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G.A. 754496

Axion miniclusters in the Milky Way

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Based on: 2011.05377, 2011.05378

The QCD axion is a well-motivated extension to SM

The axion might :

1. Solve the strong-CP problem of the neutron electric dipole moment;

2. Explain the observe dark matter (DM) abundance.

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$$\mathcal{L} = \frac{g^2}{32\pi^2}\,\frac{a}{f_a}\,G\tilde{G}$$

+ shift symmetry

$$a \to a + \kappa f_a$$

g: QCD coupling constant

G: gluon field strength

a: axion field

f_a: axion decay constant

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QCD axion mass (peculiar to QCD model)

$$m_a \approx 6\,\mu\mathrm{eV}(10^{12}\,\mathrm{GeV}/f_a)$$

The QCD axion is a well-motivated extension to SM

Additional couplings to photons and matter:

$$\mathcal{L} \supset \left(\frac{C_{a\gamma\gamma}\,\alpha_{\rm EM}}{2\pi f_a}\right)\frac{1}{4}\, a F^{\mu\nu}\tilde{F}_{\mu\nu} + \sum_f \left(\frac{C_{af}}{2f_a}\right)(\partial_\mu a)\,\bar{f}\gamma^\mu\gamma_5 f$$

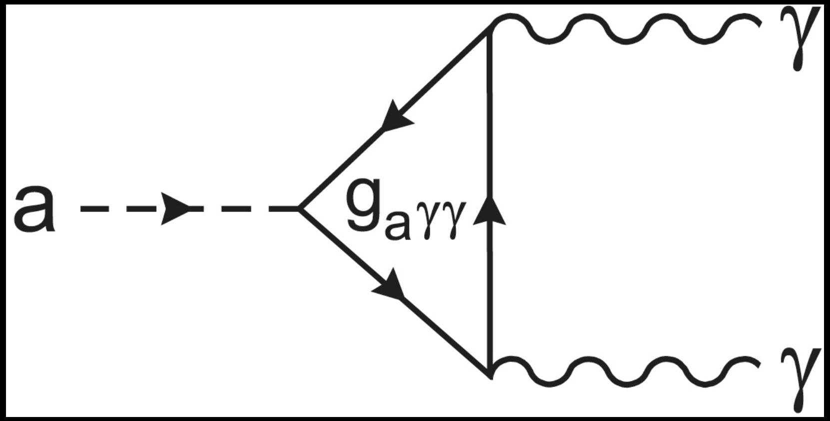
Photon field strength

Fermion field

$g_{a\gamma\gamma}$

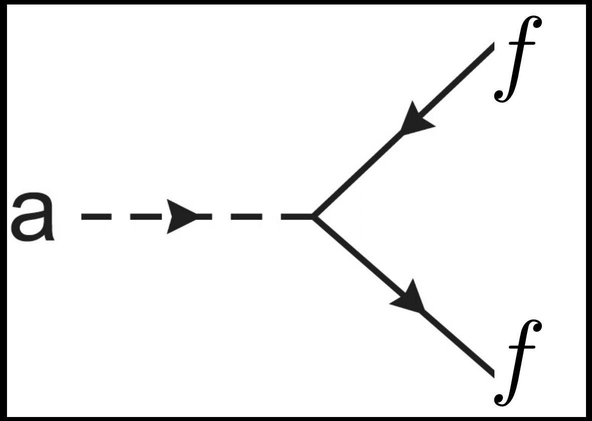
$g_{aff} \equiv C_{af}\, m_f / f_a$

Axion-photon coupling

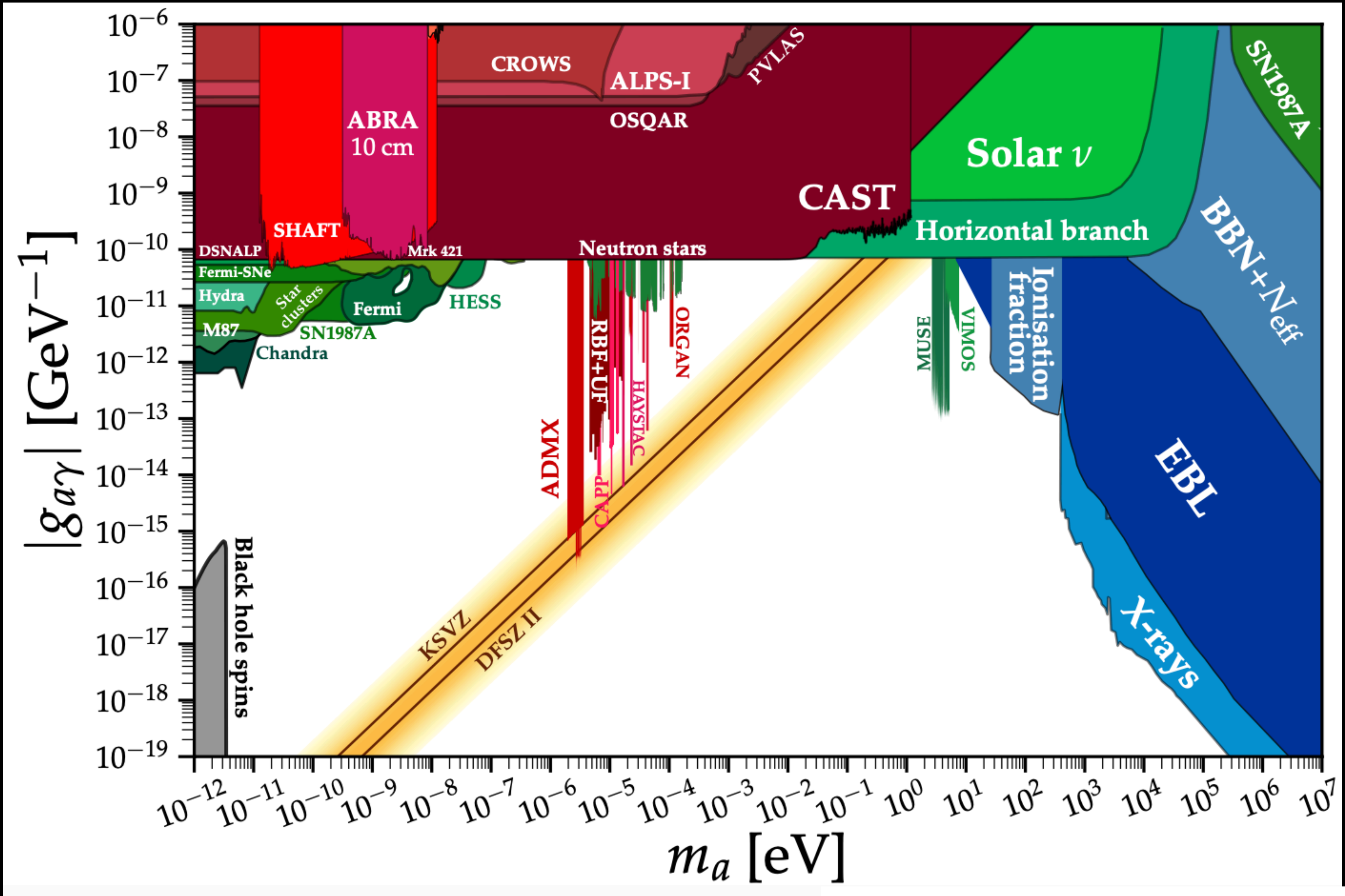


Axion-fermion coupling

(contains an extra contribution from the fermion mass m_f)

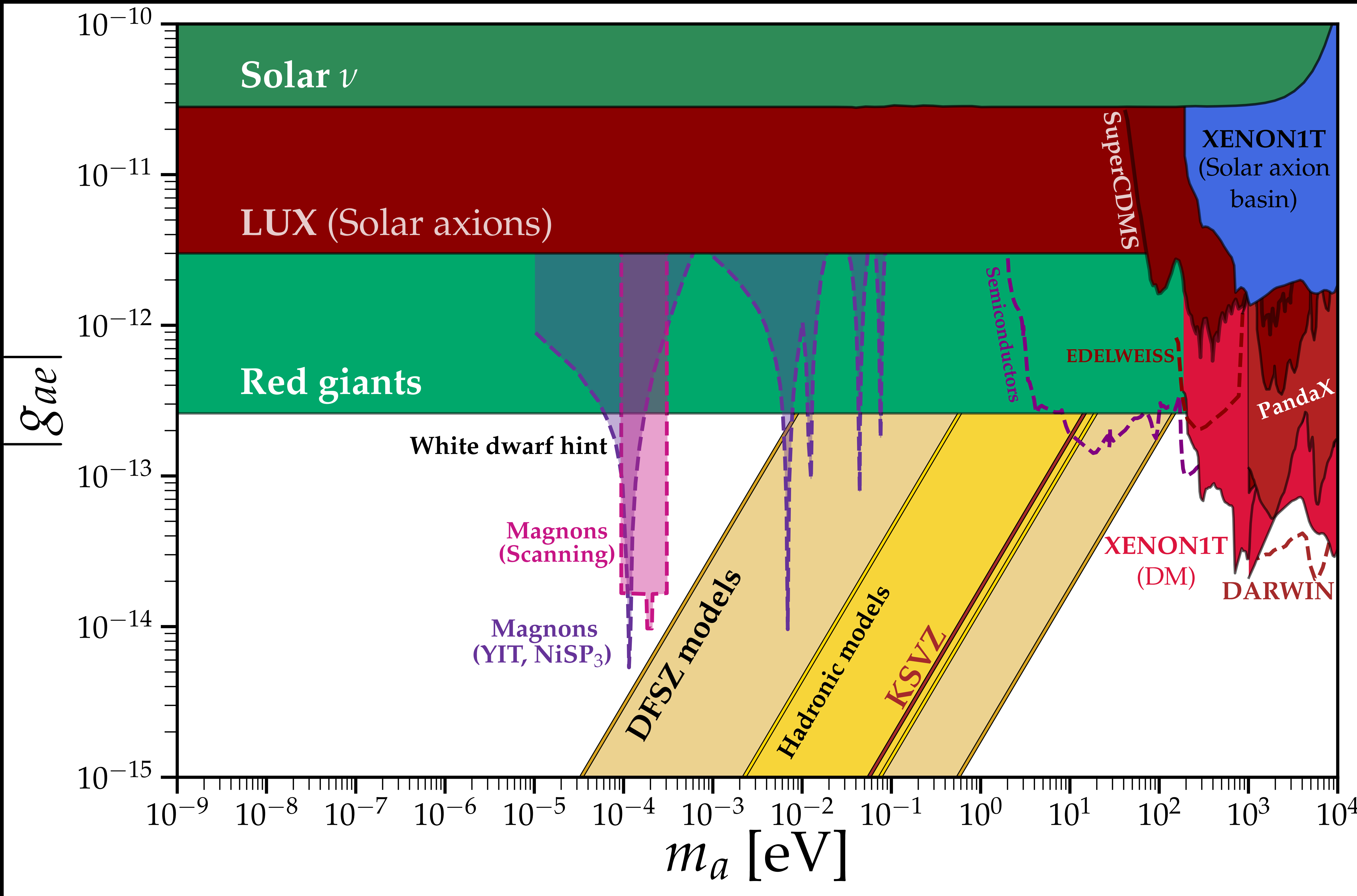


Axion-photon coupling



[O'Hare, cajohare.github.io/AxionLimits/]

