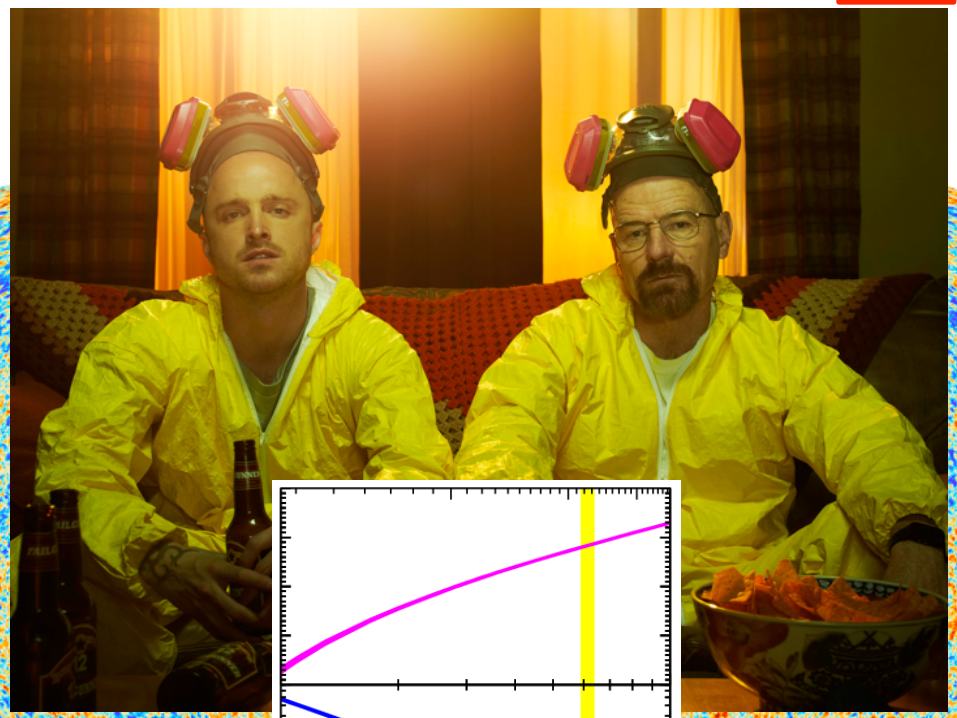
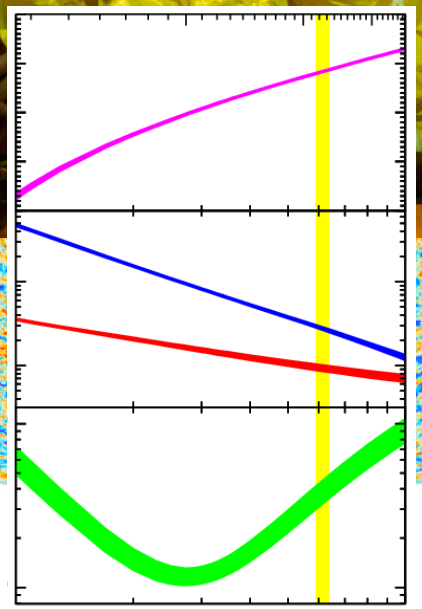
A Bitter Pill:

The Primordial Lithium Problem





Brian Fields

ESO Cosmic Duologue | 26 Jan 2021

ILLINOIS

Big Bang Nucleosynthesis:
A Symphony of Fundamental Forces

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

Standard BBN

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

Homogeneous U.

➢ Expansion adiabatic

$$\left(\frac{n_{\rm B}}{n_\gamma}\right)_{\rm BBN} = \qquad \text{oday}$$

Non-Standard BBN models
relax these assumptions
test new physics

- gives baryon density

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

Making Primordial Lithium in Standard BBN

- SBBN Lithium = ^{7}Li. ^{6}Li negligible
- ^{7}Li mostly made as ^{7}Be

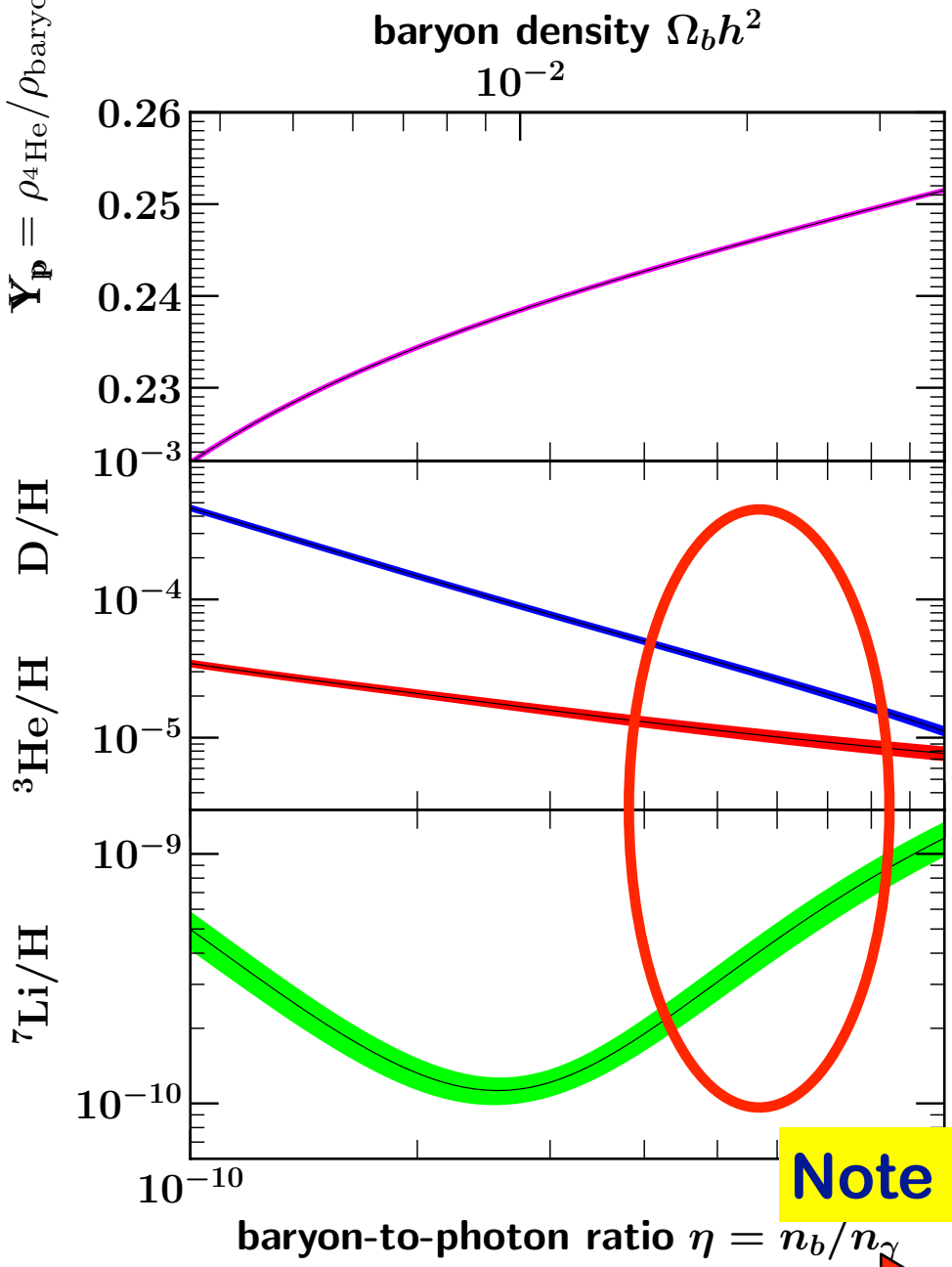
  much later $^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

