— Firenze —
2 February 2024

THE QCD AXION:
Some Like It Hot

Mauro Valli

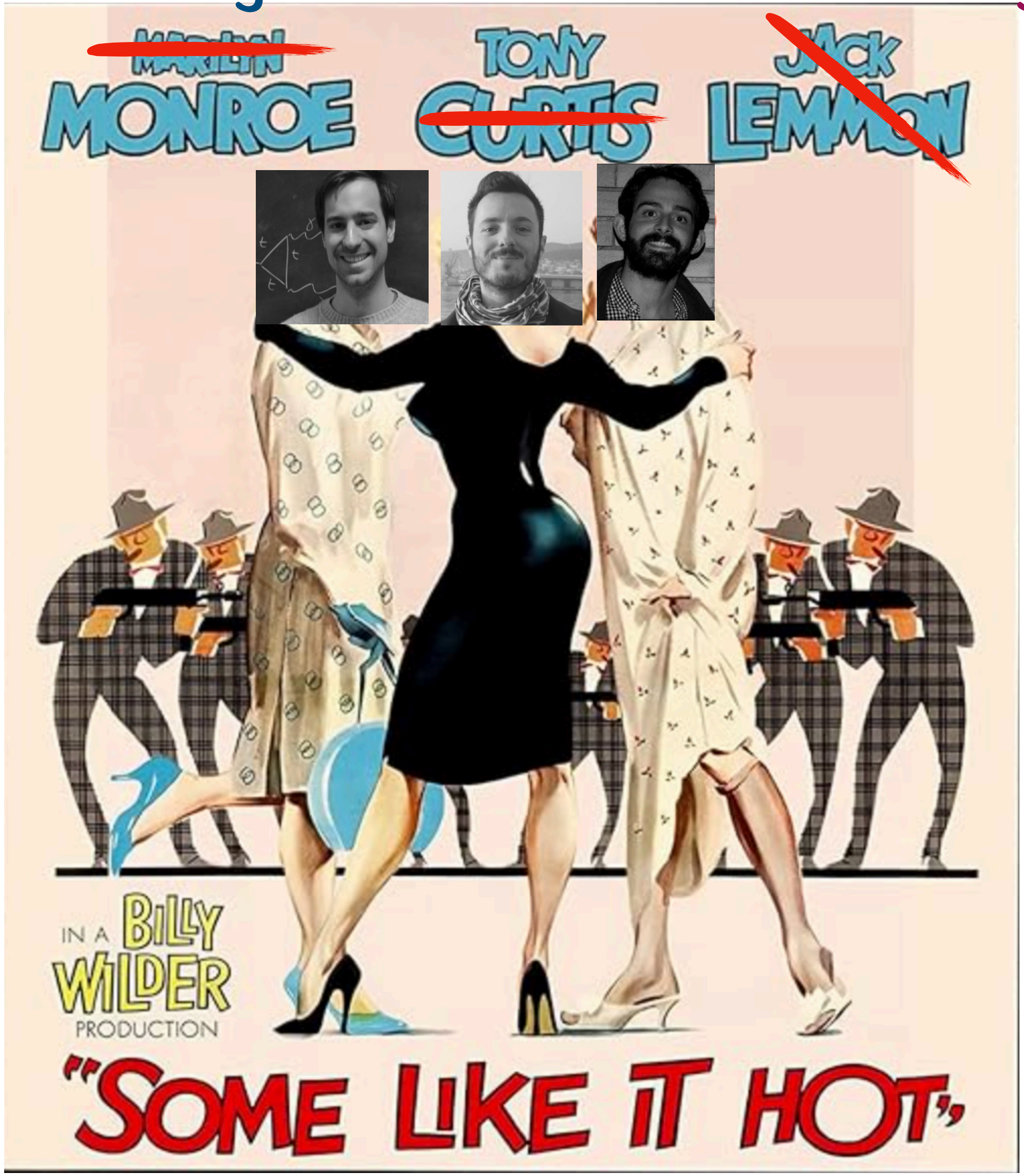
INFN Rome

A **SISSA** MOVIE

ASTROPARTICLE PHYSICS
Maurilyn

THEORETICAL PARTICLE PHYSICS
di Cortona

ASTROPHYSICS
Fred Whitey



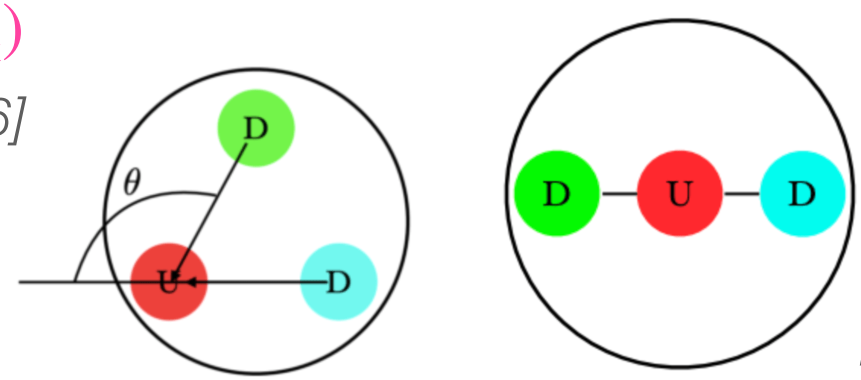
arXiv:**2310.08169**

Minimal QCD Axion

- It couples to Topological Charge Density: $\mathcal{Q} \equiv \frac{\alpha_s}{8\pi f_a} G\widetilde{G}$

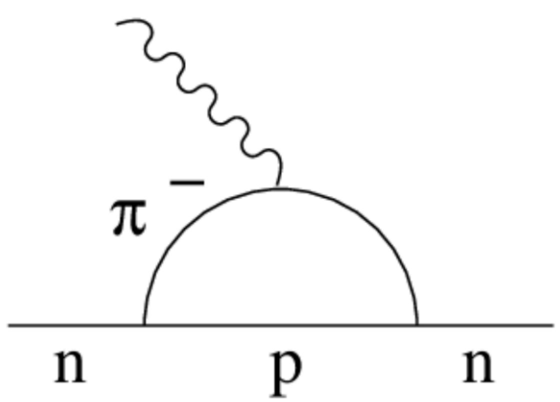
$f_a = 5.7 \times 10^6\,\mathrm{GeV}\,(\mathrm{eV}/m_a)$

[Grilli, Hardy, Pardo, Villadoro `16]



[Hook `21]

Coupling required to *"relax"* the Strong CP problem, namely:



$$\sim \theta \frac{m_q}{m_N^2} e \sim \theta \frac{10^{-2}}{\mathrm{GeV}} e \sim \theta \cdot 10^{-16}\,\mathrm{cm} \cdot e \quad \text{VS} \quad d_n^{\exp}$$

$(\mathrm{GeV}^{-1} \sim 10^{-14}\,\mathrm{cm})$

$\lesssim 10^{-26}\,\mathrm{cm} \cdot e$

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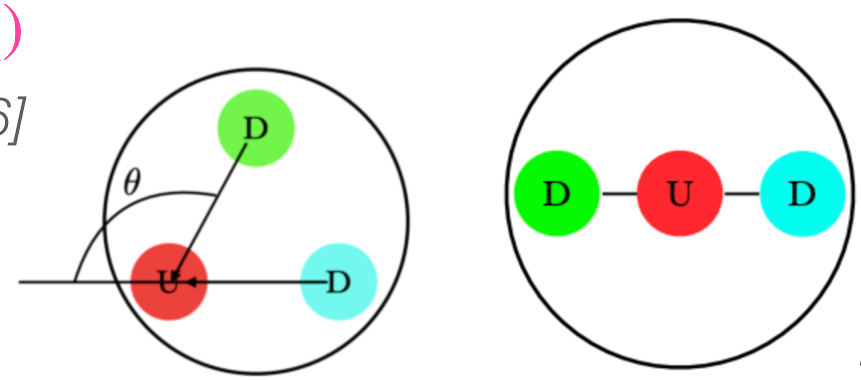

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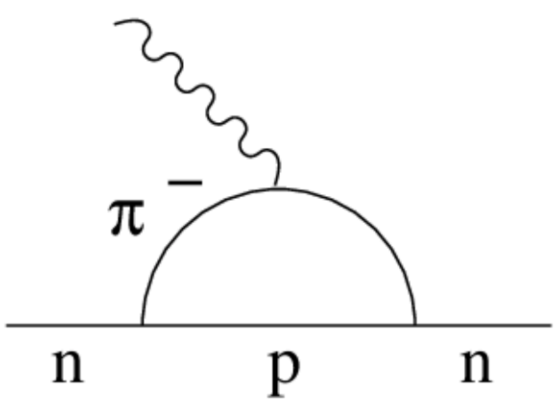

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$(\mathrm{GeV}^{-1} \sim 10^{-14}\,\mathrm{cm})$

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$$\theta \lesssim 10^{-10}$$

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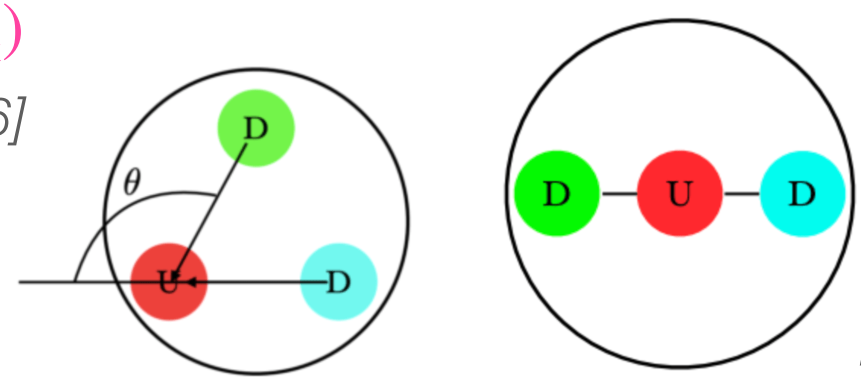
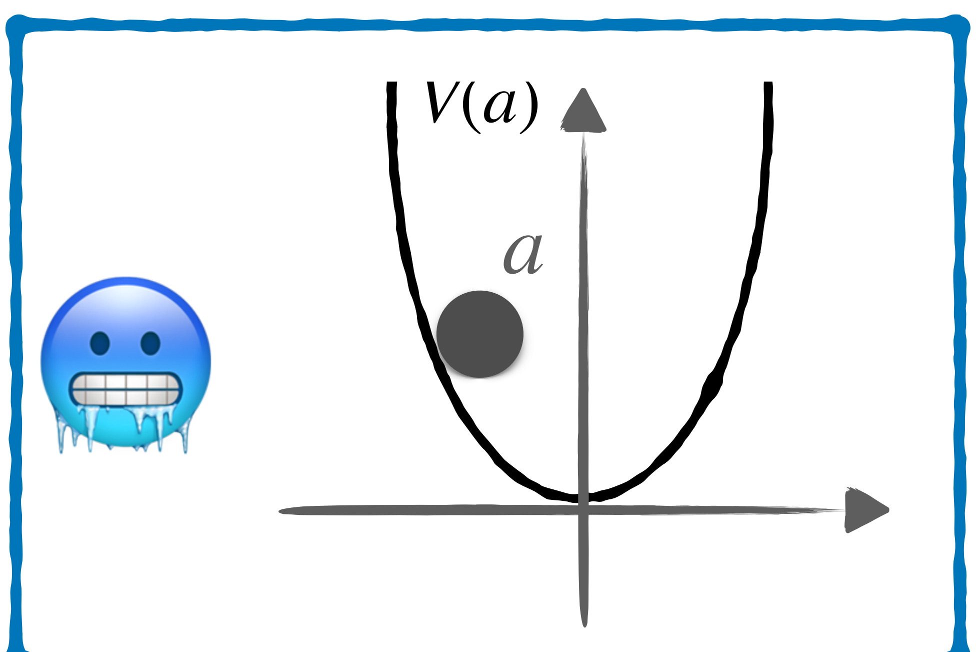
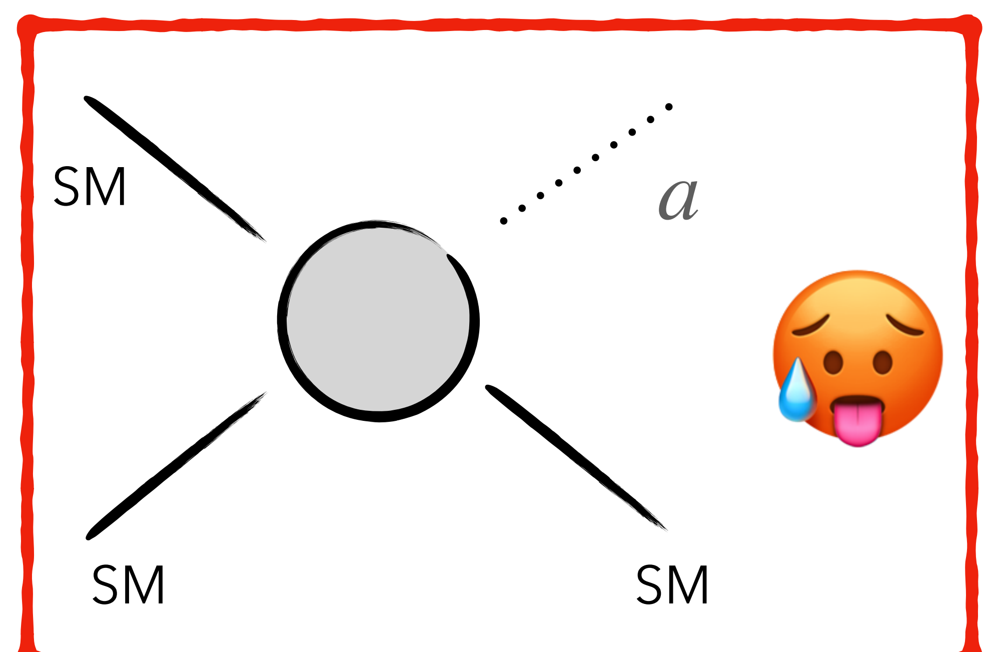


[Hook `21]

⇨ BSM imprints to cosmological history of the Universe!