Axion-electron coupling

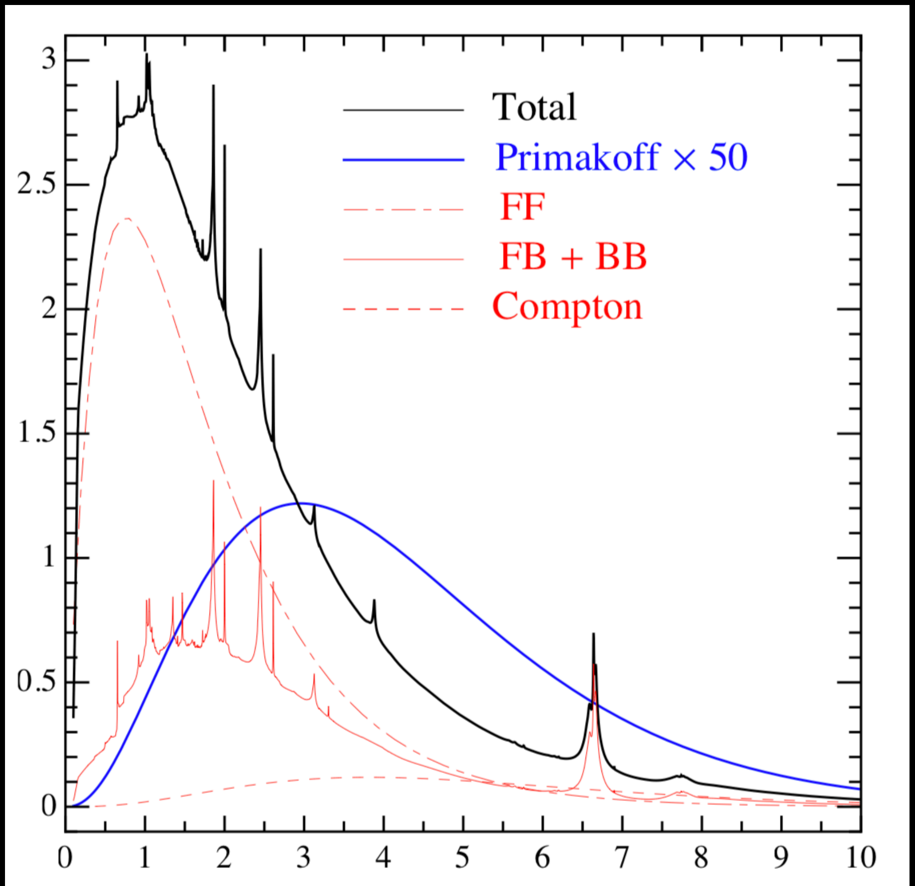


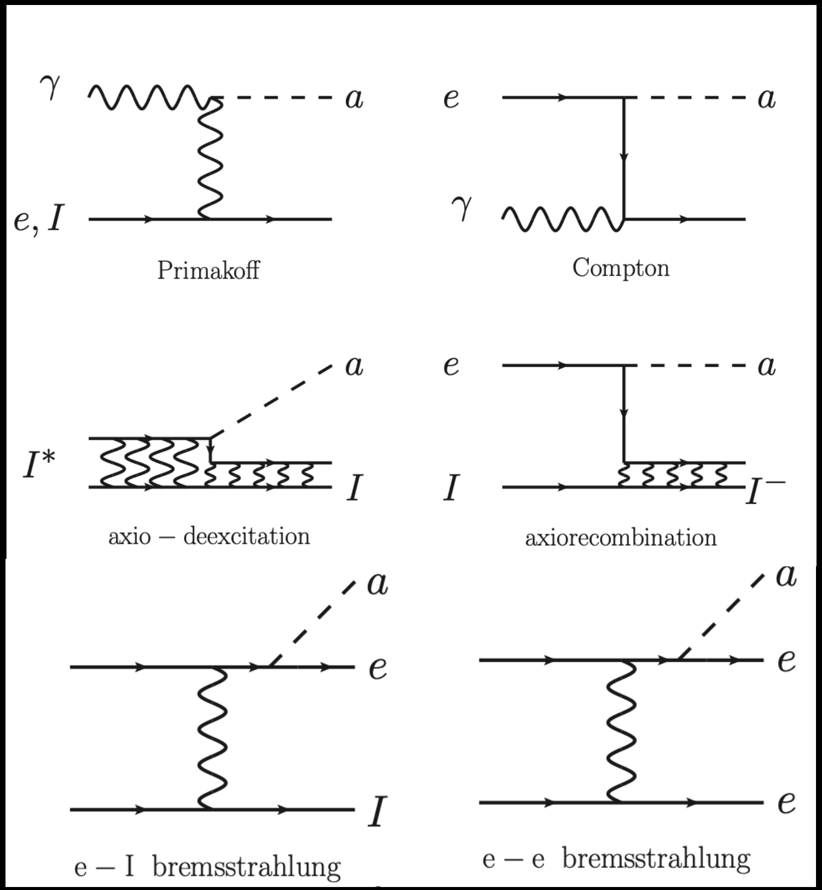
[O'Hare, cajohare.github.io/AxionLimits/]

Solar axion production

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

Raffelt 86, 88; Redondo 1310.0823





ABC (g_{ae})
+ Primakoff ($g_{a\gamma}$)

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

$$\Phi_{\rm a}^{\rm ABC} \propto g_{\rm ae}^2$$

DFSZ models: axion couples at tree level to electron (ABC dominates)
KSVZ models: axion couples to electrons through loops (Primakoff dominates)

Excess electronic recoil events in XENON1T

XENON Collaboration • E. Aprile (Columbia U.) Show All(139)

Jun 17, 2020

We report results from searches for new physics with low-energy electronic recoil data recorded with the XENON1T detector. With an exposure of 0.65 tonne-years and an unprecedentedly low background rate of 76±2stat events/(tonne×year×keV) between 1 and 30 keV, the data enable one of the most sensitive searches for solar axions, an enhanced neutrino magnetic moment using solar neutrinos, and bosonic dark matter. An excess over known backgrounds is observed at low energies and most prominent between 2 and 3 keV. The solar axion model has a 3.4σ significance, and a three-dimensional 90% confidence surface is reported for axion couplings to electrons, photons, and nucleons. This surface is inscribed in the cuboid defined by gae<3.8×10-12, gaeganeff<4.8×10-18, and gaegaγ<7.7×10-22 GeV-1, and excludes either gae=0 or gaegaγ=gaeganeff=0. The neutrino magnetic moment signal is similarly favored over background at 3.2σ, and a confidence interval of μν∈(1.4,2.9)×10-11 μB (90% C.L.) is reported. Both results are in strong tension with stellar constraints. The excess can also be explained by β decays of tritium at 3.2σ significance with a corresponding tritium concentration in xenon of (6.2±2.0)×10-25 mol/mol. Such a trace amount can neither be confirmed nor excluded with current knowledge of its production and reduction mechanisms. The significances of the solar axion and neutrino magnetic moment hypotheses are decreased to 2.0σ and 0.9σ, respectively, if an unconstrained tritium component is included in the fitting. With respect to bosonic dark matter, the excess favors a monoenergetic peak at (2.3±0.2) keV (68% C.L.) with a 3.0σ global (4.0σ local) significance over background. This analysis sets the most restrictive direct constraints to date on pseudoscalar and vector bosonic dark matter for most masses between 1 and 210 keV/c2. We also consider the possibility that Ar37 may be present in the detector, yielding a 2.82 keV peak from electron capture. Contrary to tritium, the Ar37 concentration can be tightly constrained and is found to be negligible.

26 pages

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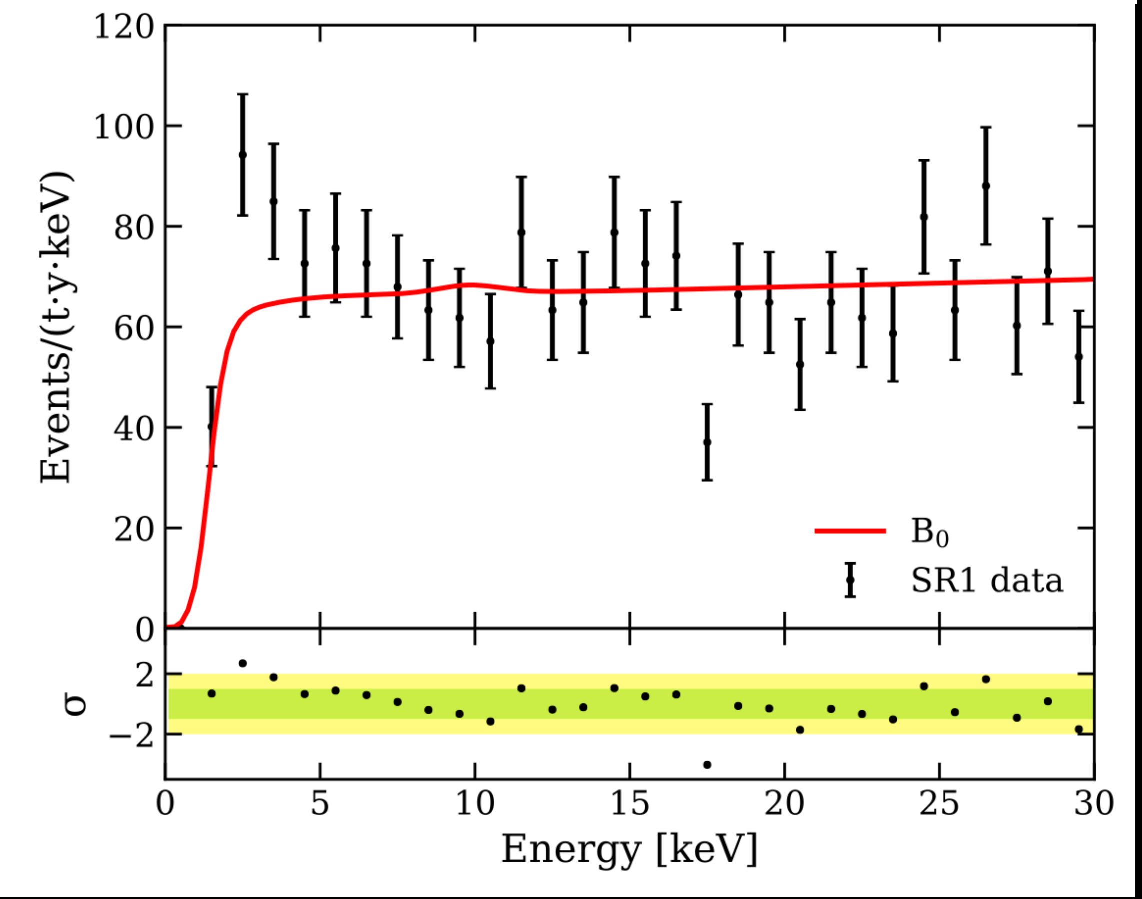
e-Print: 2006.09721 [hep-ex]

