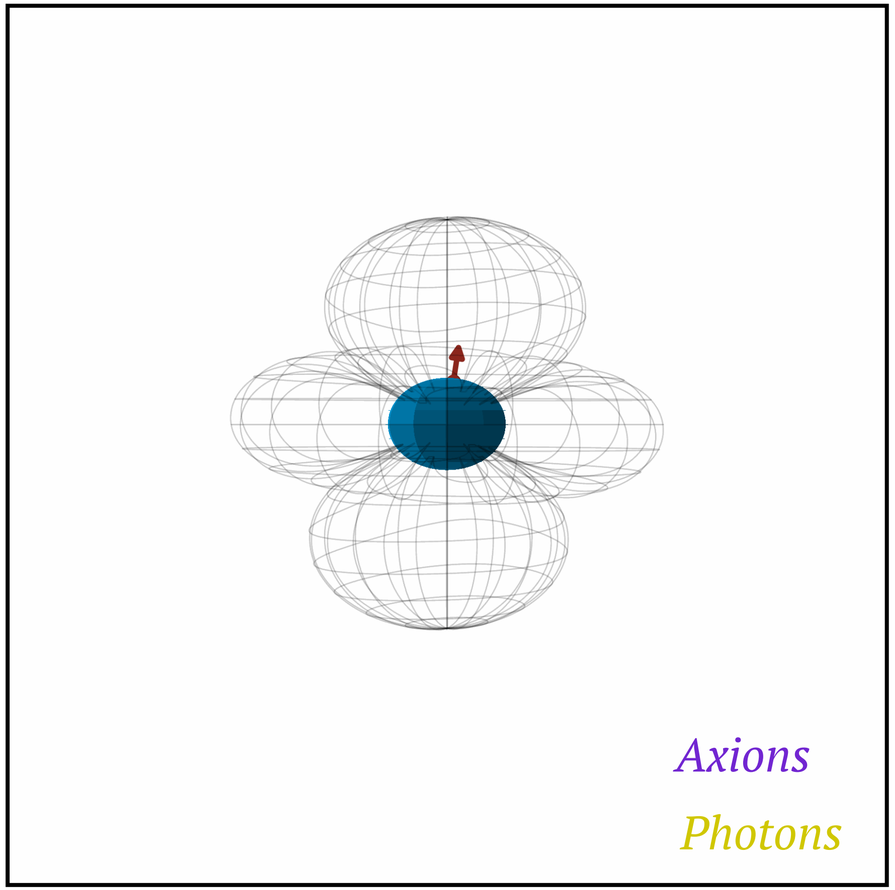
Neutron Stars as Axion Laboratories

Samuel J. Witte

Based on (*incomplete sample of relevant works...*):

Pshirkov (2009)
Hook, Kahn, Safdi, Sun (2018)
***SJW**, Noordhuis, Edwards, Weniger (2021),*
Battye, Garbrecht, McDonald, Srinivasan (2021),
*Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022),*
Prabhu (2021),
*Noordhuis, Prabhu, **SJW**, Weniger, Chen, Cruz (To appear soon),*
*Noordhuis, Prabhu, **SJW**, Weniger (To appear soon)*
+ (many more)...



Animations available at: https://github.com/SamWitte/GIF_Storage

GRAPPA
GRavitation AstroParticle Physics Amsterdam
UNIVERSITY OF AMSTERDAM

ECRS (Nijmegen, NL) July 29, 2022

Brief intro to axions

QCD Axion

- Pseudo Goldstone boson introduced to solve strong CP problem

Why does QCD conserve CP (charge-parity) symmetry?

Axion-like particles

- Pseudo Goldstone bosons, **do not** solve strong CP problem

Generically expect O(100s) of light axions in high energy theories (e.g. string theory)

At low energies, two new parameters: m_a and f_a

- Effectively a one parameter theory (or family of 1 parameter theories)

Characterized by mass m_a or decay constant f_a

- Two parameter theory (mass m_a and decay constant f_a uncorrelated)

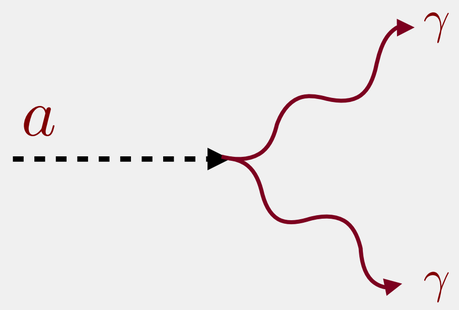
Excellent dark matter candidates

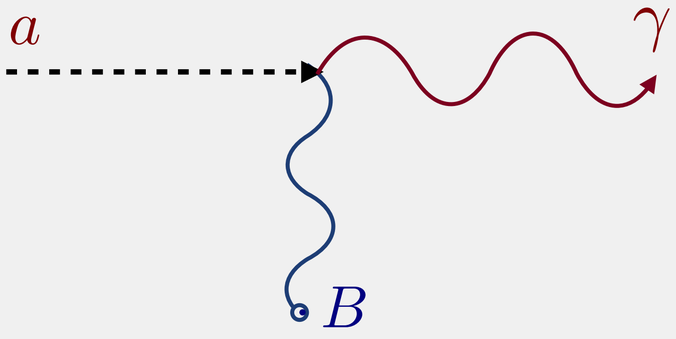
Brief intro to axions

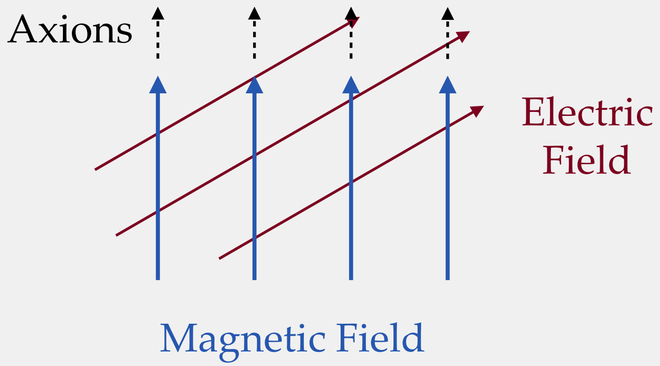
QCD Axion → ***Axions*** ← *Axion-like particles*

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$a\, \vec{E} \cdot \vec{B}$$







Axion-photon mixing

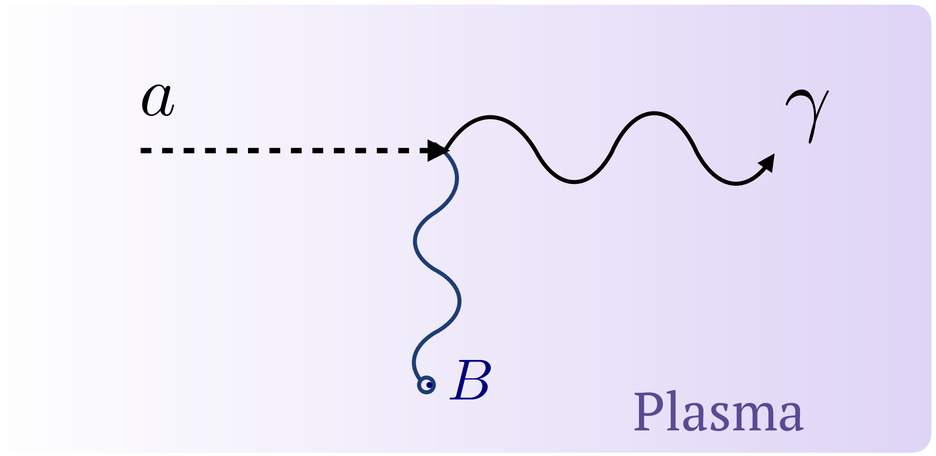
$$\mathcal{L} \sim g_{a\gamma\gamma}\, a\, E \cdot B$$

$$\downarrow$$

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2\, B^2\, L^2$$

B: Magnetic Field

L: Length scale



Requirements for large conversion probability of axions into photons:

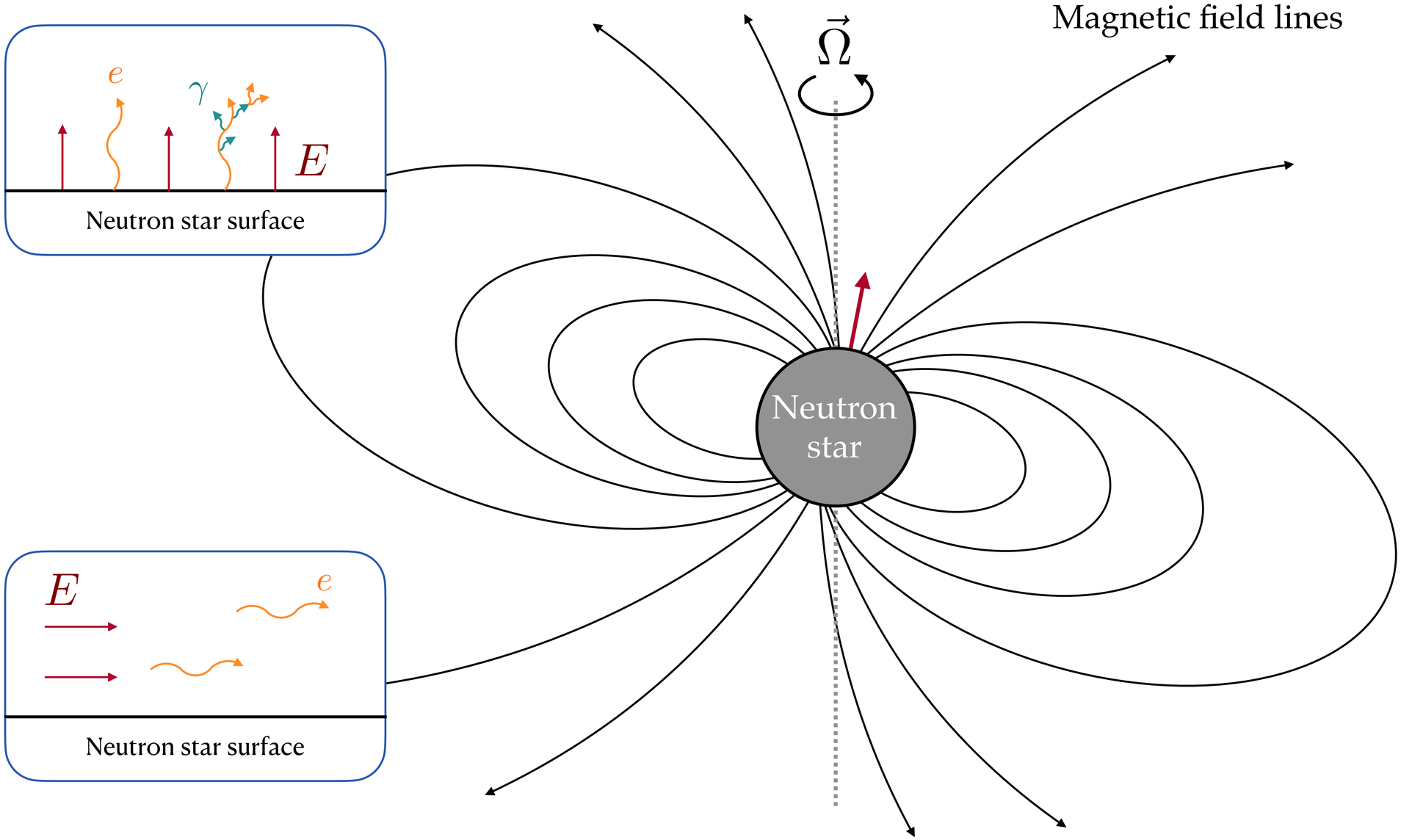
- *B must be large*
- *L must be large*: for *mildly-relativistic* to *non-relativistic* axions, $L \sim (k_a - k_\gamma)^{-1}$

In vacuum, $k_a \ll k_\gamma$

⟶ **Modify photon dispersion relation** (E.g. in a cold plasma $k_\gamma = \sqrt{\omega^2 - \omega_p^2}$, and $k_a \sim k_\gamma$ possible)

Ideal environments: ***Large coherent magnetic fields and dilute plasmas***

Neutron star magnetospheres



$$|\vec{B}| \lesssim 10^{15}\,\mathrm{G}$$

$$r_{NS} \sim 10\,\mathrm{km}$$

Resonances for:
$m_a \lesssim 10^{-4}\,\mathrm{eV}$

$$\vec{E} \cdot \vec{B} = 0$$

$$n_{GJ}(\vec{r}) = |n_+ - n_-|$$

Goldreich-Julian Model
(Force-free solution)

