A hint for new physics from primordial deuterium

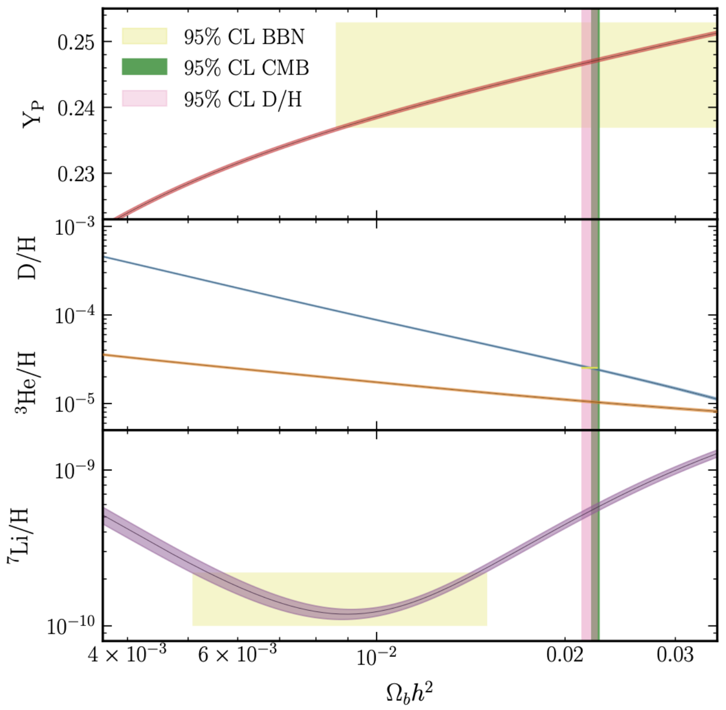
Cara Giovanetti (UC Berkeley and LBNL)

UC Davis Seminar

February 2$^{\text{nd}}$, 2026

With Tim Launders and Hongwan Liu (BU)

A quick note on ^{7}Li



C.G. et al, 2408.14538

- Recent measurements suggest ^{7}Li abundance measured in stars is depleted from primordial level Wang et al., 2021 https://doi.org/10.1093/mnras/stab2924

- Independent measurements from ISM show lower metallicity than in stars overall Molaro et al., 2407.10818
  See also Brian Fields, *A Bitter Pill: The Primordial Lithium Problem*, Opportunities and Challenges in Big Bang Nucleosynthesis (EuCAPT Workshop), 2025.

- Community consensus: **we probably do not measure primordial ^{7}Li**

A quick note on notation

$$d(d,n)^{3}He \quad \leftrightarrow \quad d + d \rightarrow n + {}^{3}He$$

Outline

- BBN Overview
- Previous determinations of the primordial deuterium abundance
- A new method
- New physics perspective

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Why BBN?

ν decoupling **BBN** Recombination

Big Bang 1 s **~2-20 min** 370,000 yr Today

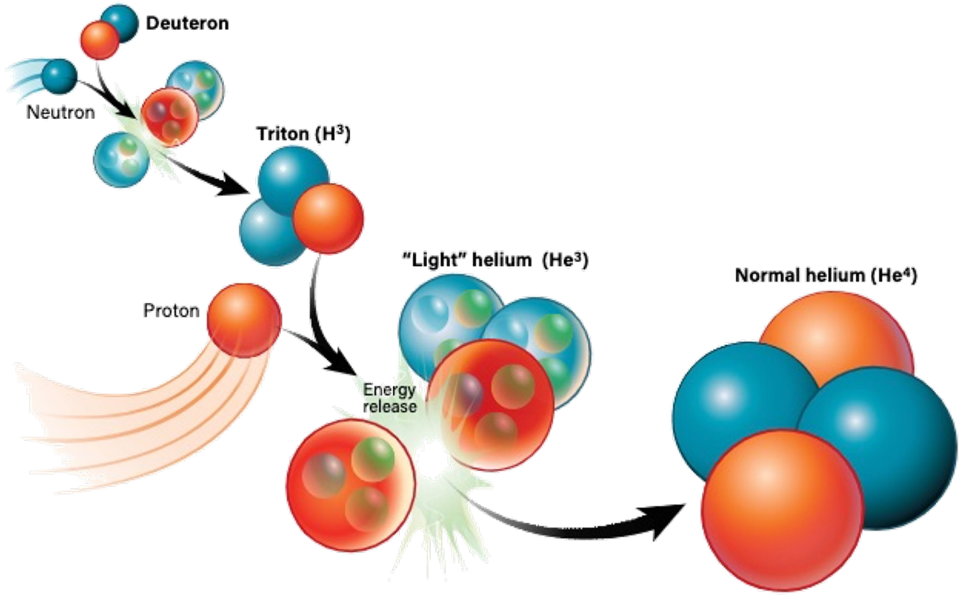


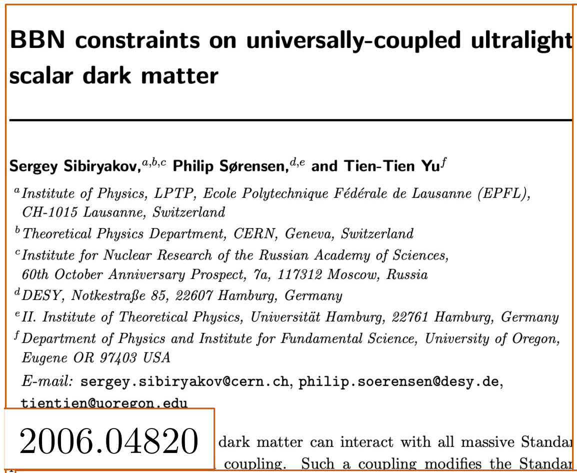
Image credit:
Roen Kelly for Astronomy Magazine

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

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

Long **times**

BBN and New Physics



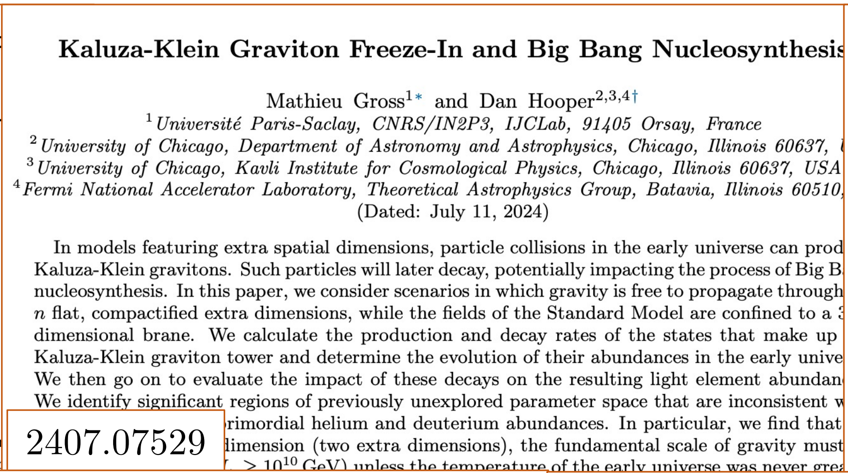
BBN constraints on universally-coupled ultralight scalar dark matter

Sergey Sibiryakov,[a,b,c] **Philip Sørensen,**[d,e] **and Tien-Tien Yu**[f]

[a] *Institute of Physics, LPTP, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*
[b] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[c] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia*
[d] *DESY, Notkestraße 85, 22607 Hamburg, Germany*
[e] *II. Institute of Theoretical Physics, Universität Hamburg, 22761 Hamburg, Germany*
[f] *Department of Physics and Institute for Fundamental Science, University of Oregon, Eugene OR 97403 USA*
E-mail: `sergey.sibiryakov@cern.ch`, `philip.soerensen@desy.de`, `tientien@uoregon.edu`

dark matter can interact with all massive Standar
coupling. Such a coupling modifies the Standar

2006.04820

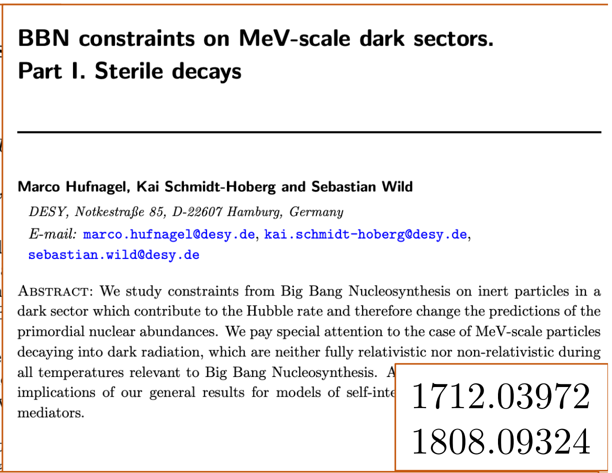


Kaluza-Klein Graviton Freeze-In and Big Bang Nucleosynthesis

Mathieu Gross[1*] and Dan Hooper[2,3,4†]
[1] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[2] *University of Chicago, Department of Astronomy and Astrophysics, Chicago, Illinois 60637,*
[3] *University of Chicago, Kavli Institute for Cosmological Physics, Chicago, Illinois 60637, USA*
[4] *Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, Illinois 60510,*
(Dated: July 11, 2024)

In models featuring extra spatial dimensions, particle collisions in the early universe can prod
Kaluza-Klein gravitons. Such particles will later decay, potentially impacting the process of Big B
nucleosynthesis. In this paper, we consider scenarios in which gravity is free to propagate through
n flat, compactified extra dimensions, while the fields of the Standard Model are confined to a
dimensional brane. We calculate the production and decay rates of the states that make up
Kaluza-Klein graviton tower and determine the evolution of their abundances in the early unive
We then go on to evaluate the impact of these decays on the resulting light element abundan
We identify significant regions of previously unexplored parameter space that are inconsistent w
rimordial helium and deuterium abundances. In particular, we find that
limension (two extra dimensions), the fundamental scale of gravity must
$\gtrsim 10^{10}$ GeV) unless the temperature of the early universe was never grea

2407.07529

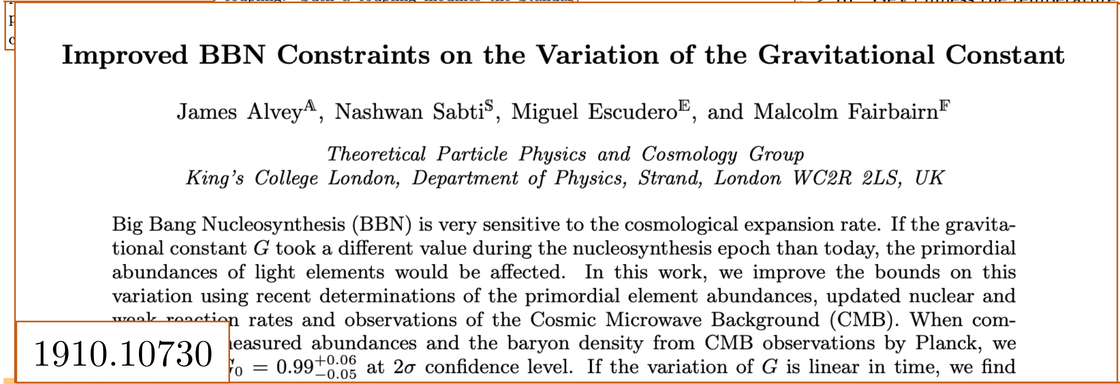


BBN constraints on MeV-scale dark sectors.
Part I. Sterile decays

Marco Hufnagel, Kai Schmidt-Hoberg and Sebastian Wild
DESY, Notkestraße 85, D-22607 Hamburg, Germany
E-mail: `marco.hufnagel@desy.de`, `kai.schmidt-hoberg@desy.de`, `sebastian.wild@desy.de`

ABSTRACT: We study constraints from Big Bang Nucleosynthesis on inert particles in a dark sector which contribute to the Hubble rate and therefore change the predictions of the primordial nuclear abundances. We pay special attention to the case of MeV-scale particles decaying into dark radiation, which are neither fully relativistic nor non-relativistic during all temperatures relevant to Big Bang Nucleosynthesis. A
implications of our general results for models of self-inte
mediators.

