Global BBN Analysis III: US Group

Latest Advances in the Physics of
BBN and Neutrino Decoupling
April 12, 2021

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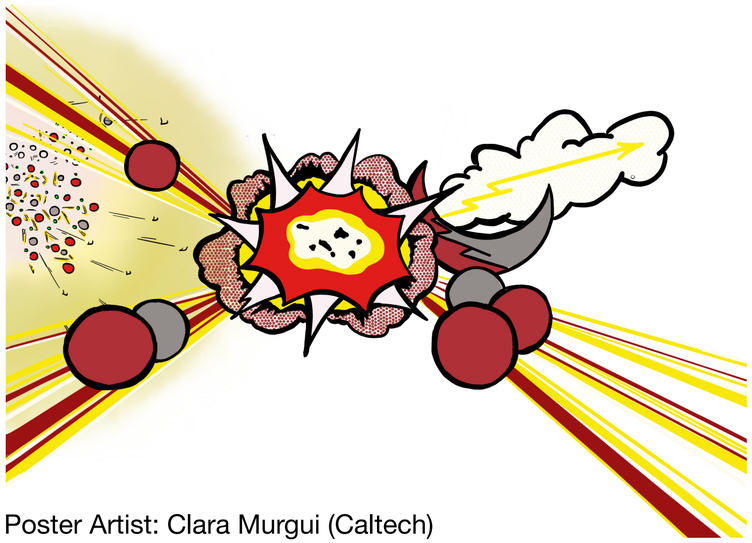
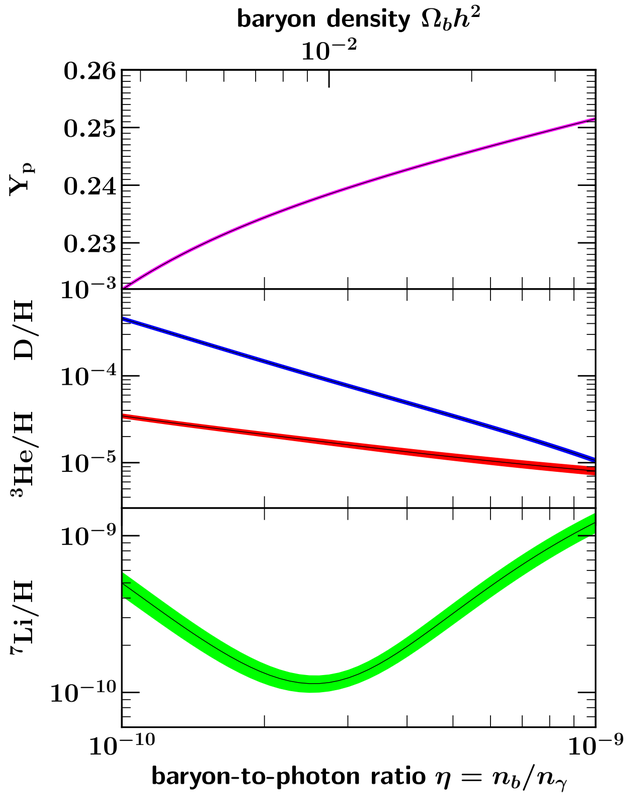
Keith Olive
Brian Fields



Poster Artist: Clara Murgui (Caltech)



Yeh, Olive, & Fields (2021)

Outline

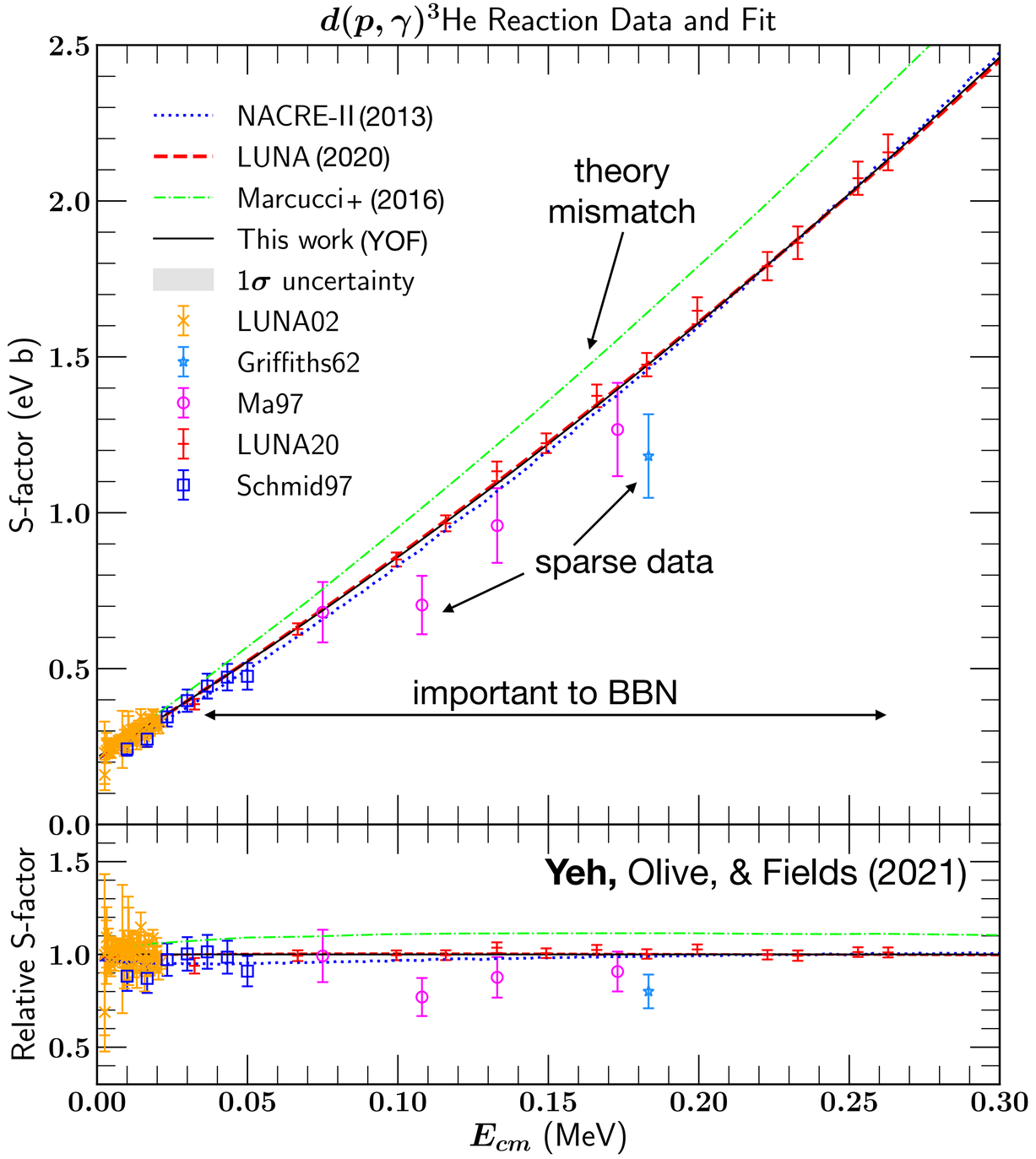
1. Impact of LUNA $d(p,\gamma)^3\mathrm{He}$ data on the prediction of deuterium abundance D/H