- Production: $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
- Destruction:

$$^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$$

$$^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

neutrons are Li poison!



abundances

baryon density

Stanard BBN Predictions

Pitrou talk

Curve Widths: Theoretical uncertainty nuclear cross sections

BDF, Olive, Yeh, Young 2020
Pitrou+ 2018
Cyburt, BDF, Olive, Yeh 2015
Descouvement poster
Cyburt, BDF, Olive 2008
Cyburt 2004
Coq et al 2004
Serpico et al 2005
Cyburt, BDF, Olive 2001
[illegible]
Hata et al 1995
Copi, Schramm, Turner 1995

Note D-Li anti correlation

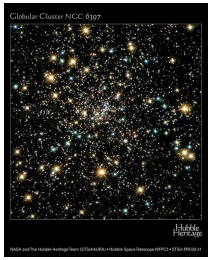
Light Elements: Sites

Deuterium

- in z~3 galaxies backlit by quasars
- New! leap in precision: Pettini, Cooke+ 2013-2019

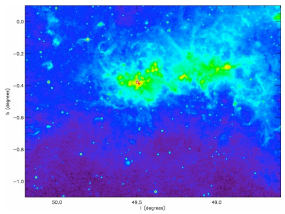
^{4}He

- ionized gas (HII regions) in metal-poor galaxies
- New! CMB damping tail: SPT 2011,2012; Planck 2013-2018



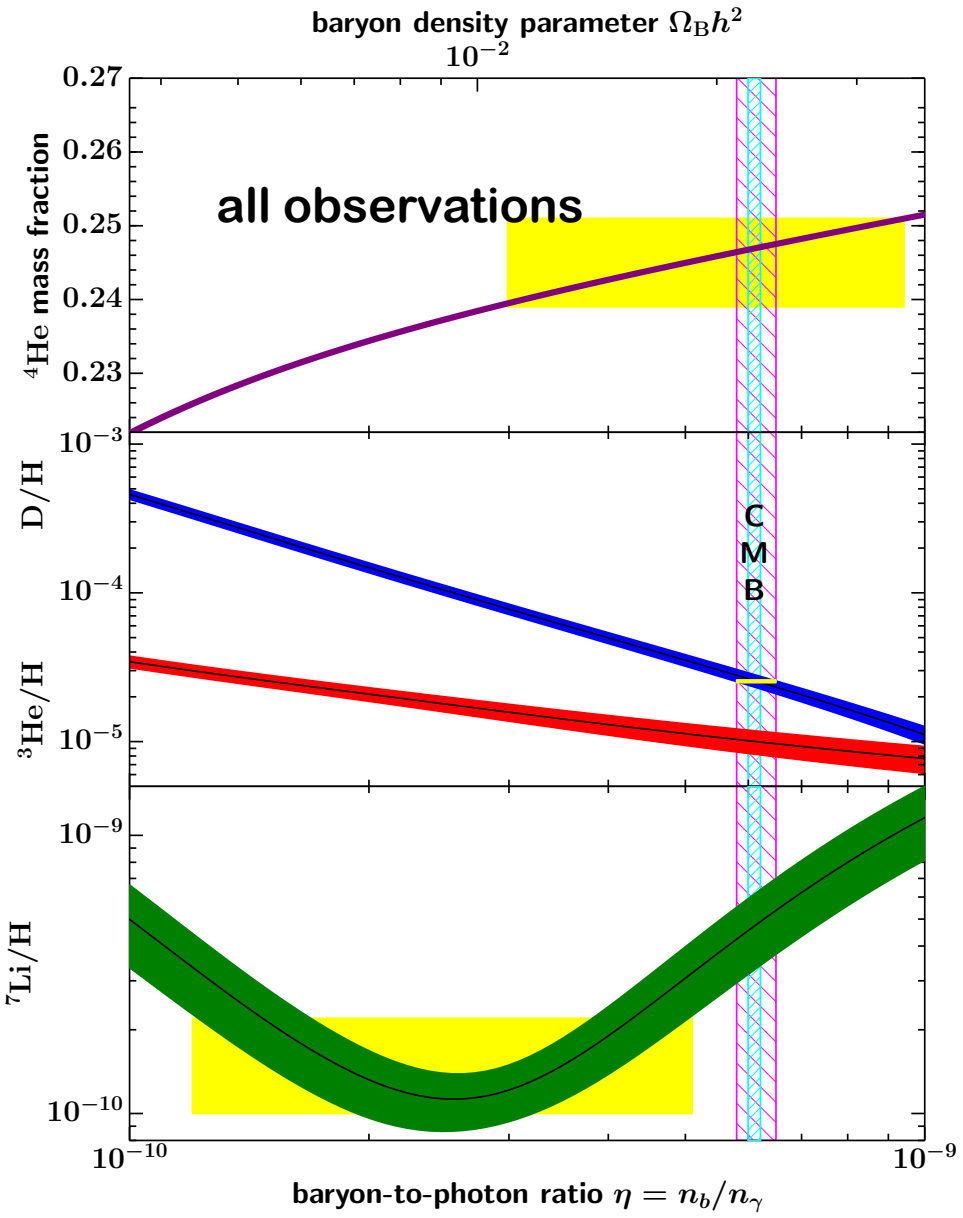
^{7}Li

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



^{3}He

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



Testing BBN: Light Element Observations

Theory:

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

Observations:

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

Comparison:

★each nuclide selects baryon density

★overconstrained--nontrivial test!

Result:

★rough concordance!

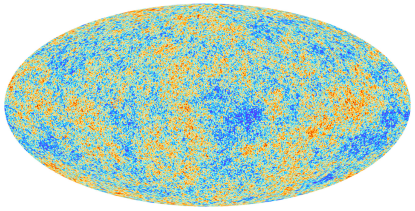
★but not in detail! D and ^{7}Li disagree

