Title: Big Bang Nucleosynthesis: New Physics and New Tools

Speakers: Cara Giovanetti

Collection/Series: Particle Physics

Subject: Particle Physics

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Abstract:

Big Bang Nucleosynthesis (BBN) is a powerful tool for probing both new physics and LCDM, and complements analyses utilizing the Cosmic Microwave Background (CMB) and results from particle experiment. I will provide two examples of BBN probes of BSM models. I will then discuss new kinds of analyses that can be performed with the recently-released fast and differentiable BBN code LINX. In particular, LINX can be used to perform full BBN+CMB joint analyses at a level of sophistication that has never been achieved before, even in LCDM analyses.

Big Bang Nucleosynthesis: New Physics and New Tools

Cara Giovanetti (NYU)

October 1st, 2024

Perimeter Institute Particle Physics Seminar

Based on work with Mariangela Lisanti, Hongwan Liu, Siddharth Mishra-Sharma, Joshua T. Ruderman, Martin Schmaltz, and Neal Weiner

Other work

- Orbital Dynamics of the Solar Basin C.G., R. Lasenby, K. Van Tilburg, 2408.16041
- Neutrino Spectral Distortions in BBN
- Gravitational Wave Constraints on PBHs
- A Fast and Differentiable Recombination Code

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Outline

- Why BBN?
  - BBN is a powerful probe of both ΛCDM and new physics
- BBN informs new physics
  - Portal Models
    - Electrophilic dark matter
    - Neutrinophilic dark matter
  - BBN still has a lot to say about new physics
- New tools for BBN
  - We can now perform sophisticated joint analyses for the first time

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Why BBN?

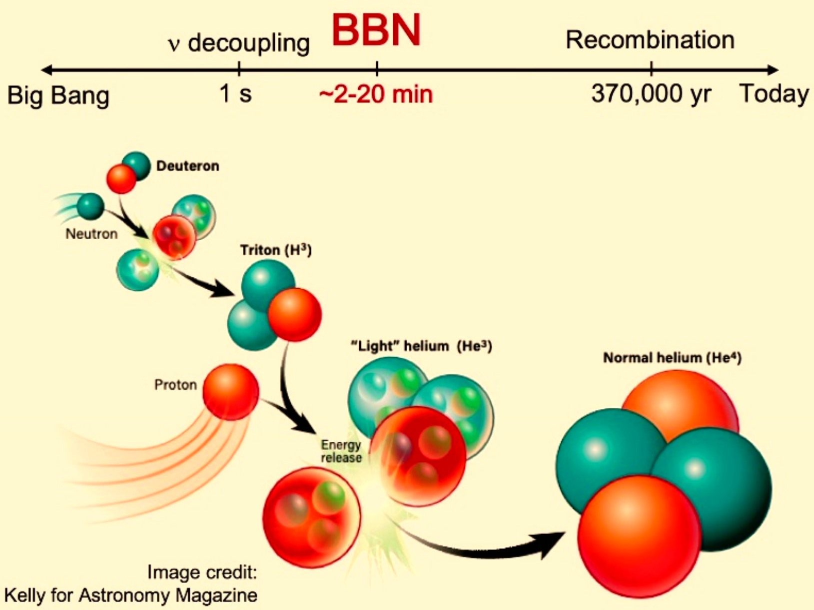


Image credit:
Roen Kelly for Astronomy Magazine

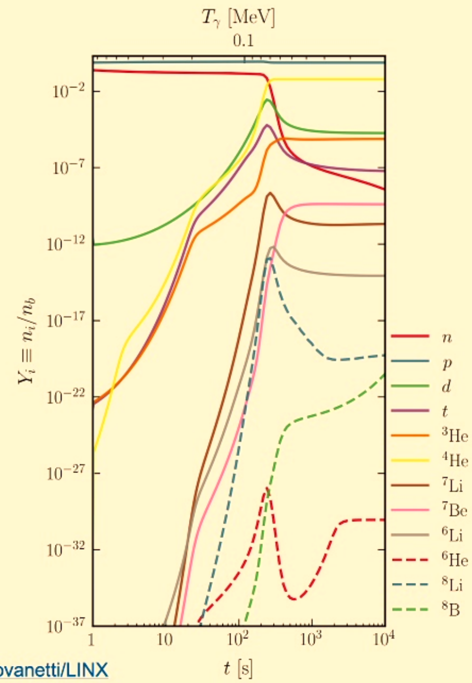
High **temperatures**
($T_{\rm SM}$~MeV-keV)

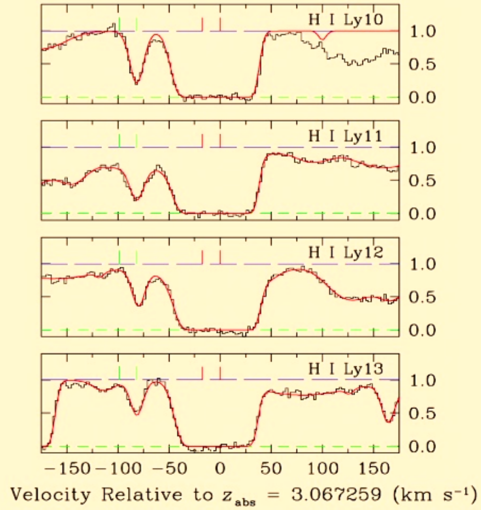
High **densities**
(a~10^{-9}-10^{-11})

Long **times**

5

Prediction meets measurement





R. Cooke et al., 1308.3240

https://github.com/cgiovanetti/LINX

Why BBN?

High temperatures

Precise measurements

BBN is a sensitive probe of ΛCDM and new physics

High densities

Precise predictions

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Precise predictions

BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**, and the **baryon-to-photon ratio**.

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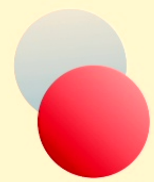
Helium-4 and Deuterium



- Large binding energy (28 MeV)
- Most neutrons end up in ^4He

- Small binding energy (2 MeV)
- Easily broken up

BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**, and the **baryon-to-photon ratio**.

Neutrino temperature and expansion rate determine freeze-out of proton-neutron interconversion.

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

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

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

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$$\left(\frac{n_n}{n_p}\right)_{\rm EQ} = e^{-\frac{m_n - m_p}{T}}$$

Kolb and Turner, Addison-Wesley

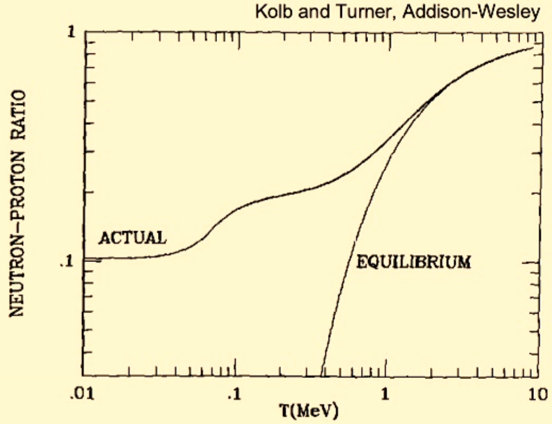


Fig. 4.1: The equilibrium and actual values of the neutron to proton ratio.

BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**, and the baryon-to-photon ratio.

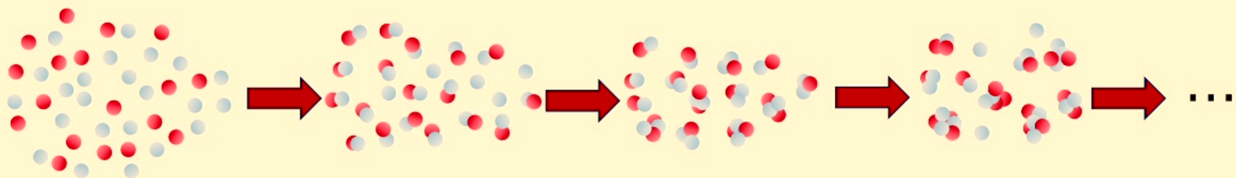
N_{eff} is impacted by the ratio of photon and neutrino temperatures. Impacts expansion rate.

$$N_{\text{eff}} = \left(\frac{\rho_R - \rho_\gamma}{\rho_{\nu,\text{std}}}\right)_0 \Rightarrow N_{\text{eff}} \sim \left(\frac{T_\nu}{T_\gamma}\right)_0^4 + \text{dark radiation}$$

BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**, and the baryon-to-photon ratio.

