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Axion Dark Matter and lattice field theory

Enrico Rinaldi

Lawrence Livermore National Laboratory

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LLNL-PRES-669543

Outline

- General features of axions as a solution of the "Strong CP" problem
- Current physical constraints on axion models' parameters based on dark matter interpretation
- Lattice simulations and input to axion cosmology

[Berkowitz, Buchoff, Rinaldi, arxiv:1505.07455, PRD 92 *034507*]

Outline

- General features of axions as a solution of the "Strong CP" problem
- Current physical constraints on axion models' parameters based on dark matter interpretation
- Lattice simulations and input to axion cosmology
- **GOAL**: Lower bound on the axion mass using lattice QCD as input to axion cosmology

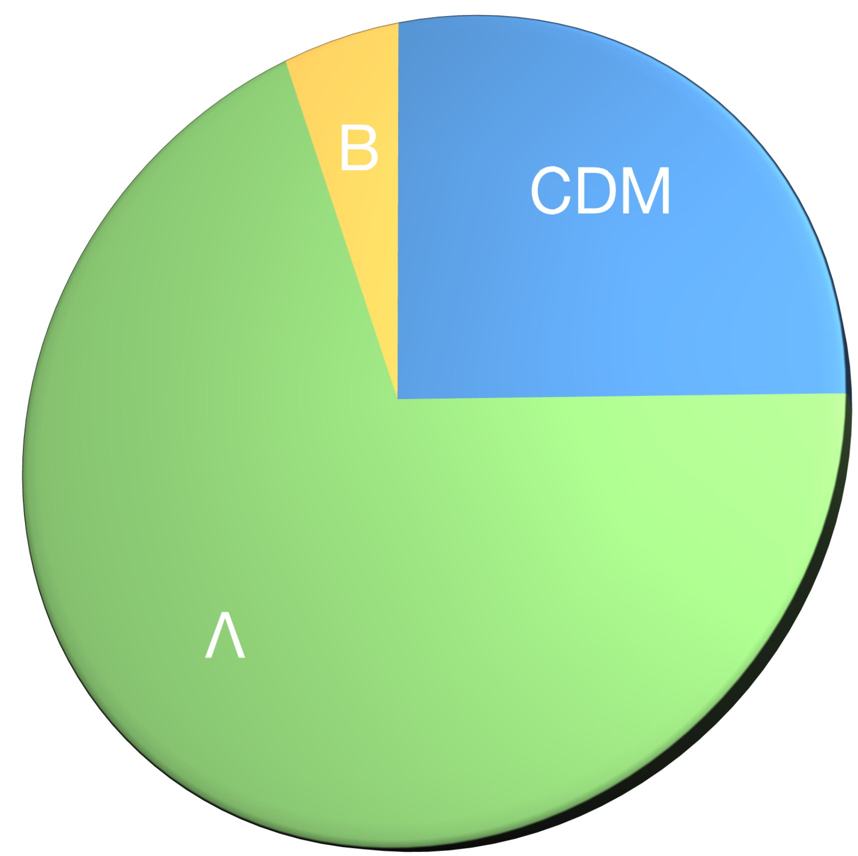
[Berkowitz, Buchoff, Rinaldi, arxiv:1505.07455, PRD 92 *034507*]

[Peccei & Quinn: PRL 38 (1977) 1440, PR D16 (1977) 1791]

[Preskill, Wise & Wilczek, Phys Lett B 120 (1983) 127-132]

Axion dark matter

- Axions were originally proposed to deal with the Strong CP Problem
  - They also form a plausible DM candidate
  - The axion energy density requires non-perturbative QCD input
- Being sought in ADMX (LLNL, UW) & CAST-IAXO (CERN) with large discovery potential in the next few years
- Requiring $\Omega_a \leq \Omega_{CDM}$ yields a lower bound on the axion mass today



Ω_{tot} = 1.000(7)
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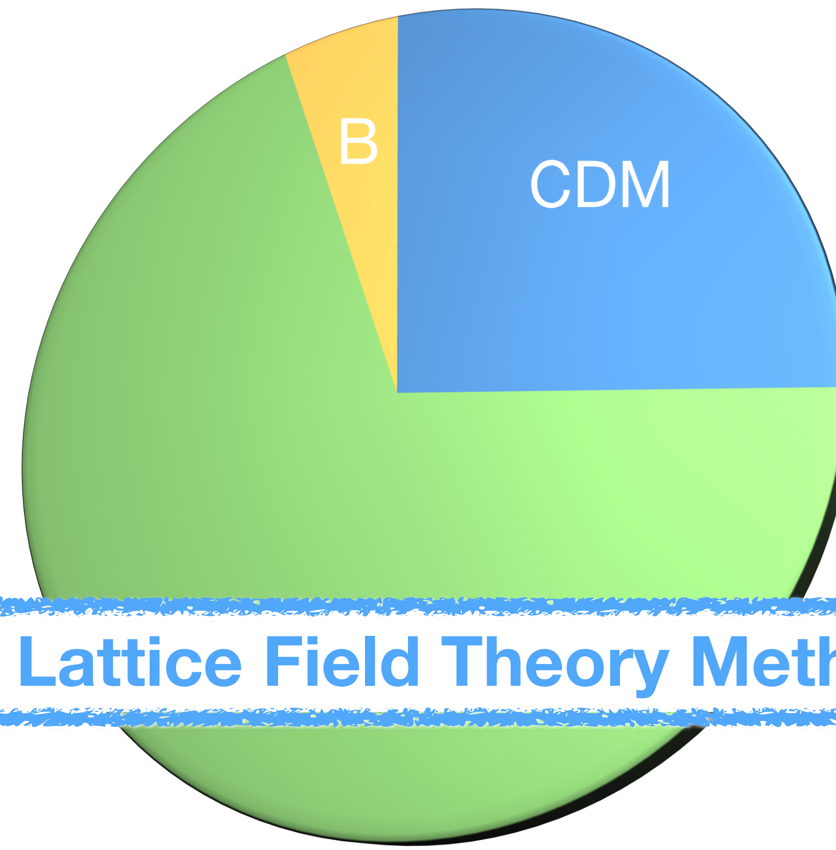
Lattice Field Theory Methods



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"Strong CP" problem

- QCD has a parameter, θ

$$\mathcal{L}_{\rm QCD} \ni \theta \, \frac{1}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

  - Controls QCD CP violation
  - Topological

$$Q = \frac{1}{32\pi^2} \int d^4x \, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \in \mathbb{Z}$$

- θ can take any value in (-π,π]

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- Neutron EDM ≲ 3 10^{-26} e cm
  [Baker et al., PRL 97, 131801 (2006) / hep-ex/0602020]
  - ⟹ |θ| ≲ 10^{-10}

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

Why is θ so small?

[Peccei & Quinn: PRL 38 (1977) 1440, PR D16 (1977) 1791]

Axions as a solution

- Couple to topological charge

$$\mathcal{L}_{\text{axions}} = \frac{1}{2}(\partial_\mu a)^2 + \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

- Otherwise have shift symmetry

$$a \to a + \alpha$$

- Amenable to effective theory treatment

$$V_{\text{eff}} \sim \cos\left(\theta + c\langle a \rangle\right)$$

- Axion mass from instantons effects

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

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QCD Topological Susceptibility

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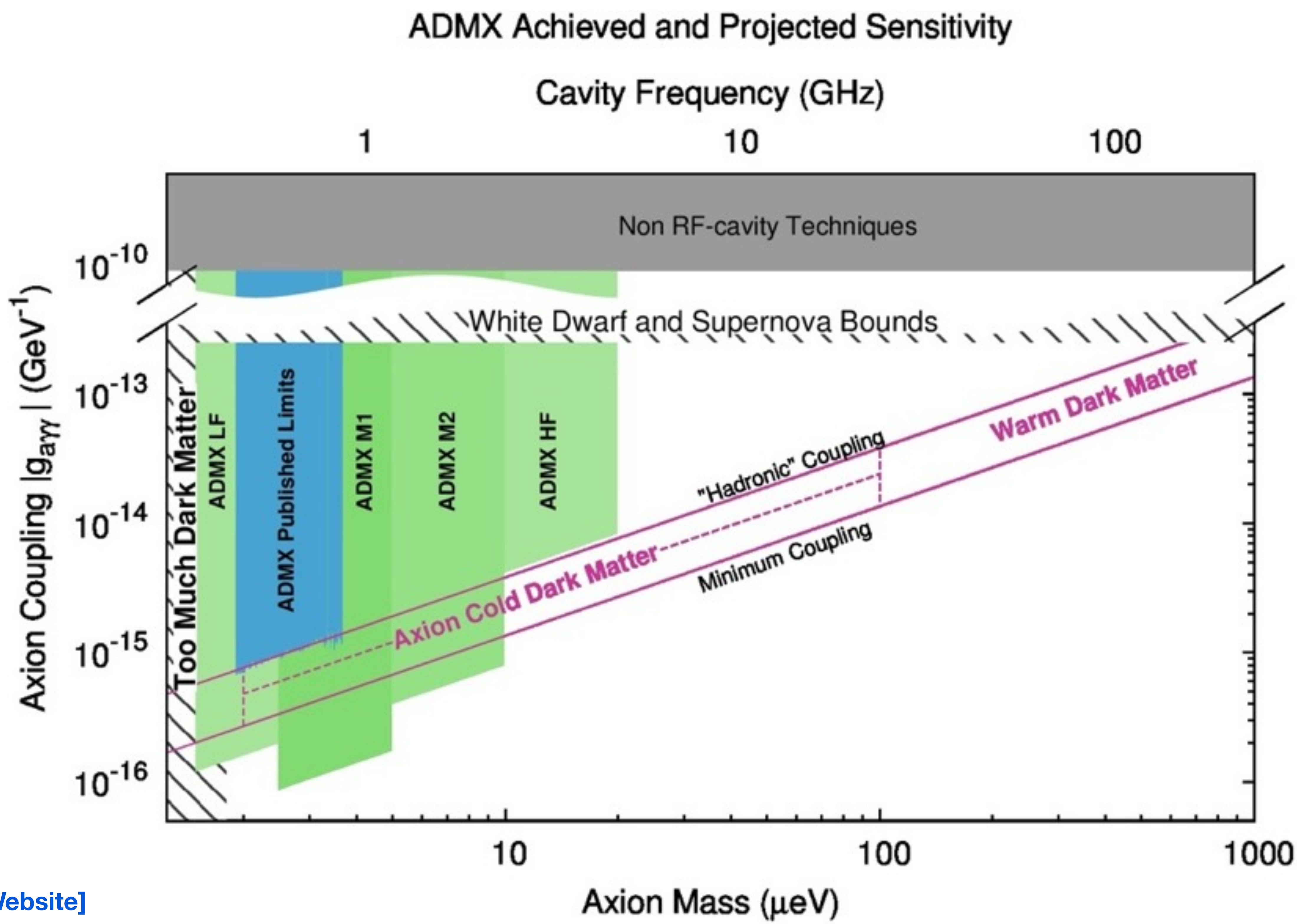
Current axion constraints



[ADMX Website]

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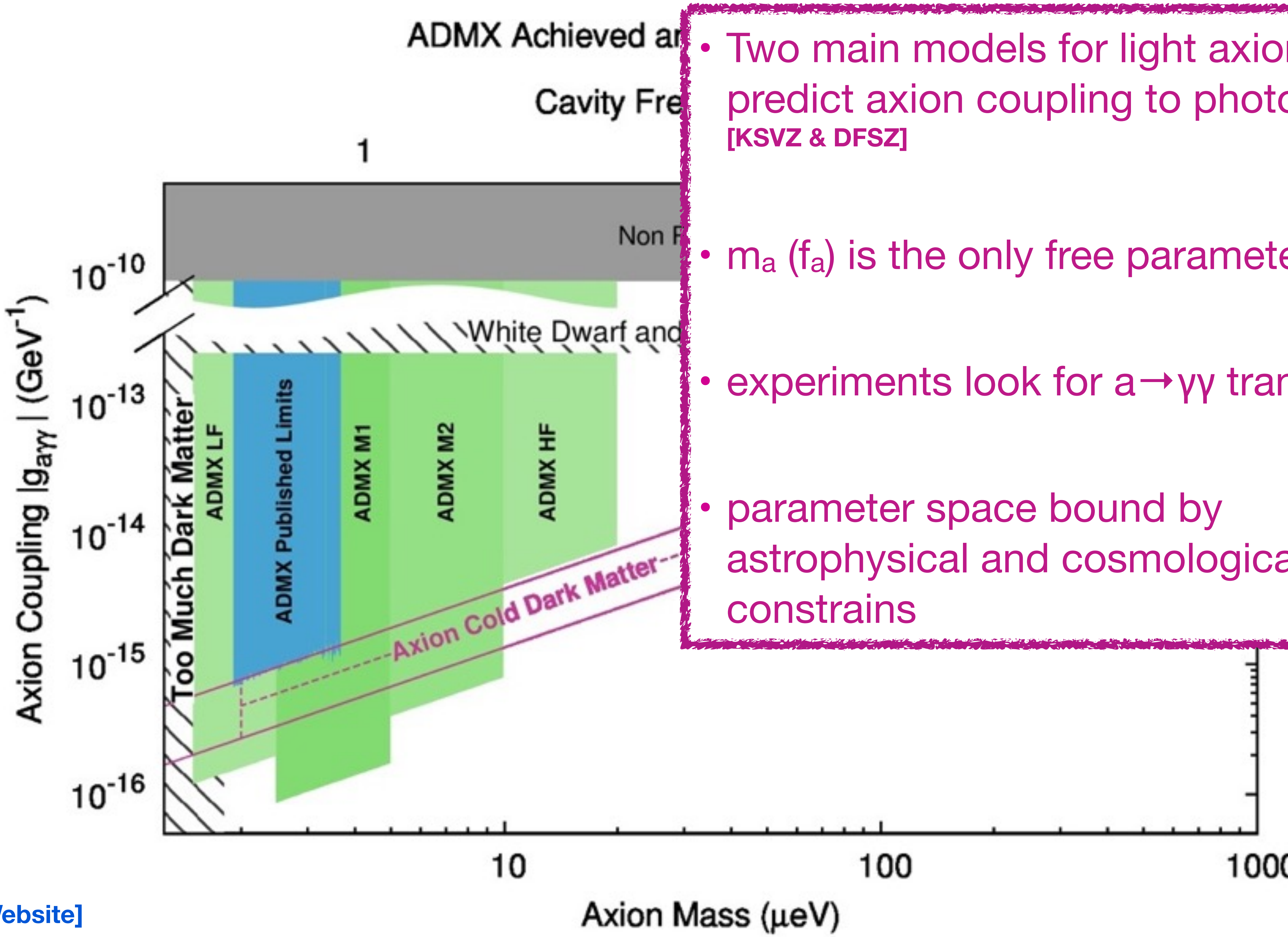

- Two main models for light axions predict axion coupling to photons **[KSVZ & DFSZ]**
- m_a (f_a) is the only free parameter
- experiments look for $a \to \gamma\gamma$ transitions
- parameter space bound by astrophysical and cosmological constrains

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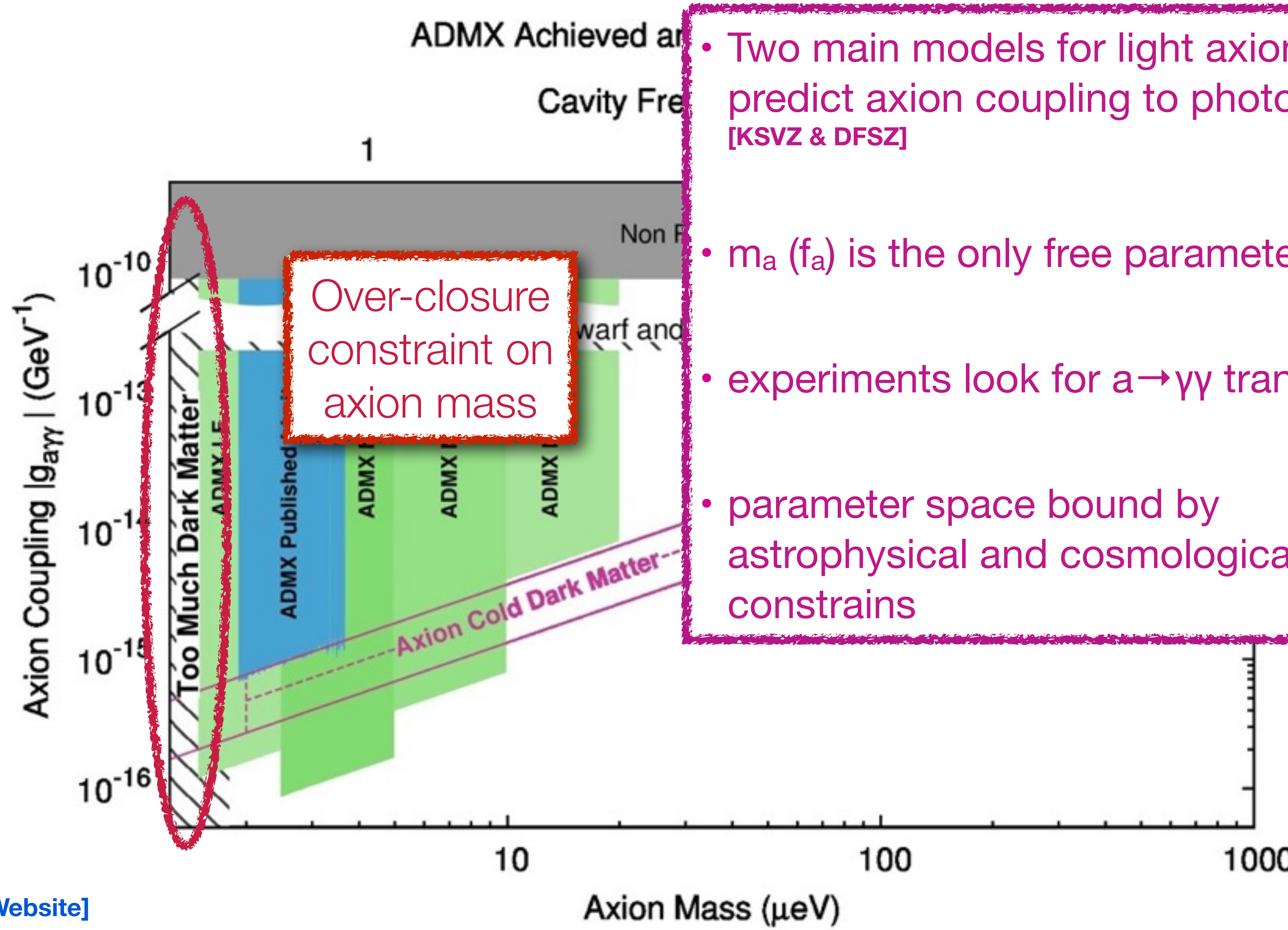

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The over-closure bound

High temperature arguments imply χ vanishes as $T \to \infty$

Sketches kindly provided by E. Berkowitz

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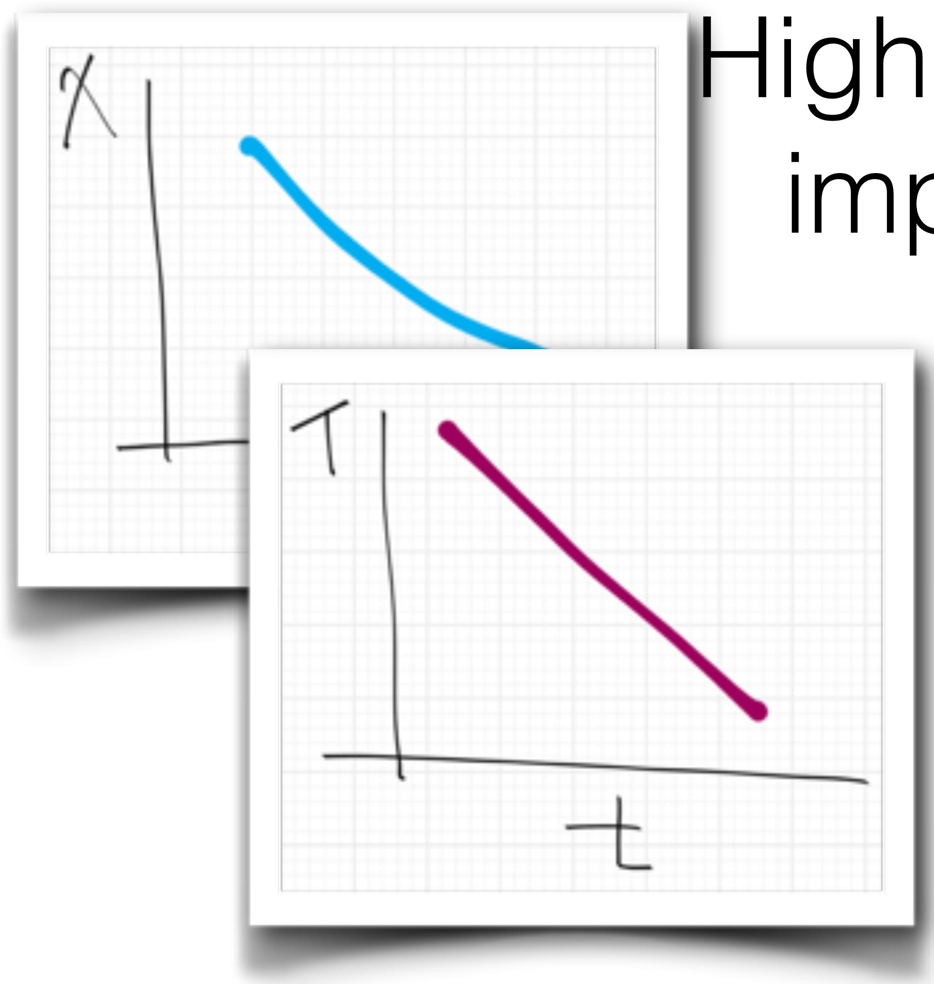