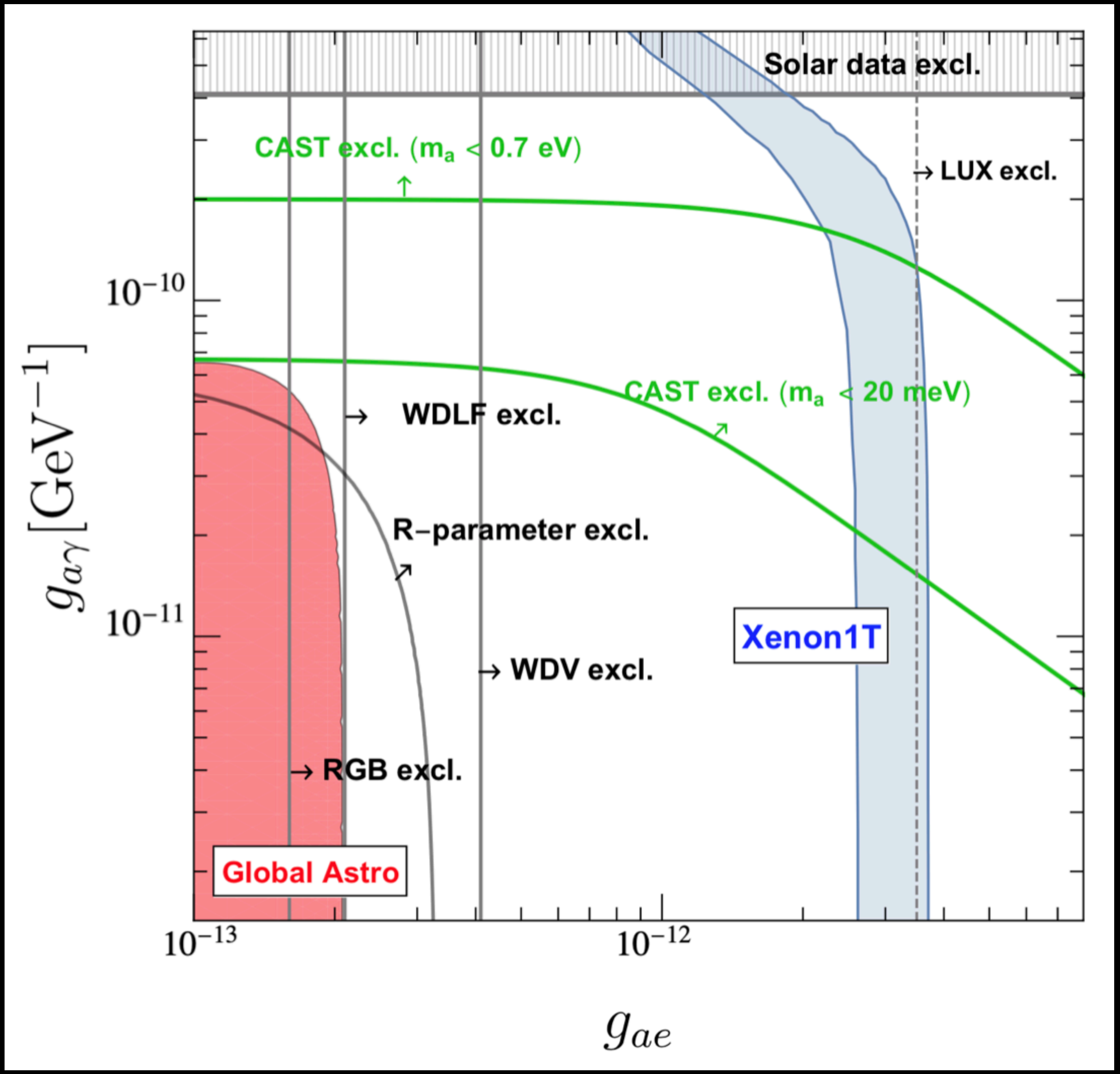
DOI: 10.1103/PhysRevD.102.072004

Experiments: XENON1T



Stellar bounds

The axion interpretation of the XENON1T excess is disfavored once the best-fit region is compared to what is expected from stellar production in RGB and white dwarfs

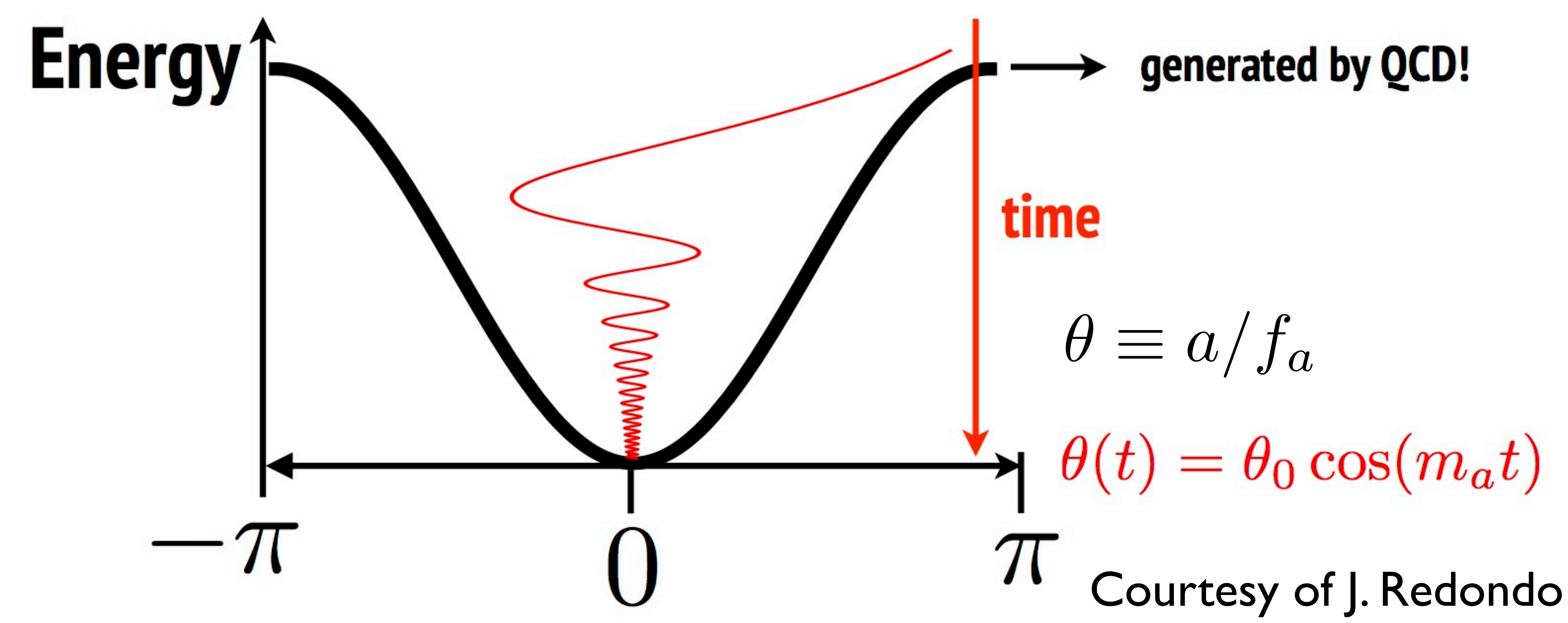


di Luzio+20

Axion DM production

Damped harmonic oscillator $\ddot{a} + 3H\dot{a} + \frac{dV(a)}{da} = 0$

(for super-horizon modes $|\nabla\theta| \approx 0$)



Courtesy of J. Redondo

when $H \lesssim m_a(T)$, the axion energy density is $\rho \propto R^{-3}$

Axion DM production

More complicated picture

$$\Phi = \frac{1}{\sqrt{2}}\left(f_a + \rho_a\right)\exp\left(\frac{ia}{f_a}\right)$$

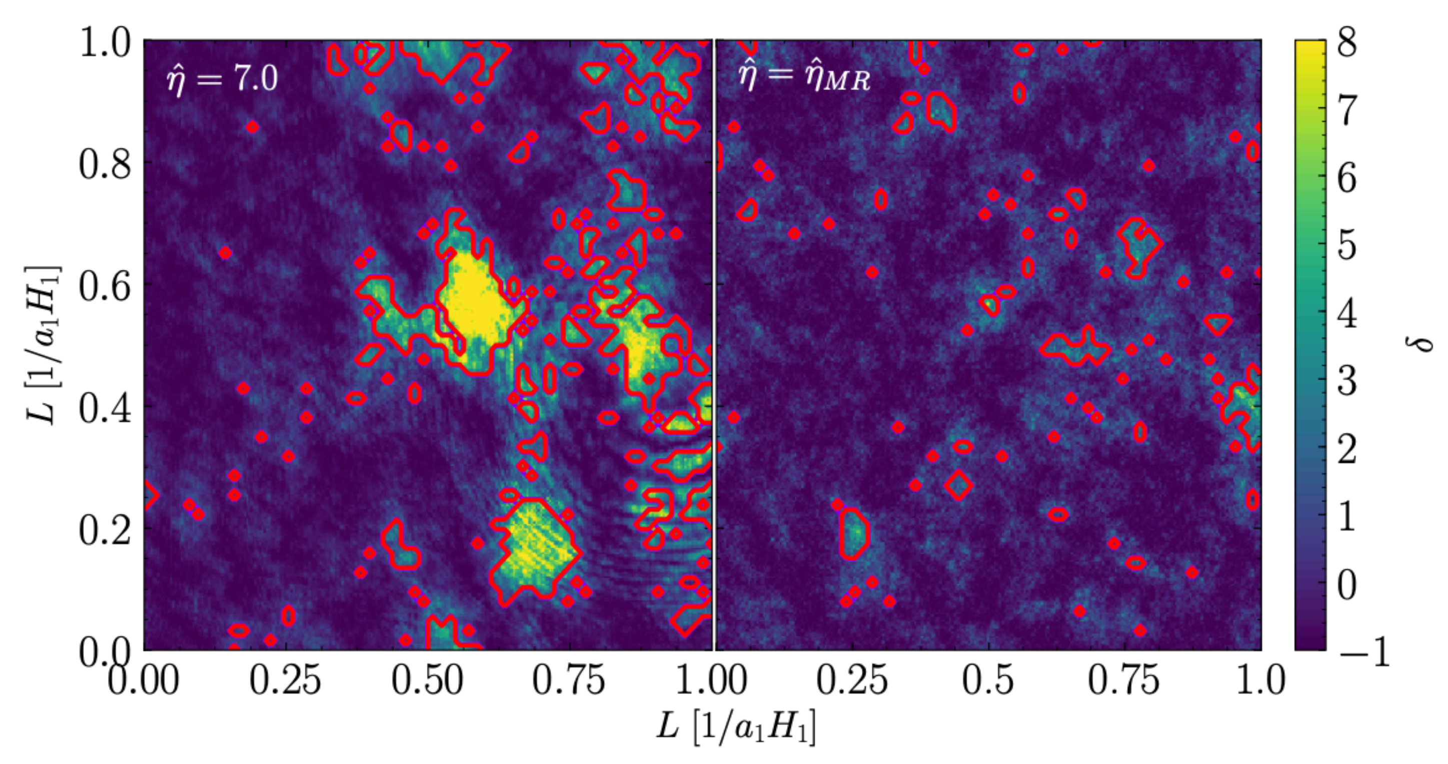
PQ field radial mode

Overdensities produced before MR act as “seeds” for bound axion *miniclusters* Hogan, Rees 88

