Cosmological Solutions to the Lithium Problem?

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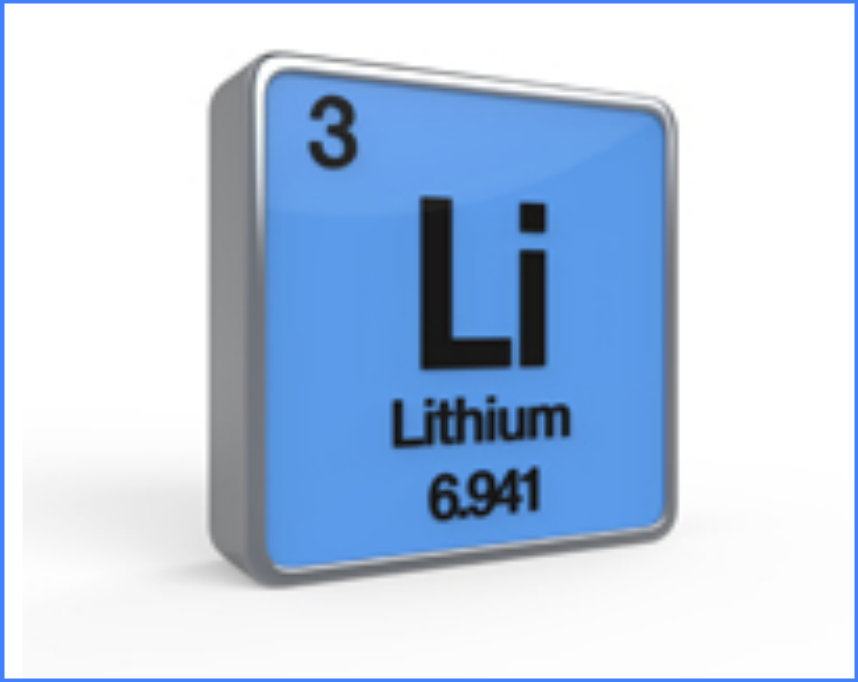
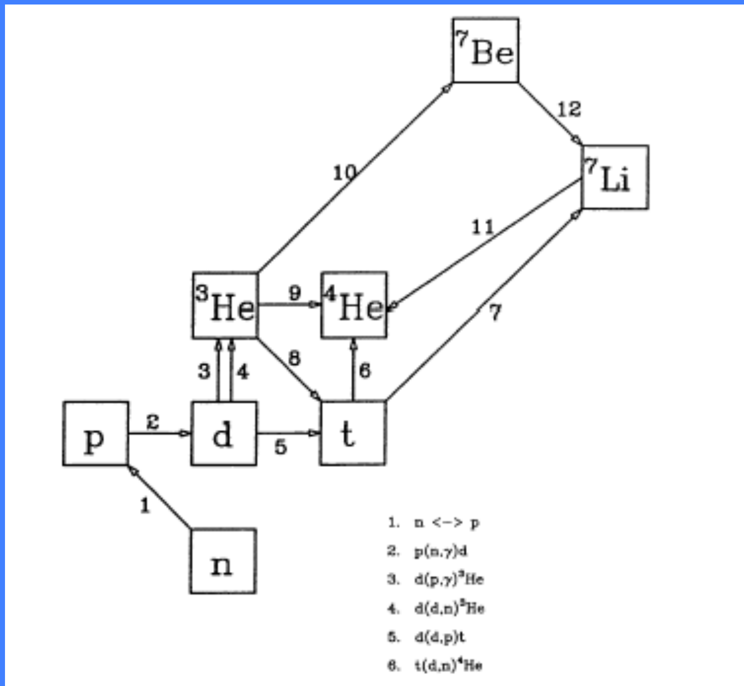


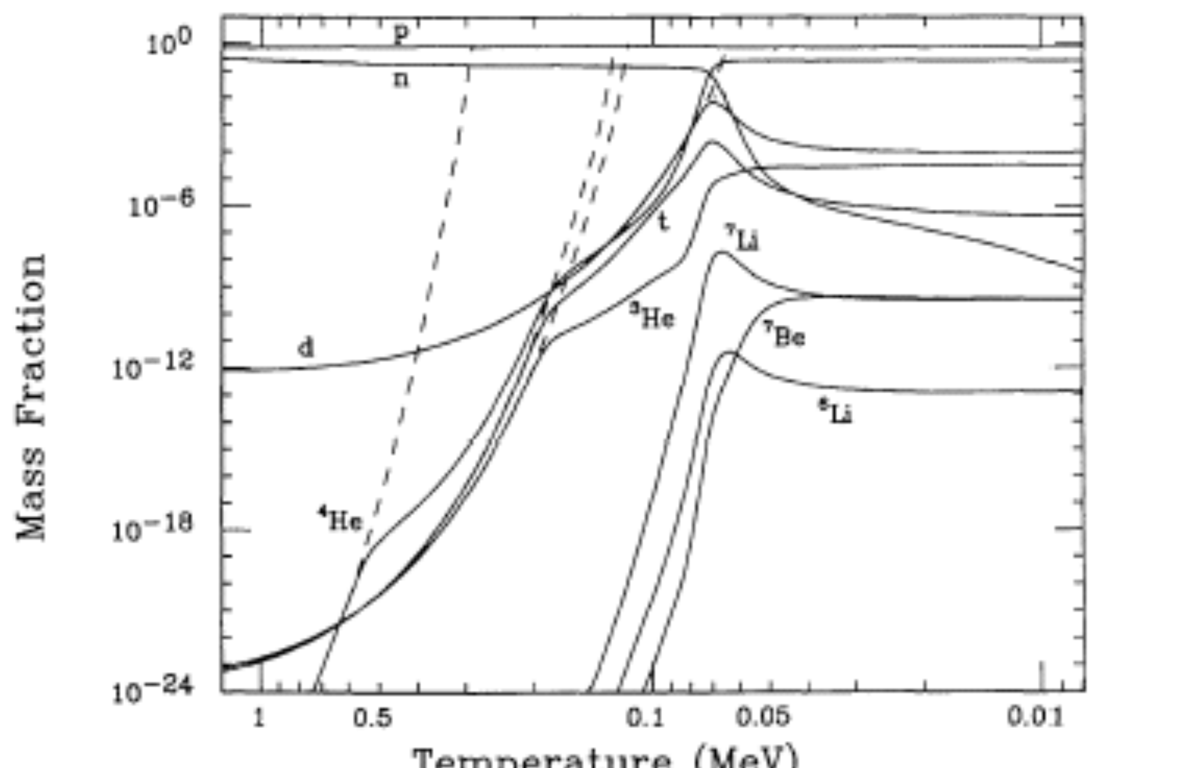
The 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15)
July 5, 2019
Panasonic Hall, Yukawa Institute for Theoretical Physics, Kyoto University

What is the Lithium Problem?

Predictions of BBN are robust



In Big Bang Nucleosynthesis most reaction rates are well known



Thermodynamic and cosmological conditions seem well posed

Reaction Rate Sensetivities

$$X_i = X_{i,0} \prod_n \left(\frac{p_n}{p_{n,0}} \right)^{\alpha_n},$$

Abundance

Parameters

Cyburt et al. RMP (2016)

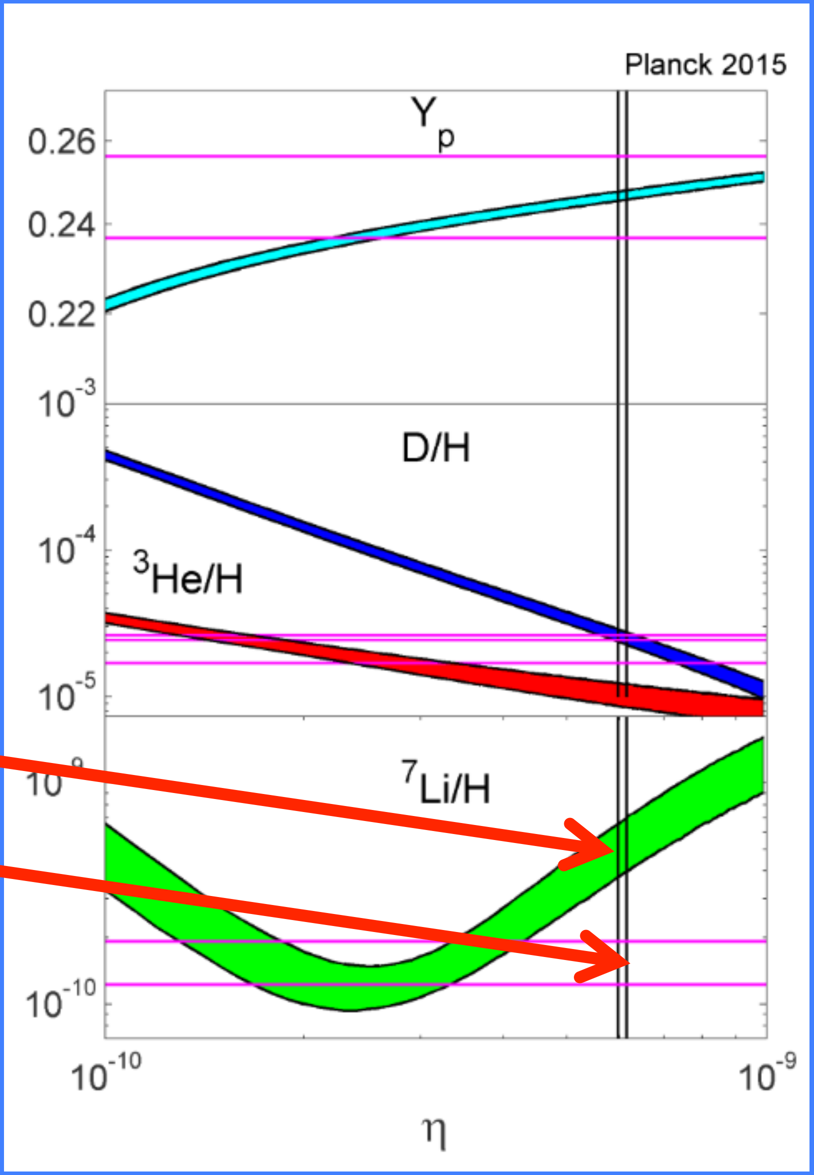
TABLE III. The sensitivities α_n's defined in Eq. (12) for each of the light-element abundance predictions, varied with respect to key parameters and reaction rates.

