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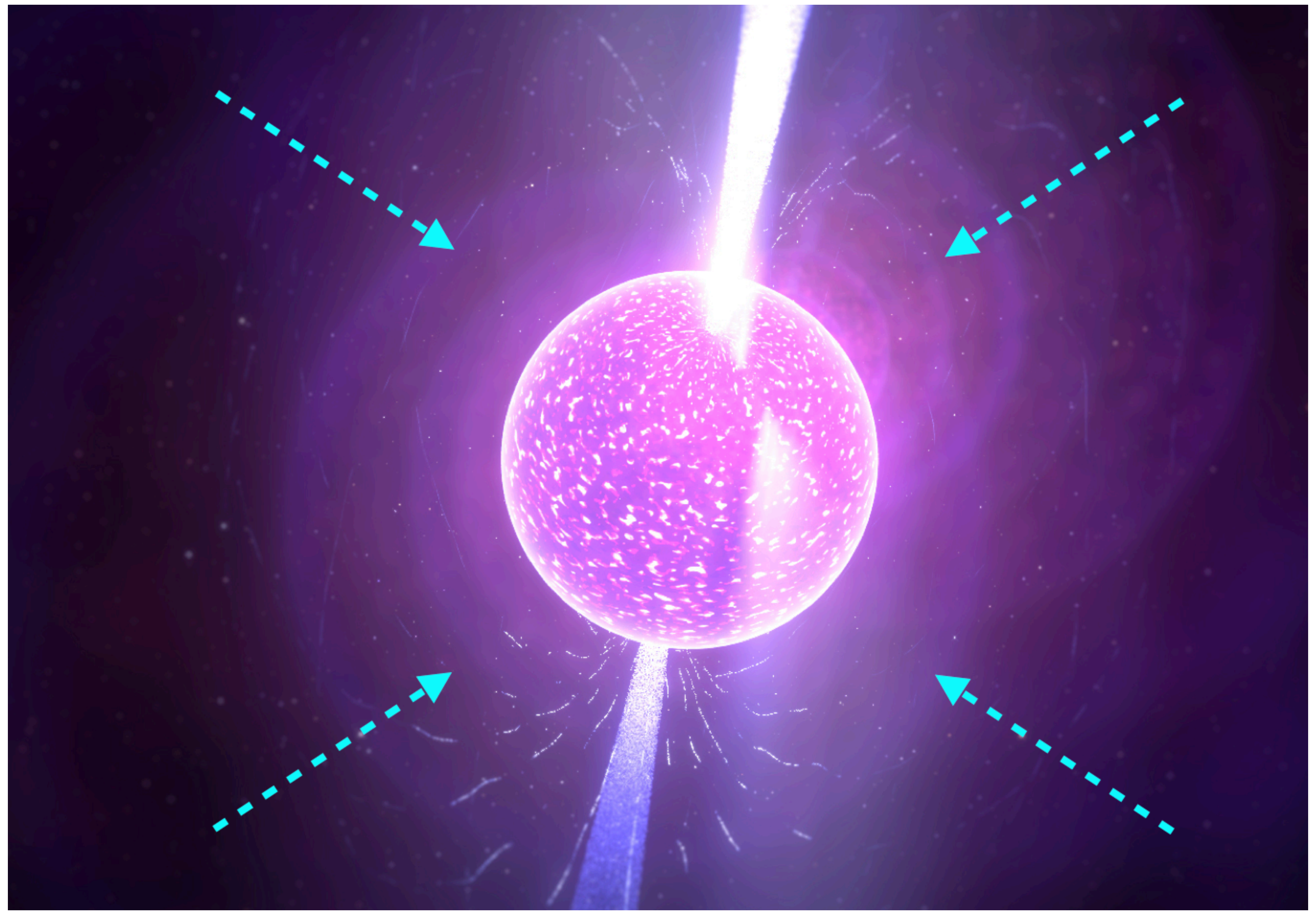
Indirect Detection of the QCD Axion: Resonant Conversion in Neutron Star Magnetospheres



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Based on: 2407.13060

July 10, 2024

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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]

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

See the talk by Luca di Luzio for all details: agenda.infn.it/event/39713/

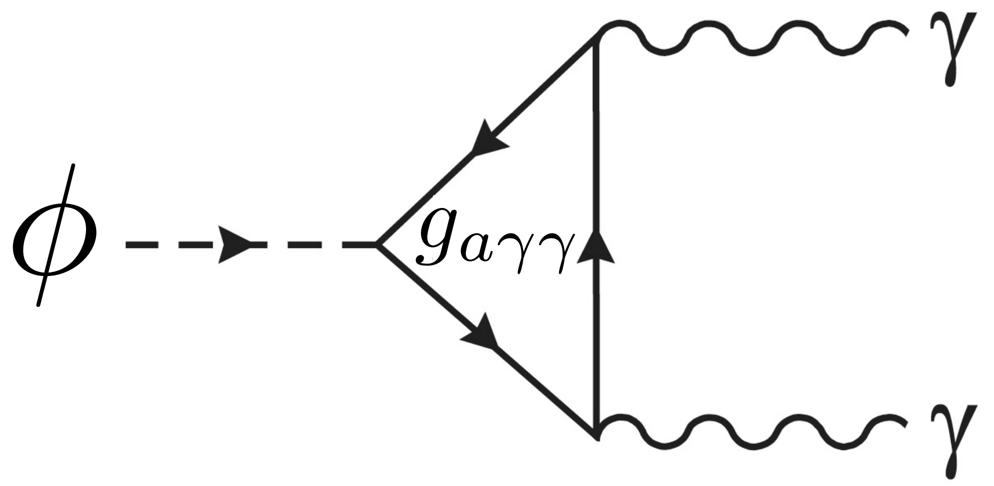
The QCD Axion: foundations

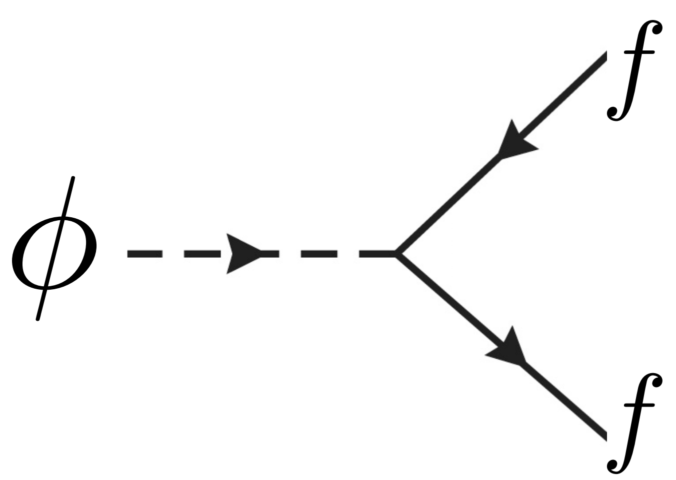
Luca Visinelli

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

Axion Miniclusters in the Milky Way

Axion miniclusters (when $f_a \lesssim H_I$)

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

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

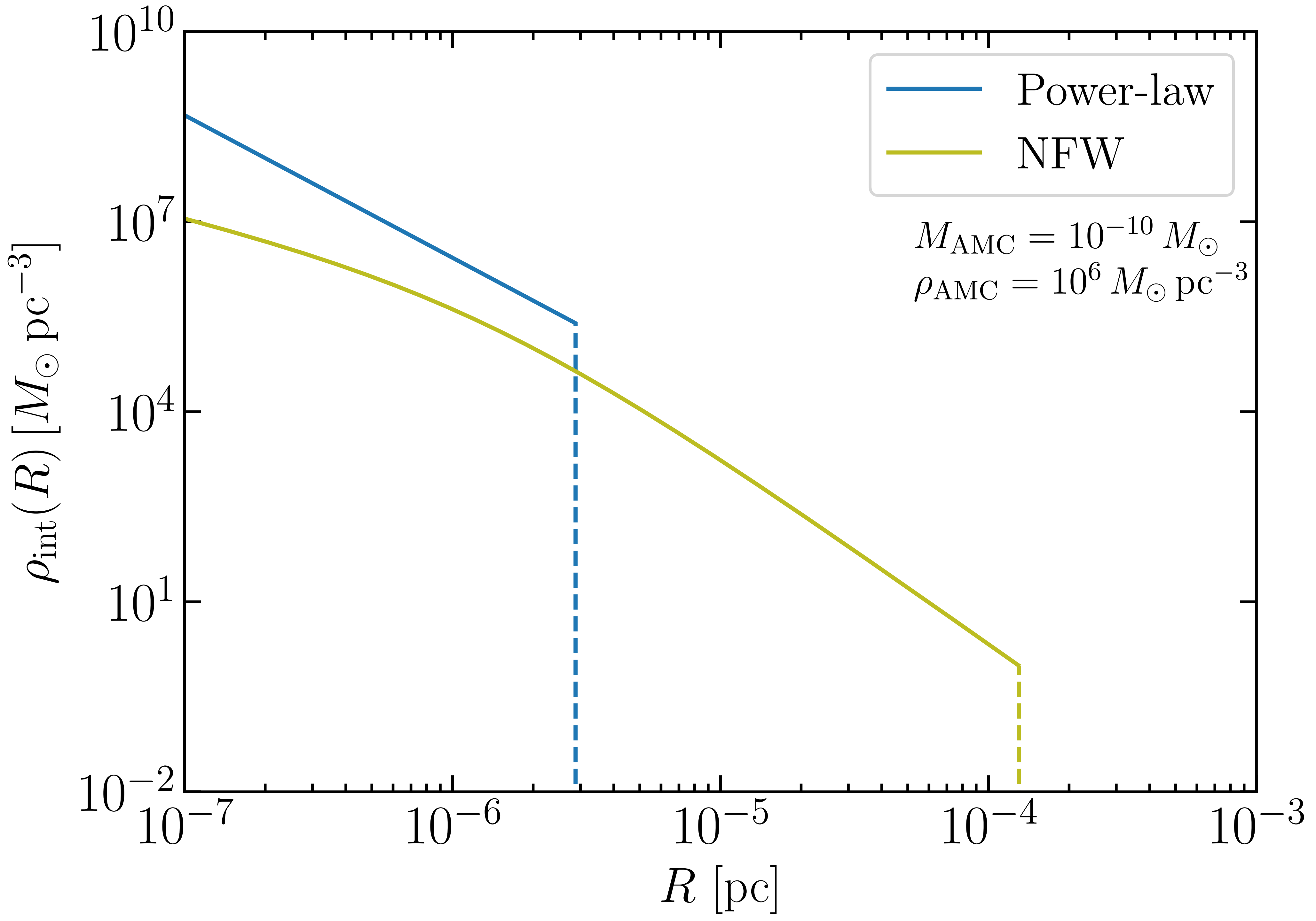
Typical minicluster mass:

$$M_{\rm AMC} = \frac{4\pi}{3} L_{\rm osc}^3\,\rho_{\rm DM} \sim 10^{-14}\,M_\odot$$

[Hogan & Rees 1988; Kolb & Tkachev 1994]

Power-law density profile from collapse:

$$\rho_{\rm AMC}(r) \propto r^{-9/4}$$



Kavanagh+ (with **LV**), 2011.05377

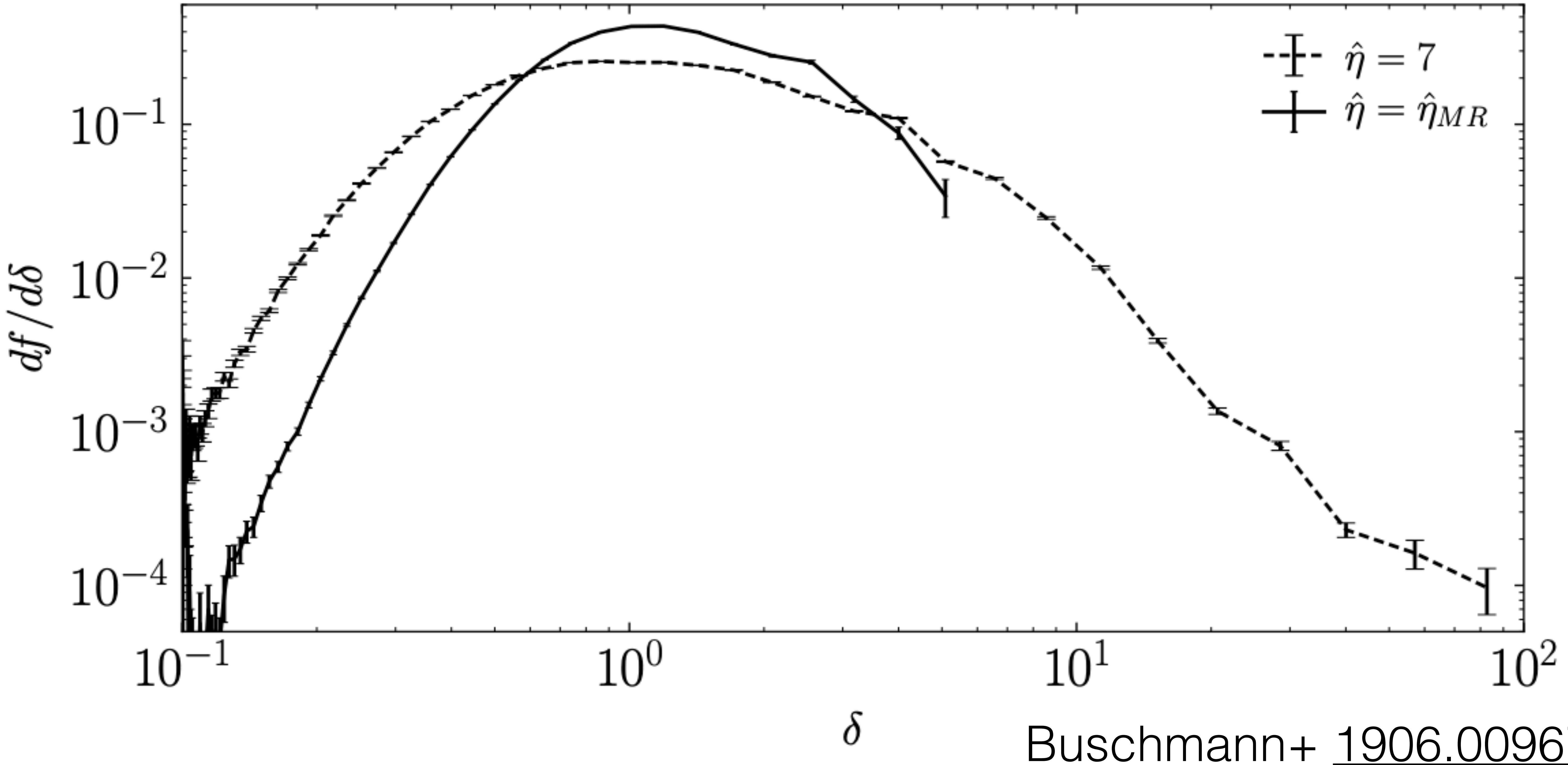
After MR, miniclusters merge hierarchically to form halos with **NFW**-like profiles [Vaquero+ 2019]