momenta $\ll$ *temperature*



momenta $\gtrsim$ *temperature*

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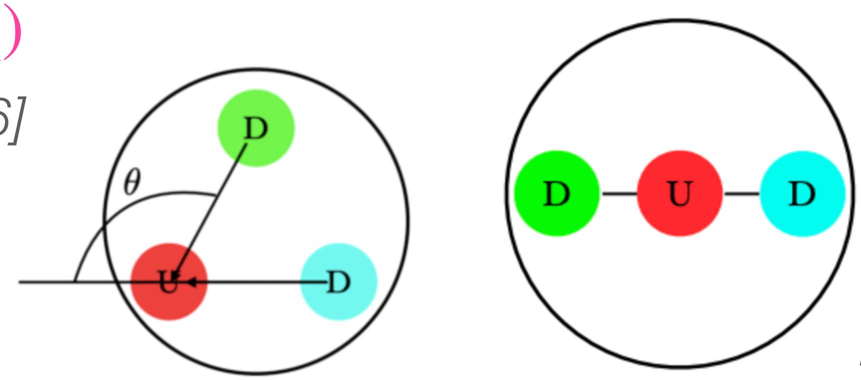

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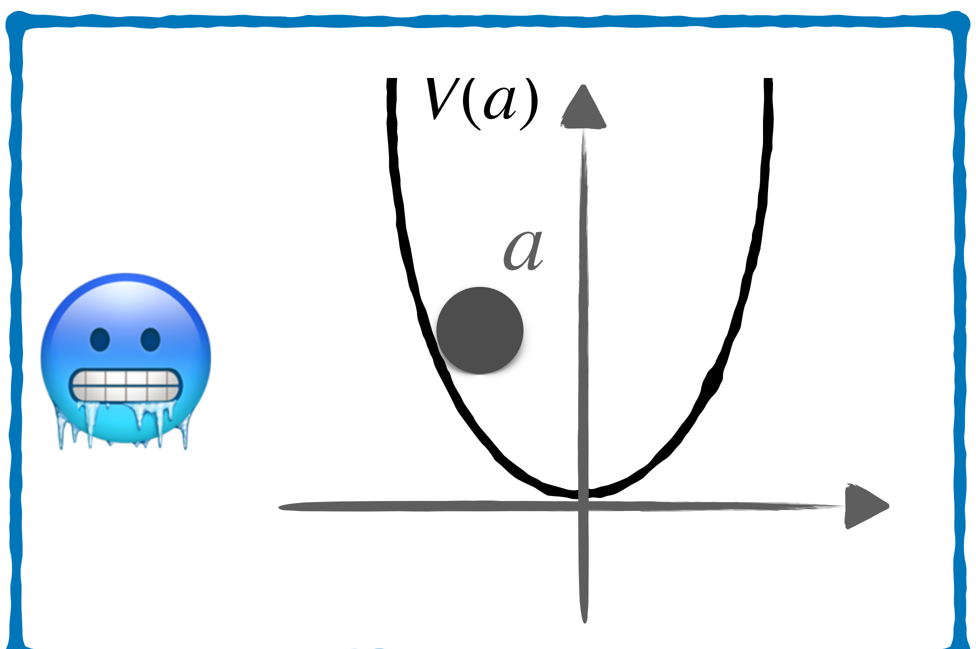
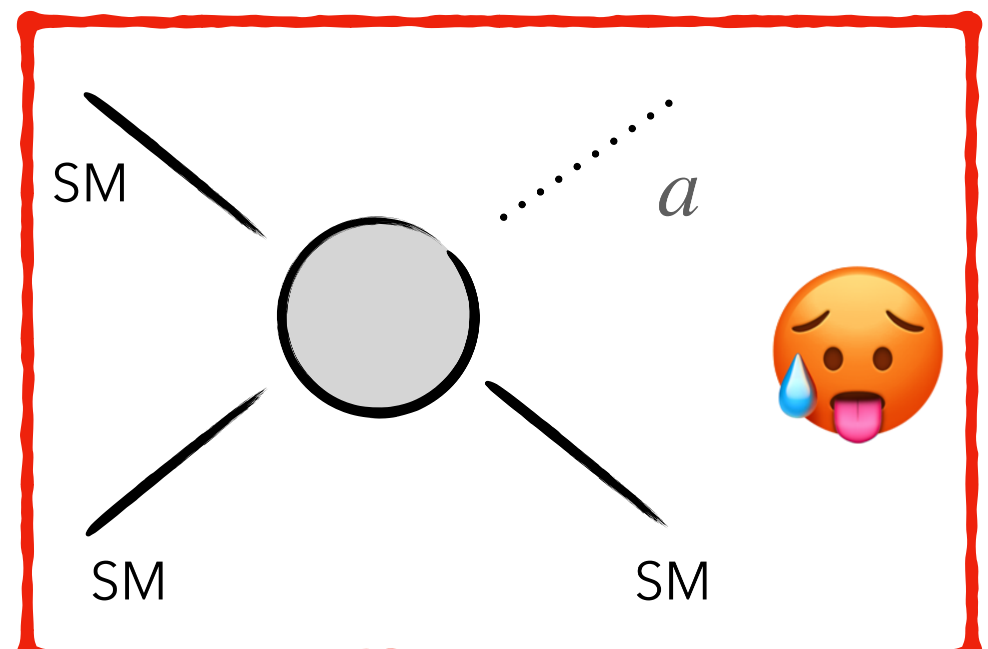


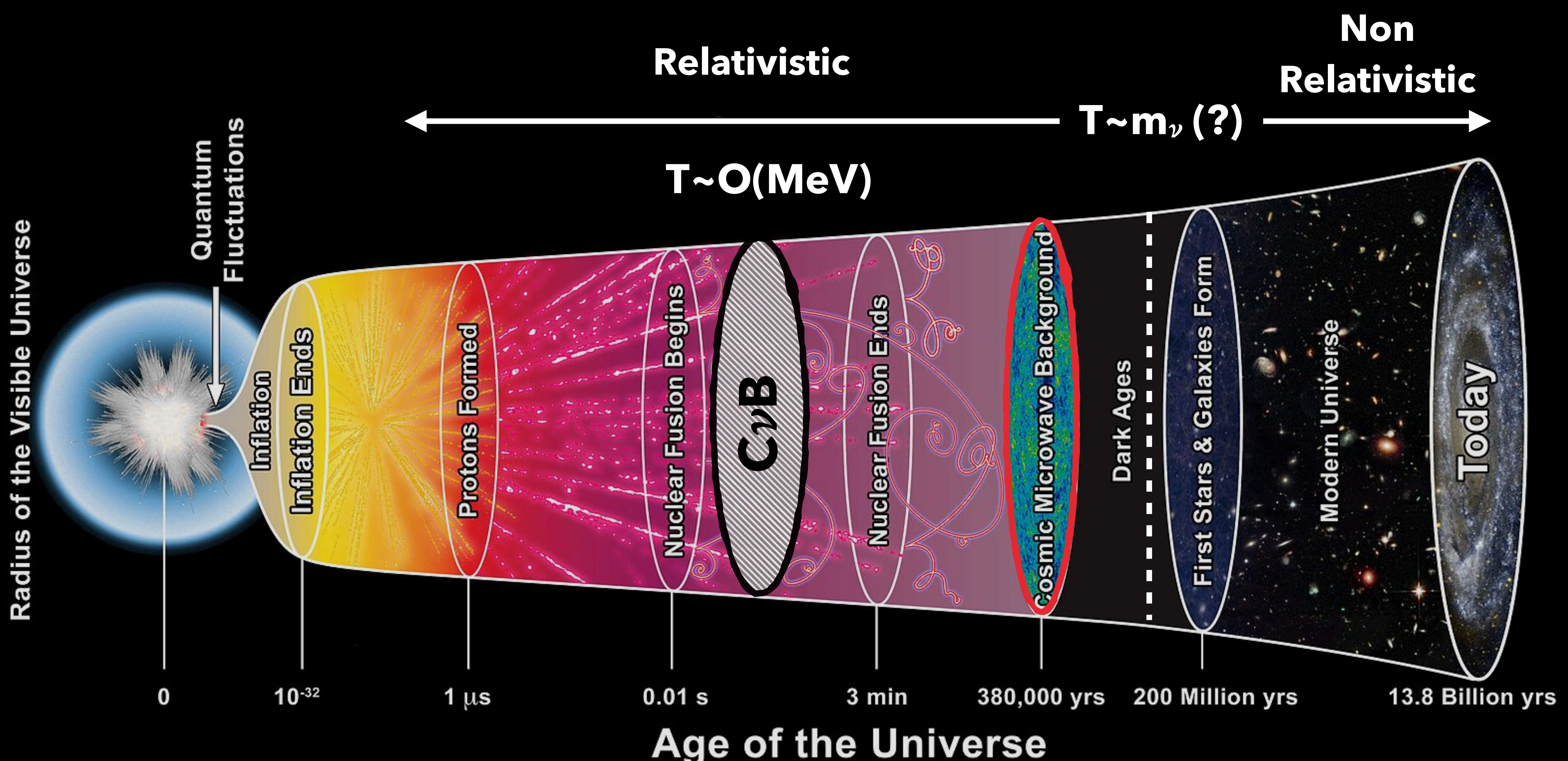


a: *MIGHT ADDRESS CDM*

a: *<u>VERY LIKELY</u> A HOT RELIC*

SOME LIKE IT HOT: Axions ~ Neutrinos

Neutrino cosmology 101



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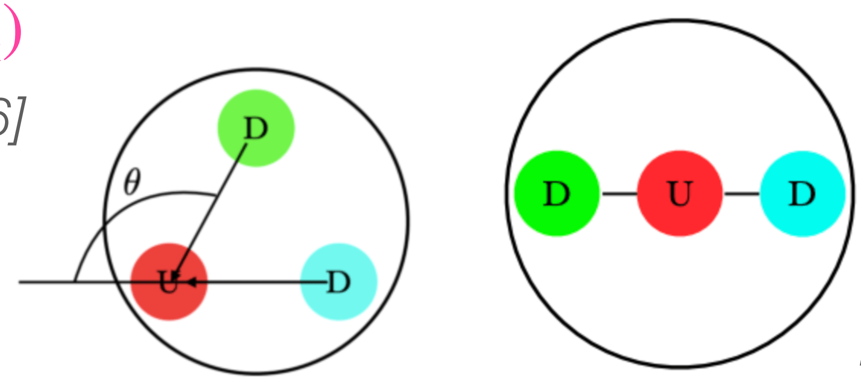


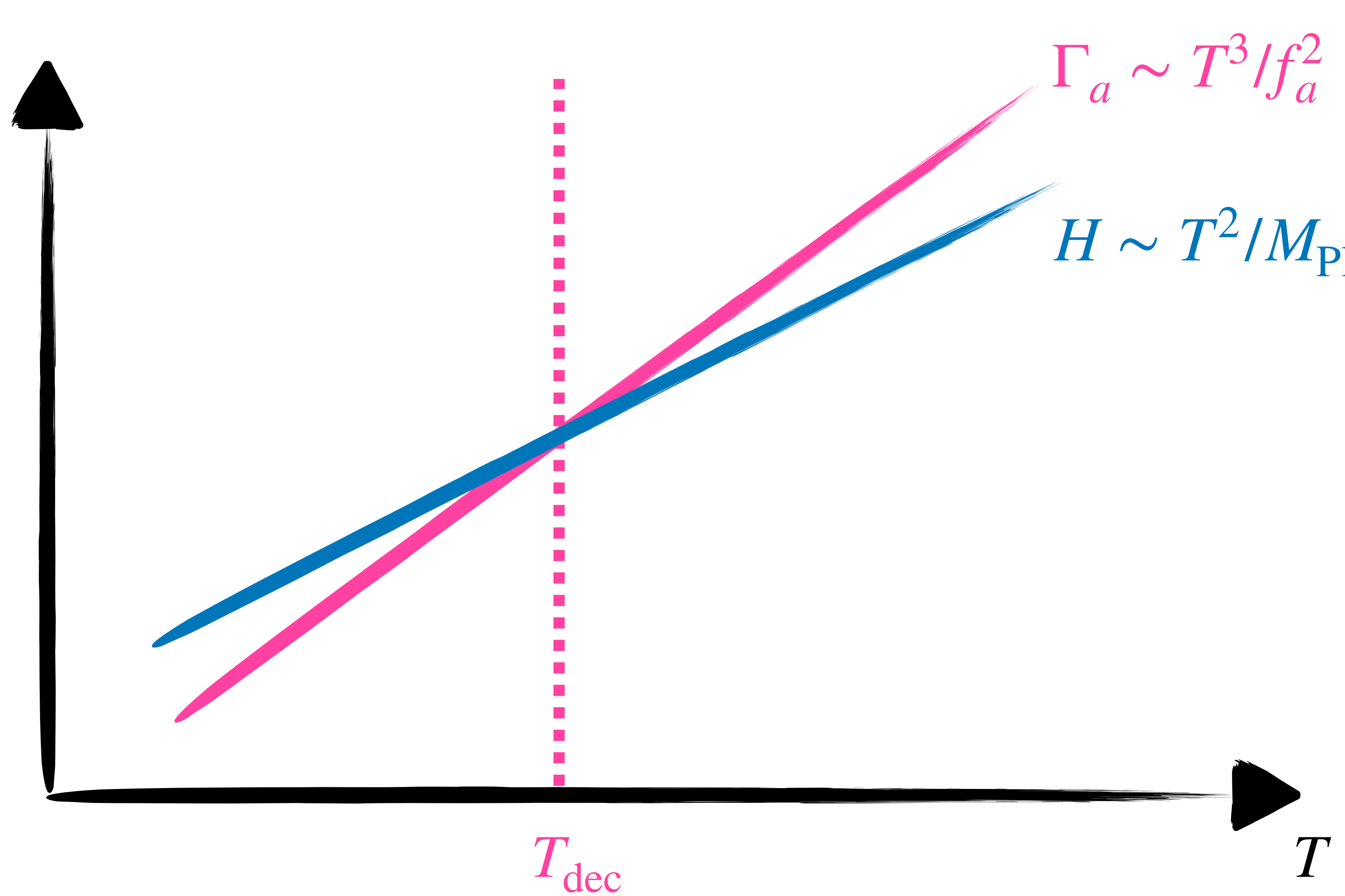
[Hook `21]

$T_{\rm dec}$

Decoupling happening roughly at temperature :

