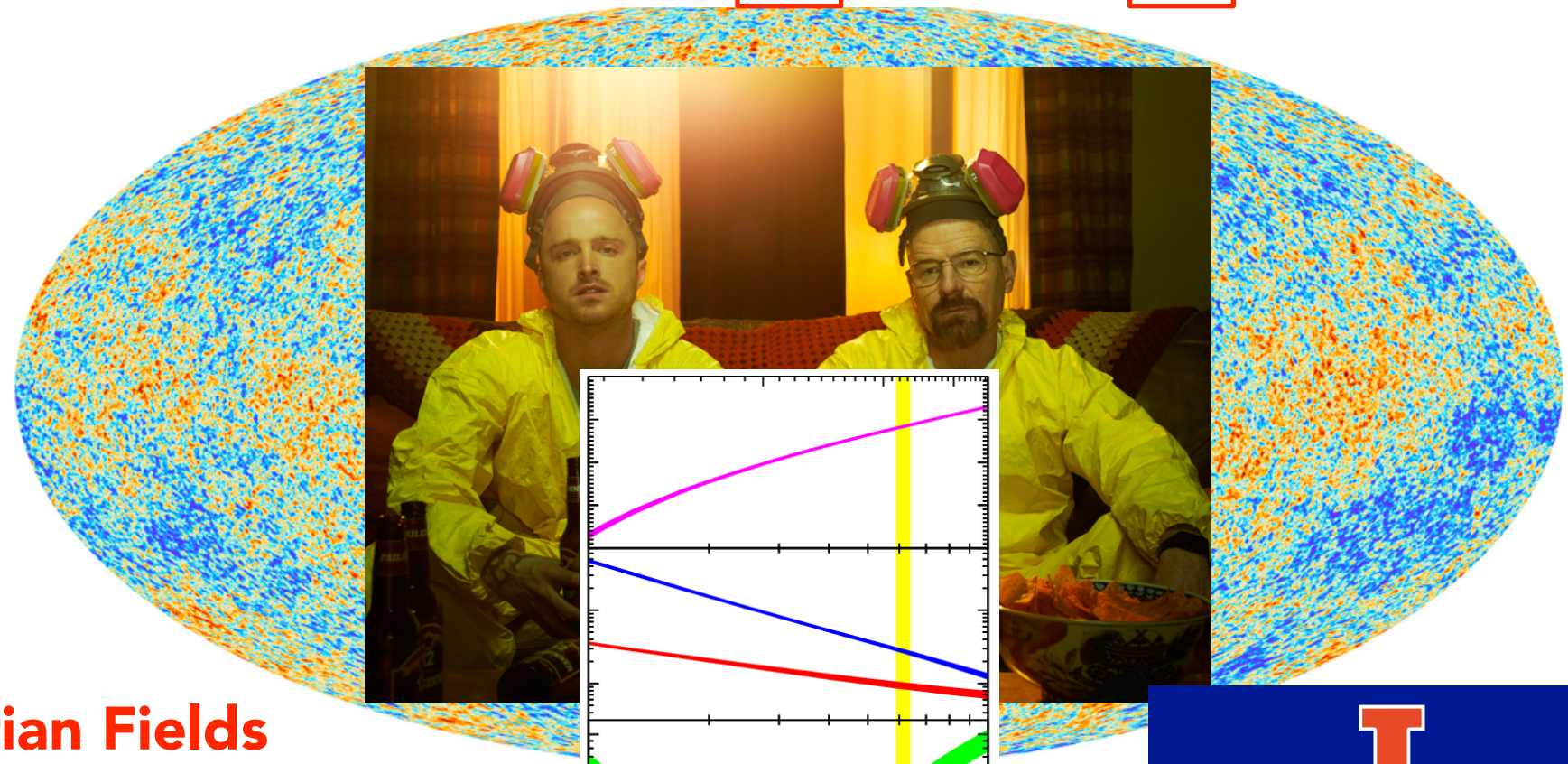
A Bitter Pill:

Overview of Primordial Nucleosythesis and the Primordial Lithium Problem

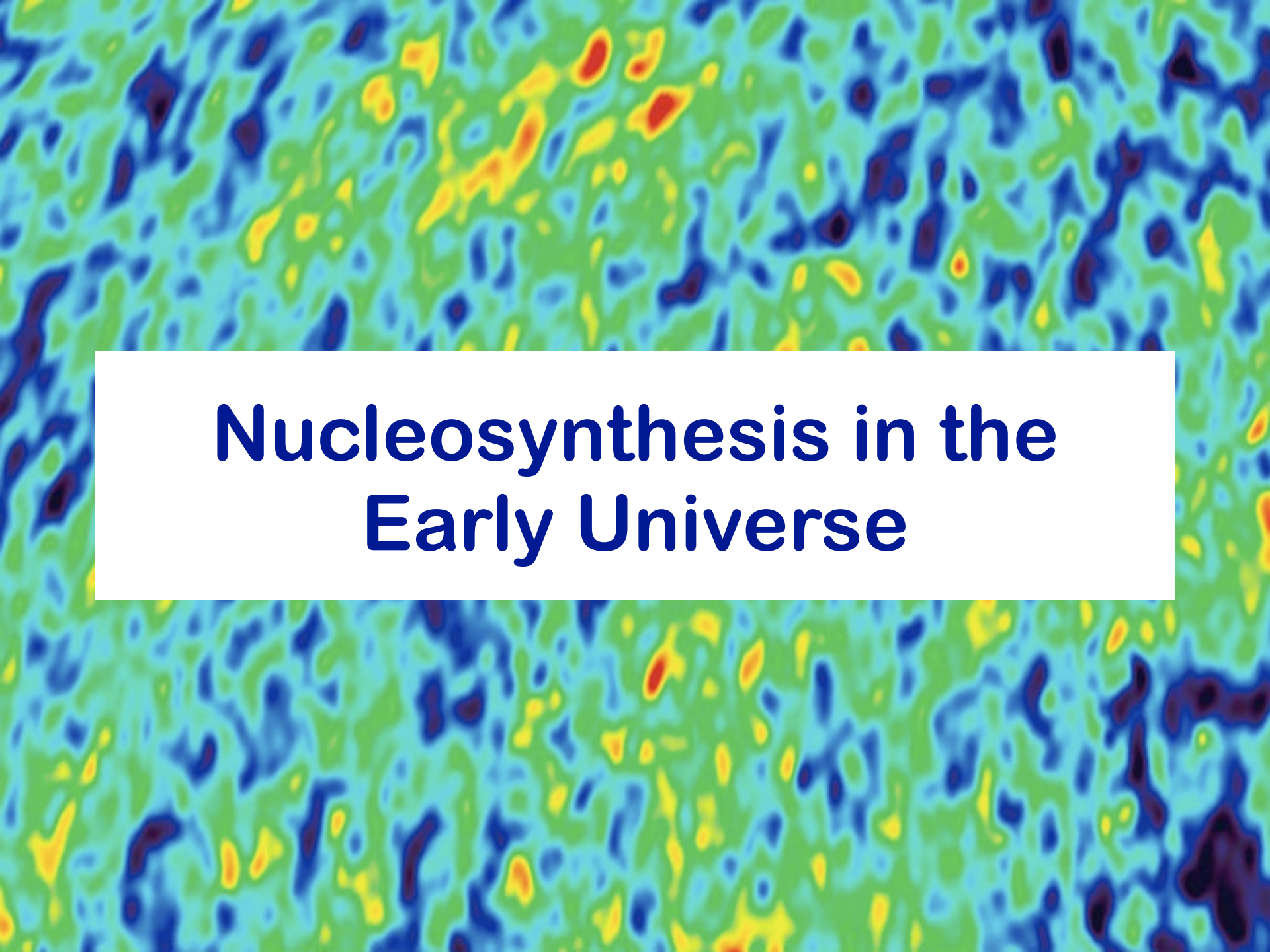


Brian Fields

Tsung-Han Yeh 葉宗翰

Keith Olive

ILLINOIS



Nucleosynthesis in the Early Universe

Big Bang Nucleosynthesis:
A Symphony of Fundamental Forces

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

Standard BBN

- Gravity = General Relativity
- Microphysics: Standard Model of Particle Physics
  - $N_\nu = 3$ neutrino species
  - $m_\nu \ll 1\ \mathrm{MeV}$
  - Left handed neutrino couplings only
  - neutrinos non-degenerate: $L \approx B$ and not $L \gg B$
- Kinetic equilibrium: Maxwell-Boltzmann nuclei
- Dark Matter and Dark Energy
  - Present (presumably) but non-interacting

Homogeneous U. ⇒ $\eta \equiv \dfrac{n_{\mathrm{baryon}}}{n_\gamma}$ Spatially const

➢ Expansion adiabatic

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

- gives baryon density

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

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Non-Standard BBN models
relax these assumptions
test new physics

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

Initial Conditions: T >> 1 MeV, t<< 1 sec

n-p weak equilibrium: $pe^- \leftrightarrow n\nu_e$

$ne^+ \leftrightarrow p\bar{\nu}_e$

neutron-to-proton ratio:

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

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

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

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

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

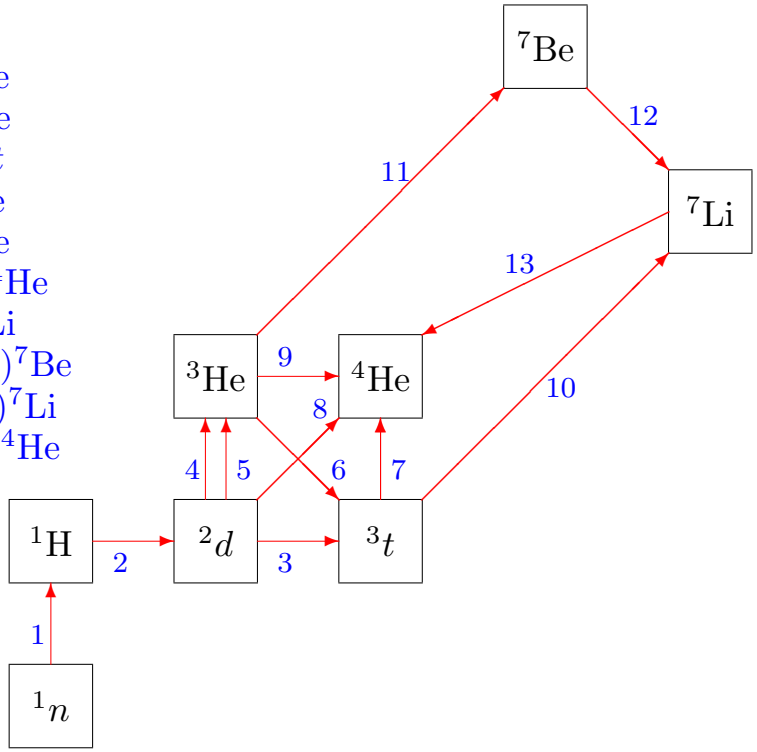
reaction flow ⇨ most stable light nucleus

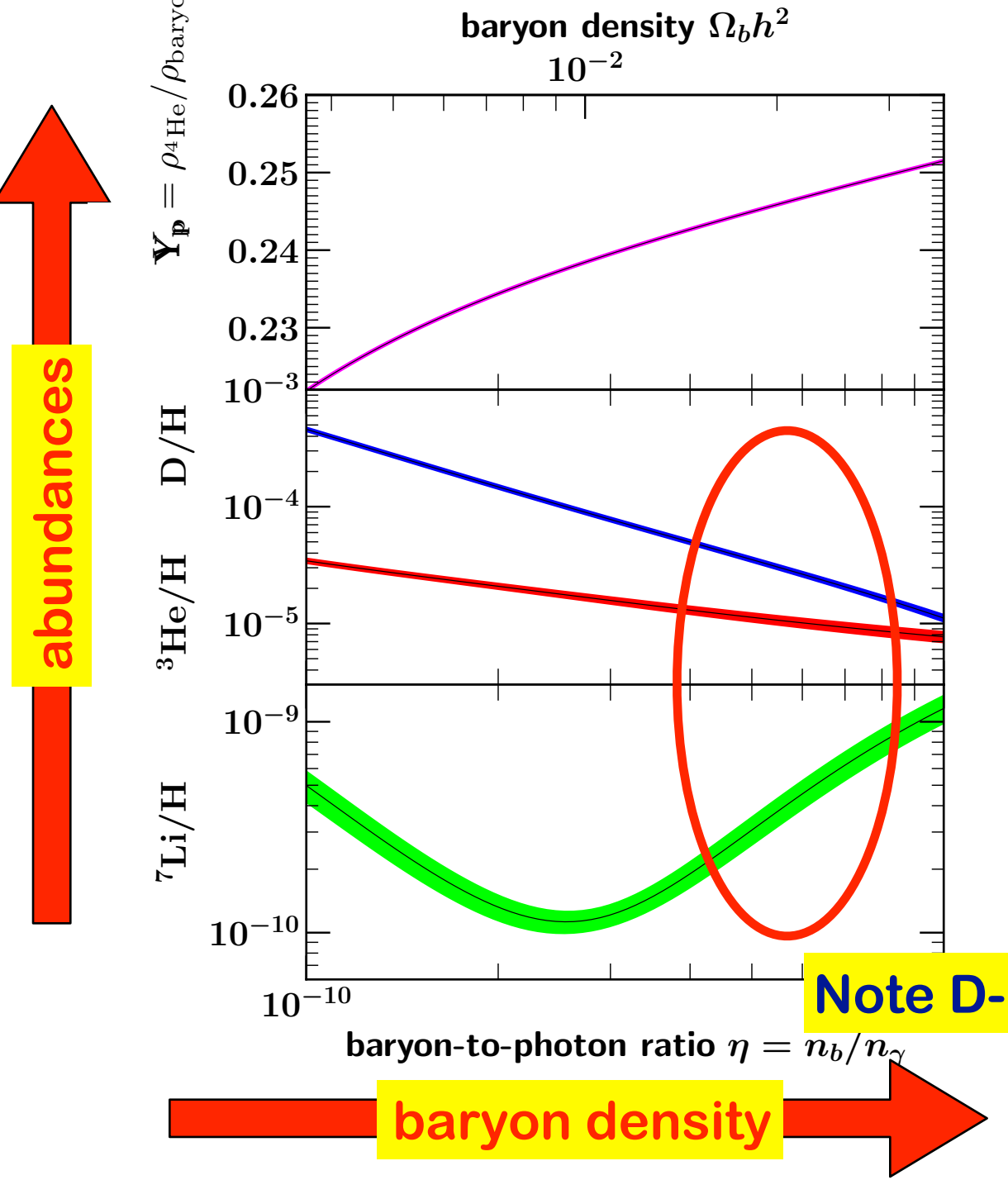
essentially all n ⇨ ^{4}He, ~24% by mass

