Precision Deuterium in Big Bang Nucleosynthesis: the Critical Role of Nuclear Reactions

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Introduction

Big Bang Nucleosynthesis (BBN) accounts for the cosmic origin of the lightest elements, such as helium and deuterium. As a fiducial BBN model, **standard BBN** (SBBN) is formulated in the context of a **ΛCDM** cosmology and the **Standard Model** of particle physics. Using precisely measured **nuclear data** and the **cosmic baryon density** determined from the cosmic microwave background (CMB) measurements as inputs, SBBN is essentially a **parameter-free** theory. Accordingly, the **comparison between SBBN predictions and observed primordial abundances** for light elements not only provides a **crucial test** to the standard cosmology but also hints at new physics. Improved precision from both theory and observation will in return improve the power of BBN in probing the physics of the early universe.

The BBN light element abundance calculations rely on a detailed **network of nuclear reaction rates** of particular importance to BBN. These rates carry uncertainties, which are propagated in simulation to predict abundance likelihoods of the light elements. Thus, **accurate precision measurement** of **nuclear cross sections** are **critical for calculating BBN abundances**.

Motivation

d(p,γ)³He is one of the **key** rates for calculating the **deuterium** abundance (D/H). By combining BBN theory and the *Planck* 2018 CMB data, we had reported the **predicted** deuterium abundance carried **~5%** uncertainty [1]. However, the **observed** counterpart has reached **~1%** precision. The theory error was dominated by the thermal rate uncertainty of d(p,γ)³He. The experimental data of this rate were sparse with large errors at energies relevant to BBN. Thanks to the **new d(p,γ)³He data** from **LUNA** [2], this rate has now been **improved** with precision cross section measurement. We present here the **new d(p,γ)³He rate** and its **impact on** the **BBN deuterium** abundance prediction. (For more details, please refer to our work [3] and references therein.)

Evaluation of d(p,γ)³He Cross Section & Rate

- use the **cross section data** from **LUNA** [2,4], and some earlier work from 1997 by Schmid et al. [5] and Ma et al. [6], and from the 1960s by Wölfli et al. [7] and Griffiths et al. [8]
- perform a **global fit** for the **astrophysical S-factor** that **minimizes** χ^2 over the energy range 2 keV to 2 MeV (covering the BBN energy window)
- add in quadrature **additional discrepancy error** that accounts **for systematic differences between data sets** beyond the statistical and systematic errors from each data set
- compute a **thermal average** to obtain a new thermonuclear rate and its uncertainty as functions of temperature

