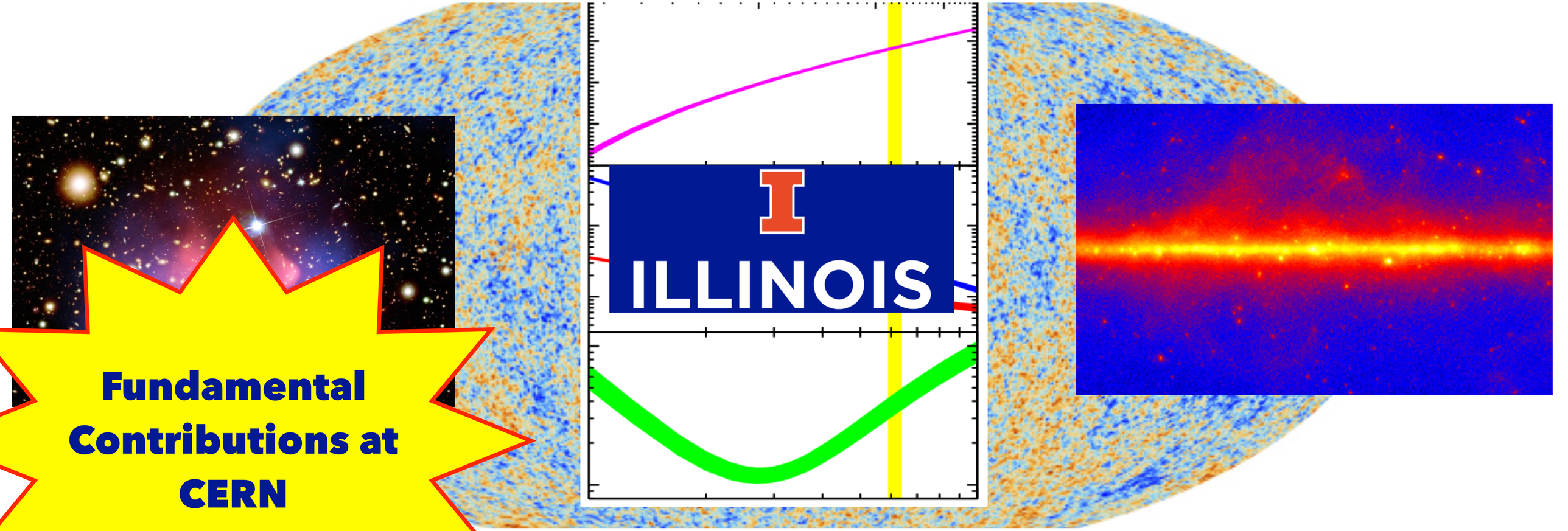
Big-Bang Nucleosynthesis

Beyond the Lithium Problem?



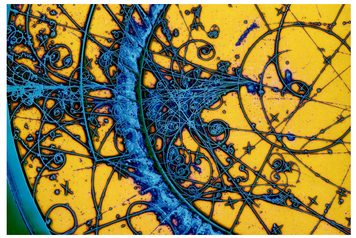
Fundamental Contributions at CERN

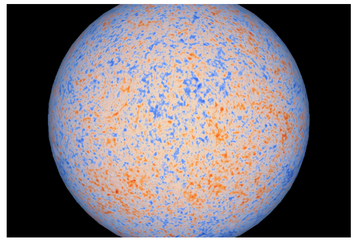
Brian Fields

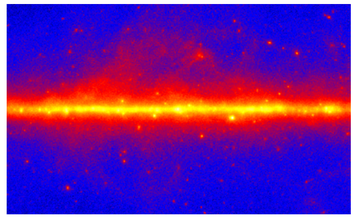
CERN Theory Colloquium

Aug 23, 2023

Big-Bang Nucleosynthesis





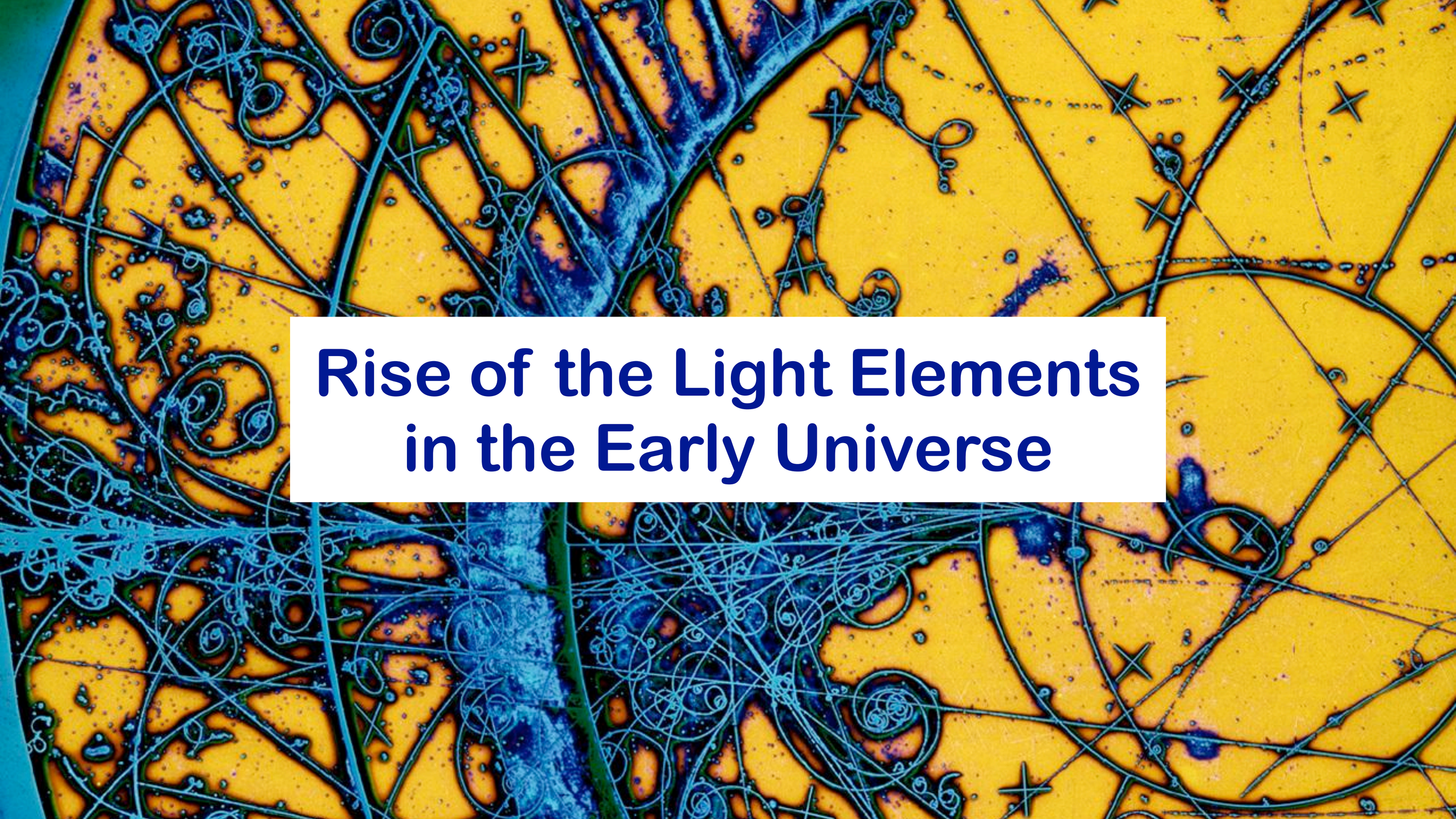


★ Rise of the Light Elements in the Early Universe

★ Cosmic Baryons and the Microwave Background

★ The Lithium Problem and Possible Resolution

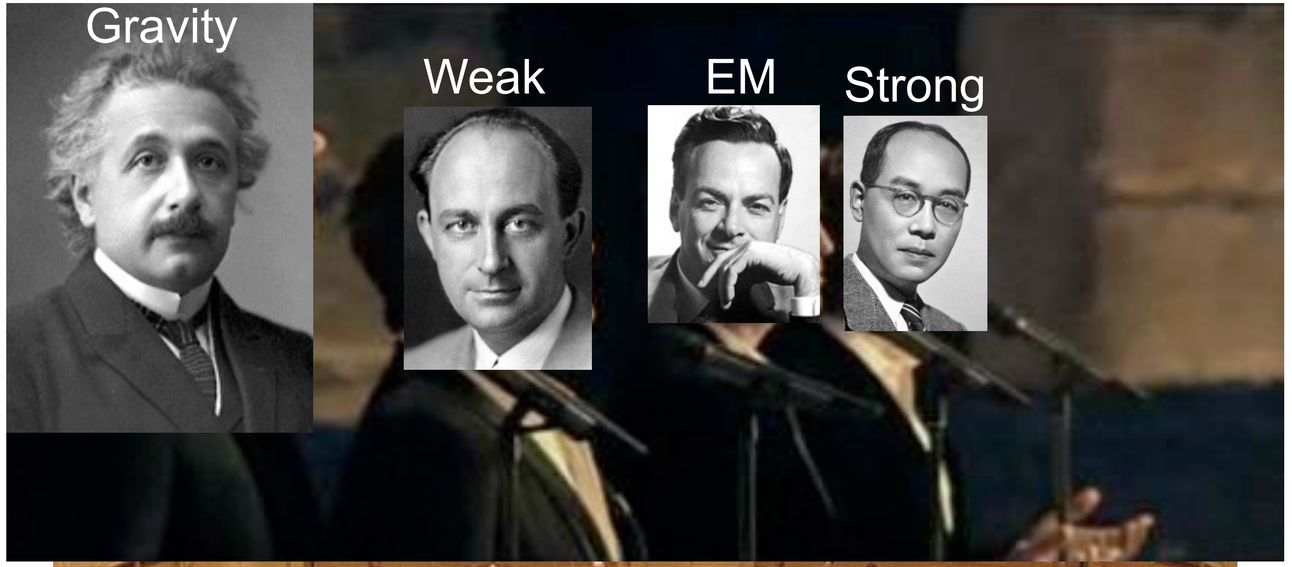
★ The Future: Probing the Early U and New Physics



Rise of the Light Elements 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. ⇒ $\eta \equiv \frac{n_{\mathrm{bary}}}{}$

➢ Expansion adiabatic

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

- gives baryon density

$\eta \propto \rho_{\mathrm{B,today}} \propto \Omega_{\mathrm{B}} h^{} \propto$ (bar on)

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

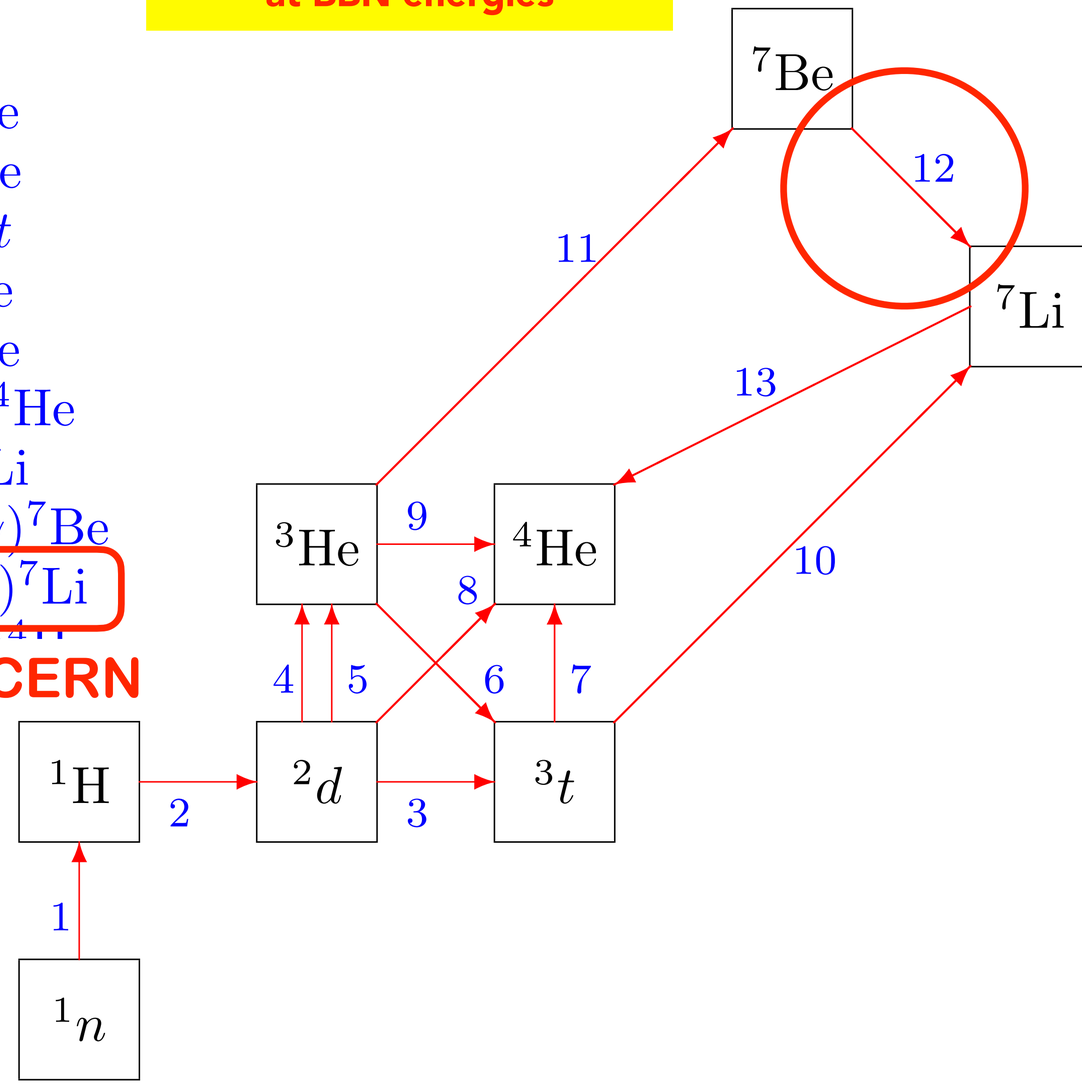
Light Elements Born: T~0.07 MeV, t~3 min