Faster expansion rate means heavy elements can't form. Larger abundance of deuterium.

Slow expansion



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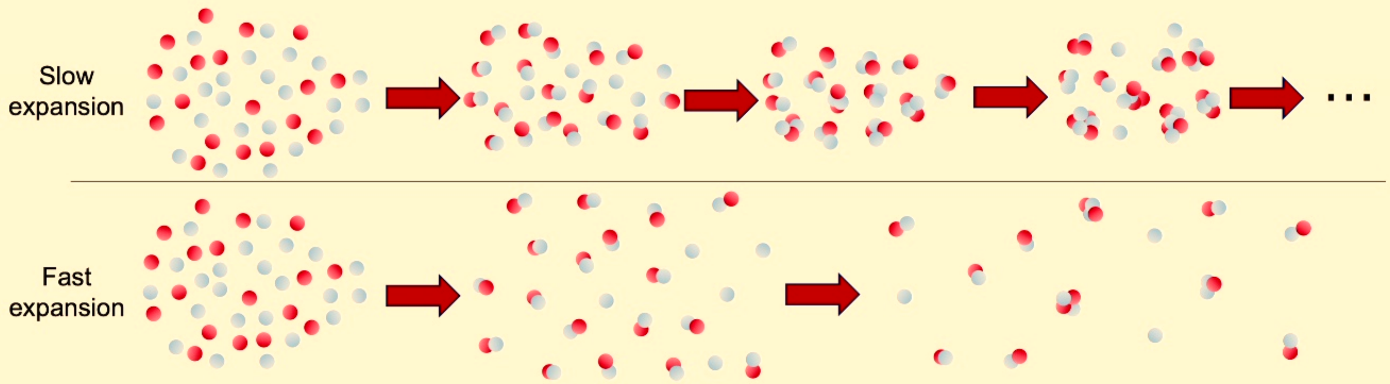

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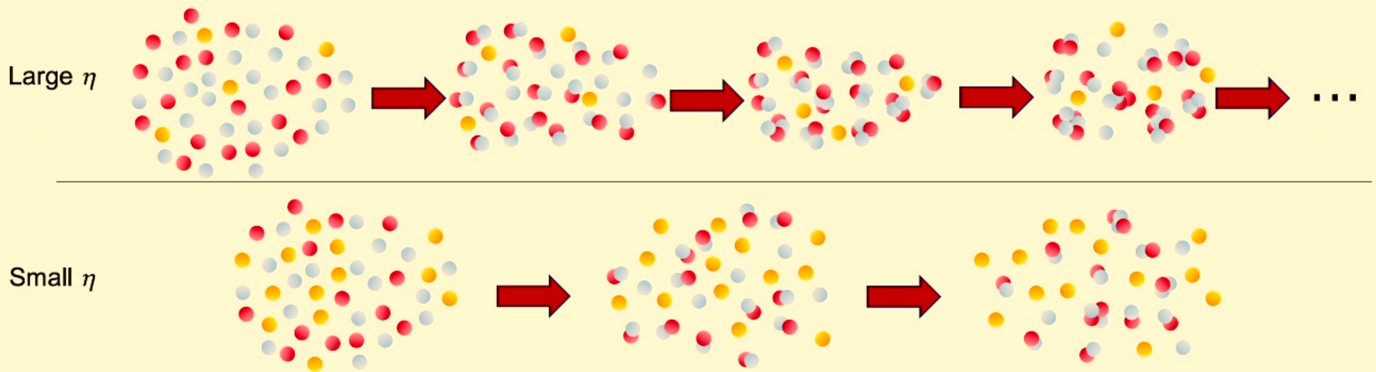
Larger η means more frequent interactions between nuclides. Destroys deuterium.



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Why BBN

- Many potential signals
  - Expansion rate (N_{eff})
  - Relative photon and neutrino temperatures
    - Weak rate freeze out
    - N_{eff}
  - Baryon-to-photon ratio

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- Complements CMB analyses
- New tools make rigorous analyses possible

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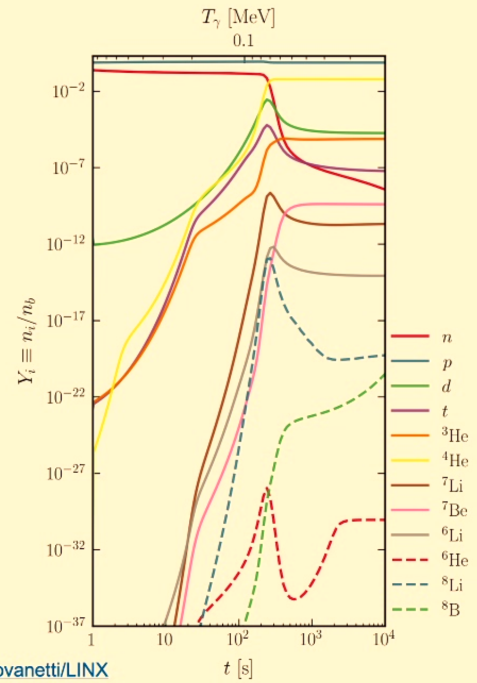

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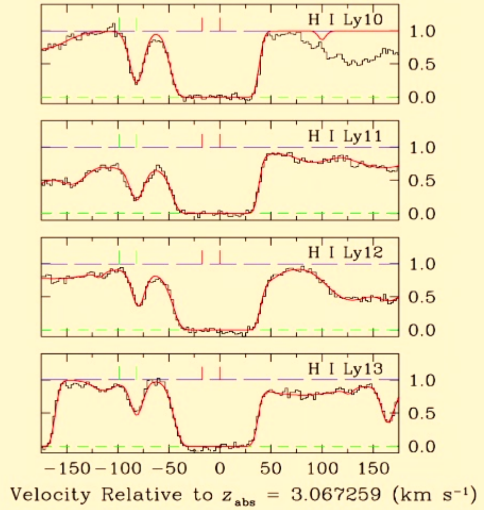

R. Cooke et al., 1308.3240

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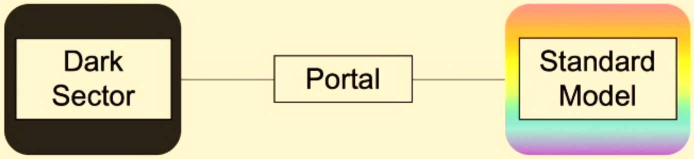
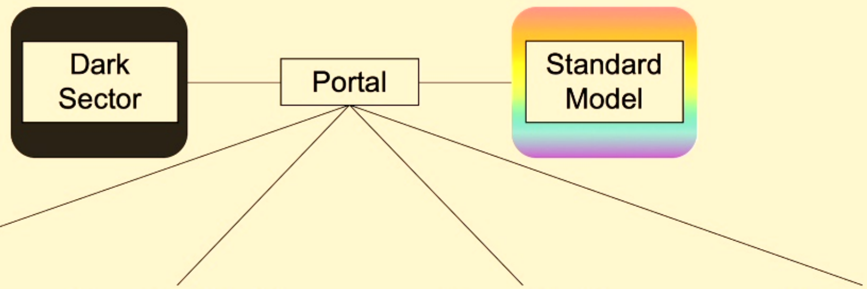
Minimal Portal Models



See Batell et al., 2207.06905 for a recent review

Minimal Portal Models



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Vector Portal

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

New gauge field with kinetic term F' mixes with Standard Model gauge fields

Neutrino Portal

$$\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$$

N is a new heavy, neutral lepton that can mix with Standard Model neutrinos

Higgs Portal

$$-\mathcal{L} \supset (A\,S + \lambda\,S^2)\,H^{\dagger} H$$

New scalar S couples to Higgs mass operator

ALP Portal

$$\mathcal{L} \supset c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$$

Axion-like particle a couples to photons and/or gluons

BBN constrains electrophilic sub-GeV dark matter

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu} + J^{\mu}_{\rm EM}\left(A_\mu - \epsilon A'_\mu\right)$$

+ massive dark matter χ
+ dark radiation

16

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- Vector Portal
- Originally linked to 511 keV Galactic center excess C. Boehm et al., astro-ph/0309686
- Common experimental benchmark

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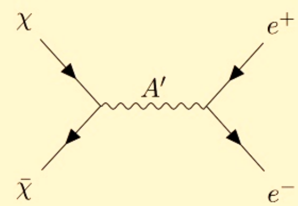
Small m_χ or $m_{A'}$ can contribute directly to N_{eff}



