



Future probes of light bosons

Luca Visinelli

Associate Professor, Shanghai Jiao Tong University
Fellow, Tsung-Dao Lee Institute (TDLI)

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Stellar disruption of axion miniclusters in the Milky Way

Bradley J. Kavanagh^{1,2,*} Thomas D. P. Edwards^{3,2,†} Luca Visinelli^{1,2,‡} and Christoph Weniger^{2,§}

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Transient Radio Signatures from Neutron Star Encounters with QCD Axion Miniclusters

Thomas D. P. Edwards^{1,2,*} Bradley J. Kavanagh^{1,3,2,†} Luca Visinelli^{1,2,‡} and Christoph Weniger^{2,§}

BOSON STARS AND OSCILLATONS: A REVIEW

2109.05481

LUCA VISINELLI

Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China

Tsung-Dao Lee Institute @ Shanghai



I) Light bosons and solitonic stars

Massless bosons

$$S = \frac{1}{2} \int d^4x \sqrt{-g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

There is an additional **shift symmetry** $\phi \rightarrow \phi + c$

The symmetry is lost whenever a potential is added, such a quadratic mass term $\sim m^2 \phi^2 / 2$

The symmetry is broken at some level, at least by QG effects that spoil all continuous global symmetries.

Nearly-massless boson  shift symmetry is “approximate”

Giving a small mass to the boson

An important example is the periodic potential, for which a residual **discrete shift symmetry** exists $\phi \rightarrow \phi + 2\pi n F$

This model has two parameters: mass m and energy scale F

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + V(\phi) \right]$$

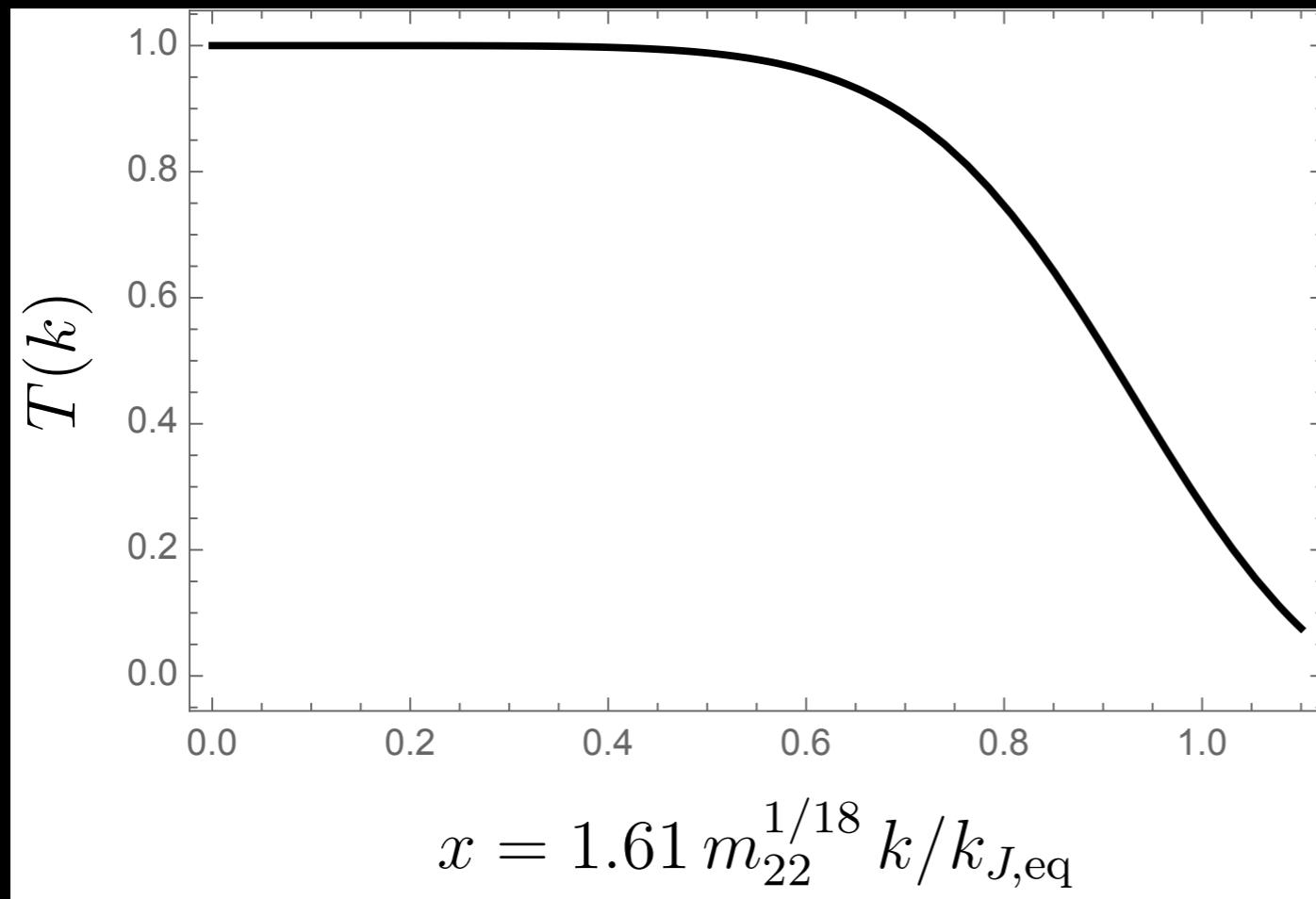
$$V(\phi) = m^2 F^2 (1 - \cos \phi/F)$$

String-inspired particle models predict numbers of these type of fields (Svrcek&Witten hep-th/0605206, Cicoli+ 2110.02964)
Important applications in cosmology (Arvanitaki+ 0905.4720)

Giving a small mass to the boson

$$P_{\text{LB}}(k) = T_F^2(k) P_{\text{CDM}}(k)$$

The transfer function suppresses energy at small scales for the boson mass $m \approx 10^{-22} \text{ eV}$



Addresses the missing satellite problem
(SIn95, Hu+00)

$$m_{22} \equiv m/(10^{-22} \text{ eV})$$

Giving a small mass to the boson

$$V(\phi) = m^2 F^2 (1 - \cos \phi/F)$$

$$m^2 F^2 = M_{\text{Pl}}^2 \Lambda^2 e^{-S}$$

Reduced Planck mass $M_{\text{Pl}} = 1/\sqrt{8\pi G} \approx 2.435 \times 10^{18} \text{ GeV}$

Instanton action $S \sim 2\pi/\alpha_{\text{SM}}$

Instanton-suppressing energy scale by SUSY Λ

Giving a small mass to the boson

$$V(\phi) = m^2 F^2 (1 - \cos \phi/F)$$

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Instanton-suppressing energy scale by SUSY Λ

$\Lambda \sim M_{\text{Pl}}$ (No suppression)  $S \sim 230$

$\Lambda \sim 10^{11} \text{ GeV}$ (Gravity-mediated
SUSY breaking)  $S \sim 200$

$\Lambda \sim 10^4 \text{ GeV}$ (Gauge-mediated
SUSY breaking)  $S \sim 170$

Light bosons forming cored DM halos

A boson of mass m has de Broglie wavelength $\lambda = \frac{\hbar}{mv}$

A self-gravitating boson condensate forms a “star”
(Kaup68; Ruffini&Bonazzola 69)

A boson star has the radius R that matches λ , and minimizes

$$E = \frac{1}{2}mv^2 - \frac{Gm}{R}$$

Maximum mass $M_{\text{Kaup}} = 0.633 (Gm)^{-1}$

Boson stars of mass $M < M_{\text{Kaup}}$ are stable (Lee&Pang 89)

See e.g. my recent review on boson stars [2109.05481](#)

Light bosons forming cored DM halos

For an ultralight boson $m \approx 10^{-22}$ eV, the maximum mass is

$$M_{\text{Kaup}} = 0.633 (Gm)^{-1} \approx 10^{12} M_{\odot} \quad (\text{SIn95, Hu+00})$$

This is the mass of the soliton core.

The virial mass can be much higher and formed of bosons not in the condensed state, distributed as NFW profile (Navarro+97)

Simulations yield (Schive+14)

$$M \simeq 2.7 \times 10^8 M_{\odot} \frac{10^{-22} \text{ eV}}{m} \left(\frac{M_{\text{vir}}}{10^{10} M_{\odot}} \right)^{1/3}$$

Explained by saturation of mass growth (Eggemeier&Niemeyer 19)

Light bosons forming cored DM halos

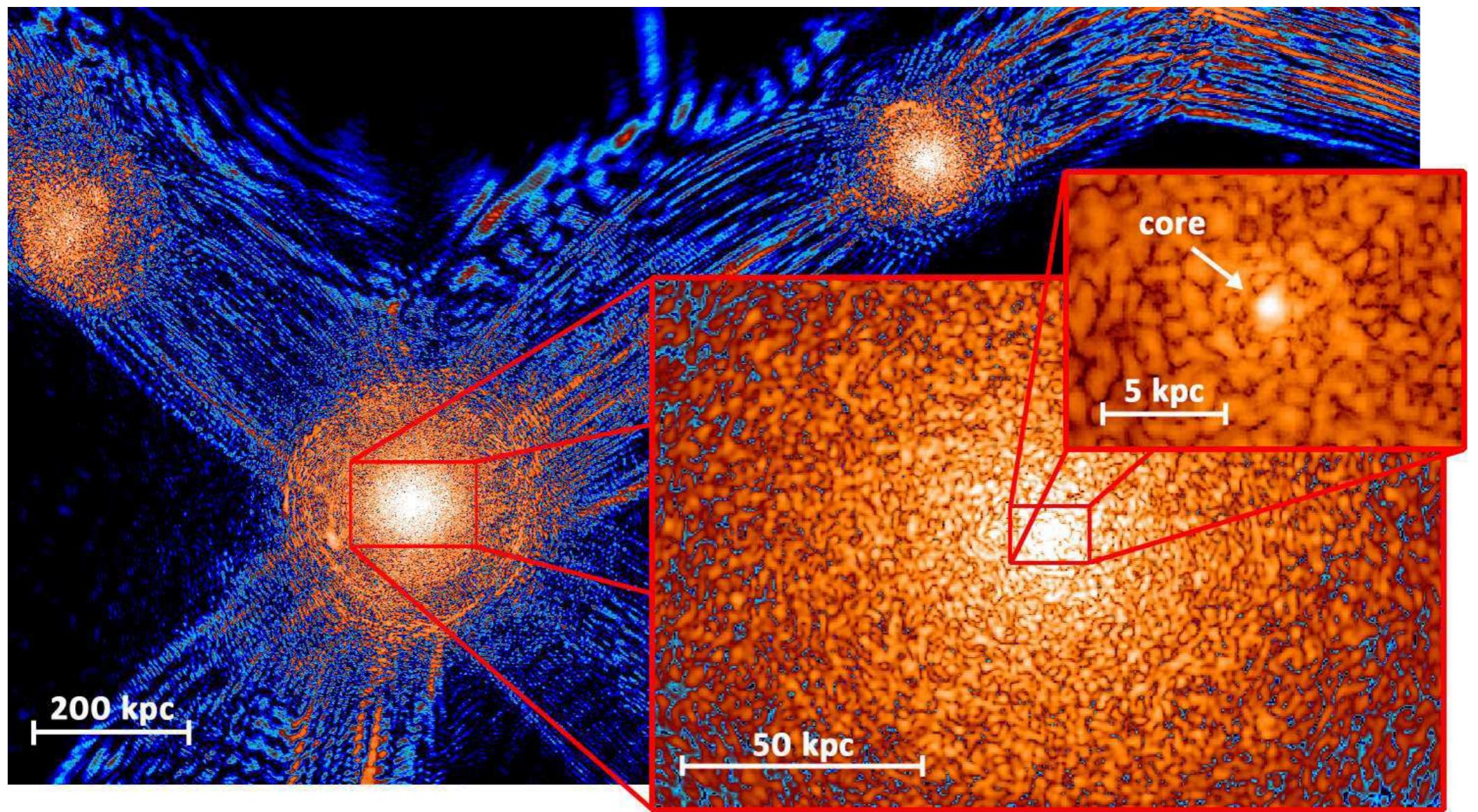
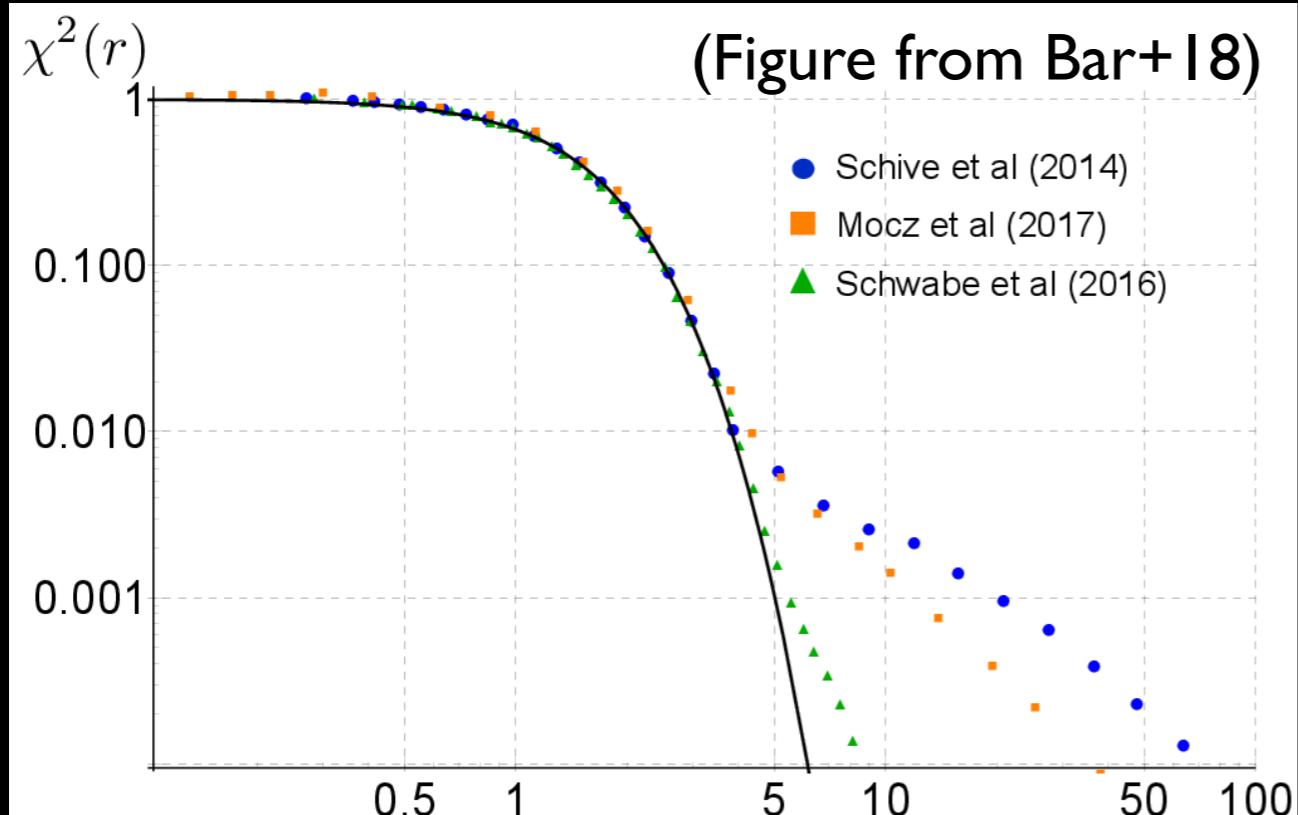


