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Lattice QCD Input to Axion Cosmology

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INT-15-3
Intersections of BSM Phenomenology and QCD for New Physics Searches
Institute for Nuclear Theory

Tuesday, October 13th, 2015
PRD **92** 034507 / arXiv:1505.07455 – E. Berkowitz, M. Buchoff, E. Rinaldi.

LLNL-PRES-669910
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Outline

- Introduction
- Whence axions?
- What is the over-closure bound?
- Inputs to the over-closure bound from lattice QCD
- Outlook

Big Idea

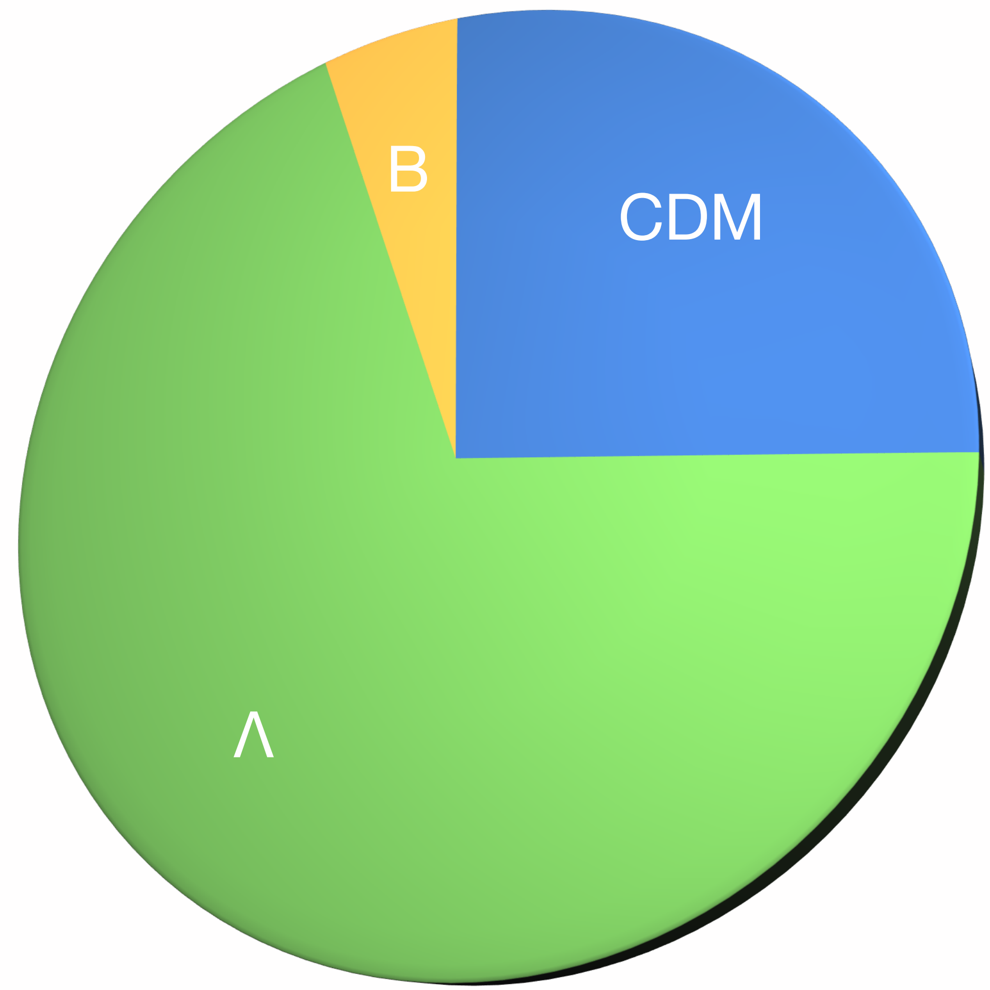
- Axions were originally proposed to deal with the Strong CP Problem, also form a plausible DM candidate.
    - Calculating the axion energy density requires nonperturbative QCD input.

- Being sought in ADMX (LLNL, UW) & CAST (CERN), and (soon) IAXO with large discovery potential in the next few years.

- Requiring $\Omega_a \leq \Omega_{CDM}$ yields a lower bound on the axion mass today.

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

The Economist, 19 Dec 2006



Ω_{tot} = 1.000(7)
PDG 2014 via
P.A.R. Ade, et al., (Planck Collab. 2013 XVI), arXiv: 1303.5076v1.

QCD Theta Term

- QCD has a parameter, θ.
    - Controls QCD CP violation.
    - Topological.
- θ can take any value in (-π,π].
- Neutron EDM ≲ 3 10^{-26}e•cm

Baker et al., PRL 97, 131801 (2006) / hep-ex/0602020

    - |θ| ≲ 10^{-10}

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

CP Violating

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

$$e^{iS} \propto e^{iQ\theta}$$

Strong CP Problem: Why is θ so small?

(Some) Resolutions of the Strong CP Problem

- Just declare CP to be good in the strong sector
  - Why in the strong and not in the weak?

- $m_u = 0$ $\quad \bar{q}\left(i\not{D} - m e^{i\theta'\gamma_5}\right)q$

  ‘t Hooft PRL **37** 8 (1976)
  Jackiw & Rebbi, PRL **37** 127 (1976)
  Callan, Dashen & Gross PLB **63** 335 (1976)
  Kaplan & Manohar PRL **56** 2004 (1986)

  - $m_u \neq 0$

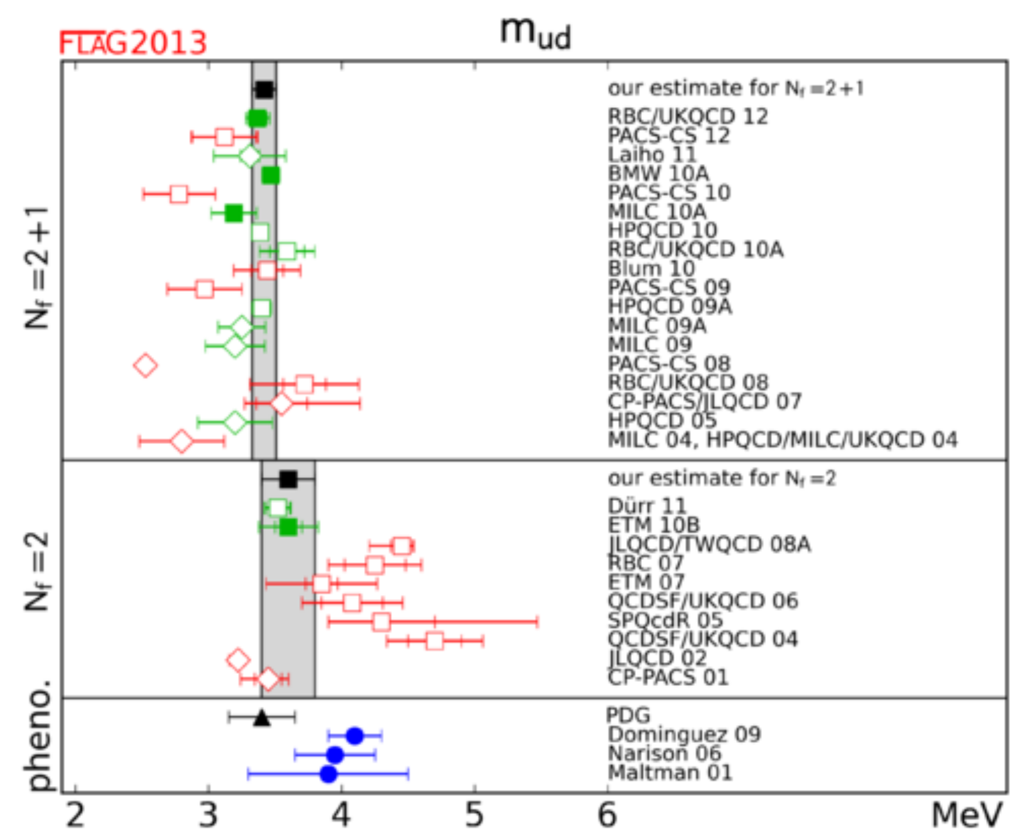
    Gasser & Leutwyler PhysRept **87** 77-169 (1982)

- Additional Peccei-Quinn symmetry & axions

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

  - Fine tuning problem can be reintroduced via high-dimensional (11^+) operators at Planck scale.

    Holman *et al.* arXiv:hep-ph/9203206
    Cheung arXiv:1003.0941



Colangelo *et al.* (FLAG) arXiv:1011.4408

Axions

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

- Couple to topological charge

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

- Otherwise have shift symmetry.

- Amenable to effective theory treatment

- PQ symmetry can break before or after inflation.

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

- Couple to topological charge

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

- Otherwise have shift symmetry.

$$a \to a + \alpha$$

- Amenable to effective theory treatment

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

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

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$$m_a^2 f_a^2 = \chi$$

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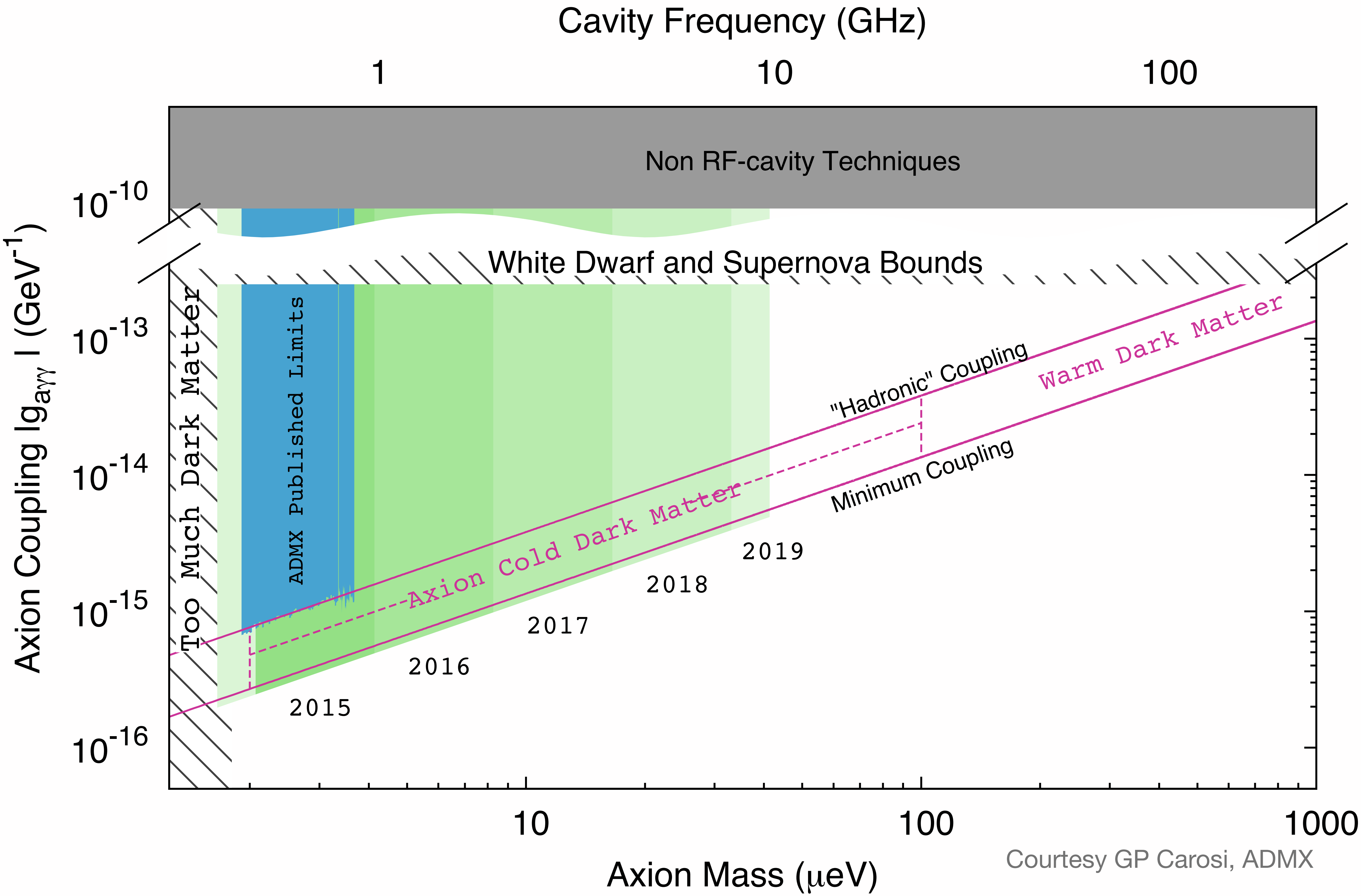
Axion mass

