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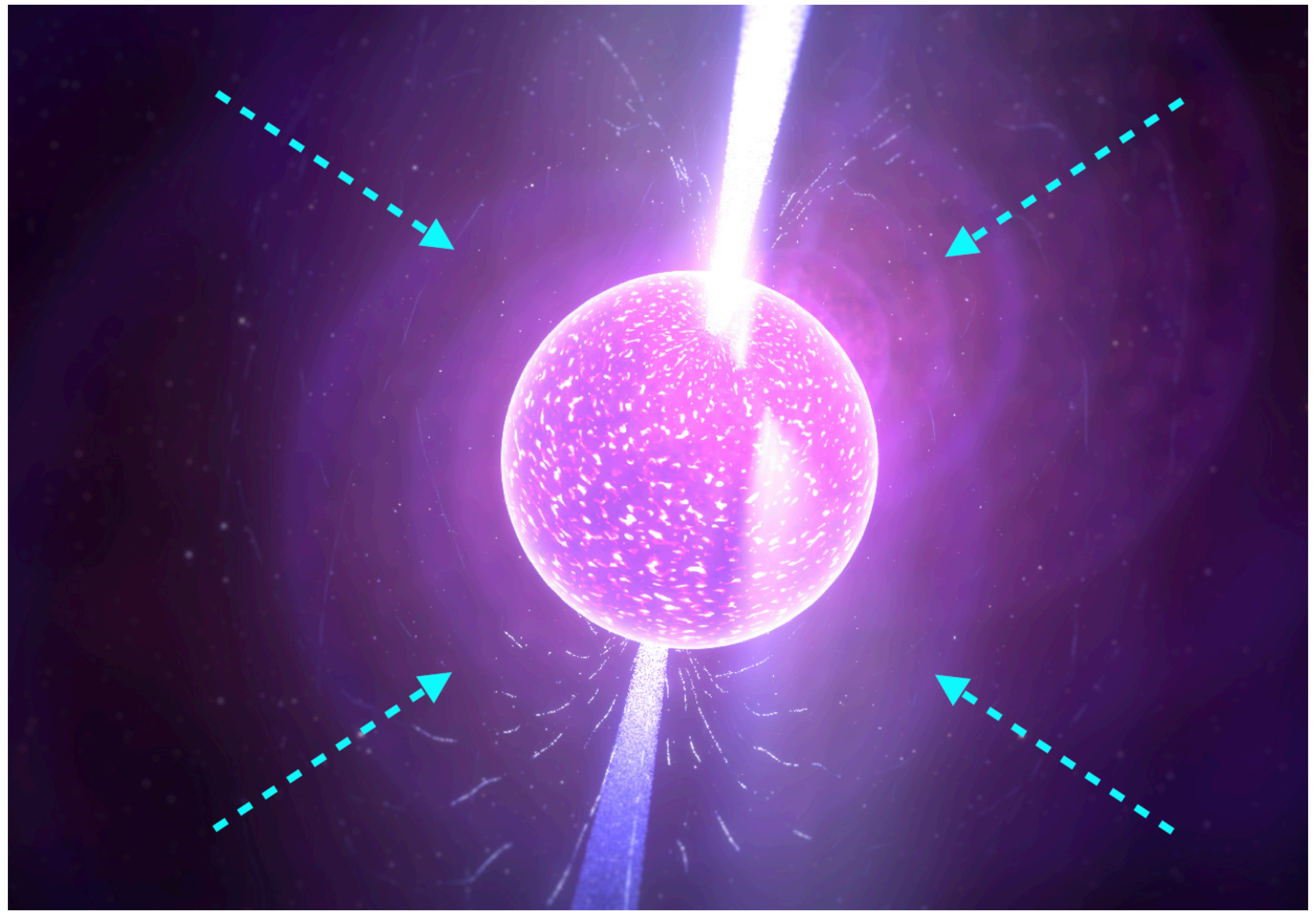
Indirect and direct detection of the QCD axion and other light bosons



Luca Visinelli

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January 16, 2025

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Outline

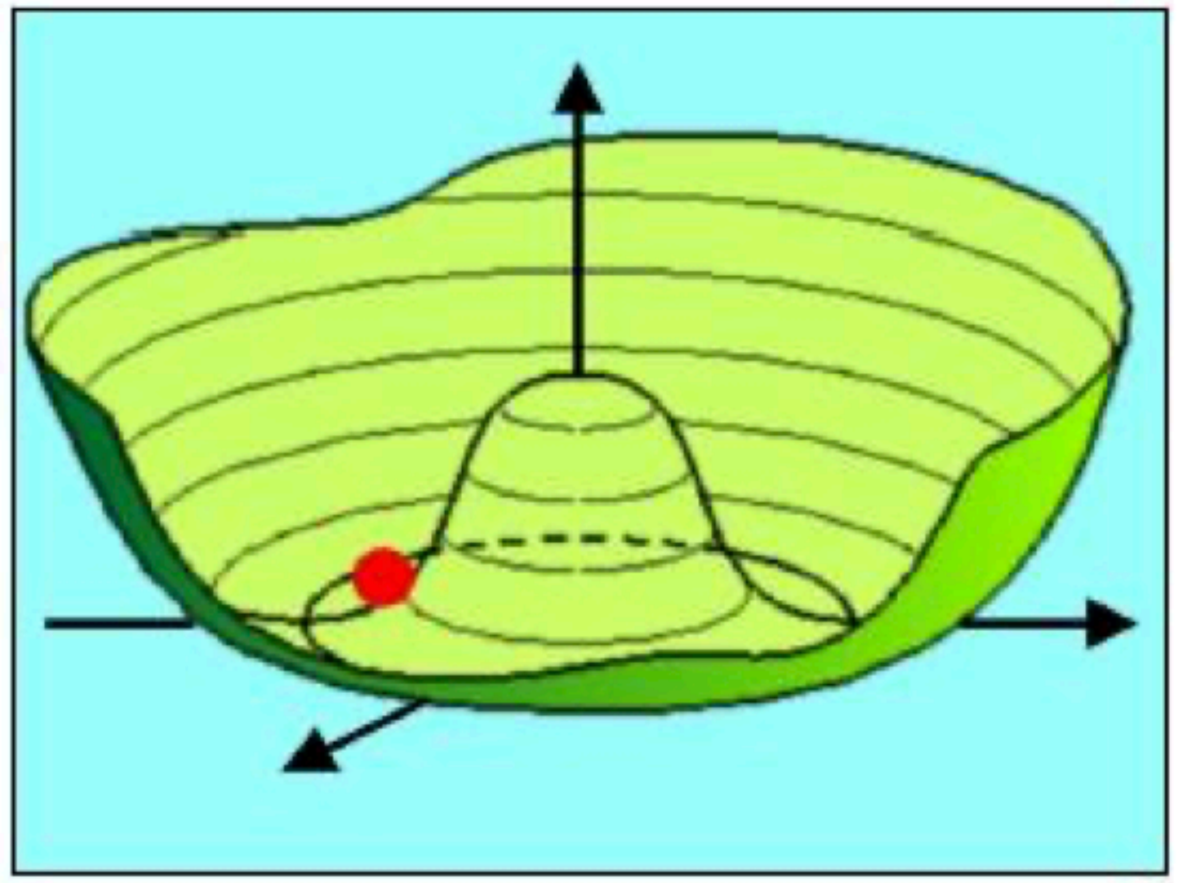
- Axion Miniclusters in the Milky Way
- Axion-photon conversion in NS magnetospheres
- Axions from the Sun
- Direct detection of the axion at INFN Frascati National Labs

Assumption: The PQ symmetry broke after inflation, $f_a \lesssim H_I$

[For the opposite limit $f_a \gtrsim H_I$ see e.g. **LV** & Gondolo, PRD 2009, PRD 2010]

The PQ field embedding the QCD axion field $\Phi = \left(r + \frac{f_a}{\sqrt{2}}\right) e^{-\phi/v}$

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



Figures from Steen Hannestad

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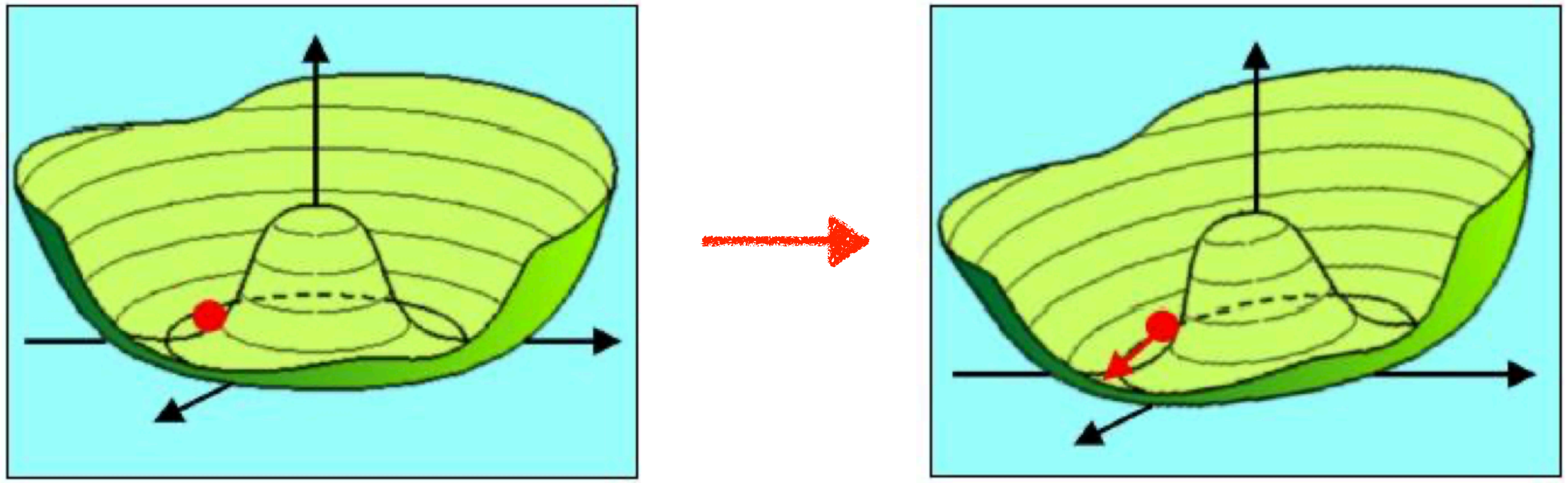


Figures from Steen Hannestad

Misalignment mechanism

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]

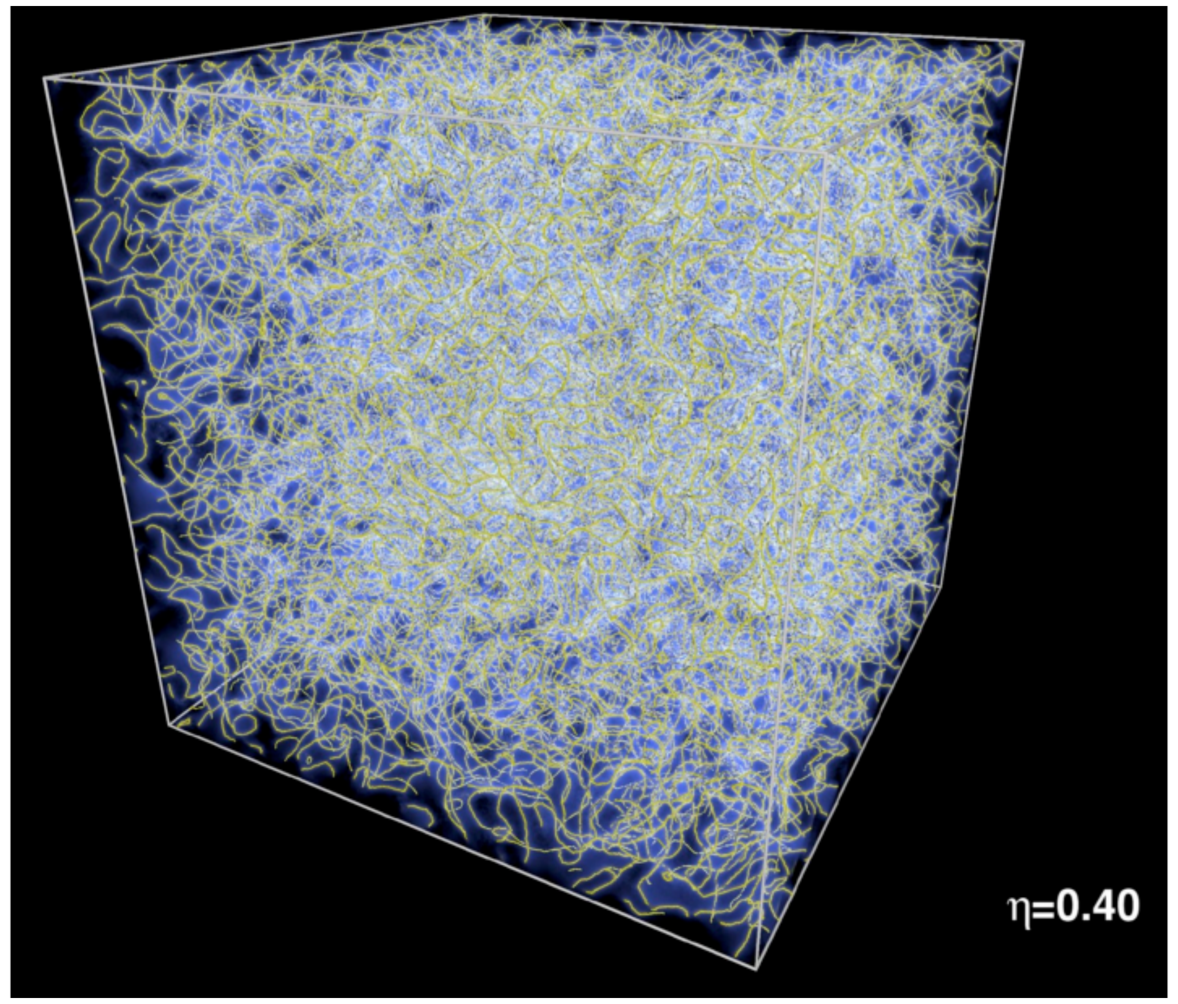
The exact assessment comes from lattice QCD computations [Borsanyi+ 2016]

Assumption: The PQ symmetry broke after inflation, $f_a \lesssim H_I$

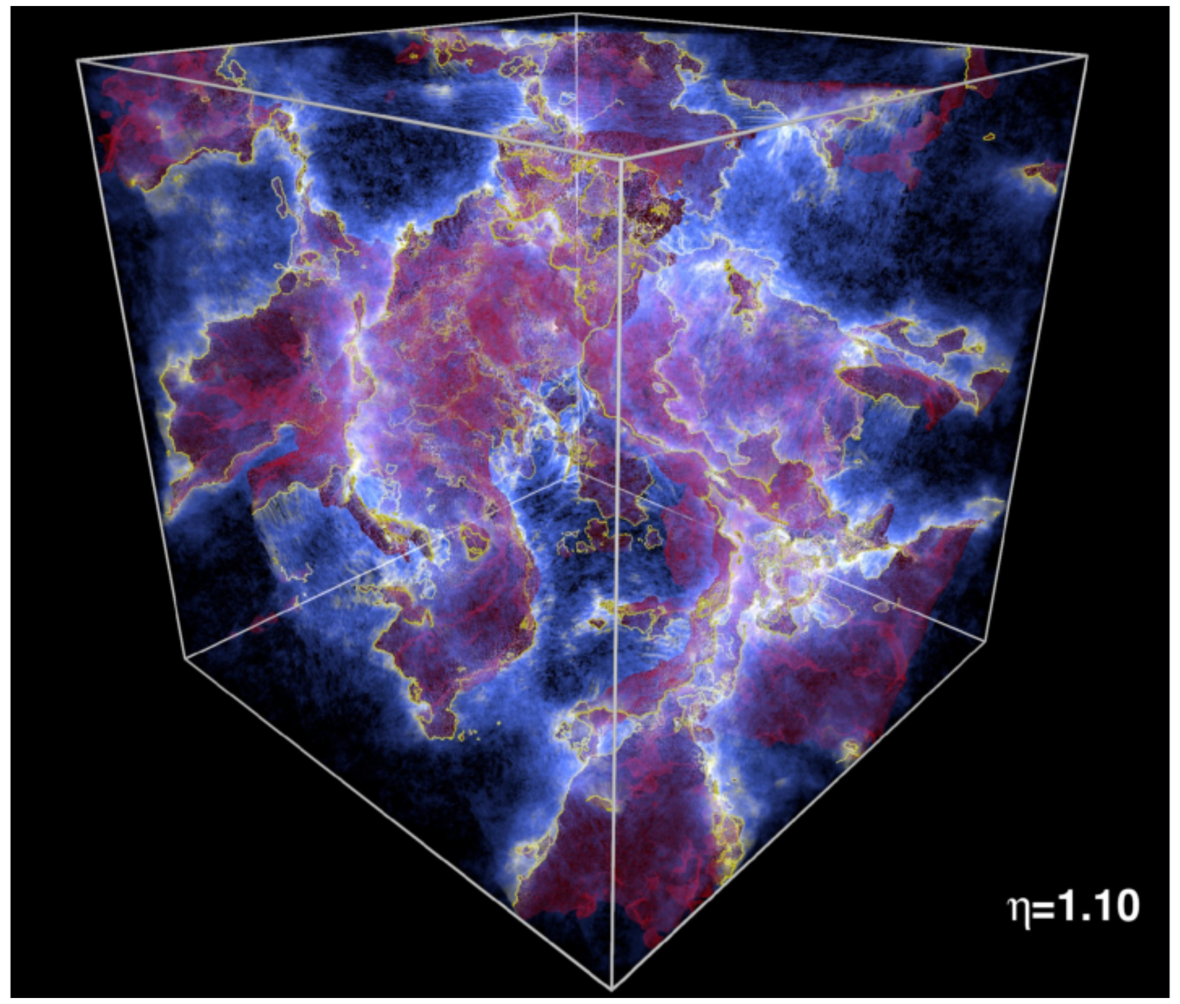
String network quickly enters a scaling regime with $\rho_{\rm scaling} = \xi\mu/t^2$

