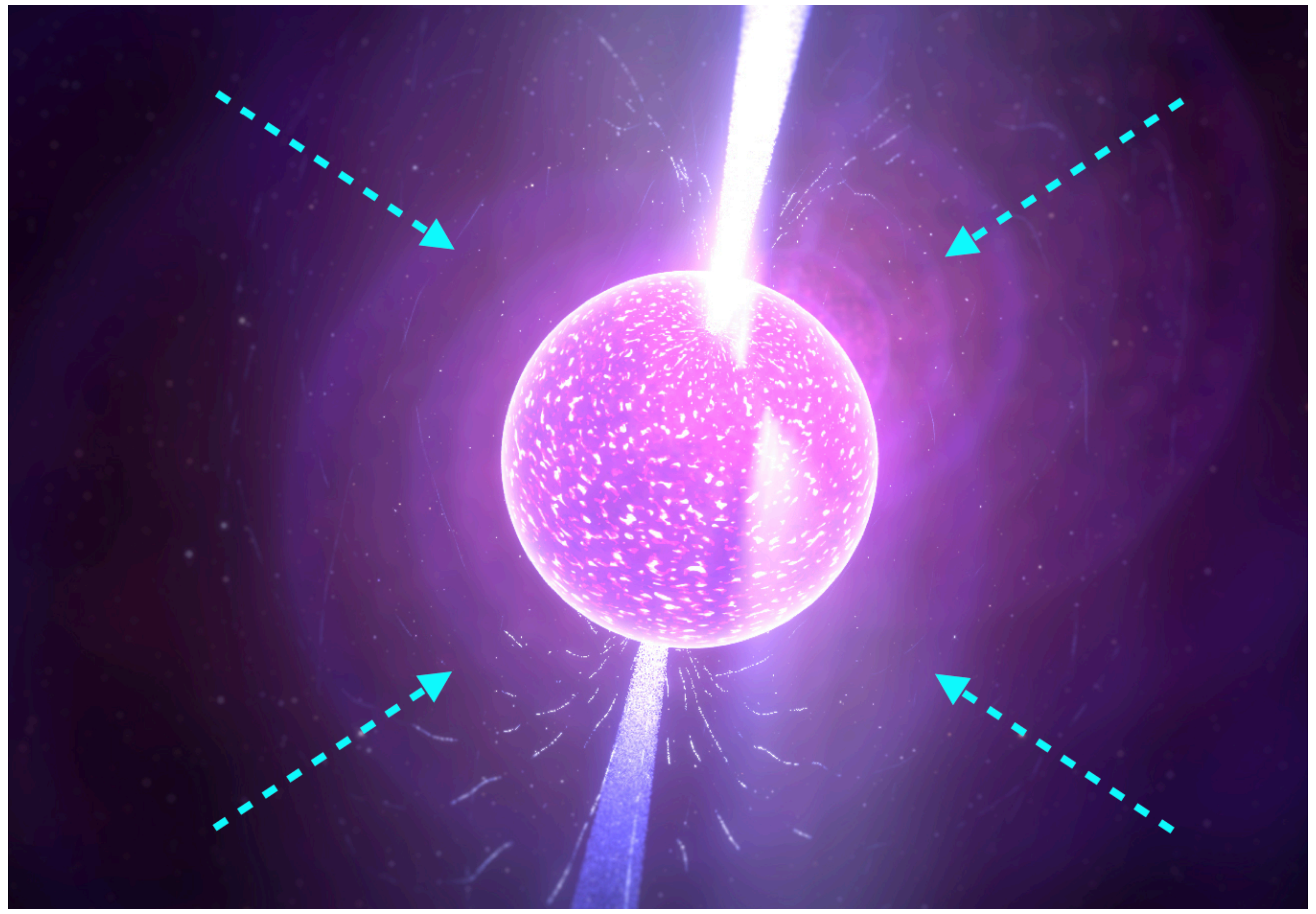
Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

UNIVERSITÀ DEGLI STUDI DI SALERNO

Searching for axion dark matter with Radio Telescopes



Luca Visinelli

Dipartmento di Fisica “E.R. Caianiello”, Università di Salerno & INFN

July 3, 2025

lvisinelli@unisa.it

Outline

- Axion Miniclusters in the Milky Way
- Axion-photon conversion in NS magnetospheres
- Searching for axions in M31 (Andromeda)
- Bonus: Direct detection of the axion at INFN Frascati National Labs

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]

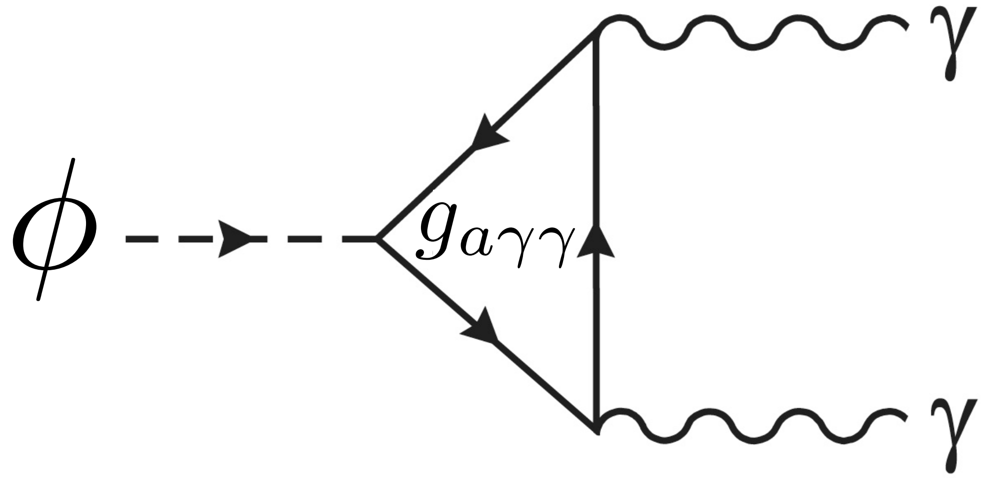
$$m_a = \frac{\Lambda^{3/2}_{\rm QCD}}{f_a}\sqrt{\frac{m_u m_d}{m_u + m_d}} \approx 5.7\,\mu{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$$

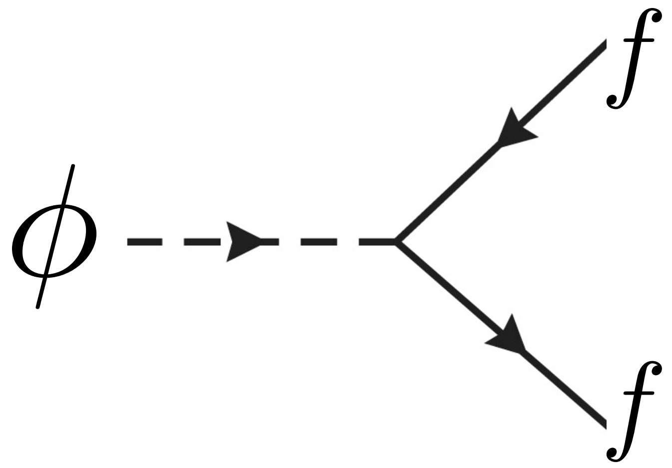
The QCD Axion: foundations

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

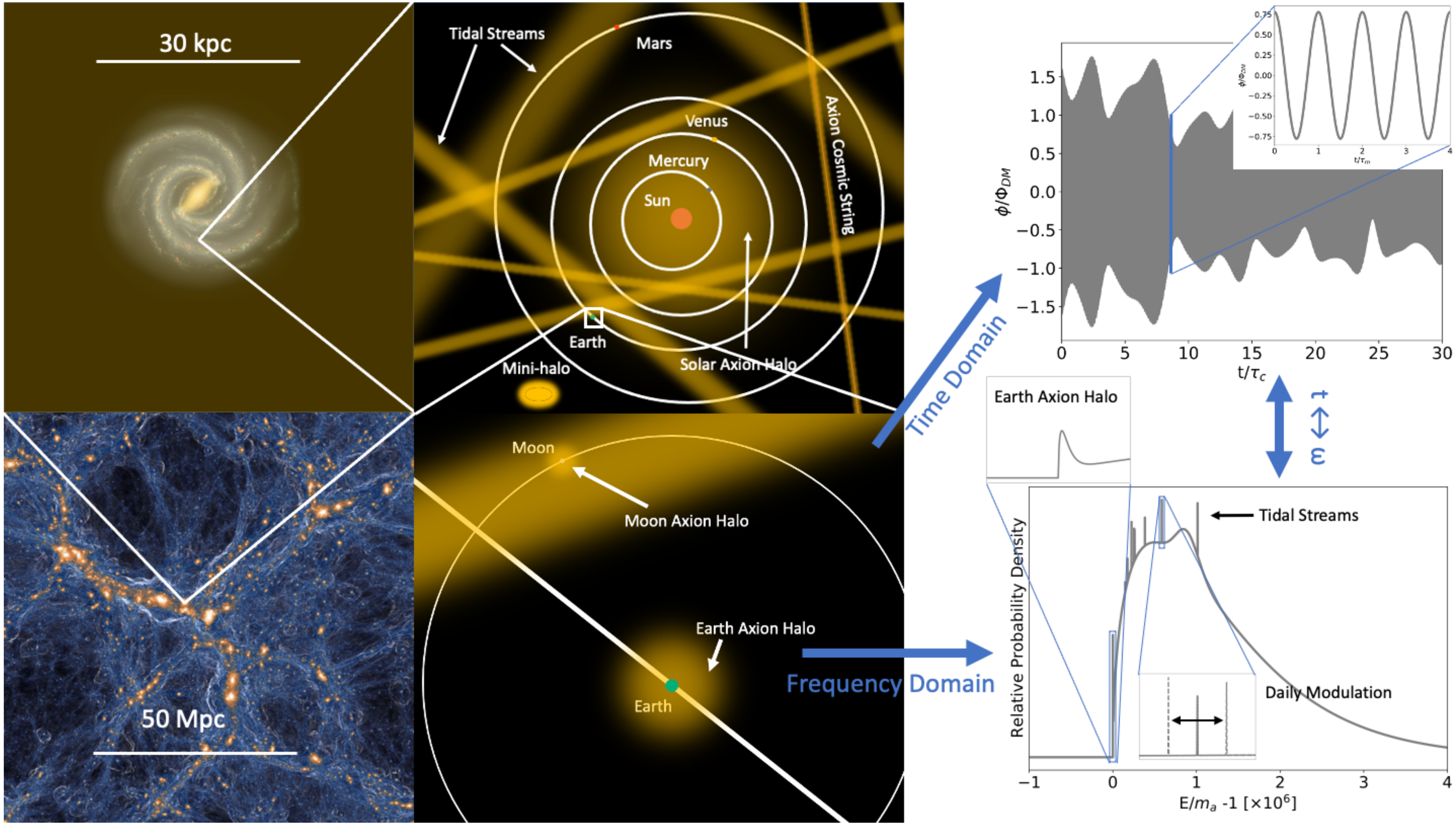




The coupling depends on color & EM anomalies $\frac{E}{N}$: $g_{a\gamma\gamma} = \frac{\alpha_{\rm EM}}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)$

Axion Miniclusters in the Milky Way

The QCD Axion: Role as the Dark Matter



"Axion Dark Matter" Snowmass 2021 White Paper 2203.14923

Axion miniclusters

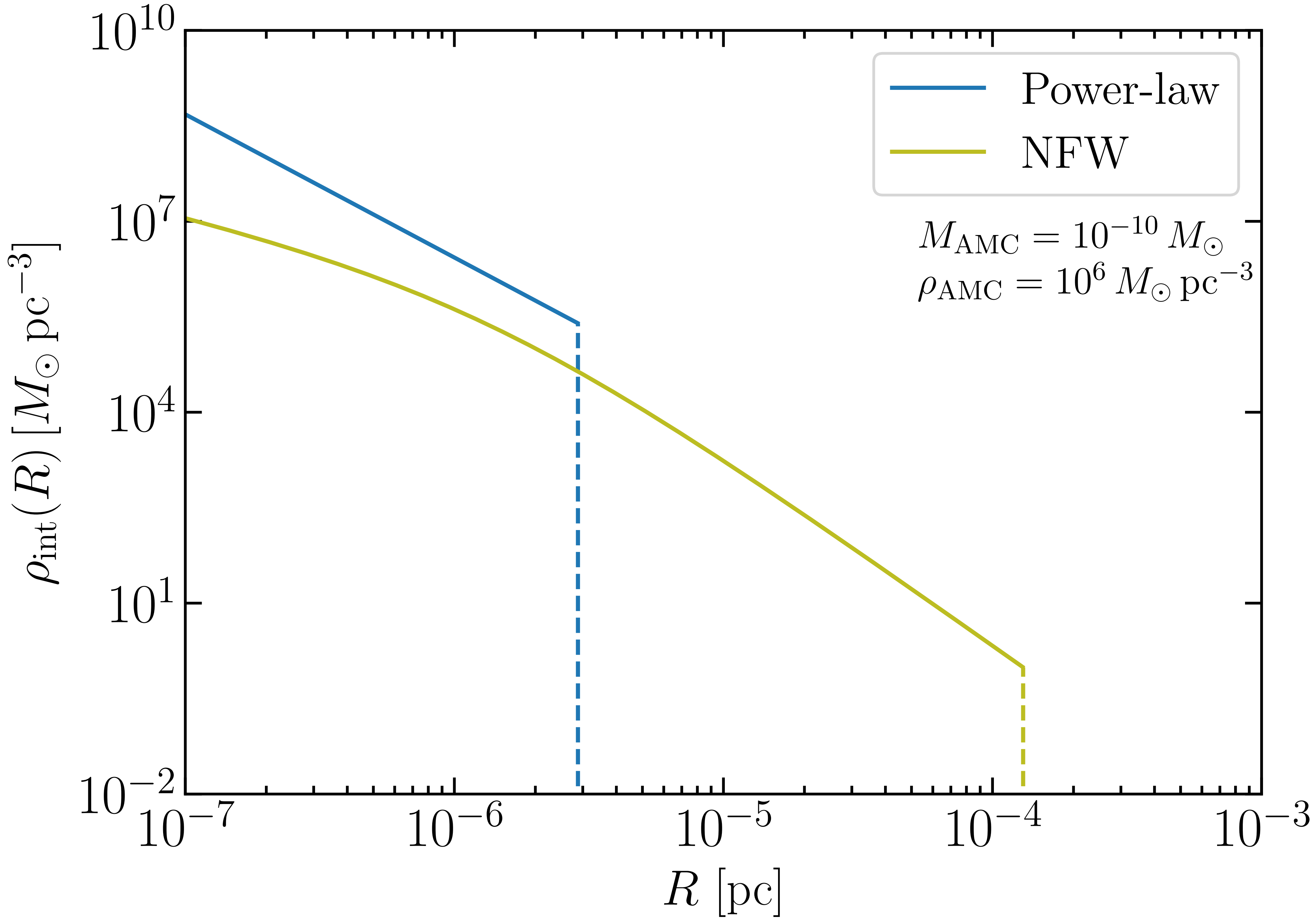
In post-inflation symmetry breaking, fluctuations are $\mathcal{O}(1)$ for $k \gg 2\pi/L_{\rm osc}$

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

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]