For an overdensity $\delta = (\rho - \bar{\rho})/\rho$ the AMC density is

$$\rho_{\rm AMC}(\delta) = 140(1+\delta)\delta^3\rho_{\rm eq}$$

Kolb, Tkachev astro-ph/9311037



Buschmann+ 1906.00967

Not to be confused with axion stars

see e.g. Visinelli+ 1710.08910

AMC halo mass function

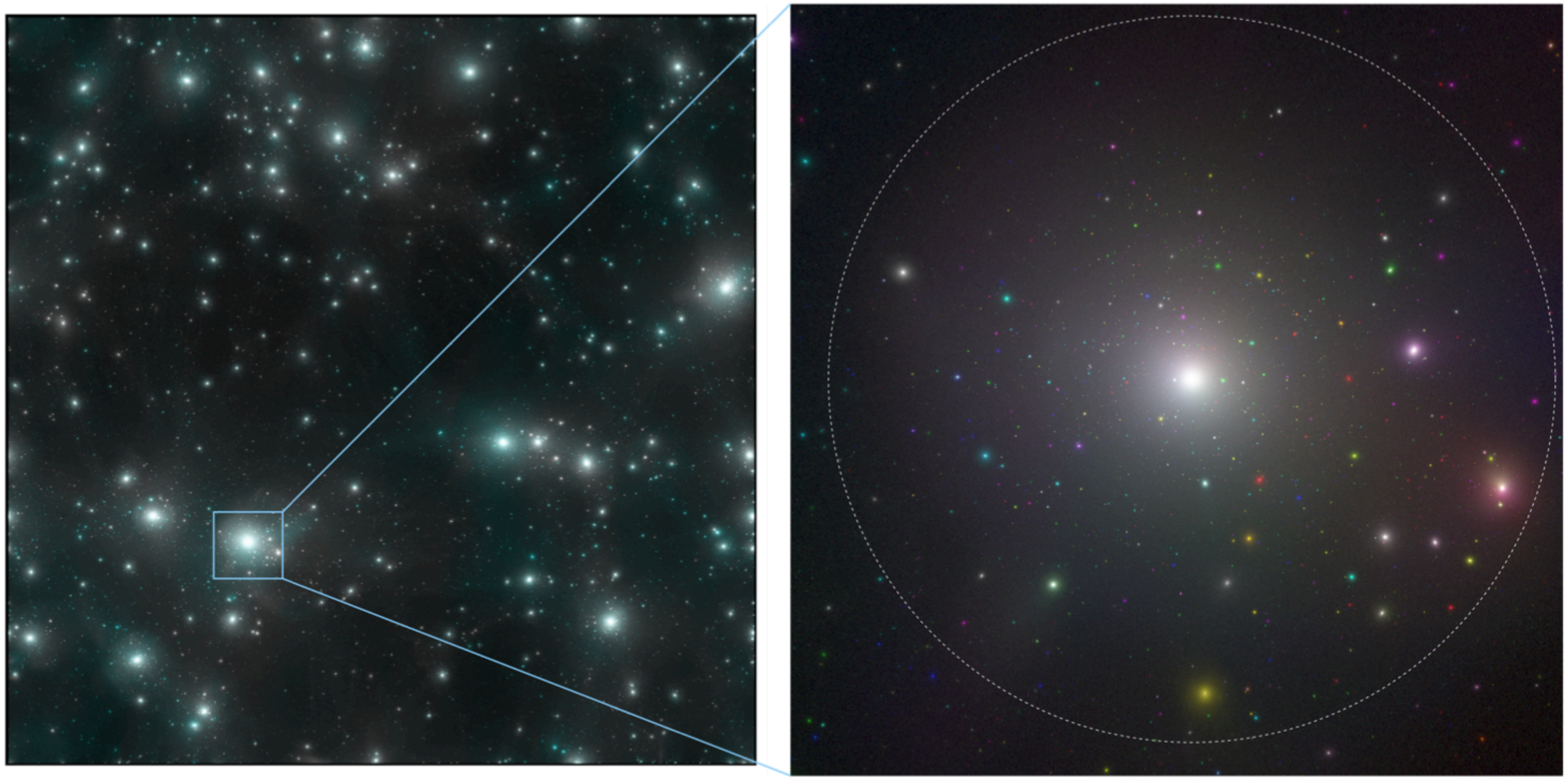
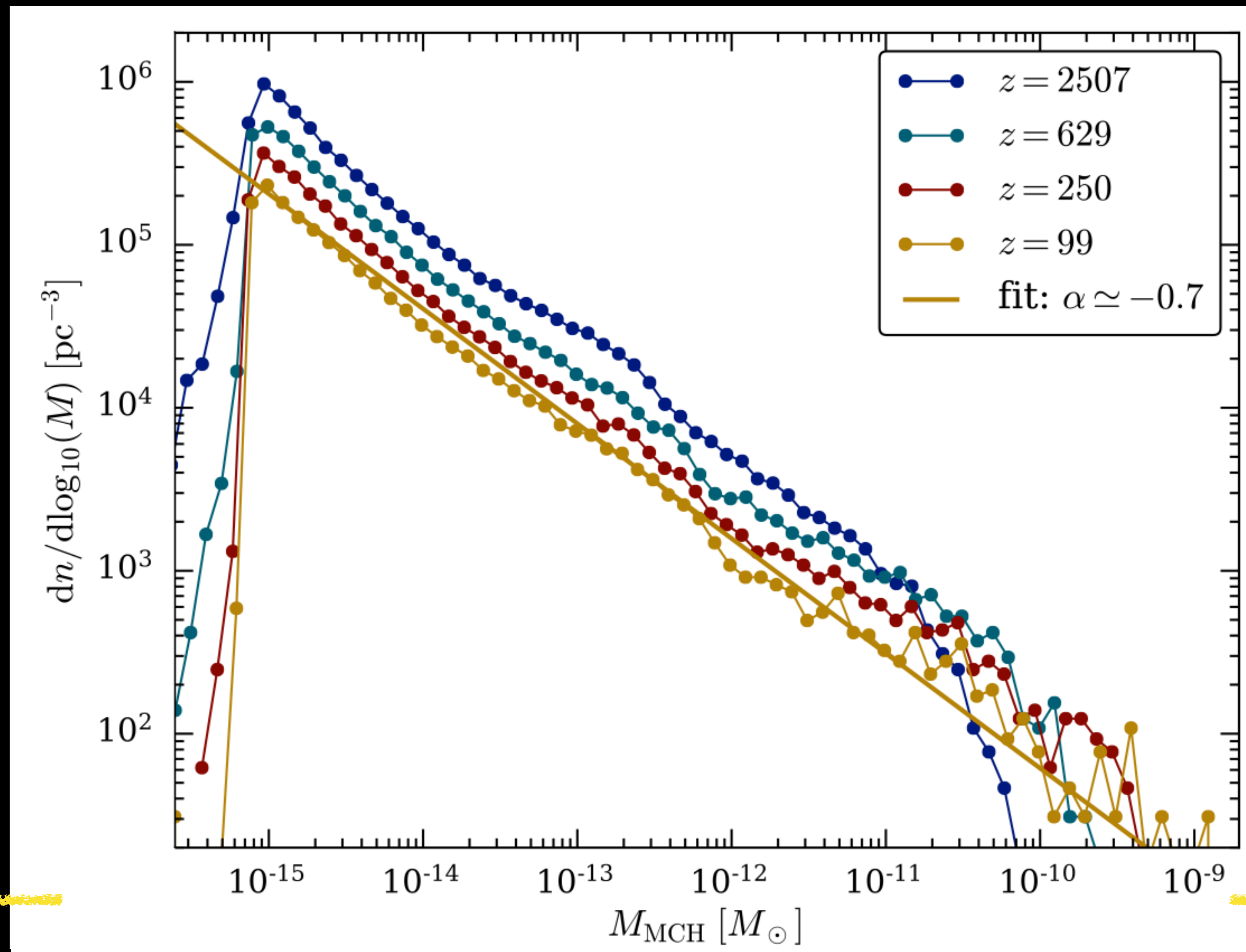


FIG. 1. Left: projected axion density of the full simulation box at $z = 99$. Right: an enlargement of the largest MCH, where the dashed circle indicates the sphere with density $\rho = 200\,\rho_{m,0}$. The sub-MCs are colored according to their orbital velocity.

