# HOT QCD AXION PRODUCTION IN THE EARLY UNIVERSE

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*based on*

2211.03799 w/ A. Notari, G. Villadoro, to appear on PRL

NPKI, Busan, 06/06/2023

*Background from Forbes/GETTY*

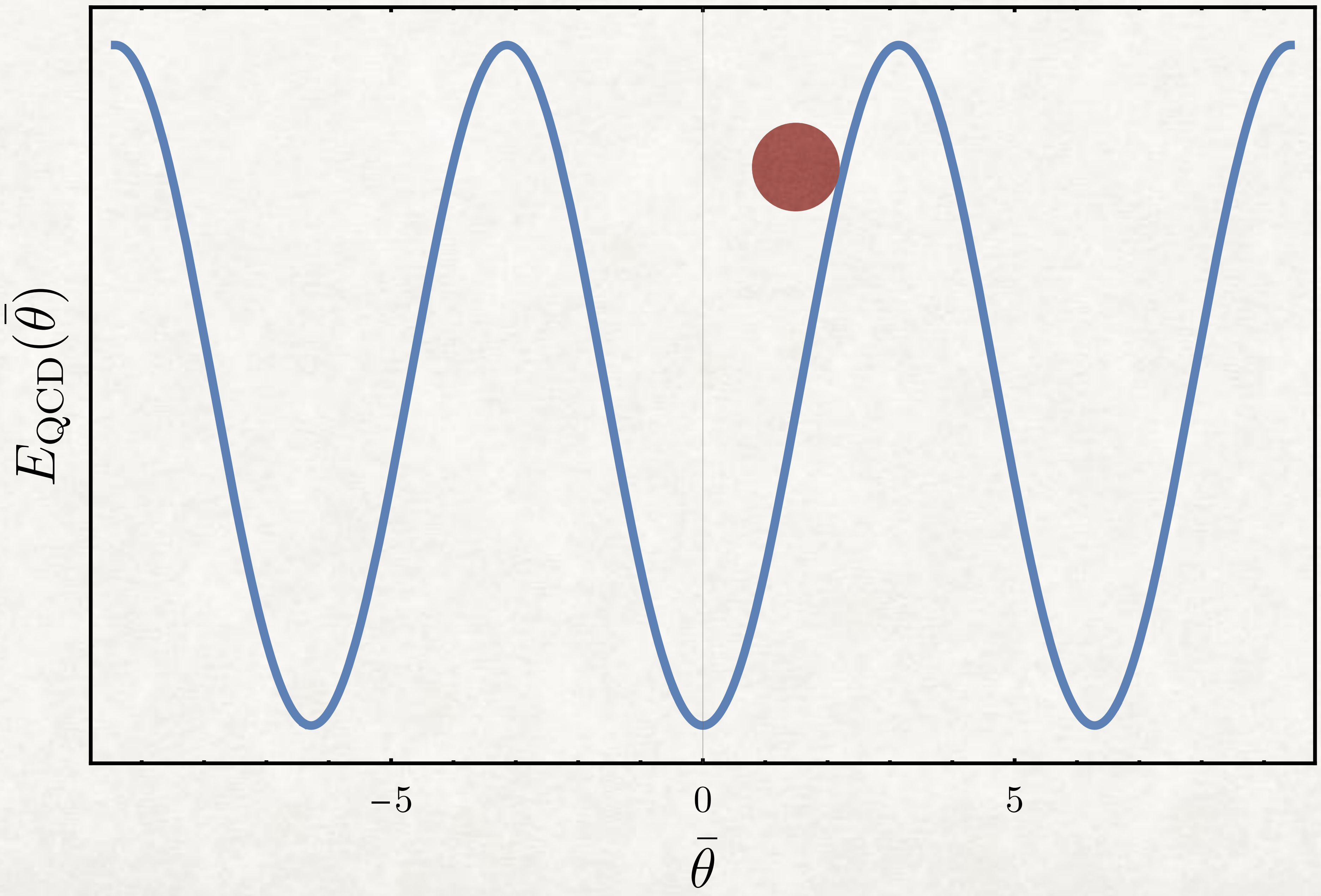
MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea

*See also talks by Surjeet, Tony, Sungwoo, Gongjun, Raffaele, Michael, Maximilian, Jeff*

# THE QCD AXION

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



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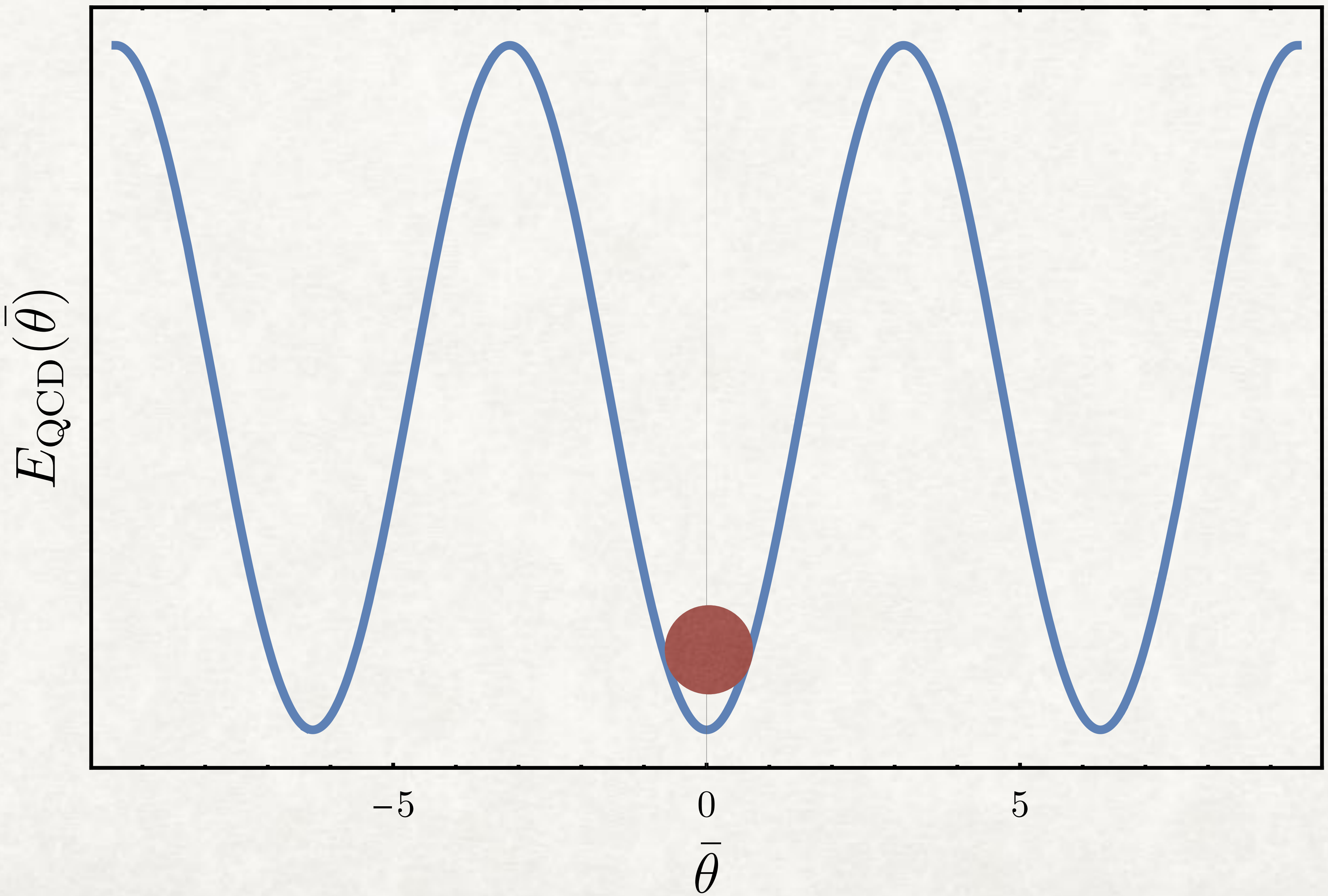

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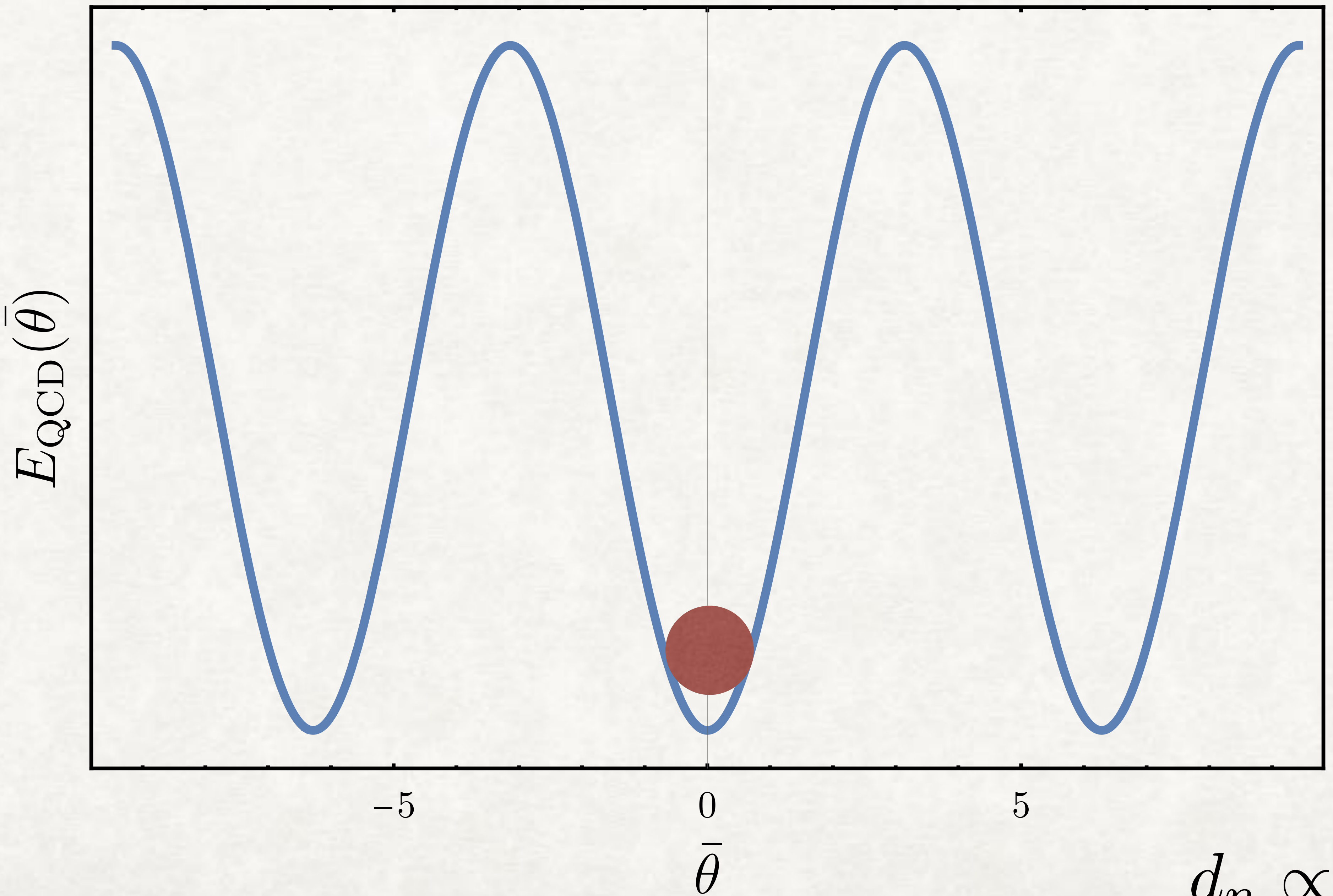



$$d_n \propto \bar{\theta} \to 0$$

For heavy QCD axion,
See talk by Tony!

# THE QCD AXION

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{\alpha_s}{8\pi}\frac{a(t,\mathbf{x})}{f_a}G\tilde{G} + \mathcal{L}_{\rm int}(\partial_\mu a, q, l) + \frac{1}{4}c_\gamma^0 aF\tilde{F}$$

For leptons,
See talk by Jeff!

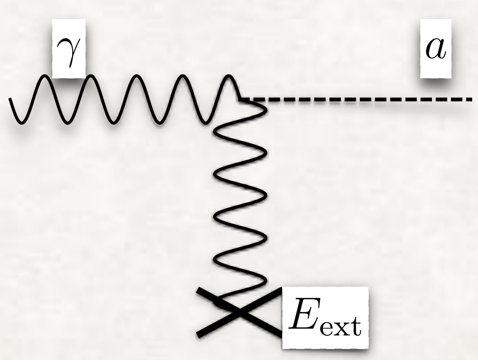
**From production in stellar environments**

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

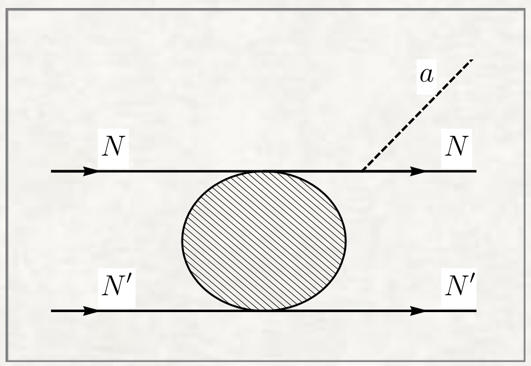
**Makes it challenging to detect in labs**

See talk by Surjeet, Raffaele

**Ayala+ 14/ Dolan+ 22**




**Raffelt 90/...**




From di Luzio+ Phys. Rep. 20

*Stronger model-dependent bounds when coupling to electrons is present*

***Caveat on stellar constraints:*** *significant uncertainties, active current debate*

Chang+ 18/Bar+19/Carenza+20

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**Model independent**
**(Minimal model)**
**Focus of this talk**

**Model dependent**
**(Can be vanishing in the UV)**

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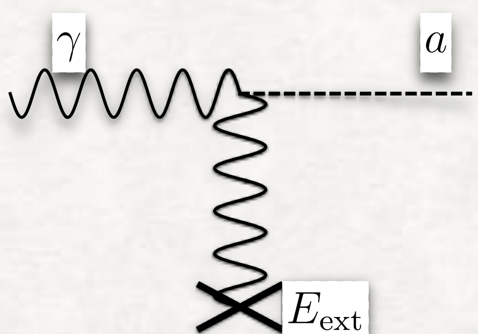


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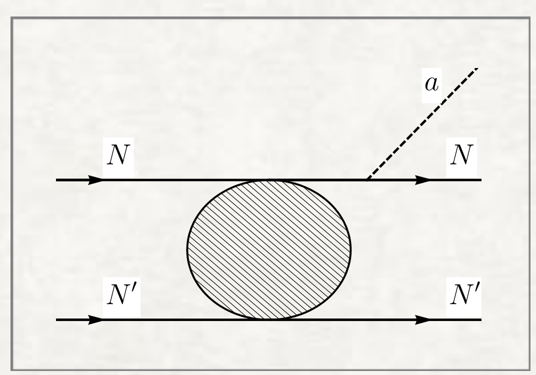


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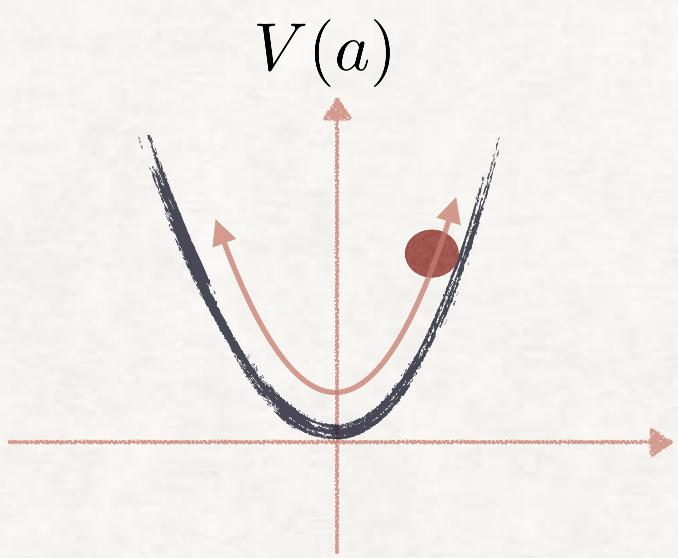
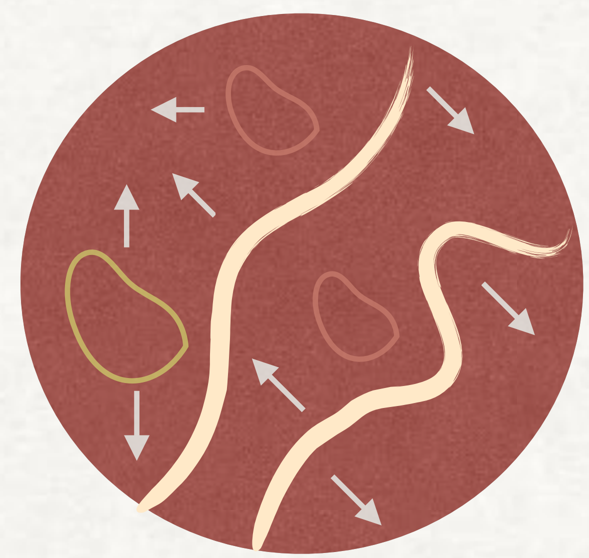
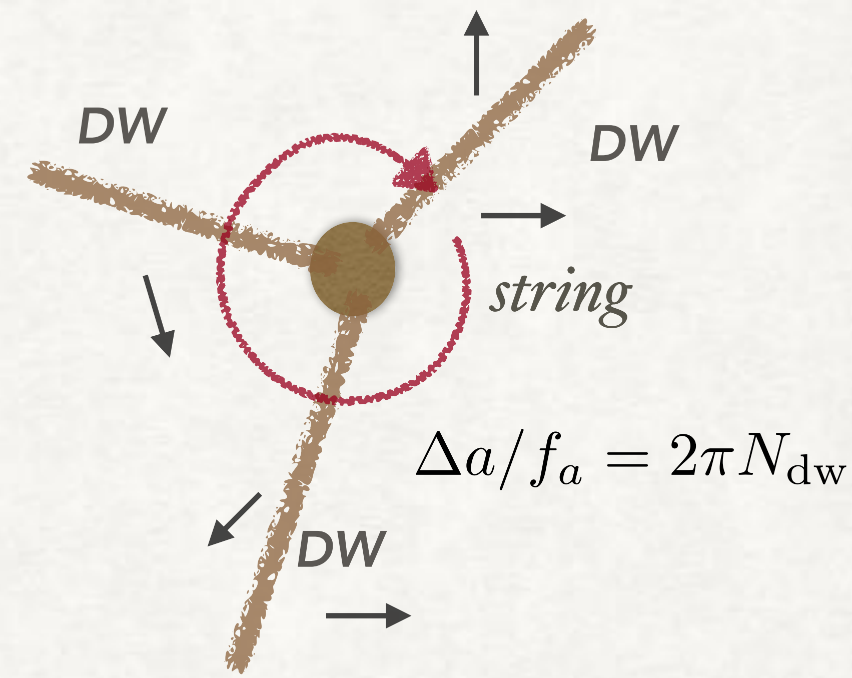
# COLD DARK MATTER

***Non-relativistic population*** *of QCD axion particles is produced in the early Universe via* ***non-thermal processes***




*Misalignment mechanism*






*Decay of topological strings and domain walls (DWs)*

*At production*

$$k_a \ll T$$

*see Gorghetto, Hardy, Villadoro 18, 20*

# DETECTING THE QCD AXION

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***i.e. axion does not need to be the dark matter!***

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***i.e. axion does not need to be the dark matter!***

*2. Depends on **axion local distribution today***

*Even if it is the dark matter,*
*it might be mostly distributed in **dense "Miniclusters/halos"**,*
*with **negligible density around us***

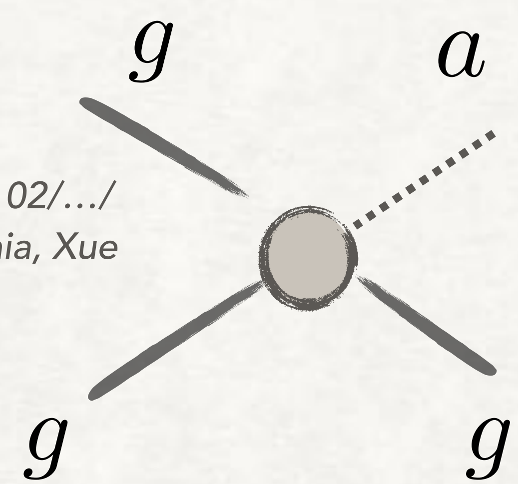
*Hogan, Rees 98*

# A COMPLEMENTARY COSMOLOGICAL PRODUCTION CHANNEL

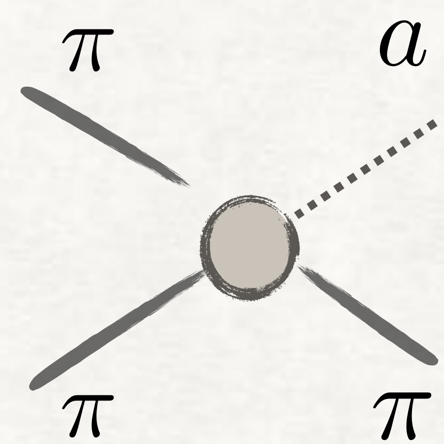
*Turner 88/*
*Berezhiani et al 92/*

*Coupling to QCD **predicts** production of QCD axions via scatterings with the Standard Model (+?) thermal bath*

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




***At weak coupling, production dominated by 2-2 processes***




*Chang, Choi 93/...*

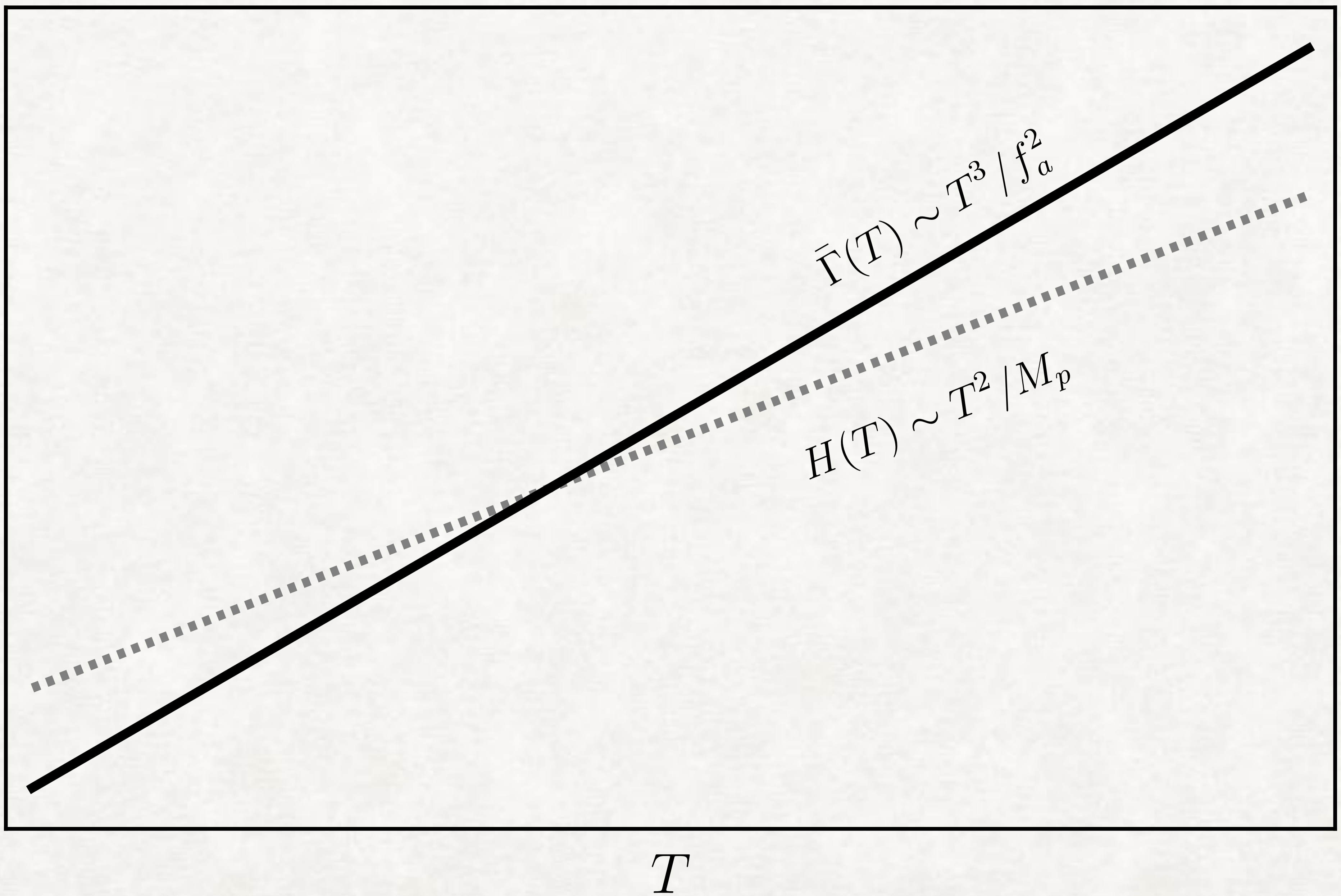
<ins>*QCD CROSSOVER*</ins>


*At production* $k_a \sim T \gg m_a \simeq 0.6\ \mathrm{meV} \left( \frac{10^{10}\ \mathrm{GeV}}{f_a} \right)$

# HOT AXION PRODUCTION

$$1, 2 \to 3, a$$

$$\bar{\Gamma} \sim \frac{n_{\mathrm{eq},1} n_{\mathrm{eq},2}}{n_{\mathrm{eq,\ a}}} \langle \sigma v \rangle$$



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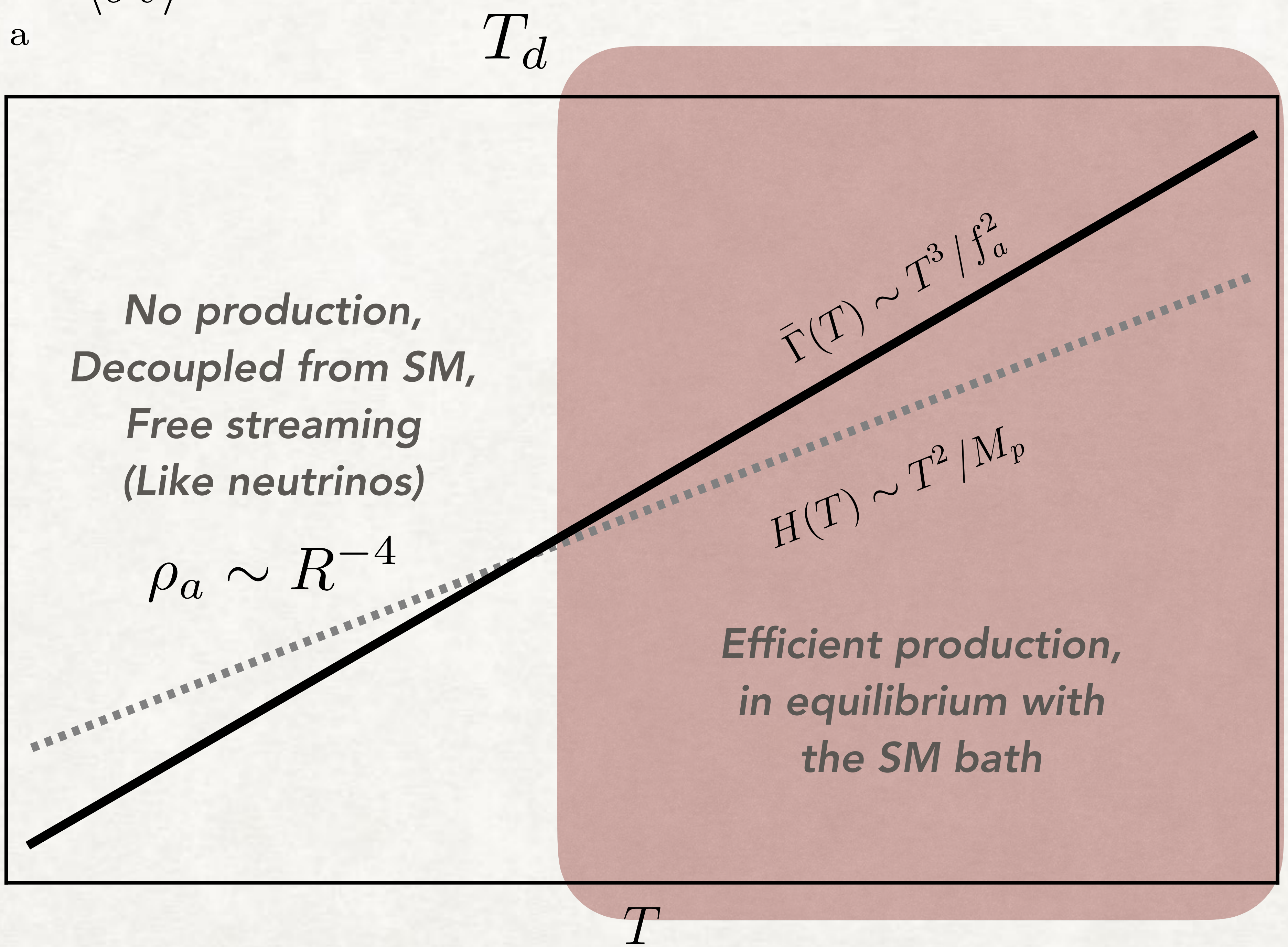
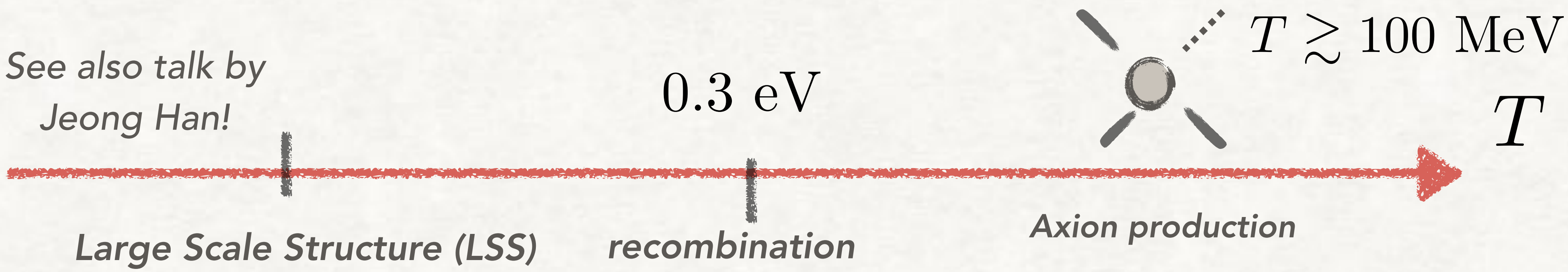