Variant	Y_p	D/H	^{3}He/H	^{7}Li/H	^{6}Li/H
η (6.1×10^{-10})	0.039	−1.598	−0.585	2.113	−1.512
N_ν (3.0)	0.163	0.395	0.140	−0.284	0.603
G_N	0.354	0.948	0.335	−0.727	1.400
n decay	0.729	0.409	0.145	0.429	1.372
$p(n,\gamma)d$	0.005	−0.194	0.088	1.339	−0.189
$^3\mathrm{He}(n,p)t$	0.000	0.023	−0.170	−0.267	0.023
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	0.000	0.000	0.000	−0.705	0.000
$d(p,\gamma)^3\mathrm{He}$	0.000	−0.312	0.375	0.589	−0.311
$d(d,\gamma)^4\mathrm{He}$	0.000	0.000	0.000	0.000	0.000
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	0.000	0.000	0.000	−0.056	0.000
$d(\alpha,\gamma)^6\mathrm{Li}$	0.000	0.000	0.000	0.000	1.000
$t(\alpha,\gamma)^7\mathrm{Li}$	0.000	0.000	0.000	0.030	0.000
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	0.000	0.000	0.000	0.963	0.000
$d(d,n)^3\mathrm{He}$	0.006	−0.529	0.213	0.698	−0.522
$d(d,p)t$	0.005	−0.470	−0.265	0.065	−0.462
$t(d,n)^4\mathrm{He}$	0.000	0.000	−0.009	−0.023	0.000
$^3\mathrm{He}(d,p)^4\mathrm{He}$	0.000	−0.012	−0.762	−0.752	−0.012

Comparison with Observations

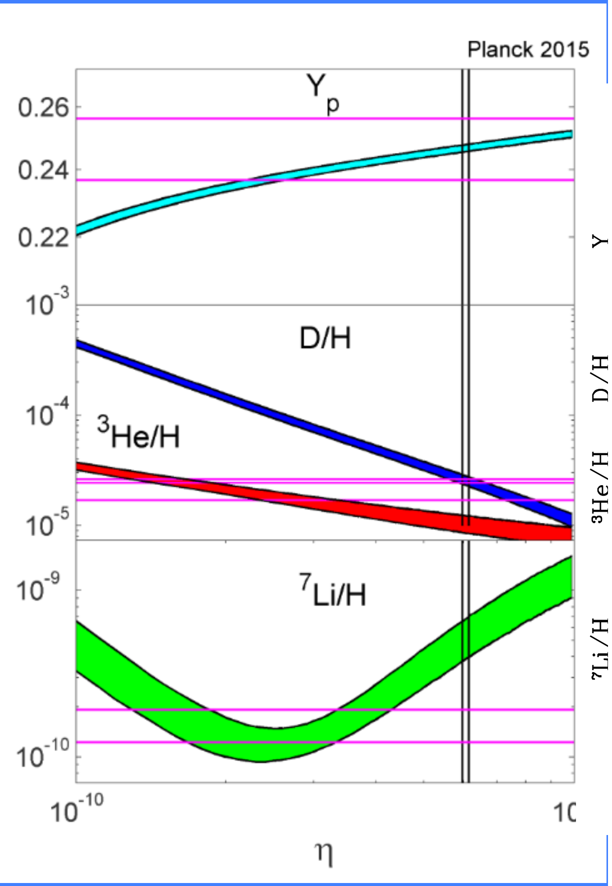
The Lithium Problem

Predicted
Lithium
3x Observed

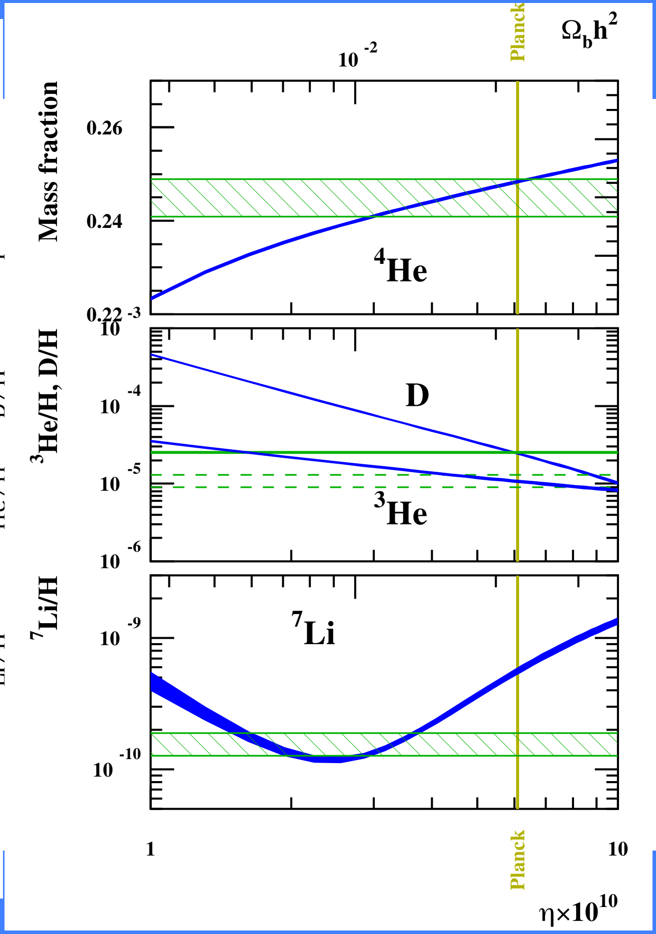


Foley, GJM, Kusakabe (2017)

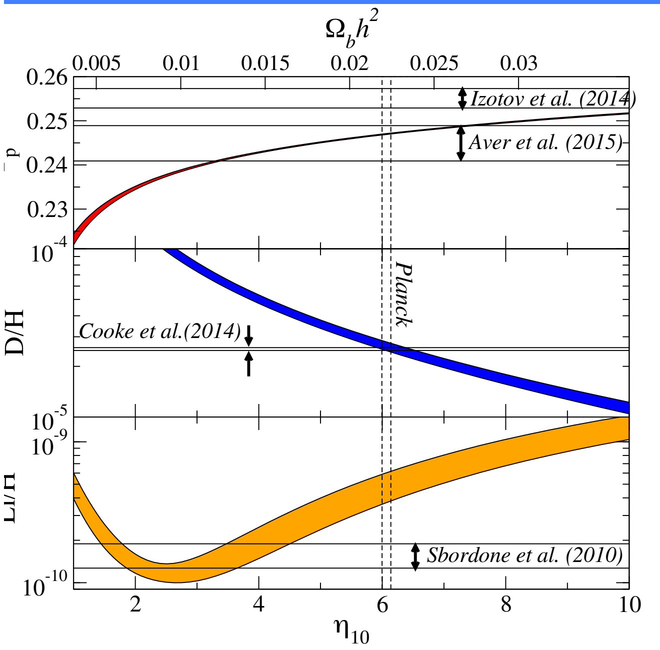
Consistent Discrepancy between Observed and Predicted Primordial