17

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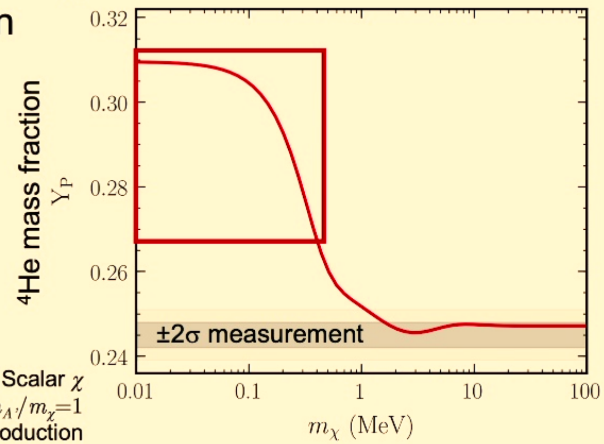

Complex Scalar χ
$m_{A'}/m_\chi$=1
Thermal Production

Measured values from
R.L. Workman *et al.* (PDG), Prog. Theor. Exp. Phys. 2022, 083C01
R. Cooke et al., 1710.11129

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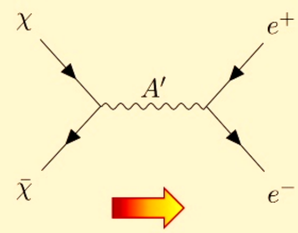

Entropy transfer from dark sector to photon sector

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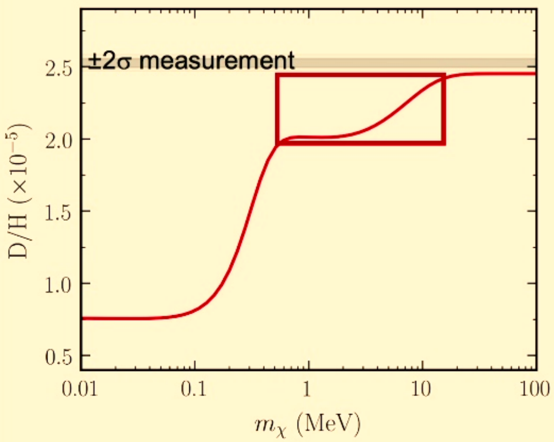

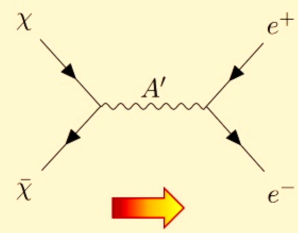

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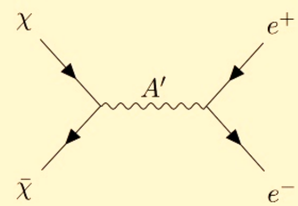

e^+e^- annihilate to photons, causing late-time changes to the baryon-to-photon ratio

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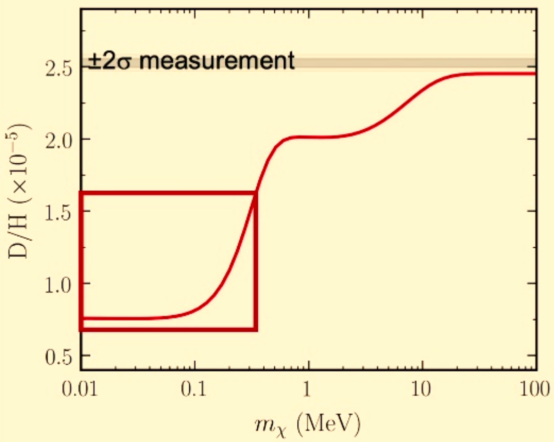

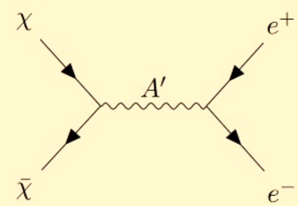

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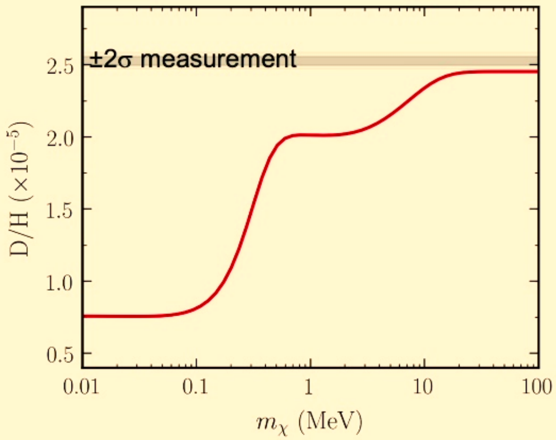
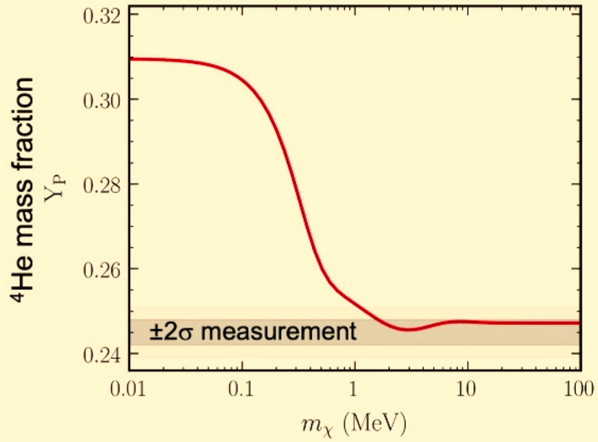
Deuterium production decreases with decreasing m_χ



^{4}He production increases with decreasing m_χ



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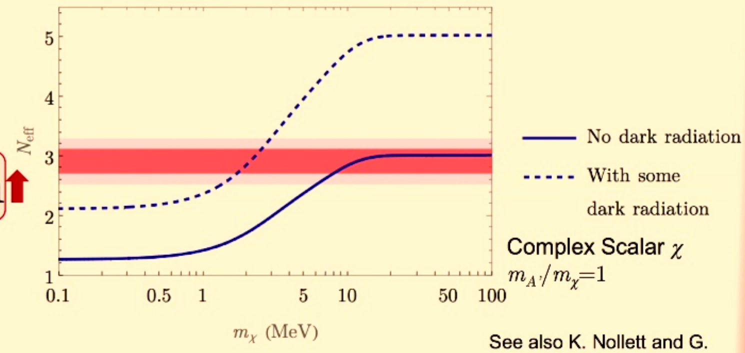
$$\updownarrow N_{\rm eff} \sim \left(\frac{T_\nu}{T_\gamma \uparrow}\right)^4_0 + \text{dark radiation}\uparrow$$



See also K. Nollett and G. Steigman, 1312.5725

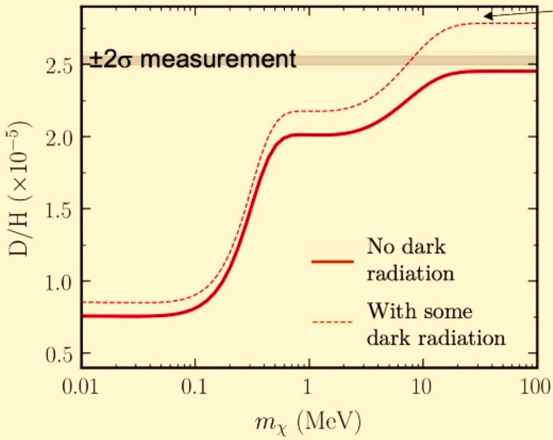
Many models include dark radiation!

