Big Bang Nucleosynthesis: New Physics and New Tools

Cara Giovanetti (NYU)

November 14th, 2024

Fermilab Theory 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

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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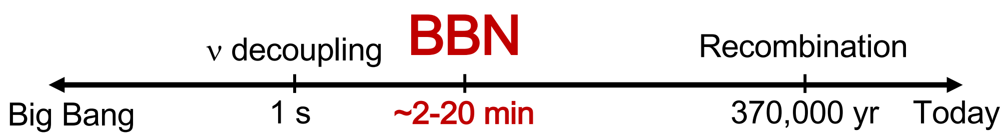
Why BBN?



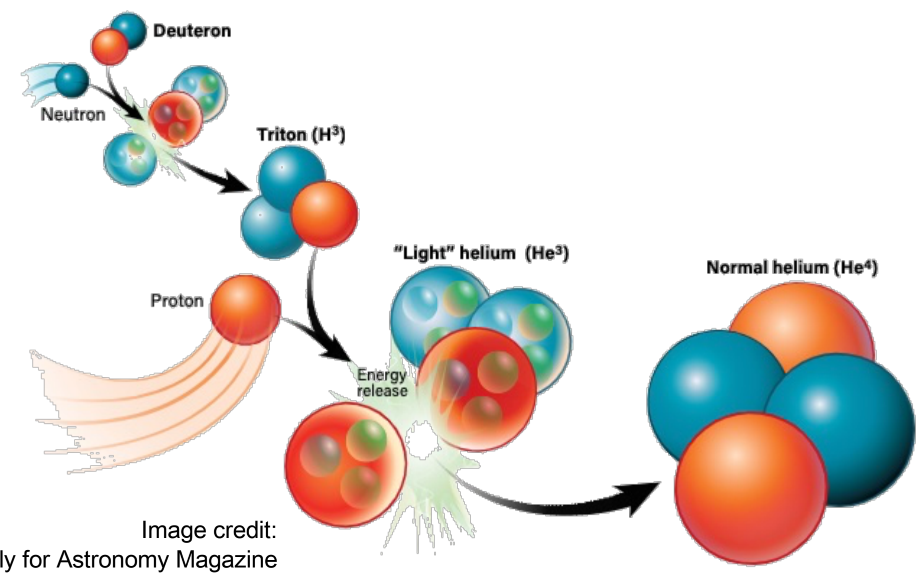


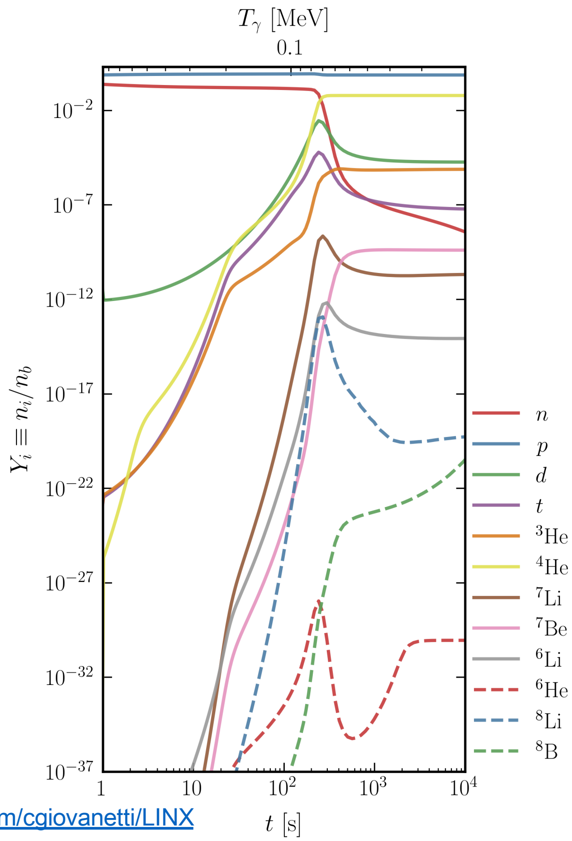
Image credit:
Roen Kelly for Astronomy Magazine

High **temperatures**
($T_{\mathrm{SM}} \sim \mathrm{MeV\text{-}keV}$)

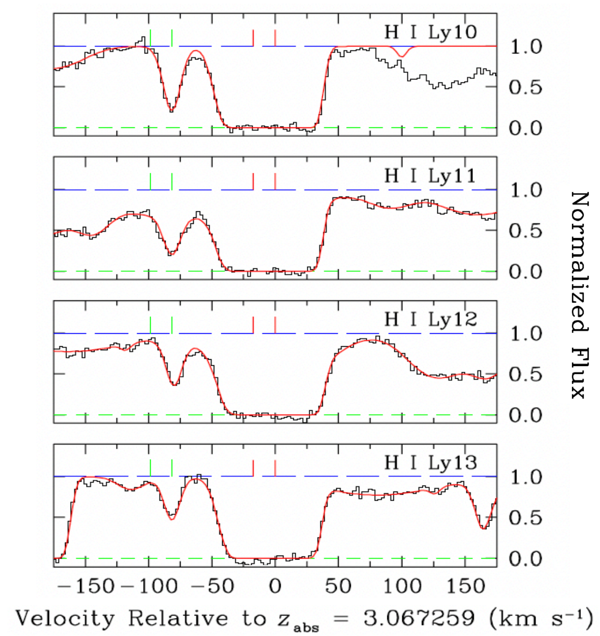
High **densities**
($a \sim 10^{-9}\text{-}10^{-11}$)

Long **times**

Prediction meets measurement



https://github.com/cgiovanetti/LINX



R. Cooke et al., 1308.3240

Why BBN?

High temperatures

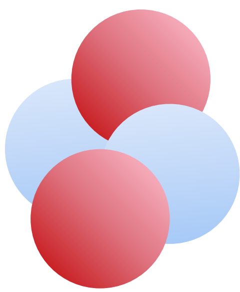
Precise measurements

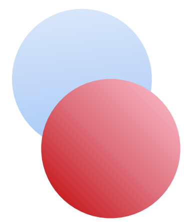
BBN is a sensitive probe of ΛCDM and new physics

High densities

Precise predictions

Helium-4 and Deuterium





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

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

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

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

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

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

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

Kolb and Turner, Addison-Wesley

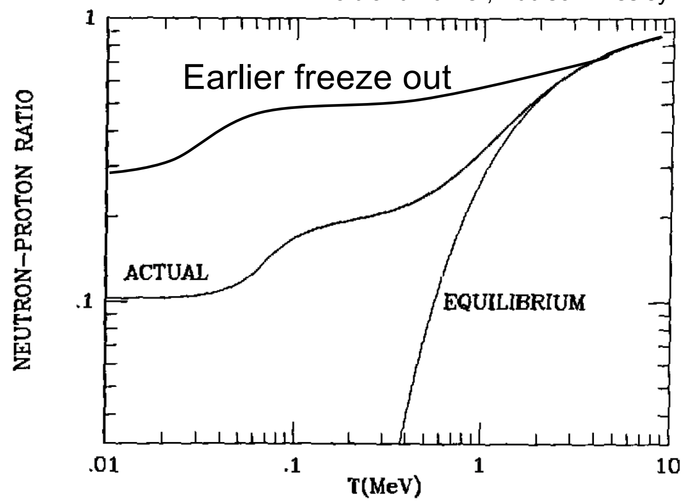


Fig. 4.1: The equilibrium and actual values of the neutron to proton ratio.

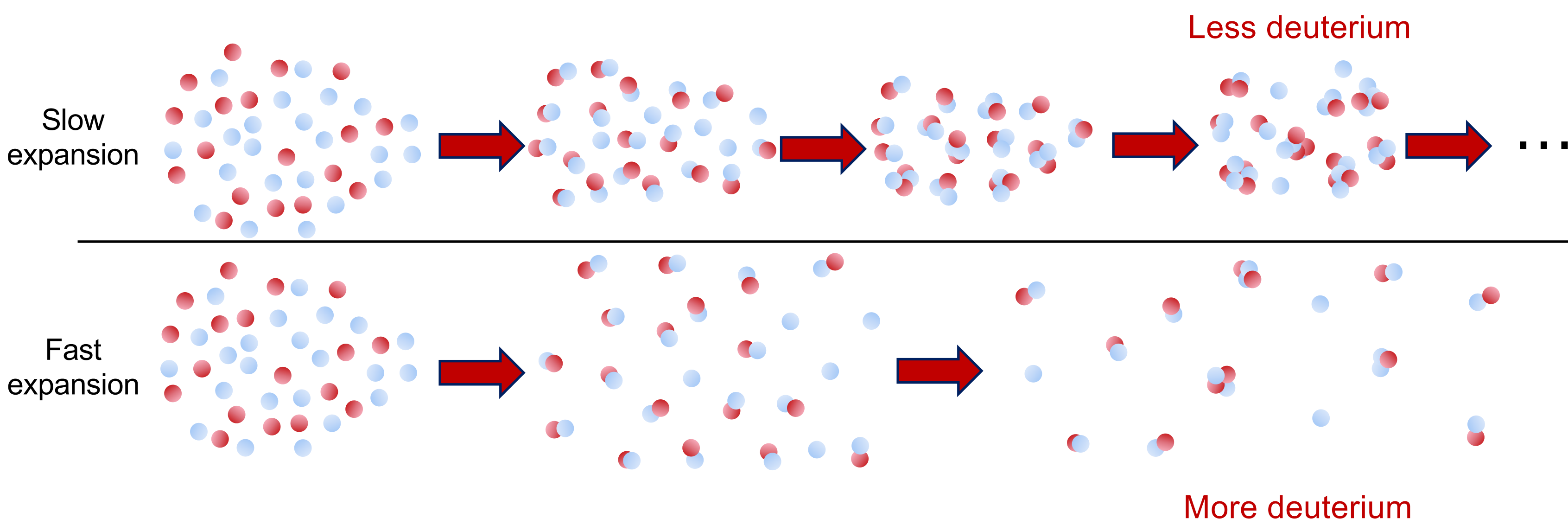
BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**