Eggemeier+ 1911.09417

AMC halo mass function



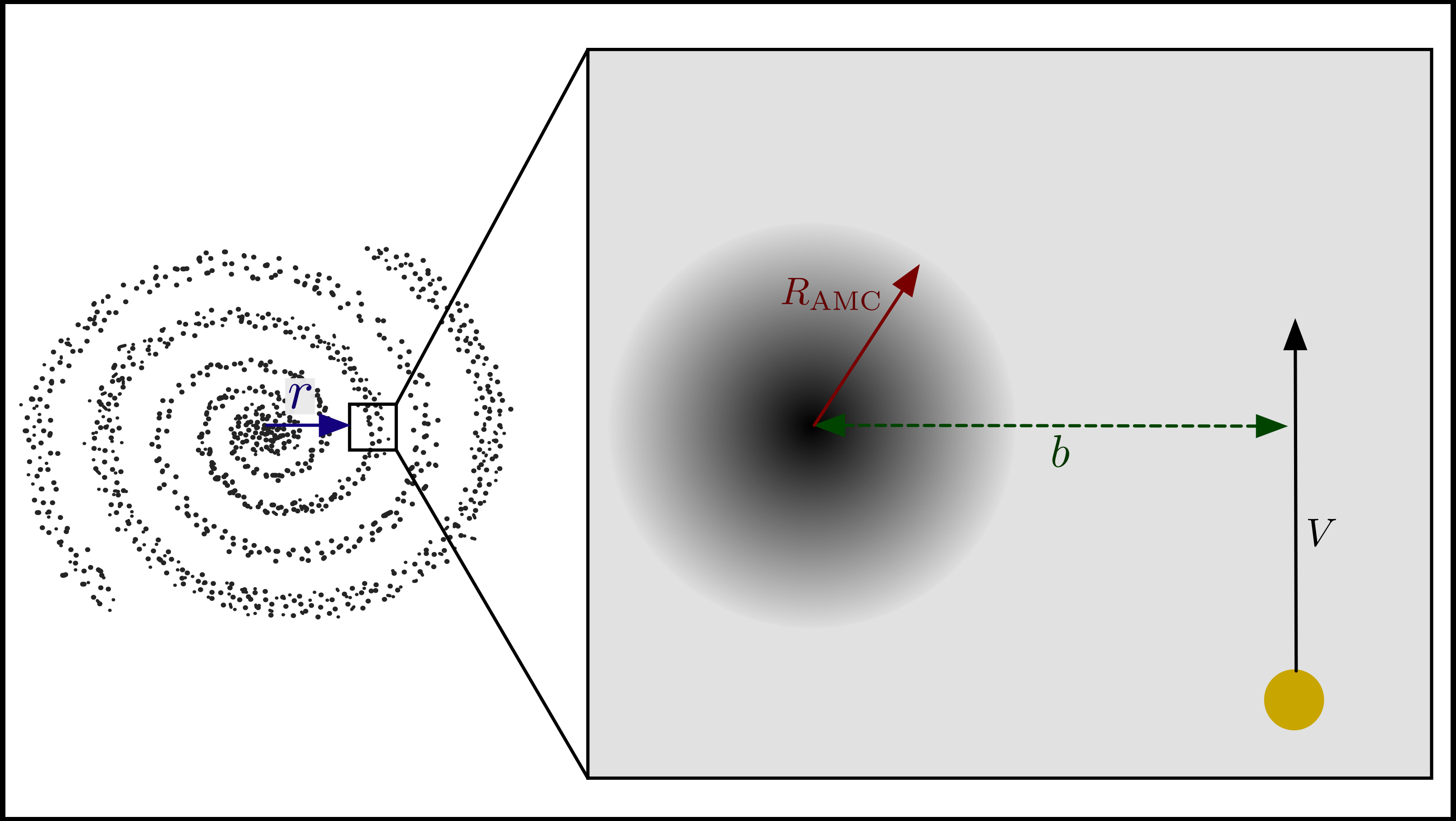
Extends down to $M_{\rm AMC} \sim 10^{-19} M_\odot$ set by the Jeans mass for $m_a = 20\,\mu$eV

$$\frac{\mathrm{d}n}{\mathrm{d}\log M_{\rm AMC}} \propto {M_{\rm AMC}}^{-0.7}$$

Extends up to $M_{\rm AMC} \sim 10^{-5} M_\odot$ growth of hierarchical structures today

see also Ellis & Marsh 2006.08637

What is missing: survival of miniclusters in the Galaxy



Edwards, Kavanagh, Visinelli, Weniger 2011.05377, 2011.05378

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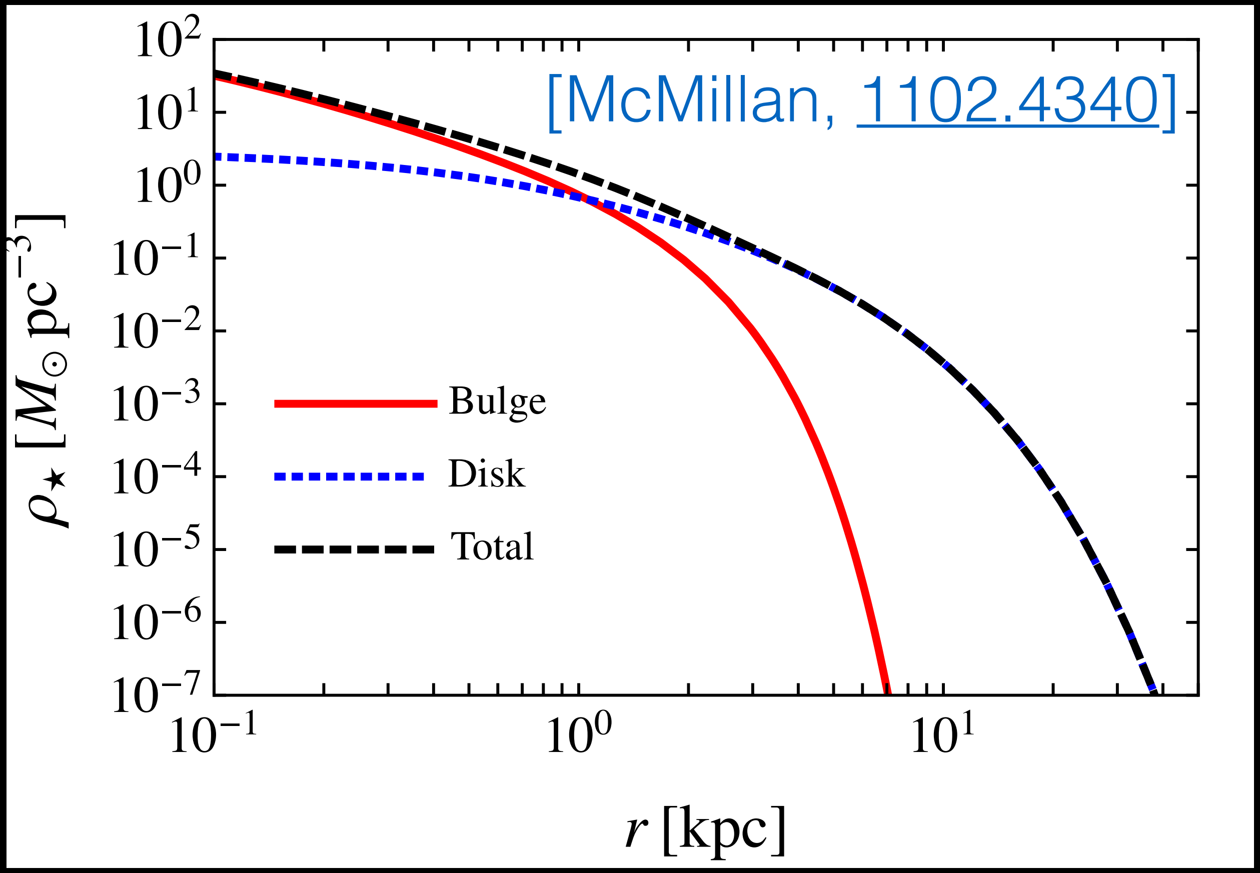
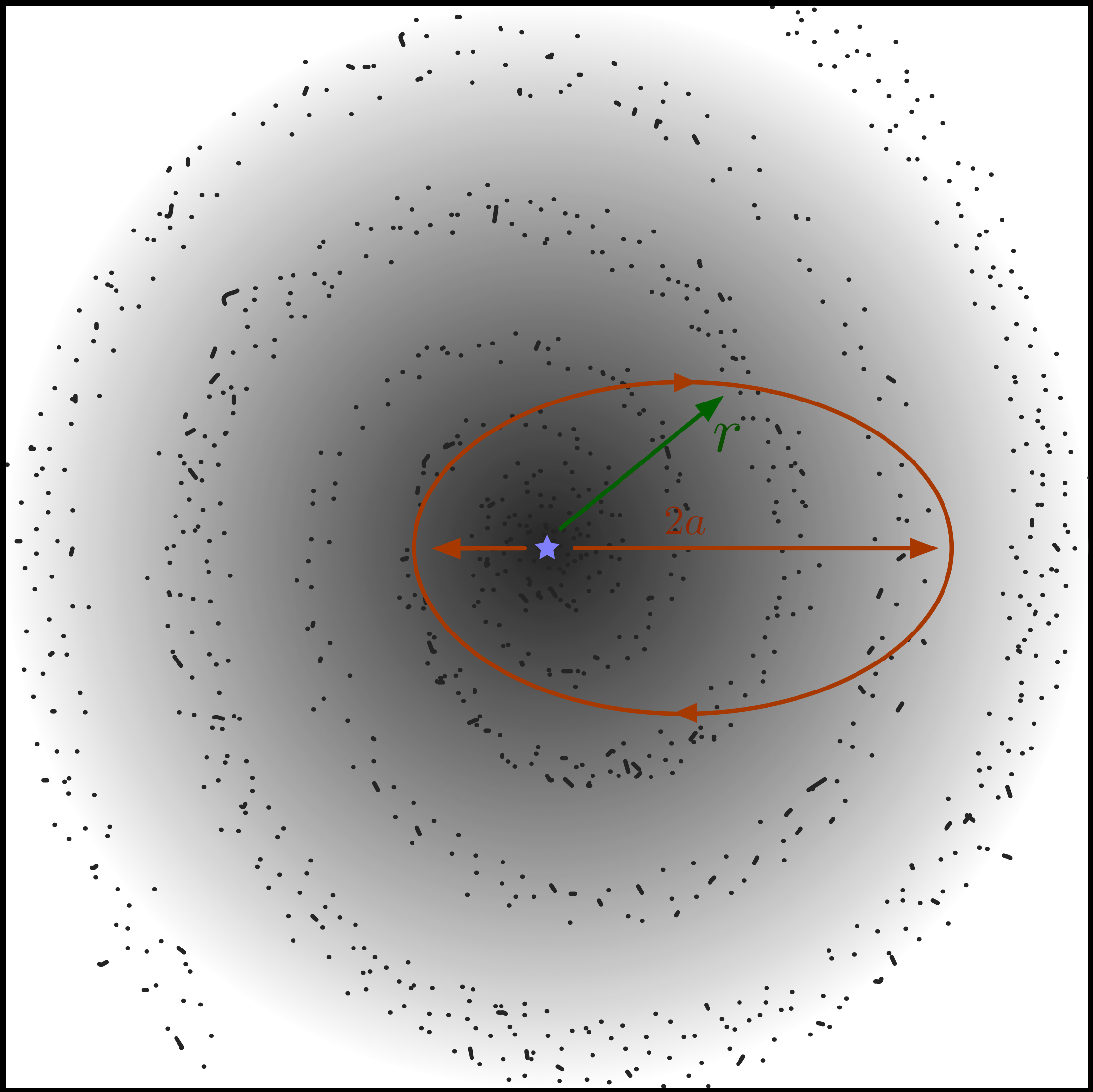
OKC Stockholm, Sweden

