Neutrino Theory and Astrophysics and Cosmology

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HEISING-SIMONS FOUNDATION

NC STATE UNIVERSITY

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

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Outline

I. Theory and Observational motivation

II. Big Bang Nucleosynthesis

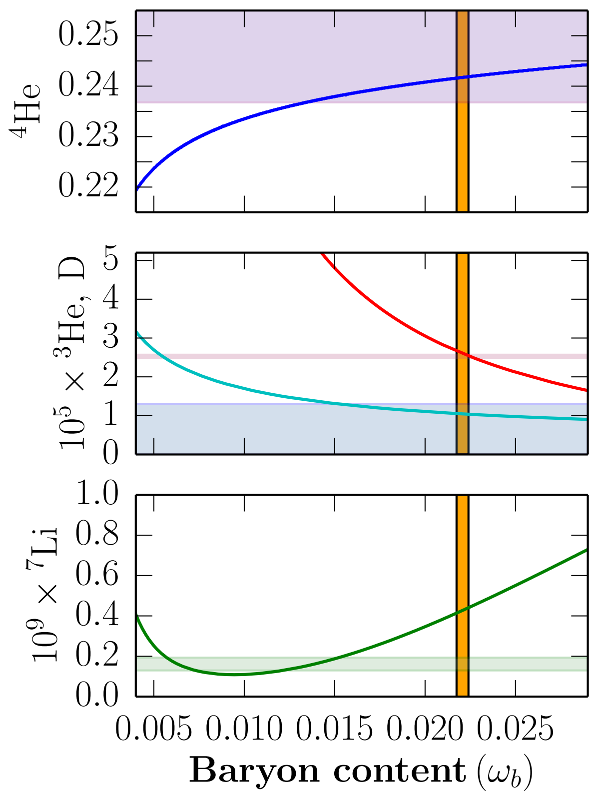
III. Radiation in the Cosmic Microwave Background

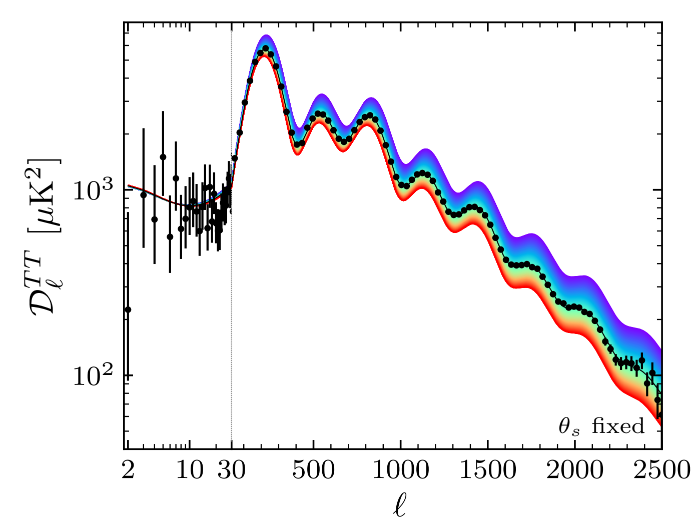
IV. Matter Power Spectrum

V. Sterile Neutrino Dark Matter

VI. Neutrino Secret Interactions

VII. Summary





Astrophysical Neutrino "*Laboratories*"

Early Universe, Weak Decoupling/BBN

Gravitation dictates a **slow expansion**, allowing very weakly interacting particles to affect the physics. **Large entropy-per-baryon**, $S/k_{\mathrm{b}} \sim 10^{10}$, simplifying the nuclear physics. **Low lepton numbers**, implying very small $\nu - \bar{\nu}$ asymmetry.
n/p, deuterium (D), helium, N_{eff} sensitive to any BSM physics that alters the time/temperature/scale factor relationship.

very tightly constrained
by CMB (soon Stage-4) observables and 30m-class telescope-determined D/H.

Stellar Collapse, supernovae, binary compact object mergers

Weak interaction dictates all aspects of evolution. Very **large** electron lepton number, so evolution is **exquisitely sensitive to lepton number violation**.

Low-to-high entropy, $S/k_{\mathrm{b}} \sim 1$ to ~ 100; primary site for intermediate and heavy nucleus nucleosynthesis; many aspects can be sensitive to neutrino flavor transformation and BSM physics.

Manufactures neutron stars and black holes.

Not well constrained

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$$

The coming era of precision cosmology

I. CMB Stage-IV (2203.07638) and others
   A. Simons Observatory - Atacama Desert, Chile
   B. South Pole Observatory - South Pole
   C. Other CMB experiments - CLASS and QUIET
   D. Satellites: LiteBIRD and PIXIE

II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT – Mauna Kea, Hawaii

III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ
   C. Vera Rubin Observatory – Cerro Pachón, Chile
   D. Satellites: Euclid, Roman, SPHEREx

Snowmass 2021 White Paper

Synergy between cosmological and laboratory searches in neutrino physics: a white paper

Editors: Martina Gerbino[1], Evan Grohs[2], Massimiliano Lattanzi[3]

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arXiv: 2203.07377

Physics of Big Bang Nucleosynthesis

Setting the stage:

a. Homogeneous & Isotropic
b. Nearly CP symmetric (10^{-10}) [cf. 2204.08668]
c. No free quarks

Synthesis of light-elements:

- Hydrogen ~ 0.75
- Helium ~ 0.25
- Deuterium $\sim 10^{-5}$
- Lithium $\sim 10^{-10}$

Sub-epochs of BBN

Weak Decoupling: $\nu(\nu,\nu)\nu$ & $e(\nu,\nu)e$

Weak Freeze Out: $n(\nu,e)p$

EM equilibrium: $e(e,\gamma)\gamma$

Nuclear Freeze Out: $n(p,\gamma)d$

Baryogenesis $\sim$?

↓

QCD Epoch $\sim 10^{-5}$ s

↓

Time $\lesssim 1$ sec.

↓

Time $\gtrsim 100$ sec.

Out-of-Equilibrium Neutrino Energy Transport

Neutrino scattering on charged leptons

$$\nu_i + \overline{\nu}_i \leftrightarrow e^- + e^+$$

$$\nu_i + e^\pm \leftrightarrow \nu_i + e^\pm$$

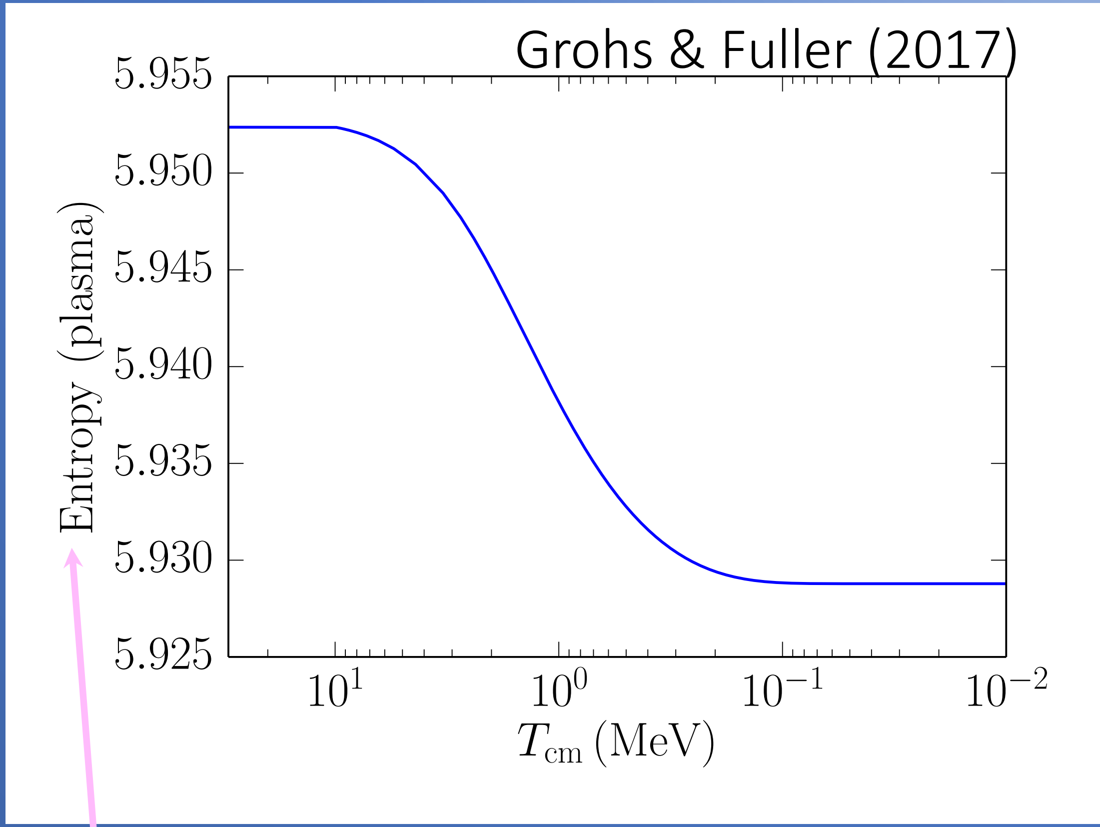
Important for CMB parameter for radiation energy density

$$\delta\rho_\nu \sim 1\%$$

Neutrino Transport coupled to Nuclear Reaction Network (Grohs et al 2016)

$$\delta(^4\text{He}) \sim 4 \times 10^{-4}$$

$$\delta(\text{D/H}) \sim 3 \times 10^{-3}$$



$\sim\omega_b$

Deuterium sensitive to entropy!

Neutron-to-Proton Rates

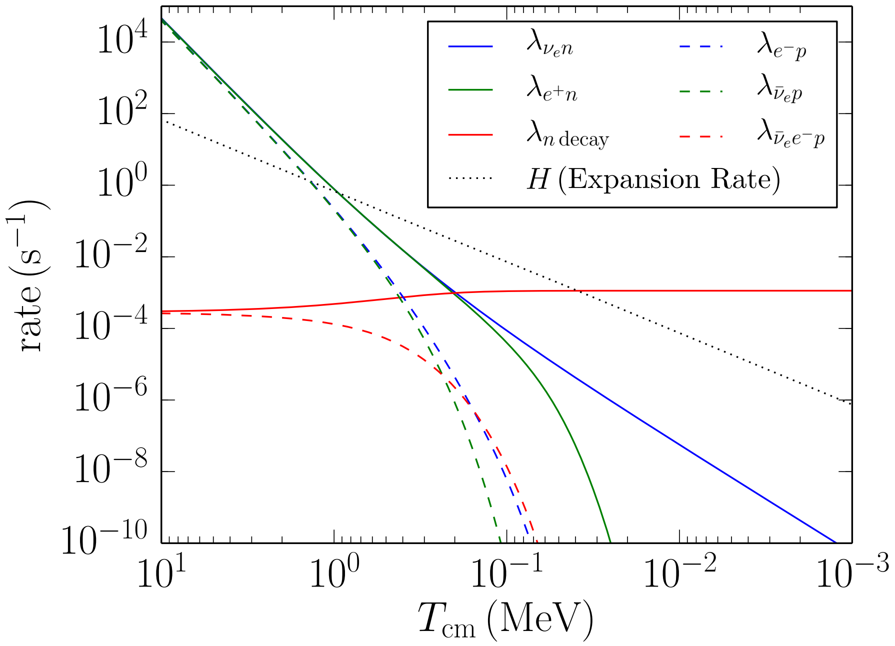
$$\nu_e + n \leftrightarrow p + e^-$$

$$e^+ + n \leftrightarrow p + \overline{\nu}_e$$

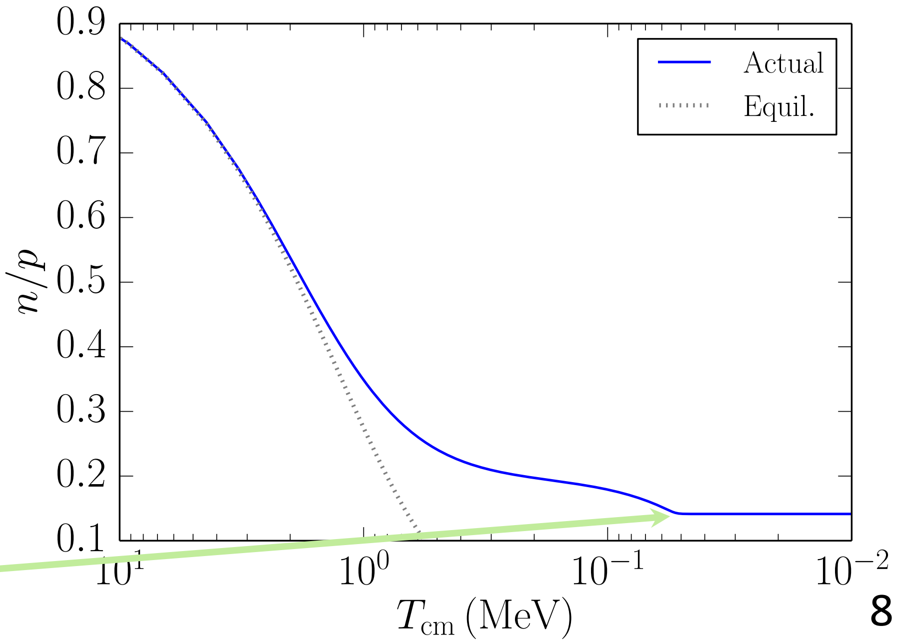
$$n \leftrightarrow p + e^- + \overline{\nu}_e$$

