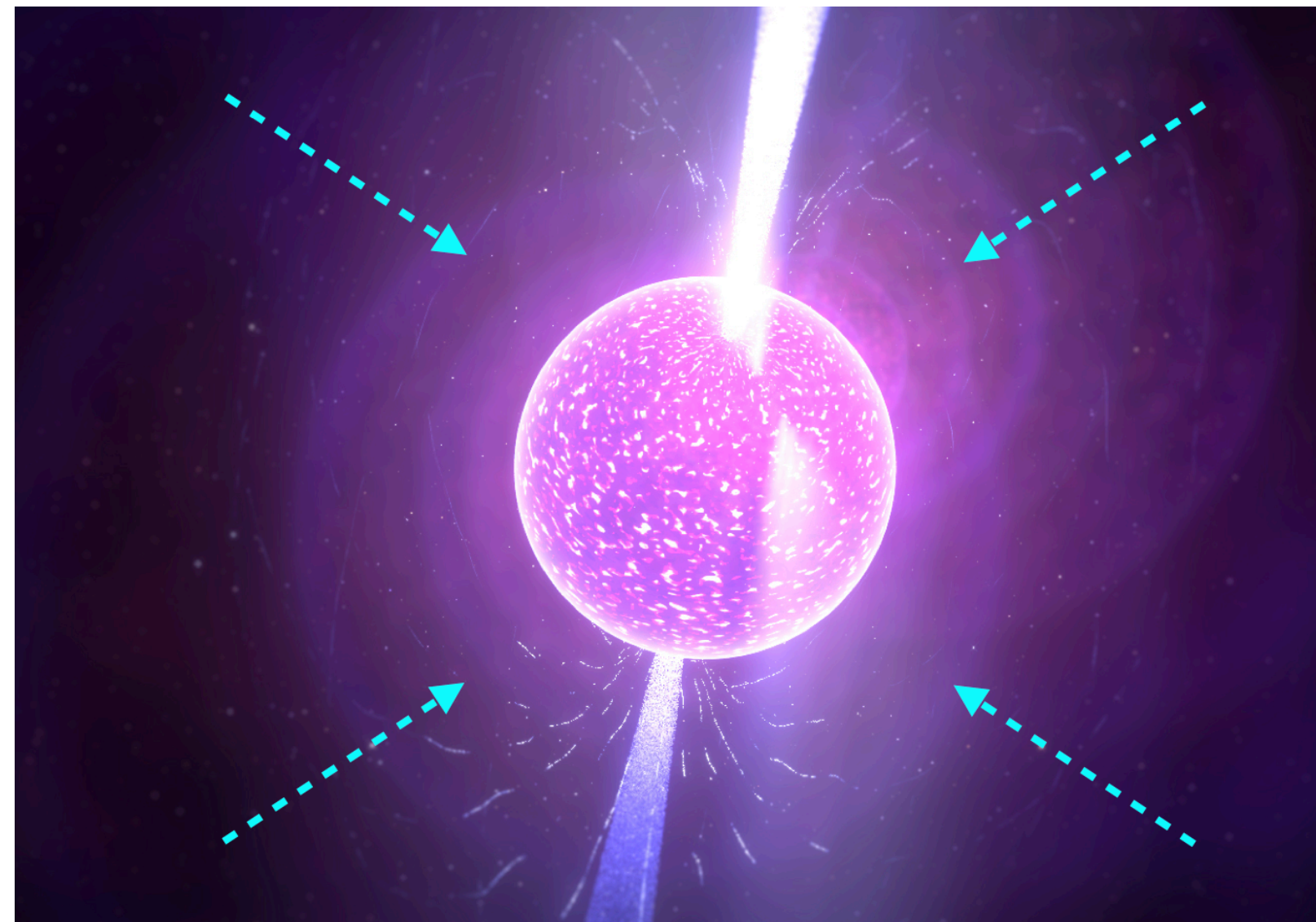


Detecting light bosons and gravitational waves



Luca Visinelli

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November 13, 2025



Ivisinelli@unisa.it

- 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:

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{\alpha_s}{8\pi} \frac{\phi}{f_a} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$$

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](#)]

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

The QCD Axion: foundations

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

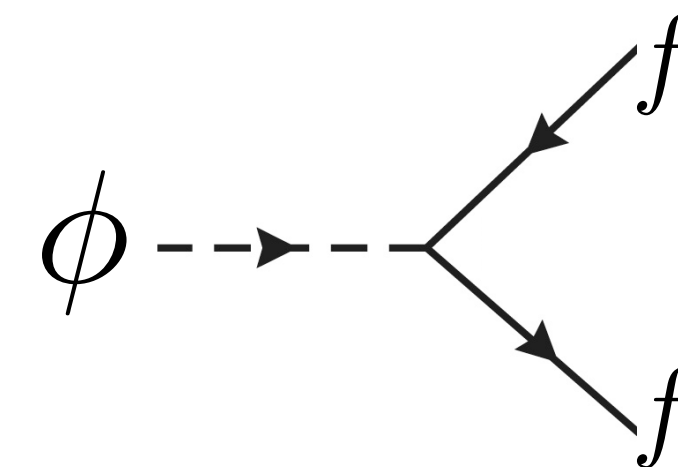
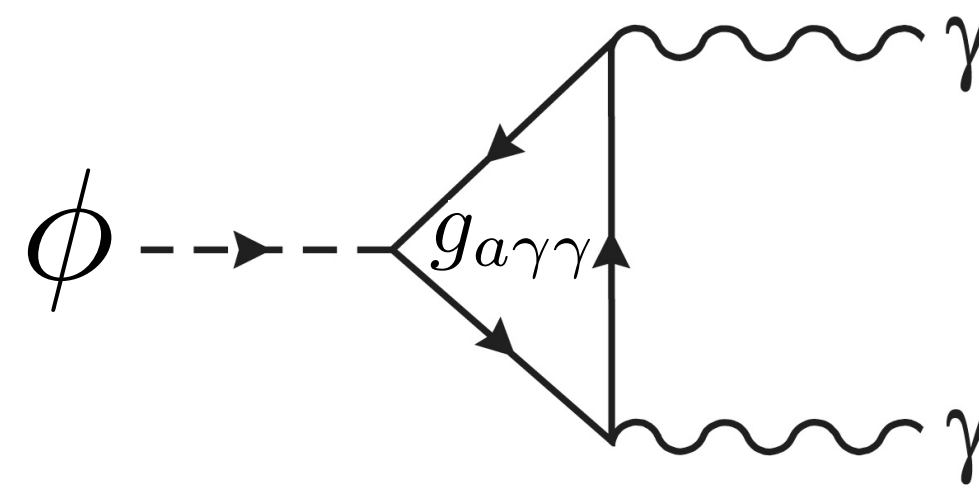
$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \frac{1}{4} g_{a\gamma\gamma} \phi \tilde{F}_{\mu\nu} F^{\mu\nu} + c_e \frac{\partial_\mu \phi}{2f_a} \bar{e} \gamma^\mu \gamma_5 e + c_N \frac{\partial_\mu \phi}{2f_a} \bar{N} \gamma^\mu \gamma_5 N$$

Self-interacting
potential

Axion-photon
coupling

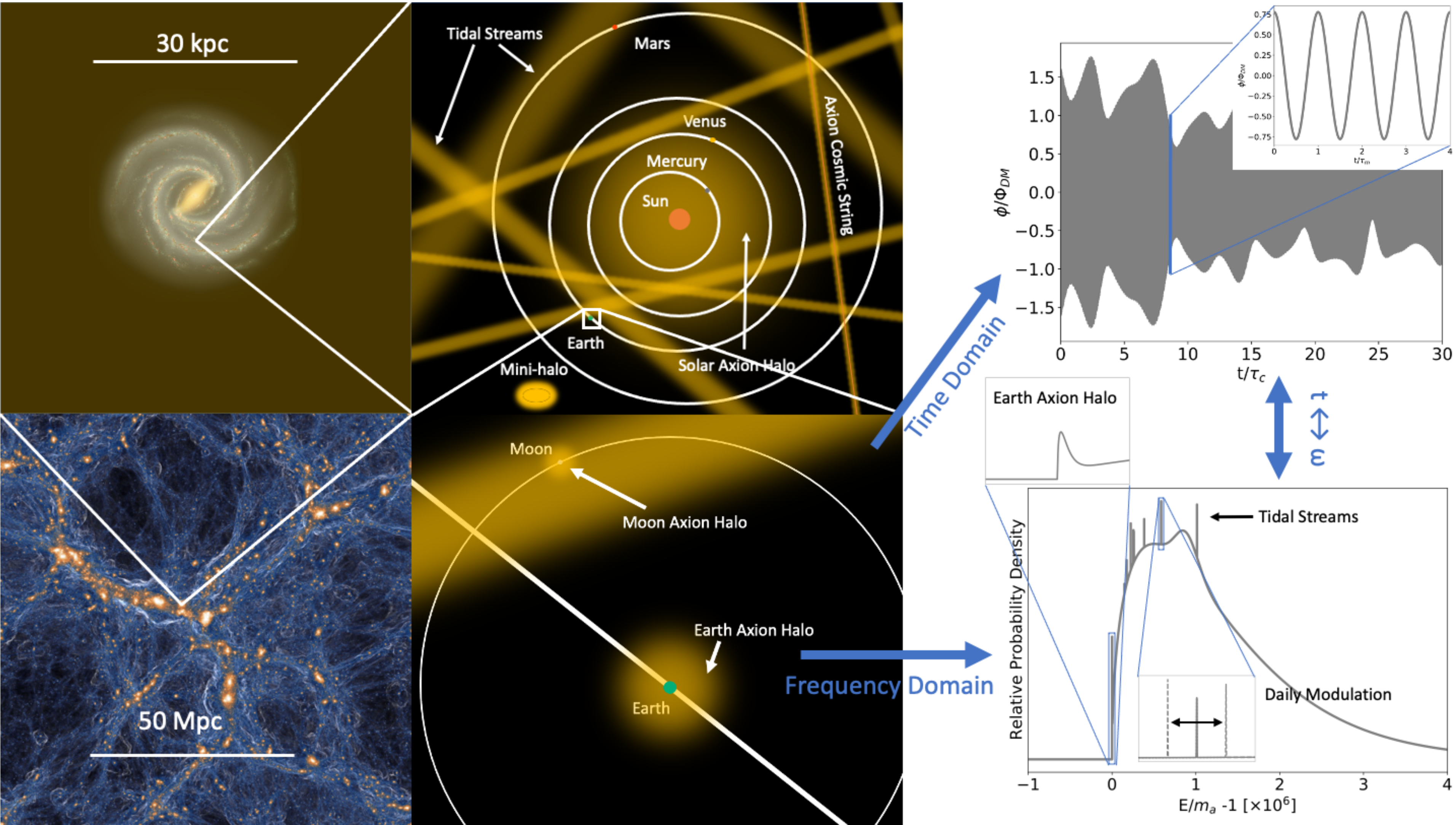
Axion-electron
coupling

Axion-nucleon
coupling



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

Axion Miniclusters in the Milky Way



Axion miniclusters

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

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

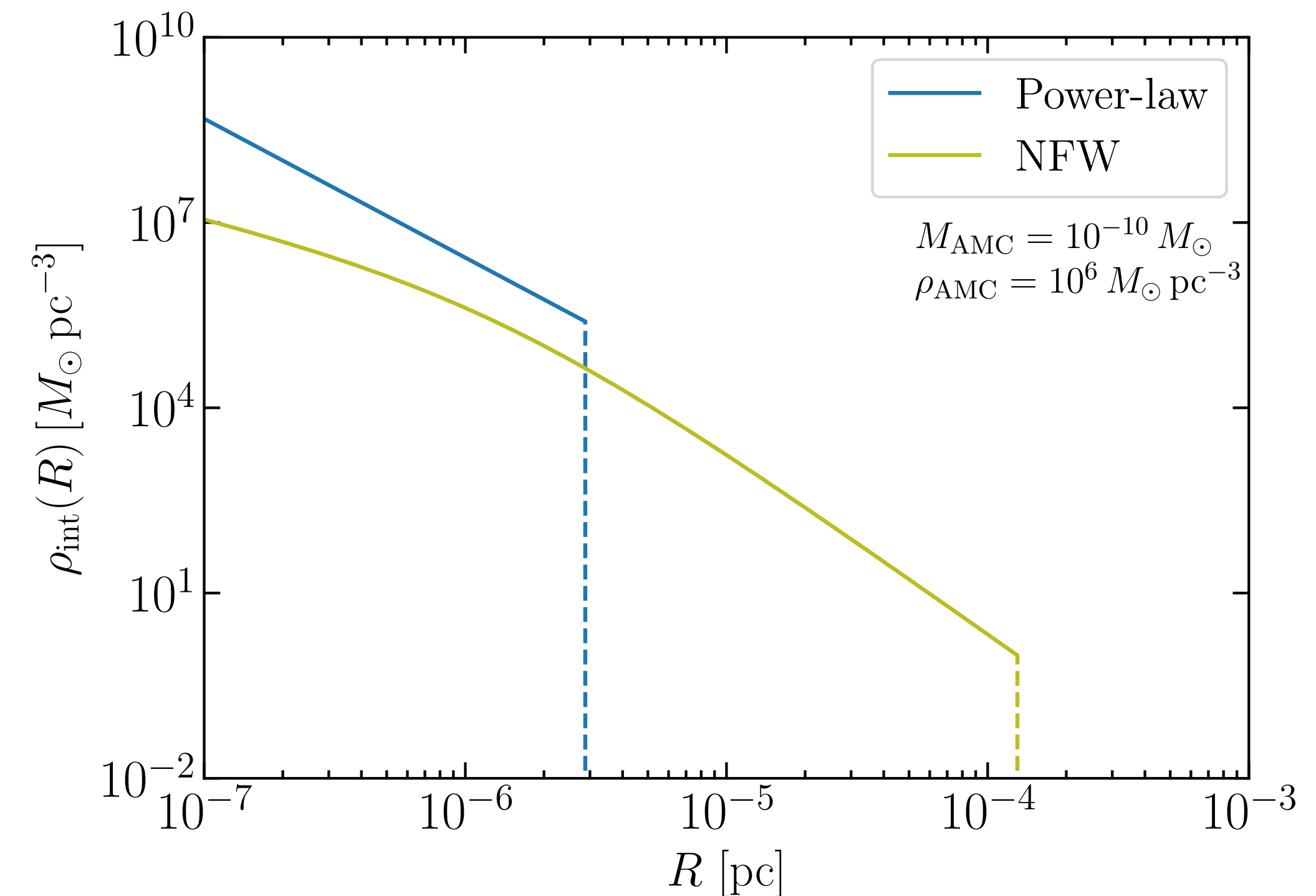
Typical minicluster mass:

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

[Hogan & Rees 1988; Kolb & Tkachev 1994]

Density profile from collapse: $\rho_{\text{mc}}(r) \propto r^{-9/4}$

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



Axion miniclusters abundance today

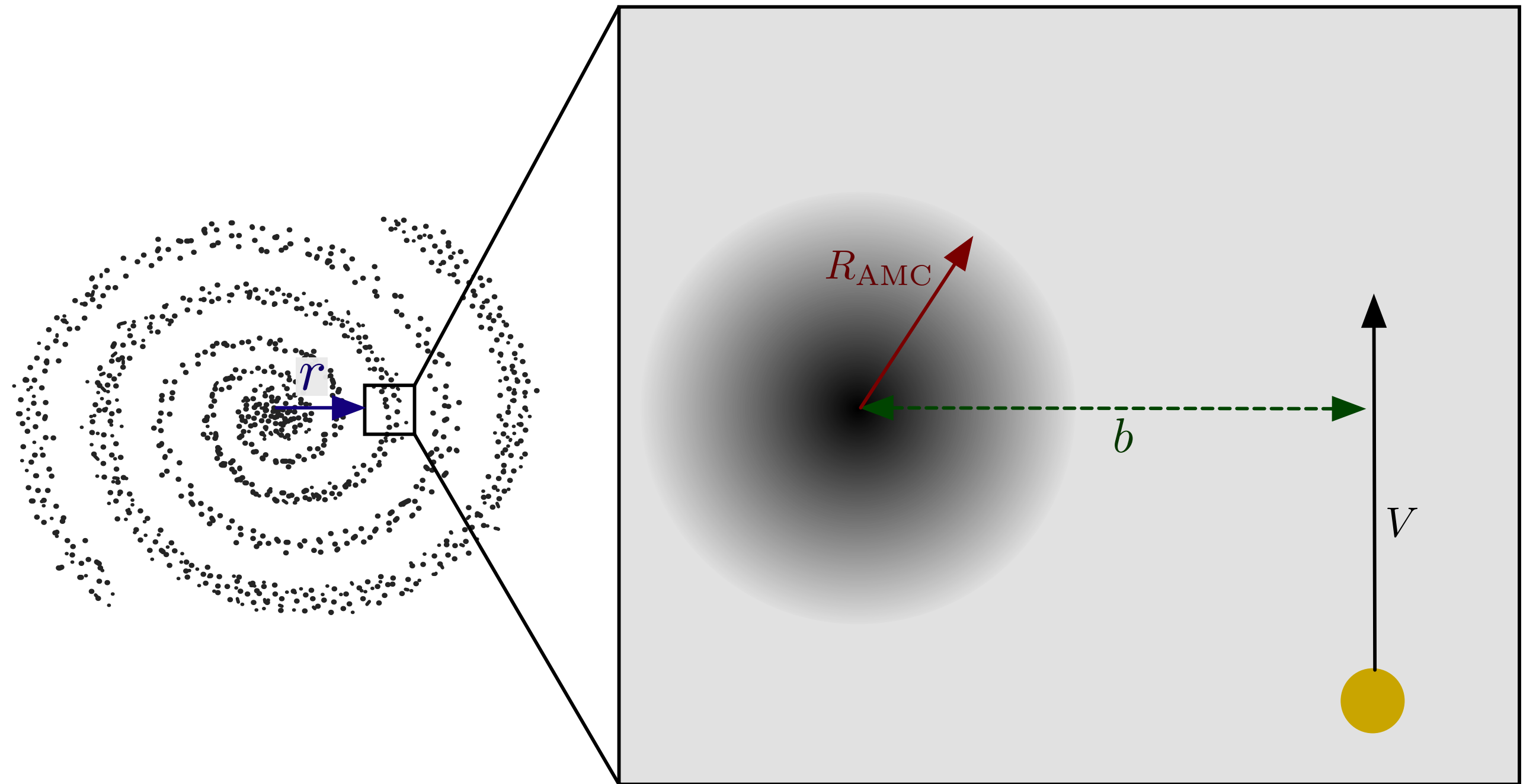
The abundance of miniclusters in galaxies is assessed via Monte Carlo simulations of tidal stripping



Bradley Kavanagh



Thomas Edwards



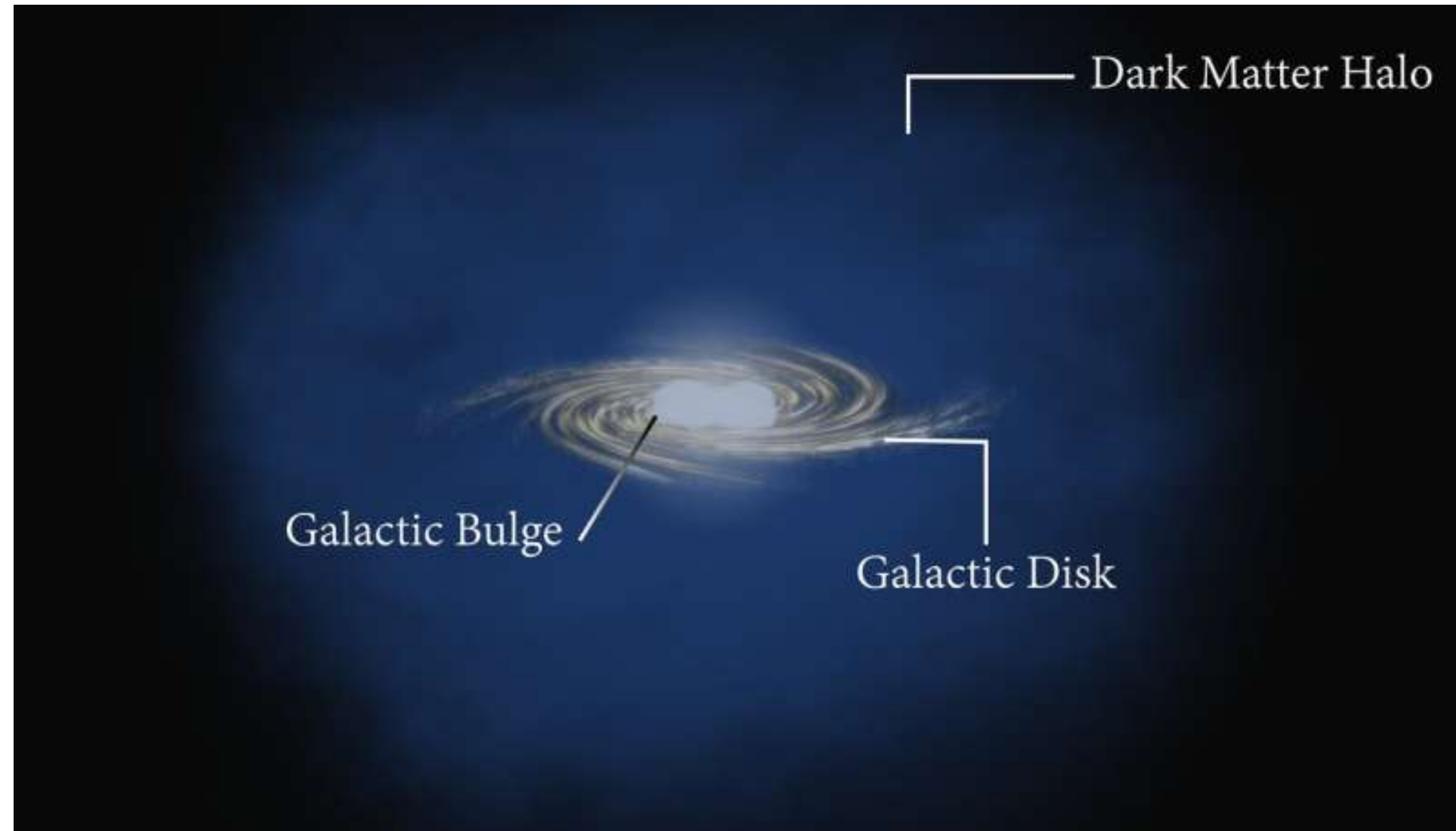
Kavanagh+ (with **LV**) [2011.05377](#)



