李政道研究所
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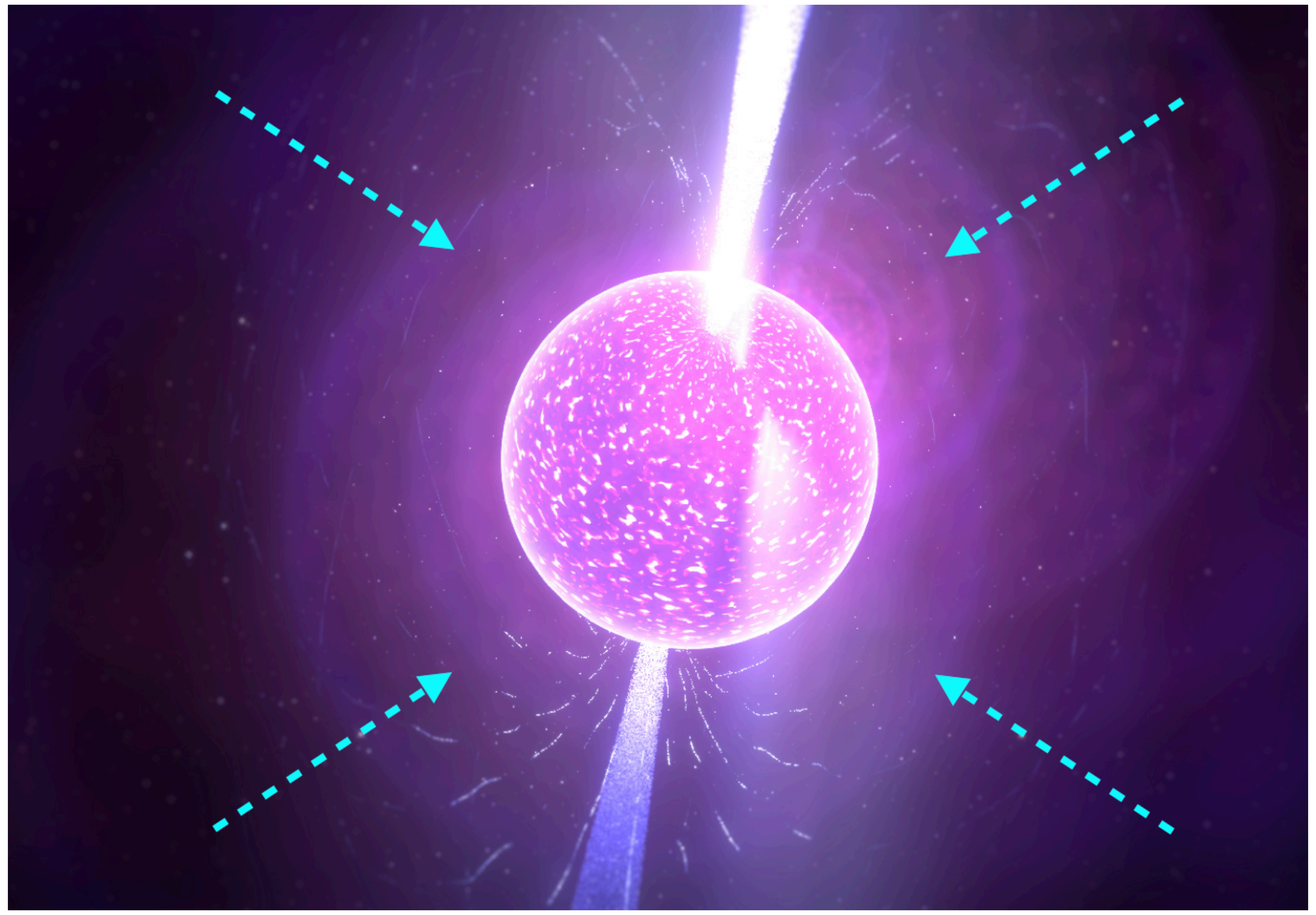
Direct and Indirect detection of the QCD axion: Recent progresses



Luca Visinelli

Tsung-Dao Lee Institute & Shanghai Jiao Tong University

September 4, 2024

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My group at TDLI

- 2022 - now: Michael Zantedeschi (Postdoc) GW theory and detection strategies
- 2024 - now: Hong-Yi Zhang (Postdoc) Soliton formation
- Ziwen Yin 尹孜文 (PhD student, SJTU) Axion star formation
- Hanyu Cheng 程涵宇 (PhD student, SJTU) Cosmic strings & GWs
- Xinhui Chu 褚鑫慧 (PhD student, SJTU) GW detection
- Yongzhi Tan 唐勇智 (PhD student, SJTU) Axion dark matter theory
- Qixuan Xu 许启炫 (Visiting student) Light scalar fields and BH superradiance

Past supervision:

1. **2022-23 — Kratika Mazde (MSc 2023, Now PhD at AIP-Sorbonne)**
2. **2019-20 — Nicklas Ramberg (MSc 2020, now Postdoc at SISSA)**

Many positions are now available at TDLI

Postdocs:

- Theory: https://academicjobsonline.org/ajo/jobs/28241
- Experimental: https://academicjobsonline.org/ajo/jobs/28240

Faculty positions:

- General ads: https://academicjobsonline.org/ajo/jobs/28235
- Trident ads: https://academicjobsonline.org/ajo/jobs/28236
- Collider ads: https://academicjobsonline.org/ajo/jobs/28237
- Multimessenger ads: https://academicjobsonline.org/ajo/jobs/28238
- Lattice QCD ads: https://academicjobsonline.org/ajo/jobs/28239

Astro-related positions to appear soon…

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

See the talk by Maurizio Giannotti for the review on the QCD axion

Axion Miniclusters in the Milky Way

Axion miniclusters

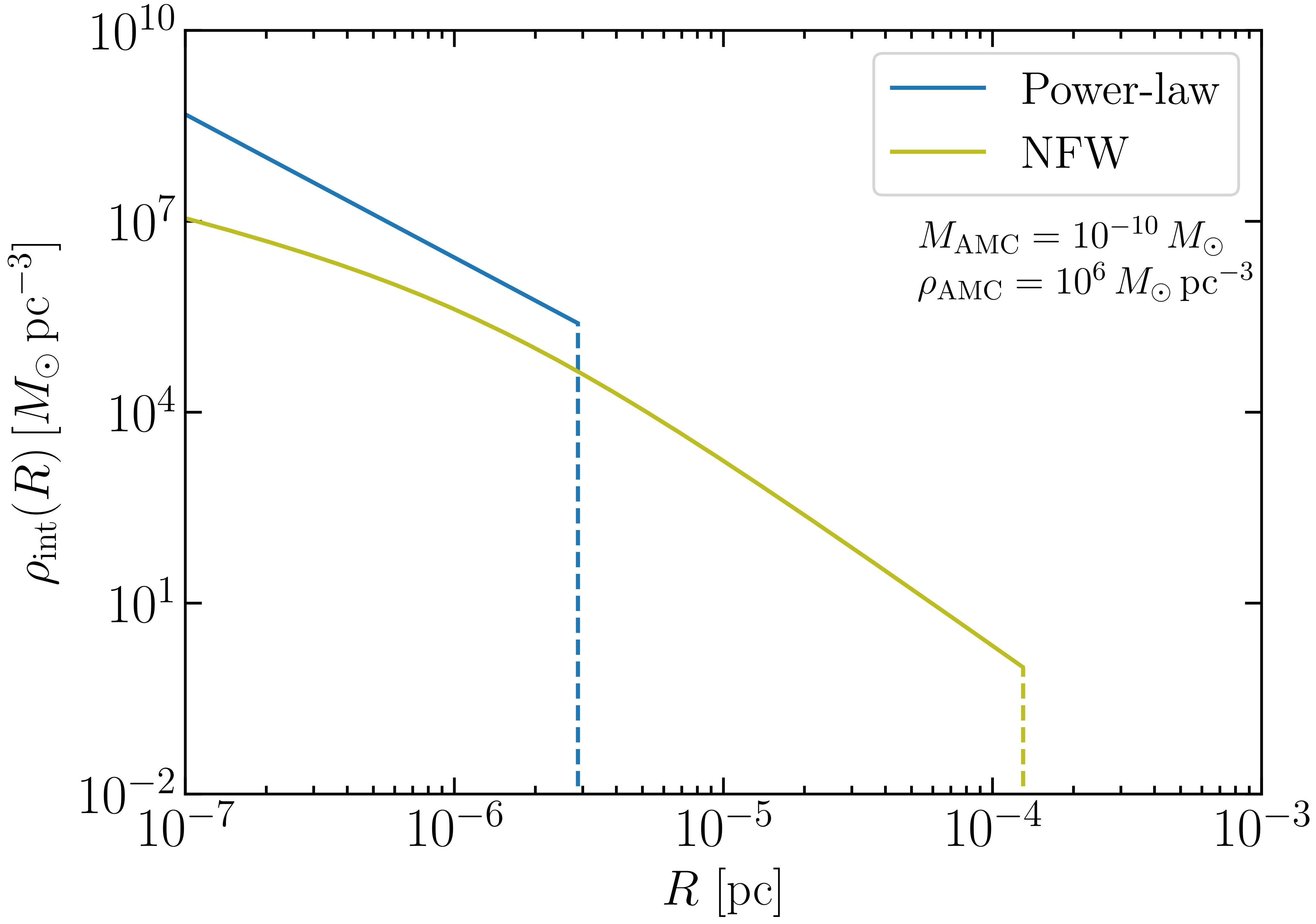
In post-inflation symmetry breaks, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

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

Typical minicluster mass:

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

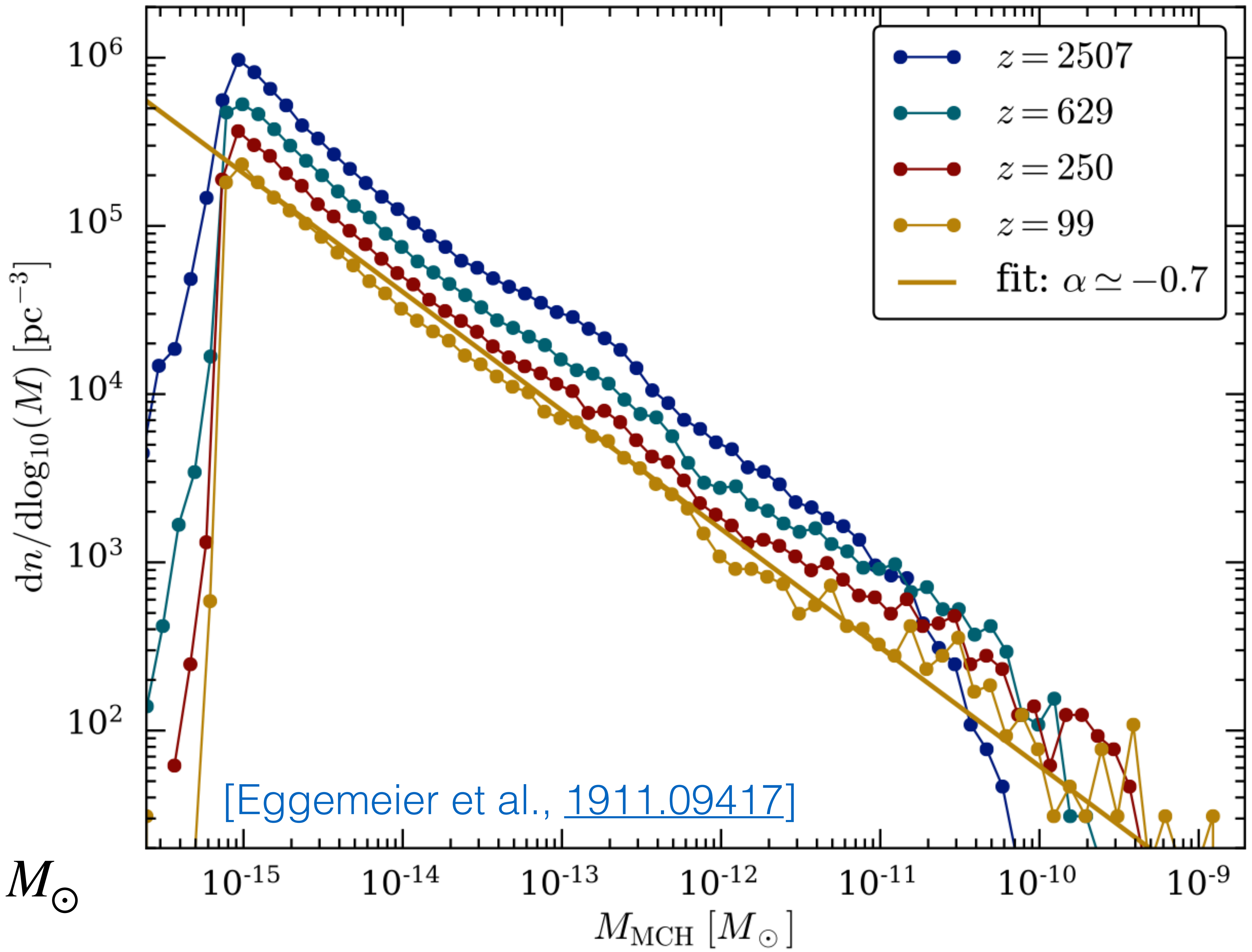
[Hogan & Rees 1988; Kolb & Tkachev 1994]



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



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

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

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 $M_{\rm AMC} \sim 10^{-5} M_\odot$

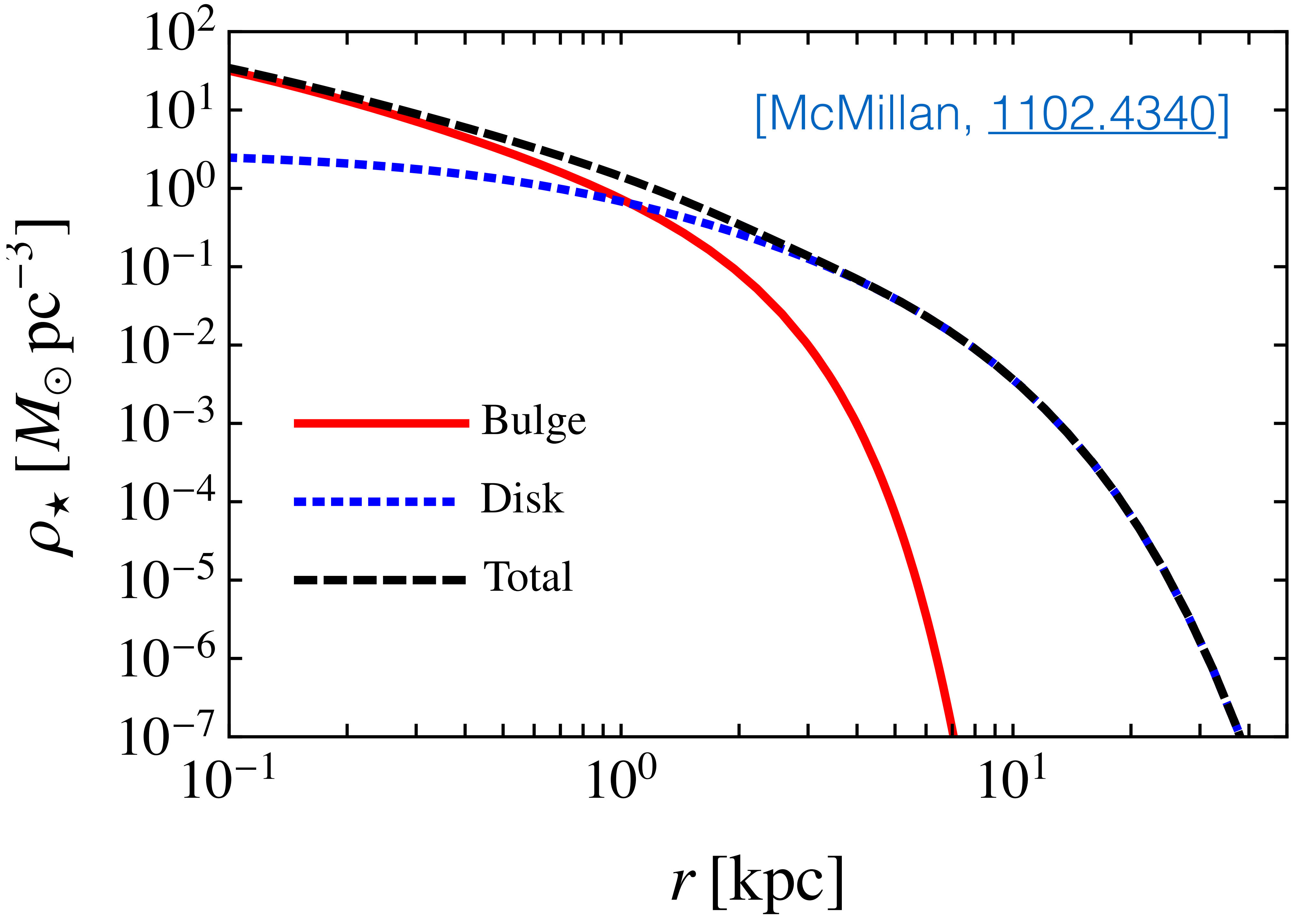
(Growth of hierarchical structure to today)