6 rates normalized to neutron lifetime

$m_n - m_p \simeq 1.3$ MeV



Grohs & Fuller (2016)



Rule of thumb: ^{4}He 25% by mass

$$\begin{matrix} p & p & p & p & p & p & p & n \\ p & p & p & p & p & p & p & n \end{matrix}$$

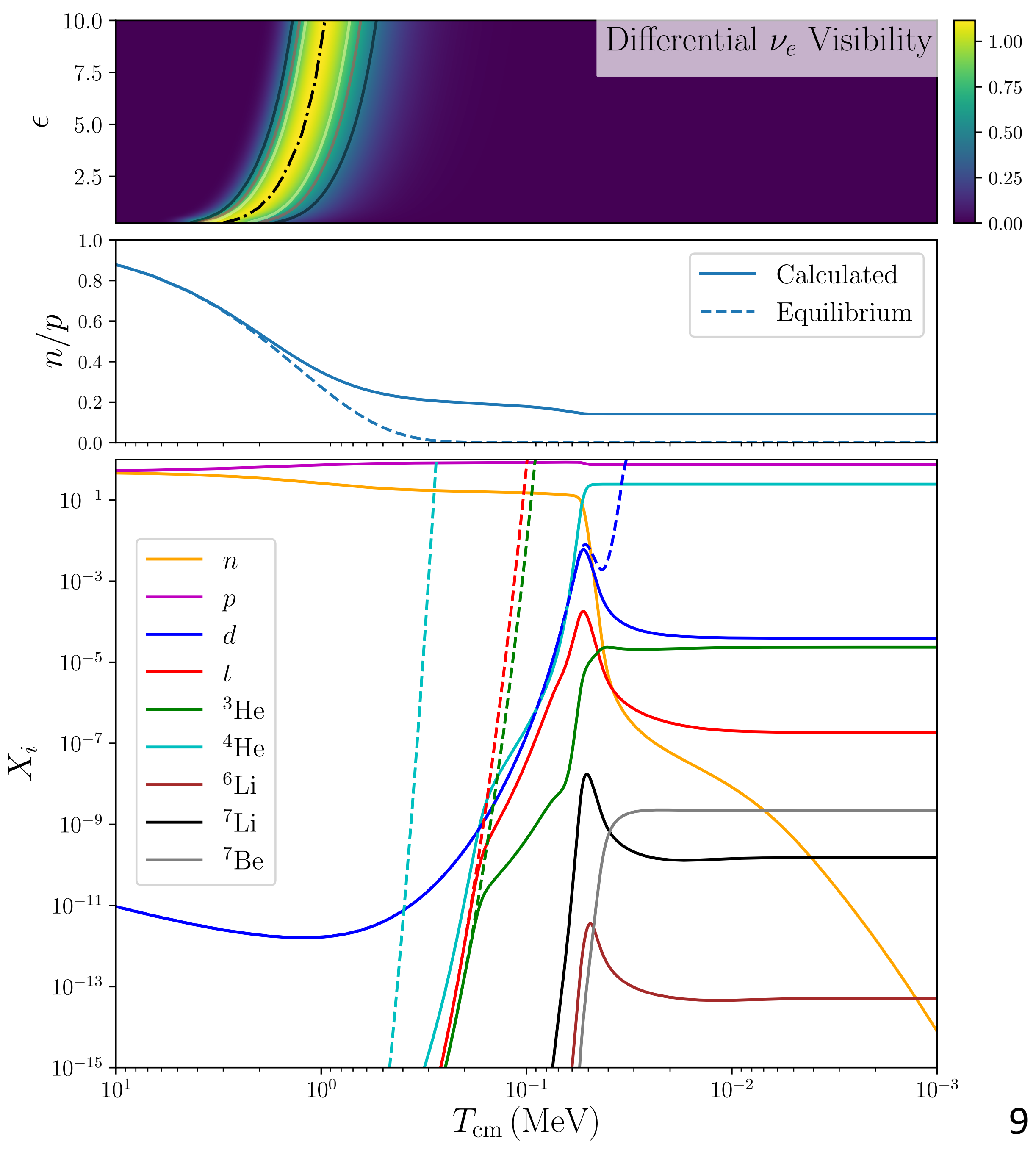
$n/p \sim 1/7$

Neutrino physics occurring during BBN

Coincident epochs during BBN:

- Weak Decoupling (Diff. Vis.)
- Weak Freeze-Out (n/p)
- Nuclear Freeze-Out (X_i)

Dashed lines: weak equilibrium or NSE



Bond+ (In Prep.)

Radiation energy density during Recombination

Computing CMB observables requires energy density

$$\rho_{\rm rad} = \rho_\gamma + \rho_{\rm other} = \left[2 + 2\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\frac{\pi^2}{30}T^4$$

Photon Contribution

Non-Photon Contribution

Effective number of neutrinos: parameter for non-photon energy density

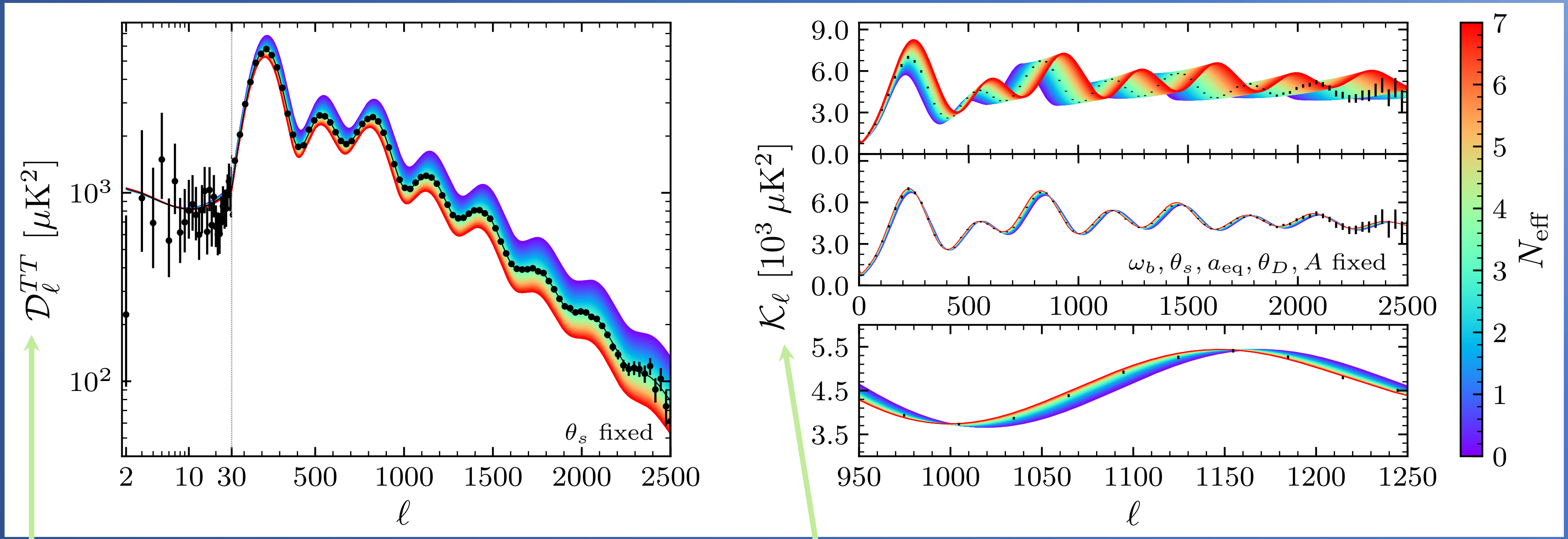
Need not be an integer!

