Big Bang Nucleosynthesis and Neutrino Cosmology

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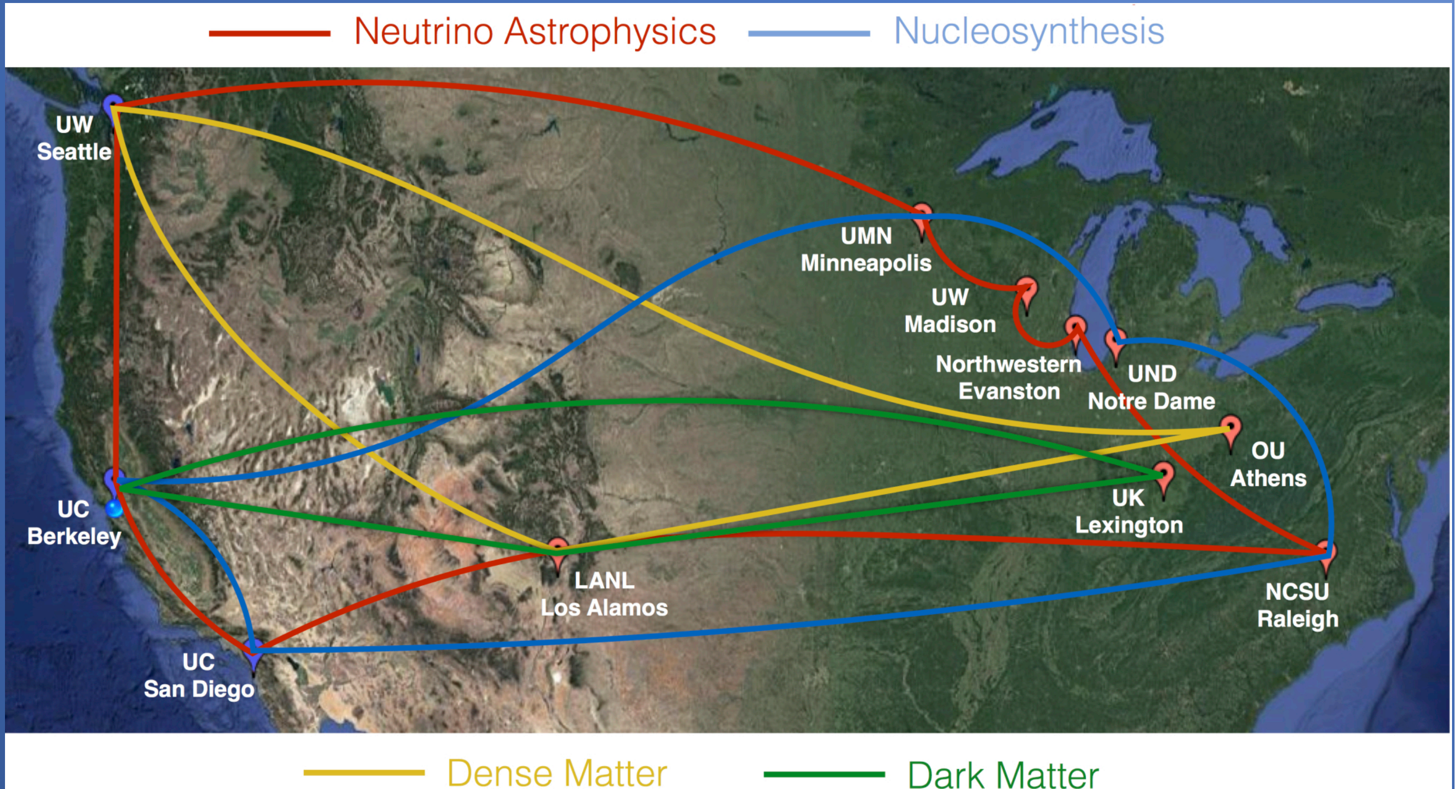
Network for Neutrinos, Nuclear Astrophysics and Symmetries

- Funded by National Science Foundation
- 11 Institutions headquartered in Berkeley, CA.
  - 10 Universities
  - 1 National Laboratory
- 8 postdoctoral research fellows
- Research thrusts including
  - Nucleosynthesis and the origin of the elements
  - Neutrinos and fundamental symmetries
  - Dense matter
  - Dark matter



Outline

- Big Bang Nucleosynthesis Theory
  - Overview: Physics and Computation
  - Beyond neutrino equilibrium
  - Neutron-to-proton rates and ratio
  - Synthesis of Helium-4 and sensitivity study
  - Future nuclear reaction networks
- Primordial-Abundance Observations
  - Helium-4
  - Deuterium and the Cosmic Microwave Background
- Summary and Conclusions