need a tiebreaker

Battle of the Baryons: II

CMB New World Order

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

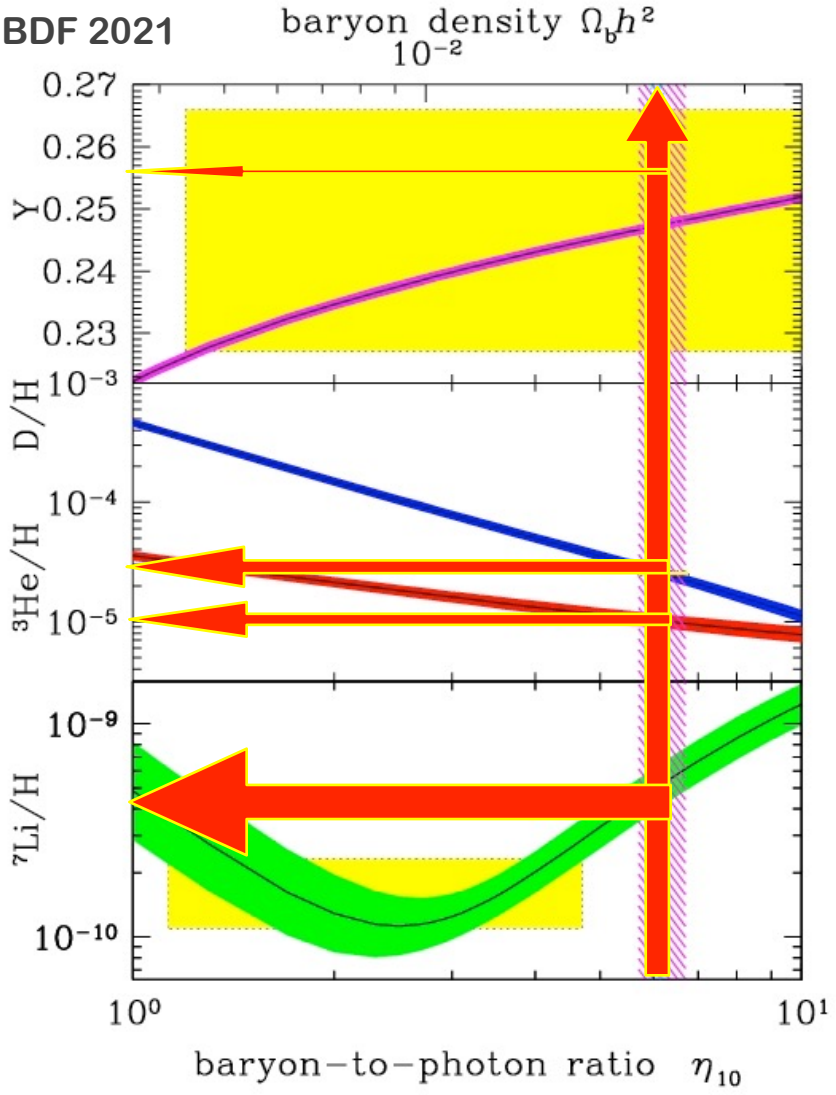


Planck baryon density very precise

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

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

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



New strategy to test BBN:

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

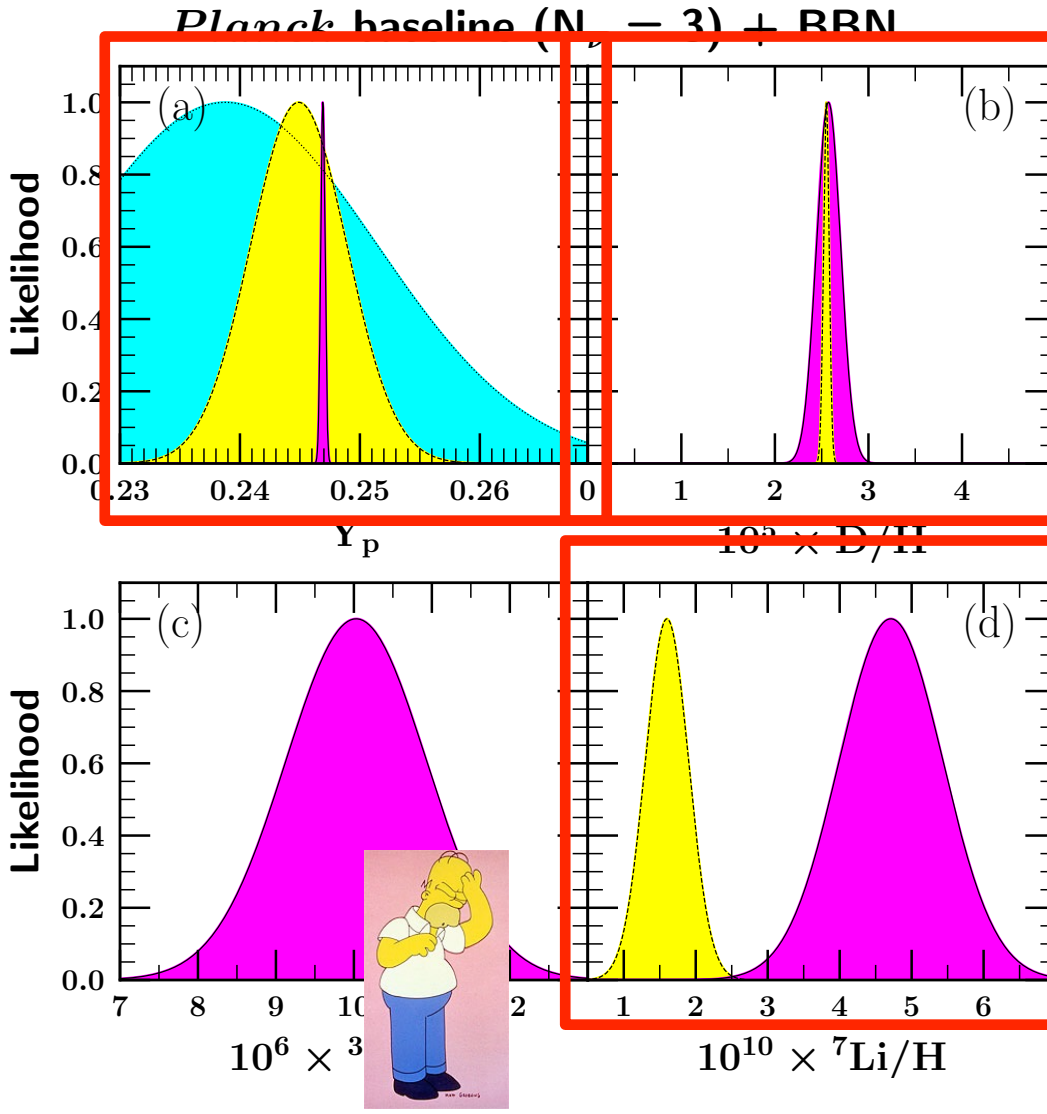
Battle of the Baryons: II
A Closer Look

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

Likelihoods

purple: BBN+CMB predictions

yellow: observations



Results:

- D excellent!
- ^{4}He great!
- ^{7}Li poor!
  - observation ~ theory/4
  - 4-5 sigma discrepancy
  - Lithium Problem