Theory: $N_{\rm eff} = 3.045$

Cf. 2203.07943 & talk by B. Wallisch

Effects of Radiation on CMB

Black points are Planck 2018 data values



Temperature Power Spectrum

Non-damped Temperature Power Spectrum

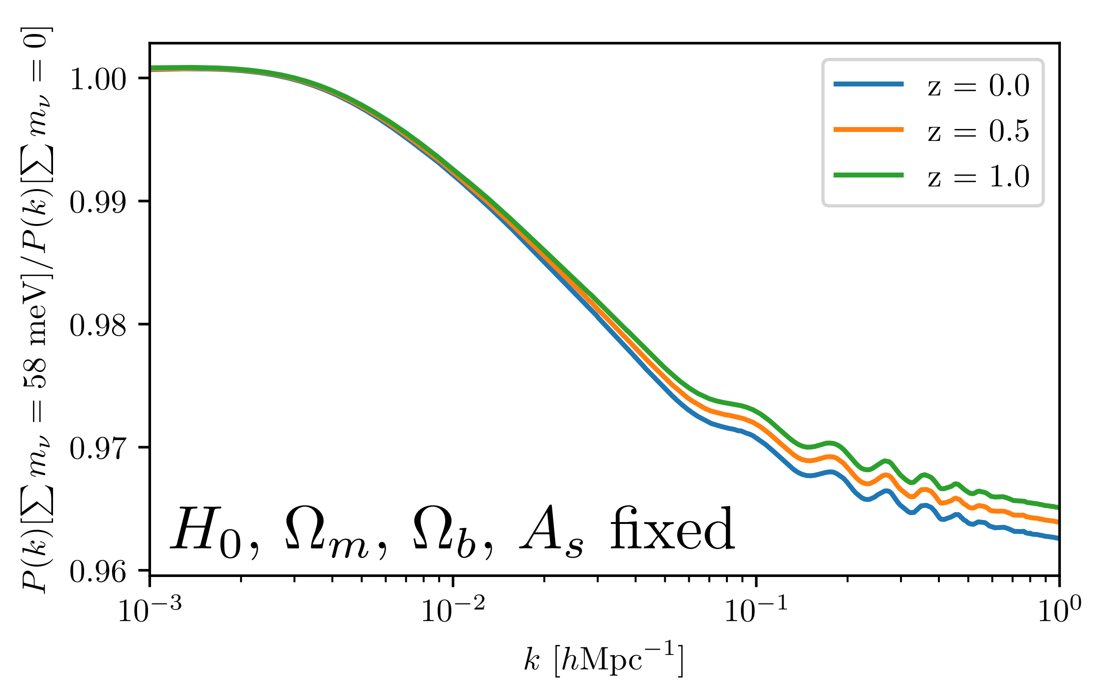
Non-photon radiation

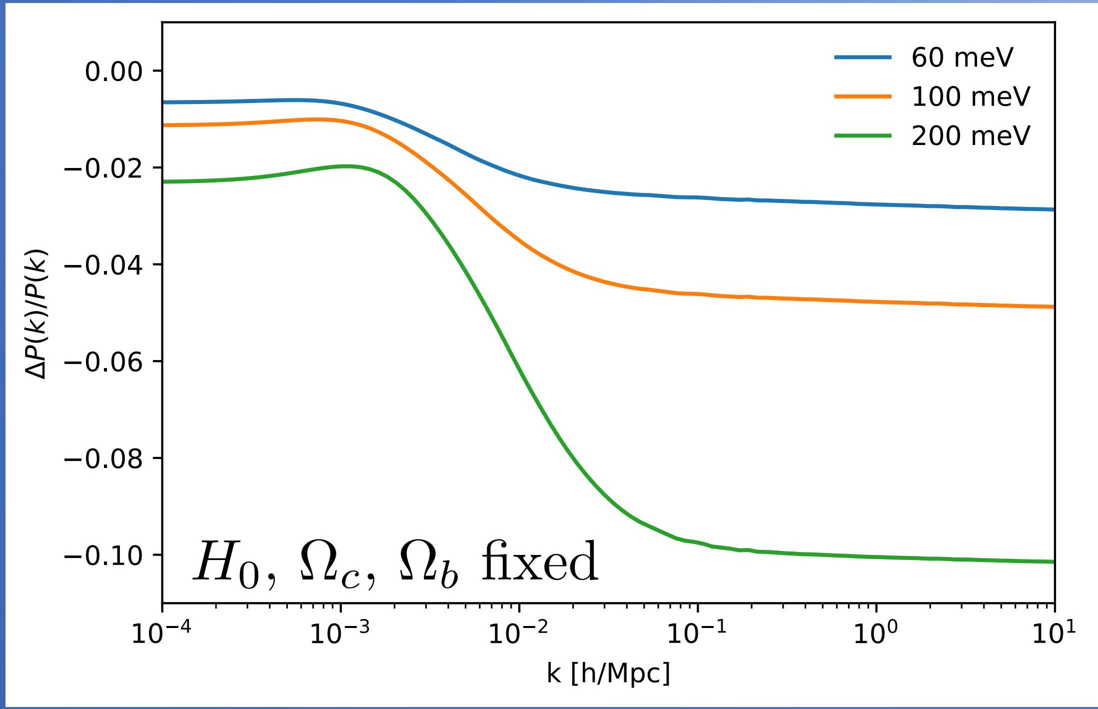
Free-streaming radiation

Planck 2018: $N_{\rm eff} = 2.92^{+0.18}_{-0.19}\,(1\sigma)$

Matter Power Spectrum

Neutrinos become non-relativistic: $z_{\rm nr} \sim 100$

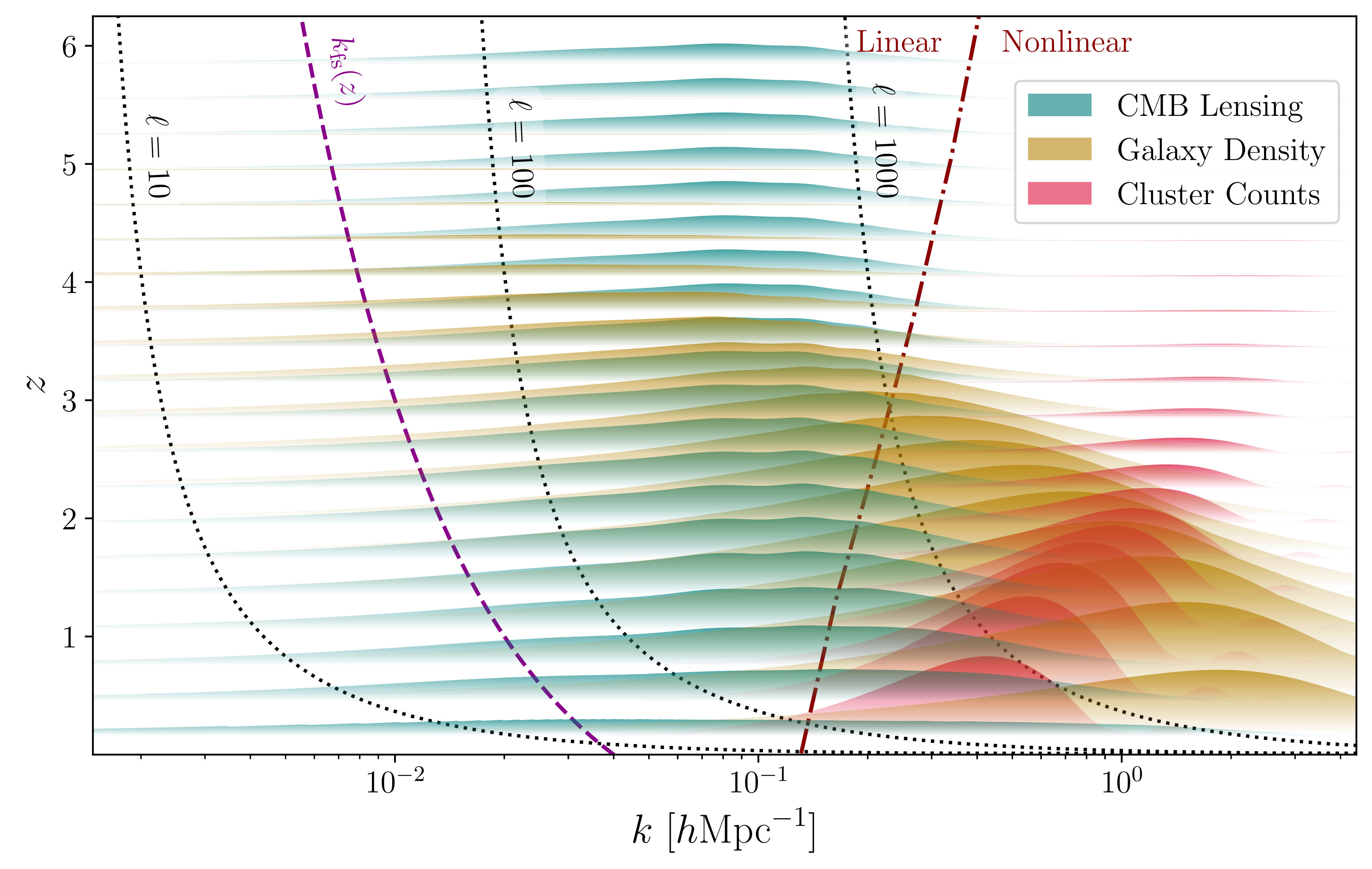




Power suppressed from neutrino free-streaming at small scales

Planck 2018: $\Sigma m_\nu < 0.120\,\mathrm{eV}\ (2\sigma)$

Contributions to Matter Power Spectrum (forecasts)



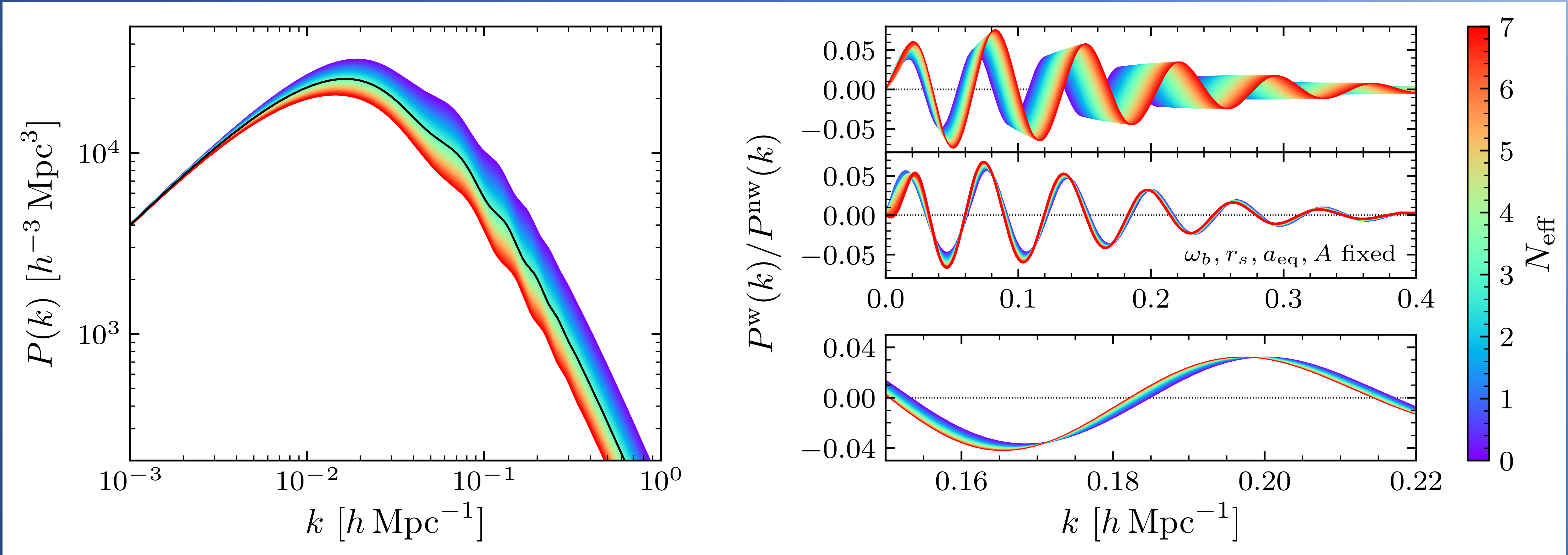
CMB Lensing
CMB-S4

Galaxy Density
VRO Gold sample

Cluster Counts
tSZ counts from CMB-S4

Contributions weighted by S/N (x3 for CMB Lensing)

Baryon-Acoustic Oscillation Phase Shift

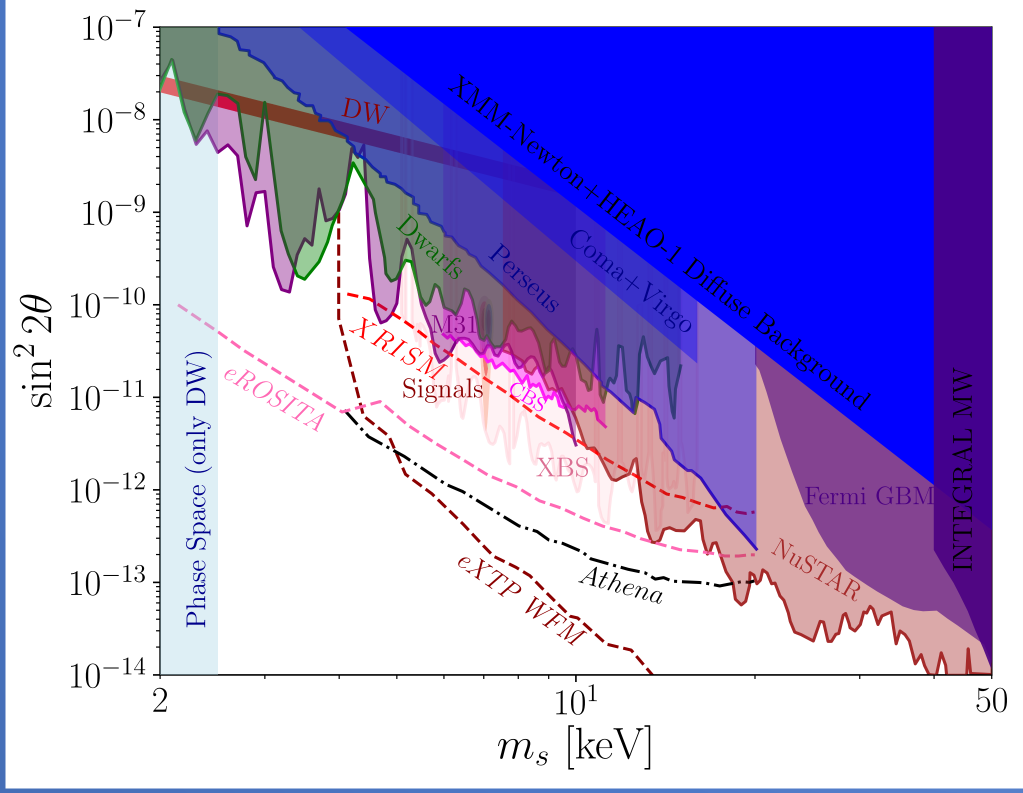


Similar physics of free-streaming radiation influencing CMB phase shifts

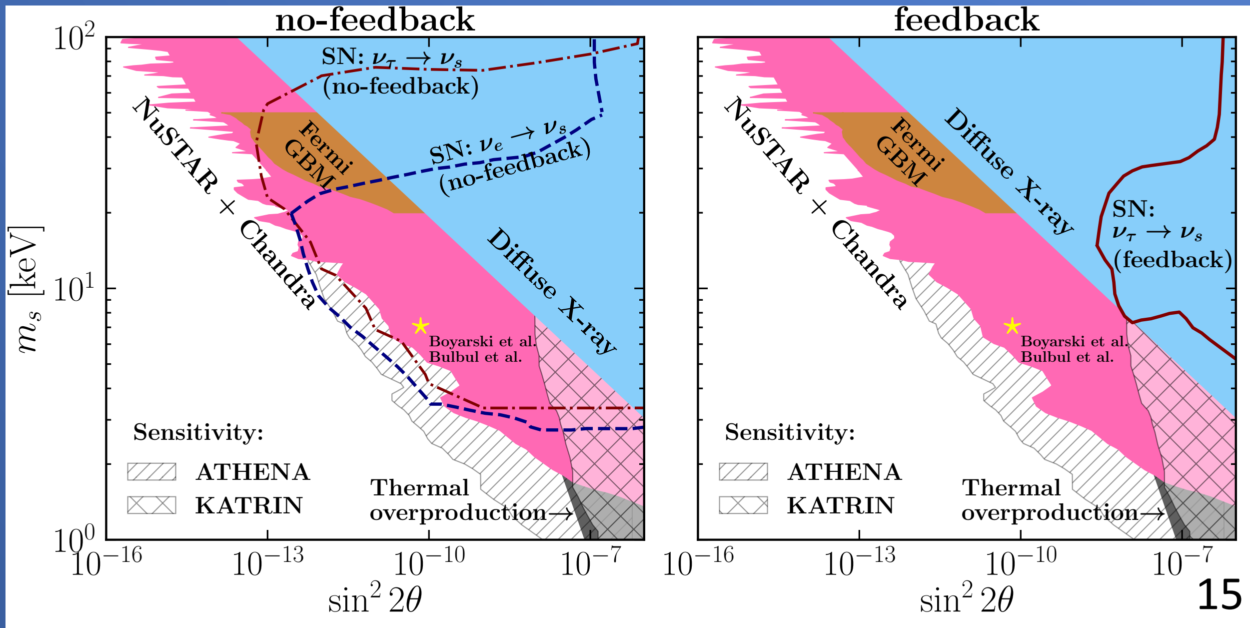
Detectable [see Baumann et al (2019)]