Figure 2: A slice of density field of ψ DM simulation on various scales at $z = 0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from the large-scale filaments, tangential fringes near the virial boundaries, to the granular structure inside the haloes. Distinct solitonic cores with radius $\sim 0.3 - 1.6$ kpc are found within each collapsed halo. The density shown here spans over nine orders of magnitude, from 10^{-1} to 10^8 (normalized to the cosmic mean density). The color map scales logarithmically, with cyan corresponding to density $\lesssim 10$.

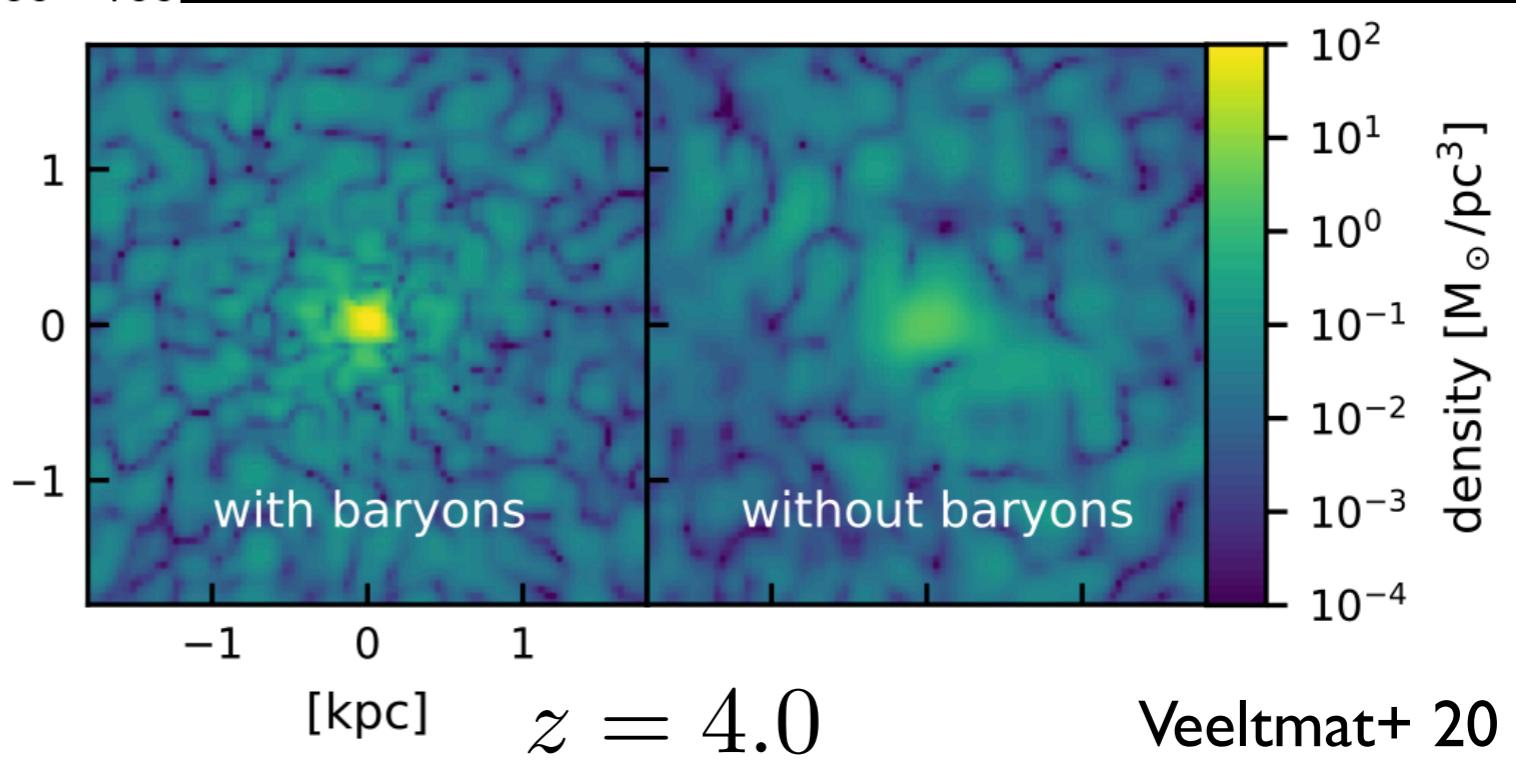
(Schive+14)

Light bosons forming cored DM halos

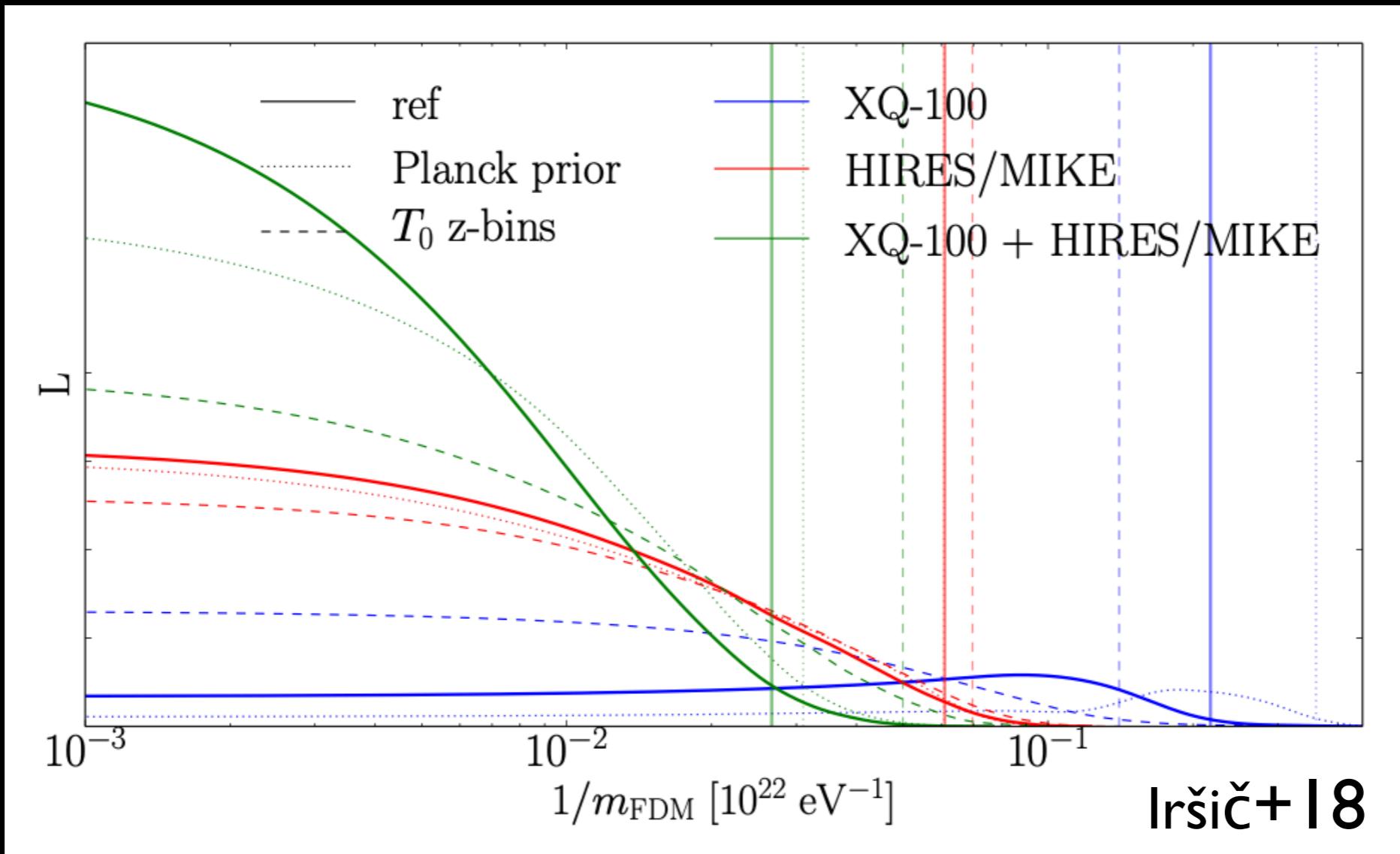


The solitonic behaviour is found in other simulations
The external profile is debated

The core profile suffers from the presence of gas, stars, BHs



Light bosons forming cored DM halos



Constraints from Lyman-alpha data lead to $m \gtrsim 20 \times 10^{-22} \text{ eV}$
XQ-100 and HIRES/MIKE quasar spectra samples

SMBH mimickers

Another possibility:
Imaging through VLBI (Akiyama+15)

