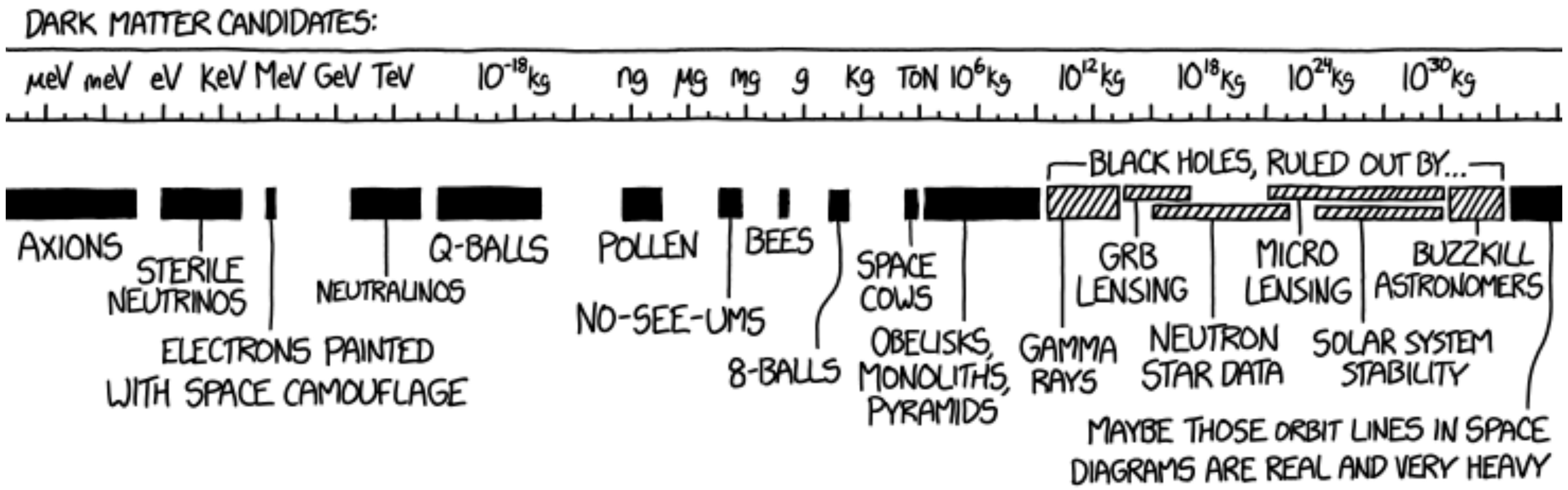
Indirect Searches for Axion Dark Matter



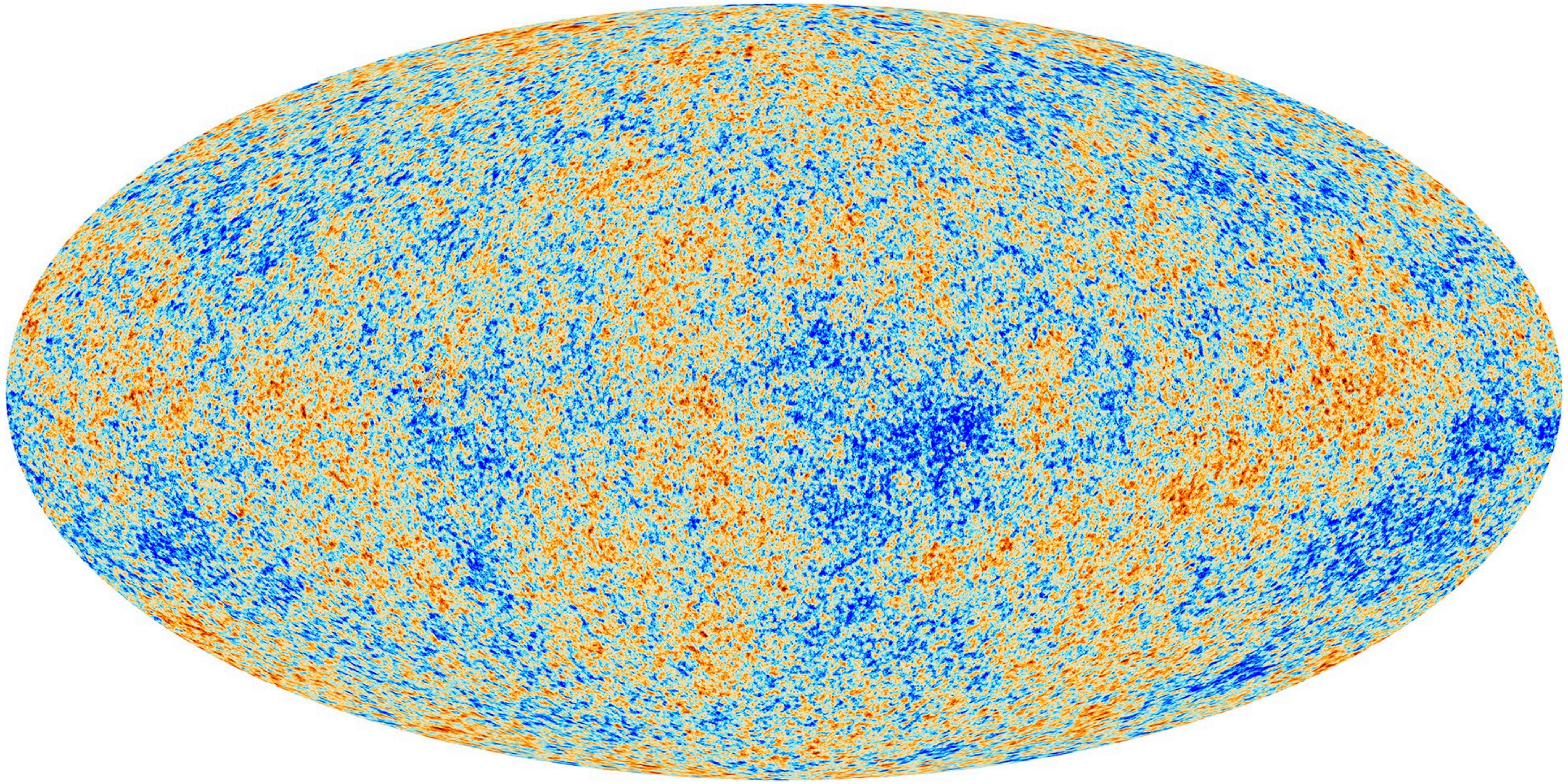
Thomas D. P. Edwards, Marco Chianese, Bradley J. Kavanagh, Mikaël Leroy,
Samaya Nissanke, and Christoph Weniger

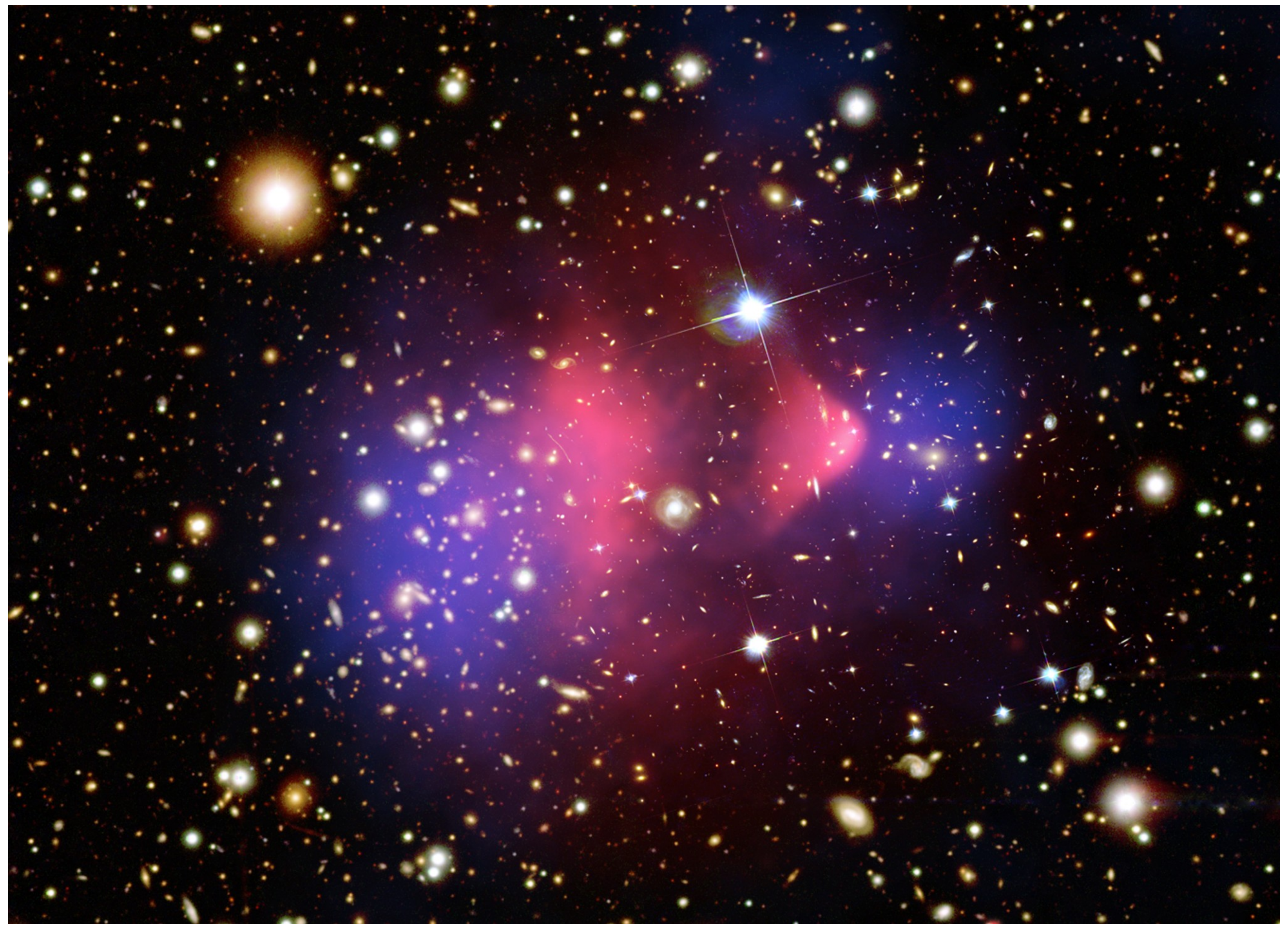
Edwards et al. 2019, Leroy et al. 2019

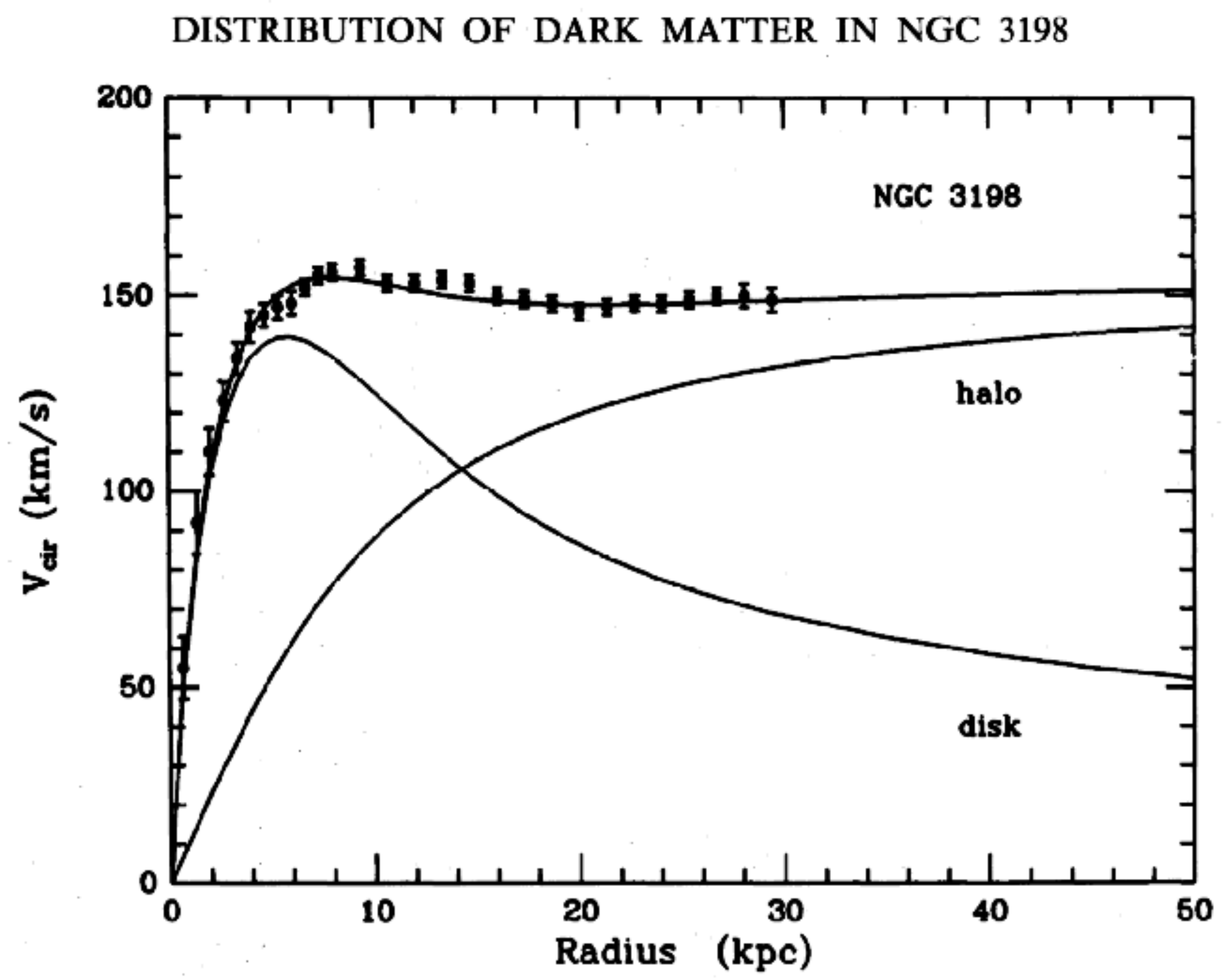
STOCKHOLMS UNIVERSITET

Oskar Klein centre

Dark Matter






DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50

Axions

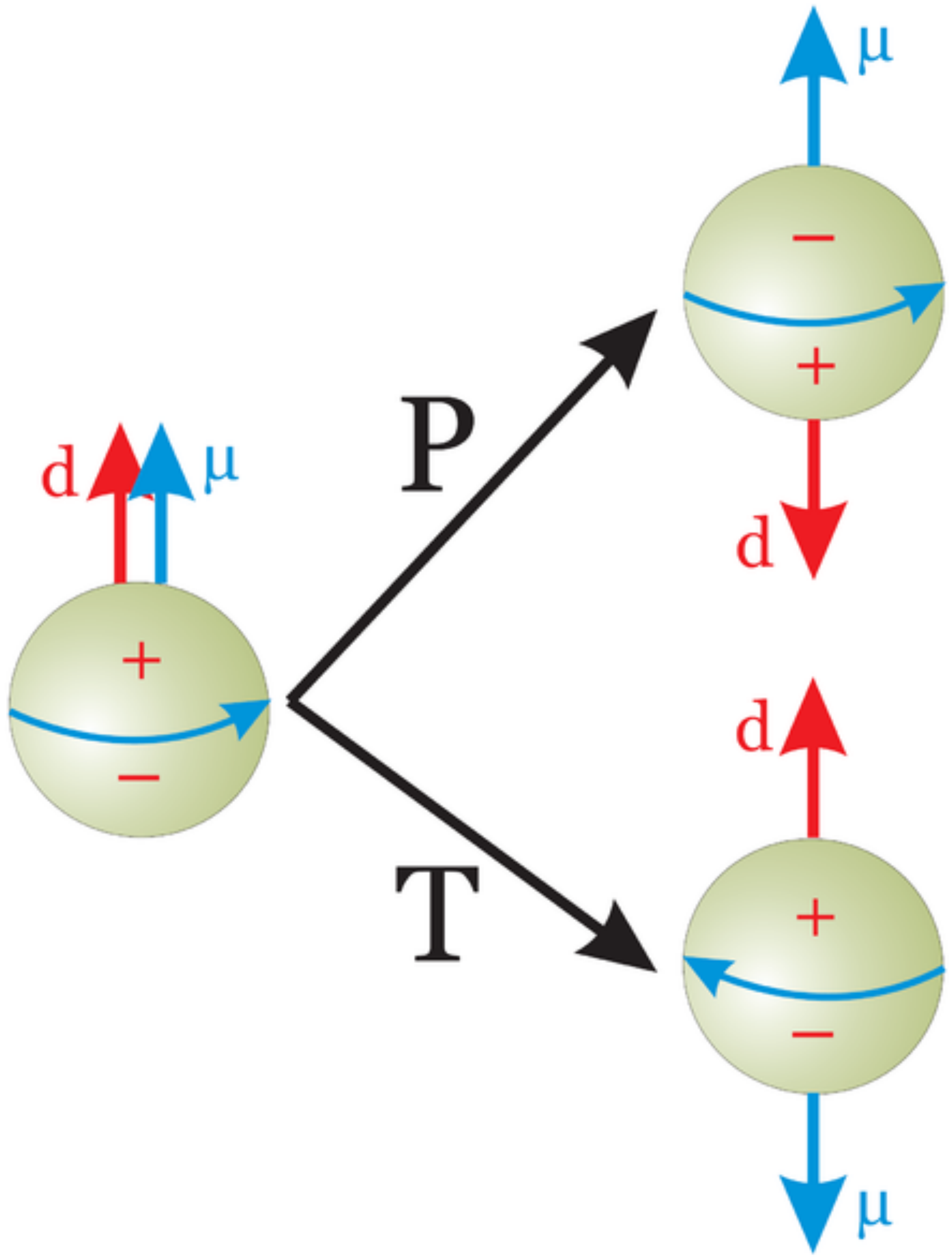
The strong interaction also admits a **CP violating term in its Lagrangian**

Promoting theta to a field allows the CP-violating term to dynamically reach zero

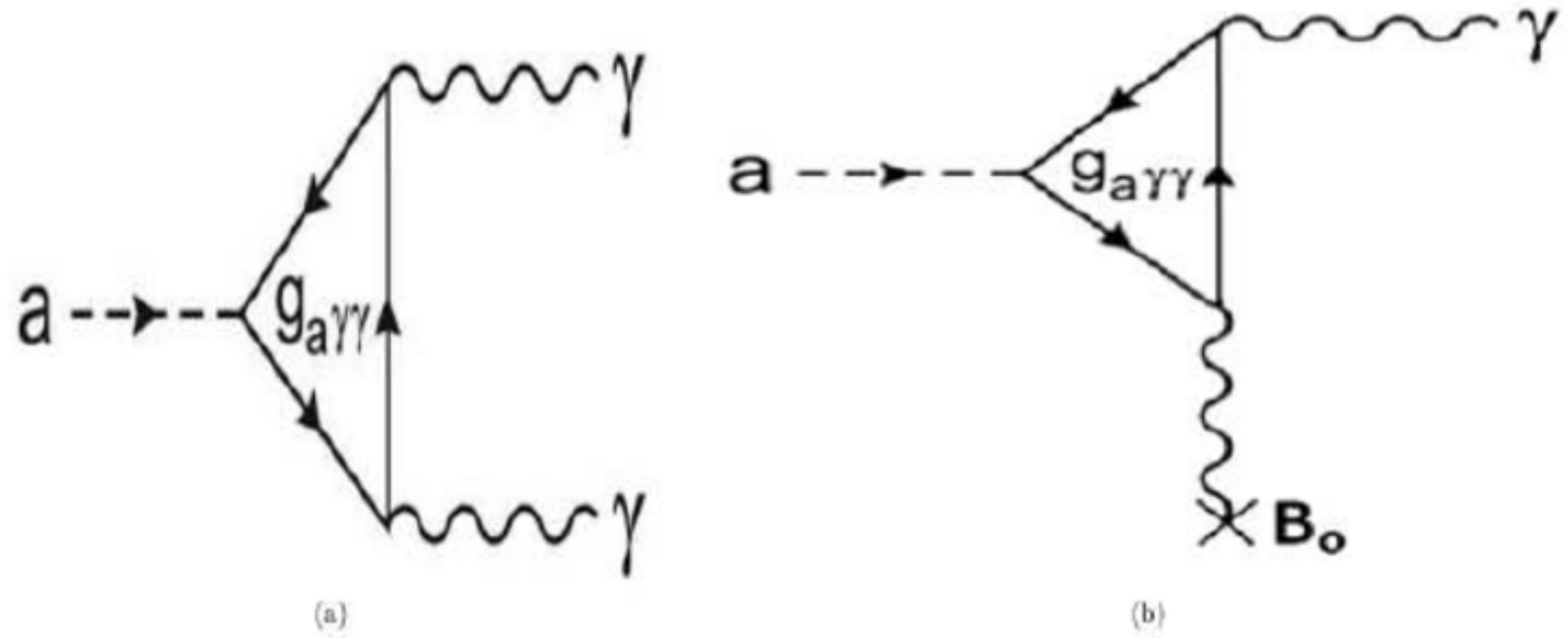
Goldstones theorem then produces a boson, **the axion**

$$\mathcal{L} = -\frac{g_s^2\theta}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$|\theta| < 10^{-10}$ $\qquad$ $|\theta| \neq \mathcal{O}(1)$