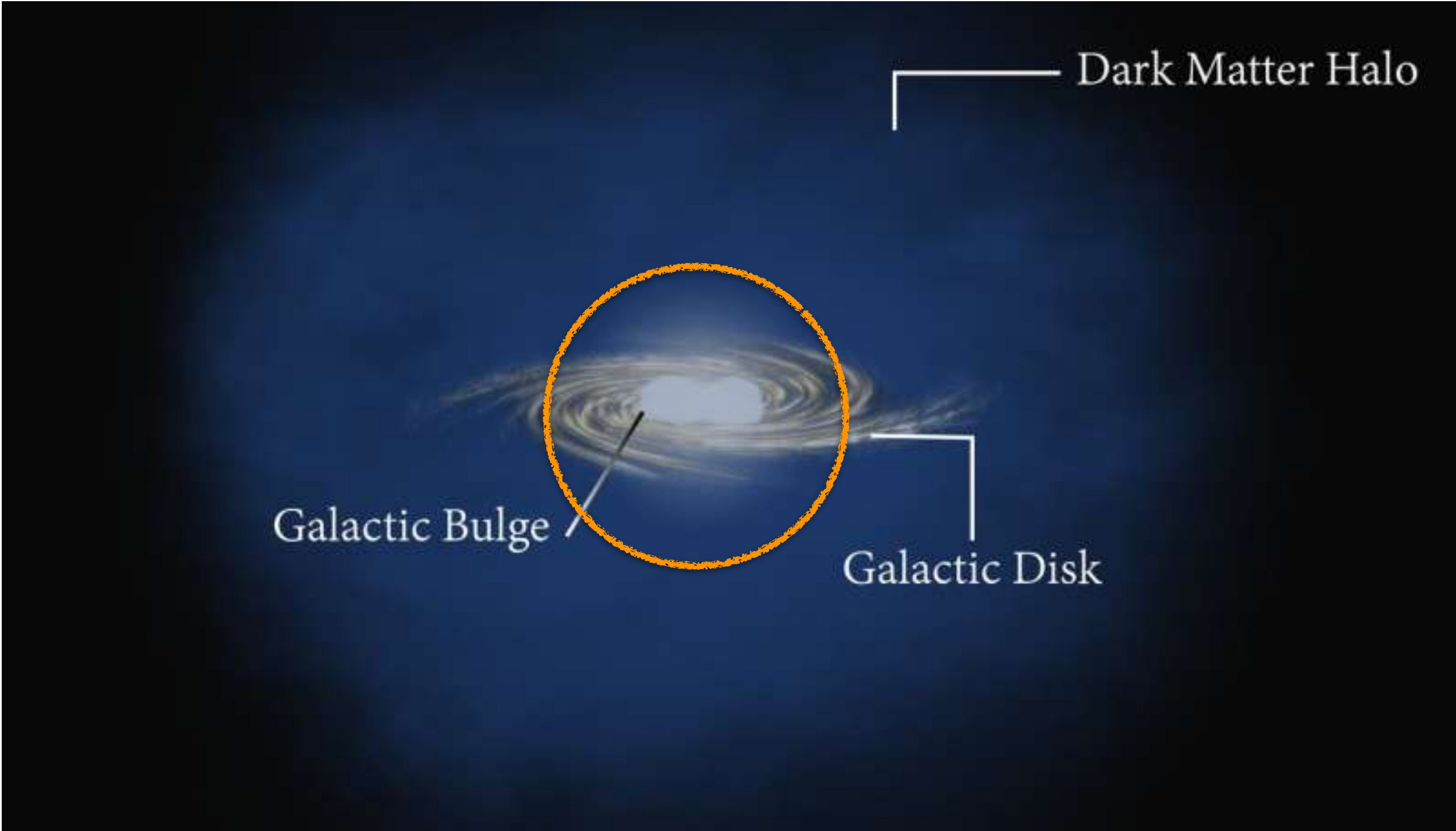
Christoph Weniger

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

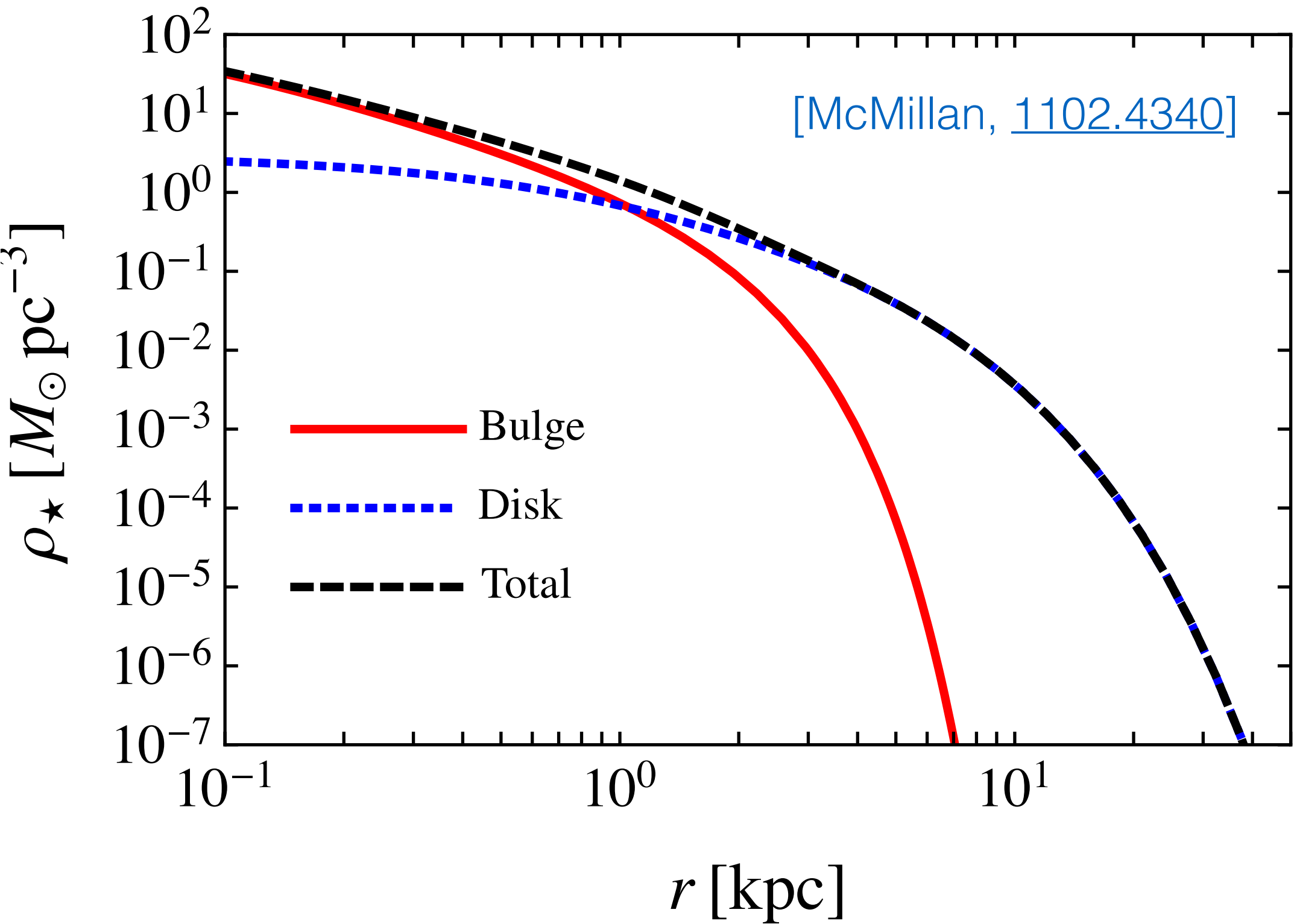
Schematic modeling of a spiral Galaxy



Schematic modeling of a spiral Galaxy

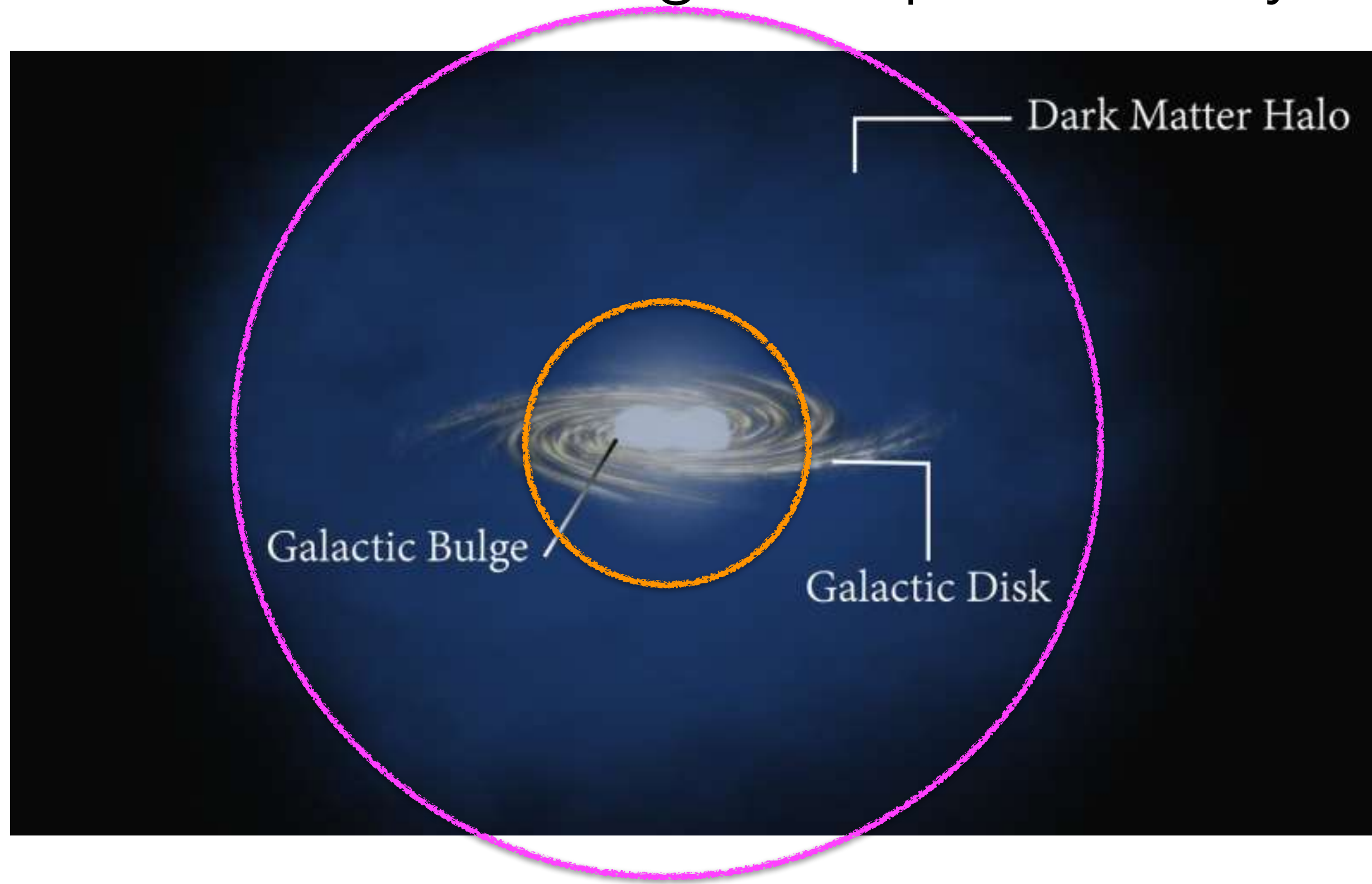


Stellar content

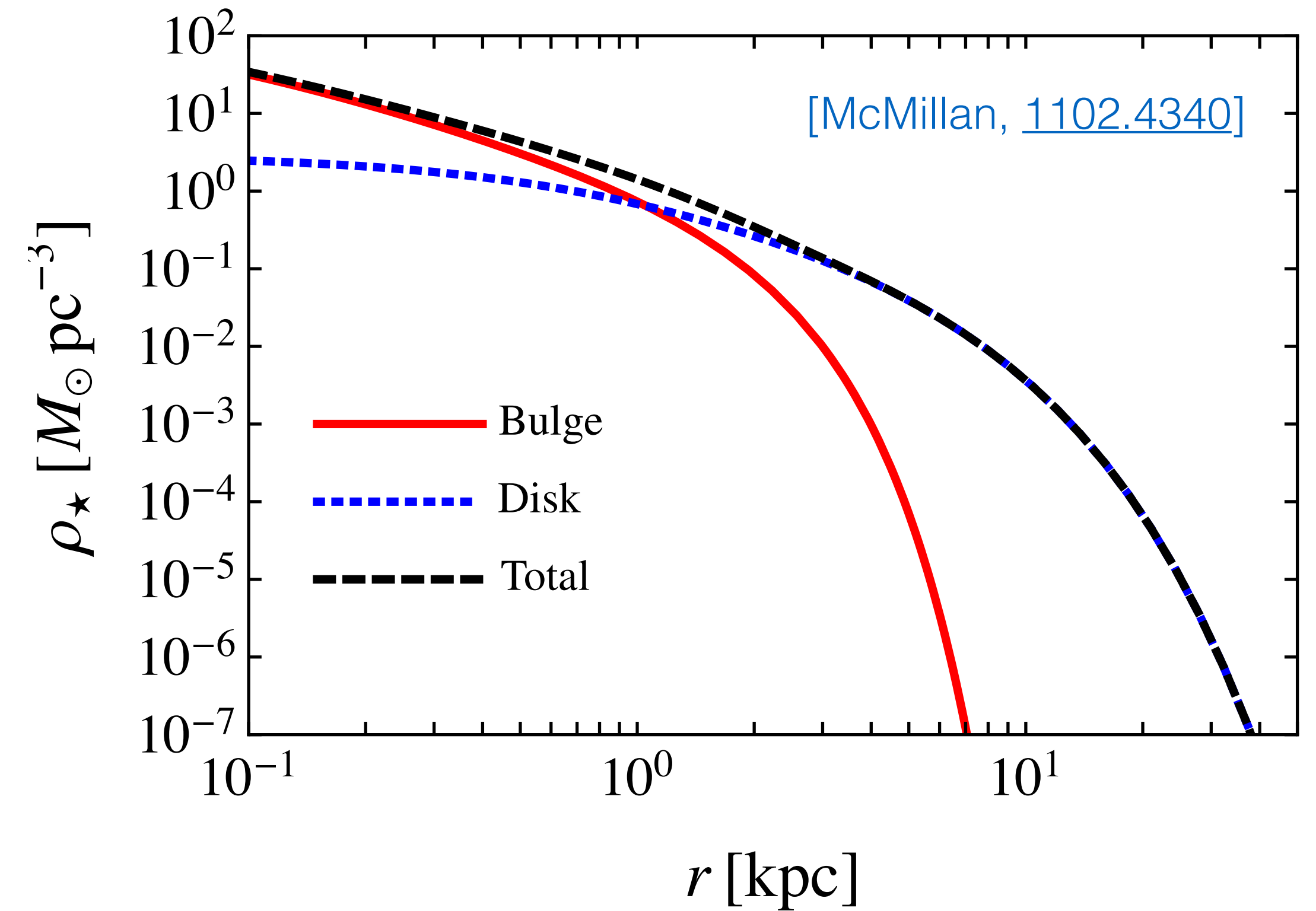


Milky Way Setup

Schematic modeling of a spiral Galaxy



Stellar content



+ spherical DM halo (NFW)

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

The AMC orbit is specified by three parameters:

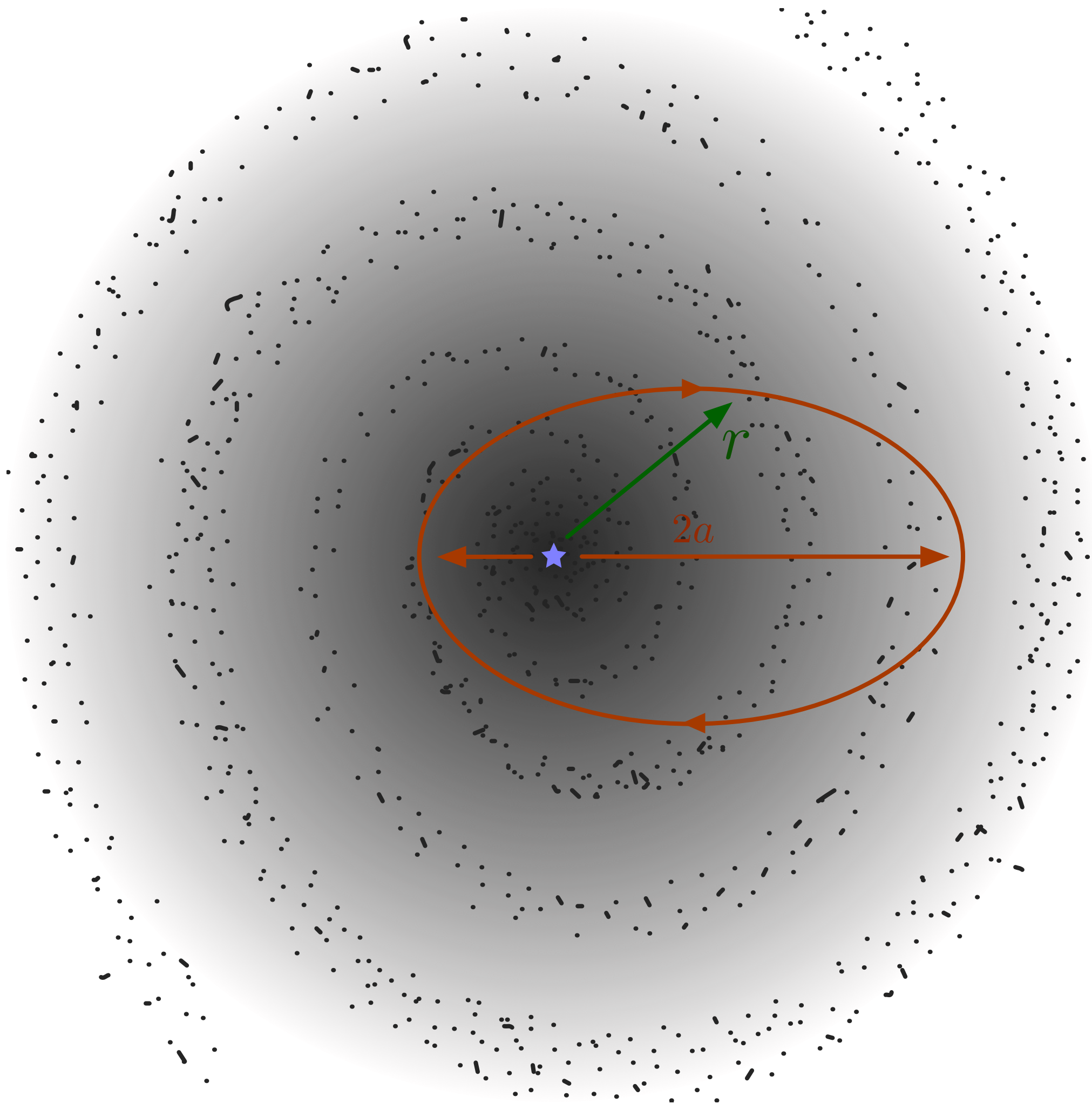
- semi-major axis a
- eccentricity ε
- Inclination w.r.t. Galactic plane ψ

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

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

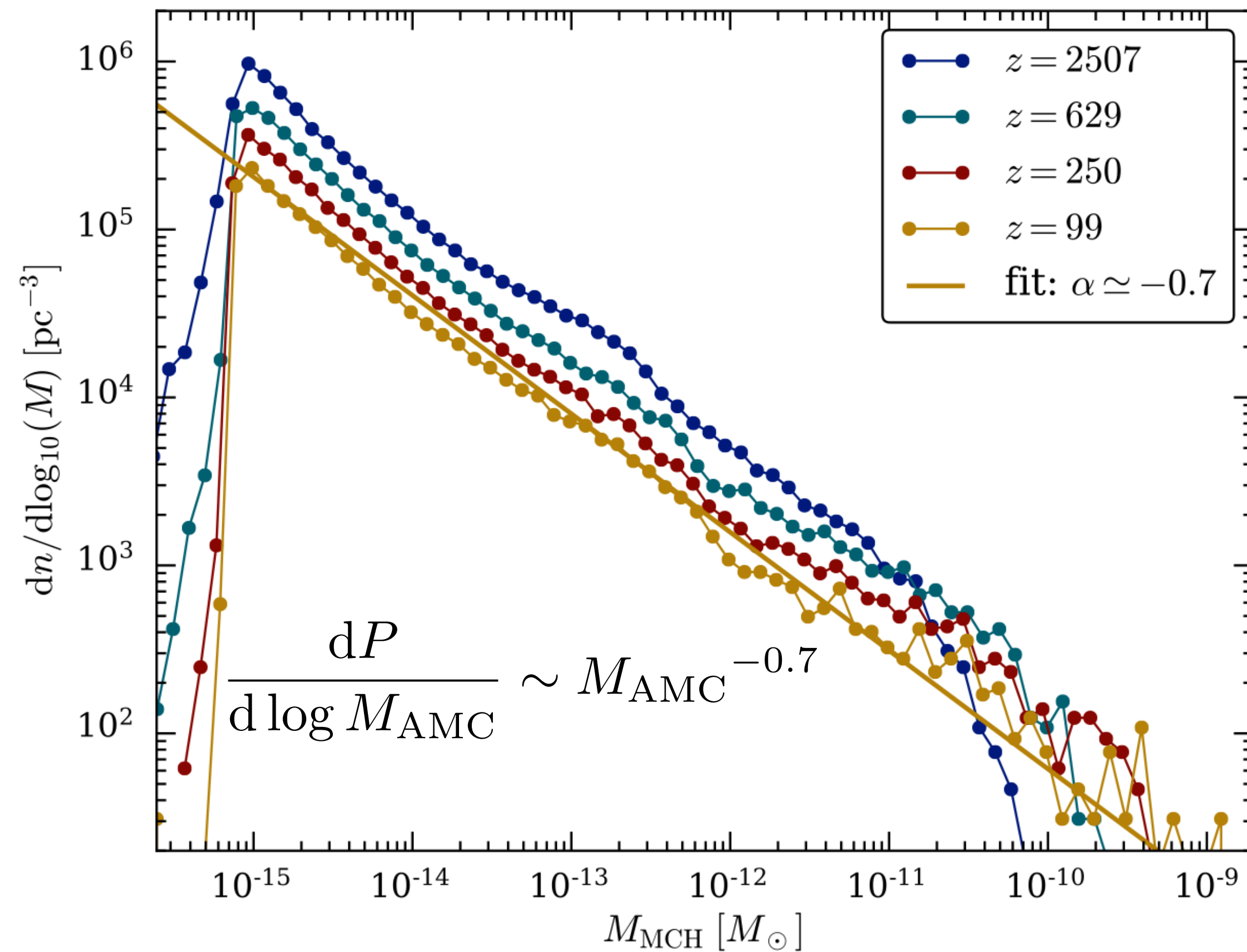
$$\langle M_{\text{AMC}} \rangle \approx 10^{-14} M_{\odot}$$

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

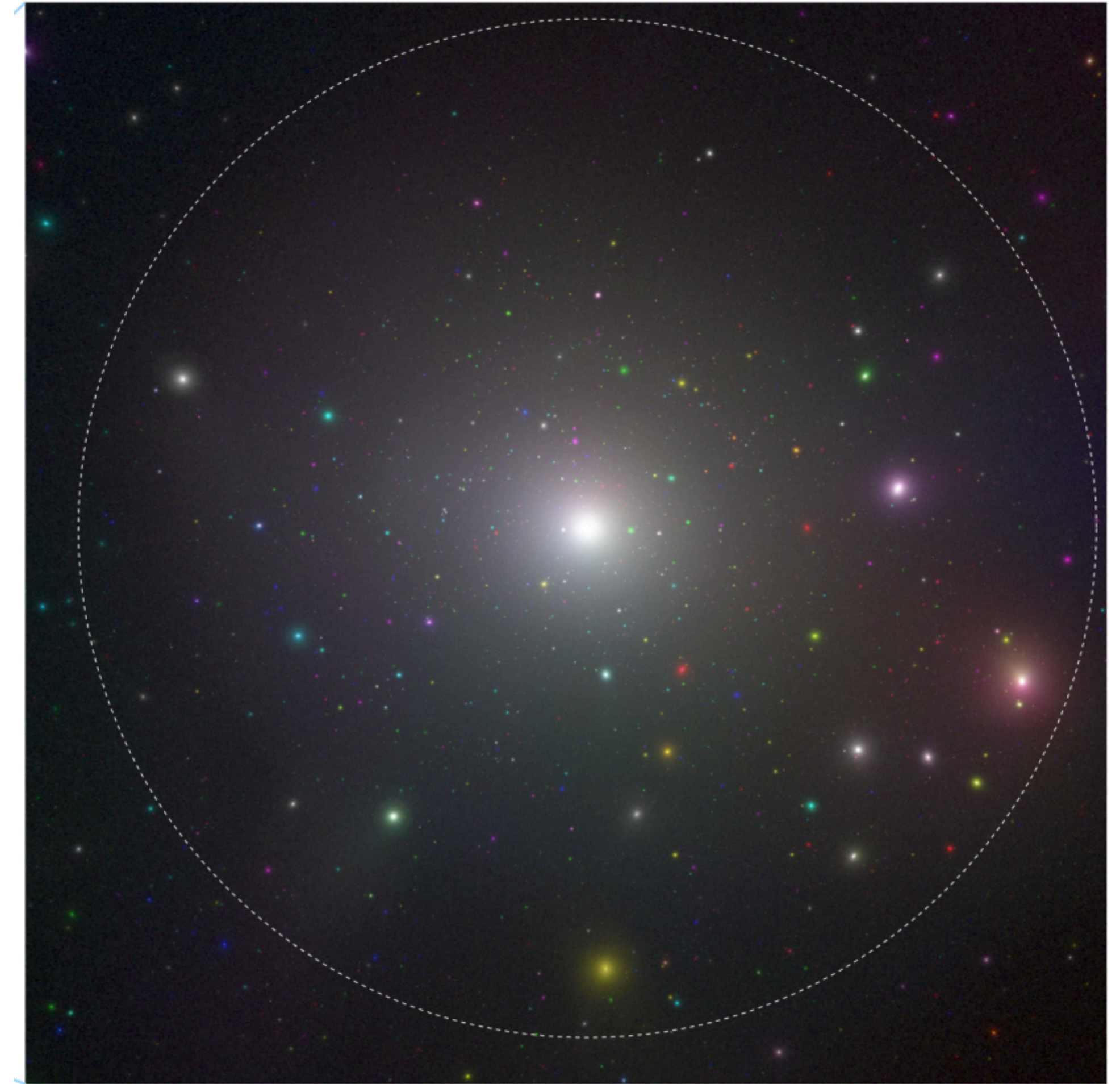


AMC mass function

Pre-infall halo mass function $\frac{dn_0}{dM}(M, z) = f(\nu) \frac{\bar{\rho}_c}{M} \frac{d\nu}{dM}$
[\[Fairbairn et al., 1707.03310\]](#)