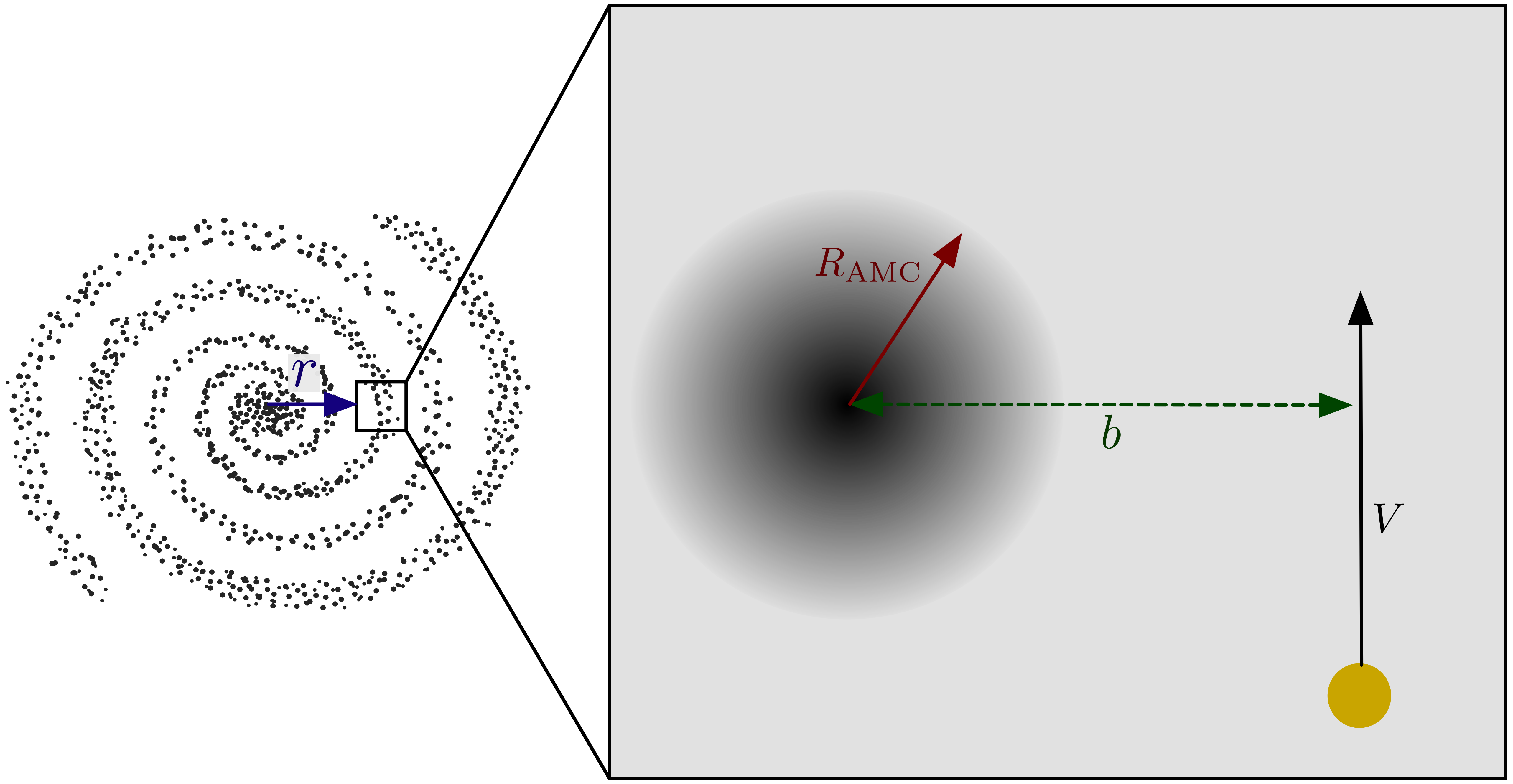
Axion miniclusters abundance today

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

Bradley Kavanagh

Thomas Edwards

Christoph Weniger

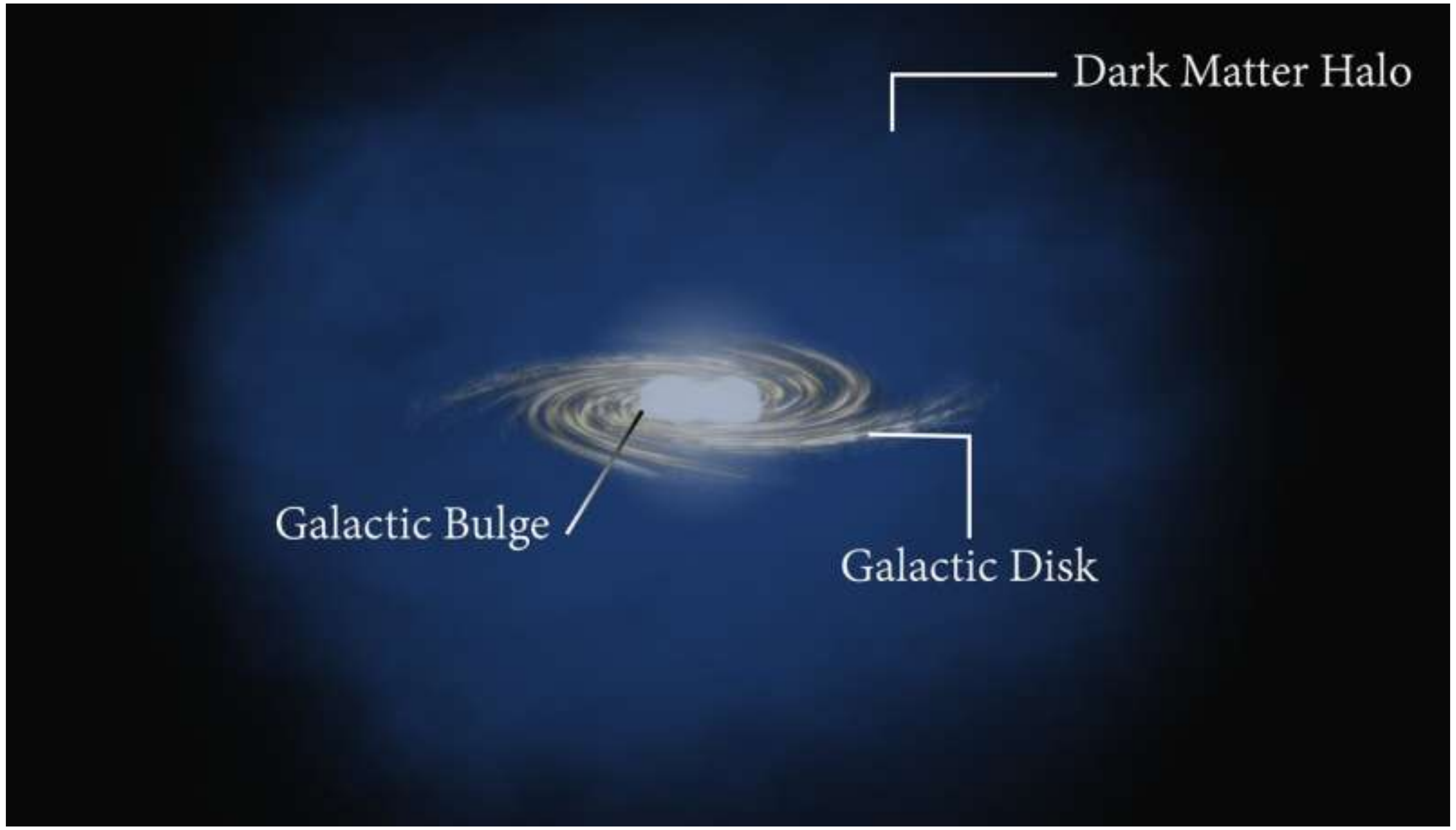


Kavanagh+ (with **LV**) 2011.05377

See also [Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586]
+ more numeric papers afterwards (DSouza+)