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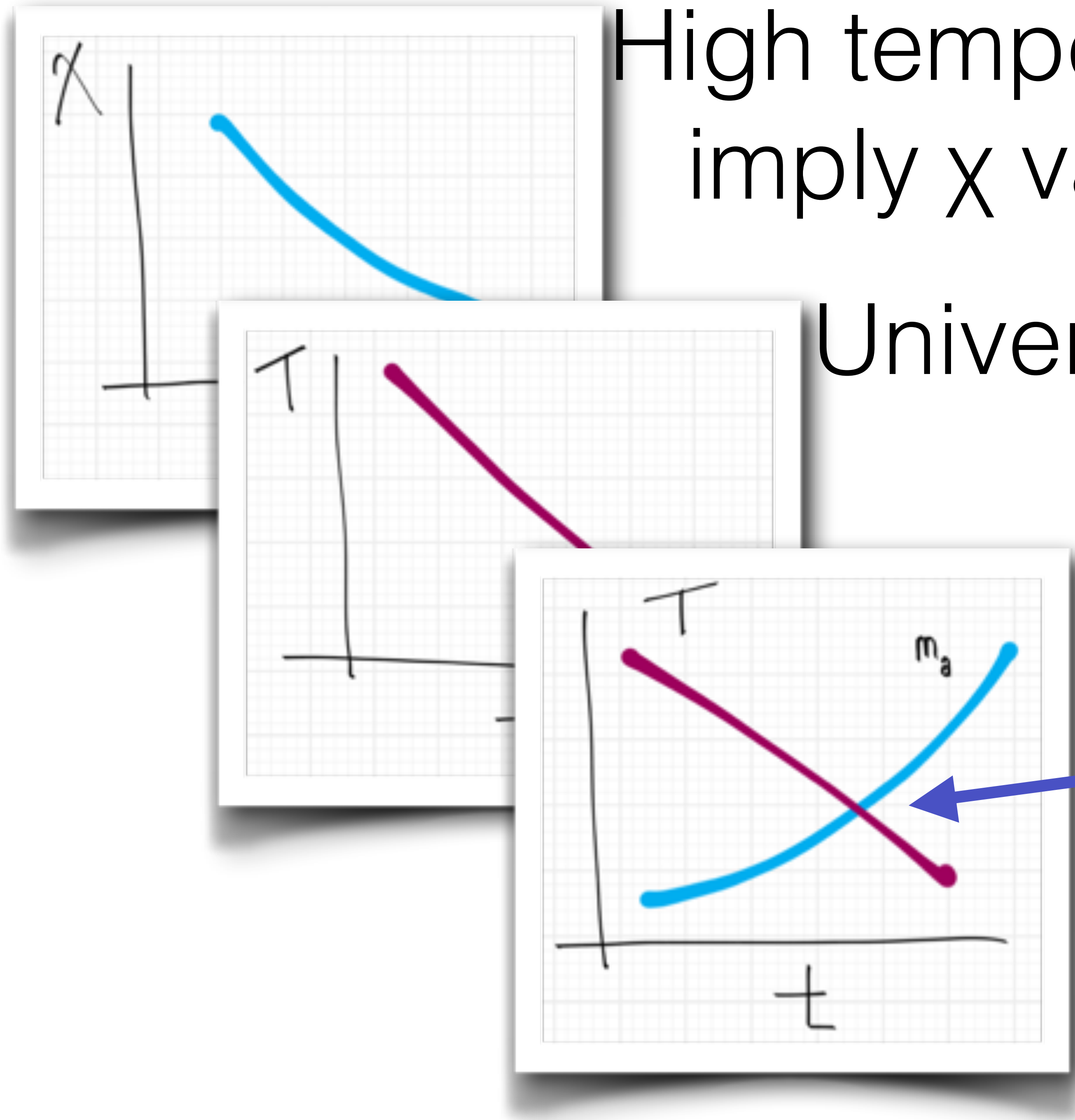

Axion's oscillations start

3H ~ m_a

H: Hubble constant

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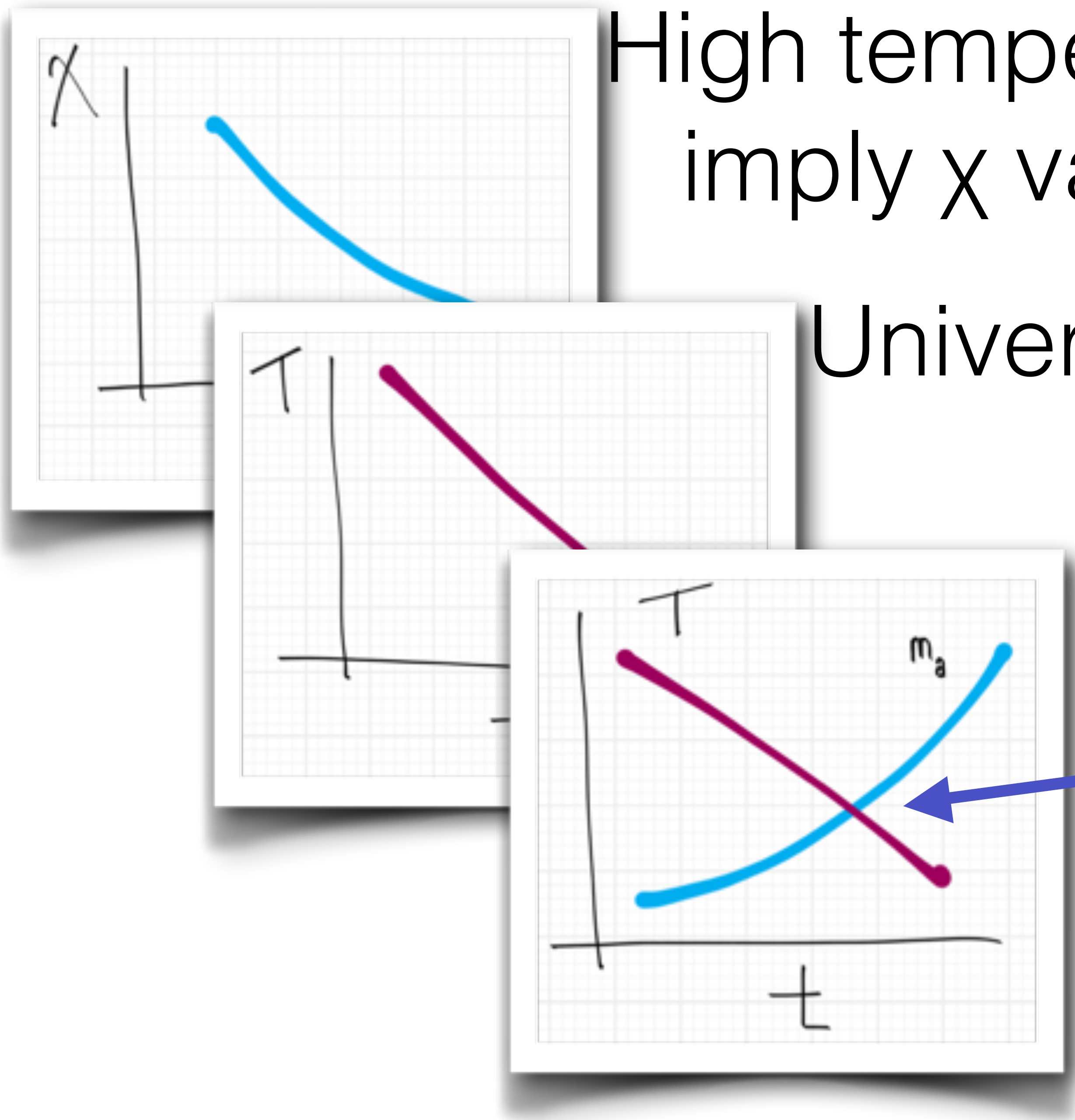

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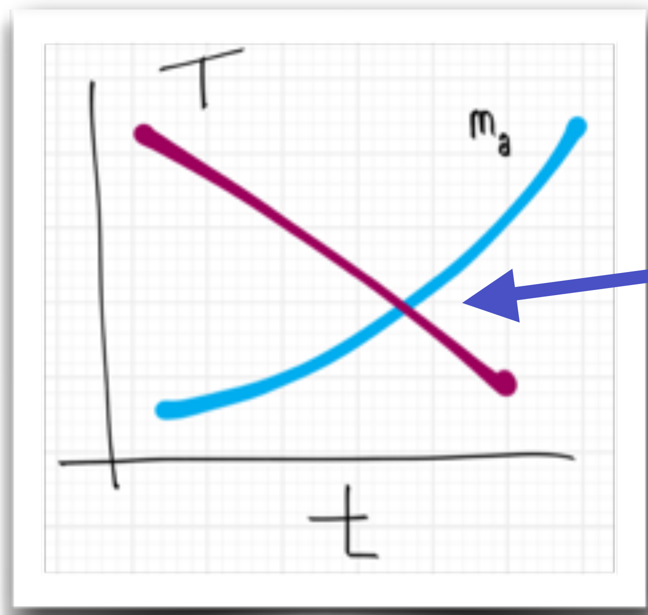

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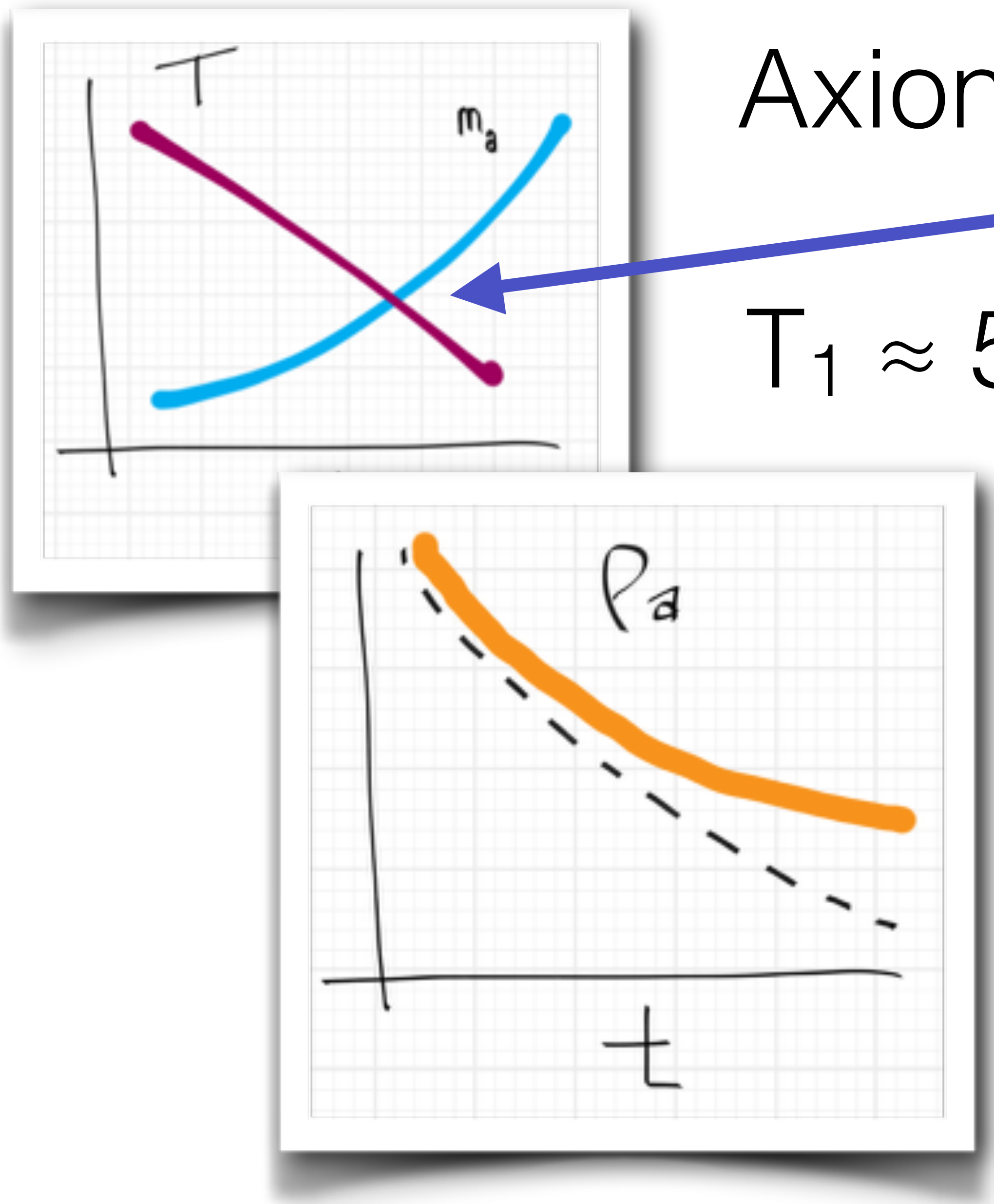

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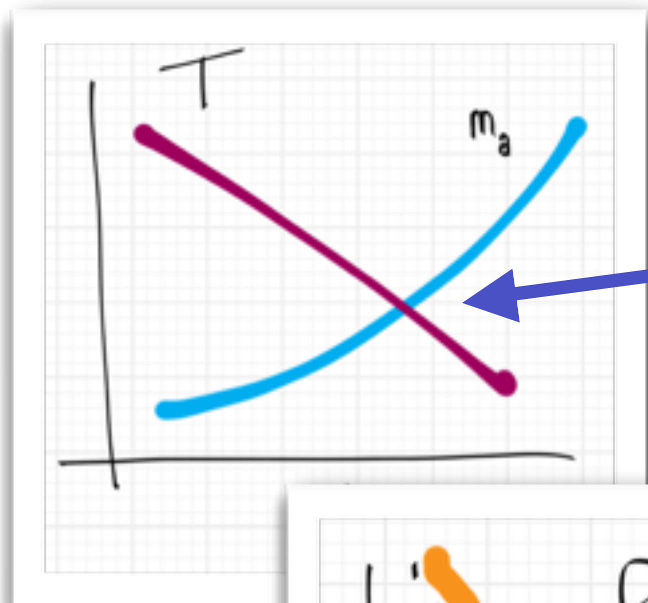

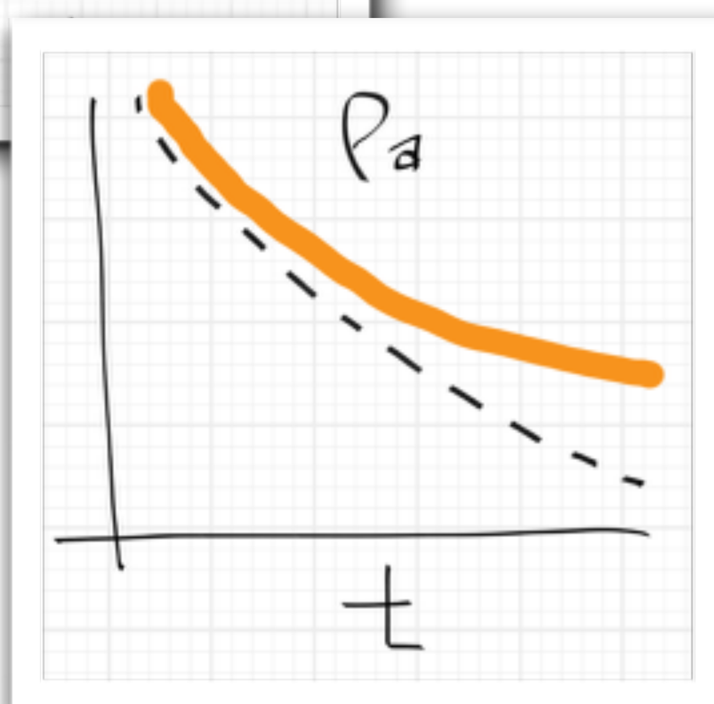

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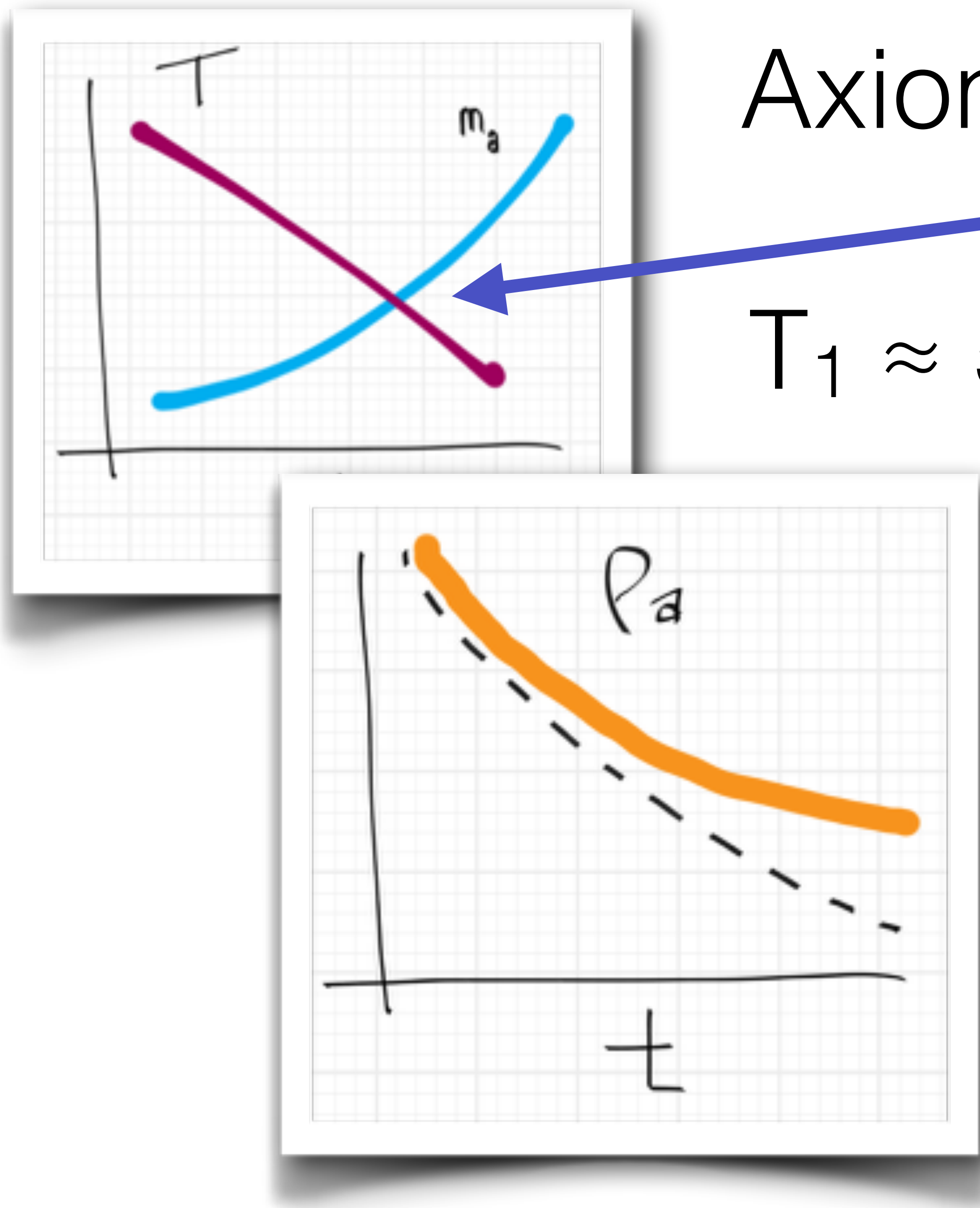

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energy density per co-moving volume is NOT invariant because the mass changes with time!