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

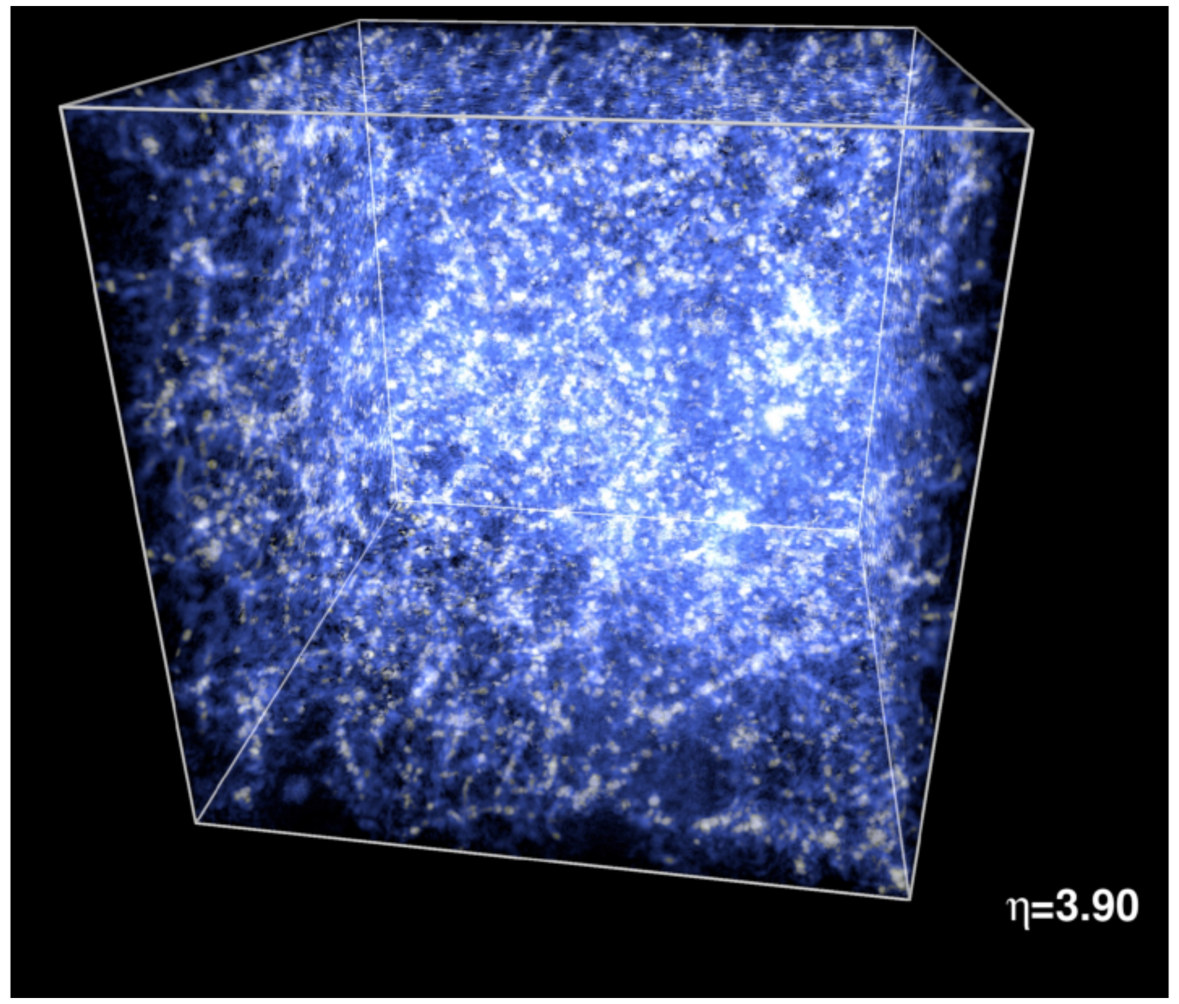
String length per Hubble volume ξ



Before QCD PT



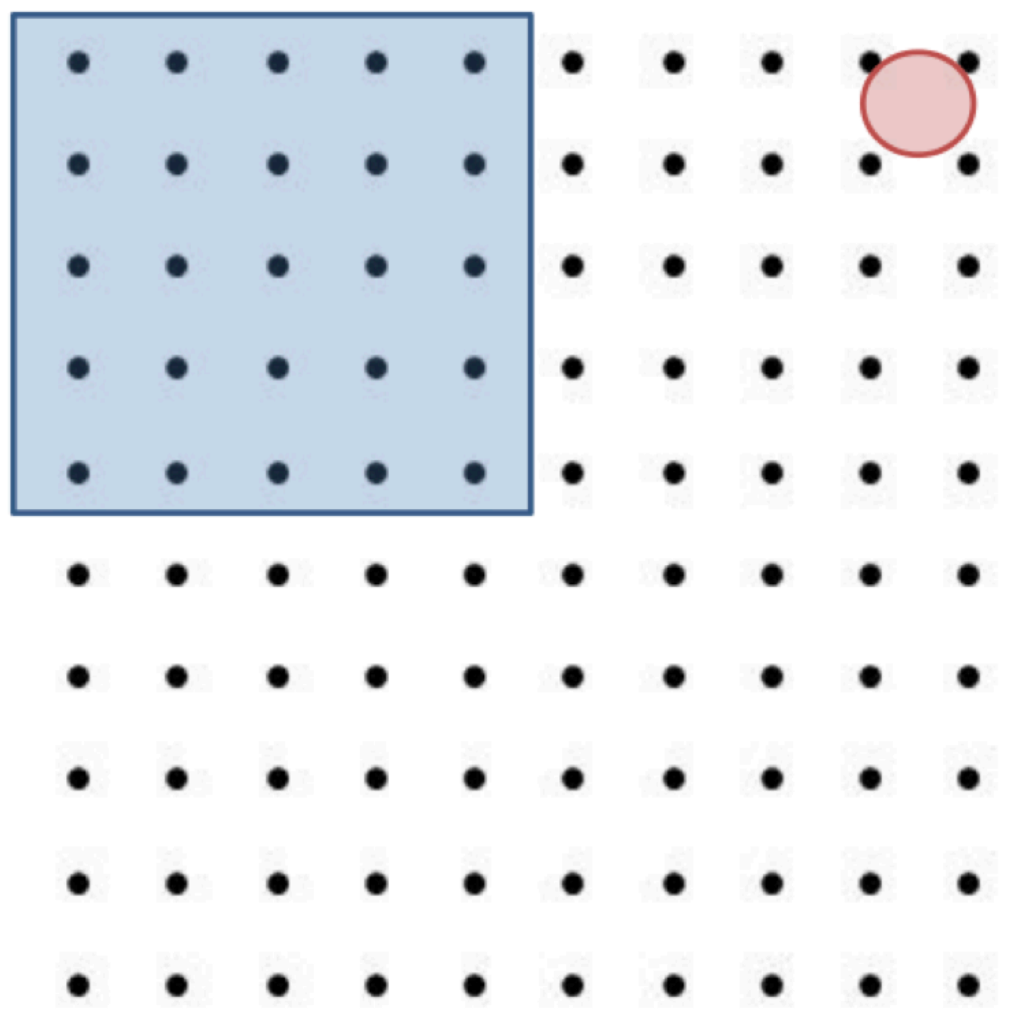
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



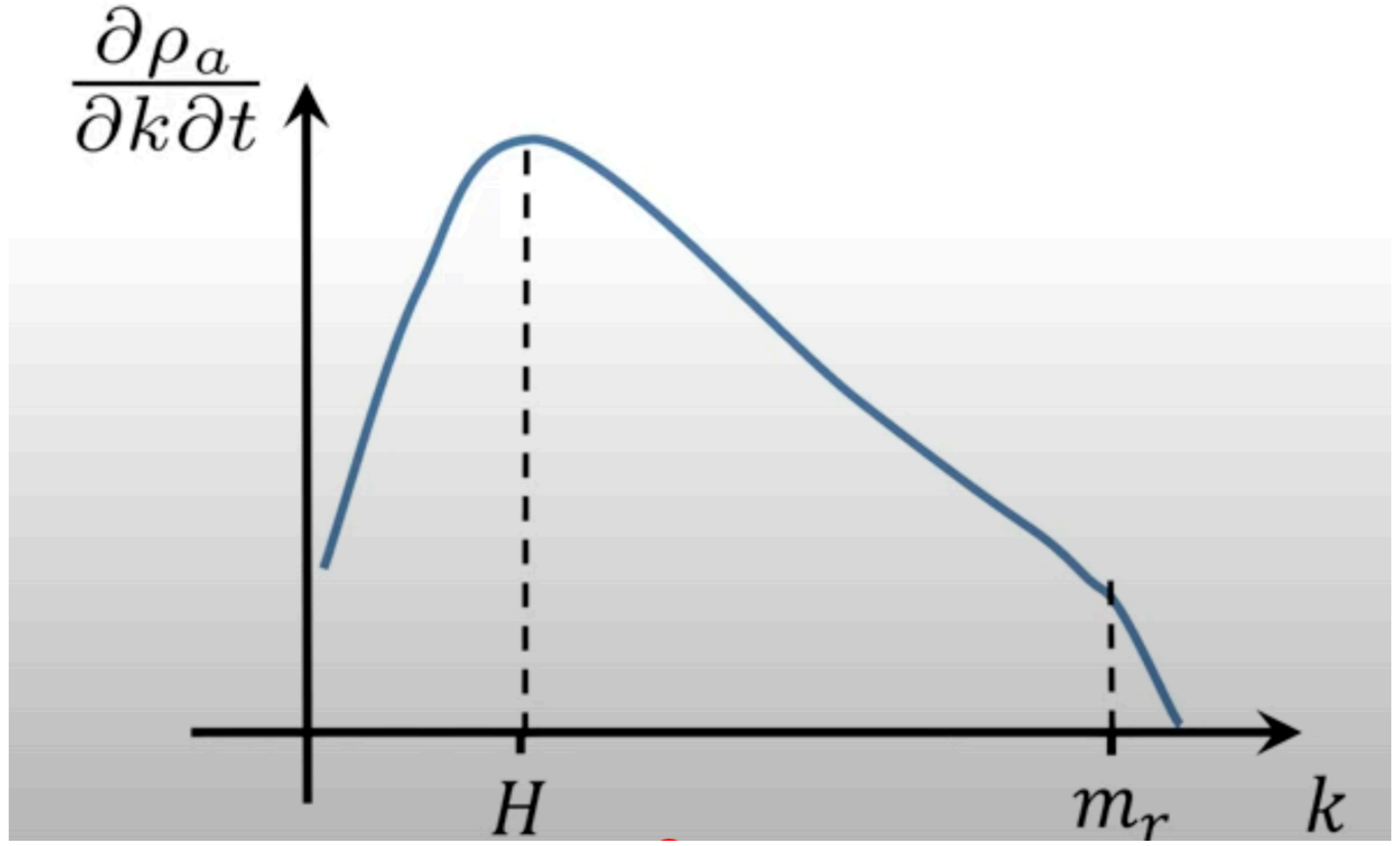
Credits: Ed Hardy

$N \approx 5000^3$

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

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 $k \approx \sqrt{2\lambda} f_a$

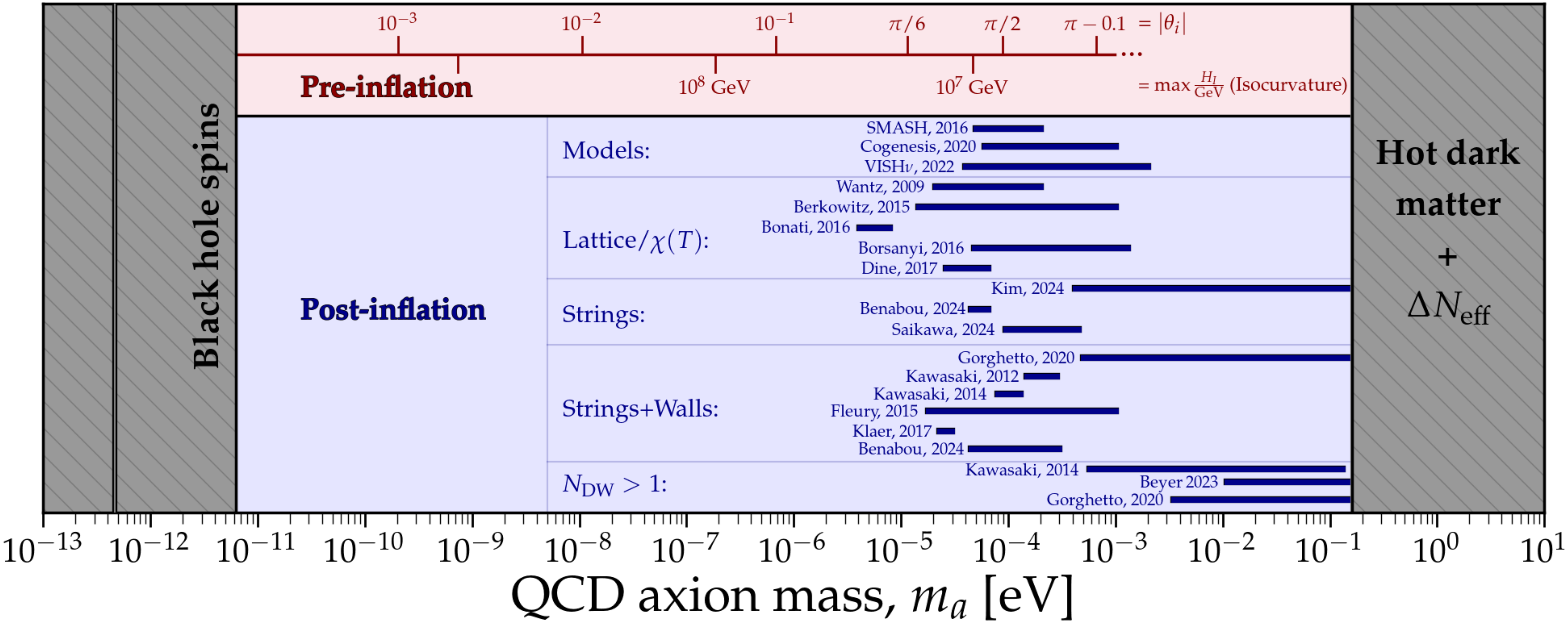
$q > 1$ "Effective Nambu–Goto string" [Davis 1985, 1986; Battye & Shellard 1994a, 1994b] leads to more axions and a higher DM mass $\sim \mathrm{meV}$ [Gorghetto+ 2018, 2021]
An IR spectrum is also found in [Hiramatsu+ 2011]

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

Predictions for the DM mass of the QCD axion

Luca Visinelli

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



The QCD Axion: foundations

We introduce the QCD 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]

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

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

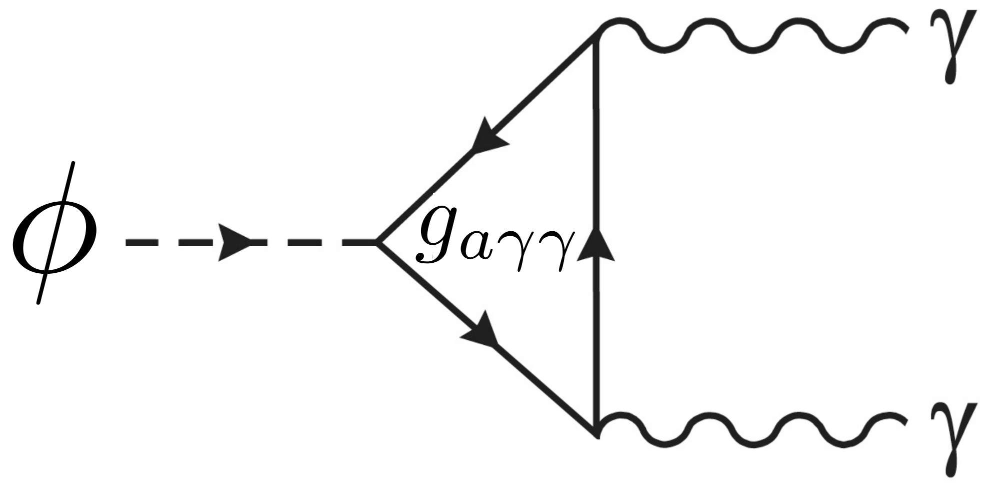
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{4}\, g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu} + c_e\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e + c_N\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N$$

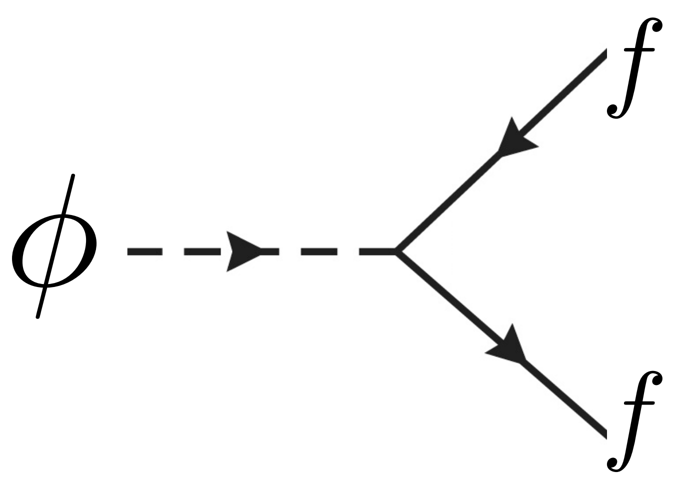
Self-interacting potential

Axion-photon coupling

Axion-electron coupling

Axion-nucleon coupling





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

Our 2020 review on the QCD axion was born here

Physics Reports 870 (2020) 1–117

Contents lists available at ScienceDirect

Physics Reports

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

The landscape of QCD axion models

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ARTICLE INFO

Article history:
Received 15 March 2020
Received in revised form 3 June 2020
Accepted 3 June 2020
Available online 24 June 2020
Editor: Dr Jonathan L. Feng

ABSTRACT

We review the landscape of QCD axion models. Theoretical constructions that extend the window for the axion mass and couplings beyond conventional regions are highlighted and classified. Bounds from cosmology, astrophysics and experimental searches are reexamined and updated.

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

Axion Miniclusters in the Milky Way

Axion miniclusters

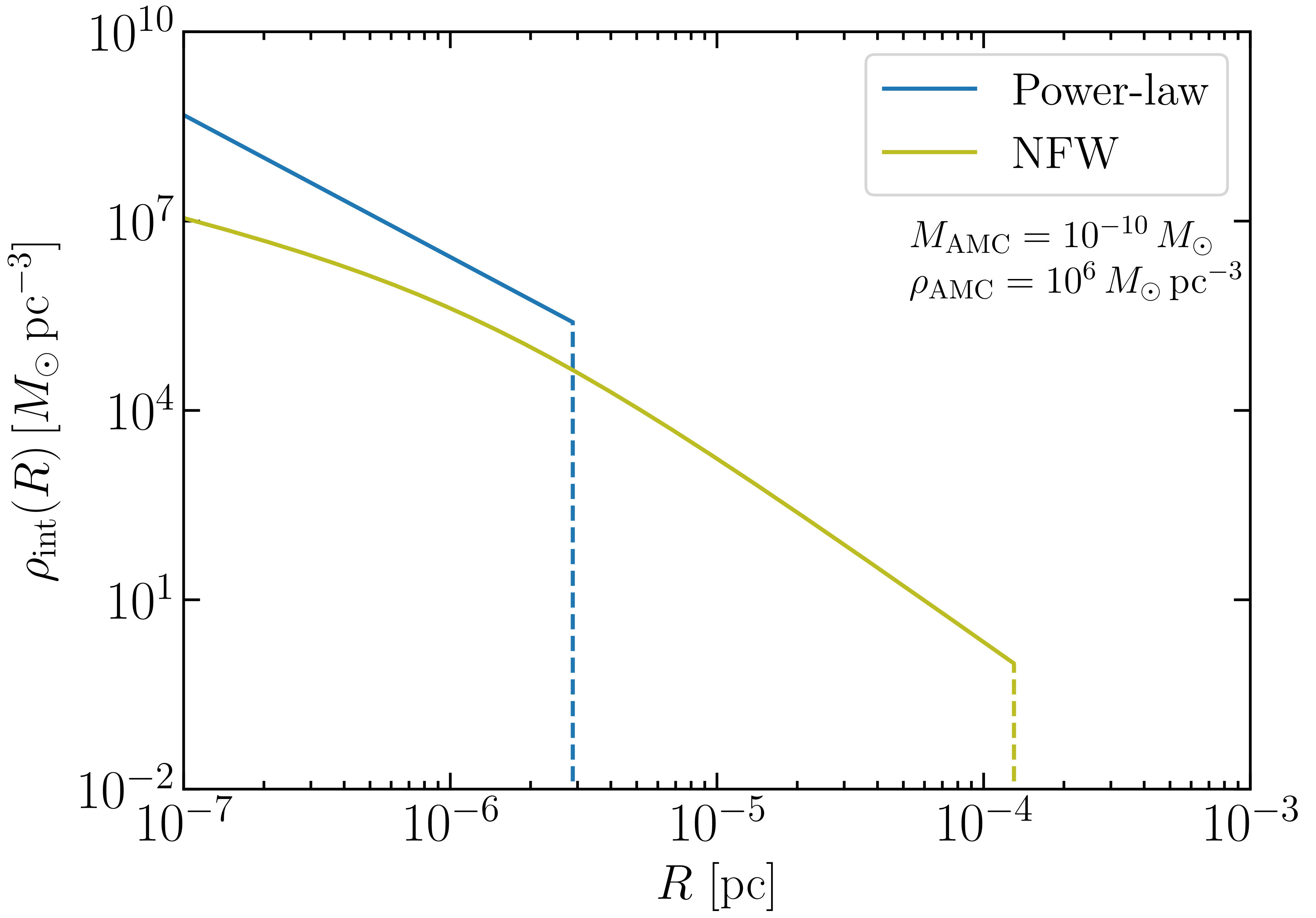
In post-inflation symmetry breaks, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