Goldreich & Julian 1969

Axion parameter space

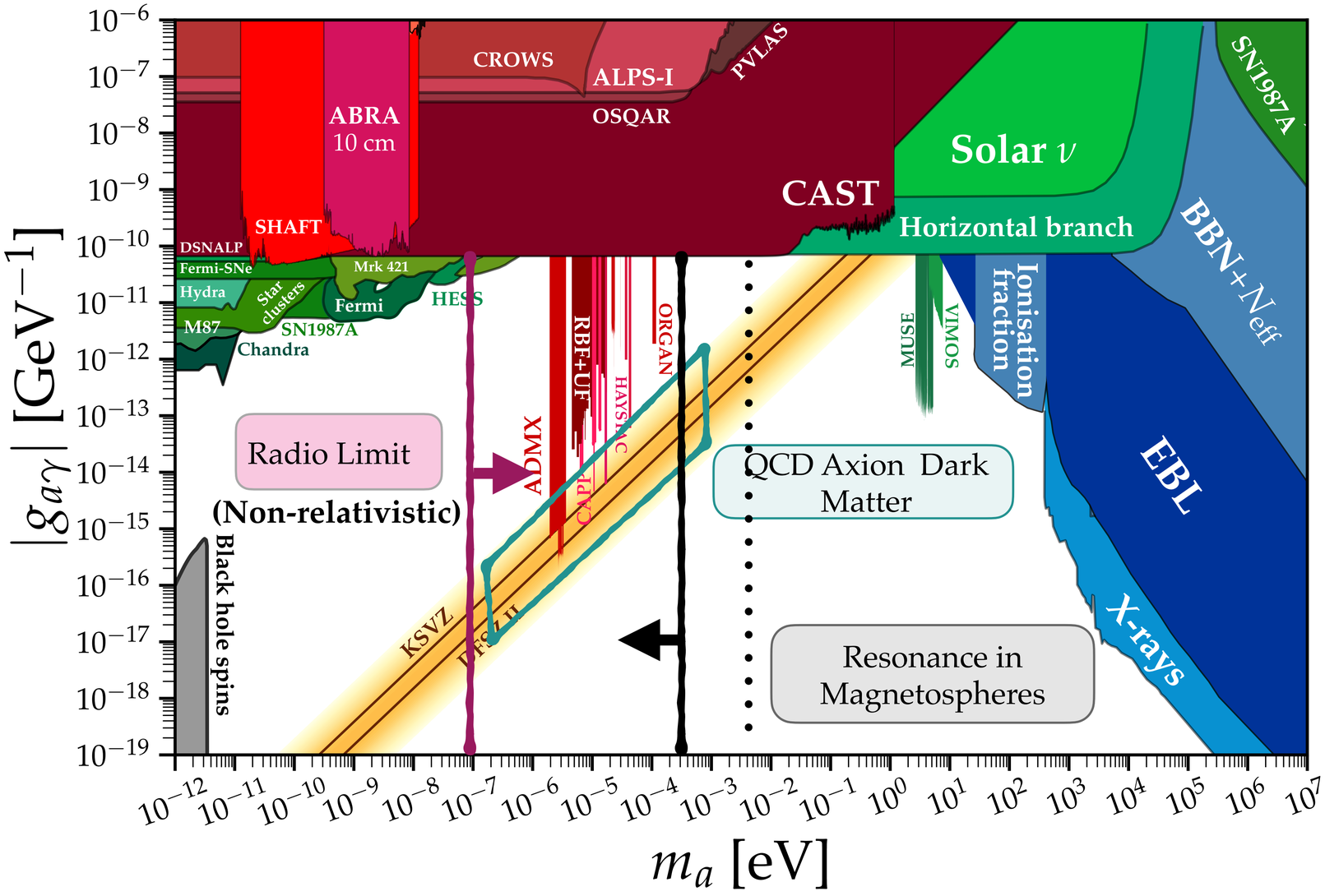
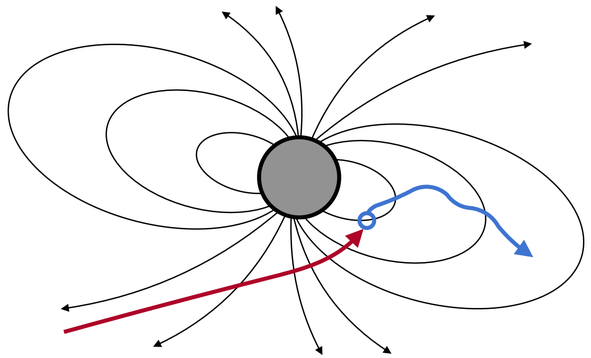
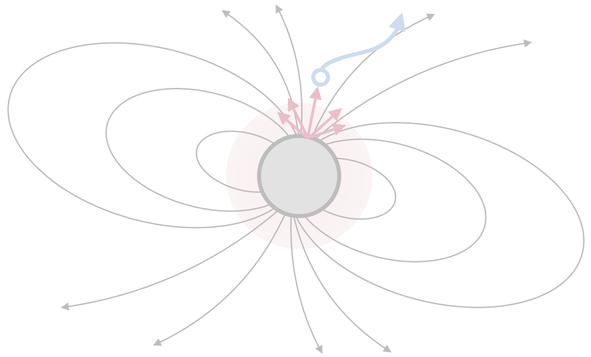


Image credit: Ciaran O'hare

Neutron stars as axion labs



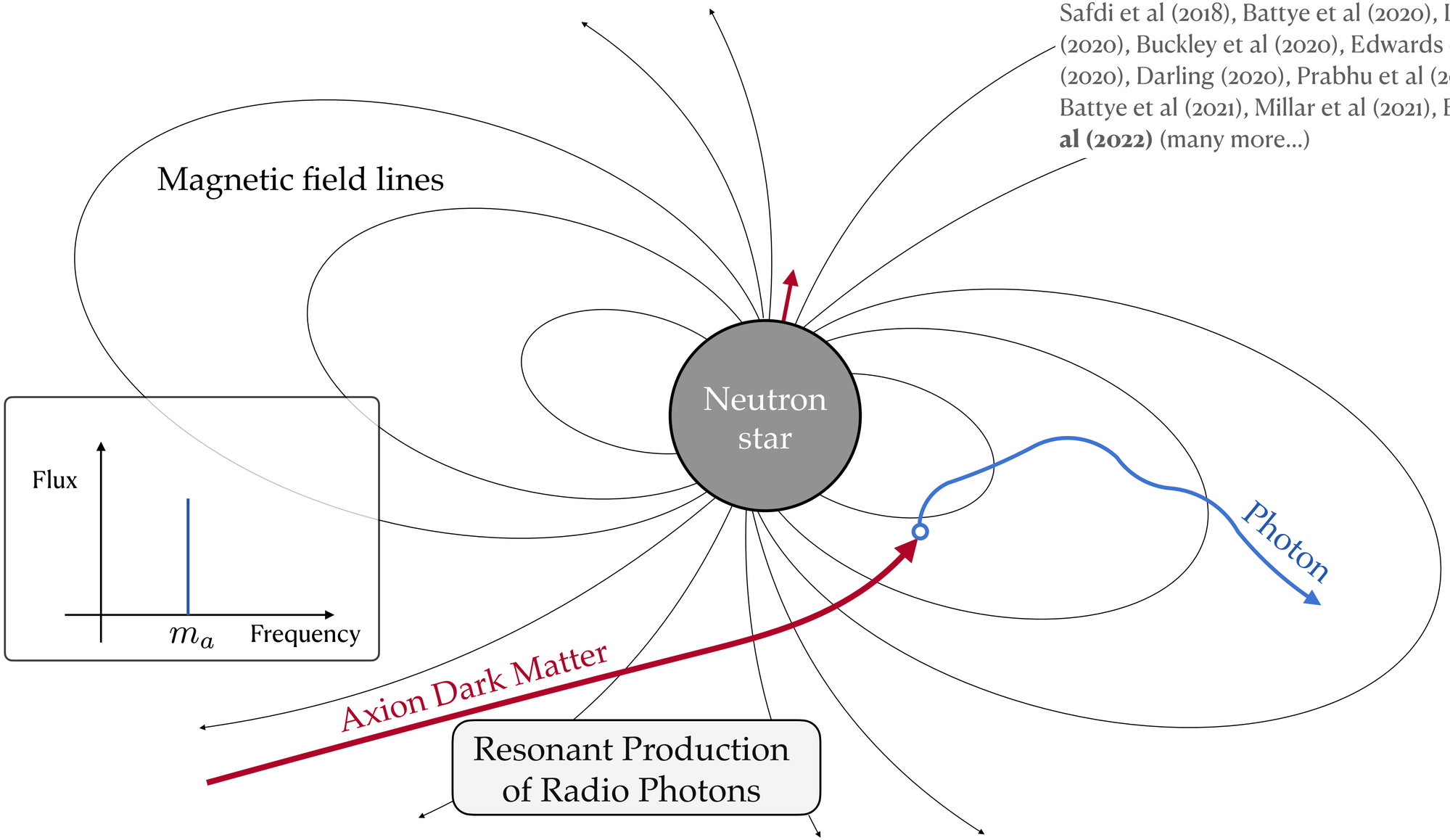
Part 1: Resonant production of radio photons from axion dark matter

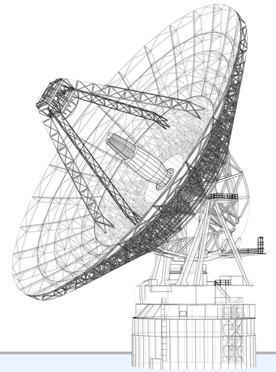


Part 2: Sourcing axions from the vacuum gap collapse

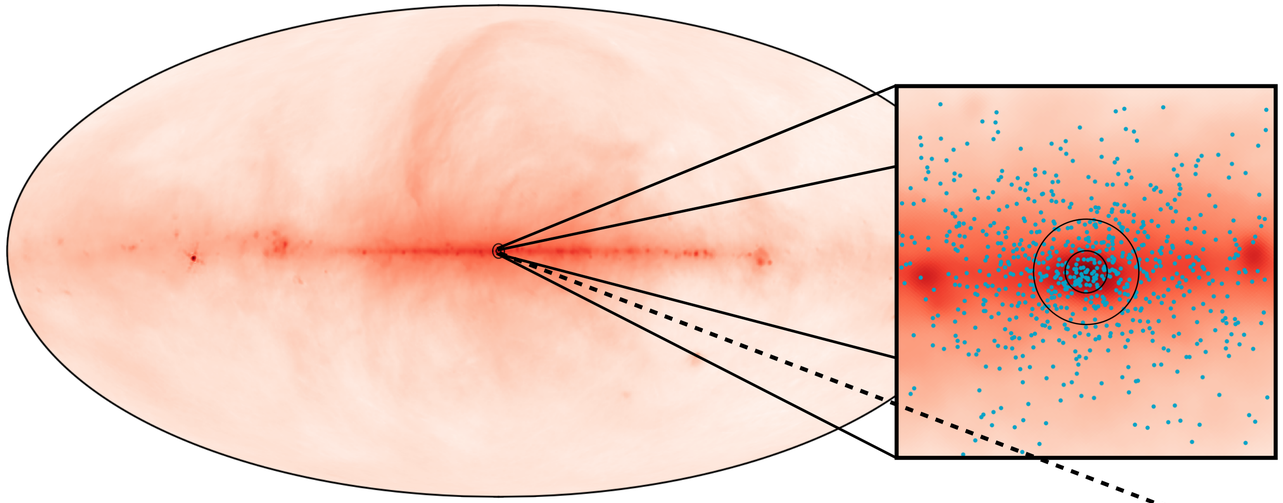
Neutron stars as axion labs

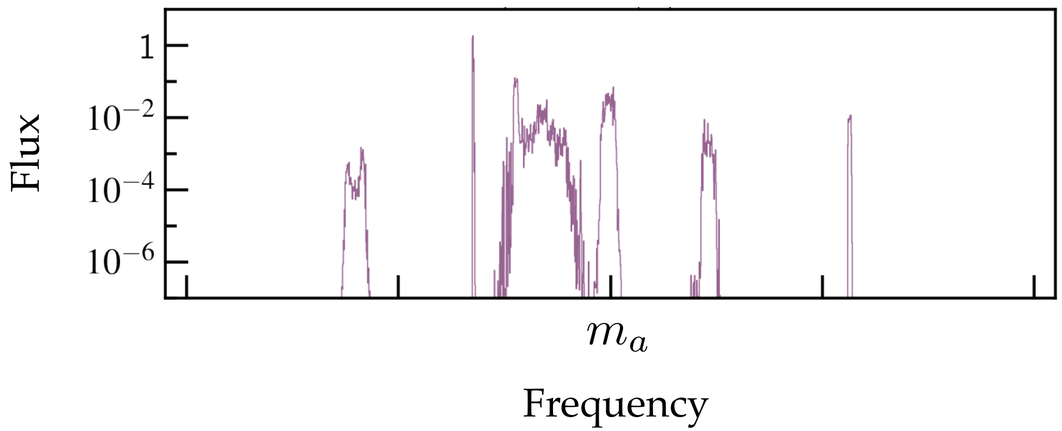
Radio Photons from Axion Dark Matter (abridged):
Pshirkov & Popov (2009), Huang et al (2018), Hook et al(2018), Safdi et al (2018), Battye et al (2020), Leroy et al (2020), Foster et al (2020), Buckley et al (2020), Edwards et al (2019), Edwards et al (2020), Darling (2020), Prabhu et al (2020), **Witte et al (2021),** Battye et al (2021), Millar et al (2021), Buckley et al (2021), **Foster et al (2022)** (many more...)





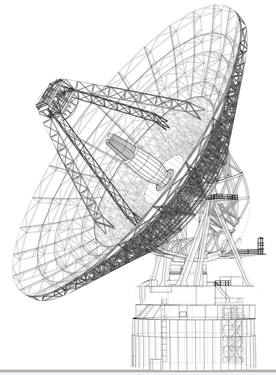
Observing the galactic center with the Green Bank Telescope





<u>Survey Details:</u>

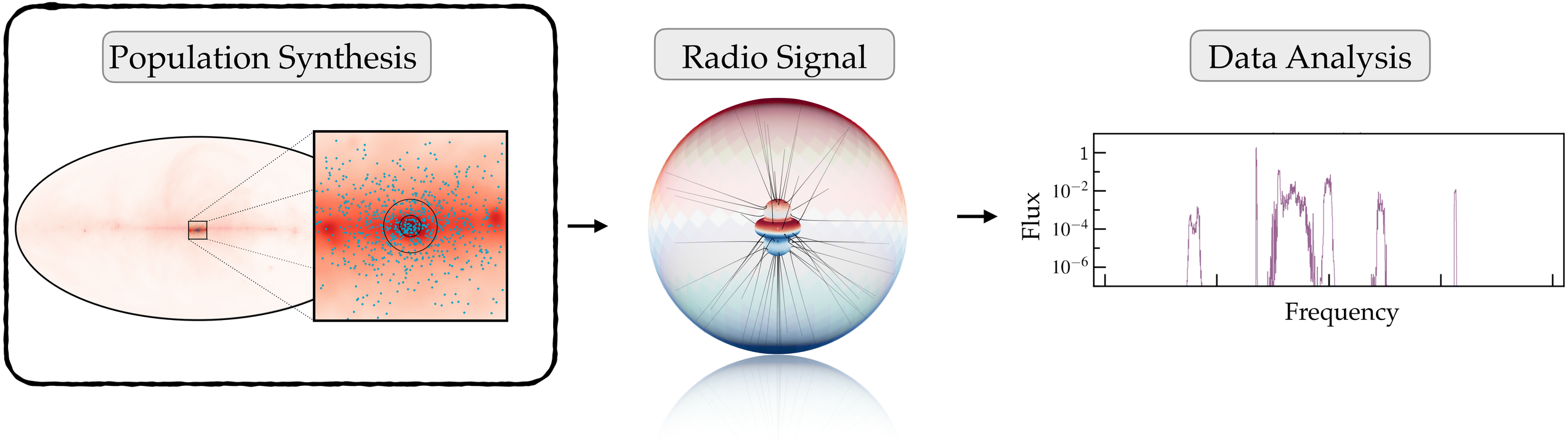
- **Telescope:** Green Bank Telescope, 100m Single Dish
- **Observation Frequency:** 4–8 GHz [C band]
- **Observation Target:** Milky Way Galactic Center [inner ~ few pcs]
  (need high dark matter densities)
- **Observation Time:** ~4.6 hours
- **Observation Strategy:** On/off target



Data courtesy of the Breakthrough Listen Initiative

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

GBT observations of galactic center



Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Neutron star population modeling

