Lawrence Livermore National Laboratory

Colgate-Palmolive

Lattice QCD Input to Axion Cosmology

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Workshop on Microwave Cavity Design for Axion Detection
LLNL

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Phys. Rev. D92.034507 - E. Berkowitz, M. Buchoff, E. Rinaldi arXiv:1505.07455

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Axions

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

- Couple to QCD topological charge

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

- Mass is temperature dependent.

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial\theta^2}\right|_{\theta=0} \equiv \chi(T)$$

Axion mass QCD Topological Susceptibility

- After production axions get diluted

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

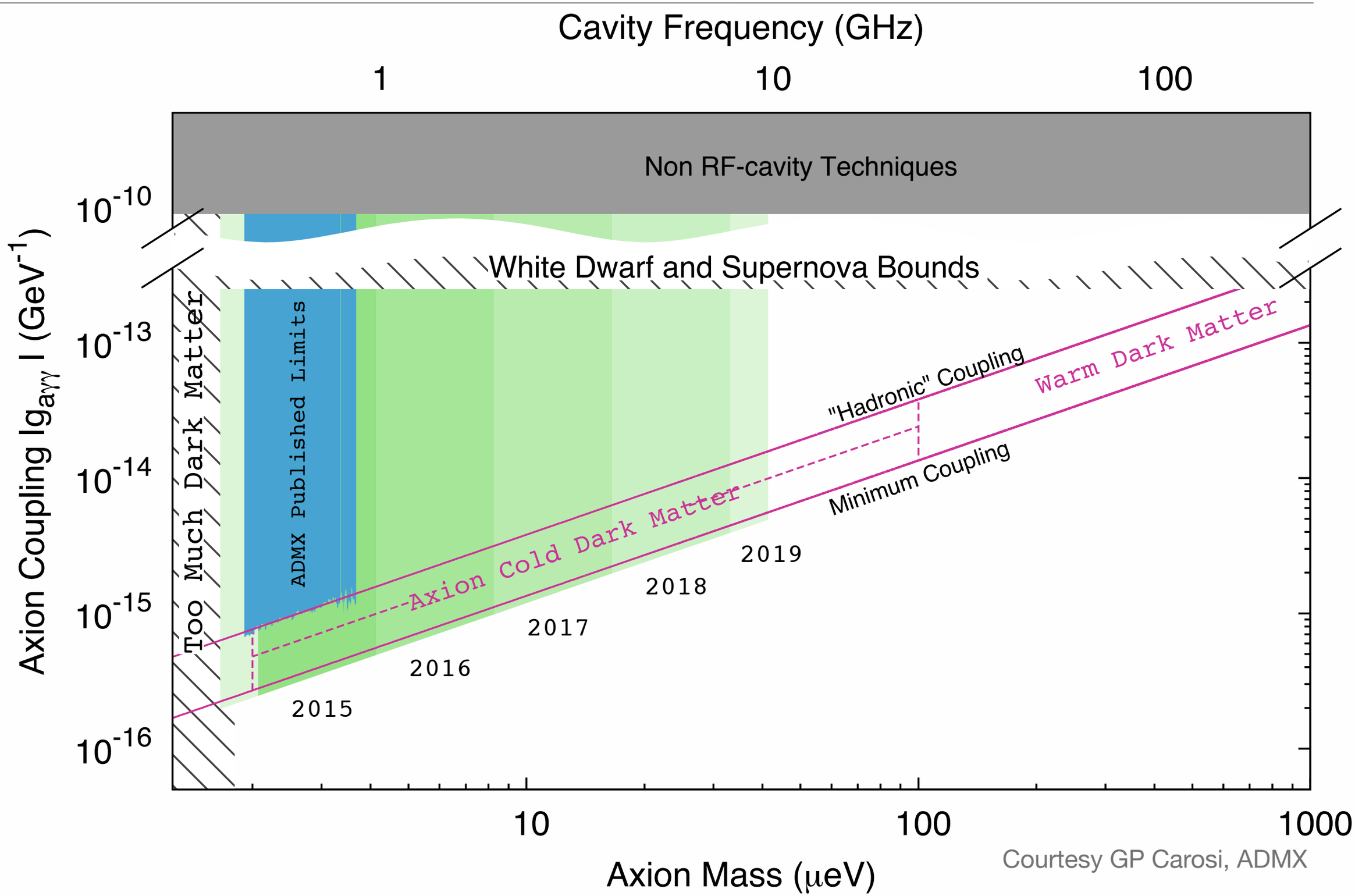
- Requiring ρ(today) ≤ ρ_{DM} gives an upper bound on f_a and a lower bound on m_a if PQ breaking is after inflation

$$\rho(T_\gamma) = \frac{\pi^2}{6}\sqrt{\chi(T_\gamma)\chi(T_1)}\left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