QCD Topological Susceptibility

Current Axion Constraints



Courtesy GP Carosi, ADMX

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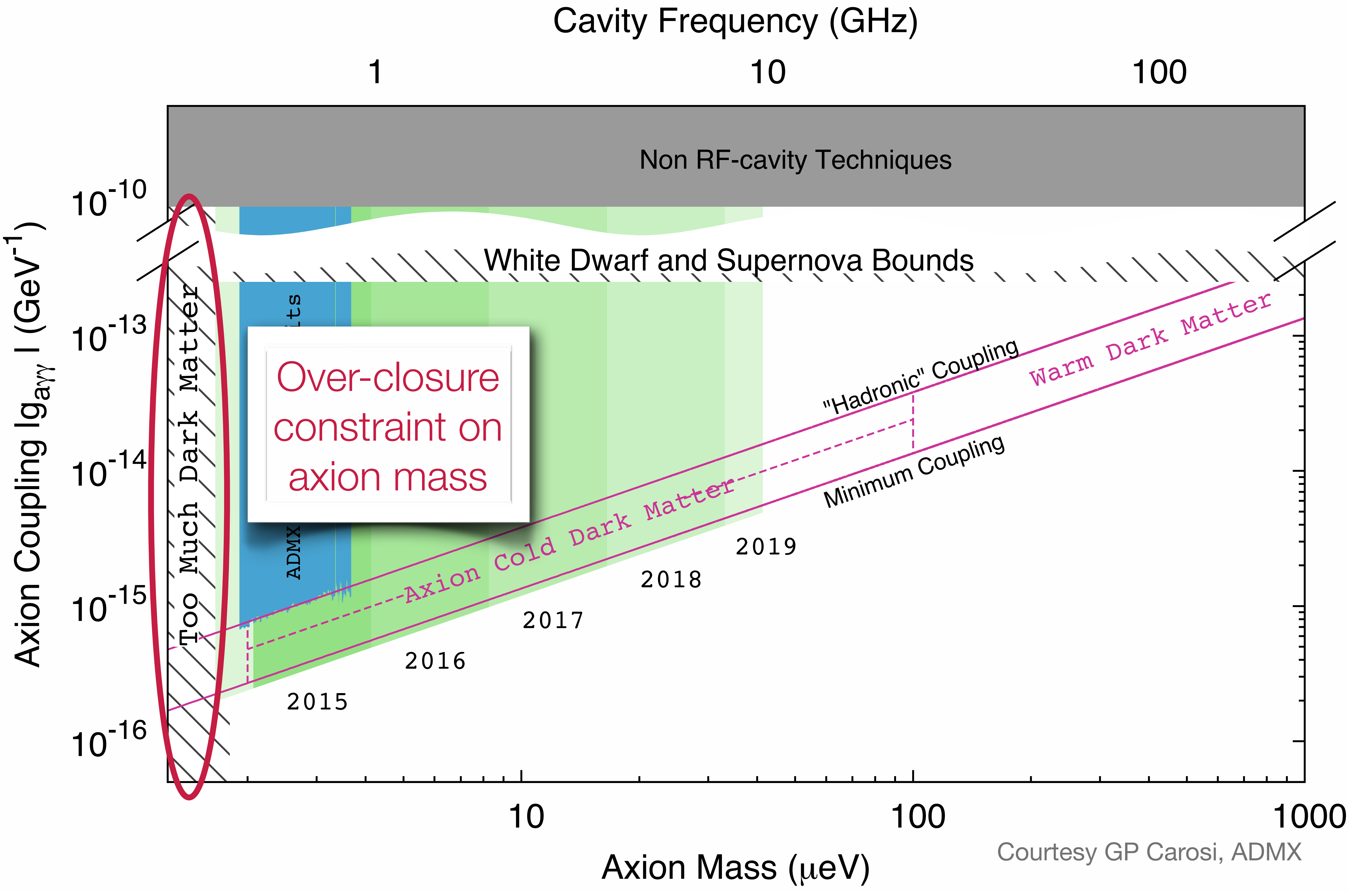

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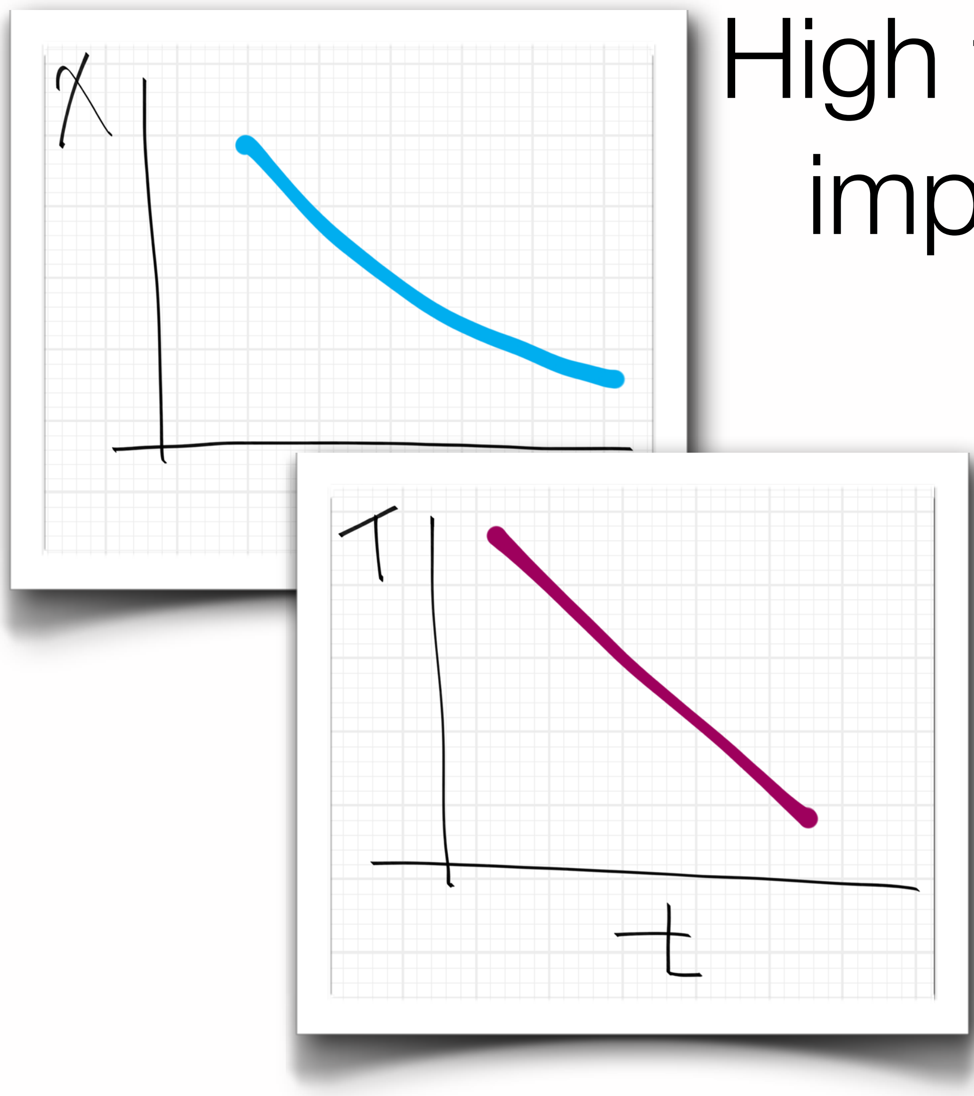
The Over-Closure Bound

High temperature arguments imply χ vanishes as T→∞

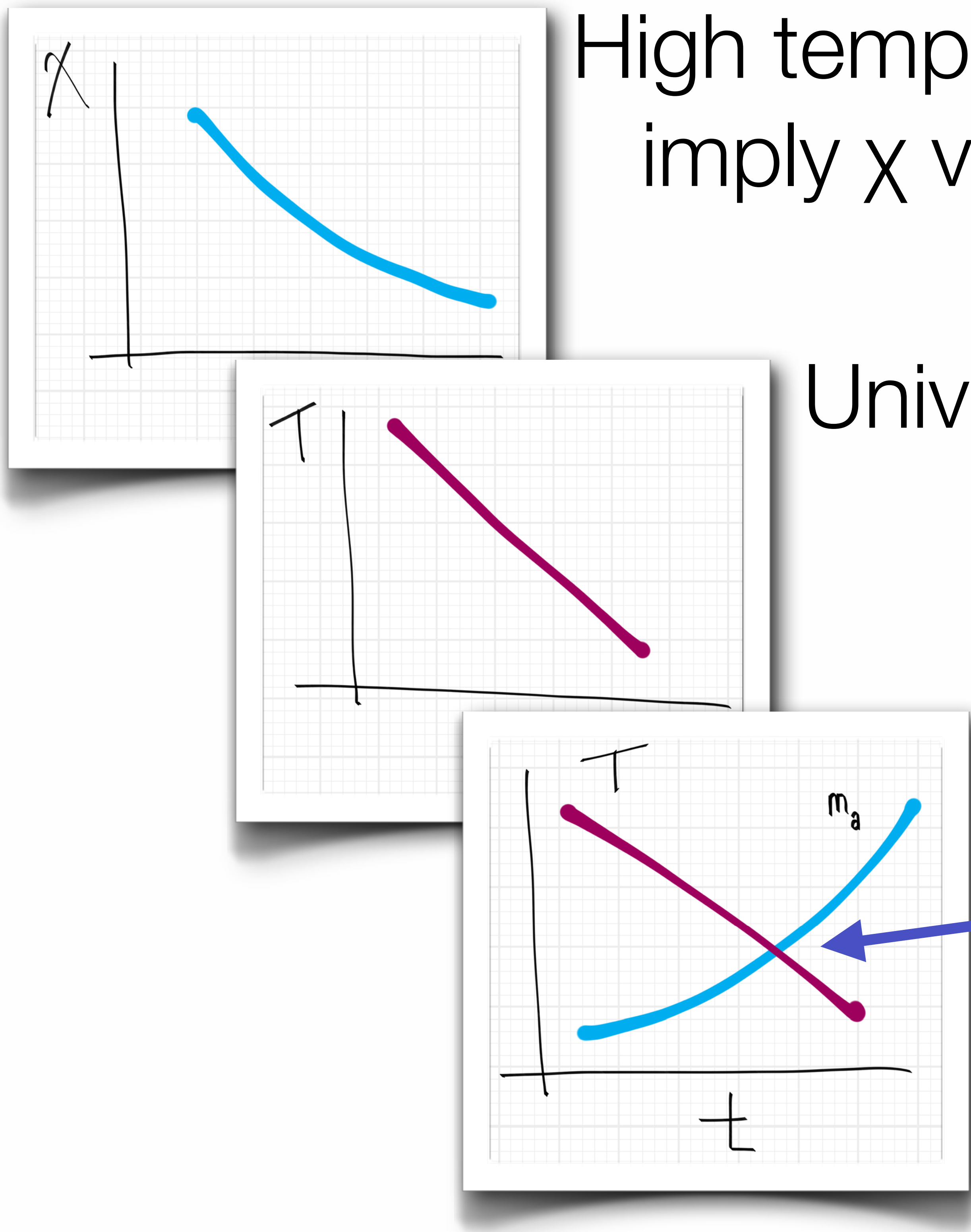
The Over-Closure Bound



High temperature arguments imply χ vanishes as T→∞

Universe cools as it expands

The Over-Closure Bound



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

Universe cools as it expands

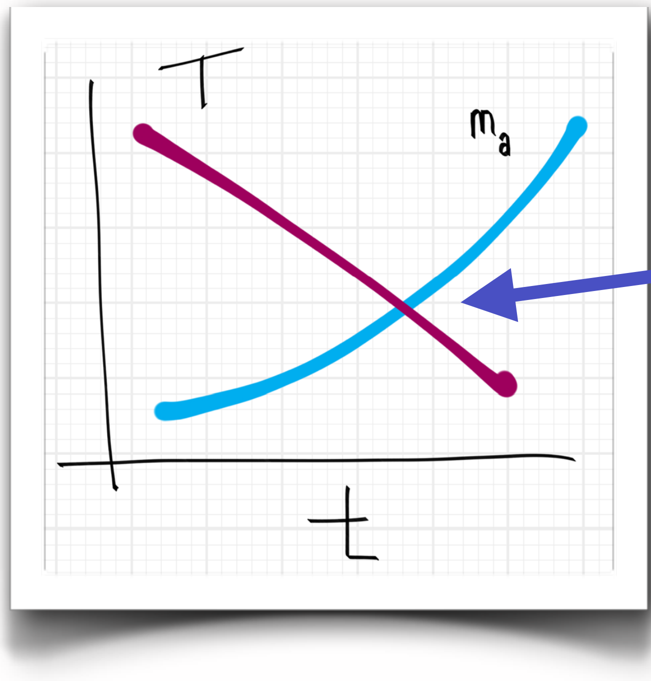
Axion number fixed when

$3H \sim m_a$

$T_1 \approx 5.5\ T_c$

H: Hubble constant

The Over-Closure Bound



Axion number fixed when

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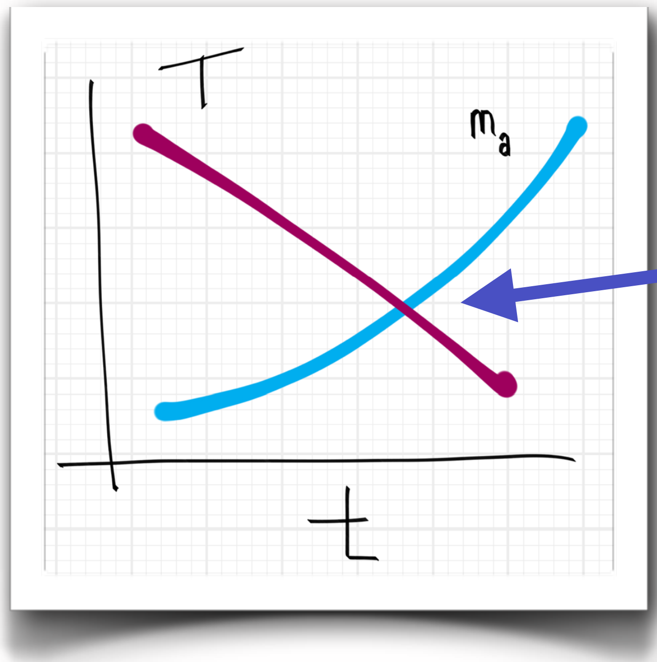
$T_1 \approx 5.5\ T_c$

