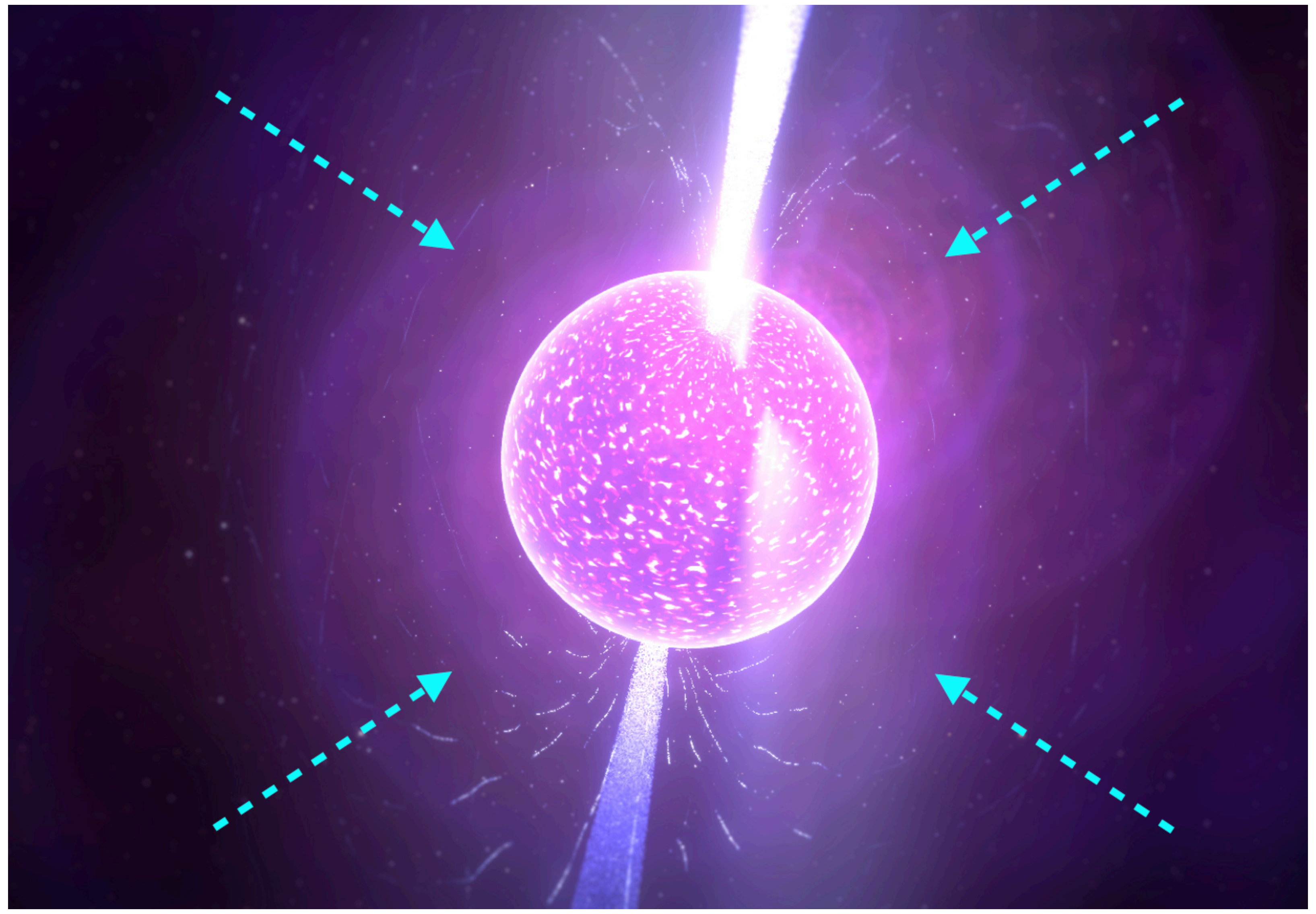
Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

UNIVERSITÀ DEGLI STUDI DI SALERNO

Searching for axion dark matter with Radio Telescopes



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May 29, 2025

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Outline

- Generalities on the QCD Axion
- Axion Miniclusters in the Milky Way
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Misalignment mechanism & Axion DM

The axion minimizes dynamically the QCD theta term to $\langle \phi / f_a \rangle = -\bar{\theta}$

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

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

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

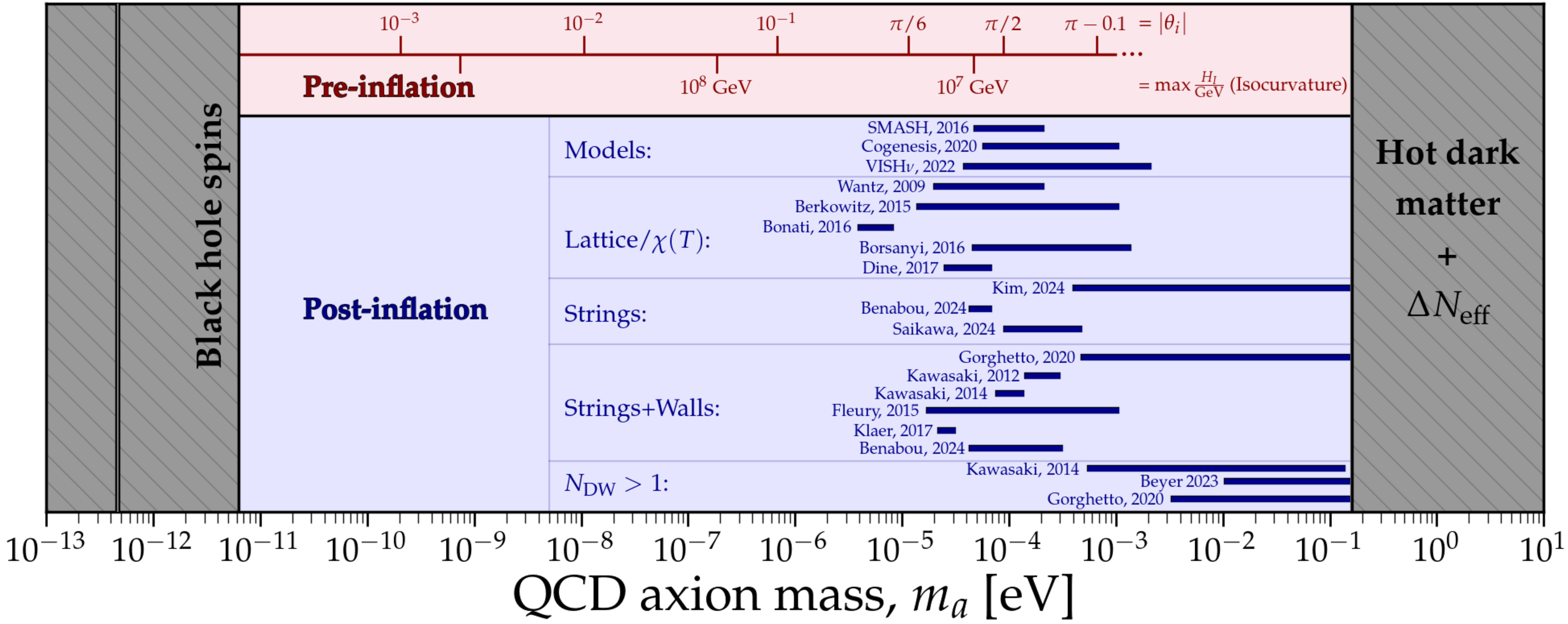
→ We are dealing with a **classical field** [see the talk by Hong-Yi Zhang]

Equation of motion in a FLRW background:

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

Predictions for the DM mass of the QCD axion

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



[See the talk by Lucy Komisel on topological defects]

The QCD Axion: foundations

[See the talk by Michael Stadlbauer on finite QCD effects]

Effective Lagrangian below QCD, e.g. [Kaplan 1985, Georgi+ 1986]:

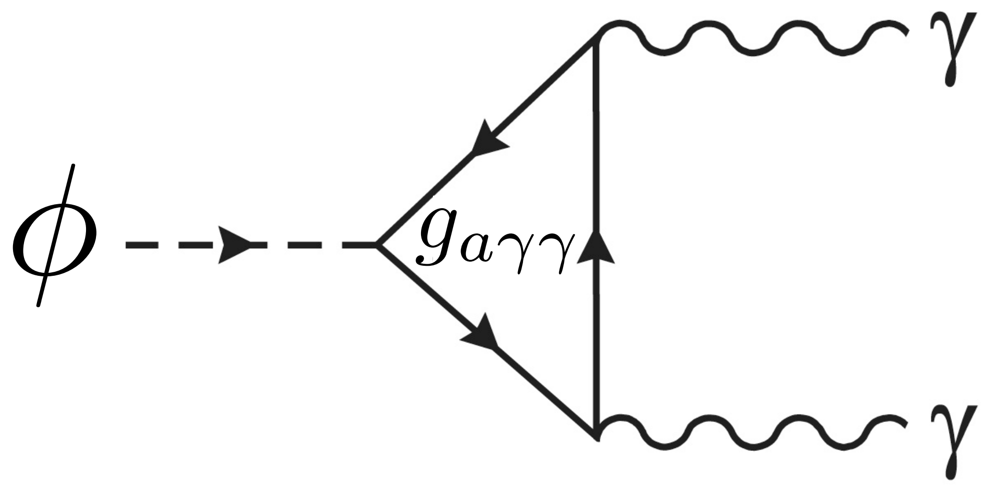
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{4}\, g_{a\gamma\gamma}\phi\tilde{F}_{\mu\nu}F^{\mu\nu} + c_e\,\frac{\partial_\mu\phi}{2f_a}\bar{e}\gamma^\mu\gamma_5 e + c_N\,\frac{\partial_\mu\phi}{2f_a}\bar{N}\gamma^\mu\gamma_5 N$$

