UNIVERSITÀ DEGLI STUDI DI SALERNO

INFN Istituto Nazionale di Fisica Nucleare

Axion Cosmology

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Based on: Lin, **LV**, Yanagida 2504.17638; Cheek, **LV**, Zhang 2503.08439 (PRL)
Yin, Cheng+ (**+LV**) 2507.03535; Cheng, Yin+ (**+LV**) 2506.19096

I. Foundations

The QCD Axion: foundations

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See the talk by Jing Shu

The axion is a light pseudo-scalar arising within QCD ($m_a \lesssim 10^{-2}\,\mathrm{eV}$)

Strong-CP problem: non-observation of neutron electric dipole moment (EDM)

$$\mathcal{L} = -\frac{\alpha_s}{8\pi}\theta G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

α_s: Strong force coupling

$G^a_{\mu\nu}$: Gluon field strength

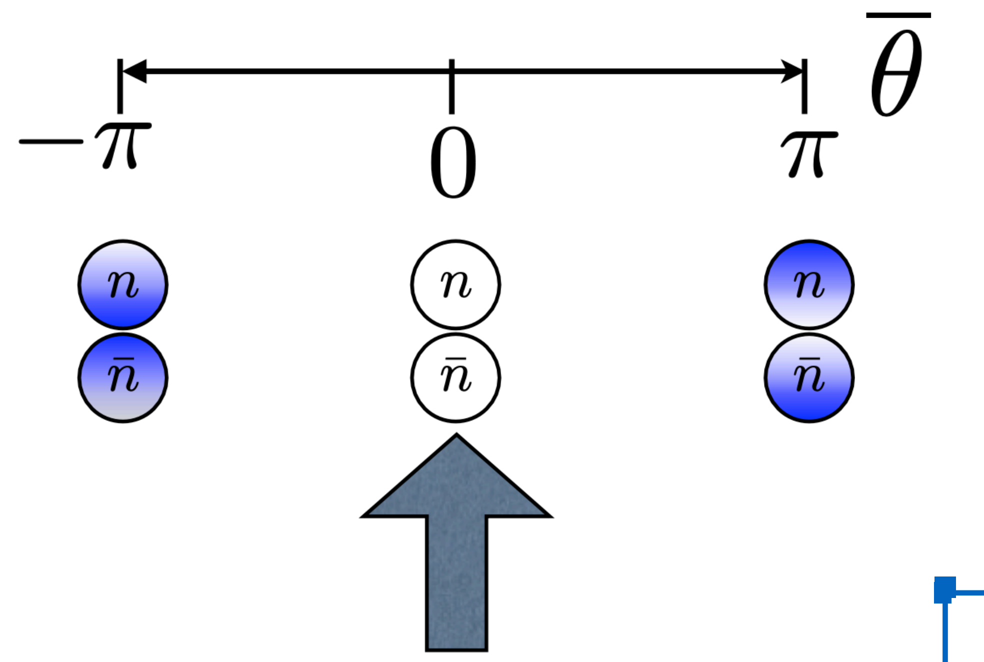
The parameter θ itself is not physical as $\bar{\theta} = \theta - \arg\det(M)$

The value of $\bar{\theta}$ controls the matter-antimatter asymmetry in QCD

The term predicts a EDM $d_n = 2.4 \times 10^{-16}\,\bar{\theta}\,\mathrm{e\,cm}$ [Pospelov & Ritz 1999]

Experiments give $|d_n| < 1.8 \times 10^{-26}\,\mathrm{e\,cm}$ [Abel+ 2020]

No observation of C and CP violation in Nature $|\bar{\theta}| \lesssim 10^{-10}$



The QCD Axion: foundations

We introduce the axion ϕ through the Lagrangian terms:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\alpha_s}{8\pi}\frac{\phi}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

The axion has no color charge

The QCD theta term is minimized dynamically to $\langle\phi/f_a\rangle = -\bar{\theta}$

This makes the neutron electric dipole moment (EDM) vanish

→ **PQ mechanism** [Peccei & Quinn 1977; Wilczek 1978; Weinberg 1978]

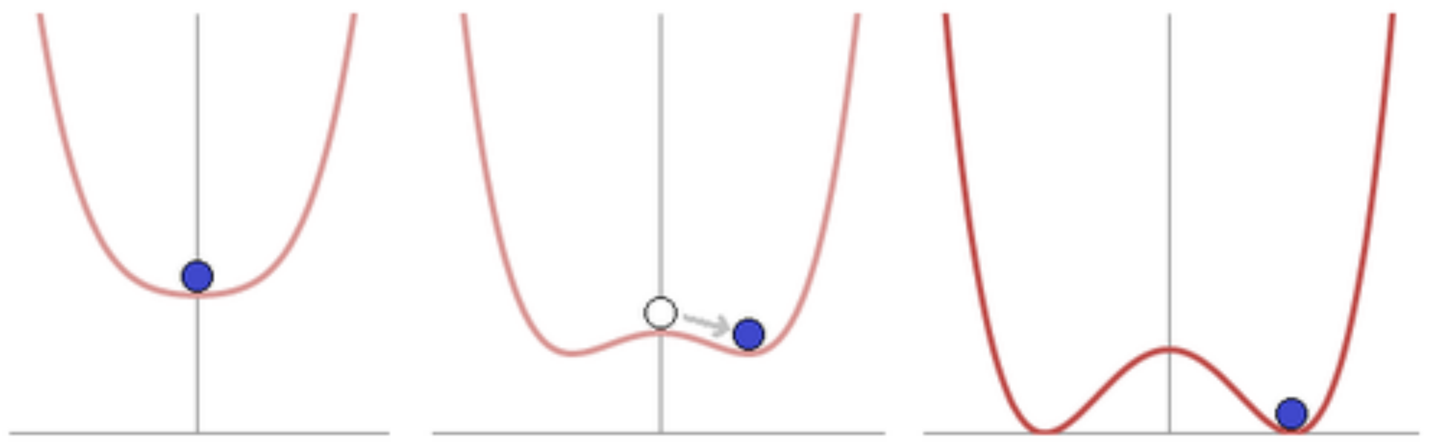
QCD axion mass [Weinberg 1978]

$$m_a = \frac{\Lambda_{\rm QCD}^{3/2}}{f_a}\sqrt{\frac{m_u m_d}{m_u + m_d}} \approx 5.7\,\mu{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$$

The QCD Axion: foundations

Complex scalar field (PQ field) $\Phi(x) = \frac{r(x) + f_a}{\sqrt{2}}\, e^{i\phi(x)/f_a}$

$$\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 - \lambda\left(|\Phi|^2 - \frac{v_a^2}{2}\right)^2 + \text{SM couplings}$$



- **KSVZ** axion [Kim 79; Shifman, Vainshtein, Zakharov 80]

  Aka "hadronic axion": lepton couplings are suppressed.

- **DFSZ** axion [Zhitnitsky 80; Dine, Fischler, Srednicki 81]

  Allows to decouple the PQ breaking scale from the electroweak scale.

- **REVIEW** on axion models: Di Luzio, Giannotti, Nardi, **LV** 2003.01100

The QCD Axion: foundations

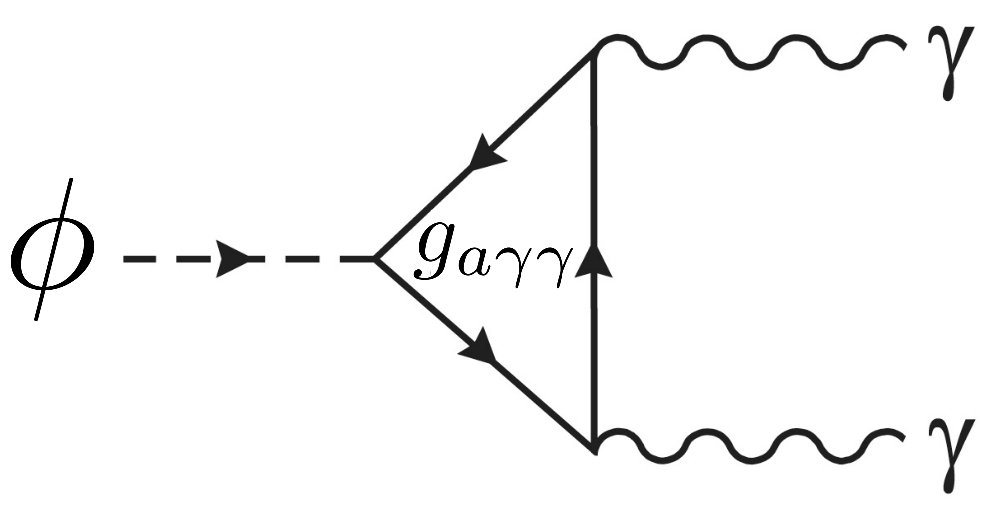
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{4}\,g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu} + c_e\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e + c_N\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N$$

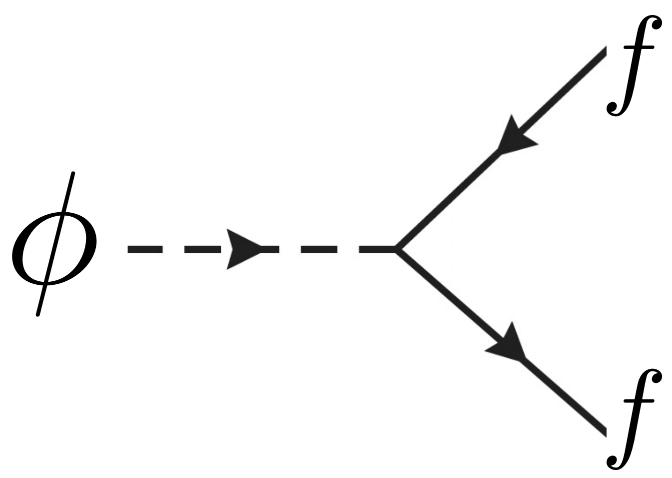
Self-interacting potential

Axion-photon coupling

Axion-electron coupling

Axion-nucleon coupling





The coupling depends on color & EM anomalies $\frac{E}{N}$: $g_{a\gamma\gamma} = \frac{\alpha_{\rm EM}}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)$

II. Axion cosmology

Cosmology of the axion

Large occupation number: $\mathcal{N} \sim \lambda_c^{-3}(\rho_{\rm DM}/m_a) \approx 10^{27}(\mu{\rm eV}/m_a)^4$

→ We are dealing with a **classical field**

Equation of motion in a FLRW background:

$$\ddot{\phi} - \frac{1}{a^2}\nabla^2\phi + 3H\dot{\phi} + \frac{\partial V(\phi, T)}{\partial \phi} = 0$$

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Kinetic term

Gradient term

Hubble friction

Scalar potential

Cosmology of the axion

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$$\ddot{\phi} - \frac{1}{a^2}\nabla^2\phi + 3H\dot{\phi} + \frac{\partial V(\phi,T)}{\partial\phi} = 0$$

Zero temperature: $V(\phi, T=0) = V_{\rm CPT}(\phi)$ [Di Vecchia & Veneziano 1980]

Finite temperature, QCD instantons effectively couple the axion to the plasma

$$m_a^2(T) \approx \min\left(m_a^2, \frac{\Lambda^4}{f_a^2\,(T/\Lambda)^n}\right)$$

[Gross+ 1981]

The exact assessment comes from lattice QCD computations [Borsanyi+ 2016]

Cosmology of the axion

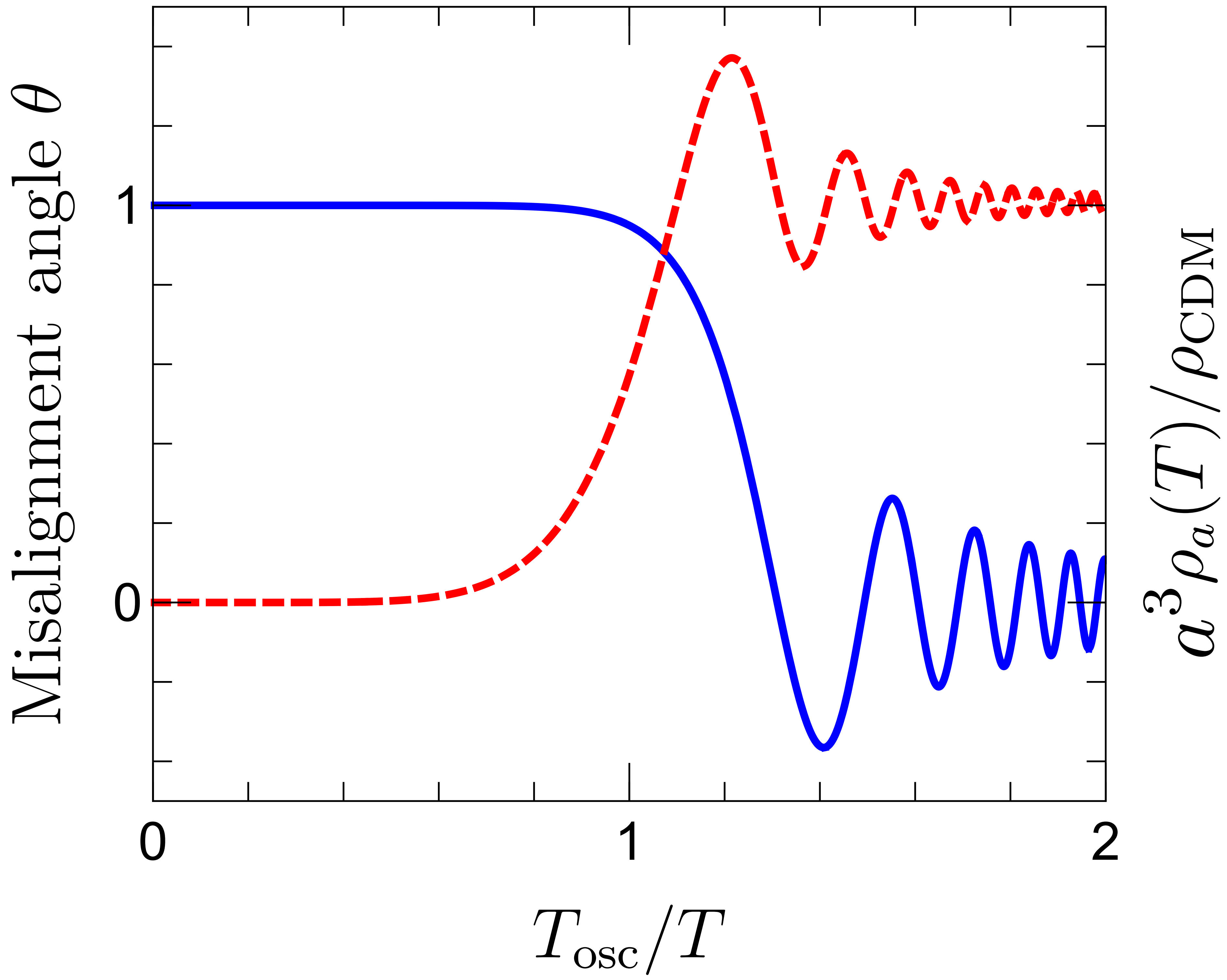
Naïve computation on super-horizon scales $\nabla^2\phi \approx 0$

Coherent oscillations in the axion field when

$$m_a(T_{\rm osc}) \sim 3H(T_{\rm osc})$$

Axion angle: $\theta \equiv \phi/f_a$

Energy density: $\rho_a = \langle \frac{1}{2}\dot{\phi}^2 + V(\phi, T)\rangle$



In practice we get **two** different scenarios:

Scenario 1: The PQ symmetry broke during inflation $f_a \gtrsim H_I$

Scenario 2: The PQ symmetry broke after inflation $f_a \lesssim H_I$

Scenario 1: The PQ symmetry broke during inflation

Linearized EoM: $$\ddot{\phi} + 3H\dot{\phi} + m_a^2(T)\phi = 0$$

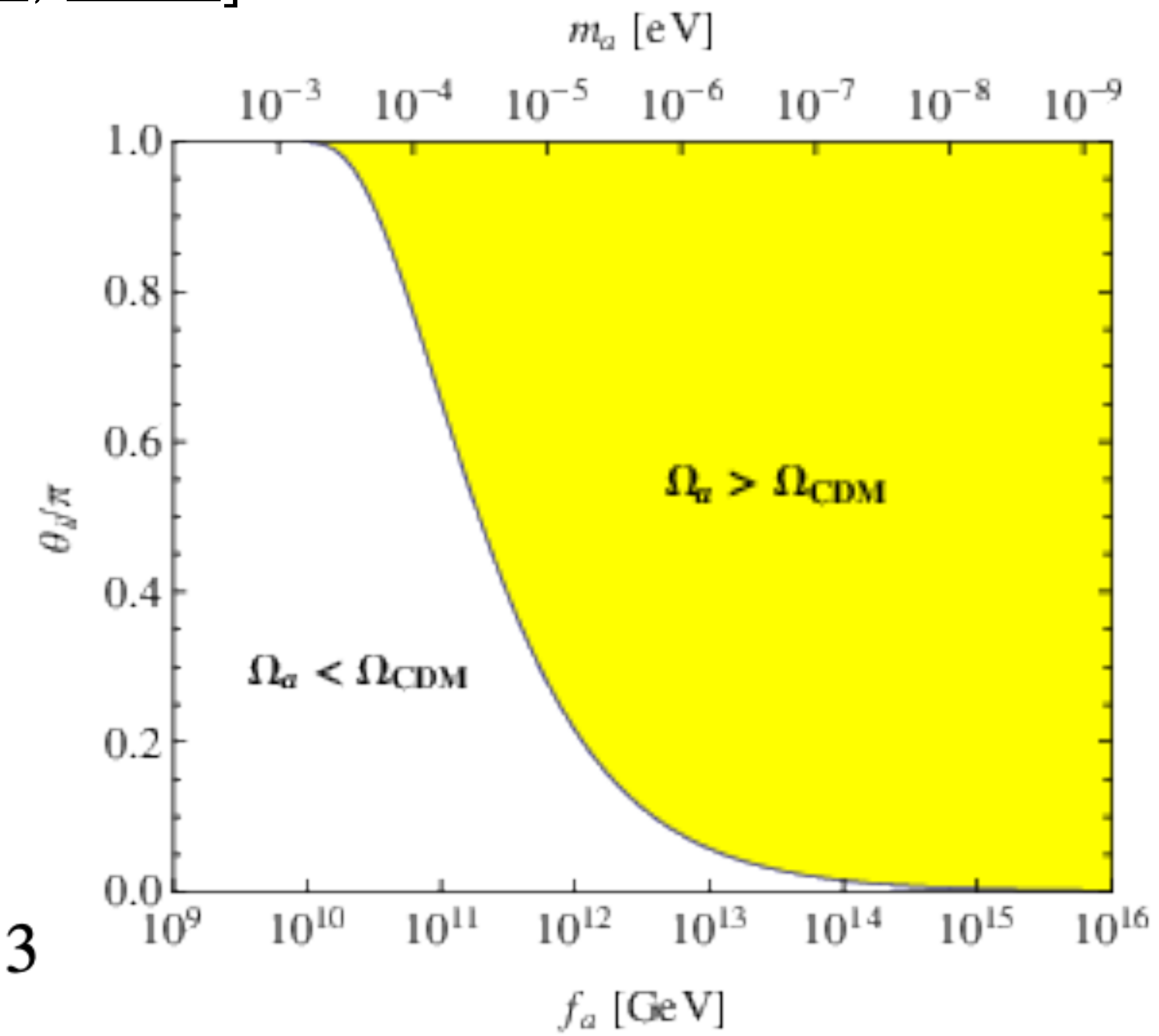
Non-linear terms might matter [**LV** & Gondolo, PRD 2009, 2010]

Axion energy density at onset of oscillations:

$$\rho_a(T_{\rm osc}) \approx \frac{1}{2} m_a^2(T_{\rm osc}) f_a^2 \theta_i^2$$

We demand that the axion density explains the **dark matter abundance**:

$$\rho_{\rm DM}(1+z_{\rm MR})^3 = \frac{m_a}{m_a(T_{\rm osc})}\rho_a(T_{\rm osc})\frac{g_{*s}(T_{\rm MR})}{g_{*s}(T_{\rm osc})}\left(\frac{T_{\rm MR}}{T_{\rm osc}}\right)^3$$



[**LV** & Gondolo, PRD 2009]

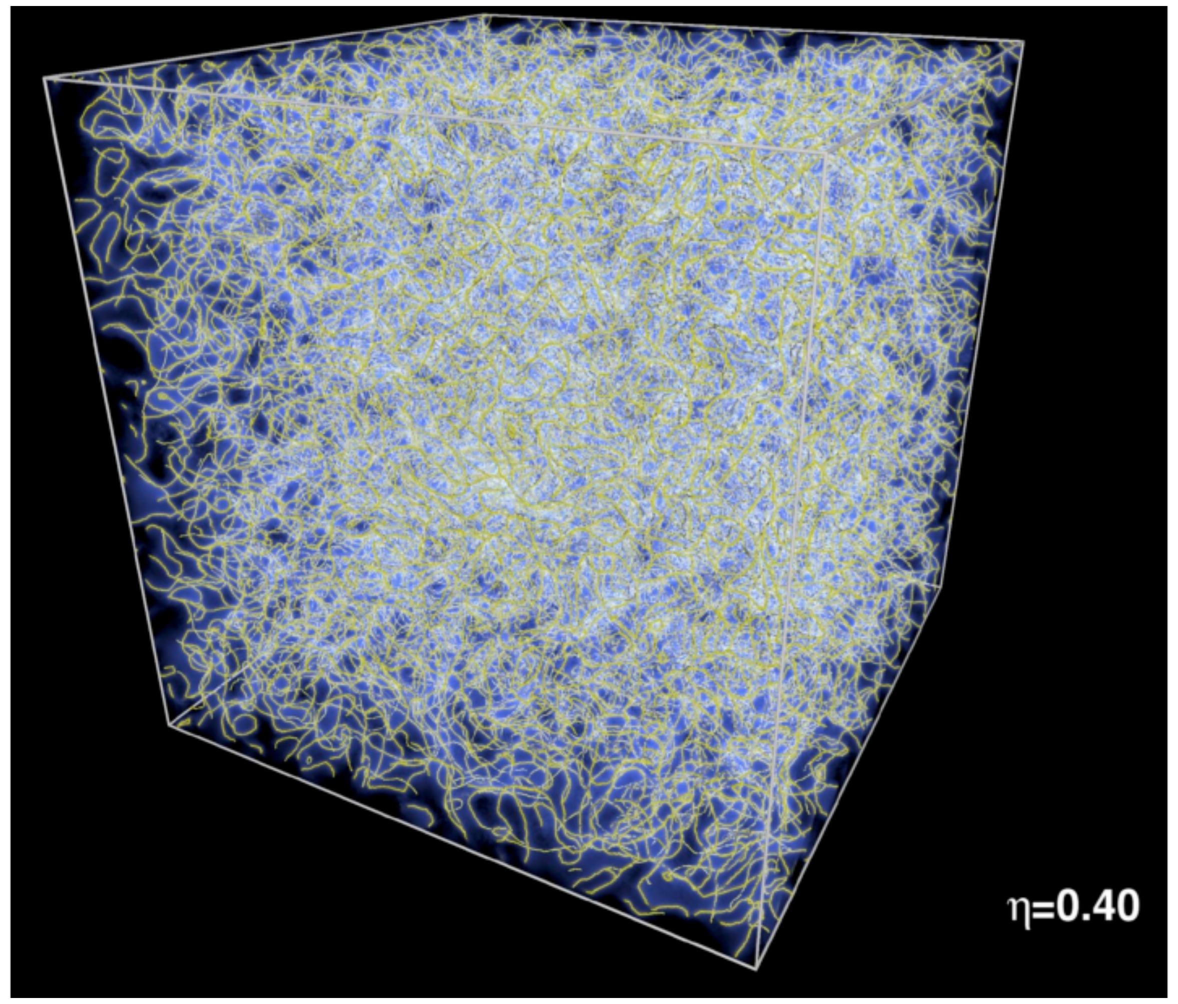
Scenario 2: The PQ symmetry broke after inflation

EoM for the PQ field: $$\ddot{\Phi} - \frac{1}{a^2}\nabla^2\Phi + 3H\dot{\Phi} + 2\lambda\Phi\left(|\Phi|^2 - \frac{f_a^2}{2}\right) = 0$$

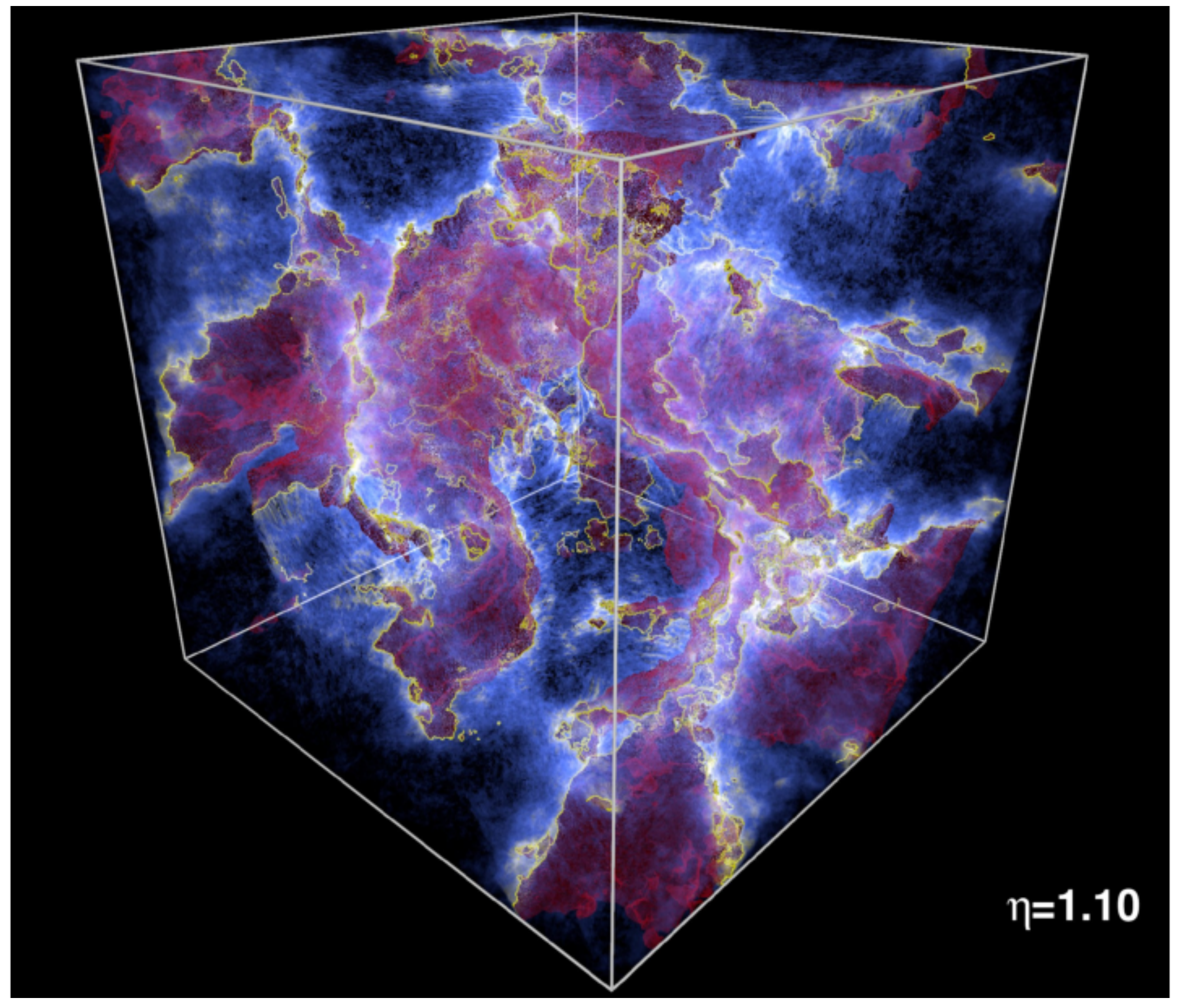
String network quickly enters a scaling regime with $\rho_{\rm scaling} = \xi\mu/t^2$

