Meandering Through Theory Space

Tim M.P. Tait
University of California, Irvine

BSM from Colliders to the Early Universe

May 28, 2023

Beginnings

- Though it took me longer to start working with her, I met Marcela before Carlos, when I was a graduate student visiting Argonne sometime around 1998.
- She came and gave a seminar about Higgs searches in the MSSM.
- I remember being impressed that everyone wanted to talk to her. But she made time to chat with me, and we talked about Higgs physics in the MSSM. It was hard to keep up. (It still is…)
- A few weeks later, Carlos (who was working at CERN at the time) arrived for a mini-workshop about SUSY at Argonne.
- I later figured out that this event had more to do with planting the seeds that eventually brought him to Chicagoland.

Image Credit: Marcela Carena

Light Gluinos & Sbottoms

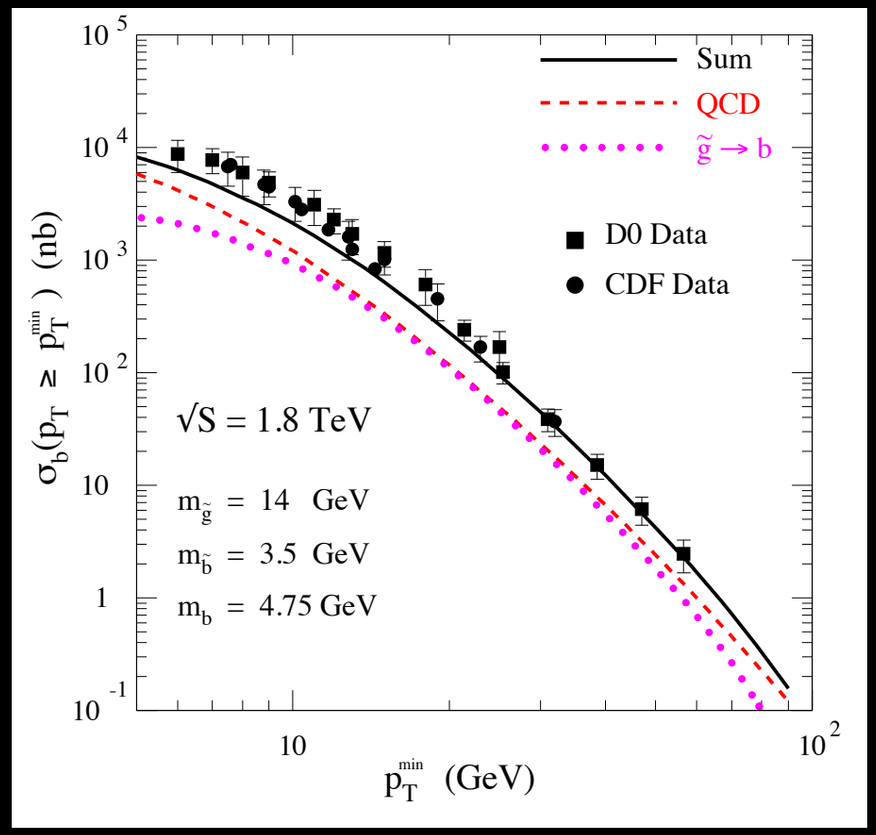
- Carlos arrived at Argonne in the fall of 1999, the same time I came back as a newly minted postdoc.
- Upon arrival, Carlos gave a great talk about baryogenesis in the MSSM and told us that if were correct, LEP-2 would discover the Higgs in the next year or so.
- It was a good time at Argonne. Ed Berger had become interested in QCD, and there was a big and dynamic group of postdocs: Brian Harris, David E Kaplan, Zack Sullivan, and Gordon Chalmers.

We pooled our various expertise and worked on an audacious (fun!) explanation for a long-standing excess of bottom quarks produced at colliders, using light gluinos and bottom squarks, which decayed into jets via RPV.

ANL-HEP-PR-00-116

Low-Energy Supersymmetry and the Tevatron Bottom-Quark Cross Section

E. L. Berger[1], B. W. Harris[1], D. E. Kaplan[1,2], Z. Sullivan[1], T. M. P. Tait[1] and C. E. M. Wagner[1,2]
[1] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439*
[2] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*
(November 30, 2000)



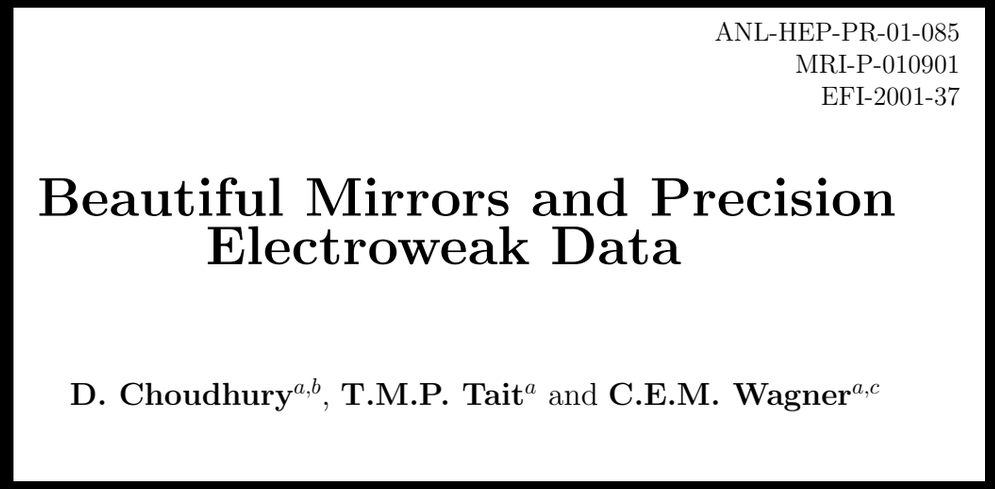
This paper was formative for me, because it was my first experience following a mystery in observation, and engineering one's way out of constraints.

It also pounded home the message that observation is king, and phenomenologists should see anything allowed by it as fair game.

Brian Harris referred to the whole enterprise as 'conspiracy theory'.

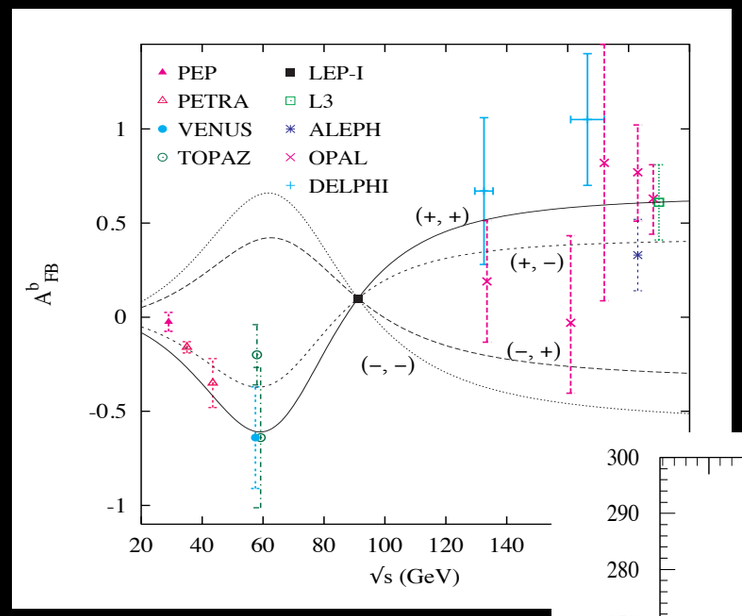
Beautiful Mirrors

- Bill Bardeen suggested we try to use our light bottoms to explain the forward-backward asymmetry of the b quark.
- That didn't work, but apparently stuck in our minds. Debajyoti Chaudhuri visited Argonne for a few months, and we started exploring theories with heavy Higgses.
- Large mH went well with A^{FB}_b : Chanowitz had recently made his point that the tension in the EW fit to the SM favored large mH.
- We ended up redoing the whole fit so we could add new physics. It was a lot of fun.
- I was also surprised, because I thought of Carlos as someone who only loved supersymmetry.
- I never really loved supersymmetry.


ANL-HEP-PR-01-085
MRI-P-010901
EFI-2001-37

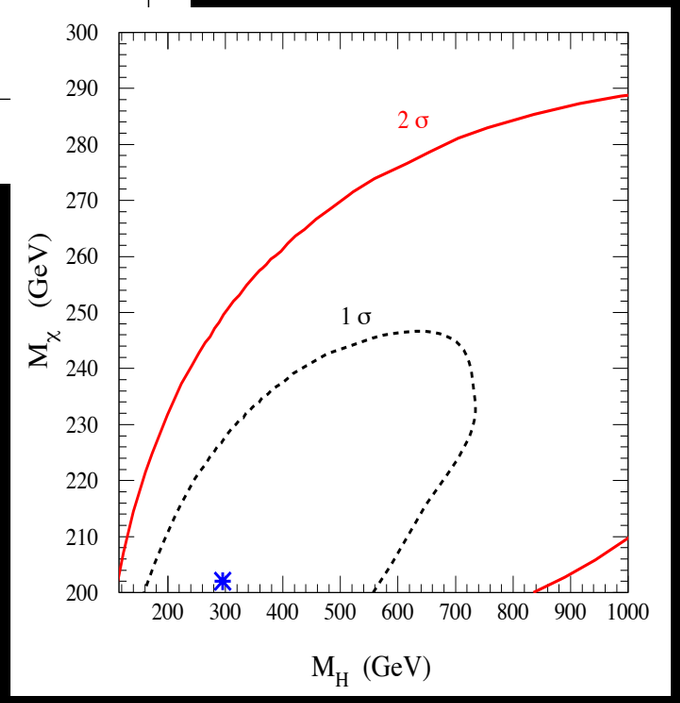
Beautiful Mirrors and Precision Electroweak Data

D. Choudhury[a,b], T.M.P. Tait[a] and C.E.M. Wagner[a,c]



Right-handed b couplings were *really* badly constrained…

"Standard Mirrors"



This paper should have appeared on the arXiv on Carlos's birthday, 9/11 2001.

I was (trying to) fly back to the US from Italy.

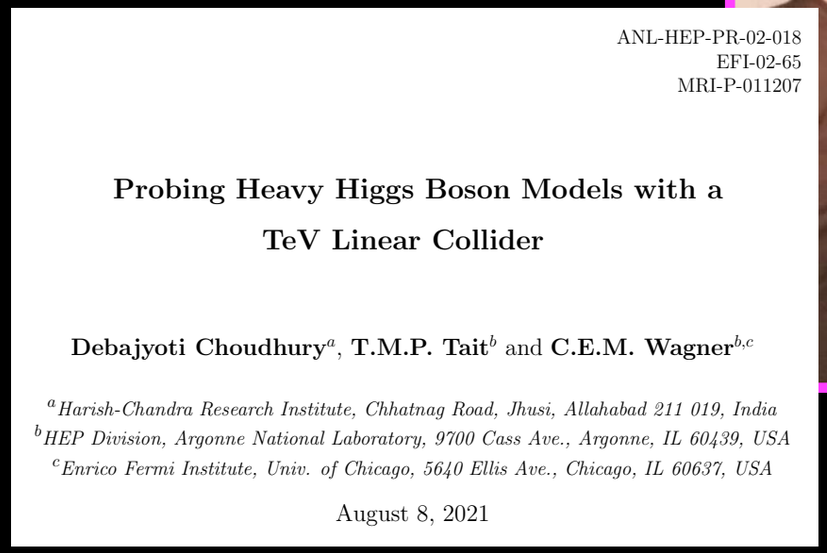
Supersymmetry

Those days I was fired twice a week, on the average.

(Though to be accurate, never in the presence of Cecilia or Daniel…)

Heavy Higgs @ ILC

- Eventually we got back to heavy Higgses.
- Sadly, neither they nor the ILC were destined to arrive since. Still. It was fun!
- But more importantly, there were lots and lots of parties.



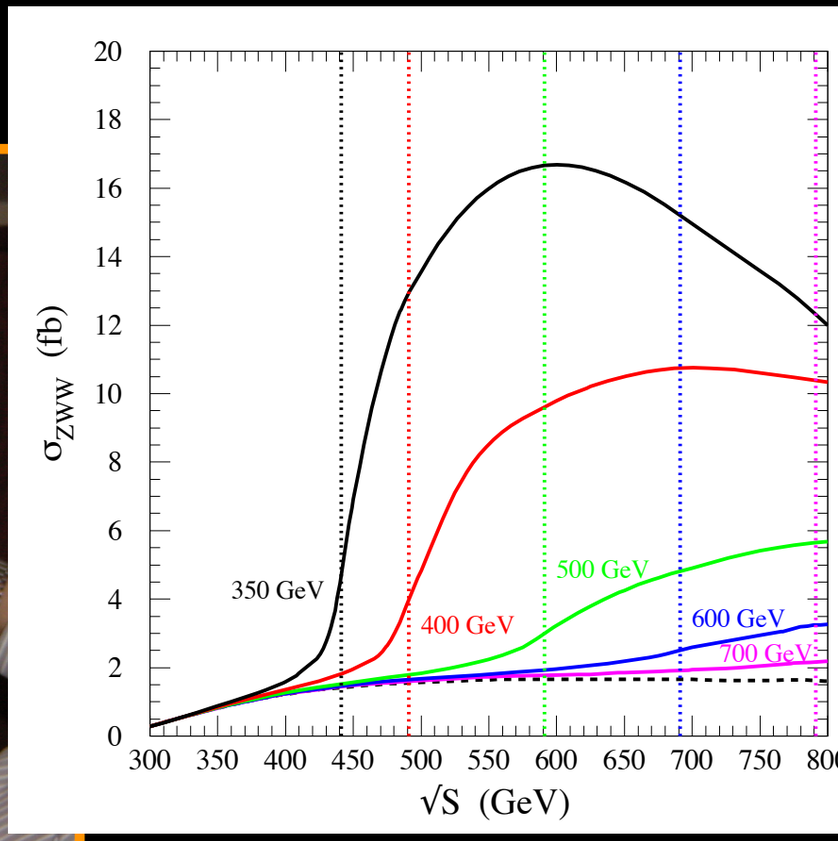
ANL-HEP-PR-02-018
EFI-02-65
MRI-P-011207

Probing Heavy Higgs Boson Models with a TeV Linear Collider

Debajyoti Choudhury[a], **T.M.P. Tait**[b] and **C.E.M. Wagner**[b,c]

[a] *Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211 019, India*
[b] *HEP Division, Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439, USA*
[c] *Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis Ave., Chicago, IL 60637, USA*

August 8, 2021



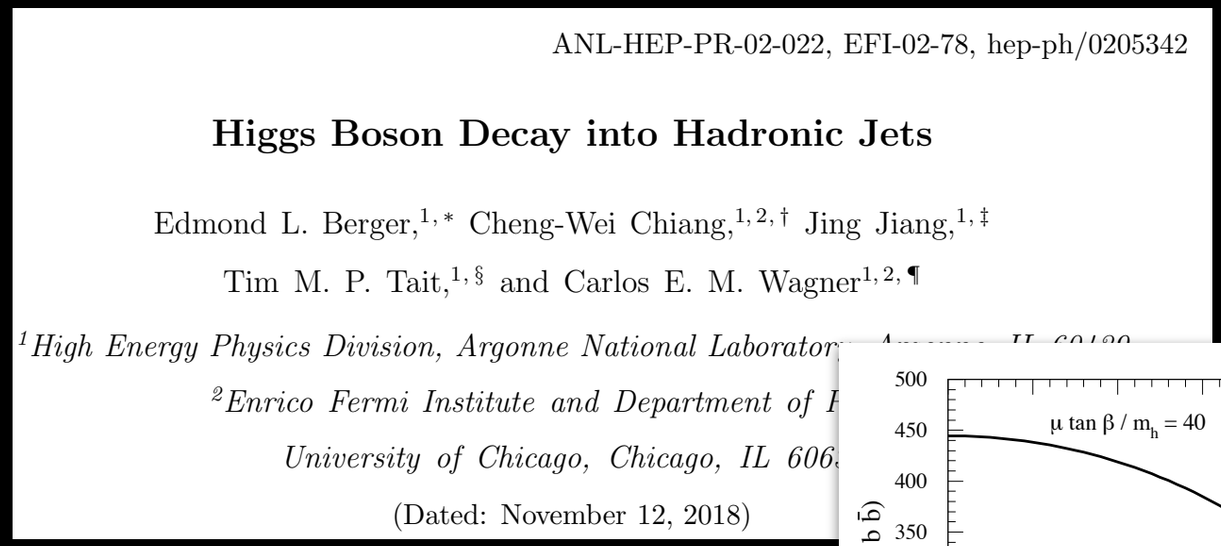
Higgs into Jets

- Several of the more senior postdocs graduated from Argonne to bigger and better things. New people arrived, and the fun continued.

- Carlos realized that the light sbottoms would likely dominate Higgs decays. At the time that seemed awful (but today would have been dealt with using jet substructure techniques).

- SPIRE started truncating at one middle initial in its automatically generated latex references. That was sad for the CEMW's and TMPT's of the world.

- Also: there were more parties!



