(SUB)eV SECTORS IN THE CMB AND LSS

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based on

2211.03799 w/ A. Notari, G. Villadoro

2305.14166 w/ I. Allali, M. Hertzberg

New Physics from Galaxy Clustering II, IFPU Trieste

FREE STREAMING SECTORS

See talks by Marilena, Francis

For recombination, if

$$\boxed{m_\phi \ll 0.1 \text{ eV}}$$

ϕ

Generic light species

If no interactions, new physics behaves like free-streaming "dark radiation" (DR) at CMB epoch

Effective number of neutrino species

$$N_{\text{eff}} = 3.044 + \Delta N_{\text{eff}} \qquad \Delta N_{\text{eff}} \equiv \frac{\rho_{\text{DR}}}{\rho_\nu}|_{\text{rec}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\text{DR}}}{\rho_\gamma}|_{\text{rec}}$$

Change in the expansion rate (CMB damping tail, phase of BAOs)

HOT DARK MATTER/COLD DARK RADIATION

See talks by Marilena, Francis

For recombination, if

$$\boxed{m_\phi \gtrsim (0.01 - 0.1)\ \mathrm{eV}}$$

Really just like neutrinos, but colder

e.g. for a scalar dof

$$T_\phi = T_\nu \left(\frac{7}{4}\right)^{\frac{1}{4}} \Delta N_{\mathrm{eff}}$$

Become non-relativistic at

$$\boxed{z_{\mathrm{nr}} \simeq 772 \ \left(\frac{m_\phi}{0.3\ \mathrm{eV}}\right)\left(\frac{0.3}{\Delta N_{\mathrm{eff}}}\right)^{\frac{1}{4}} - 1}$$

See also Lesgourgues, Mangano, Miele, Pastor , CUP 13

COLD DARK RADIATION / HOT DARK MATTER

See talks by Marilena, Francis

Really just like neutrinos, but colder

e.g. for a scalar dof

If during matter domination

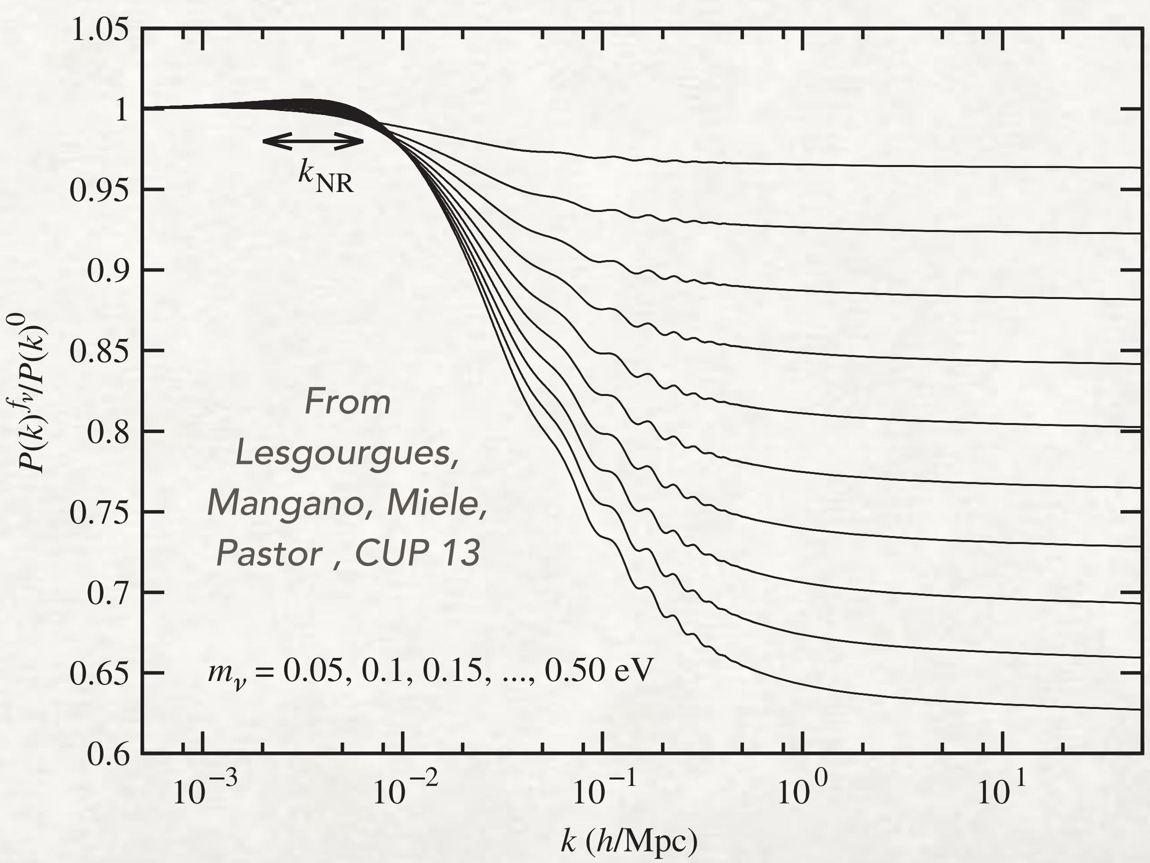
$$k_{\rm nr} \simeq 0.01\sqrt{\Omega_m}\left(\frac{0.3}{\Delta N_{\rm eff}}\right)^{\frac{1}{8}}\left(\frac{m}{0.3~{\rm eV}}\right)^{\frac{1}{2}} h~{\rm Mpc}^{-1}$$

Suppression of linear matter power spectrum

$$\frac{\Delta P_\phi}{P} \propto m_\phi~\Delta N_{\rm eff}^{\frac{3}{4}}$$

Stronger constraints on $\Delta N_{\rm eff}$ *than in massless case, for*

$$m_\phi \gtrsim 0.1~{\rm eV}$$

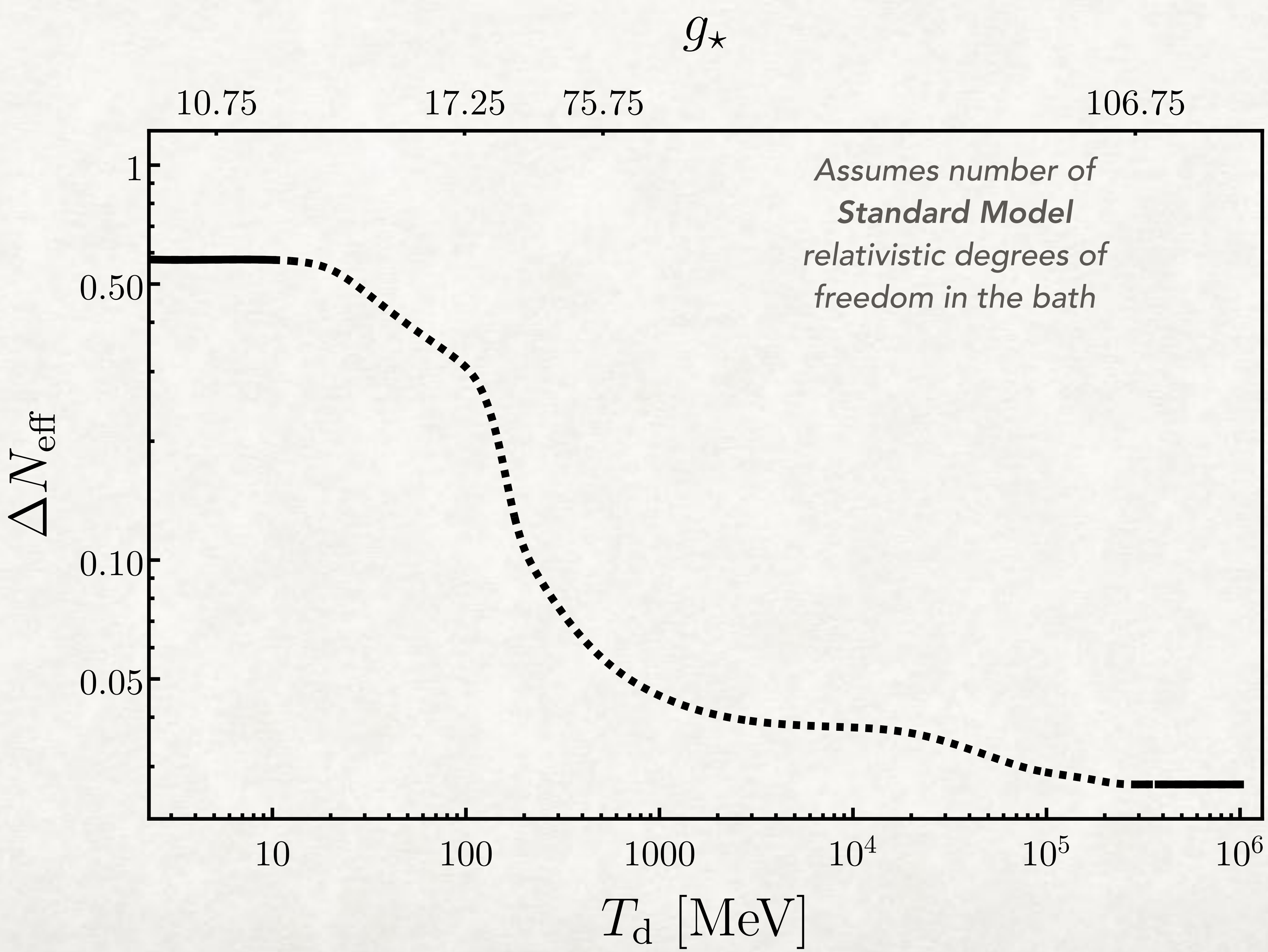


See also Xu+ 21 for heavier sector

THERMAL PRODUCTION

For instantaneous decoupling from equilibrium

$$\Delta N_{\mathrm{eff}} \simeq 0.3 \left[\frac{g_\star(100\ \mathrm{MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$



FREE STREAMING DARK RADIATION

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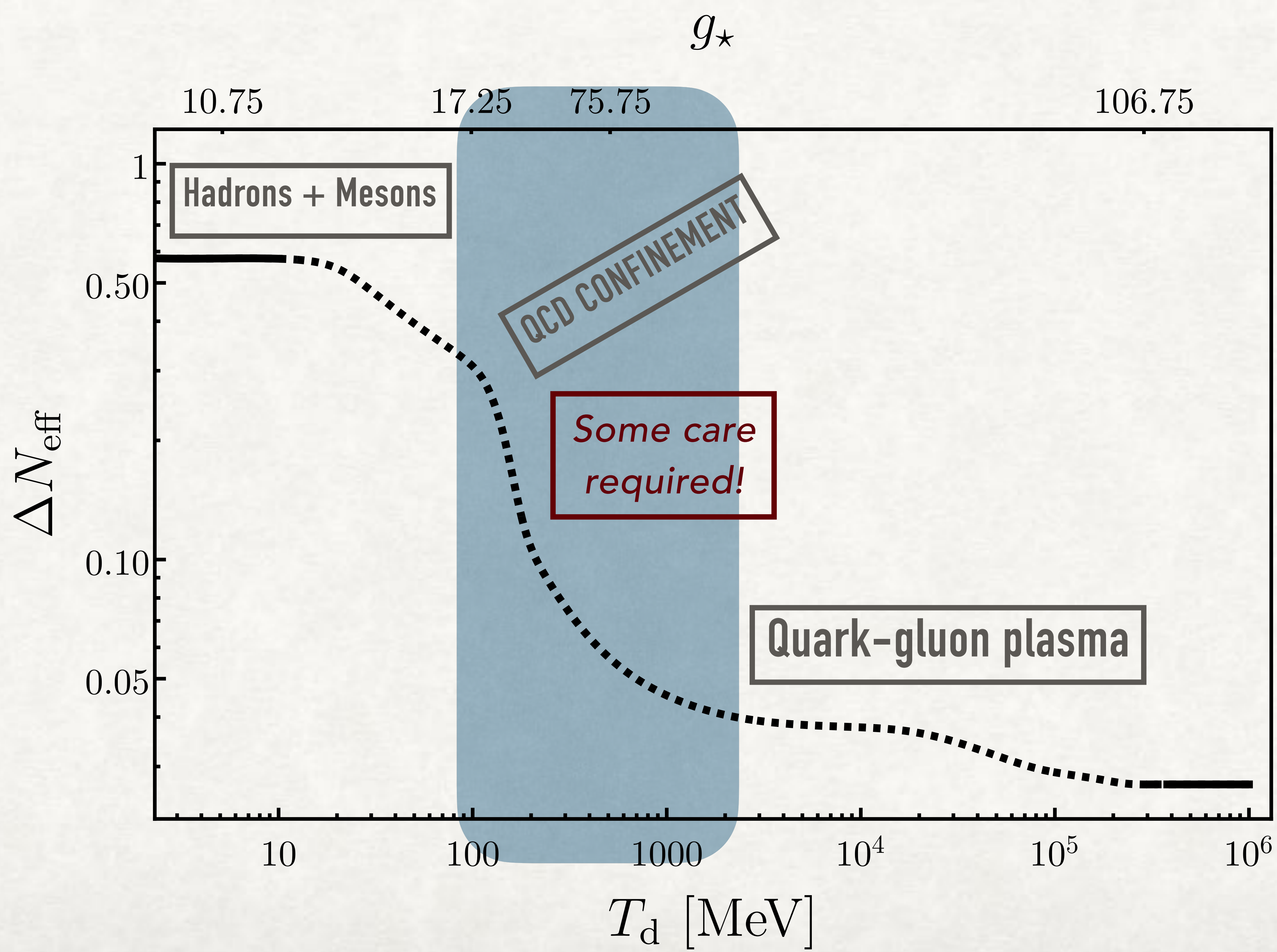

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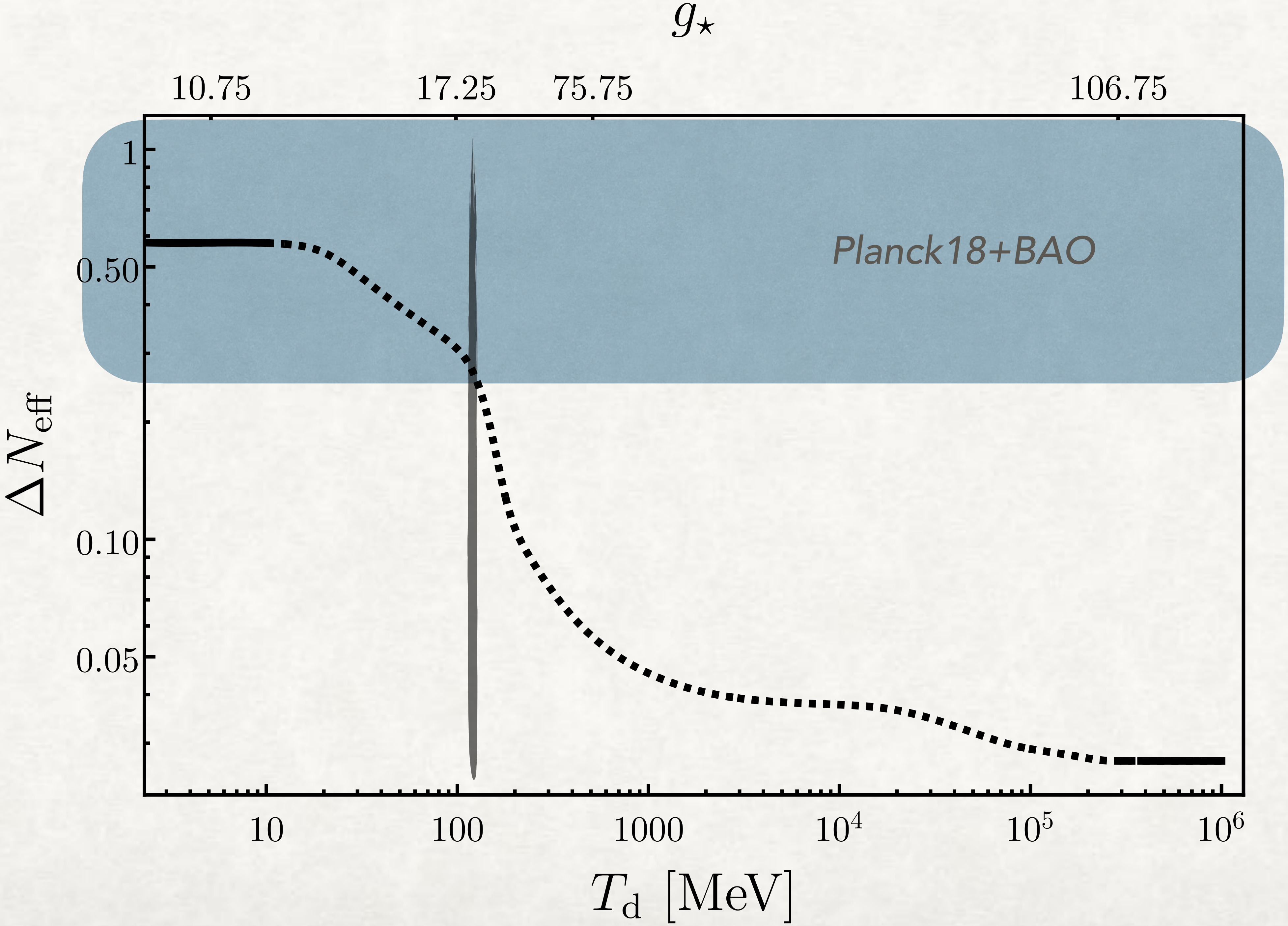

95%C.L.

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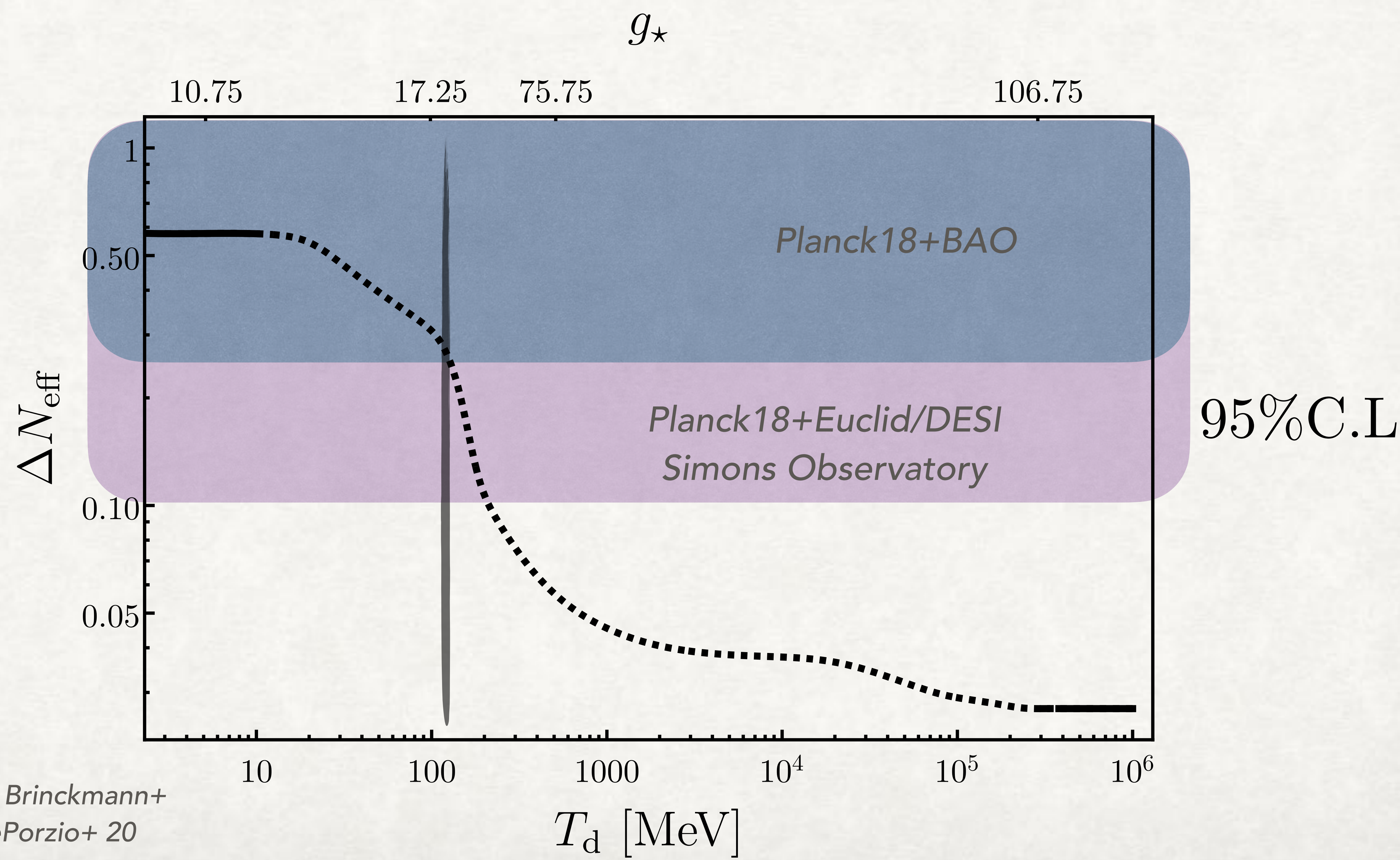

See also Brinckmann+ 18/DePorzio+ 20

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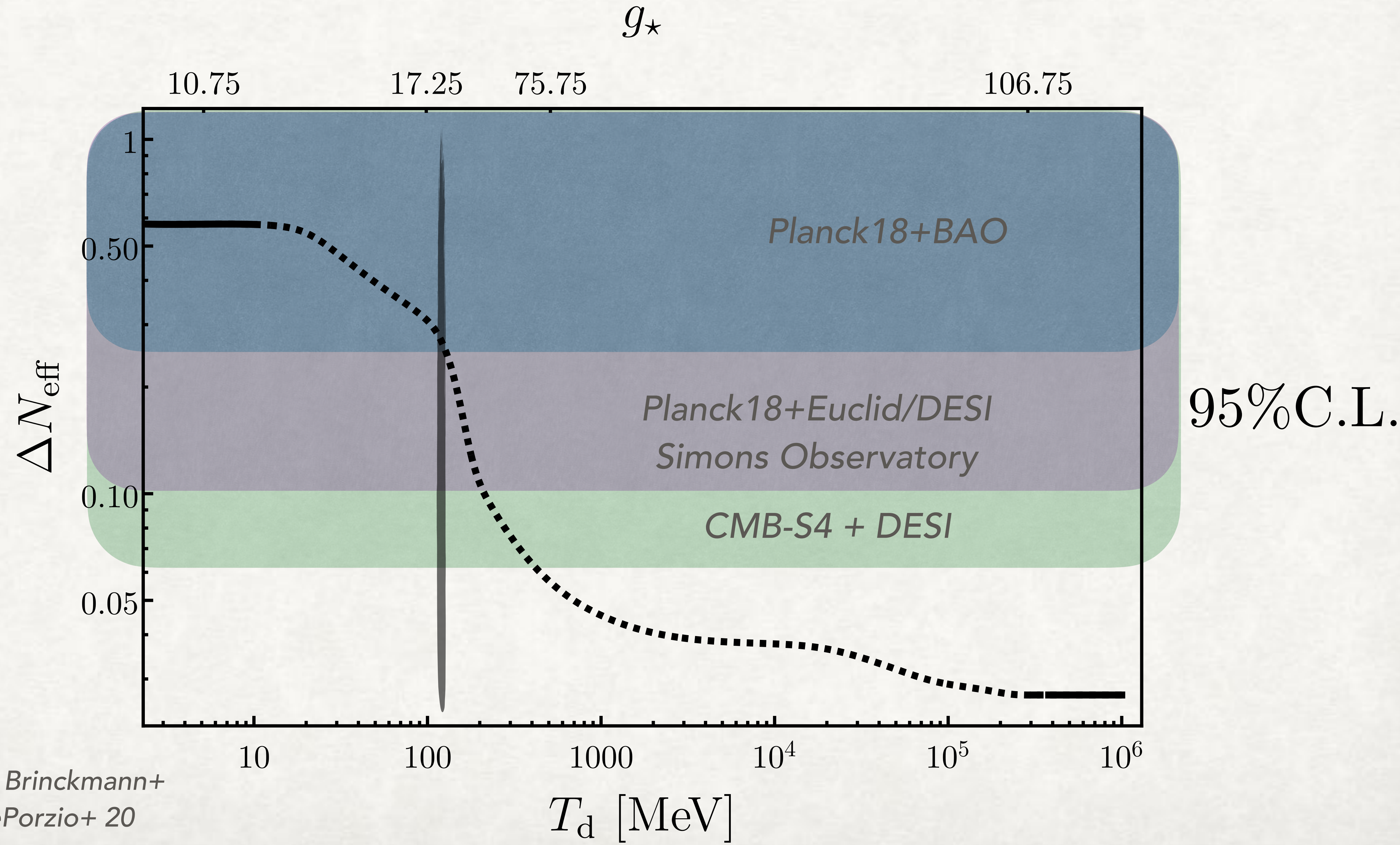

