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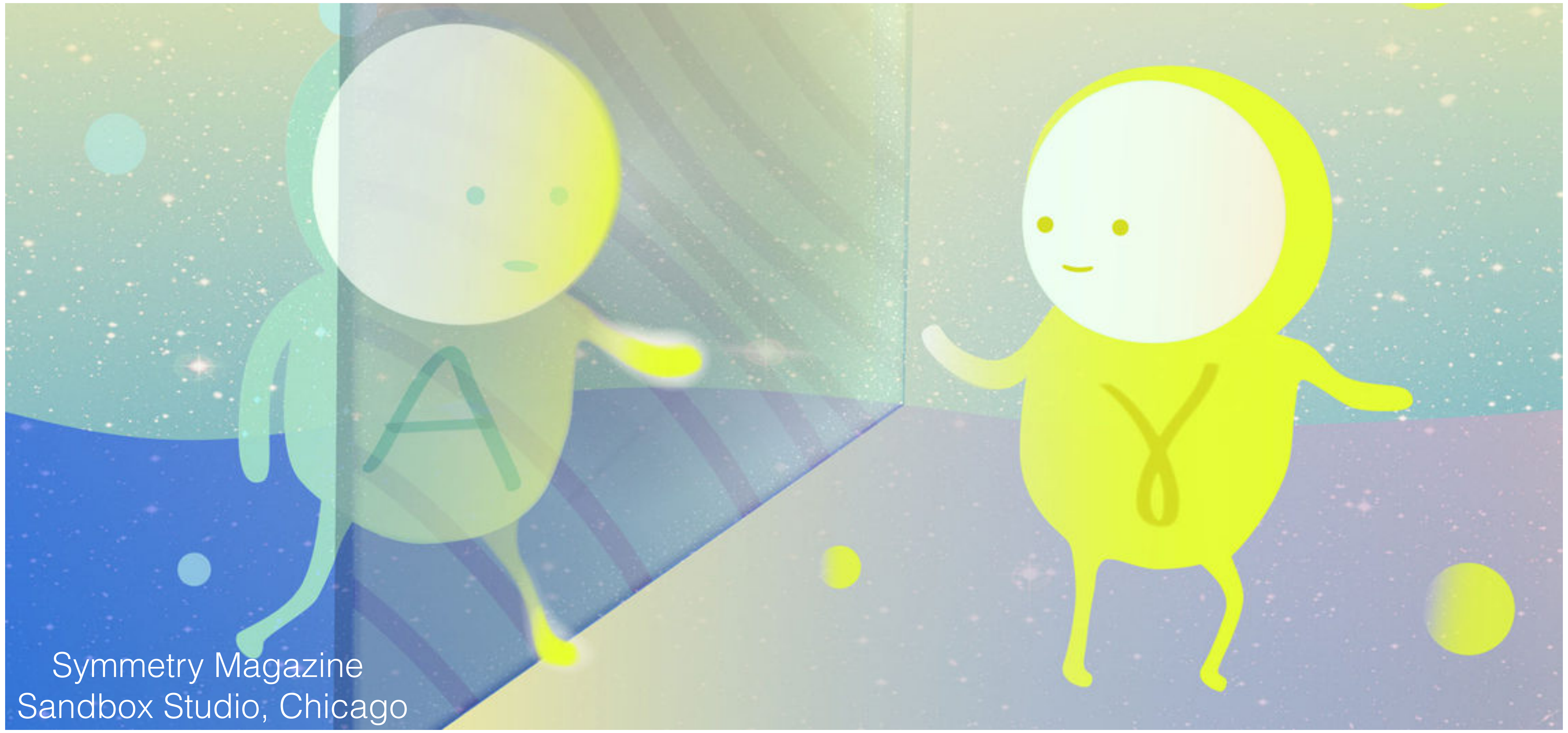
The QCD axion:

theory, phenomenology, and searches



Symmetry Magazine
Sandbox Studio, Chicago

Luca Visinelli (He/Him)
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The QCD Axion: foundations

Luca Visinelli

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)

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

α_s: Strong force coupling

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

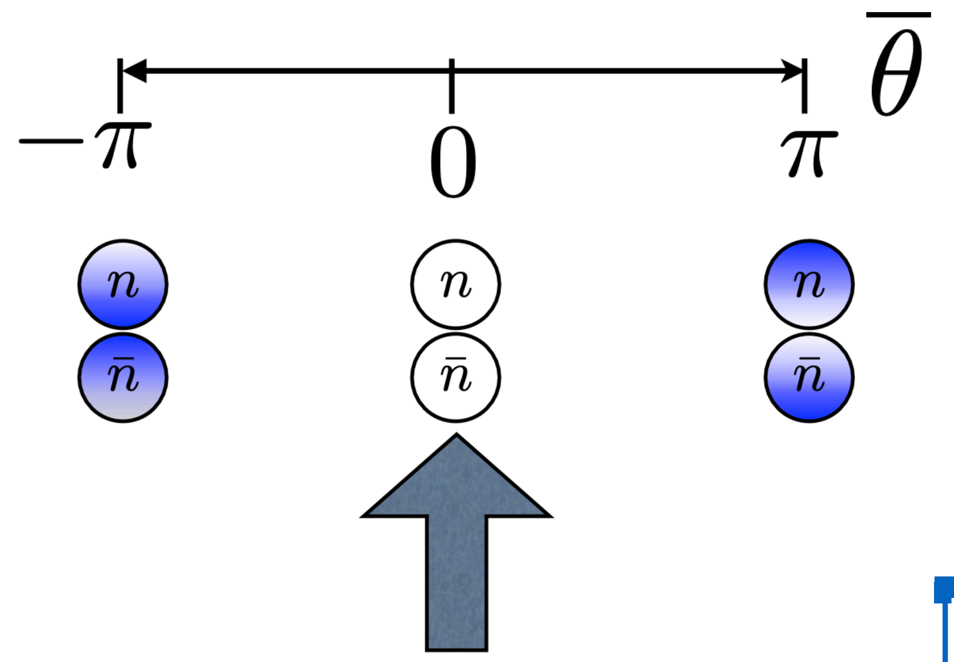
The parameter θ itself is not physical as $\bar{\theta} = \theta - \arg\det(M)$

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 $\boxed{|\bar{\theta}| \lesssim 10^{-10}}$



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 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]

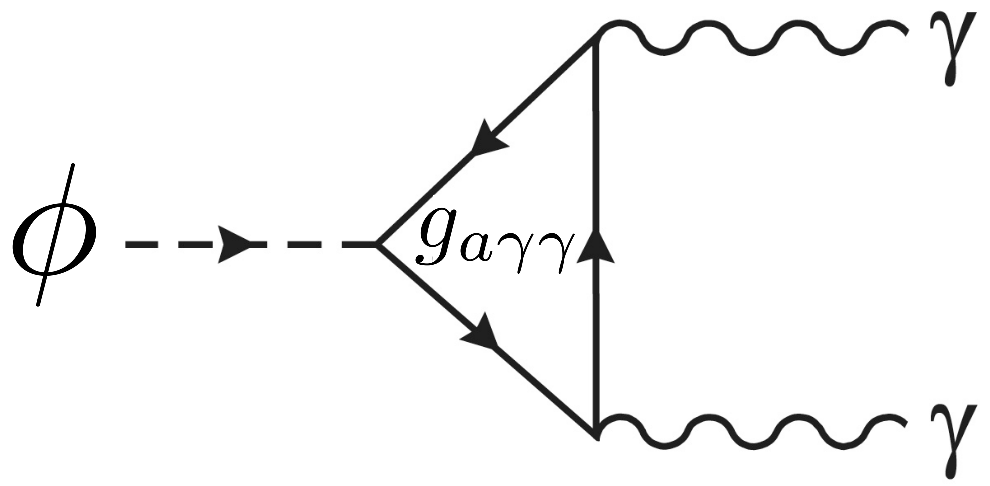
  Allows to decouple the PQ breaking scale from the electroweak scale.

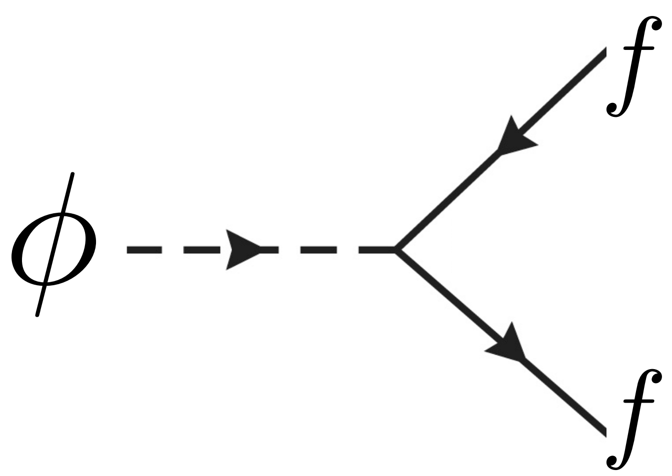
- **REVIEW** on axion models [di Luzio+ 2020 (**+LV**)]

The QCD Axion: foundations

Effective Lagrangian below QCD, e.g. [Georgi+ 1986]:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \underbrace{V(\phi)}_{\text{Self-interacting potential}} + \frac{1}{4}\,\underbrace{g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu}}_{\text{Axion-photon coupling}} + \underbrace{c_e\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e}_{\text{Axion-electron coupling}} + \underbrace{c_N\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N}_{\text{Axion-nucleon coupling}}$$





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

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:

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

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

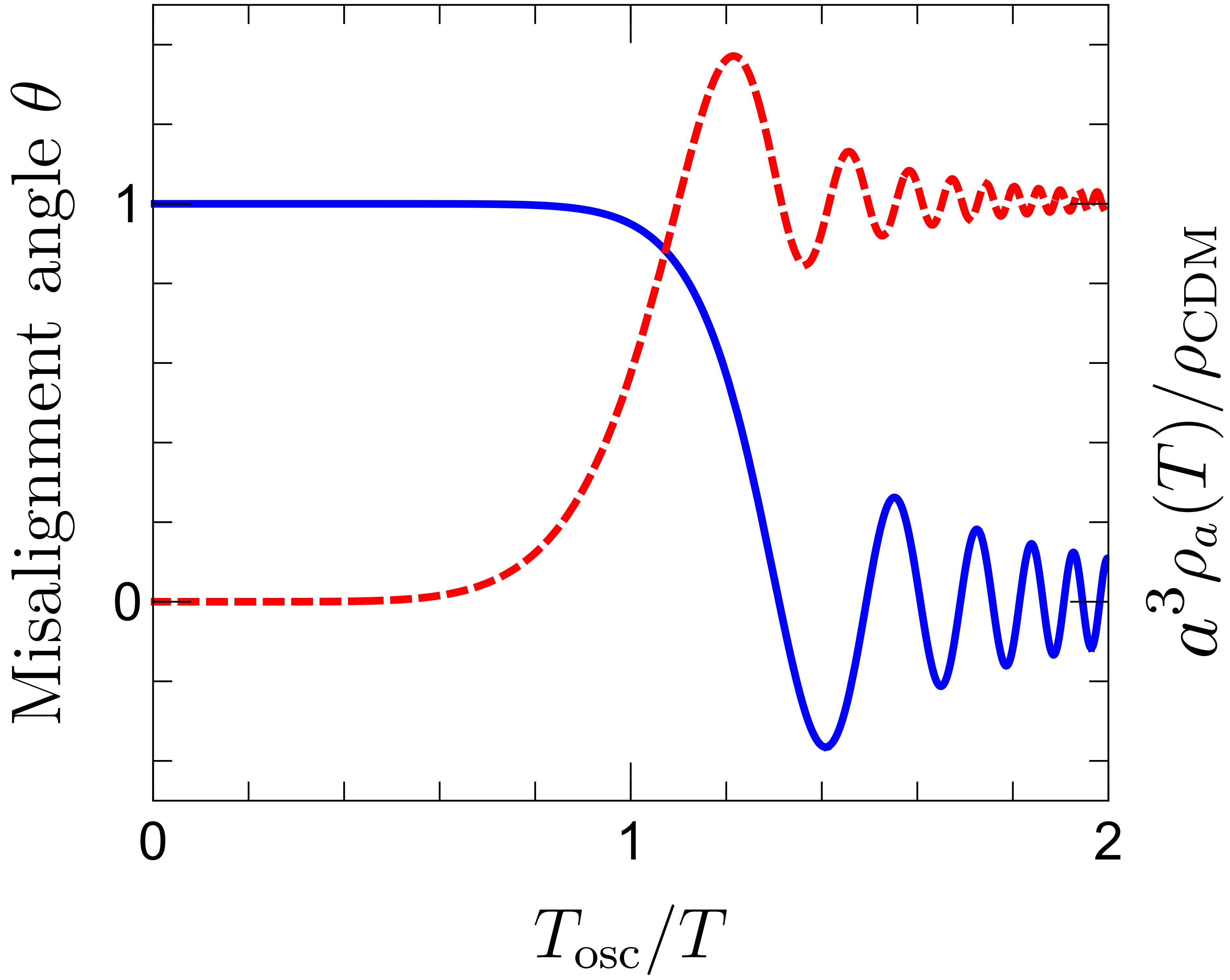
Naïve computation on super-horizon scales $\nabla^2\phi \approx 0$