$\chi(T) \longleftarrow$ our lattice QCD calculation $\longrightarrow$

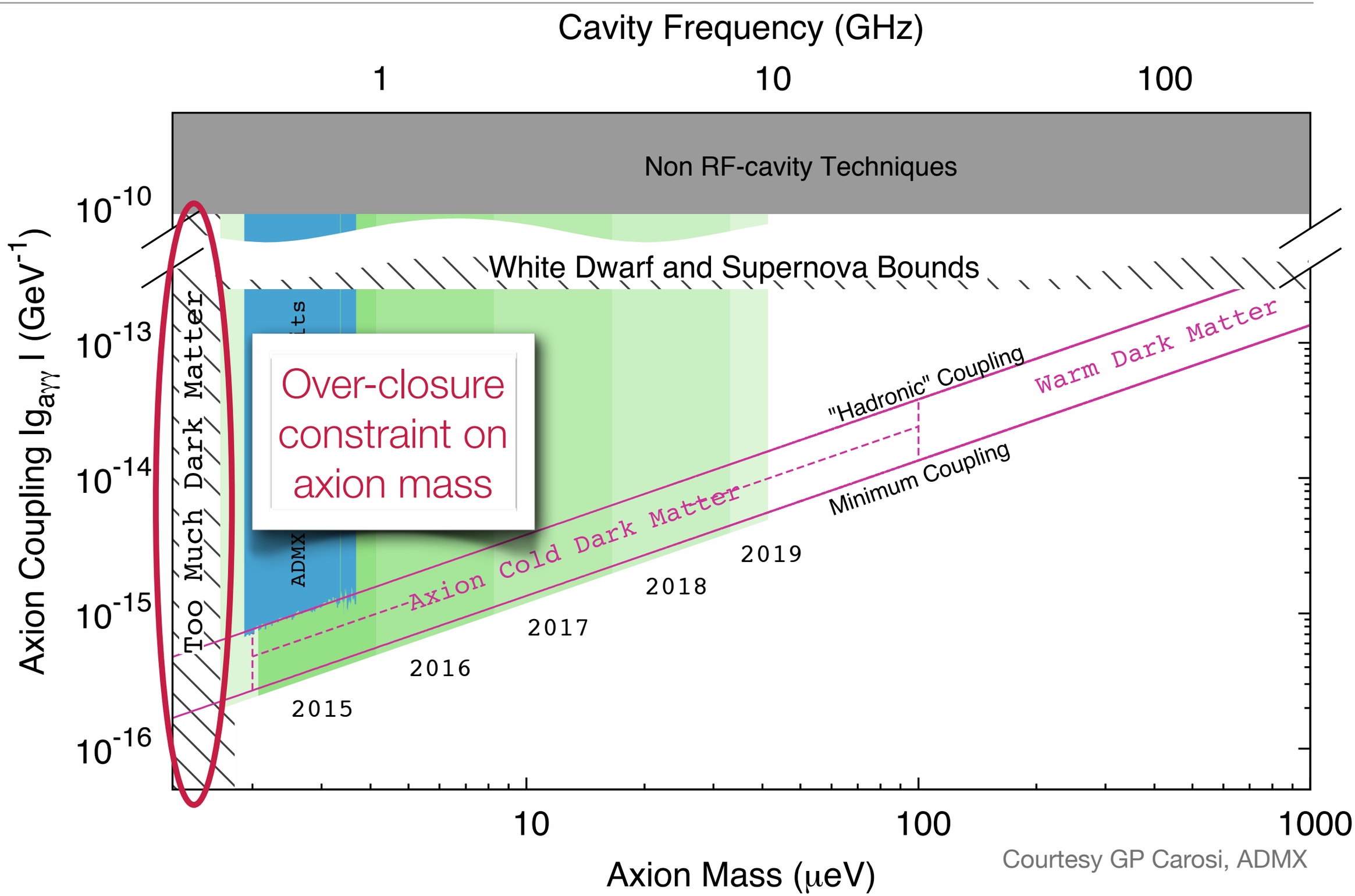
T_γ	today
T_1	production ceased
R	GR scale factor

Axion Constraints



Courtesy GP Carosi, ADMX

Axion Constraints



Courtesy GP Carosi, ADMX

CAVEAT

We currently study pure Yang-Mills (gluons only) and not yet full QCD!

