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Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN

Missione 4
Istruzione e Ricerca

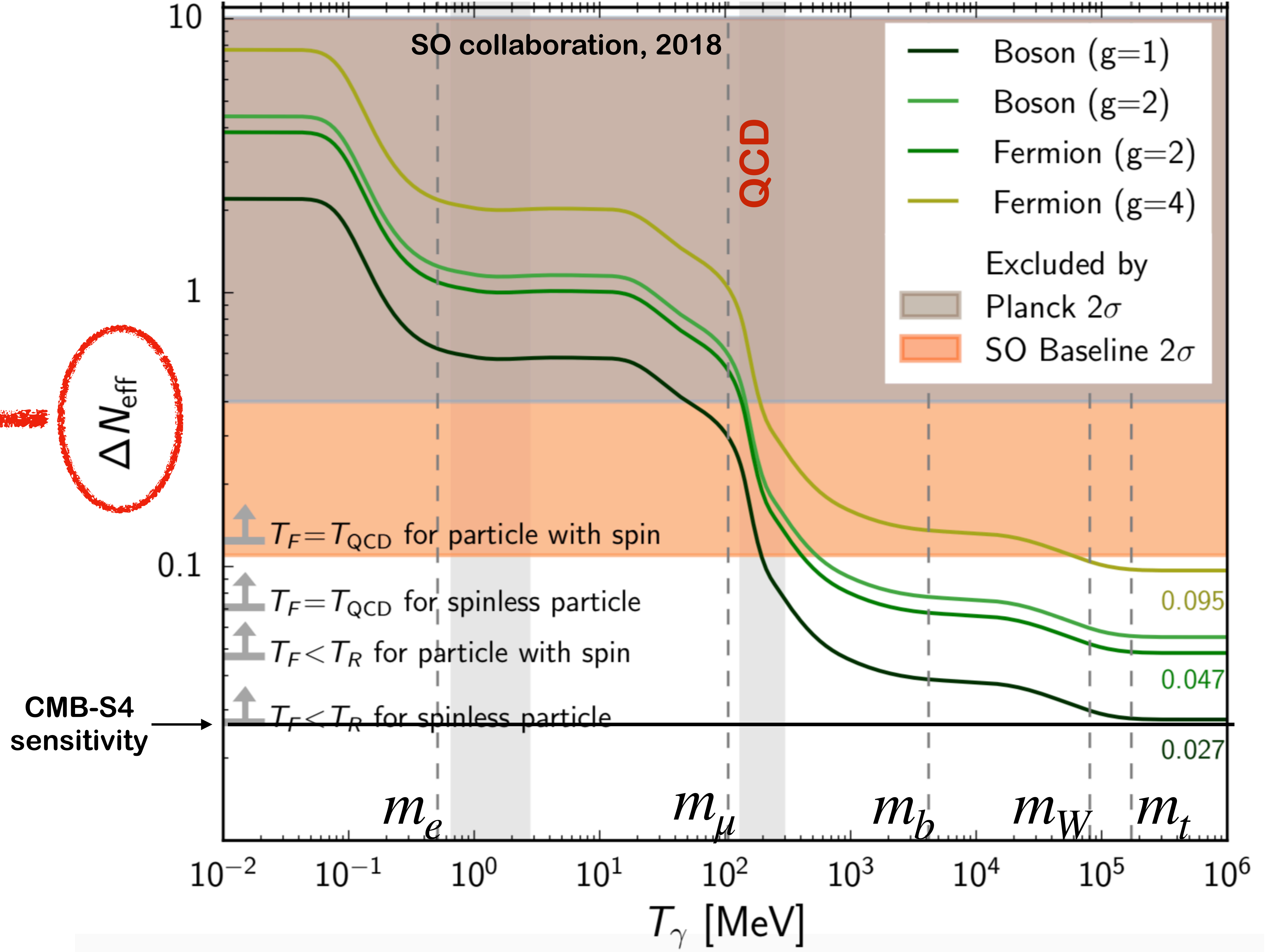
Cosmological phenomenology of axion-like particles

Martina Gerbino (INFN Ferrara),
AxionOrigins Kickoff meeting,
26 Jan 2024

Based on
L. Caloni,
MG, M. Lattanzi and L. Visinelli, JCAP 2022

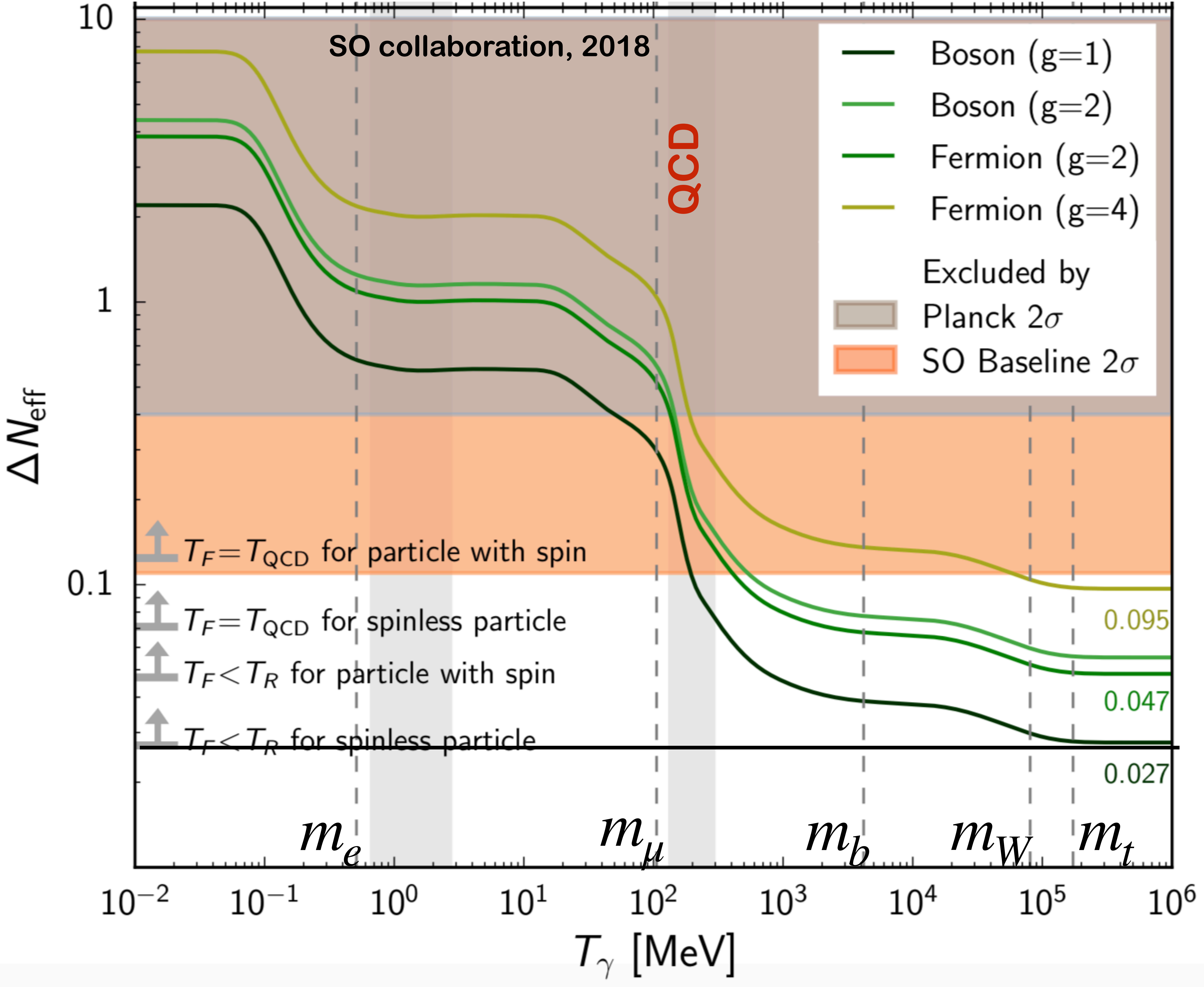
The money plot for light relics

Extra (relativistic) contributions
beyond photons
and
active neutrinos



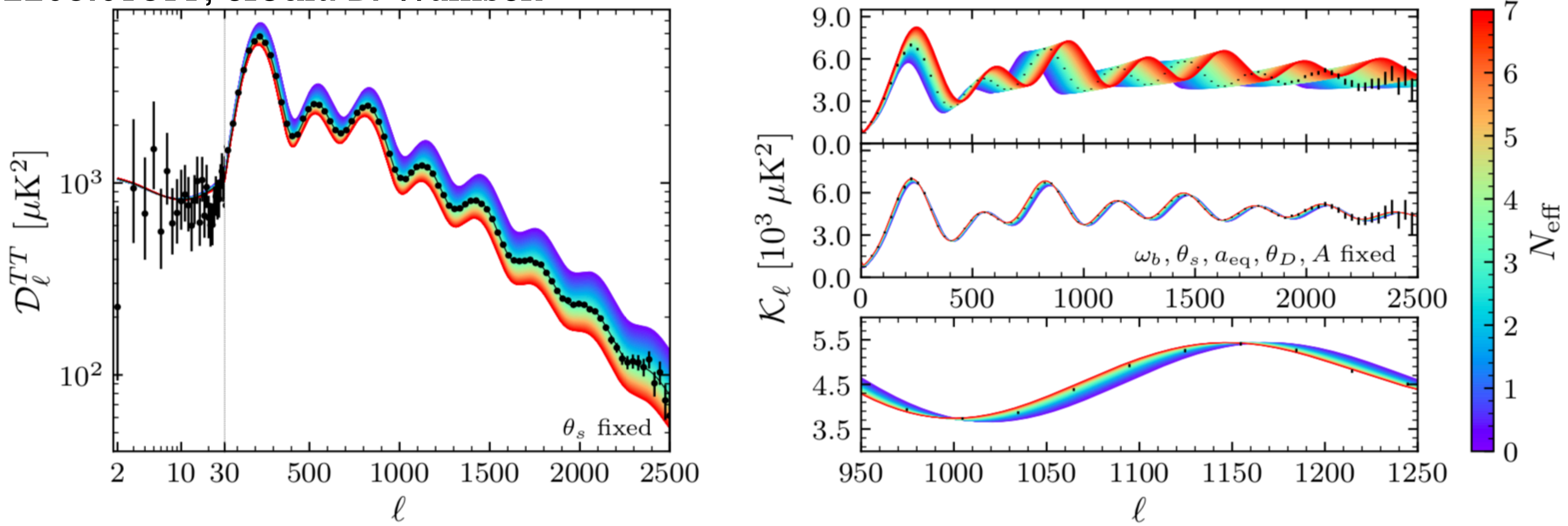
The money plot for light relics

Must account for additional effects
if light relics are massive
(and ALPs do have masses!)



Cosmological phenomenology

2203.07377, credit: B. Wallisch



<u>Massless/highly relativistic</u>

Damping tail suppression:
theta_d~sqrt(H(Neff))

Shift of acoustic peak position:
phi~Neff

Cosmological phenomenology

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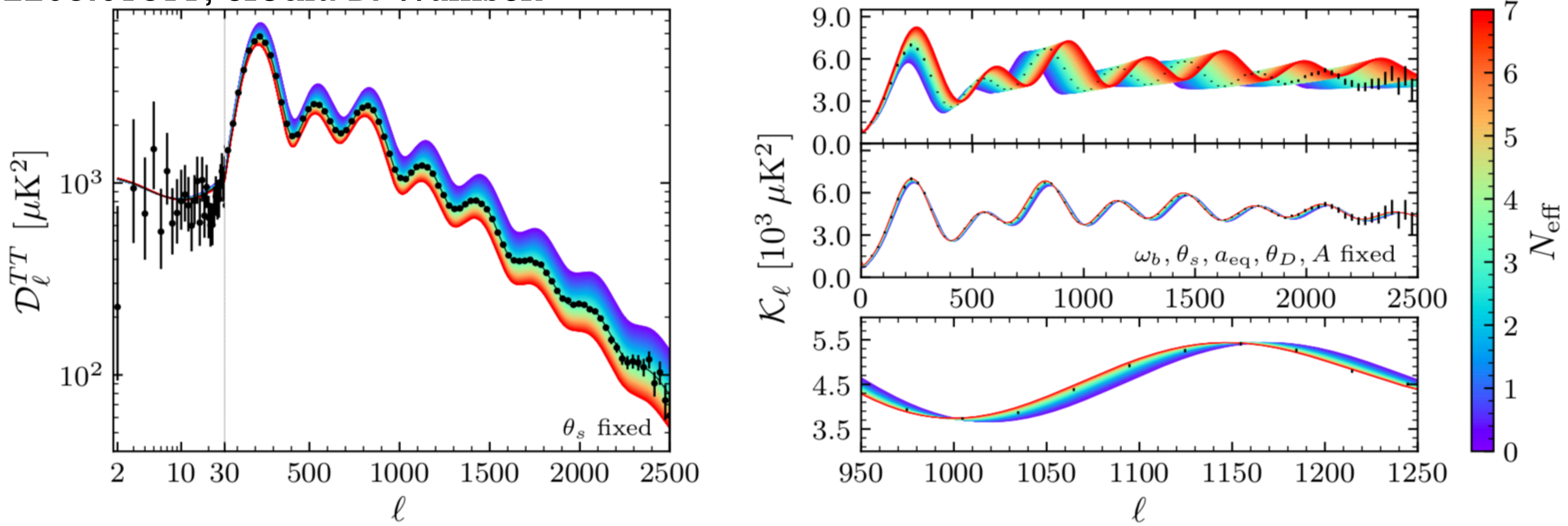

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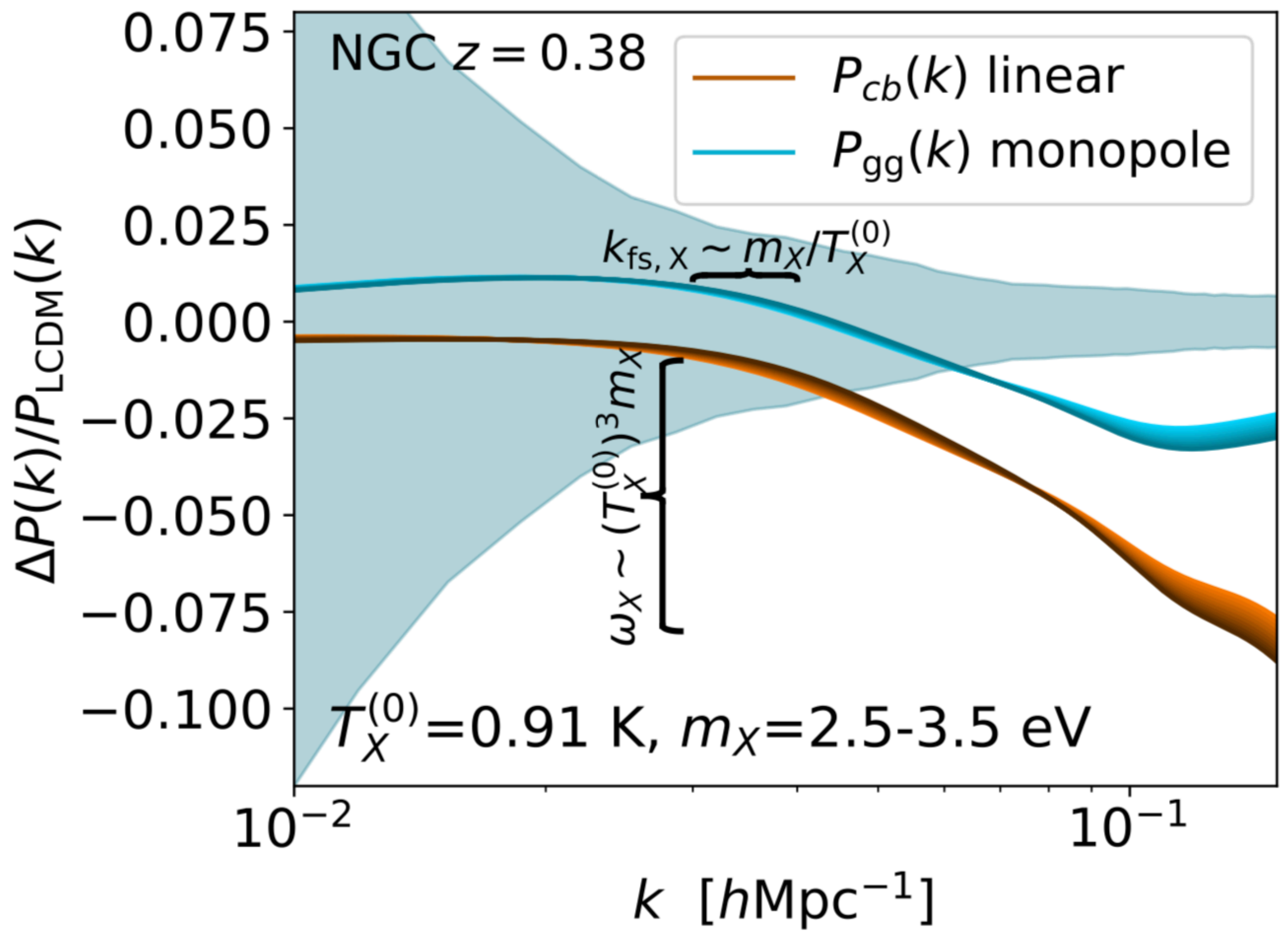
Shift of acoustic peak position: phi~Neff

Massive/non-relativistic

Amplitude from abundance: omega_a ~ma/g*s(Td)

Suppression from free-streaming scale: kfs~ma g*s(Td)^1/3



Xu,Munoz,Dvorkin,2022

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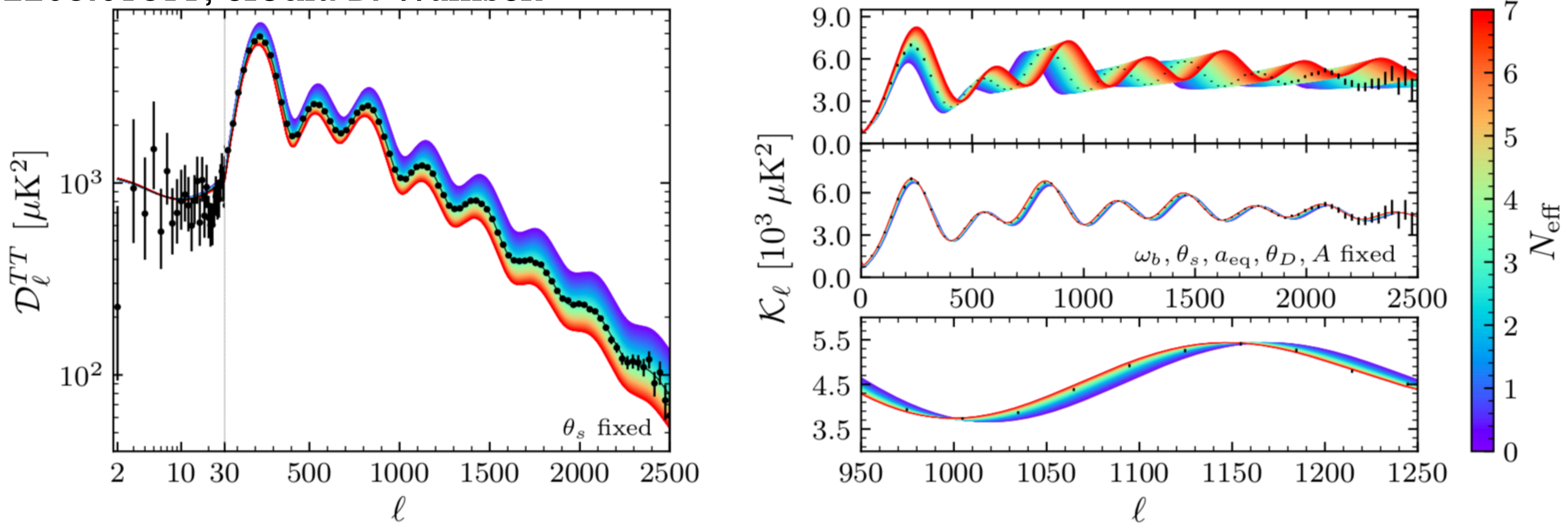