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

Luca Visinelli

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

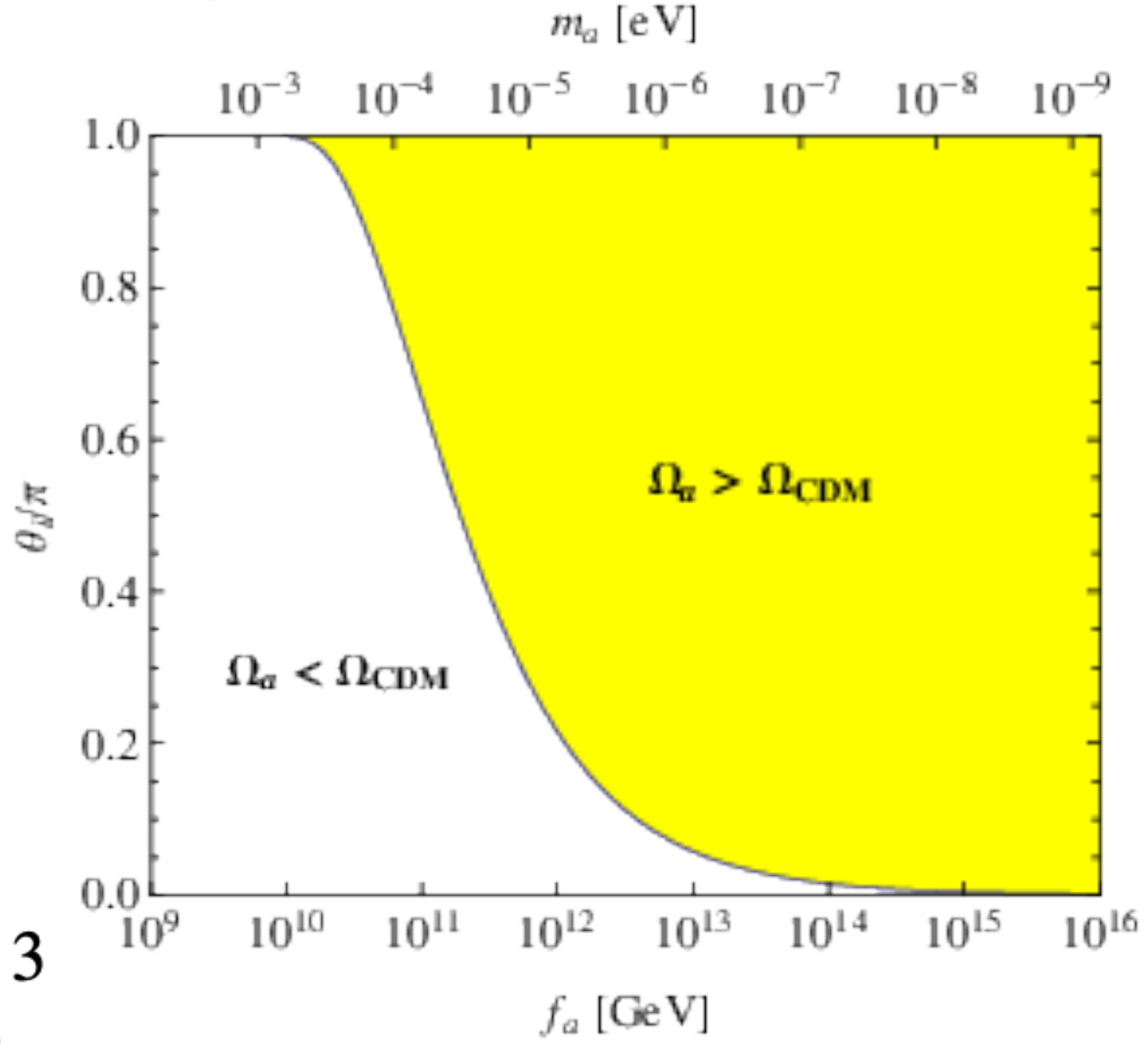
Non-linear terms might matter [**LV** & Gondolo, PRD 2009, 2010]

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 1: The PQ symmetry broke during inflation

Quantum fluctuations during inflation $$\delta\phi = \frac{H_I}{2\pi}$$

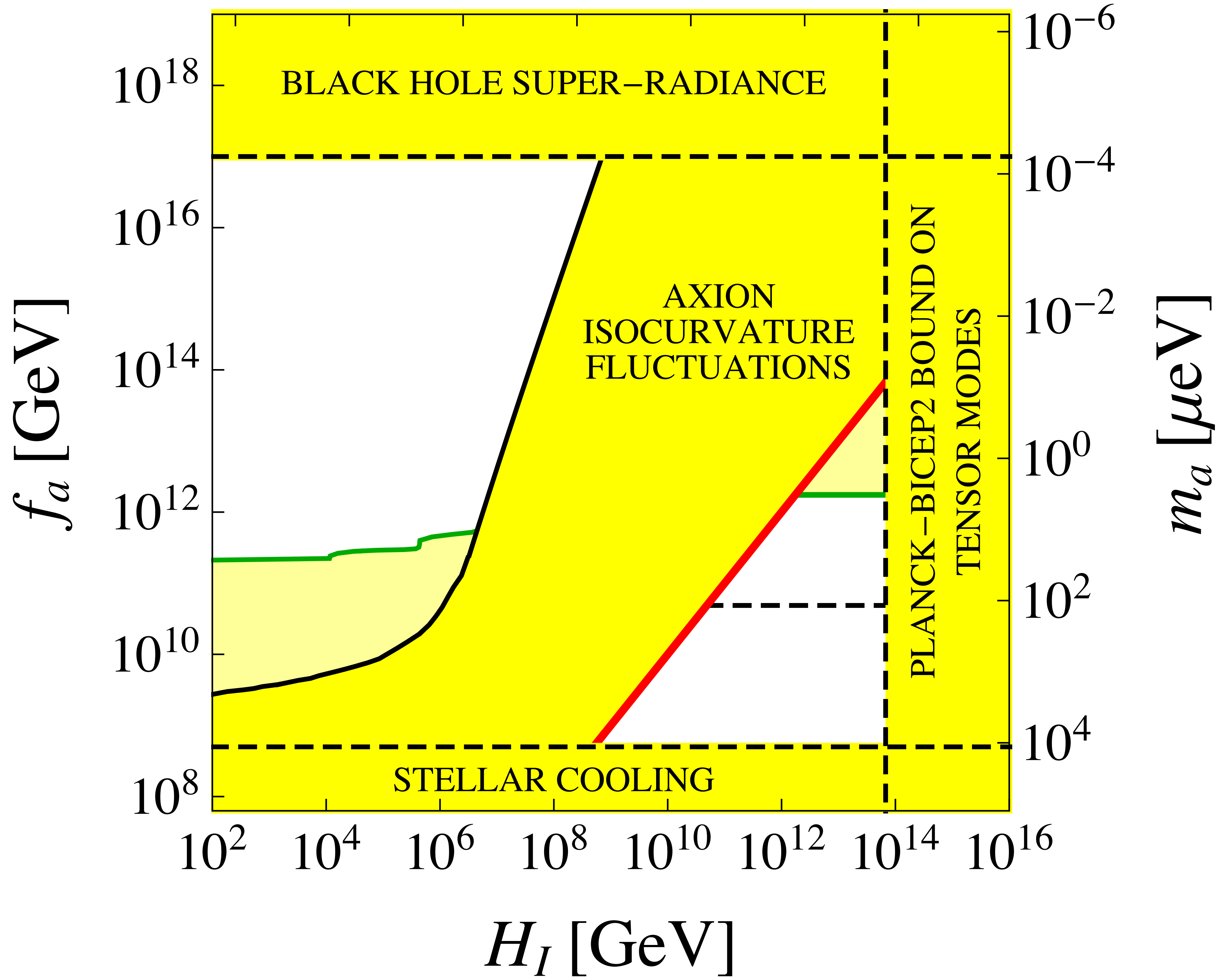
Leads to axion isocurvature perturbations $$\delta\rho_a^{\rm iso} \sim m_a^2 f_a \theta_i \frac{H_I}{2\pi}$$

CMB isocurvature bounds yield:

$$H_I \lesssim 2 \times 10^9\,{\rm GeV}\left(\frac{f_a}{10^{16}\,{\rm GeV}}\right)^{0.45}$$

Detection of a larger scale of inflation would disprove this scenario

e.g. [Gondolo & **LV**, PRL 2014]



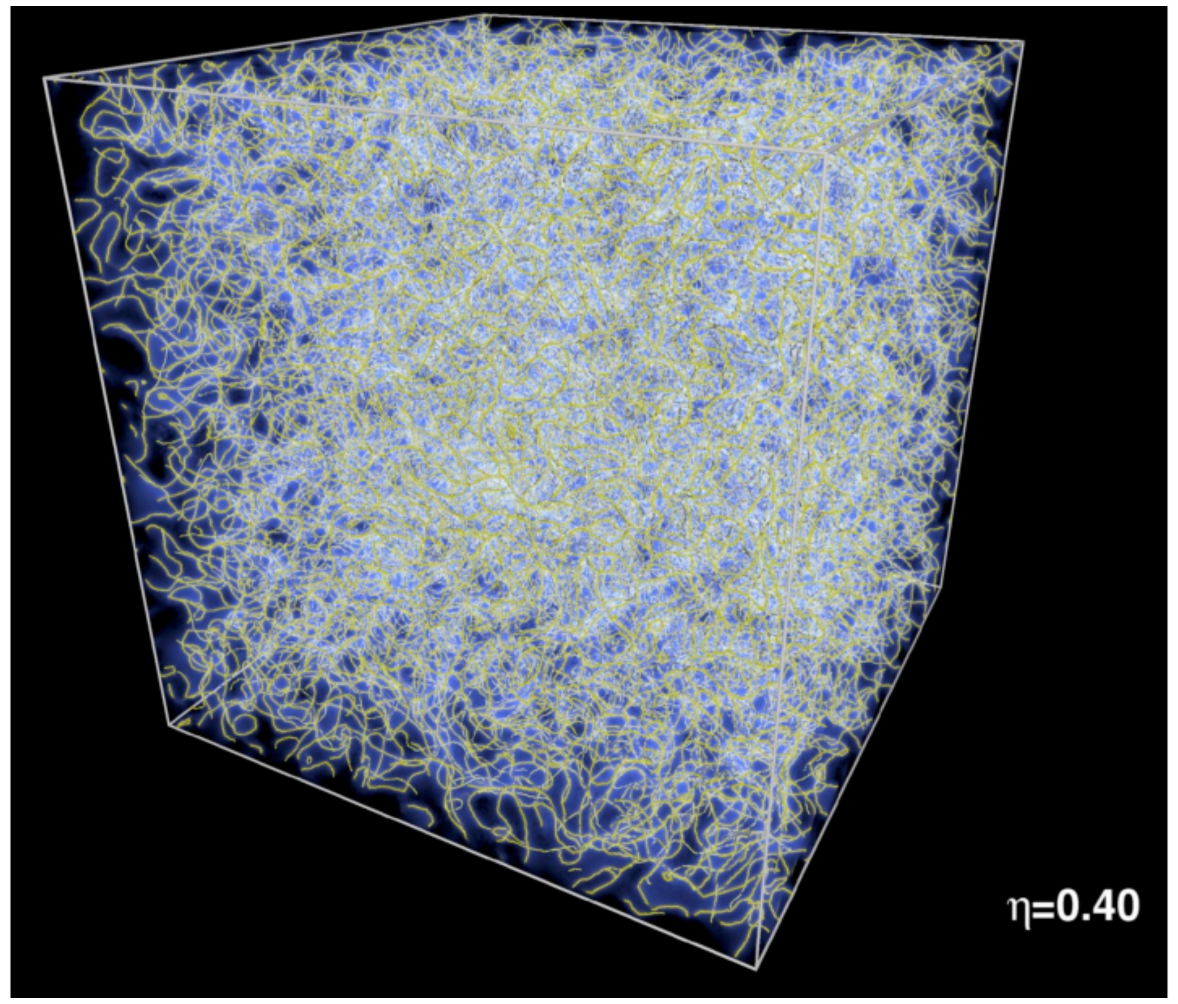
Scenario 2: The PQ symmetry broke after inflation

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

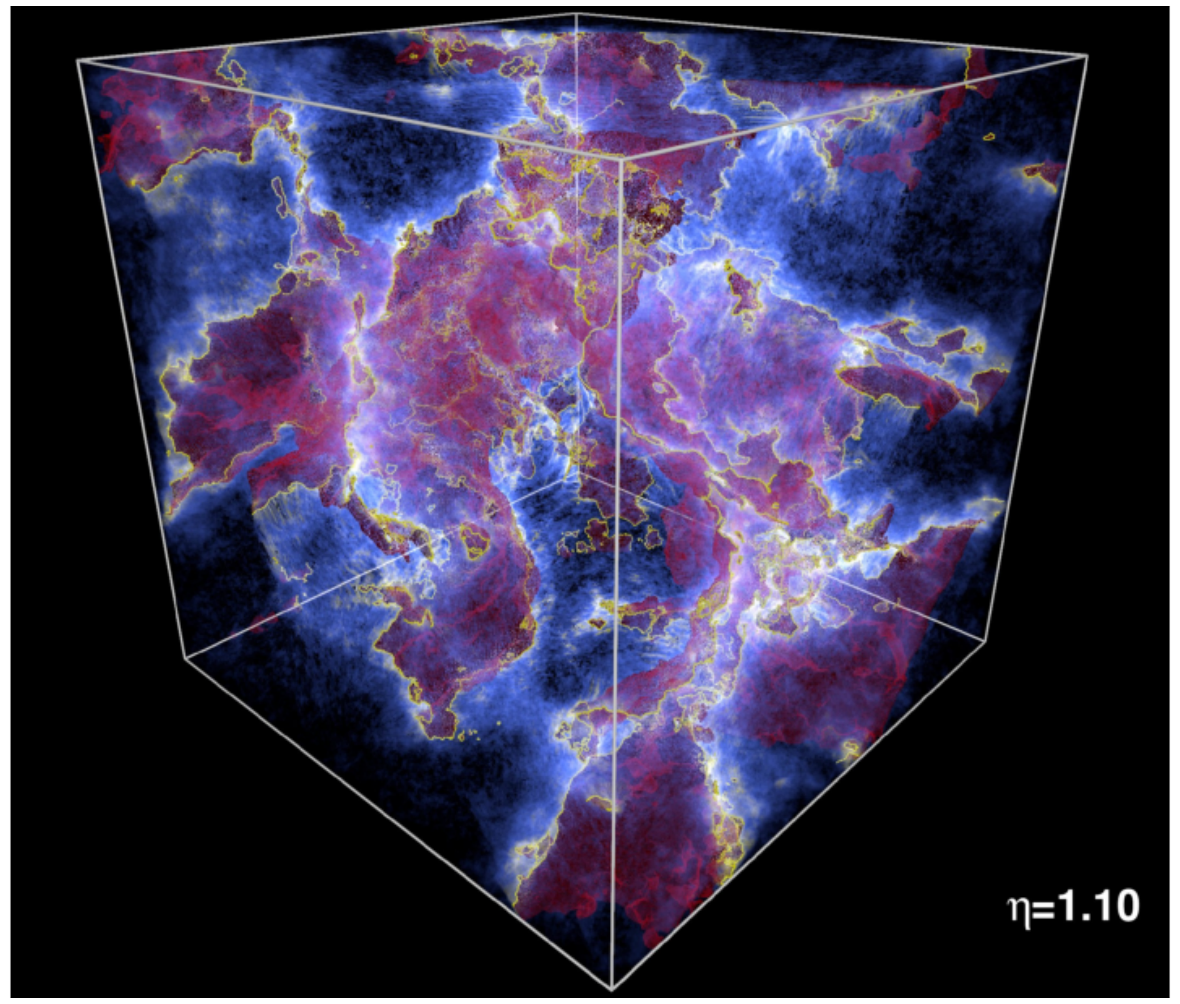
String network quickly enters a scaling regime with $\rho_{\rm scaling} = \xi\mu/t^2$