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

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

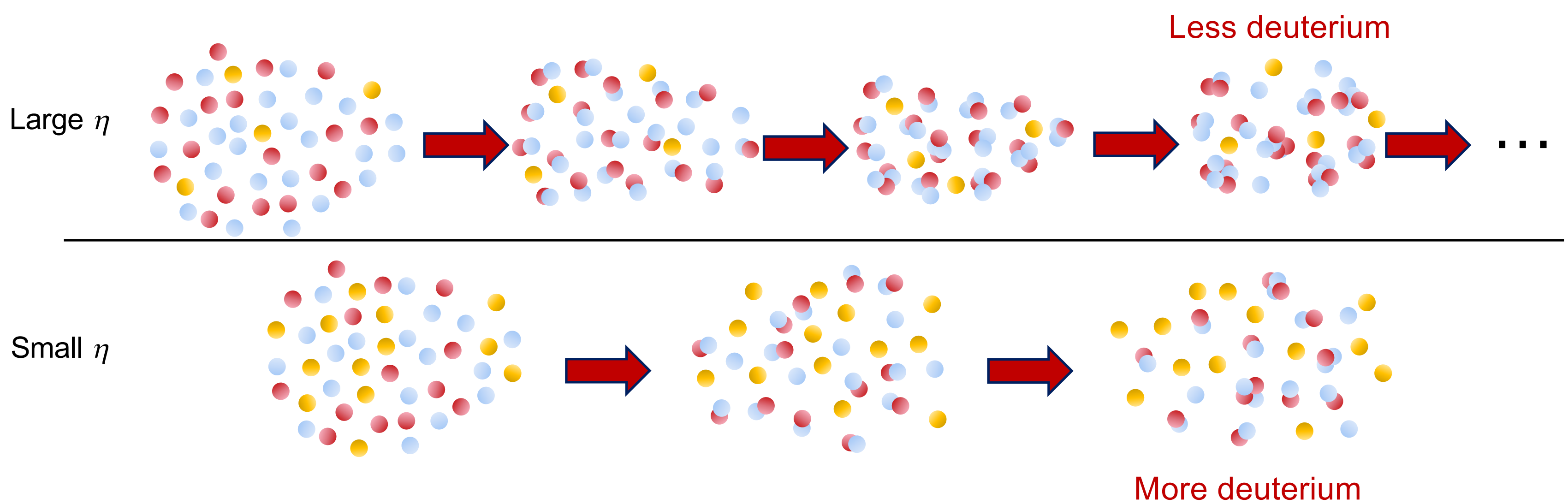
BBN is sensitive to the **expansion rate**, the **photon** and **neutrino temperatures**

Faster expansion rate means heavy elements can't form.



BBN is sensitive to the **expansion rate**

Larger η means more frequent interactions between nuclides.



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

Why BBN

- Many potential signals
  - Expansion rate (N_{eff})
  - Relative photon and neutrino temperatures
    - Weak rate freeze out
    - N_{eff}
  - Baryon-to-photon ratio
- Complements CMB analyses
- New tools make rigorous analyses possible

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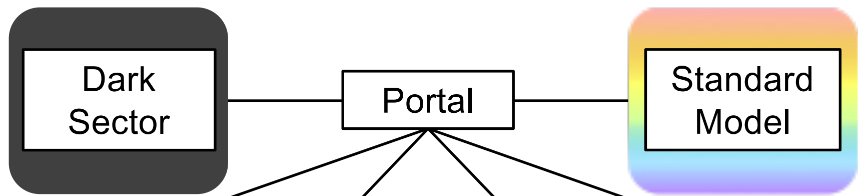
Minimal Portal Models



See Batell et al., 2207.06905 for a recent review

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

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

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

Electrophilic sub-GeV dark matter

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

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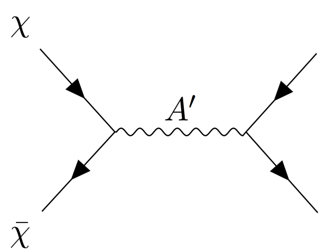
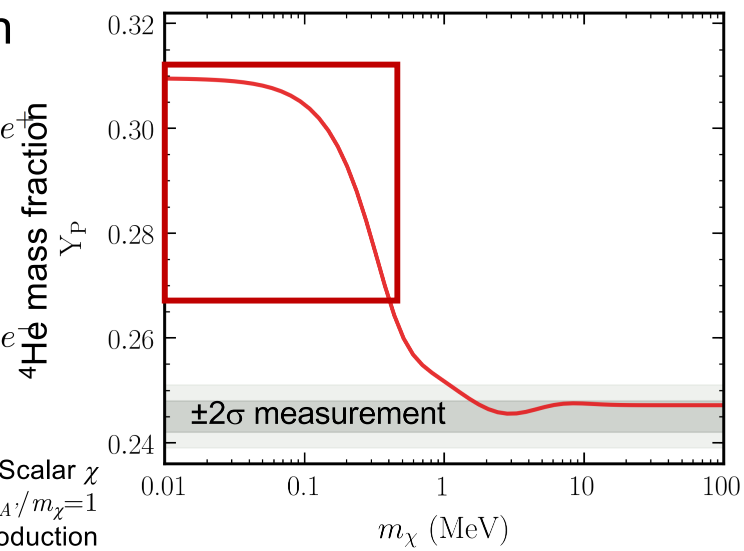
Small m_χ or $m_{A'}$ can contribute directly to $N_{\rm eff}$





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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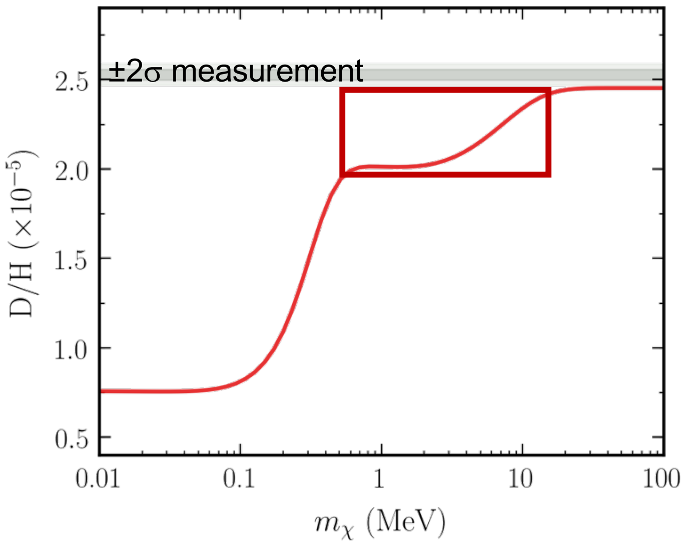

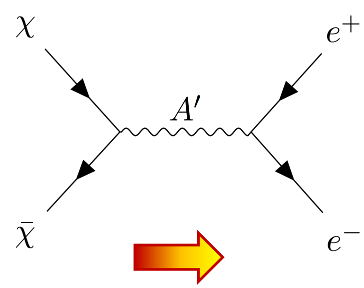

Entropy transfer from dark sector to photon sector

Complex Scalar χ
$m_{A'}/m_\chi$=1
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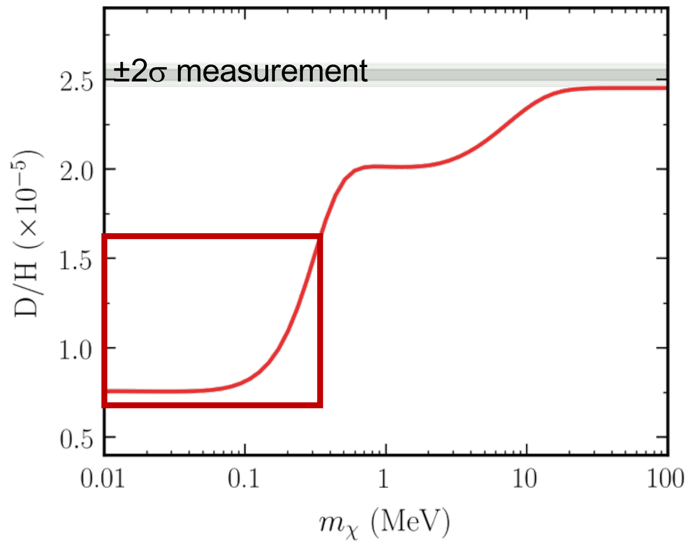
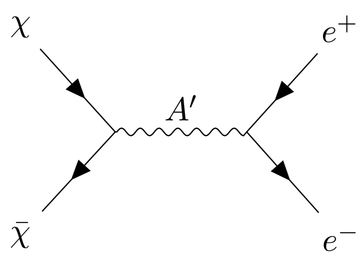