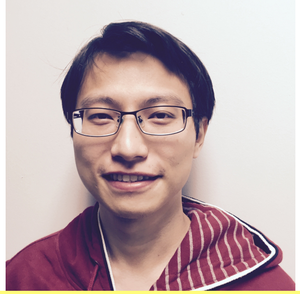
- **reaction flow ⇨ most stable light nucleus**
- **essentially all n ⇨ ^{4}He, ~25% by mass**
- **also: traces of D, ^{3}He, ^{7}Li**

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: $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

nTOF @ CERN

all reactions measured in lab at BBN energies





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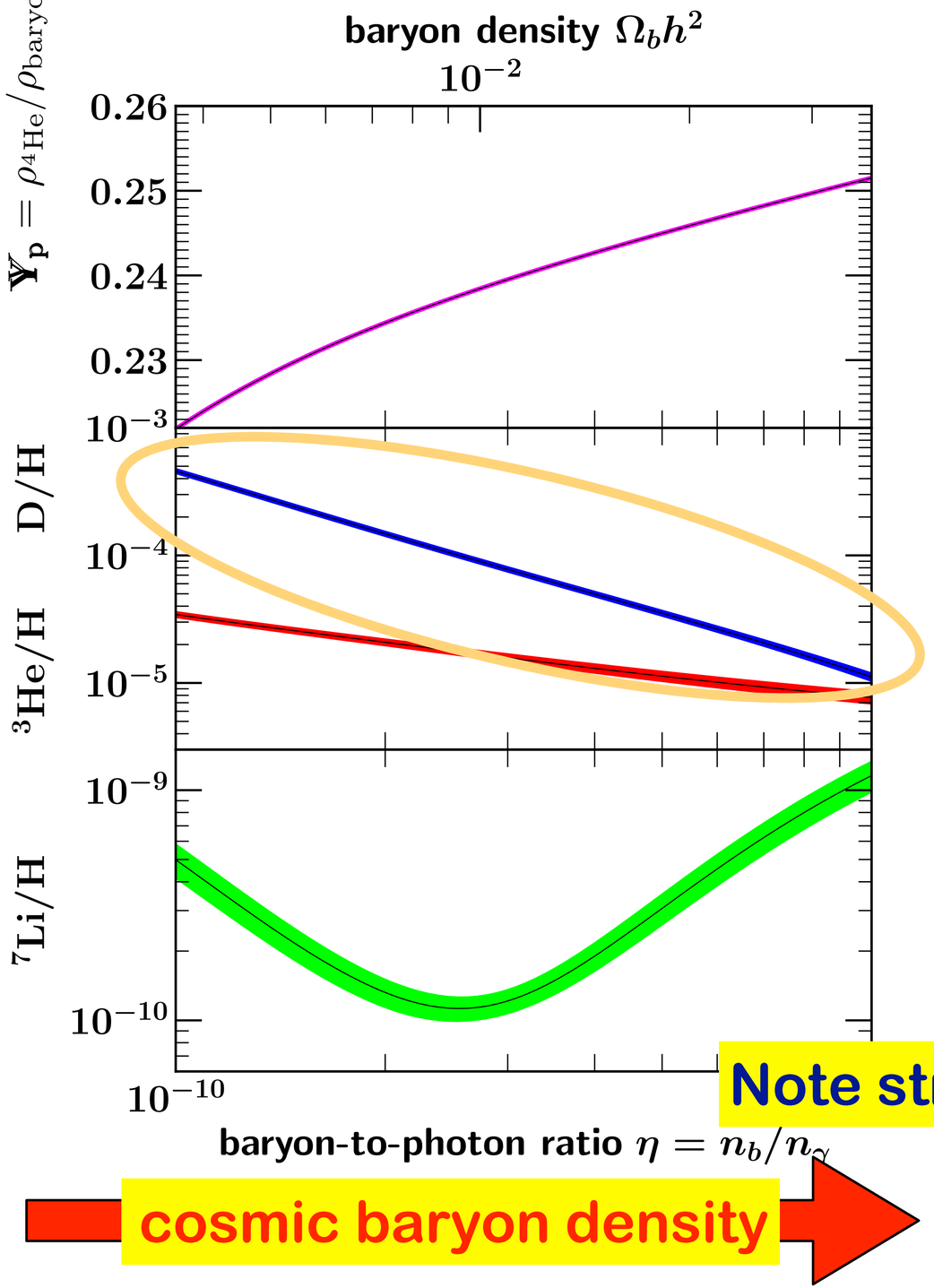
abundances



cosmic baryon density

Stanard 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 strong D sensitivity to density

Light Elements: Sites

Deuterium

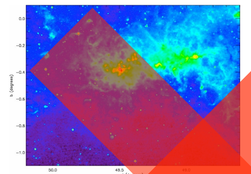
- in z~3 galaxies backlit by quasars
- New! leap in precision: Pettini, Cooke+ 2013-2019

^{4}He

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

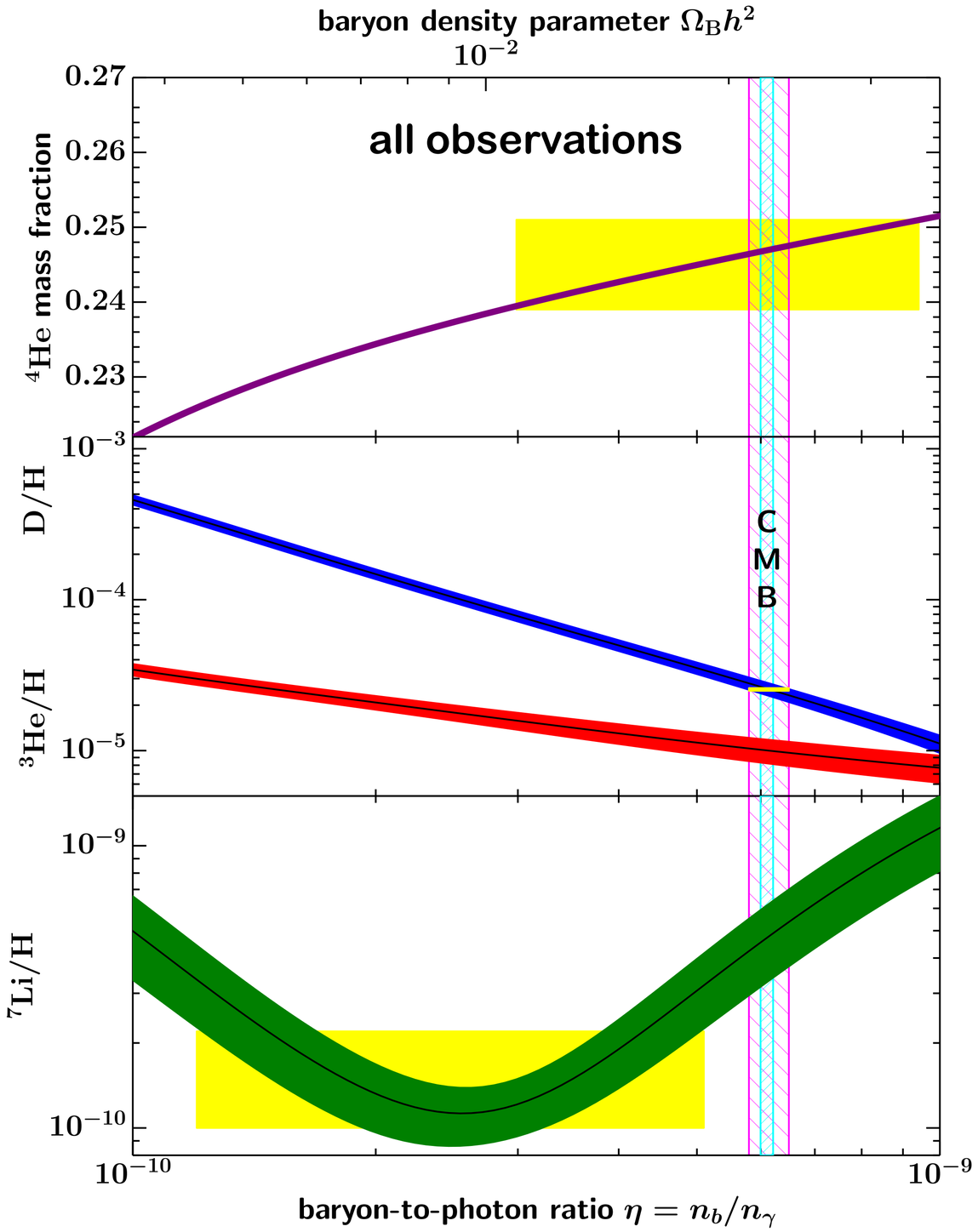
^{7}Li

- 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!

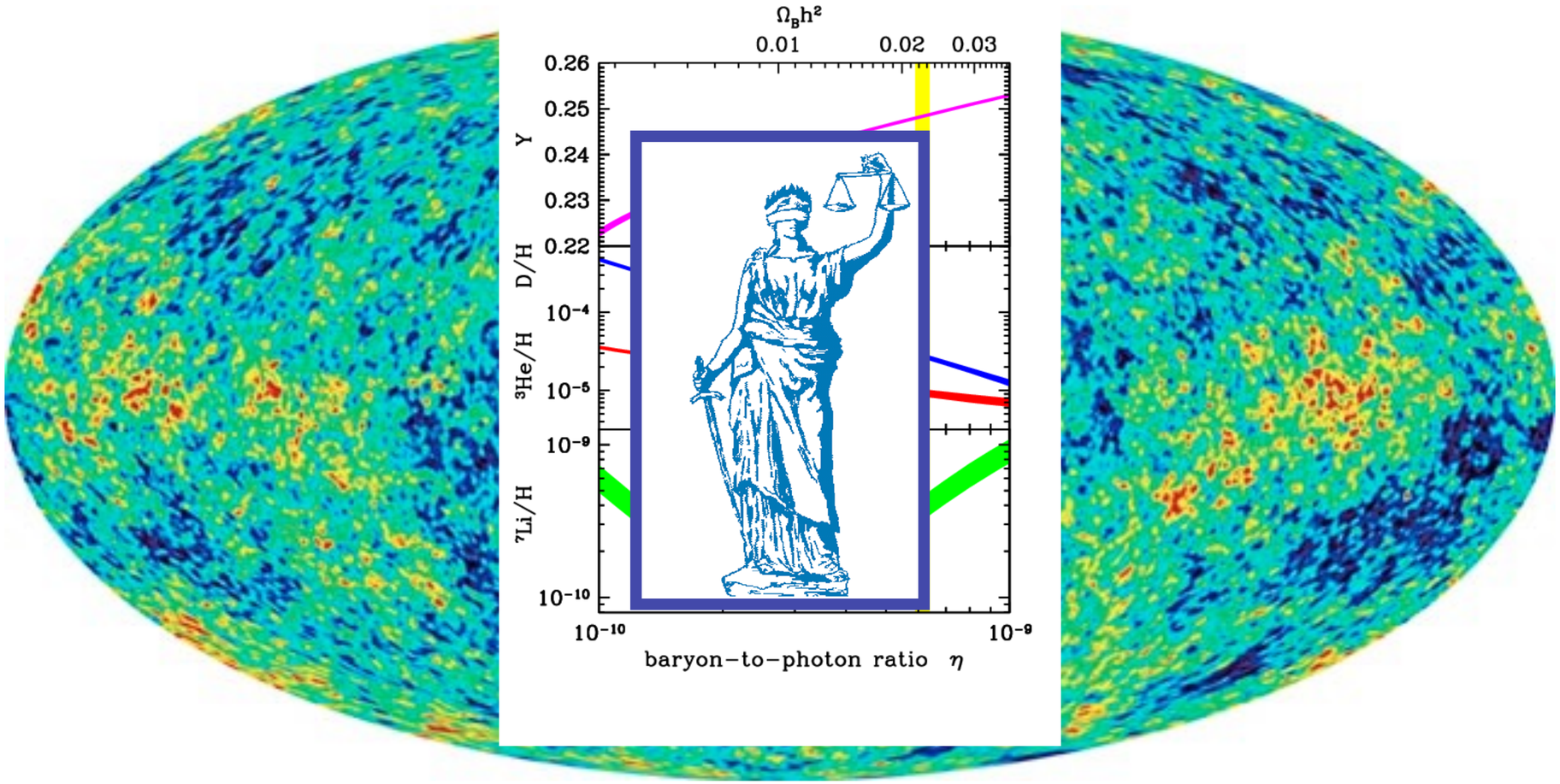
Result:

★rough concordance!