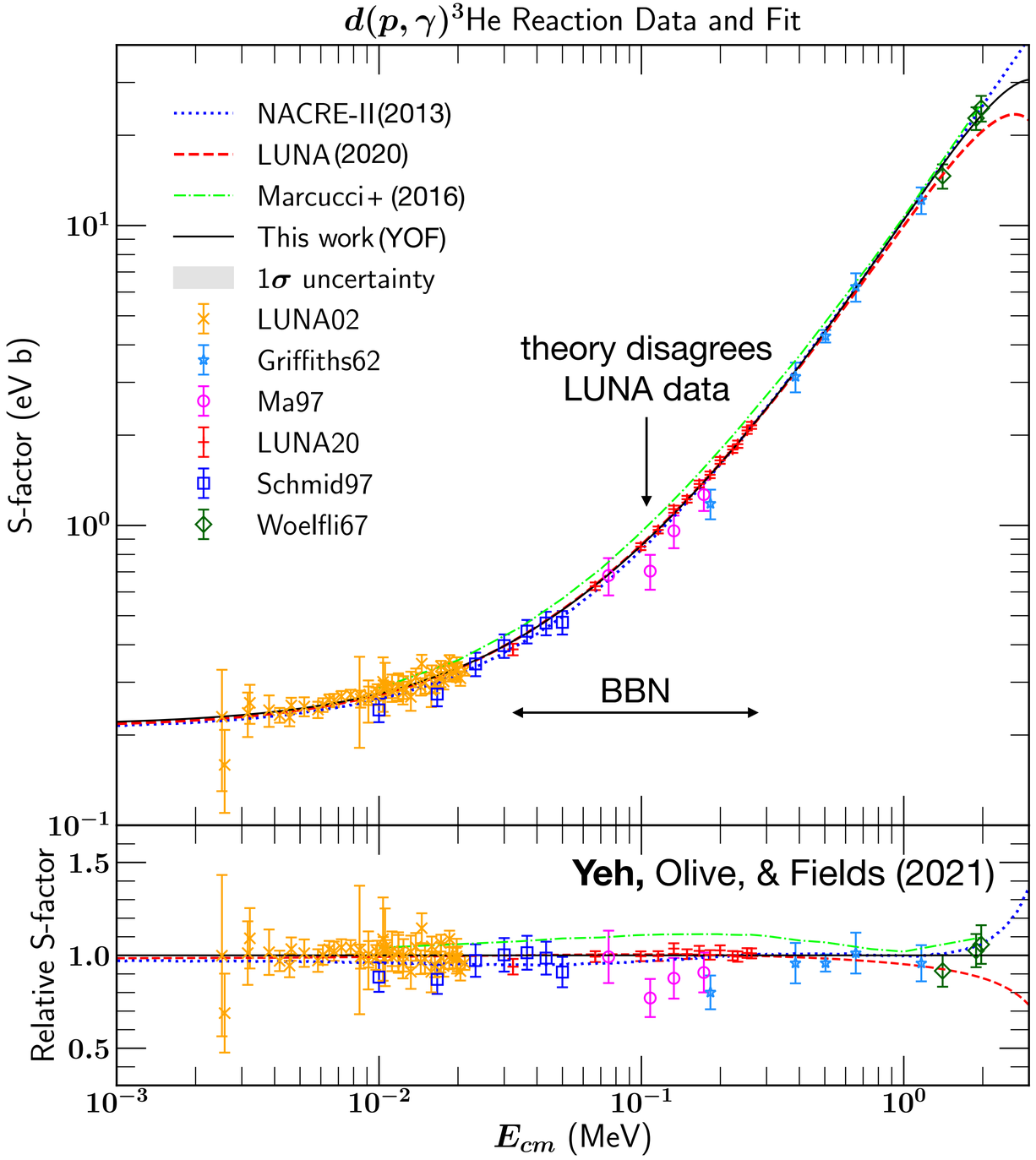
2. Re-evaluation of $d(d,n)^3\mathrm{He}$ & $d(d,p)t$, and D/H uncertainty analysis with new rates

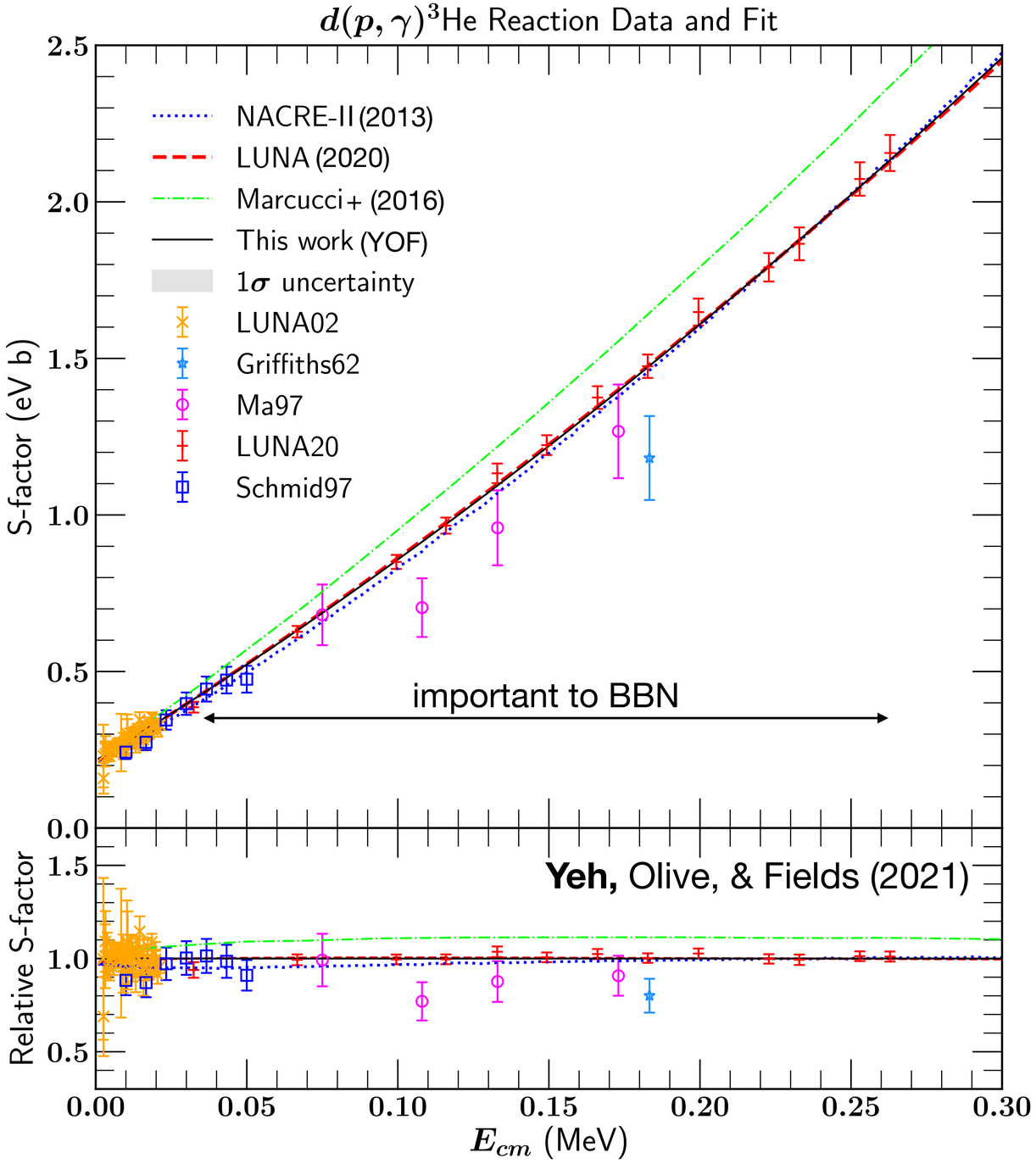
3. Our latest BBN constraints on cosmic baryon density and neutrino species