Compactness $\mathcal{C} \equiv M/R$

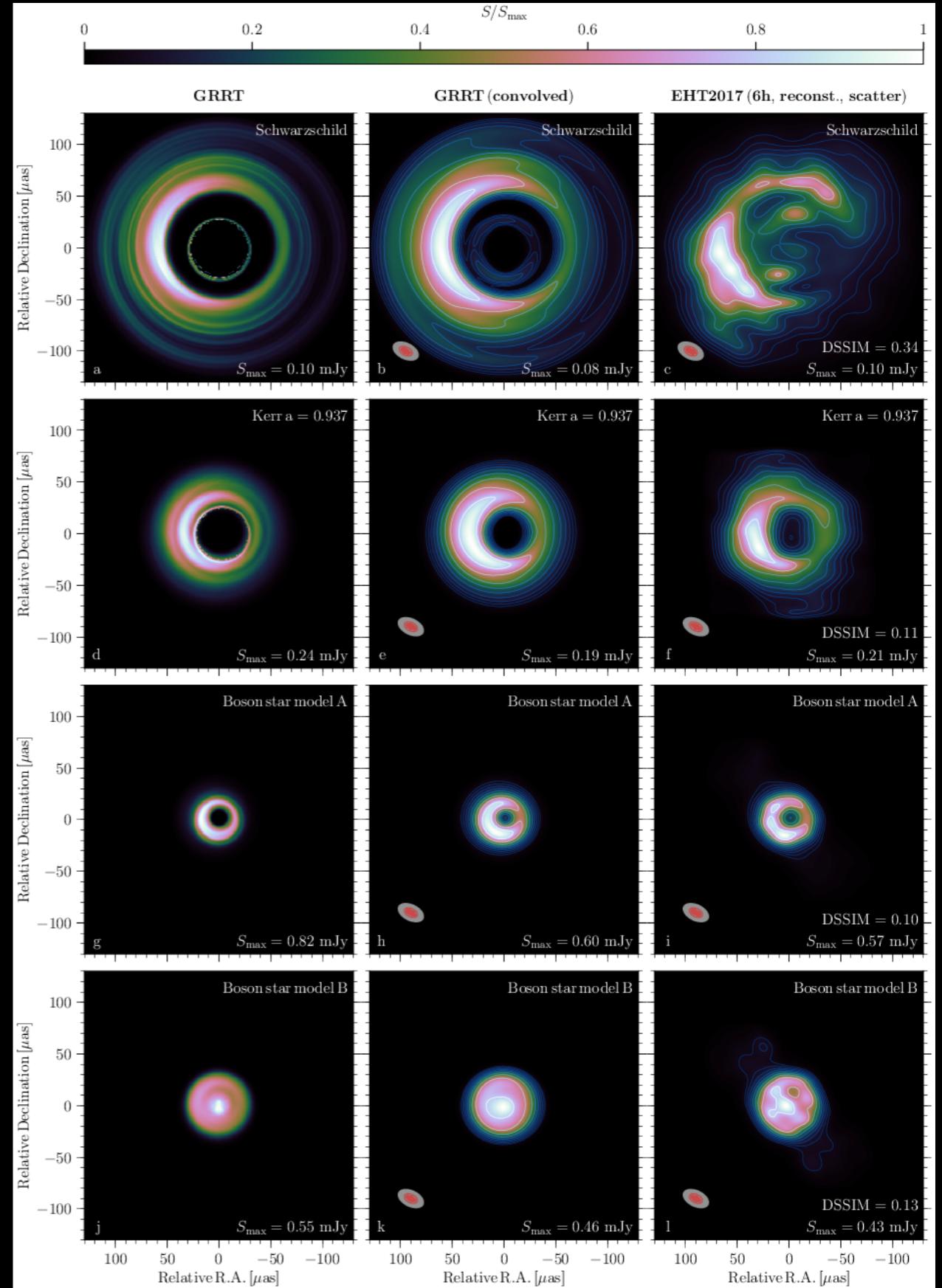
Boson star Model A: $\mathcal{C} = 0.098$

Boson star Model B: $\mathcal{C} = 0.075$

Compactness is a measure of the
“importance” of GR effects

Closed photon orbits for $\mathcal{C} > 1/3$

(Olivares+19; Fromm+21)



II) An intriguing light boson: the axion

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.

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

+ shift symmetry

$$a \rightarrow a + \kappa f_a$$

g : QCD coupling constant

G : gluon field strength

a : axion field

f_a : axion decay constant

The QCD axion is a well-motivated extension to SM

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QCD axion mass
(peculiar to QCD model)

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

The QCD axion is a well-motivated extension to SM

Additional couplings to photons and matter:

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

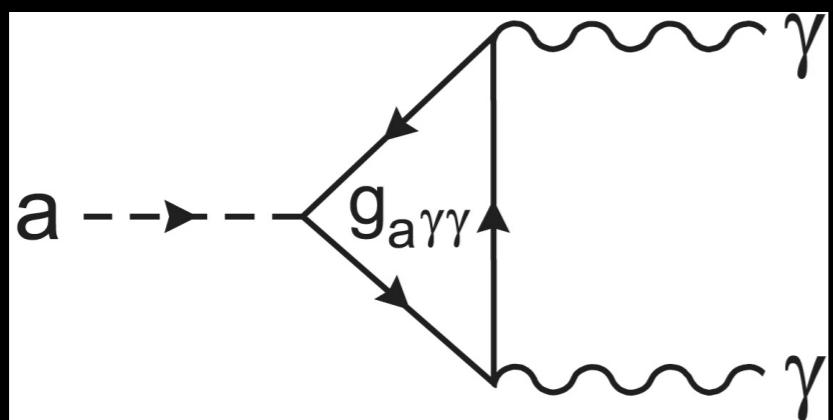
$g_{a\gamma\gamma}$

↑
Photon field strength

↑
 $g_{aff} \equiv C_{af} m_f / f_a$

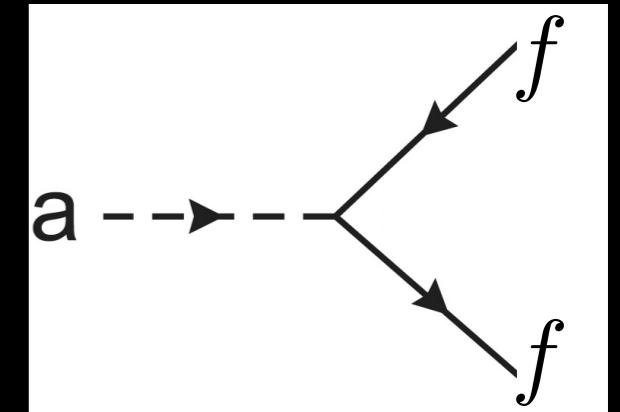
↑
Fermion field

Axion-photon coupling

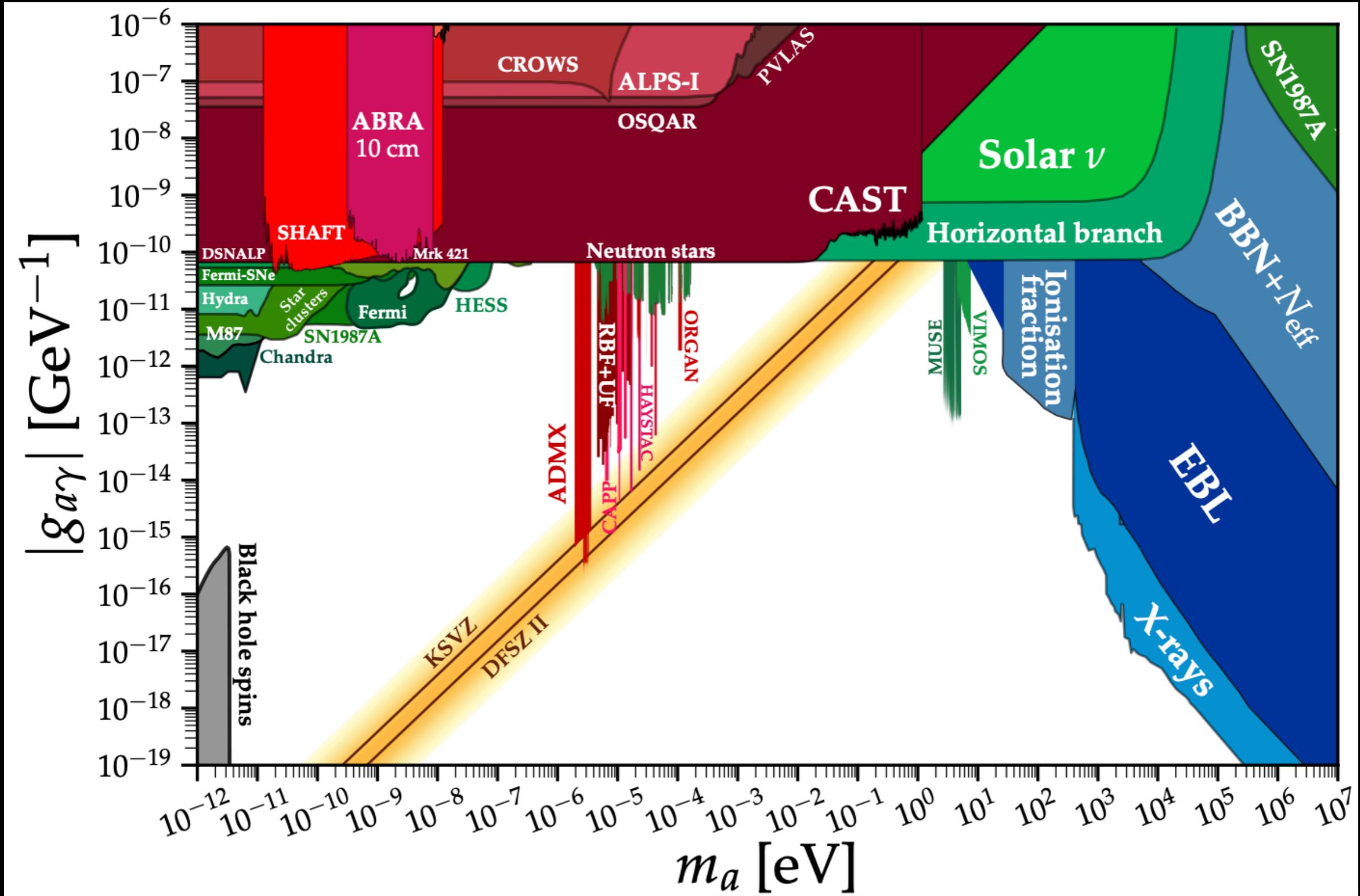


Axion-fermion coupling

(contains an extra contribution from the fermion mass m_f)