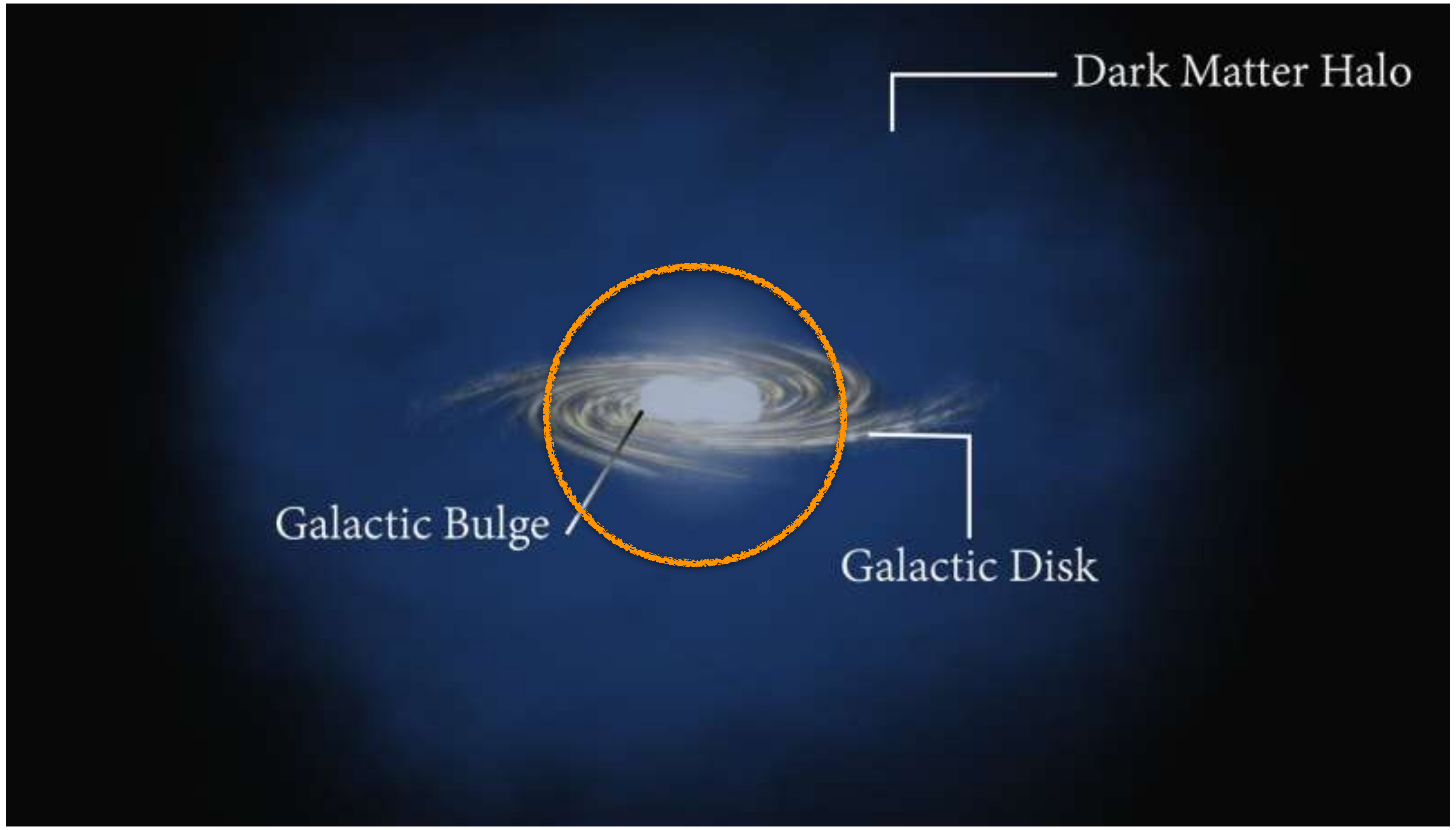
Milky Way Setup

Schematic modeling of a spiral Galaxy

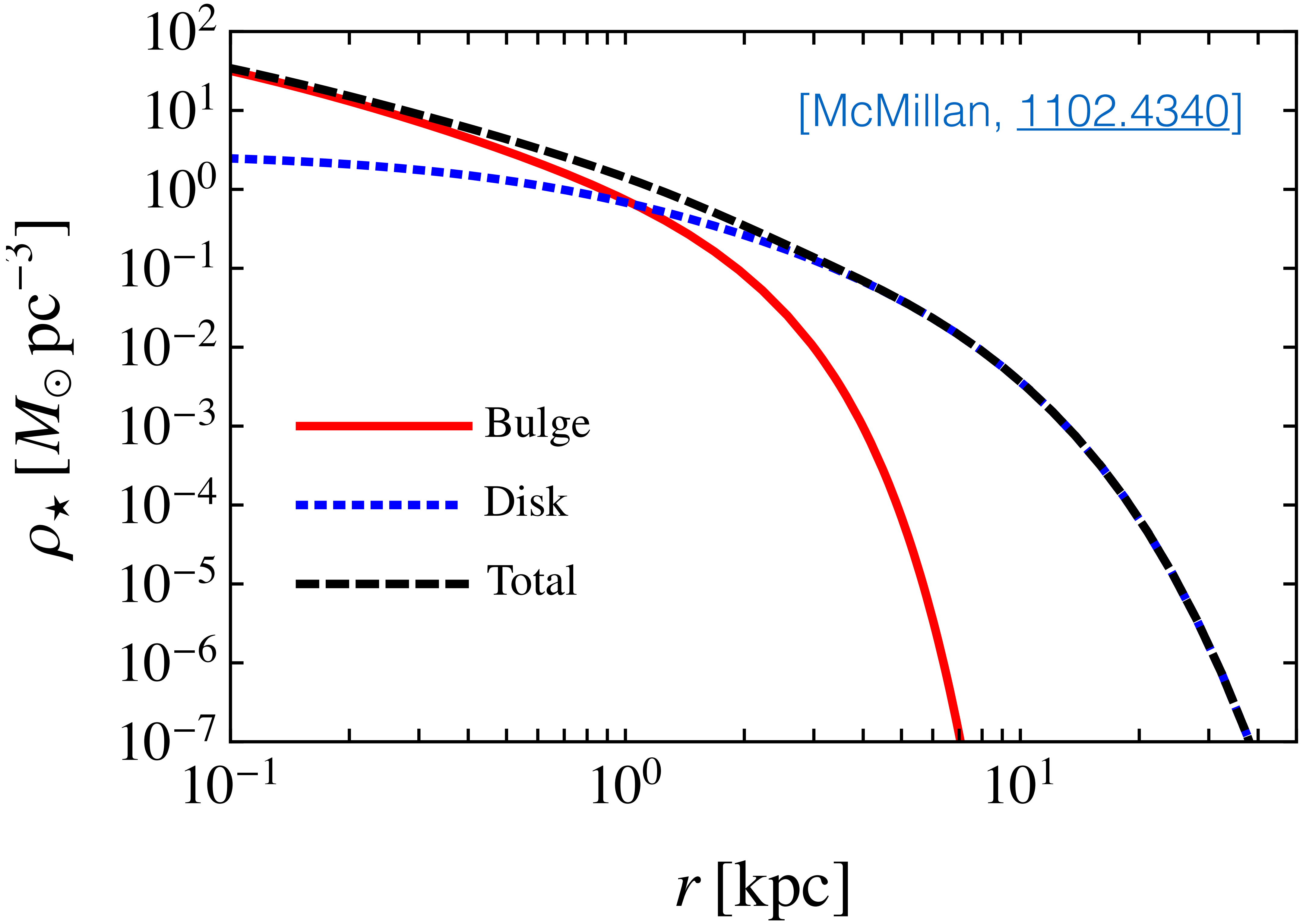


Milky Way Setup

Schematic modeling of a spiral Galaxy

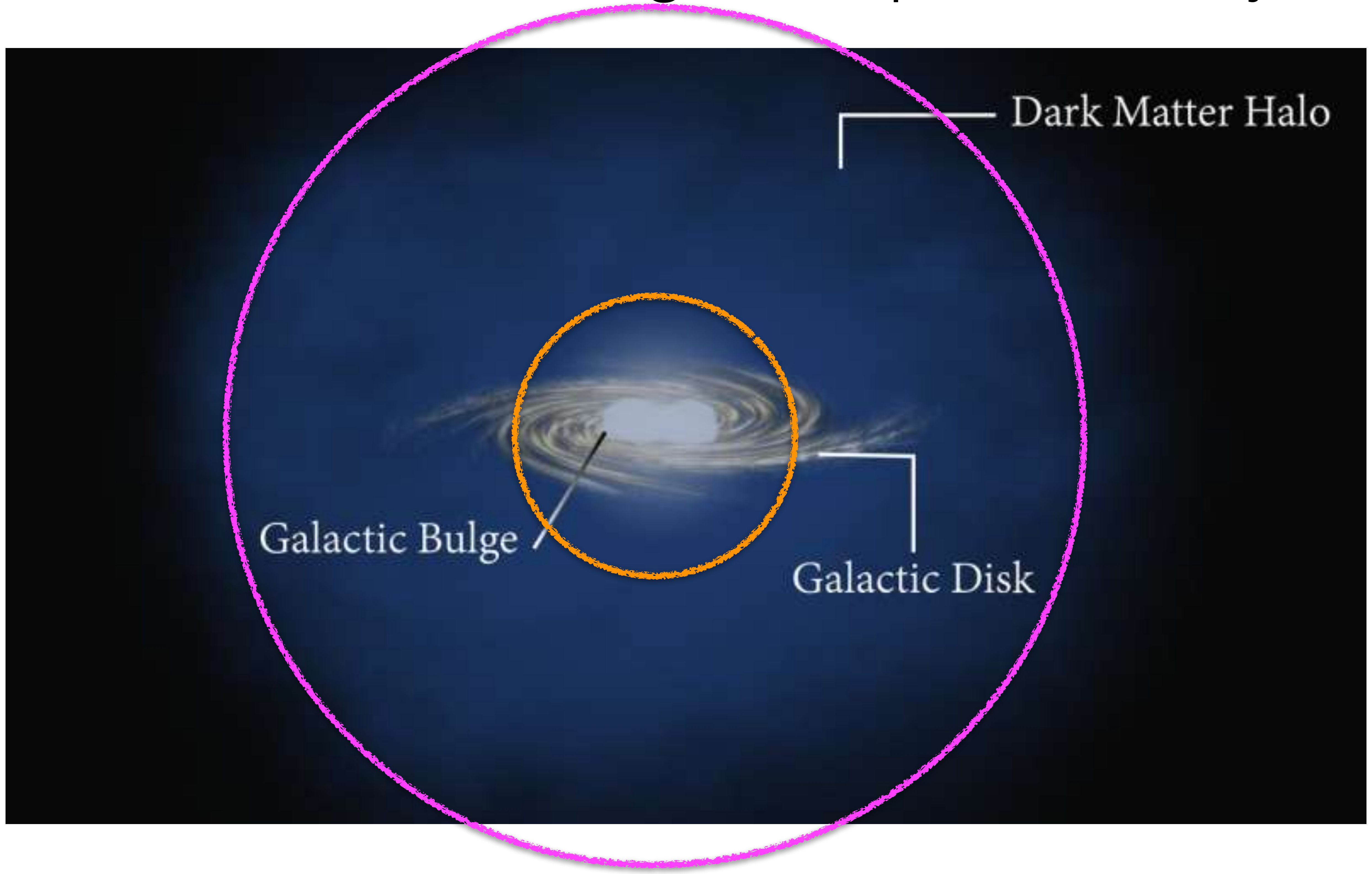


Stellar content

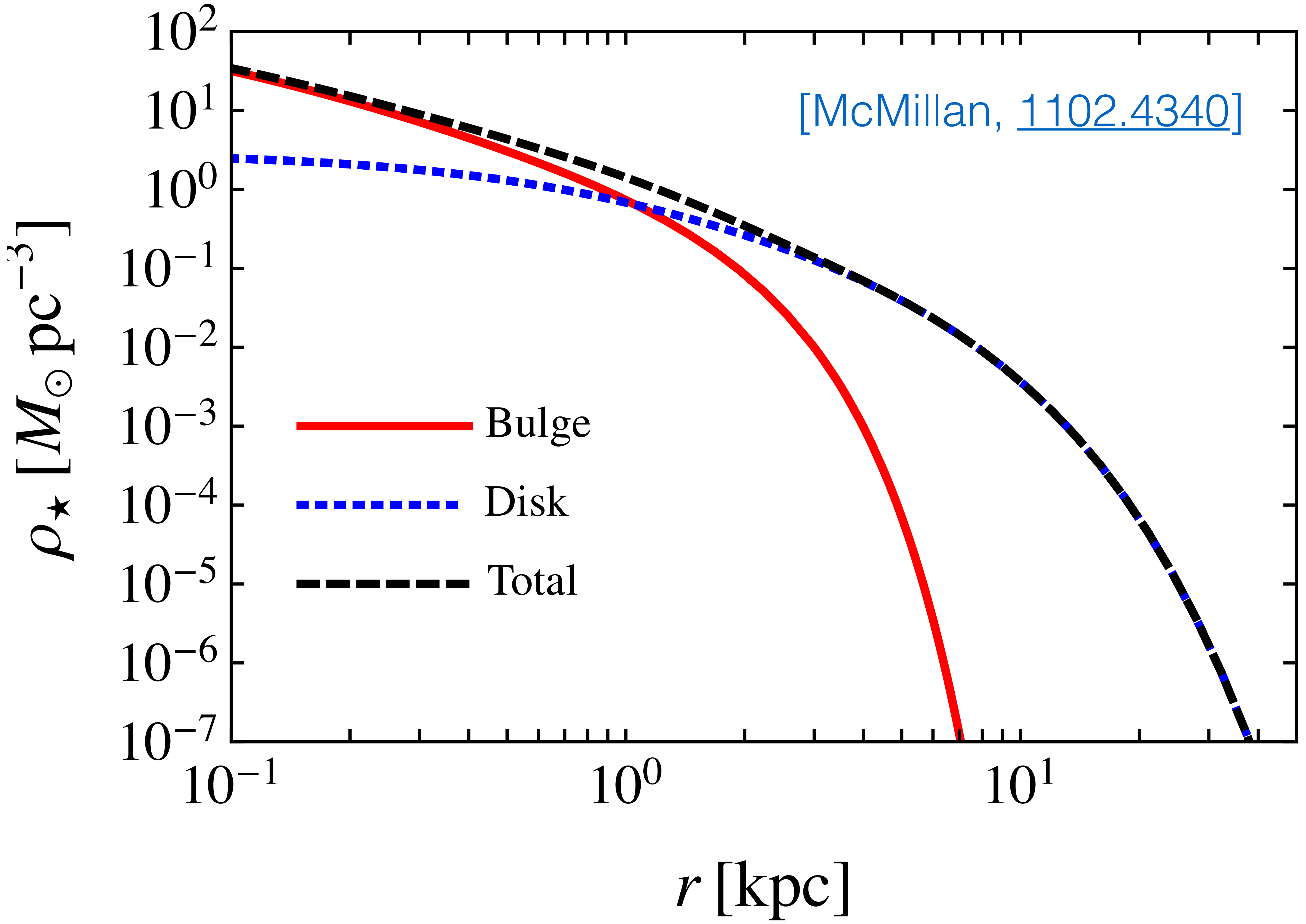


Milky Way Setup

Schematic modeling of a spiral Galaxy



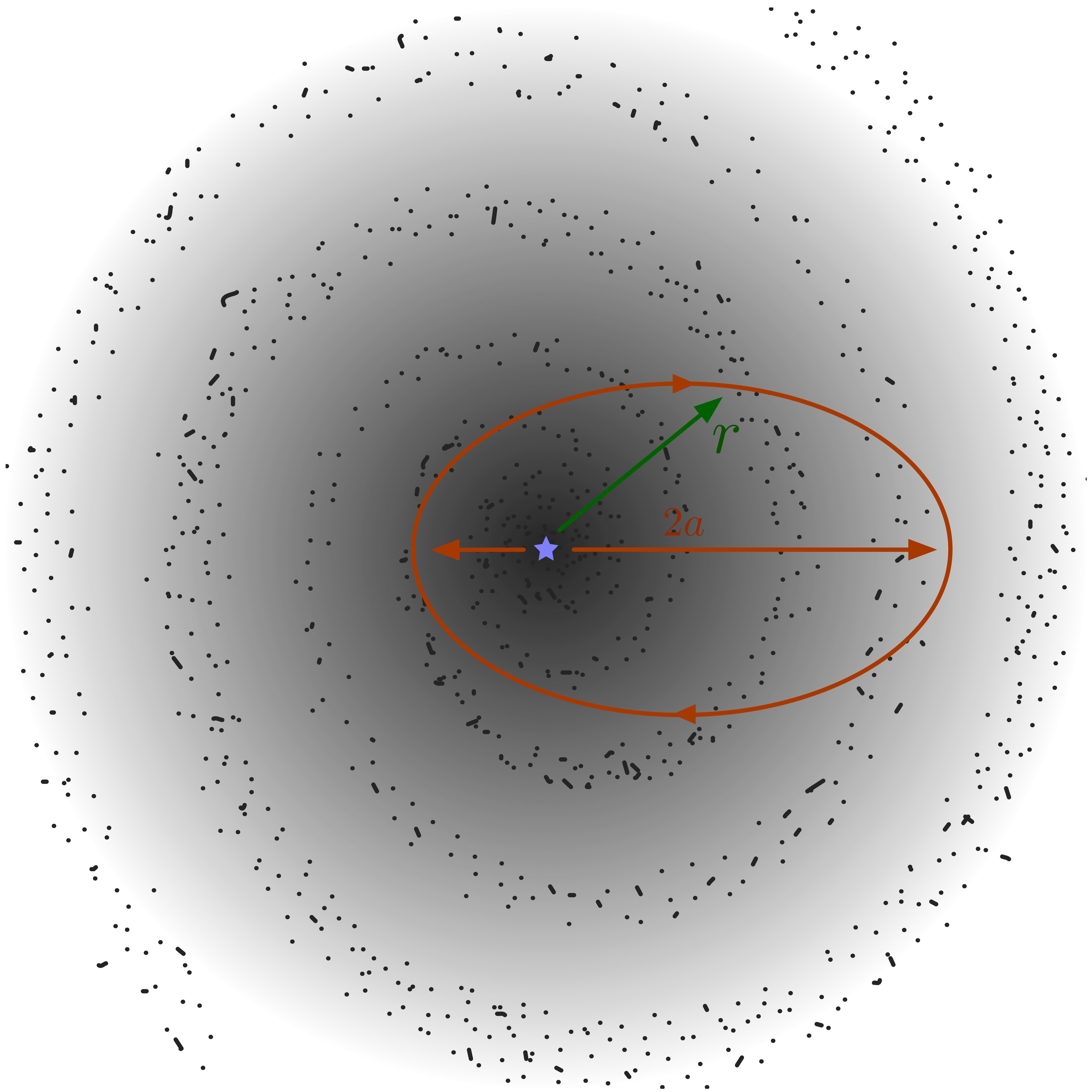
Stellar content



+ spherical DM halo (NFW)

$$\rho_{\rm DM}(r) = \frac{r_s}{r}\,\frac{\rho_s}{(1+r/r_s)^2}$$

Milky Way Setup



The AMC orbit is specified by three parameters:

- semi-major axis a
- eccentricity ε
- Inclination w.r.t. Galactic plane ψ

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

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

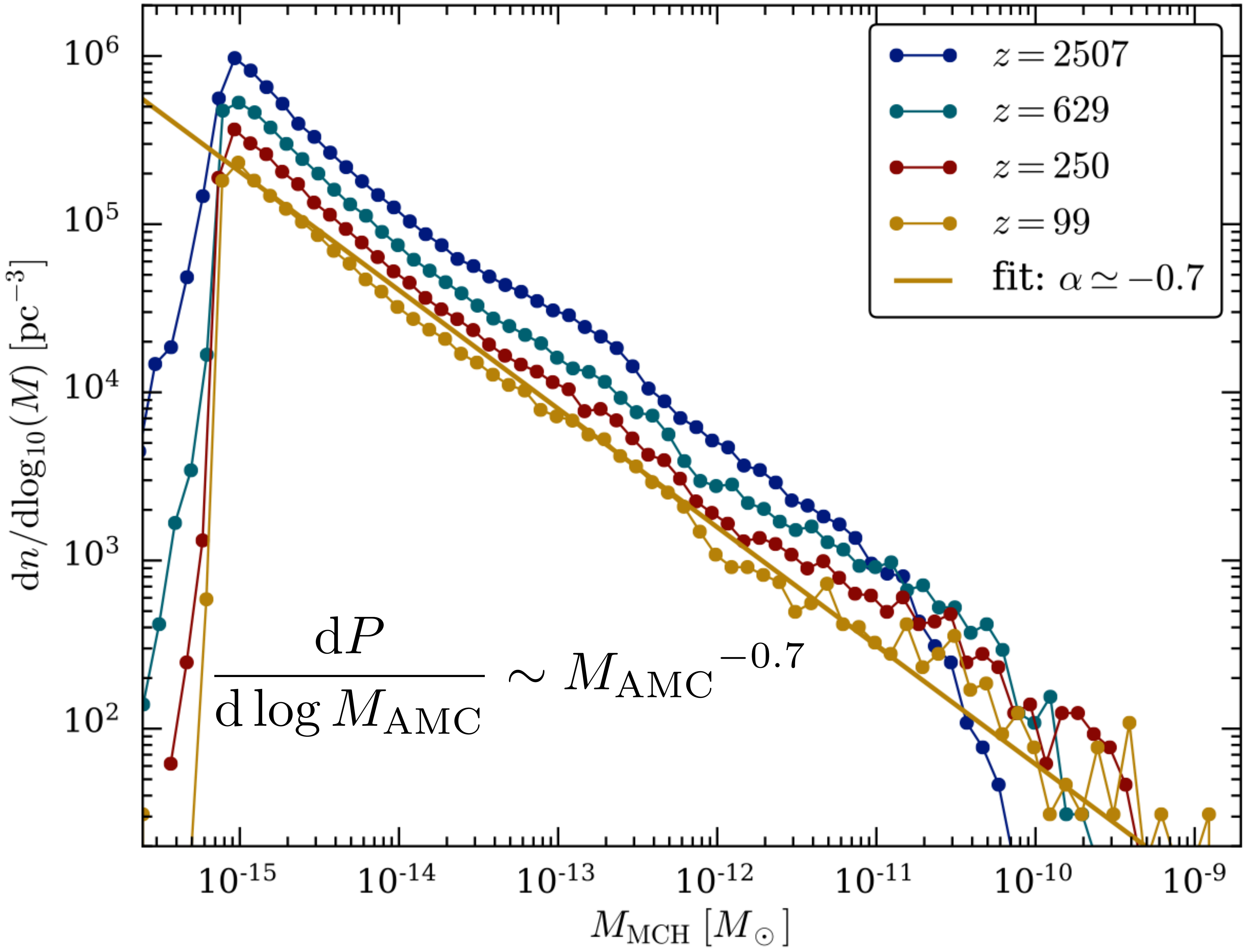
$$\langle M_{\rm AMC}\rangle \approx 10^{-14}\,M_\odot$$

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

AMC mass function

Pre-infall halo mass function $\frac{dn_0}{dM}(M,z) = f(\nu)\,\frac{\bar{\rho}_c}{M}\frac{d\nu}{dM}$

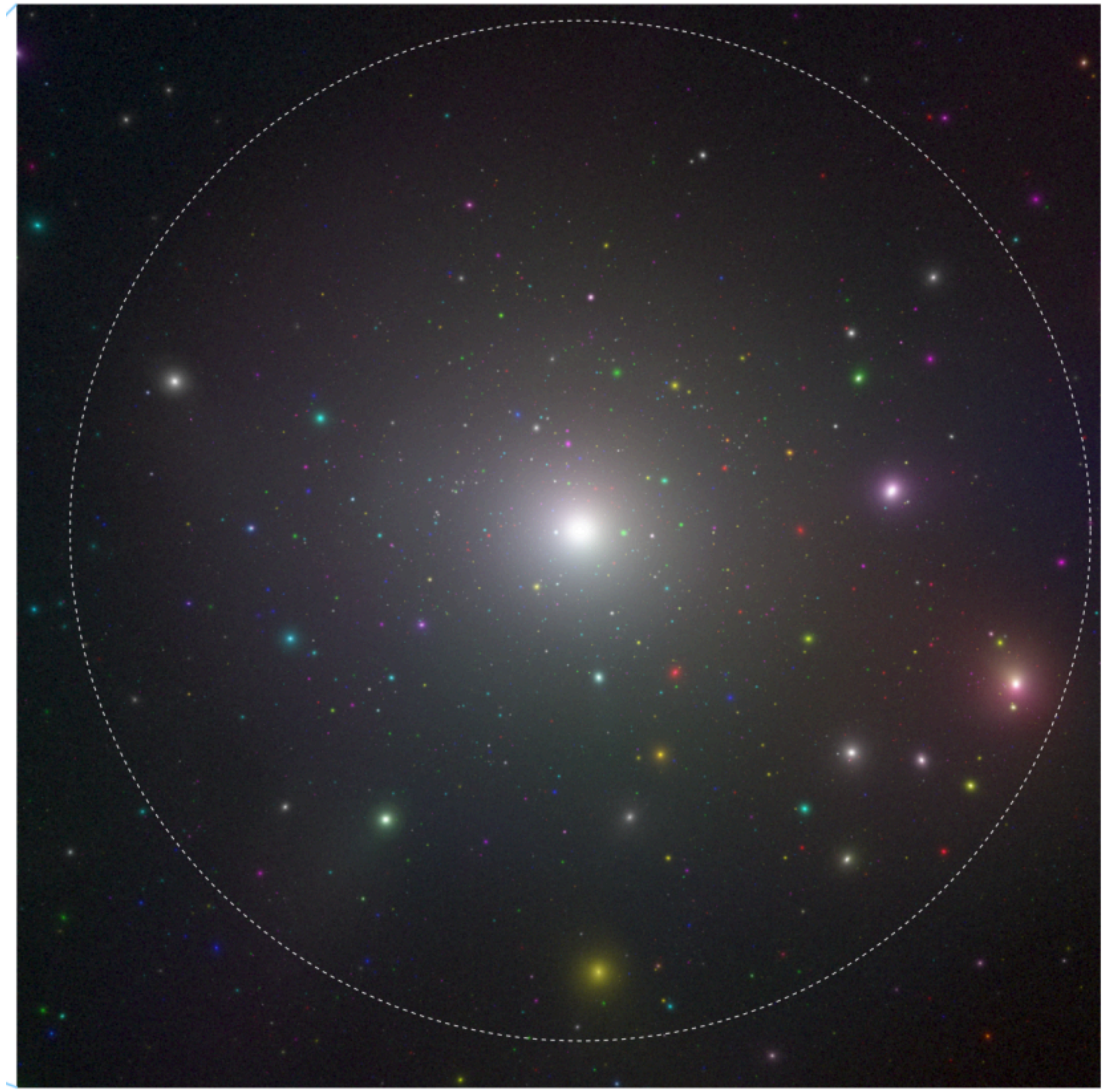
[Fairbairn et al., 1707.03310]