$R(T) \equiv$

*Scale factor*

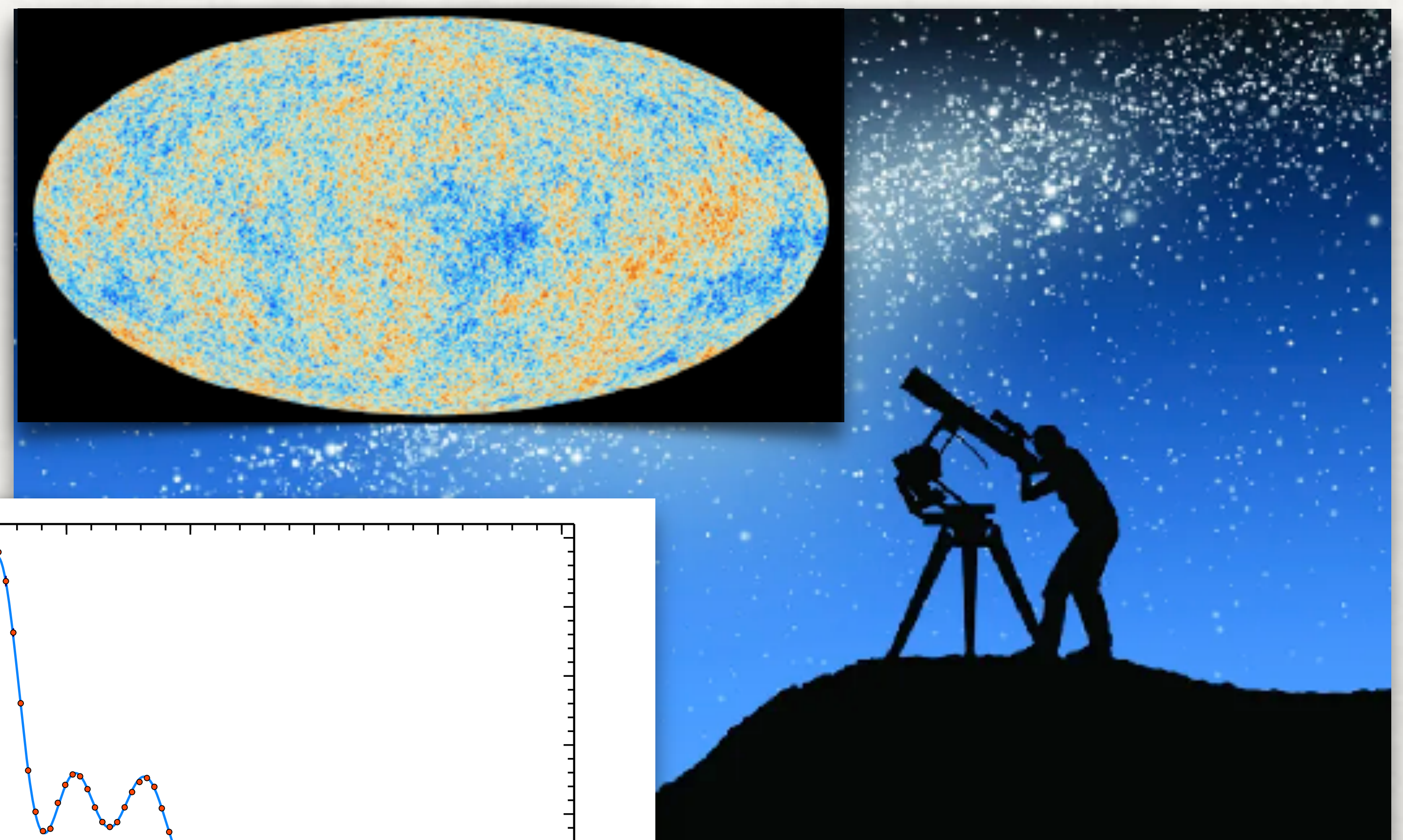
# DISCOVERING/CONSTRAINING THE QCD AXION AS A LIGHT RELIC

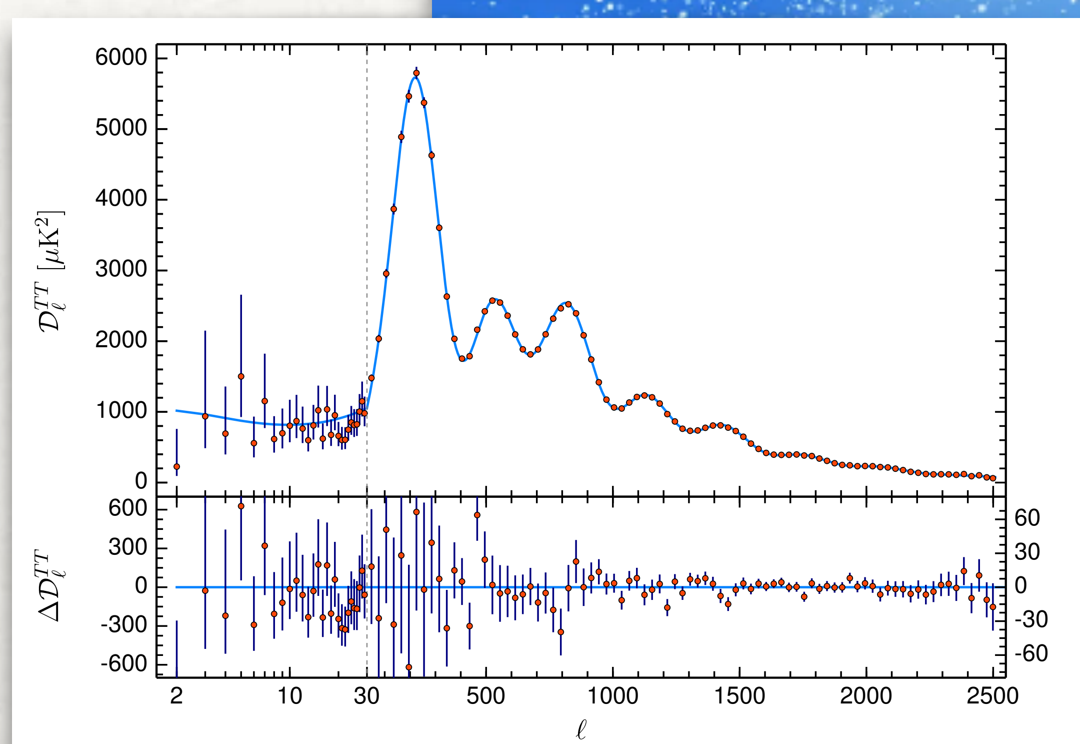
*See also talk by Jeong Han!*




**Cosmic Microwave Background (CMB)**

**(ESA, *Planck 18*)**






*Hot QCD axion population impacts* ***CMB anisotropies & LSS matter power spectrum***

# THE HOT QCD AXION AS A LIGHT RELIC

*Baumann+15*

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$$\boxed{m_a \ll 0.1\ \mathrm{eV} \Rightarrow f_a \gg 5 \cdot 10^7\ \mathrm{GeV}}$$

***Hot axions behave as free-streaming "dark radiation" (DR) at CMB epoch***

*"Effective number of neutrino species"*

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

*Changes expansion rate + induces phase shift of acoustic peaks*

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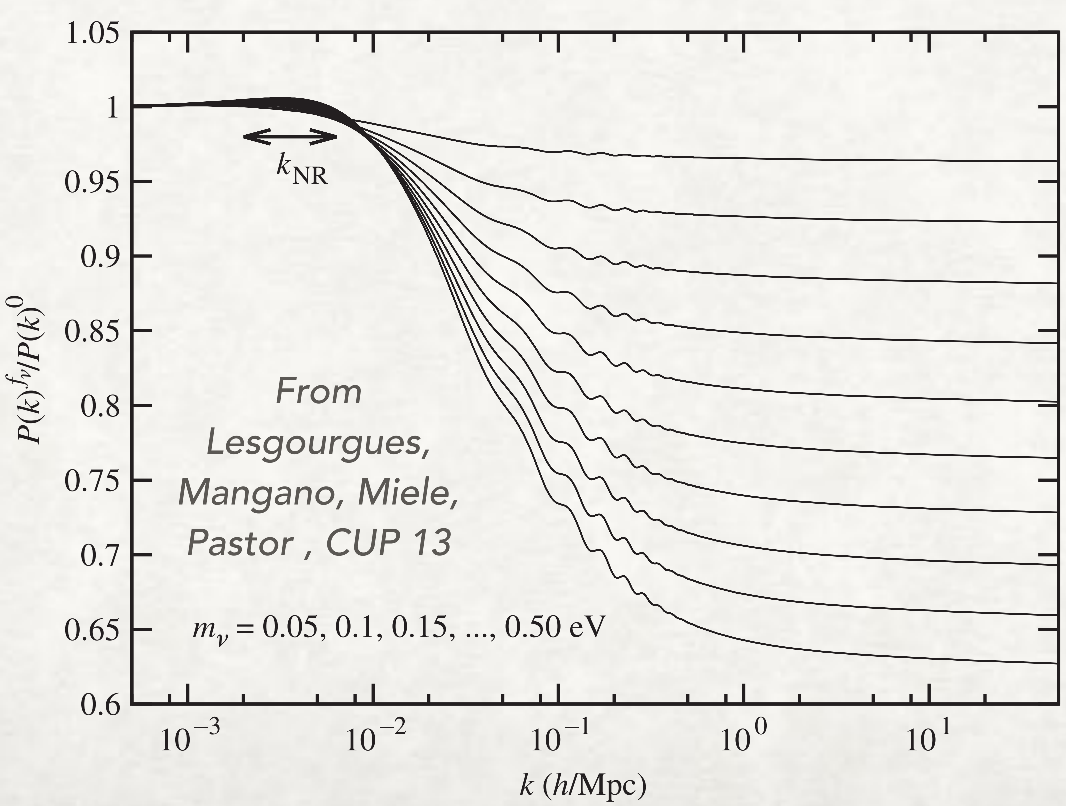



*From Lesgourgues, Mangano, Miele, Pastor , CUP 13*

$$m_a \gtrsim 0.1 \text{ eV} \Rightarrow f_a \lesssim 5 \cdot 10^7 \text{ GeV}$$

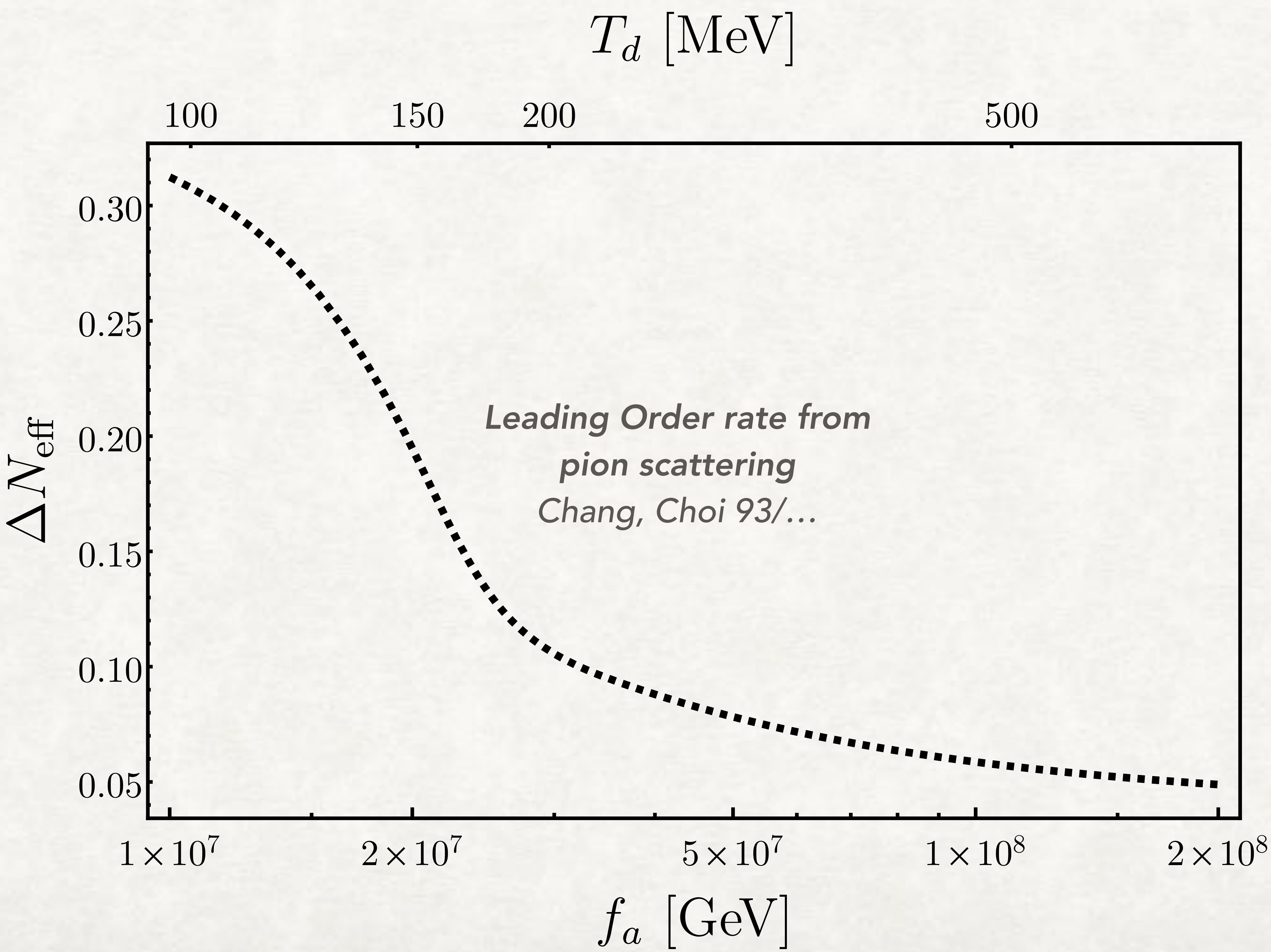
***Hot axions behave as "hot dark matter" (HDM) at CMB epoch***
*(Really just like neutrinos, cannot be the observed DM)*

*Additionally* ***suppresses matter fluctuations at small scales***

# FIRST ESTIMATE

*Number of relativistic degrees of freedom in the bath*

*For instantaneous decoupling from equilibrium*



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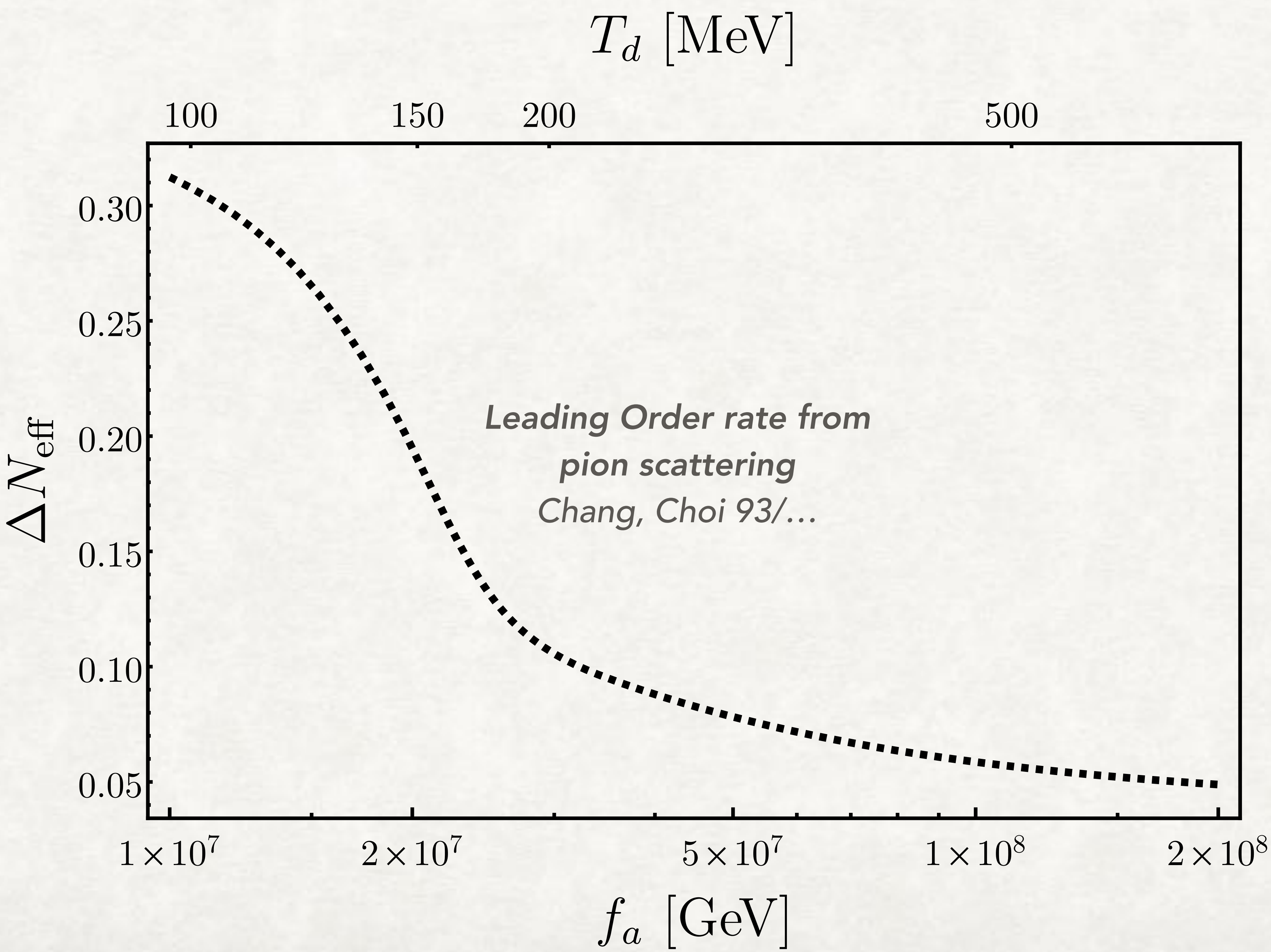

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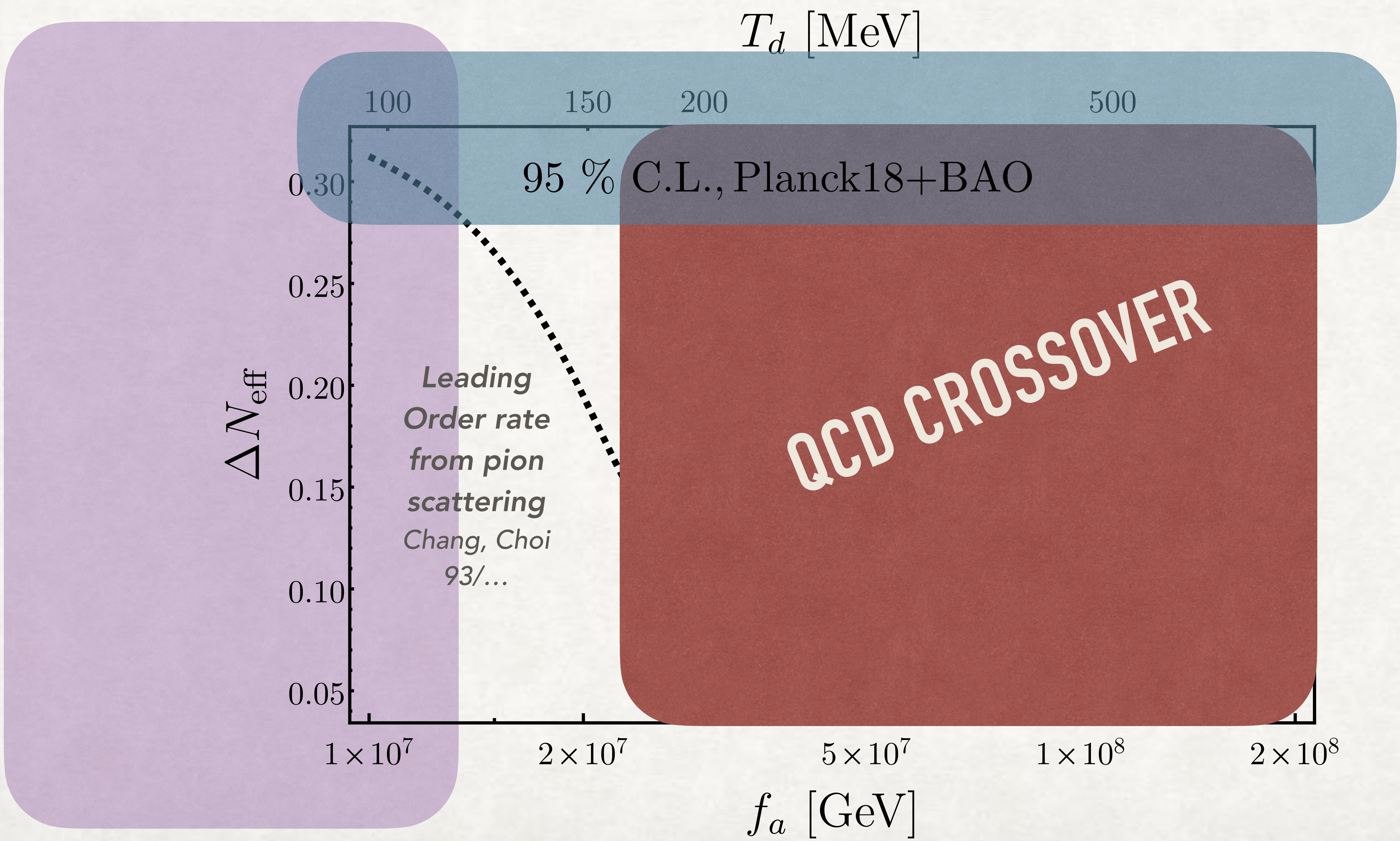

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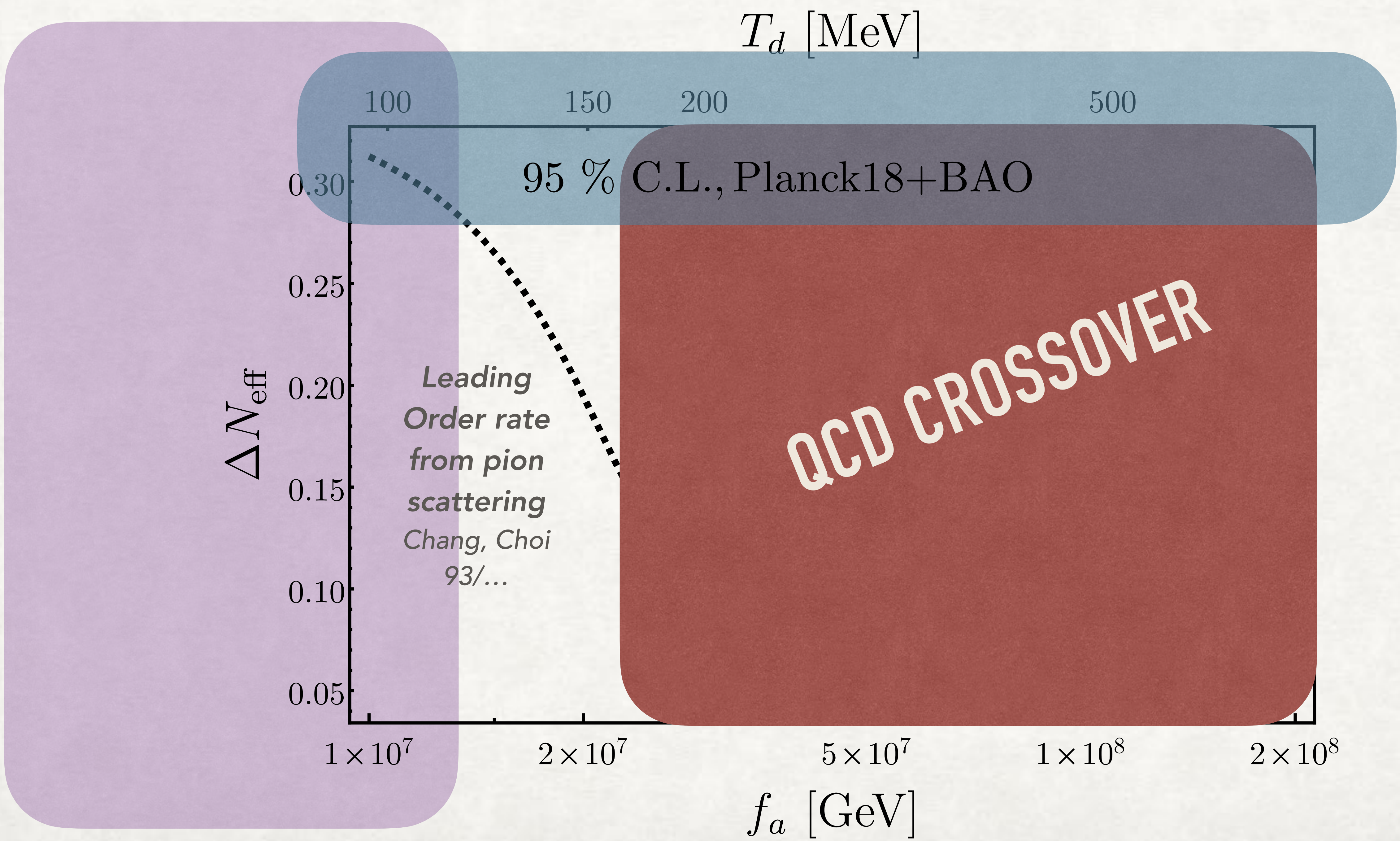


# THE HOT QCD AXION PROGRAM

*Obtain reliable theoretical prediction for hot QCD axion population*

*Constrain QCD axion with current CMB and LSS datasets*

*Forecast discovery potential of upcoming CMB and LSS surveys*

## KEY ADVANTAGES

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

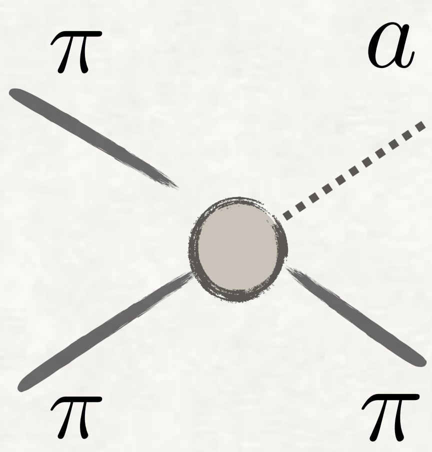
*Probes QCD axion **independently of cold dark matter** contribution*

*Relies on minimal coupling to QCD*
*(e.g. not model-dependent coupling to photons) +*
*Standard cosmology below decoupling*

***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*

# AXION PRODUCTION FROM PION SCATTERING



# BEYOND THE FIRST ESTIMATE

*Rate is computed at Leading Order (LO) in Chiral Perturbation Theory*

$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

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

*Used to set Hot Dark Matter Bound since the 00s, extending to T~200 MeV*

*Chang, Choi 93/Hannestad et al 05, 07/Melchiorri et al 07/Di Valentino et al 16*

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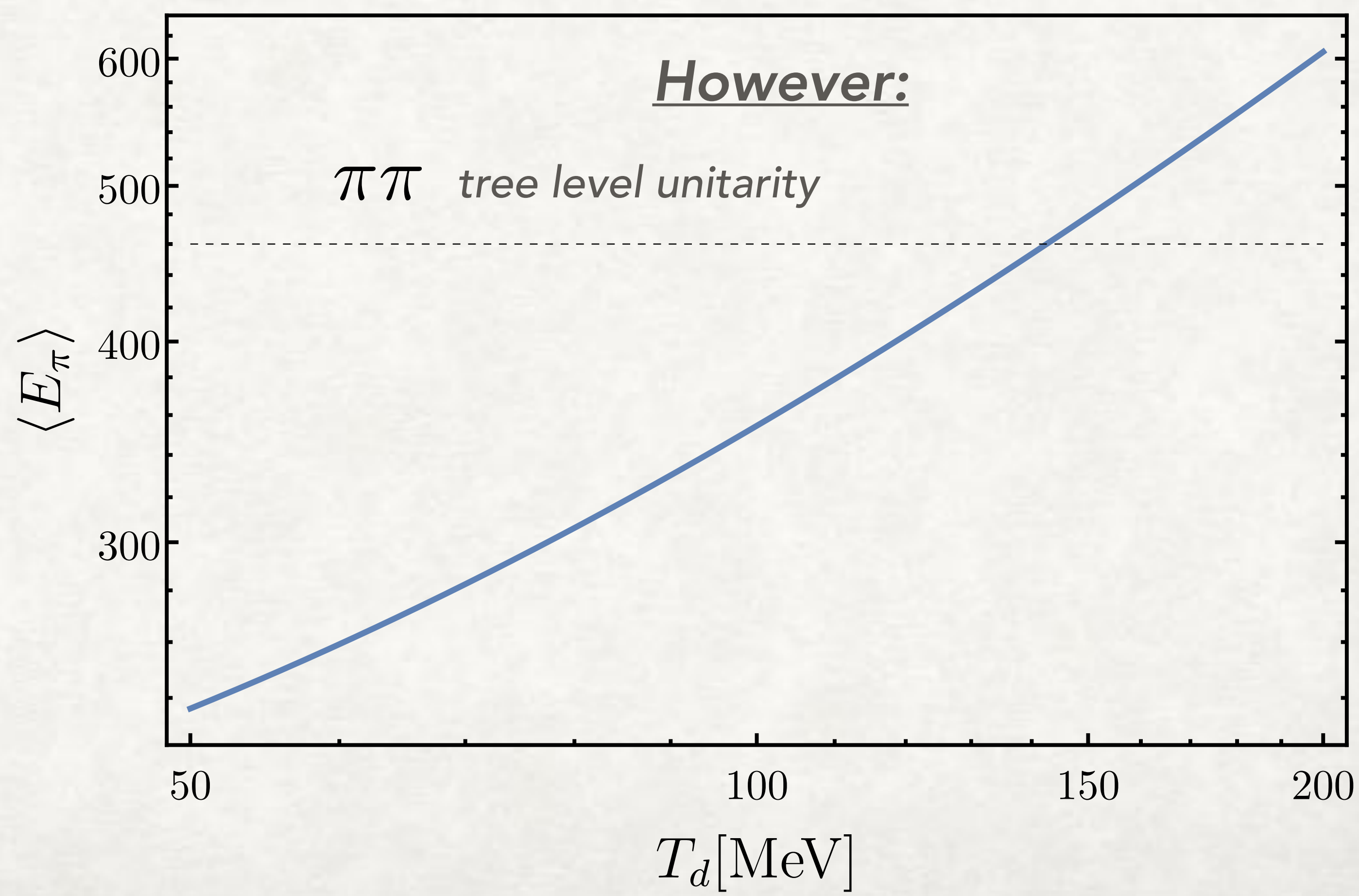