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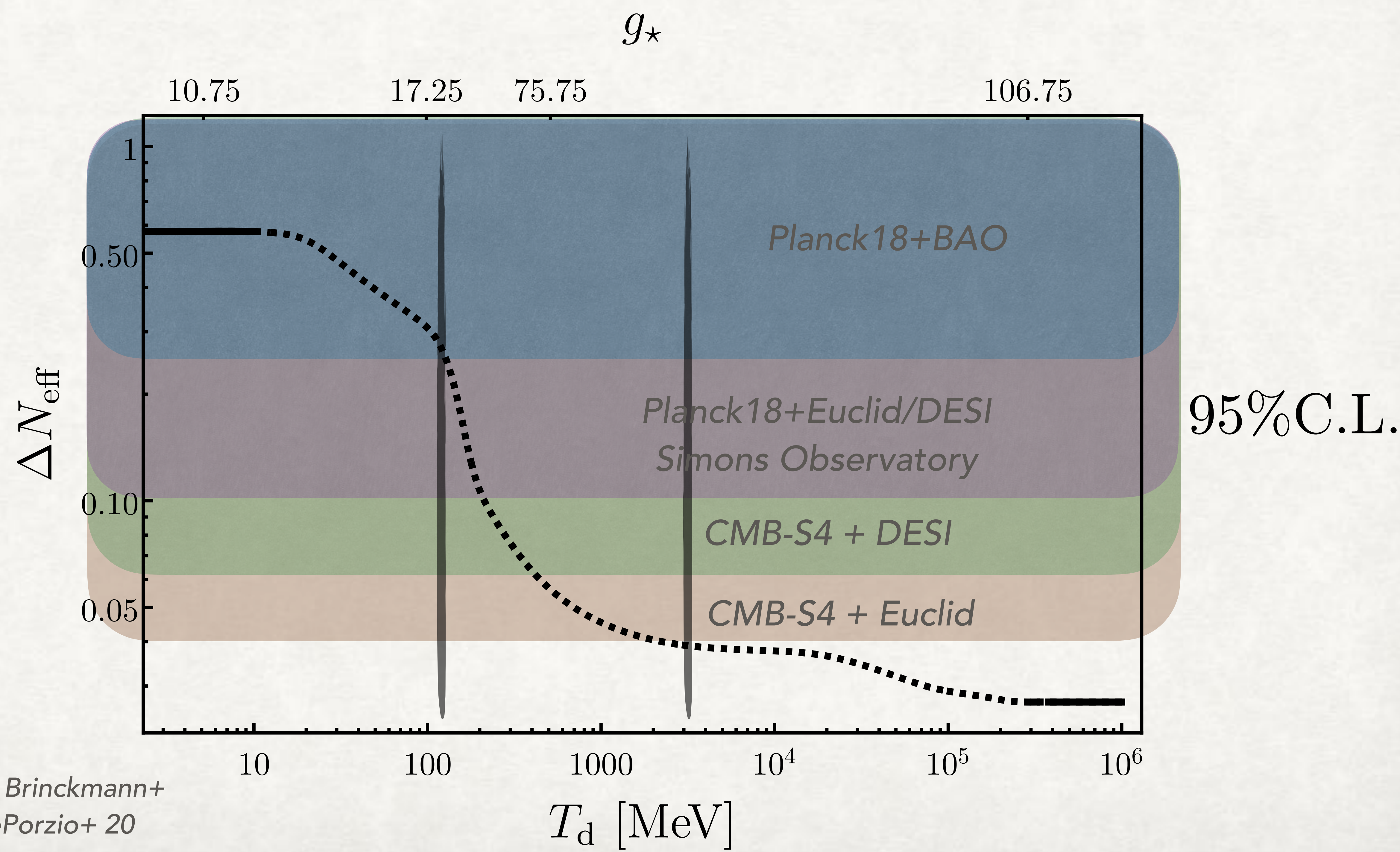

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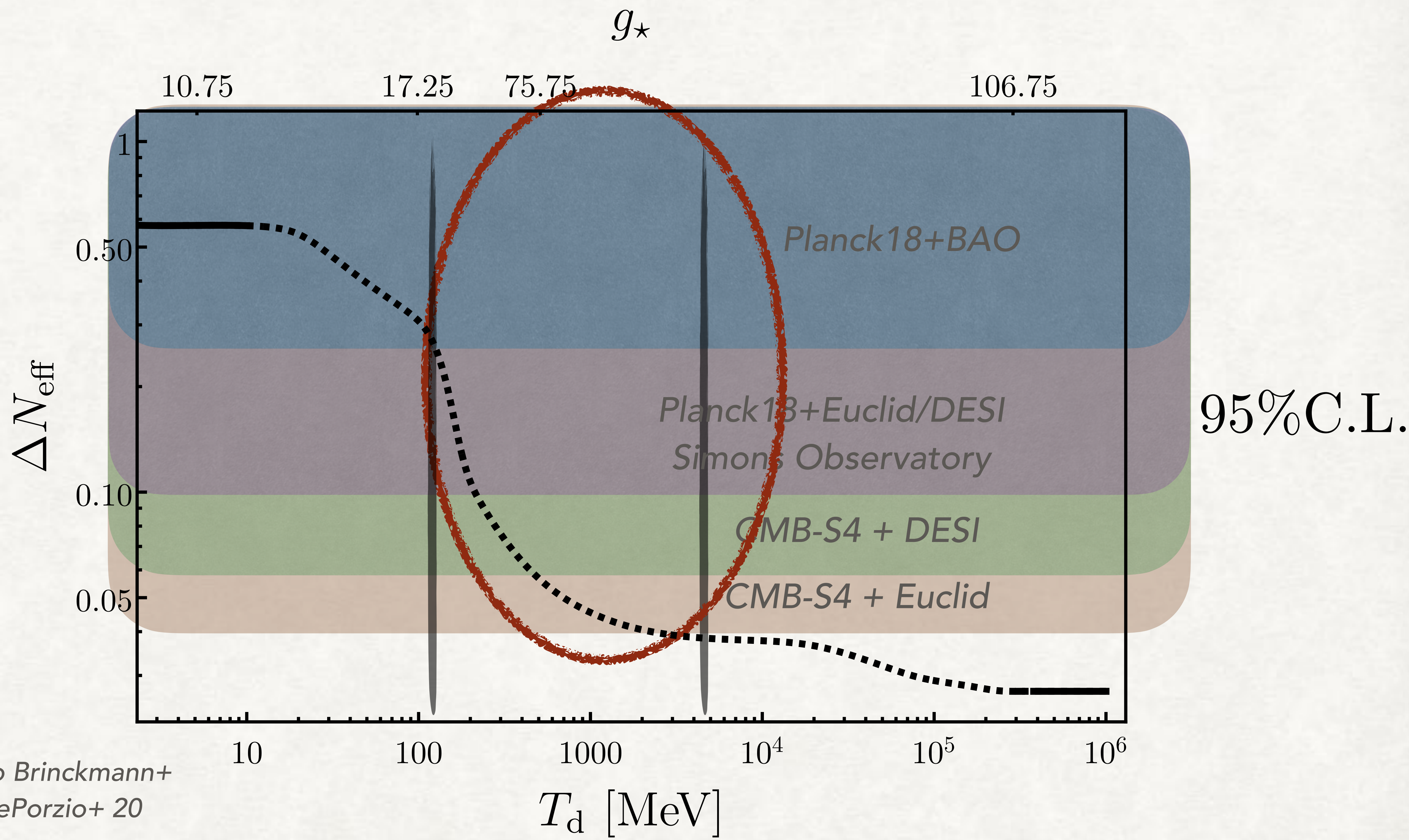


See also Brinckmann+ 18/DePorzio+ 20

Near future CMB and LSS surveys probe light thermal sectors ***that decouple during the QCD crossover transitions!***

PARTICLE PHYSICS AT THE eV?!

Want: (a) light particle(s) (with (sub)-eV mass) that decouples around the QCD epoch

UV-MOTIVATED

TENSIONS

SIGNAL BUILDING

PARTICLE PHYSICS AT THE EV?

Want: (a) light particle(s) (with (sub)-eV mass) that decouples around the QCD epoch

UV-MOTIVATED

2211.03799 w/ A. Notari, G. Villadoro

TENSIONS

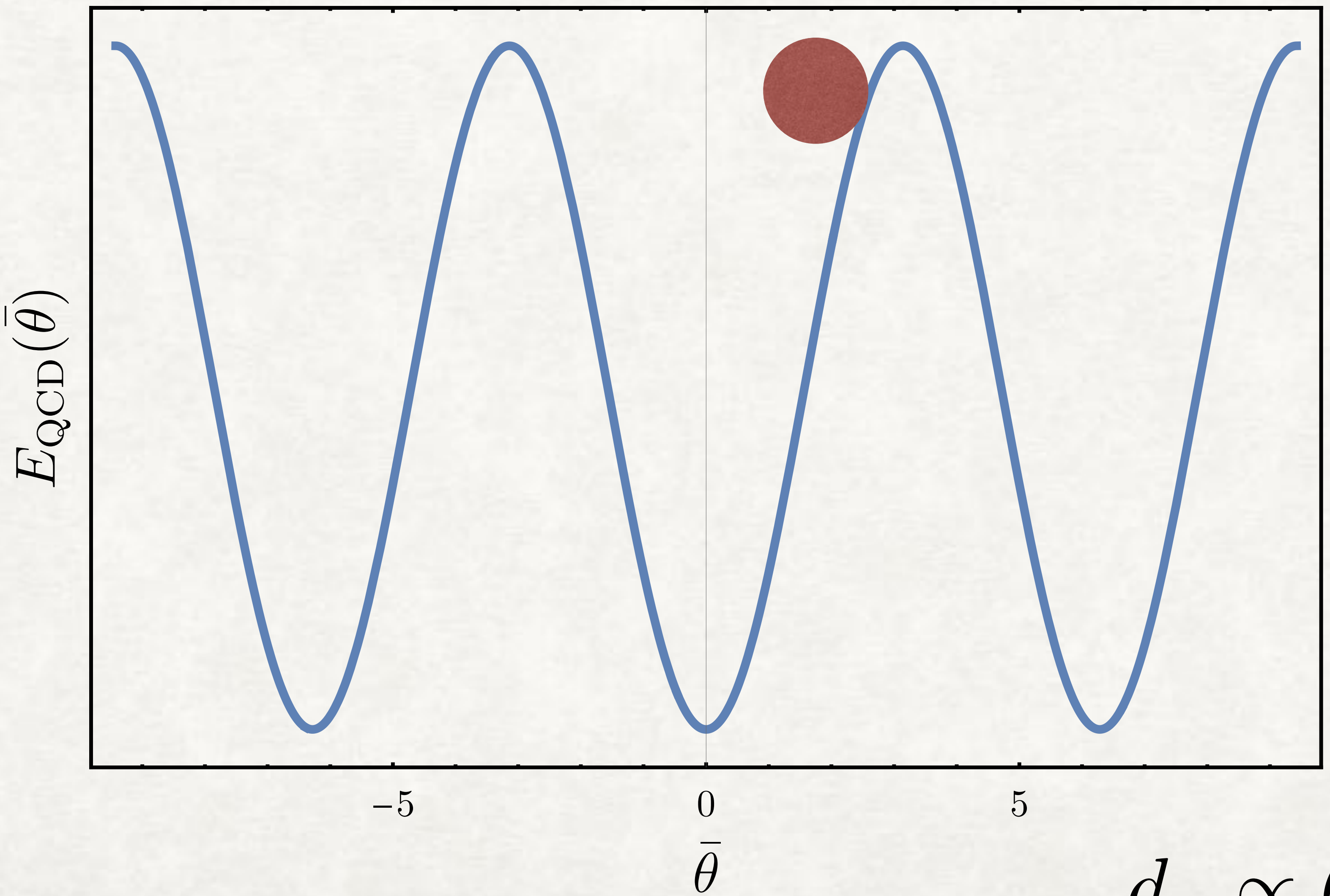
SIGNAL BUILDING

Decoupling temperature suggests coupling to QCD

THE USUAL SUSPECT

The QCD axion

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}, \quad \bar{\theta} \to \frac{a(t,\mathbf{x})}{f_a}$$



$$d_n \propto \bar{\theta} \to 0$$

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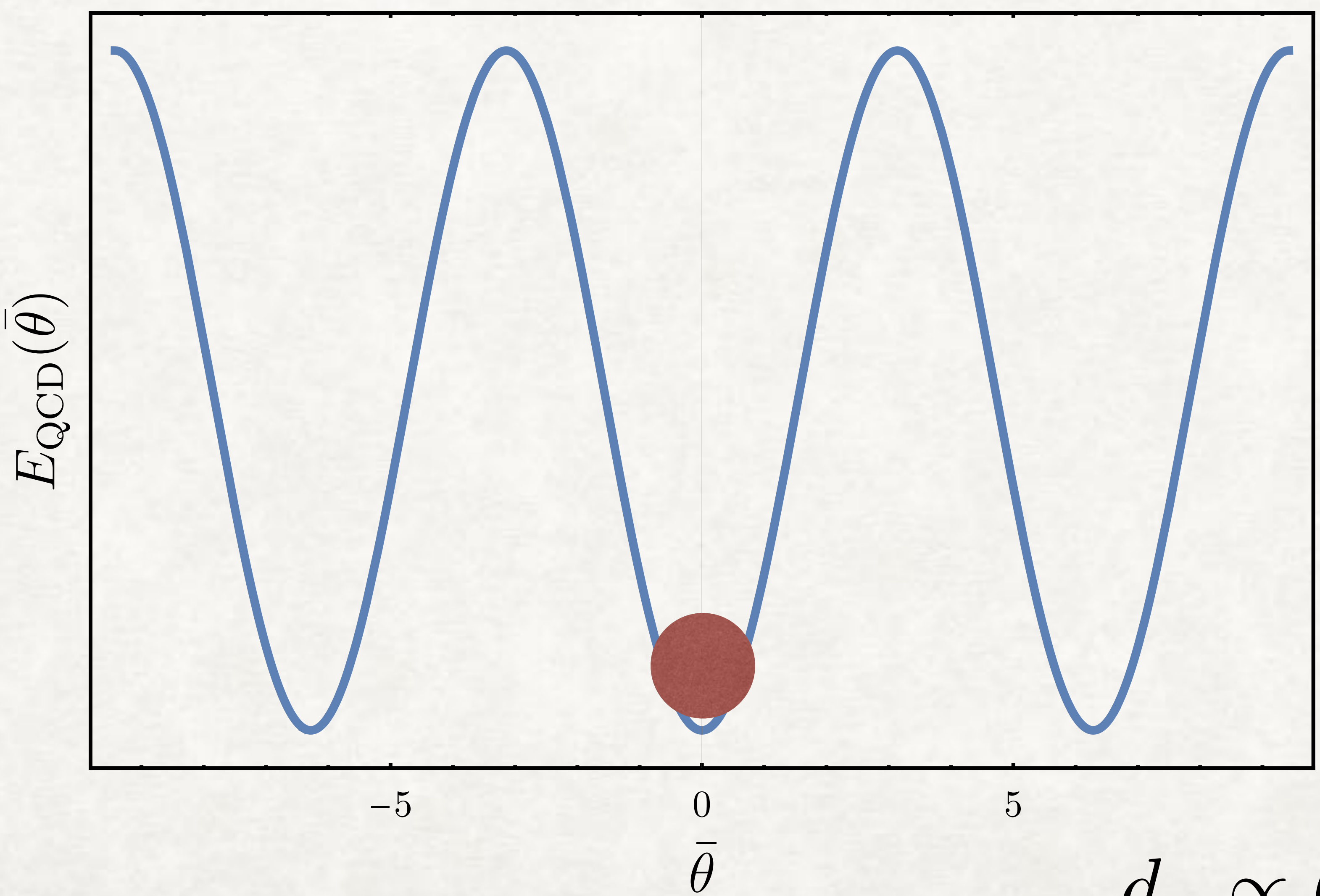


$$d_n \propto \bar{\theta} \to 0$$

THE QCD AXION

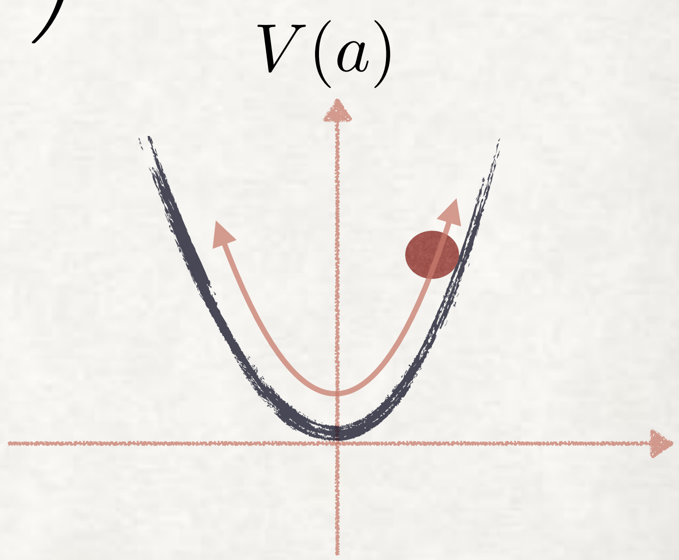
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{\alpha_s}{8\pi}\frac{a(t,\mathbf{x})}{f_a}G^{\mu\nu}\tilde{G}_{\mu\nu} + \dots$$

Small mass set by interplay between UV (Peccei-Quinn) and IR (QCD) scale

Decay of topological defects

$$m_a = \kappa_q \frac{\Lambda^2_{\mathrm{QCD}}}{f_a} \simeq 0.057\ \mathrm{eV}\left(\frac{10^8\ \mathrm{GeV}}{f_a}\right)$$

Misalignment mechanism



Mostly discussed as CDM candidate, From non-thermally produced population

But coupling to QCD implies thermal production!

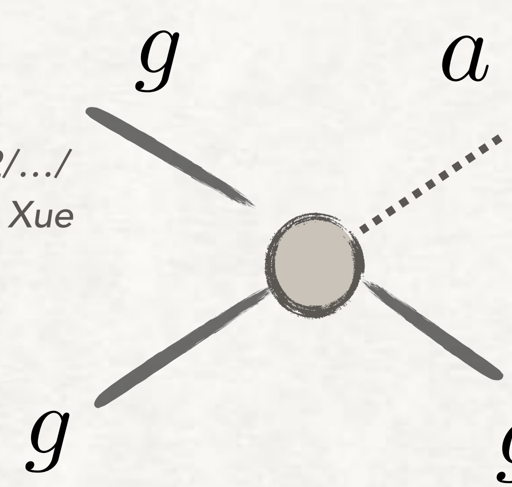
THE HOT QCD AXION: PRODUCTION

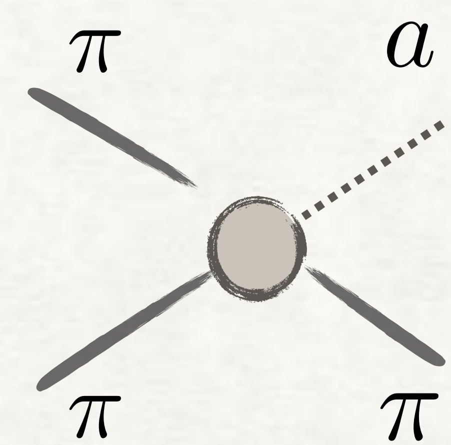
Turner 88/
Berezhiani et al 92/

$$\mathcal{L}_{a\pi} = \frac{\epsilon}{3 f_a f_\pi} \partial_\mu a (2 \partial^\mu \pi^0 \pi^+ \pi^- + \ldots)$$

At weak coupling, production dominated by 2-2 processes

Masso, Rota 02/.../
Salvio, Strumia, Xue 14/...





Chang, Choi 93/...

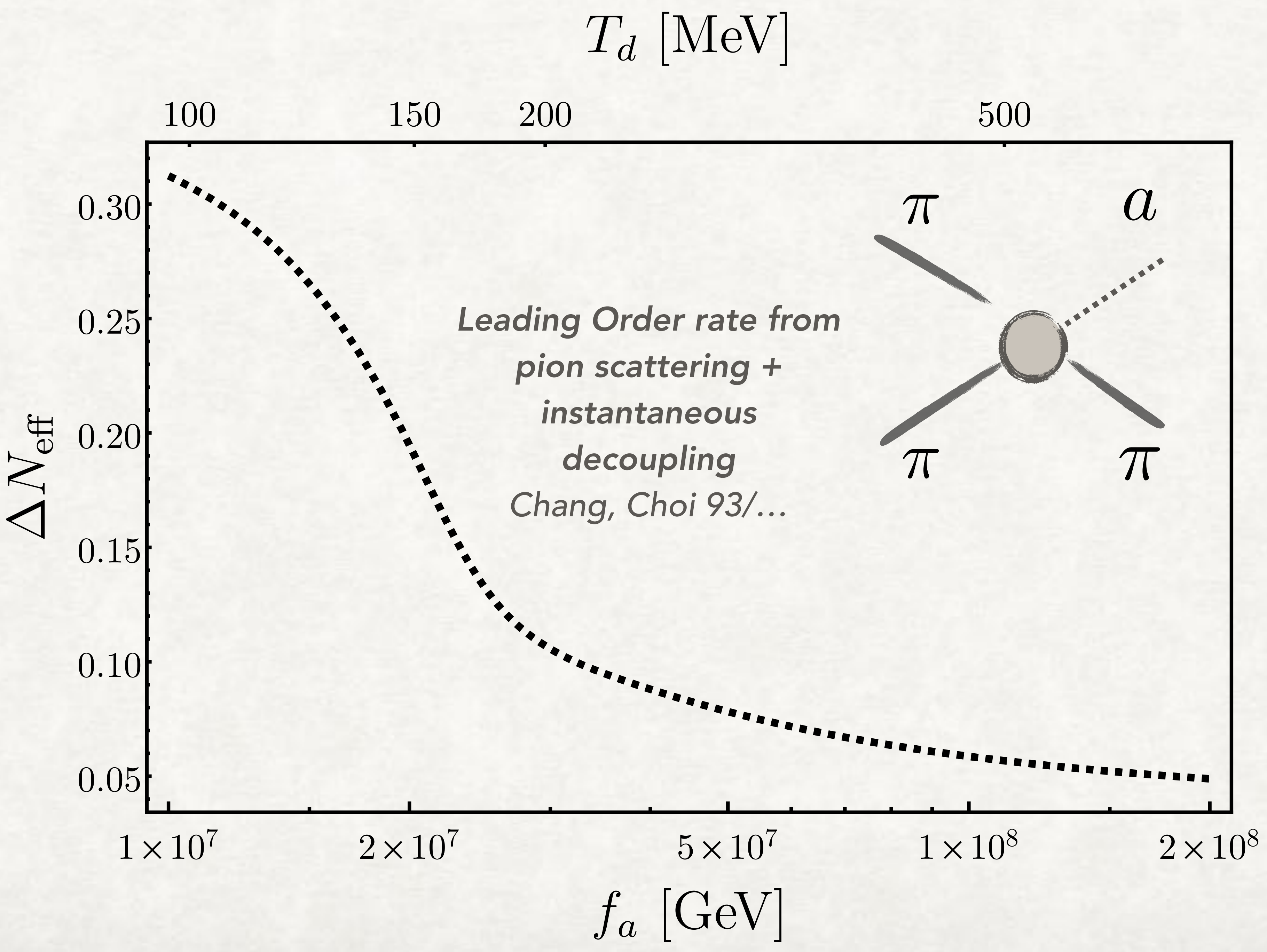
QCD CROSSOVER

$$\bar{\Gamma}_a \propto \frac{T^3}{f_a^2}$$

$$\bar{\Gamma}_a \propto \frac{T^5}{f_a^2 f_\pi^2}$$

FIRST ESTIMATE

For instantaneous decoupling from equilibrium



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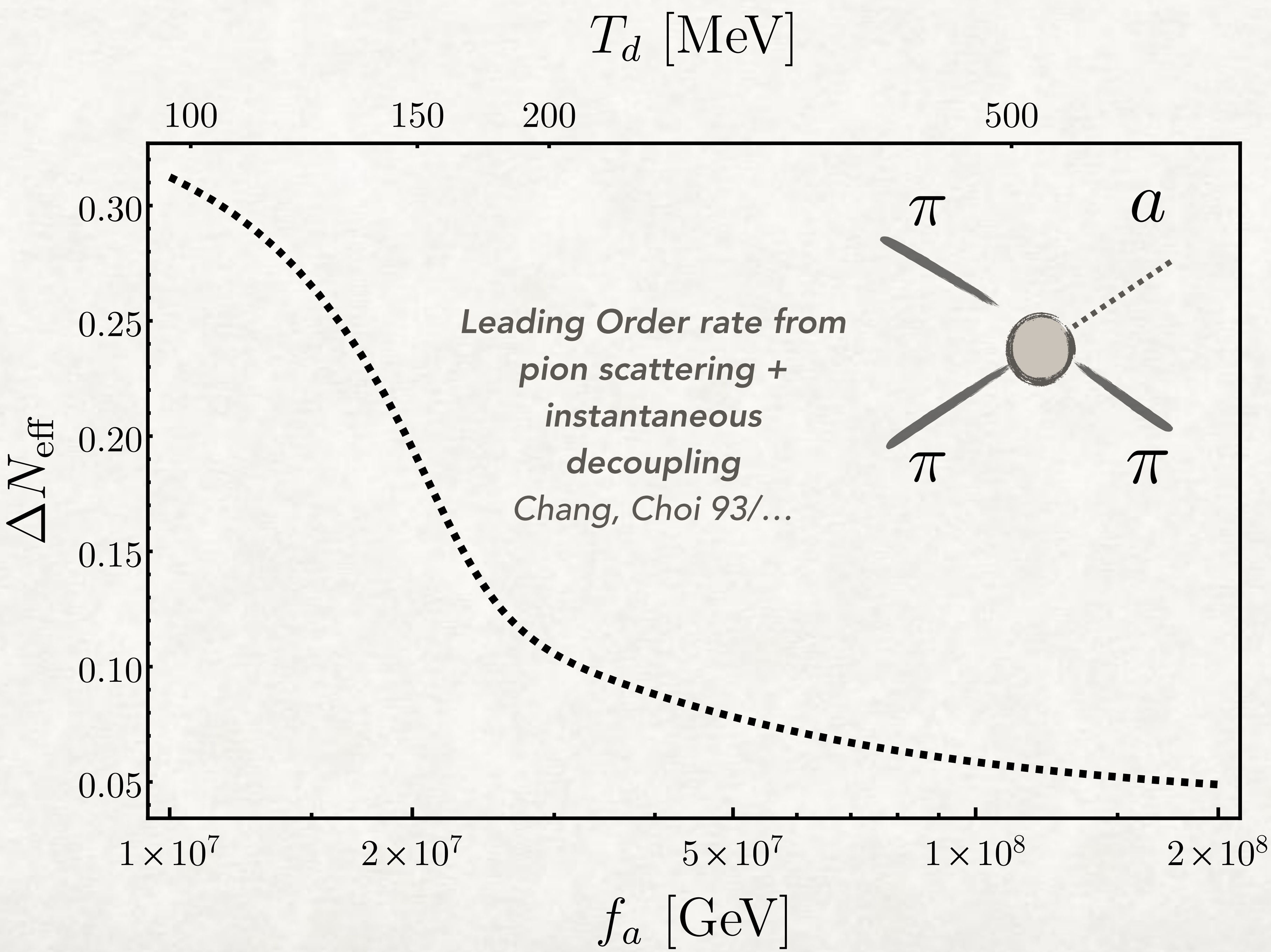