AMC overdensity function

Density of a minicluster: $\rho_{\rm AMC}(\delta) \approx 140\,(1+\delta)\,\delta^3\,\rho_{\rm eq}$

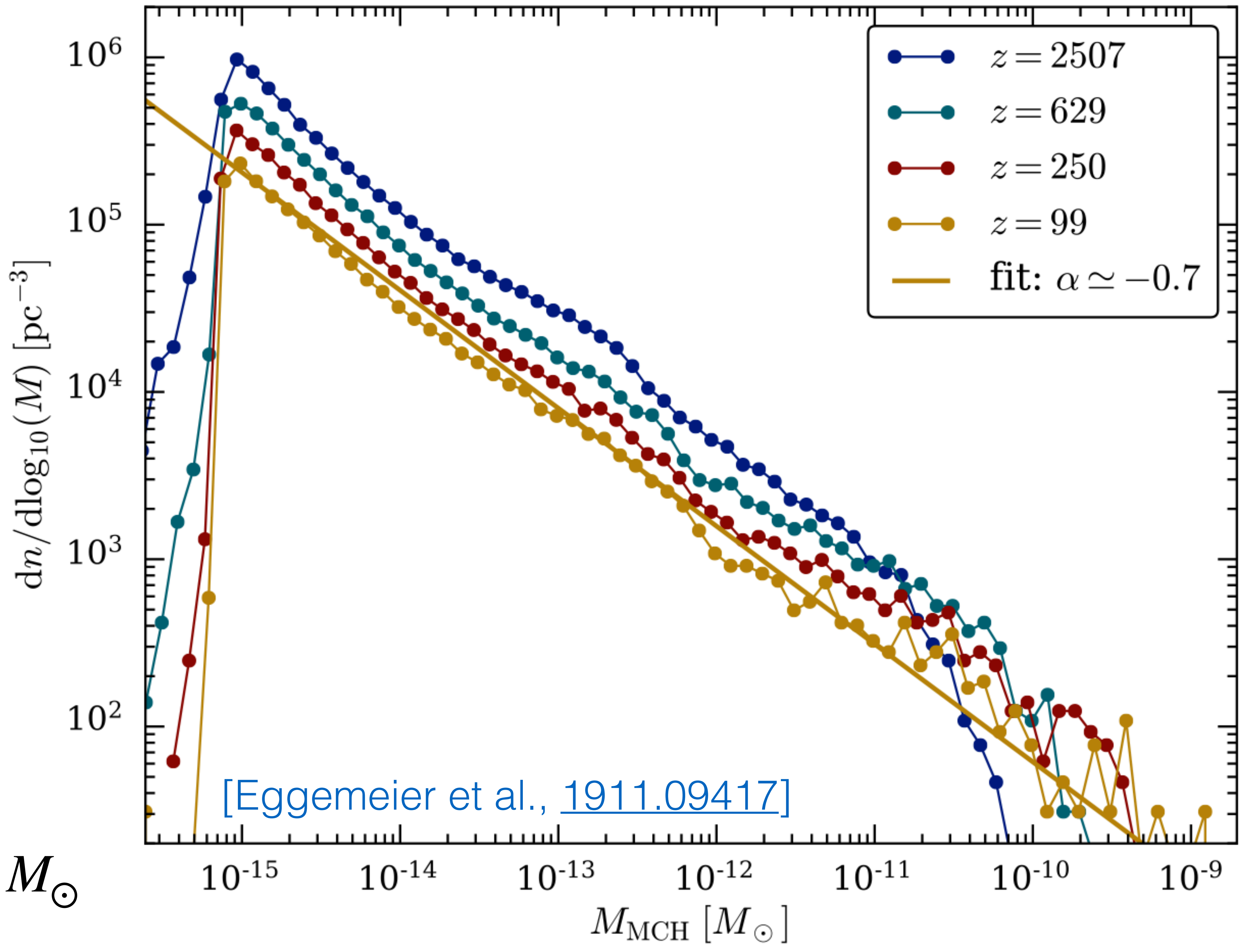
Kolb & Tkachev 1993, 1994

Marginal distribution from numerical simulations



Buschmann+ 1906.00967

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 $(M_{\rm AMC}, \delta)$ or equivalently $(M_{\rm AMC}, \rho_{\rm AMC})$!

[github.com/bradkav/axion-miniclusters]

Milky Way Setup

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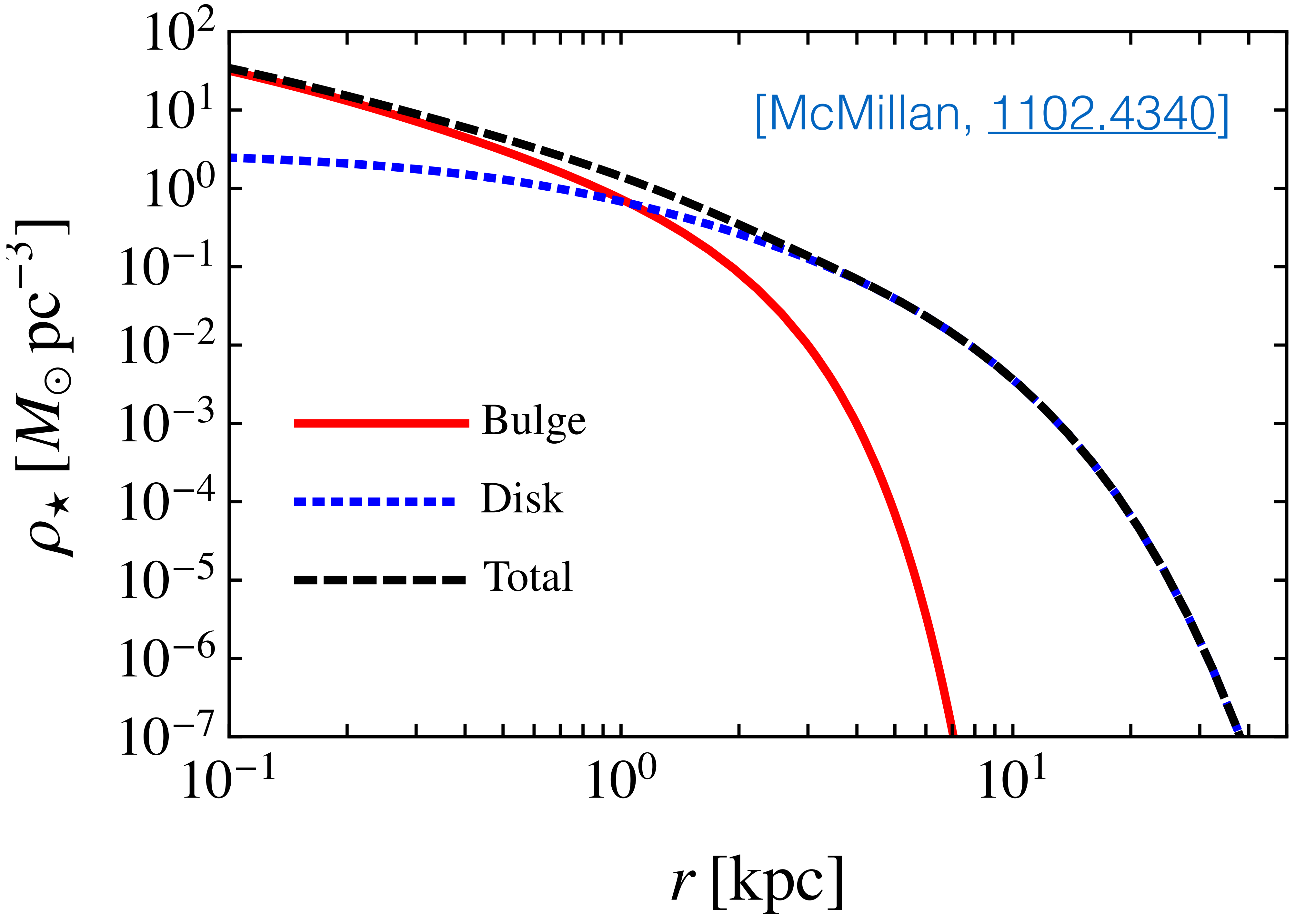
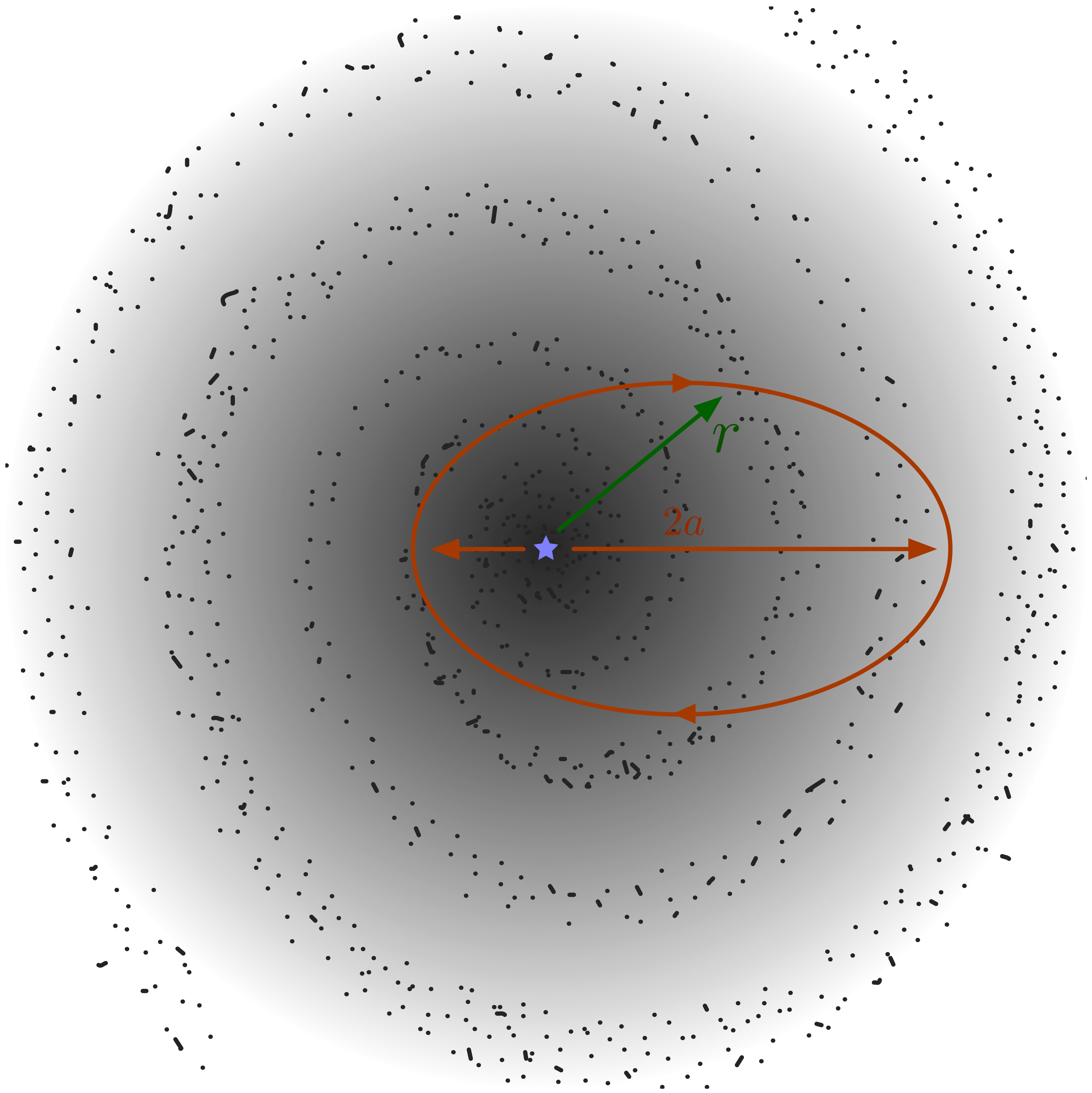




$$n_{\rm AMC}(r) = f_{\rm AMC}\frac{\rho_{\rm DM}(r)}{\langle M_{\rm AMC}\rangle}$$

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

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

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:

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

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

AMC not disrupted

AMC disrupted

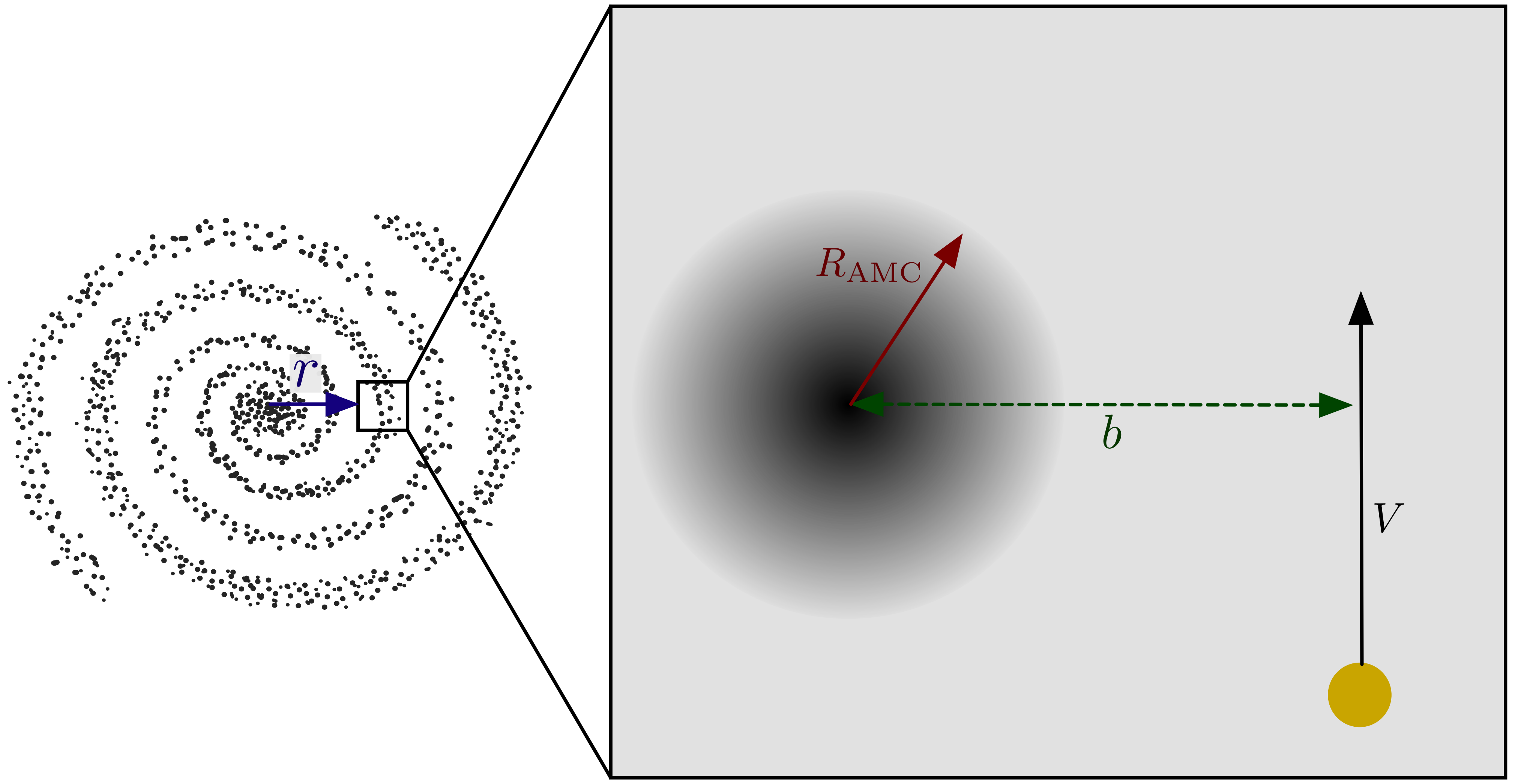
Remove AMC from simulation

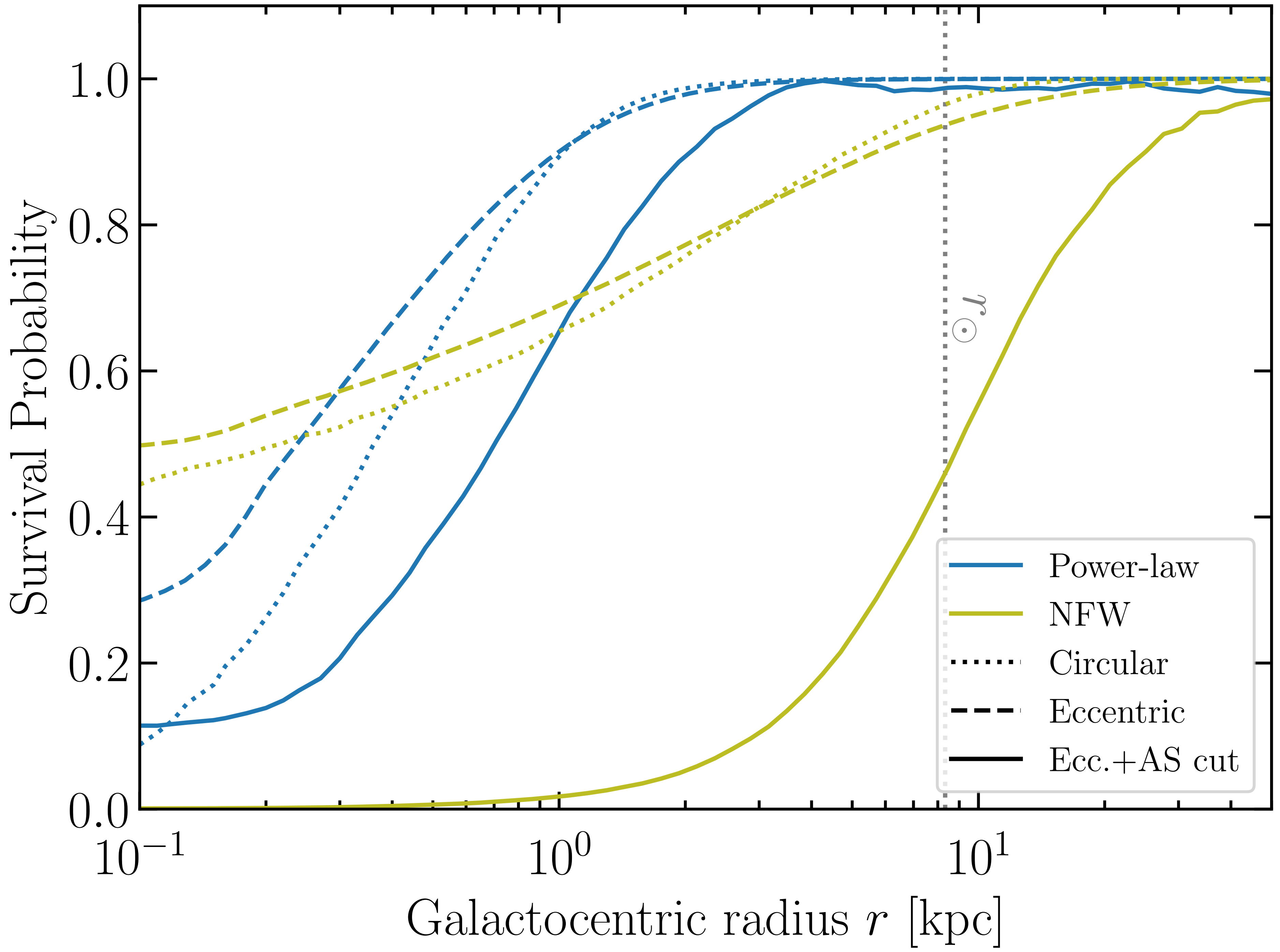
Collect surviving AMCs and reconstruct true properties

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+ (with **LV**), 2011.05377

See also [Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586]

Axion stars nucleation: see Yin & **LV** 2403.18610

Observational Consequences

Axion-photon conversion in NS magnetospheres

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

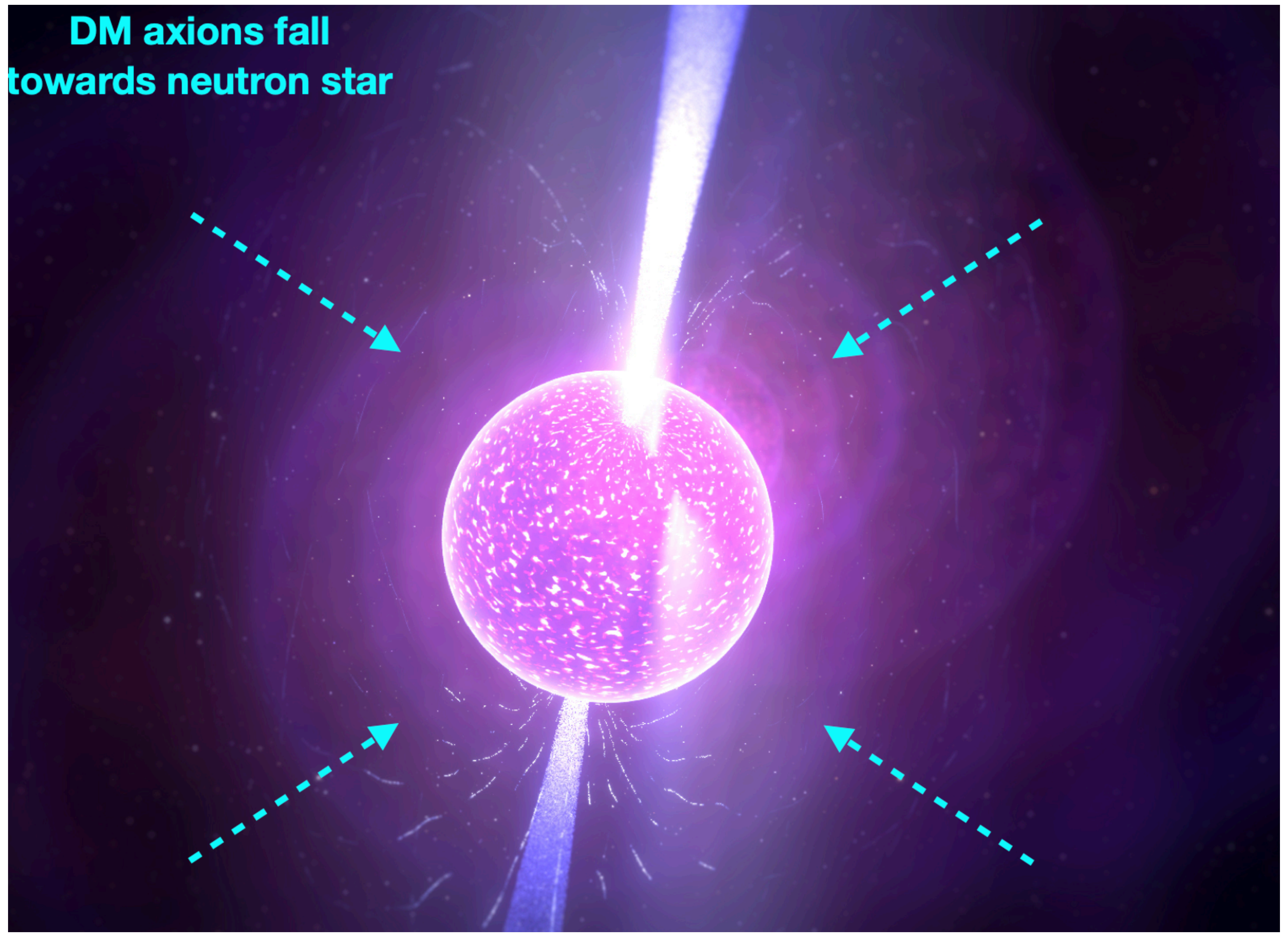
$$\frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega} \sim \frac{\pi}{3}\, g_{a\gamma\gamma}^2 B_0^2 \frac{{R_{\rm NS}}^6}{{R_c}^3} \frac{\rho_c}{m_a}$$

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

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

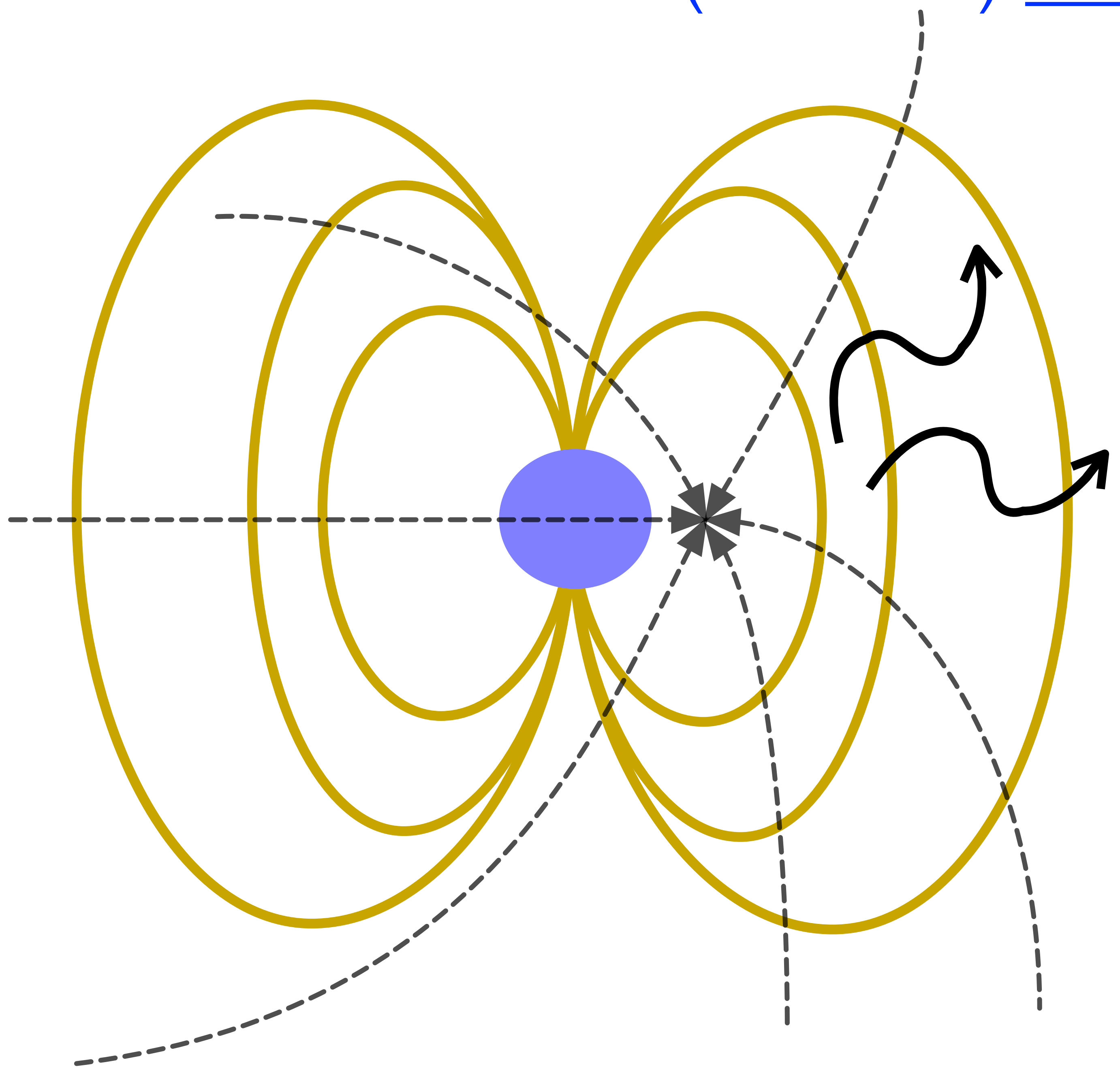
Look for axion-photon conversion from an individual NS