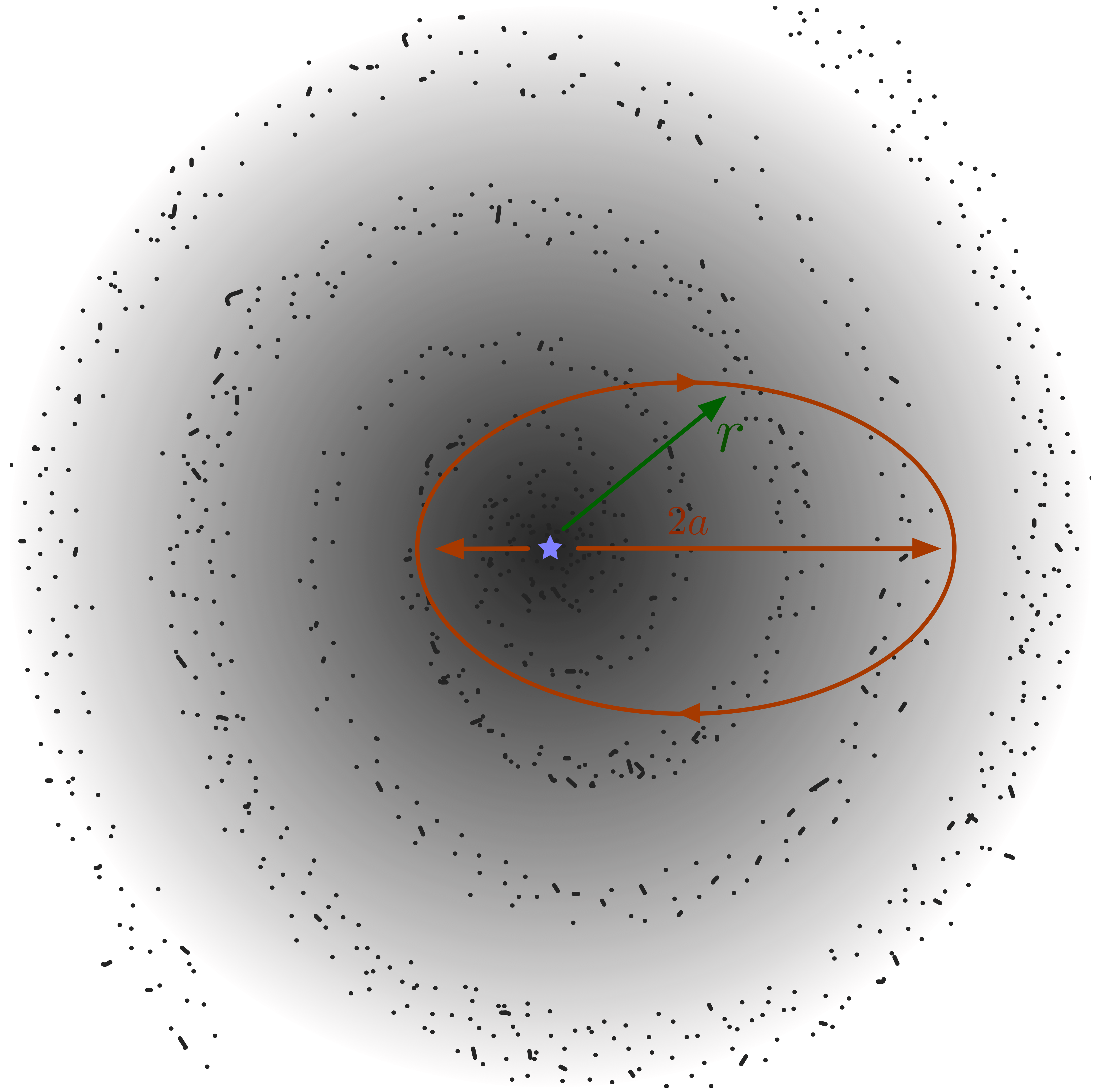
[Fairbairn et al., 1707.03310]

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

[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

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

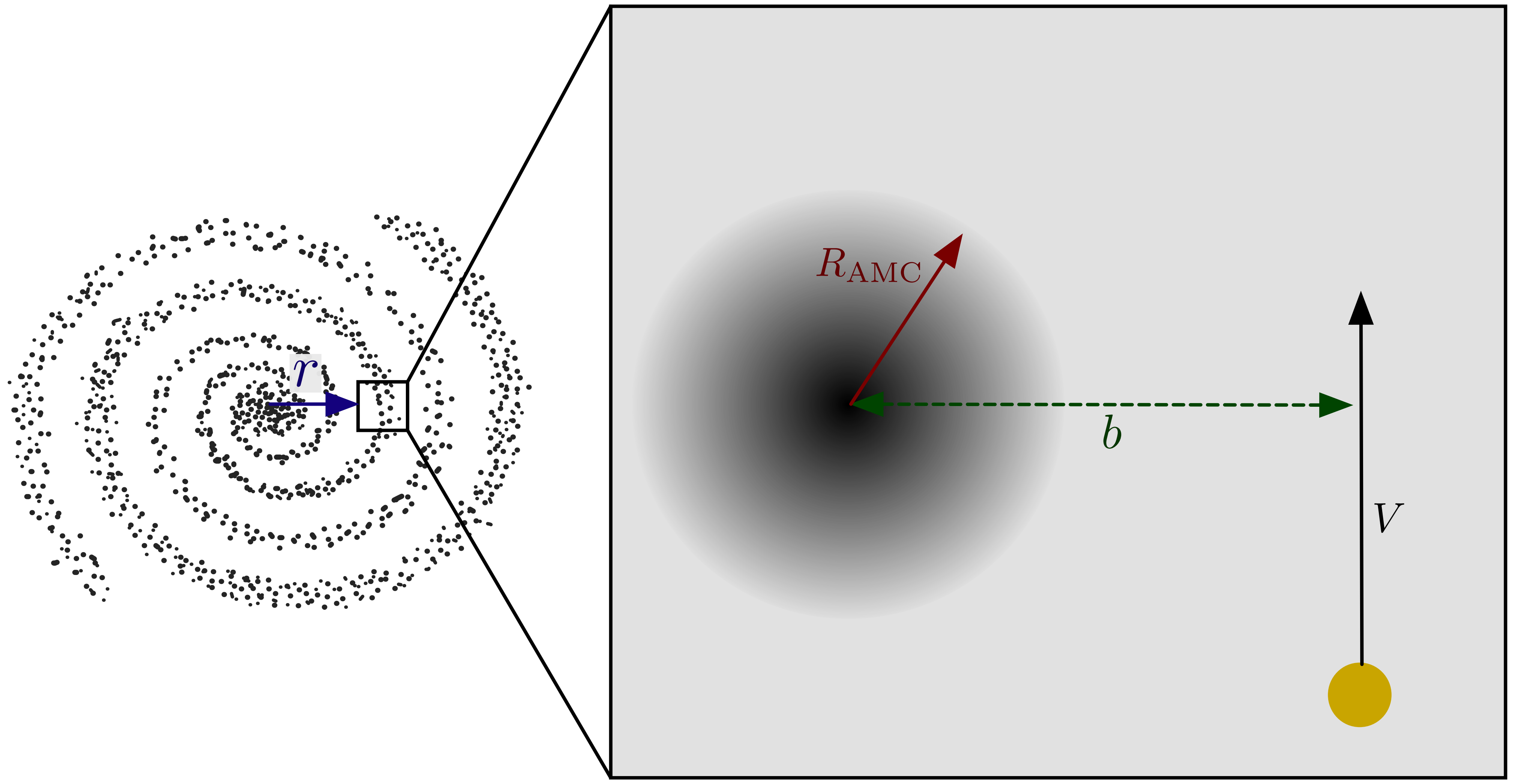
Remove AMC from simulation

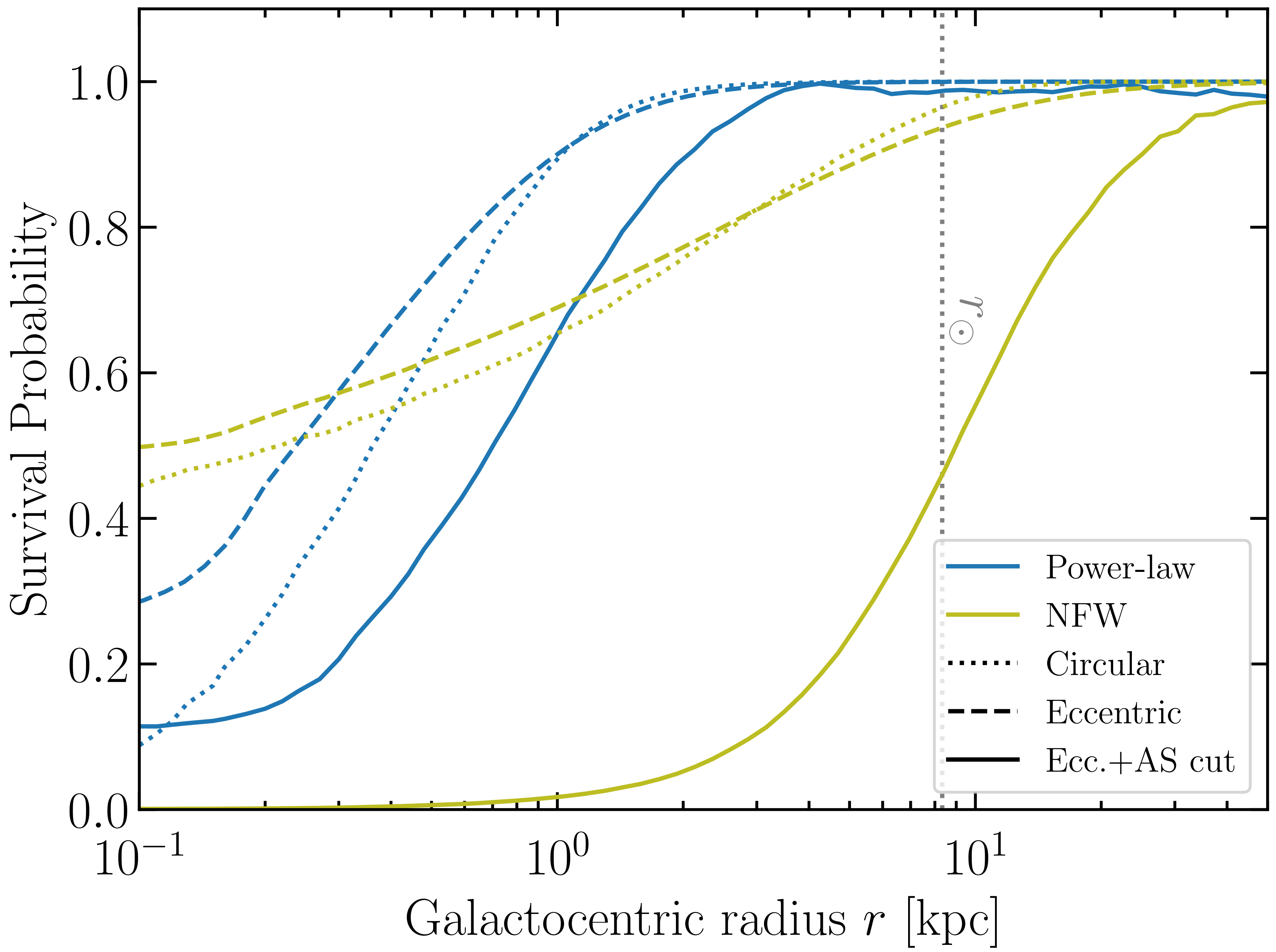
Collect surviving AMCs and reconstruct true properties

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]

Observational Consequences

Axion-photon conversion in NS magnetospheres

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

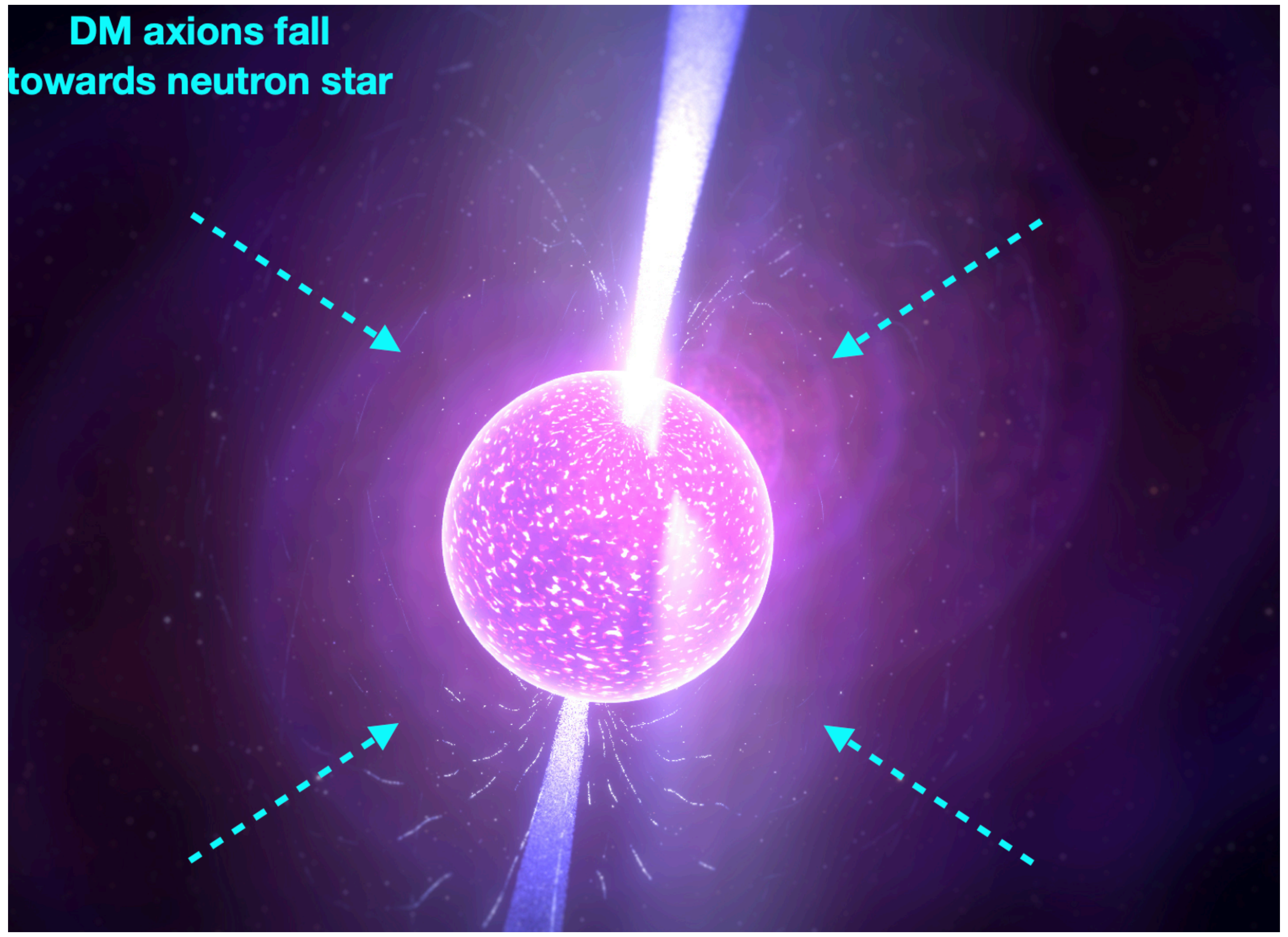
$$\frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega} \sim \frac{\pi}{3}\, g_{a\gamma\gamma}^2 B_0^2 \frac{{R_{\mathrm{NS}}}^6}{{R_c}^3} \frac{\rho_c}{m_a}$$

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

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

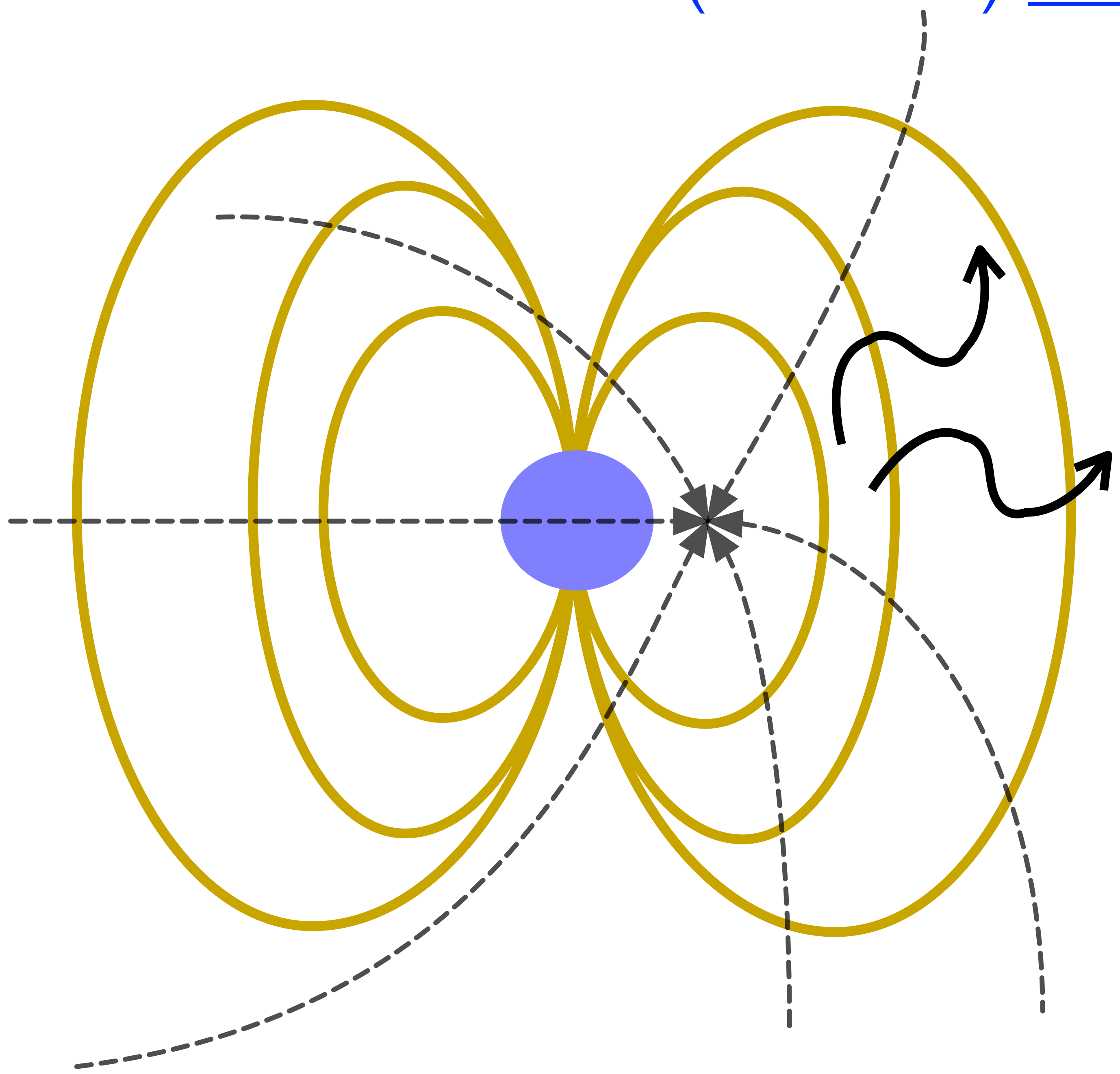
Look for axion-photon conversion from an individual NS