$d(p,\gamma)^3\mathrm{He}$ **S-factor**

- Before LUNA 2020, theory agrees data outside BBN window, but not inside!
- data sparse with large errors at BBN range
- LUNA data change the landscape!!!
- data-driven polynomial fit minimizing χ^2




$d(p,\gamma)^3$He Reaction Data and Fit
NACRE-II(2013)
LUNA(2020)
Marcucci+ (2016)
This work(YOF)
1σ uncertainty
LUNA02
Griffiths62
Ma97
LUNA20
Schmid97
Woelfli67
theory disagrees
LUNA data
BBN
S-factor (eV b)
Relative S-factor
Yeh, Olive, & Fields (2021)
E_{cm} (MeV)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important to BBN
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$d(p,\gamma)^3\mathrm{He}$ Relative Thermal Rates & Impacts

- Fields, Olive, **Yeh**, & Young (2020): previous analysis based on NACRE

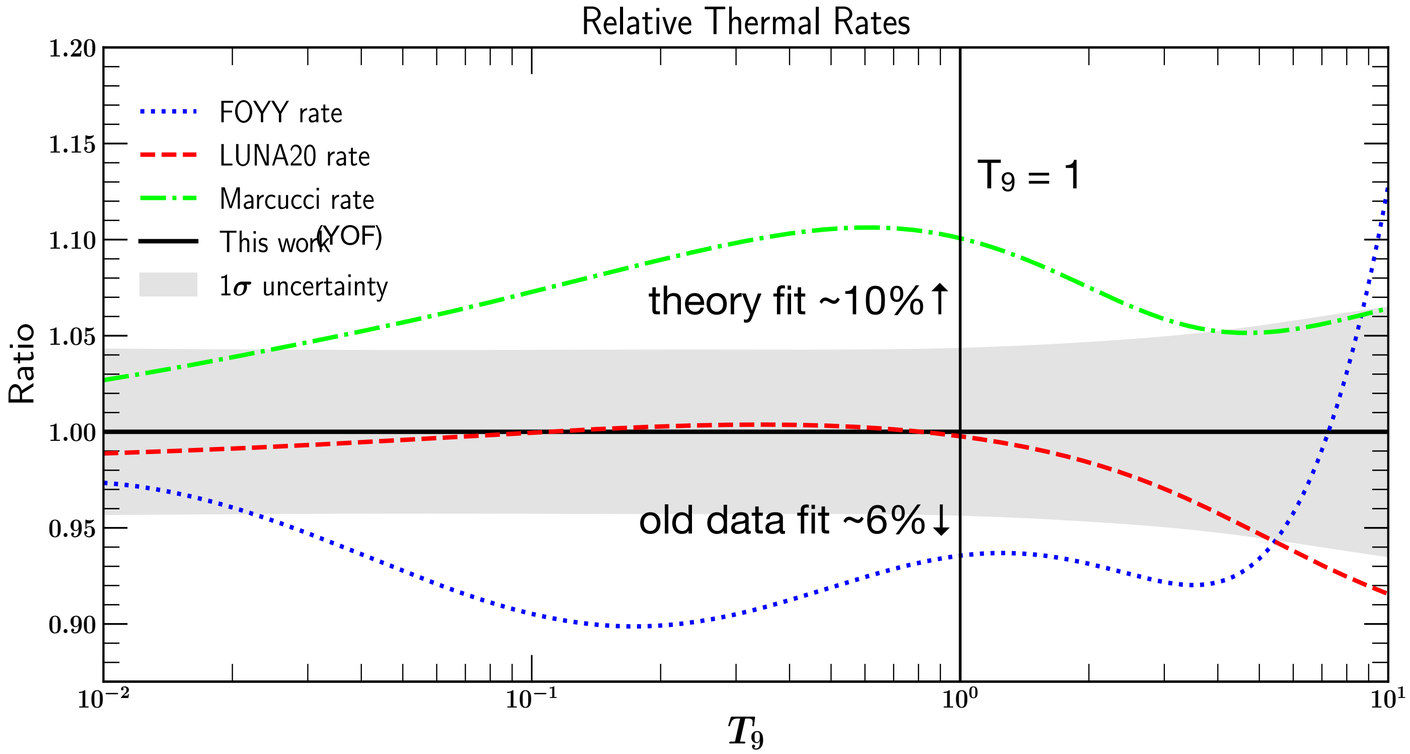
- relative D production as a function of