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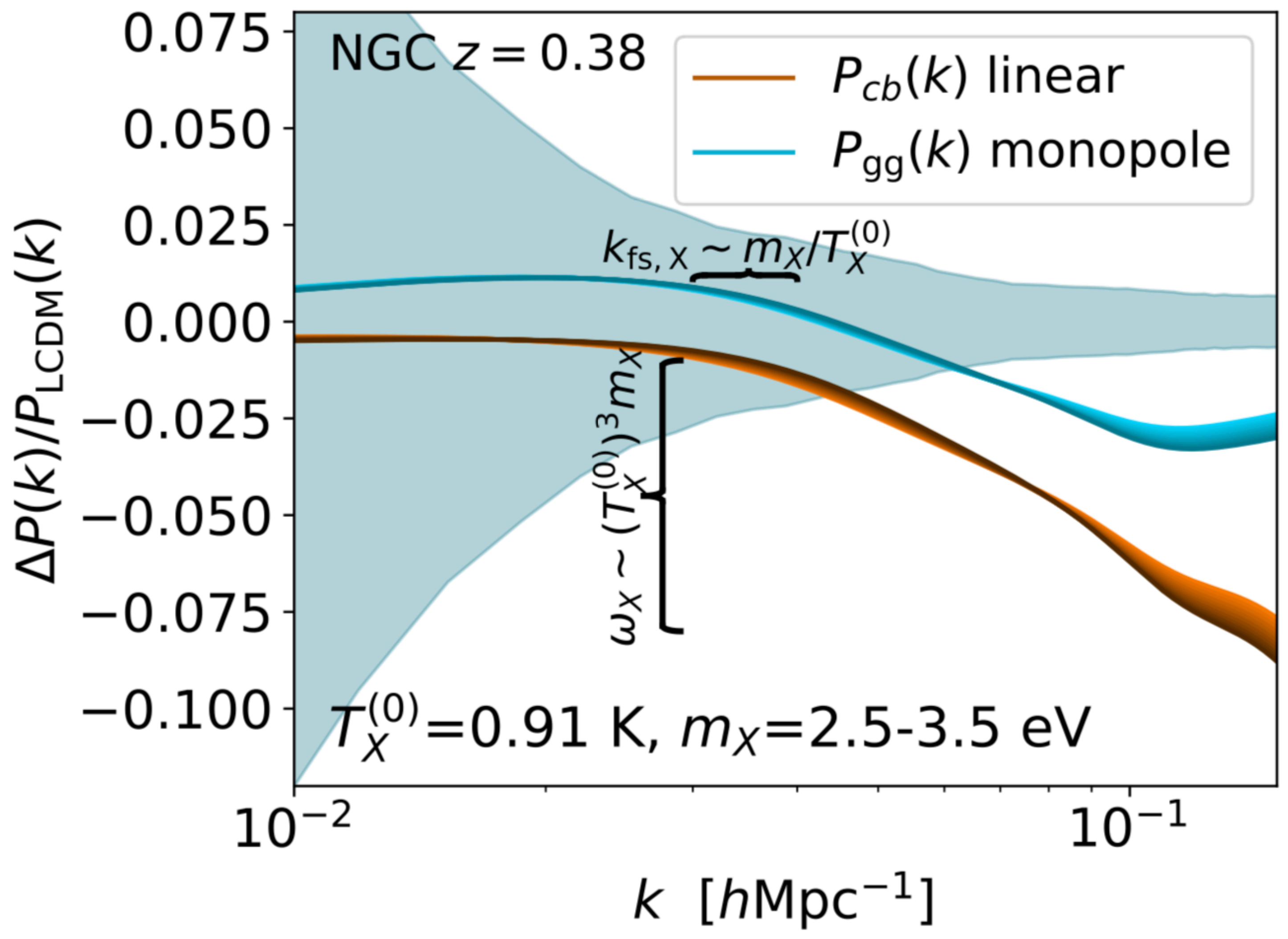
This effect propagates
to all matter tracers
including gravitational lensing of CMB



Xu,Munoz,Dvorkin,2022

Cosmological phenomenology

Thermally produced axions via coupling with gluons and photons in the early Universe

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \mathcal{L}_{ag} + \mathcal{L}_{a\gamma} \,,$$

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After rotation of the quark fields and explicit mass breaking:

$$m_a^2 = m_0^2 + \left(\frac{C_g}{f_a}\right)^2 F_\pi^2 m_\pi^2 \frac{z}{(1+z)^2} \approx m_0^2 + \left(5.8\,\mu\text{eV}\,\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)^2$$

Effective axion mass

$$\gamma_g = \frac{\zeta(3)}{4\pi^5}\,\alpha_s^2\,T^6 \boxed{\left(\frac{C_g}{f_a}\right)}^2 F_g(T)$$

Axion-gluon coupling

$$g_{a\gamma} = g_{a\gamma}^0 - \frac{\alpha_{\rm EM}}{3\pi}\frac{C_g}{f_a}\frac{4+z}{1+z} \approx g_{a\gamma}^0 - 2.3\times10^{-15}\,\text{GeV}^{-1}\left(\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)$$

Axion-photon coupling

Cosmological phenomenology

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Axion-gluon coupling

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We want to constrain these parameters!

Cosmological phenomenology

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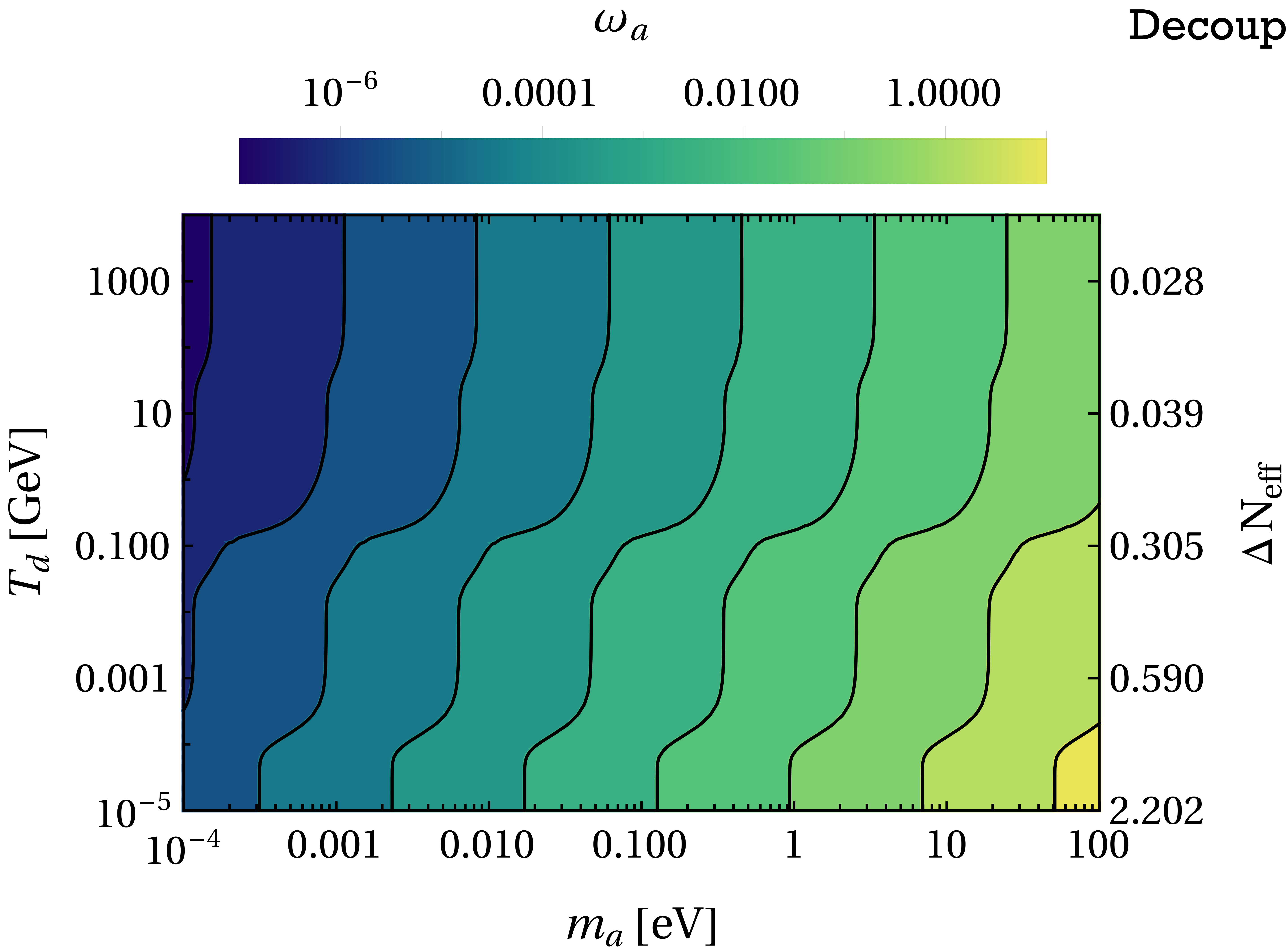
Thermally produced axions via coupling with gluons and photons in the early Universe

Relic population established at freeze-out condition $\Gamma(T_d) = H(T_d)$

Decoupling temperature T_d sets axion abundance ω_a

Cosmological phenomenology



Decoupling temperature T_d sets axion abundance ω_a

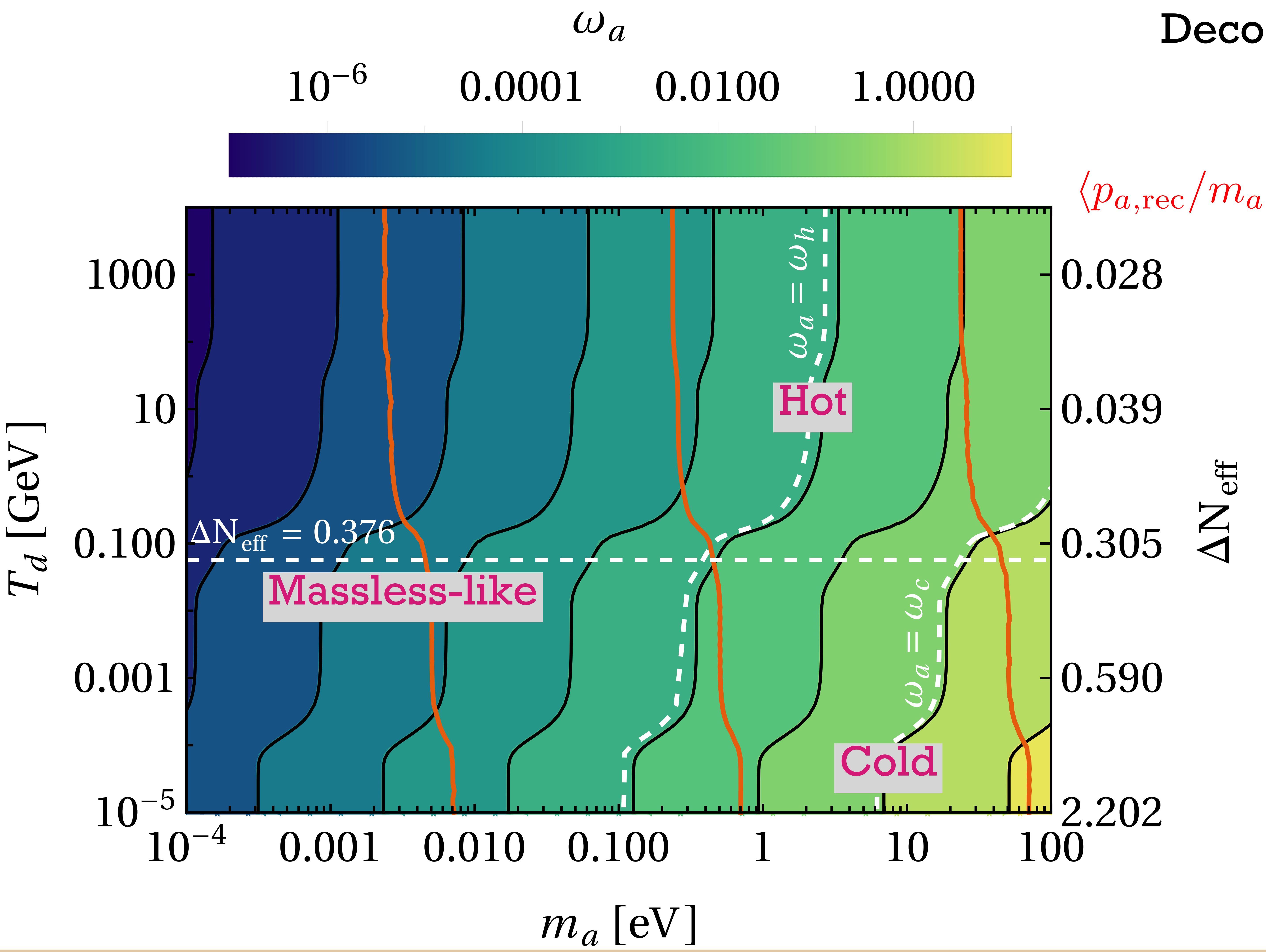
$$\boxed{\omega_a \simeq m_a n_a \simeq \left(\frac{m_a}{130\,\mathrm{eV}}\right)\left(\frac{g_{*,s}(T_d)}{10}\right)^{-1} = 0.011\left(\frac{m_a}{\mathrm{eV}}\right)\Delta N_{\rm eff}^{3/4}}$$

$$\boxed{\Delta N_{\rm eff} \equiv \frac{\rho_a^{\rm mless}}{\rho_\nu^{\rm mless}} \propto \frac{g_a}{g_\gamma}\left(\frac{T_a}{T_\gamma}\right)^4 \simeq 0.027\left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}}$$

Phenomenology fully determined by any 2 of $\omega_a, m_a, T_d, N_{\rm eff}$

Cosmological phenomenology

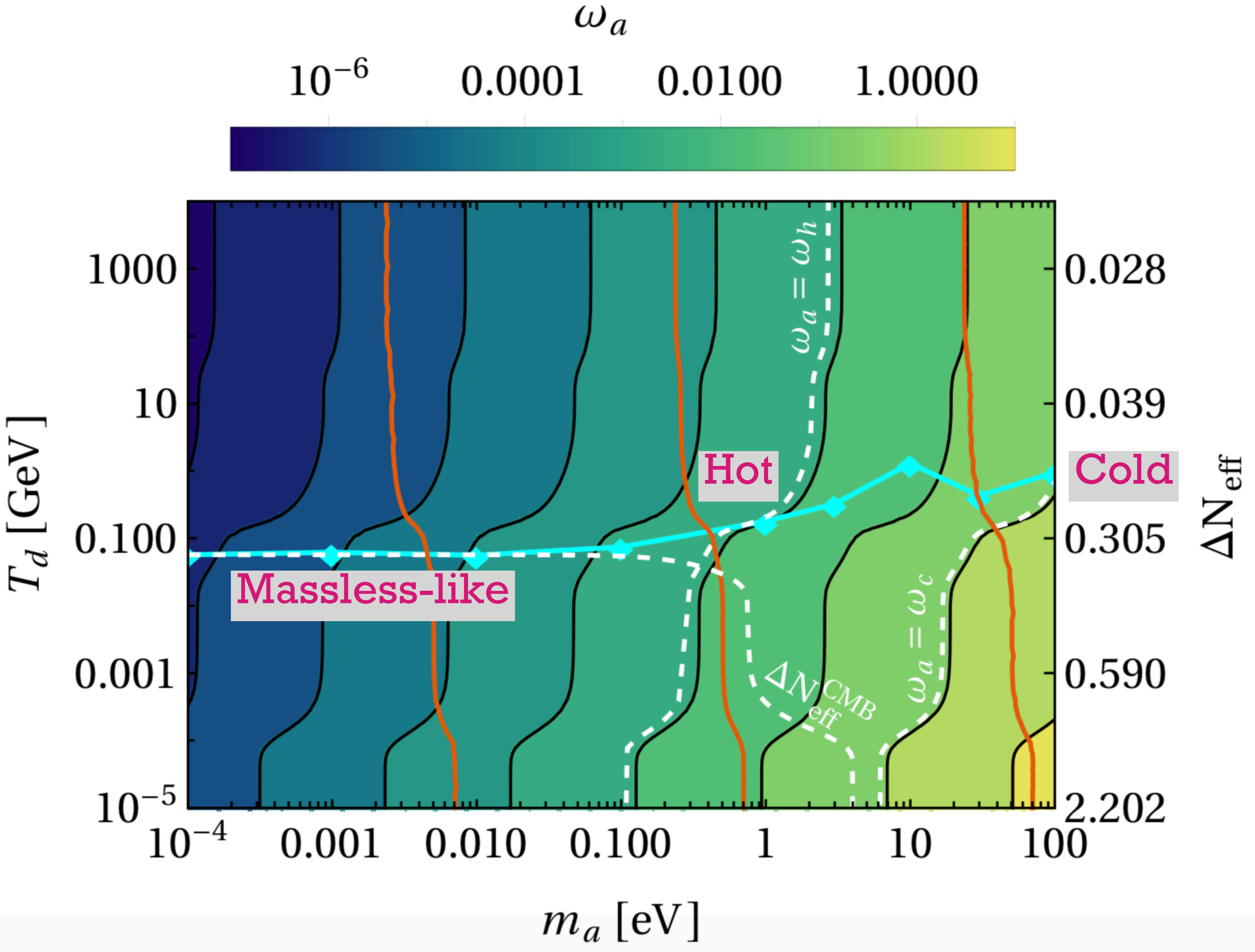
Decoupling temperature T_d sets axion abundance ω_a



$\langle p_{a,\rm rec}/m_a \rangle = [10^2,\, 1,\, 10^{-2}]$

Depending on the ALP mass, we expect cosmological bounds to follow any of the white line