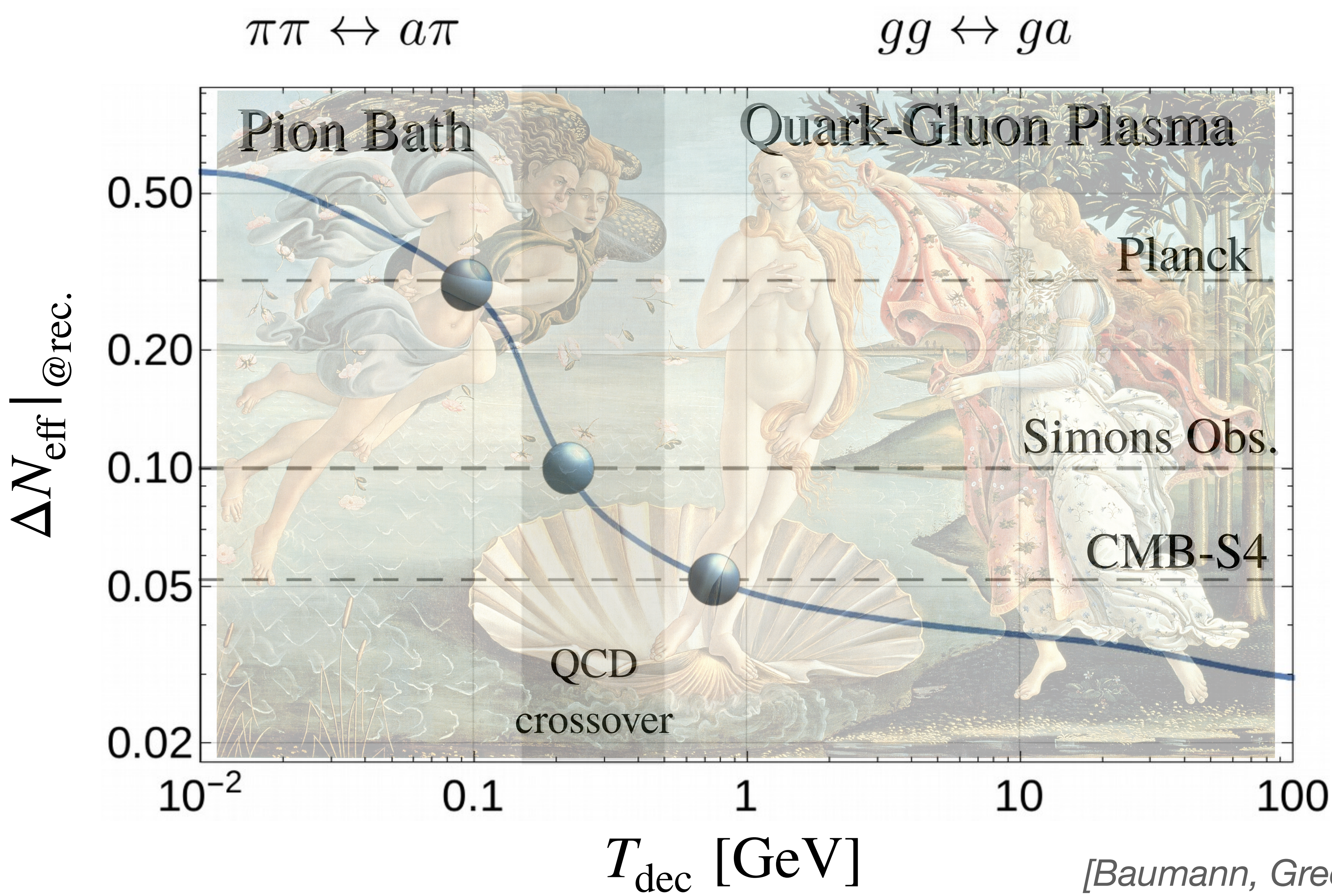
$\mathcal{O}(\mathrm{MeV}) \times (\mathrm{eV}/m_a)^2$

i.e. smaller mass, higher decoupling temperature!



Minimal QCD Axion

$$\Delta N_{\text{eff}}\big|_{@\text{rec.}} \equiv \frac{\rho_a(m_a)}{\rho_\nu}\bigg|_{T_{\text{CMB}}} \simeq \frac{4}{7}\left(\frac{11}{4}\frac{g_\star(T_{\text{CMB}})}{g_\star(T_D(m_a))}\right)^{4/3}$$

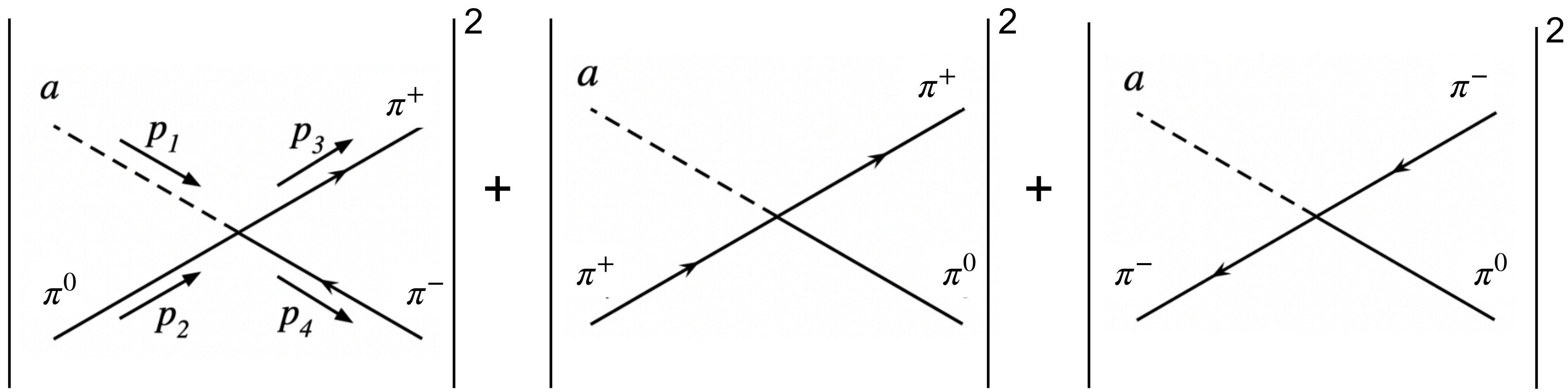


[Baumann, Green, Wallisch `16]

Hot Axions from pions

[Georgi, Kaplan, Randall `86]

$$\mathscr{L}_{a\pi}^{\rm LO} = \frac{C_{a\pi}}{f_a f_\pi}\partial^\mu a \left(2\partial_\mu\pi^0\pi^+\pi^- - \pi^0\partial_\mu\pi^+\pi^- - \pi^0\pi^+\partial_\mu\pi^-\right)$$



$$\sum |\mathcal{M}|^2_{\rm LO} = \left(\frac{C_{a\pi}}{f_a f_\pi}\right)^2 \frac{9}{4}\left[s^2 + t^2 + u^2 - 3m_\pi^4\right]$$

- $\langle E_\pi \rangle \simeq \rho_\pi / n_\pi \simeq 3T \;\Rightarrow \sqrt{s} \gtrsim 500\,\text{MeV} \;@\; T \sim 100\,\text{MeV}$
- $\Gamma_a^{\rm (NLO)} \sim \Gamma_a^{\rm (LO)}$ for T > 70 MeV [Di Luzio, Martinelli, Piazza `21]

Hot Axions from pions

General form of low energy axion QCD Lagrangian:

$$\mathcal{L} = \bar{q}\left(i\partial\!\!\!/ + \frac{c_0}{2f_a}\partial\!\!\!/ a\,\gamma_5\right) q - \bar{q}_L M_a q_R + h.c.\,, \qquad M_a \equiv \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} e^{i\frac{a}{2f_a}(1+c_3\sigma^3)}$$

$$\frac{\partial_\mu a}{2f_a} j_A^\mu \overset{\chi\mathrm{PT}}{=} \mathcal{O}(M_q)$$

$$\pi^0 = \cos(\theta_{a\pi})\,\pi^0_{\mathrm{phys}} + \sin(\theta_{a\pi})\,a_{\mathrm{phys}} \simeq \pi^0_{\mathrm{phys}} + \theta_{a\pi} a_{\mathrm{phys}}$$

<u>@ all orders in χPT</u>

$$\mathcal{M}_{a\pi^i\to\pi^j\pi^k} = \theta_{a\pi}\cdot\mathcal{M}_{\pi^0\pi^i\to\pi^j\pi^k} + \mathcal{O}\left(\frac{m_\pi^2}{s}\right)$$

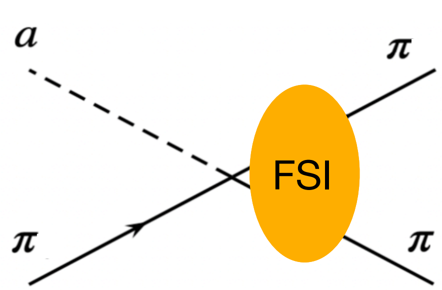
$\lesssim 10\%$

e.g. @ LO

$$|\mathcal{M}^{\mathrm{LO}}|^2 = \theta_{a\pi}^2\frac{s^2+t^2+u^2-3m_\pi^4}{f_\pi^4} \qquad |\mathcal{M}^{\mathrm{LO}}_{\pi\pi}|^2 = \frac{s^2+t^2+u^2-4m_\pi^4}{f_\pi^4}$$

Hot Axions from pions

G.Piazza @ NP Signal `23



$\pi\pi$ final-state interactions (FSI) are resonant

ChPT cannot produce resonances

σ or $f_0(500)$ in $I = L = 0$

$\rho(770)$ in $I = L = 1$

✤Inverse Amplitude Method (IAM): [Truong, PRL **61**, 2526]

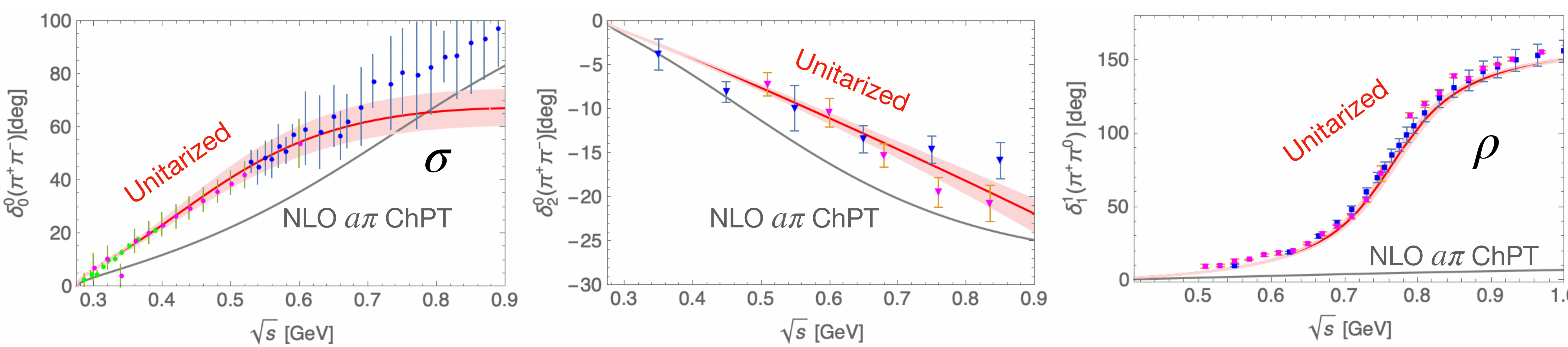
Definite I, J amplitudes

$$A_{IJ}(s) = \frac{A_{IJ}^{(2)}(s)}{1 - A_{IJ}^{(4)}(s)/A_{IJ}^{(2)}(s)}$$

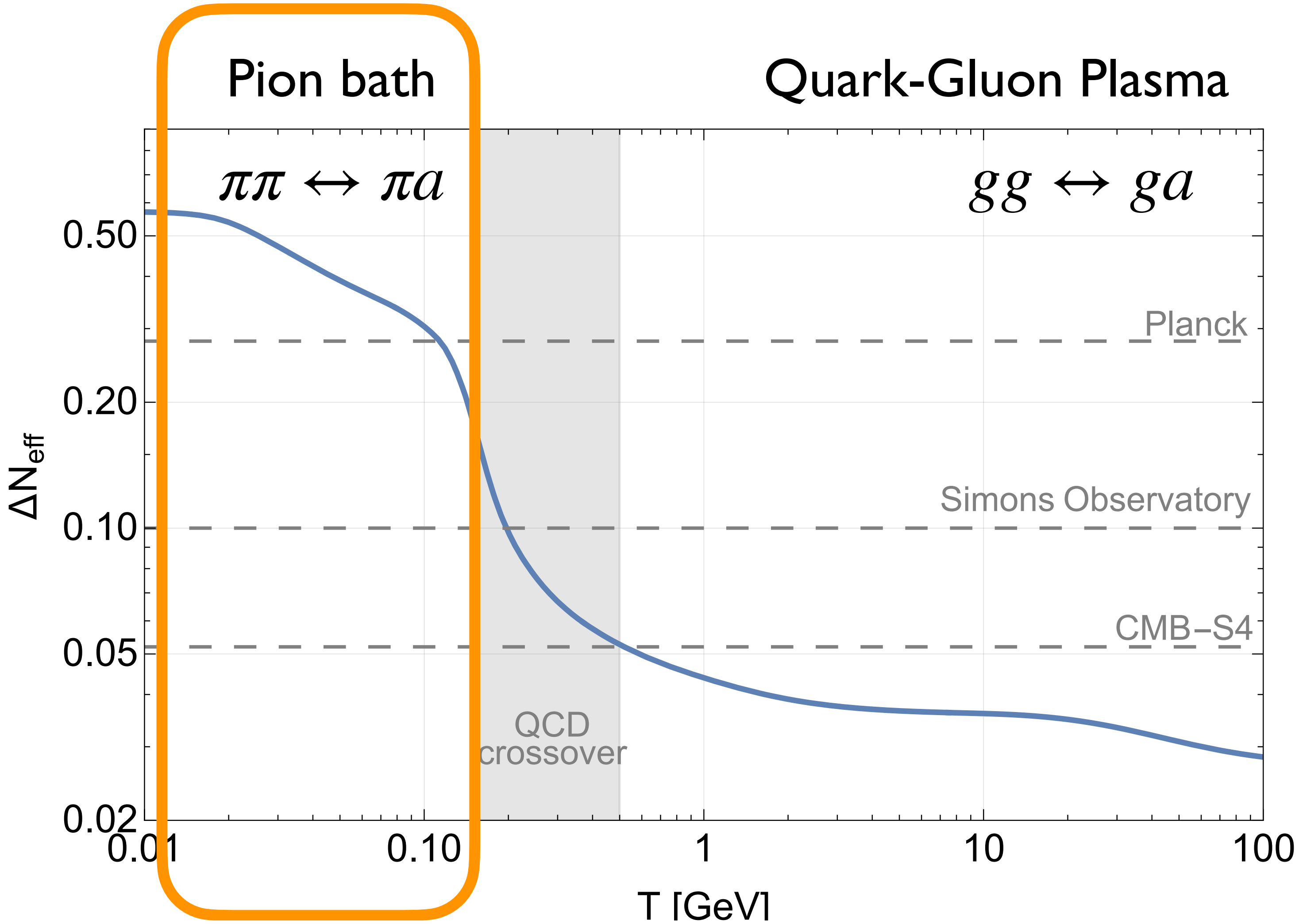
The IAM amplitude satisfies unitarity and has the correct low-energy expansion of ChPT up to $\mathcal{O}(p^4)$