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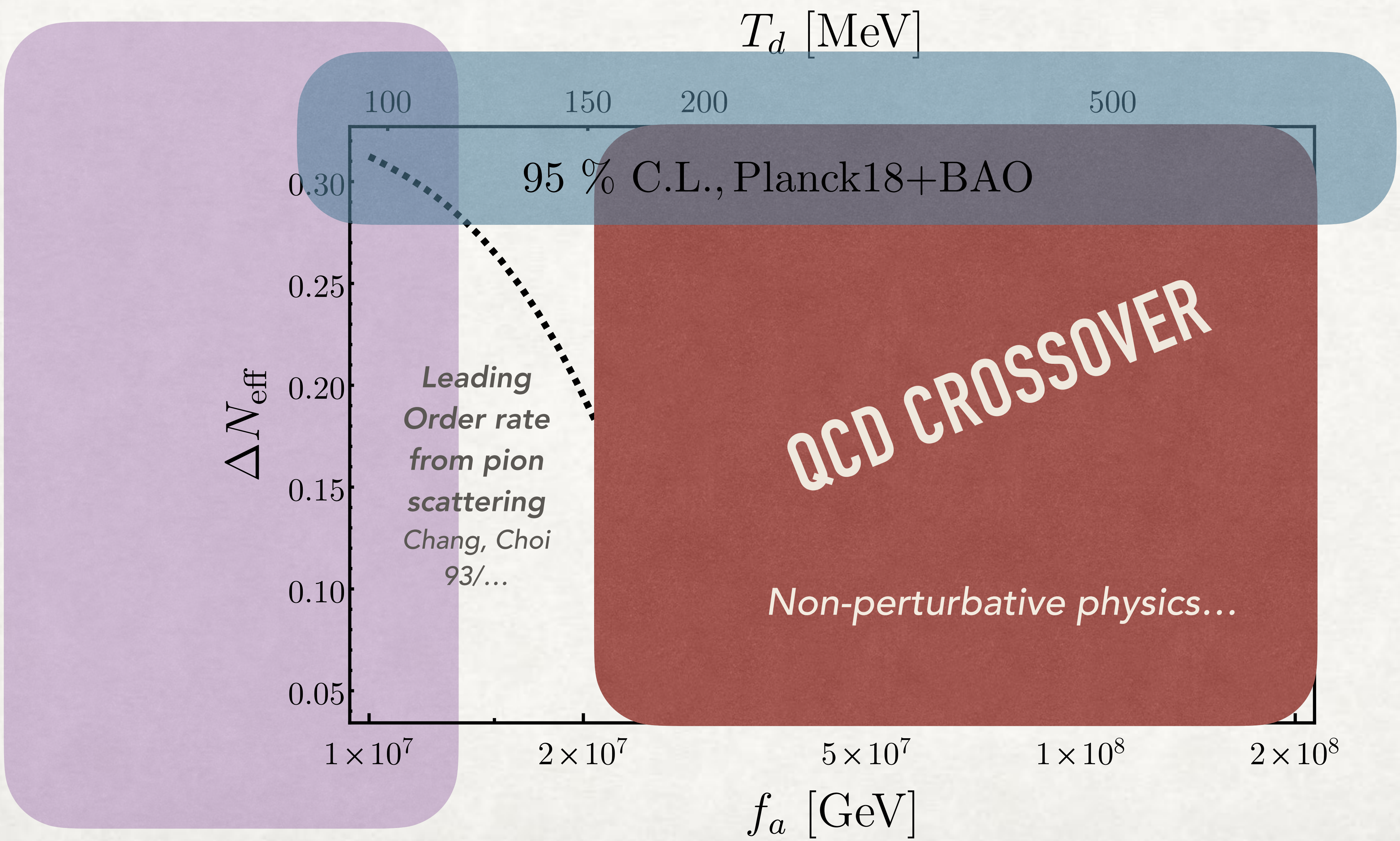


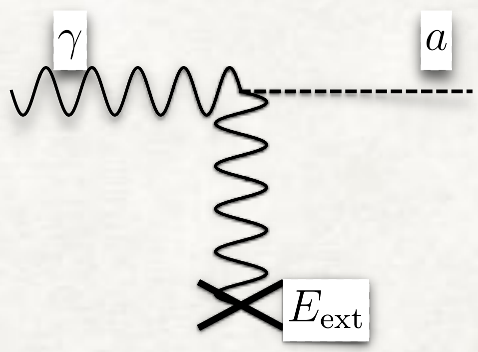
...YES, THERE ARE ASTROPHYSICAL BOUNDS

From production in stellar environments

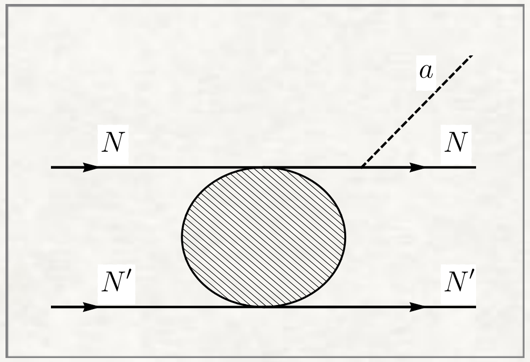
$$f_a \gtrsim (10^7 - 10^8)\ \text{GeV}$$

Stronger model-dependent bounds when coupling to electrons is present

Ayala+ 14/ Dolan+ 22



Raffelt 90/...



From di Luzio+ Phys. Rep. 20

Strongest bounds come from SN1987A, possibly characterised by significant uncertainties, currently under active reassessments/debate

See e.g. Chang+ 18/Bar+19/Carenza+20

OPPORTUNITY FOR COSMOLOGICAL SURVEYS

CMB and LSS data provide opportunity to discover/constrain the QCD axion

KEY ADVANTAGES

*Uses **precise cosmological measurements**, independent of astrophysics*

*Probes QCD axion **independently of cold dark matter** contribution*

Relies on minimal coupling to QCD
+
(Standard cosmology below GeV)

Does not need dedicated experiment!

*Hannestad+ 08, 13/Di Valentino+ 15/Ferreira, Notari 18/+ Arias-Aragon, D'Eramo et al 18,20…/Ferreira, Notari, **FR** 20/ Giaré+ 20/Di Luzio+21/D'Eramo+21,22/Di Luzio+22*

OPPORTUNITY FOR COSMOLOGICAL SURVEYS

CMB and LSS data provide opportunity to discover/constrain the QCD axion

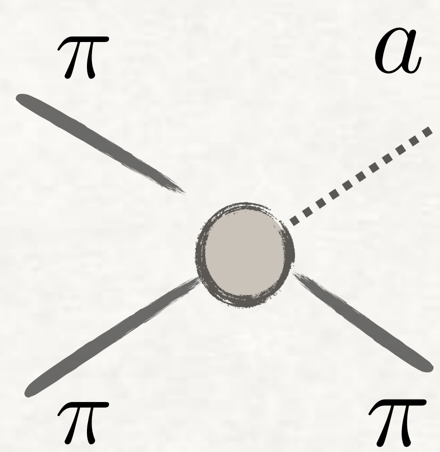
KEY CHALLENGES/DIRECTIONS

Particle physics: Obtain reliable production rate

Cosmology: Find ways to distinguish axion from other possible dark radiation/hot DM

PRODUCTION FROM PIONS

Below 150 MeV



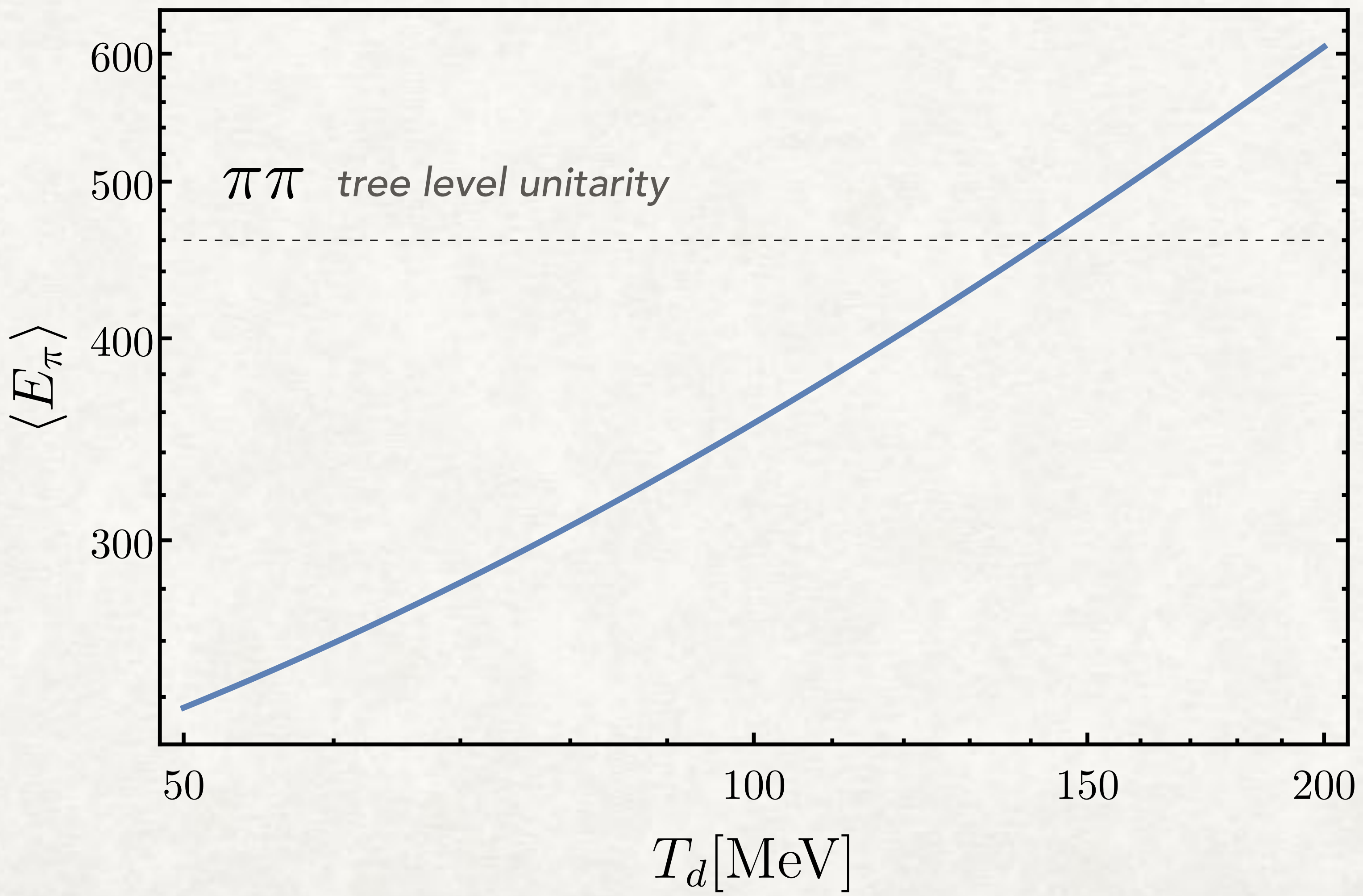
Two problems with simple estimate
both due to decoupling during the QCD crossover

Features discussed here possibly relevant for other candidates that can be seen in the near future at CMB/LSS

CALCULATION OF THE PRODUCTION RATE FROM PIONS

Simple estimate does not work because

1. Leading order (in chiral perturbation theory) rate is not valid at the temperatures of interest, because:



Can be (partially) overcome by relating axion rate to pion rate, extracted from experiment

See also Di Luzio+22 for unitarization approach

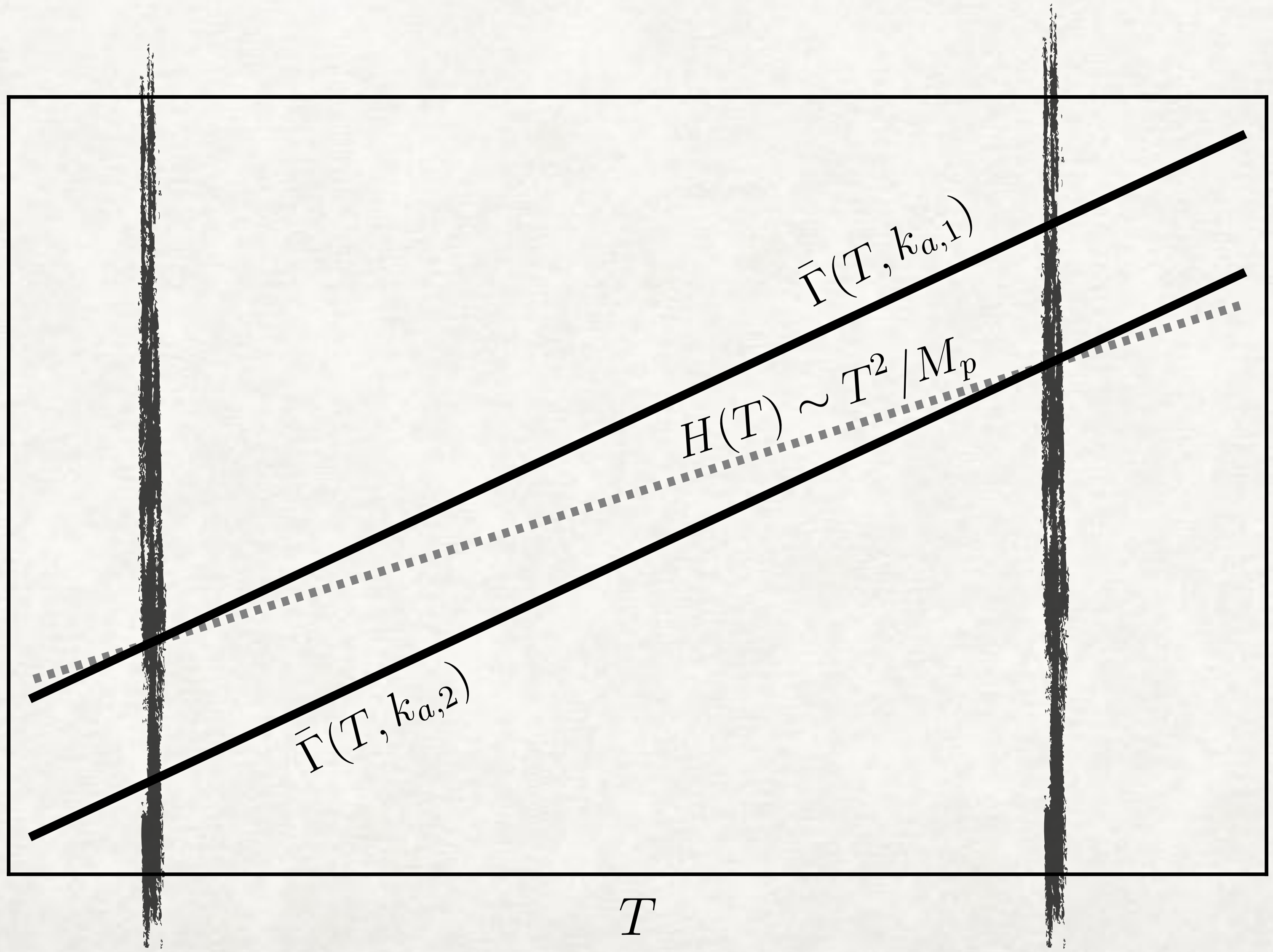
CALCULATION OF THE ABUNDANCE

Simple estimate does not work because

2. Instantaneous decoupling + thermal equilibrium not justified

$$\mathcal{M}_{\pi\pi\to a\pi} \propto s^2 \quad \Rightarrow \quad \bar{\Gamma}_a(T) \to \bar{\Gamma}_a(k,T)$$

Higher momentum modes interact more, Decouple at lower temperature!



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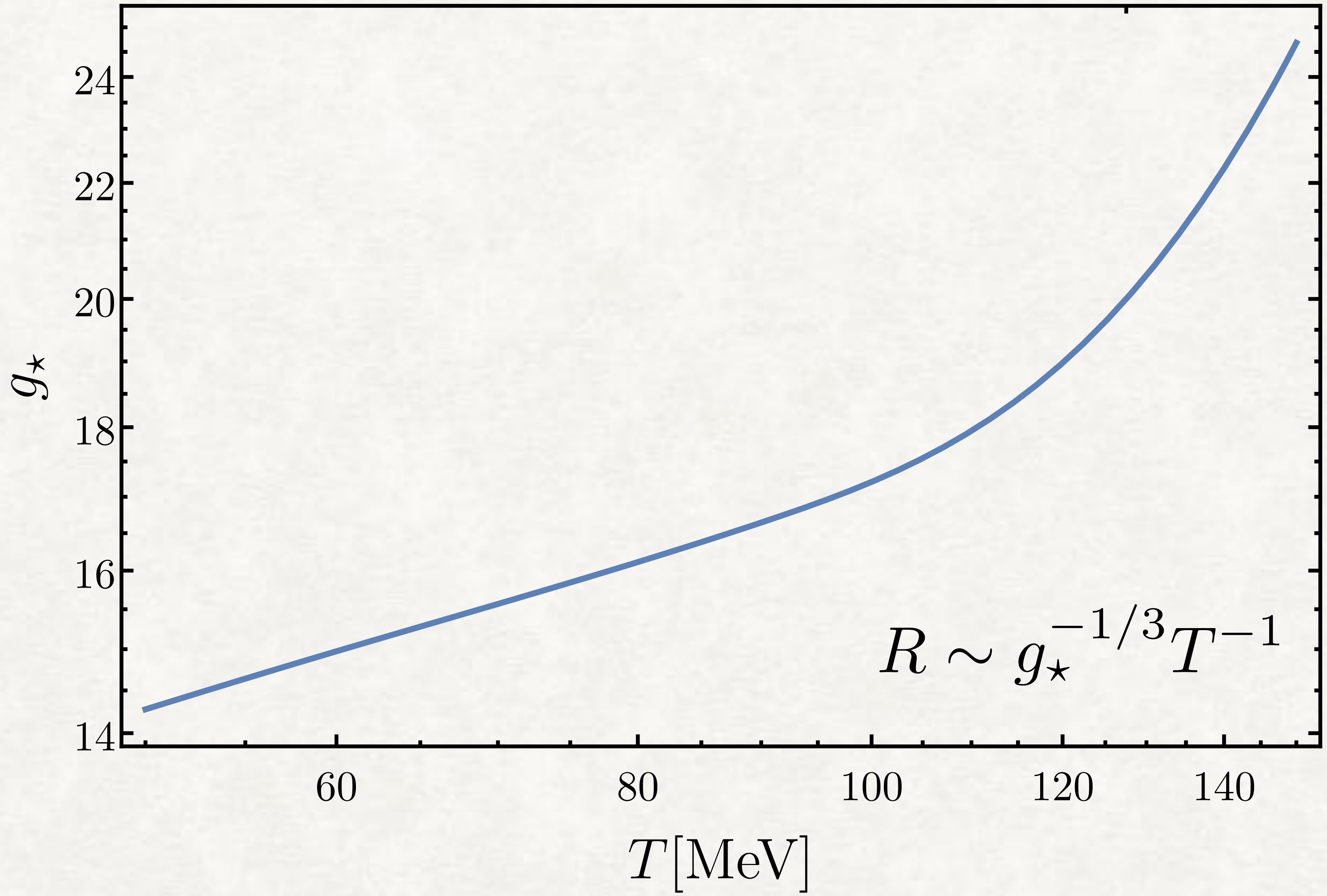

g_* from Borsanyi et al, Nature 539 (2016)

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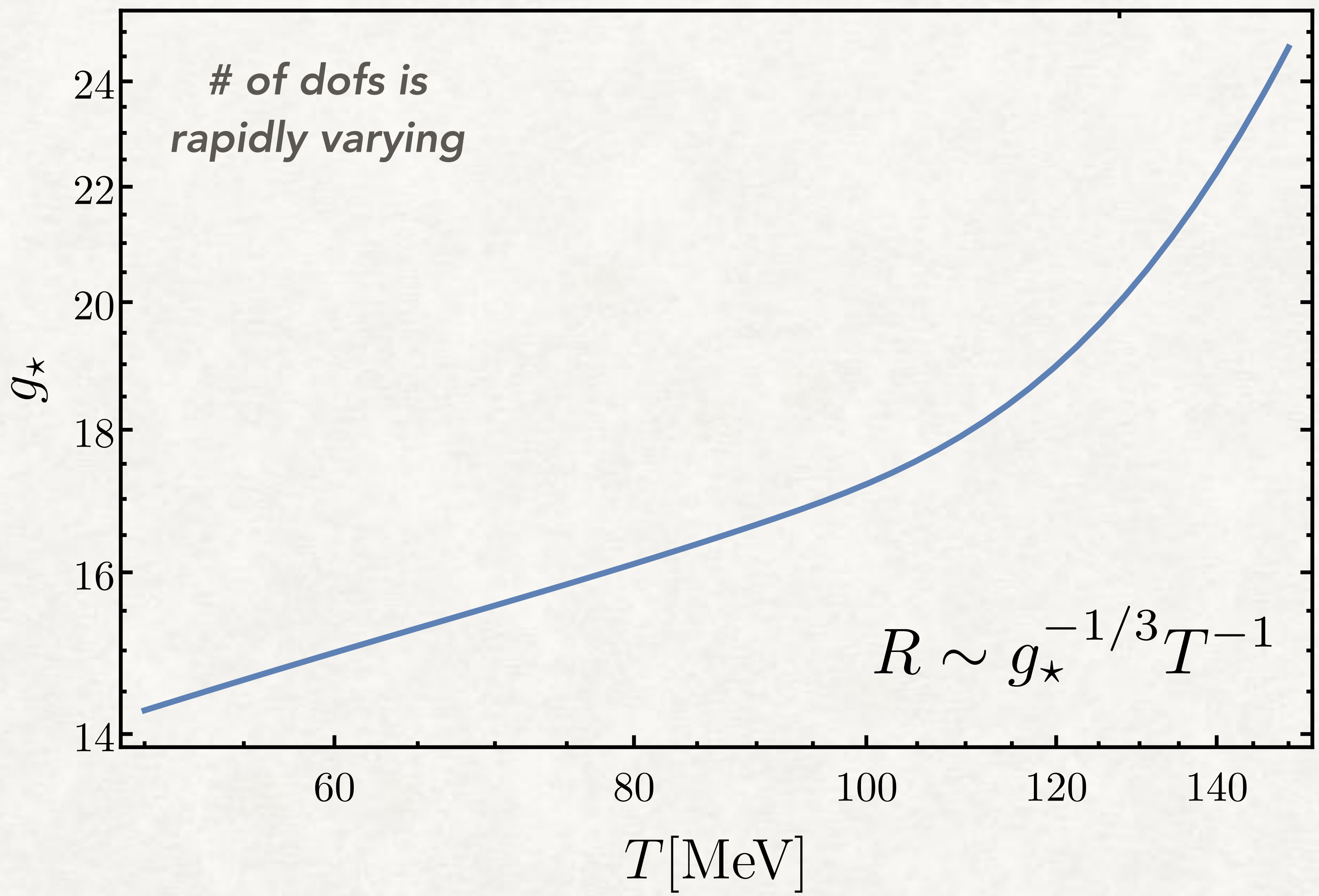

g_* from Borsanyi et al, Nature 539 (2016)

Higher momentum modes are less diluted!