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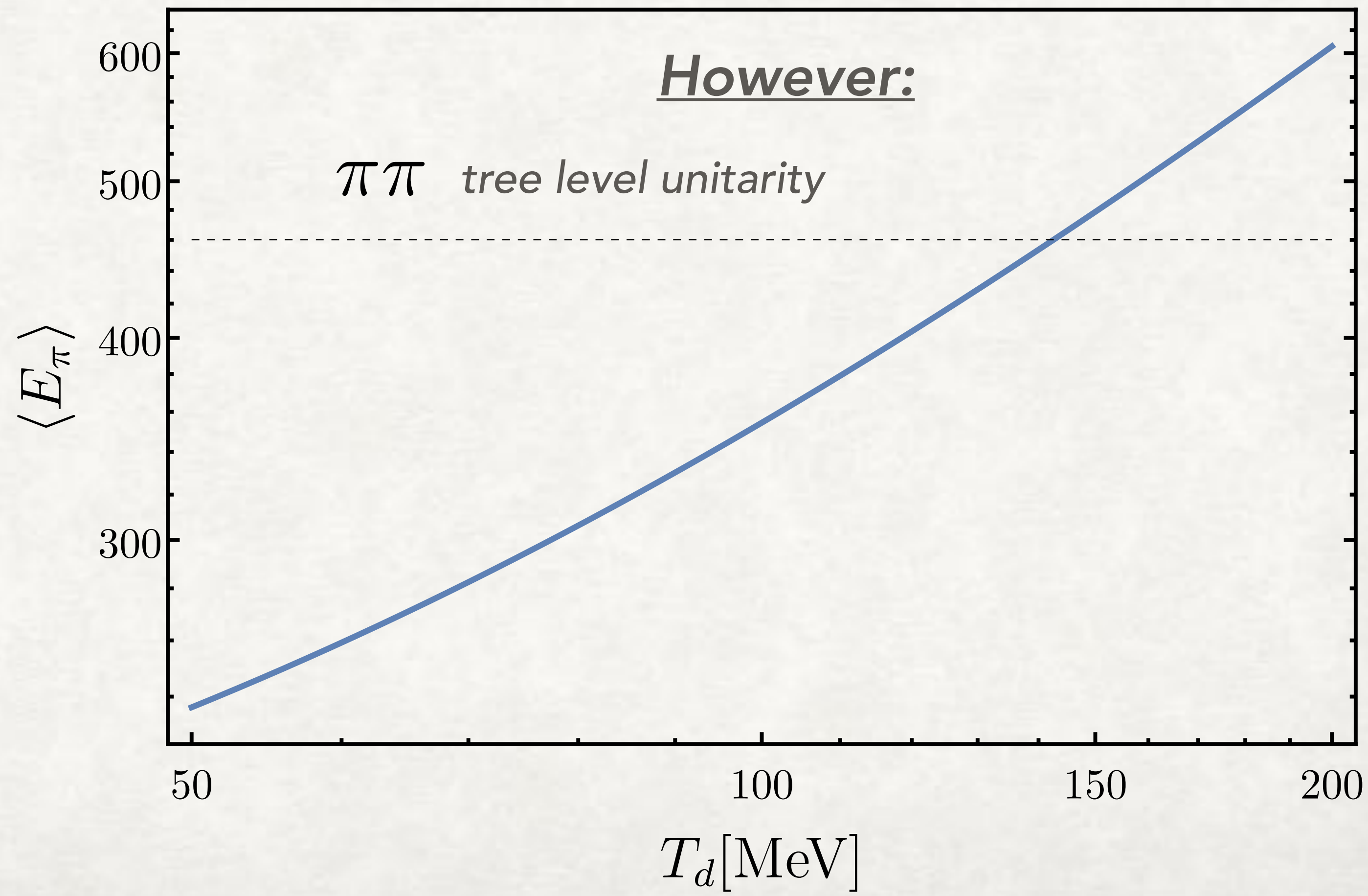
*Center of mass energies are above validity of LO rate already at T~70 MeV!*

*Di Luzio, Martinelli, Piazza 21*



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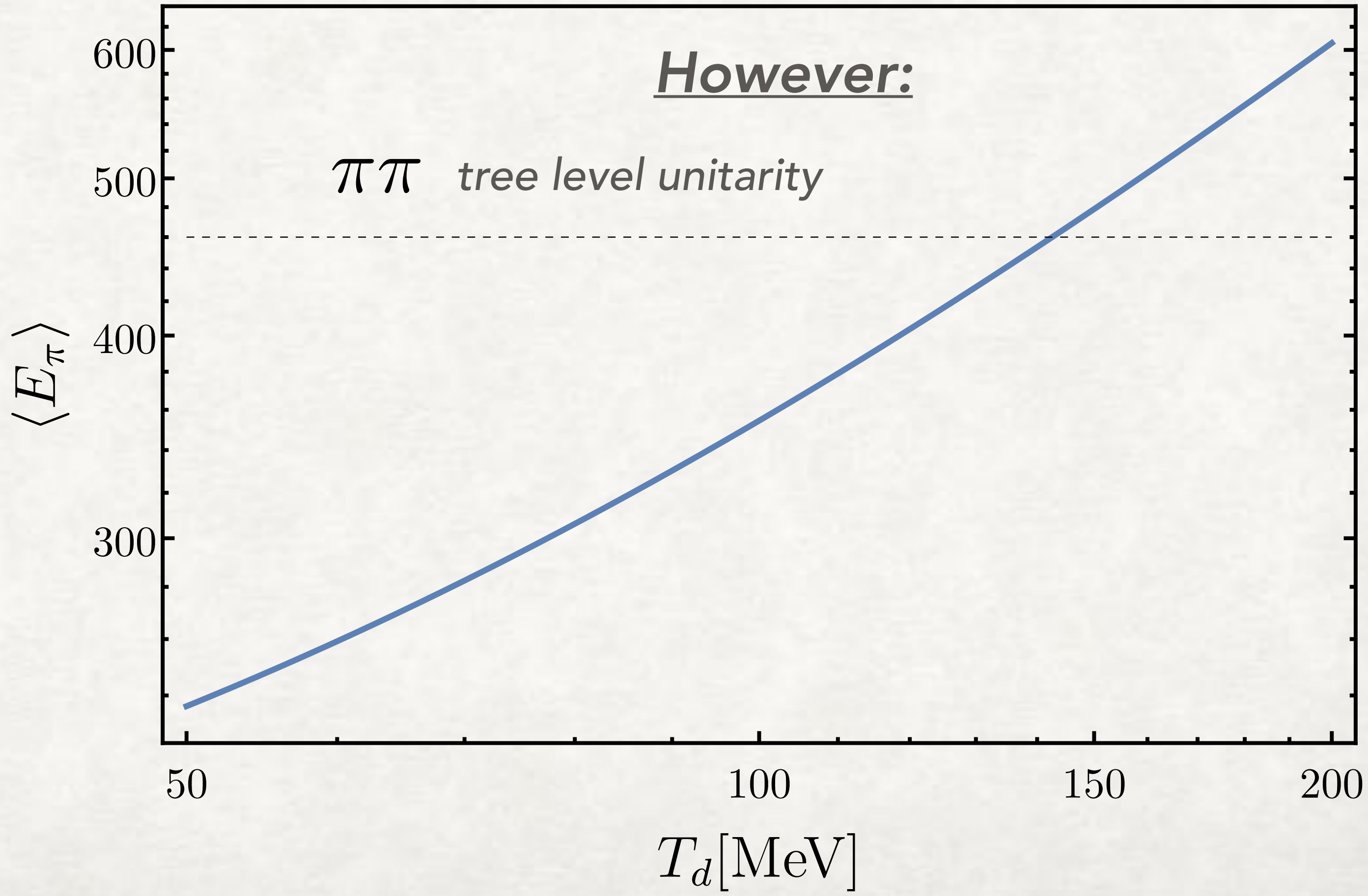
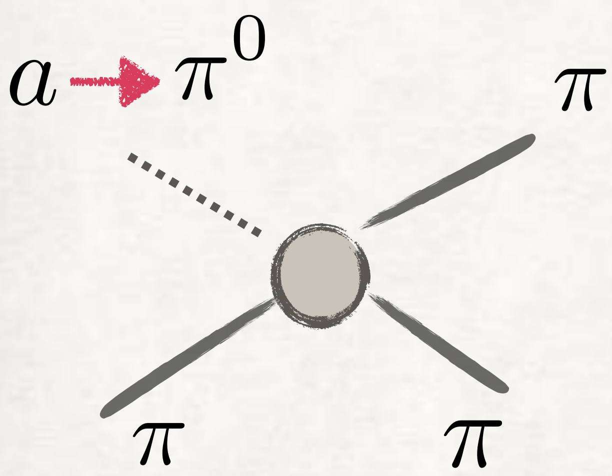
*Larger axion momenta count more!*



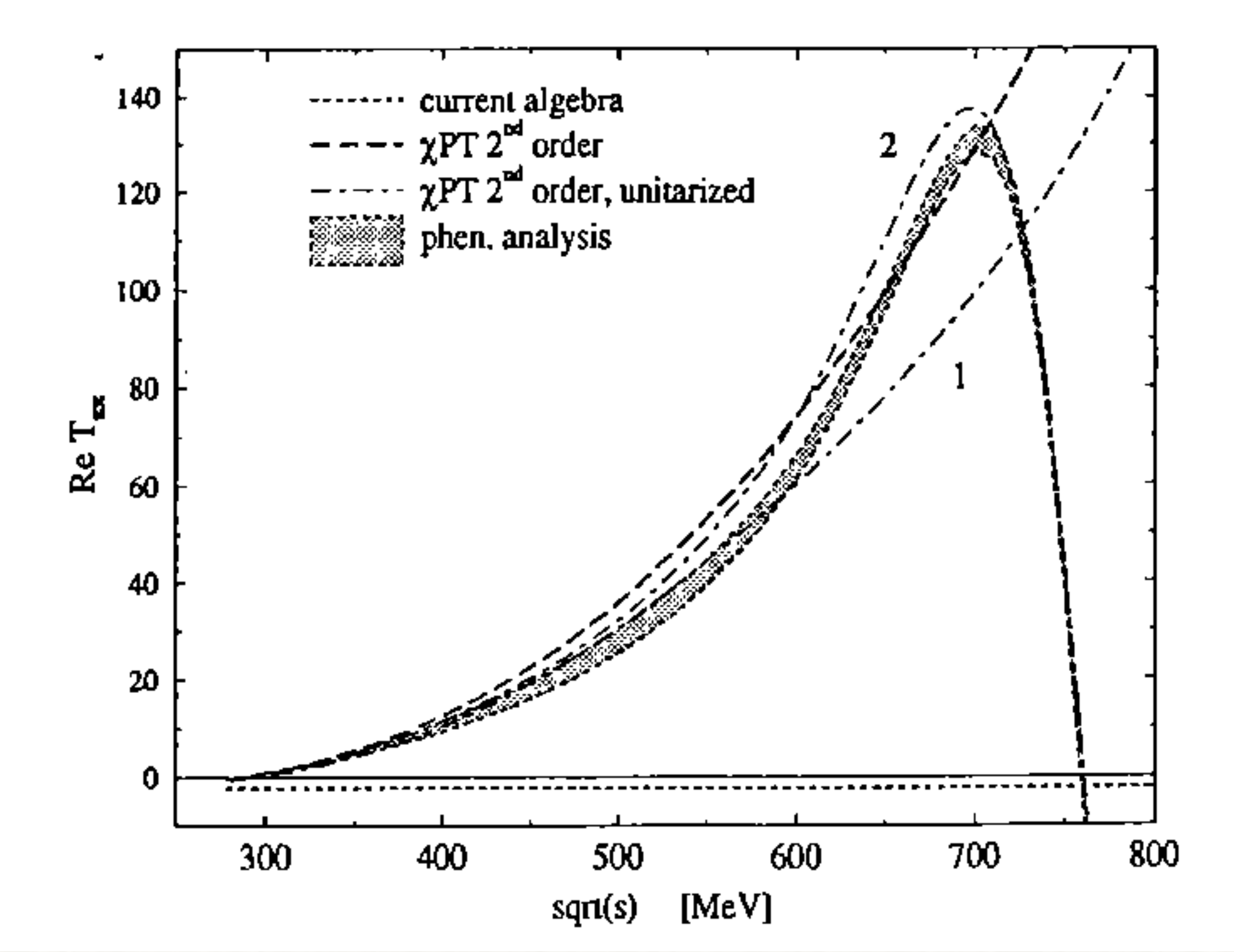
# LESSON FROM PIONS

Goity, Leutwyler 89/
Schenck 93/…

*The breakdown of ChPT is well known in pion-pion scattering*




*Forward scattering amplitude*




*Schenck 93*

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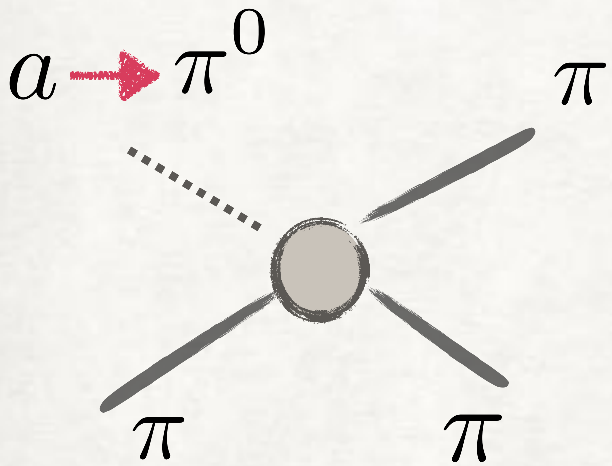


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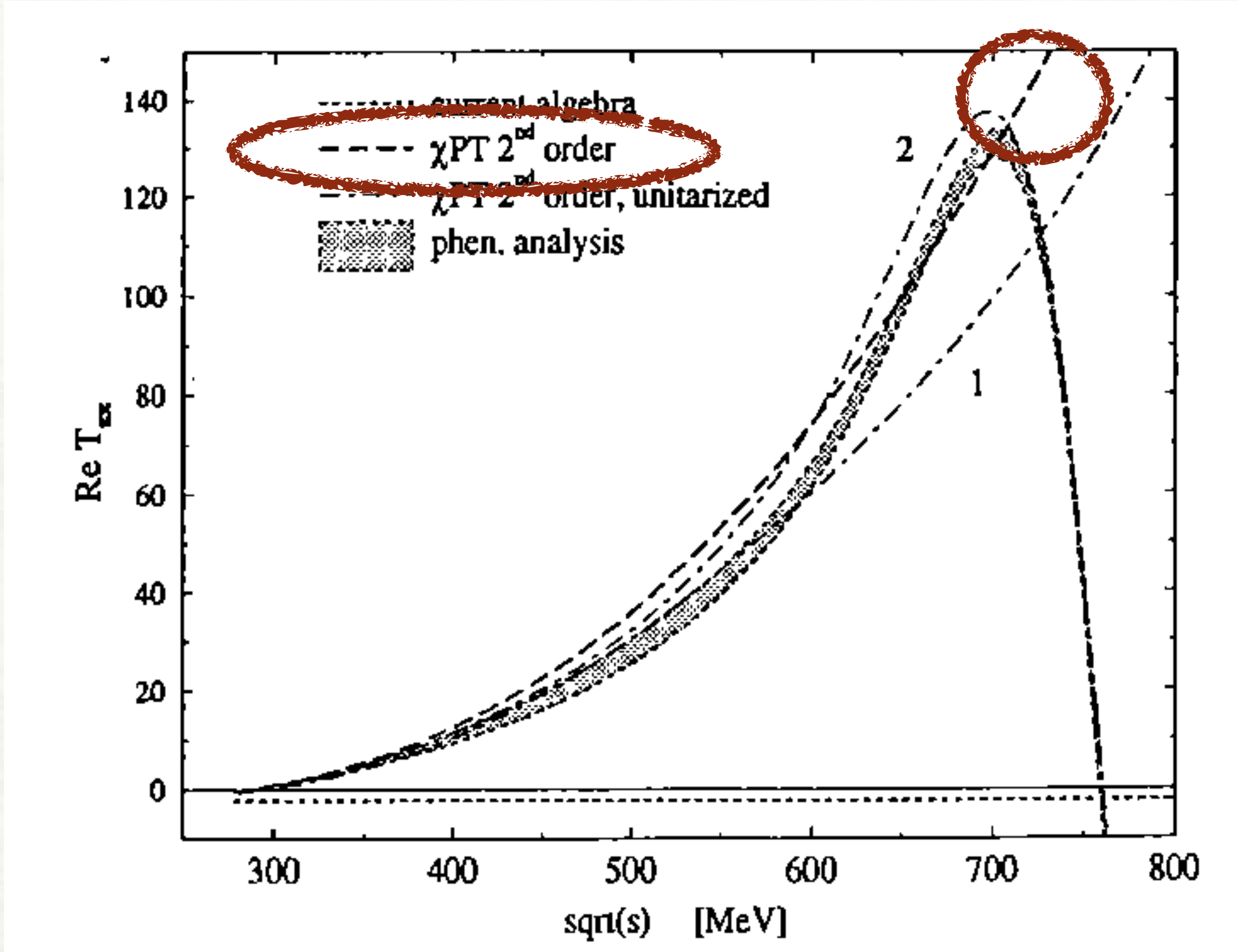


*Schenck 93*

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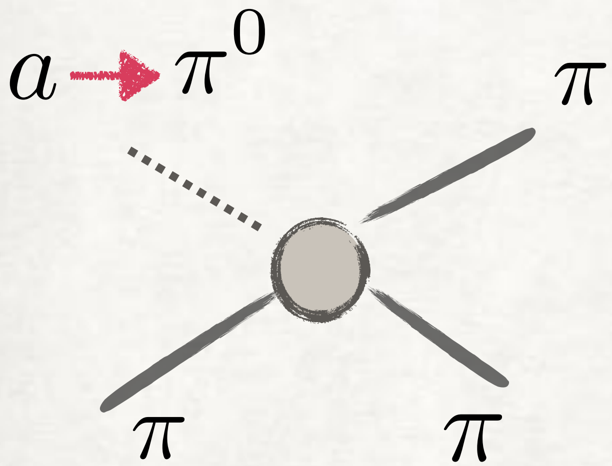
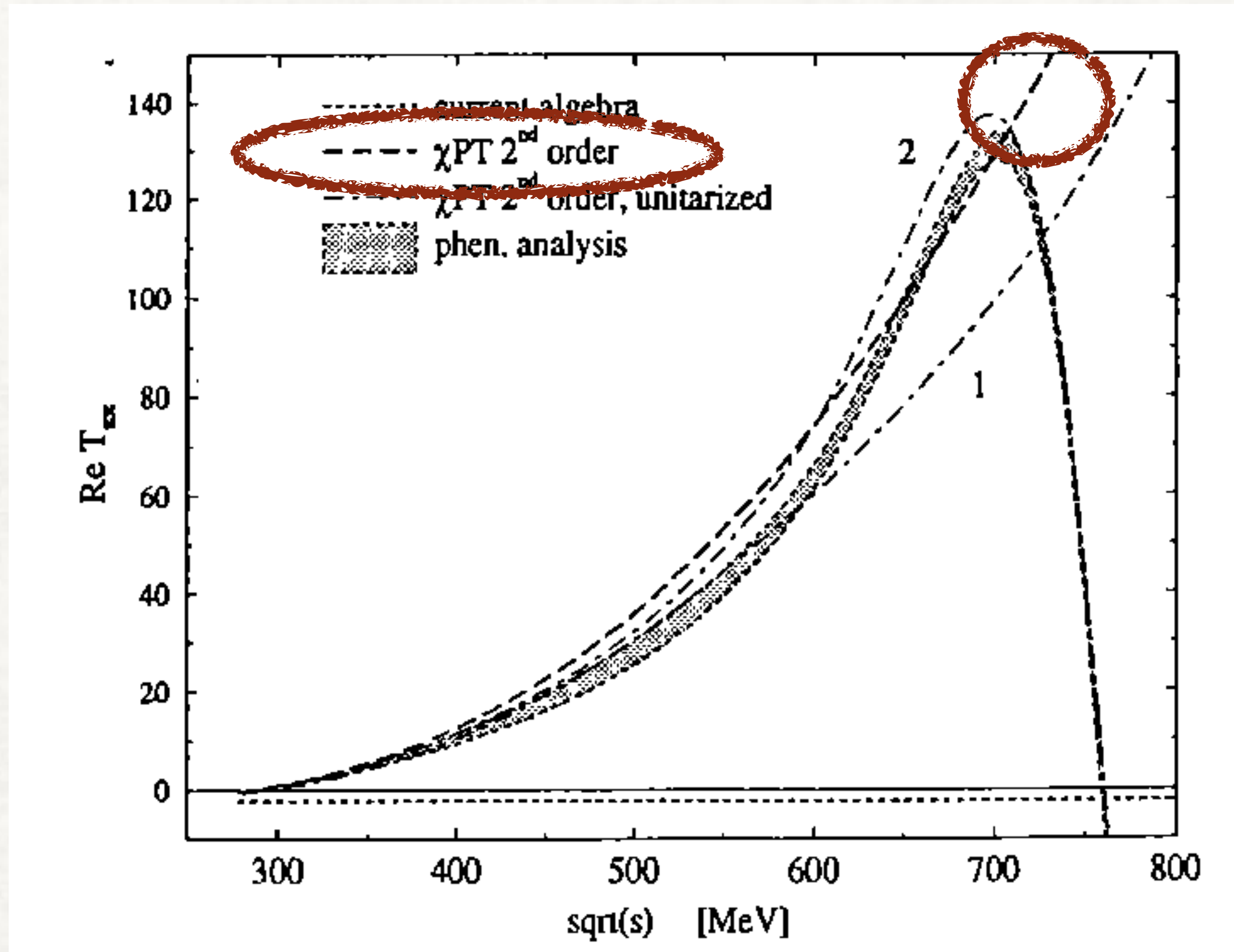



Forward
scattering
amplitude




Schenck 93

In this case we have data
**(Phase shifts)**

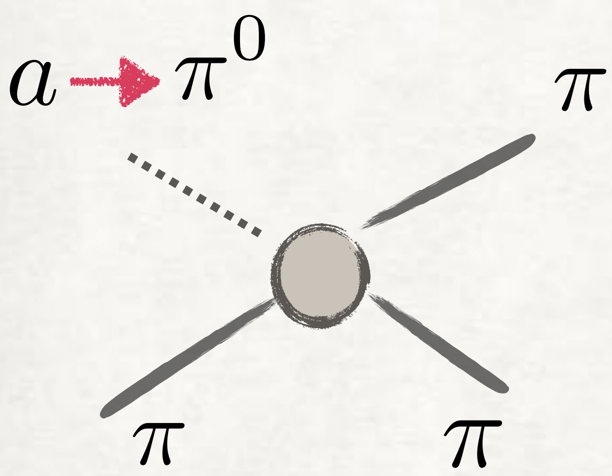
$$t_l^I = \sqrt{\frac{s}{s-4\,m_\pi^2}}\,\frac{e^{2i\delta_l^I(s)}-1}{2i}$$

*"Phenomenological" amplitude can be built from fits of phase shifts*

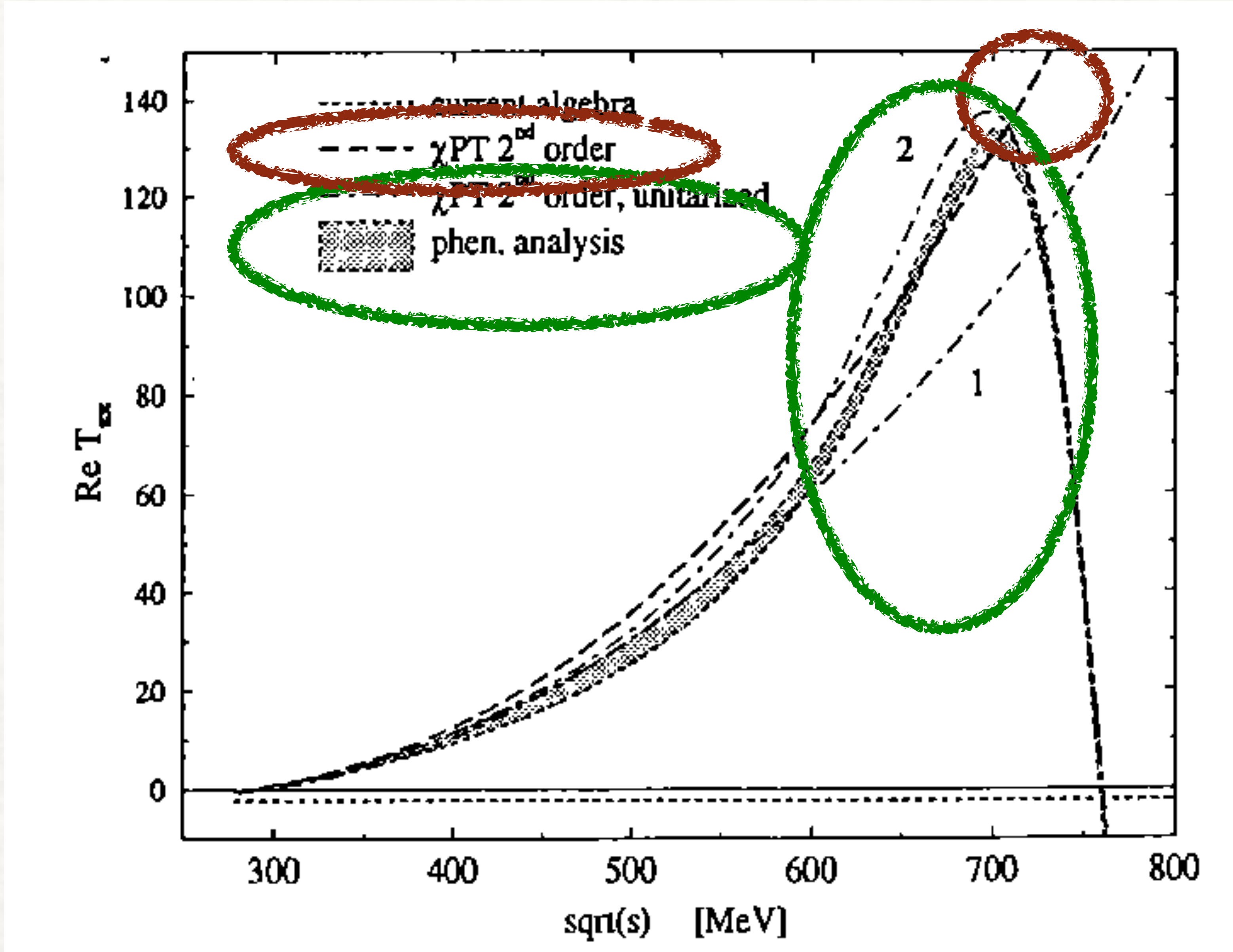
# LESSON FROM PIONS

*Goity, Leutwyler 89/ Schenck 93/...*

*The breakdown of ChPT is well known in pion-pion scattering*




*Forward scattering amplitude*




*Schenck 93*

*In this case we have data (Phase shifts)*

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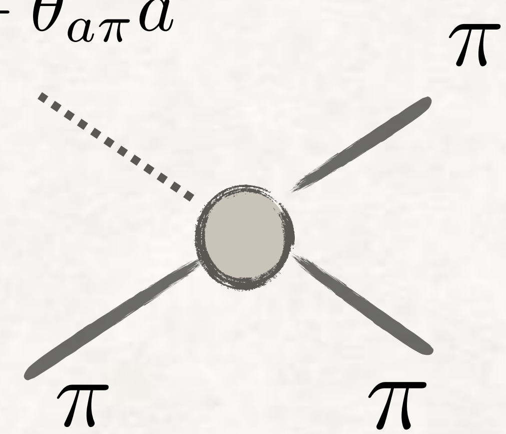
*"Phenomenological" amplitude can be built from fits of phase shifts*

# OUR STRATEGY FOR THE AXION-PION RATE

*For the QCD axion we don't have data…or do we?*

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$




*See also Leigh, Rattazzi 95*

*Axion-Pion amplitude is related to Pion-Pion by simple rescaling*

$$\mathcal{M}_{a\pi^i \to \pi^j \pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \cdot \mathcal{M}_{\pi^0 \pi^i \to \pi^j \pi^k} \; + \mathcal{O}(m_\pi^2/s)$$

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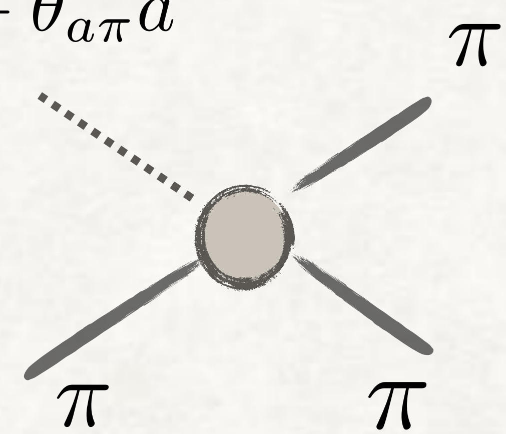


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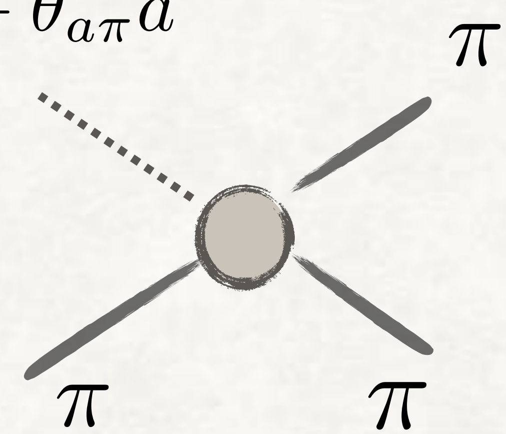


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$\theta_{a\pi}$ $\qquad\qquad\qquad\qquad$ $\lesssim 10\%$

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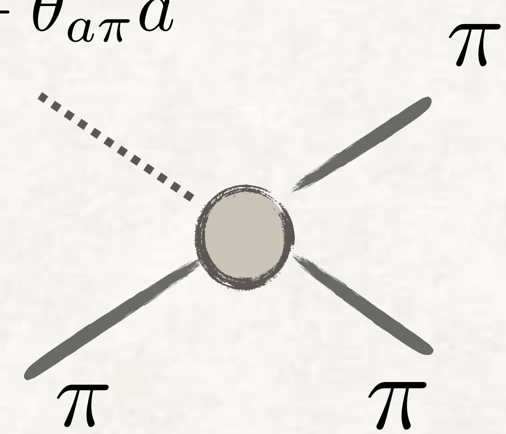