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Axion energy density

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$$\rho(T_\gamma) = \rho(T_1)\frac{m_a(T_\gamma)}{m_a(T_1)}\left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

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How do we get this?

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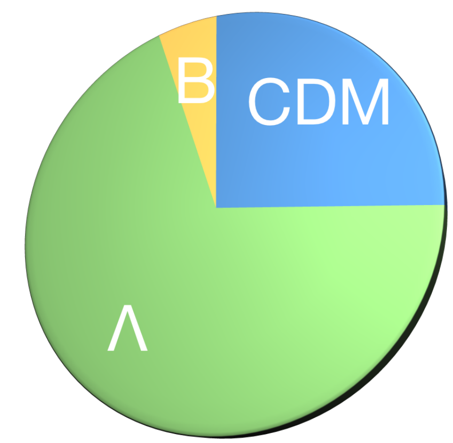
[Wantz & Shellard, arXiv:0910.1066]

Axion bound from models

- Value of ρ when oscillations start given by FRW equations, EOM and $m_a(T)$

$$\frac{\rho}{\rho_c} < \Omega_{\mathrm{CDM}} = 0.12$$



- χPT today yields

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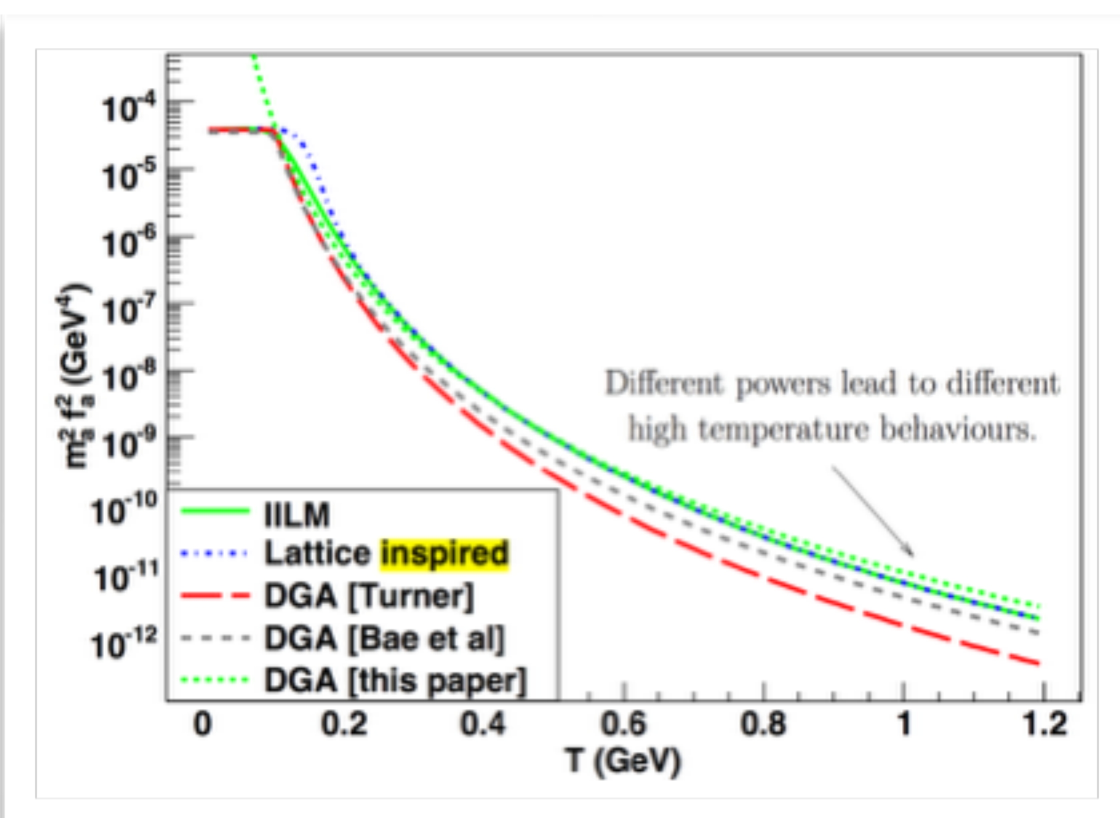

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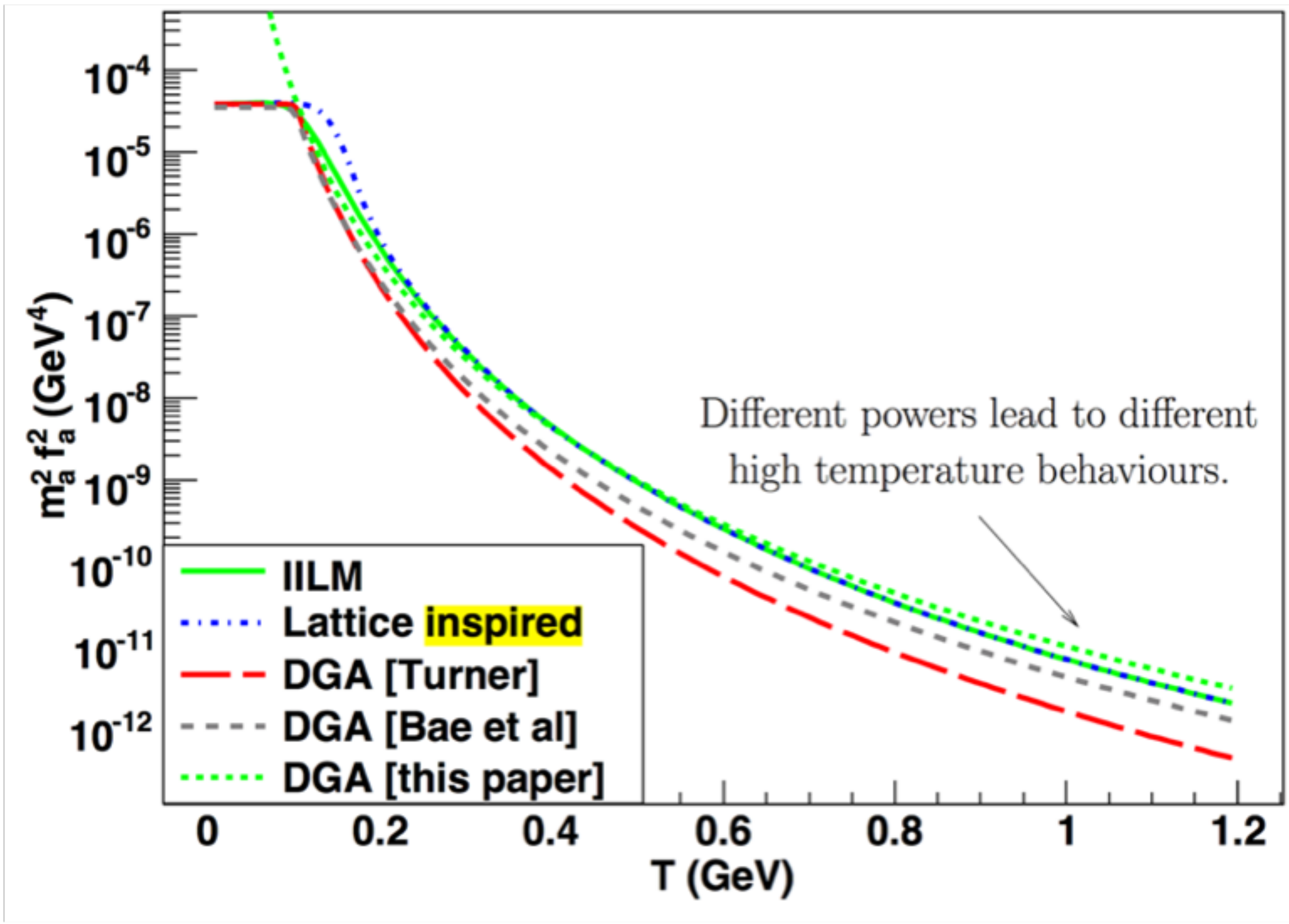

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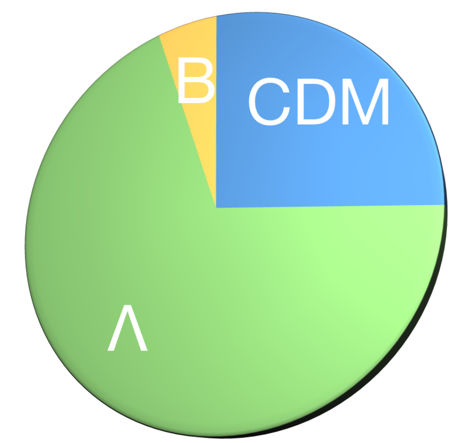

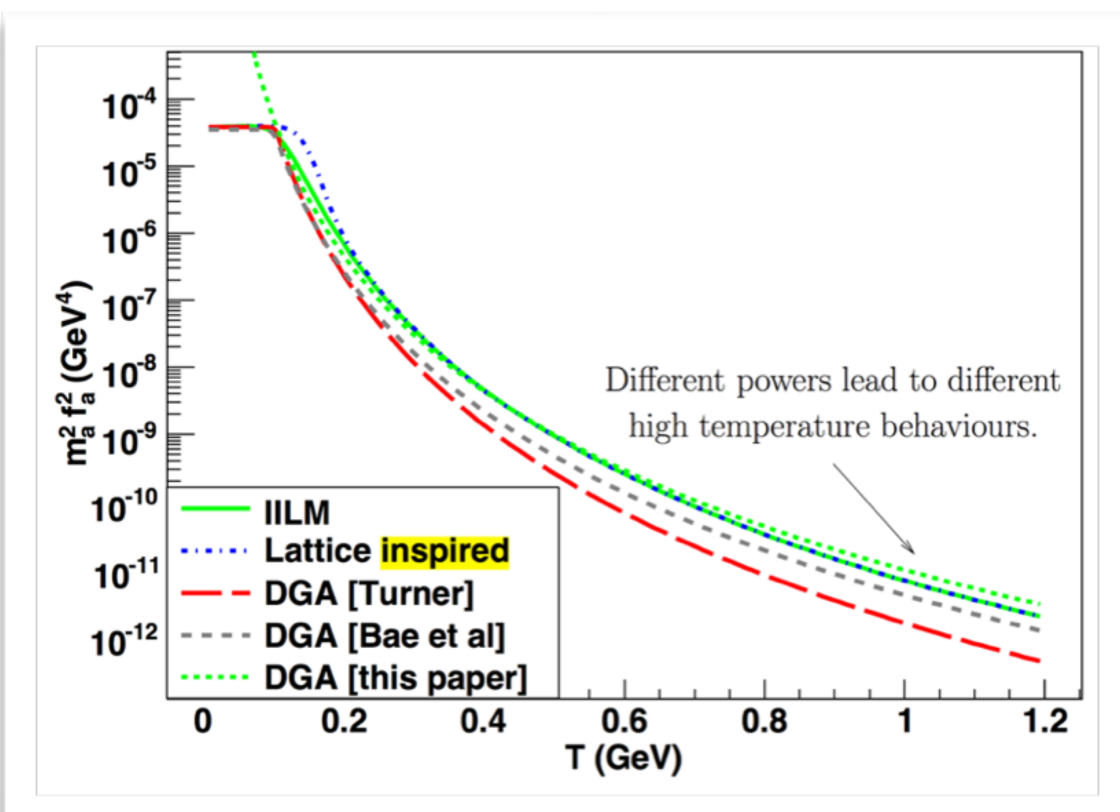

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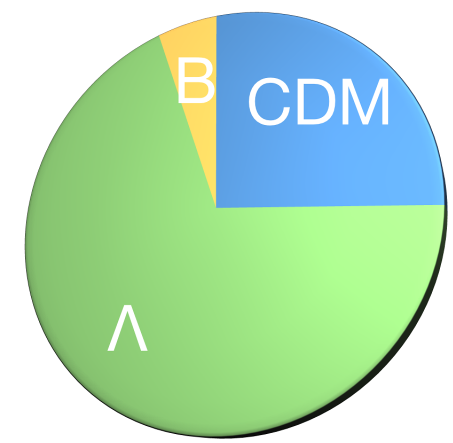

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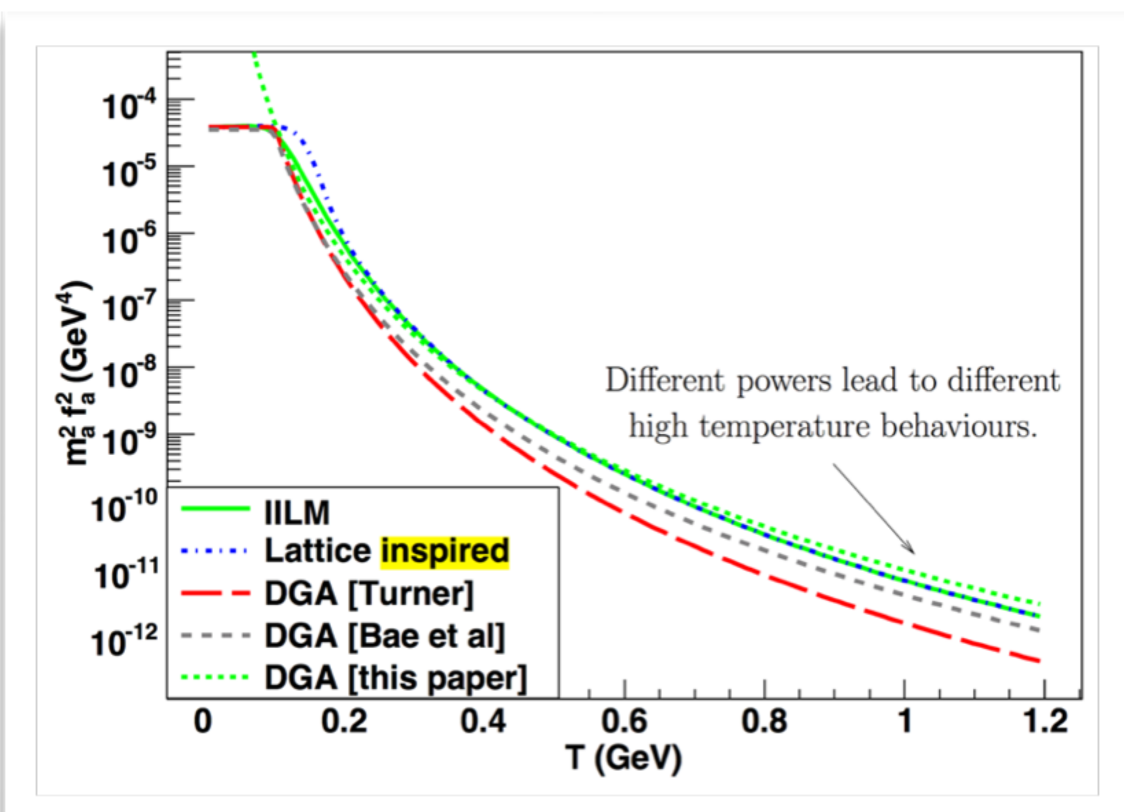

$f_a \leq (2.8 \pm 2)\ 10^{11}$ GeV

$m_a \geq 21 \pm 2$ μeV

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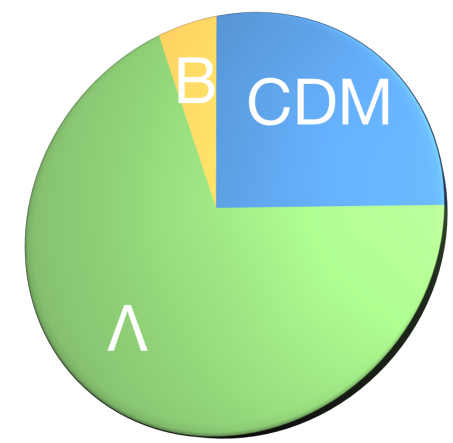

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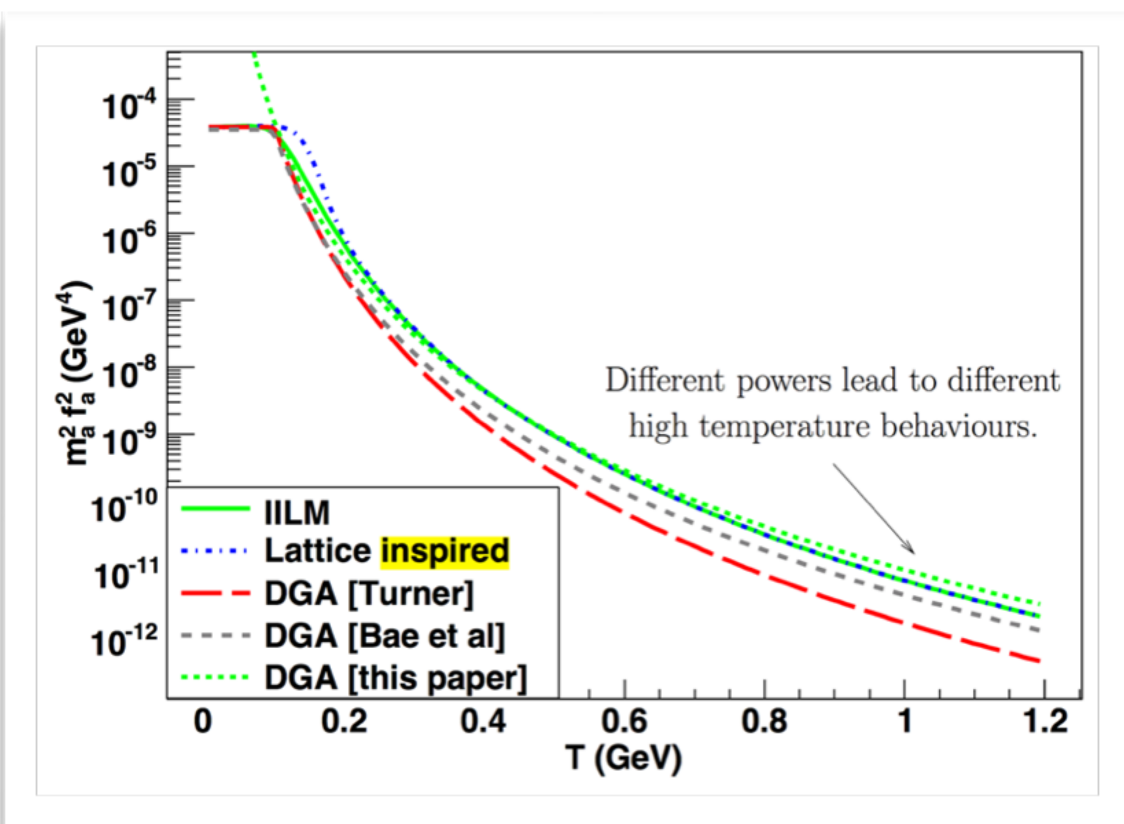