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

⇨ need a tiebreaker

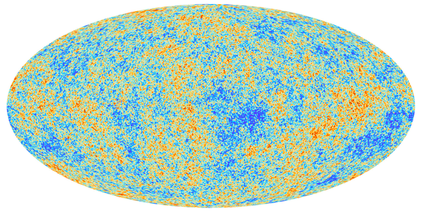
COSMIC BARYONS
and the
MICROWAVE BACKGROUND



Battle of the Baryons: II

CMB New World Order

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

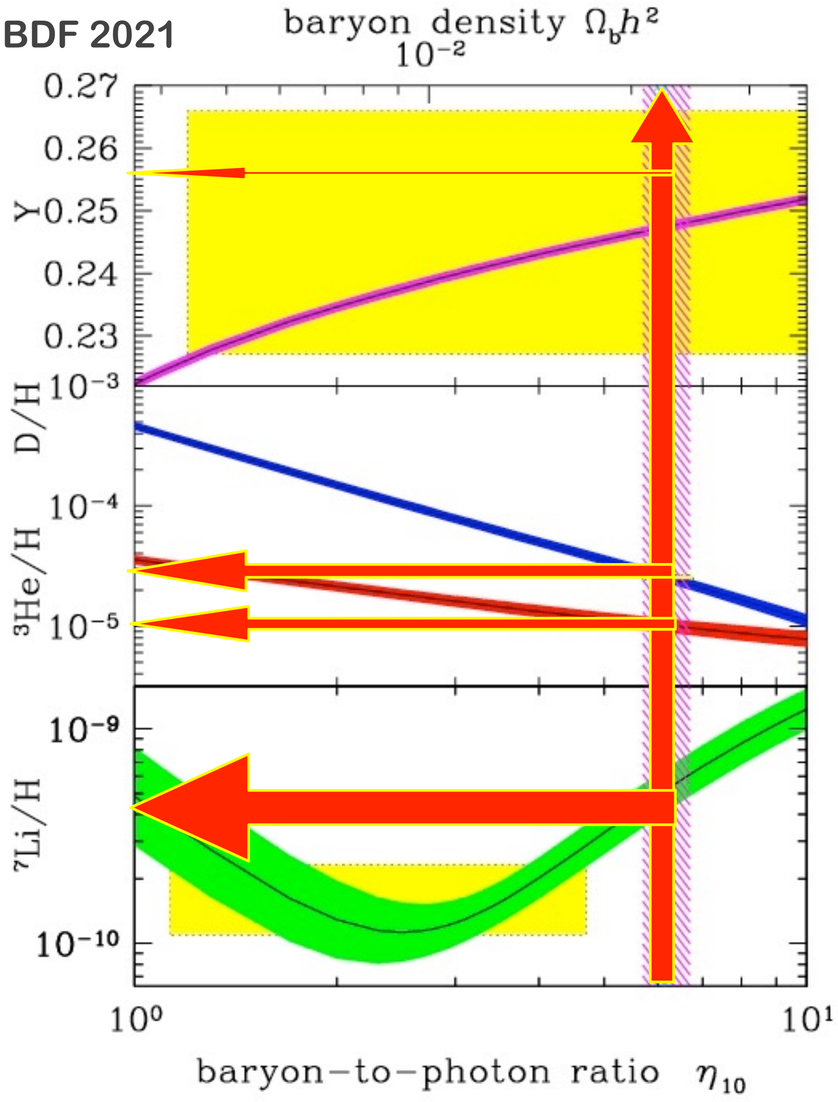


Planck baryon density very precise

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

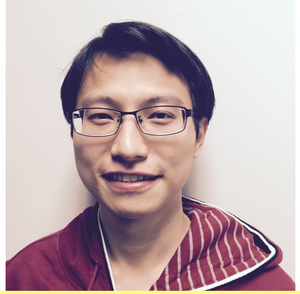
$$\eta = (6.104 \pm 0.058) \times 10^{-10}$$

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



New strategy to test BBN:

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



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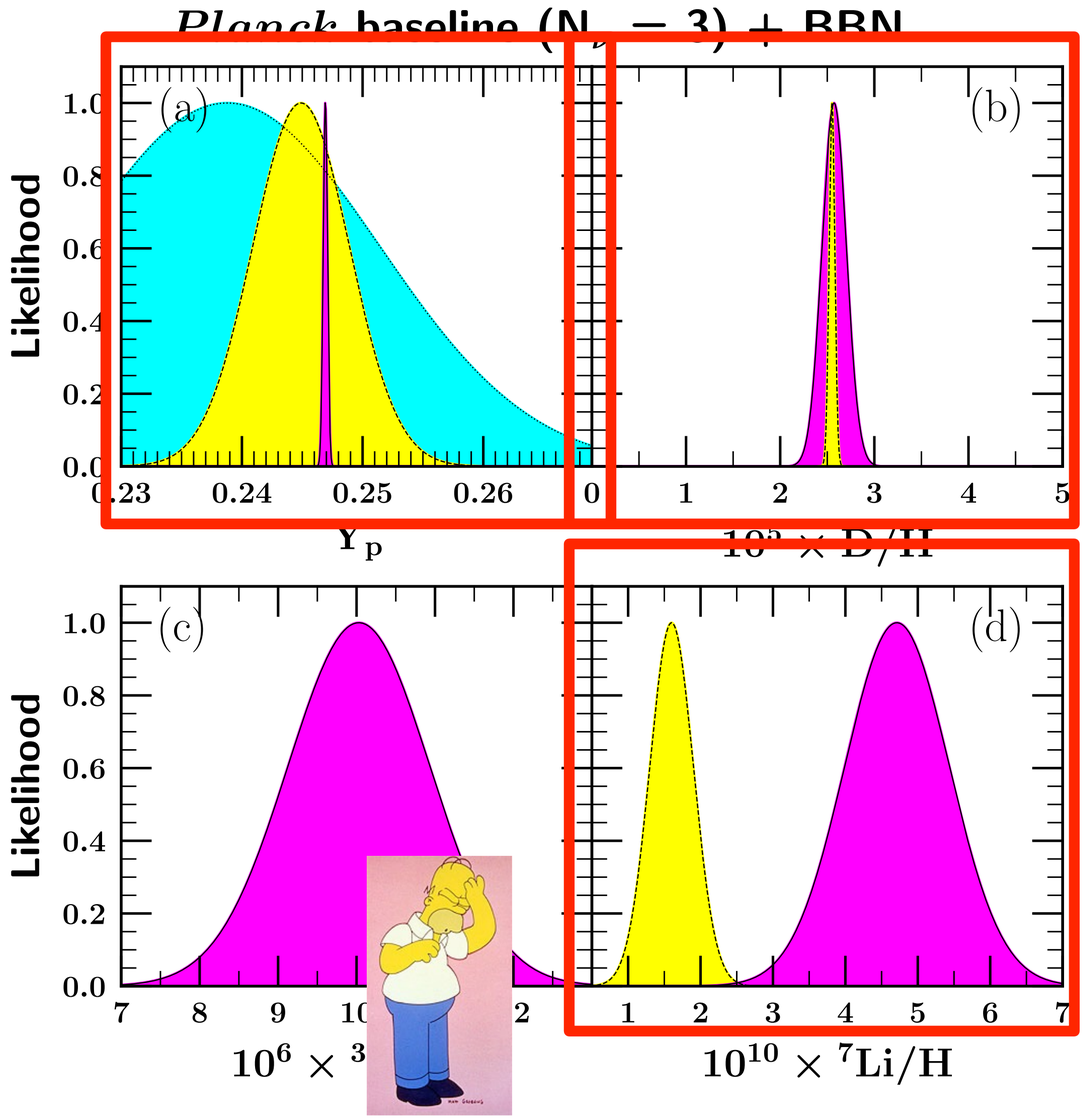
Battle of the Baryons: II
A Closer Look

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

Likelihoods

purple: BBN+CMB predictions

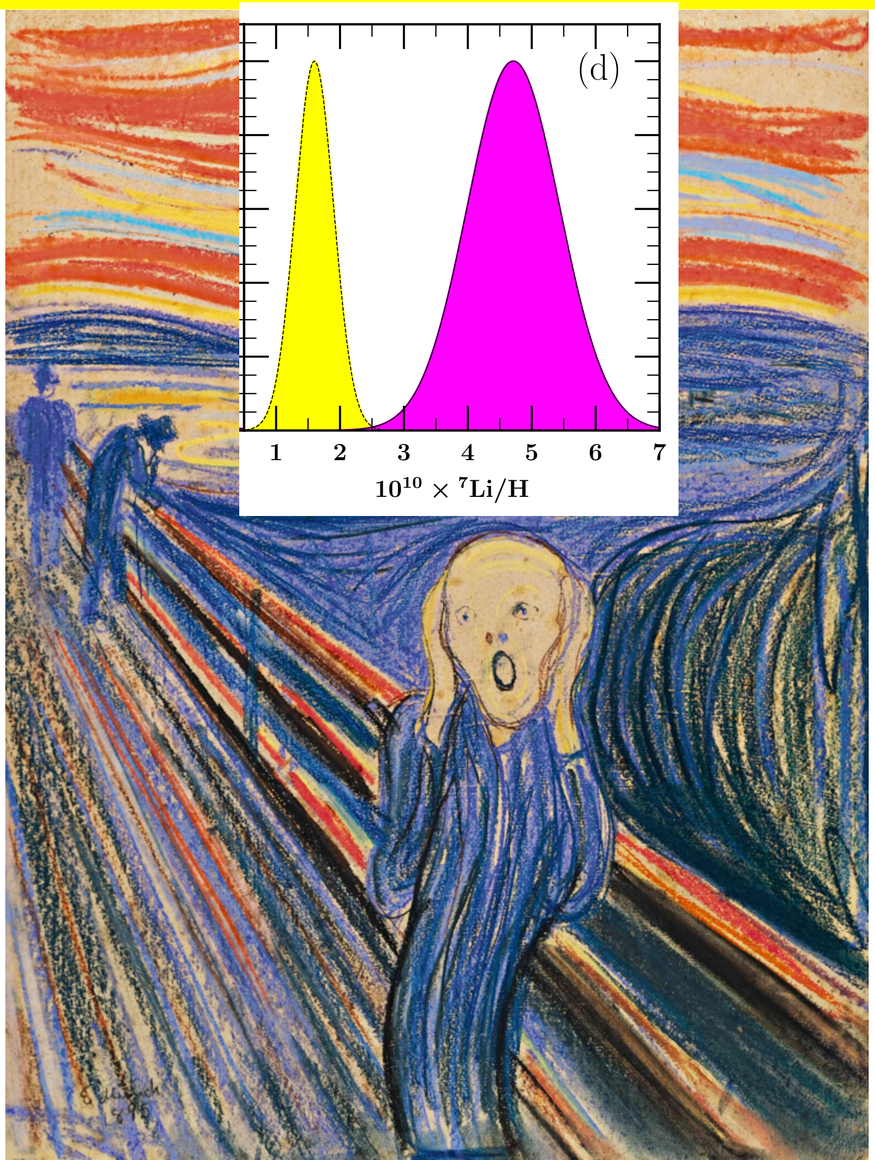
yellow: observations



Results:

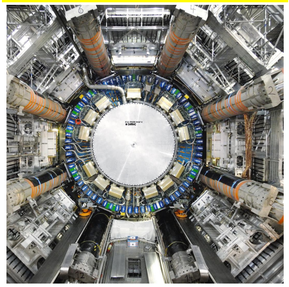
- D excellent!
- ^{4}He great!
- ^{7}Li poor!
  - observation ~ theory/4
  - 4-5 sigma discrepancy
  - Lithium Problem