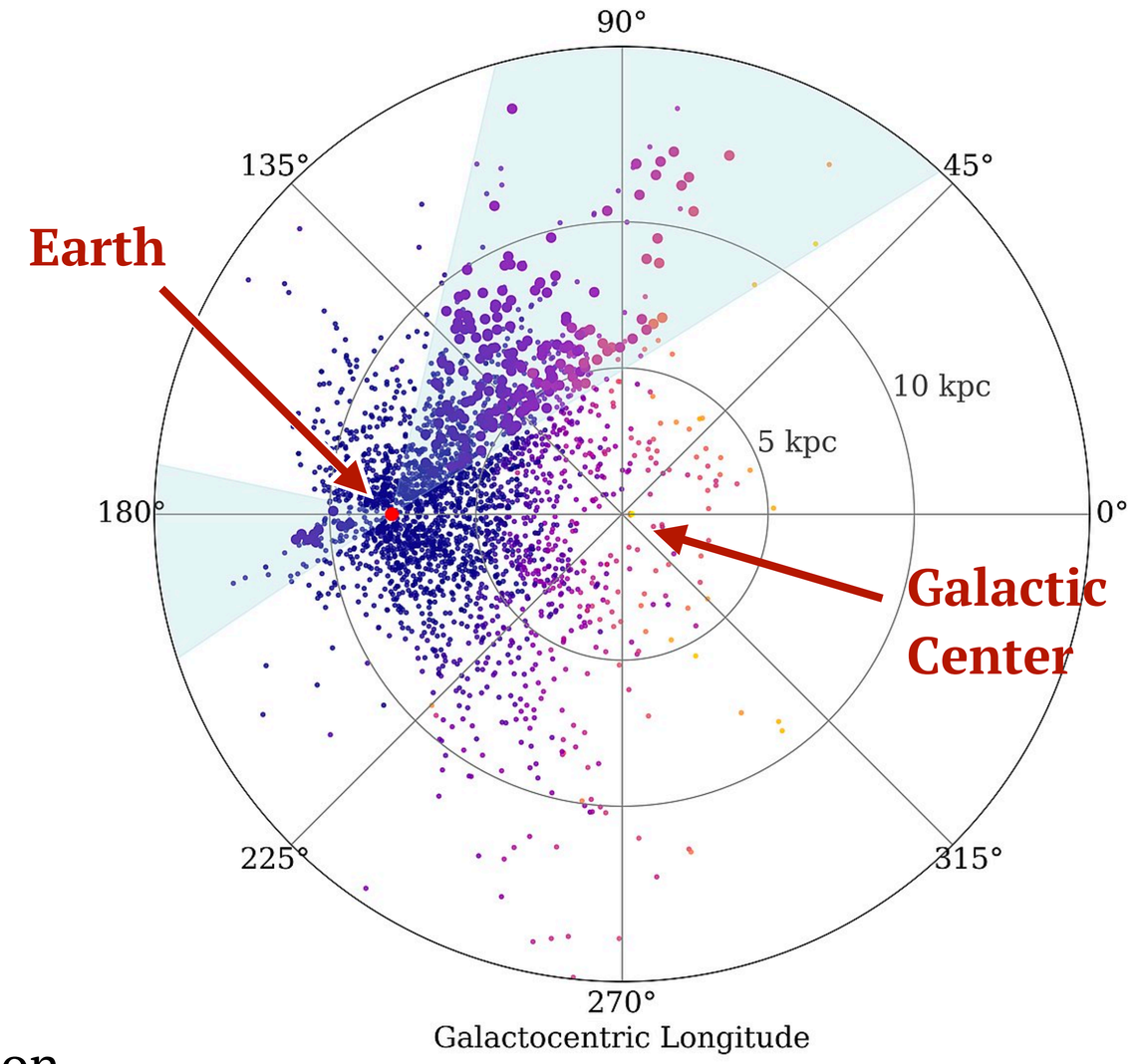
How do we predict what Galactic Center neutron star population looks like?

Lets focus for now on the ***young*** neutron star population

- Star formation rates + stellar mass distributions
  → neutron star formation rate
- Spatial distribution of stars is tracer for spatial distribution of neutron stars

Do et al (2013), Lu et al (2013), Yusef-Zadeh (2017)

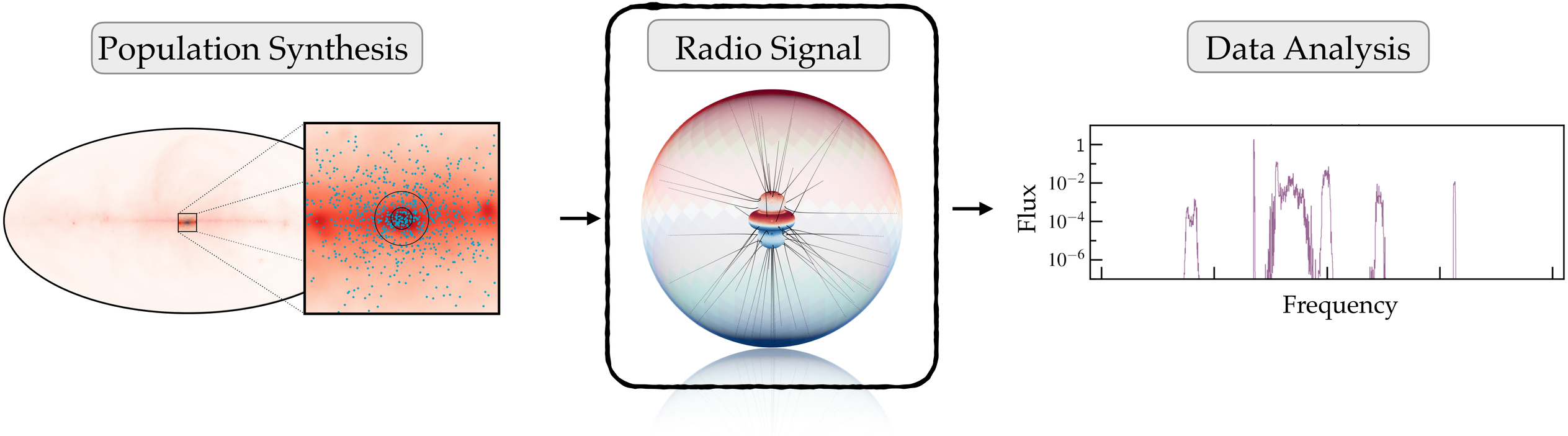
Gives predictions: $n_{NS}(\vec{r})$ *and* $p(t_{\mathrm{NS-birth}})$



Wikipedia: ALPA Pulsars

Construct $p(P, B_0, \theta_m \,|\, t_{age})$ by simulating magneto-rotational spin-down, and fitting to observed population

GBT observations of galactic center



Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2022)

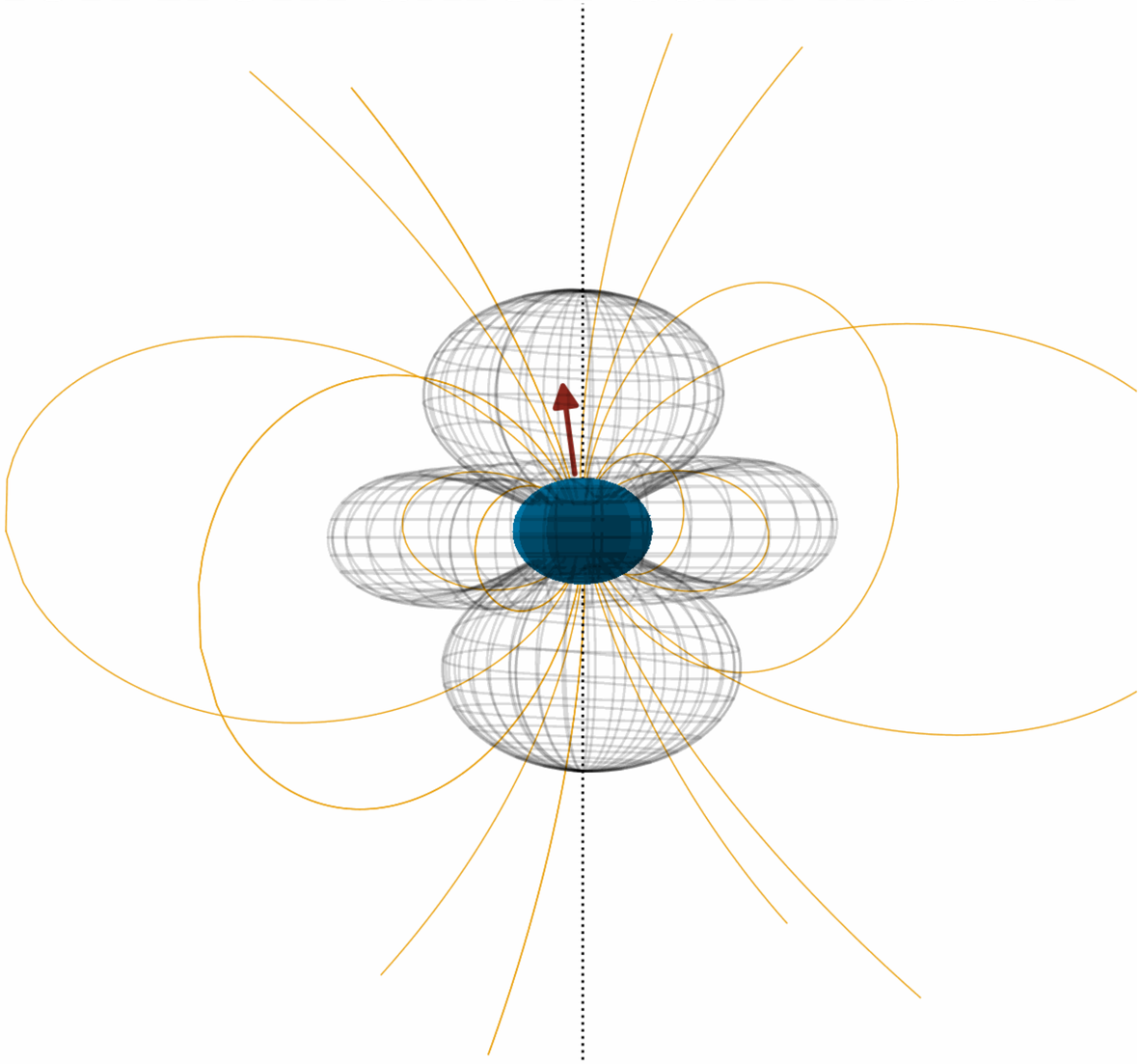
Photon production from axion dark matter