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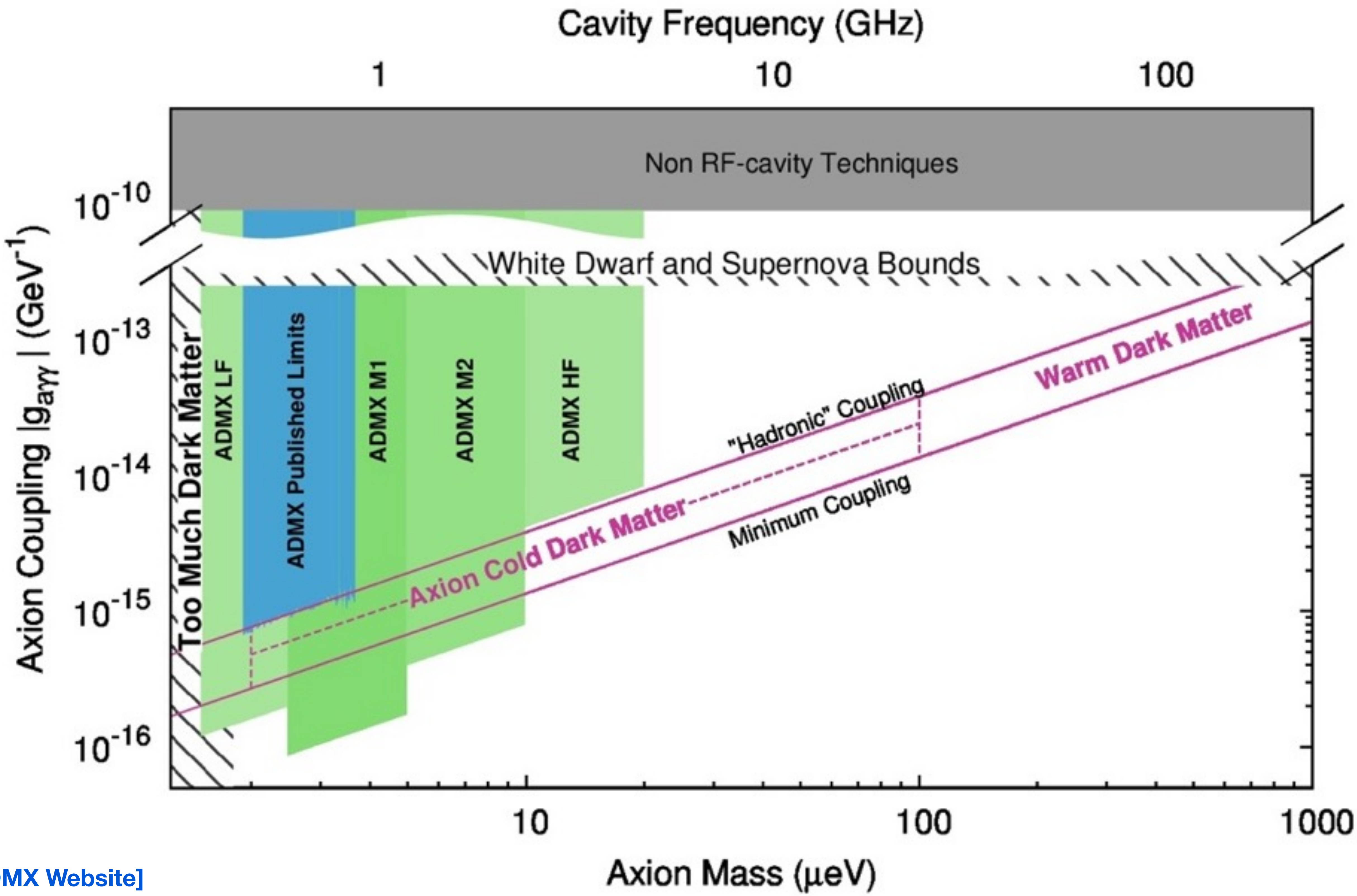

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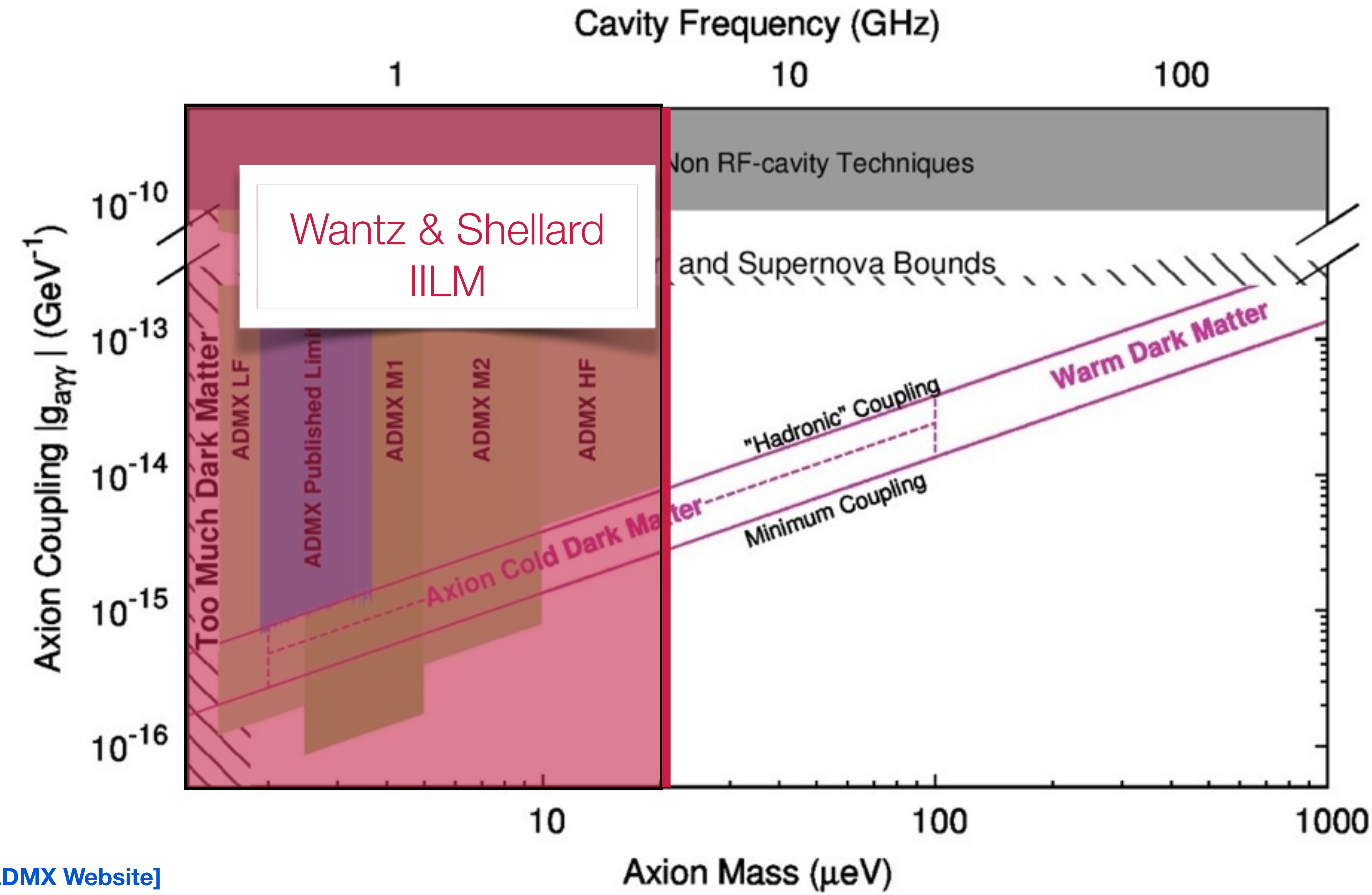

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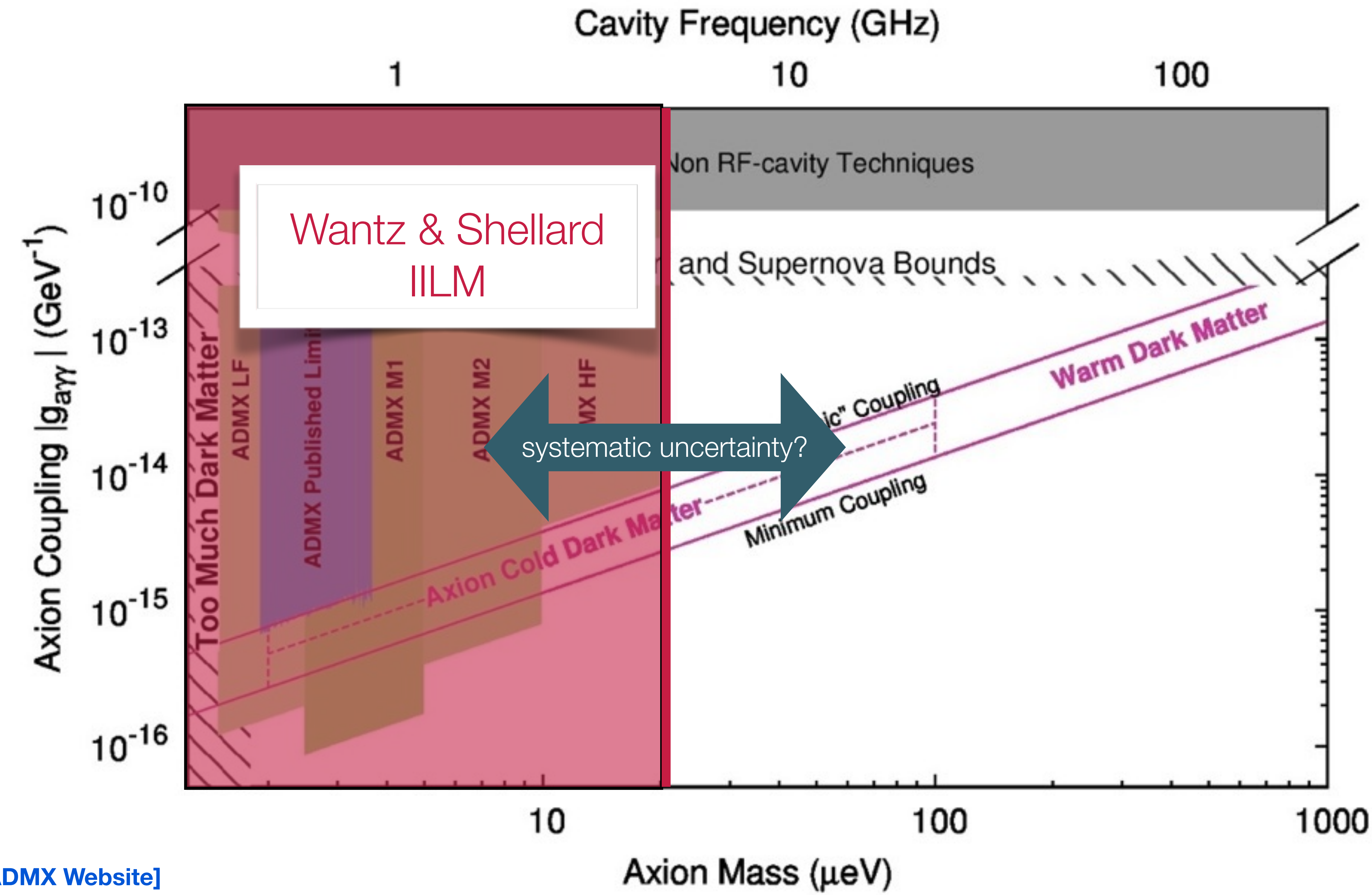

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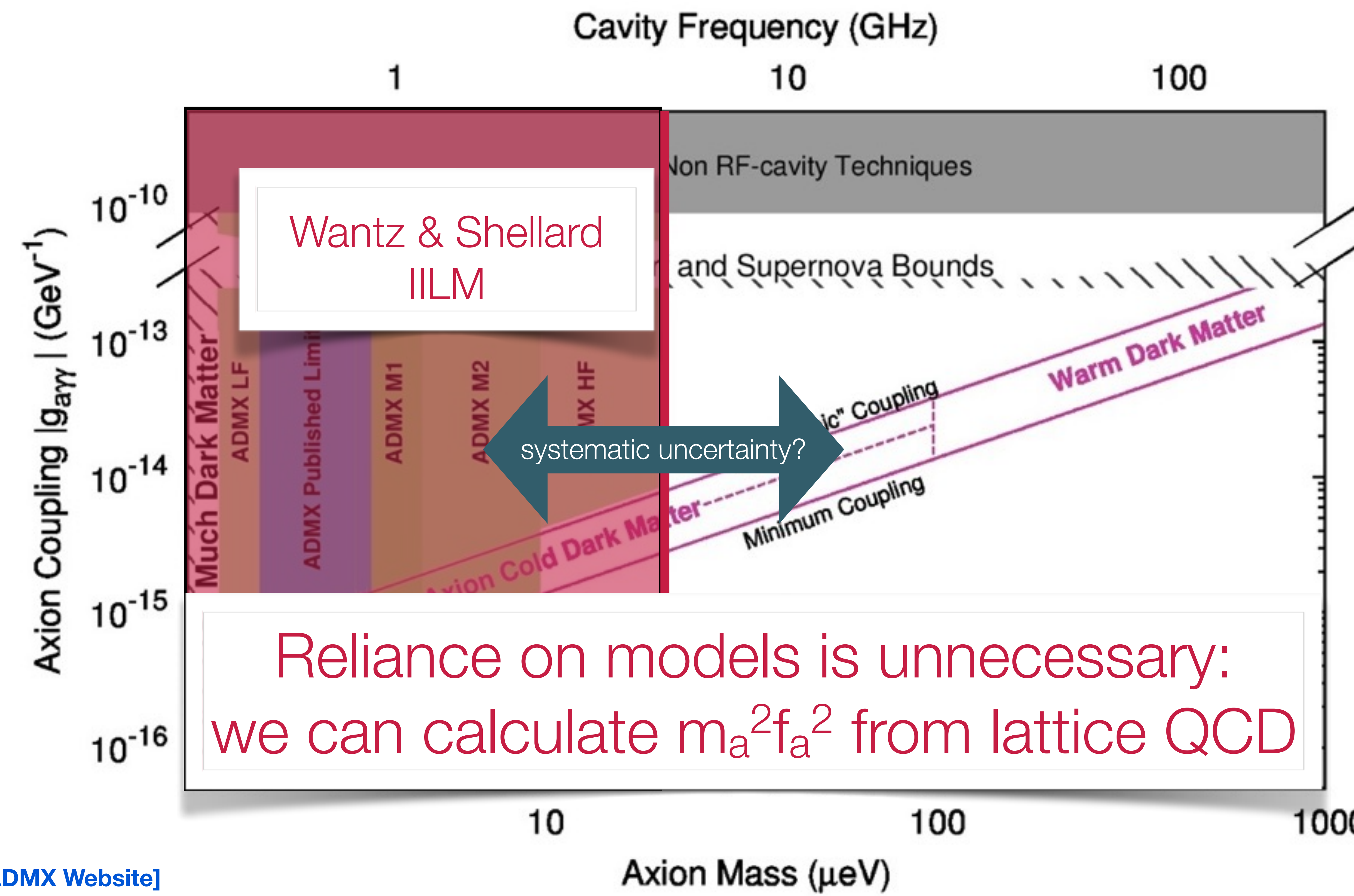

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[Berkowitz, Buchoff, Rinaldi, arxiv:1505.07455, PRD]

Lattice simulations

- SU(3) YM with Wilson plaquette action
- Temperature between 1.2 and 2.5 T_c
- N_σ between 48 and 144 (large aspect ratio)
- N_τ chosen to be 4, 6 or 8
- Between 14K and 52K measurements
  - Combined hot & cold starts
  - Cut of 3000 cfg.s for thermalization
  - Negligible autocorrelations
  - Gauge smoothing via "cooling"
- Different bosonic definitions of the topological charge Q_i on the lattice (and susceptibility)

$$\frac{1}{32\pi^2}\sum_x \epsilon^{\mu\nu\rho\sigma}\Box_{\mu\nu}\Box_{\rho\sigma}$$

$Q_{\mathbb{R}}$ raw measurement

$Q_{\mathbb{Z}}$ naïve rounding

Q_a artifact corrected
Lucini & Teper, hep-lat/0103027

Q_f globally fit
del Debbio *et al.*, hep-th/0204125

$$\chi_i = \lim_{V\to\infty}\frac{\langle Q_i^2\rangle}{V}$$

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- Different bosonic definitions of the topological charge Q_i on the lattice (and susceptibility)

$$\frac{1}{32\pi^2}\sum_x \epsilon^{\mu\nu\rho\sigma}\Box_{\mu\nu}\Box_{\rho\sigma}$$

$Q_{\mathbb{R}}$ raw measurement

$Q_{\mathbb{Z}}$ naïve rounding

Q_a artifact corrected
Lucini & Teper, hep-lat/0103027

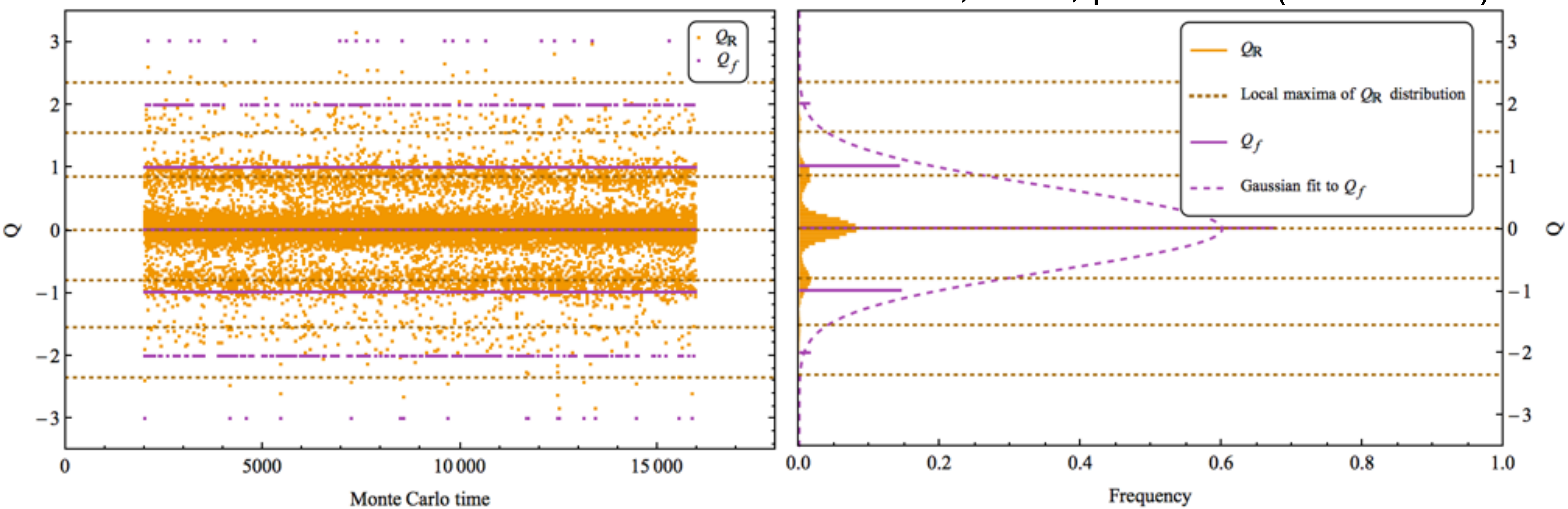
Q_f globally fit
del Debbio *et al.*, hep-th/0204125

Essentially no discretization or finite volume corrections

$$\chi_i = \lim_{V\to\infty}\frac{\langle Q_i^2\rangle}{V}$$

Fluctuations of topology

N_σ=96, N_τ=6, β = 6.338 (ie. T/T_c = 2)