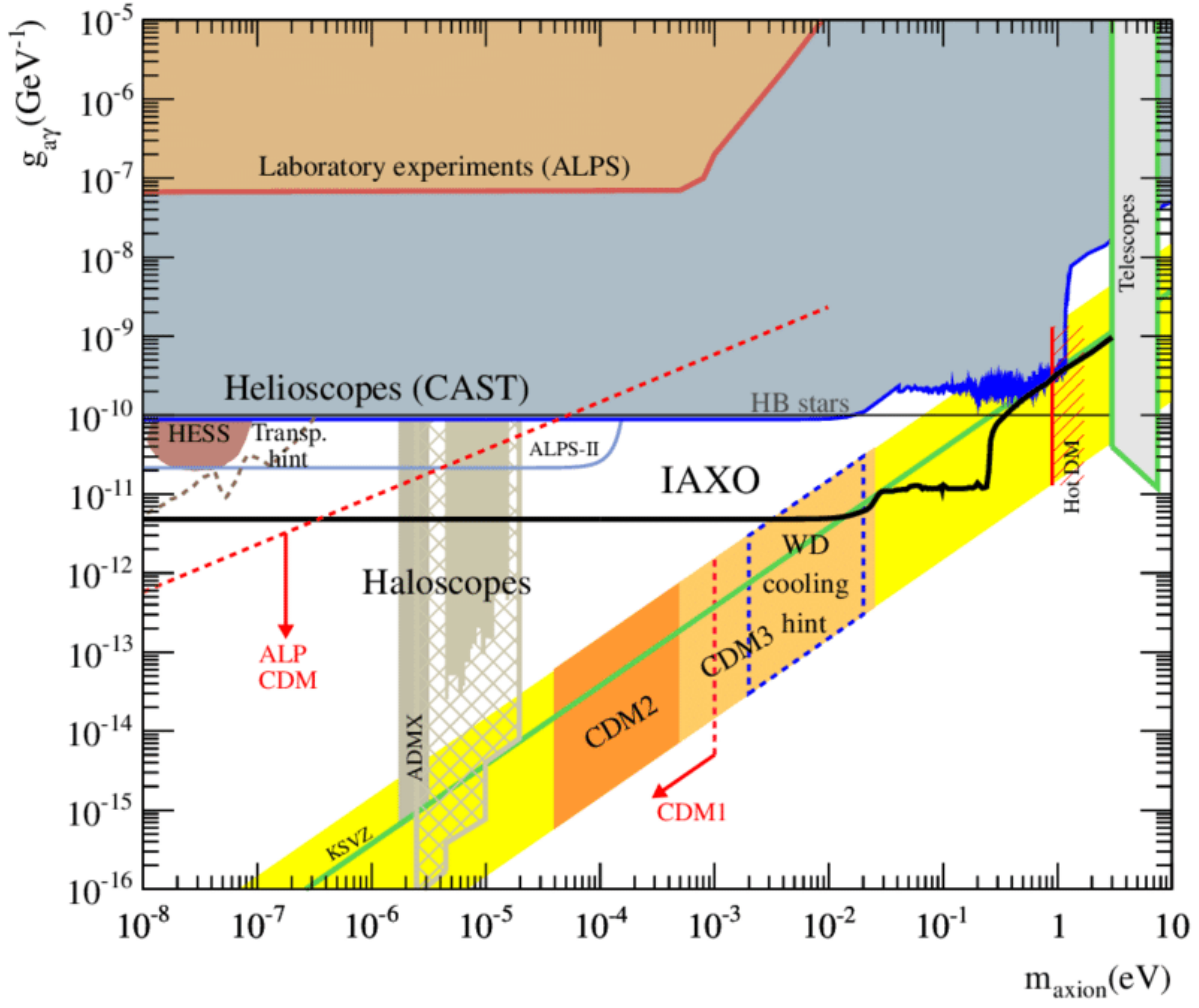


Axion Coupling to Photons



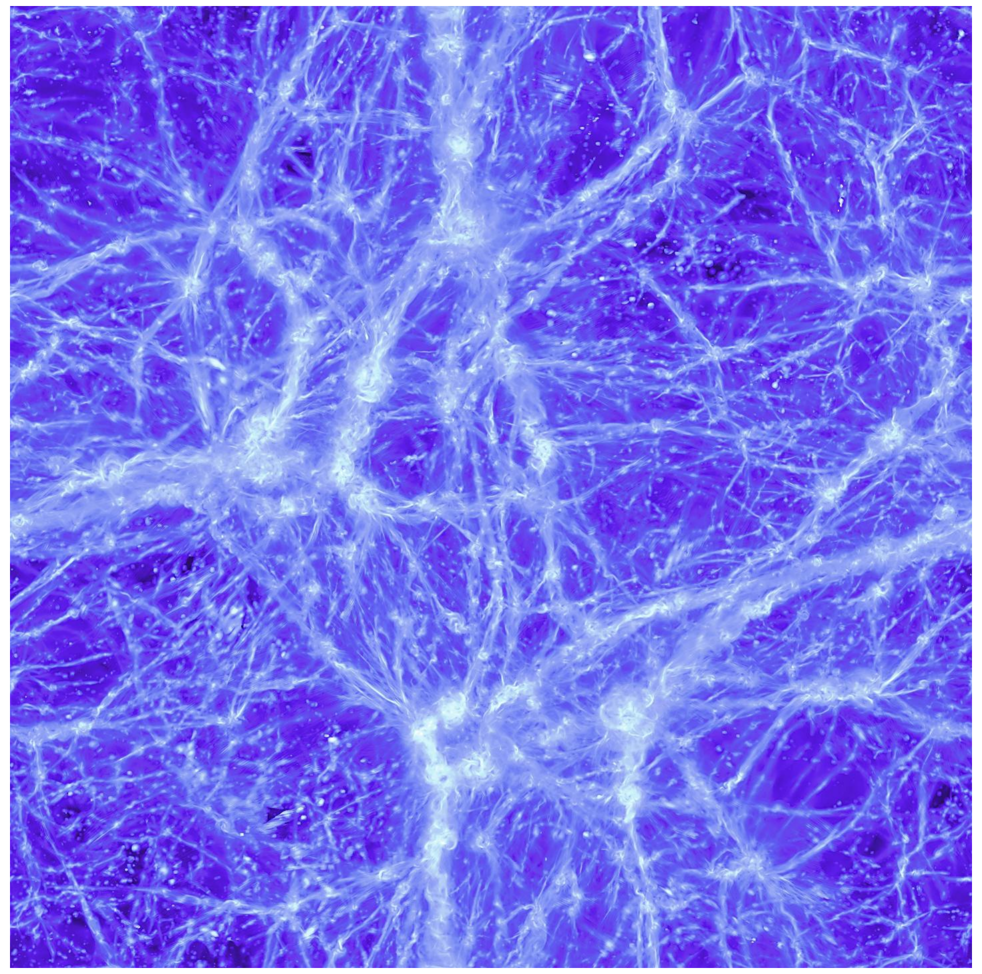
$$\mathcal{L} \propto g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Galan et al. 2015



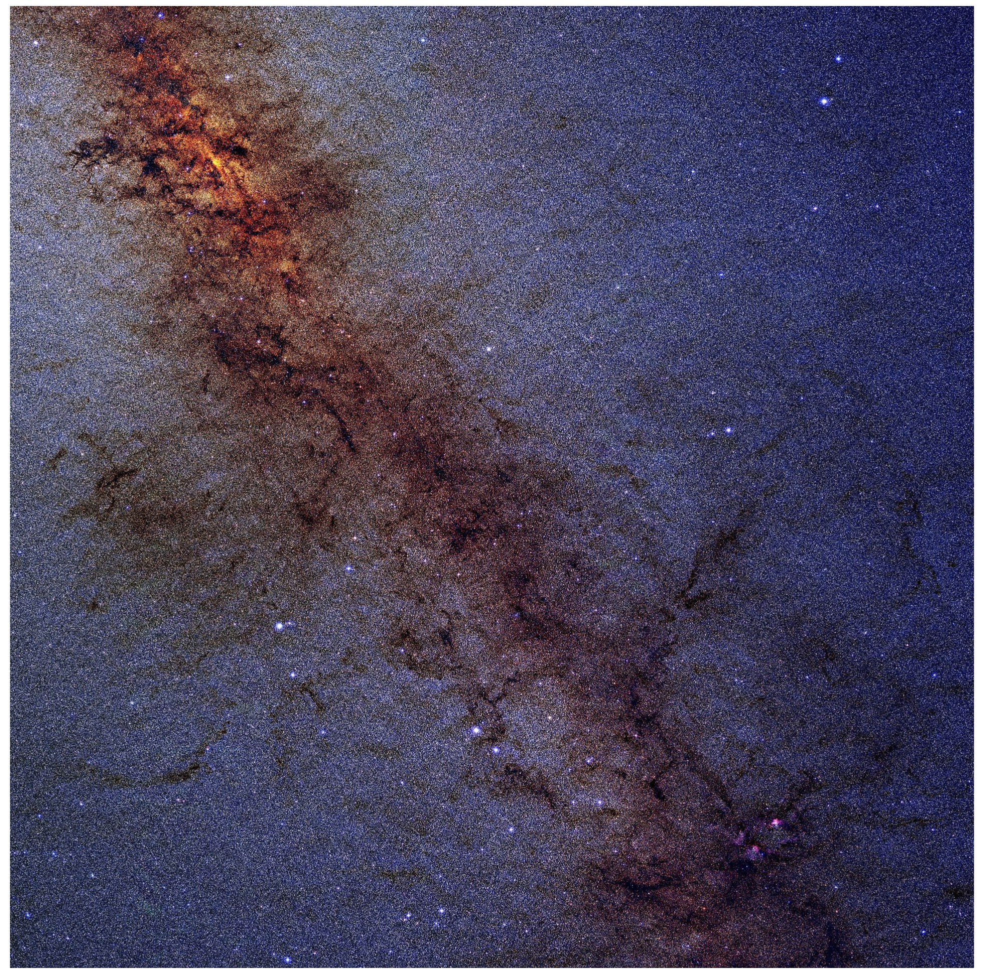
Astrophysical Magnetic Fields

Oskar Klein centre

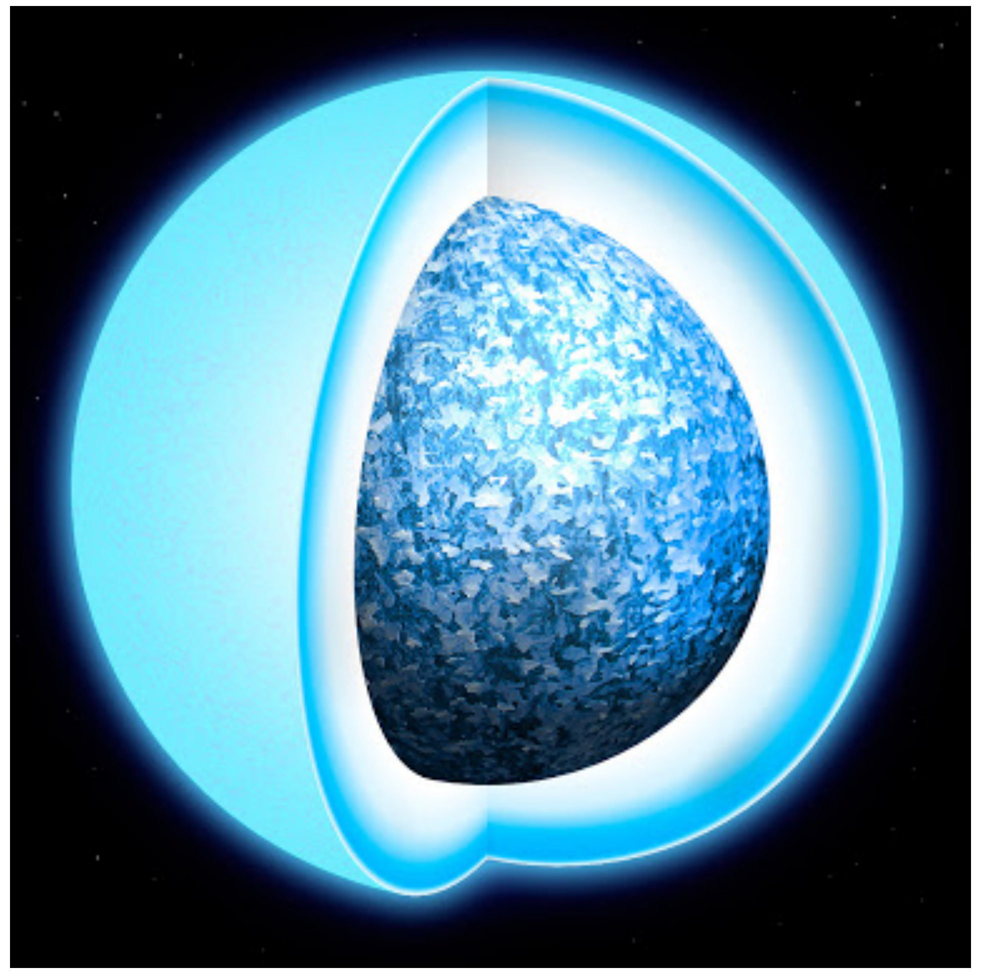


$B \sim 10^{-7}\,\mathrm{G}$

$B \sim 10^{-4}\,\mathrm{G}$



$B \sim 10^{-1}\,\mathrm{G}$



$B \sim 10^{6-9}\,\mathrm{G}$

$B \sim 10^{9-15}\,\mathrm{G}$

Searching for Axions:

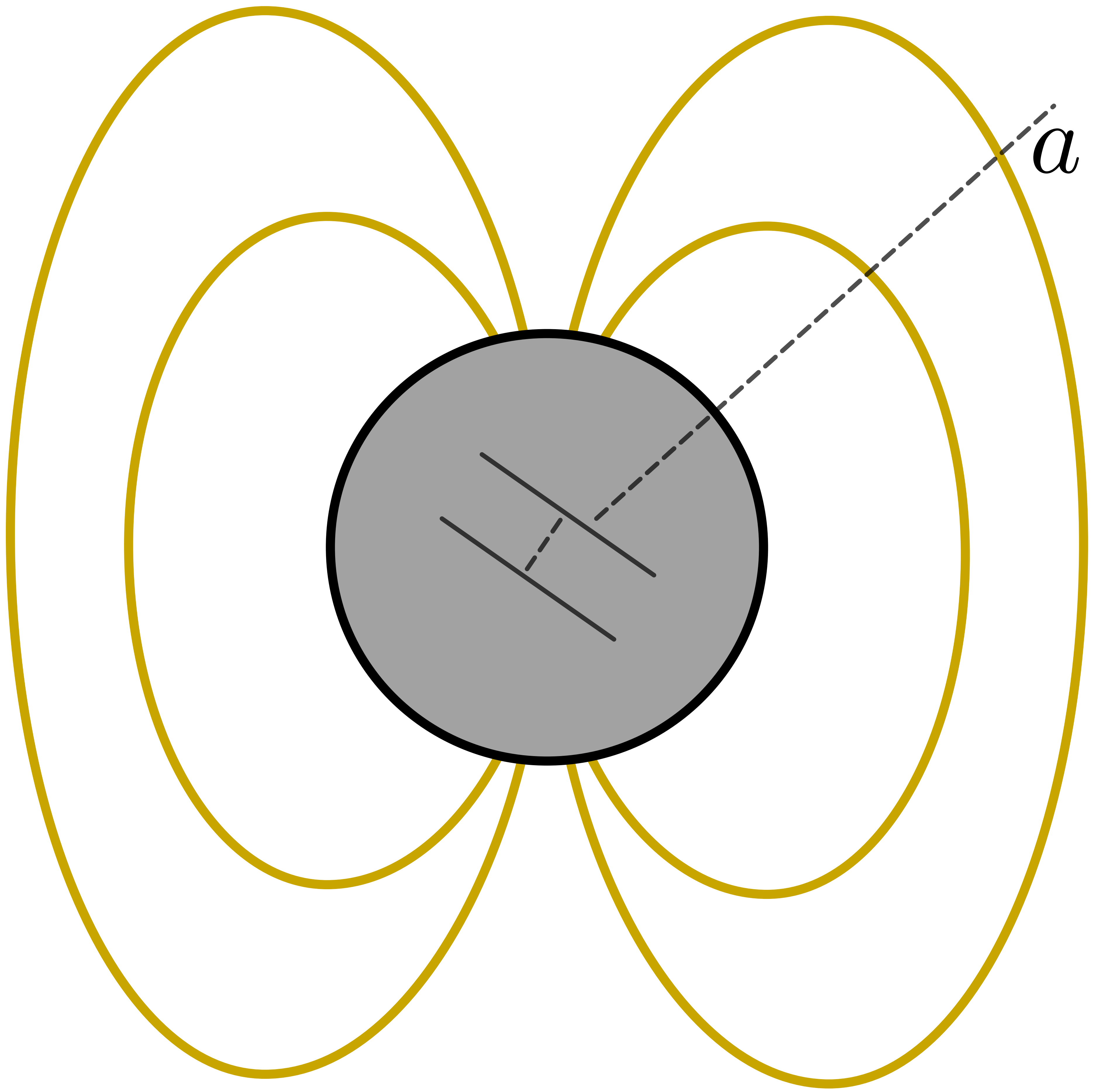
1. Astrophysics

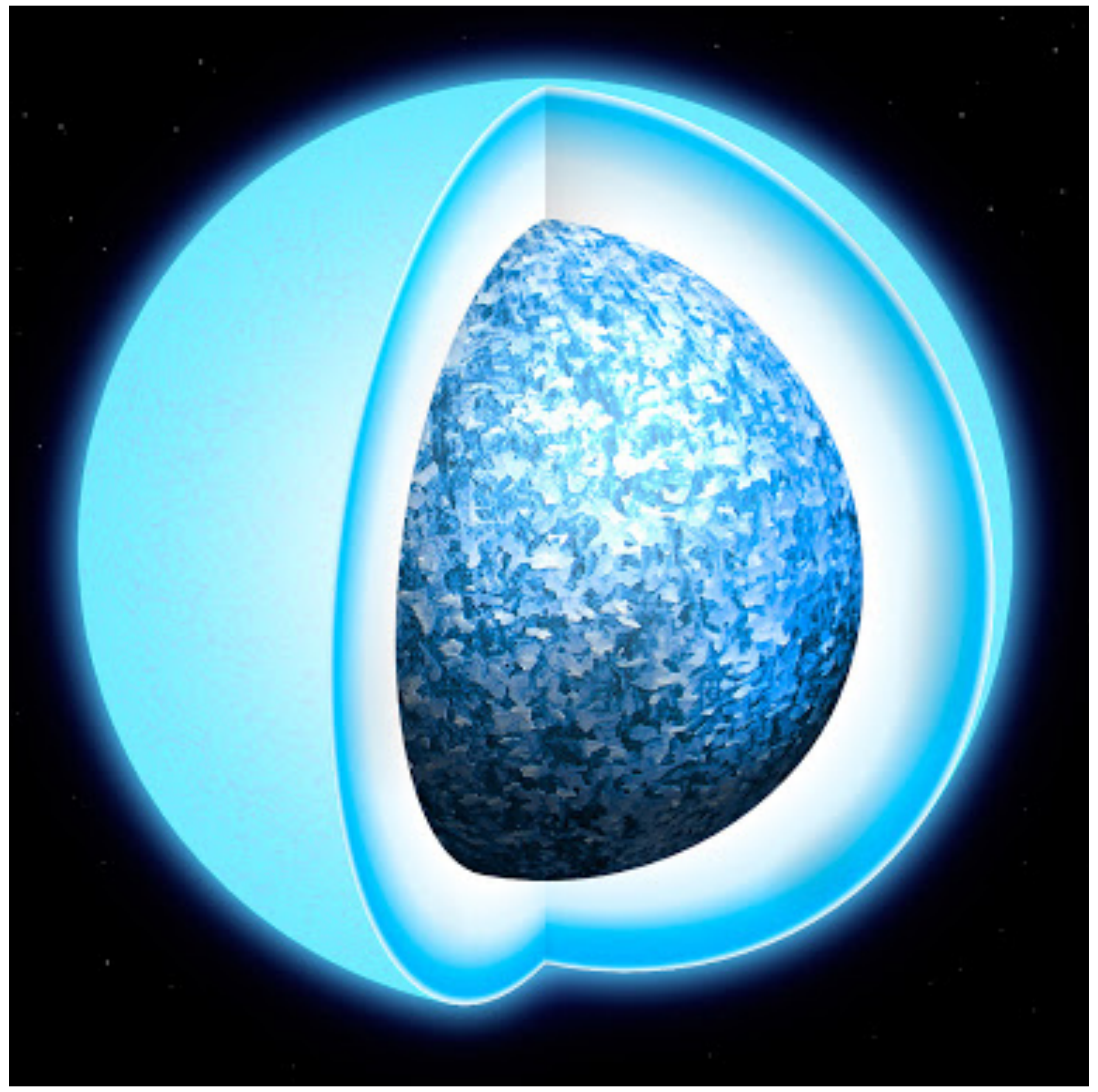
2. Radio Observations of Nearby Neutron Stars