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

BBN Beyond the Standard Model:
Probing Particle Physics

Lite elements probe cosmic expansion history

Radiation domination

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

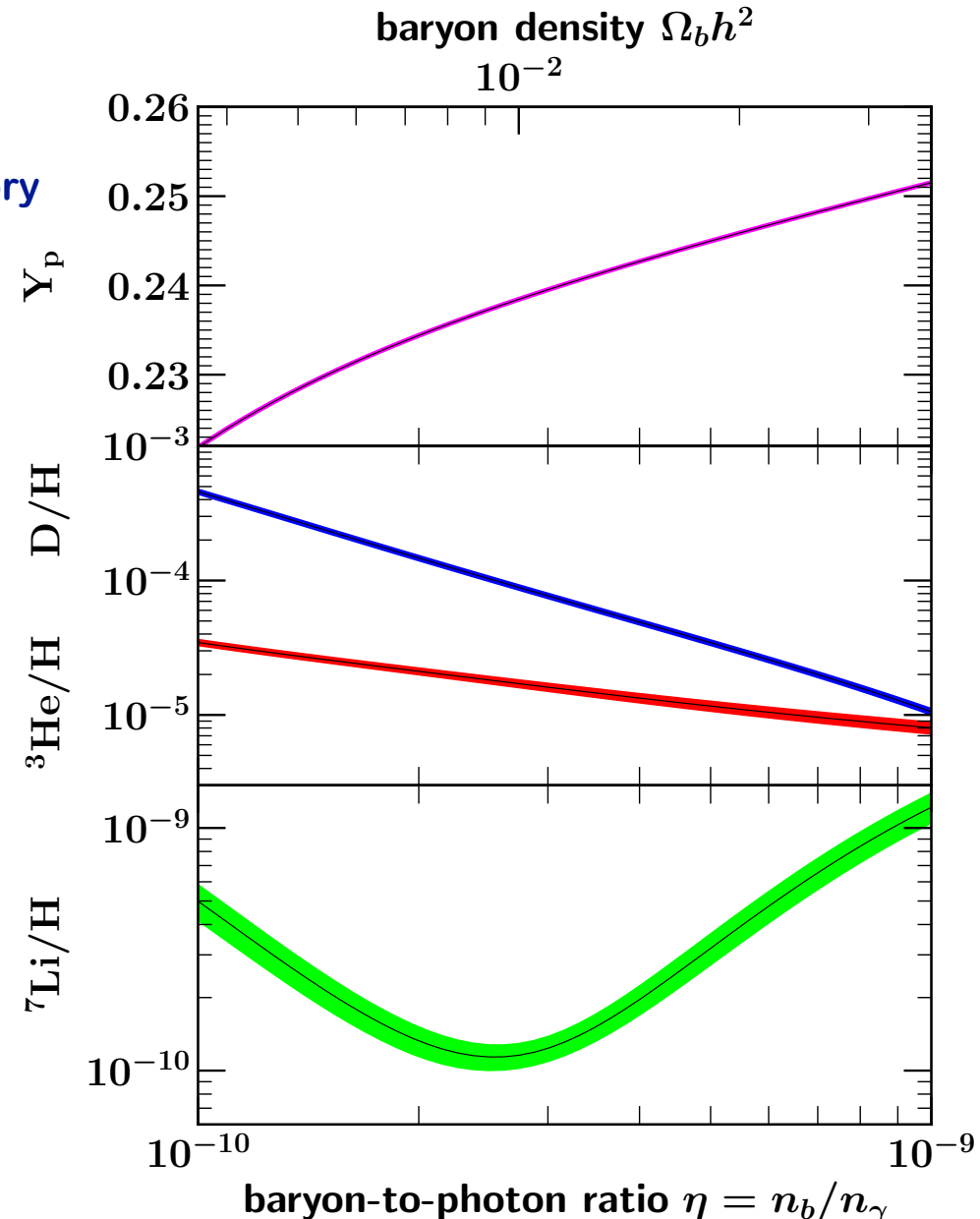
Controlled by

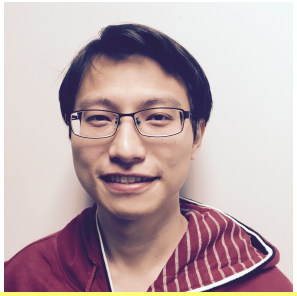
$$\rho_{\text{tot,rel}} = \rho_{\text{EM}} + N_{\nu,\text{eff}}\ \rho_{\nu\bar{\nu}}$$