The Lithium Problem

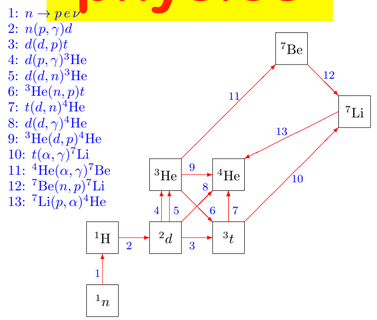


Lithium Problem Overview

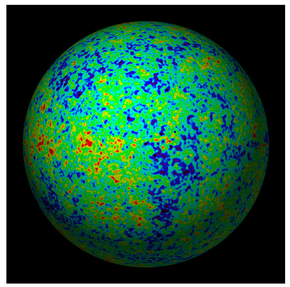
standard particle physics

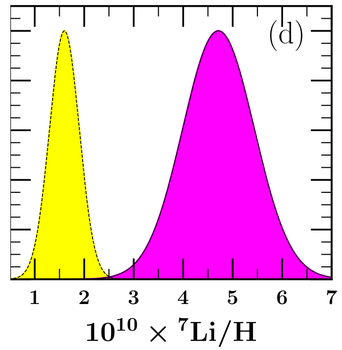


standard nuclear physics



standard cosmology $\neq$ **observed lithium**





Solutions: one of these is wrong

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

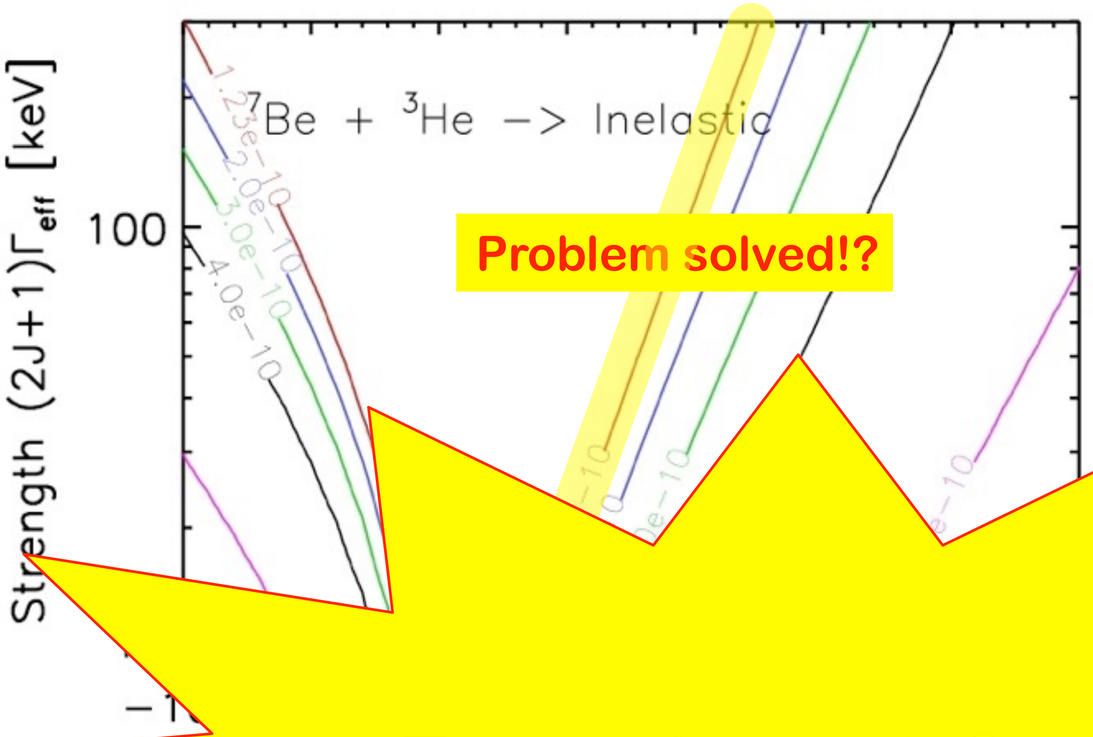
Chakraborty, BDF, & Olive 2011

- systematic study of all A=7 destruction rxns

  ✓ confirms $^{7}Be+d \Rightarrow {}^{9}B^{*}$

  ✓ even better: $^{3}He+{}^{7}Be \Rightarrow {}^{10}C^{*}$

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



Problem solved!?

Experiment Says: Not there!

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

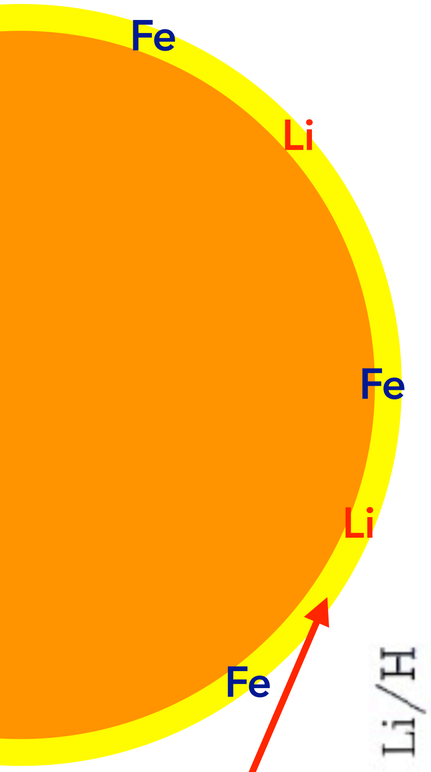
$^{9}Be^{*}$: O'Malley+ 2011

New Physics Lithium Solutions
an Incomplete Survey

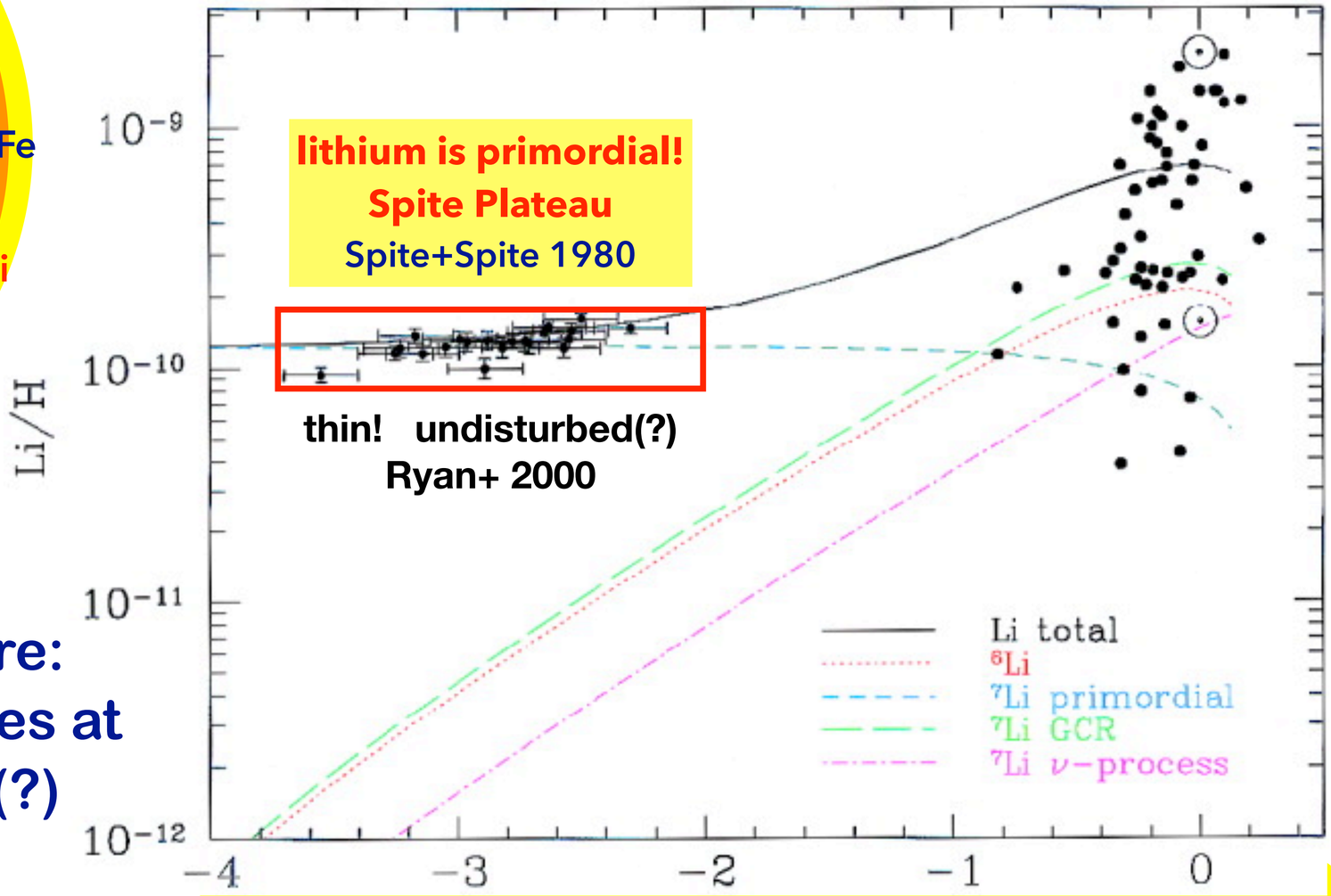
- **Particle Physics Beyond the Standard Model**
  - decaying particles Supersymmetry Cyburt+ 2012
  - mirror neutrons Coc+ 2013
  - magnetic fields+decays Yamazaki+ 2014
  - lepton asymmetry (degenerate neutrinos) Makki+ 2019
  - light particles with nucleon interactions Goudelis+ 2016
  - sterile neutrinos Salvati+ 2016
  - axion quark nuggets Flambaum+ 2019
  - Stable ^{8}Be Scherrer+ 2017
  - Non-extensive statistics Hou+ 2017
- **Evolving Fundamental Constants**
- **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

Primordial Lithium Observed: Halo Stars & the Spite Plateau



Observe atmosphere: abundances at star birth (?)



Monique & François Spite

Ryan, Olive, Beers, BDF, Norris 2000

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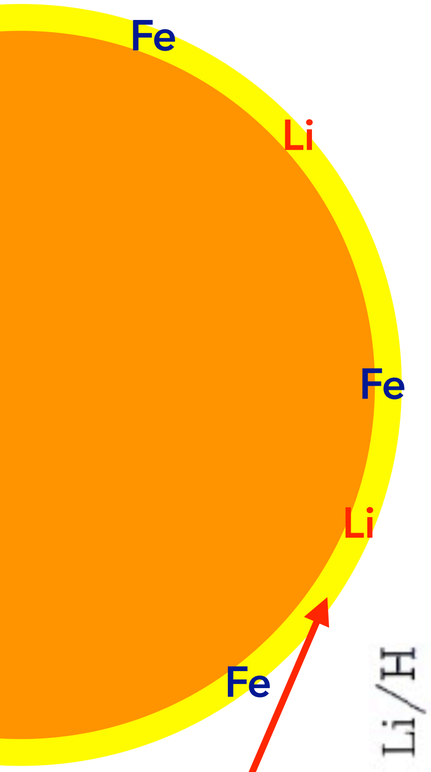

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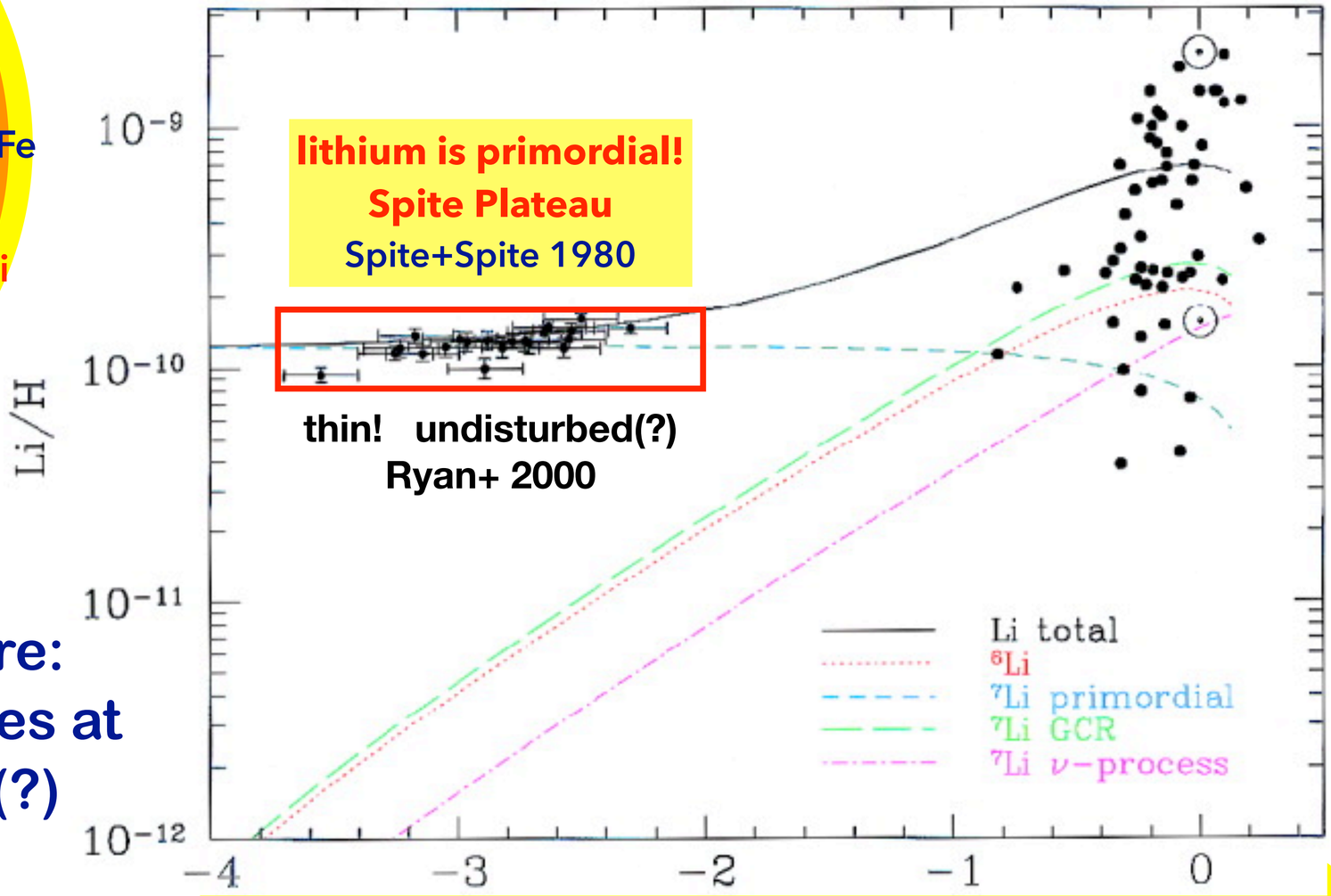


Monique & François Spite

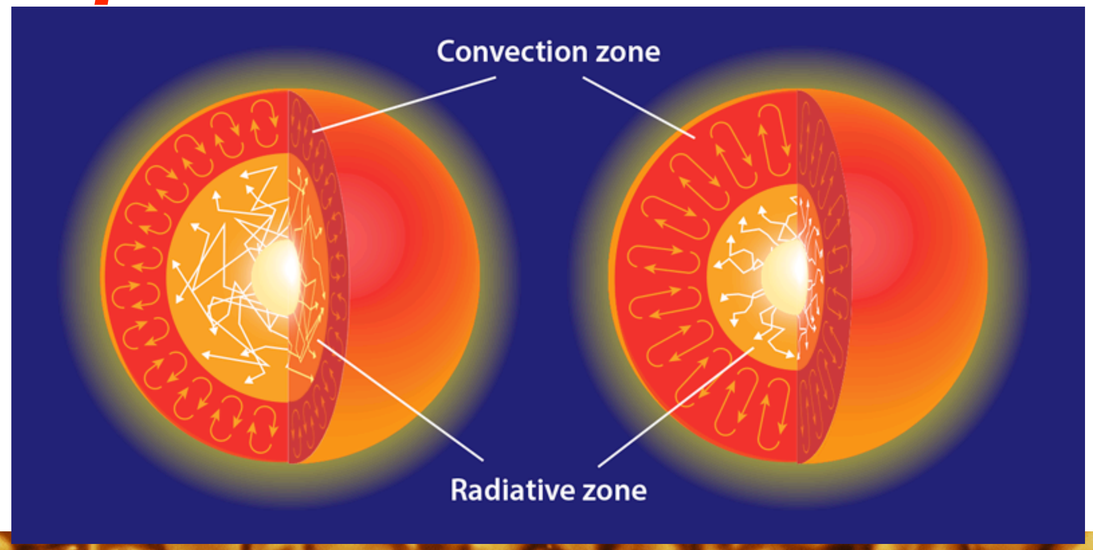
Ryan, Olive, Beers, BDF, Norris 2000

Lithium is Primordial

But is Spite Plateau the primordial value?