$$3H(T_1) \sim m_a(T_1)$$

$$9H^2(T_1)f_a^2 \sim \chi(T_1)$$

$$T_1 = T_1(f_a, \chi(T))$$

The Over-Closure Bound



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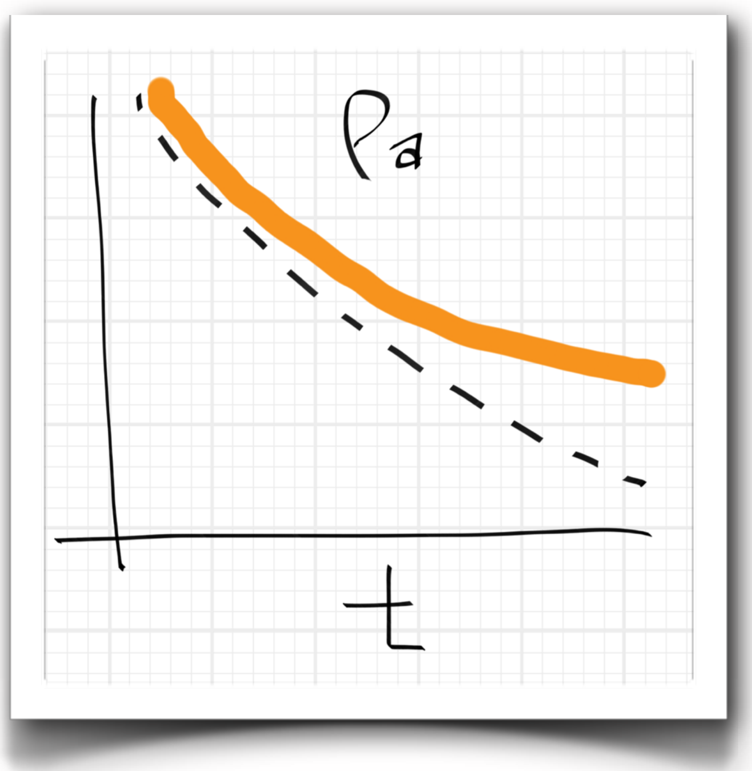
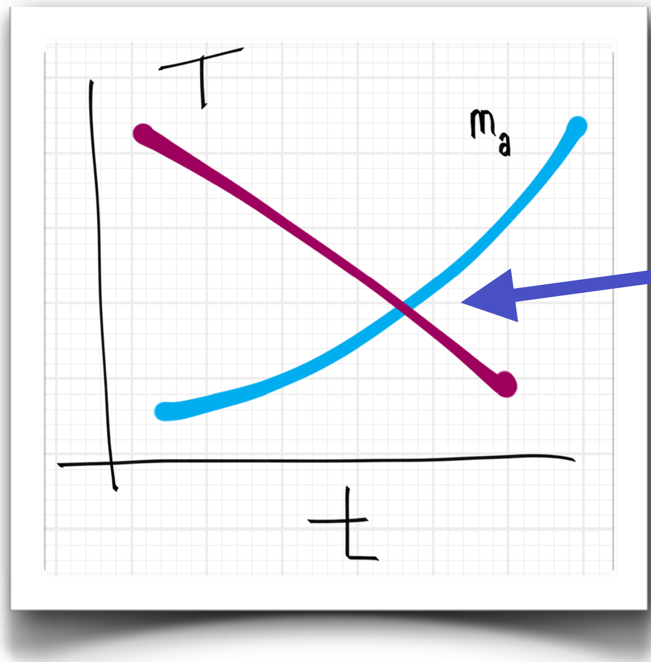


Axions continue to get heavier after production stops!

$$\rho(t) \neq \left(\frac{a(t_1)}{a(t)}\right)^3 \rho(t_1)$$

The Over-Closure Bound



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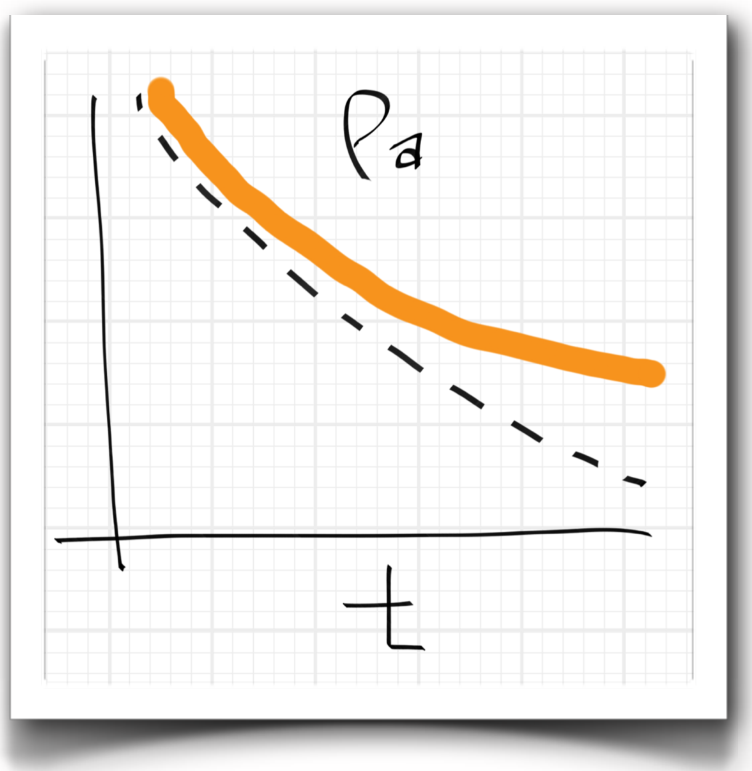

Axions continue to get heavier after production stops!

$$\frac{\rho(t) R^3}{m_a(t)} = \#\ \text{axions in a fixed comoving volume}$$

Axion Density

$$\frac{\rho(t)R^3}{m_a(t)} = \#\ \text{axions in a fixed comoving volume}$$

Cosmological EOM:

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

$$\rho(T_\gamma) = \frac{1}{2}\theta_1^2 \sqrt{\chi(T_\gamma)\chi(T_1)} \left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

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χPT

$$f_a^2 m_a^2(T_\gamma) = \frac{m_u m_d}{(m_u + m_d)^2} f_\pi^2 m_\pi^2$$

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3H ~ m_a

χPT

Cosmology

Strong Dynamics

Axion Density $\dfrac{\rho(t)R^3}{m_a(t)} = \#\ \text{axions in a fixed comoving volume}$

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Cosmology

Strong Dynamics

Initial conditions

Axion Density $\dfrac{\rho(t)R^3}{m_a(t)} = \#\text{ axions in a fixed comoving volume}$

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$$\rho(T_\gamma) = \frac{1}{2}\theta_1^2 \sqrt{\chi(T_\gamma)\chi(T_1)} \left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

Initial conditions

χPT

Strong Dynamics

Cosmology

3H ~ m_a

Late PQ breaking: $\langle\theta_1^2\rangle = \dfrac{\pi^2}{3}$

constraints on m_a, f_a

Early PQ breaking: constraints depend on θ_1

Axion Density

$$\frac{\rho(t)R^3}{m_a(t)} = \#\text{ axions in a fixed comoving volume}$$

$$\rho(T_\gamma) = \frac{1}{2}\theta_1^2\sqrt{\chi(T_\gamma)\chi(T_1)}\left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

If T_1 goes down, $\rho(T_\gamma)$ goes up...

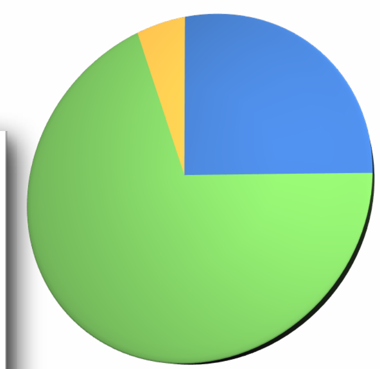
$$9H^2(T_1)f_a^2 \sim \chi(T_1)$$

T_1 goes down as f_a goes up.

If f_a goes up, $\rho(T_\gamma)$ goes up...

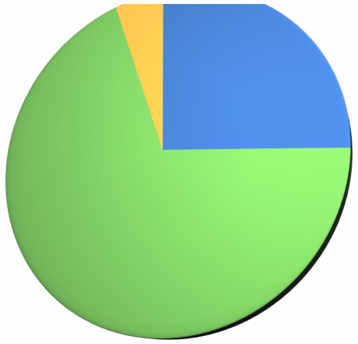
$$m_a^2 f_a^2 = \chi$$

Small m_a are excluded by observed dark matter abundances!



Prior Over-Closure Bound

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

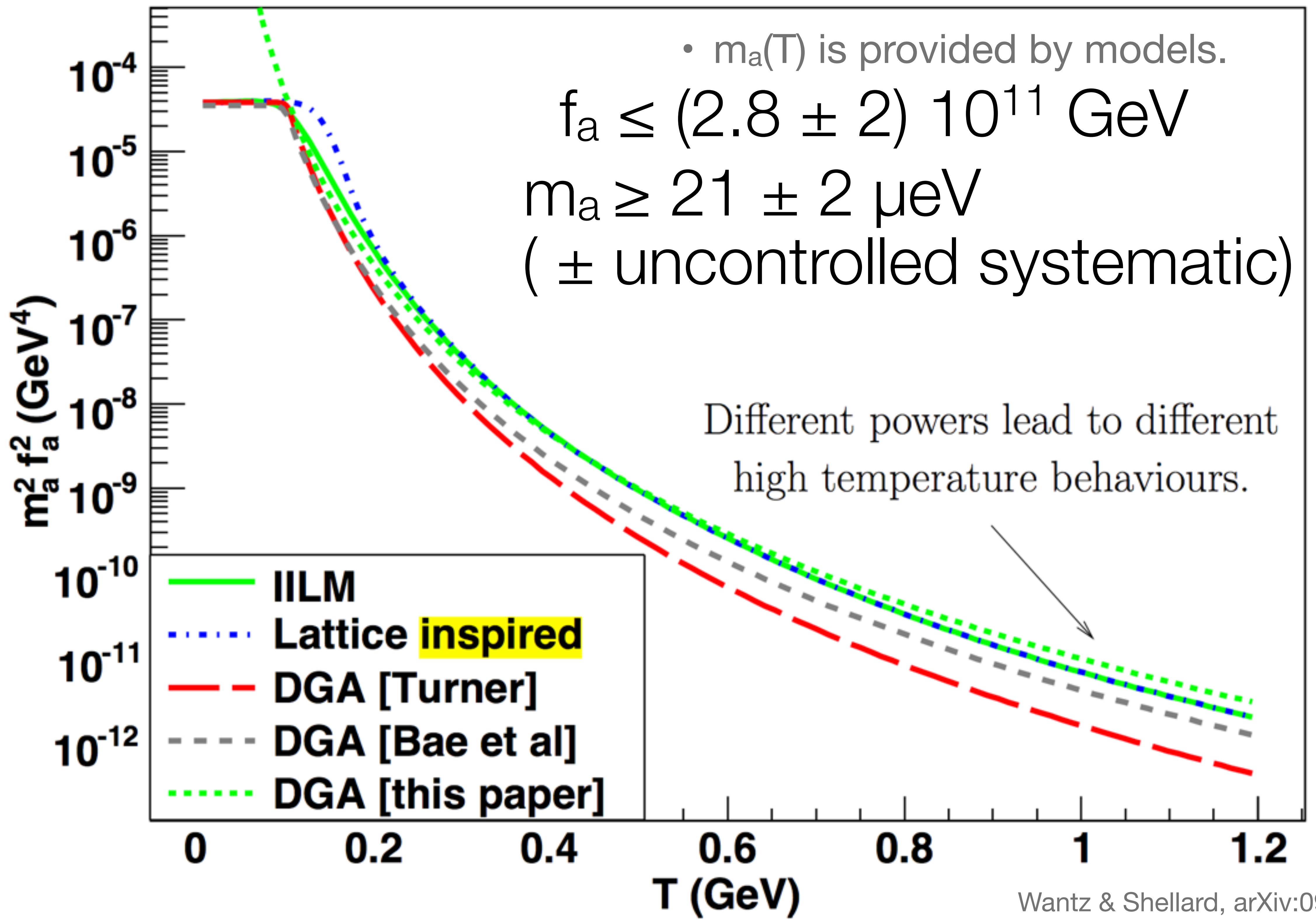


- $m_a(T)$ is provided by models.

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

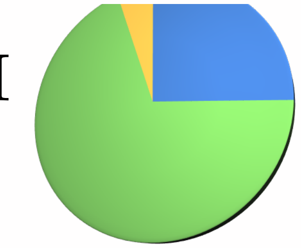
$m_a \geq 21 \pm 2$ μeV

(± uncontrolled systematic)