Observed abundances constrain anything that

- ✓ Couples to gravity
- ✓ Perturbs relativistic energy density

Stiegman, Schramm, & Gunn 77

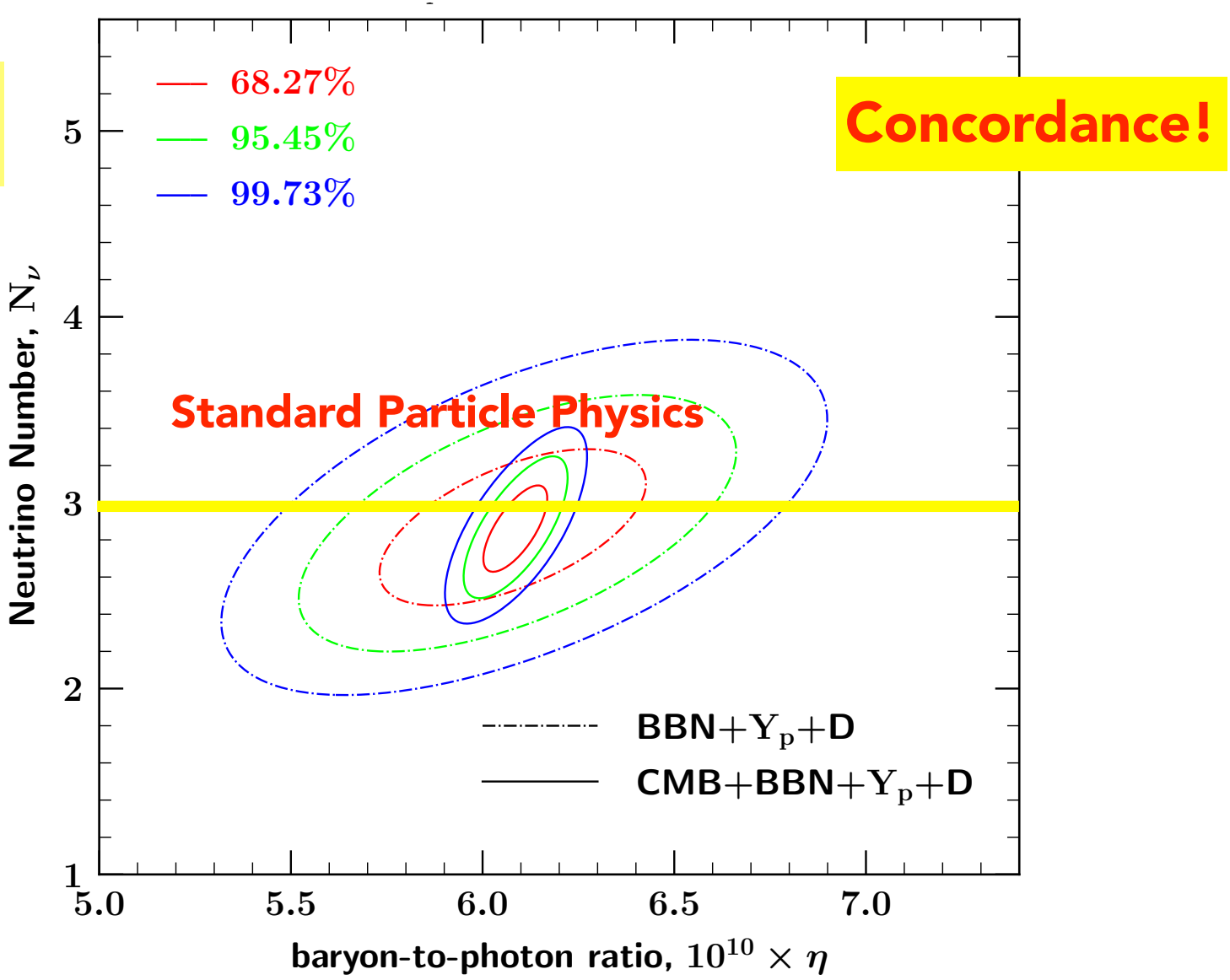




Tsung-Han Yeh
葉宗翰

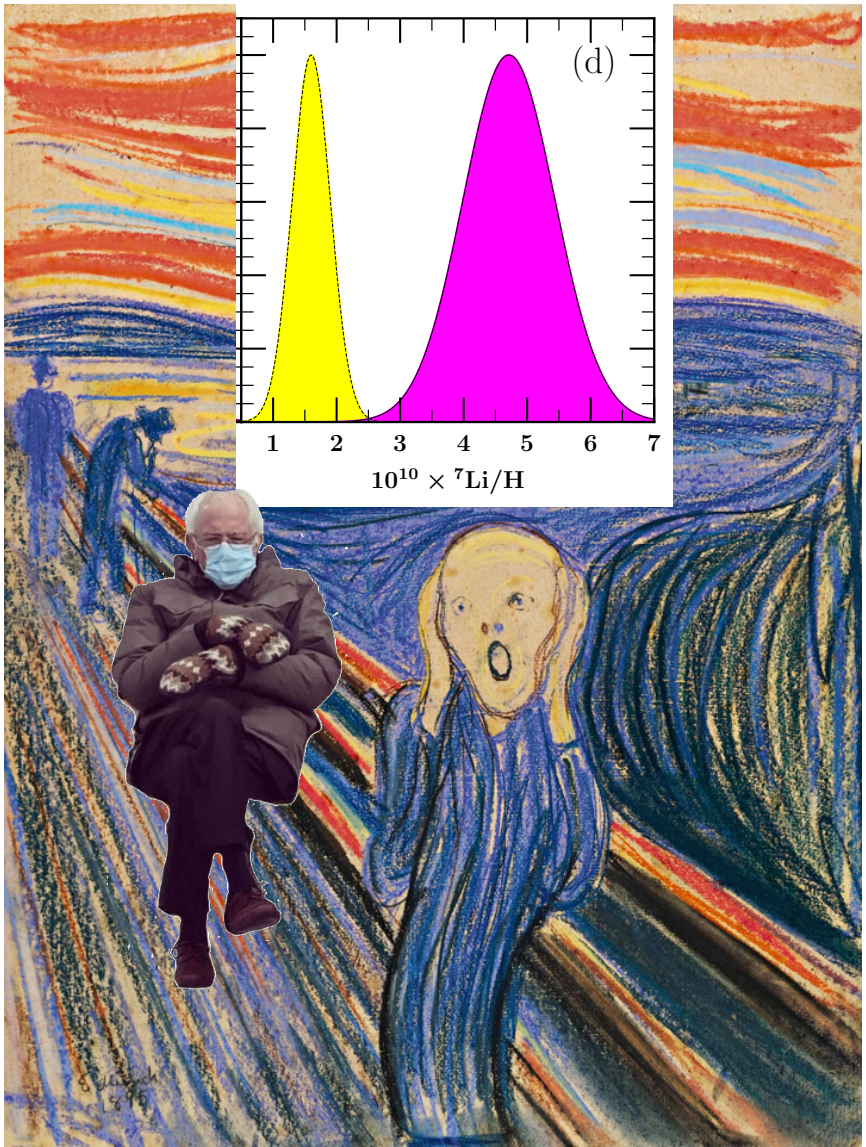
Planck 2018 + BBN

BDF, Olive, Yeh, Young 2020



Lithium Strategy II:

Worry



Primordial Lithium

Observe in primitive stars (Pop II)

Li versus Fe ⇨ evolution

Plateau at low Fe — Spite & Spite 82

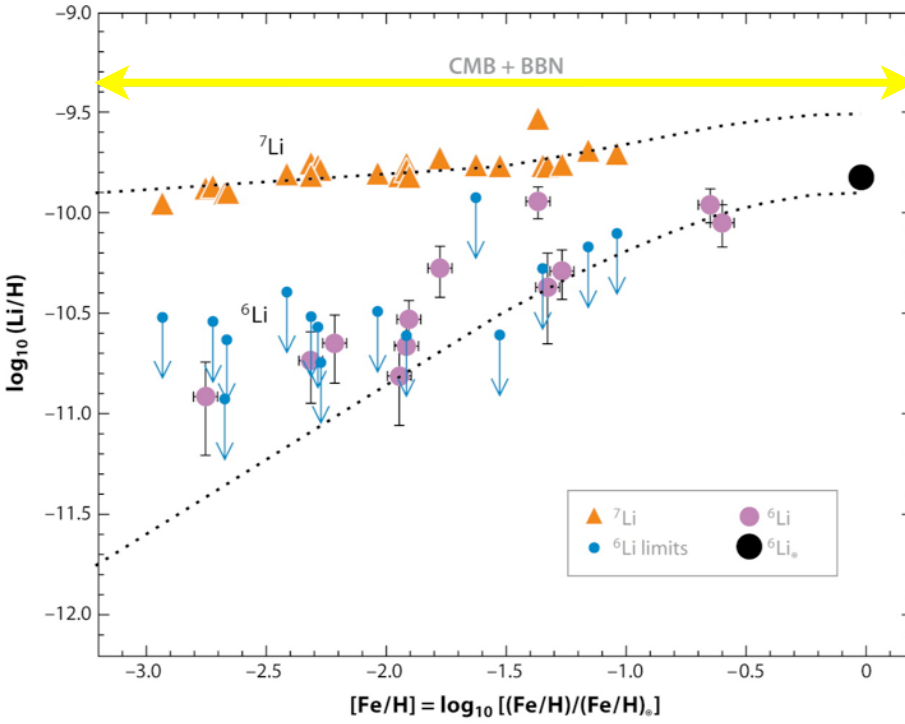
★ Li is primordial

But is the plateau at Li_p?

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

lithium abundances

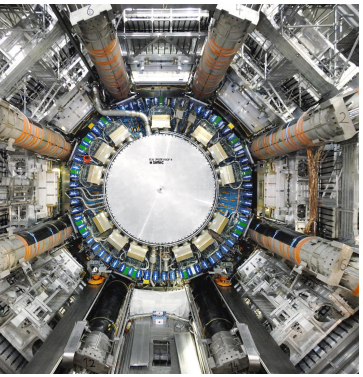
CMB+BBN prediction



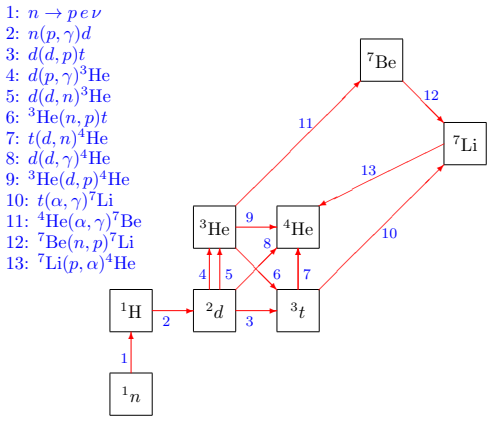
metallicity = "time"