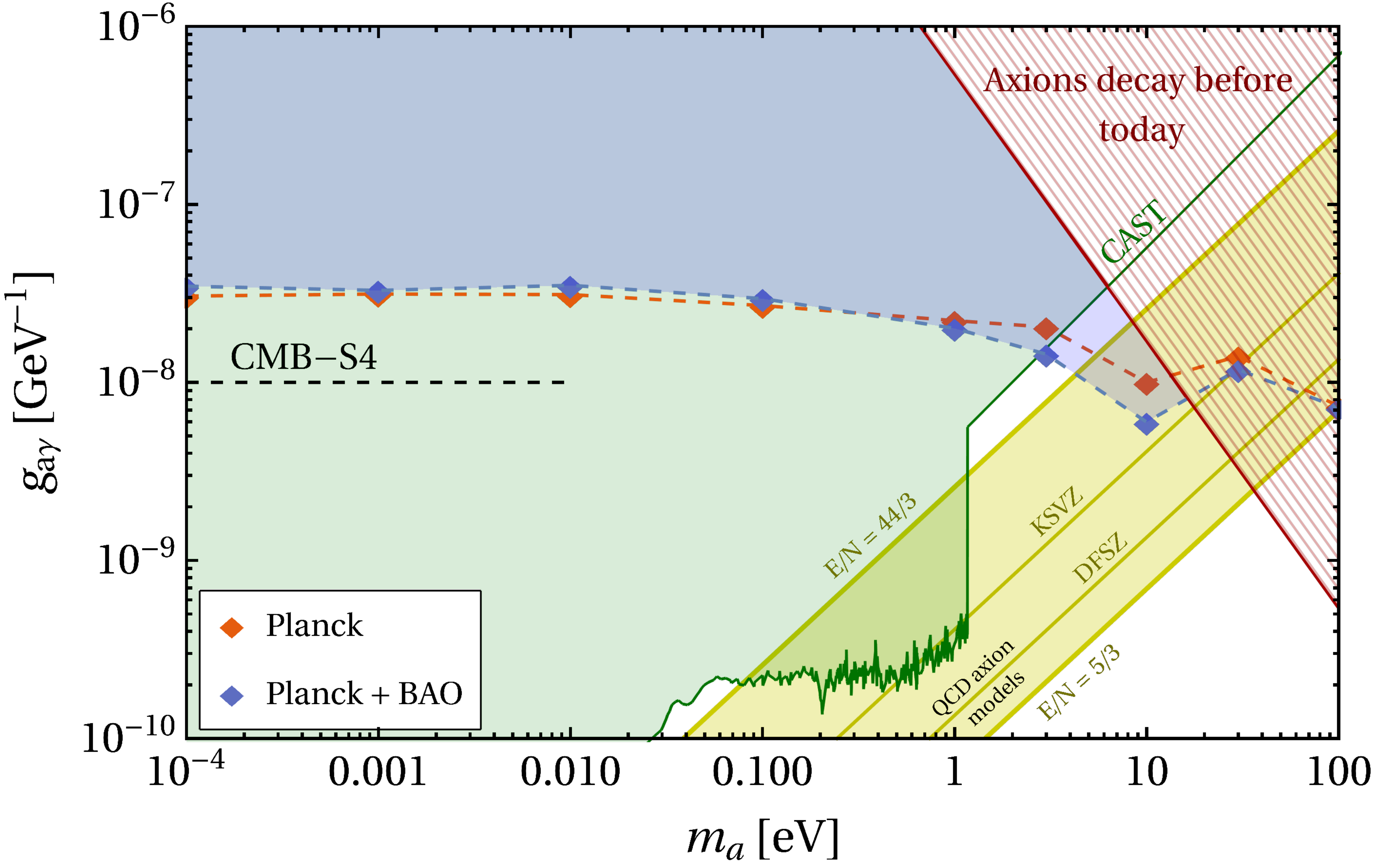
Summary of cosmological results



Bounds follow expectations
in extreme regimes

Need for dedicated numerical analysis
in intermediate (~eV) regime

Bounds on axion-photon coupling



Broader than CAST below eV
Excludes viable region
in the ~10eV mass range

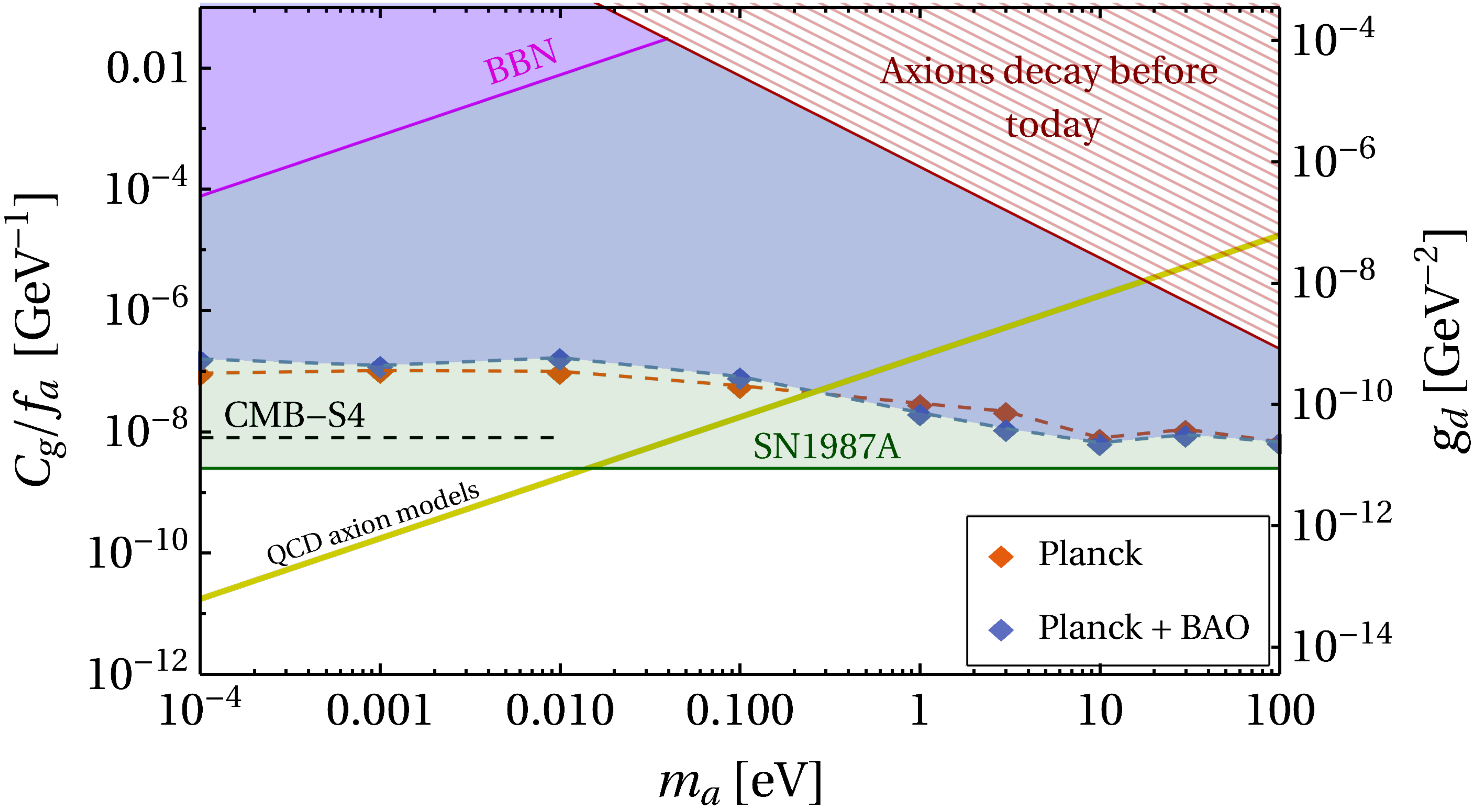
ma>20eV,
account for radiative decay

+current CMB small-scale:
1.6x stronger bounds
in the low-mass regime

+future CMB:
3x stronger bounds

For light axions:
From stellar evolution:
2x stronger bounds
From globular clusters:
3x stronger bounds

Bounds on axion-gluon coupling



Current cosmology:

Complementary to astro bounds

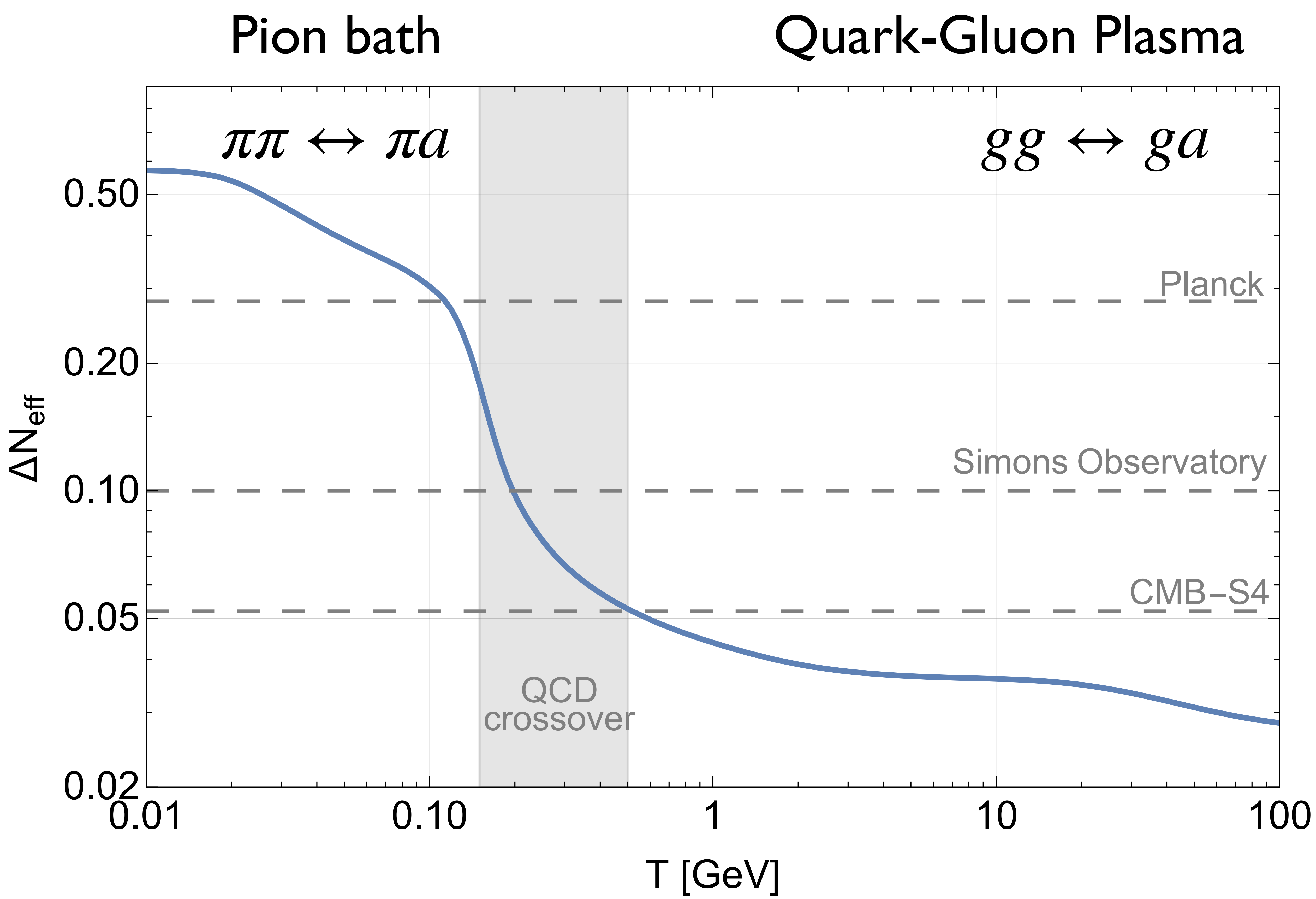
+current CMB small-scale:
~6x stronger bounds
in the low-mass regime

+future CMB:
>10x stronger bounds
in low-mass regime

KSVZ QCD axion: fa>2 10^7 GeV
-> ma < 0.3 eV

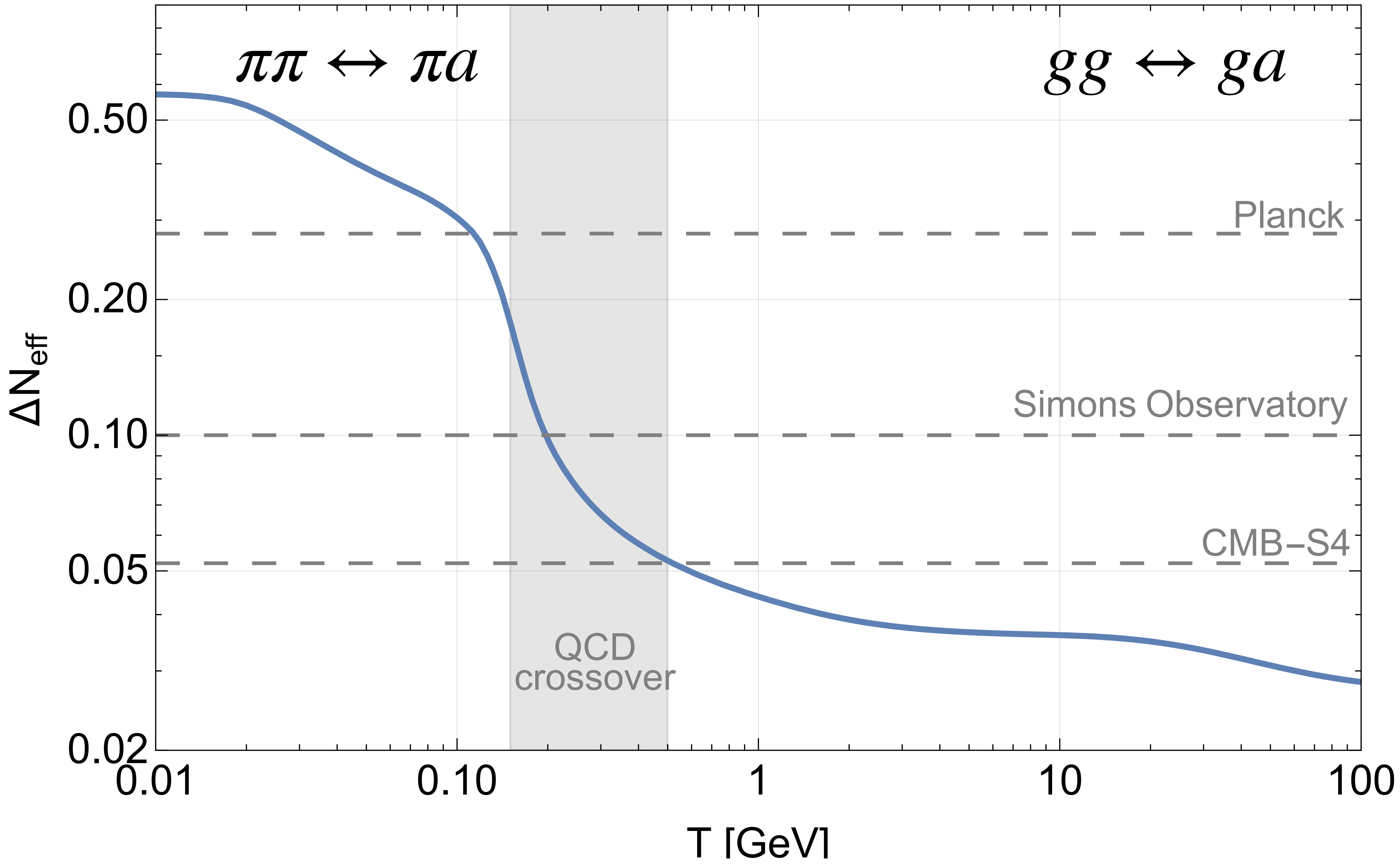
QCD axion thermal production

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{\alpha_s}{8\pi}\frac{a}{f_a}G^{a,\mu\nu}\tilde{G}^a_{\mu\nu}$$



$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{\rho_a}{\rho_\gamma}\right)_{\rm CMB} \simeq 0.027\left(\frac{106.75}{g_{*,s}(T_d)}\right)^{4/3}$$

Pion bath   Quark-Gluon Plasma



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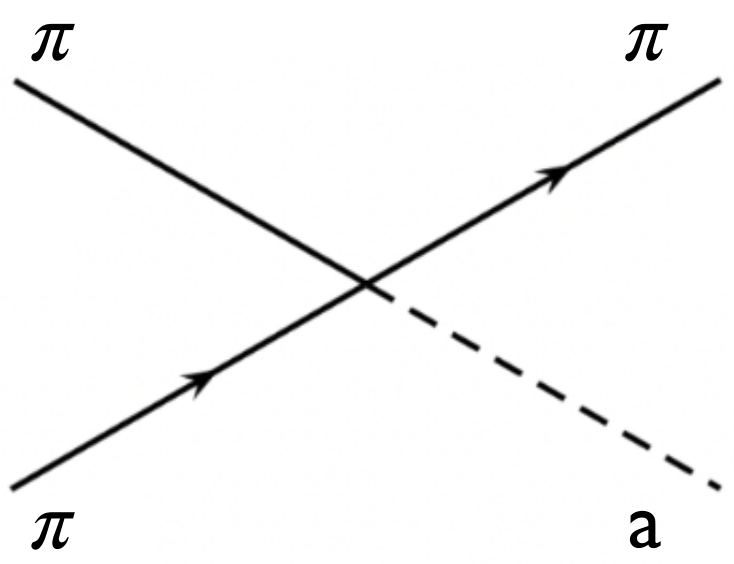