PRODUCTION FROM PIONS

Simple estimate does not work because

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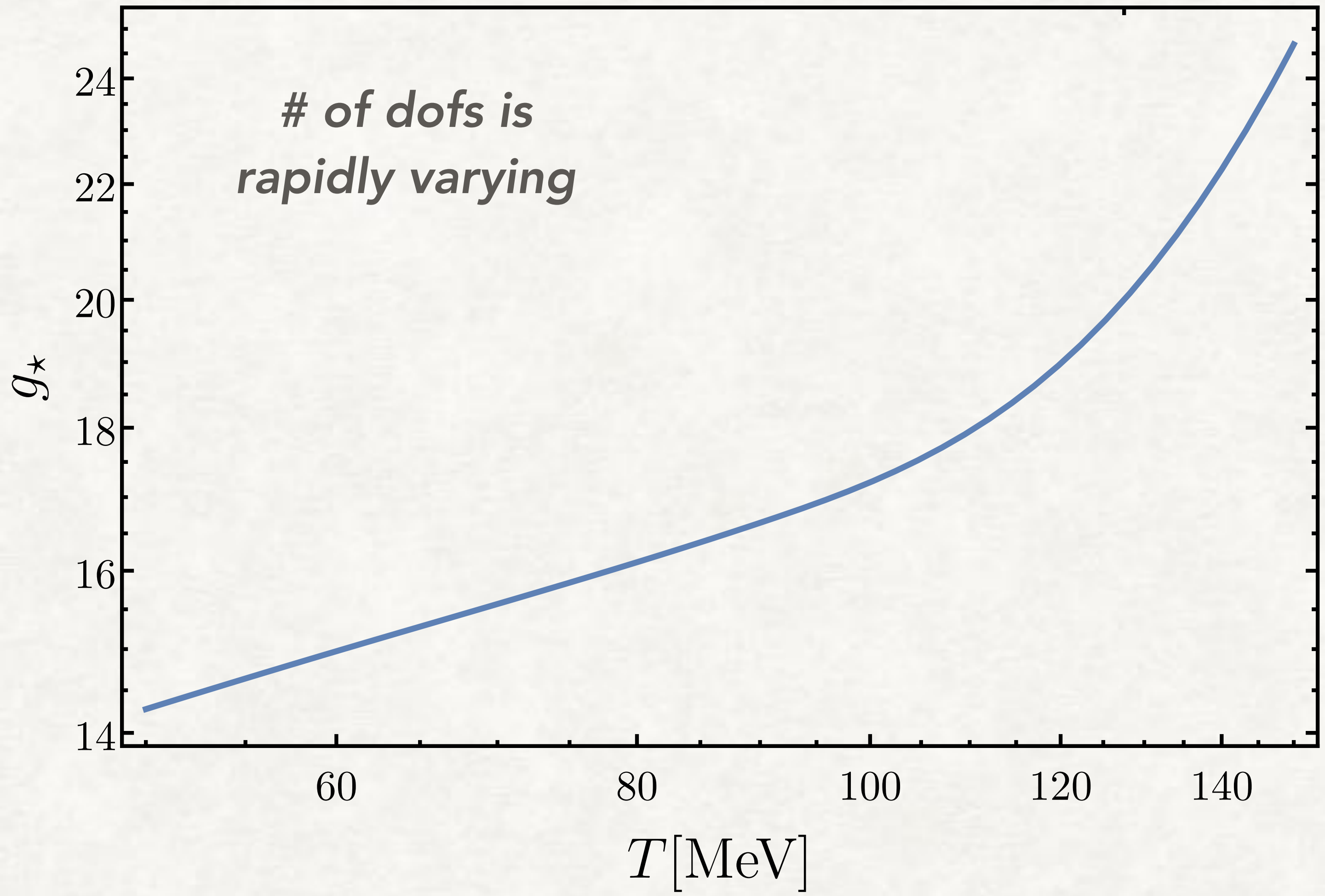

$g_\star$ from Borsanyi et al, Nature 539 (2016)

Expect strong spectral distortion! → ***Enhanced abundance***

Similar to neutrinos, (3 + 0.043), but much larger effect due to change of dofs + behaviour of rate

MOMENTUM-DEPENDENT BOLTZMANN EQUATION

Solve for axion distribution function

Boltzmann equation in comoving momenta $\mathbf{p} = R(t)\mathbf{k}$

Creation **Destruction**

$$\frac{df_{\mathbf{p}}}{dt} = (1+f_{\mathbf{p}})\,\Gamma^{<} - f_{\mathbf{p}}\,\Gamma^{>}\,, \quad \Gamma^{<} = e^{-\frac{E}{T}}\,\Gamma^{>}$$

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\mathrm{eq}}(1+f_2^{\mathrm{eq}})(1+f_3^{\mathrm{eq}})(2\pi)^4\delta^{(4)}(k^\mu + k_1^\mu - k_2^\mu - k_3^\mu)|\mathcal{M}|^2$$

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Bose-Einstein

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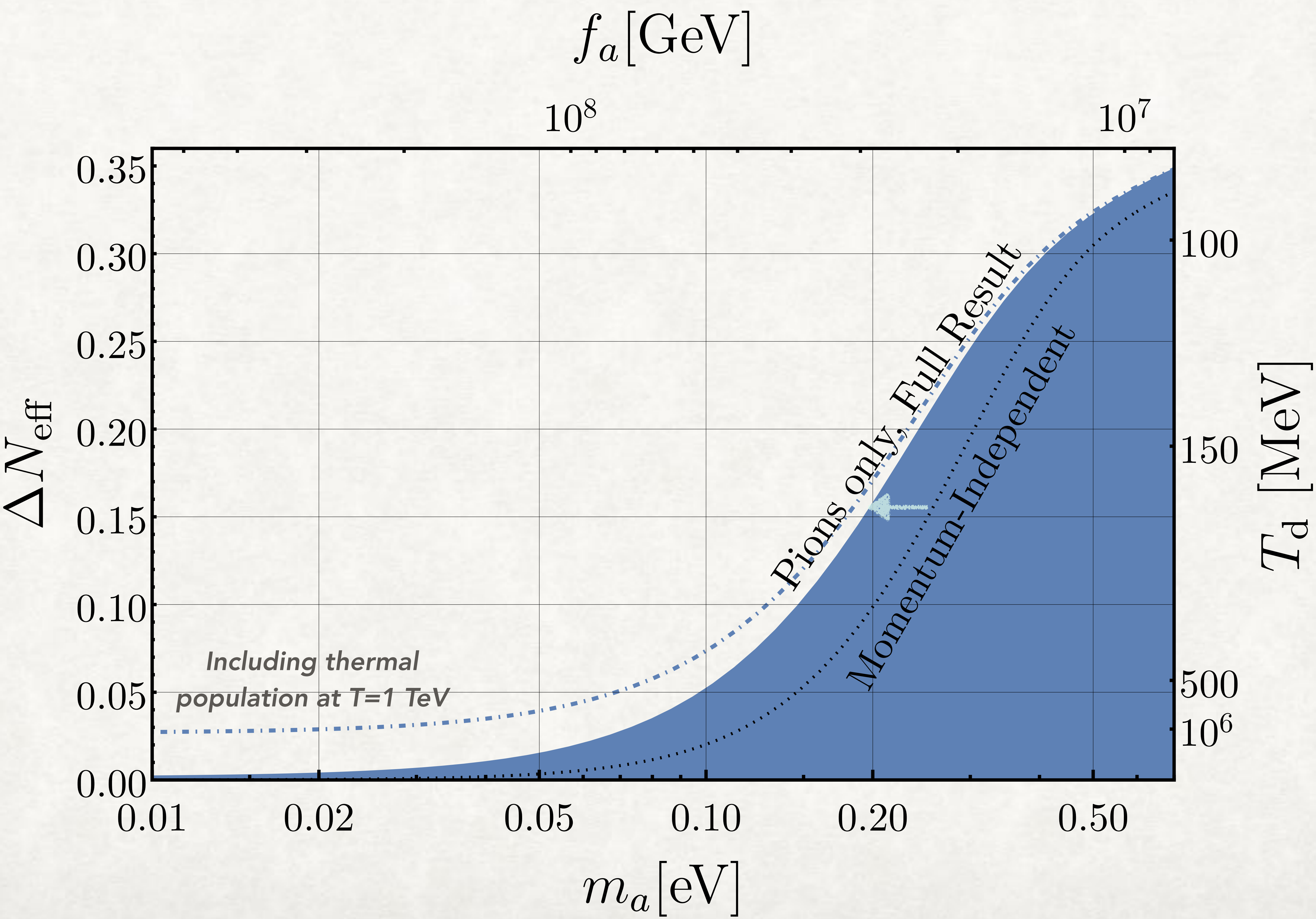
Bose-Einstein

$$\rho_a = R^{-4}\int\frac{d^3\mathbf{p}}{(2\pi)^3}|\mathbf{p}|f_{\mathbf{p}} \rightarrow \Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\frac{\rho_a}{\rho_\gamma}|_{\rm rec}$$

RESULTS

Minimal KSVZ model



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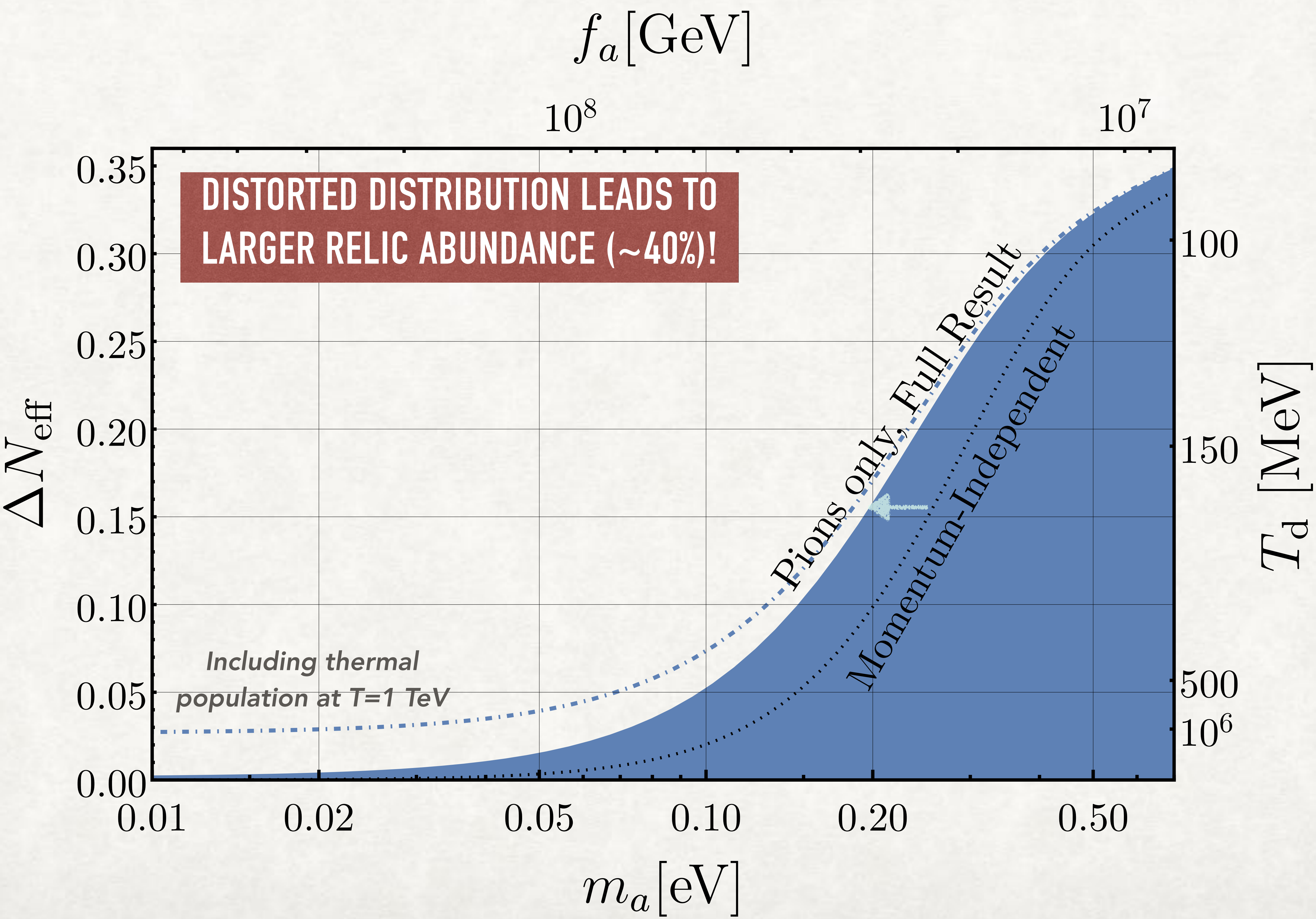
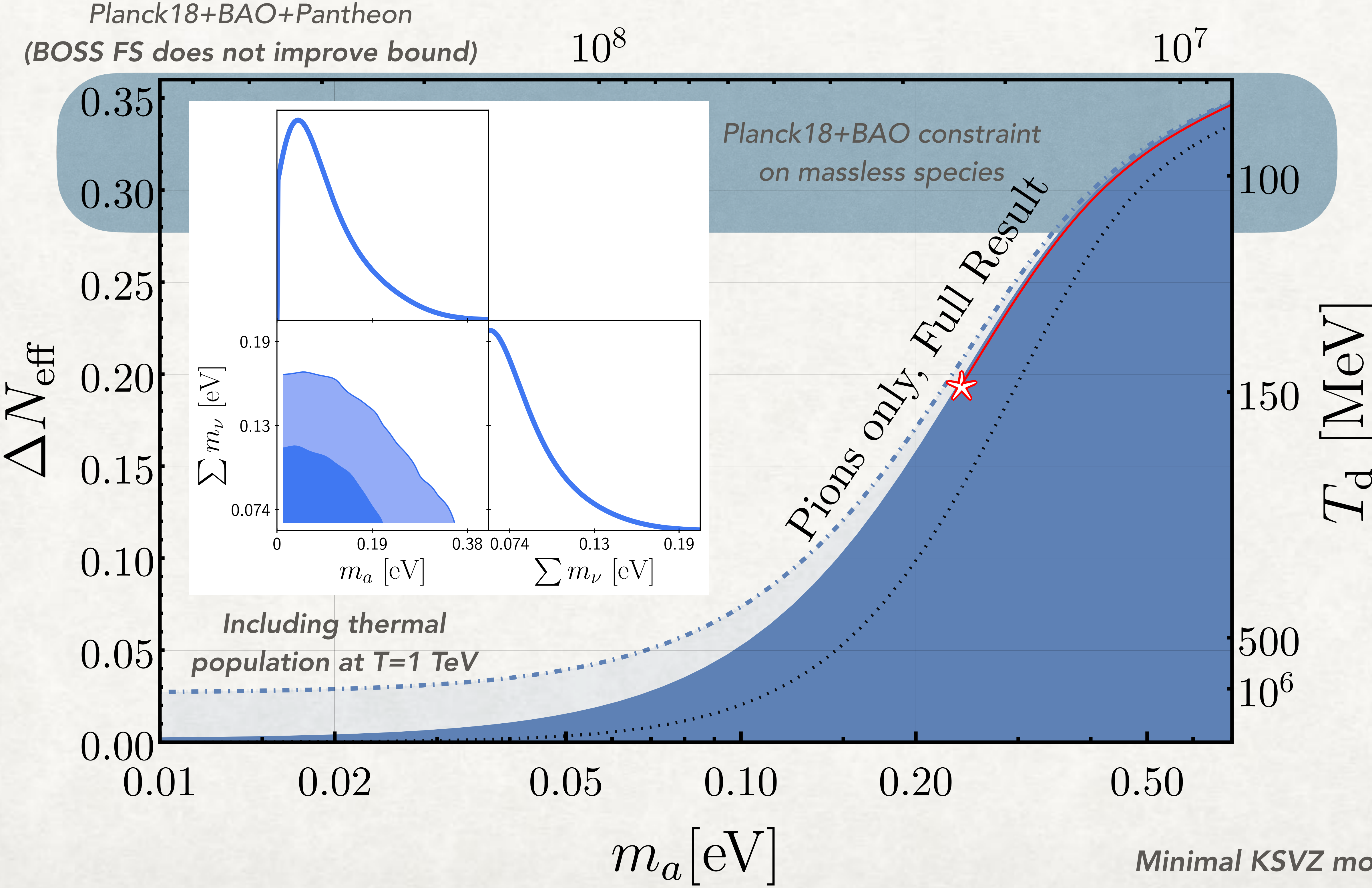


RESULTS

$$\Lambda\text{CDM} + \sum m_\nu + m_a$$

$$m_a \leq 0.24\ \text{eV}, 95\%\ \text{C.L.}$$
$$\sum_\nu m_\nu \leq 0.14\ \text{eV}, 95\%\ \text{C.L.}$$

Planck18+BAO+Pantheon
(BOSS FS does not improve bound)



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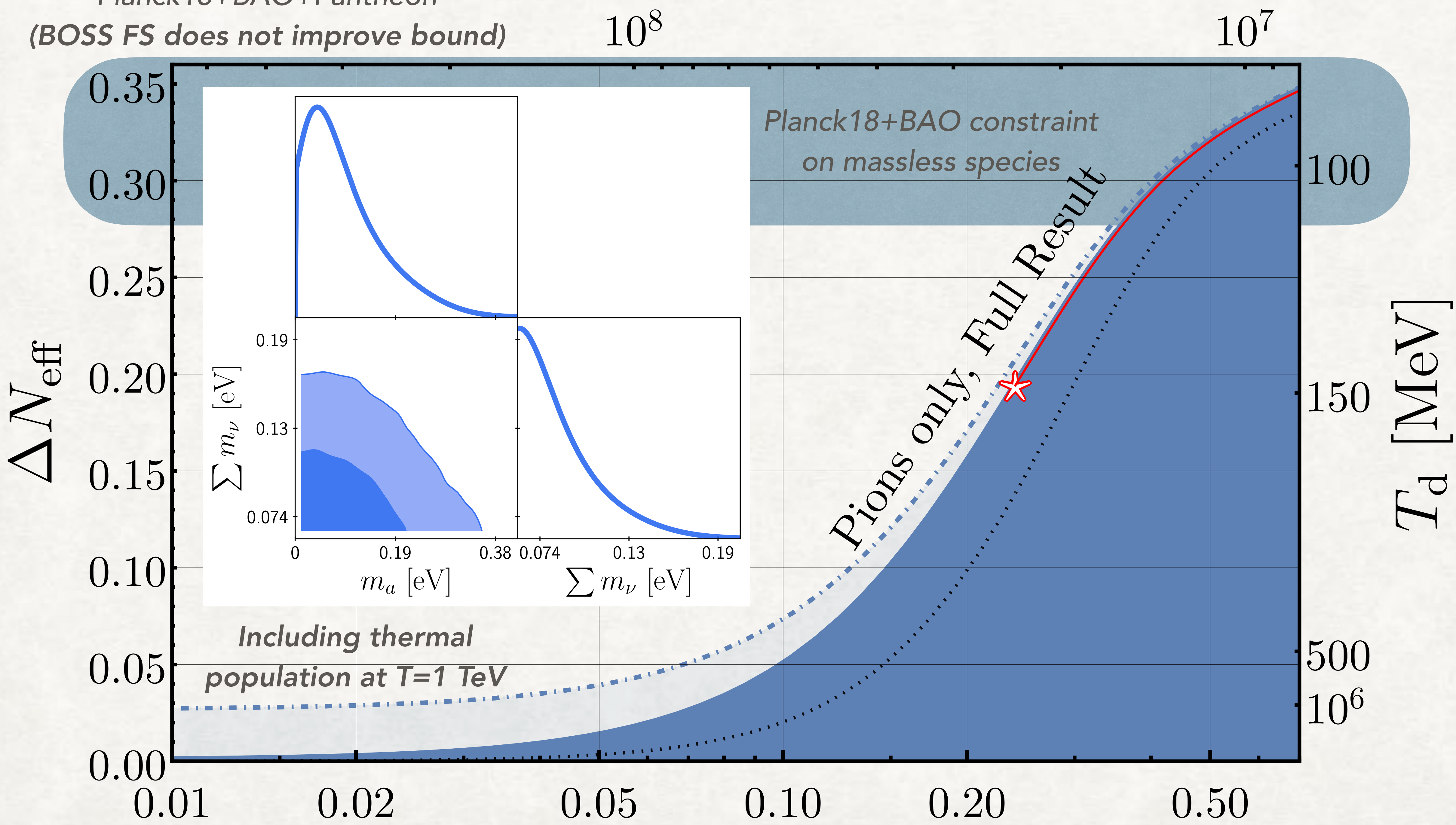


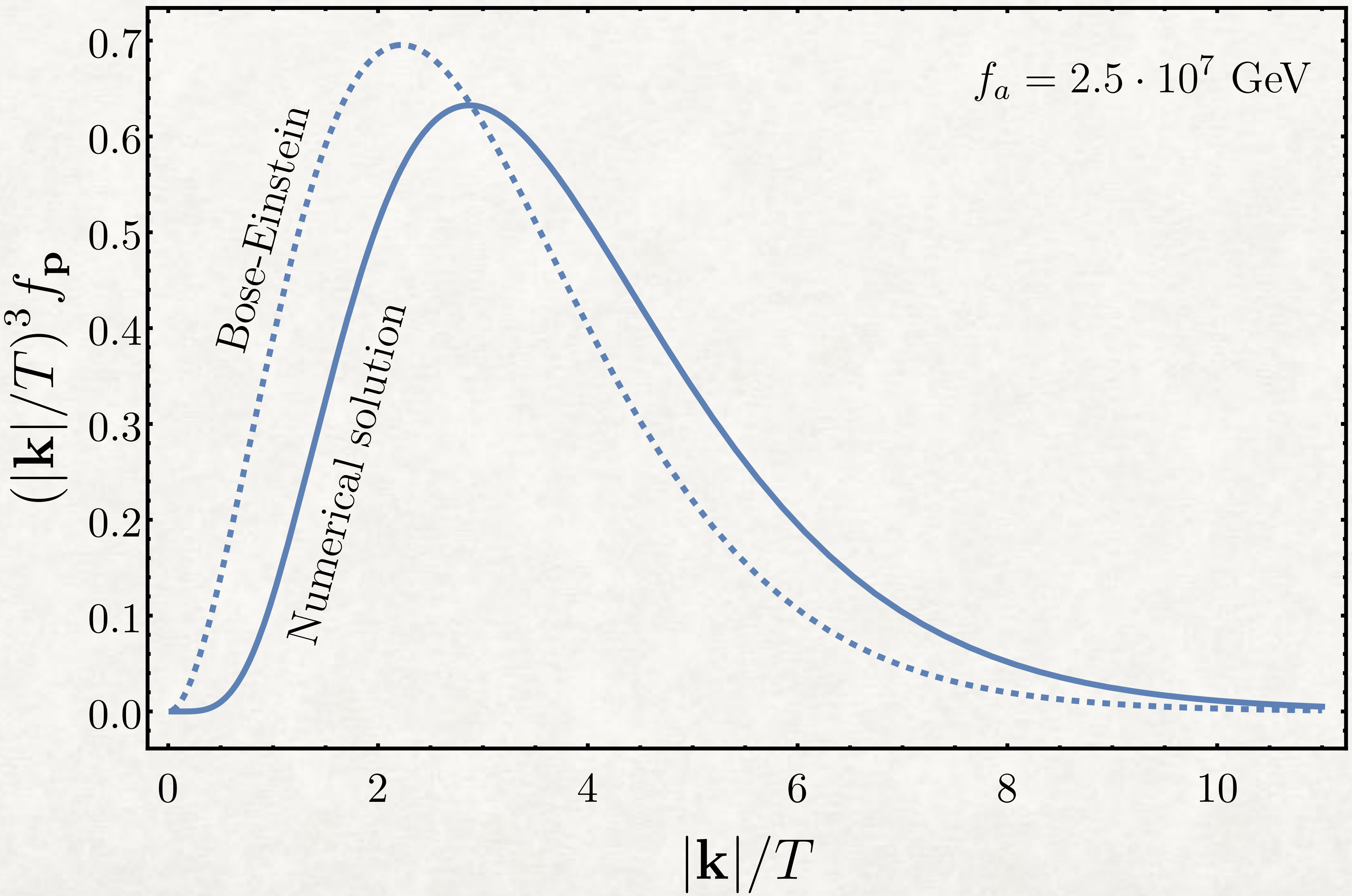
CLASS + MontePython, Lesgourgues 11/../ +
Audren 12/+Brinckmann 18