Lower cutoff set by the Jeans mass

Upper cutoff from hierarchical growth

Axion minicluster halo at z = 99



[Eggemeier et al., 1911.09417]

Monte Carlo procedure

[github.com/bradkav/axion-miniclusters]

Generate sample of AMCs (with correct density distribution but *log-flat* mass function)

Sample orbital parameters (ε, 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

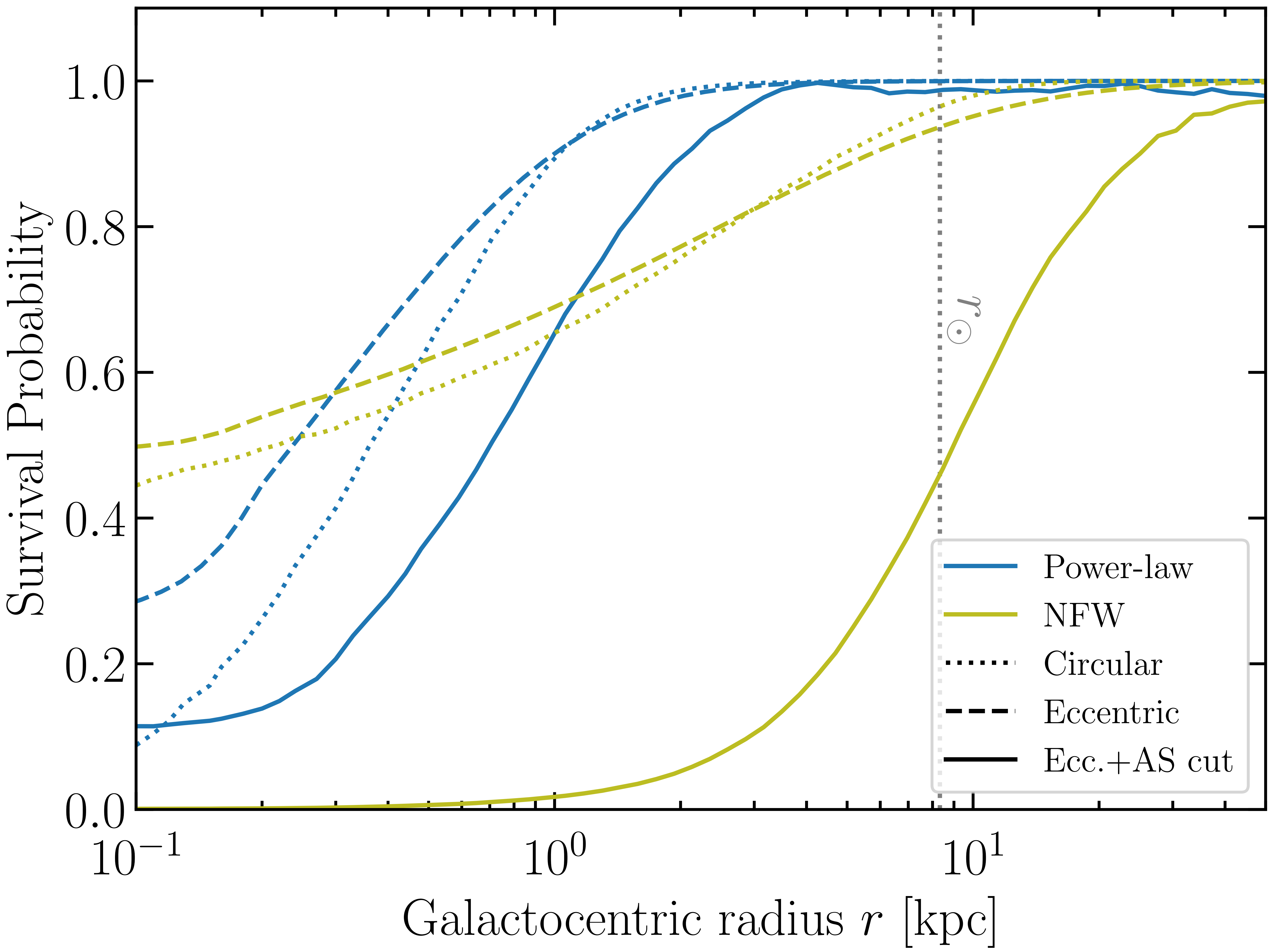
AMC disrupted

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



Kavanagh+ (with **LV**) [2011.05377]

Axion-photon conversion in NS magnetospheres

Axion-photon conversion in NS magnetospheres

We assume a **Goldreich-Julian** (GJ) model for the NS magnetosphere

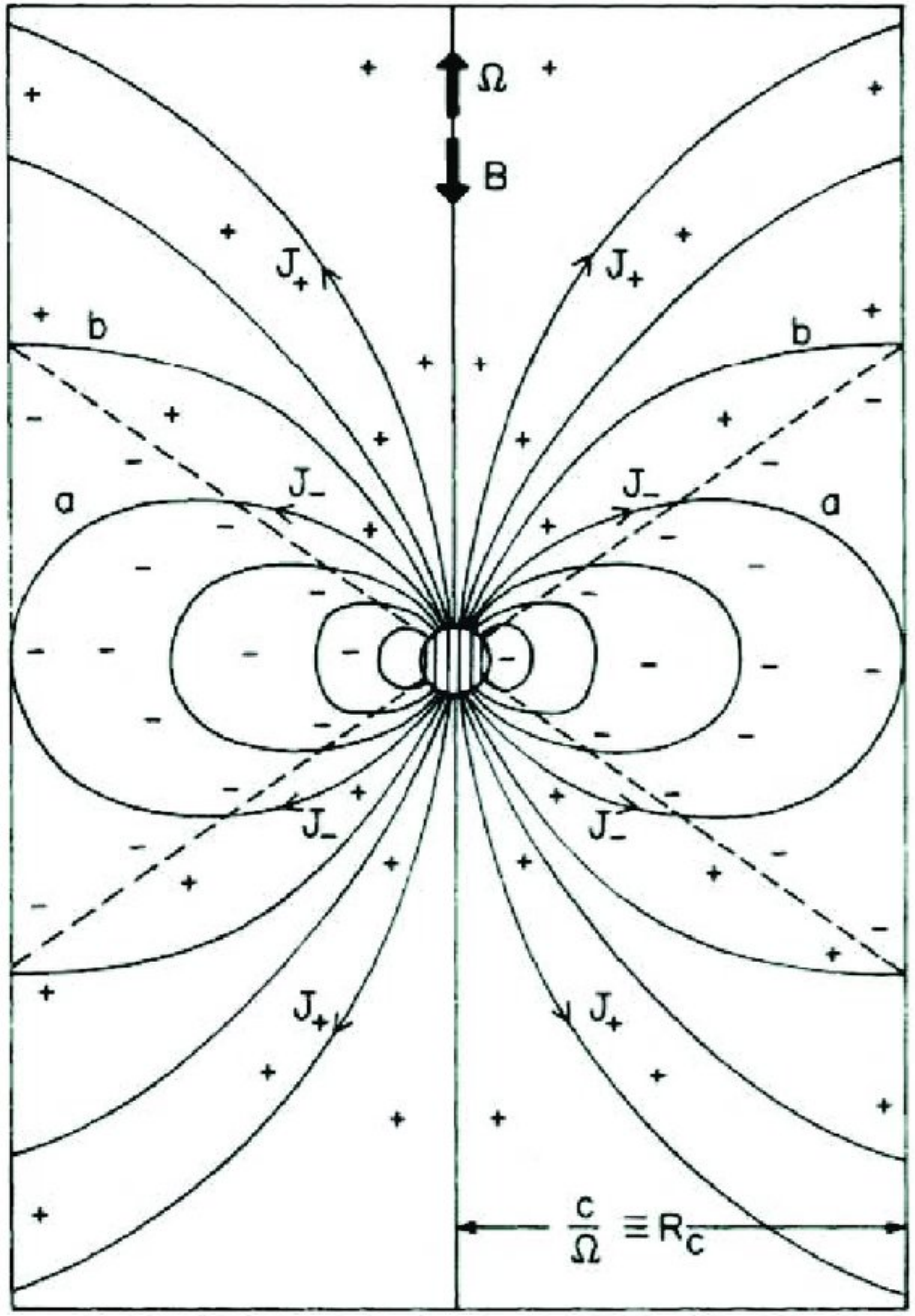
NS **B** field described in the magnetic dipole approximation:

$$\mathbf{B} = \frac{1}{r^3}\left[3(\mu\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mu\right]$$

Maxwell-Faraday law: $\mathbf{E} + \frac{\mathbf{\Omega}\times\mathbf{r}}{c}\times\mathbf{B} = 0$

Leads to the charge density In the magnetosphere:

$$\rho_{\rm GJ} = \frac{1}{4\pi}\nabla\cdot\mathbf{E} \approx -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$



Axion-photon conversion in NS magnetospheres

We might look for axion-photon conversion from an individual NS

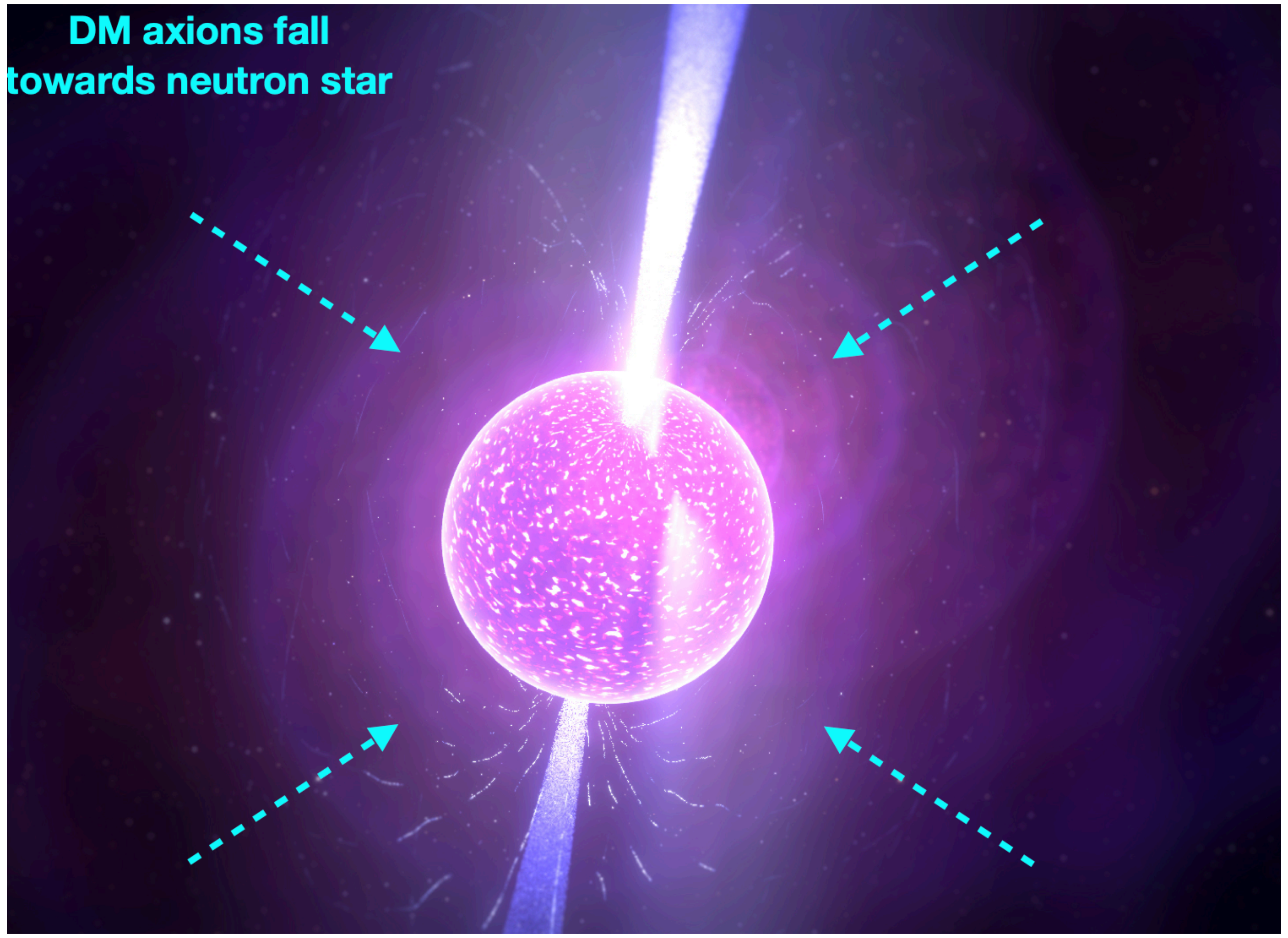
[Battye et al., 1910.11907; Leroy et al., 1912.08815]

Assume axion dark matter falling into the gravity potential of the NS.