The Worry:

★**Convection** can lead to Li destruction

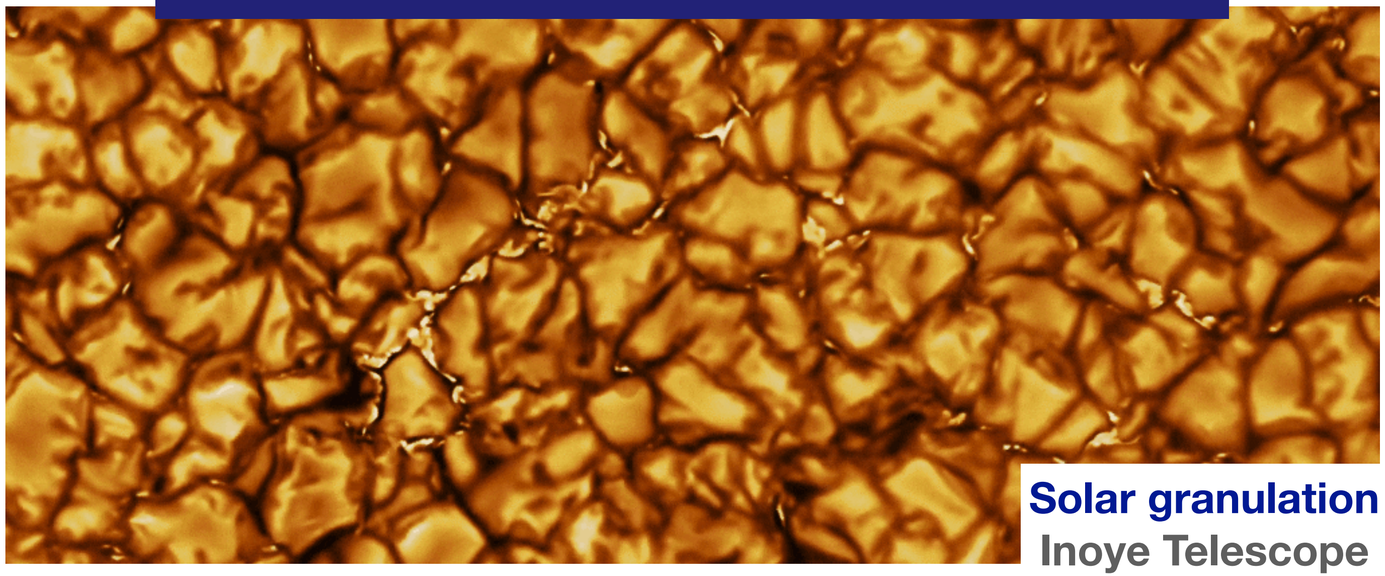


The Fix:

★select stars with thin convection zone

★empirically show largest Li levels

★consistent with thin Spite plateau

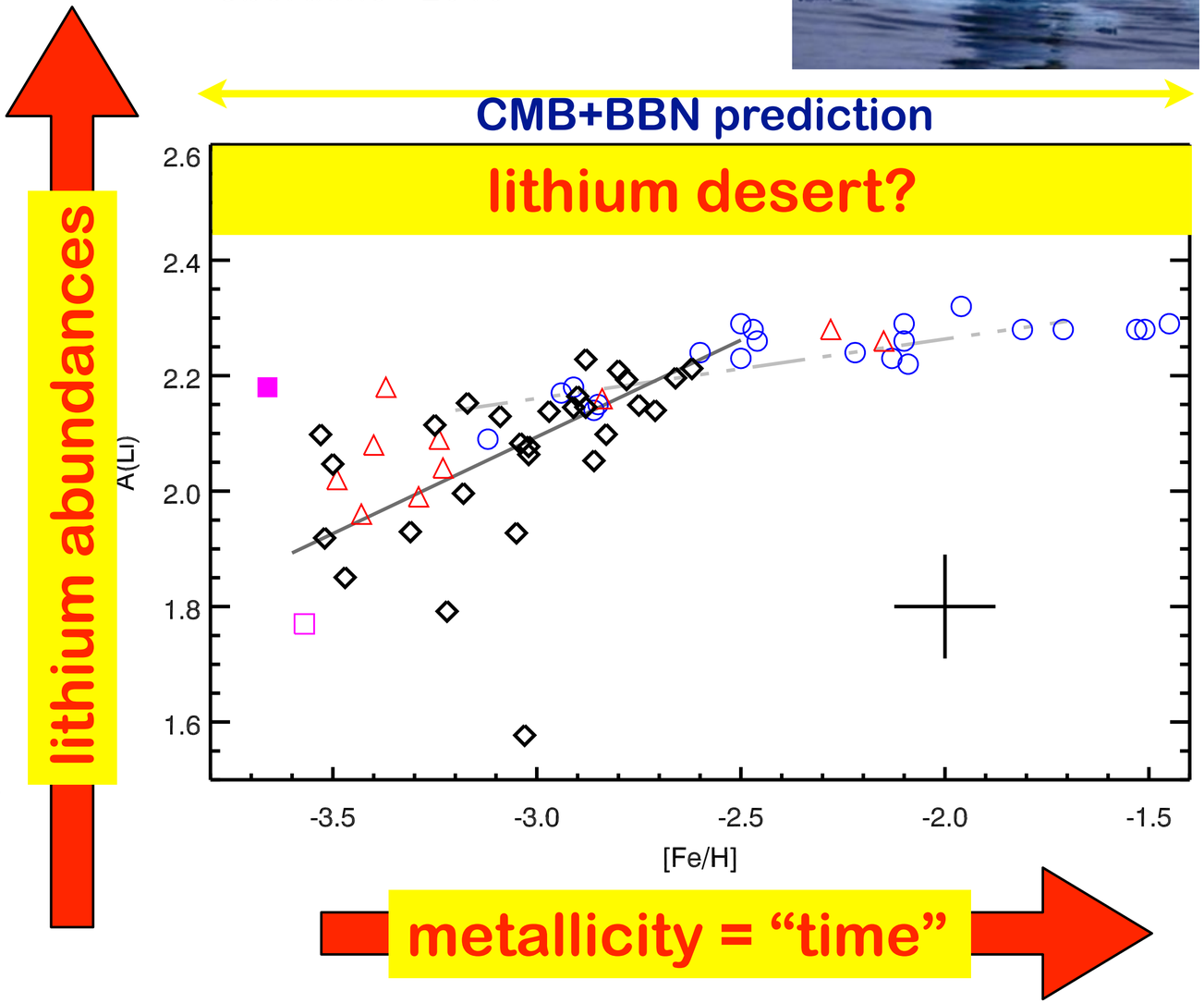


Solar granulation
Inoye Telescope

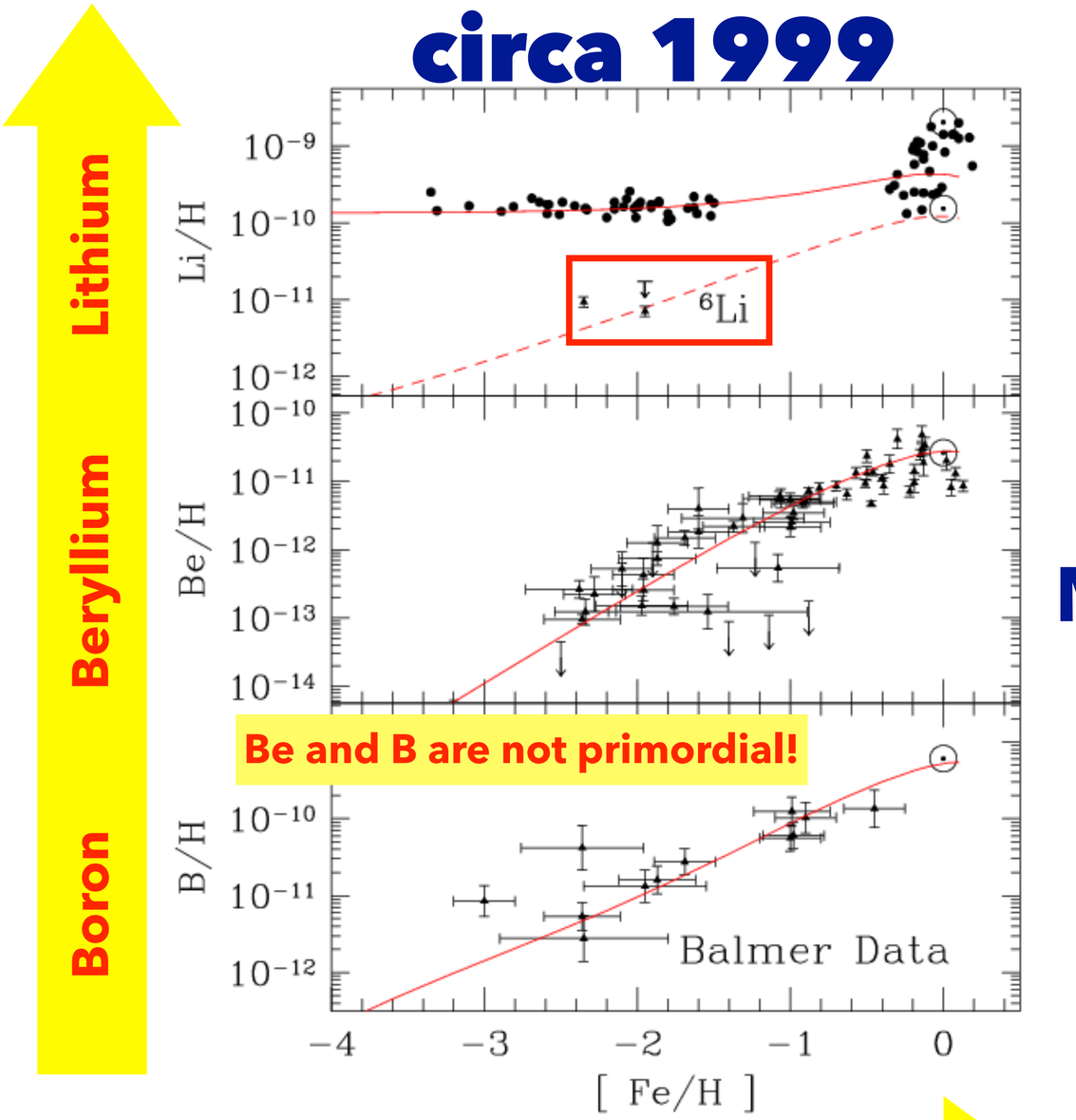
Update: Nuclear Meltdown

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



^{6}Li Constraints on Depletion circa 1999



^{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

Cosmic-Ray Nucleosynthesis of LiBeB

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

Cosmic Rays interact with ISM

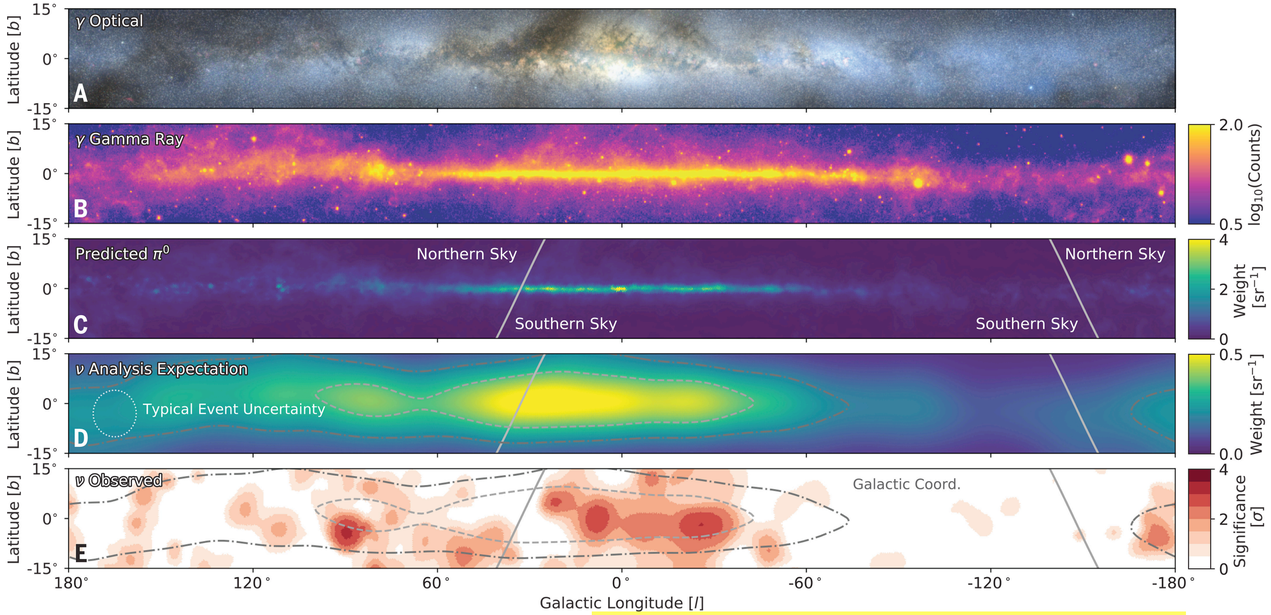
Interstellar gas: beam dump

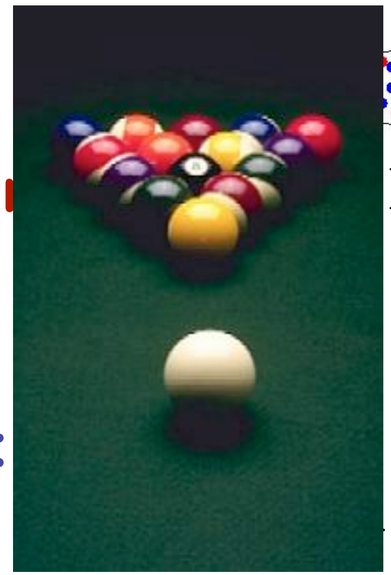
- Observe in gamma-ray sky

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

$$\pi^0 \longrightarrow \gamma\gamma$$

- Charged pions: IceCube signal
- Stable debris created





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

Fusion: α → ^{6}Li and ^{7}Li *only*

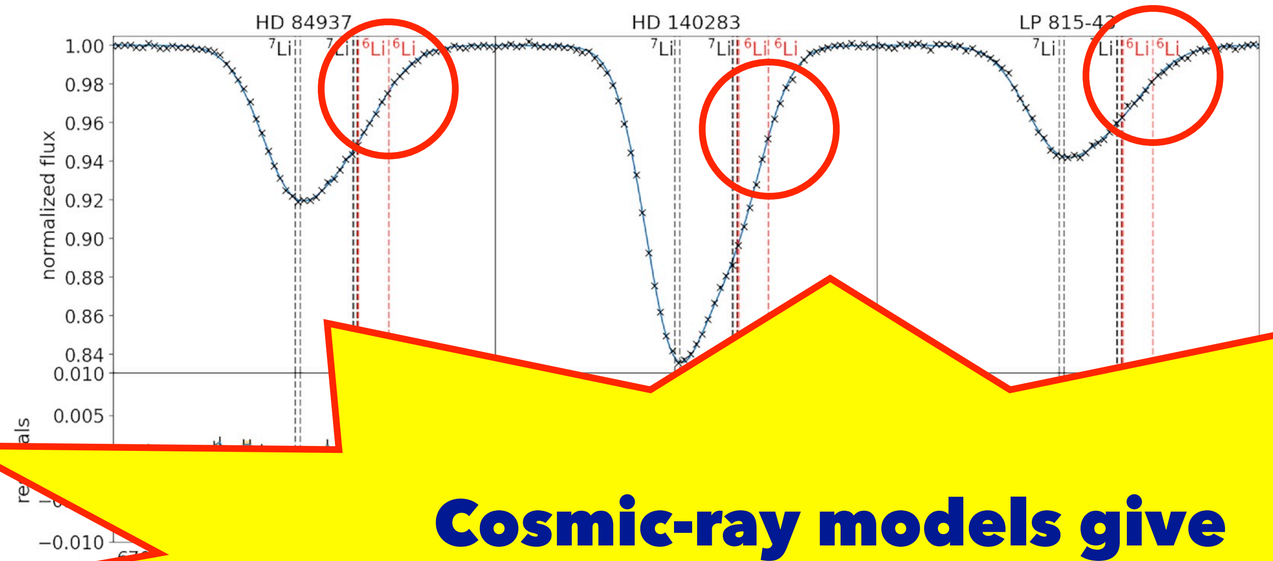
Cosmic Rays: guaranteed source of Li, Be, and B

Cosmic-ray Be and B demands ^{6,7}Li too!

Update: ^{6}Li Vanishes

- Wang+ 2021: high-precision spectroscopy
- no ^{6}Li signal as previously claimed
- Removes ^{6}Li argument against depletion
- No longer confident Li plateau is primordial level

Wang+ 2010:
Lithium Spectral Feature in 3 Ancient Stars



Cosmic-ray models give Li depletion allows BBN+CMB!

Implications: Lithium Problem Solved?

Good news—without lithium problem…

- agreement with many stellar evolution models
- BBN says hot big bang works back to 1 sec
- BBN+CMB concordance = cosmo triumph
- probes dark matter & other new physics

Bad news—Li unreliable for cosmo

…for now. Clever ideas needed!

No Lithium Worries?
BBN Probes New Physics

Dark Matter

Census of cosmic matter

- ★ BBN: baryons
- ★ CMB: all gravitating matter
- ★ Optical galaxy surveys: luminous matter

Mismatch demands dark matter: two kinds!

Baryonic Dark Matter:

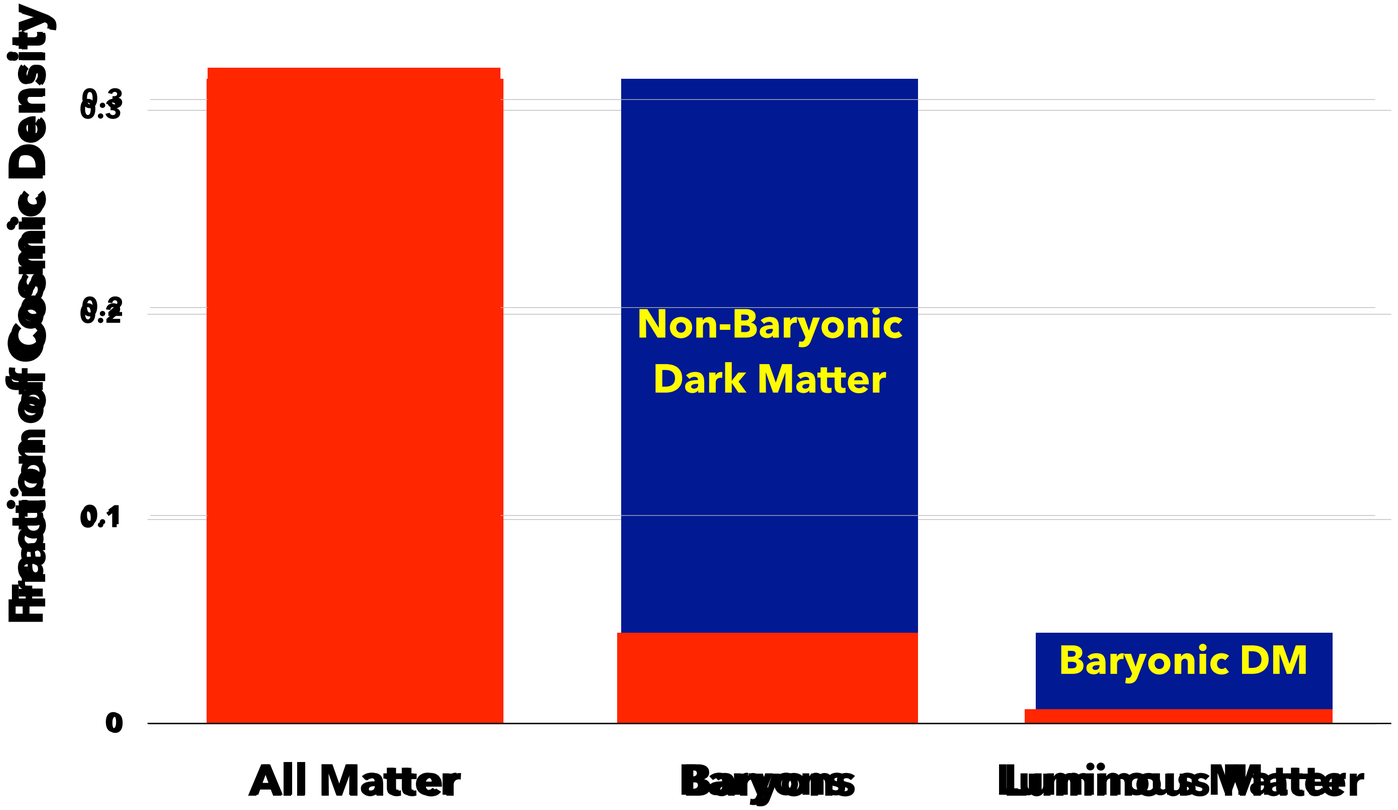
➡ most (?) is hot intergalactic gas

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

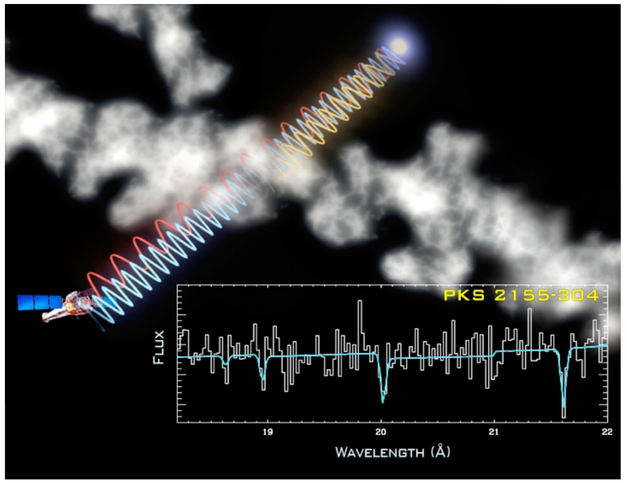
Non-Baryonic Dark Matter:

➡ most of cosmic matter!