Standard BBN - Physics

Definition: Primordial synthesis of ≥ 9 light elements

$$n,\ p,\ d,\ {}^{3}\mathrm{H},\ {}^{3}\mathrm{He},\ {}^{4}\mathrm{He},\ {}^{6}\mathrm{Li},\ {}^{7}\mathrm{Li},\ {}^{7}\mathrm{Be}$$

$$Y_i \equiv n_i/n_b$$

$$Y_\mathrm{P} = 4Y_{^4\mathrm{He}}$$

High Entropy per Baryon in relativistic components

$$s_\mathrm{pl} = \frac{1}{n_b}\frac{\rho + P}{T} \sim 10^9$$

Relativistic species in thermally populated states

Initial equilibrium (10 MeV)

Bosons	Fermions
γ	$e^\pm$
	ν_e, ν_μ, ν_τ
	$\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$

After weak decoupling (100 keV):

$$\gamma \quad e^\pm \quad (\nu)$$

After e± annihilation (10 keV):

$$\gamma \quad (\nu)$$

Conservation of comoving entropy per baryon

$$\left.\frac{T_\mathrm{cm}}{T}\right|_\mathrm{f.o.} = \left(\frac{4}{11}\right)^{1/3}$$

Standard BBN – Basic Computation

Numerical treatments:

- First complete calculation: Wagoner, Fowler, Hoyle (1967)
- Updated calculation: Smith, Kawano, Malaney (1993)
- Modern codes: PArthENoPE; AlterBBN; PRIMAT

Isotropic and Homogeneous geometry

Evolution of three thermodynamic/cosmological variables:

$$\begin{cases} T & : \text{photon (plasma) temperature} \\ h_v & : \text{ratio of baryon energy density to } T^3 \\ \phi_e & : \text{electron degeneracy parameter} \end{cases}$$

≥25 Nuclear Reactions: $$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!}[ij]_k + \frac{Y_k^{N_k} Y_l^{N_l}}{N_k! N_l!}[kl]_j \right)$$

Neutrinos preserve Fermi-Dirac shape: $$f(\epsilon) = \frac{1}{e^{\epsilon}+1} \qquad \epsilon = E_\nu / T_{\rm cm}$$

Differential Visibility of Neutrino-Electron Scattering

Out-of-Equilibrium Neutrino Transport

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

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

Red contours of constant differential visibility

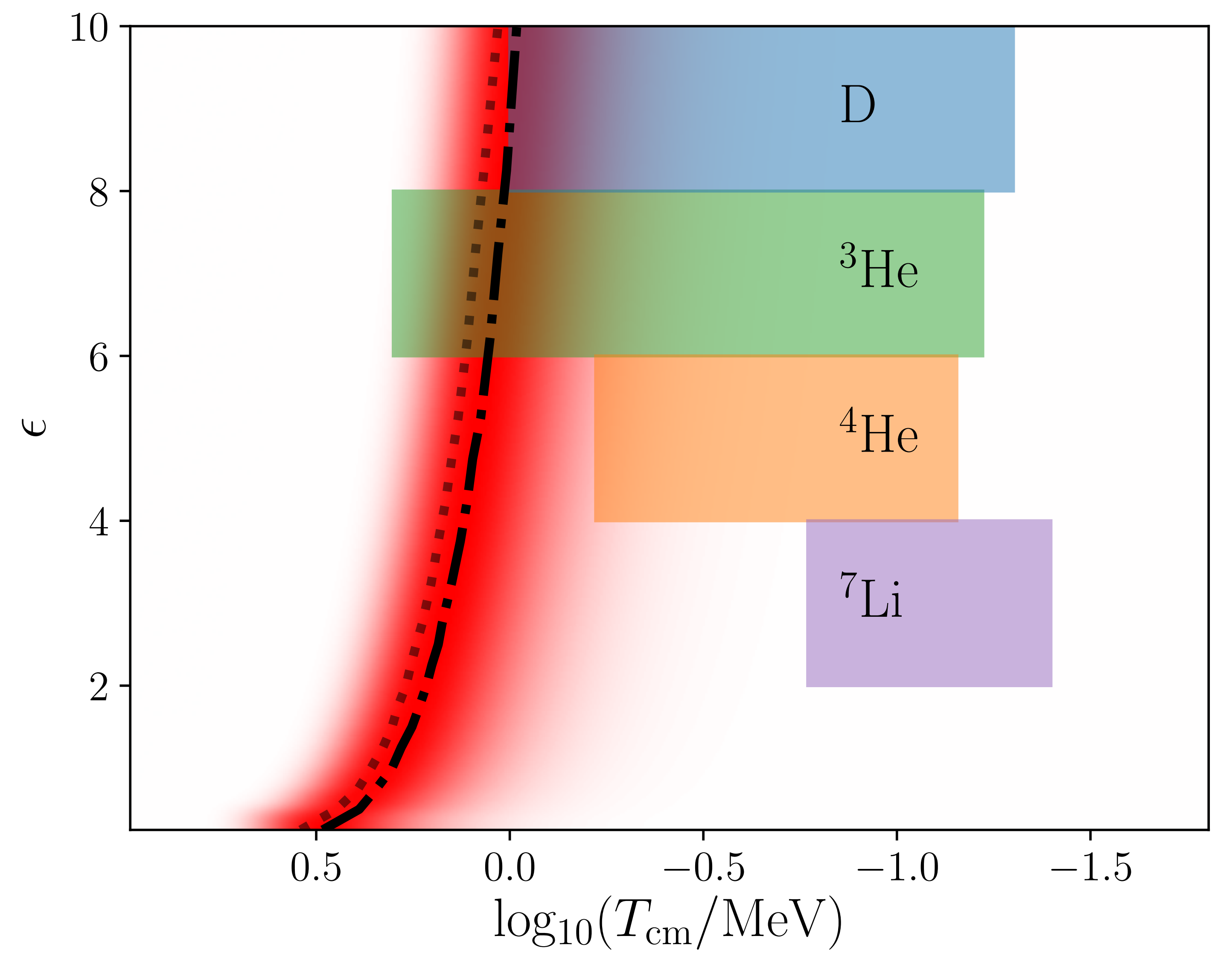
$$\frac{\Gamma'_{\nu_i}}{H} e^{-\tau_{\nu_i}}$$