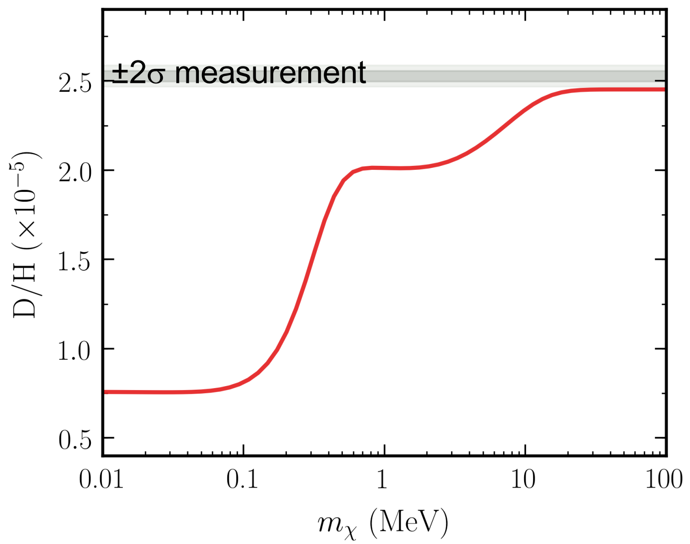


Complex Scalar χ
$m_{A'}/m_\chi$=1
Thermal Production

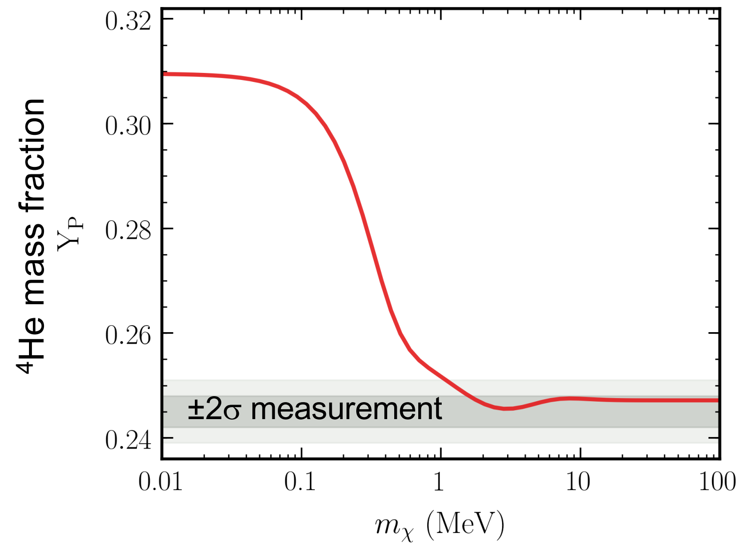
e^+e^- annihilate to photons, causing late-time changes to the baryon-to-photon ratio

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

Deuterium production **decreases** with decreasing m_χ



^{4}He production **increases** with decreasing m_χ



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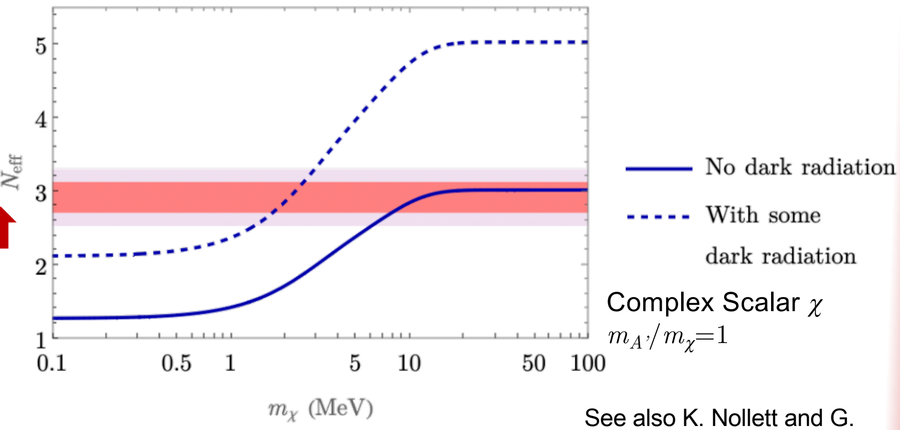
$$N_{\rm eff} \sim \left(\frac{T_\nu}{T_\gamma}\right)^4_0 + \text{dark radiation}$$

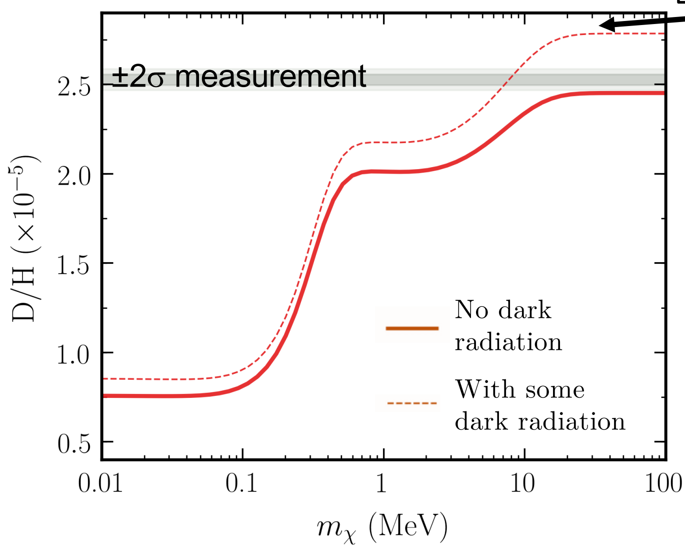


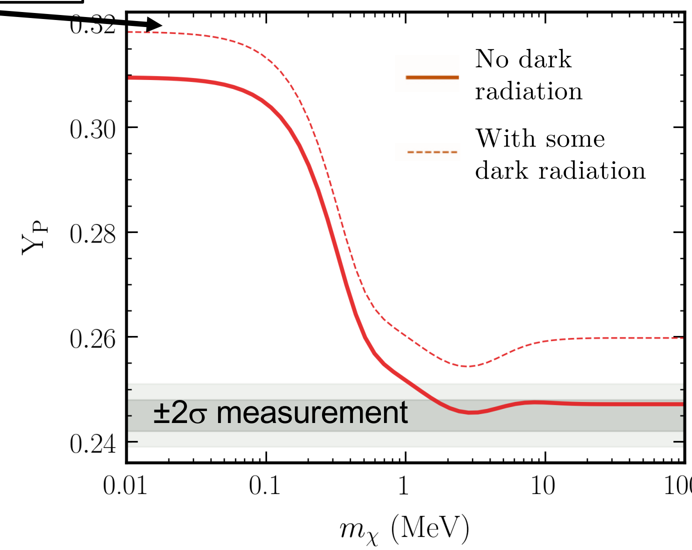
See also K. Nollett and G. Steigman, 1312.5725

Many models include dark radiation!

- Warm Hawking Relics From PBH Domination C. Shallue, J. Muñoz, G. Krnjaic, 2406.08535
- Twin Sterile Neutrino Dark Matter I. Holst, D. Hooper, G. Krnjaic, D. Song, 2305.06364
- “Stepped” dark radiation to resolve the Hubble tension D. Aloni, A. Berlin et al., 2111.00014

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





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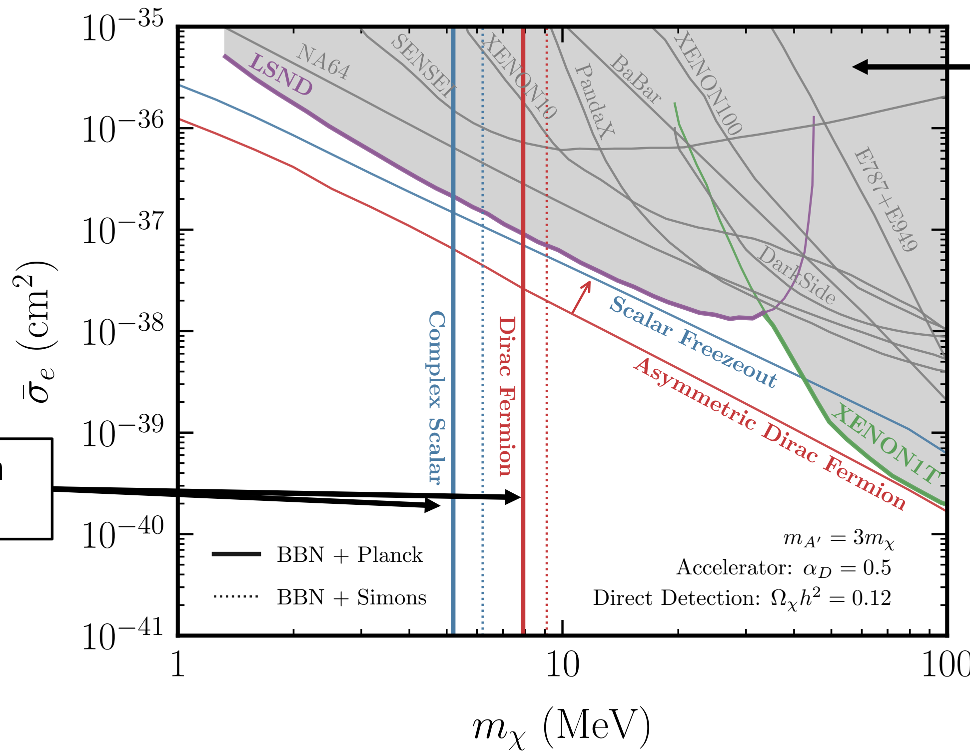
R. Cooke et al., 1710.11129

Complex Scalar χ
$m_{A'}/m_\chi=1$

BBN constraints

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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An aside: the 2σ deuterium tension?