1712.03972
1808.09324



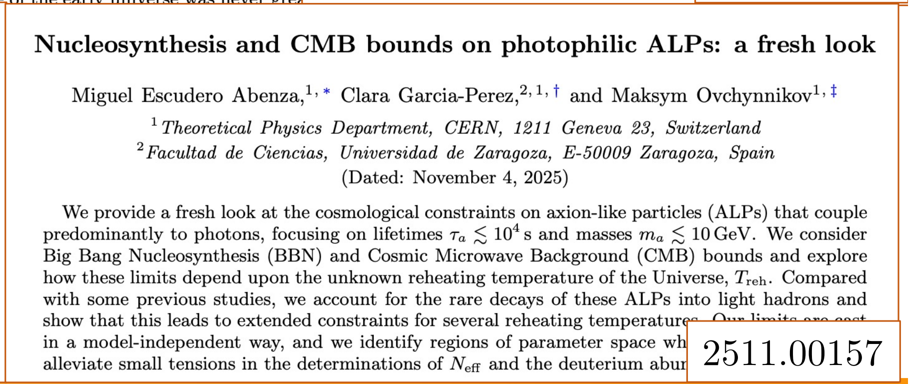
Improved BBN Constraints on the Variation of the Gravitational Constant

James Alvey[𝔸], Nashwan Sabti[𝕊], Miguel Escudero[𝔼], and Malcolm Fairbairn[𝔽]

Theoretical Particle Physics and Cosmology Group
King's College London, Department of Physics, Strand, London WC2R 2LS, UK

Big Bang Nucleosynthesis (BBN) is very sensitive to the cosmological expansion rate. If the gravitational constant G took a different value during the nucleosynthesis epoch than today, the primordial abundances of light elements would be affected. In this work, we improve the bounds on this variation using recent determinations of the primordial element abundances, updated nuclear and
n rates and observations of the Cosmic Microwave Background (CMB). When com-
easured abundances and the baryon density from CMB observations by Planck, we
$_0 = 0.99^{+0.06}_{-0.05}$ at 2σ confidence level. If the variation of G is linear in time, we find

1910.10730



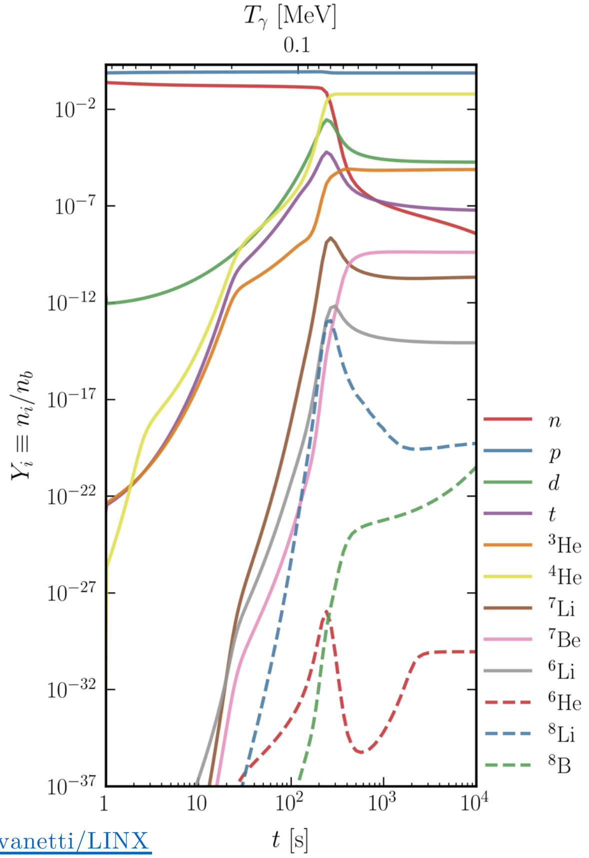
Nucleosynthesis and CMB bounds on photophilic ALPs: a fresh look

Miguel Escudero Abenza,[1,*] Clara Garcia-Perez,[2,1,†] and Maksym Ovchynnikov[1,‡]
[1] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
[2] *Facultad de Ciencias, Universidad de Zaragoza, E-50009 Zaragoza, Spain*
(Dated: November 4, 2025)

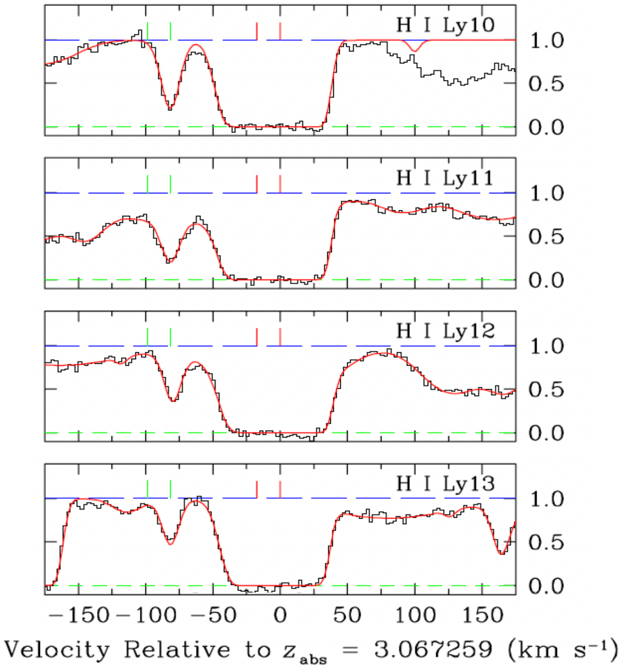
We provide a fresh look at the cosmological constraints on axion-like particles (ALPs) that couple predominantly to photons, focusing on lifetimes $\tau_a \lesssim 10^4$ s and masses $m_a \lesssim 10$ GeV. We consider Big Bang Nucleosynthesis (BBN) and Cosmic Microwave Background (CMB) bounds and explore how these limits depend upon the unknown reheating temperature of the Universe, $T_{\rm reh}$. Compared with some previous studies, we account for the rare decays of these ALPs into light hadrons and show that this leads to extended constraints for several reheating temperature
in a model-independent way, and we identify regions of parameter space wh
alleviate small tensions in the determinations of $N_{\rm eff}$ and the deuterium abur

2511.00157

Prediction meets measurement

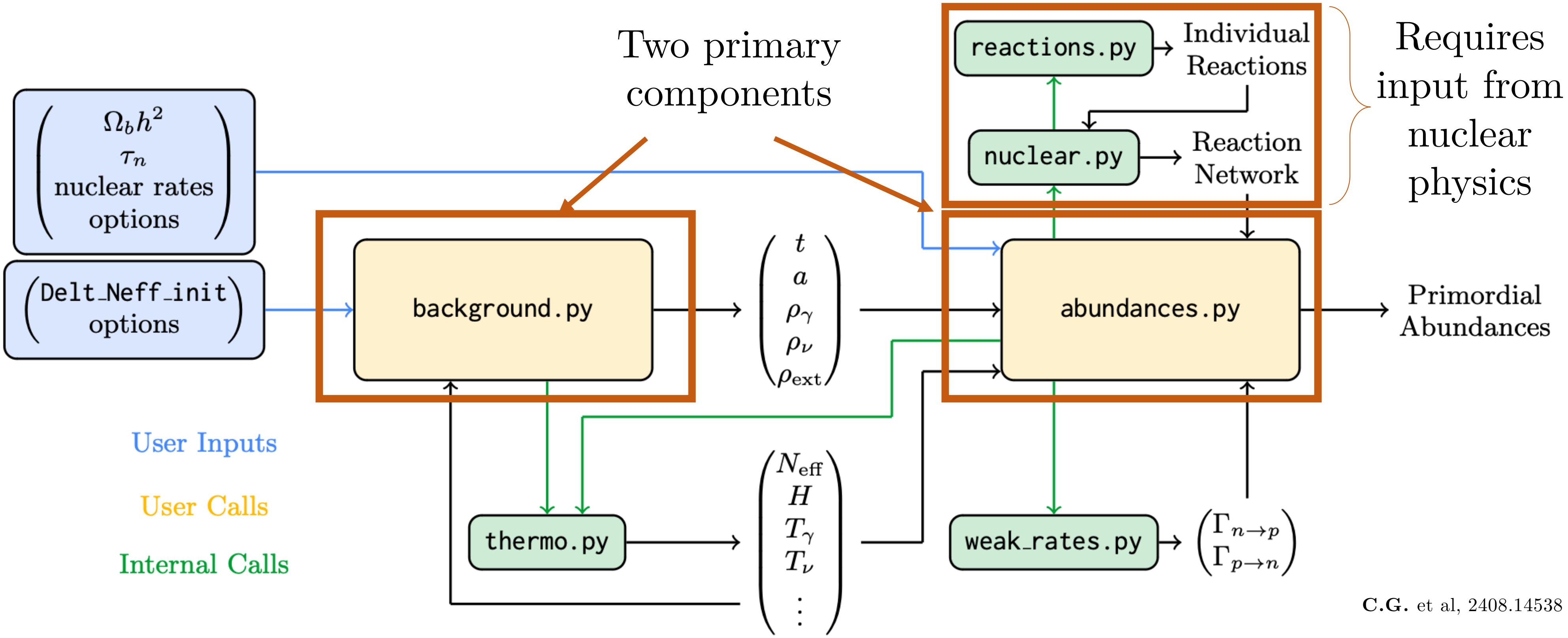


https://github.com/cgiovanetti/LINX



R. Cooke et al., 1308.3240

Where does a BBN prediction come from?



Two primary components

Requires input from nuclear physics

$\begin{pmatrix} \Omega_b h^2 \\ \tau_n \\ \text{nuclear rates} \\ \text{options} \end{pmatrix}$

$\begin{pmatrix} \texttt{Delt\_Neff\_init} \\ \text{options} \end{pmatrix}$

`background.py`

$\begin{pmatrix} t \\ a \\ \rho_\gamma \\ \rho_\nu \\ \rho_{\text{ext}} \end{pmatrix}$

`thermo.py`

$\begin{pmatrix} N_{\text{eff}} \\ H \\ T_\gamma \\ T_\nu \\ \vdots \end{pmatrix}$

`reactions.py` → Individual Reactions

`nuclear.py` → Reaction Network

`abundances.py` → Primordial Abundances

`weak_rates.py` → $\begin{pmatrix} \Gamma_{n \to p} \\ \Gamma_{p \to n} \end{pmatrix}$

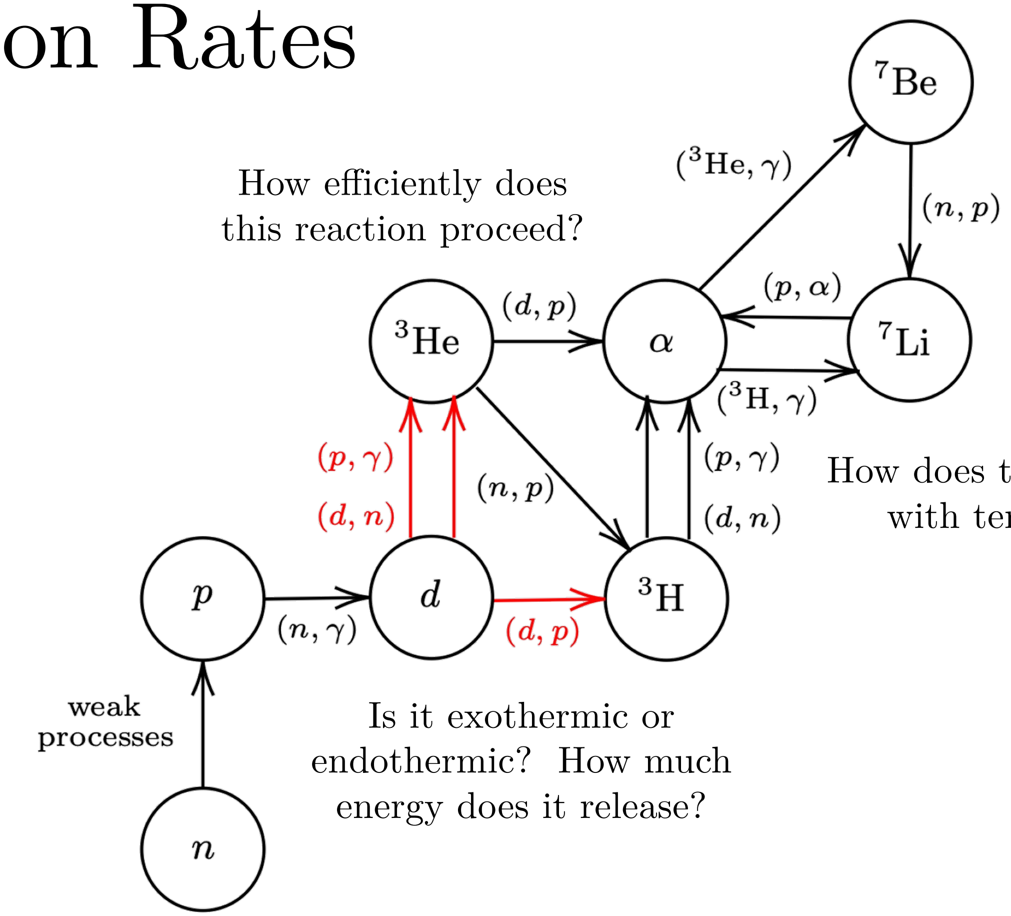
User Inputs

User Calls

Internal Calls

C.G. et al, 2408.14538

Reaction Rates



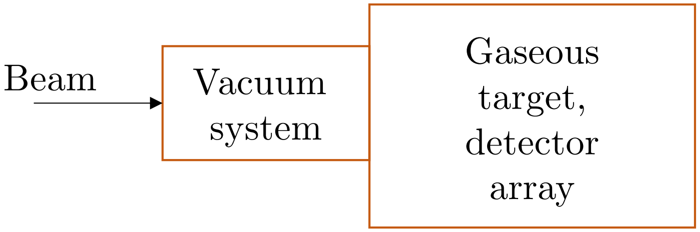
How efficiently does this reaction proceed?