String energy per unit length: $\mu \equiv \int \mathrm{d}^2x H = \pi f_a^2 \ln(\sqrt{2\lambda} f_a/H)$

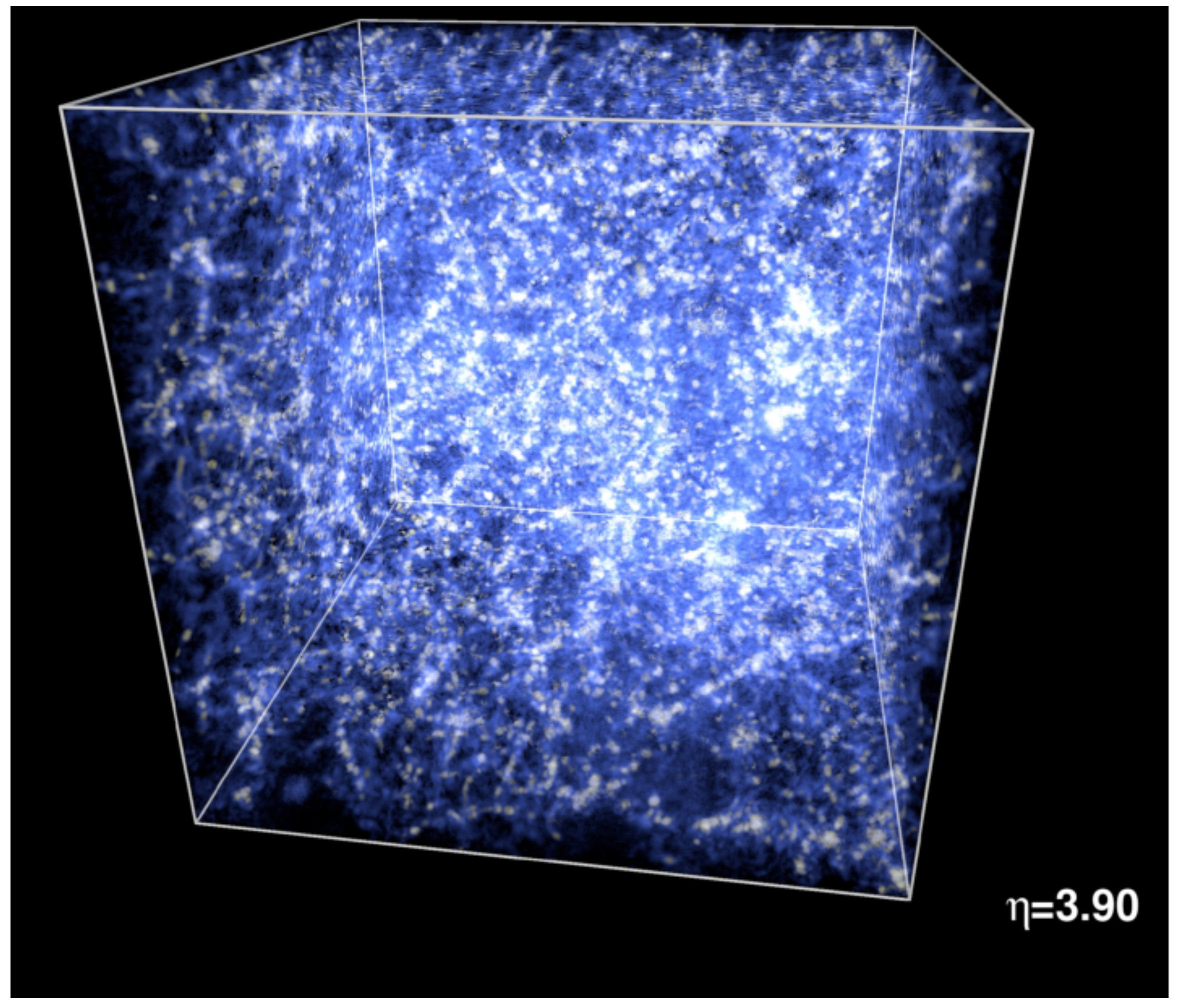
String length per Hubble volume ξ



Before QCD PT



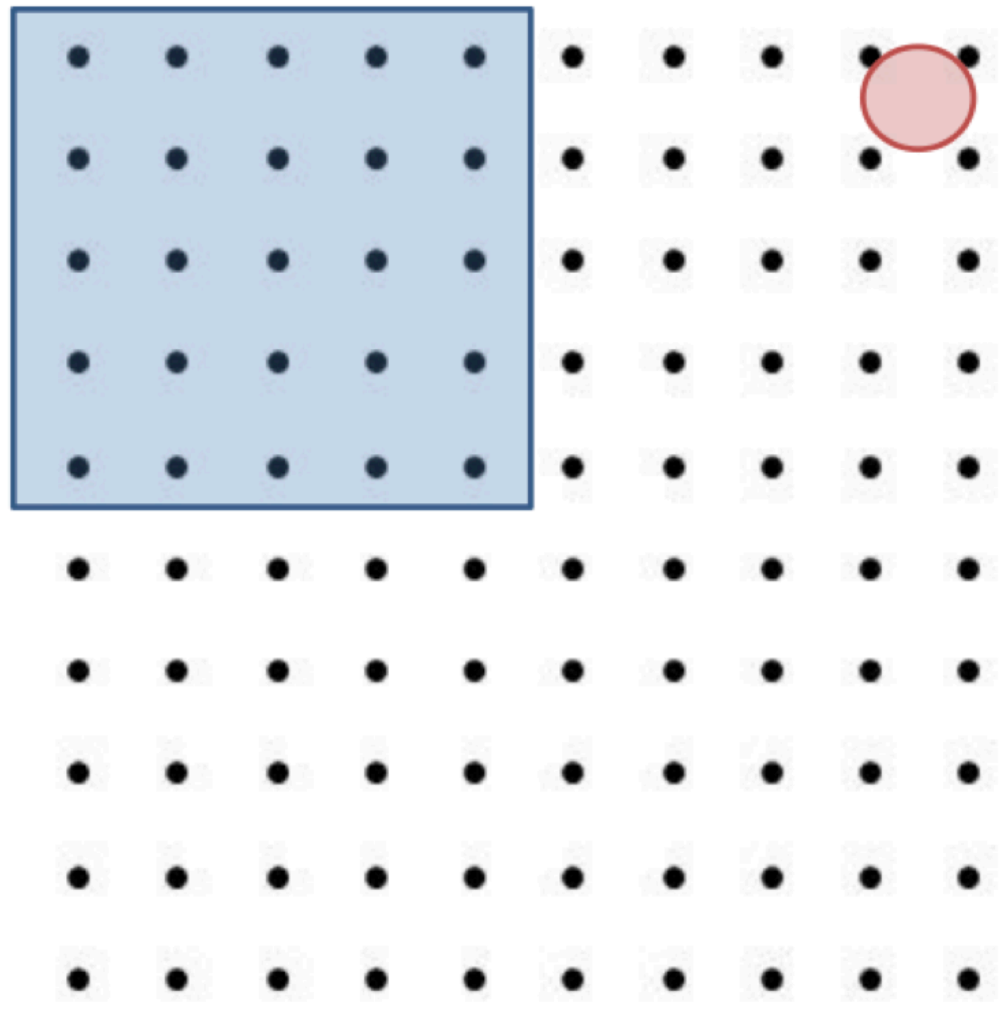
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



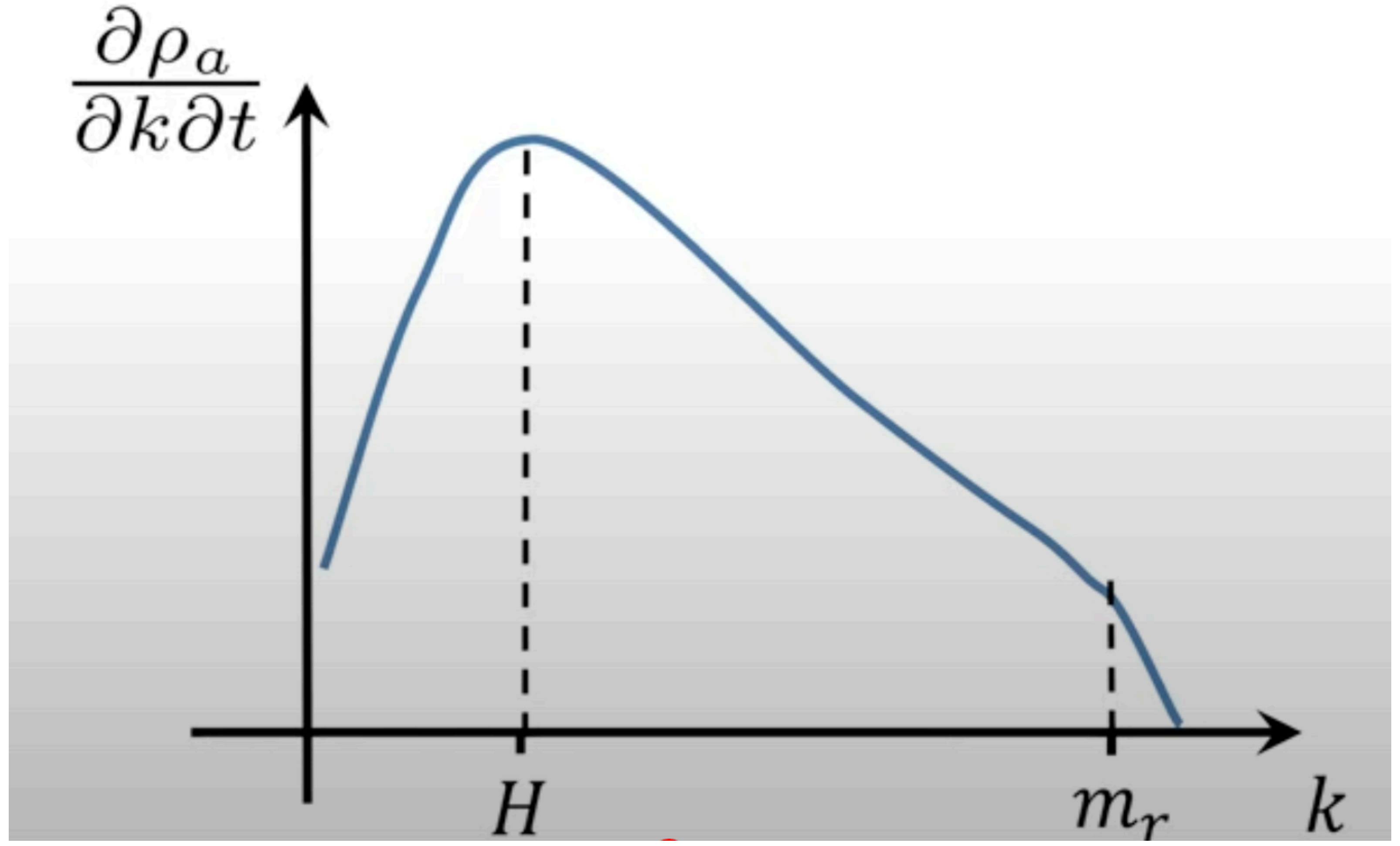
Credits: Ed Hardy

$N \approx 5000^3$

simulations: $\log \alpha \leq \log(\frac{\square}{\bigcirc}) \simeq 7$

Yet $\log(f_a\, t) \approx 70$ needed

$$\frac{\partial \rho_a}{\partial k \partial t} \propto \frac{1}{k^q}$$ Energy spectrum of emitted axions



The spectrum peaks at $k \approx H$ (string curvature). Cutoff at $k \approx \sqrt{2\lambda} f_a$

$q > 1$ "Effective Nambu–Goto string" [Davis 1985, 1986; Battye & Shellard 1994a, 1994b]
leads to more axions and a higher DM mass $\sim$ meV [Gorghetto+ 2018, 2021]
An IR spectrum is also found in [Hiramatsu+ 2011]

$q = 1$ "Collapsing loops" with $\xi \approx 1$. [Harari & Sikivie 1987; Hagmann+ 1999]
Supported recently by [Buschmann+ 2020, 2022]

Various groups work on axion string simulations: no agreement

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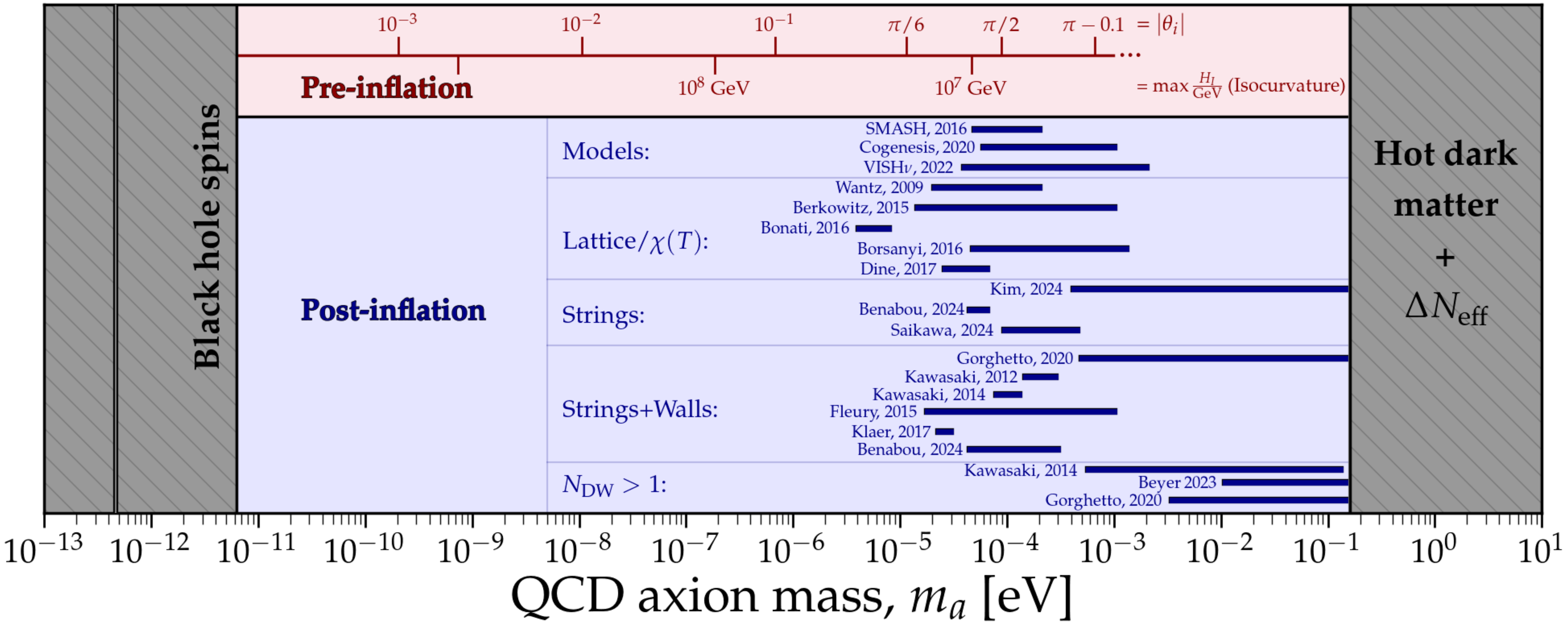

Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

QCD axion parameter space

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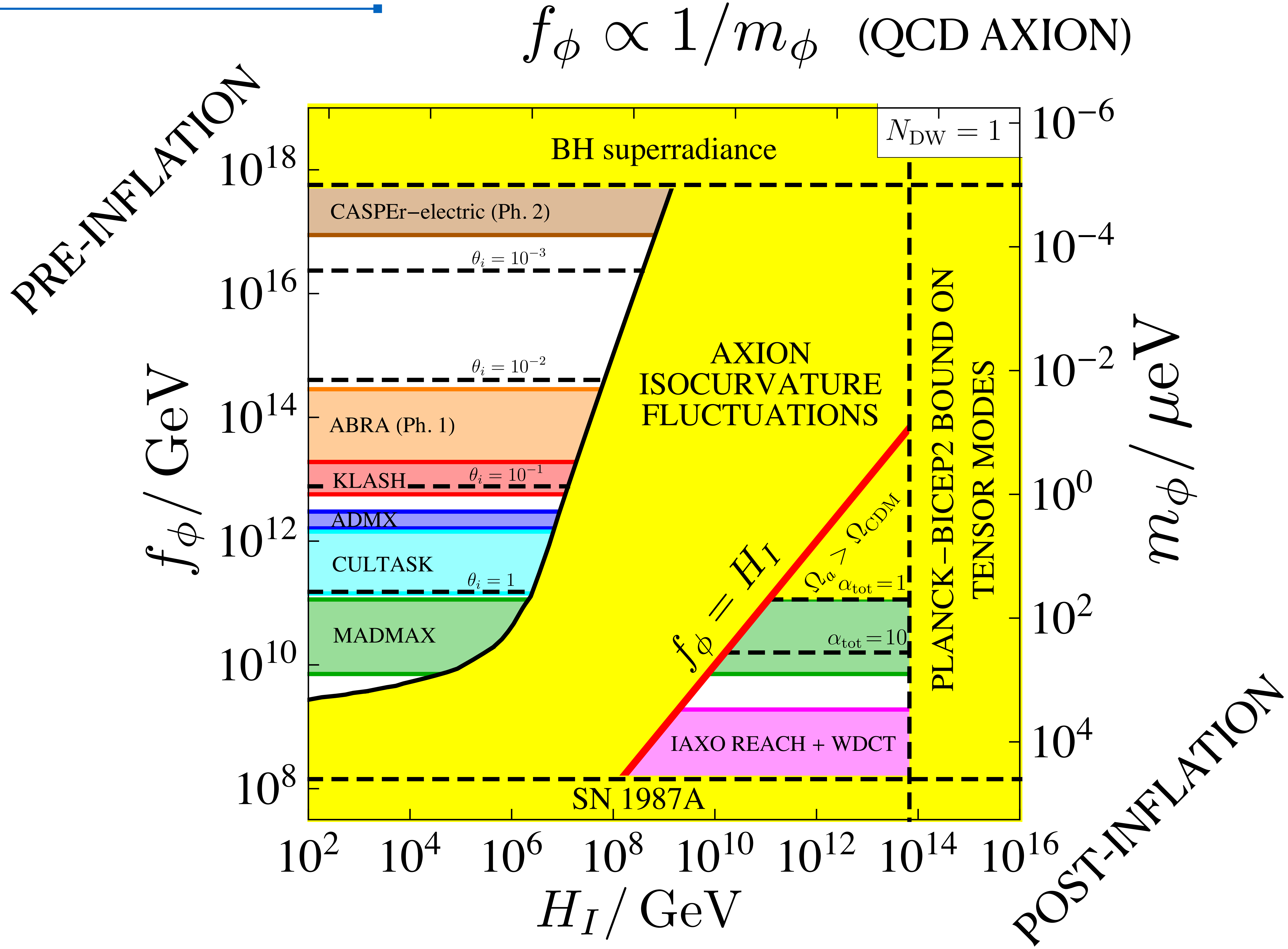


Di Luzio, Giannotti, Nardi, **LV** 2003.01100

III. Axions as dark radiation

Extra relativistic species

Contribution to the relativistic degrees of freedom:

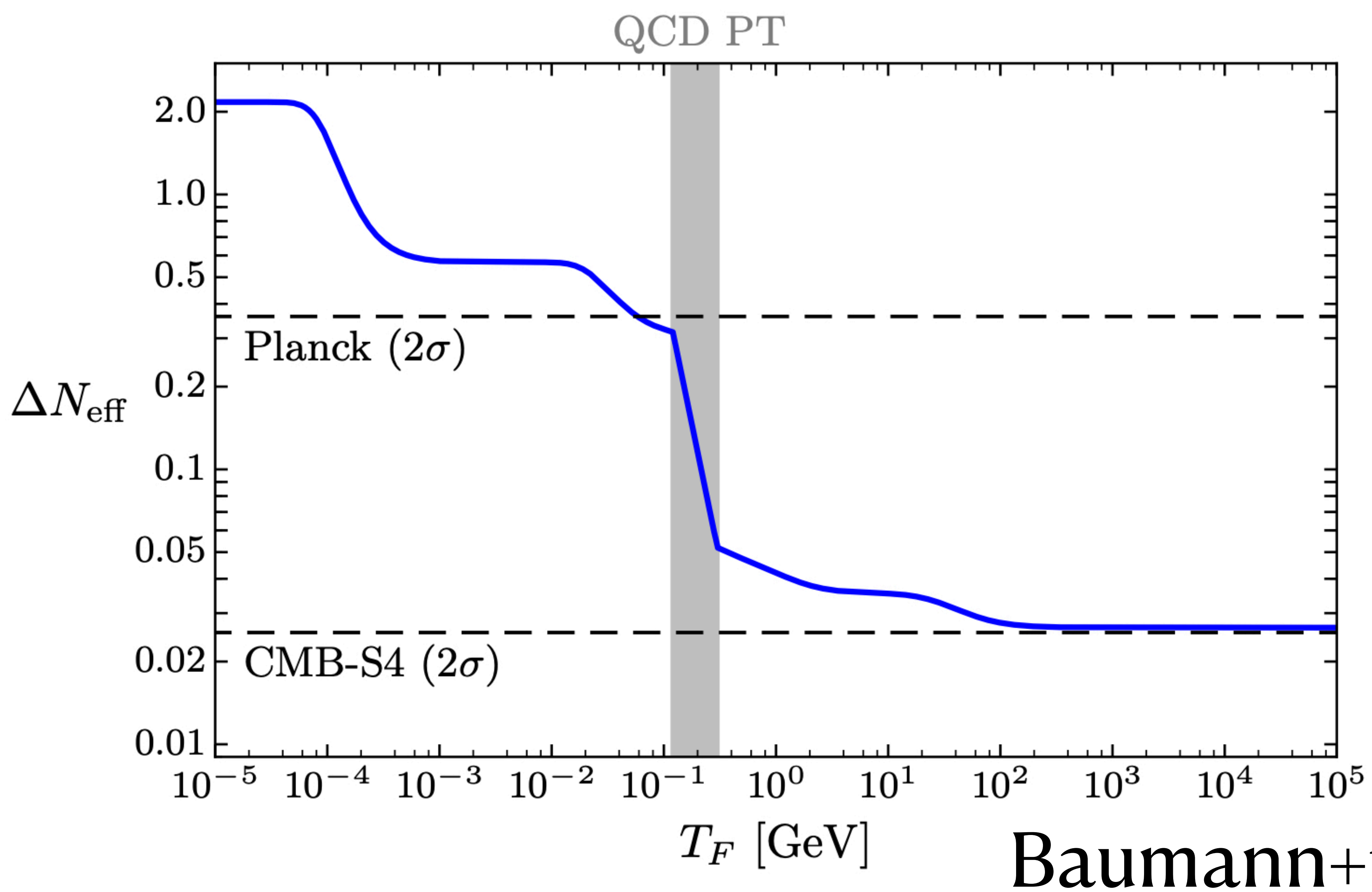
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Effective number of neutrinos $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$

$N_{\rm eff}^{\rm SM} \approx 3.046$ (Bari and Valencia groups)

$N_{\rm eff} = 2.99 \pm 0.17$

(One sigma, CMB+BAO, 1807.06209)



Baumann+18

Extra relativistic species

The excess in the number of relativistic degrees of freedom counts the *massless* axions:

$$\Delta N_{\rm eff} \equiv \frac{\rho_a(m_a=0)}{\rho_\nu(m_\nu=0)} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{g_a}{g_\nu}\left(\frac{T_a}{T_\gamma}\right)^4$$

Axion decoupling from the plasma do not benefit from further energy injection in CMB photons

$$\frac{T_a}{T_\gamma} = \left(\frac{g_{*s}(T_{\rm CMB})}{g_{*s}(T_d)}\right)^{1/3}$$

T_d : axion decoupling temperature

$T_{\rm CMB} \simeq 0.26\,{\rm eV}$

Main result: $$\Delta N_{\rm eff} \simeq 0.027\left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$

Axion-like particles

We consider axion-like particles (or axions) with a generic mass term and couplings

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \mathcal{L}_{ag} + \mathcal{L}_{a\gamma}$$

a : axion field

m_0 : axion mass

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(Explicit mass breaking term)

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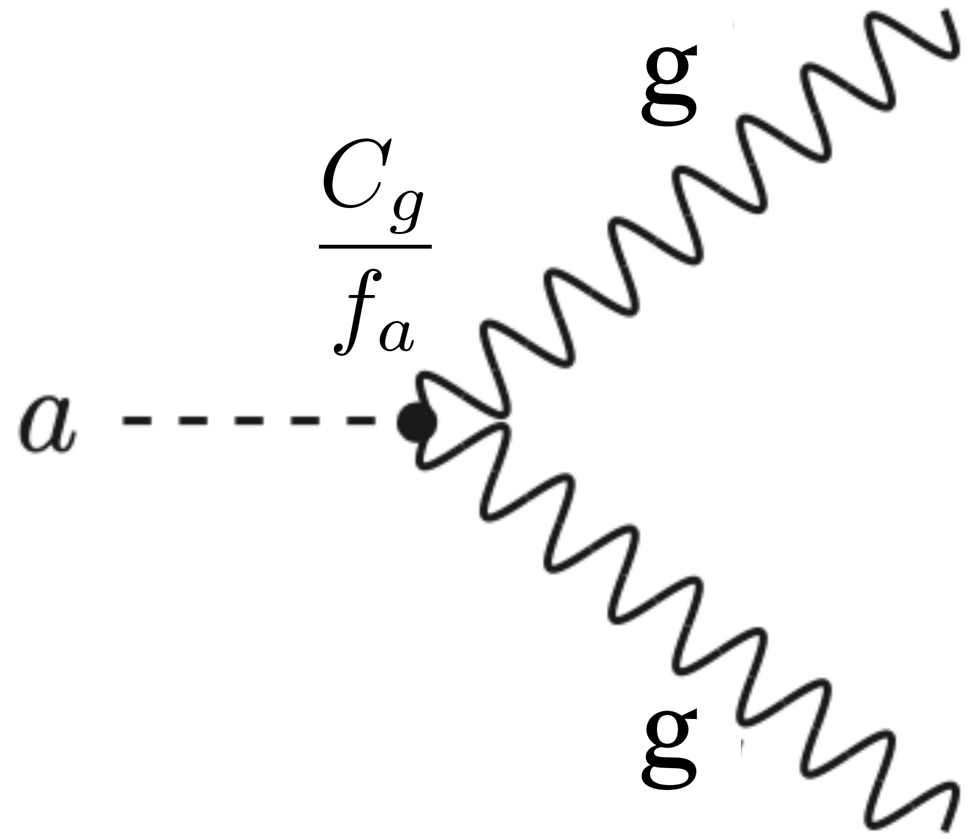
m_0 : axion mass

axion-gluon coupling $\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu}_i$