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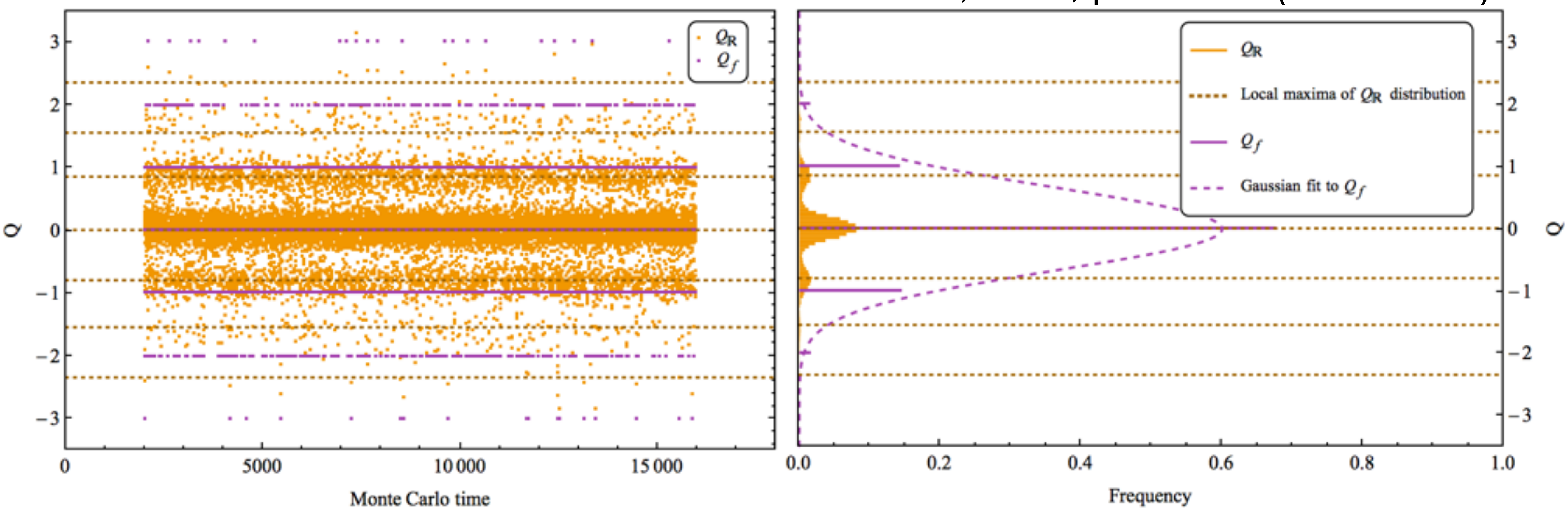
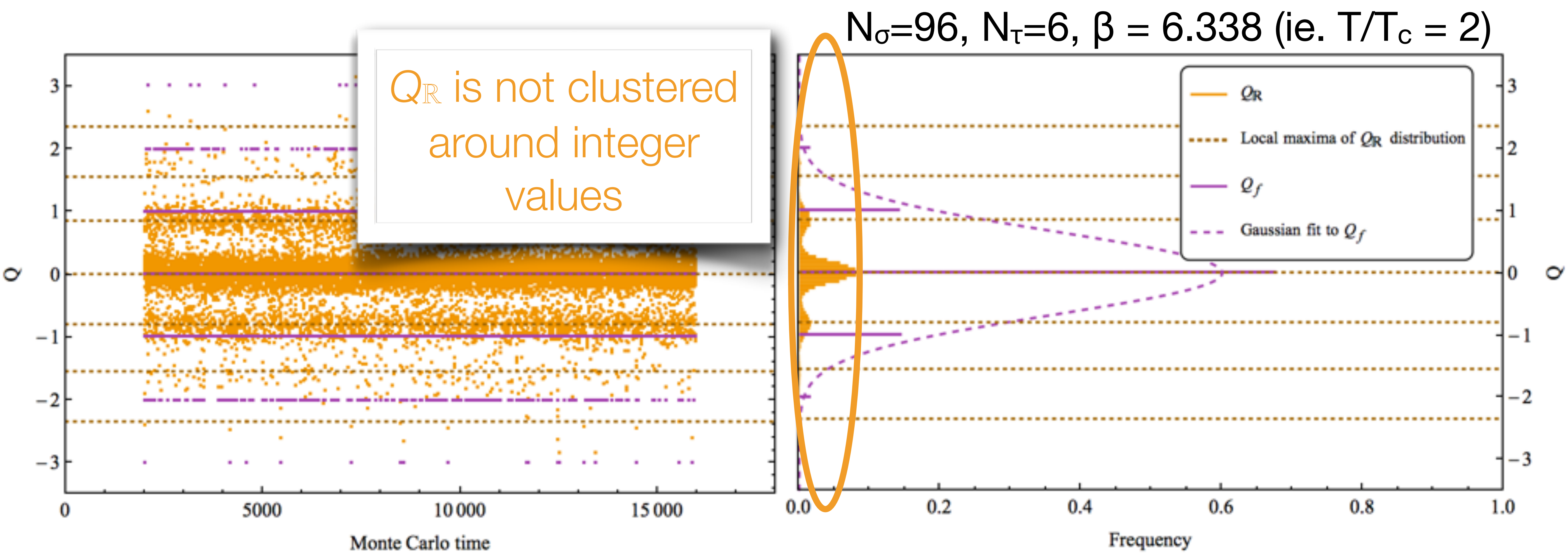


- Topology fluctuates sufficiently for measuring χ

Fluctuations of topology



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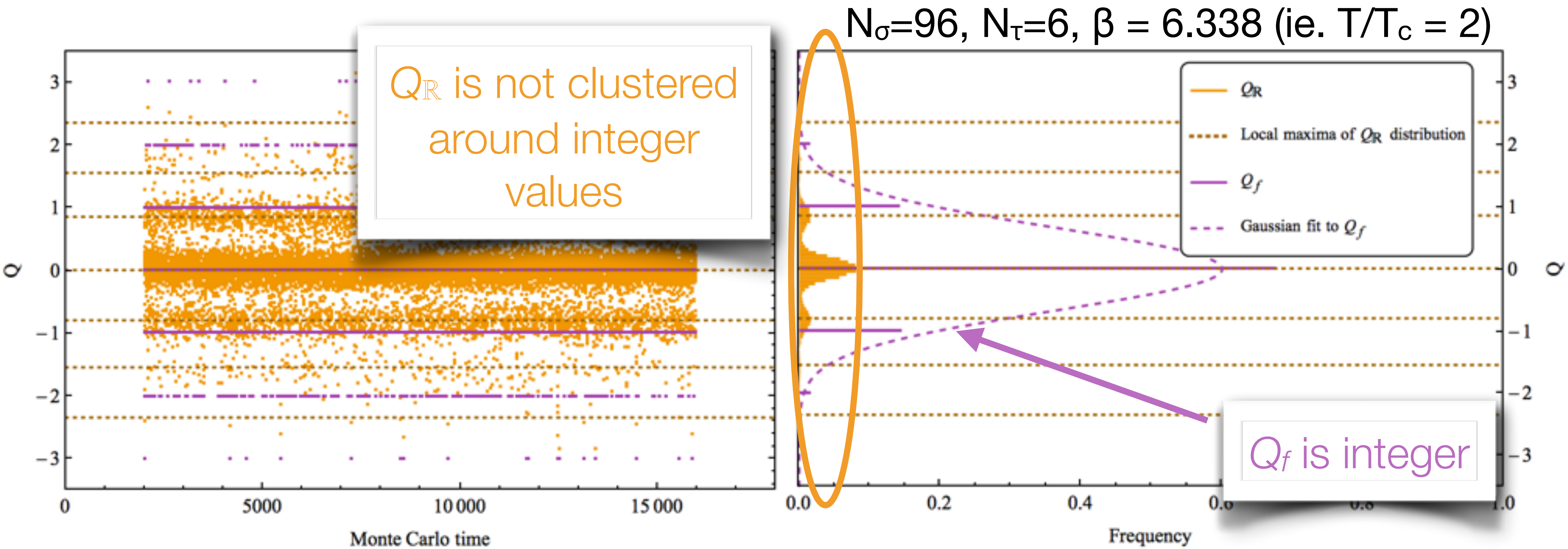

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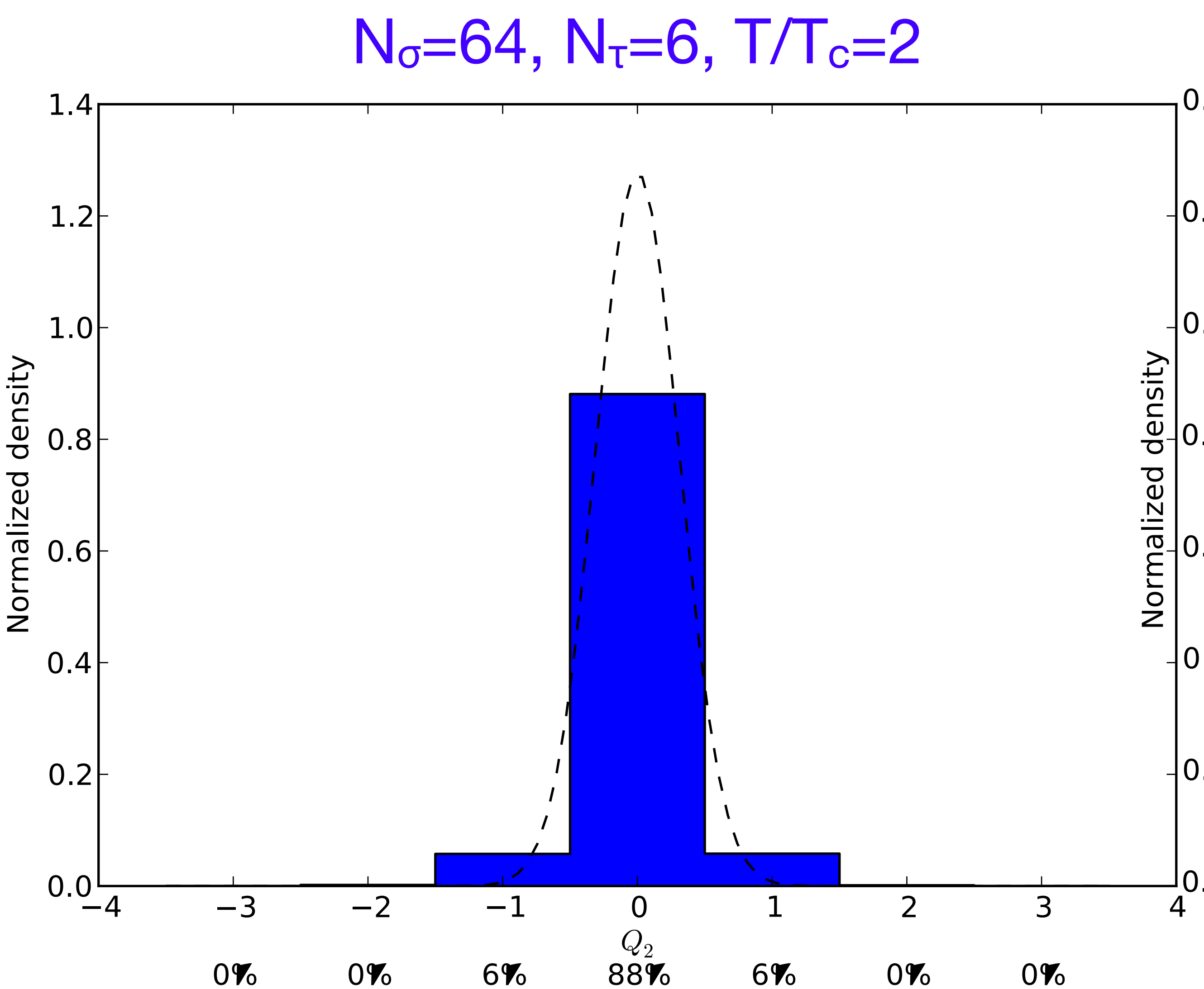
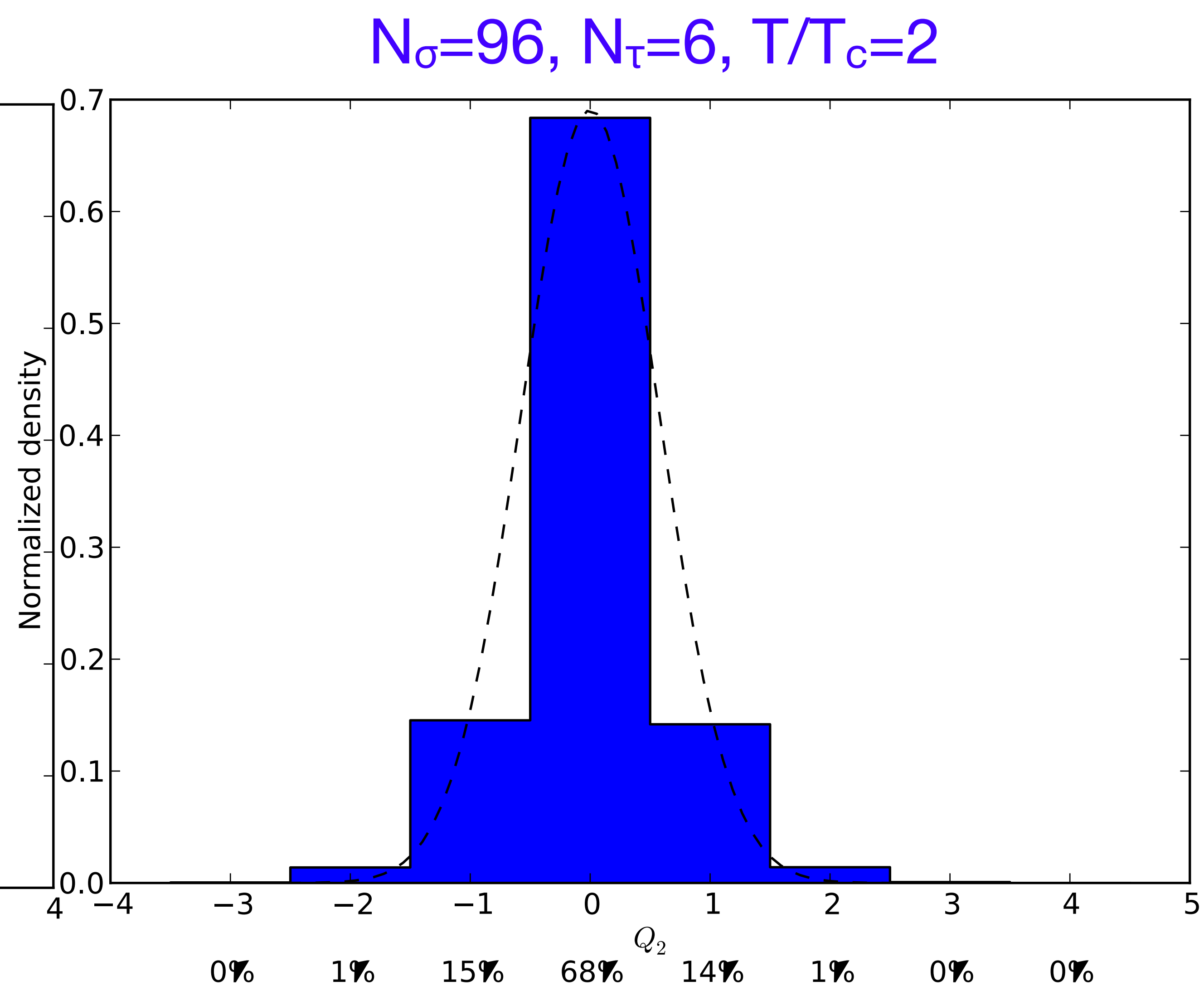
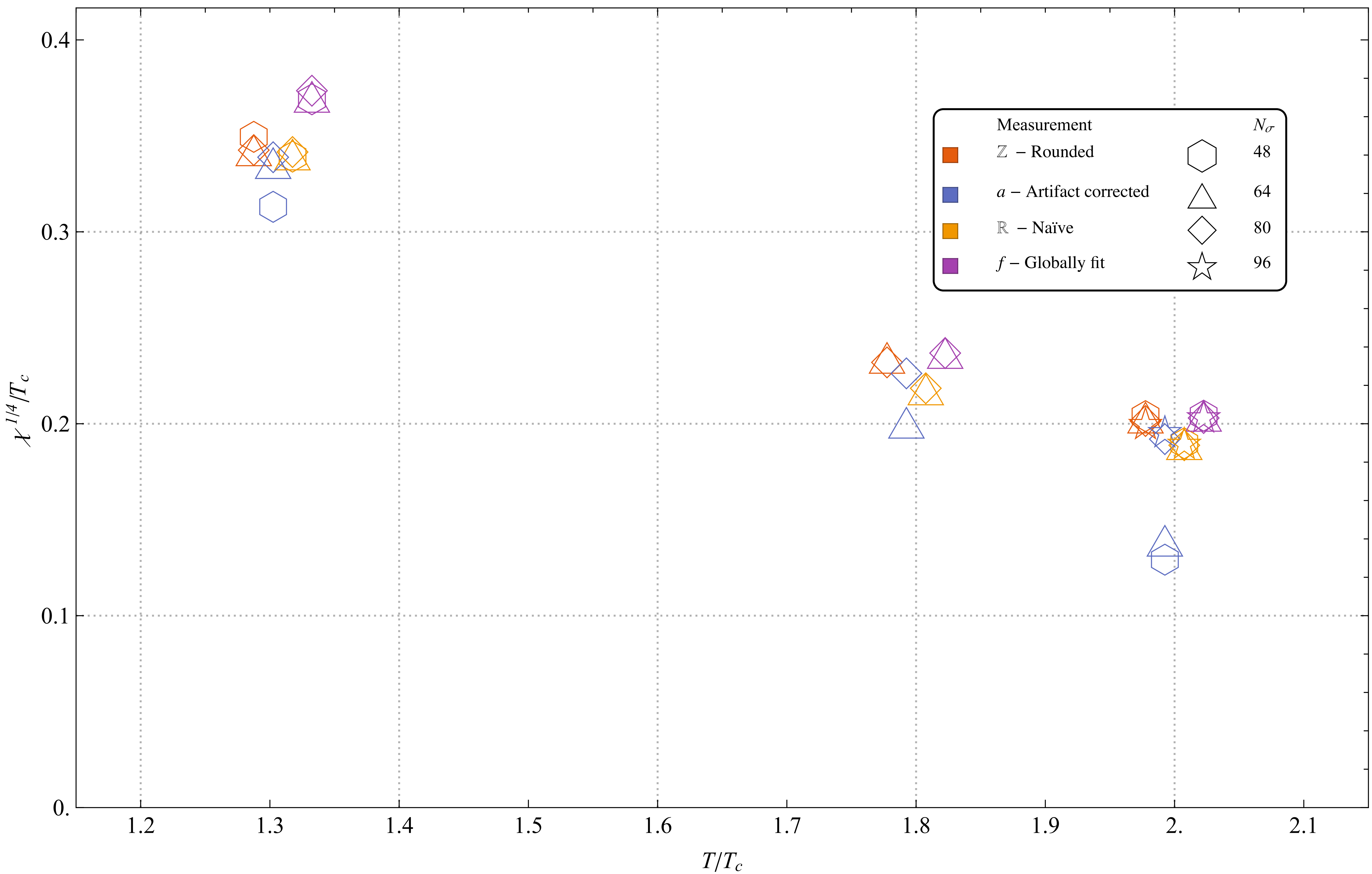


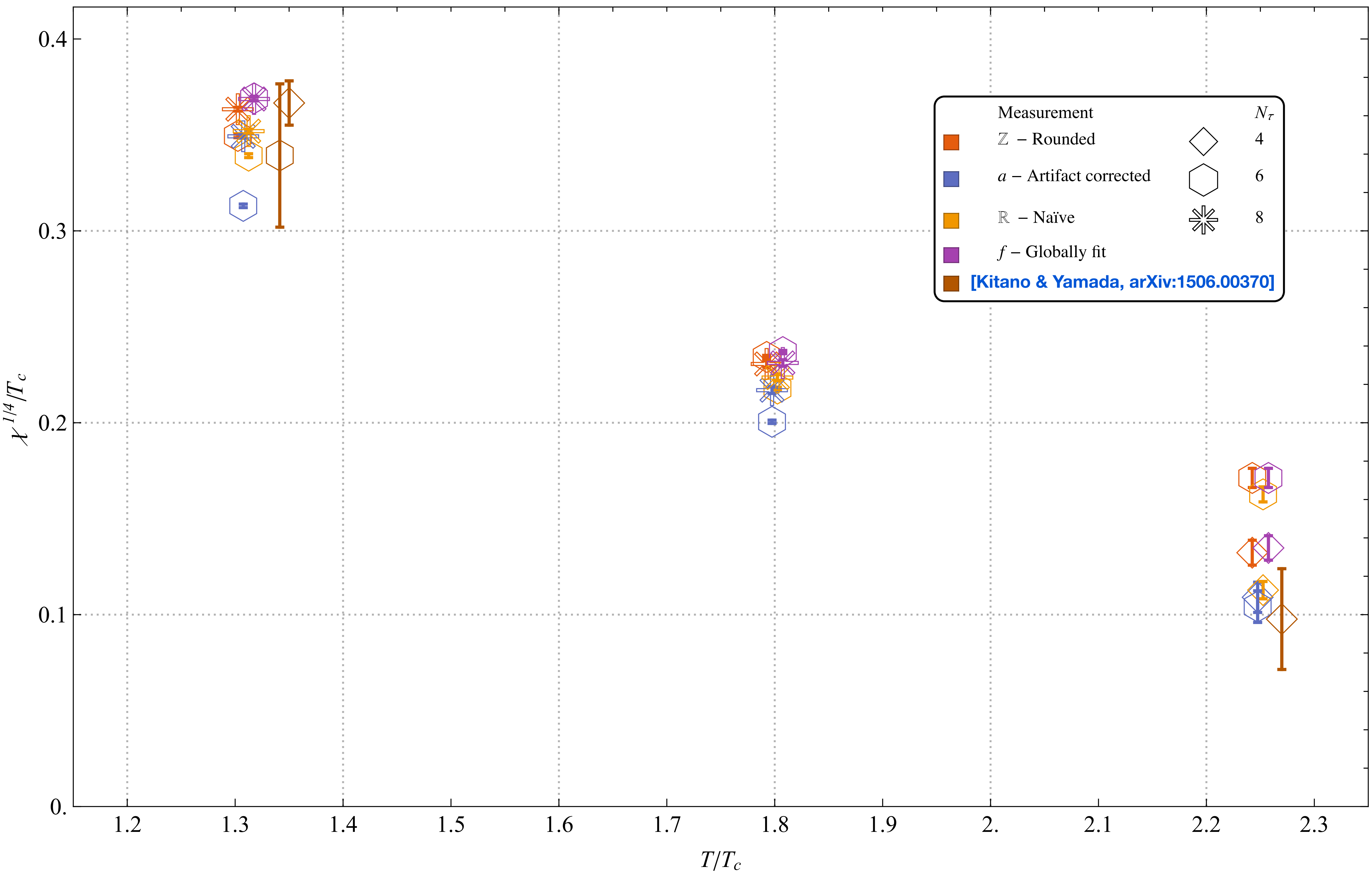


- Topology fluctuates sufficiently for measuring χ
- Large volumes help obtaining a more reliable χ