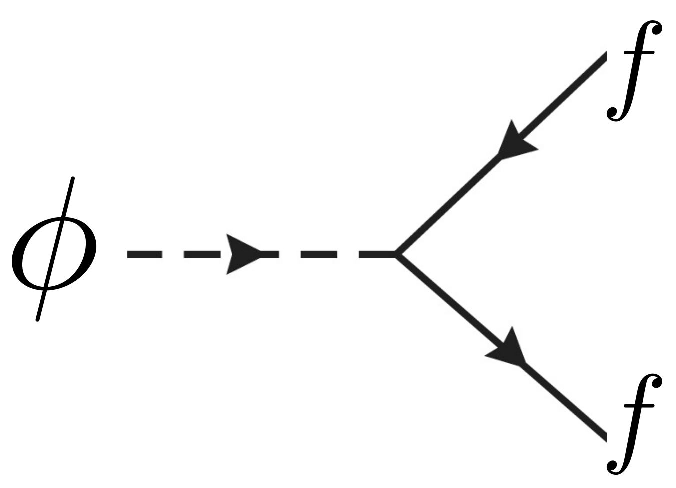
Self-interacting potential

Axion-photon coupling

Axion-electron coupling

Axion-nucleon coupling





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

The QCD Axion: foundations

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](2003.01100)

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Axion miniclusters

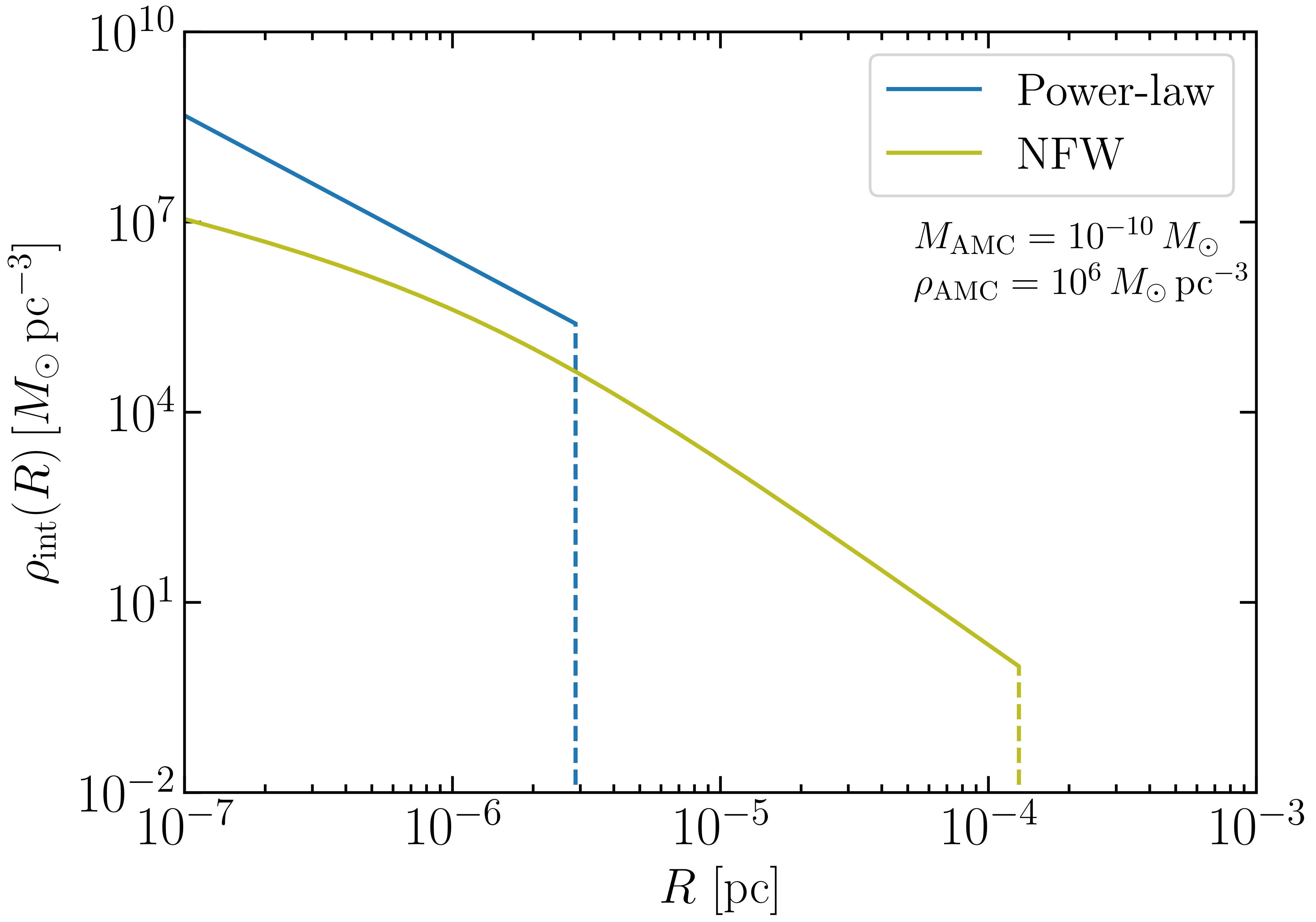
In post-inflation symmetry breaks, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

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

Typical minicluster mass:

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

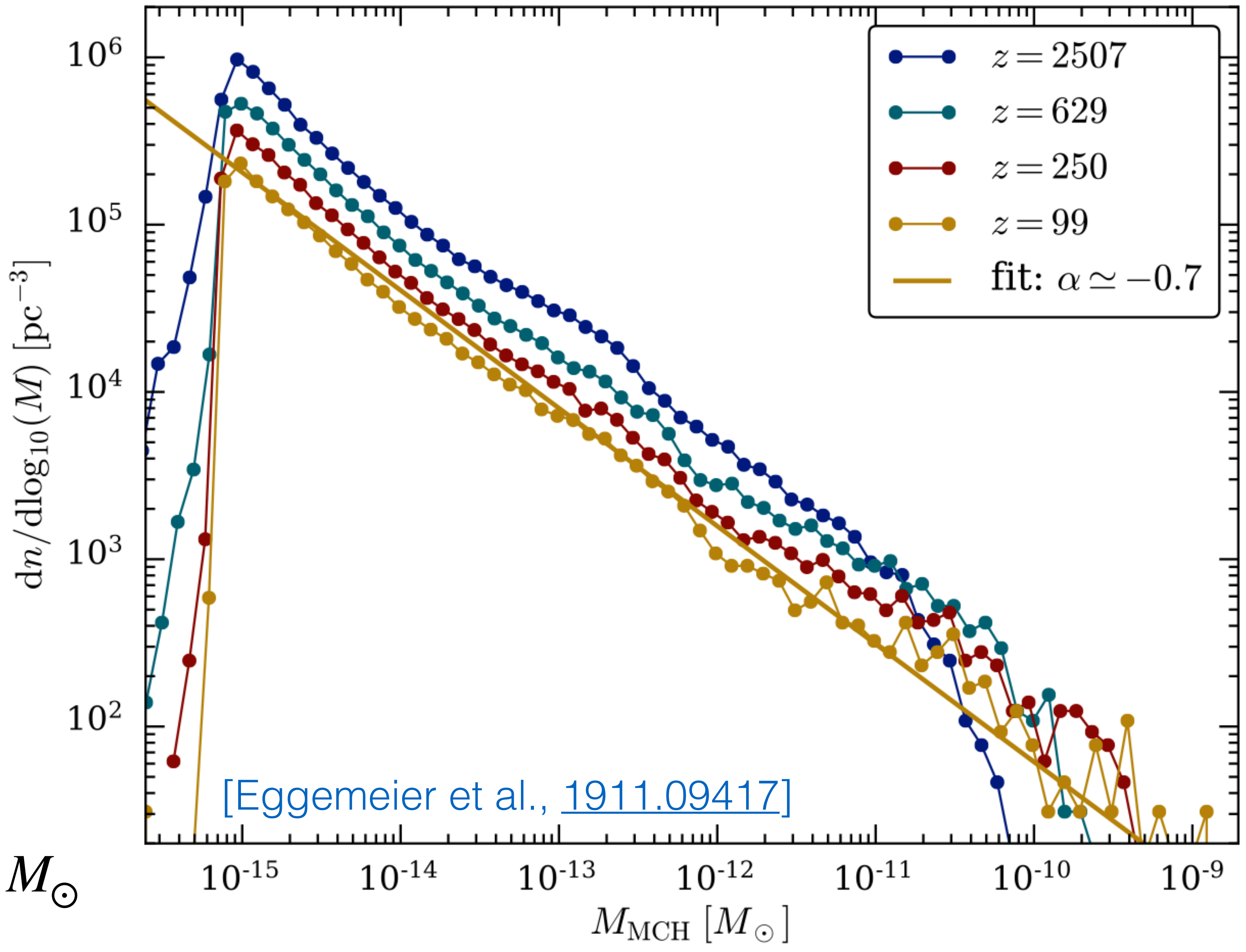
[Hogan & Rees 1988; Kolb & Tkachev 1994]