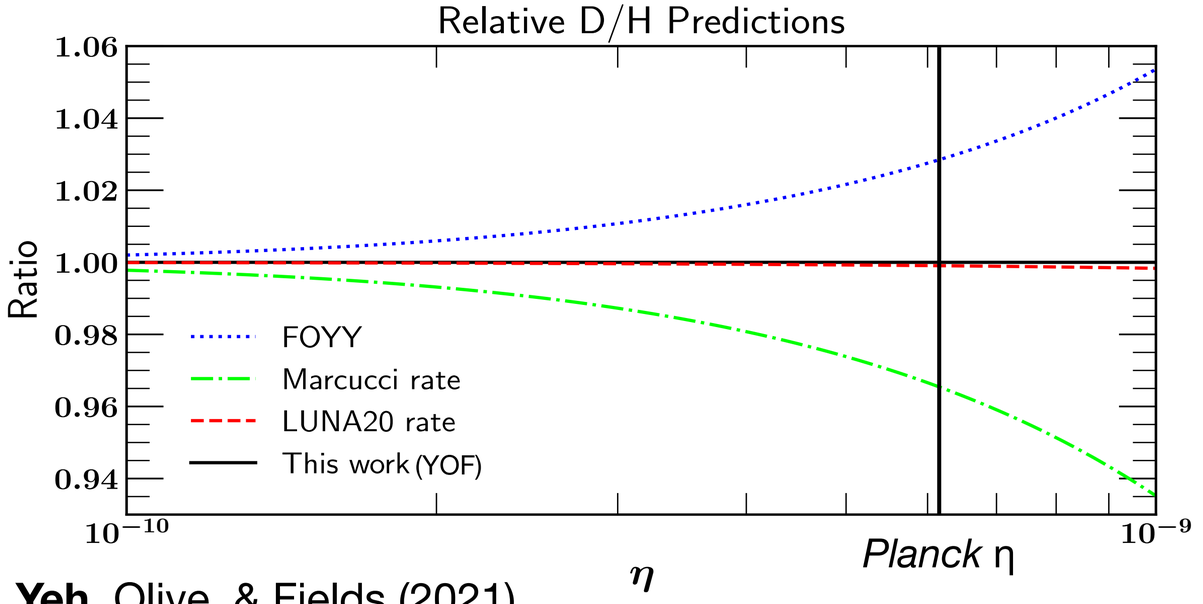
  baryon-to-photon ratio $\eta = n_b/n_\gamma$

  (equivalent to baryon density $\Omega_b h^2$)

- using *Planck* 2018 CMB data to determine

  $\eta_{10} = 10^{10} \times \eta = 6.104$





Yeh, Olive, & Fields (2021)

D/H Predictions using Different $d(p,\gamma)^3\mathrm{He}$ Rates

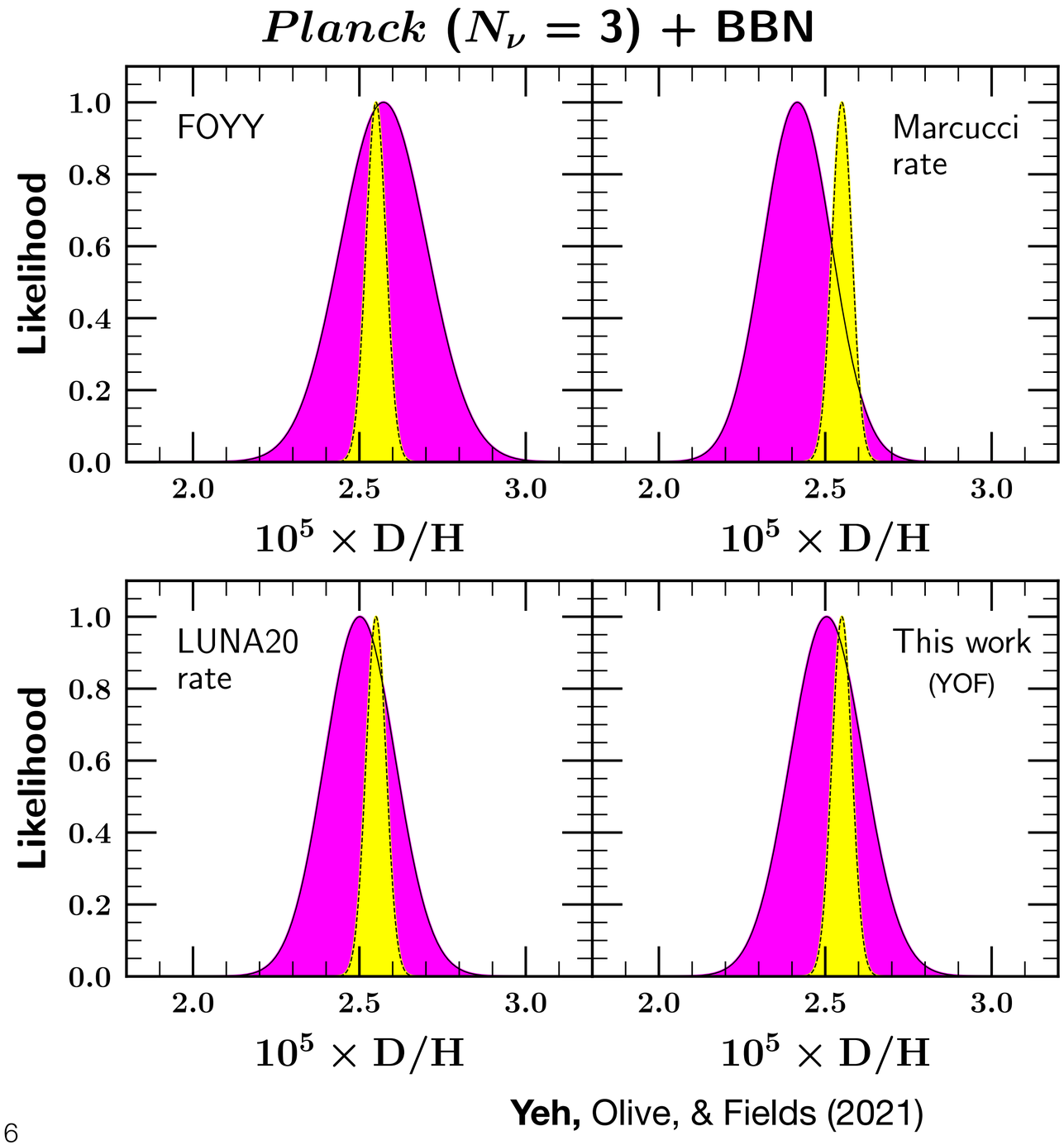
- evaluate D production at Planck η ± σ(η)
- D observation (weighted average):

$(D/H)_{obs} \times 10^5 = 2.55 \pm 0.03$ (in yellow)

summary statistics with different dpg rates

$d(p,\gamma)^3$He rate	10^5 x mean	10^5 x σ	10^5 x peak
FOYY (2020)	2.574	0.129	2.572
Marcucci+ (2016)	2.417	0.103	2.416
LUNA (2020)	2.503	0.106	2.502
YOF (2021)	2.506	0.110	2.504