3. With Multi-messenger Signals

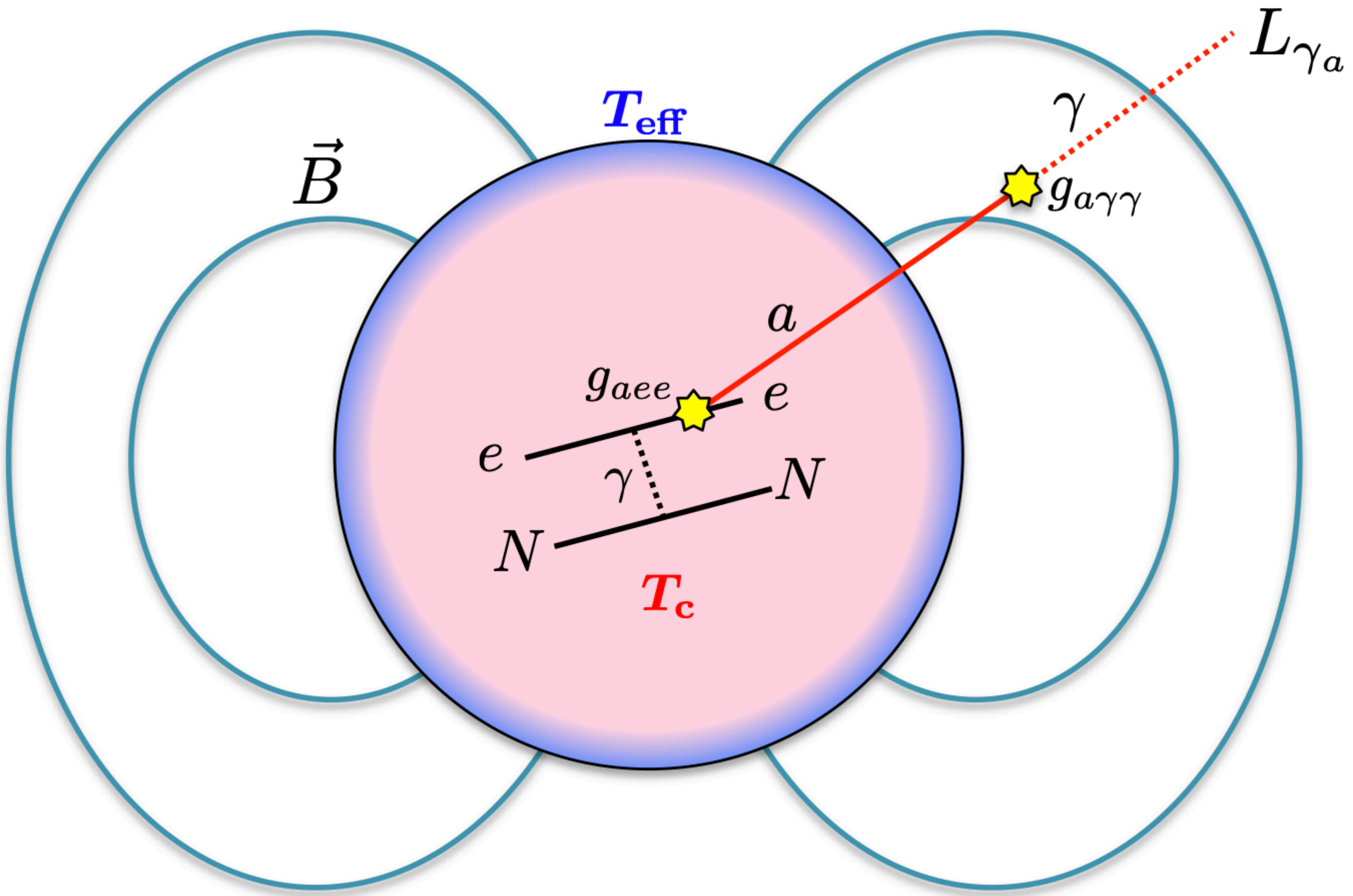
Astrophysical Searches for Axions

Cooling in Massive Stars



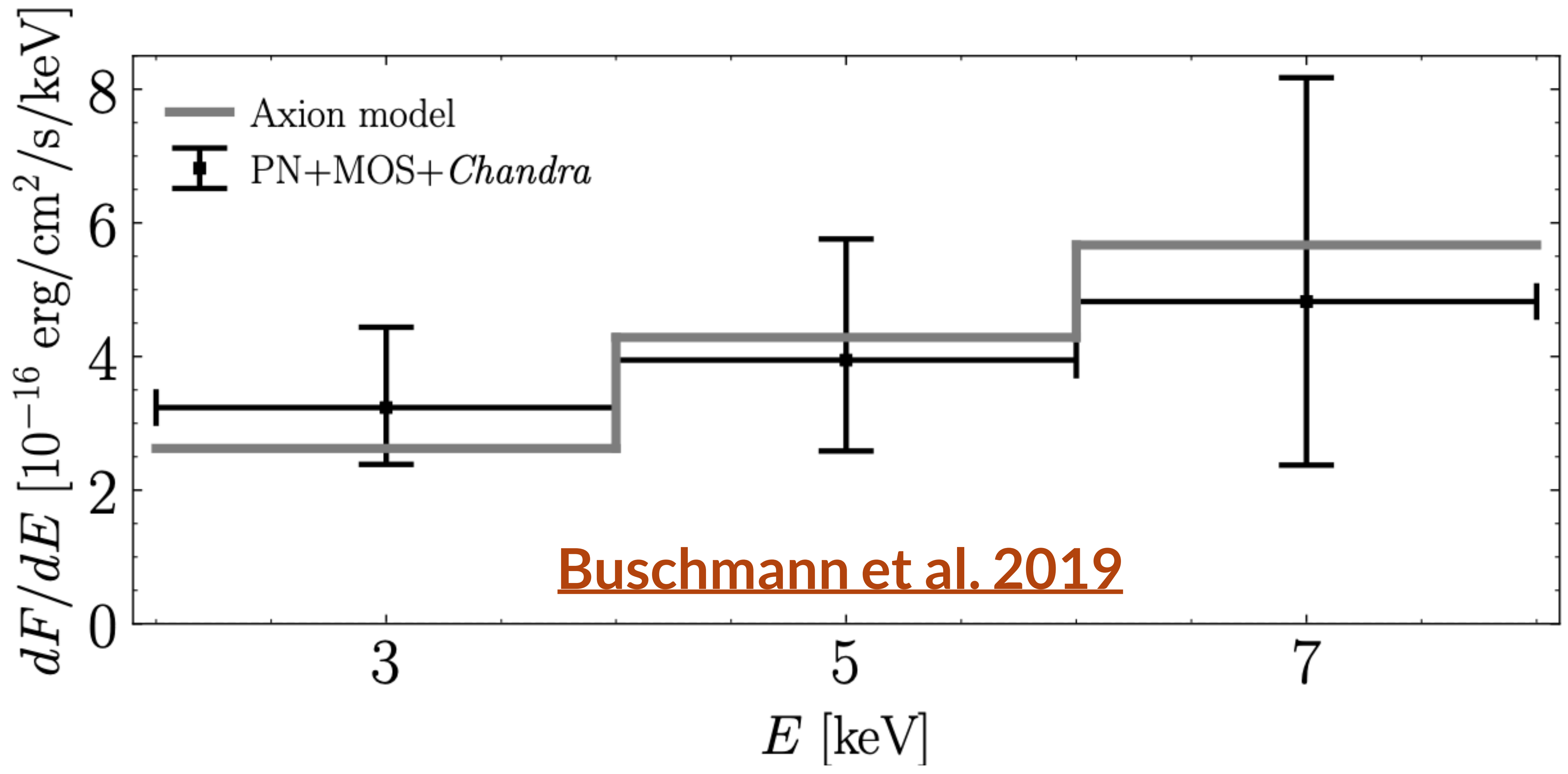


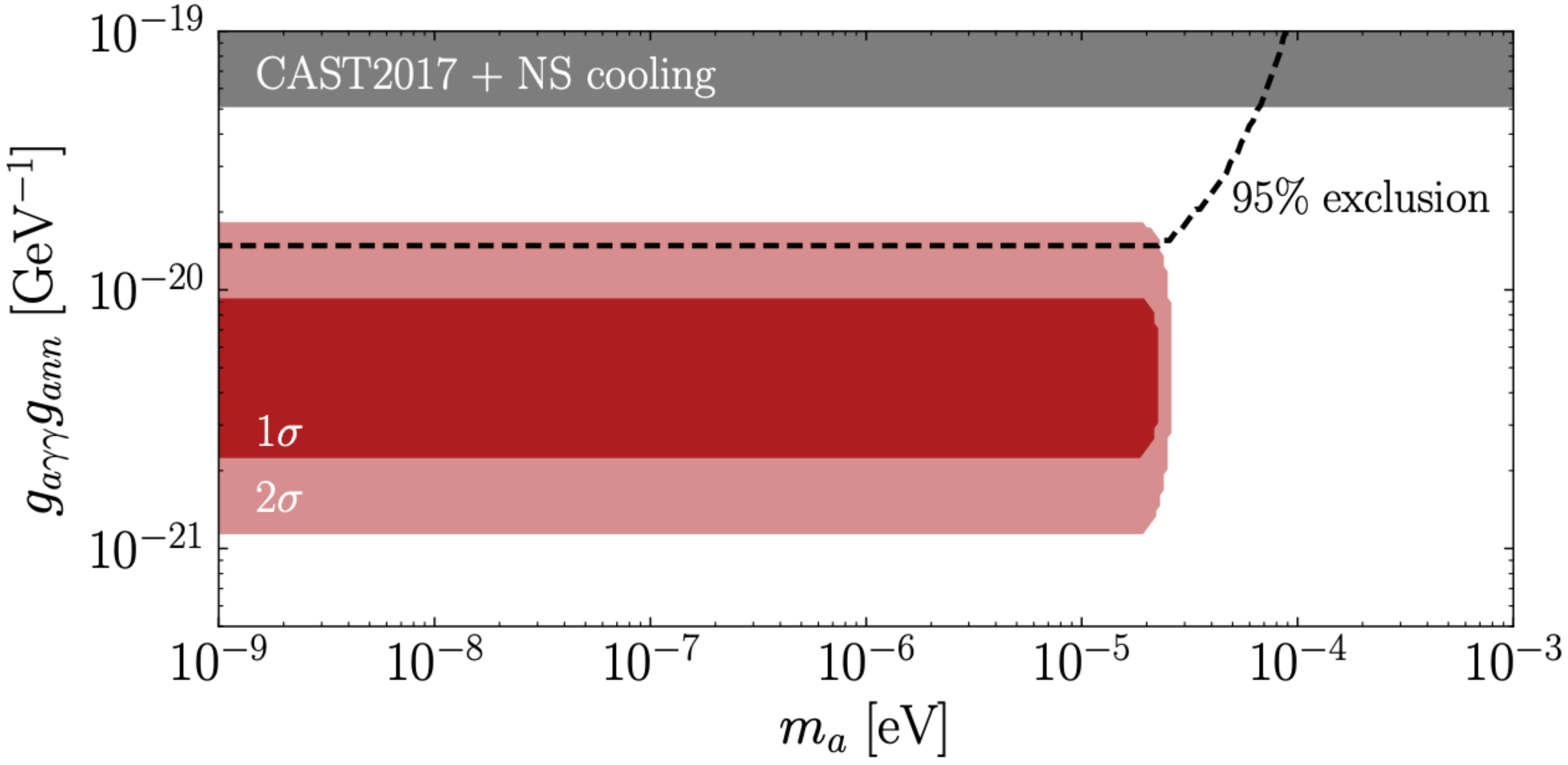
X-ray Searches of Neutron Stars



Dessert et al. 2019

Recently Reported Excess



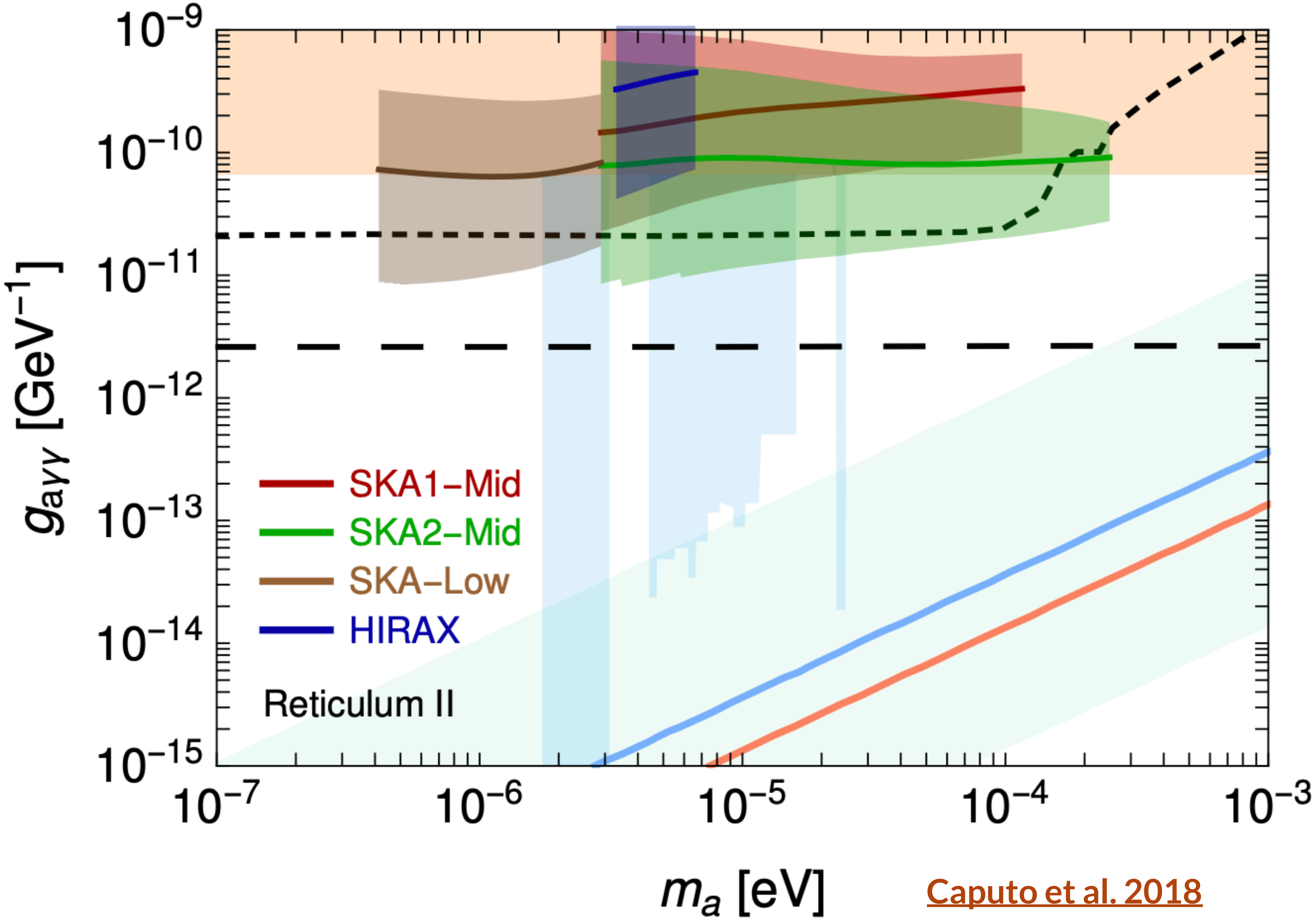


Archival Chandra shows a **5 sigma** excess and a couple of **3 sigma** excesses through observations of the M7

No **expected background**, although several plausible mechanisms

Observations at higher energies will be **almost background free**

Stimulated Decay

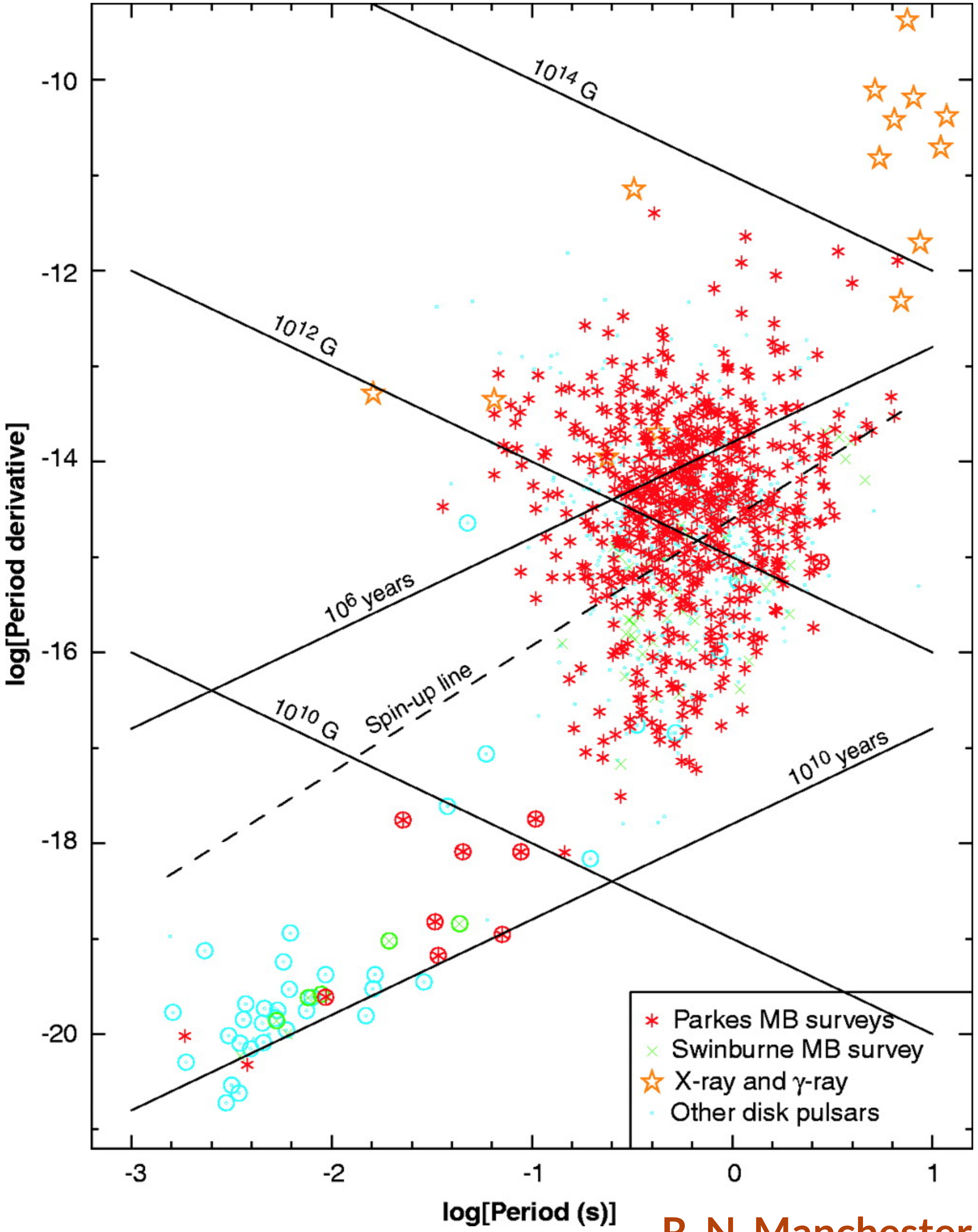


Caputo et al. 2018

Neutron Stars for Axion Searches

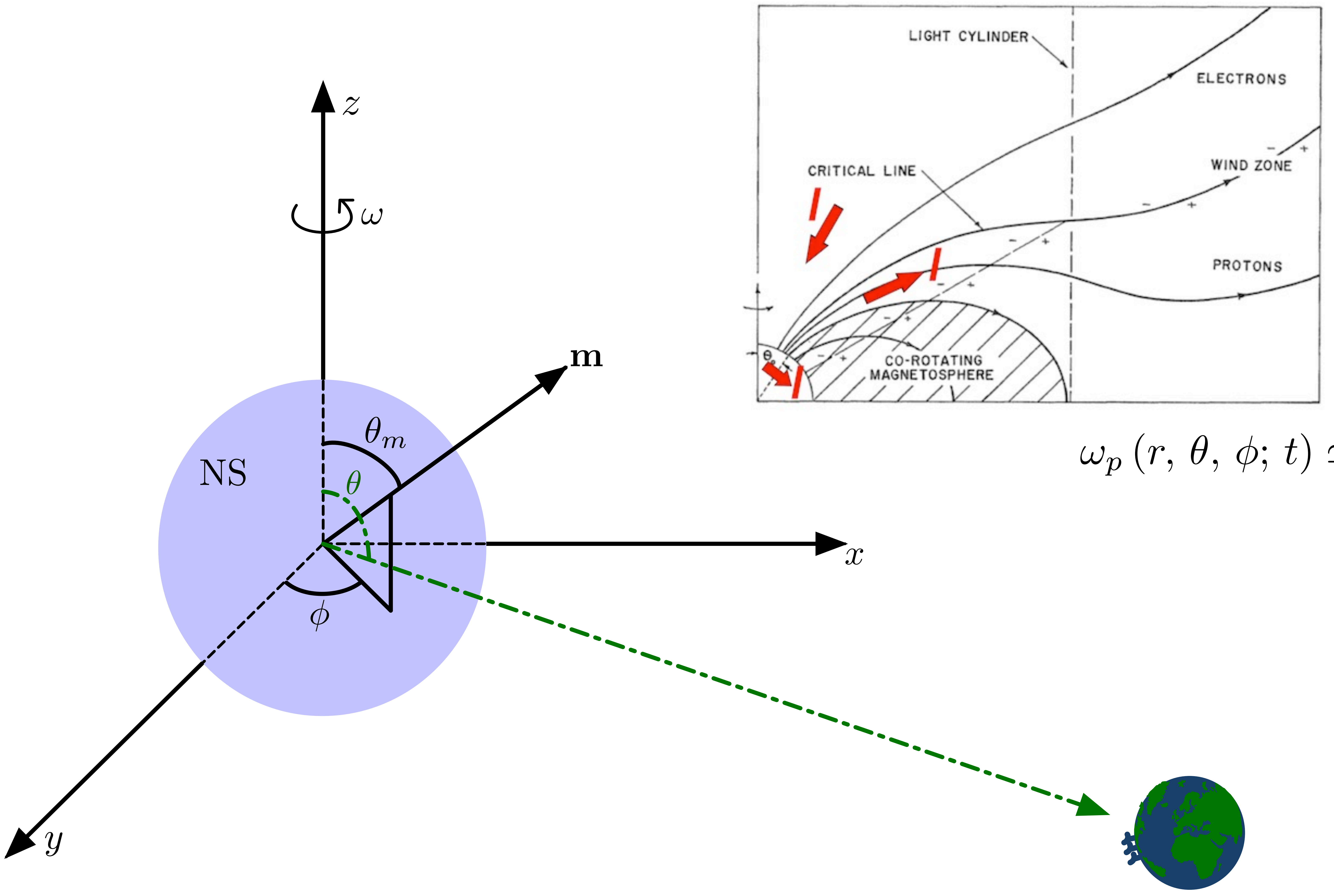
Neutron stars

$$B \sim 10^{9-15}\,\mathrm{G}$$



R. N. Manchester 2004

Neutron stars - Goldreich Julien Model

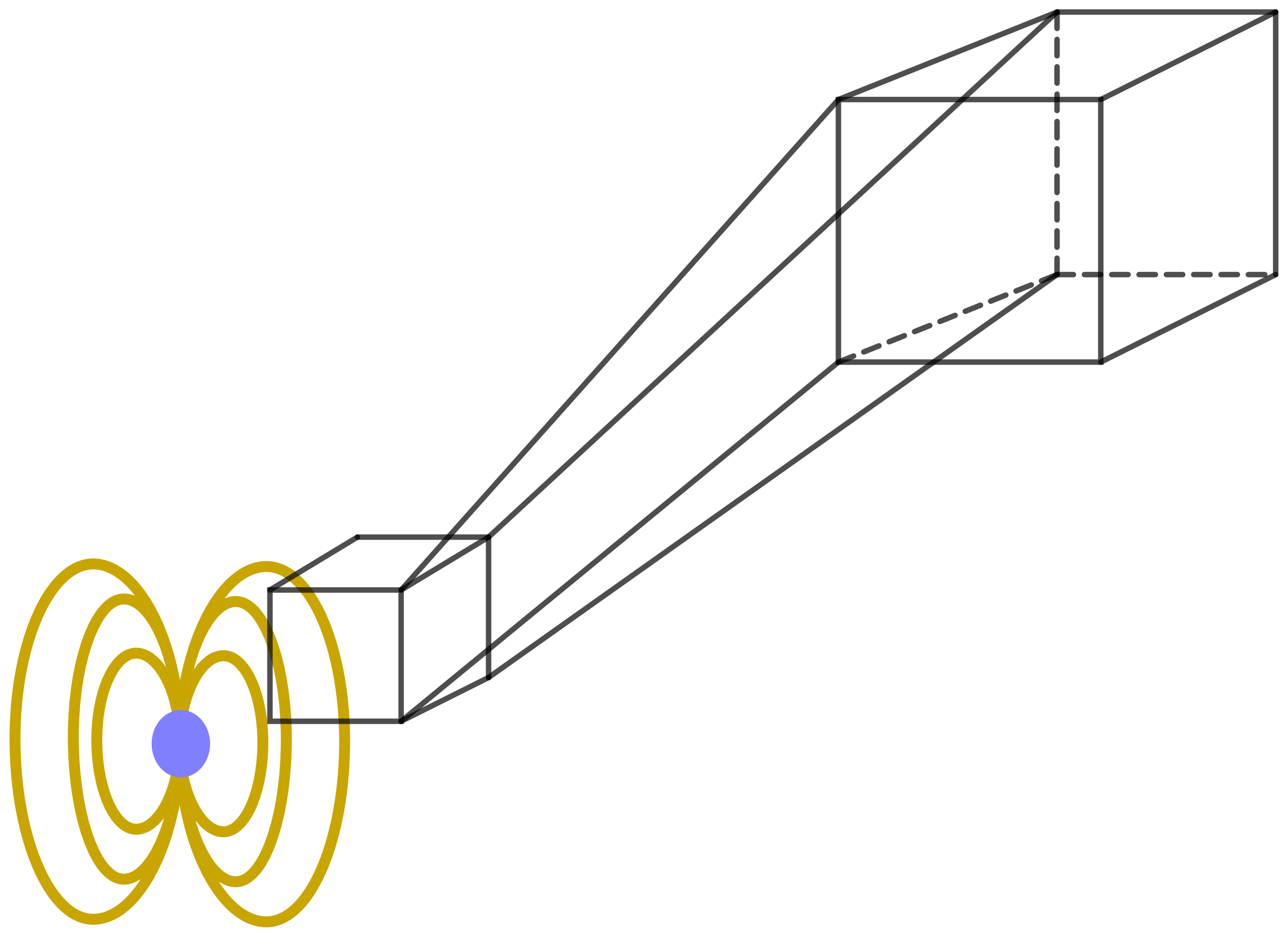


$$n_{\rm GJ}(\mathbf{r}) = \frac{2\,\boldsymbol{\omega}\cdot\mathbf{B}}{e}\,\frac{1}{1-\omega^2\,r^2\,\sin^2\theta}$$