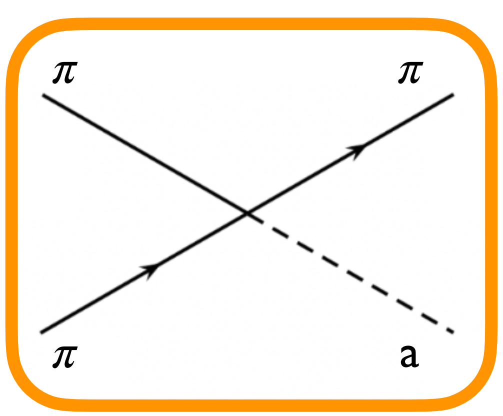
IAM LECs from fit to $\pi\pi$ scatt. [Dobado, Pelaez 1997]

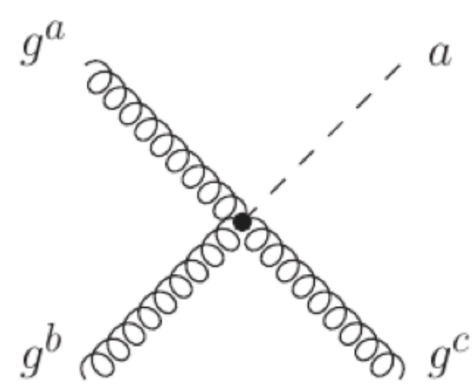
✓ Phases obtained in IAM correspond to phases of $\pi\pi$ scattering: Watson th.!



Hot Axions from pions







Integrated Boltzmann eq.

$$\frac{dY}{d\log x} = (Y^{eq} - Y)\frac{\Gamma}{H}\left(1 - \frac{1}{3}\frac{d\log g_{*S}}{d\log x}\right)$$

Momentum-dependent rates

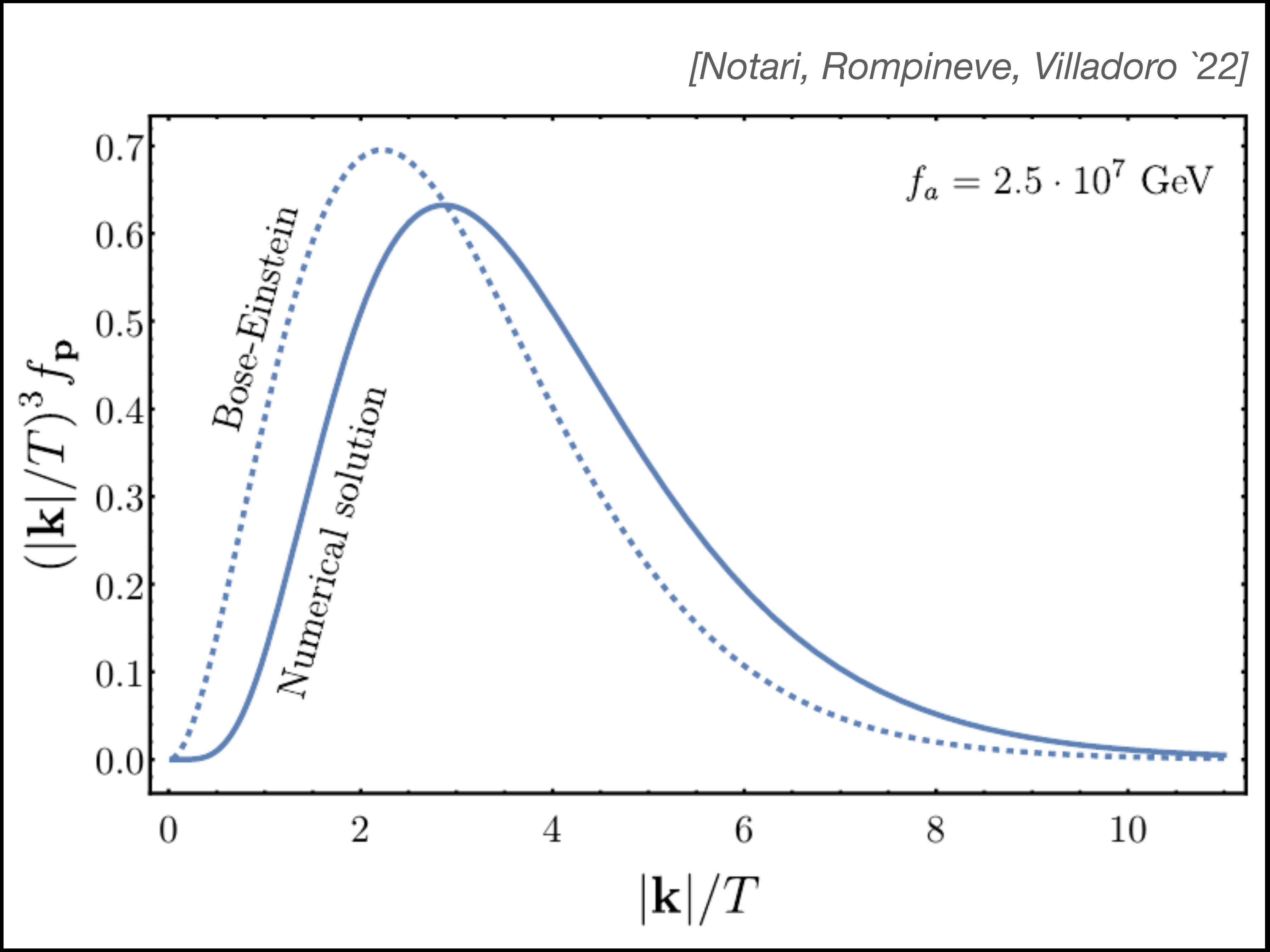
VS

Change in # of entropic d.o.f.s

Momentum-dependent Boltzmann

$$\frac{\partial \mathcal{F}_a}{\partial t} - H\,|\mathbf{k}|\frac{\partial \mathcal{F}_a}{\partial |\mathbf{k}|} = \Gamma_a\left(\mathcal{F}_a^{eq} - \mathcal{F}_a\right)$$

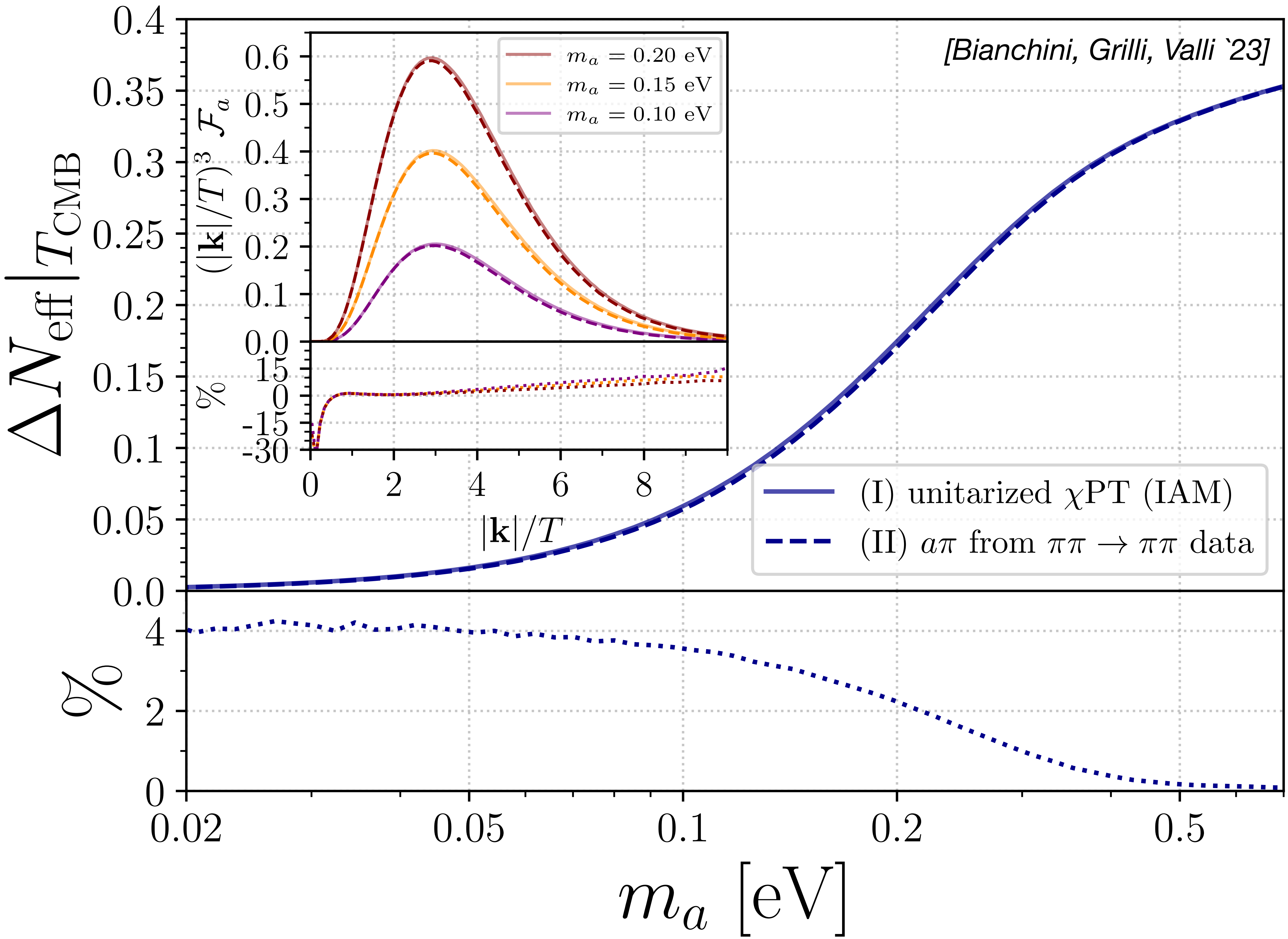
Axion spectral distortions do matter …



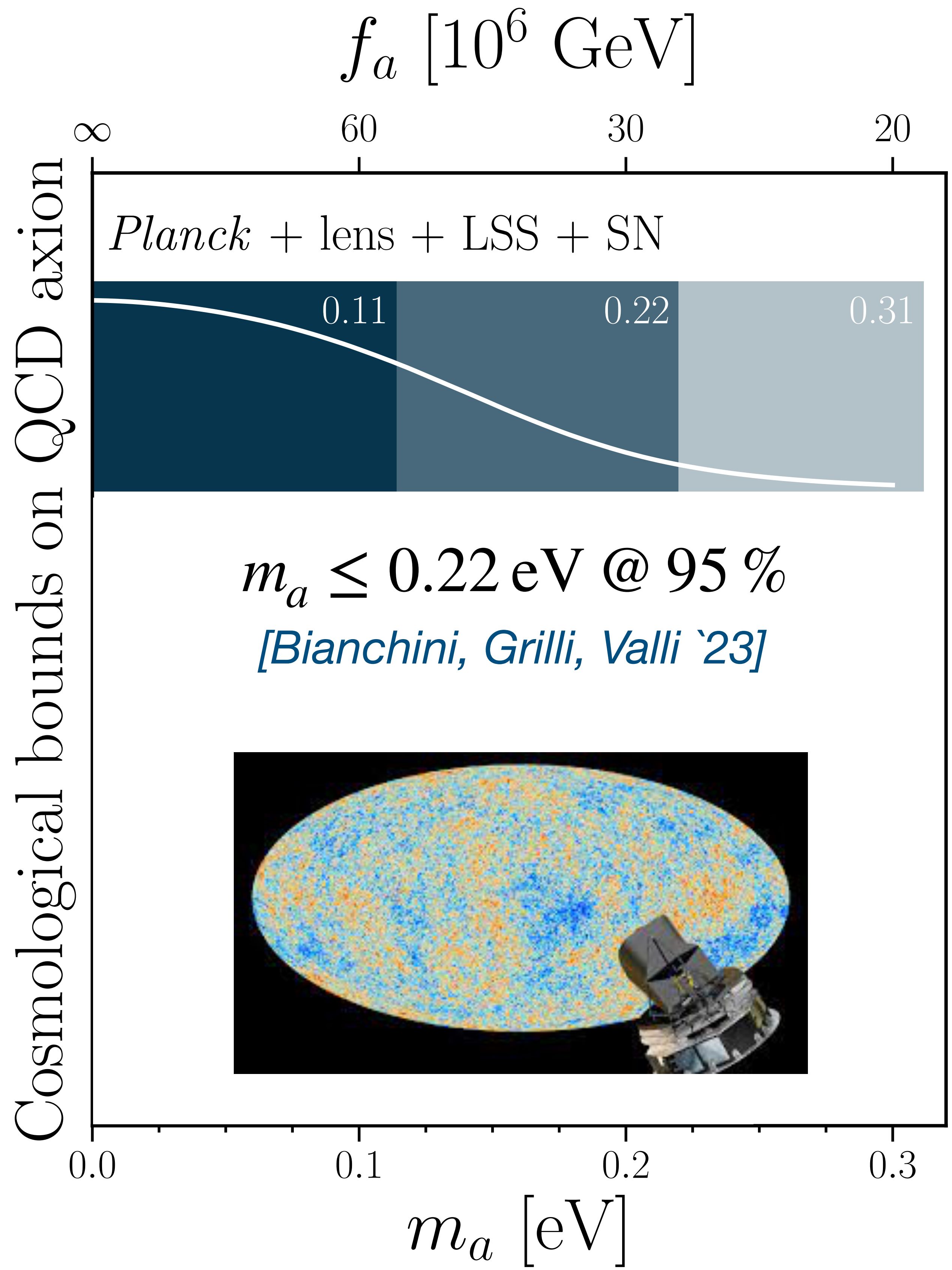
High momenta *k* decouple later than low *k.*