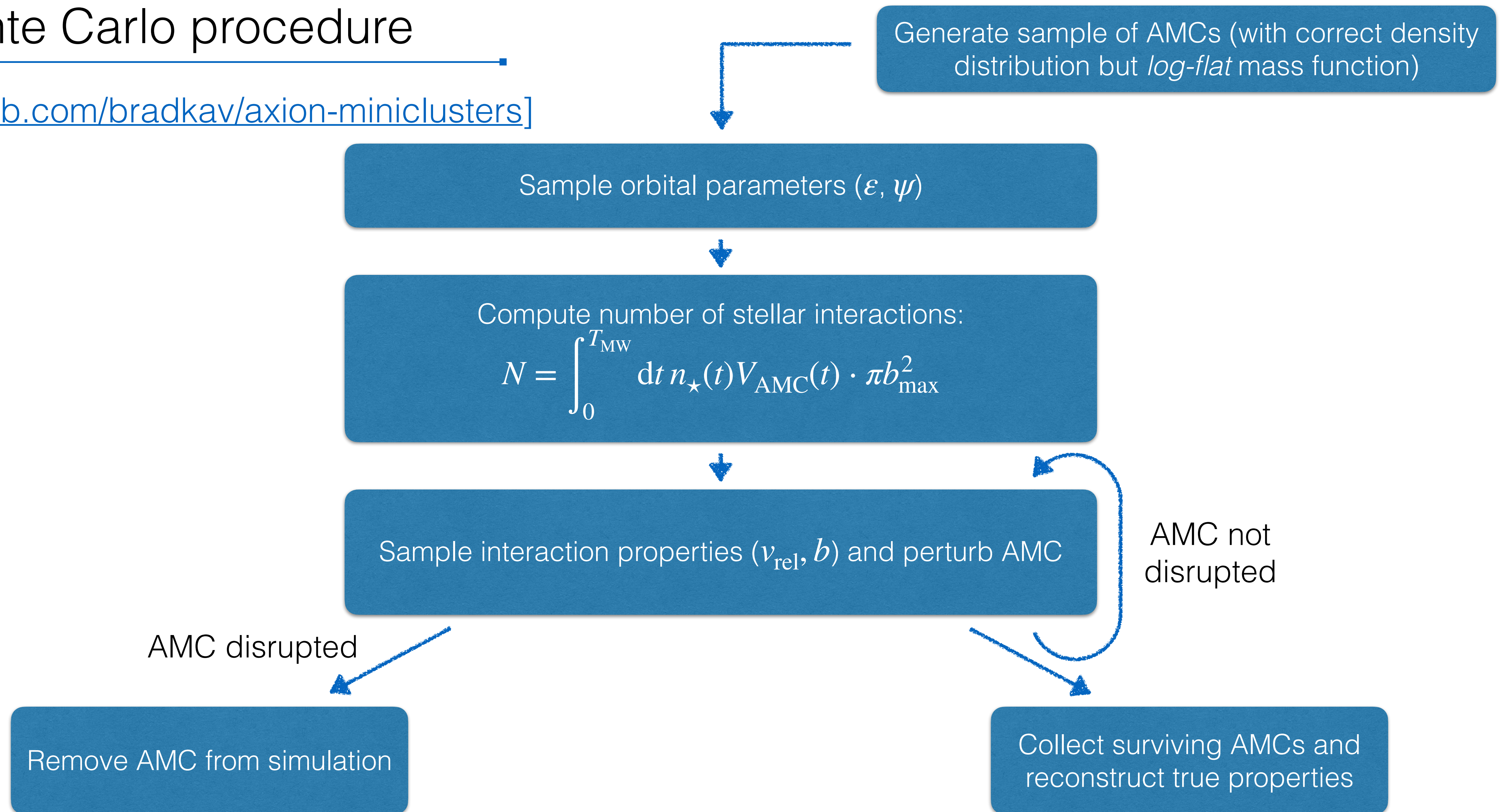
Axion minicluster halo at $z = 99$



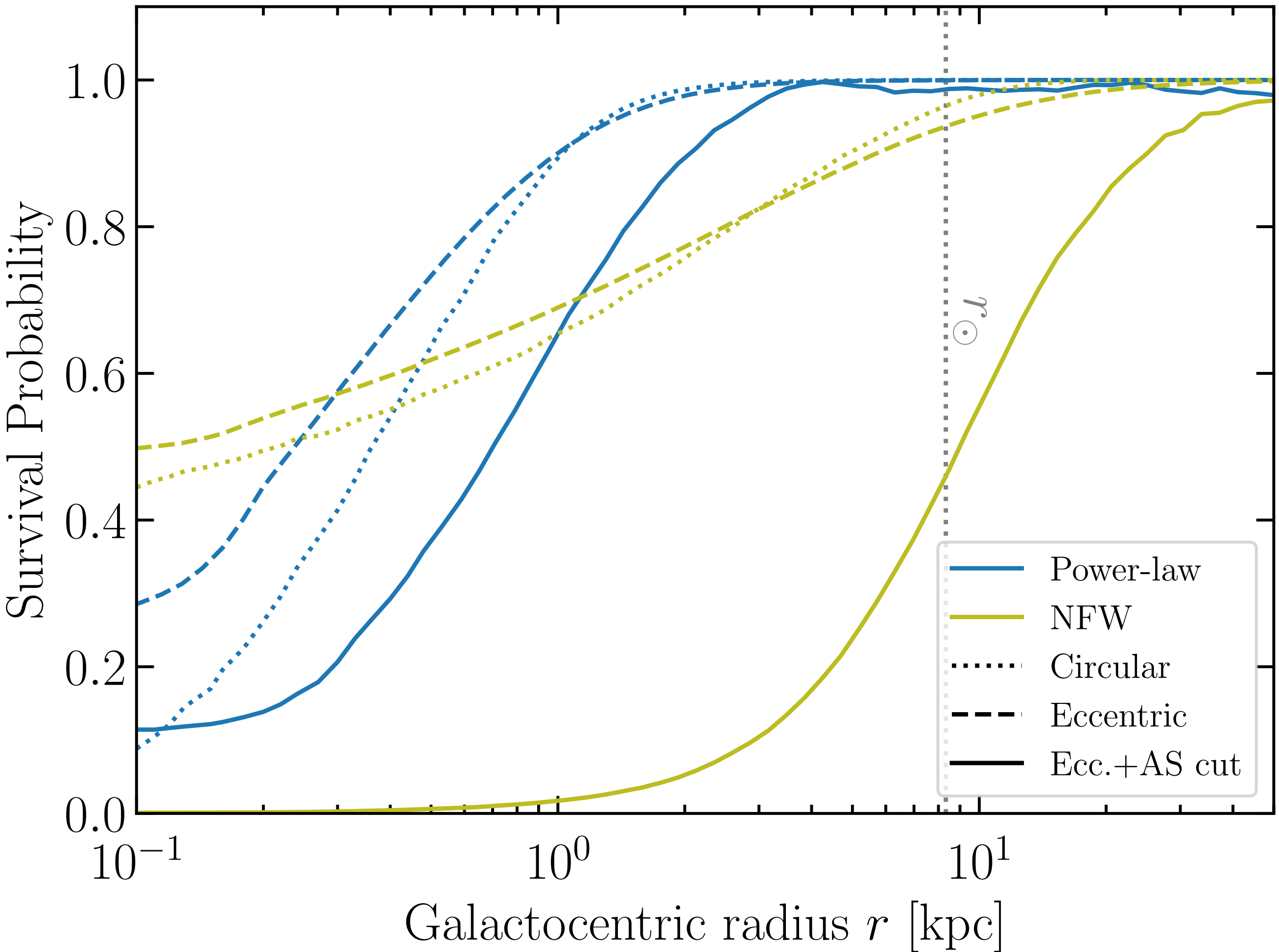
[\[Eggemeier et al., 1911.09417\]](#)

Monte Carlo procedure

[\[github.com/bradkav/axion-miniclusters\]](https://github.com/bradkav/axion-miniclusters)



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



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

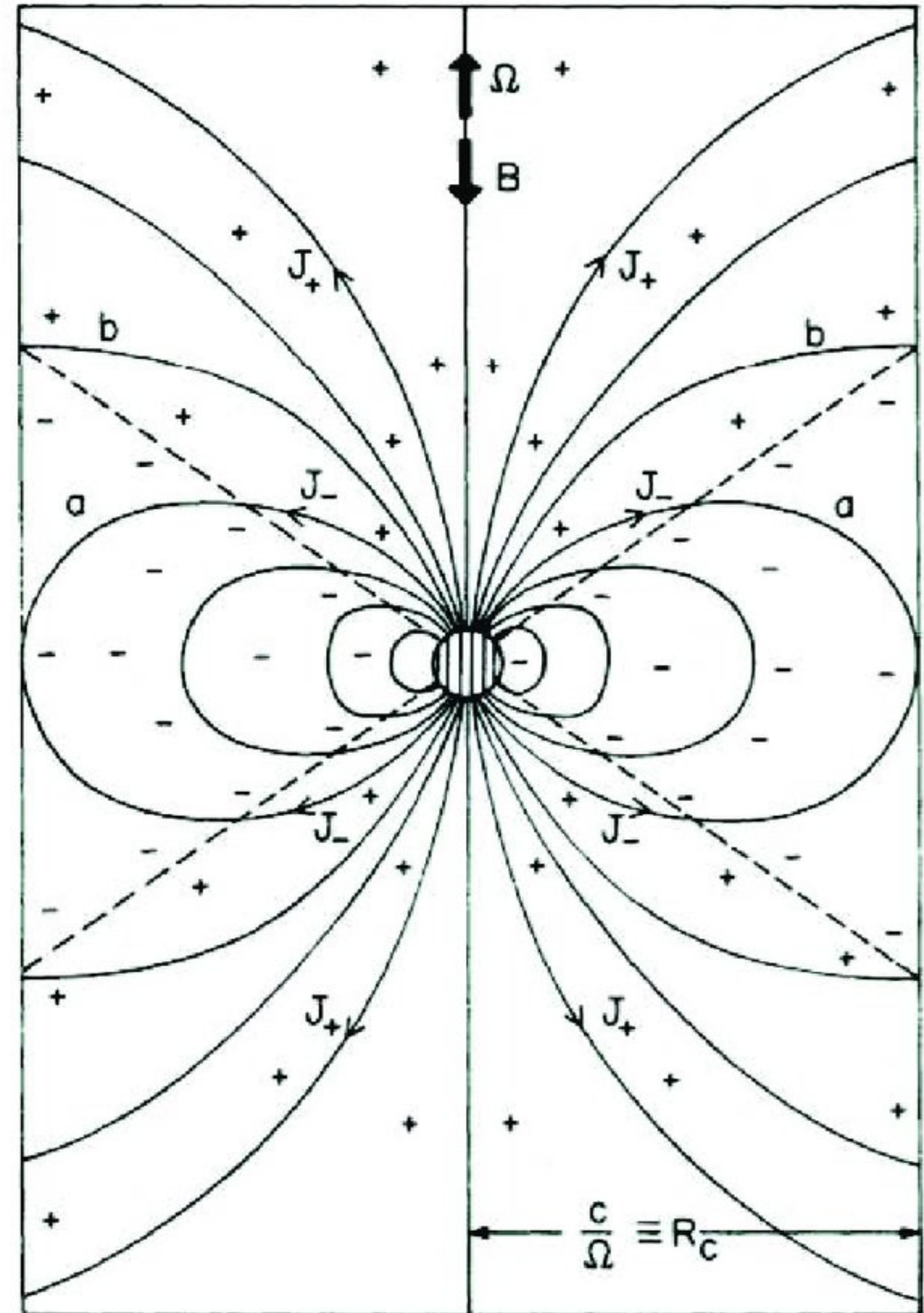
NS **B** field described in the magnetic dipole approximation:

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

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

Leads to the charge density in the magnetosphere:

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



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](#)]

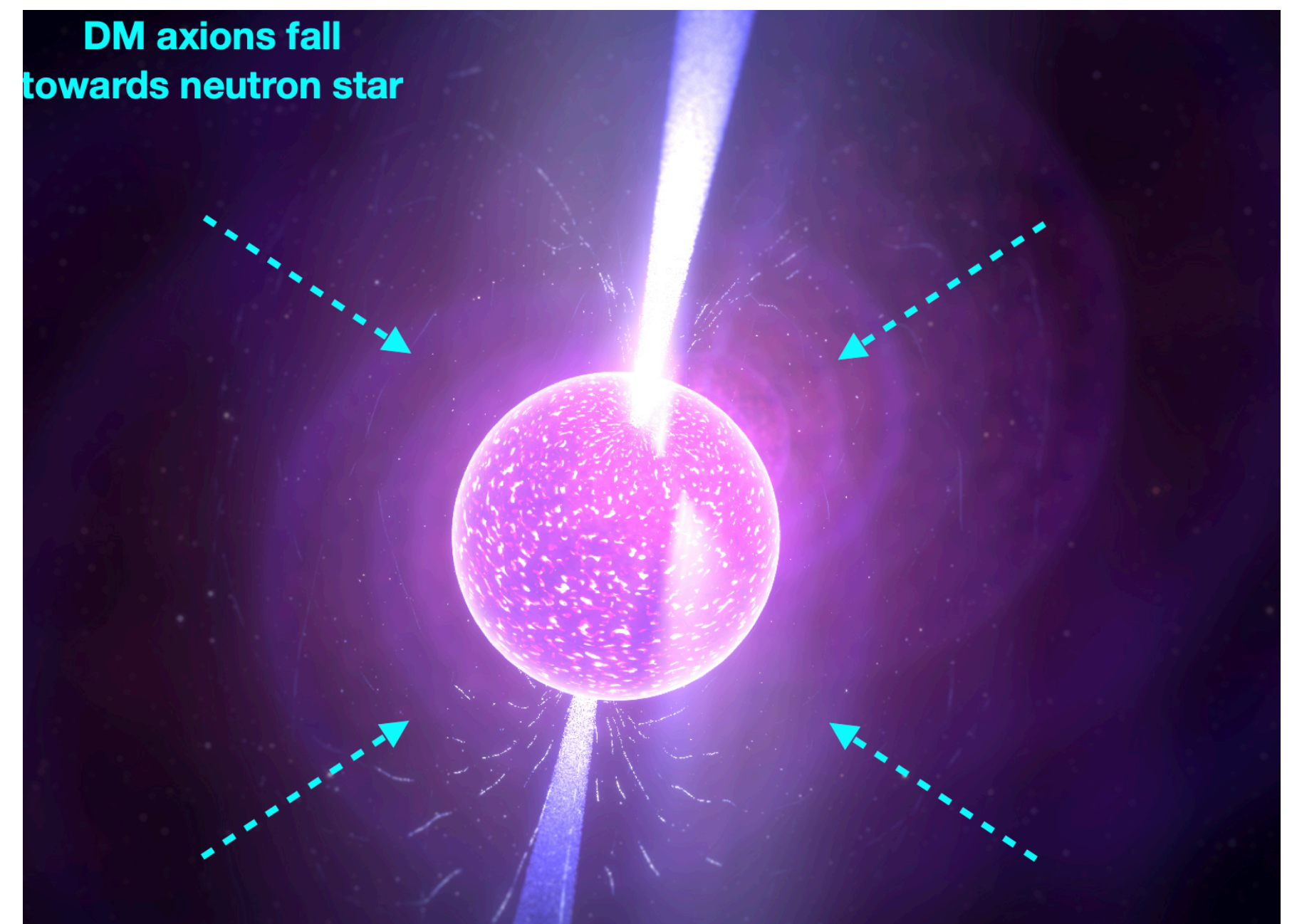
Assume axion dark matter falling into the gravity potential of the NS.

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

Emitted radio power: $\frac{d\mathcal{P}_a}{d\Omega} \sim \frac{\pi}{3} g_{a\gamma\gamma}^2 B_0^2 \frac{R_{\text{NS}}^6}{R_c^3} \frac{\rho_c}{m_a}$

[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

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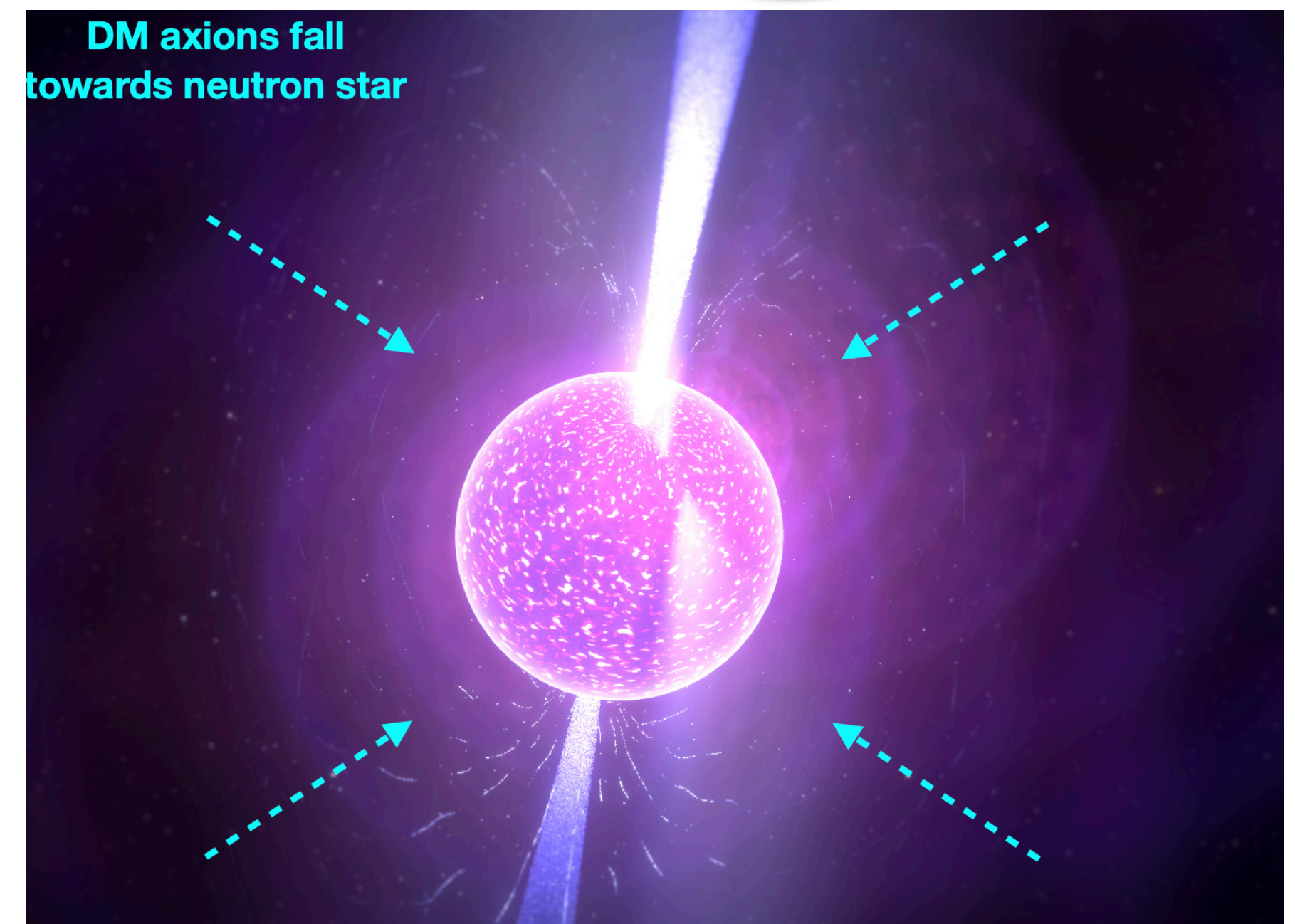
Width of the conversion shell

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

Emitted radio power: $\frac{d\mathcal{P}_a}{d\Omega} \sim \frac{\pi}{3} g_{a\gamma\gamma}^2 B_0^2 \frac{R_{\text{NS}}^6}{R_c^3} \frac{\rho_c}{m_a}$

[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

Question: Can we exploit the environment within axion miniclusters?

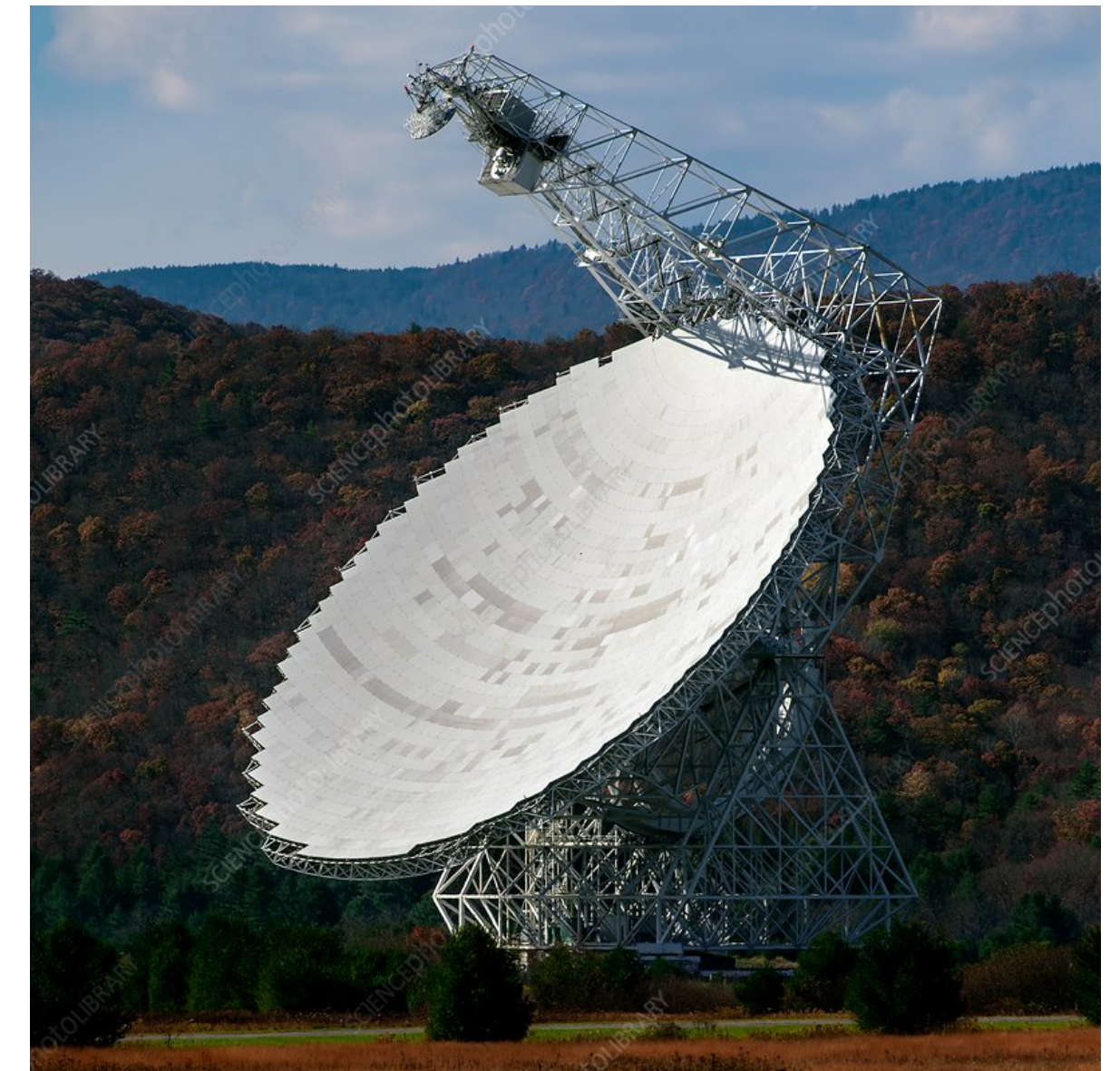
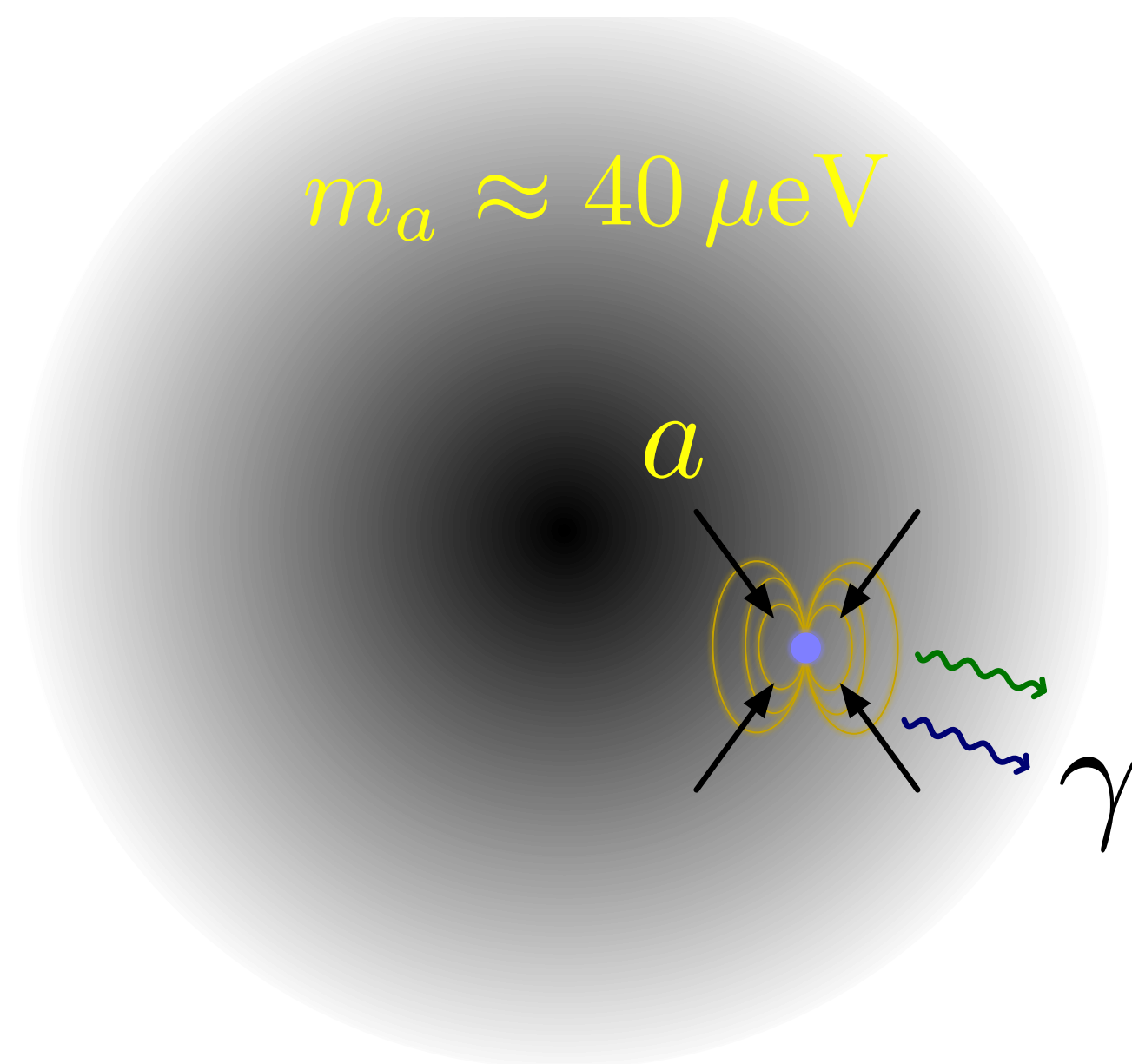
$$\frac{d\mathcal{P}_a}{d\Omega} \sim \frac{\pi}{3} g_{a\gamma\gamma}^2 B_0^2 \frac{R_{\text{NS}}^6}{R_c^3} \frac{\rho_c}{m_a}$$

Transient enhancements to ρ_c from AMC encounters [Edwards+ \(with LV\), PRL 2021 2011.05378](#)

Frequency of emitted photon in the GHz:

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

can be picked up at Earth
by radio telescopes

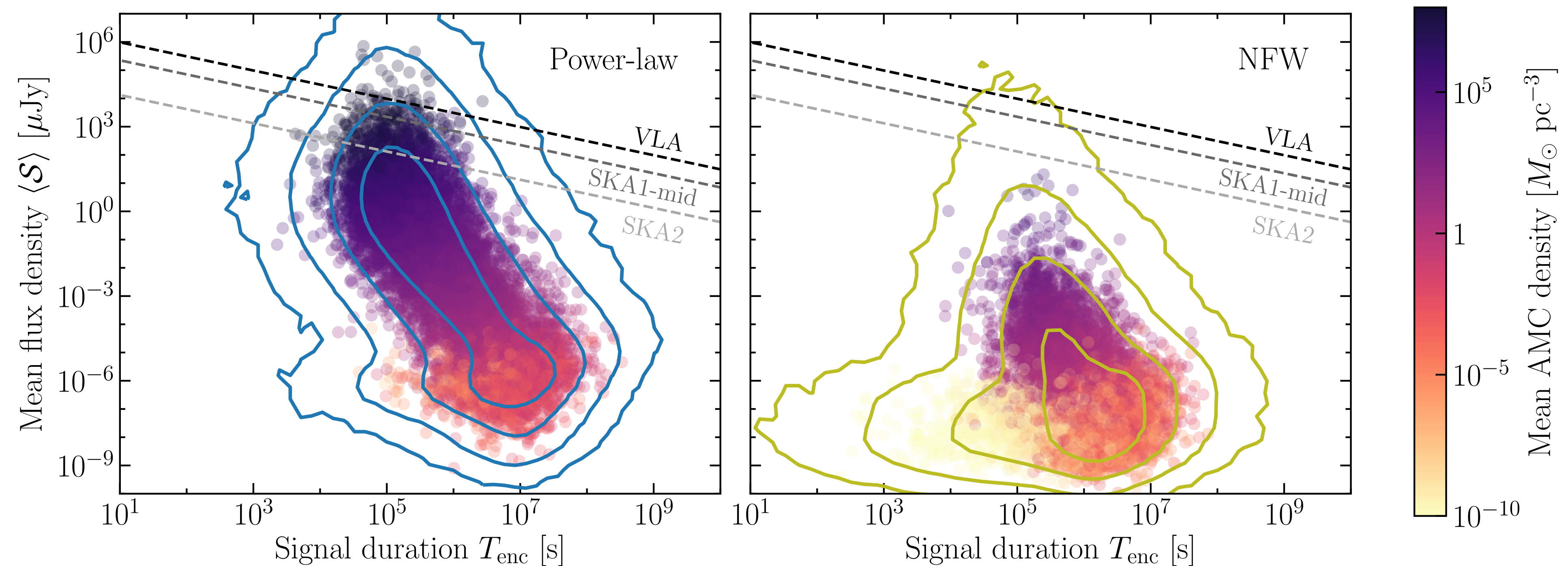


Axion-photon conversion in NS magnetospheres

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

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

Instead, fix bandwidth $\text{BW} = 1 \text{ kHz}$ (based on telescope resolution).