Step 1: Define plasma structure of magnetosphere

Resonant Conversion

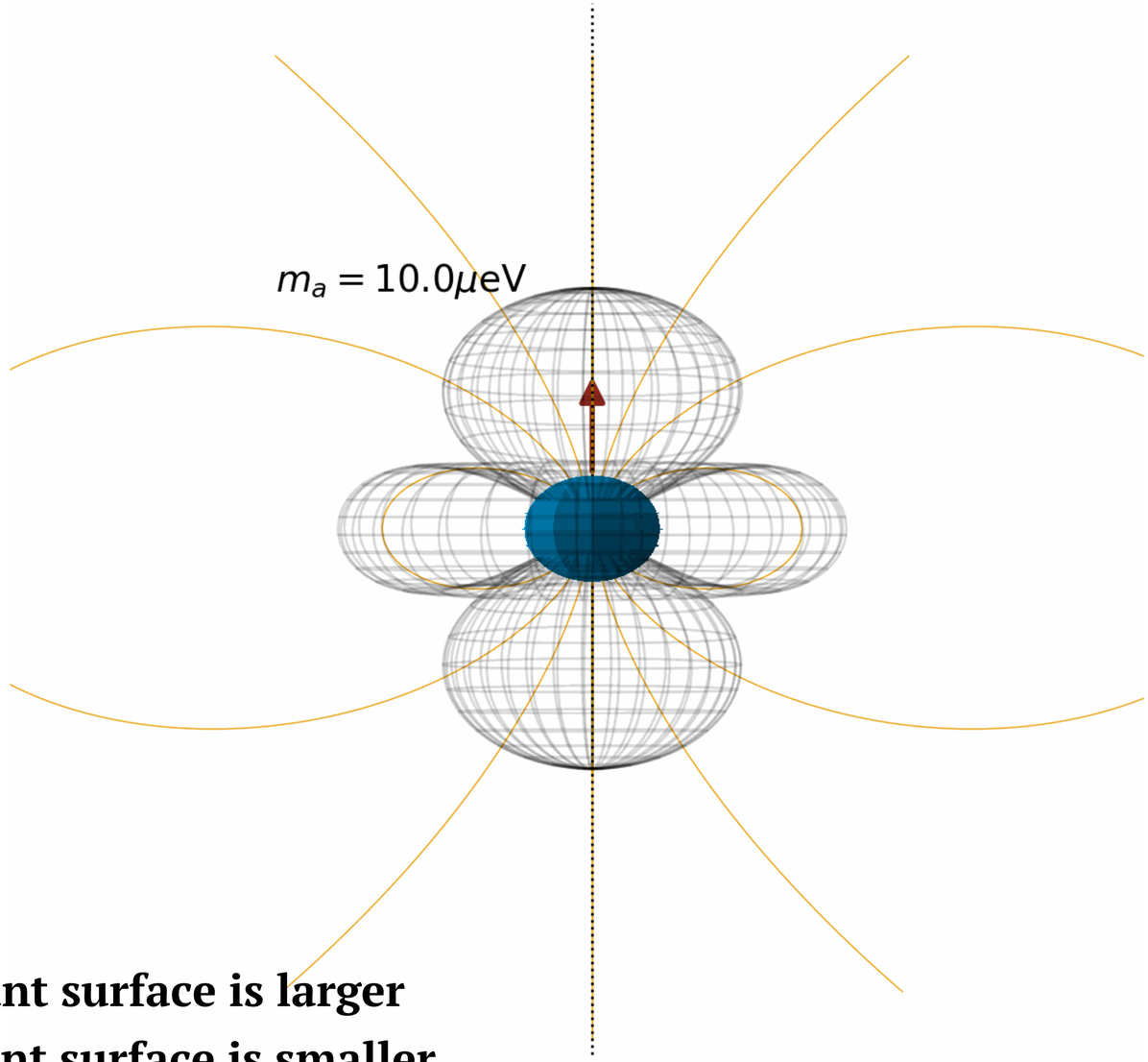
Location: $m_a \sim \omega_p$

Efficiency: $\propto (\partial_x \omega_p)^{-1}$



Animations available at: https://github.com/SamWitte/GIF_Storage

Photon production from axion dark matter



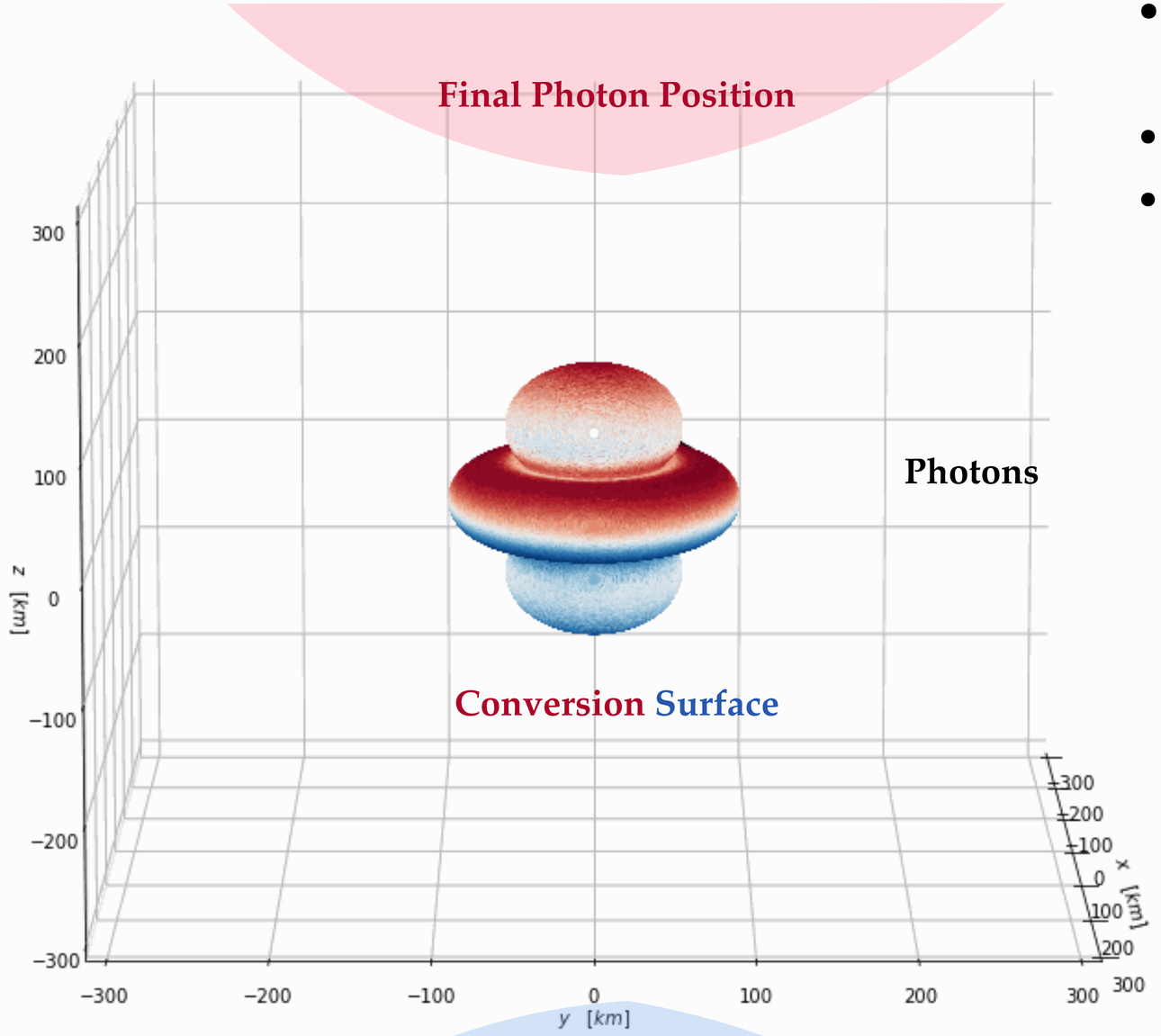
Smaller axion mass → resonant surface is larger

Larger axion mass → resonant surface is smaller

Animations available at: https://github.com/SamWitte/GIF_Storage

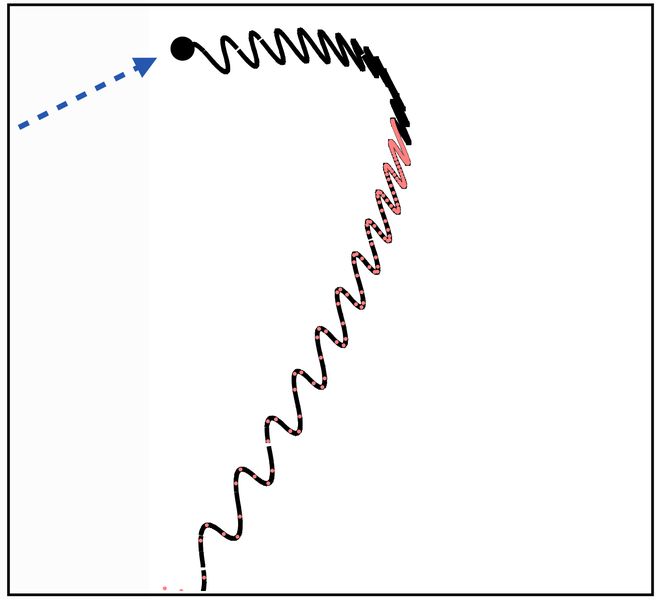
Ray tracing

Step 2: Axion phase space to photon flux



Ray tracing allows for:

- Accurate mapping of radio flux
- Line broadening effects
- Path-dependent absorption



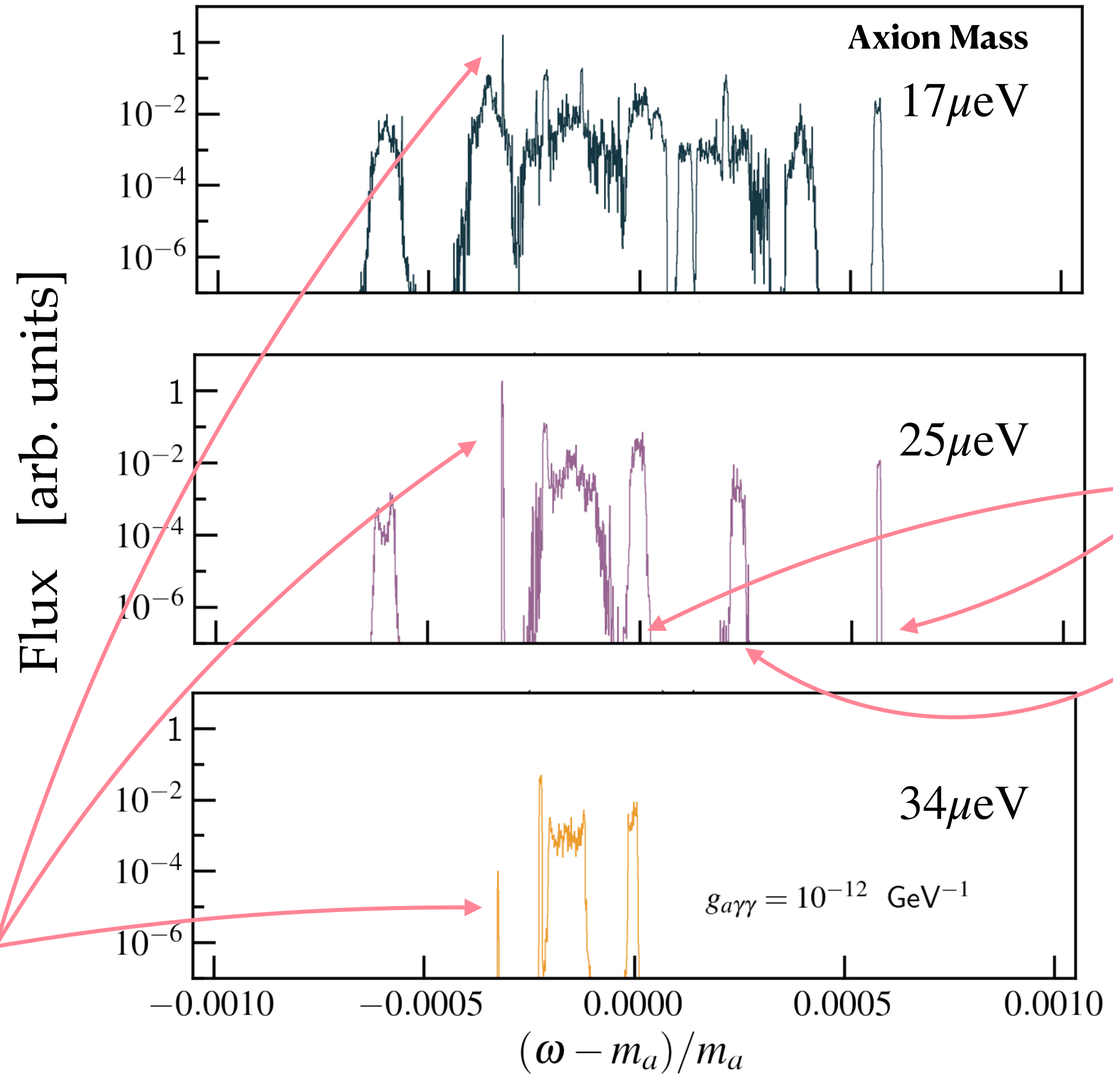
~ 500 meters

SJW, Noordhuis, Edwards, Weniger (2021)

Animations available at: https://github.com/SamWitte/GIF_Storage

Stacked signal

Step 3: Generating the axion 'forest'



Doppler Broadening

Plasma Broadening

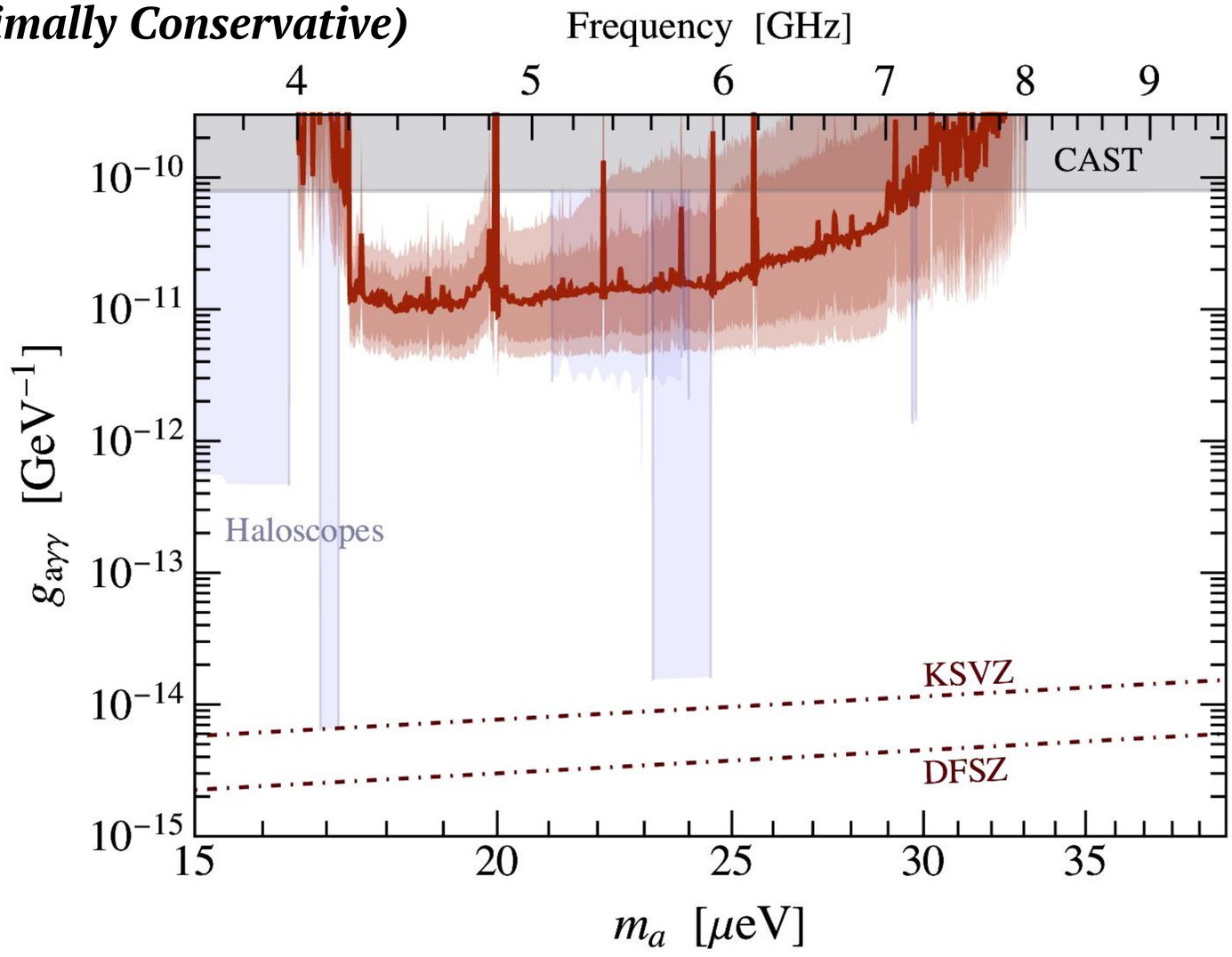
Neutron Stars Disappear

Individual Neutron Stars

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

GBT axion search

Fiducial Model (Maximally Conservative)



QCD axion benchmarks

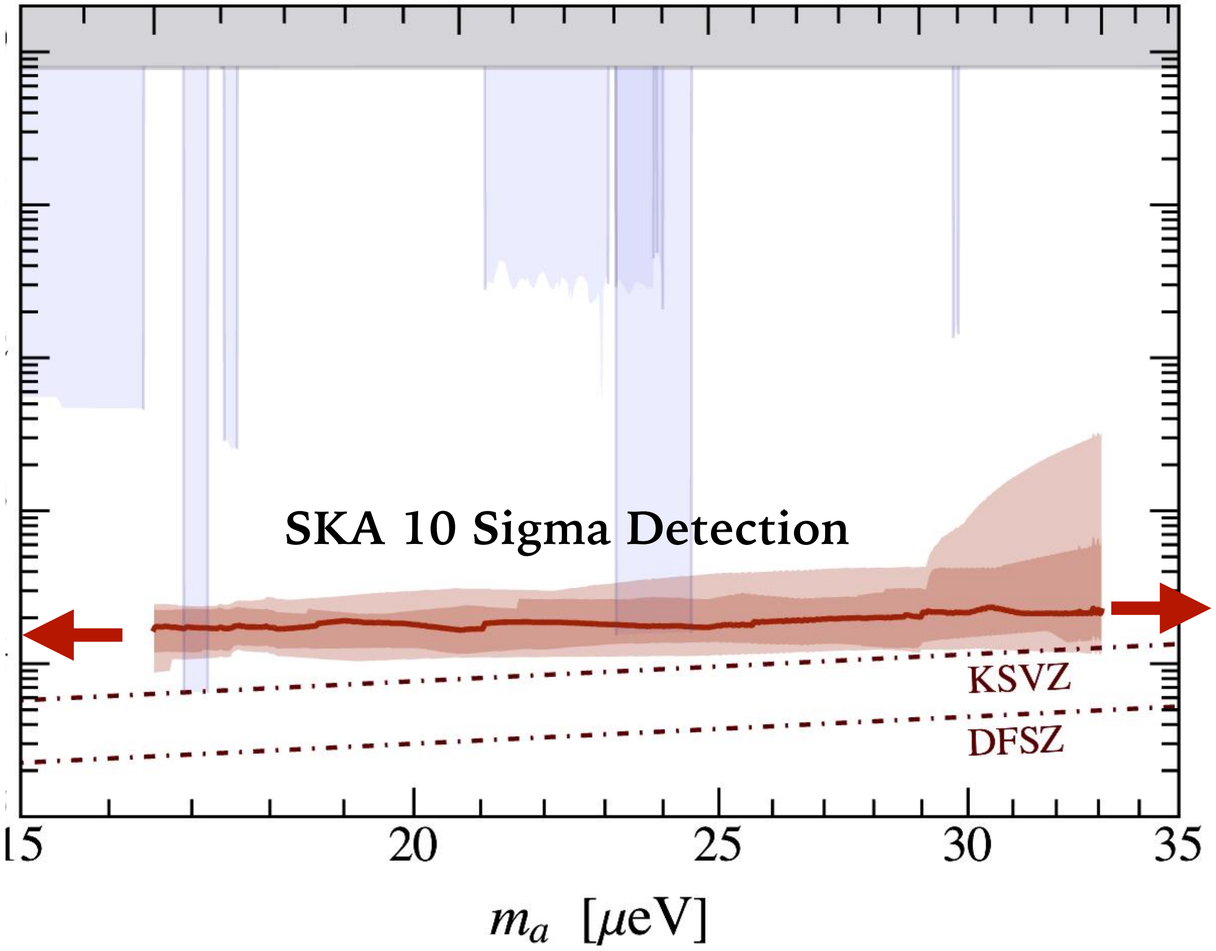
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Future prospects

Improvements:

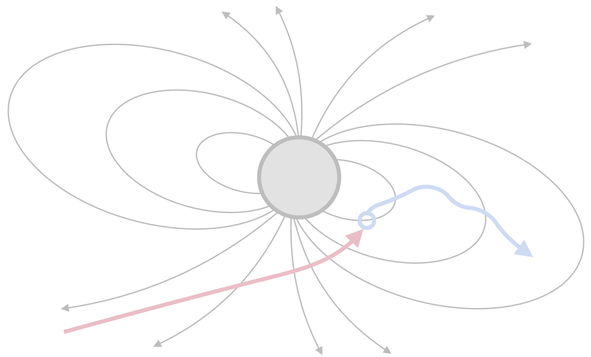
- Better understanding of axion-photon mixing
- Exploit time / frequency domain information
- Better telescopes
- ....