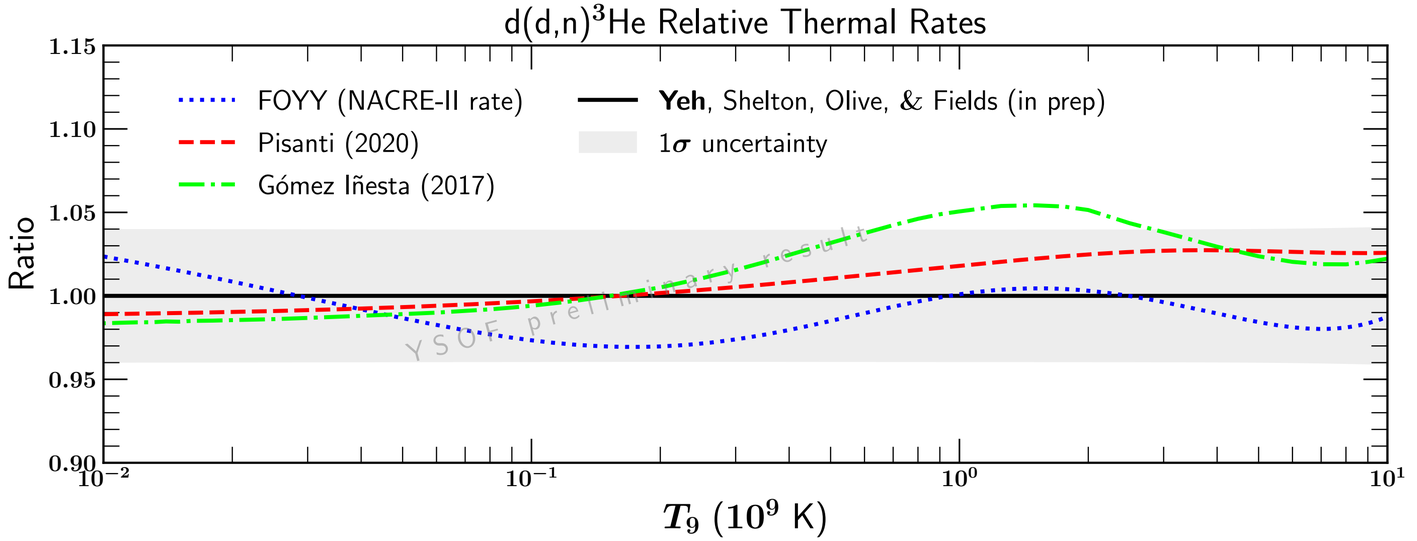
(using the same rates for other reactions)

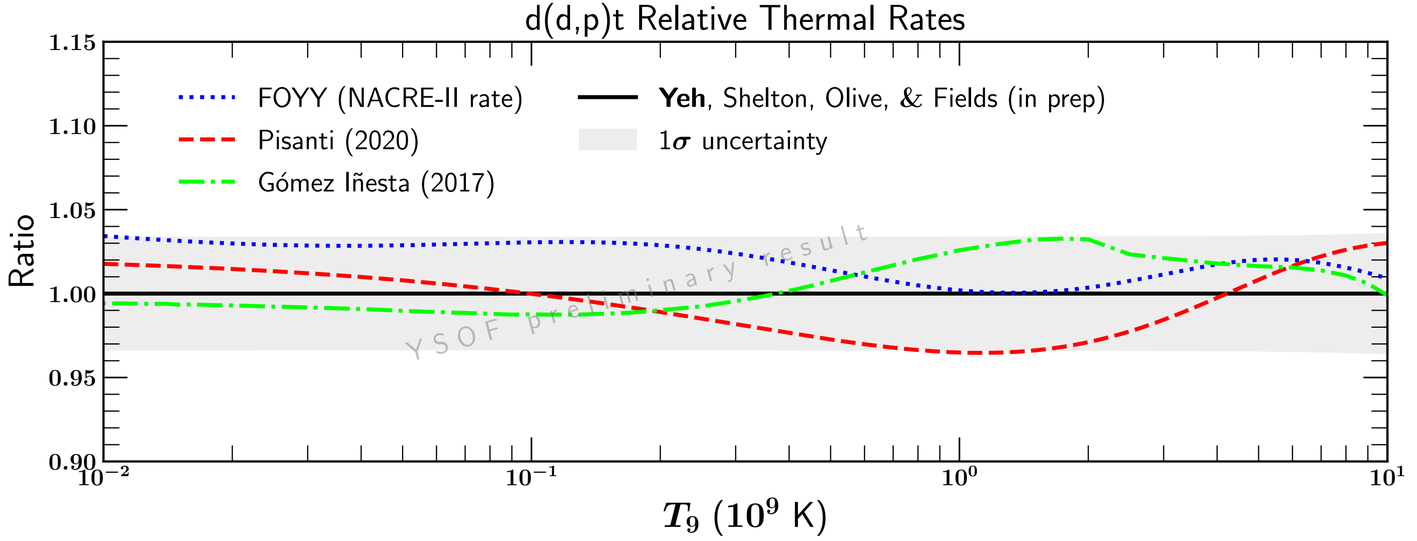


Yeh, Olive, & Fields (2021)

Re-evaluation of $d(d,n)^3\mathrm{He}$ & $d(d,p)t$ Thermal Rates

- consistent d rate evaluation: same code applied to dd rates
- discard low energy data (< 10 KeV) due to electron screening effect
- consistent dd rates around $T_9 \sim 1$ in our old and new studies
- dd rates disagree at $T_9 \sim 1$ across three groups!