Wantz & Shellard, arXiv:0910.1066

$$\Omega_a \leq \Omega_{\mathrm{CDM}}$$



Current Axion Constraints

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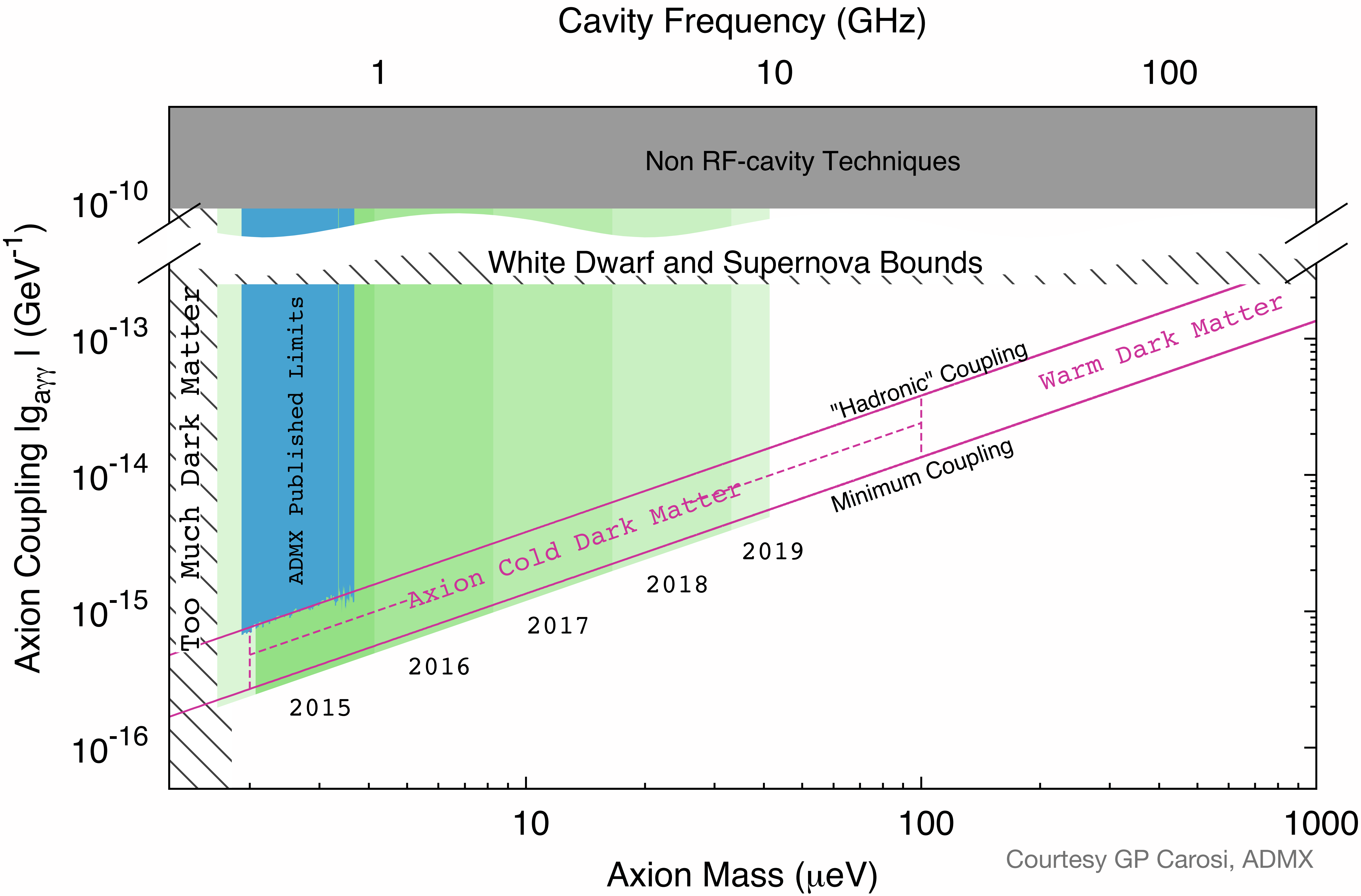

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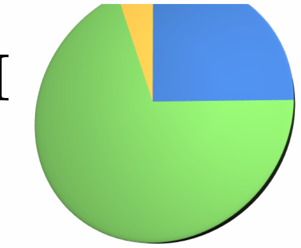

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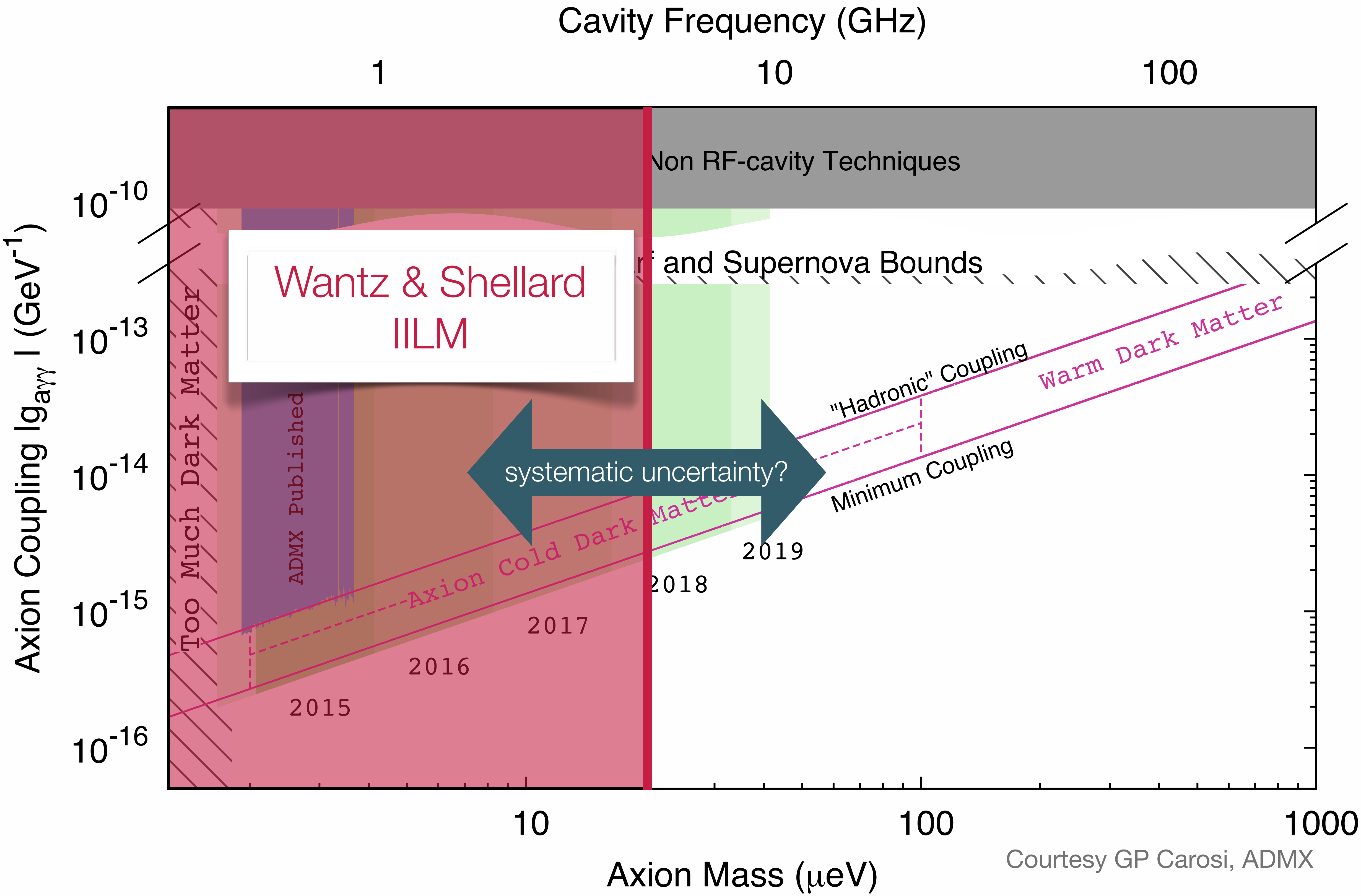

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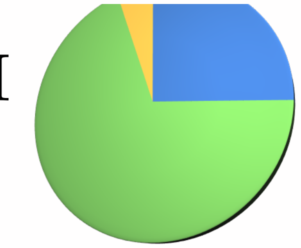

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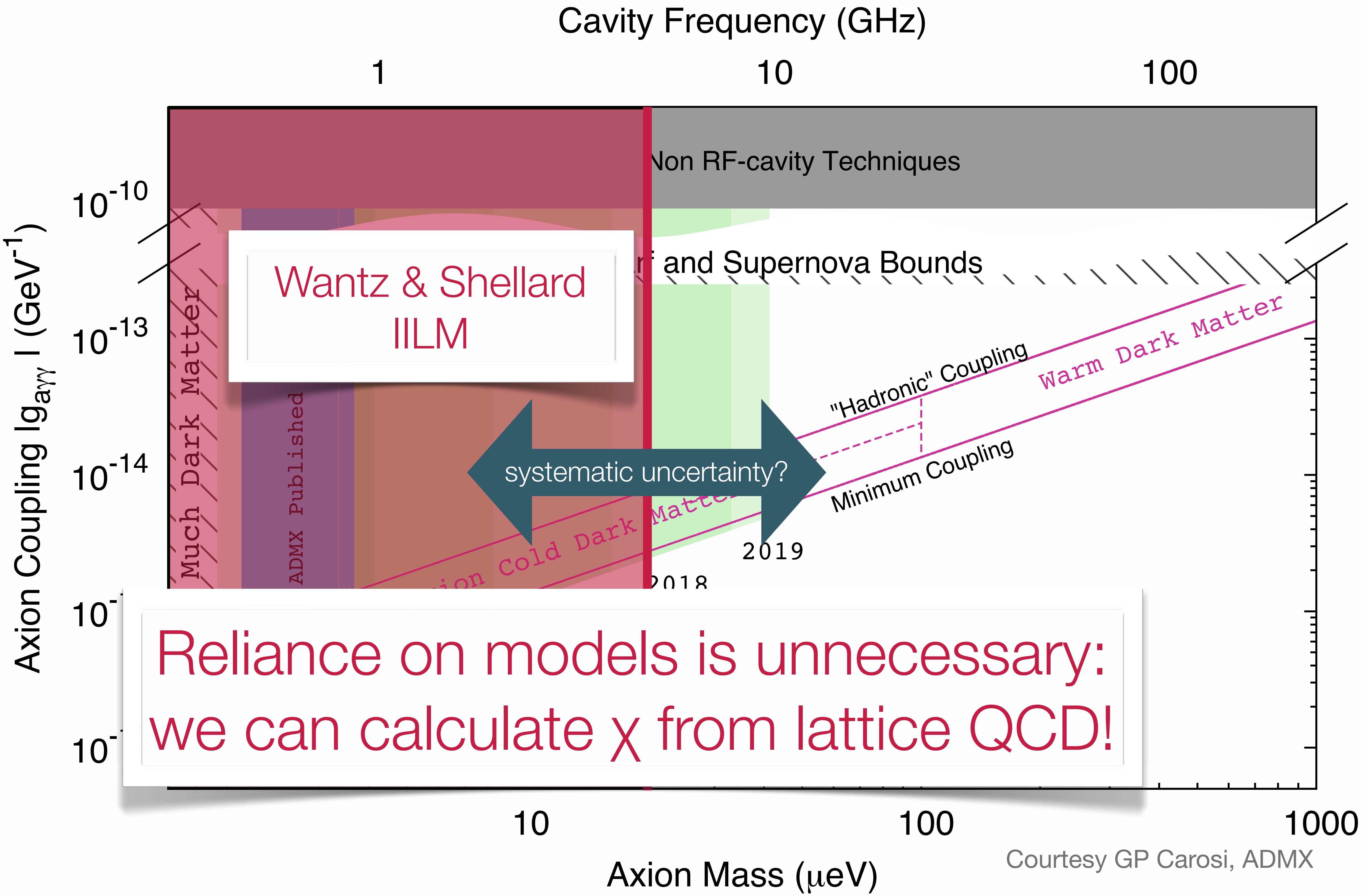

Reliance on models is unnecessary: we can calculate χ from lattice QCD!

Courtesy GP Carosi, ADMX

CAVEAT

We study pure Yang-Mills, and not yet full QCD.

- Dramatically more efficient algorithms enable huge statistics and volumes, shorter autocorrelation times.
- Tc is ~284 MeV, compared to 154 MeV in QCD.
- High temperature tends to suppress quark loops.
  - What counts as high temperature?
  - Unclear if this holds true for topological observables.

But: for getting a lower bound on m_a it's not so bad!

Overview of Lattice Ensembles & Measurements

Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455

- SU(3) YM with Wilson plaquette action
- T between 1.2 and 2.5
- N_σ between 48 and 144 (larger at higher T)
- N_τ either 6 or 8
- Between 14000 and 52000 measurements
  - Combined hot & cold starts
  - Cut of 2000 cfg.s for thermalization
  - 10 compound sweeps of 1 heatbath step and 8 over-relaxation steps

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

$Q_\mathbb{R}$ 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

Q_{OV} overlap

Q_{WF} Wilson Flow

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Essentially no discretization or finite volume corrections

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T/T_c	β	$a\sqrt{\sigma}$	N_τ	N_σ	N_{meas}	central value $\chi^{1/4}/T_c \pm \delta\chi^{1/4}/T_c$ statistical error for							
						$\chi_\mathbb{R}$		$\chi_\mathbb{Z}$		χ_a		χ_f	
1.2	6.001	0.2161	6	64	14000	0.3880	0.0012	0.3814	0.0012	0.3871	0.0012	**0.4192**	**0.0013**
1.31	6.053	0.1979	6	48	15600	0.3495	0.0009	0.3130	0.0009	0.3392	0.0010	0.3691	0.0011
				64	36000	0.3424	0.0006	0.3358	0.0006	0.3402	0.0007	0.3703	0.0007
				80	14000	0.3426	0.0010	0.3389	0.0010	0.3416	0.0010	**0.3735**	**0.0011**
	6.242	0.1484	8	64	33998	0.3634	0.0010	0.3493	0.0010	0.3520	0.0010	0.3687	0.0010
				96	14000	0.3556	0.0015	0.3533	0.0014	0.3537	0.0015	0.3703	0.0015
1.4	6.095	0.1852	6	64	54000	0.3153	0.0005	0.3077	0.0005	0.3095	0.0005	**0.3370**	**0.0005**
1.5	6.139	0.1729	6	64	54000	0.2928	0.0005	0.2833	0.0005	0.2814	0.0005	**0.3068**	**0.0005**
1.6	6.182	0.1621	6	64	53998	0.2721	0.0005	0.2587	0.0005	0.2568	0.0005	**0.2799**	**0.0005**
1.7	6.223	0.1525	6	64	24000	0.2536	0.0008	0.2330	0.0008	0.2369	0.0008	**0.2585**	**0.0008**
1.8	6.263	0.1441	6	64	24000	0.2343	0.0008	0.2005	0.0009	0.2178	0.0008	0.2368	0.0008
				80	32000	0.2320	0.0006	0.2262	0.0006	0.2185	0.0006	**0.2368**	**0.0006**
	6.471	0.1080	8	96	14000	0.2306	0.0016	0.2170	0.0017	0.2236	0.0015	0.2312	0.0016
1.9	6.301	0.1365	6	64	24000	0.2175	0.0009	0.1672	0.0011	0.2019	0.0008	0.2190	0.0009
				80	34000	0.2164	0.0006	0.2095	0.0006	0.2026	0.0006	**0.2189**	**0.0006**
1.99	6.550	0.0973	8	64	14795	0.2013	0.0034	0.1800	0.0036	0.1986	0.0029	0.2013	0.0034
2.0	6.338	0.1297	6	48	15600	0.2040	0.0018	0.1292	0.0027	0.1898	0.0016	0.2042	0.0018
				64	25598	0.2032	0.0010	0.1390	0.0014	0.1893	0.0009	0.2041	0.0010
				80	26000	0.2014	0.0008	0.1920	0.0008	0.1888	0.0007	0.2030	0.0008
				96	14000	0.2004	0.0008	0.1961	0.0008	0.1900	0.0008	**0.2038**	**0.0009**
2.1	6.373	0.1235	6	80	24000	0.1880	0.0009	0.1749	0.0009	0.1774	0.0008	**0.1889**	**0.0009**
2.5	6.502	0.1037	6	128	14000	0.1497	0.0010	0.1479	0.0010	0.1494	0.0008	0.1492	0.0010
				144	15797	0.1525	0.0008	0.1513	0.0008	0.1495	0.0006	**0.1518**	**0.0008**