Improvement needed from theory + experiment

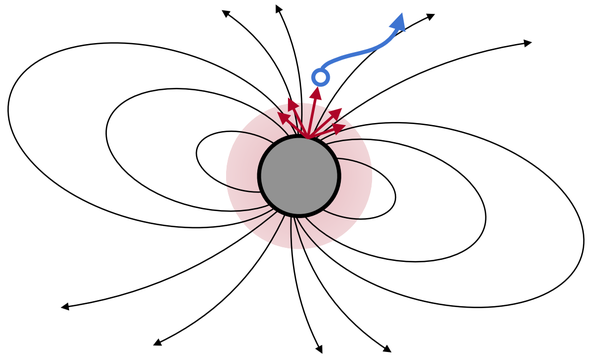


Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Neutron stars as axion labs

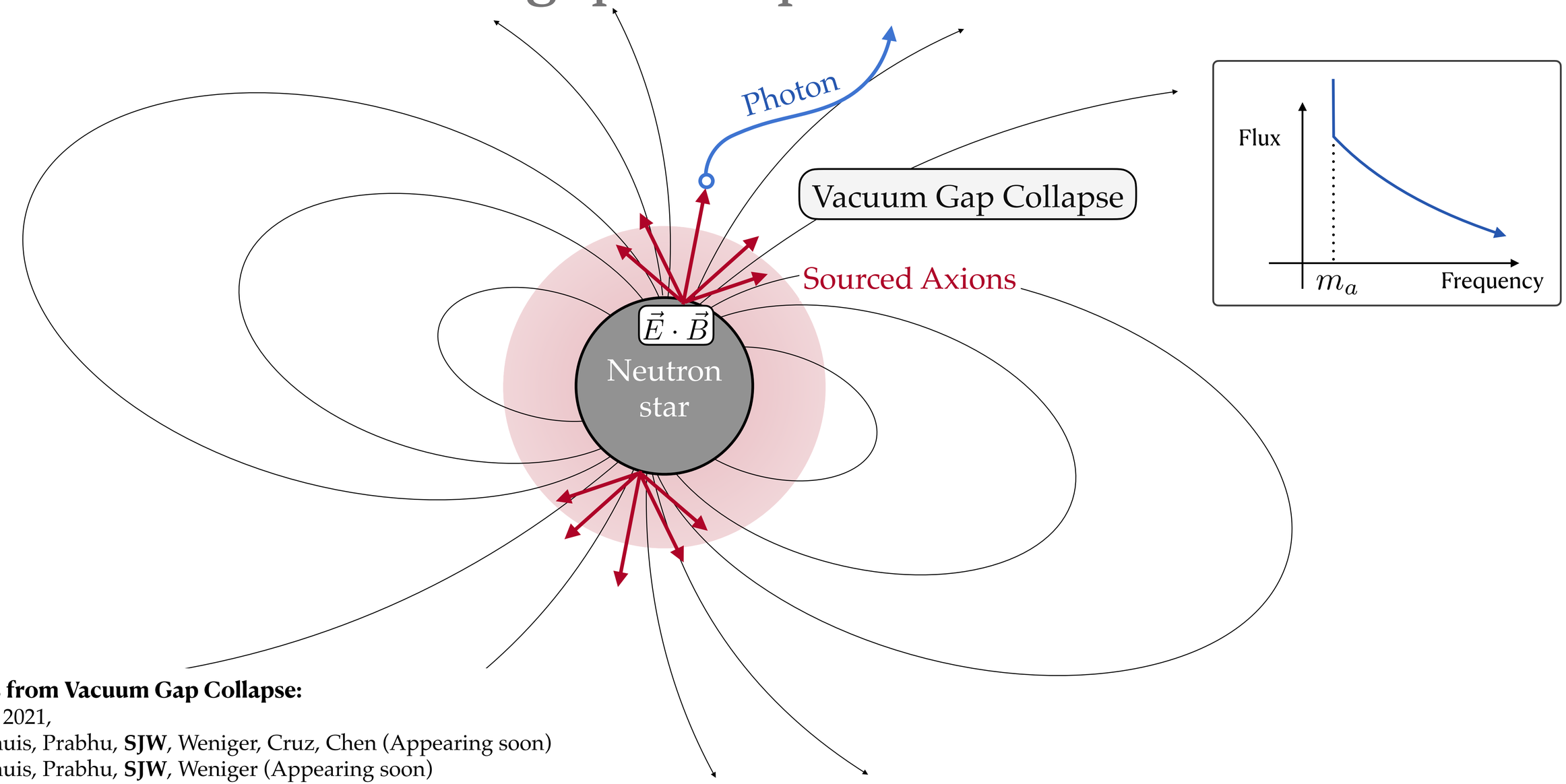


Part 1: Resonant production of radio photons from axion dark matter



Part 2: Sourcing axions from the vacuum gap collapse

Axions from vacuum gap collapse

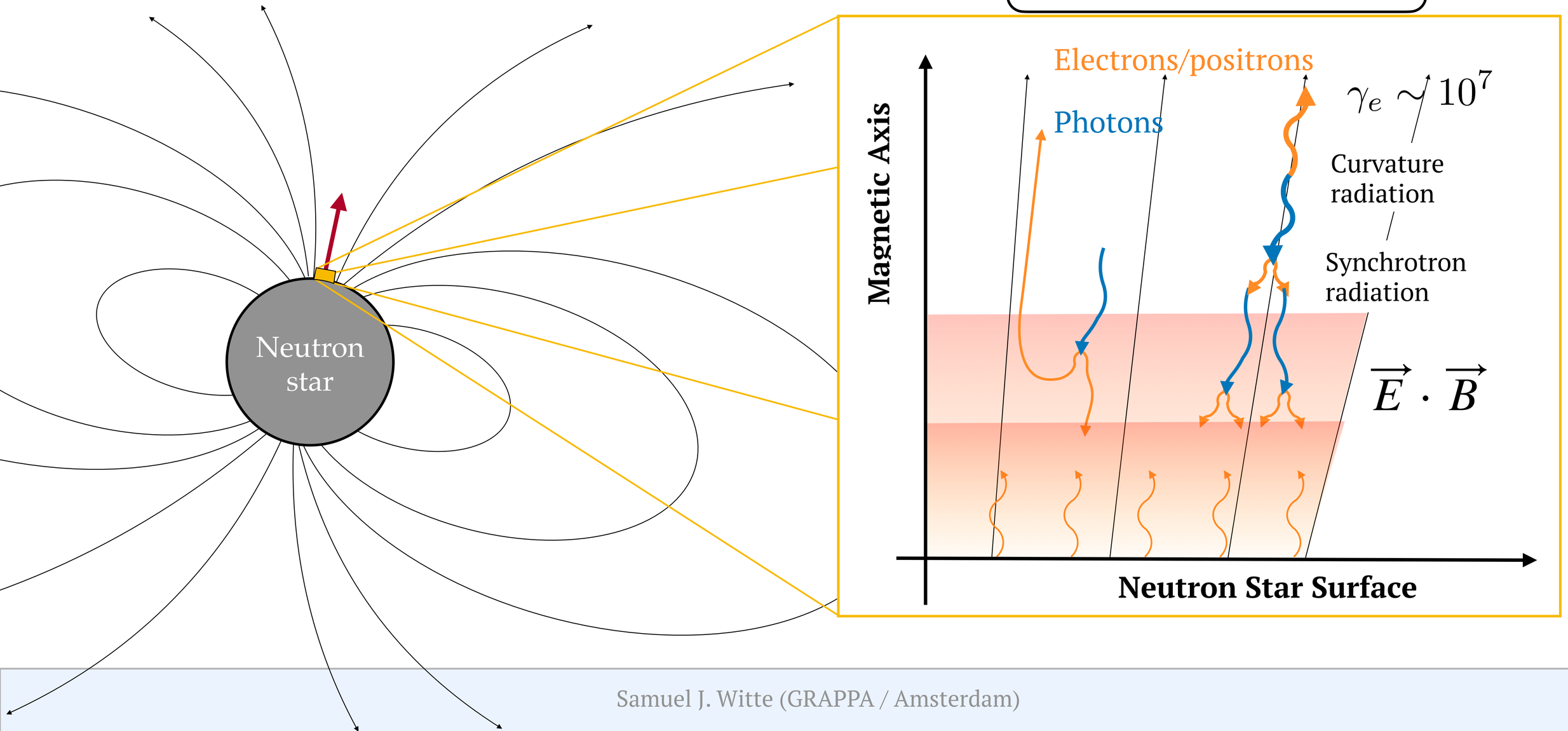


Axions from Vacuum Gap Collapse:
Prabhu 2021,
Noordhuis, Prabhu, **SJW**, Weniger, Cruz, Chen (Appearing soon)
Noordhuis, Prabhu, **SJW**, Weniger (Appearing soon)