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



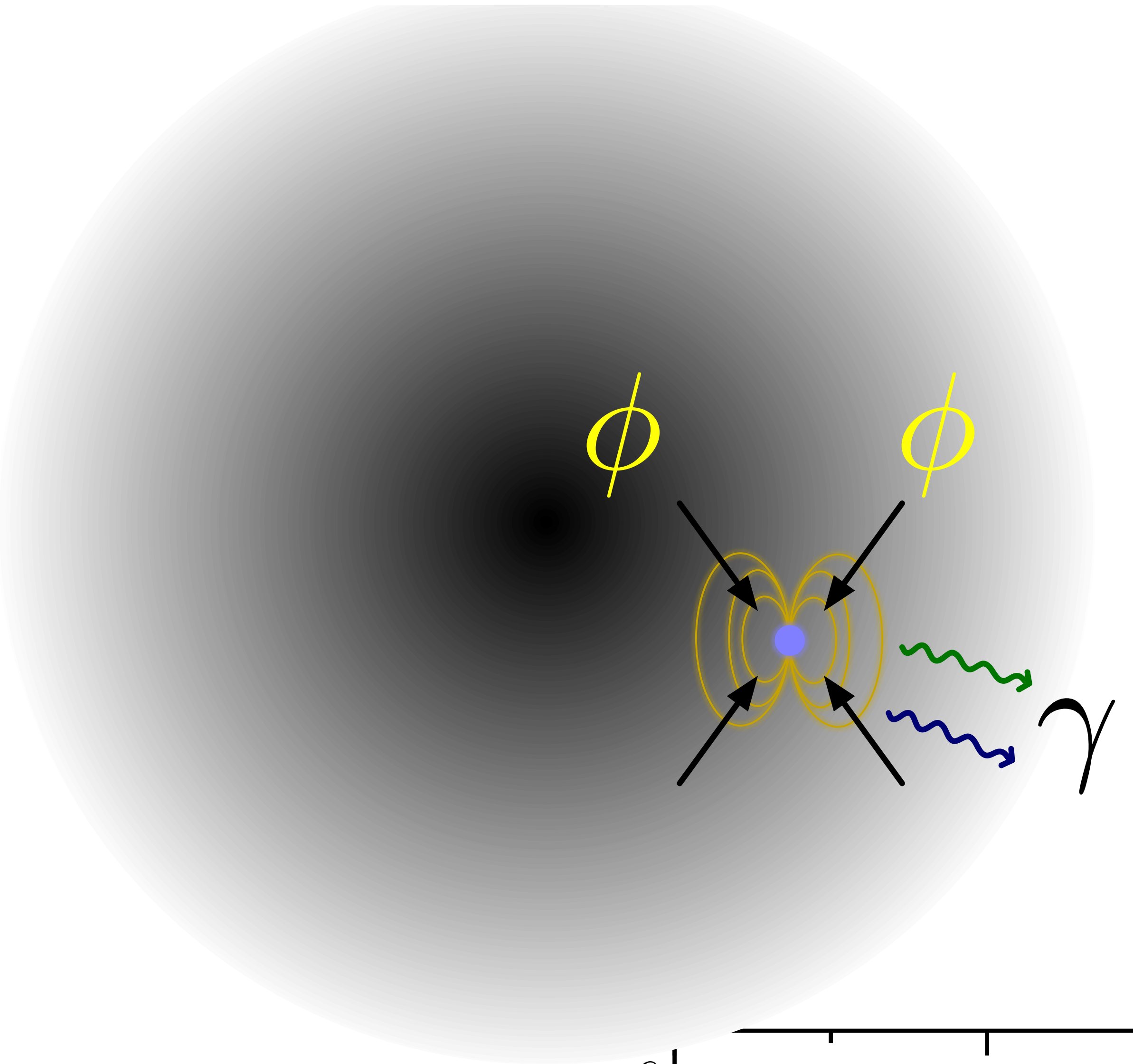
Transient enhancements to ρ_c from AMC encounters

Edwards+ (with **LV**) 2011.05378



Axion-photon conversion in NS magnetospheres

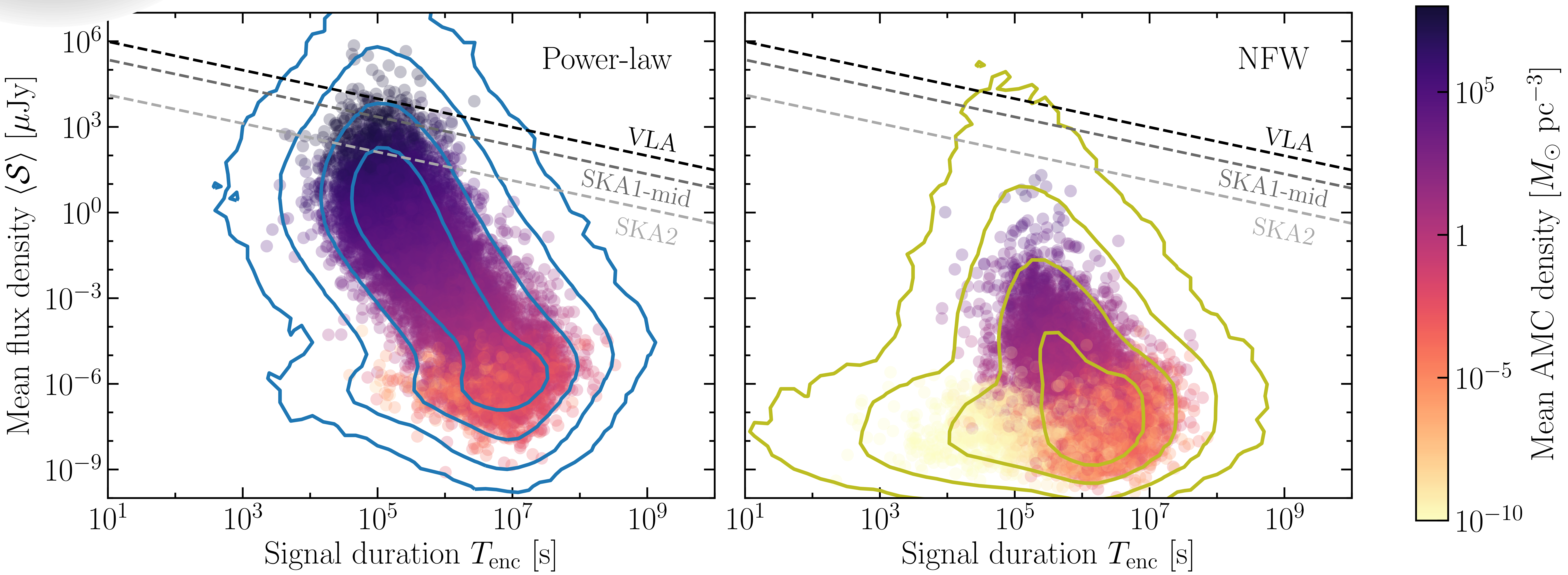
Luca Visinelli



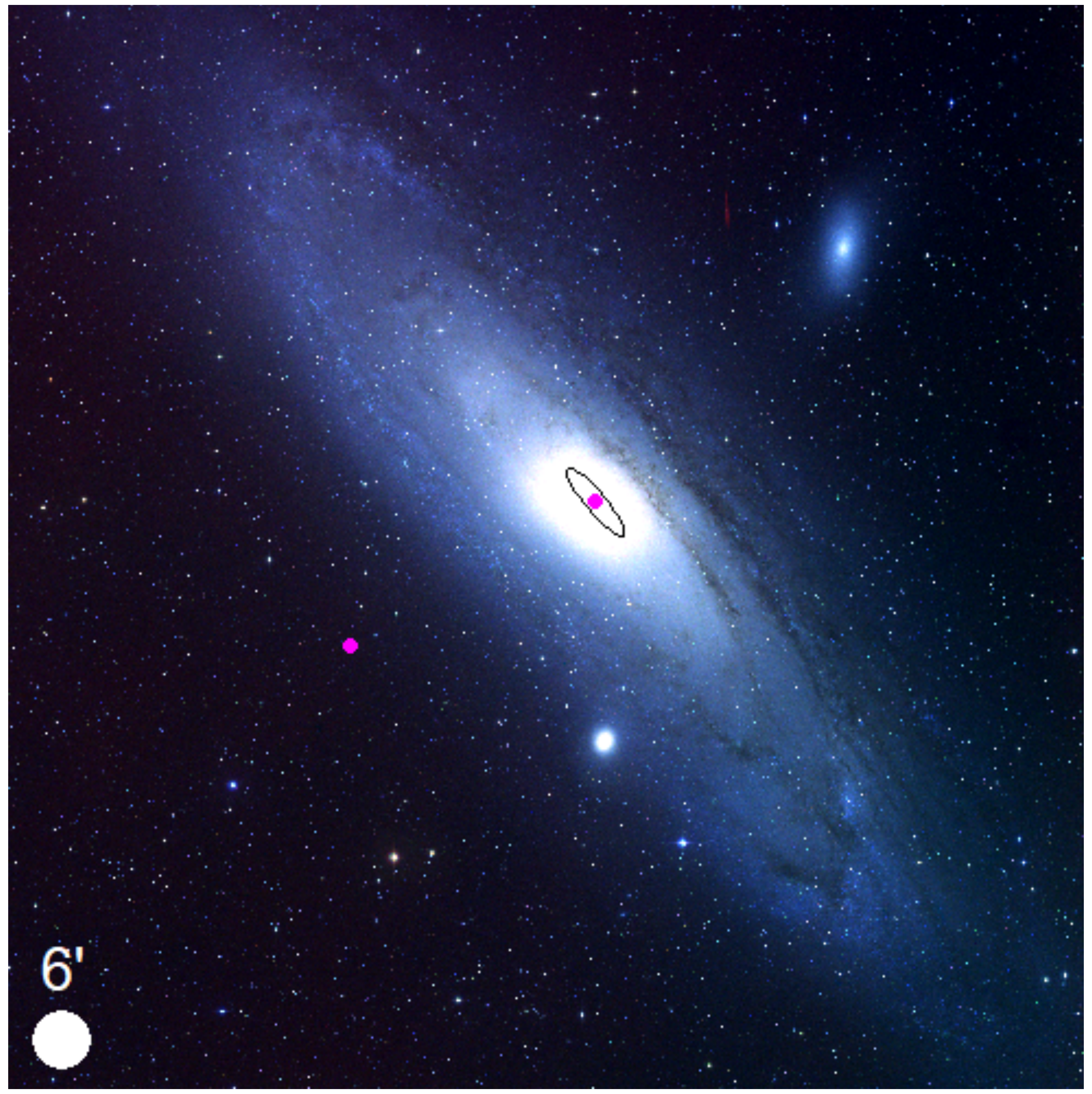
$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$

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

Edwards+ (with **LV**) 2011.05378



Can we pick up this signal in radio?



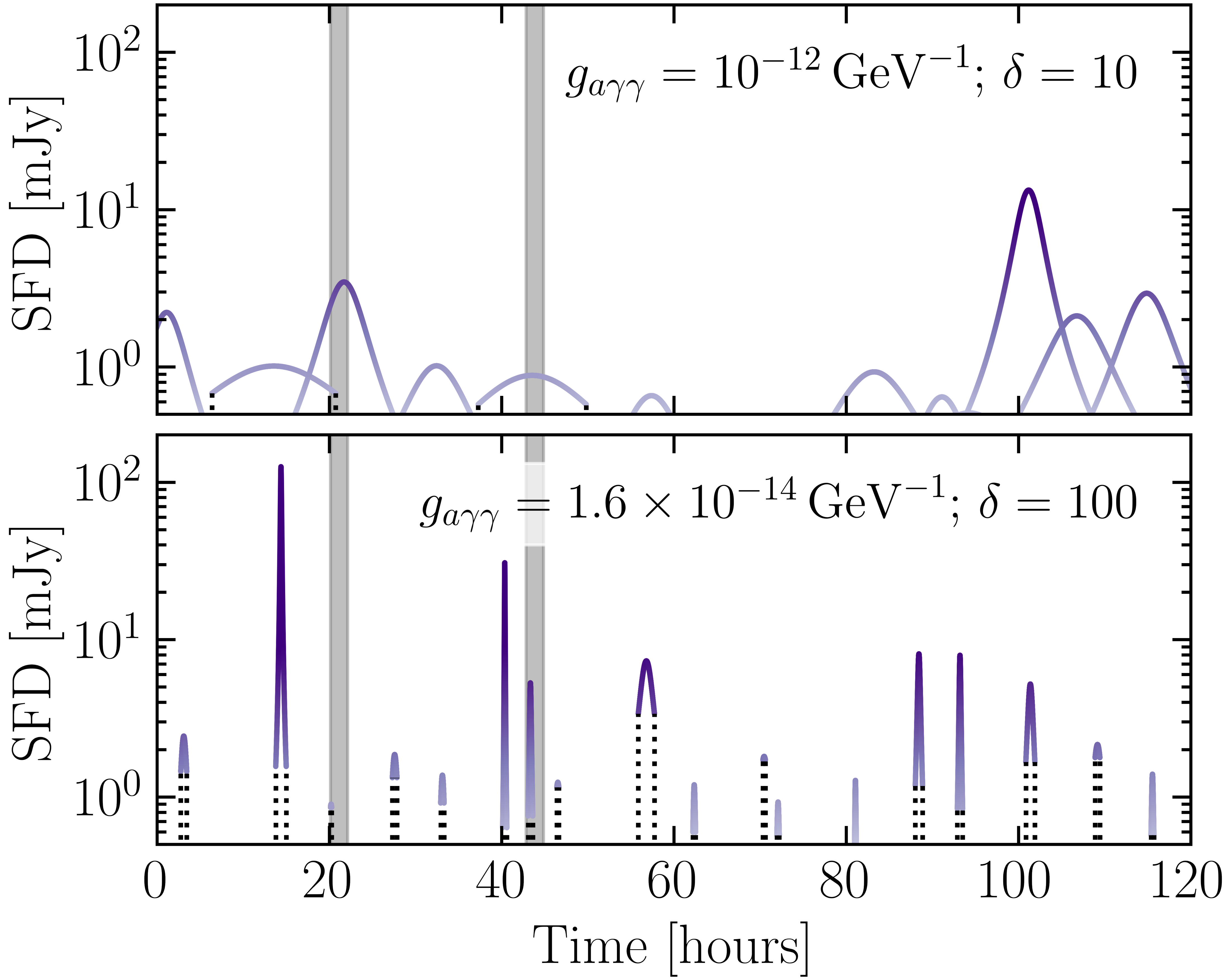
2 grant proposals accepted
by the Green Bank Telescope.
We have observed Andromeda

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

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

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

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



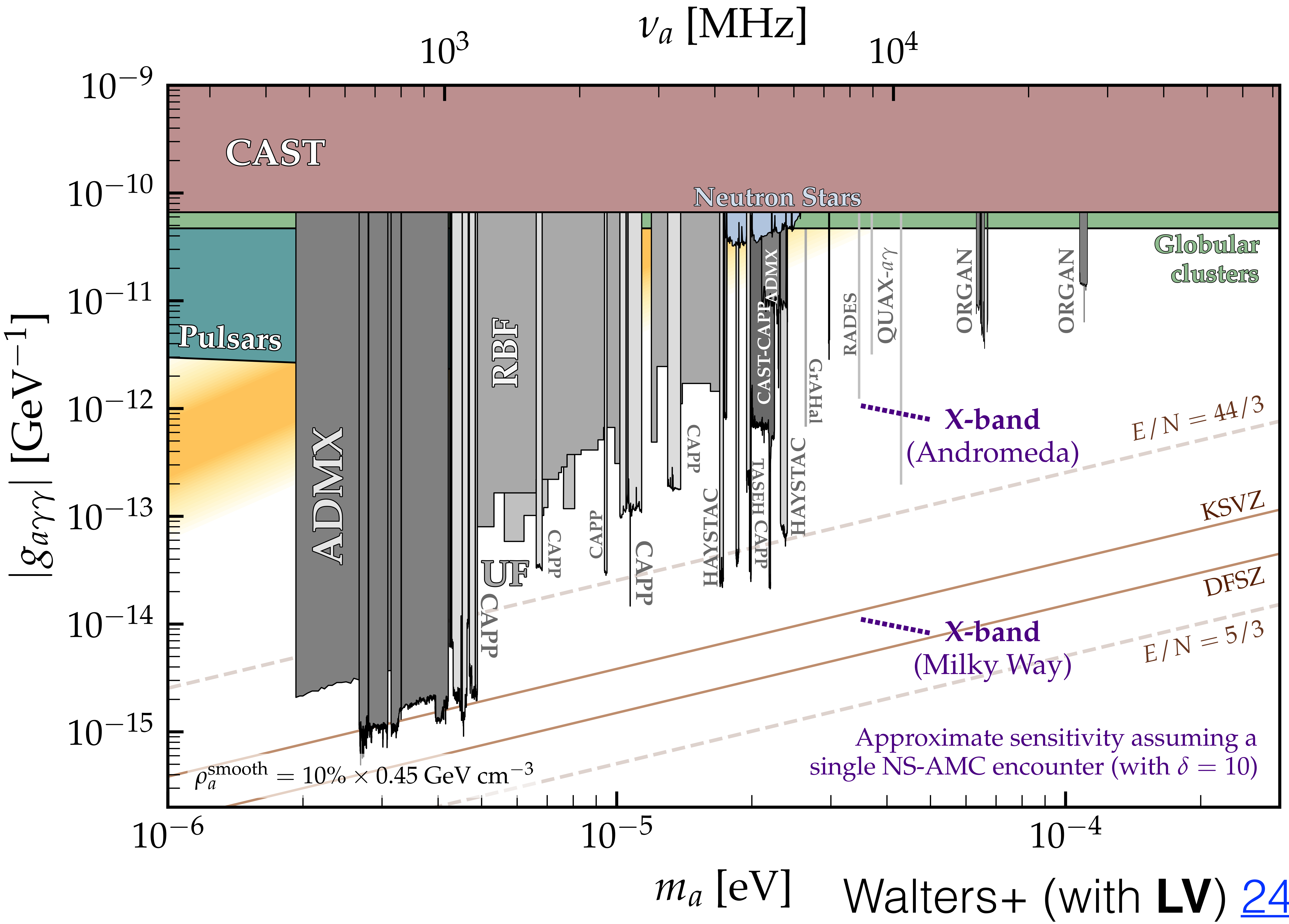
Walters+ (with **LV**) 2407.13060

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

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

Signal lasting min to hour

Can we pick up this signal in radio?