How does the rate change with temperature?

Is it exothermic or endothermic? How much energy does it release?

How are nuclear rates measured?

Windowless gas targets



Beam

Vacuum system

Gaseous target, detector array

Requires complicated system of vacuum pumps

Large uncertainty from gas density nonuniformity

Solid targets

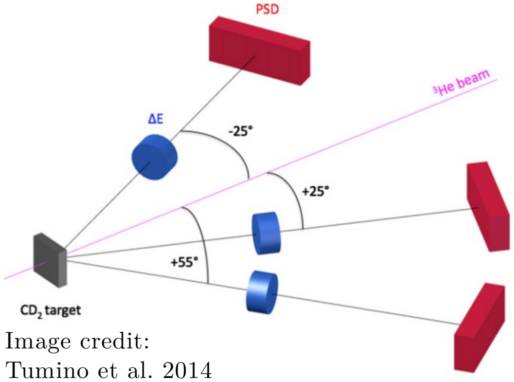
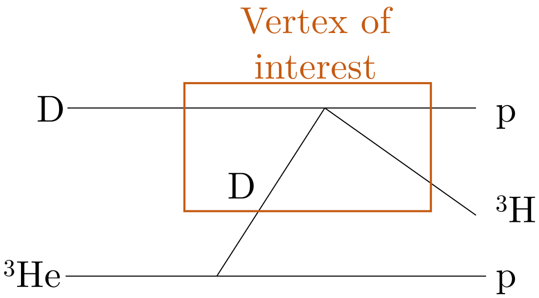


Image credit:
Tumino et al. 2014

Targets chip as experiment runs

Trojan Horse



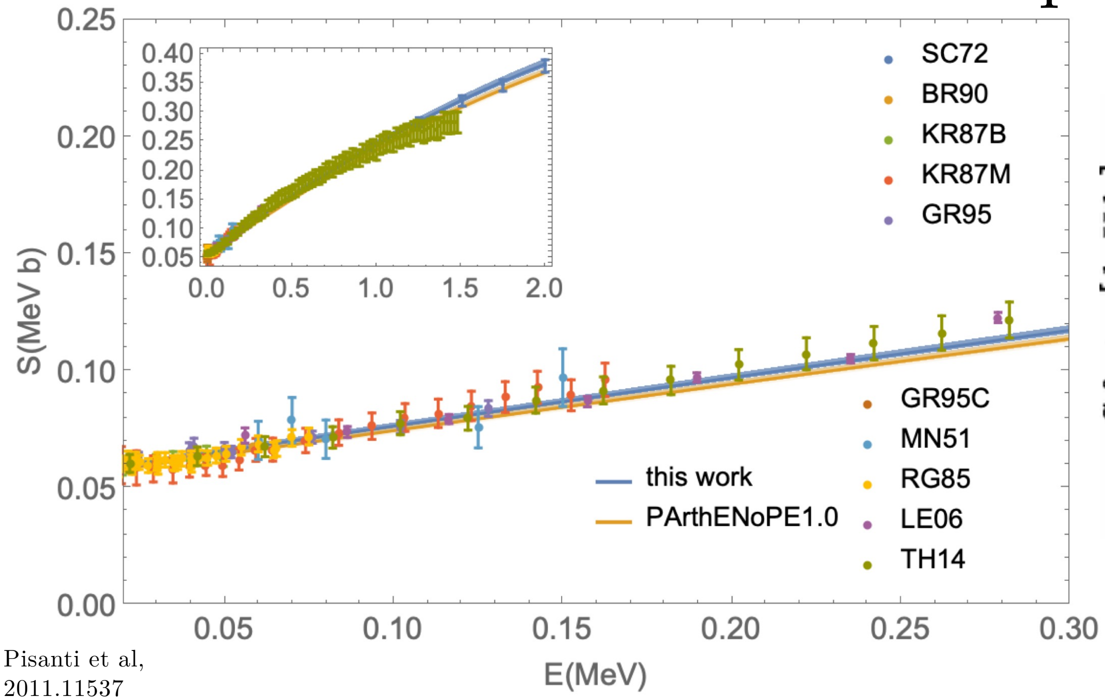
Tumino et al. 2014

Avoids electron screening

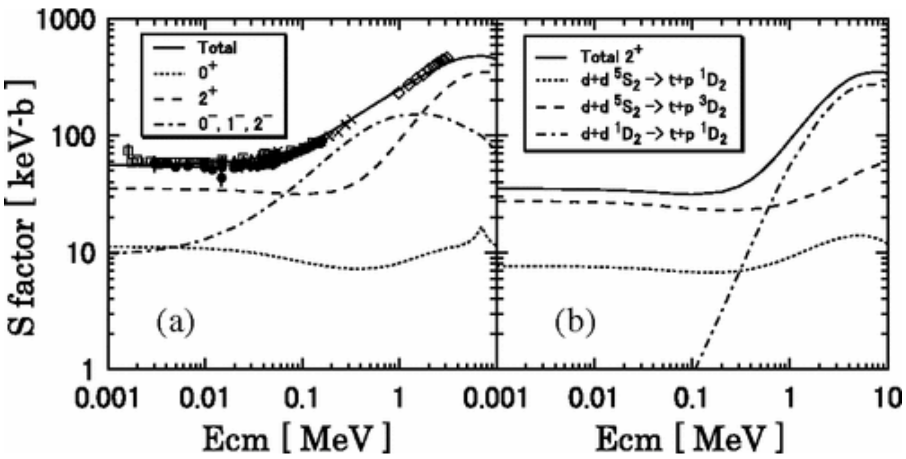
Impossible to know overall normalization

How are nuclear rates measured?

$d + d \rightarrow p + {}^{3}\mathrm{H}$



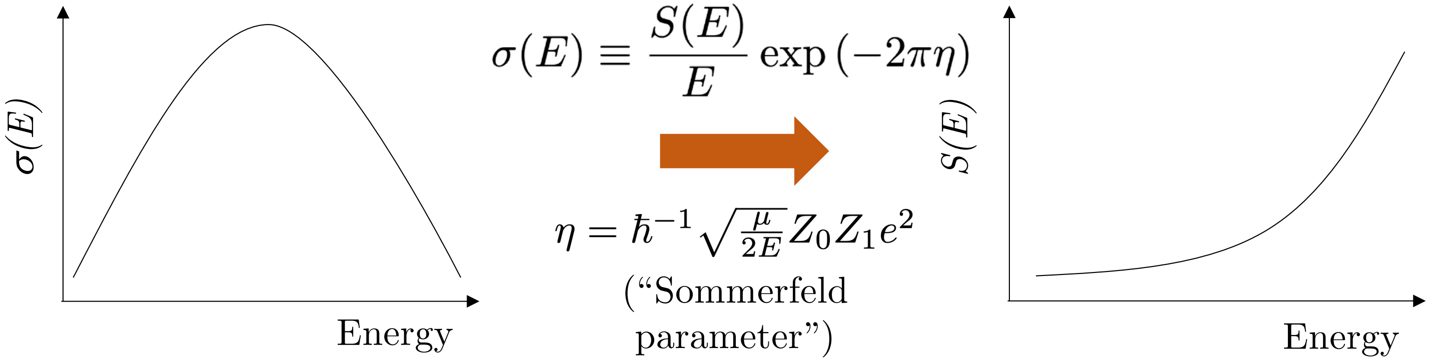
Pisanti et al,
2011.11537



Arai et al, PRL,
2011

What is *S(E)*?

- Cross sections have strong energy-dependence



$$\sigma(E) \equiv \frac{S(E)}{E} \exp\left(-2\pi\eta\right)$$

$$\eta = \hbar^{-1}\sqrt{\frac{\mu}{2E}}Z_0 Z_1 e^2$$

("Sommerfeld parameter")

- Work back to get rate $N_A\langle\sigma v\rangle = N_A\int_0^\infty \sigma(v)\phi_{\mathrm{MB}}(v)v dv$

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- BBN Overview
- Previous determinations of the primordial deuterium abundance
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Two teams, two deuterium predictions

PArthENoPE

Pisanti et al. 0705.0290
Consiglio et al. 1712.04378

FORTRAN77 code with GUI originally released in 2008, updated 2018 and regularly since then

Used by the Planck team

D/H x 10^5 : 2.51 ± 0.04*

PRIMAT

Pitrou et al. 1801.08023

Mathematica code originally released 2018

Improved ^{4}He predictions from updated weak rate calculations, large reaction network

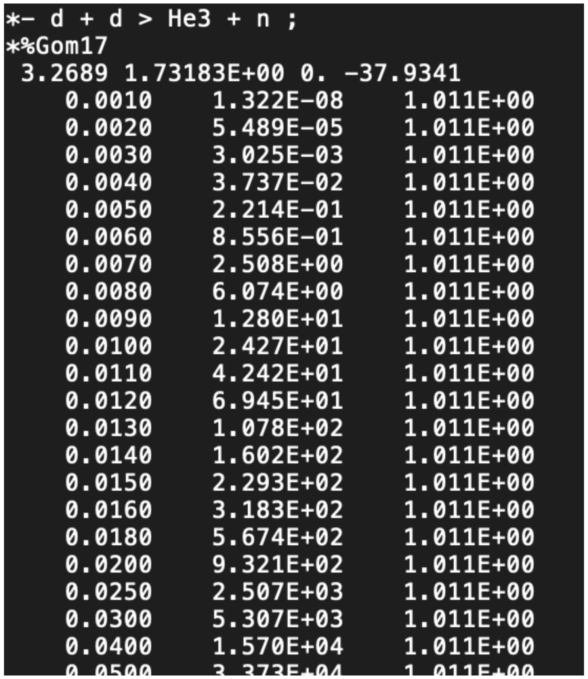
D/H x 10^5: 2.44 ± 0.04*

*assuming $\Omega_b h^2 = .02237 \pm .00015$

Reaction network

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

- d + d → ^{3}He + n and d + d → t + p rates **differ** between PRIMAT and PArthENoPE



```
*- d + d > He3 + n ;
*%Gom17
 3.2689 1.73183E+00 0. -37.9341
    0.0010     1.322E-08     1.011E+00
    0.0020     5.489E-05     1.011E+00
    0.0030     3.025E-03     1.011E+00
    0.0040     3.737E-02     1.011E+00
    0.0050     2.214E-01     1.011E+00
    0.0060     8.556E-01     1.011E+00
    0.0070     2.508E+00     1.011E+00
    0.0080     6.074E+00     1.011E+00
    0.0090     1.280E+01     1.011E+00
    0.0100     2.427E+01     1.011E+00
    0.0110     4.242E+01     1.011E+00
    0.0120     6.945E+01     1.011E+00
    0.0130     1.078E+02     1.011E+00
    0.0140     1.602E+02     1.011E+00
    0.0150     2.293E+02     1.011E+00
    0.0160     3.183E+02     1.011E+00
    0.0180     5.674E+02     1.011E+00
    0.0200     9.321E+02     1.011E+00
    0.0250     2.507E+03     1.011E+00
    0.0300     5.307E+03     1.011E+00
    0.0400     1.570E+04     1.011E+00
    0.0500     3.373E+04     1.011E+00
```