Axion-photon conversion occurs with probability $$P_{a\to\gamma} = \frac{\pi}{2v_c^2}\left(\frac{g_{a\gamma\gamma}\,B}{\sin\theta}\right)^2 |\partial_\ell k_\gamma|^{-1}\frac{1}{\sin^2\theta}$$

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…

Axion-photon conversion in NS magnetospheres

We might look for axion-photon conversion from an individual NS

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

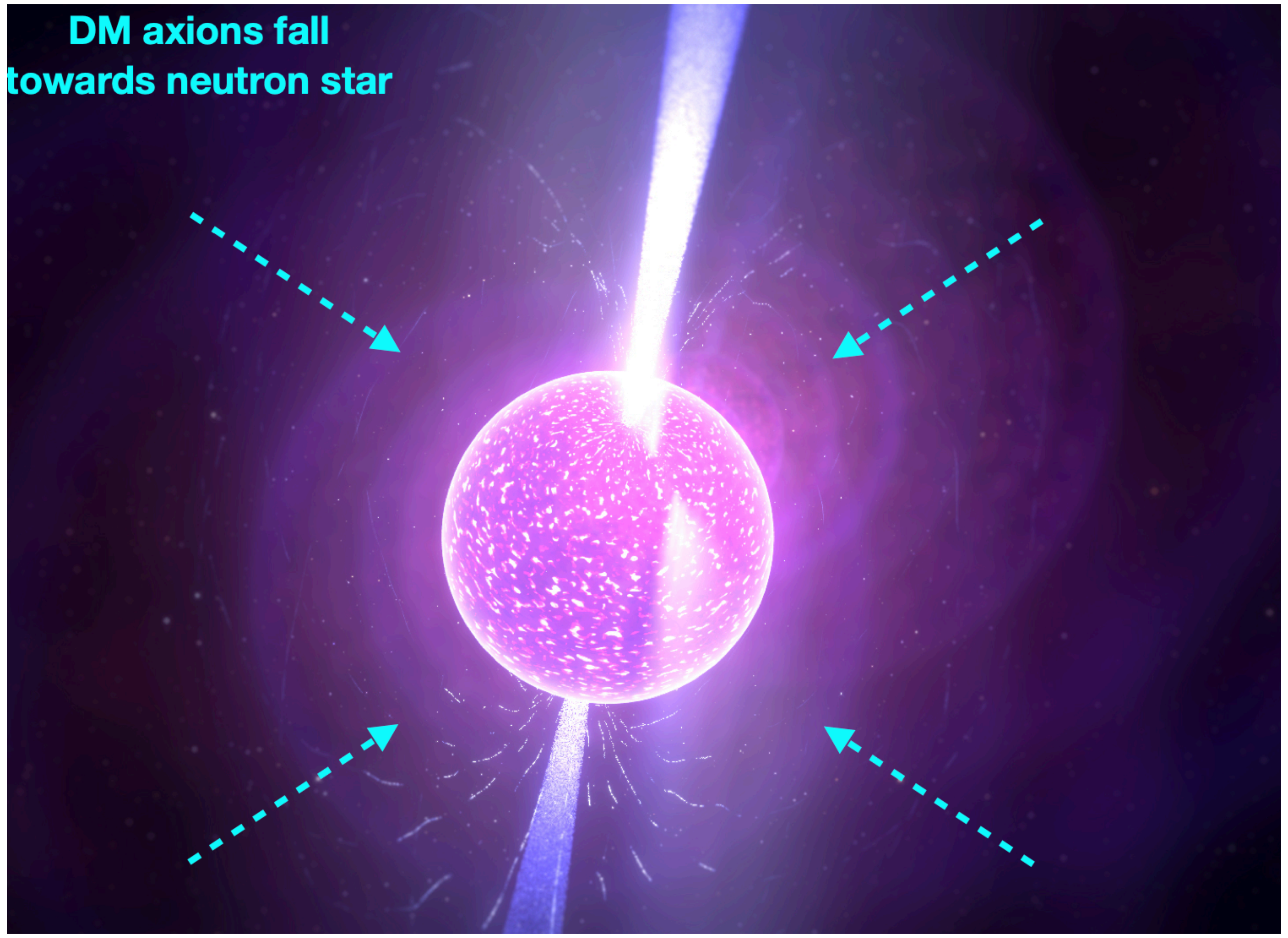
Assume axion dark matter falling into the gravity potential of the NS.

Width of the conversion shell

Axion-photon conversion occurs with probability $P_{a\to\gamma} = \frac{\pi}{2v_c^2}\left(\frac{g_{a\gamma\gamma}\,B}{\sin\theta}\right)^2 |\partial_\ell k_\gamma|^{-1}\frac{1}{\sin^2\theta}$

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…

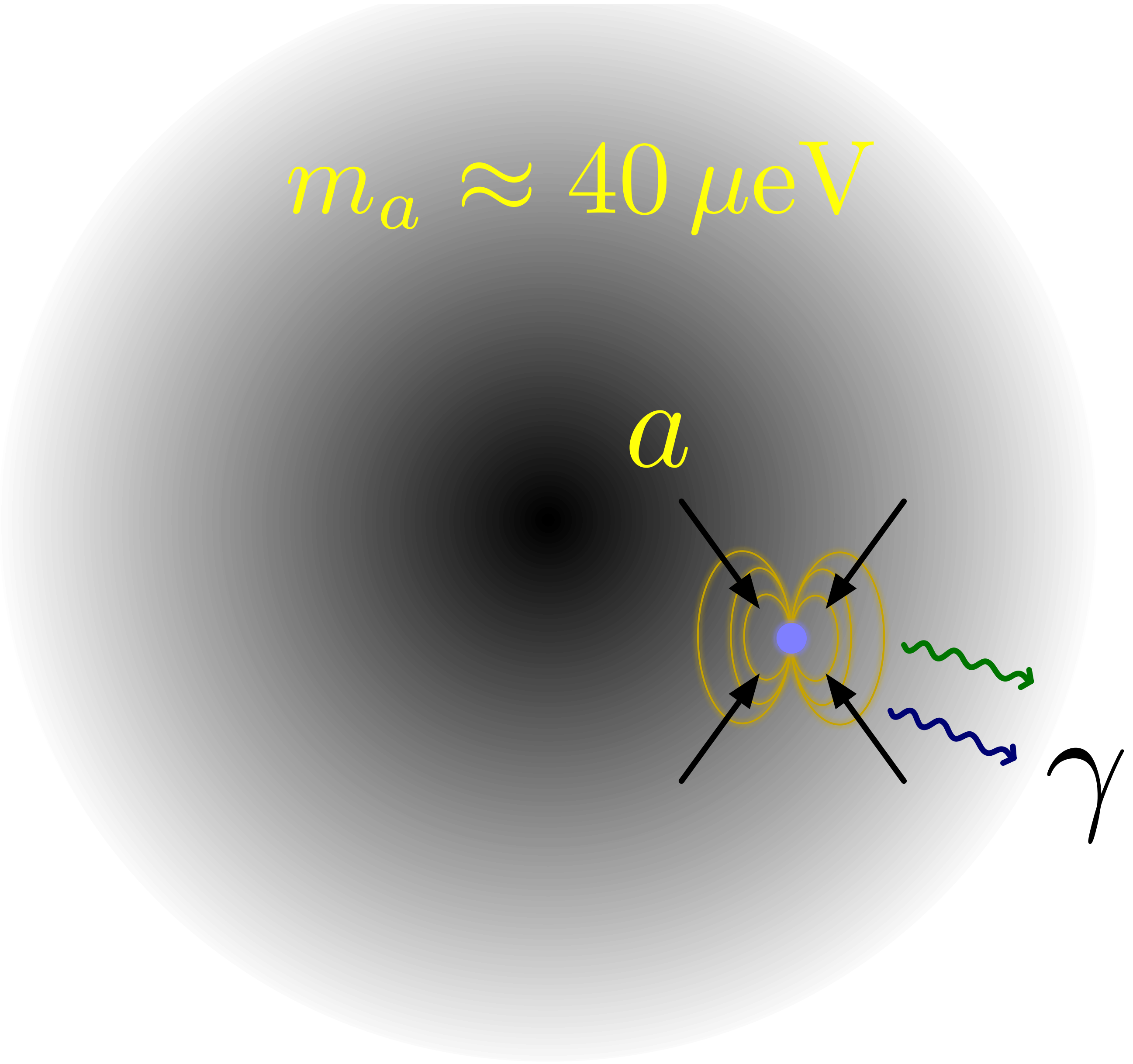
Luca Visinelli

Axion-photon conversion in NS magnetospheres

Question: Can we exploit the environment within axion miniclusters?

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

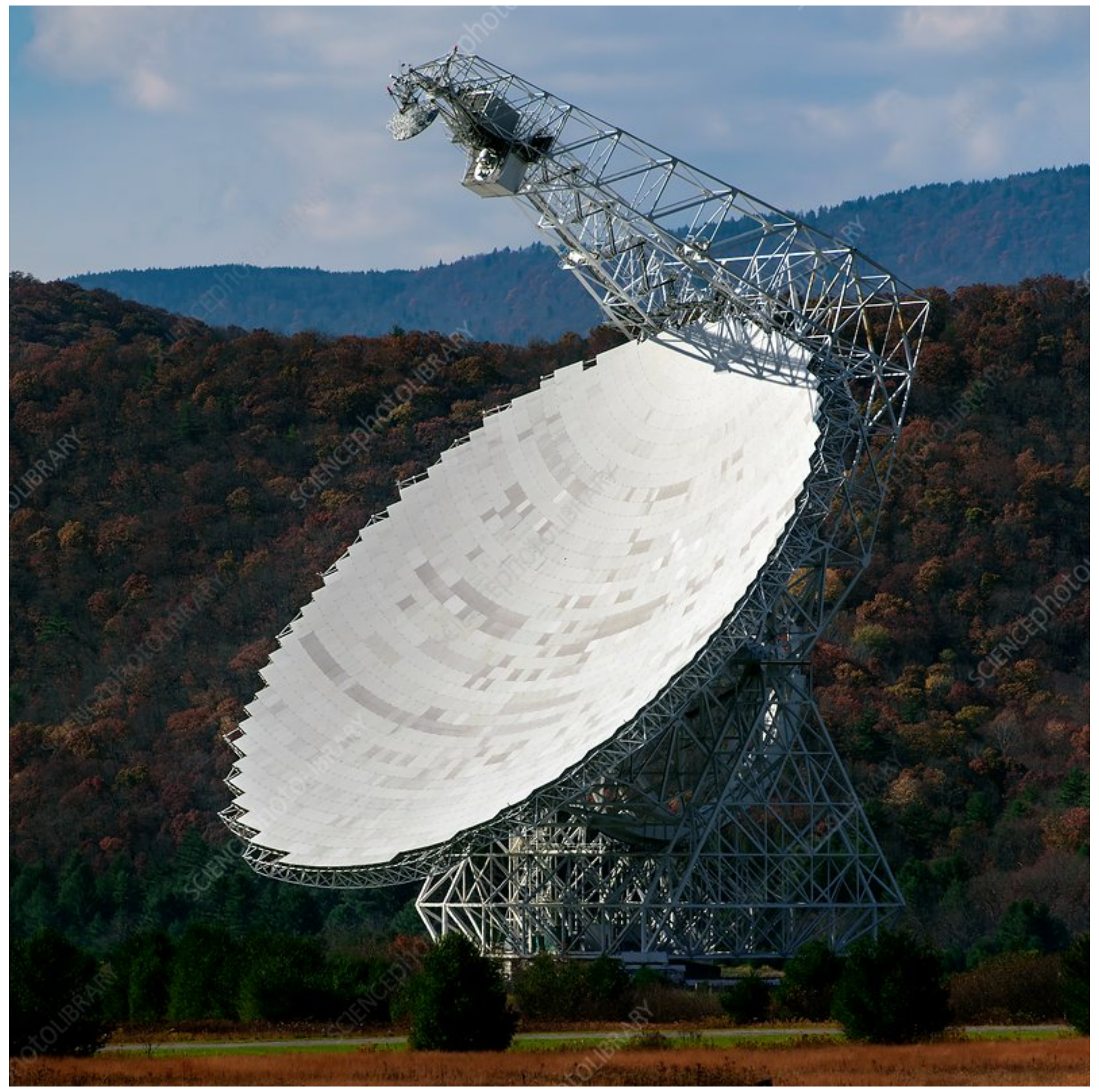
Transient enhancements to ρ_c from AMC encounters Edwards+ (with **LV**), PRL 2021 2011.05378



Frequency of emitted photon in the GHz:

$$f_\gamma = 9.7\,\mathrm{GHz}\,\frac{m_a}{40\,\mu\mathrm{eV}}$$

can be picked up at Earth
by radio telescopes

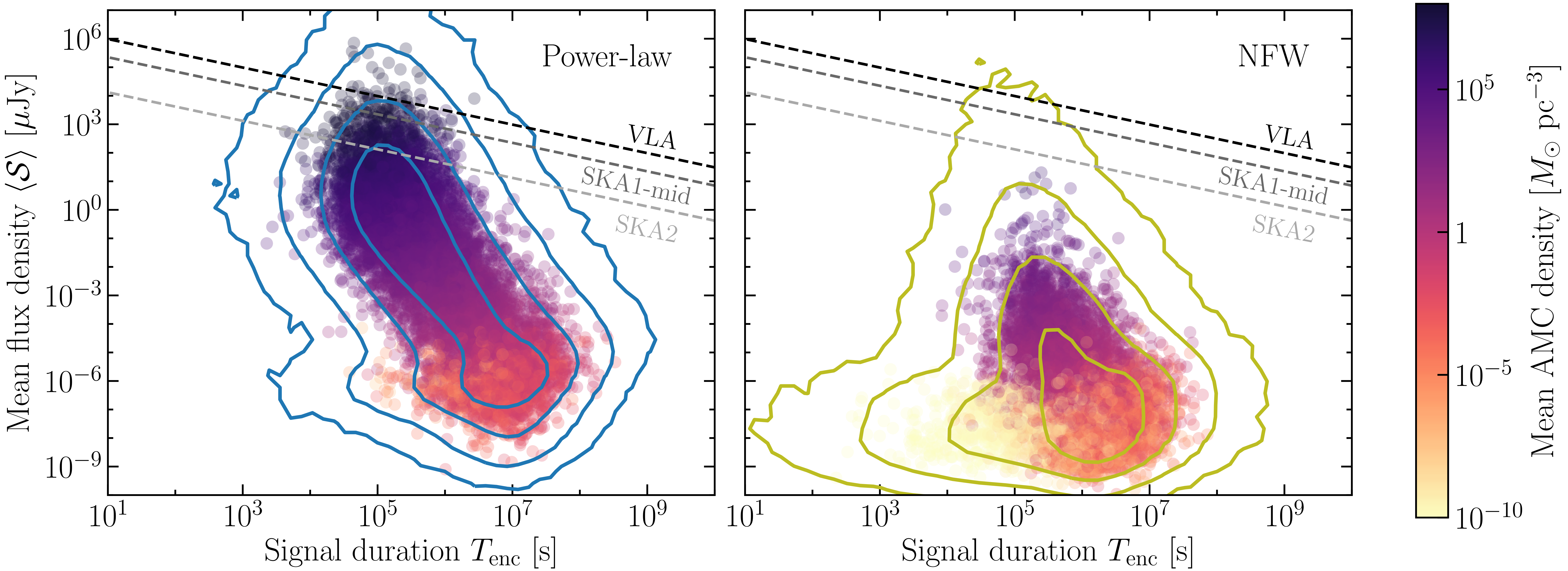


Axion-photon conversion in NS magnetospheres

Based on velocity dispersion of AMC, expect an *incredibly narrow line.*

The mean flux density (relevant for radio searches) is: $\mathcal{S} = \frac{1}{\mathrm{BW}} \frac{1}{4\pi s^2} \frac{\mathrm{d}\mathcal{P}_a}{\mathrm{d}\Omega}$

Instead, fix bandwidth BW = 1 kHz (based on telescope resolution).



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

Searching for axions in M31

Can we pick up this signal in radio?