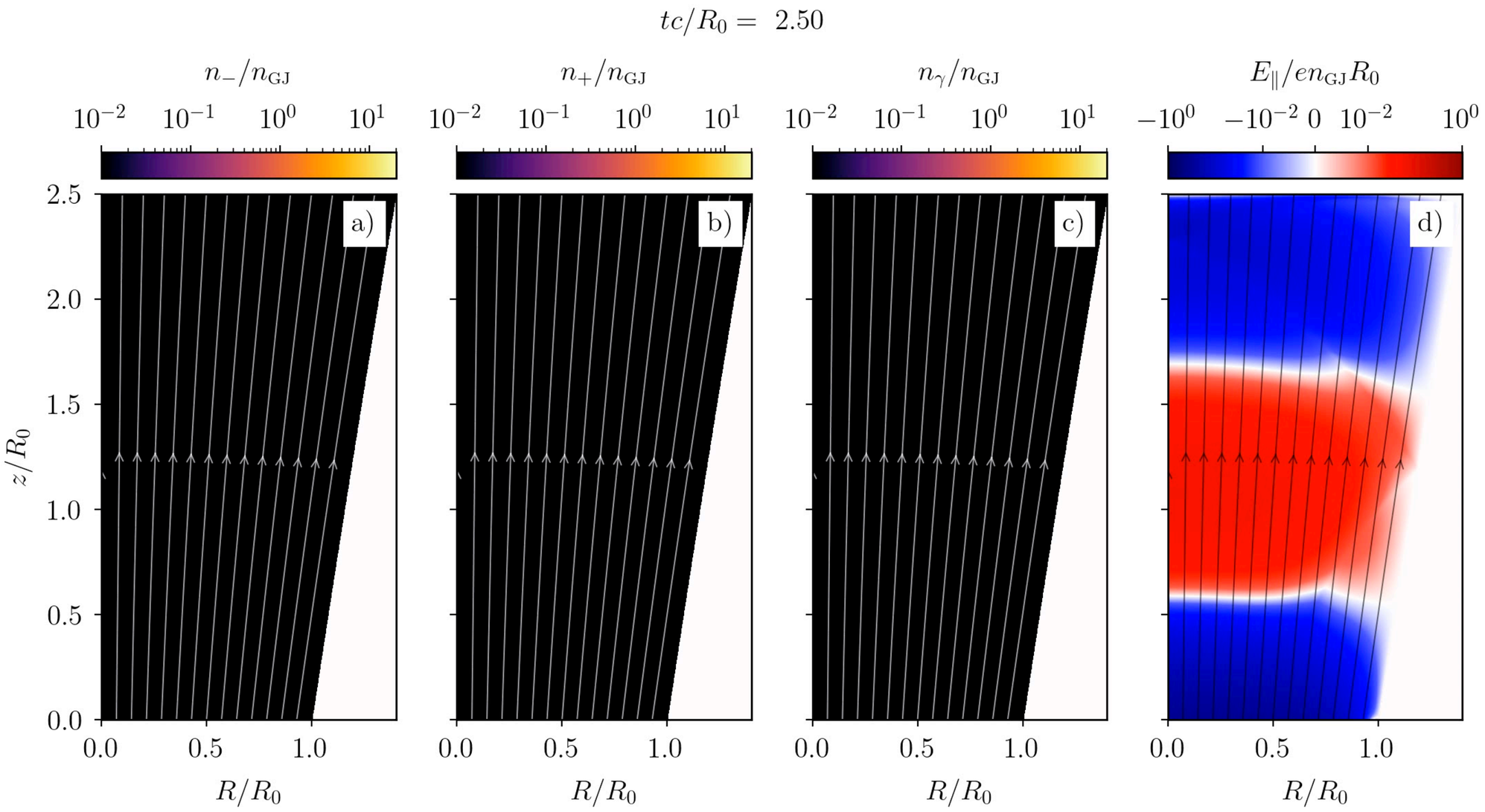
Axions from vacuum gap collapse

Axion spectra

$$\dot{N}_a(\vec{k}) \propto |FT(g_{a\gamma\gamma}\vec{E}\cdot\vec{B})|^2$$

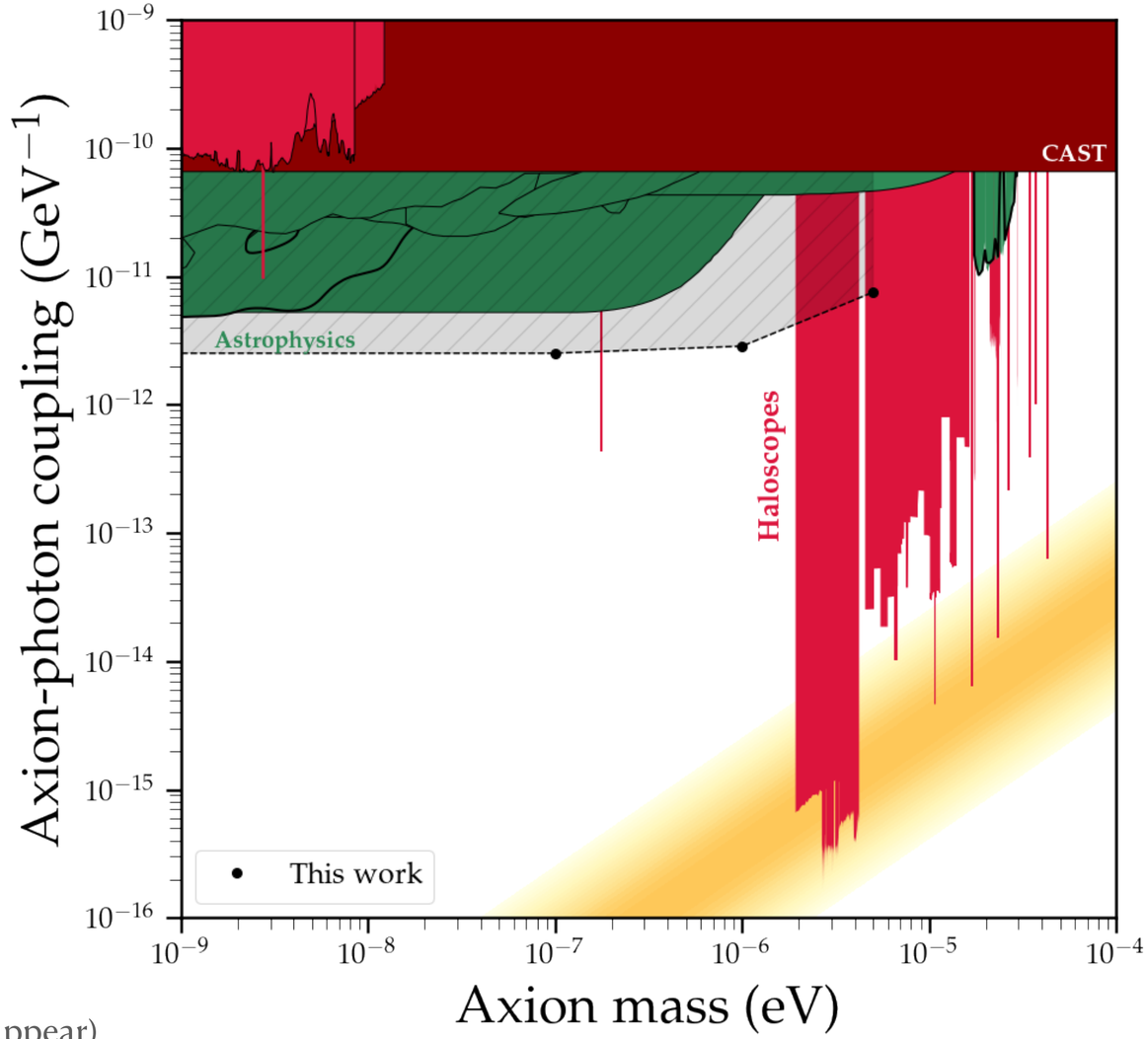


Vacuum gap collapse



Simulations curtesy of F. Cruz and A. Chen

Relativistic axion population



Noordhuis, Prabhu, **SJW**, Chen, Cruz (To appear)
Plot made using cajohare.github.io/AxionLimits/

Conclusions

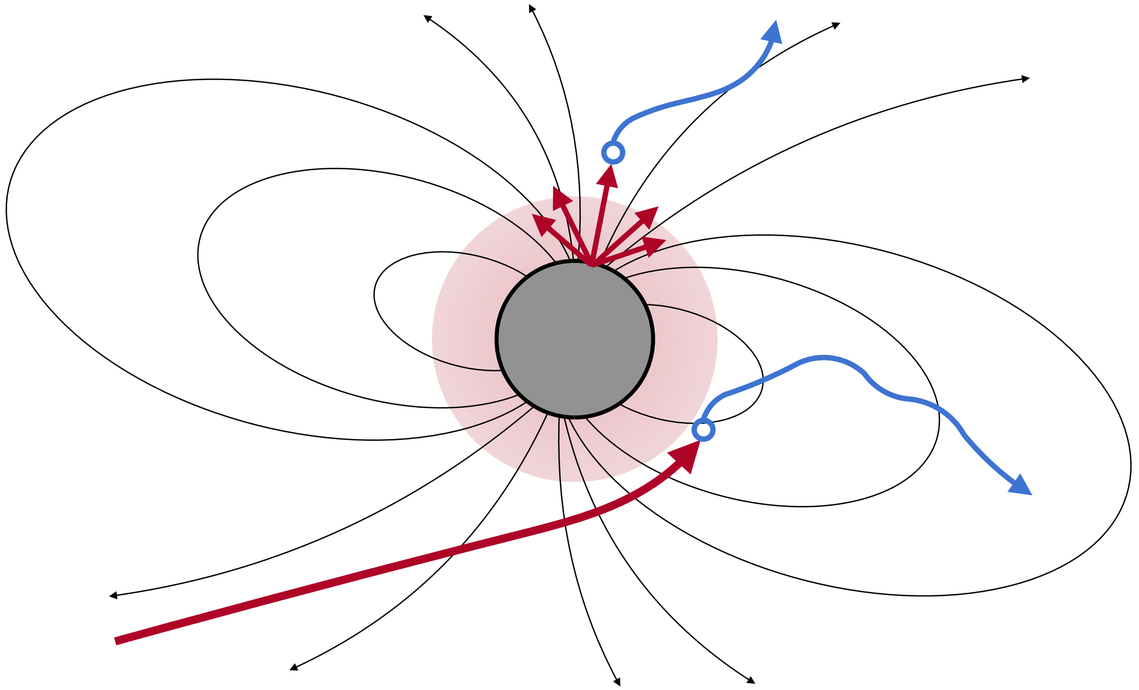
Neutron stars offer powerful and rich laboratory in which to probe axion physics

Axion Dark Matter

- *Look for:* Radio lines from smooth dark matter distribution
- *Look for:* Transient lines from minicluster and axion star encounters (extragalactic / cosmological)

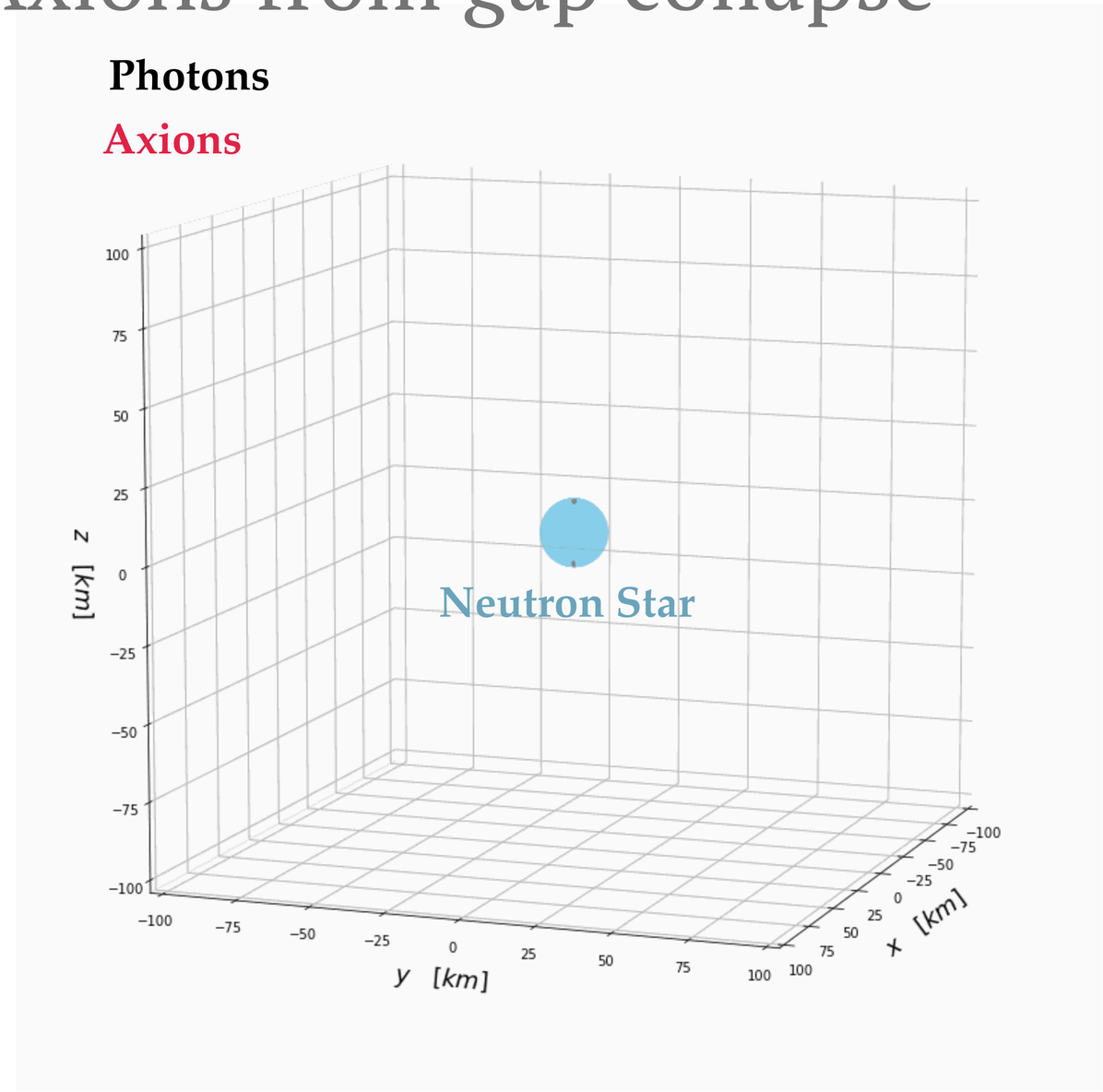
(Axions need not be dark matter)

- *Look for:* smooth radio flux from relativistic axions produced in polar caps
- *Look for:* Narrow lines from dense axion clouds bound to the neutron star



This is a quickly evolving field with enormous discovery potential!

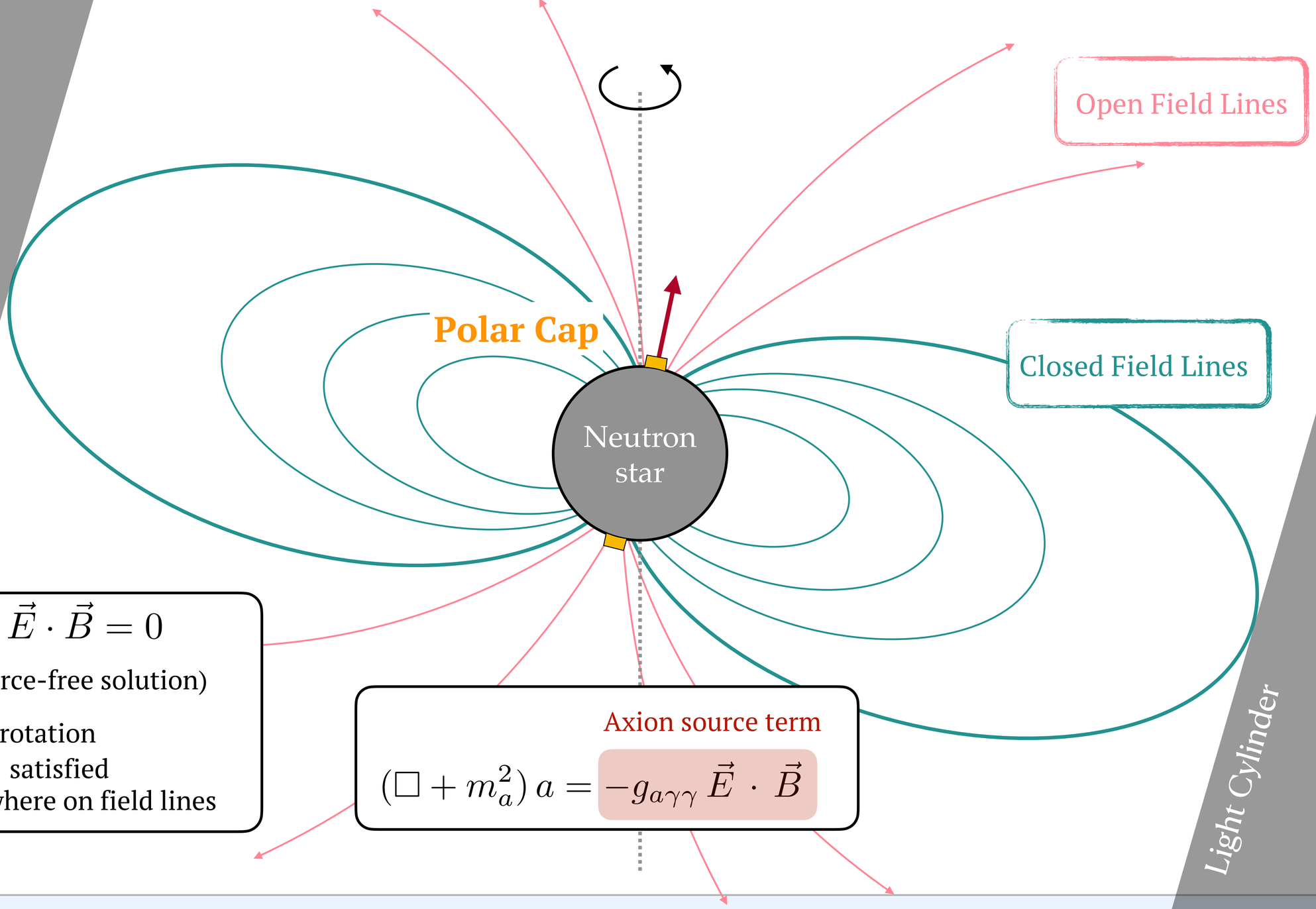
Axions from gap collapse



Resonant Conversion (relativistic limit)

$$\omega_p \sim m_a / \sin\theta_{\hat{k}\cdot\hat{B}}$$

Noordhuis, Prabhu, **SJW**, Chen, Cruz (To appear)



$$\vec{E} \cdot \vec{B} = 0$$

(Force-free solution)