Foley, GJM et al. 2017
NACRE II

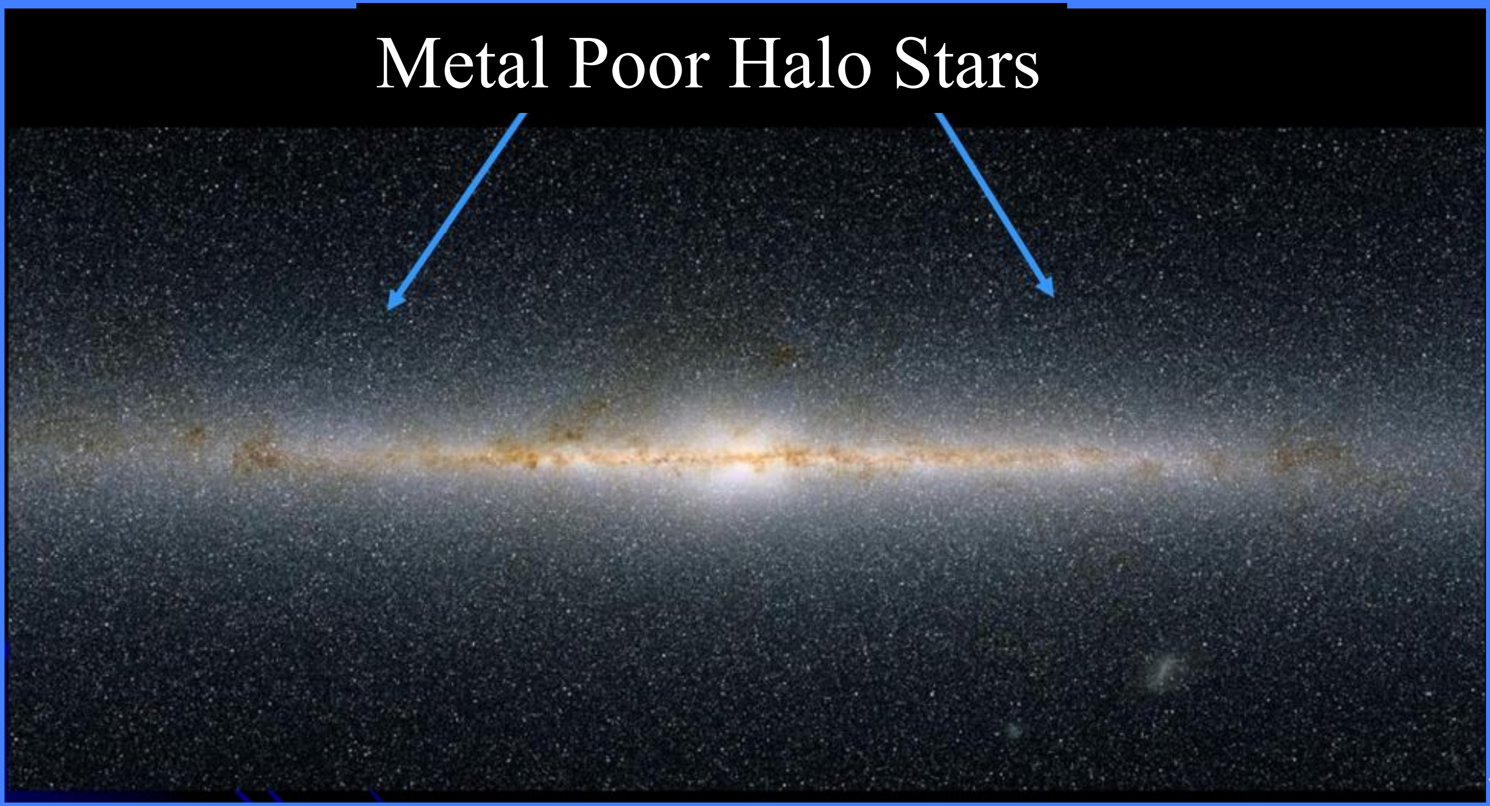


Coc & Vangioni 2017
Monte-Carlo
NACRE II + Statistical Theory

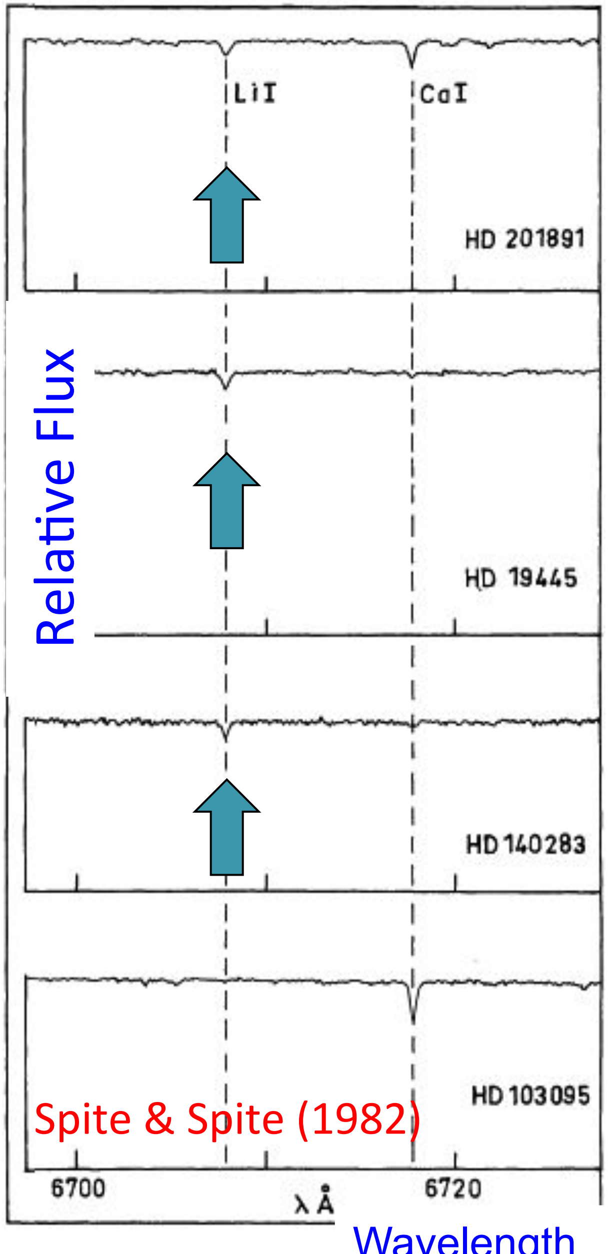


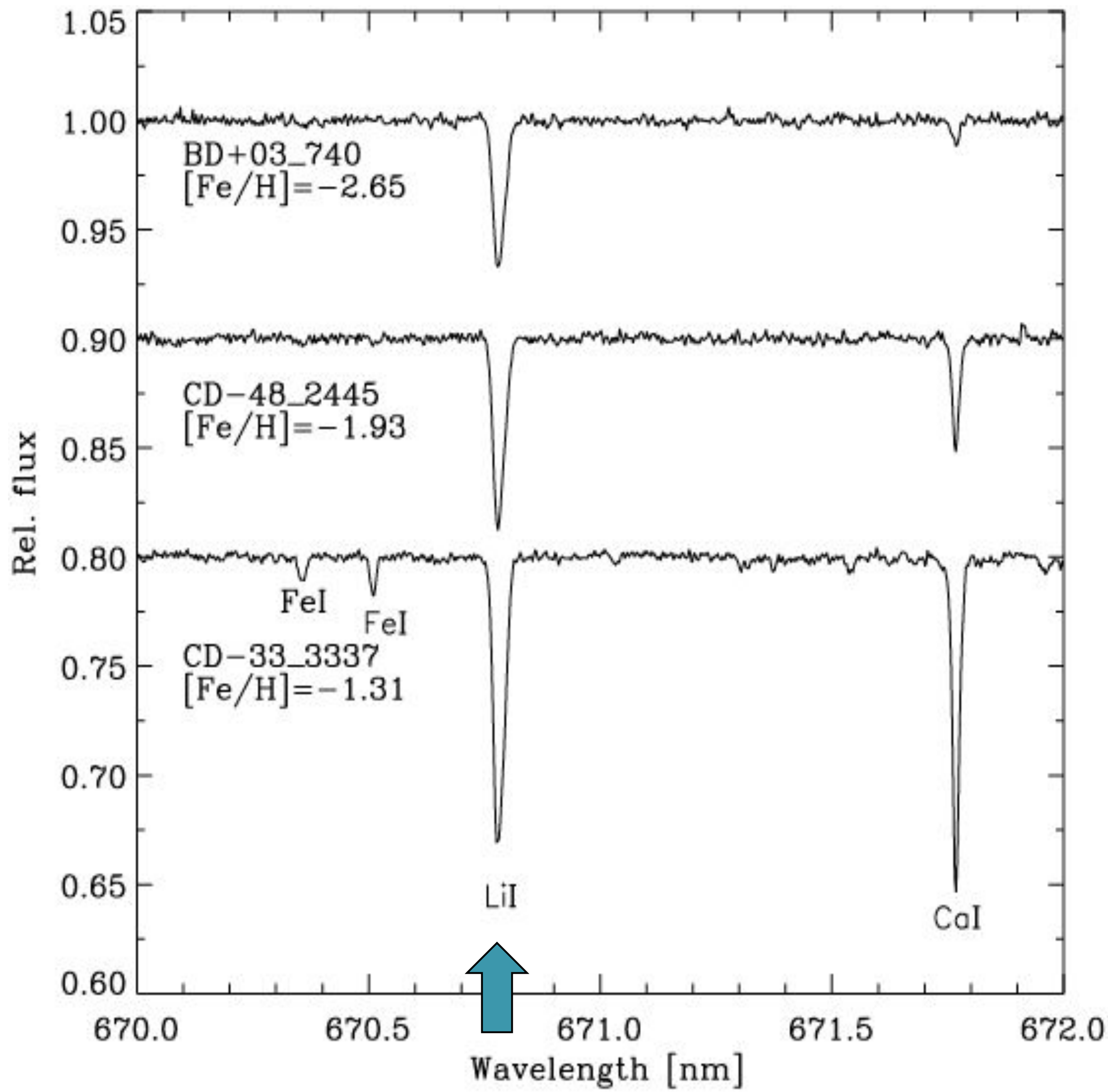
Nakamura et al. 2017
NACRE II+Descouvemont 04

How is the Cosmic Abundance of Lithium Determined?



Relic Li observed in metal-poor stars ([Fe/H] < -1)

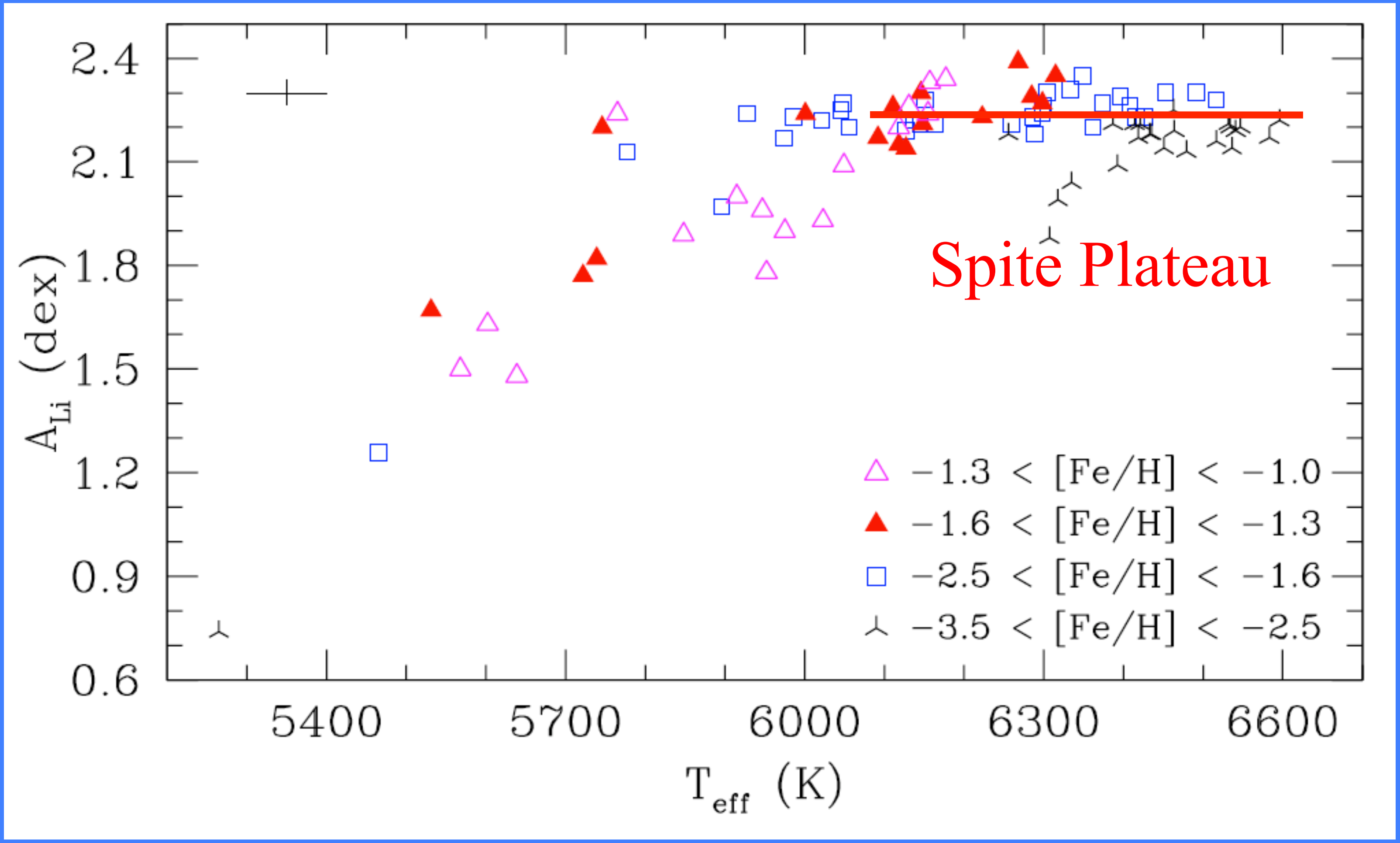




Asplund et al. (2006)

Primordial Lithium Abundance

Determined from the Spite plateau



$^7Li/H = 1.58 \pm 0.35 \times 10^{-10}$

Solutions to the Lithium Problem?

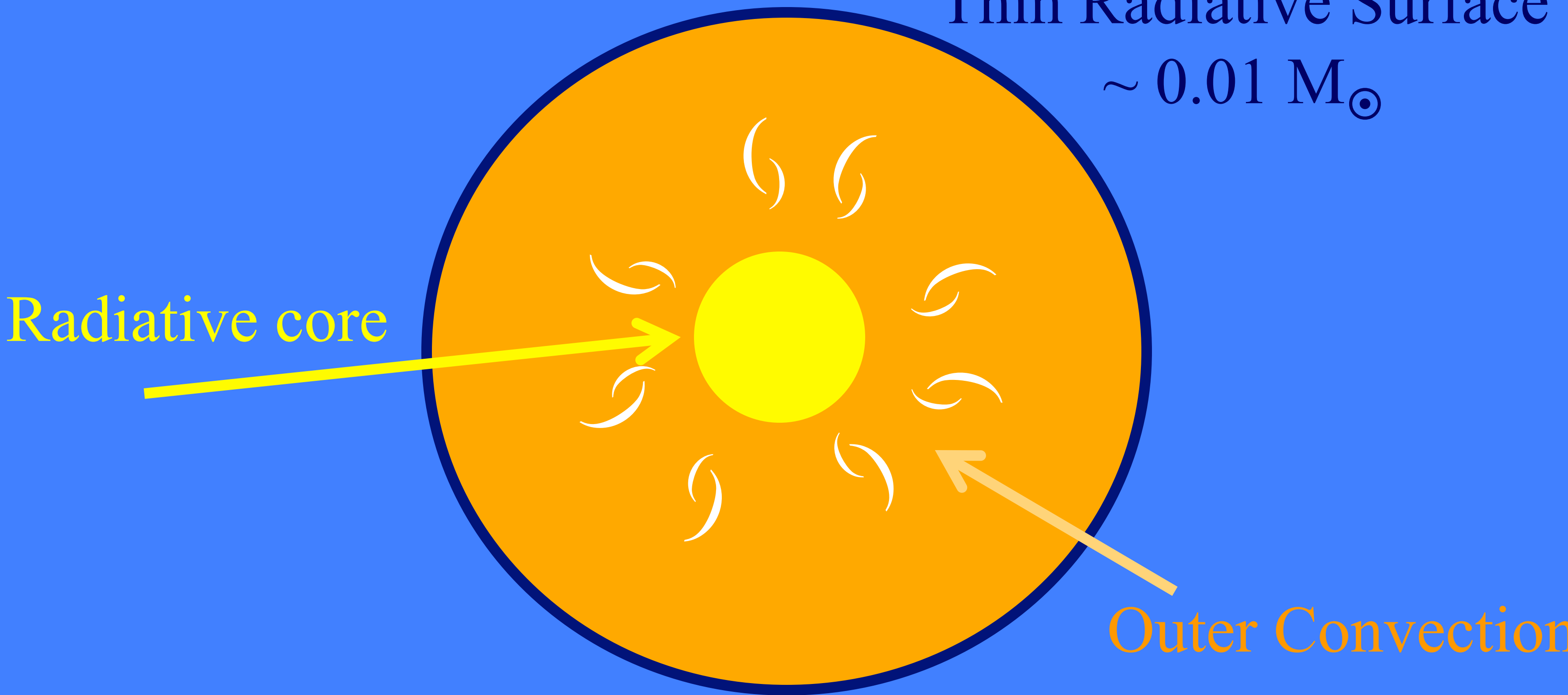
- New Nuclear Physics?
- New Astrophysics?
  - Stellar destruction?
  - Galactic Chemical Evolution?
- Cosmological Solutions?
  - New Statistical Physics?
  - Primordial Magnetic Field?
  - Neutrino degeneracy?
  - Non-standard model Physics?
    - Supersymmetric Particles
    - Axion Condensates
    - Dark Matter
    - Mirror Matter
    - Time varying constants

Talks by Hayakawa and Ishikawa

Stellar Solutions?