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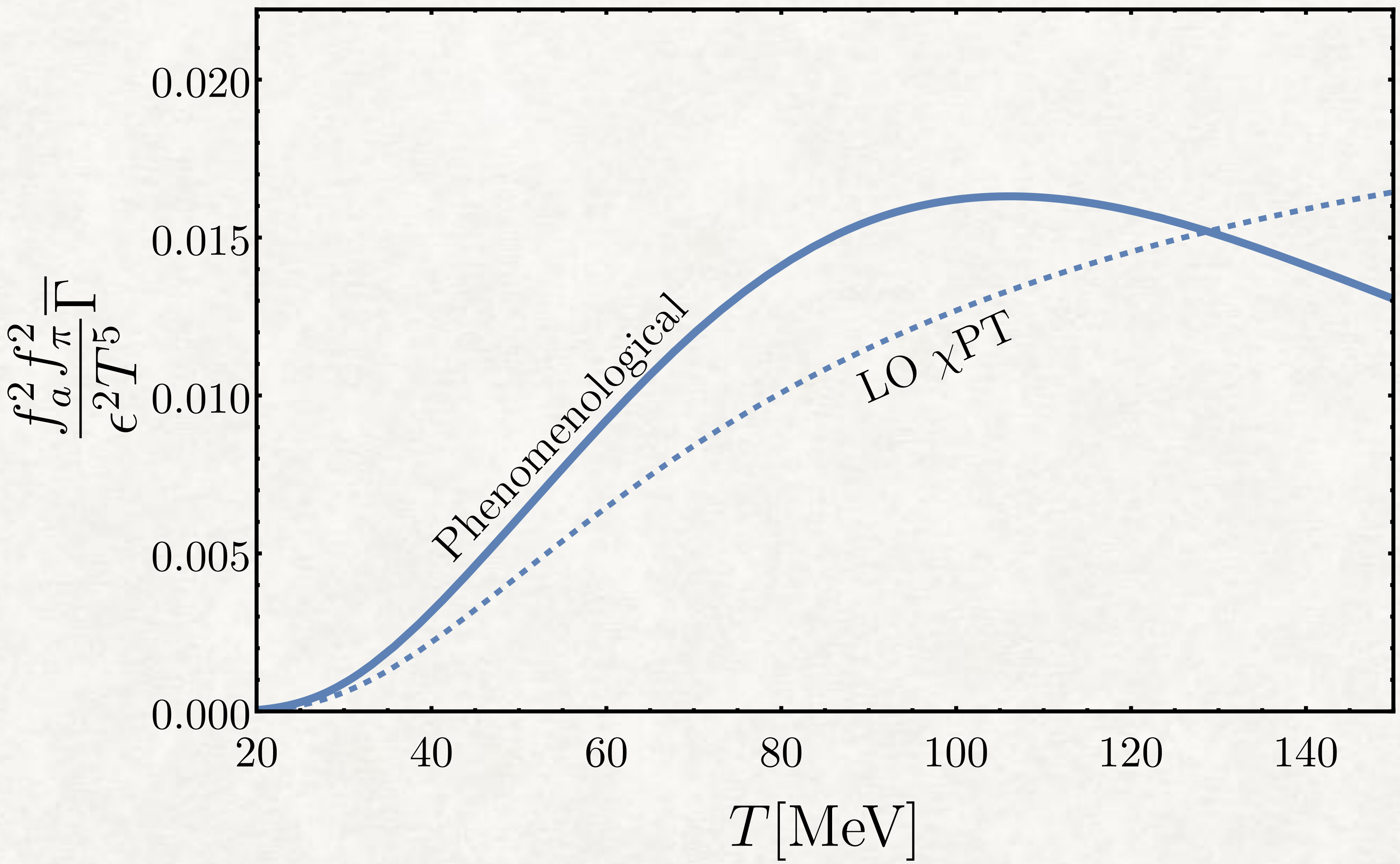
*This is valid **at all orders in ChPT**, which we trust only up to* $\sqrt{s} \leq 1 \text{ GeV}$

# NEW AXION-PION RATE



# NEW AXION–PION RATE

*Turndown corresponds to*
*new production channels (kaons, nucleons),*
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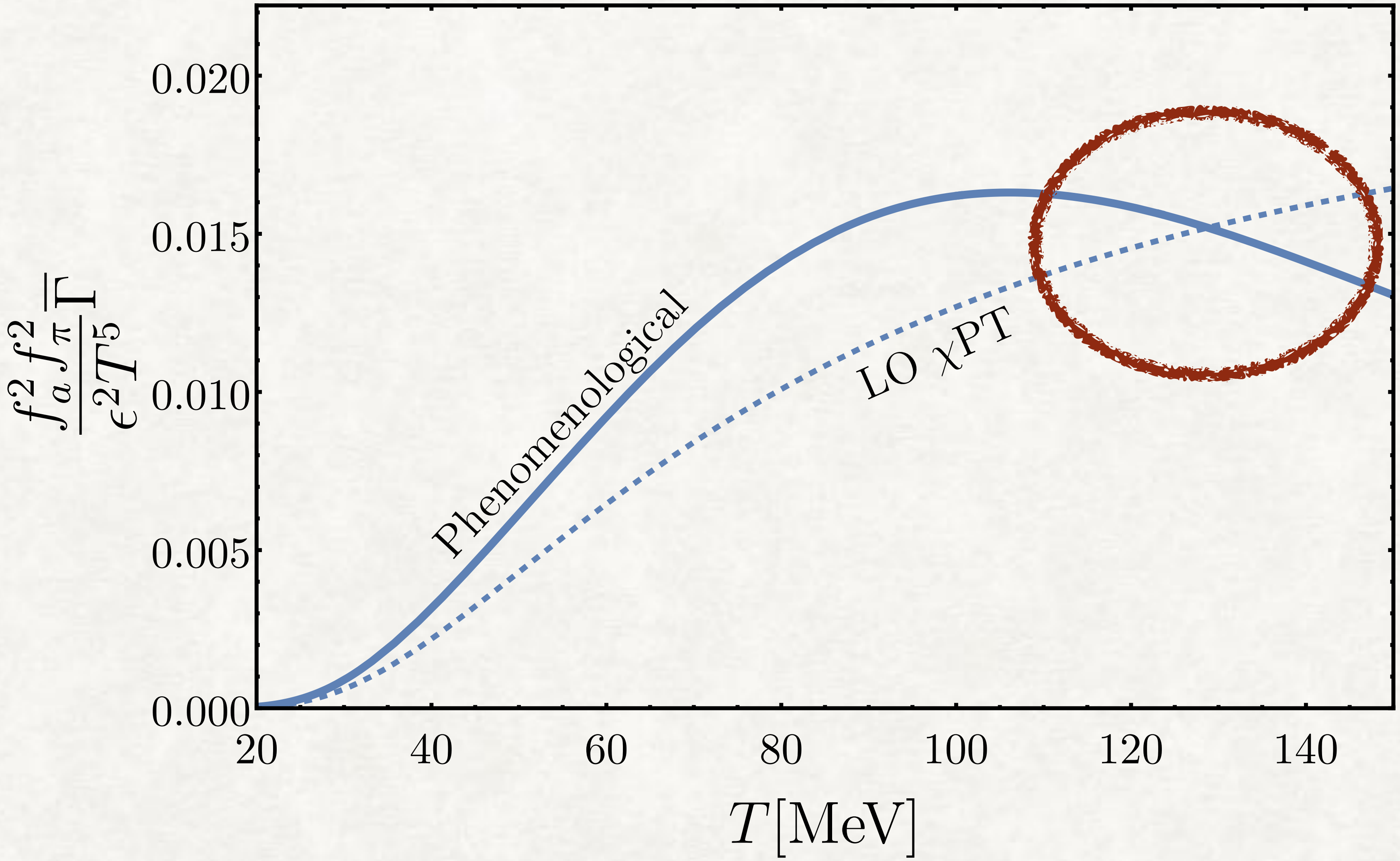

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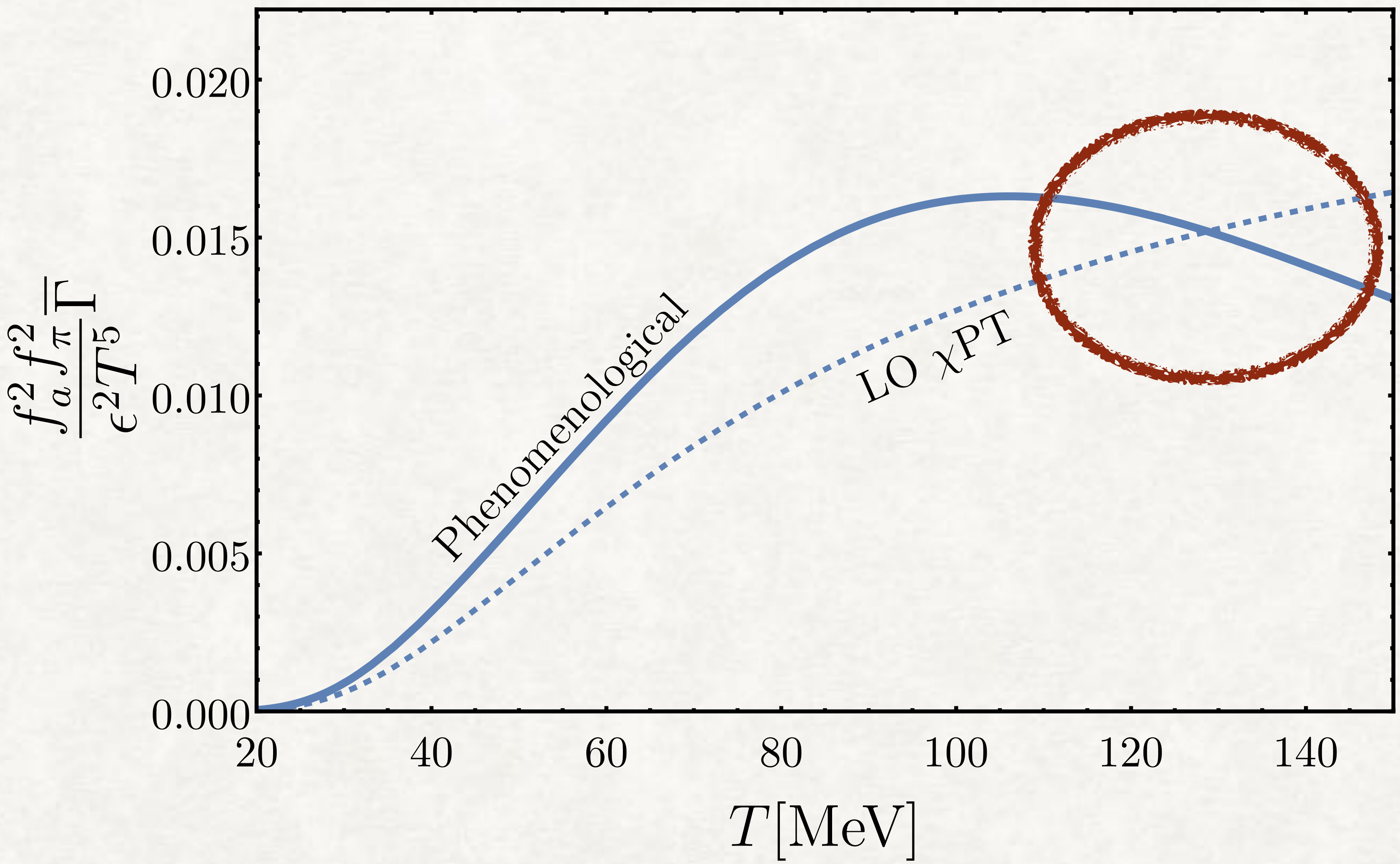


*Differs by 30% compared to LO result*

# AXION SPECTRAL DISTORTION

*Previous computation of hot axion relic abundance based on instantaneous decoupling from equilibrium or Boltzmann equation for axion yield.*

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***Cross section depends on axion momentum***

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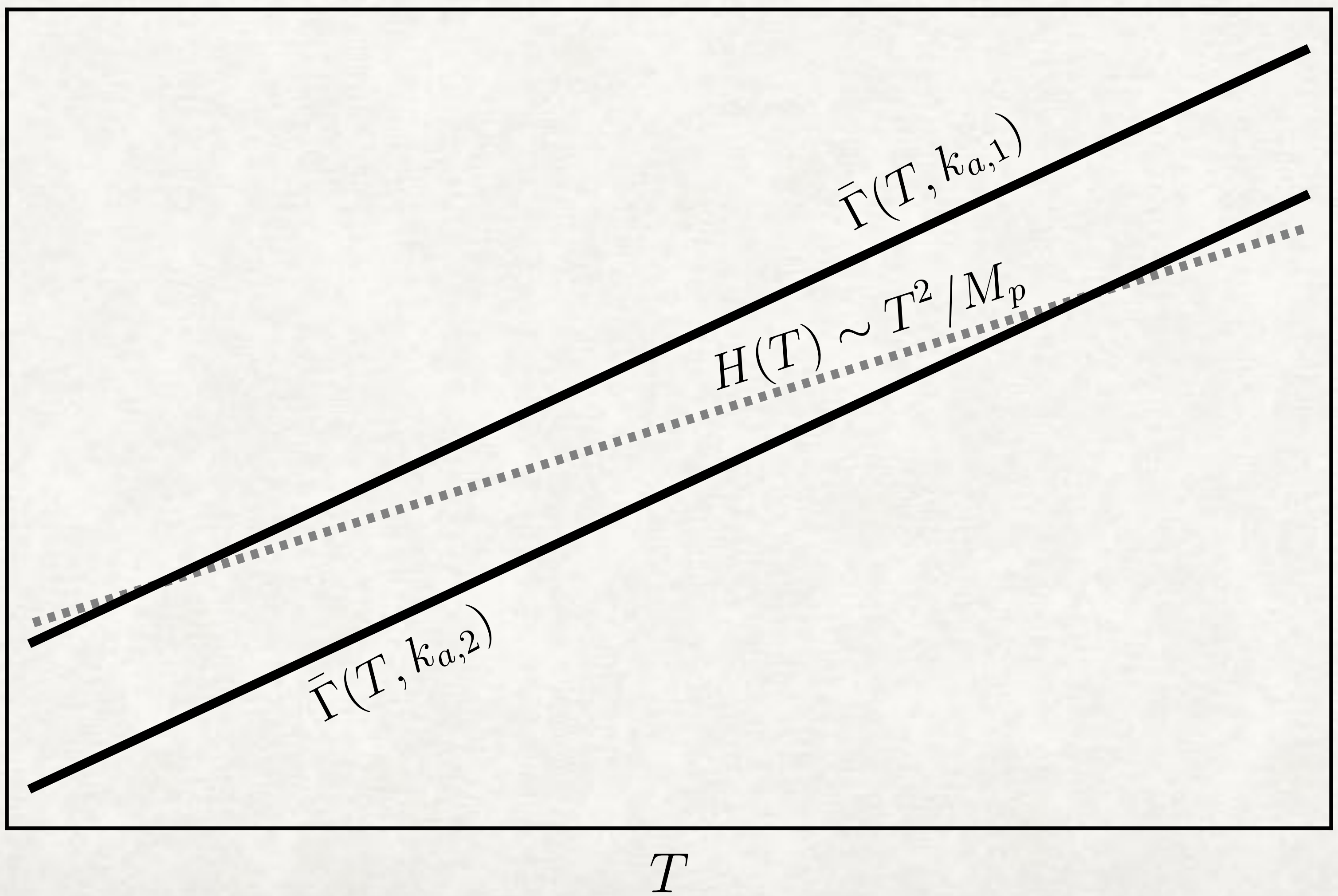

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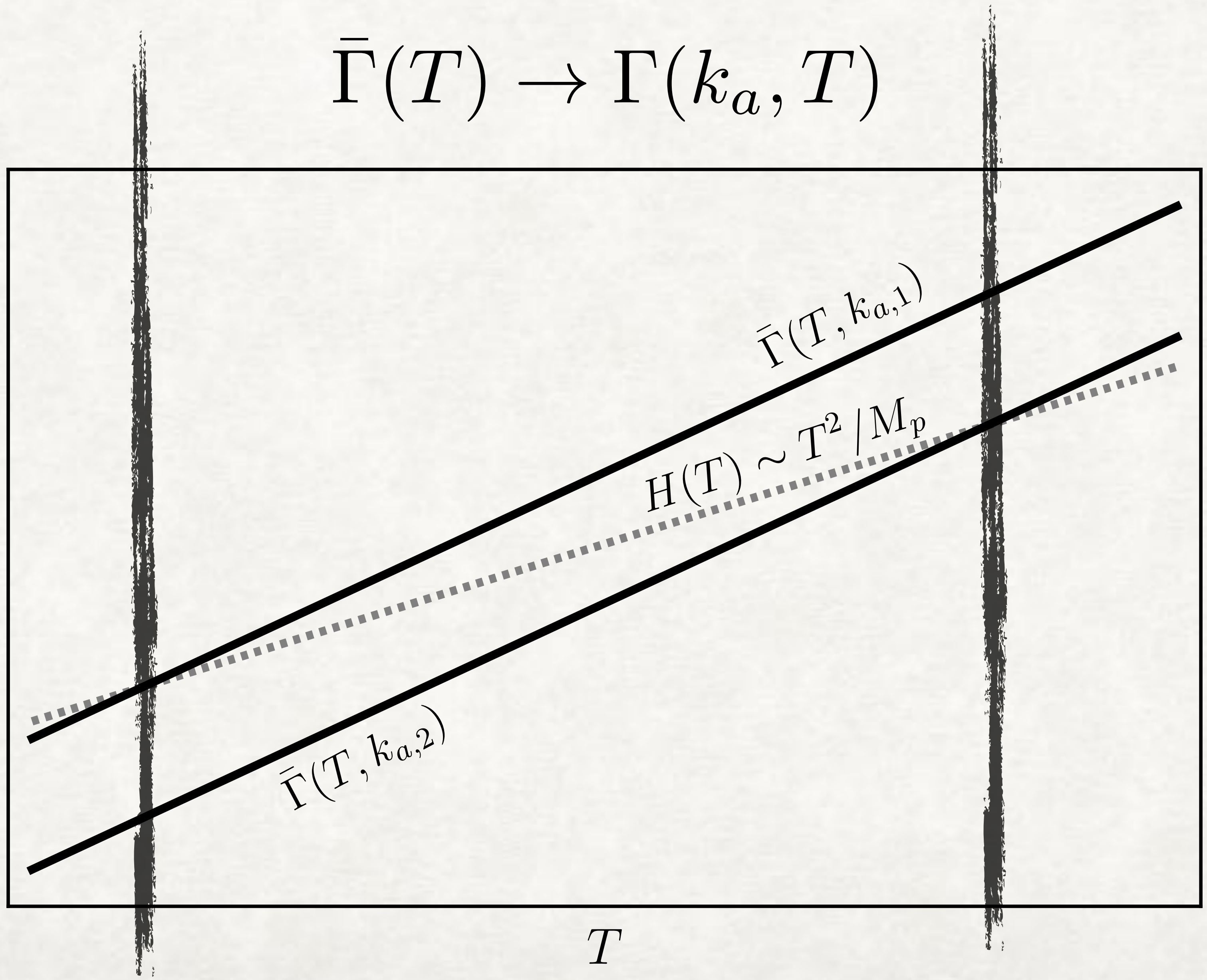
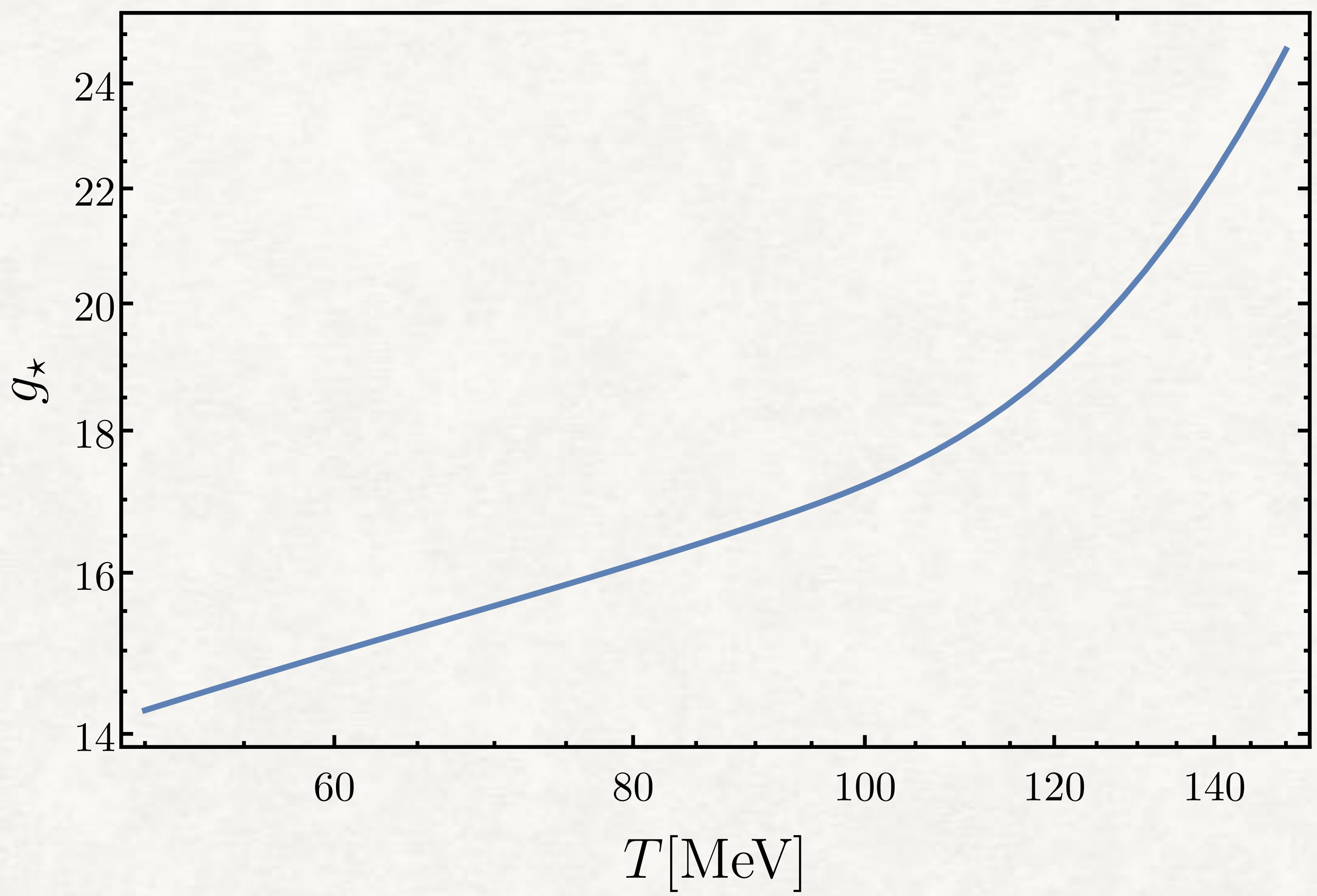



***Higher momentum modes interact more, Decouple at lower temperature!***

# AXION SPECTRAL DISTORTION

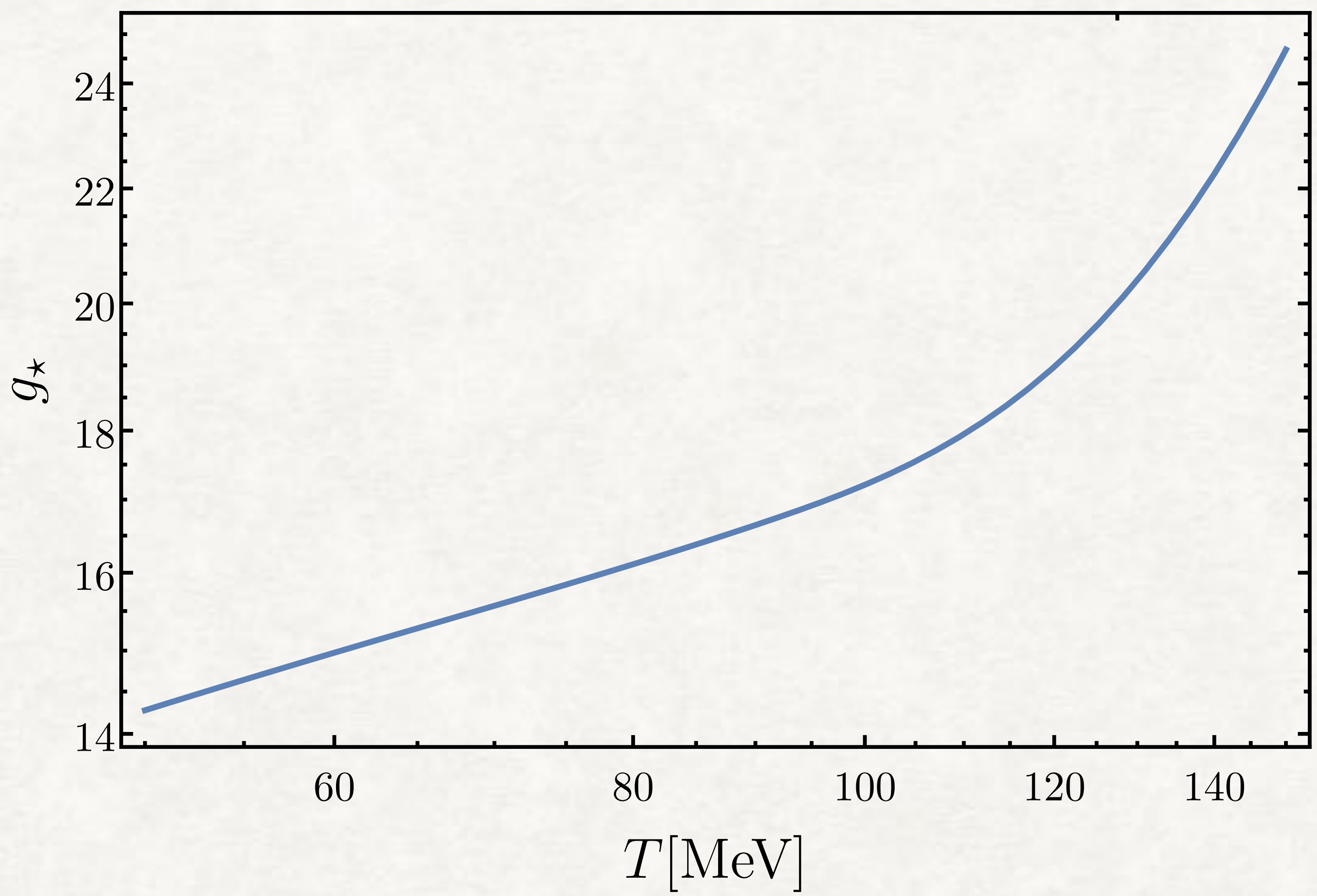



$g_*$ from Borsanyi et al, *Nature* 539 (2016)

$$\rho_a \sim R^{-4}, \quad R(T) \sim g_*(T)^{-1/3} T^{-1}$$

# AXION SPECTRAL DISTORTION

***At temperatures of interest, number of relativistic degrees of freedom is rapidly varying***




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

***Relic abundance is enhanced***

$$\rho_a \sim R^{-4}, \quad R(T) \sim g_*(T)^{-1/3} T^{-1}$$

***Higher momentum modes are less diluted by expansion!***

# MOMENTUM-DEPENDENT BOLTZMANN EQUATION

*We solve for axion distribution function*

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

**Creation** **Destruction**

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

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

*Common parametrization,*
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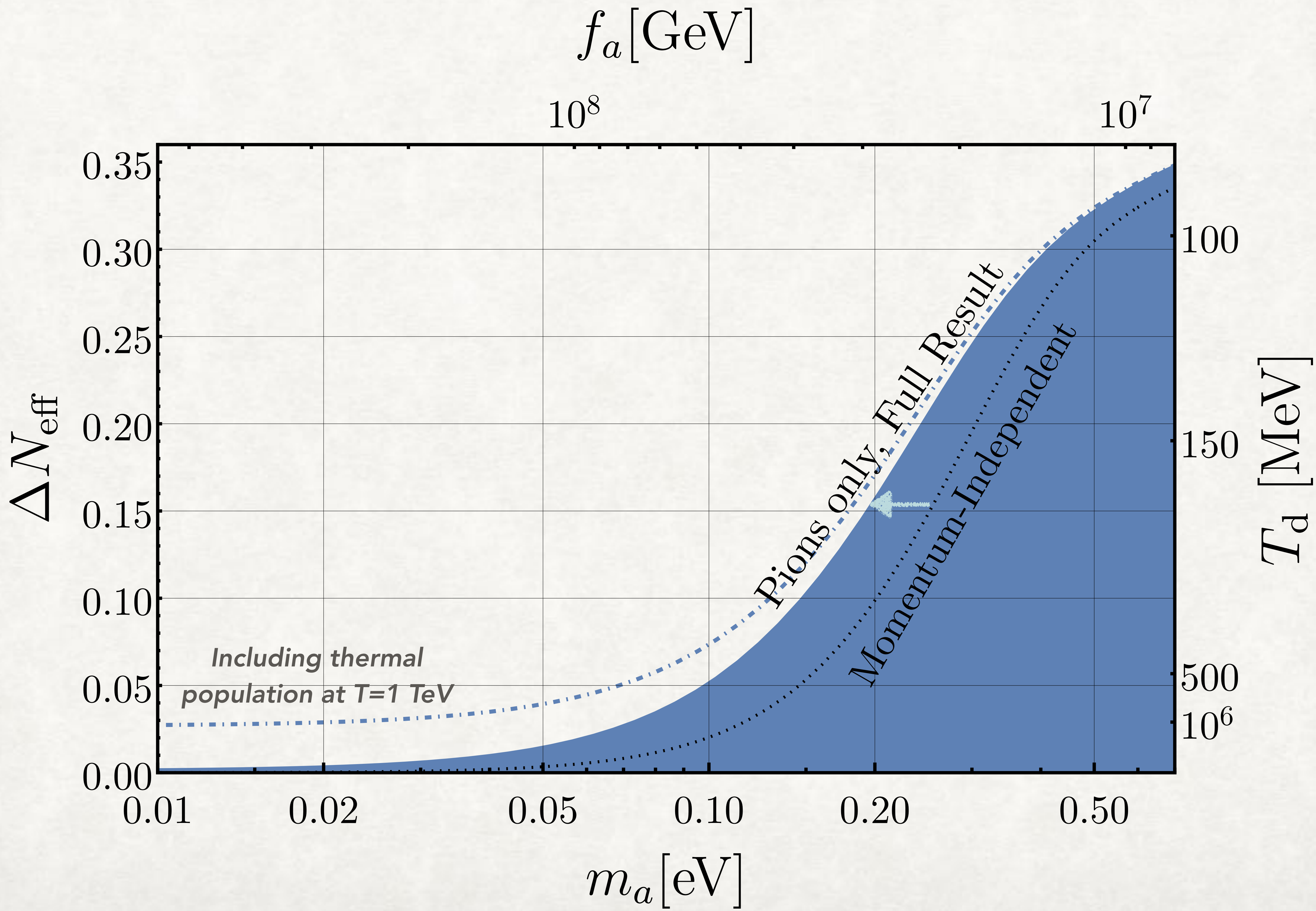
*Common parametrization, even in massive case*