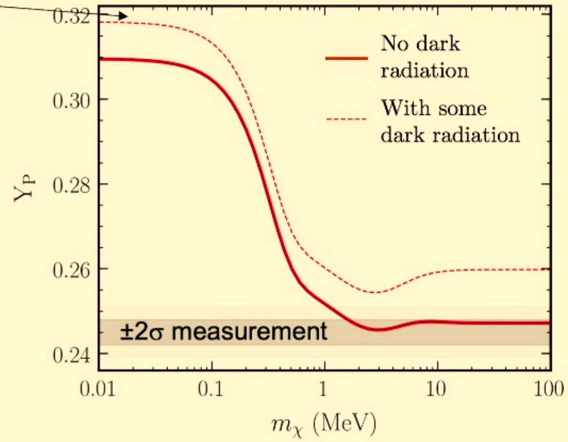
- Dark Higgs Dark Matter — C. Mondino, M. Pospelov, et al., 2005.02397

- Heavy Particle Decay models — As considered in K. Bleau, J. Bramante, and C. Cappiello, 2309.06482

- Dark QED avoids $N_{\rm eff}$ constraint on dark photons — A. Arvanitaki, S. Dimopoulos,M. Galanis, D. Racco et al., 2108.04823

Dark radiation increases expansion rate, favoring deuterium and early weak rate freeze out





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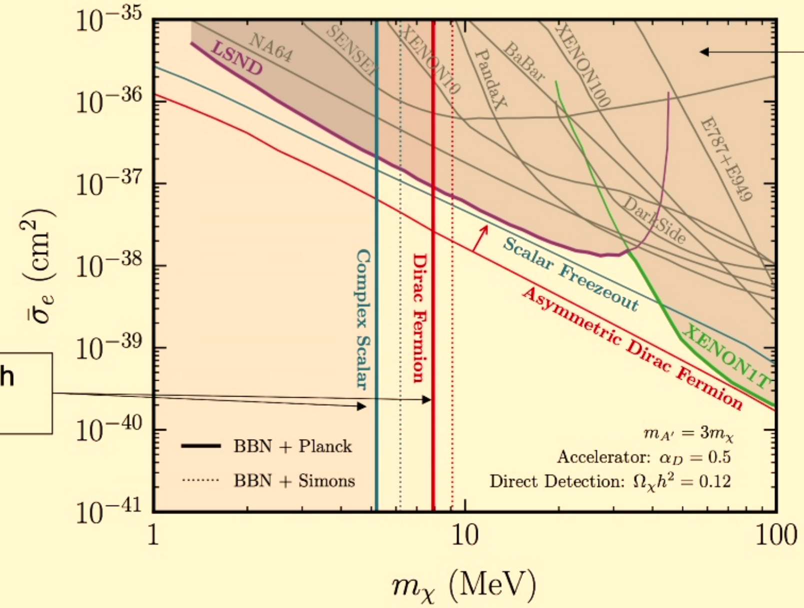

Existing constraints from direct detection, beam dump,…

New constraints with BBN!

C.G., M. Lisanti, H. Liu, J. T. Ruderman, 2109.03246

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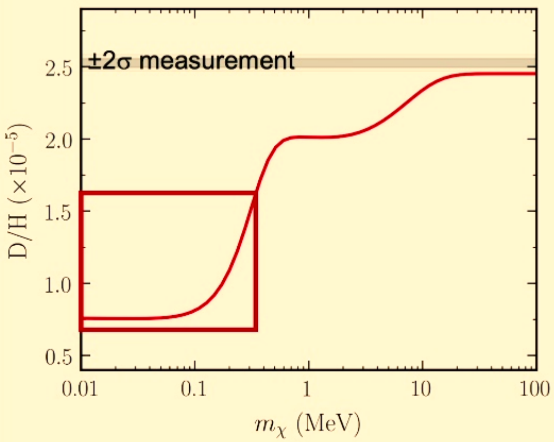

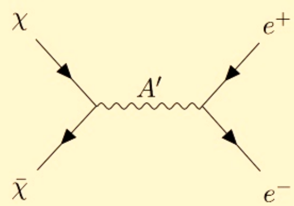

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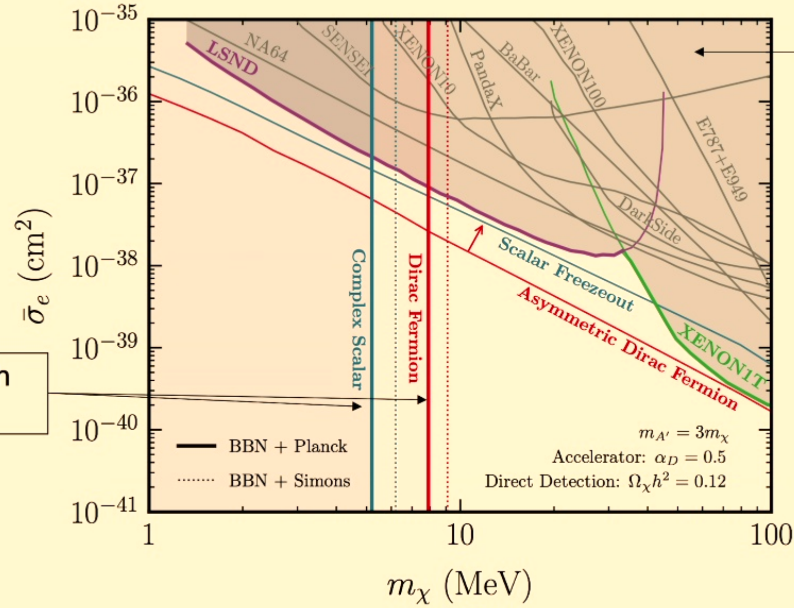

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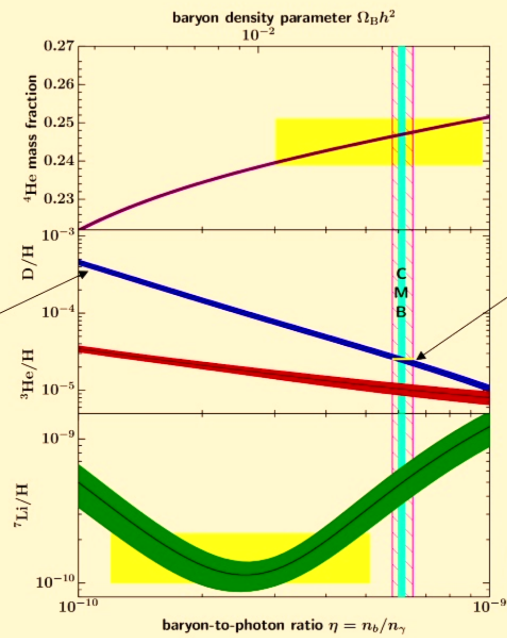
Tension between CMB and BBN η



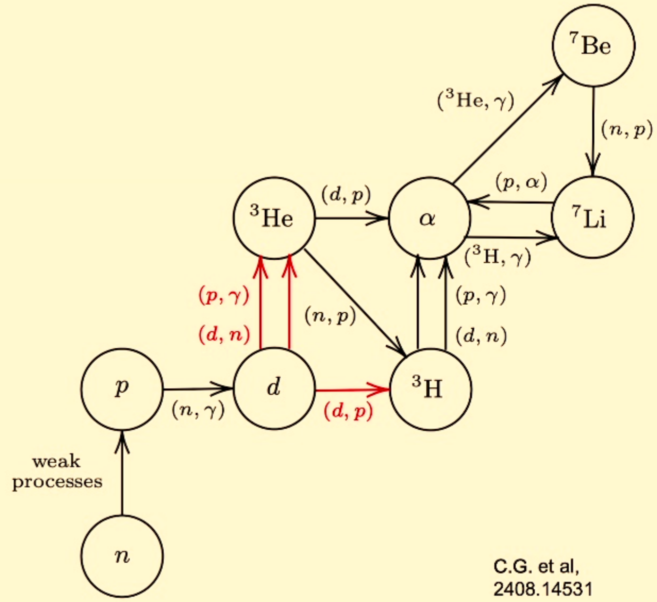
Deuterium prediction (PDG)

Measured deuterium abundance (PDG average*)

PDG, RPP 2021, Section 24

Reaction network

- Main input to BBN codes is a reaction network.
  - Includes rates for all reactions in the network



C.G. et al, 2408.14531

Reaction network

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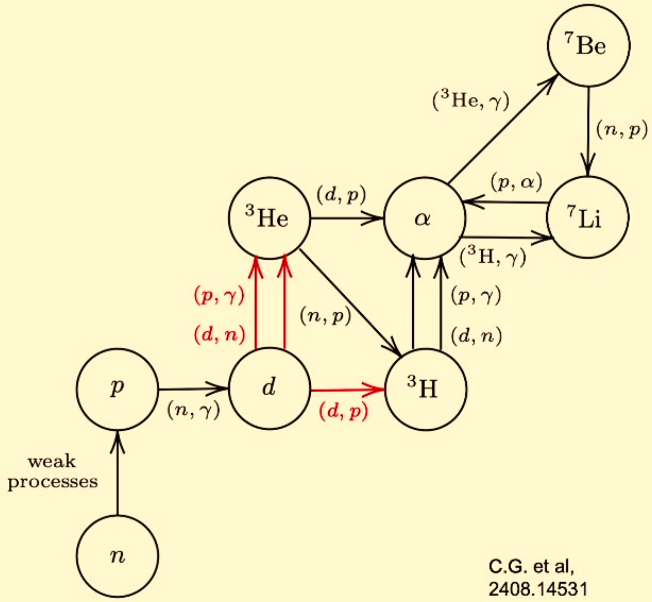
- Treatment of nuclear physics data differs between major BBN codes.
- **Absence or presence of tension is due entirely to choice of reaction network.**