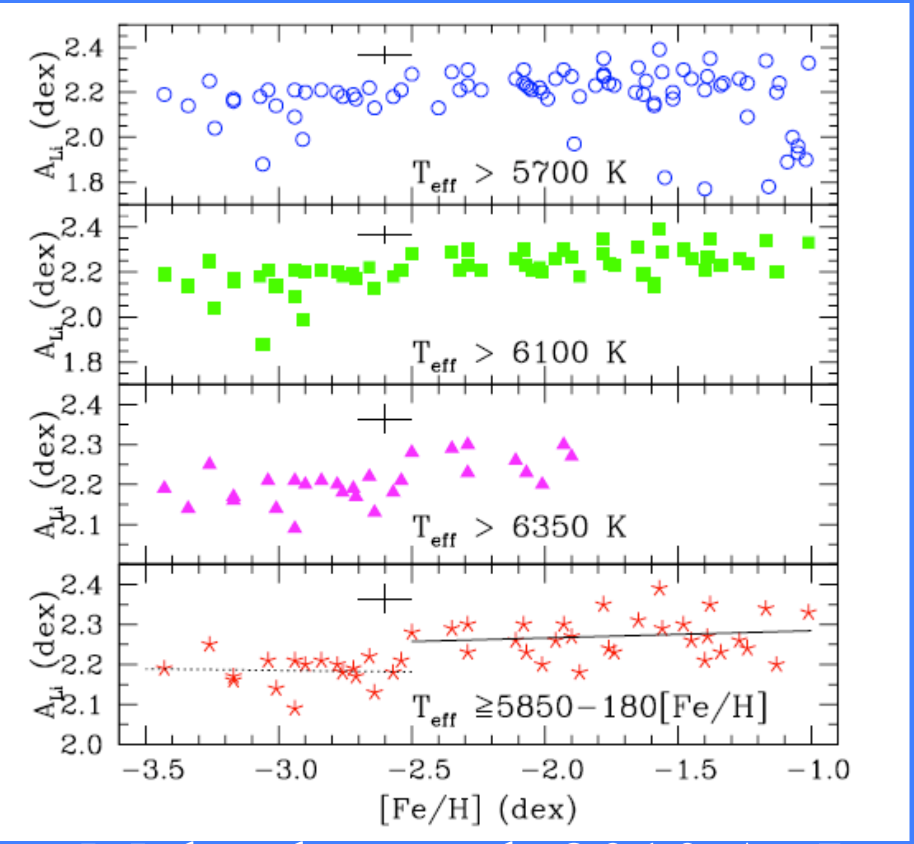
Structure of a MPH star

Lithium Resides in
Thin Radiative Surface
$\sim 0.01\ M_{\odot}$

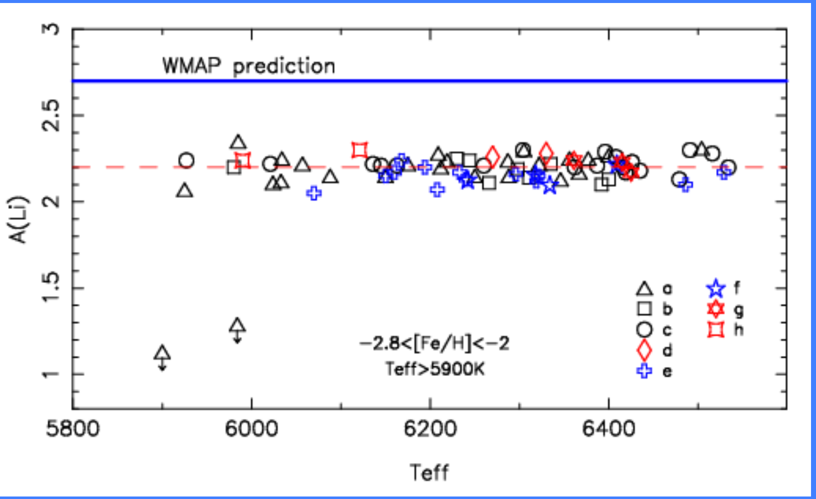


Can MPH Stars Gradually Deplete Lithium?

Plateau changes with Metallicity suggests stellar processing



Melendez et al. 2010 ApJ



Narrow dispersion in Spite plateau suggest lack of stellar processing

Models can achieve uniform depletion

Fu, X. arXiv:1702.02932

Convective overshoot plus accretion

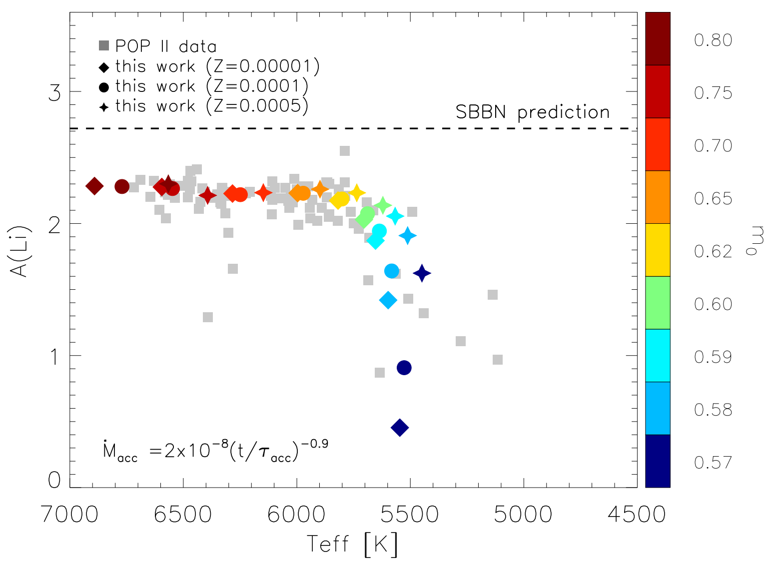
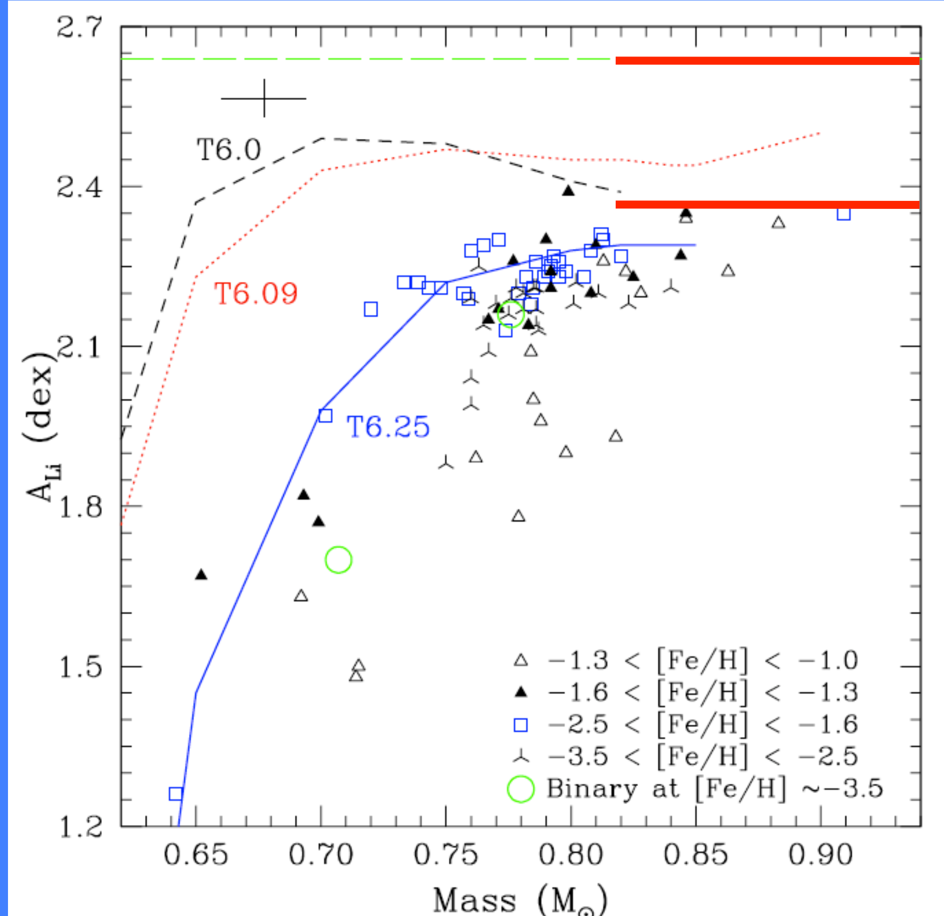


Figure 7.9: By applying the same parameter of envelope overshooting and accretion, we could reproduce the Spite plateau and the first Li decline branch for a wide range of metallicities (from Z=0.00001 to Z= 0.0005). The compared POP II data are the same as in figure 7.8. The model results are all main sequence stars at age 10 Gyr, with initial mass 0.80 $M_\odot$ to 0.57 $M_\odot$ from the left to the right for each metallicity as shown in the color-bar label.

Turbulent Diffusion Models (Richard, et al. 2005)



New Statistics?

The Astrophysical Journal, 834:165 (5pp), 2017 January 10
doi:10.3847/1538-4357/834/2/165

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NON-EXTENSIVE STATISTICS TO THE COSMOLOGICAL LITHIUM PROBLEM

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$$\langle \sigma v \rangle_{12} = \sqrt{\frac{8}{\pi \mu_{12} (kT)^3}} \int_0^{\infty} \sigma(E)_{12} E \exp\left(-\frac{E}{kT}\right) dE,$$

=>

$$\langle \sigma v \rangle_{12} = B_q \sqrt{\frac{8}{\pi \mu_{12}}} \times \frac{1}{(kT)^{3/2}} \times \int_0^{E_{\max}} \sigma_{12}(E) E \left[1 - (q-1)\frac{E}{kT}\right]^{\frac{1}{q-1}} dE,$$

Tsalis Statistics

Modified Distribution suppresses high energy tail in MB distribution

HOU ET AL.

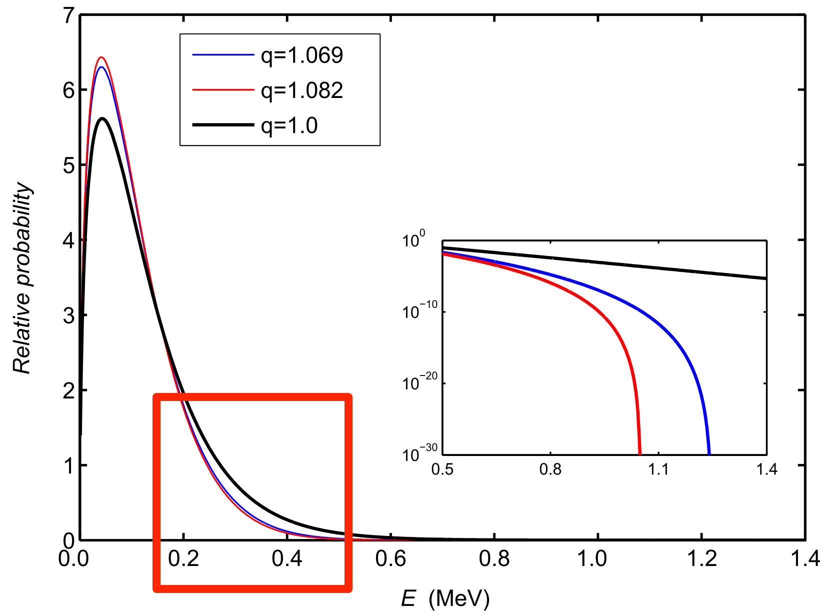


Figure 2. Normalized relative probabilities for non-extensive energy distributions and for the standard MB distribution ($q = 1$) at a temperature of 1 GK. The enlarged insert plot shows the tails, which are cut off at $E_{\max} = kT/(q-1)$ for the non-extensive distributions.