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



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

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

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

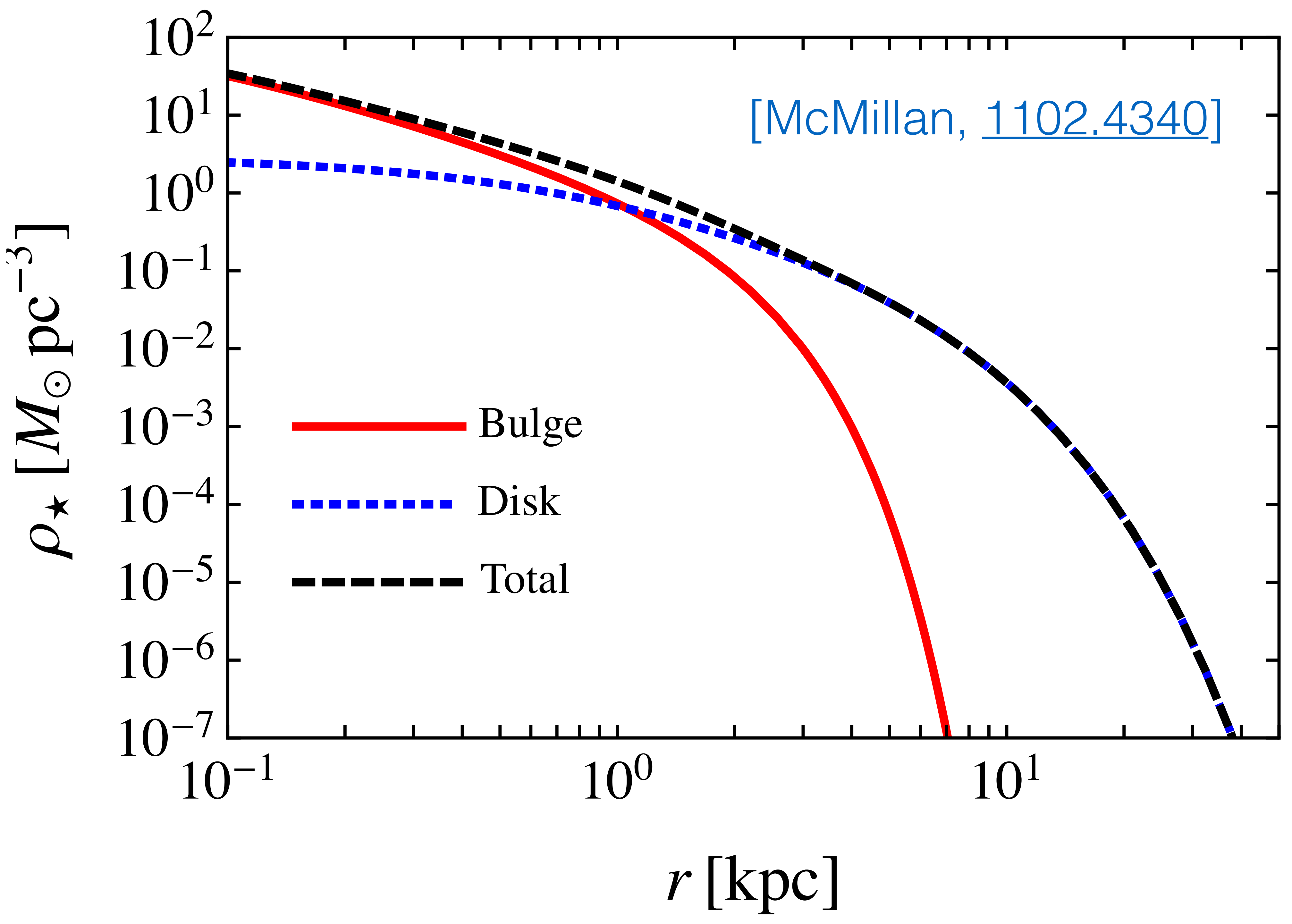
(Growth of hierarchical structure to today)

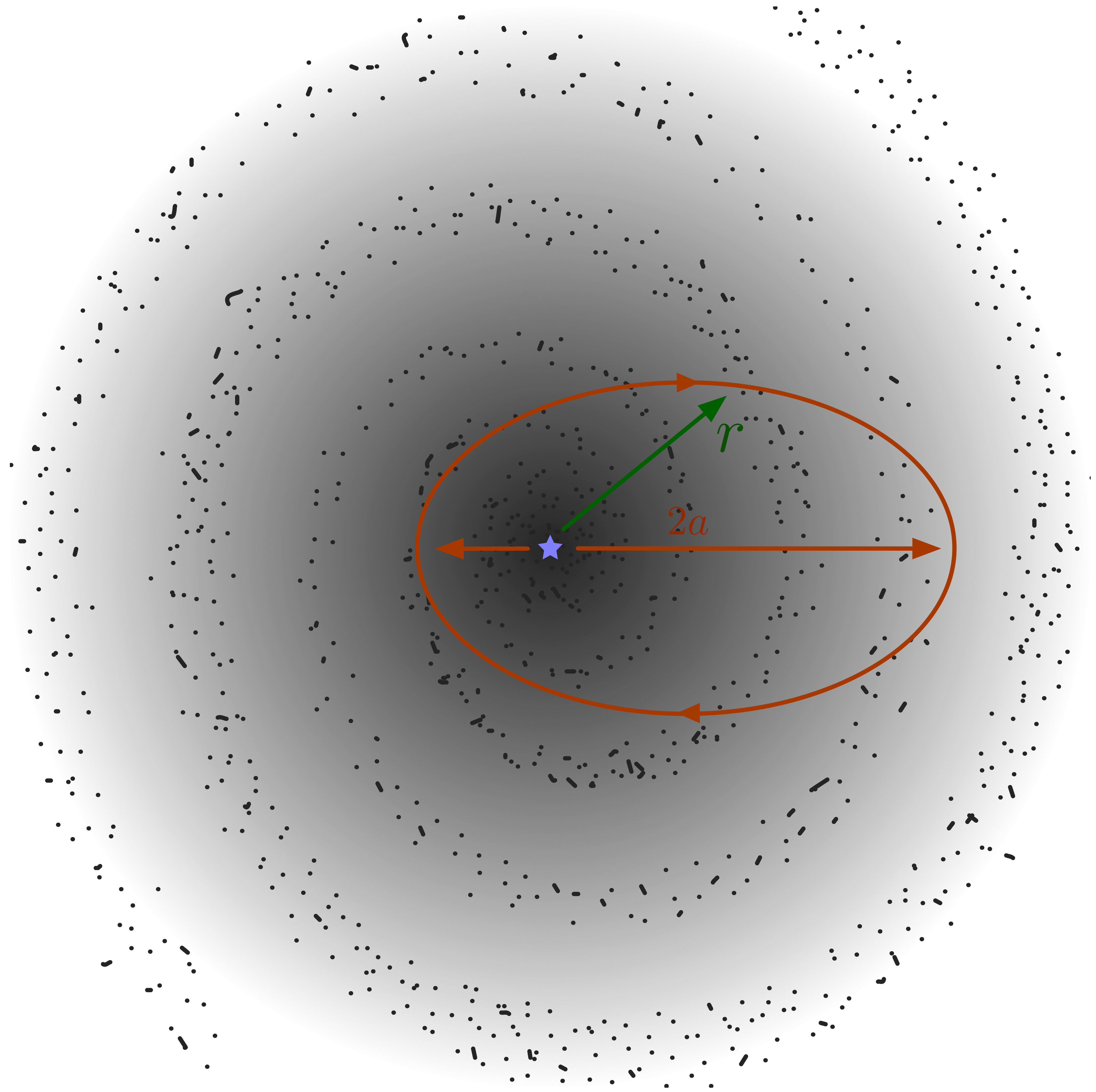
[Fairbairn et al., 1707.03310]