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

Typical minicluster mass:

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

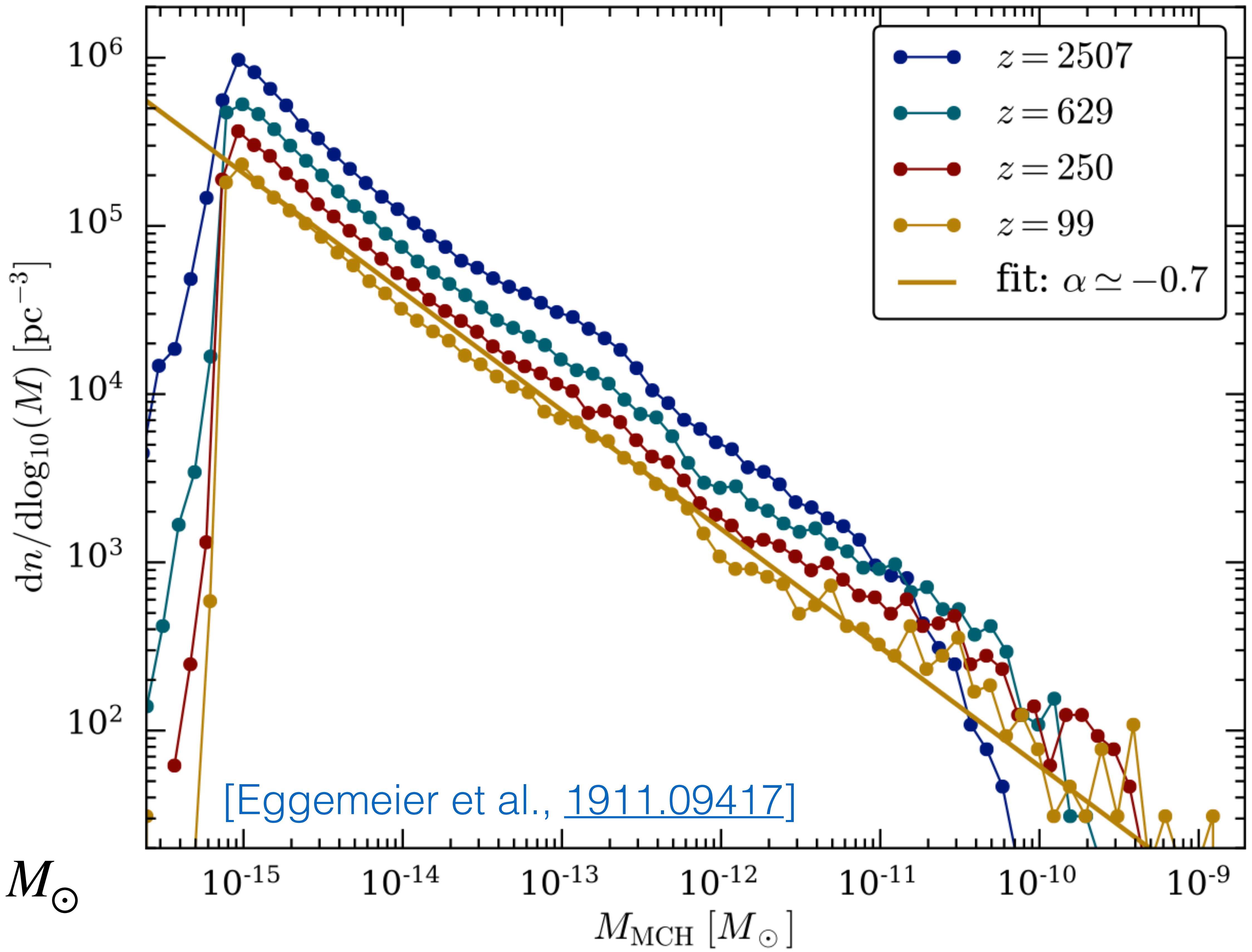
[Hogan & Rees 1988; Kolb & Tkachev 1994]



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



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

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

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

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

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

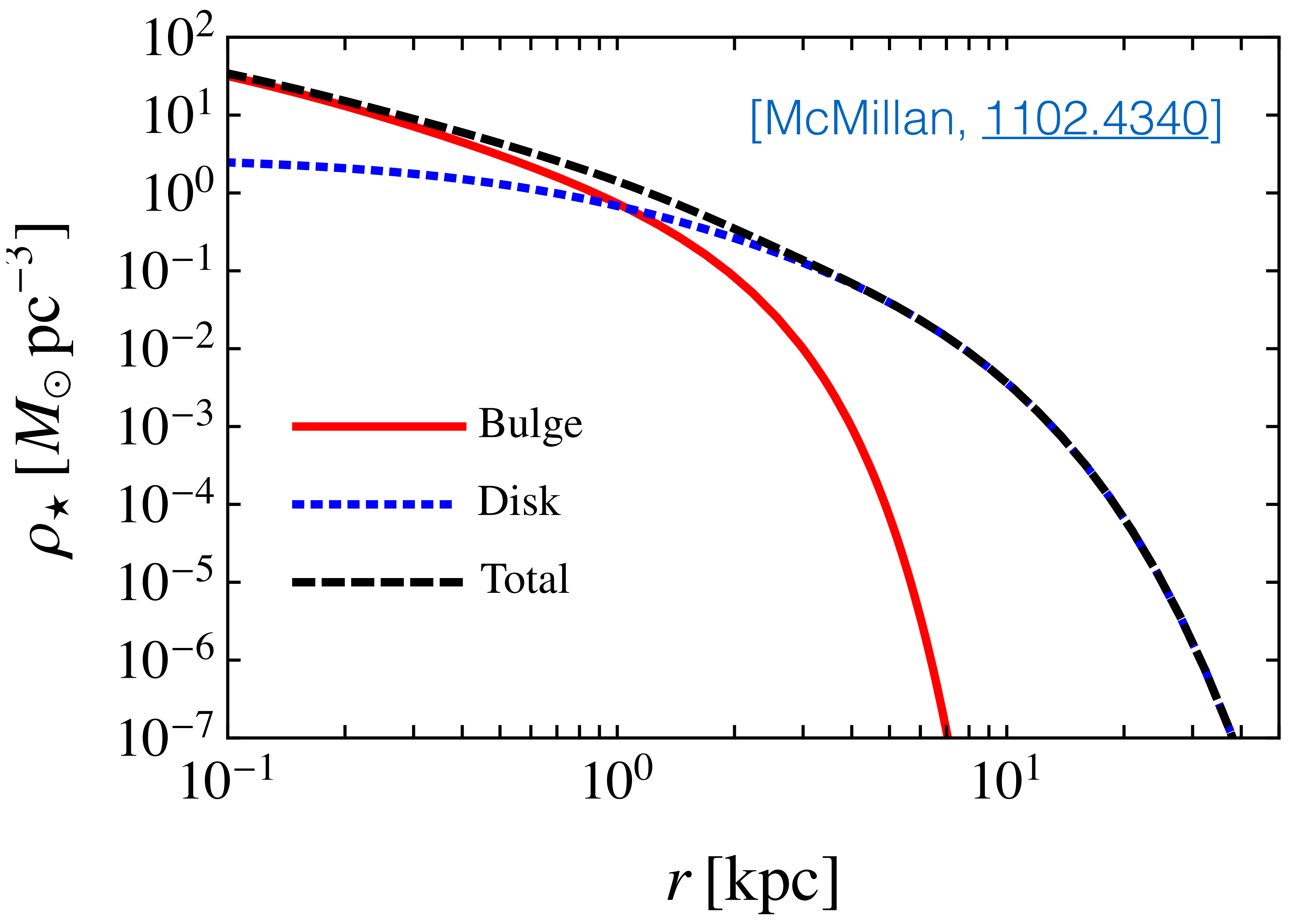
(Growth of hierarchical structure to today)

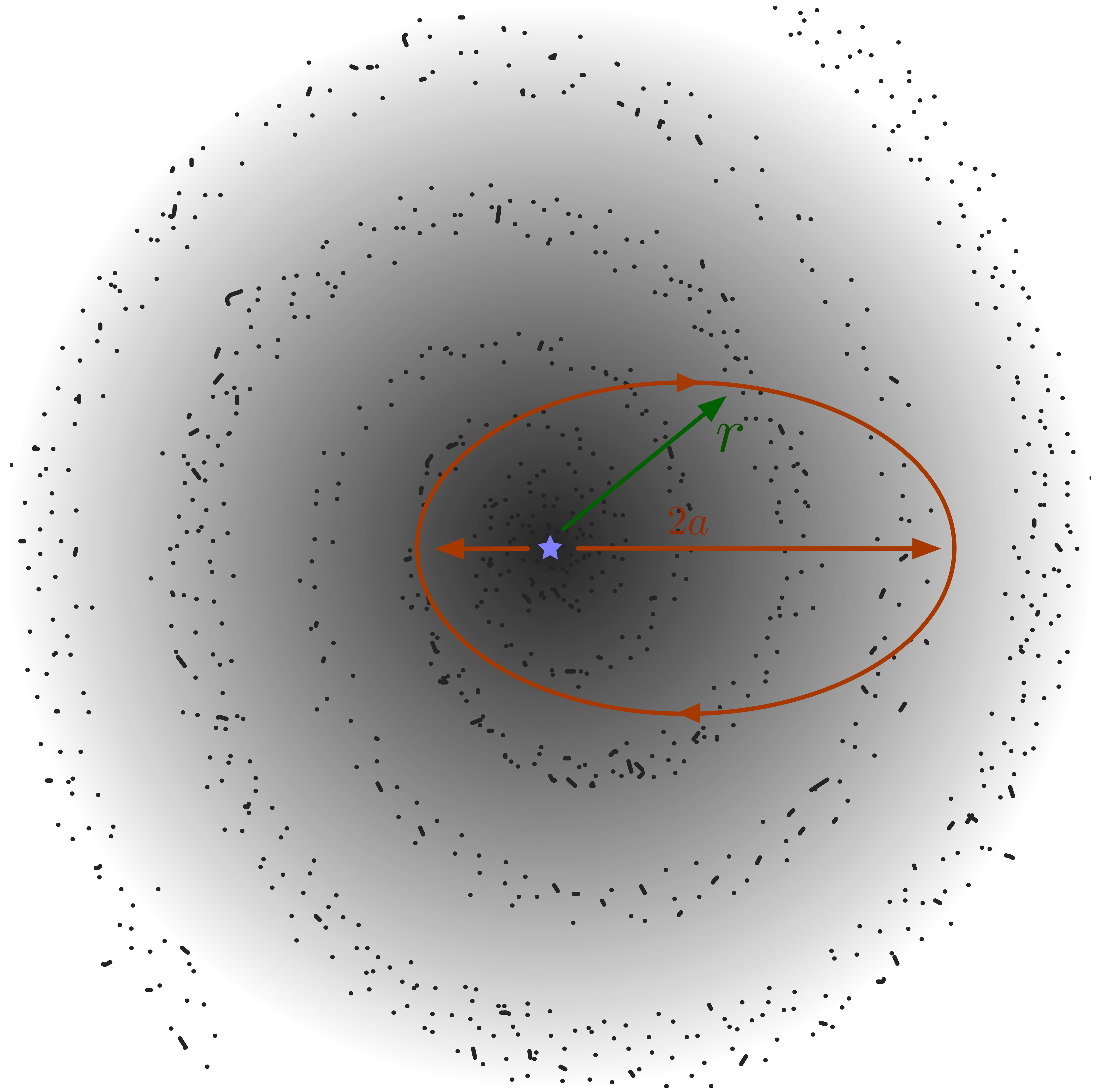
[Fairbairn et al., 1707.03310]

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

[github.com/bradkav/axion-miniclusters]

Milky Way Setup





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

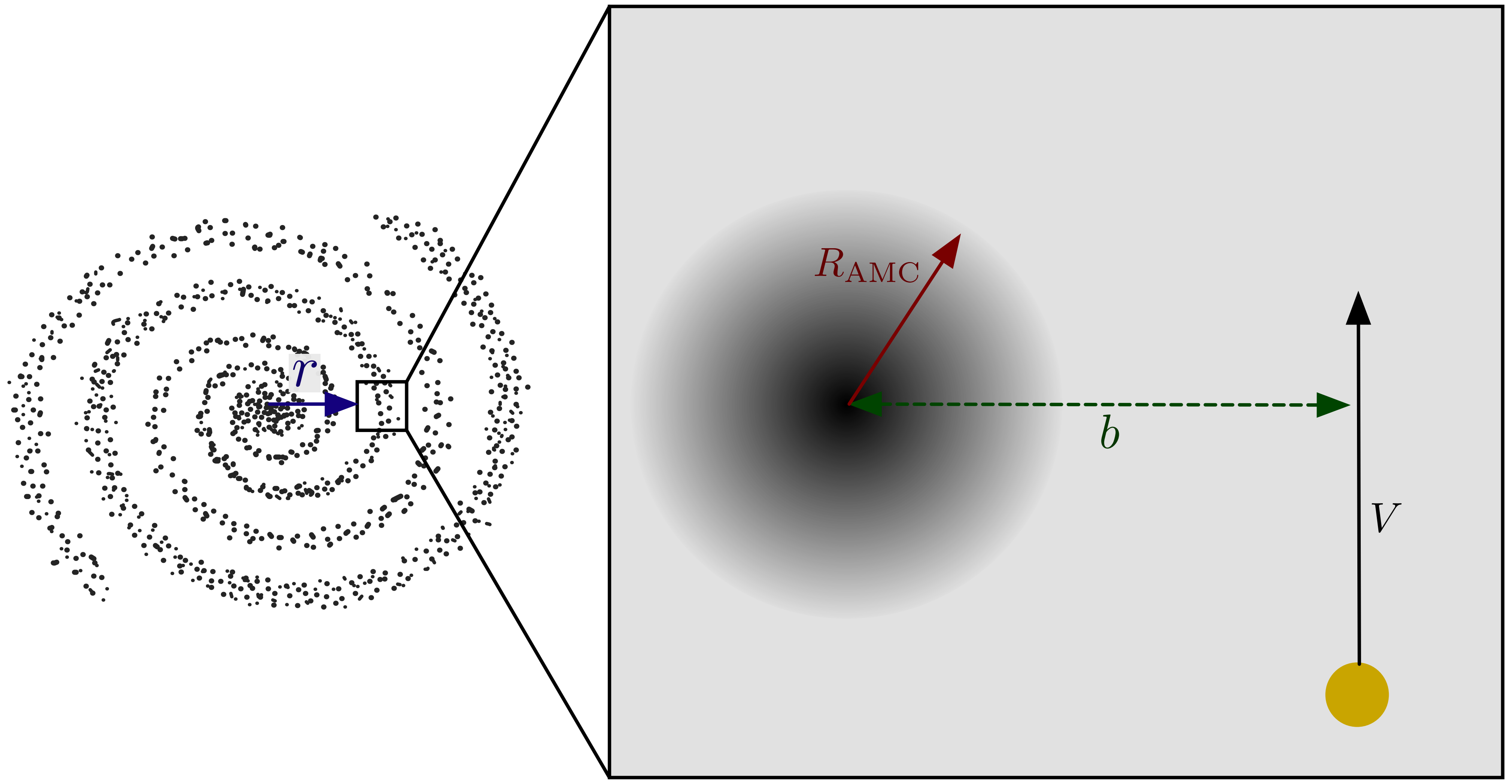
$$f_{\rm AMC} \approx 100\%$$

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

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

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 2011.05377

See also [Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586]

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…

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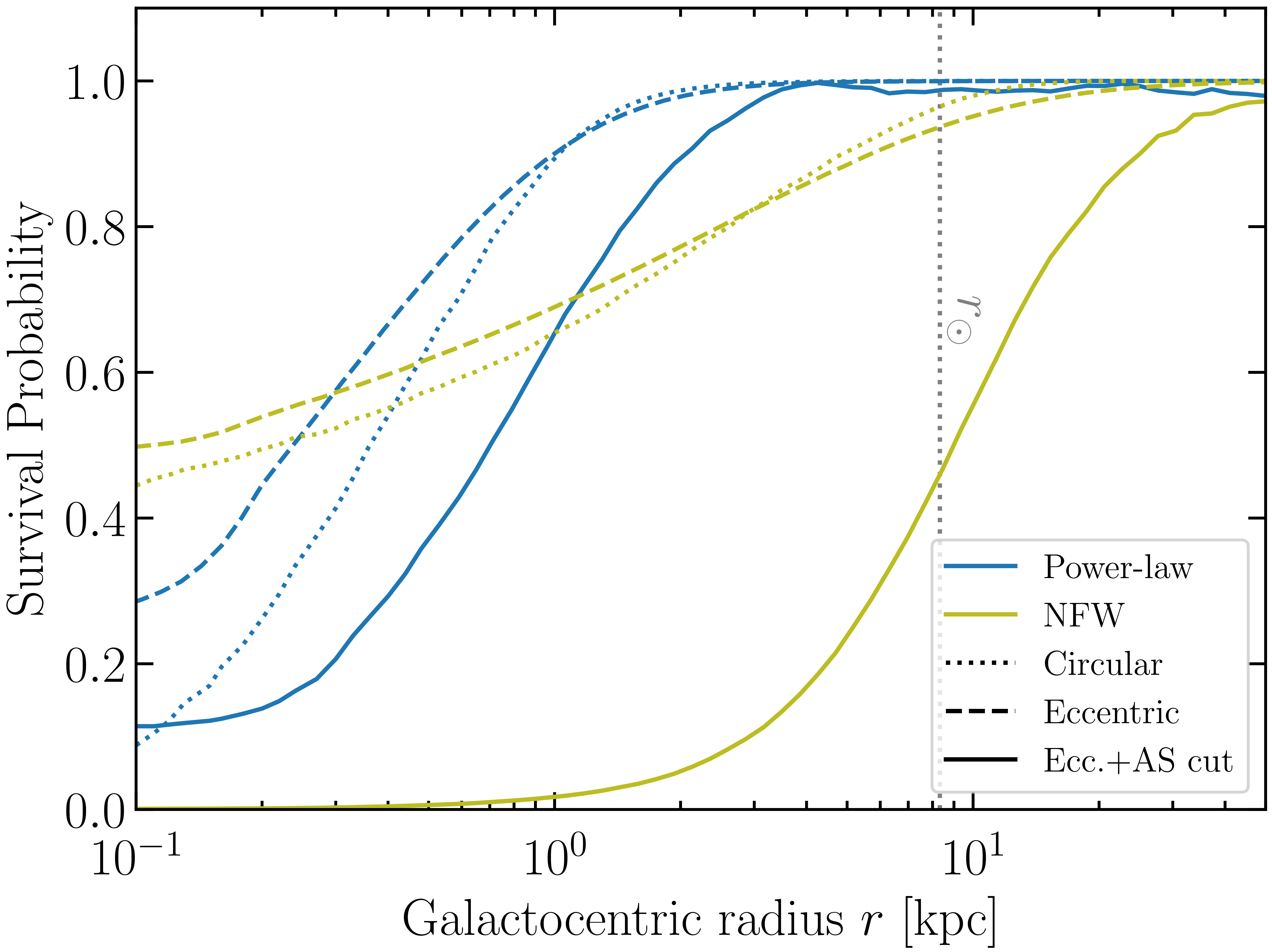
Axion miniclusters abundance today