$$\omega_p\,(r,\,\theta,\,\phi;\,t) \simeq 69.2\;\mu\text{eV}\times\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}}-\cos\theta_m\right|^{1/2} \times\left[\frac{B_0}{10^{14}\ \text{G}}\,\frac{1\ \text{s}}{P}\,\left(\frac{r_{\rm NS}}{r}\right)^3\right]^{1/2}$$

GJ model gives the minimum co-rotating plasma density required for self-consistency of Maxwells equations

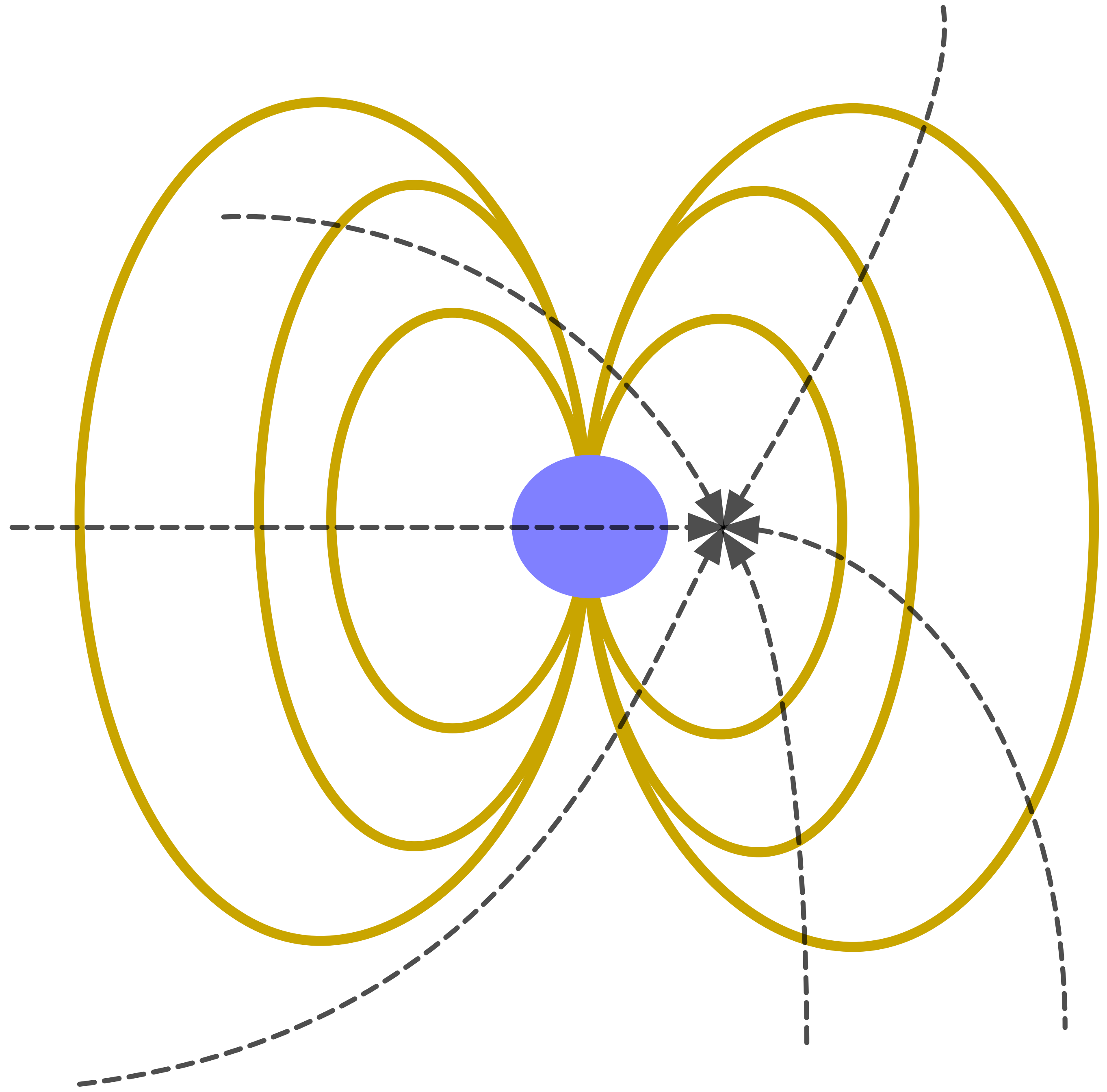
Mapping the Phase Space from Infinity to Close By



$$f(\mathbf{r}, \mathbf{v}) = f_\infty(\mathbf{r}_\infty, \mathbf{v}_\infty)$$

$$\varrho(r) = \frac{2\varrho_\infty^{\mathrm{DM}}}{\sqrt{\pi}} \sqrt{\frac{2GM_{\mathrm{NS}}}{r}} \frac{1}{v_0}$$

Is the phase space completely isotropic or completely radial?



PSD is compressed in space by a factor of 100

Axion-Photon Conversion

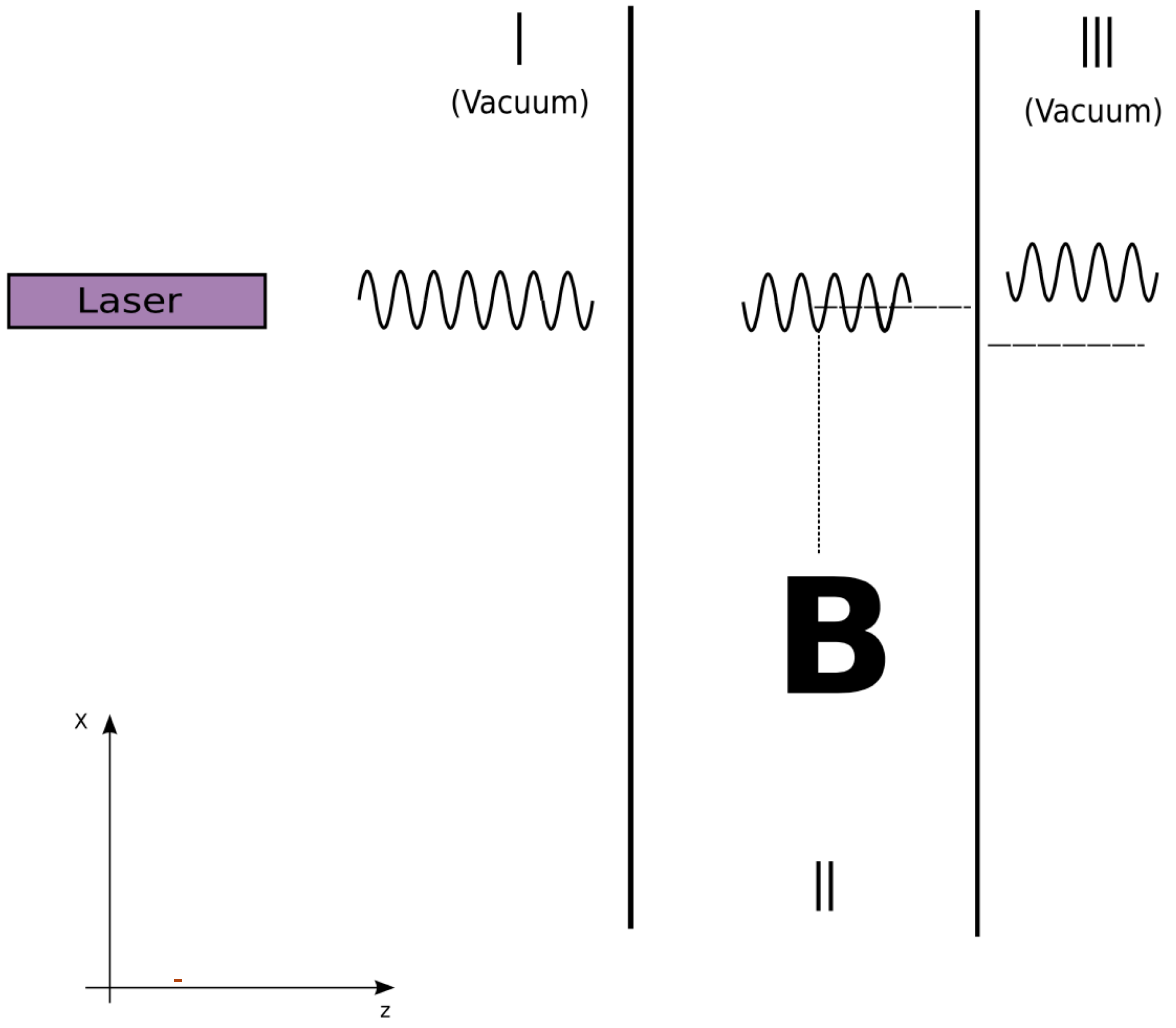
$$P_{a\to\gamma} := \frac{k_\gamma(z)^2}{k_\phi(0)^2}\left|\frac{a_x(z,t)}{\phi(0,t)}\right|^2$$

Similar to light shining through a wall calculations, but the inverse process

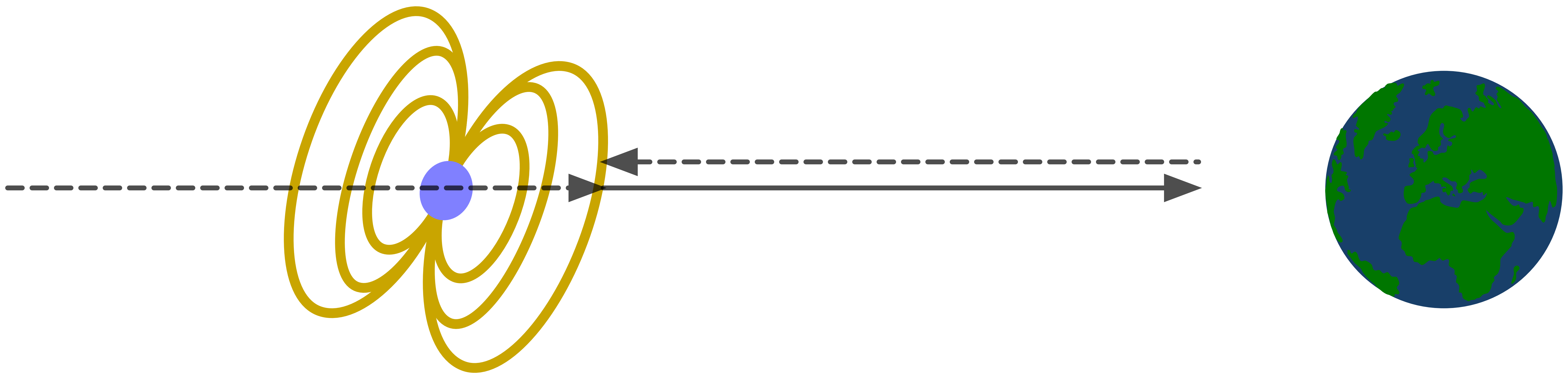
Calculated using the **plane wave and WKB approximatons**

$$P_{a\to\gamma} \simeq \frac{\pi(gB)^2}{2|\omega_p'|v_\phi}$$

Adler et al. 2008



Radial Approximation



$$\frac{d\mathcal{P}\left(\theta = \frac{\pi}{2}, \theta_m = 0\right)}{d\Omega} \approx 4.5 \times 10^{8}\mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\mathrm{GeV}^{-1}}\right)^2$$

$$\left(\frac{r_0}{10\mathrm{km}}\right)^2\left(\frac{m_a}{1\mathrm{GHz}}\right)^{5/3}\left(\frac{B_0}{10^{14}\mathrm{G}}\right)^{2/3}\left(\frac{P}{1\mathrm{sec}}\right)^{4/3}$$

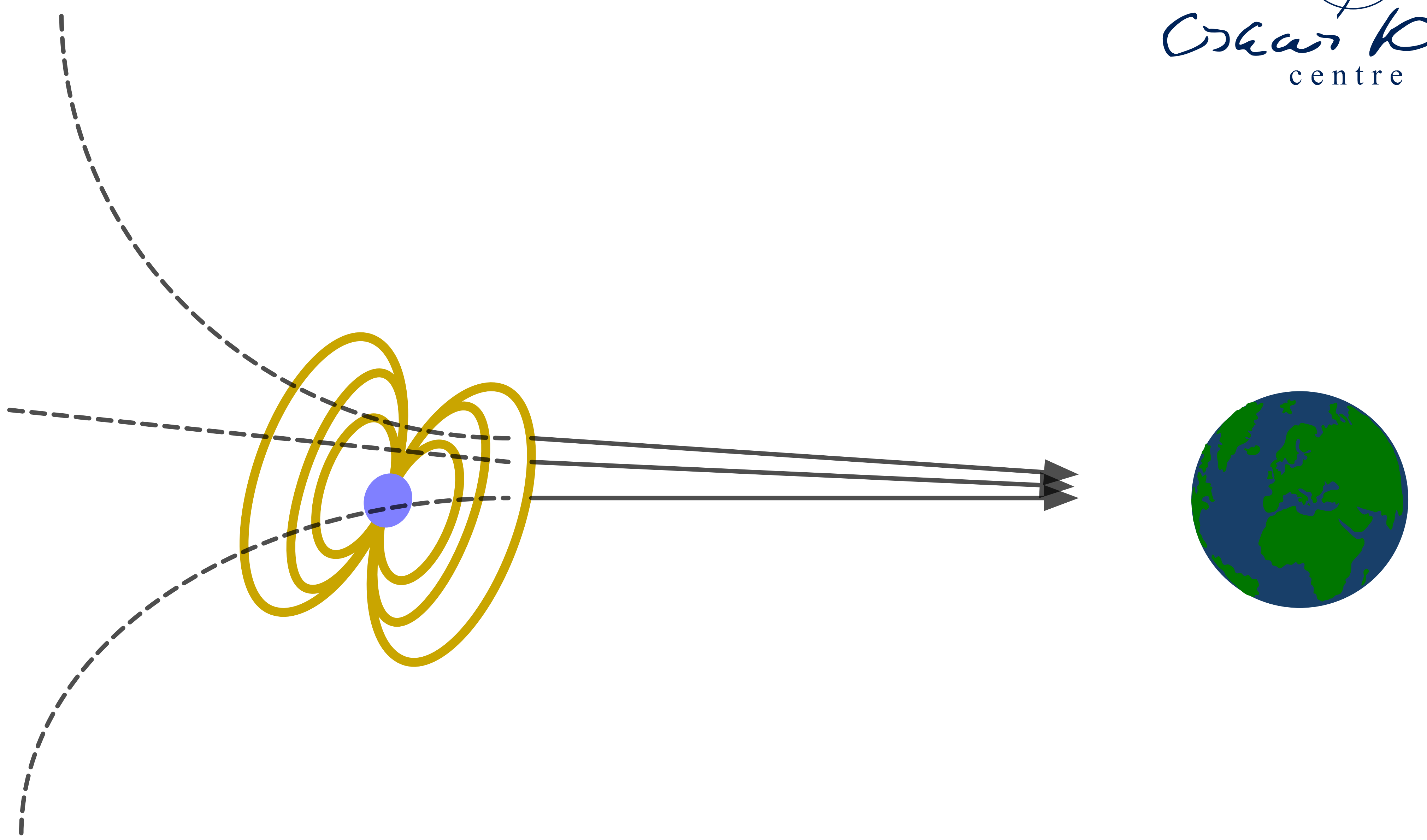
$$\left(\frac{\rho_\infty}{0.3\mathrm{GeV}/\mathrm{cm}^3}\right)\left(\frac{M_{\mathrm{NS}}}{1M_\odot}\right)\left(\frac{200\mathrm{km/s}}{v_0}\right)$$