Minimal KSVZ model

AXION DISTRIBUTION FUNCTION

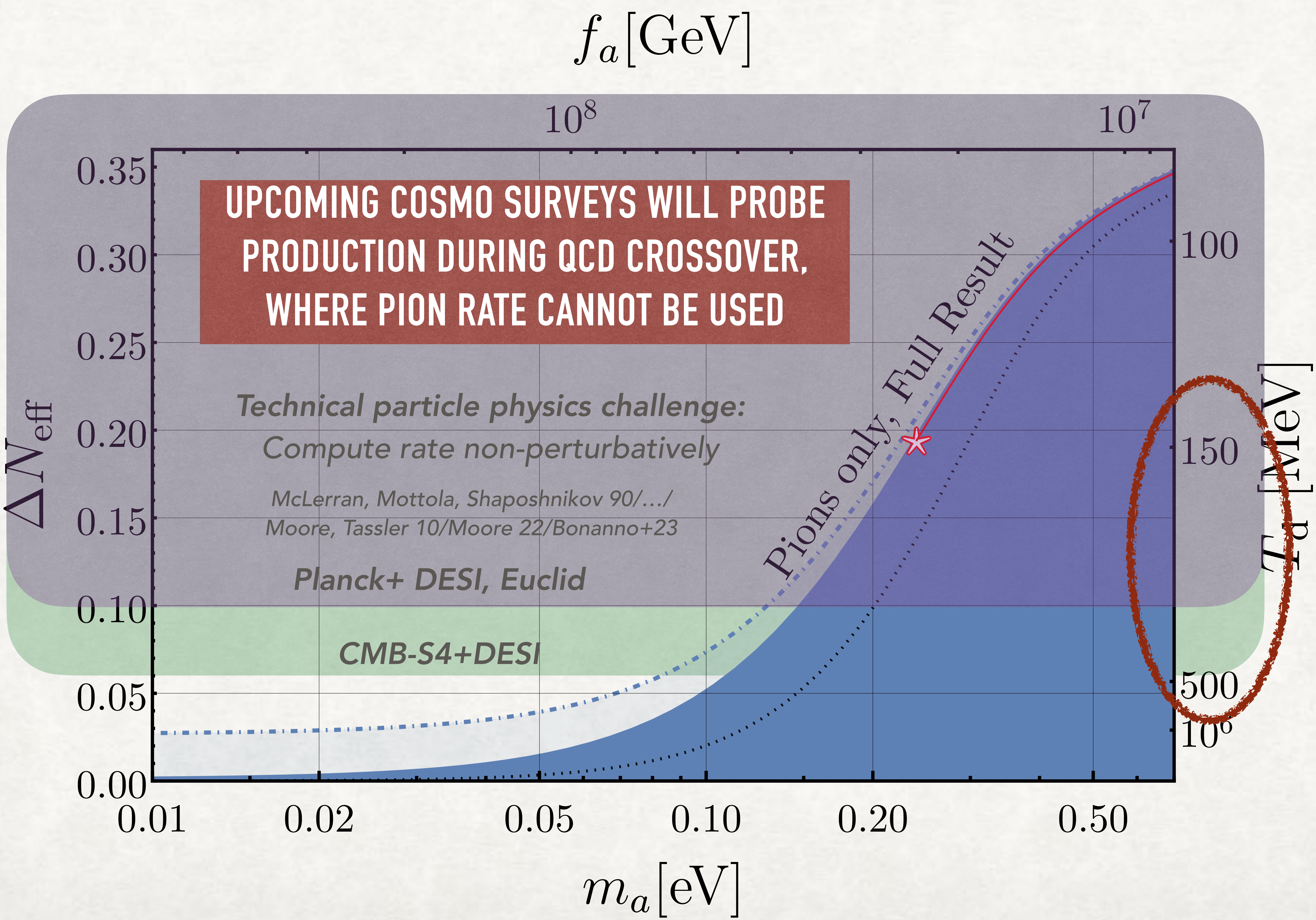
Minimal KSVZ model

Comparison with thermal distribution
with ***same energy density***



THE (NEAR) FUTURE

OUTLOOK

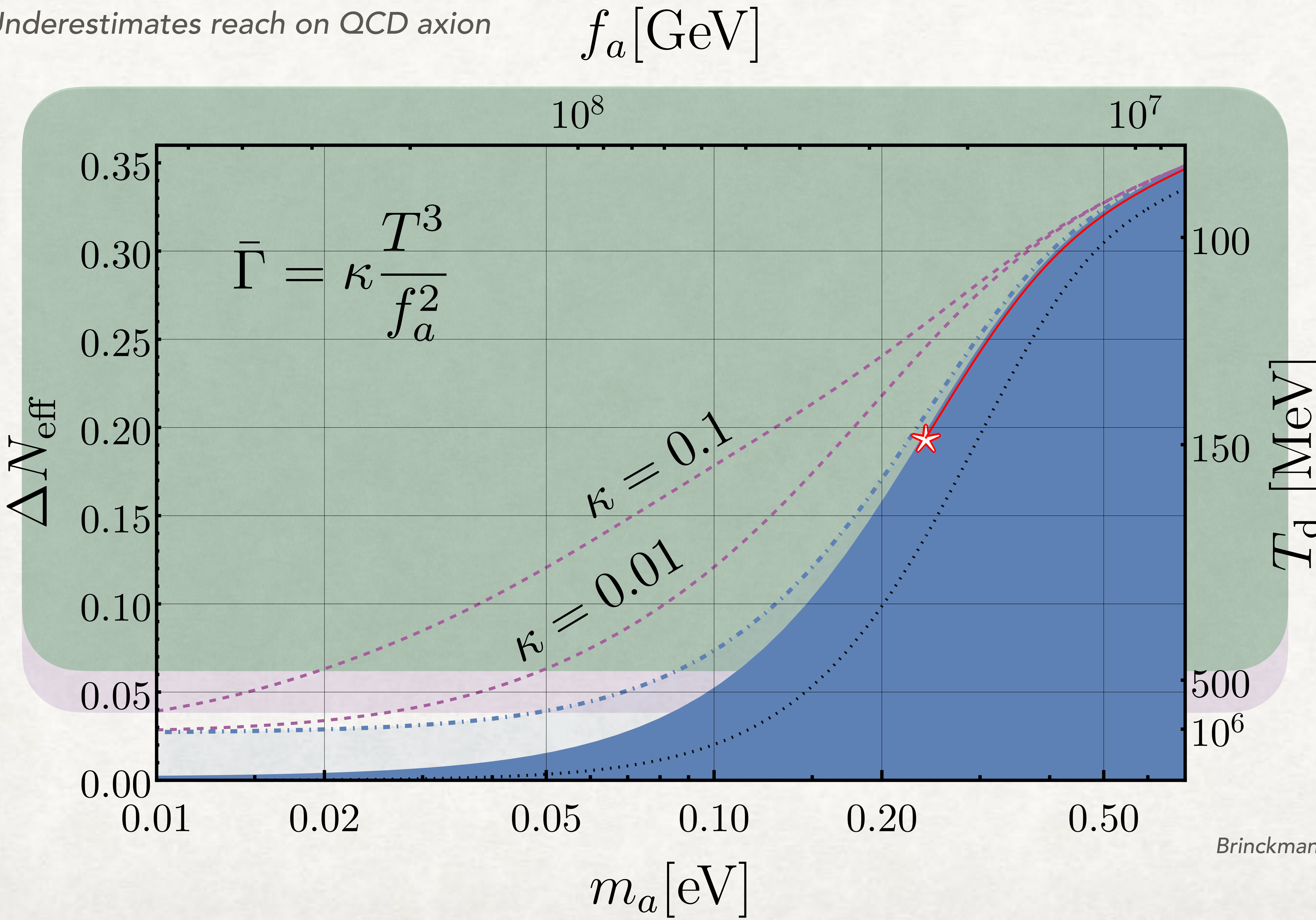


f_a[GeV]
10^8
10^7
UPCOMING COSMO SURVEYS WILL PROBE PRODUCTION DURING QCD CROSSOVER, WHERE PION RATE CANNOT BE USED
Technical particle physics challenge:
Compute rate non-perturbatively
McLerran, Mottola, Shaposhnikov 90/…/
Moore, Tassler 10/Moore 22/Bonanno+23
Planck+ DESI, Euclid
CMB-S4+DESI
Pions only, Full Result
$\Delta N_{\rm eff}$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.01
0.02
0.05
0.10
0.20
0.50
m_a[eV]
T_d [MeV]
100
150
500
10^6

OUTLOOK

Caveat:

Sensitivity reach to massless species,
Underestimates reach on QCD axion



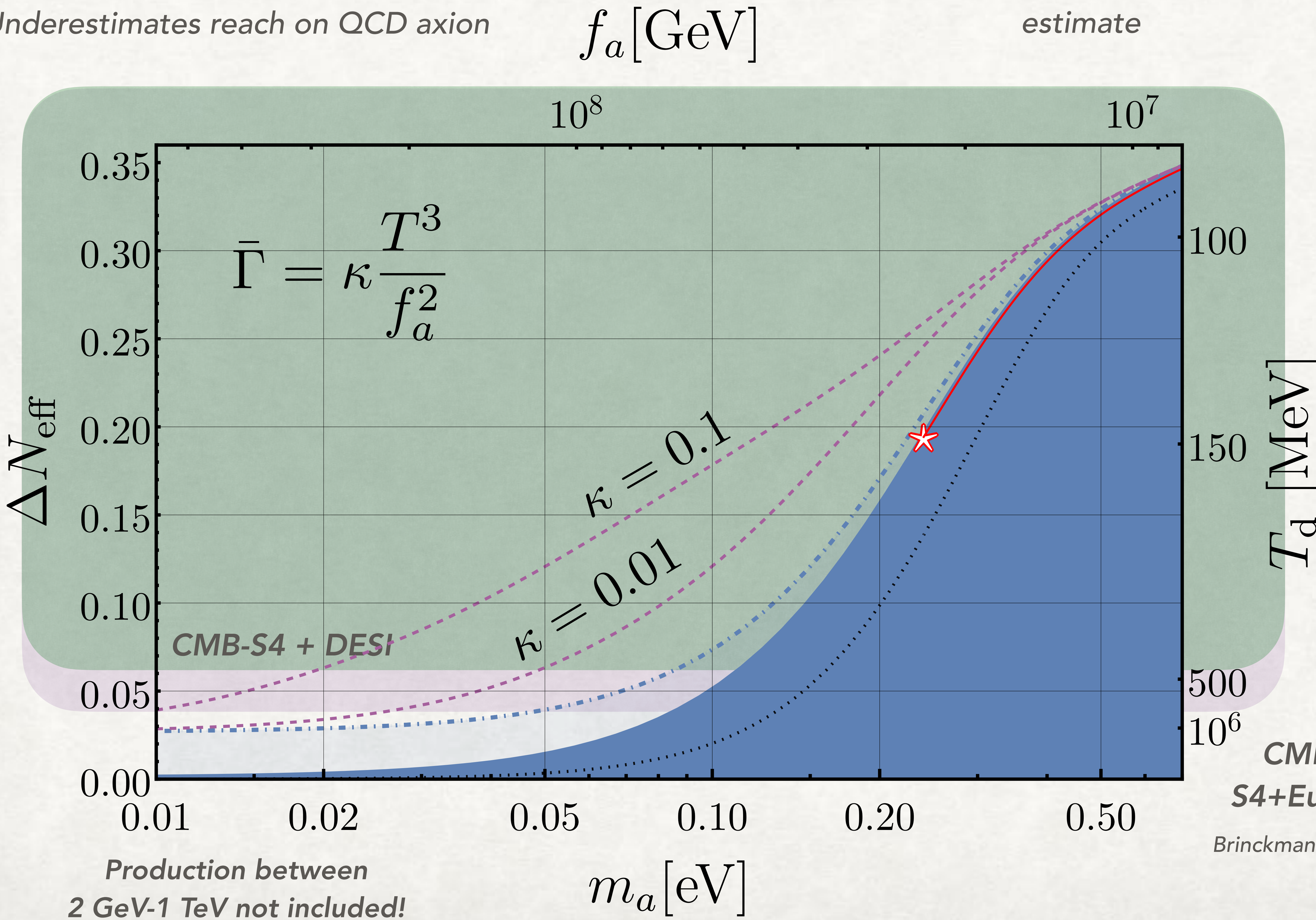
Brinckmann+18

OUTLOOK

Caveat:

Sensitivity reach to massless species,
Underestimates reach on QCD axion

Tentative *dimensional analysis estimate*

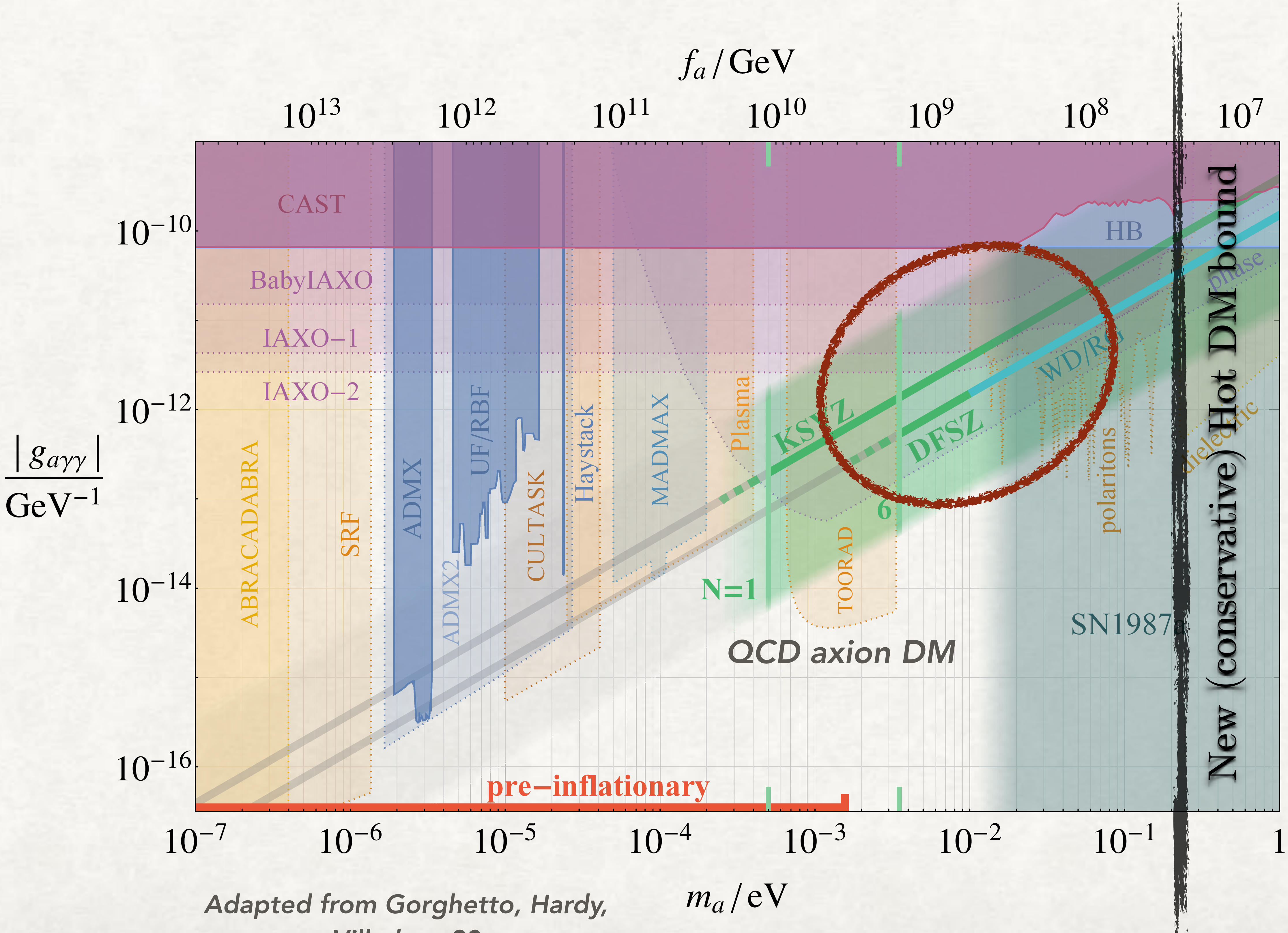


CMB-S4+Euclid

Brinckmann+18

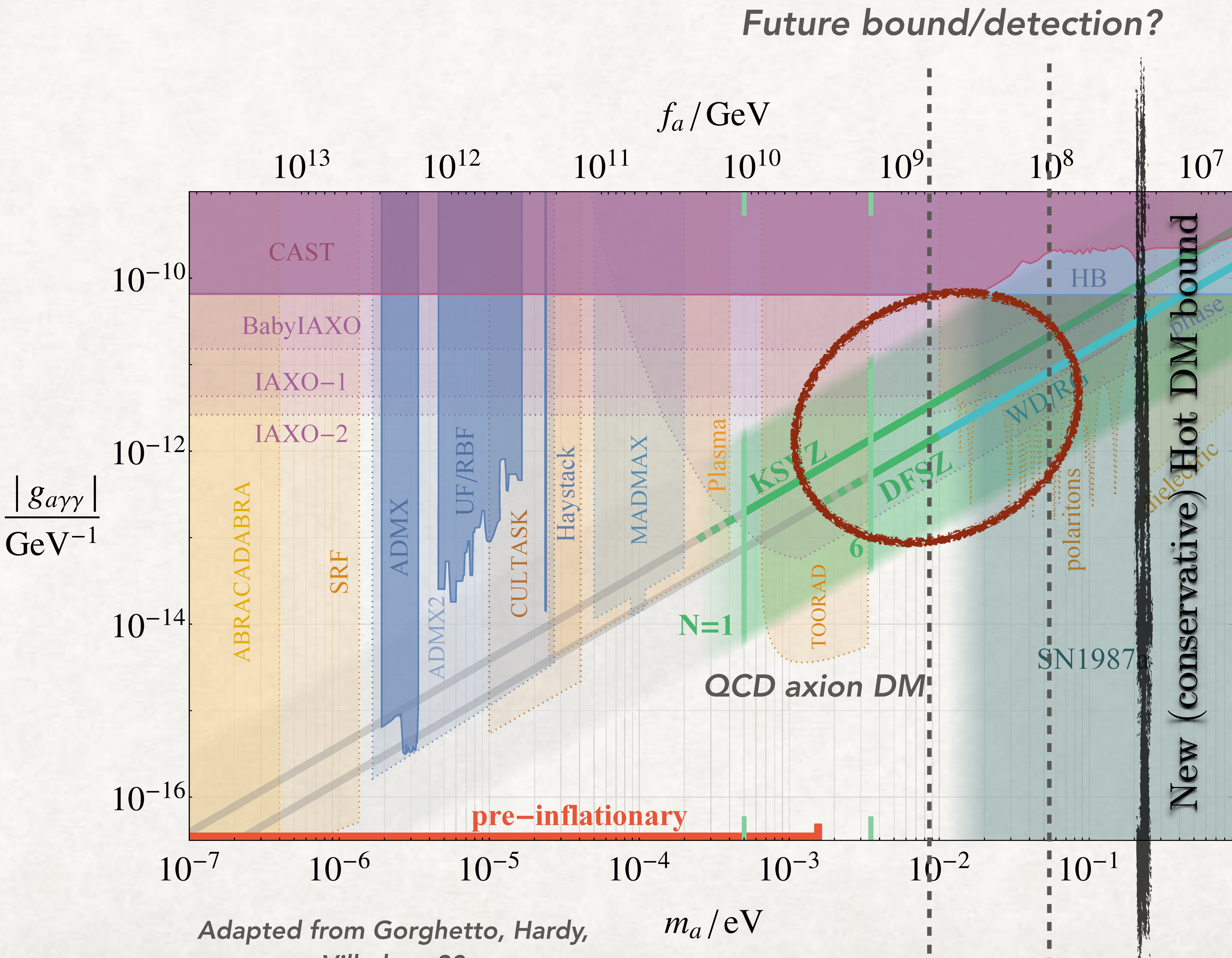
Production between 2 GeV-1 TeV not included!

DISCOVERING THE QCD AXION WITH COSMOLOGY?



Adapted from Gorghetto, Hardy, Villadoro 20

DISCOVERING THE QCD AXION WITH COSMOLOGY?



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SUMMARY/QUESTIONS FOR LSS

Near future reach on thermally produced dark radiation/hot DM w/ sub-eV mass restricted to production during QCD crossover

Variation of # of dofs can cause strong spectral distortion, enhanced abundance

Well-motivated candidate: QCD axion

Full reach of DESI/Euclid?

Observable effects of spectral distortion beyond enhanced abundance?

Impact on neutrino masses?

PARTICLE PHYSICS AT THE EV?

Want: (a) light particle(s) (with (sub)-eV mass) that decouples around the QCD epoch

UV-MOTIVATED

TENSIONS

SIGNAL BUILDING

2305.14166 w/ I. Allali, M. Hertzberg

See talk by Martin!

INTERACTING DARK SECTOR WITH MASS THRESHOLDS

a.k.a. "Stepped Dark Radiation" (SDR)

Aloni, Berlin, Joseph, Schmaltz, Weiner 21/+Sivarajan 22/

See talk by Martin!

$$g_\star^{T<m} < g_\star^{T\gtrsim m}$$

$$g_\star^{T\gtrsim m}$$

Agnostic about production of initial population (but produced after BBN)

Massive species annihilate away (No hot DM constraints)

m

$\nu, \bar{\nu}$ $\qquad$ $\nu, \bar{\nu}$ $\qquad$ T

Dark sector abundance increases

$$\Delta N_{\rm eff}^{T<m} = \Delta N_{\rm eff}^{T\gtrsim m} \left(\frac{g_\star^{T\gtrsim m}}{g_\star^{T<m}}\right)^{\frac{1}{3}}$$

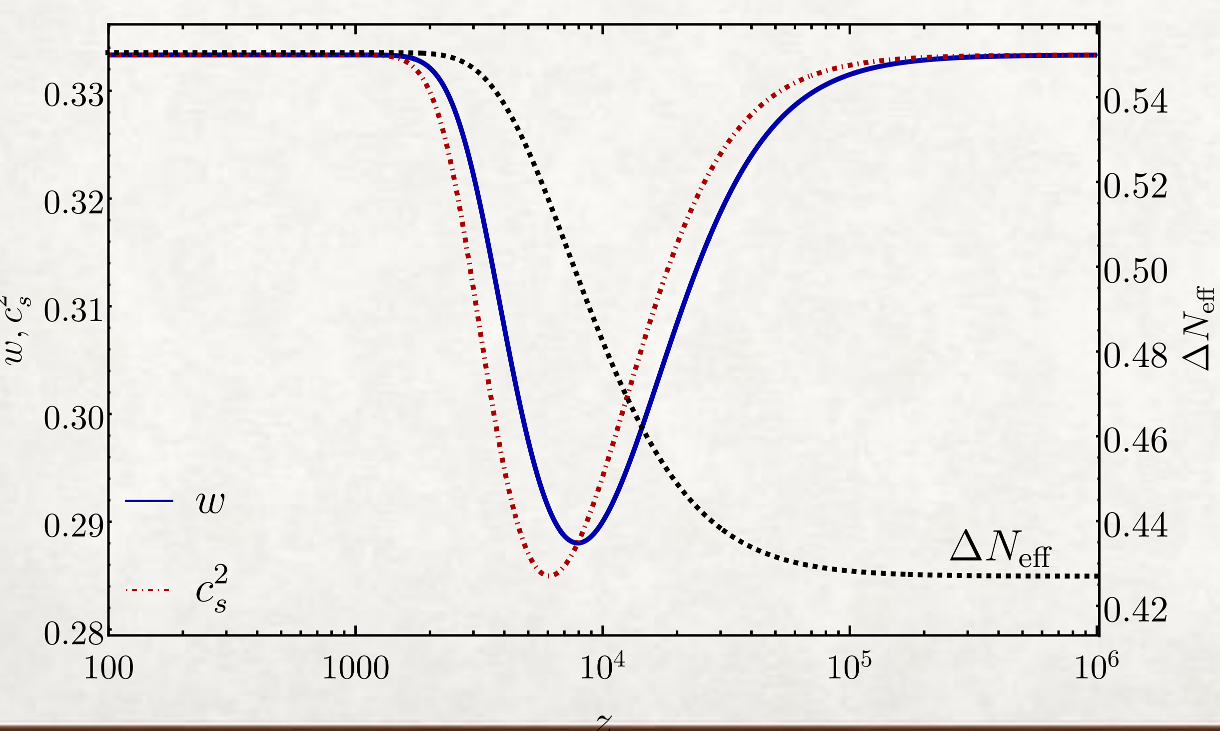
Several possible particle physics realisations: scalars+fermions, fermions+dark photon, QCD-like sector …