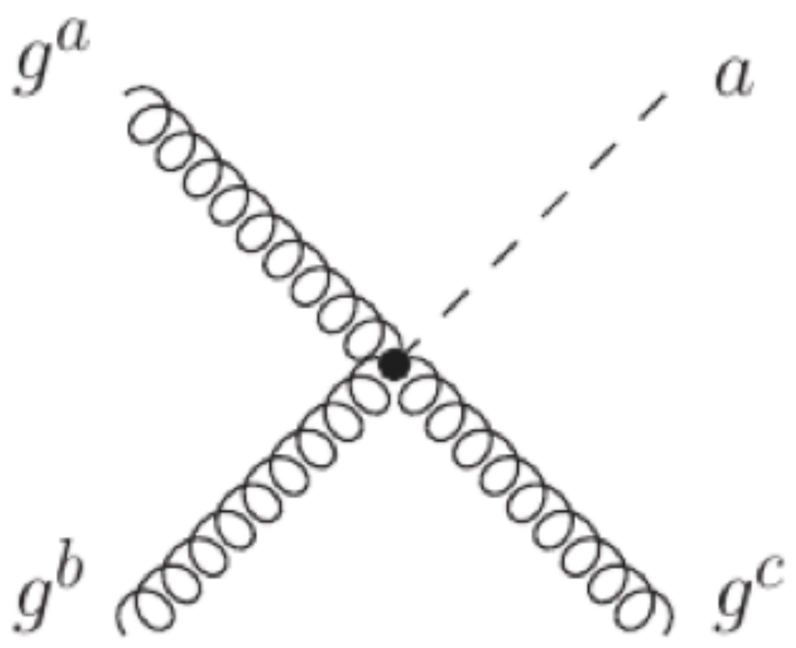

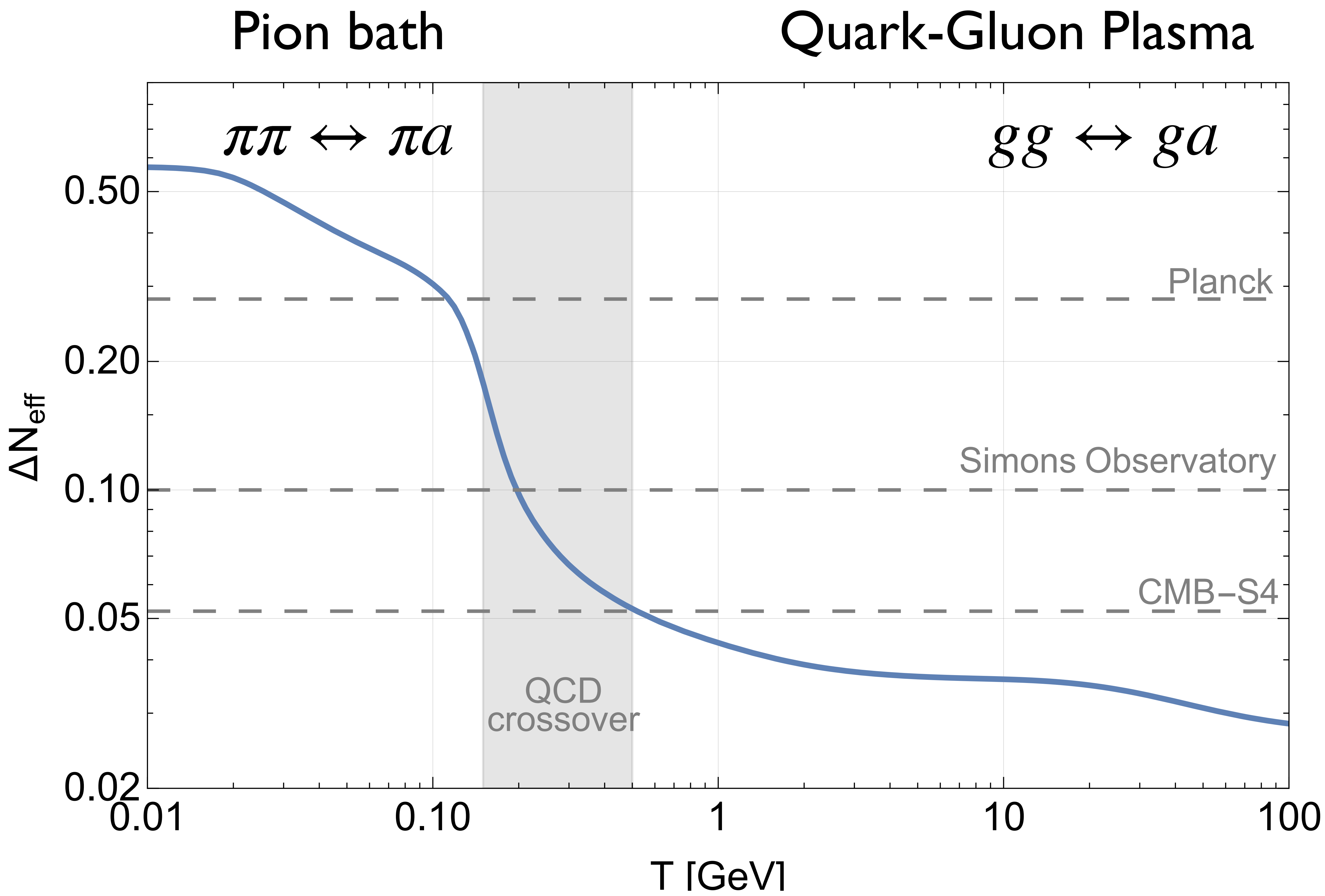

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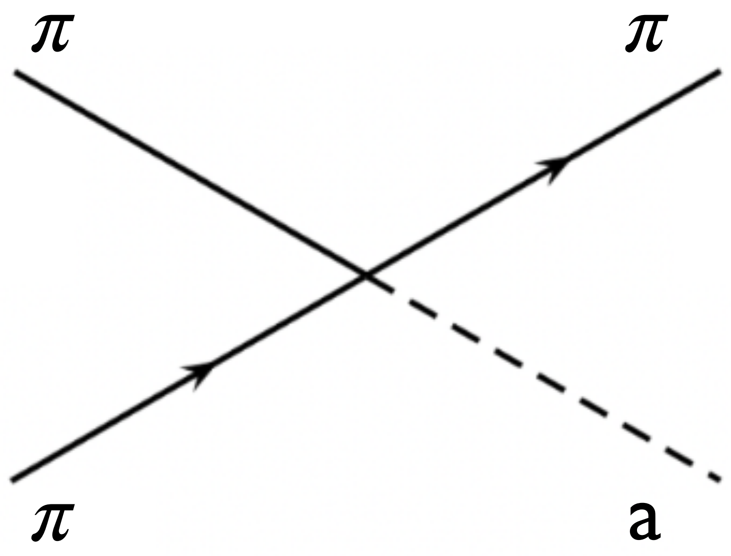
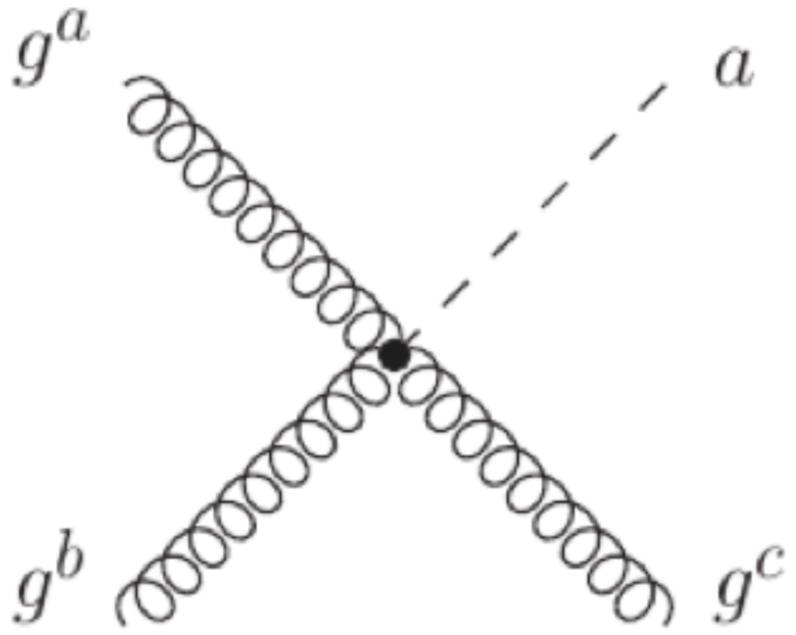
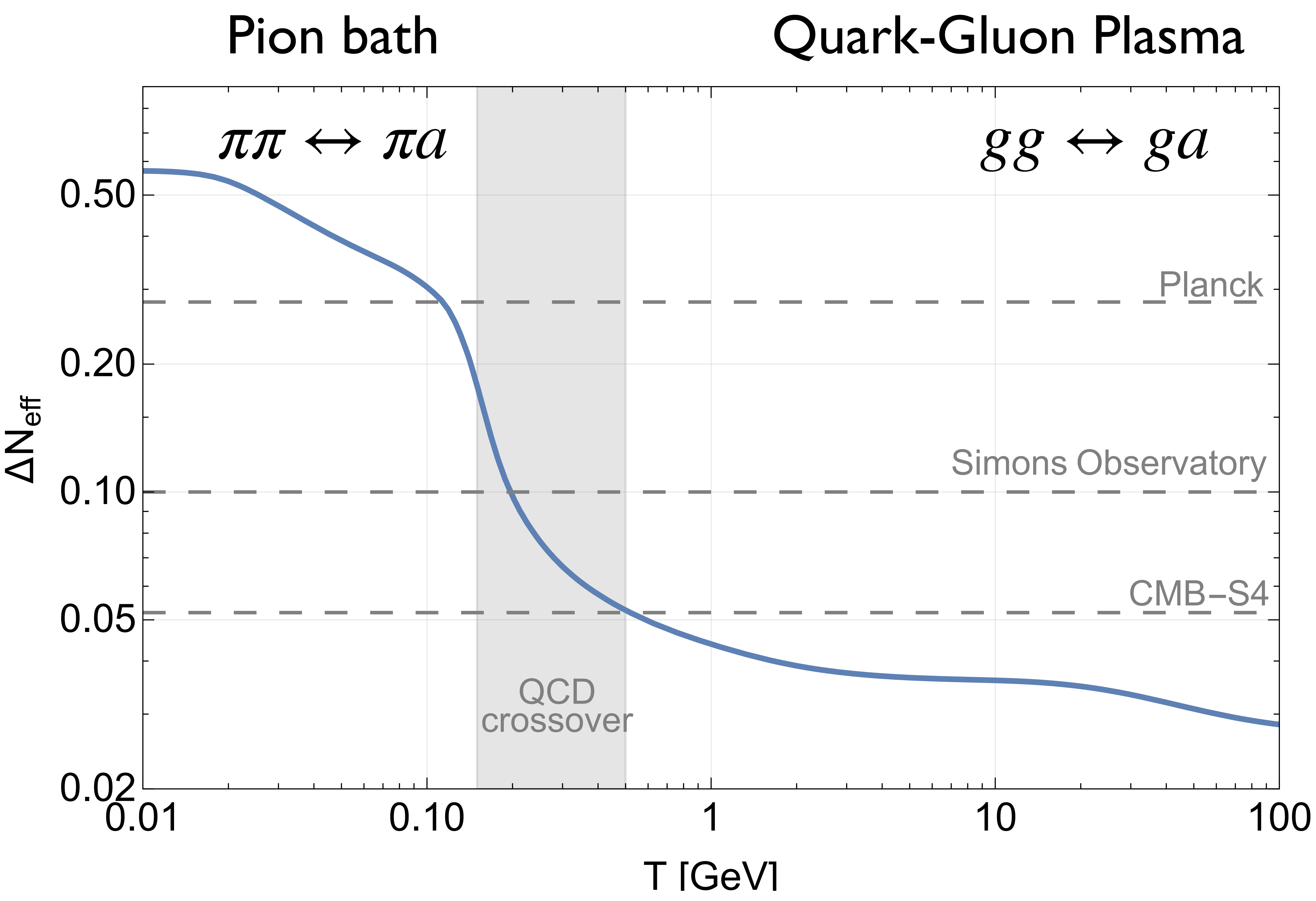
Solve Boltzmann equations

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







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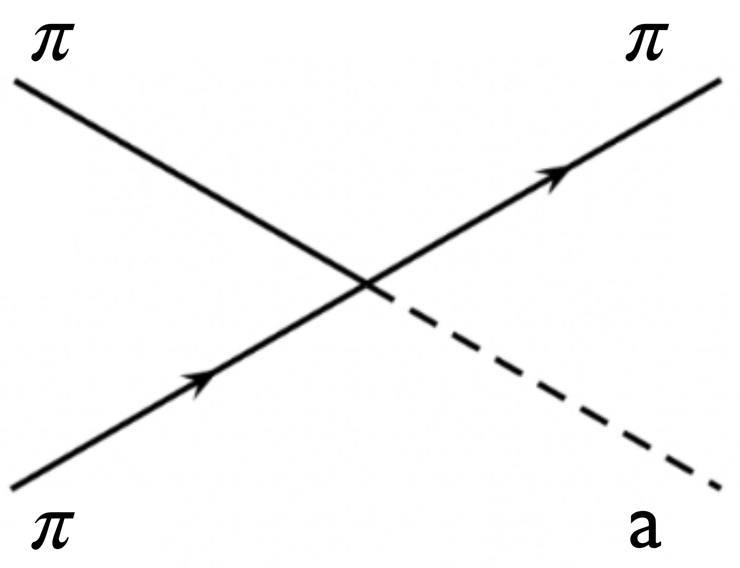
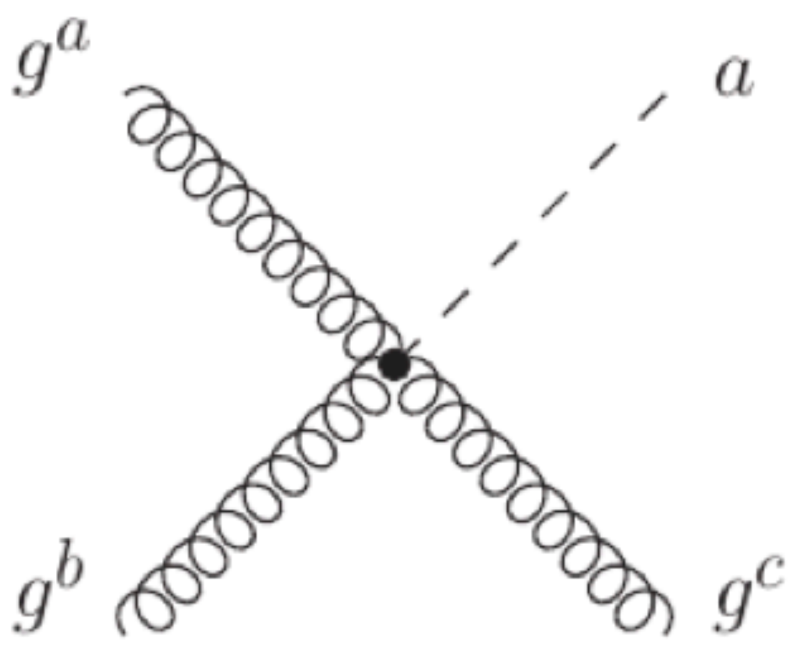
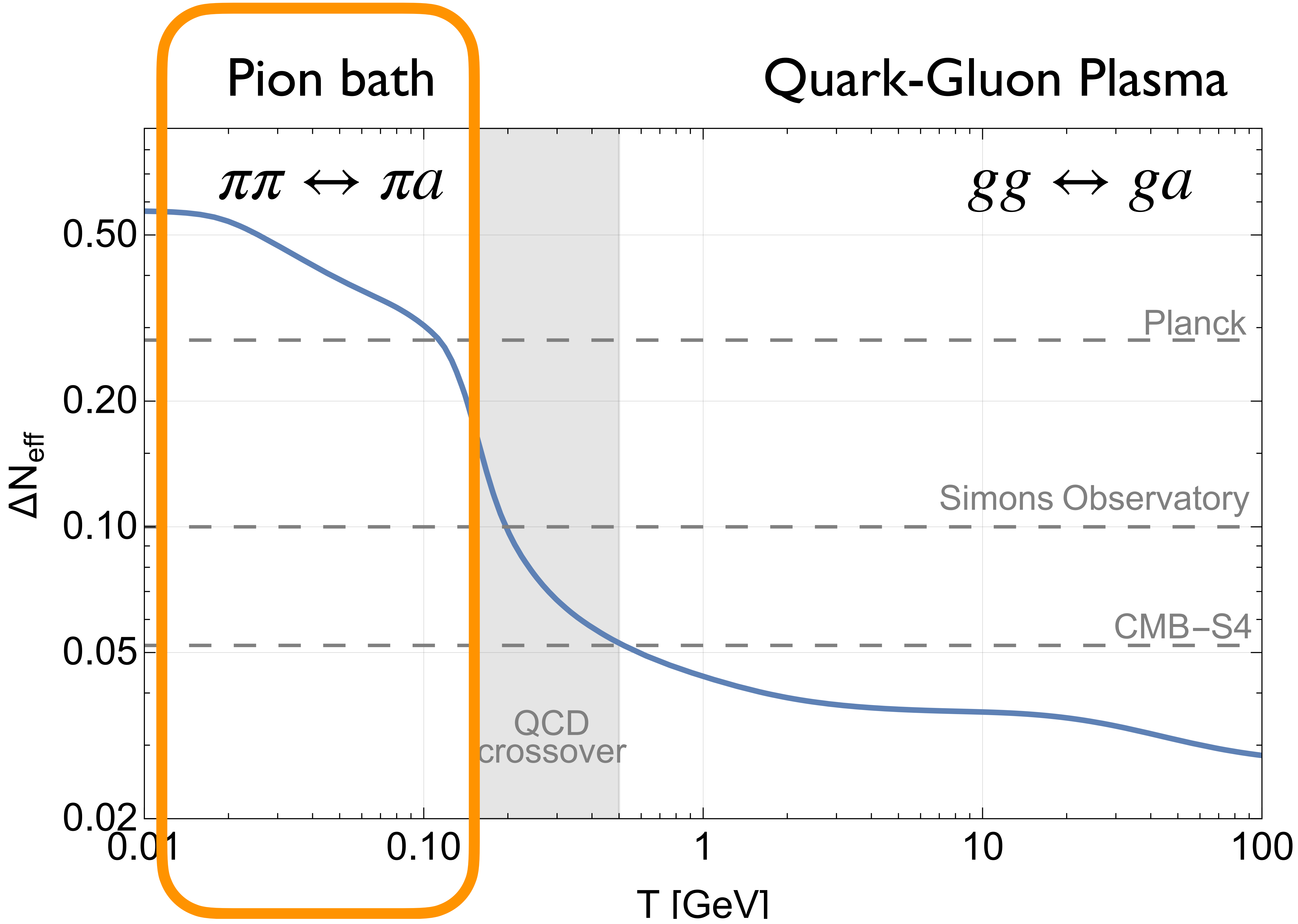
This formula may not be precise enough:

1. if the cross section depends on momentum, since different momenta will decouple at different times;
2. if the number of degrees of freedom decrease rapidly, higher momenta will be less diluted, leading to spectral distortions;
3. because production may be never in thermal equilibrium.





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



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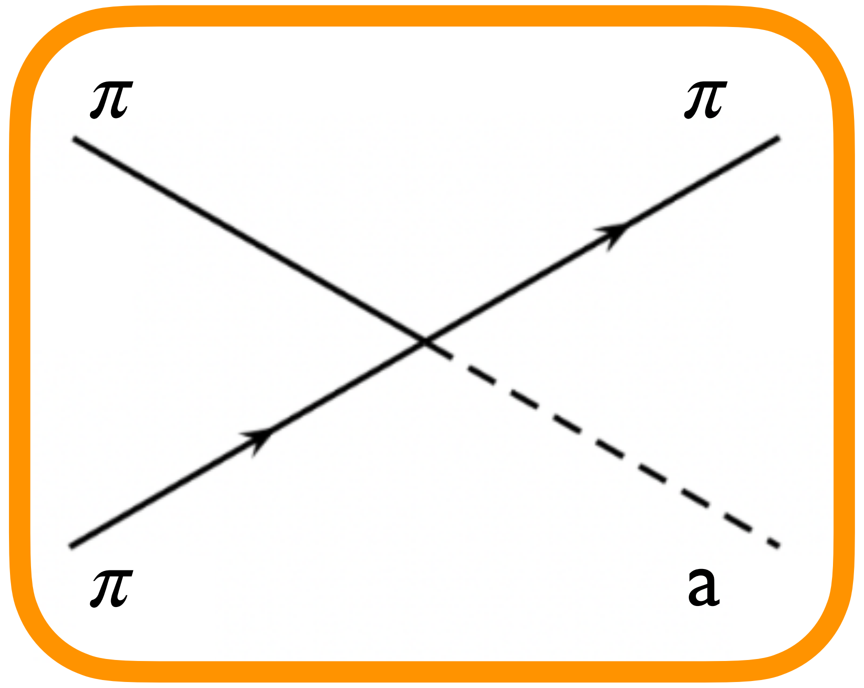

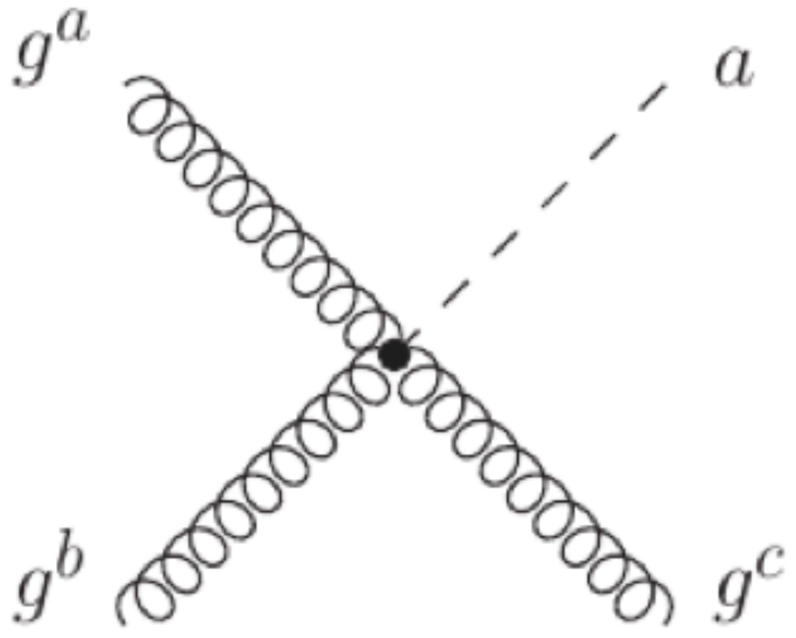

$$\boxed{C_{a\pi} = \frac{1}{3}\left(\frac{m_d - m_u}{m_d + m_u} + c_d^0 - c_u^0\right)}$$

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

[Chang and Choi, hep-ph/9306216]

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

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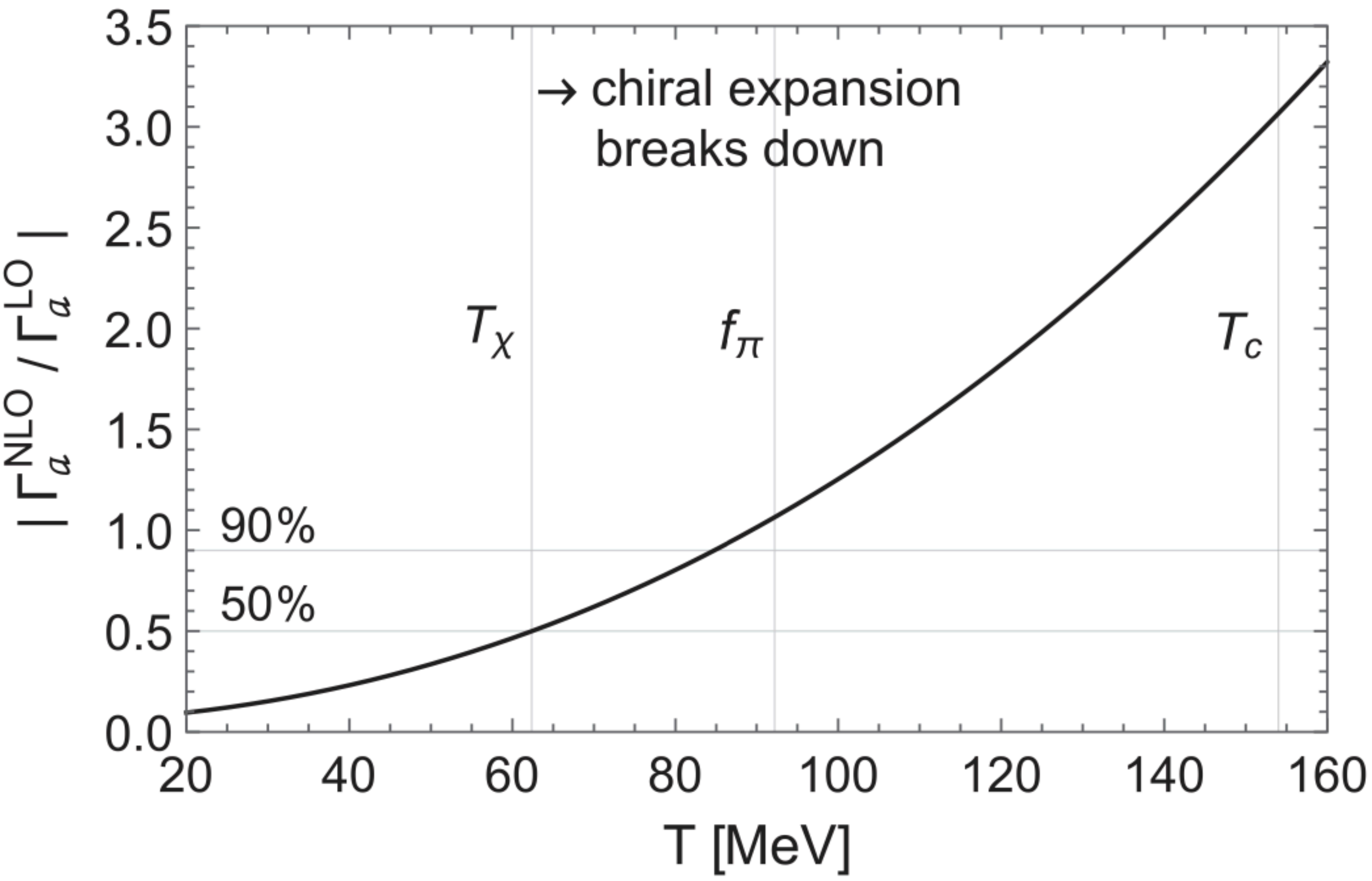
[Di Luzio, Martinelli and Piazza, 2101.10330]