Bradley Johnson

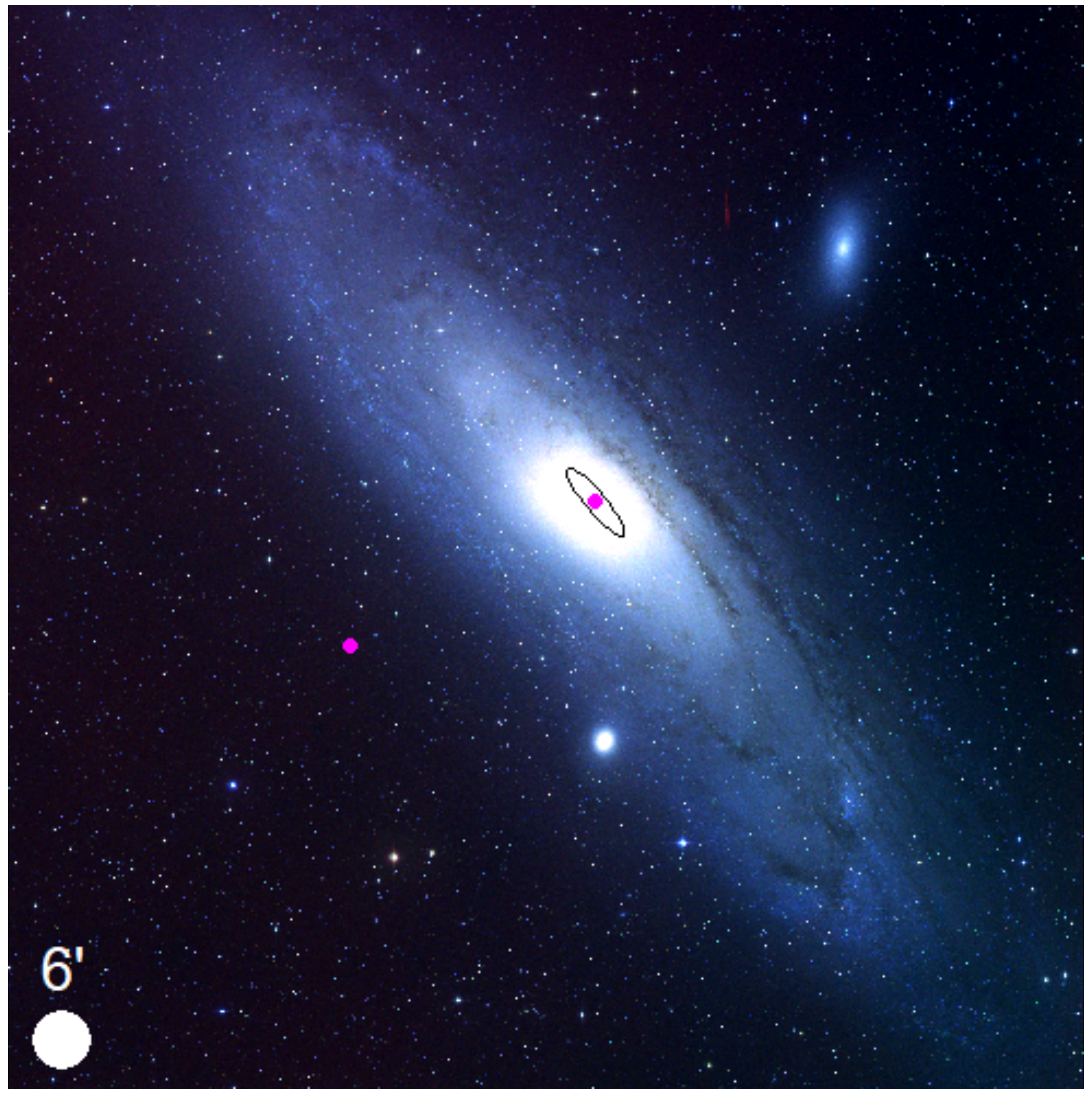
Liam Walters

Prakamya Agrawal

Jordan E. Shroyer

Madeleine Edenton

David Marsh



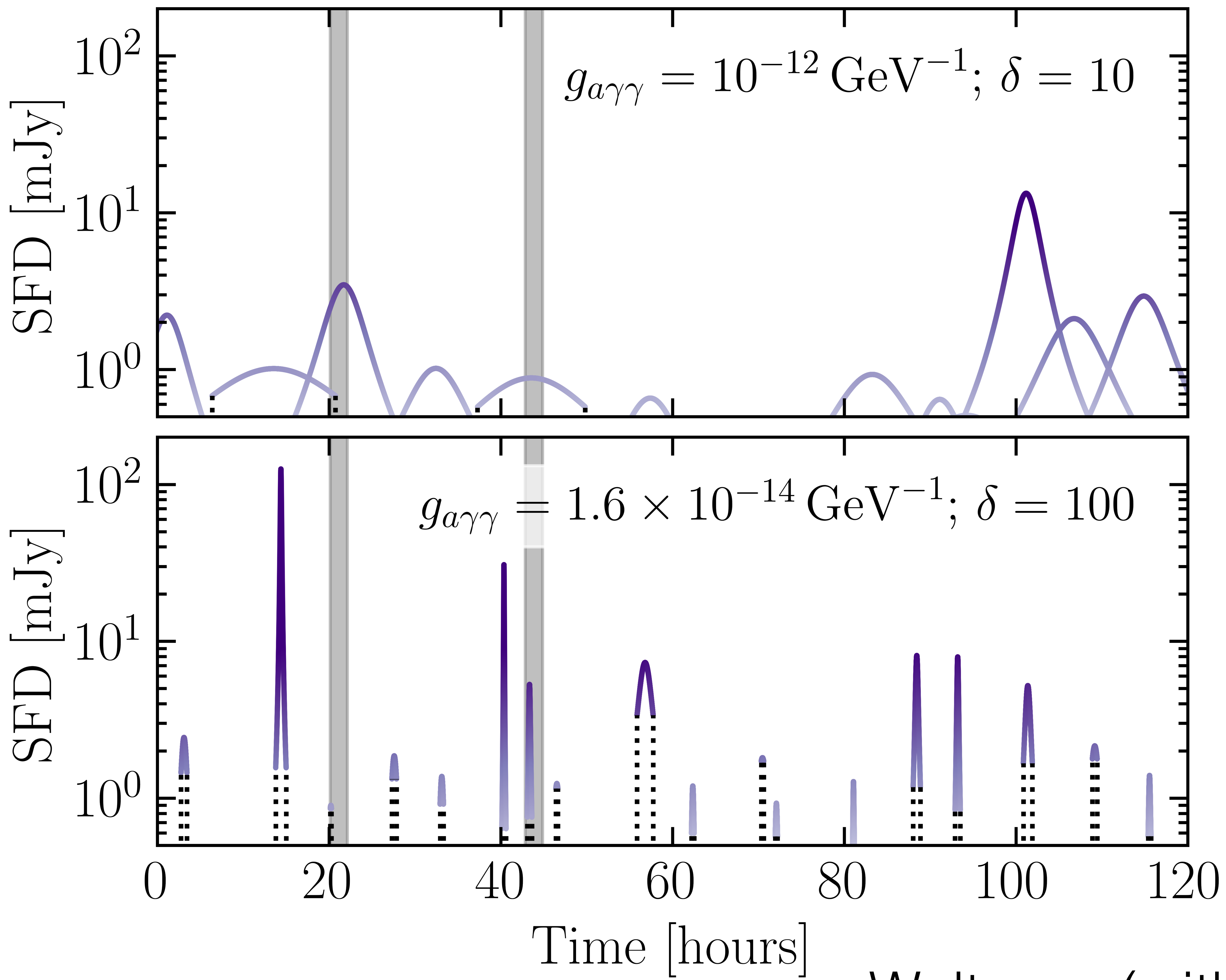
2 grant proposals accepted by the Green Bank Telescope
We have observed Andromeda
The diameters give the telescope beam size at 1.4 arcmin angular resolution

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

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

Can we pick up this signal in radio?

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



Axion mass: $m_a = 40\,\mu\mathrm{eV}$

Minicluster mass: $M_{\rm AMC} = 10^{-10}\,M_\odot$

Simulate 20 encounters with a NS of

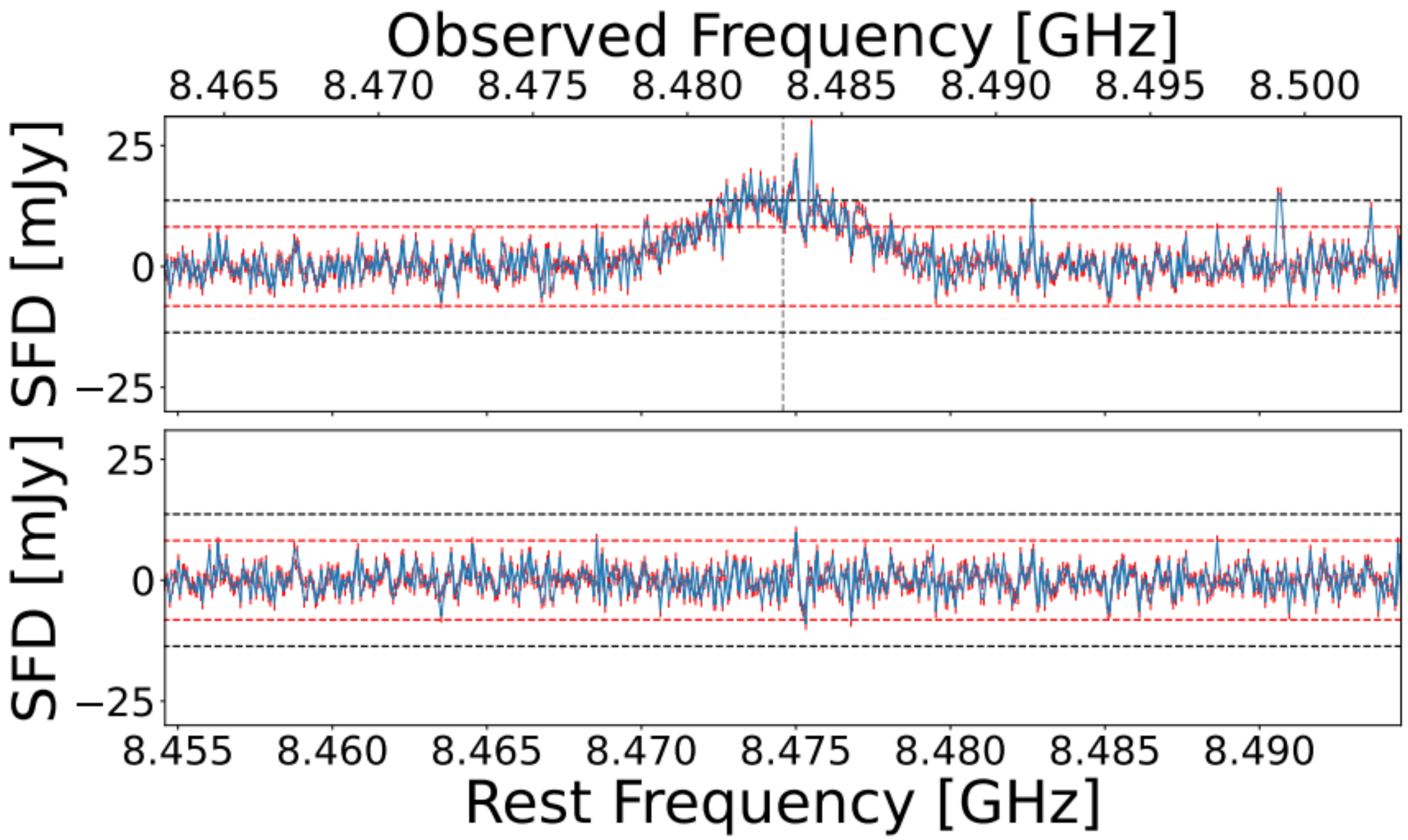
Period: $P = 1\,\mathrm{s}$ B field: $B_0 = 10^{14}\,\mathrm{G}$

Signal lasting min to hour

Walters+ (with **LV**) 2407.13060

Can we pick up this signal in radio?

How would a signal look like?

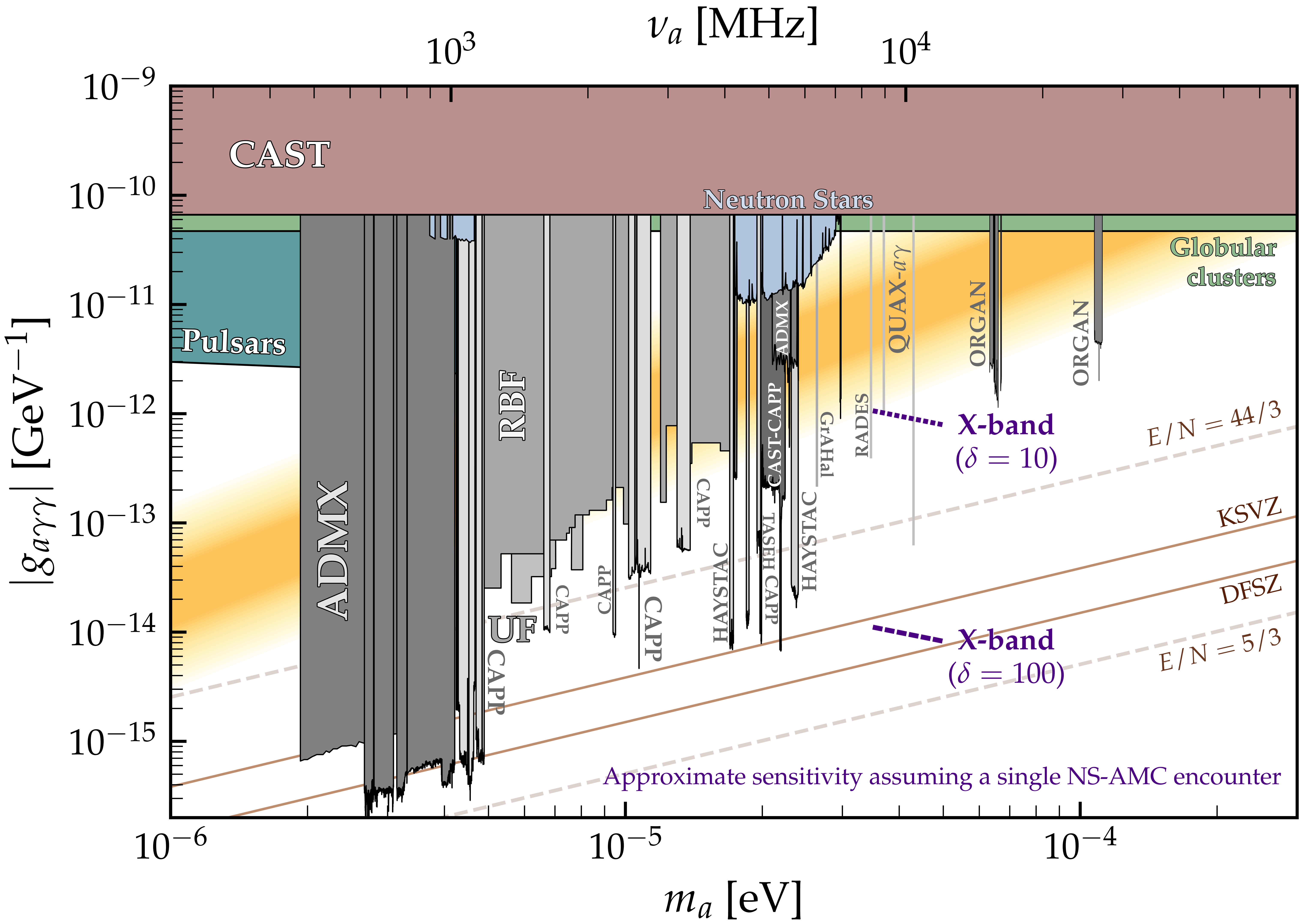


Hydrogen recombination line at 8.483 GHz when not accounting for M31 blueshift.

Possibly, an emission from a molecular cloud in the MW

Signals are filtered with an excess kurtosis test to disqualify radio interferences.
Known emission spectral lines disqualify
By comparison with Splatalogue

Results



(Dis)advantages w.r.t. lab:

Scan is much faster because all frequencies are picked up by the broad-band receiver.

However, astrophysics unknowns are severe (e.g. minicluster histories, shapes and abundances)

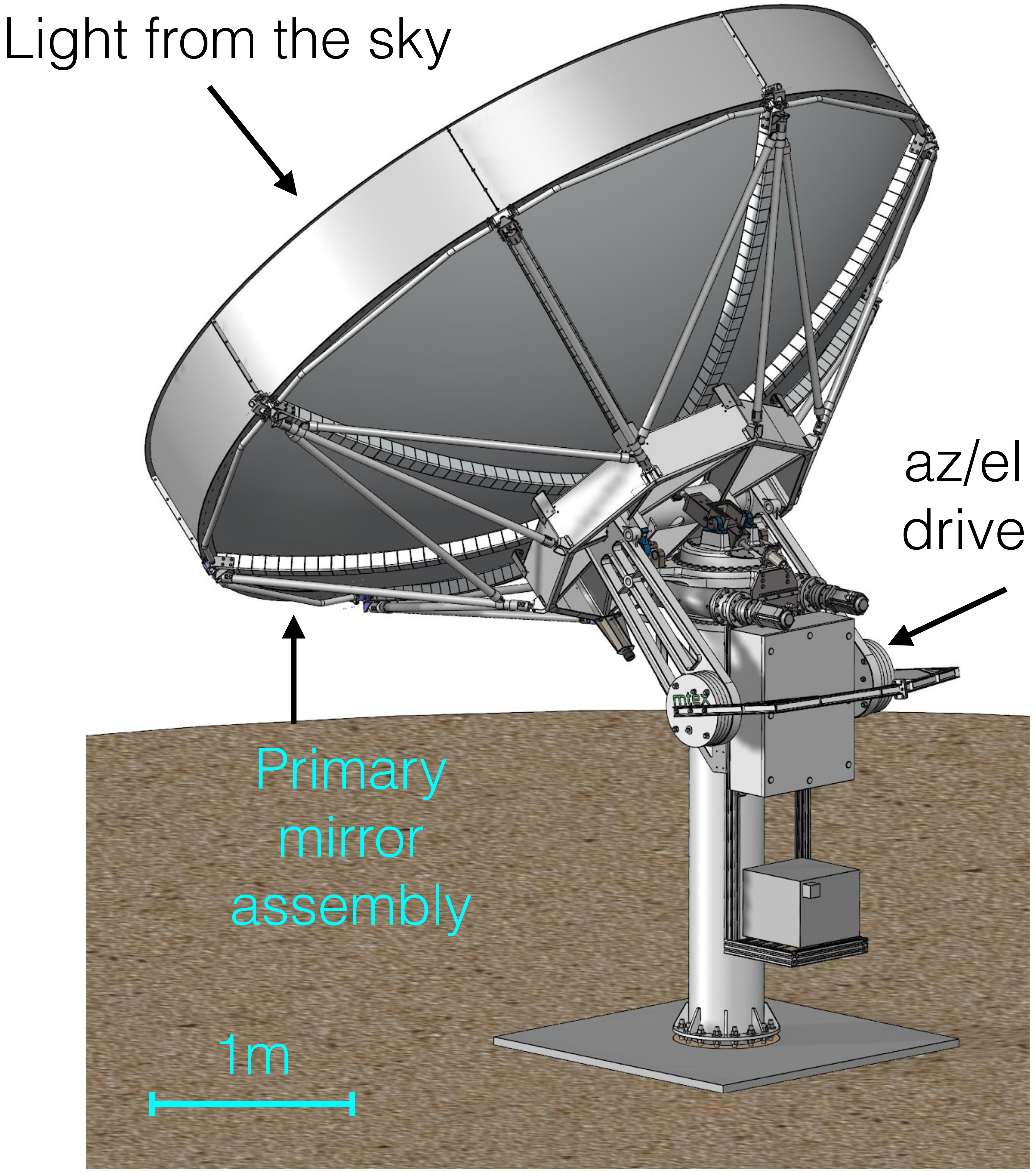
We see these as possible hints for excesses to be revealed in the lab.