also: traces of D, ^{3}He, ^{7}Li

1: $n \to p\,e\,\nu$
2: $n(p,\gamma)d$
3: $d(d,p)t$
4: $d(p,\gamma)^3\mathrm{He}$
5: $d(d,n)^3\mathrm{He}$
6: $^3\mathrm{He}(n,p)t$
7: $t(d,n)^4\mathrm{He}$
8: $d(d,\gamma)^4\mathrm{He}$
9: $^3\mathrm{He}(d,p)^4\mathrm{He}$
10: $t(\alpha,\gamma)^7\mathrm{Li}$
11: $^4\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
12: $^7\mathrm{Be}(n,p)^7\mathrm{Li}$
13: $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$

all reactions measured in lab at BBN energies





Standard BBN Predictions

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
Krauss & Romanelli 1988
Smith, Kawano, Malaney 1993
Nollett & Burles 2000

Note D-Li anti correlation

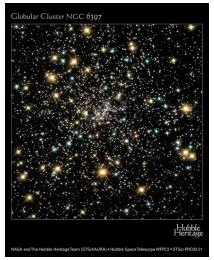
Light Elements: Sites

Deuterium

- see in galaxies backlit by quasars
- now to <1% precision! Pettini, Cooke+ 2013-2019

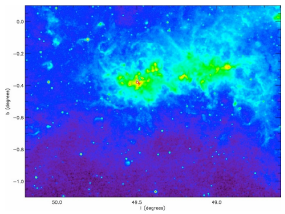
^{4}He

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



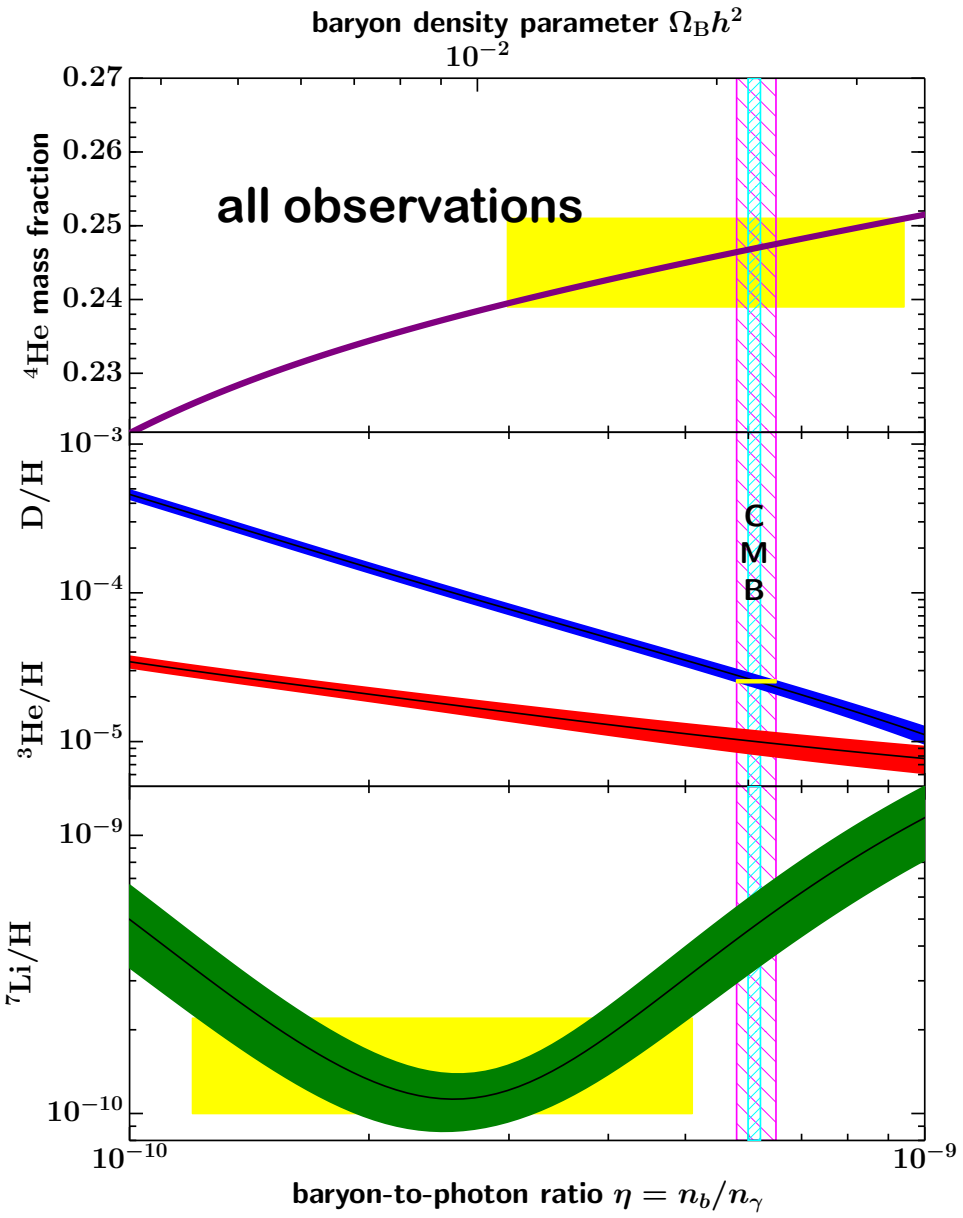
^{7}Li

- metal-poor halo stars in Milky Way
- 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!