High $T_{\rm cm}$

$\tau_{\nu_i} >> 1$

Low $T_{\rm cm}$

$\Gamma'_{\nu_i} << H$



c/o Matthew J. Wilson

Neutron to proton rates I

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

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

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

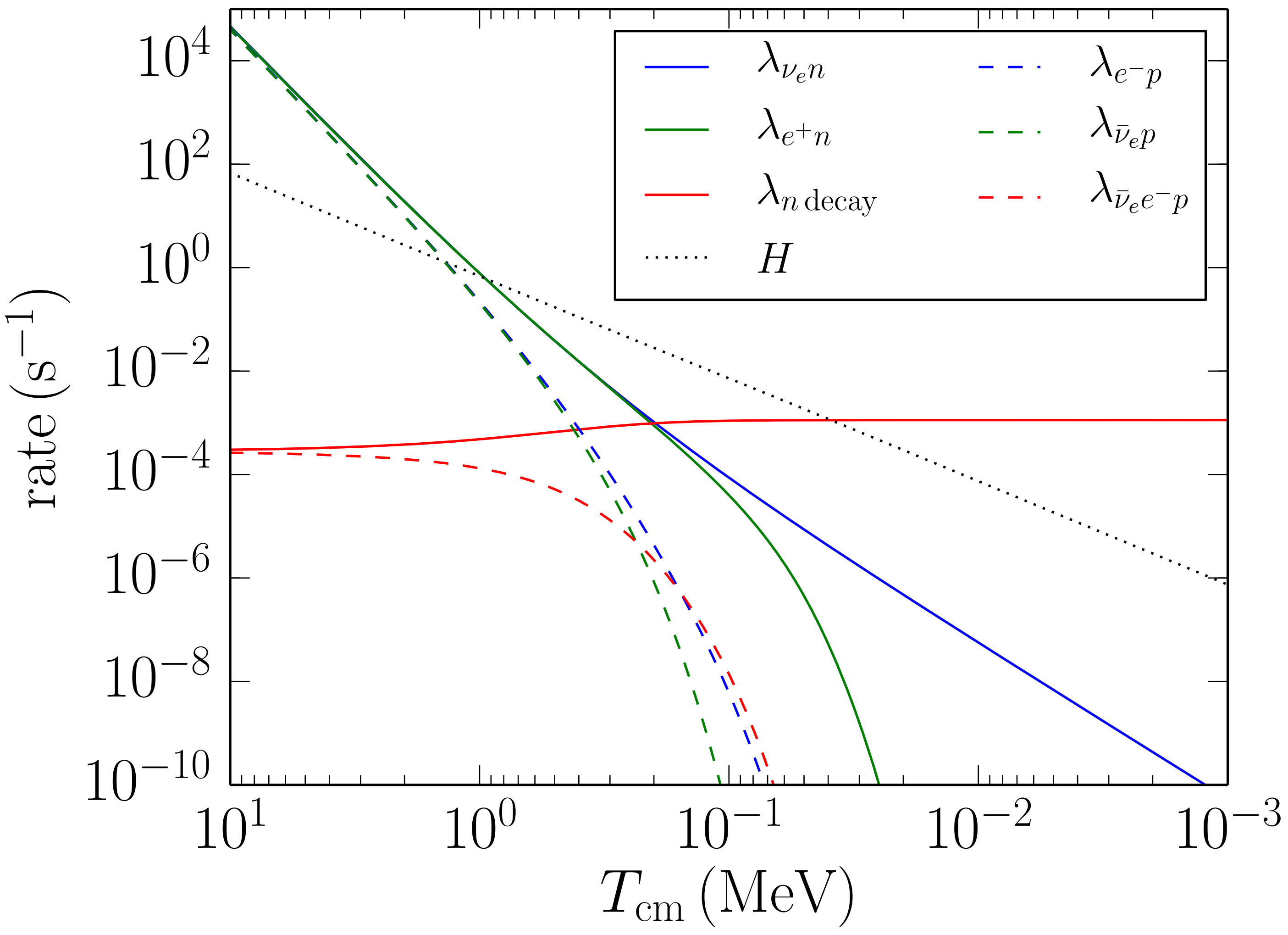
6 Neutron-to-proton rates set n/p

ν_e capture on neutron, normalized to neutron lifetime

$$\lambda_{\nu_e n \to p e^-} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int_0^\infty dE_\nu C(E_\nu + \delta m_{np}) Z(E_\nu + \delta m_{np}, E_\nu) \times E_\nu^2 (E_\nu + \delta m_{np}) \sqrt{(E_\nu + \delta m_{np})^2 - m_e^2} \times [f_{\nu_e}(E_\nu)][1 - g_{e^-}(E_\nu + \delta m_{np})]$$

$$\frac{1}{\tau_n} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int_0^{\delta m_{np} - m_e} dE_\nu C(\delta m_{np} - E_\nu) Z(\delta m_{np} - E_\nu, E_\nu) \times E_\nu^2 (\delta m_{np} - E_\nu) \sqrt{(\delta m_{np} - E_\nu)^2 - m_e^2}$$

Neutron to proton rates II



Neutron to proton ratio – Primordial Helium

Equilibrium:

$$\mu_{\nu_e} + \mu_n = \mu_p + \mu_{e^-}$$

$$n/p = \exp\left[-\frac{\delta m_{np}}{T} + \phi_e - \xi_{\nu_e}\right]$$

Common Approximation at late times after Weak Freeze-Out (WFO):

$$n/p(t) = e^{-\delta m_{np}/T_{\mathrm{WFO}}} e^{-(t-t_{\mathrm{WFO}})/\tau_n}$$