A new tension in the cosmological model from primordial deuterium?

Cyril Pitrou,[1⋆] Alain Coc,[2] Jean-Philippe Uzan,[1] Elisabeth Vangioni[1]
[1] *Institut d'Astrophysique de Paris, CNRS UMR 7095, 98 bis Bd Arago, 75014 Paris, France*
Sorbonne Université, Institut Lagrange de Paris, 98 bis Bd Arago, 75014 Paris, France
[2] *IJCLab, CNRS IN2P3, Université Paris-Saclay, Bâtiment 104, F-91405 Orsay Campus France*

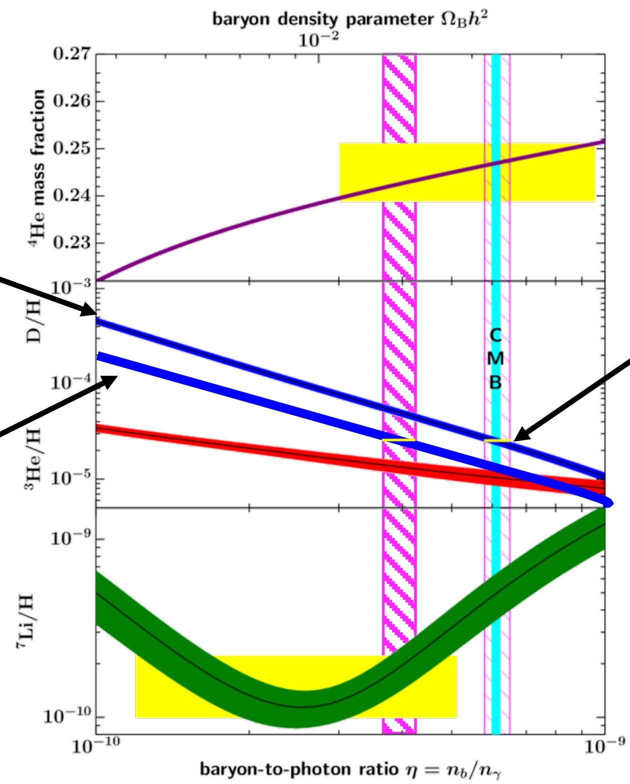
C. Pitrou et al, 2011.11320

26 January 2021

Tension between CMB and BBN η

Deuterium prediction (PDG)

New deuterium prediction (illustration)

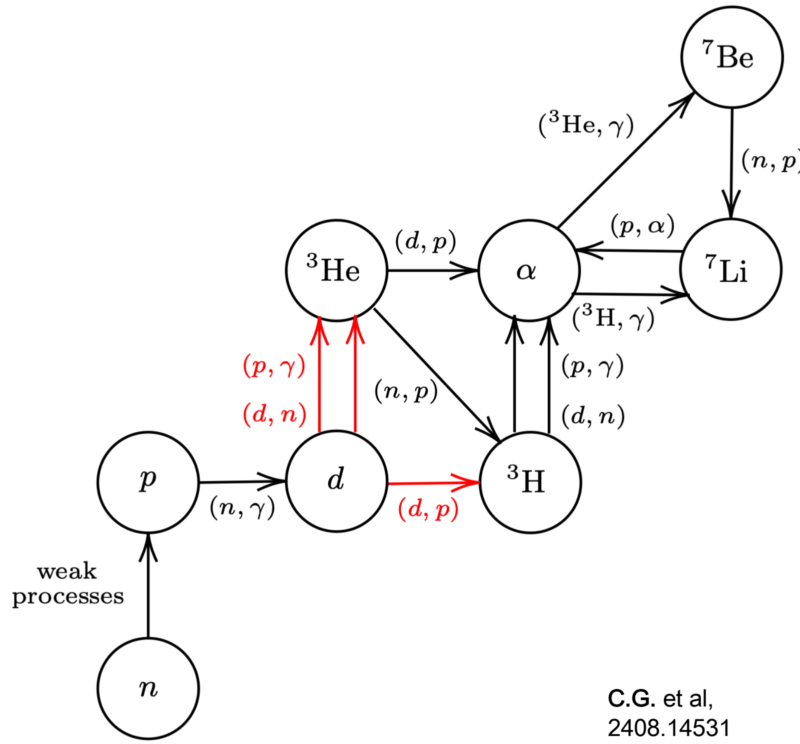


Measured deuterium abundance (PDG average)

PDG, RPP 2021, Section 24

Reaction network

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

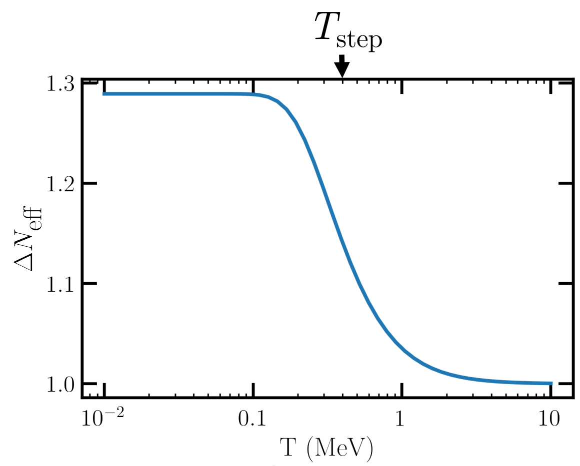
The model

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

- 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

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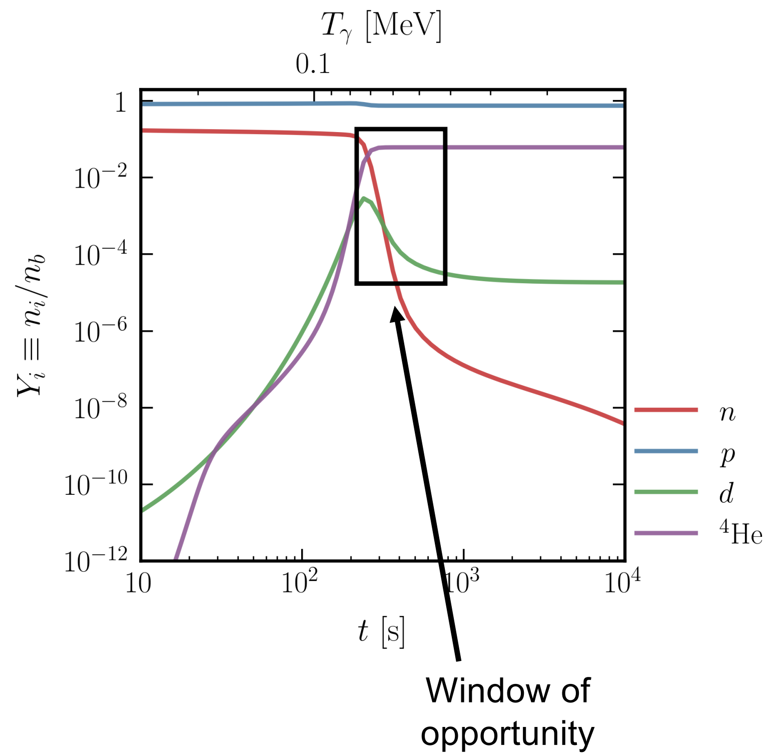
D. Aloni et al, 2111.00014

A step in understanding the deuterium "tension"