Walters+ (with **LV**) 2407.13060

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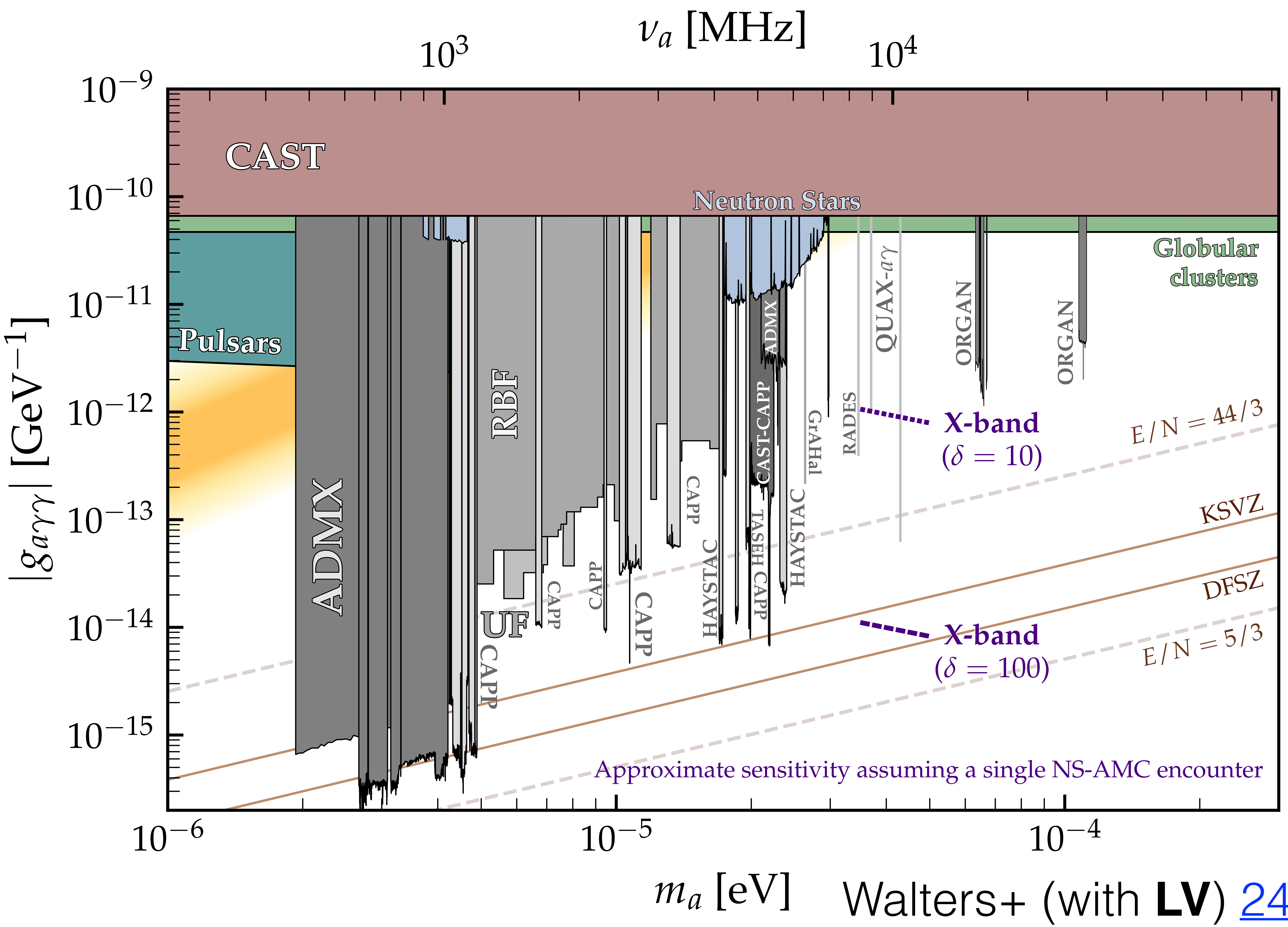
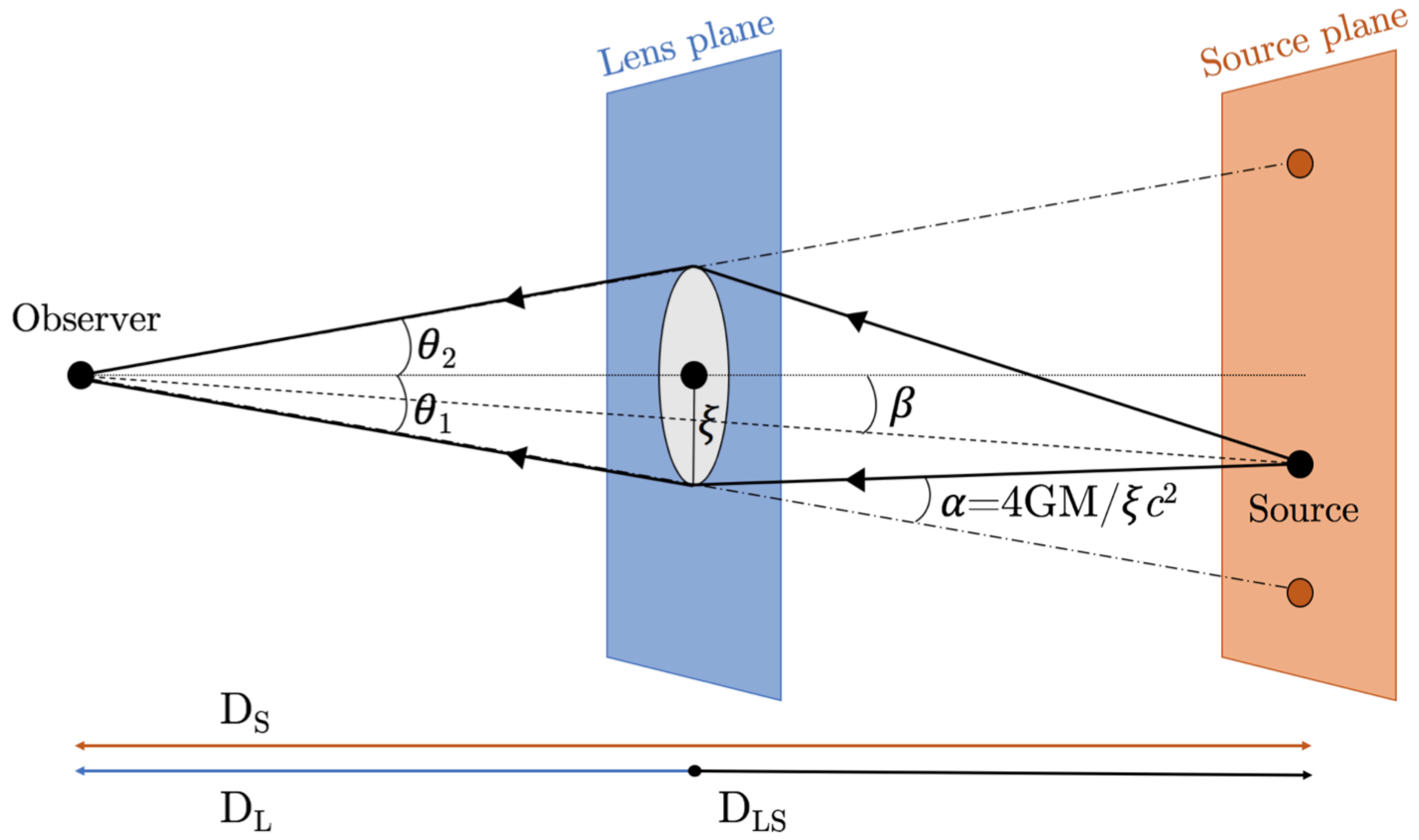


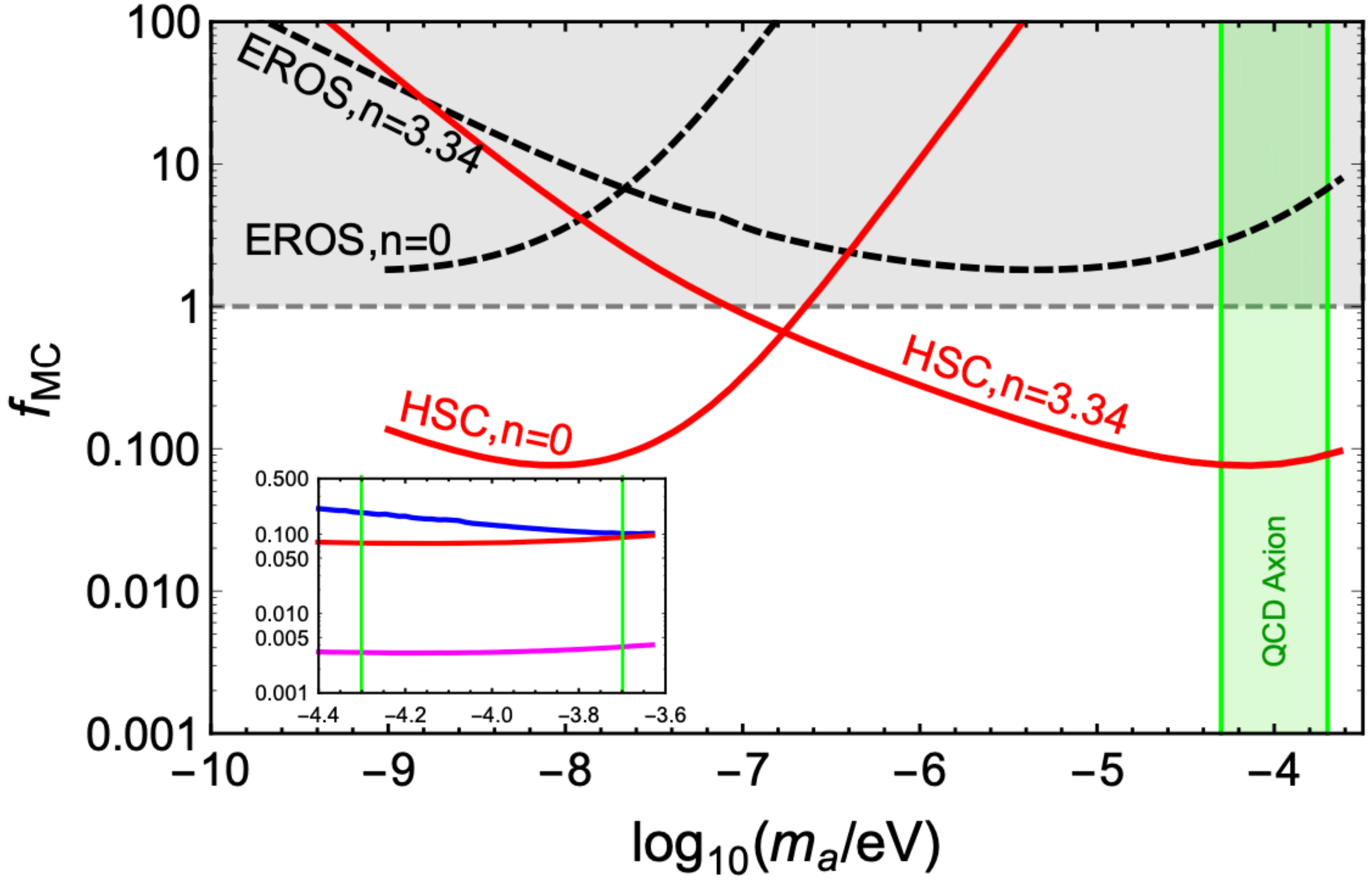
Walters+ (with **LV**) 2407.13060

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





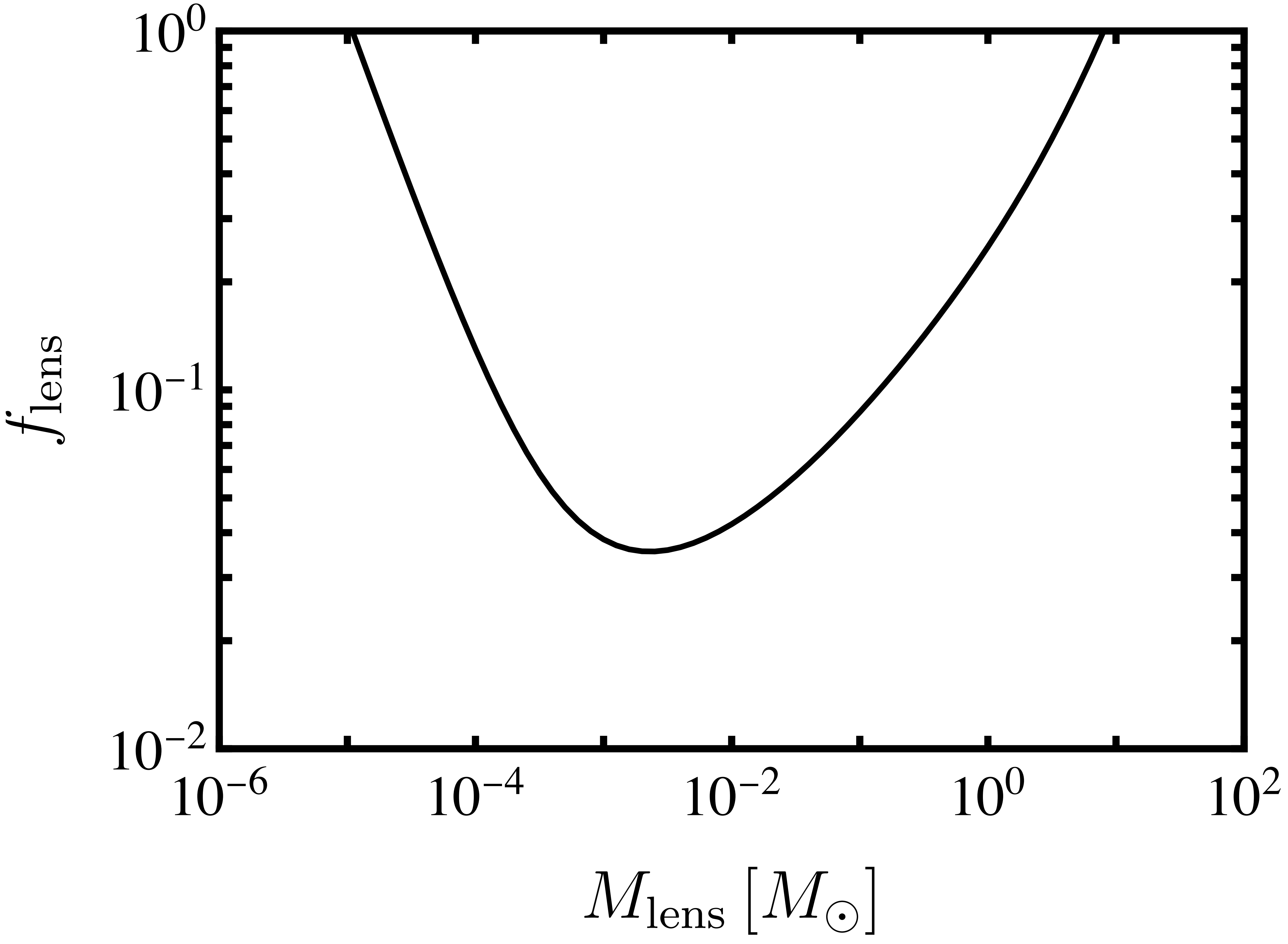
Fairbairn+ 1707.03310

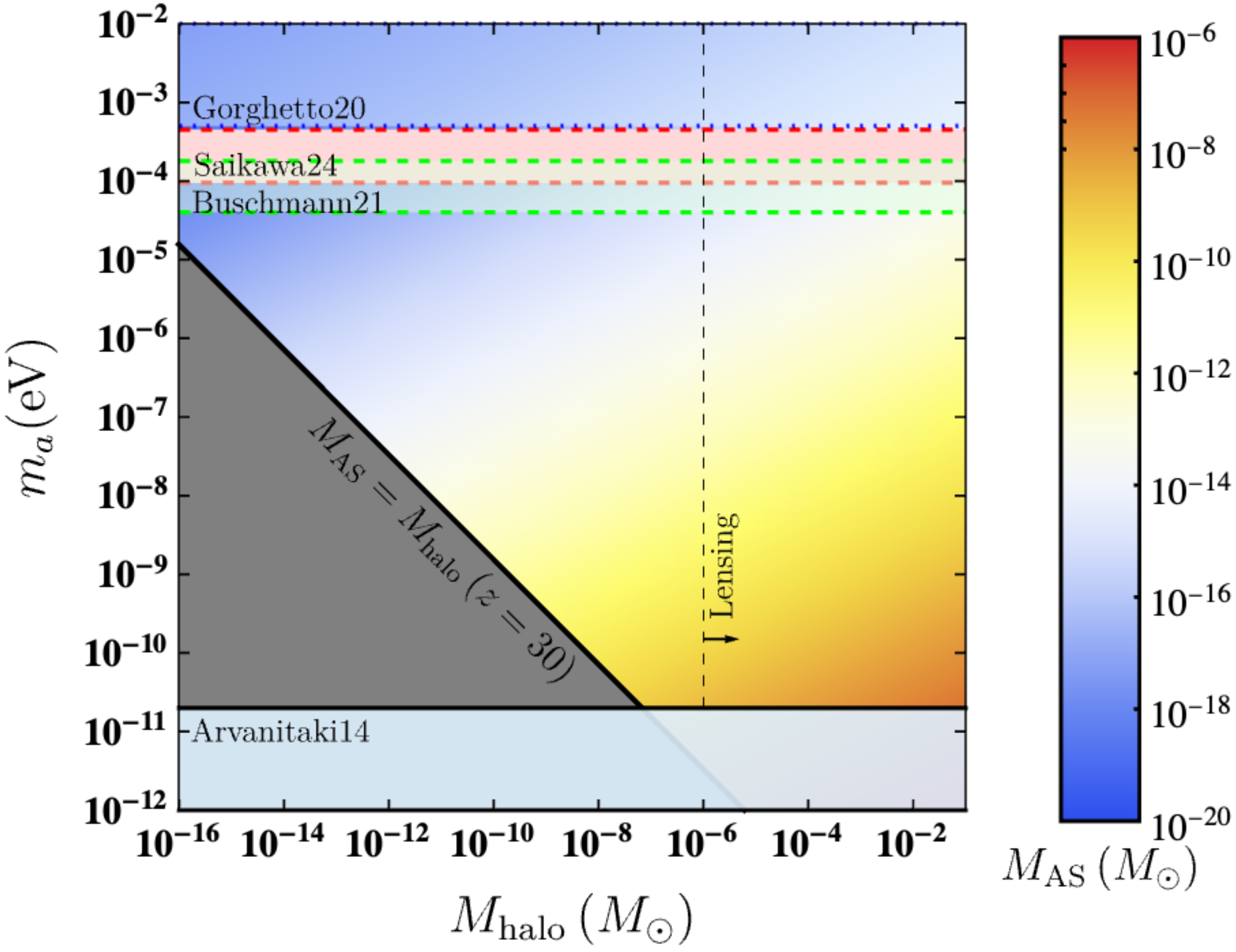
Indirect searches for the axion: lensing