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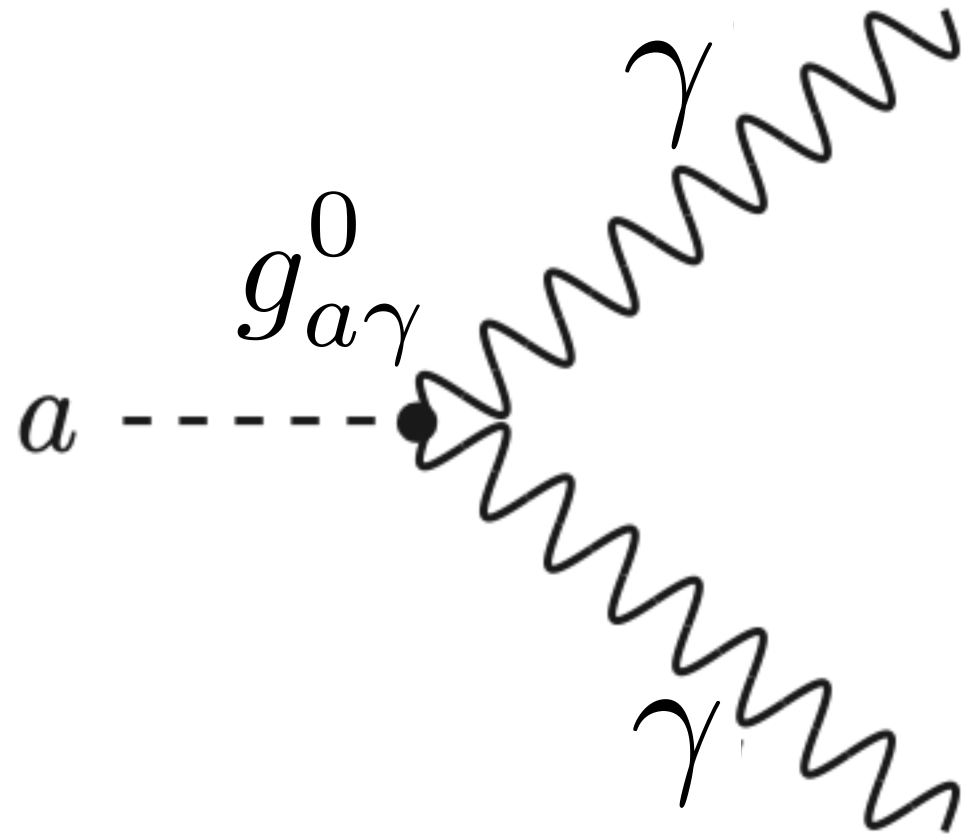
axion-photon coupling $\mathcal{L}_{a\gamma} = \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$



Thermal axion production

Luca Visinelli

Freeze-out of thermal particles from the plasma occurs when $H \approx \Gamma$ at decoupling

Boltzmann equation:

$$\frac{\mathrm{d}n_a}{\mathrm{d}t} + 3H(T)n_a = \Gamma\,\left(n_a^{\mathrm{eq}} - n_a\right)$$

We study axion-gluon and axion-photon productions separately

$$\Gamma_{ag} = \frac{1}{(4\pi^3)}\alpha_s^2\,T^3\left(\frac{C_g}{f_a}\right)^2 F_g(T)$$

$$\Gamma_{Q\gamma\to Qa} = \frac{\alpha_{\mathrm{EM}}\pi^2 g_{a\gamma}^2}{36\zeta(3)}\left[\ln\left(\frac{T^2}{m_\gamma^2}\right) + 0.8194\right] n_Q$$

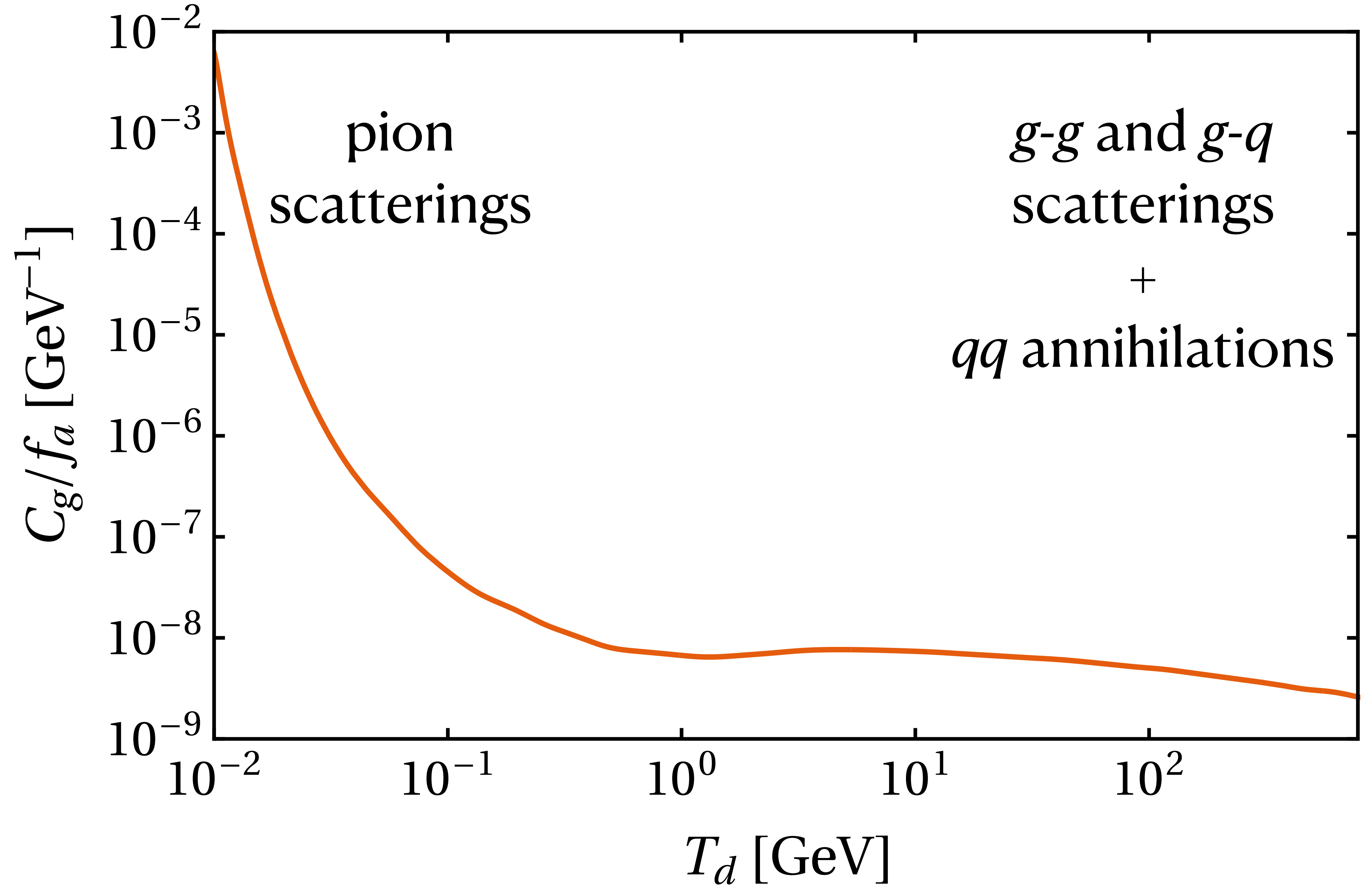
Axion-SM production is given by $F_g(T)$ (Salvio+13)

Plasmon mass m_γ

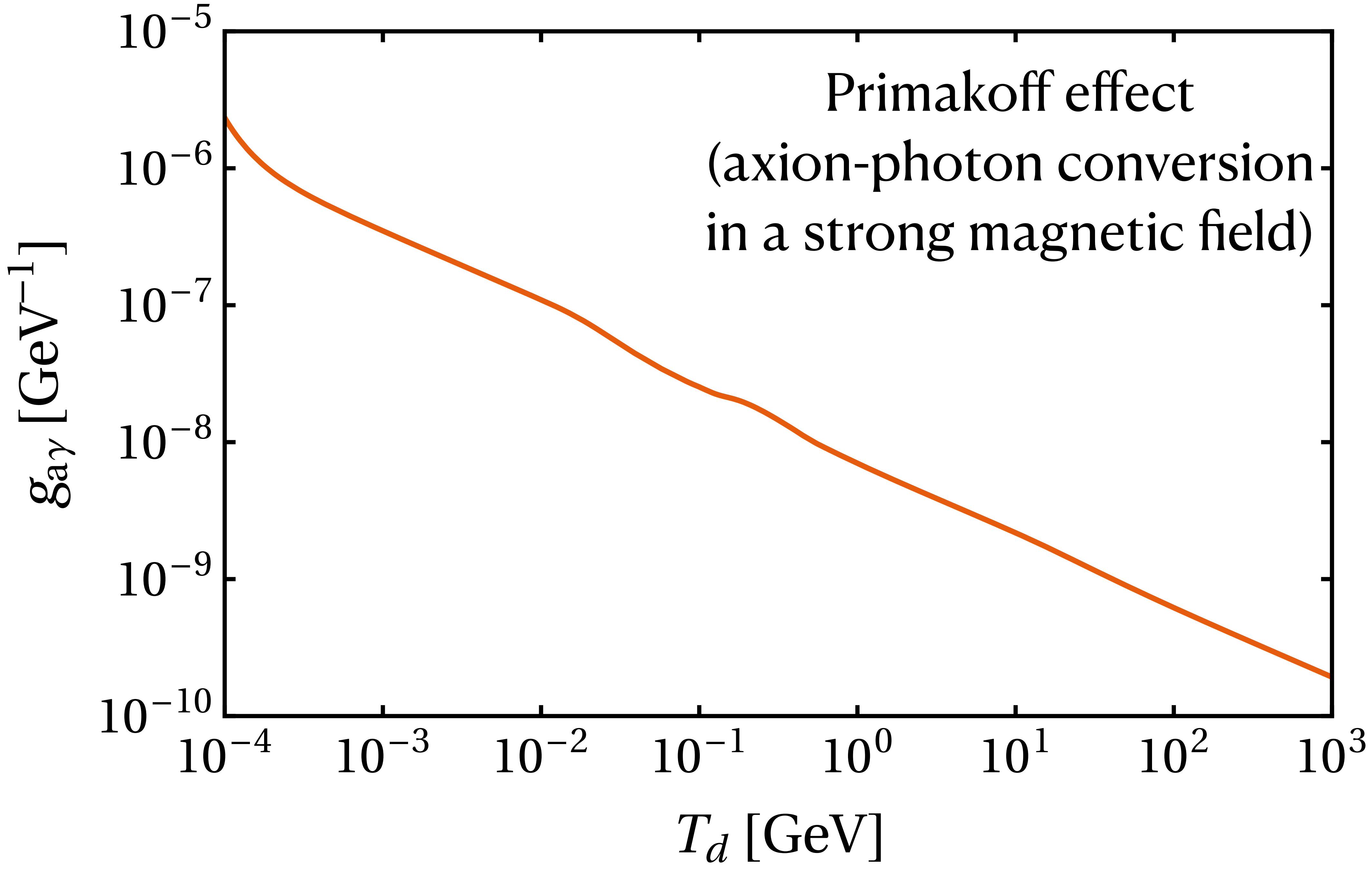
Charged particles density n_Q

Thermal axion production

Recall: $$\Delta N_{\rm eff} \simeq 0.027 \left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$



[D'Eramo+ `21]



[Bolz+ `92; Cadamuro&Redondo `12]

We find a relation between $\Delta N_{\rm eff}$ and either C_g/f_a (axion-gluon) or $g_{a\gamma}$ (axion-photon)

Thermal axion production

We consider thermal axions in the mass range $m_a \in [10^{-4}, 10^2]\,\mathrm{eV}$

Axion decoupling occurs at temperature T_d where $\Gamma(T_d) \simeq H(T_d)$

Small axion mass $(m_a \lesssim 0.1\,\mathrm{eV})$

- Light axions contribute to the energy density of radiation

$$\Delta N_{\rm eff} \equiv \frac{\rho_a(m_a = 0)}{\rho_\nu,\,\mathrm{massless}} \simeq 0.027 \left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$

Large axion mass $(m_a \gtrsim 30\,\mathrm{eV})$

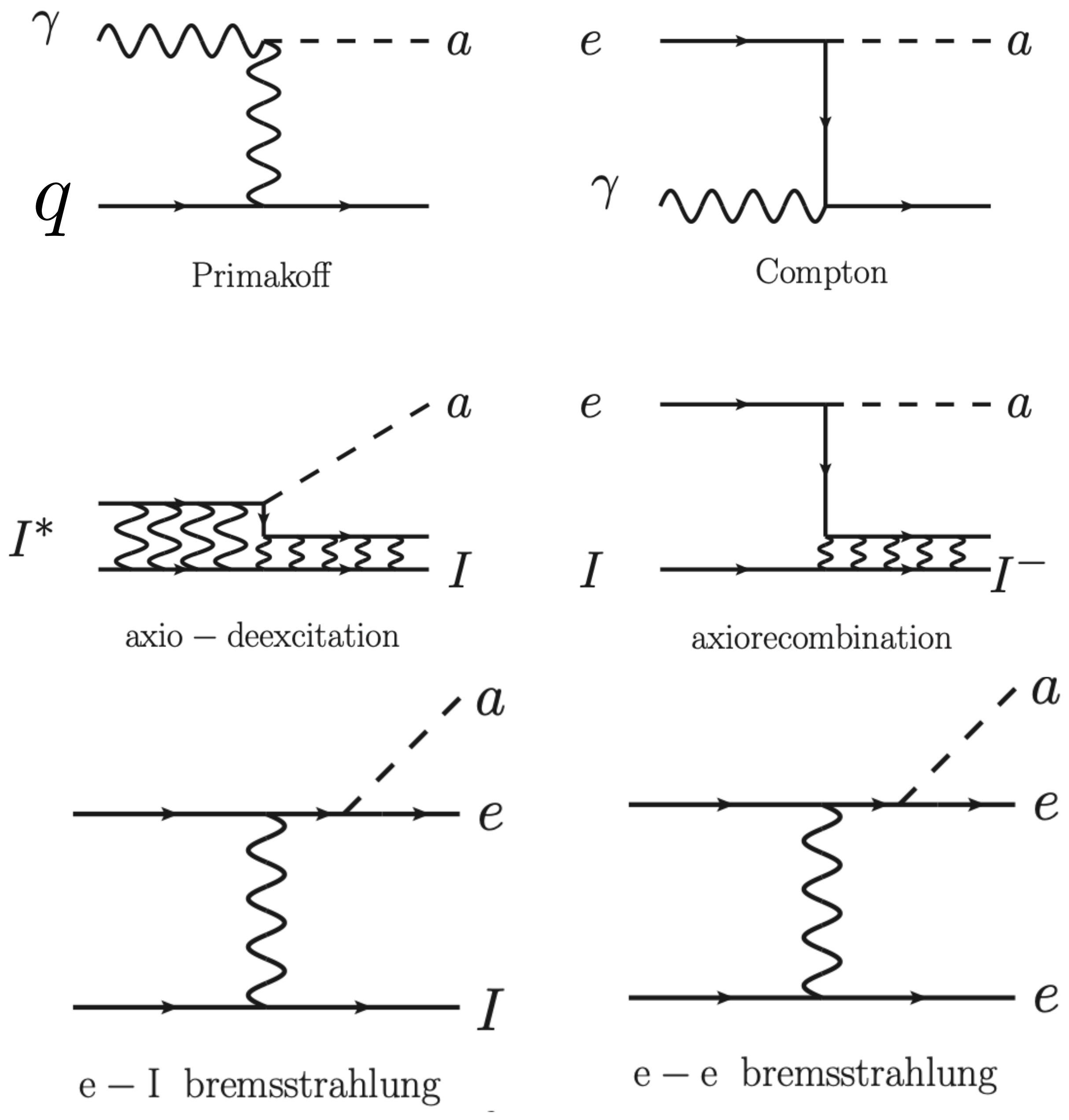
- Heavier axions contribute to the energy density of matter

$$\omega_a \simeq m_a n_a h^2 \simeq 0.011 \left(\frac{m_a}{\mathrm{eV}}\right) \Delta N_{\rm eff}^{3/4}$$

Similar techniques for other production channels (Not covered here)

- Axion-electron
- Axion-quark

Primakoff + ABC



Thermal axion production

OPPORTUNITY: heavy axions decay into two photons through the same interaction term:

$$\tau_{\phi\to\gamma\gamma} = \frac{64\pi}{g^2_{\phi\gamma\gamma} m_\pi^3} \sim 400,000\,\mathrm{yr}\left(\frac{10^{-13}\,\mathrm{GeV}^{-1}}{g_{\phi\gamma\gamma}}\right)^2\left(\frac{1\,\mathrm{MeV}}{m_\phi}\right)^3$$

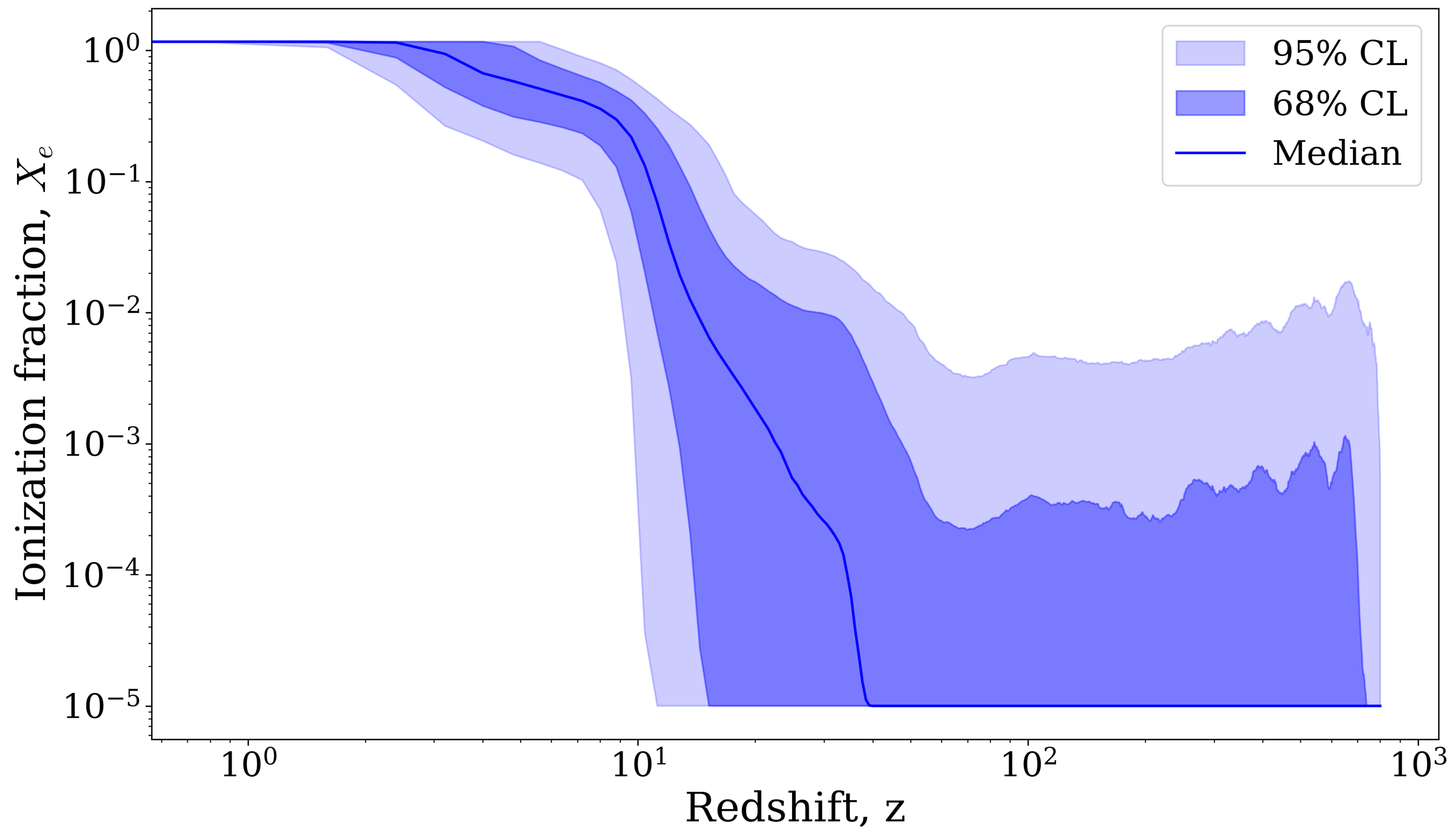
Slightly lighter or more weakly coupled axions would decay after recombination and reionize

Photon deposit energy into cosmic electrons and affect the *optical depth at redshift z*:

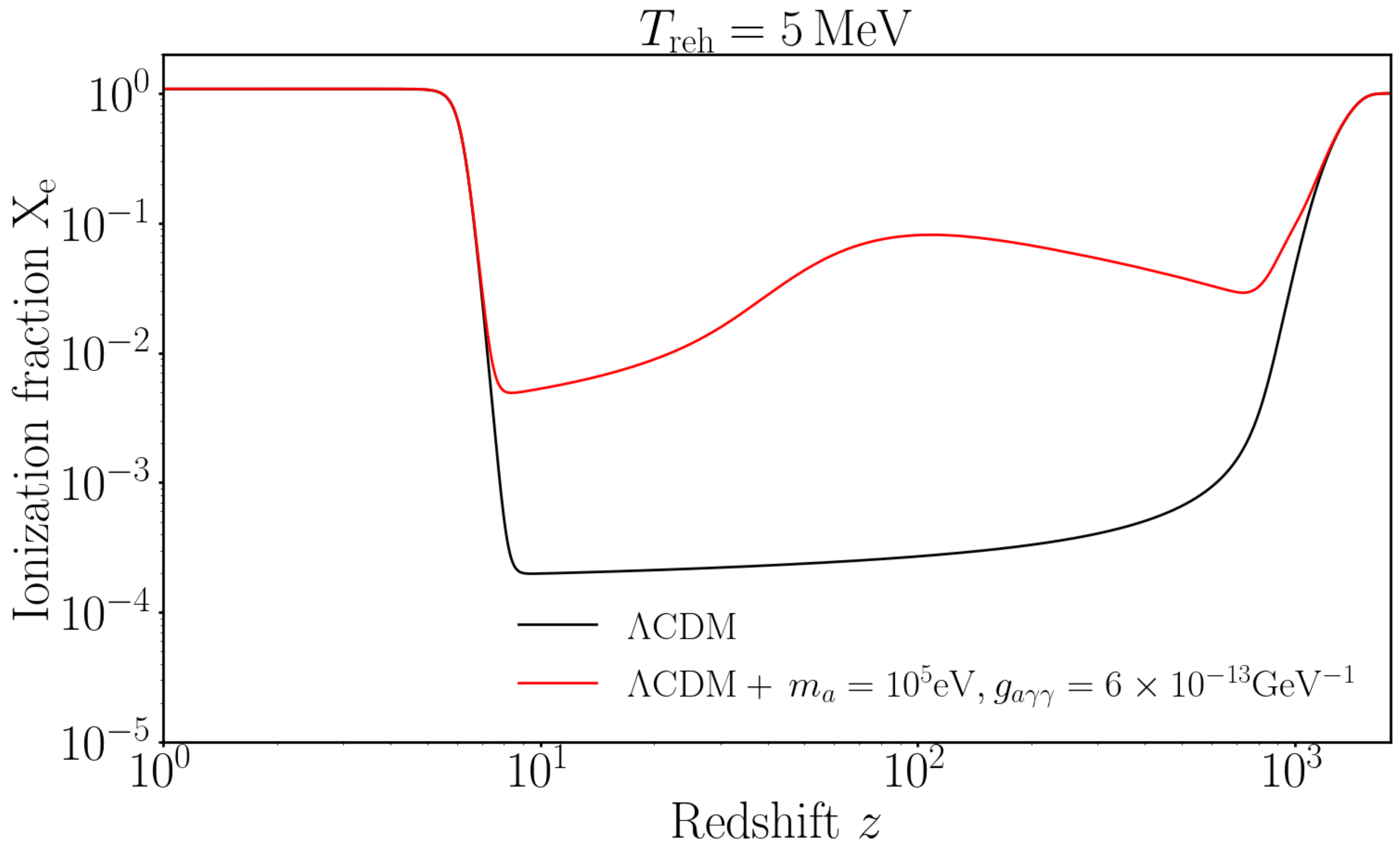
$$\tau_{\rm reio}(z) \equiv \int_{\rm today}^{t(z)} \mathrm{d}t\,\sigma_T\,n_e(z)$$

This is testable with CMB EE data

Thermal axion production



Gaussian process, model independent reconstruction of the free electron fraction from Planck large angle E-mode CMB polarization data



Axion-induced ionization fraction from energy deposition

Cheng, Yin, Di Valentino, Marsh, **LV** 2506.19096
Yin, Cheng, Di Valentino, Gendler, Marsh, **LV** 2507.03535

Details on GPU approach in **Hanyu Cheng**'s talk from Monday

Details on applications to the string axiverse in **Ziwen Yin**'s talk from Monday

IV. Axions as dark energy

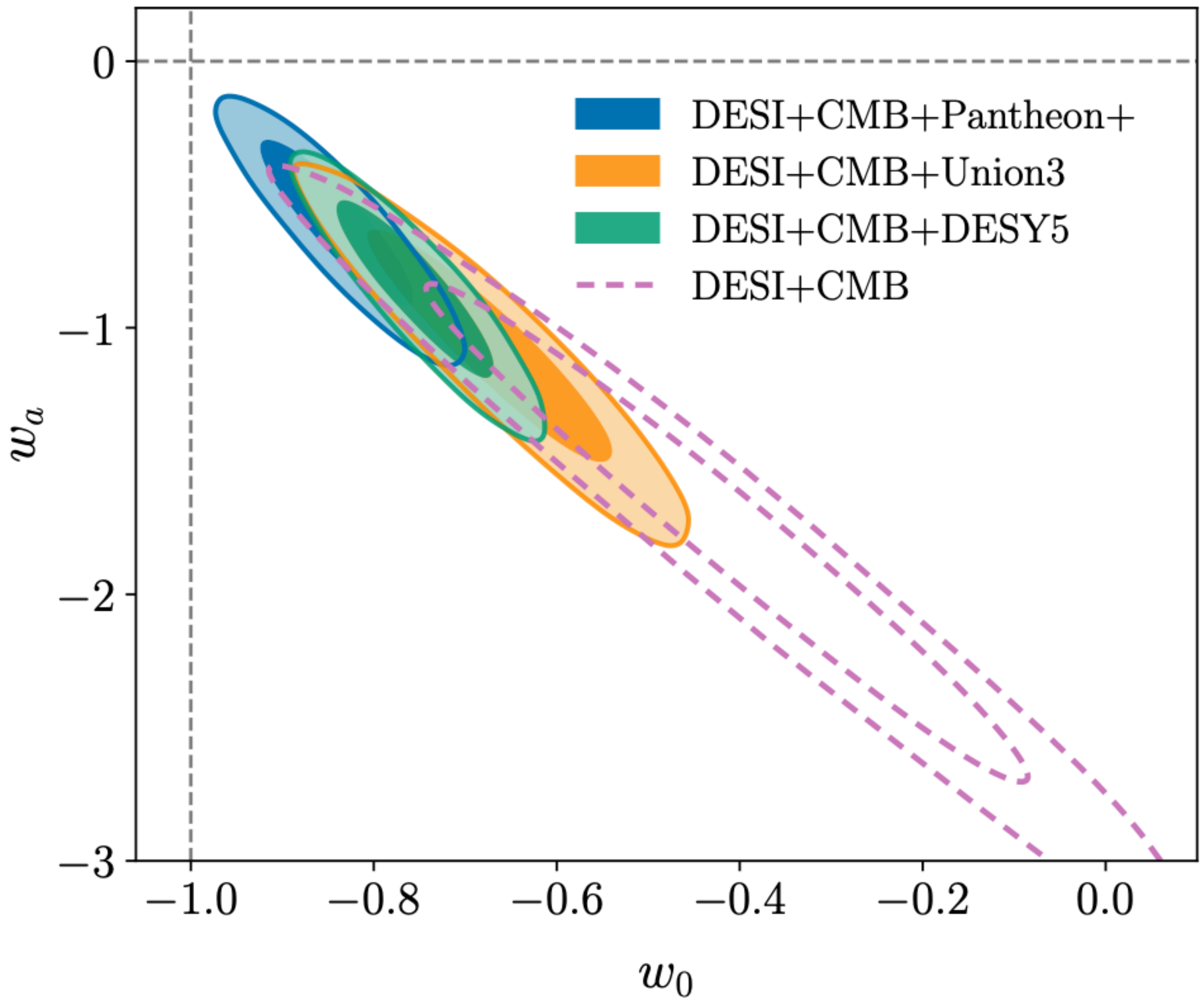
Hints of evolving dark energy?