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



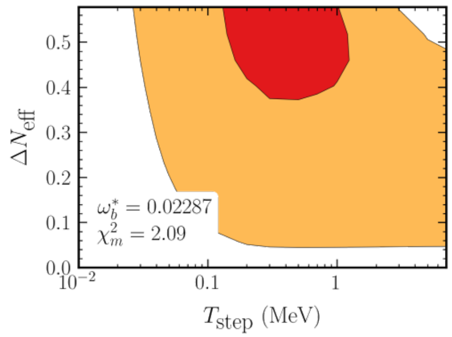
See also A. Berlin et al., 1904.04256

1σ allowed

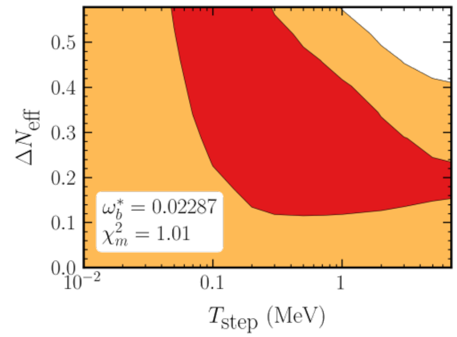
2σ allowed

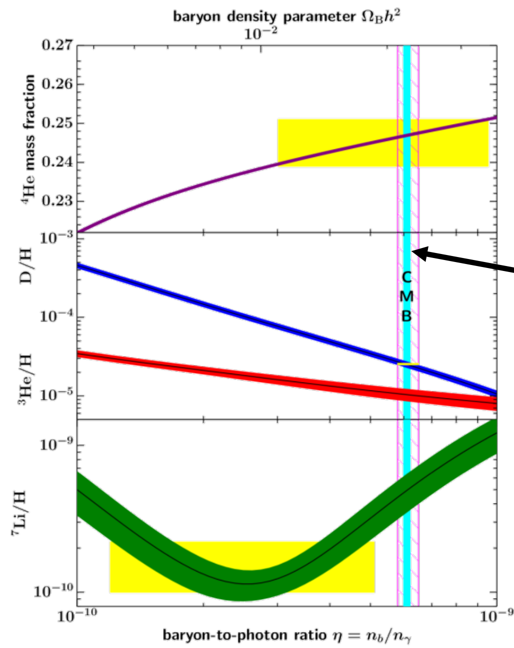
High $\Omega_b h^2$

Deuterium tension network



No-deuterium-tension network





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

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

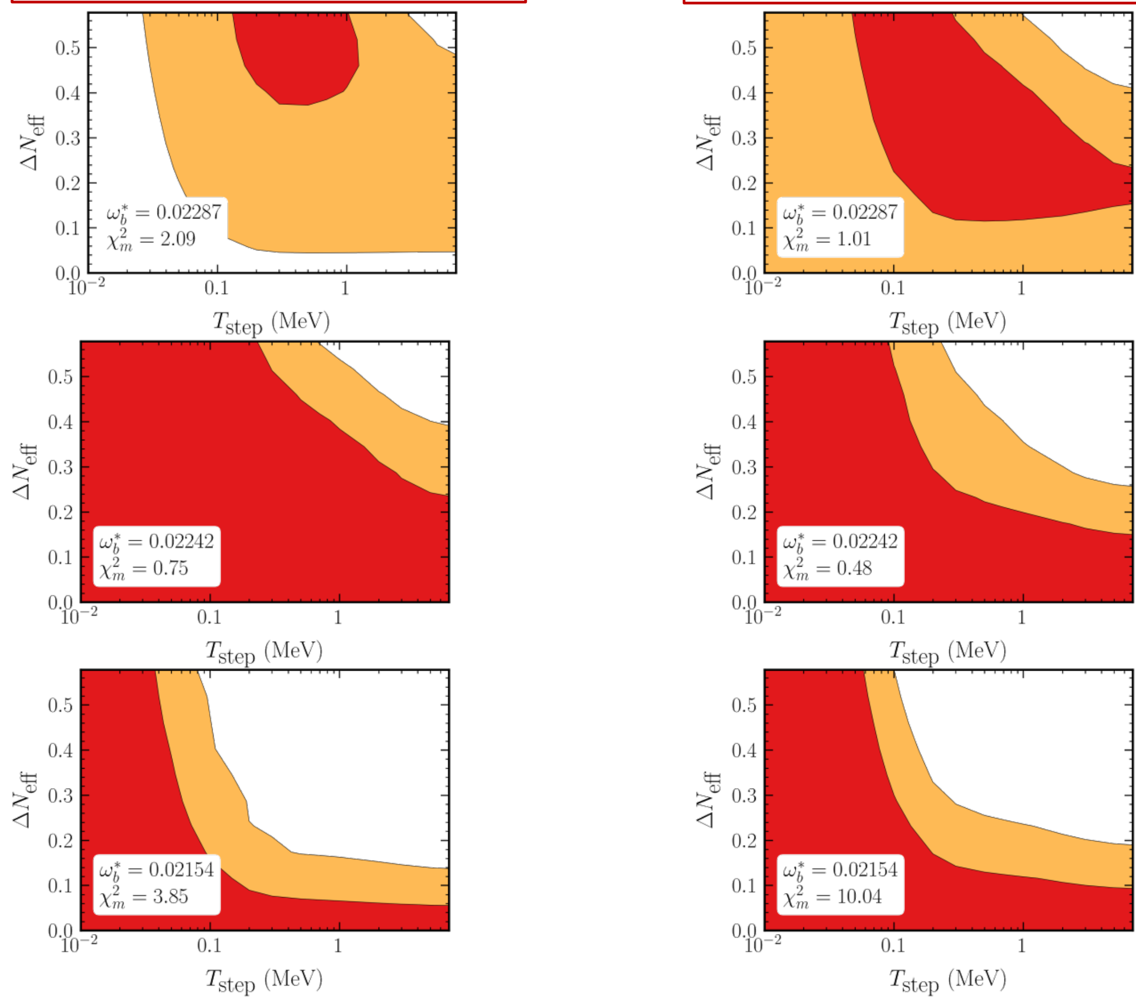
1σ allowed
2σ allowed

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

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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Goals:

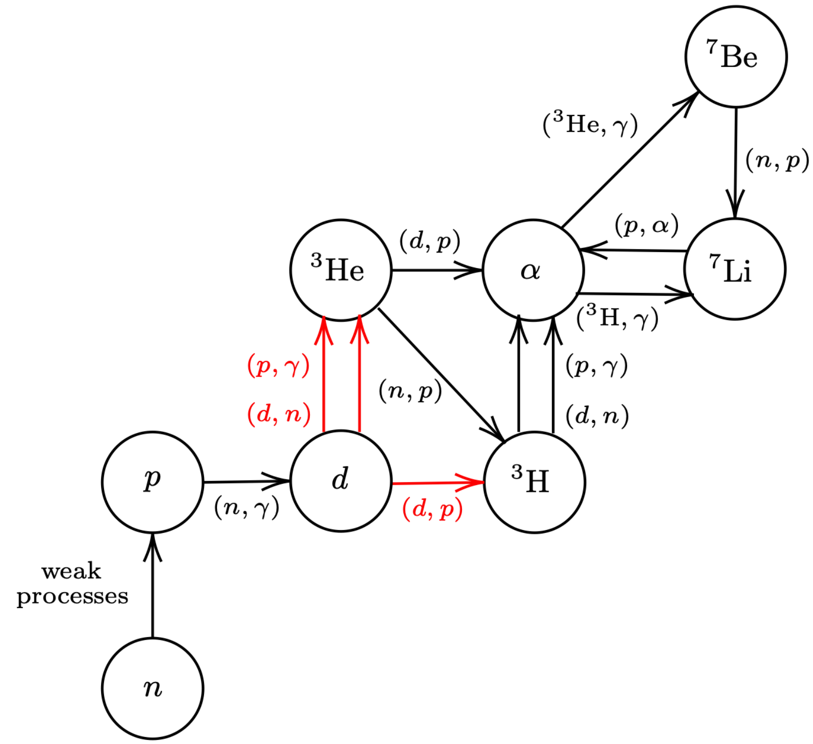
1) A fast BBN code
2) Easy calculation of uncertainties
3) Easy switching between reaction networks

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!



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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PRyMordial	Python	O(10 s)	Accurate. Full parameter estimation possible, but slow. Written with new physics in mind.
LINX	**Python+JAX**	**<0.1s**	**As accurate as PRyMordial. Fast enough for MCMC methods.**