NLO:



Decompose amplitude into isospin channels:

$$T_{\pi\pi} = \frac{1}{3}\left(T^0(s) + 3\,T^1(s) + 5\,T^2(s)\right)$$

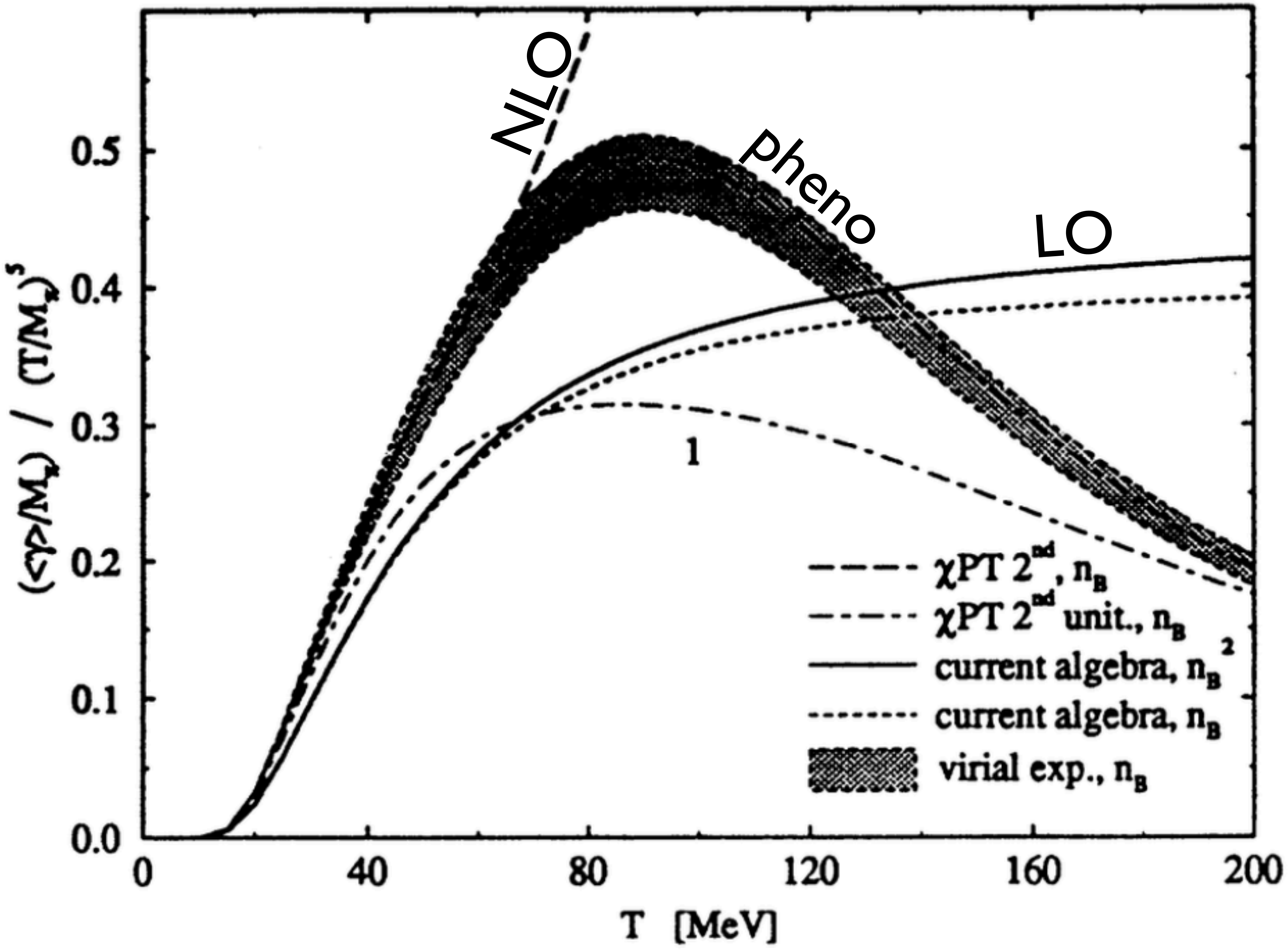
expand into partial waves

$$T^I = 32\pi \sum_{\ell=0}^{\infty} (2\ell+1) P_\ell(\cos\theta) t_\ell^I(s)$$

unitarity implies (in the elastic region)

$$t_\ell^I = \sqrt{\frac{s}{s-4m_\pi^2}}\frac{e^{2i\delta_\ell^I(s)}-1}{2i}$$

[Schenk, Phys. Rev. D 47 (1993) 11]



[Notari, Rompineve and Villadoro, 2211.03799]

$$\mathscr{L} \supset \frac{\partial_\mu a}{2f_a} c_0\, \bar{q}\gamma^\mu\gamma_5 q - \bar{q}_L M_a q_R + \mathrm{h.c.}$$

$$\boxed{M_a \equiv \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} e^{i\frac{a}{2f_a}(1+c_3\sigma^3)}}$$

[Notari, Rompineve and Villadoro, 2211.03799]

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at low energies

$$\mathscr{L}_{\chi PT} \supset \frac{f_\pi^2}{4}\mathrm{Tr}[\partial_\mu U \partial^\mu U^\dagger + 2B_0(M_a U^\dagger + U M_a^\dagger)] + \ldots$$

$$\boxed{U \equiv e^{i\vec{\pi}\cdot\vec{\sigma}/f_\pi}}$$

[Notari, Rompineve and Villadoro, 2211.03799]

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$a - \pi^0$ mixing rotated away by orthogonal

rotation with angle $\theta_{a\pi} \simeq \frac{f_\pi}{2f_a}\left(\frac{m_d - m_u}{m_d + m_u} - c_3\right)$

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

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

1. $\pi\pi$ final-state interactions are resonant: σ for I=L=0, ρ for I=L=1
2. Chiral Perturbation theory cannot produce these resonances
3. the unitarity relation implies that the phase shifts of the ChPT axion amplitude and $\pi\pi$ amplitude are the same

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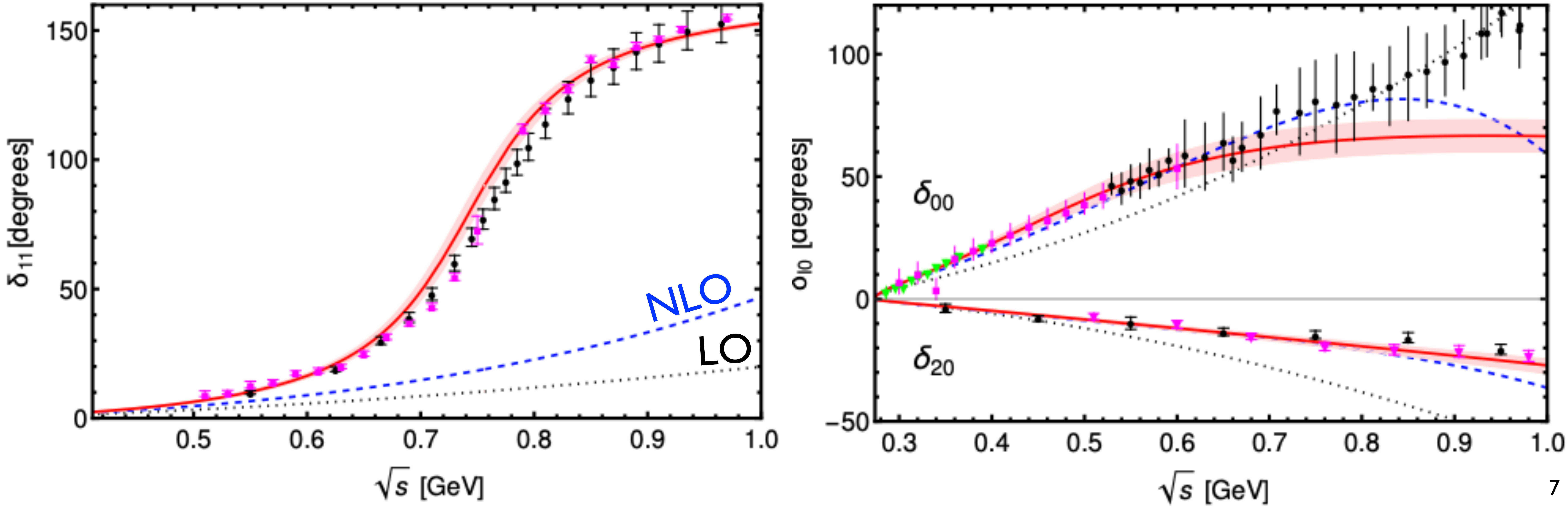
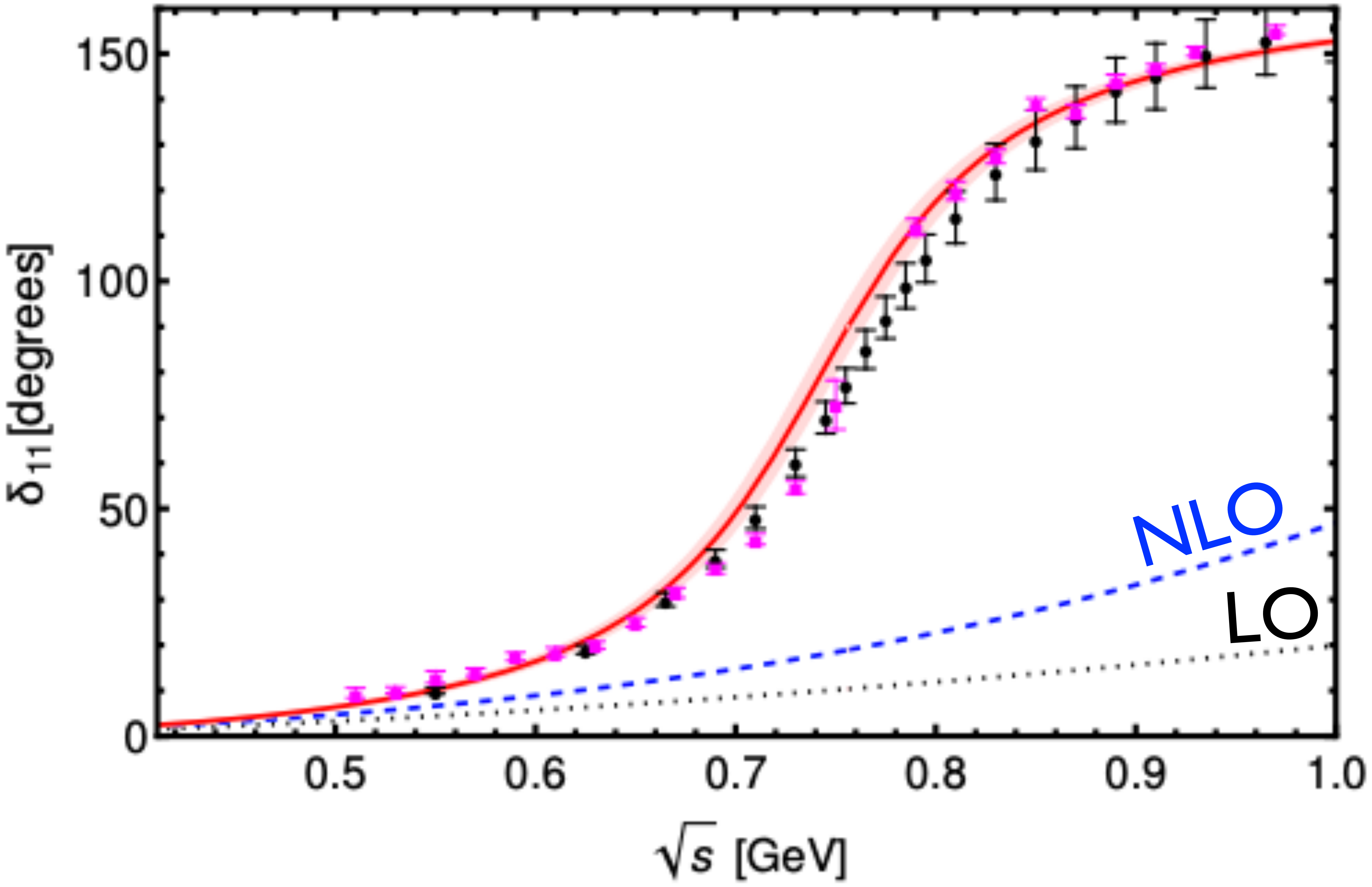
[Di Luzio, Camalich, Martinelli, Oller and Piazza, 2211.05073]

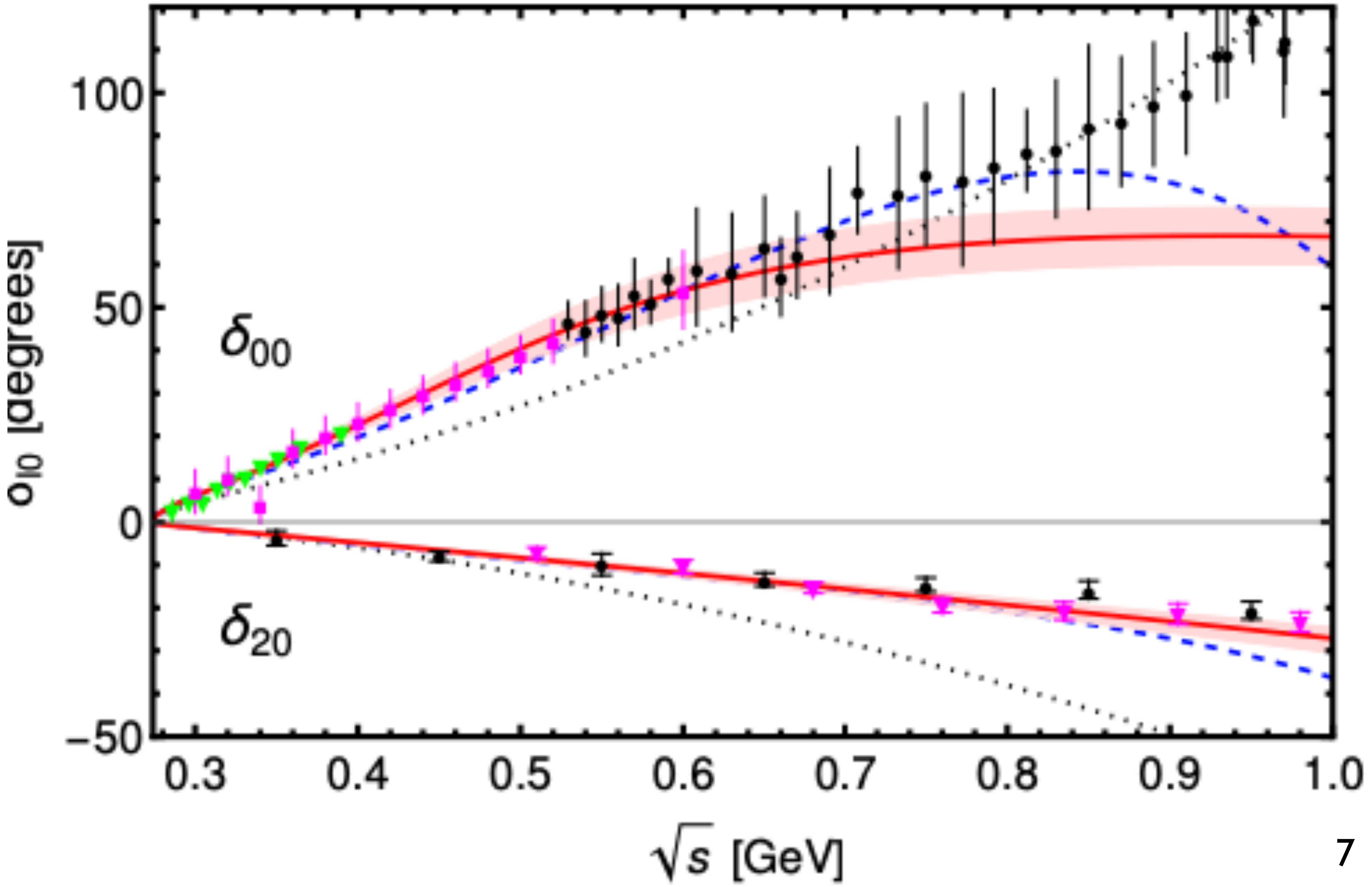


$$A_{IJ}(s) = \frac{A^{(2)}_{IJ}(s)}{1 - A^{(4)}_{IJ}(s)/A^{(2)}_{IJ}(s)}$$

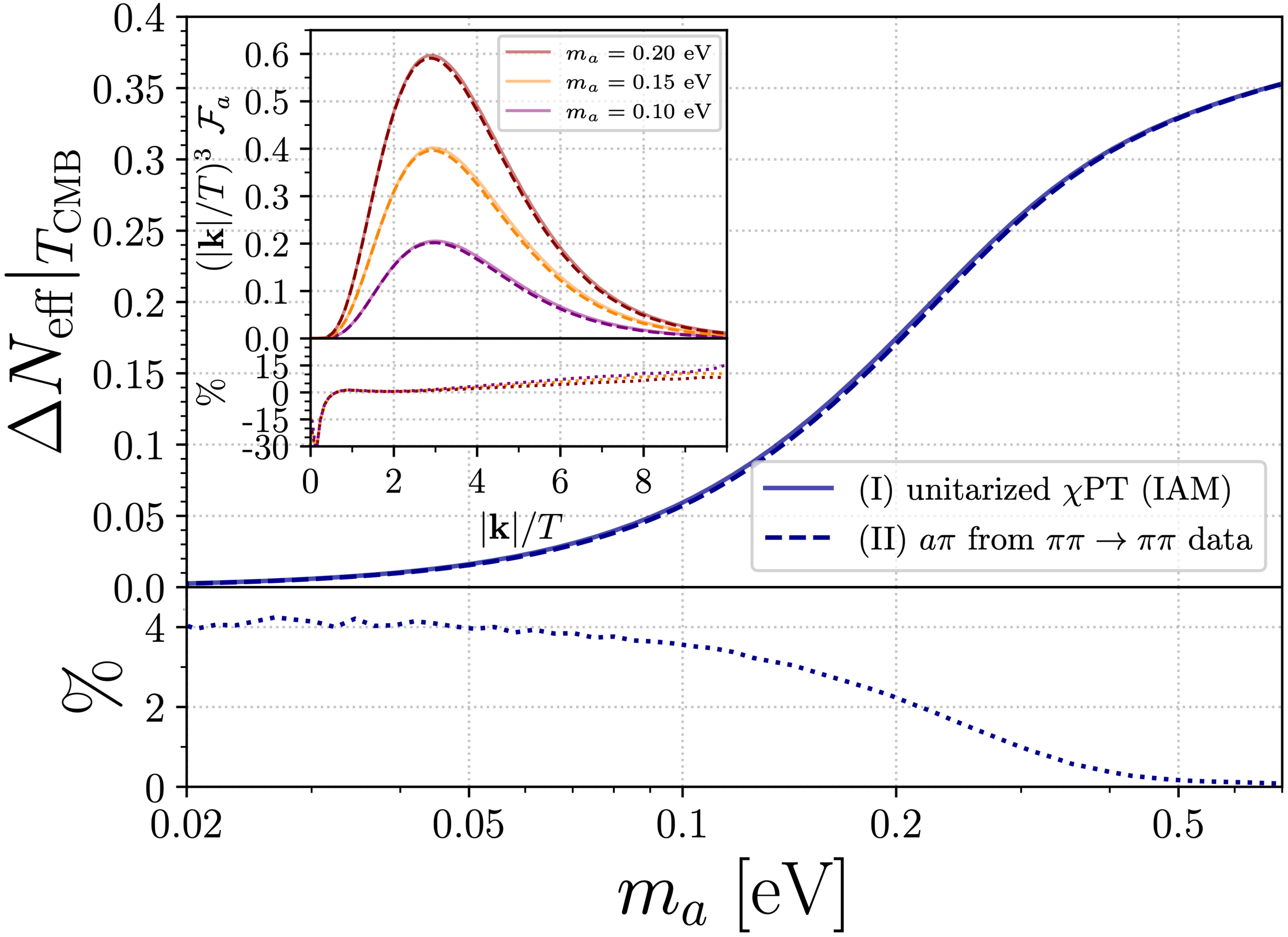
Inverse Amplitude Method

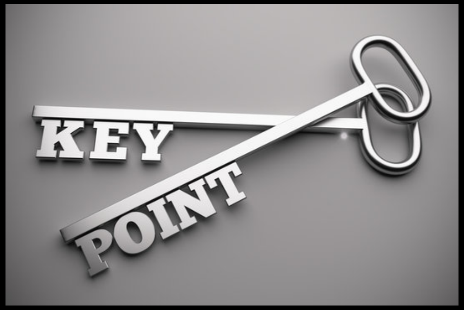
[Di Luzio, Camalich, Martinelli, Oller and Piazza, 2211.05073]



