiment tightly linked: e.g., $d(p,\gamma)^3\mathrm{He}$

Lithium Problem Resolved?

- nuclear physics solutions ruled out
- new physics solutions highly constrained
- stellar depletion supported by ^{6}Li non-detections

BBN & CMB: Probes of Fundamental Physics

- basic concordance: big bang working to t~1 sec
- BBN + CMB probe dark matter, neutrinos, new physics…

The Future is Bright:

- Need precision cross sections for $d(d,n)^3\mathrm{He}$ $d(d,p)^3\mathrm{H}$
- Even better CMB measurements (S4)
- Stellar models for Li depletion & interplay with cosmic-ray nuke
- New light element measures: stellar, interstellar, extragalactic ^{6,7}Li
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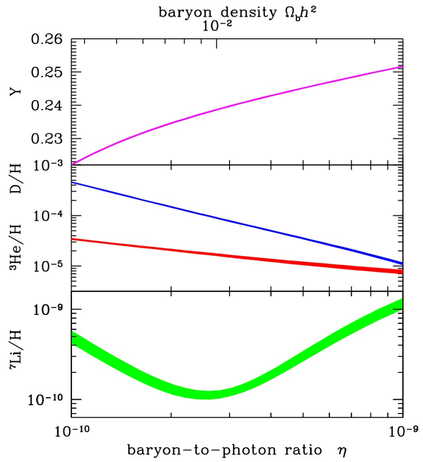

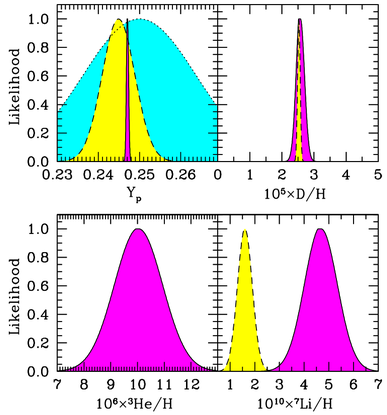

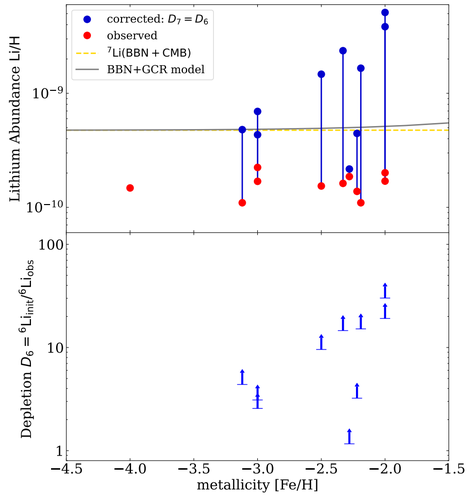

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OUTLOOK

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Stay Tuned!