Temperature Rate Uncertainty

Two teams, two deuterium predictions

PArthENoPE

Uses phenomenological (polynomial) fits

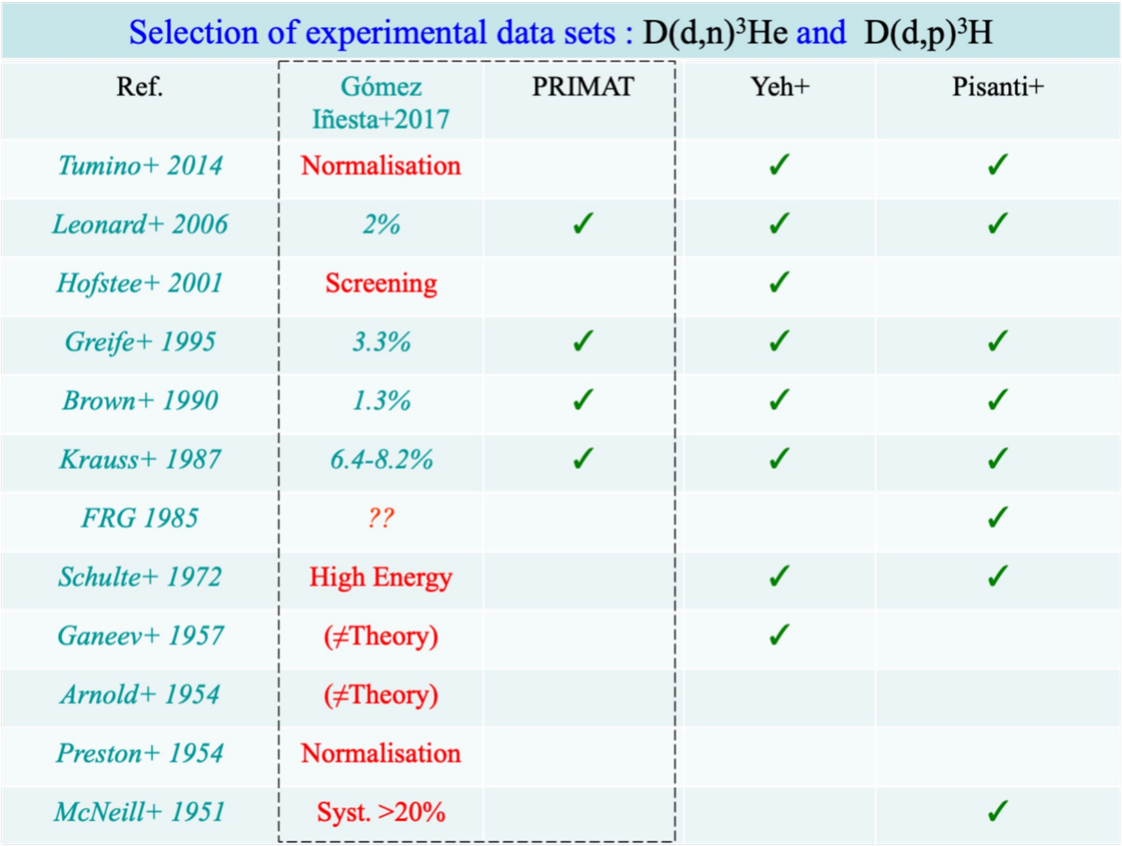
Agrees with the Standard Model

PRIMAT

Uses theory curve for fits

Produces deuterium tension

Dataset selection



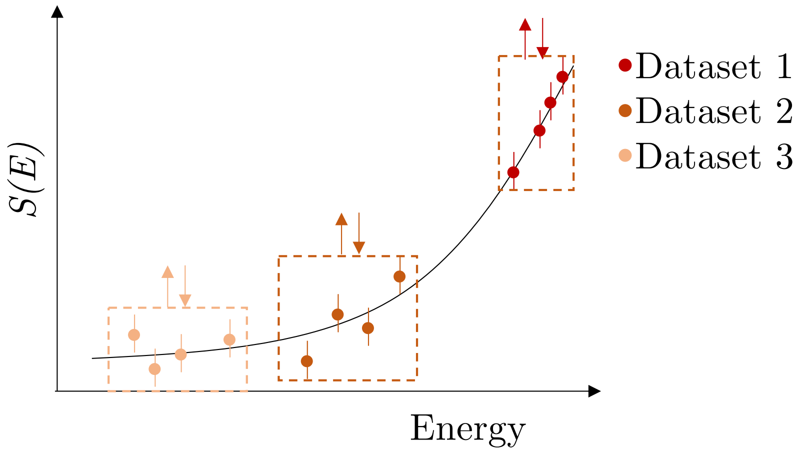
Selection of experimental data sets : D(d,n)^{3}He and D(d,p)^{3}H

Ref.	Gómez Iñesta+2017	PRIMAT	Yeh+	Pisanti+
Tumino+ 2014	Normalisation		✓	✓
Leonard+ 2006	*2%*	✓	✓	✓
Hofstee+ 2001	Screening		✓	
Greife+ 1995	*3.3%*	✓	✓	✓
Brown+ 1990	*1.3%*	✓	✓	✓
Krauss+ 1987	*6.4-8.2%*	✓	✓	✓
FRG 1985	*??*			✓
Schulte+ 1972	High Energy		✓	✓
Ganeev+ 1957	(≠Theory)		✓	
Arnold+ 1954	(≠Theory)			
Preston+ 1954	Normalisation			
McNeill+ 1951	Syst. >20%			✓

Alain Coc, *The BBN nuclear reaction network (D and ^{7}Li)*. News, Opportunities and Challenges in Big Bang Nucleosynthesis (EuCAPT Workshop), 2025.

PArthENoPE: Phenomenological Fits

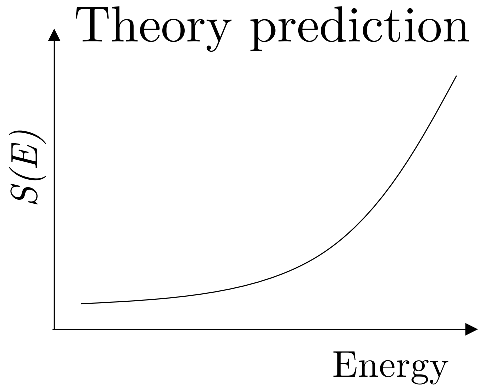
- Follow the data
- Degree 2-4 polynomial, float dataset normalizations in χ^2 minimization

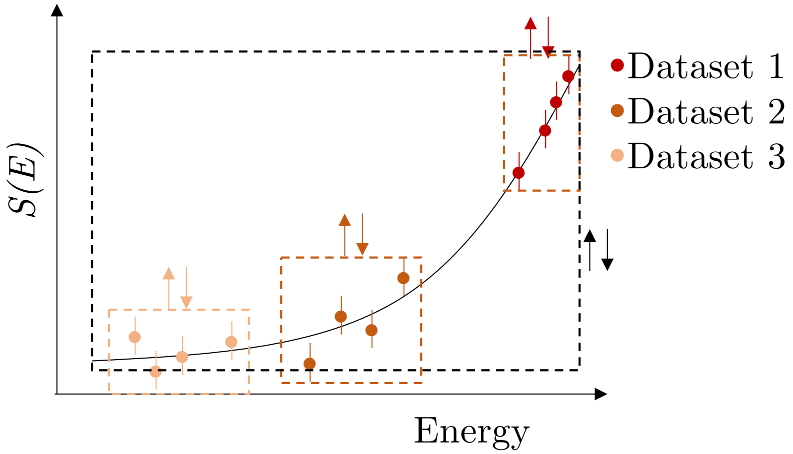


Total number of parameters:
3 (data normalization) + degree of polynomial

PRIMAT: Theory-informed fits

- Use what you know
- Nuclear theory uncertainties are not known, ***only available up to 0.6 MeV***
- Float theory and data normalization





Total number of parameters:
3 (data normalization) +
1 (theory normalization)

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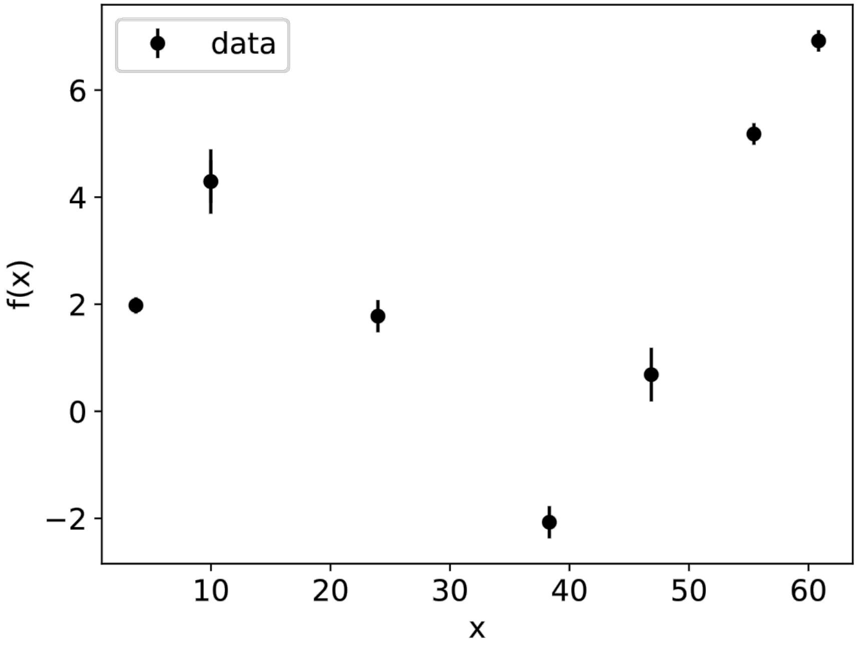
Gaussian Processes

- Using Gaussian Process Regression to fit data

- Treats your data as if it comes from some highly multivariate Gaussian

- Kernel parameters indicate correlations between data points to constrain the problem

Gaussian Processes



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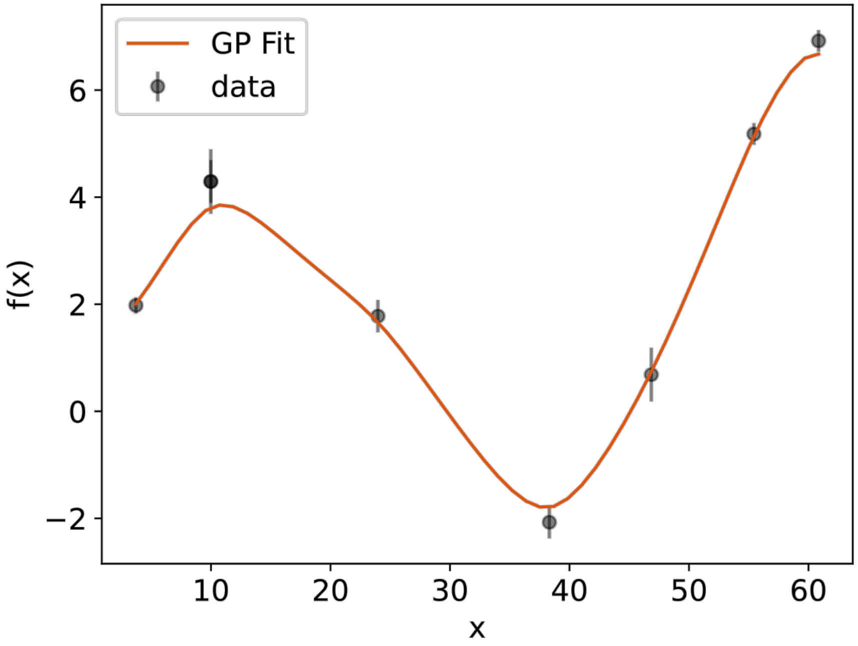

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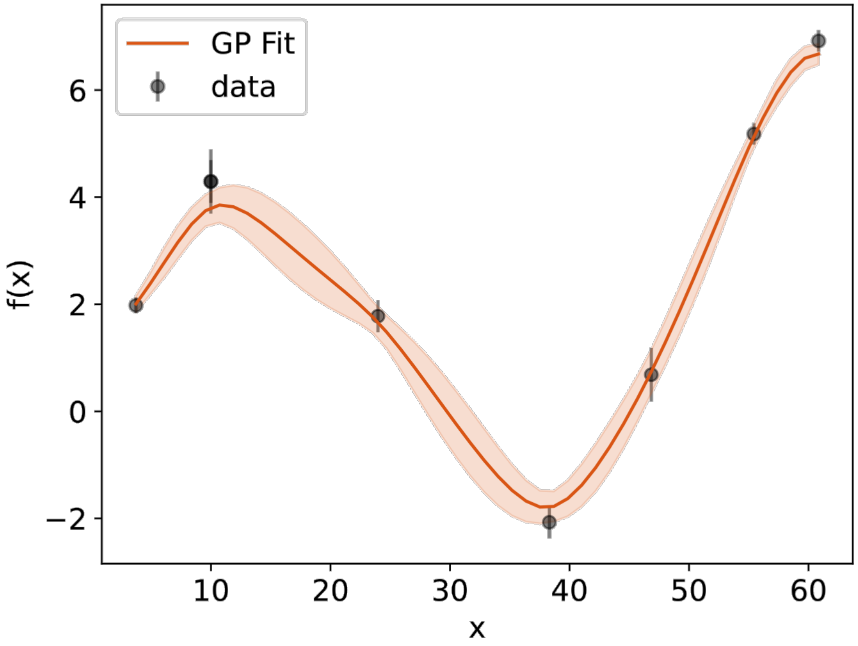

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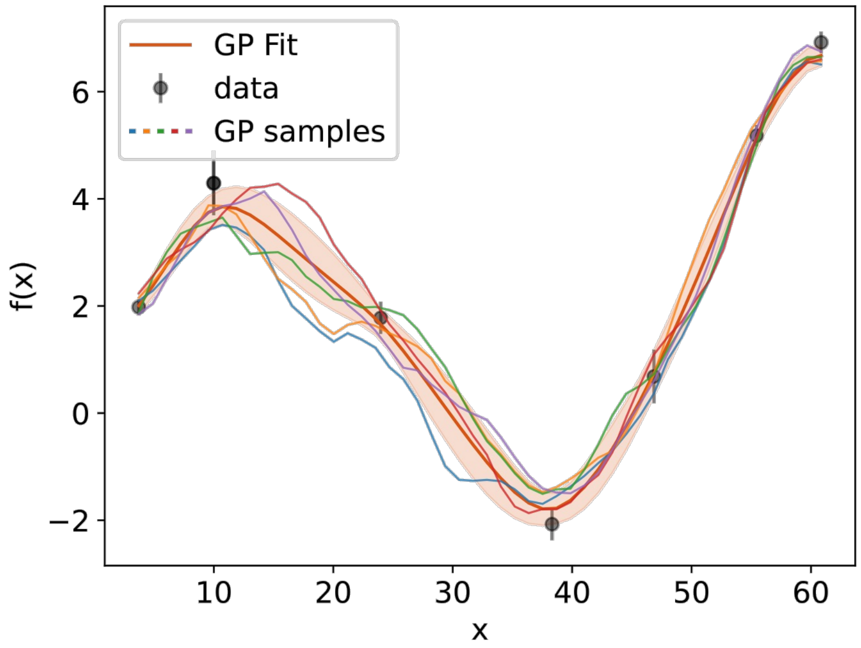