C.G. et al, 2408.14531

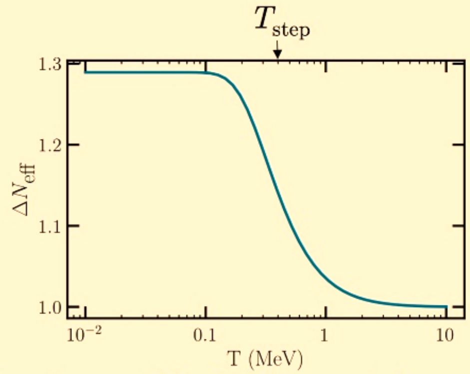
The model

$$\mathcal{L} \supset \underbrace{m_{\rm dark}\nu_d\nu_d + m_{\rm mix}\nu_d\nu_{\rm SM}}_{\text{Dark fermion, MeV-scale mass}} + \underbrace{\lambda\phi\nu_d\nu_d}_{\text{Light scalar}}$$

- Dark sector equilibrates with SM neutrinos via repeated oscillation and scattering
- Freeze out at $T_{\rm step}$
- Dominant effect is a “step” in $N_{\rm eff}$

D. Aloni et al, 2111.00014

The model

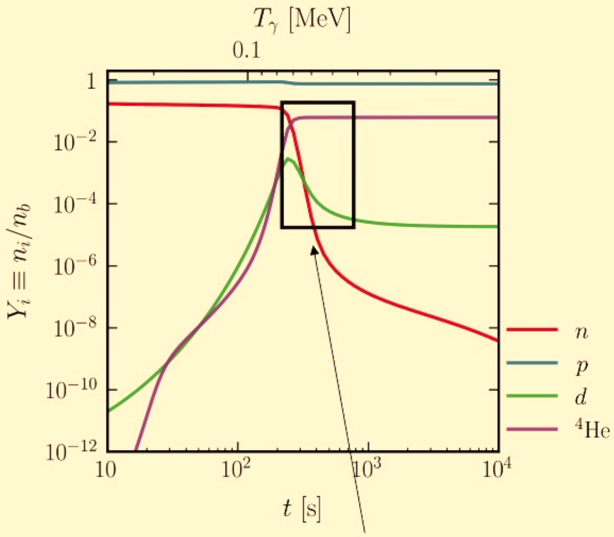


- Dark sector equilibrates with SM neutrinos via repeated oscillation and scattering
- Freeze out at $T_{\rm step}$
- Dominant effect is a “step” in $N_{\rm eff}$

D. Aloni et al, 2111.00014

A step in understanding the deuterium "tension"

- Increasing $N_{\rm eff}$ increases D/H, but also increases ^{4}He
- Step in $N_{\rm eff}$ modifies D/H without modifying ^{4}He

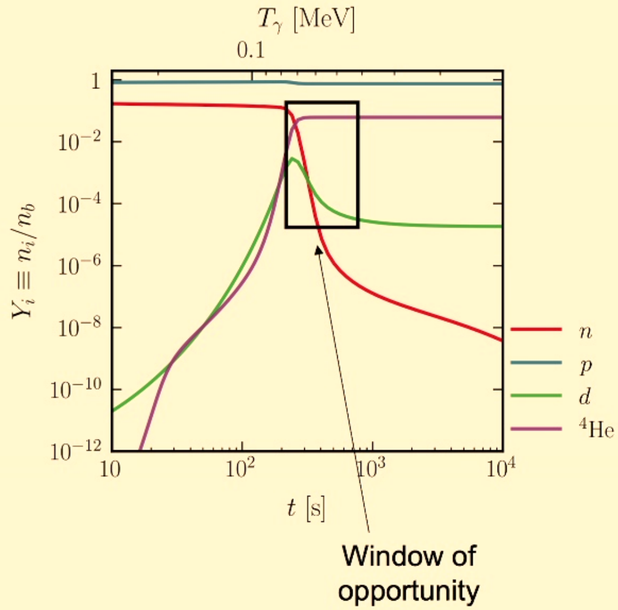


See also A. Berlin et al., 1904.04256

30

A step in understanding the deuterium "tension"

- Increasing $N_{\rm eff}$ increases D/H, but also increases ^{4}He
- Step in $N_{\rm eff}$ modifies D/H without modifying ^{4}He
- This works across a wide range of step temperatures and changes to $N_{\rm eff}$



See also A. Berlin et al., 1904.04256

30

The model

$$\mathcal{L} \supset \underbrace{m_{\rm dark}\nu_d\nu_d + m_{\rm mix}\nu_d\nu_{\rm SM}}_{\text{Dark fermion, MeV-scale mass}} + \underbrace{\lambda\phi\nu_d\nu_d}_{\text{Light scalar}}$$

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D. Aloni et al, 2111.00014

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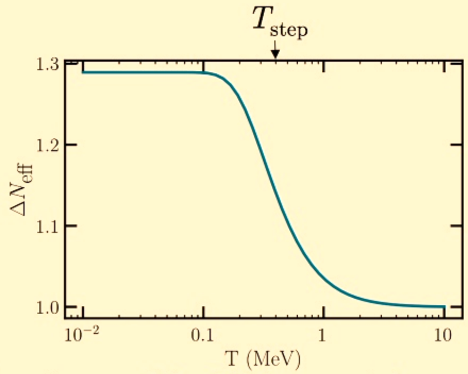
The model



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D. Aloni et al, 2111.00014

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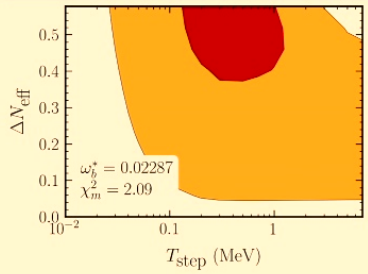
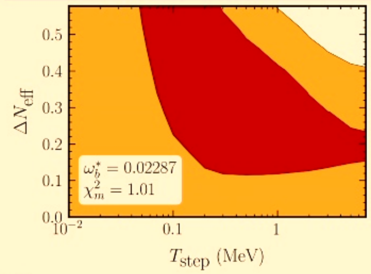
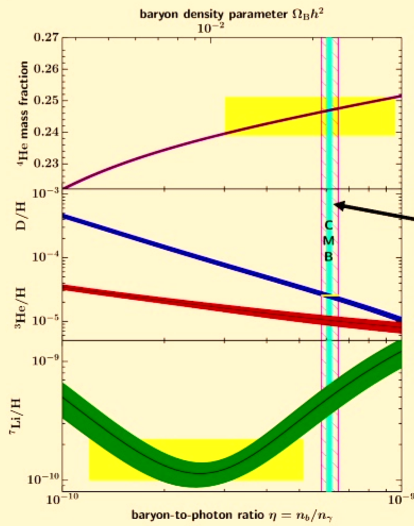
D. Aloni et al, 2111.00014