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





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

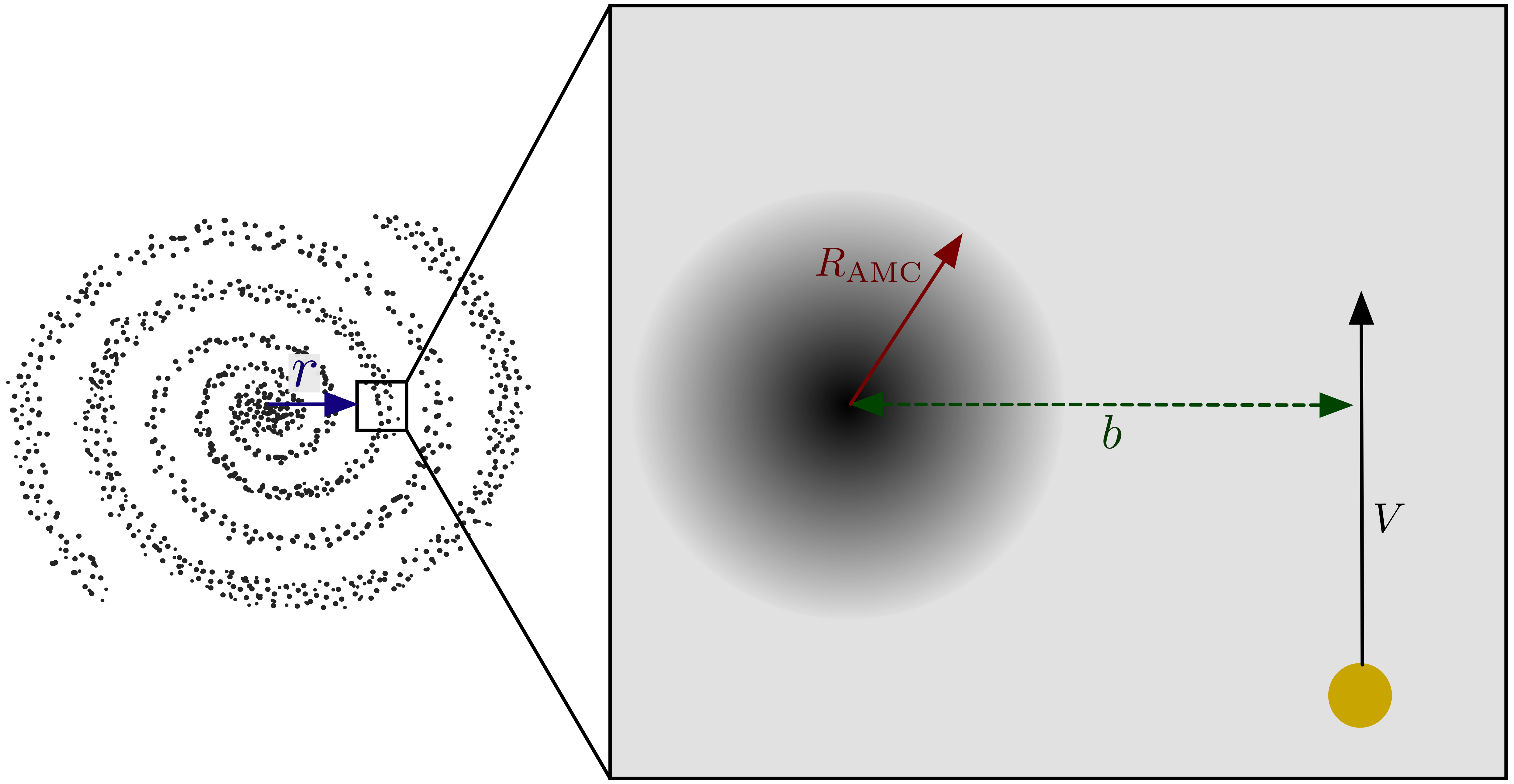
$$f_{\rm AMC} \approx 100\%$$

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

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

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

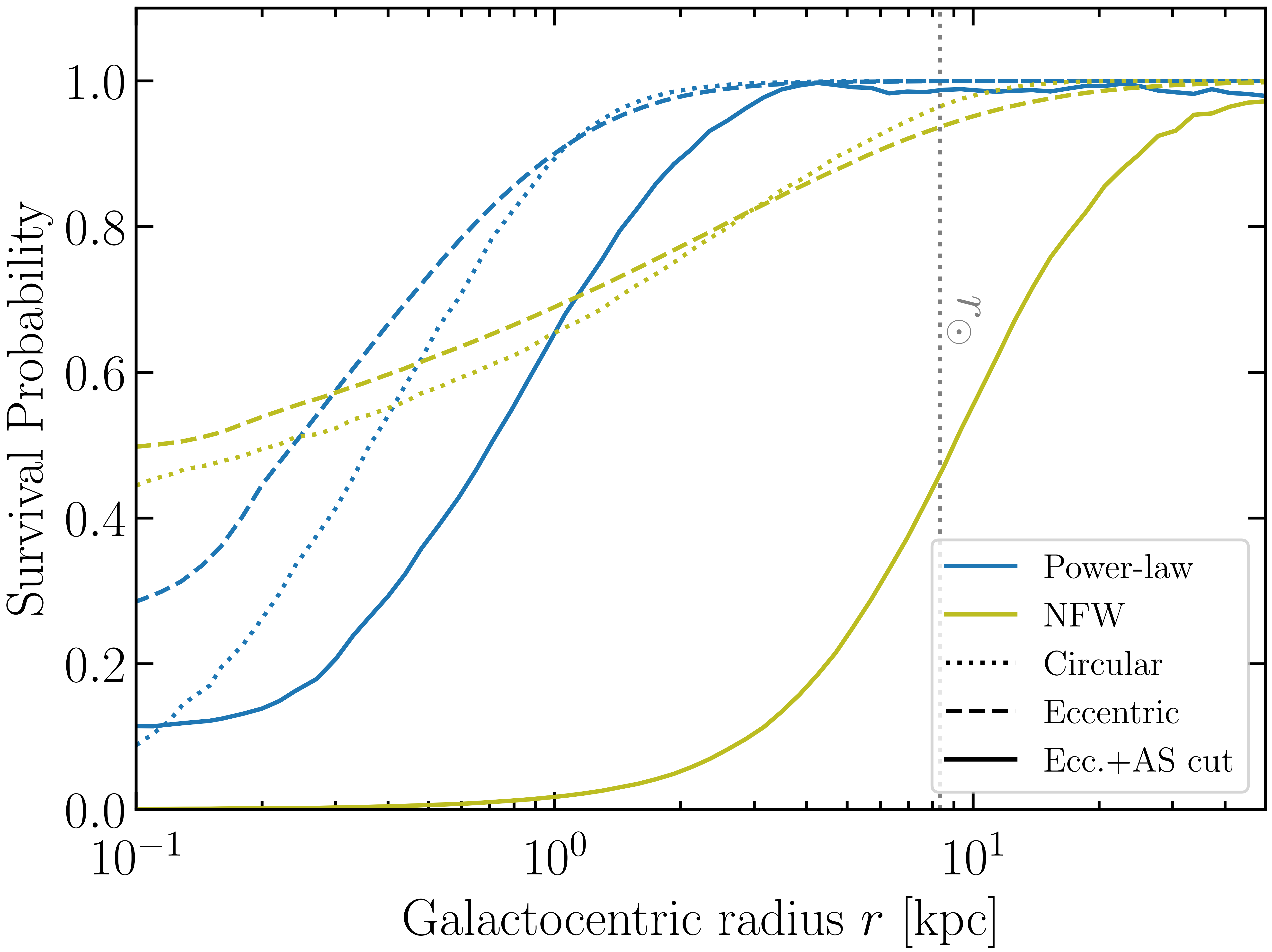
AMC disrupted

Remove AMC from simulation

Collect surviving AMCs and reconstruct true properties

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

Axion miniclusters abundance today



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Axion-photon conversion in NS magnetospheres

[See the talk by Maxim Pospelov (NS labs) and Ben Safdi (SNe and new physics)]

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

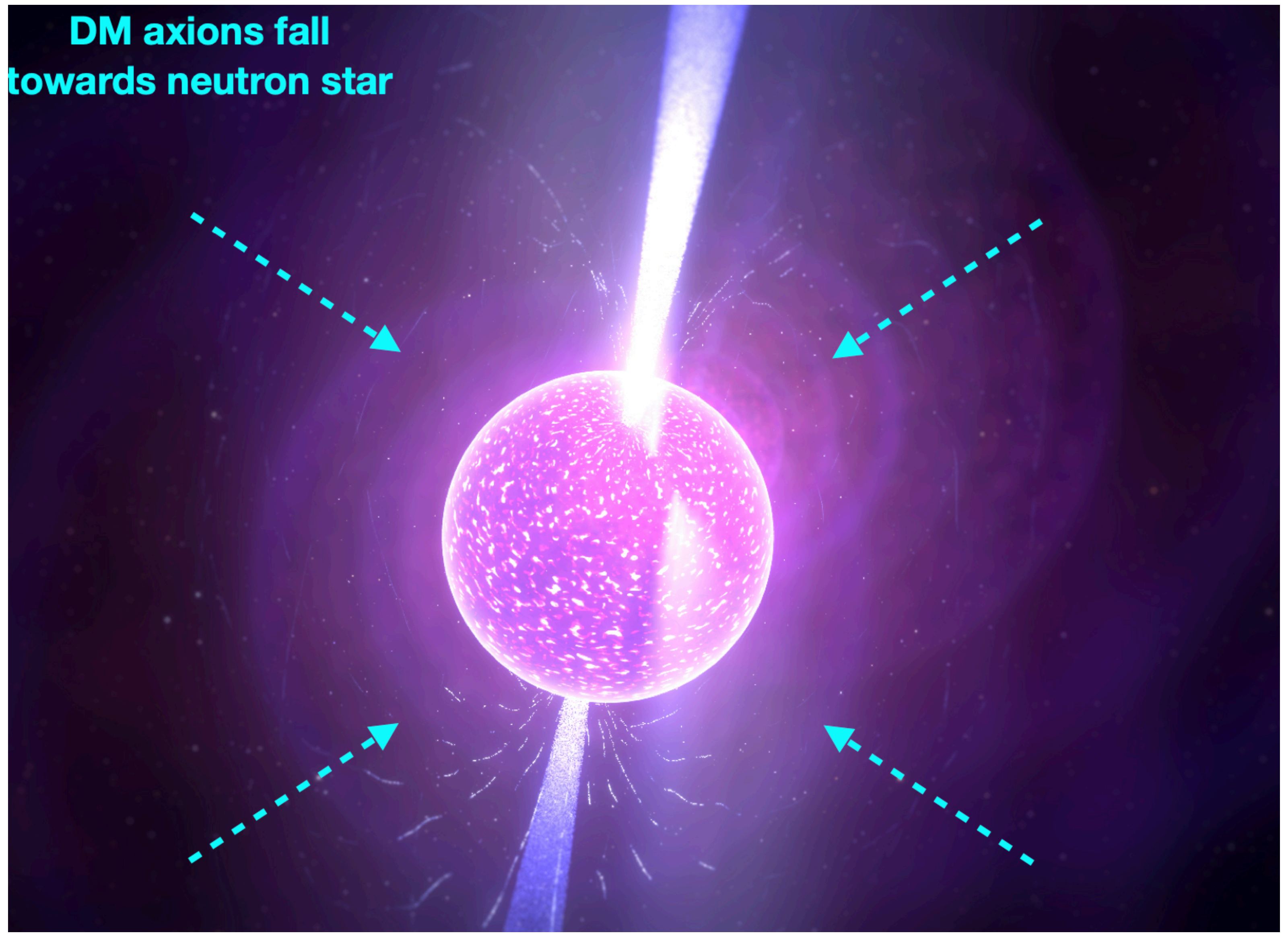
$$\frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega} \sim \frac{\pi}{3}\, g_{a\gamma\gamma}^2 B_0^2 \,\frac{{R_{\rm NS}}^6}{{R_c}^3}\, \frac{\rho_c}{m_a}$$