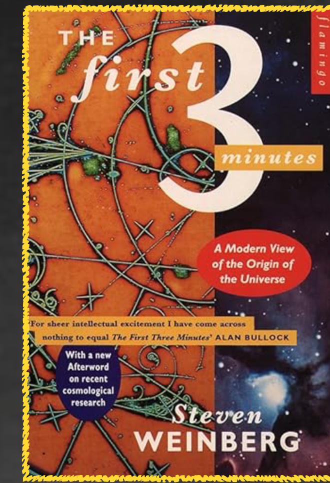
They see a lower g_* —> Greater $\Delta N_{\rm eff}$

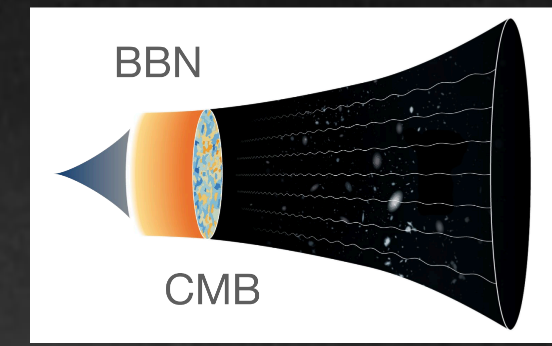
Hot Axions from pions



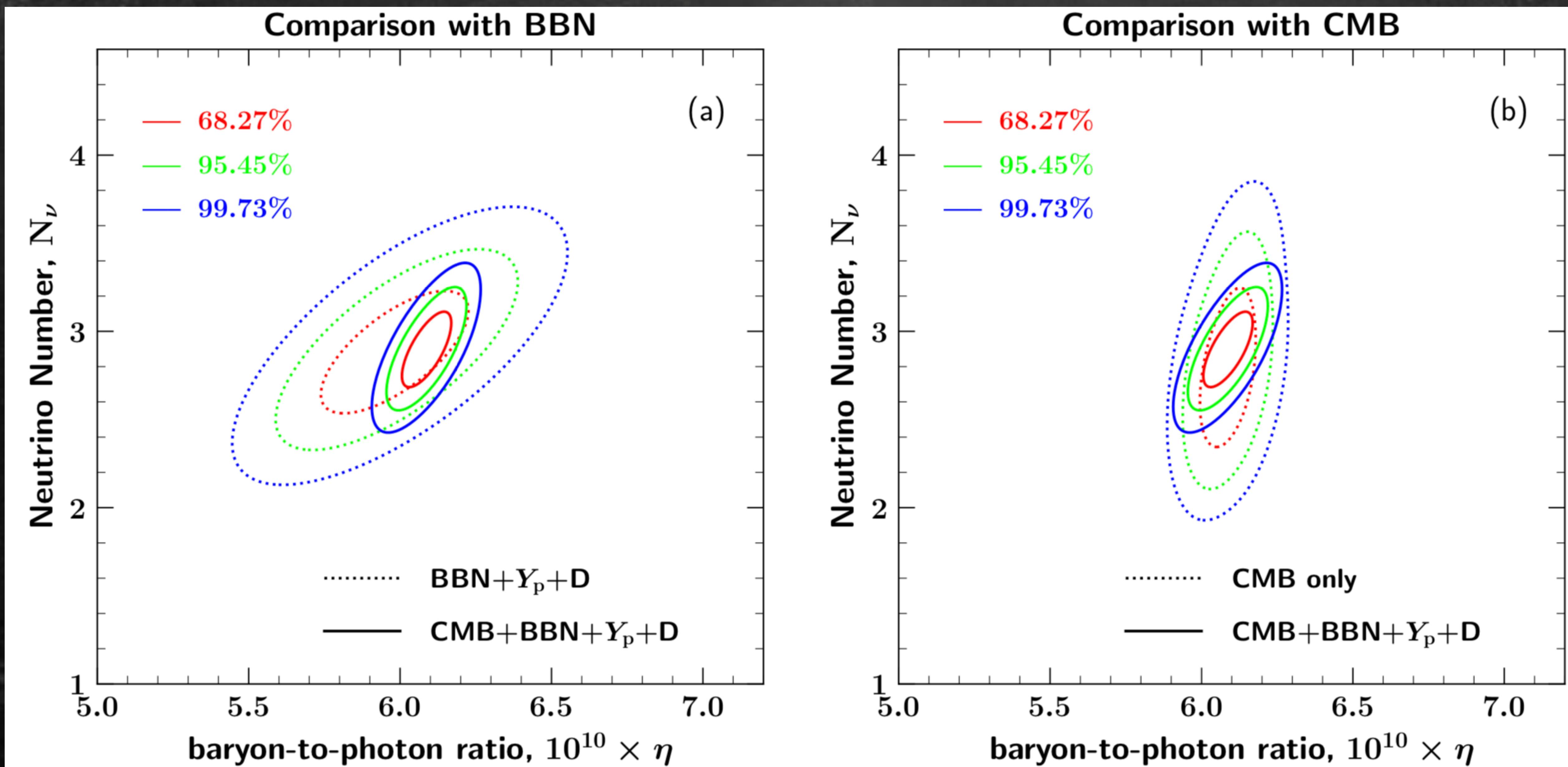
Minimal QCD Axion ($T_{dec} < T_c$)