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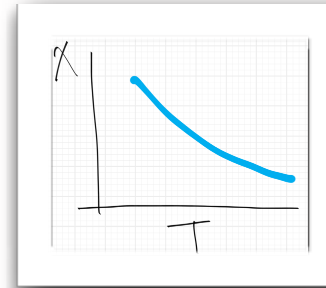
Q_a artifact corrected
Lucini & Teper, hep-lat/0

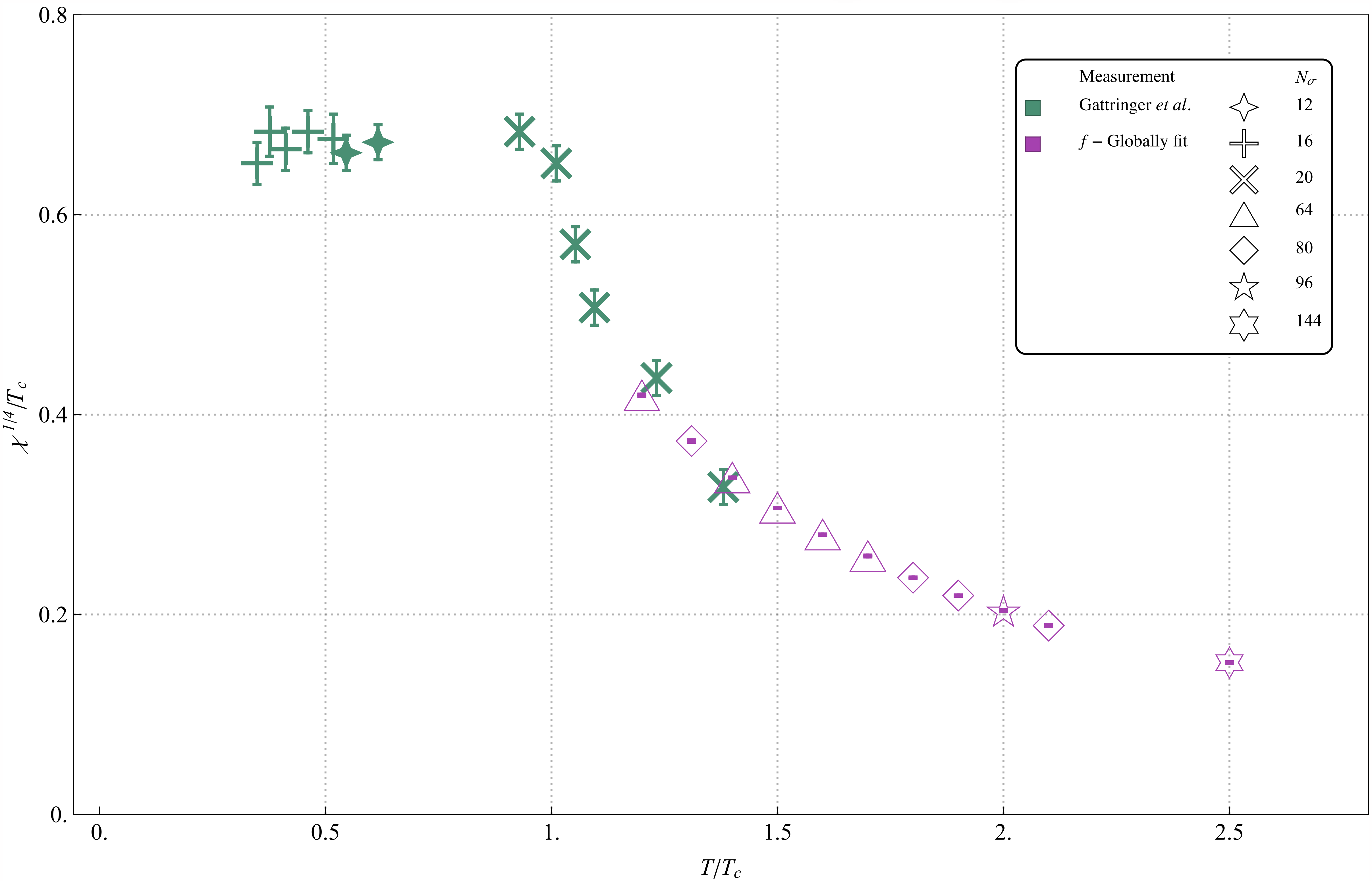
Q_f globally fit
del Debbio *et al.*, hep-th/



Pure glue measurements show χ vanishes as T→∞

Best Lattice Results

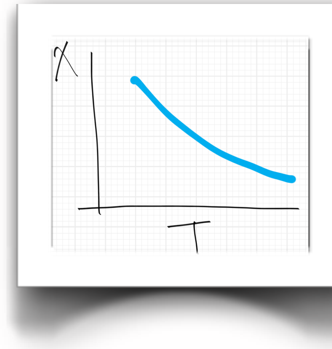
Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455



Gattringer et al., arXiv:hep-lat/0203013 up to T/T_c ~ 1.3

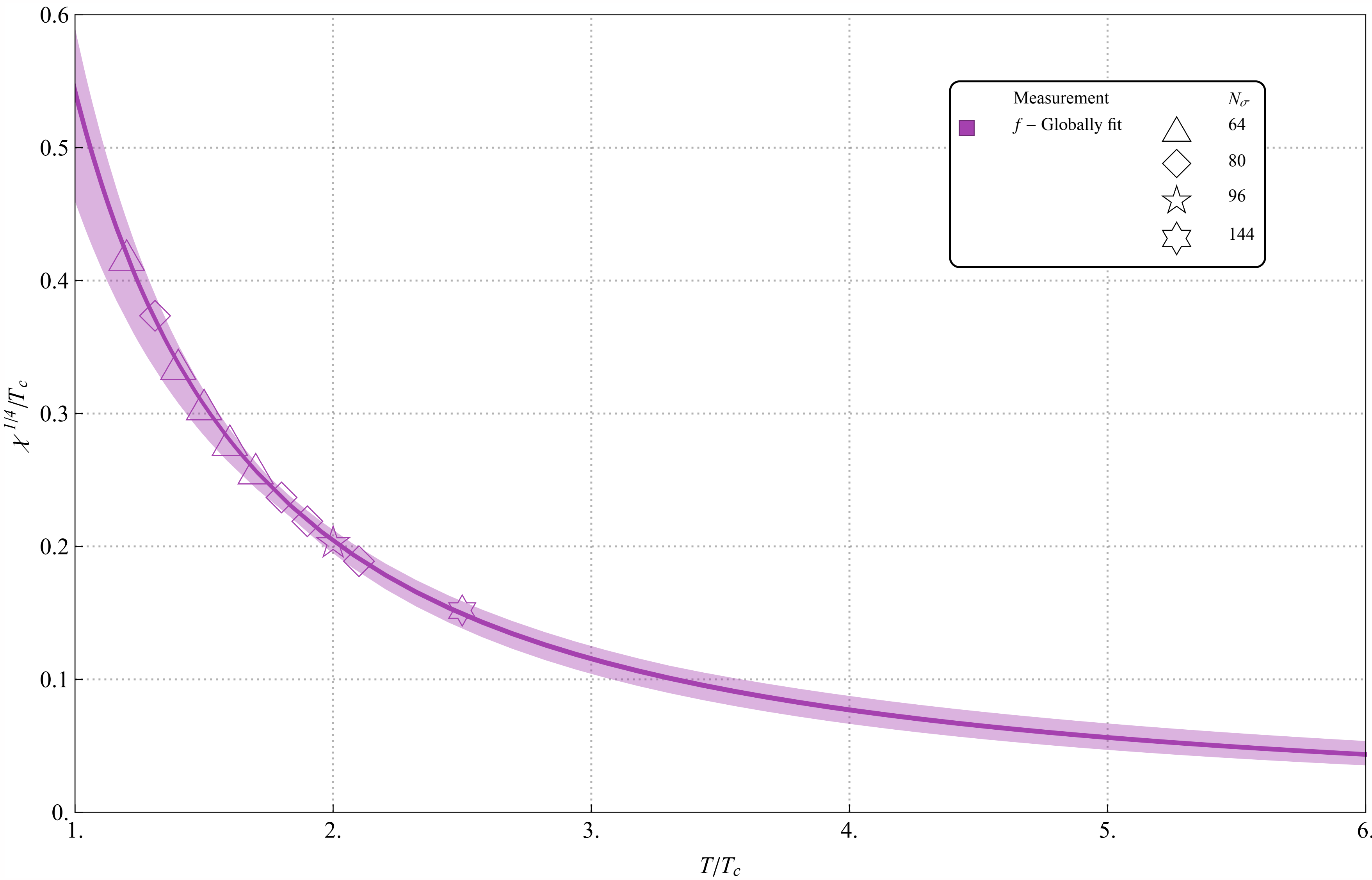
DIGM Best Fit & Extrapolation

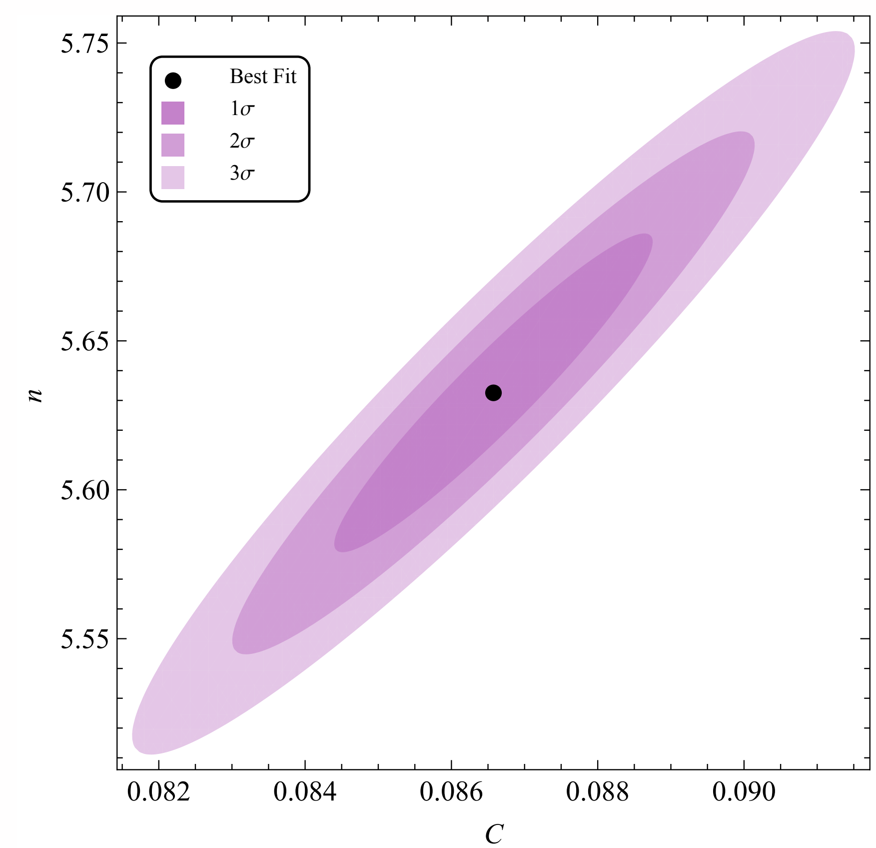
Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455