Sterile Neutrinos as DM

I. X-ray/γ-ray constraints
   a. Current constraints solid
   b. Possible signal for $m_s \sim 7.1$ keV
   c. Dashed lines future sensitivity



I. CCSNe model specific constraints
   a. Feedback on explosion (2004.11389)
   b. No feedback (1908.11382)
   c. Dashed lines future sensitivity



Neutrino non-standard (secret) interactions

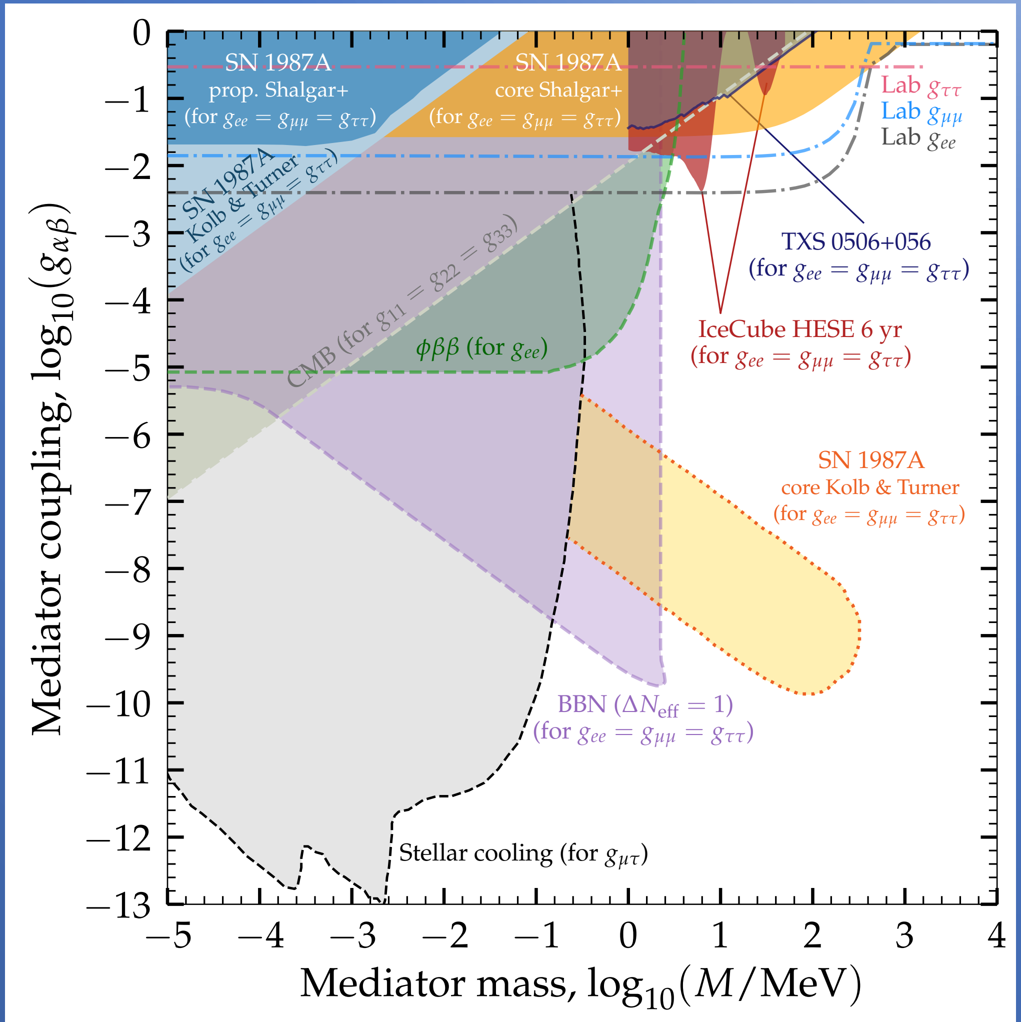
N. Blinov, M. Bustamente, K. Kelly, Y. Zhang and et al: 2203.01955

Cosmology Constraints/Improvements

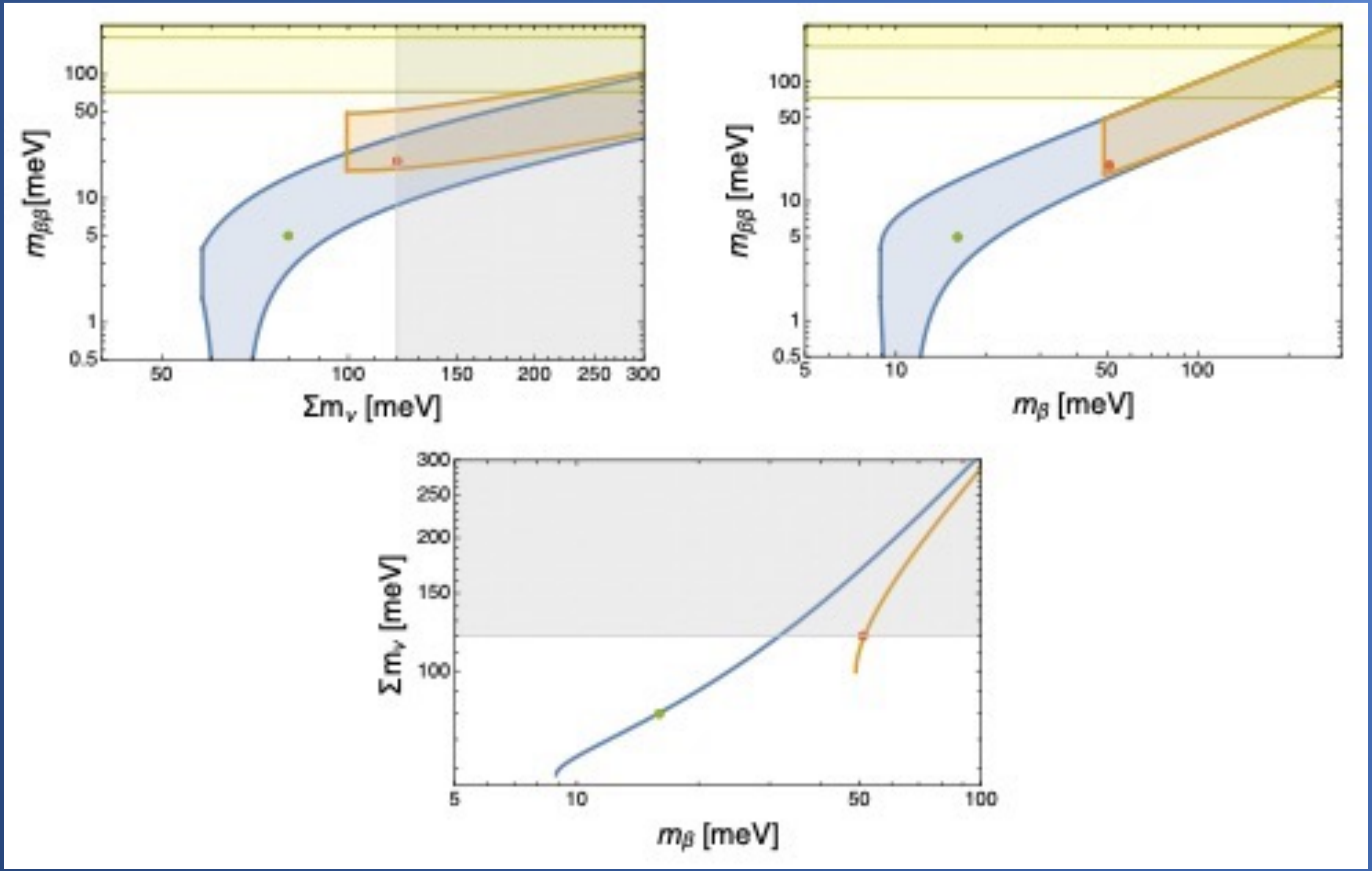
a. Possible amelioration of Hubble Tension (2203.06142)
b. Additional radiation energy density
c. No useful constraints from neutrino decoupling (2002.08557)

SN 1987A constraints from Kolb & Turner (1987)
Updated by Shalgar+ (2021)

a. Rapid thermalization in core
b. Propagation and detection at Earth



Neutrino Mass Complementarity



Cross Frontier
Discussion w/
M. Lattanzi

8:00 am – 9:30 am
Friday, 22 Jul 2022
HUB 307

Summary

1. Solid evidence for the existence of neutrinos in hot big bang cosmology
   a. CMB and BAO show N_{eff} not equal to zero
   b. BBN shows neutrinos have ∼thermal spectra

2. Future probes will show even more sensitivity to neutrino energy spectra

3. Convolution of terrestrial experiments and cosmological probes may reveal basic neutrino properties

4. Discordance between terrestrial and cosmology will undoubtedly reveal new physics

Backup Slides

Constraints on non-standard Neutrino Cosmologies

I. Sterile Neutrinos
   a. N_{eff} sensitivity from O(eV)
   b. Dark matter contribution for O(keV)
   c. Early Universe dynamics O(MeV)

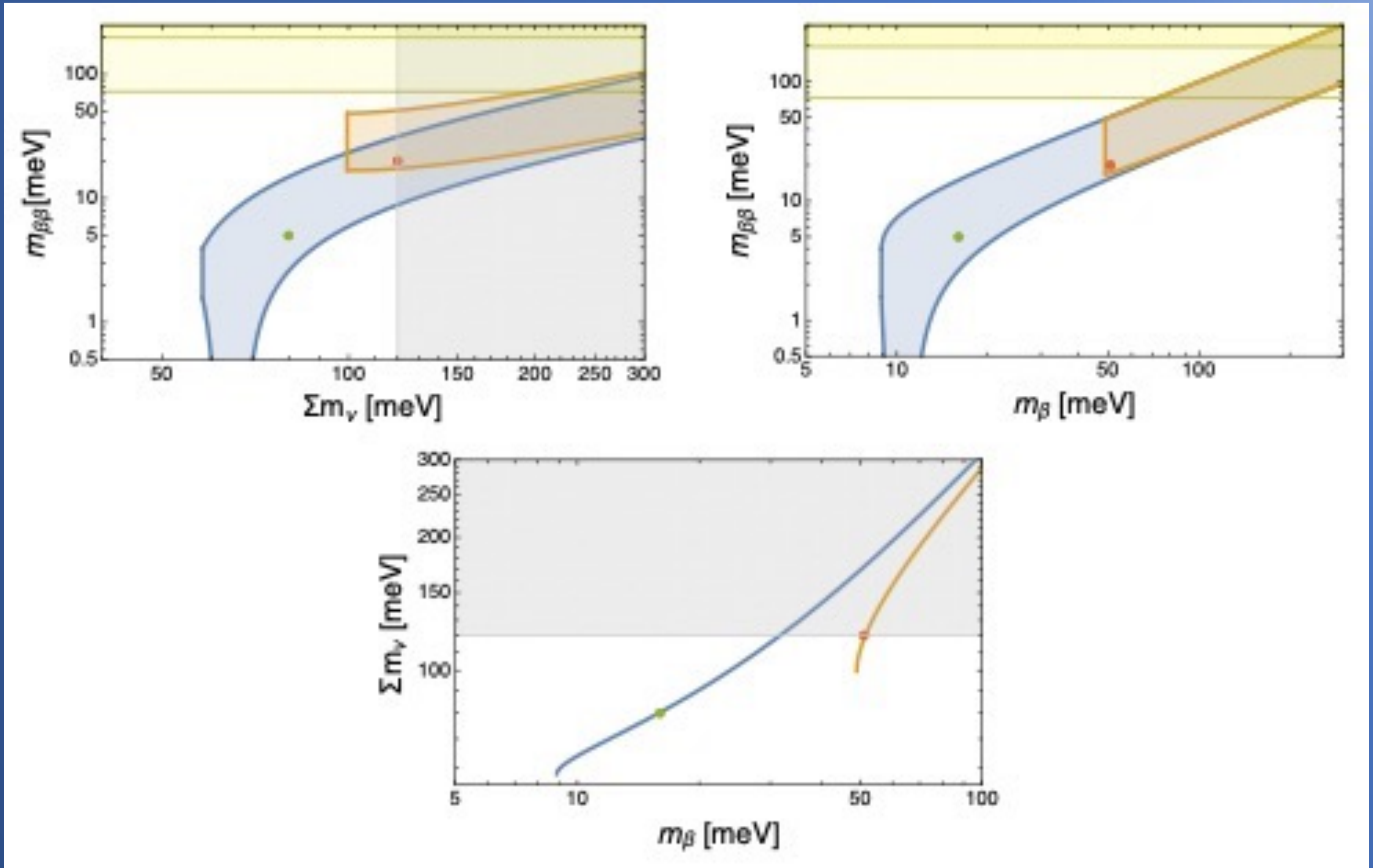
II. Neutrino non-standard interactions
   a. Influence on free-streaming assumptions (possible Hubble tension amelioration)