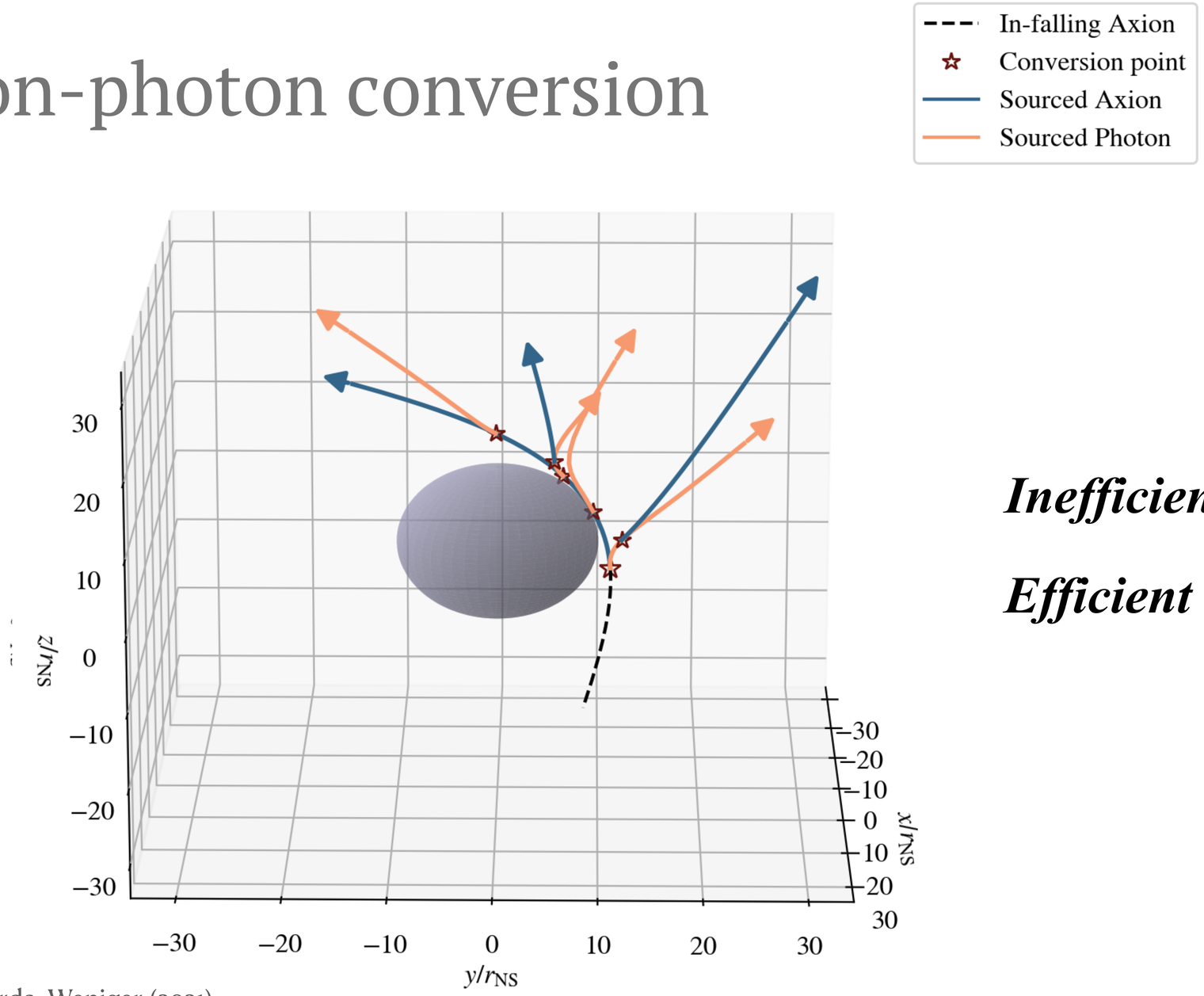
1.) Co-rotation
2.) ρ_{GJ} satisfied everywhere on field lines

Axion source term

$$(\Box + m_a^2)\, a = -g_{a\gamma\gamma}\, \vec{E} \cdot \vec{B}$$

Tracking axion-photon conversion

Step 2: Axion phase space to photon flux



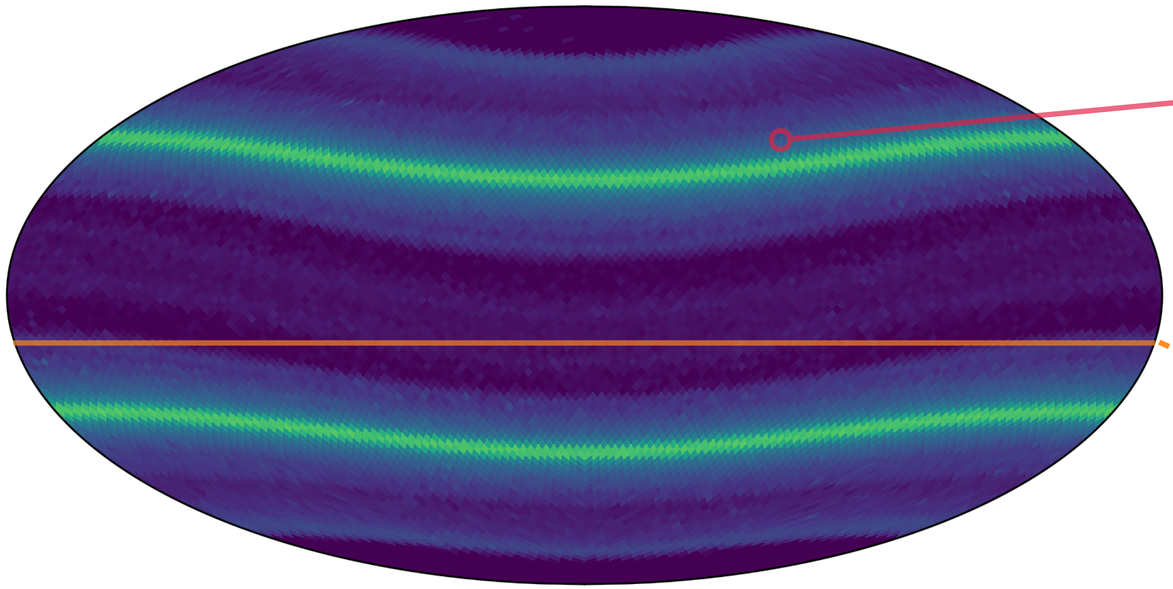
Inefficient conversion

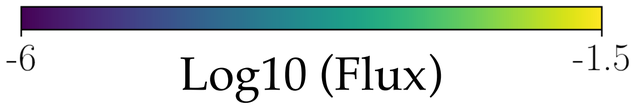
Efficient conversion

Non-adiabatic: **SJW**, Noordhuis, Edwards, Weniger (2021)
Adiabatic: Thjemsland, **SJW**, McDonald (To appear)

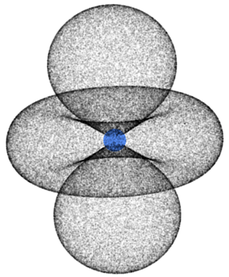
Radio signal from isolated neutron star

Projected sky flux as viewed from neutron star

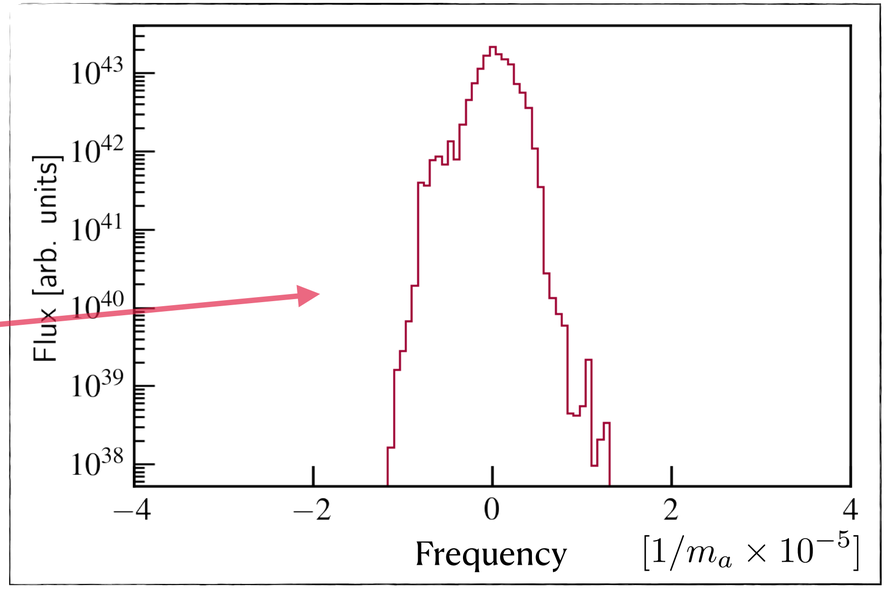


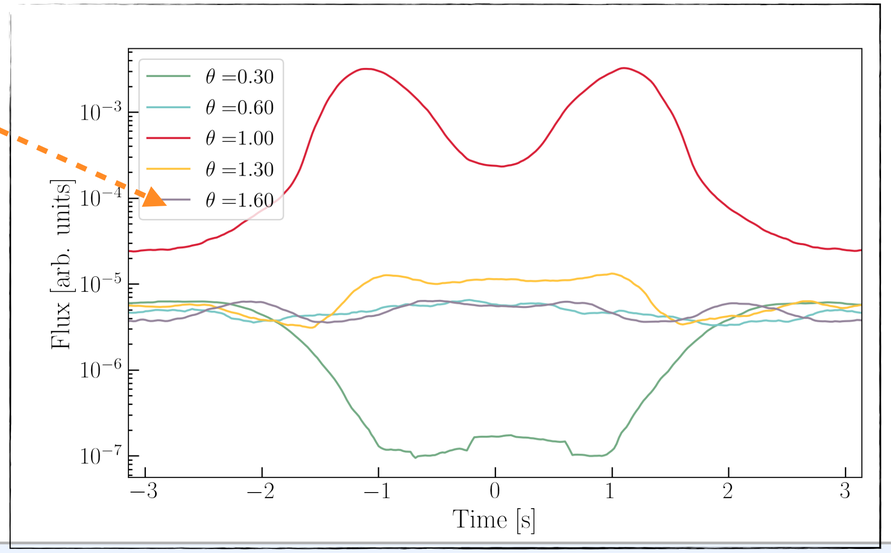


[Arb. Units]



SJW, Noordhuis, Edwards, Weniger (2021)





Neutron star population modeling

What about the properties of these neutron stars?

We want conditional probability: $p(P, B_0, \theta_m \,|\, t_{age})$

Well-measured quantities:

- Rotational period P
- Spin-down rate $\dot{P}$
- $B_0 \propto \sqrt{P\dot{P}}$

Values today…

- $\theta_m(t_{\text{birth}})$ random, and evolution known

Adopt initial distributions, simulate evolutionary tracks, and fit to the distributions we observe today

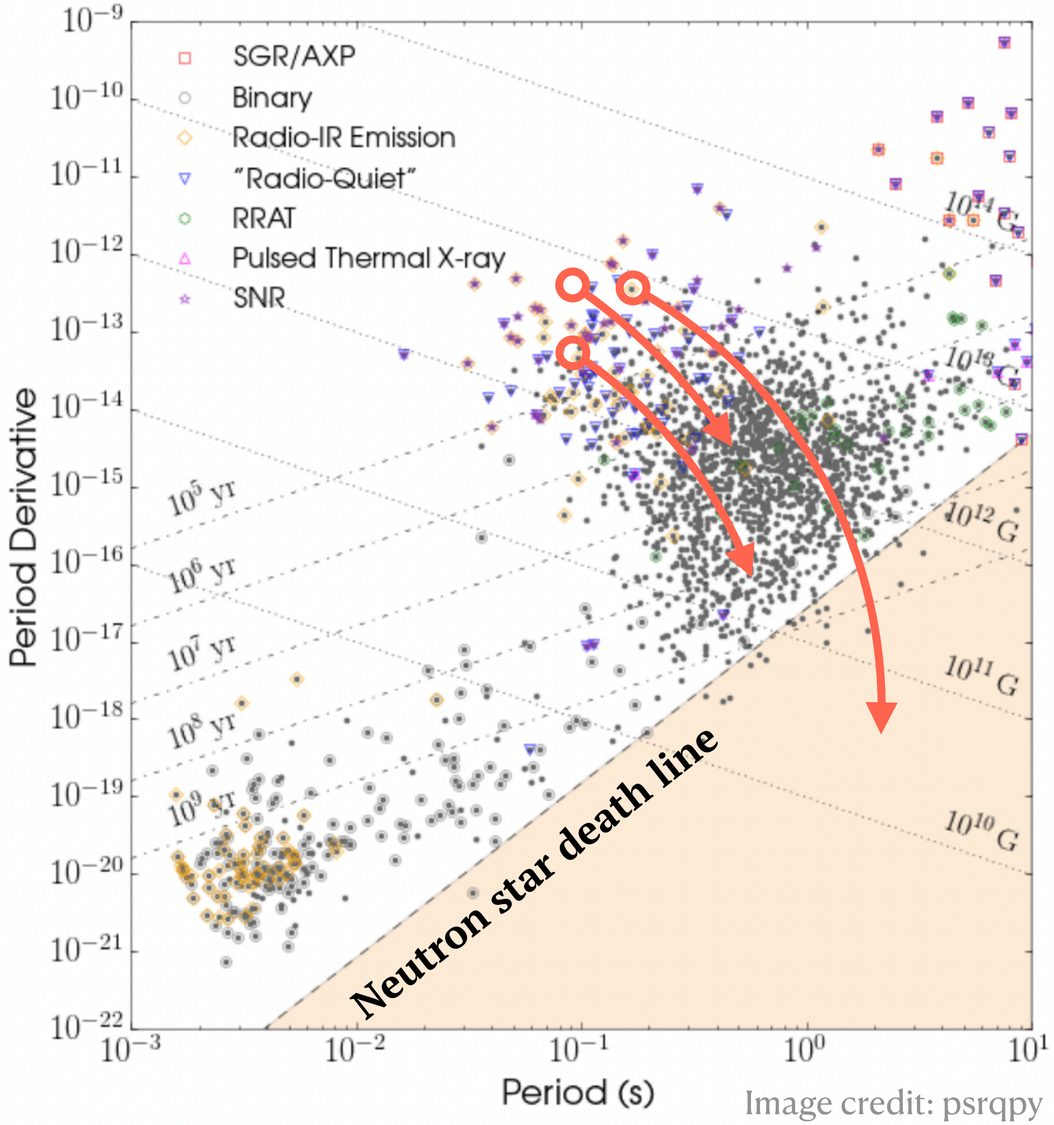


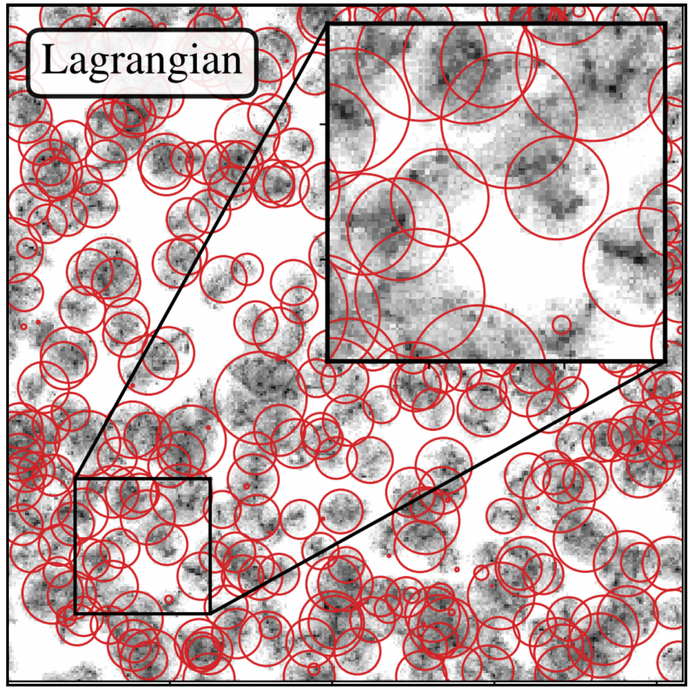
Image credit: psrqpy

Philippov, Tchekhovskoy, Li (2014)
Gullón et al (2014)