Walters+ (with **LV**) 2407.13060

Future and ongoing progresses

Luca Visinelli

- Ongoing analysis of the 2023 data in C-band
- The UV group has secured funds via Jefferson Trust, to build a telescope operating at < 2GHz
- Ongoing evaluation for a radio telescope named **ASTRA** (Axion Search via Telescope for Radio Astronomy), to explore the axion mass range [40, 180] micro-eV

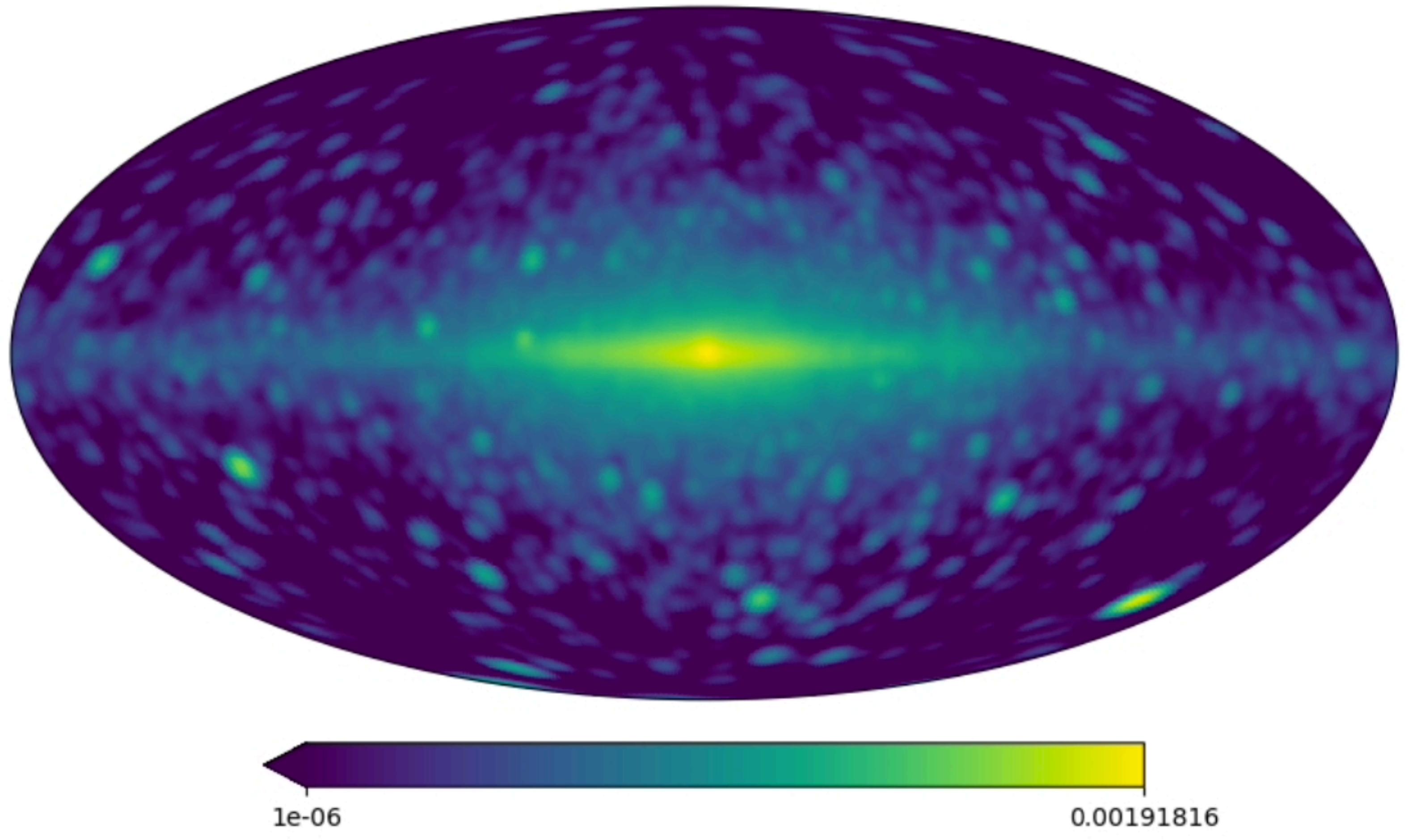


Future and ongoing progresses

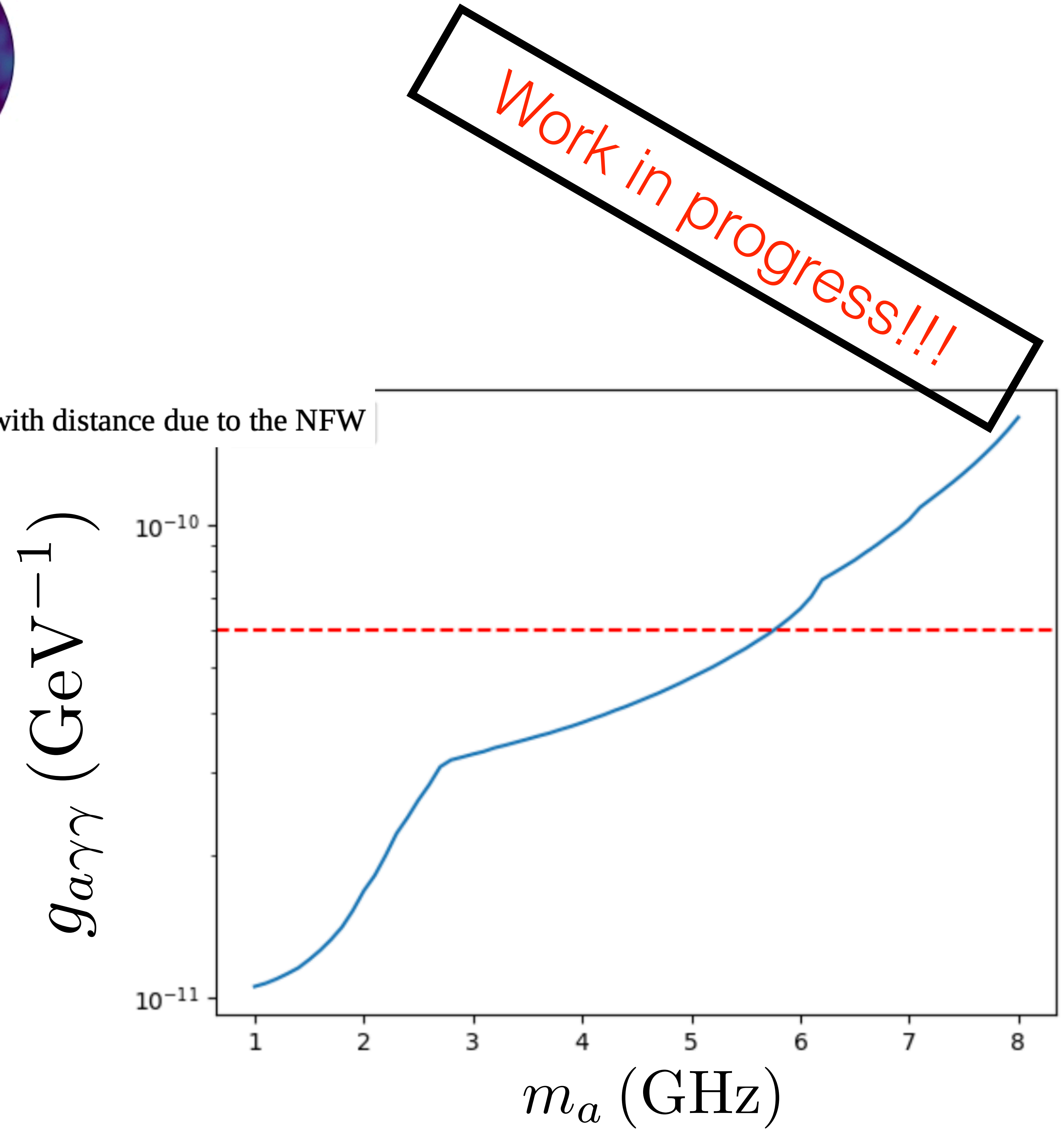
Utkarsh Bhura

David Marsh

Fan Mountain observes the sky at a range of frequencies from 1 to 8 GHz. Using the PsrPopPy population model the sky map at 1 GHz would appear as follows:

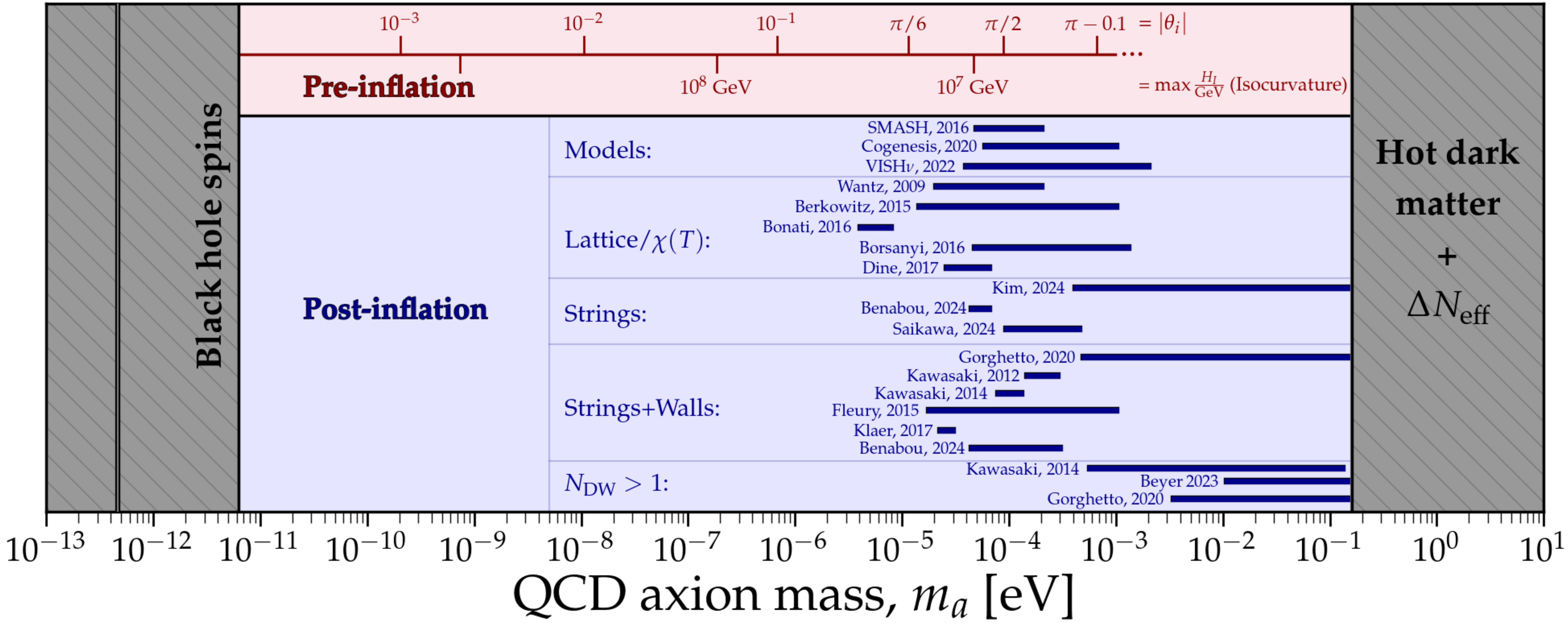


The peak at centre is due to the dark matter density, which falls down with distance due to the NFW



Direct detection of the axion at INFN Frascati National Labs

Predictions for the DM mass of the QCD axion



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

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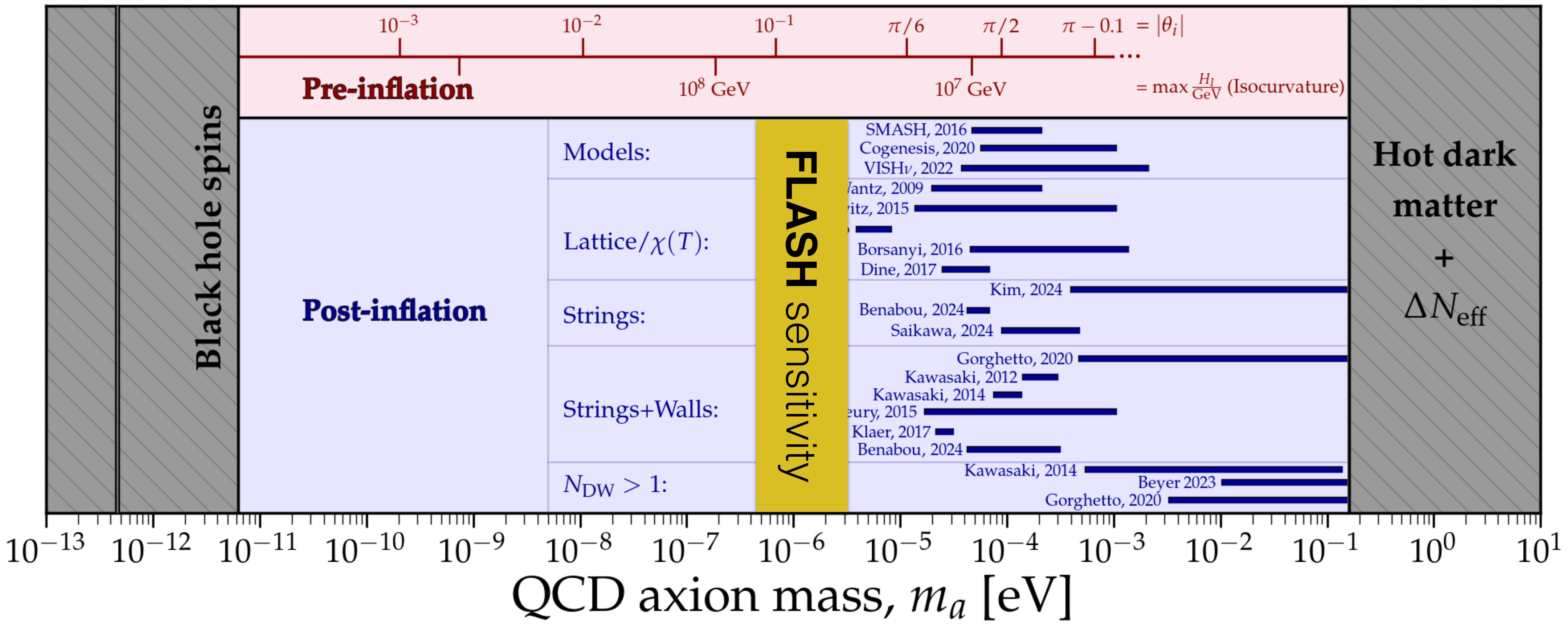