ANL-HEP-PR-02-022, EFI-02-78, hep-ph/0205342

Higgs Boson Decay into Hadronic Jets

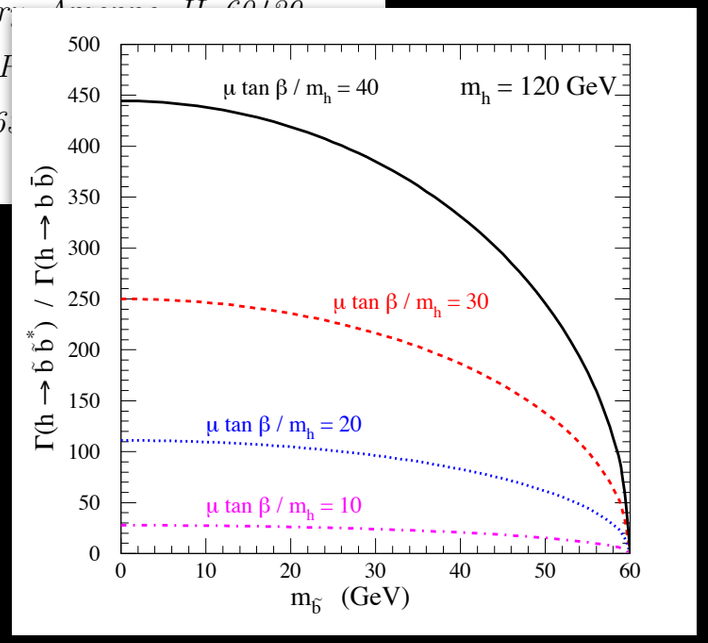
Edmond L. Berger,[1,*] Cheng-Wei Chiang,[1,2,†] Jing Jiang,[1,‡]
Tim M. P. Tait,[1,§] and Carlos E. M. Wagner[1,2,¶]

[1]*High Energy Physics Division, Argonne National Laborator*

[2]*Enrico Fermi Institute and Department of*

University of Chicago, Chicago, IL 606

(Dated: November 12, 2018)

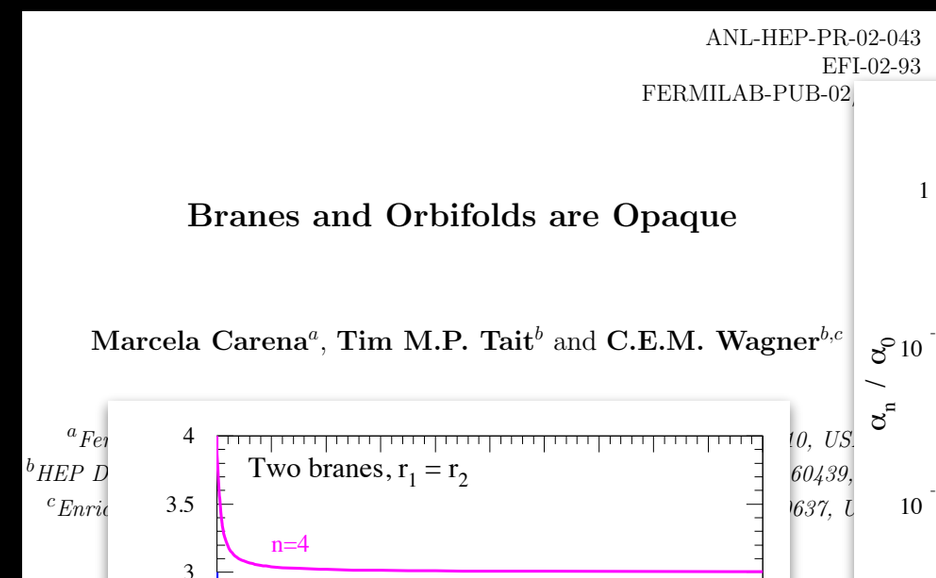


The Wagner Golden Rules

- It was around this time that I first heard Carlos state his "Golden Rules for Doing Research":
  - If you think about something, work it out.
  - If you work it out, write a draft.
  - If you write a draft, put it on the arXiv.
  - If you put it on the arXiv, publish it.
  - BE CAREFUL WHAT YOU THINK ABOUT!

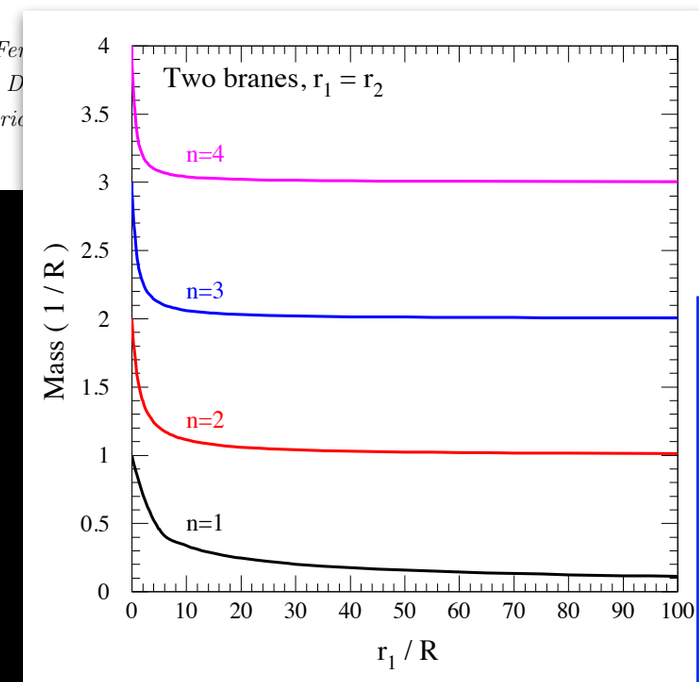
Opaque Branes & Orbifolds

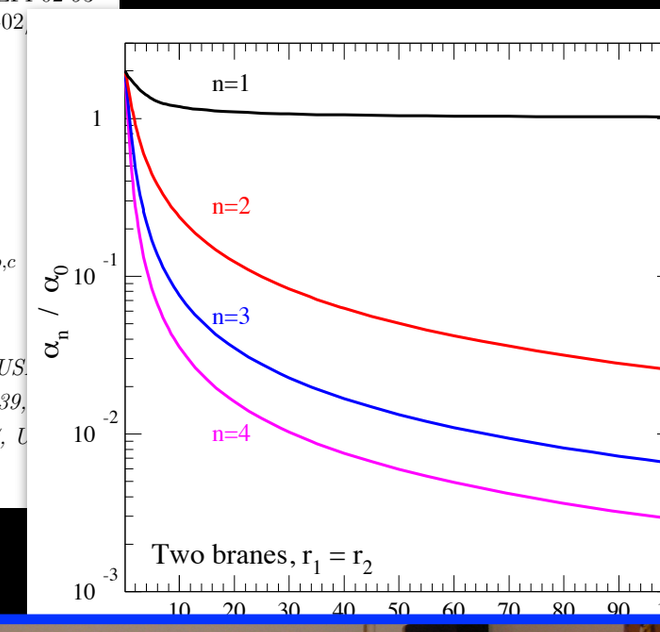
- In 2002, with my move to Fermilab for my second postdoc imminent, we started working with Marcela.
- DGP was hot both as a theory of gravity in extra dimensions as well as a theoretical curiosity.
- We decided to play around with the variant involving gauge fields.
- It was a lot of fun, and a cool new tool that one could use for extra-dimensional model-building.
- Carlos: "If extra dimensions are real, I'll become a Tibetan monk."


ANL-HEP-PR-02-043
EFI-02-93
FERMILAB-PUB-02

Branes and Orbifolds are Opaque

Marcela Carena[a], Tim M.P. Tait[b] and C.E.M. Wagner[b,c]

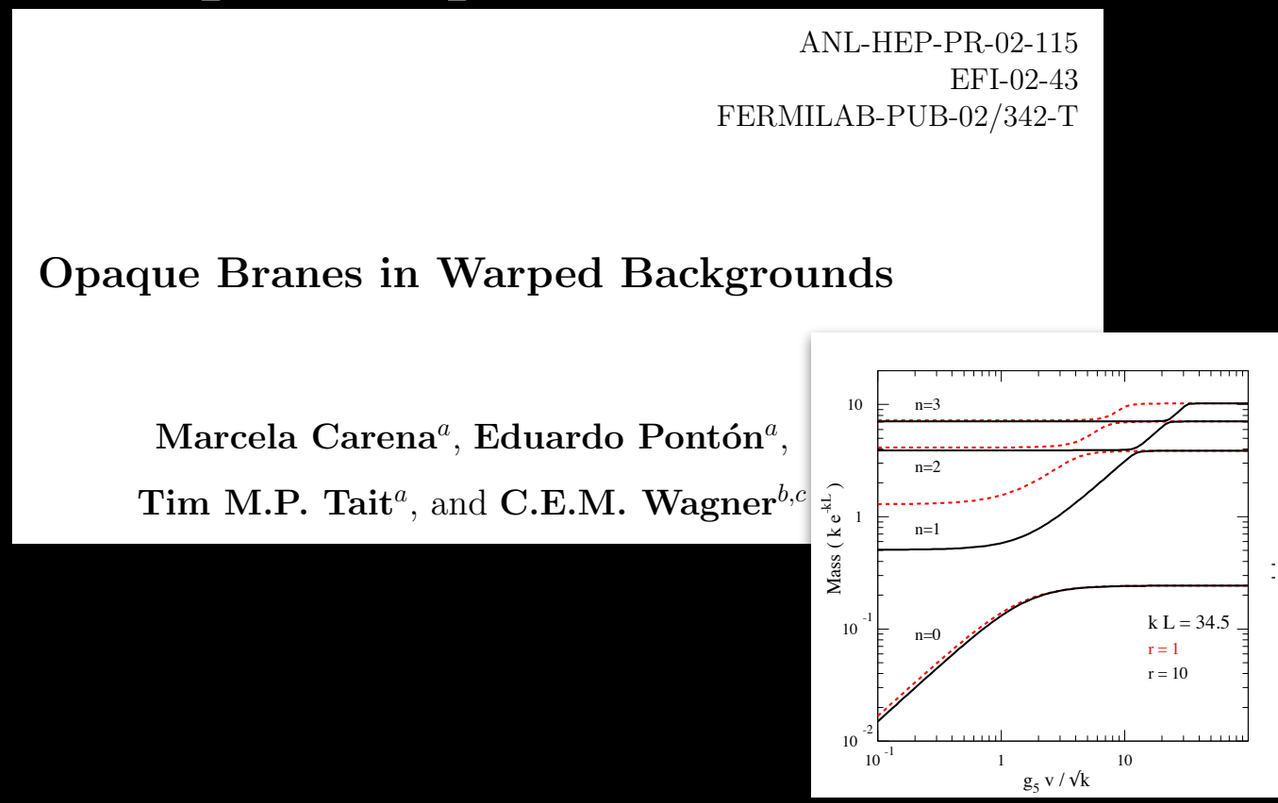




Warped Opaque

- Eduardo Ponton and I arrived at Fermilab at the same time, along with Ayres Freitas, Uli Haisch. Zack and Andre De Gouvea had moved the year before. Giulia Zanderighi and Olga Mena the year after.

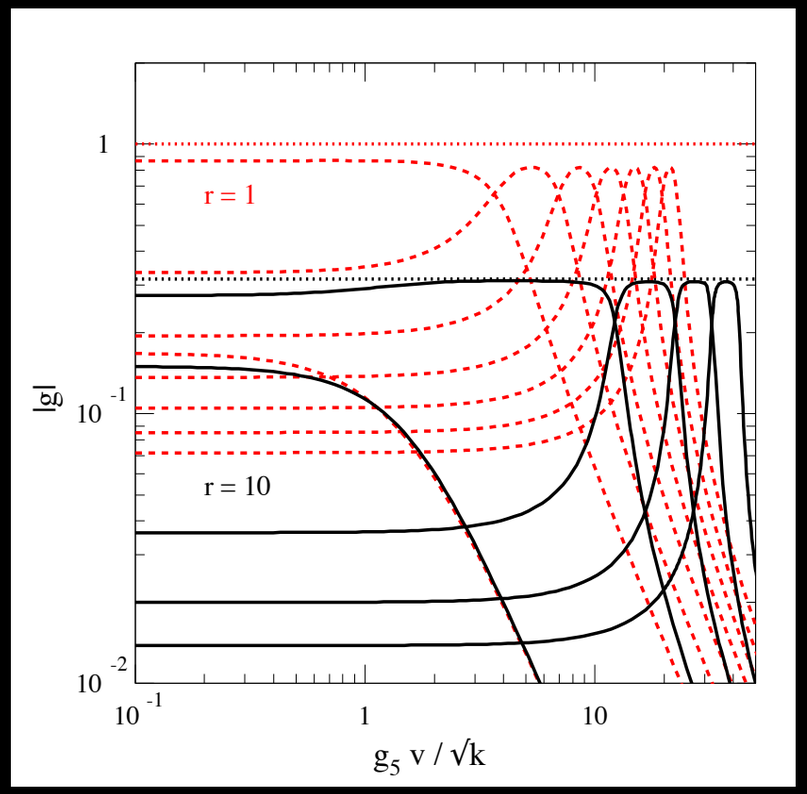
- Interest in warped extra dimensions was surging, and since their construction was based on an orbifold, it was natural to consider opacity for them too.


ANL-HEP-PR-02-115
EFI-02-43
FERMILAB-PUB-02/342-T

Opaque Branes in Warped Backgrounds

Marcela Carena[a], Eduardo Pontón[a], Tim M.P. Tait[a], and C.E.M. Wagner[b,c]

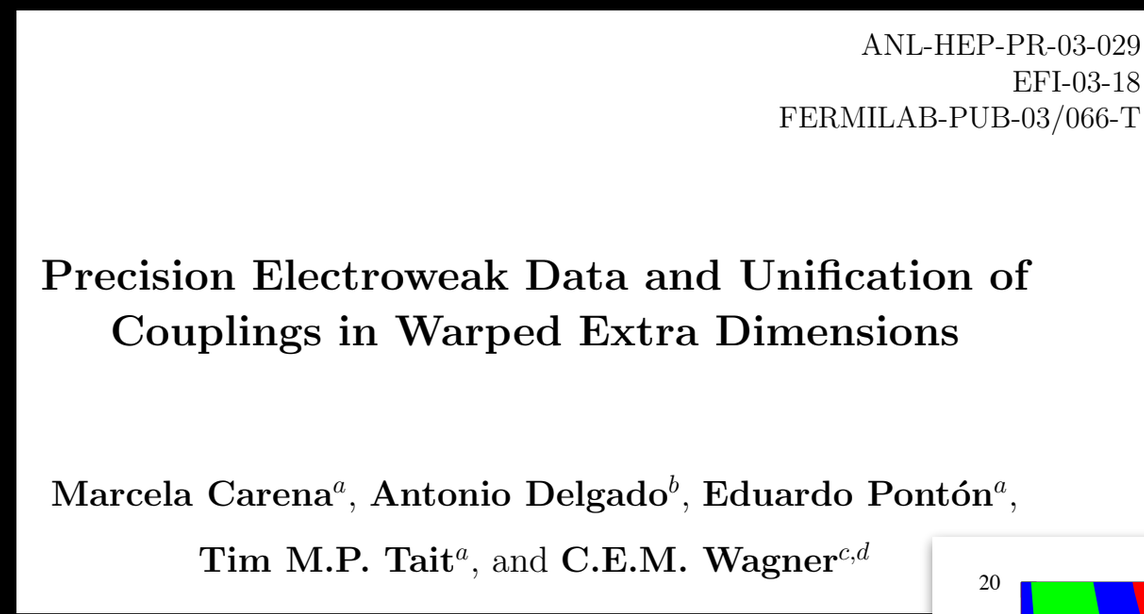
- That also lead us to explore a localized Higgs VEV, which is some ways was even more cool.



RS Unification

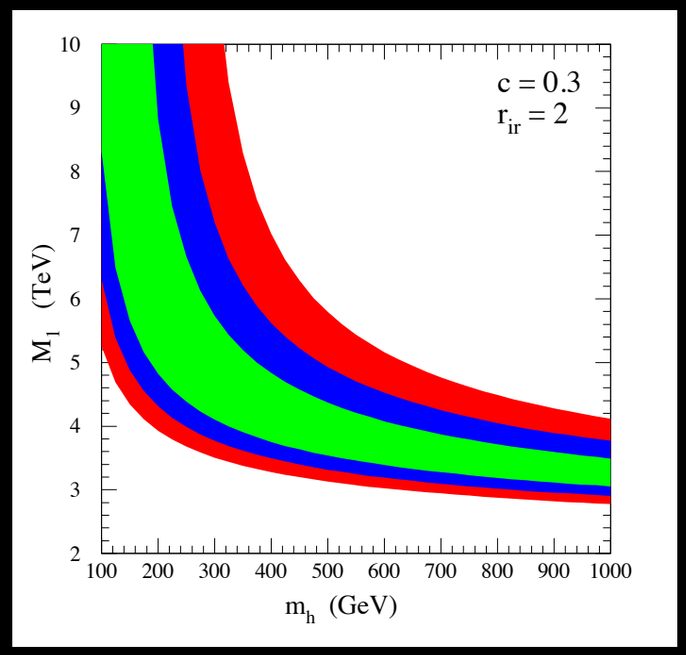
- We realized that the running couplings in RS, which were a big deal because of RS Grand Unification, could be understood as opacity terms on the UV brane.

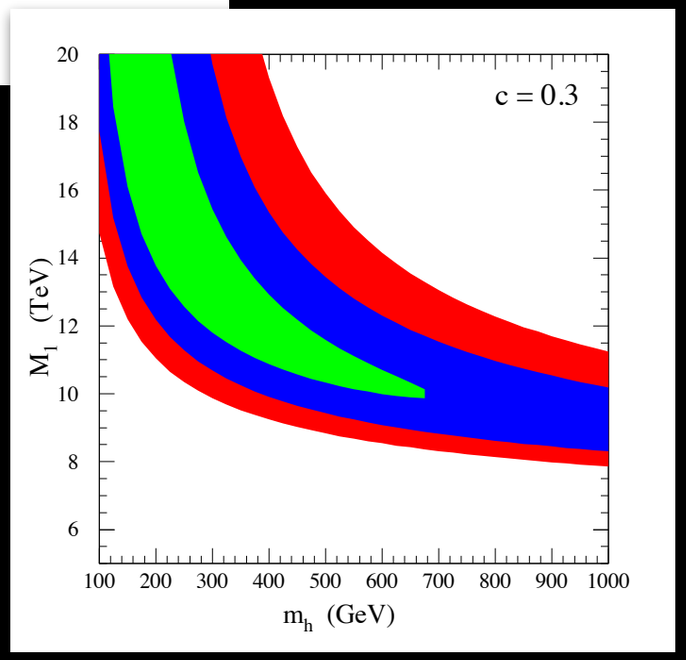
- Antonio Delgado joined our collaboration, spent a good time visiting Fermilab while we had fun feverishly working out the EW constraints.