Kavanagh, Edwards, **LV**, Weniger, PRD 2020 2011.05377

Observational Consequences:
Indirect searches

Axion-photon conversion in NS magnetospheres

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

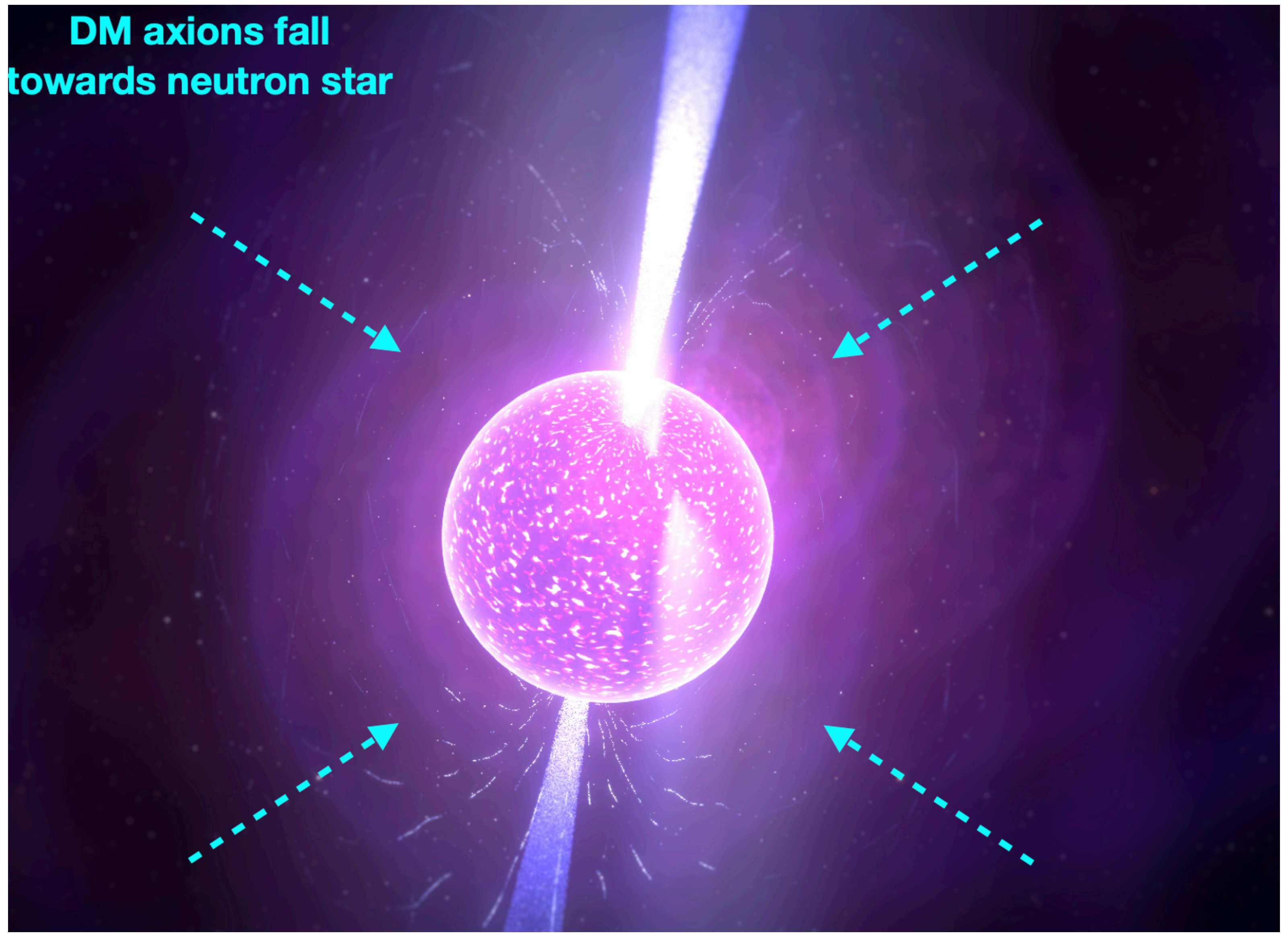
$$\frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega} \sim \frac{\pi}{3}\, g_{a\gamma\gamma}^2 B_0^2 \frac{{R_{\rm NS}}^6}{{R_c}^3} \frac{\rho_c}{m_a}$$

[Hook et al., 1804.03145; Safdi et al., 1811.01020]

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

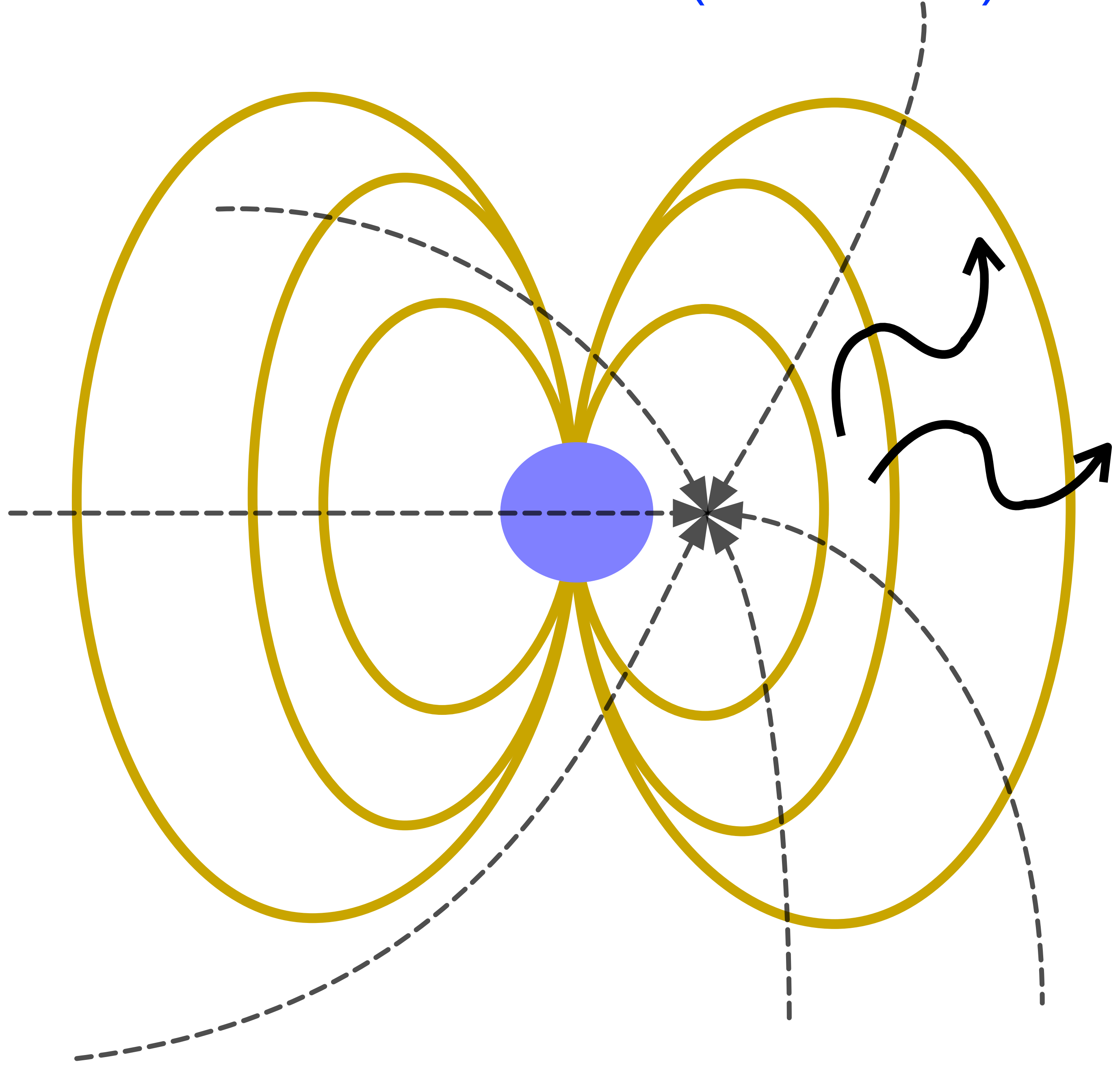
Look for axion-photon conversion from an individual NS

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



Transient enhancements to ρ_c from AMC encounters

Edwards+ (with **LV**) 2011.05378



Axion-photon conversion in NS magnetospheres

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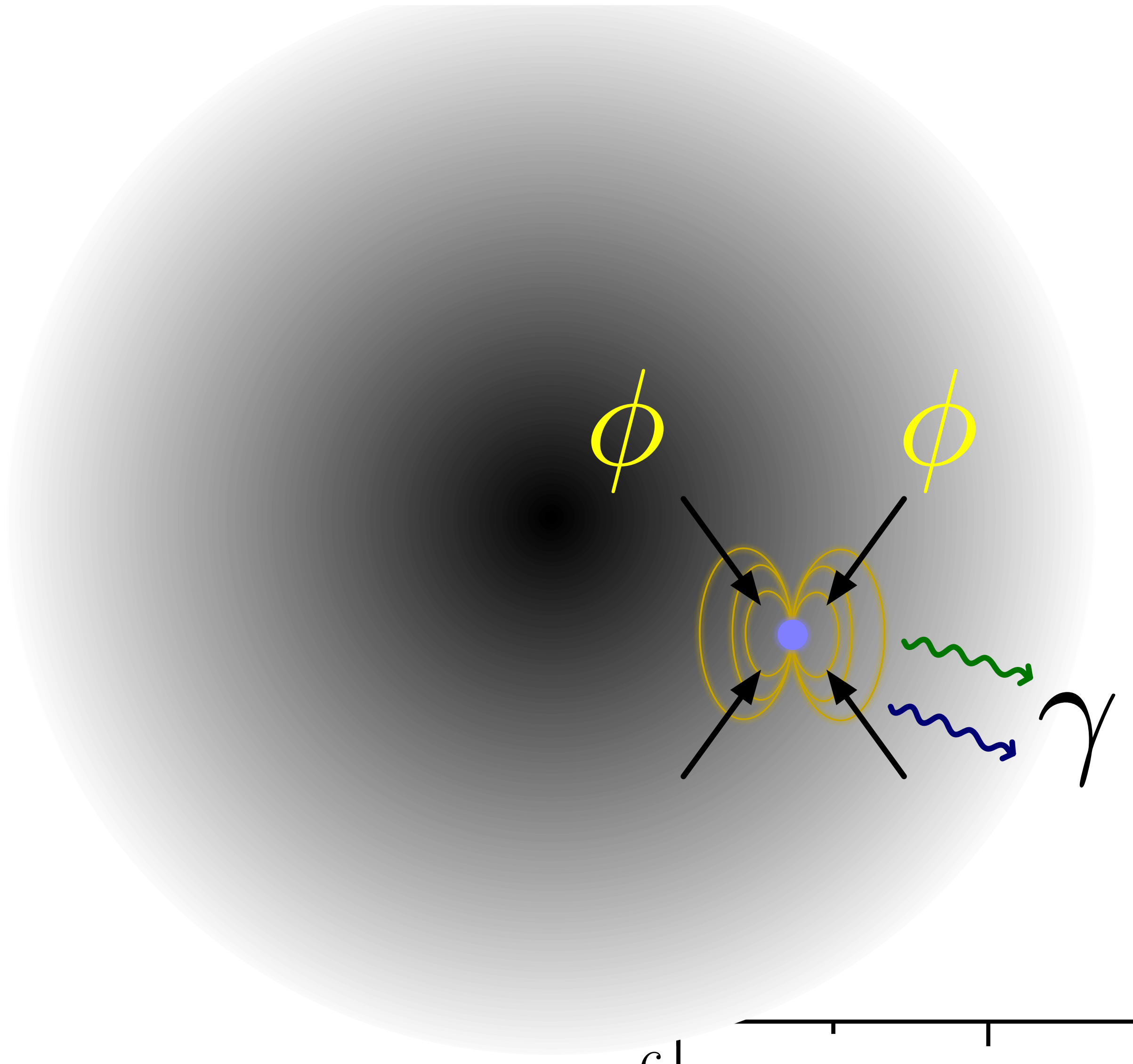
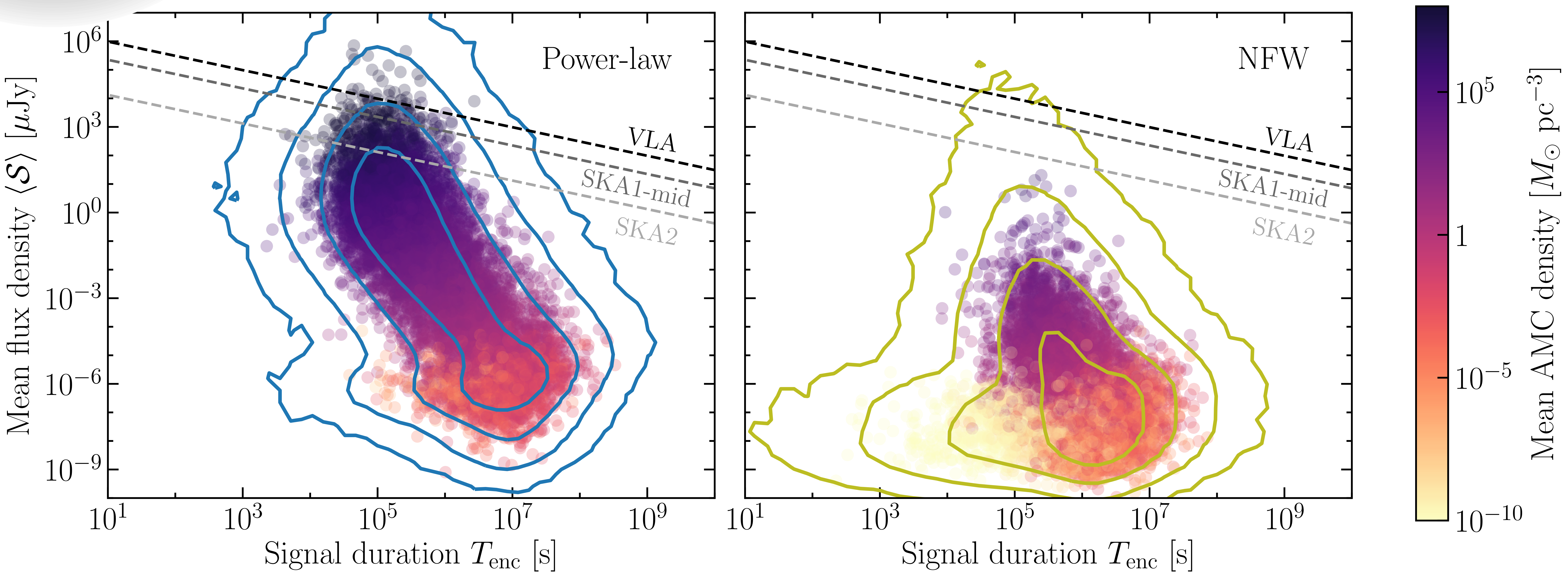


$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$

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

Edwards+ (with **LV**) PRL 2021 2011.05378



Can we pick up this signal in radio?

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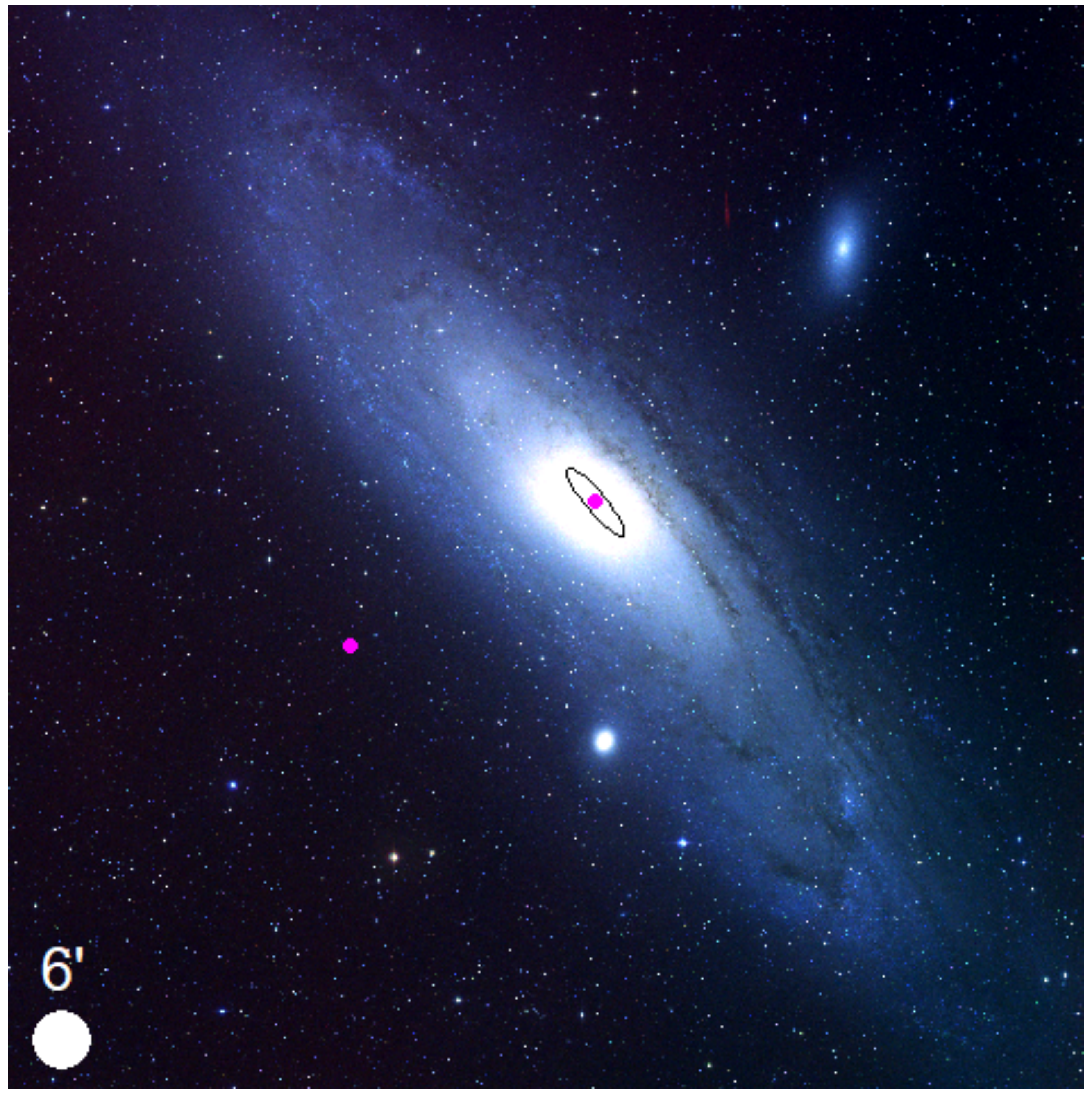