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

We have recently revisited microlensing constraints from axion stars

[Yin, **LV** 2403.18610]

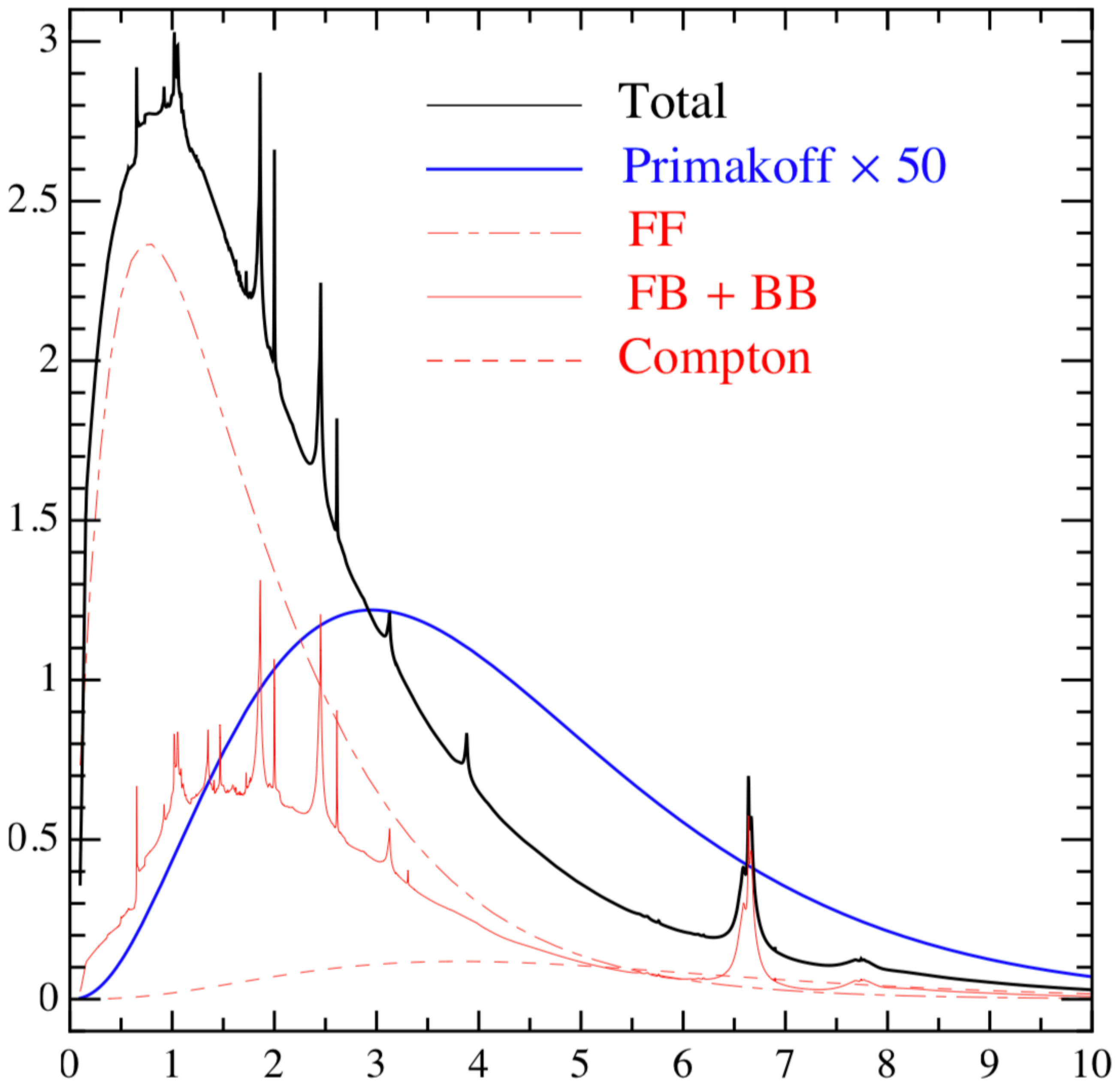




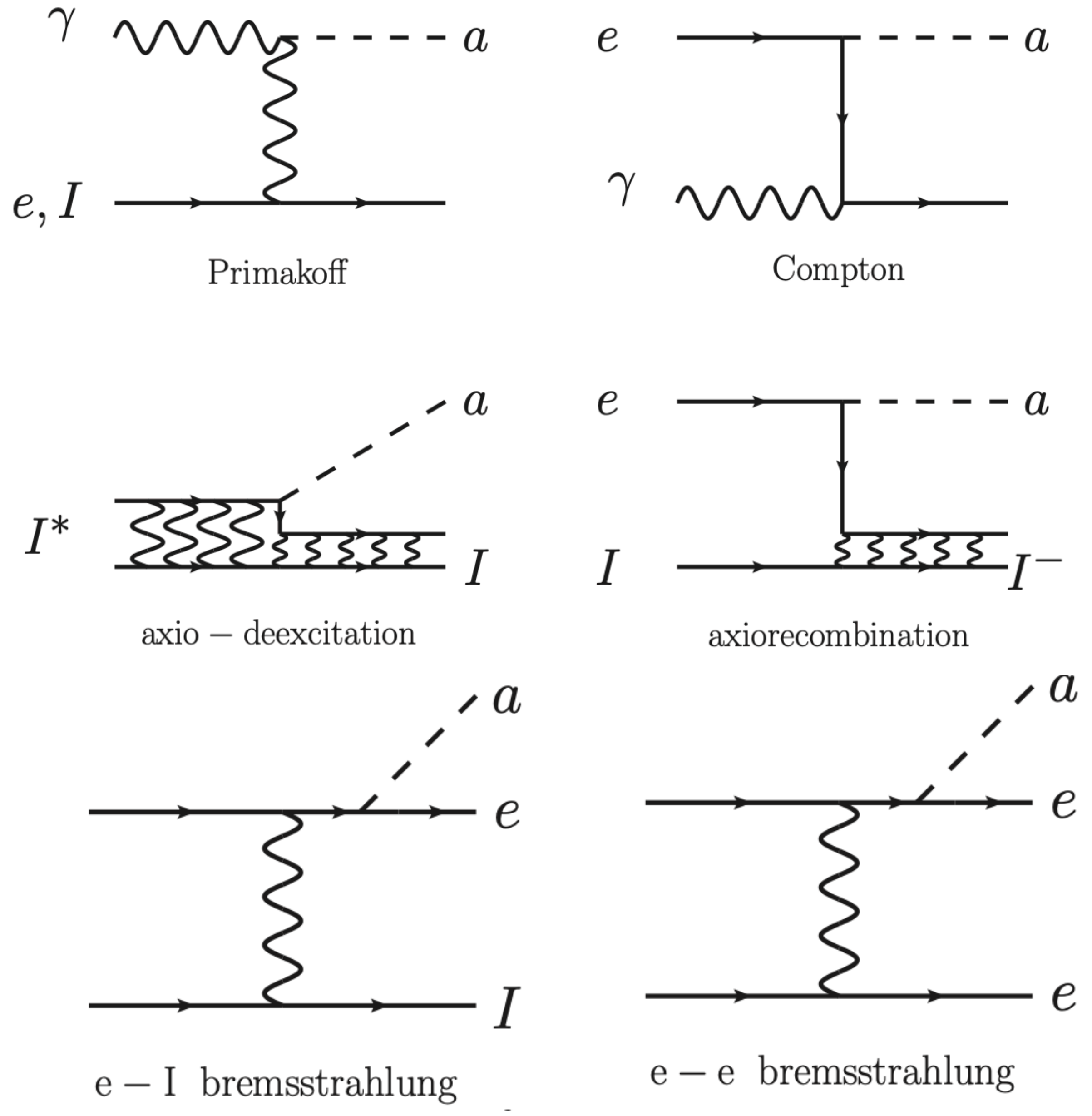
Axions from the Sun

Luca Visinelli

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!

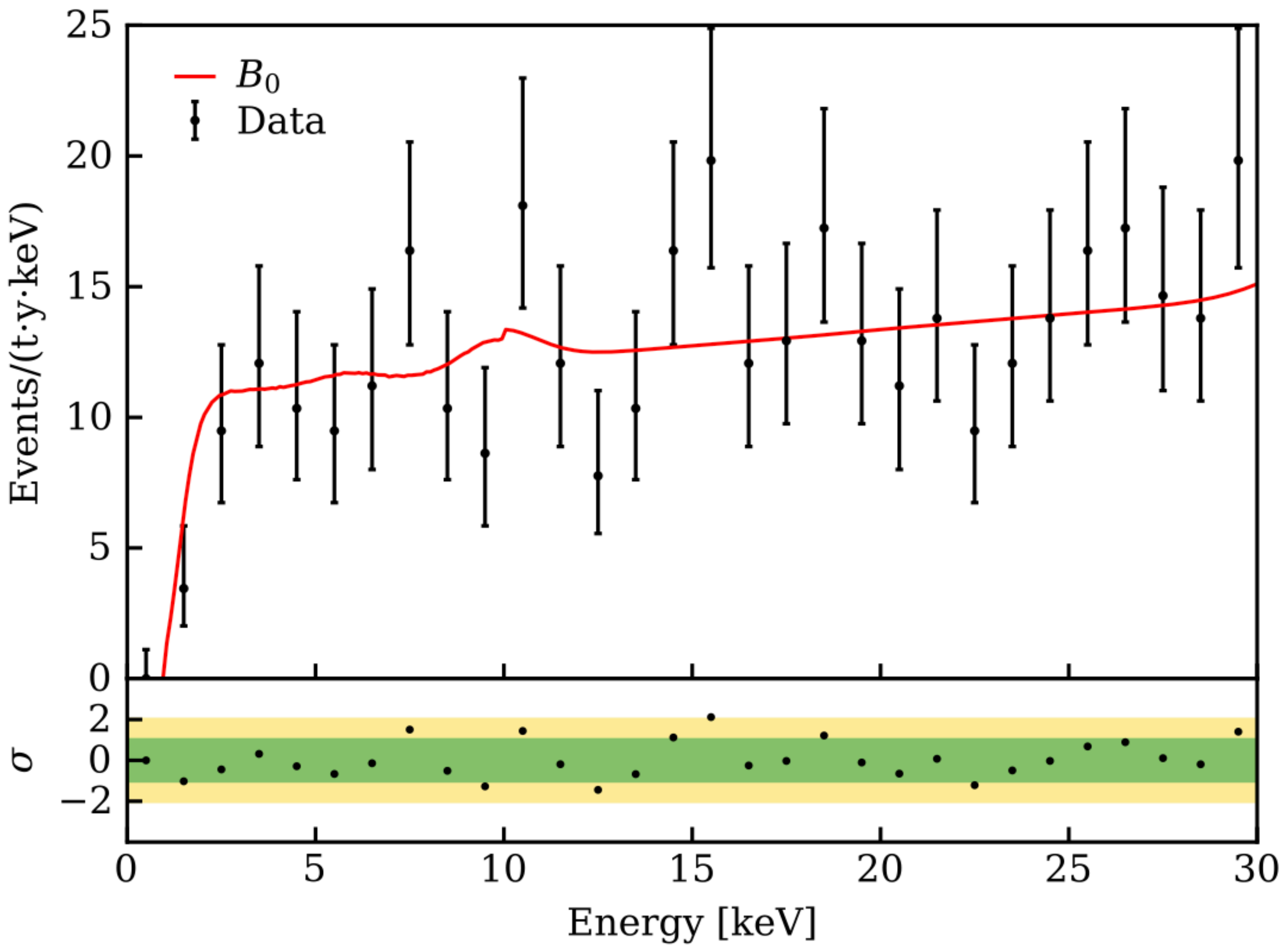
$$\omega_a \sim T_{\rm core} \approx {\rm keV}$$

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

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

Figure from Ben Safdi

Axions from the Sun

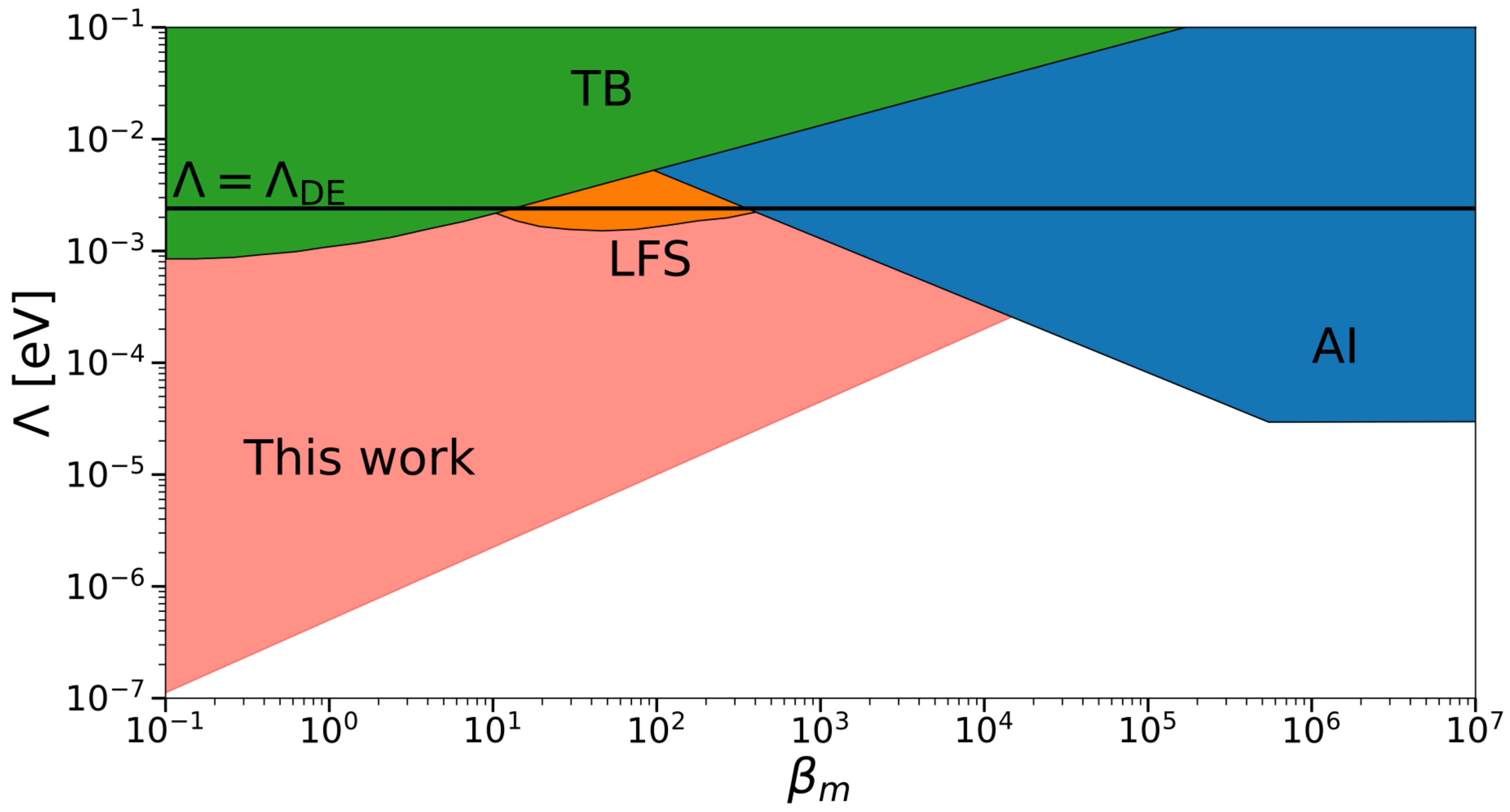


New exploration frontier:
Scalar field production in the Sun

We have considered solar chameleon

See the talk by **Tom O'Shea**
(This afternoon, first parallel session)

O'Shea, Davis, Giannotti, Vagnozzi, **LV**, Vogel
[2406.01691] (To appear on PRD)



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

Previous results "XENON1T excess" [2006.09721]