III. Neutrino lepton numbers
   a. Leptogenesis models
   b. BBN abundances (put in constraints)

IV. Neutrino lifetime (from free-streaming): $\tau_\nu \geq 4 \times 10^6 (m_\nu / 0.05\,\mathrm{eV})^5$

V. Low-temperature Reheating from Inflation (decrease in N_{eff})

Concordance Scenarios for neutrino mass



Beyond Concordance for neutrino mass

1. First Scenario
    a. Signal in $0\nu 2\beta$
    b. No detection of $\Sigma m_\nu \neq 0$
    c. Severe challenge to ΛCDM and thermal history of neutrino spectra
    d. Any detection from endpoint experiments would further challenge ΛCDM

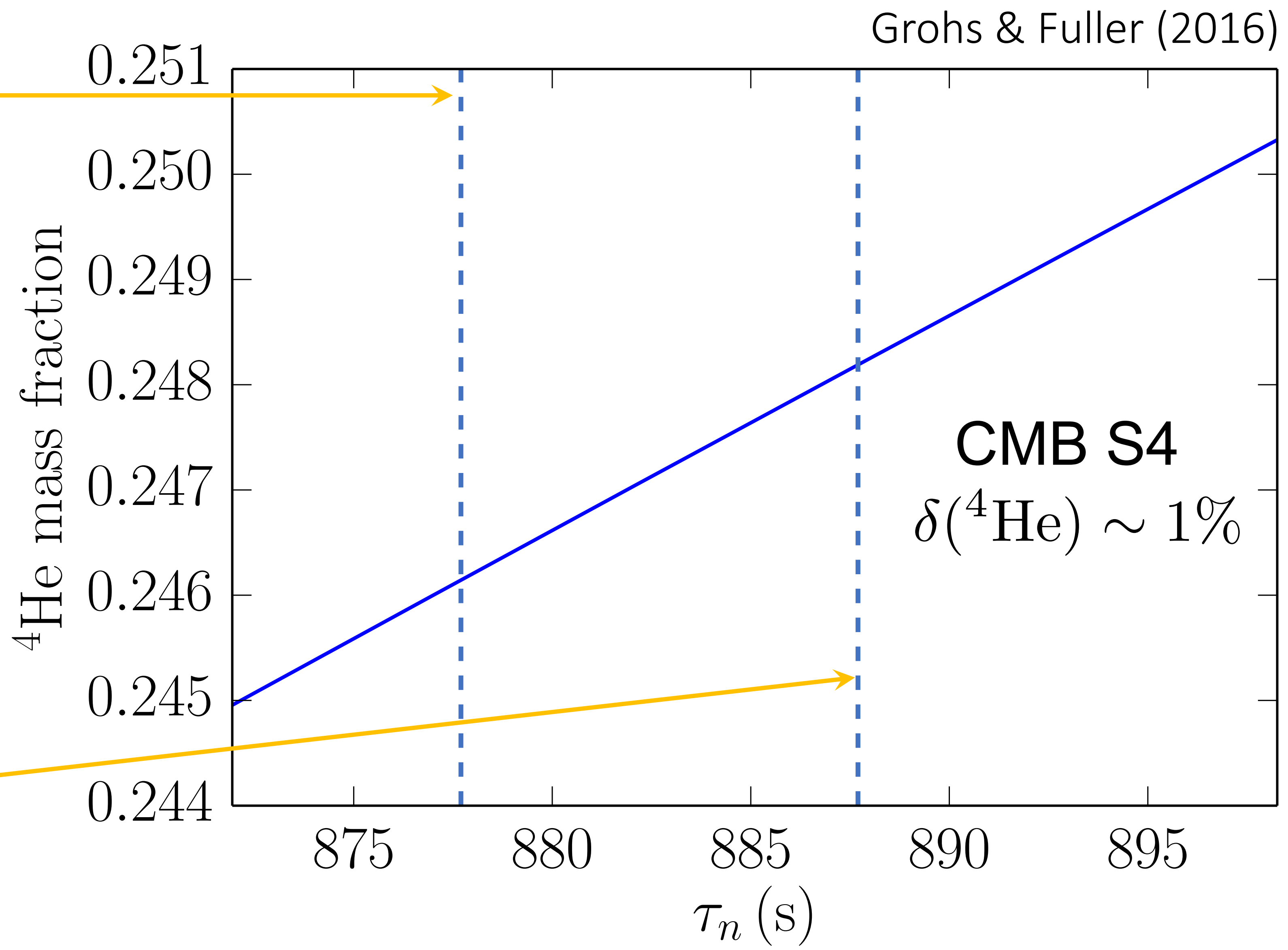
2. Second Scenario
    a. Signal in $0\nu 2\beta$
    b. Detection of $\Sigma m_\nu \neq 0$
    c. Signals discordant, i.e., do not lie in bounded areas of previous plot
    d. Possible Causes:
        i. Another challenge to ΛCDM
        ii. Sterile states contributing to $m_{\beta\beta}$
        iii. Exotic physics beyond neutrino mass

Helium vs. Neutron lifetime

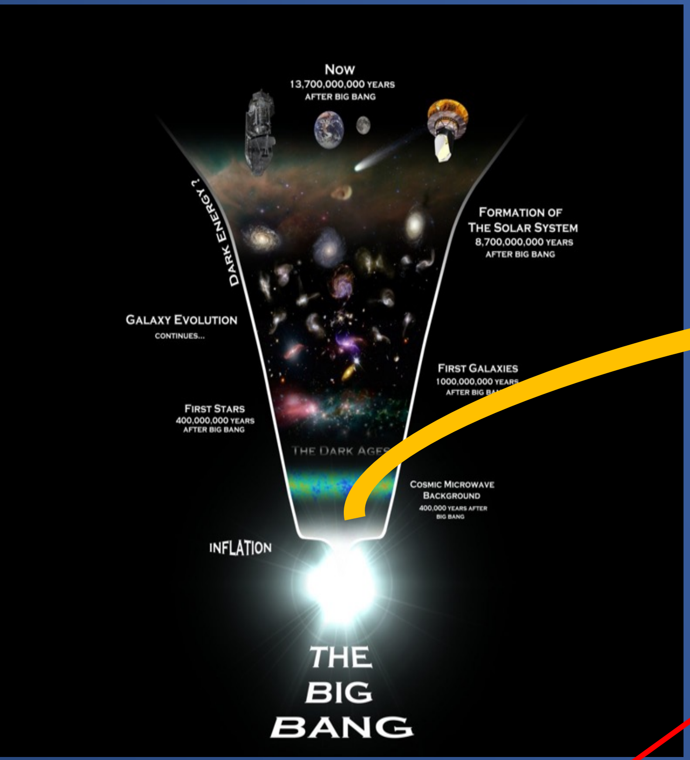
UCNτ
Bottle expt.
(1707.01817)
$\tau_n = 877.7 \pm 1.1\,\mathrm{s}$

Tension ~4σ

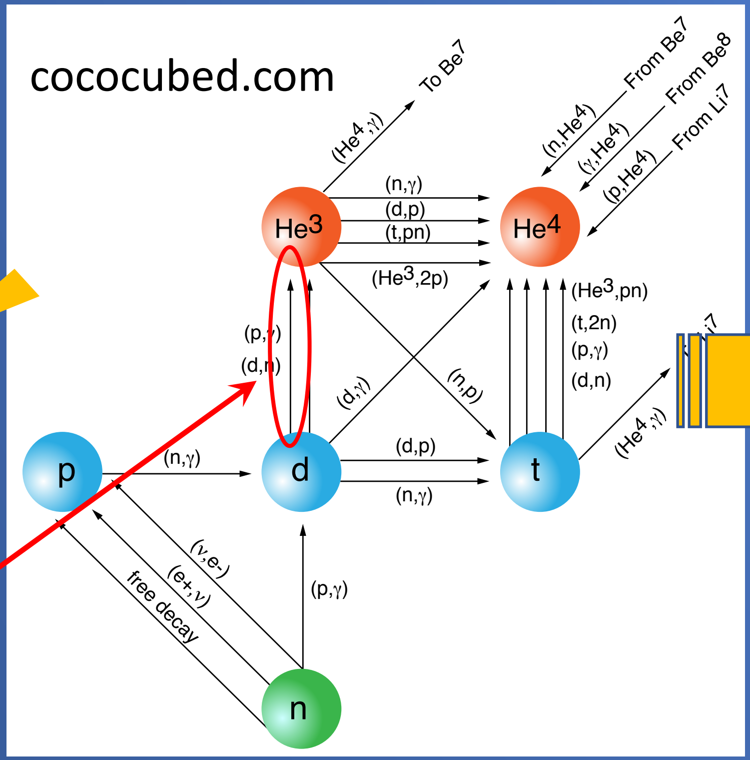
NCNR
Beam expt.
(1309.2623)
$\tau_n = 887.7 \pm 3.1\,\mathrm{s}$



Big Bang Nucleosynthesis



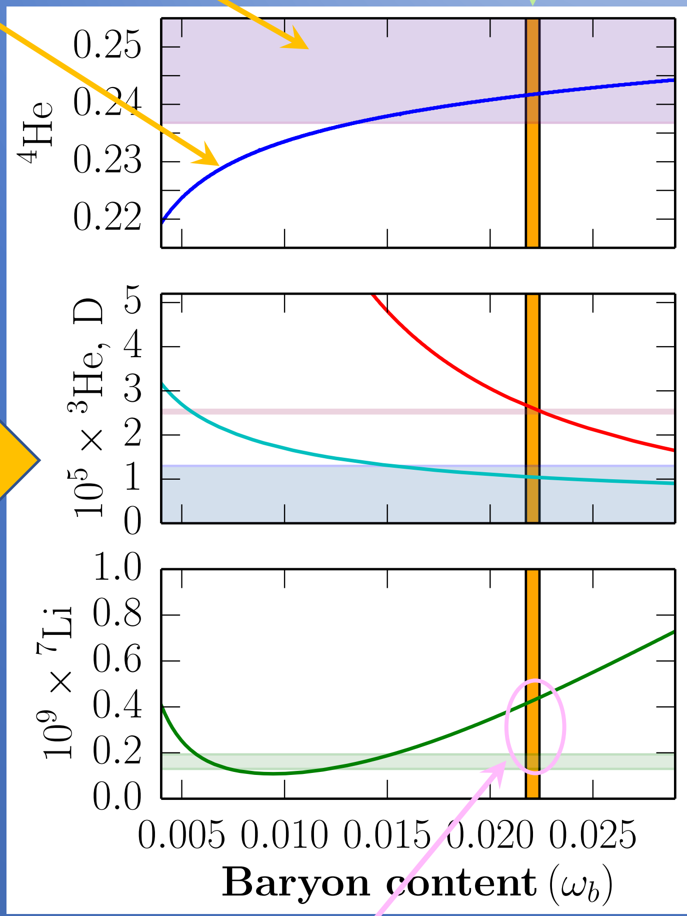
c/o Planck



Observation

Theory

CMB Data



Grohs et al 2015

Problem

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

Entropy and Nuclear Statistical Equilibrium

Nuclear Reactions are fast in both directions at high temperature

$$Zp + (A-Z)n \leftrightarrow {}^A_Z X$$

Entropy of universe is LARGE
(for nuclear environment)

$$s_{\rm pl} = \frac{1}{n_b}\frac{\rho + P}{T} \sim \frac{T^3}{n_b} \sim 10^{10}$$