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

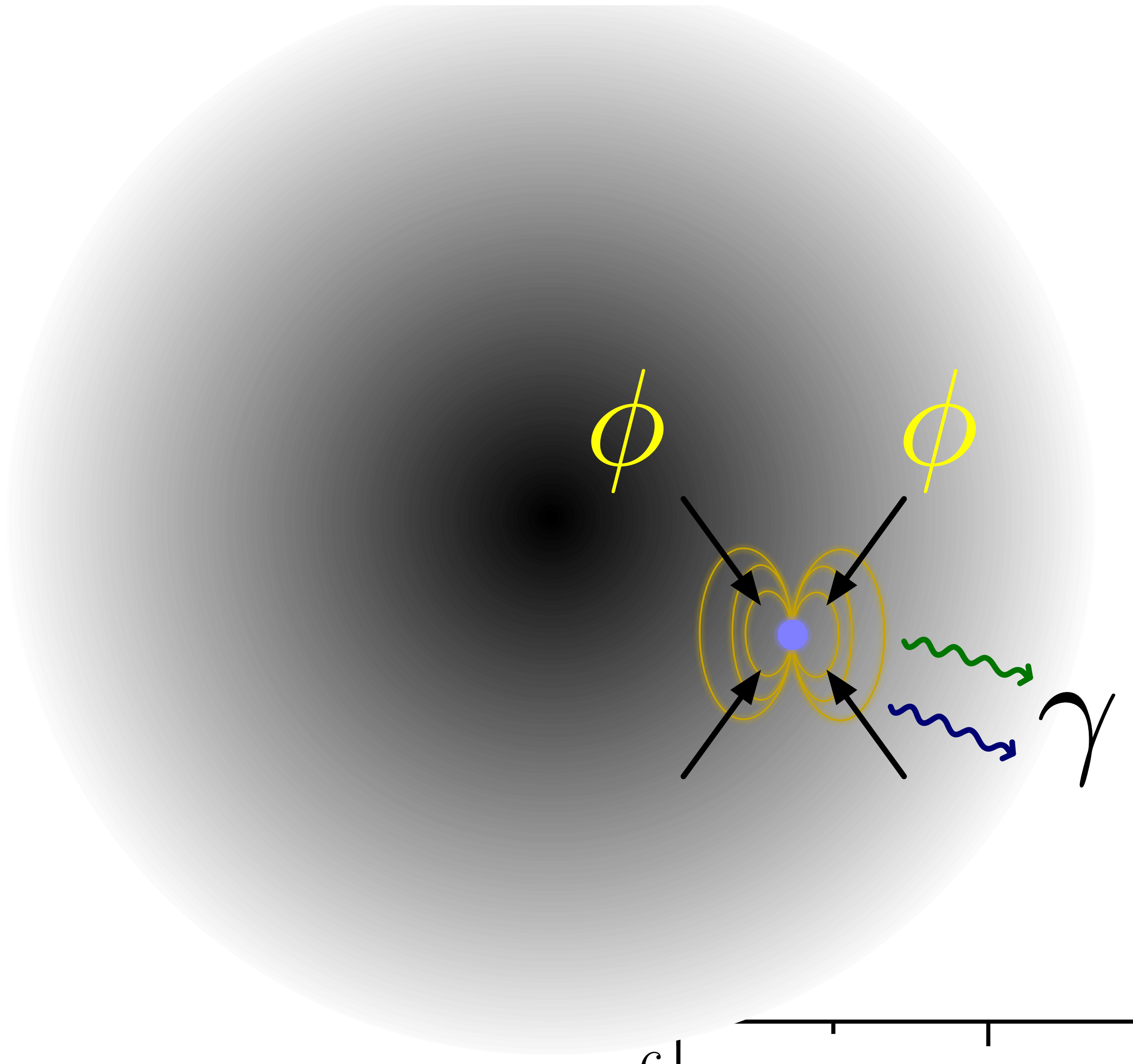


Transient enhancements to ρ_c from AMC encounters

Edwards+ (with **LV**) 2011.05378



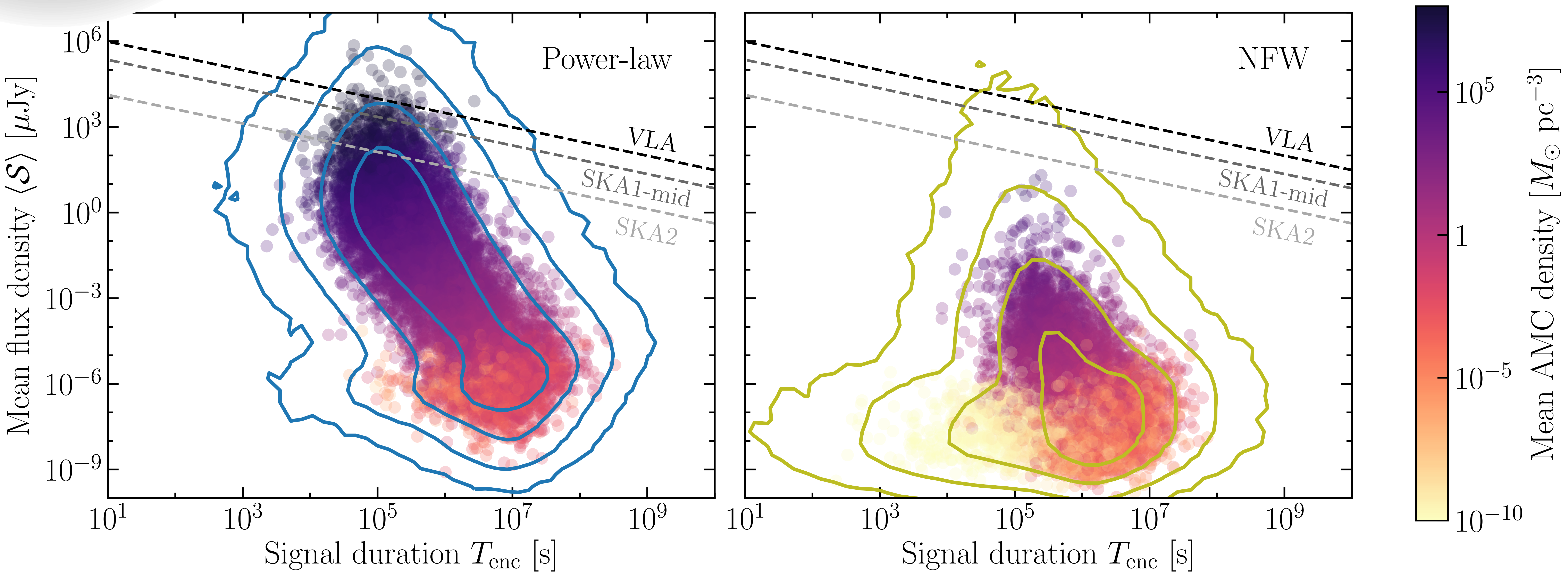
Axion-photon conversion in NS magnetospheres



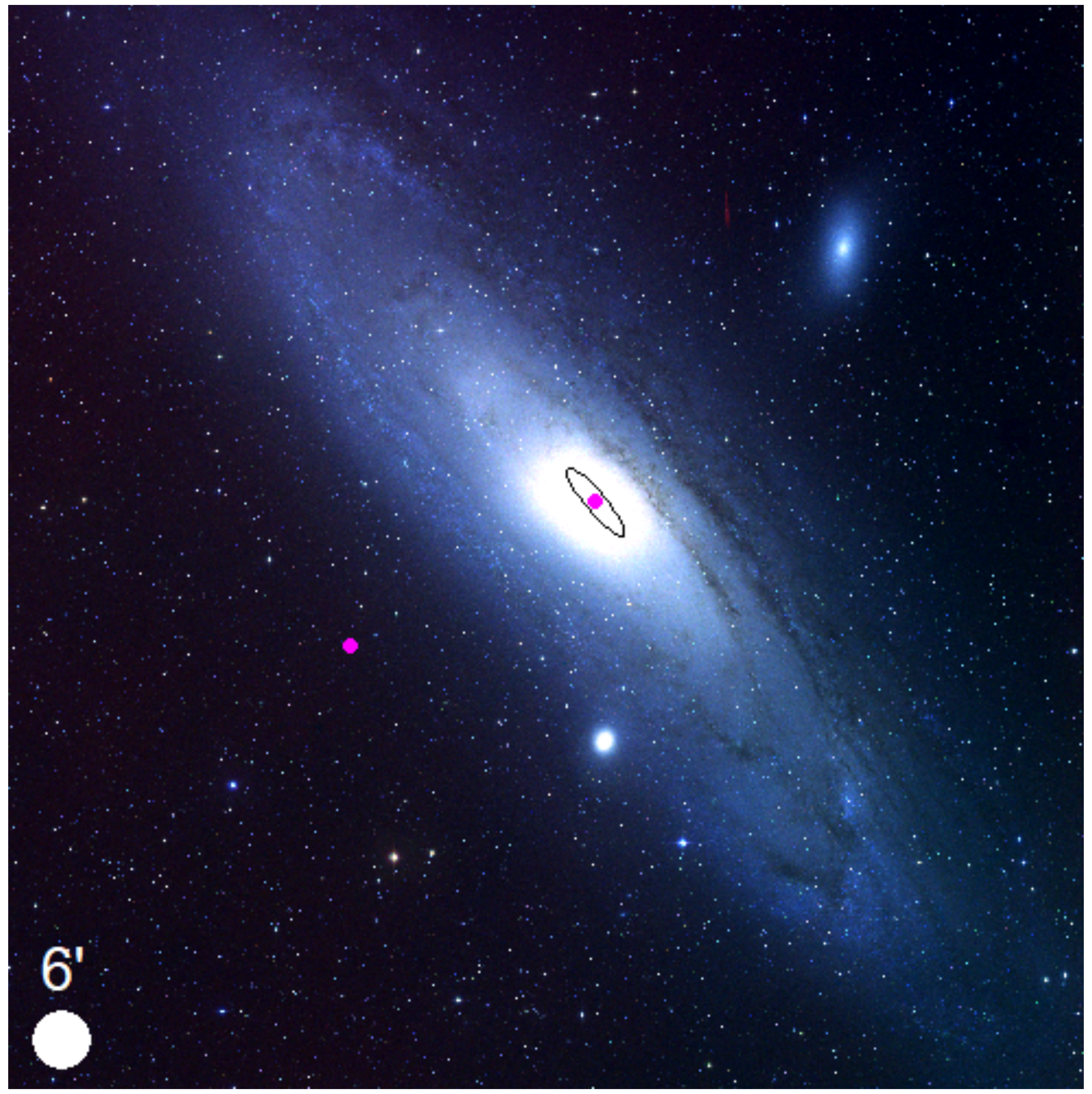
$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$

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?