Deuterium tension network



No-deuterium-tension network





Model-dependent determination of $\Omega_b h^2$

C.G., M. Schmaltz, N. Weiner, 2402.10264

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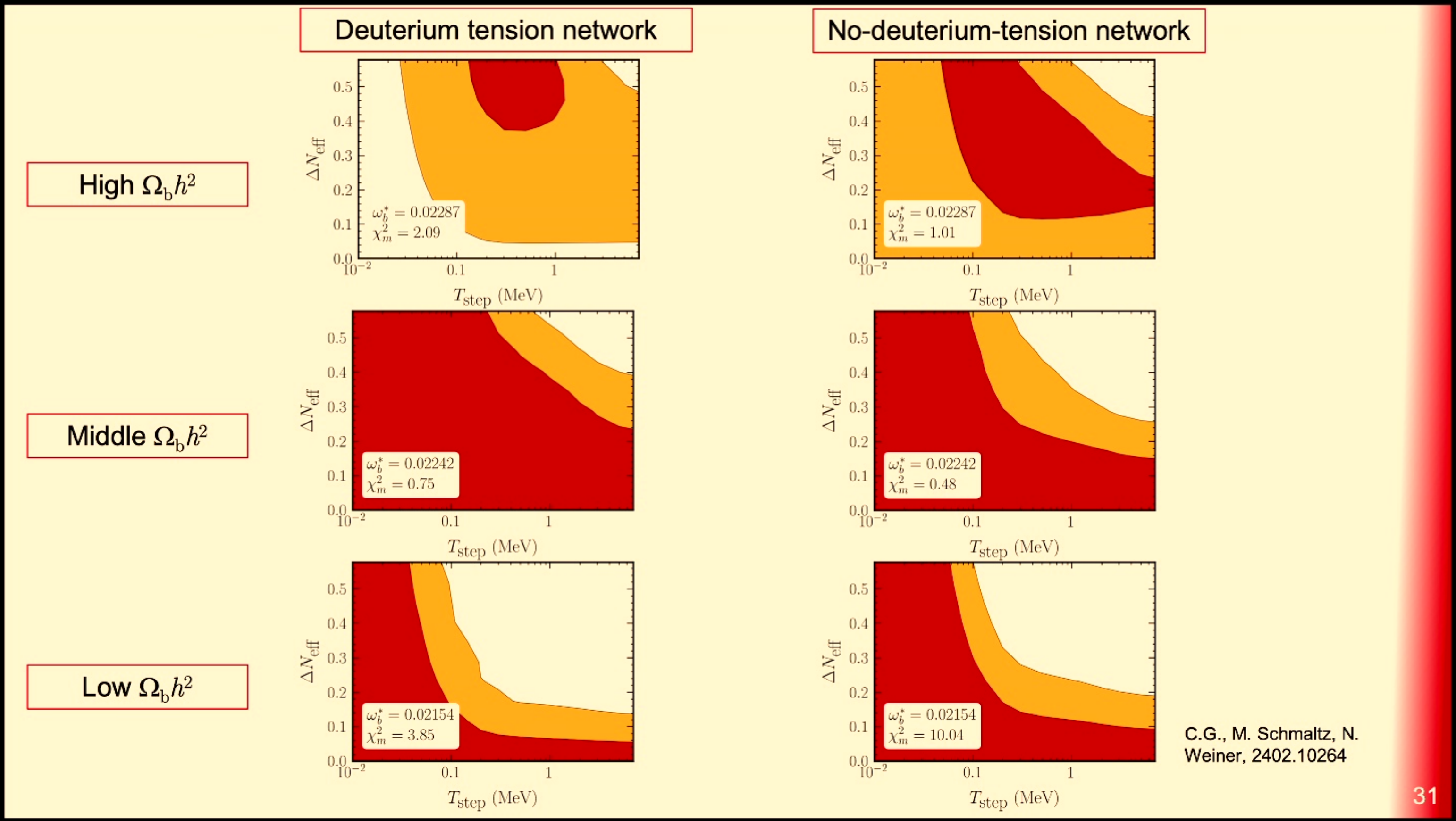

Deuterium tension network
No-deuterium-tension network
High $\Omega_b h^2$
Middle $\Omega_b h^2$
Low $\Omega_b h^2$
$\omega_b^* = 0.02287$ $\chi_m^2 = 2.09$
$\omega_b^* = 0.02287$ $\chi_m^2 = 1.01$
$\omega_b^* = 0.02242$ $\chi_m^2 = 0.75$
$\omega_b^* = 0.02242$ $\chi_m^2 = 0.48$
$\omega_b^* = 0.02154$ $\chi_m^2 = 3.85$
$\omega_b^* = 0.02154$ $\chi_m^2 = 10.04$
$\Delta N_{\rm eff}$
$T_{\rm step}$ (MeV)
C.G., M. Schmaltz, N. Weiner, 2402.10264
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Major hurdles in these analyses

- Switching reaction networks is hard, **but important**.
- Scans take **several days** to run.
- Calculating uncertainties is **hard**.

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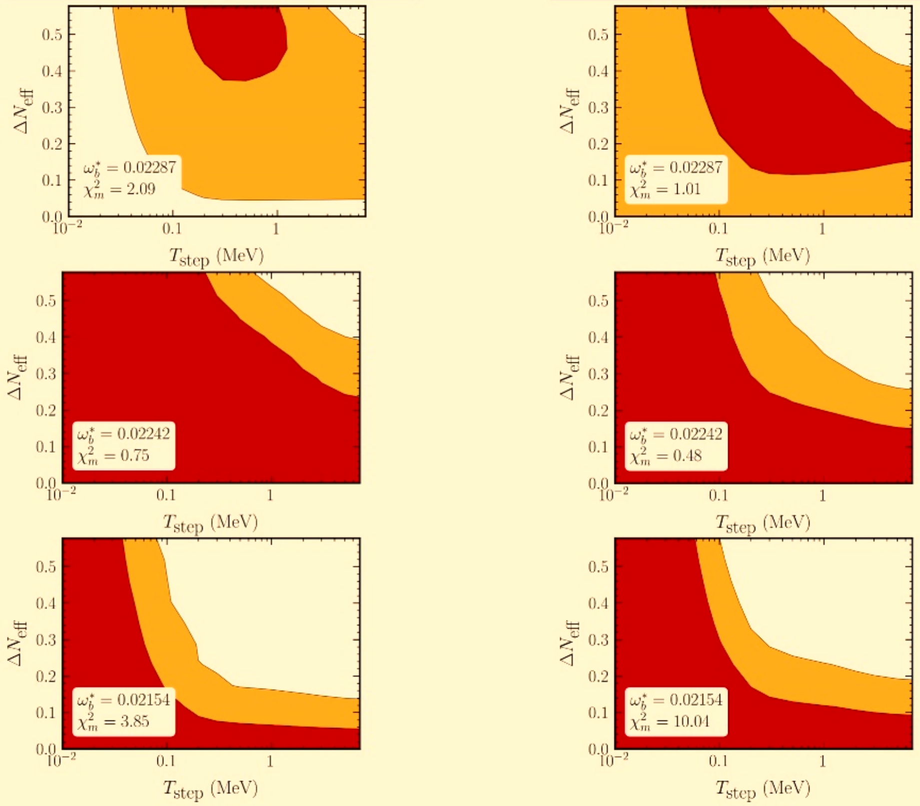
Deuterium tension network

No-deuterium-tension network

High $\Omega_b h^2$

Middle $\Omega_b h^2$

Low $\Omega_b h^2$



C.G., M. Schmaltz, N. Weiner, 2402.10264

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Outline

- Why BBN?
  - BBN is a powerful probe of both ΛCDM and new physics
- BBN informs new physics
  - Portal Models
    - Electrophilic dark matter
    - Neutrinophilic dark matter
  - BBN still has a lot to say about new physics
- New tools for BBN
  - We can now perform sophisticated joint analyses for the first time

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Goals:

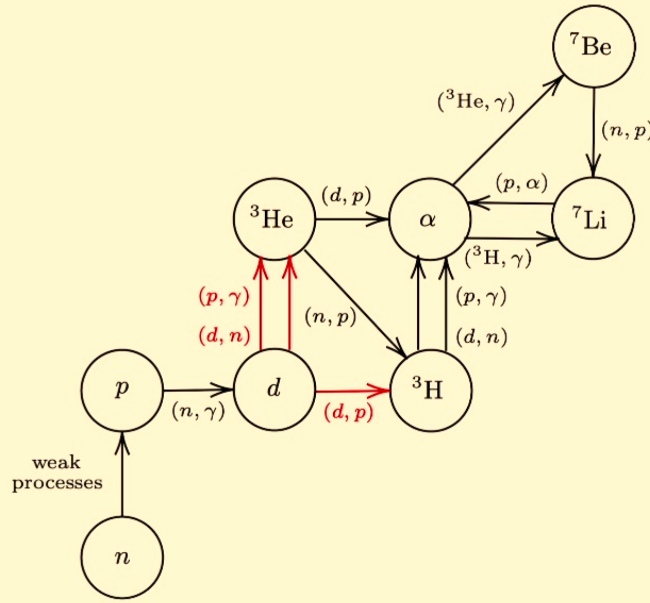
1) A fast BBN code
2) Easy calculation of uncertainties
3) Easy switching between reaction networks

We want to put BBN analyses on the same footing as CMB analyses when performing *parameter estimation*.

BBN Nuisance Parameters

Nuclear physics gives us an uncertain rate for each reaction.

Need to sample reaction rates as nuisance parameters!