Bradley Kavanagh
IFCA Santander, Spain

Christoph Weniger
GRAPPA Amsterdam, Netherlands

Milky Way setup





DM distribution in the Milky Way $\rho_{\rm DM}(r)$

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

We set $f_{\rm AMC} = 100\%$

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

Caveats: we do not deal with current stellar formation and structure formation

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

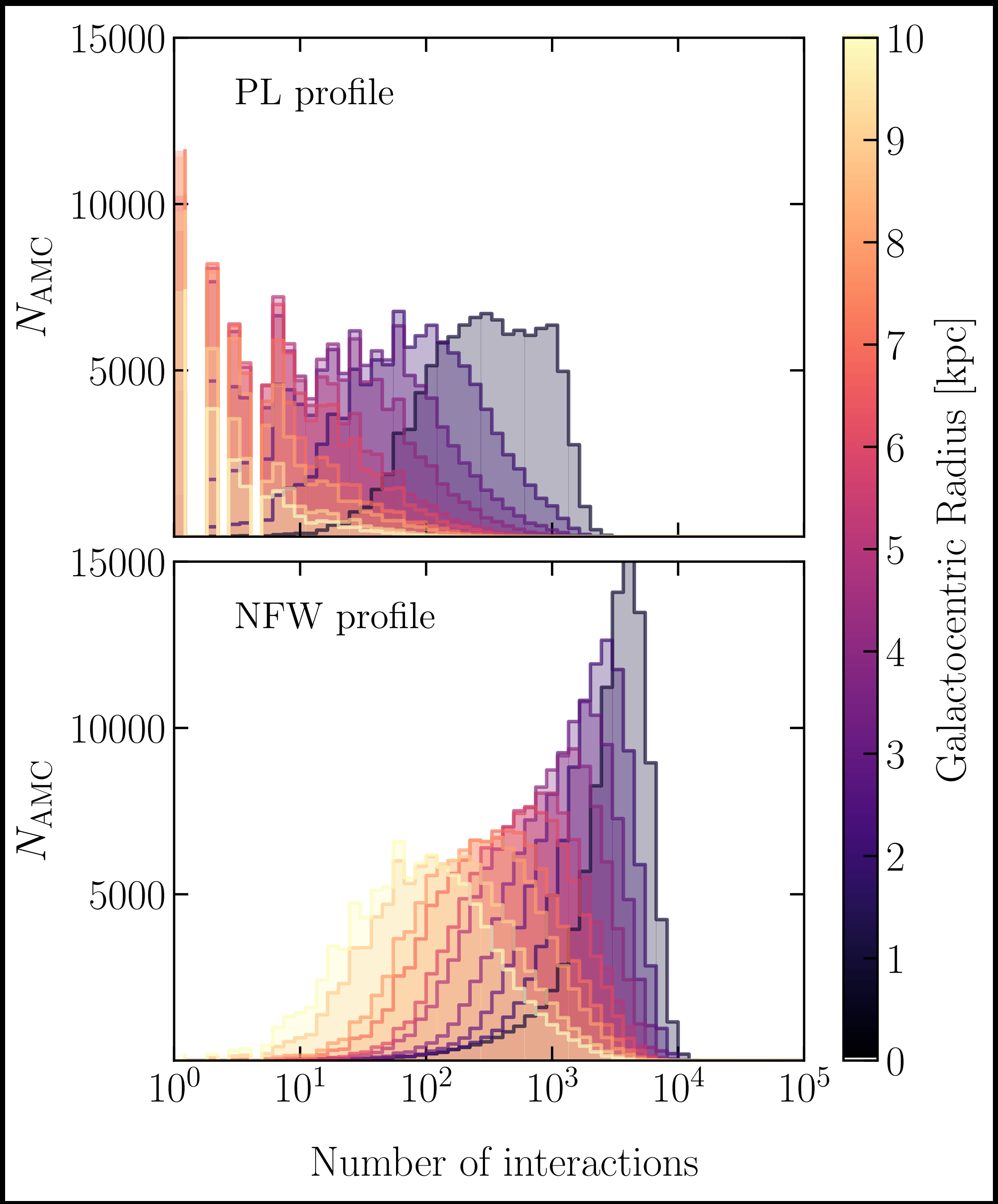
Remove AMC from simulation

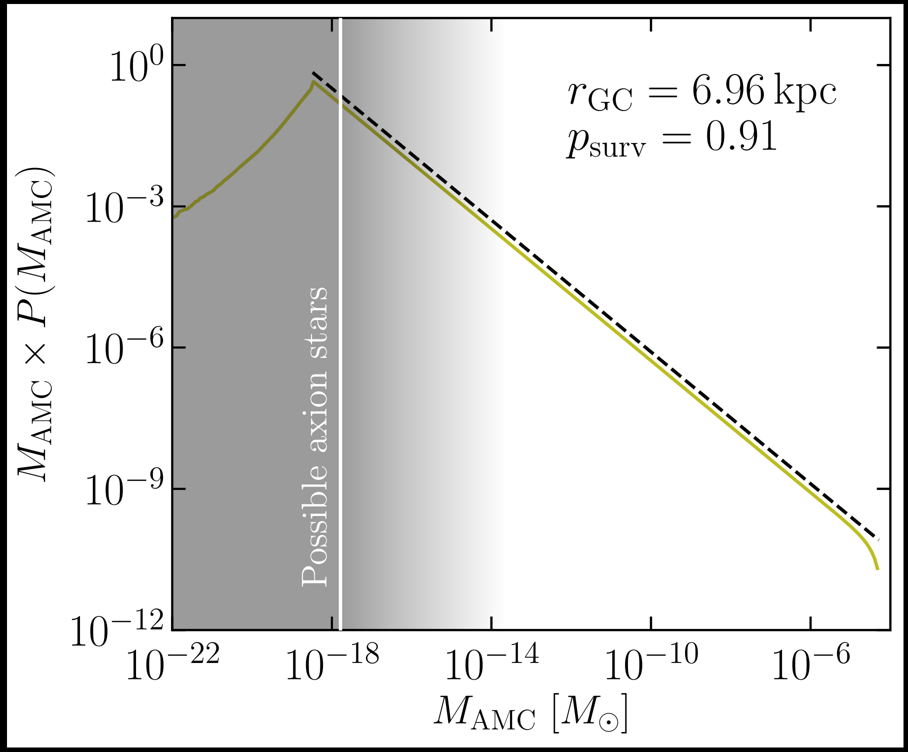
Collect surviving AMCs and reconstruct true properties

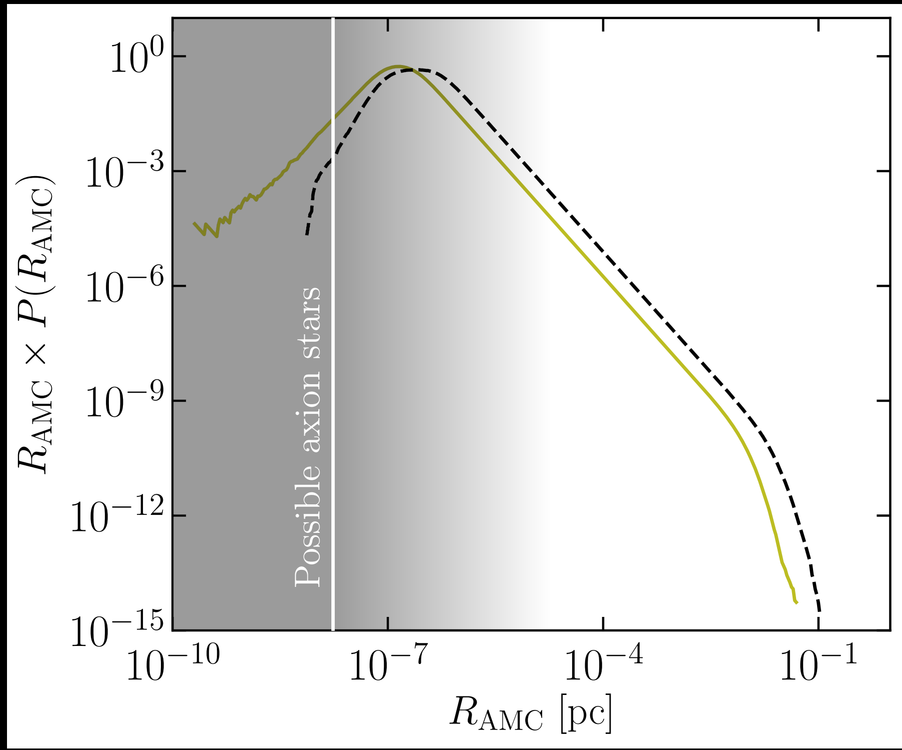
[Distributions and tools for re-casting available online: github.com/bradkav/axion-miniclusters]