IMPACT ON CMB

$$\Delta N_{\rm eff}^{z<z_t} > \Delta N_{\rm eff}^{z>z_t}$$

$$\Delta N_{\rm eff}^{z \gtrsim z_t}$$

low-ℓ $\quad z_t \sim 10^4 \left(\frac{m}{\rm eV}\right)$ $\quad$ high-ℓ $\quad z$



$$\dot\delta = -(1+w)(\theta + \frac{\dot h}{2}) - 3\mathcal{H}(c_s^2 - w)\delta$$

$$\dot\theta = -\mathcal{H}(1-3w)\theta - \frac{\dot w}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma$$

IMPACT ON CMB

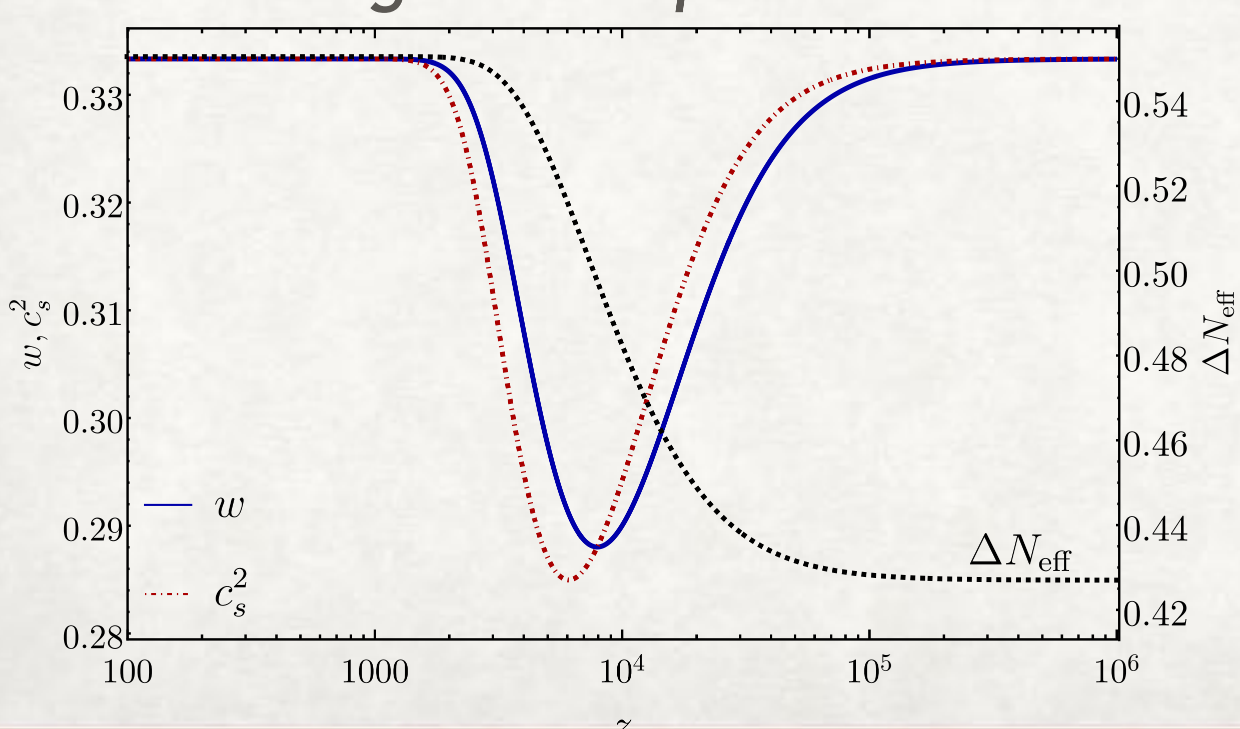
Background

$$\Delta N_{\rm eff}^{z<z_t} > \Delta N_{\rm eff}^{z>z_t}$$

$$\Delta N_{\rm eff}^{z\gtrsim z_t}$$

low-ℓ $\quad z_t \sim 10^4 \left(\frac{m}{\rm eV}\right)$ $\quad$ high-ℓ $\quad z$

Softening of the equation of state



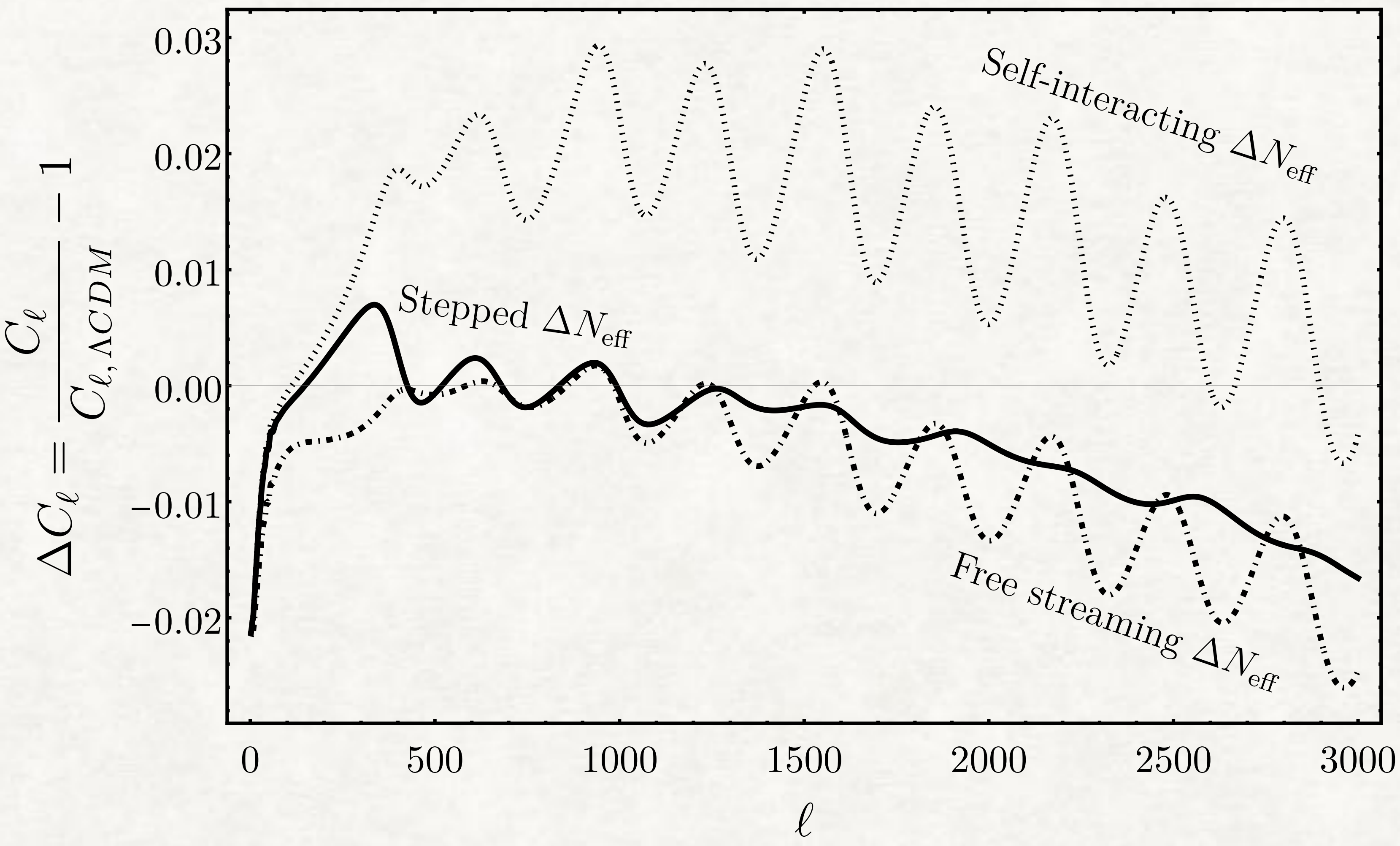
Perturbations

$$\dot{\delta} = -(1+w)(\theta + \frac{\dot{h}}{2}) - 3\mathcal{H}(c_s^2 - w)\delta$$

$$\dot{\theta} = -\mathcal{H}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma$$

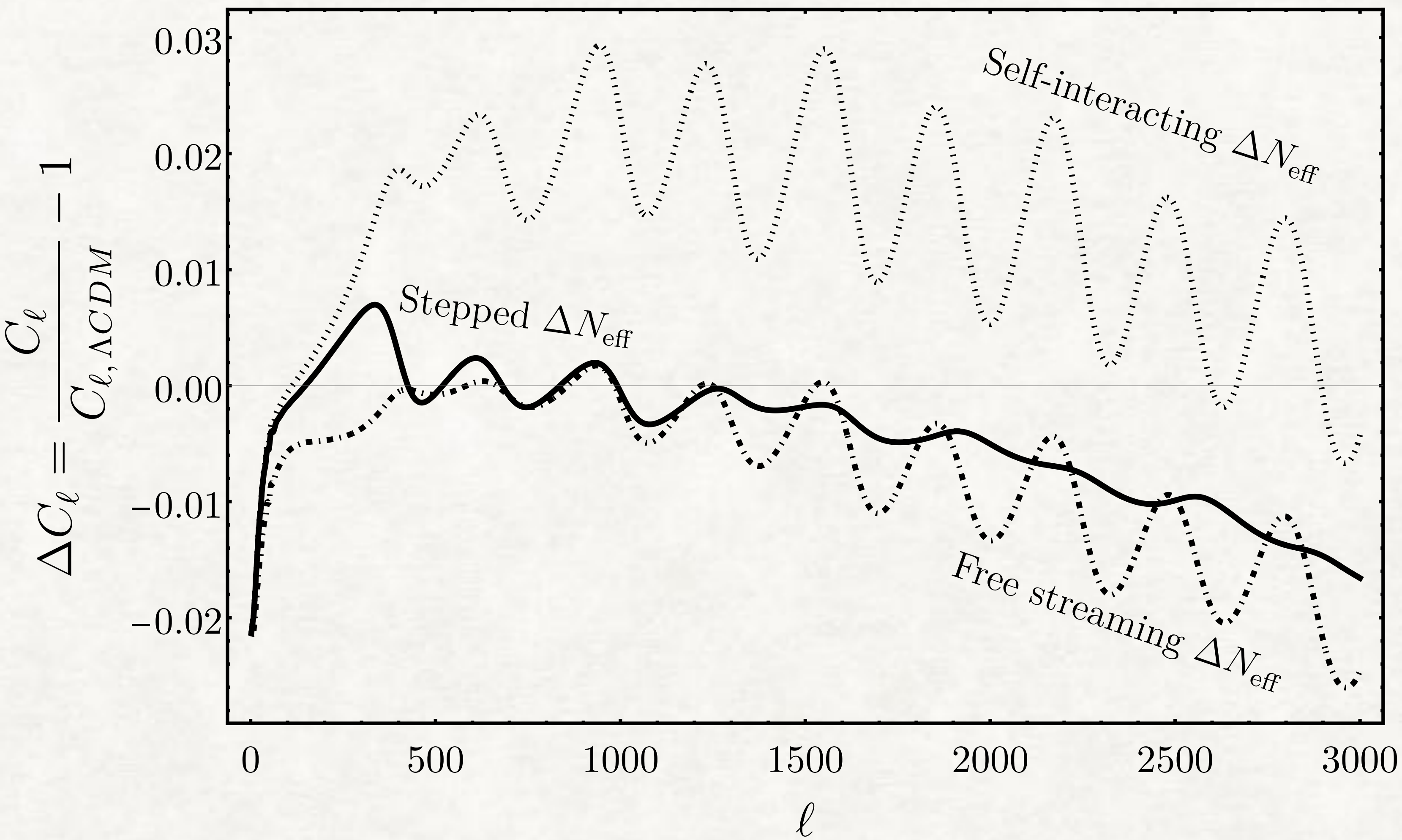
Radiation fluid is self-interacting, behaves like ideal fluid (not free streaming)

IMPACT ON CMB



$\Delta N_{\rm eff}$

IMPACT ON CMB



Fixed

$\Delta N_{\rm eff}$

Motivation from Hubble tension

Simple (free streaming or not) dark radiation not enough to address tension

Time-dependent properties allow for larger relic abundance, degenerate with larger Hubble constant

IMPACT ON HUBBLE TENSION

$$\Delta N_{\rm eff}^{\rm IR}, \quad z_t, \quad r_g \equiv \frac{g_\star^{\rm UV} - g_\star^{\rm IR}}{g_\star^{\rm IR}}$$

$$\text{IR (UV)} \equiv z < (>) z_t,$$

See also Schöneberg, Abellan 22

IMPACT ON HUBBLE TENSION

Effective fluid model is characterised by three extra parameters

$$\Delta N_{\rm eff}^{\rm IR}, \quad z_t, \quad r_g \equiv \frac{g_\star^{\rm UV} - g_\star^{\rm IR}}{g_\star^{\rm IR}}$$

$$\mathrm{IR}\ (\mathrm{UV}) \equiv z < (>) z_t,$$

Model shown to be effective in reducing Hubble tension

With tight priors on redshift of the transition, fitting to Planck18+BAO

Prior dependence?

Look elsewhere effect

See also Schöneberg, Abellan 22

Similar questions addressed for Early Dark Energy

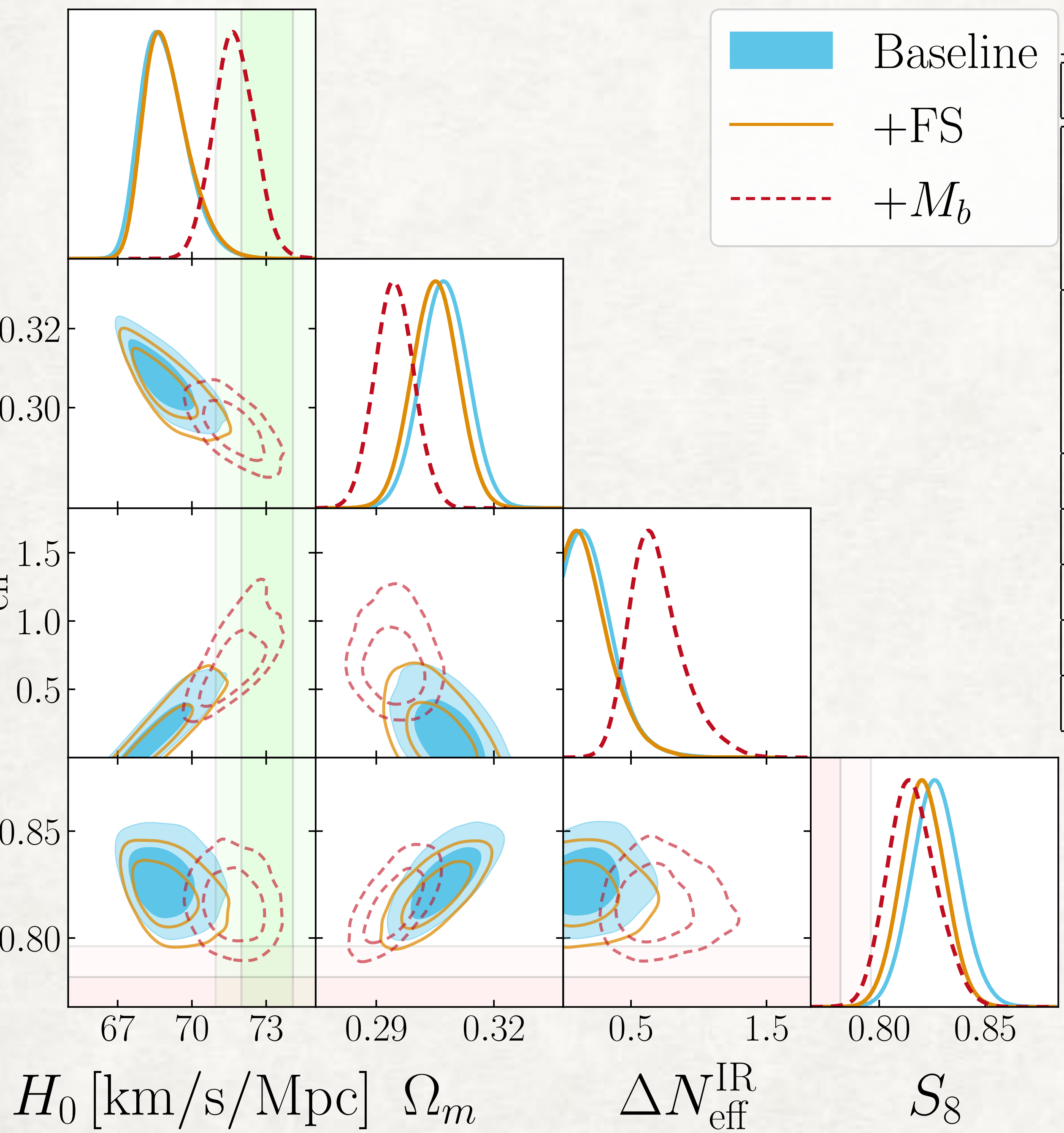
Constraints from BOSS with EFTofLSS?

Shifts of other parameters to keep goodness of fit (CDM, S8)

CONSTRAINTS WITH FULL-SHAPE INFORMATION

`PyBird`

$z_t \in [3, 5]$



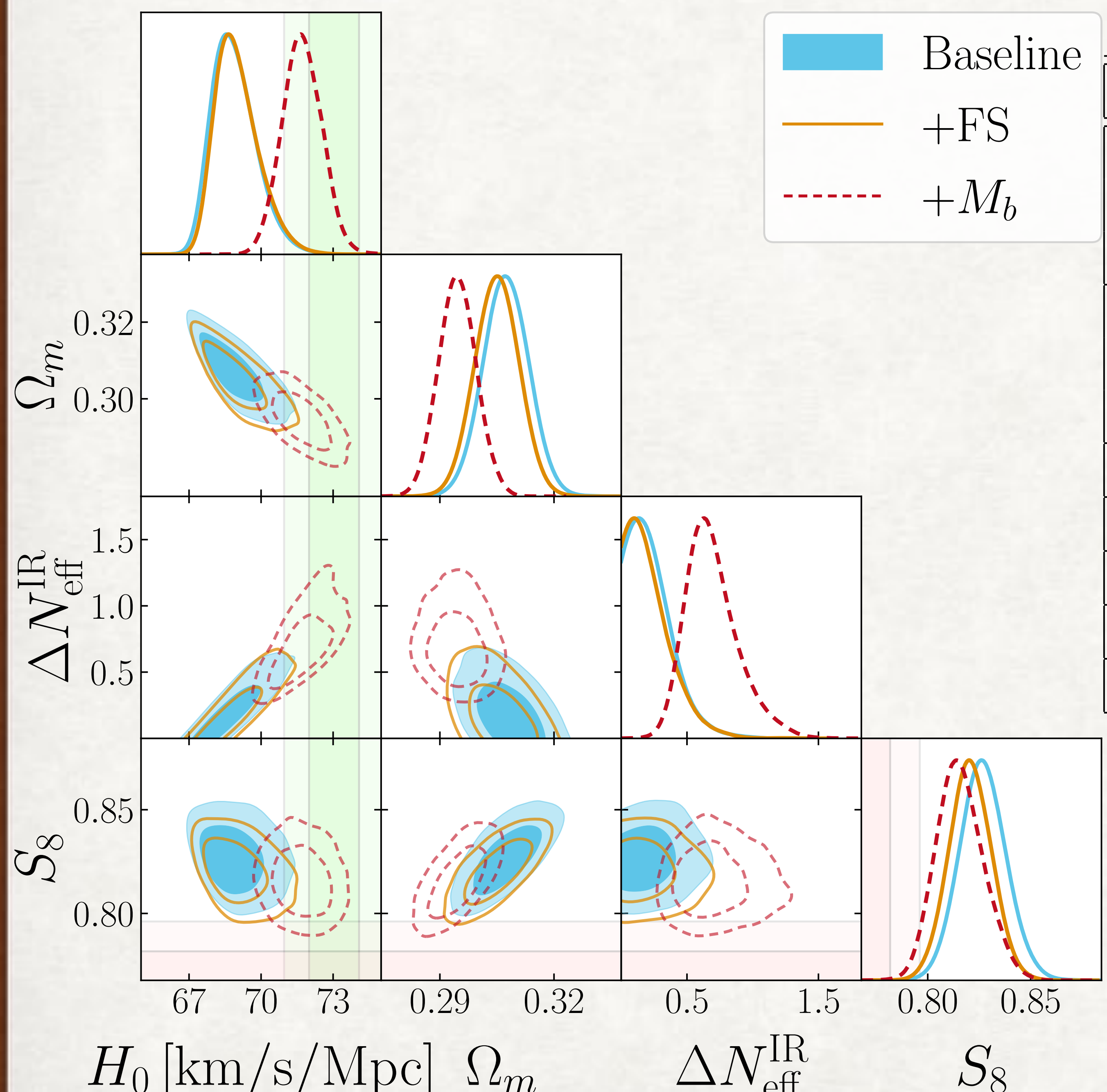
Parameter	Baseline	Baseline + FS
$\Delta N_{\rm eff}^{\rm IR}$	< 0.546 (0.289)	< 0.55 (0.08)
$\log_{10} z_t$	Unconstrained (4.29)	Unconstrained (4.97)
r_g	Unconstrained (4.0)	Unconstrained (2.34)
H_0 [km/s/Mpc]	$68.89\ (69.34)^{+0.71}_{-1.1}$	$69.01\ (68.37)^{+0.66}_{-1.1}$
S_8	$0.827\ (0.834)^{+0.011}_{-0.011}$	$0.821\ (0.824)^{+0.010}_{-0.010}$
M_b	$-19.381\ (-19.369)^{+0.021}_{-0.032}$	$-19.378\ (-19.4)^{+0.019}_{-0.032}$
$\Delta\chi^2$	-1.4	-1.62
$Q_{\rm DMAP}^{M_b}$	2.74σ	2.72σ
M_b GT	3.74σ	3.77σ
M_b IT	3.03σ	2.94σ
$\Delta{\rm AIC}^{M_b}$	-20.67	-18.68

$\gtrsim 3\sigma$

CONSTRAINTS WITH FULL-SHAPE INFORMATION

PyBird

D'Amico, Senatore, Zhang 20



Very mild impact on posteriors

$z_t \in [3, 5]$

Baseline = Planck18+BAO+Pantheon

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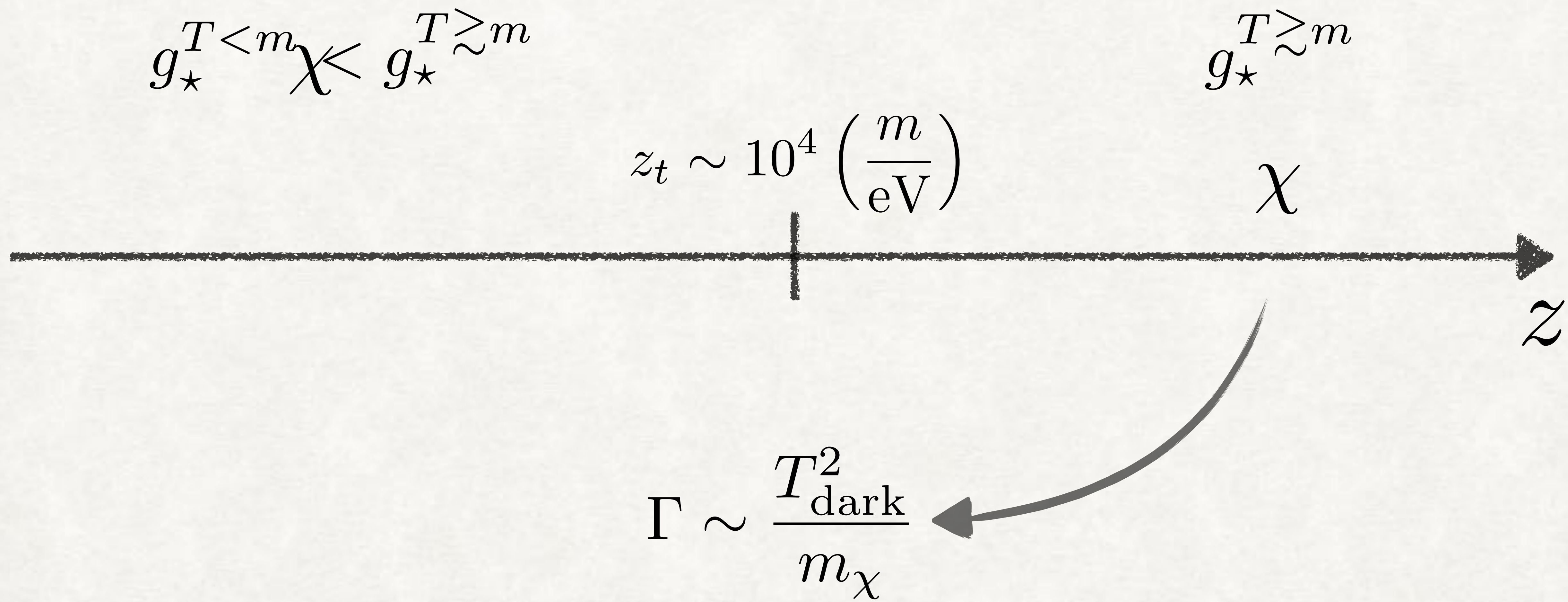
Very mild impact on posteriors