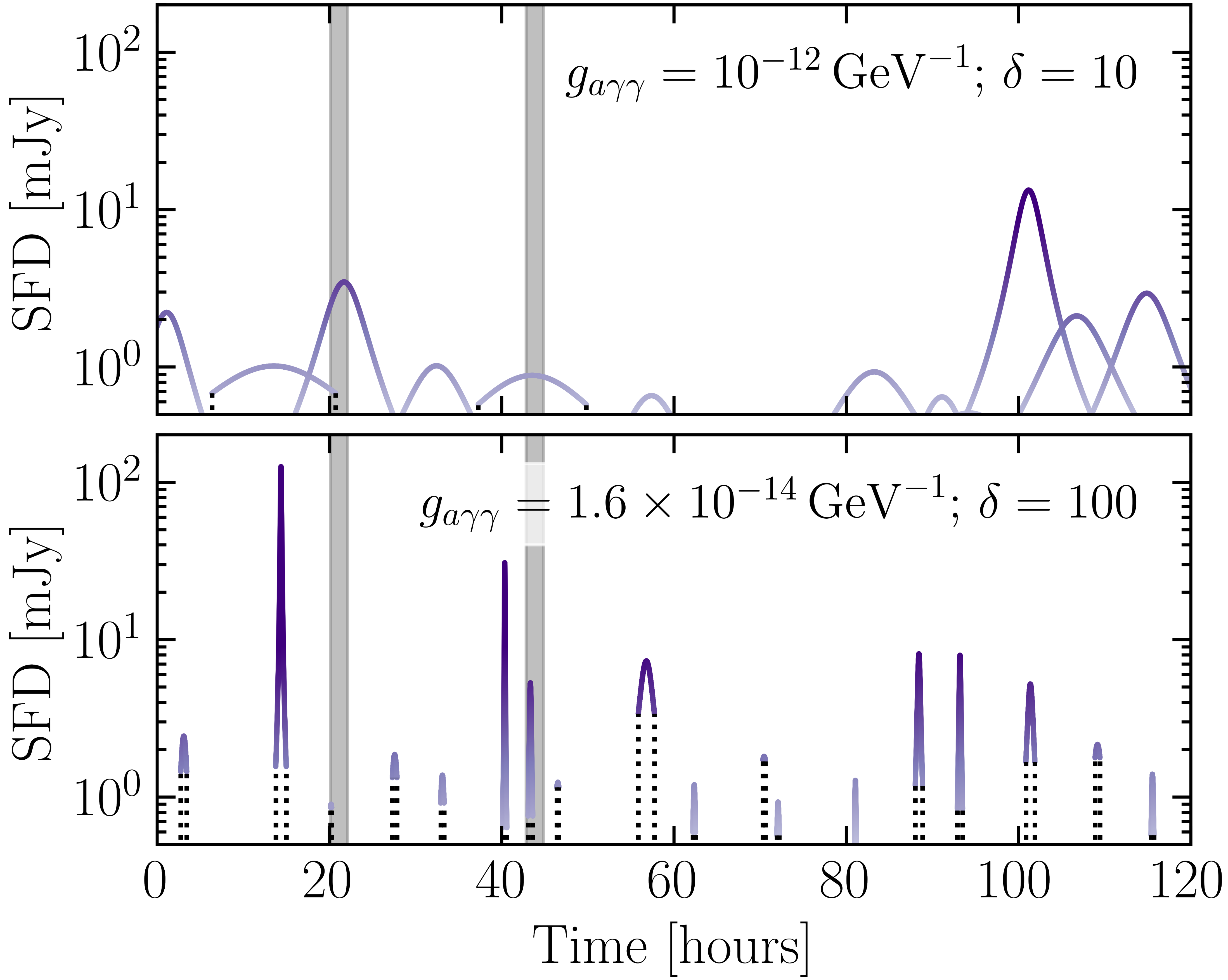
2 grant proposals accepted by the Green Bank Telescope. We have observed Andromeda

2022: X-band observation (8-12 GHz)

2023: C-band observation (4-8 GHz)

(10 GHz $\approx 40\,\mu\text{eV}$)

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



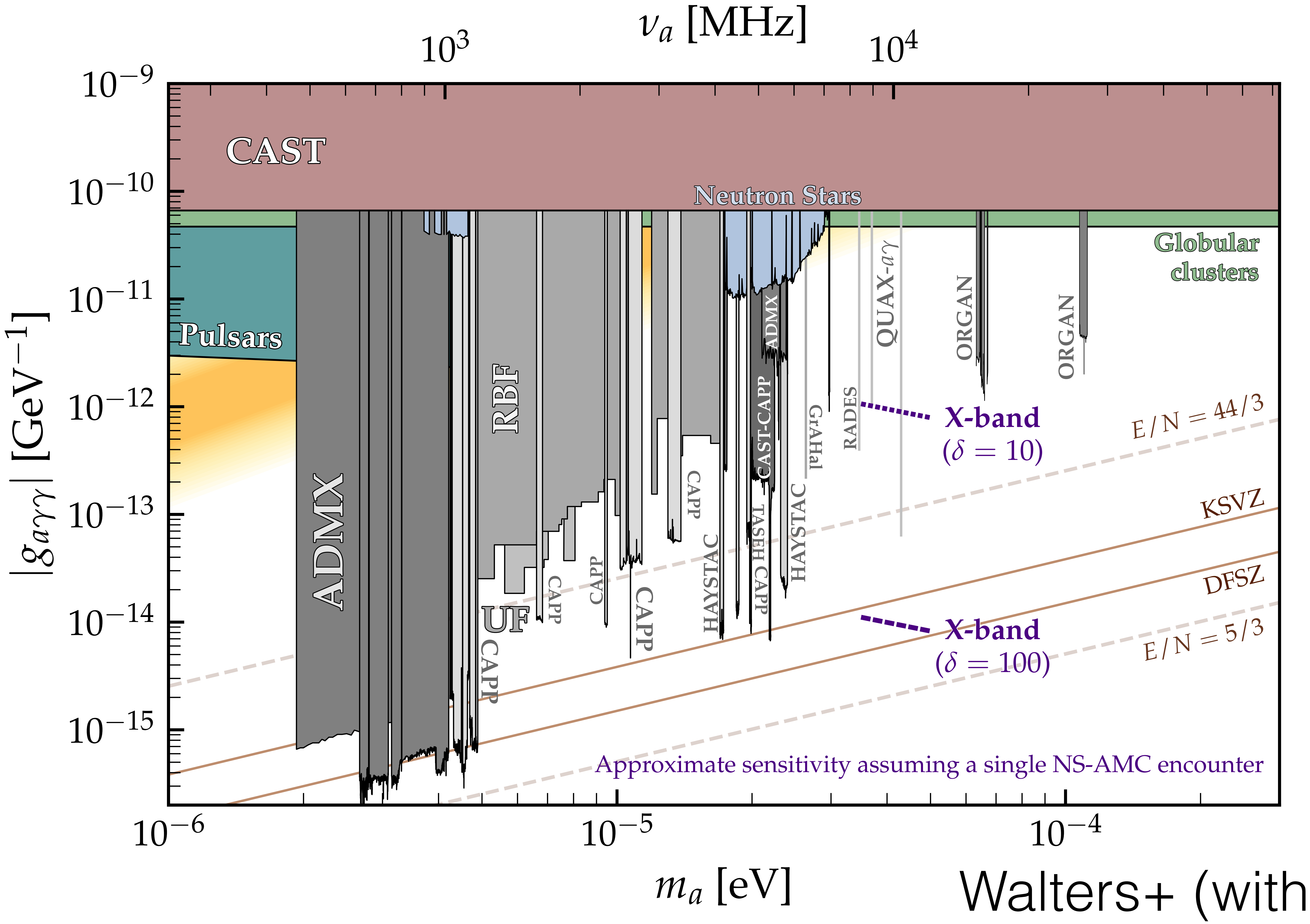
Walters+ (with **LV**) 2407.13060

Axion mass $m_a = 40\,\mu\text{eV}$ and AMC mass $M_{\rm AMC} = 10^{-10}\,M_\odot$

Simulate 20 encounters with NS of $B_0 = 10^{14}\,\text{G}$ and $P = 1\,\text{s}$

Signal lasting min to hour

Can we pick up this signal in radio?



Walters+ (with **LV**) [2407.13060]

Ongoing work with theorists & lab experts (Wilczek, Van Bibber, Rybka).
We formed **ASTRA** (Axion Search via Telescope for Radio Astronomy)

NEWS: funded by Jefferson Trust for a telescope < 2 GHz.

Observational Consequences: direct detection

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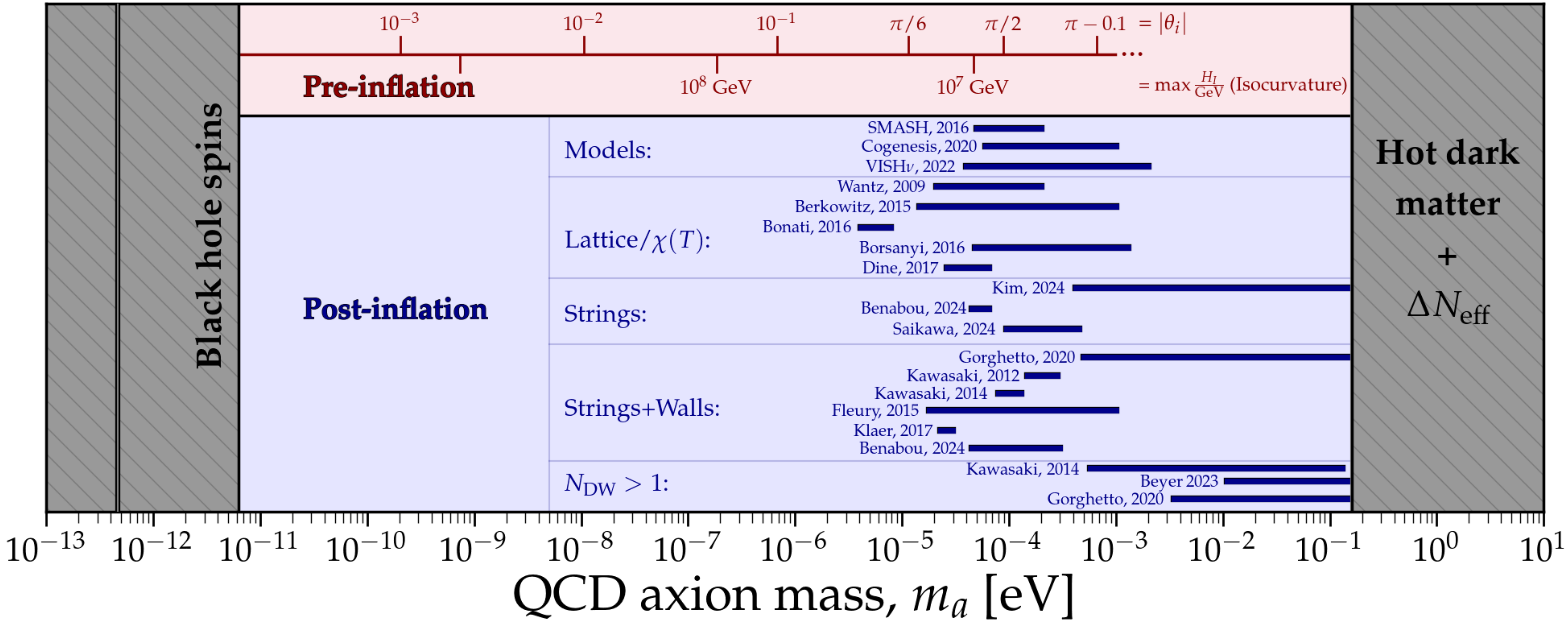
Predictions for the DM mass of the QCD axion

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



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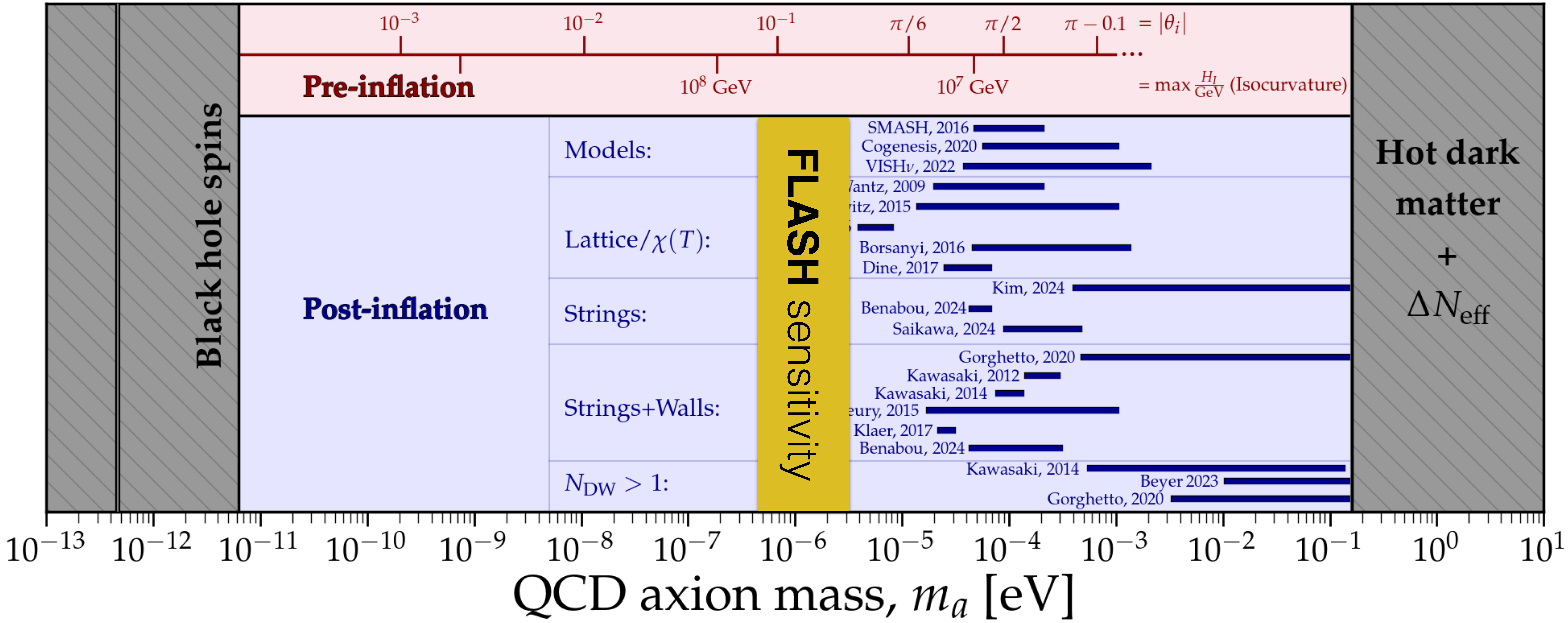
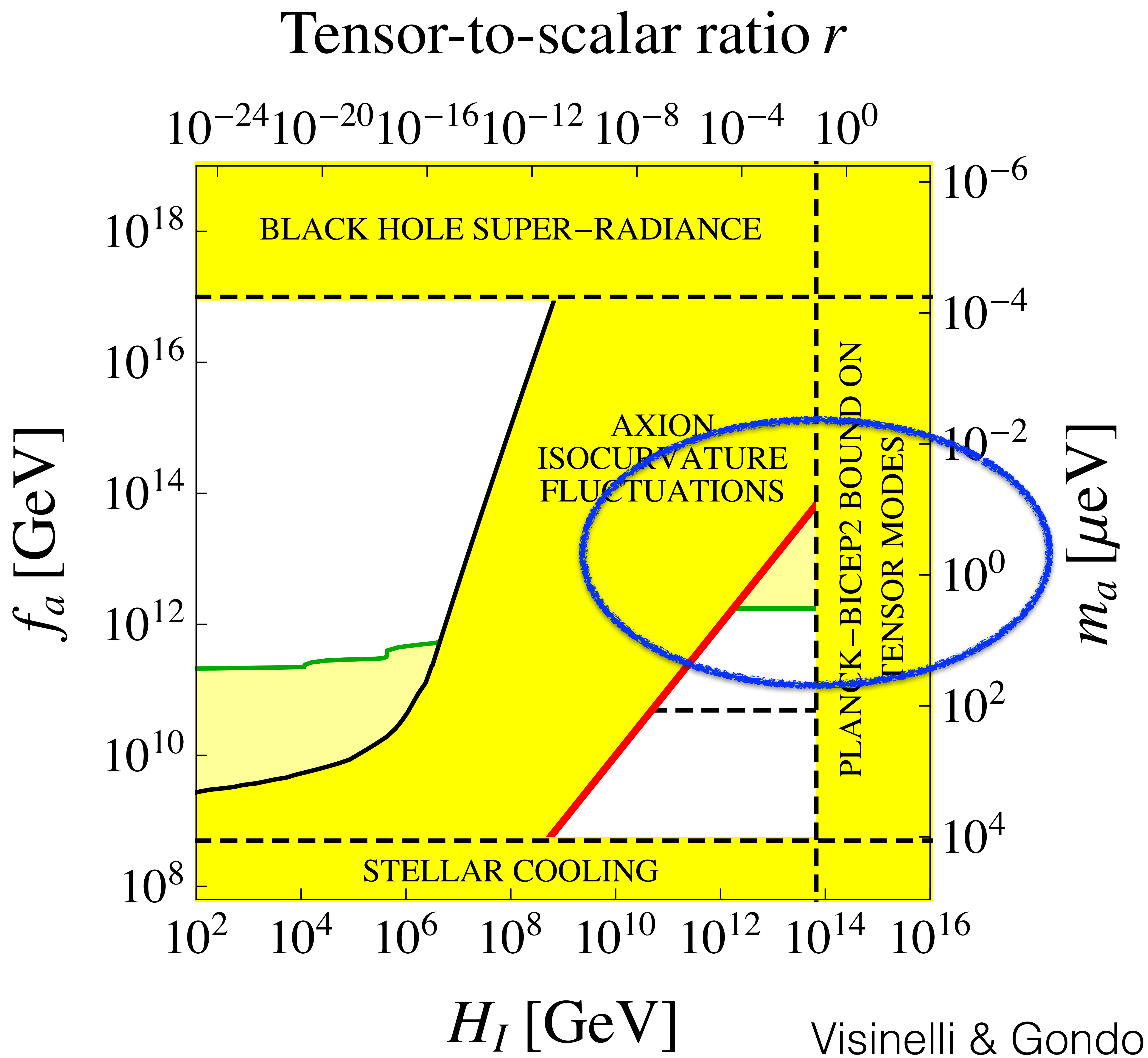


Predictions for the DM mass of the QCD axion



New physics in the form of
entropy release, modified cosmology,
new particles…
make lighter axions suitable DM candidates

Visinelli & Gondolo 0912.0015

Power transfer from axion DM to the cavity

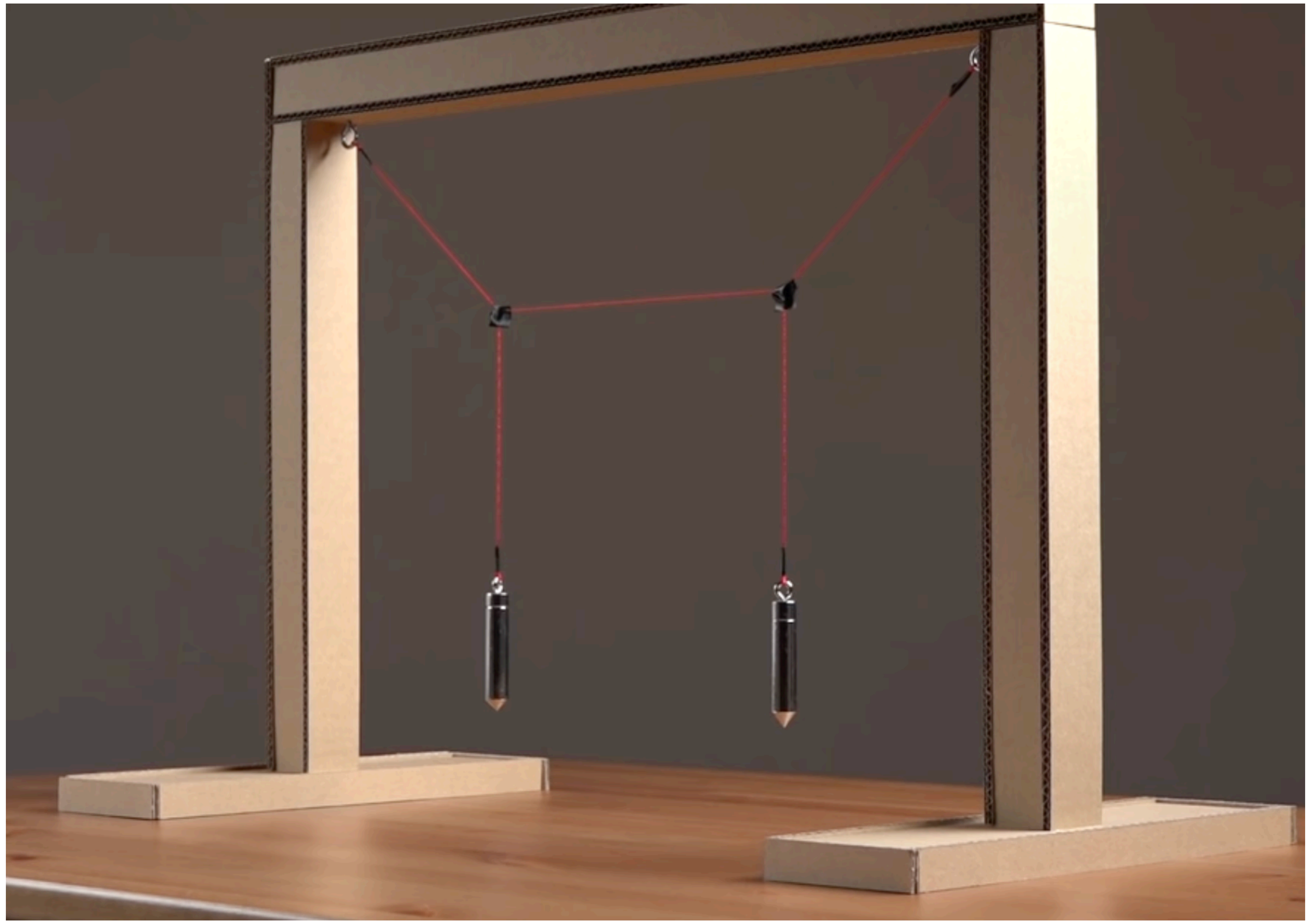
<u>Weak coupling</u>
Takes many swings to fully transfer the wave amplitude.