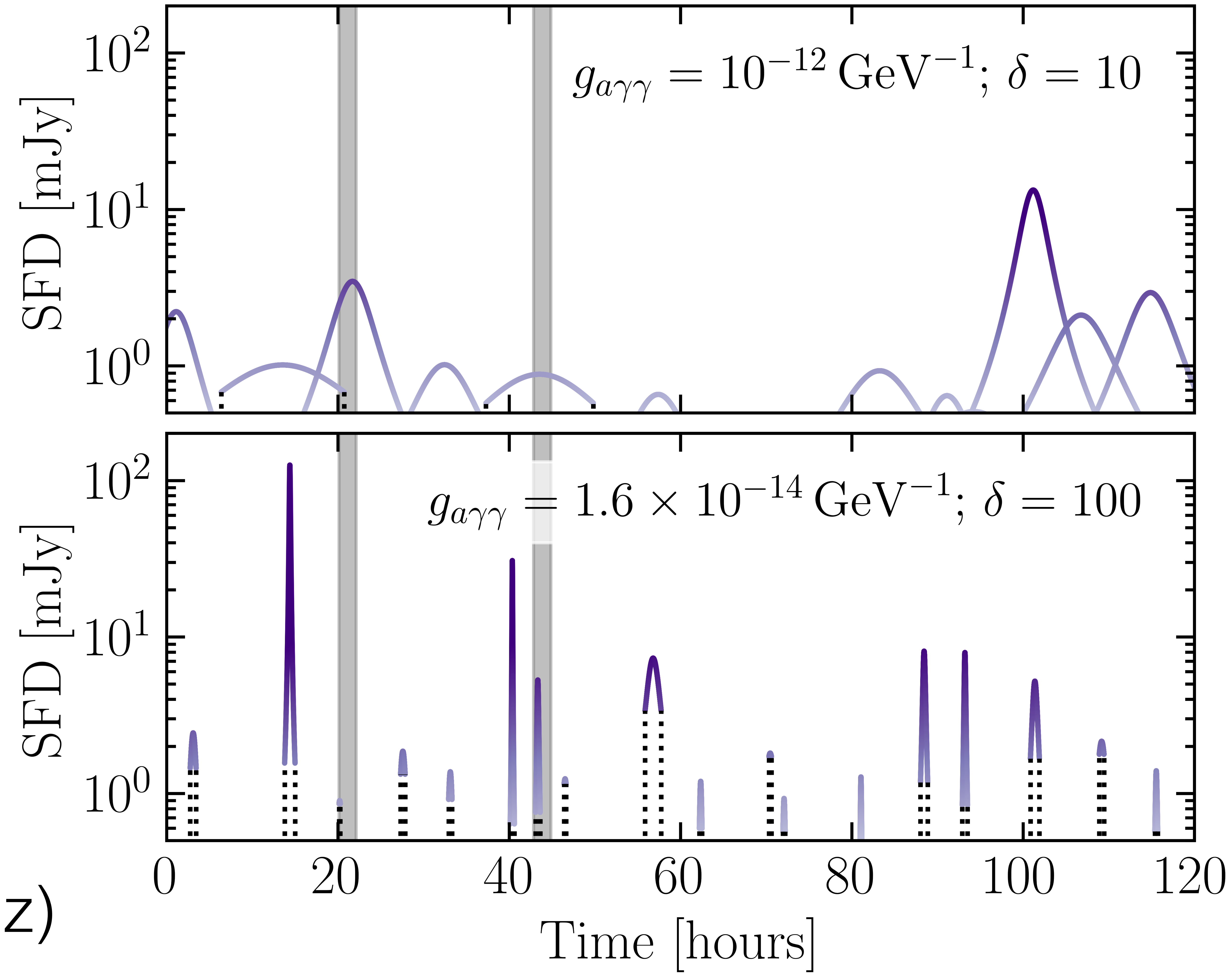
2 grant proposals accepted by the Green Bank Telescope. We have observed Andromeda

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

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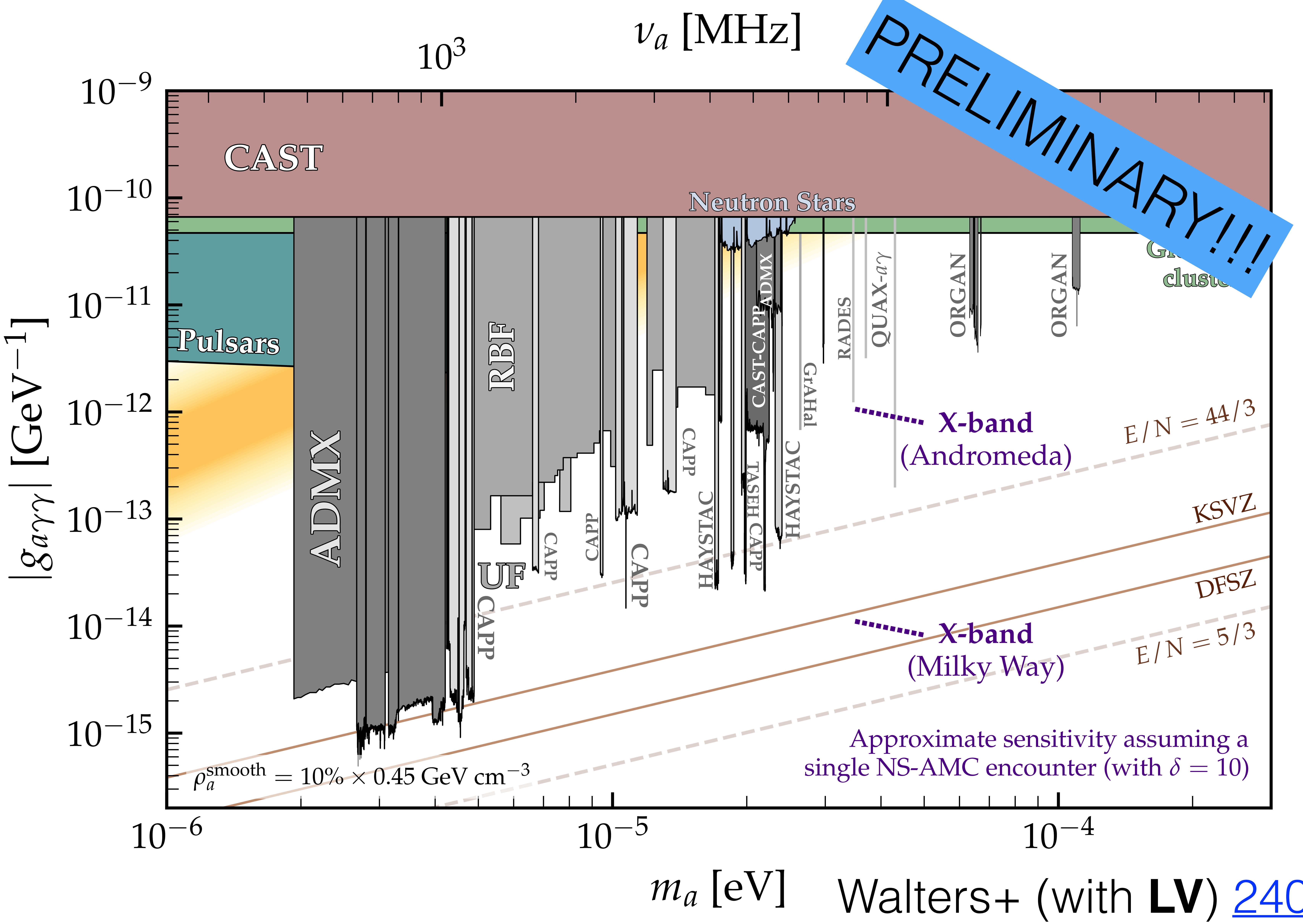

Walters+ (with **LV**) 2407.13060

Can we pick up this signal in radio?

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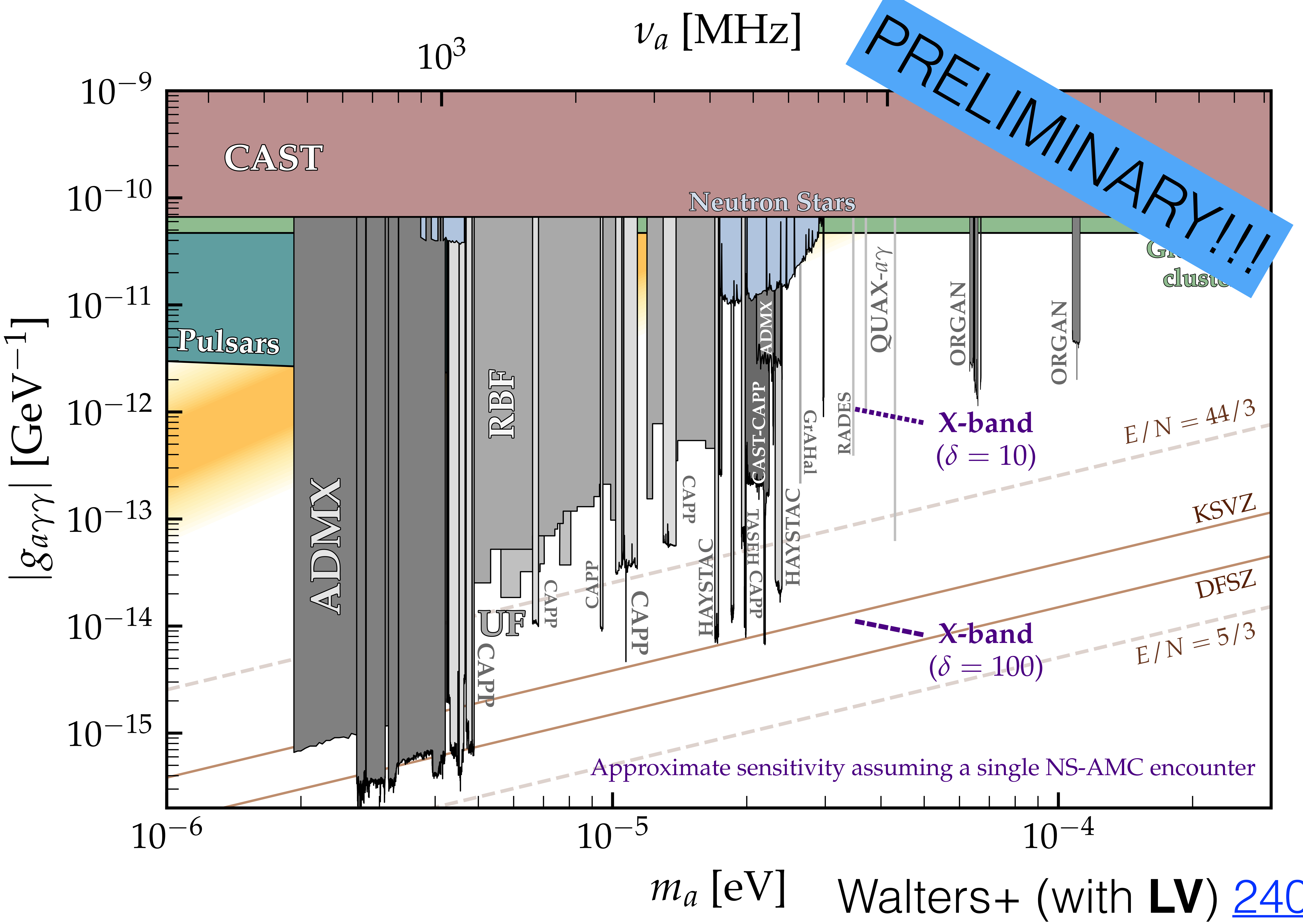


Walters+ (with **LV**) [2407.13060](2407.13060)

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]