Searching for axions in M31

Can we pick up this signal in radio?



Bradley Johnson



Liam Walters



Prakamya Agrawal



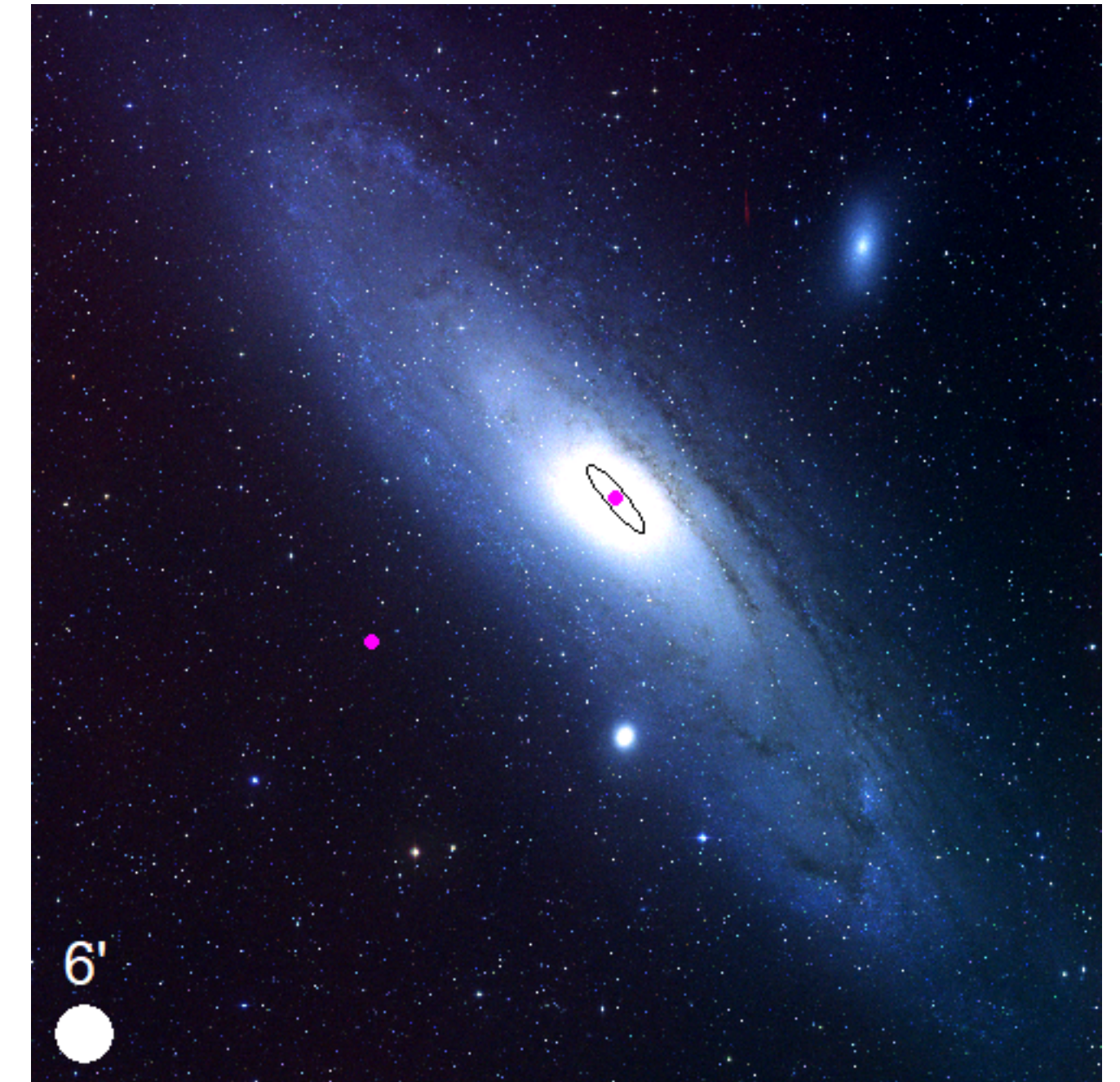
Jordan E. Shroyer



Madeleine Edenton



David Marsh



2 grant proposals accepted by the Green Bank Telescope

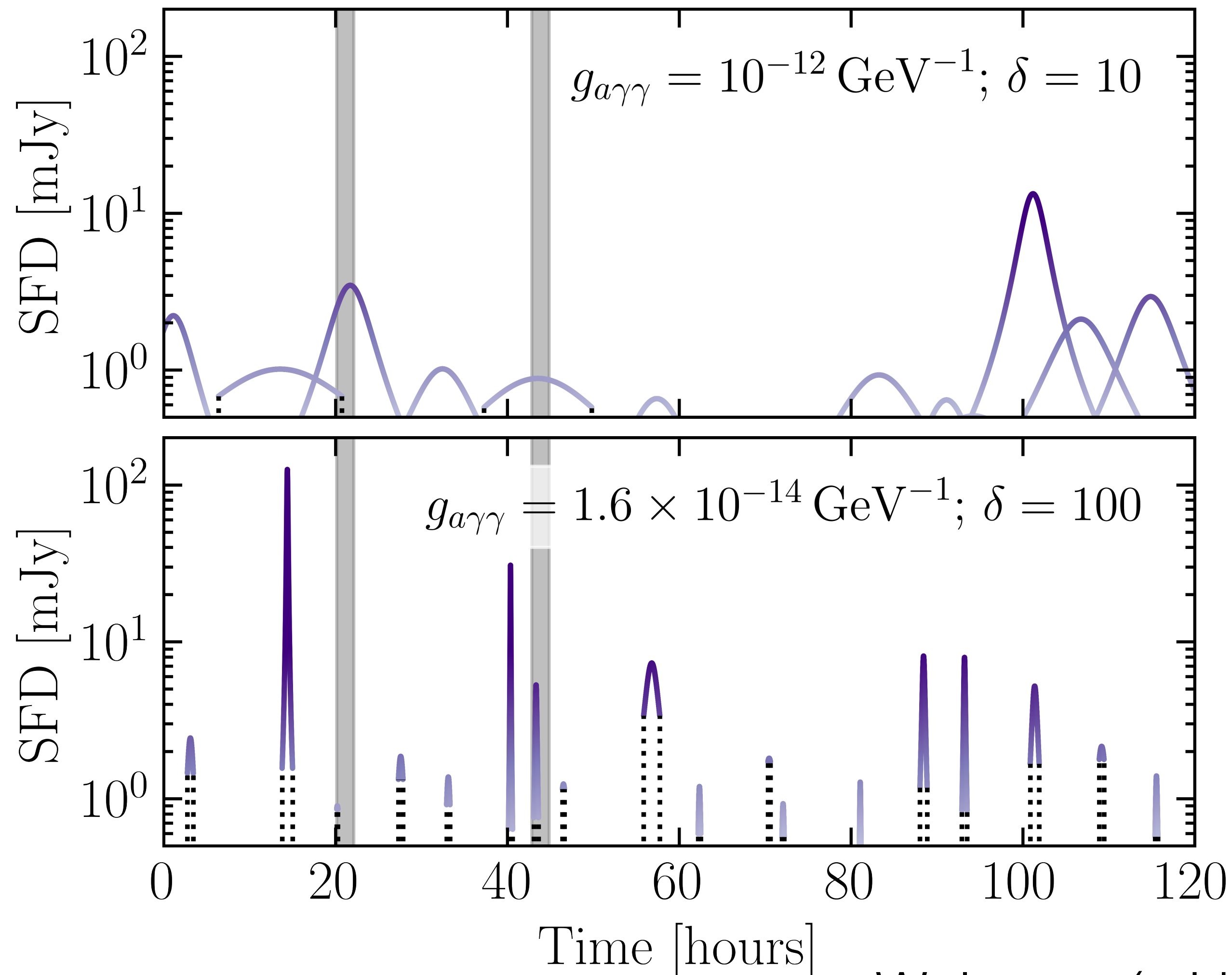
We have observed Andromeda
The diameters give the telescope beam size at 1.4 arcmin angular resolution

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: $m_a = 40 \mu\text{eV}$

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

Simulate 20 encounters with a NS of

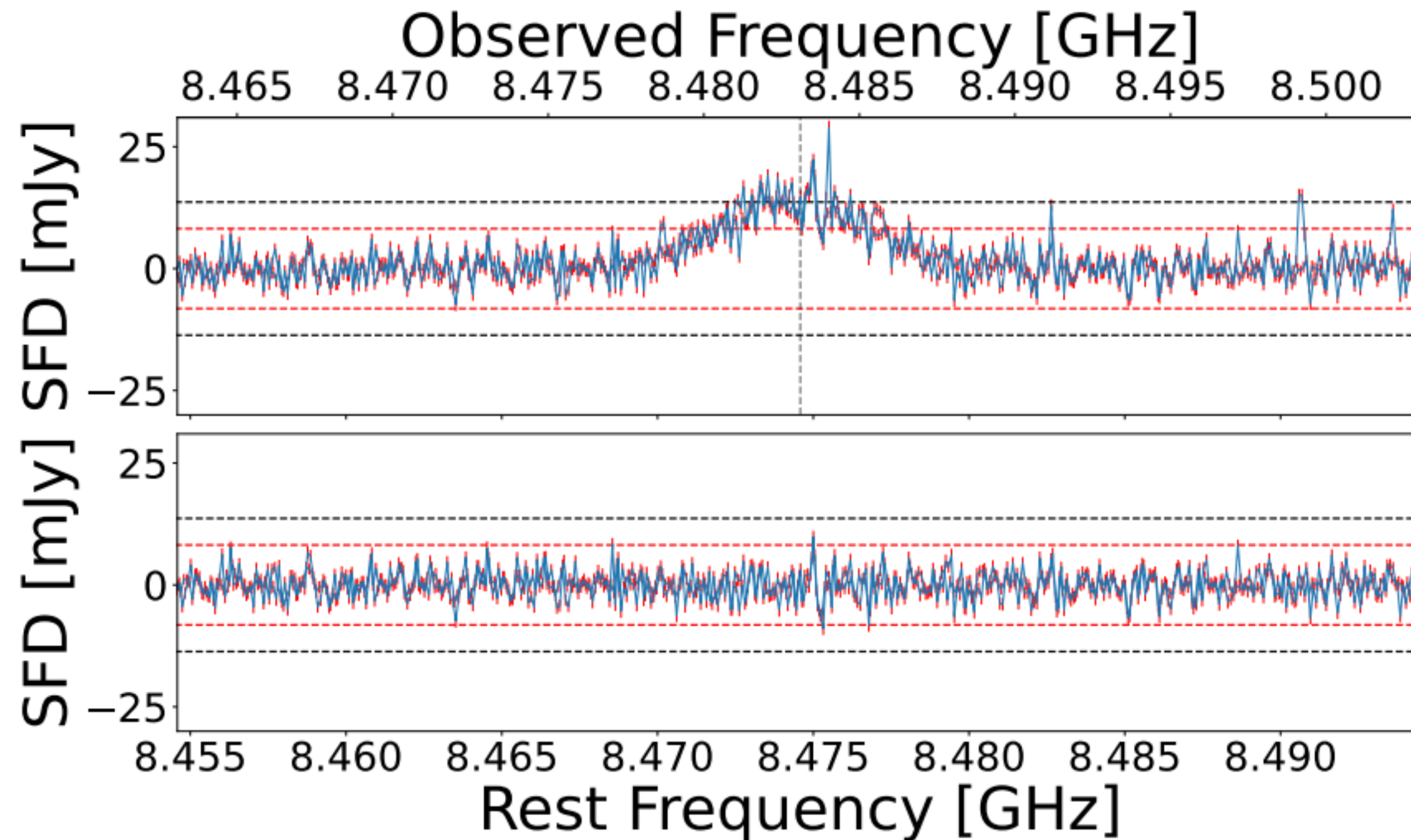
Period: $P = 1 \text{ s}$ B field: $B_0 = 10^{14} \text{ G}$

Signal lasting min to hour

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

Can we pick up this signal in radio?

How would a signal look like?



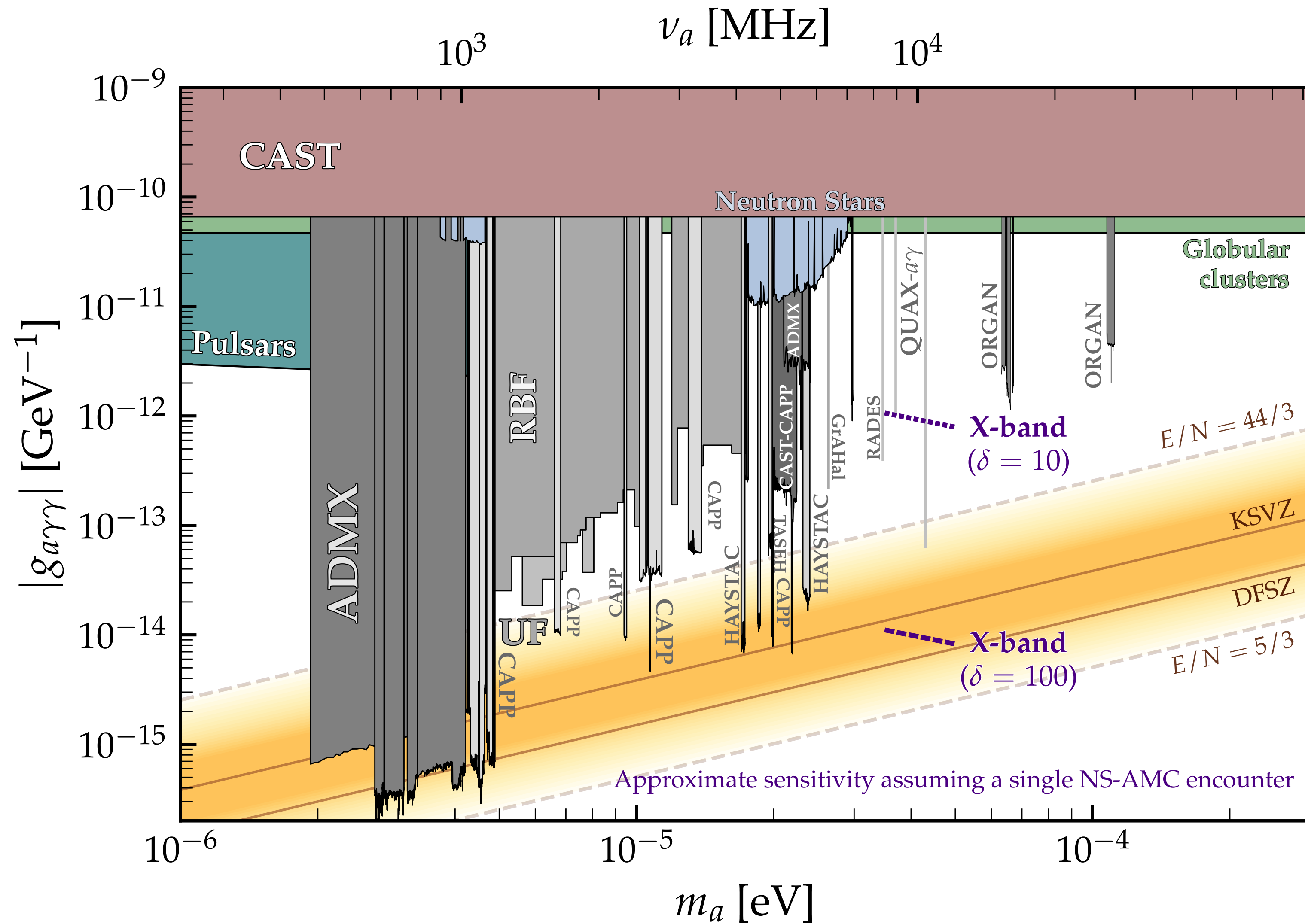
Hydrogen recombination line at 8.483 GHz when not accounting for M31 blueshift.

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.

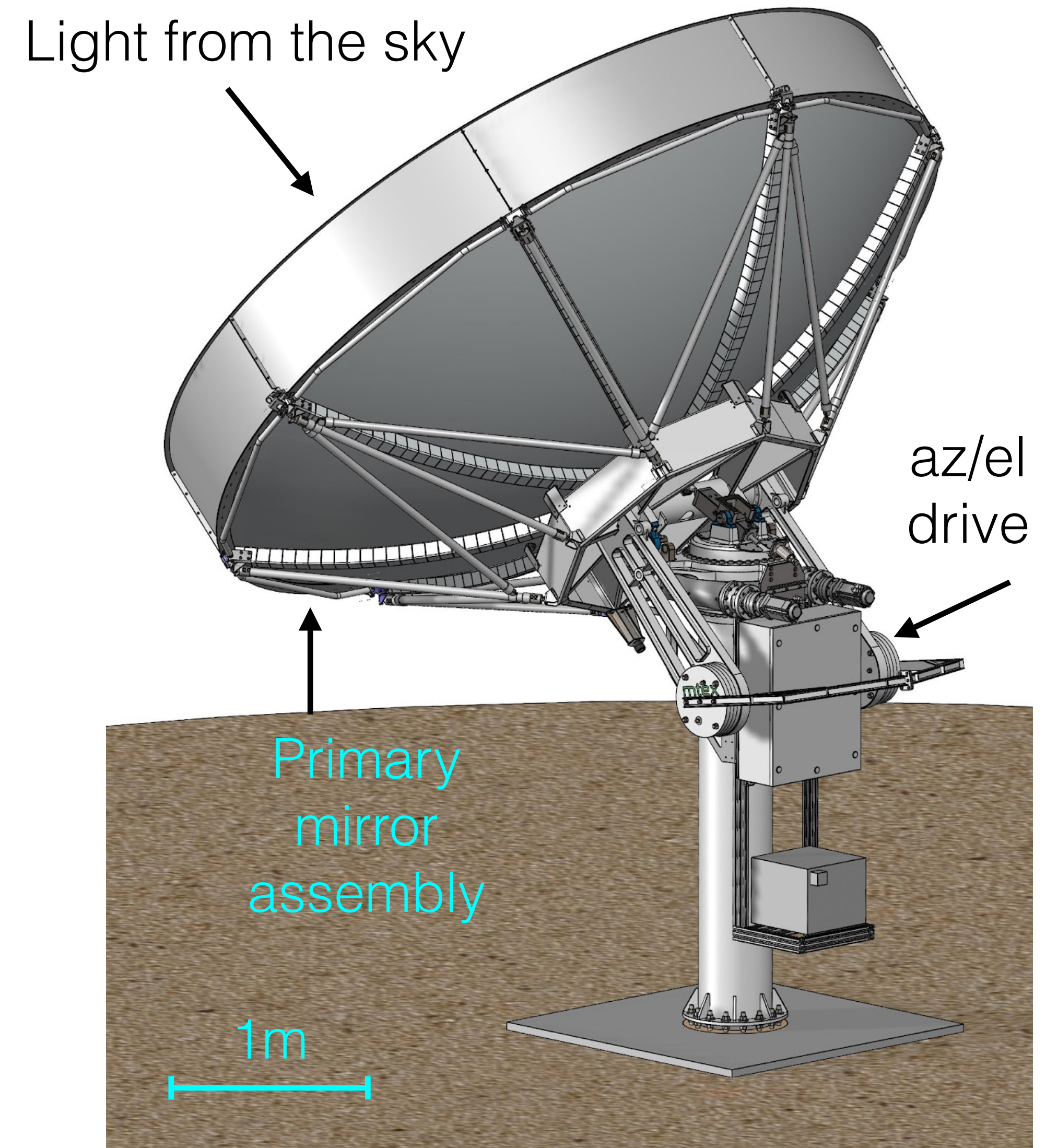
However, astrophysics unknowns are severe (e.g. minicluster histories, shapes and abundances)

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

Walters+ (with **LV**) [2407.13060](https://arxiv.org/abs/2407.13060)

Future and ongoing progresses

- Ongoing analysis of the 2023 data in C-band
- The UV group has secured funds via Jefferson Trust, to build a telescope operating at $< 2\text{GHz}$
- 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