ANL-HEP-PR-03-029
EFI-03-18
FERMILAB-PUB-03/066-T

Precision Electroweak Data and Unification of Couplings in Warped Extra Dimensions

Marcela Carena[a], **Antonio Delgado**[b], **Eduardo Pontón**[a], **Tim M.P. Tait**[a], and **C.E.M. Wagner**[c,d]

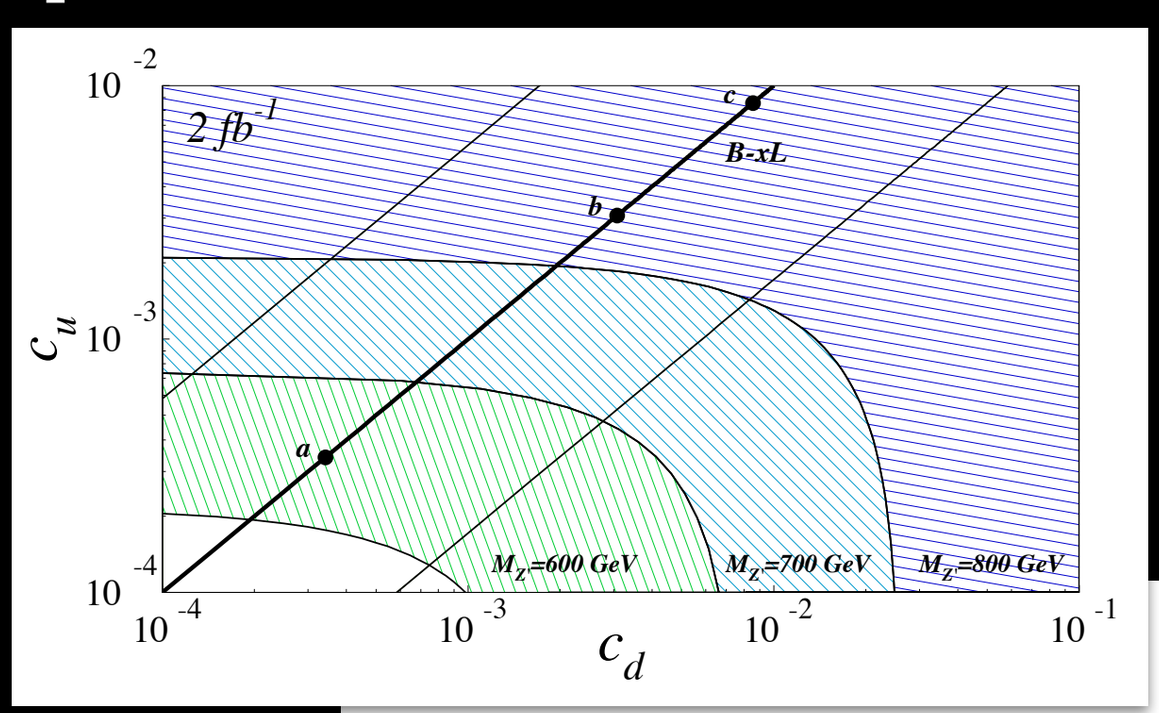




Why is everyone always looking at that wall?

Z-primes

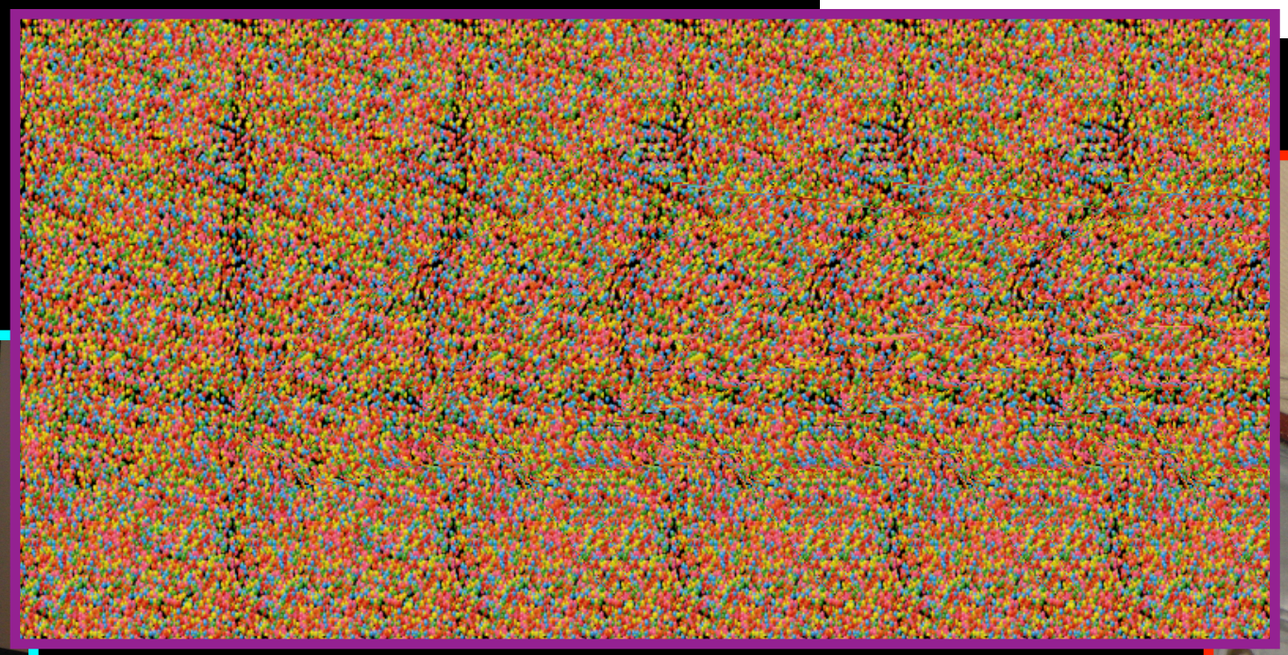
- As the Tevatron Run II started, I worked with Marcela on the signals that one could reasonably expect from a Z-prime boson.
- It was a lot of fun, and had a lasting impact on both the collider phenomenology of Z's and the theoretical construction of anomaly-free models.



FERMILAB-Pub-04/129
hep-ph/0408098

Z' Gauge Bosons at the Tevatron

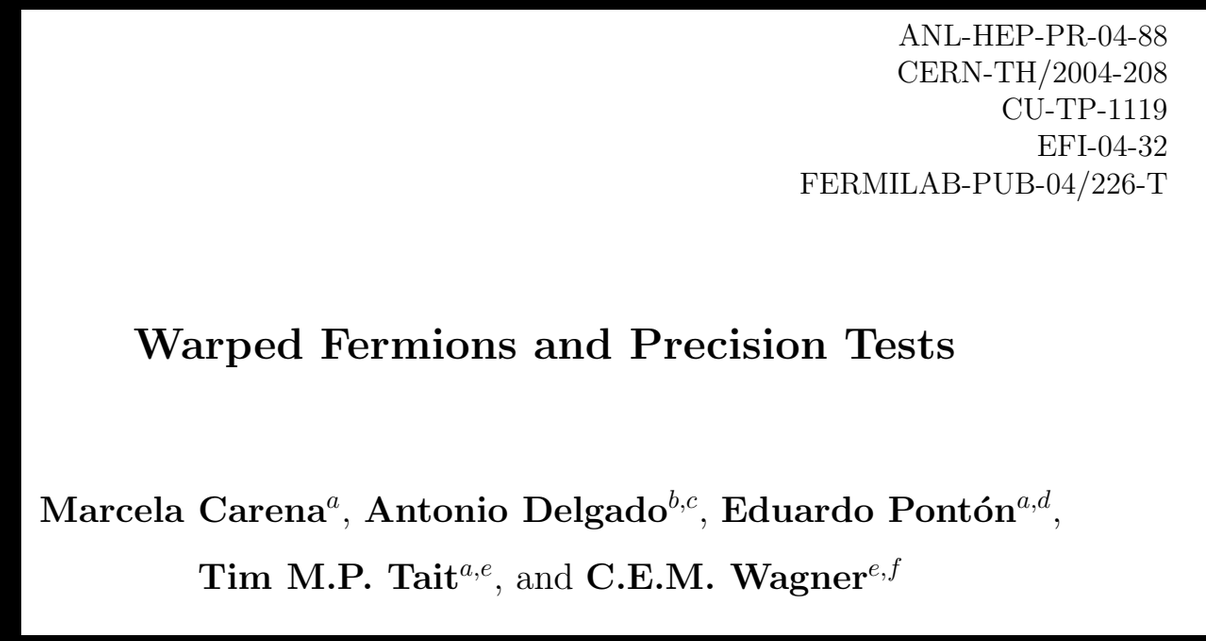
Marcela Carena[1], Alejandro Daleo[1,2] Bogdan A. Dobrescu[1], Tim M.P. Ta



The wall had a large framed stereogram (3d picture) of a shark in an underwater scene. It lead to a lot of time spent staring, but it was worth it when someone finally 'saw' it!

Warped Fermions

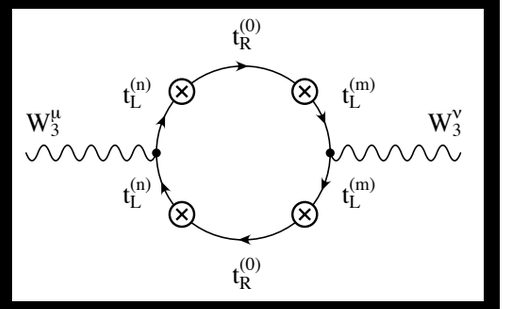
- Putting fermions in the bulk completed the layer of complication and lead to complicated new challenges in figuring out what they did to the low energy physics.
- It was around this time that we moved to downtown Chicago. That sadly meant a little less time with our friends in Naperville, but the views were nice!

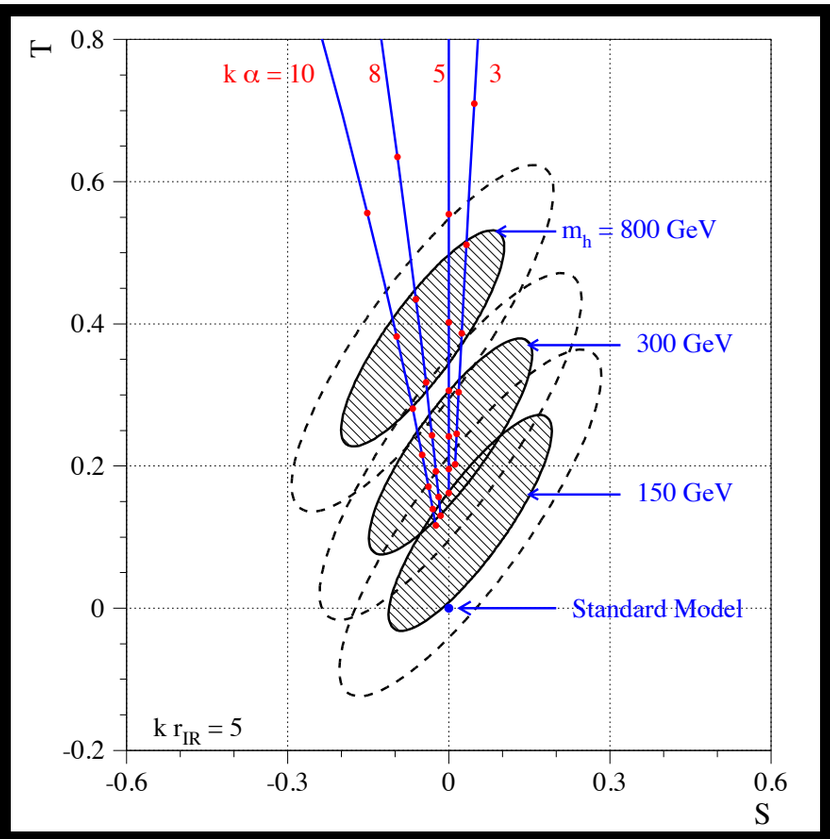


ANL-HEP-PR-04-88
CERN-TH/2004-208
CU-TP-1119
EFI-04-32
FERMILAB-PUB-04/226-T

Warped Fermions and Precision Tests

Marcela Carena[a], **Antonio Delgado**[b,c], **Eduardo Pontón**[a,d], **Tim M.P. Tait**[a,e], and **C.E.M. Wagner**[e,f]





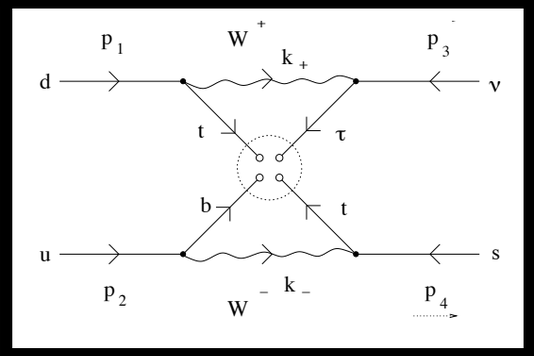
Interestingly enough, I did a lot of work with supersymmetric theories during this period, but never with Carlos or Marcela!

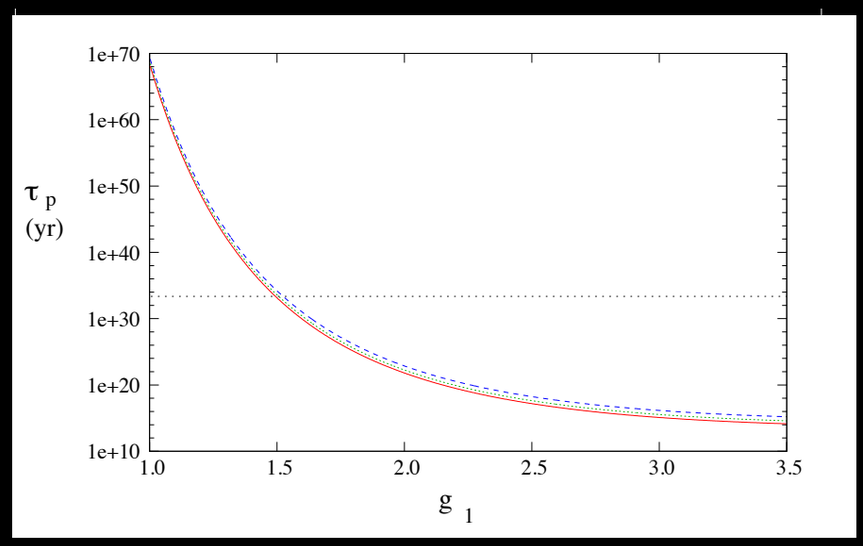
Topflavor Instantons

ANL-HEP-PR-05-48
EFI-05-03

Proton Lifetime and Baryon Number Violating Signatures at the LHC in Gauge Extended Models

D.E. Morrissey[a,b], **T.M.P. Tait**[a] and **C.E.M. Wagner**[a,b]

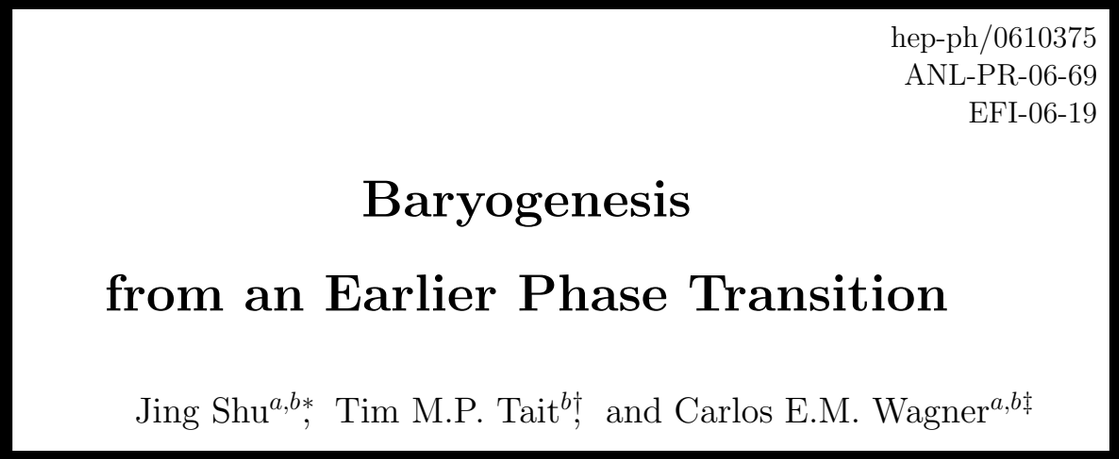




- In 2005, I moved back to Argonne as a staff member.
- David Morrisey spent a lot of time at Argonne as a student, and we started working on the instanton sector of a theory with SU(2) x SU(2) weak interactions, which I had worked on periodically throughout my career…

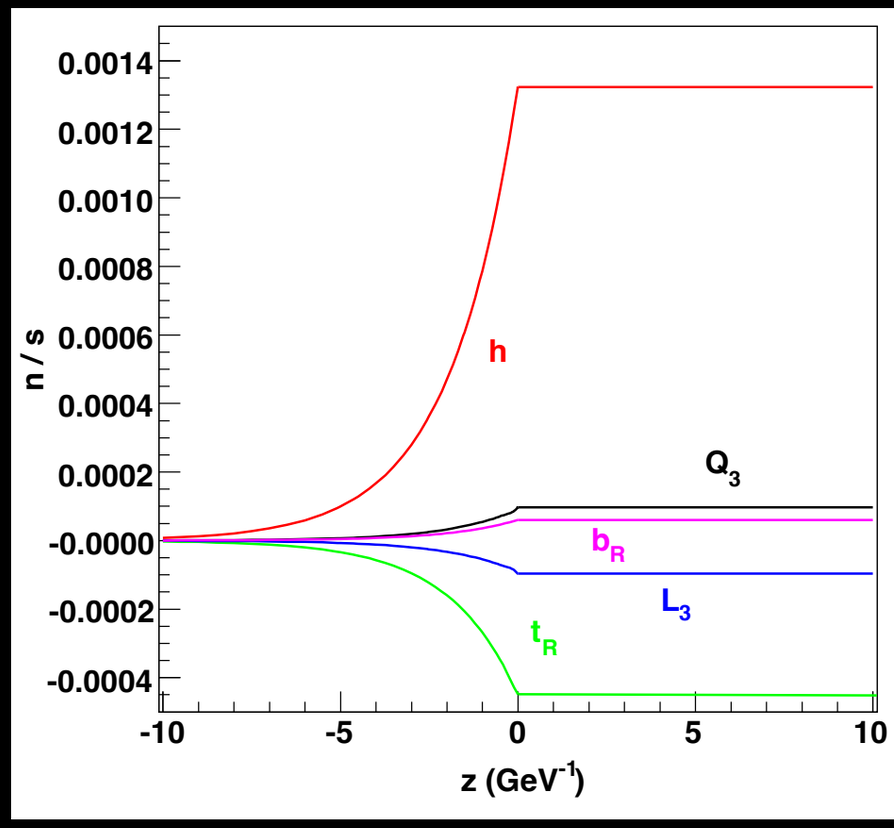
Baryogenesis

- More excellent students followed David, and it was great to interact and work with Nausheen, Arjun, Jing, and Patrick as well.
- Jing synthesized the work we had done with David into a model of electroweak-style baryogenesis based on a top-flavor phase transition.