Finite Volume Effects



Discretization Effects



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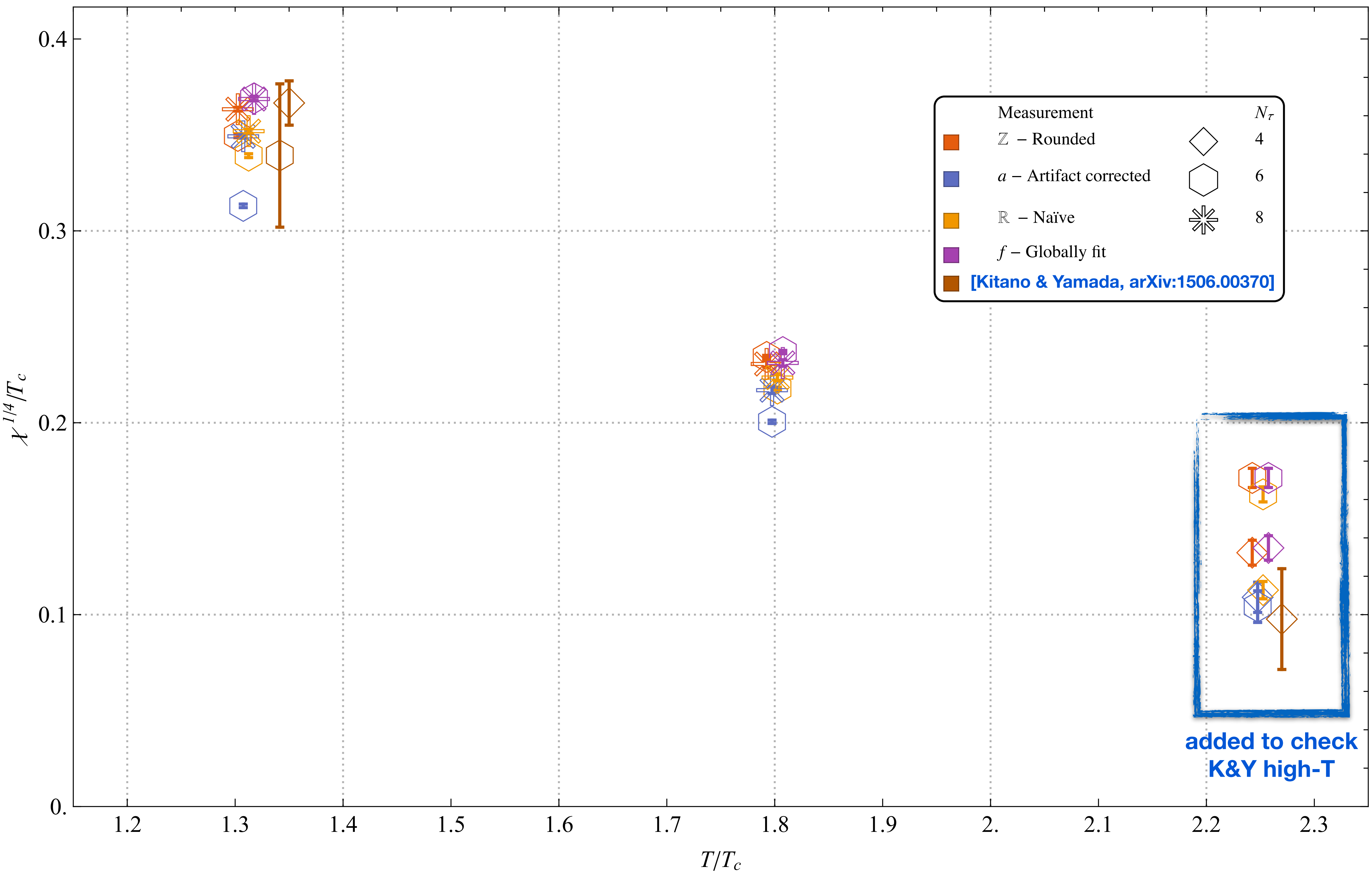

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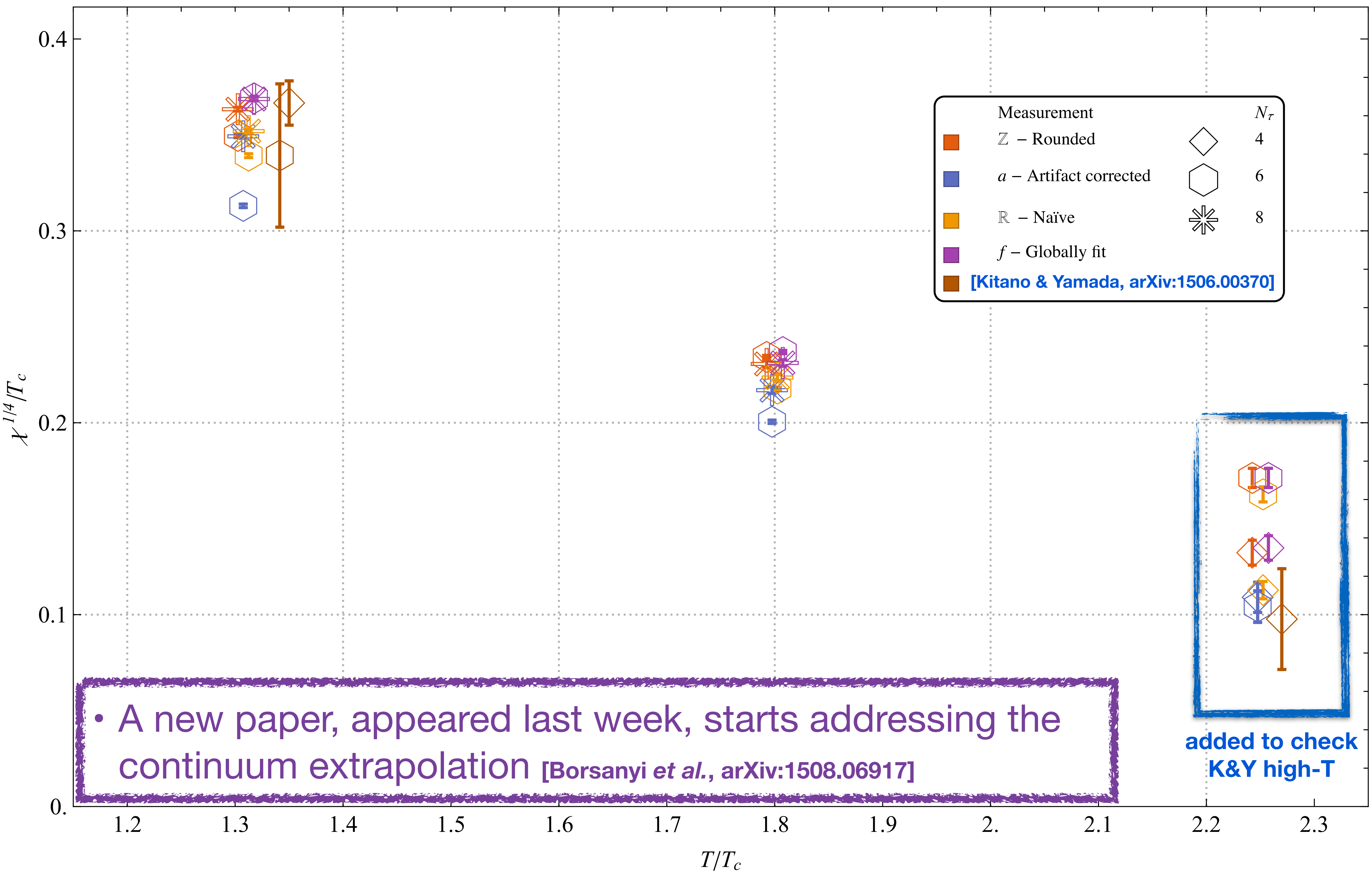
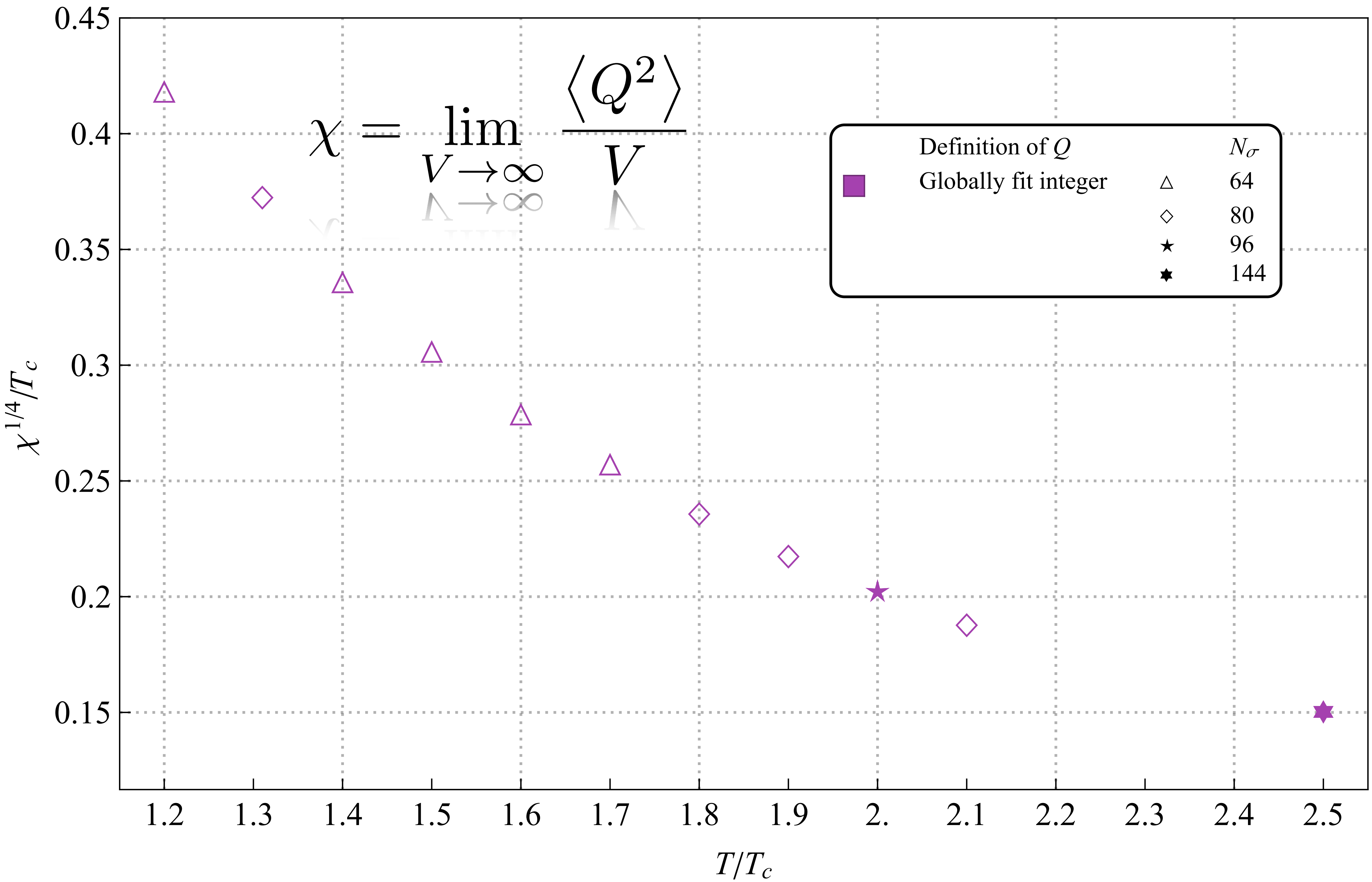


- A new paper, appeared last week, starts addressing the continuum extrapolation **[Borsanyi *et al.*, arXiv:1508.06917]**

[Berkowitz, Buchoff, Rinaldi, arxiv:1505.07455, PRD]

Lattice results

$$\chi = \lim_{V\to\infty} \frac{\langle Q^2 \rangle}{V}$$



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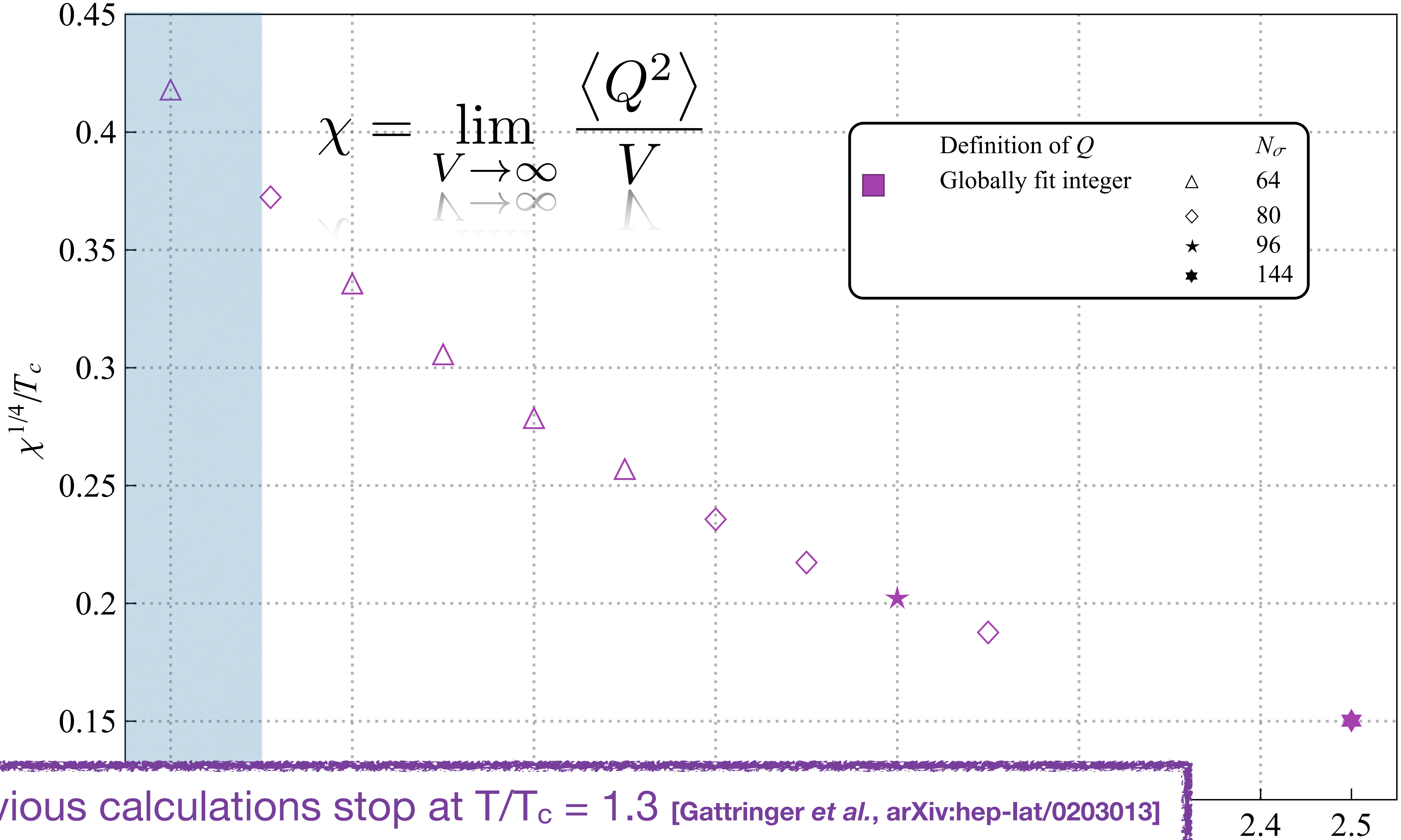
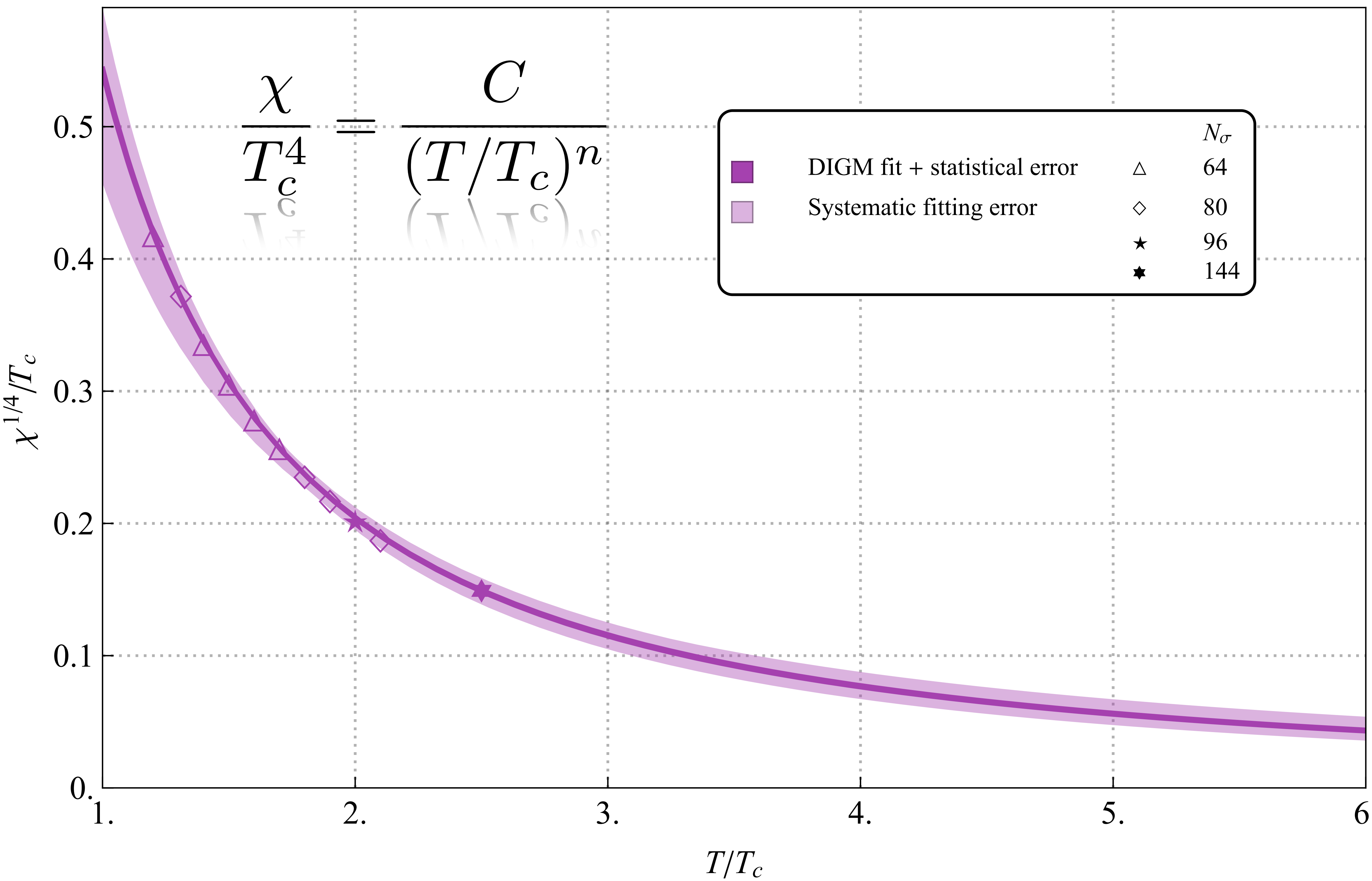


- previous calculations stop at T/T_C = 1.3 **[Gattringer *et al.*, arXiv:hep-lat/0203013]**
- newest calculation stops at T/T_C = 4.0 **[Borsanyi *et al.*, arXiv:1508.06917]**