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

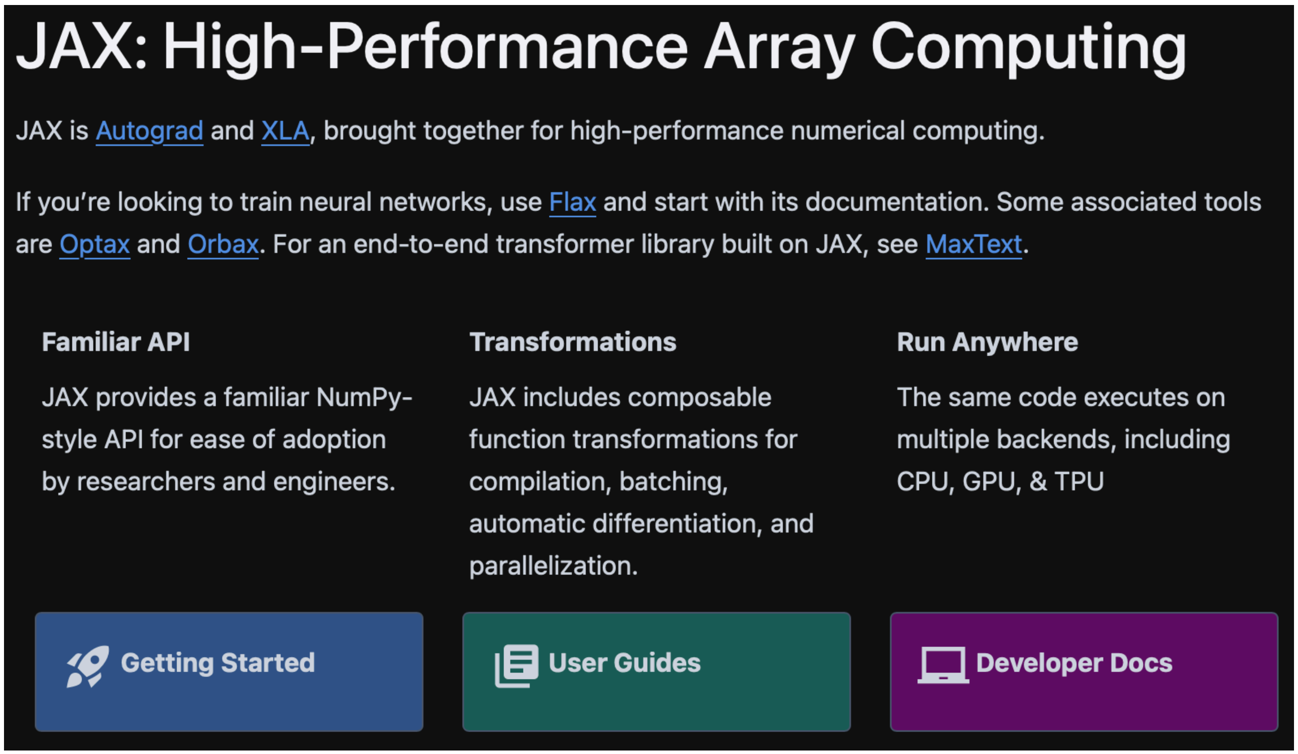
C.G. et al., 2408.14538

No new approximations, not an emulator

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

Slide courtesy of Hongwan Liu

JAX



JAX: High-Performance Array Computing

JAX is Autograd and XLA, brought together for high-performance numerical computing.

If you're looking to train neural networks, use Flax and start with its documentation. Some associated tools are Optax and Orbax. For an end-to-end transformer library built on JAX, see MaxText.

Familiar API

JAX provides a familiar NumPy-style API for ease of adoption by researchers and engineers.

Transformations

JAX includes composable function transformations for compilation, batching, automatic differentiation, and parallelization.

Run Anywhere

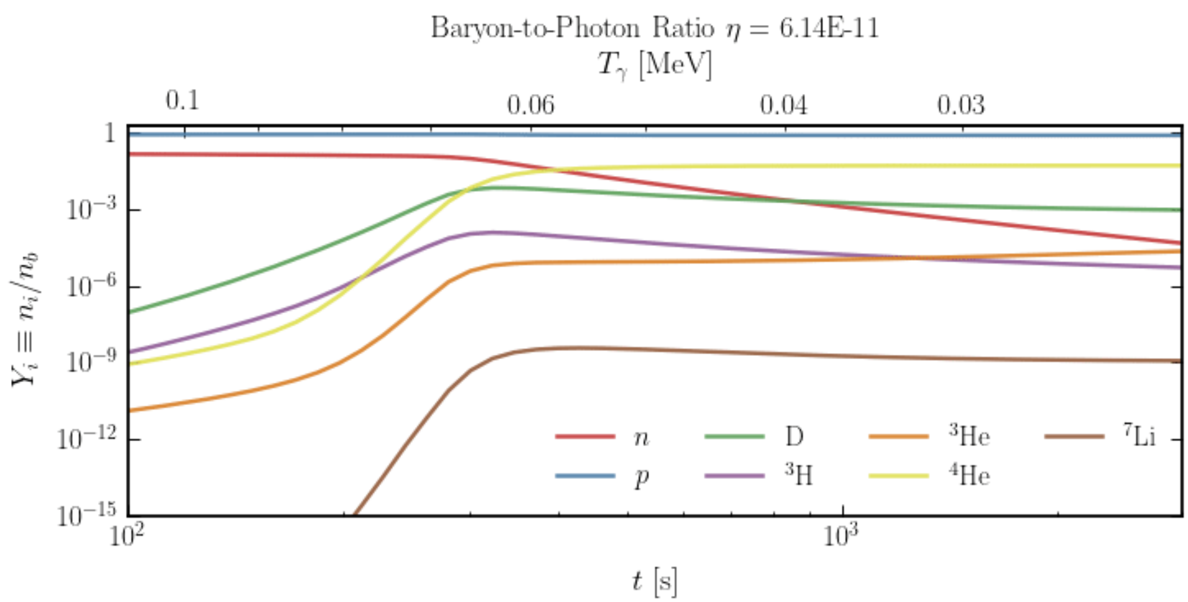
The same code executes on multiple backends, including CPU, GPU, & TPU

Getting Started | **User Guides** | **Developer Docs**

https://jax.readthedocs.io/en/latest/index.html

JAX + JIT runs orders of magnitude faster than ordinary python code.

Automatic differentiation provides gradients automatically and opens up new methods of parameter estimation.



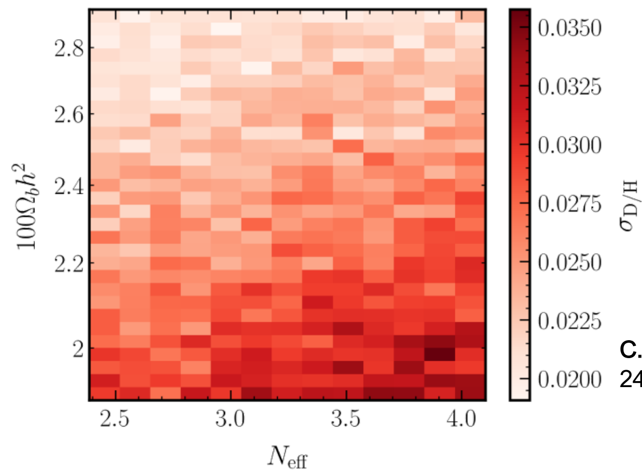
~60 second compile time + ~2 second runtime.
10 minutes to generate matplotlib animation.