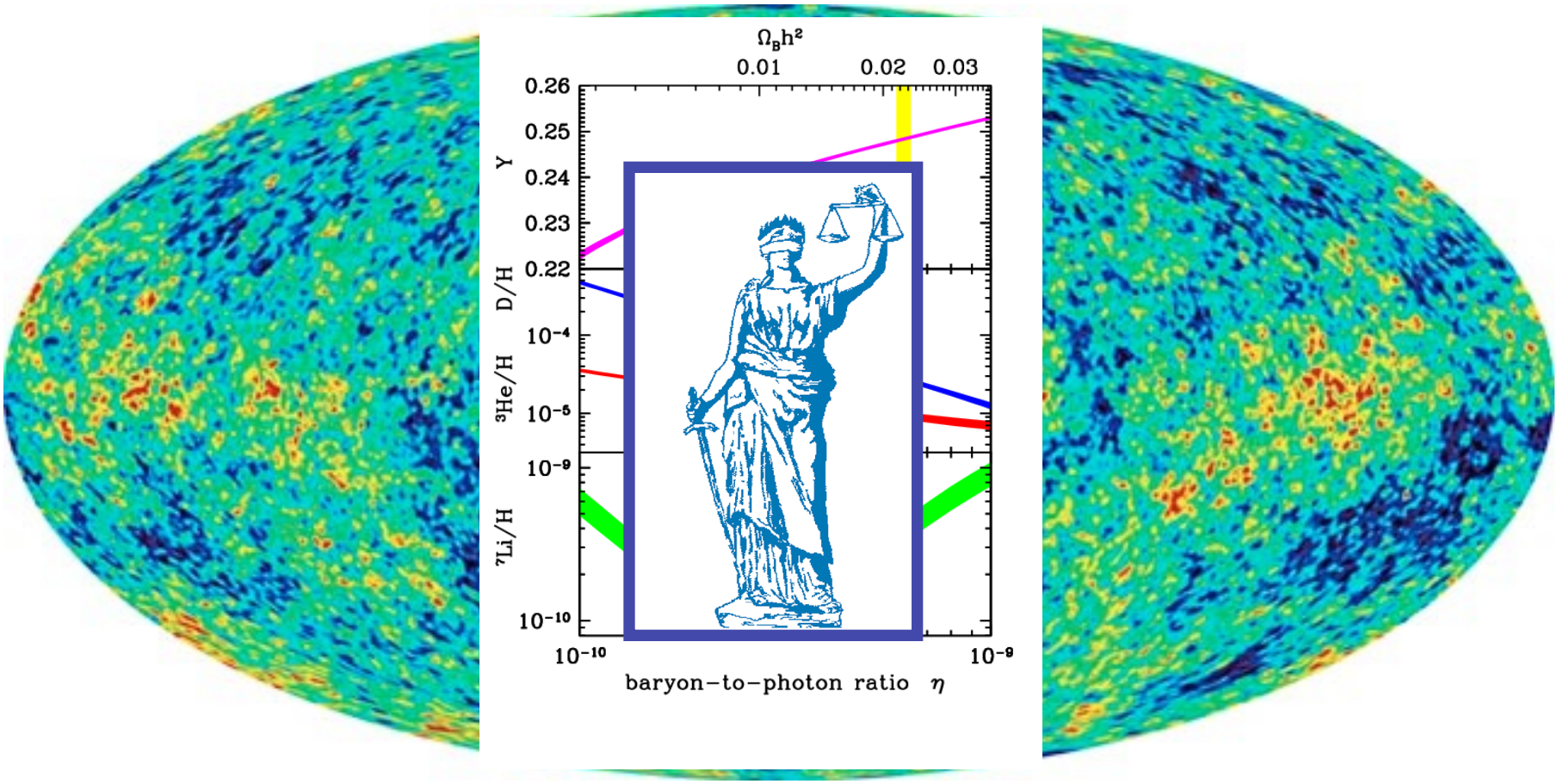
Result:

★rough concordance!

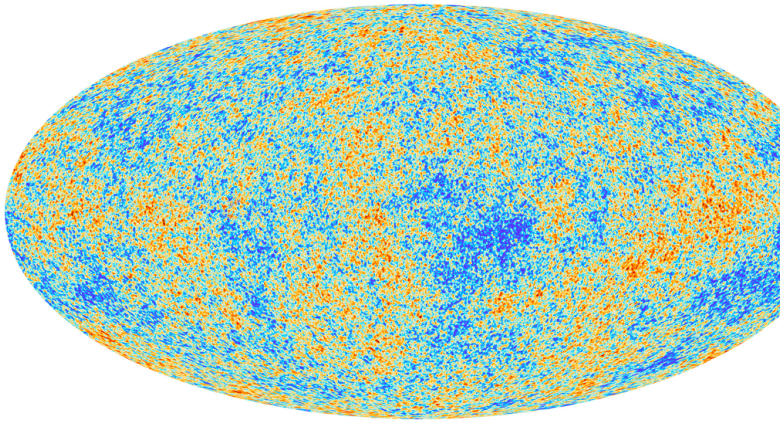
★but not in detail! D and ^{7}Li disagree

need a tiebreaker

Battle of the Baryons:
BBN+CMB



The Cosmic Microwave Background: CMB
A Powerful Baryometer

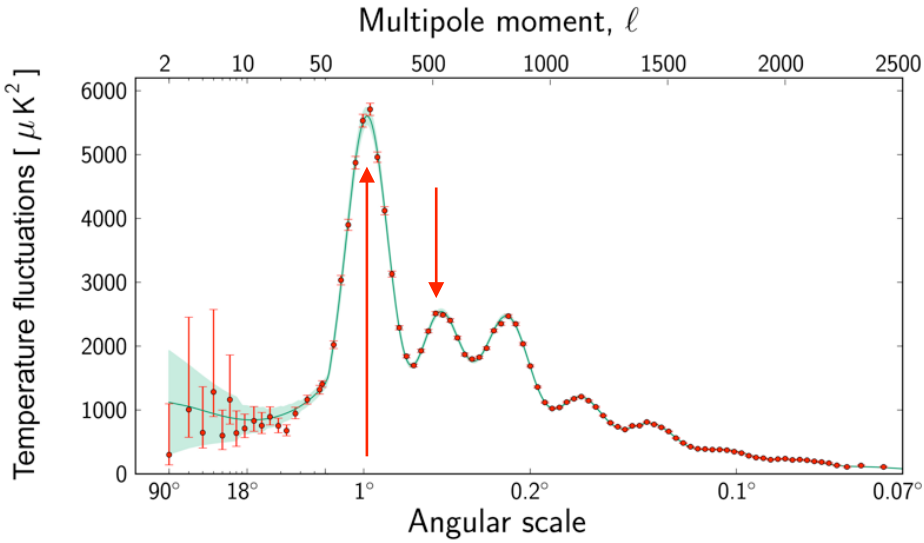


CMB ΔT_ℓ independent measure of $\Omega_{\rm B}$

Twitter version: in recombining plasma

- **baryon gravity boosts compression**
- **baryon inertia damps rarefaction peaks**