JCAP 10 (2022) 046

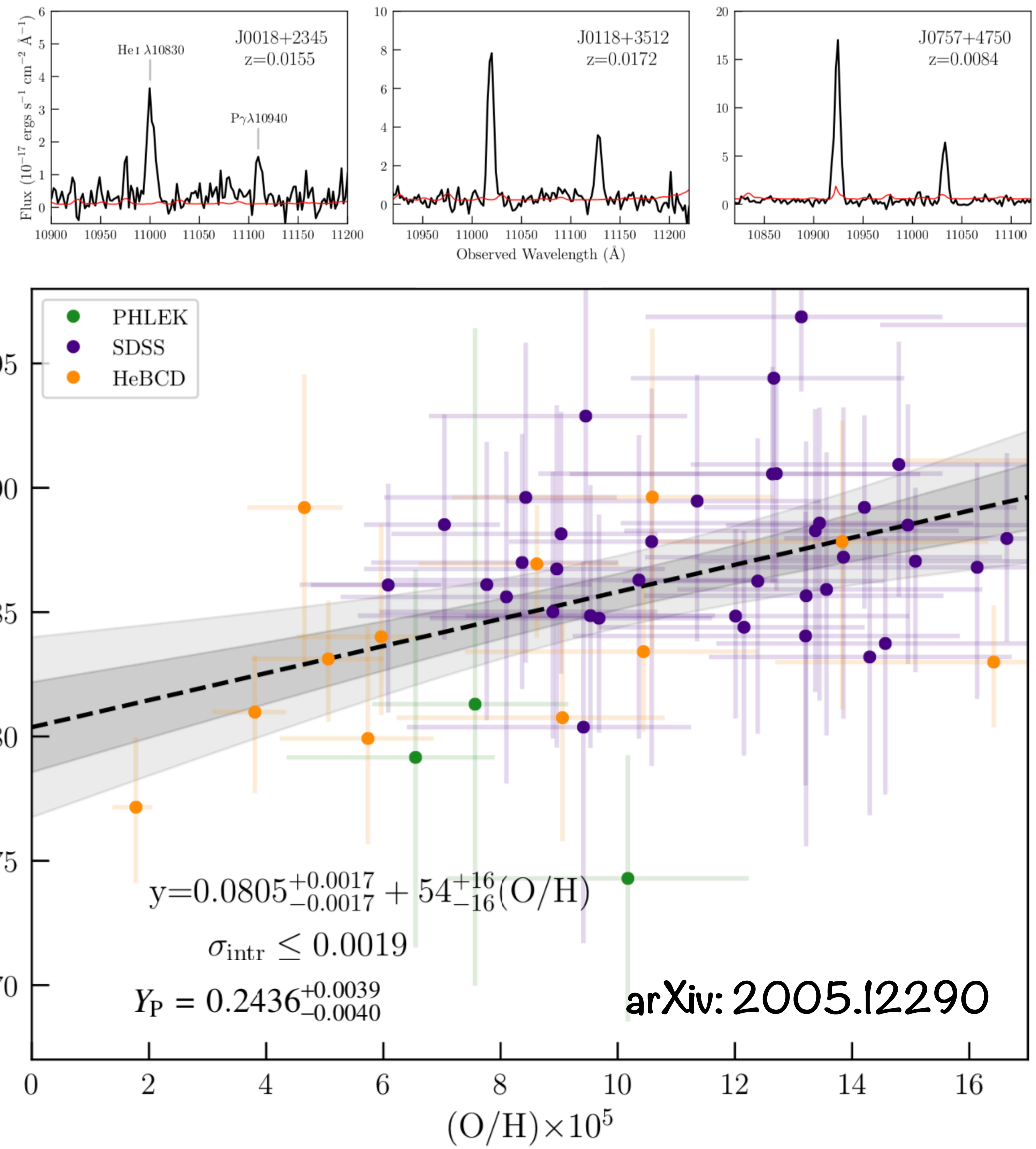


BBN IS COMPETITIVE WITH CMB TO CONSTRAIN $\Delta N_{\rm eff}$

^4He

PDG 2021: $Y_P = 0.245 \pm 0.003$

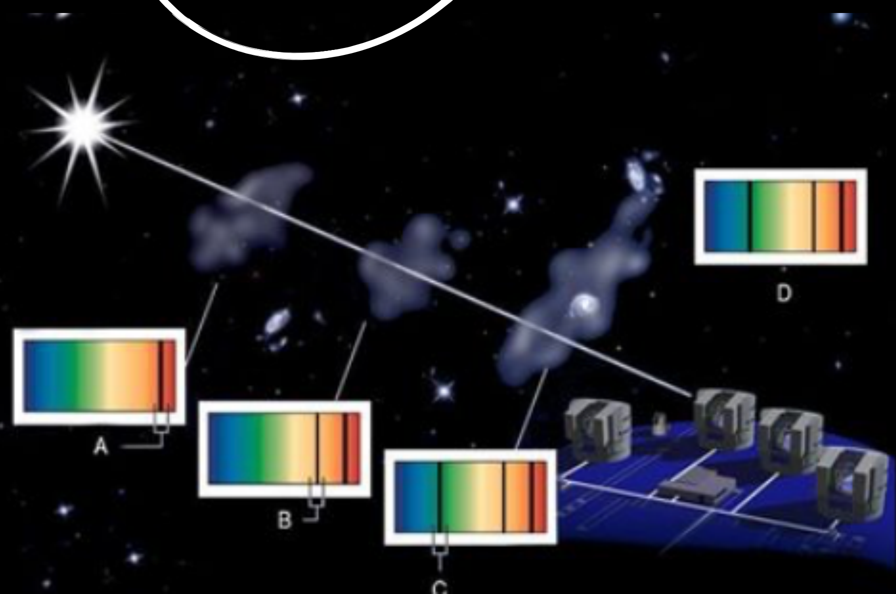
% level measurement

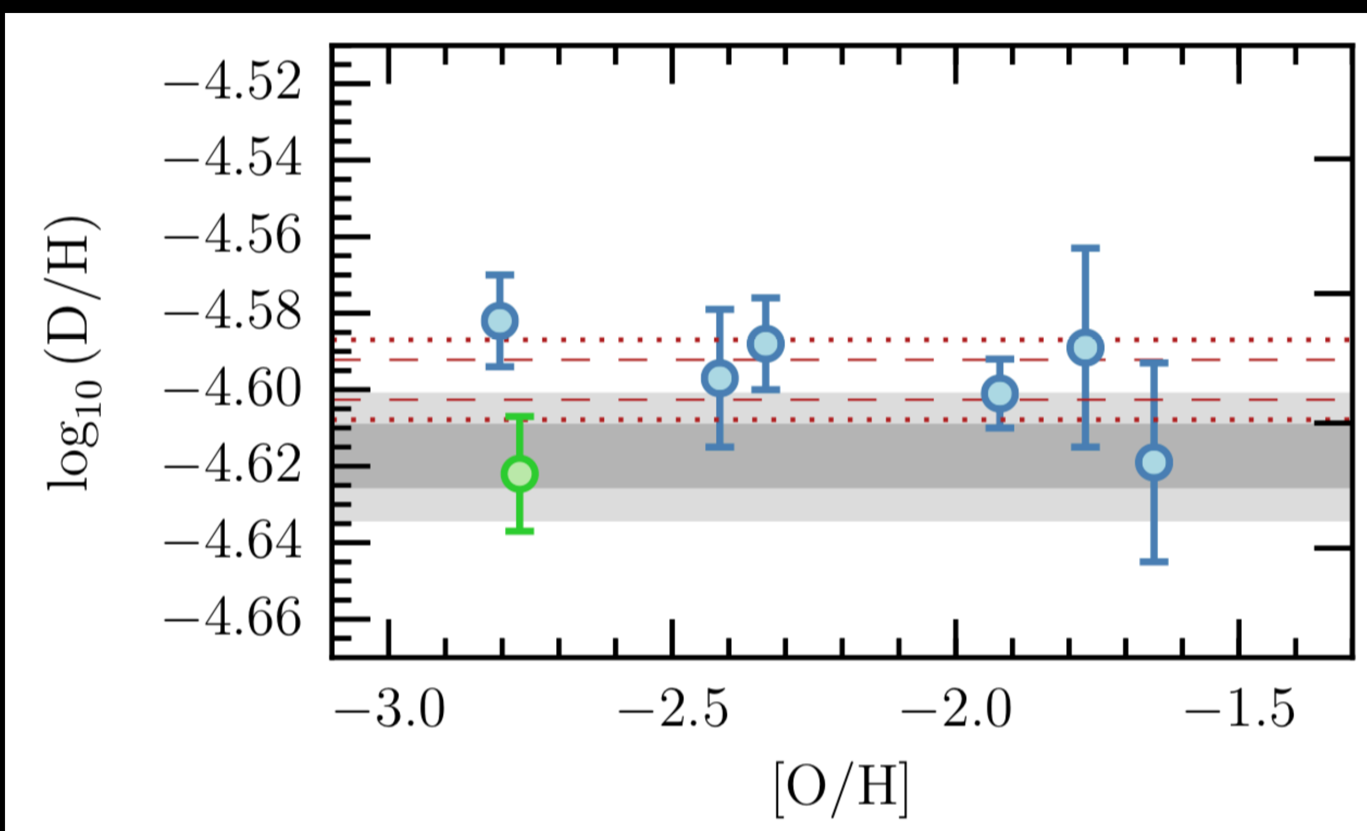


D

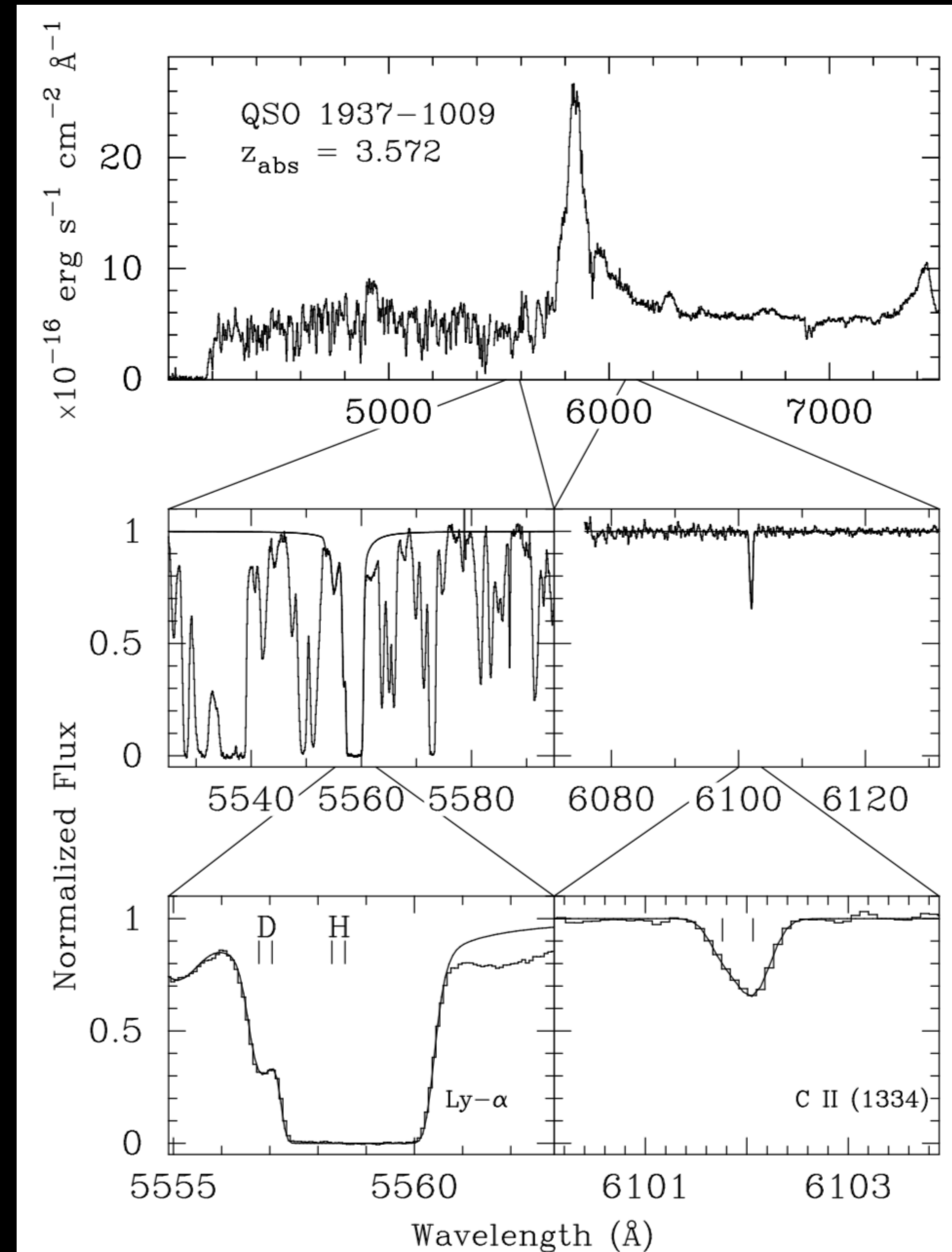
% level measurement

PDG 2021: $(D/H) \times 10^5 = 2.547 \pm 0.025$





arXiv: 1710.11129



astro-ph/9803071

BBN era in ΛCDM

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

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

$m_n - m_p \simeq 1.3\, MeV$

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

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

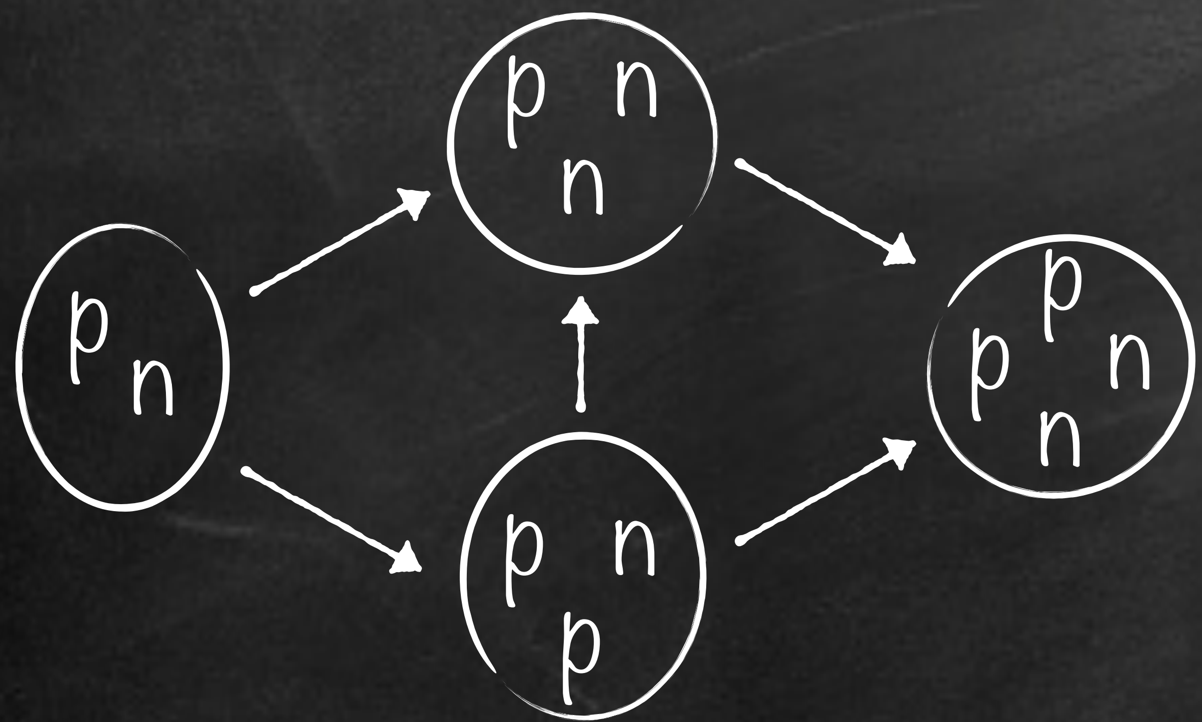
$$\Gamma(n + p \to D + \gamma) \sim n_B \langle \sigma v \rangle_{D\gamma}$$

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

i.e., it really starts at $T_{nucl.}$ such that: $\eta_B \simeq \exp(-B_D/T_{nucl.})$

BBN era in ΛCDM

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



~ all neutrons into helium-4

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

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

Baryon mass fraction in helium-4

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

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

Eur. Phys. J. C (2024) 84:86
https://doi.org/10.1140/epjc/s10052-024-12442-0

THE EUROPEAN PHYSICAL JOURNAL C

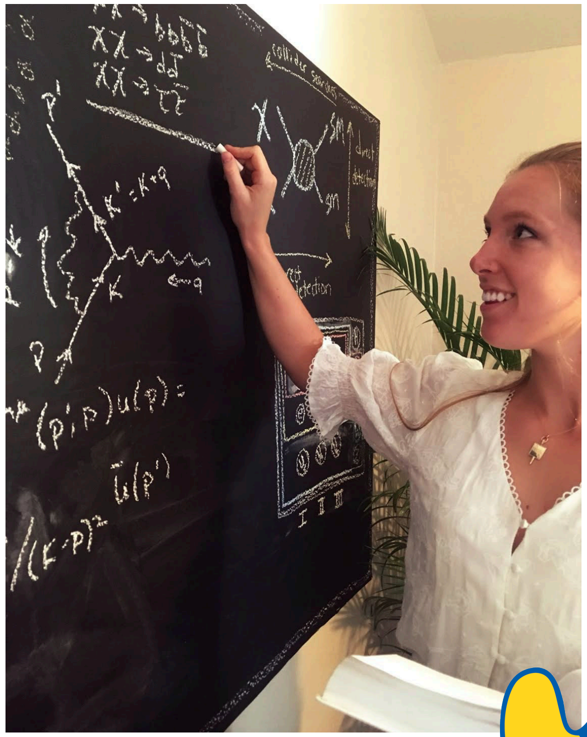
Check for updates

Regular Article - Theoretical Physics

`PRyMordial`: the first three minutes, within and beyond the standard model

PRyMordial: The first 3 min in $\mathcal{O}(10)$ sec

Anne-Katherine Burns



Younger Tim

Californian Me

PRyMordial: Overview

- **PRyMordial** A new package for BBN phenomenology
- Featuring:
  — simplified, but precise, method for ν decoupling
  — ab-initio efficient computation of n <—> p
  — a customizable up-to-date nuclear network
  — several built-in options for New Physics

Meets precision for state-of-the-art SM predictions.

Opens up uncharted territory for BSM in BBN era.