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

# RESULTS

*Minimal KSVZ model*



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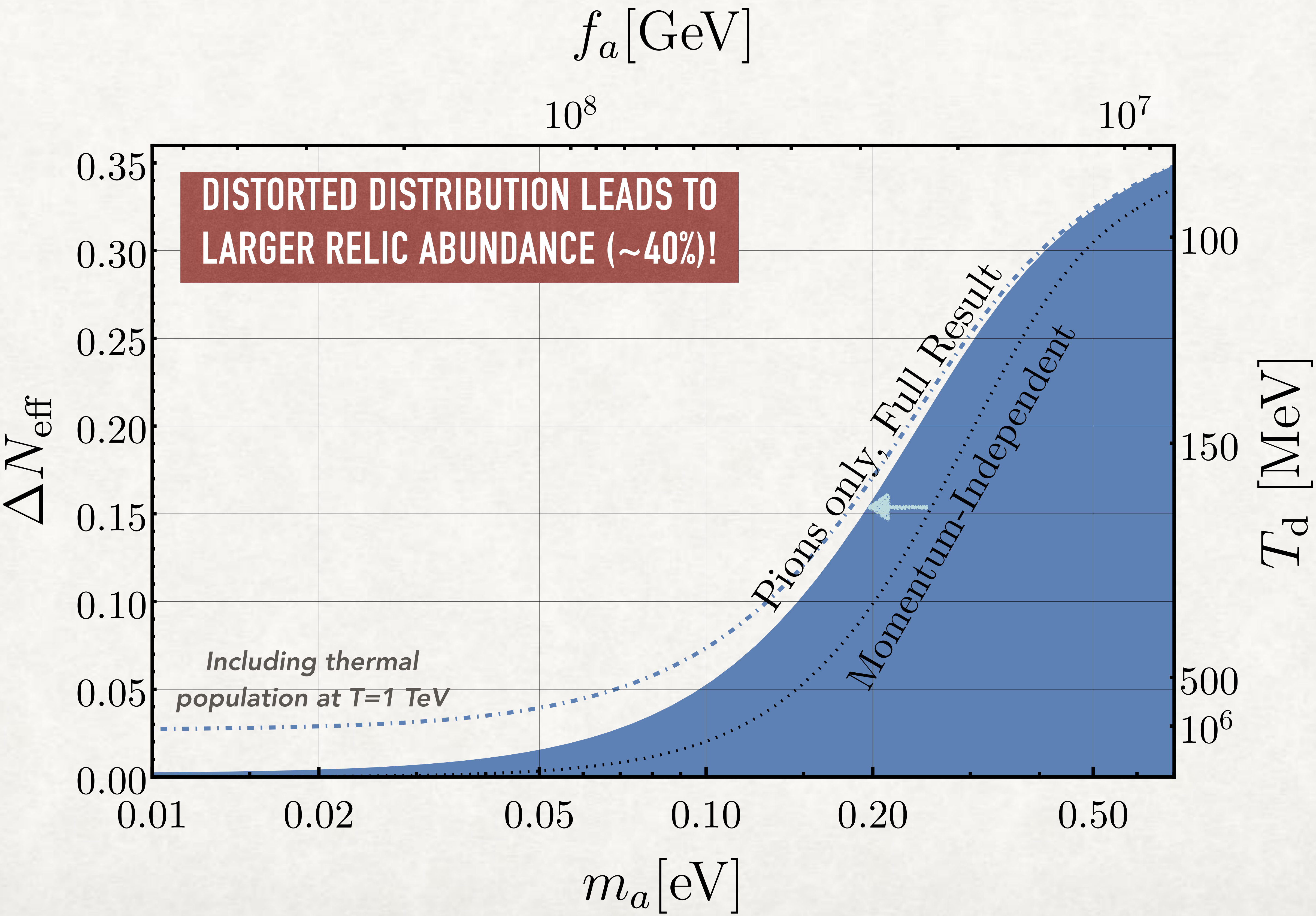
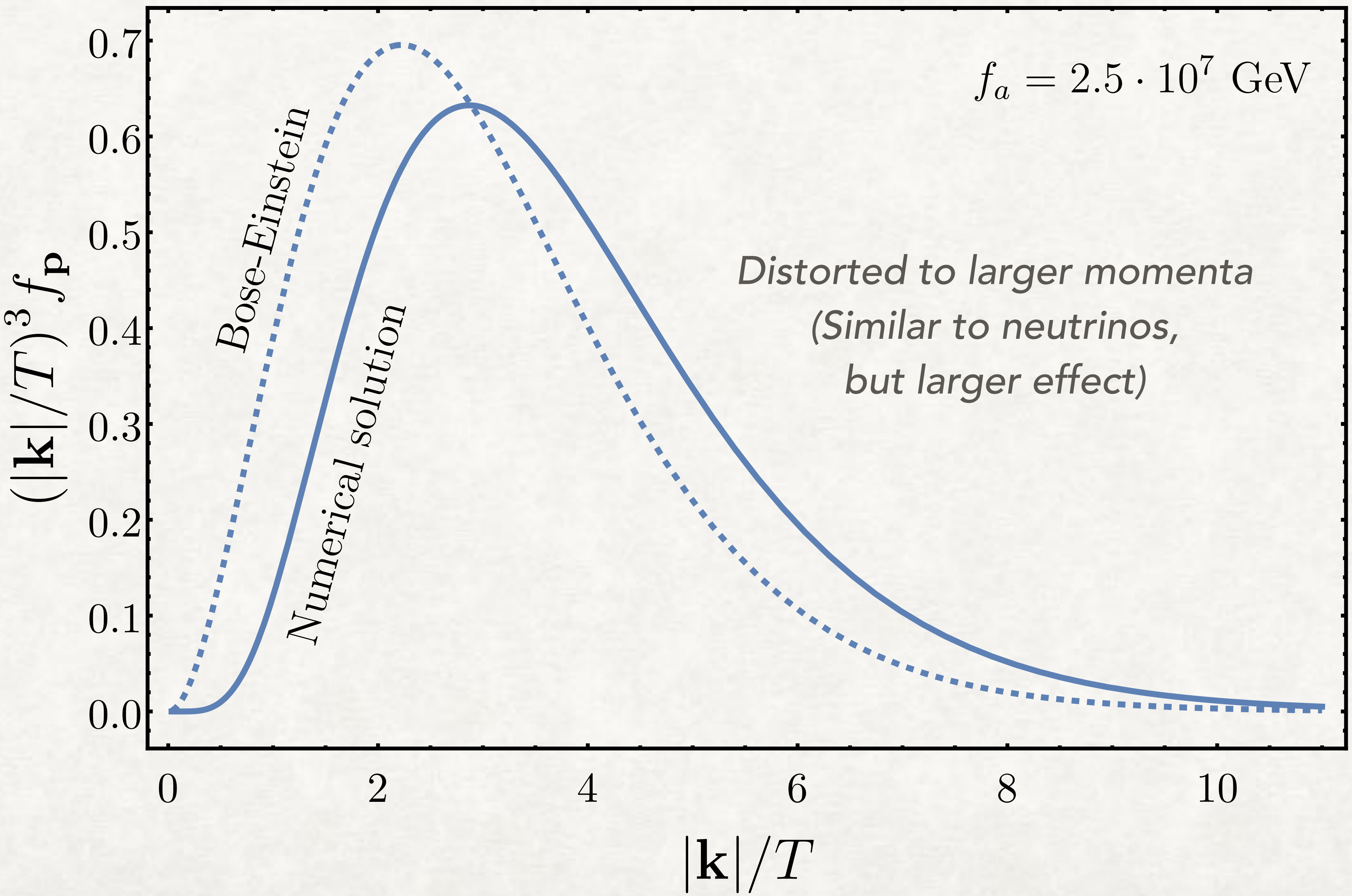


# AXION DISTRIBUTION FUNCTION

***Minimal KSVZ model***

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



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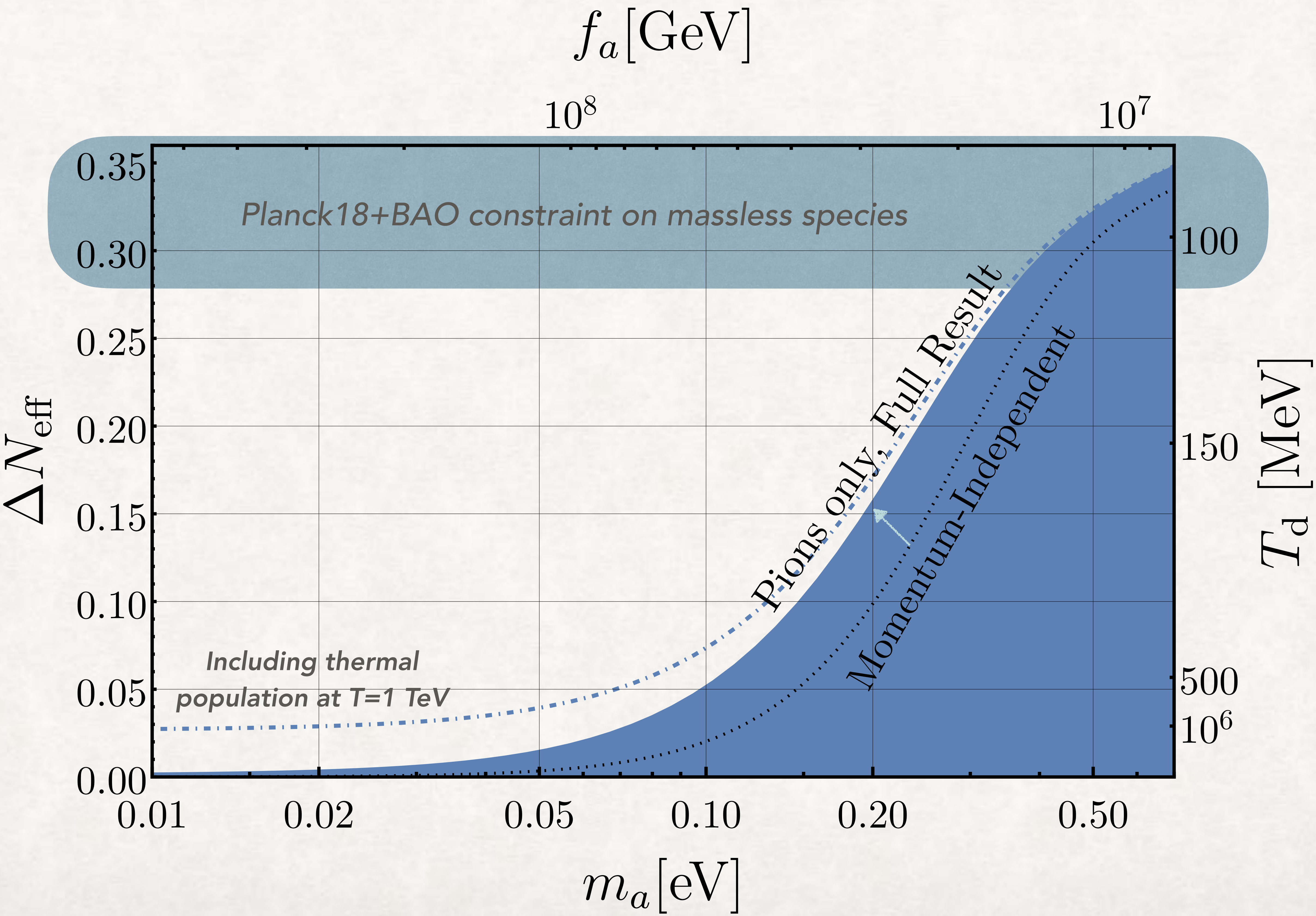

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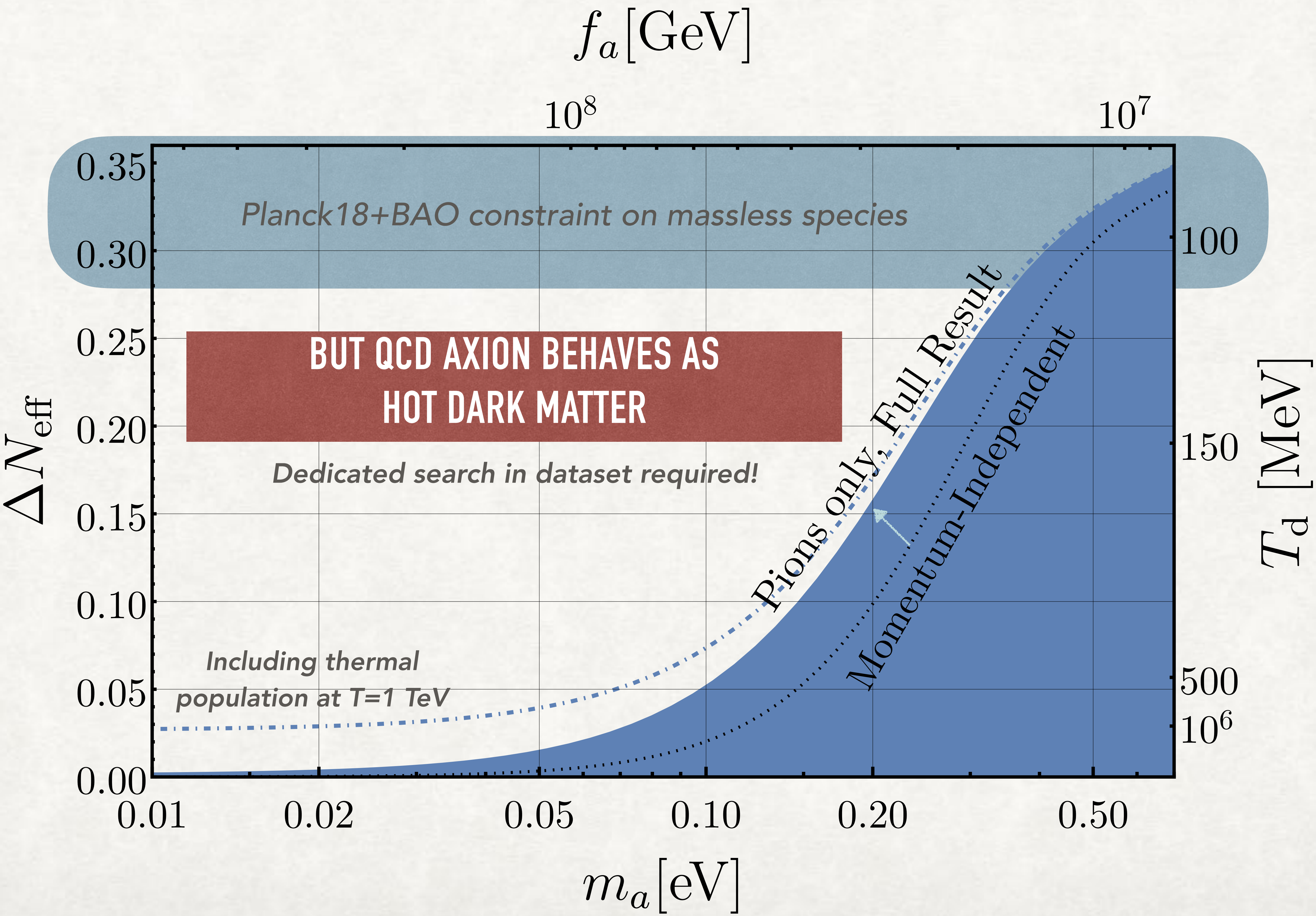
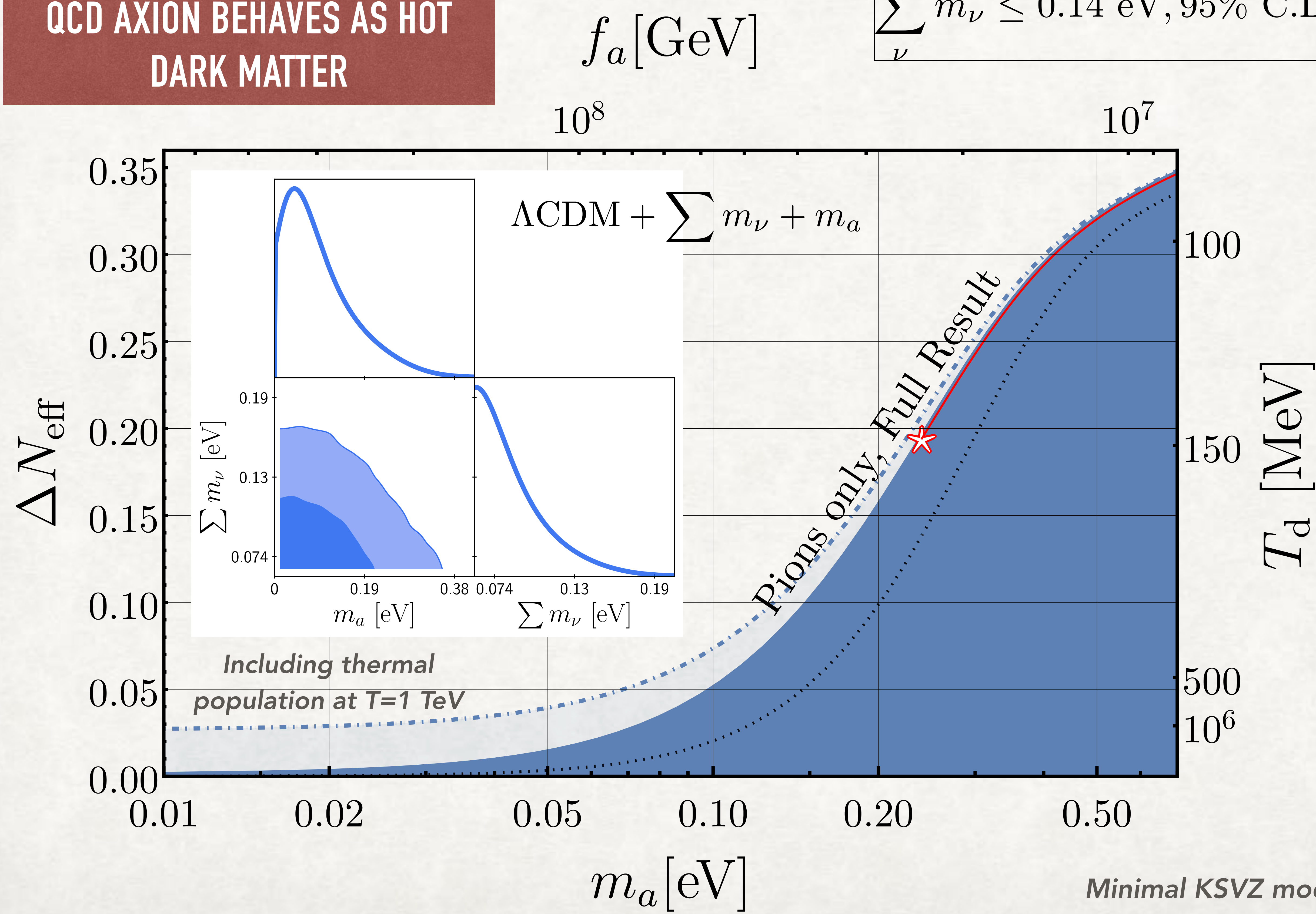


# RESULTS

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

**QCD AXION BEHAVES AS HOT DARK MATTER**

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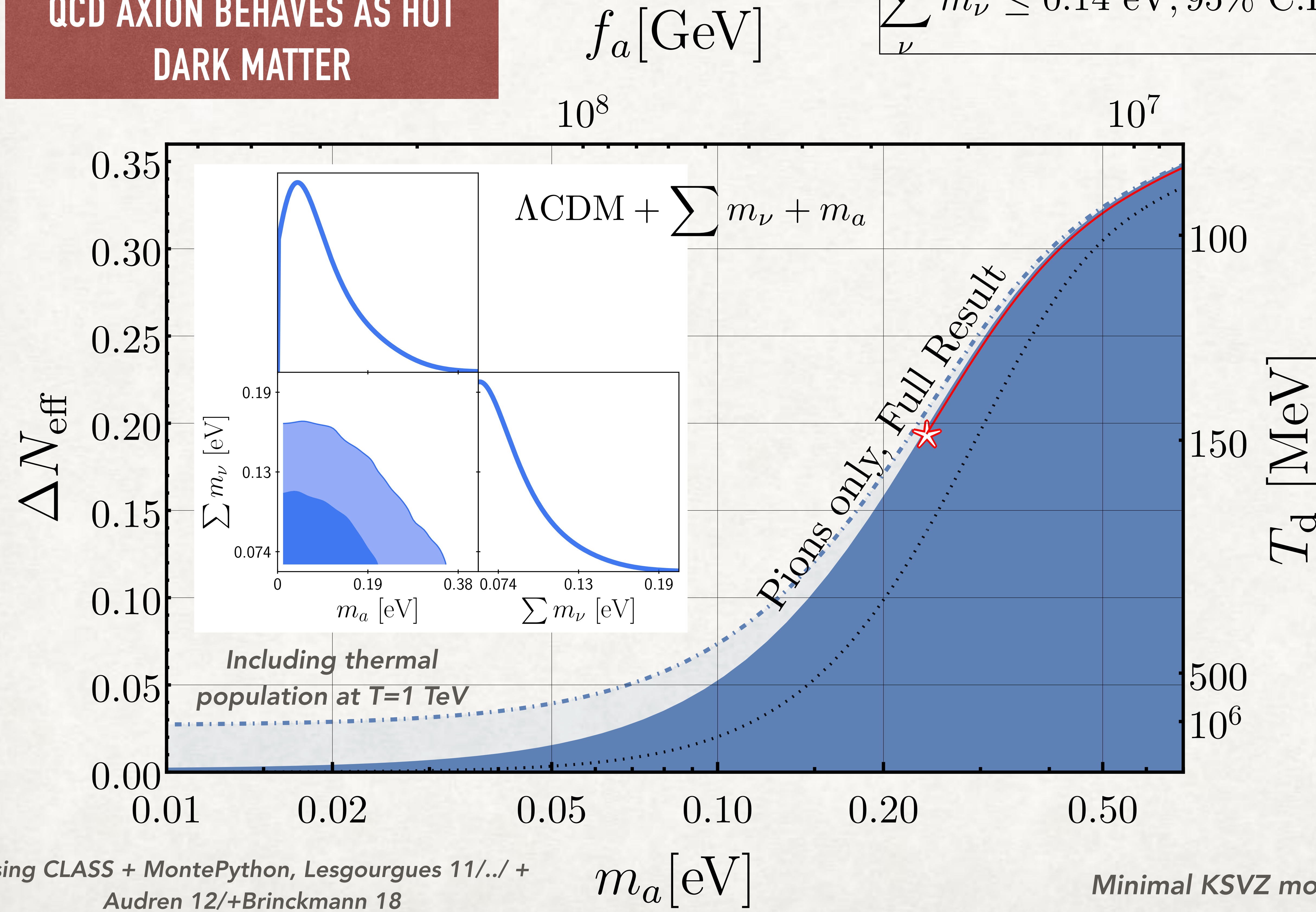


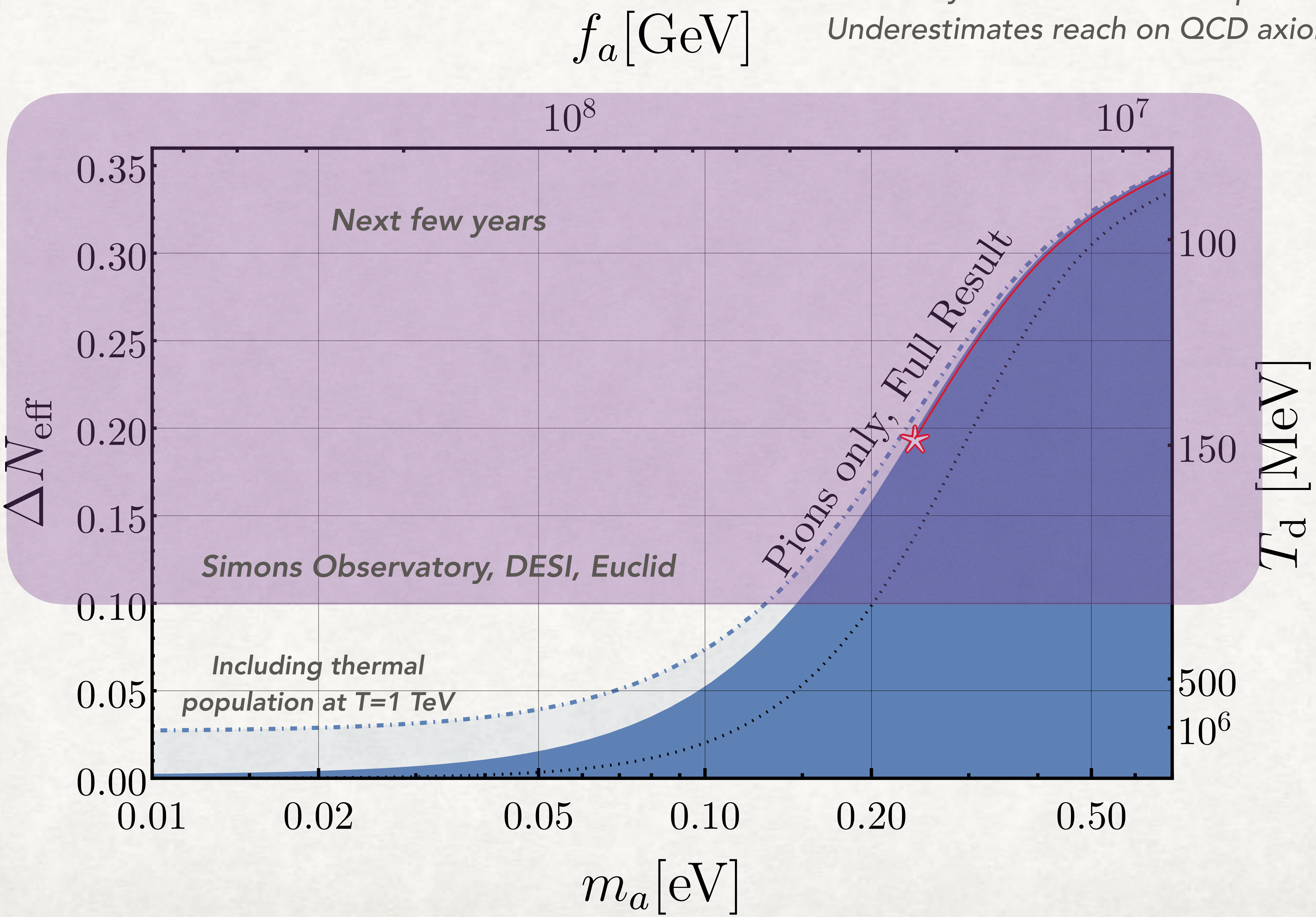

*Using CLASS + MontePython, Lesgourgues 11/../ + Audren 12/+Brinckmann 18*

*Minimal KSVZ model*

# THE (NEAR) FUTURE

# OUTLOOK

***Caveat:***
*Sensitivity reach to massless species,*
*Underestimates reach on QCD axion*



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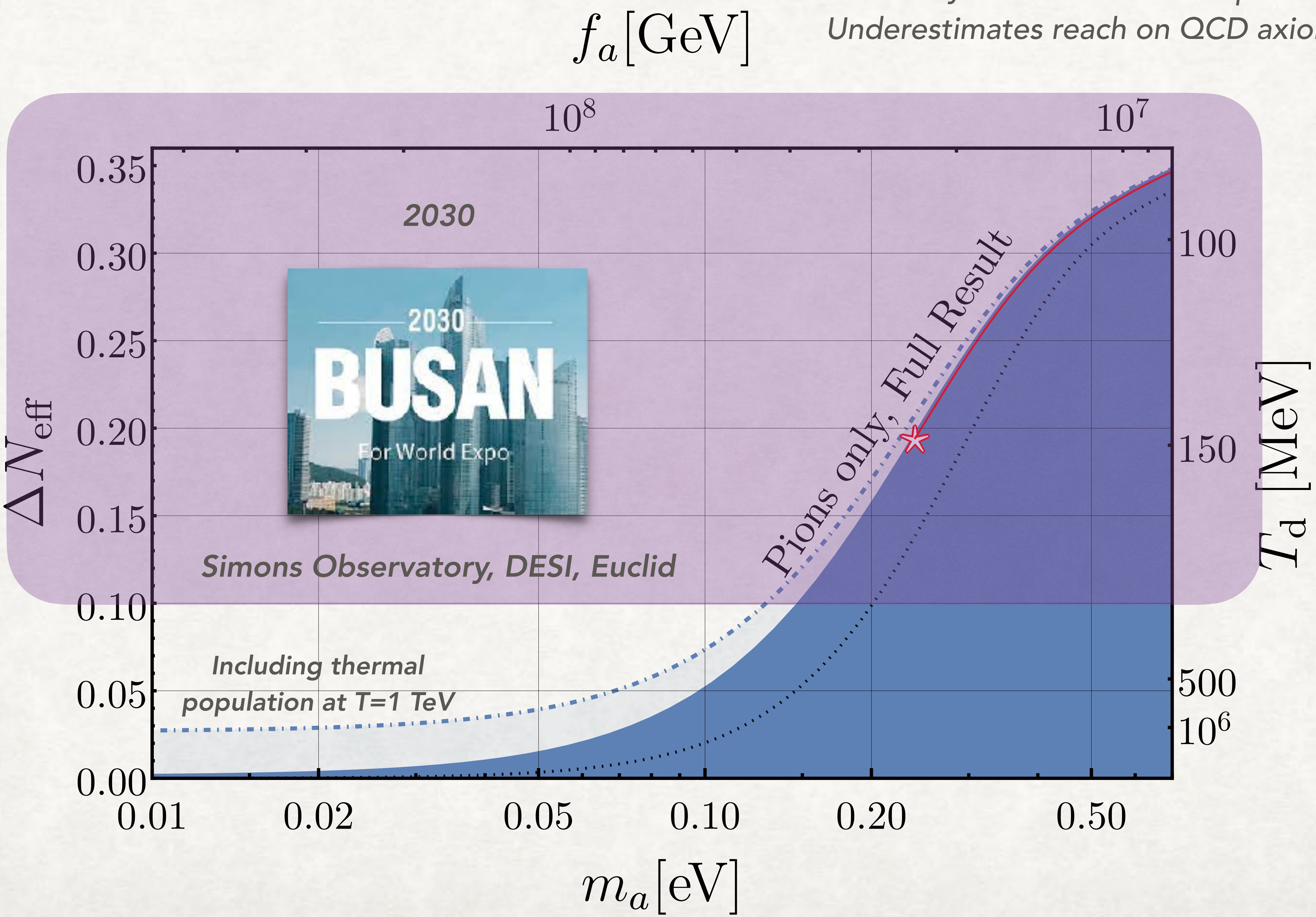

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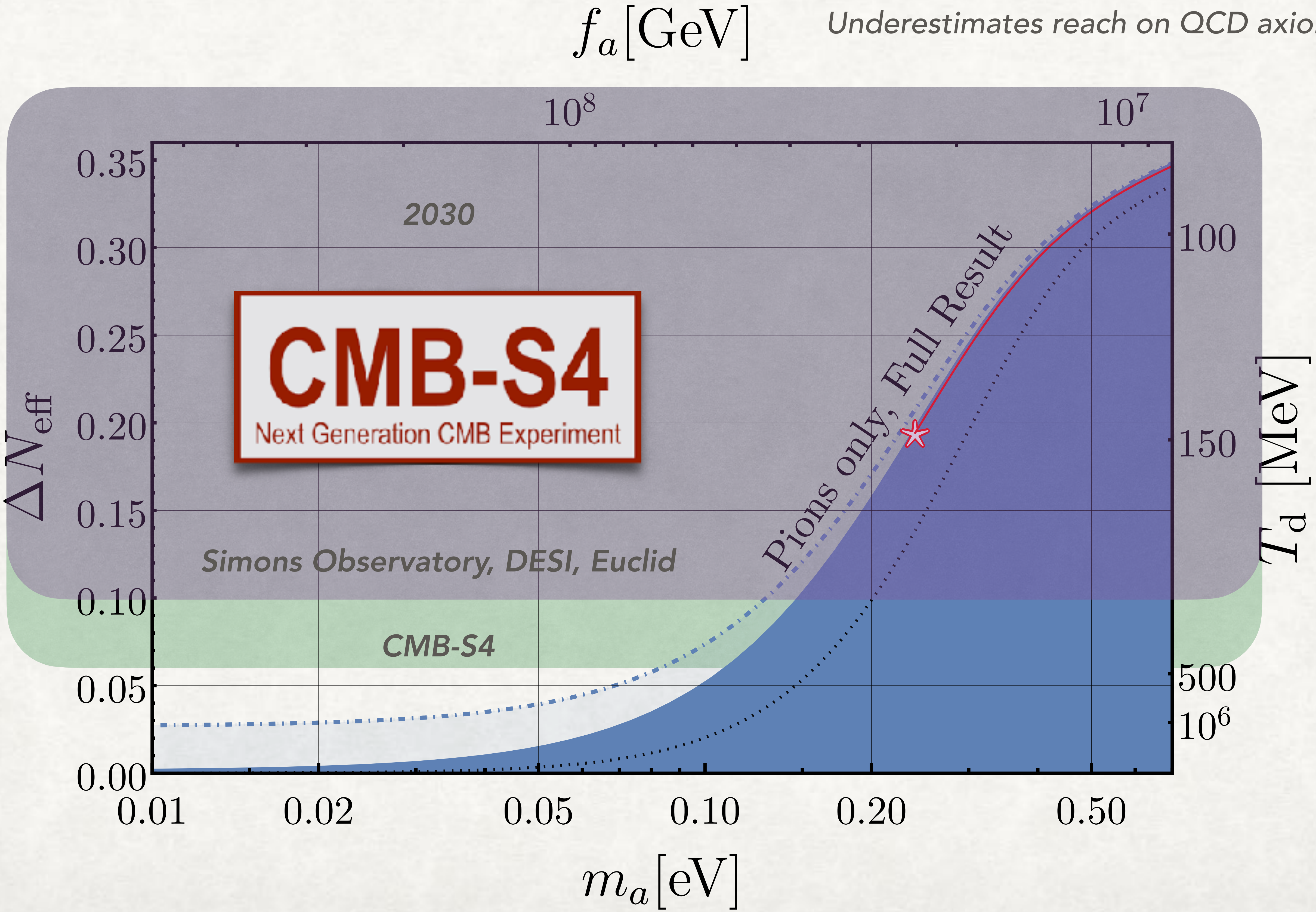