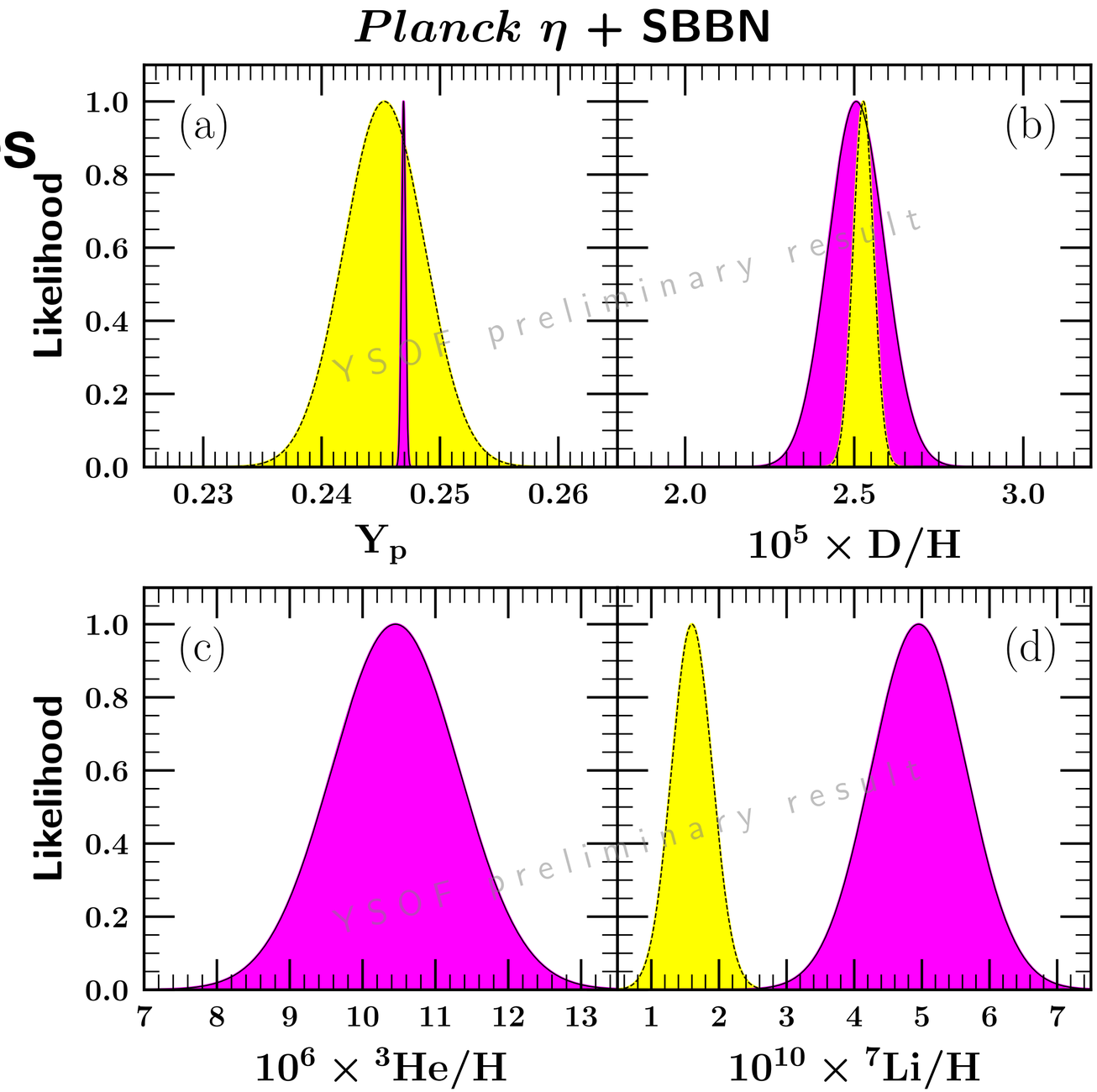
SBBN Light Element Abundances using New Rates

summary statistics of predictions (magenta)

	mean	σ	peak
(a) Y_p (^{4}He)	0.24692	0.00017	0.24691
(b) D/H x 10^5	2.507	0.083	2.506
(c) ^{3}He/H x 10^6	10.45	0.87	10.45
(d) ^{7}Li/H x 10^{10}	4.958	0.703	4.955

summary of observations (yellow)

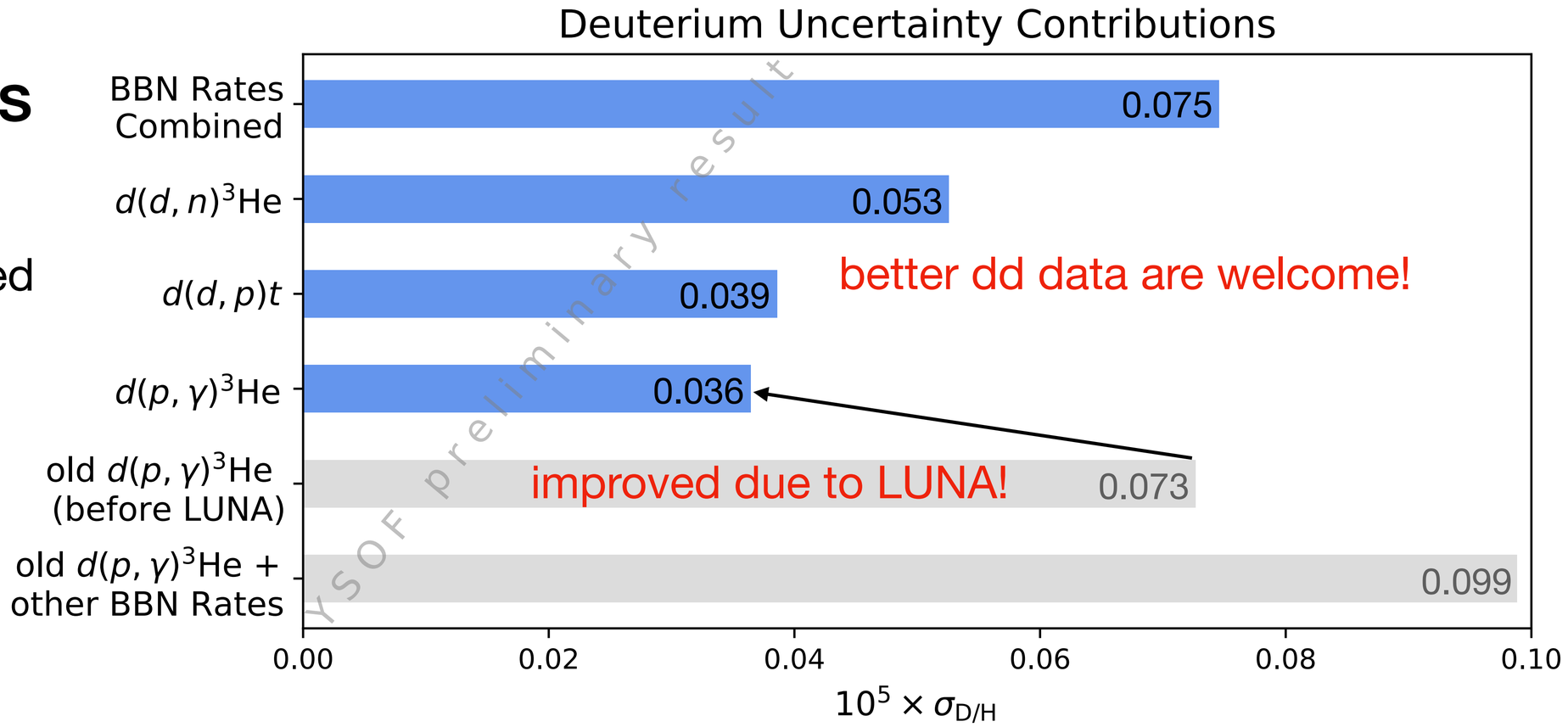
	mean	σ	source
(a) Y_p (^{4}He)	0.2453	0.0034	Aver+ (2020)
(b) D/H x 10^5	2.527	0.030	Cooke+ (2018)
(d) ^{7}Li/H x 10^{10}	1.6	0.3	Sbordone+ (2010)