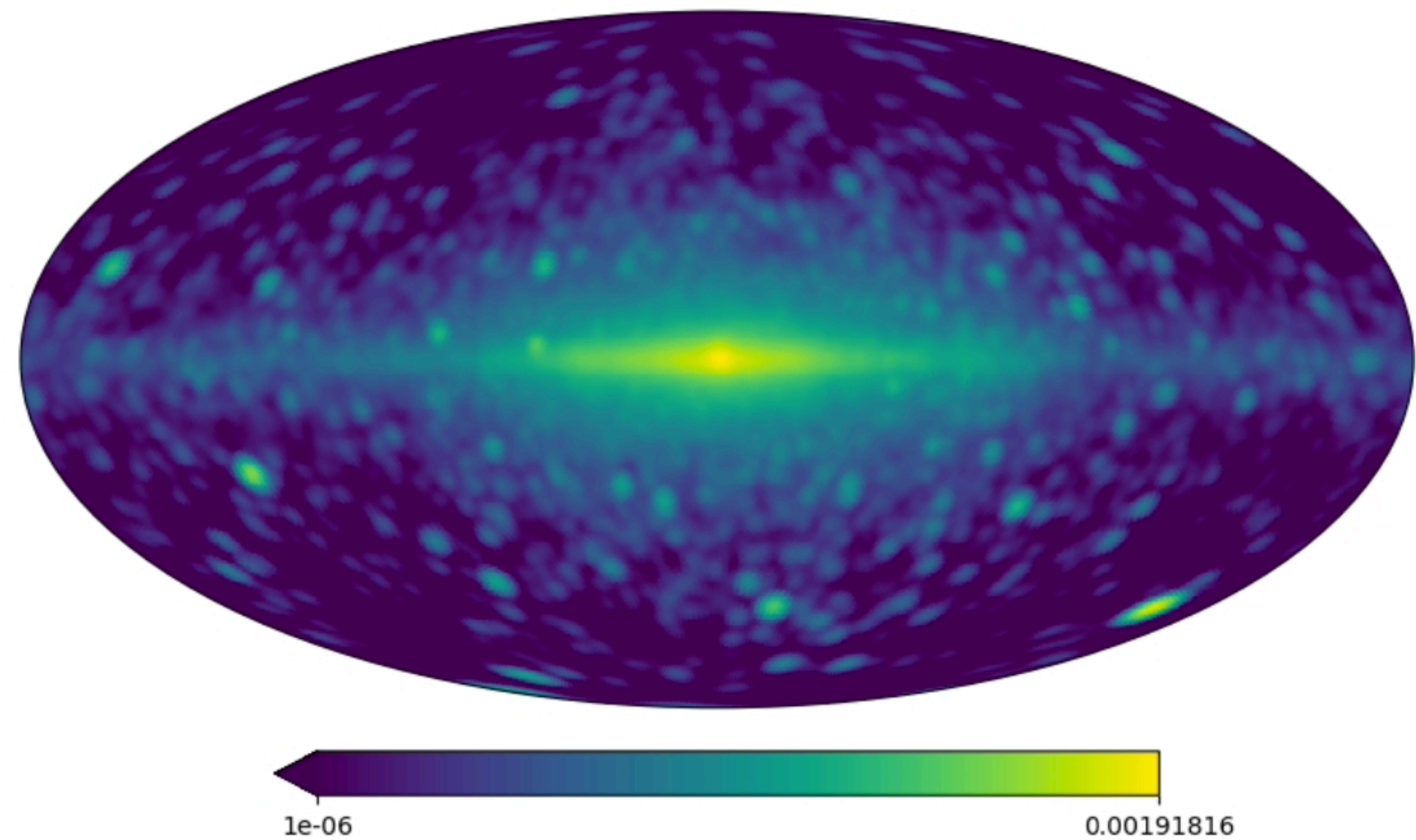


Utkarsh Bhura

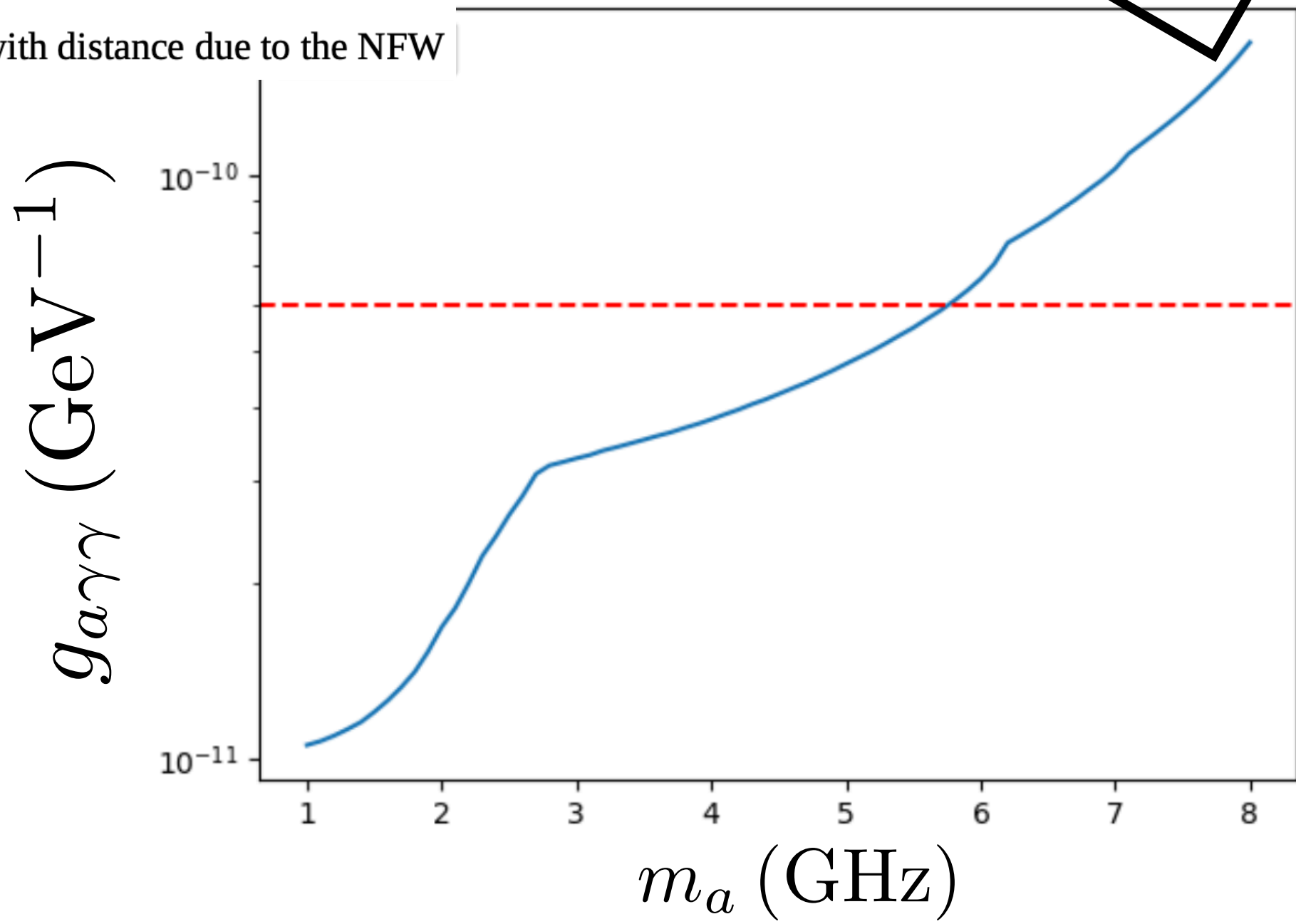


David Marsh

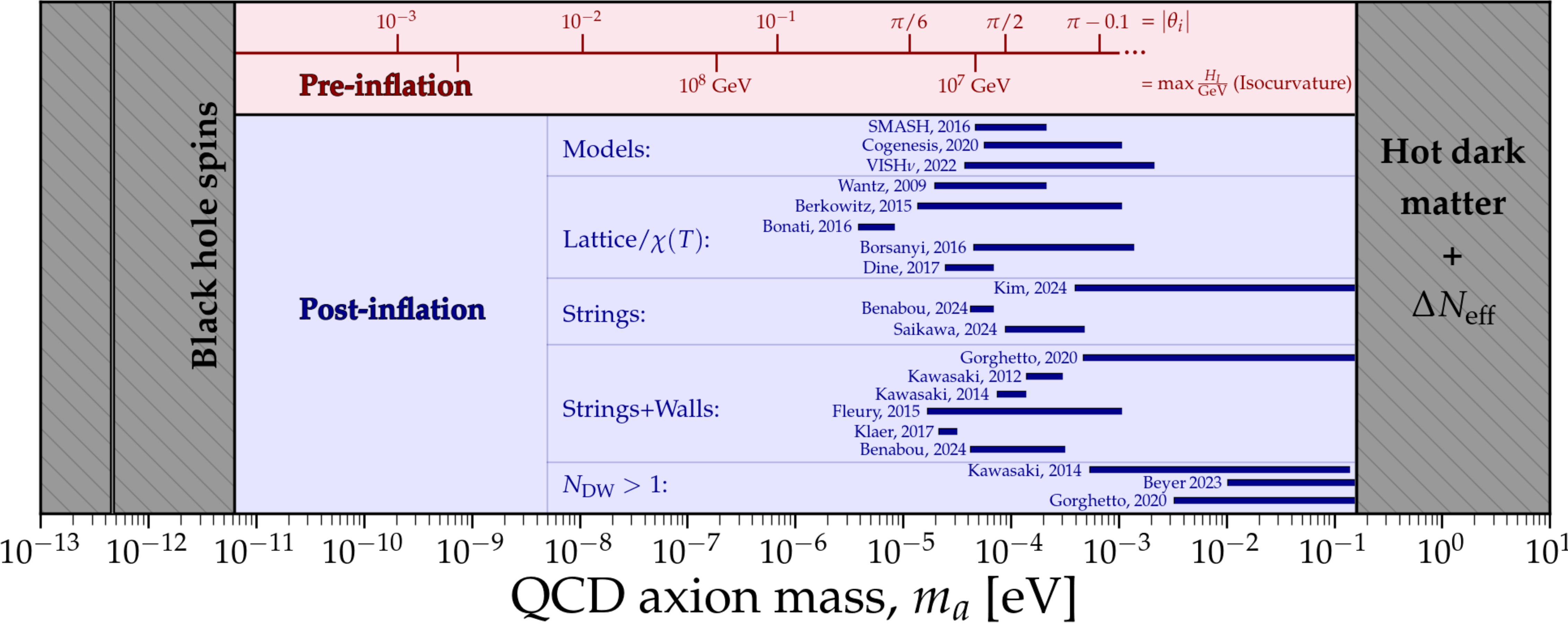
Fan Mountain observes the sky at a range of frequencies from 1 to 8 GHz. Using the PsrPopPy population model the sky map at 1 GHz would appear as follows:



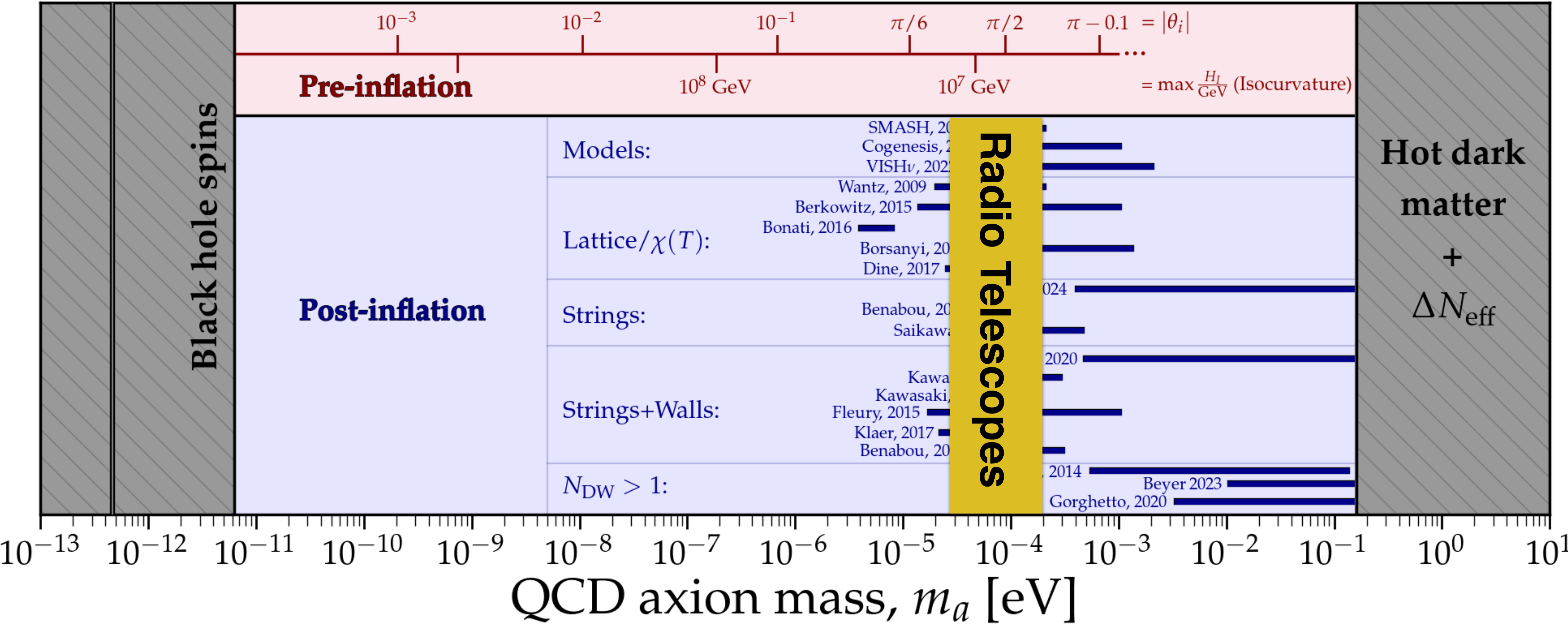
The peak at centre is due to the dark matter density, which falls down with distance due to the NFW



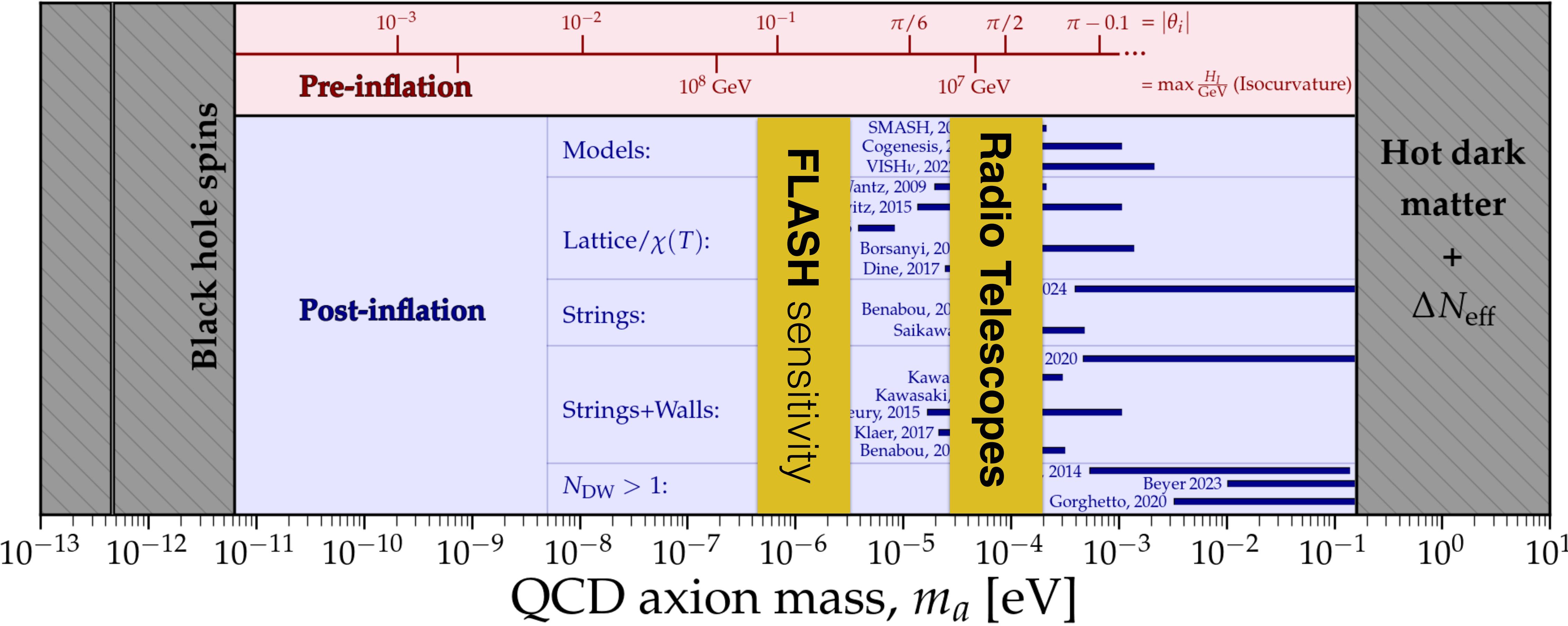
Direct detection of the axion at INFN Frascati National Labs



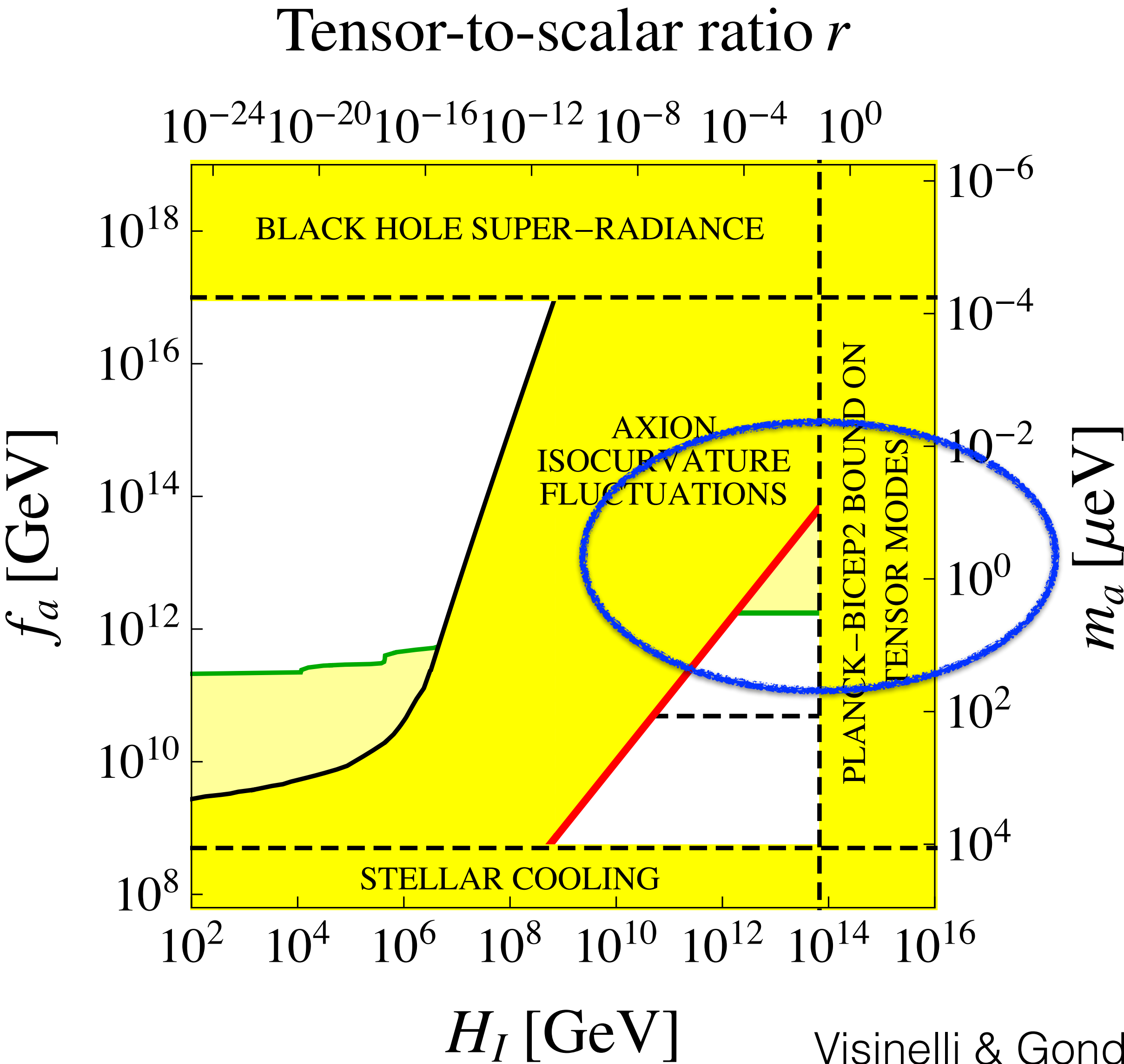
Ciaran O'Hare, AxionLimits: <https://cajohare.github.io/AxionLimits/>



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

Power transfer from axion DM to the cavity

Weak coupling

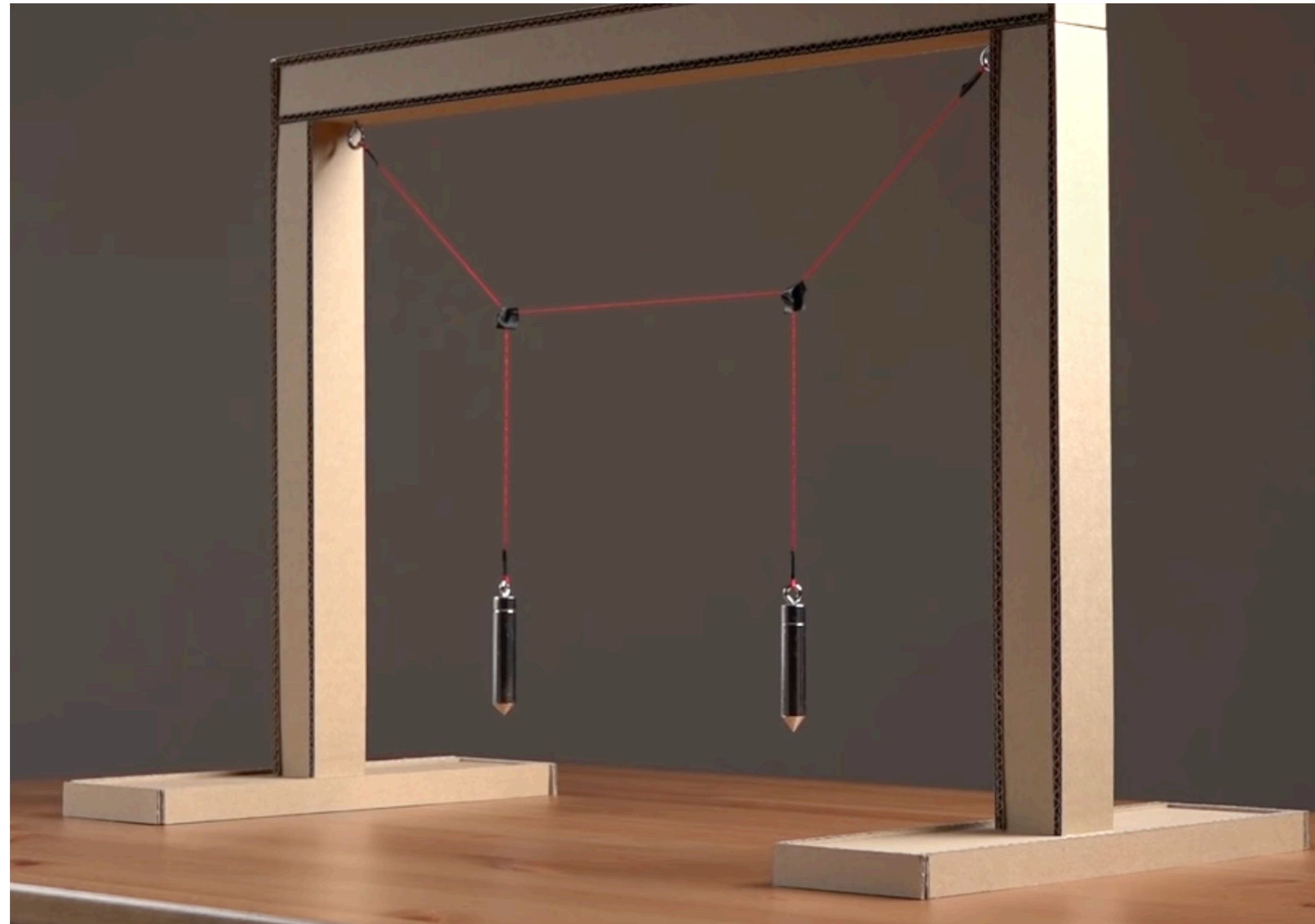
Takes many swings to fully transfer the wave amplitude.

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

Narrowband cavity response $\rightarrow$ iterative scan through frequency space.

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

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



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]

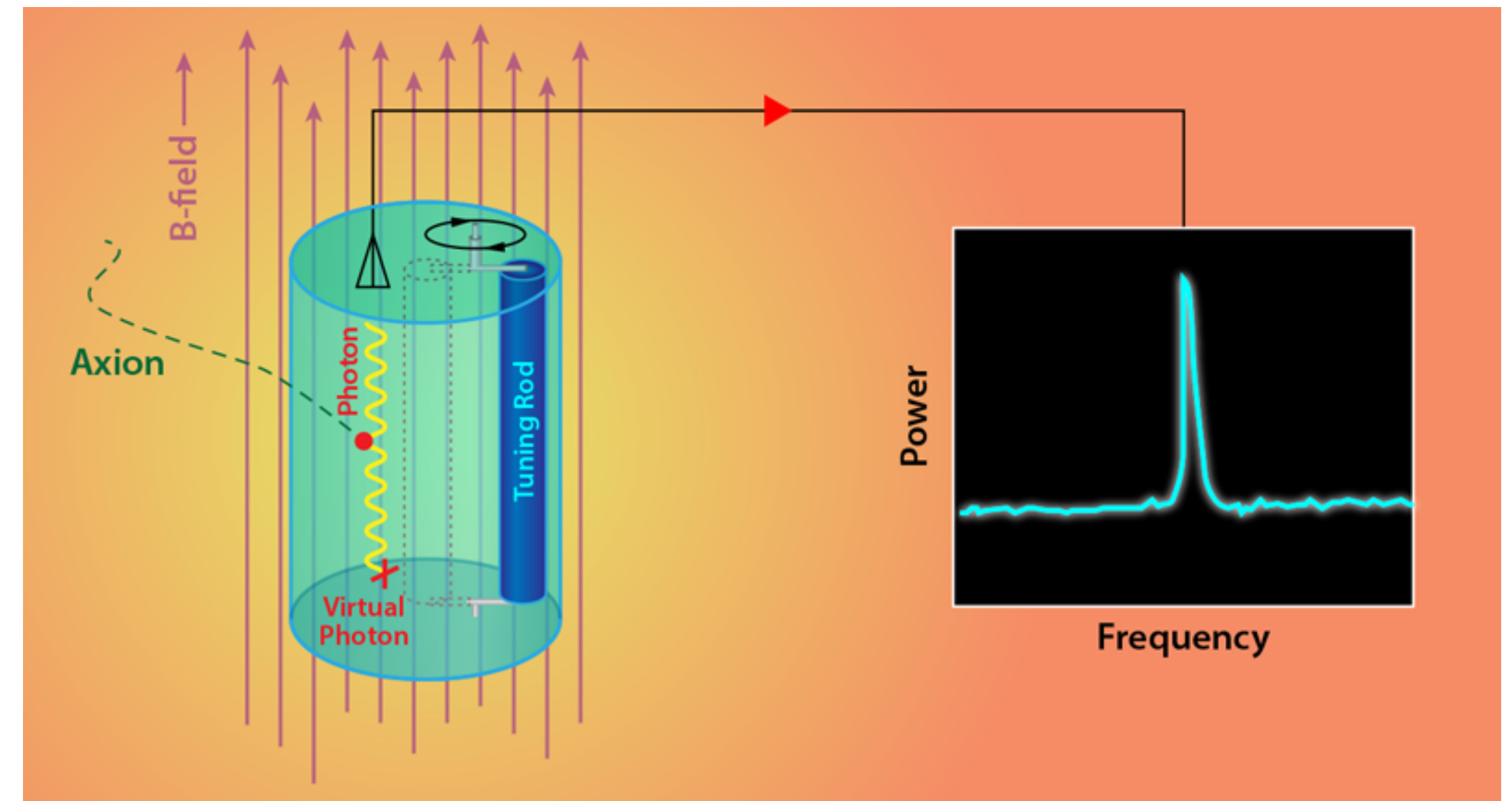
Significant enhancement when

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

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

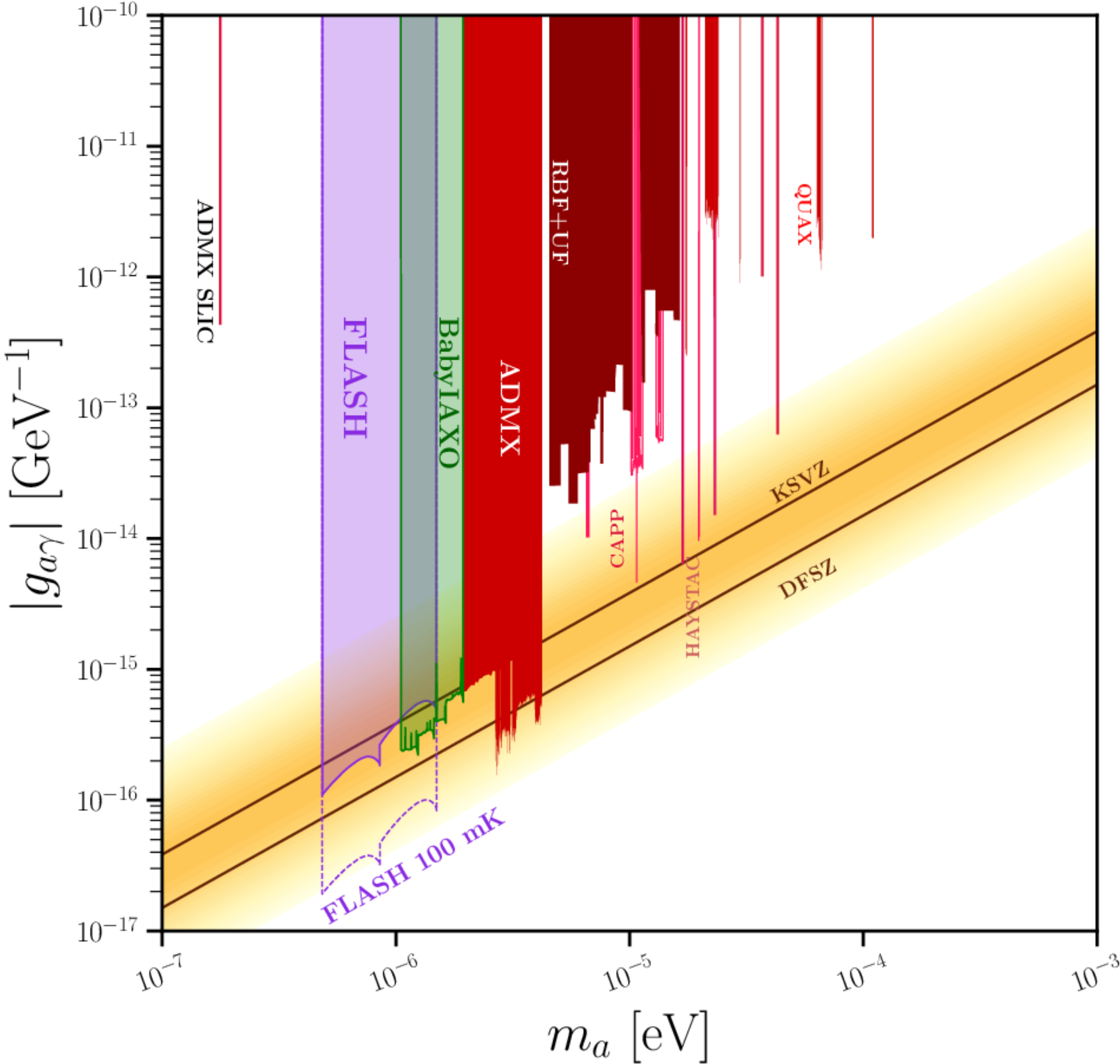
Q_L Quality factor V Cavity volume

B_0 Magnetic field C_{nml} Geometric factor



Courtesy of ADMX collaboration

Cavity search at INFN Frascati National Labs



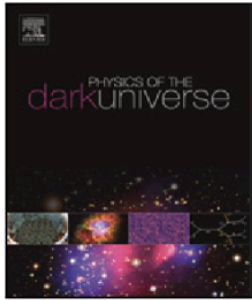
FLASH cavity search with
Claudio Gatti's group (INFN-LNF)
Alesini+ [2309.00351](#), with **LV**