- Dramatically more efficient algorithms enable huge statistics and volumes, shorter autocorrelation times.

- Should agree at (asymptotically) high temperatures

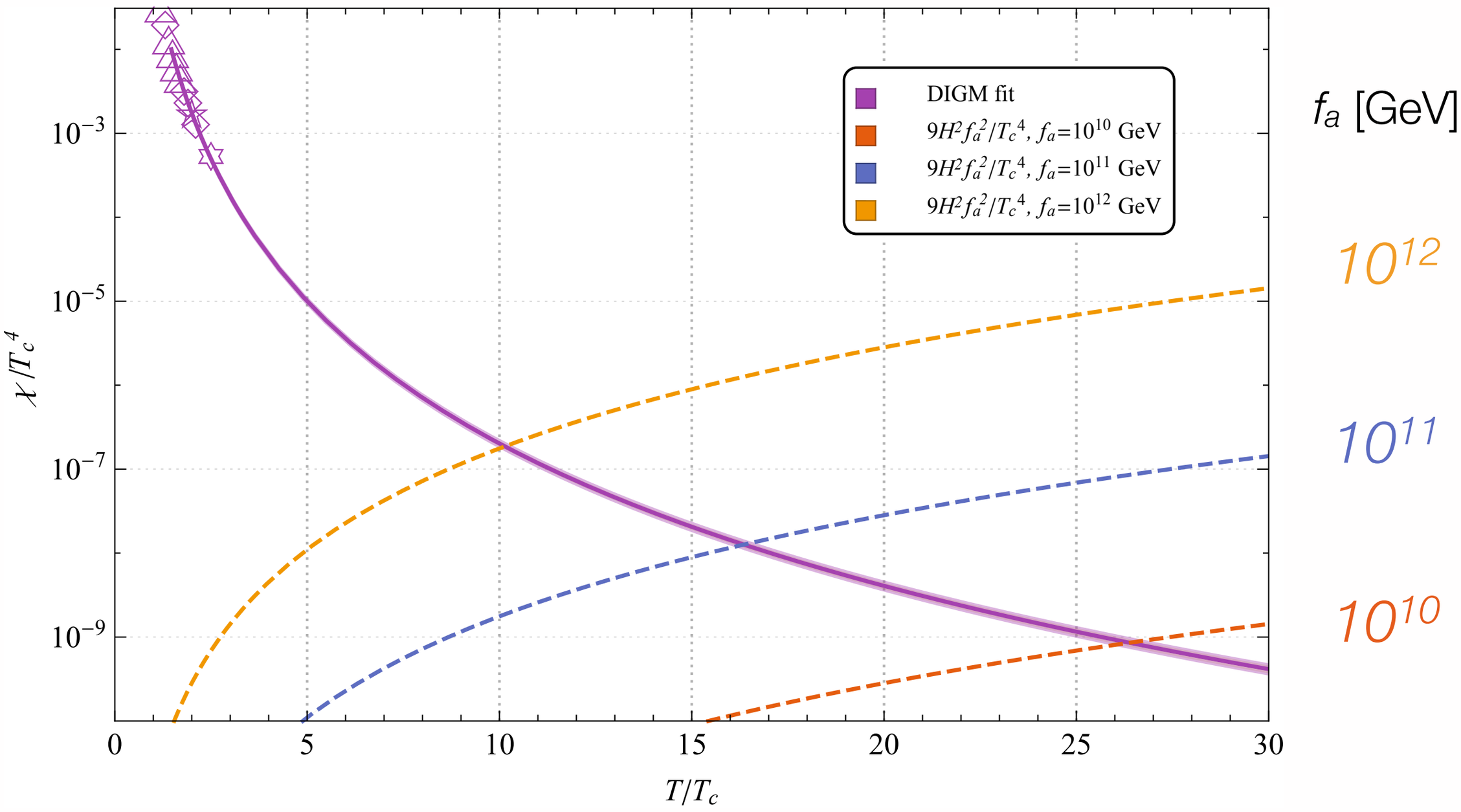
But: for getting a lower bound on m_a it's not so bad!