Yeh, Shelton, Olive, & Fields (in prep)

D Uncertainties

- Uncertainties at fixed *Planck* $\eta_{10} = 6.104$



- D/H error budgets:

	10^5 x mean	10^5 x σ_{tot}	%
at fixed *Planck* η	2.507	0.075	2.99
Planck η ± σ(η)	2.507	0.083	3.31
Cooke+ (2018)	2.527	0.030	1.19

theory error > observation error

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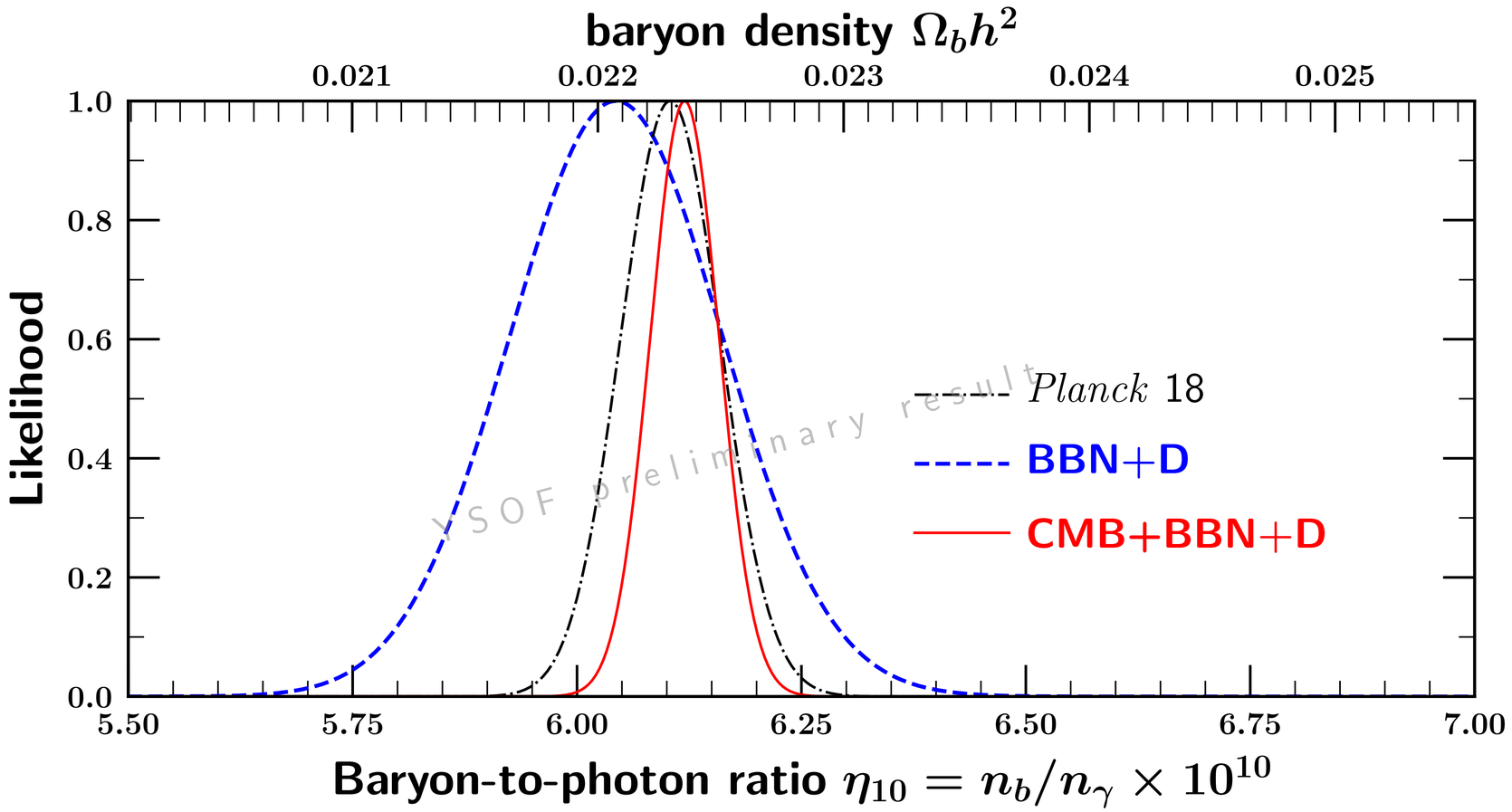
CMB v.s. SBBN Baryometers

summary statistics in η_{10}

	mean	σ	peak
Planck 18	6.104	0.055	6.104
BBN+D_{obs}	6.044	0.118	6.043
combined	6.120	0.038	6.120

in $\Omega_b h^2$

	mean	σ	peak
Planck 18	0.02230	0.00020	0.02230
BBN+D_{obs}	0.02208	0.00043	0.02207
combined	0.02235	0.00014	0.02235



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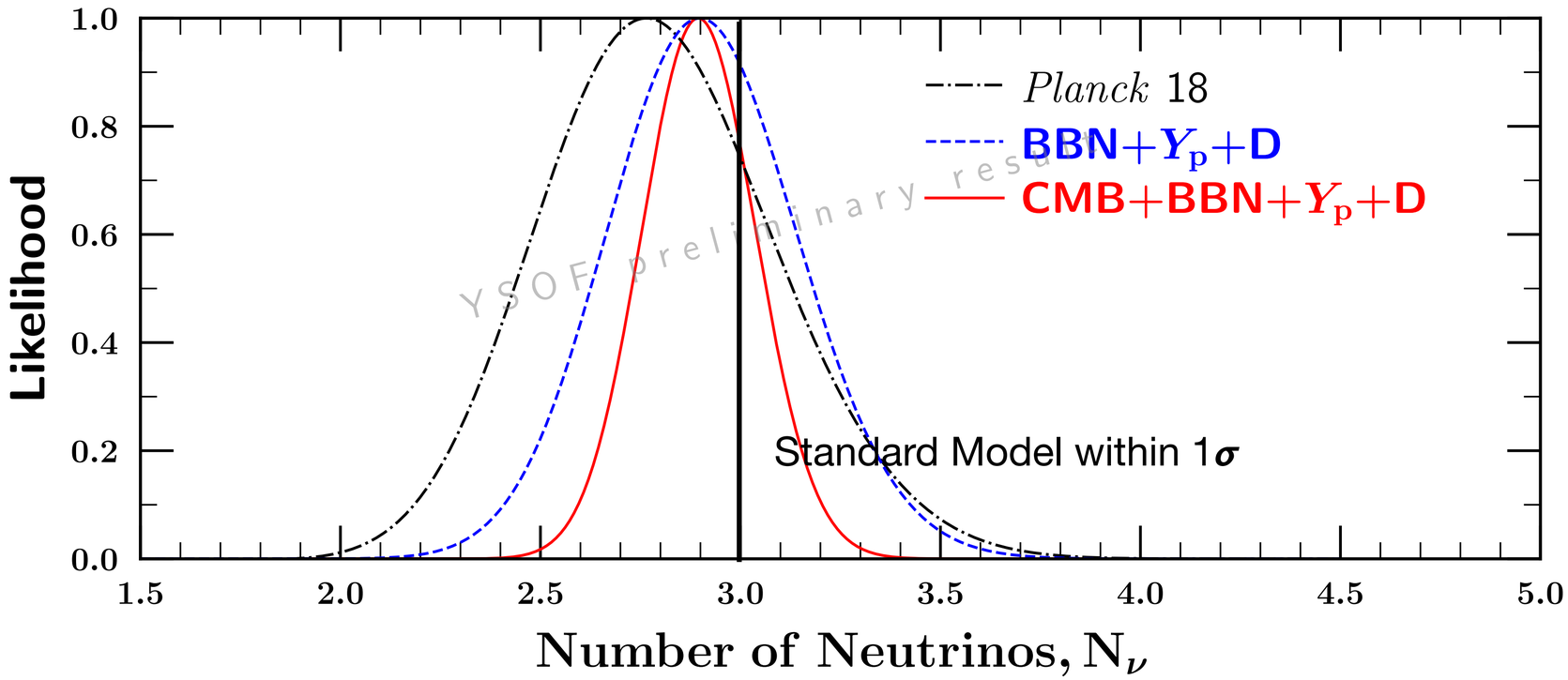
Limits on neutrino flavors N_ν