Baryon acoustic oscillation measurements by DESI suggest a preference for evolving dark energy.

The CPL parametrization:

$$w(a) = w_0 + w_a(1 - a)$$

is favored over $w_\Lambda = -1$ at 3.1 σ using CMB+DESI



Abdul Karim+ (DESI) 2503.14738

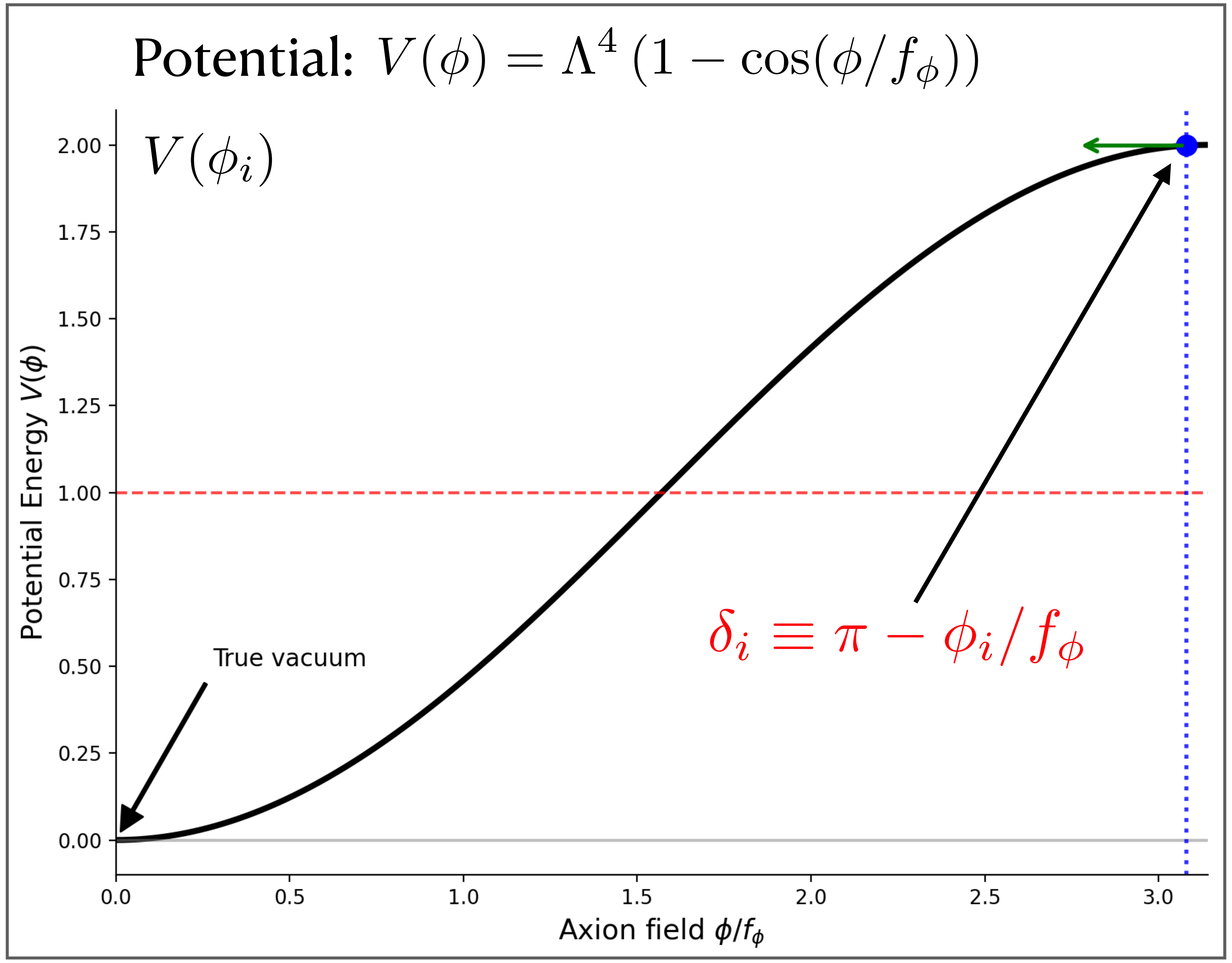
Axions as Dark Energy?

Luca Visinelli

A light boson field is an excellent candidate for *quintessence*, i.e. dynamical dark energy

Hubble friction keeps a light boson frozen to its initial configuration $\phi = \phi_i$

The zero-energy of the field $V(\phi_i)$ acts as a dark energy component



Once the Hubble rate falls below the boson mass, the field starts to move: $m_\phi \simeq H_0 \sim 10^{-33}\,\mathrm{eV}$

Not so simple to fit!

$$w_\phi \equiv \frac{p_\phi}{\rho_\phi} = \frac{\dot\phi^2 - 2V(\phi)}{\dot\phi^2 + 2V(\phi)} \sim -1$$

$$\rho_\phi \equiv \frac{1}{2}\dot\phi^2 + V(\phi) \sim \rho_{\rm DE}$$

Axions as Dark Energy?

Luca Visinelli

Protection of Mass Hierarchy: The axion shift symmetry $\phi \to \phi + c$ protects the small mass of the pseudo scalar m_ϕ from quantum corrections

Evading Fifth-Force Constraints: Axion couplings with matter are derivative:

$$\mathcal{L} \propto (\partial_\mu \phi)\, \bar{\psi}\gamma^\mu\psi$$

This leads to spin-dependent, velocity-suppressed forces that evade experimental bounds

String Theory Motivation: Large ensembles of axions with a spectrum of masses are expected from compactifications of extra dimensions, giving a natural UV-completed framework.

Unique Observational Signatures: The parity-odd nature of axions leads to distinct signatures, such as *cosmic birefringence* and astrophysical probes of magnetic fields.

Light axion model of dark energy

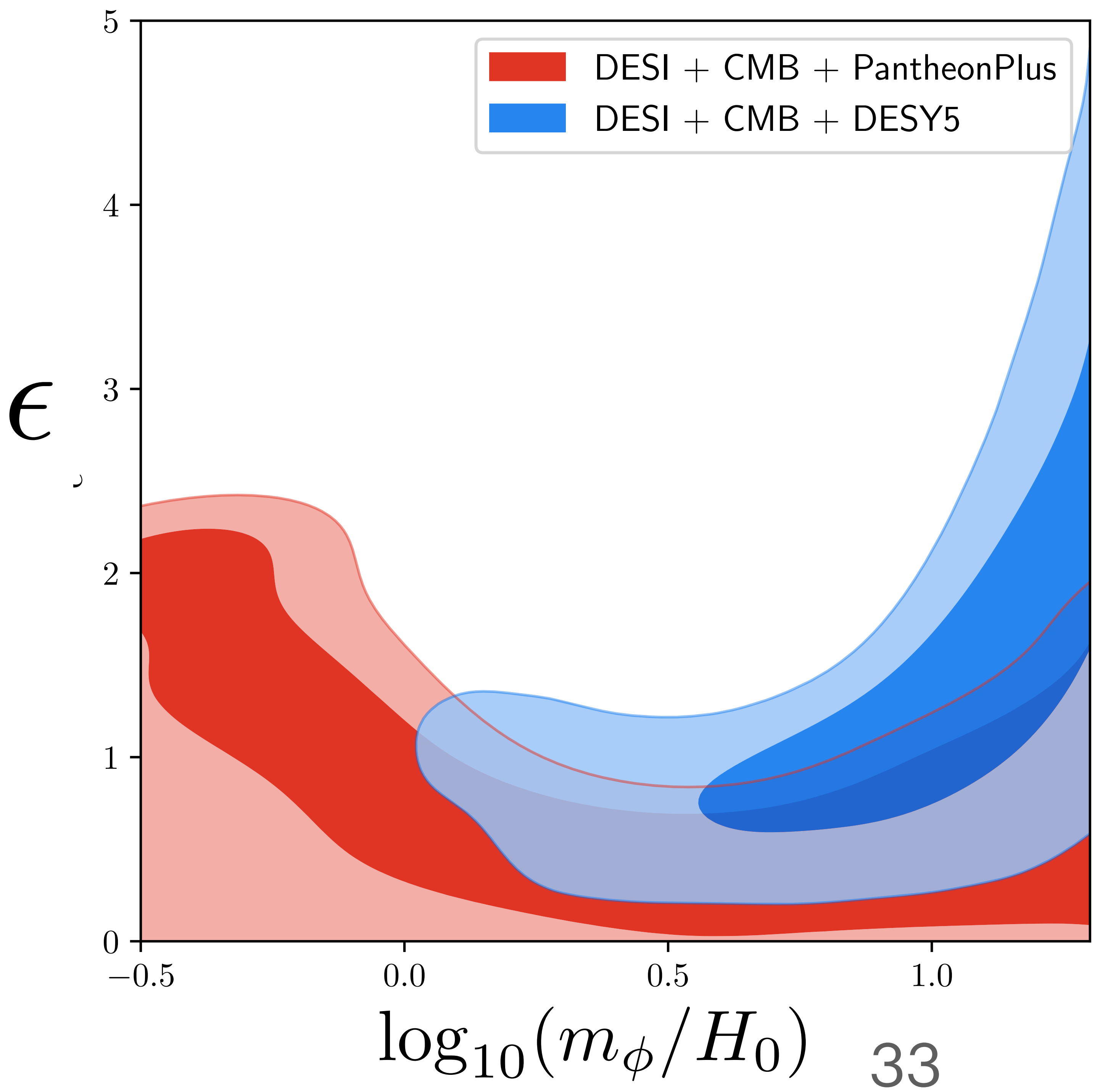
Accurate sampling strategy to explore low-masses:

$$\delta_i \equiv \pi - \phi_i/f_\phi = \epsilon \left(\frac{m_\phi}{H_0} + 1\right)^{1.5} \exp\left(-\frac{m_\phi}{H_0}\right)$$

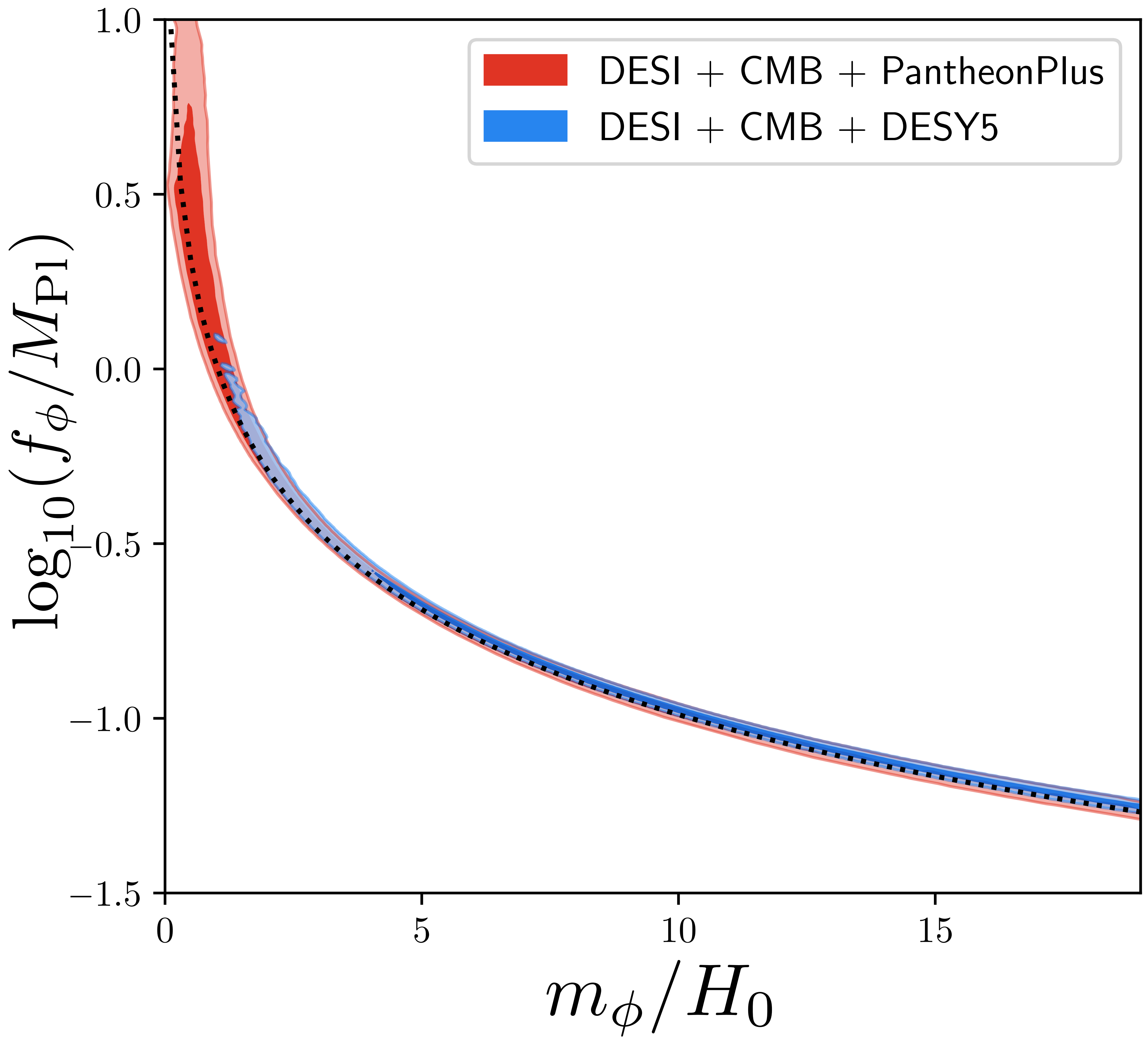
$\epsilon \in [0, 25]$ Uniform

$\epsilon = 0$ is excluded at 2σ

by DESY+DESY5



The correct sampling of initial conditions reveals a region with low mass and high f_ϕ



Lin, **LV**, Yanagida 2504.17638

Conclusions

Many ideas are coming to test, some has to be right!!

QCD axion as a light dark matter candidate:
theory and experimental fields are in a mature stage to come up with reliable predictions and testings across different mass ranges and couplings.
Still work to do to refine mass predictions, cosmology uncertainties, substructures.

Axion as dark energy: hints and probes (e.g. cosmic birefringence) are emerging.

Thermal/heavy axions: parallel avenue of production and multiple detection strategies (decaying prior reionization, cosmology, large scale structure).

Axion Miniclusters in the Milky Way

Axion miniclusters (scenario 2)

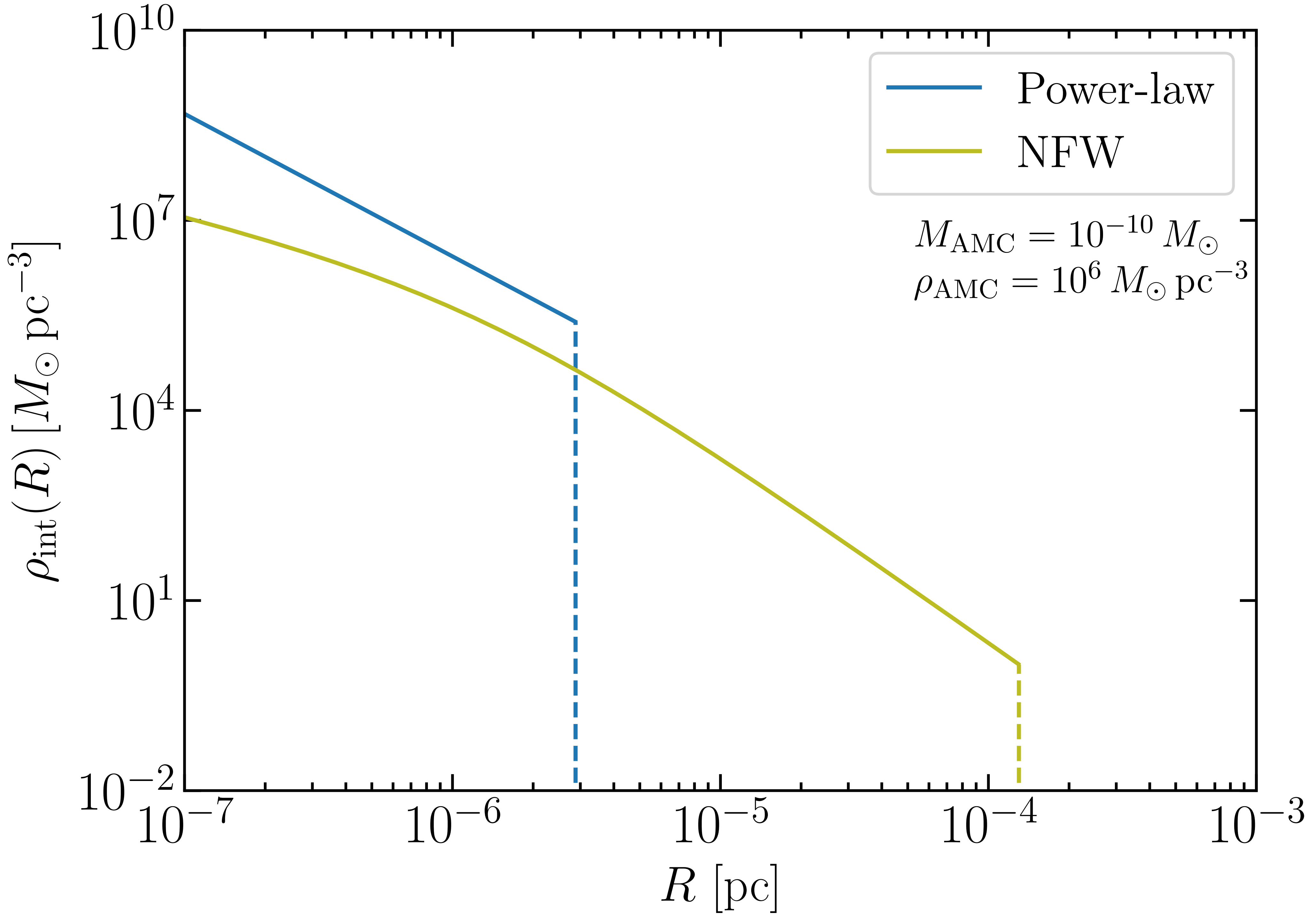
In post-inflation symmetry breaks, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

$$L_{\rm osc} \sim 1/[a_{\rm osc} H(T_{\rm osc})] \sim 10^{-3}\,{\rm pc}$$

Typical minicluster mass:

$$M_{\rm mc} = \frac{4\pi}{3} L_{\rm osc}^3 \rho_{\rm DM} \sim 10^{-16}\,M_\odot$$

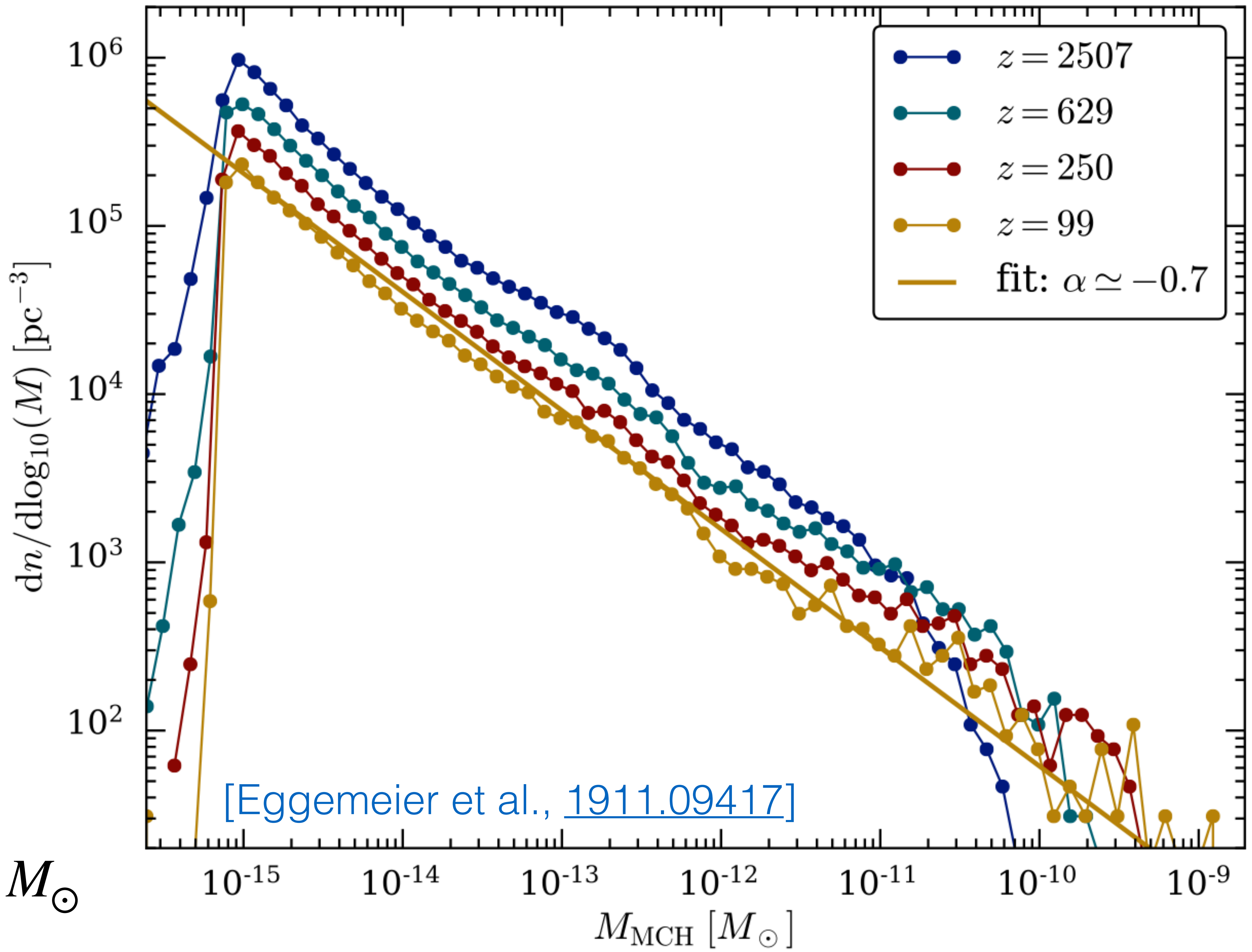
[Hogan & Rees 1988; Kolb & Tkachev 1994]



Density profile from collapse: $\rho_{\rm mc}(r) \propto r^{-9/4}$

After MR, miniclusters merge hierarchically
to form halos with NFW-like profiles [Vaquero+ 2019]

AMC mass function



$$M_0 \approx 10^{-11} M_\odot (1+\delta) \left(\frac{20\mu\mathrm{eV}}{m_a}\right)^{1/2}$$

$$\frac{\mathrm{d}P}{\mathrm{d}\log M_{\rm AMC}} \sim M_{\rm AMC}{}^{-0.7}$$

Extend down to $M_{\rm AMC} \sim 10^{-19}\, M_\odot$

(Set by the Jeans mass for $m_a = 20\,\mu\mathrm{eV}$)

Extend up to $M_{\rm AMC} \sim 10^{-5}\, M_\odot$

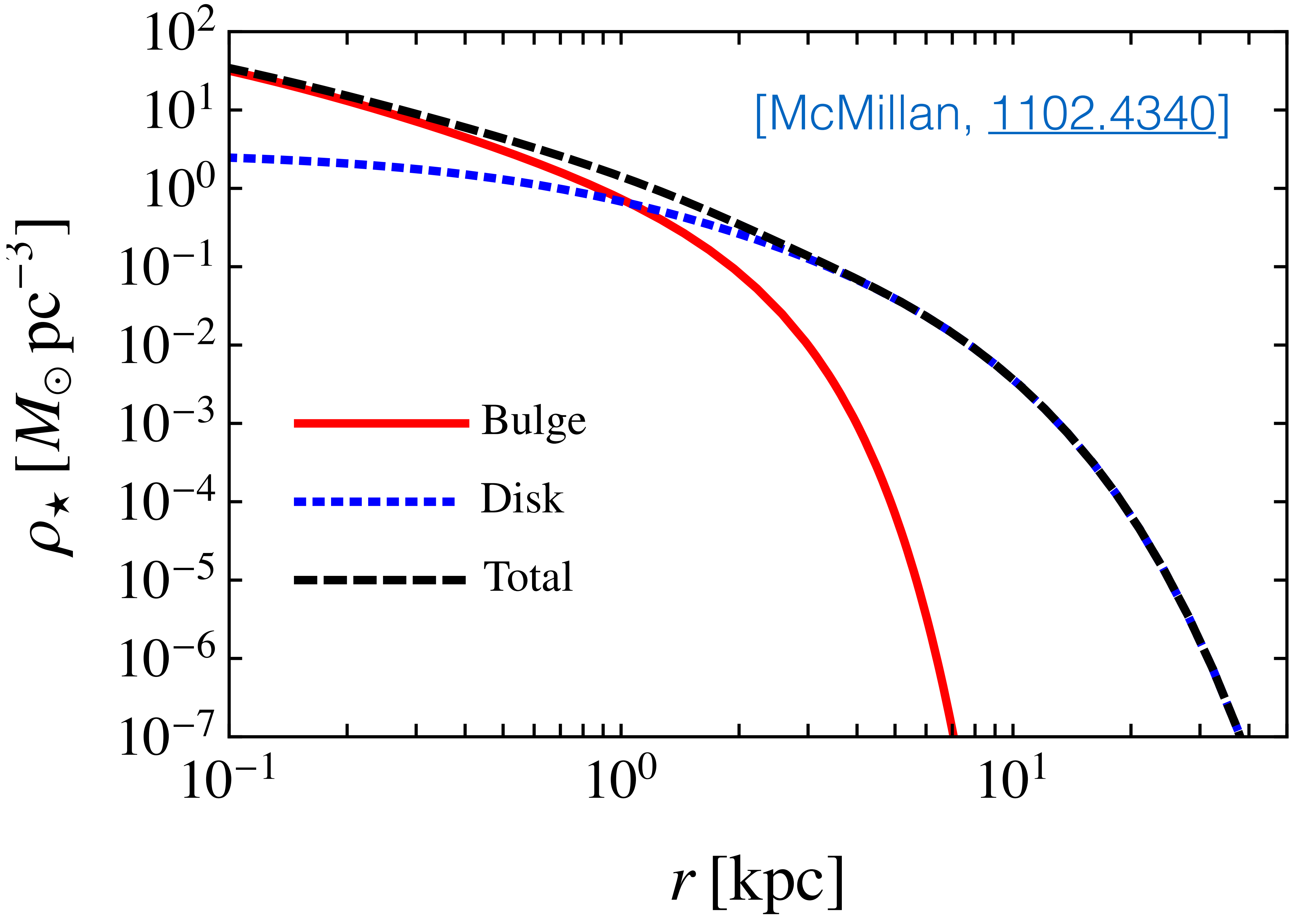
(Growth of hierarchical structure to today)

[Fairbairn et al., 1707.03310]

Everything can be recast for different distributions of $(M_{\rm AMC}, \delta)$ or equivalently $(M_{\rm AMC}, \rho_{\rm AMC})$!