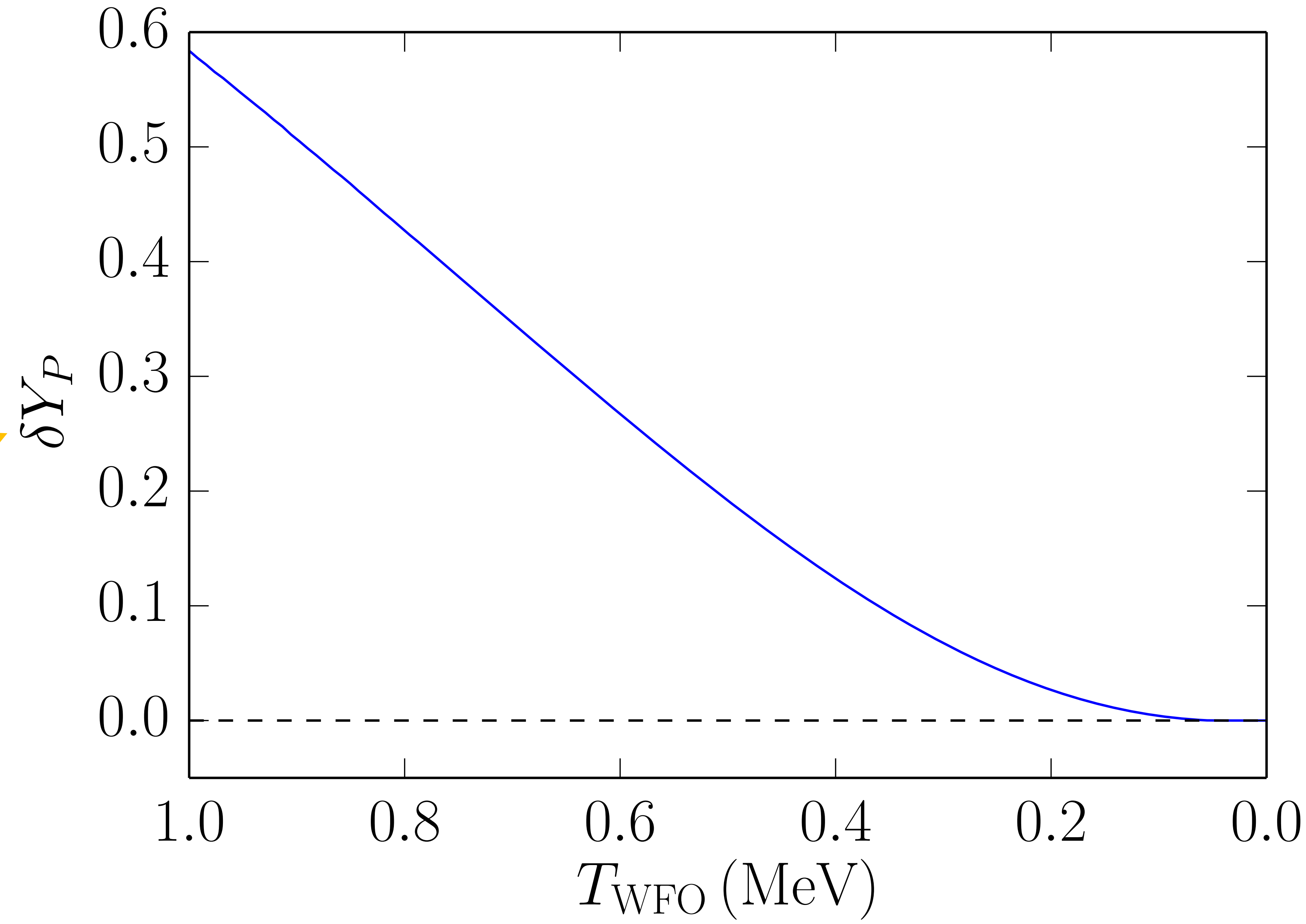
$T_{\mathrm{WFO}} \simeq$ 0.7 keV

How Accurate is the WFO approximation?