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](#)]

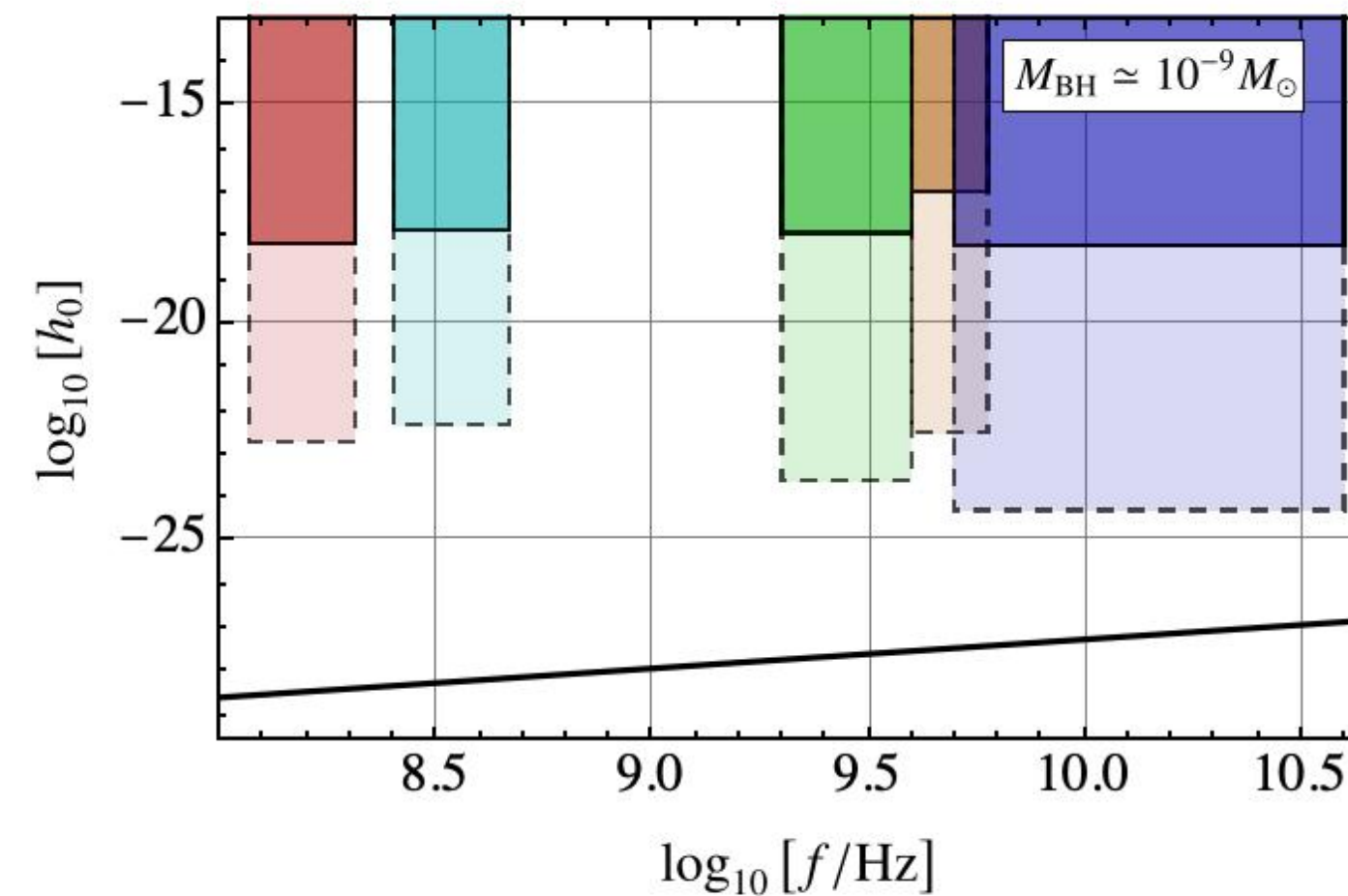
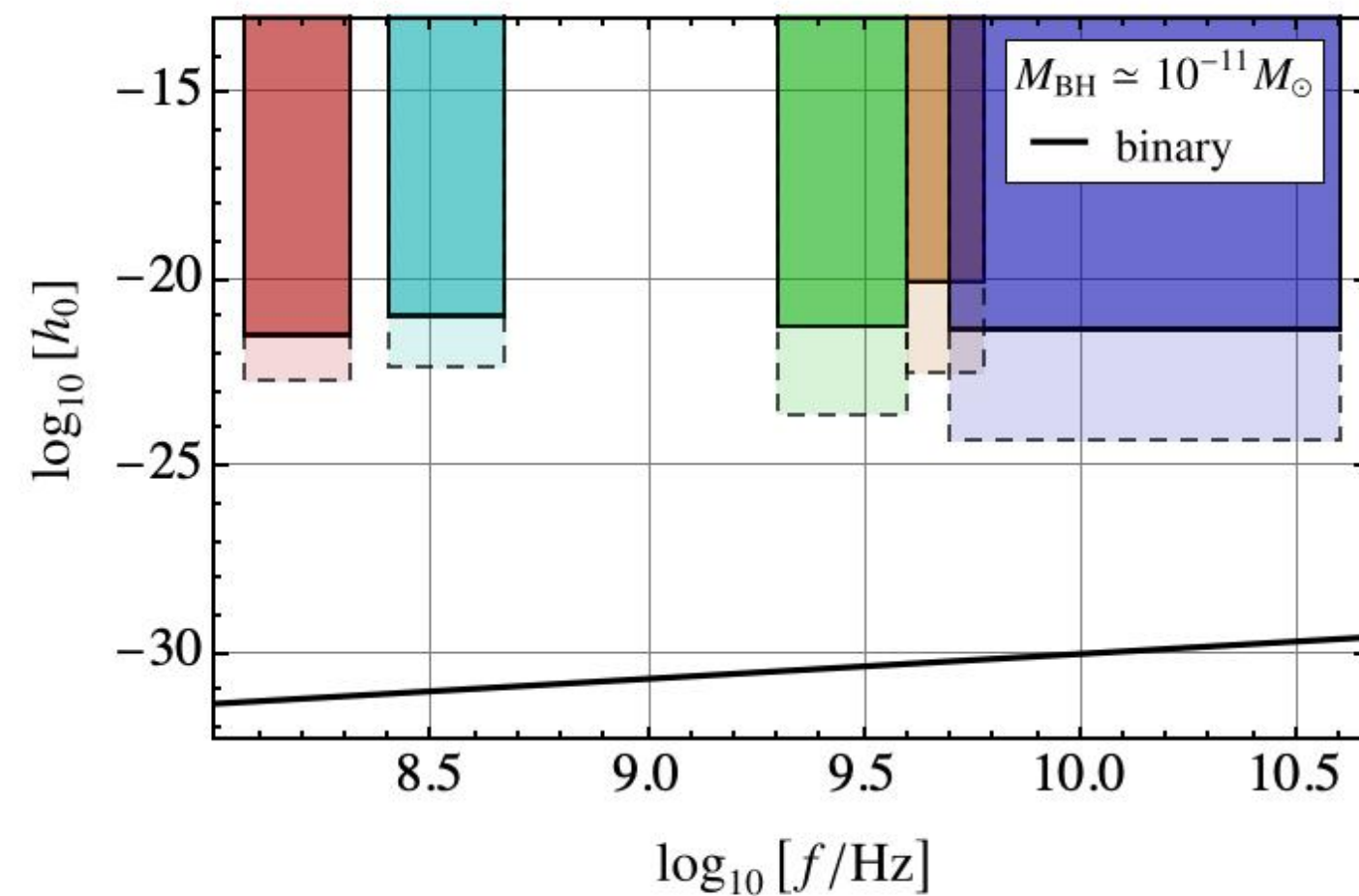
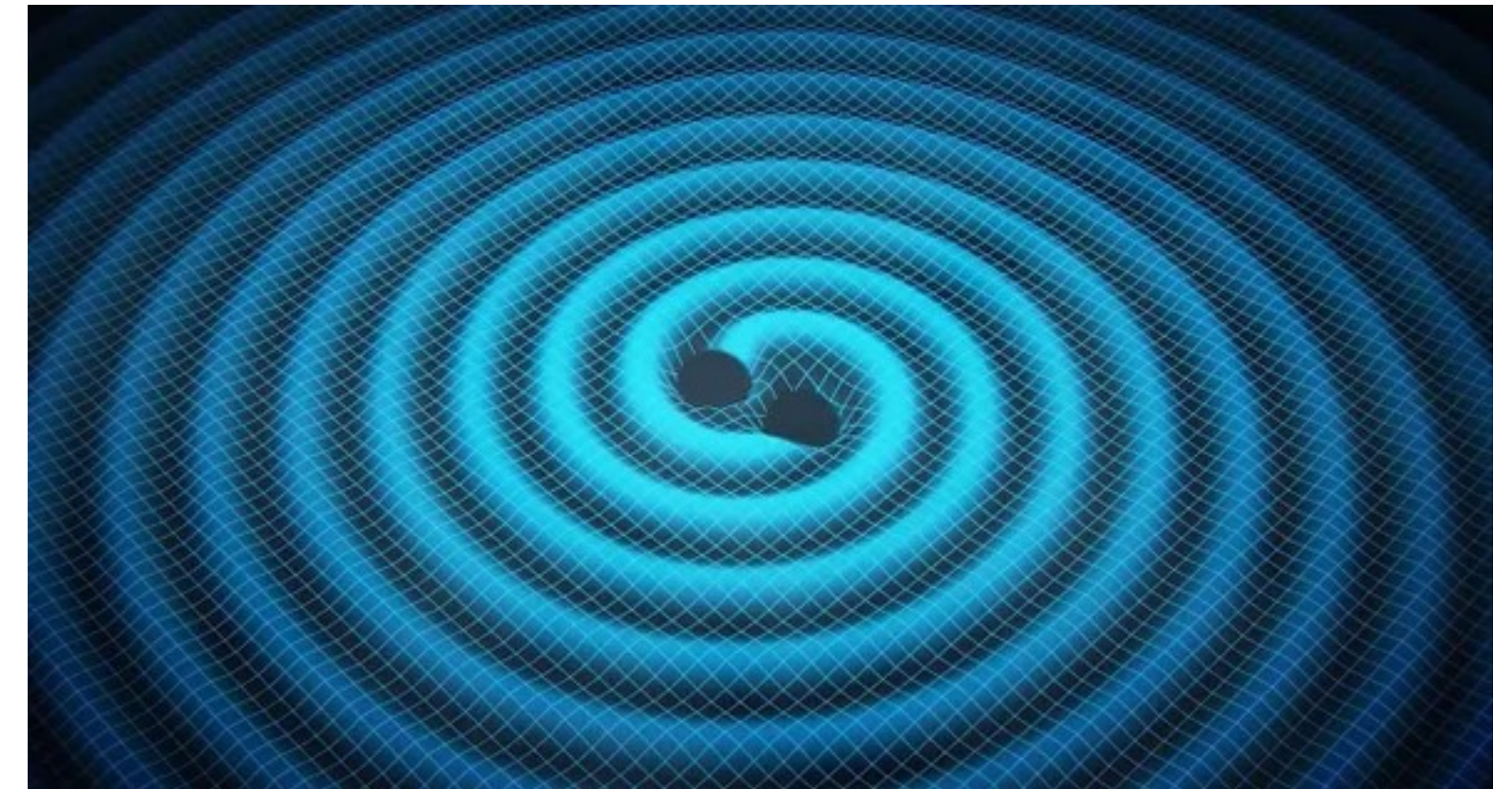
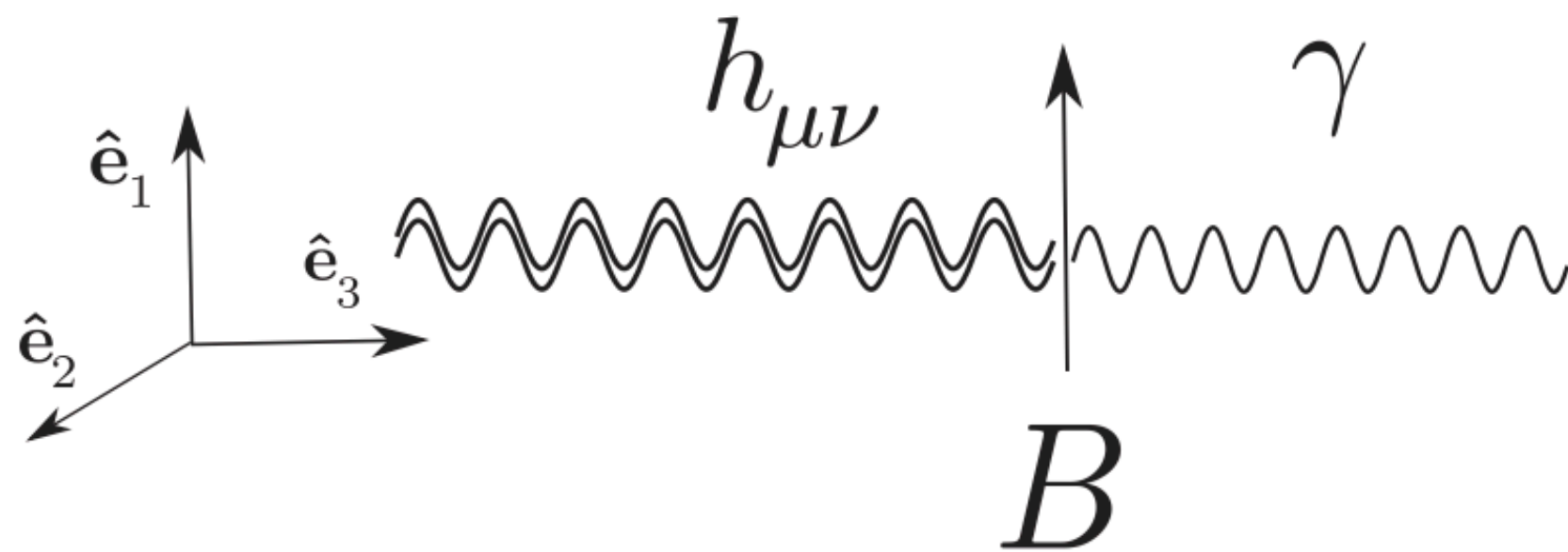
See also CADEX, PAS



High-frequency gravitational waves

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

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



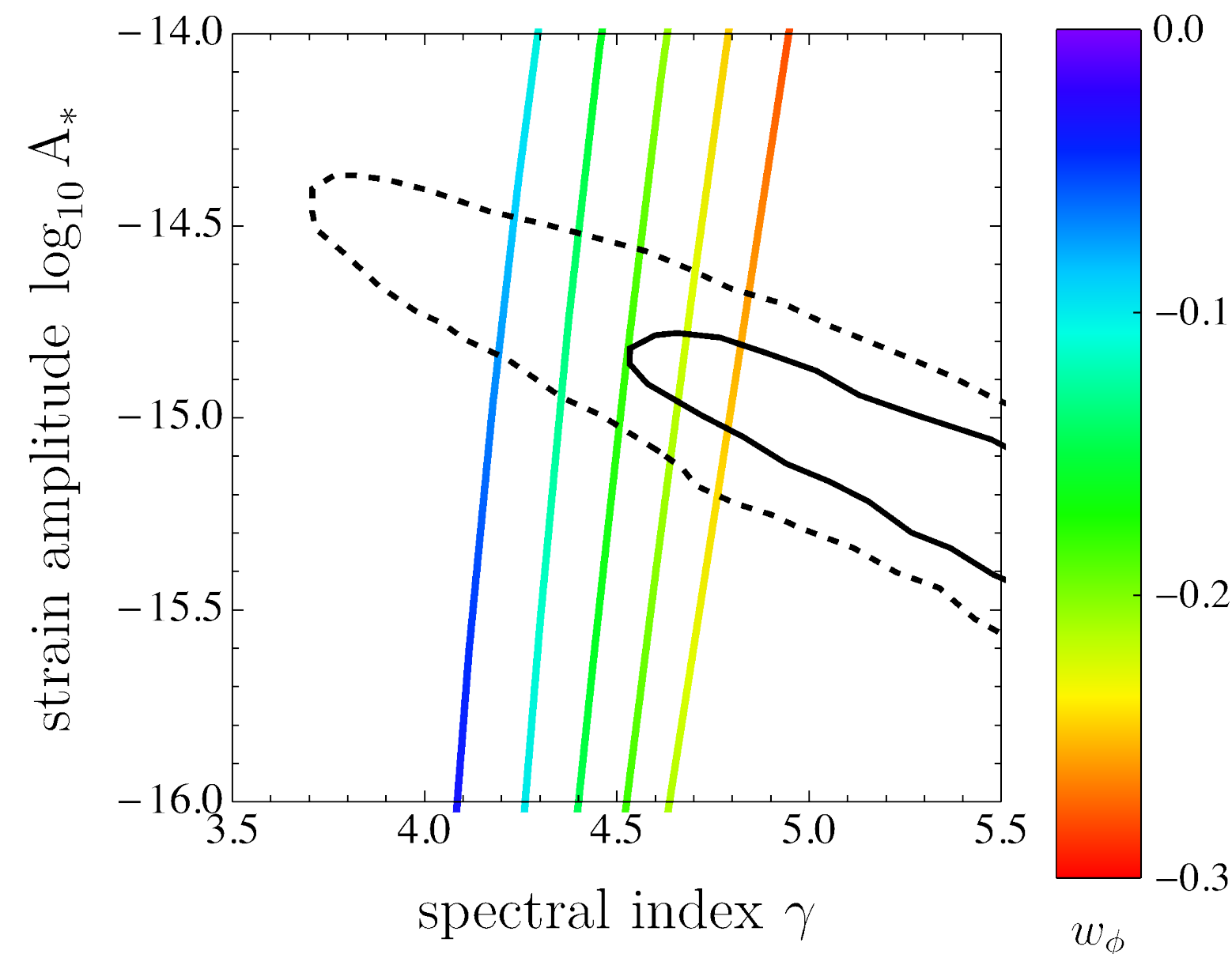
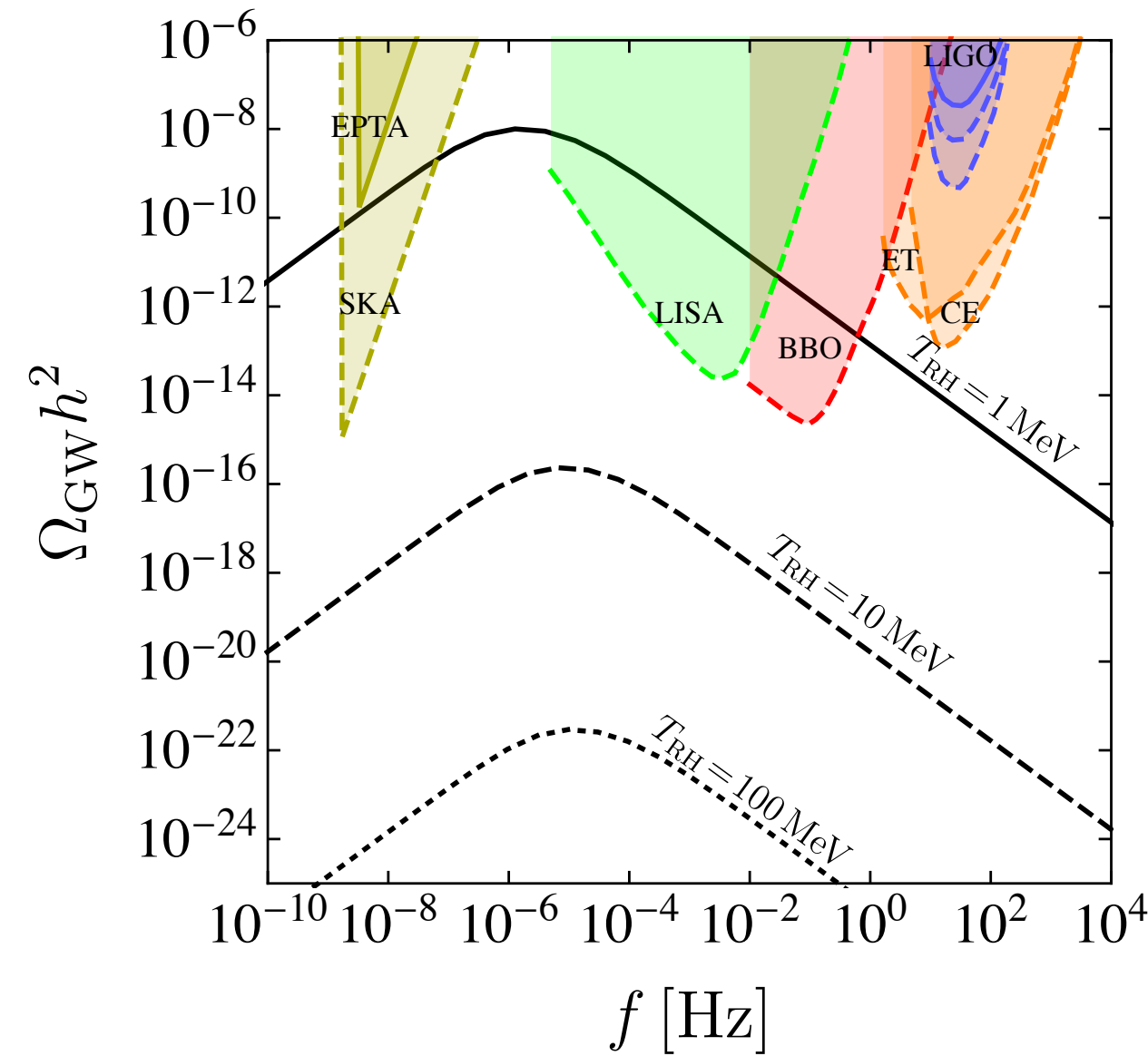
- FLASH LowT
- BabyIAXO
- ADMX EFR
- HAYSTAC
- ALPHA



Gatti, **LV**, Zantedeschi [2403.18610](https://arxiv.org/abs/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

Nicklas Ramberg^{1,*} and Luca Visinelli^{1,2,†}

¹*Department of Physics and Astronomy, Uppsala University, Lägerhyddsvägen 1, 75120 Uppsala, Sweden*

²*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden*

 (Received 20 April 2019; published 13 June 2019)

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

QCD axion and gravitational waves in light of NANOGrav results

Nicklas Ramberg^{1,*} and Luca Visinelli^{2,†}

¹*PRISMA+ Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

²*INFN, Laboratori Nazionali di Frascati, C.P. 13, 100044 Frascati, Italy*

 (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.