Gaussian Processes: The Weeds

Real data points

Real data abscissae

$$\begin{bmatrix} y \\ y_* \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mu \\ \mu_* \end{bmatrix}, \begin{bmatrix} K(X,X)+\sigma & K(X,X_*) \\ K(X_*,X) & K(X_*,X_*) \end{bmatrix}\right)$$

Interpolated points

Target abscissae

$$y_* | X, y, X_* \sim \mathcal{N}(\mu_*, \Sigma_*)$$

$$\mu_* = K(X_*, X)(K(X,X) + \sigma^2 I)^{-1} y$$

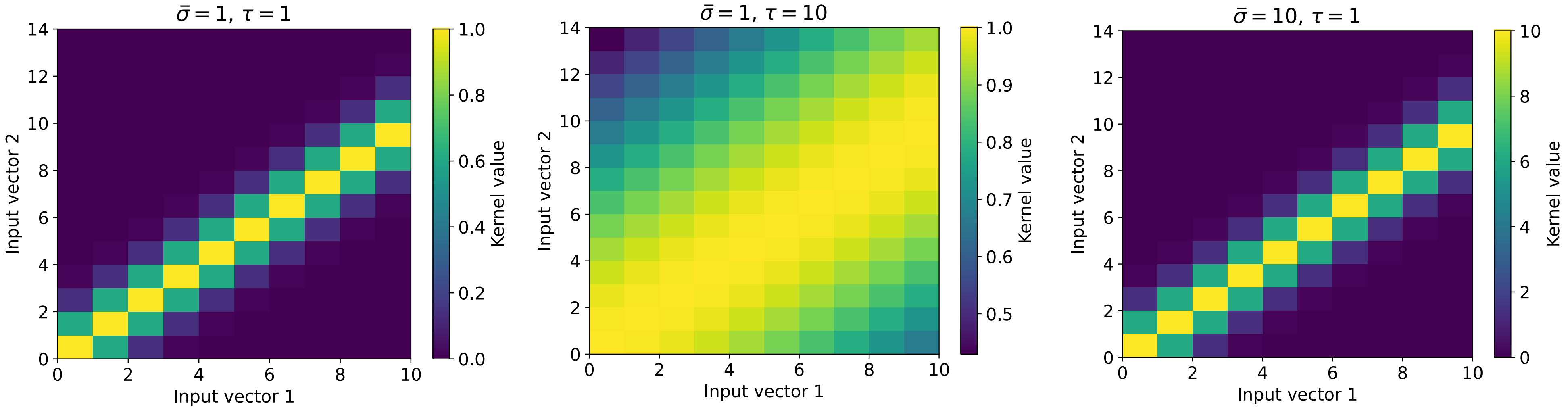
Kernel (“If I know $f(x_1)$, what do I know about $f(x_2)$?”)

Kernel parameters

Kernel amplitude

Distant points are less related

- Consider a kernel $K(X_*, X) = \bar{\sigma} e^{-(X_* - X)^2/(2\tau^2)}$



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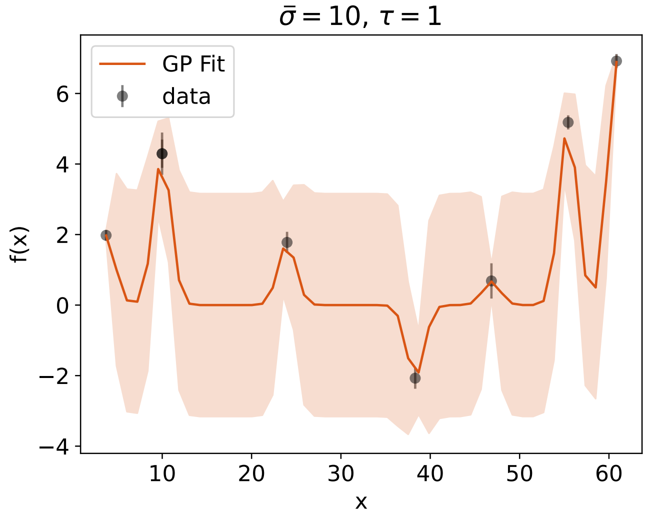

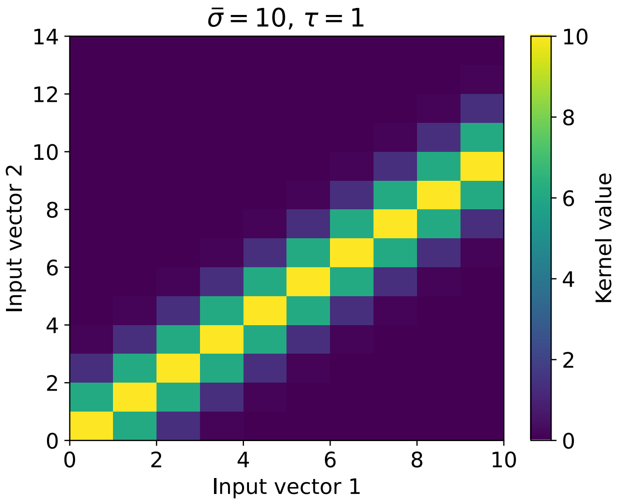

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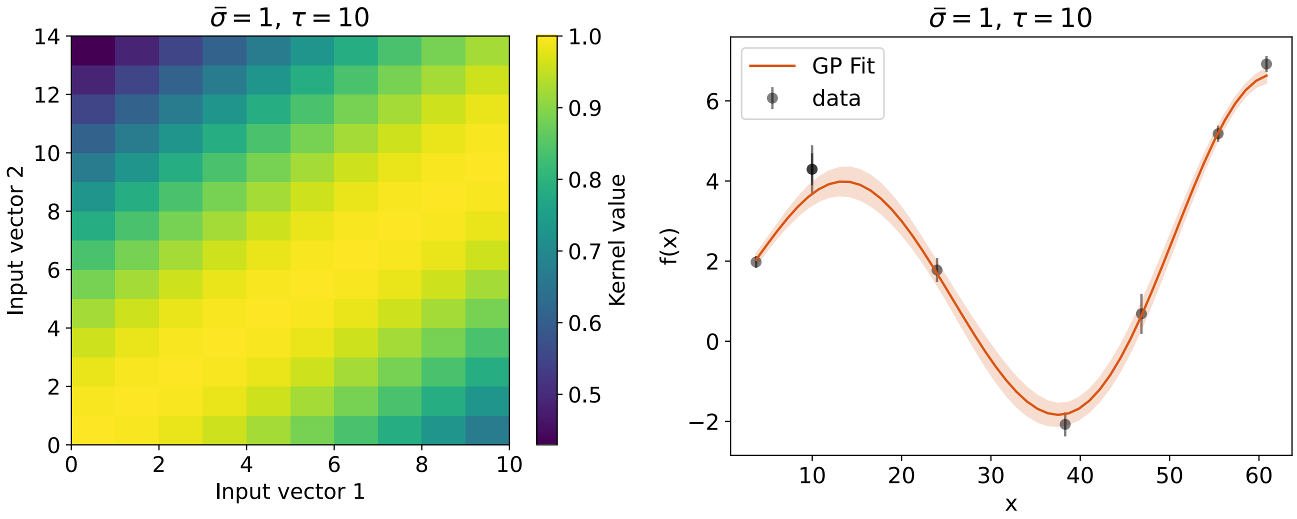


$$\mu_* = K(X_*, X)(K(X, X) + \sigma^2 I)^{-1} y$$

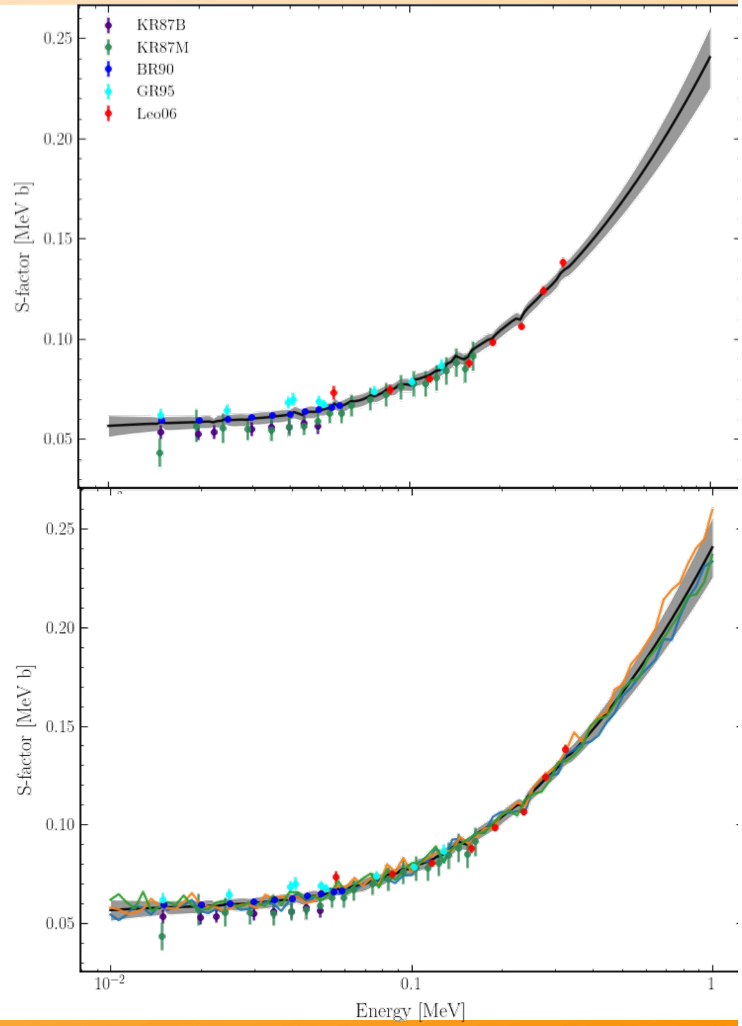
Kernel (“If I know $f(x_1)$, what do I know about $f(x_2)$?”)

A deuterium prediction from a GP

- Fit a GP to key deuterium rates
  - d(d,p)^{3}H, d(d,n)^{3}He, and d(p,γ)^{3}He

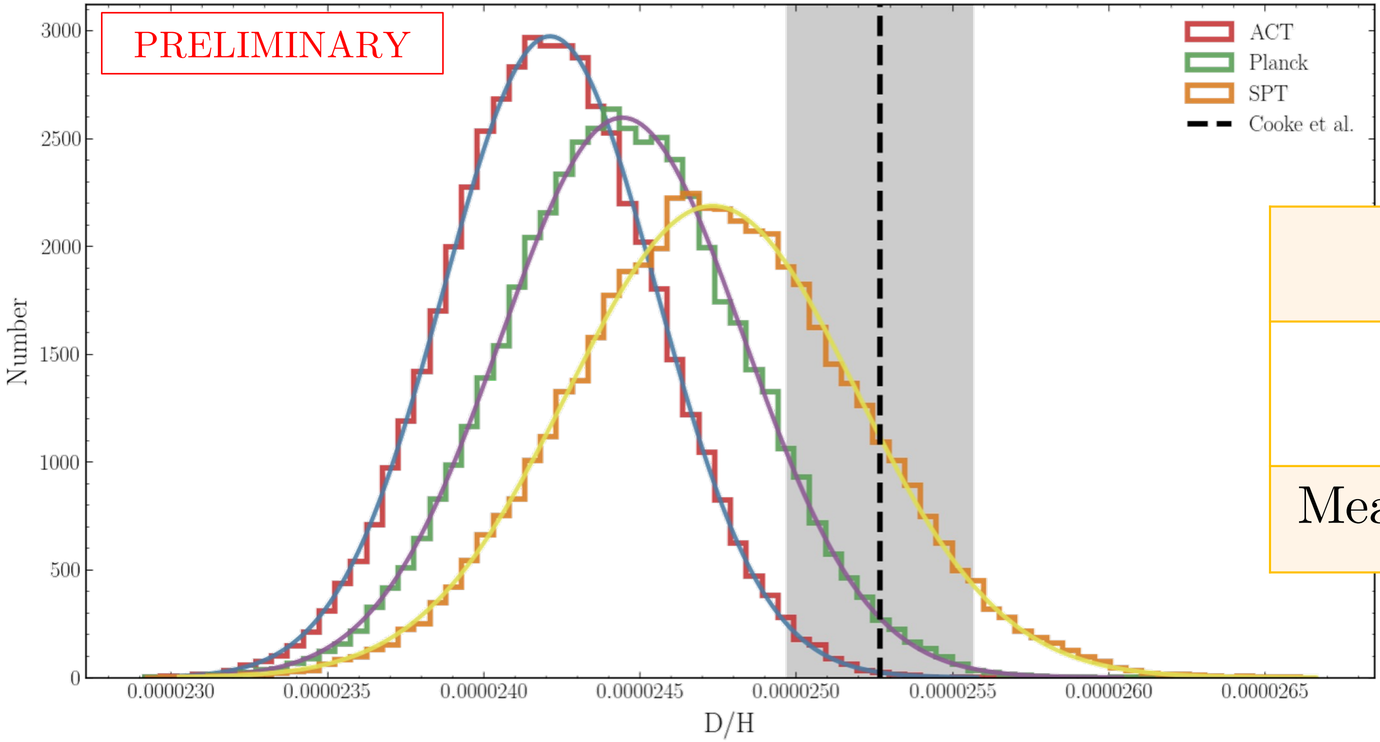
- Sample rate uncertainties by sampling GP posterior