https://github.com/cgiovanetti/LINX

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



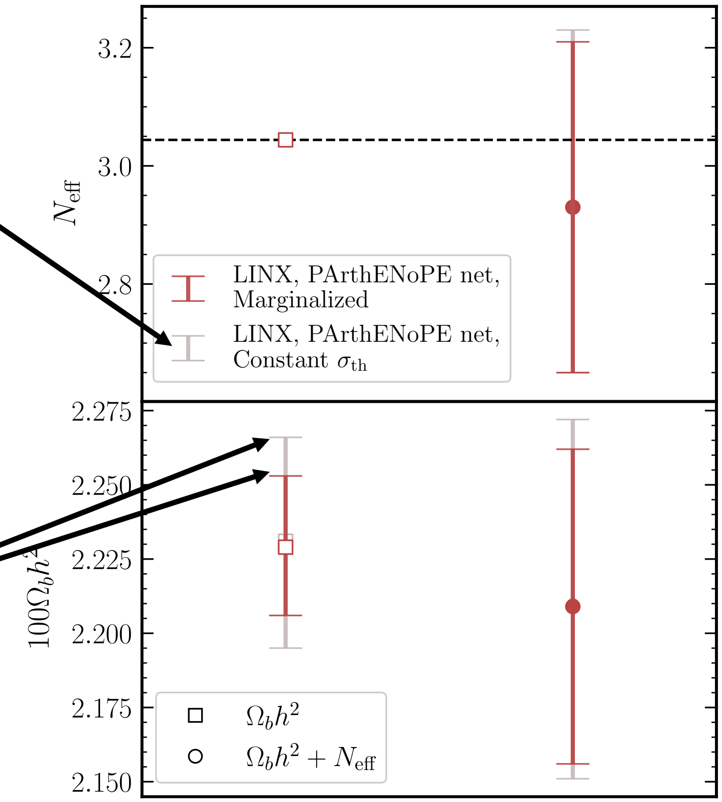
C.G. et al, 2408.14531

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

BBN Nuisance Parameters

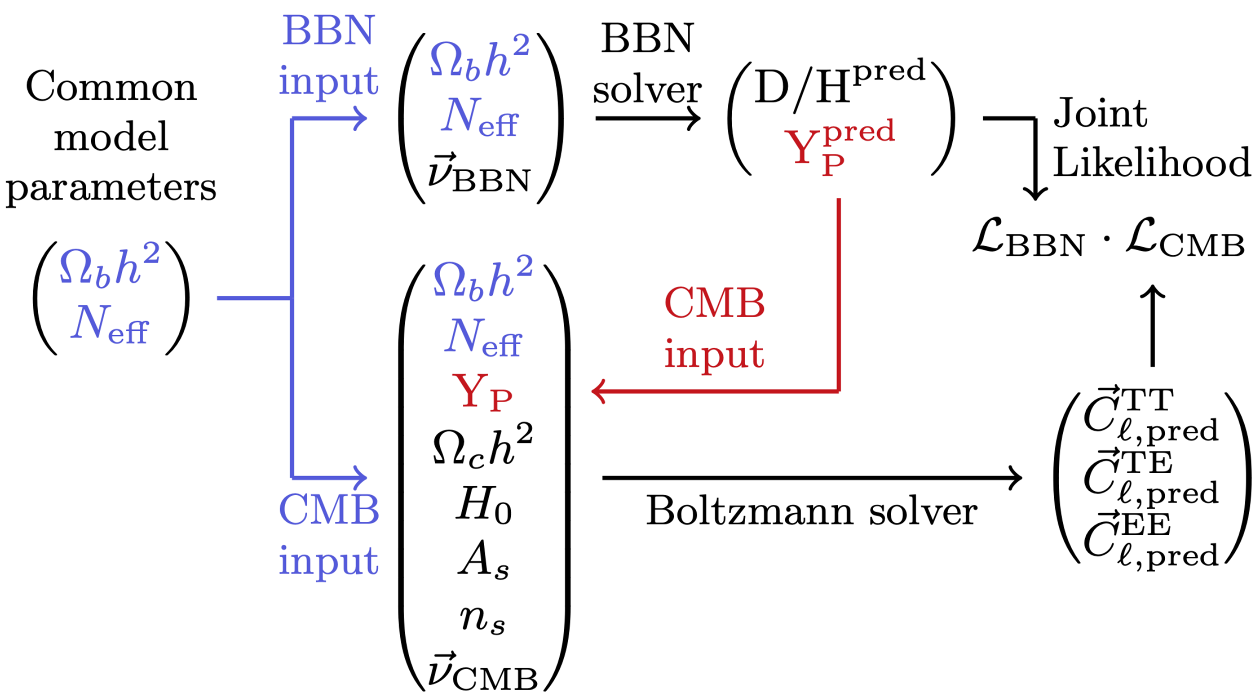
Old analyses (see e.g. Schöneberg 2401.15054, Planck 1807.06209) assume a constant theory uncertainty

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



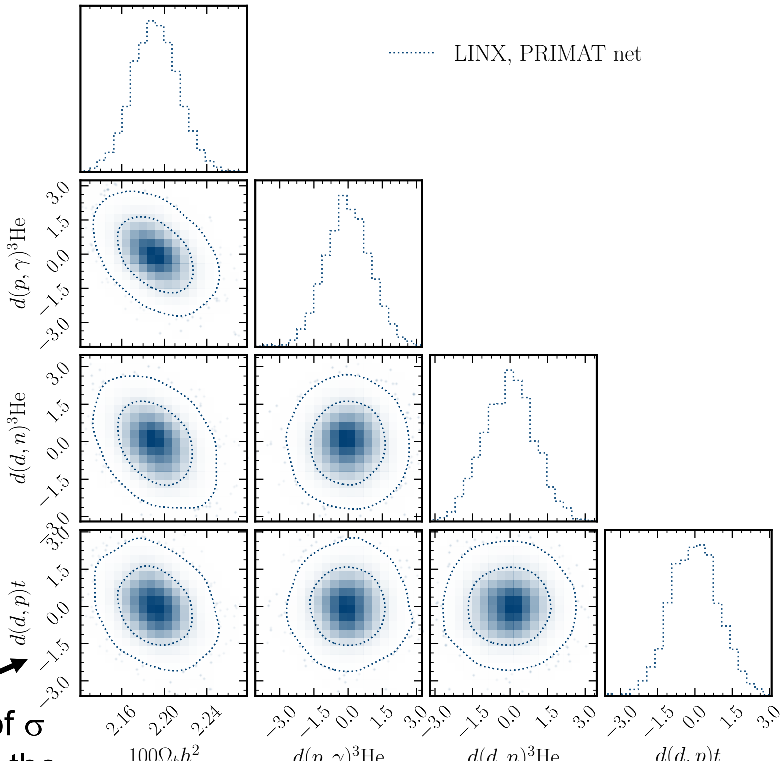
C.G. et al, 2408.14531

CMB + BBN Joint Fit

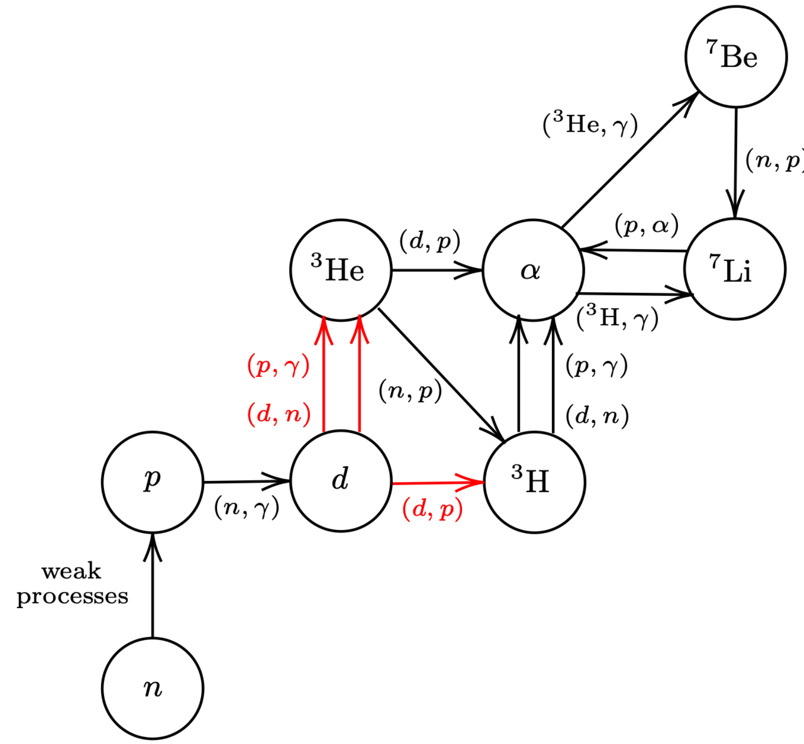


C.G. et al,
2408.14531

Why track nuisance parameters?

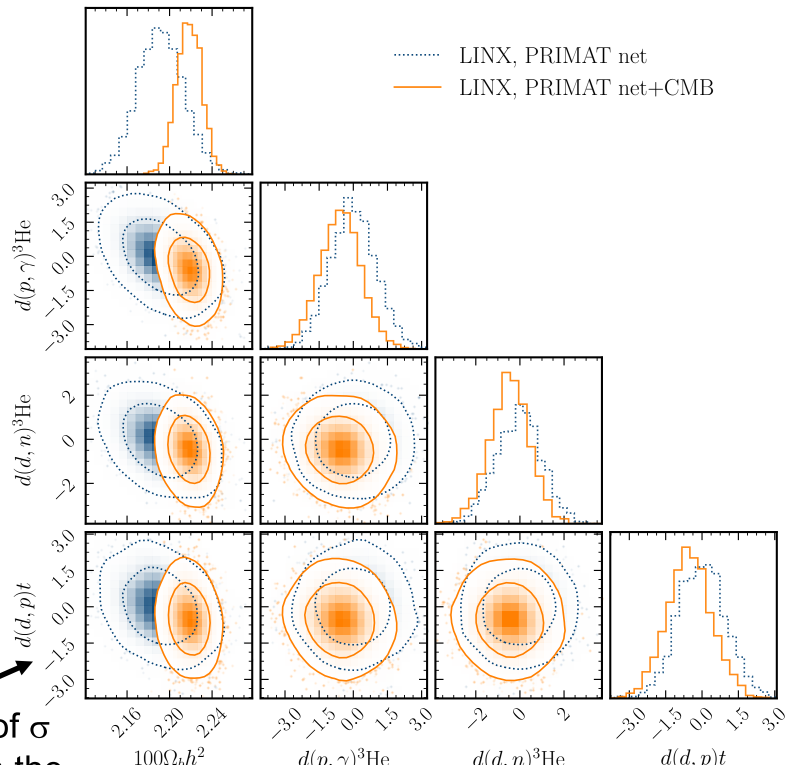


Number of σ away from the median rate

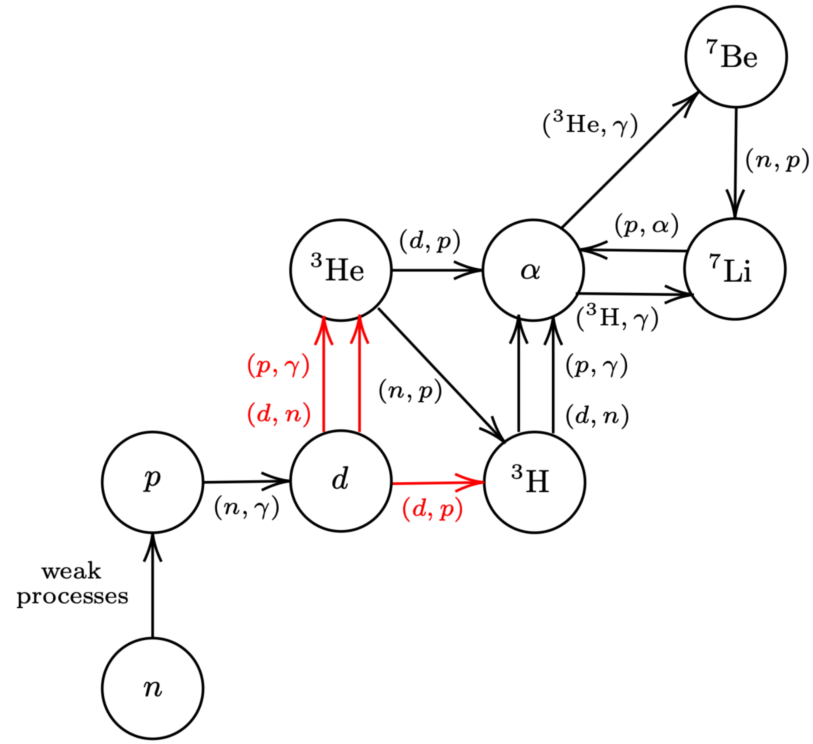


C.G. et al, 2408.14531

Why track nuisance parameters?