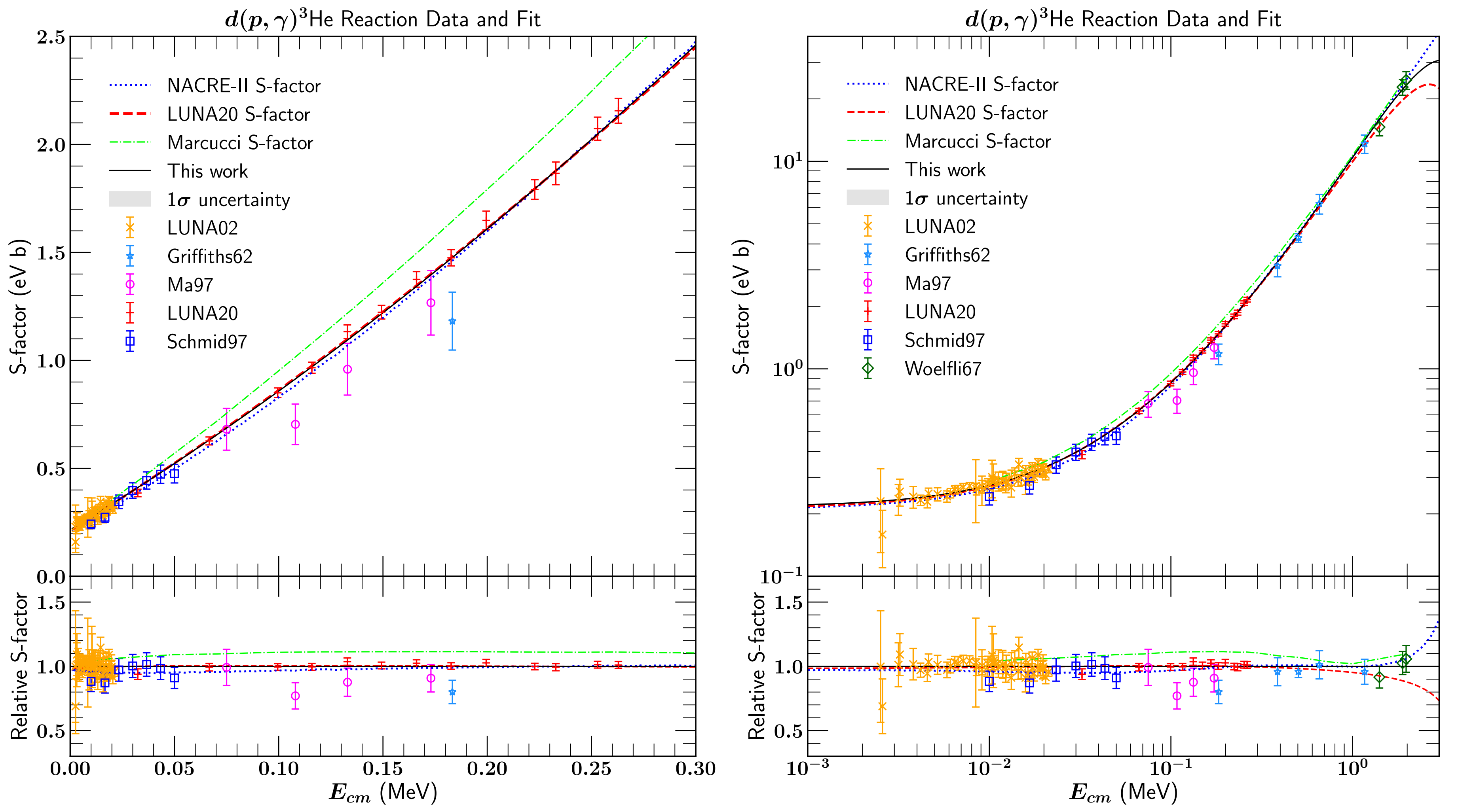

Figure 1. The ***astrophysical S-factor for d(p,γ)³He*** *showing 1) the NACRE-II [9] S-factor used in our previous study FOYY [1] (blue dotted); 2) the LUNA global average [2] (red dashed); 3) the theoretical S-factor from Marcucci et al. [10] (green dot-dashed); and* ***4) our new world average rate*** *[3]* ***(black solid)****. The shading corresponds to the 68% uncertainty we assign to the average rate. In the left panel, the S-factor is shown against a linear energy scale centered on the BBN energies. In the right panel, we show an extended energy range on a log scale.*