[github.com/bradkav/axion-miniclusters]

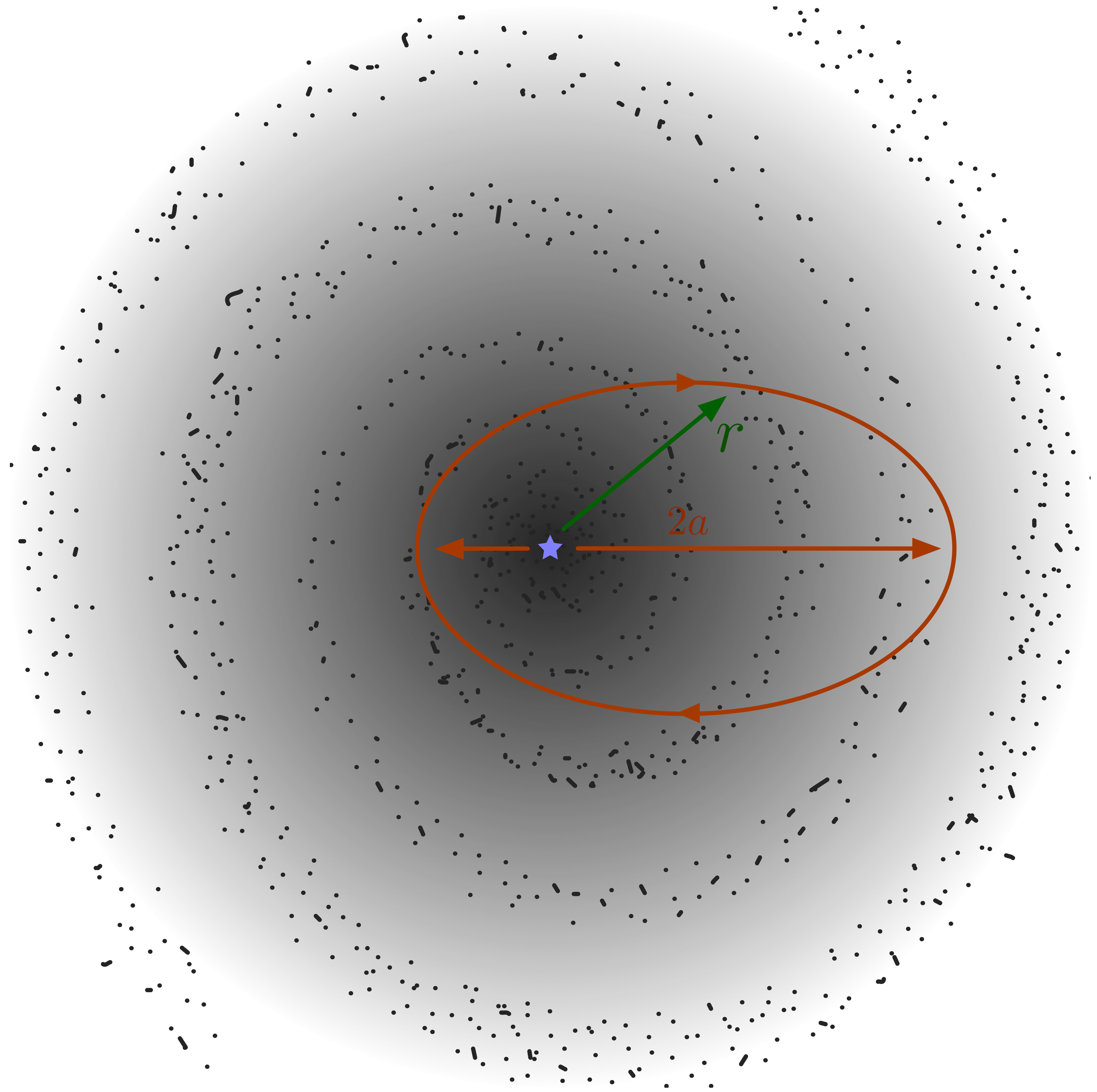
Milky Way Setup



$$n_{\rm AMC}(r) = f_{\rm AMC}\,\frac{\rho_{\rm DM}(r)}{\langle M_{\rm AMC}\rangle}$$

$$f_{\rm AMC} \approx 100\%$$

$$\langle M_{\rm AMC}\rangle \approx 10^{-14}\,M_\odot$$



Caveat: we do not deal with concurrent structure formation, stellar formation & AMC distruption

Monte Carlo procedure

Generate sample of AMCs (with correct density distribution but *log-flat* mass function)

Sample orbital parameters (e, ψ)

Compute number of stellar interactions:

$$N = \int_0^{T_{\mathrm{MW}}} \mathrm{d}t \, n_\star(t) V_{\mathrm{AMC}}(t) \cdot \pi b_{\mathrm{max}}^2$$

Sample interaction properties (v_{rel}, b) and perturb AMC

AMC not disrupted

AMC disrupted

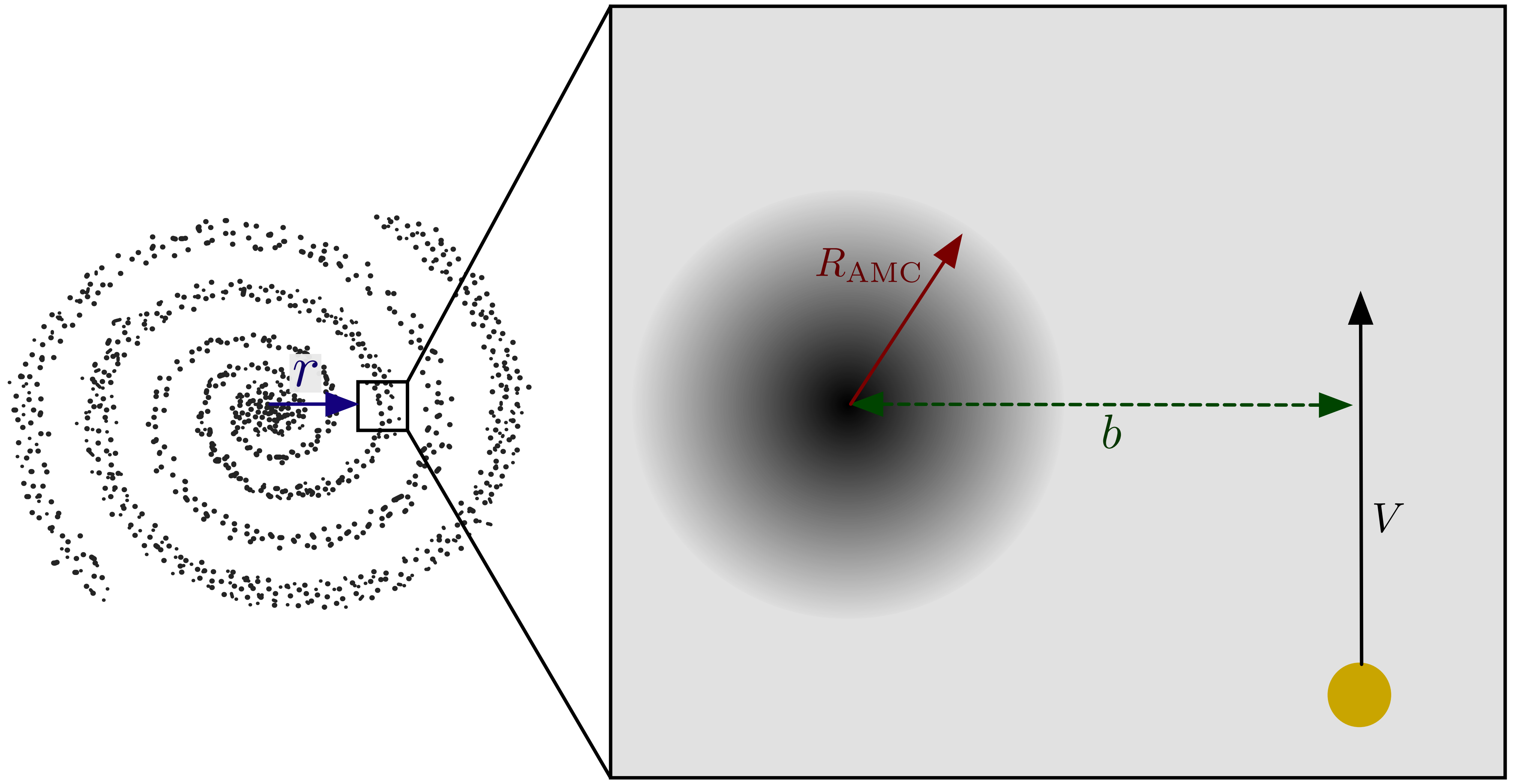
Remove AMC from simulation

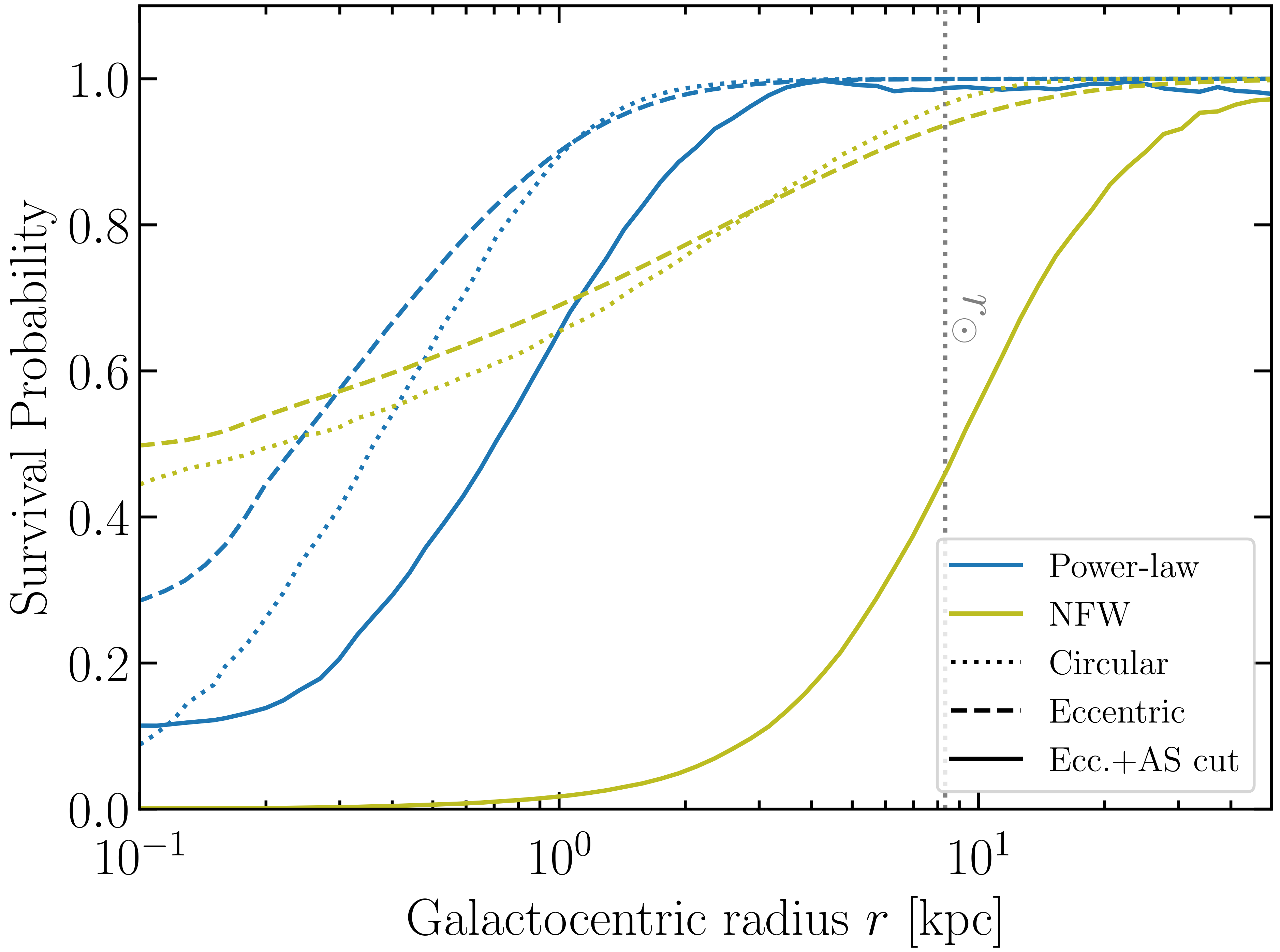
Collect surviving AMCs and reconstruct true properties

But! Need to know the response of an AMC to stellar perturbations…

Axion miniclusters abundance today

The abundance of miniclusters in galaxies is assessed via Monte Carlo simulations of tidal stripping





Kavanagh, Edwards, **LV**, Weniger, PRD 2020

See also [Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586]

Axion stars nucleation: Current work with Zi-Wen Yin (SJTU)

Observational Consequences

Luca Visinelli

Axion-photon conversion in NS magnetospheres

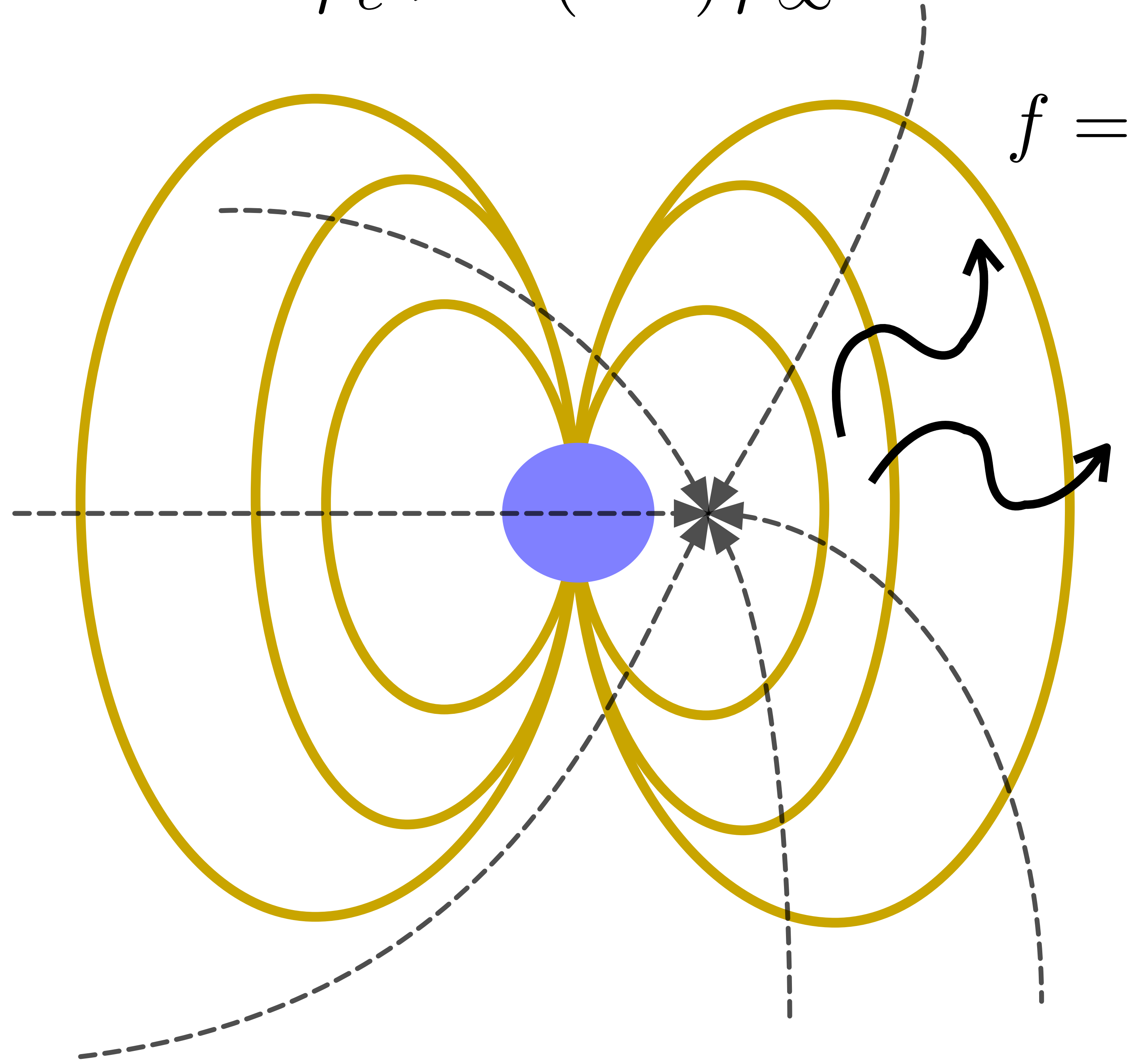
Assuming a **Goldreich-Julian** model for the NS magnetosphere, emitted radio power:

[Goldreich & Julian (1969)]

$$\frac{d\mathcal{P}_a}{d\Omega} \sim \frac{\pi}{3} g_{a\gamma\gamma}^2 B_0^2 \frac{{R_{\rm NS}}^6}{{R_c}^3} \frac{\rho_c}{m_a}$$

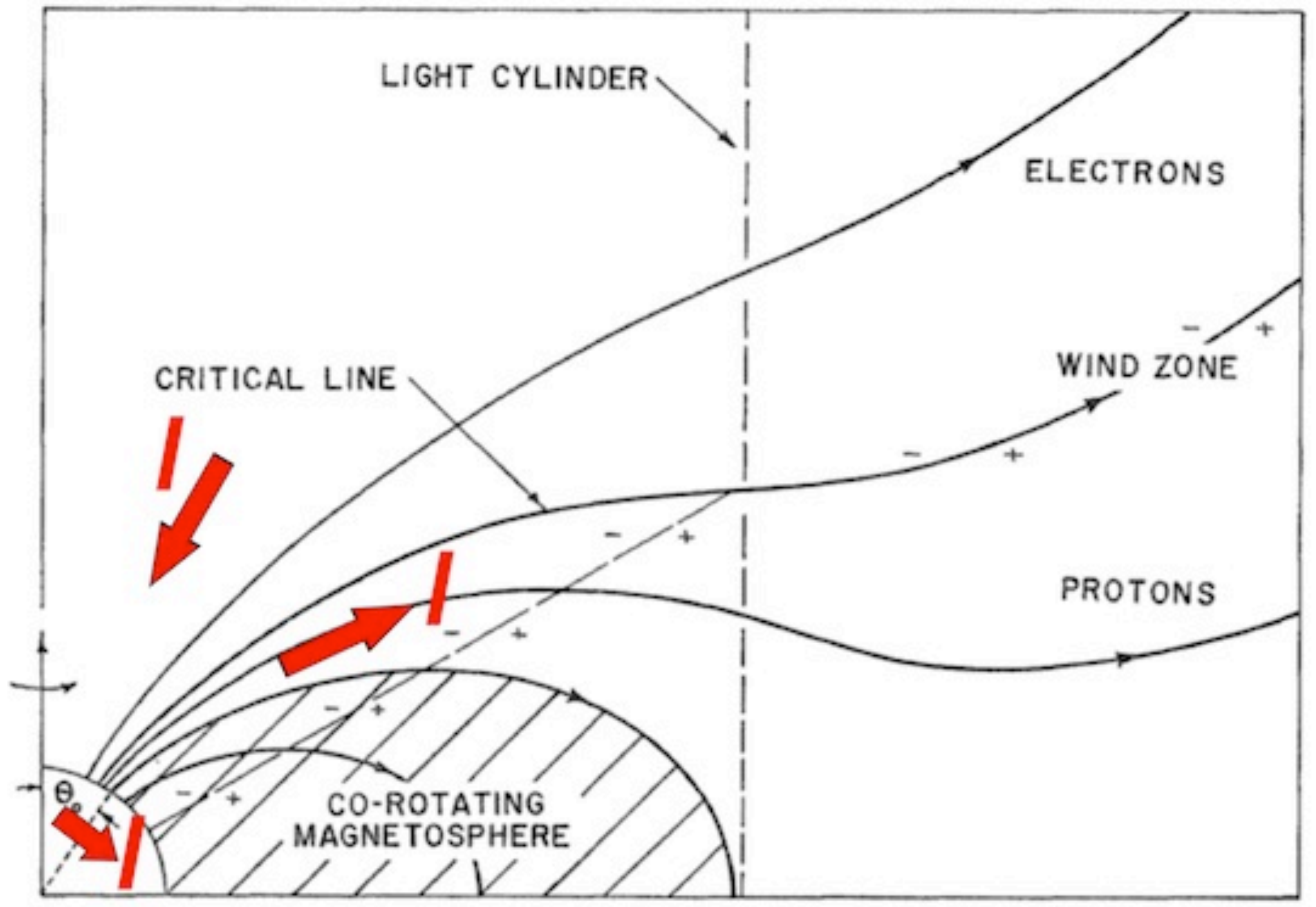
$\rho_c > \mathcal{O}(100)\,\rho_\infty$

$f = 4.84\,\mathrm{GHz}$



Plenty of uncertainties on magnetosphere properties, conversion probabilities, anisotropy…

[Battye et al., 1910.11907; Leroy et al., 1912.08815]



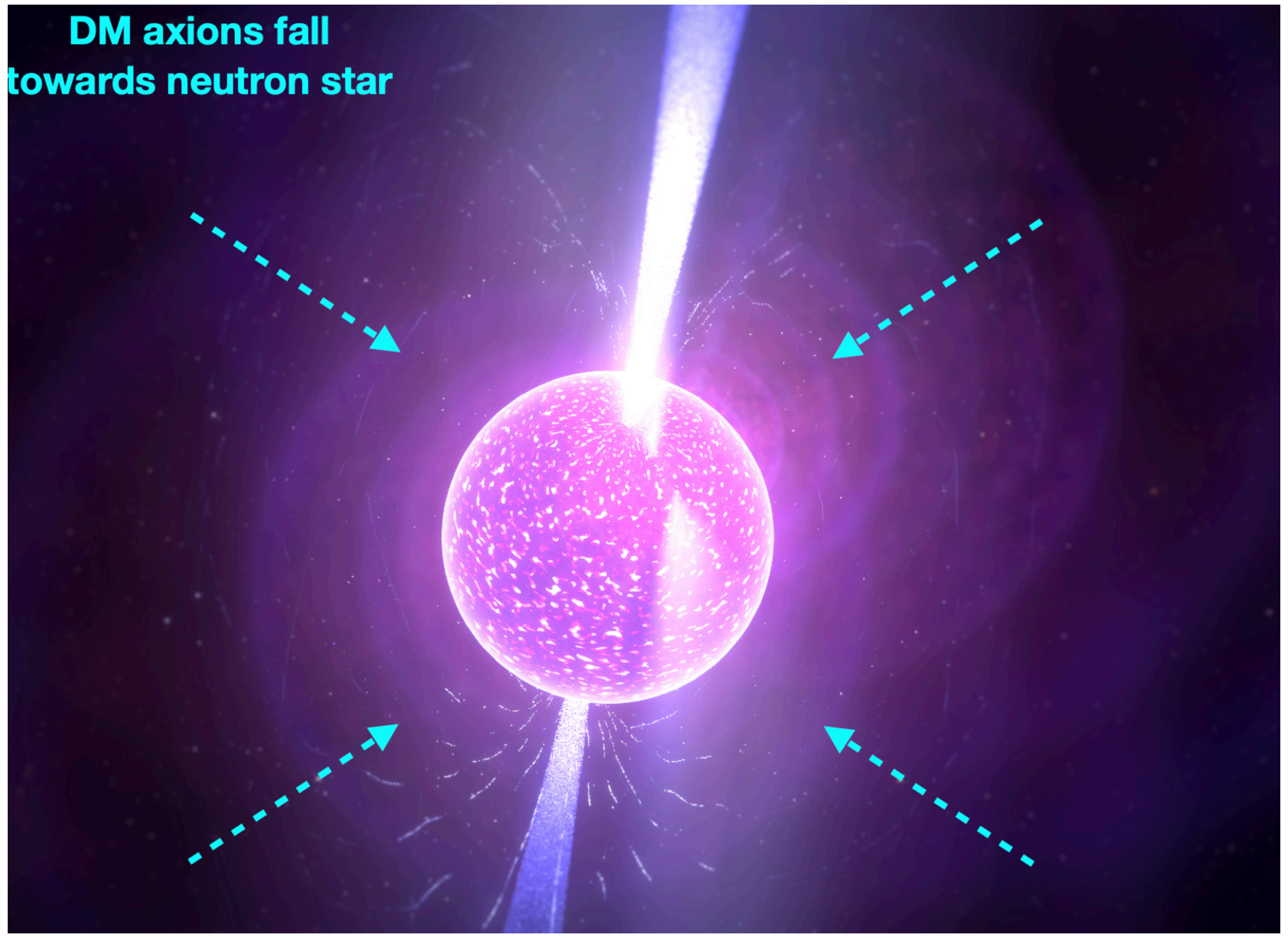
Assume isotropic emission and focus on enhancements to ρ_c due to AMC encounters.