- Pure glue is the ∞ quark mass limit, and theory arguments imply $\chi(T)$ should go to 0 when even one quark mass → 0. So plausibly $\chi(T)_{QCD} < \chi(T)_{glue}$

- Bound gets stronger when $\chi(T)$ gets smaller.

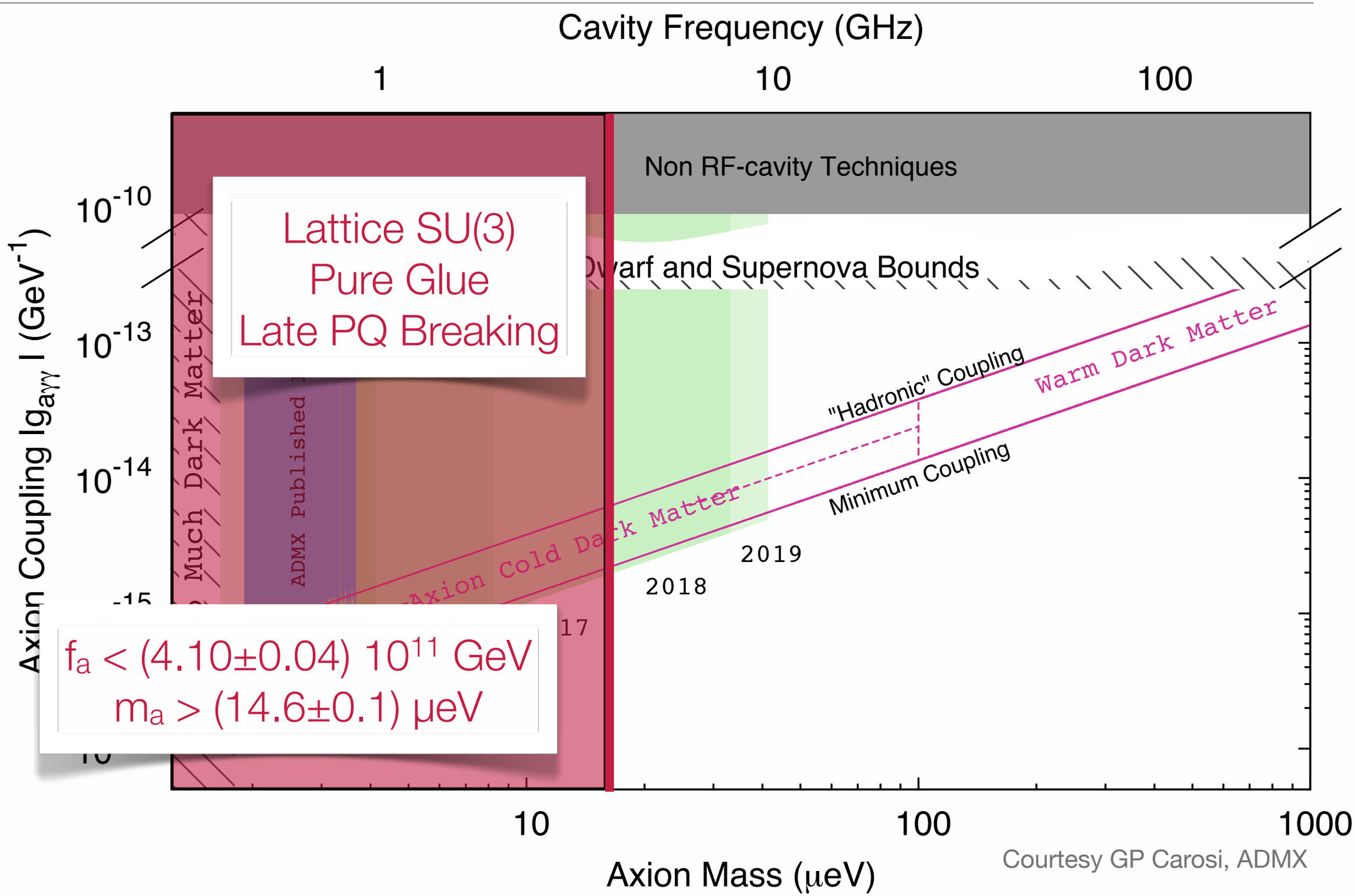
Axion production ceases when $9H^2 f_a^2 = m_a^2 f_a^2 = \chi$