hep-ph/0610375
ANL-PR-06-69
EFI-06-19

Baryogenesis from an Earlier Phase Transition

Jing Shu[a,b*], Tim M.P. Tait[b†], and Carlos E.M. Wagner[a,b‡]



I'm not sure when (or why) our parties started including yoga sessions…

I'm not sure when our parties started including yoga sessions…

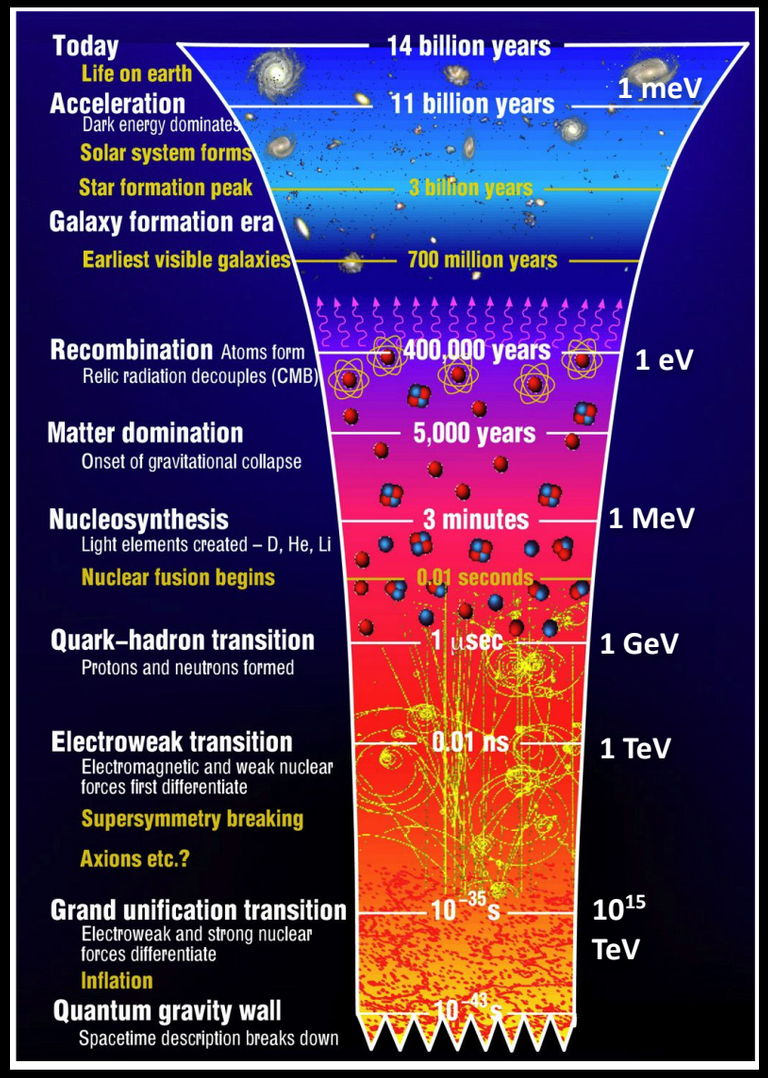
…But clearly they were exhausting…

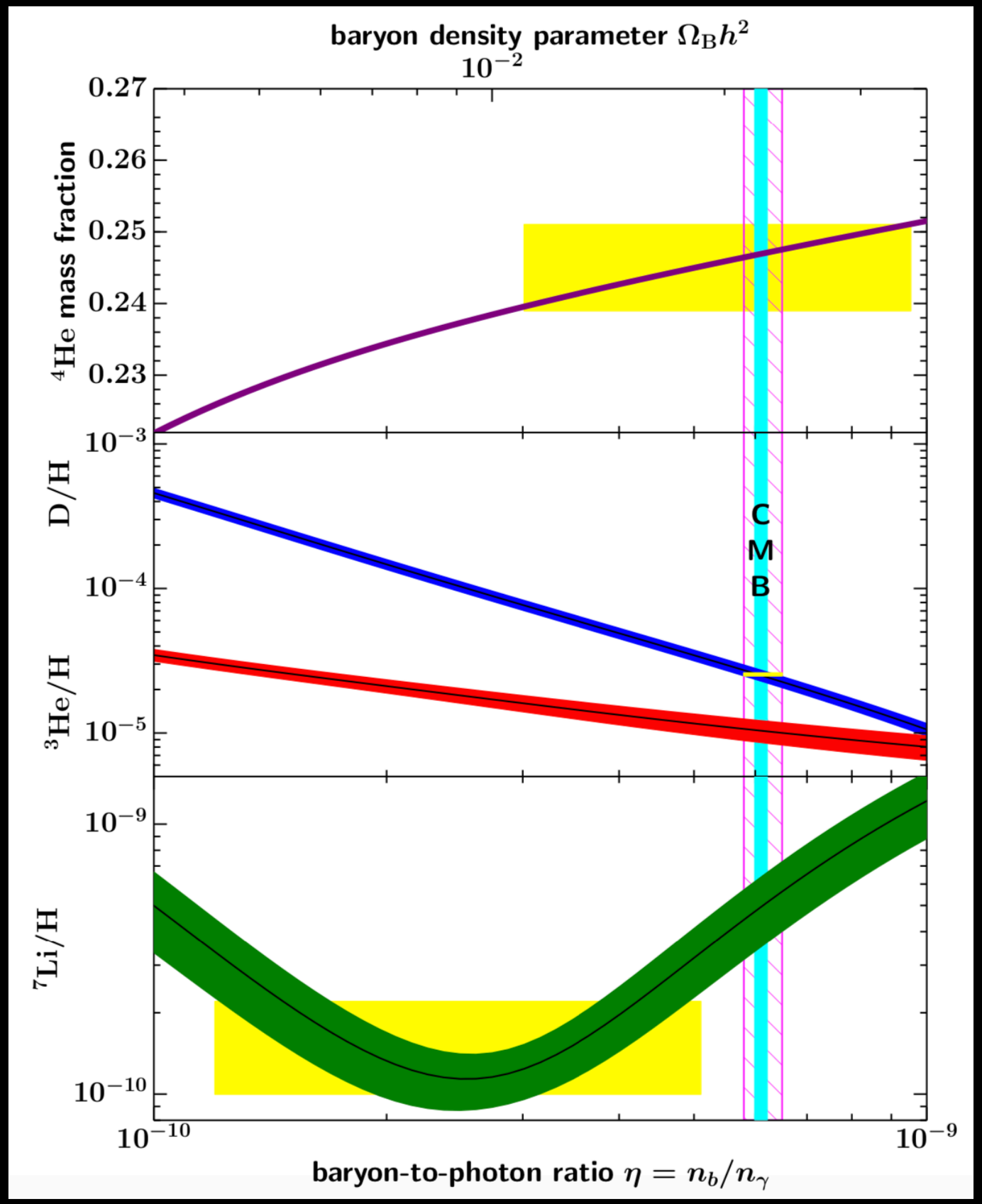
So What's this about a Lepton Asymmetry?!

(Sorry, there's actually a serious physics talk for the next few slides…)

Work with:
Anne-Katherine Burns and Mauro Valli
arXiv: 2206.00693
PRL 130, 13 31001 (2023)
&
arXiv:2306.xxxxx

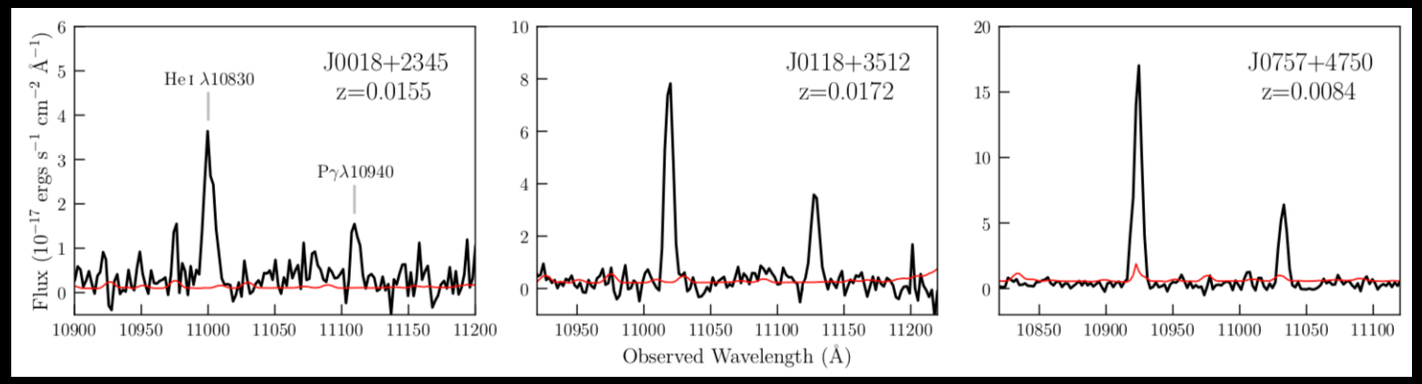
BBN





BBN is remarkably successful, connecting particle & nuclear physics to cosmology, and making a convincing case that we understand the Universe pretty well back to temperatures of O(MeV) — and it places important constraints on new physics.

^{4}He circa 2021

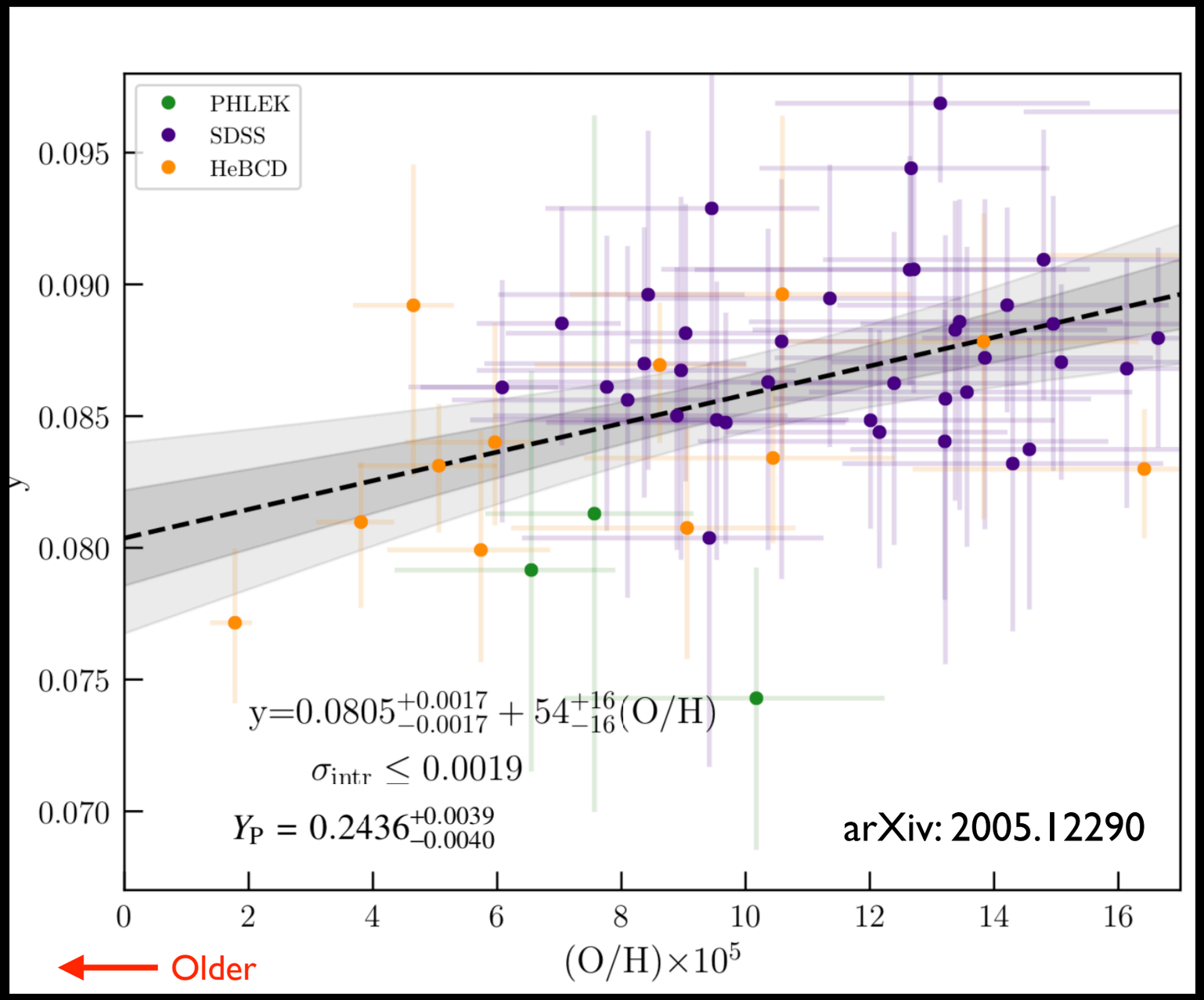


2021: 51 metal-poor galaxies + 3 EMPGs

PDG 2021:

$$Y_P = 0.245 \pm 0.003$$

% level measurement

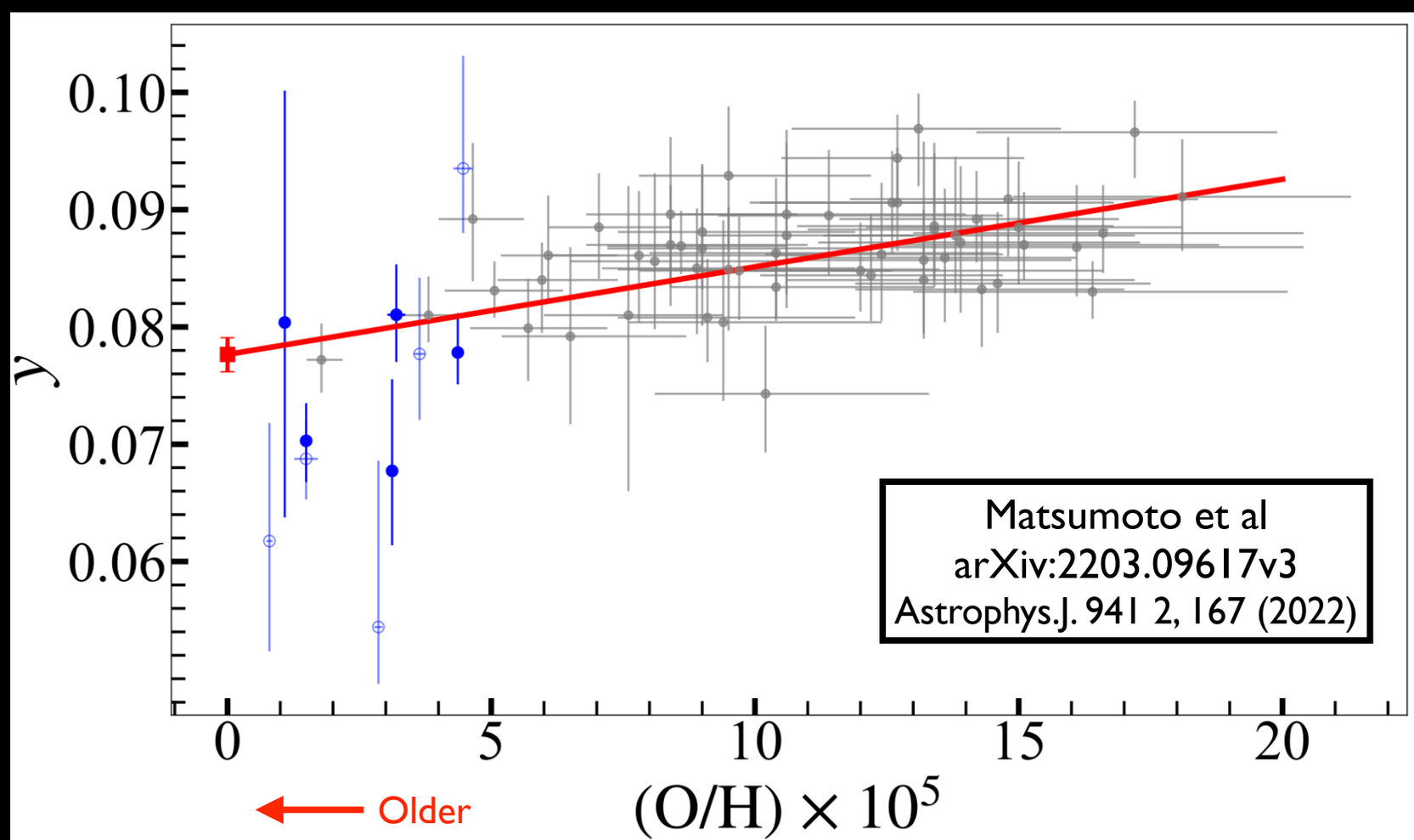


A New ^{4}He Measurement

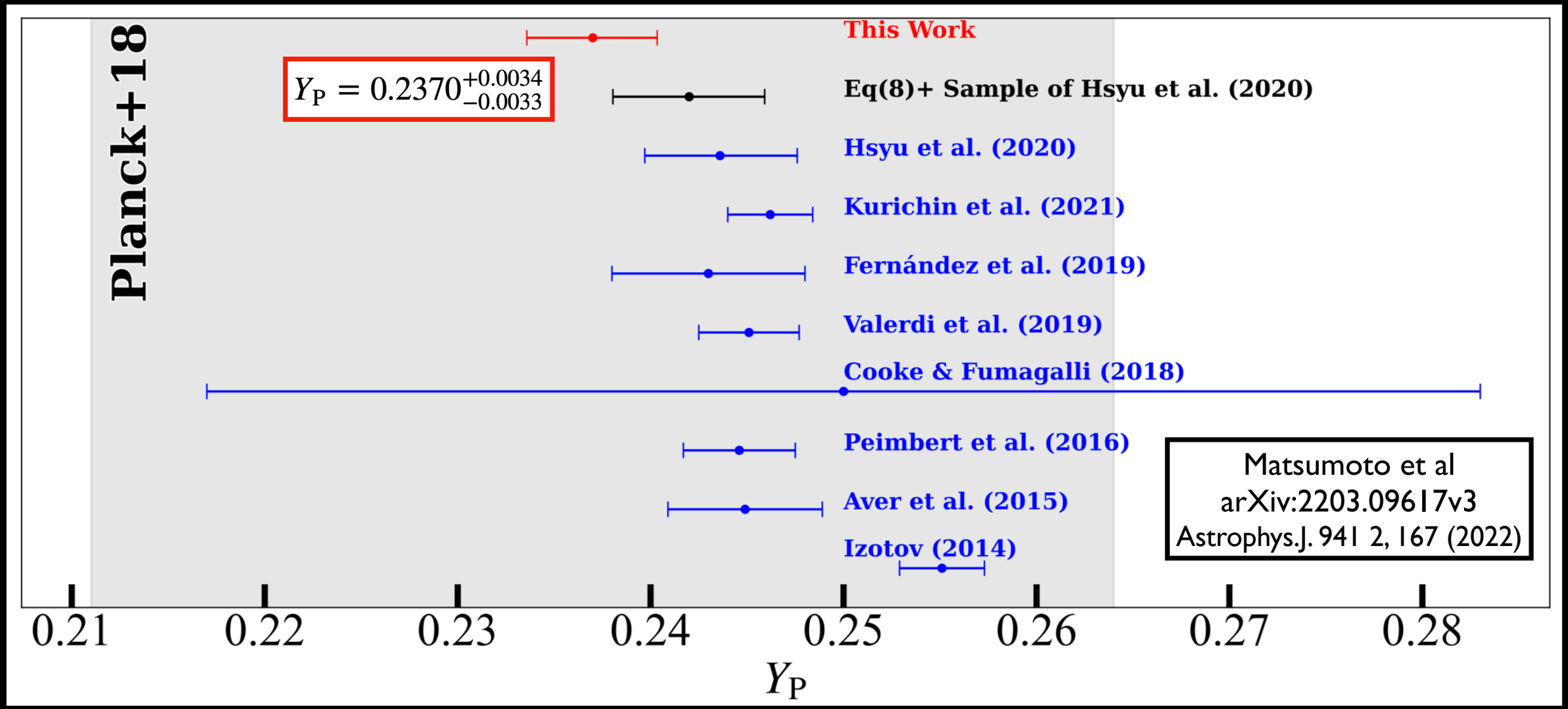
Extremely metal-poor galaxies (EMPGs) provide pristine environments for primordial ^{4}He measurements.