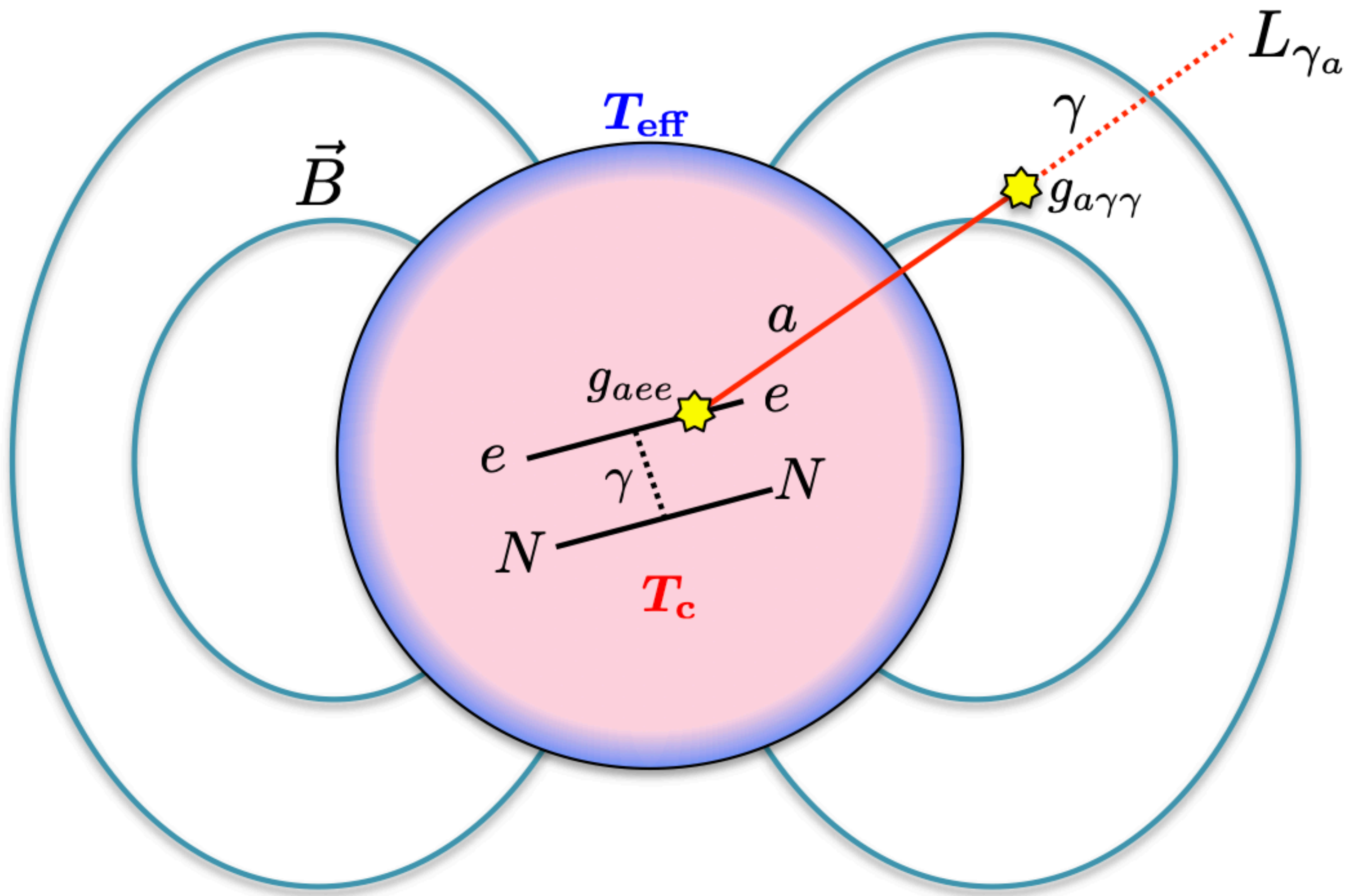
[Hook et al., 1804.03145; Safdi et al., 1811.01020; Edwards et al. 1905.04686; Foster et al., 2004.00011]

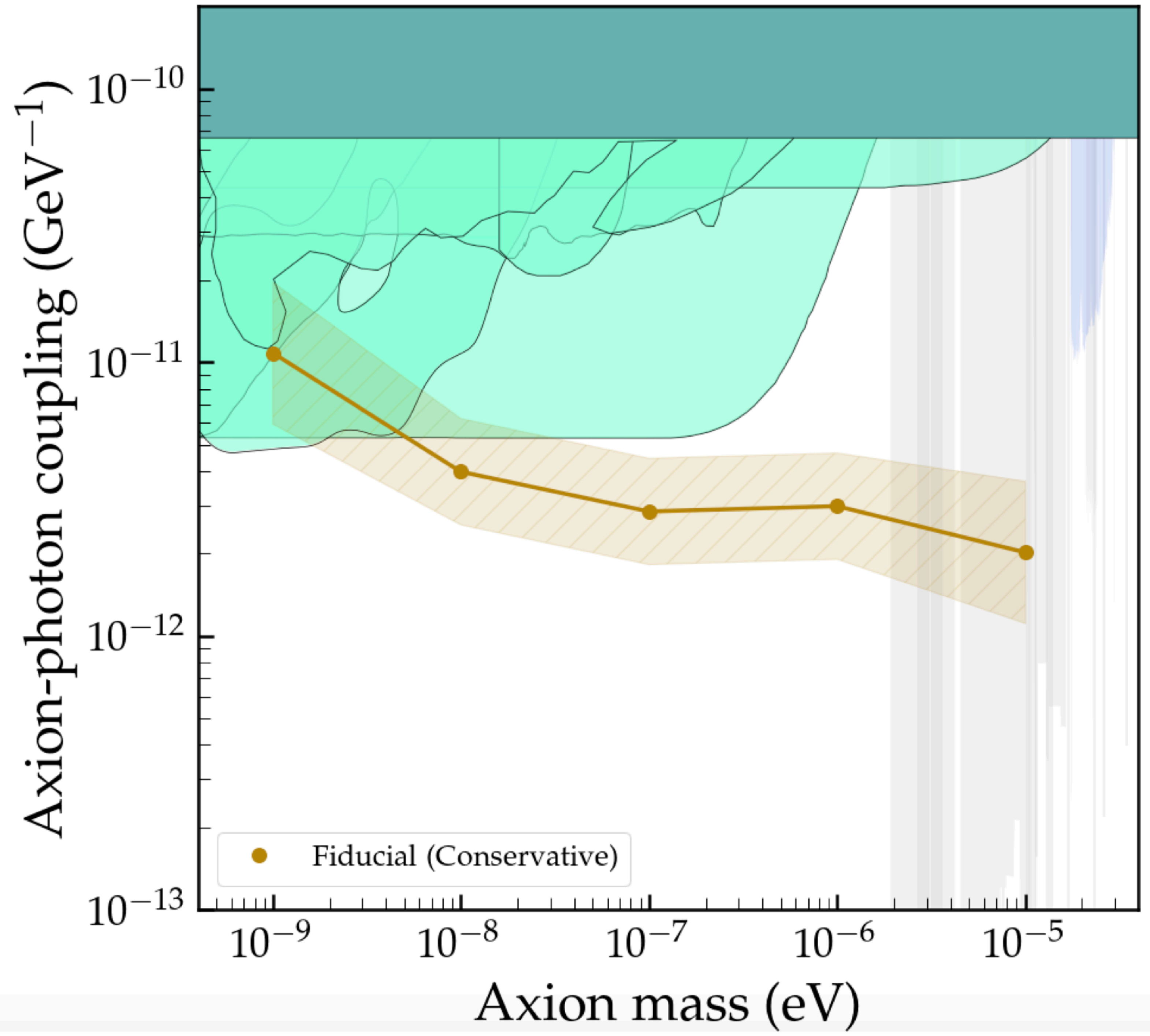
Axion-photon conversion in NS magnetospheres

Neutron stars as laboratories for DM searches

Radio observations of neutron stars is a promising avenue to detect axion DM







DM axions fall into neutron stars convert in the magnetosphere

[Hook+ 2018; Safdi+ 2019]

Axion production in NS cores +conversion in magnetosphere

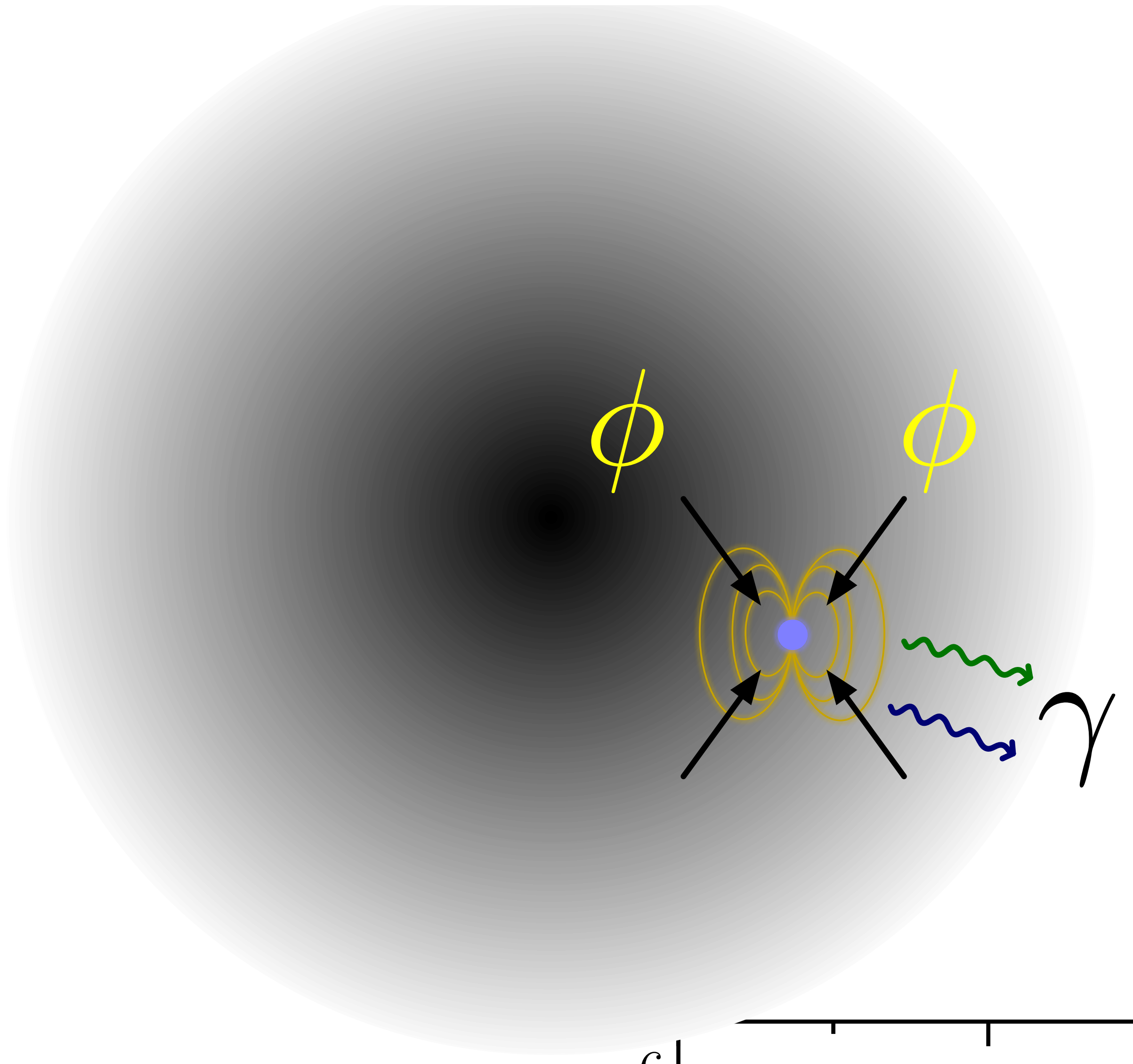
[Dessert+ 2021]

Bound obtained using 27 pulsars from ATNF catalog

[Noordhuis+ 2209.09917]

Axion-photon conversion in NS magnetospheres

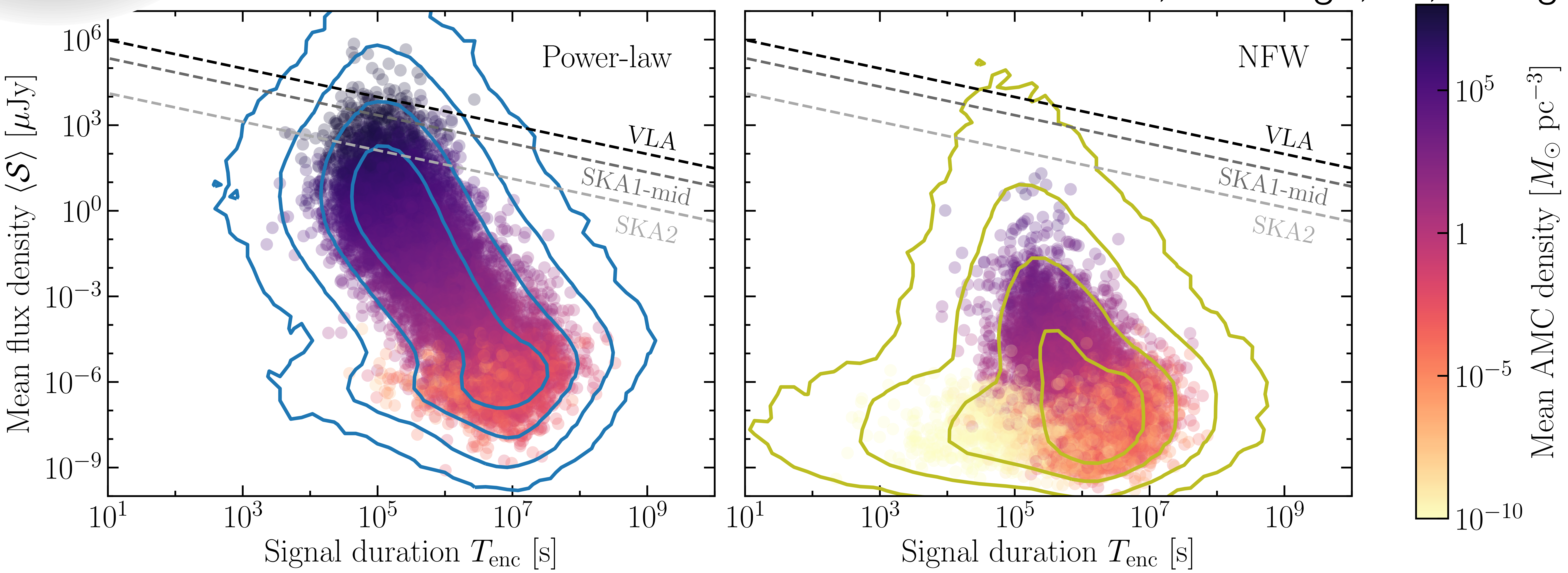
Luca Visinelli



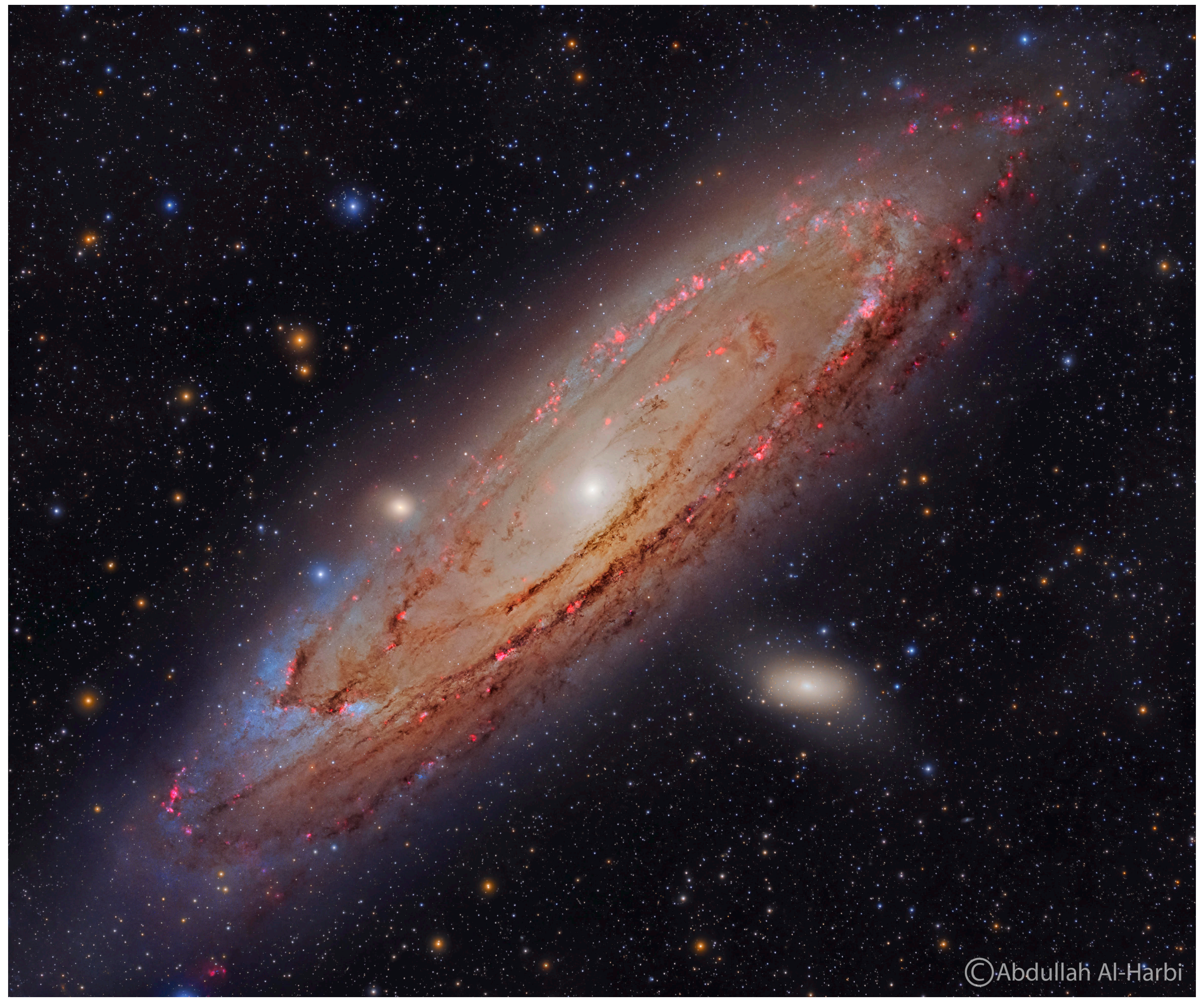
$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$

Based on velocity dispersion of AMC, expect an *incredibly narrow line.*
Instead, fix bandwidth BW = 1 kHz (based on telescope resolution).

Edwards, Kavanagh, **LV**, Weniger, PRL 2021



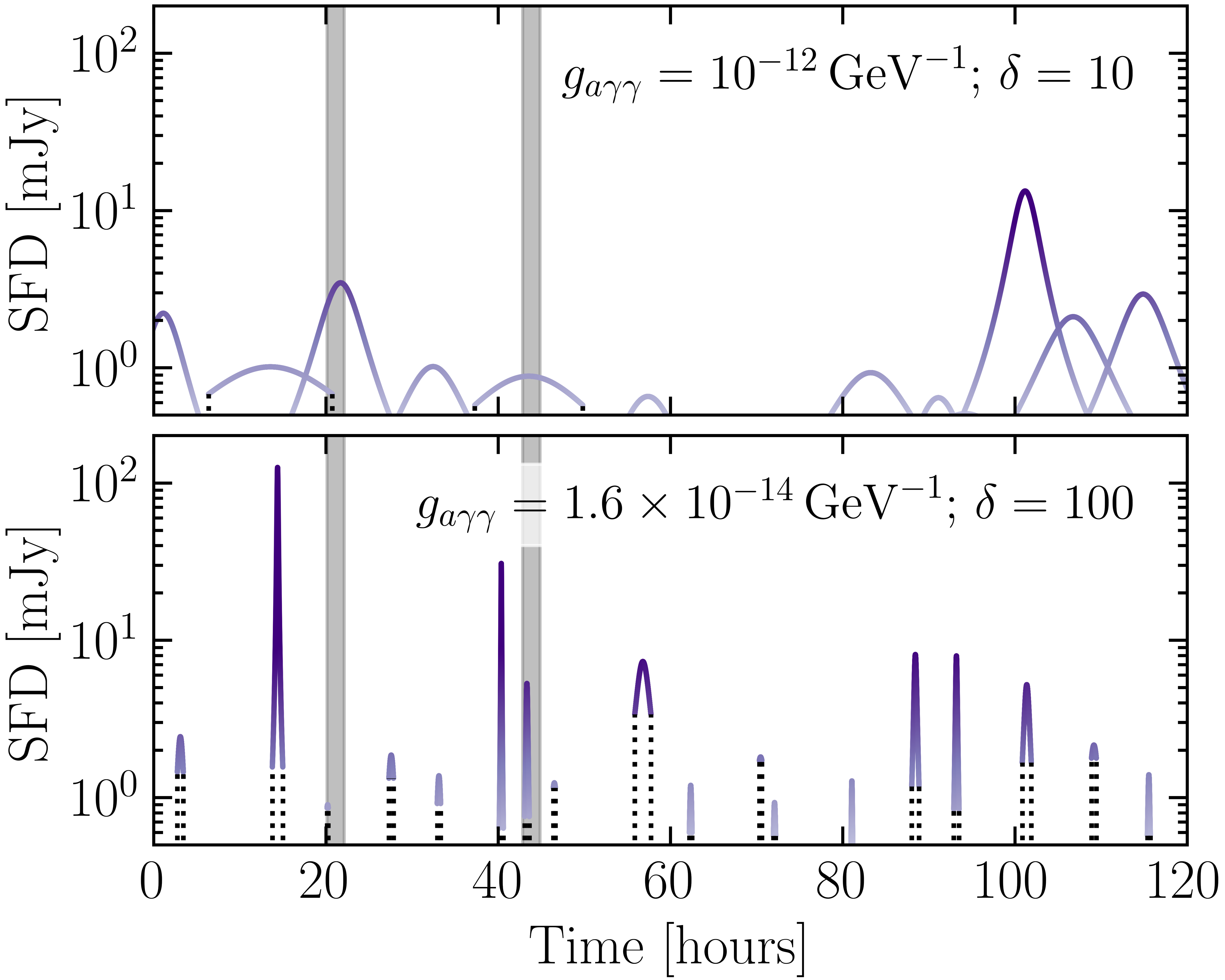
Can we pick up this signal in radio?



2 grant proposals accepted by the Green Bank Telescope currently observing Andromeda

Paper in the making (Walters+ Kavanagh & **LV**)

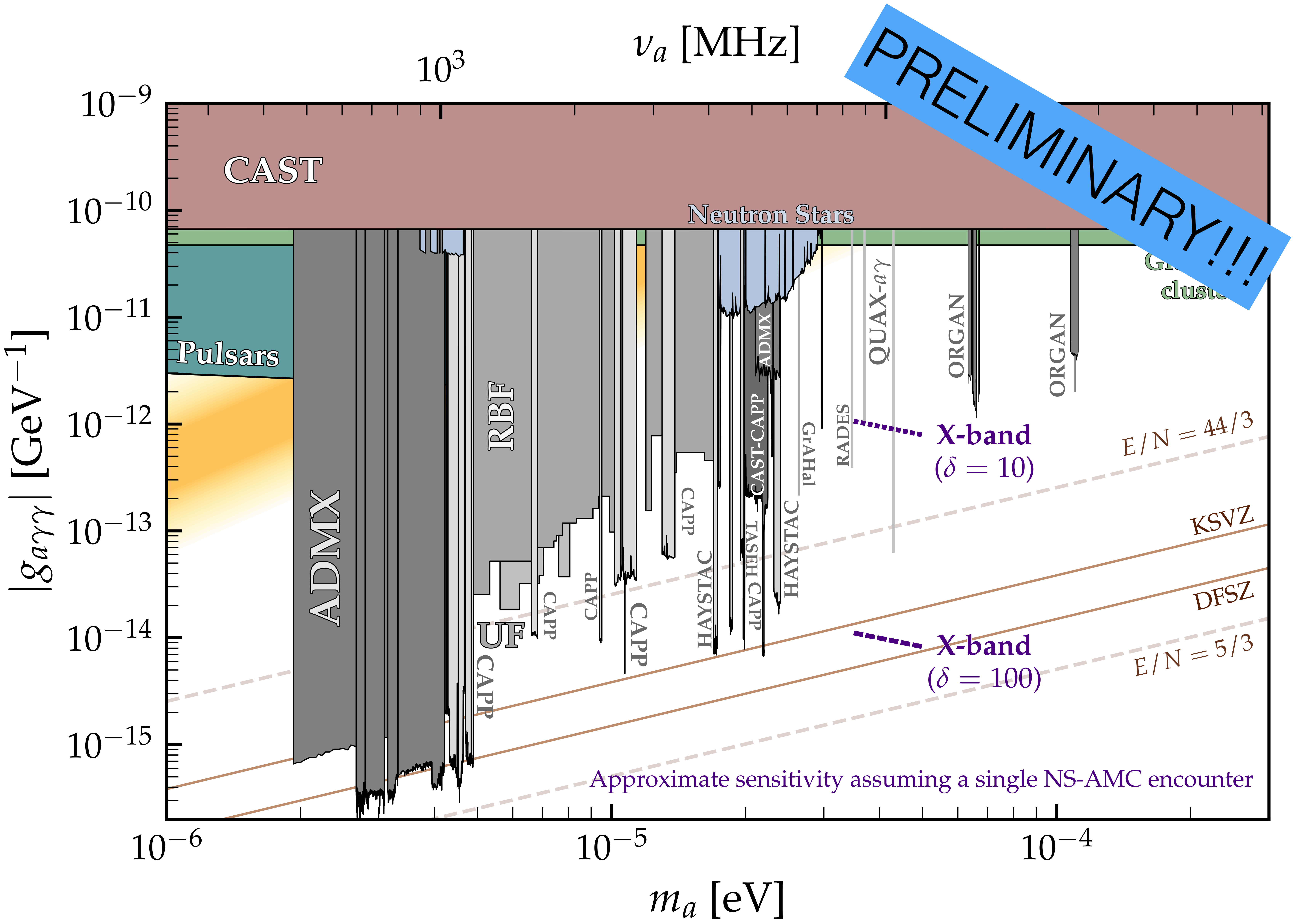
Expected spectral flux densities (SFDs) from NS-AMC encounters



X-band observation (8-12 GHz)

Can we pick up this signal in radio?