Lithium Problem Overview

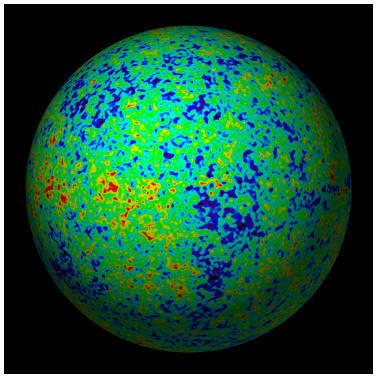
standard particle physics



standard nuclear physics

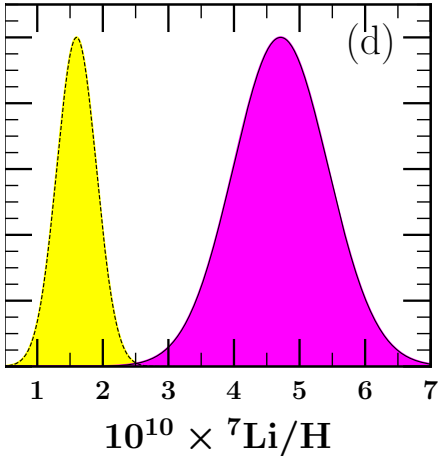


standard cosmology



$\neq$

observed lithium



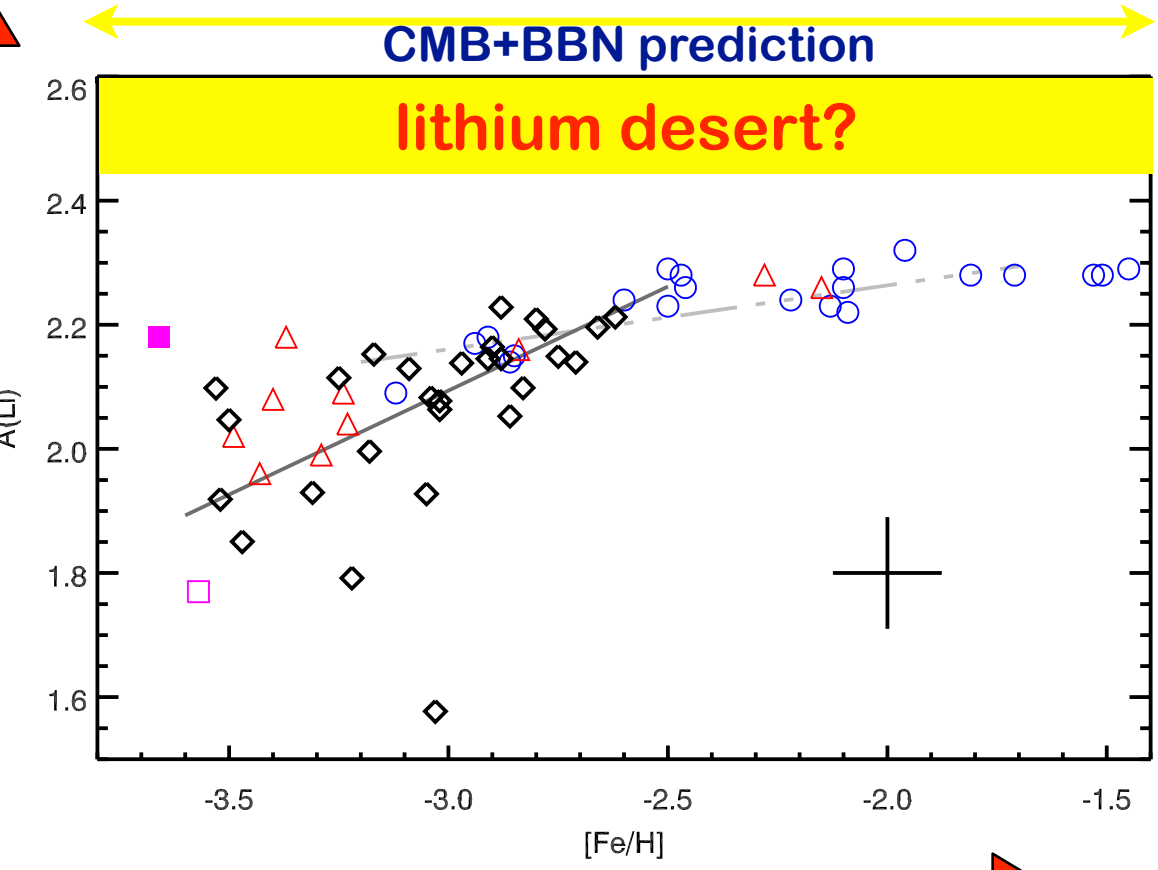
Solutions: one of these is wrong

Astrophysics: Nuclear Meltdown

Sbordone+ 2010

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

lithium abundances



metallicity = "time"

Nuclear Physics: Hoyle's Revenge?

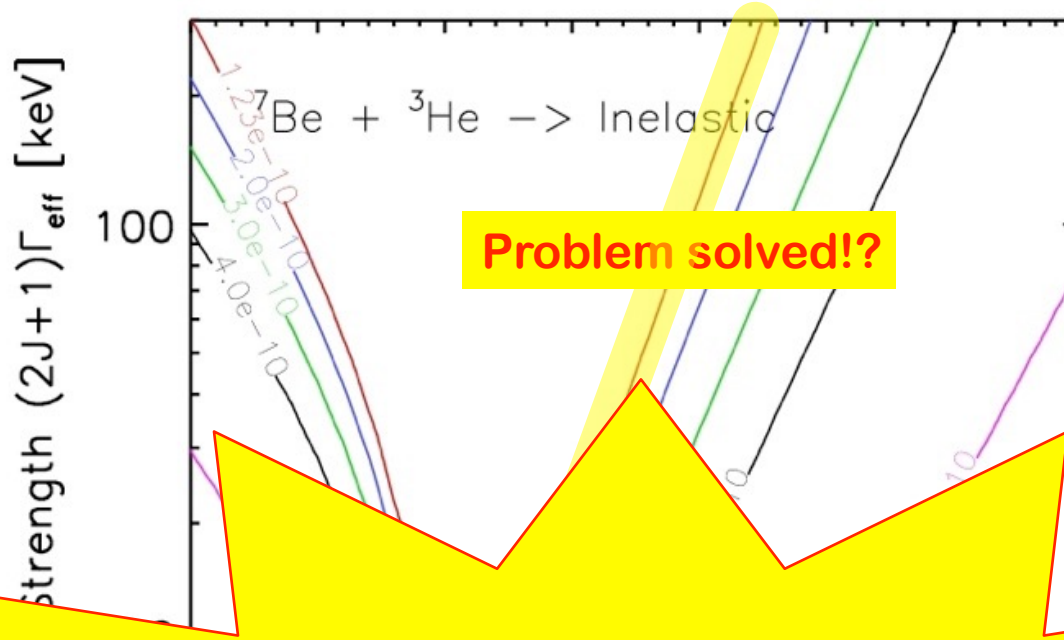
Nachiketa Chakraborty

Cyburt & Pospelov 2009

- "sub-dominant" Li reactions important if narrow resonance missed
  - cf Hoyle state in ^{12}C burning
- proposal: $^{7}Be+d$ inelastic

Chakraborty, BDF, & Olive 2011

- systematic study of all A=7 destruction rxns
  - ✓ confirms $^{7}Be+d \Rightarrow {}^{9}B^{*}$
  - ✓ even better: $^{3}He+{}^{7}Be$ / $t+{}^{7}Be \Rightarrow {}^{10}B^{*}$



Problem solved!?

Experiment Says: Not there!

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

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

Lithium Problem: New Physics Solutions

Li Solutions Beyond the Standard Model

- ⋆ **strategy:** new process changes light elements
- ⋆ **bonus:** perturbation physically motivated
- ⋆ **goal:** fix ^{7}Li discrepancy
- ⋆ **challenge:** retain D, ^{4}He success
  - D vs Li anticorrelation is quite general
    n+^{7}Be destruction inevitably changes D
  - D precision < 1% — no room for mischief!

New Physics Example: Could Lithium Be SUSY-licious?