Model and extrapolation



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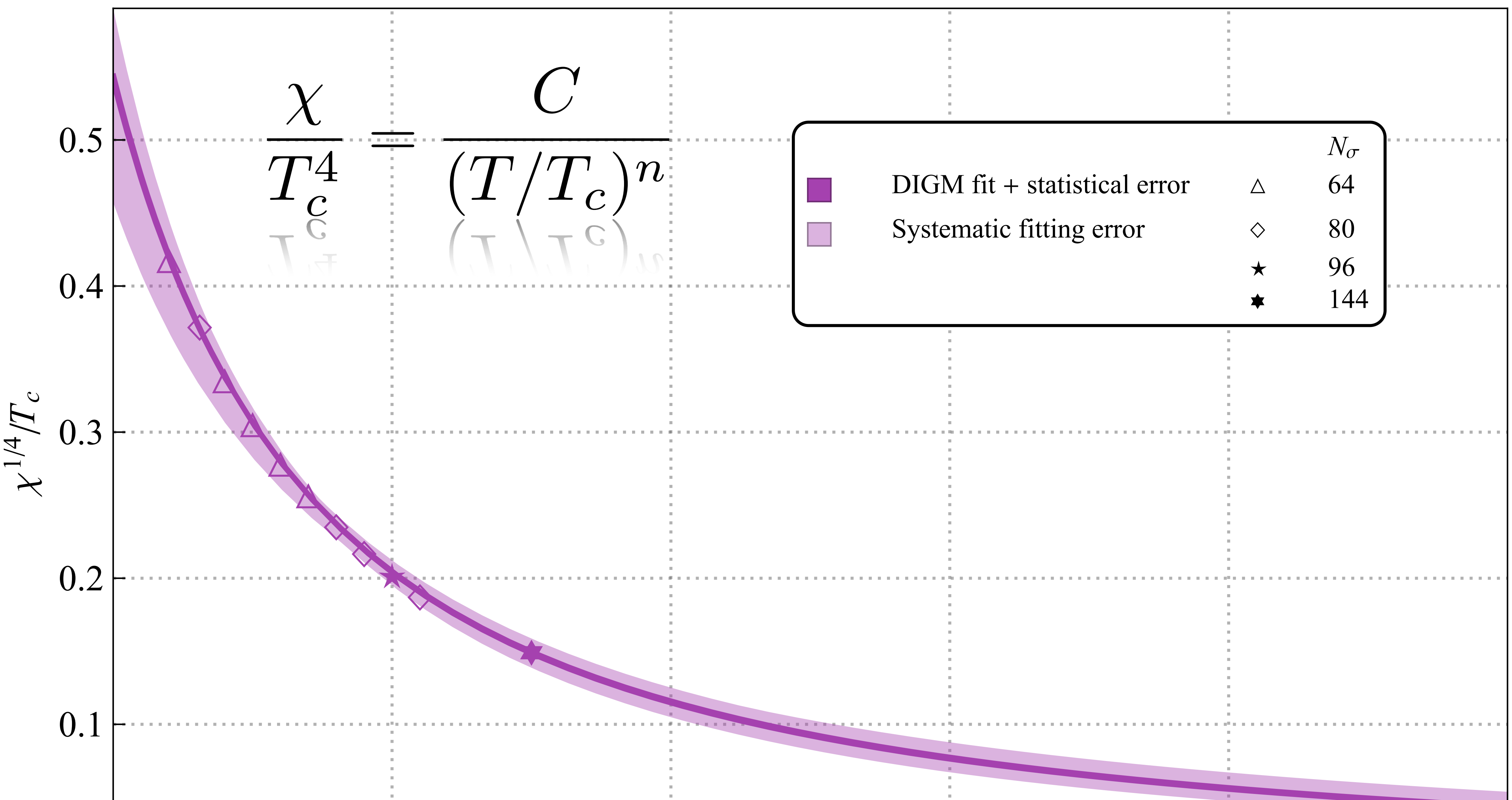
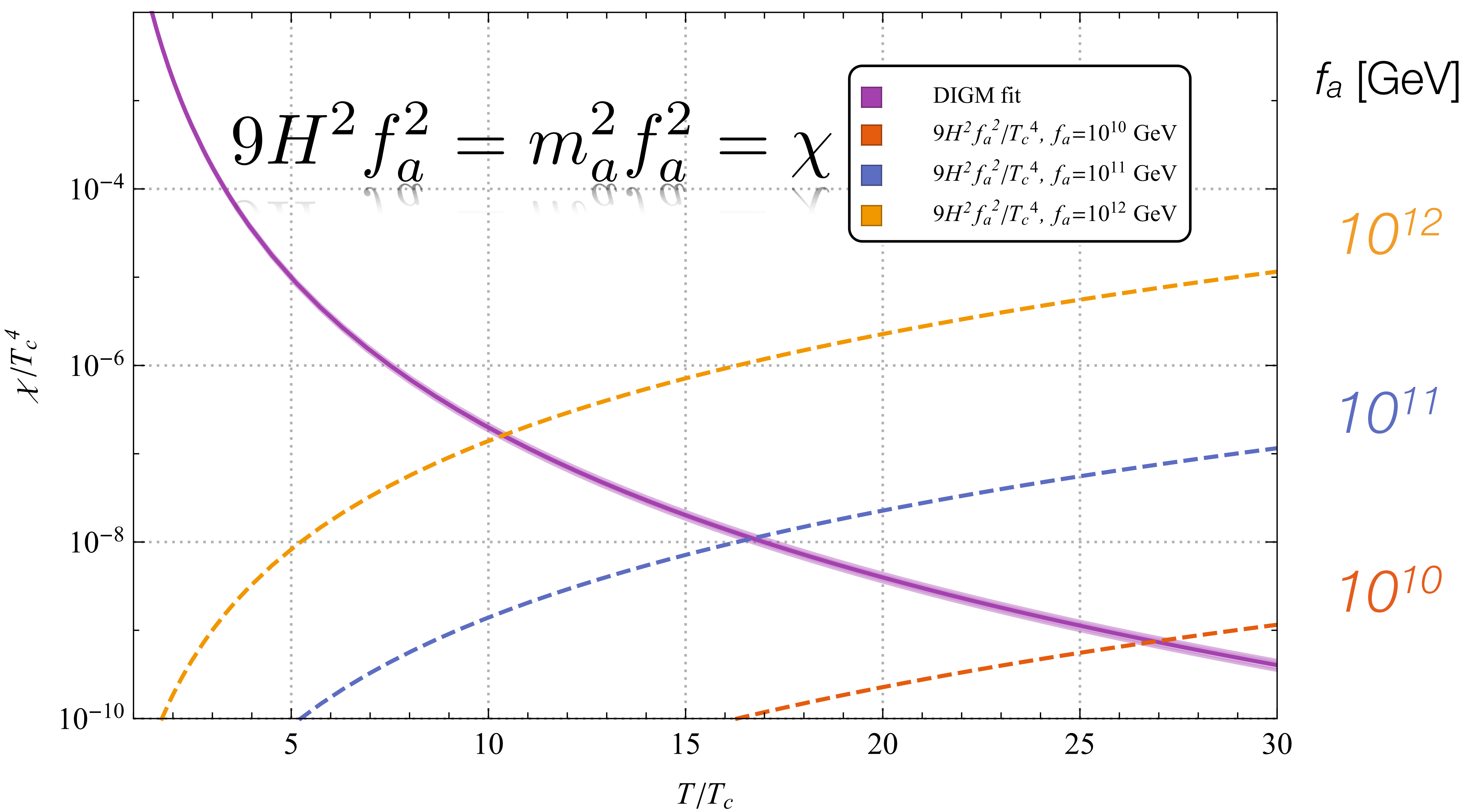


- asymptotic large-T susceptibility in the DIG model [Gross&Yaffe, RevModPhys.53.43]
- fits lattice data of χ remarkably well for all temperatures: first high-temperature comparison of DIGM to lattice data!

Axion oscillations



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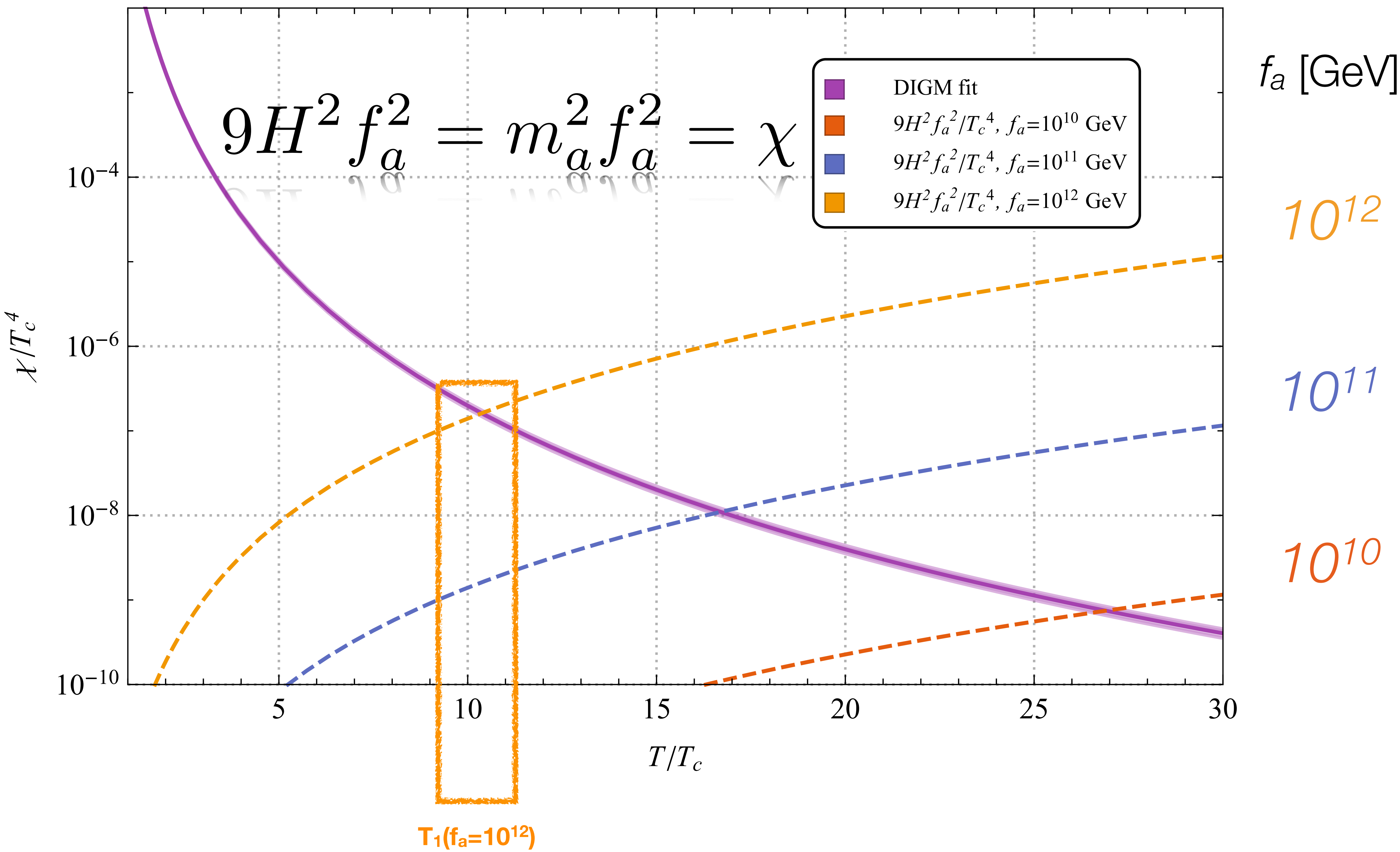

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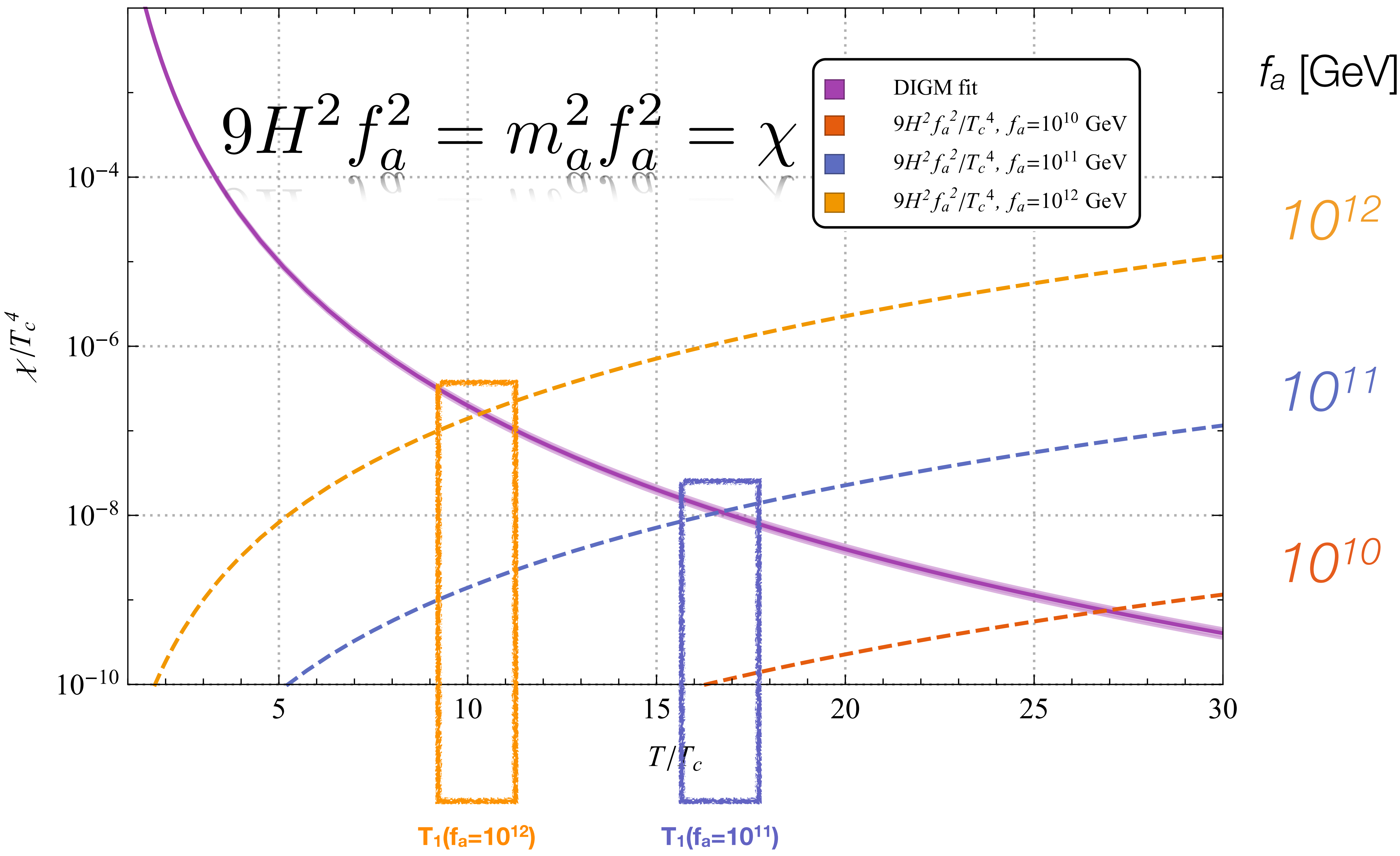

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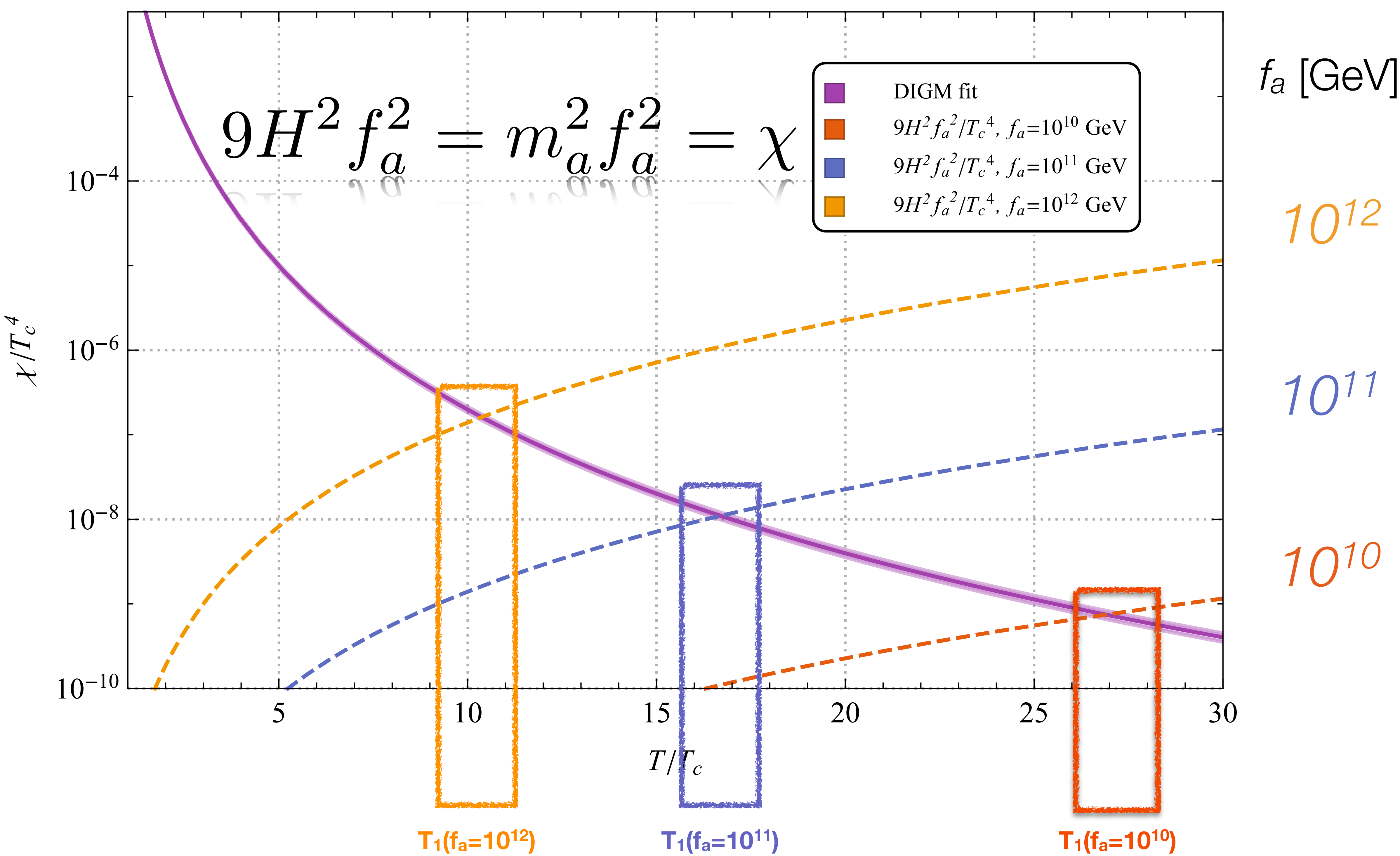

[Wantz & Shellard, arXiv:0910.1066]