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



Bullet Cluster



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

BBN Probes New 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**

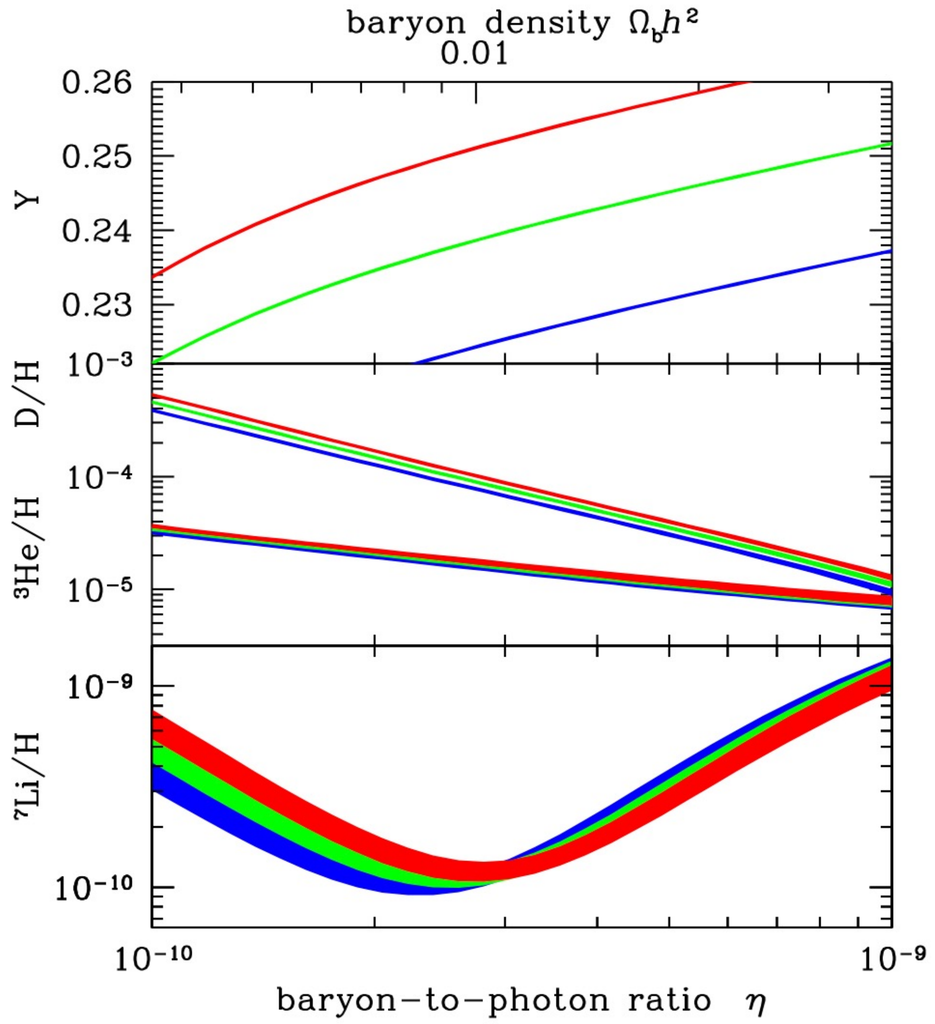
Stiegman, Schramm, & Gunn 77

All light elements sensitive to $N_{\nu,\text{eff}}$

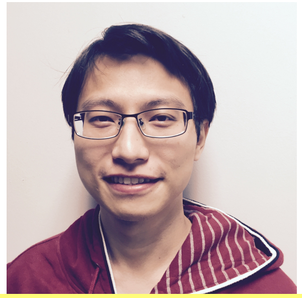
New! D/H now an interesting probe

7Li shift right direction but small

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



Cyburt, BDF, Olive, Yeh 2015



Tsung-Han Yeh
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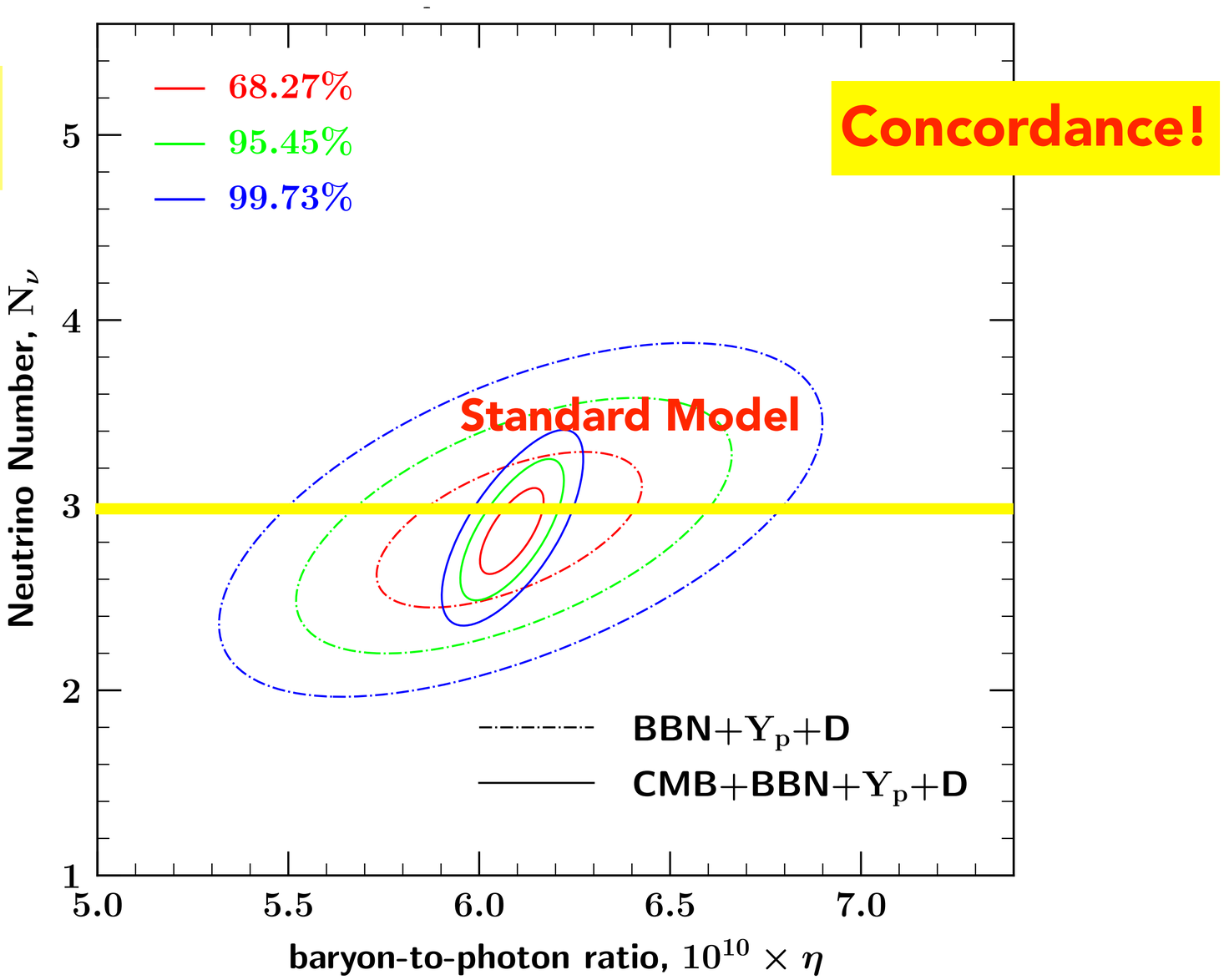
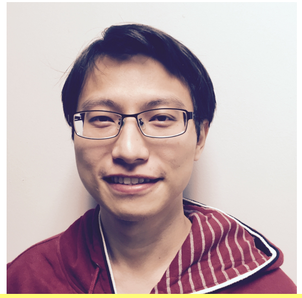
Planck 2018 + BBN

BDF, Olive, Yeh, Young 2020





Tsung-Han Yeh
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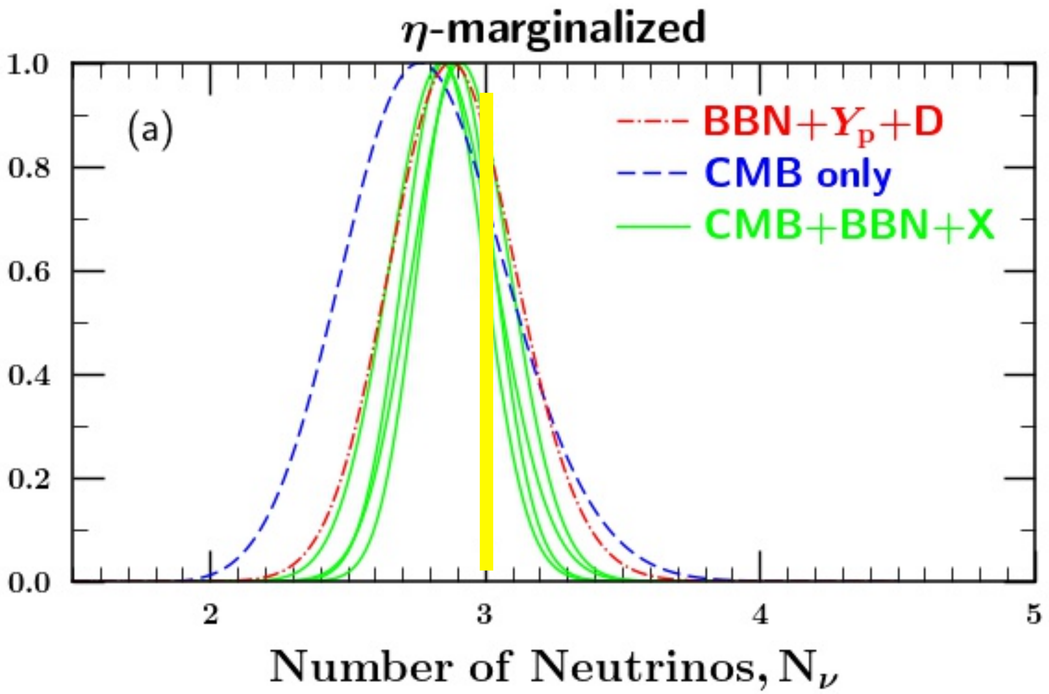
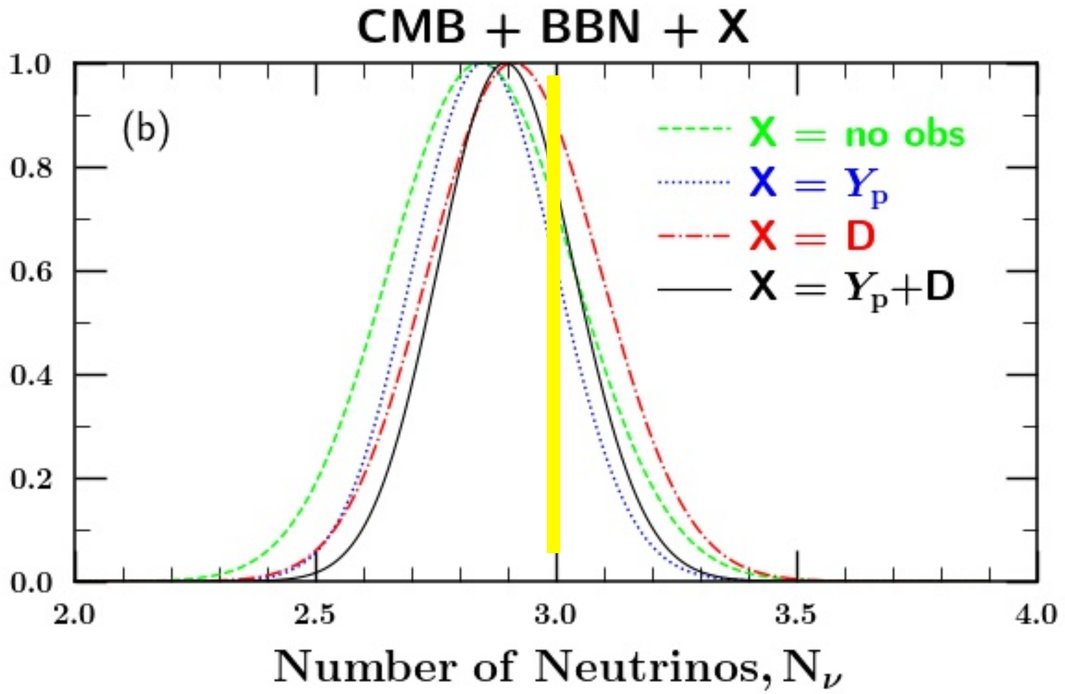
Planck 2018 + BBN

Yeh, Shelton, Olive, BDF 2022





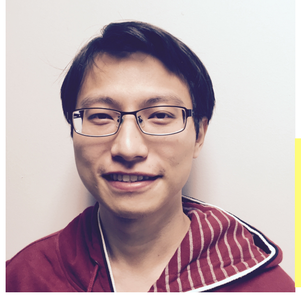
$$N_\nu = 2.898 \pm 0.141$$

$$N_\nu < 3.180 \quad (2\sigma)$$

Consistent with the Standard Model!

Implications for, e.g.,

- ✓ right-handed neutrinos
- ✓ dark radiation
- ✓ stochastic gravitational waves
- ✓ tracker fields
- ✓ primordial magnetism



Searching for New Physics Between BBN & CMB

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Yeh, Shelton, Olive, BDF 2022

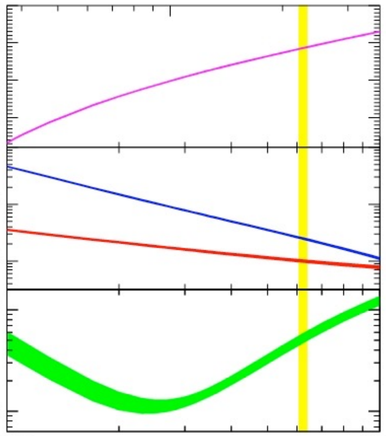
Jessie Shelton

Big-Bang Nucleosynthesis (BBN)

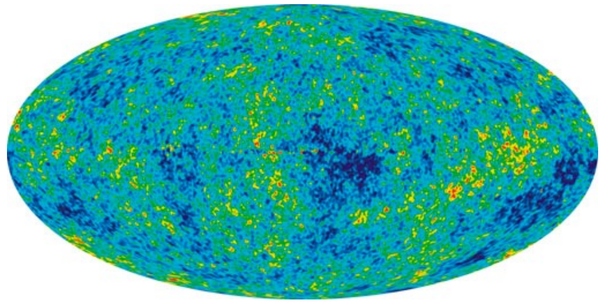
t~1 sec, T~1 MeV nuclear physics

Cosmic Microwave Background (CMB)

t~400,000 yr; T~1 eV atomic physics



Wagoner, Fowler, & Hoyle 1967;
Yeh, BDF, & Olive 2021



Penzis & Wilson 1965; Planck 2018

Now ***independently*** probe

- baryon-to-photon ratio

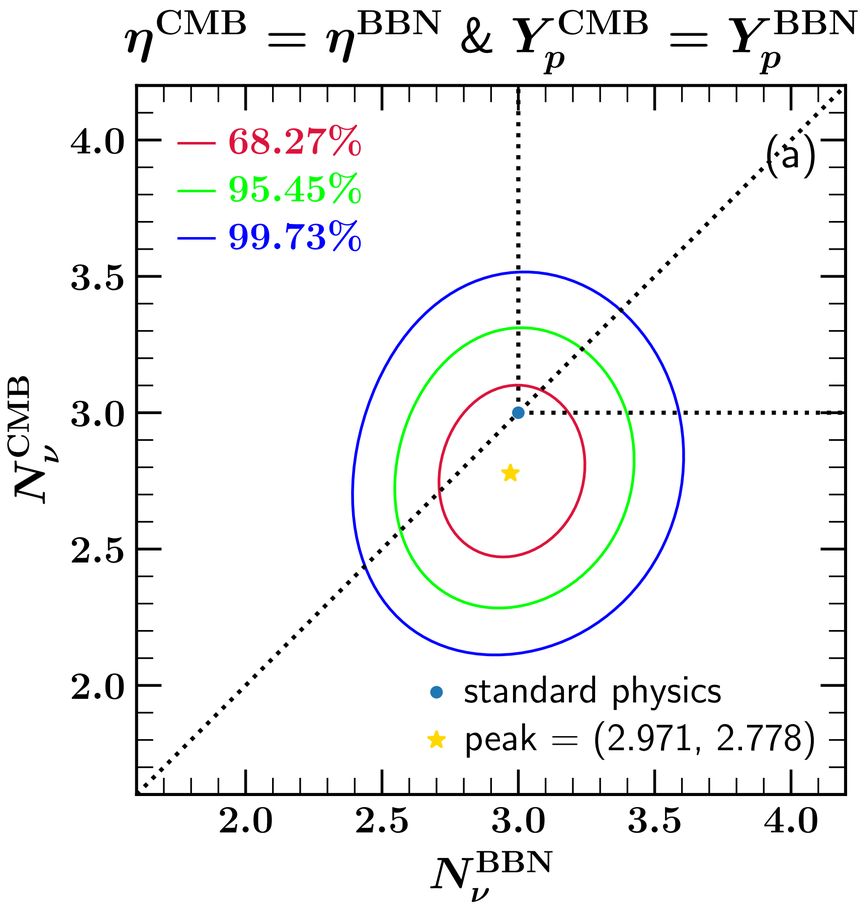
  usual cosmo: $\left(\frac{n_{\rm B}}{n_\gamma}\right)_{\rm BBN} = \left(\frac{n_{\rm B}}{n_\gamma}\right)_{\rm CMB}$ no important photon (entropy) production