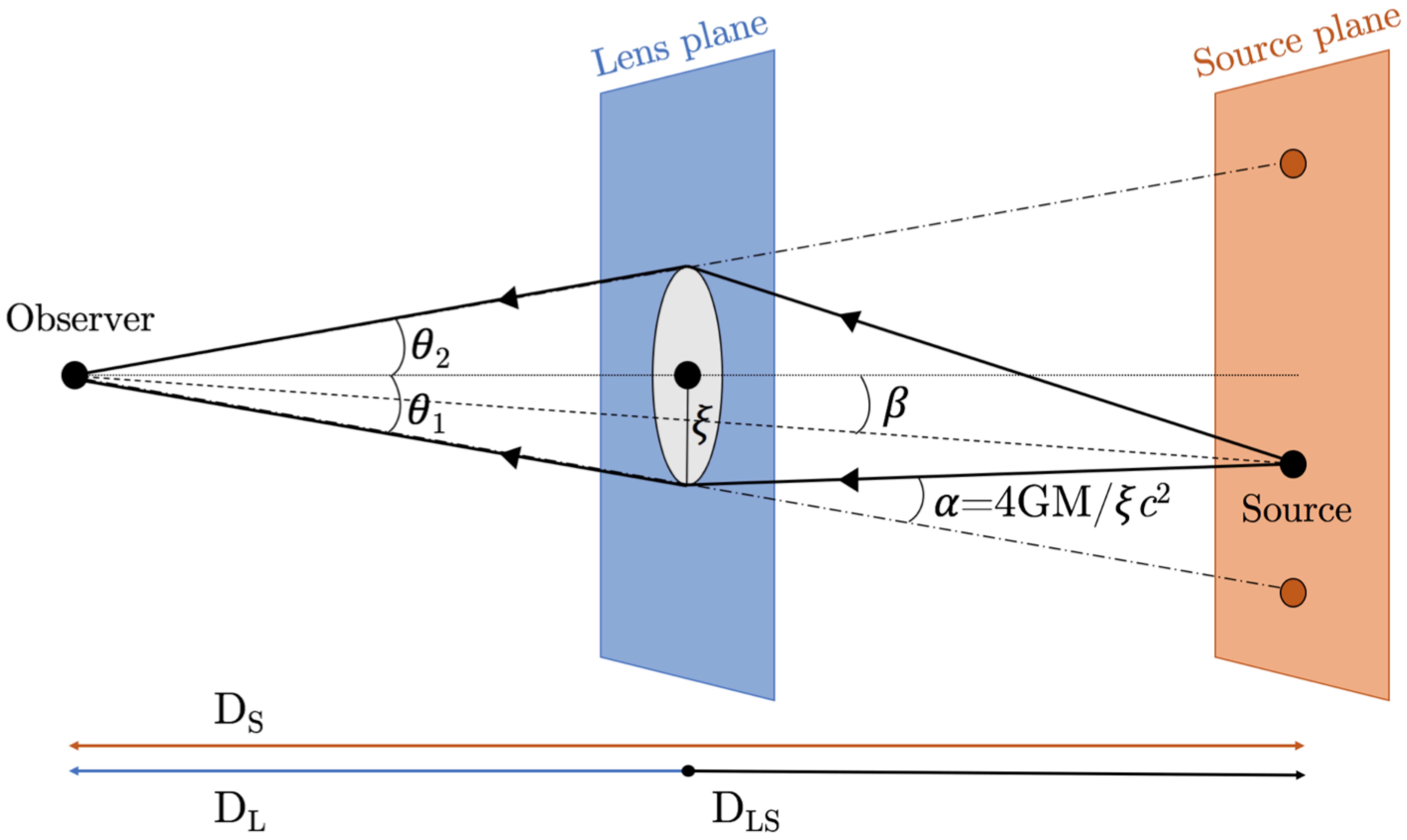
Luca Visinelli

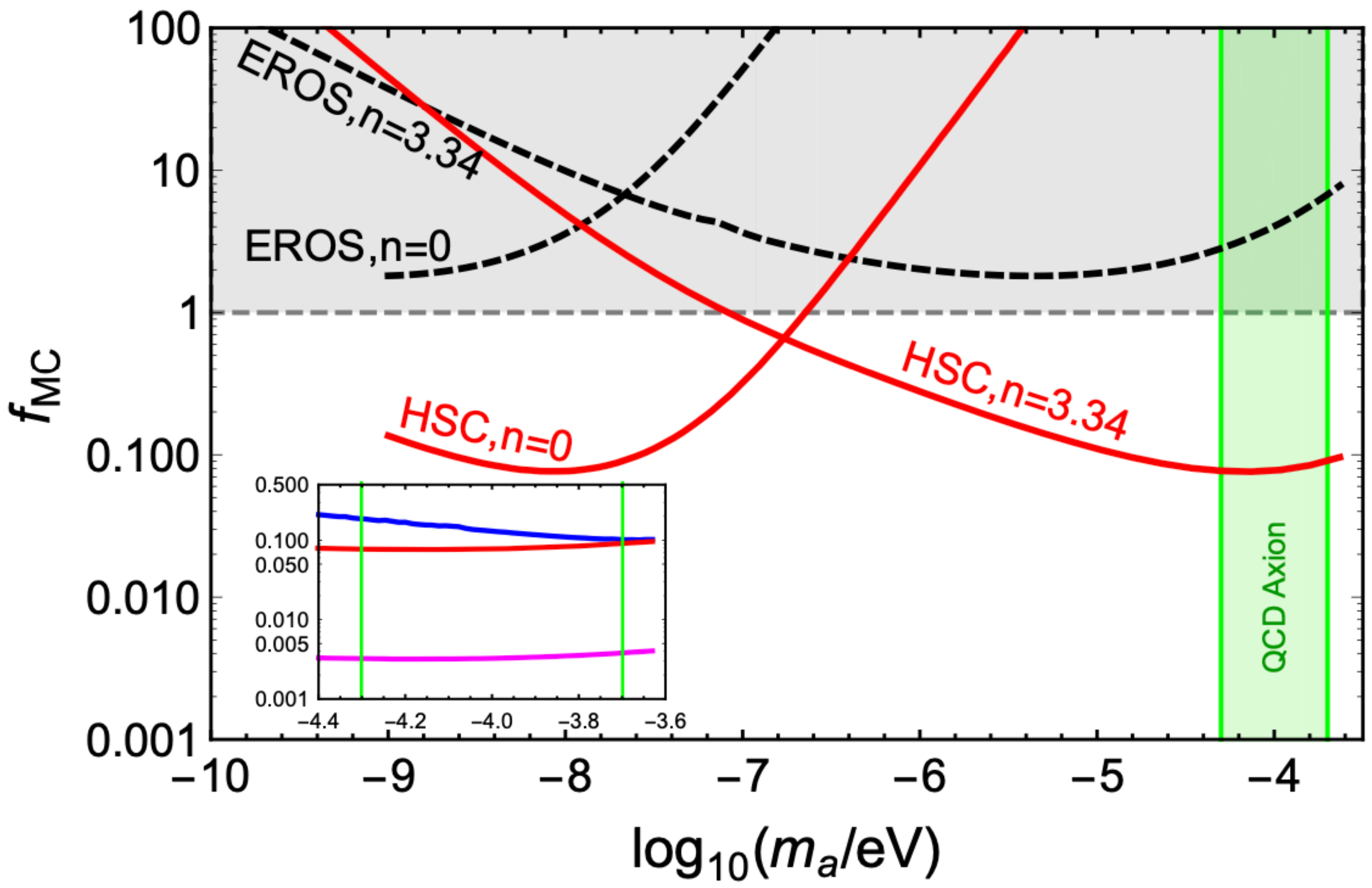


Indirect searches for the axion: lensing

Microlensing by point-like or extended DM substructures

Fairbairn+ 1707.03310; Sugiyama+ 2108.03063; Fujikura+ 2109.04283; Croon + 2002.08962

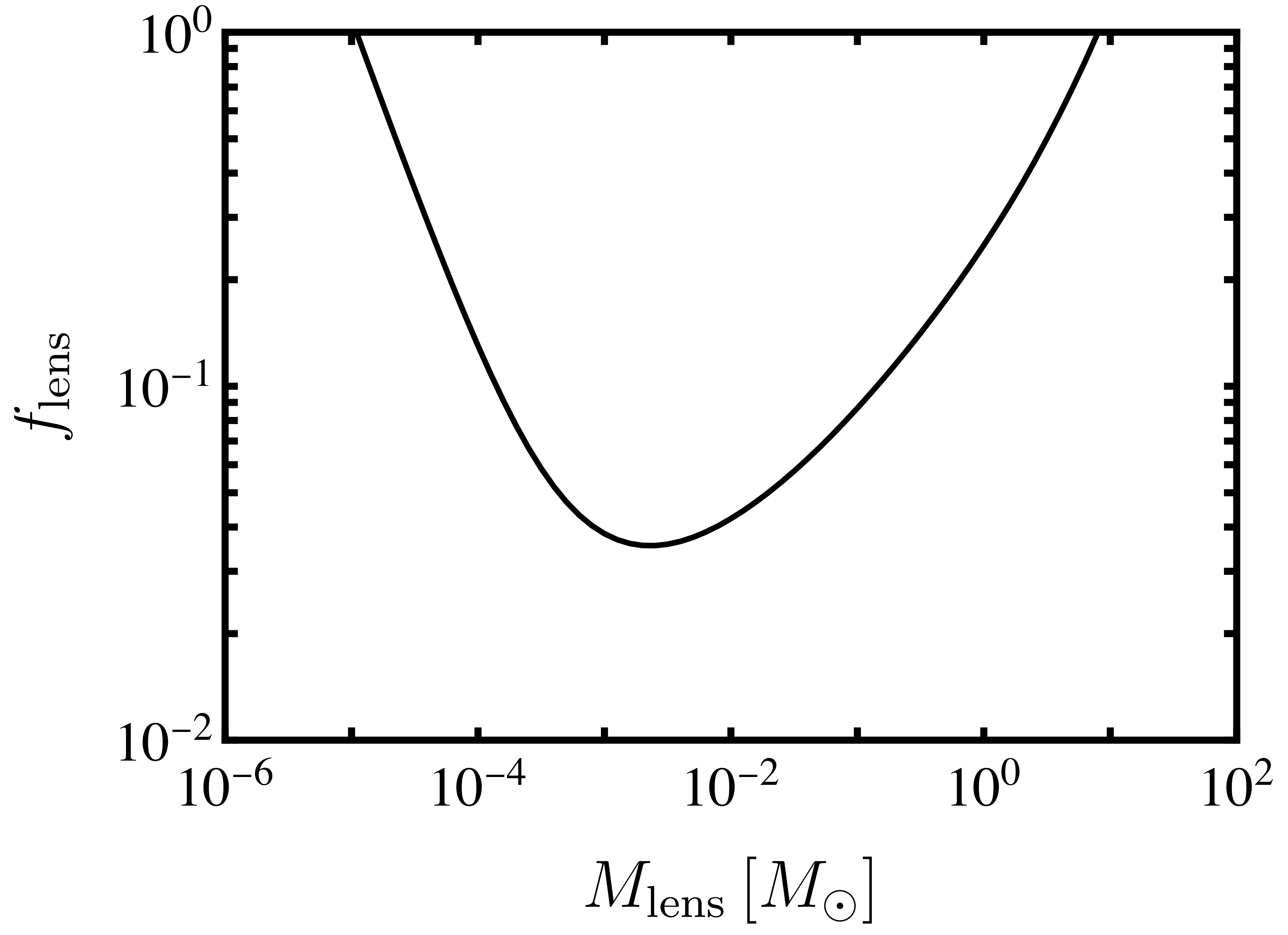


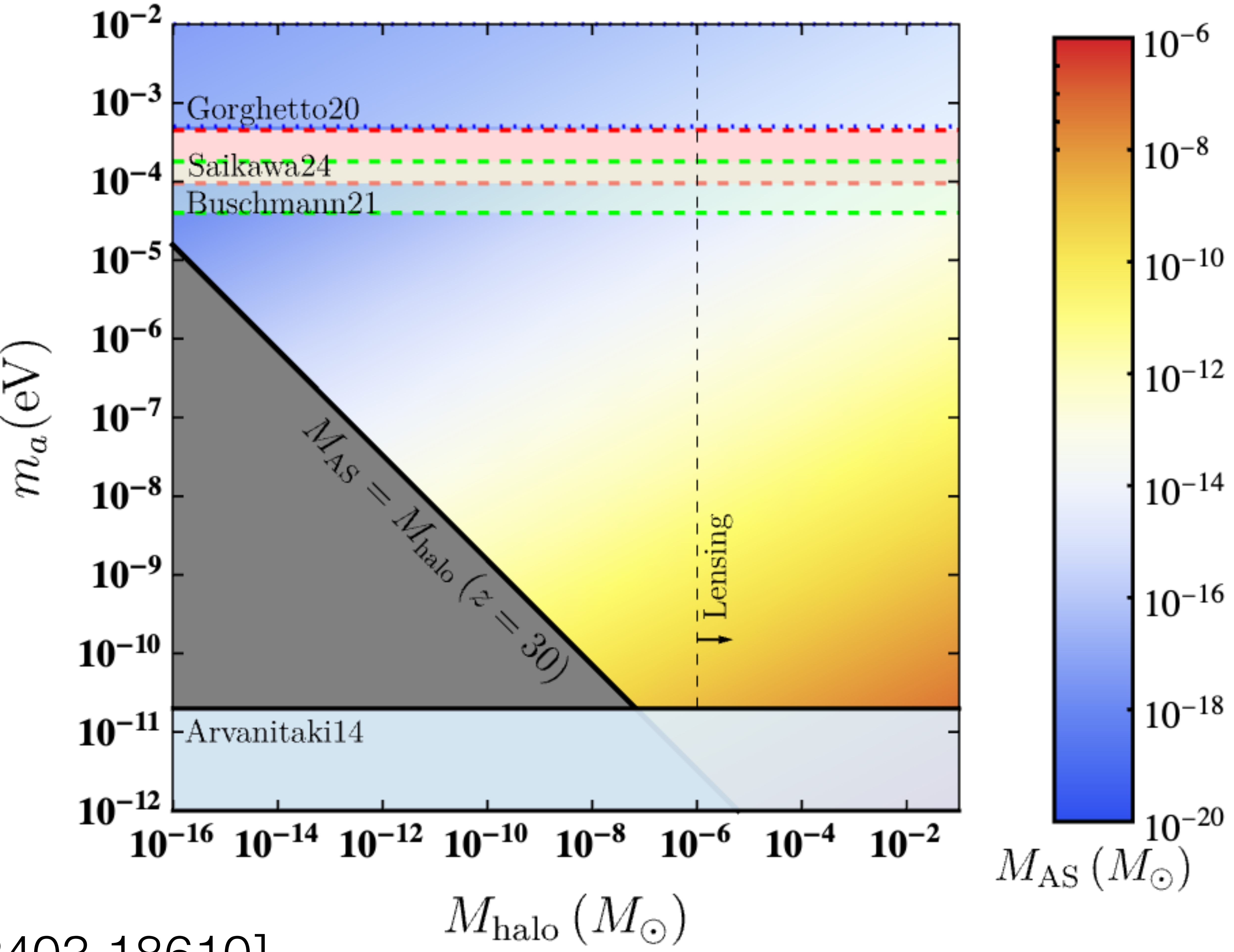


Fairbairn+ 1707.03310

Indirect searches for the axion: lensing

We have recently revisited microlensing constraints from axion stars





[Yin, **LV** 2403.18610]

Direct searches: Haloscope

Recall the effective Lagrangian below QCD:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \boxed{\frac{1}{4}g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu}} + c_e\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e + c_N\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N$$

The axion-photon coupling modifies Maxwell's equations [Sikivie 83; 85]

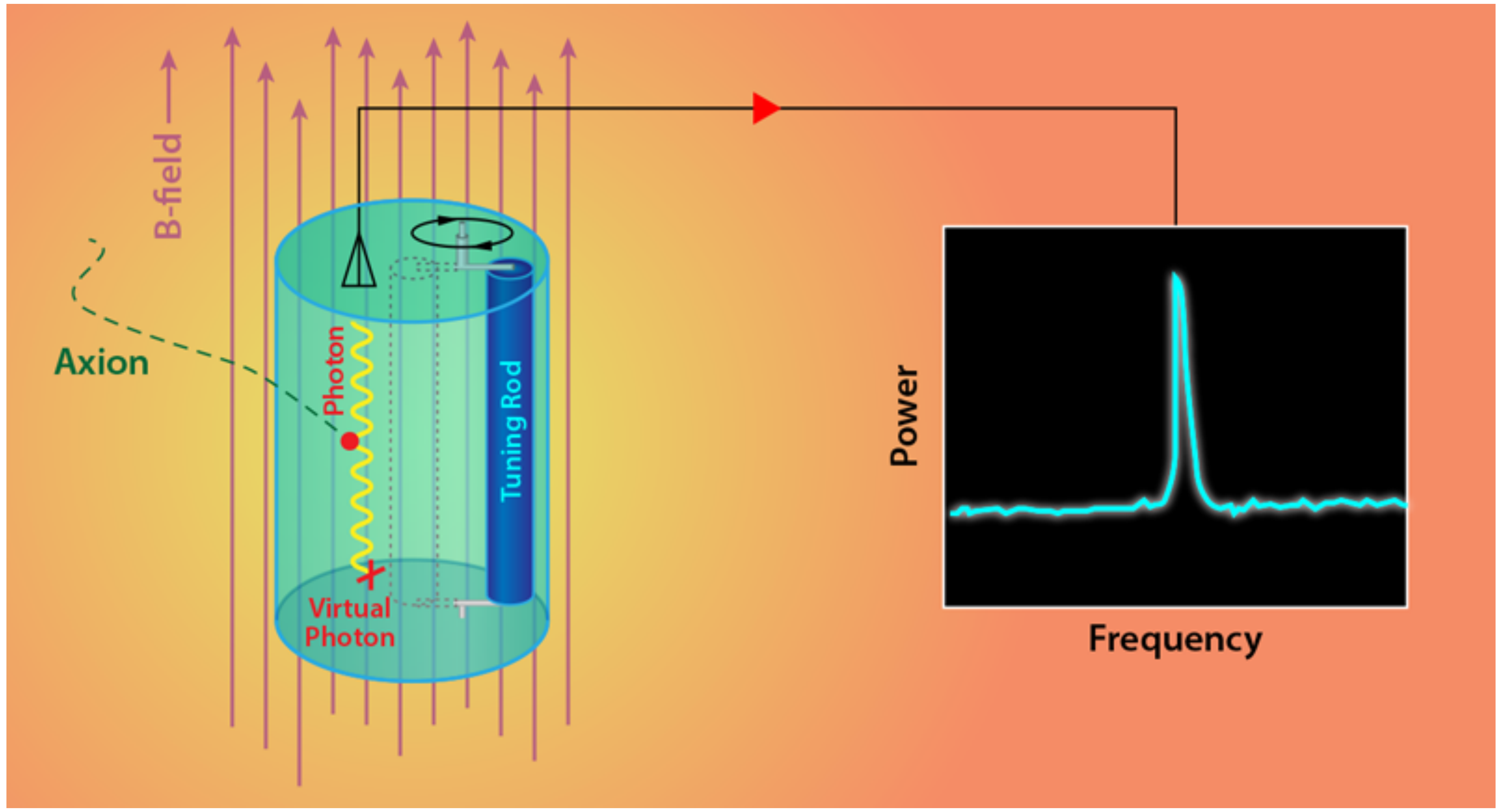
Significant enhancement when

$$2\pi\nu_c = m_a \pm m_a/Q_L$$

$$\boxed{P_{\rm sig} = (g_{a\gamma\gamma}^2 n_a) \times (Q_L B_0^2 V C_{nml})}$$

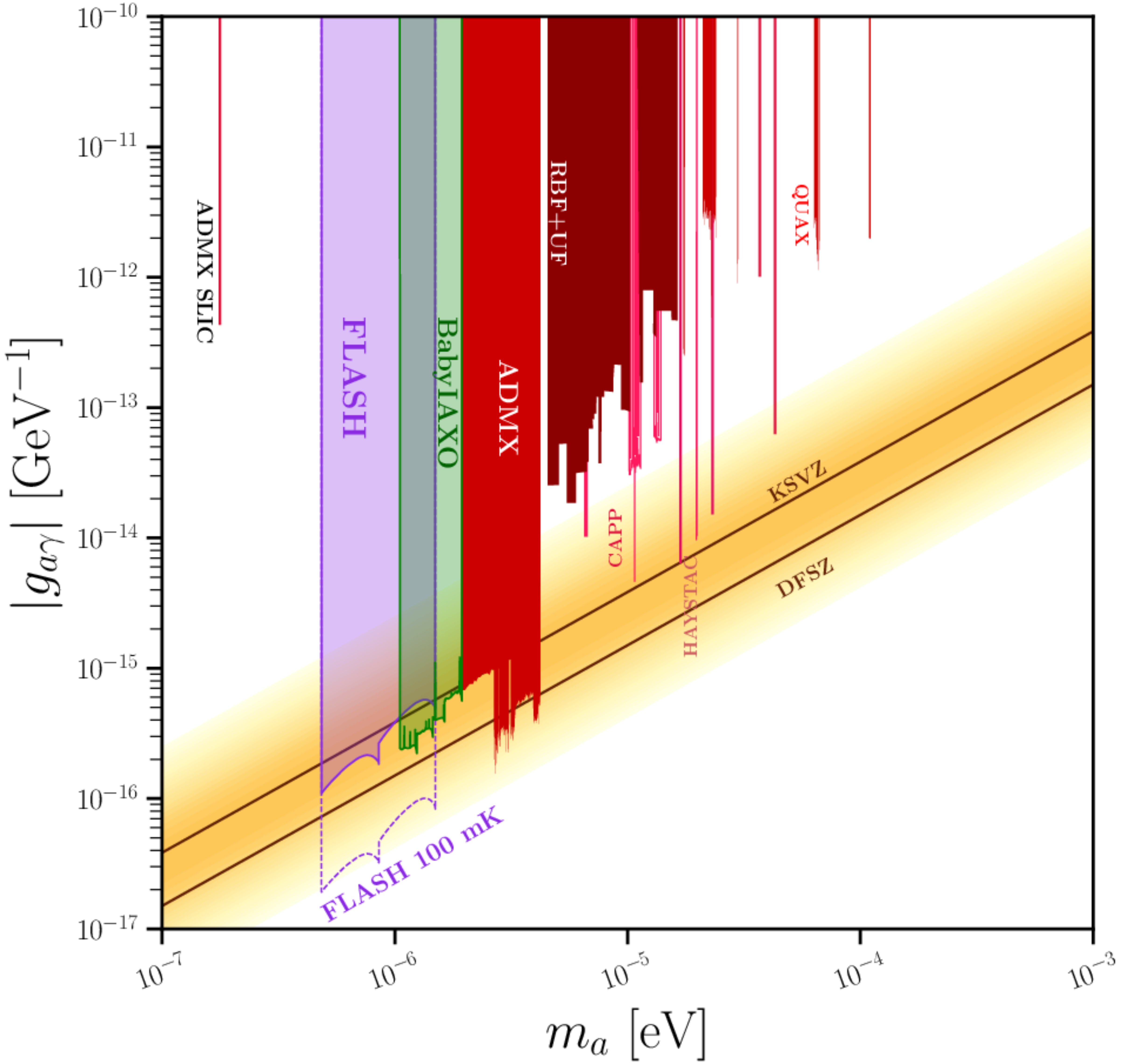
Q_L Quality factor V Cavity volume

B_0 Magnetic field C_{nml} Geometric factor



Courtesy of ADMX collaboration

Cavity search in Frascati (Rome)



FLASH cavity search with Claudio Gatti's group (INFN-LNF) [Alesini+ 2309.00351] (**+LV**)