- Draw ~10,000 times to infer D/H



Results

Tim Launders,
BU



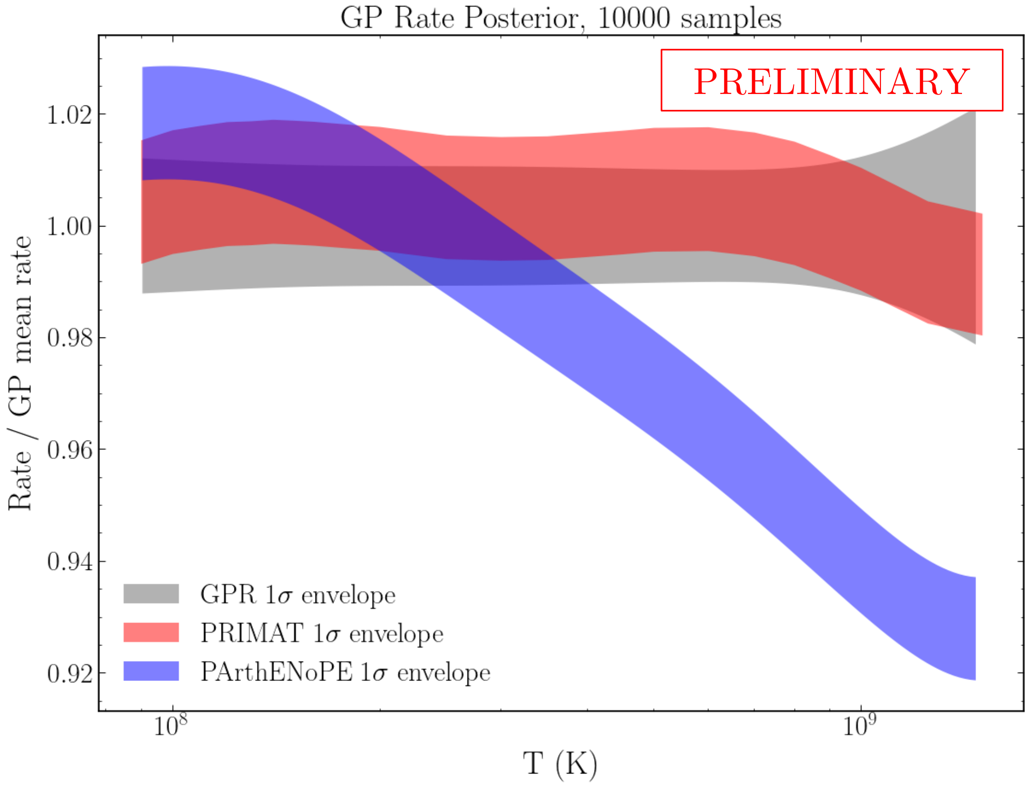
Planck TT,TE,EE+lowE+lensing
$\Omega_b h^2$=0.02237 ± .00015

	D/H x 10^5
GP	2.45 ± 0.04 PRELIMINARY
Measurement	2.53 ± 0.03 Cooke et al., 1710.11129

Results

Tim Launders,
BU

$d + d \rightarrow p + {}^3H$



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	D/H x 10^5
PArthENoPE	2.51 ± 0.04
PRIMAT	2.44 ± 0.04
GP	2.45 ± 0.04 PRELIMINARY
Measurement	2.53 ± 0.03 Cooke et al., 1710.11129

Gaussian Process result agrees with less-flexible, theory-informed fit.

	D/H x 10^5
PArthENoPE	2.54 ± 0.04
PRIMAT	2.44 ± 0.04
GP	2.45 ± 0.04 PRELIMINARY
Measurement	2.53 ± 0.03

Why?

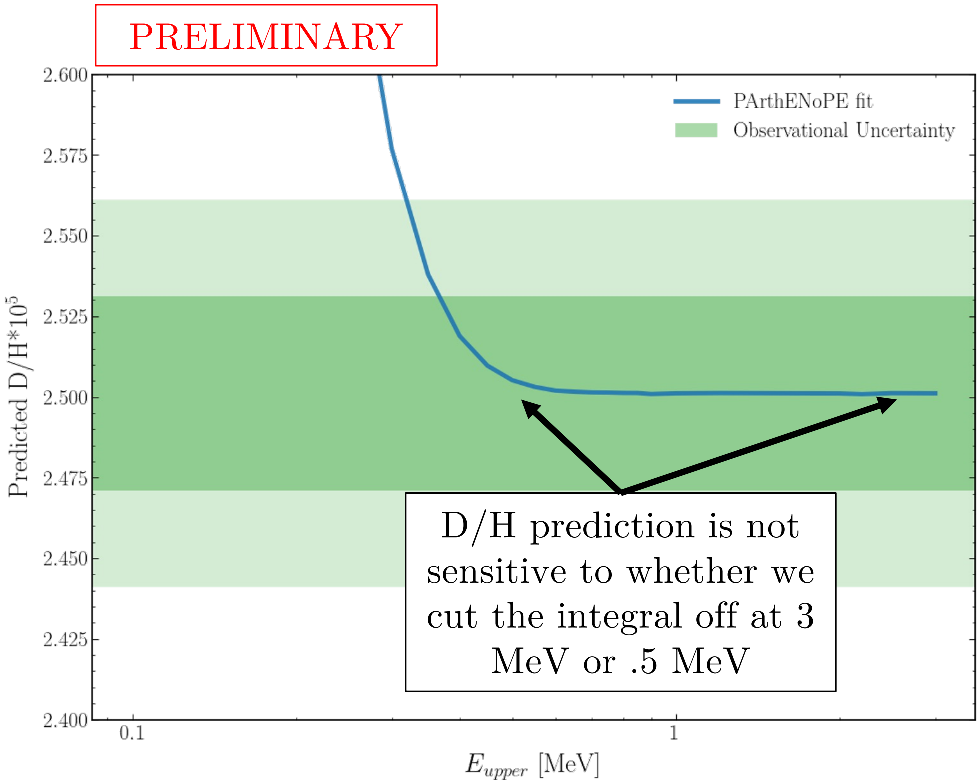
Problems with a low-degree polynomial

- High-energy systematics
- Shape is just not flexible enough
- Frequentist analysis: care needed to define penalized likelihood

Systematics

- $S(E)$ is not a rate. The rate is $N_A \langle \sigma v \rangle = N_A \int_0^\infty \sigma(v) \phi_{\mathrm{MB}}(v) v dv$
- Involves a thermal average
- On paper, that thermal average should extend up to infinity

Systematics



D/H prediction is not sensitive to whether we cut the integral off at 3 MeV or .5 MeV

$$N_A\langle\sigma v\rangle = N_A\int_0^{\infty}\sigma(v)\phi_{\mathrm{MB}}(v)v\,dv$$

$$= N_A\int_0^{E\,=\,0.5\text{ MeV}}\sigma(v)\phi_{\mathrm{MB}}(v)v\,dv$$

empirically

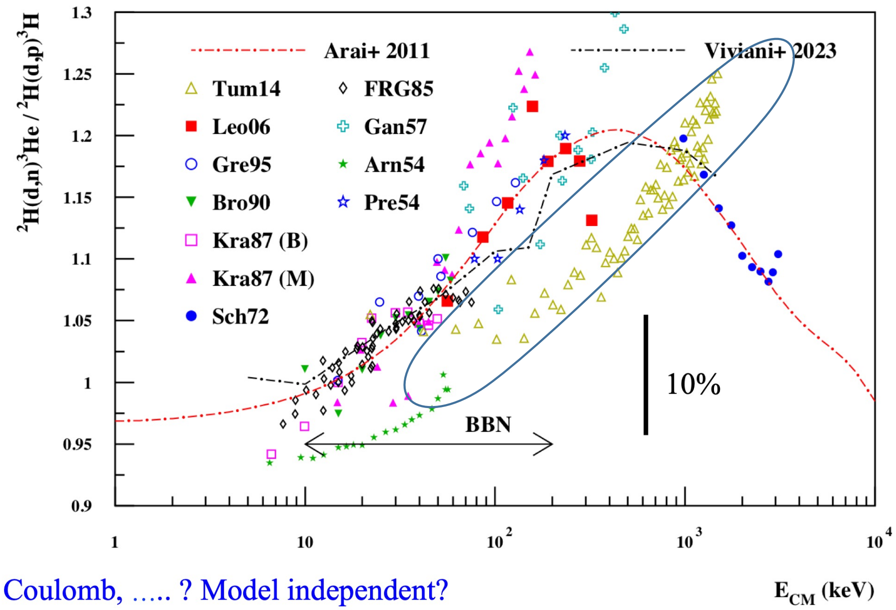
There is simply **no need for data above 0.5 MeV!**

The danger of high-energy data

Selection of experimental data sets : D(d,n)^{3}He and D(d,p)^{3}H

Ref.	Gómez Iñesta+2017	PRIMAT	Yeh+	Pisanti+
Tumino+ 2014	Normalisation		✓	✓
Leonard+ 2006	*2%*	✓	✓	✓
Hofstee+ 2001	Screening		✓	
Greife+ 1995	*3.3%*	✓	✓	✓
Brown+ 1990	*1.3%*	✓	✓	✓
Krauss+ 1987	*6.4-8.2%*	✓	✓	✓
FRG 1985	*??*			✓
Schulte+ 1972	High Energy		✓	✓
Ganeev+ 1957	(≠Theory)		✓	
Arnold+ 1954	(≠Theory)			
Preston+ 1954	Normalisation			
McNeill+ 1951	Syst. >20%			✓

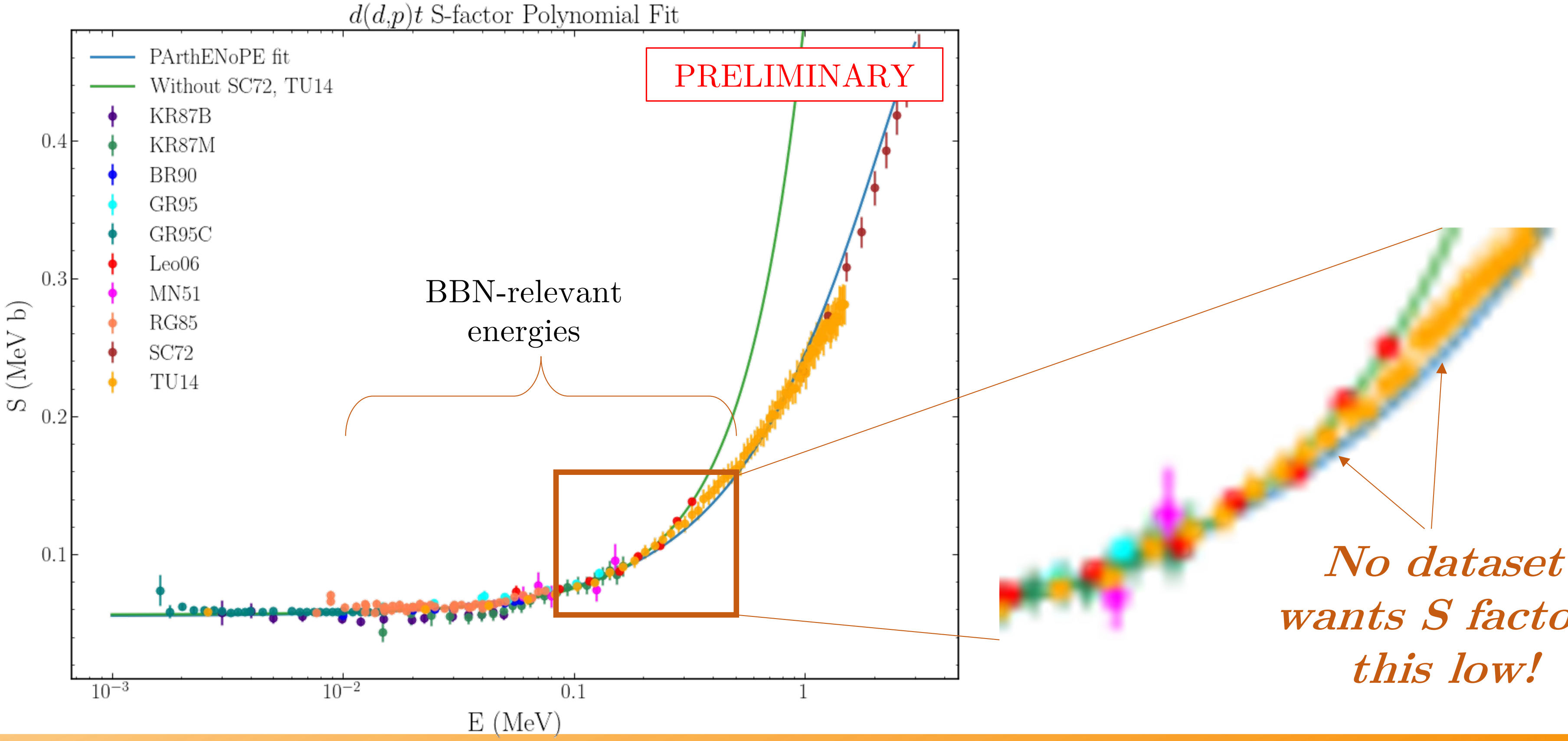
Ratio partially eliminates experimental and theoretical normalization concern



Coulomb, ….. ? Model independent?