- Fully Python-based, user-friendly & **numerically fast …**

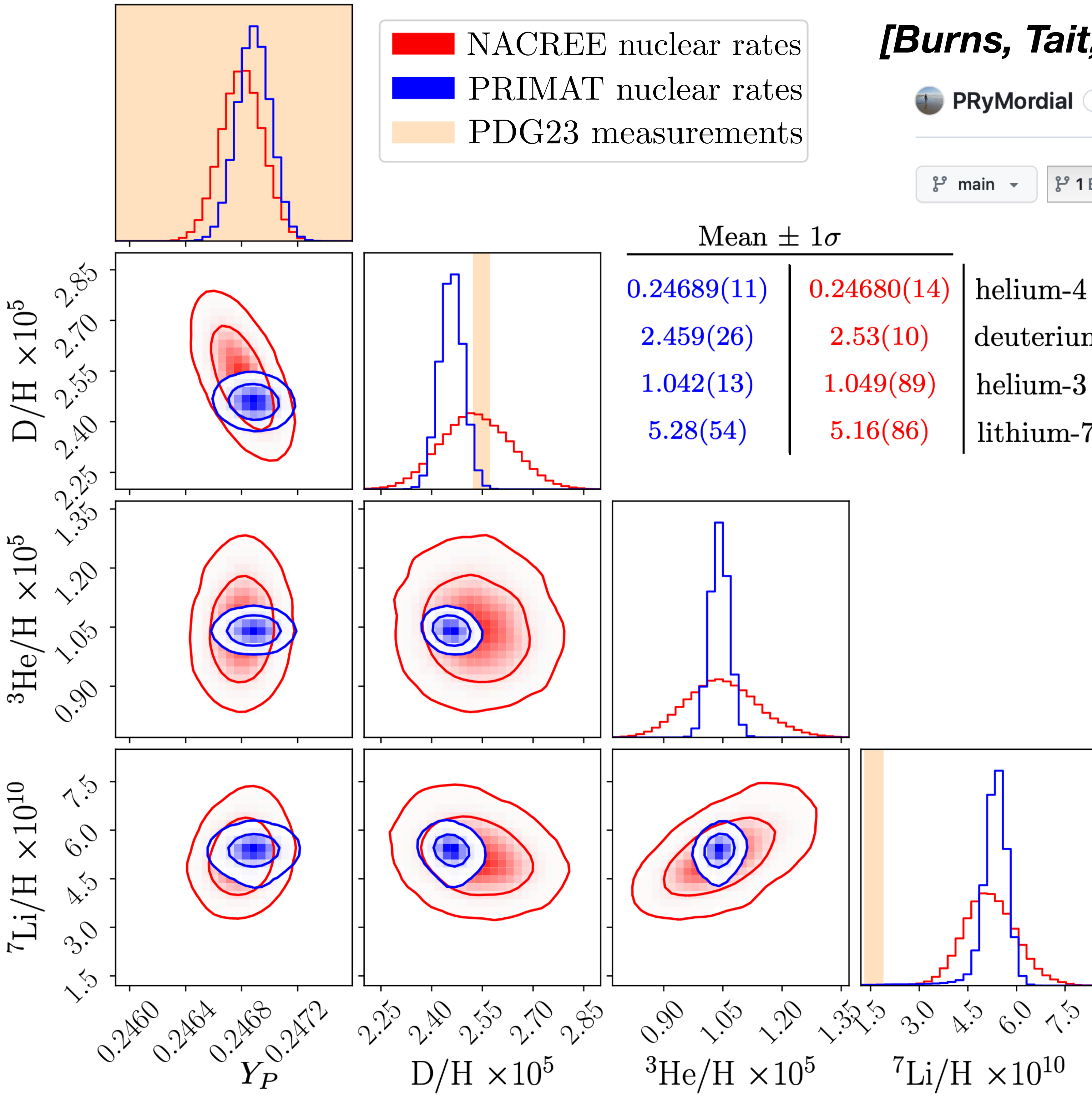
vallima

github.com/vallima/PRyMordial

DiffEq.jl from Sci Machine Learning kit in julia

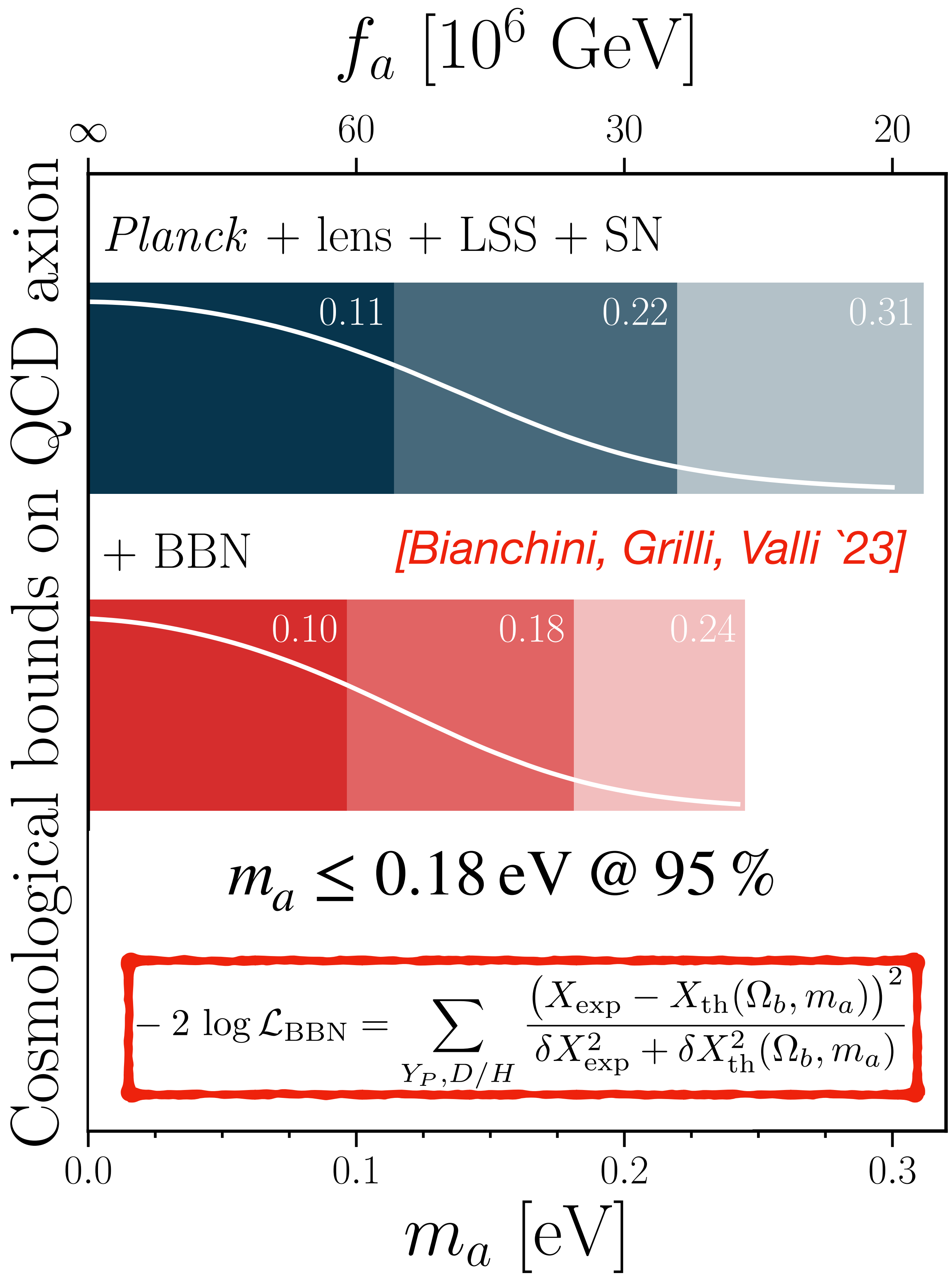
PRyMordial: BBN state-of-the-art predictions

[Burns, Tait, Valli `23]

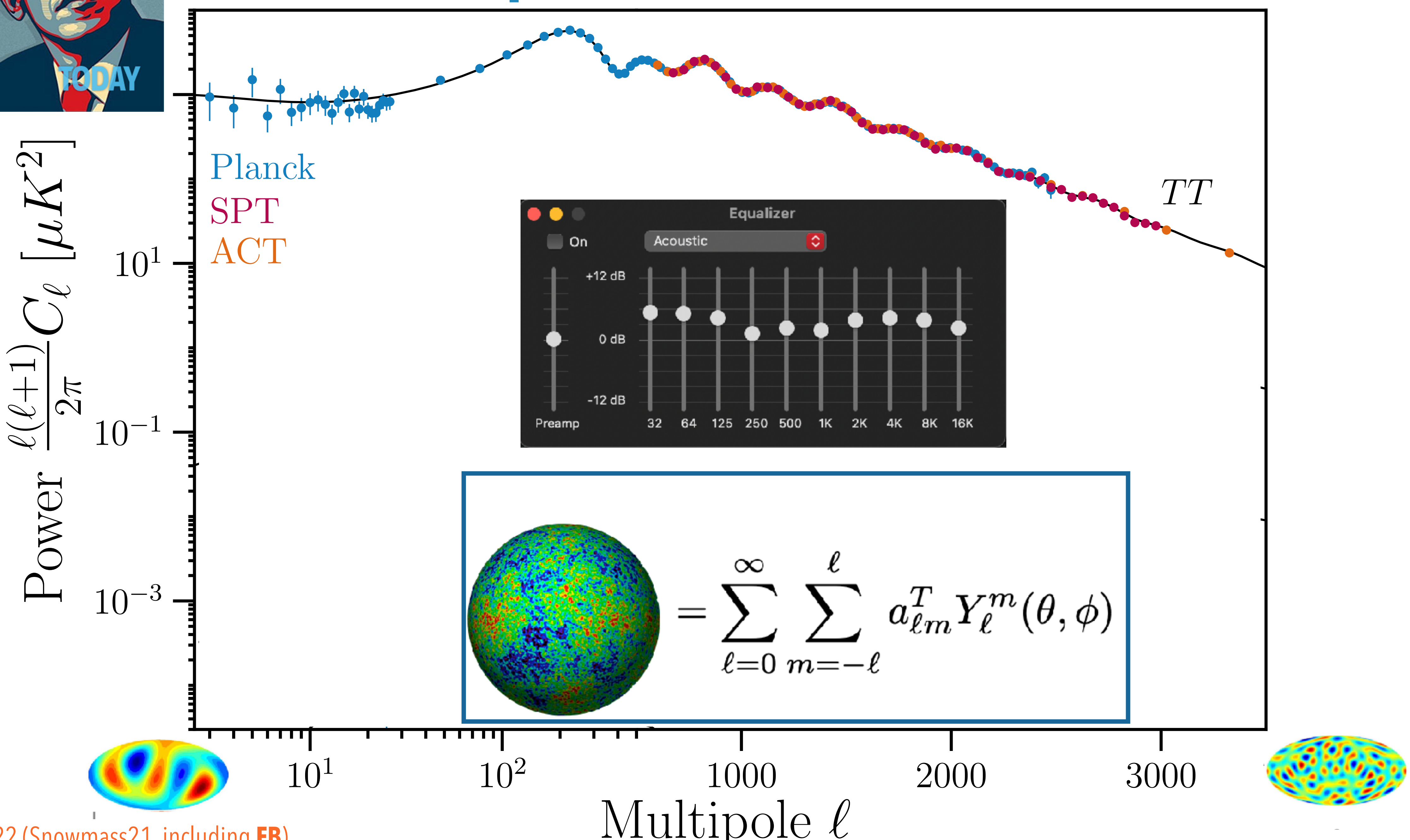


Mean $\pm\, 1\sigma$		
0.24689(11)	0.24680(14)	helium-4
2.459(26)	2.53(10)	deuterium
1.042(13)	1.049(89)	helium-3
5.28(54)	5.16(86)	lithium-7

Minimal QCD Axion (Tdec < Tc)

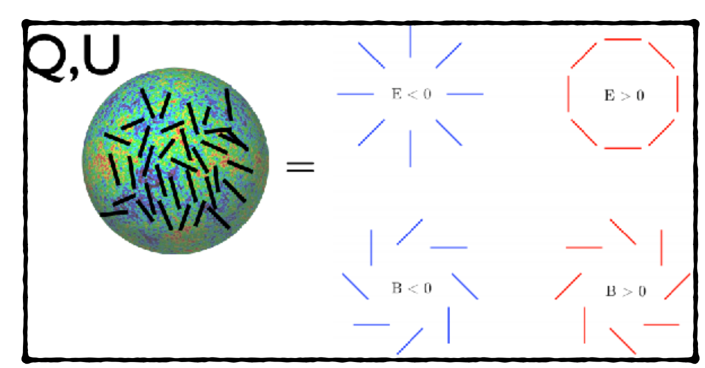


CMB temperature measurements

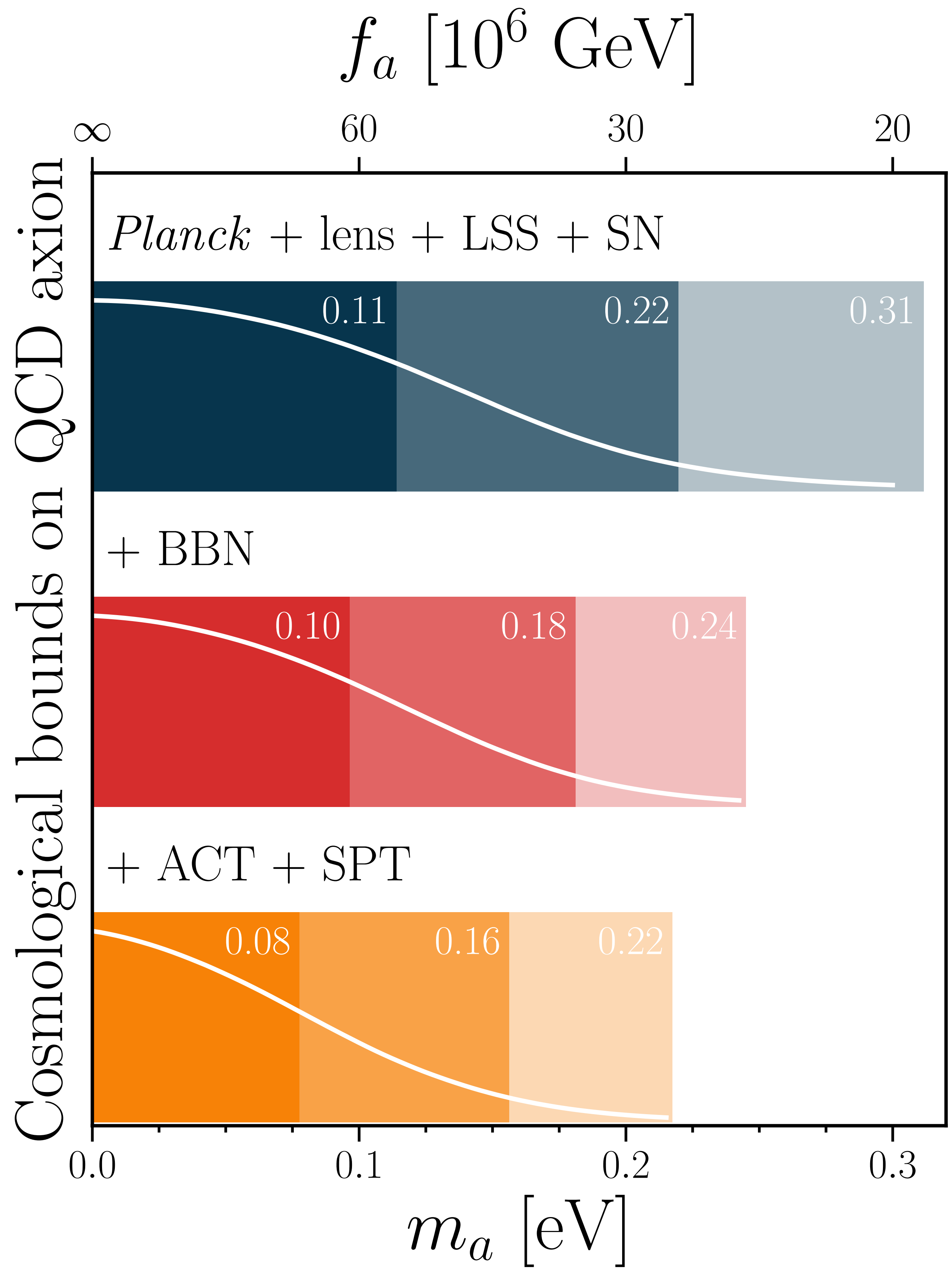


Chang+22 (Snowmass21, including **FB**)

CMB polarization



Minimal QCD Axion ($T_{dec} < T_c$)



30% improvement with respect to

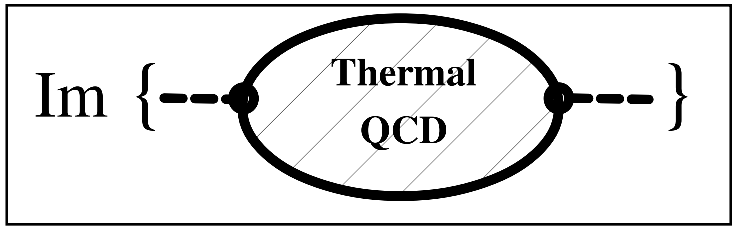
[Notari, Rompineve, Villadoro`22]