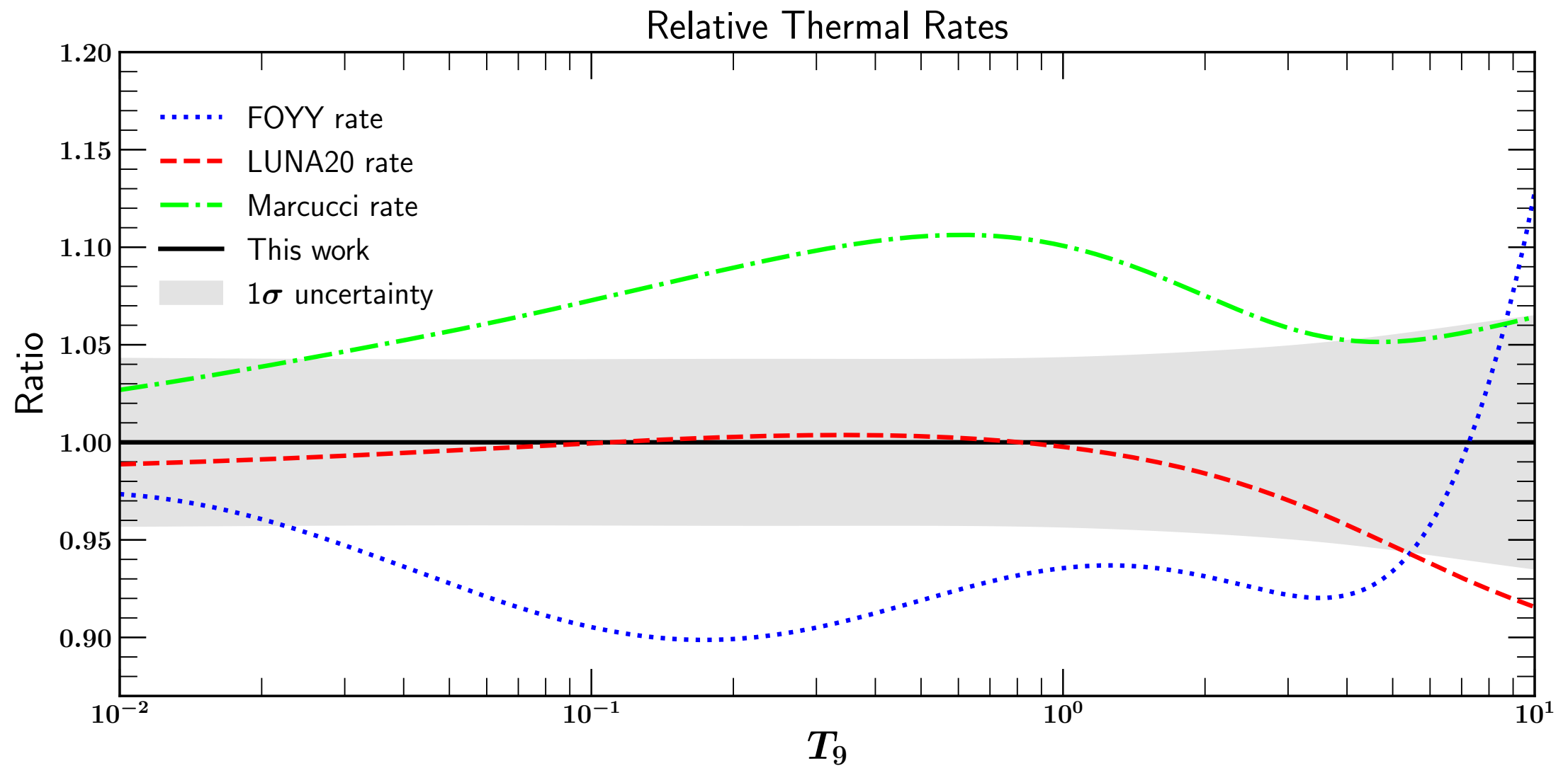

Figure 2. The ***relative thermal rates*** *with respect to our new baseline average rate* $\lambda_i(T_9)/\lambda_{\text{base}}(T_9)$ *[3]. Shown here as a function of temperature in units of* $T_9 = 10^9$ *K.*