Monte Carlo procedure

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

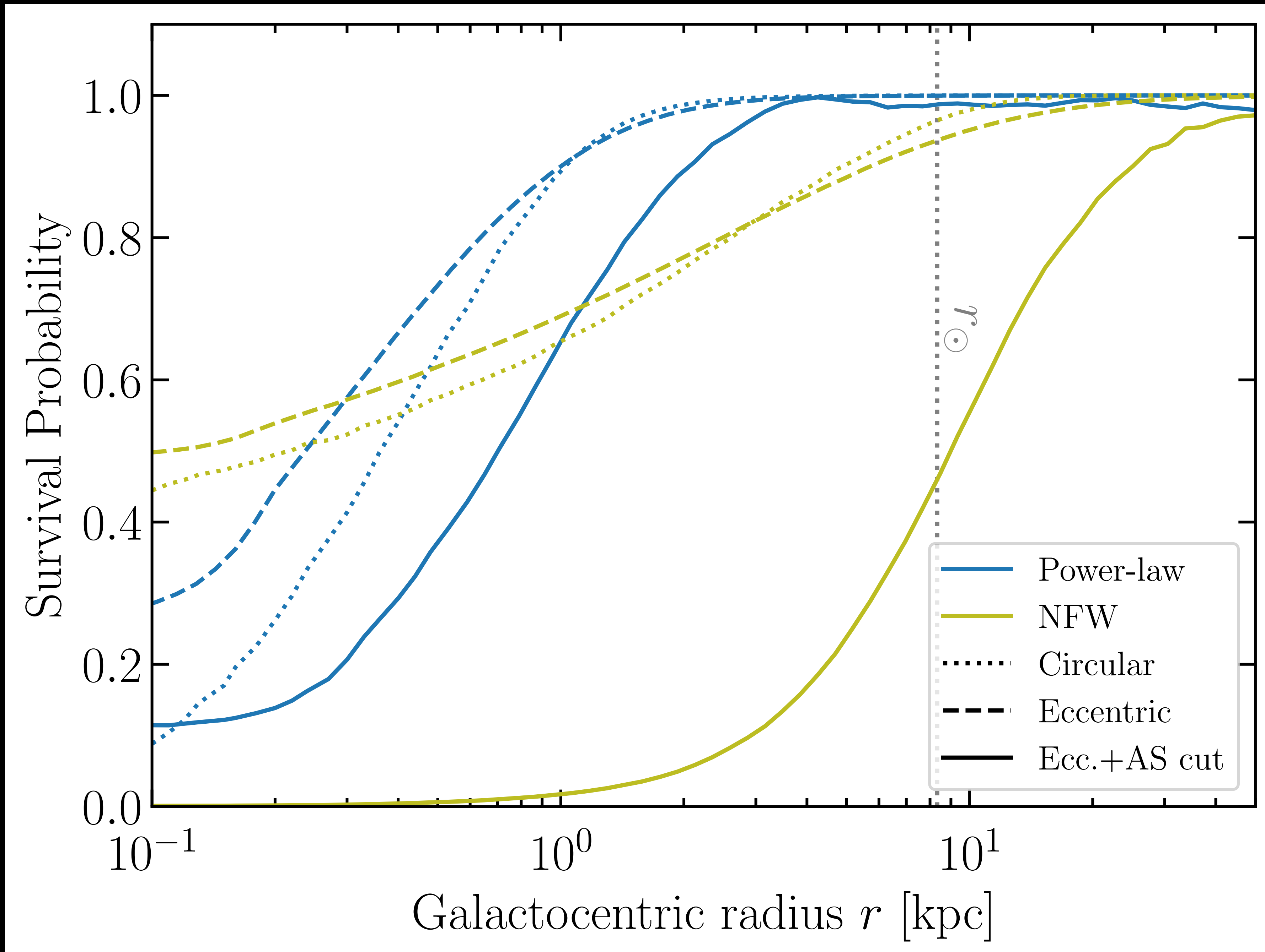






Axion stars modeled after the work of Schive et al. 1406.6586; 1407.7762

Axion minicluster survival probability



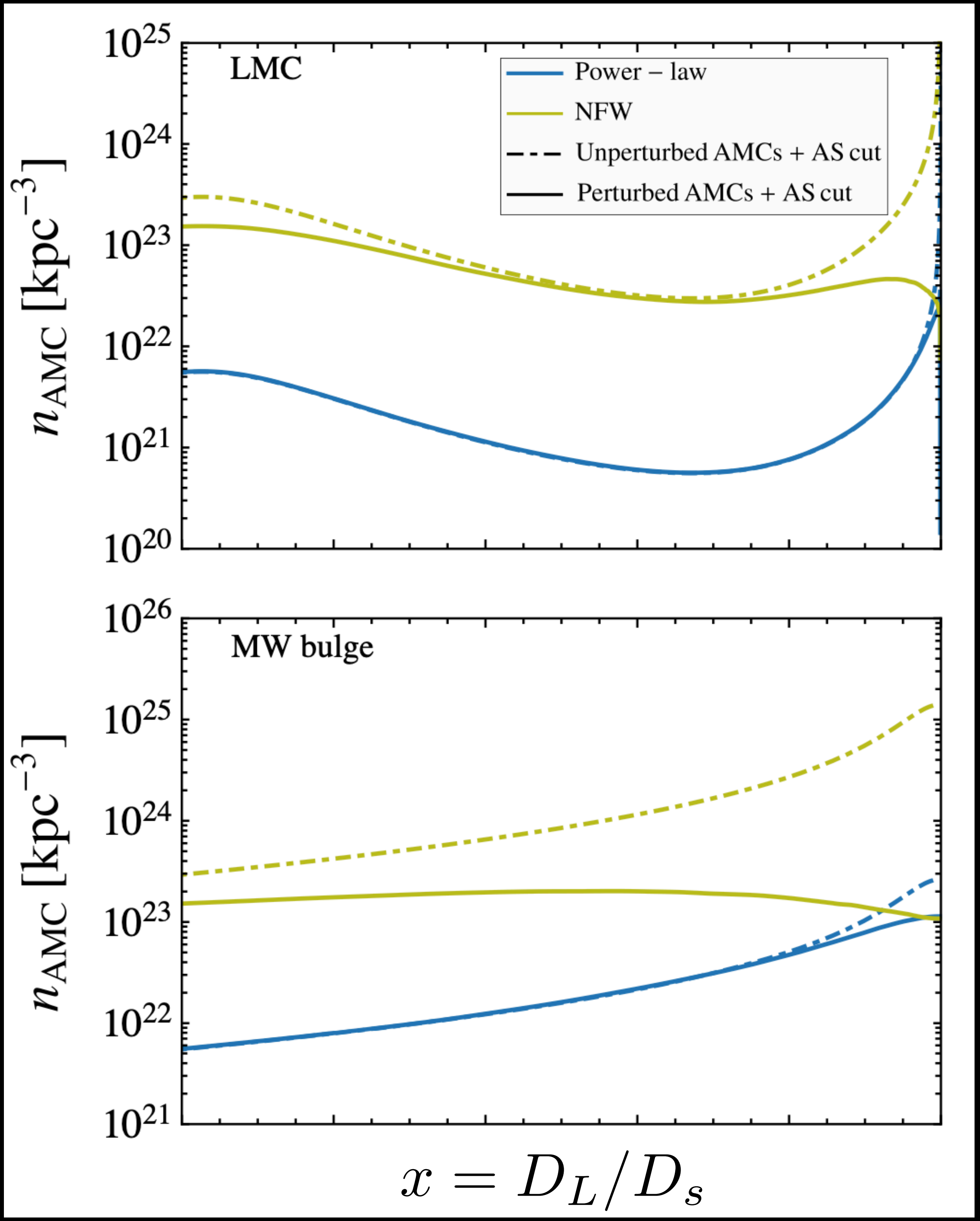
Survival probability at Solar circle:
$\mathcal{O}(40\%)$ for NFW profiles
$\mathcal{O}(99\%)$ for PL profiles

see also Tinyakov+ 1512.02884; Dokuchaev+ 1710.09586

Application: axion minicluster lensing

$$\bar{N}_{\rm ex} \propto \int {\rm d}t \int {\rm d}x \frac{{\rm d}\Gamma}{{\rm d}x{\rm d}t}$$

$$\frac{{\rm d}\Gamma}{{\rm d}x{\rm d}t} \sim n_{\rm AMC}(x)$$



[See Fairbairn+ 1701.04787, 1707.03310]

Summary I

Tidal stripping

- Axion miniclusters survive stripping
- Sizeable contributions today regardless of the inner distribution
- Affect lensing and indirect detection

Missing ingredients

- Concurrent structure formation & disruption
- Realistic input to Monte Carlo simulations (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!

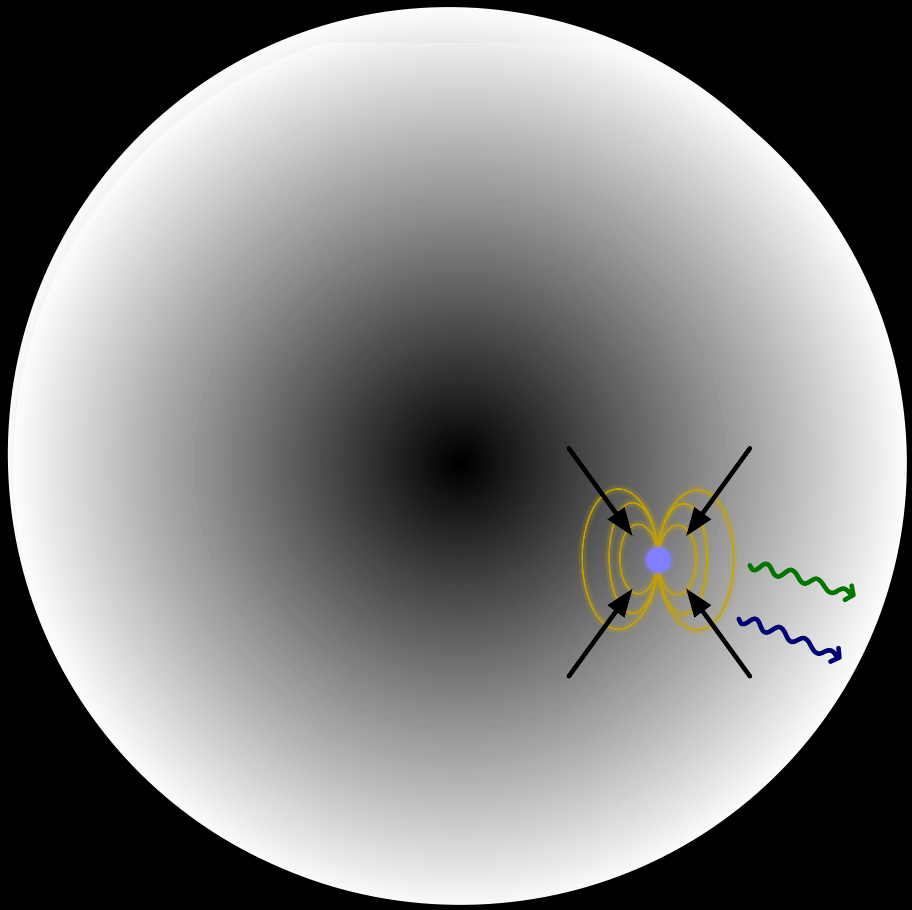
Application: axion conversion in NS

Only sketched here; see talk by Safdi for more details!

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

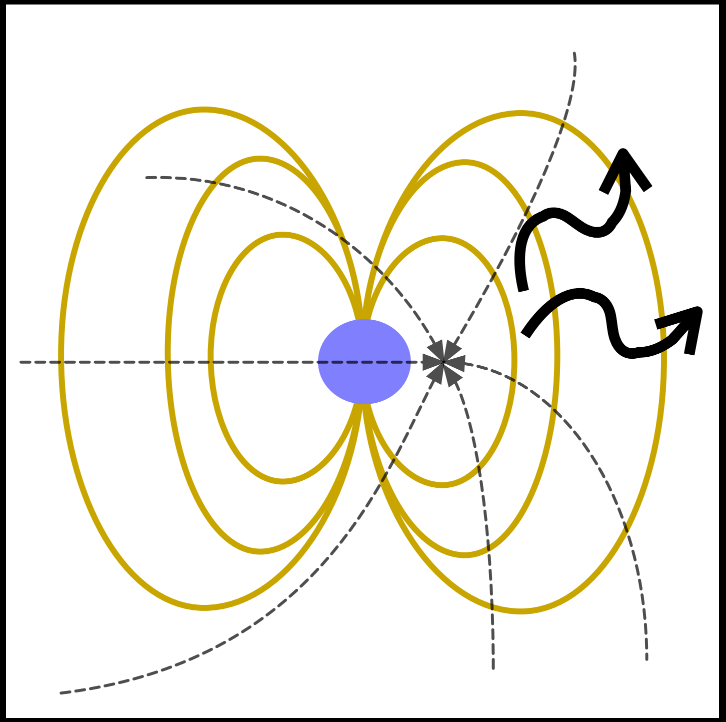
[Goldreich & Julian (1969)]

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



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

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



Assume isotropic emission and focus on enhancements to ρ_c due to AMC encounters.