$$Y_{\mathrm{P}} \simeq \left.\frac{2n/p}{1+n/p}\right|_{\mathrm{f.o.}}$$

Lepton capture rates set to zero at T_{WFO}

No Pauli blocking in free neutron decay



Helium-4 Deviation from Baseline

arXiv: 1607.02797

Unitarity: consequences on T matrix

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

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

Theoretical Predictions

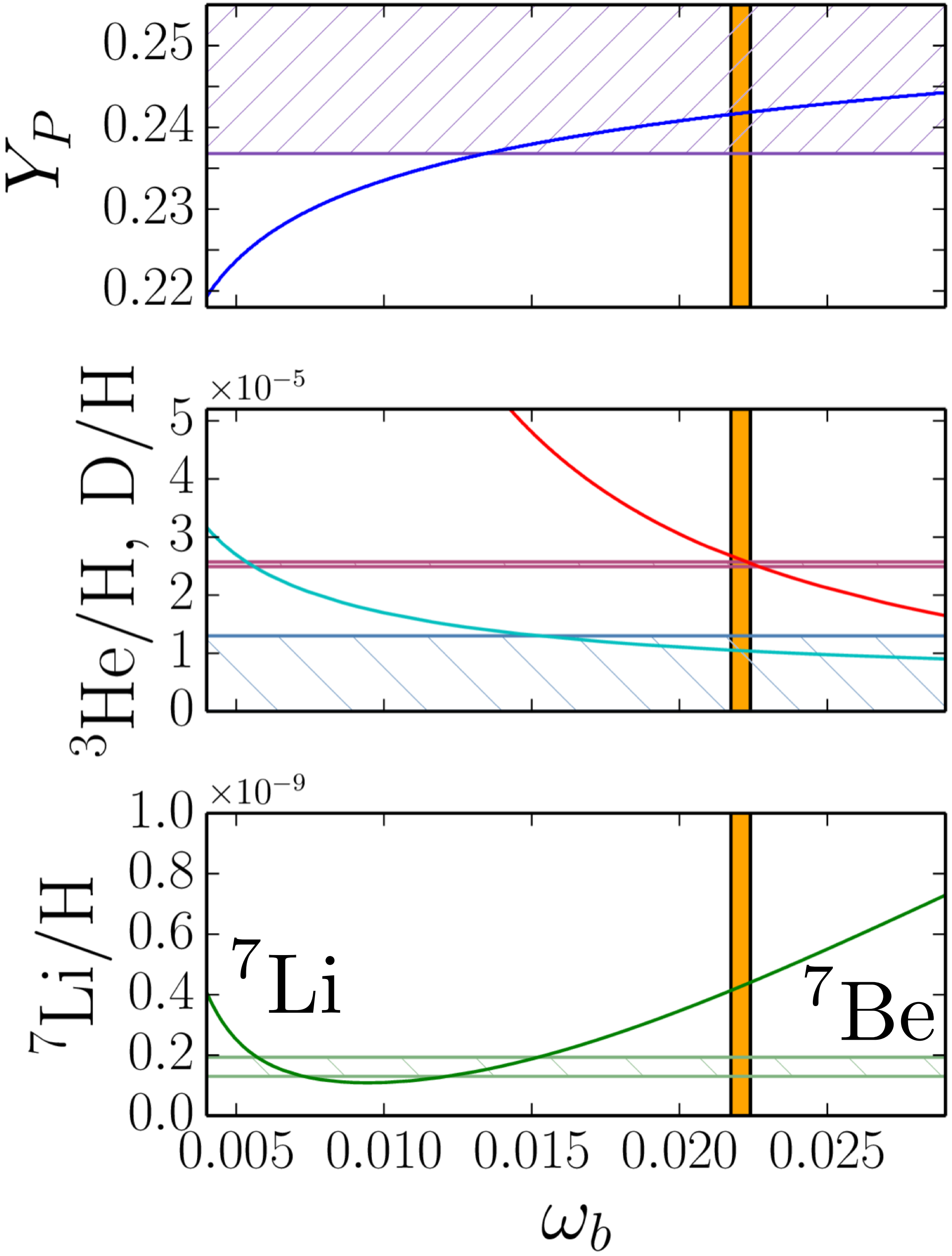
$$Y_{\mathrm{P}} = 0.247$$

$$\mathrm{D/H} = 2.66 \times 10^{-5}$$

$$^{3}\mathrm{He/H} = 1.05 \times 10^{-5}$$

$$^{7}\mathrm{Li/H} = 4.29 \times 10^{-10}$$