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](#)

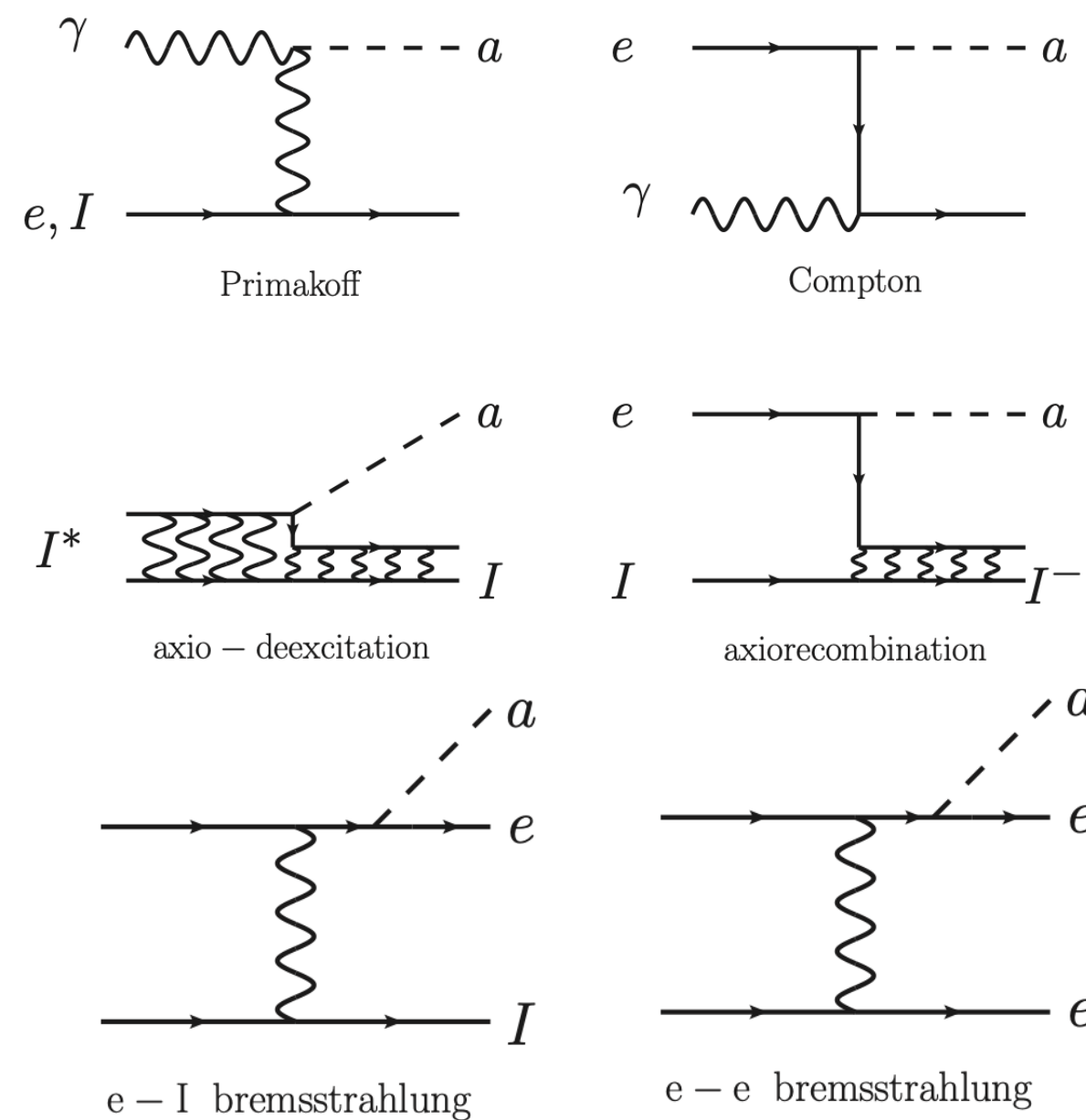
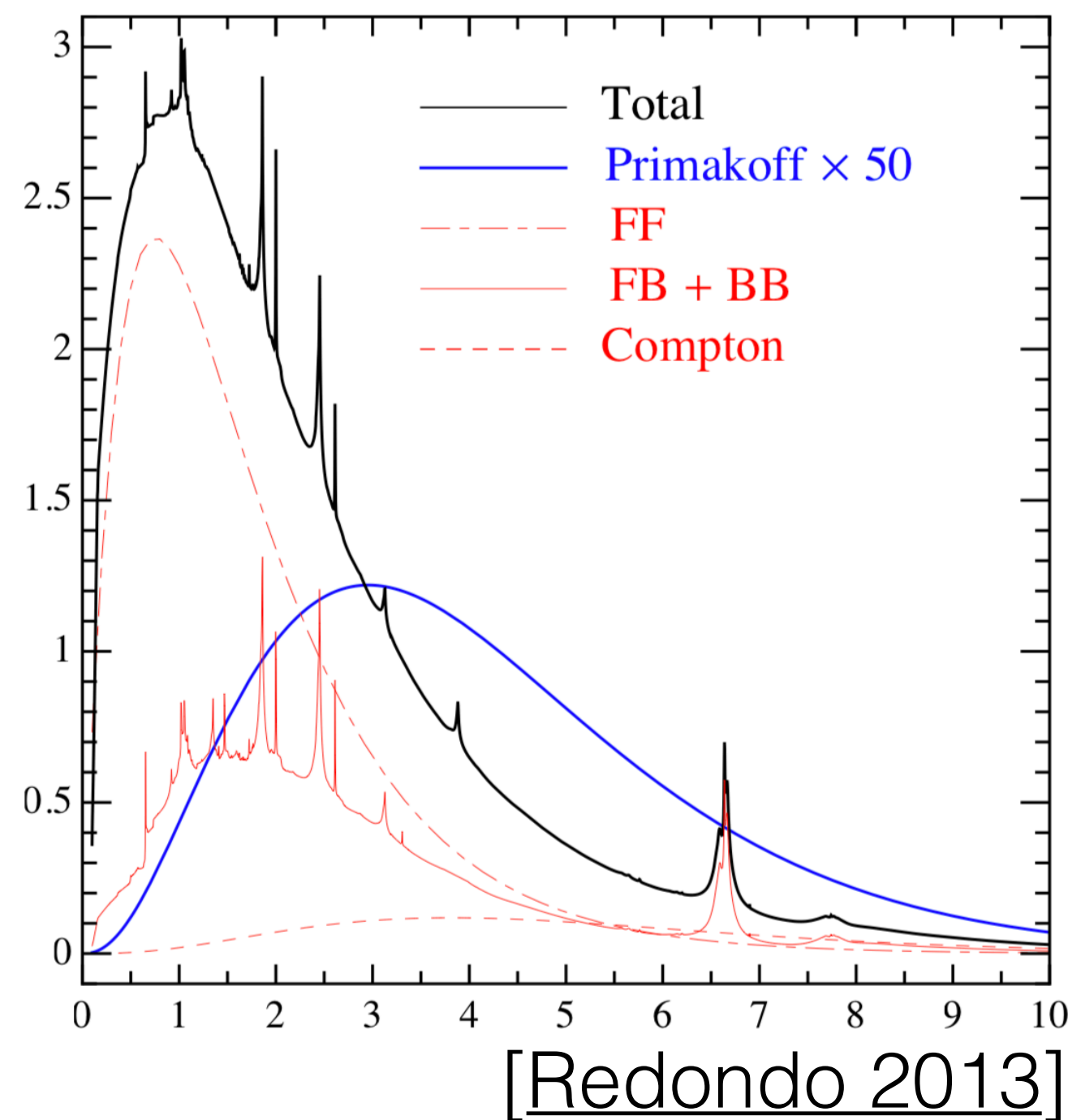
Please re-cast the results and re-use the code!

[2011.05377](#), [2011.05378](#)
github.com/bradkav/axion-miniclusters

Thank you!

Axion production in the Sun

$$\mathcal{L}_{\text{int}} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + g_{ae} \frac{\partial_\mu a}{2m_e} \bar{e} \gamma^\mu \gamma_5 e,$$



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

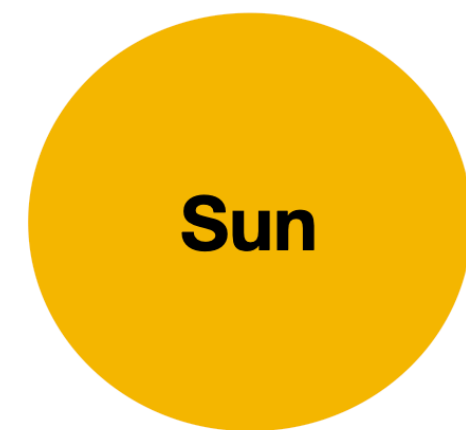
$$\Phi_a^{\text{ABC}} \propto g_{ae}^2$$

These are relativistic axions, not the DM!

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

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

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



keV plasma
produces
axions

relativistic
axions
→

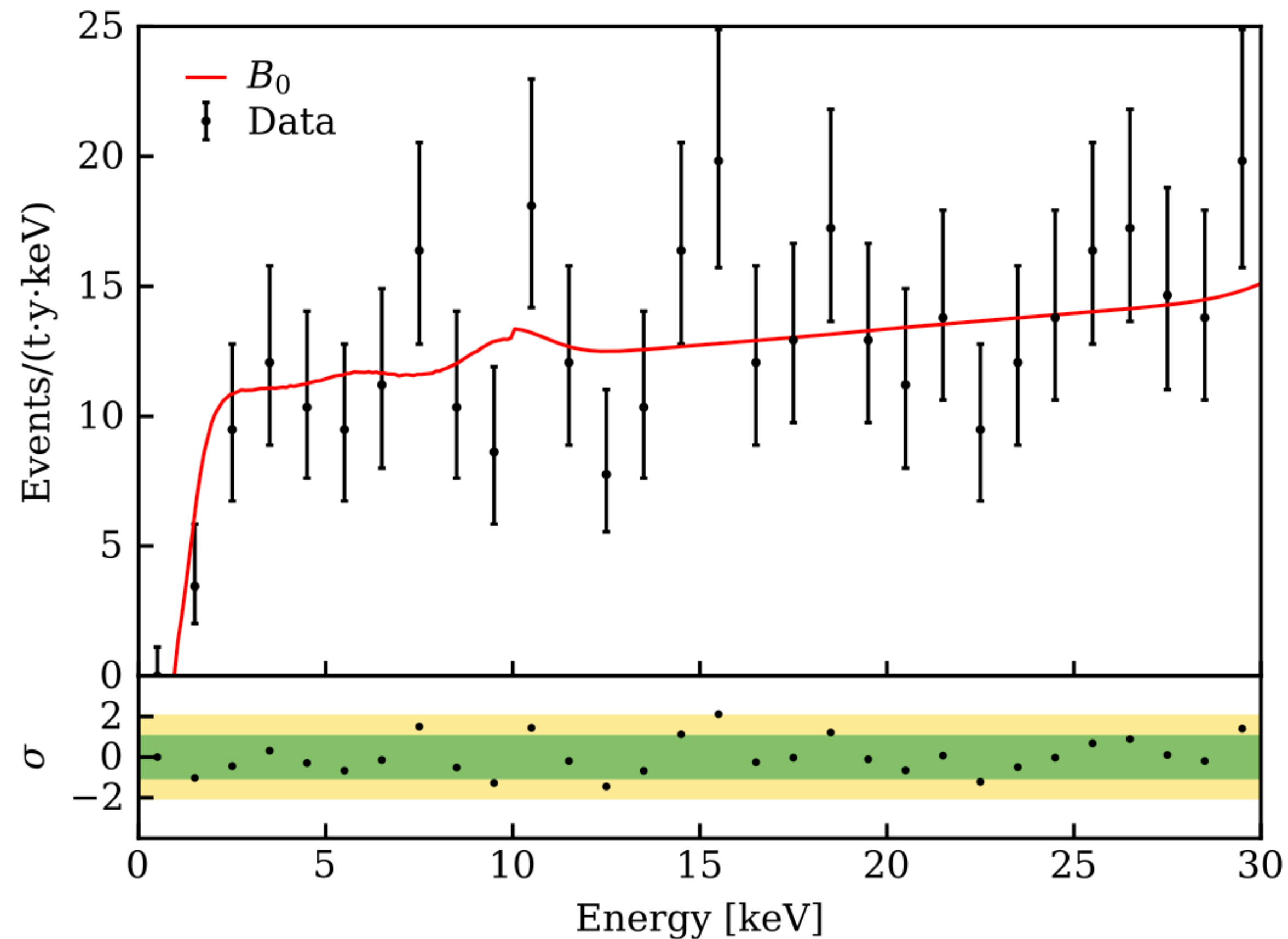


X-rays
→

High B field converts axions → photons

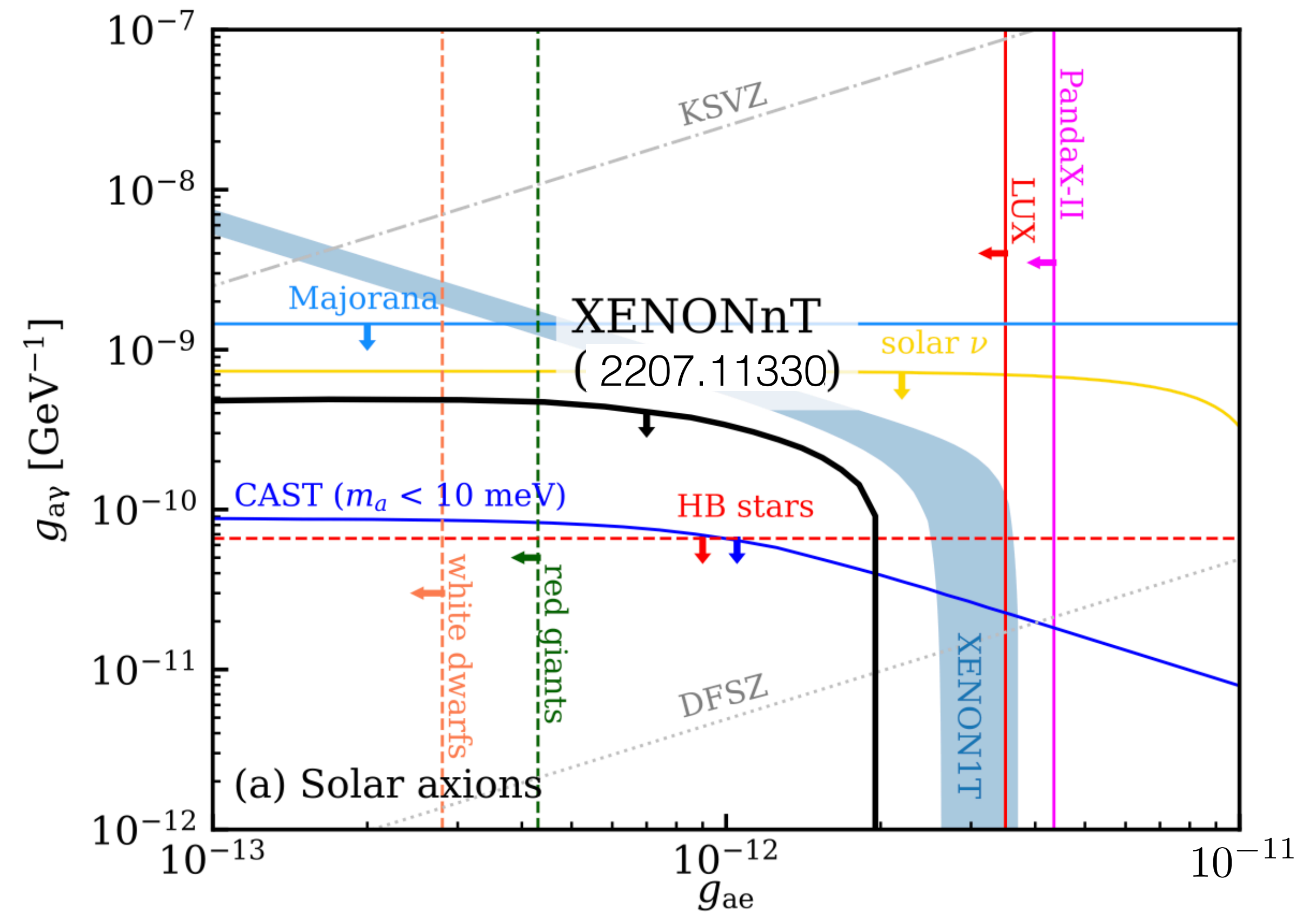
Figure from Ben Safdi

Axions from the Sun



Previous results “XENON1T excess” [[2006.09721](#)]

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



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

LZ searches: [2307.15753](#)

Axions and scalars from the Sun

New exploration frontier: Scalar field production in the Sun

We have considered solar chameleons produced from

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

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

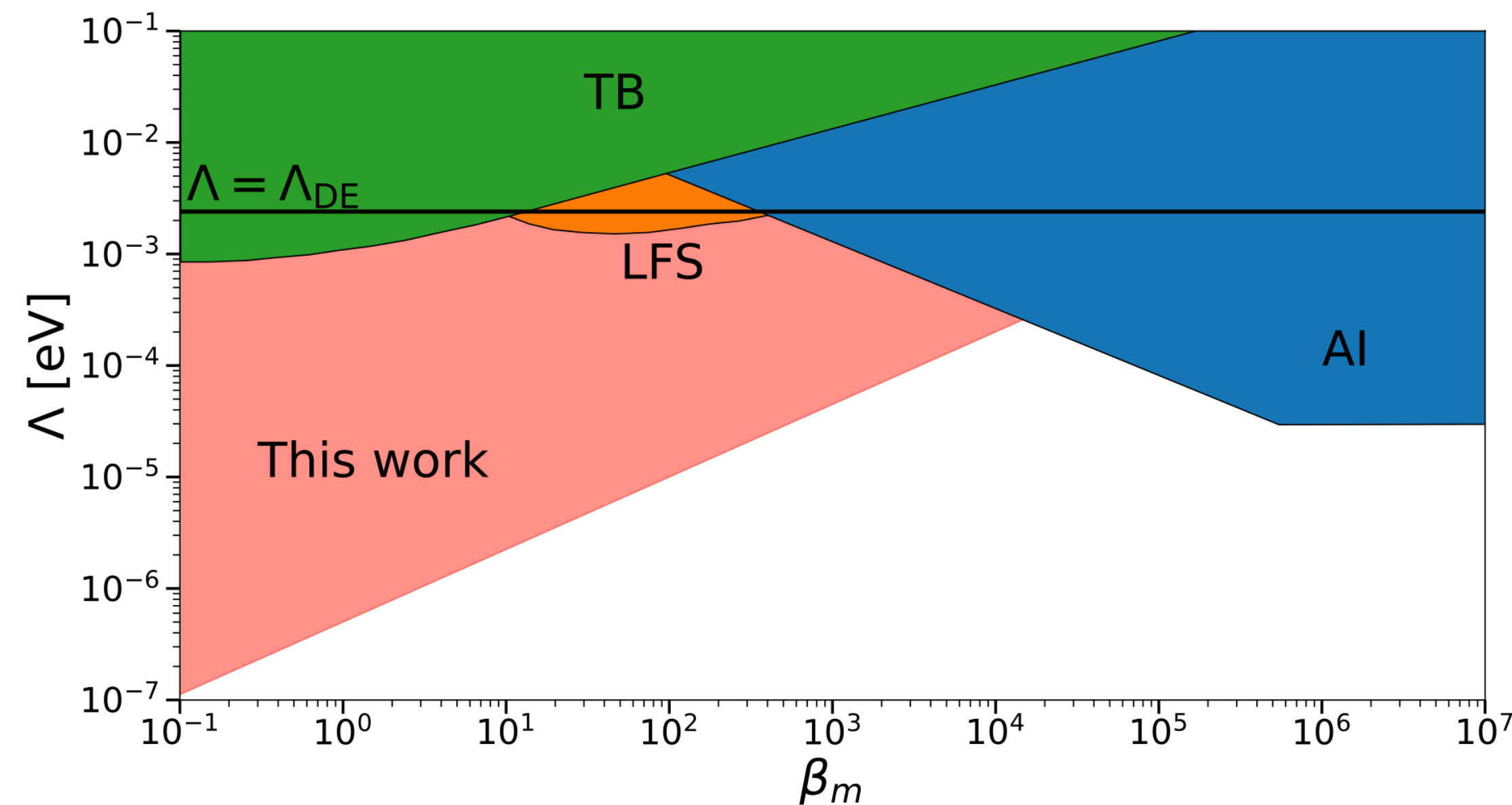
Axions and scalars from the Sun

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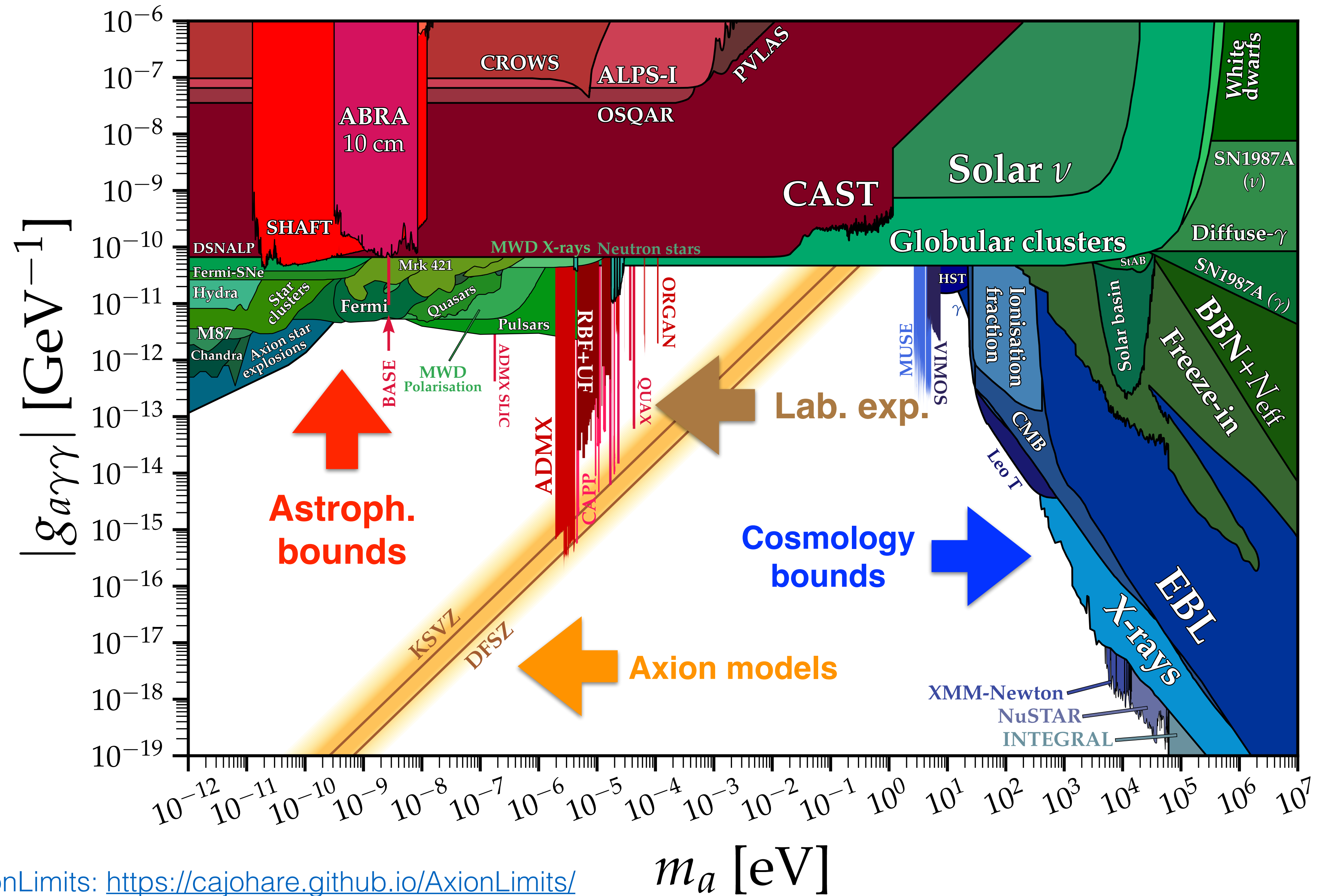
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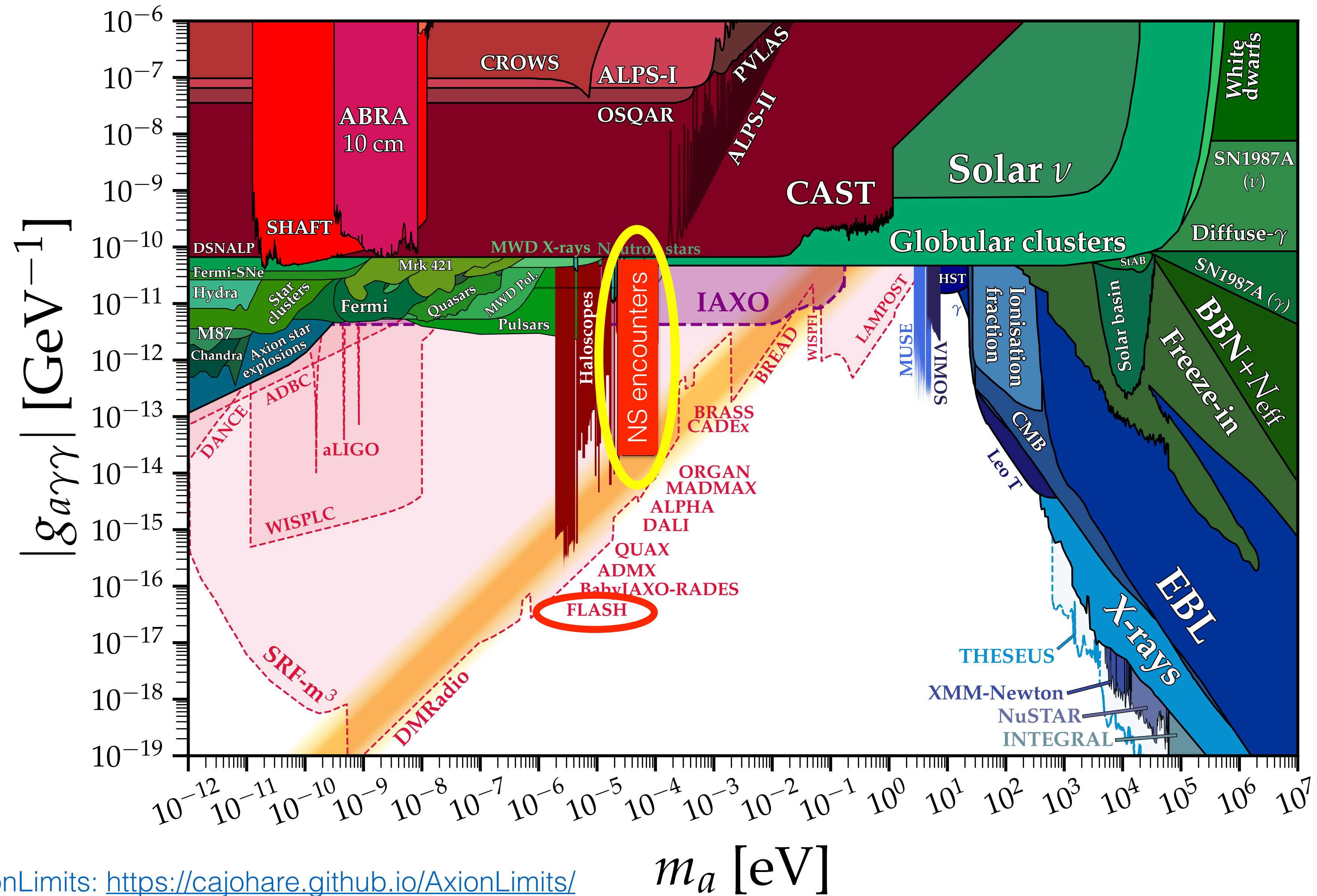


O'Shea, Davis, Giannotti, Vagnozzi, **LV**, Vogel
[\[2406.01691\]](#)