Number of swings is equivalent to cavity *Quality factor (Q)*.

Narrowband cavity response → iterative scan through frequency space.

$$k_a = (m_a, 10^{-6}\, m_a)$$

$$k_\gamma = (\omega, \omega) \longrightarrow \quad Q \sim 10^6$$



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

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

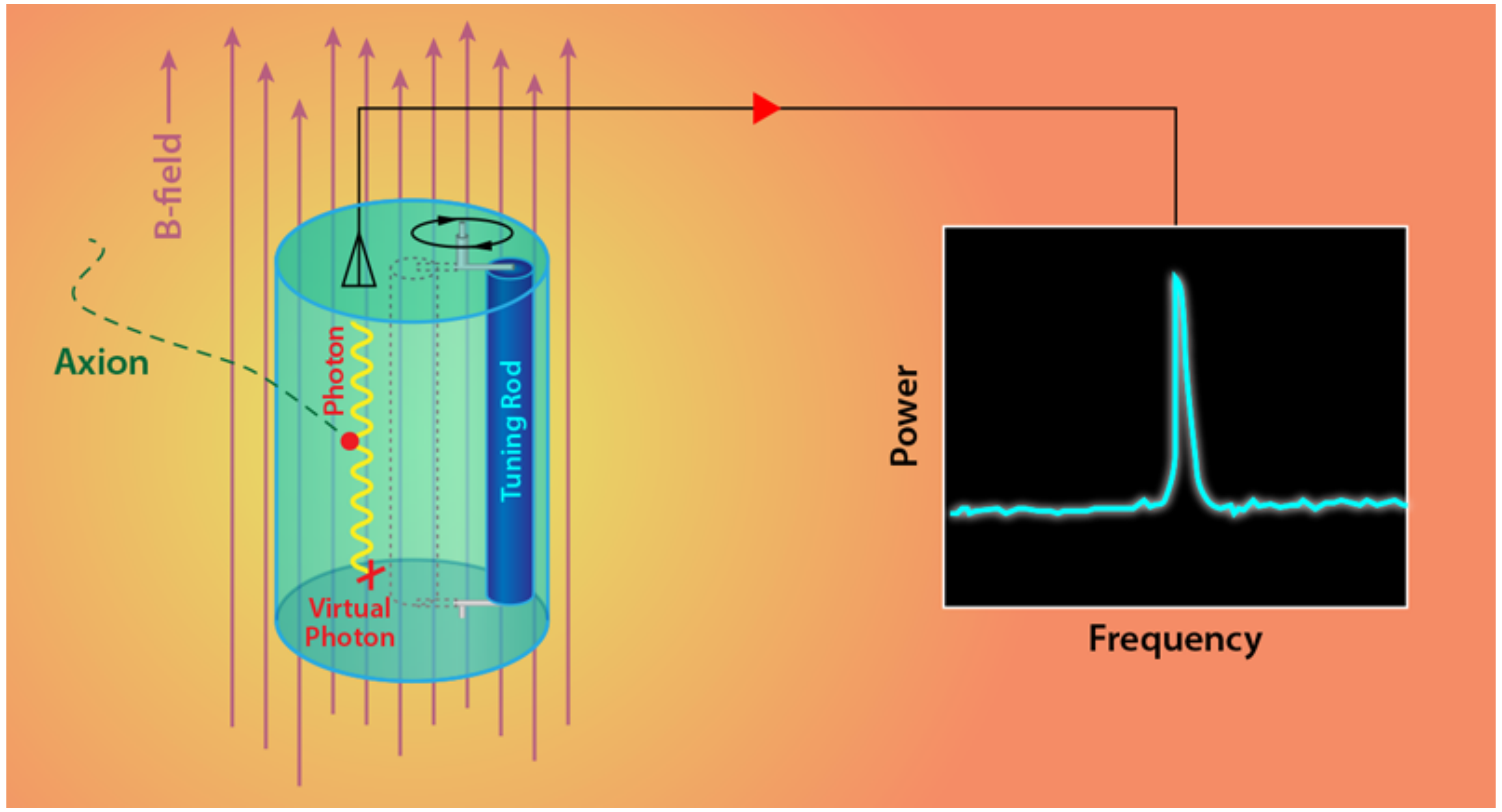
$$\boxed{P_{\rm sig} = (g_{a\gamma\gamma}^2 n_a) \times \left(Q_L B_0^2 V C_{nml}\right)}$$

Q_L Quality factor

V Cavity volume

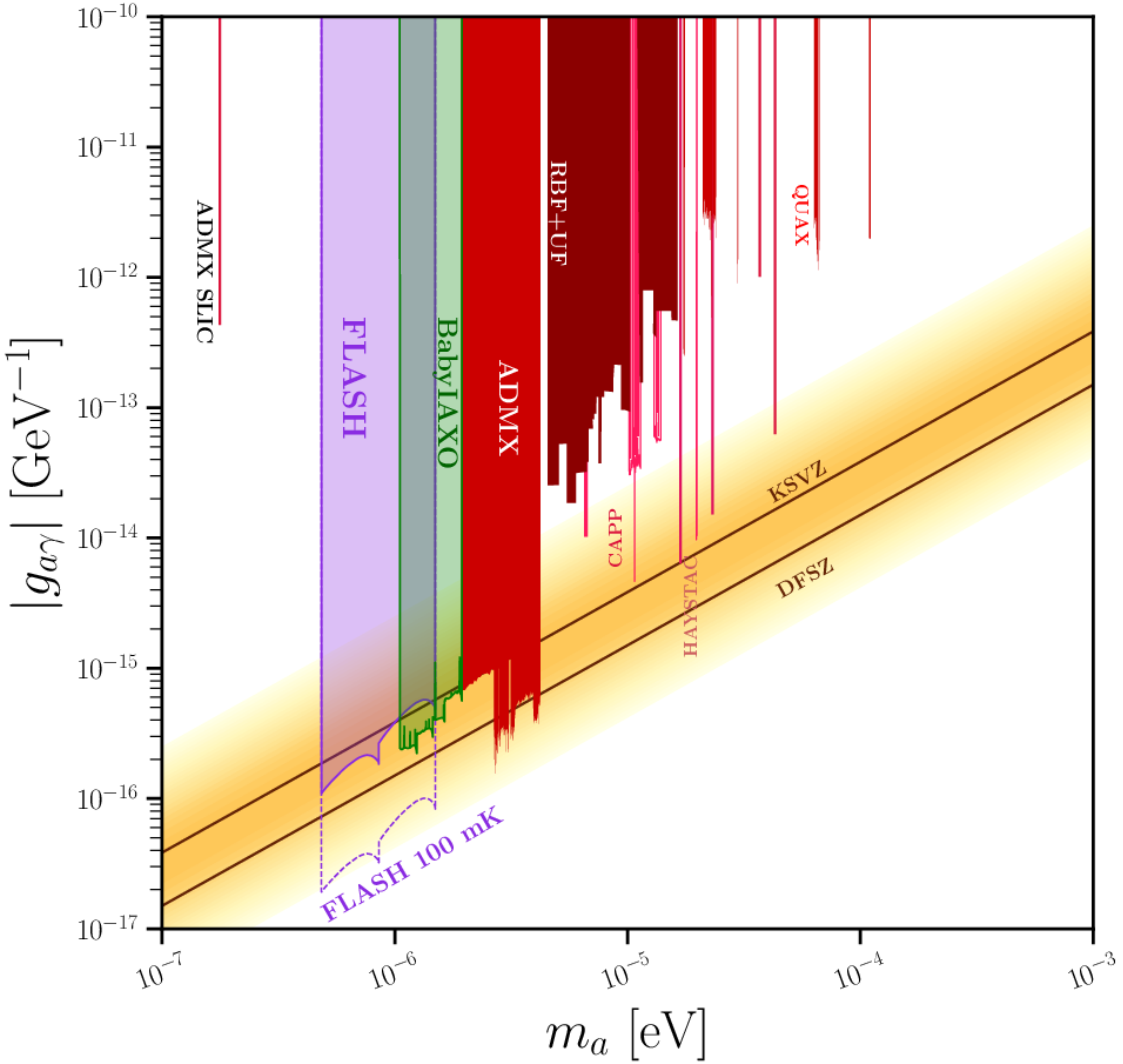
B_0 Magnetic field

C_{nml} Geometric factor

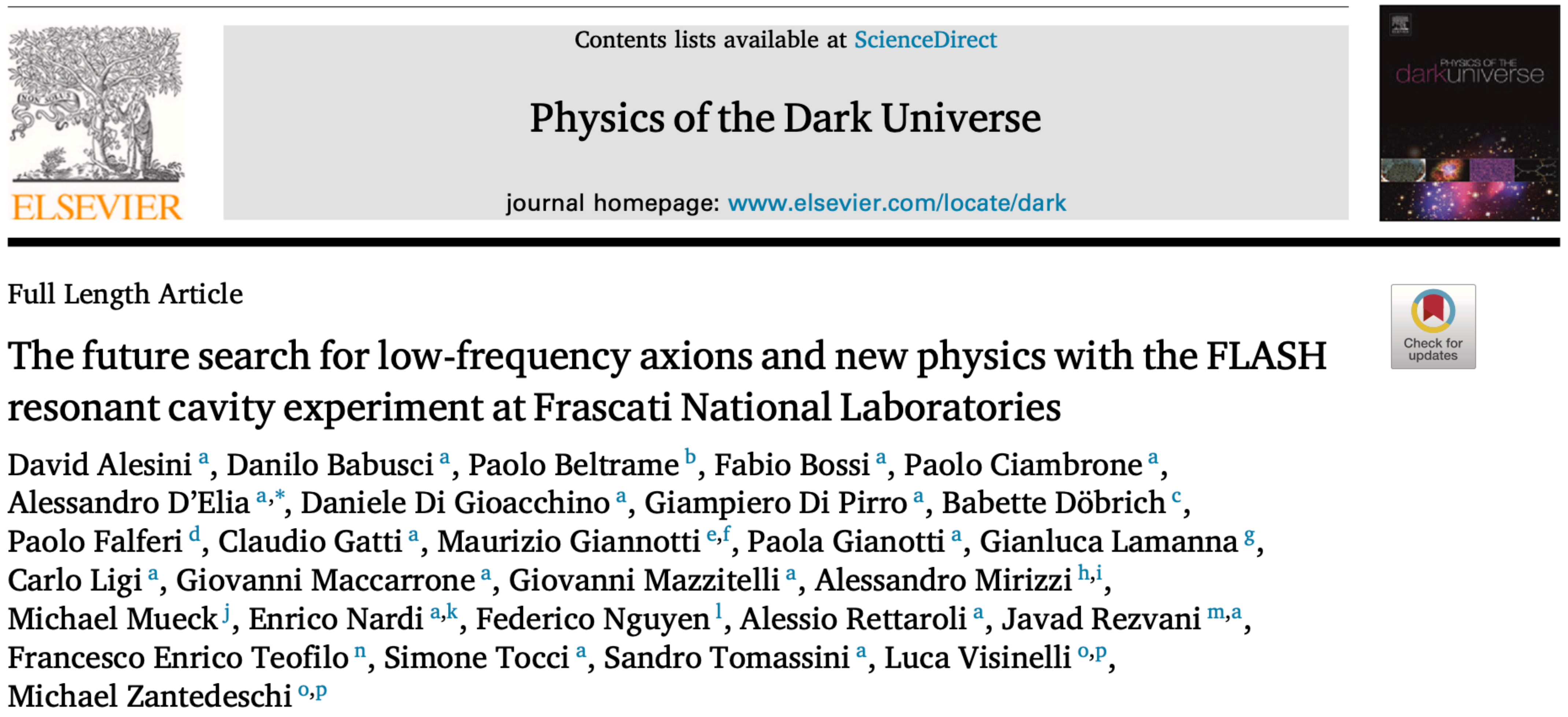


Courtesy of ADMX collaboration

Cavity search at INFN Frascati National Labs



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

ELSEVIER

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]

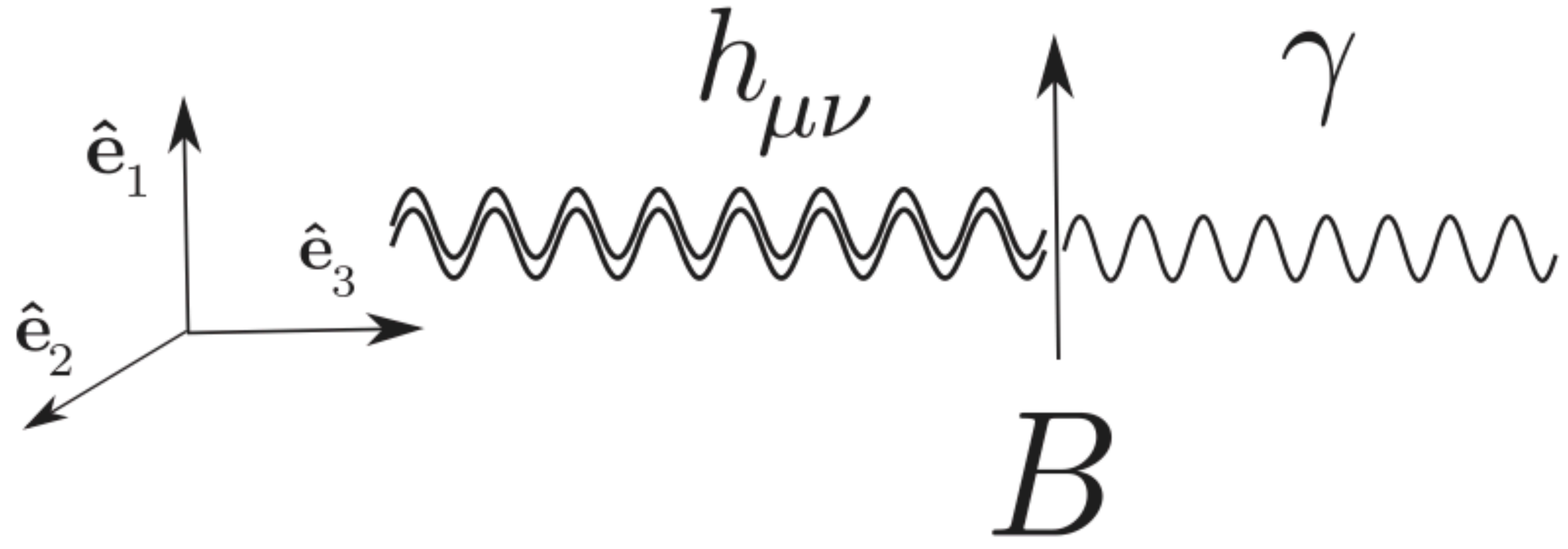
Partial overlap with BabyIAXO reaches when used as a haloscope [2306.17243]

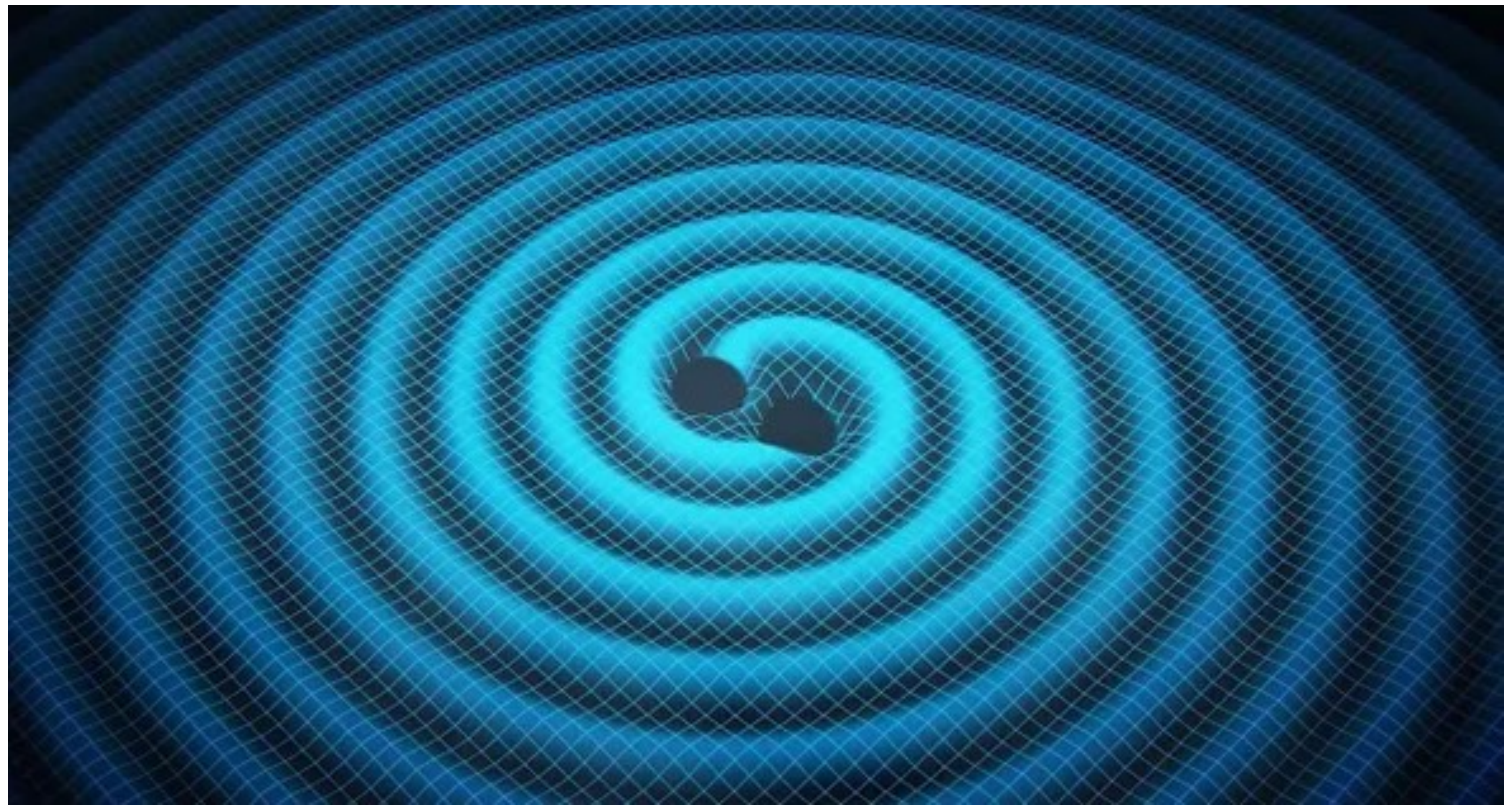
See also the CADEx talk by Jordi Miranda Escudé