BBN vs CMB: fundamental test of cosmology



Battle of the Baryons: II

New World Order

Cyburt, BDF, Olive 2003, …, BDF, Olive, Yeh, Young 2020

Planck baryon density very precise

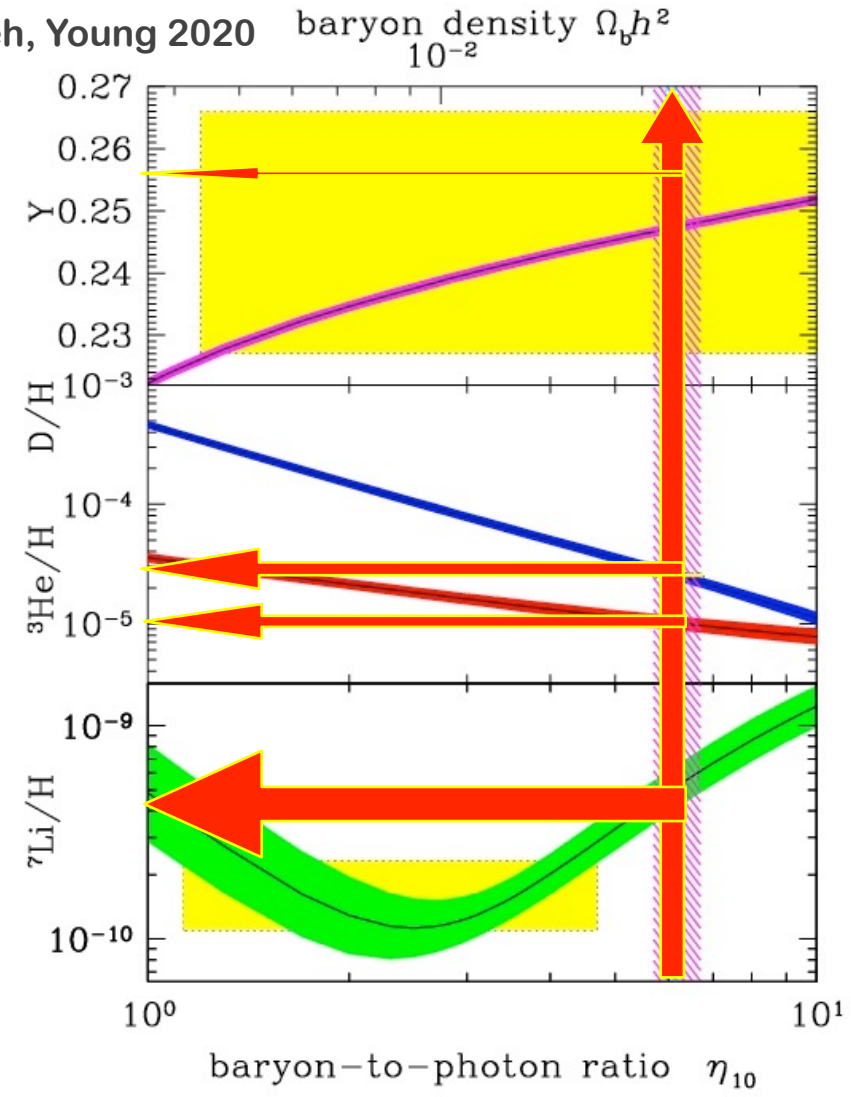
$$\Omega_{\rm B}\, h^2 \;=\; 0.022298 \pm 0.000020$$

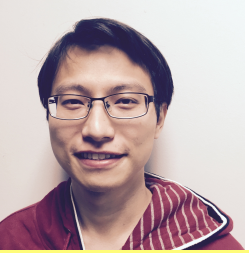
$$\eta \;=\; (6.104 \pm 0.058) \times 10^{-10}$$

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





Tsung-Han Yeh
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Battle of the Baryons: II
A Closer Look

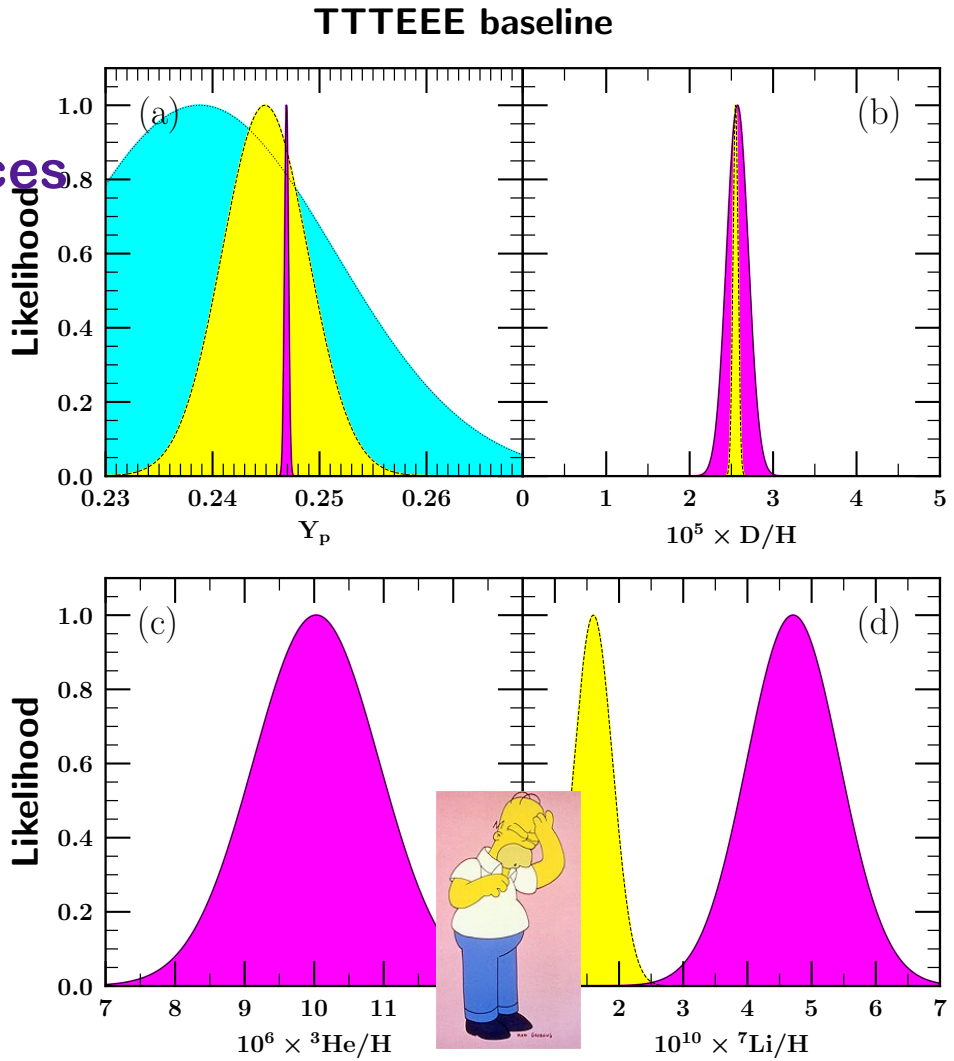
Cyburt, BDF, Olive 2003, 2008, 2015; BDF, Olive, Yeh, Young 2020

Predict:

BBN theory: abundances vs η

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

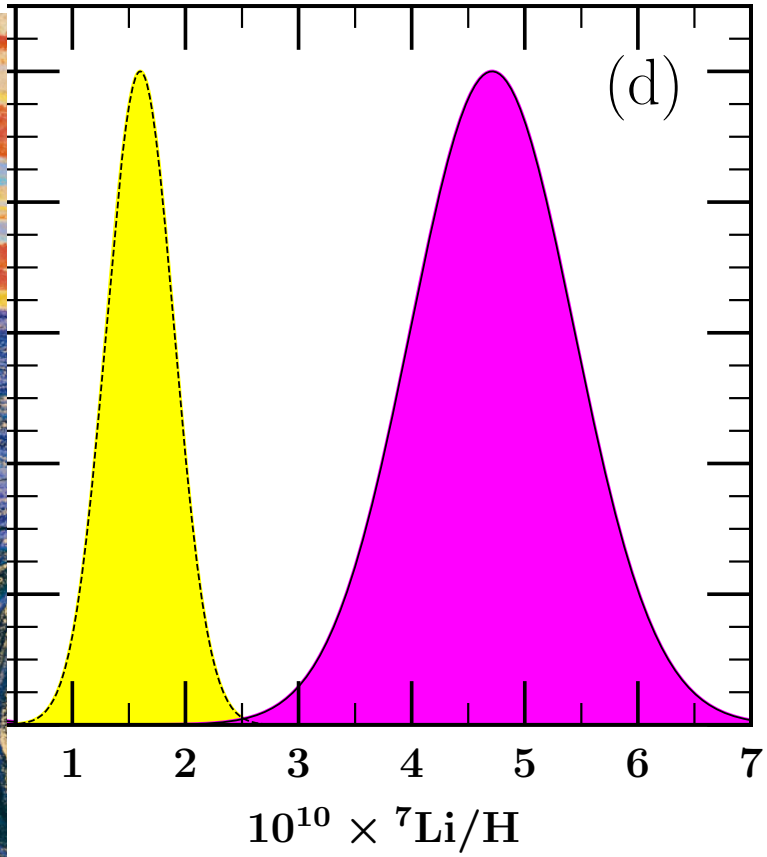
Compare with Observations (yellow)