Very active field of search in recent years

[Hook+ 1804.03145; Safdi+ 1811.01020; Edwards+ 1905.04686; Foster+ 2004.00011]

Encounter rate of axion minicluster and neutron star

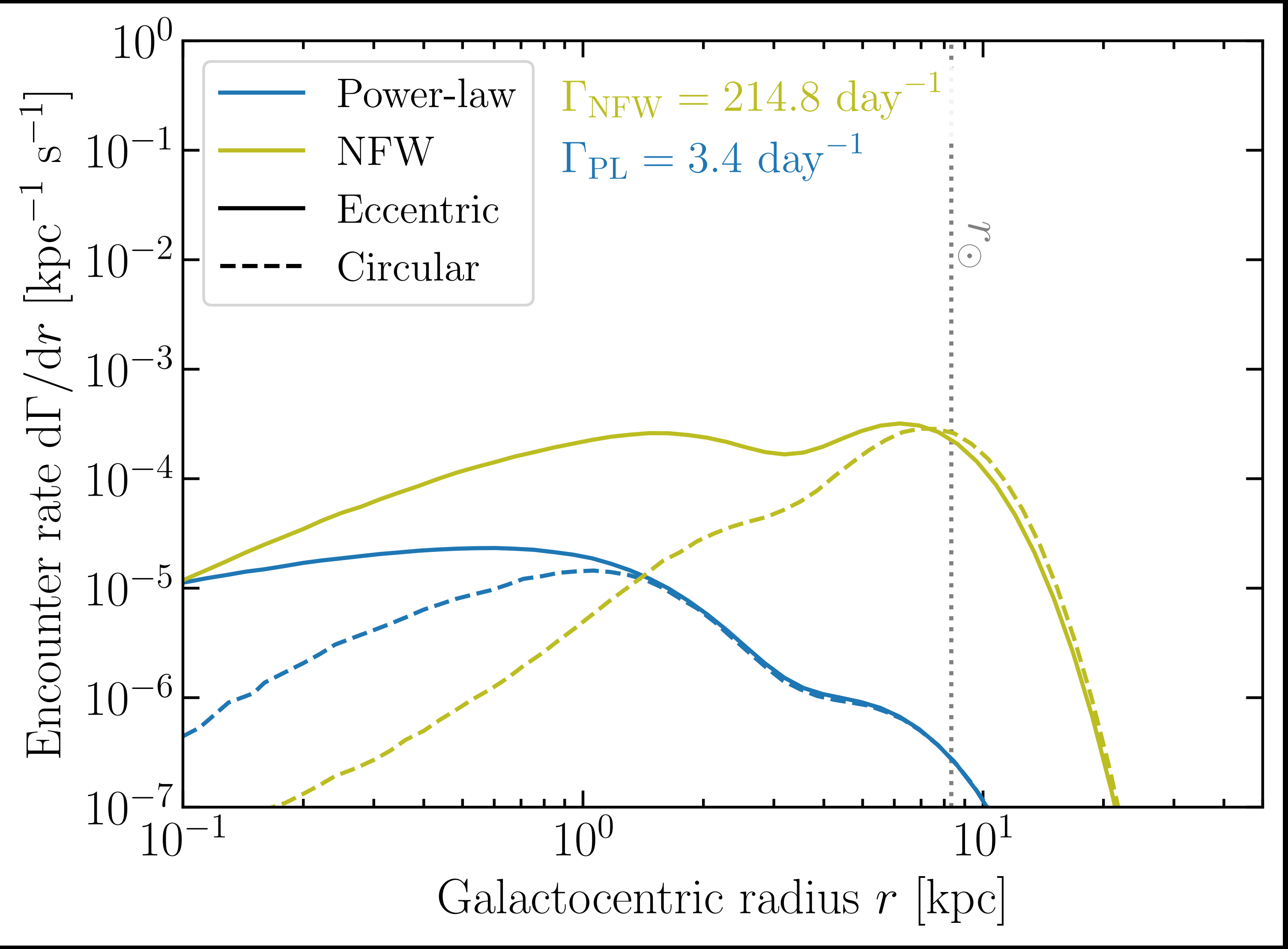
$$\Gamma = \int \mathrm{d}^3\mathbf{r} \int \mathrm{d}R \frac{\mathrm{d}n_{\mathrm{AMC}}(r)}{\mathrm{d}R} n_{\mathrm{NS}}(\mathbf{r})\langle\sigma u\rangle(r)$$

R Radial coordinate of the AMC

$\frac{\mathrm{d}n_{\mathrm{AMC}}(r)}{\mathrm{d}R}$ Inner radial distribution of the AMC

$$\langle\sigma u\rangle(r) \sim R^2\sigma_u$$

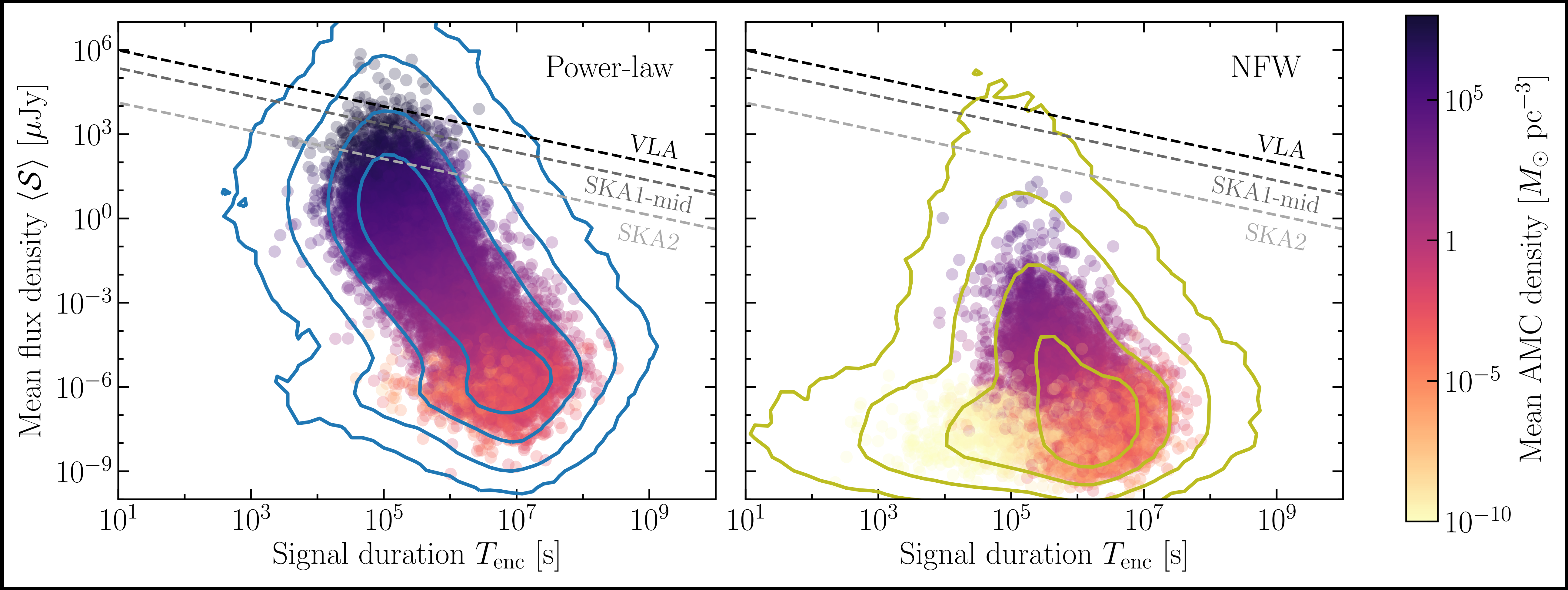
Without stellar disruption,
the encounter rate would be:
39.3x larger for NFW profiles
1.4x larger for PL profiles



Signal flux and duration

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

We fix bandwidth BW = 1 kHz (based on telescope resolution)



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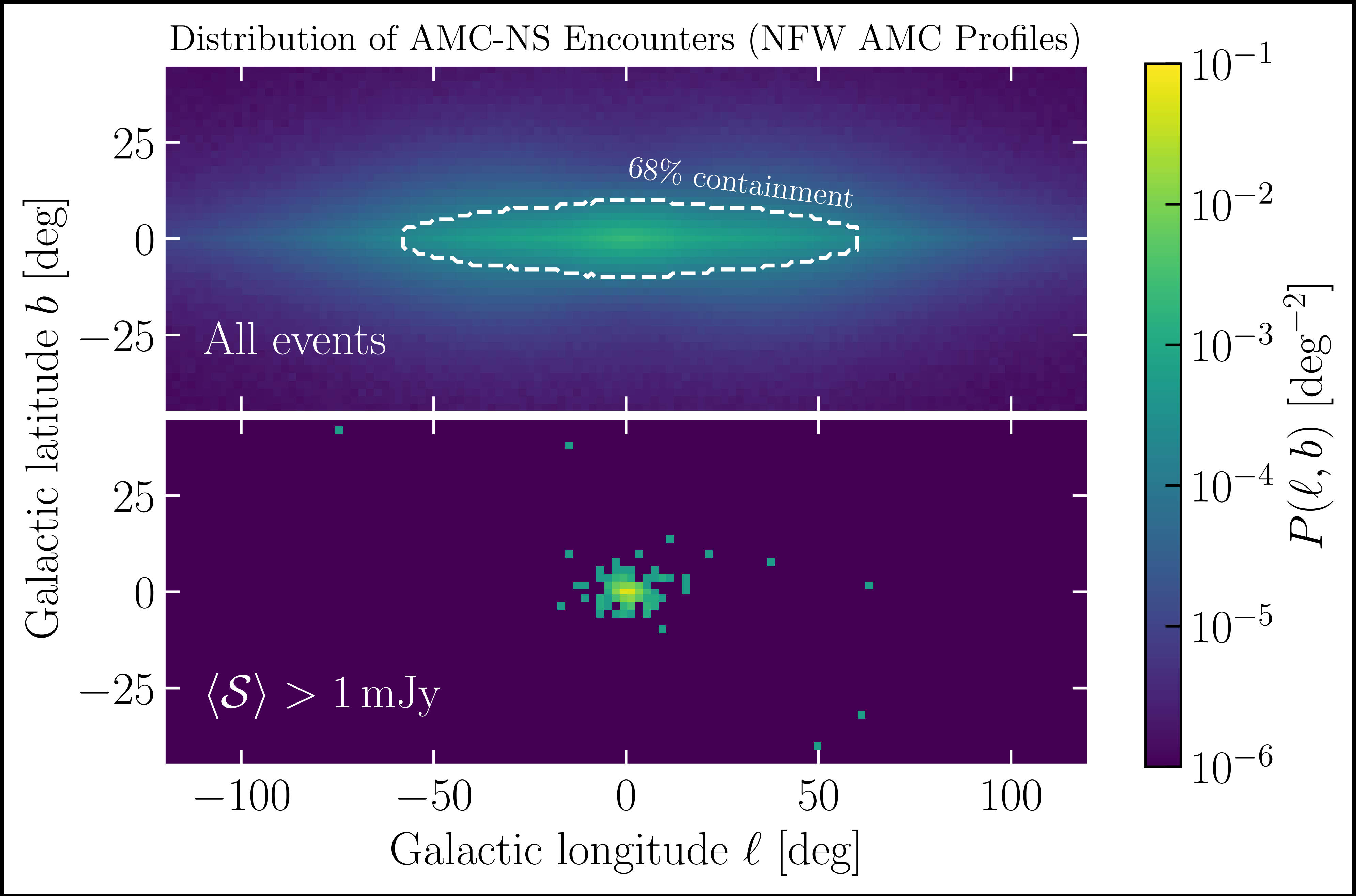
Sky distribution



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Summary II

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

Missing ingredients

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