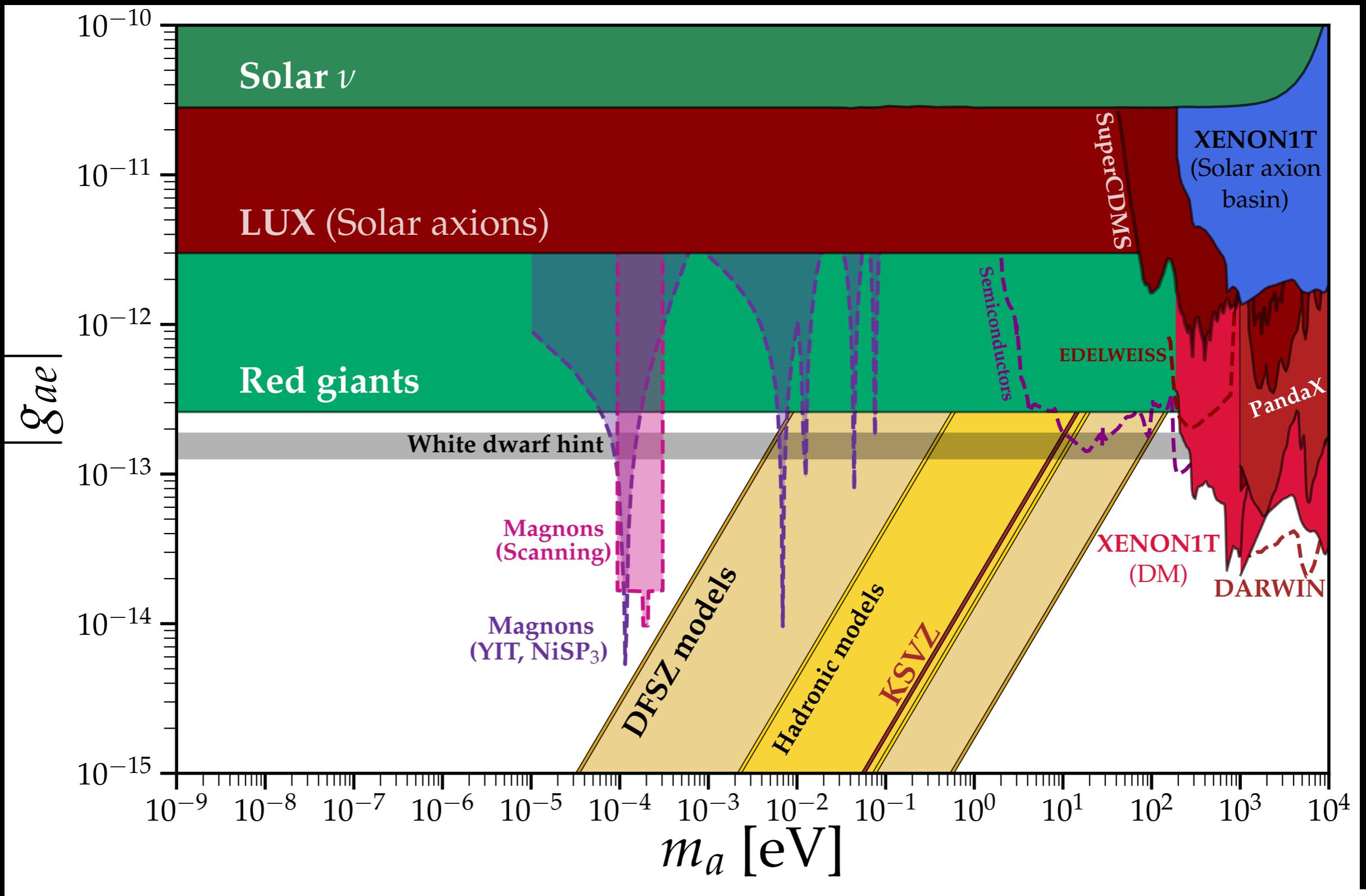


Axion-photon coupling



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

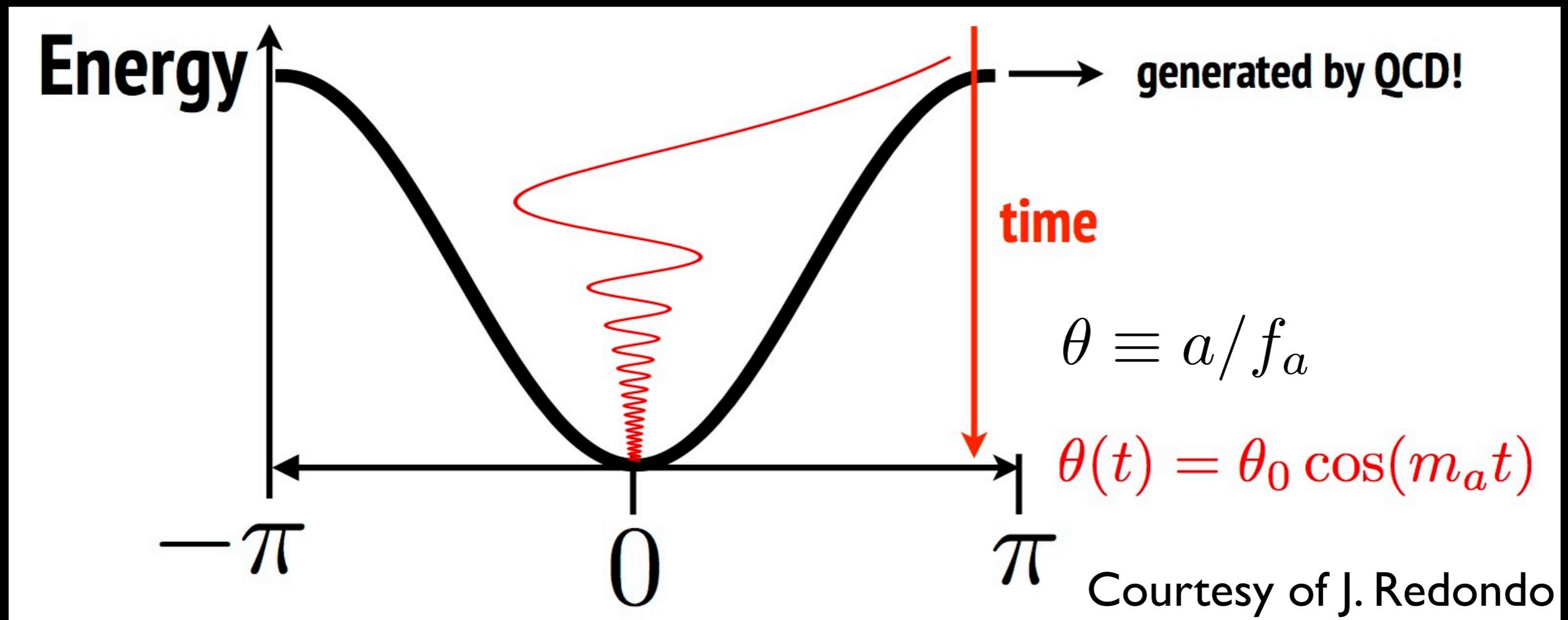
Axion-electron coupling



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

Axion DM production

Damped harmonic oscillator $\ddot{a} + 3H\dot{a} + \frac{dV(a)}{da} = 0$
(for super-horizon modes $|\nabla\theta| \approx 0$)



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

Axion DM production

More complicated picture

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

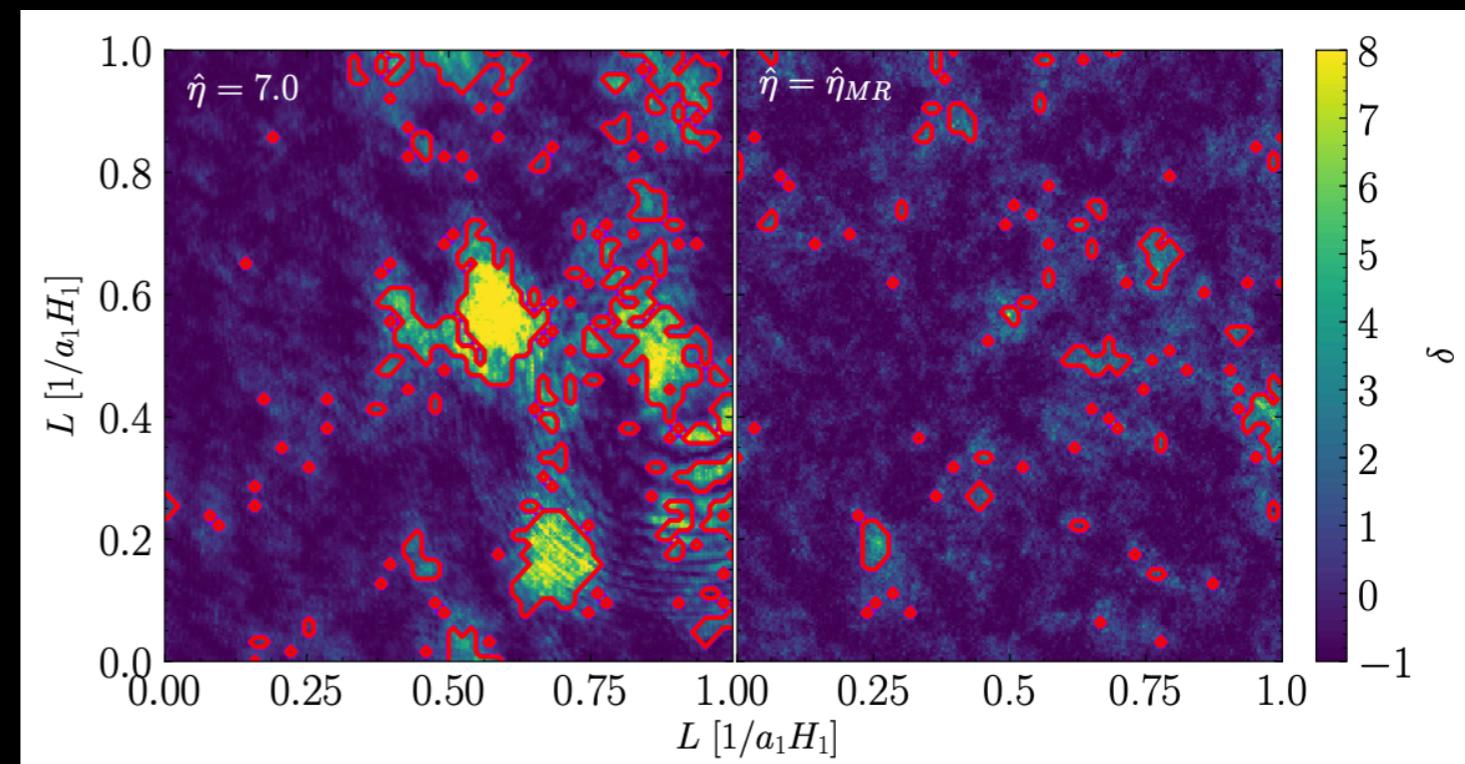
PQ field radial mode

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

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

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

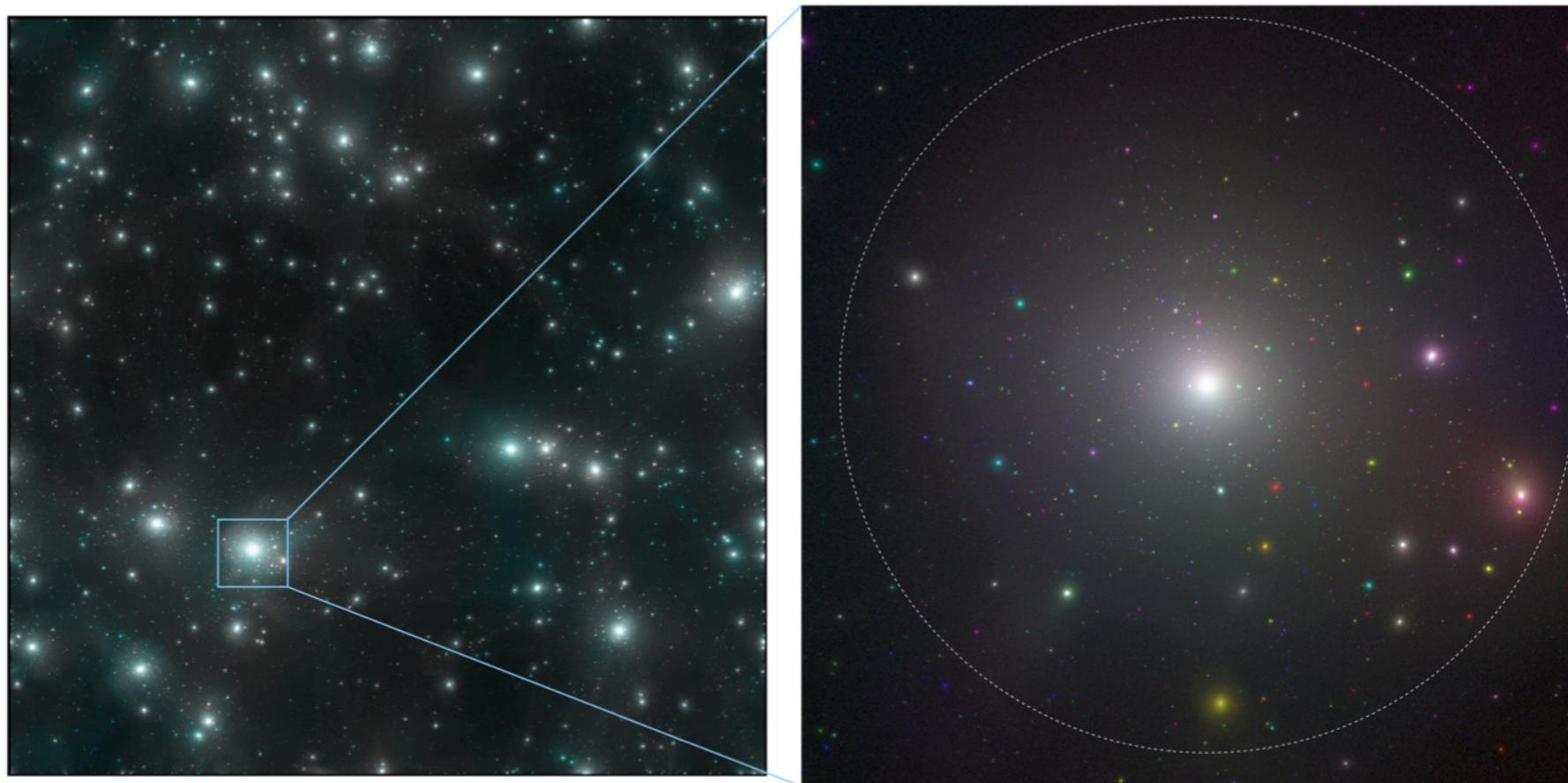
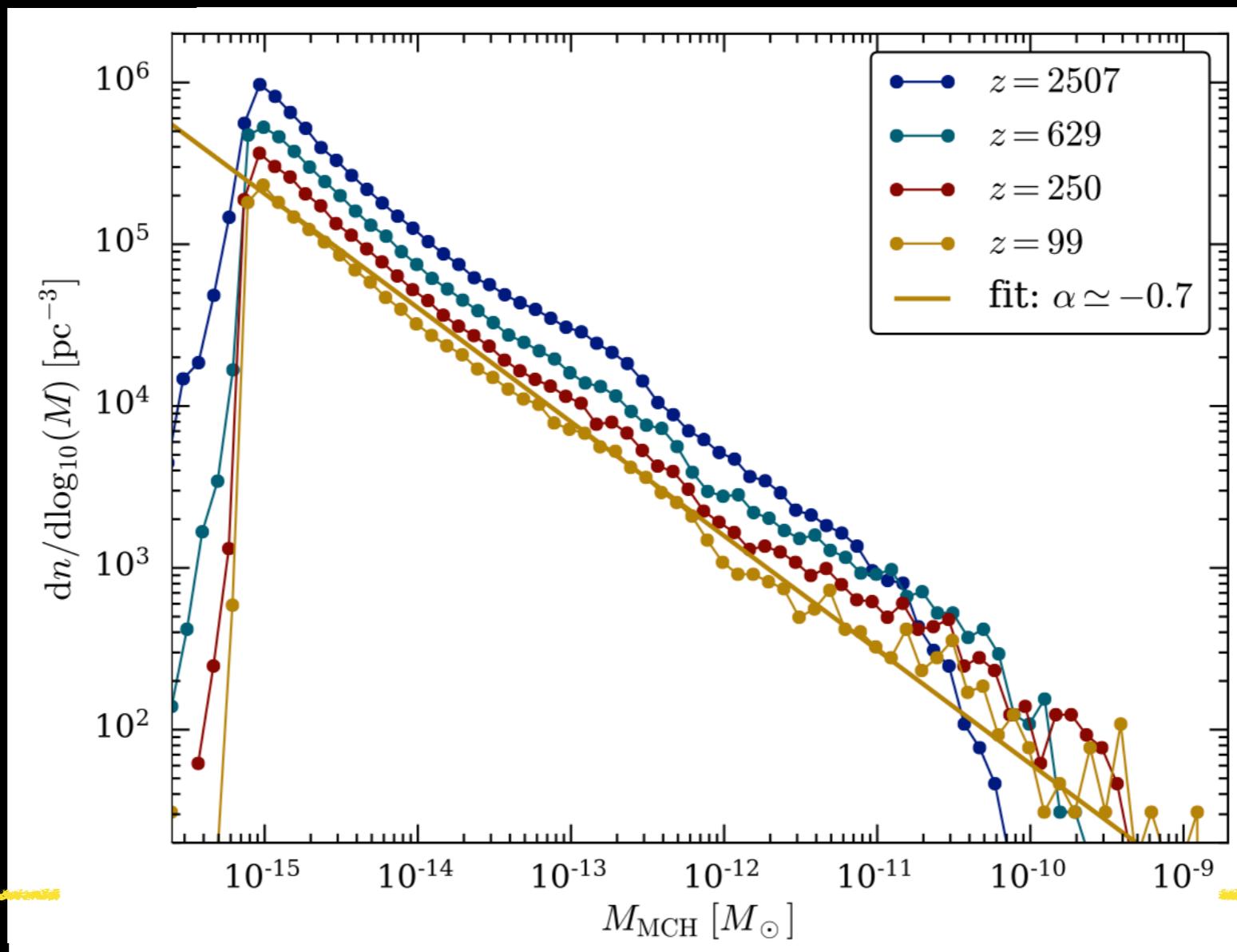