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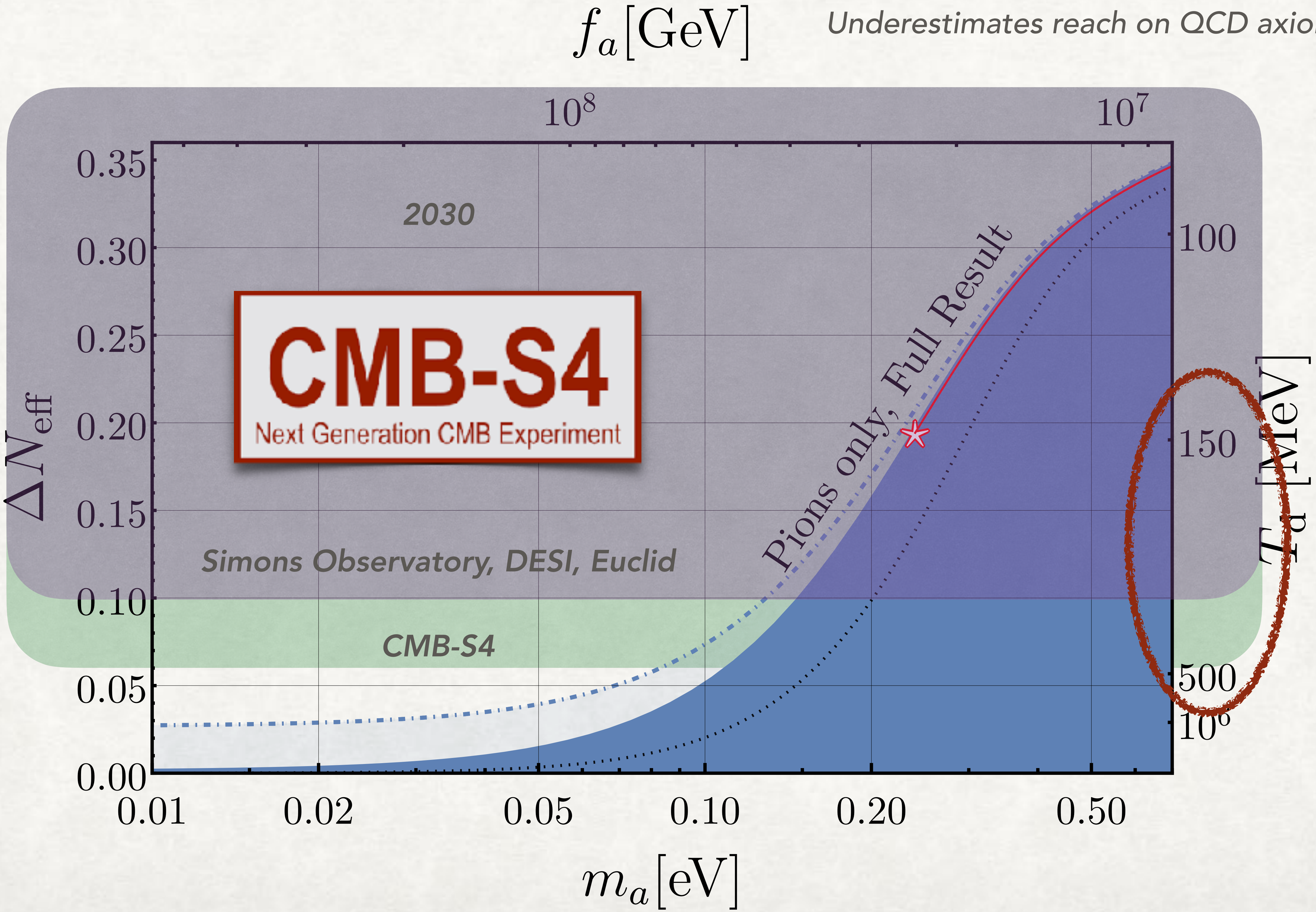

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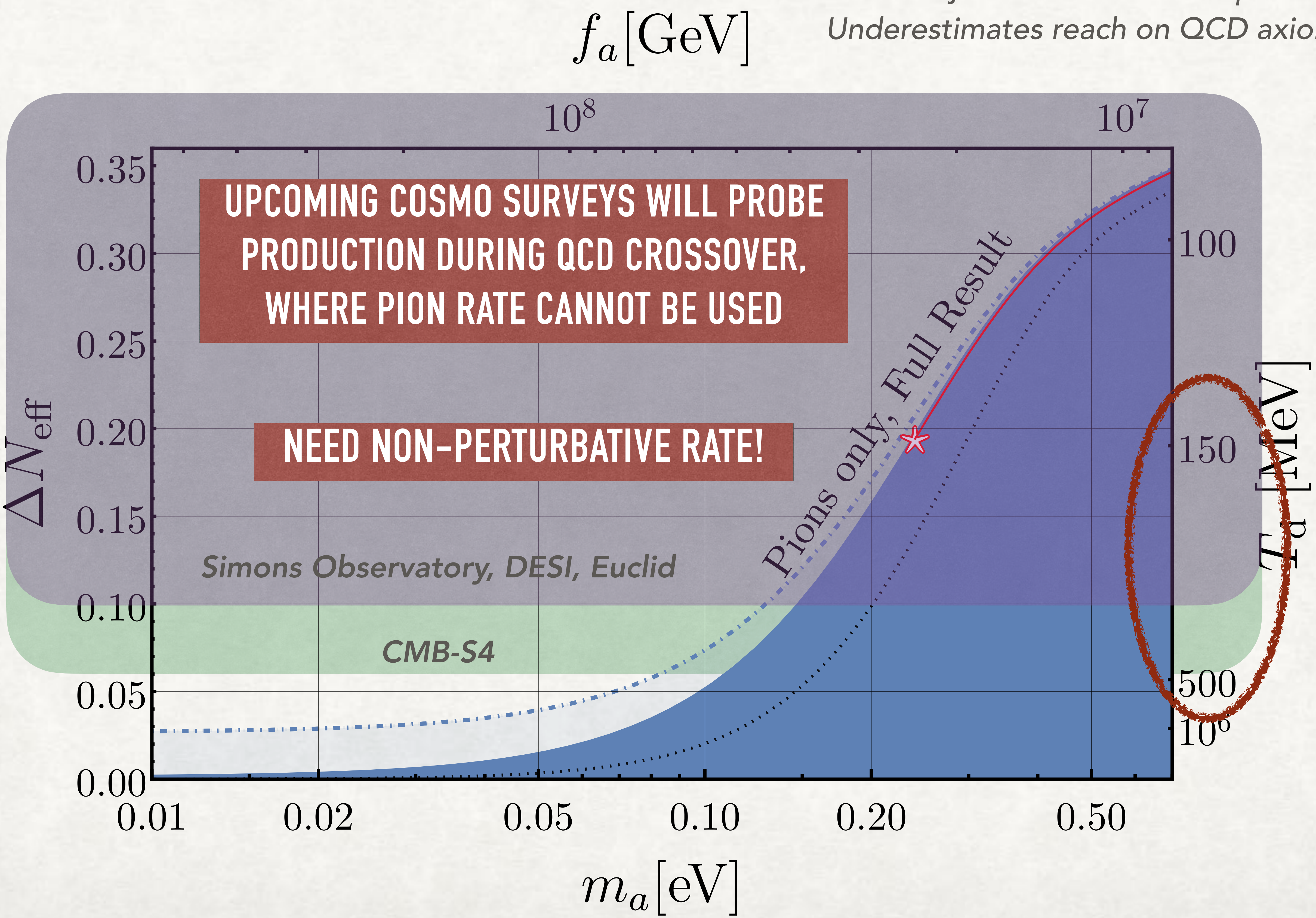
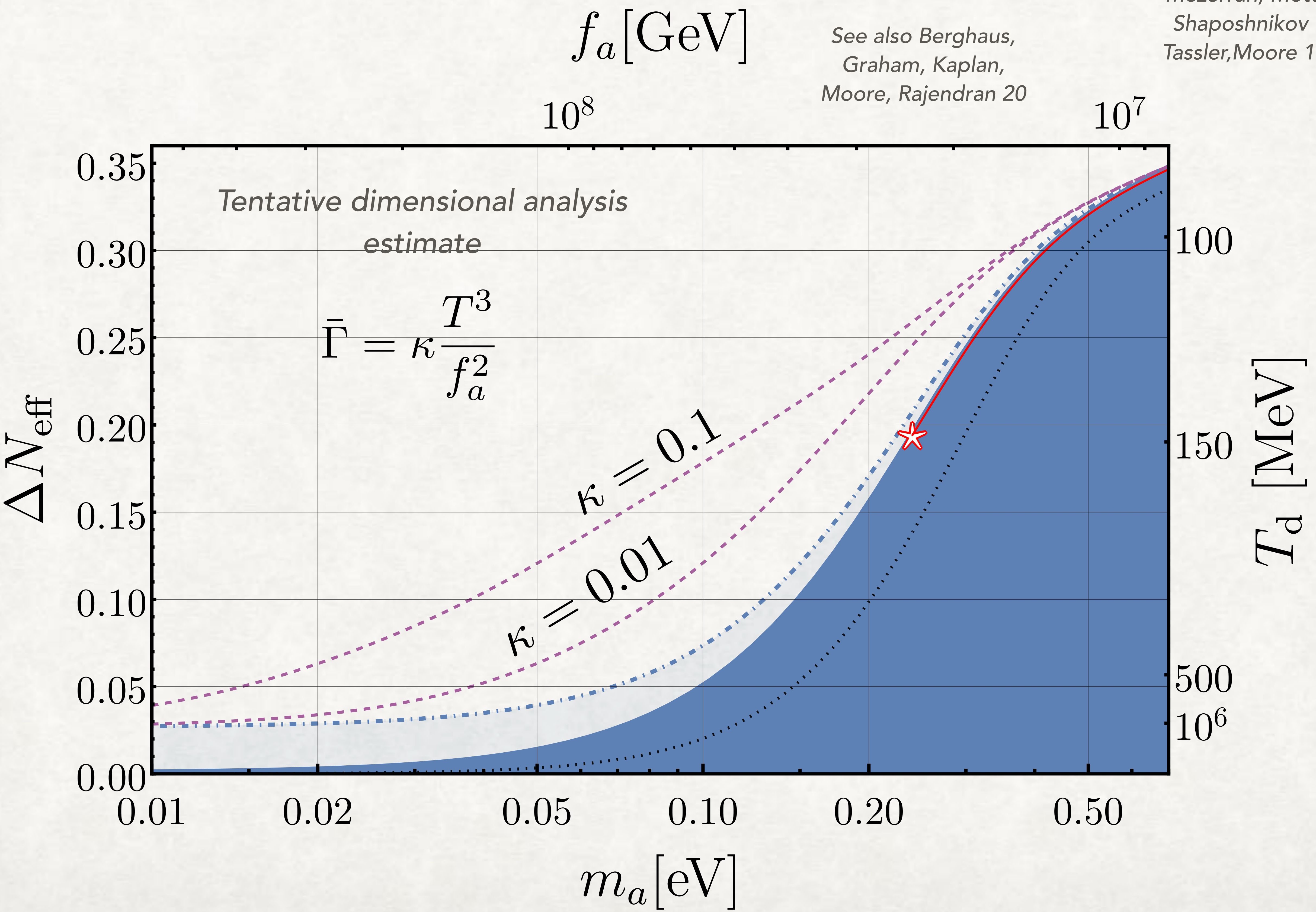


# OUTLOOK

*Inspired by*
*"Strong sphalerons"*

*McLerran, Mottola, Shaposhnikov 90/ Tassler, Moore 10/…*

*See also Berghaus, Graham, Kaplan, Moore, Rajendran 20*



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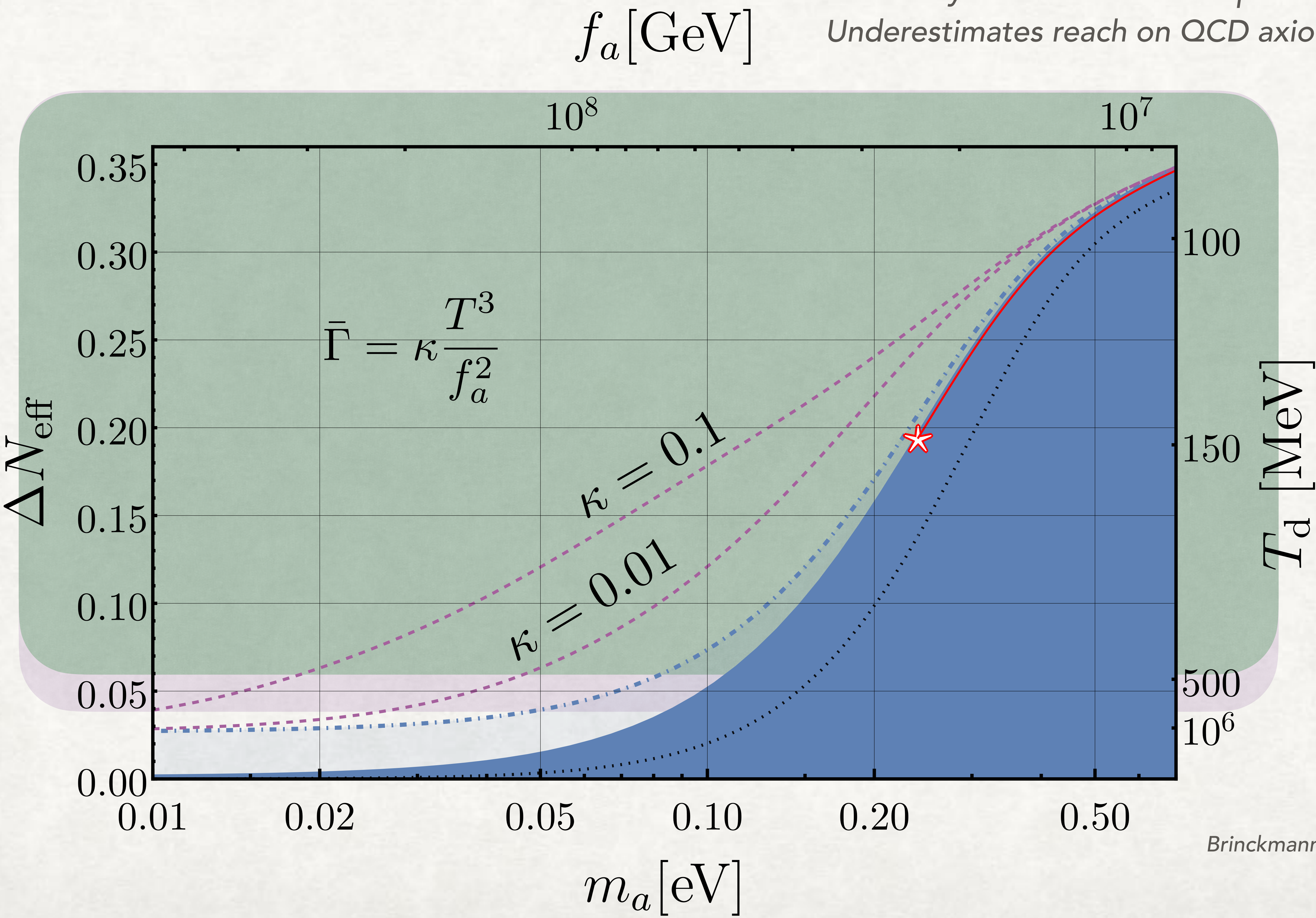


Brinckmann+18

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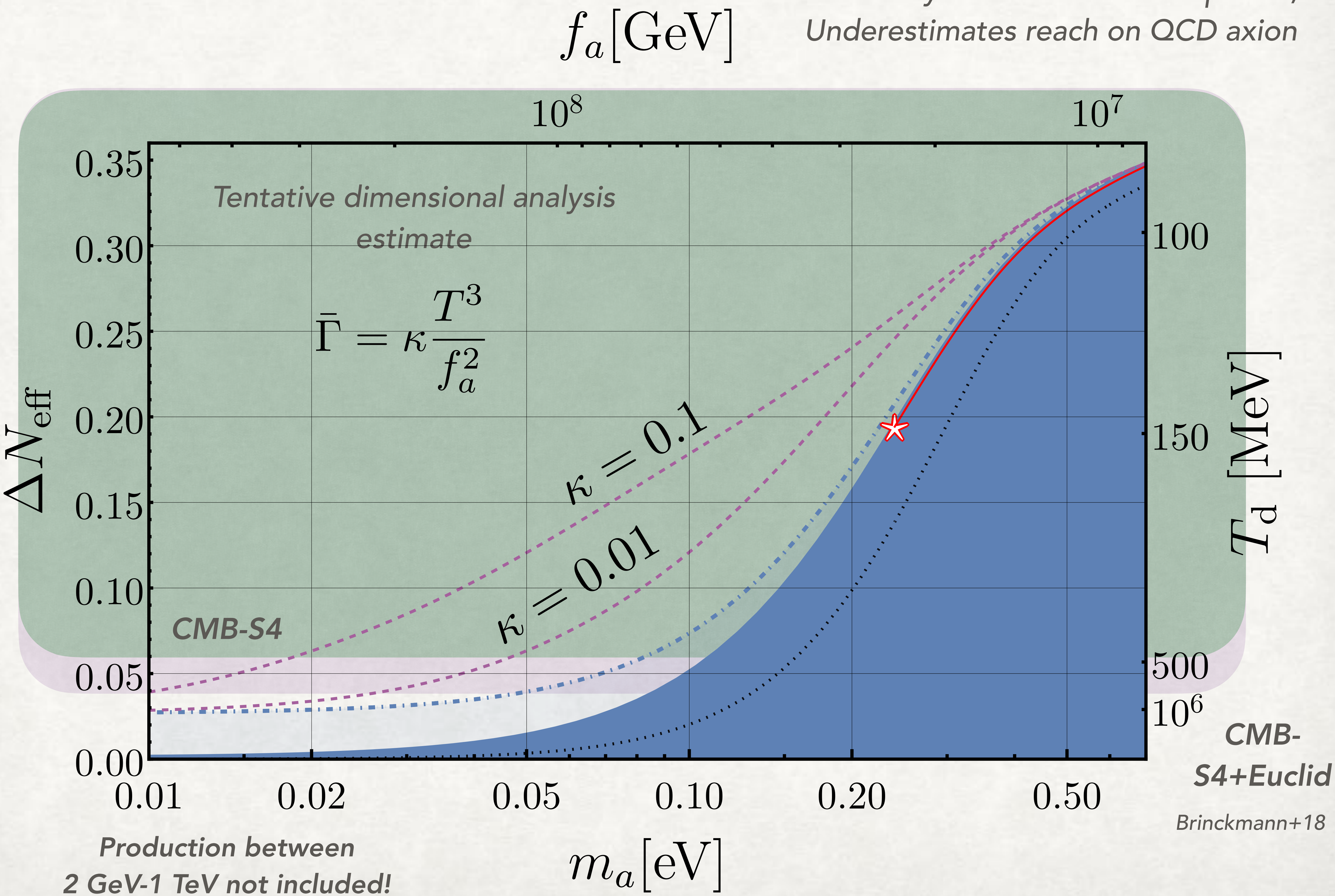



**Production between 2 GeV-1 TeV not included!**

# CONCLUSIONS

IN THE EARLY UNIVERSE, QCD AXION IS PRODUCED BOTH NON-THERMALLY
&
VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS).

HOT QCD AXION POPULATION OBSERVABLE
AS DARK RADIATION OR HOT DARK MATTER IN
CMB AND LSS SURVEYS

PROVIDES DIFFERENT AXION DETECTION STRATEGY,
INDEPENDENT OF ASTROPHYSICS AND
COLD DARK MATTER ABUNDANCE

# CONCLUSIONS

WE HAVE NOW OBTAINED A RELIABLE PRODUCTION RATE
FROM PIONS BELOW THE QCD CROSSOVER, OVERCOMING BREAKDOWN OF CHPT

INTERESTING PREDICTION: QCD AXION SPECTRUM IS SIGNIFICANTLY DISTORTED.
ENHANCEMENT OF RELIC ABUNDANCE!

NEW CONSERVATIVE “HOT DM BOUND” ON QCD AXION SET WITH COSMOLOGICAL
DATASETS CONSIDERING ONLY PRODUCTION BELOW THE CROSSOVER

UPCOMING CMB SURVEYS REQUIRE NEW (NON-PERTURBATIVE)
THEORY CALCULATION TO CONSTRAIN/DISCOVER QCD AXION

# THANK YOU!

# BACK-UP SLIDES

# PION RATE

# SCATTERING RATE

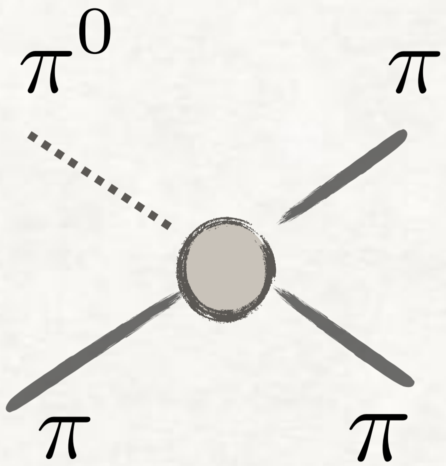
$$\Gamma^{>} = e^{\frac{E}{T}}\Gamma^{<} = \Gamma^{>}_{\rm top}/(2Ef_a^2)$$

$$\Gamma^{>}_{\rm top} \equiv \int d^4x\, e^{ik^\mu x_\mu} \left\langle \frac{\alpha_s}{8\pi} G\tilde{G}(x^\mu)\, \frac{\alpha_s}{8\pi} G\tilde{G}(0) \right\rangle$$

*During QCD crossover, quantity to be evaluated on the lattice*

*At weak coupling, the rate above is dominated by 2->2 scatterings*
*(e.g. axion-gluon->gluon-gluon, axion-pion->pion-pion)*

# LESSON FROM PIONS




*Decomposition into isospin I=0,1,2*

$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
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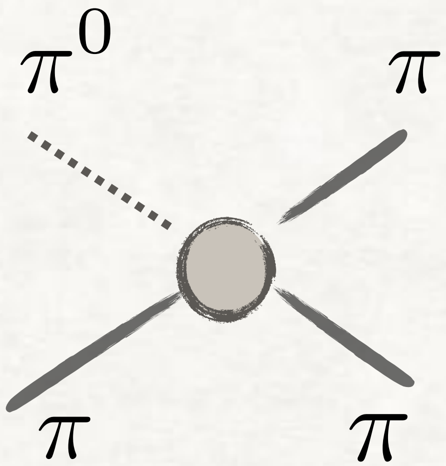


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*Expansion into partial waves*

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

*In the elastic region (<1 GeV), unitarity implies*

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

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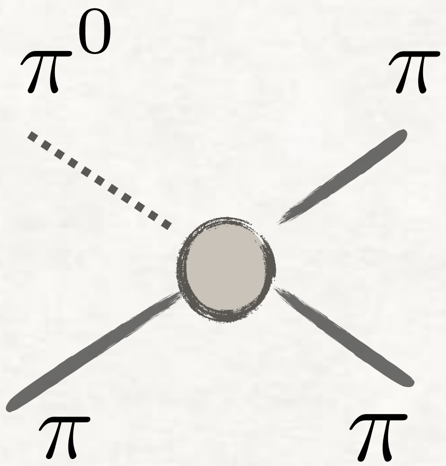


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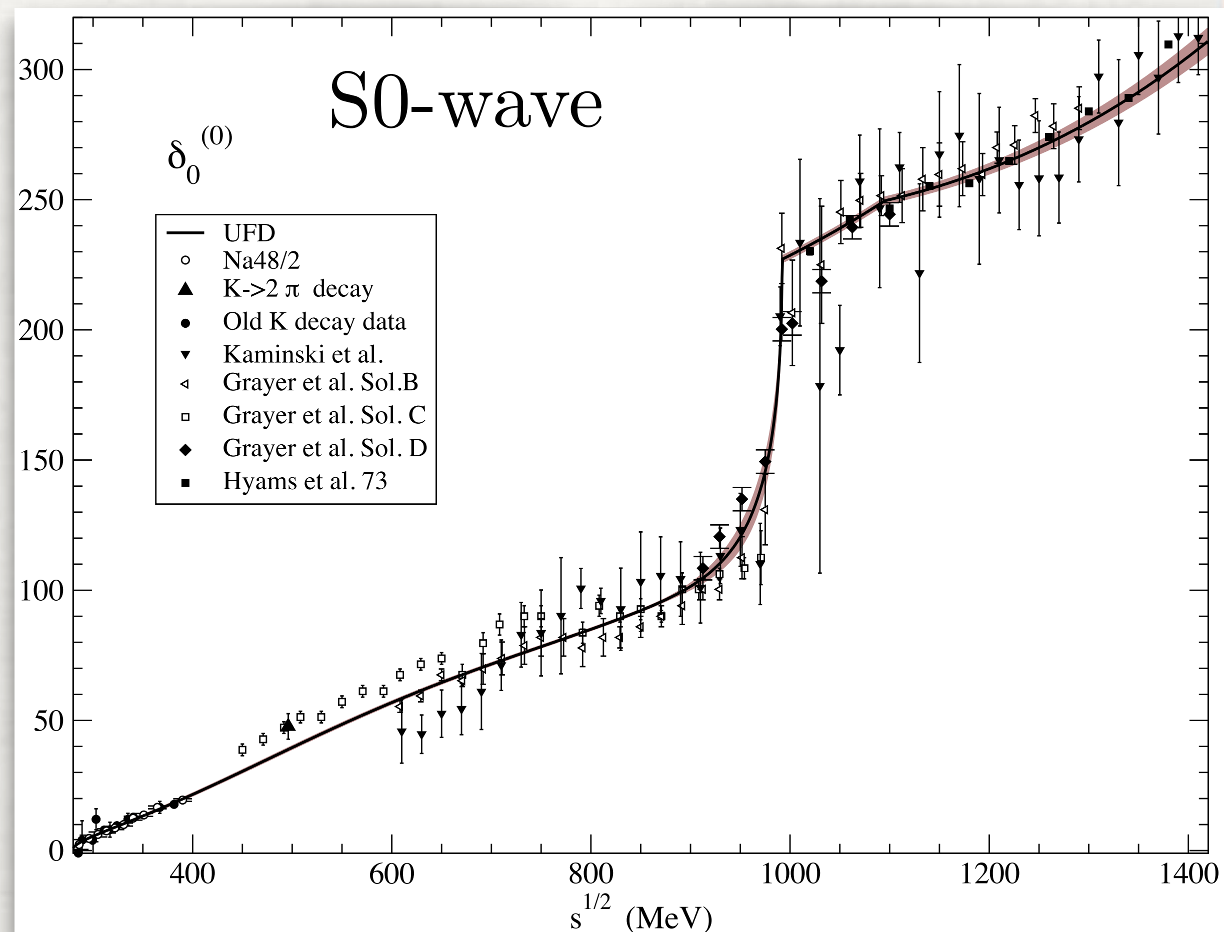


Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11

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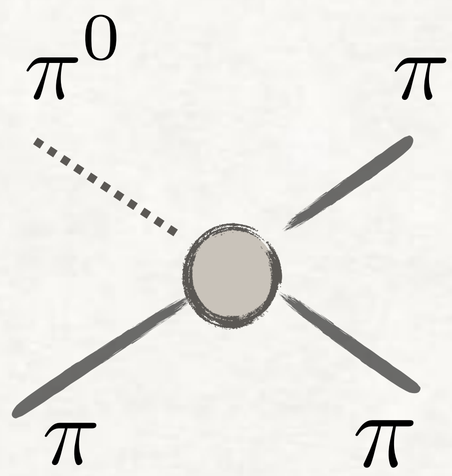


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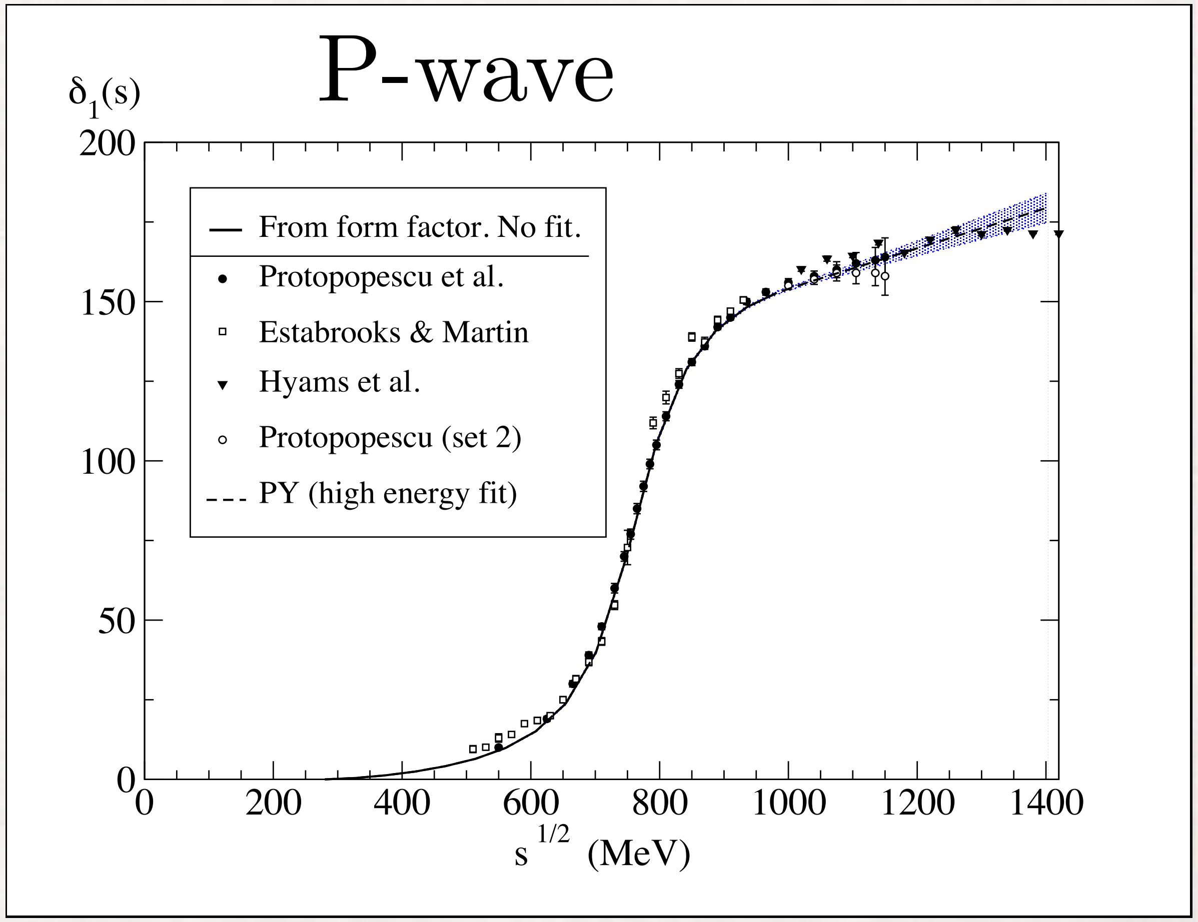
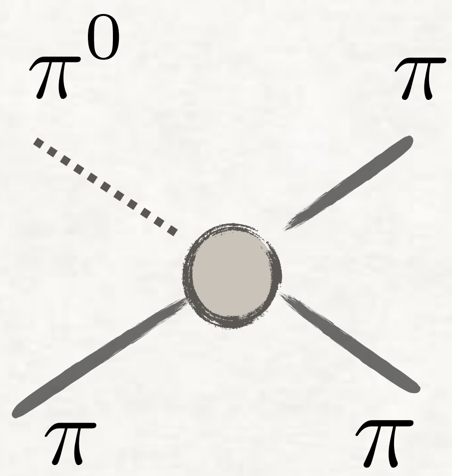



*Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11*

# LESSON FROM PIONS




*Decomposition into isospin I=0,1,2*

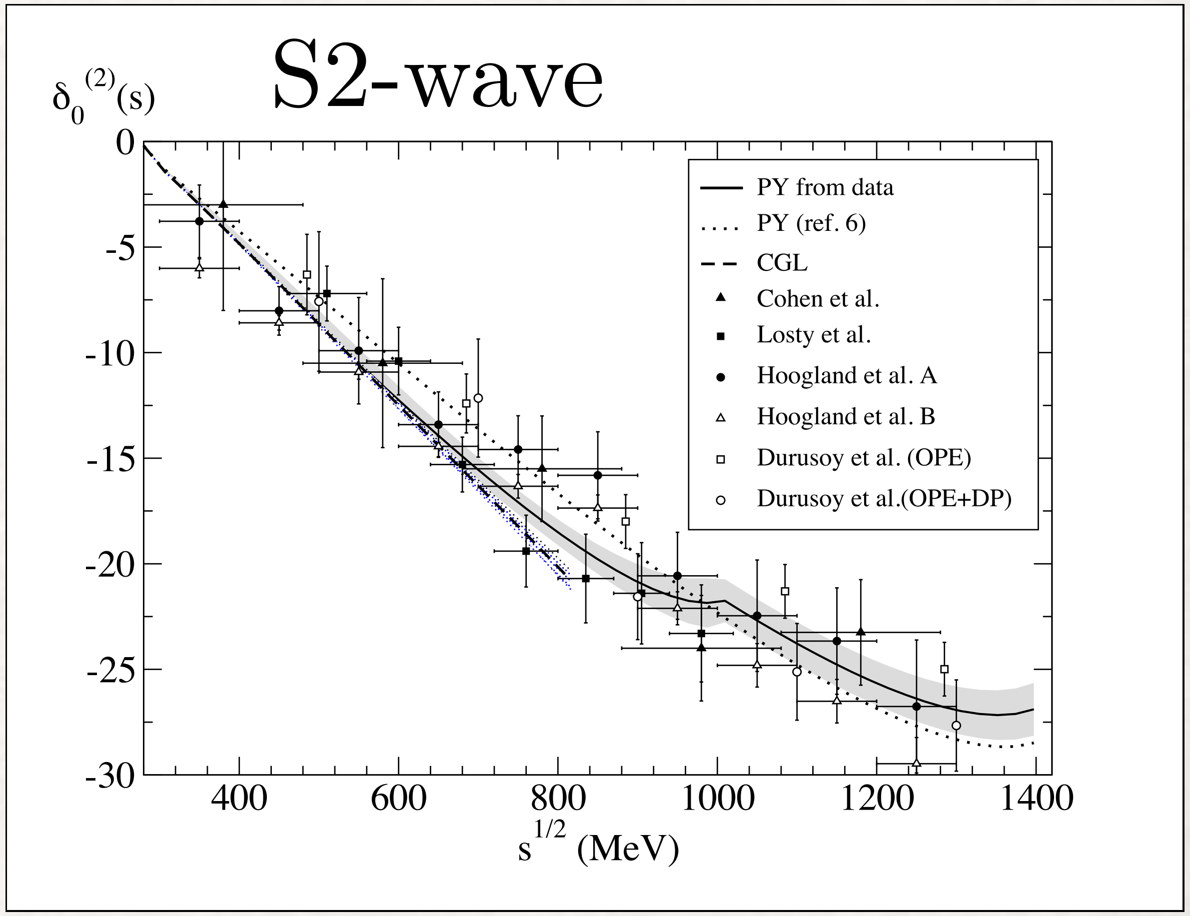
$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

*Expansion into partial waves*

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

*In the elastic region (<1 GeV), unitarity implies*

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




*Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11*

# RELATION BETWEEN AXION AND PION RATES

*Iso-singlet* *Axion-quark Lagrangian (after chiral rotations)*

*Iso-triplet*

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

*Leading Order Low Energy axion-pion Lagrangian*

$$\mathcal{L}_\pi = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger + 2B_0(M_a U^\dagger + U M_a^\dagger)\right] + \ldots \qquad U \equiv \exp(i\vec{\pi}\cdot\vec{\sigma}/f_\pi)\,,$$

*At LO axion appears only in*

$$\frac{\partial_\mu a}{2f_a} j_A^\mu \sim \mathcal{O}(M_q) \qquad \frac{m_\pi^2 f_\pi^2}{2}\mathrm{Re\,Tr}\left[(1-\epsilon\sigma^3)\left(U e^{-i\frac{a}{2f_a}(1+c_3\sigma^3)}\right)\right]\,.$$

$U(1)_A \perp SU(2)_A$
for $M_q \to 0$

*And diagonalising one gets axion couplings from*

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

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# RELATION BETWEEN AXION AND PION RATES

*At all orders in ChPT*

$$\mathcal{M}_{a\pi^i \to \pi^j \pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \cdot \mathcal{M}_{\pi^0 \pi^i \to \pi^j \pi^k} \; + \mathcal{O}(m_\pi^2 / s)$$

*E.g.*

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

*And we also checked @NLO*

*Gasser, Leutwyler*

*Di Luzio, Martinelli, Piazza 21 + Camalich, Oller 22*

# PION RATE

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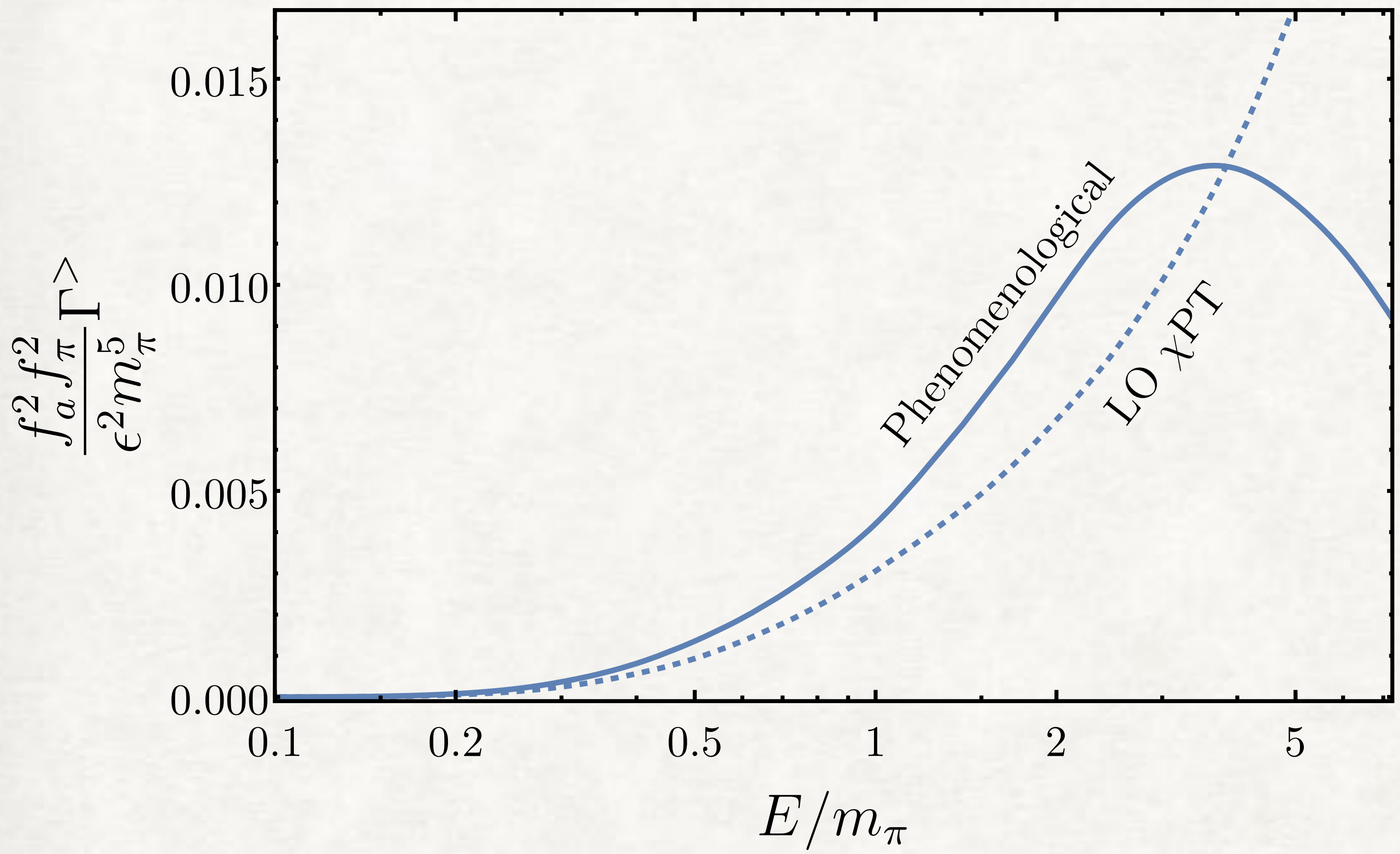
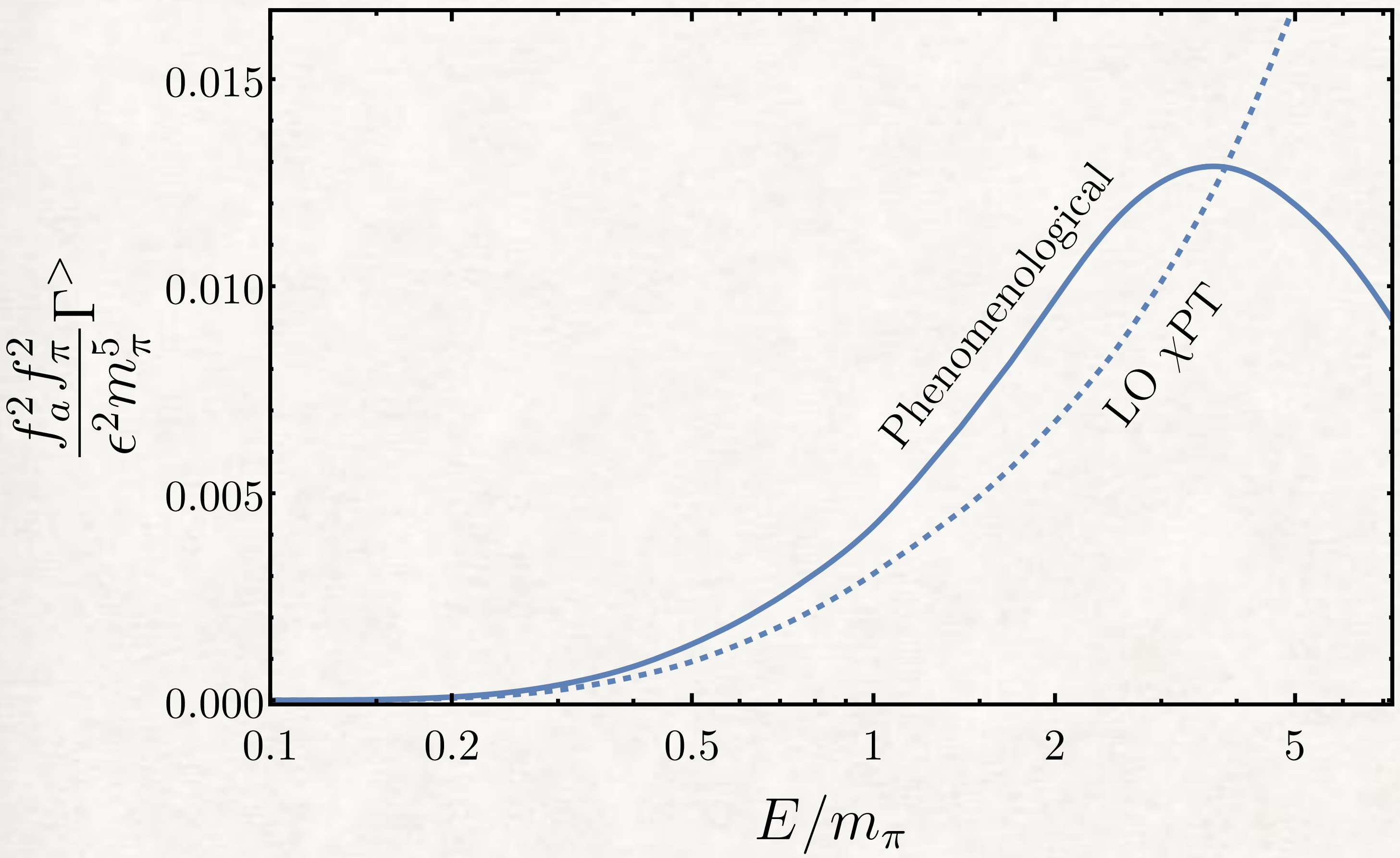
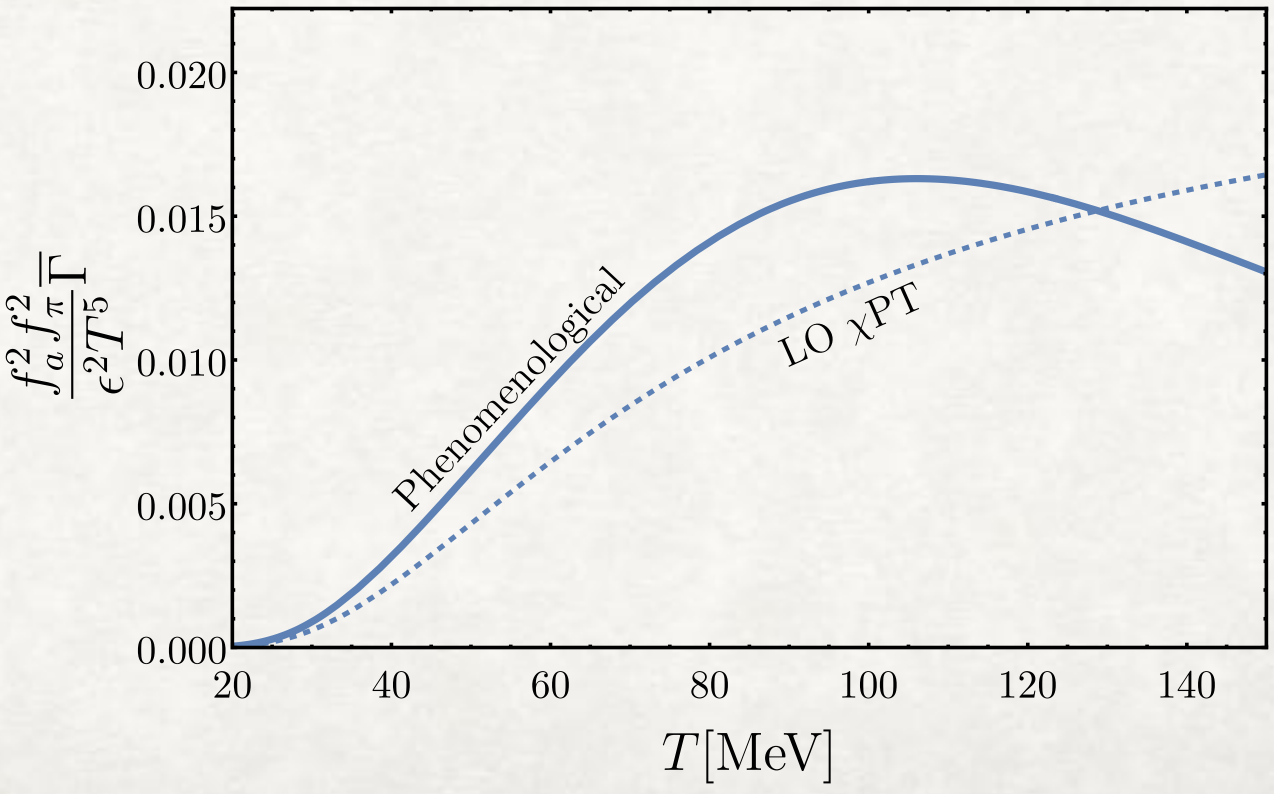


Phenomenological
LO χPT
0.015
0.010
0.005
0.000
0.1
0.2
0.5
1
2
5
$E/m_\pi$
$\frac{f_a^2 f_\pi^2}{\epsilon^2 m_\pi^5}\Gamma^>$

# PION RATE



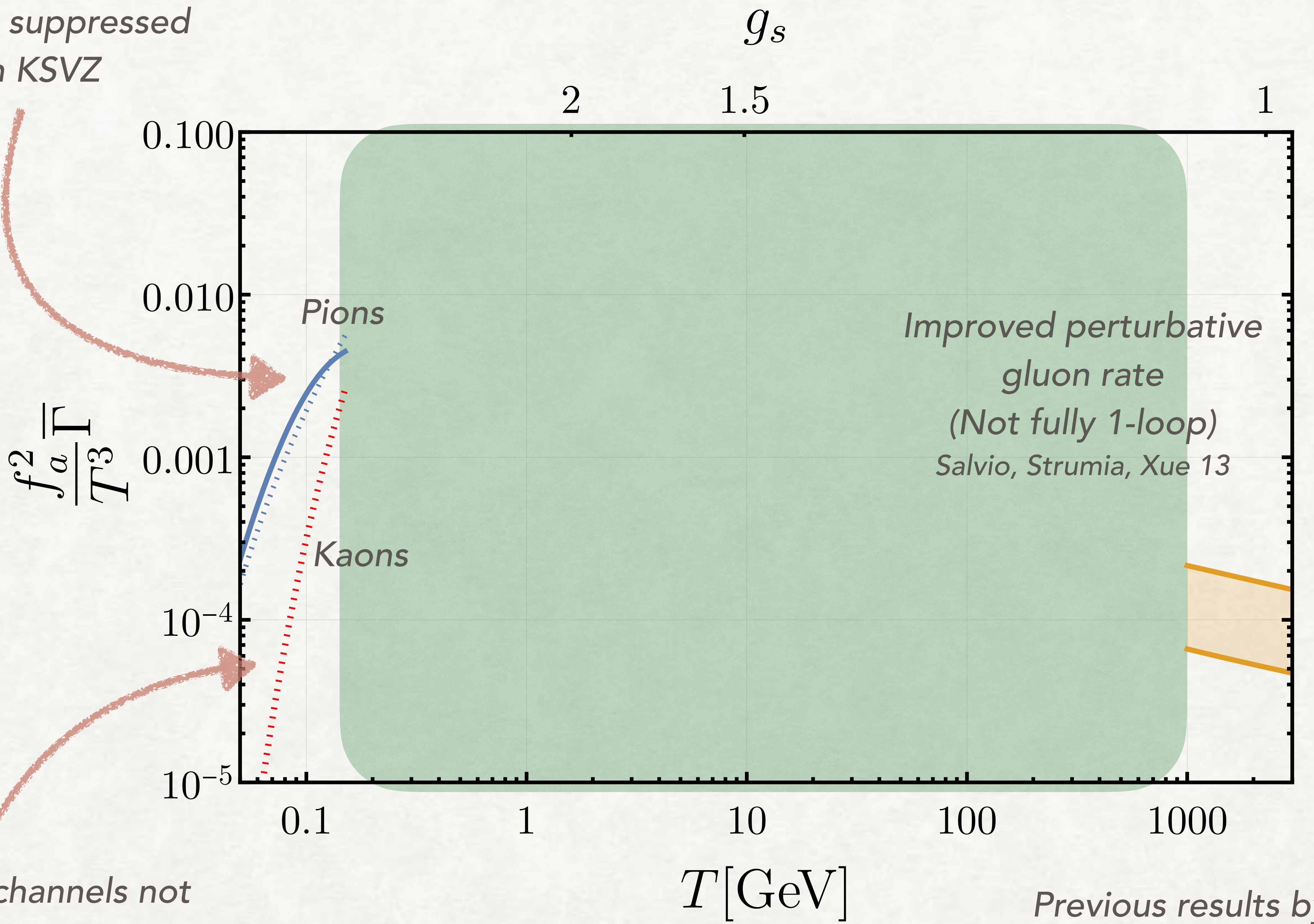

$$\overline{\Gamma} \equiv \frac{1}{n^{\text{eq}}} \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{-\frac{E}{T}} \Gamma^>$$



# MATCHING WITH HIGH-T

# MATCHING WITH HIGH-T RATE?

*Isospin suppressed in KSVZ*




*Other channels not suppressed*

*Previous results by*
*Masso, Rota, Zsembinszki 02*
*Graf, Steffen 10*

# MATCHING WITH HIGH-T RATE?

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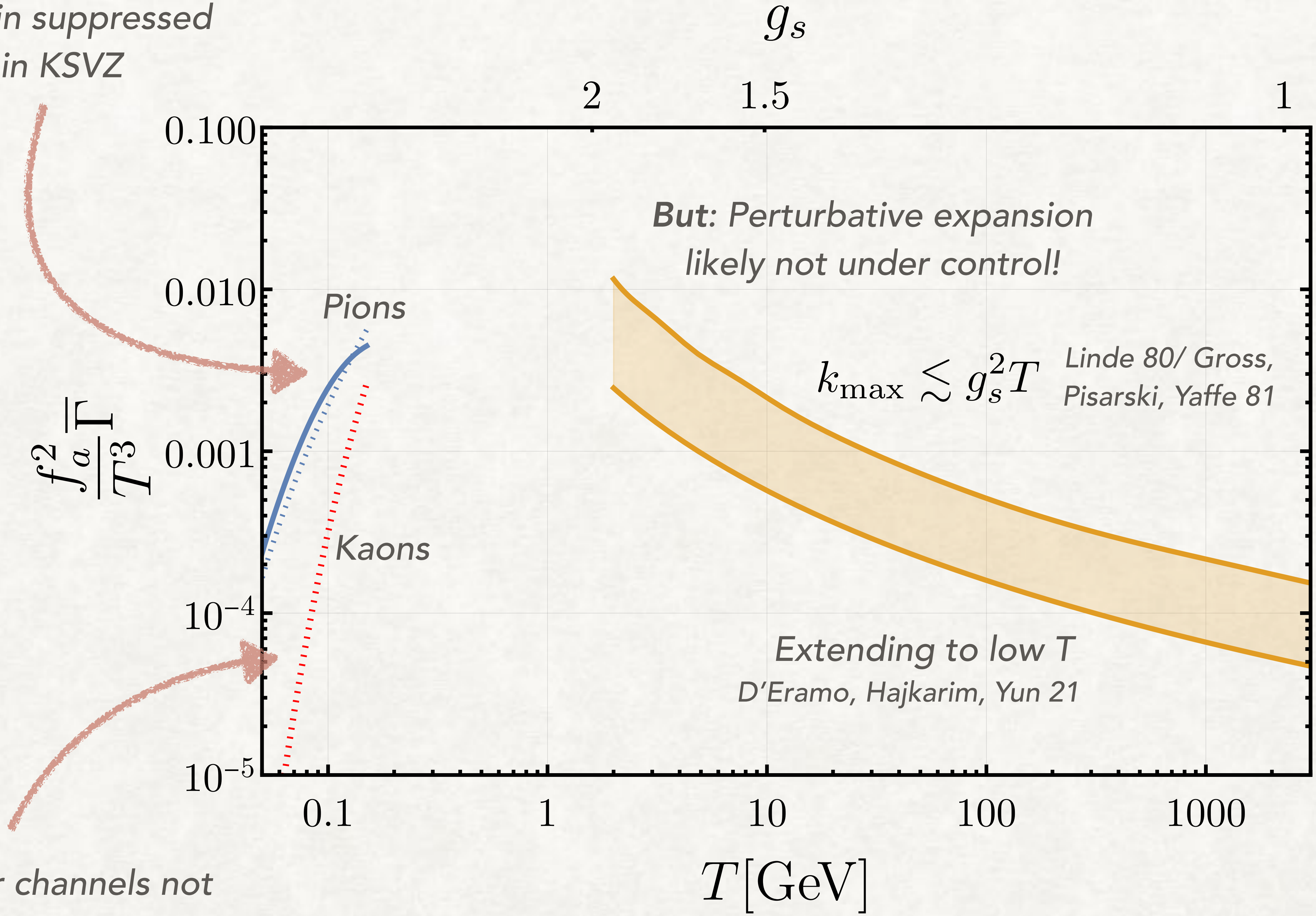
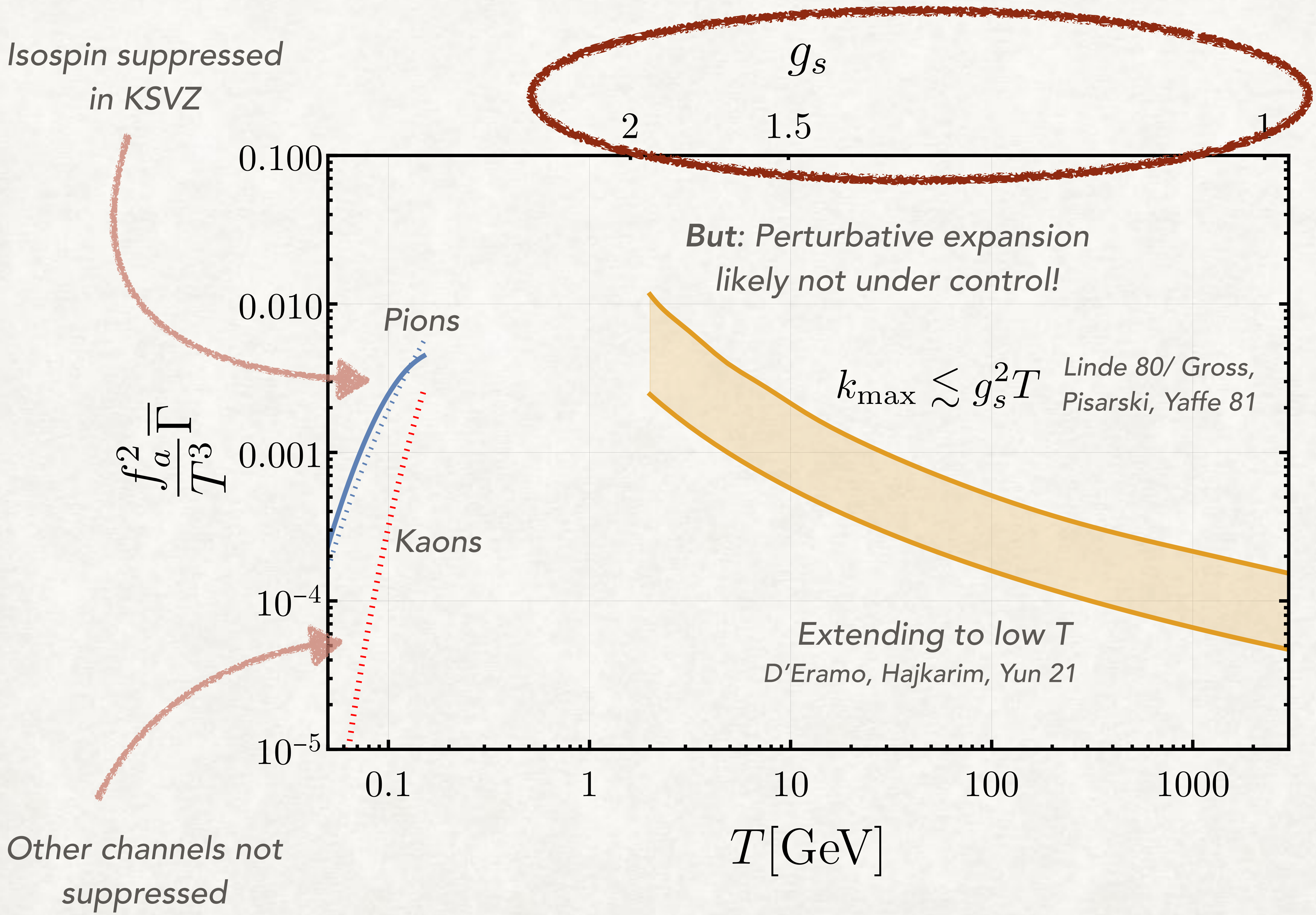



*Other channels not suppressed*

# MATCHING WITH HIGH-T RATE?



# “STRONG” SPHALERONS

*McLerran, Mottola, Shaposhnikov 90*

*In pure SU(N)*

*Non-perturbative field configurations of size*

$$\lambda_s \sim (N_c \alpha_s T)^{-1}$$

$$\Gamma^{>}_{\rm top}(k^\mu = 0) \to \Gamma_{\rm sphal} \simeq (N_c \alpha_s)^5 T^4$$