Pure glue measurements show χ vanishes as T→∞

$$\frac{\chi}{T_c^4} = \frac{C}{(T/T_c)^n}$$

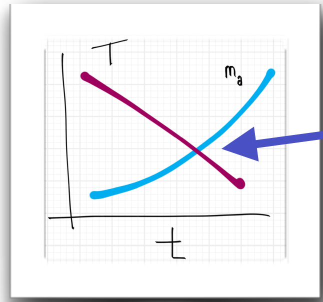




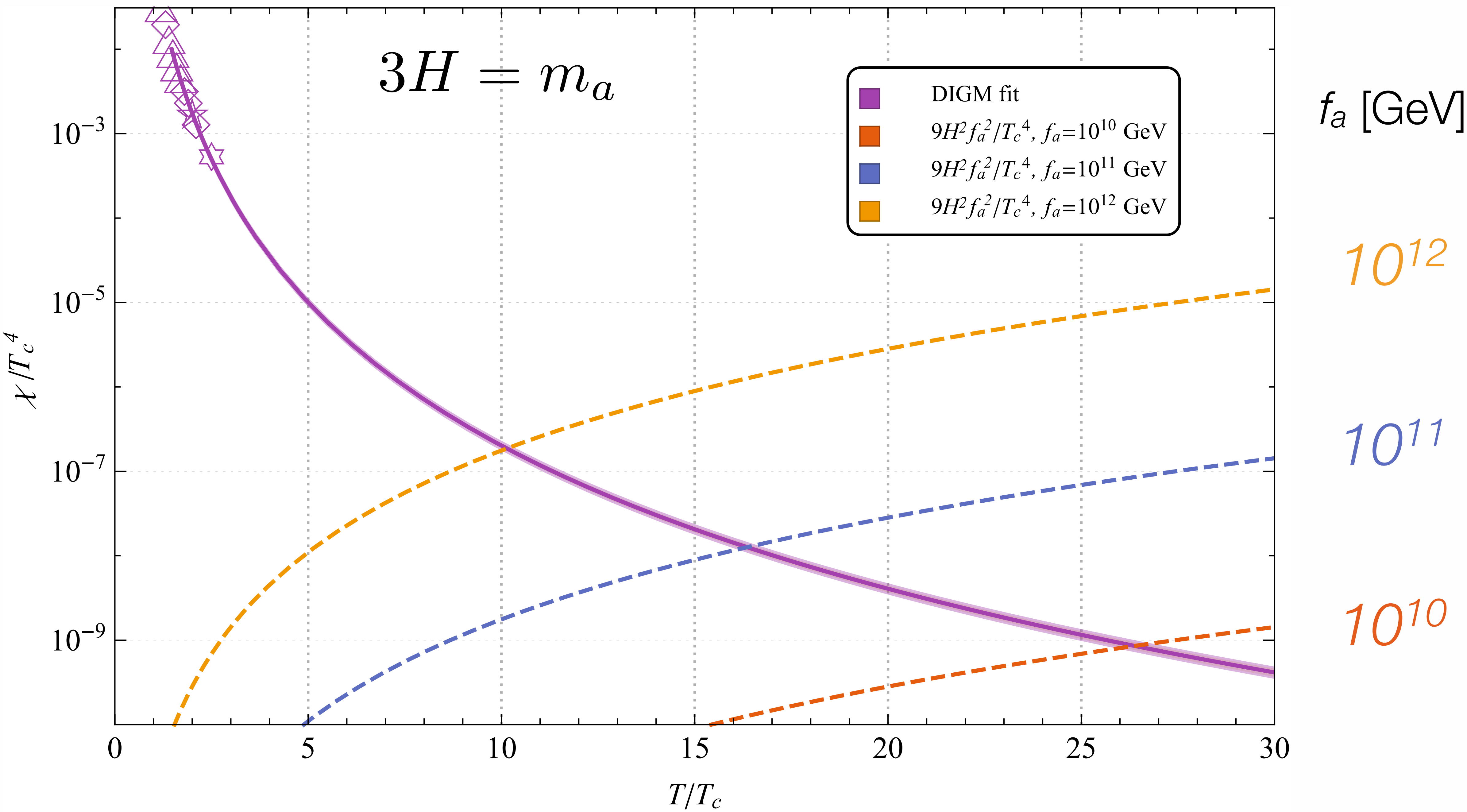
	C	n
Best Fit	0.0865	5.63
Covariance Matrix		
C	$2.\times10^{-6}$	$5.\times10^{-5}$
n	$5.\times10^{-5}$	0.0012

Axion Production Ceases

Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455



Axions production stops when
3H ~ m_a
$T_1 \approx 5.5\, T_c$ from models



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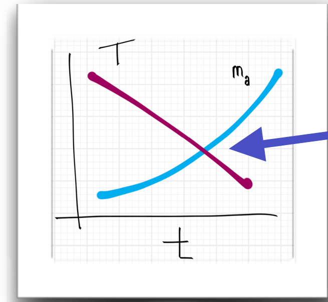

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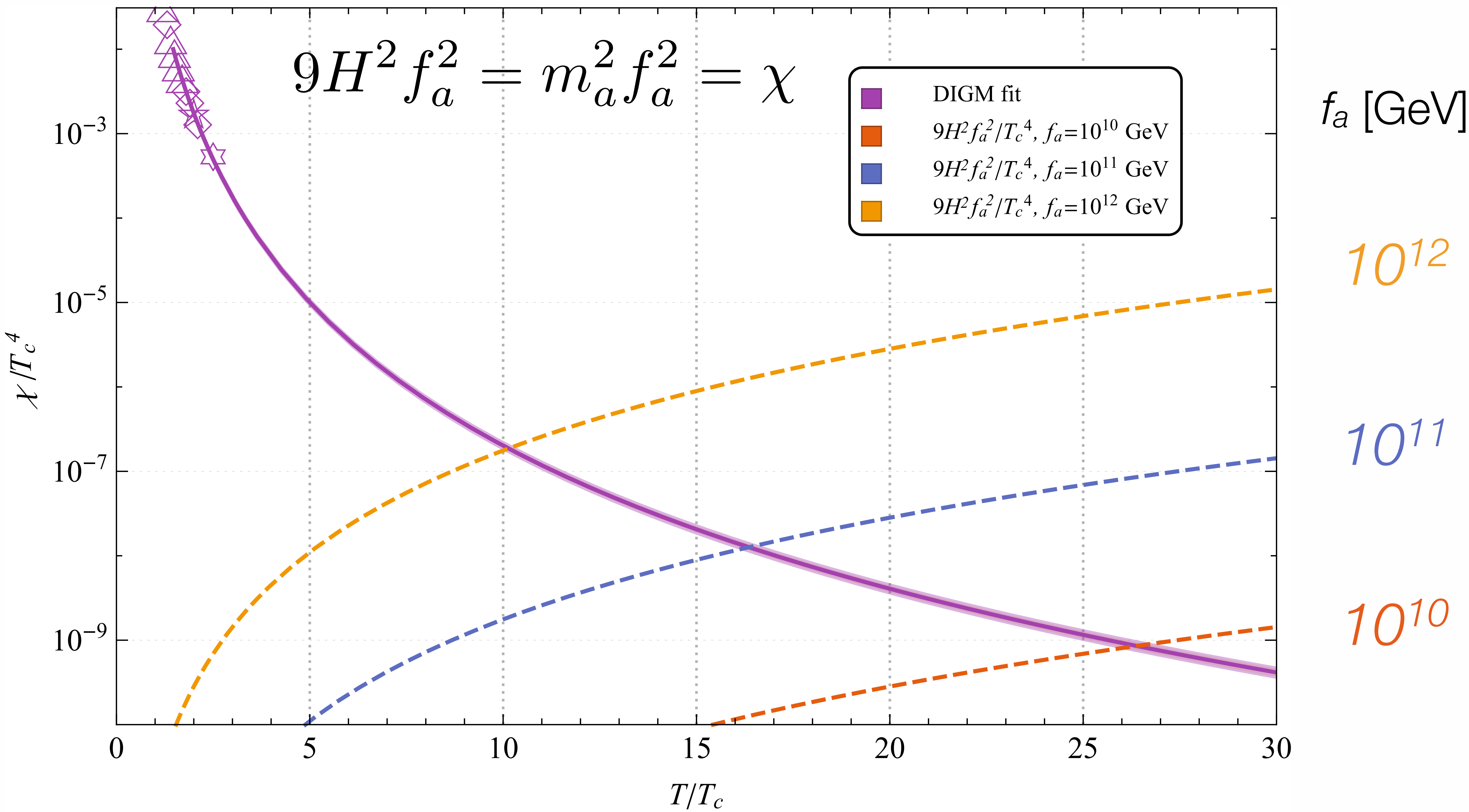

$$H^2 = \frac{\pi^2}{90} \frac{1}{m_P^2}\, g_{*R}(T)\, T^4$$

Axion Density $\dfrac{\rho(t)R^3}{m_a(t)} = \#$ axions in a fixed comoving volume

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Cosmological EOM: $\rho(T_1) = \dfrac{1}{2}\theta_1^2 m_a^2 f_a^2 = \dfrac{1}{2}\theta_1^2 \chi(T_1)$

$$\rho(T_\gamma) = \frac{1}{2}\theta_1^2 \sqrt{\chi(T_\gamma)\chi(T_1)} \left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

3H ~ m_a

χPT

Cosmology

Strong Dynamics

Initial conditions

Axion Density $\frac{\rho(t)R^3}{m_a(t)} = \#\text{ axions in a fixed comoving volume}$

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3H ~ m_a

χPT

Cosmology

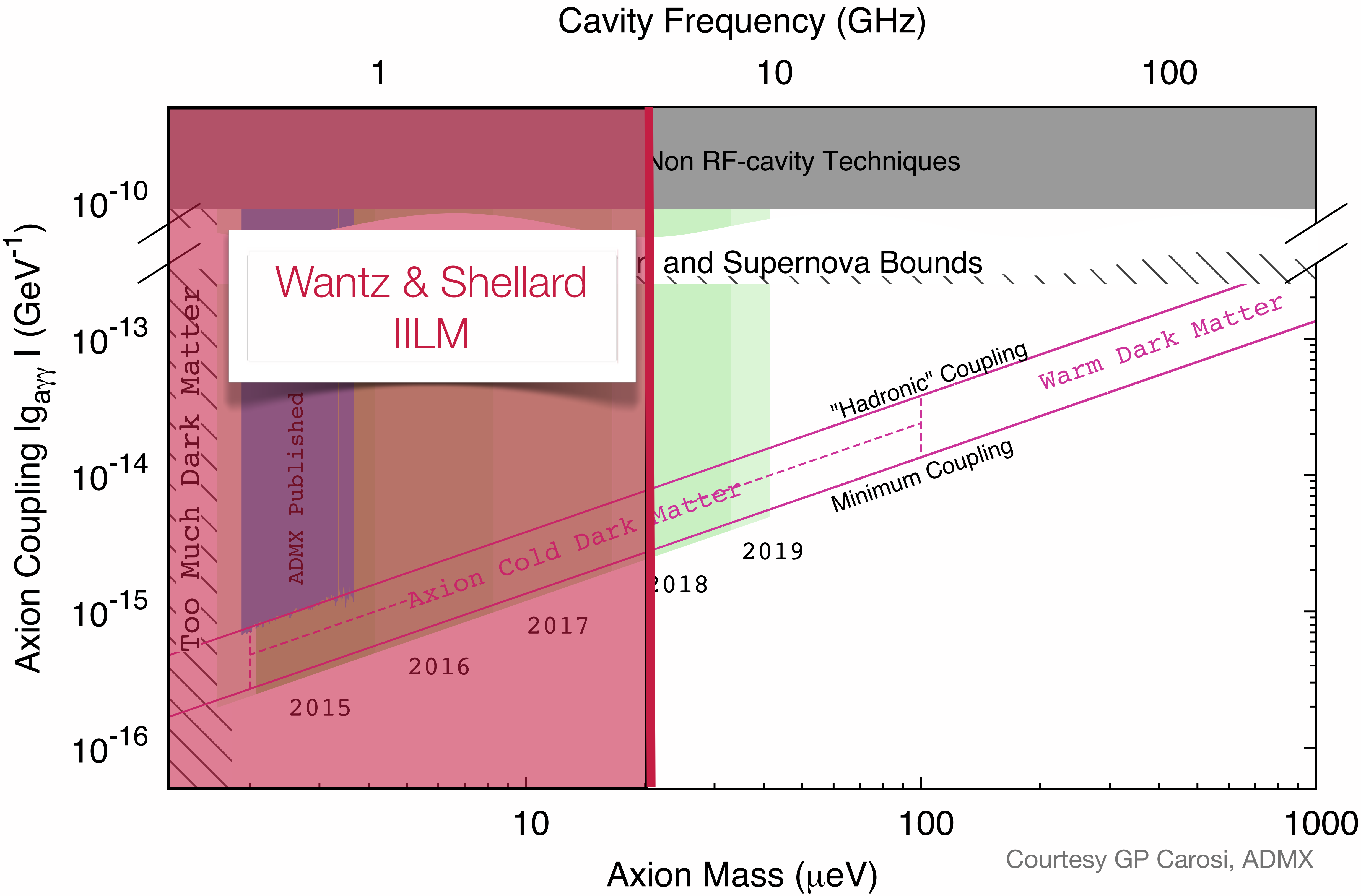
Lattice!

Initial conditions

$$\Omega_a \leq \Omega_{\mathrm{CDM}}$$

The Over-Closure Bound As It Stands Today

Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455



Courtesy GP Carosi, ADMX

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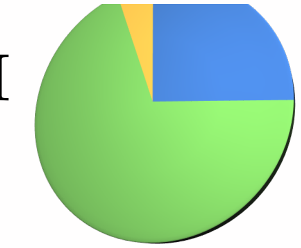