FIG. 1. Left: projected axion density of the full simulation box at $z = 99$. Right: an enlargement of the largest MCH, where the dashed circle indicates the sphere with density $\rho = 200 \rho_{m,0}$. The sub-MCs are colored according to their orbital velocity.

Eggemeier+ 1911.09417

AMC halo mass function



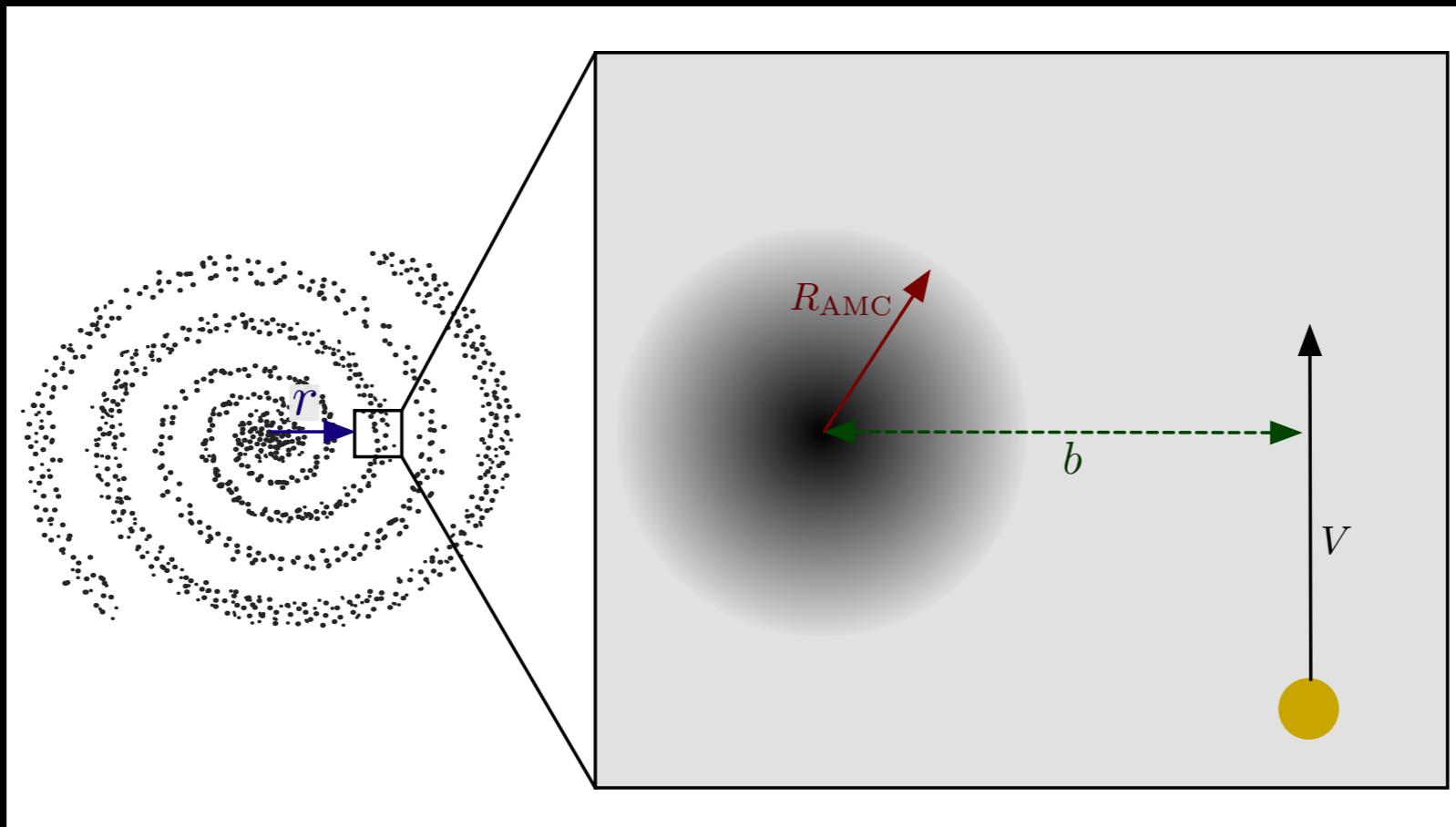
Extends down to
 $M_{\text{AMC}} \sim 10^{-19} M_\odot$
set by the Jeans mass
for $m_a = 20 \mu\text{eV}$

$$\frac{dn}{d \log M_{\text{AMC}}} \propto M_{\text{AMC}}^{-0.7}$$

see also [Ellis & Marsh 2006.08637](#)