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

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

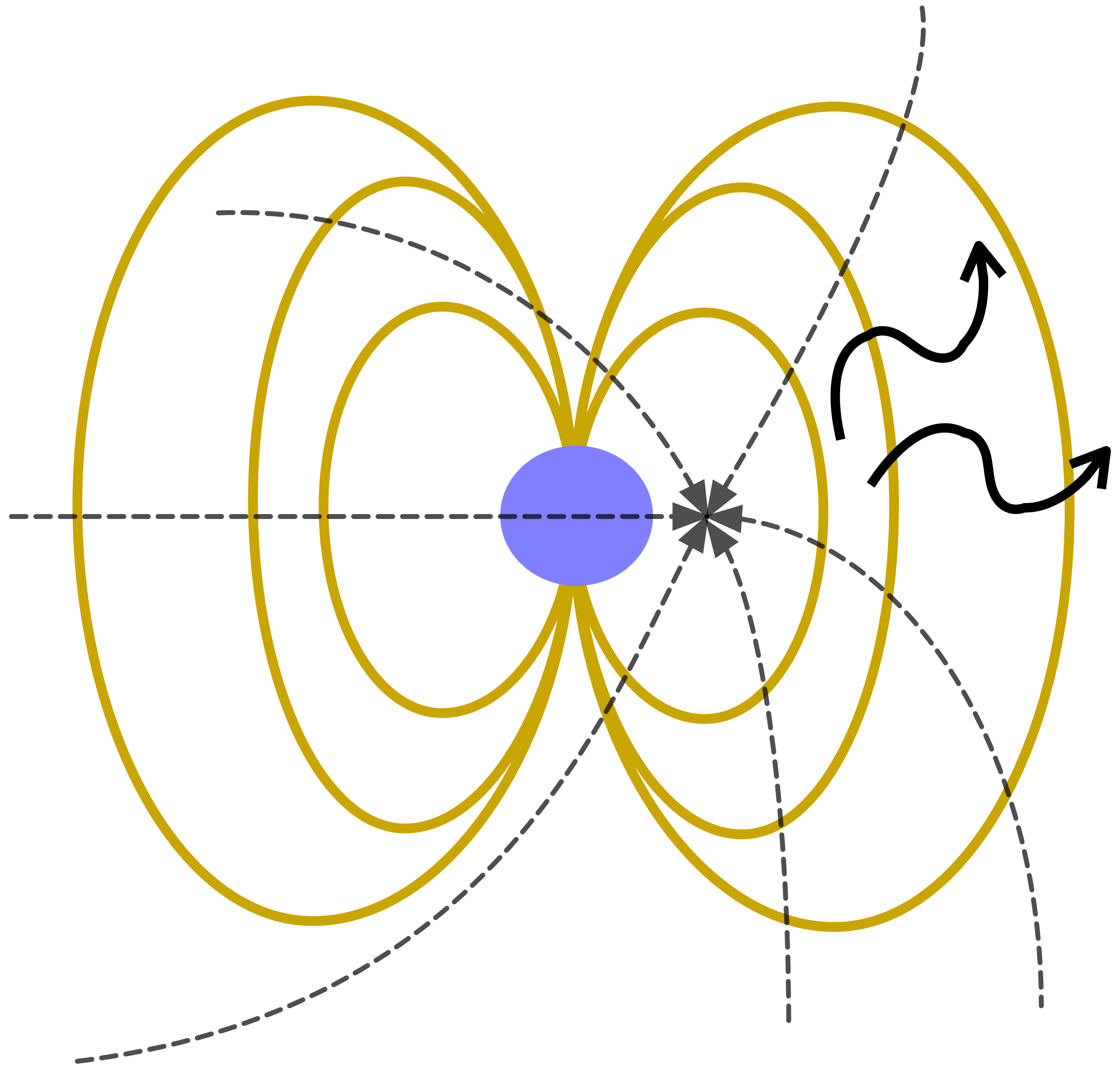
Look for axion-photon conversion from an individual NS

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



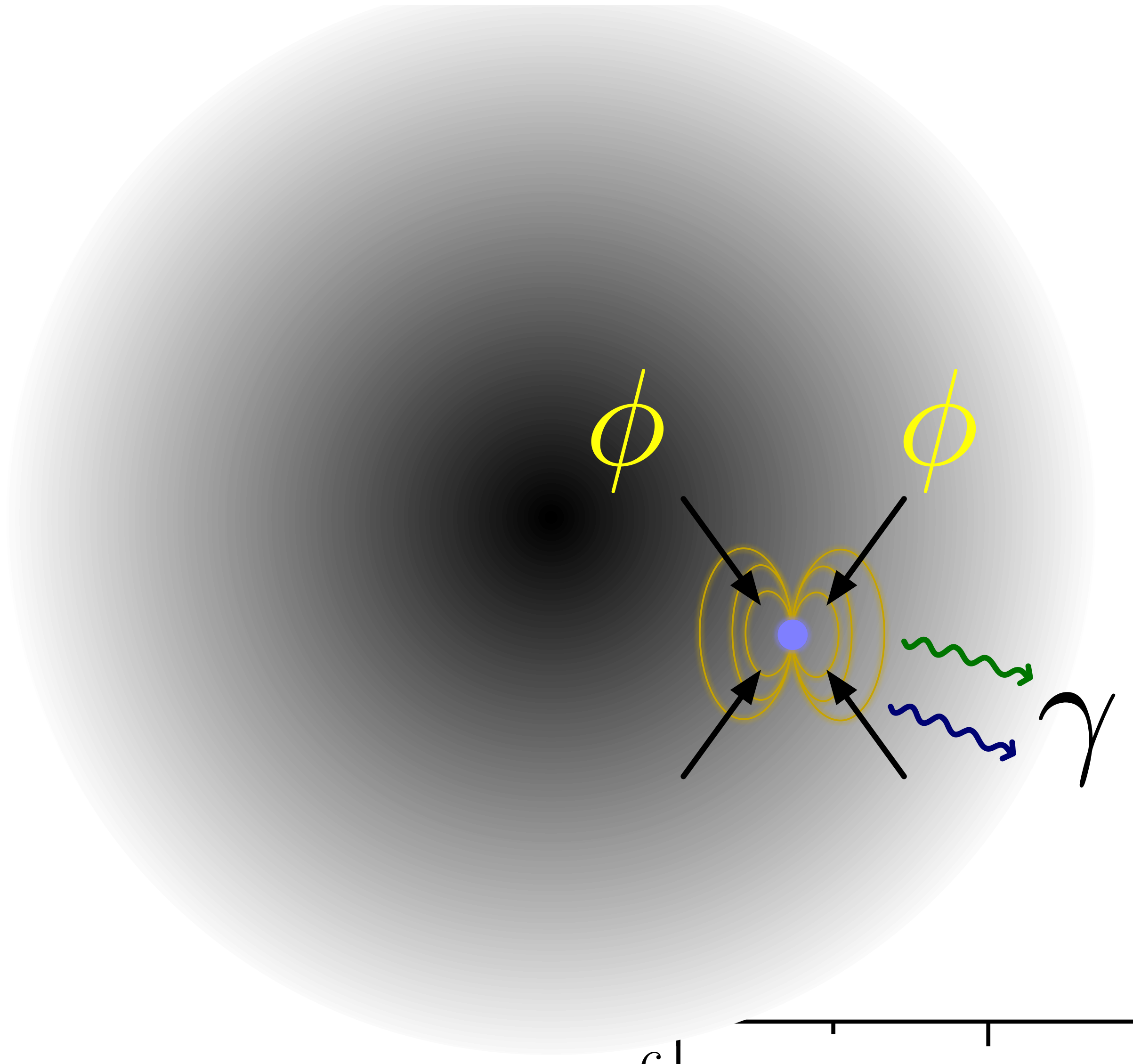
Transient enhancements to ρ_c from AMC encounters