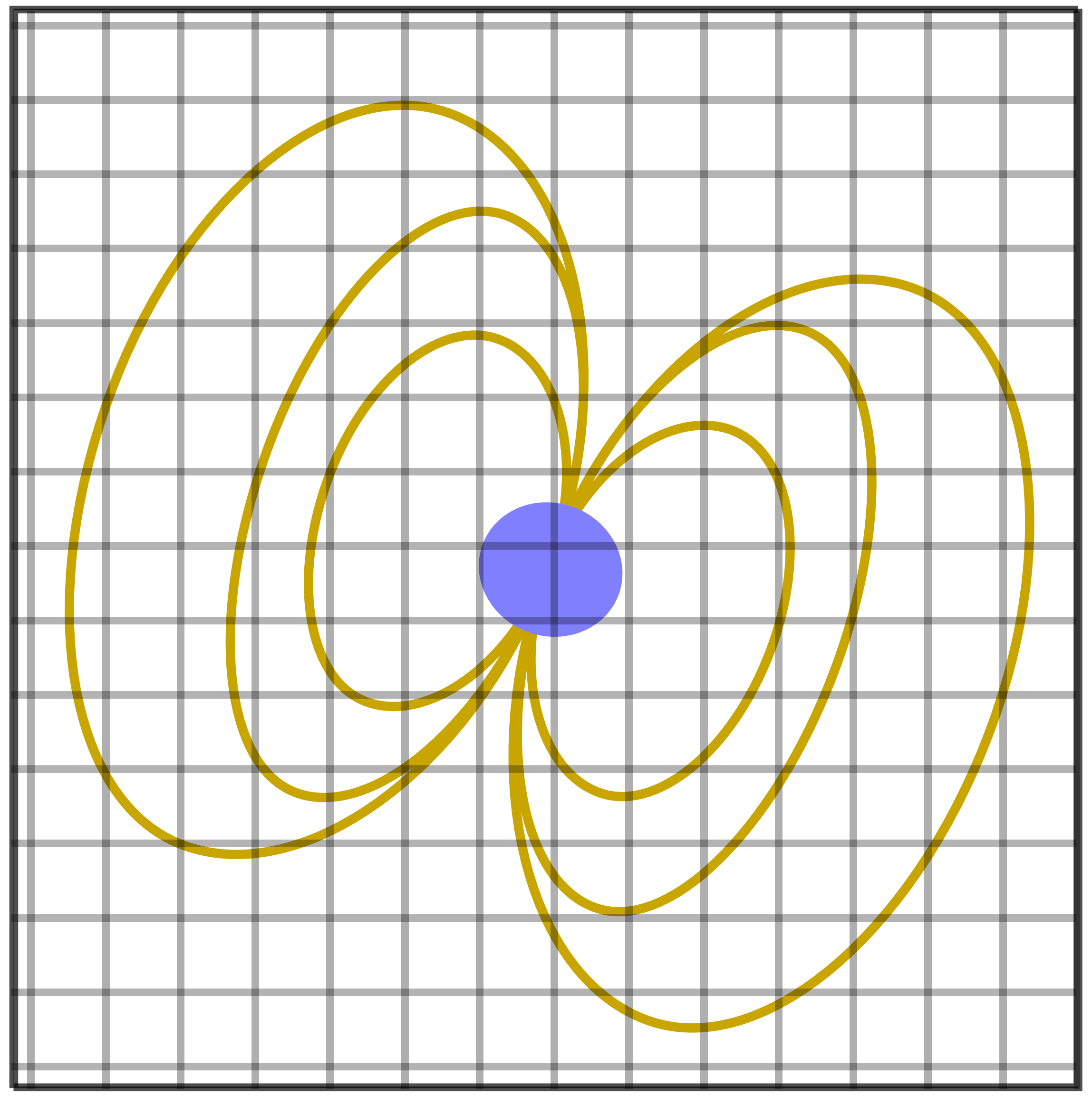
Going to the full PSD

1. Define a grid. All photons trajectories are parallel since the source is far away

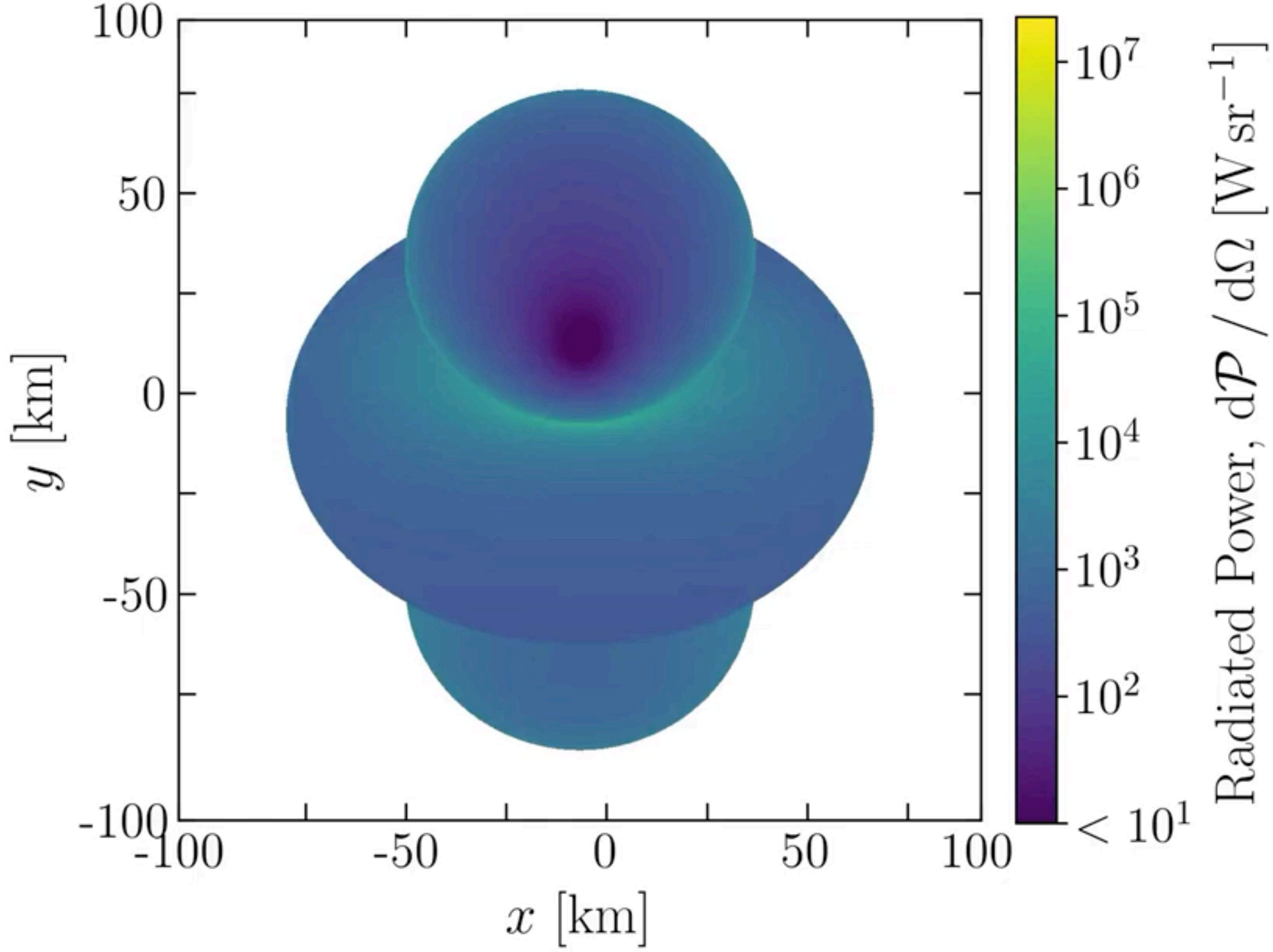
2. Trace back trajectories (assumed to be straight) on to the magnetosphere to calculate conversion radius

3. Compute luminosity at conversion radius and sum up overall signal



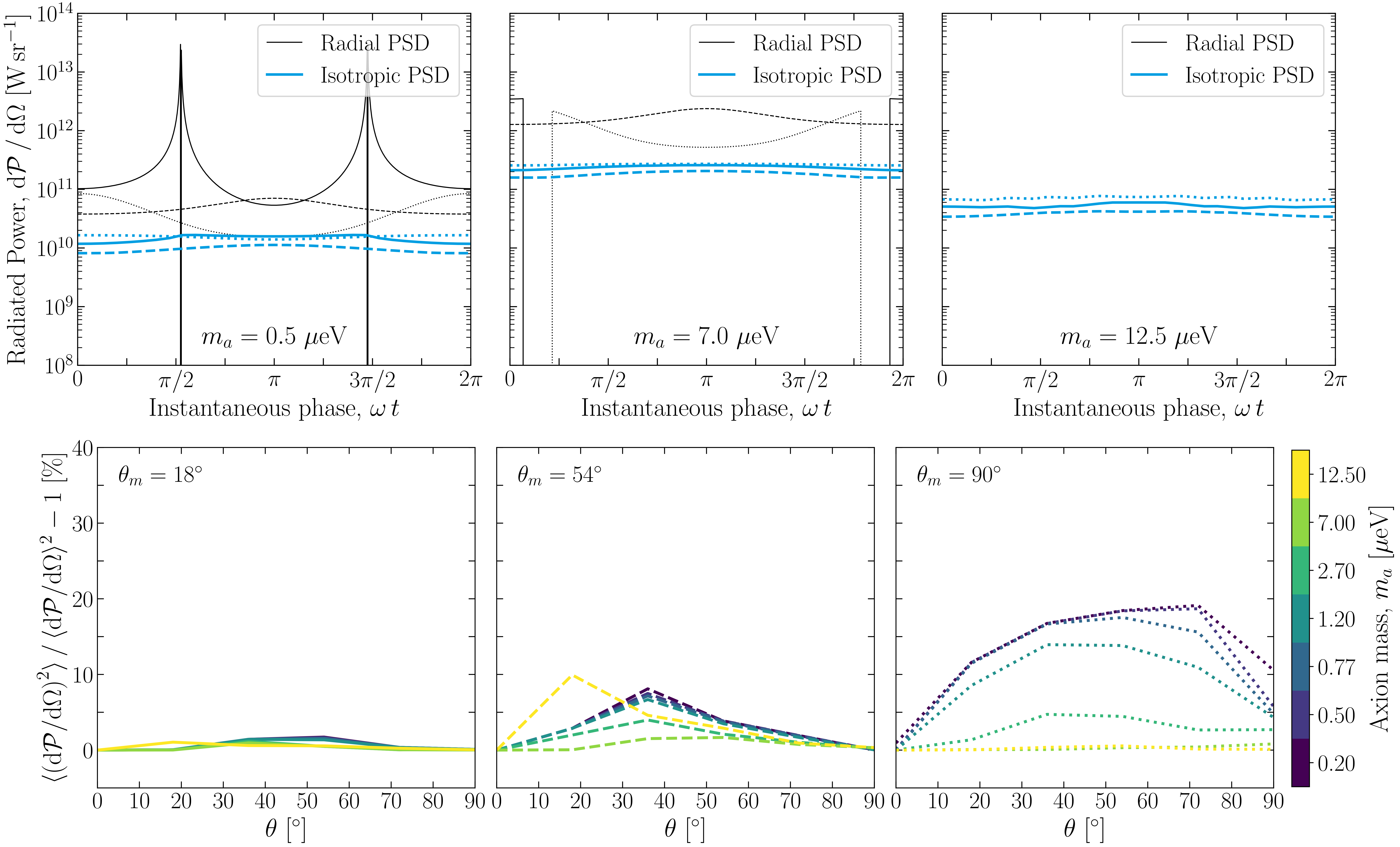


Signal



100
50
0
-50
-100
y [km]
-100
-50
0
50
100
x [km]
10^7
10^6
10^5
10^4
10^3
10^2
$< 10^1$
Radiated Power, $\mathrm{d}\mathcal{P} / \mathrm{d}\Omega$ [W sr^{-1}]

Time Variation



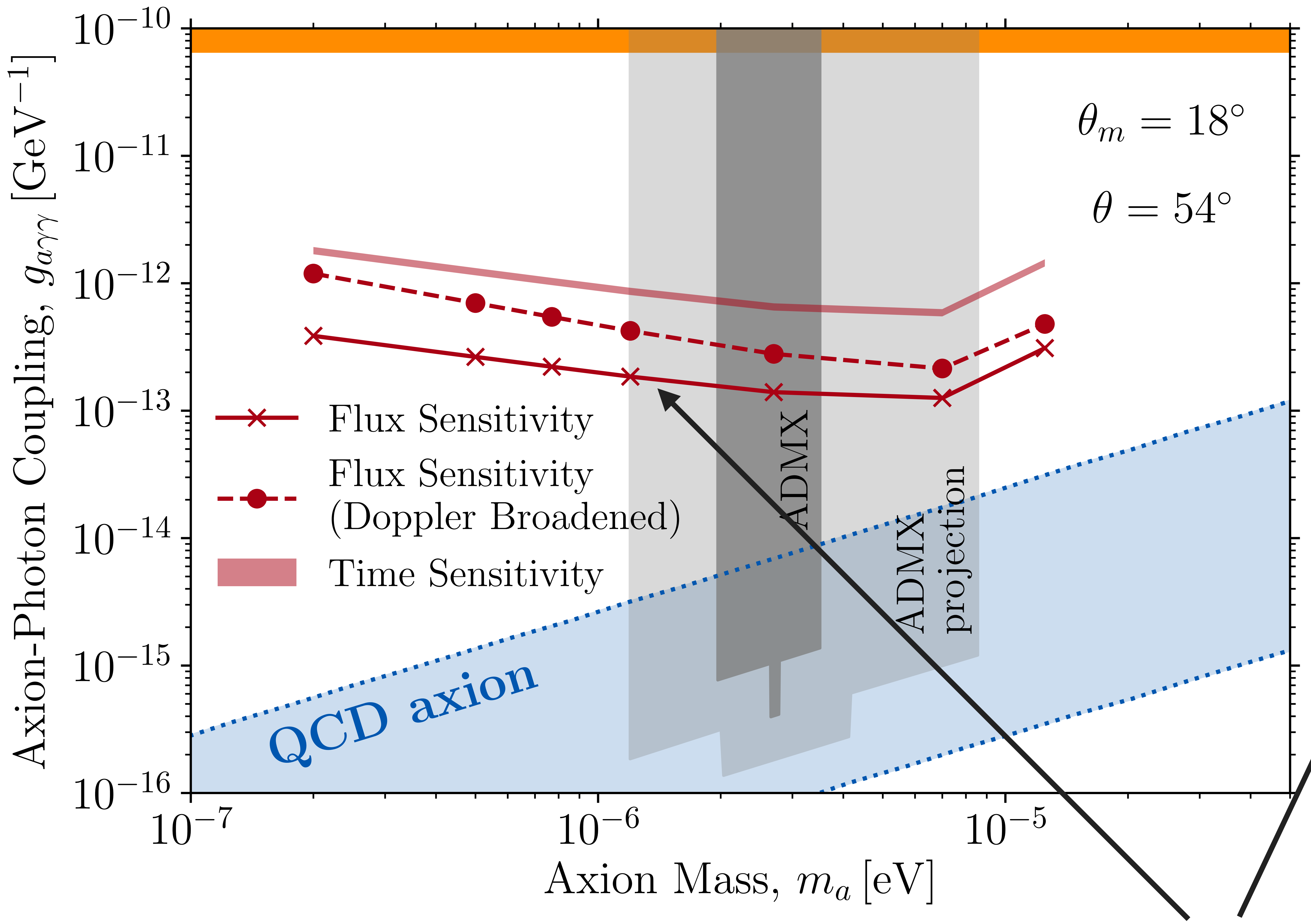
Sensitivity of a Radio Telescope

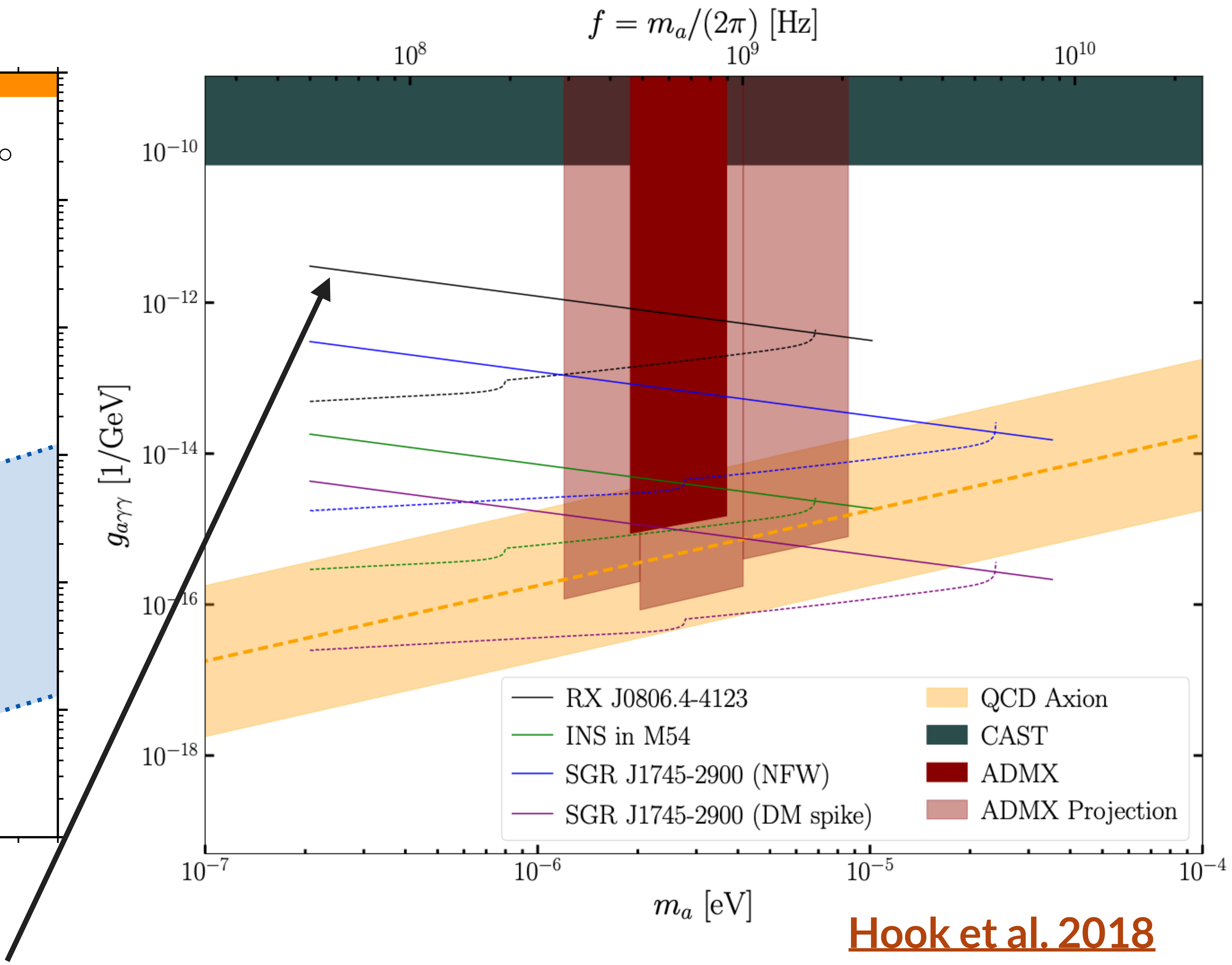
$$S_{\text{min}} = \frac{\text{SEFD}}{\sqrt{2B_a T_{\text{obs}}}}$$

The important quantity of a radio telescope is the **SEFD (noise level)**

Since radio lines are common, **ON/OFF observations** are necessary to conclusively **observe radio line**

Sensitivity Plot





Hook et al. 2018

These lines are considering the same NS J0806.4-4123 **but assume different observations**

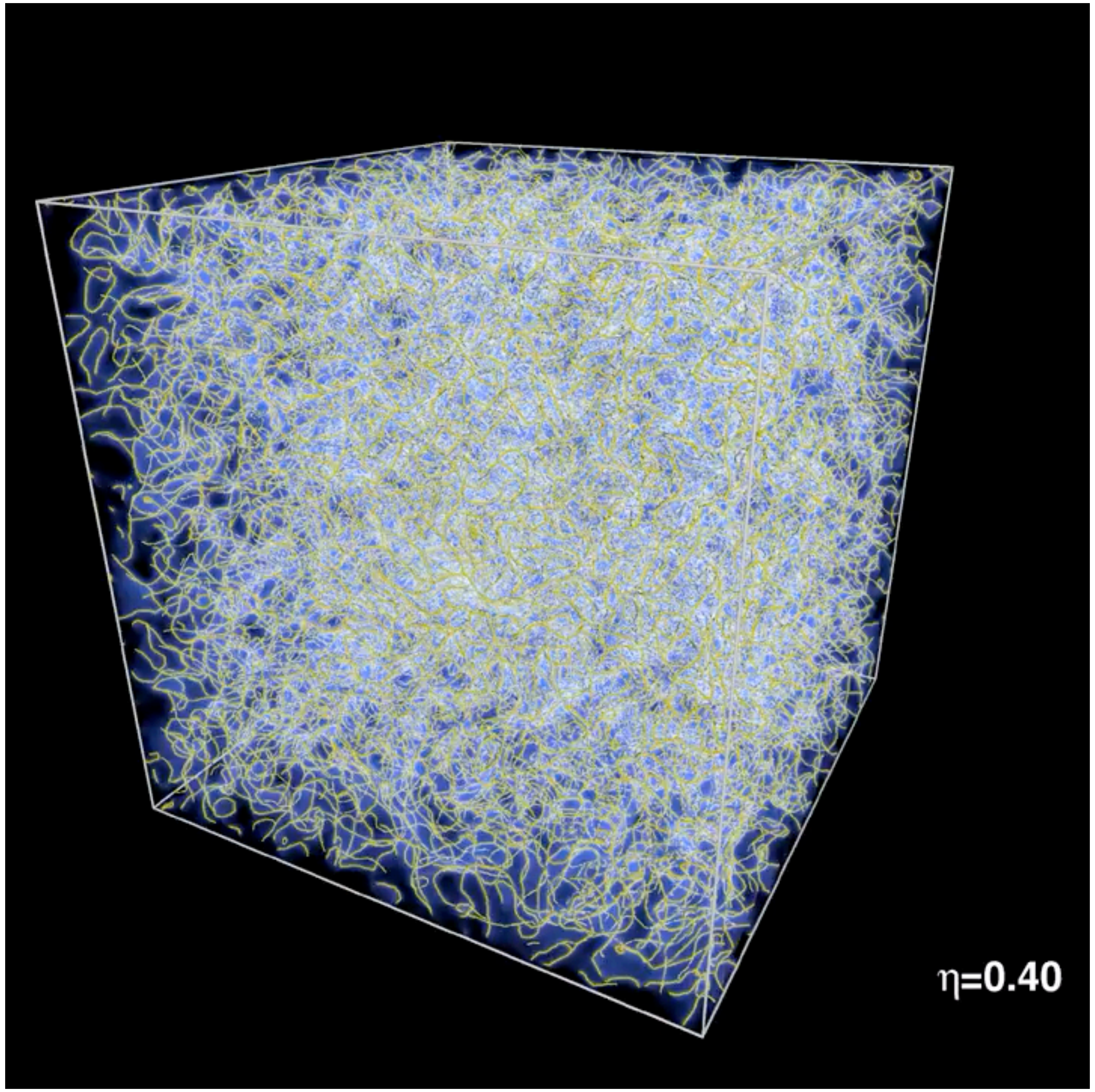
Axion Miniclusters

Axions can form dense miniclusters if te PQ symmetry is broken **after inflation**

They are around the size of the solar system and are around 10^{-12} solar masses