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

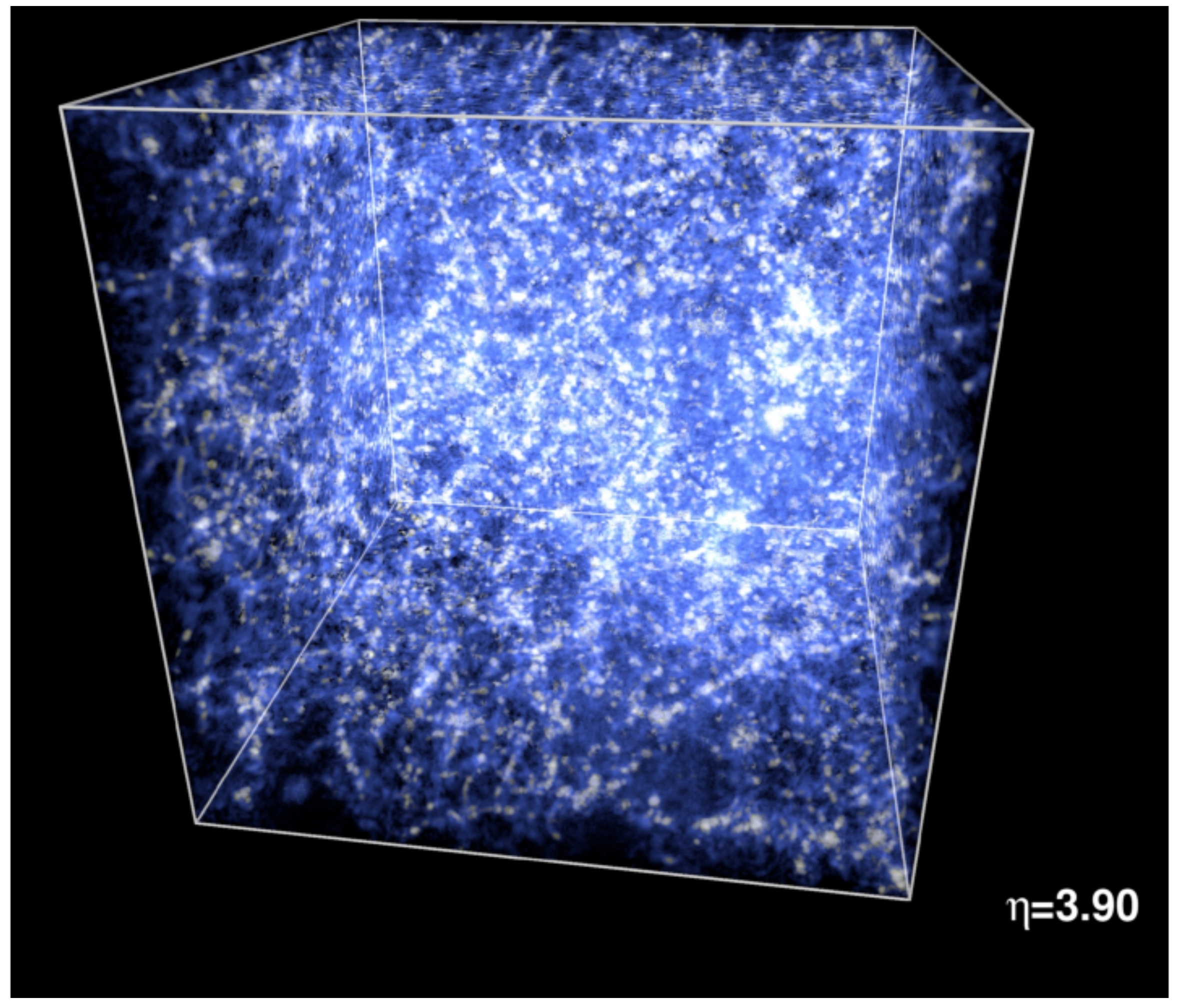
String length per Hubble volume ξ



Before QCD PT



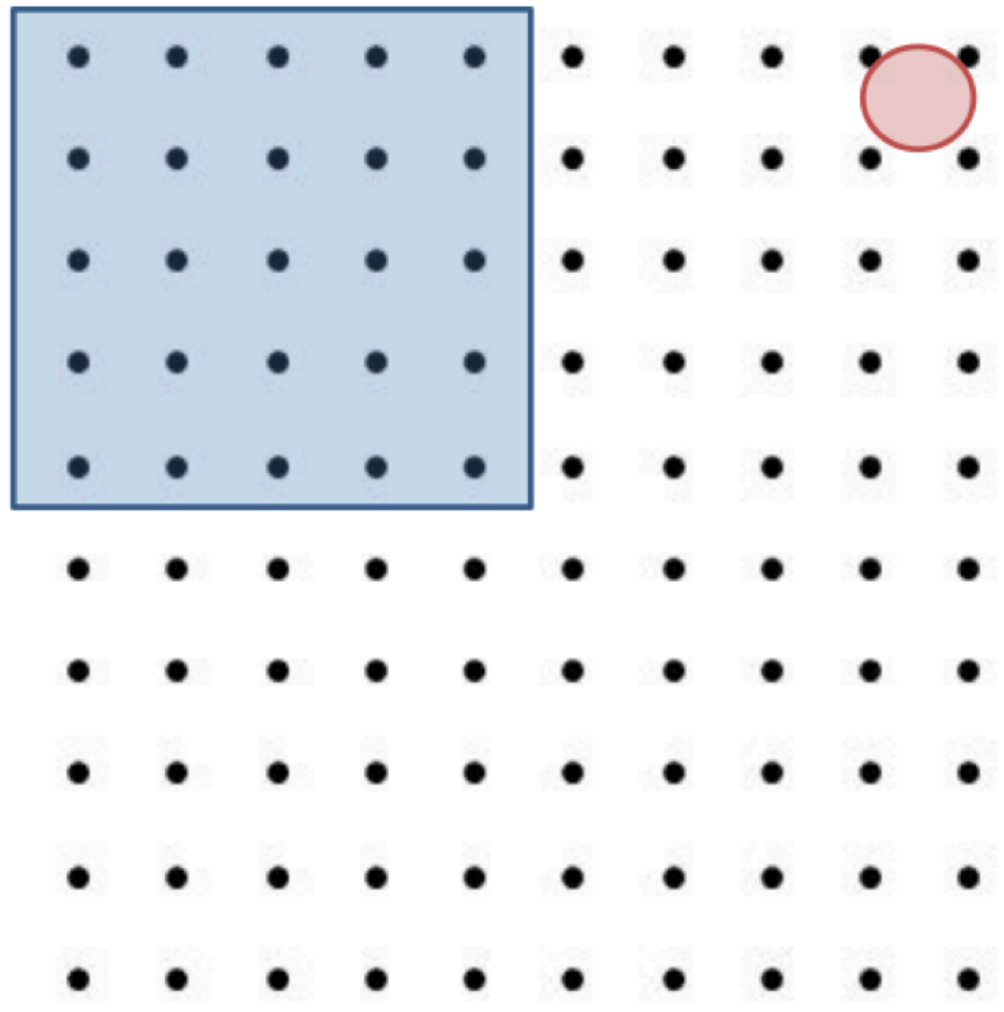
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



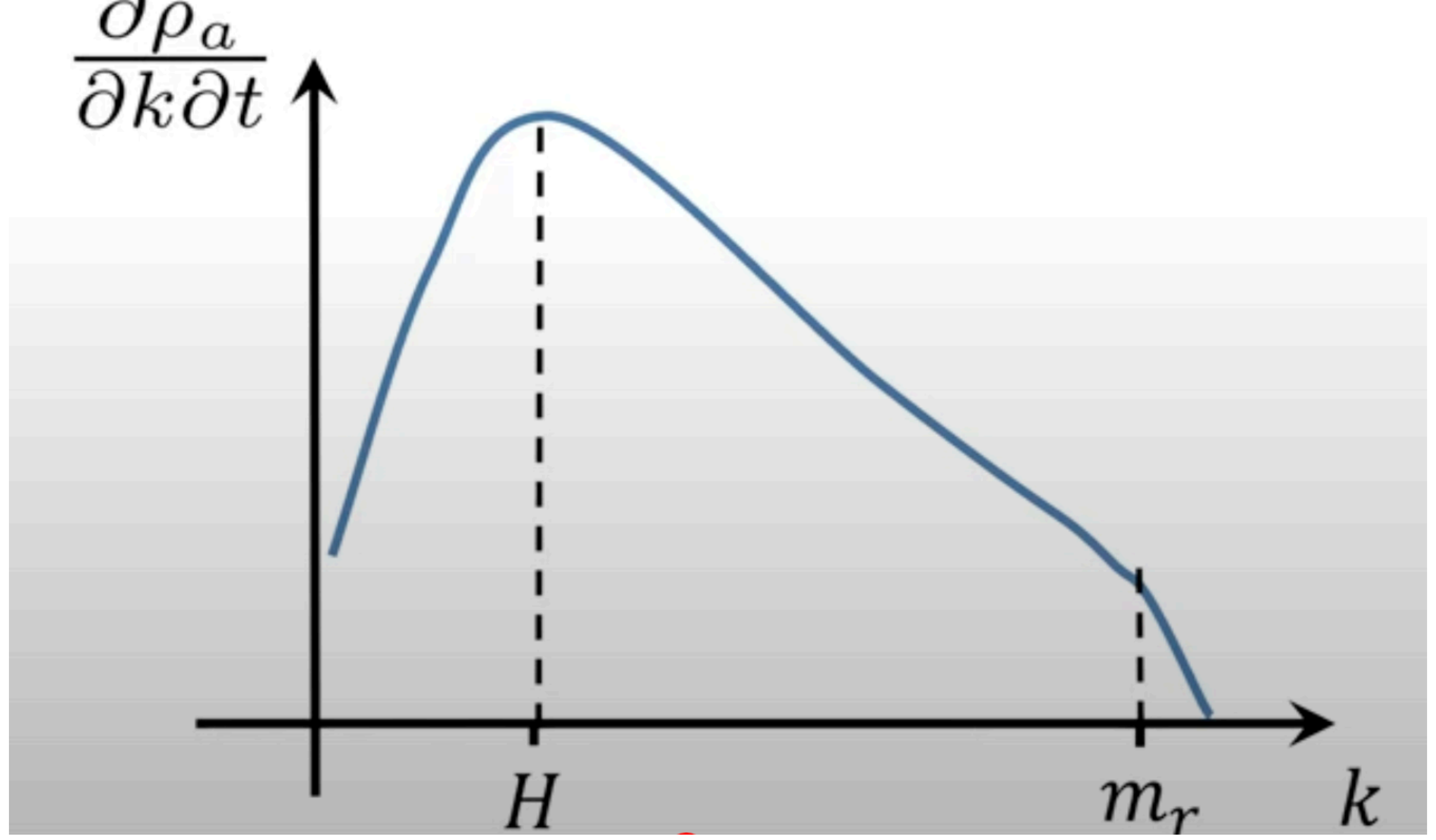
Credits: Ed Hardy

$$N \approx 5000^3$$

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

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 $\sim \mathrm{meV}$ [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]

Axion miniclusters (scenario 2)

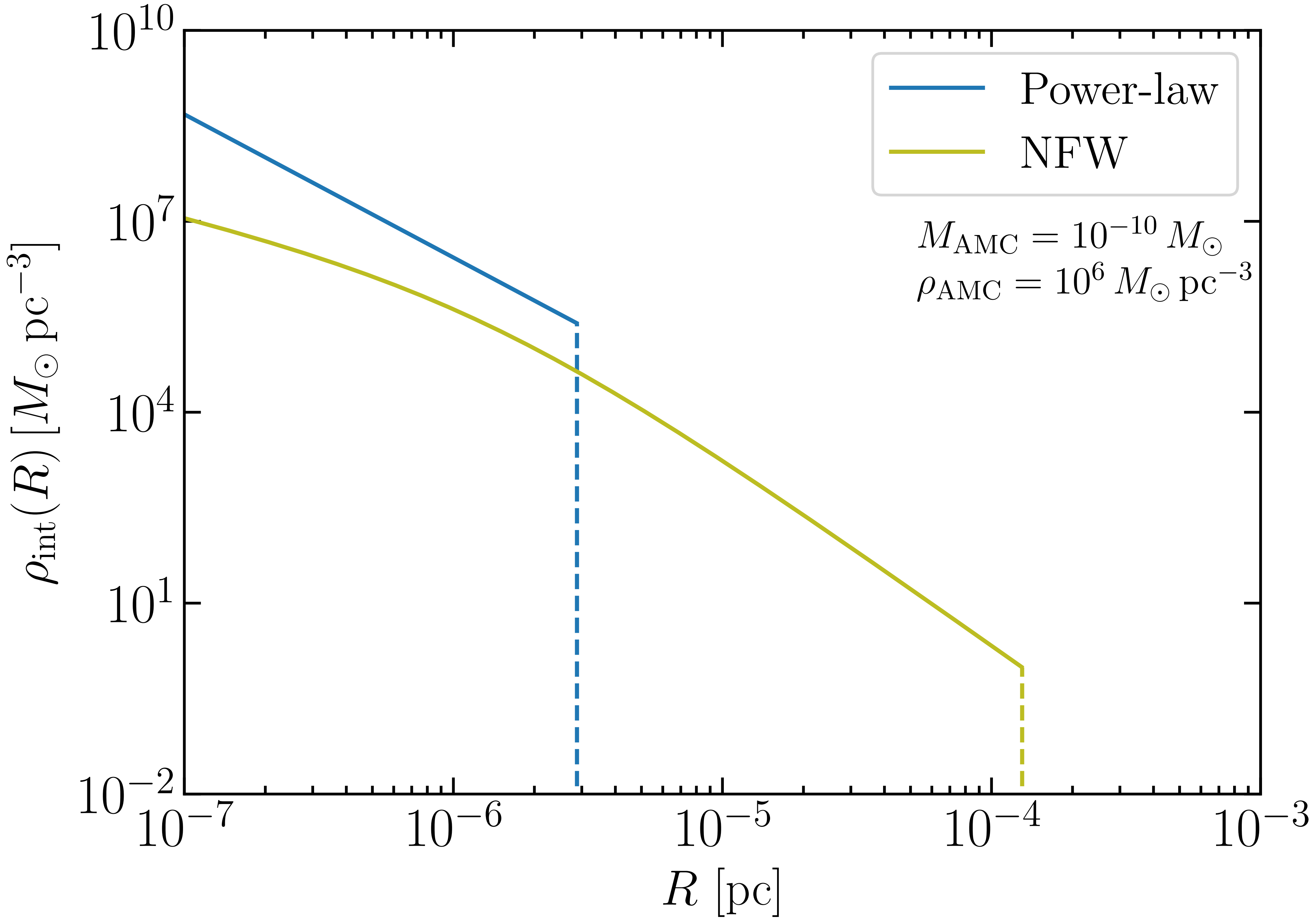
In post-inflation symmetry breaks, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

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

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]