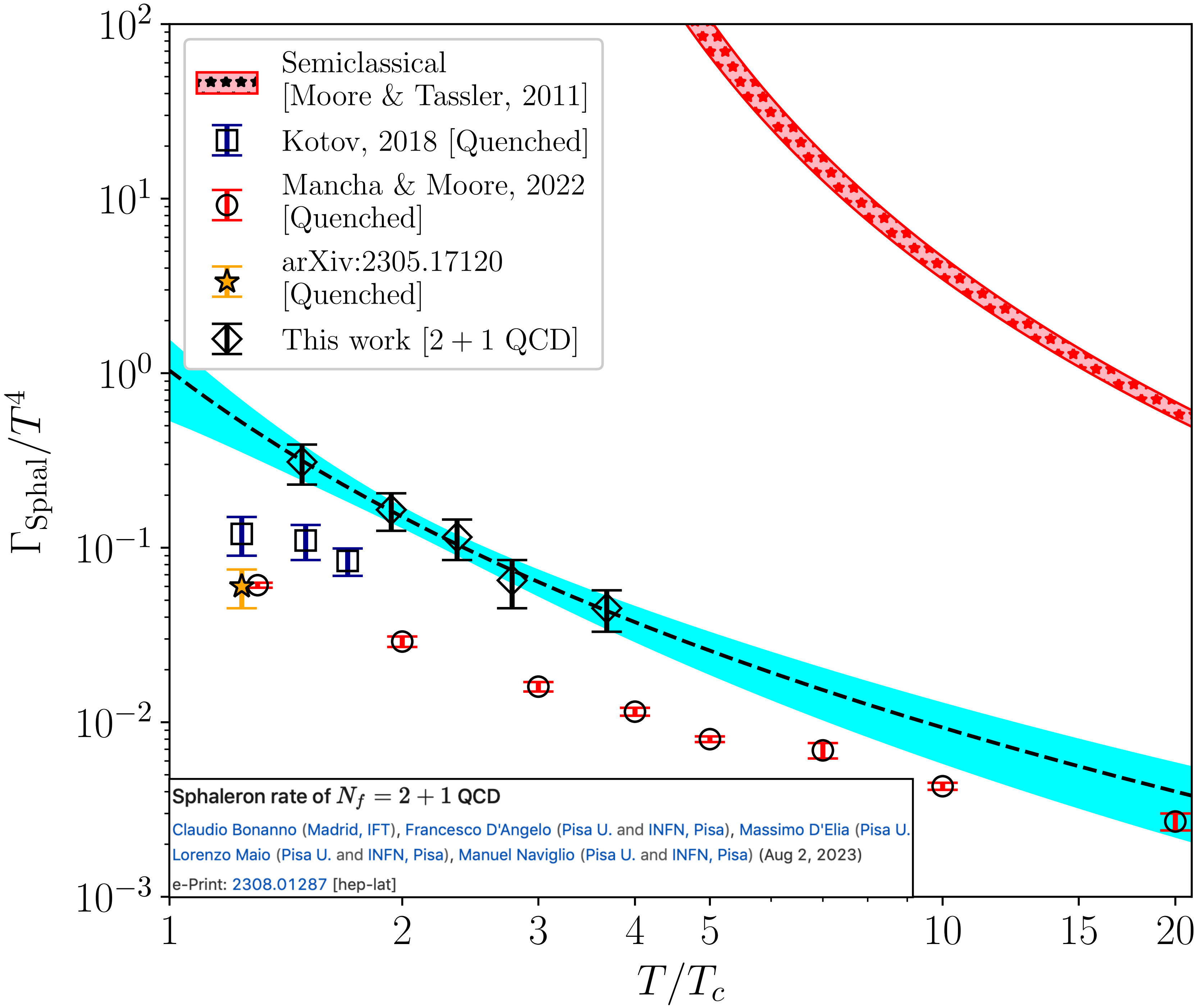
[Bianchini, Grilli, Valli `23]

$m_a \leq 0.16\,\mathrm{eV}$
@ 95 % HDI

Minimal QCD Axion $(T_{dec} \gtrsim T_c)$

$$\Gamma_a = \int d^4x\, e^{ikx} \langle \mathcal{Q}(x)\mathcal{Q}(0) \rangle$$





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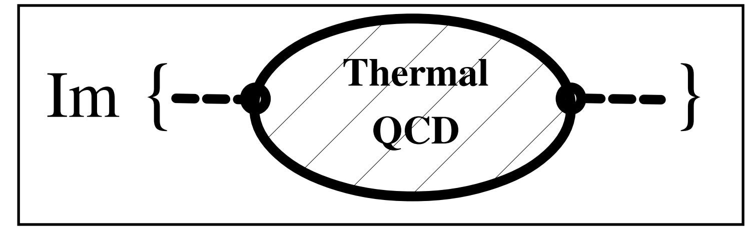


150 MeV < T < 600 MeV

$$\Gamma_{\rm sph}(|\mathbf{k}| = 0) = \Lambda_0^4 \, (T/T_c)^{\epsilon}$$

$$\Lambda_0 \simeq 142.3 \text{ MeV}, \; \epsilon \simeq 1.81 \;, \; T_c = 155 \text{ MeV}$$

[Bonanno, D'Angelo, D'Elia, Maio, Naviglio `23]

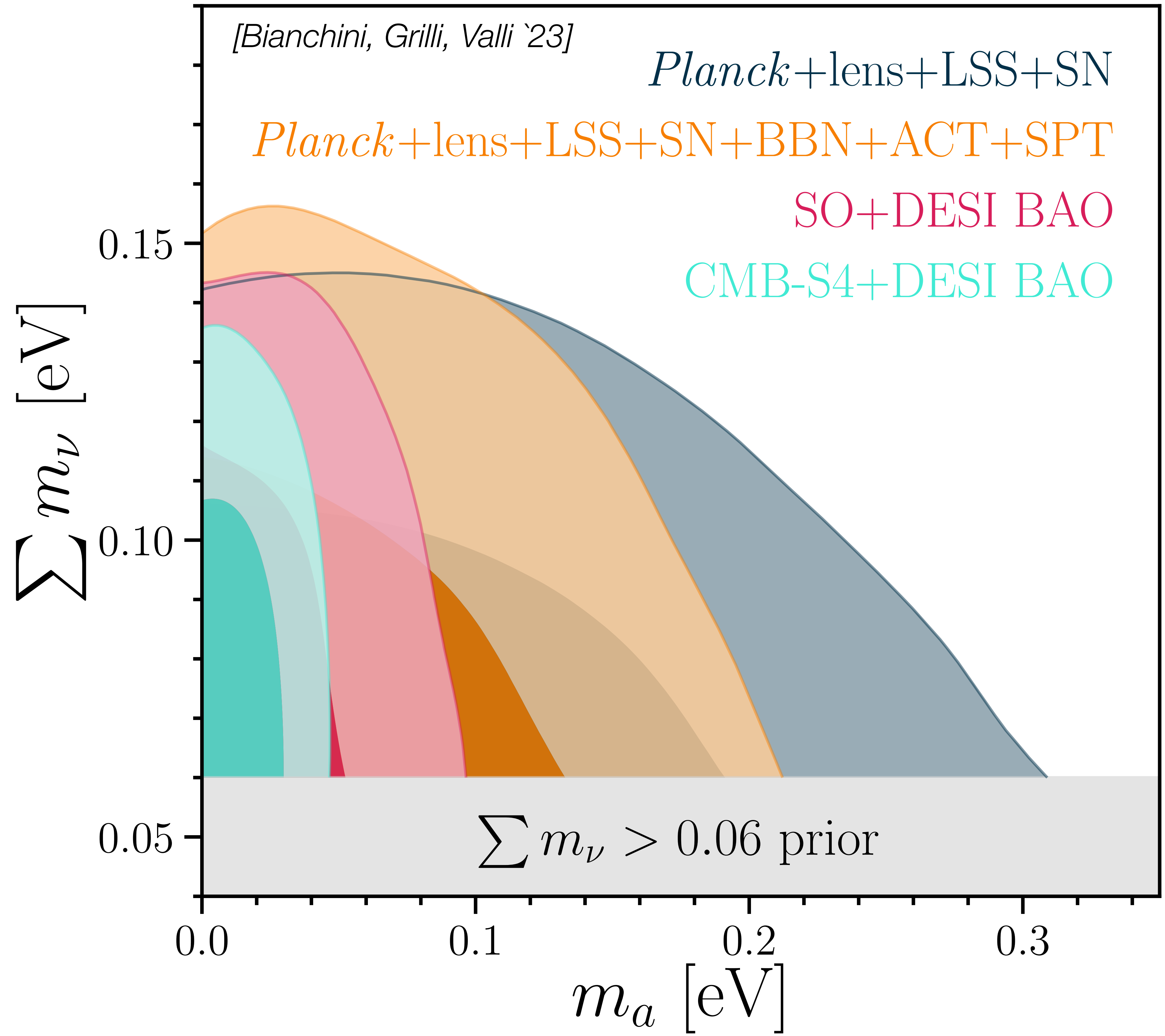
- **Recipe for a reasonable (?) forecast:**

  (I) Axion initially in thermal equilibrium

  (II) Extrapolate somehow sphaleron rate at non-zero momentum (e.g. constant within sphaleron size)

  (III) Set initial condition @ T_c : $\dfrac{dY_a}{dt} = \dfrac{\overline{\Gamma}_a}{H}(Y_a^{\rm eq} - Y_a)$

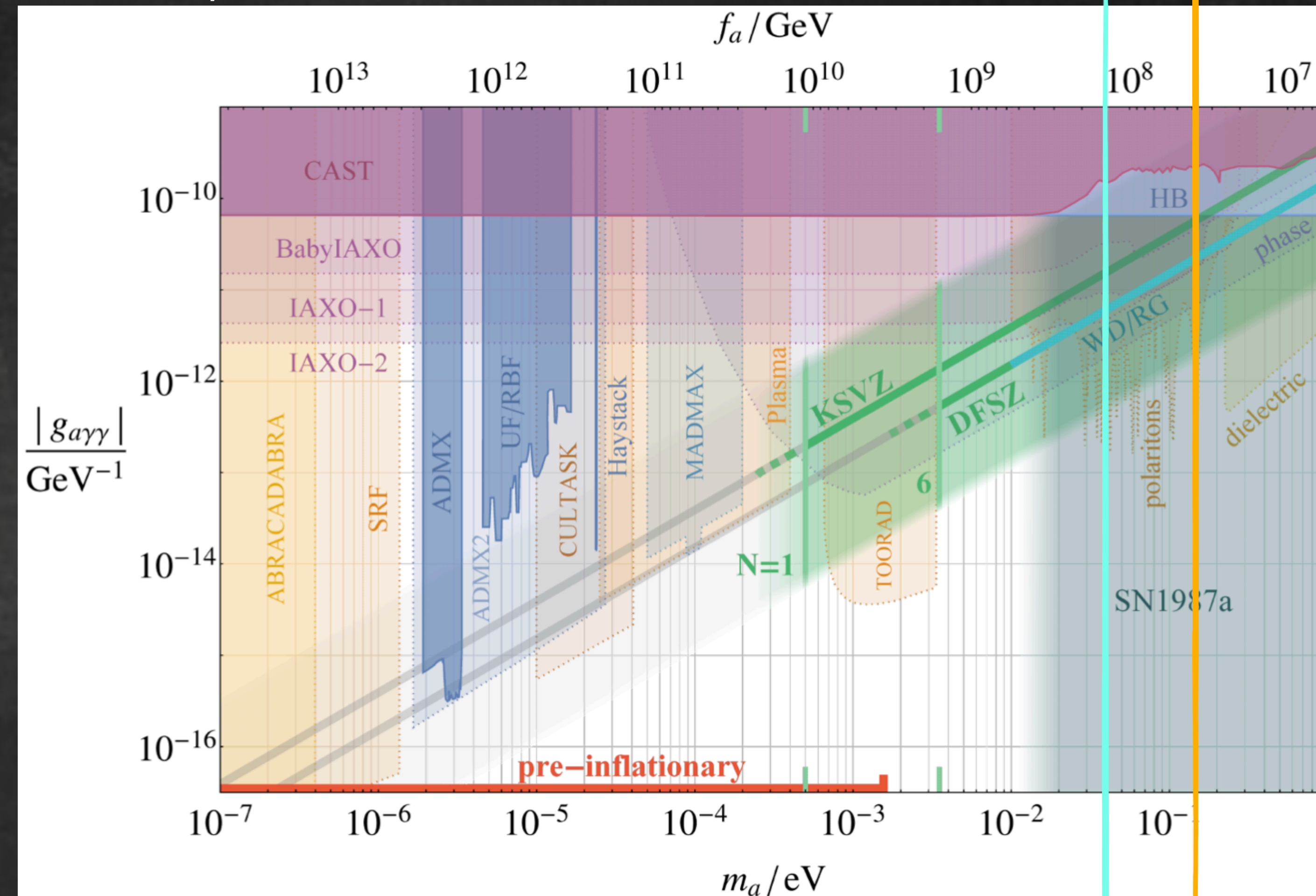
Cosmo **Present & Future** of QCD Axion



(Minimal) QCD axion
shows up as cosmological
— **Hot Dark Matter** —

SciPost Phys. 10, 050 (2021)



0.16 eV

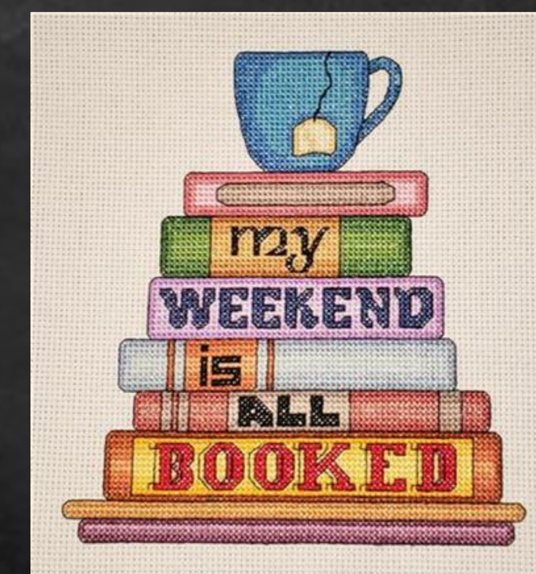
0.04 eV

- TODAY —> linear Cosmology + improved ChPT :

  $m_a \leq 0.16$ eV @ 95 % probability (CMB + LSS + BBN)

- FUTURE —> cosmo bound competitive w/ current astro probes

- HOW TO IMPROVE ON AXION THERMAL RATE
  - — going beyond $SU(2)_F$ ChPT @ T = 0
  - — strong sphalerons VS quark-gluon plasma



- MINIMAL QCD AXION VS AXION UV MODELS
- NON-LINEAR COSMOLOGICAL OBSERVABLES
  - — Lyman-α constraints
  - — **EFTofLSS** (CLASS-PT / PyBird)
  - — other measurements / forecasts