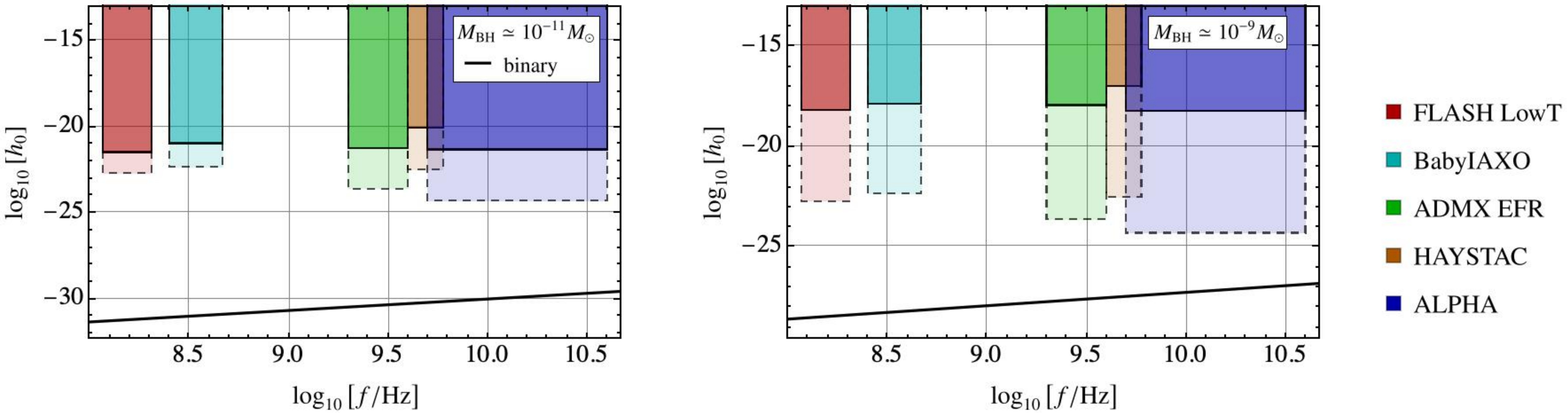
High-frequency gravitational waves

Inverse Gertsenshtein effect (see e.g. Camilo Garcia work)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad h_0 \sim |h_{\mu\nu}|$$



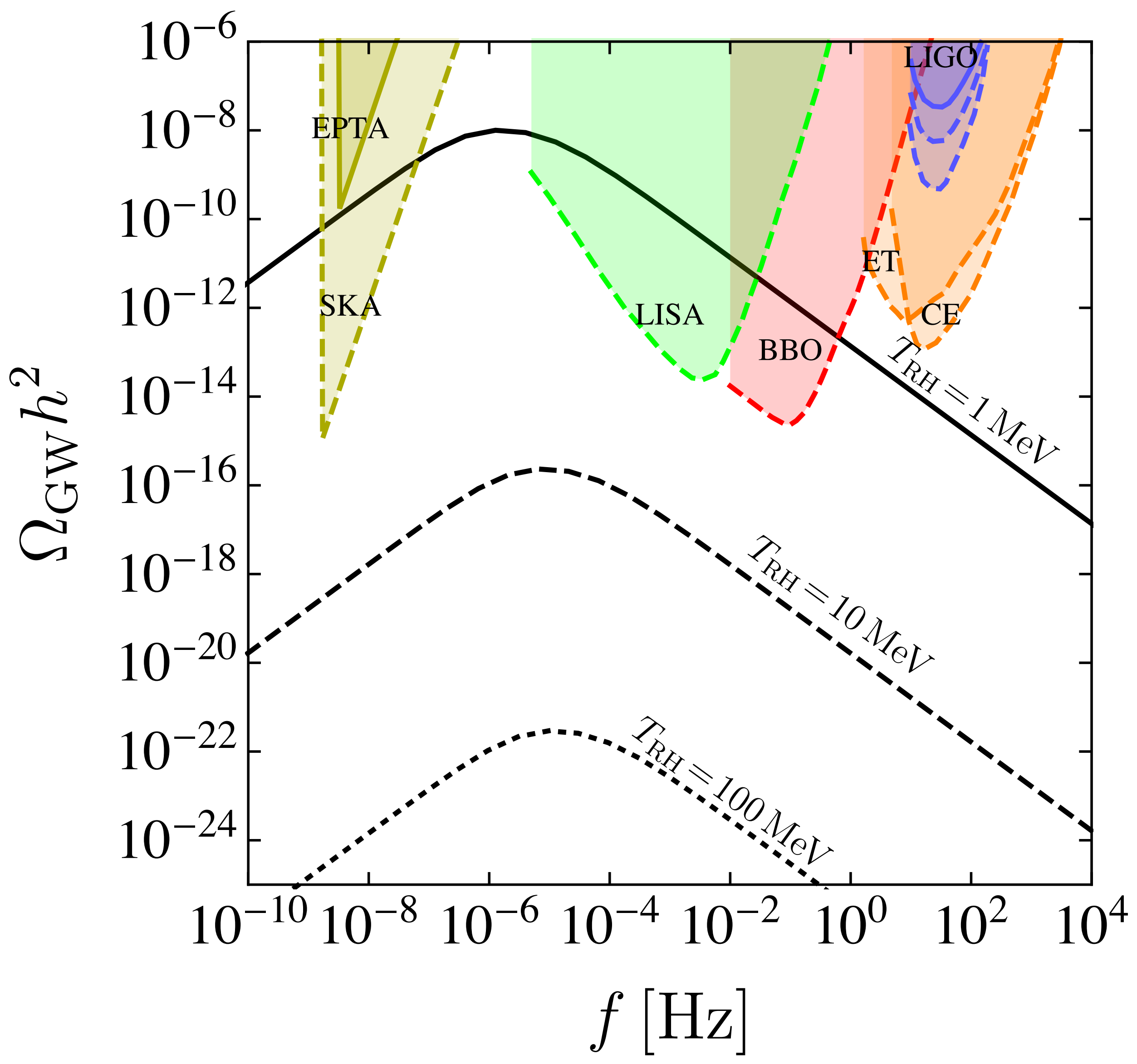


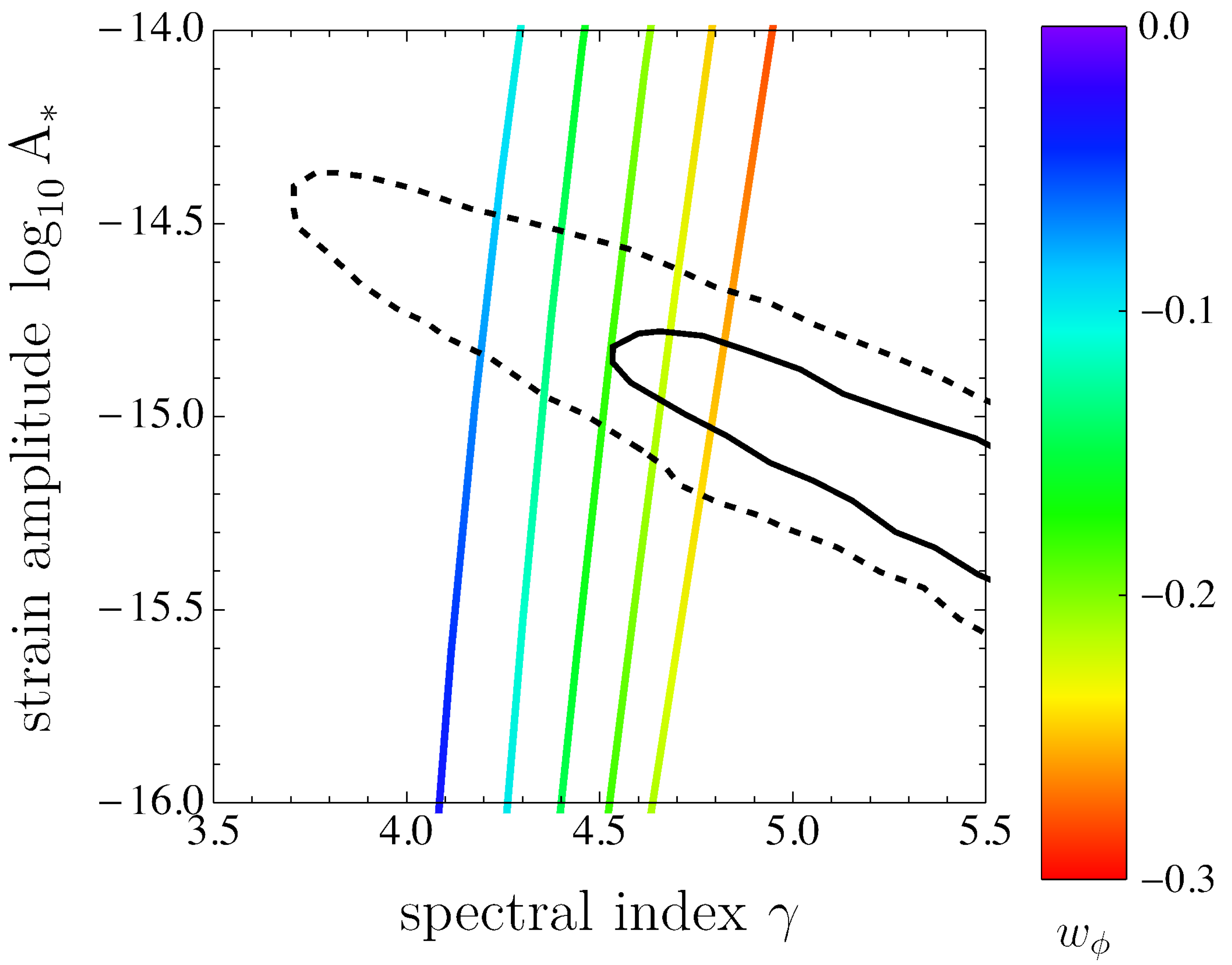


Gatti, **LV**, Zantedeschi 2403.18610, PRD

Work with
Michael Zantedeschi

GWs from axionic strings?





PHYSICAL REVIEW D **99,** 123513 (2019)

Probing the early Universe with axion physics and gravitational waves

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(Received 20 April 2019; published 13 June 2019)

PHYSICAL REVIEW D **103,** 063031 (2021)

QCD axion and gravitational waves in light of NANOGrav results

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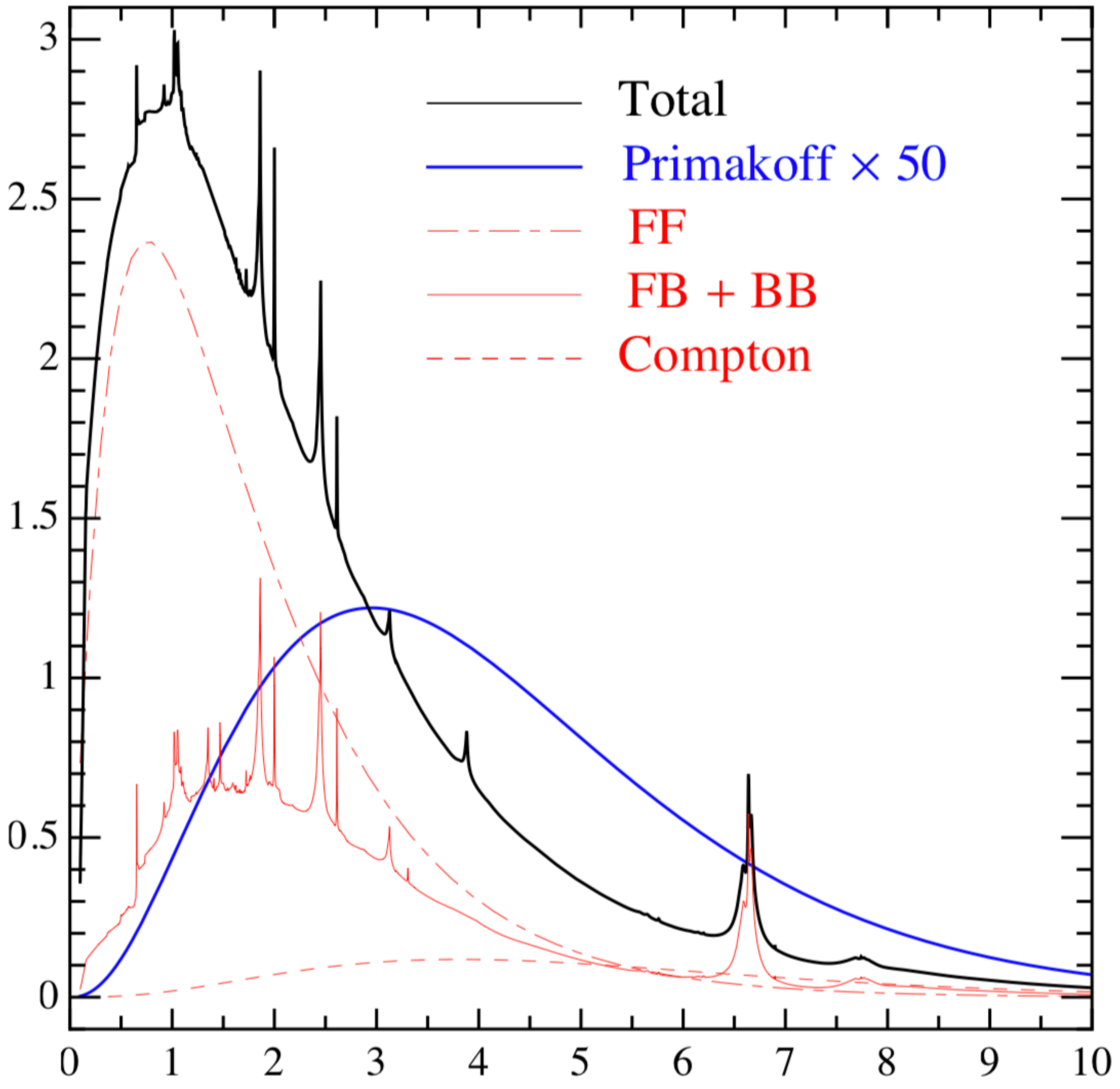
(Received 12 December 2020; accepted 7 March 2021; published 22 March 2021)

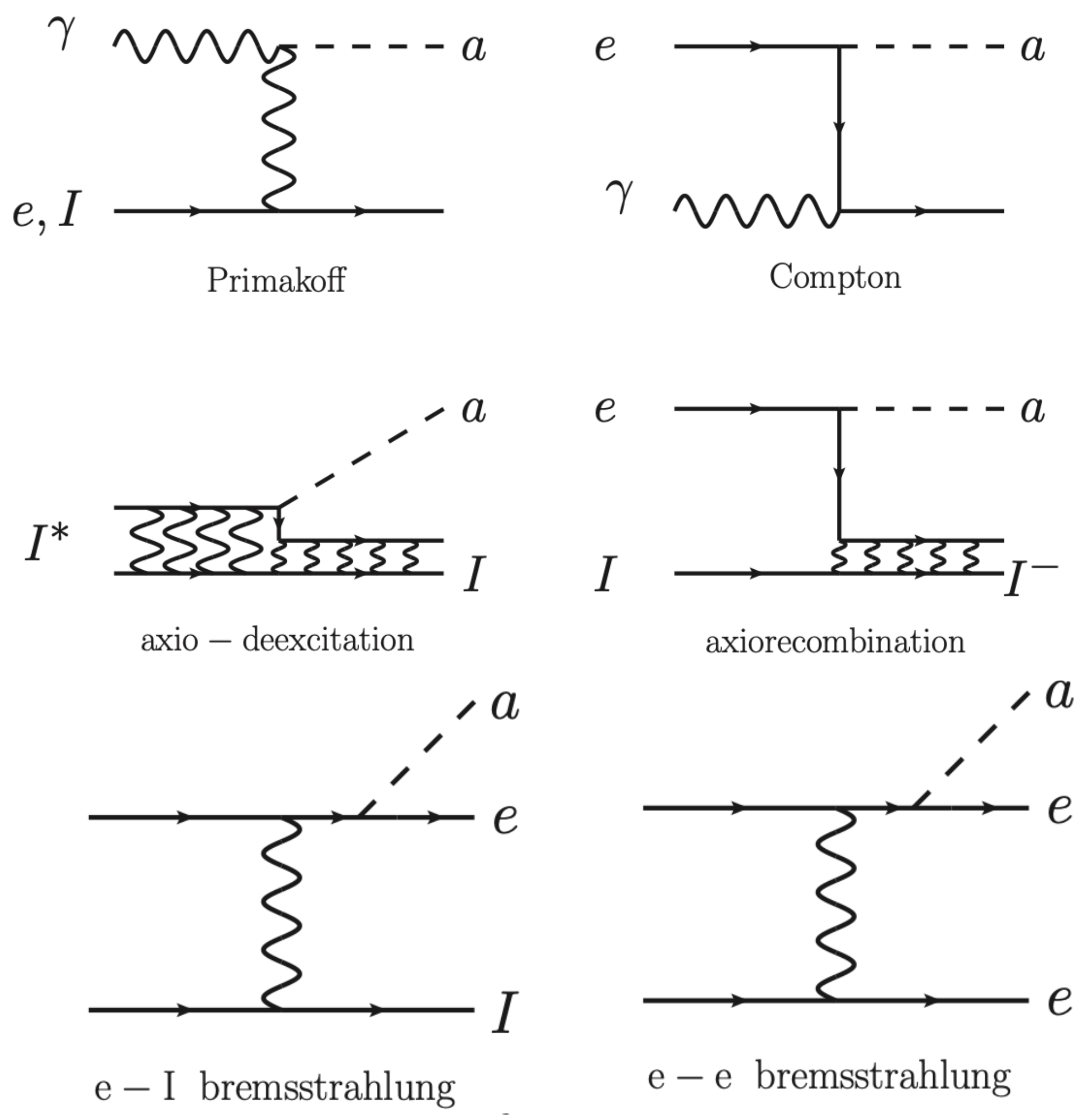
For some low-reheat temperature scenarios, GWs from axionic strings are detectable in various frequency ranges, because f_a in these models is higher when QCD axion is the DM.