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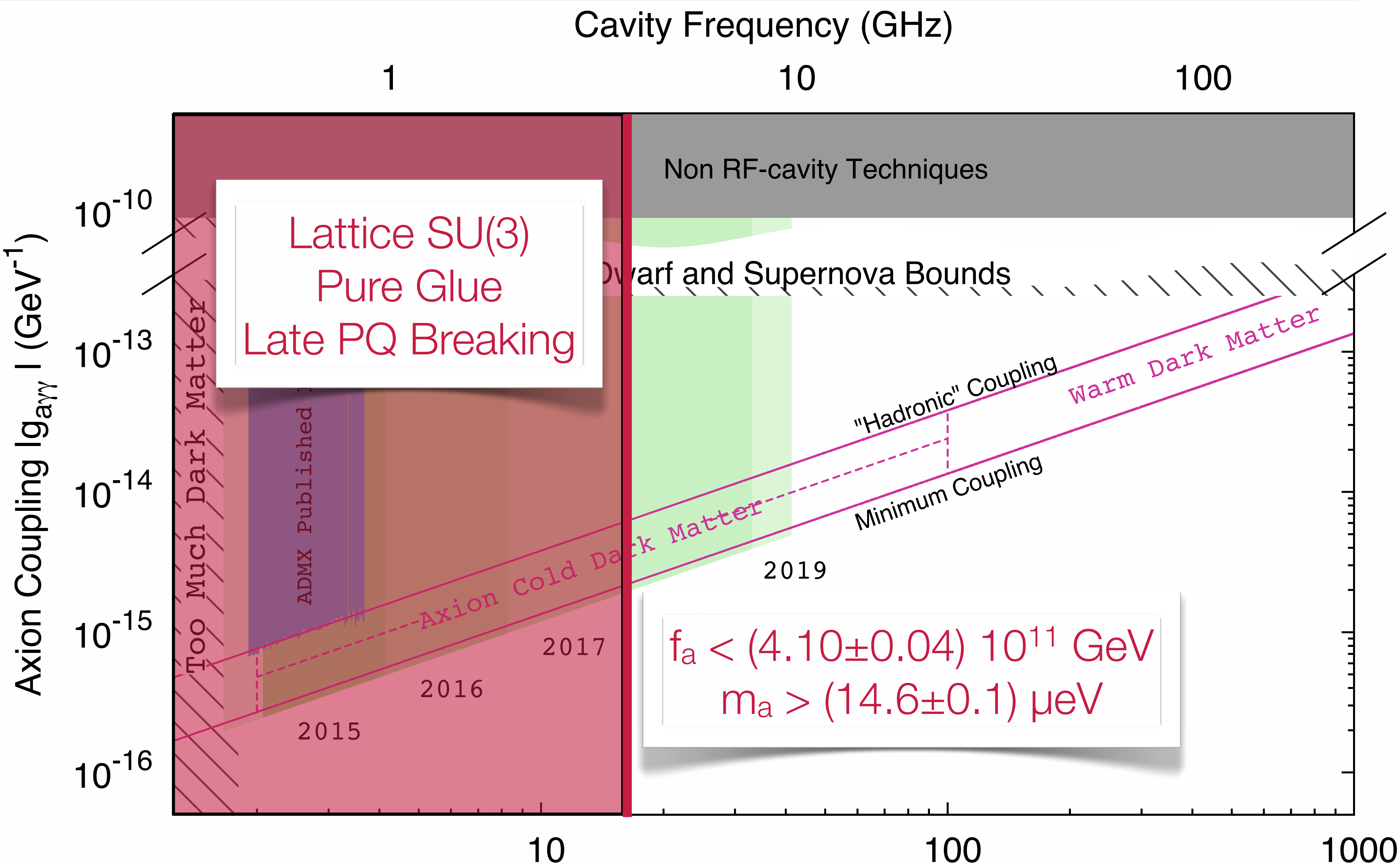

Courtesy GP Carosi, ADMX

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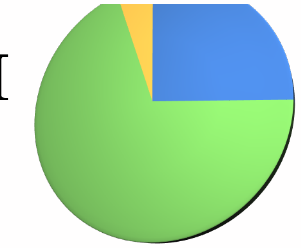

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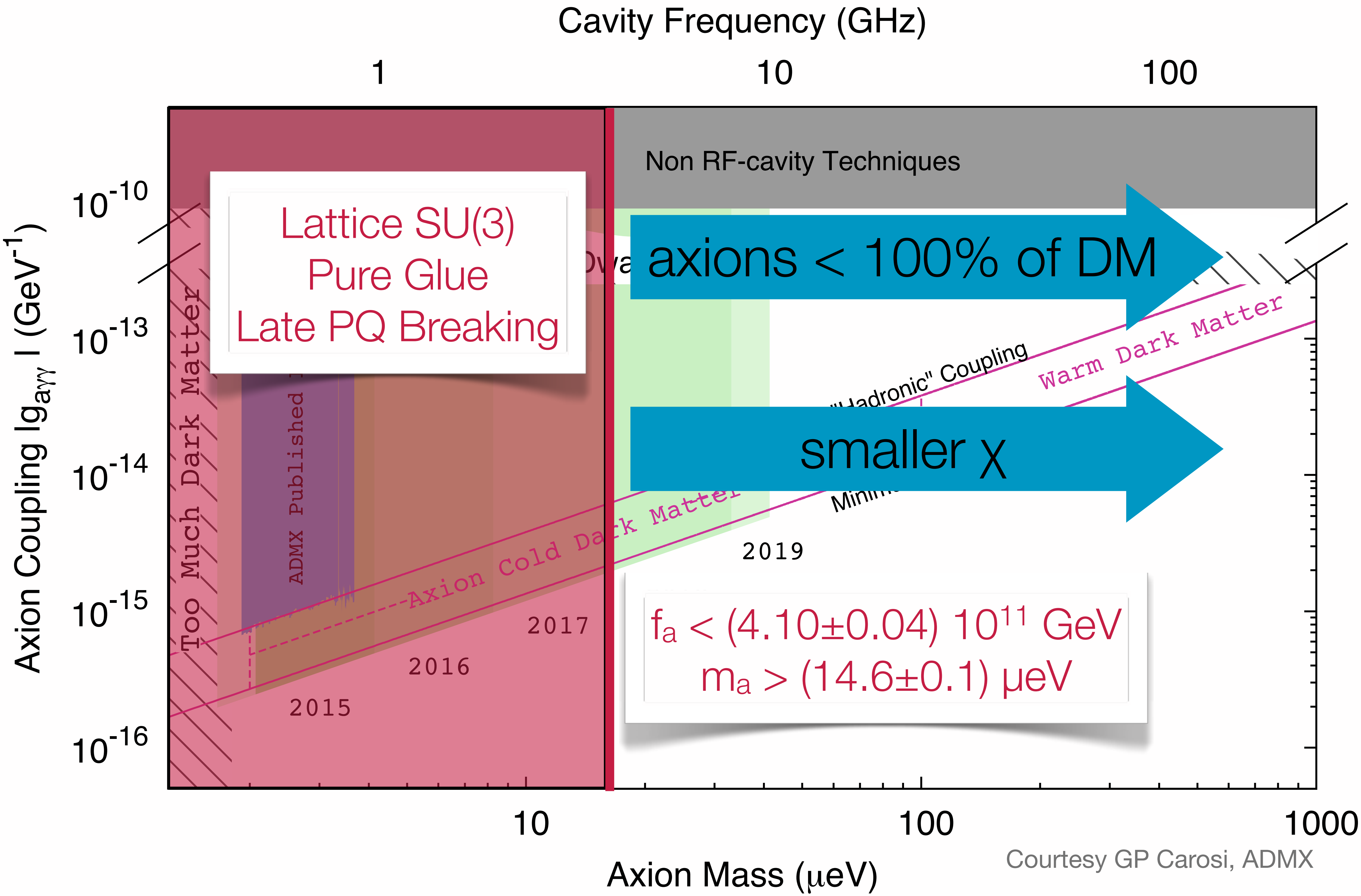


Courtesy GP Carosi, ADMX

Conclusions & Outlook

The Economist, 19 Dec 2006

- PQ symmetry:
  - cleans up the Strong CP problem
  - provides a plausible, largely unconstrained DM candidate: the axion.
- Axion searches will search large swaths of interesting parameter space soon.
- Power law (DIGM-inspired) fits outstandingly to pure glue at high temperature.

Lattice QCD can provide important nonperturbative input for calculating Ω_a

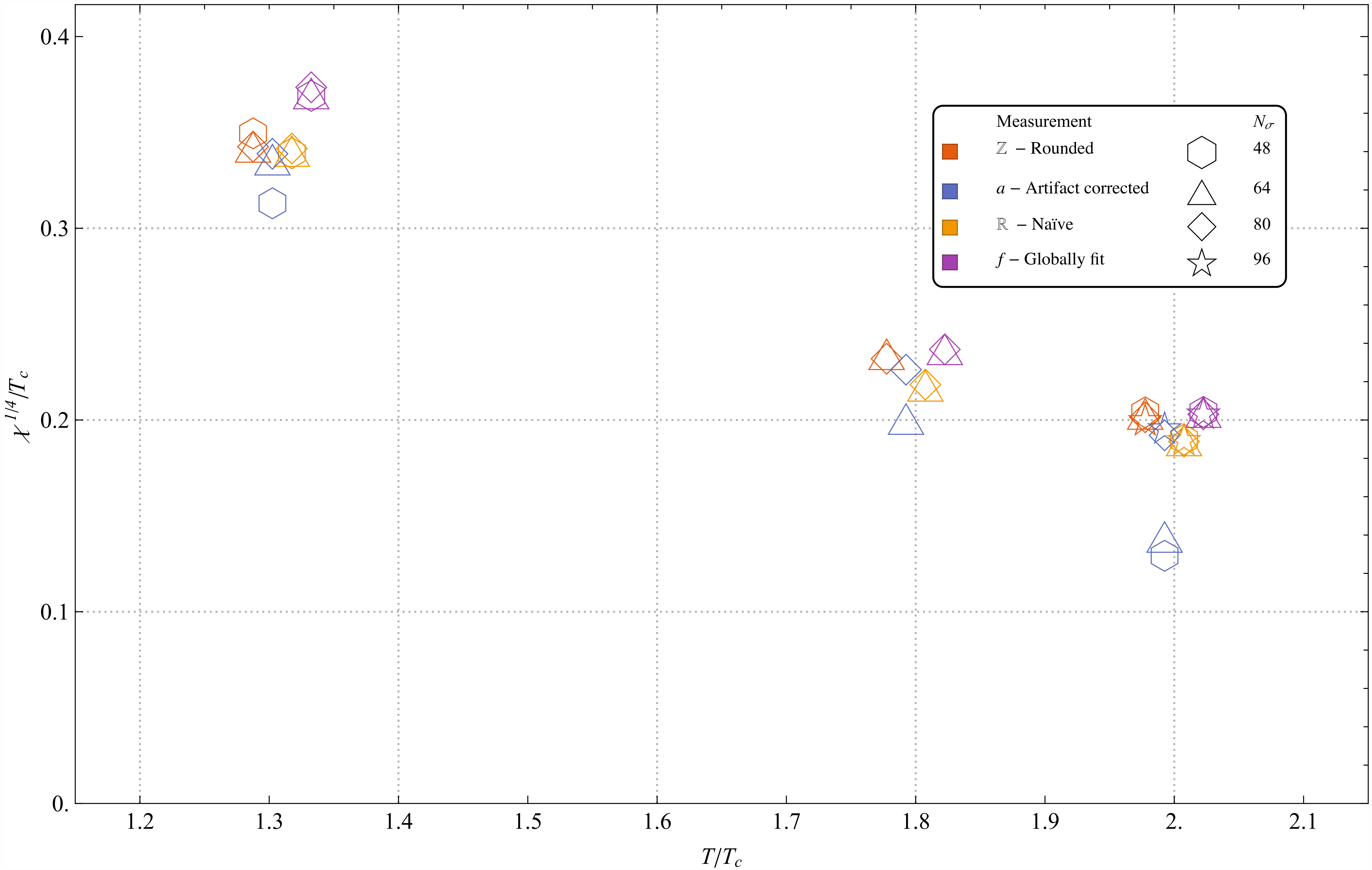
Future Steps

- Measure higher moments? May be able to get χ_4, χ_6.
  T=0: Cé, Consonni, Engle & Giusti, arXiv:1506.06052
- Incorporate quarks
- Move to Wilson Flow definition
- Move to anisotropic lattices to alleviate finite-volume effects at high T.
- 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