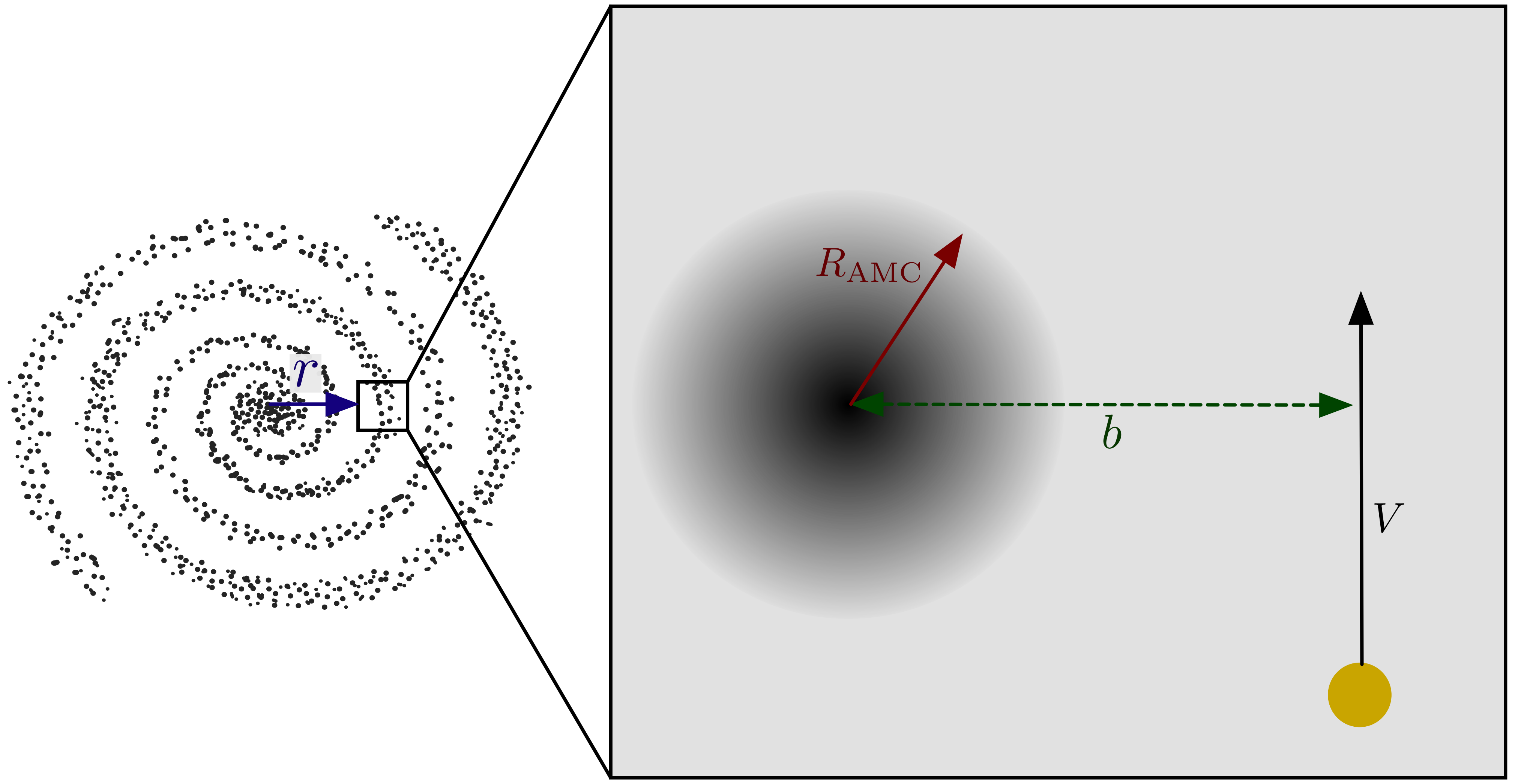


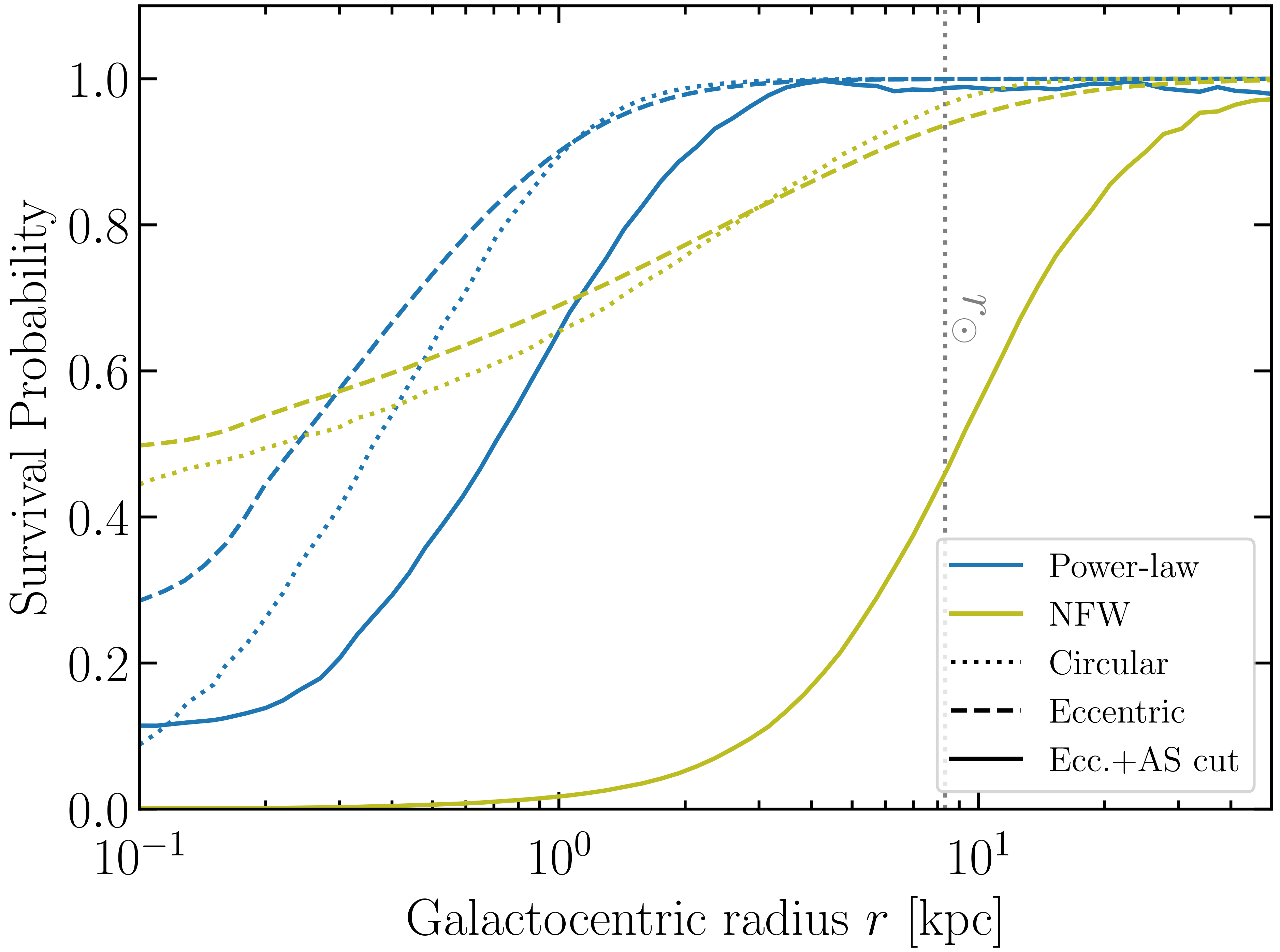
Density profile from collapse: $\rho_{\rm mc}(r) \propto r^{-9/4}$

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

Axion miniclusters (scenario 2)

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





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

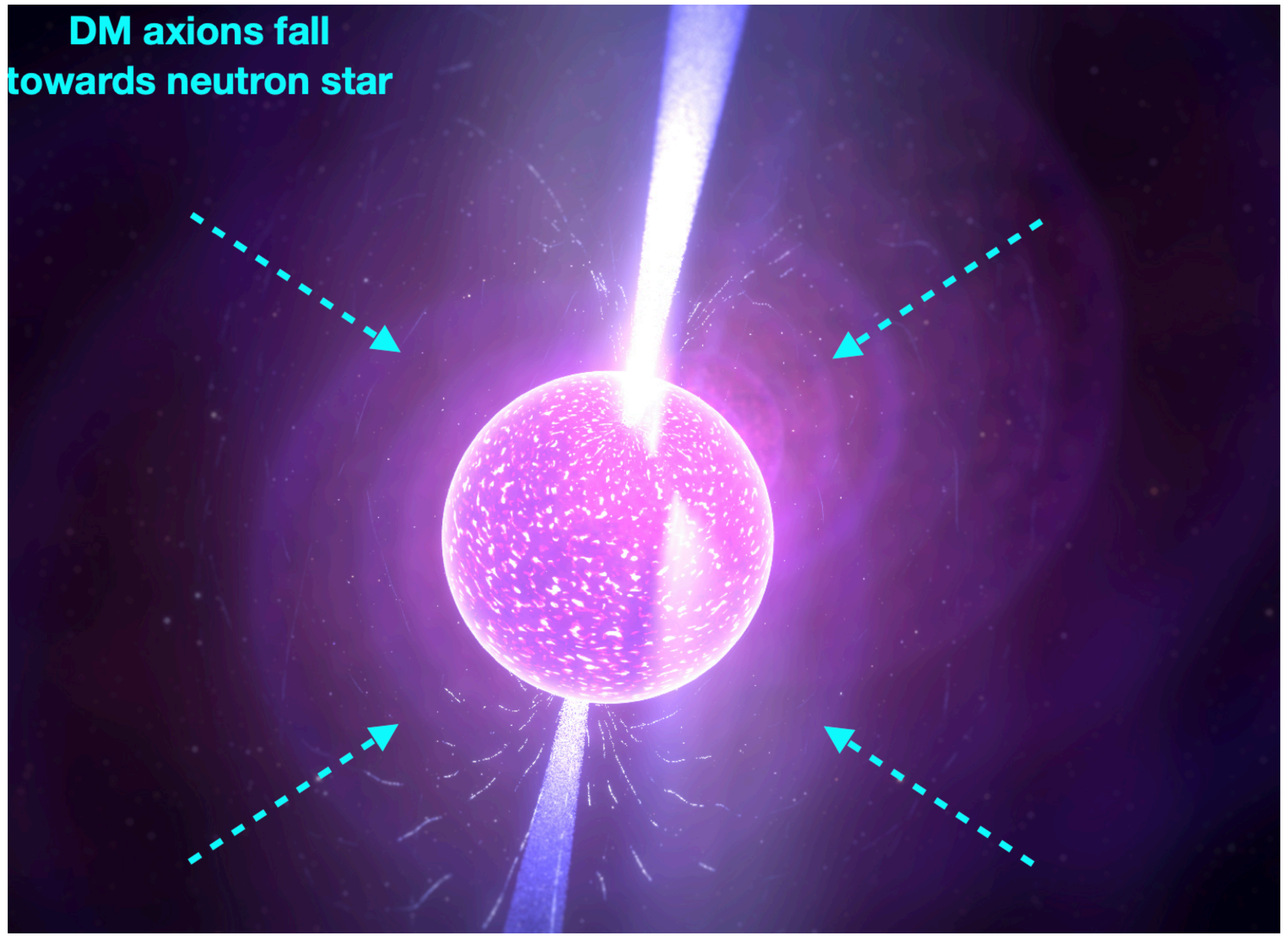
See also [Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586]

Axion stars: see talks by Malcolm Fairbairn & Lars Sivertsen and **LV+** 1710.08910

Axion-photon conversion in NS magnetospheres

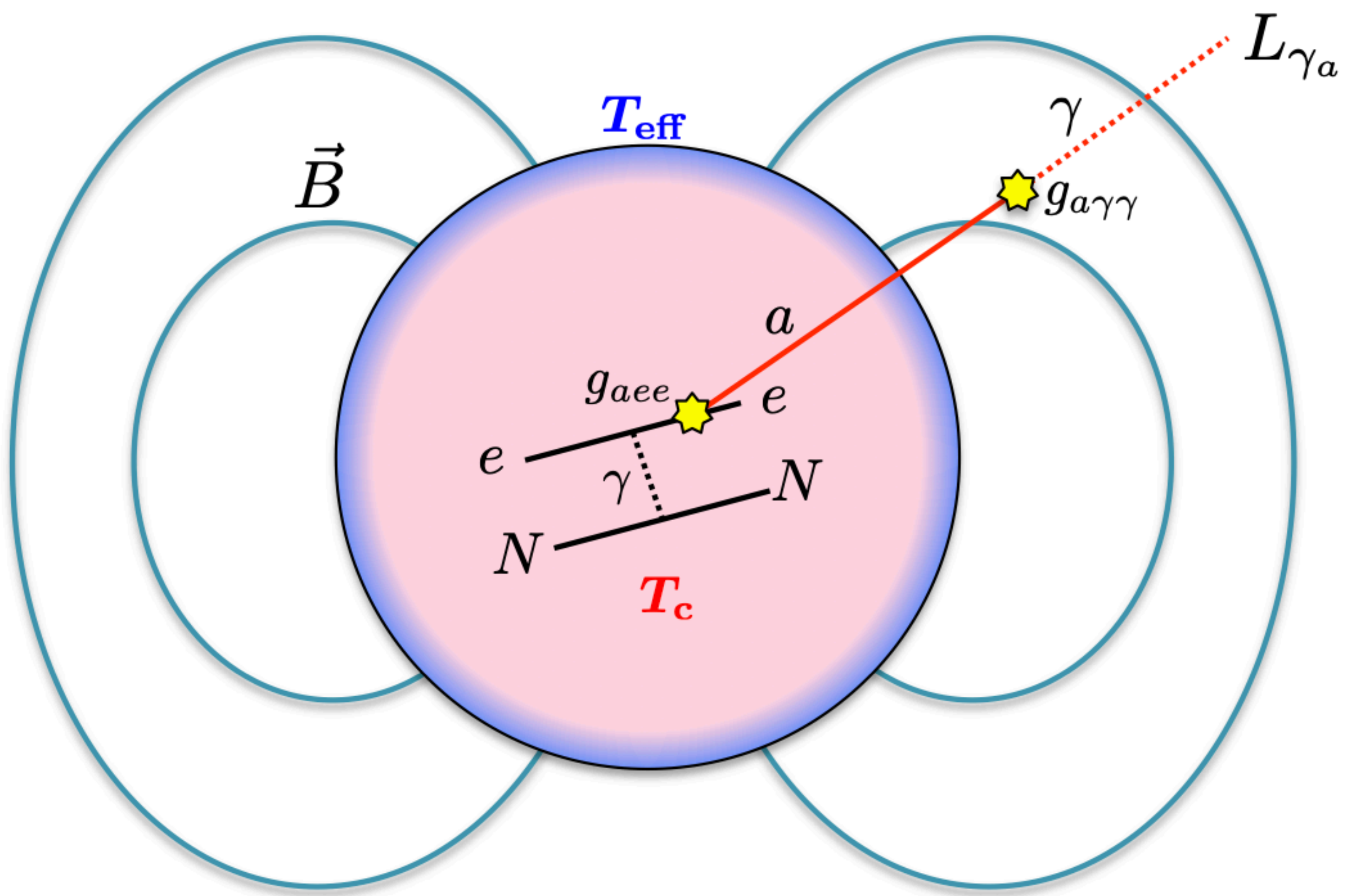
Neutron stars as laboratory for DM searches, see talk by Sandra Robles