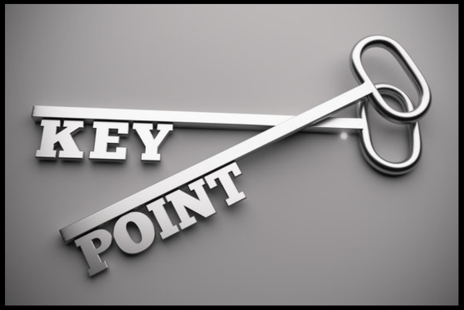


[Bianchini, Grilli di Cortona and Valli 2310.08169]

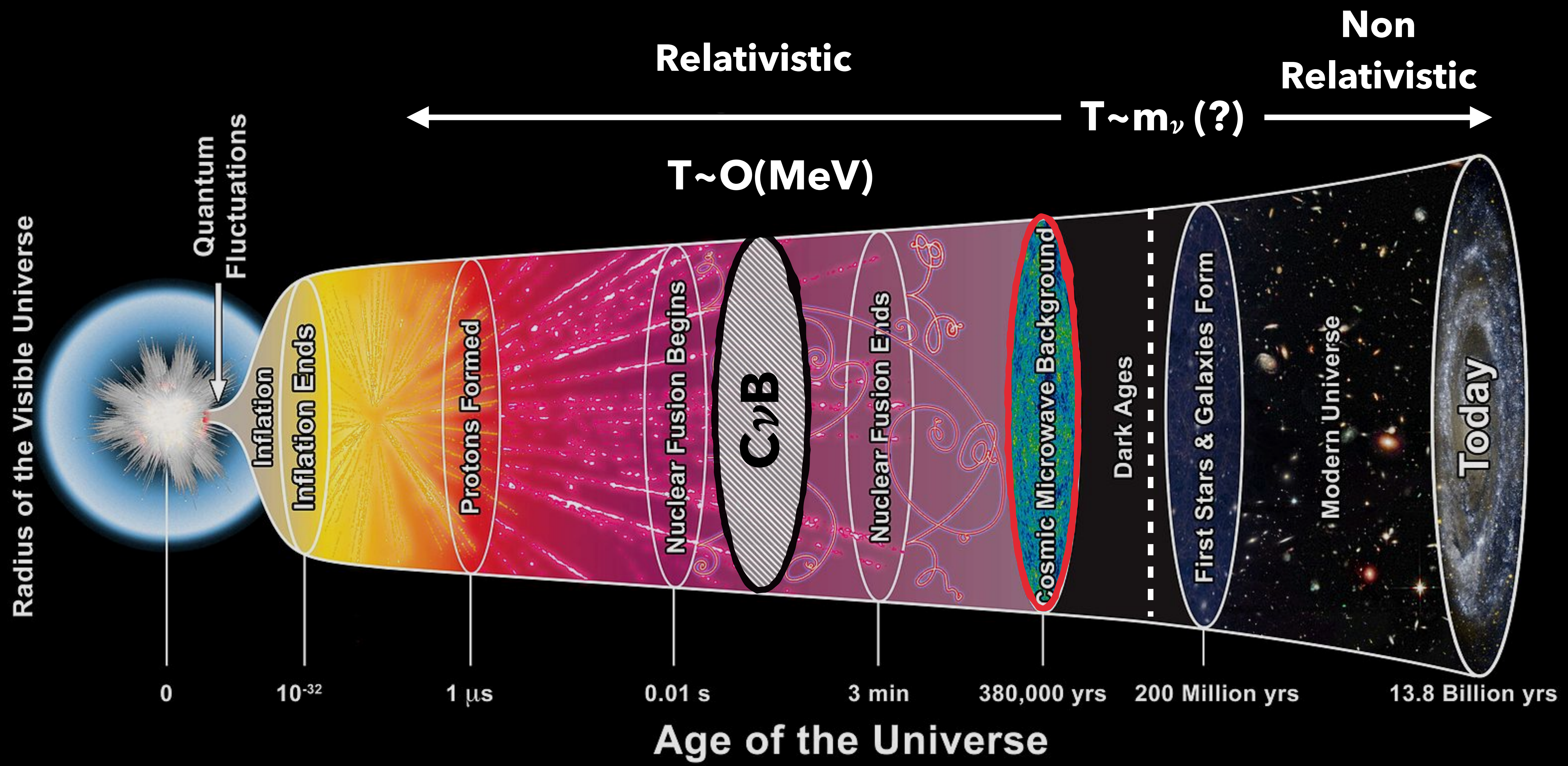




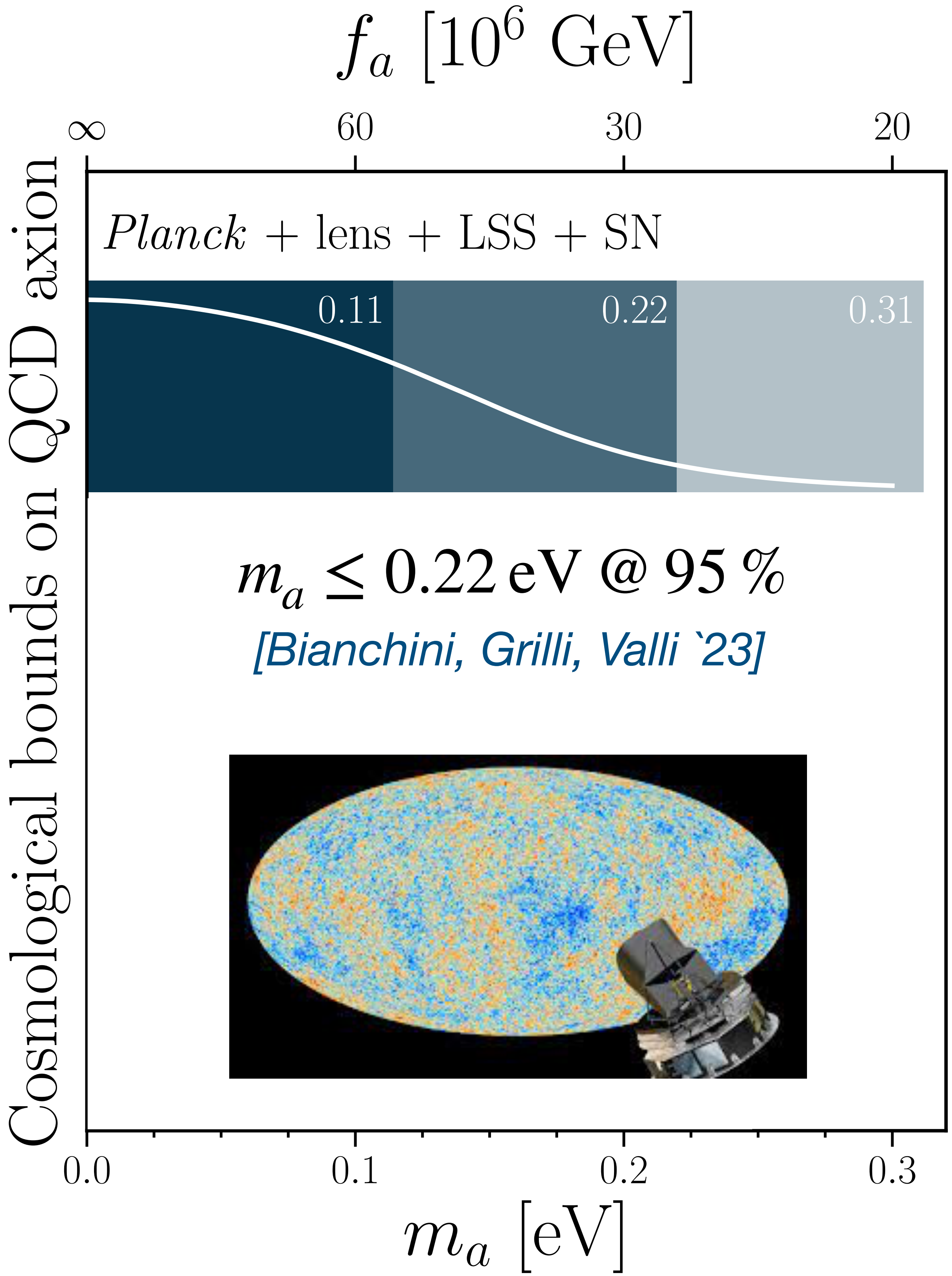
(Hot) Axions ~ Neutrinos



Neutrino cosmology 101

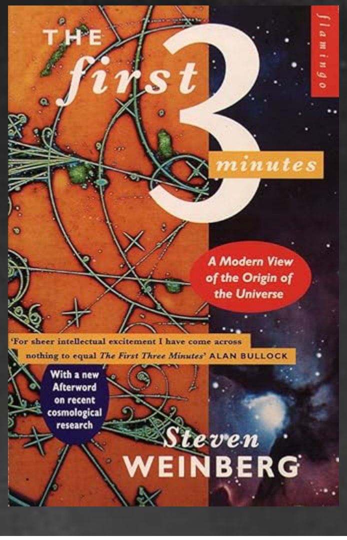


Minimal QCD Axion ($T_{dec} < T_c$)



$m_a \leq 0.22\,\mathrm{eV}$ @ 95 %

[Bianchini, Grilli, Valli `23]



THE *first* 3 *minutes*

A Modern View of the Origin of the Universe

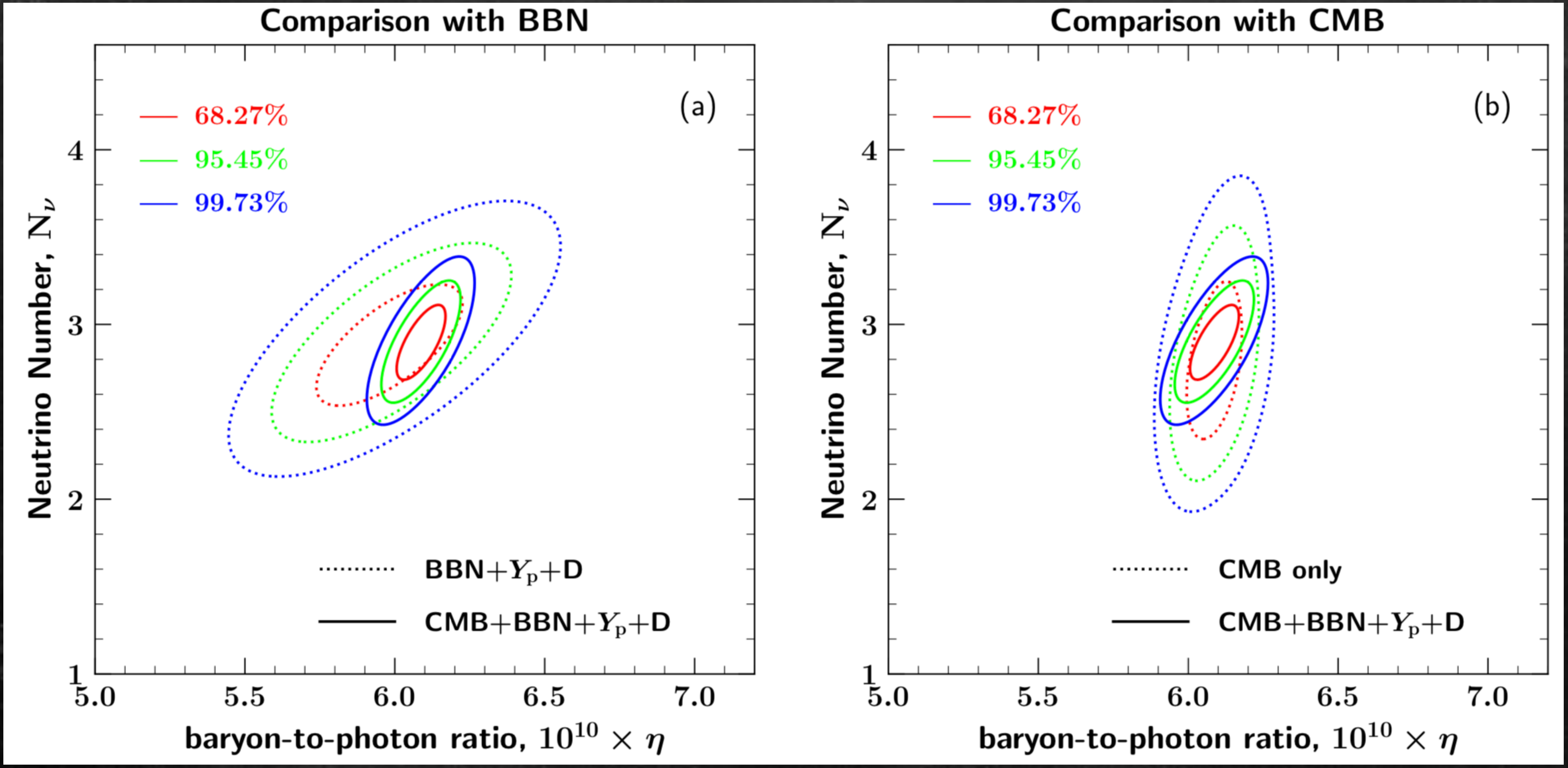
'For sheer intellectual excitement I have come across nothing to equal *The First Three Minutes*' ALAN BULLOCK

With a new Afterword on recent cosmological research

Steven WEINBERG

flamingo

arXiv: ***2207.13133***

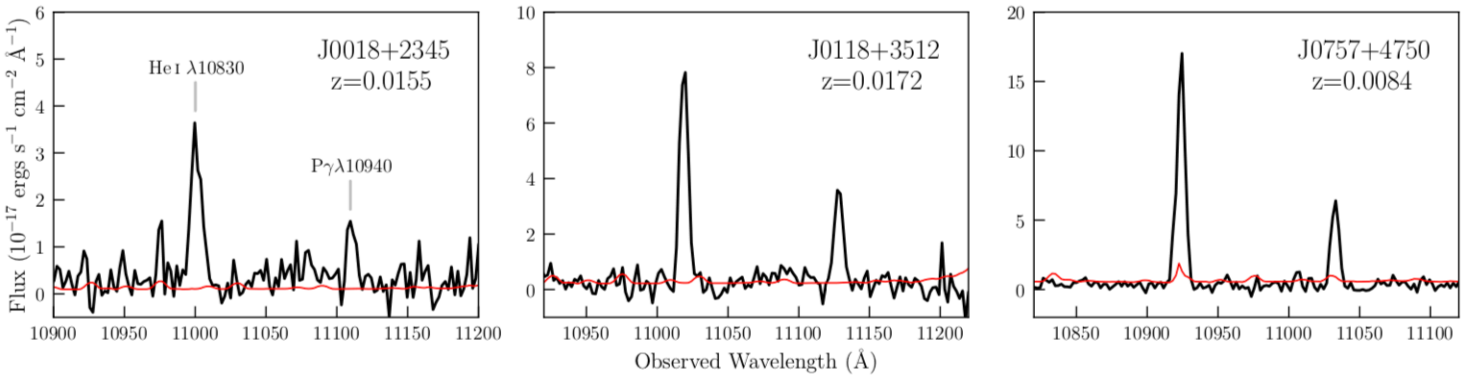


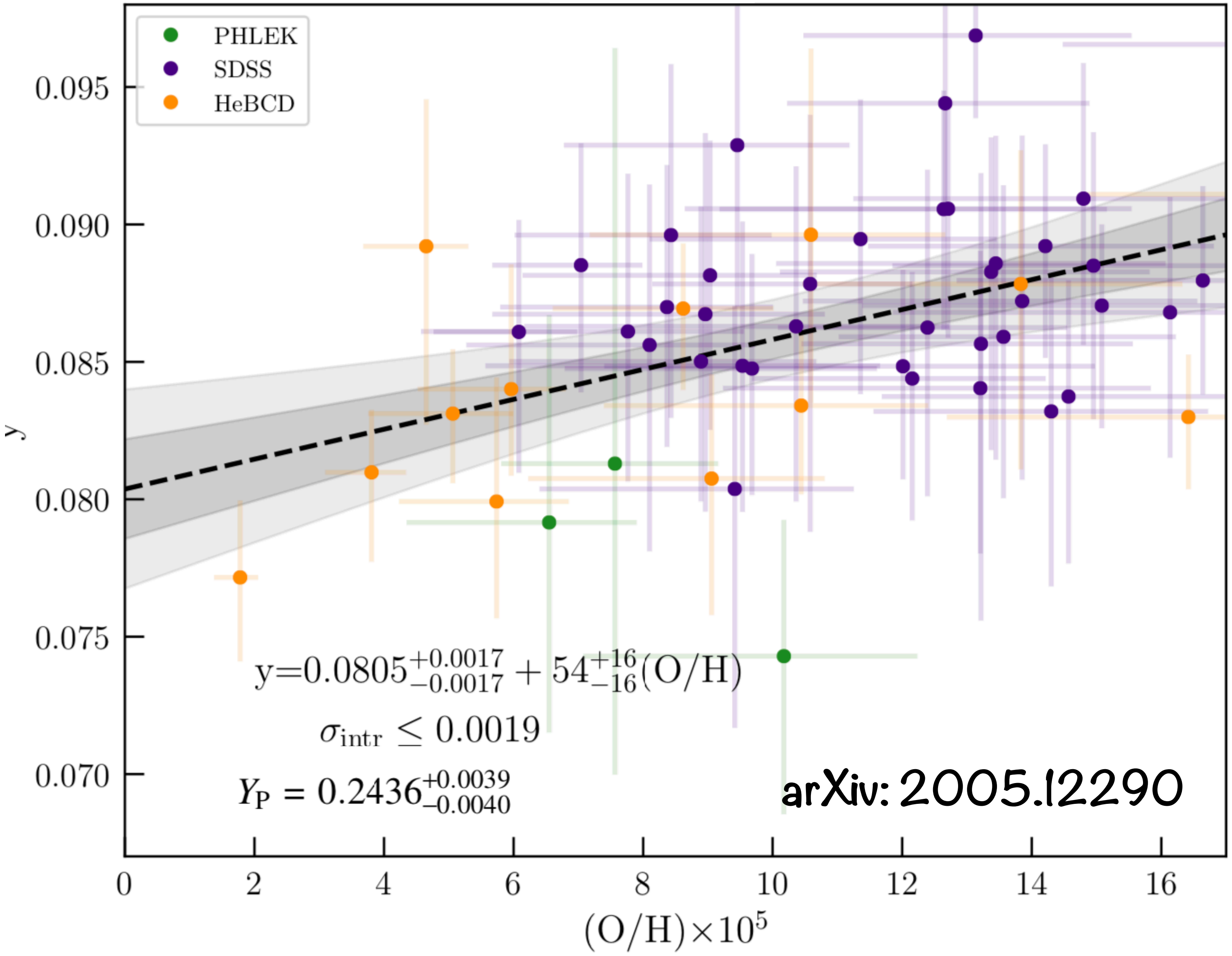
BBN IS COMPETITIVE WITH CMB TO CONSTRAIN $\Delta N_{\rm eff}$