2021: 51 metal-poor galaxies + 3 EMPGs

2022: deep NIR spectroscopy from Subaru Telescope adds 10 new EMPGs!



A New ^{4}He Measurement



Precision BBN

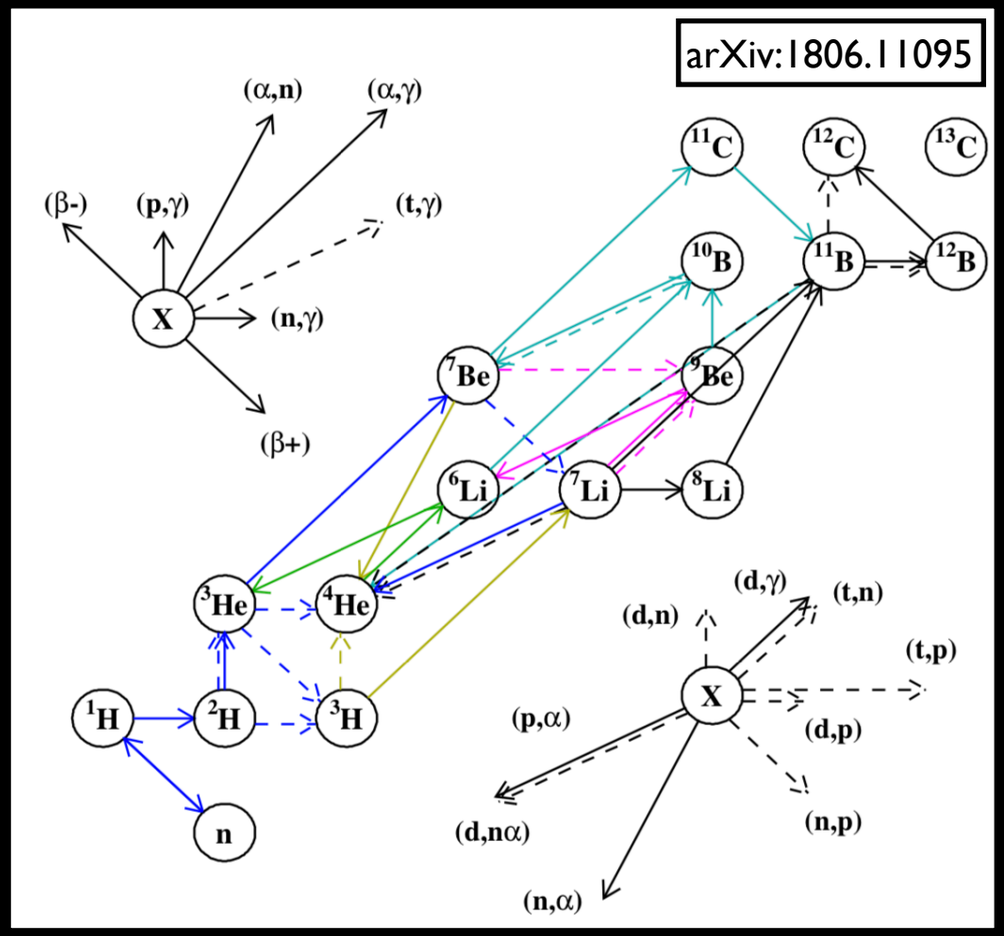
- A significant shift in the primordial abundance of ^{4}He is both interesting and alarming.
- The new result is about 2.5σ from the old one, which resulted in a very consistent picture with theoretical predictions from BBN in the SM.
- How significant are the differences in BBN? What role do theory uncertainties play?
- What role do other measurements such as deuterium play? Are there tensions within BBN?
- Is this a hint for BSM physics? Are there surprises about cosmology to be gleaned from understanding BBN at the % level?
- The answers to these questions require us to go beyond the qualitative picture of BBN to more precise modeling of the web of nuclear reactions, with a framework that allows us to more robustly explore uncertainties…

PDG 2021:

$$Y_P = 0.245 \pm 0.003$$

Subaru 2022:

$$Y_{\rm P} = 0.2370^{+0.0034}_{-0.0033}$$



$$\dot{Y}_i \sim n_B \left(\langle \sigma v \rangle_{kl \to ij} Y_k Y_l - \langle \sigma v \rangle_{ij \to kl} Y_i Y_j \right)$$

PRyMordial

Burns, TMPT, Valli, arXiv: 2305.XXXXX

- To answer these questions, we have developed a new tool (PRyMordial) to investigate BBN both within the SM and beyond.
- PRyMordial is written in python, and runs very quickly using DiffEq.jl from the Sci Machine Learning kit implemented in Julia.
- PRyMordial fully models neutrino decoupling and computes $N_{eff.}$, allowing for precise constraints on dark sectors.

Escudero, arXiv:1812.05605 & arXiv: 2001.04466

- PRyMordial allows for precision treatment of electroweak rates, including mass effects and O(α) corrections.

Based on PRIMAT's Mathematica implementation, but in python!

- PRyMordial implements network of O(10/50) nuclear reactions in a modular format, making it easy to compare different treatments of T-dependence.

NACRE & PRIMAT approaches

THE C PROGRAMMING LANGUAGE

AlterBBN

NEW AlterBBN v2.2

arXiv:1106.1363, arXiv:1806.11095

PRIMAT

PRImordial MATter

arXiv:1806.11095, arXiv: 2011.11320

WHY A NEW BBN CODE ?

THERE ARE NO BUGS

IF YOU DON'T WRITE ANY CODE

Fortran

PArthENoPE

Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements

arXiv:0705.0290, arXiv:1712.04378, arXiv:2103.05027

PRyMordial

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THE C PROGRAMMING LANGUAGE

AlterBBN

NEW AlterBBN v2.2

arXiv:1106.1363, arXiv:1806.11095

PRIMAT

PRImordial MATter

arXiv:1806.11095, arXiv: 2011.11320

Escudero, arXiv:1812.05605 & arXiv: 2001.04466

julia python™

PRyMordial

Burns, TMPT, Valli, arXiv: 2306.XXXXX

Based on PRIMAT's Mathematica implementation, but in python!

NACRE & PRIMAT approaches

Fortran

PArthENoPE

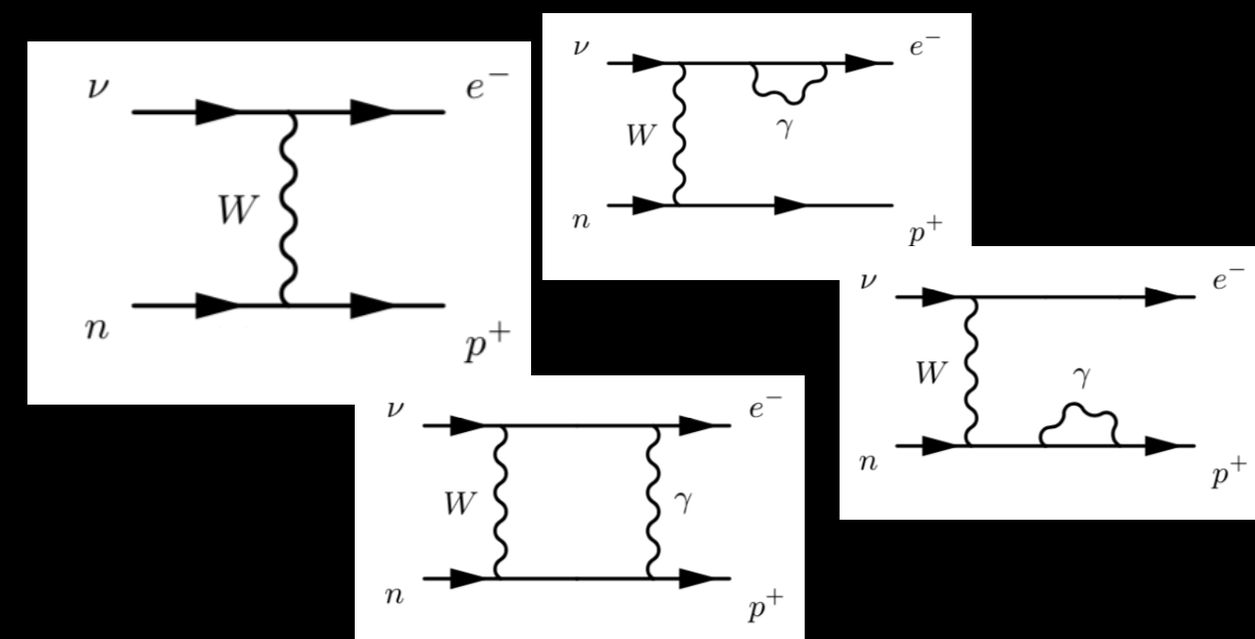
Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements

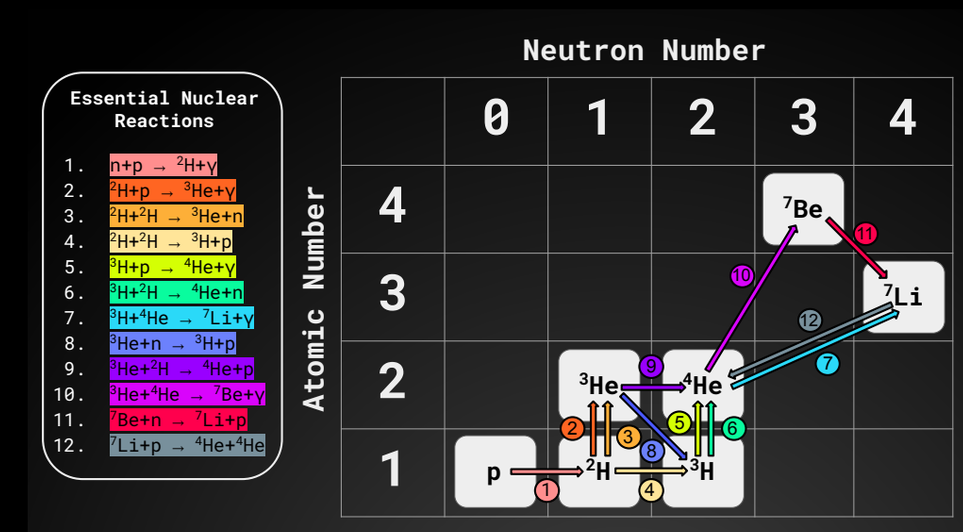
arXiv:0705.0290, arXiv:1712.04378, arXiv:2103.05027

PRyMordial

Burns, TMPT, Valli, arXiv: 2305.XXXXX

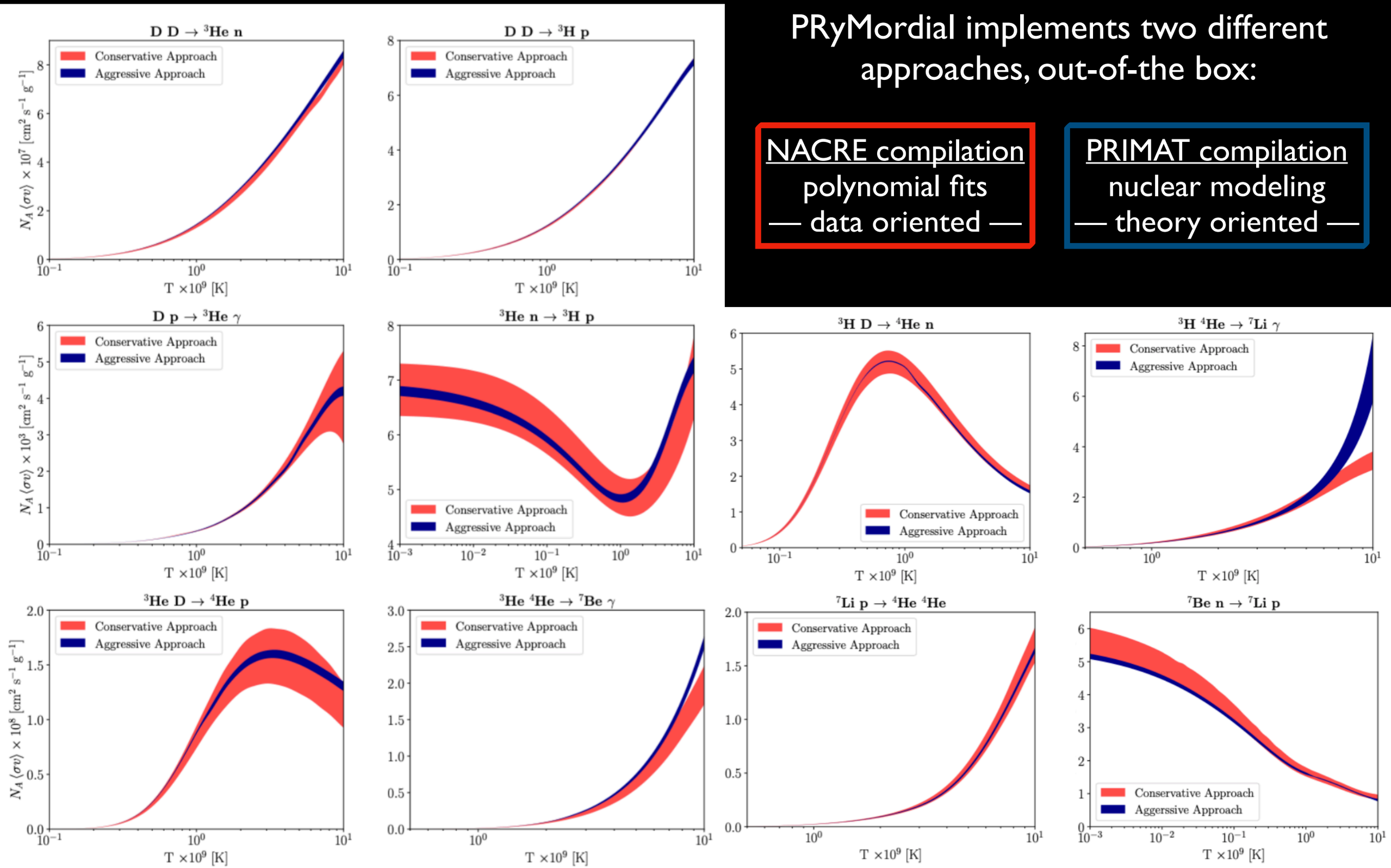
- To answer these questions, we have developed a new tool (PRyMordial) to investigate BBN both within the SM and beyond.
- PRyMordial is written in python, and runs very quickly using DiffEq.jl from the Sci Machine Learning kit implemented in Julia.
- PRyMordial fully models neutrino decoupling and computes $N_{eff.}$, allowing for precise constraints on dark sectors.
- PRyMordial allows for precision treatment of electroweak rates, including mass effects and O(α) corrections.
- PRyMordial implements network of O(10/50) nuclear reactions in a modular format, making it easy to compare different treatments of T-dependence.