=>

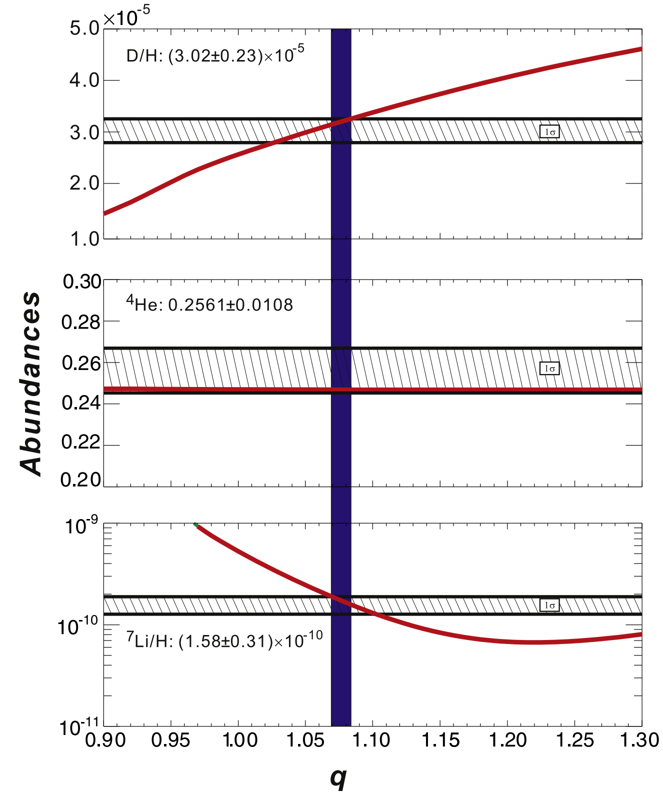
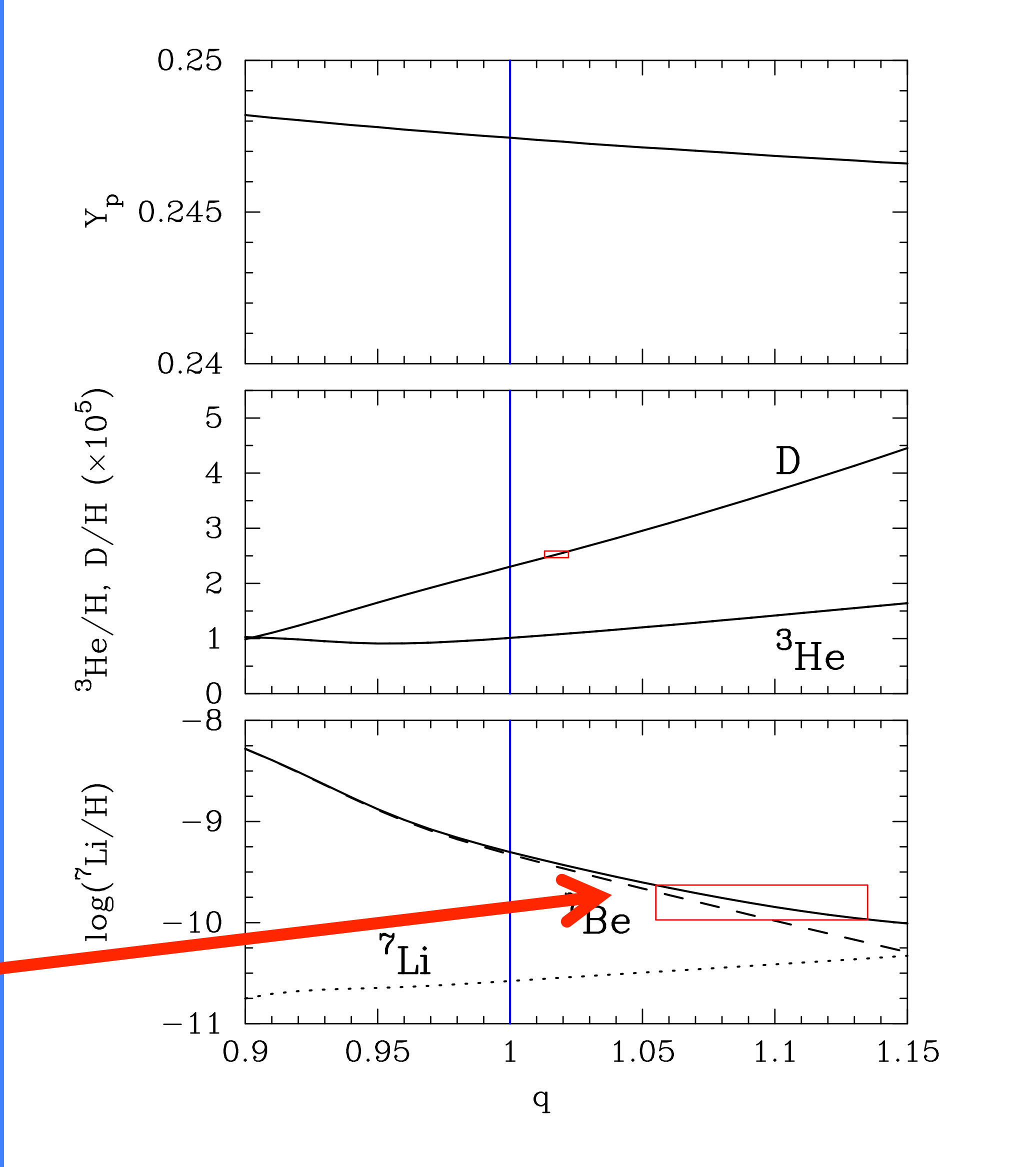


Figure 1. Predicted primordial abundances as a function of parameter q (in red solid lines). The observed primordial abundances (Aver et al. 2010; Sbordone et al. 2010; Olive et al. 2012) with 1σ uncertainty for D, ^{4}He, and ^{7}Li are indicated as hatched horizontal bands. The vertical (blue) band constrains the range of the parameter q to $1.069 \leqslant q \leqslant 1.082$. Note that the "abundance" of ^{4}He exactly refers to its mass fraction.

Reduces Li production
by ^{3}He(α,γ)^{7}Be

But a pure Tsalis velocity distribution must conserve momentum

Kusakabe, Kajino, GJM, Lou, PRD, 99, 043505 (2019)



Li problem not resolved

Need Physical Model for Modified Statistics

The Astrophysical Journal, 872:172 (9pp), 2019 February 20
https://doi.org/10.3847/1538-4357/ab0088

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Big Bang Nucleosynthesis with an Inhomogeneous Primordial Magnetic Field Strength

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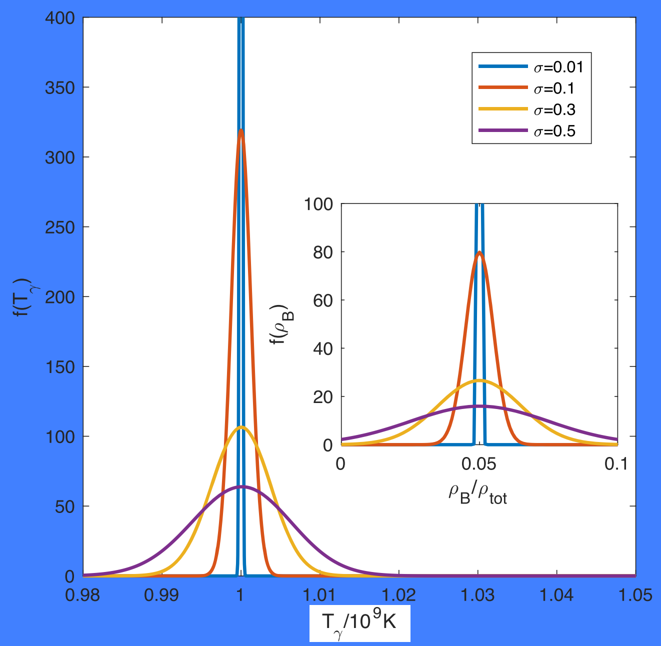
Received 2018 June 26; revised 2018 December 24; accepted 2019 January 16; published 2019 February 20

See Poster no. 7, Youdong Luo

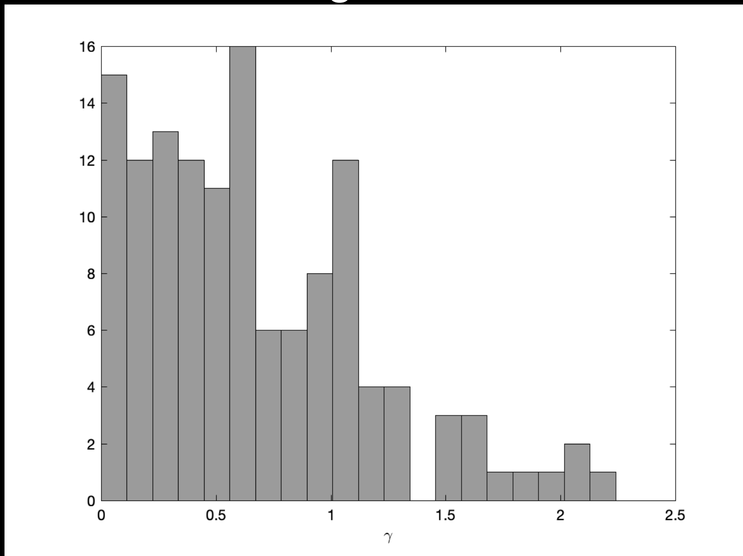


$$\rho_{\rm tot} = \rho_{\rm B} + \rho_{\rm rad} = \text{const.}$$

Multi-Zone BBN (non-dynamical)

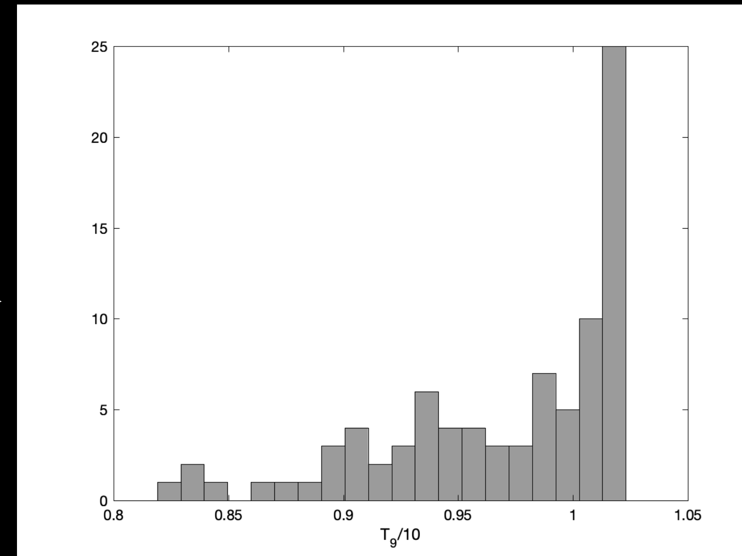
Initial distribution function set-up
@ T9=10