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

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Full Length Article

The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories

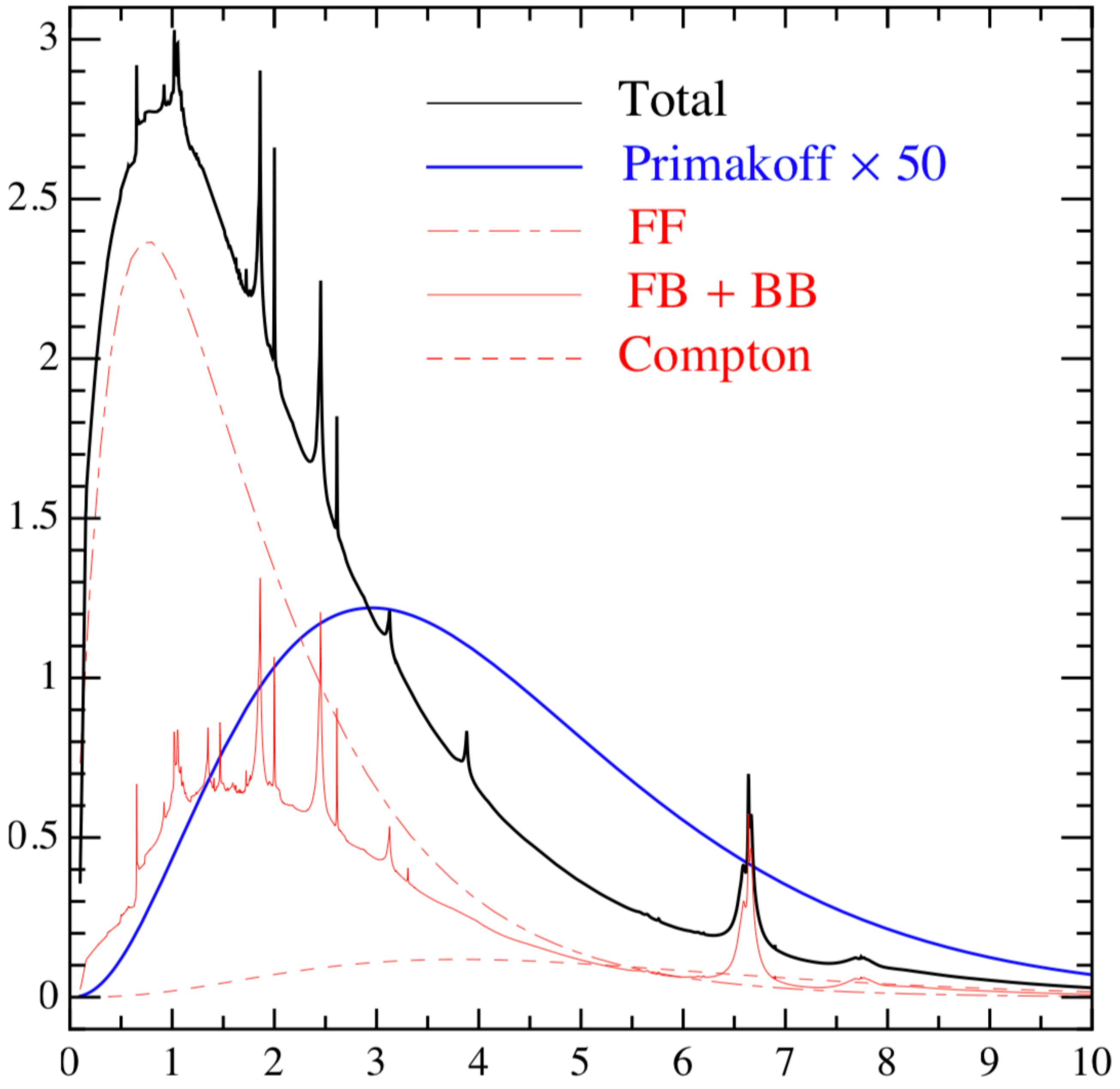
David Alesini [a], Danilo Babusci [a], Paolo Beltrame [b], Fabio Bossi [a], Paolo Ciambrone [a], Alessandro D'Elia [a,*], Daniele Di Gioacchino [a], Giampiero Di Pirro [a], Babette Döbrich [c], Paolo Falferi [d], Claudio Gatti [a], Maurizio Giannotti [e,f], Paola Gianotti [a], Gianluca Lamanna [g], Carlo Ligi [a], Giovanni Maccarrone [a], Giovanni Mazzitelli [a], Alessandro Mirizzi [h,i], Michael Mueck [j], Enrico Nardi [a,k], Federico Nguyen [l], Alessio Rettaroli [a], Javad Rezvani [m,a], Francesco Enrico Teofilo [n], Simone Tocci [a], Sandro Tomassini [a], Luca Visinelli [o,p], Michael Zantedeschi [o,p]

Partial overlap with BabyIAXO reaches when used as a haloscope [2306.17243]

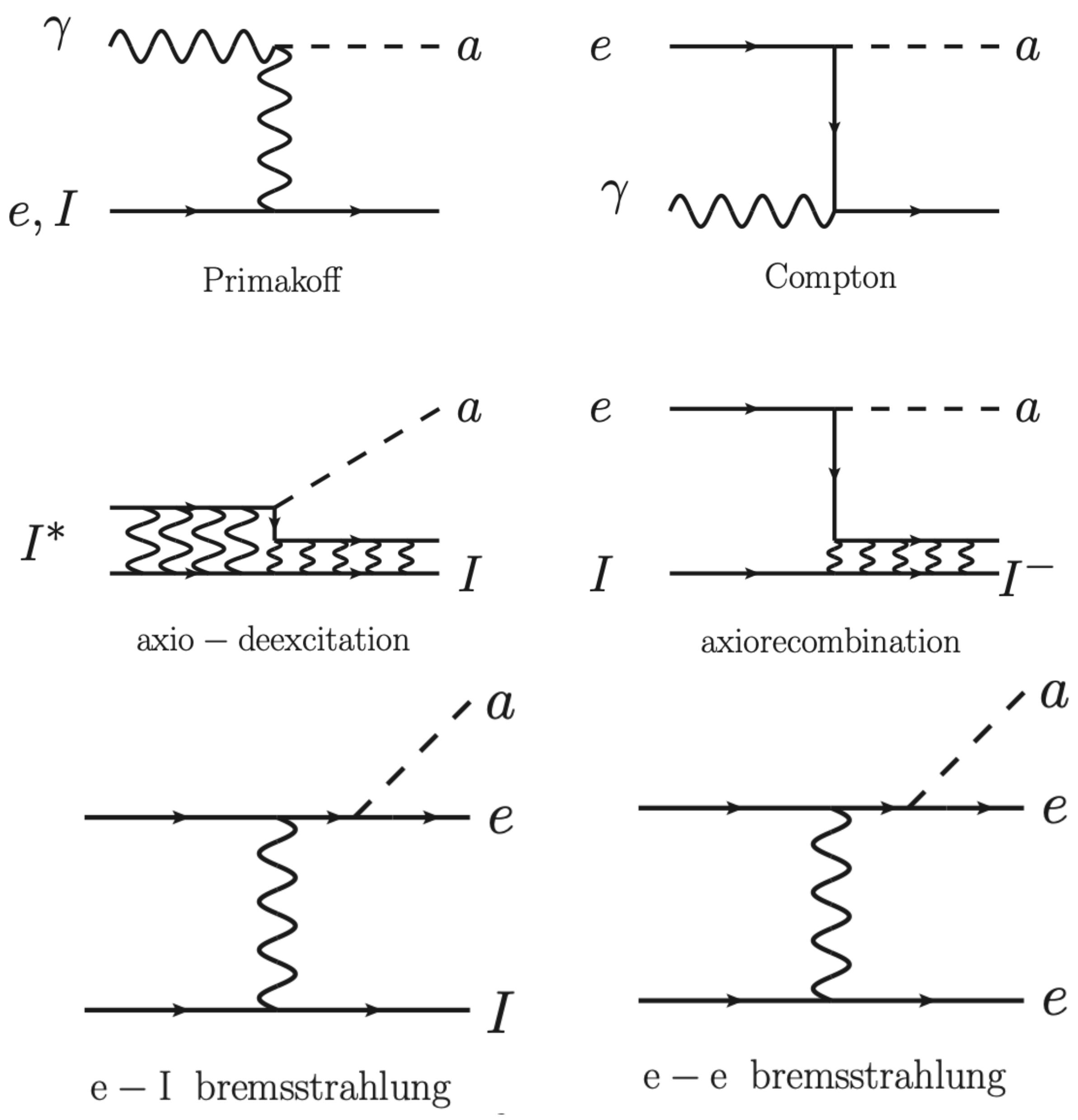
See also the proposal by the RADES collaboration [Díaz-Morcillo+ 2021]

Searches with helioscopes

Axion production in the Sun $$\mathcal{L}_{\rm int} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{ae}\frac{\partial_\mu a}{2m_e}\bar{e}\gamma^\mu\gamma_5 e\,,$$



[Redondo 2013]



$$\frac{d\Phi_{\rm a}^{\rm Prim}}{dE_{\rm a}} = \left(\frac{g_{{\rm a}\gamma}}{\rm GeV^{-1}}\right)^2 \left(\frac{E_{\rm a}}{\rm keV}\right)^{2.481} e^{-E_{\rm a}/(1.205\ {\rm keV})} \times 6\times 10^{30}\ \ {\rm cm^{-2}s^{-1}keV^{-1}},$$

$$\Phi_{\rm a}^{\rm ABC} \propto g_{\rm ae}^2$$

These are relativistic axions, not the DM!

$$\omega_a \sim T_{\rm core} \approx {\rm keV}$$

Searched for in CAST and in proposed (Baby)-IAXO

For exhaustive lists of experiments see [Irastorza & Redondo 2018]

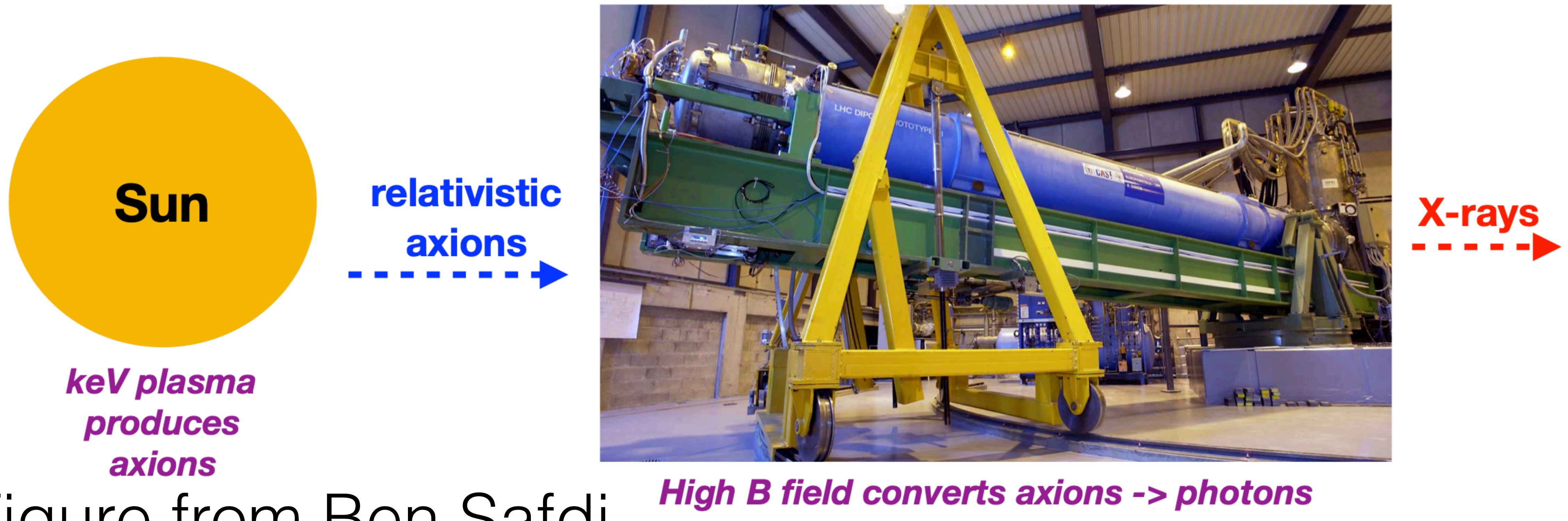
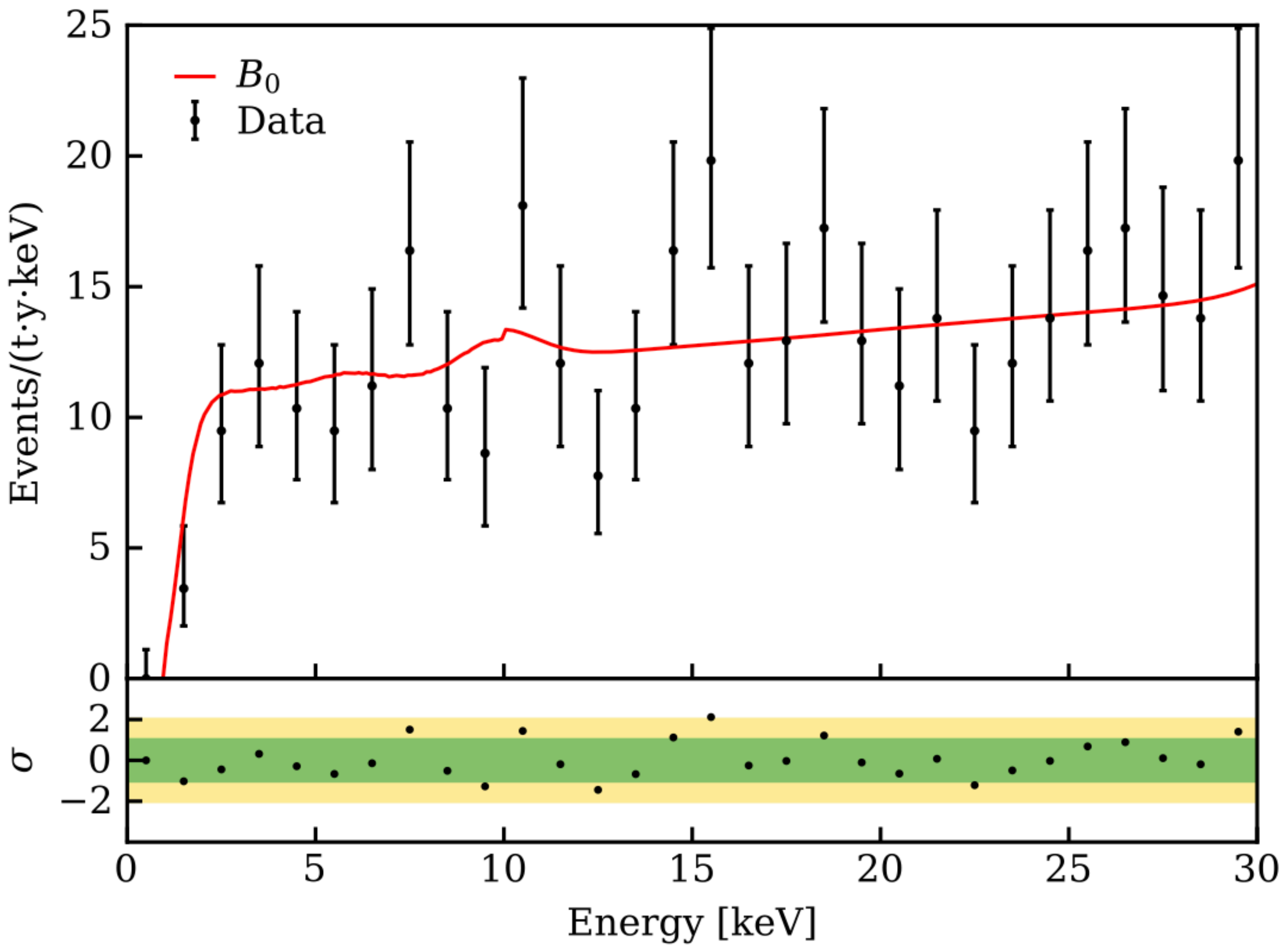


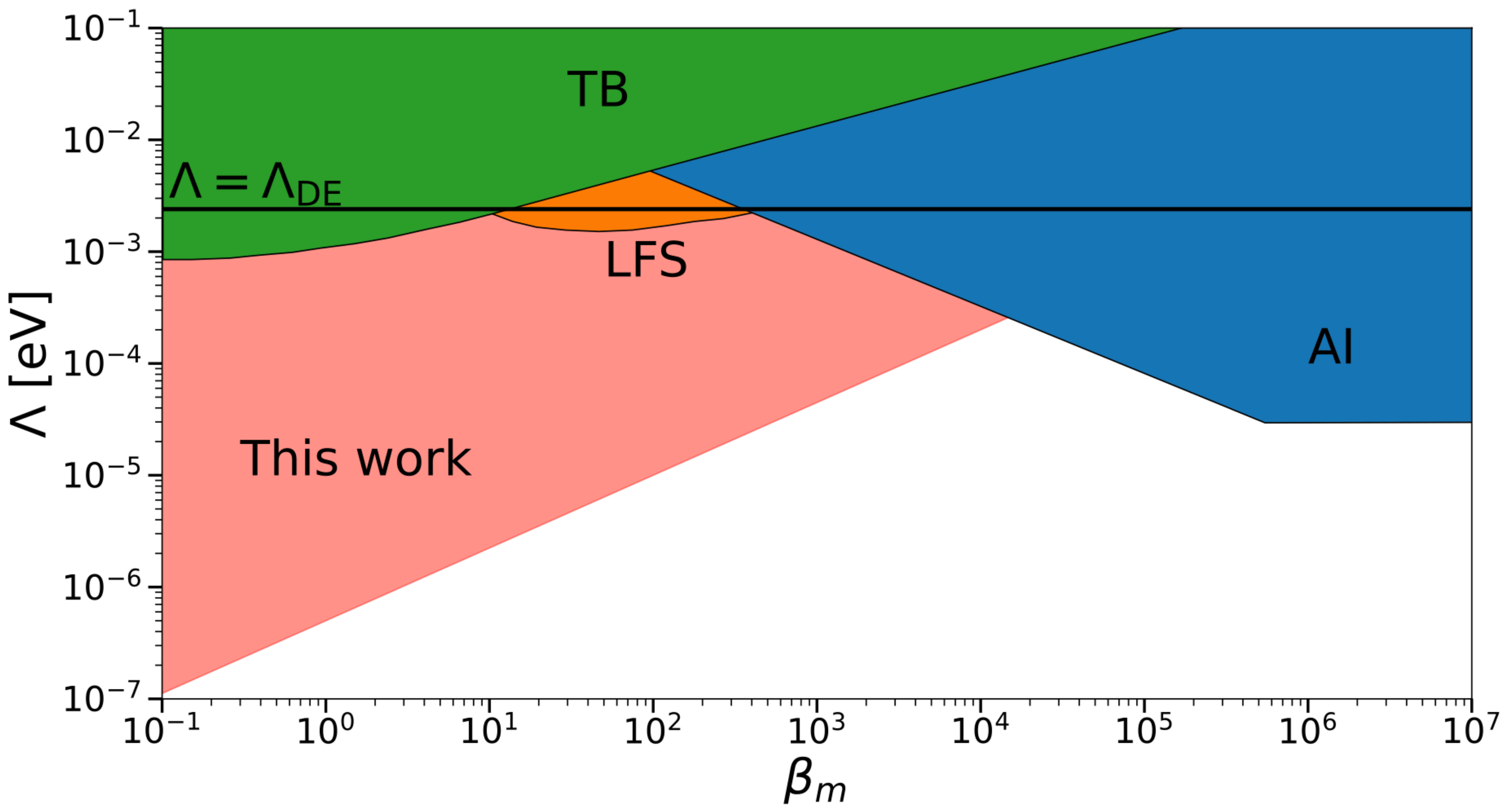
Figure from Ben Safdi

Solar axions scattering with electrons

Luca Visinelli



New work in progress:
Scalar field production in the Sun



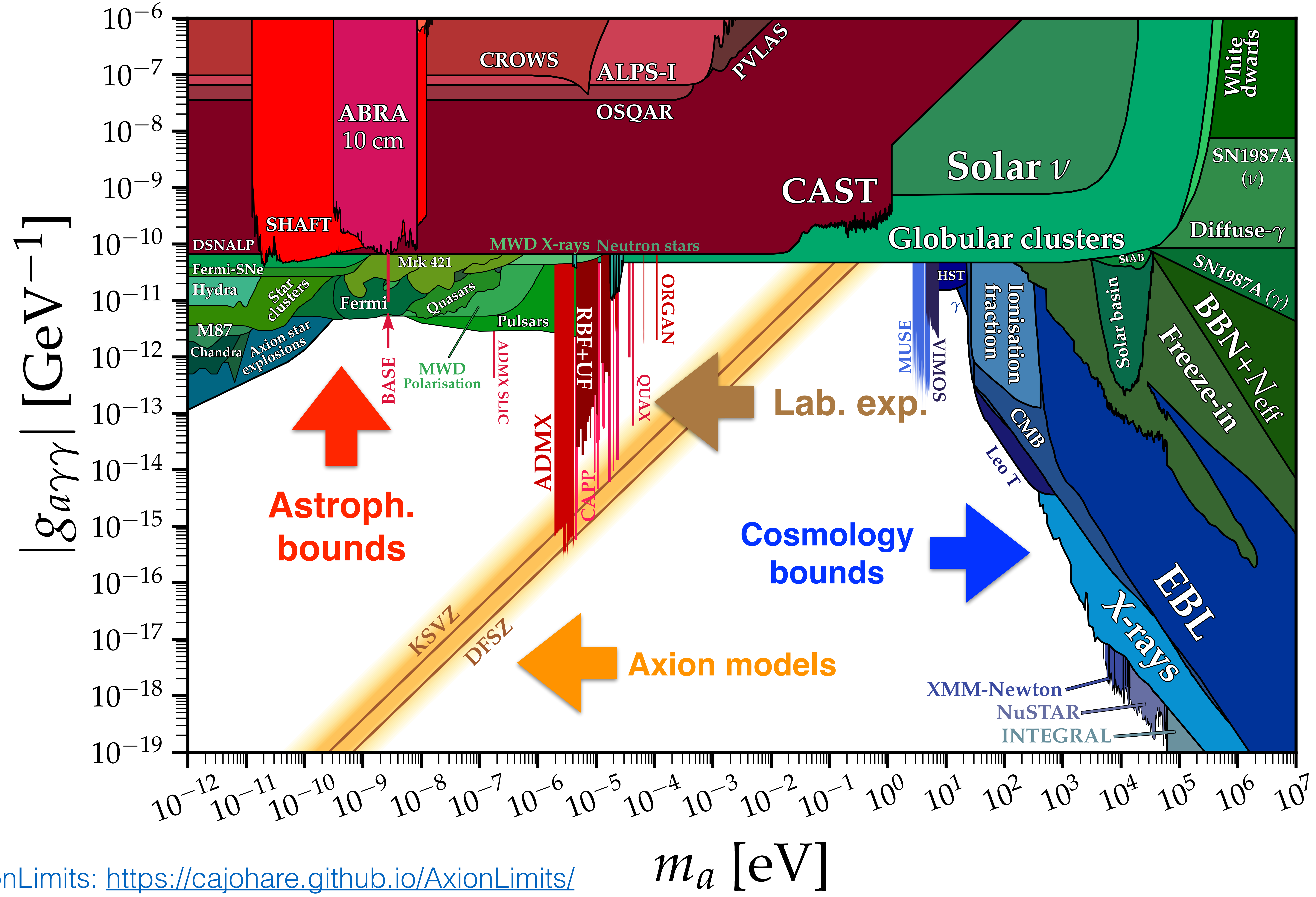
Paper coming out tomorrow!
With Sunny Vagnozzi

XENONnT bound on ($g_{a\gamma} - g_{ae}$) [2207.11330]

Previous results “XENON1T excess” [2006.09721]

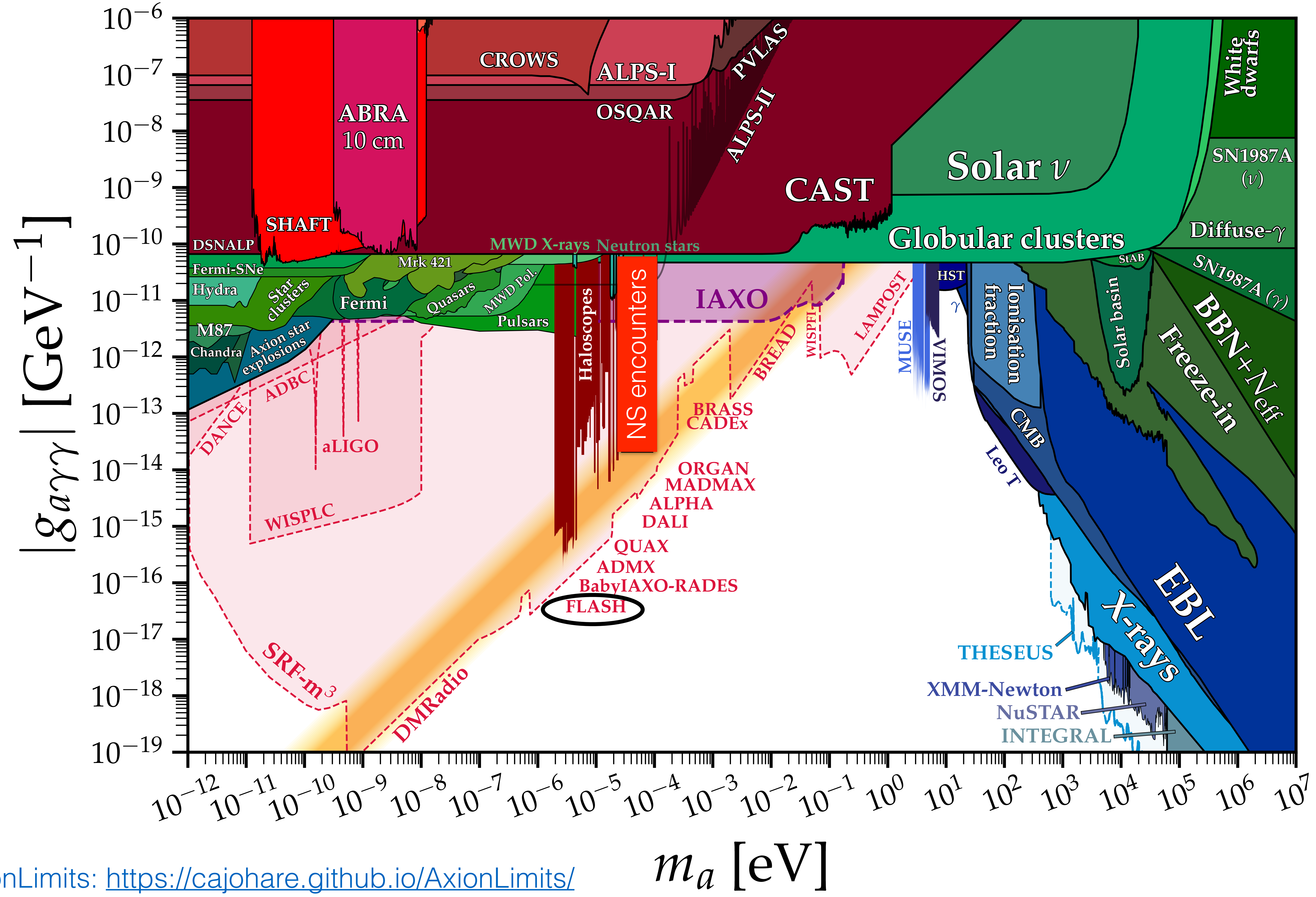
See also Vagnozzi, **LV**+ [2103.15834]

Summary of axion-photon coupling bounds



Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

Summary of axion-photon coupling bounds



Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

Summary

AMC-NS radio transients

- Lasting days to years
- Within reach of current & future searches
- Expect O(1) bright event on the sky at all times
- Concentrated towards the Galactic Centre

Missing ingredients

- Concurrent structure formation & disruption
- Realistic input to Monte Carlo simulations (e.g. density profiles, $P(M, \delta)$)
- Understanding axion star formation at the low-mass end

Please re-cast the results and re-use the code!

[2011.05377](), [2011.05378]()
[github.com/bradkav/axion-miniclusters]()

Thank you!