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



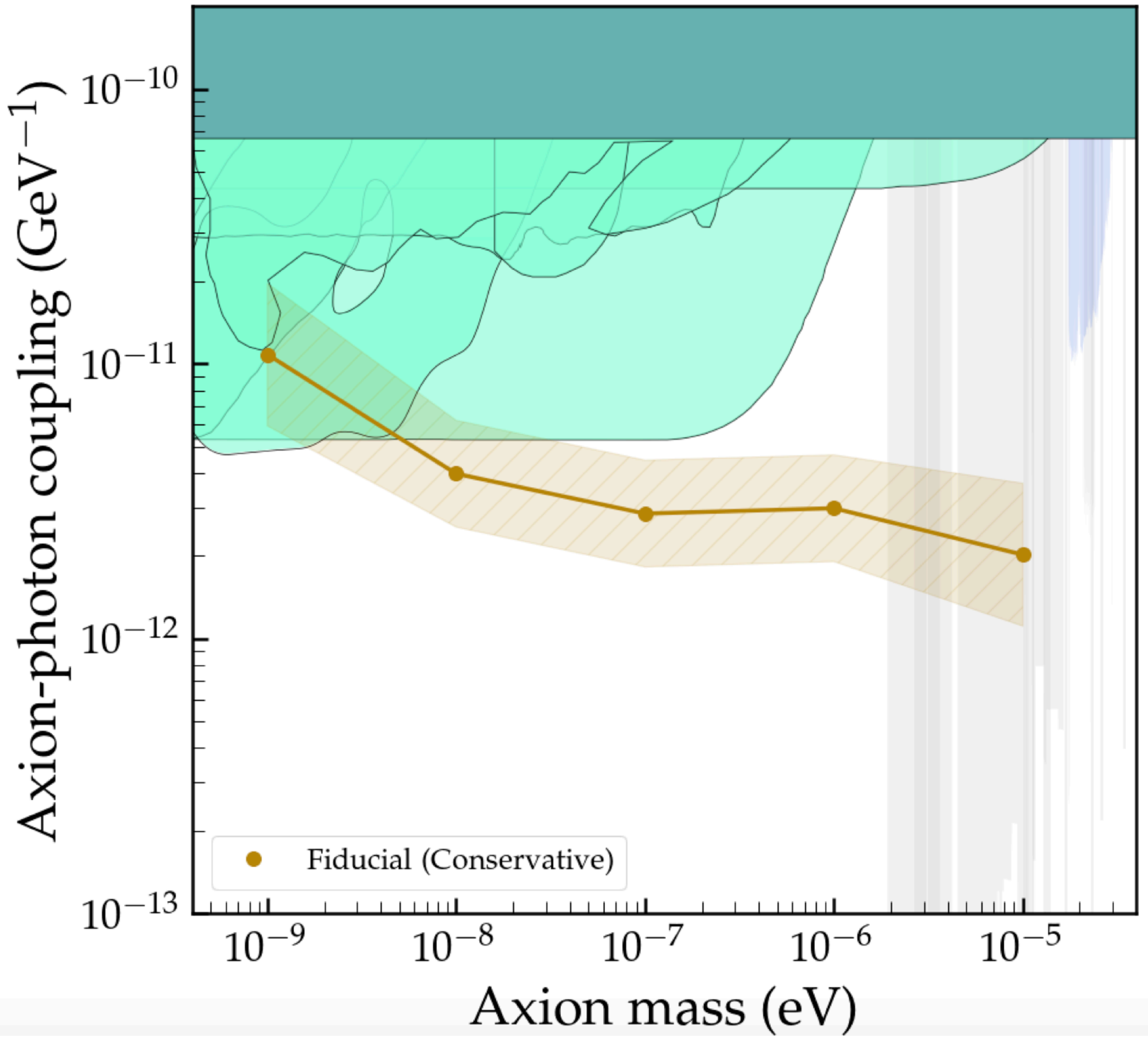
DM axions fall into neutron stars convert in the magnetosphere

[Hook+ 2018; Safdi+ 2019]



Axion production in NS cores +conversion in magnetosphere

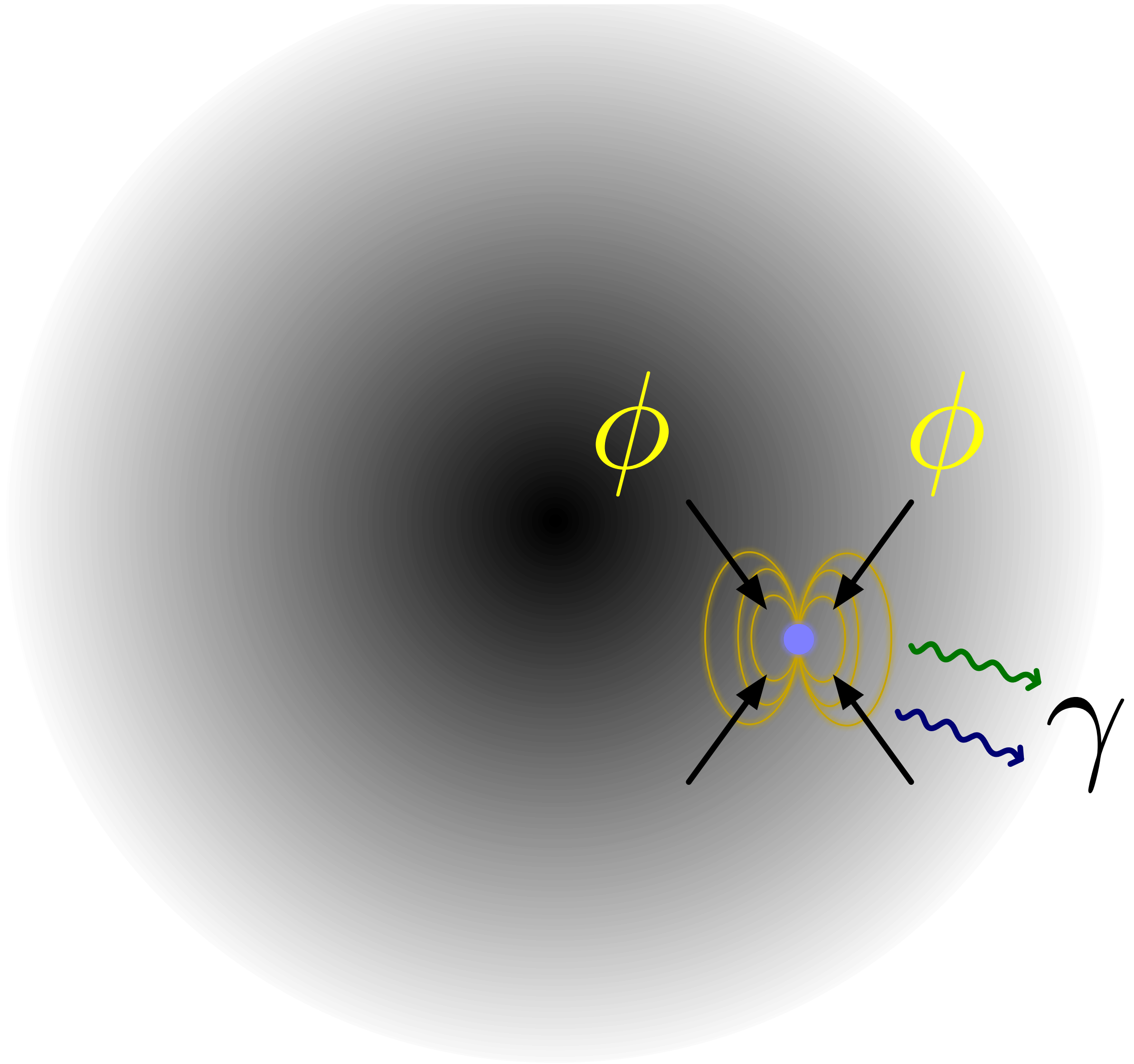
[Dessert+ 2021]



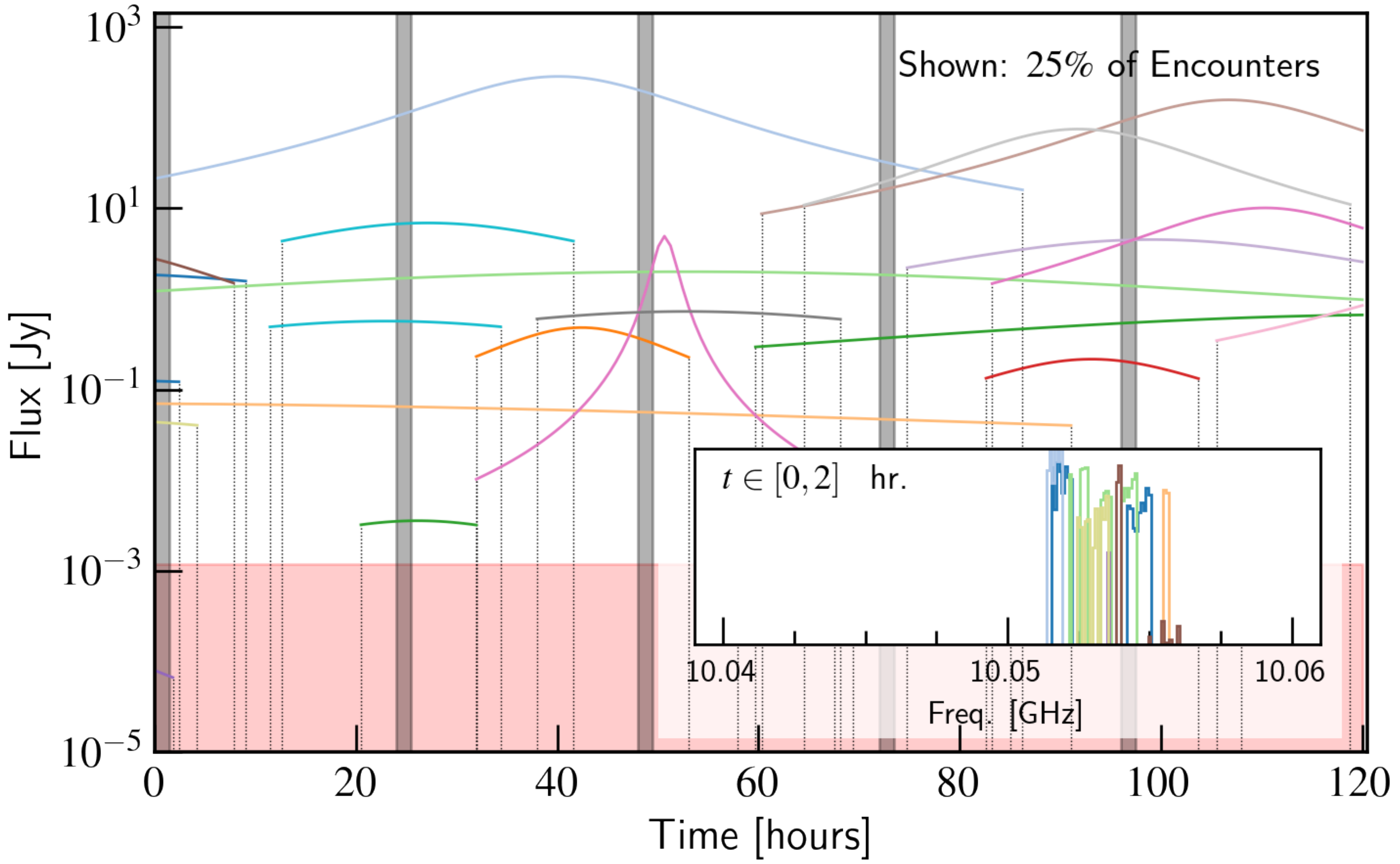
[Noordhuis+ 2209.09917]

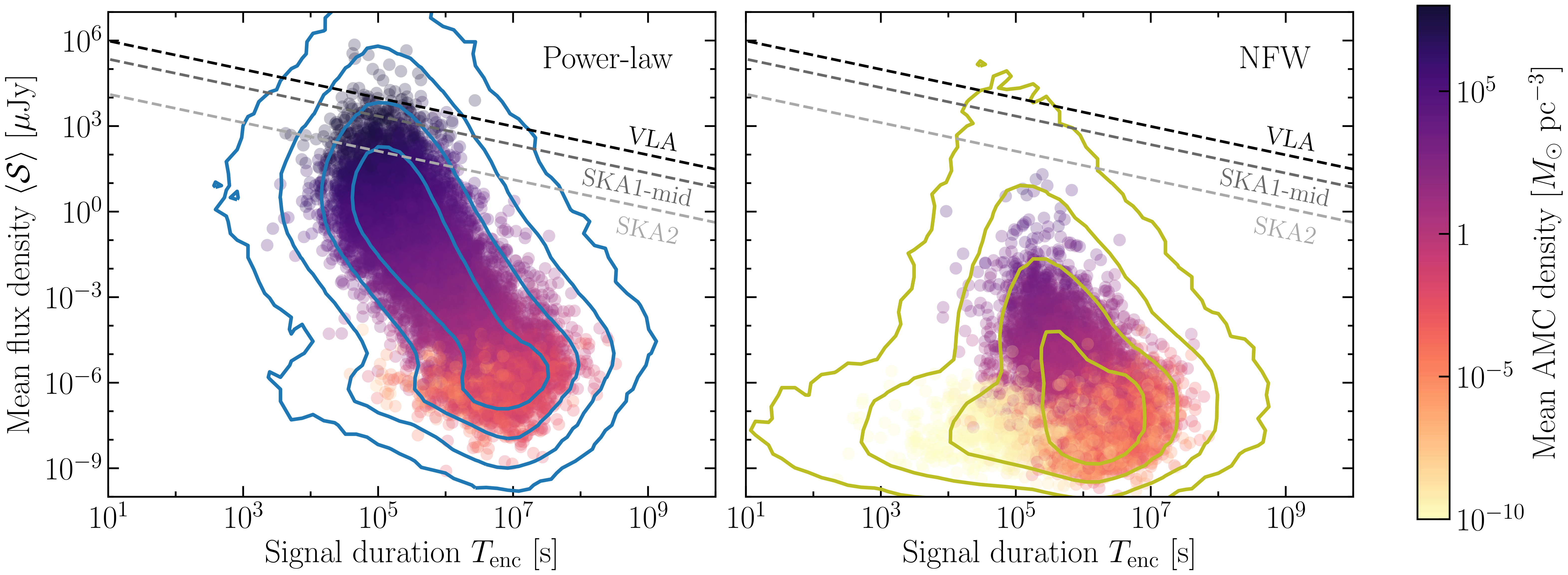
See talk by Dion Noordhuis

Axion-photon conversion in NS magnetospheres



Can we pick up this signal in radio?