Edwards+ (with **LV**) 2011.05378



Axion-photon conversion in NS magnetospheres

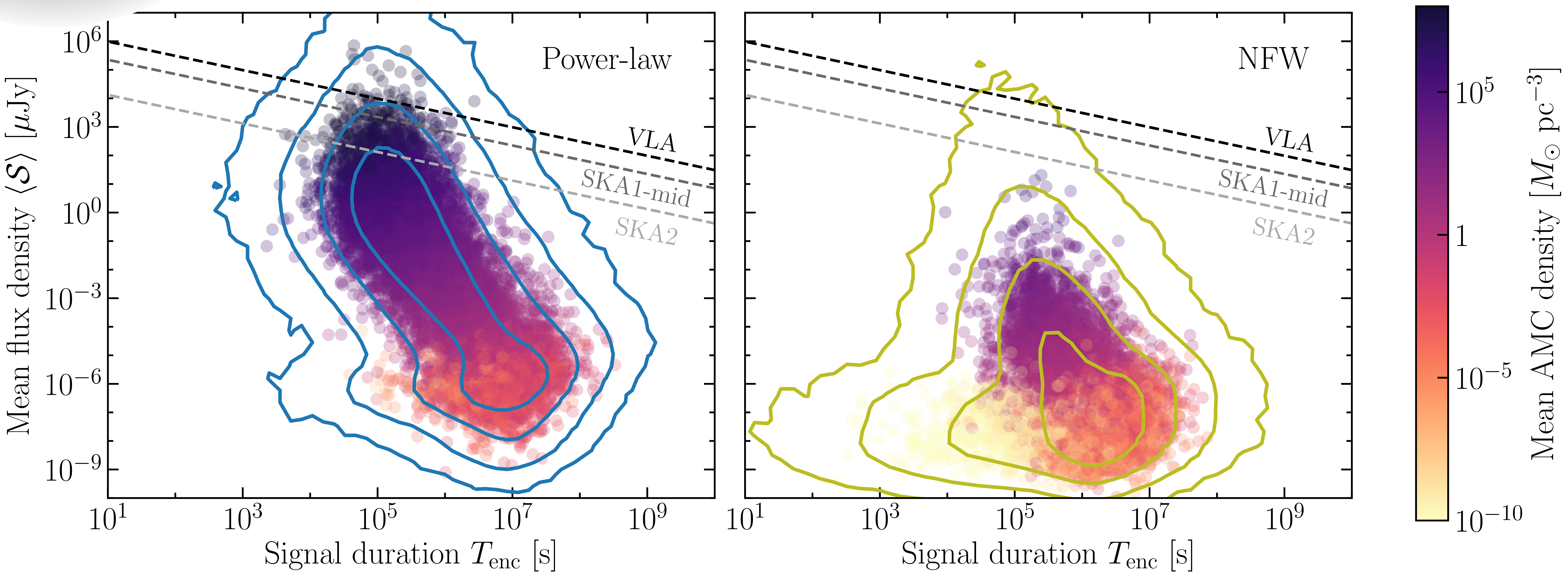
Luca Visinelli



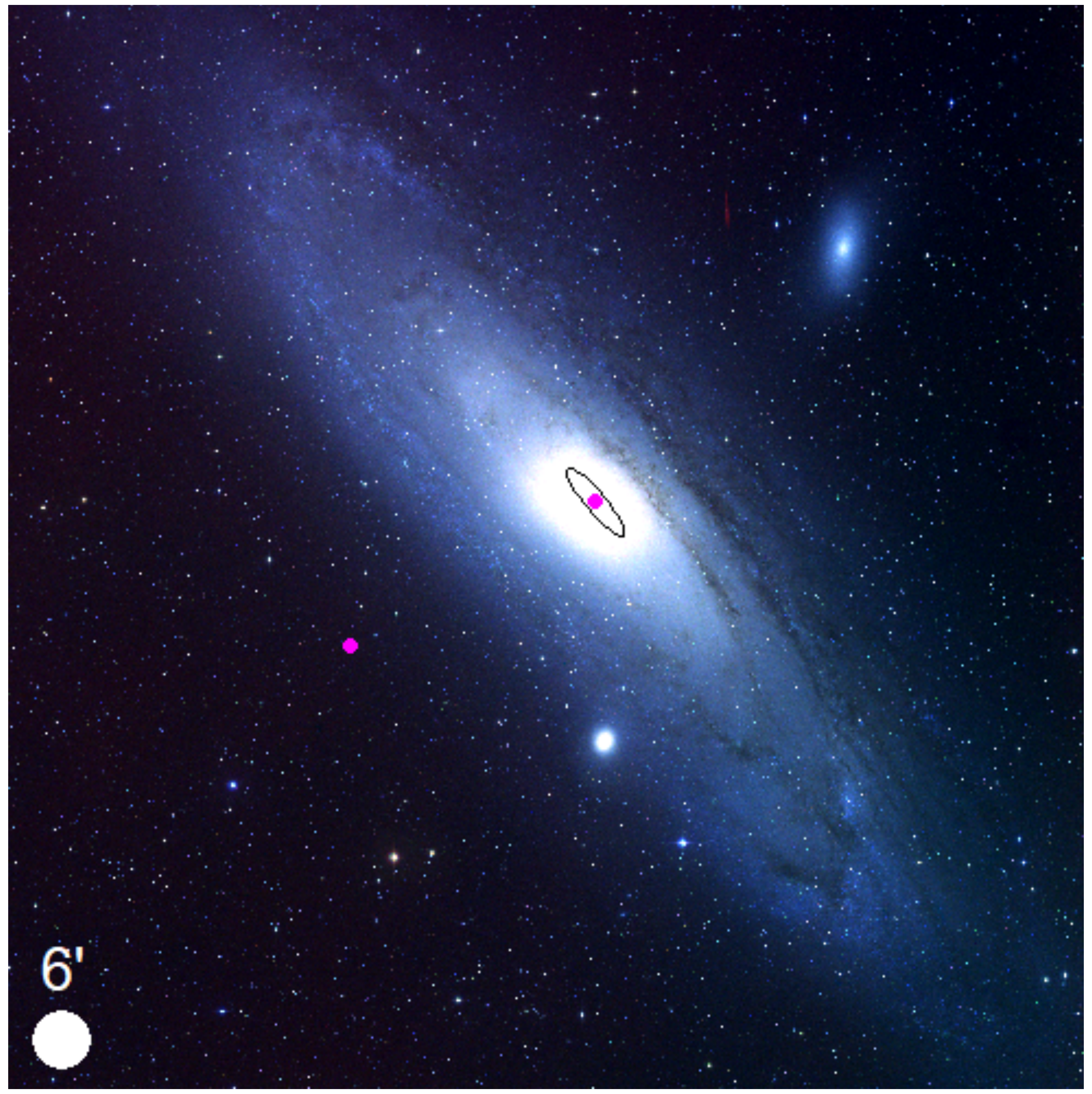
$$\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$$

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

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



Can we pick up this signal in radio?



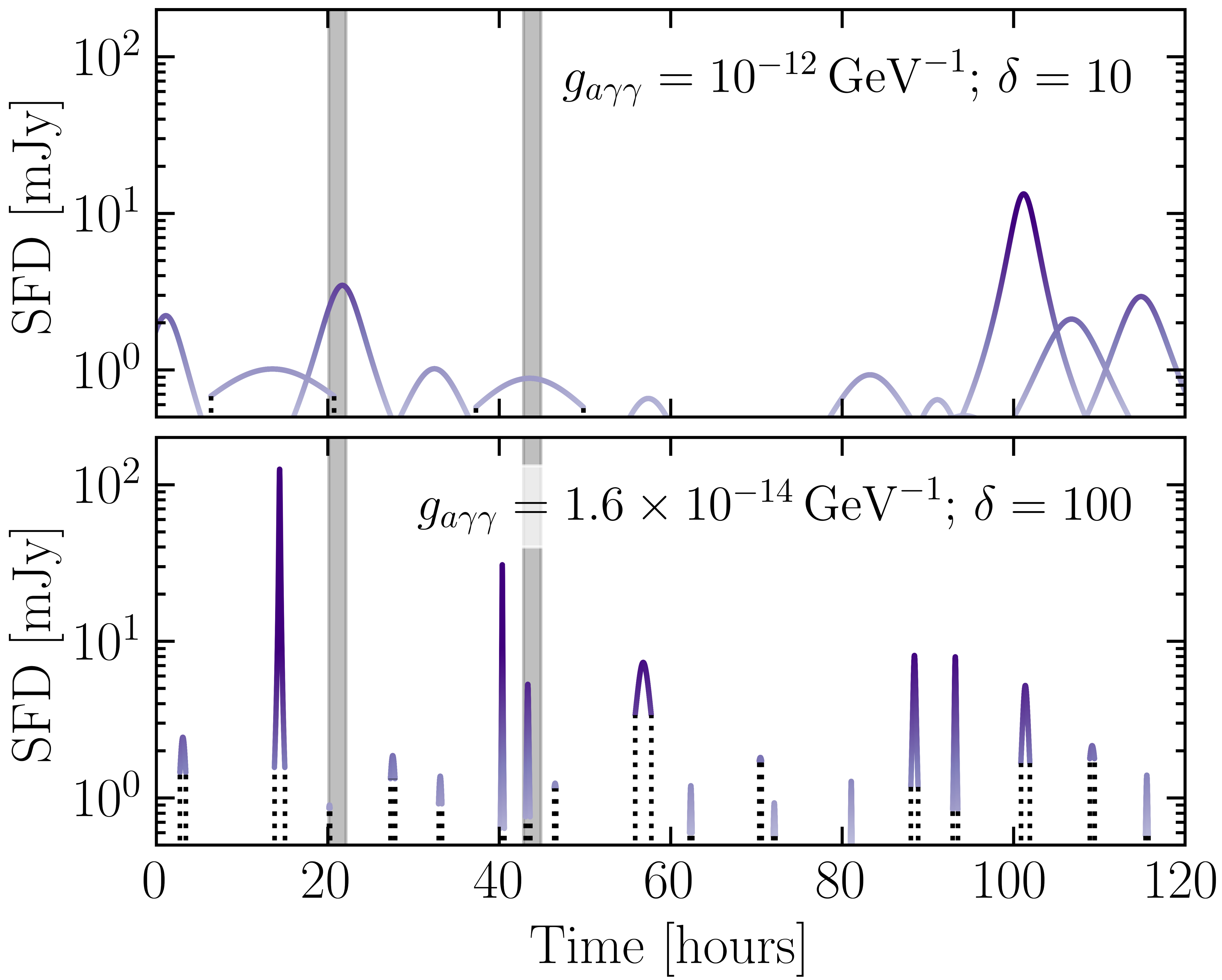
2 grant proposals accepted
by the Green Bank Telescope.
We have observed Andromeda

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



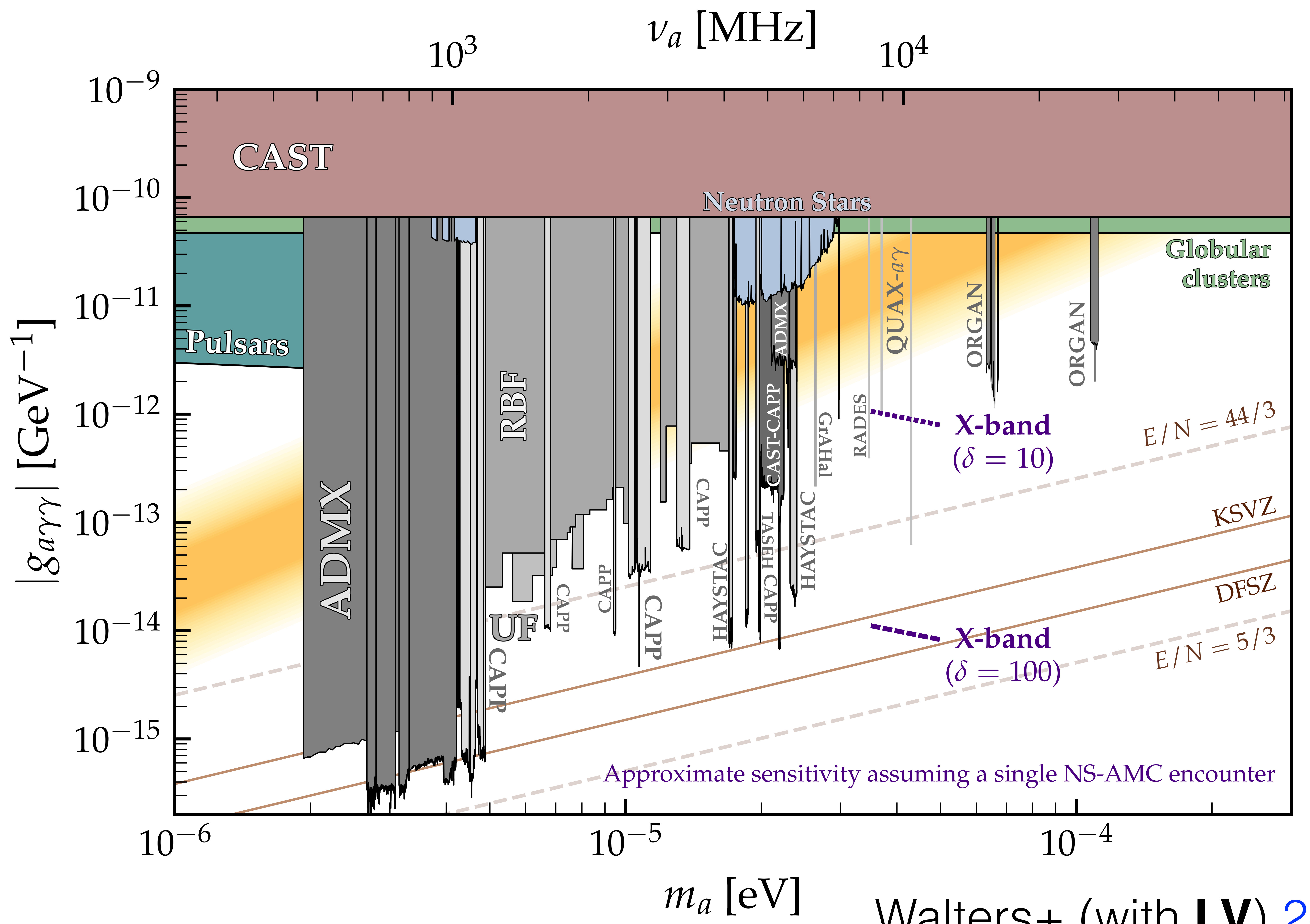
Walters+ (with **LV**) 2407.13060

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?