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Public BBN Codes

Name	Language	Time Per Solve	Comments
AlterBBN	C	< 1s	Incomplete implementation of neutrino decoupling, weak rates; old nuclear rates.
PRIMAT	Mathematica	O(1 min)	Extremely accurate, but very slow.
PArthENoPE	Fortran	< 1s	Fast, but challenging to modify for parameter estimation.
PRyMordial	Python	O(10 s)	Accurate. Full parameter estimation possible, but slow. Written with new physics in mind.

All current BBN codes have to make compromises when it comes to parameter estimation.

O. Pisanti et al., 0705.0290
A. Arbey, 1106.1363
R. Consiglio et al., 1712.04378
A. Arbey et al., 1806.11095
C. Pitrou et al., 1801.08023
S. Gariazzo et al., 2103.05027
A.K. Burns et al., 2307.07061

Slide courtesy of Hongwan Liu

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LINX	**Python+JAX**	**<0.1s**	**As accurate as PRyMordial. Fast enough for MCMC methods.**

*LINX: **L**ight **I**sotope **N**ucleosynthesis with JA**X**

C.G. et al., 2408.14538

No new approximations, not an emulator

Publicly available at https://github.com/cgiovanetti/LINX

Slide courtesy of Hongwan Liu

BBN Nuisance Parameters

$$\log \mathcal{L}_{\mathrm{BBN,PArth.}} = -\frac{1}{2}\left[\frac{\left(\mathrm{Y_P}(\Omega_b h^2, N_{\mathrm{eff}}) - \mathrm{Y_P^{obs}}\right)^2}{\sigma^2_{\mathrm{Y_P^{obs}}} + \sigma^{\mathrm{th}\,2}_{\mathrm{Y_P}}} + \frac{\left(\mathrm{D/H}(\Omega_b h^2, N_{\mathrm{eff}}) - \mathrm{D/H^{obs}}\right)^2}{\sigma^2_{\mathrm{D/H^{obs}}} + \sigma^{\mathrm{th}\,2}_{\mathrm{D/H}}}\right]$$

Constant theory uncertainty

BBN Nuisance Parameters

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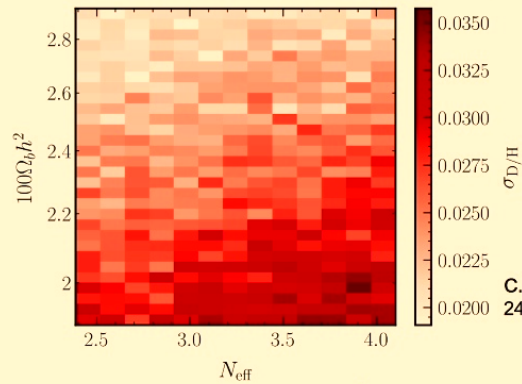
Constant theory uncertainty



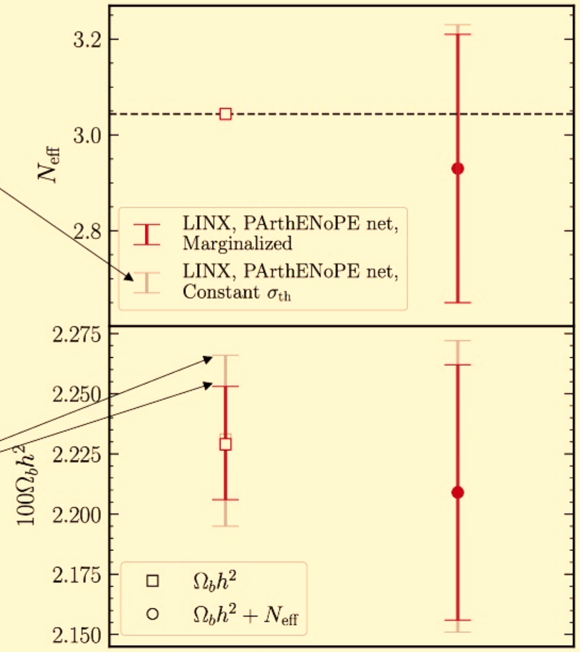
C.G. et al, 2408.14531

$$\log \mathcal{L}_{\rm BBN,LINX} = -\frac{1}{2}\left[\left(\frac{\mathrm{Y_P}(\Omega_b h^2, N_{\rm eff}, \vec{\nu}_{\rm BBN}) - \mathrm{Y_P^{obs}}}{\sigma_{\mathrm{Y_P^{obs}}}}\right)^2 + \left(\frac{\mathrm{D/H}(\Omega_b h^2, N_{\rm eff}, \vec{\nu}_{\rm BBN}) - \mathrm{D/H^{obs}}}{\sigma_{\mathrm{D/H^{obs}}}}\right)^2\right]$$

BBN Nuisance Parameters

Old analyses (see e.g. Schöneberg 2401.15054, Planck 1807.06209) assume a constant theory uncertainty

LINX performs marginalization to better estimate error bars—in some cases, a 30% reduction from previous work!



C.G. et al, 2408.14531

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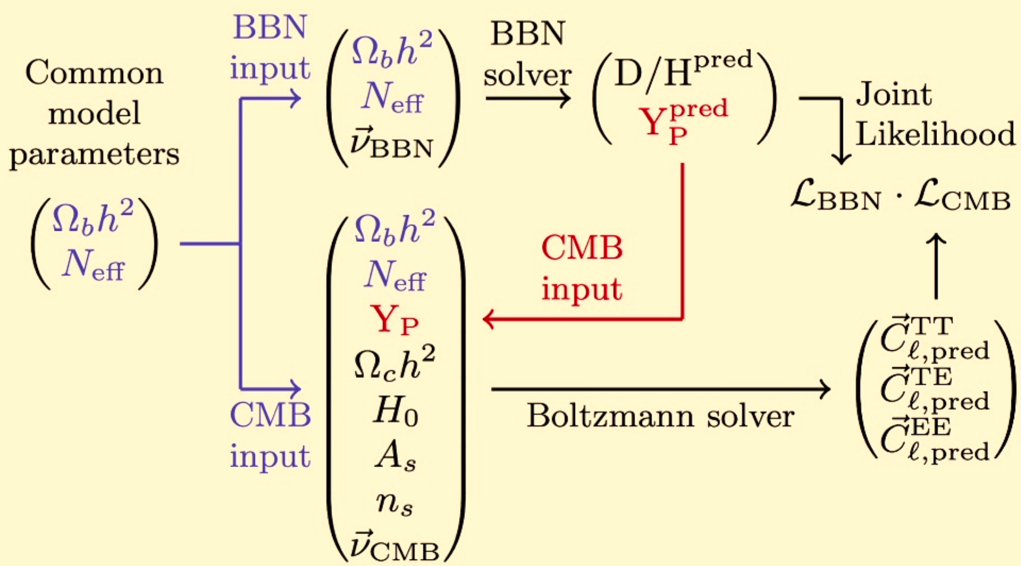
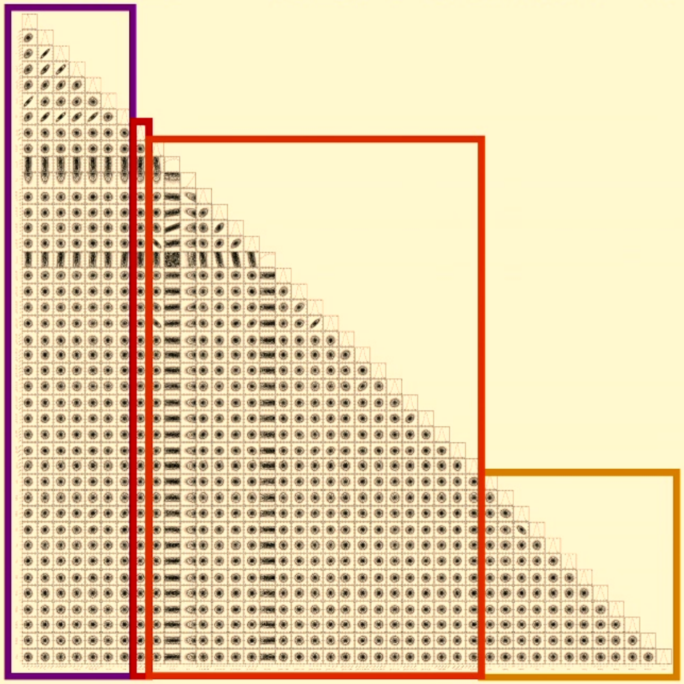
CMB + BBN Joint Fit



C.G. et al,
2408.14531

CMB + BBN Joint Fit



Can vary **cosmological parameters**, **neutron lifetime**, **CMB nuisance parameters**, and **individual reaction rates**

Runtime of ~2 days on 192 standard memory cores using nested sampling.