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

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

+ 2 grant proposals accepted by the Green Bank Telescope, currently observing

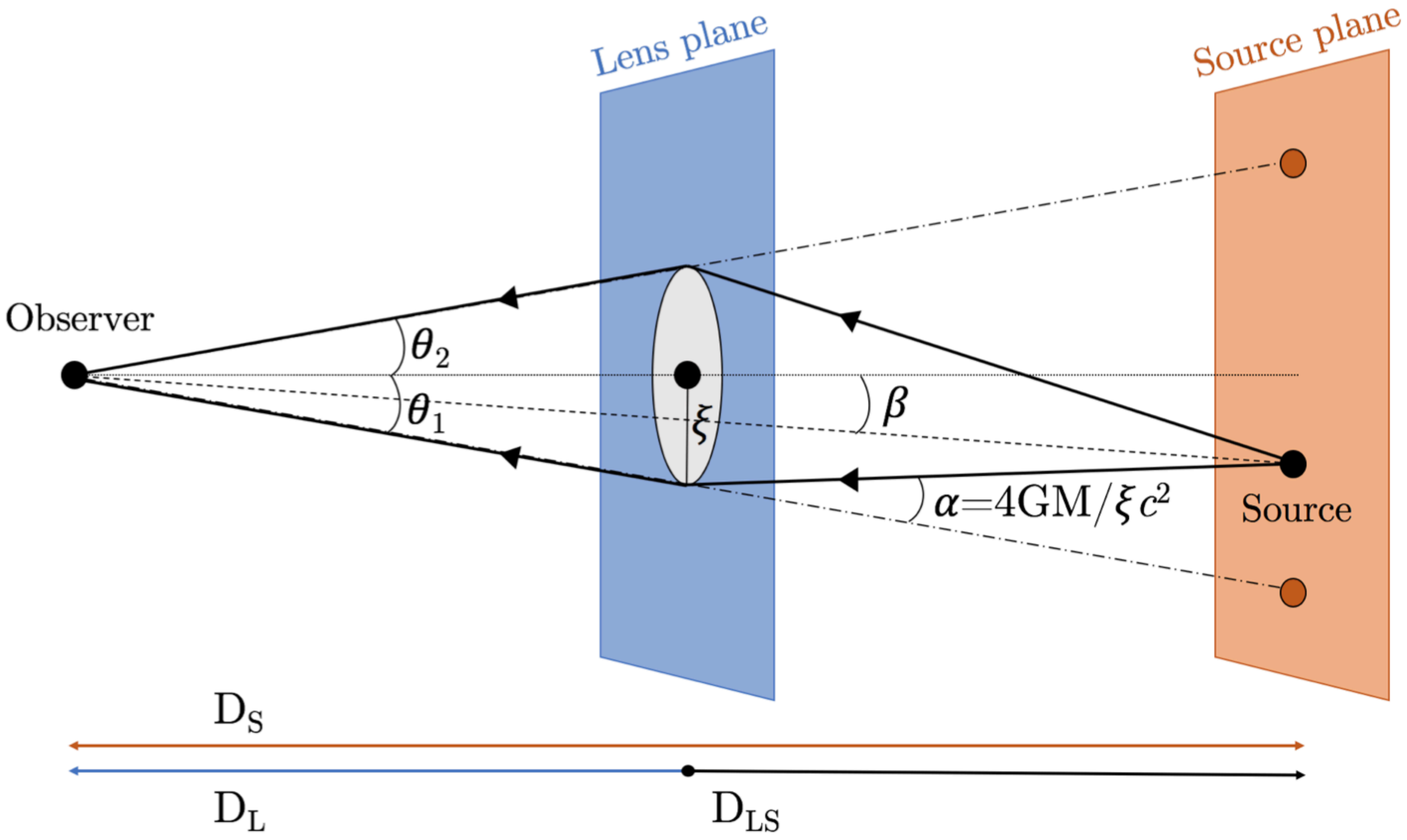
Paper in the making (Walters+ Kavanagh & **LV**)

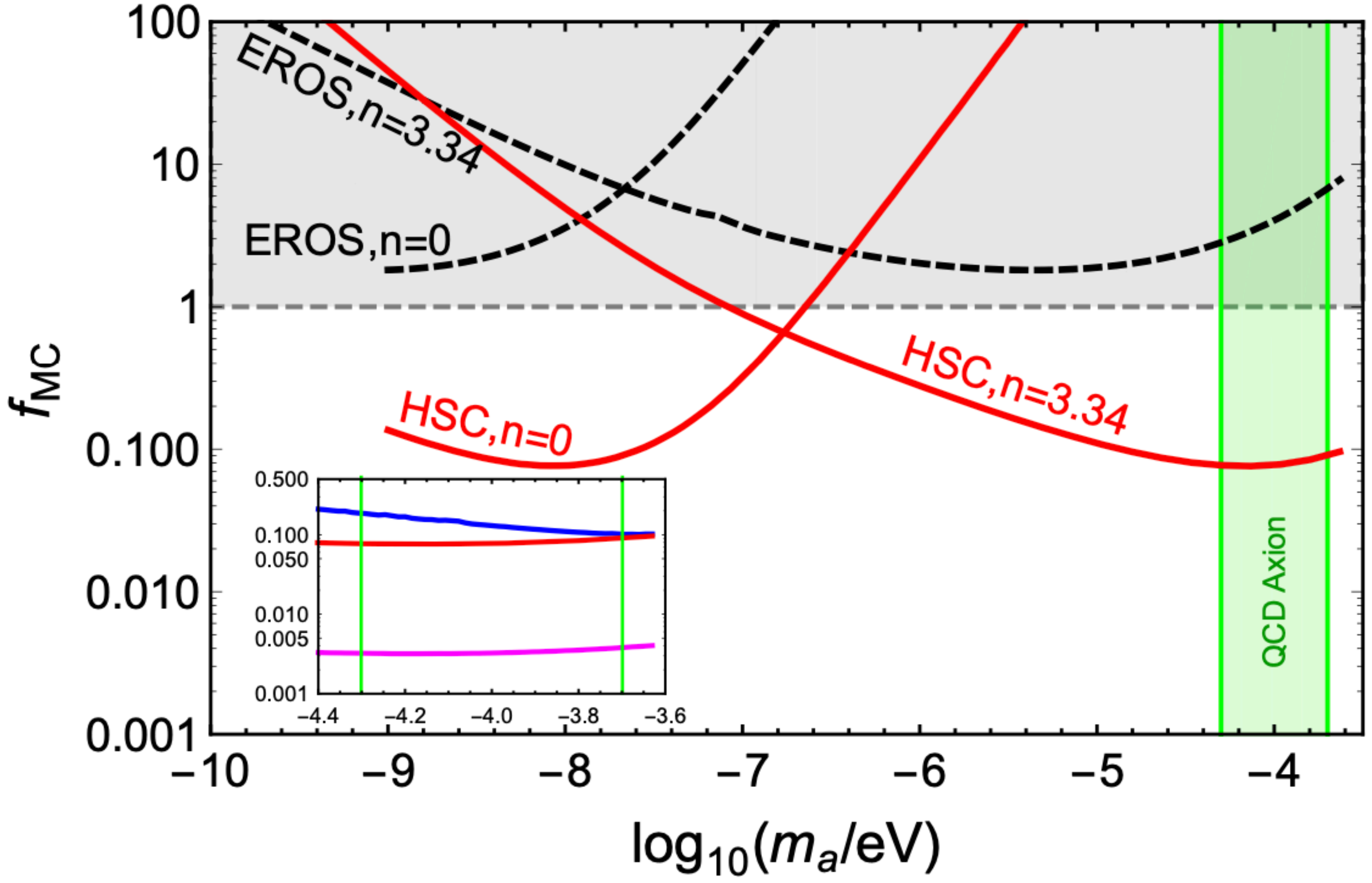
Code: github.com/bradkav/axion-miniclusters

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

Direct searches: Haloscope

Recall the effective Lagrangian below QCD:

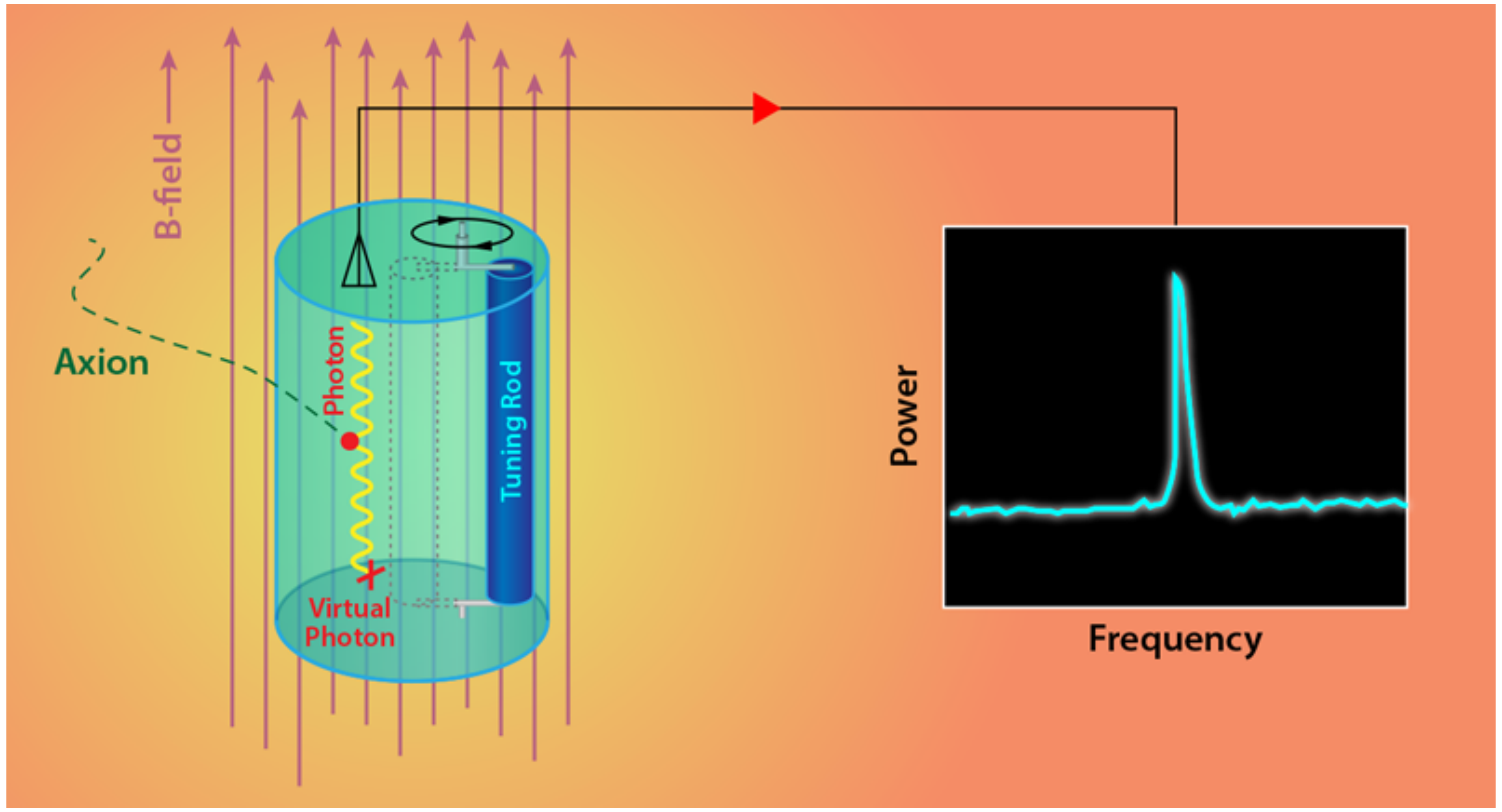
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \boxed{\frac{1}{4}g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu}} + c_e\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e + c_N\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N$$