Ongoing work: we formed **ASTRA** (Axion Search via Telescope for Radio Astronomy)

NEWS: Jefferson Trust fund for telescope <2 GHz

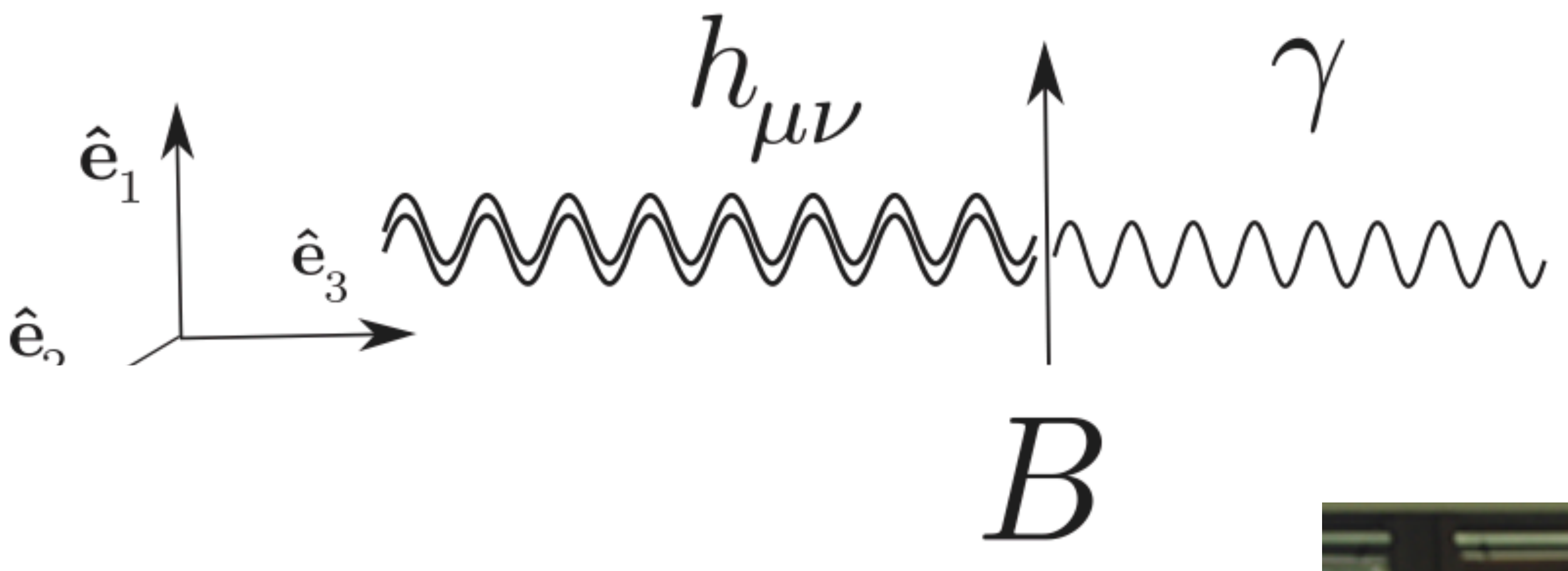
Walters+ (with **LV**) 2407.13060

Observational Consequences: direct detection

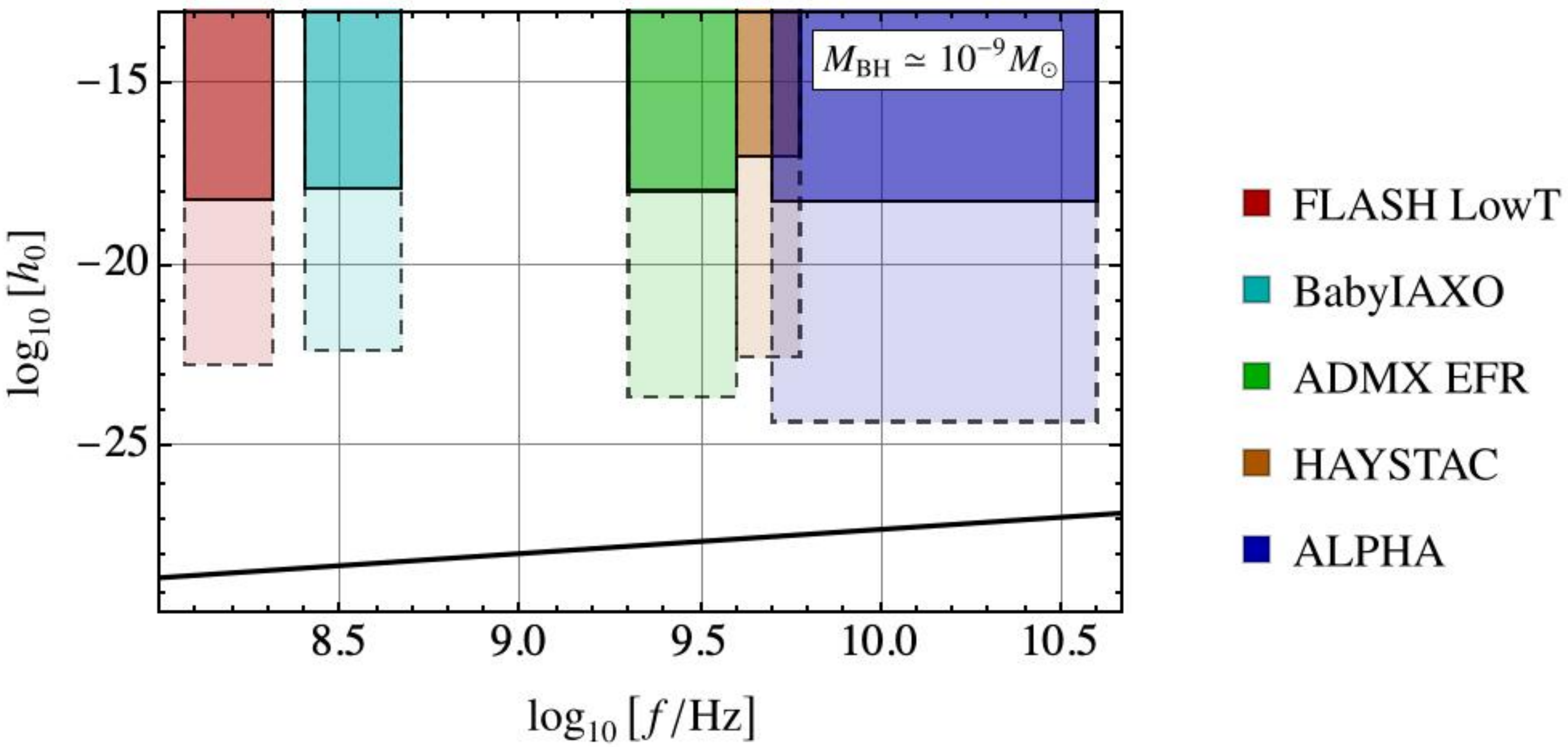
High-frequency gravitational waves

String axions and their GW signals are gaining attention
see insights by Margherita Putti and Nicole Righi