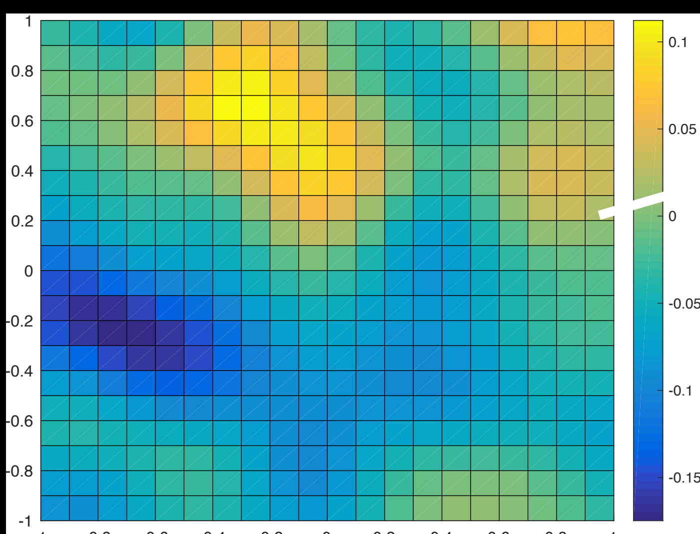
Histogram of γ



$1/T \propto \rho_{rad}^{-1/4}$

Histogram of T_9





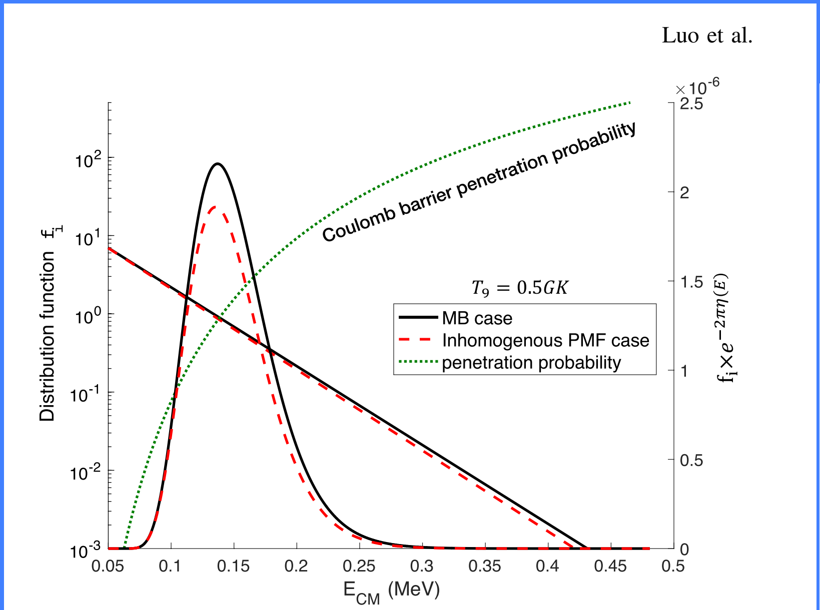
Evolve BBN code with

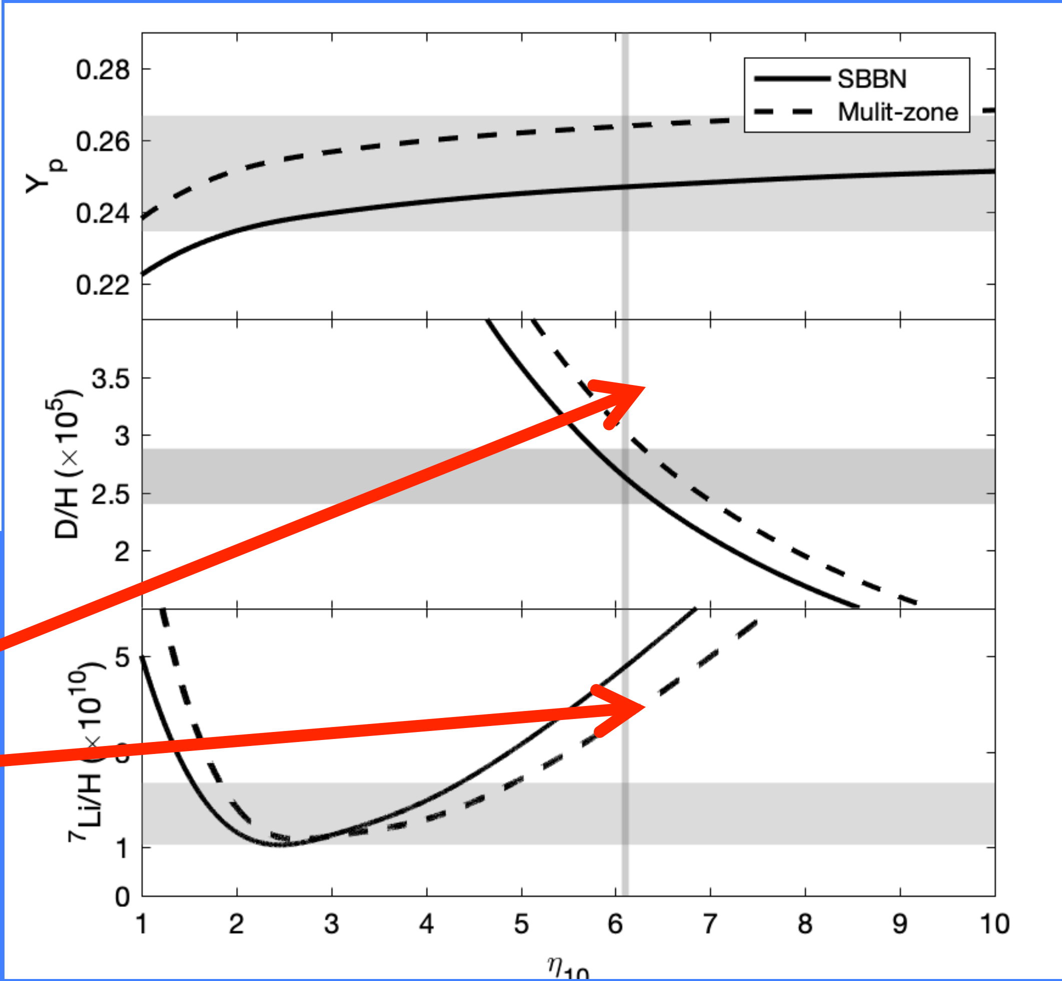
Approximation formula
$n_e(B); \rho_e(B); P_e(B)$

\+ Time-temperature relation w/B-filed

\+ Weak Interaction w/B-field

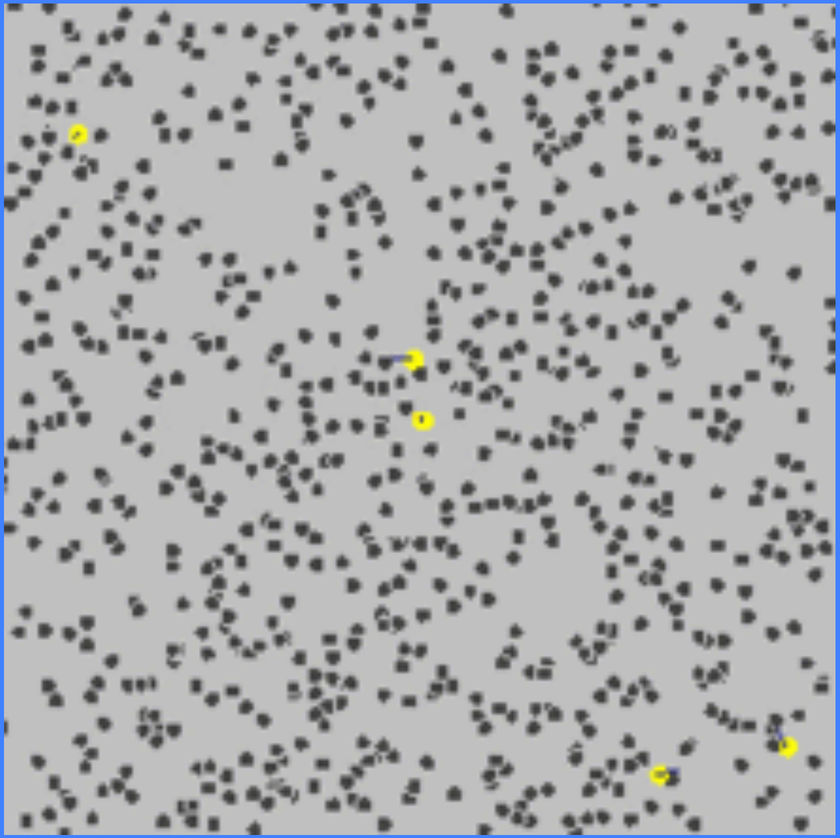
Modified average distribution function





Decreases Li

What is the Thermal Environment during BBN?

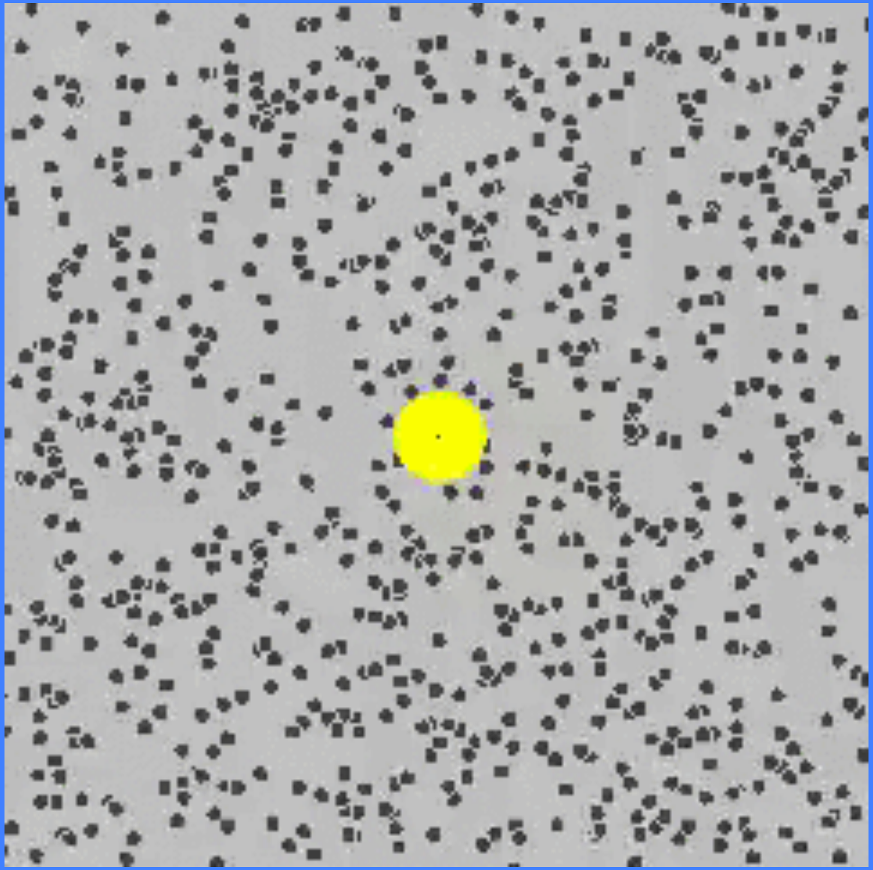


In stars scattering among Nonrelativistic particles => Maxwell-Boltzmann distribution

What is the Thermal Environment during BBN?

BBN is dominated by elastic scattering with mildly relativistic electrons

=> Fermi-Dirac Distribution?



Relativistic Electron Scattering and Big Bang Nucleosynthesis

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(Dated: October 26, 2018)

TABLE I: Calculated ratios of reaction rates for $e^- - e^+$ pair plasma relative to photons. We use the minimum among the two cross section ratios (4th and 5th columns) to get the reaction rate ratio (last column).