Nuclei in NSE at high temperature/initial conditions

$$Y_X^{(\rm NSE)} \simeq Y_p^Z Y_n^{A-Z} 2^{(A-3)/2} \pi^{3(A-1)/2} g_X A^{3/2} \left[\frac{n_b}{(T m_b)^3}\right]^{A-1} e^{B_X/T}$$

$$\simeq \boxed{s_{\rm pl}^{1-A}}\, T^{3(A-1)/2} \boxed{e^{B_X/T}}$$

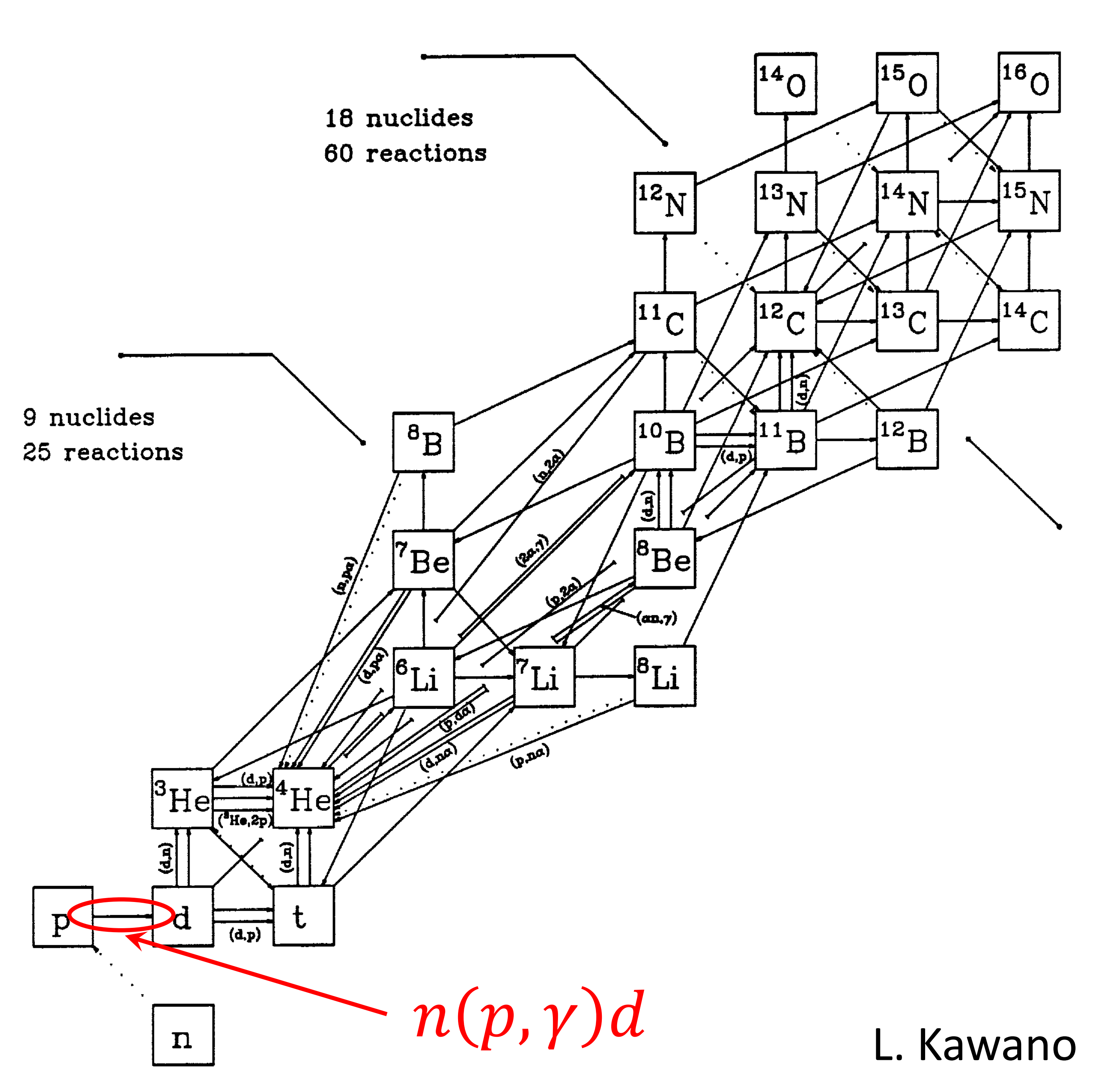
Nuclear reactions in BBN

First BBN calculation:
Wagoner, Fowler, Hoyle 1967

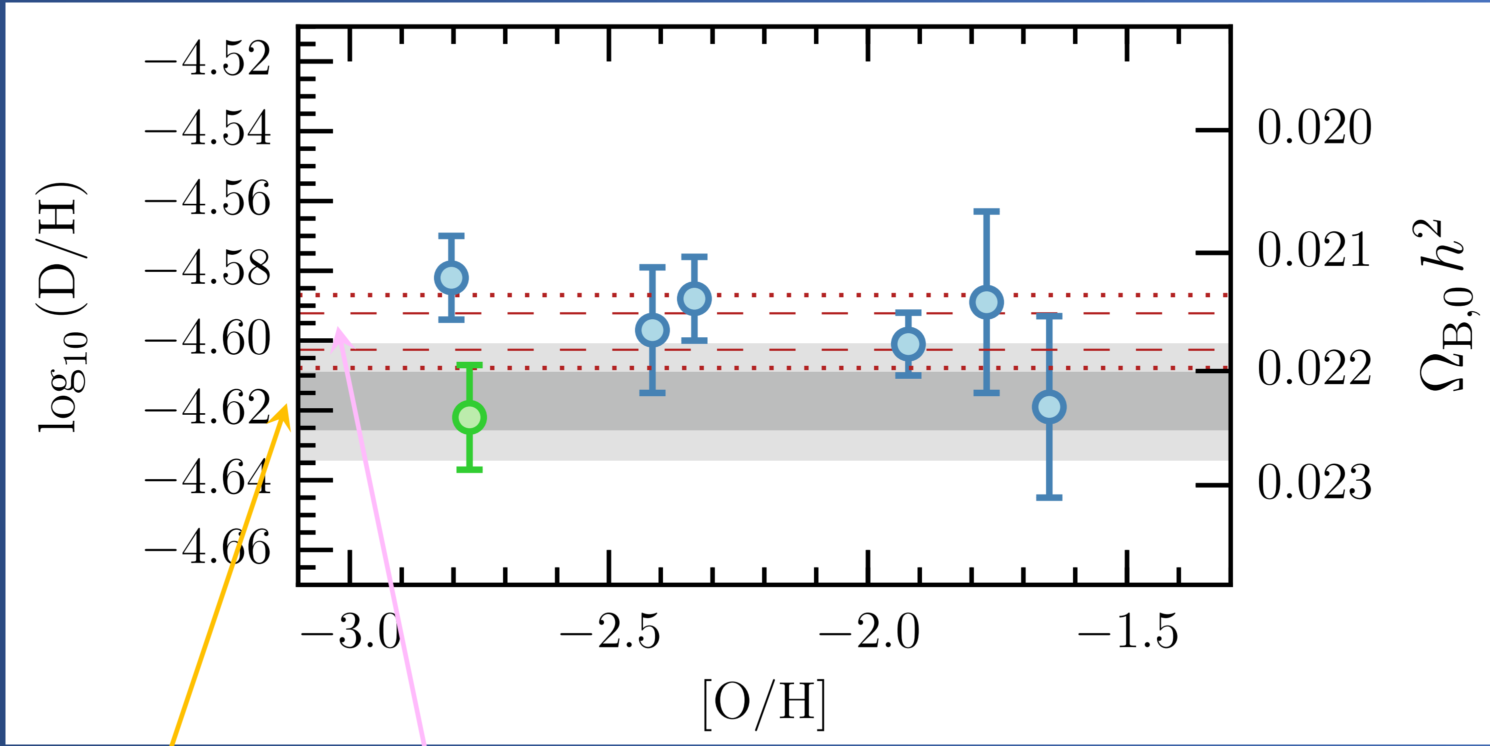
Lines between boxes denote reactions

Ignoring weak interactions, number of protons and neutrons separately conserved

Only one way to make deuterium
"deuterium bottleneck"



Observations of Primordial Deuterium



Cooke et al (2018)

$$10^5 \times \mathrm{D/H} = 2.53 \pm 0.03$$

Planck (2015): Success of Modern Cosmology

Number of systems → 70

$$\delta(\mathrm{D/H}) < 1\%$$

New Results from LUNA on $d(p,\gamma)^3$He

Deuterium sensitive to nuclear reaction rates.

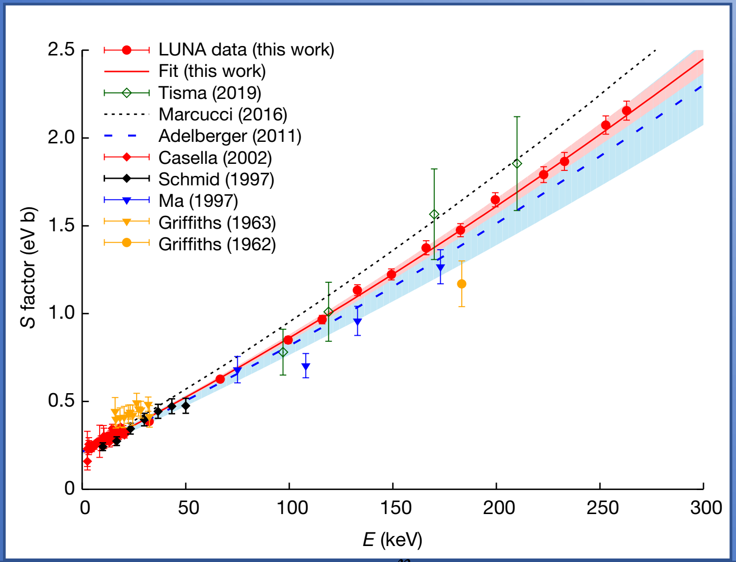
Previously (Di Valentino et al, 2014):

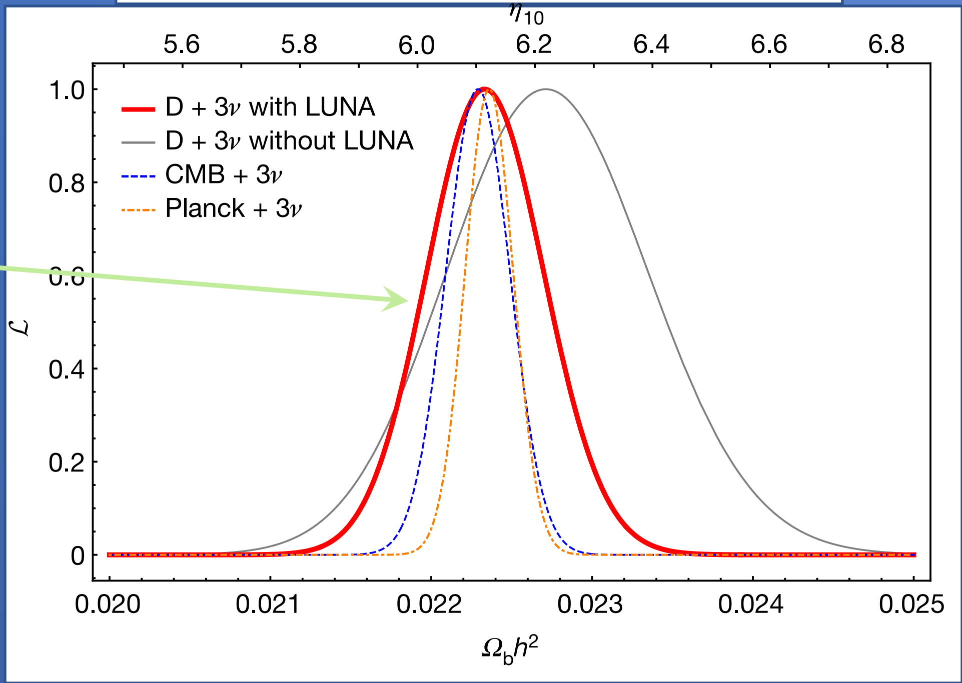
Reaction	Rate symbol	$\sigma_{^2\mathrm{H/H}} \times 10^5$
$p(n,\gamma)^2$H	R_1	± 0.002
$d(p,\gamma)^3$He	R_2	± 0.062
$d(d,n)^3$He	R_3	± 0.020
$d(d,p)^3$H	R_4	± 0.013