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

Significant enhancement when

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

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

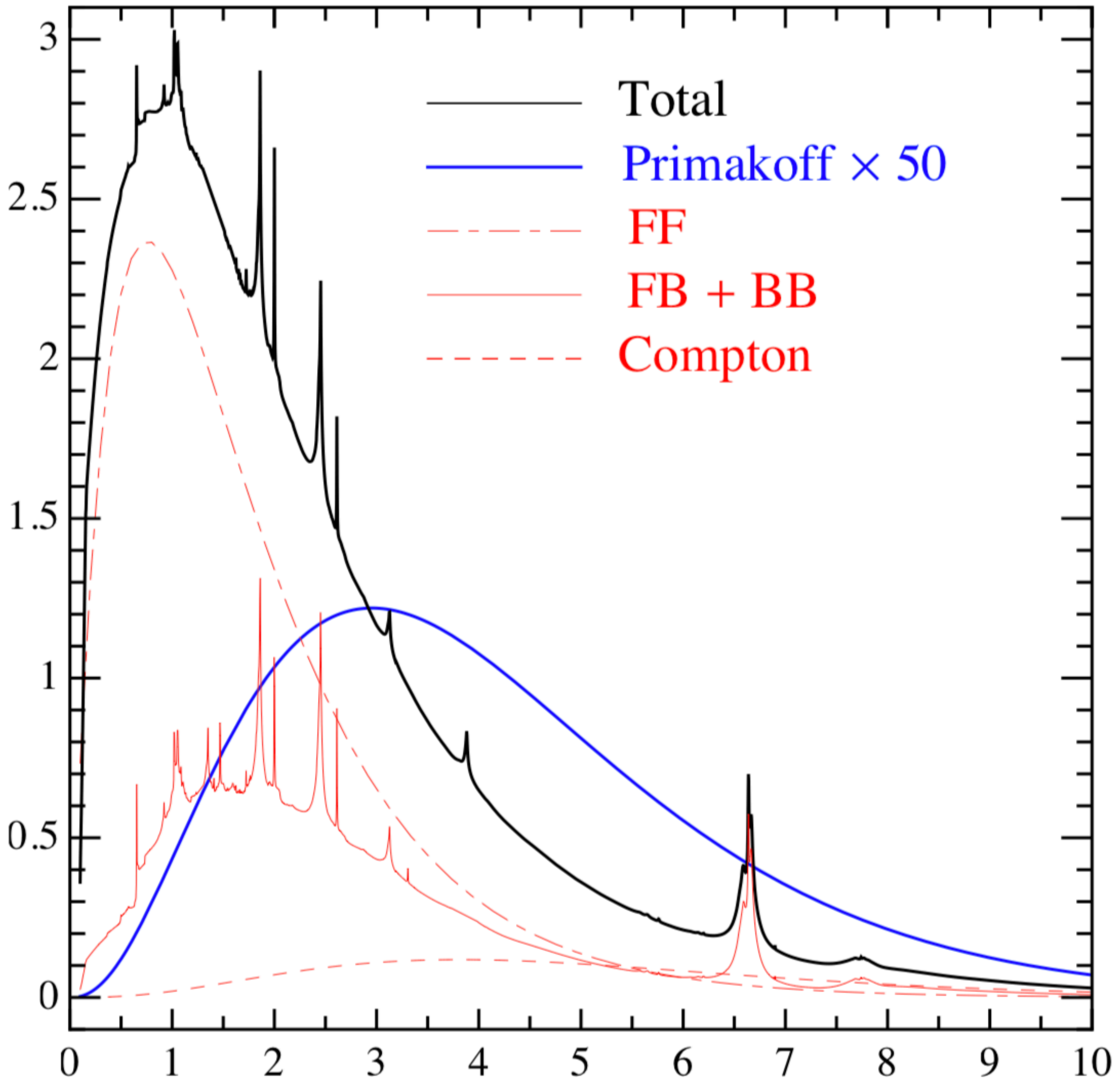


Q_L	Quality factor	V	Cavity volume
B_0	Magnetic field	C_{nml}	Geometric factor

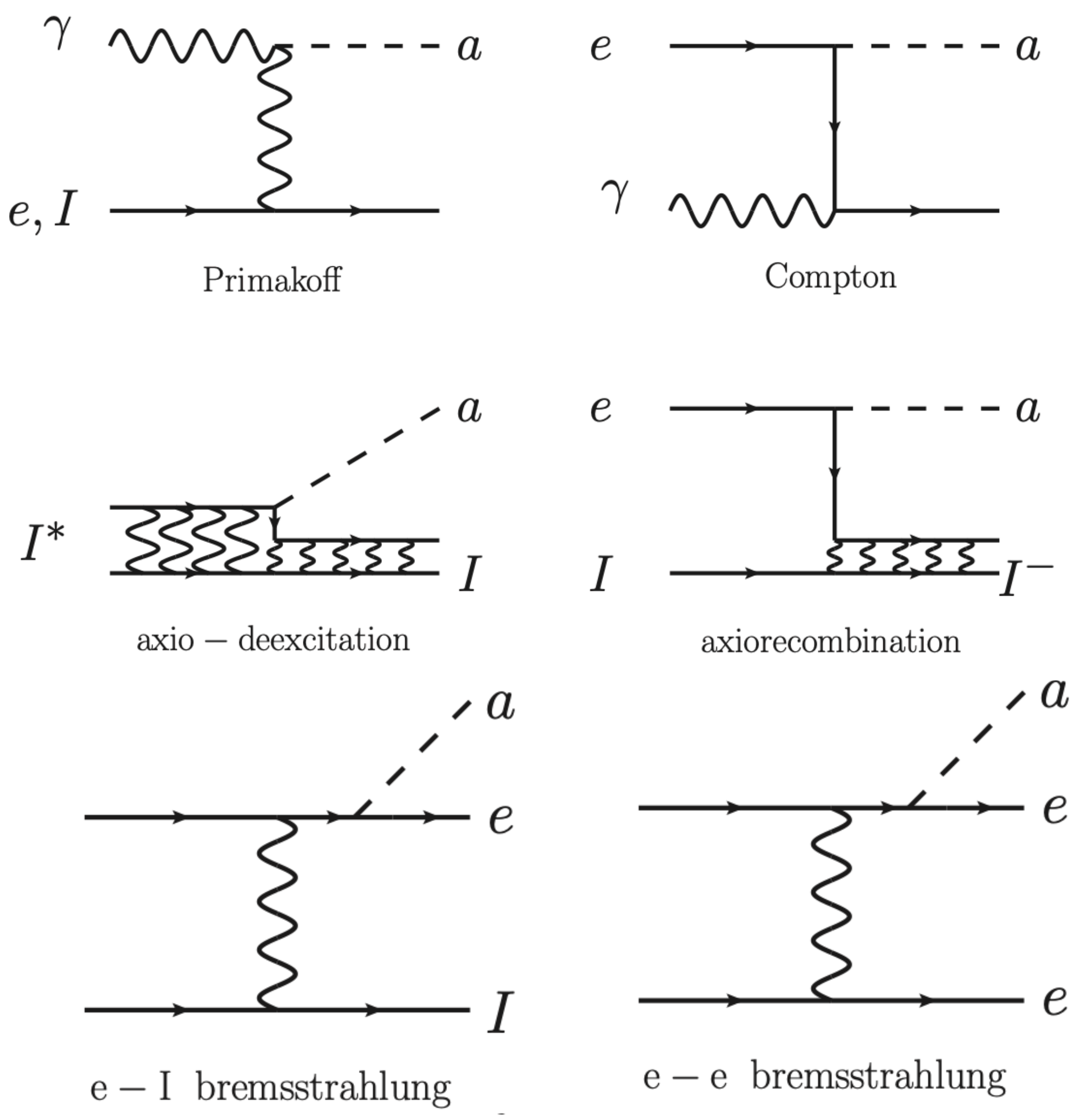
Courtesy of ADMX collaboration

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]



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

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

These are relativistic axions, not the DM!

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

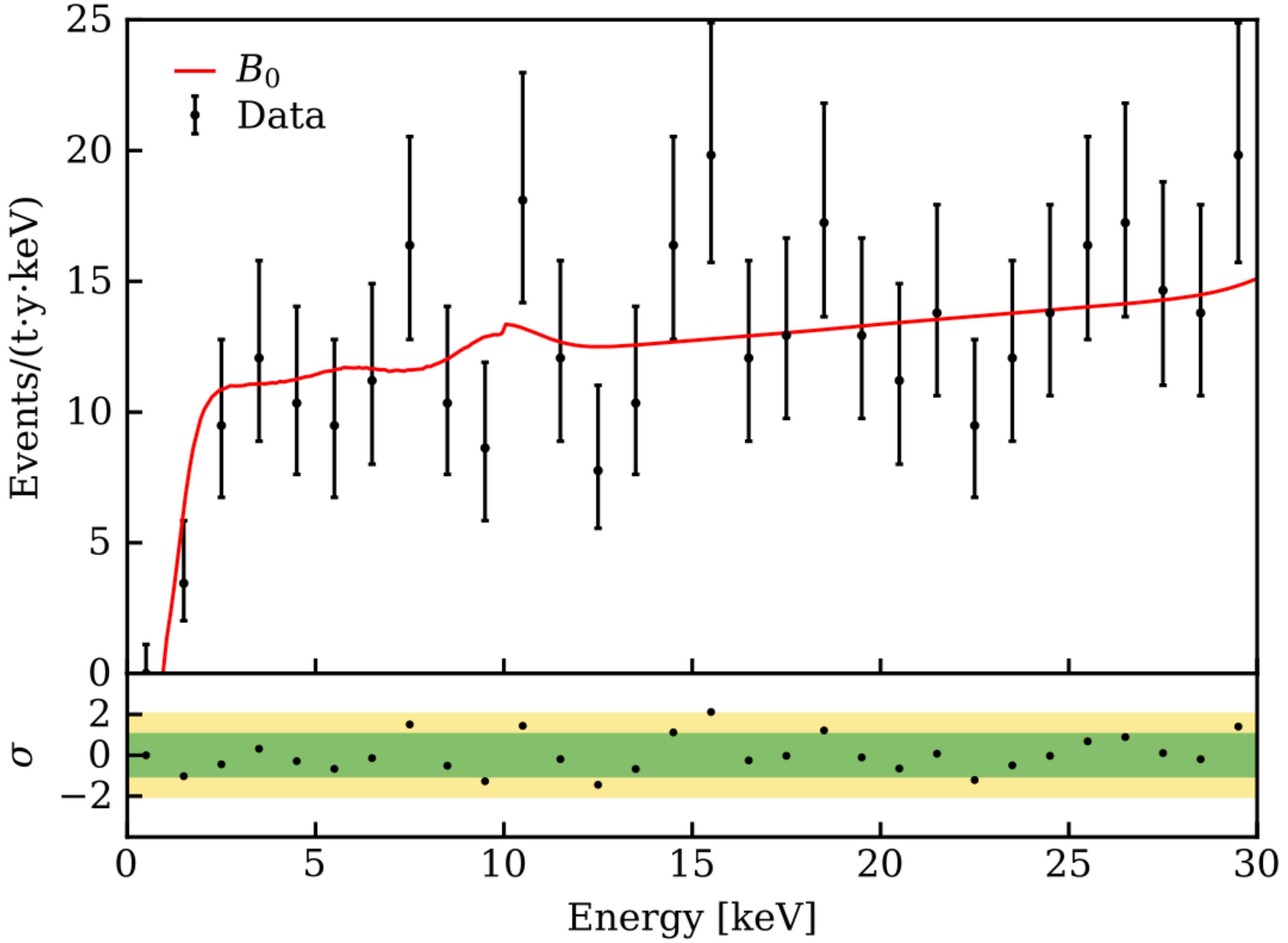
Searched for in CAST and in proposed (Baby)-IAXO

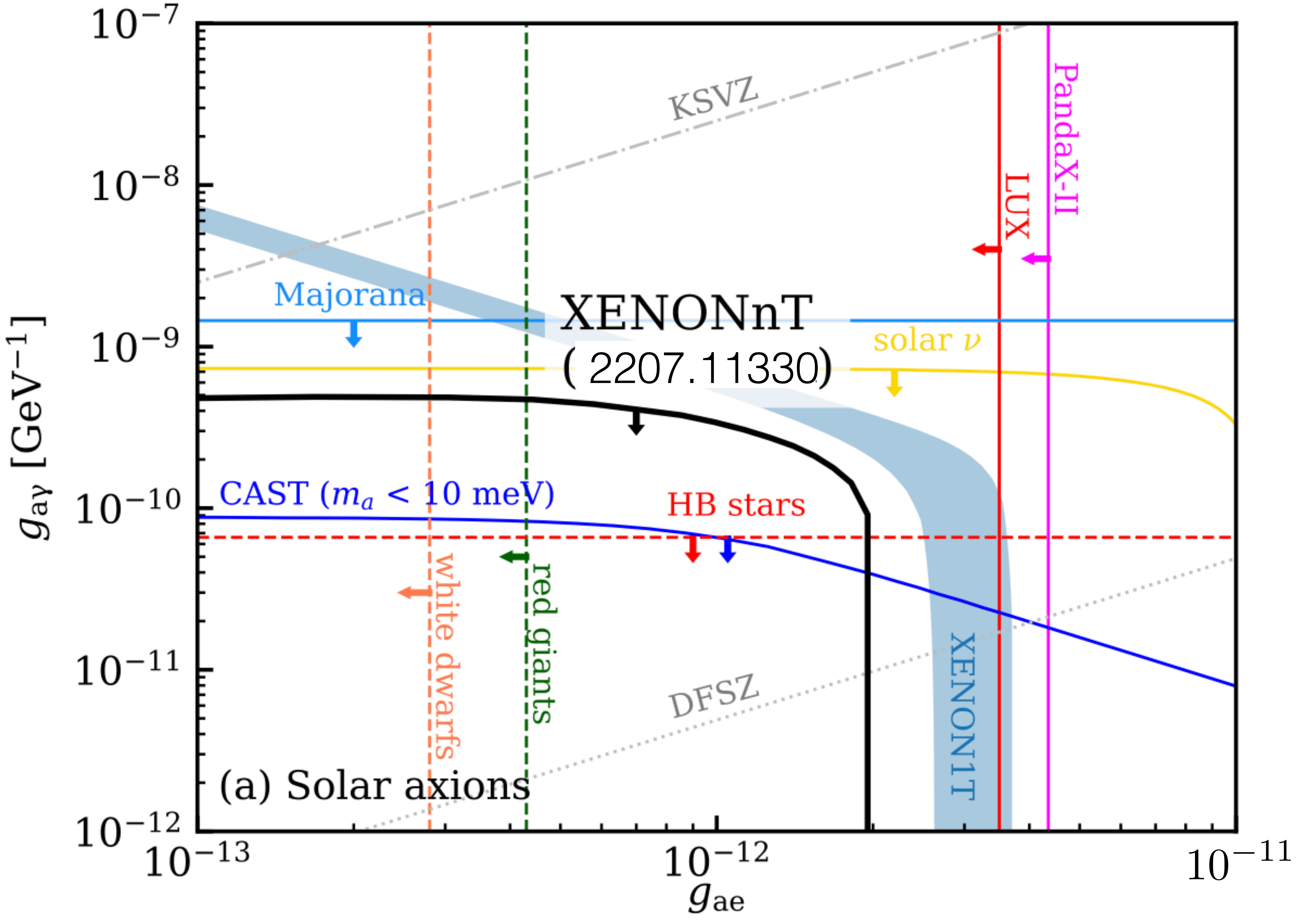
For exhaustive lists of experiments see [Irastorza & Redondo 2018]

Figure from Ben Safdi

Solar axions scattering with electrons

Luca Visinelli





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

Previous results “XENON1T excess” [2006.09721]

See also Vagnozzi+ [2103.15834] (**+LV**)