Results:

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

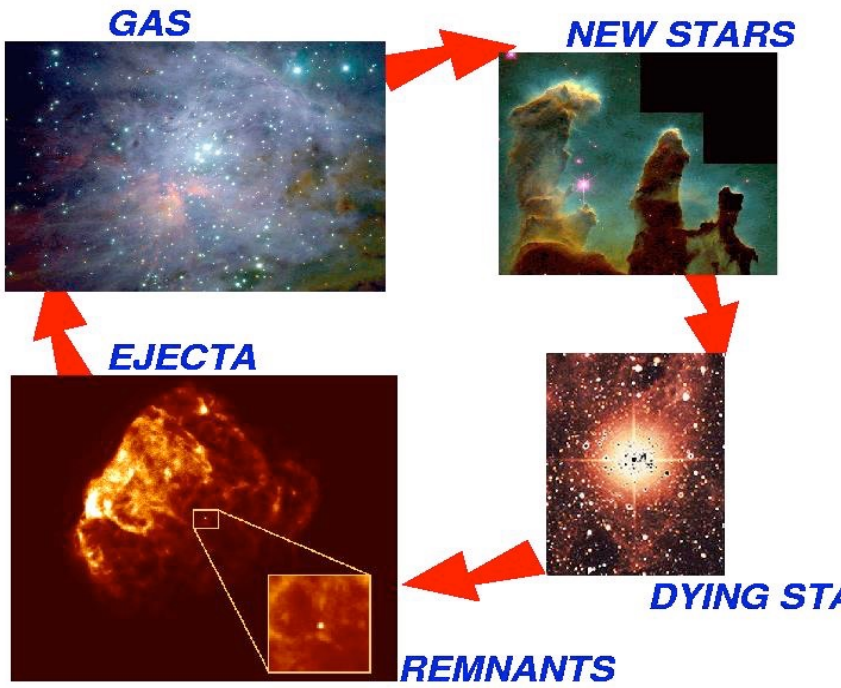
The Lithium Problem



BBN Observations:
Light Element Abundances

The Problem

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



The Solution

- correct for post-BBN processing:

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

Primordial Lithium

Observe in primitive (Pop II) stars

Li-Fe ⇨ evolution

Plateau at low Fe Spite & Spite 82

★ down to [Fe/H]~-2.75

★ const. abundance at early epochs

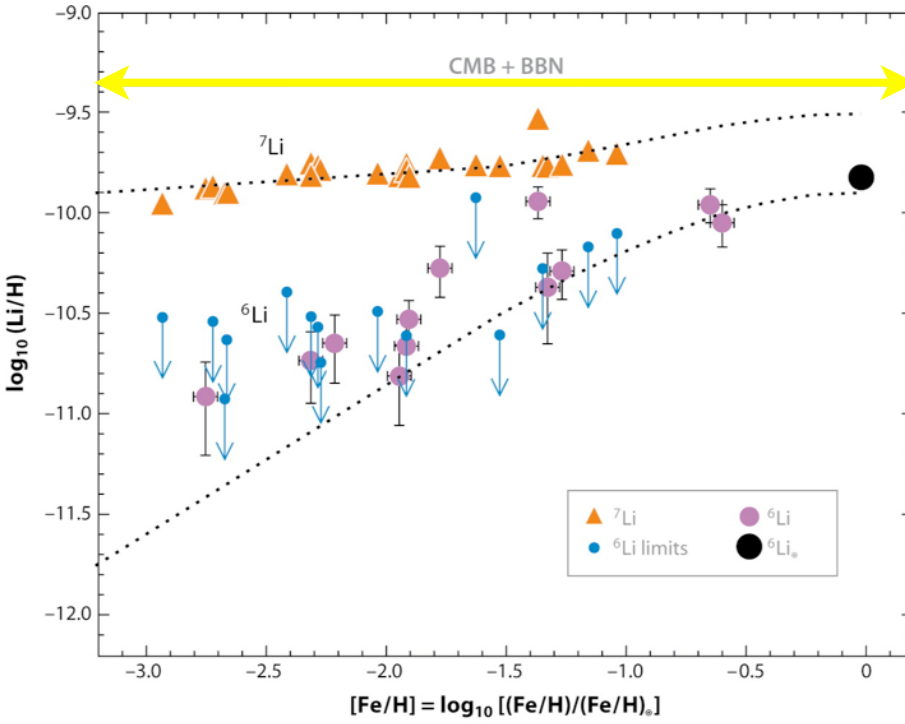
★ Li is primordial

But is the plateau at Li_p?

- Li_{Planck}/Li_{obs} ~ 4
- Why?