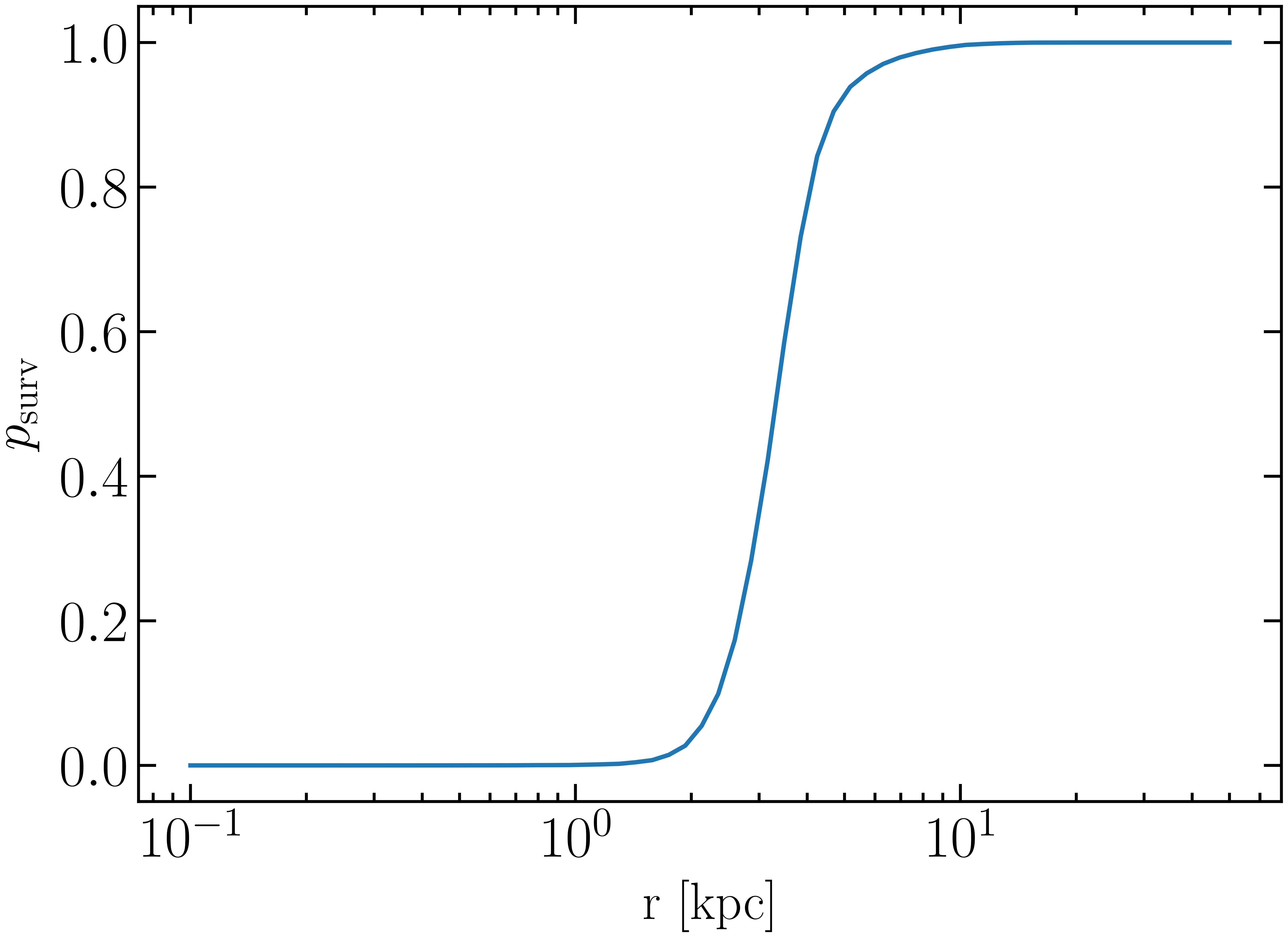
Importantly, they can be a factor of 10-10^5 more dense at formation

Buschmann et al. 2019



Survival Probability and the Goldilocks zone

AMCs in the centre of the galaxy or high ellipticity will be disrupted by stars

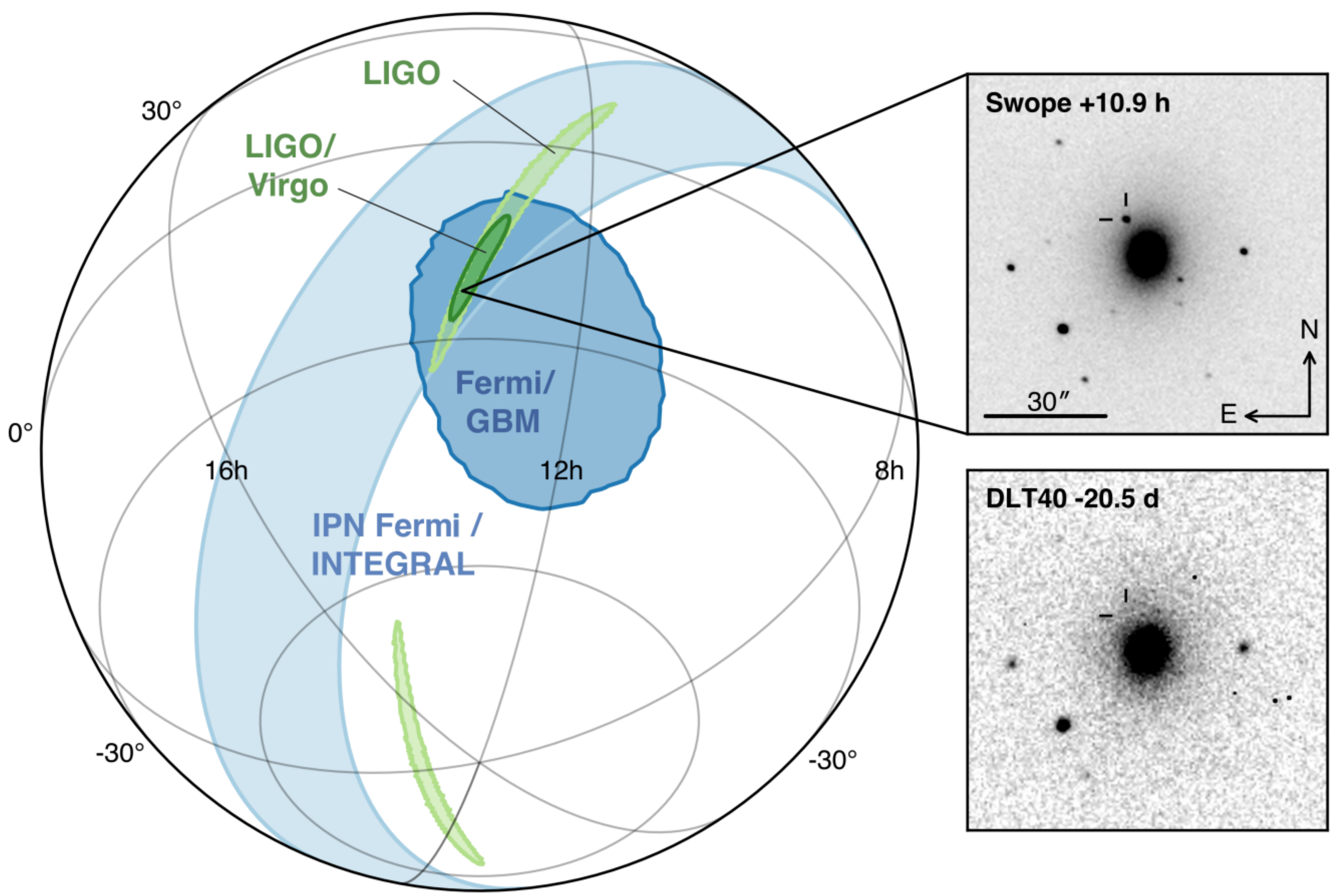


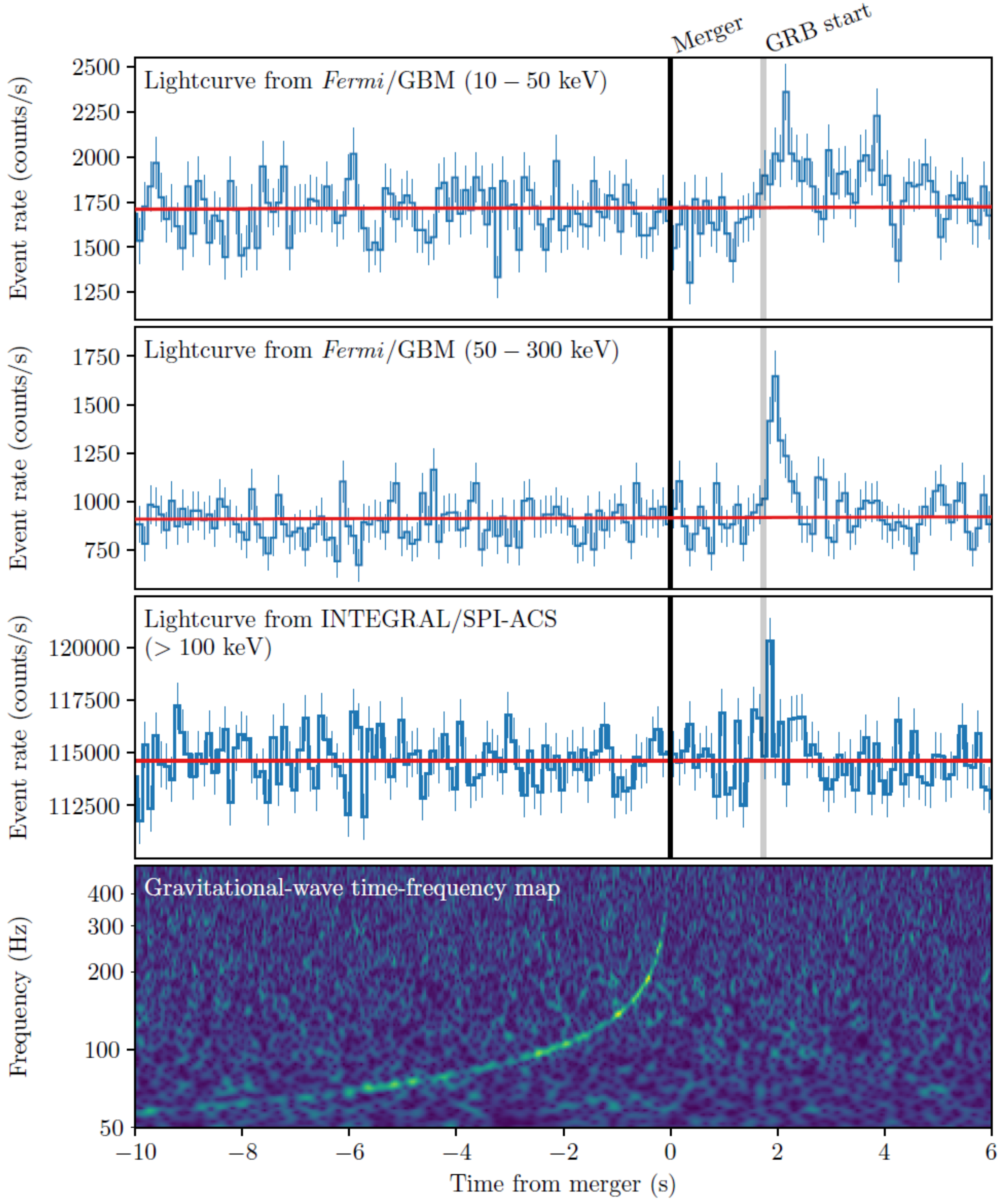
At large galactocentric radii, the AMCs have no interactions and therefore remain intact

There is a Goldilocks zone where there is a **significant rate of encounters today**