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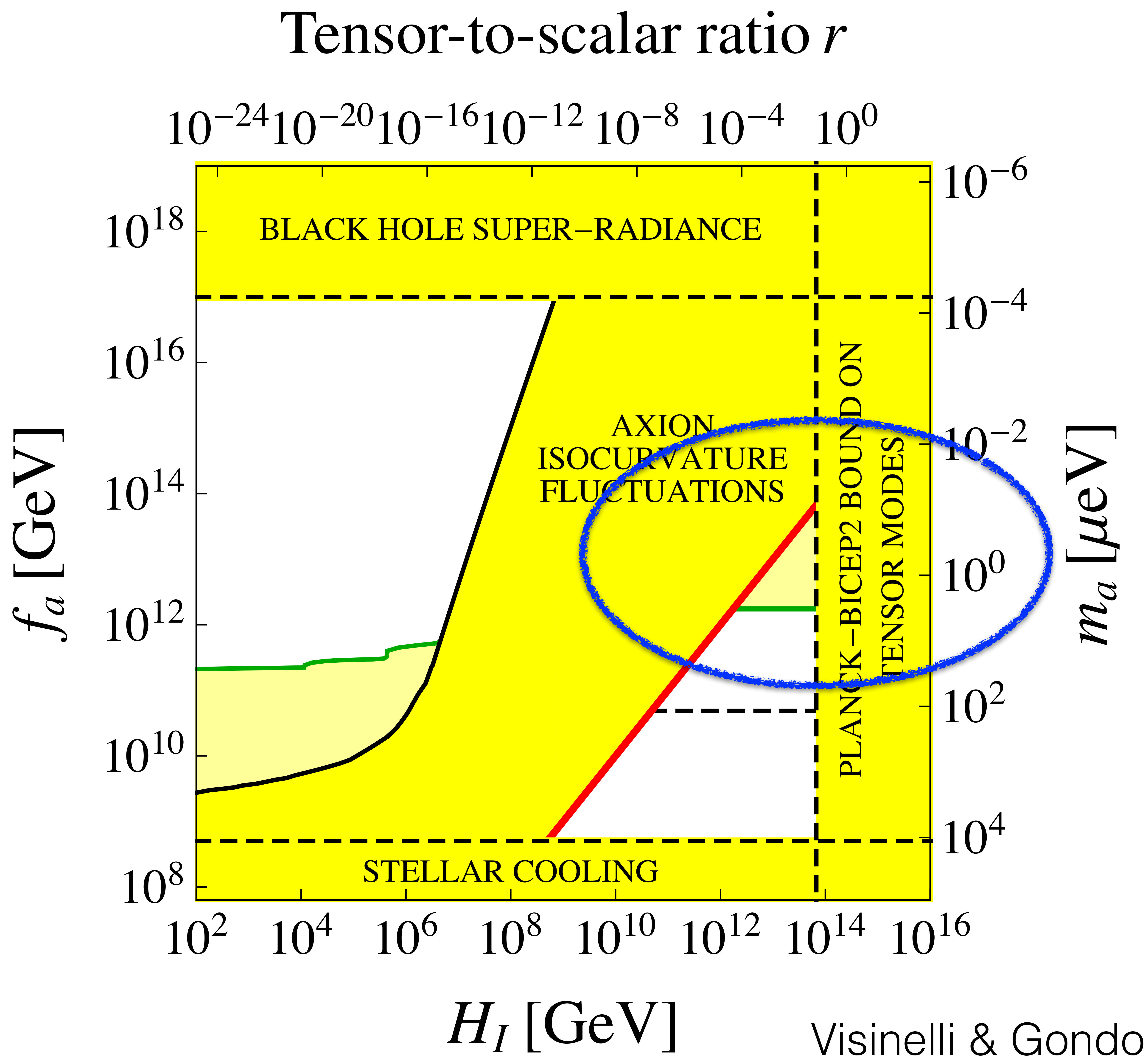
Predictions for the DM mass of the QCD axion

Luca Visinelli



Visinelli & Gondolo 0912.0015

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

See the talk of G. Gelmini

Power transfer from axion DM to the cavity

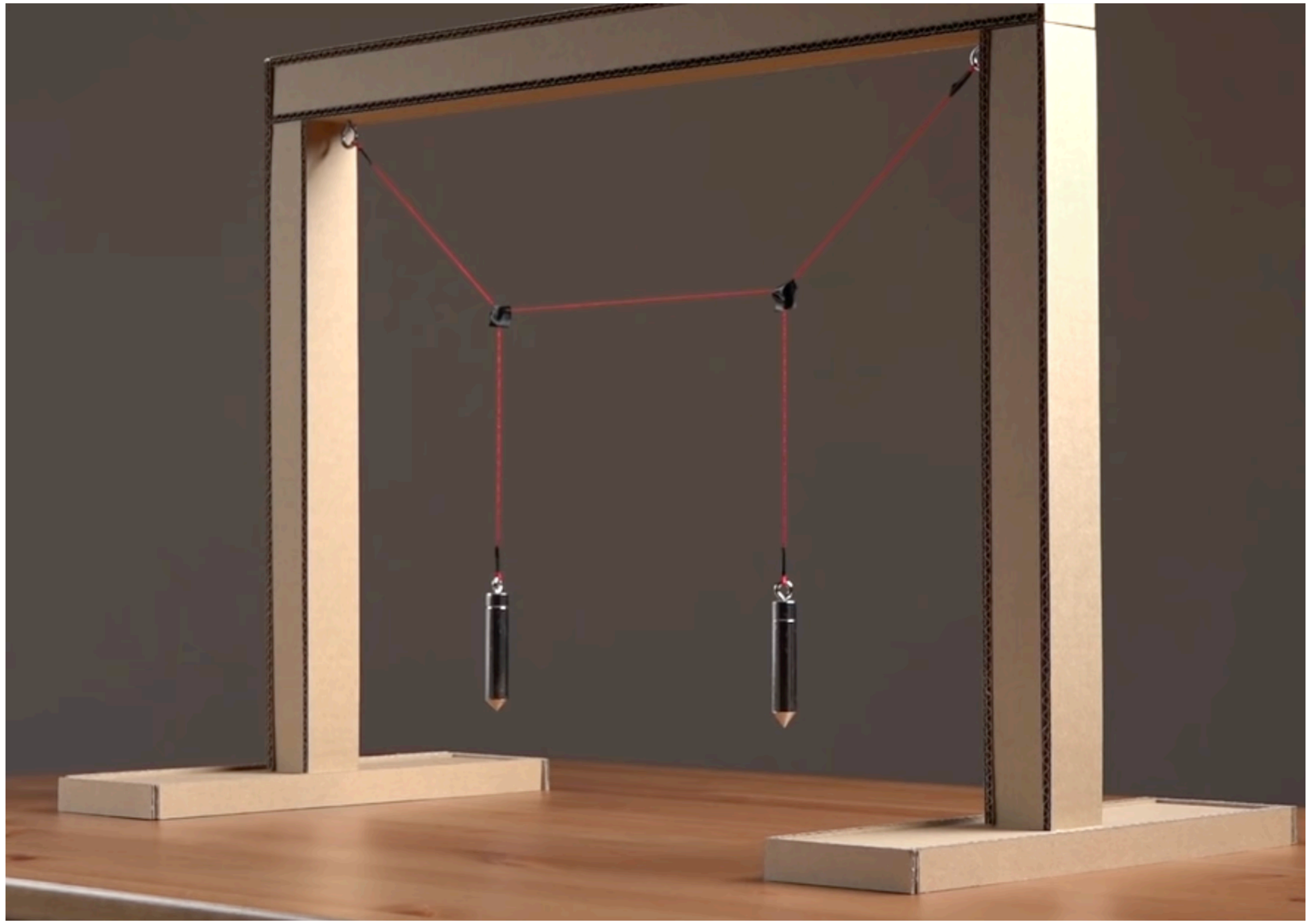
<u>Weak coupling</u>
Takes many swings to fully transfer the wave amplitude.

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

Narrowband cavity response → iterative scan through frequency space.

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

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



See the talk of R. Maruyama for more

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

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

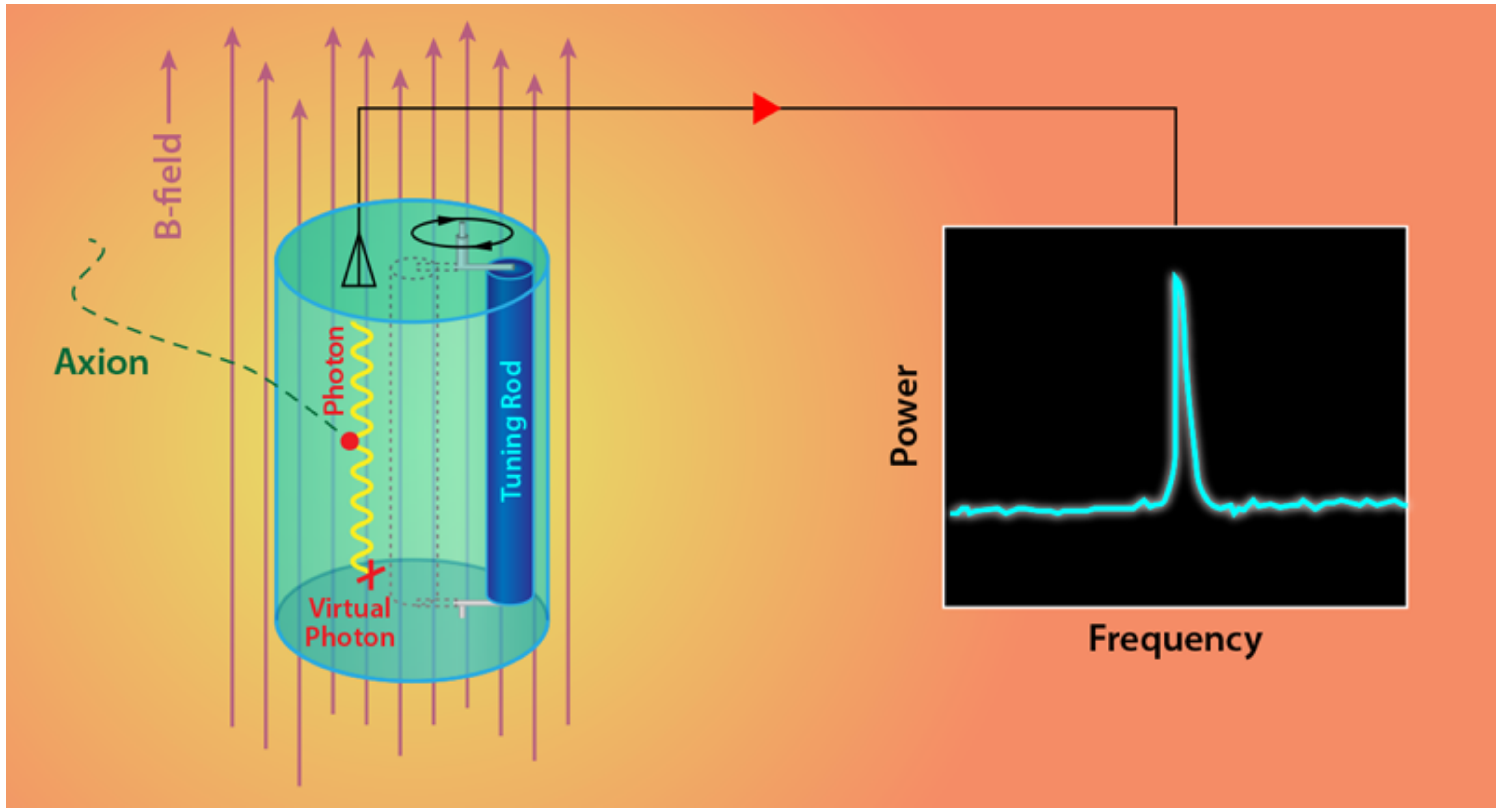
$$\boxed{P_{\rm sig} = (g_{a\gamma\gamma}^2 n_a) \times \left(Q_L B_0^2 V C_{nml}\right)}$$

Q_L Quality factor

V Cavity volume

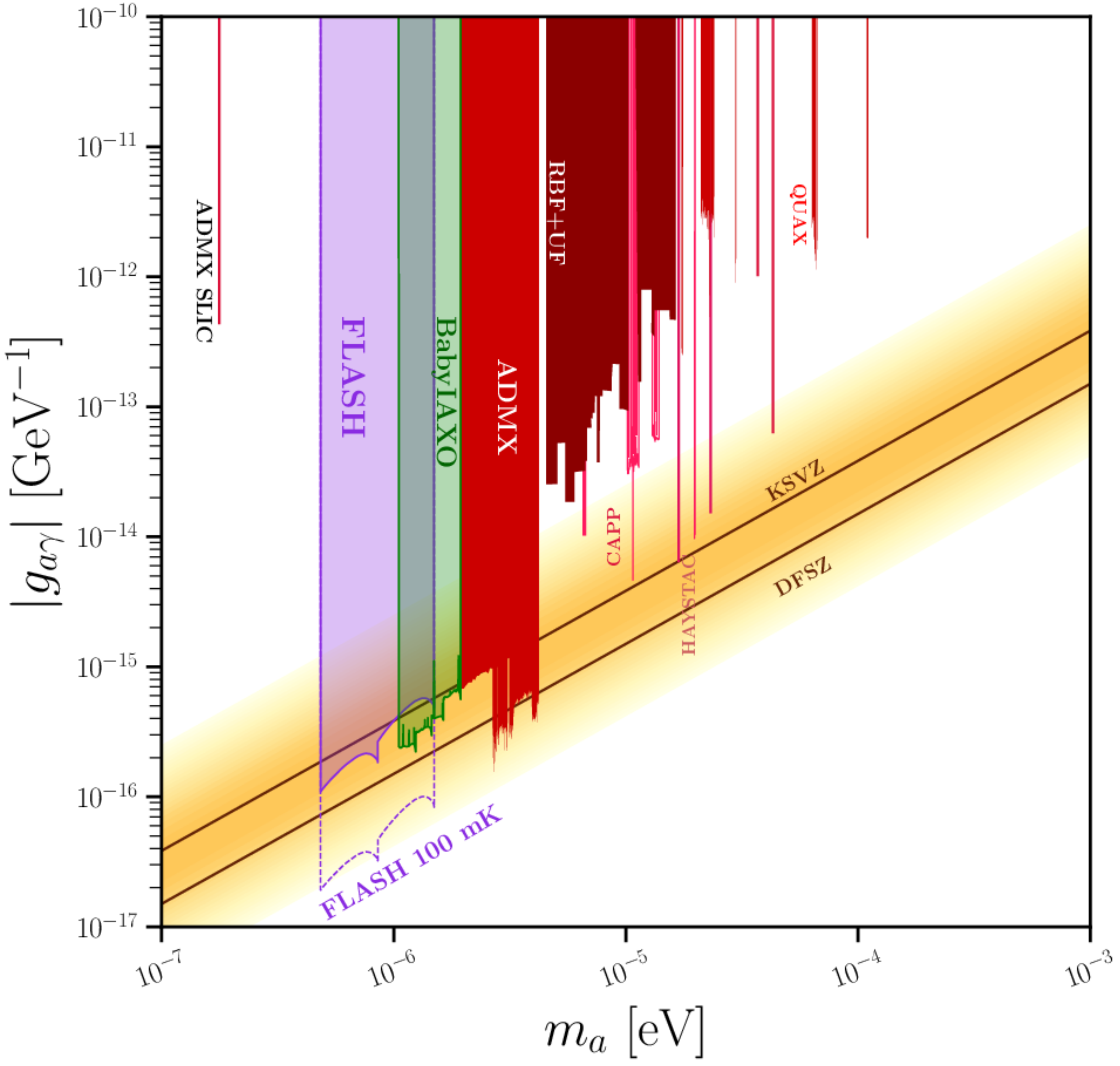
B_0 Magnetic field

C_{nml} Geometric factor



Courtesy of ADMX collaboration

Cavity search at INFN Frascati National Labs



FLASH cavity search with

Claudio Gatti's group (INFN-LNF)

Alesini+ 2309.00351, with **LV**

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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 CADEx, PAS

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!