Alain Coc, *The BBN nuclear reaction network (D and ^{7}Li)*. News, Opportunities and Challenges in Big Bang Nucleosynthesis (EuCAPT Workshop), 2025. See also 1511.03843

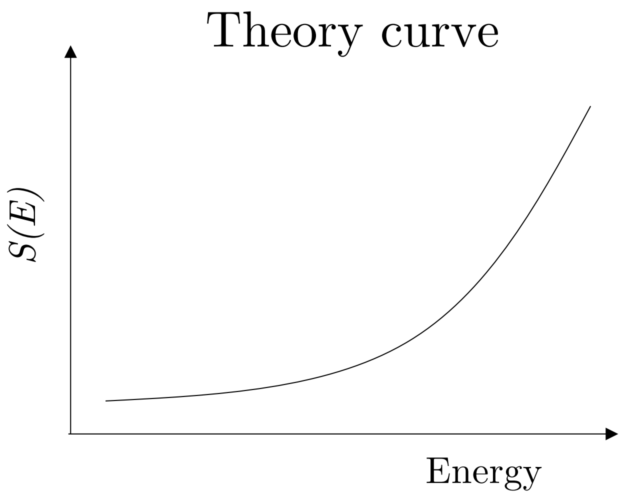
Exclude high-energy data...



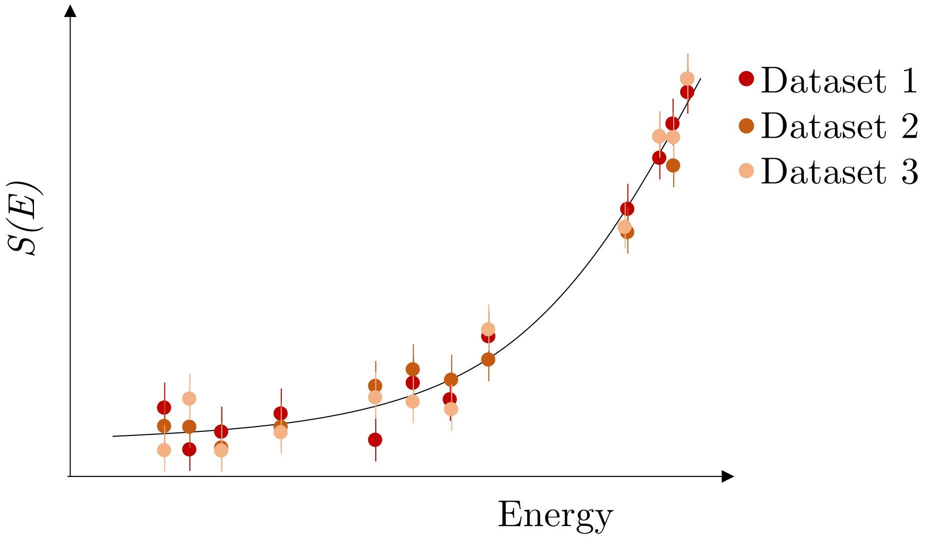
No dataset wants S factors this low!

Low-degree polynomials not flexible

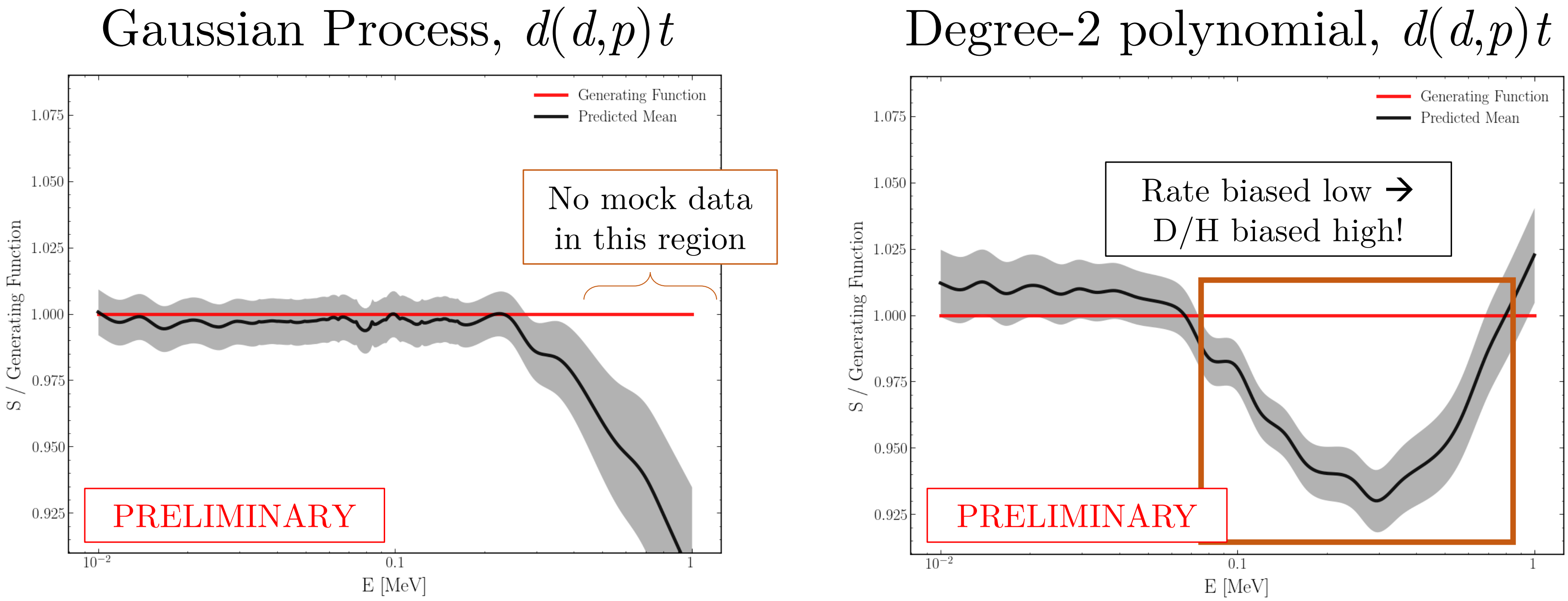
Arai et al.
2011



Theory curve



Low-degree polynomials not flexible



Gaussian Process, $d(d,p)t$

Degree-2 polynomial, $d(d,p)t$

No mock data in this region

Rate biased low → D/H biased high!

PRELIMINARY

PRELIMINARY

Arai et al. 2011 generating function

Is there a tension?

- Systematics and inflexible model ***preliminarily*** seem to explain why PArthENoPE disagrees with PRIMAT

- Gaussian Process was **not susceptible to these issues** because of increased fit flexibility

- All signs point to a ~2σ tension in deuterium

Should I care?

- Only two abundances are reliably measured (and one upper bound)

- D/H measurement is **statistics limited**
  - Plans to use 30m telescopes to find more systems and push error bars down Cooke and Pettini, "Precision Cosmology with the Lightest Elements", Gruber Cosmology Prize Symposium, 2025

- Nuclear physics experiment side: **need to make the case for new experiments**

Outline

- BBN Overview
- Previous determinations of the primordial deuterium abundance
- A new method
- New physics perspective

Particle interactions

- Nuclear physics—no new particles involved?

- Late-time photo/hadrodissociation of ^{3}He/^{4}He

e.g. Bianco et al., 2505.01492

- Photo/hadrodissociation of ^{4}He during BBN

Escudero Abenza, Garcia-Perez, Ovchynnikov, 2511.00157

Thermodynamics

- Increase N_{eff}
  - BBN ends sooner → no time for deuterium to be burned

- Increase neutrino temperature relative to photons
  - Increases N_{eff}

- Decrease baryon-to-photon ratio during BBN
  - BBN starts later, is shorter → less time for deuterium burning

Outlook

- **All signs point to a 2σ deuterium** ~~tension~~ **hint**

- New deuterium measurements, or even ^{3}He measurements, on the horizon, **could provide a clearer picture**

- **Exciting BSM solutions**—neutrino portals, decaying axions, etc. e.g. **C.G.**, M. Schmaltz, N. Weiner, 2402.10264

Backup Slides

Gaussian Processes: The Weeds

$$\begin{bmatrix} y \\ y_* \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mu \\ \mu_* \end{bmatrix}, \begin{bmatrix} K(X,X)+\sigma & K(X,X_*) \\ K(X_*,X) & K(X_*,X_*) \end{bmatrix} \right)$$

$$y_* \big|_{X,y,X_*} \sim \mathcal{N}(\mu_*, \Sigma_*)$$

Interpolated points

$$\mu_* = K(X_*,X)(K(X,X)+\sigma^2 I)^{-1} y$$

Kernel (“If I know *f(x_1)*, what do I know about *f(x_2)*?”)

$$\Sigma_* = K(X_*,X_*) - K(X_*,X)(K(X,X)+\sigma^2 I)^{-1} K(X,X_*)$$

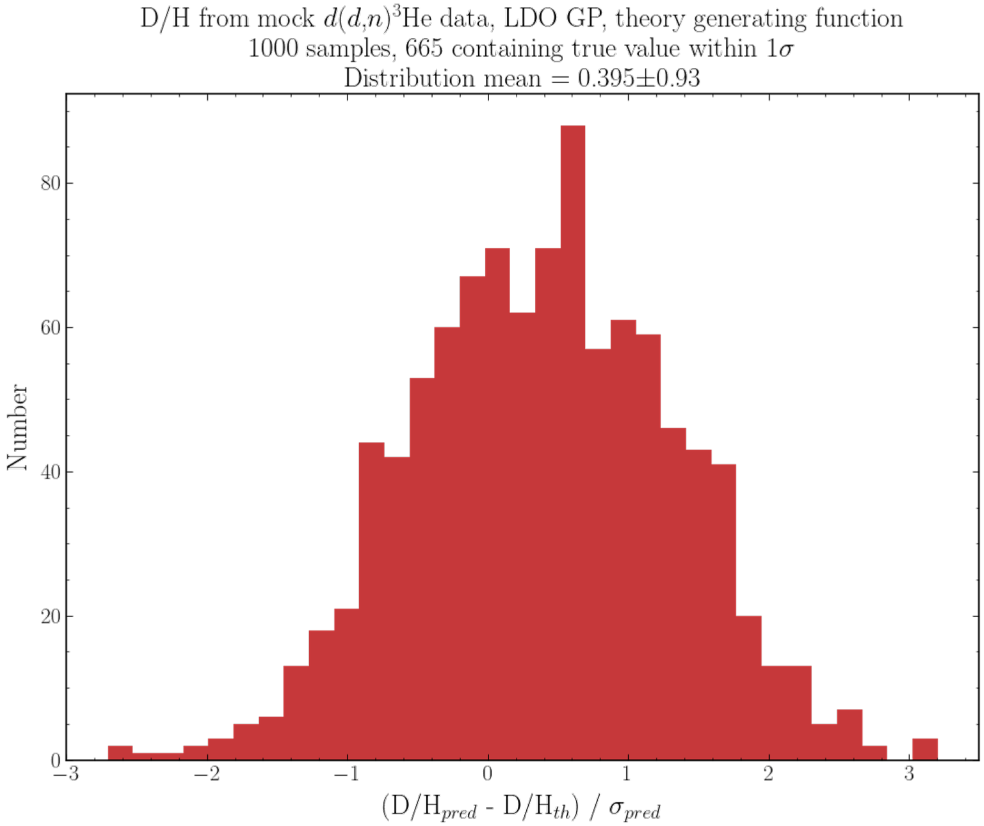
Highly Correlated Gaussian Processes

Block covariance matrix
including systematic and
statistical uncertainties

$$\begin{bmatrix} y \\ y_* \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mu \\ \mu_* \end{bmatrix}, \begin{bmatrix} K(X,X) + C_{\text{full}} & K(X,X_*) \\ K(X_*,X) & K(X_*,X_*) \end{bmatrix} \right)$$