^4He

PDG 2021: $Y_P = 0.245 \pm 0.003$

% level measurement



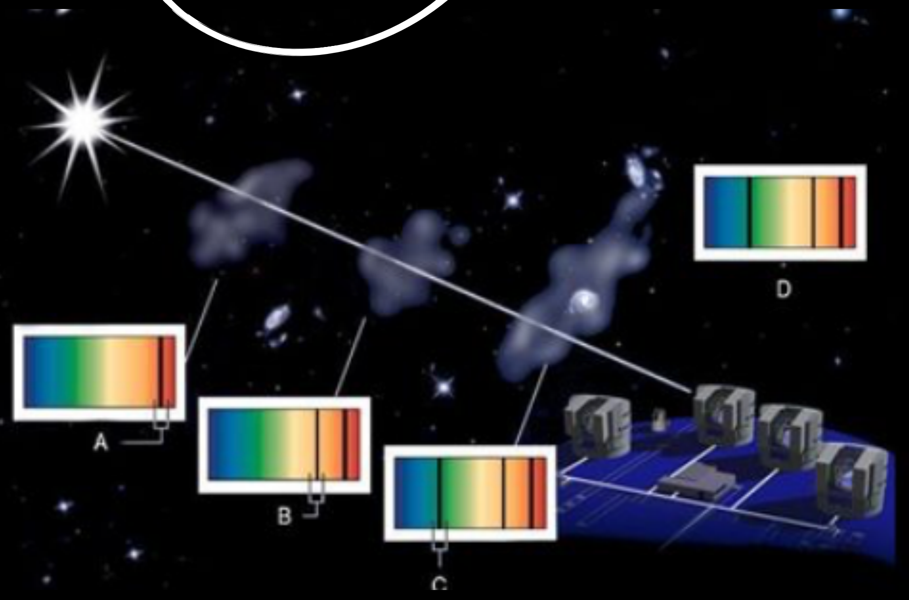


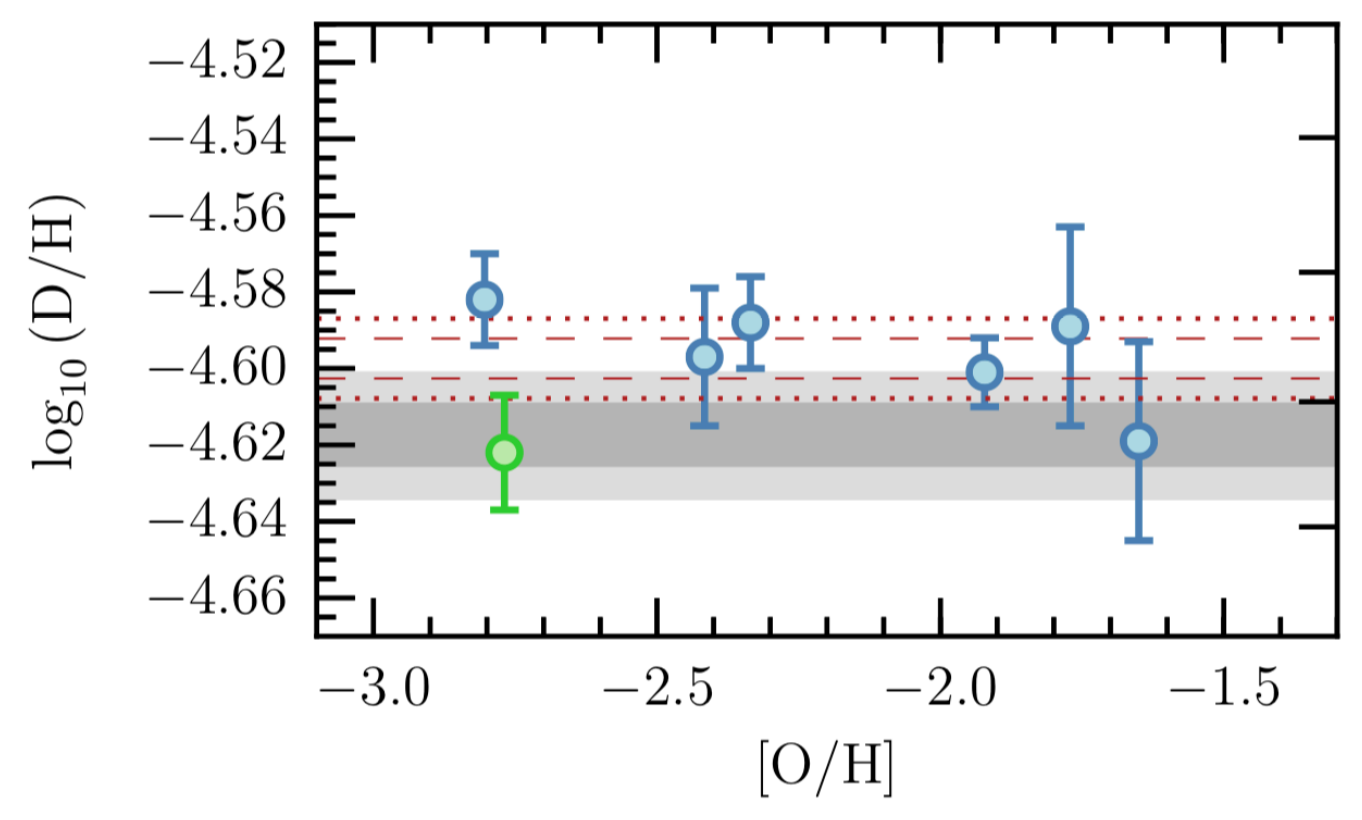
arXiv: 2005.12290

D

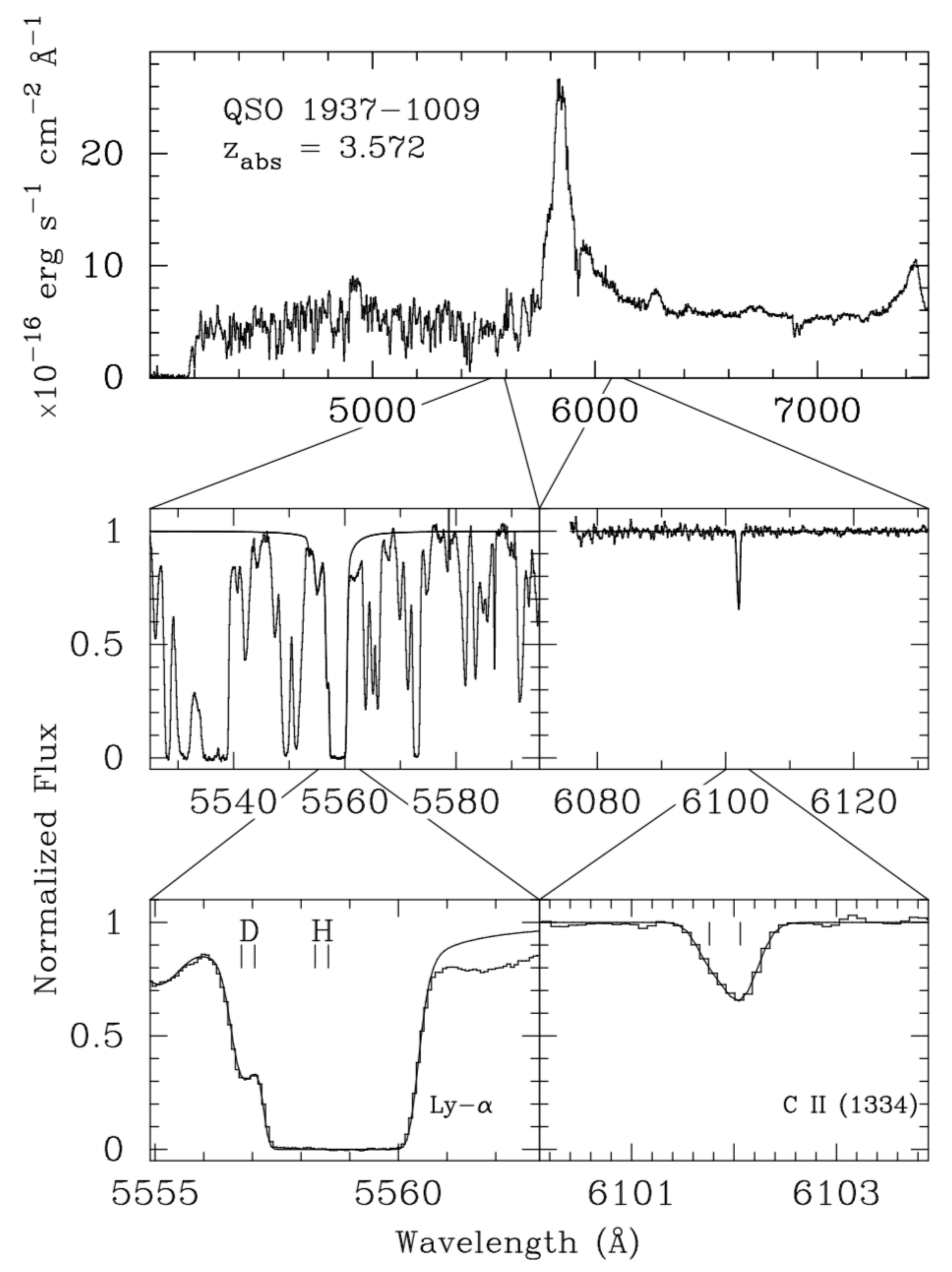
% level measurement

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





arXiv: 1710.11129



astro-ph/9803071

BBN ERA IN ΛCDM

$$\boxed{\begin{array}{l} n+\nu_e \leftrightarrow p+e^- \\ n+e^+ \leftrightarrow p+\bar{\nu}_e \end{array}}$$

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

$m_n - m_p \simeq 1.3\,MeV$

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

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

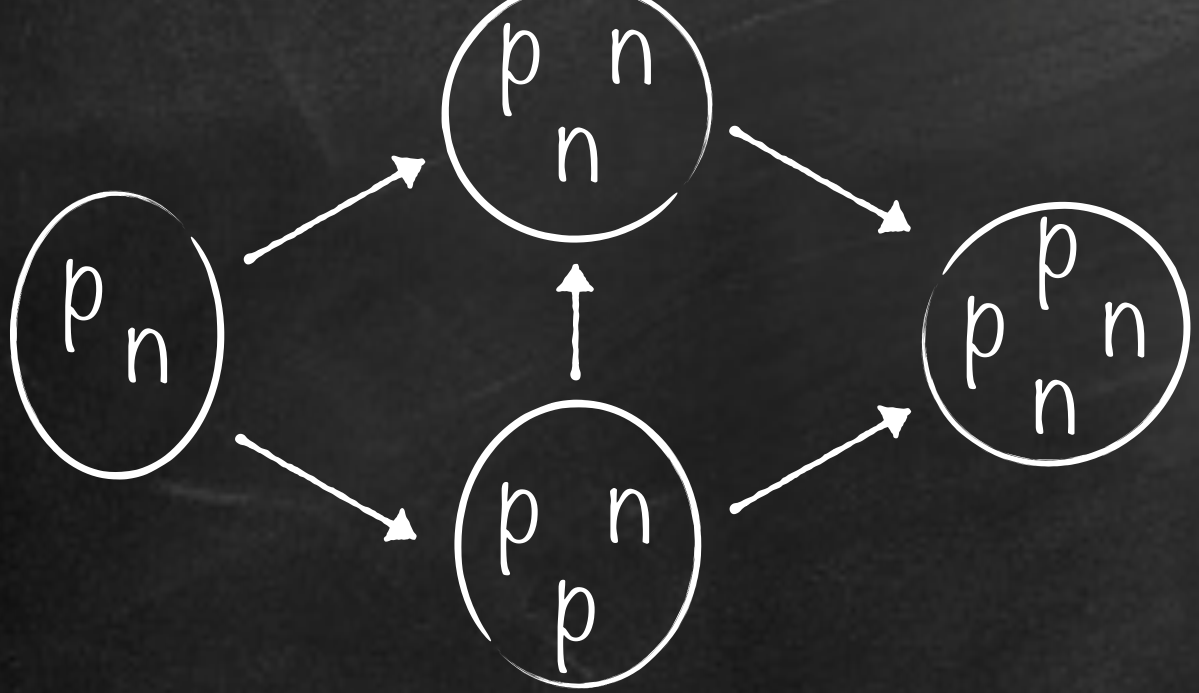
$$\Gamma(n+p \rightarrow D+\gamma) \sim n_B \langle \sigma v \rangle_{D\gamma}$$

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

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

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

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

Baryon mass fraction in helium-4

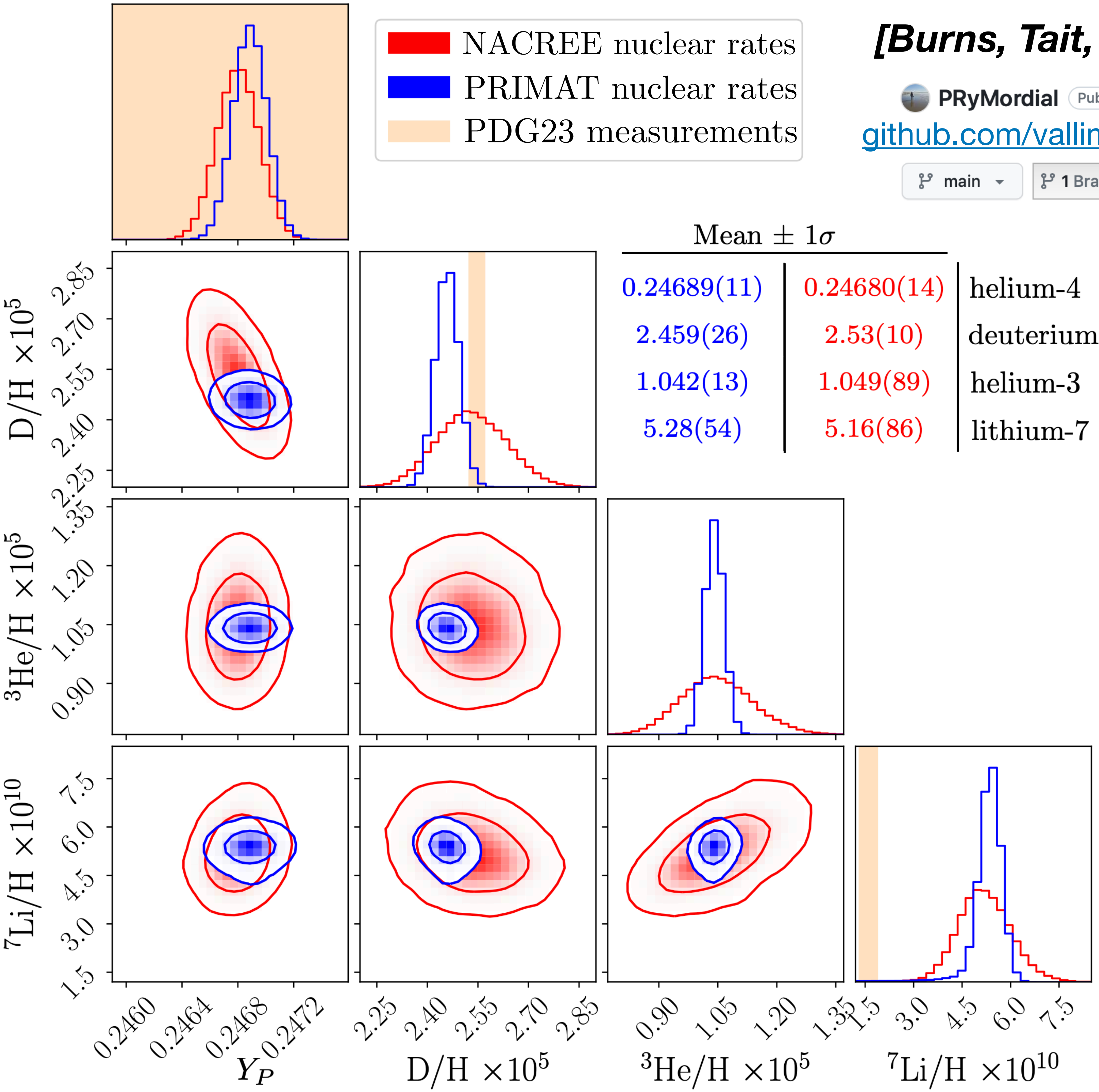
$\mathcal{O}(10^{-5})$ residual amount of deuterium and helium-3 relative to p.

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

PRyMordial: BBN state-of-the-art predictions

[Burns, Tait, Valli `23]

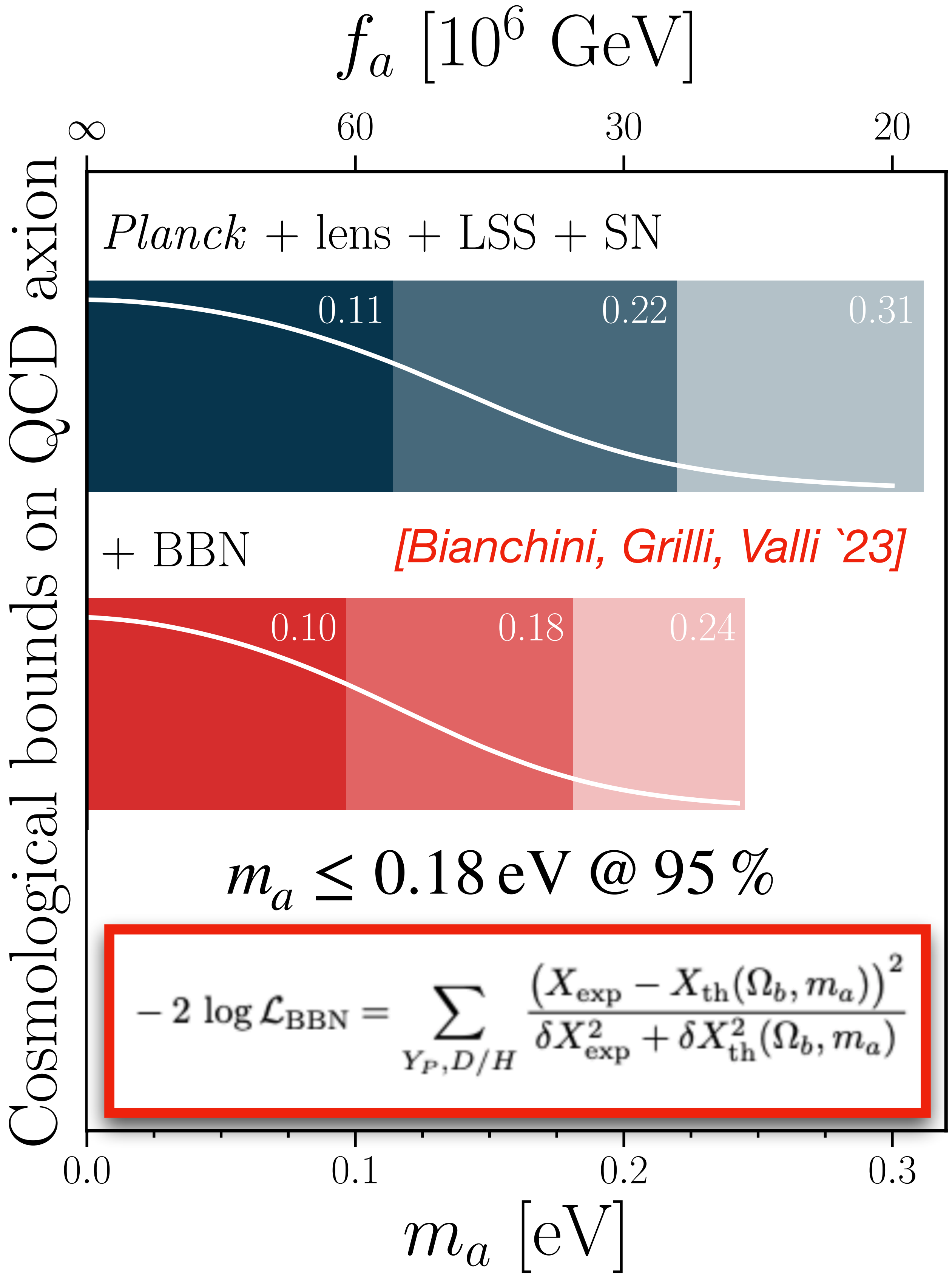
PRyMordial Public
github.com/vallima/PRyMordial
main · 1 Branch · 0 Tags