lithium abundances

CMB+BBN prediction

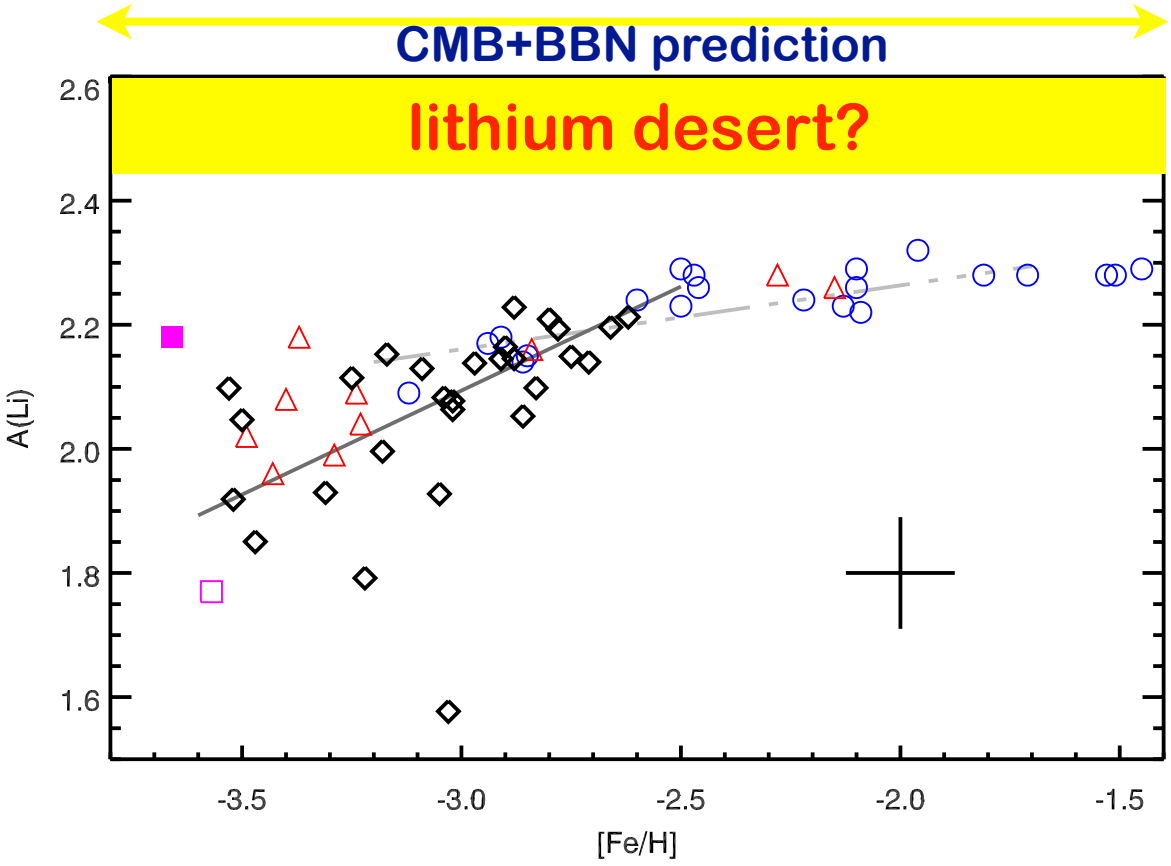


metallicity = "time"

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

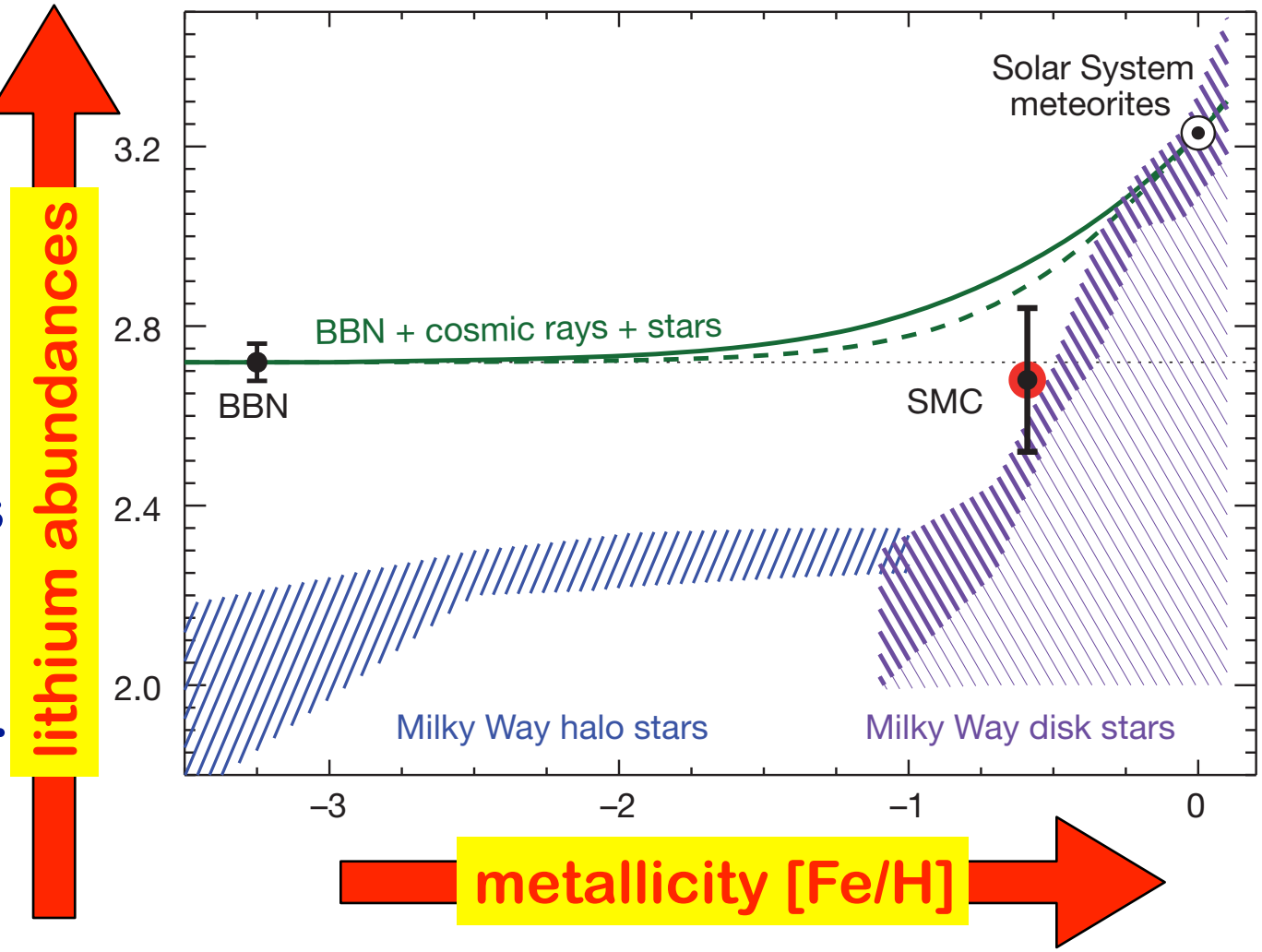


A New Lampost:
Interstellar Lithium

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

A New Lampost: Interstellar Lithium

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



Howk, Lehner, BDF, & Mathews 2013

Hoyle's Revenge?

A Resonatingly Pretty Solution to Lithium?

Cyburt & Pospelov 2009

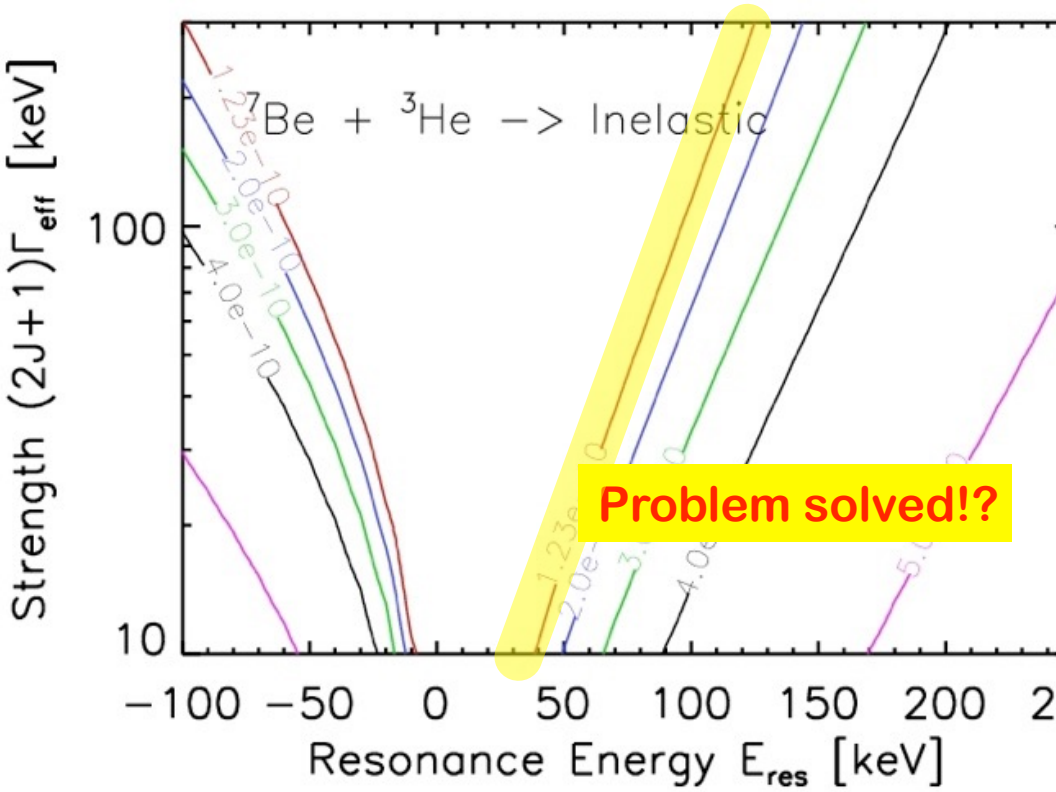
- 11 dominant BBN reactions already well-studied
- no room for factor ~3 surprises
- but "sub-dominant" reactions important if narrow resonance missed