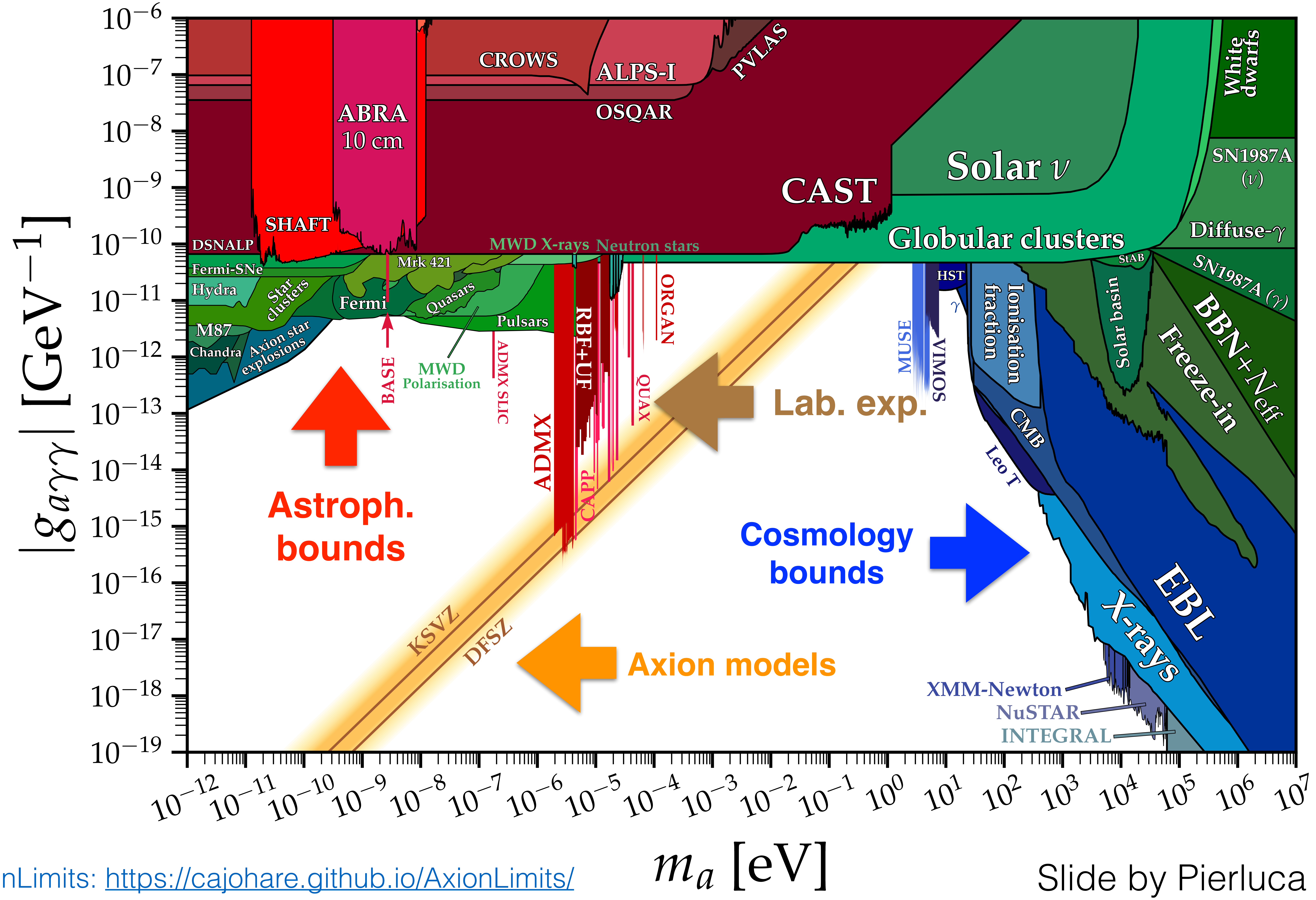
See talk by Cecilia Ferrari (XENONnT)

See talk by Pierluca Carenza (Stellar & SN bounds)

LZ searches: 2307.15753

Summary of axion-photon coupling bounds

Luca Visinelli



Astroph. bounds

Lab. exp.

Cosmology bounds

Axion models

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

Slide by Pierluca Carenza

Summary of axion-photon coupling bounds

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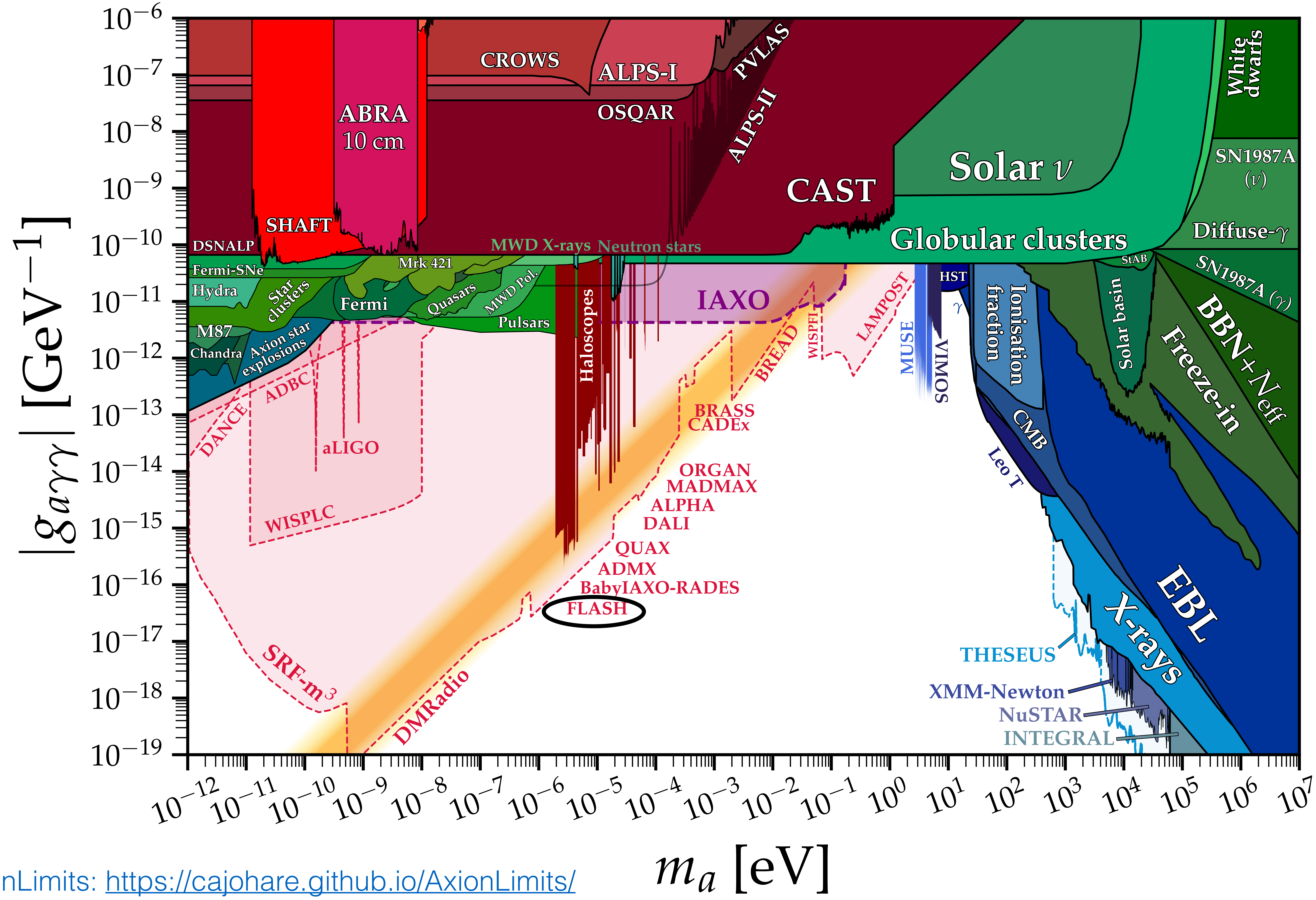
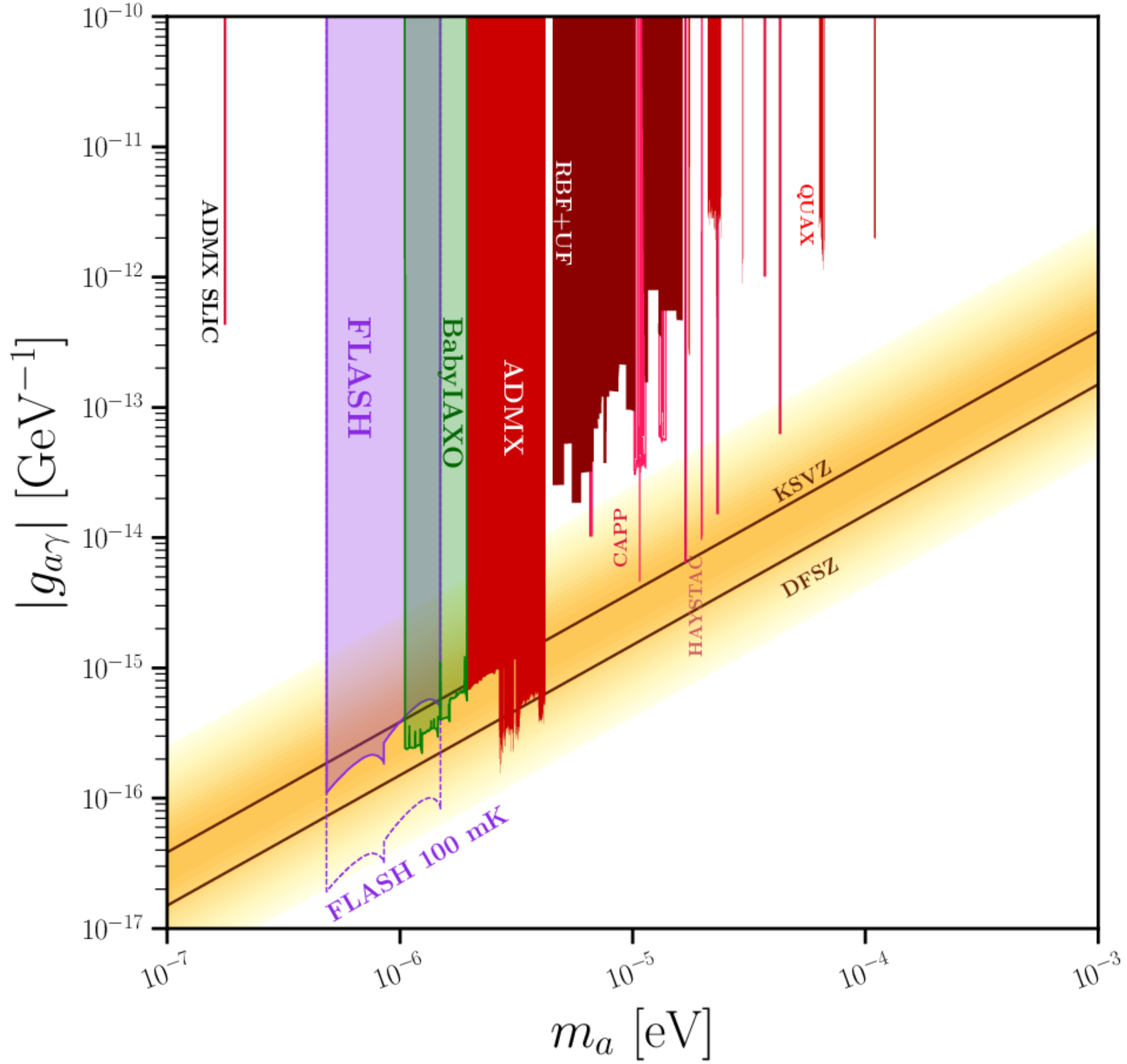


Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

Cavity search in Frascati (Rome)



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

Includes M. Zantedeschi
(Postdoc at TDLI)

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

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

See the talk by Bradley Kavanagh for the CADEx proposal a higher masses

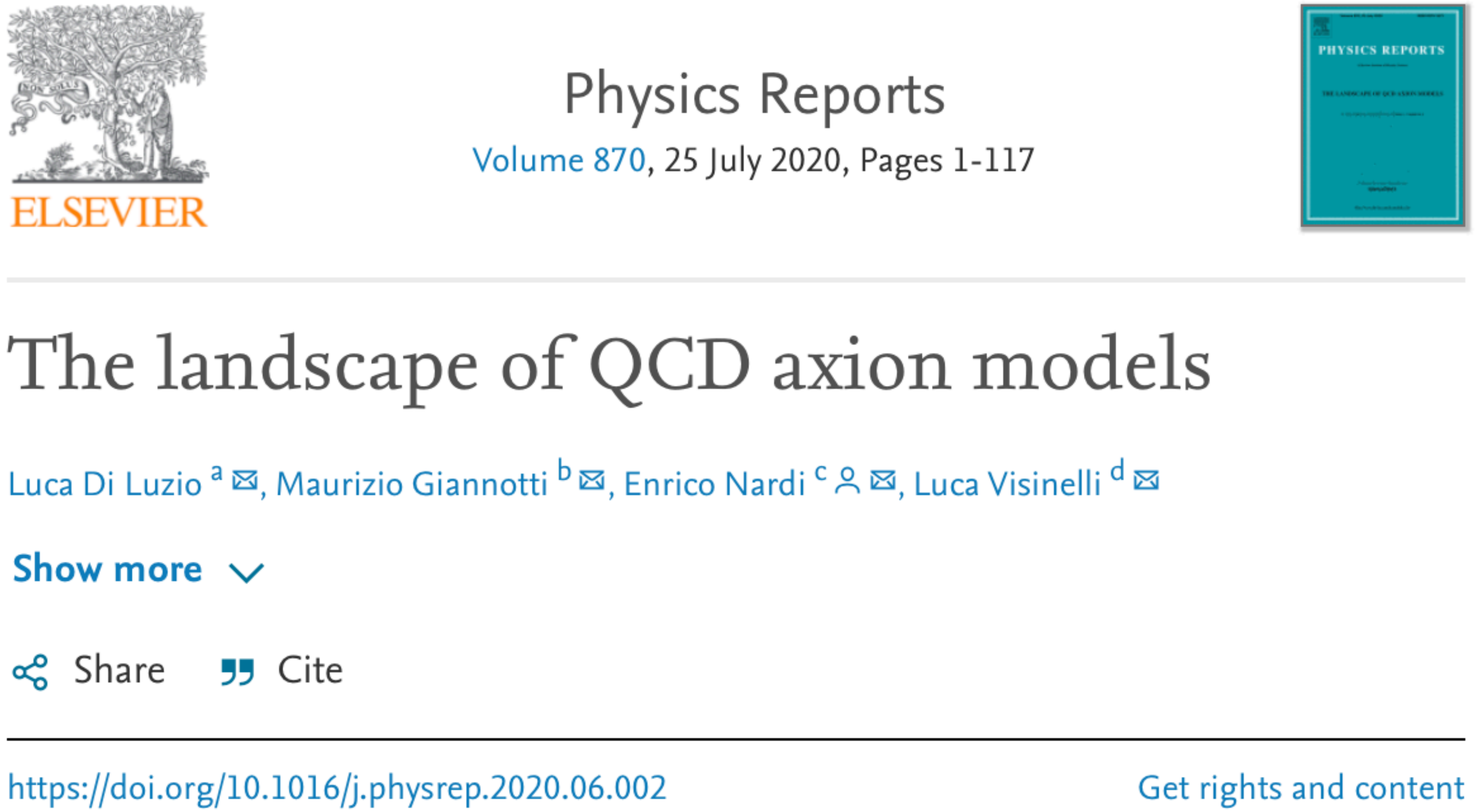
Conclusions and further read

Oct. 16-18 2023
Online workshop on axions (~2.5 hours per day)

https://sites.google.com/view/axionworkshop

Mostly PhD students with novel contributions
\+ one senior per day
(DJE Marsh, J. Redondo, F. Takahashi)

Thanks to all my collaborators and to the audience!



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Physics Reports
Volume 870, 25 July 2020, Pages 1-117

PHYSICS REPORTS

The landscape of QCD axion models

Luca Di Luzio [a], Maurizio Giannotti [b], Enrico Nardi [c], Luca Visinelli [d]

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My review on Physics Reports: 2003.01100

DJE Marsh, “Axion Cosmology” (2015)

P. Sikivie, “Invisible axion search methods” (2021)

Irastorza & Redondo 2018