Multi-Messenger Signals of Axion Dark Matter

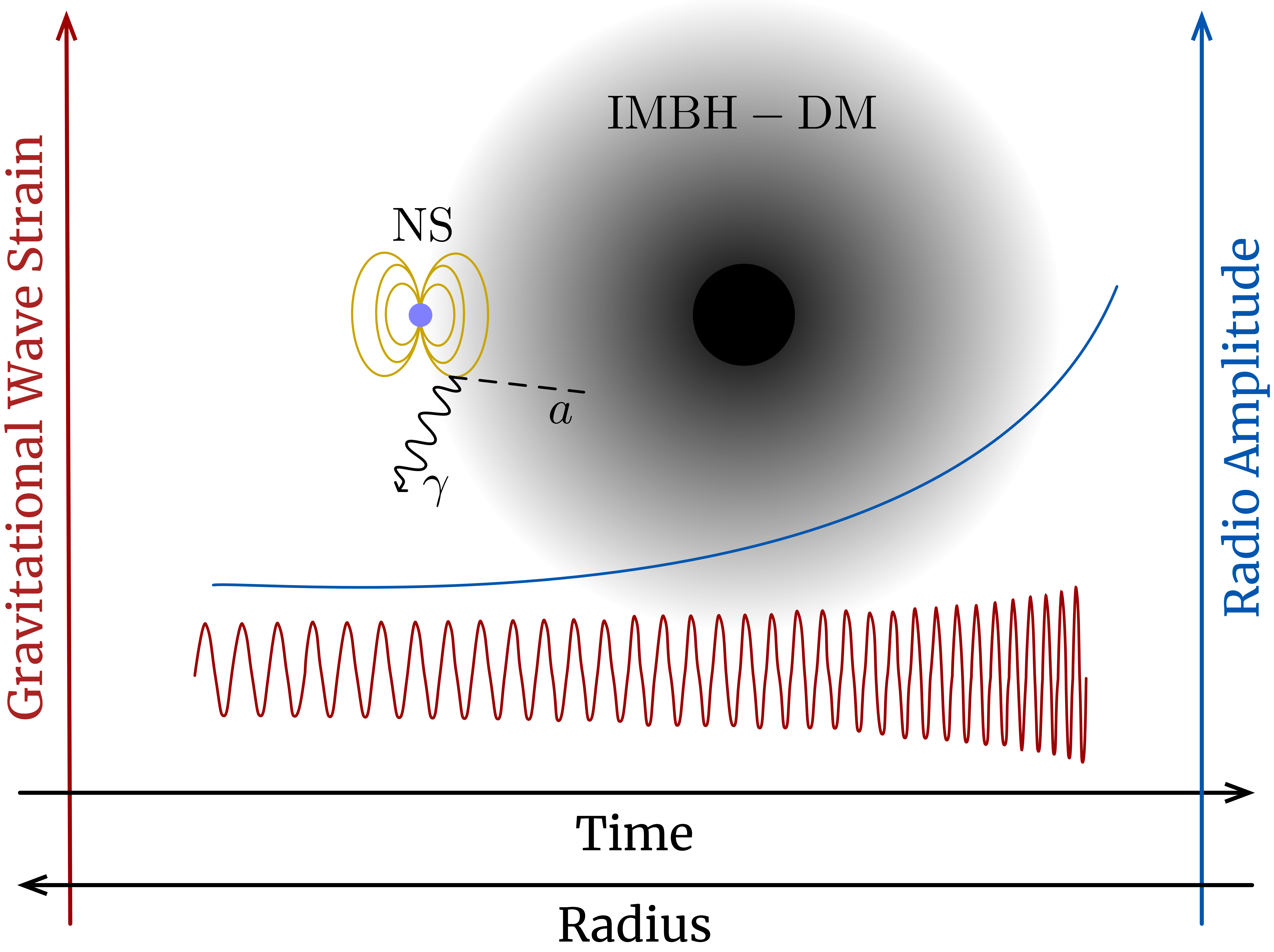
Multi-Messenger Astrophysics is Here





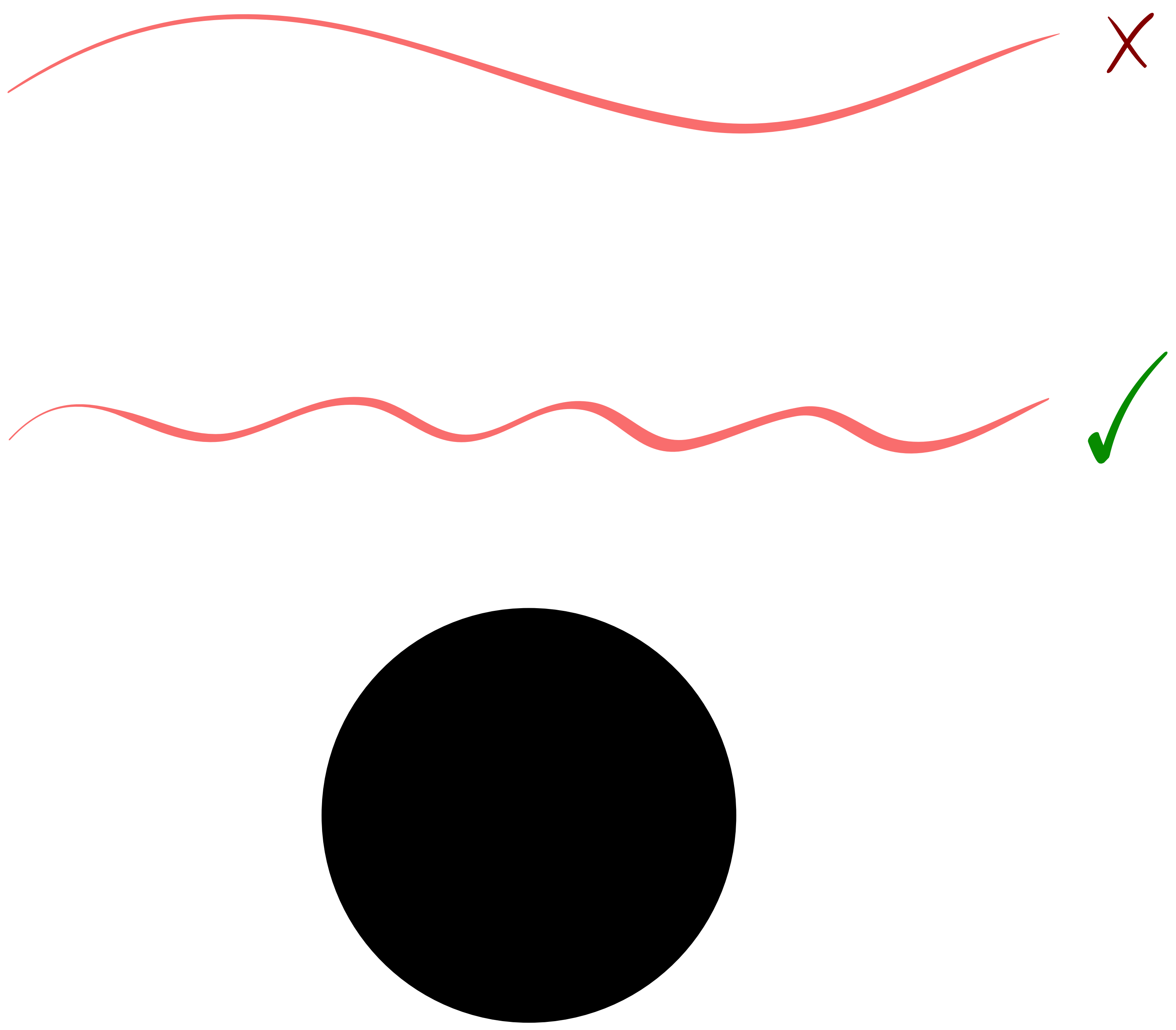
1710.05834

Multi-Messenger Signal of QCD Axion



Restricted Axion Mass Range

$$\lambda = \frac{h}{mc}$$



$$m > 10^{-7}\mathrm{eV}$$

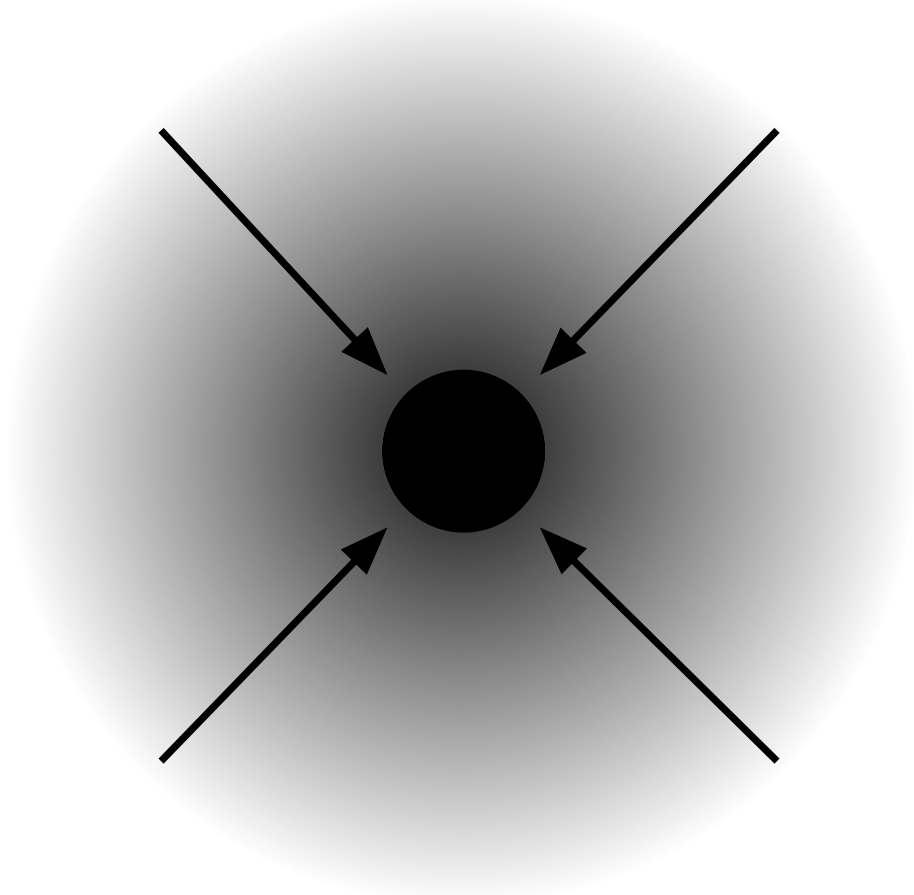
1904.12803

Intermediate Mass Black Holes and DM Spikes

1311.6918 1702.02149

$$M_{\rm DM} = 10^6\,[\mathrm{M}_\odot]$$

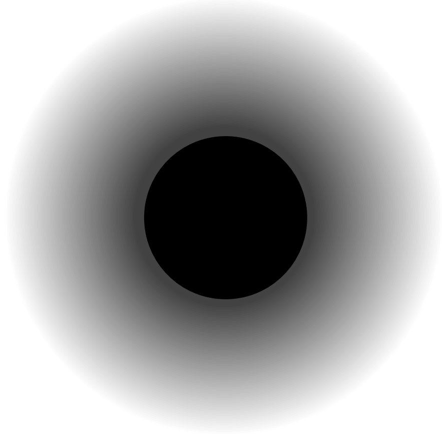
$z = 20$



9906391, 0501625, 1904.12803

$$f_{\rm ini}(E,L) \to f_{\rm fin}(E,L)$$

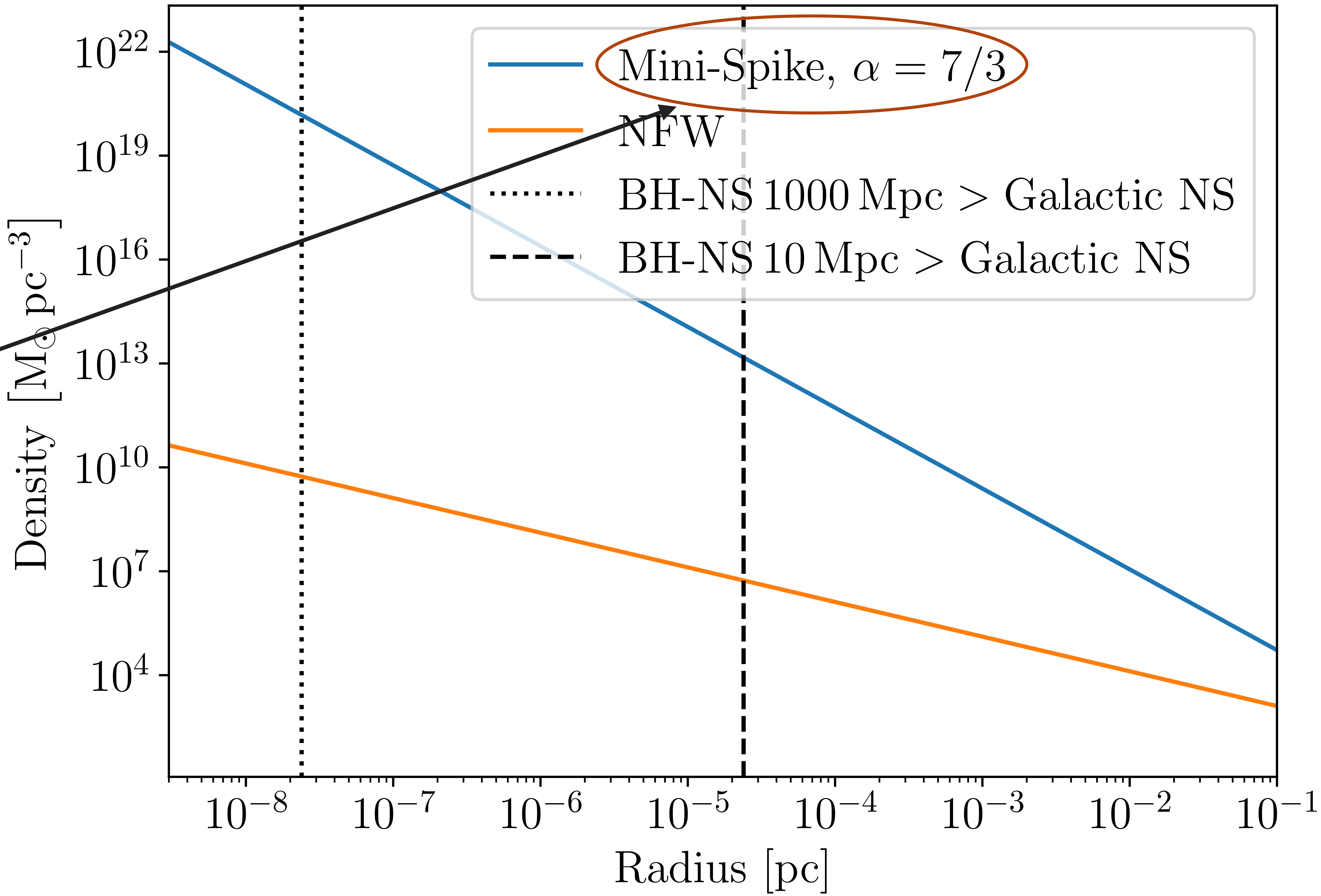
$z = 0$



Structure of the Mini-Spike

Density slope depends on **initial slope**

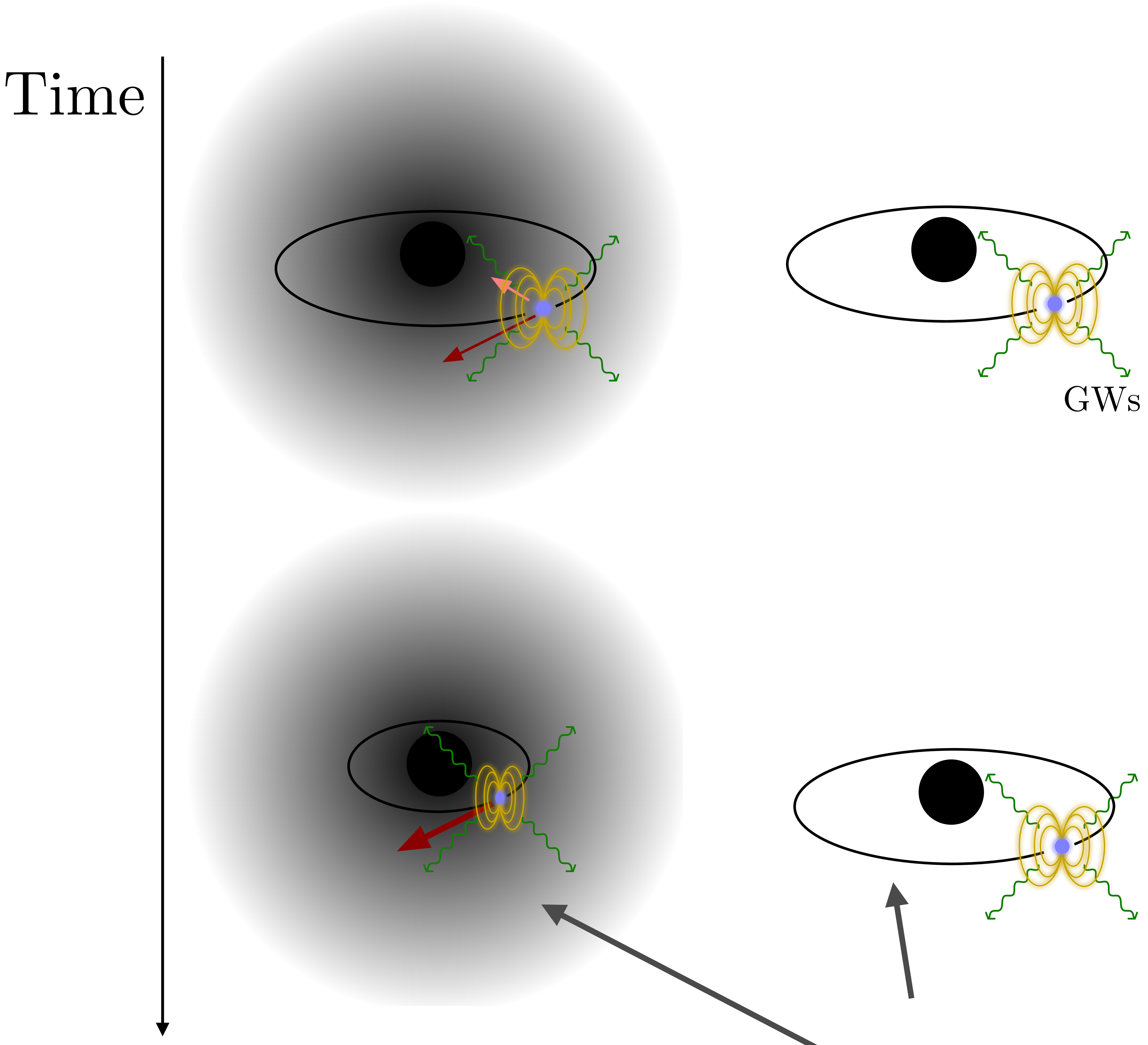
7/3 corresponds to an initially **NFW like** density profile

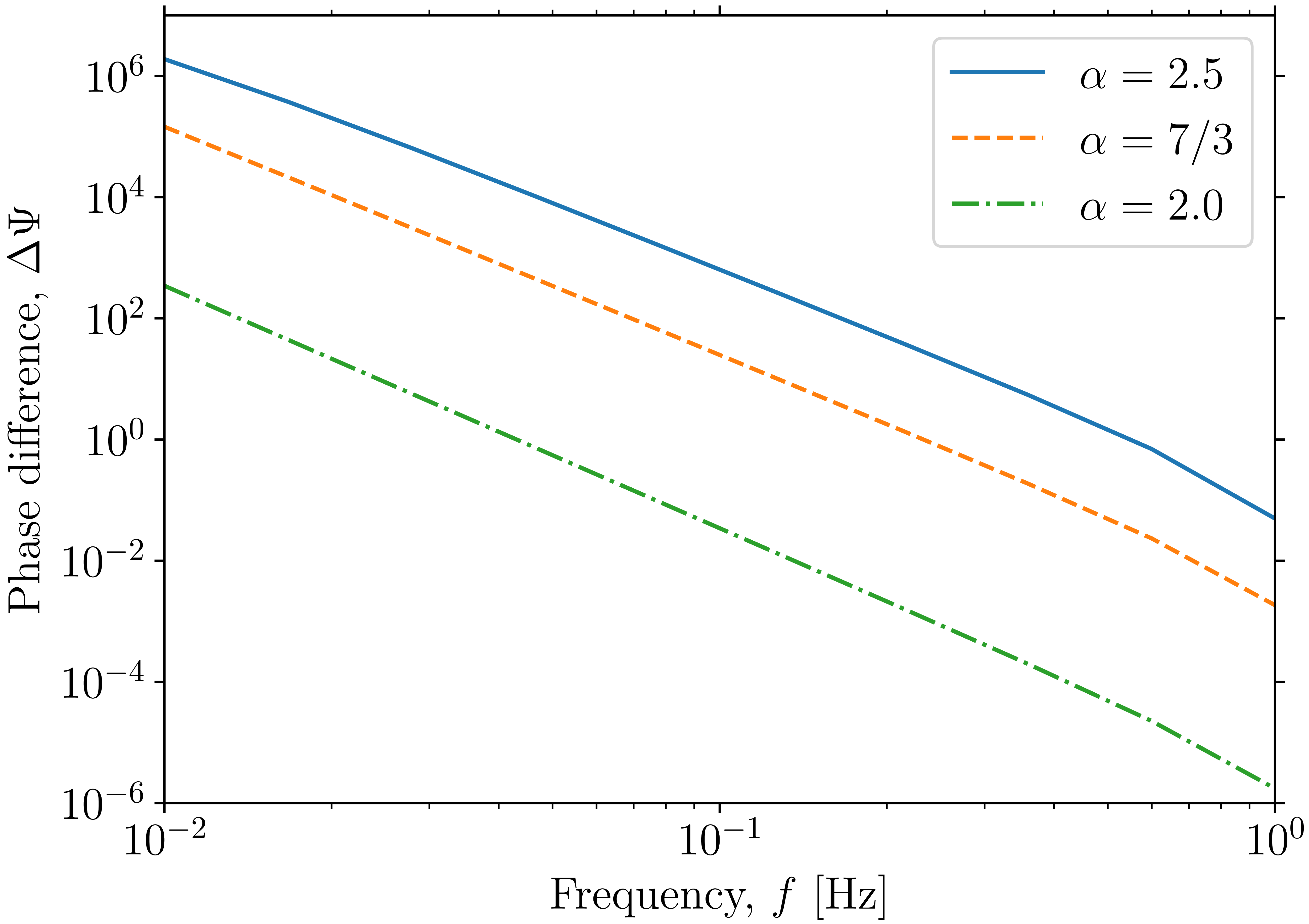


Dynamical Friction

$$f_{\mathrm{DF}} = 12\pi G^2 m_{\mathrm{NS}}^2 \frac{\rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}^2}$$

Dynamical Friction in a Binary System

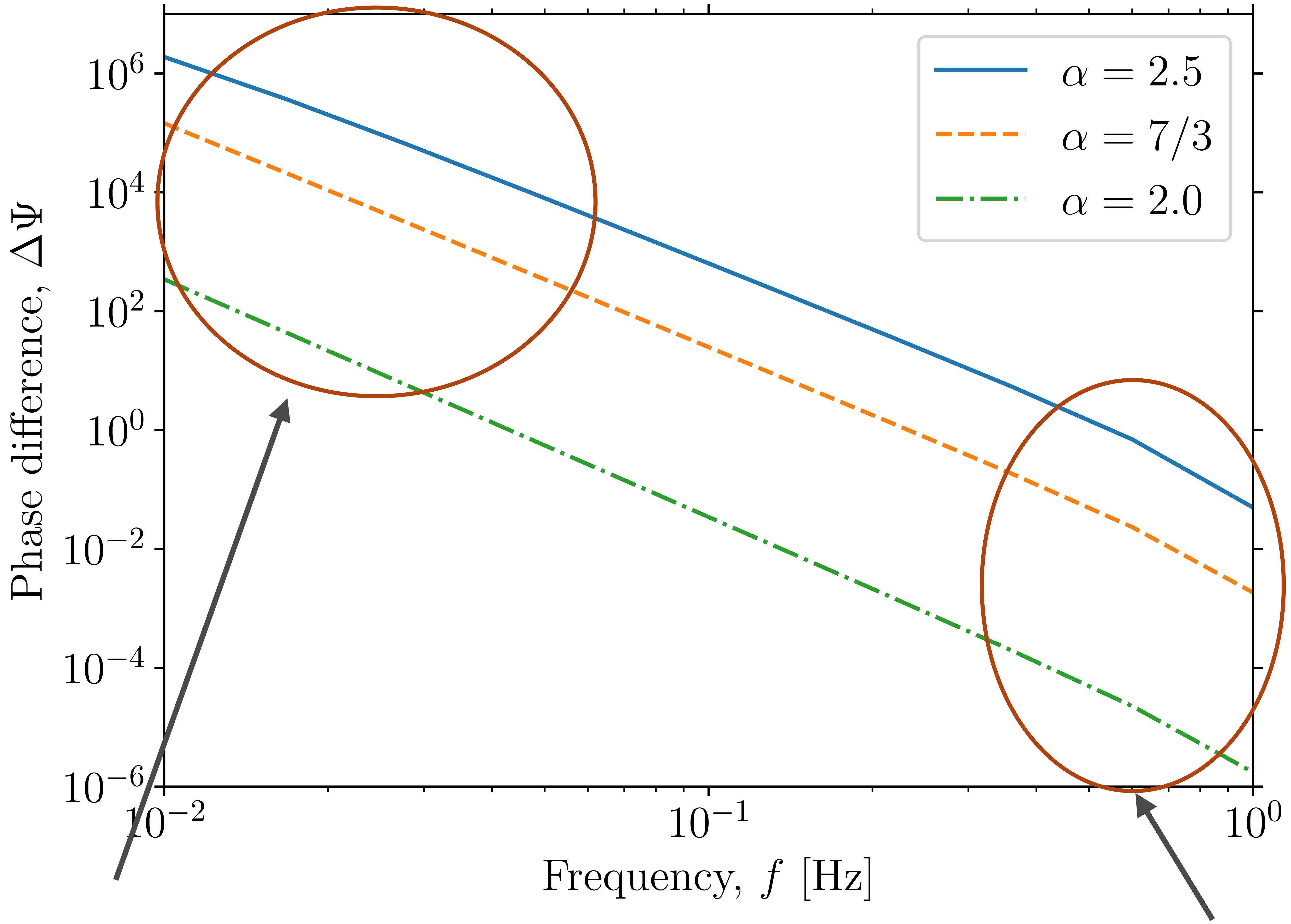




The smaller partner will reach merger **faster than in a vacuum** inspiral = Change in Phase evolution

1408.353

Dephasing of the GW Signal

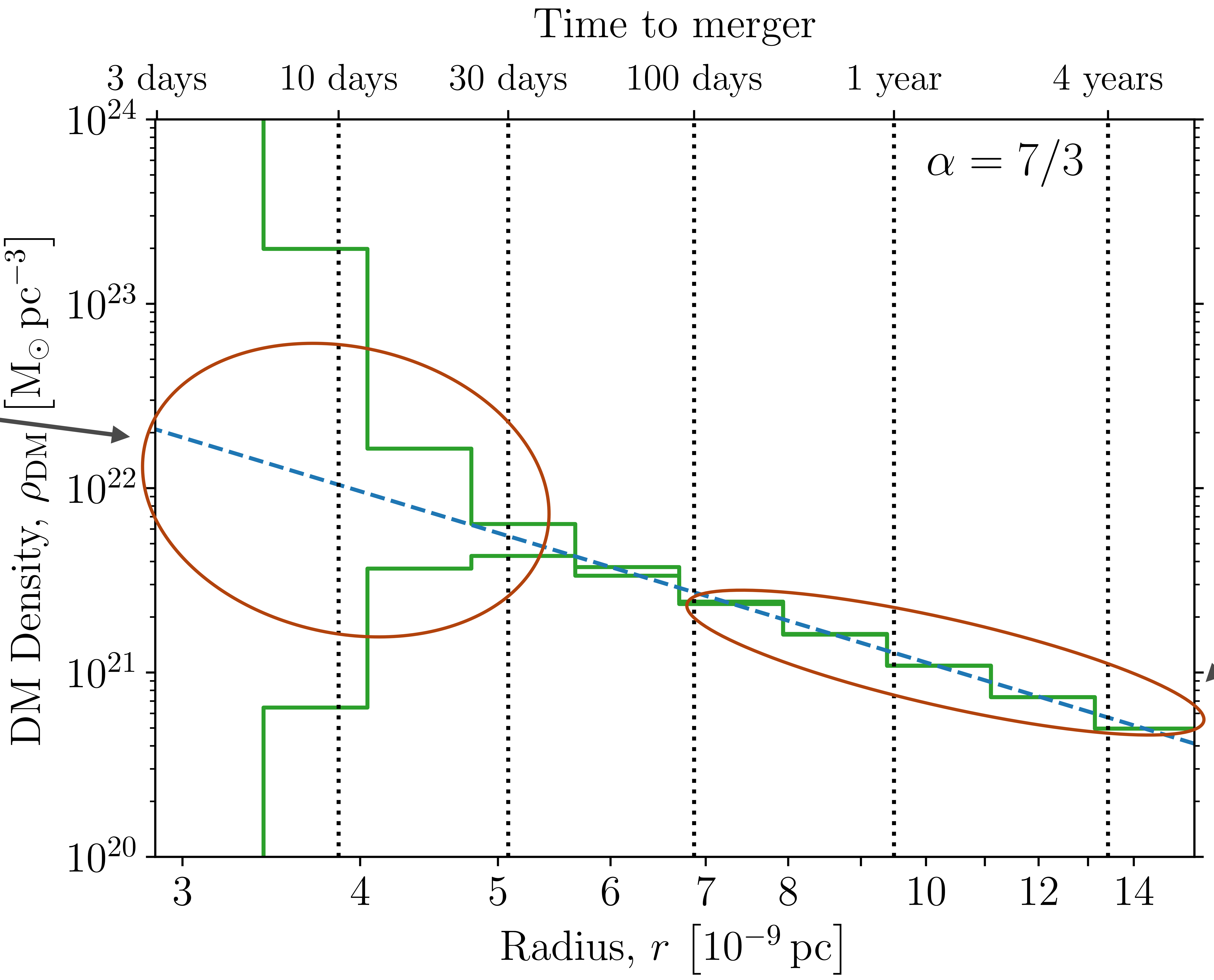


Majority of the phase difference occurs at **large separations**

Number of **cycles low in the final stages** of the evolution

1408.3534

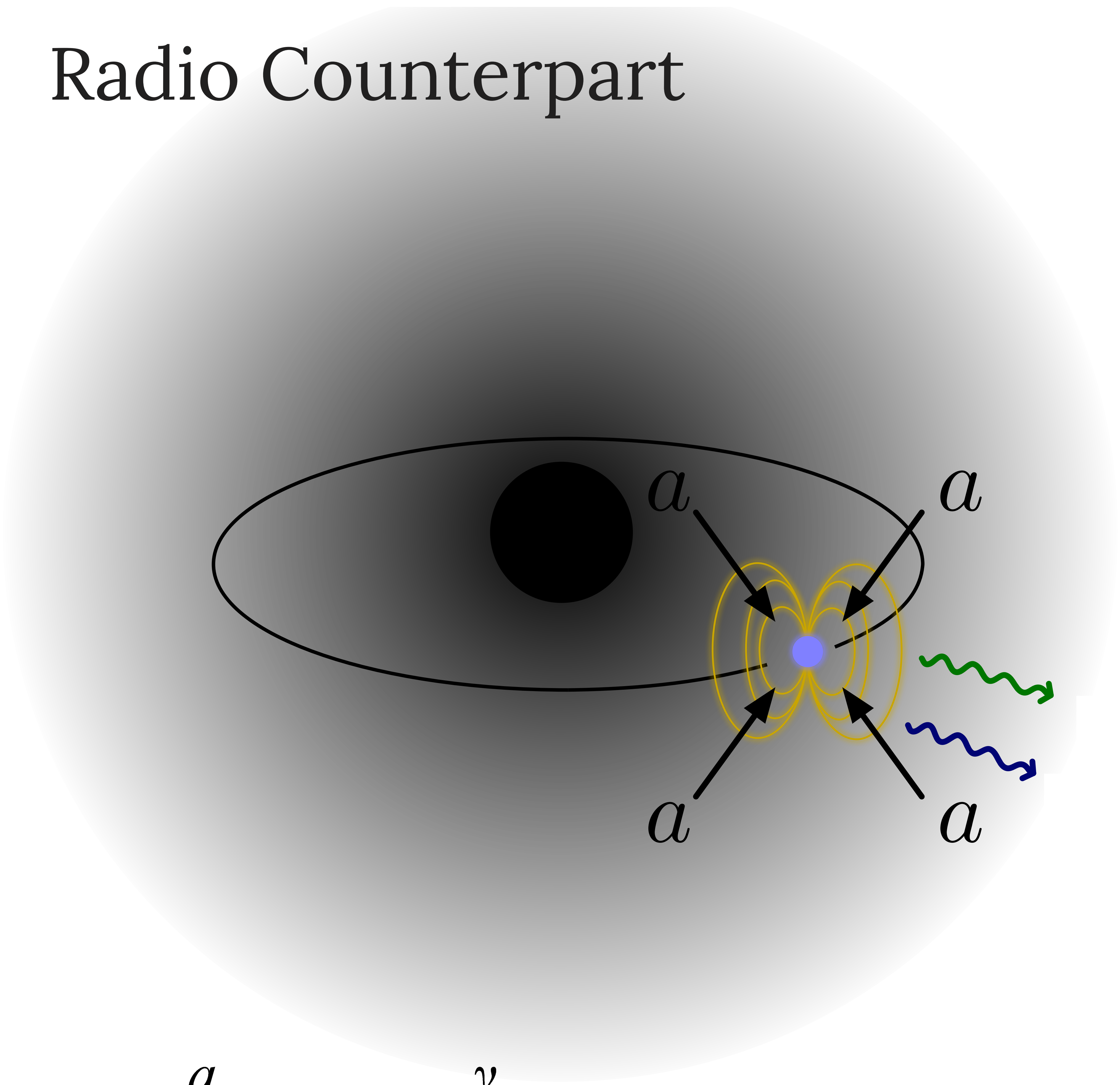
Gravitational Waves Constrain the Slope of the Density Profile