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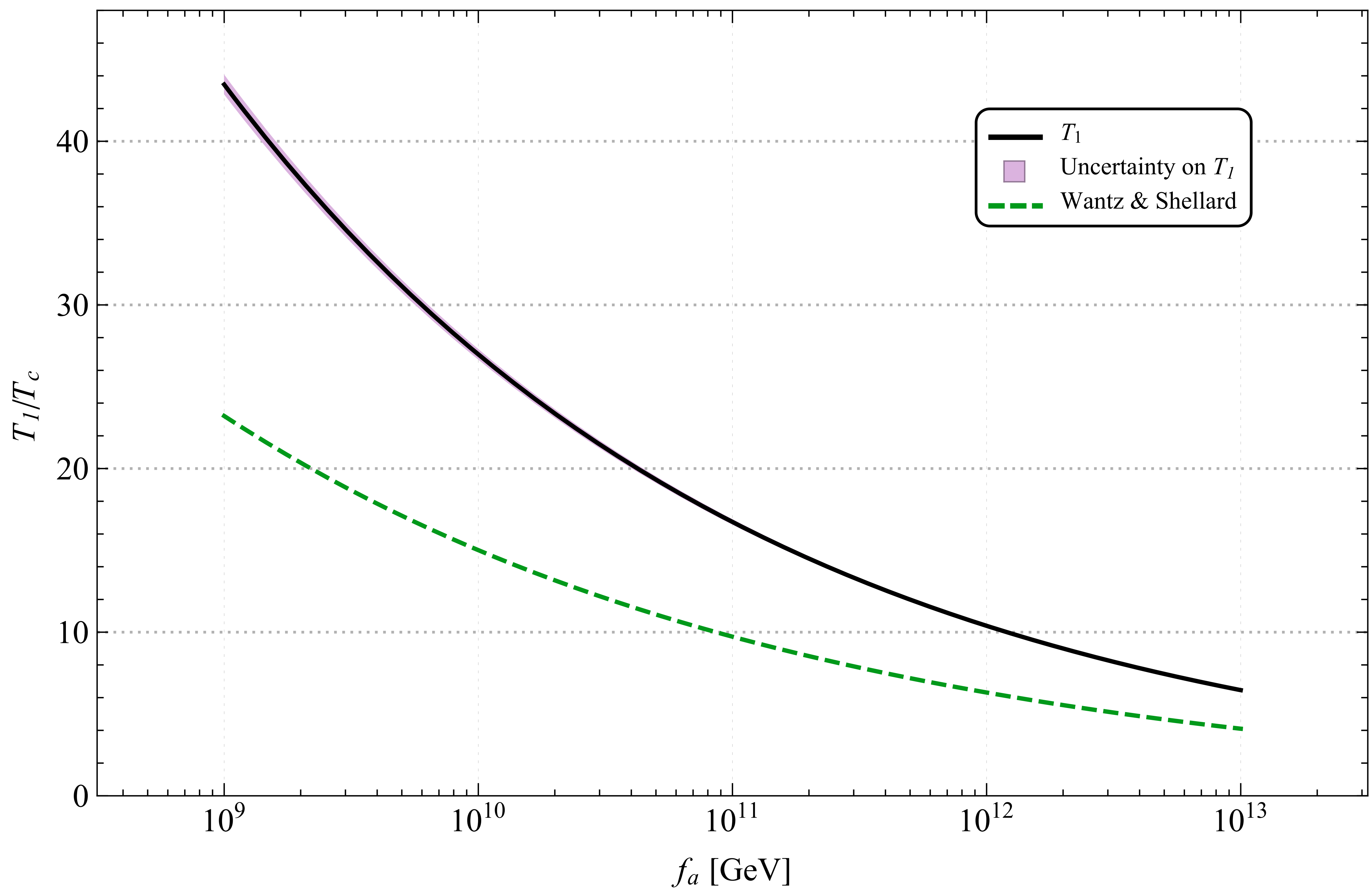

Axion energy density

$$\rho(T_\gamma) = \rho(T_1)\frac{m_a(T_\gamma)}{m_a(T_1)}\left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

$$T_\gamma = 2.73\text{K}$$

$$T_1 = T_1(f_a)$$

$$m_a(T_1) = \frac{\sqrt{\chi(T_1)}}{f_a}$$

$$m_a(T_\gamma) = \frac{1}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} f_\pi m_\pi$$ from χPT

$R(T)$ from cosmology

$$\rho(T_1) = \frac{1}{2} m_a^2 f_a^2 \theta_1^2$$

θ_1 random: PQ breaks after inflation

$$\langle \theta_1^2 \rangle = \frac{\pi^2}{3}$$

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Rely on our lattice calculation!

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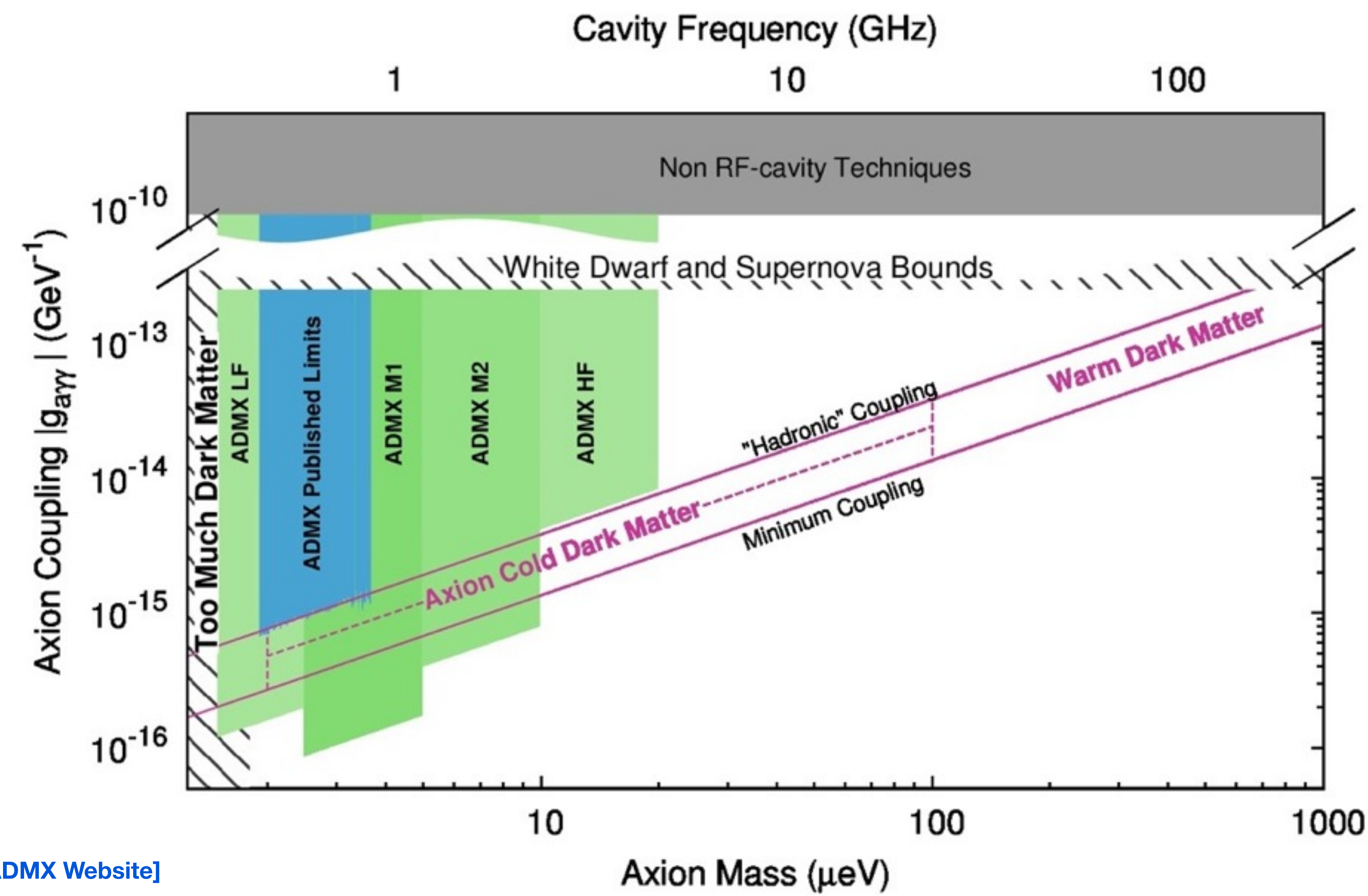
Lattice lower bound



[ADMX Website]

[Berkowitz, Buchoff, Rinaldi, arxiv:1505.07455, PRD]

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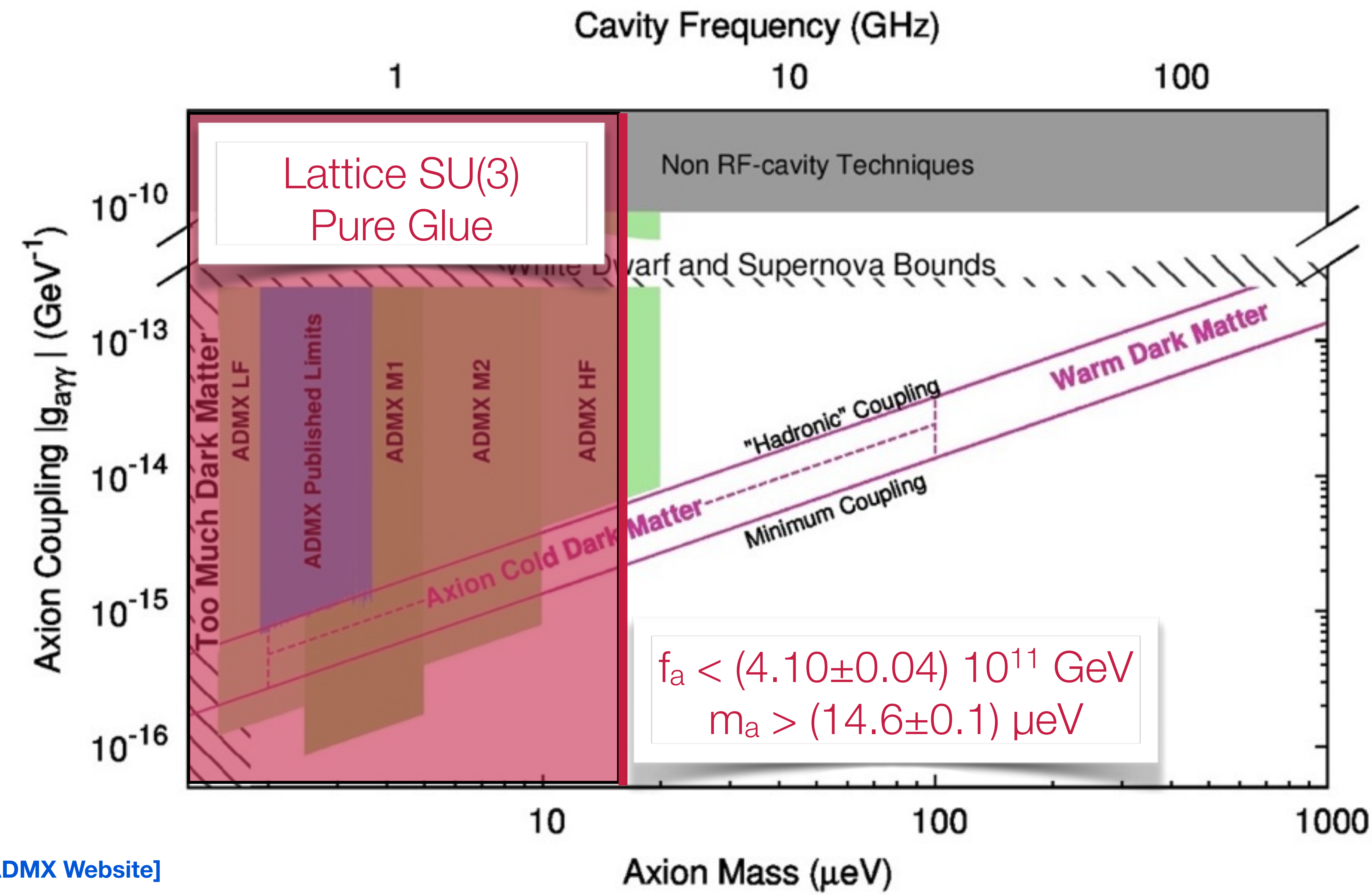

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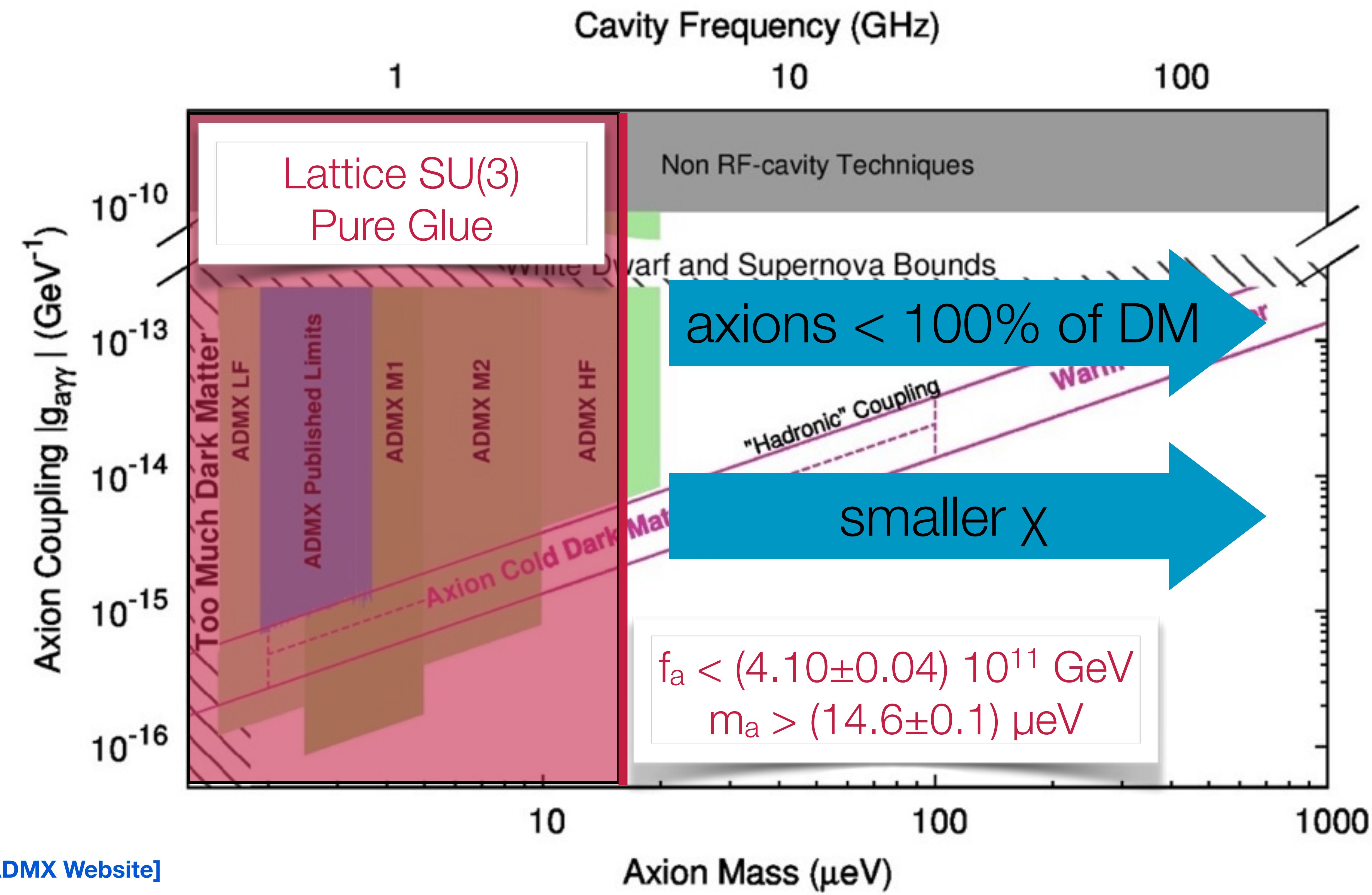

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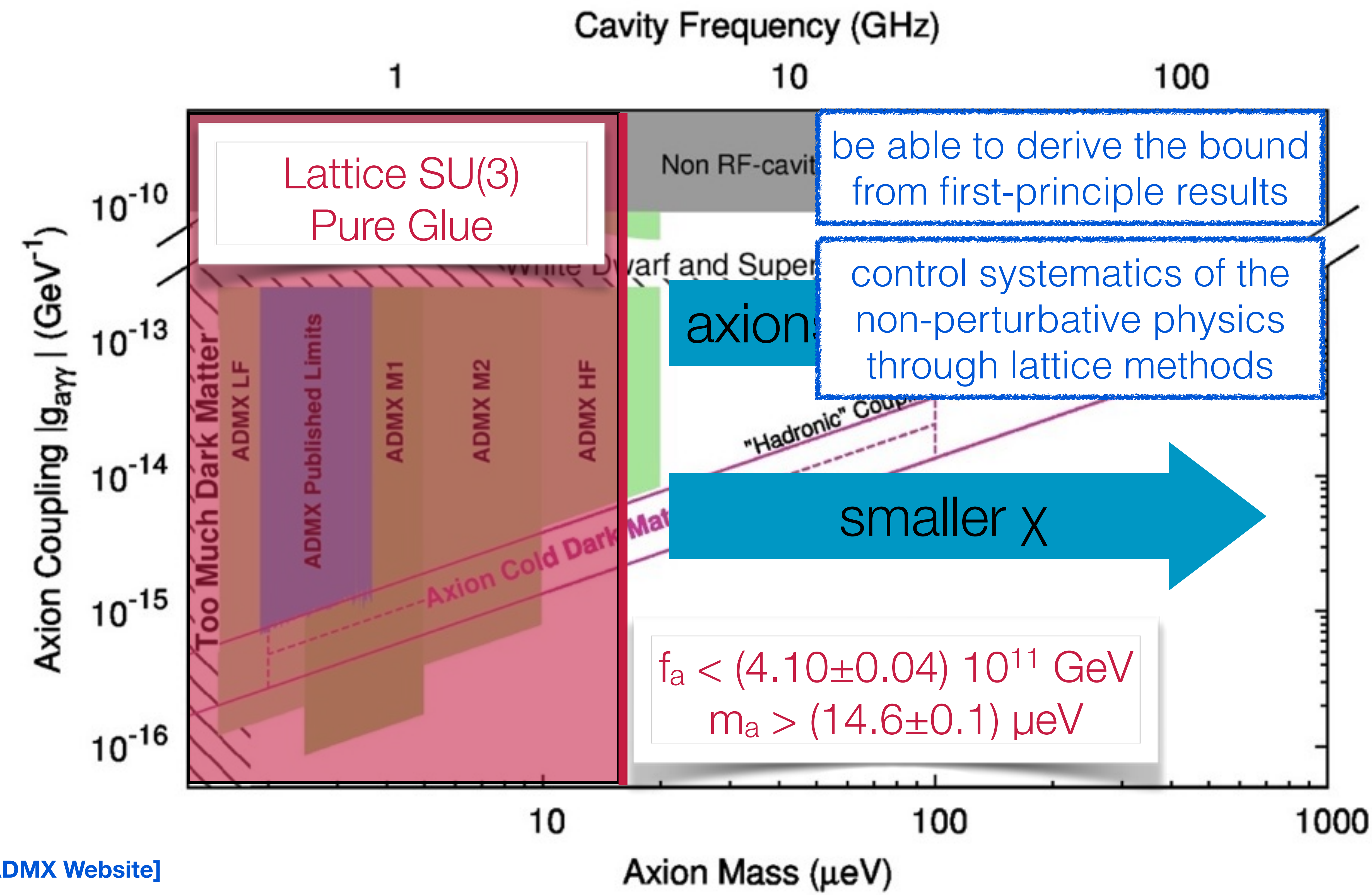

be able to derive the bound from first-principle results

control systematics of the non-perturbative physics through lattice methods

$f_a < (4.10 \pm 0.04)\ 10^{11}$ GeV
$m_a > (14.6 \pm 0.1)$ μeV

[ADMX Website]

Conclusions

- Peccei-Quinn symmetry:
  - cleans up the Strong CP problem
  - provides a plausible, largely unconstrained DM candidate: the axion.
- Axion searches will probe interesting parameter space soon:
  - lattice QCD can provide important non-perturbative input for calculating the axion energy density
- DIGM fits outstandingly to SU(3) YM data at high temperature.
- First steps toward a full QCD non-perturbative lower bound for the axion mass have been taken

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after our work: [Kitano & *Yamada*, arXiv:1506.00370] [Borsanyi *et al.*, arXiv:1508.06917]

Future Steps

- Measure higher moments? Possible to get χ_4 at zero temperature and at finite temperature. **[Cé *et al.*, arXiv:1506.06052]** **[Borsanyi *et al.*, arXiv:1508.06917]**
- Incorporate quarks: use heavy quarks? match with Yang-Mills?
- Fermionic definition of Q (Overlap) to reduce misidentification **[Kitano & *Yamada*, arXiv:1506.00370]**
- Wilson Flow smoothing to address a robust continuum limit **[Borsanyi *et al.*, arXiv:1508.06917]**
- Move to anisotropic lattices to alleviate finite-volume effects at high T and slow tunneling **[Xiong *et al.*, arXiv:1508.07704]**
- Fixed topology methods / open boundary conditions at high T. **[Aoki *et al.*, arXiv:0707.0396v2]** **[Lüscher & Schæfer, arXiv:1105.4749]**
- Finite θ:
  - Imaginary-θ has no sign problem
  - Real, finite θ may be amenable to Langevin methods