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

Axions and scalars from the Sun

Luca Visinelli

New exploration frontier: Scalar field production in the Sun

We have considered solar chameleons produced from

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

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

See the talk by **Anne Davis** right after mine

Axions and scalars from the Sun

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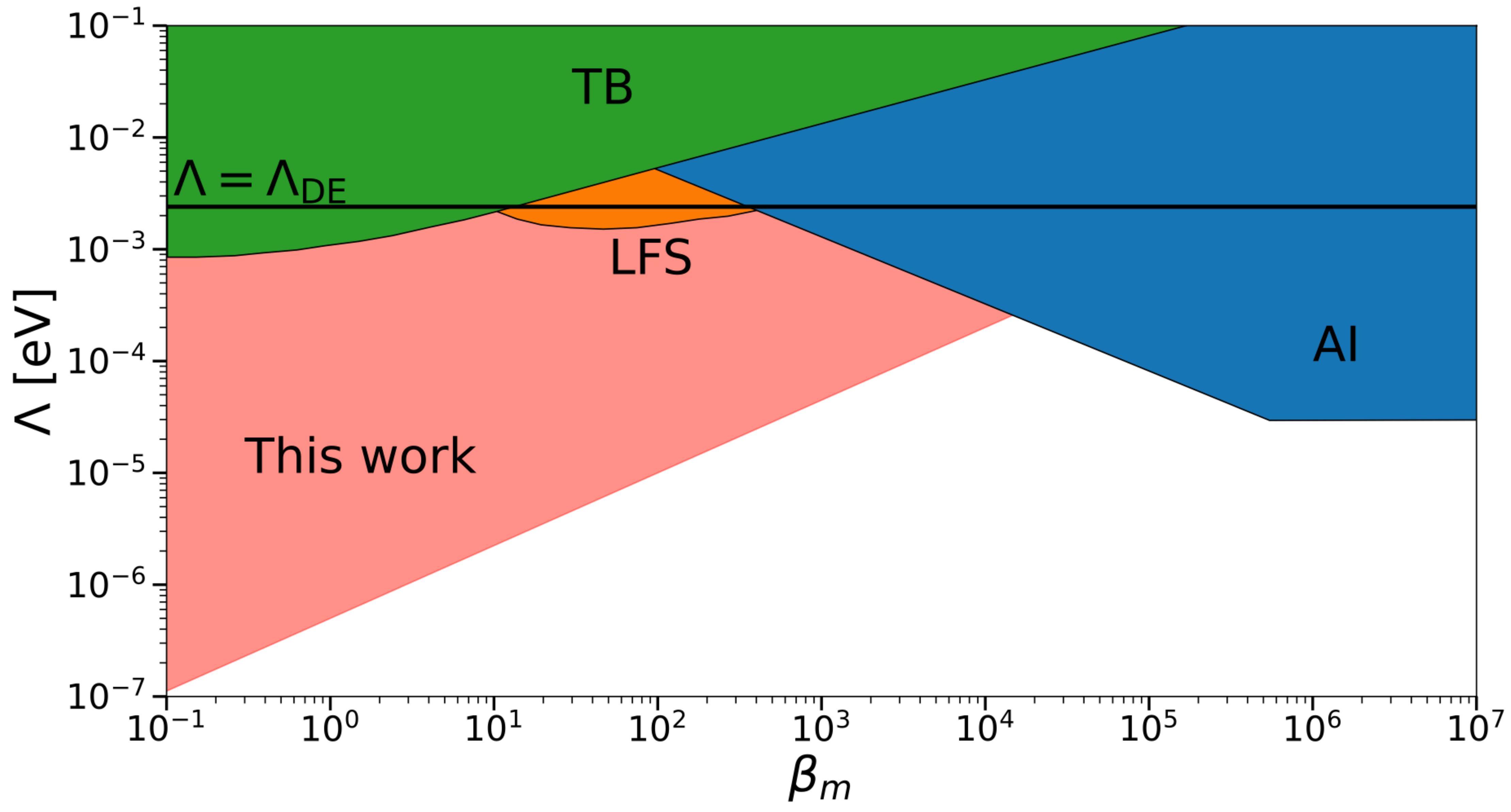


O'Shea, Davis, Giannotti, Vagnozzi, **LV**, Vogel [2406.01691] (To appear on PRD)

See the talk by **Tom O'Shea**
(This afternoon, first parallel session)

Direct searches: Haloscope

Luca Visinelli

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]

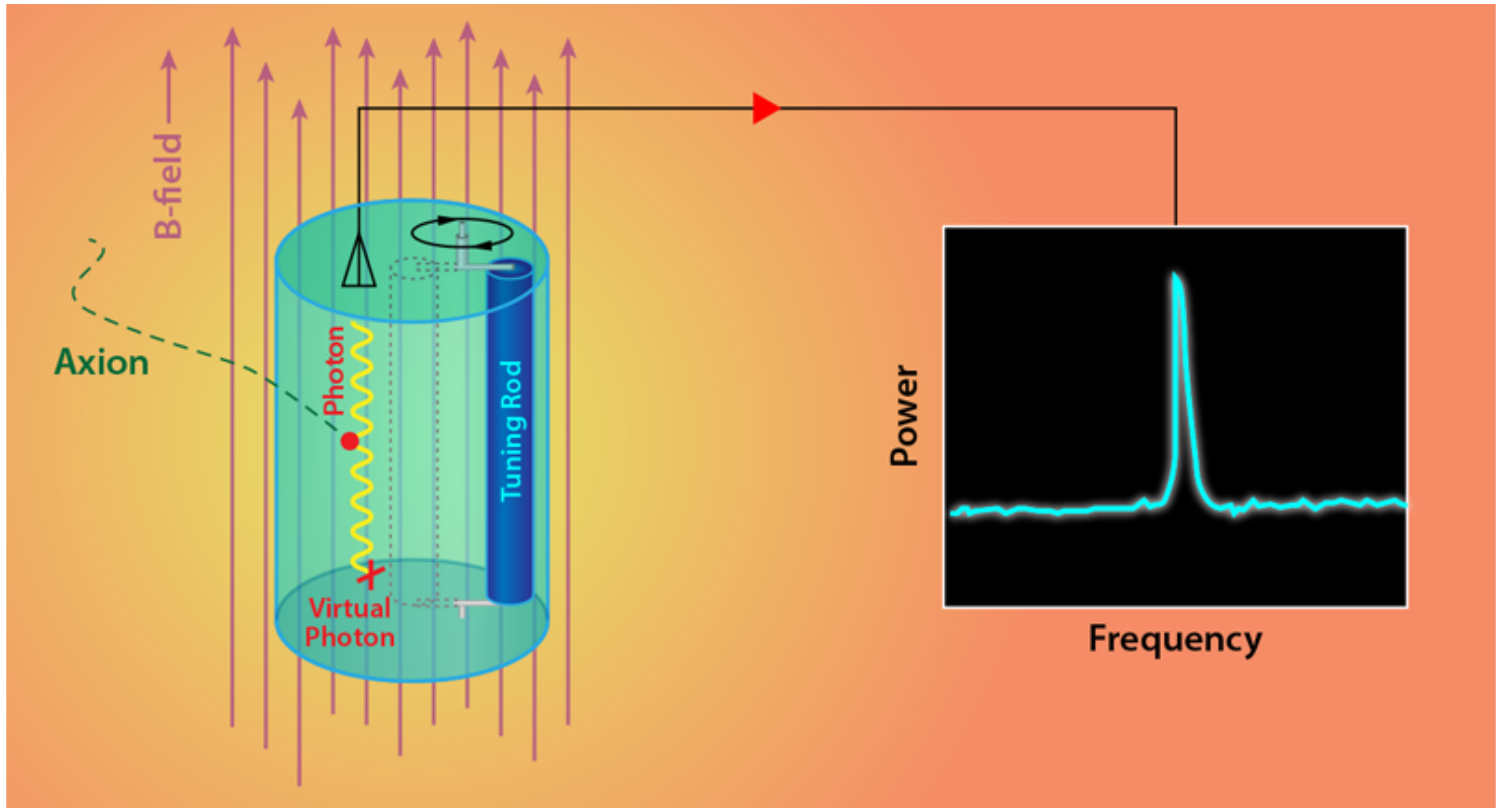
Significant enhancement when

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

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

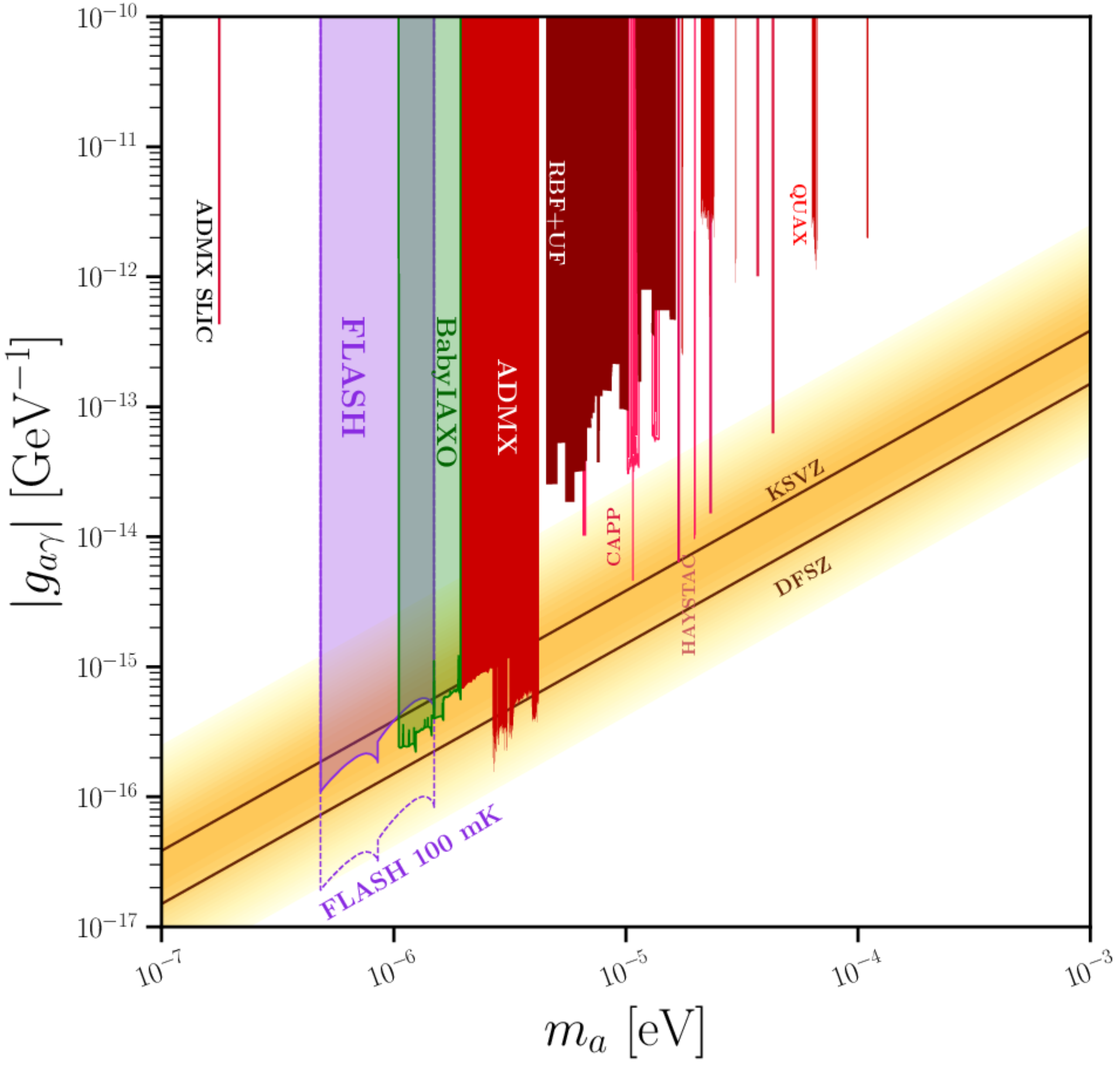
Q_L Quality factor V Cavity volume

B_0 Magnetic field C_{nml} Geometric factor

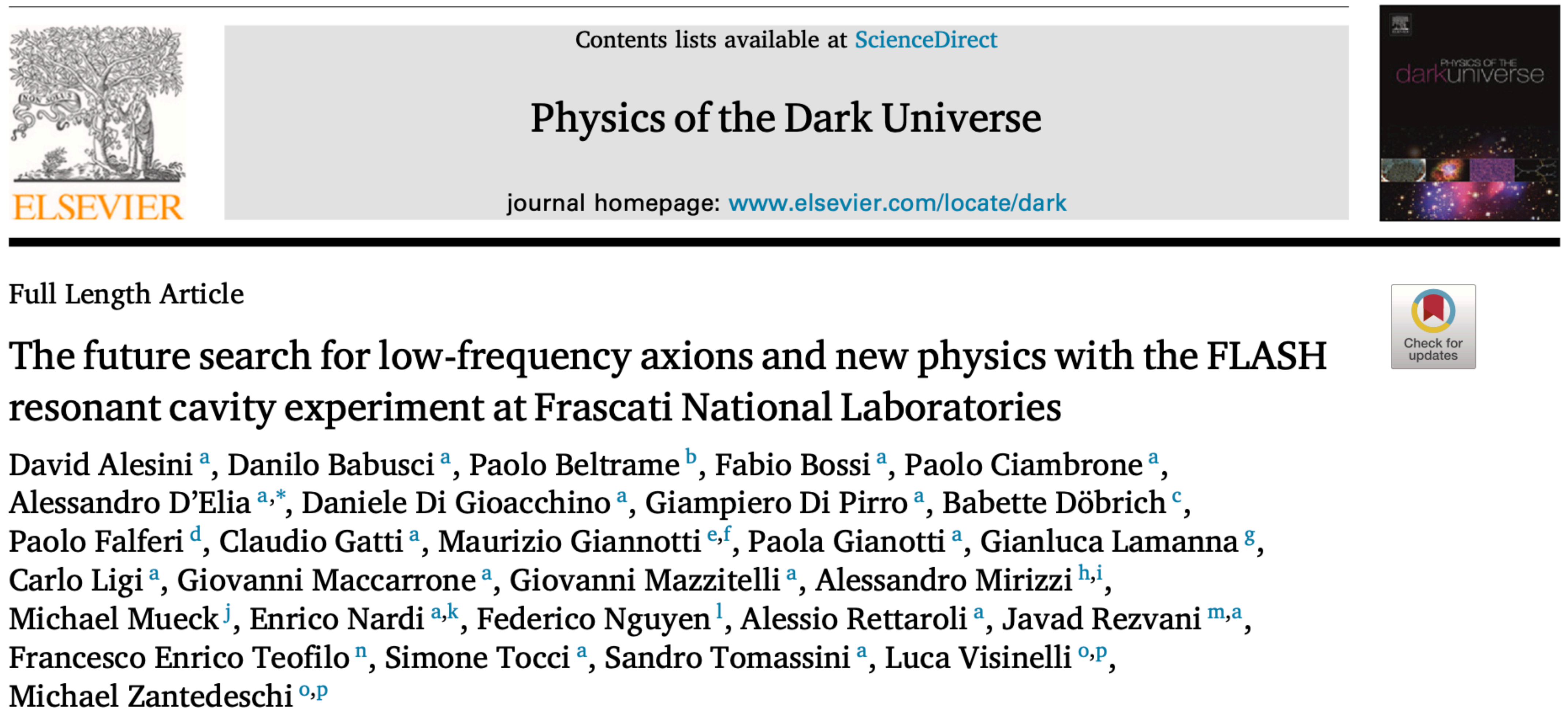


Courtesy of ADMX collaboration

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]

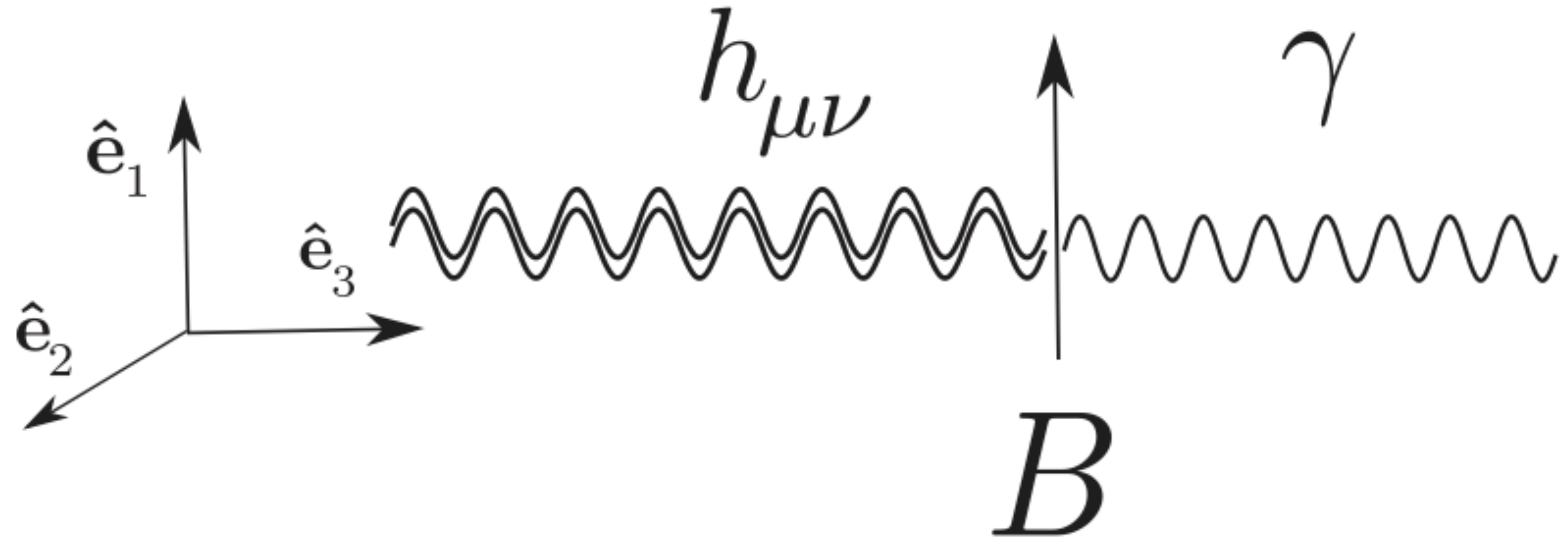
Partial overlap with BabyIAXO reaches when used as a haloscope [2306.17243]