$$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 2.69 \times 10^{-5}$$

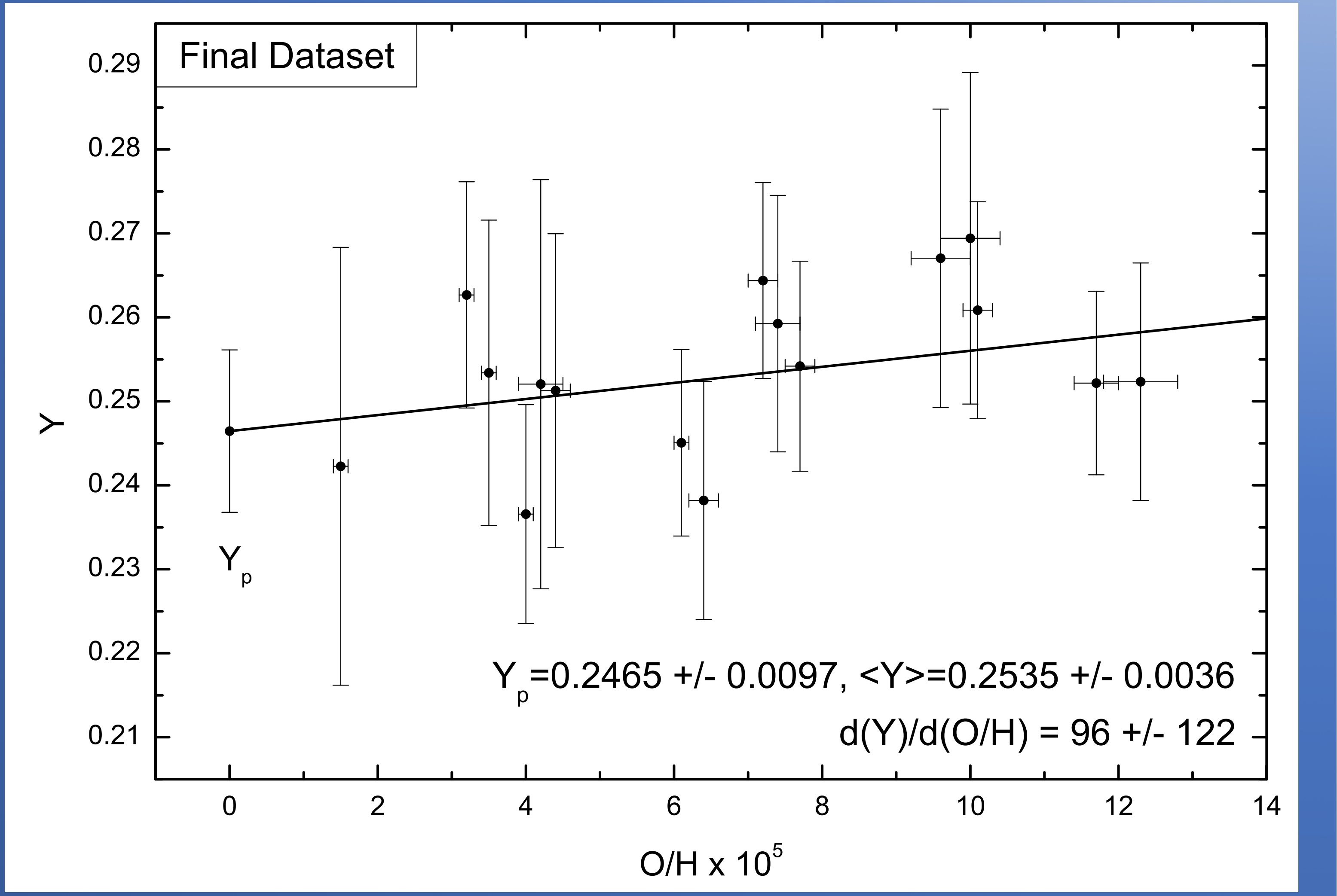


Observations of Primordial Helium

Linear regression of HII regions in metal-poor galaxies

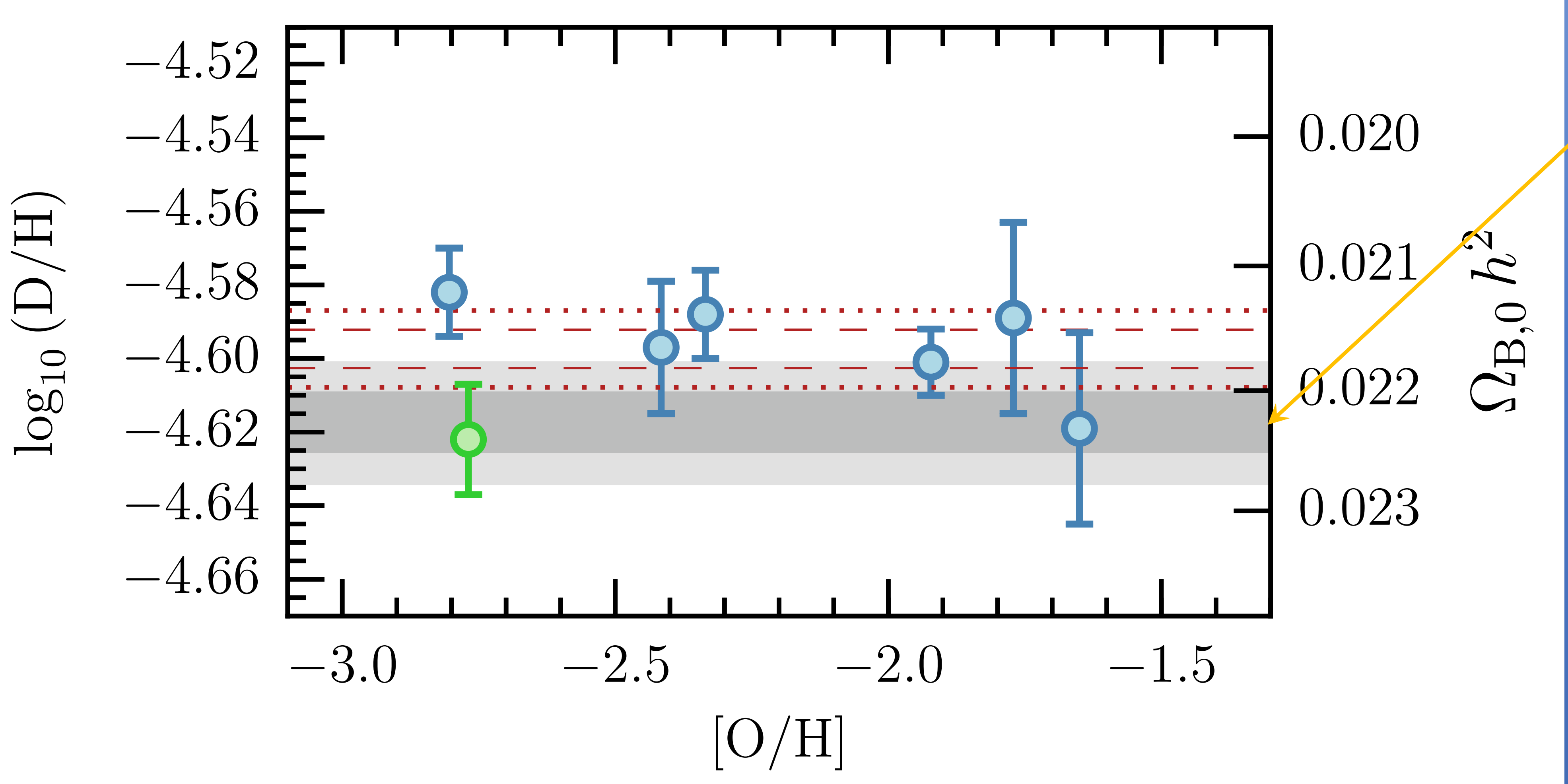
Also see Izotov and Thuan

Competitive CMB measurements forthcoming



Aver et al (2013)