PRyMordial

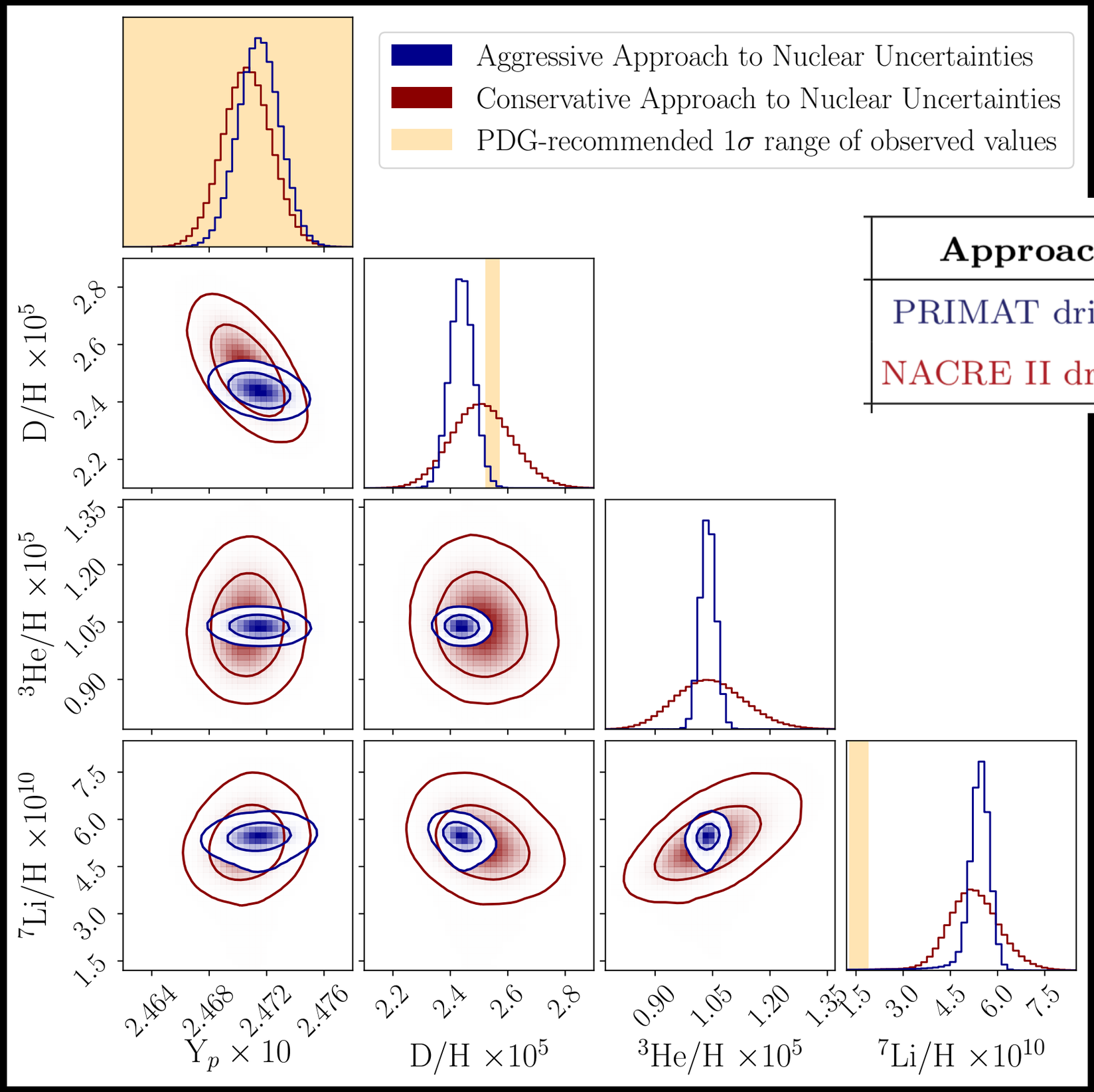
Nuclear Rates



PRyMordial implements two different approaches, out-of-the box:

NACRE compilation	PRIMAT compilation
polynomial fits	nuclear modeling
— data oriented —	— theory oriented —

PRyMordial: SM BBN



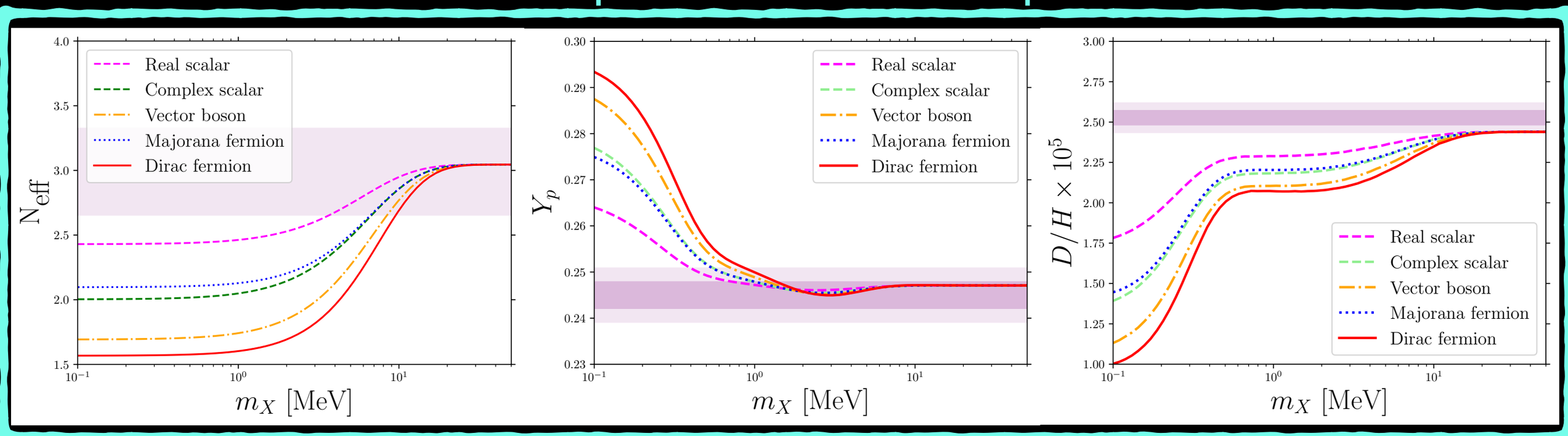
Approach	$Y_P \times 10$	$D/H \times 10^5$
PRIMAT driven	2.4715(14)	2.439(36)
NACRE II driven	2.4706(16)	2.51(10)

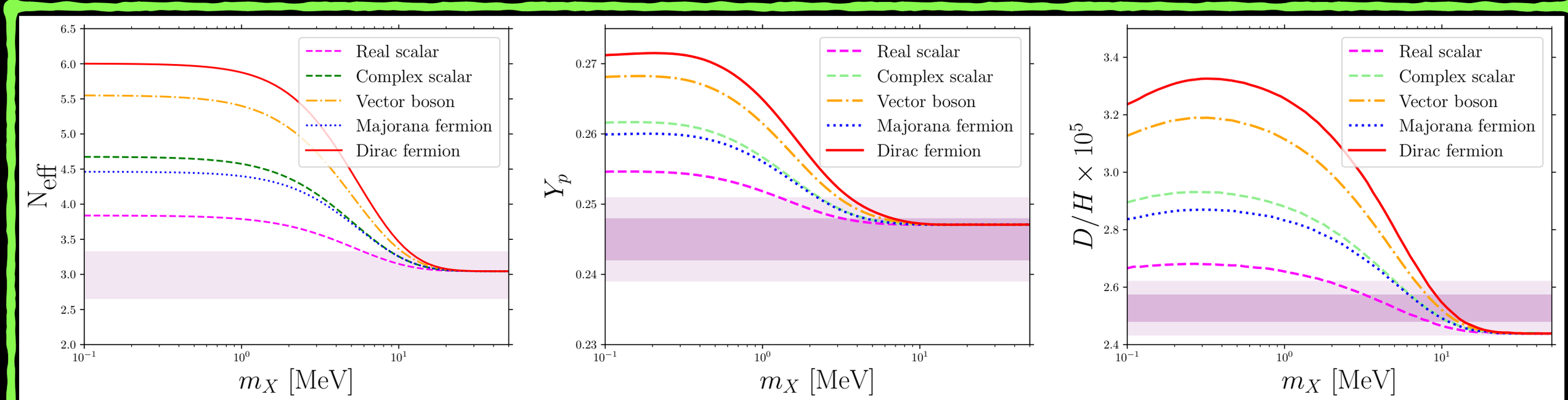
0.5‰ 1.5% vs 4%

Theoretical Uncertainty Estimates

PRyMordial: BSM Example

Electrophillic-thermalized X particle





Neutrinophillic-thermalized X particle

Hints for a Lepton Asymmetry?

- The primordial abundance of ^{4}He is sensitive to an asymmetry in the lepton sector.
- Charge neutrality forbids a large asymmetry in the charged leptons, but still allows an asymmetry between neutrinos and anti-neutrinos.
- A chemical potential for neutrinos would impact the total energy density, and contribute to ΔN_{eff}, but this is negligible for the CMB as long as:

$$|\xi_\nu| \lesssim \mathcal{O}(0.1)$$

- But in the BBN era, it also impacts the neutron-to-proton ratio, and thus production of ^{4}He!
- Helium-4 is a very sensitive *leptometer*…

$$e^- + e^+ \leftrightarrow 2\gamma\ ,\ 3\gamma$$

$$\Downarrow$$

$$\mu_\gamma = 0\ ,\ \mu_{e^-} = -\mu_{e^+} \equiv \mu_e$$

$$n_{e^-} - n_{e^+} = n_p$$

$$\Downarrow$$

$$\eta_e \propto \mu_e/T_\gamma \lesssim \eta_B \sim 10^{-10}$$

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

$$\mu_n + \mu_\nu \simeq \mu_p$$

$$\Downarrow$$

$$(n_n/n_p)|_{eq.} \simeq \exp(-Q/T - \xi_\nu)$$

PRyMordial: Lepton Asymmetry

Burns, TMPT, Valli, 2206.00693 (& PRL)

Bayes Theorem : Posterior ~ Likelihood **x** Prior

Joint analysis of BBN and CMB data (including correlations!)

$$\mathrm{TS}_{\mathrm{cosmo}} \equiv -2(\log \mathcal{L}_{\mathrm{CMB}} + \log \mathcal{L}_{\mathrm{BBN}})$$

$$\log \mathcal{L}_{\mathrm{CMB}} = -\frac{1}{2}\Delta\vec{v}^{\,T}\,\mathcal{C}_{\mathrm{CMB}}^{-1}\,\Delta\vec{v}$$

$$\Delta\vec{v} \equiv \vec{v}^{\,\mathrm{th}} - \vec{v},\ \vec{v} = (\mathrm{Y_P}, \Omega_B h^2, N_{\mathrm{eff}})^T$$

Planck 2018 TTTEEE + low-ℓ + BAO + lensing

$$\log \mathcal{L}_{\mathrm{BBN}} = -\frac{1}{2}\sum_X \left(\frac{X^{\mathrm{th}} - X}{\sigma_X}\right)^2$$

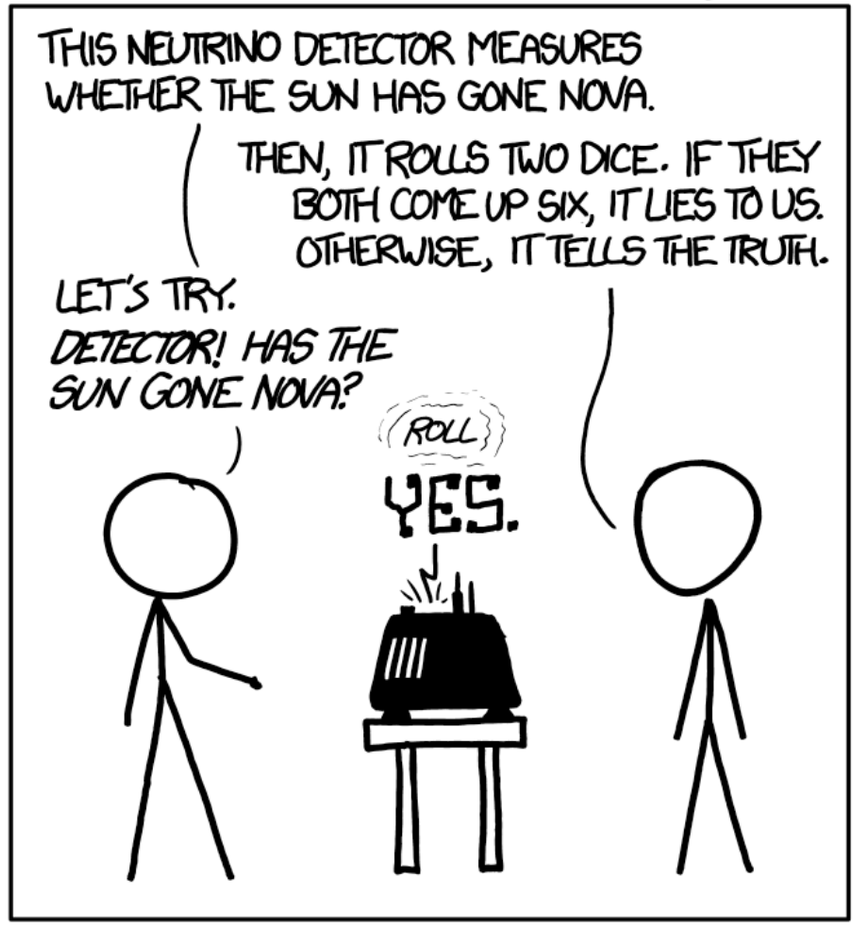
$X = {}^4He$ [Subaru 2022] , D [PDG 2021]

MAIN PARAMETERS

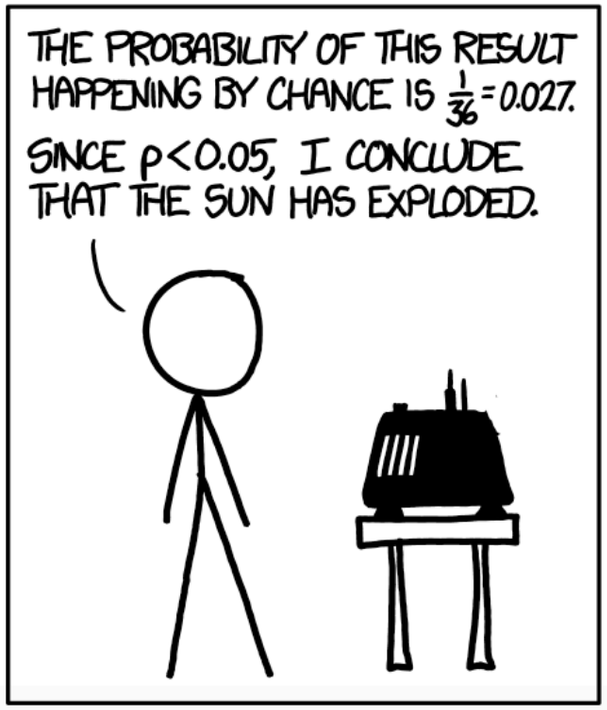
$-2 \leq \Delta N_{eff} \leq 2$ $\quad 1 \leq \eta_B \times 10^{10} \leq 10$ $\quad -0.2 \leq \xi_\nu \leq 0.2$

NUISANCE PARAMETERS: neutron lifetime [PDG 2021] (Gaussian prior), nuclear x-sec uncertainties (log-normal prior)

DID THE SUN JUST EXPLODE?
(IT'S NIGHT, SO WE'RE NOT SURE.)



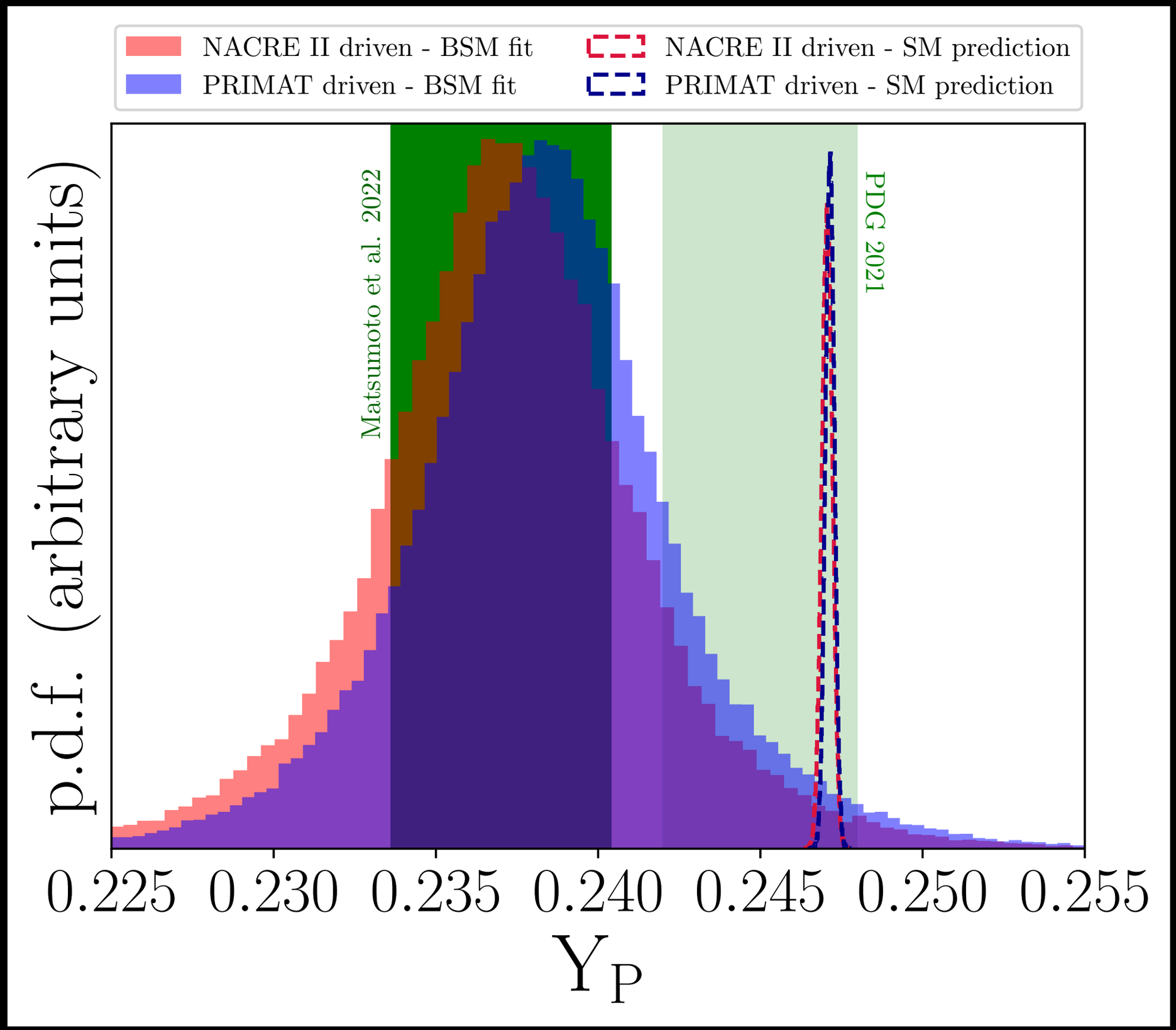
FREQUENTIST STATISTICIAN:



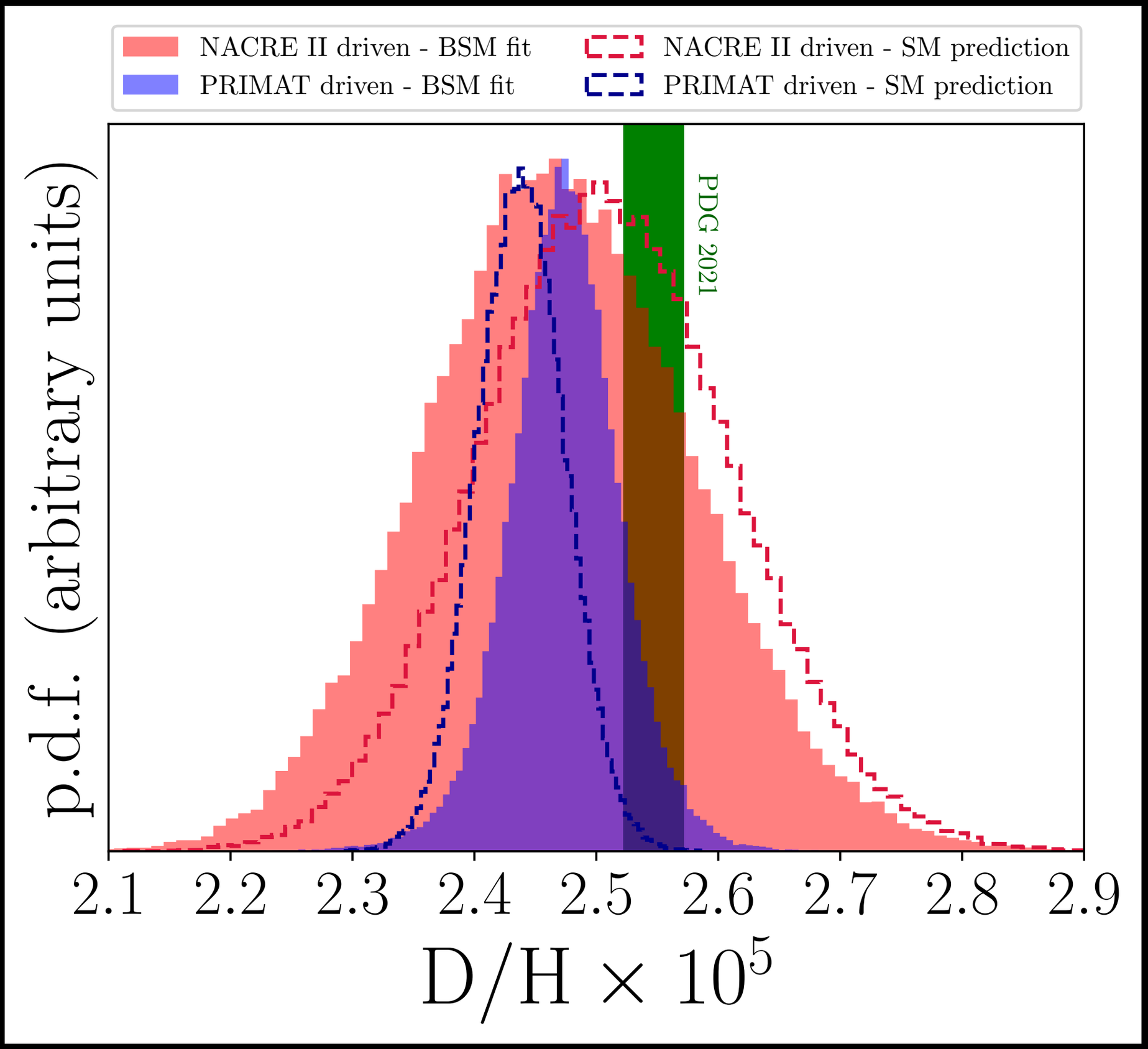
BAYESIAN STATISTICIAN:

Results: Helium-4

Burns, TMPT, Valli, 2206.00693 (& PRL)

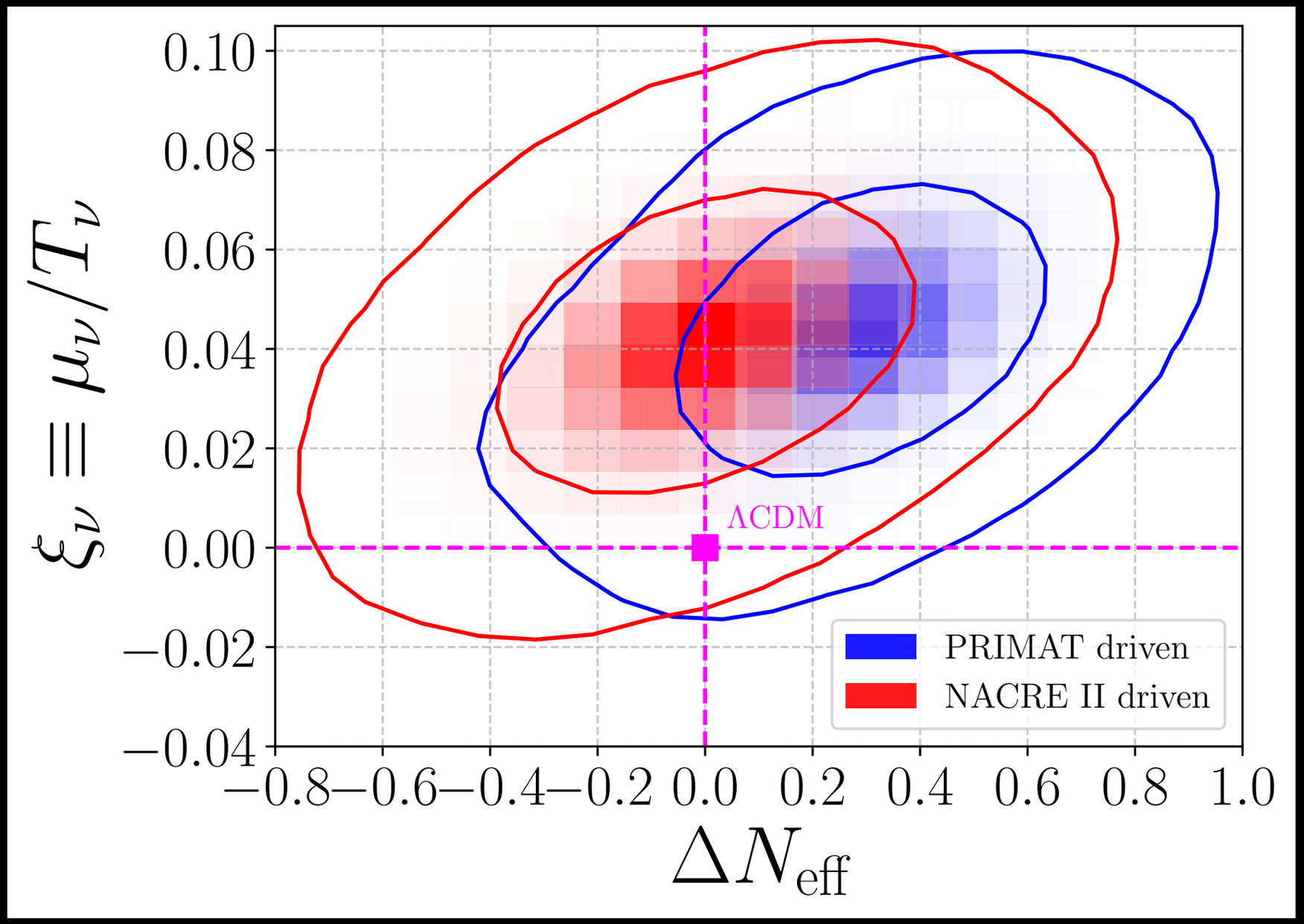


Results: Deuterium



Burns, TMPT, Valli, 2206.00693 (& PRL)

BBN 2022: New Physics Inference



Burns, TMPT, Valli, 2206.00693 (& PRL)

A non-zero lepton asymmetry is detected at the ~2σ level. The central value of the fit is ~ 0.04, independent of the implementation of the nuclear reaction network.

BBN 2022: Summary

Burns, TMPT, Valli, 2206.00693 (& PRL)

Scenario	Approach	Y_P	$D/H \times 10^5$	ΔN_{eff}	ξ_ν	$\eta_B \times 10^{10}$	ΔIC
SM prediction	PRIMAT driven	0.24715(14)	2.439(36)	–	–	6.137(38)	–
	NACRE II driven	0.24706(16)	2.51(10)	–	–	6.137(38)	–
ΔN_{eff} *BSM fit*	PRIMAT driven	0.2472(13)	2.472(45)	0.02(20)	–	6.091(66)	2
	NACRE II driven	0.2455(15)	2.46(11)	-0.26(23)	–	6.093(67)	0
$(\Delta N_{eff}, \xi_\nu)$ *BSM fit*	PRIMAT driven	0.2383(42)	2.474(46)	0.29(23)	0.044(20)	6.119(65)	8
	NACRE II driven	0.2372(43)	2.47(11)	0.00(23)	0.041(21)	6.114(68)	5

$$\Delta IC = IC_{\rm SM} - IC_{\rm NP}$$

1 to 3	Not worth more than a bare mention
3 to 20	Positive
20 to 150	Strong
>150	Very strong

Kass and Raftery `95

Akaike Information Criterion (*IC*):

$$IC \equiv 2 \times (\# d.o.f.) - 2\log(\hat{L}_{BBN})$$

to perform model comparison.

"Positive" evidence for models with non-zero lepton asymmetry.

Outlook

What does the inferred $\overline{\xi_\nu} \simeq 0.04$ imply?

Our inference *a priori* involves **only** the electron-flavor neutrino.

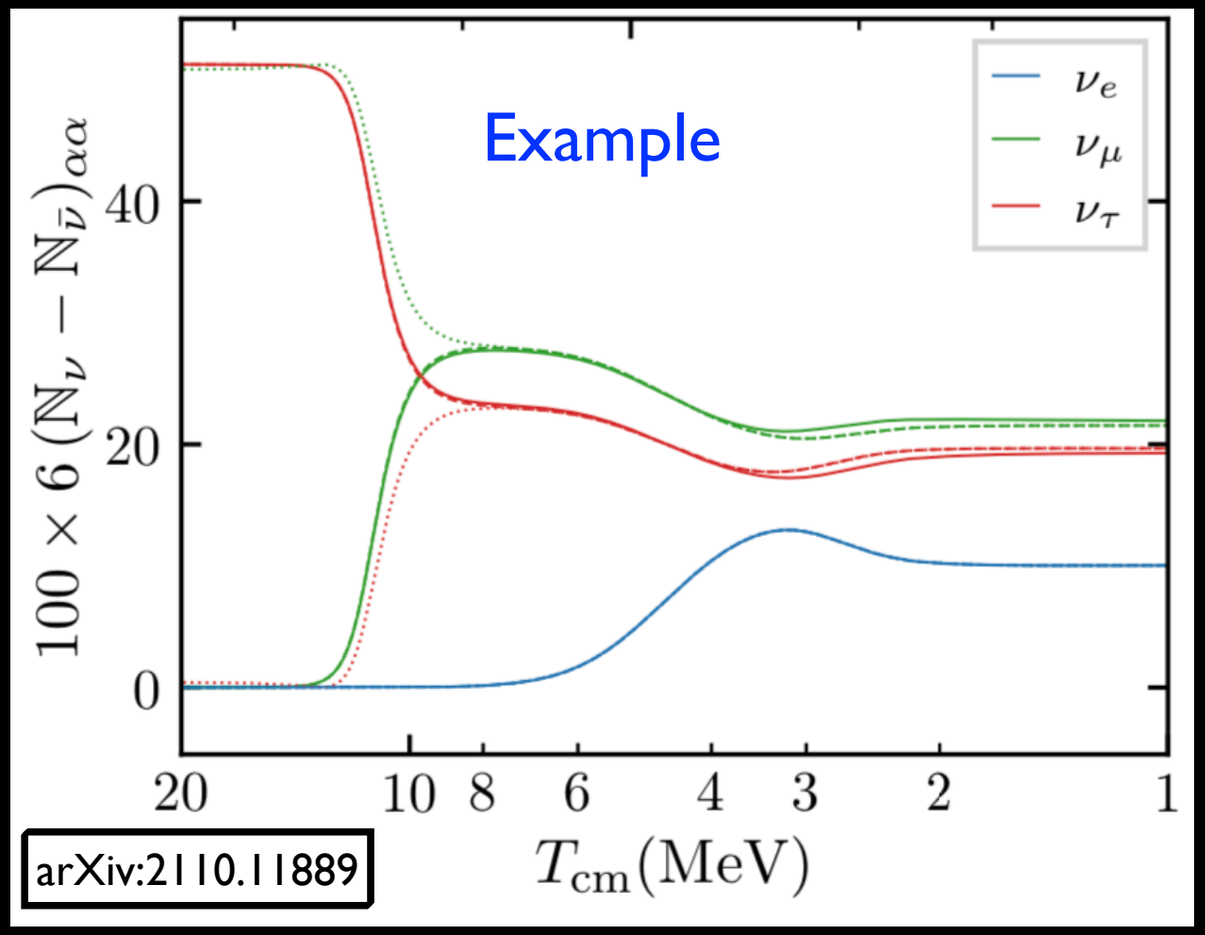
$$\eta_L \simeq \sum_{i=e,\mu,\tau} \frac{n_{\nu_i} - n_{\bar{\nu}_i}}{n_\gamma} \simeq \frac{\pi^2}{12\zeta(3)} \sum_{i=e,\mu,\tau} \left(\frac{T_{\nu_i}}{T_\gamma}\right)^3 \xi_{\nu_i} \quad \Rightarrow \quad \eta_L^0 \in (10^{-2}, 1/4)$$

LOWER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\,,\ \xi_{\nu_{\mu,\tau}} = 0$

UPPER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\,,\ \xi_{\nu_{\mu,\tau}} = 0.5$

$(\Delta N_{eff} \sim 0.1)$

Initial conditions: $\xi_{e,\mu,\tau} = (0, 0, 0.5)$



The muon & tau sectors mix efficiently @ ~ 10 MeV [astro-ph/0203442]

The final lepton asymmetry depends on the initial asymmetries and details of the PMNS matrix.

Outlook

$T \gg 100$ GeV

✳ EW symmetry unbroken, sphalerons equilibrate B+L —> $\mathcal{O}(\eta_L) \sim \mathcal{O}(\eta_B)$

POSSIBLE WAY OUT: Models where the total L asymmetry << individual ones

E.g., hep-ph/9908396:

The Small Observed Baryon Asymmetry from a Large Lepton Asymmetry*

John March-Russell[a], Hitoshi Murayama[b,c], and Antonio Riotto[a]

BUT …

arXiv:2208.03237: large lepton-flavored asymmetry → large baryon asymmetry!

chiral plasma instability

(See Kohei Kamada's talk in Thursday parallels!)

Also reminds me of: hep-ph/0610375:

Baryogenesis from an Earlier Phase Transition

Jing Shu[a,b*], Tim M.P. Tait[b†], and Carlos E.M. Wagner[a,b‡]

$T \lesssim 100$ GeV

✳ Asymmetry generated once sphalerons are inactive (but before BBN)

— Out-of-equilibrium processes w/ RH neutrinos

see, e.g., 2206.14722

— Variations of Affleck-Dine mechanism

see, e.g. 2203.09713

Outlook

✳ BBN gives us a unique view of BSM physics from the Early Universe

PRyMordial

Coming soon to an arXiv near you!

Burns, TMPT, Valli,
arXiv: 2306.XXXXX

(Already in use! See, e.g., 2210.12031)

✳ Two ongoing "anomalies": Helium-4 (obs?) & Deuterium (theory?)

$$\eta_L \simeq \eta_\nu \gg \eta_B$$

Burns, TMPT, Valli,
2206.00693 (& PRL)

✳ Bucket list for the future:

— Measuring Helium-4 beyond % level

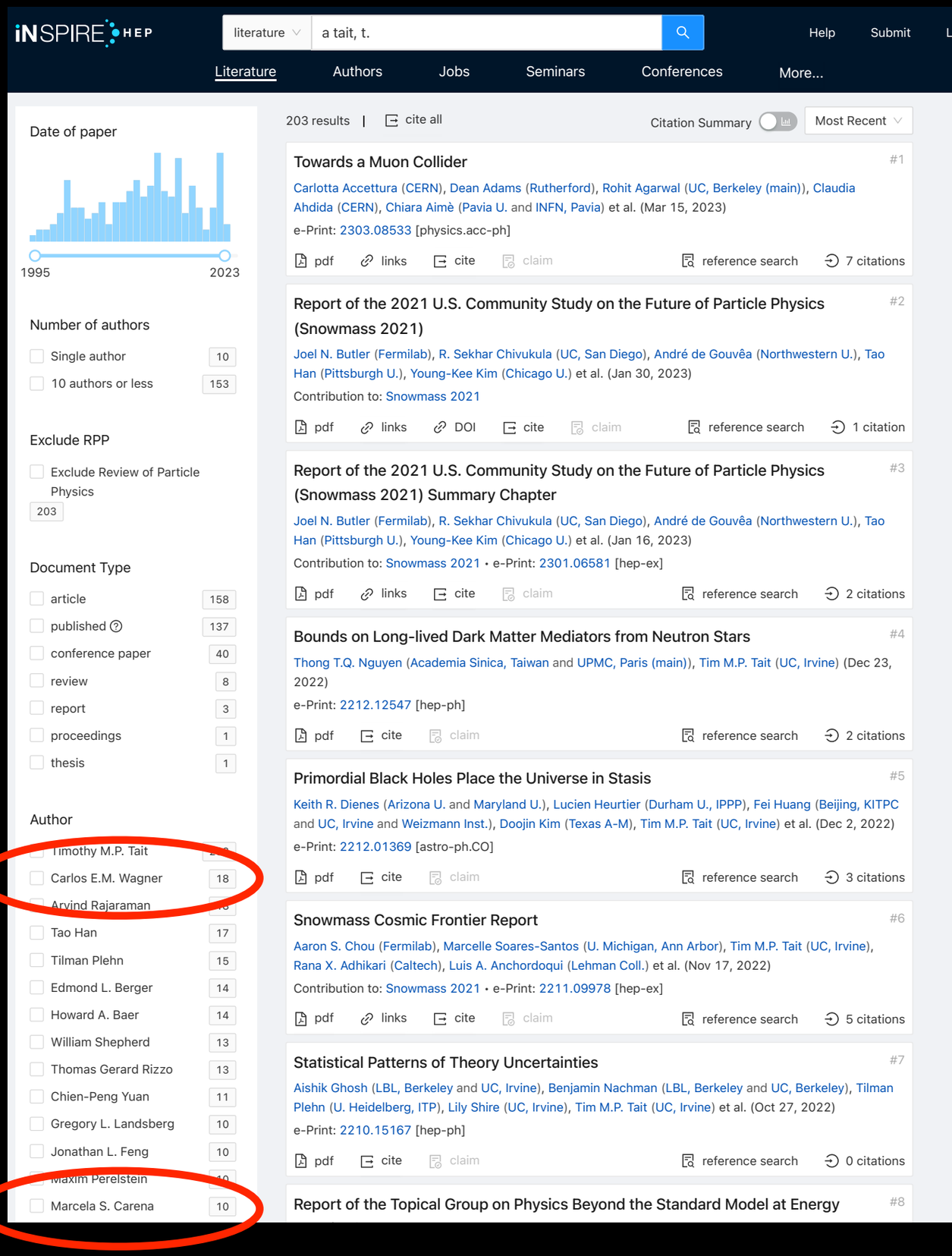
— More data on DD fusion x-sections

— Next-gen CMB observations

(see projections in 2208.03201)

Impact

- As is true for many in this room, Marcela and Carlos have had a profound impact on my career.
- I'm lucky that I have had many important and effective mentors at every stage of my development as a physicist.
- Marcela and Carlos stand out as the mentors who were perhaps more like the physicist that I aspired to be than any of the others.
- At a time in my career when I could have fallen through the cracks, they both took care to make sure that it didn't happen.