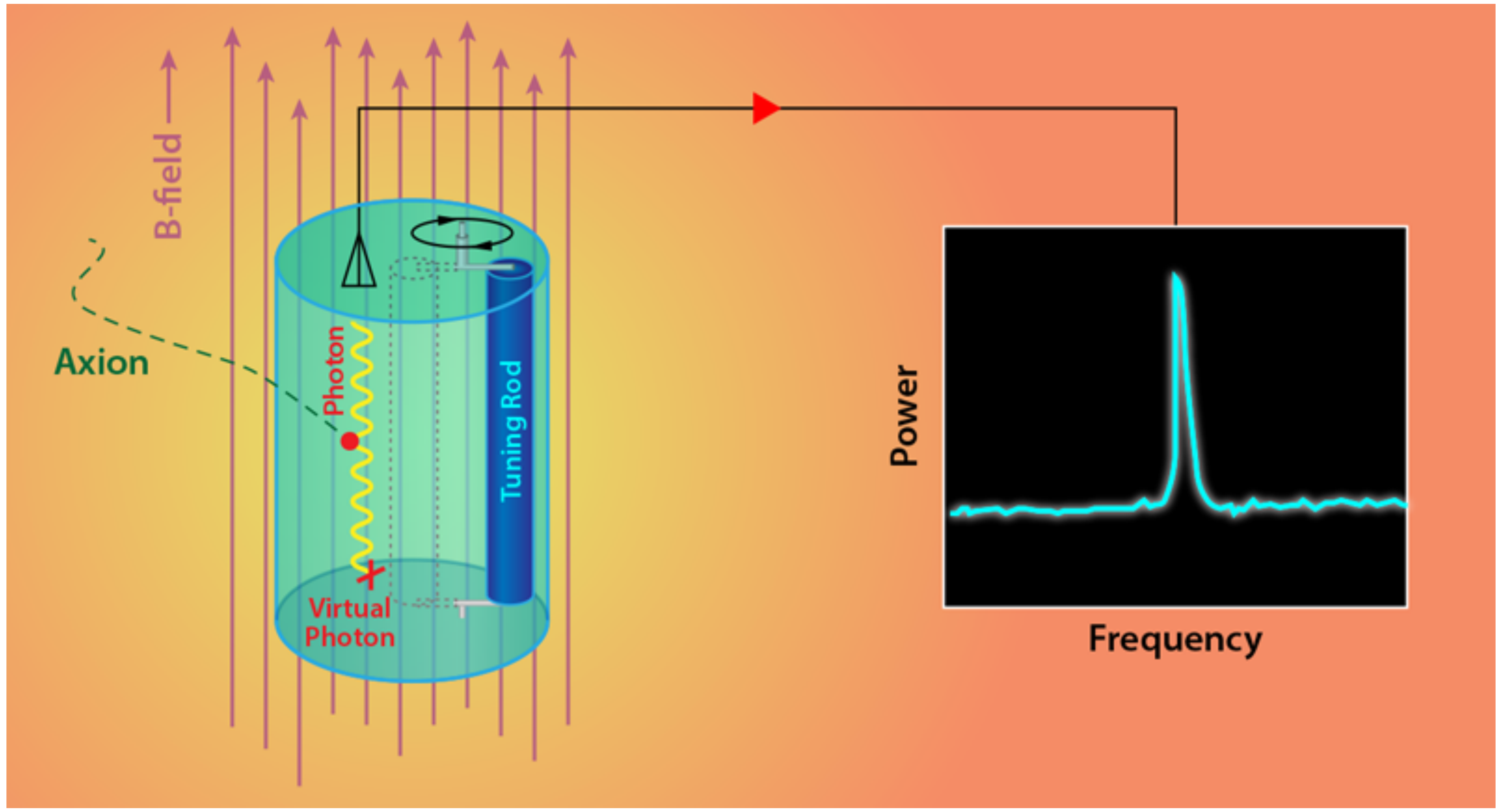
Significant enhancement when

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

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

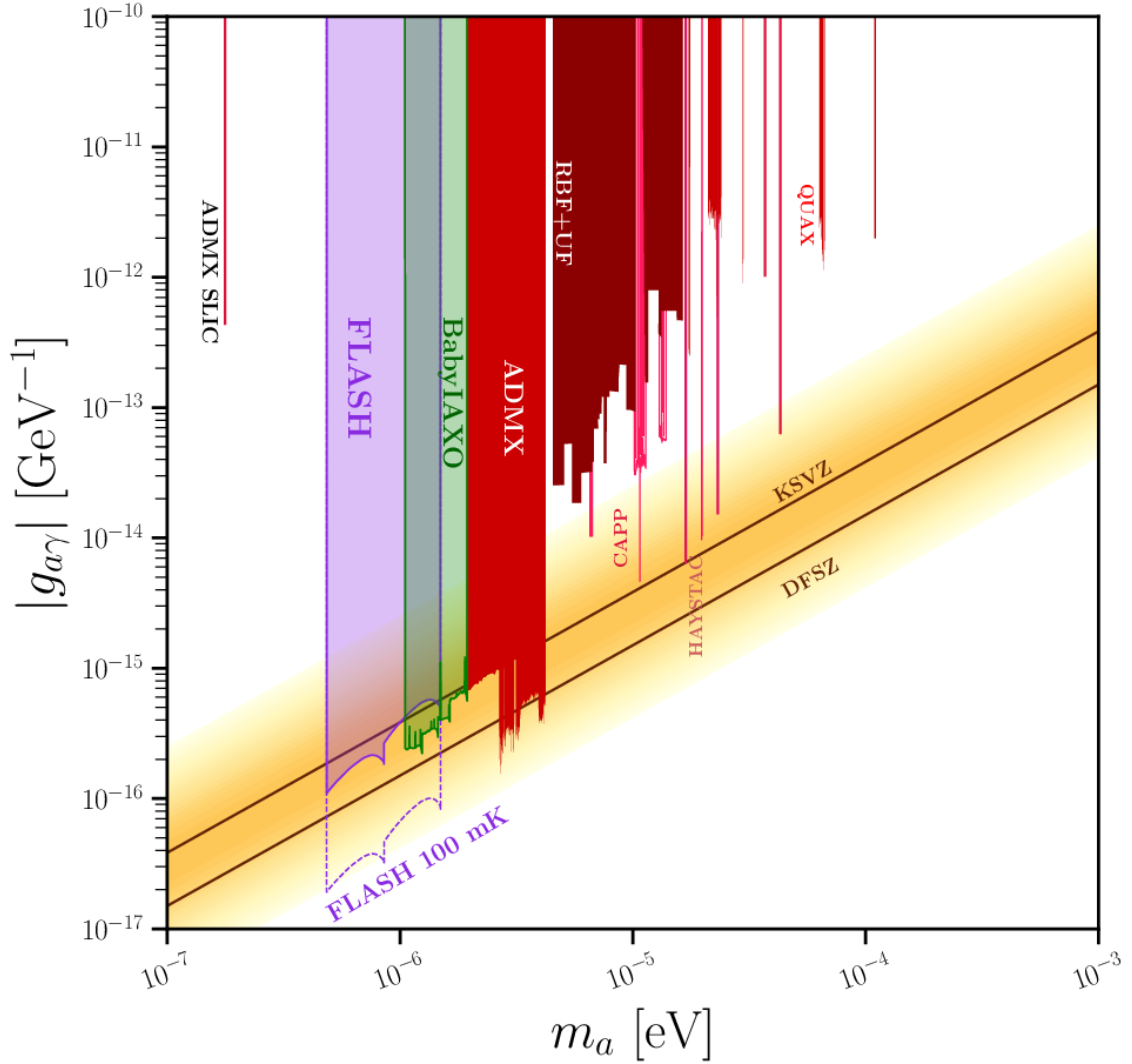
Q_L Quality factor V Cavity volume

B_0 Magnetic field C_{nml} Geometric factor



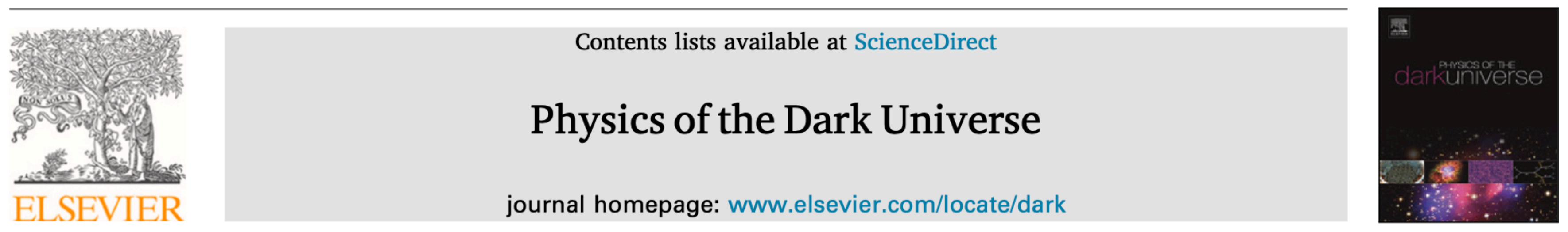
Courtesy of ADMX collaboration

Cavity search in Frascati (Rome)



FLASH cavity search with
Claudio Gatti's group (INFN-LNF)

Alesini+ (with **LV**) 2309.00351



Contents lists available at ScienceDirect

Physics of the Dark Universe

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

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]

Summary of axion-photon coupling bounds

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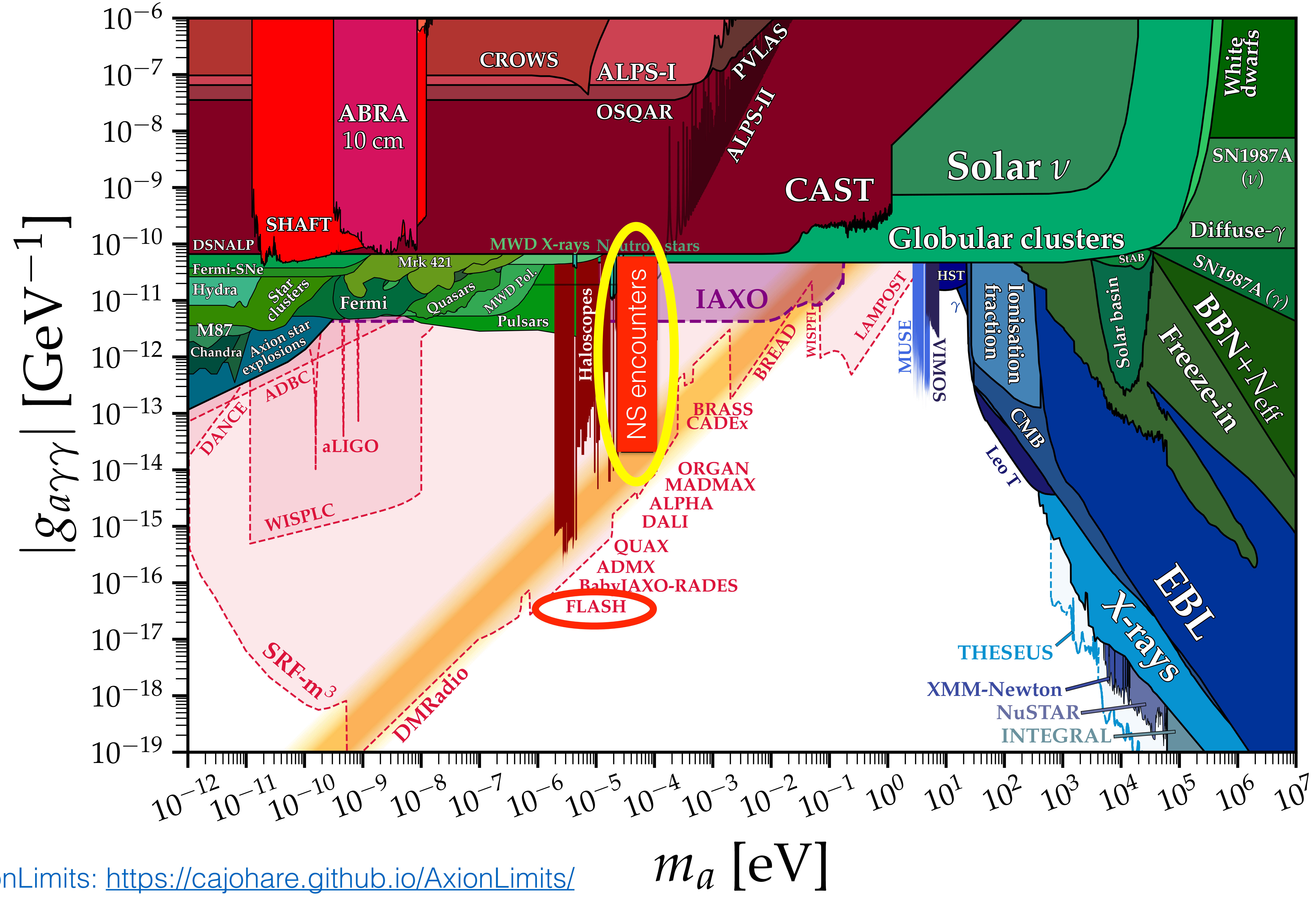
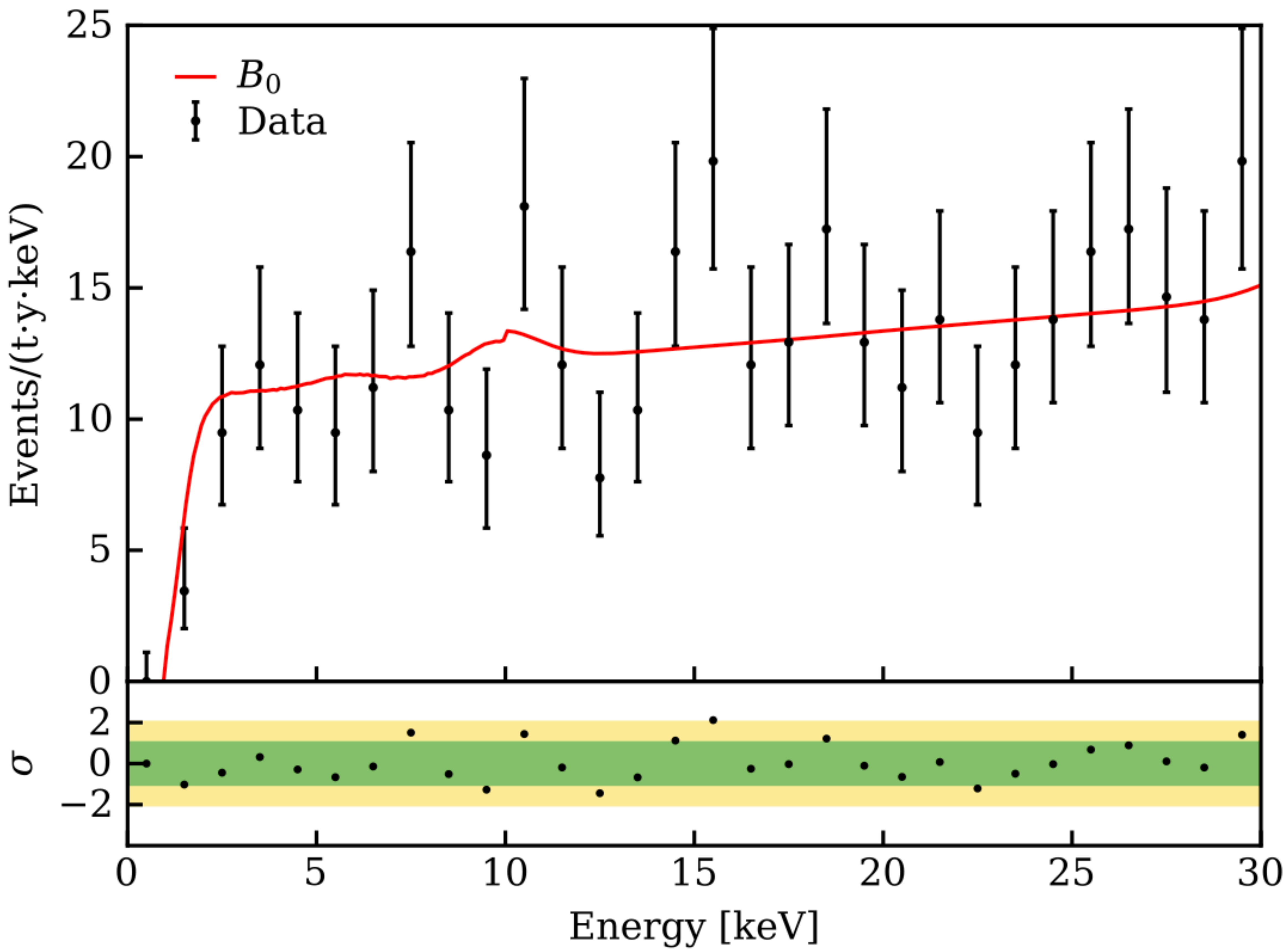


Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

Solar axions scattering with electrons

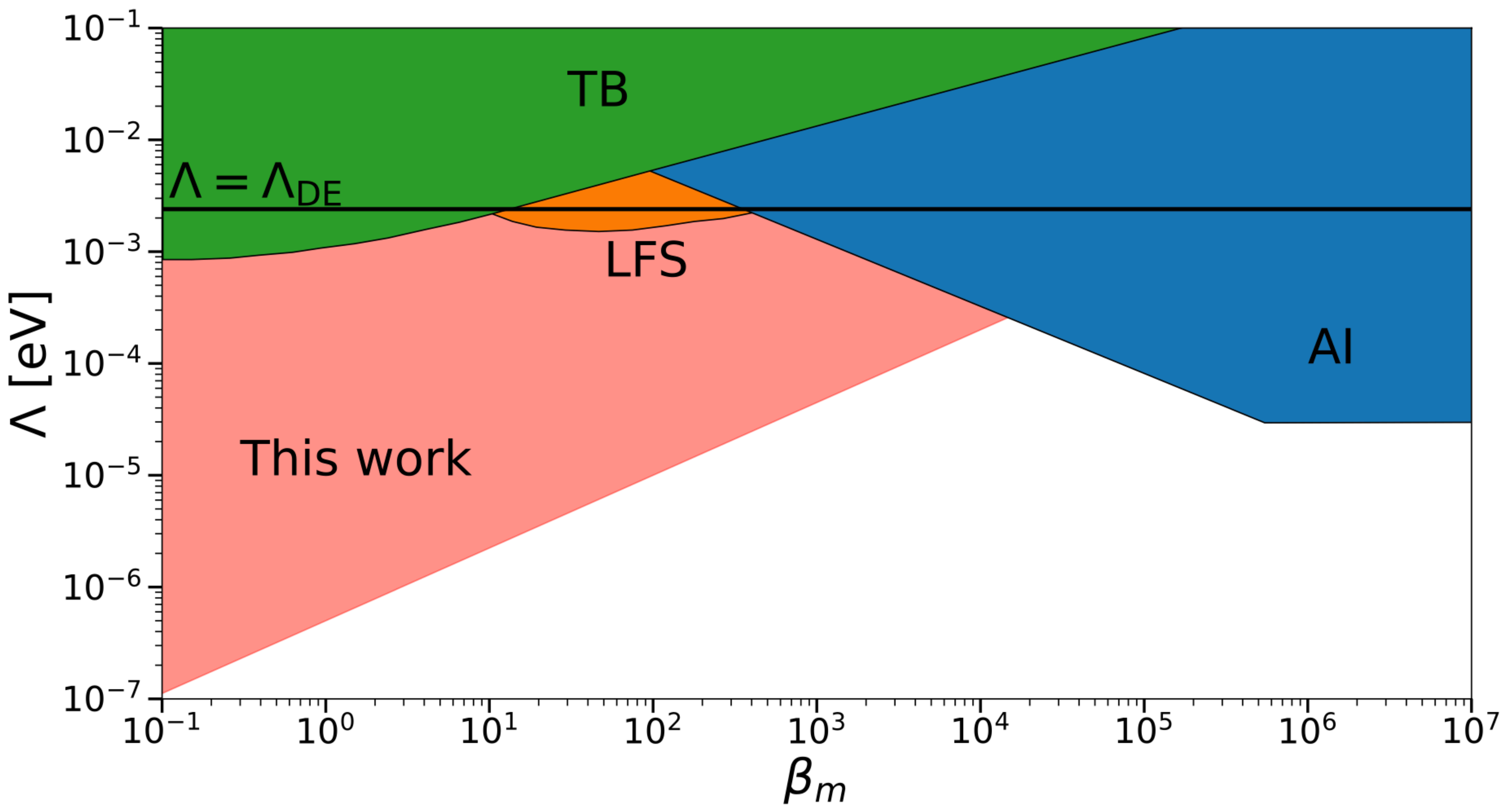


XENONnT bound on ($g_{a\gamma} - g_{ae}$) [2207.11330]

Previous results "XENON1T excess" [2006.09721]

See also Vagnozzi+ (with **LV**) 2103.15834

Scalar field production in the Sun
The parameter space is constrained by energy considerations



T. O'Shea+ (with **LV**) 2406.01691

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

See Walters+ (with **LV**) 2407.13060

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

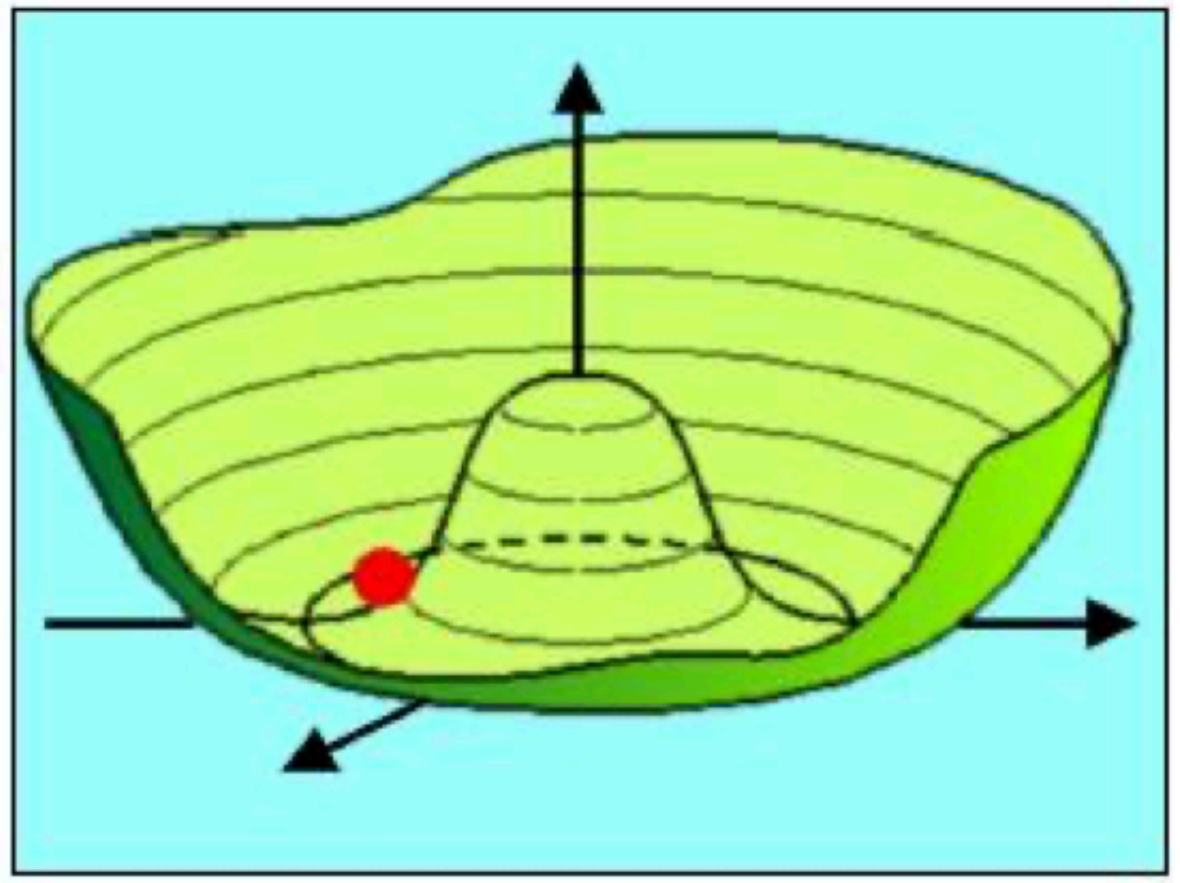
Thank you!

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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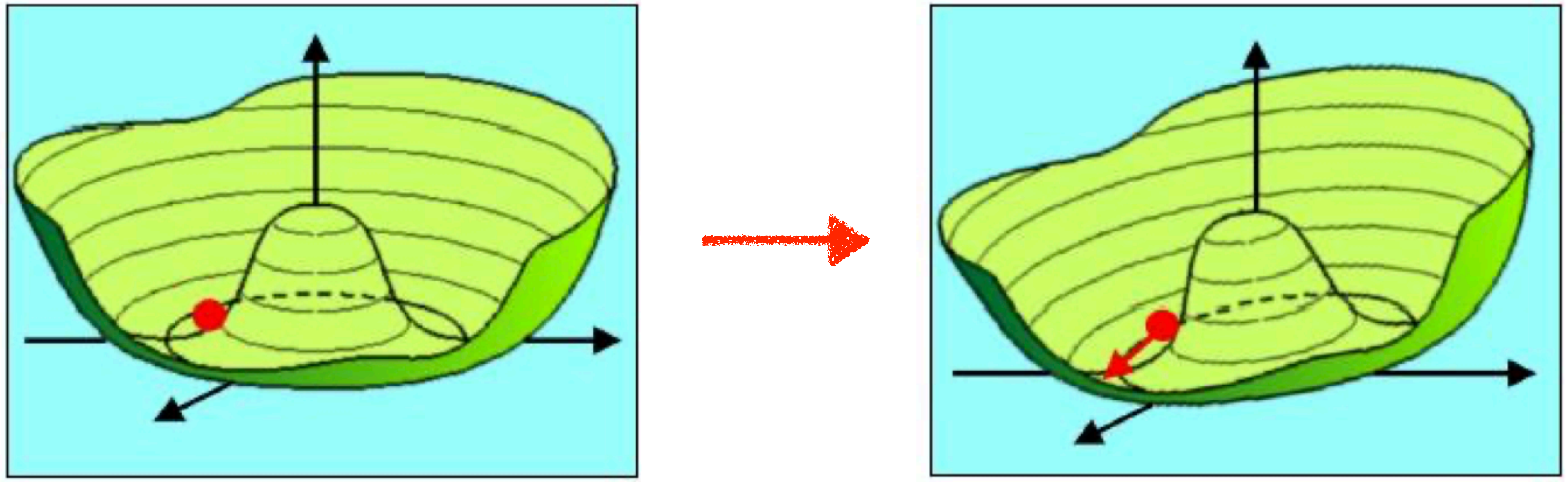


Figures from Steen Hannestad

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]

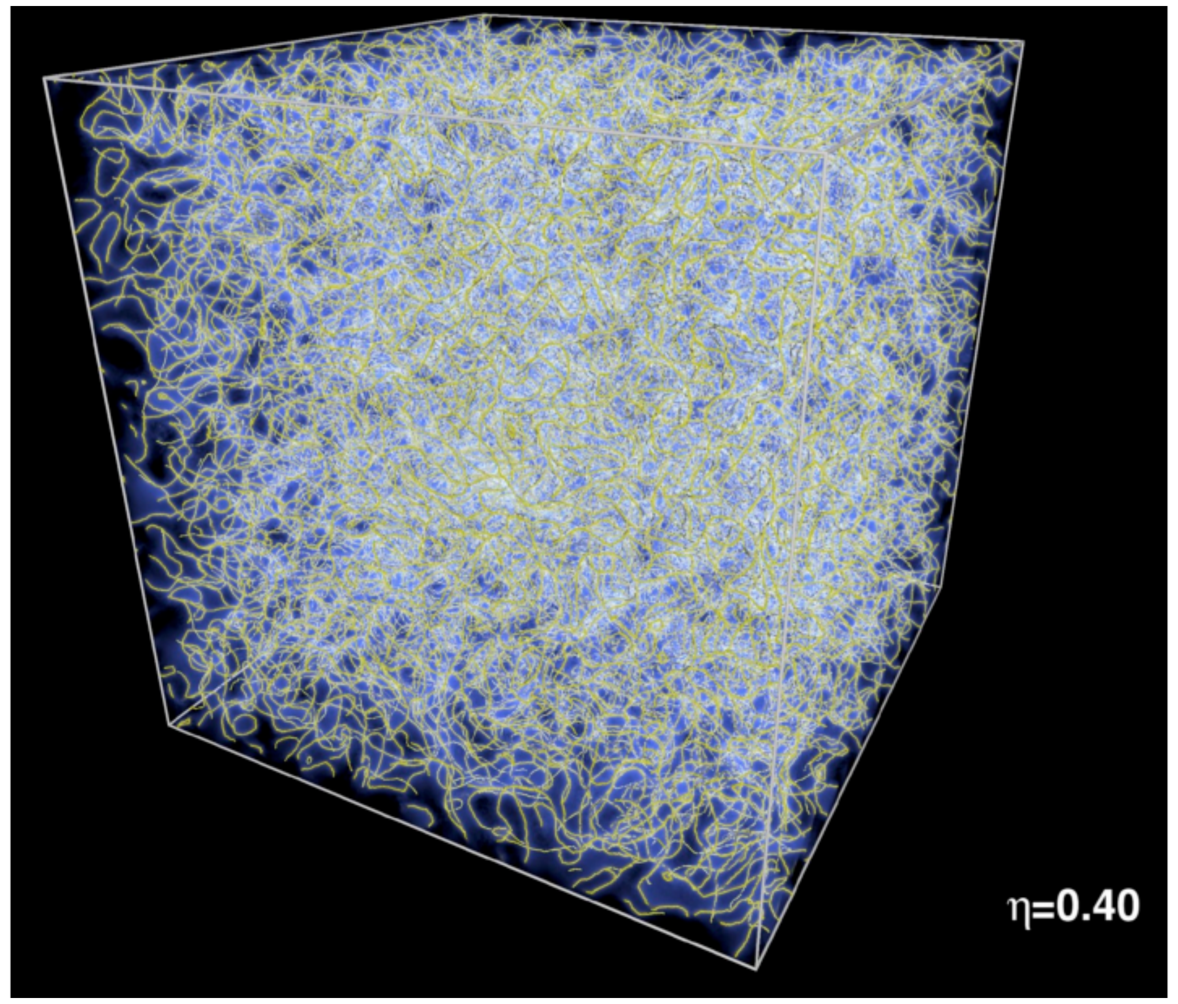
The exact assessment comes from lattice QCD computations [Borsanyi+ 2016]