LSS shifts bestfit values towards LambdaCDM

Hubble Tension $\gtrsim 3\sigma$

ADDING INTERACTIONS WITH DARK MATTER

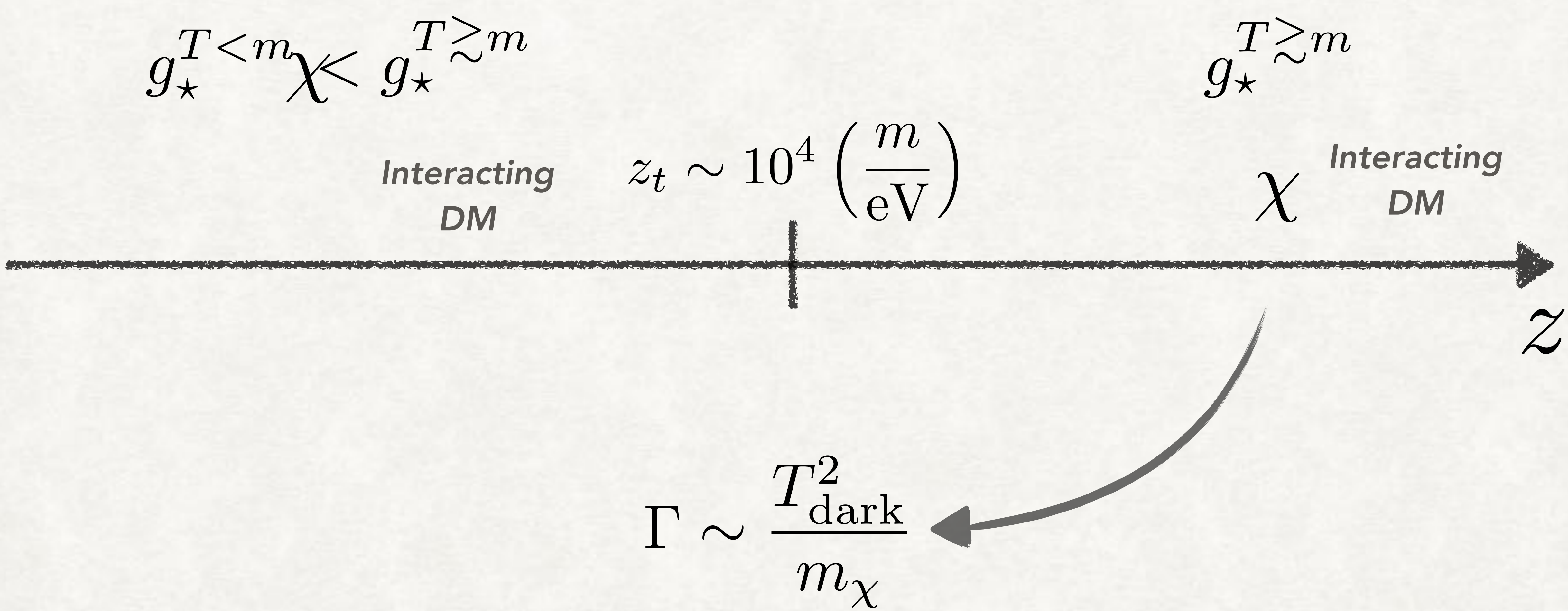
Needed? *See new KiDS+DES analysis…*



ADDING INTERACTIONS WITH DARK MATTER

Motivation from S8: suppression of matter power spectrum

Needed? *See new KiDS+DES analysis…*

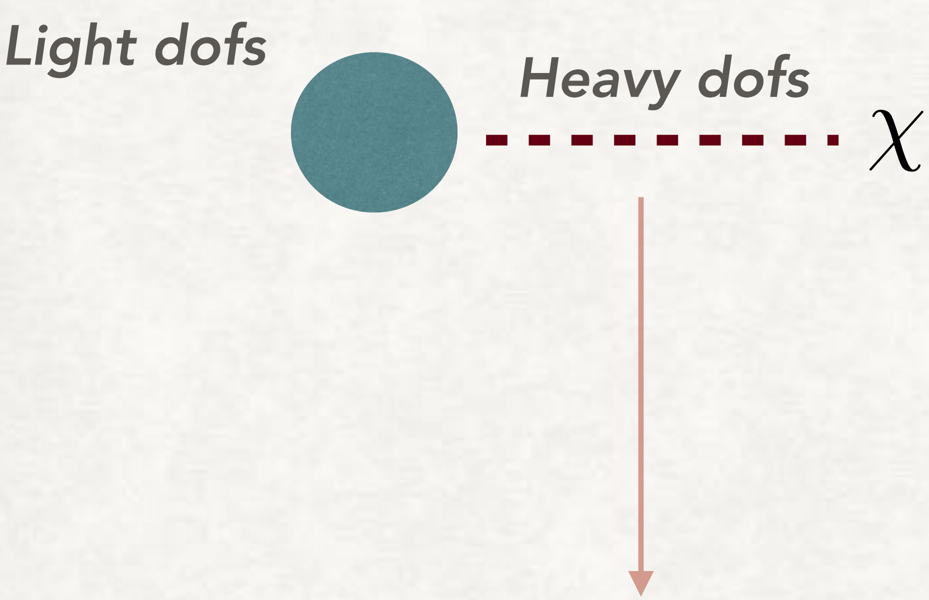


TWO SCENARIOS

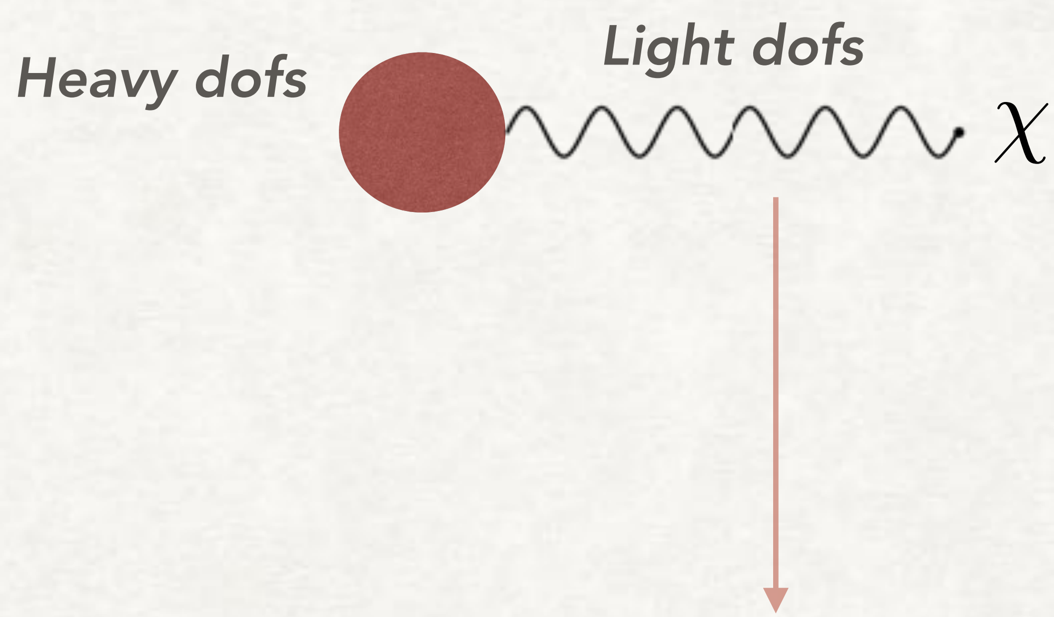
Joseph, Aloni, Schmaltz, Sivarajan, Weiner 22

$$z \lesssim z_t$$

Buen-Abad, Chako, Kilic, Marques-Tavares, Youn 22, 23



$$\Gamma_{z \lesssim z_t} \sim \frac{T_{\text{dark}}^2}{m_\chi} \left(\frac{T_{\text{dark}}}{m} \right)^4$$



$$\Gamma_{z \lesssim z_t} \sim \frac{T_{\text{dark}}^2}{m_\chi} e^{-\frac{m}{T_{\text{dark}}}}$$

TWO SCENARIOS

Joseph, Aloni, Schmaltz, Sivarajan, Weiner 22

$$\boxed{z \lesssim z_t}$$

Buen-Abad, Chako, Kilic, Marques-Tavares, Youn 22, 23

Massive mediator, light (e.g. Yukawa interactions)

Light dofs

Heavy dofs

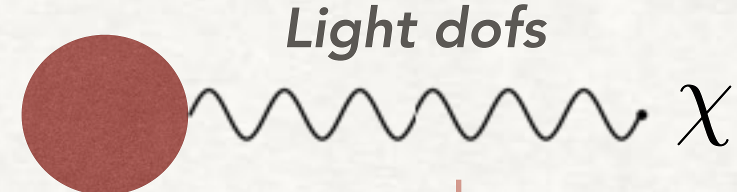
"Weakly IDM"

$$\Gamma_{z \lesssim z_t} \sim \frac{T_{\rm dark}^2}{m_\chi} \left(\frac{T_{\rm dark}}{m} \right)^4$$

Massless mediator e.g. scalar-fermion mediated by dark U(1)

Heavy dofs

Light dofs



"Strongly IDM"

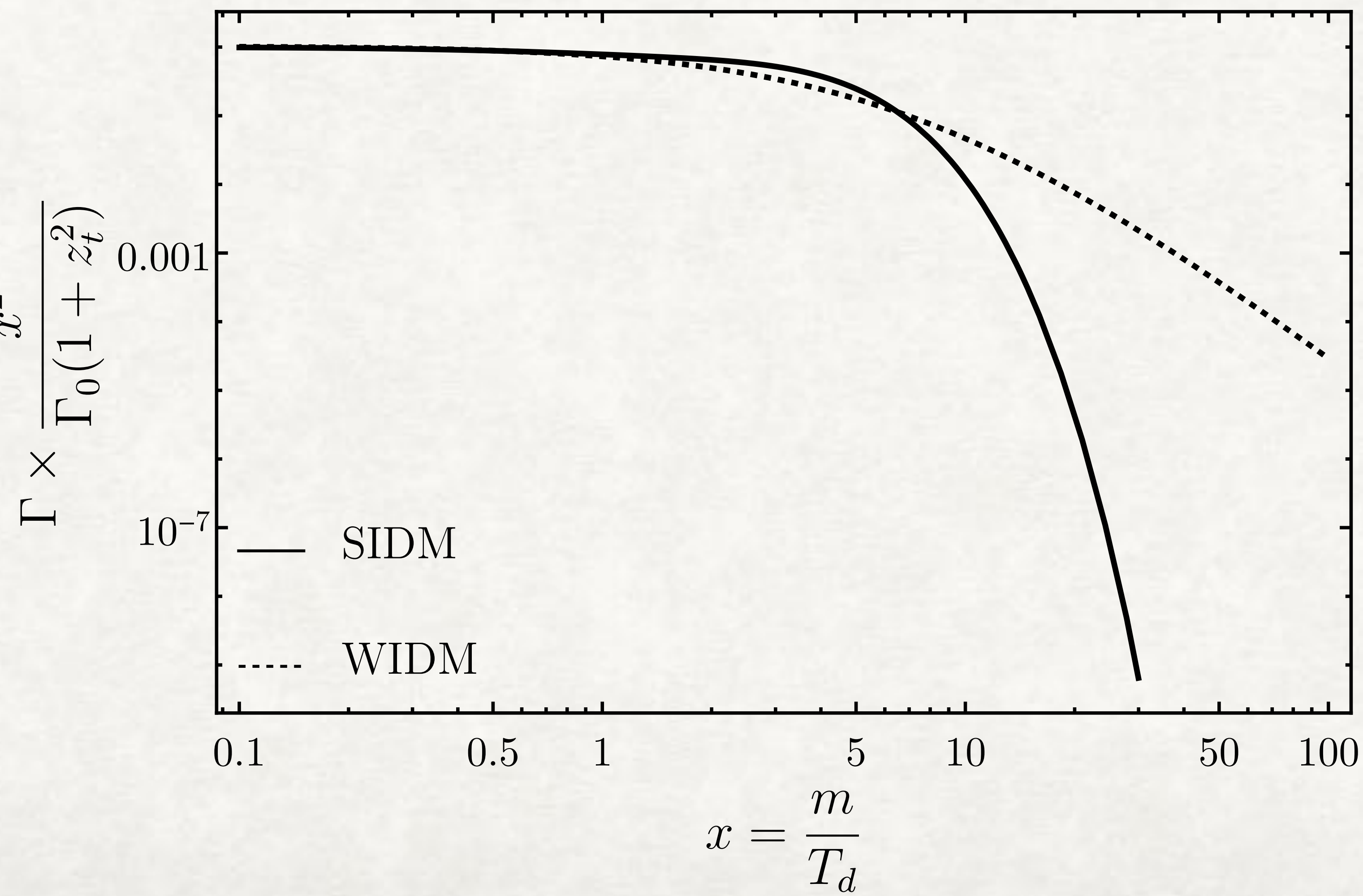
Boltzmann suppressed

$$\Gamma_{z \lesssim z_t} \sim \frac{T_{\rm dark}^2}{m_\chi} e^{-\frac{m}{T_{\rm dark}}}$$

INTERACTING DARK SECTOR WITH MASS THRESHOLD

$$\Gamma = \Gamma_0 \left(\frac{1 + z_t}{x} \right)^2 h(x)$$

$$x \equiv m/T_{\rm dark}, h(x \to 0) \to 1$$

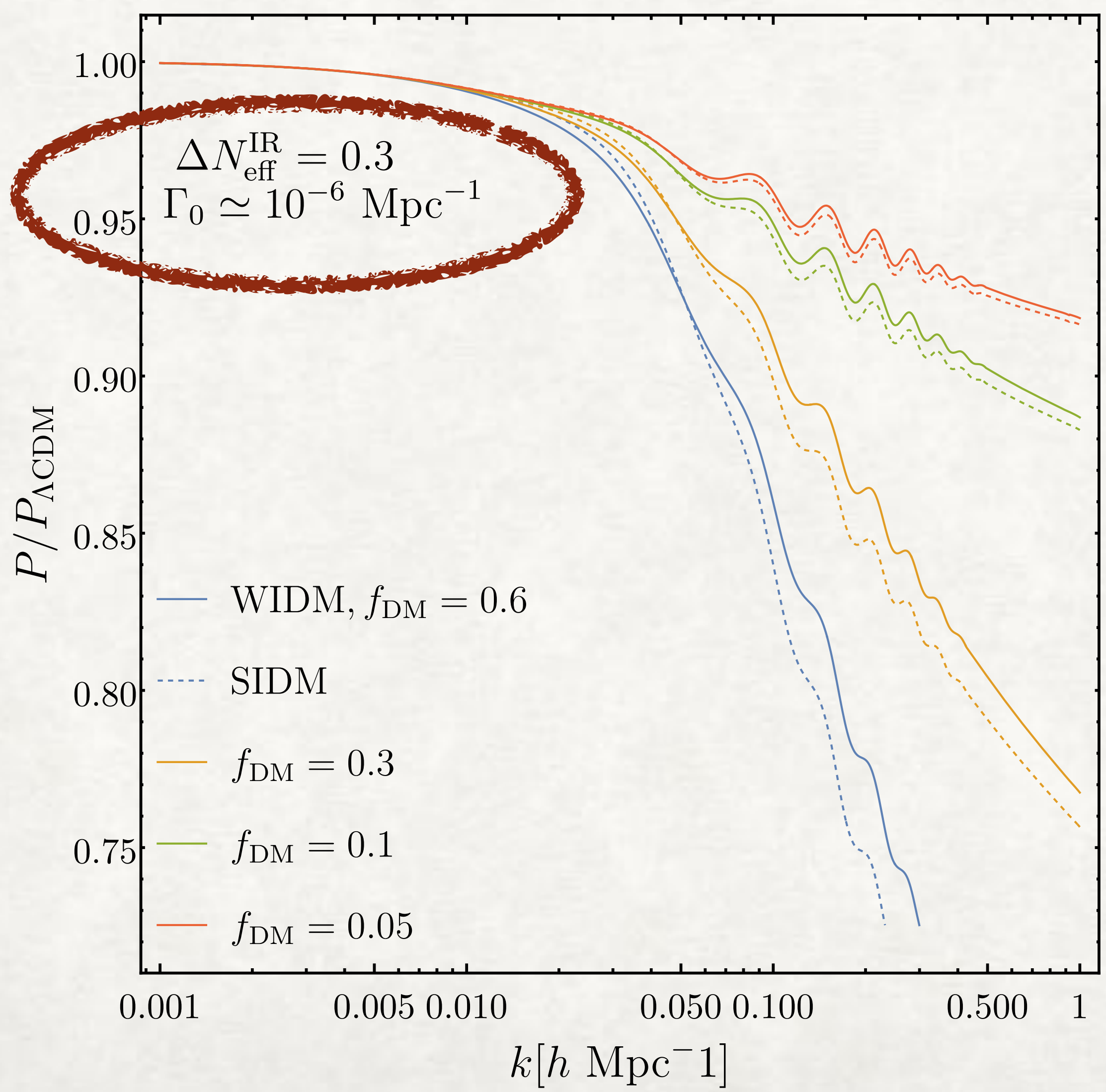


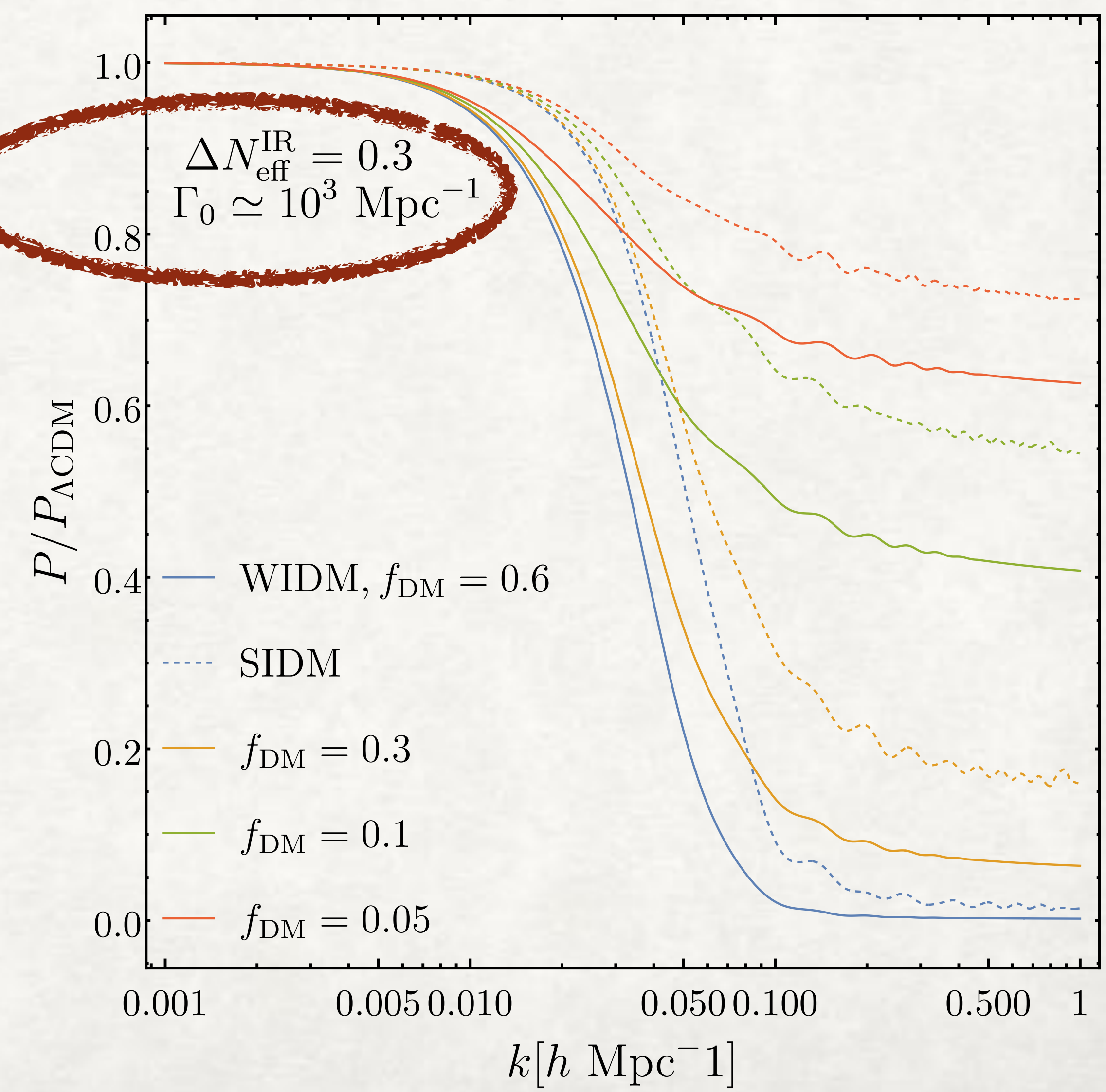
SUPPRESSION OF MATTER POWER SPECTRUM

$$z \gg z_t$$

$$f_{\mathrm{DM}} \equiv$$

$$\frac{\Gamma}{H} \sim \frac{\Gamma_0}{10^{-6}\,\mathrm{Mpc}^{-1}} \left(\frac{\Delta N_{\mathrm{eff}}^{\mathrm{IR}}}{0.3}\right)^{1/2} \left(\frac{2}{g_*^{\mathrm{IR}}}\right)^{1/2}$$