Carlos Wagner is with **Marcela Carena** and **2 others**.
October 8, 2019 ·

It is amazing how fast the children grow ! And I am not necessarily talking about Sebastian... Encountering familiar faces at the Cosmic Controversies conference in Chicago.

You, Howard Haber, Thomas G Rizzo and 75 others 5 comments

Like Comment Share

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Jürgen R. Reuter
Haha, I know that this is not a respectful statement, but it is not meant disrepectful: **Carlos Wagner** still looks (and will always look) like a 10-year old boy who is going to steal the chocolate next

Like Reply 3y 2

Carena-Wagner Golden Rules

- Synthesizing my observations, I would like to suggest that Carlos and Marcela's lived behavior suggests a new set of 'Golden rules':
  - The world is filled with interesting phenomena. Physics is how we engage with them.
  - More impoprtantly, Physics is fun, and you should always have fun doing it.
  - The friends that you assemble along the way are a network that will enrich your life and your work.
  - Your investment in them is also an investment in yourself.
  - And BE CAREFUL WHAT YOU THINK ABOUT!

    (Especially if it is SUSY…)

Thank You!

Visit to UC Irvine, about one week before the pandemic started…

Bonus

The BBN Era

At the qualitative level, BBN is fairly easy to understand.

For T $\gtrsim$ 10 MeV, the SM contains relativistic species $(\gamma, e^{\pm}, \nu)$:

$$H^2 \simeq \frac{1}{3M_{Pl}^2}\,\frac{\pi^2}{30}\left(2 + 2\times 2\times\frac{7}{8} + 2\times\frac{7}{8}N_\nu\right)T_\gamma^4$$

From the 2nd law of thermodynamics and energy-momentum conservation:

$$d(sa^3)/dt = 0 \quad , \quad s = (\rho + P)/T_\gamma$$

One can derive the temperature of the photons as a function of time/scale factor:

$$T_\gamma(t)\ ,\ T_\gamma(a)$$

The BBN Era

As the Universe expands and cools, eventually the weak interactions freeze out:

$$H \sim \Gamma_{weak} \sim n\langle \sigma v \rangle \sim T^3 \times G_F^2 T^2 \quad \Rightarrow \quad T_{f.o.}^{(weak)} \sim \text{MeV}$$

Based on entropy conservation, for $T_\gamma \leq m_e$:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \;\Leftrightarrow\; N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{tot.} - \rho_\gamma}{\rho_\gamma}\right) = 3.044$$

SM prediction

e.g., arXiv: 2210.10307

Thus, one can derive the temperature of the photons as a function of time/scale factor and relate it to the temperature of the neutrinos:

$$T_\gamma(t)\ ,\ T_\gamma(a)\ ,\ \boxed{T_\nu(T_\gamma)}$$

The BBN Era

$T_\nu(T_\gamma)$ is relevant for the β-equilibrium, $n \leftrightarrow p$:

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

$$(n_n/n_p)\,|_{T \gtrsim MeV} \simeq \exp(-Q/T)$$

$Q \equiv m_n - m_p \simeq 1.3\,\mathrm{MeV}$

$$(n_n/n_p)\,|_{T \simeq MeV} \simeq 1/6$$

Nucleosynthesis is naively at $T_{nucl.} \sim B_D \simeq 2.2$ MeV … BUT:

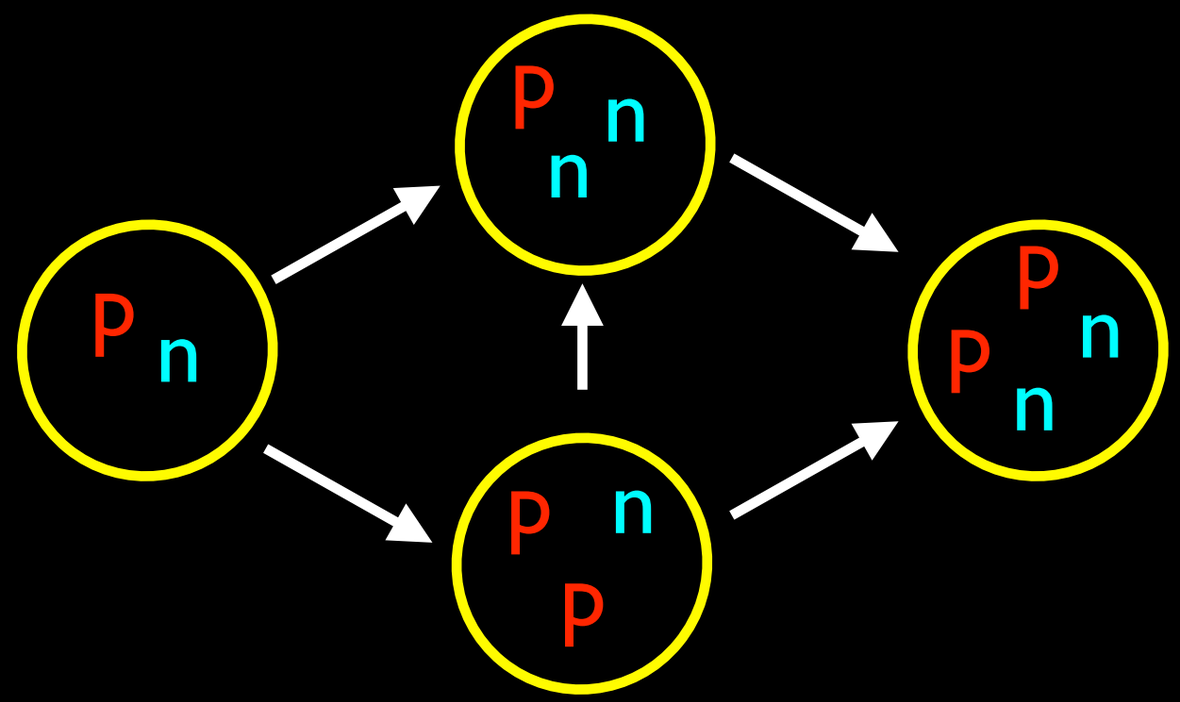
$$\Gamma(n + p \to D + \gamma) \sim n_B \langle \sigma v \rangle_{D\gamma}$$

$$\Gamma(n + p \leftarrow D + \gamma) \sim n_\gamma \exp(-B_D/T_\gamma) \langle \sigma v \rangle_{D\gamma}$$

It *really* starts at T_{nucl} such that: $\eta_B \simeq \exp(-B_D/T_{nucl.})$

The BBN Era

The deuterium "bottleneck" implies $T_{nucl} \simeq 0.1$ MeV. After that :



Essentially all of the neutrons are bound into helium-4…

$$(n_n/n_p)|_{T \simeq 0.1 \text{ MeV}} \simeq 1/7$$

$$Y_P \equiv \frac{m_{^4He}}{m_B} \simeq \frac{4(n_n/2)}{n_n + n_p} \simeq 0.25$$

Baryon mass fraction in helium-4

$\mathcal{O}(10^{-5})$ residual amount of deuterium and helium-3 relative to p.

Lithium-7 "survives" in a much smaller relative abundance, $\mathcal{O}(10^{-10})$.

BBN Observations

To match theory, we need quality measurements of the primordial abundances of the light elements: D, ^3He, ^4He, ^7Li

★ Helium-4 observed in extragalactic HII regions

Emission spectra of gas clouds (detailed line modeling required)

★ Deuterium observed in Quasar absorption systems

Damped Lyman-α spectra from intervening gas along l.o.s.

★ Helium-3 observed in the Solar neighborhood

Solar winds, meteorites, ISM … stellar nucleosynthesis uncertainties!

★ Lithium-7 in the atmosphere of dwarf halo stars

Physics of convection, depletion indicators … needs support from data

BBN Observations

To learn something, we need quality measurements of the primordial abundances of the light elements: D, ^3He, ^4He, ^7Li

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? Lithium-7 in the atmosphere of dwarf halo stars

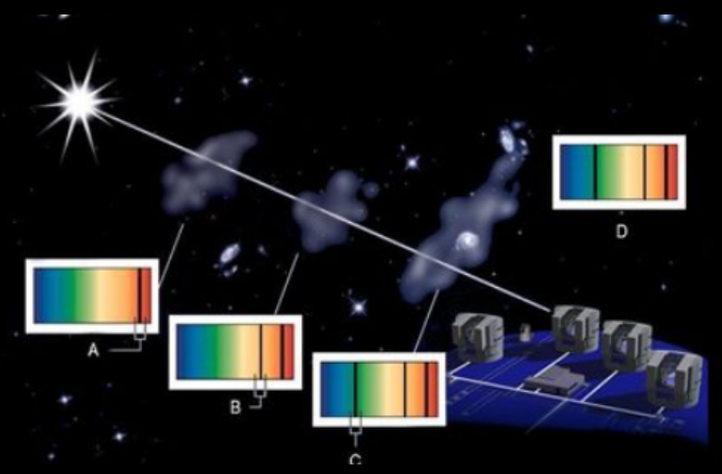
Physics of convection, depletion indicators … needs support from data

Fields, Olive arXiv:2204.03167

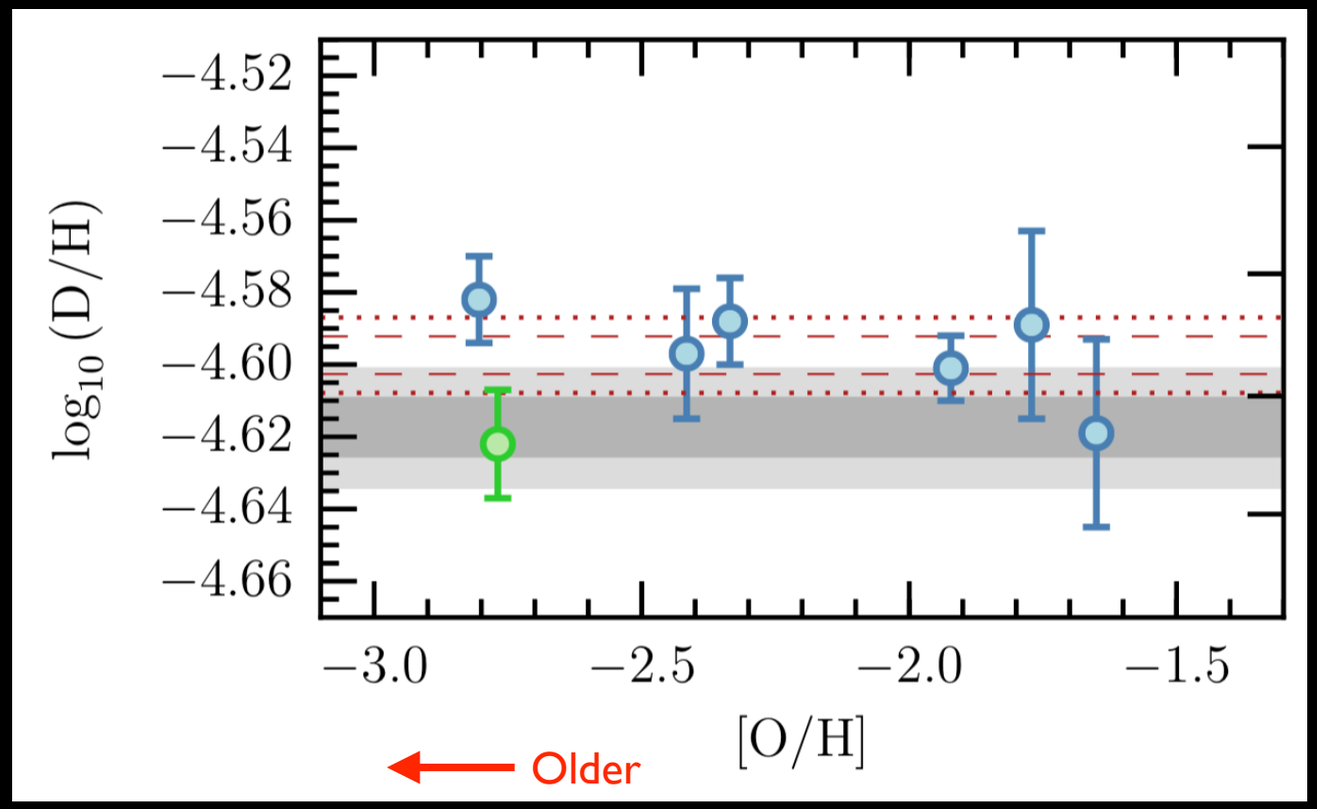
Deuterium

PDG 2021:

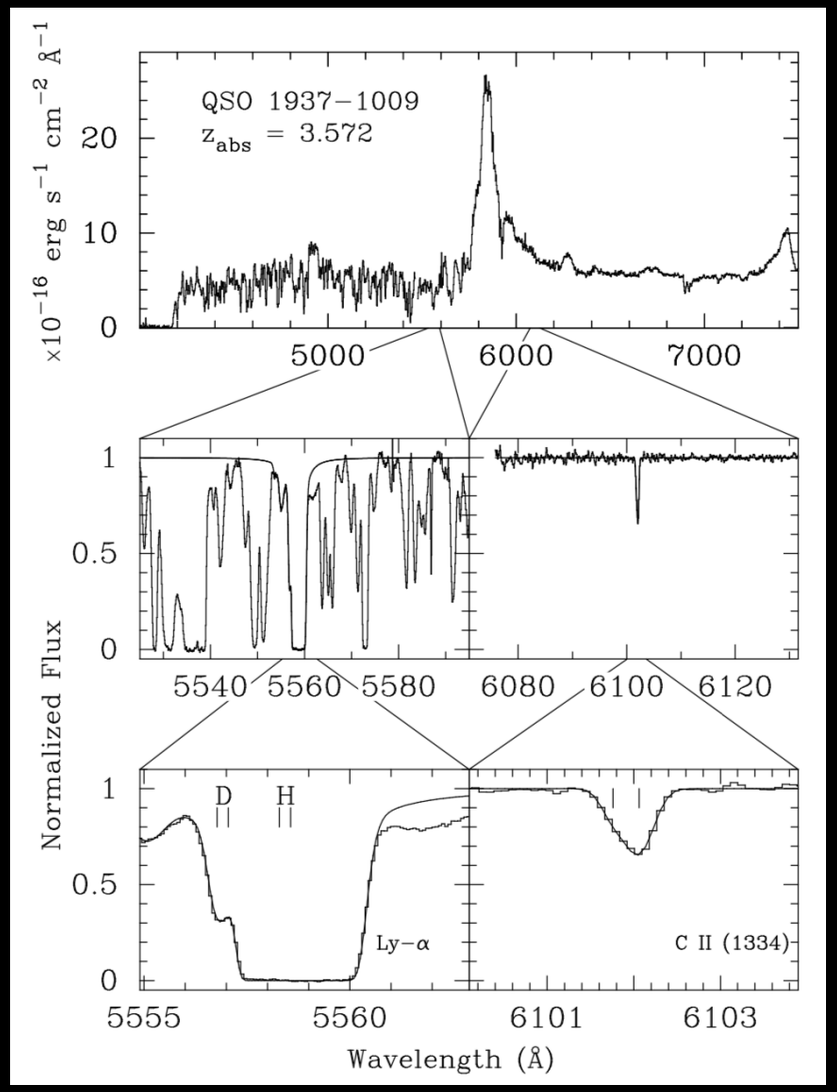
$$(D/H) \times 10^5 = 2.547 \pm 0.025$$



% level measurement



arXiv: 1710.11129



astro-ph/9803071

wikiHow: PRyMordial

```
PRyMordial_vBeta — Python runPRyM_SM_example.py — 80×10
Last login: Wed Nov 10 17:59:54 on ttys000
mbp-di-mauro:~ mauro_87$ cd Desktop/PRyMordial_vBeta/
mbp-di-mauro:PRyMordial_vBeta mauro_87$ python3 runPRyM_SM_example.py
```

runPRyM_XX_example.py

#0

PRyM_init.py

#1

PRyM_thermo.py

#2 : bckg + N_{eff}

PRyM_main.py

PRyM_nTOp.py

#3 : weak rates

#5 : interpolation

#4

PRyM_eval_nTOp.py

#6 : ODE systems

PRyM_nuclear_net.py

#7

```
##################
PRyMordial results
##################
Neff -->  3.0452714140682438
Yp -->  0.24709402881702736
D/H x 10^5 -->  2.438952842054179
(He3+T)/H x 10^5 -->  1.03826086327731
(Li7+Be7)/H x 10^10 -->  5.545267496680167

--- running time: 16.100466012954712 seconds ---
mbp-di-mauro:PRyMordial_vBeta mauro_87$
```