LUNA Collaboration, 2020:

$$E = 32 - 263\,\mathrm{keV}$$

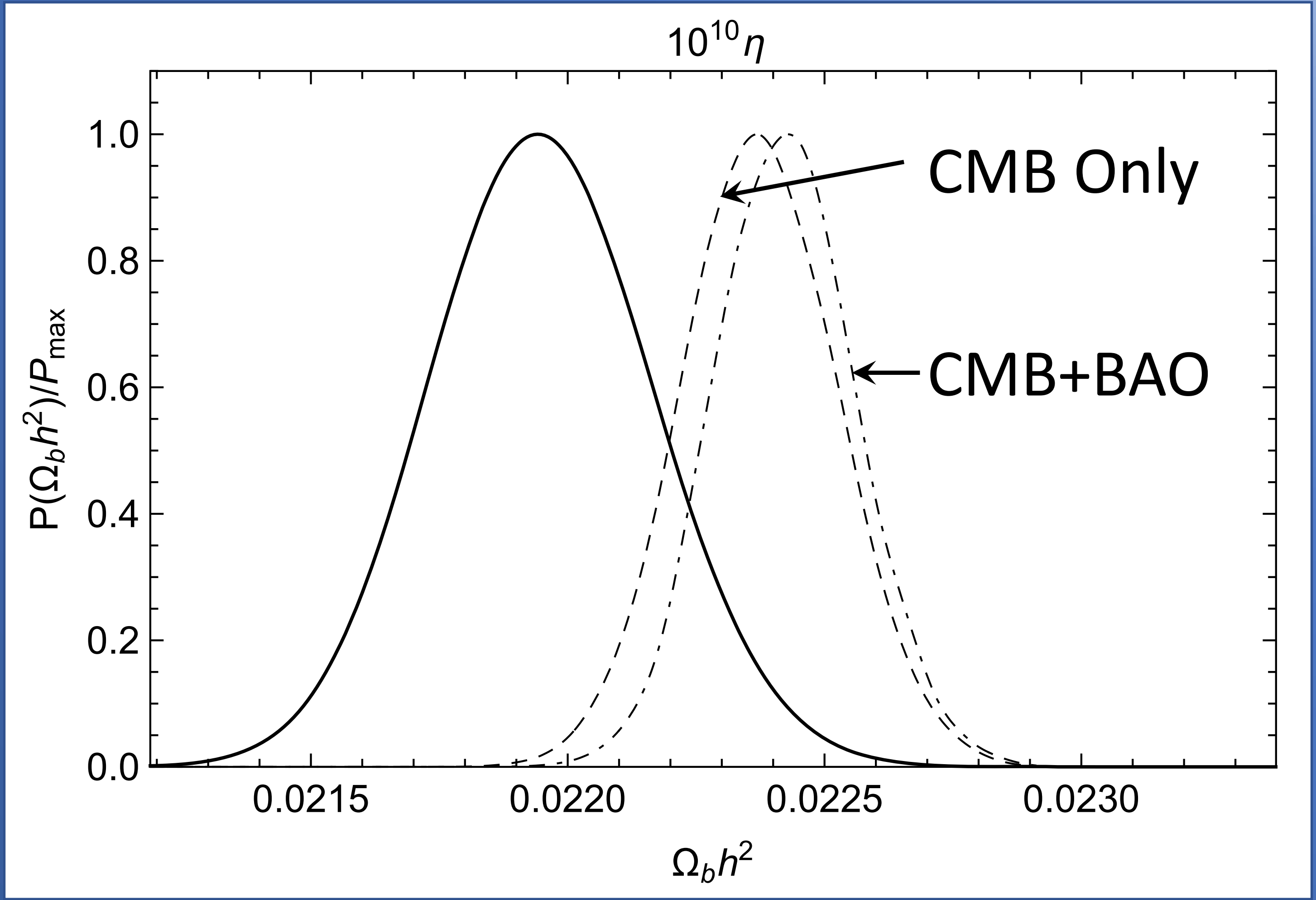
$$\delta \sim 3\%$$





Pitrou et al, 2021

1.8σ tension between BBN (D/H) and CMB



Want experimental data on transfer rxns:

$$d(d,p)t$$

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

BBN Comparisons (c/o Alain Côc)

$d(p,\gamma)^3$He Data Set

Reference	Present	Pitrou et al. (2018)[a]	Yeh et al. (2020)	Pisanti et al. (2020)[b]
Mossa et al. (2020)[c]	✓	✗	✓	✓
Tišma et al. (2019)[c]	✓	✗	✗	✓
Bystritsky et al. (2008)	✗	✓	✗	✗
Casella et al. (2002)[c]	✓	✓	✓	✓
Schmid et al. (1997)[c]	✓	✓	✓	✓
Ma et al. (1997)[c]	✓	✓	✓	✓
Bailey et al. (1970)	✓[e]	✗	✗	✗
Wölfli et al. (1967)	✗	✗	✓	✗
Geller et al. (1967)	✗	✗	✗	✓
Warren et al. (1963)[c,d]	✓	✗	✗	✓
Griffiths et al. (1963)	✓[e]	✗	✗	✓
Griffiths et al. (1962)	✓[e]	✗	✓	✓
Griffiths & Warren (1955)	✓[e]	✗	✗	✗

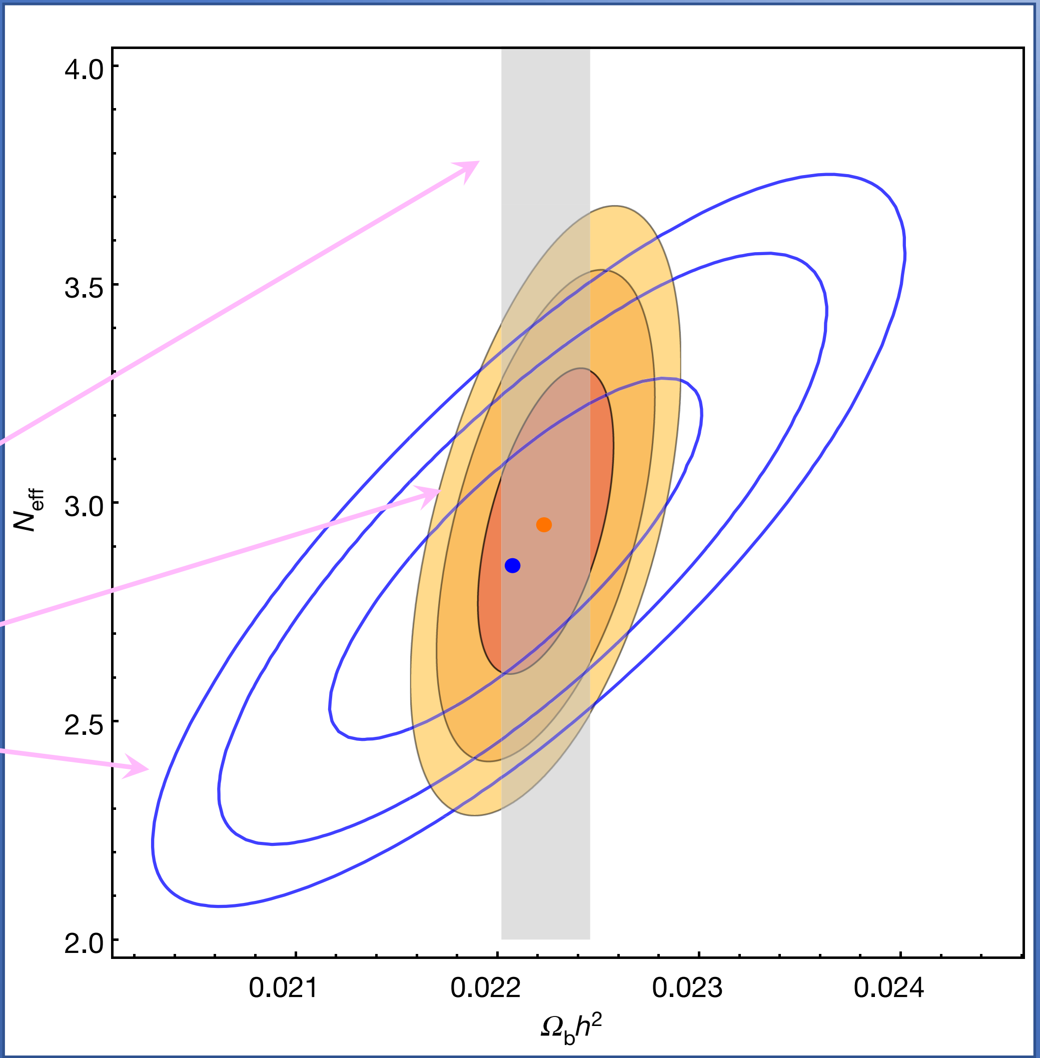
Bayesian minimization

χ^2 minimization

Takeaway: D/H sensitive to nuclear physics
⇒ need precise networks

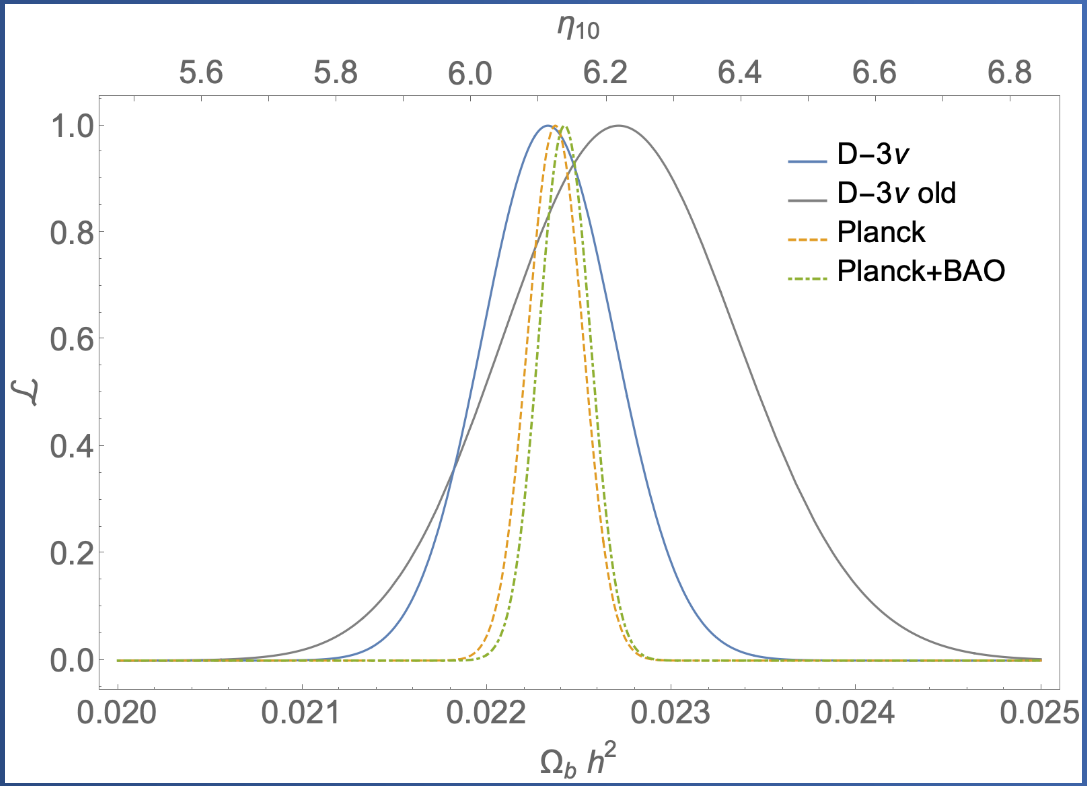
LUNA Results with Helium

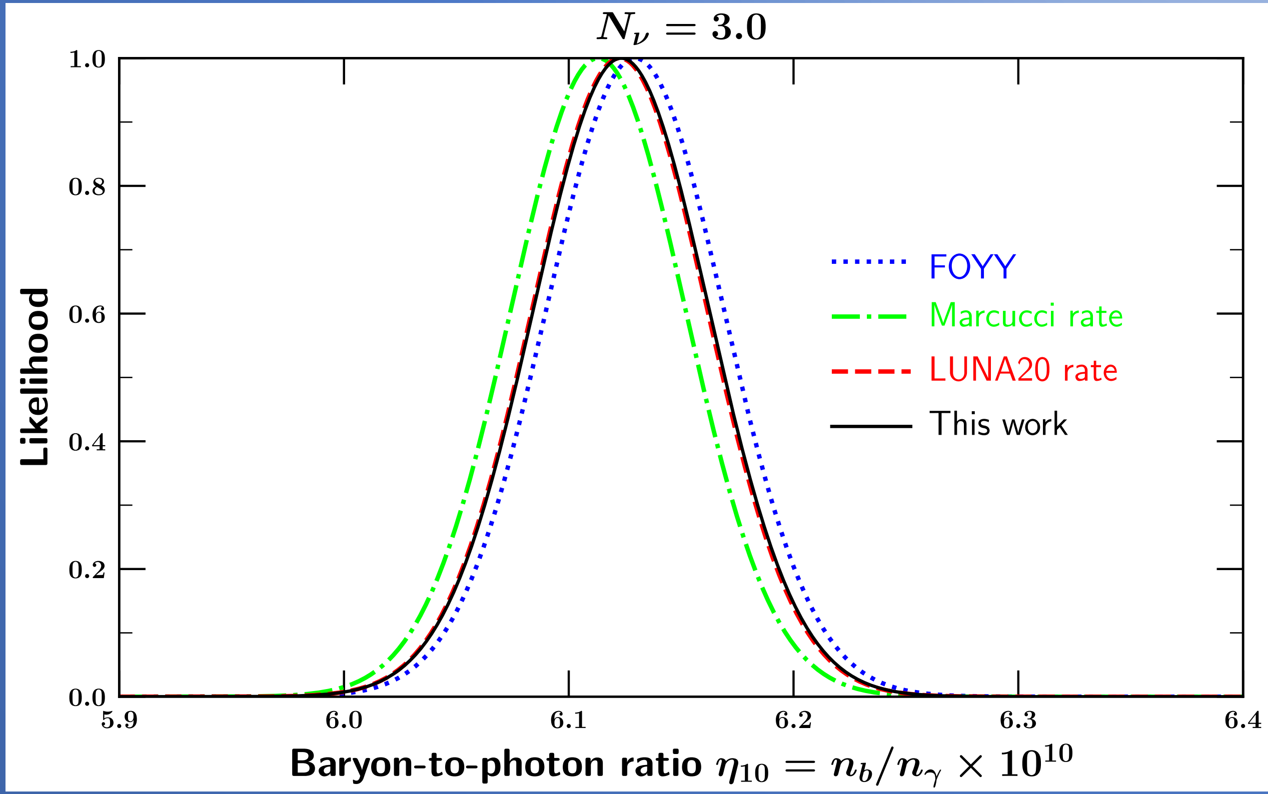
	$\Omega_b h^2$	δ (%)	N_{eff}
D + 3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D + 3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB + 3ν	0.02230 ± 0.00021[a]	0.94	3.045
Planck + 3ν	0.02236 ± 0.00015	0.67	3.045
(D + CMB)	0.02224 ± 0.00022	0.99	2.95 ± 0.22
(D + Y_p)	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$