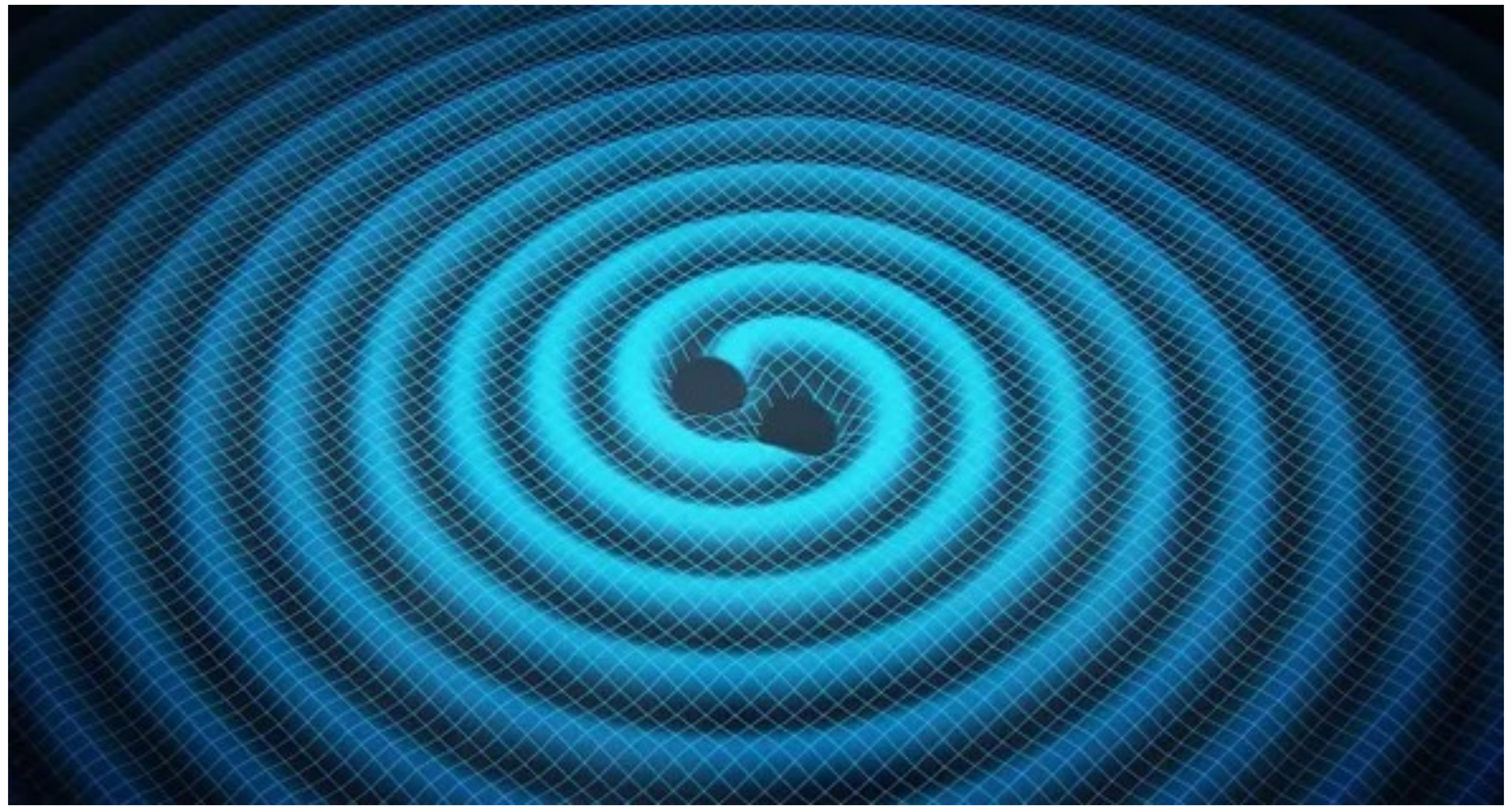
See also the CADEx talk by Jordi Miranda Escudé

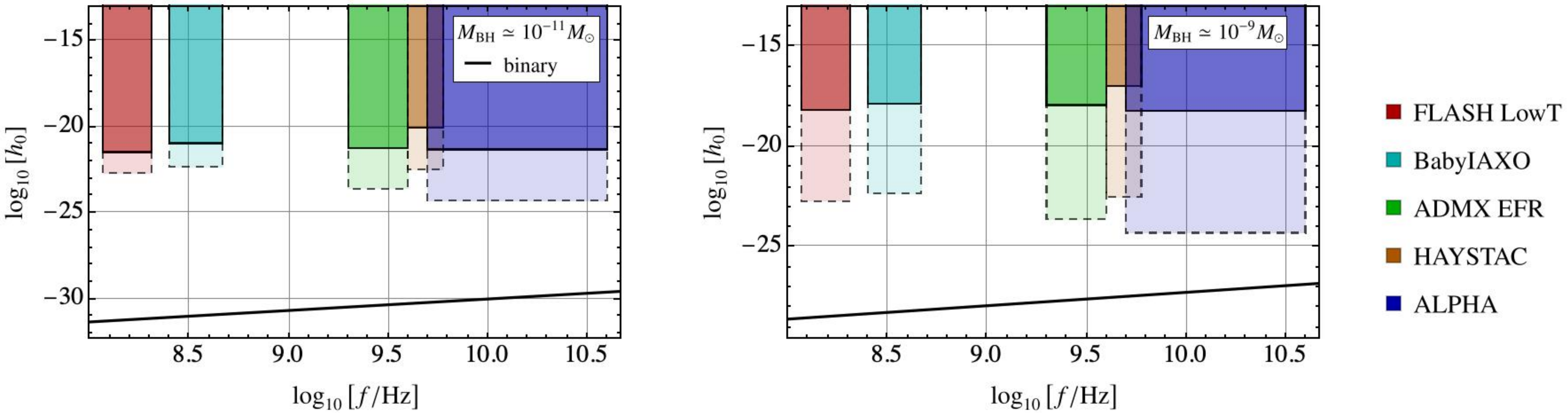
High-frequency gravitational waves

Inverse Gertsenshtein effect (see the talk by Camilo Garcia Cely)

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





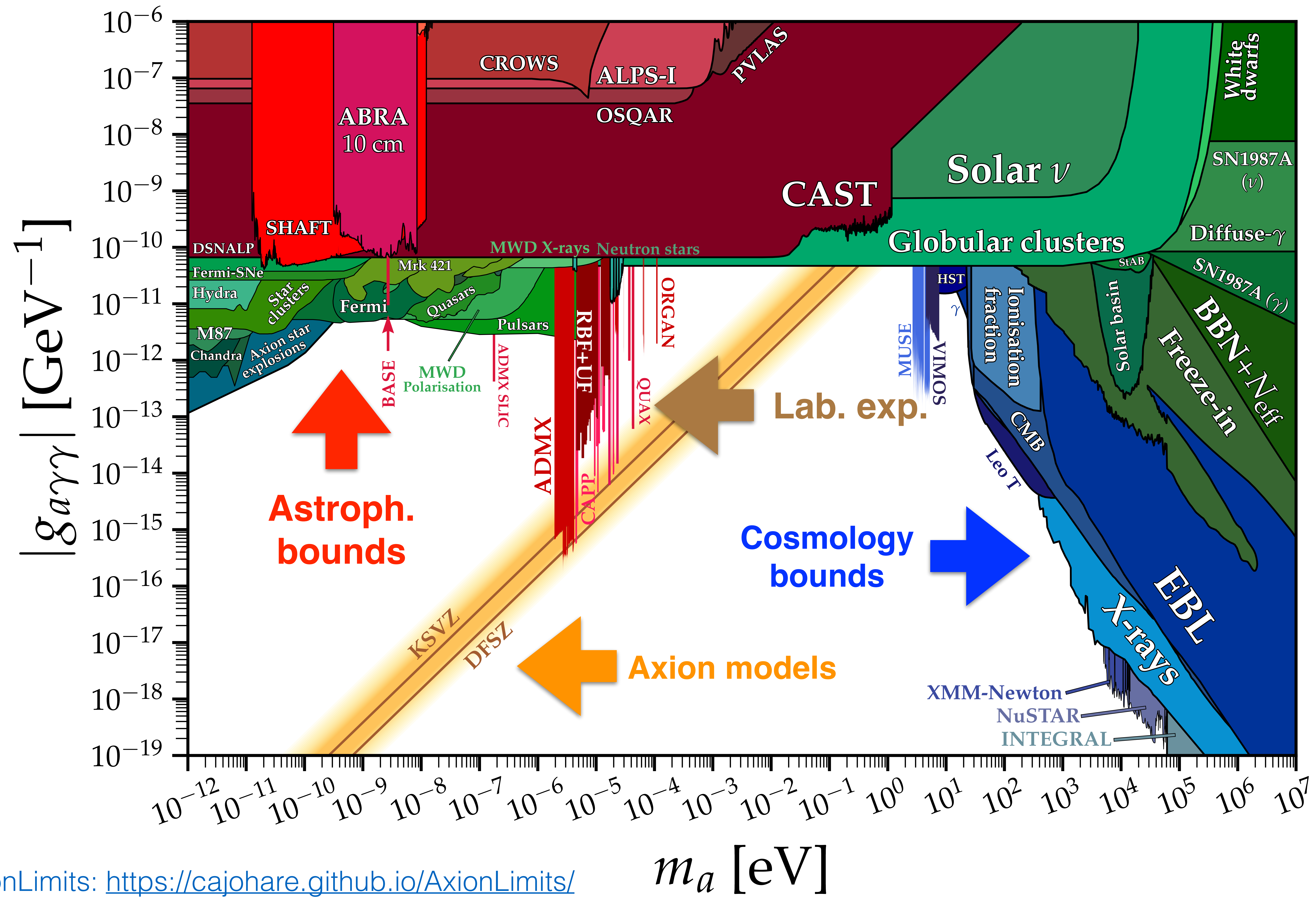


Gatti, **LV**, Zantedeschi [2403.18610](2403.18610), PRD

Work with
Michael Zantedeschi
(postdoc @TDLI)

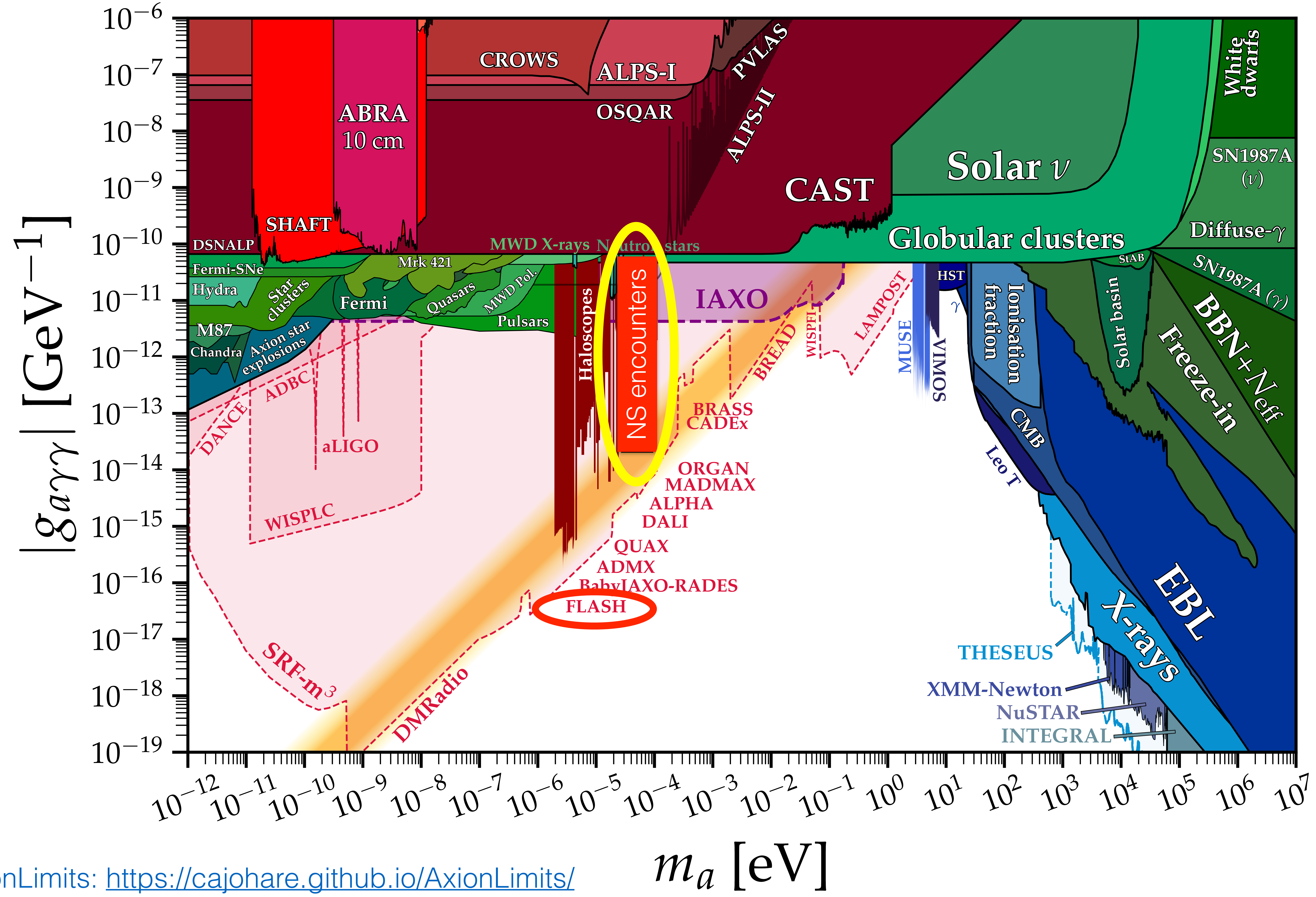
Summary of axion-photon coupling bounds

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

- See the review by Maurizio Giannotti
- Road to lab detection @ INFN-LNF
- 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

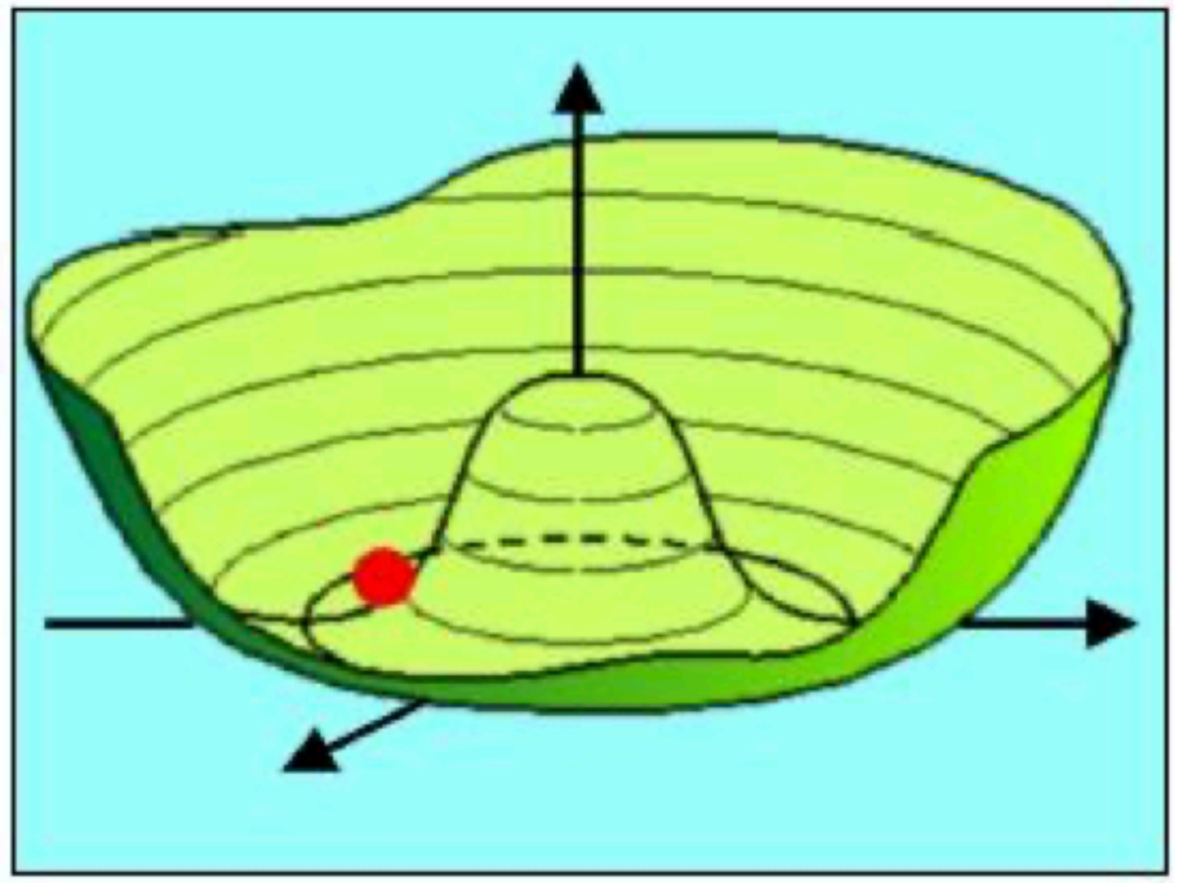
Thank you!

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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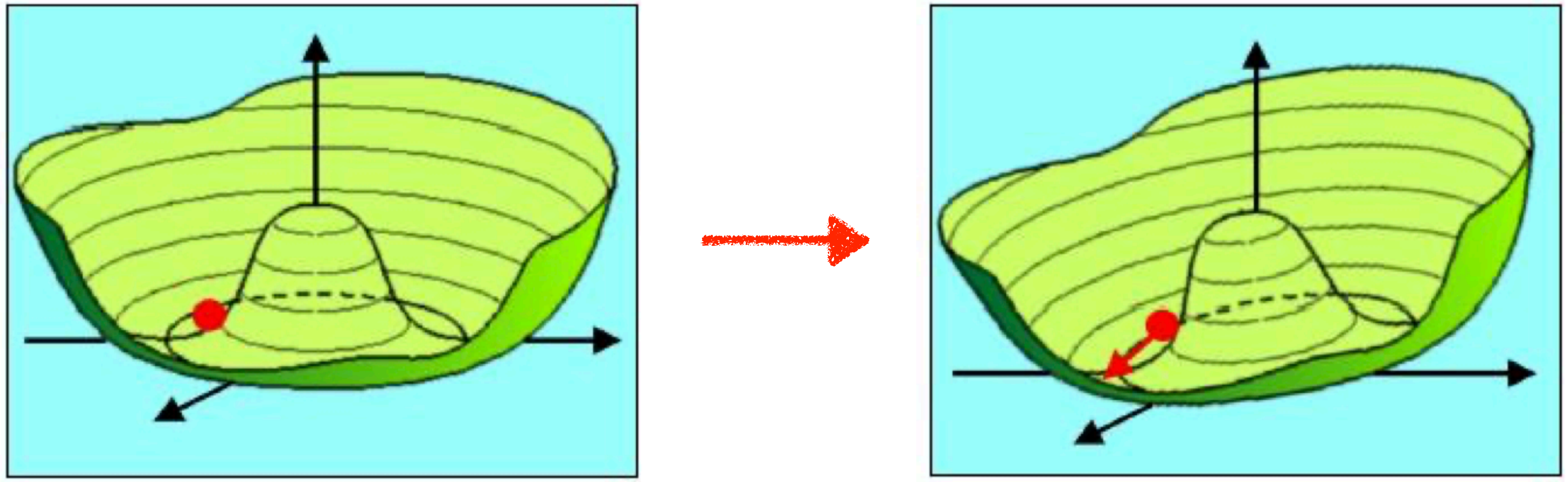


Figures from Steen Hannestad

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]

See the talk by Grilli di Cortona

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]