  cf Hoyle state in ^{12}C burning
- 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: $^{3}He+{}^{7}Be \Rightarrow {}^{10}C^{*}$

    $t+{}^{7}Be \Rightarrow {}^{10}B^{*}$



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cf Hoyle st…

- pro…

Chakraborty 2011

- syste… …study of destruction rxns
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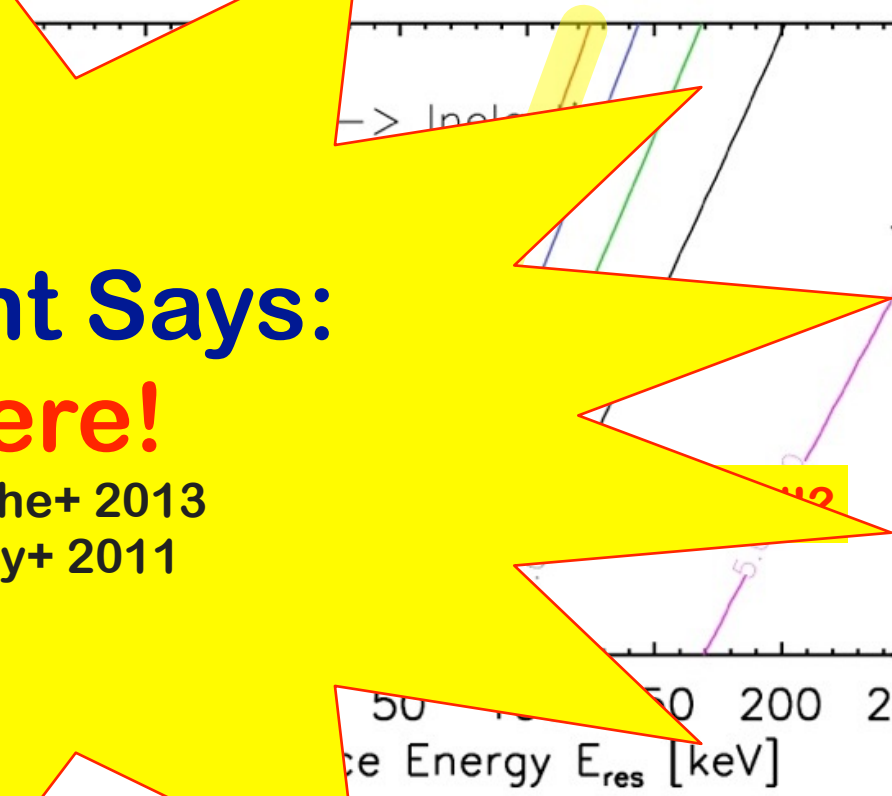
    t+^{7}Be ⇨ ^{10}B*

Experiment Says:

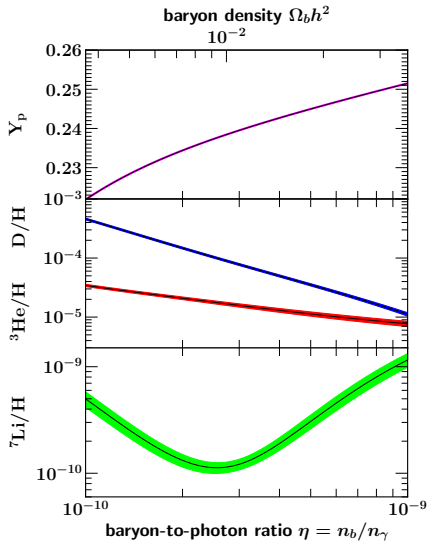
Not there!

^{10}C*: Hammache+ 2013

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



OUTLOOK



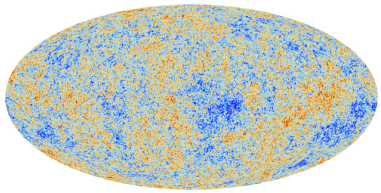
Convergence of Particle Physics and Cosmology

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

BBN & CMB: Gates to the Early Universe

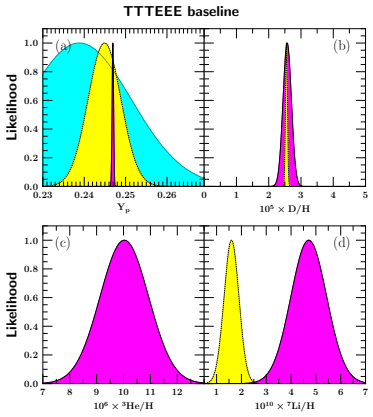
- basic concordance: big bang working to t~1 sec
- CMB alone now independently tests BBN!
- BBN + CMB powerfully probe new physics: dark matter, early Universe

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



- problem has worsened from WMAP 2003 to Planck 2018
- astrophysics solutions possible but highly constrained
- nuclear physics precision needed: d(p,g)3He; 7Be(n,p)7Li
- new physics: dark matter? see Pradler talk

The Future:



- Even better CMB measurements (S4)
- New light element measures, stellar theory and data
- Interplay with nuclear, dark matter & accelerator physics

Stay Tuned!

Ask me to philosophize!

The Lithium Problem: Thoughts on the Way Forward

- New Physics solutions challenged by D precision
  - if new physics, seems very unusual and specific
  - yet dark matter non-detection invites new ideas
- Cosmology solutions face CMB LCDM consistency
- Nuclear Experiment lags observations! unacceptable!
- Stellar Models:
  - 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

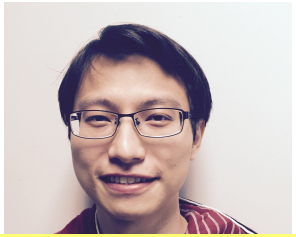
Paleolithography Collaborators

Richard Cyburt

Nachiketa Chakraborty

Vasilis Spanos

Tijana Prodanovic



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