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

What is missing: survival of miniclusters in the Galaxy



Edwards, Kavanagh, Visinelli, Weniger 2011.05377, 2011.05378



Thomas Edwards
OKC Stockholm, Sweden

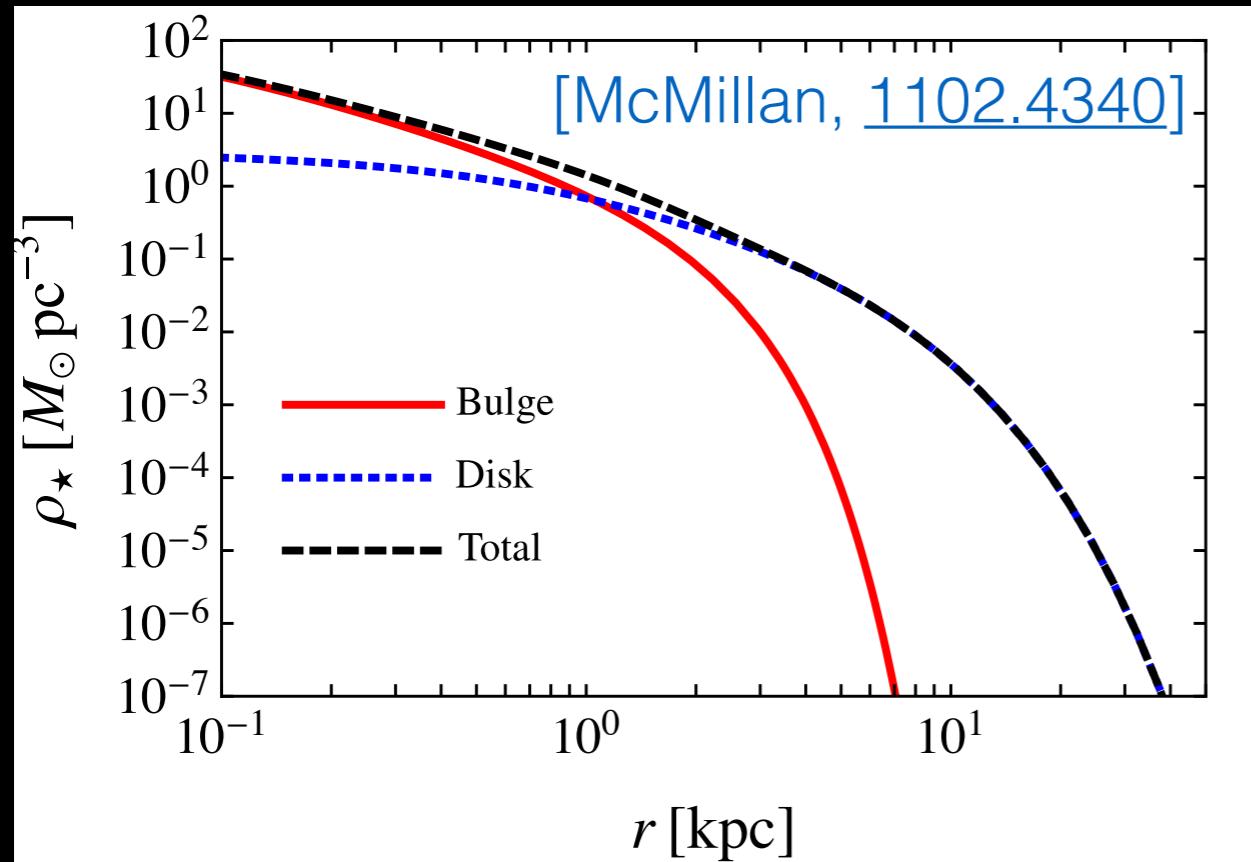


Bradley Kavanagh
IFCA Santander, Spain



Christoph Weniger
GRAPPA Amsterdam, Netherlands

Milky Way setup

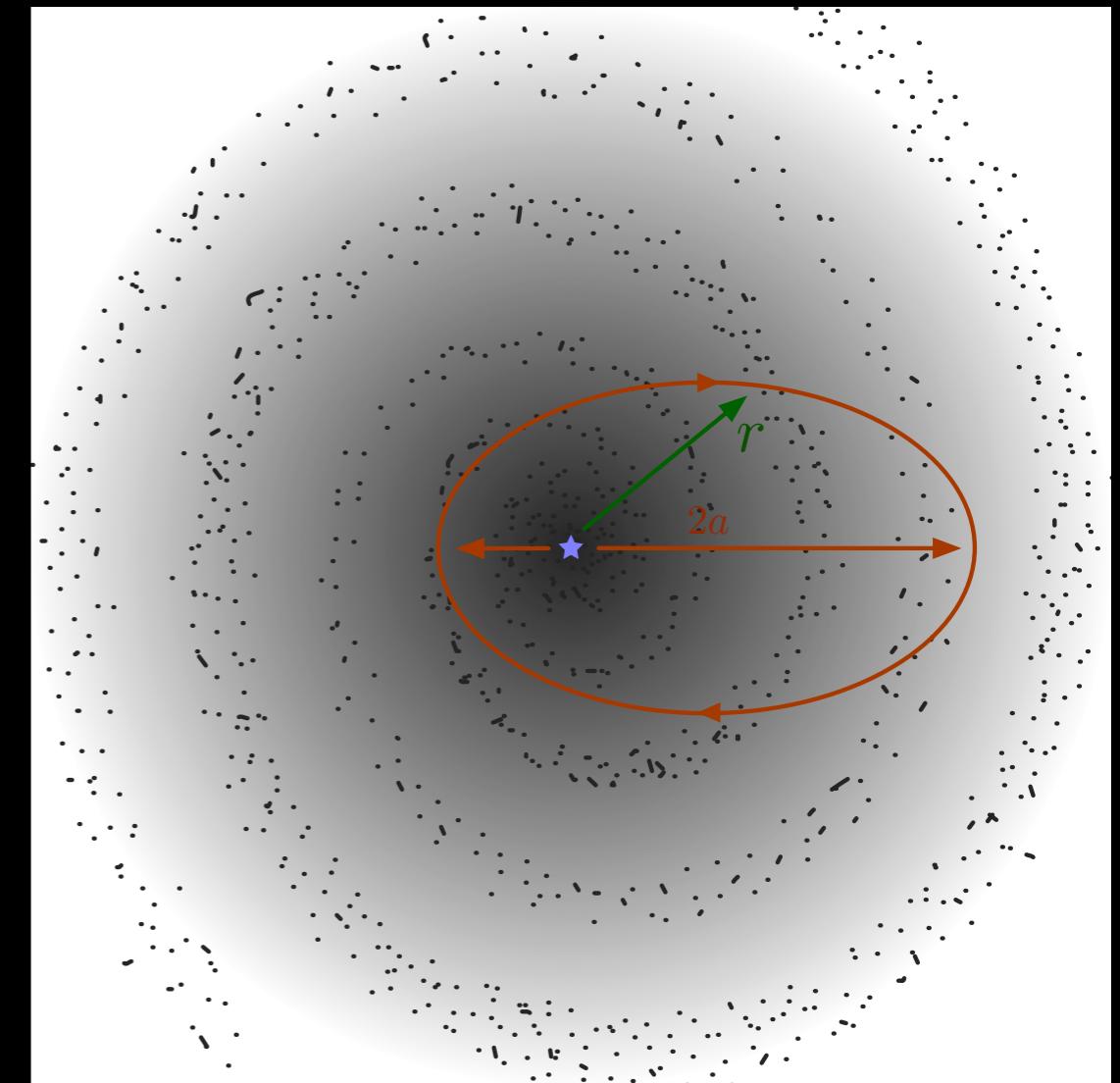


DM distribution in the Milky Way $\rho_{\text{DM}}(r)$

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

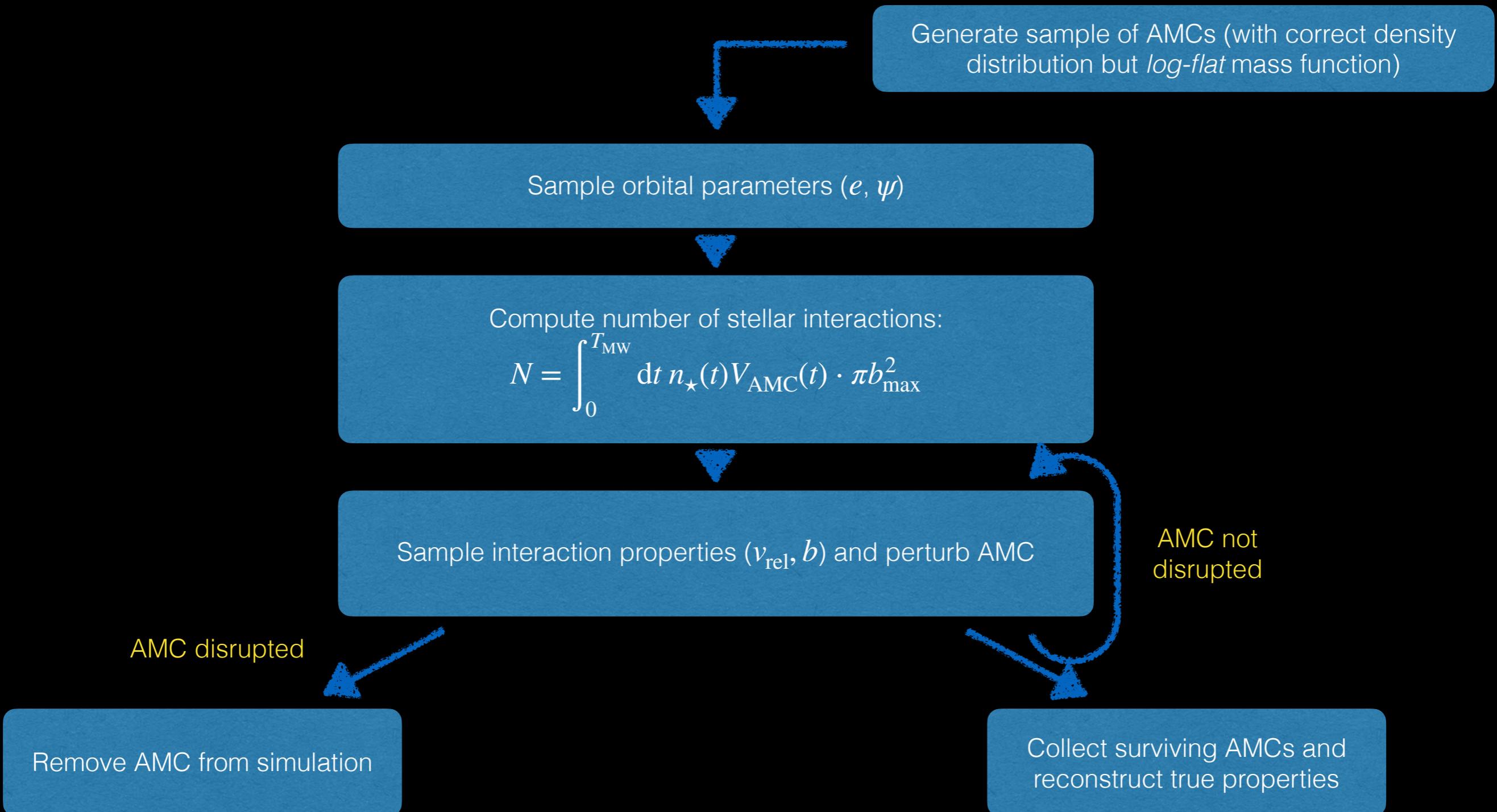
We set $f_{\text{AMC}} = 100\%$

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



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

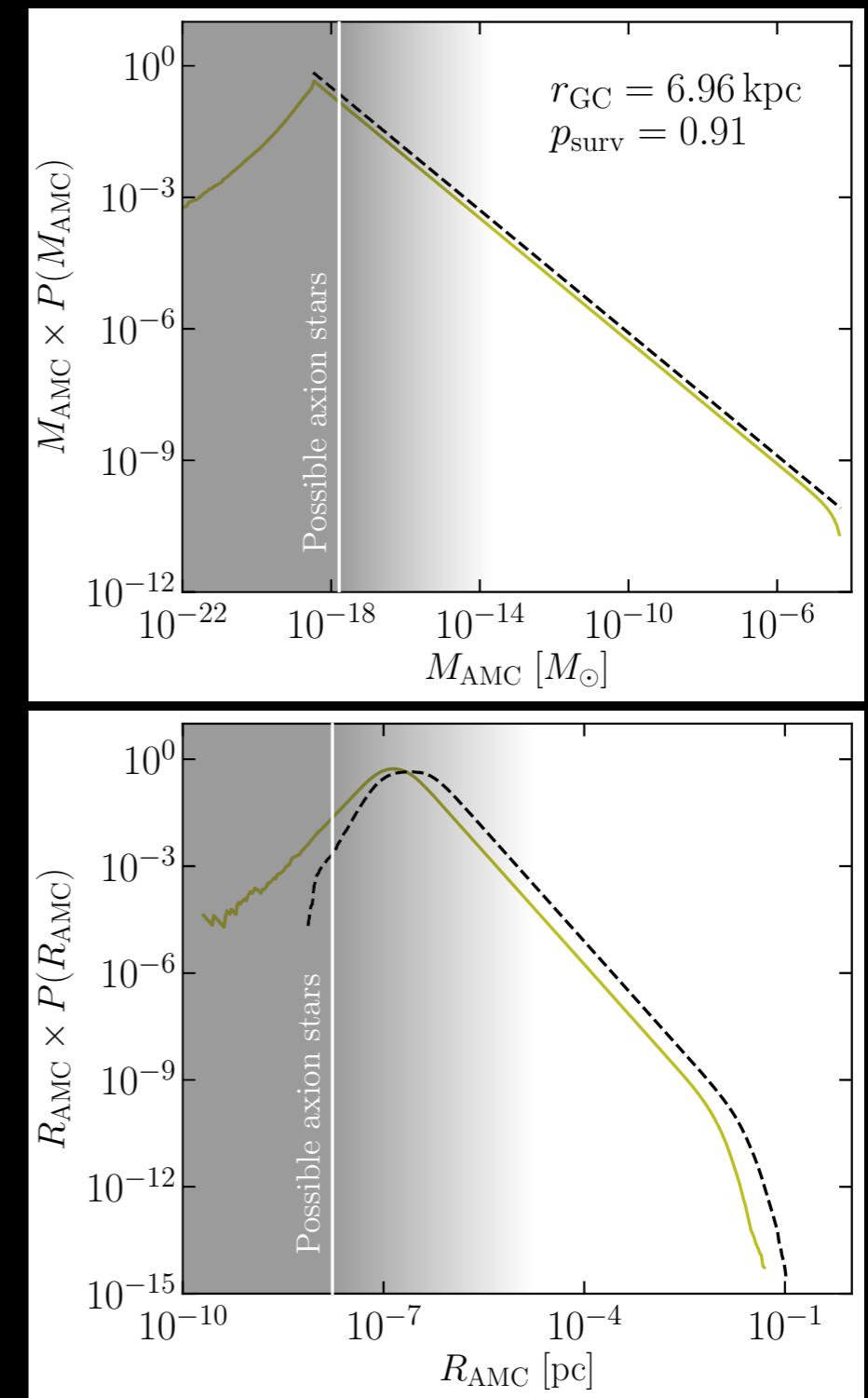
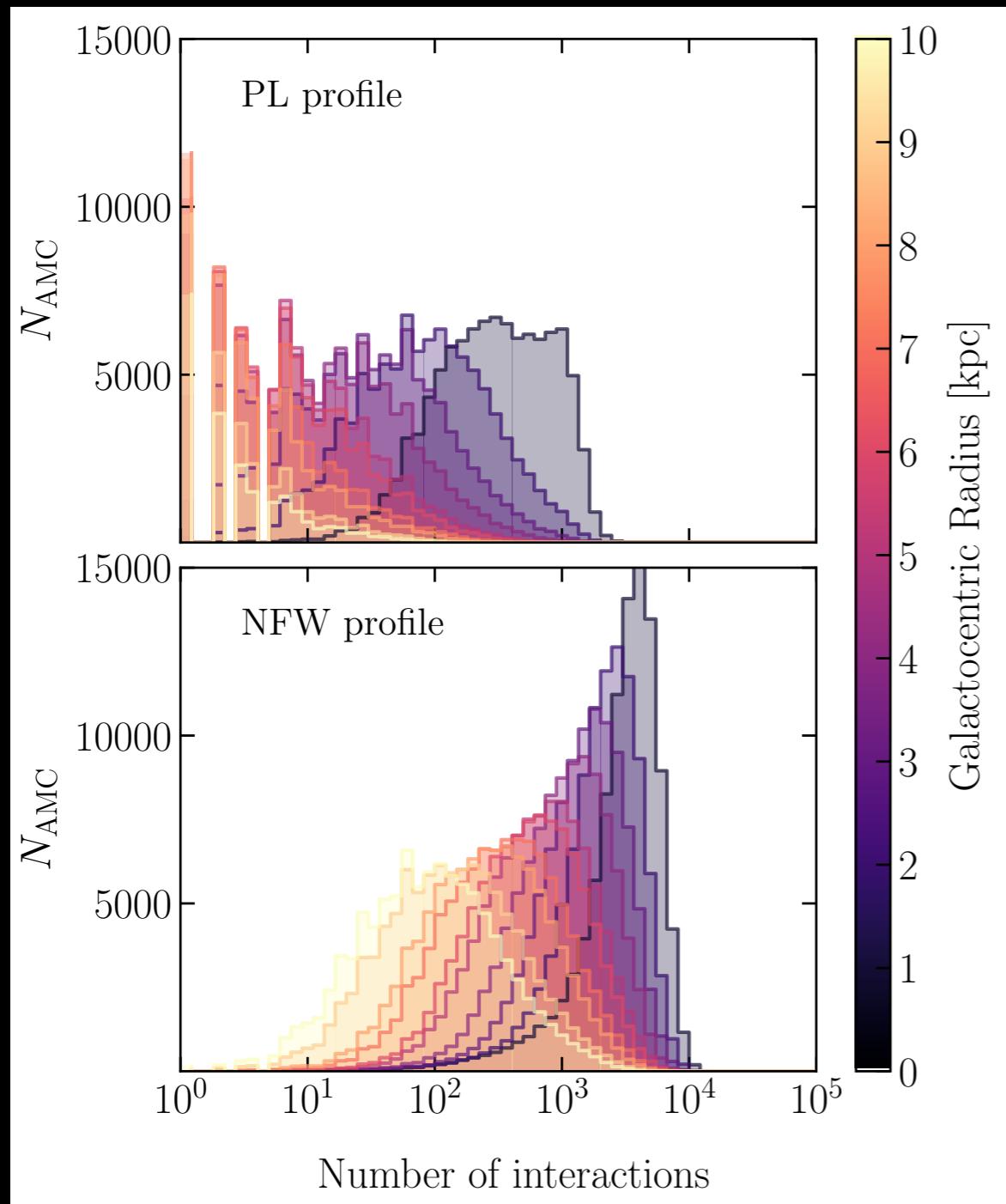
Monte Carlo procedure