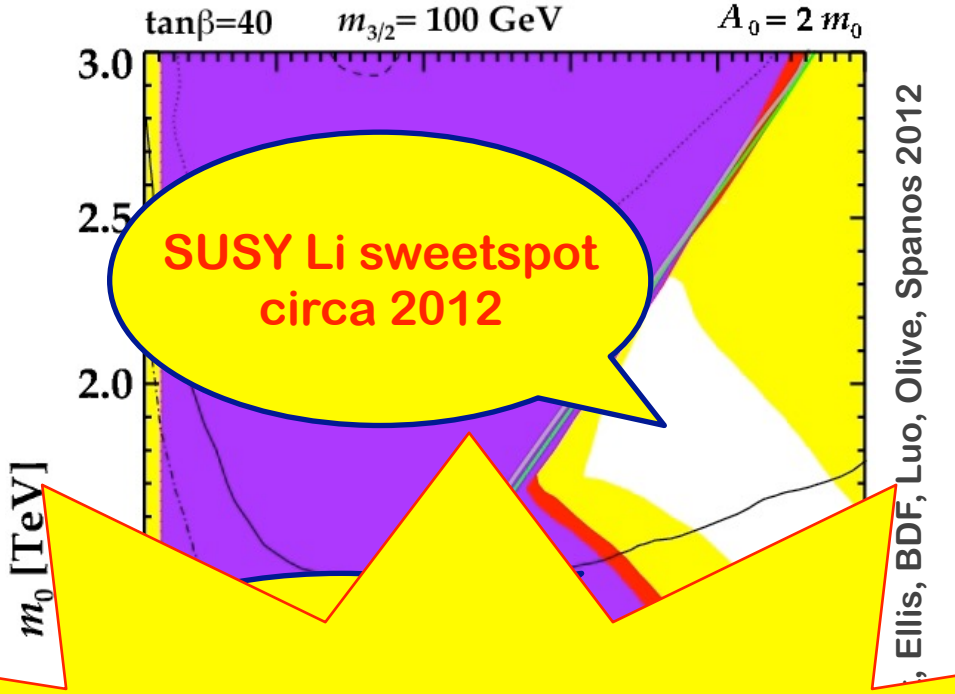
Supersymmetry

- complex dark sector
- decays in early U

Light elements are a strong SUSY probe

- ✓ rule out much parameter space
- ✓ complementary to LHC

Illustrates tight
among nucleo-cosm
astro-particle ph

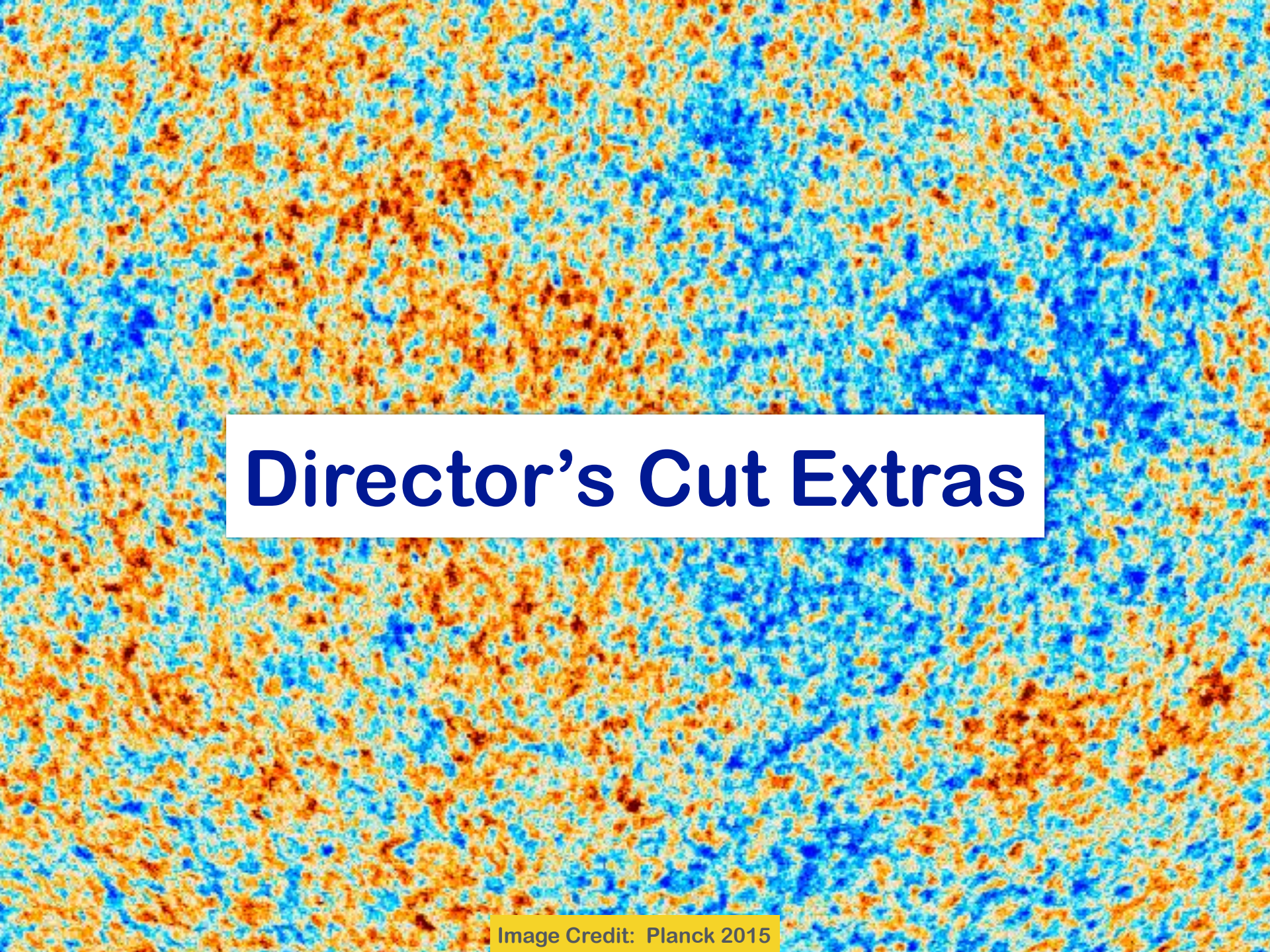


Latest D/H says:
Sweetspot gone sour
Li window closed!

The Lithium Problem: Thoughts on the Way Forward

- **New Physics** solutions challenged by D precision
  - if new physics, finely tuned?
  - yet dark matter non-detection invites new ideas
- **Cosmology solutions** face CMB LCDM consistency
- **Nuclear Experiment** lags observations! $d(d,n)^3\mathrm{He}$
- **Stellar Models**: $d(d,p)t$
  - also delicately tuned
  - why does meltdown start and stop?
  - why small scatter along Spite plateau?
  - do we understand Li pre-main sequence?
- **Observations:** ^{6}Li — is it even present in halo stars? intererstellar Li as depletion and isotope probe

Ask me: Philosophize? new physics ideas? deuterium status? ^{6}Li?

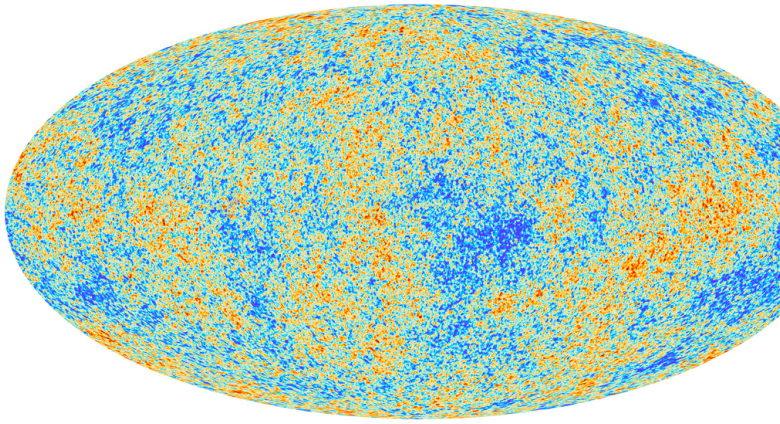

Director's Cut Extras
Image Credit: Planck 2015

New Physics Lithium Solutions
an Incomplete Survey

- Particle Physics Beyond the Standard Model
  - decaying particles Supersymmetry Cyburt+ 2012
  - mirror neutrons Coc+ 2013
  - magnetic fields+decays Yamazaki+ 2014
  - lepton asymmetry (degenerate neutrinos) Makki+ 2019
  - light particles with nucleon interactions Goudelis+ 2016
  - sterile neutrinos Salvati+ 2016
  - axion quark nuggets Flambaum+ 2019
  - Stable ^{8}Be Scherrer+ 2017
  - Non-extensive statistics Hou+ 2017
- Evolving Fundamental Constants
  - see Martins talk
- Nonstandard Cosmology
  - Lithium diffusion after recombination Pospelov 2012
  - "Hubble bubble" of inhomogeneous abundances Regis+ 2010
  - Cosmic deuterium destruction via early stellar processing Piau+ 2006
  - Nonthermal "cosmic rays" during BBN Kang+ 2019