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

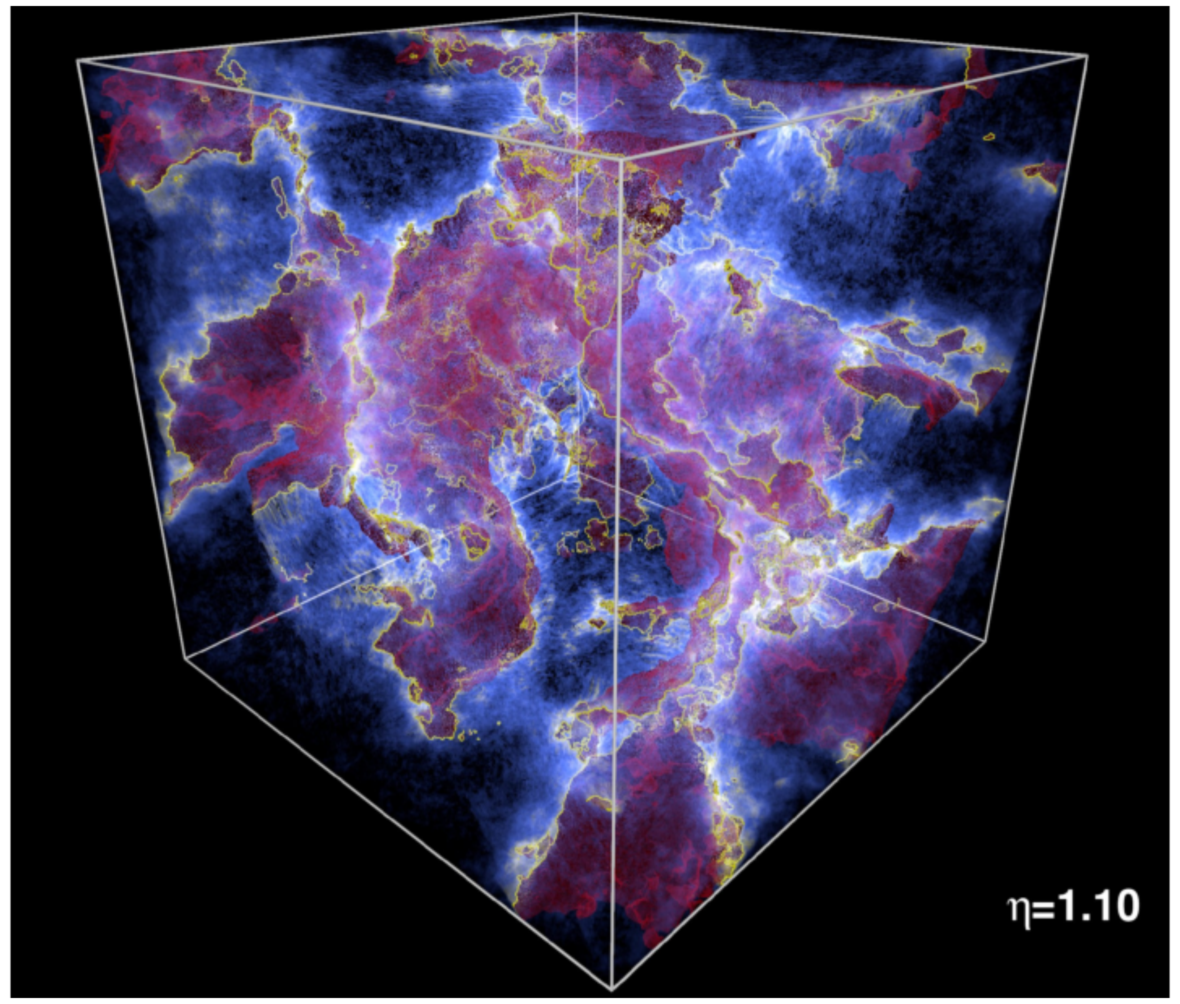
String network quickly enters a scaling regime with $\rho_{\rm scaling} = \xi\mu/t^2$

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

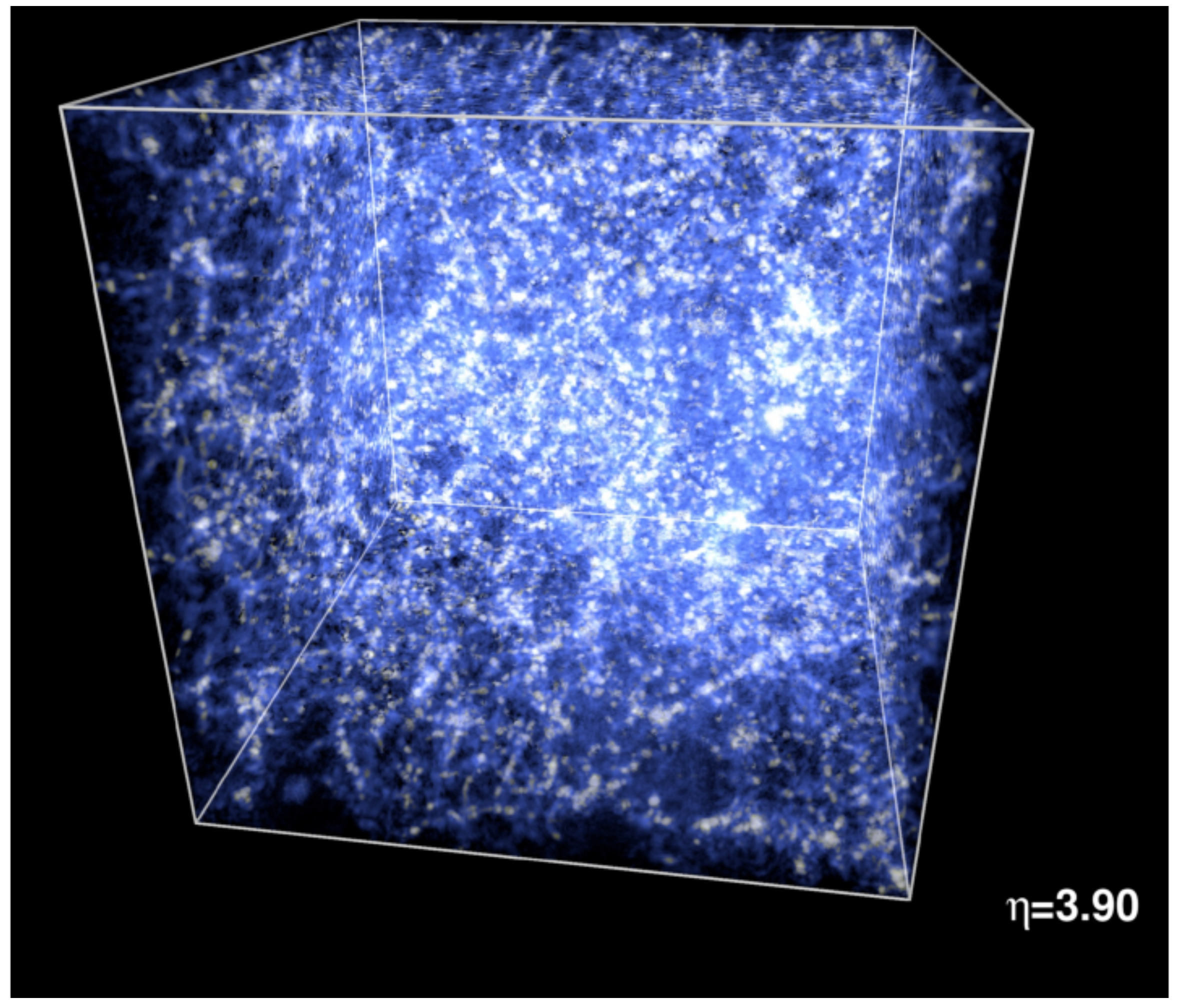
String length per Hubble volume ξ



Before QCD PT



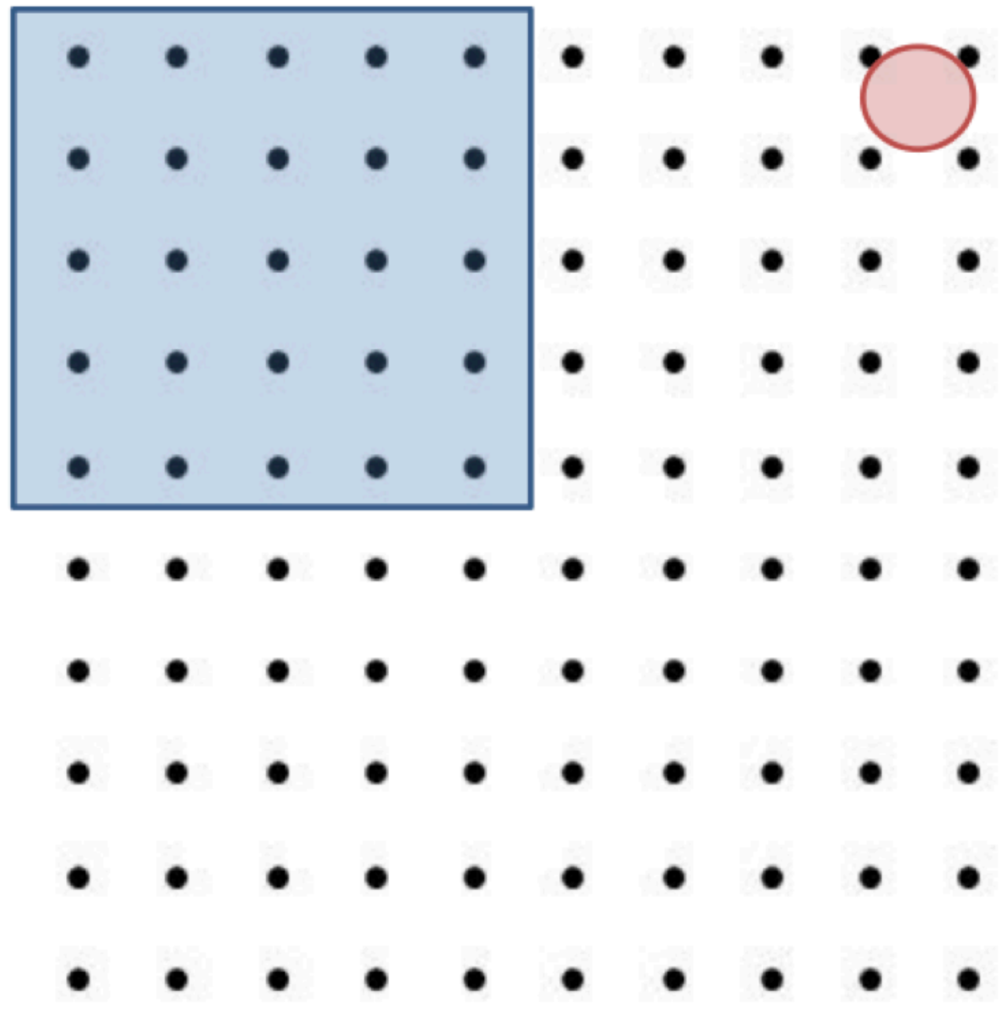
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



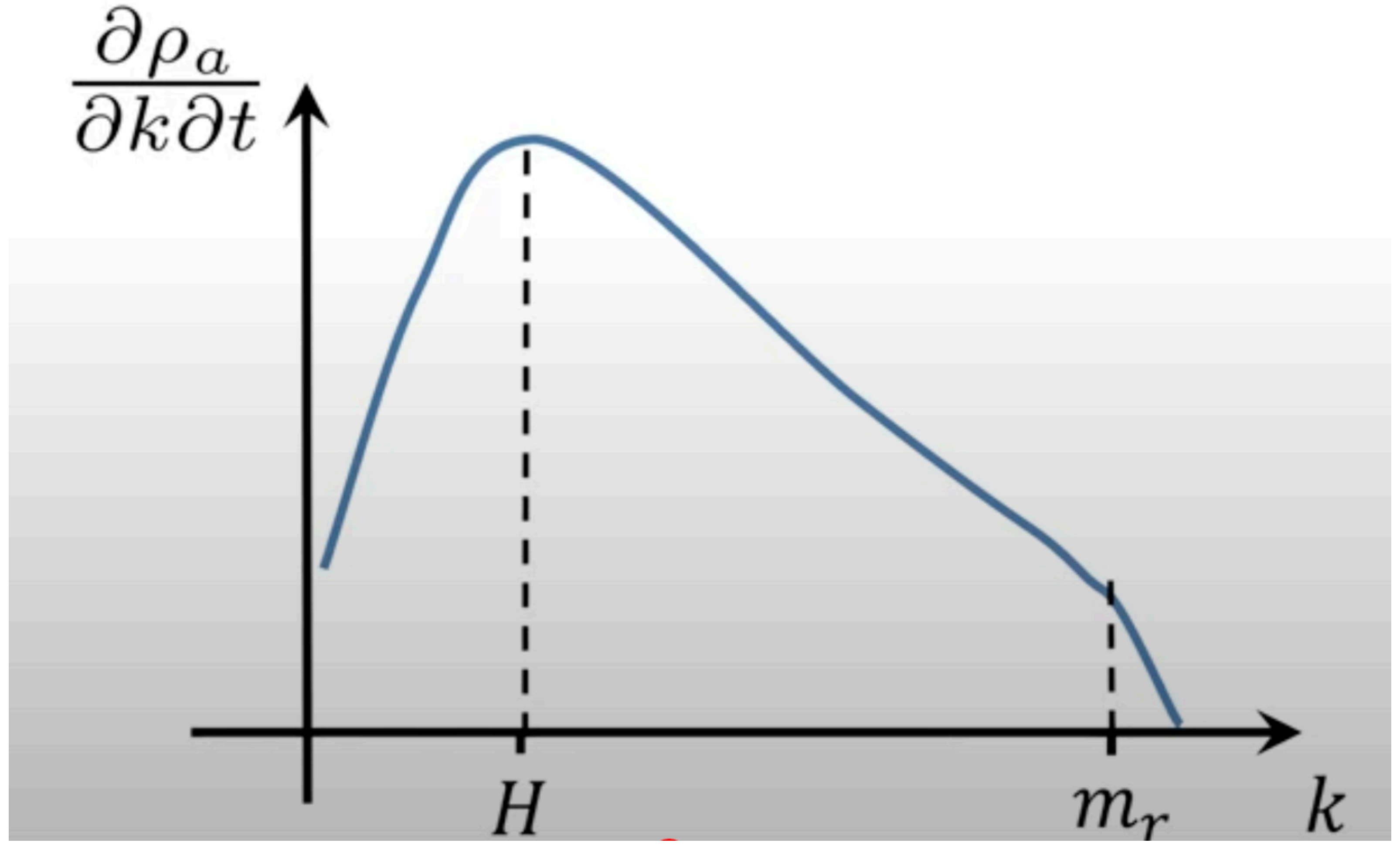
Credits: Ed Hardy

$N \approx 5000^3$

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

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/