scaling of effective # of neutrinos

$$N_{\rm eff} = \frac{3.044}{3} N_\nu$$

summary statistics for N_ν

	mean	σ	peak
Planck 18	2.800	0.294	2.764
BBN+Obs	2.910	0.237	2.898
combined	2.898	0.142	2.894



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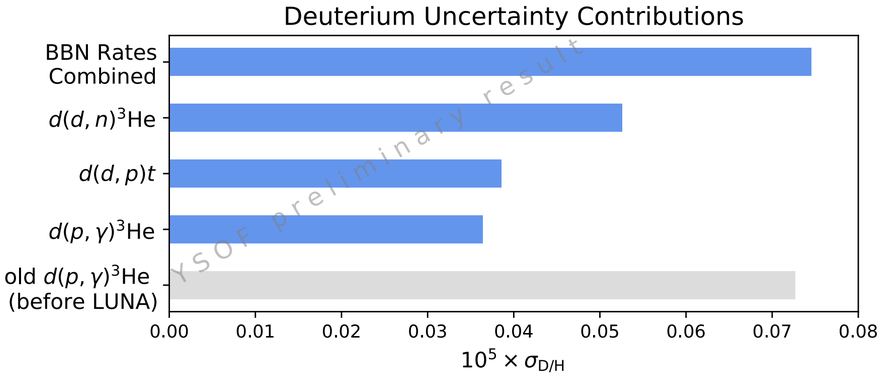
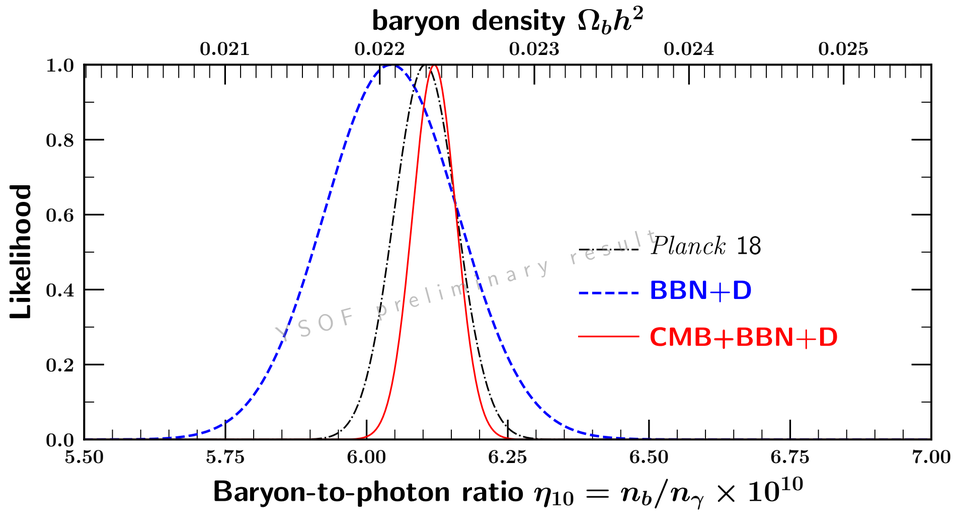
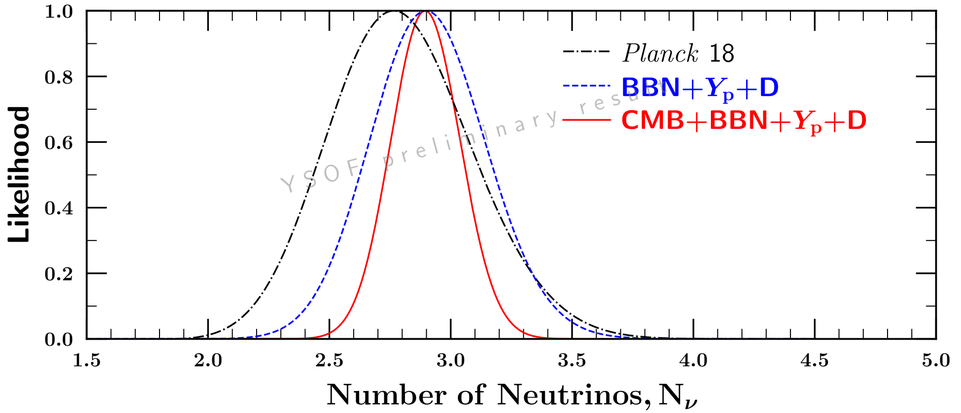
Summary





- LUNA data substantially improve $d(p,\gamma)^3\mathrm{He}$ uncertainty!
- D predicted uncertainty (~3%) > observed one (~1%)
- $d(d,n)^3\mathrm{He}$ & $d(d,p)^3\mathrm{t}$ dominate the D error budget
  -> new measurements needed



- Data-driven rate fits give CMB and BBN baryon determinations in good agreement
- CMB and BBN neutrino numbers are consistent within uncertainties
  -> future measurements could reveal any beyond-Standard-Model ΔN_ν (or ΔN_{eff})

Plots from **Yeh,** Shelton, Olive, & Fields (in prep)