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]



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

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

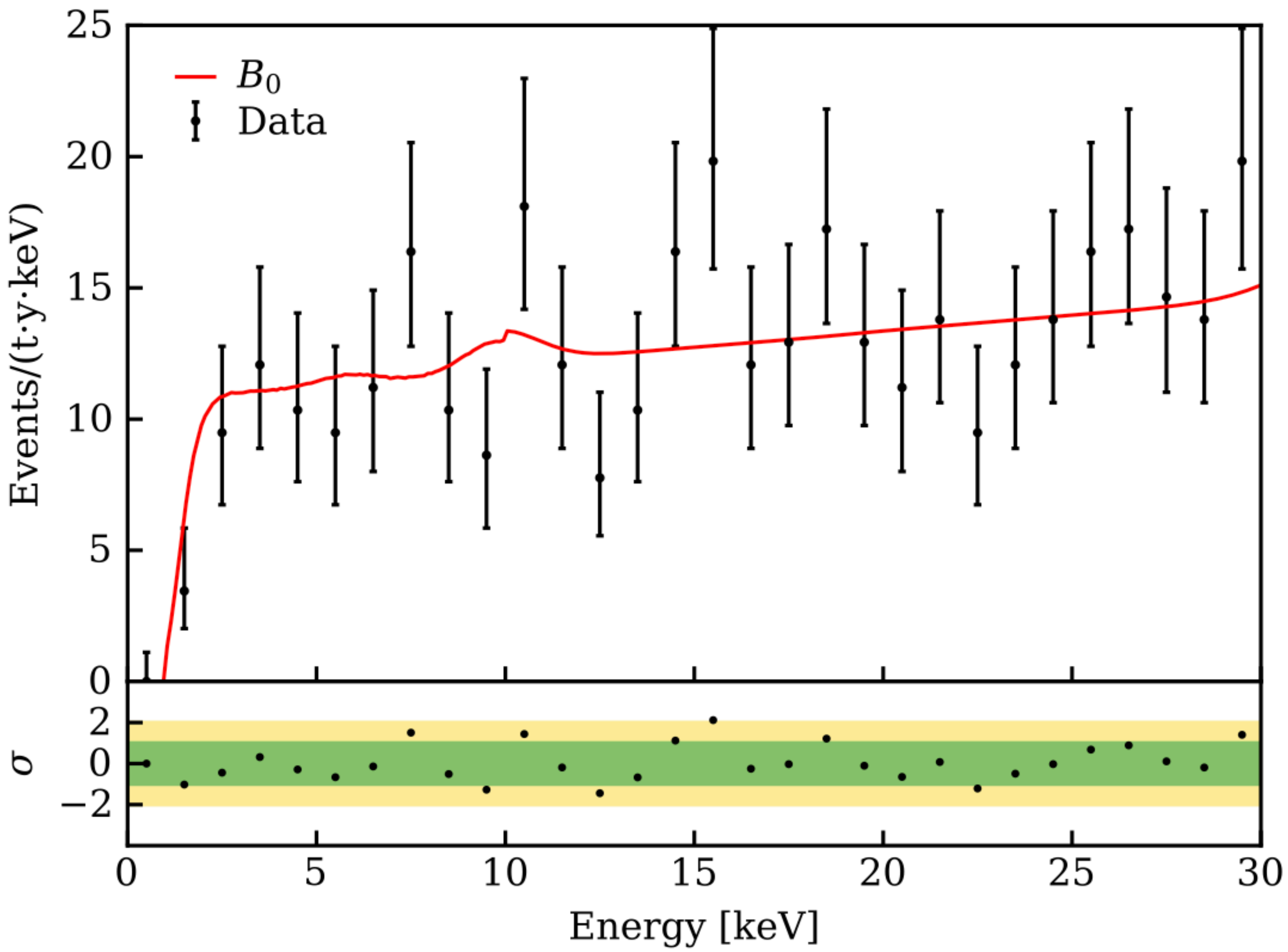
These are relativistic axions, not the DM!

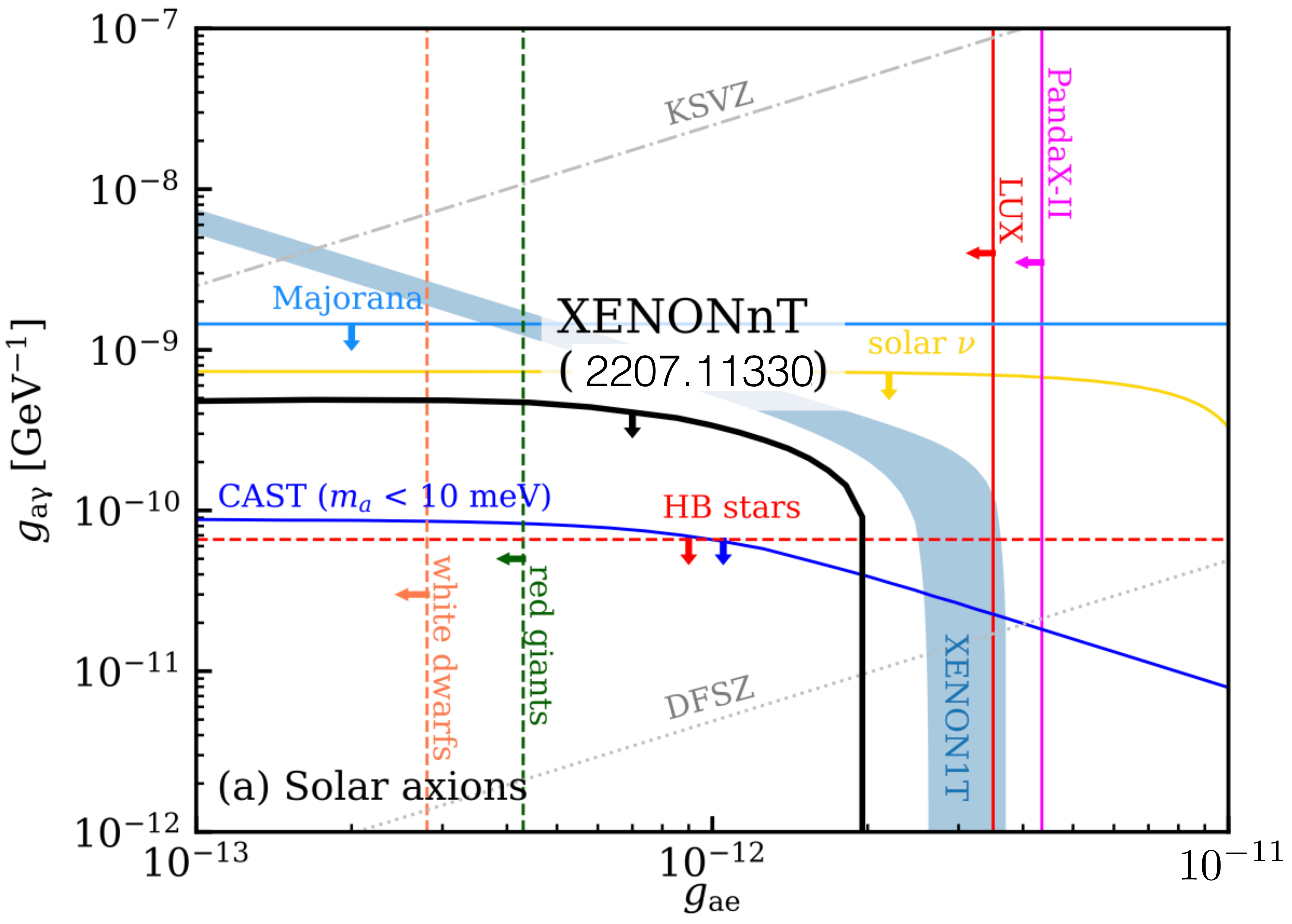
$$\omega_a \sim T_{\rm core} \approx {\rm keV}$$

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

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

Figure from Ben Safdi





Previous results "XENON1T excess" [2006.09721]

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

See: Vagnozzi, **LV** Brax, Davis, Sakstein [2103.15834]

LZ searches: 2307.15753

New exploration frontier: Scalar field production in the Sun

We have considered solar chameleons produced from

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - V_{\rm eff}(\phi) + \frac{1}{M_\gamma^4}(\partial_\mu\phi)(\partial_\nu\phi)T_\gamma^{\mu\nu}\right] + S_{\rm SM}$$

$$V_{\rm eff}(\phi) = V_{\rm self}(\phi) + \frac{\beta_m}{M_{\rm Pl}}\rho_m\phi + \frac{\beta_\gamma}{M_{\rm Pl}}\phi\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \qquad V_{\rm self} \sim \Lambda^4$$

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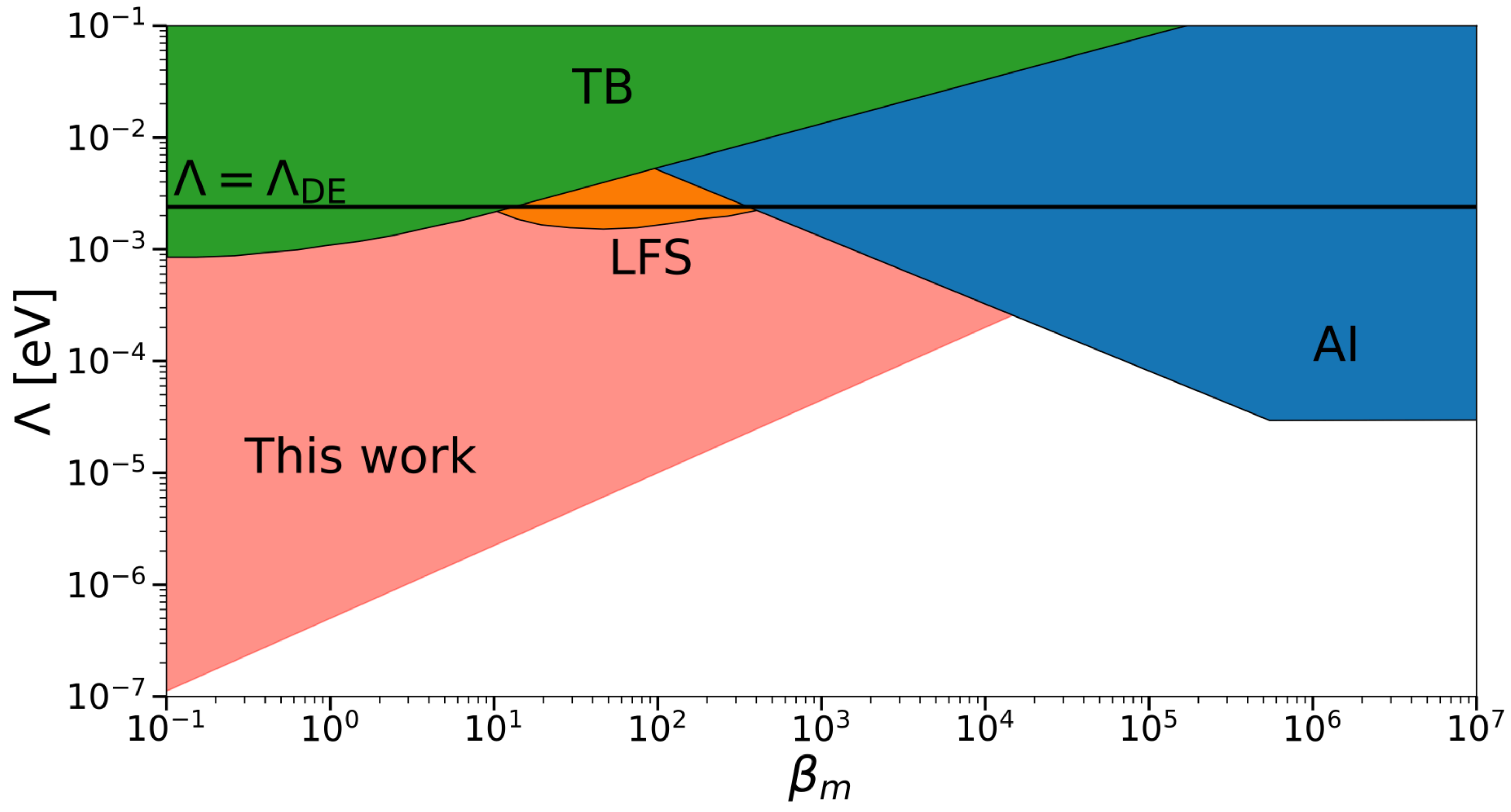
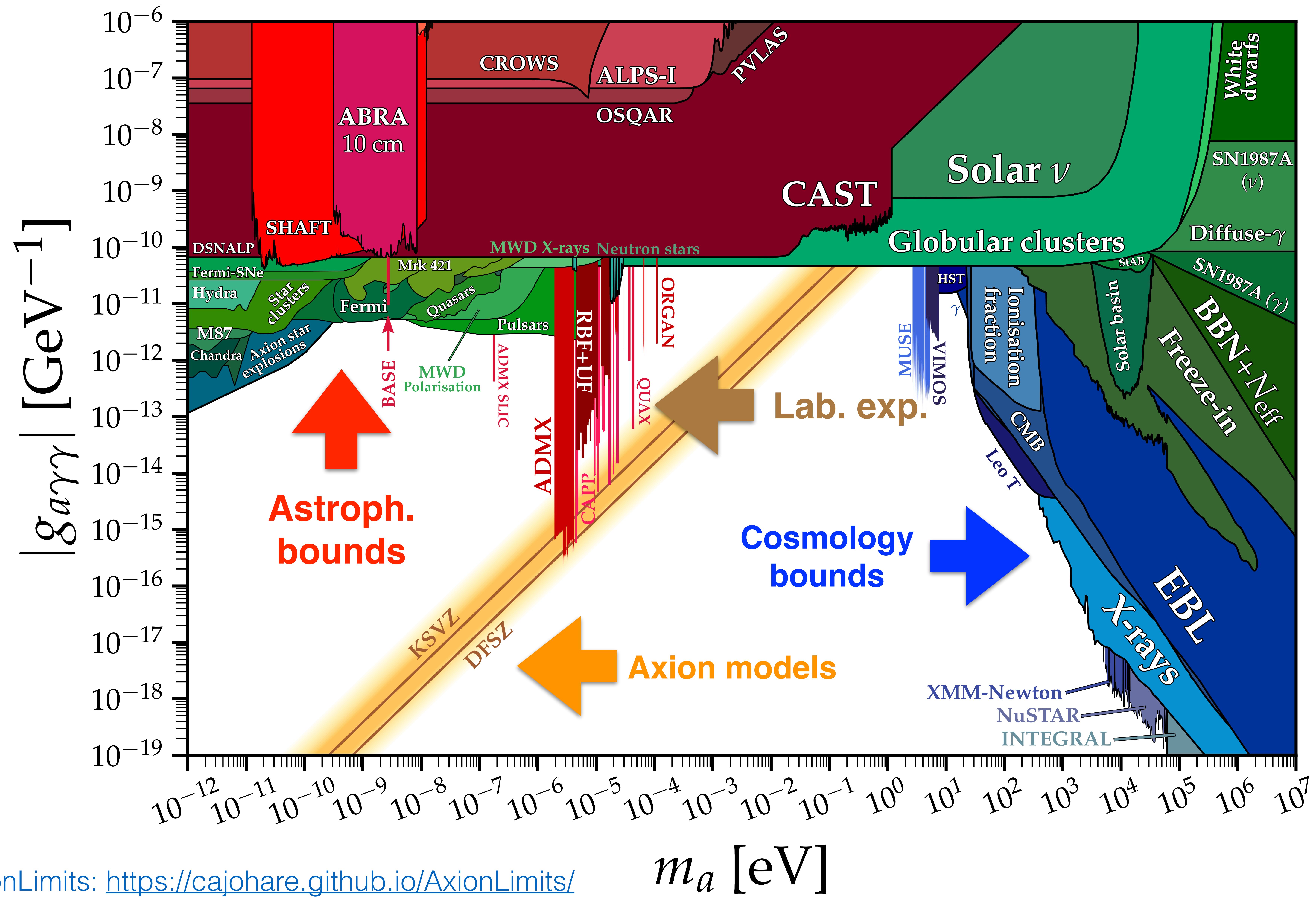


O'Shea, Davis, Giannotti, Vagnozzi, **LV**, Vogel [2406.01691]

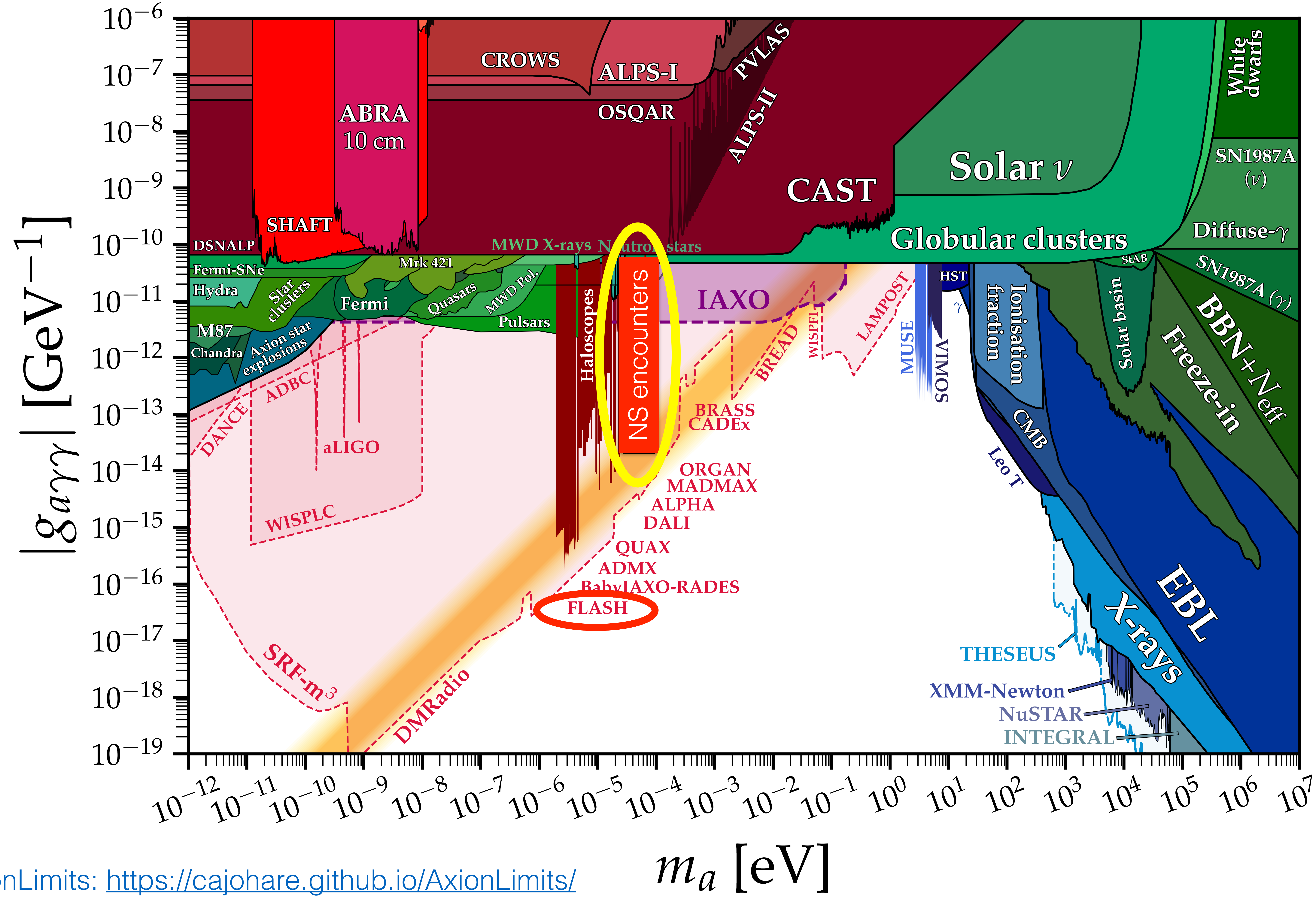
Summary of axion-photon coupling bounds

Luca Visinelli



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 searches
- Expect O(1) bright event on the sky at all times
- Explored in Andromeda through GBT
- More developments to come soon

Direct searches

- Road to lab detection @ INFN-LNF
- Dawn of HFGW searches
- For details, see FLASH CDR 2309.00351

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

2011.05377, 2011.05378
github.com/bradkav/axion-miniclusters

Thank you!