Summary of axion-photon coupling bounds



Summary of axion-photon coupling bounds

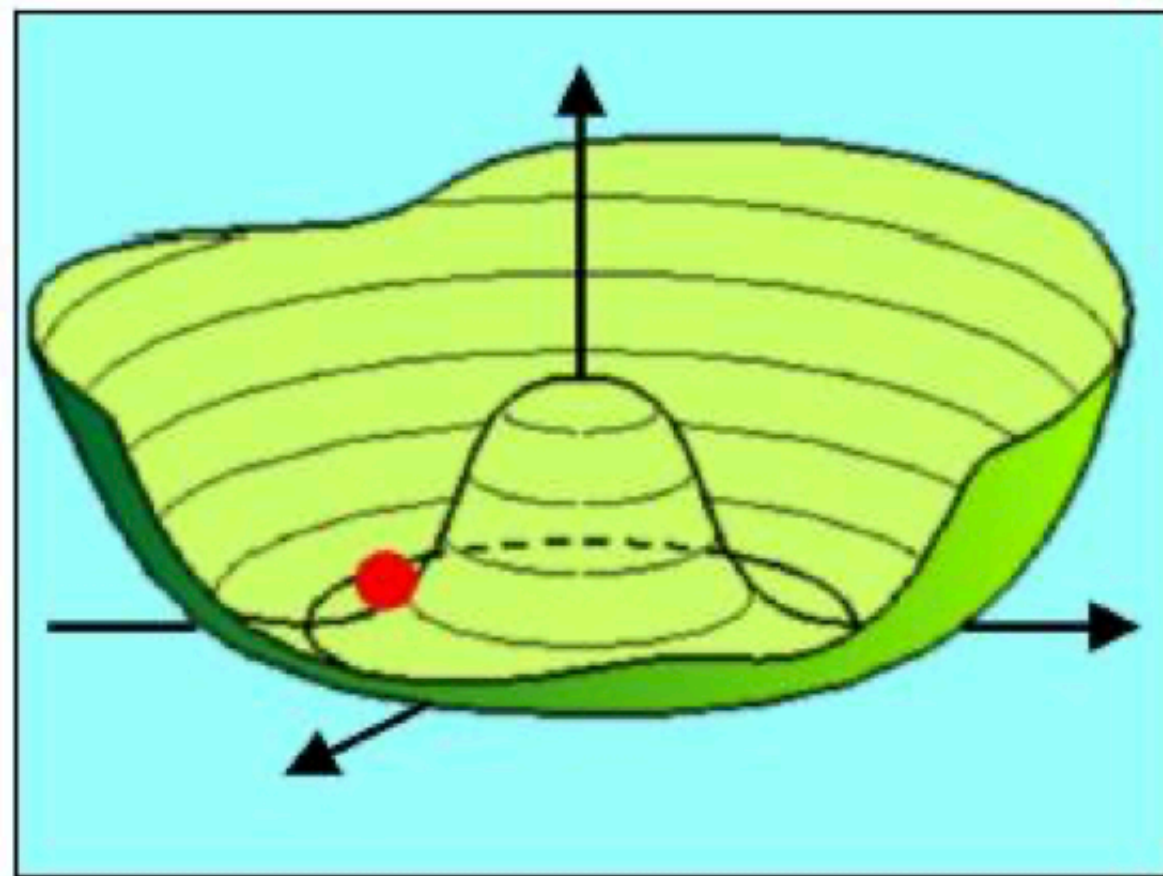


Assumption: The PQ symmetry broke after inflation, $f_a \lesssim H_I$

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



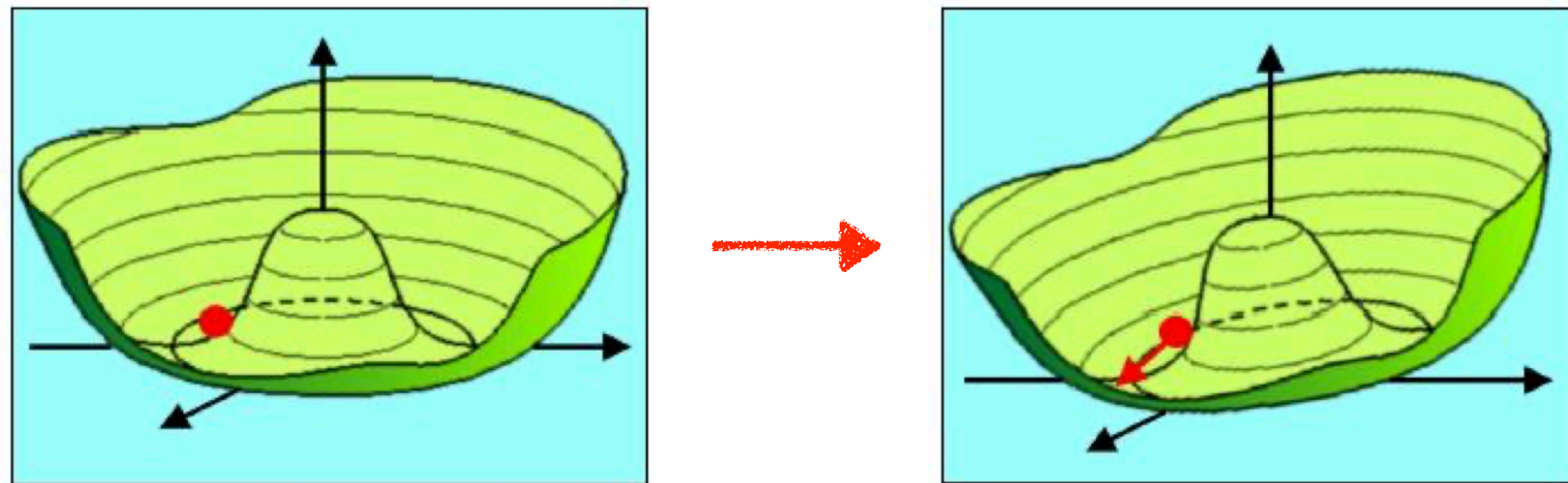
Figures from Steen Hannestad

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Figures from Steen Hannestad

Misalignment mechanism

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

→ 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: $V(\phi, T = 0) = V_{\text{CPT}}(\phi)$ [Di Vecchia & Veneziano 1980]

Finite temperature, QCD instantons effectively couple the axion to the plasma

$$m_a^2(T) \approx \min \left(m_a^2, \frac{\Lambda^4}{f_a^2 (T/\Lambda)^n} \right) \quad [\text{Gross+ 1981}]$$

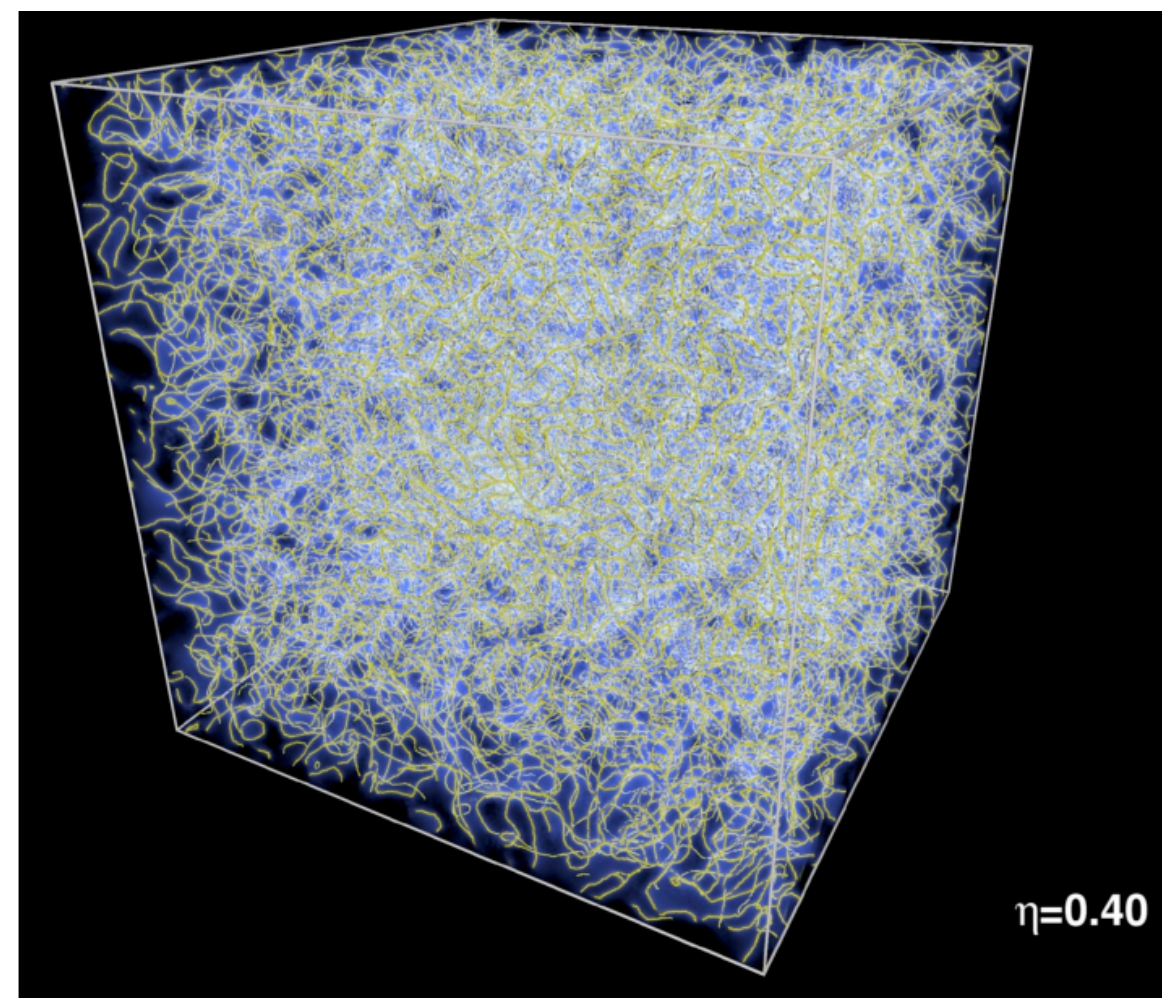
The exact assessment comes from lattice QCD computations [Borsanyi+ 2016]

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

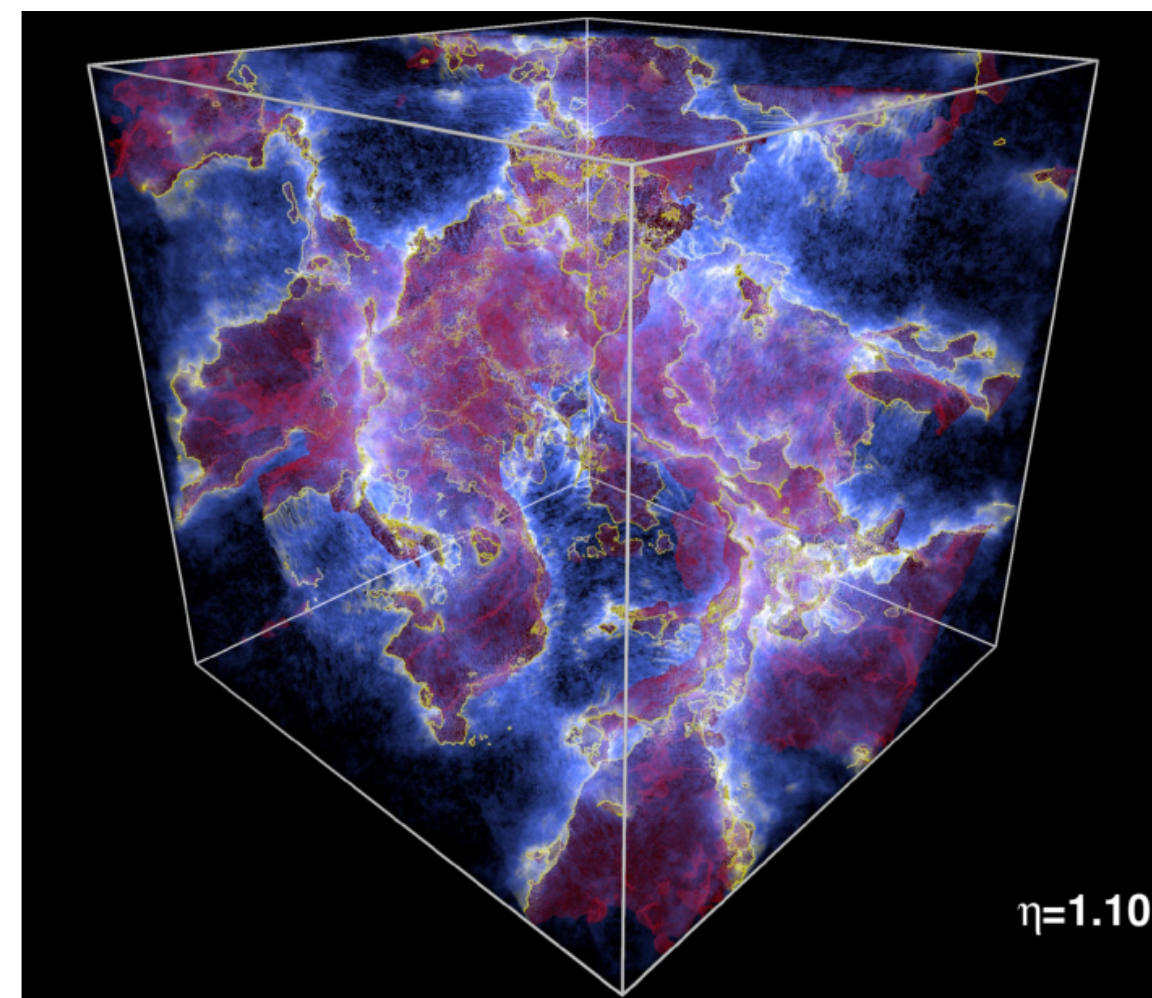
String network quickly enters a scaling regime with $\rho_{\text{scaling}} = \xi\mu/t^2$

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

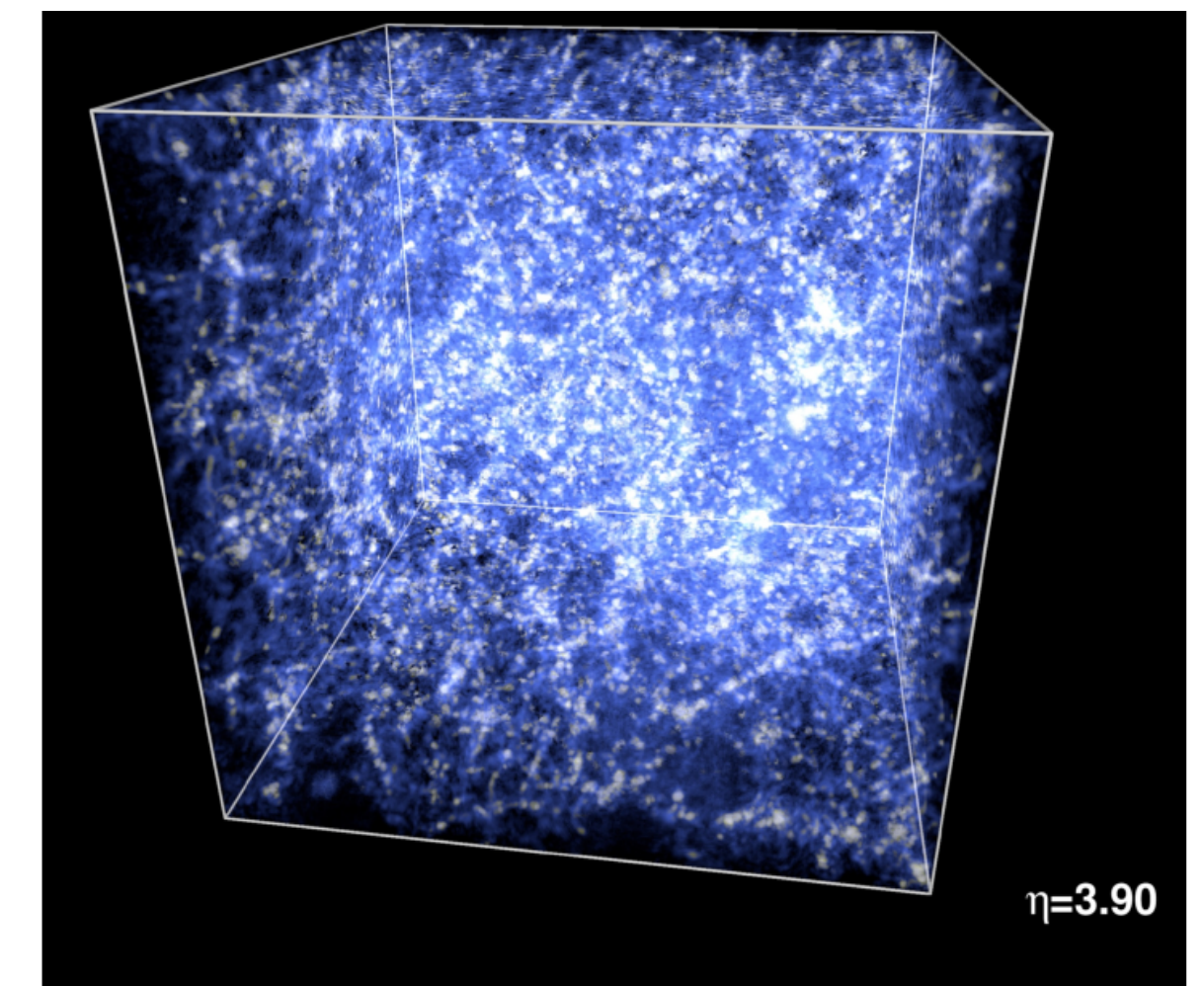
String length per Hubble volume ξ



Before QCD PT



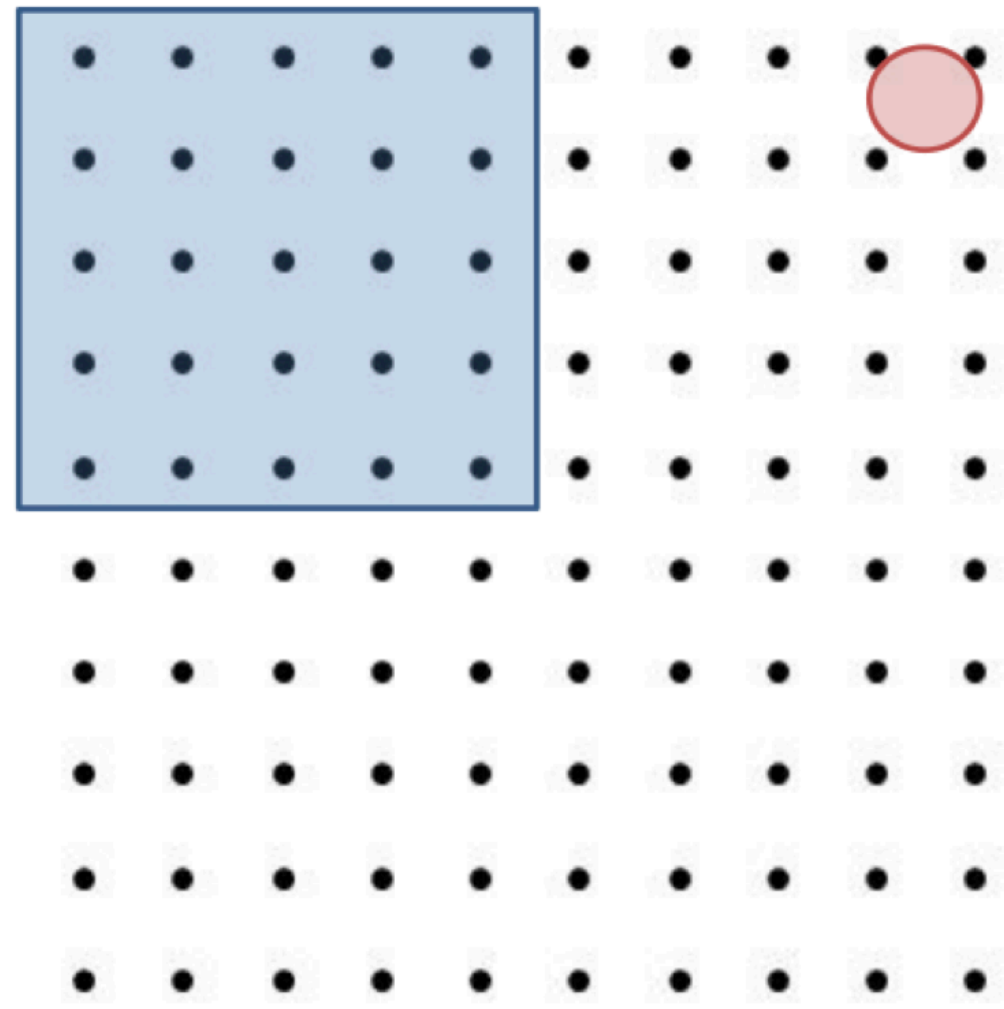
During QCD PT



After QCD PT

Figures from [Buschmann+ 2020]

Various groups work on axion string simulations: no agreement



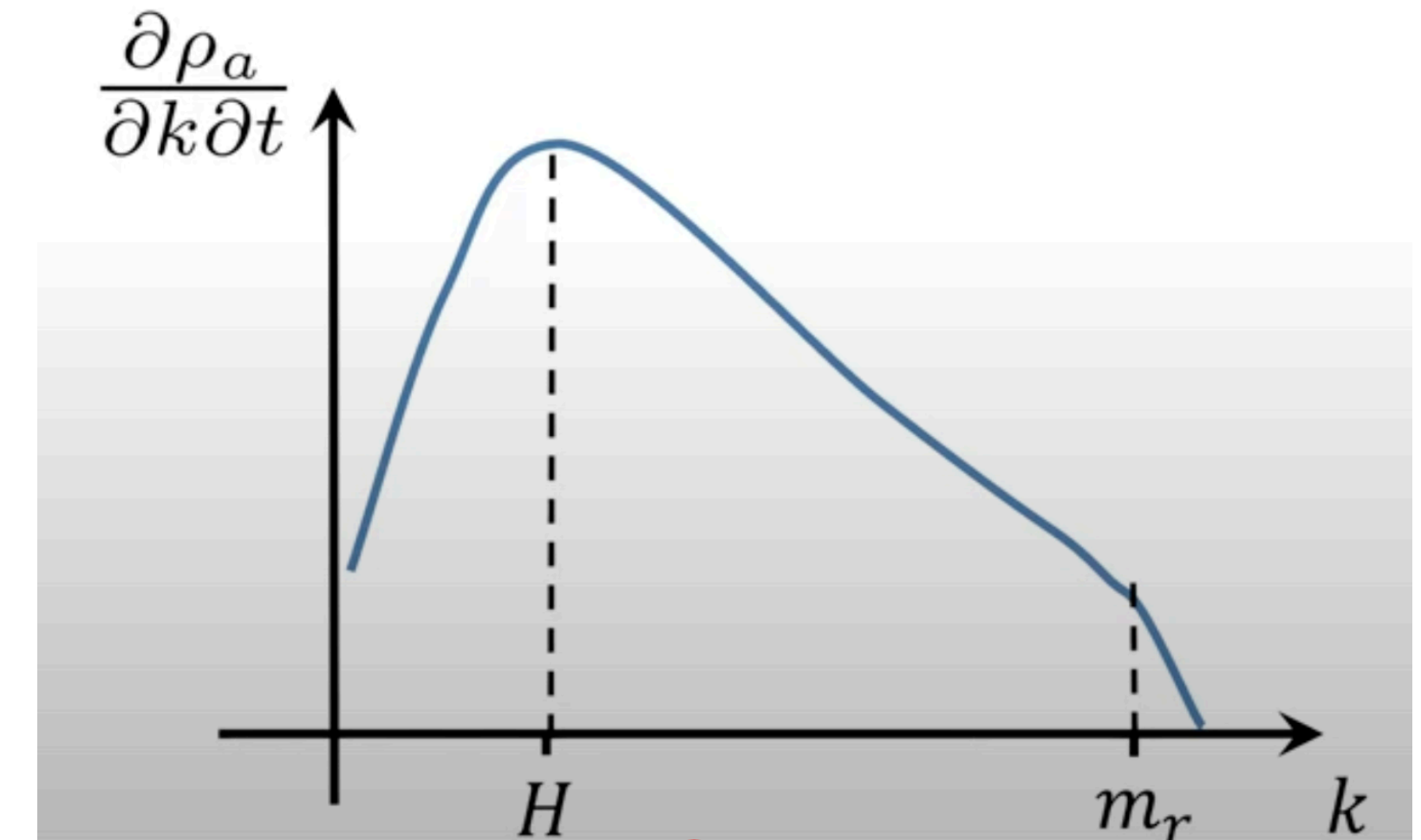
$$N \approx 5000^3$$

$$\text{simulations: } \log \alpha \leq \log\left(\frac{\square}{\circ}\right) \simeq 7$$

Yet $\log(f_a t) \approx 70$ needed

$$\frac{\partial \rho_a}{\partial k \partial t} \propto \frac{1}{k^q} \quad \text{Energy spectrum of emitted axions}$$

Credits: Ed Hardy



The spectrum peaks at $k \approx H$ (string curvature). Cutoff at $k \approx \sqrt{2\lambda} f_a$

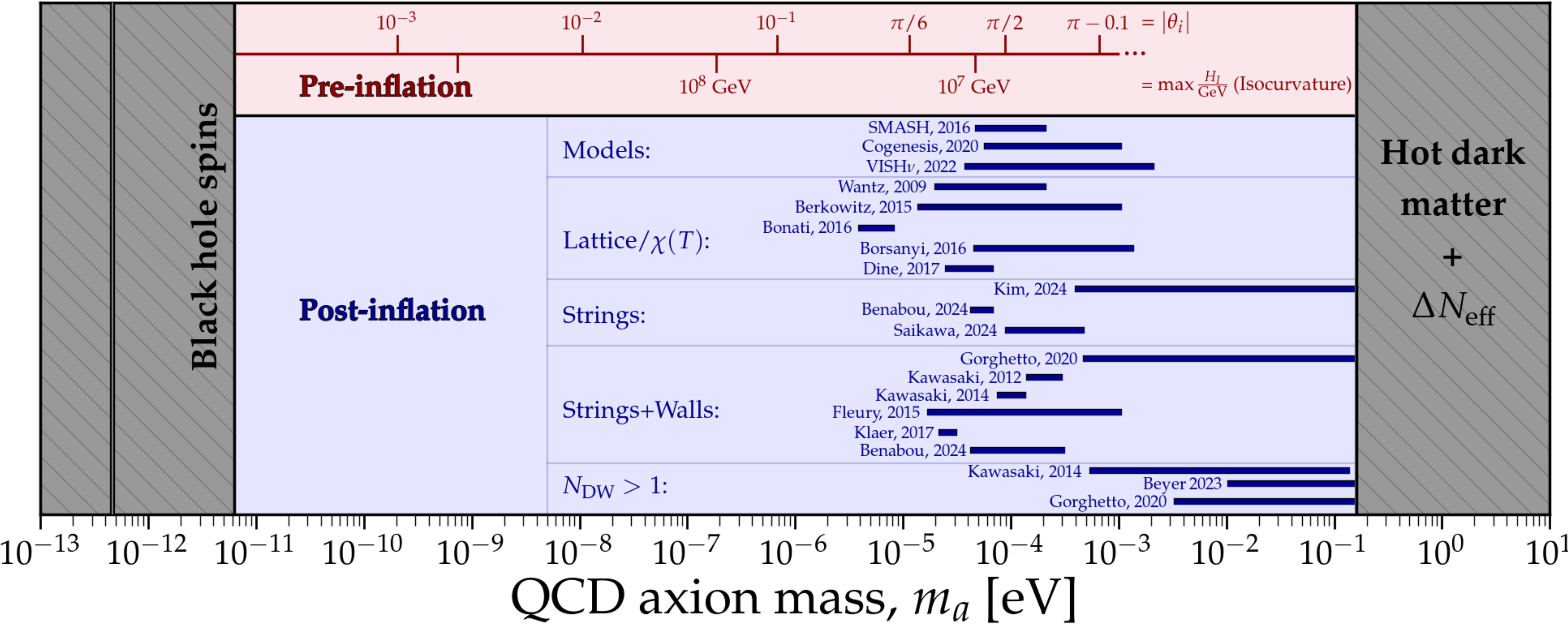
“Effective Nambu–Goto string” [Davis [1985](#), [1986](#); Battye & Shellard [1994a](#), [1994b](#)]
 $q > 1$ leads to more axions and a higher DM mass $\sim \text{meV}$ [Gorghetto+ [2018](#), [2021](#)]

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](#)]

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



Our 2020 review on the QCD axion was born here

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The landscape of QCD axion models

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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.

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Di Luzio, Giannotti, Nardi, **LV** [2003.01100](#)