Berkowitz, Buchoff & Rinaldi, PRD92.034507 arXiv:1505.07455



Intersection gives T_1 as a function of f_a

The Over-Closure Bound As It Stands Today



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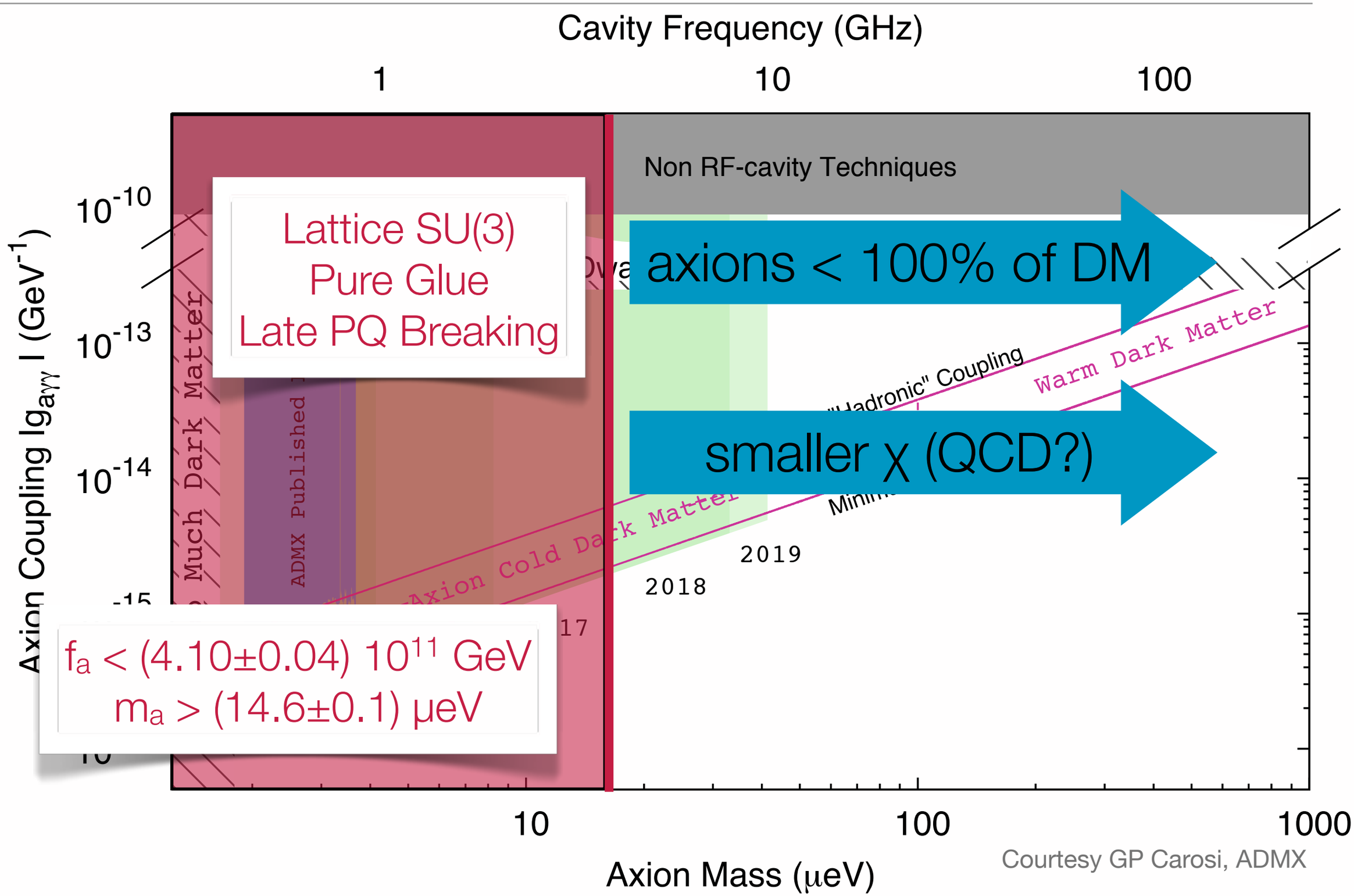

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