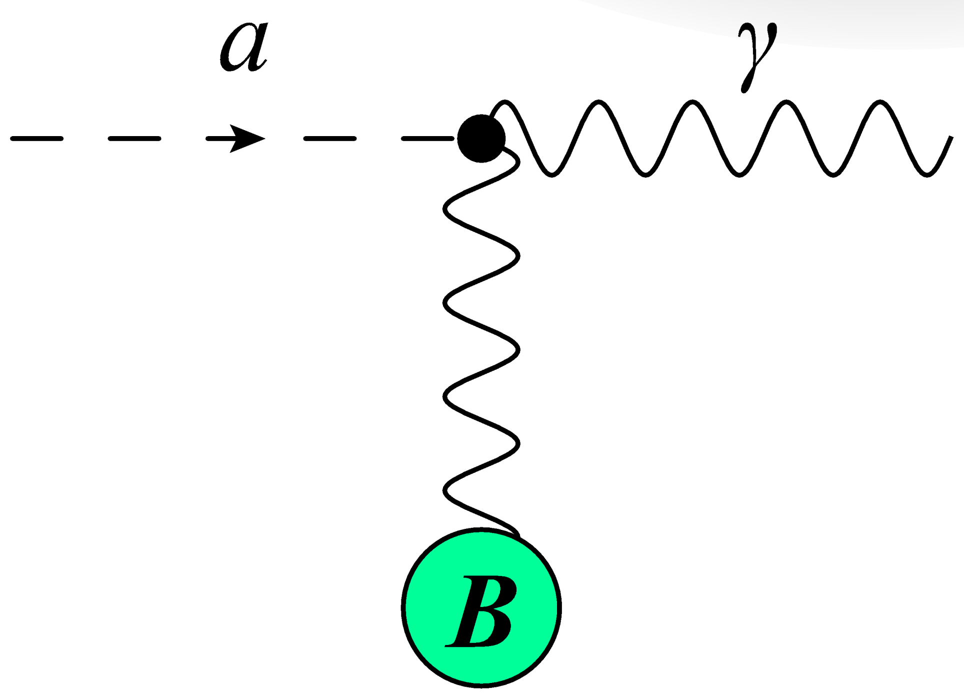


Effect on GW small towards the end of the inspiral

Tight constraints at larger radii

Radio Counterpart





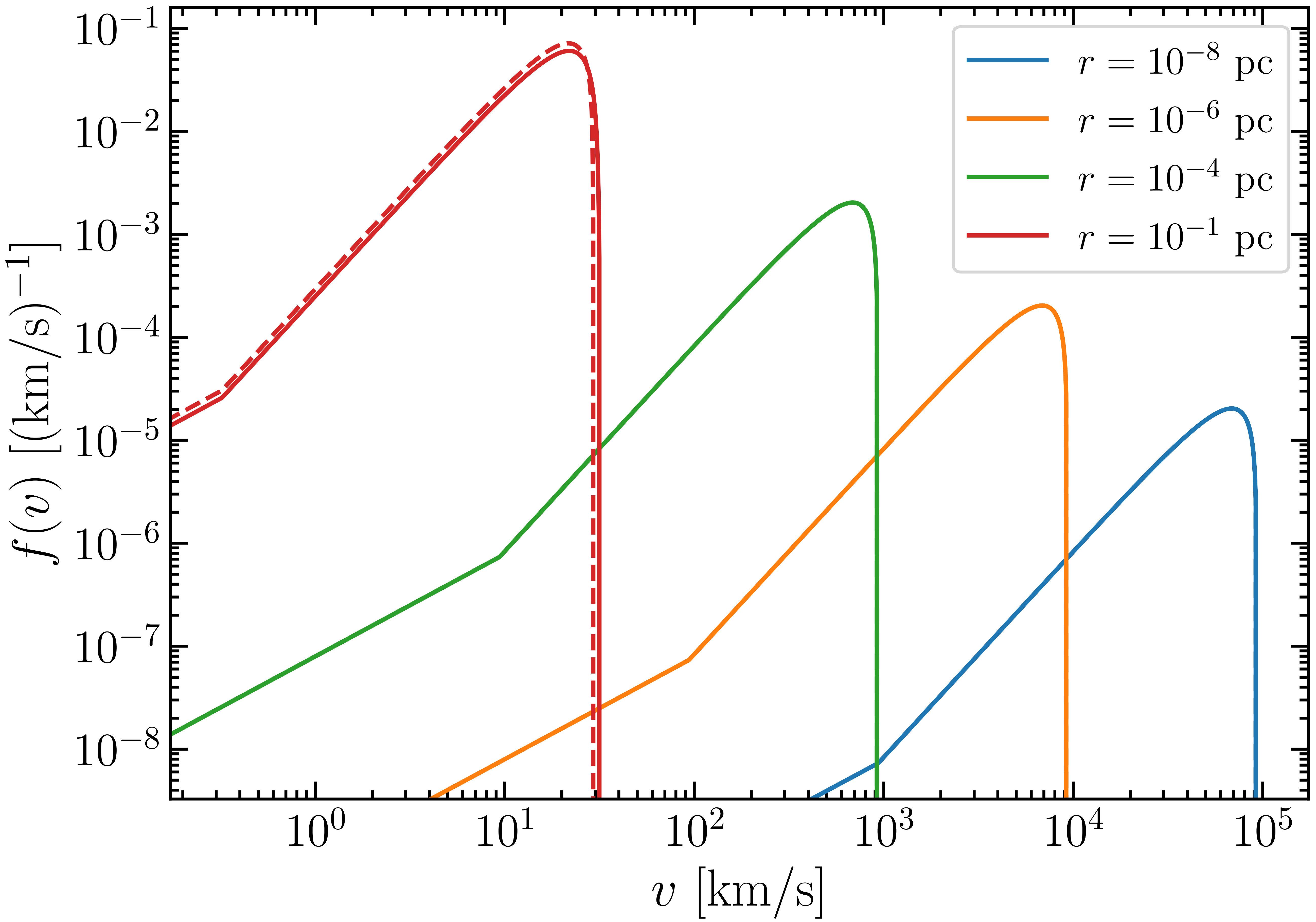
$$\frac{d\mathcal{P}}{d\Omega} \propto p$$

Phase Space Density close to the IMBH

We use **Eddingtons inversion formula**, a unique solution to collision less particles in a background potential in equilibrium

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}\right)_{\Psi=0}\right]$$

$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$



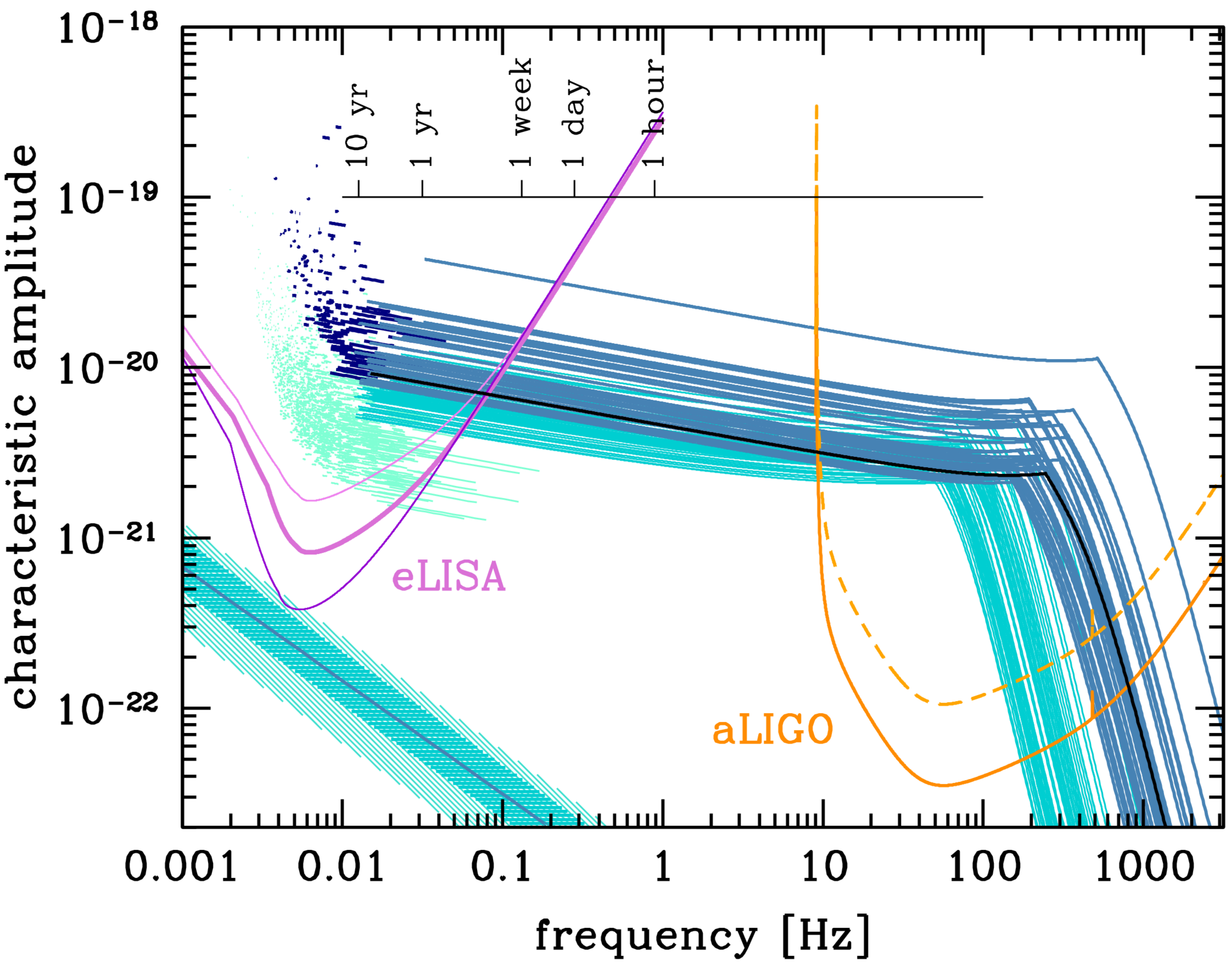
LISA Rates

Uncertainty in IMBH formation channels make merger rate calculations **extremely uncertain**

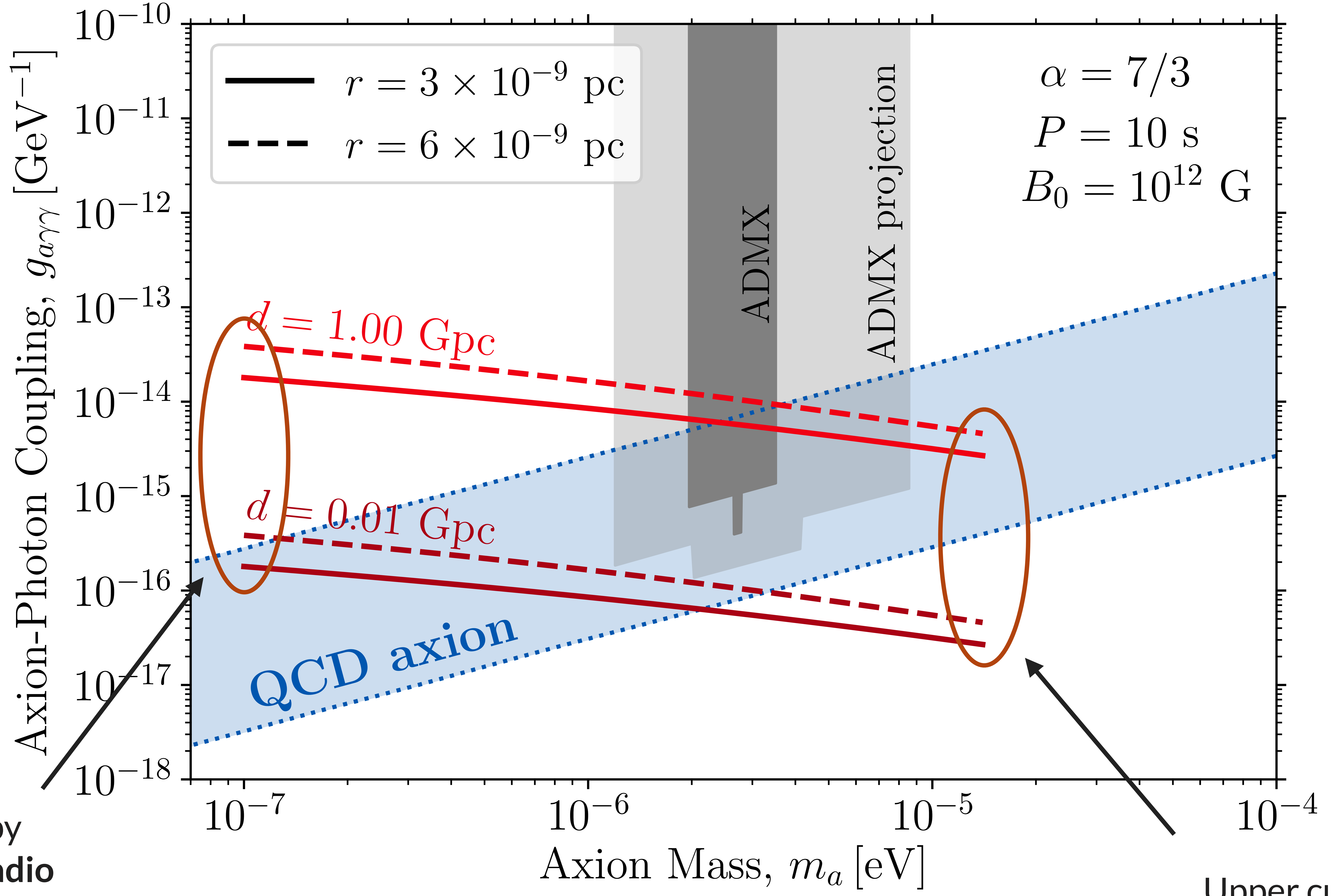
Lisa will see these objects for **5 years prior to merger**

$$\mathcal{R} \sim 3 - 10\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Rates for IMBH mergers with stellar mass objects



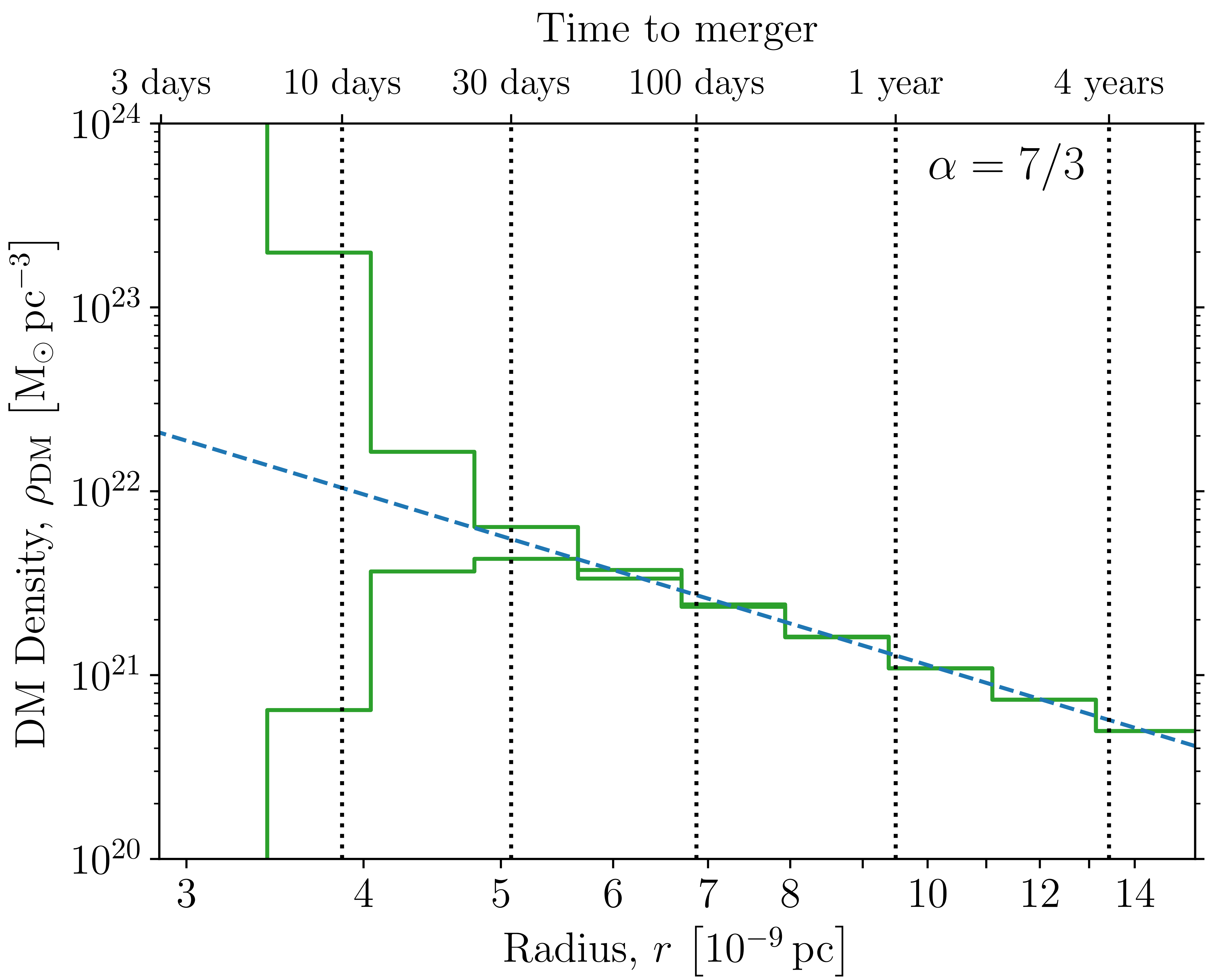
Sensitivity of SKA

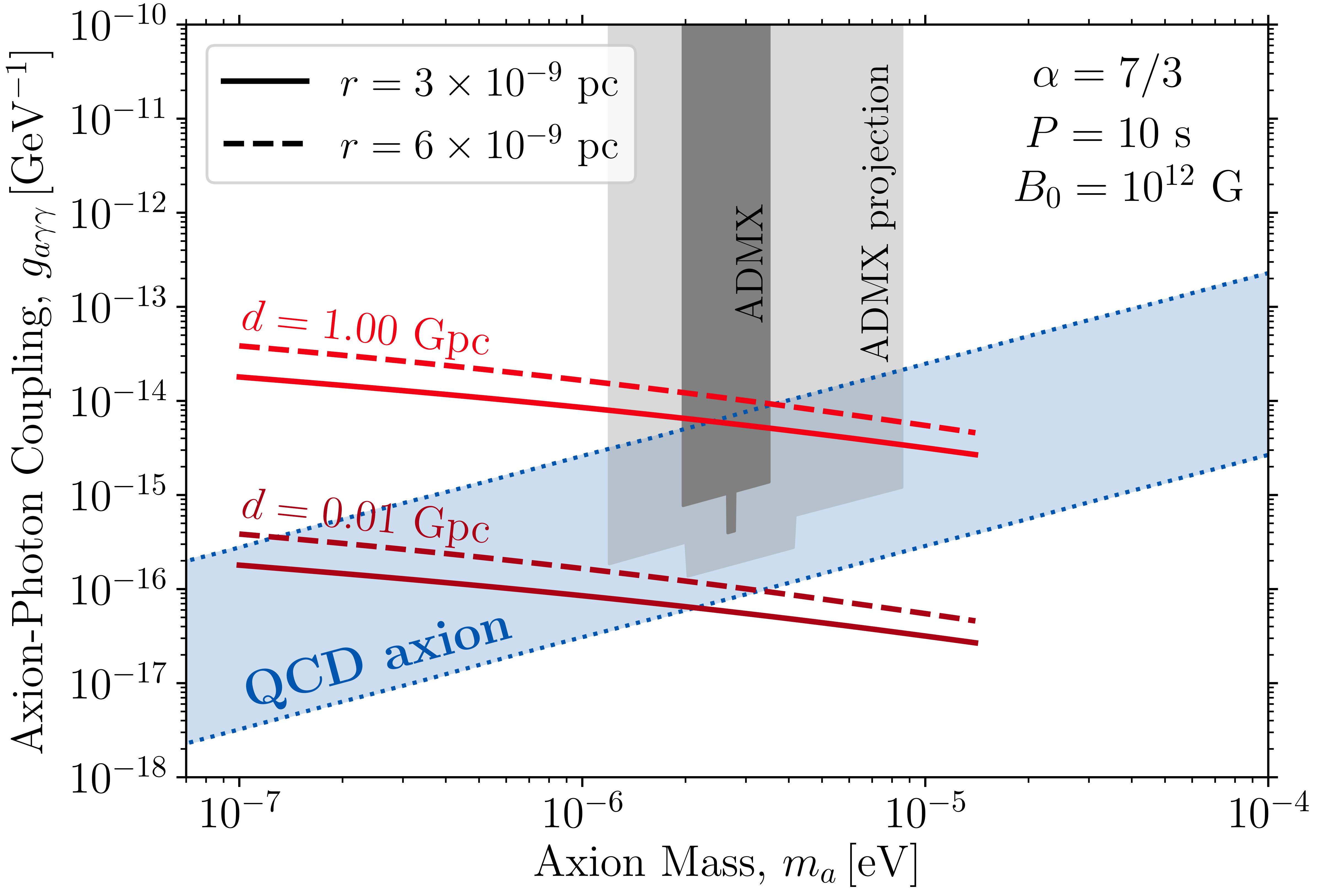


Lower cut off - set by **frequency range of radio telescopes**

Upper cut off - conversion to photons must happen **outside of the NS**

Two Messengers can be Combined for Robust Signal





Difficult to set robust limits due to the **uncertainty in the NS properties**, magnetic field etc.

If many are found, utilising **NS population properties** will allow for a more robust constraint

Conclusions

1. Axions and axion like particles are primary candidates for both dark matter and BSM physics

2. Astrophysical searches are useful way to constrain and potentially detect axions