LUNA Collaboration, 2020

Other Analyses with LUNA data





Pisanti et al, 2021
(cf. LUNA, 2020)

Yeh et al, 2021

Good Agreement

Unitarity: consequences on T matrix

$$\left.\begin{aligned} \delta_{fi} &= \textstyle\sum_n S^\dagger_{fn} S_{ni} \\ S_{fi} &= \delta_{fi} + 2i\rho_f T_{fi} \\ \rho_n &= \delta(H_0 - E_n) \end{aligned}\right\}$$

$$T_{fi} - T^\dagger_{fi} = 2i \sum_n T^\dagger_{fn} \rho_n T_{ni}$$

NB: unitarity implies *optical theorem* $\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im } f(0)$; but *not only* the O.T.

- **Implications of unitarity constraint on transition matrix**
  1. Doesn't uniquely determine T_{ij}; highly restrictive, however
     Elastic: $\text{Im } T_{11}^{-1} = -\rho_1$ (assuming T & P invariance)
     Multichannel: $\text{Im } \mathbf{T}^{-1} = -\boldsymbol{\rho}$
  2. Unitarity violating transformations
     - cannot scale ***any*** set: $T_{ij} \to \alpha_{ij} T_{ij} \qquad \alpha_{ij} \in \mathbb{R}$
     - cannot rotate ***any*** set: $T_{ij} \to e^{i\theta_{ij}} T_{ij} \qquad \theta_{ij} \in \mathbb{R}$

     ★ consequence of linear 'LHS' $\propto$ quadratic 'RHS'
  3. Unitary parametrizations constrain the experimental data itself
     ★ *normalization*, in particular

Most important feature:
linear ~ quadratic

Goal: *Create self-consistent nuclear reaction network for BBN*

c/o
Mark Paris

Precision Nuclear Reaction Calculations

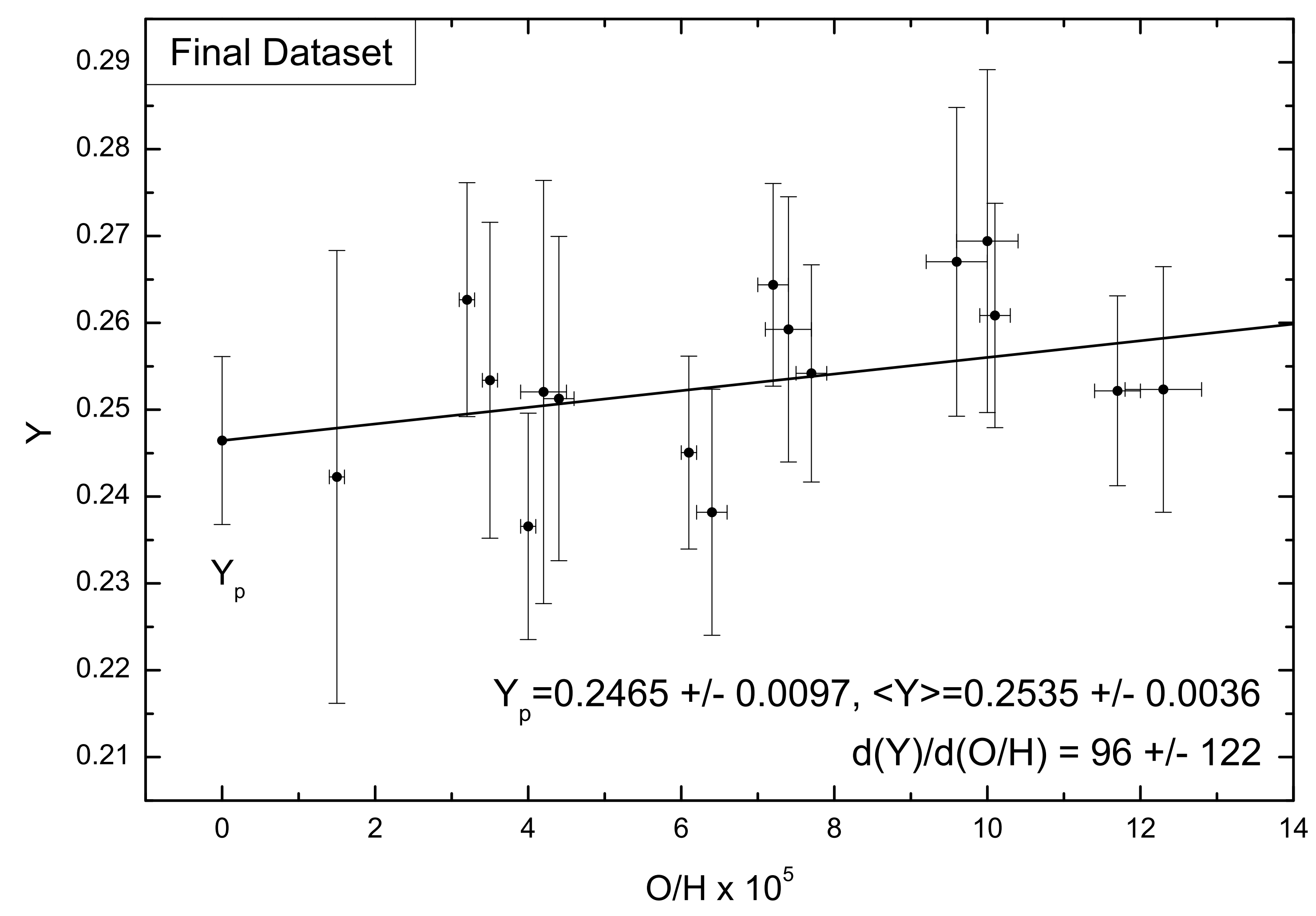
- Monte Carlo Variational Methods
  - Krauss & Romanelli, ApJ (1990)
  - Fiorentini et al, Phys. Rev. D (1998)
- Ab Initio Calculations
  - Marcucci et al, Phys. Rev. Lett. (2016)
- Lattice QCD
  - Beane et al, Phys. Rev. Lett. (2015)
  - Savage et al, Phys. Rev. Lett. (2017)
- Bayesian Estimation
  - Iliadis et al, ApJ (2016)
  - Gomez-Inesta et al, ApJ (2017)
  - de Souza et al, Phys. Rev. C (2019)
- R-matrix theory
  - Descouvemont & Baye, Rep. on Prog. in Phys. (2010)
  - Paris et al, Nucl. Data Sheets (2014)

Observations of Primordial Helium

Linear regression of HII regions in metal-poor galaxies

Also see Izotov and Thuan

Competitive CMB measurements forthcoming



Aver et al (2013)

Observations of Helium-3

Bania, Rood, Balser (2002):

$$10^5 \times {}^3\mathrm{He}/\mathrm{H} = 1.1 \pm 0.2$$

Cooke (2015): Proposal to measure ratio ^{3}He/^{4}He in DLAs

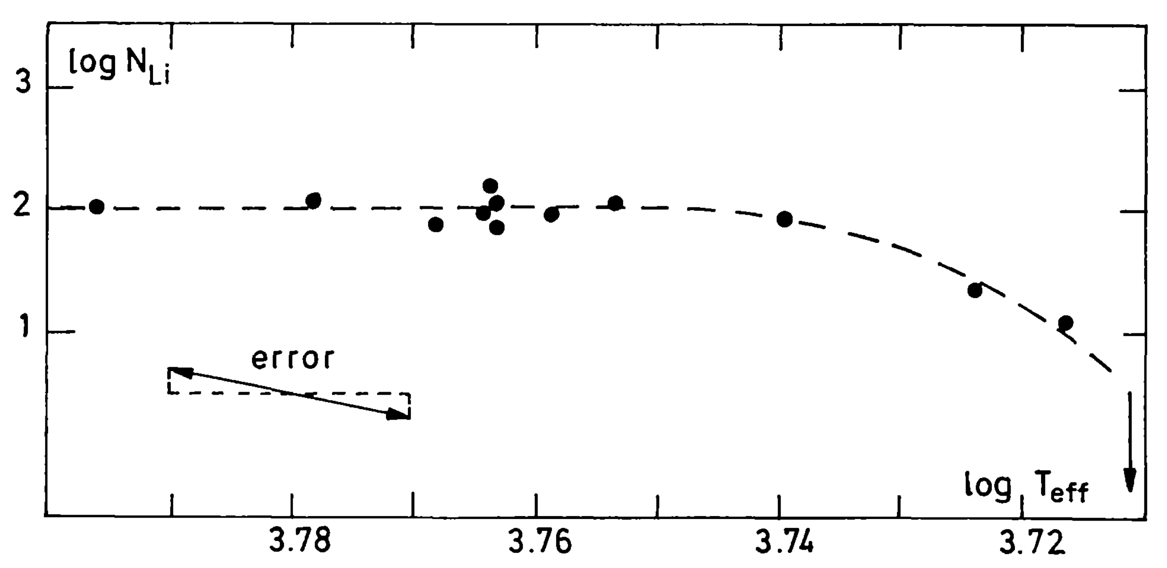
Observations of Lithium

Spite and Spite (1982):

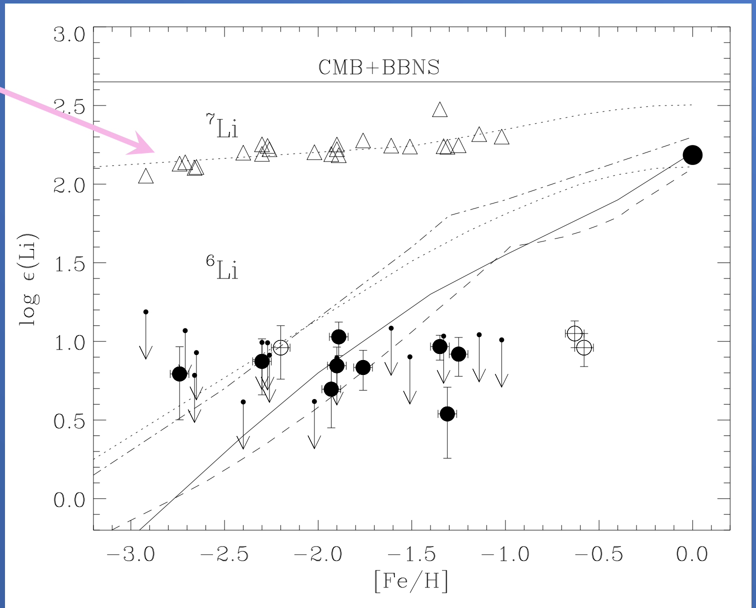
Pop II Halo stars

Abundance vs. Temperature

$$^{7}\mathrm{Li/H} = 1.12 \times 10^{-10}$$



Slope?



Asplund et al (2006): Abundance vs. Metallicity

$$\langle ^{7}\mathrm{Li/H} \rangle = 1.3 \times 10^{-10}$$

$$^{6}\mathrm{Li}/\,^{7}\mathrm{Li} = 0.042$$

A Lithium-6 Problem?

Detection of ^{6}Li would create strong tension with SBBN

Asplund et al (2006): Modeled dwarf stars with 1D and 3D Local Thermodynamic Equilibrium (LTE) analyses. Detected blending of 670.8 nm line.

Cayrel et al (2007): NLTE effects important in modeling redward wing of 670.8. Previous detections should be taken as upper limits. Very little effect on ^{7}Li abundance.

Lind et al (2013): More sophisticated 3D NLTE model with Li, Na, and Ca. Reached same conclusions.

No evidence for ^{6}Li anomaly.