Many now excluded by precision D observations

The Cosmic Microwave Background: CMB
A Powerful New Baryometer

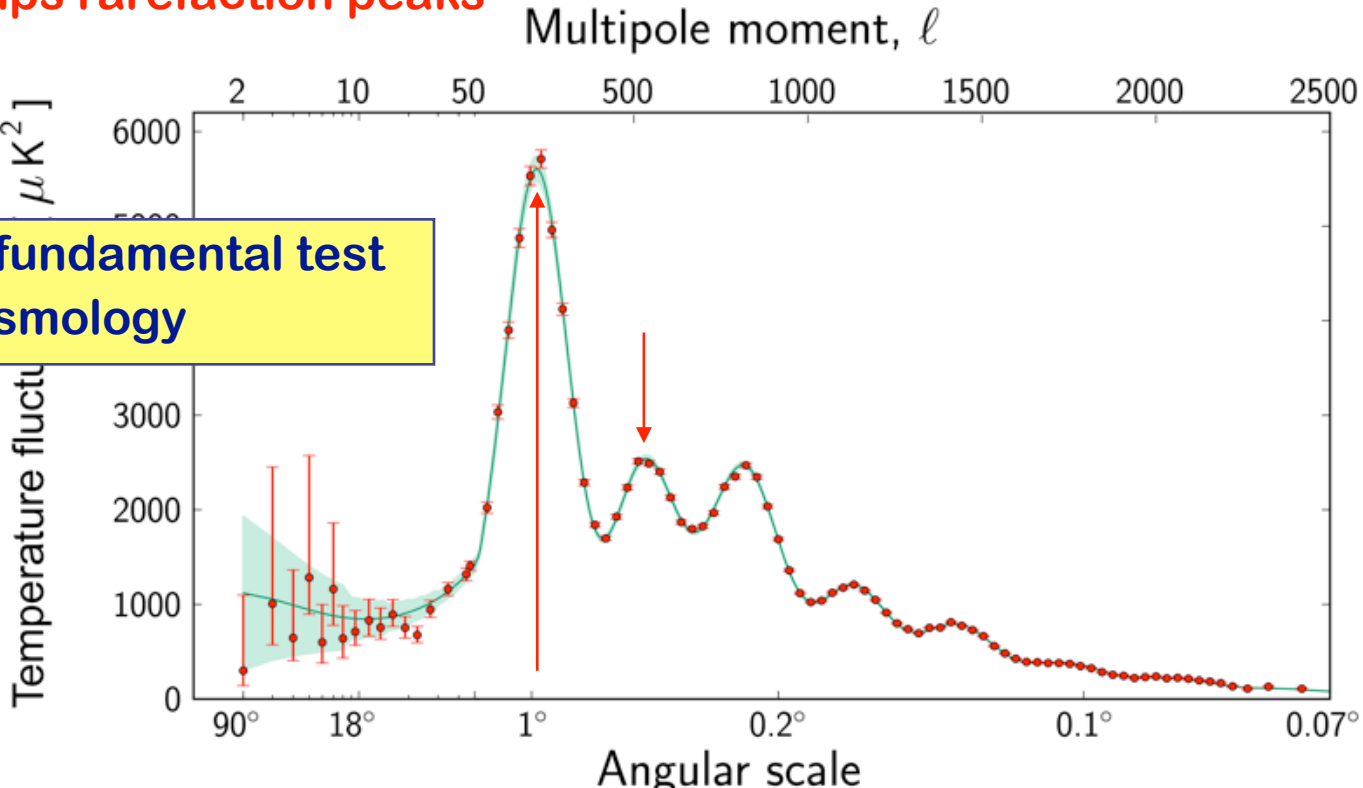


CMB ΔT_ℓ independent measure of $\Omega_{\rm B}$

Twitter version: in recombining plasma

- baryon gravity boosts compression
- baryon inertia damps rarefaction peaks

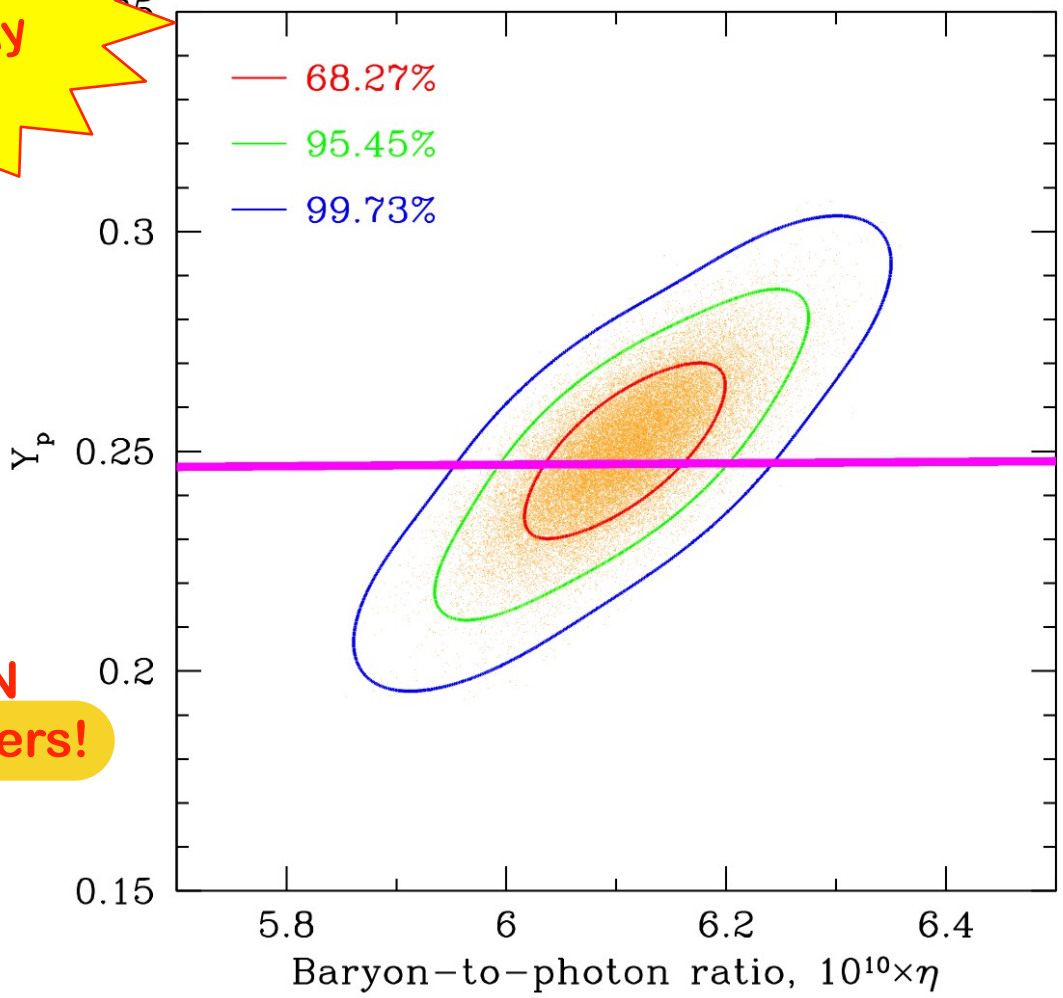
BBN vs CMB: fundamental test of cosmology



Standard BBN Tested With CMB Only

Planck Baryons & Helium!

New!
Immaculate!
Cosmically clean!



Contours:
Planck

Curve:
Standard BBN
zero parameters!