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



Inverse Gertsenshtein effect (e.g. Domcke & Garcia-Cel



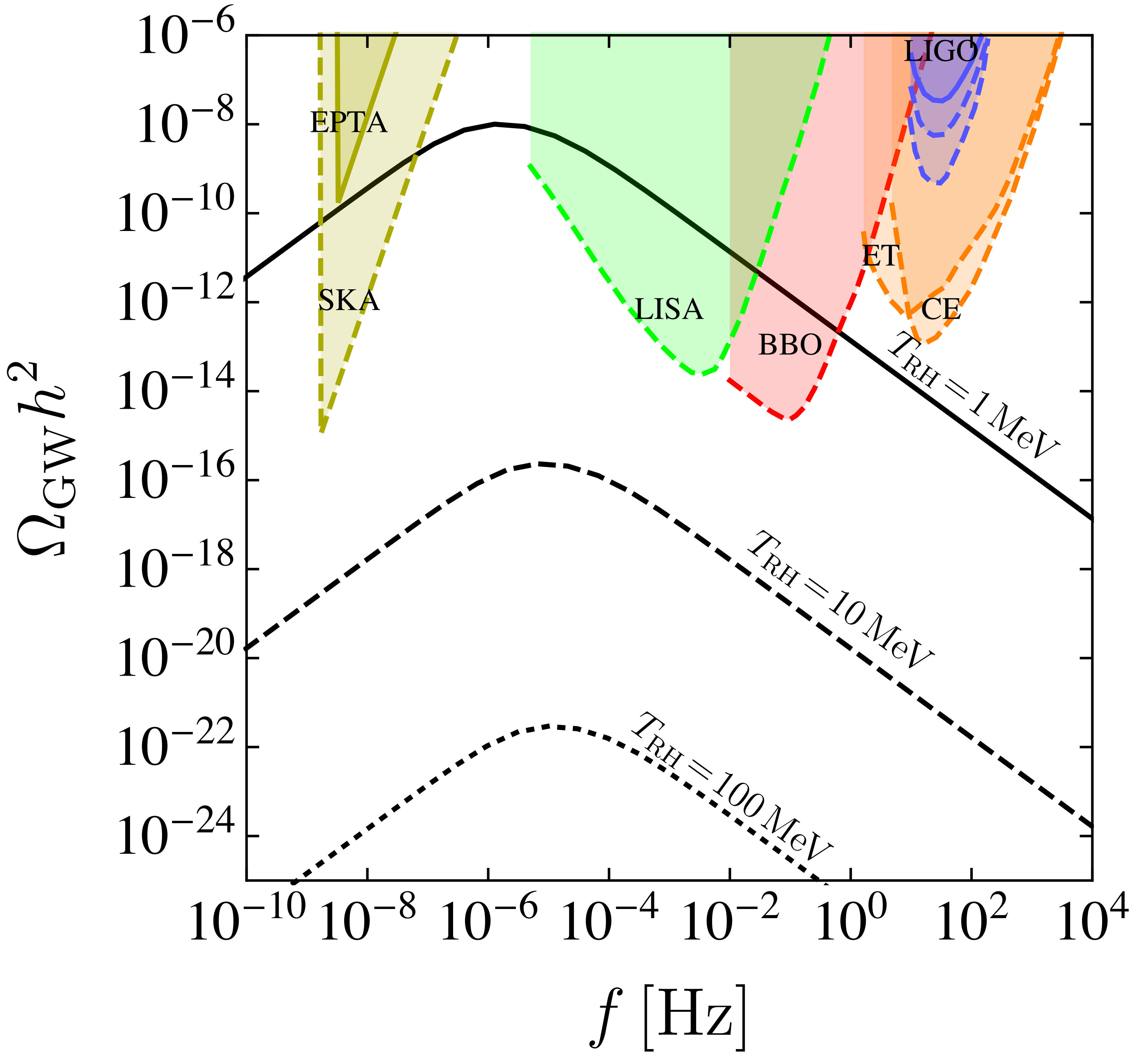
Gatti, **LV**, Zantedeschi 2403.18610, PRD

Work with
Michael Zantedeschi

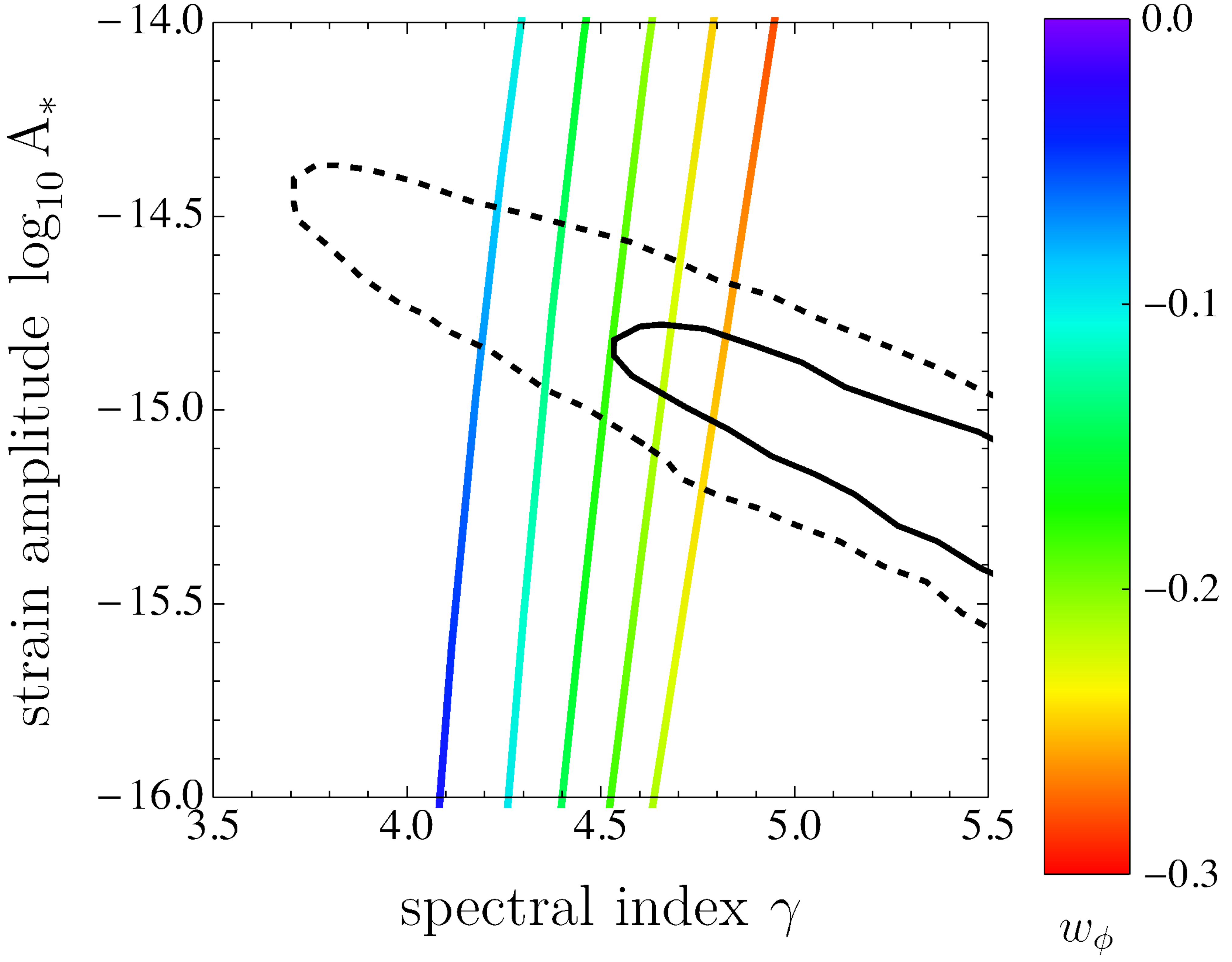
GWs from axionic strings?

- Low-reheat scenarios with QCD axion dark matter predict higher f_a

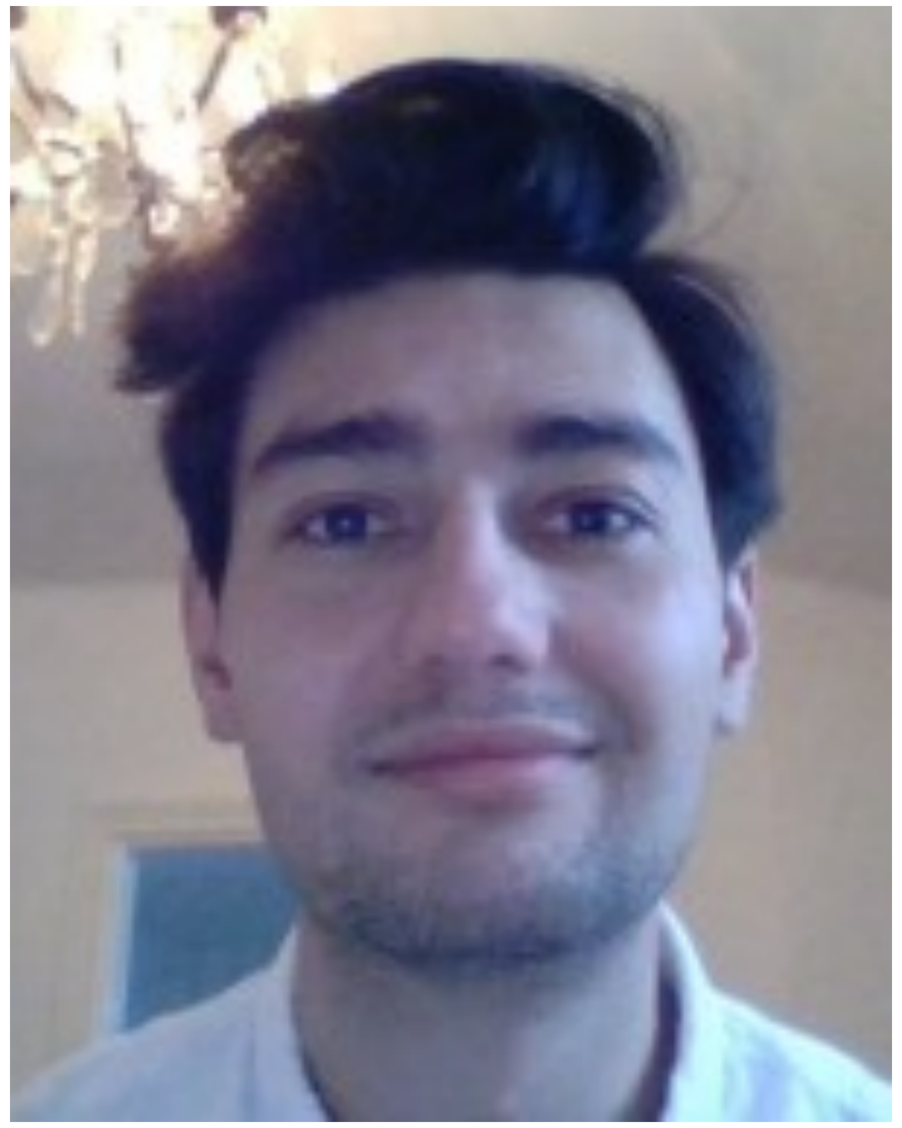
- This makes GWs from axion strings observable across diverse frequency bands.



Ramberg & **LV** [1904.05707](), PRD



Ramberg & **LV** [2012.06882](), PRD



Work with
Nicklas Ramberg

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

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

2011.05377, 2011.05378, 2407.13060

github.com/bradkav/axion-miniclusters

Thank you!