T		$\frac{n_\pm}{n_\gamma}$	$\frac{\sigma_\pm}{\sigma_\gamma}$		$\frac{\Gamma_\pm}{\Gamma_\gamma}$
T_9	MeV		$\sigma_\pm = \pi r_D^2$	$\sigma_\pm =$ Mott X-sec.	$\sim \frac{n_\pm \sigma_\pm}{n_\gamma \sigma_\gamma}$
11.6	1	1.43	5×10^4	10^5	10^5
1.16	0.1	0.102	10^7	10^5	10^4
0.116	0.01	10^{-13}	2×10^{28}	10^{29}	10^{15}

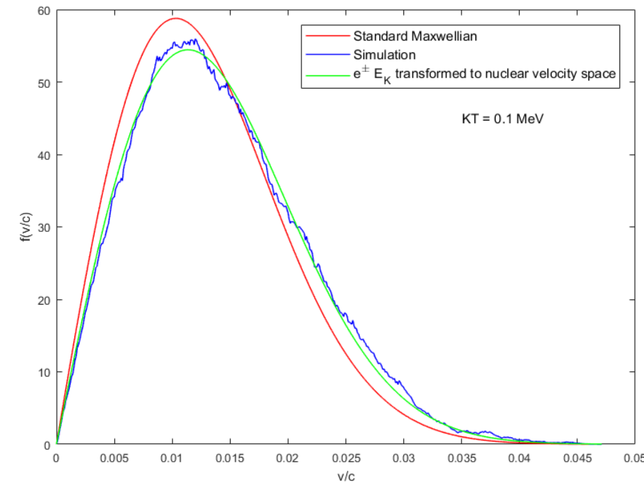


FIG. 3: Simulated proton velocity (v/c) distribution (blue curve) after 10^7 scattering events at $kT = 0.1$ MeV near the onset of BBN. These are compared with the mildly relativistic electron plasma distribution, and the usual MB distribution. Clearly, the nuclear velocity distribution more closely resembles the MJ distribution of the electrons than the usually assumed MB distribution.

Multi-Component Relativistic Boltzmann Eq.

$$p_a^\alpha \partial_\alpha f_a = \sum_{a=1}^{r} \int (f'_a f'_b - f_a f_b) F_{ba} \sigma_{ab} d\Omega \frac{d^3 p_b}{p_{b0}}$$

$$f_{\rm eq}(p) = \exp\left[A - \zeta(U^\alpha p_\alpha)\right]$$

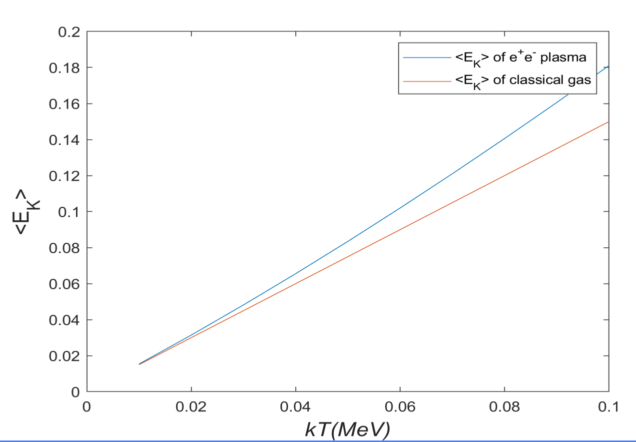
$$S_E^\alpha = \int p^\alpha f \Bigg[-k \ln\left(\frac{f h^3}{g_s}\right) + k\left(1 + \frac{g_s}{\epsilon f h^3}\right) \ln\left(1 + \frac{\epsilon f h^3}{g_s}\right)\Bigg] \frac{d^3 p}{p_0}$$

$$s_E = \frac{k\zeta}{m}(e - \frac{P}{n}) \quad => \quad s_E = \frac{1}{T}(e - \frac{P}{n})$$

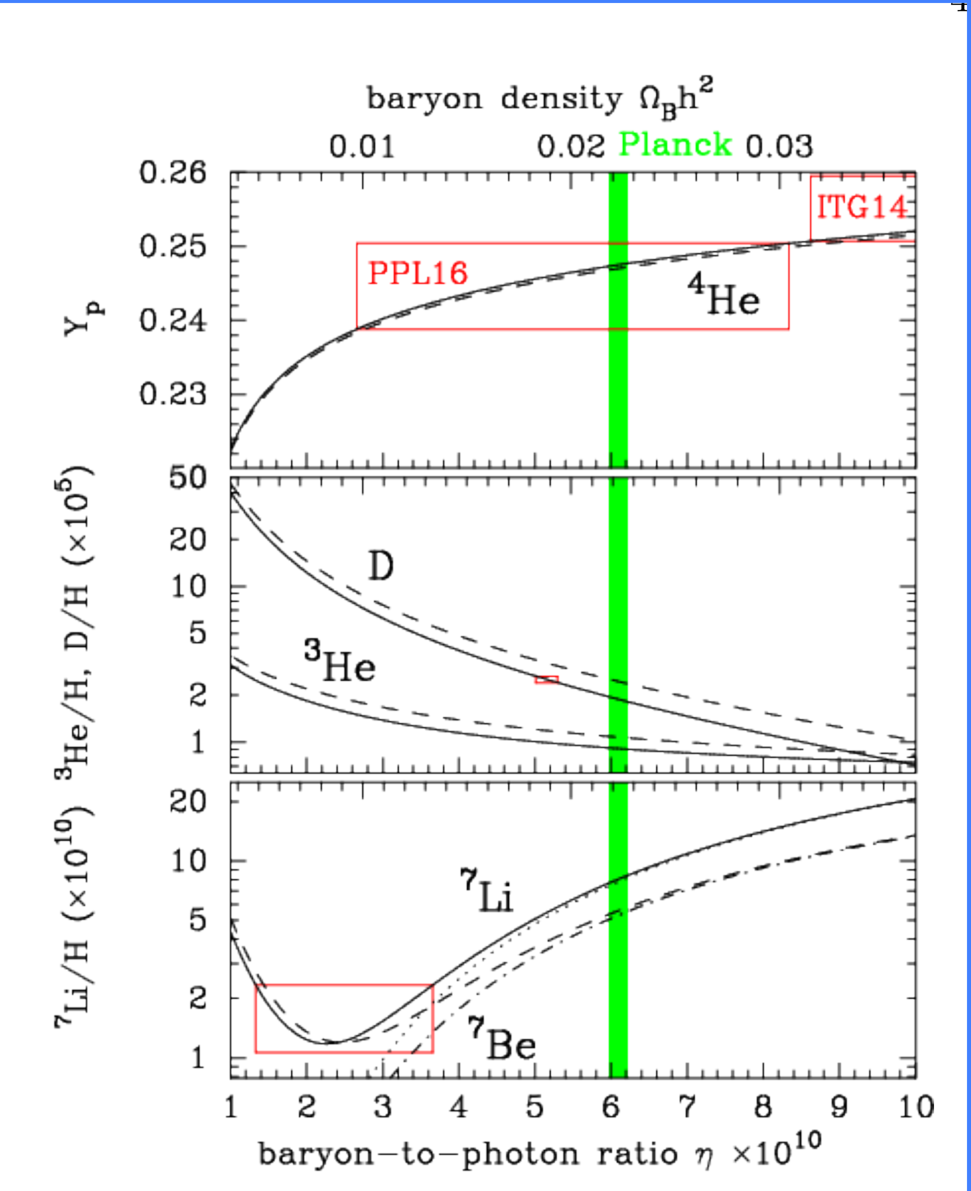
Pressure and energy from recoils

$$P = T^{ii} = \sum_a \frac{p^i(a) p^i(a)}{p^0(a)} \delta^{(3)}(\vec{x} - \vec{x}(a)) = \sum_a \frac{\langle p^i(a)^2 \rangle}{\gamma m(a)}$$

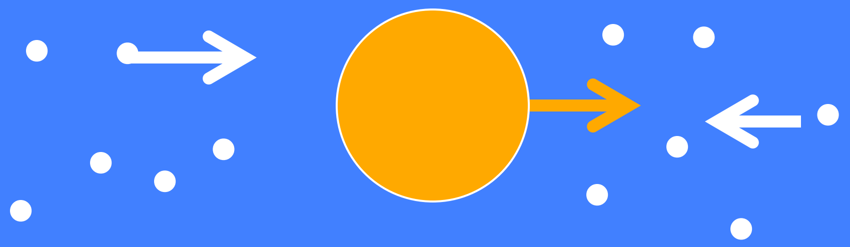
$$f_B = \exp\left[\frac{-(1/2) m_B v^2}{kT} \frac{2}{5}(\mathcal{L} + 1)\right]$$



This makes the Lithium Problem Worse!!