Impact of New d(p,γ)³He Rate on BBN D/H Prediction

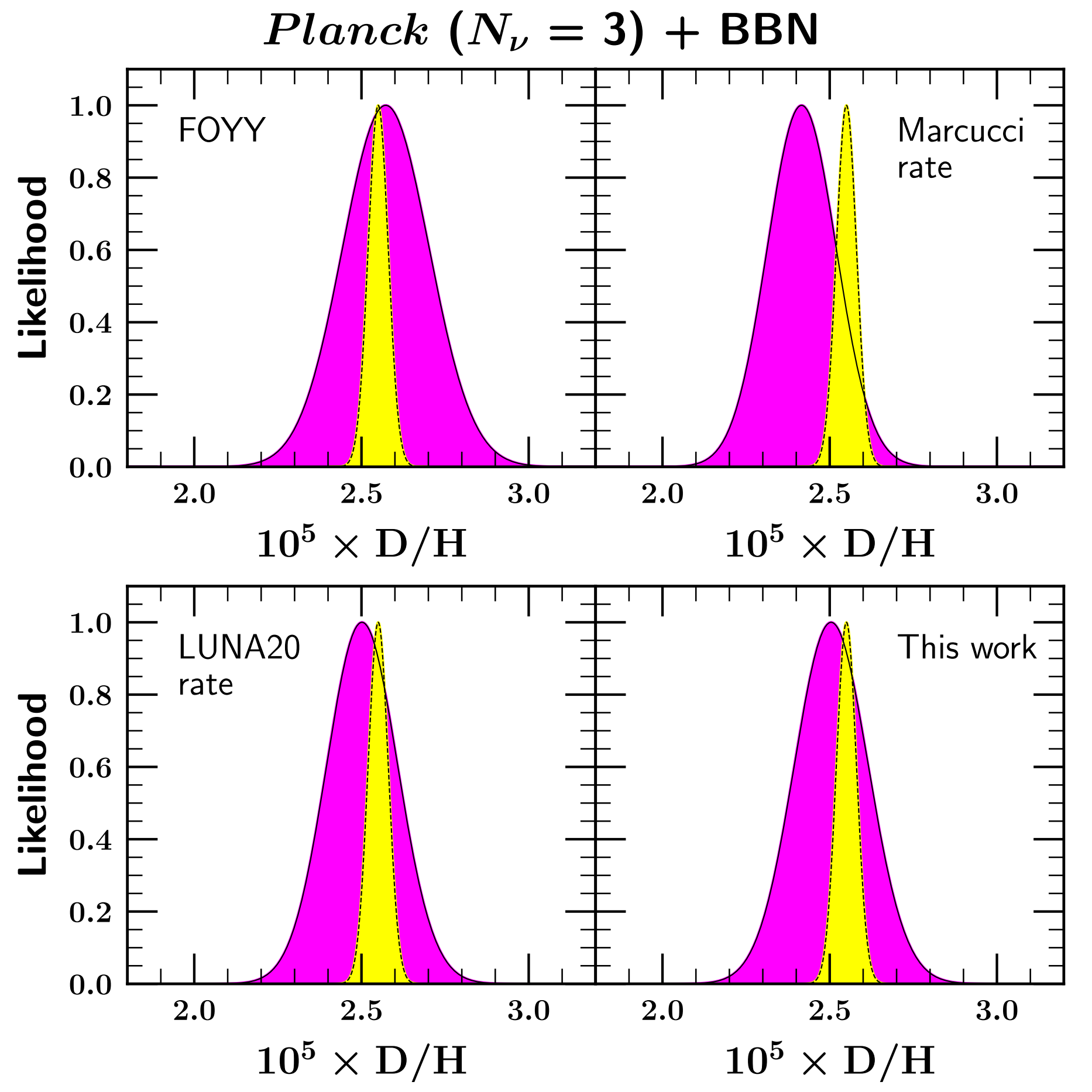

Figure 3. ***D/H likelihoods*** *with different d(p,γ)³He rates: 1) the FOYY rate [1] (upper left), 2) the theoretical rate [10] (upper right), 3) the new LUNA rate [2] (lower left), and* ***4) our new combined rate*** *[3]* ***(lower right)****. The solid-lined, purple-shaded curves are the BBN+CMB predictions, based on Planck 2018 inputs. The dashed-lined, yellow-shaded curves show* ***weighted observations*** *from quasar absorption systems:* ***D/H = (2.55 ± 0.03) × 10⁻⁵ [3]****.*

d(p,γ)³He rate	D/H ×10⁵
FOYY [1]	2.574 ± 0.129
Theory [10]	2.417 ± 0.103
LUNA20 [2]	2.503 ± 0.106
This Work [3]	2.506 ± 0.110

Table 1. D/H predictions for each of the adopted rates for d(p,γ)³He in Fig. 3 (purple-shaded).

Key Messages

- **New precision cross section data from LUNA** has **improved** the **d(p,γ)³He** thermal rate error **by a factor of ~2**, compared to the old rate from NACRE-II [9].
- Our new d(p,γ)³He rate evaluation reaffirms the **excellent agreement** between SBBN+CMB D/H prediction and its observed primordial abundance (Fig 3 lower-right panel).
- In addition to d(p,γ)³He, D/H also has strong sensitivity to reactions d(d,n)³He and d(d,p)t. With improved d(p,γ)³He, **d(d,n)³He** now **dominates** the **remaining error** budget, with **d(d,p)t** in the **second place**.

Latest Update

- We apply the same nuclear rate evaluation procedure to re-evaluate the d(d,n)³He and d(d,p)t rates with existing cross section data [11]. We update these d+d rates with improved uncertainties. Our most recent calculation gives

$$\text{D/H} = (2.506 \pm 0.083) \times 10^{-5}$$

, with **~3%** uncertainty. (Note: observed D/H error **~1%**)

Outlook

- To further improve BBN D/H prediction, we calls for **new** precision measurements of **d(d,n)³He** and **d(d,p)t** at the BBN energies. Fortunately, both rates have the same initial state and can be **accessible in the same experiment**.
- The Marcucci **theory rate** [10], which is based on *ab initio* quantum mechanics calculation using nucleon interaction potentials, **deviates** from the precise **LUNA** d(p,γ)³He data while agreeing with other experimental datasets outside the BBN range (Fig 1). Thus, **additional theoretical study for d(p,γ)³He** thermal rate is also **welcome** to understand such a puzzling deviation.

References

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