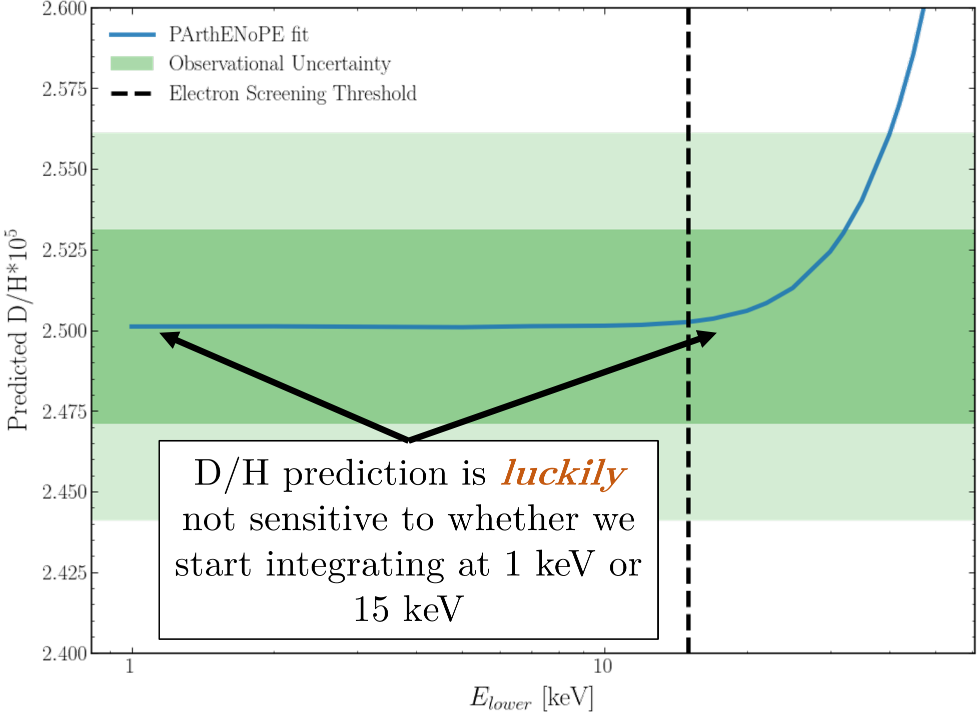
Kernel: Squared Exponential + Matérn for globally smooth function with small-scale fluctuations

Low-bias estimator



Screening and systematics

PRELIMINARY



D/H prediction is ***luckily*** not sensitive to whether we start integrating at 1 keV or 15 keV

$$N_A\langle\sigma v\rangle = N_A\int_0^\infty \sigma(v)\phi_{\mathrm{MB}}(v)vdv$$

$$= N_A\int_{E\,=\,15\text{ keV}}^{E\,=\,0.5\text{ MeV}} \sigma(v)\phi_{\mathrm{MB}}(v)vdv$$

empirically

There is fortunately **no need for data below 15 keV!**

See also Greife et al 1995, PRC

PArthENoPE Likelihood

- PArthENoPE analysis includes normalization errors as a penalty term in their parameter estimation

Penalty

S factor

Measured S factor

Normalization parameter

$$-2\log f(\boldsymbol{S}; a_0, \omega) - 2\log p(\omega) = \sum_i \frac{(S_i - a_0/\omega)^2}{\sigma^2} + \frac{(\omega - 1)^2}{\alpha\epsilon^2}$$

Likelihood

Statistical uncertainty

Systematic/normalization uncertainty

- This procedure estimates $\sigma_\omega^2 = \left(1 + \frac{N}{\sigma^2}\langle\mu\rangle^2 + \frac{1}{\alpha\epsilon^2}\right)^{-1}$ (N the number of data points

Mean S

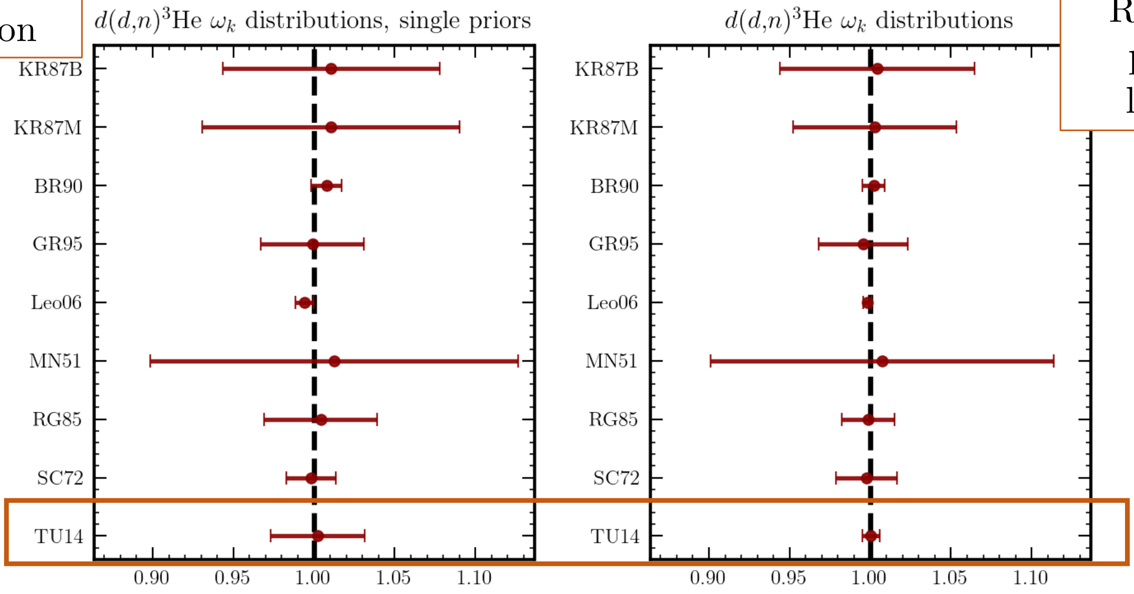
- When penalty ($\alpha\varepsilon^2$) is large, $\sigma_w \rightarrow \varepsilon/N << \varepsilon$ ($\alpha = 1/N$)

PArthENoPE Likelihood

- Normalization uncertainty you infer (ε/N)<< normalization uncertainty you expect (ε).

Expectation

Result with penalized likelihood

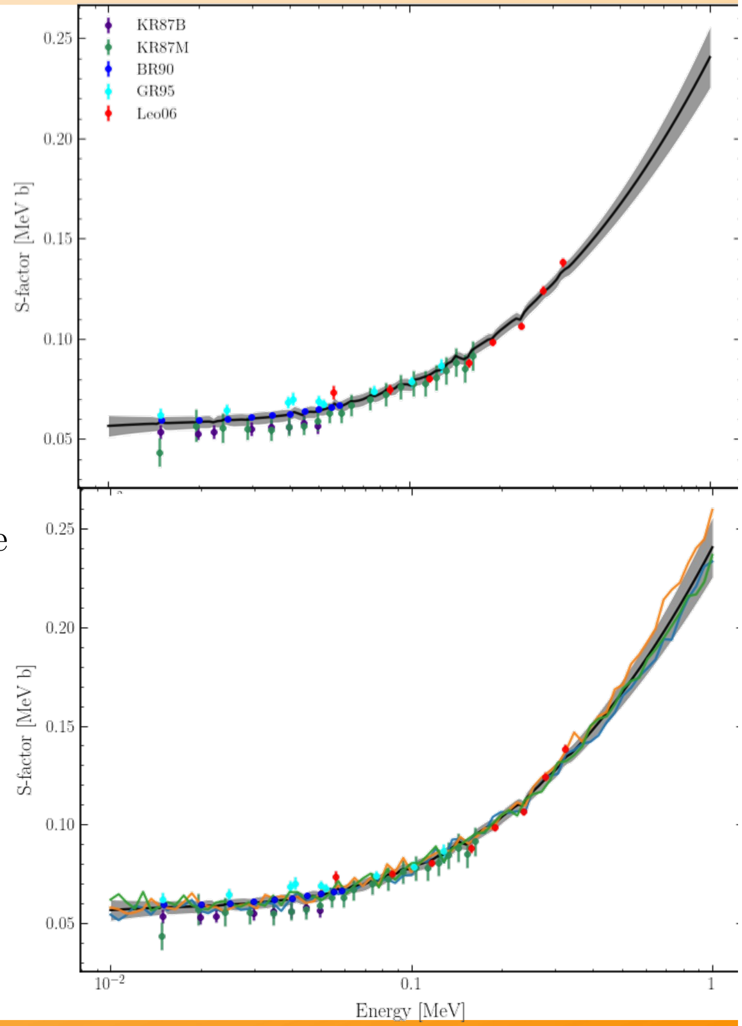


Most pronounced in datasets with many data points

- May lead to underestimation of S-factor error bars

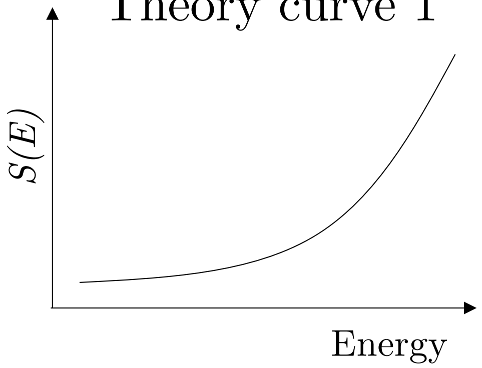
A deuterium prediction from a GP

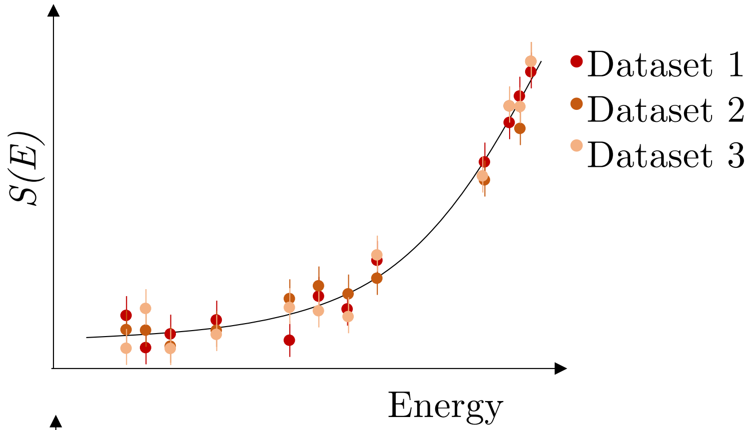
- Fit a GP to key deuterium rates
  - d(d,p)^{3}H, d(d,n)^{3}He, and d(p,γ)^{3}He
- Replace $\log \underset{\text{Rate in BBN code}}{\lambda}(T) = \log \underset{\text{Mean}}{\overline{\lambda}}(T) + \overset{\text{Unit Gaussian variable}}{q}\underset{\text{Uncertainty}}{\sigma}(T)$ with GP draws
- Draw ~10,000 times to infer D/H



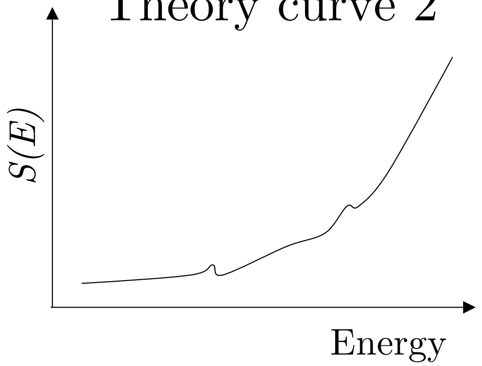
Low-degree polynomials not flexible

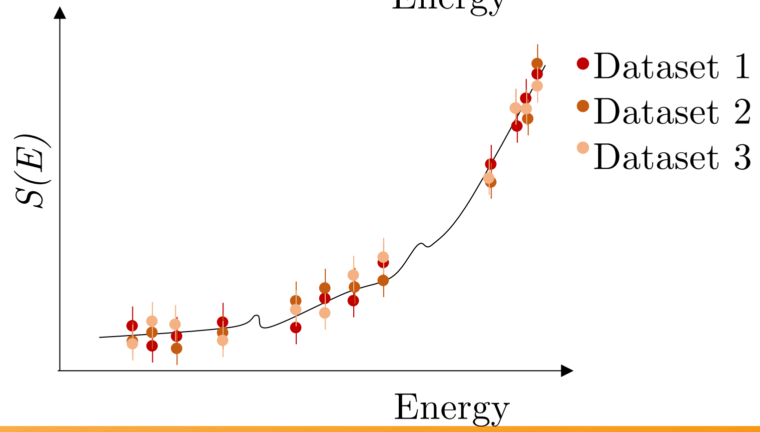
Arai et al. 2011


Theory curve 1



GP


Theory curve 2



Insensitivity to kernel choice