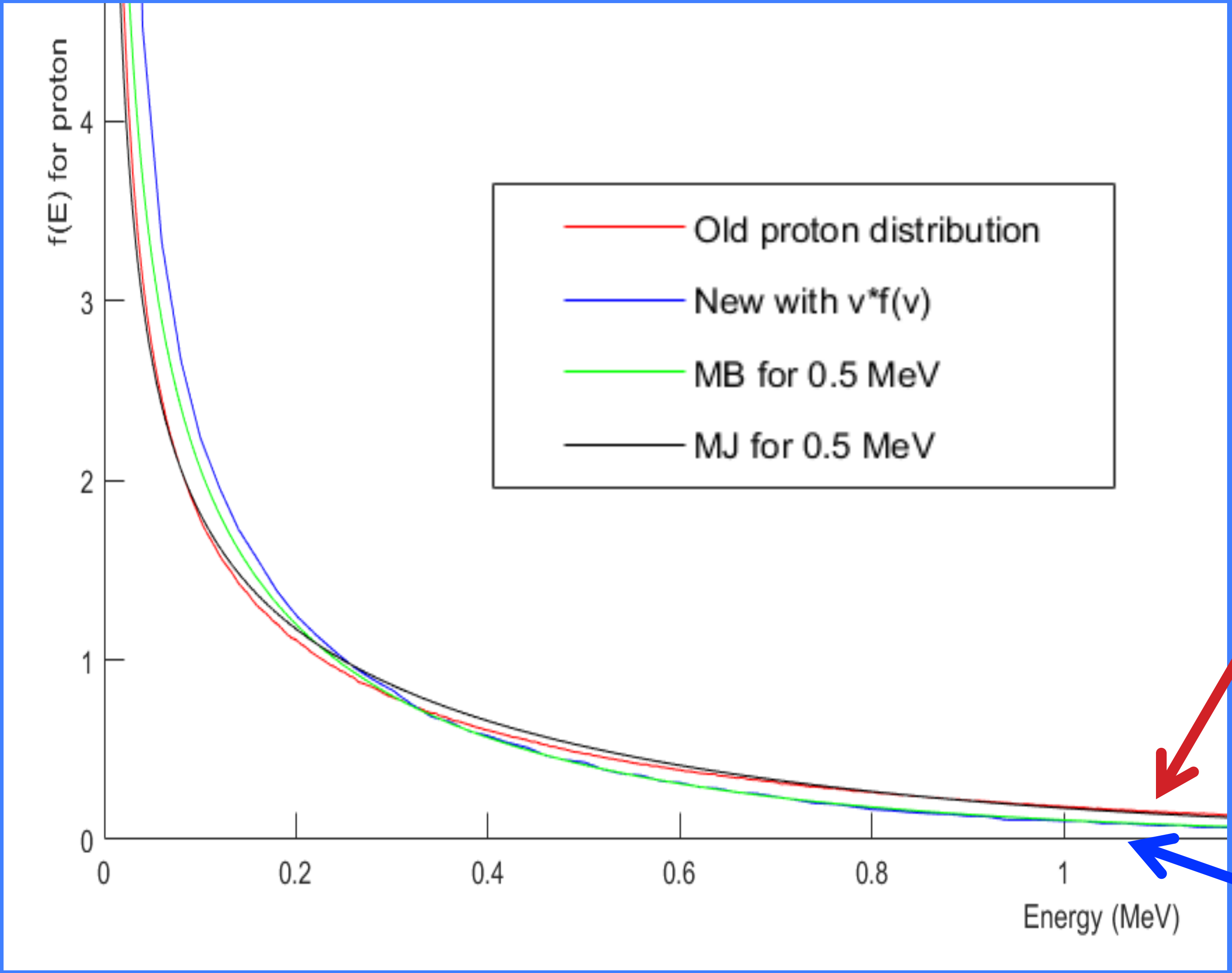
There is a viscosity correction



More energetic scattering along direction of motion of the nucleus

This damps high energy tail

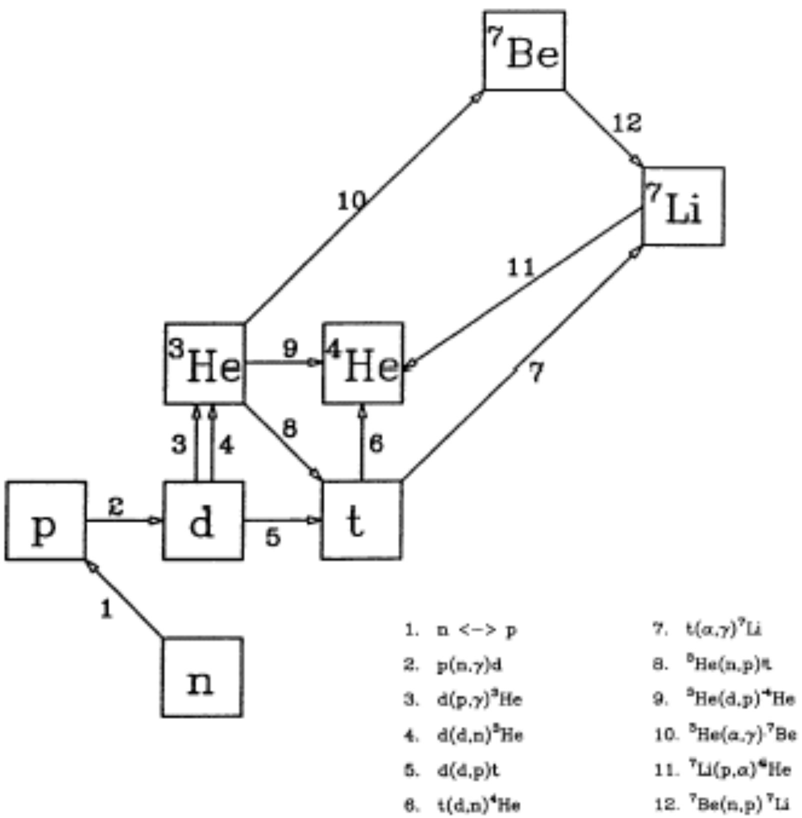
With viscosity correction

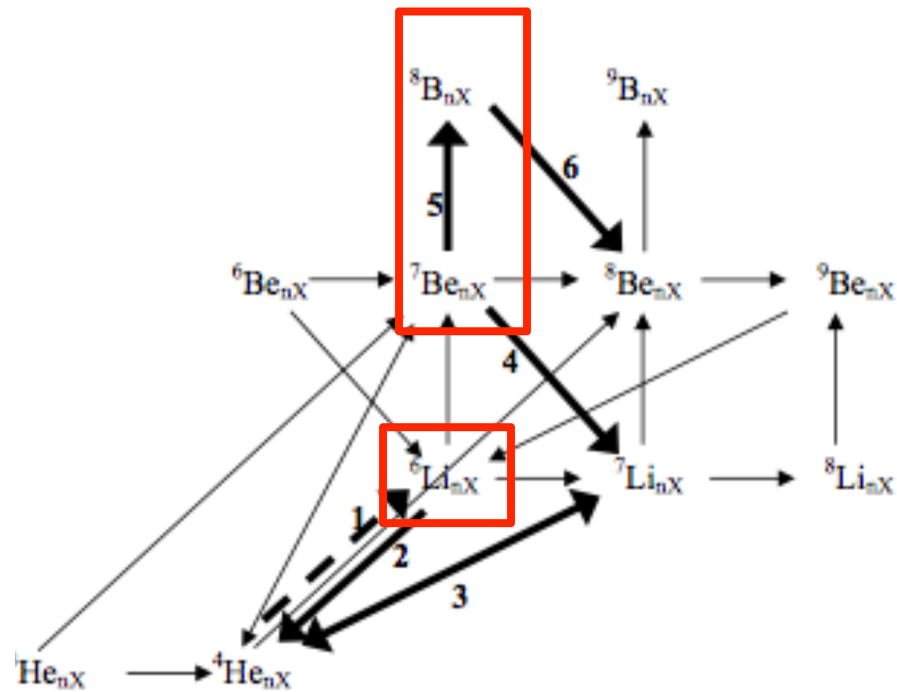


Reduces high energy tail

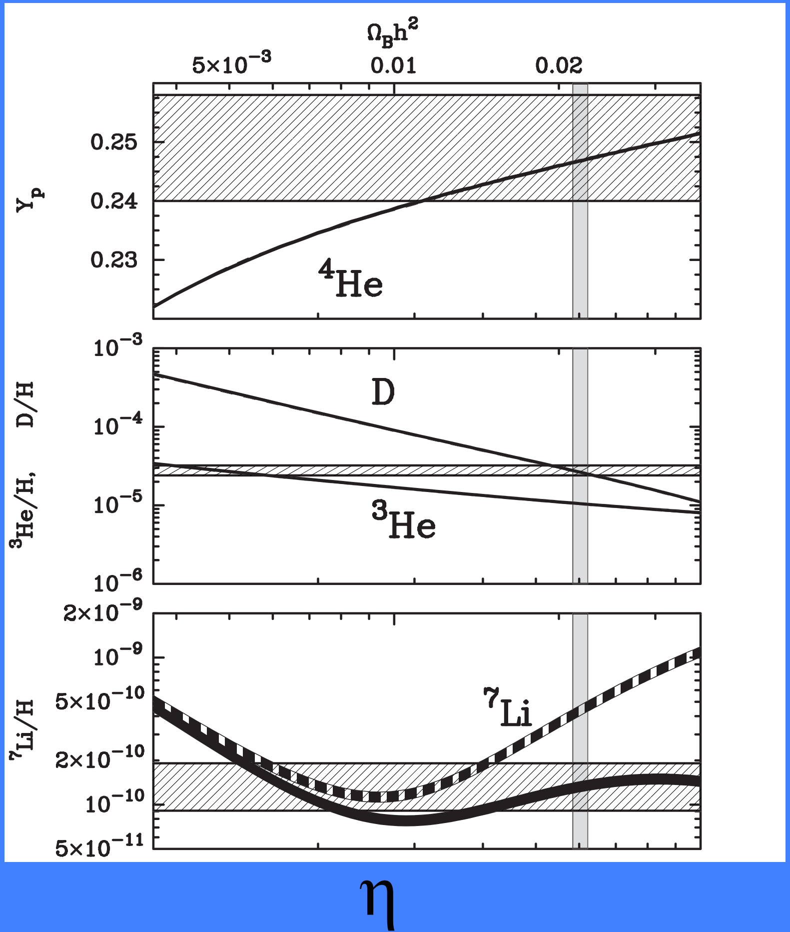
Catalyzed BBN by negatively-CHArged Massive SUSY Particles "CHAMPS"

Stau?
Selectron?





Effect on BBN

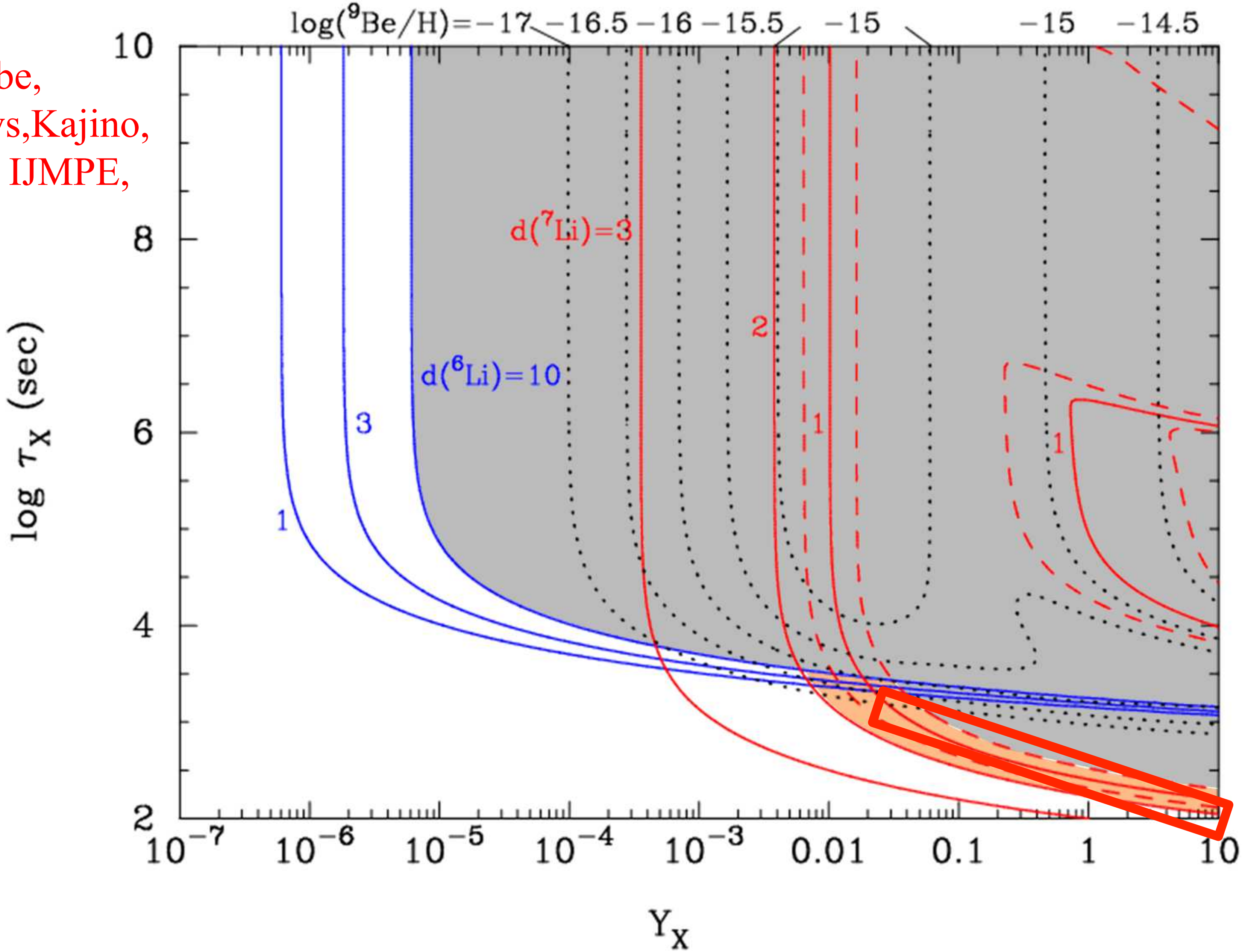


$$^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$$

$$^7\mathrm{Be}_X \rightarrow {}^7\mathrm{Li} + X^0$$

Can reduce Primordial Lithium

Kusakabe, Mathews,Kajino, Cheoun IJMPE, 2017



Conclusions

- There is no obvious cosmological solution to the lithium problem

Synthesis of the Elements in Stars*

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)