SUPPRESSION OF MATTER POWER SPECTRUM

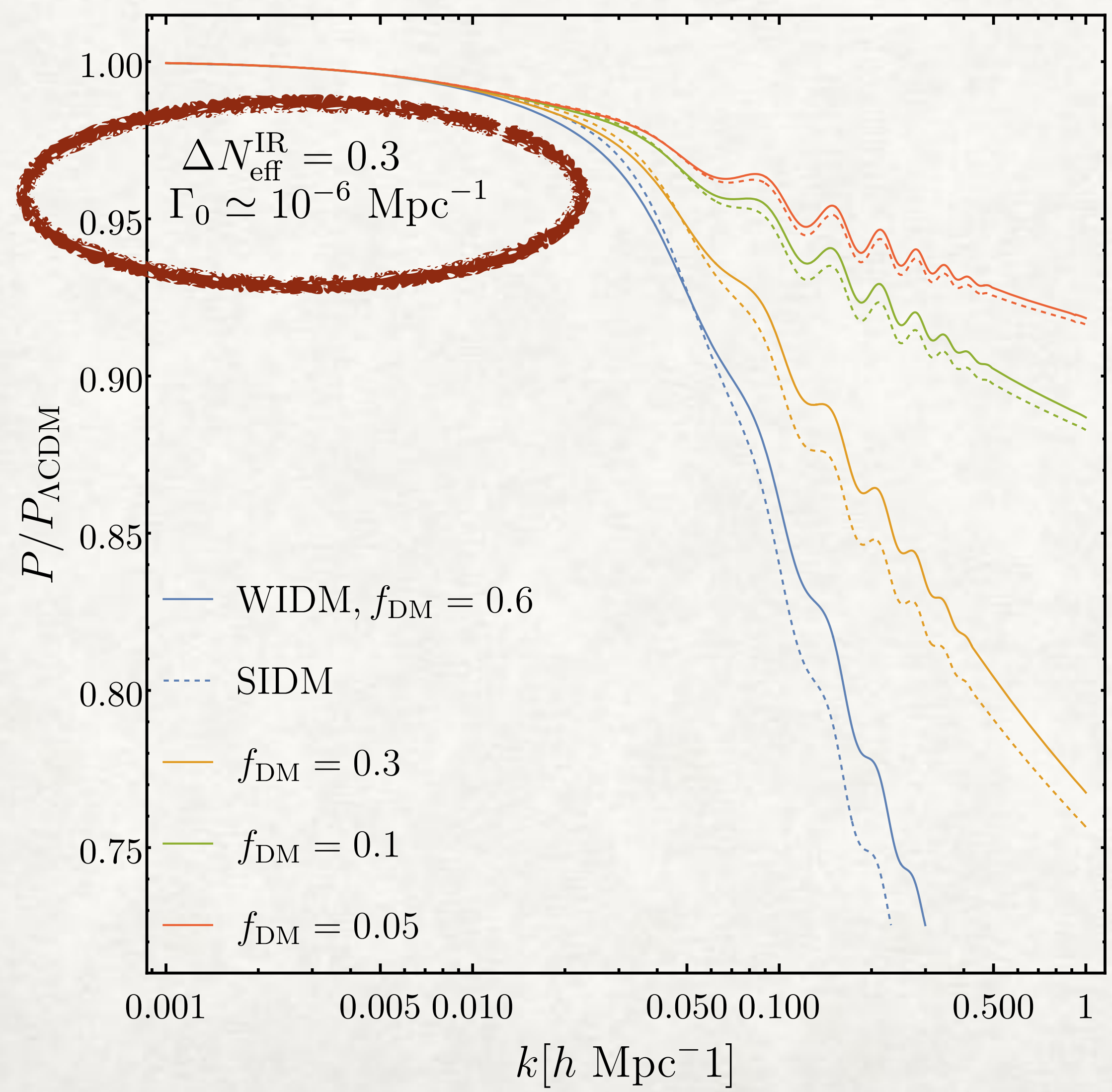
For $z \gg z_t$

$f_{\mathrm{DM}} \equiv$

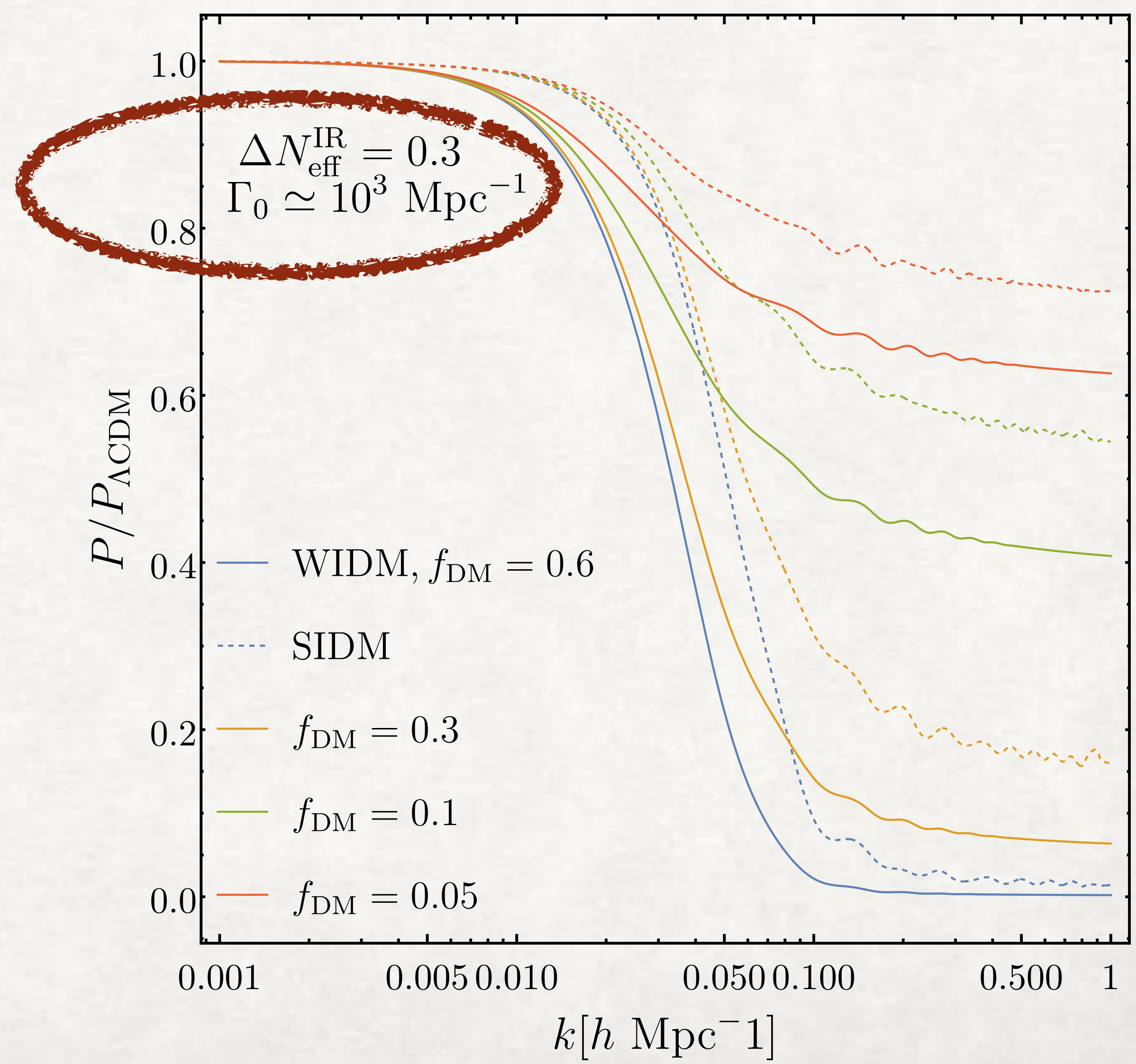
Interacting fraction of CDM

$$\frac{\Gamma}{H} \sim \frac{\Gamma_0}{10^{-6}\,\mathrm{Mpc}^{-1}} \left(\frac{\Delta N_{\mathrm{eff}}^{\mathrm{IR}}}{0.3}\right)^{1/2} \left(\frac{2}{g_*^{\mathrm{IR}}}\right)^{1/2}$$

Barely efficient, similar suppression



Efficient at early times, different suppression



CONSTRAINTS FROM CMB+LSS

	$\log_{10}\Gamma_0 \in [-9,-5]$	$\log_{10}\Gamma_0 \in [-2,6]$
Parameter	WIDM	SIDM
$\Delta N_{\rm eff}^{\rm IR}$	< 0.531 (0.092)	< 0.519 (0.268)
$\log_{10} z_t$	Unconstrained (4.18)	Unconstrained (4.38)
r_g	Unconstrained (4.87)	Unconstrained (4.39)
$\log_{10}\Gamma_0$	< -6.156 (-8.231)	< 4.259 (3.723)
$\log_{10} f_{\rm DM}$	Unconstrained (-0.806)	< -2.031 (-3.903)
H_0 [km/s/Mpc]	$68.97\ (68.37)^{+0.65}_{-1.1}$	$68.96\ (69.45)^{+0.67}_{-1.1}$
S_8	$0.818\ (0.826)^{+0.011}_{-0.011}$	$0.820\ (0.828)^{+0.011}_{-0.011}$
M_b	$-19.379\ (-19.396)^{+0.019}_{-0.031}$	$-19.380\ (-19.364)^{+0.020}_{-0.032}$
$\Delta\chi^2$	-0.63	-1.04
$Q_{\rm DMAP}^{S_8}$	2.75σ	2.55σ
S_8 GT	2.82σ	2.89σ
S_8 IT	2.63σ	2.65σ
$\Delta{\rm AIC}^{S_8}$	7.9	6.43

CONSTRAINTS FROM CMB+LSS

Model has 2 extra parameters in addition to stepped DR (5 total)

Priors	$\log_{10}\Gamma_0 \in [-9,-5]$	$\log_{10}\Gamma_0 \in [-2,6]$
Parameter	WIDM	SIDM
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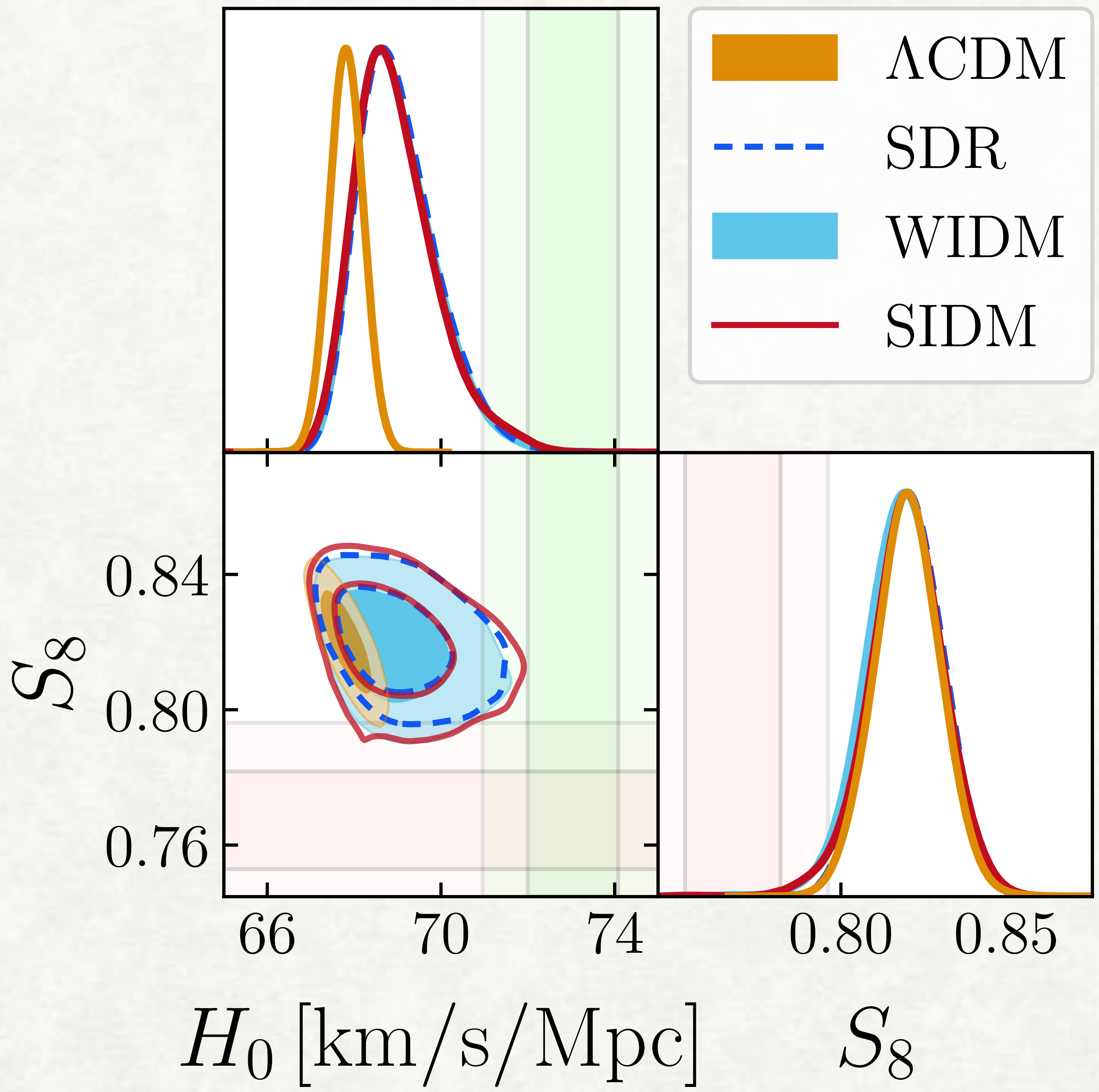
Strong bound on interacting DM fraction in SIDM (<1%)

IMPACT ON S8



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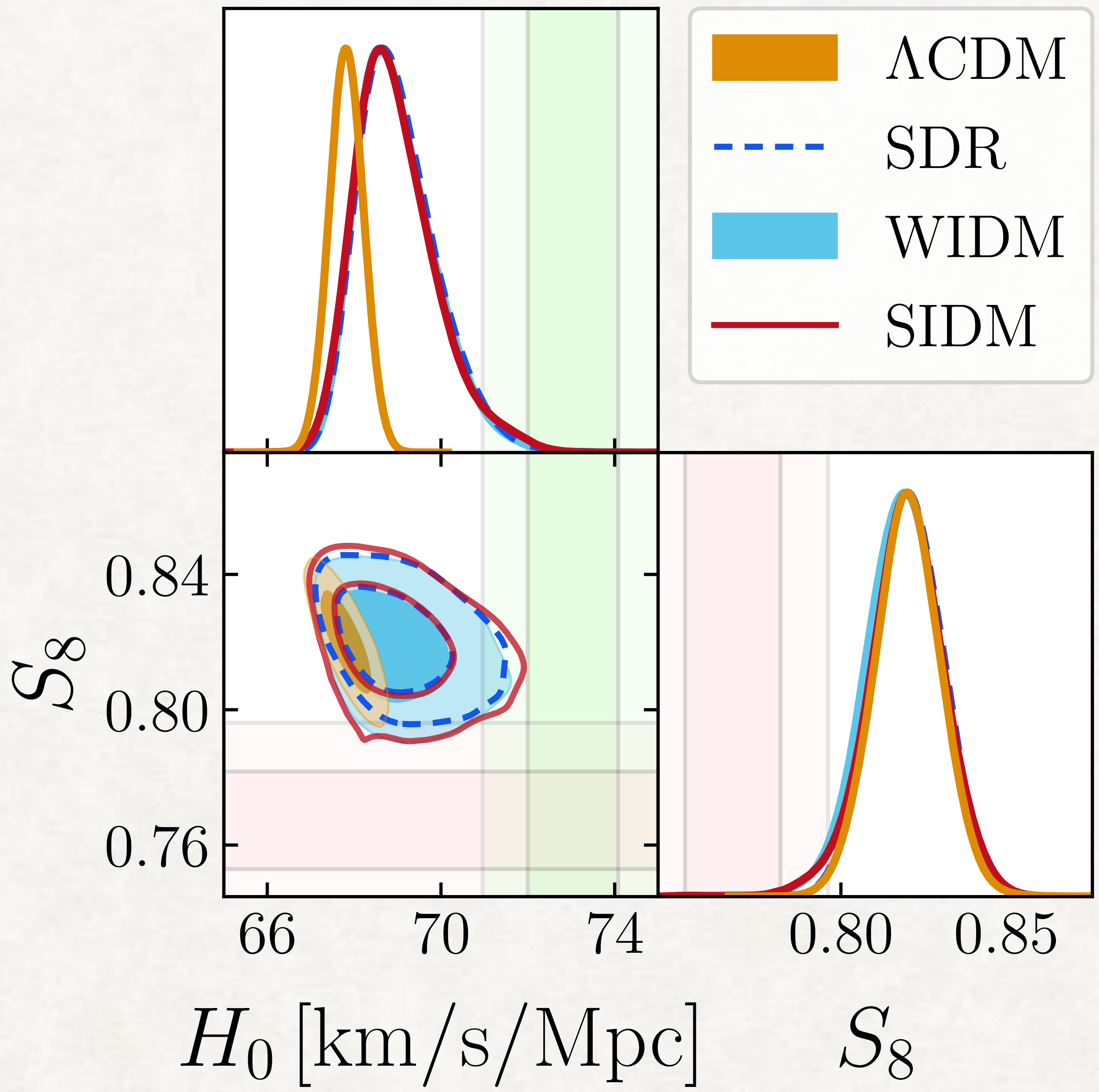

Old KiDS+DES measurement

Minor impact on S8 w.r.t. model w/o interactions

SUMMARY

Interacting sectors with mass thresholds are interesting examples of more complex (realistic) dark sectors

Provide way to alleviate constraints on $\Delta N_{\rm eff}$

CMB+LSS data constrain model ability to address tension(s)

BACK-UP SLIDES

Joseph, Aloni, Schmaltz, Sivarajan, Weiner 22

ADDING INTERACTIONS WITH CDM

$$\dot{\theta}_{\rm sdr} = -\mathcal{H}(1-3w)\theta_{\rm sdr} - \frac{\dot{w}}{1+w}\theta_{\rm sdr} + \frac{\delta P/\delta\rho}{1+w}k^2\delta_{\rm sdr} + a\Gamma\frac{\rho_{\rm idm}}{\rho_{\rm sdr}(1+w)}(\theta_{\rm sdr}-\theta_{\rm idm})$$

$$\dot{\theta}_{\rm idm} = -\mathcal{H}\theta_{\rm idm} + a\Gamma(\theta_{\rm sdr}-\theta_{\rm idm}),$$

Joseph, Aloni, Schmaltz, Sivarajan, Weiner 22

ADDING INTERACTIONS WITH CDM

Consider heavy CDM component (idm) to be interacting with light dark sector (sdr)

$$\dot{\theta}_{\rm sdr} = -\mathcal{H}(1-3w)\theta_{\rm sdr} - \frac{\dot{w}}{1+w}\theta_{\rm sdr} + \frac{\delta P/\delta\rho}{1+w}k^2\delta_{\rm sdr} + a\Gamma\frac{\rho_{\rm idm}}{\rho_{\rm sdr}(1+w)}(\theta_{\rm sdr}-\theta_{\rm idm})$$

$$\dot{\theta}_{\rm idm} = -\mathcal{H}\theta_{\rm idm} + a\Gamma(\theta_{\rm sdr}-\theta_{\rm idm}),$$

Motivation from S8: suppression of matter power spectrum

However: *(2-3)sigma tension on S8 between weak lensing and CMB severely reduced with new KiDS+DES analysis…*

Independently, can put constraints

PRIOR DEPENDENCE

Parameter	SIDR	SDR (i)	SDR (ii)
$\Delta N_{\rm eff}^{\rm IR}$	< 0.456 (95% CL)	< 0.597 (0.551)	< 0.546 (0.289)
H_0 [km/s/Mpc]	$68.95\ (68.38)^{+0.73}_{-1.2}$	$69.30\ (70.68)^{+0.86}_{-1.3}$	$68.89\ (69.34)^{+0.71}_{-1.1}$
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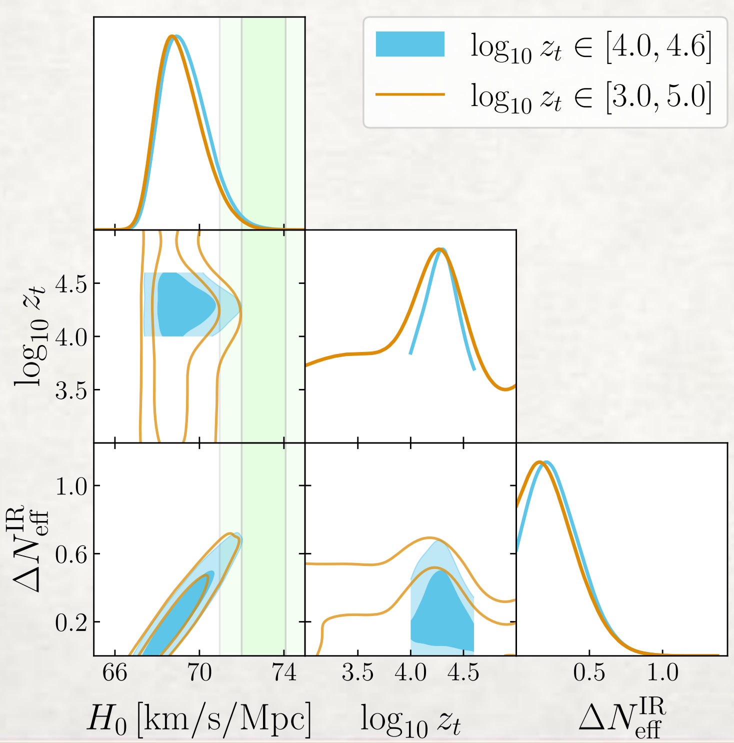
$\Delta\chi^2$	-0.22	-0.41	-1.4
$Q_{\rm DMAP}^{M_b}$	3.48σ	2.55σ	2.74σ
M_b GT	3.66σ	3.12σ	3.74σ
M_b IT	2.95σ	2.56σ	3.03σ
$\Delta{\rm AIC}^{M_b}$	-18.88	-22.67	-20.67



$$(i)\ r_g\ \text{fixed}, \log_{10} z_t \in [4.0, 4.6]$$

$$(ii)\ r_g\ \text{free}, \log_{10} z_t \in [3.0, 5.0]$$

$$\gtrsim 3\sigma$$

PRIOR DEPENDENCE

Planck18+BAO+Pantheon

	W/o threshold	*W/ threshold*	
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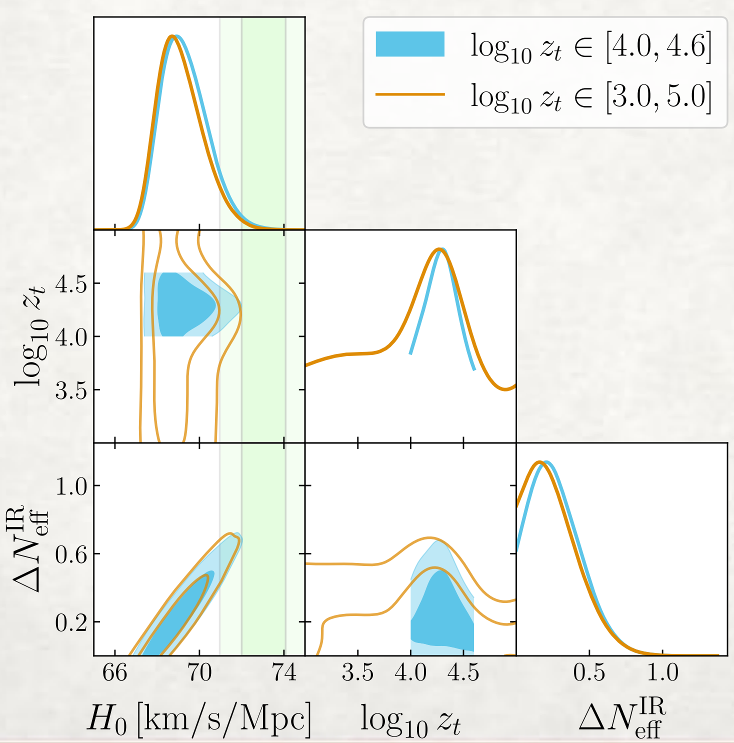

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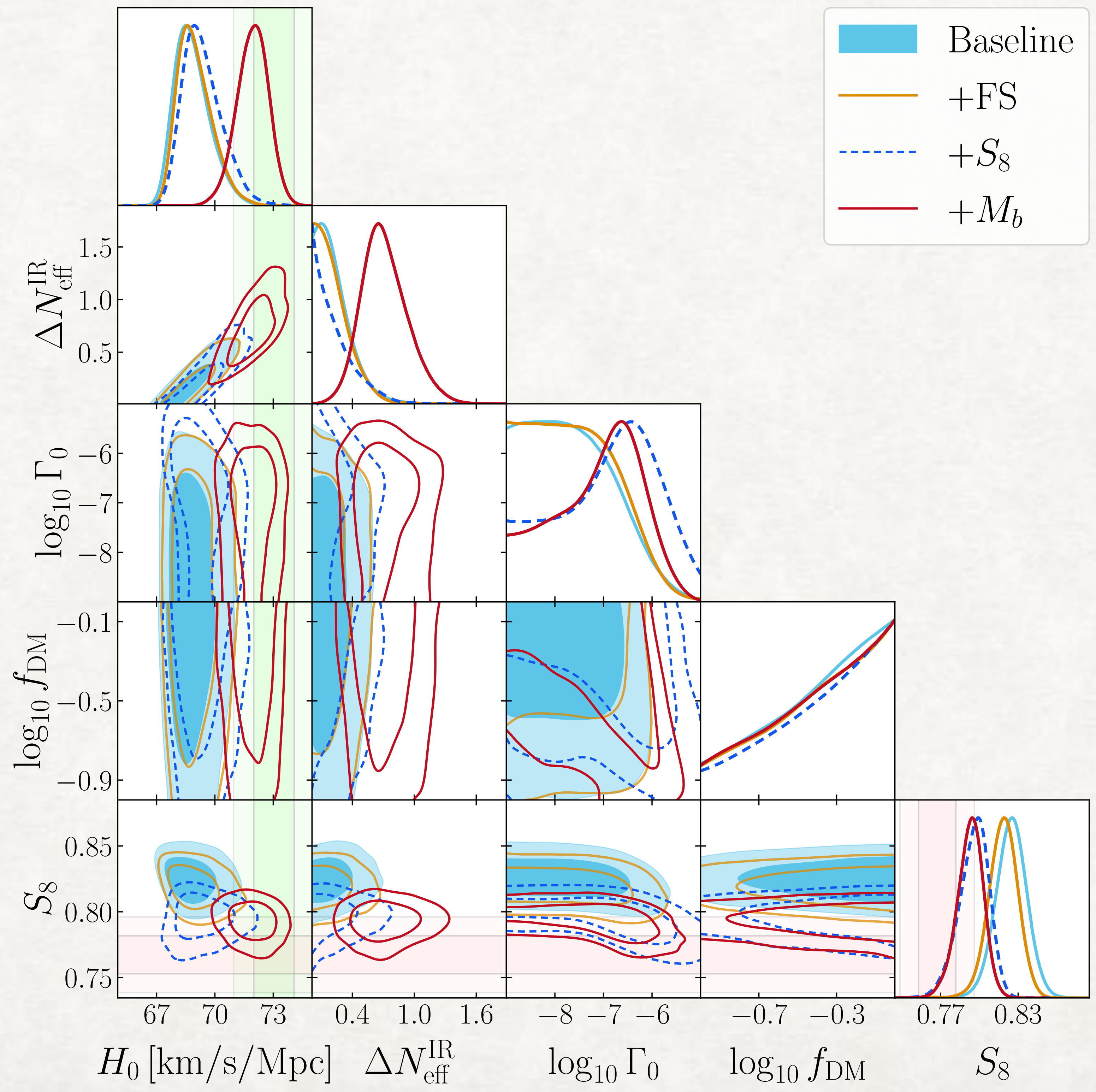
$$(ii)\ r_g\ \text{free}, \log_{10} z_t \in [3.0, 5.0]$$

Better fit, increased tensions

$$\gtrsim 3\sigma$$

WIDM POSTERIORS



SIDM POSTERIORS