Long runtime dominated by CLASS

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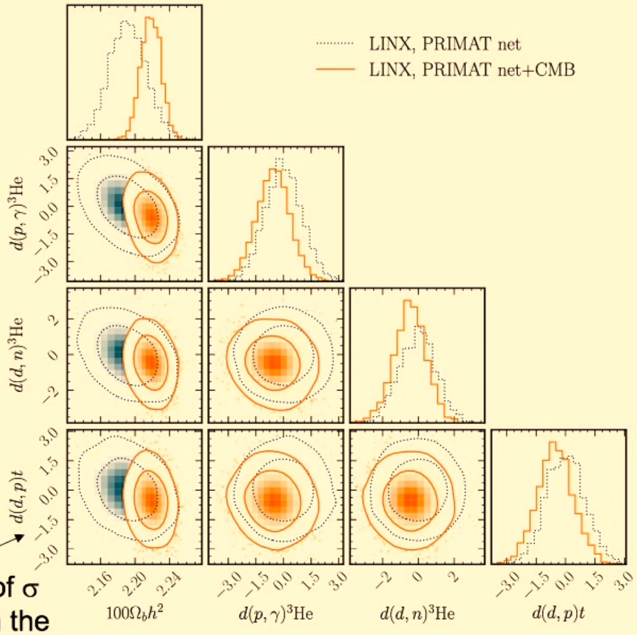
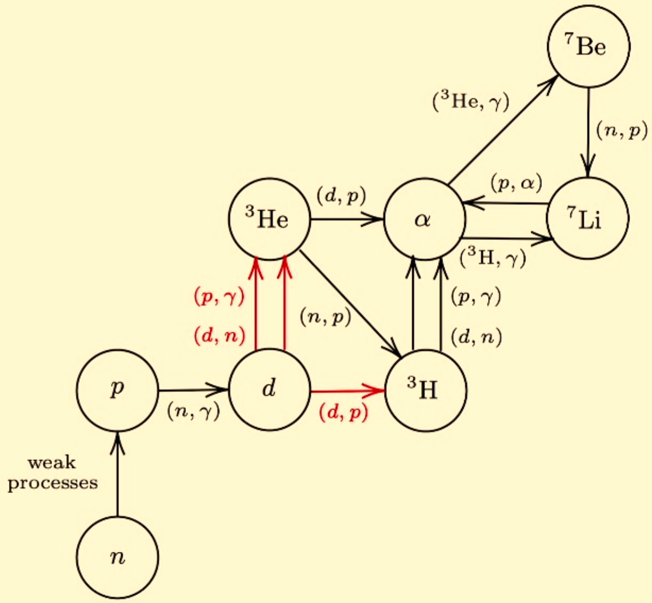
Why track nuisance parameters?



Number of σ away from the median rate



C.G. et al, 2408.14531

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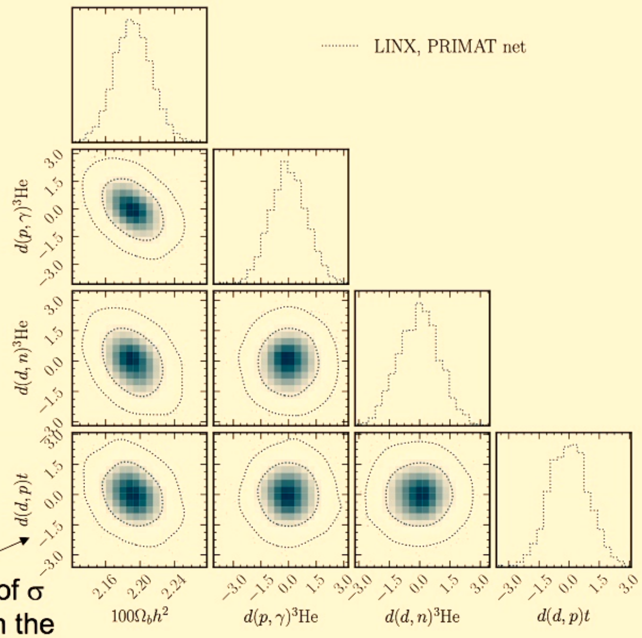

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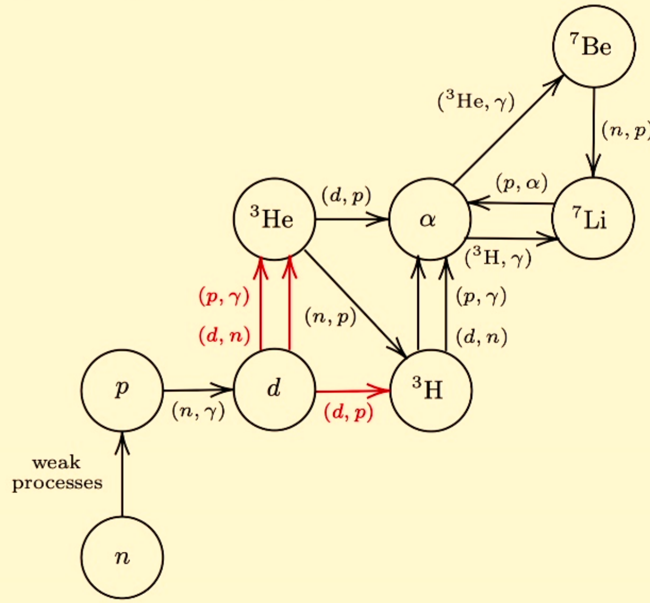

C.G. et al, 2408.14531

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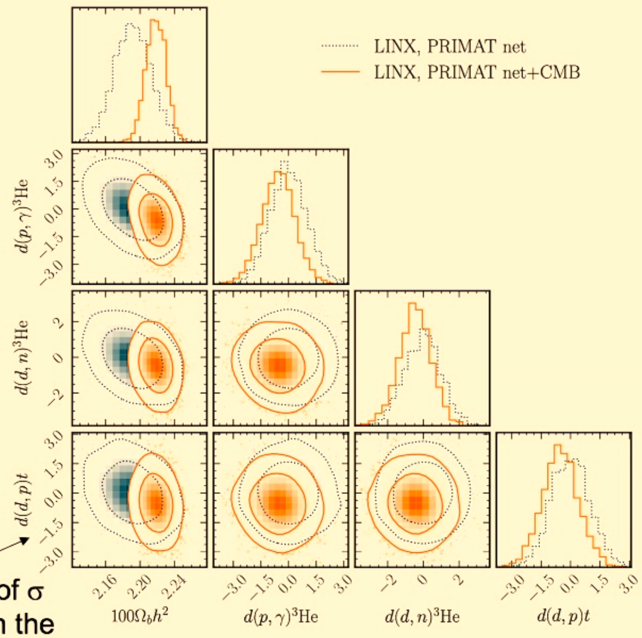

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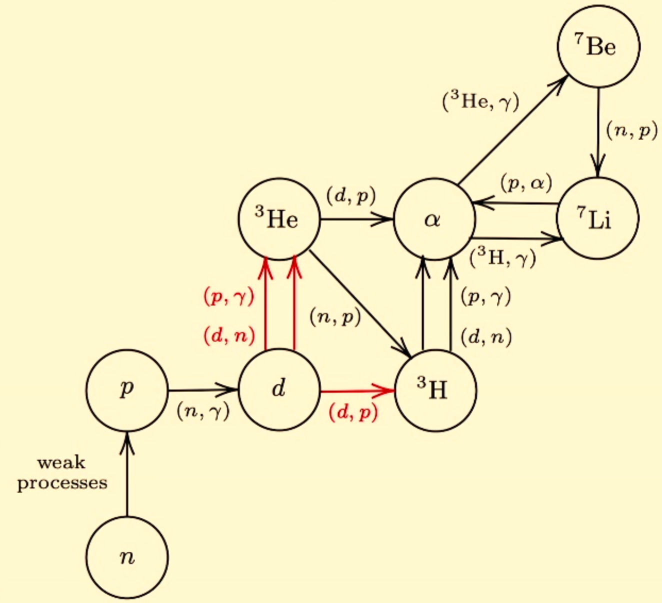

C.G. et al, 2408.14531