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

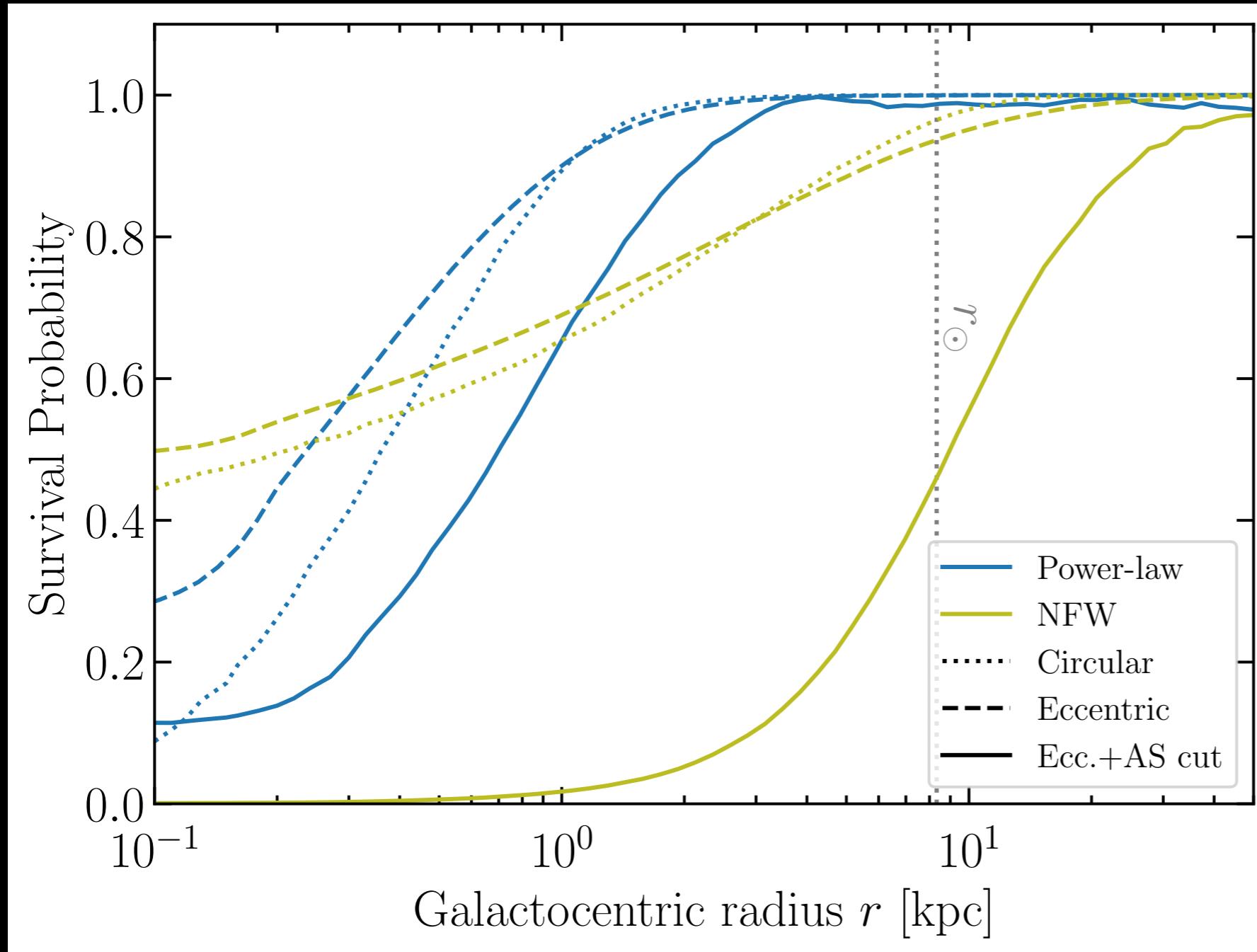
Monte Carlo procedure

$$N = \int_0^{T_{\text{MW}}} dt n_\star V_{\text{AMC}}(t) \pi b_{\text{max}}^2$$



Axion stars modeled after the work of
Schive et al. I406.6586; I407.7762

Axion minicluster survival probability



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

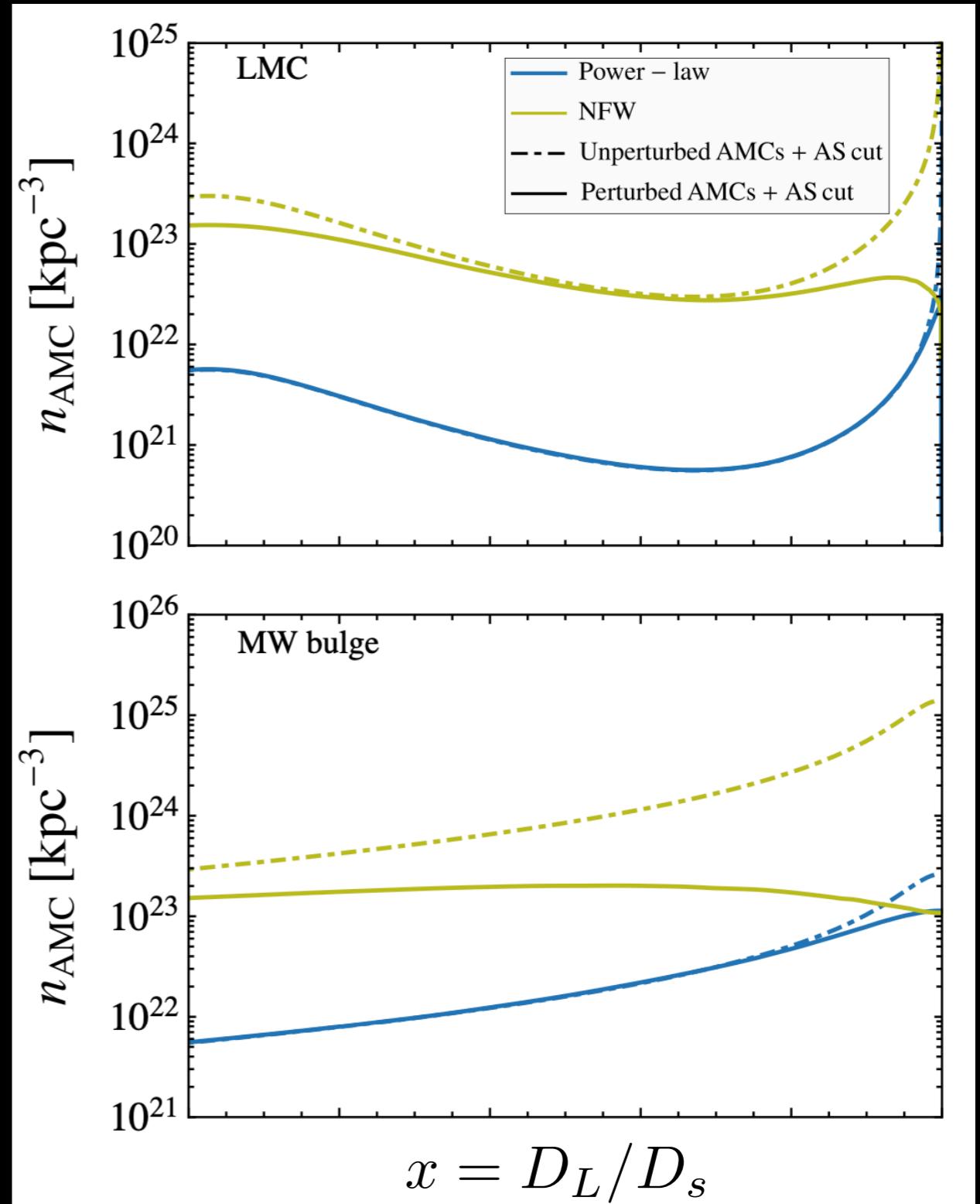
see also [Tinyakov+ 1512.02884](#); [Dokuchaev+ 1710.09586](#)

Application: axion minicluster lensing

$$\bar{N}_{\text{ex}} \propto \int dt \int dx \frac{d\Gamma}{dxdt}$$

$$\frac{d\Gamma}{dxdt} \sim n_{\text{AMC}}(x)$$

[See Fairbairn+ [1701.04787](#), [1707.03310](#)]

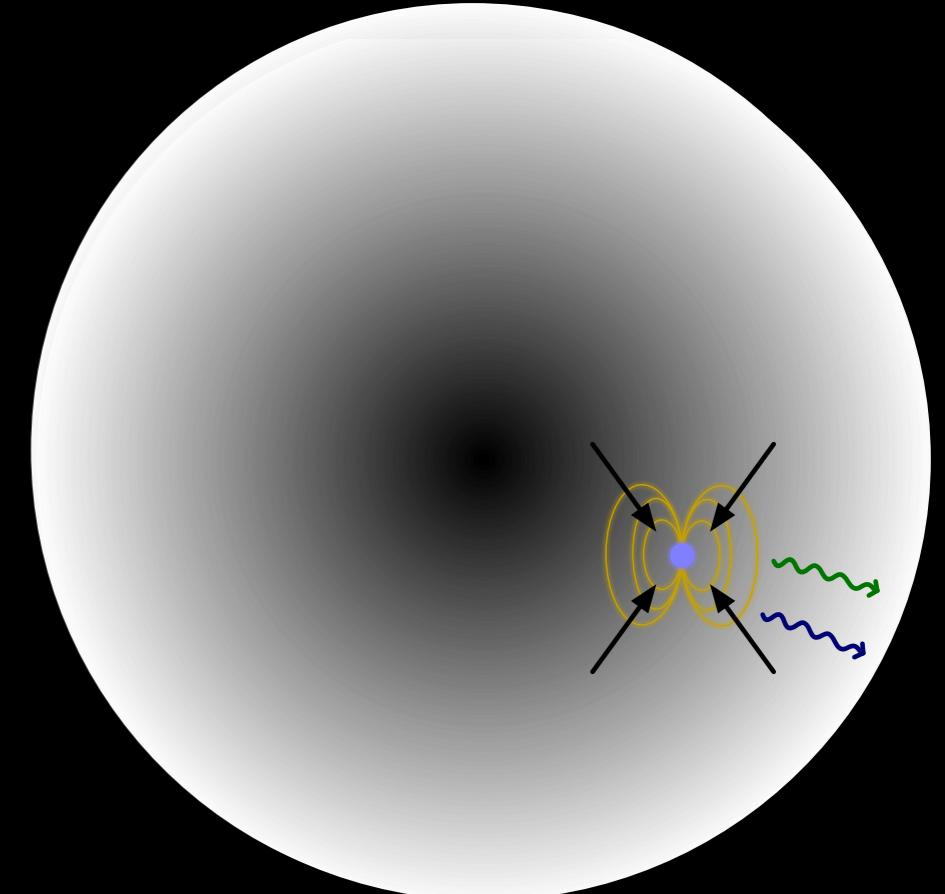


Application: axion conversion in NS

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

[Goldreich & Julian (1969)]

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



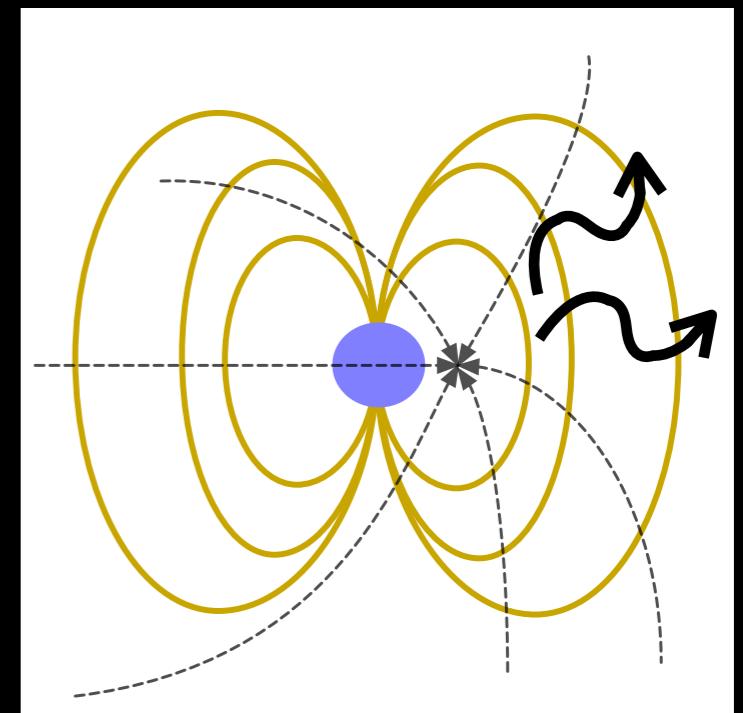
Plenty of uncertainties on magnetosphere properties, conversion probabilities, anisotropy...