- effective number of neutrino species

  usual cosmo: $N_\nu^{\rm BBN} = N_\nu^{\rm CMB}$ no change* in relativistic degrees of freedom

*aside from e+e- neutrino heating $N_{\rm eff}^{\rm CMB} = N_\nu^{\rm CMB} + 0.044$

Limits on N_{nu} Change



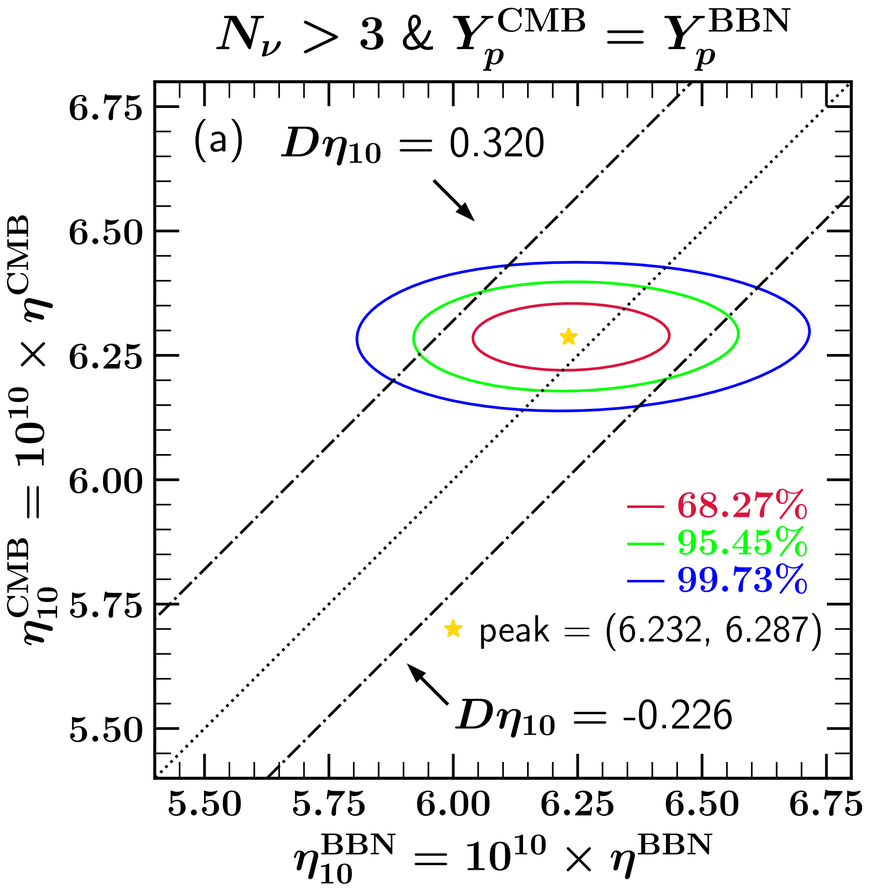
Yeh, Shelton, Olive, BDF 2022

Consistent with standard cosmology

Implications for, e.g.,

- ✓ early dark energy models for H_0 problem
- ✓ relativistic relic becoming non-relativistic
- ✓ late equilibrium with neutrinos

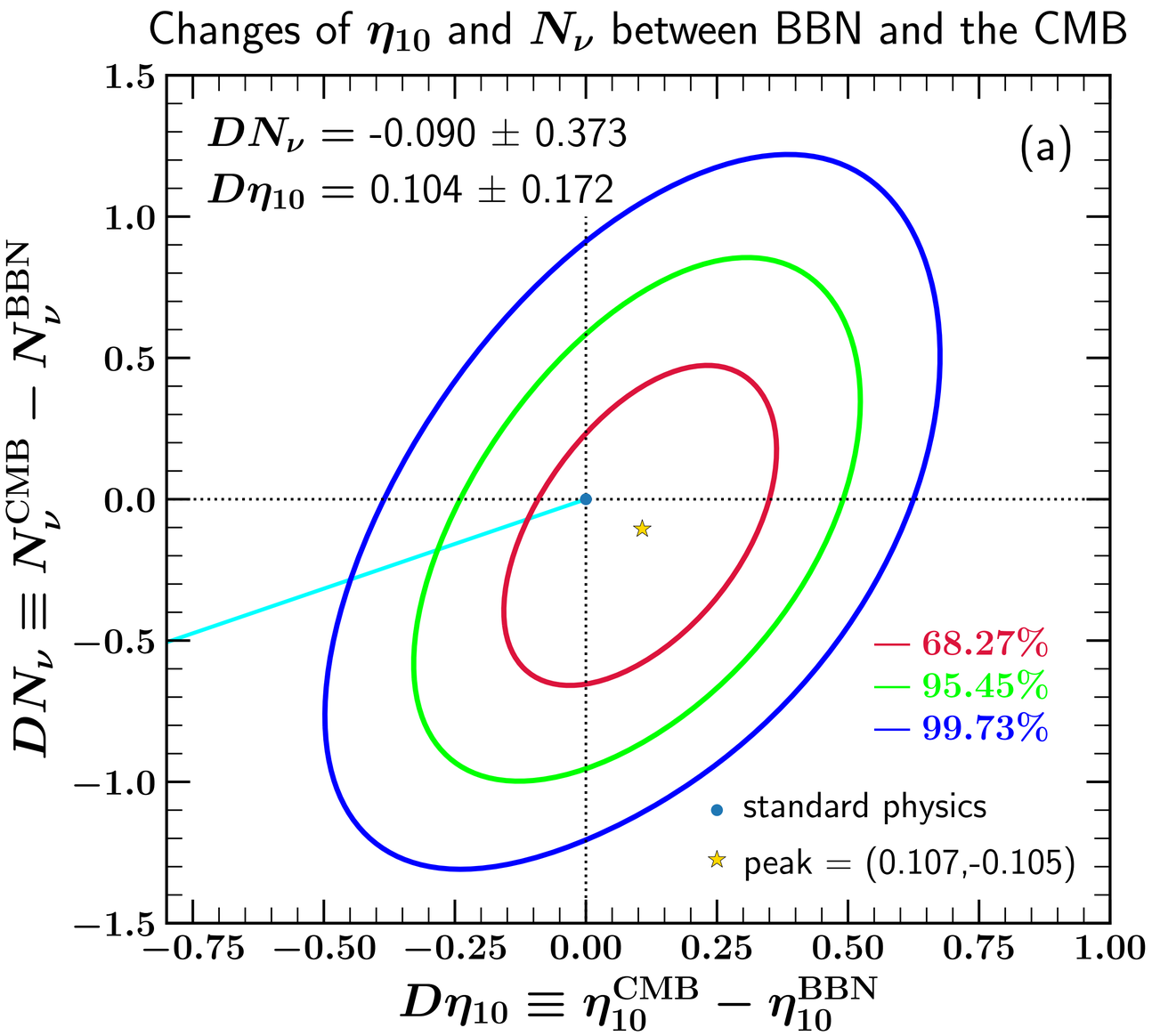
Limits on Baryon-to-Photon Change



Yeh, Shelton, Olive, BDF 2022

Consistent with standard cosmology

Limits on Change in Both



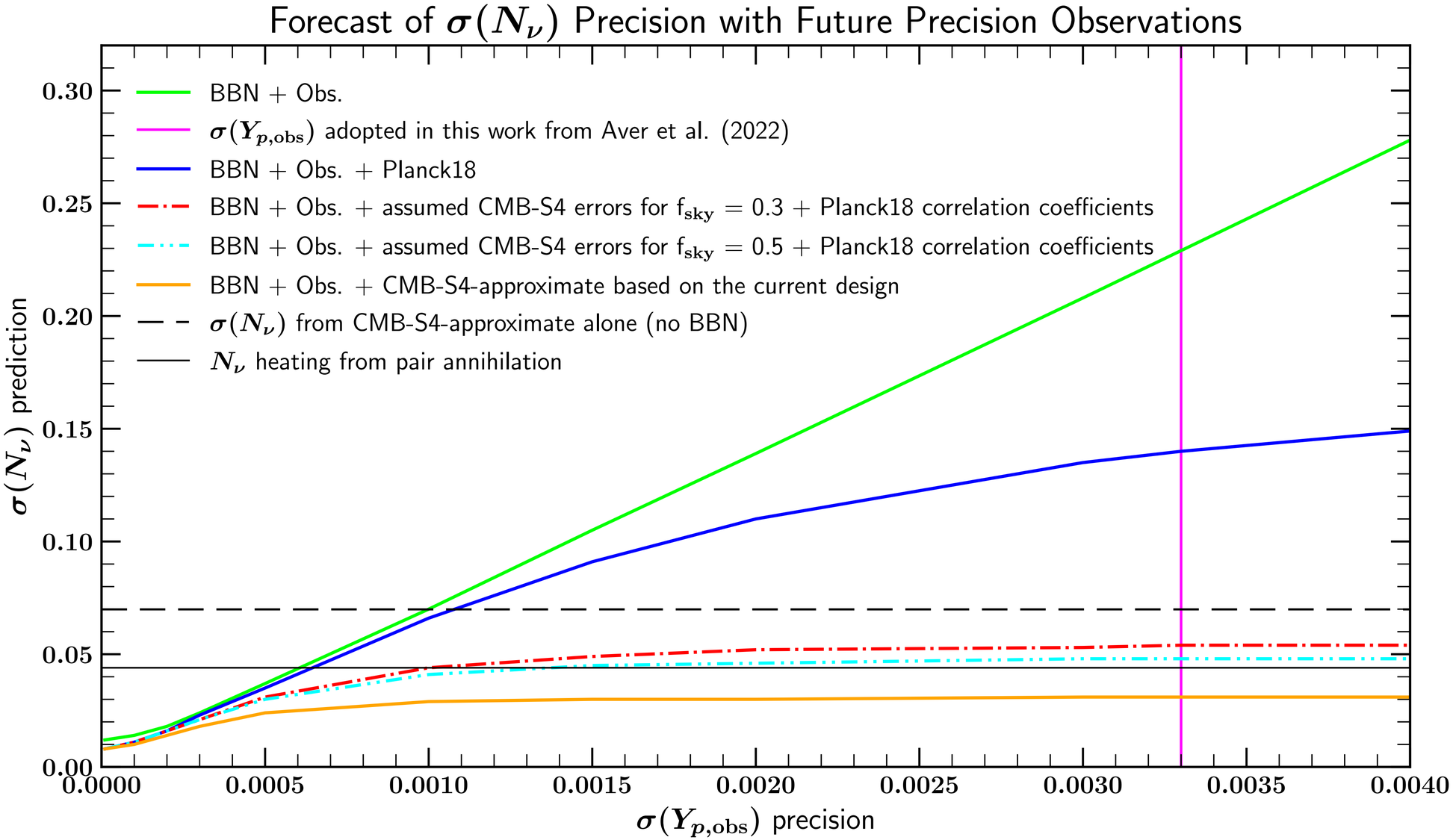
Consistent with standard cosmo

Implications for, e.g.

✓ out-of equilibrium decay between BBN and CMB epochs

Yeh, Shelton, Olive, BDF 2022

The Future: CMB – Stage 4



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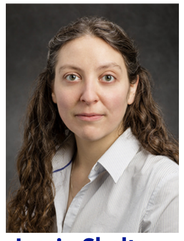
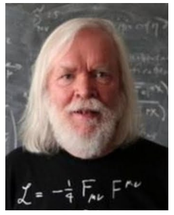
Nachiketa Chakraborty

Richard Cyburt

Keith Olive



Jessie Shelton



John Ellis

OUTLOOK

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
- Closer interplay with dark matter & accelerator physics

Stay Tuned!