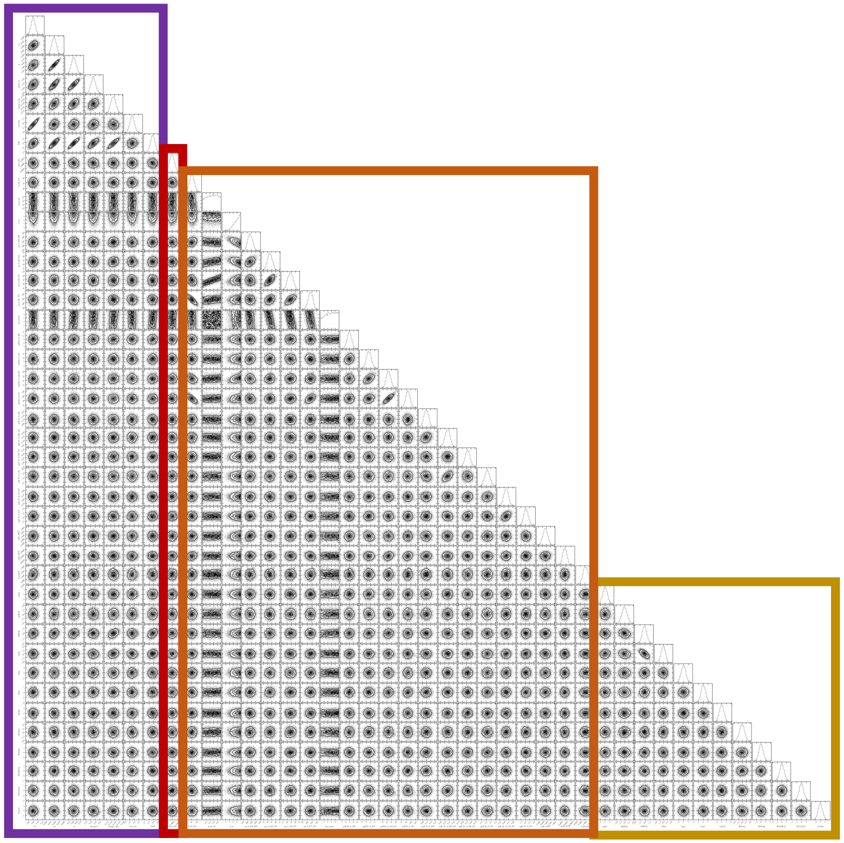


Number of σ away from the median rate



C.G. et al, 2408.14531

CMB + BBN Joint Fit

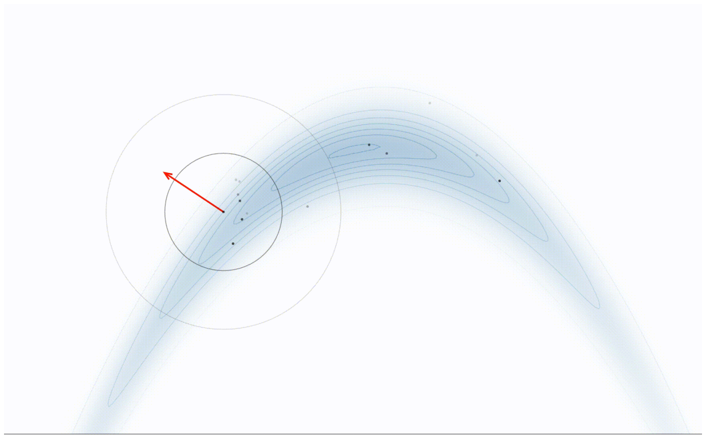


Can vary **cosmological parameters**, **neutron lifetime**, **CMB nuisance parameters**, and **individual reaction rates**

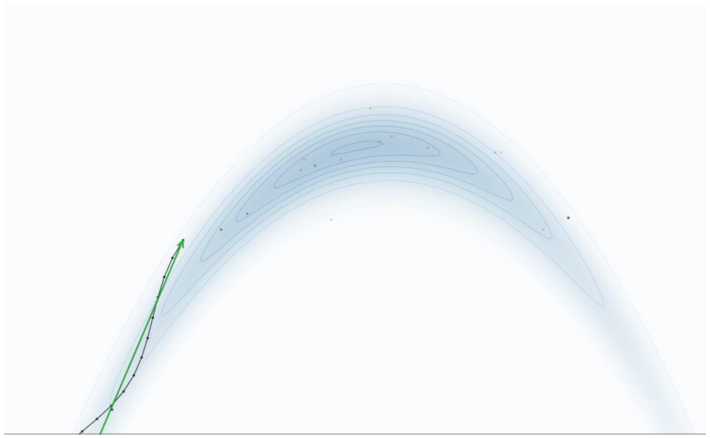
Runtime of ~2 days on 192 standard memory cores using nested sampling.

Long runtime dominated by CLASS

Improving runtime



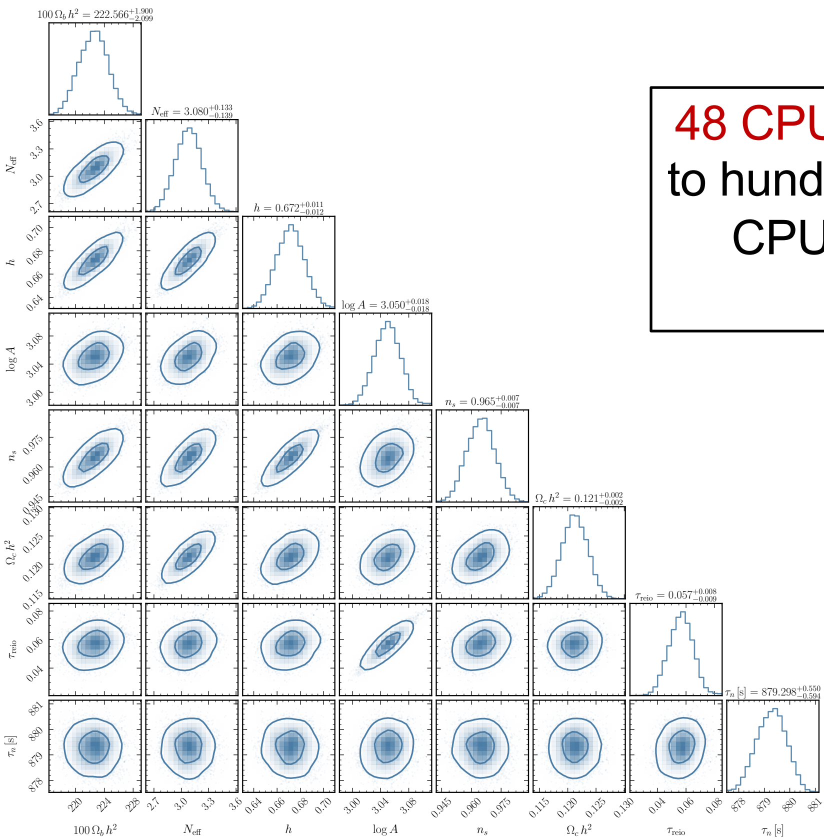
Traditional MCMC is inefficient for high-dimensional distributions



Hamiltonian Monte Carlo uses gradients to compute a "trajectory". Makes large jumps in parameter space that are frequently accepted. Needs fewer samples overall.

https://github.com/chi-feng/mcmc-demo

Differentiable analysis



48 CPU-hours, as opposed to hundreds to thousands of CPU-hours for nested sampling.

C.G. et al, 2408.14531

Combine LINX with CosmoPower (Spurio Mancini et al., 2106.03846), perform HMC with neural transport reparameterization

Future Outlook

- Need resolution on whether there's a deuterium tension
  - Will it get larger?
- A new determination of the primordial ^{3}He abundance?
- Future work: probing thermodynamic histories? Probing beyond CDM?
- Future work: a differentiable recombination code? A differentiable CLASS?

Summary

- BBN is a sensitive probe of cosmology, complementary to the CMB
- BBN has much to say about new physics
  - Constraints on dark photons complementary to experiment
  - Analyses of neutrinophilic dark matter provide insights into deuterium tension
- New tools like LINX make BBN analyses more efficient, reveal the role of nuisance parameters, and enable joint CMB+BBN analyses