Backup Slides

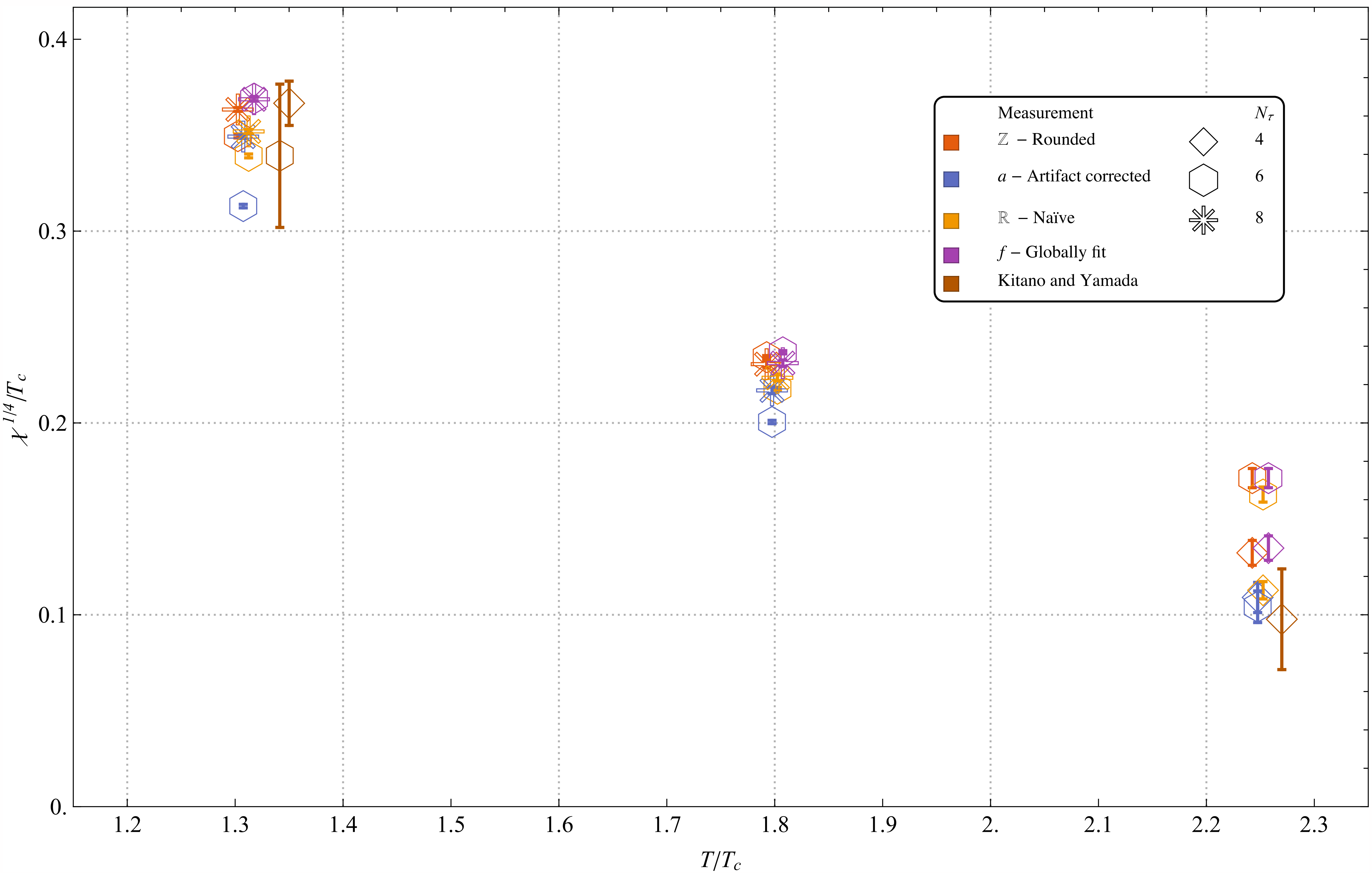
Finite Volume Effects

Berkowitz, Buchoff, and Rinaldi, arXiv:1505.07455

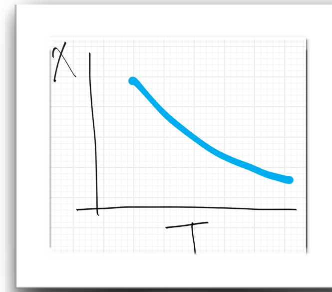


Discretization Effects

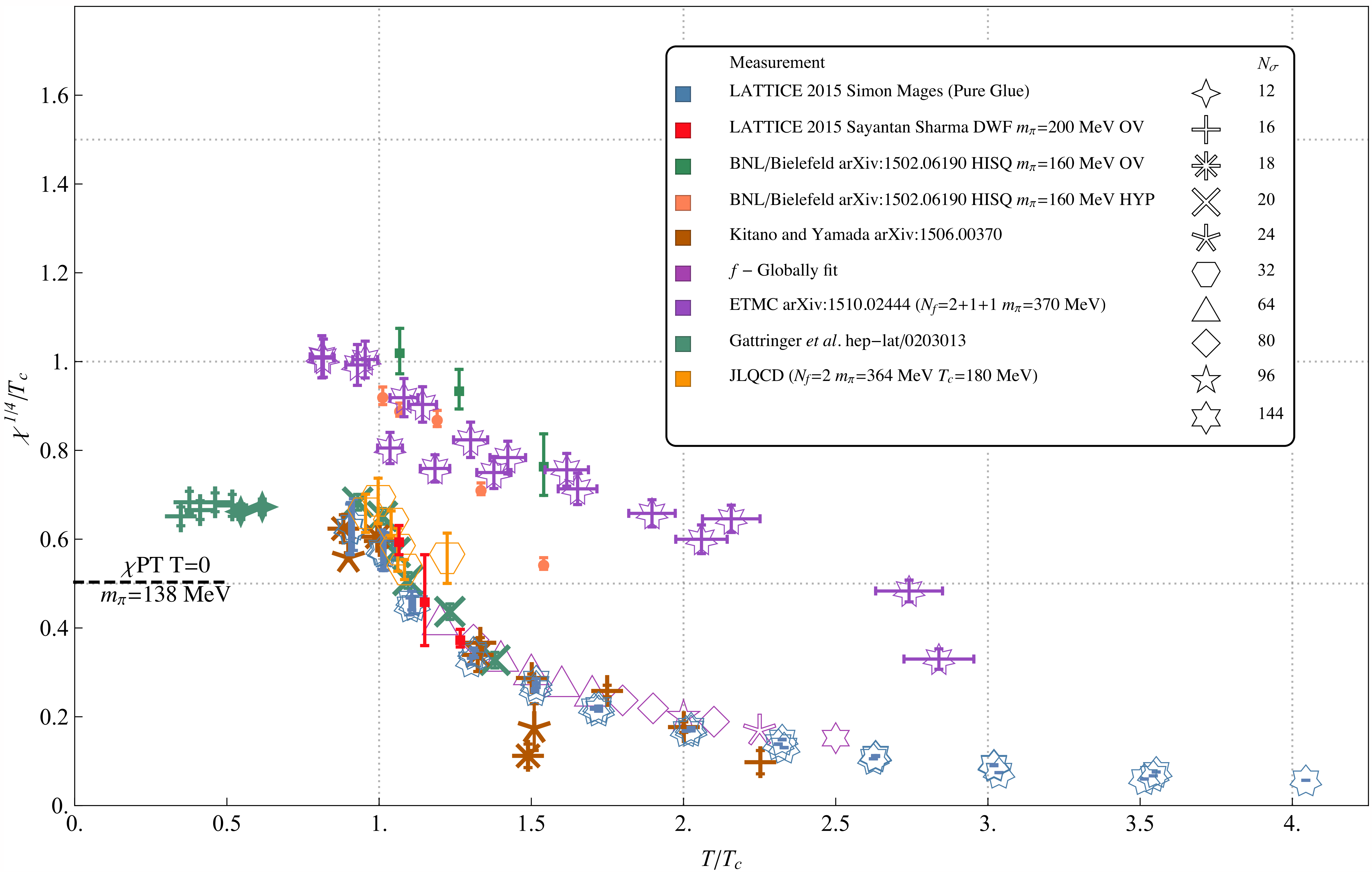
Berkowitz, Buchoff, and Rinaldi (arXiv:1505.07455), Kitano & Yamada (arXiv:1506.00370)



Comparisons



Pure glue measurements show χ vanishes as T→∞



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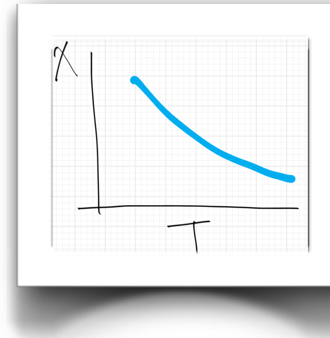

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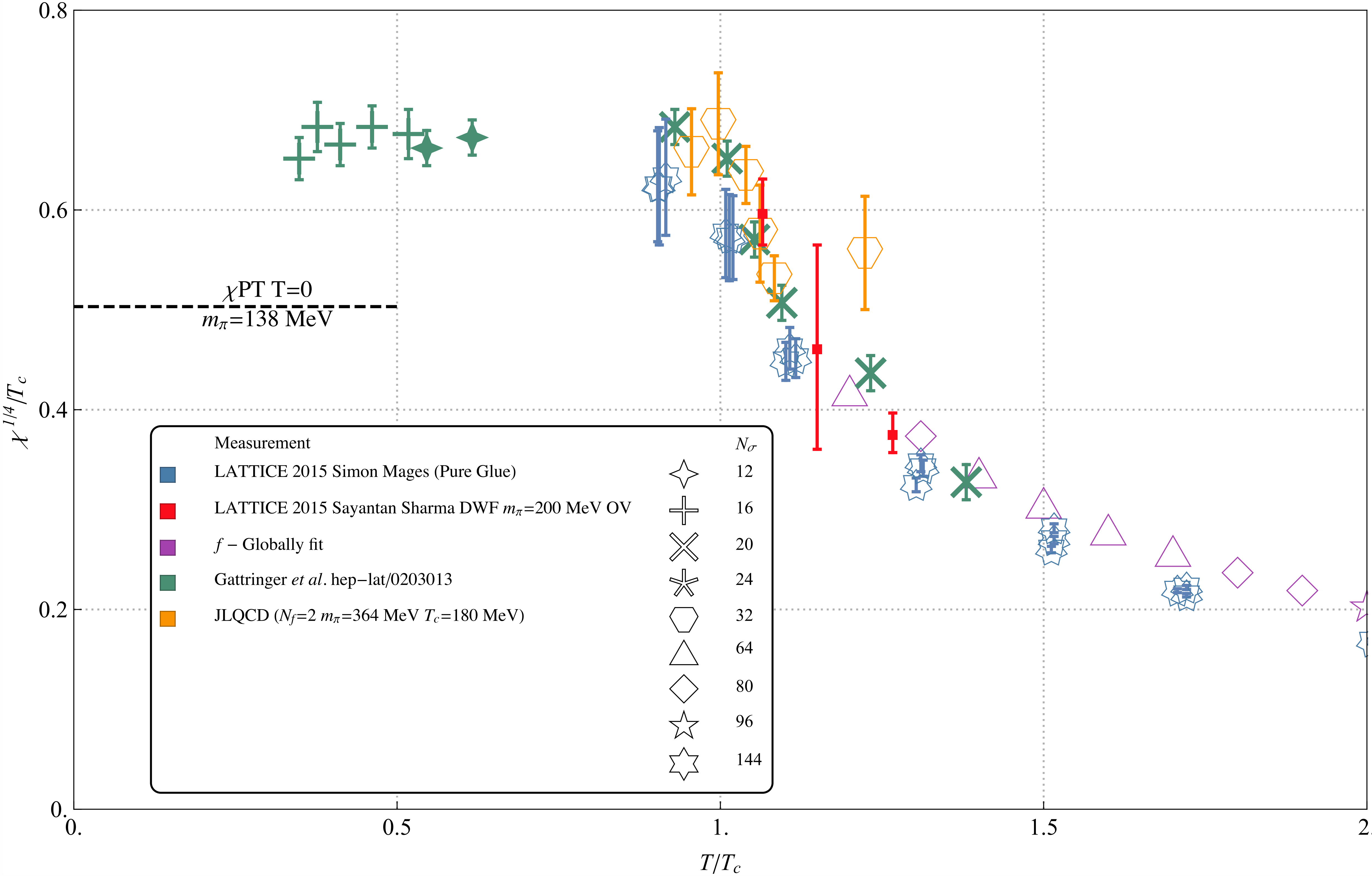
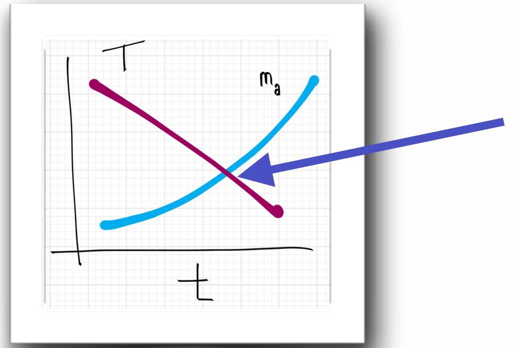
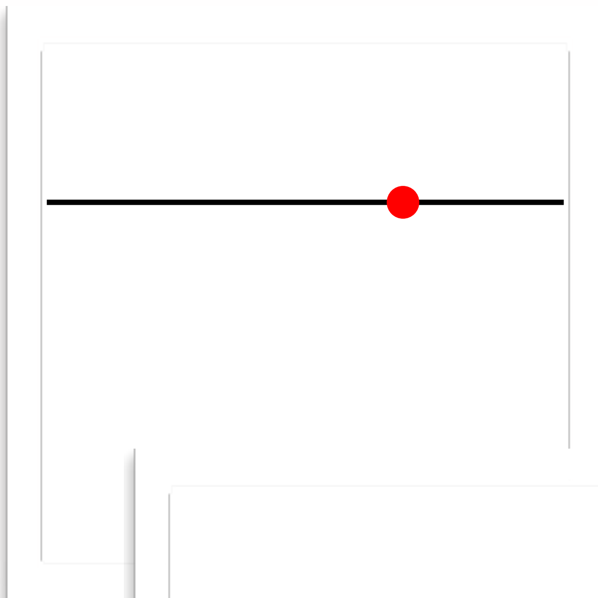
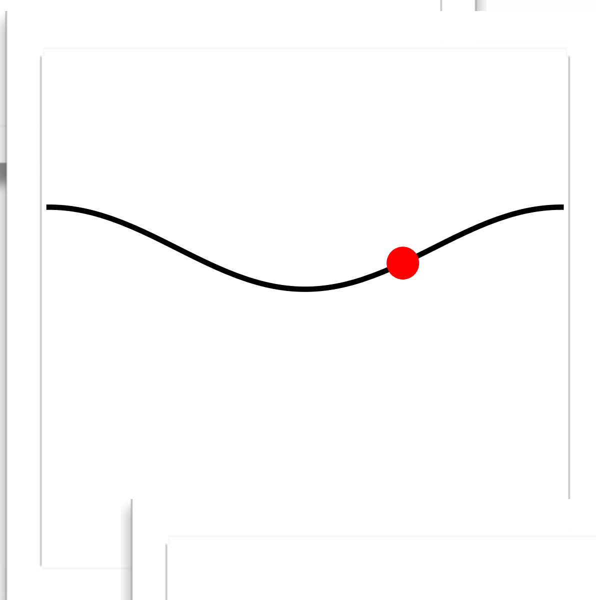


The Misalignment Mechanism

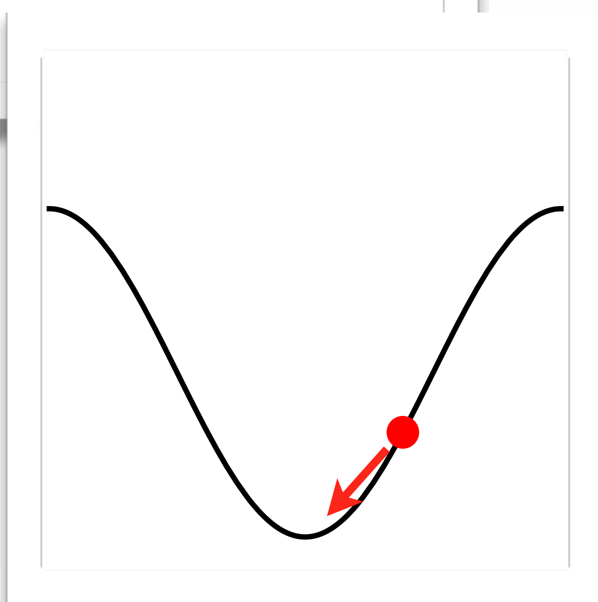




At high temperature, the axion potential is flat.



At T ~ 1 GeV, potential develops and axion mass begins to grow.



Axion begins to oscillate when Compton λ fits inside the universe

$$3H \sim m_a$$