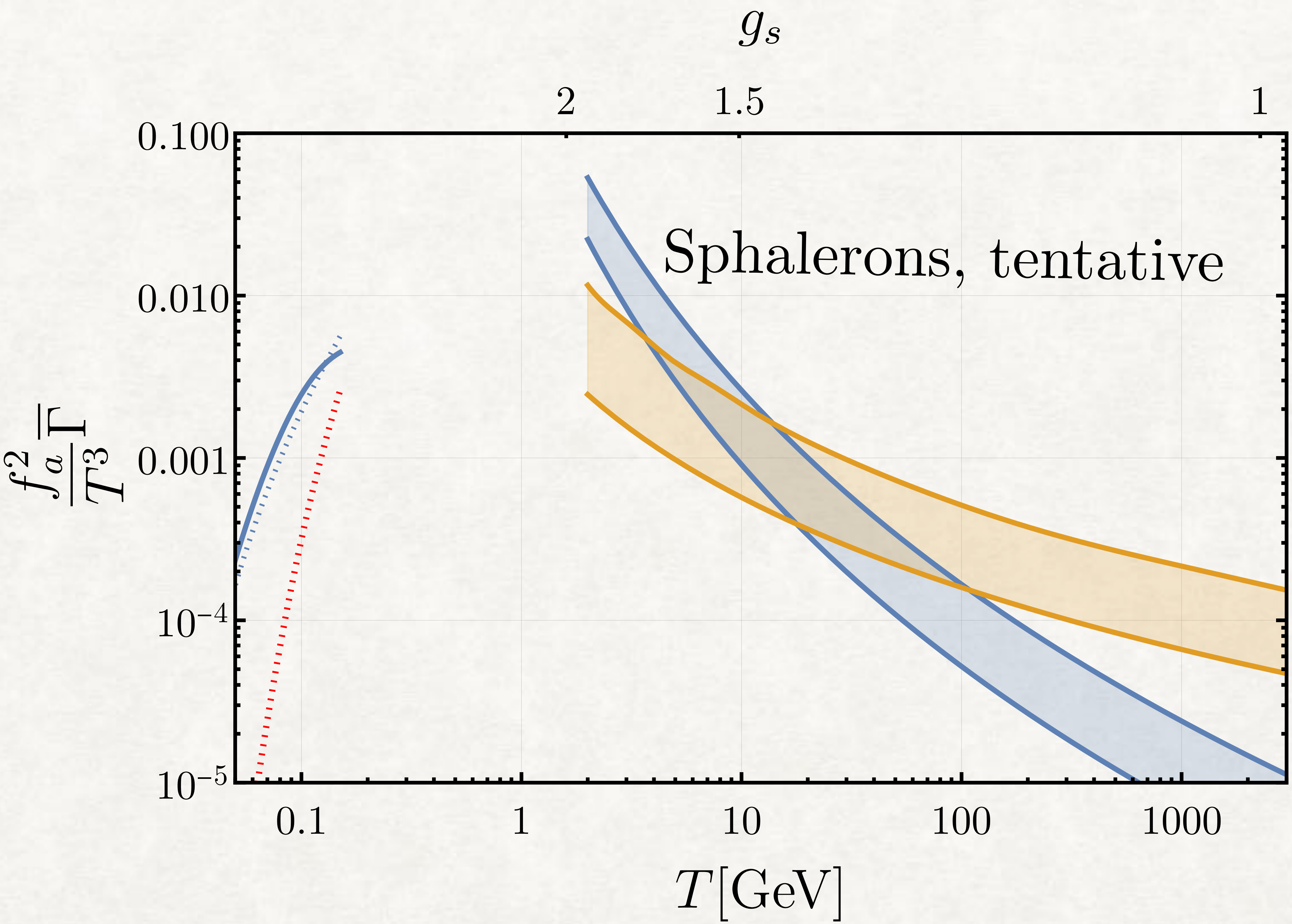
*Moore, Tassler 10*

*One then expects*

$$\overline{\Gamma}_{\rm sphal} = \frac{1}{n^{\rm eq}} \int^{|\mathbf{k}|<|\mathbf{k}_s|} \frac{d^3\mathbf{k}}{(2\pi)^3 2E} \frac{\Gamma_{\rm sphal}}{f_a^2} e^{-E/T} = \frac{(N_c\alpha_s)^5 T^3}{4\zeta_3 f_a^2} \left(1 - \left(1 + \frac{|\mathbf{k}_s|}{T}\right) e^{-|\mathbf{k}_s|/T}\right)$$

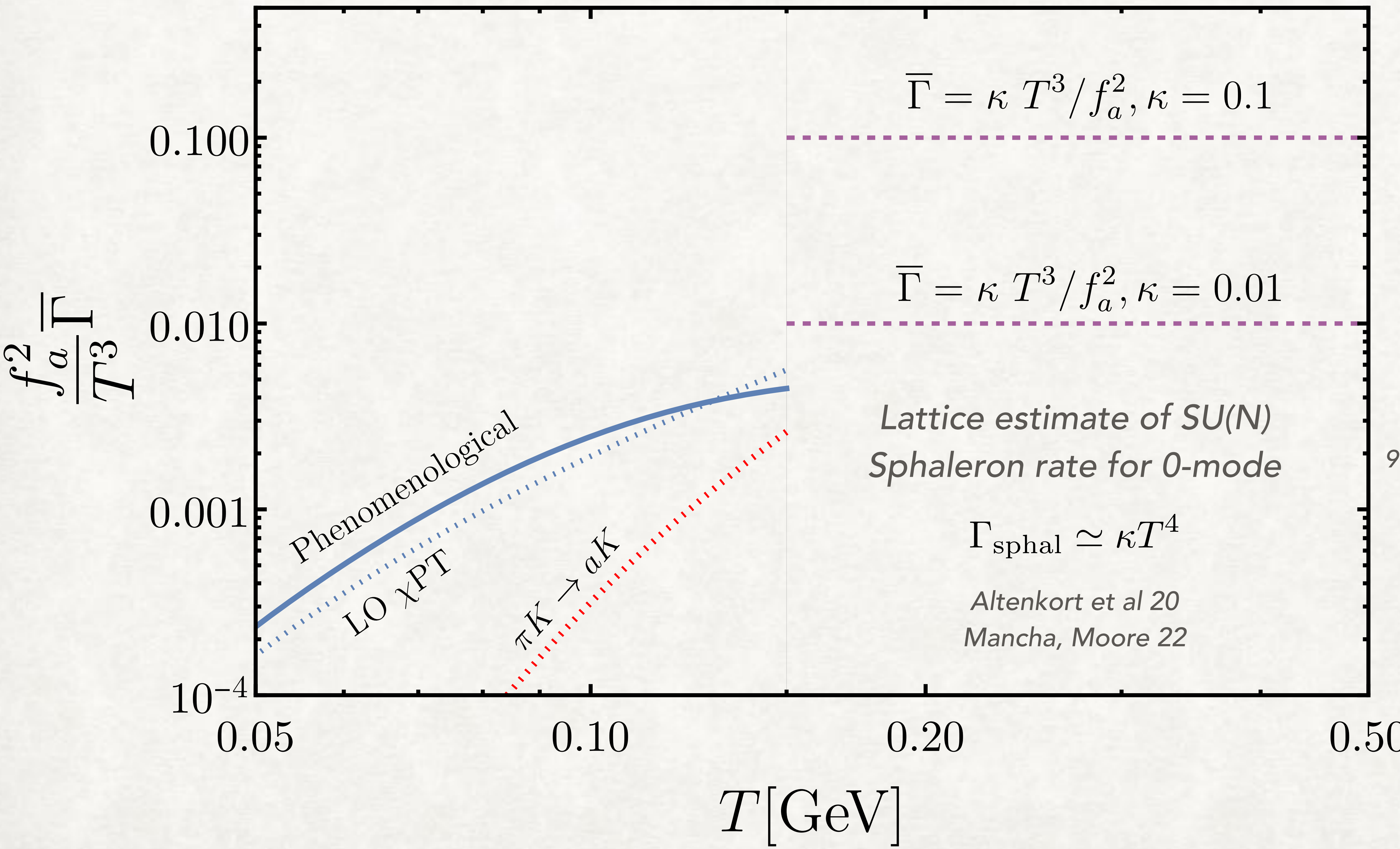
*Which can be compared with perturbative a+g rates derived in the literature*
*(which are not expected to be reliable down to T~2 GeV )*

# "STRONG" SPHALERONS




*Signals that non-perturbative effects may become important at T>>GeV*

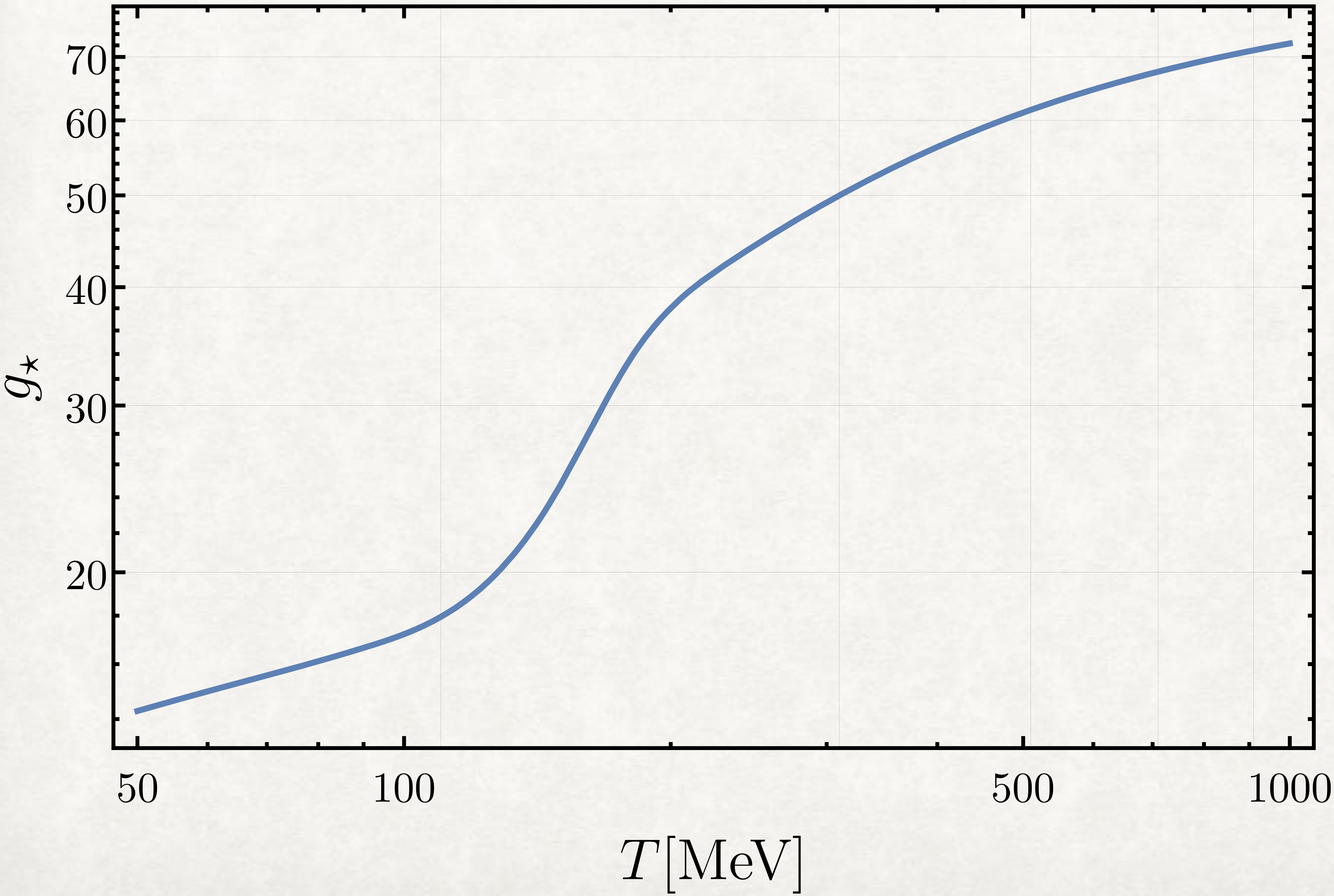
# RATE ESTIMATES



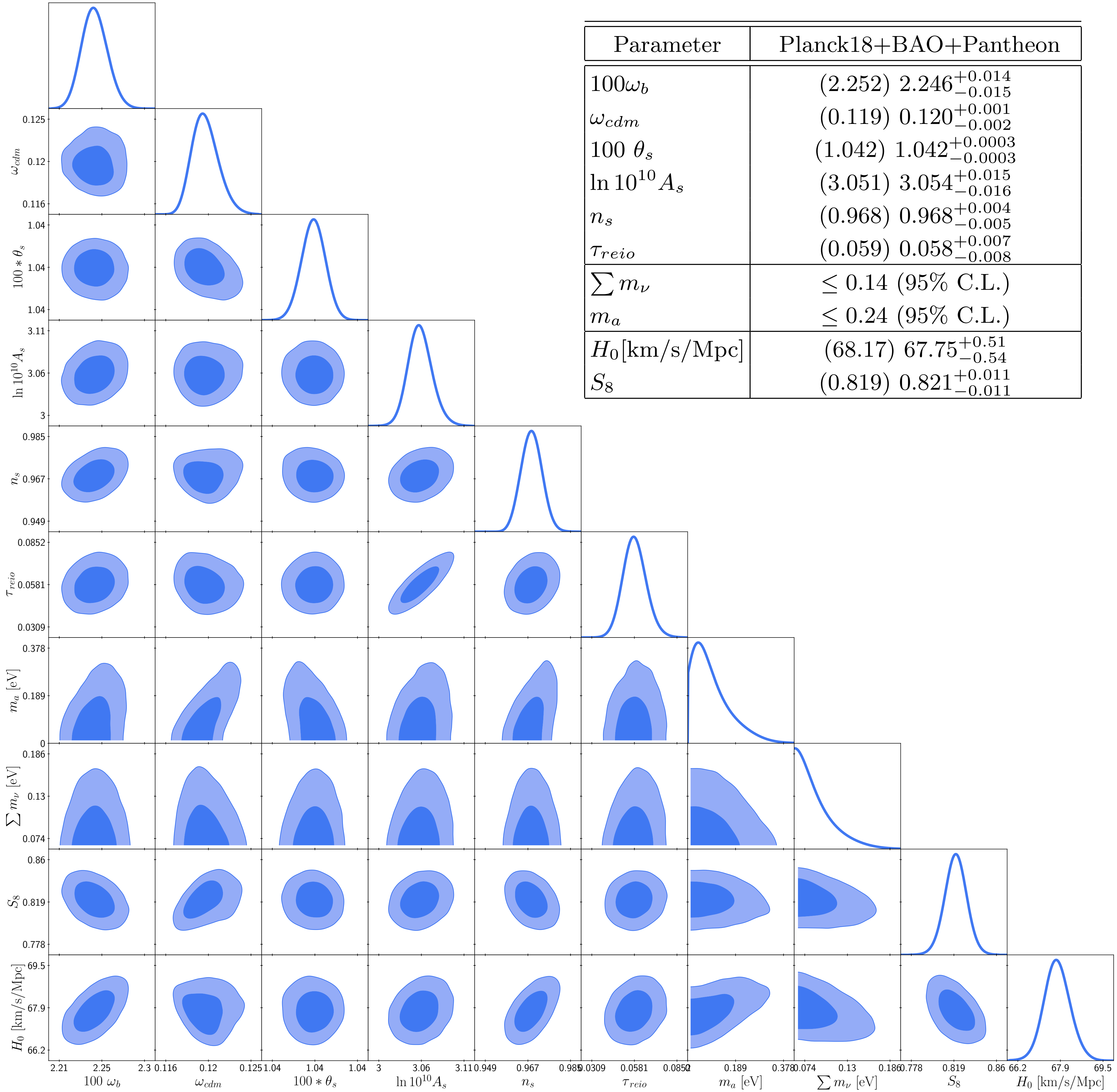

McLerran et al 90/Tassler,Moore 10/…

# OTHER

## Number of relativistic degrees of freedom



# POSTERIORS



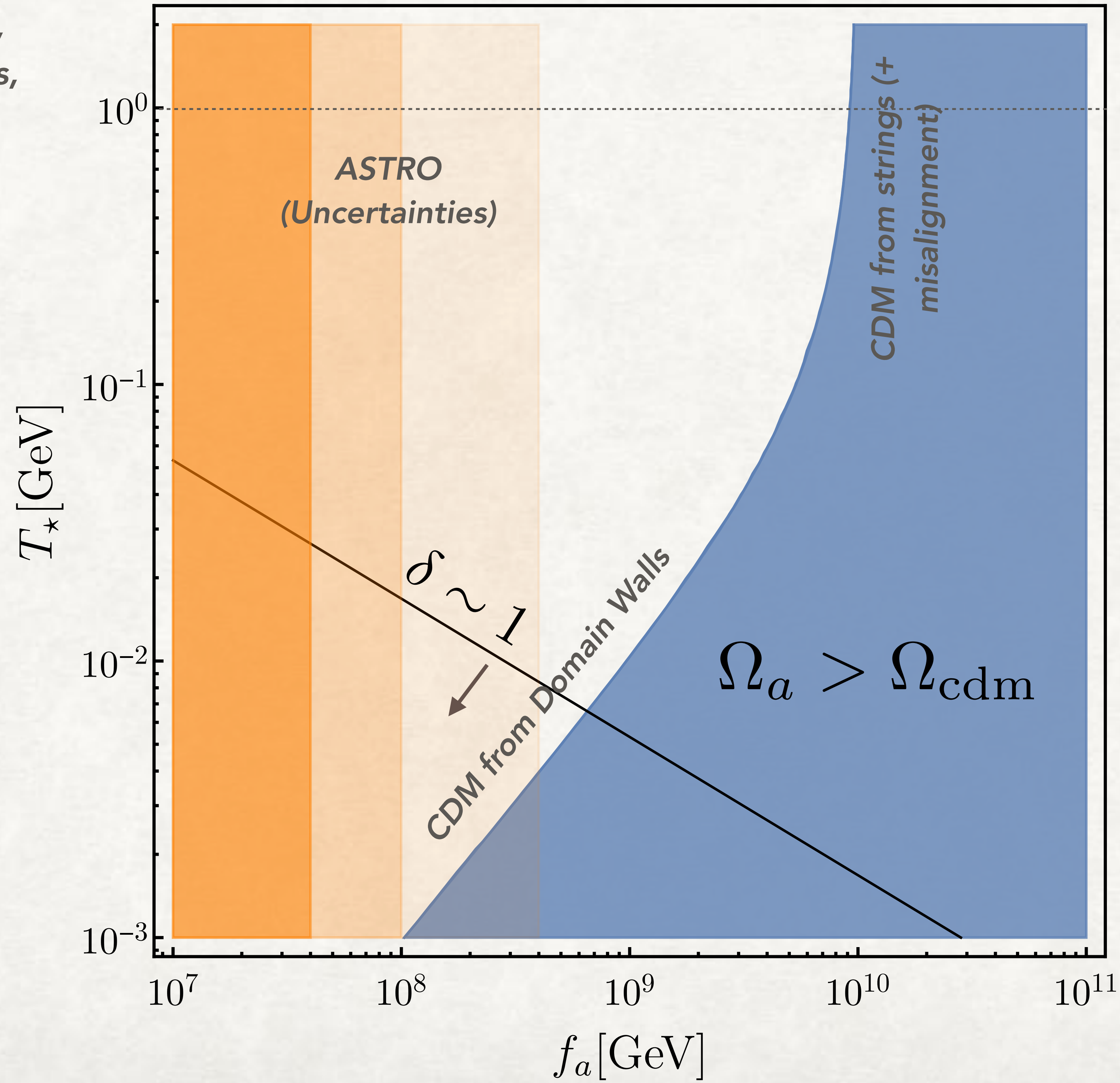

| Parameter | Planck18+BAO+Pantheon |
|---|---|
| $100\omega_b$ | $(2.252)\ 2.246^{+0.014}_{-0.015}$ |
| $\omega_{cdm}$ | $(0.119)\ 0.120^{+0.001}_{-0.002}$ |
| $100\ \theta_s$ | $(1.042)\ 1.042^{+0.0003}_{-0.0003}$ |
| $\ln 10^{10} A_s$ | $(3.051)\ 3.054^{+0.015}_{-0.016}$ |
| $n_s$ | $(0.968)\ 0.968^{+0.004}_{-0.005}$ |
| $\tau_{reio}$ | $(0.059)\ 0.058^{+0.007}_{-0.008}$ |
| $\sum m_\nu$ | $\leq 0.14$ (95% C.L.) |
| $m_a$ | $\leq 0.24$ (95% C.L.) |
| $H_0$[km/s/Mpc] | $(68.17)\ 67.75^{+0.51}_{-0.54}$ |
| $S_8$ | $(0.819)\ 0.821^{+0.011}_{-0.011}$ |

# AXION COLD DARK MATTER

## (PQ SYMMETRY BROKEN AFTER INFLATION)

$$\Omega_a = \Omega_{\rm mis} + \Omega_{\rm strings} + \Omega_{\rm dw}$$

*Adapted from Ferrer, Masso, Panico, Pujolàs, FR 18*



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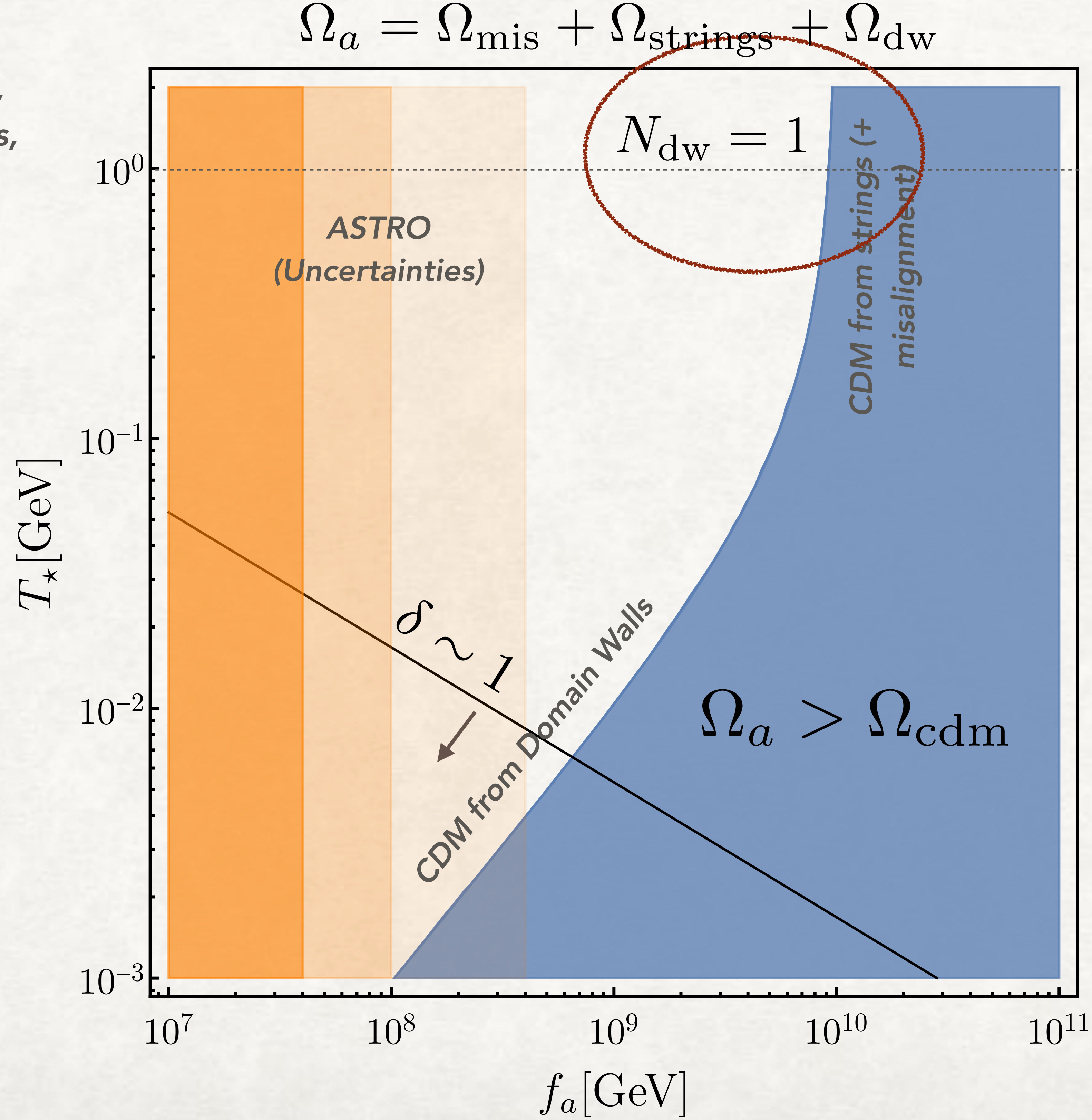


*Generically only in toy model with one fermion charged under PQ*

*Relic abundance from strings under active investigation*

*.../Gorghetto, Hardy, Villadoro 18, 20/ Hindmarsh+19,21/ Buschmann+21*

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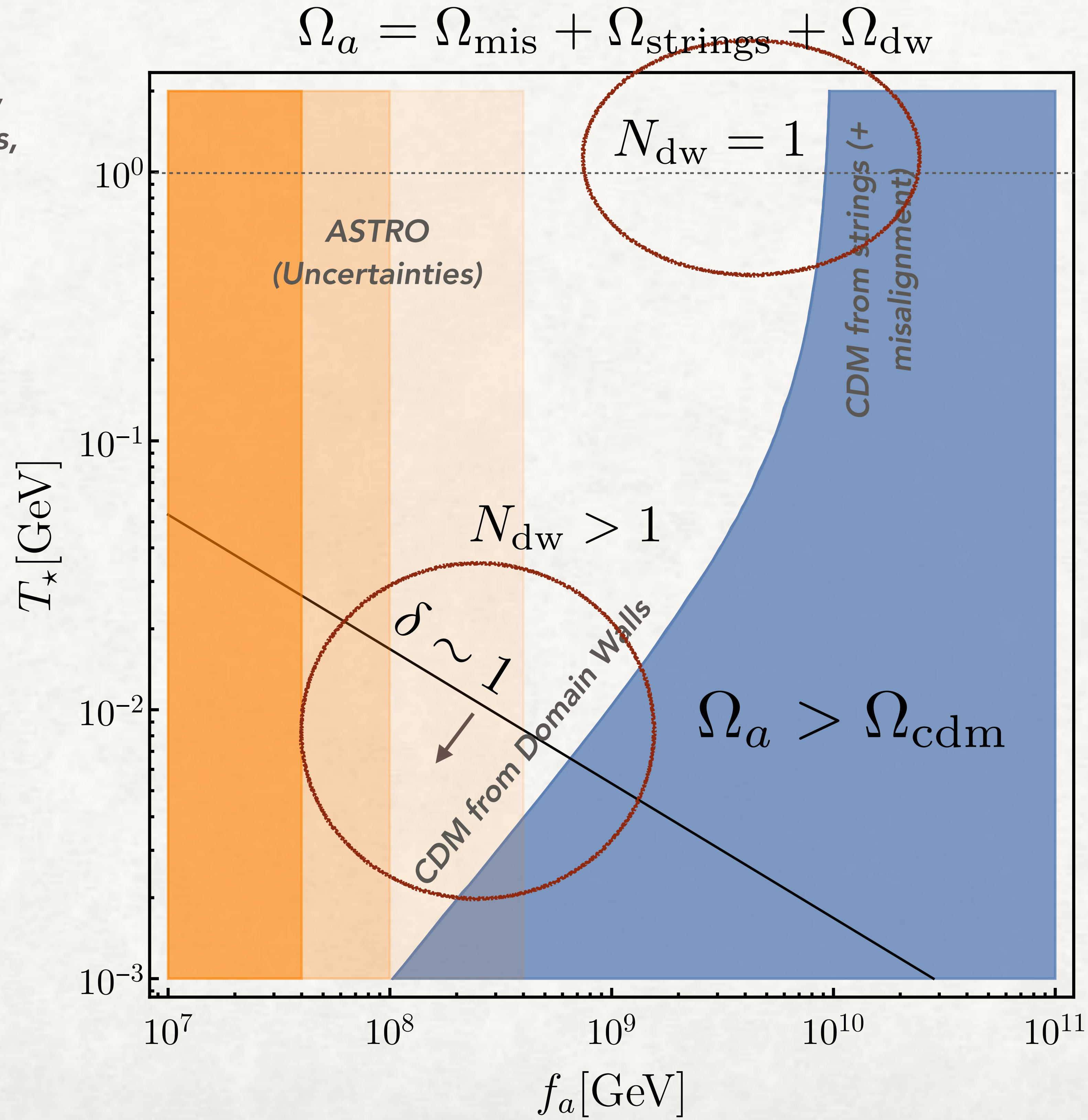


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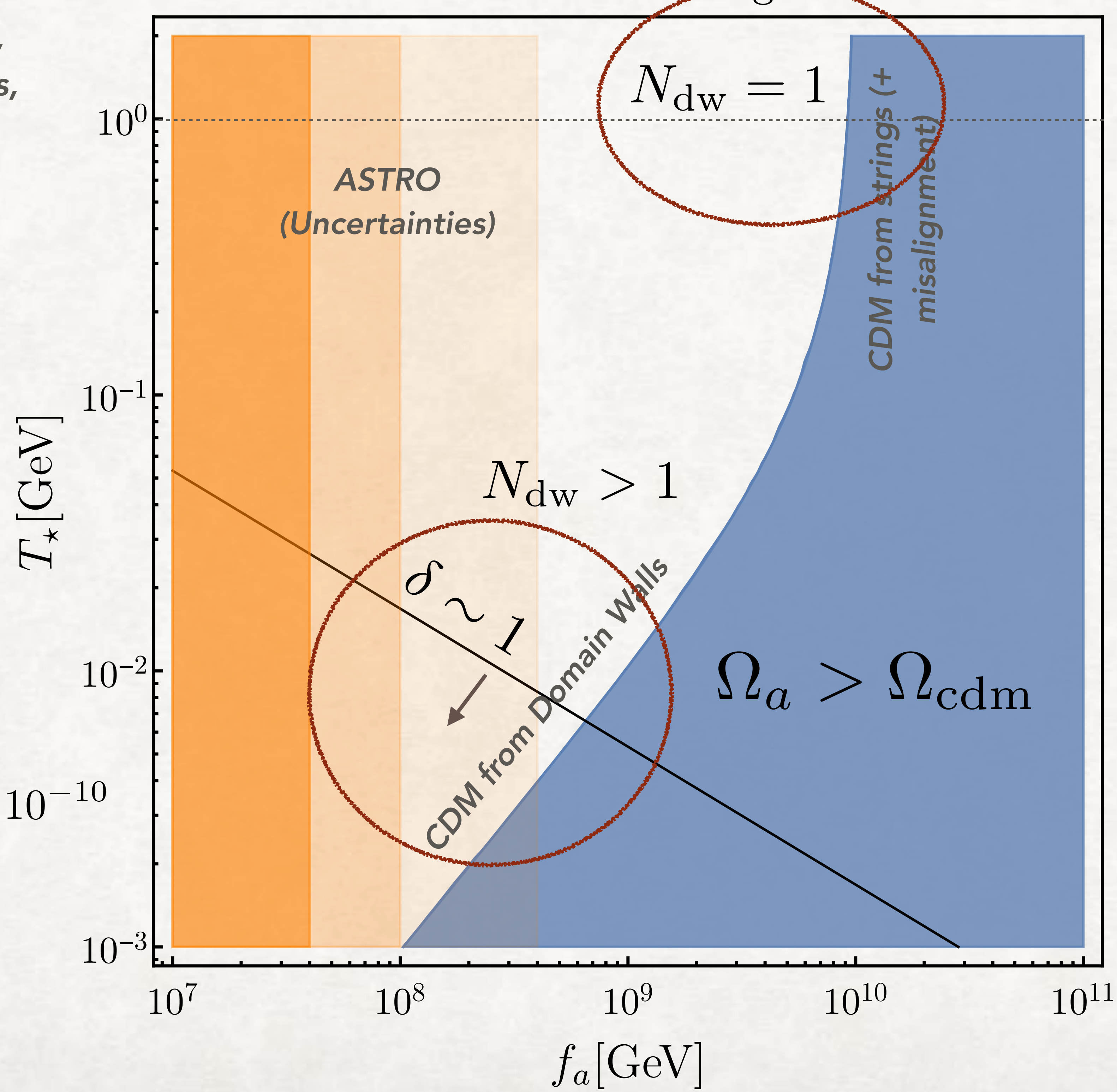


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*.../Gorghetto, Hardy, Villadoro 18, 20/ Hindmarsh+19,21/ Buschmann+21*

*More generic, but leaves only small region depending on astro*

$$\Delta\bar{\theta} \sim \Delta V/\Lambda_{\text{QCD}}^4 \lesssim 10^{-10}$$

*+ Observable nEDM/pEDM!*

*Relic abundance from DWs not totally settled, serves as estimate*

*.../Kawasaki, Saikawa 14/...*