Mean ± 1σ		
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 ($T_D < T_C$)

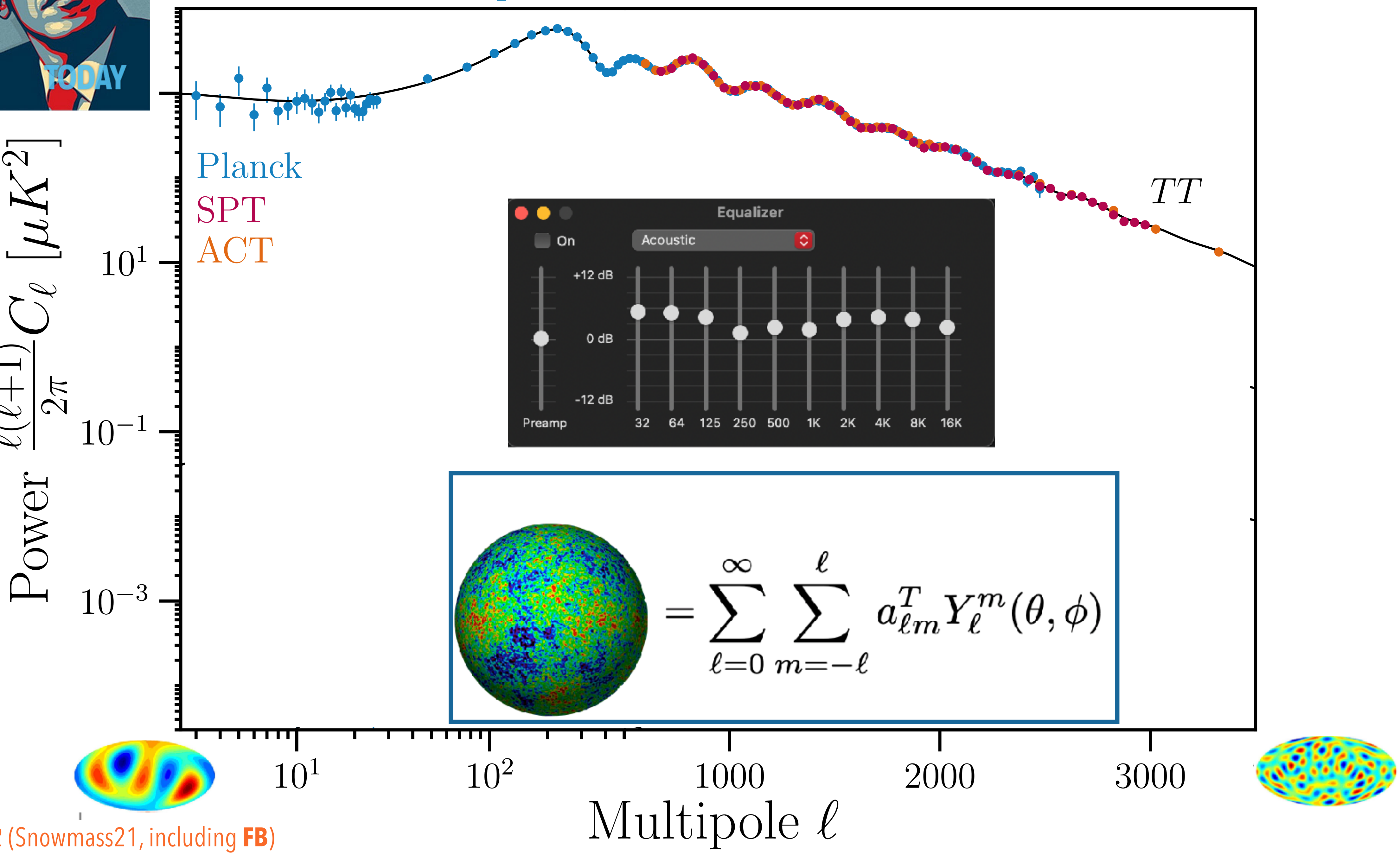
[Bianchini, Grilli, Valli `23]



$$m_a \leq 0.18\,\mathrm{eV}\ @\ 95\,\%$$

$$-2\log\mathcal{L}_{\mathrm{BBN}} = \sum_{Y_P,D/H} \frac{\left(X_{\mathrm{exp}} - X_{\mathrm{th}}(\Omega_b, m_a)\right)^2}{\delta X^2_{\mathrm{exp}} + \delta X^2_{\mathrm{th}}(\Omega_b, m_a)}$$

CMB temperature measurements

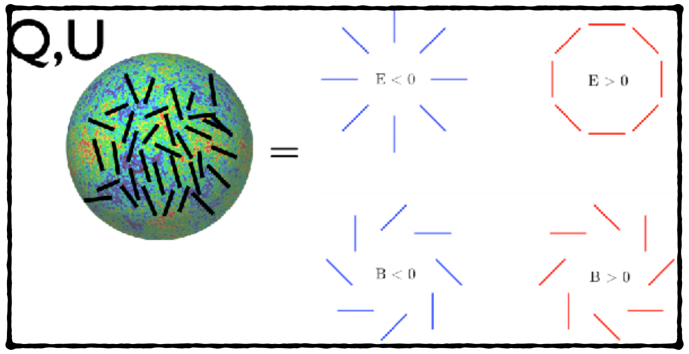


Acoustic

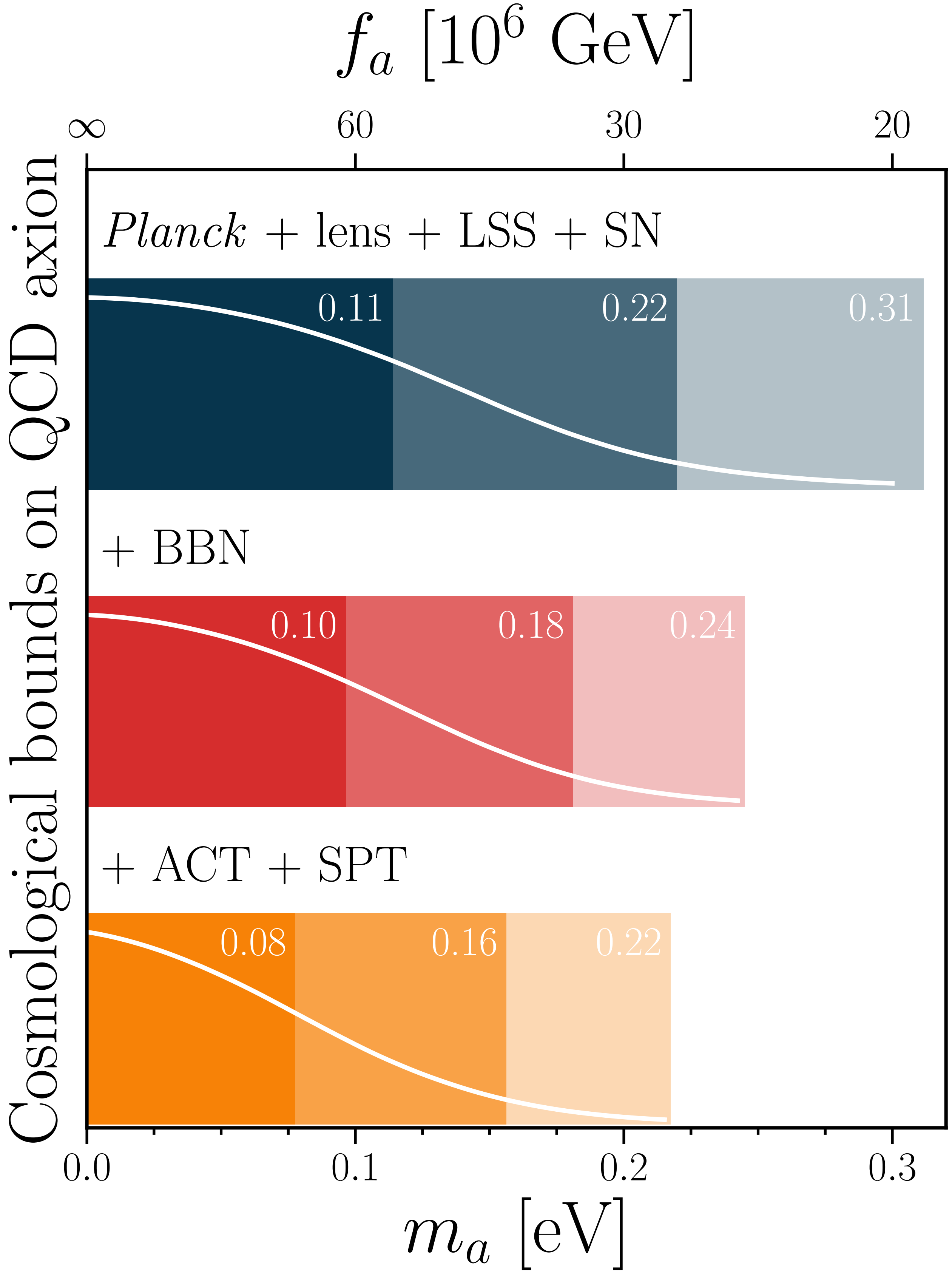
$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_\ell^m(\theta, \phi)$$

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

CMB polarization



Minimal QCD Axion (T$_{dec}$ < T$_c$)



30% improvement
with respect to

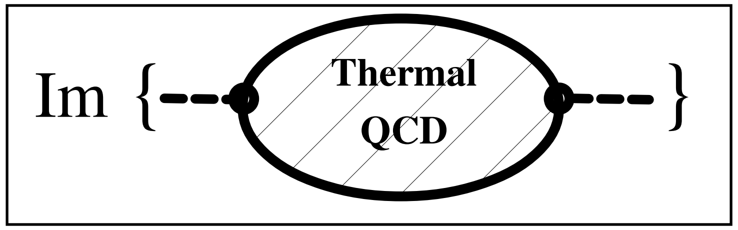
[Notari, Rompineve, Villadoro`23]

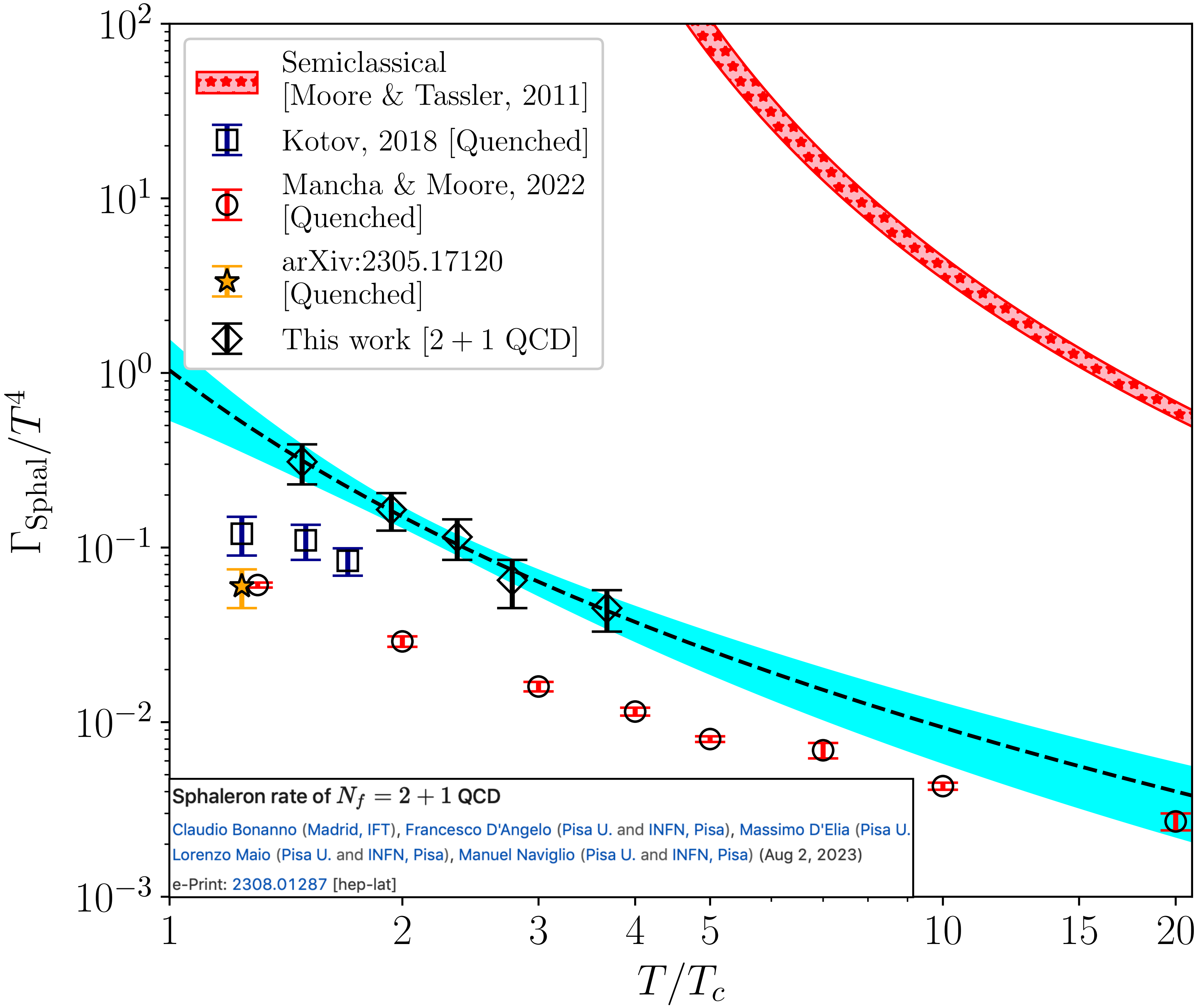
[Bianchini, Grilli, Valli `23]

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

Minimal QCD Axion ($T_D > T_c$)

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





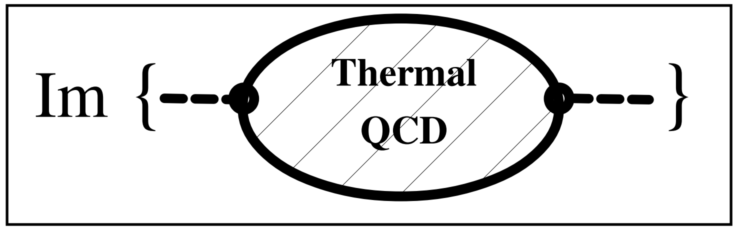
Sphaleron rate of $N_f = 2+1$ QCD

Claudio Bonanno (Madrid, IFT), Francesco D'Angelo (Pisa U. and INFN, Pisa), Massimo D'Elia (Pisa U. Lorenzo Maio (Pisa U. and INFN, Pisa), Manuel Naviglio (Pisa U. and INFN, Pisa) (Aug 2, 2023)

e-Print: 2308.01287 [hep-lat]

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

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



150 MeV < T < 600 MeV

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

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

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

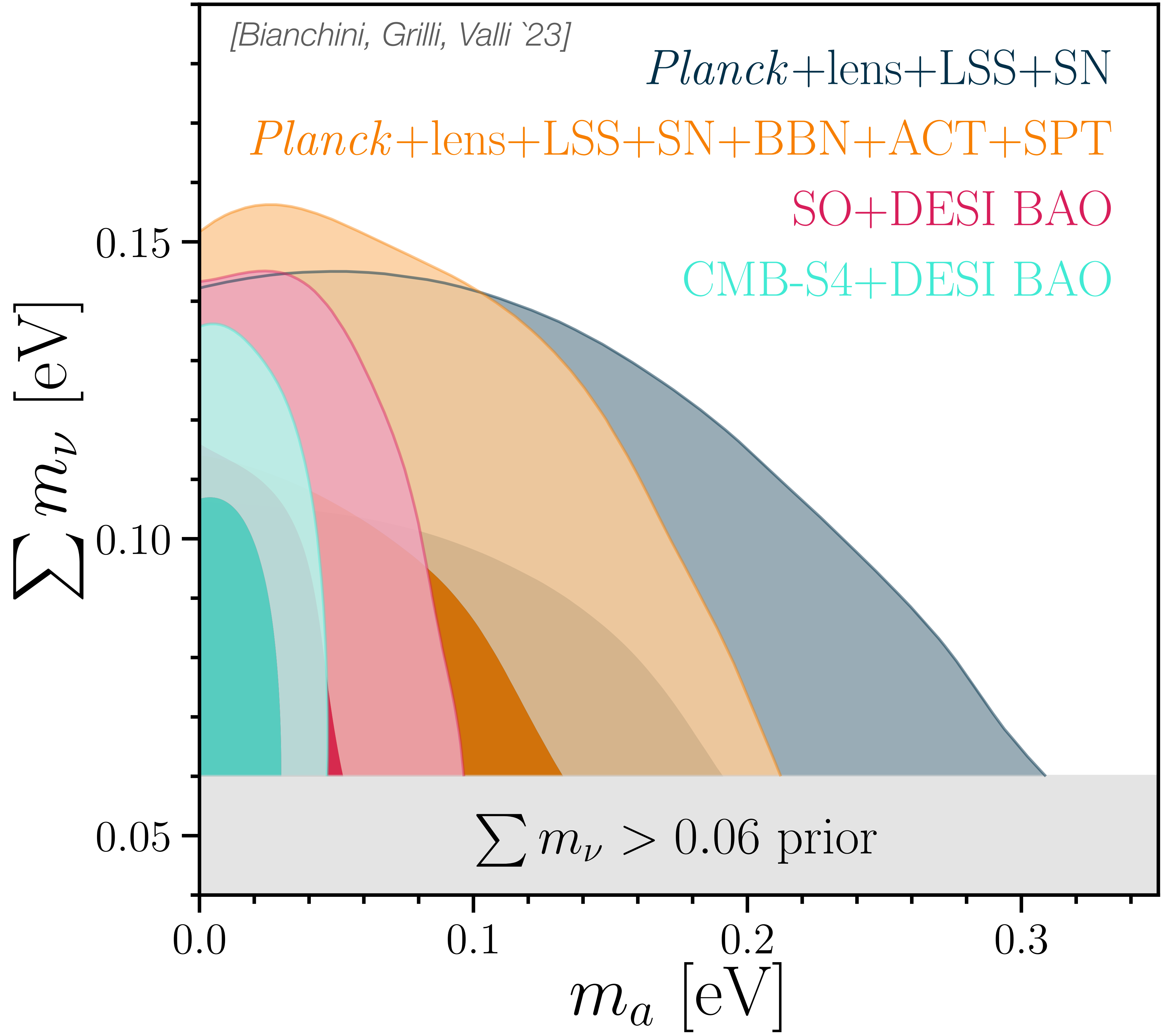
- Recipe for a reasonable (?) forecast:

  (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



REMARK: Minimal QCD axion —> “unavoidable” Hot Dark Matter

- TODAY —> linear Cosmology + improved ChPT :

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

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

- FINITE T EFFECTS IN AXION-PION SCATTERING ?

  arXiv:2312.15240

- THERMAL PRODUCTION BEYOND $SU(2)_F$ ChPT ?

  arXiv:2211.03799

- STRONG SPHALERONS BEYOND 0-MOMENTUM ?

  arXiv:2308.01287

- UV MODELS BEYOND THE MINIMAL QCD AXION ?

  arXiv:2108.05371

- NON-LINEAR COSMOLOGY OBSERVABLES ?

  — Lyman - α constraints <—> targeted simulations ?

  — EFTofLSS (PyBird / CLASS-PT) <—> dedicated study ?

  — other current observables / exciting future forecasts ?