Observations of Primordial Deuterium



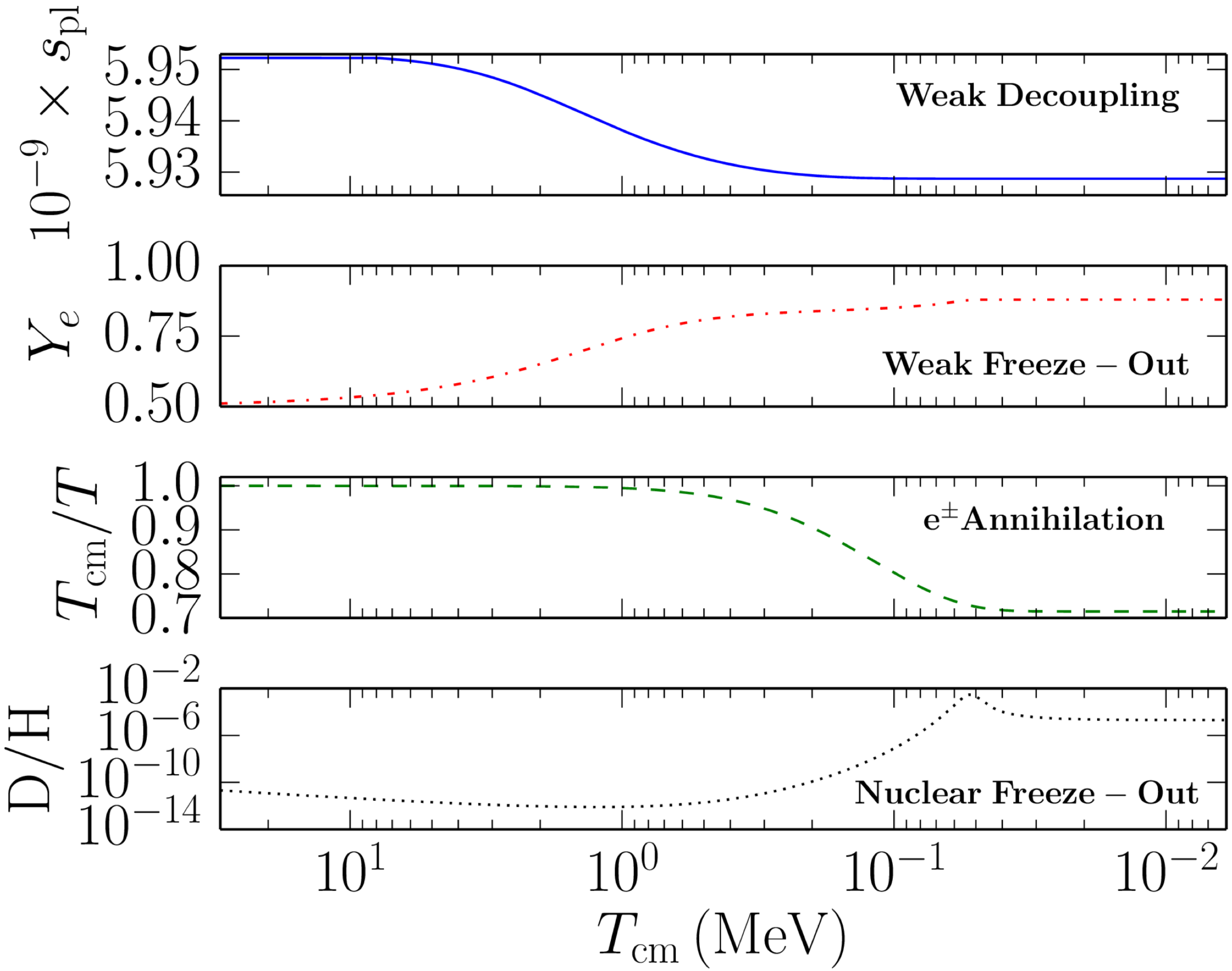
Planck (2015)

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

Cooke et al (2018)

Concurrent epochs of BBN

Equilibrium initial conditions
Nonequilibrium evolution



Weak interactions
between leptons

Weak interactions
between leptons
and baryons

EM interactions
between leptons and photons

Strong and EM interactions
between baryons
and photons

Summary and Conclusions

1. Standard BBN theoretically well-understood
    a) n/p set by weak interactions; sensitive to neutrinos
2. Observations
    a) D/H excellent agreement with CMB
    b) Potential to measure Y_P to same precision as D/H
3. Future utility of particle-astrophysics tool
    a) Neutrino
    b) Nuclear
    c) BSM