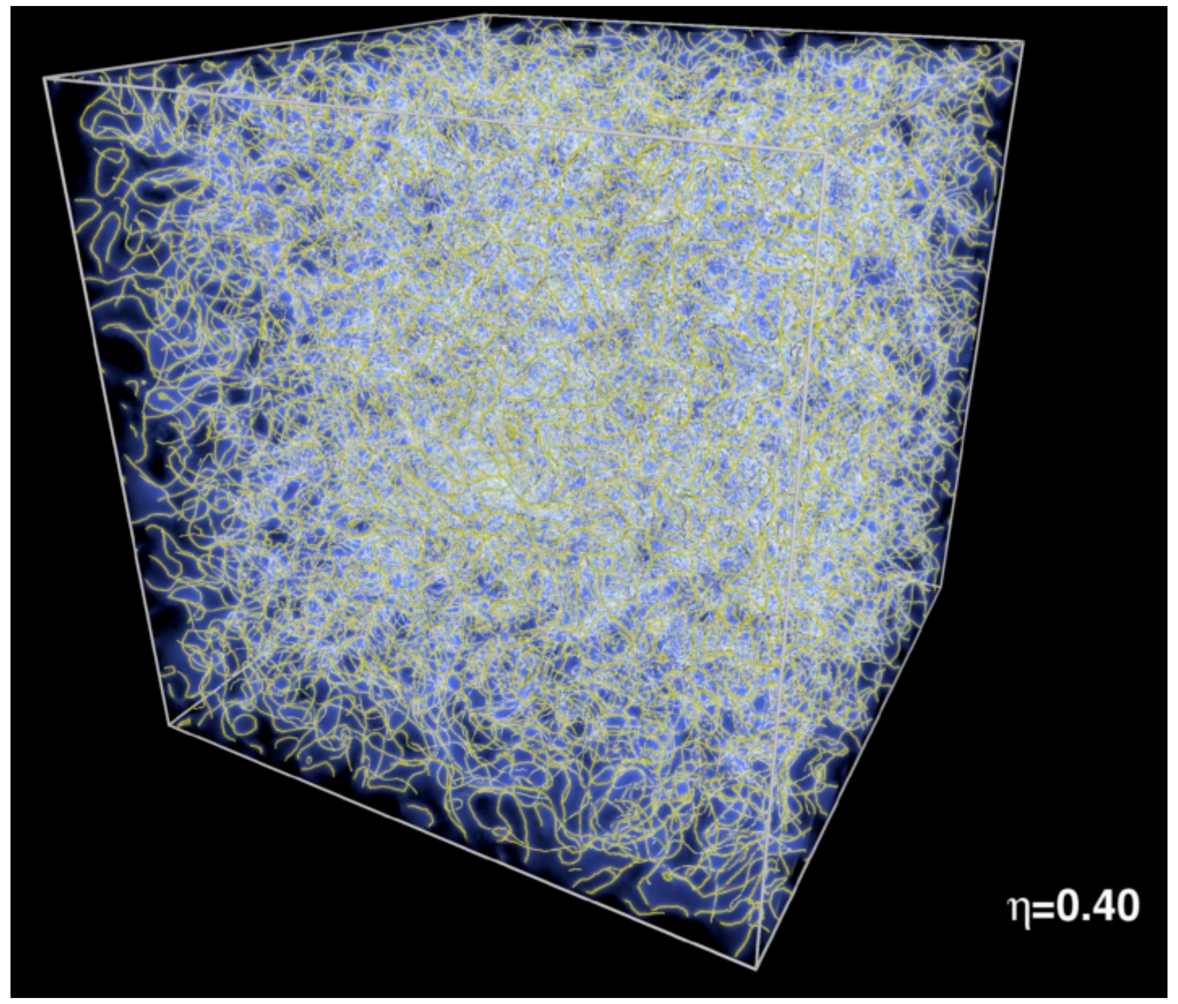
Luca Visinelli

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

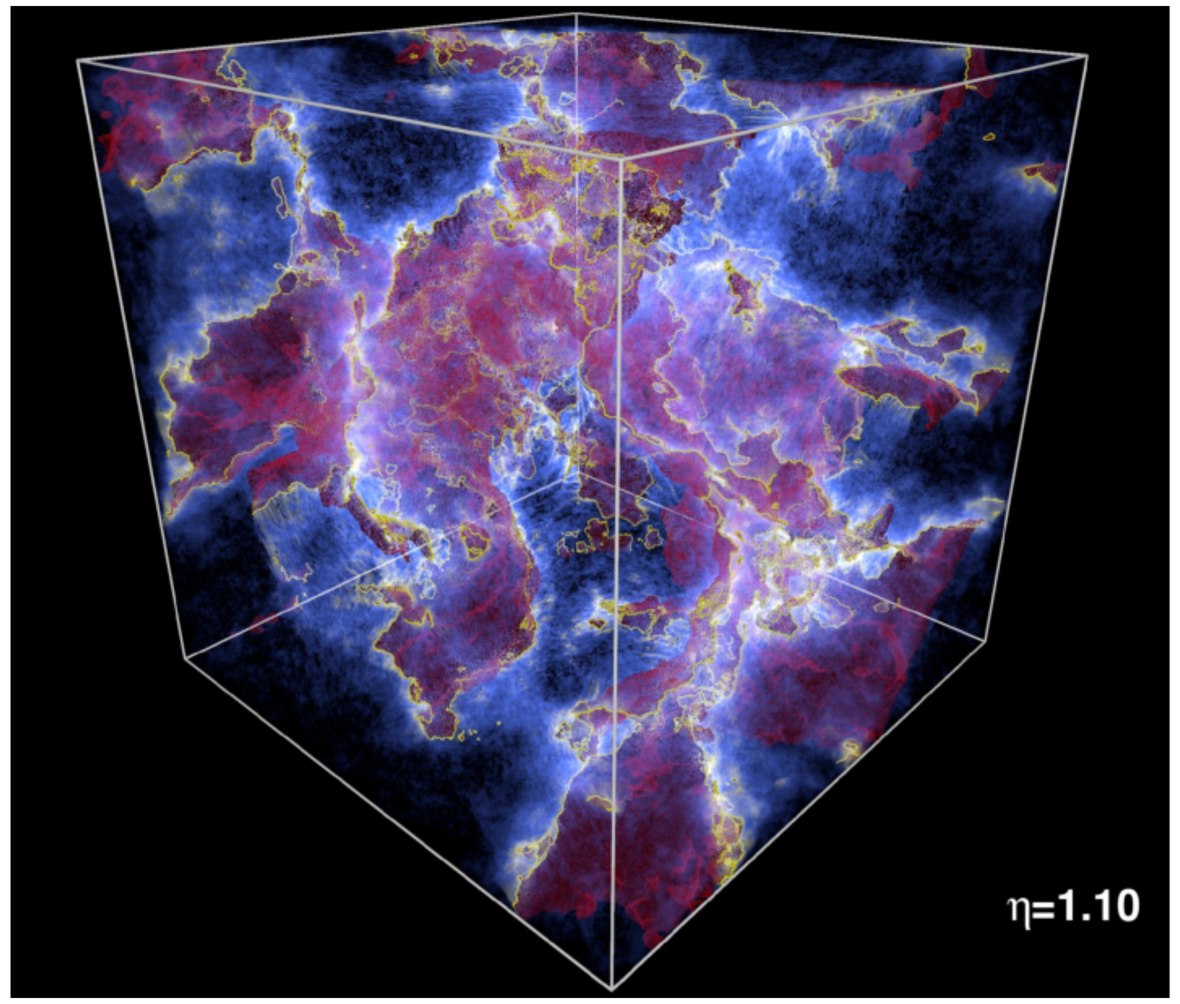
String network quickly enters a scaling regime with $\rho_{\rm scaling} = \xi\mu/t^2$

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

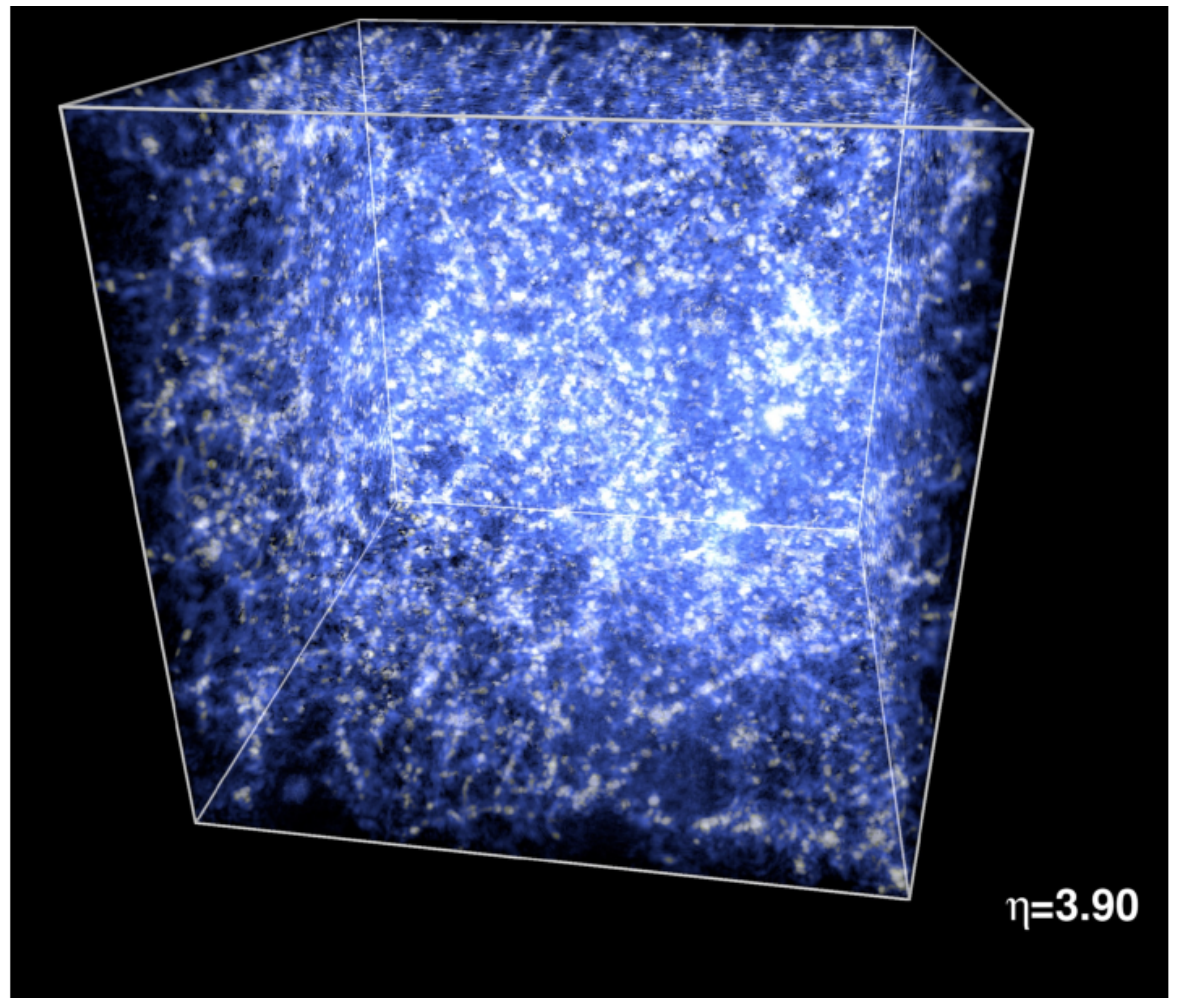
String length per Hubble volume ξ



Before QCD PT



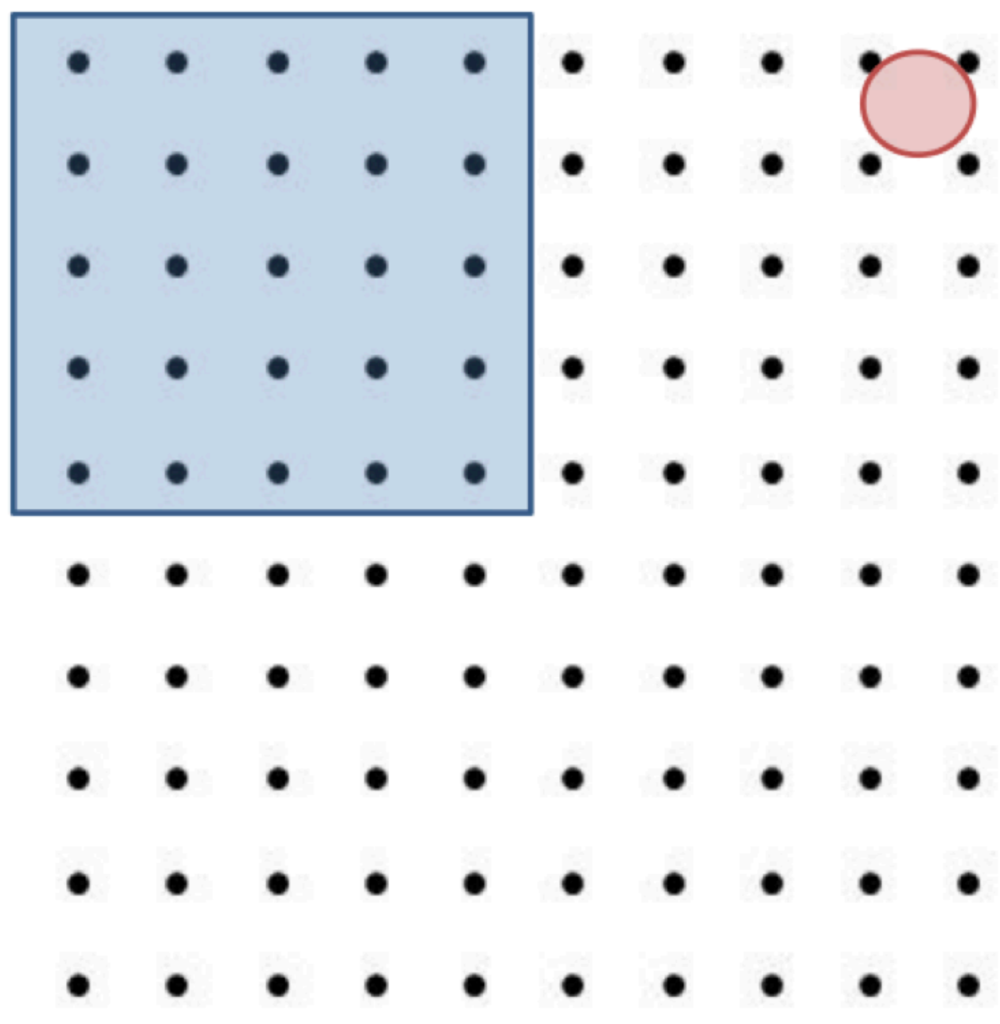
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



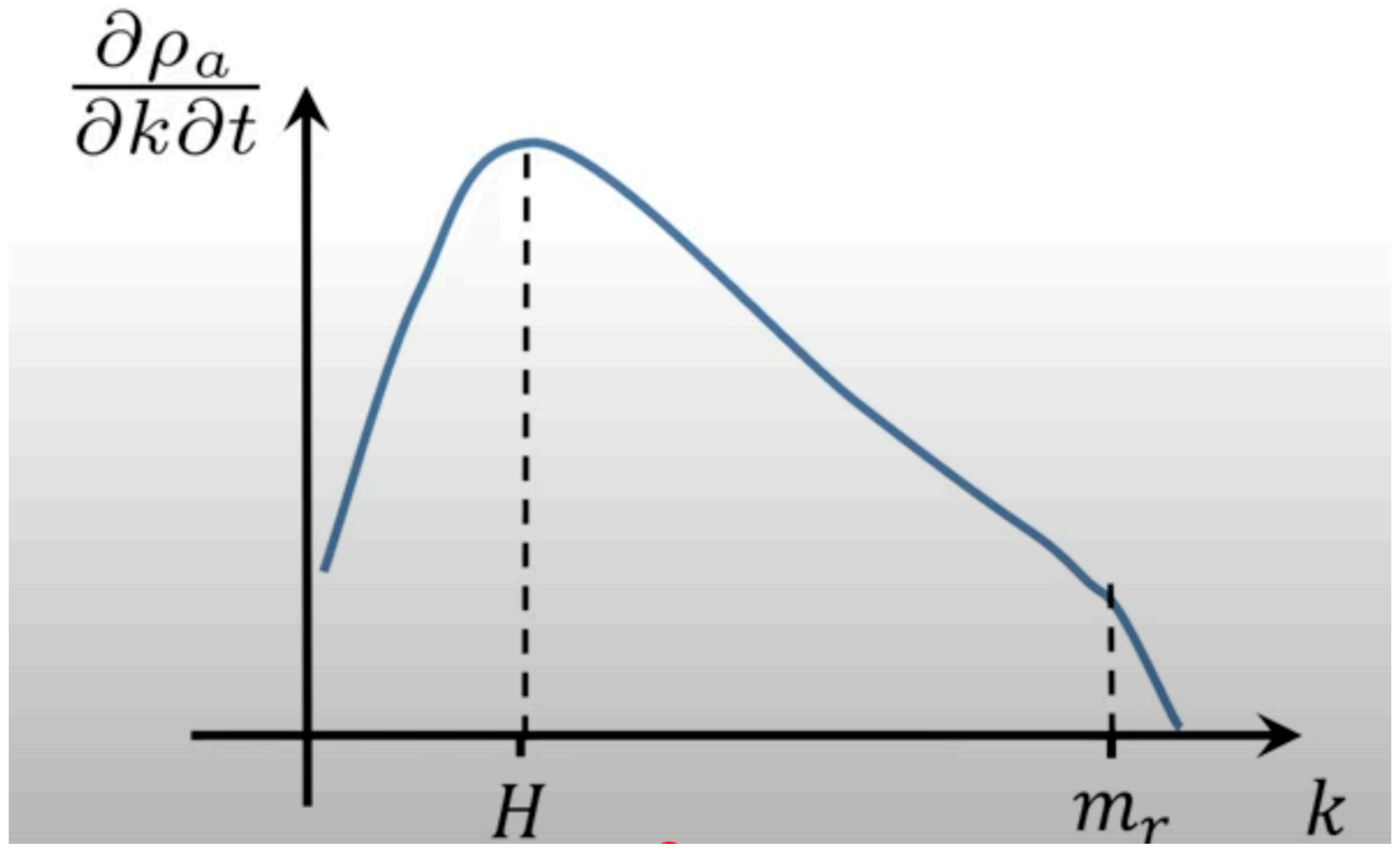
Credits: Ed Hardy

$N \approx 5000^3$

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 $\sim \mathrm{meV}$ [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

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