[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

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

R

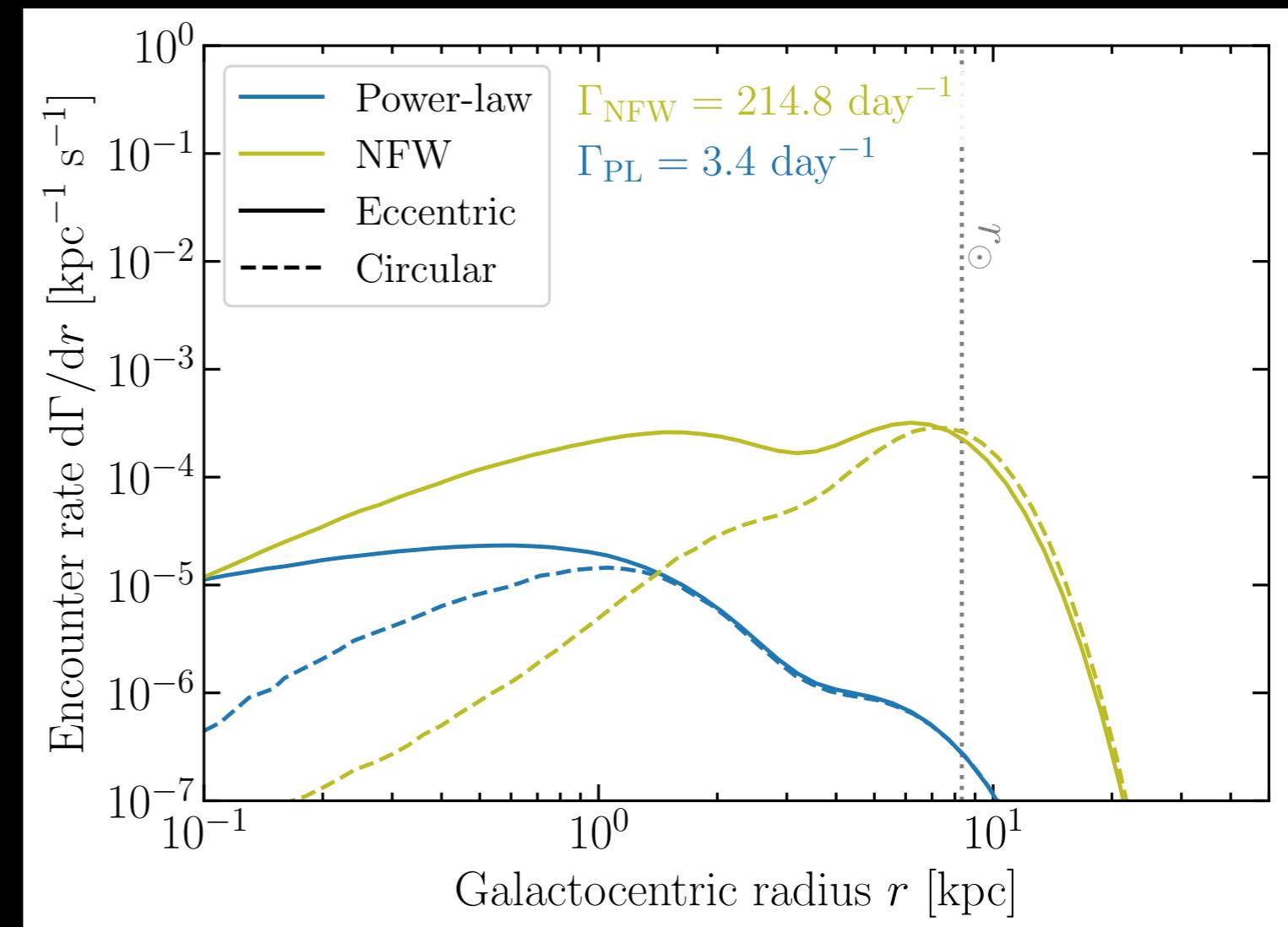
Radial coordinate
of the AMC

$\frac{dn_{\text{AMC}}(r)}{dR}$

Inner radial distribution
of the AMC

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

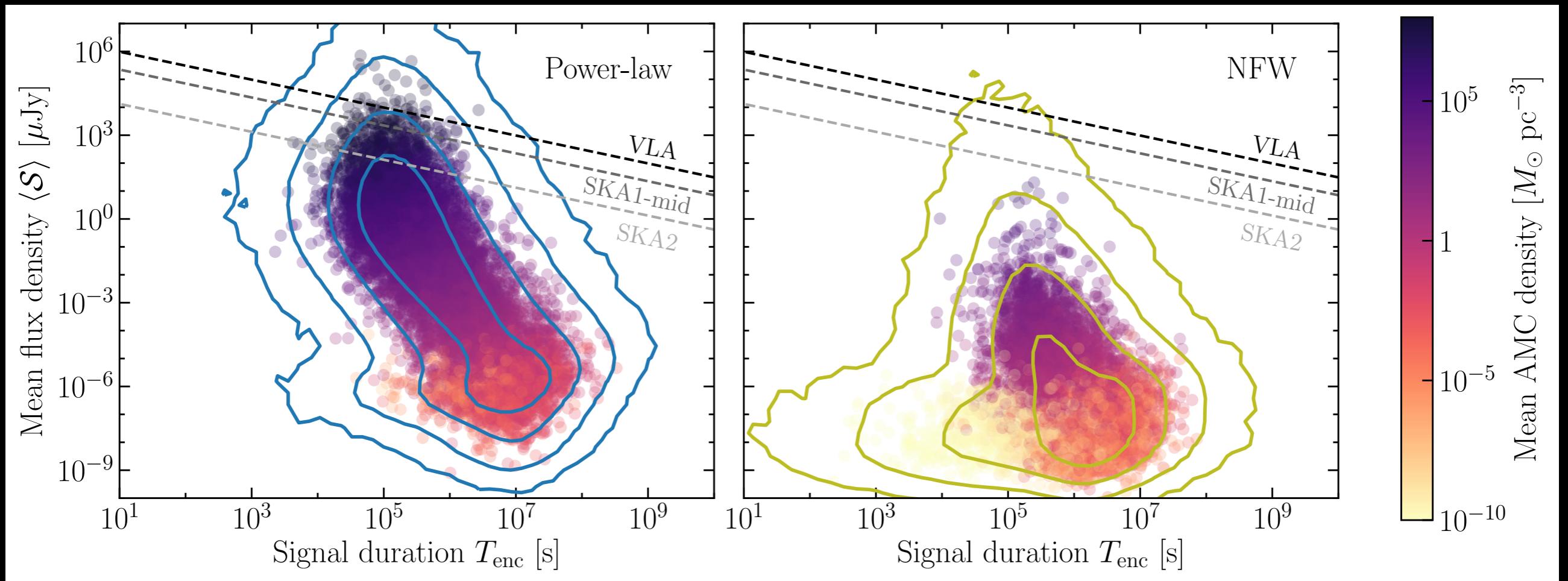
Without stellar disruption,
the encounter rate would be:
39.3x larger for NFW profiles
1.4x larger for PL profiles



Signal flux and duration

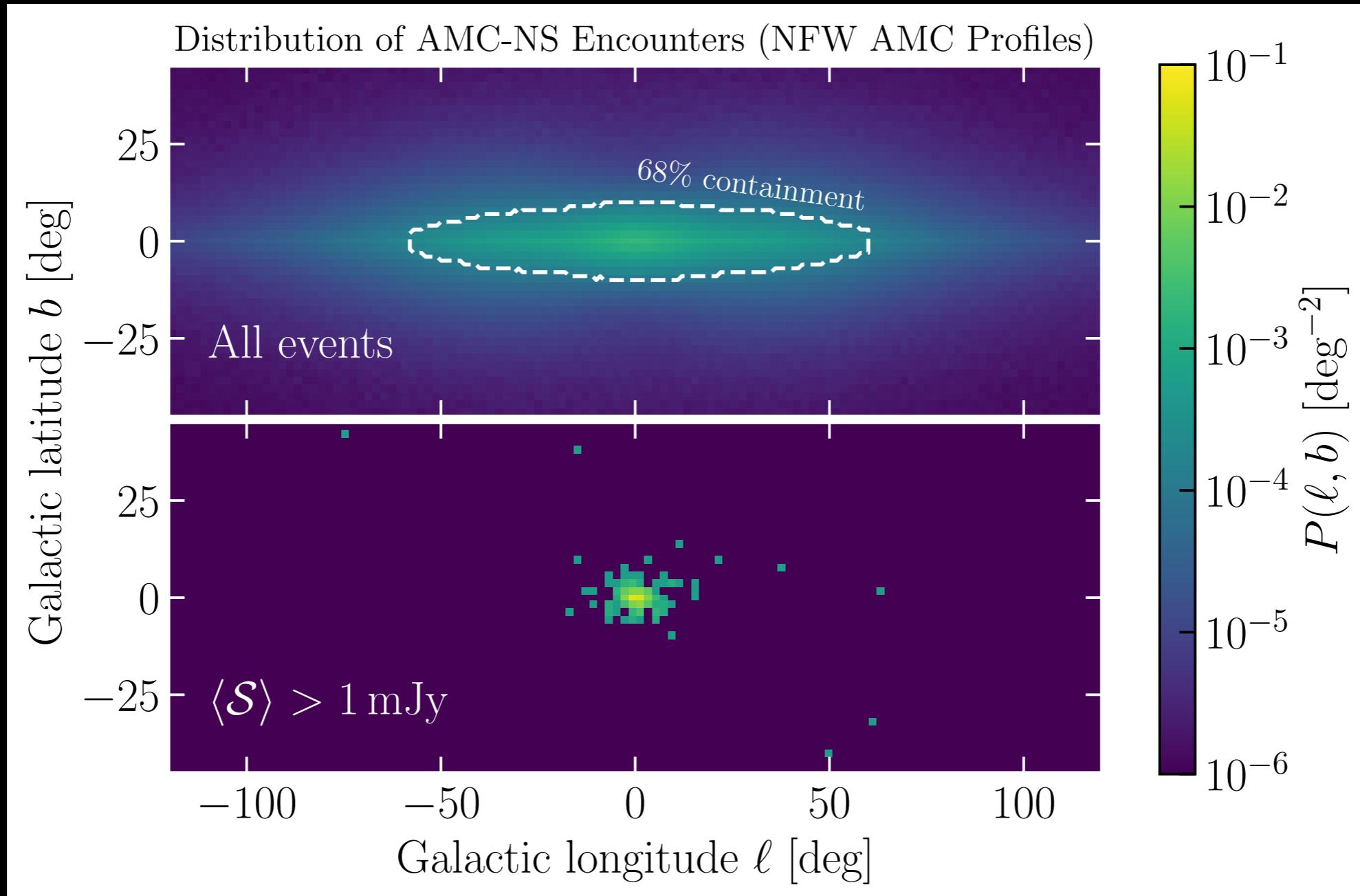
$$\mathcal{S} = \frac{1}{\text{BW}} \frac{1}{4\pi s^2} \frac{d\mathcal{P}_a}{d\omega}$$

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



Edwards, Kavanagh, Visinelli, Weniger 2011.05378

Sky distribution



Edwards, Kavanagh, Visinelli, Weniger 2011.05378

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

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

Thank you!