Transient radio lines from axion miniclusters

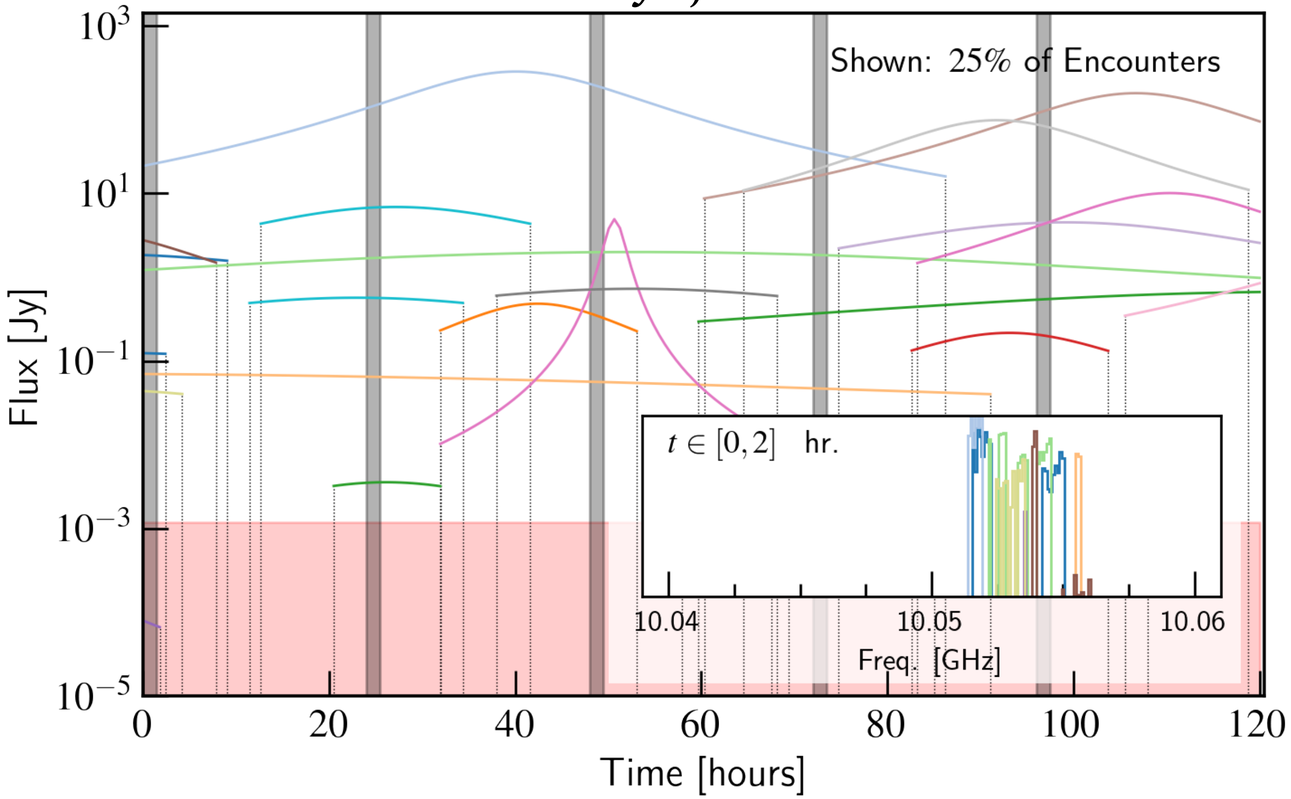
Rare encounters of miniclusters/stars with neutron stars generate transient radio lines

Density field at matter-radiation equality



Ellis et al (2022)

The taxonomy of axion transients



SJW, Salinas, Baum, Lawson, Millar, Marsh, Weniger (To appear)
Agrawal, Johsnon, Edwards, Kavanaguh, Marsh, Ransom, Shroyer, Visinelli, **SJW**, Weniger (Data analysis ongoing)

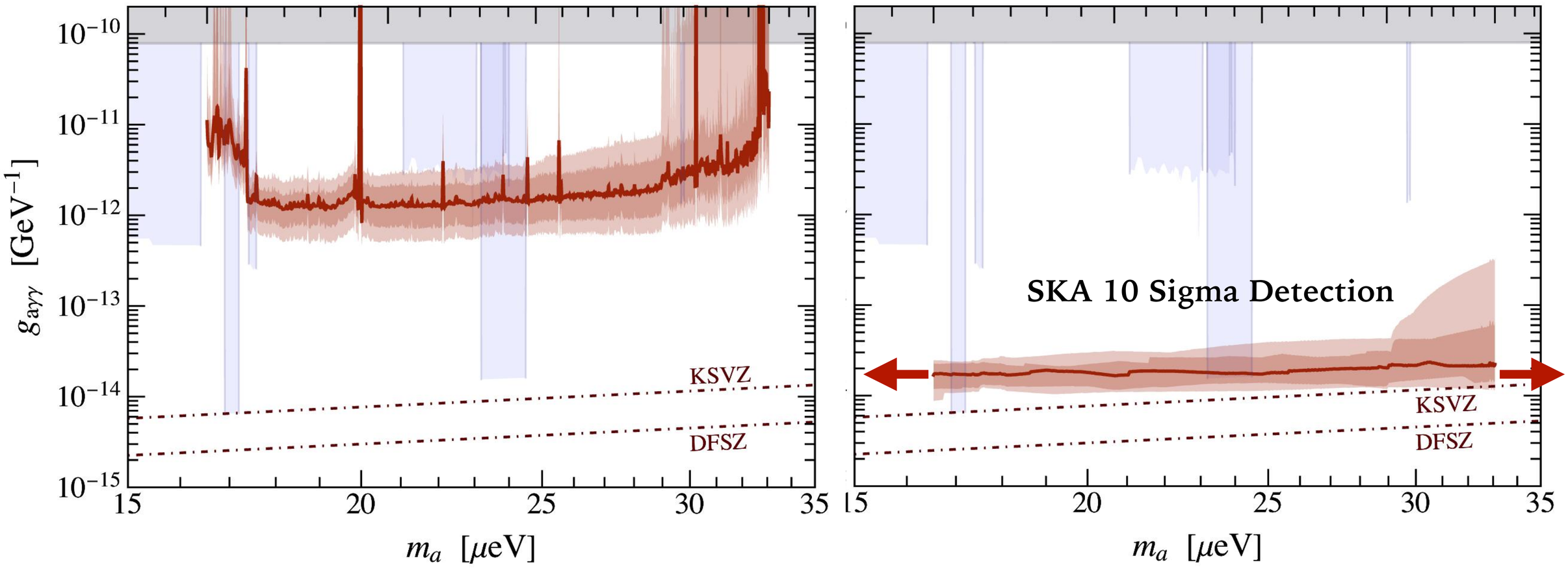
Future prospects

Improvement needed from theory…

(e.g. Axion-photon mixing)

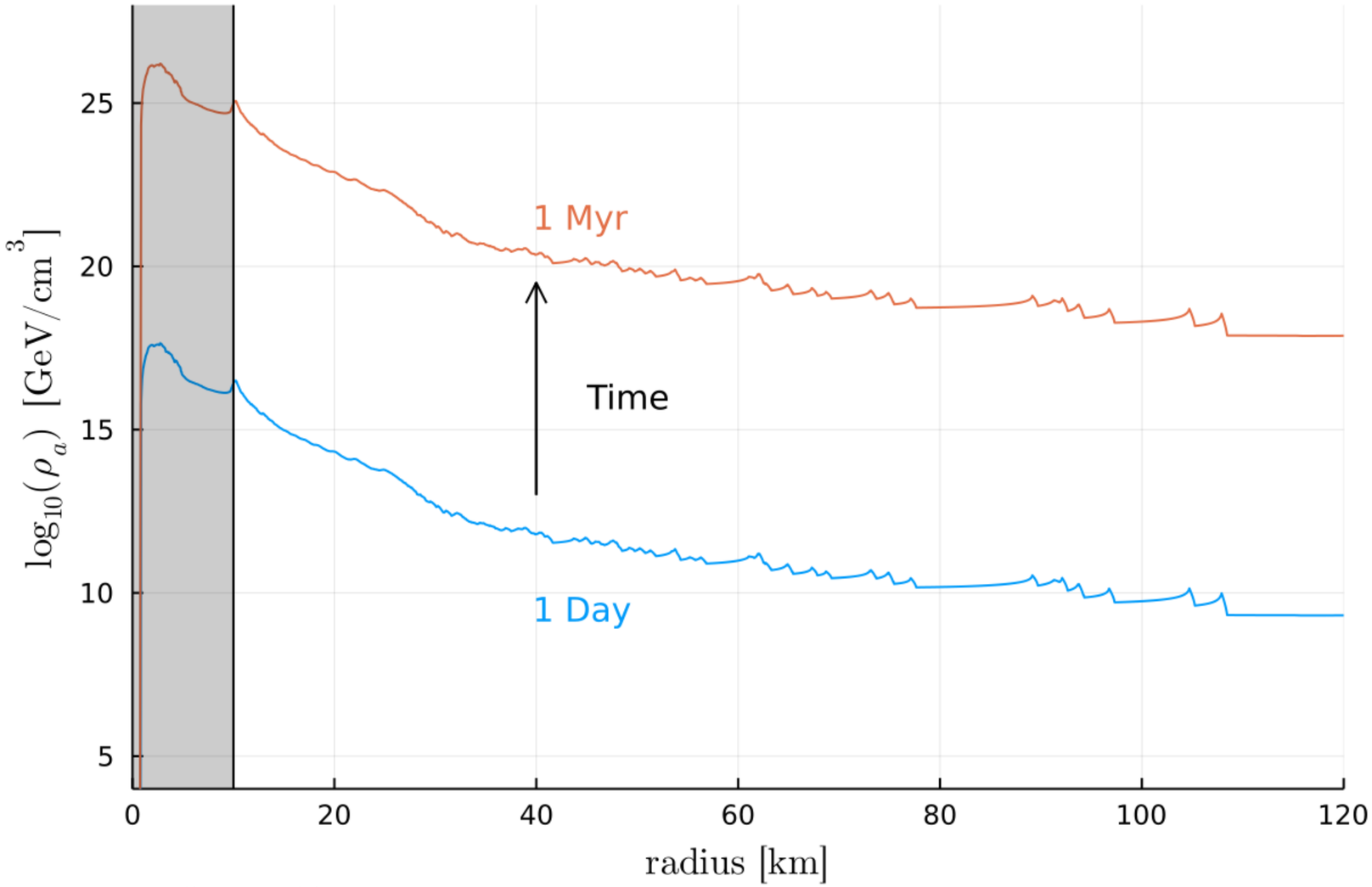
+ experiment…

(e.g. better telescopes, time domain information)

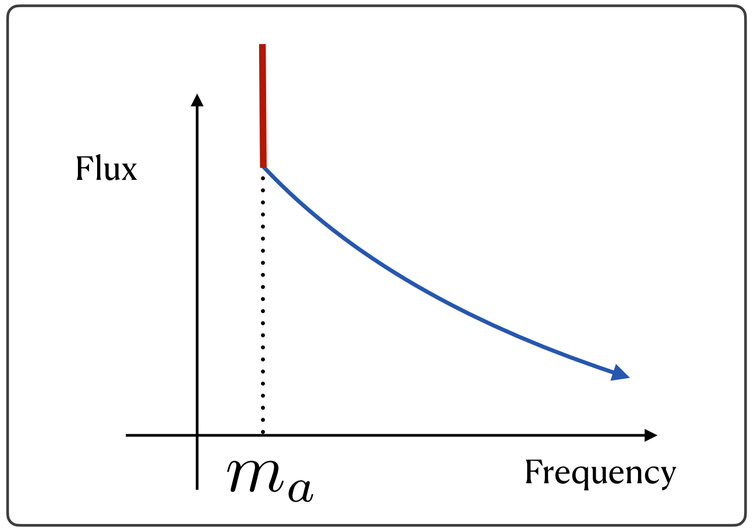


Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Bound state profiles



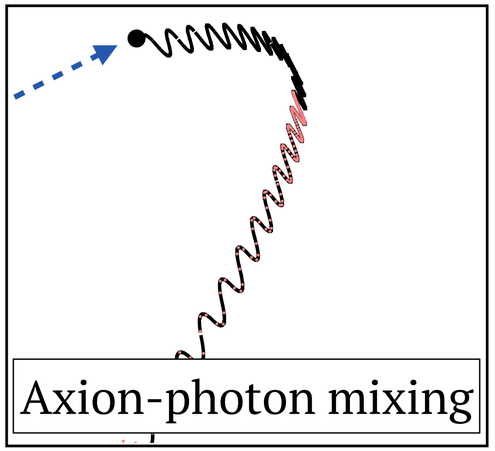
Noordhuis, Prabhu, **SJW**(To appear)



Quenching / back-reaction opens novel observables

Future outlook

Uncertainties & Systematics



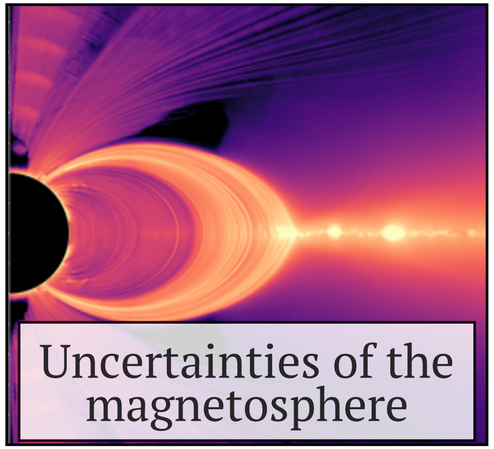
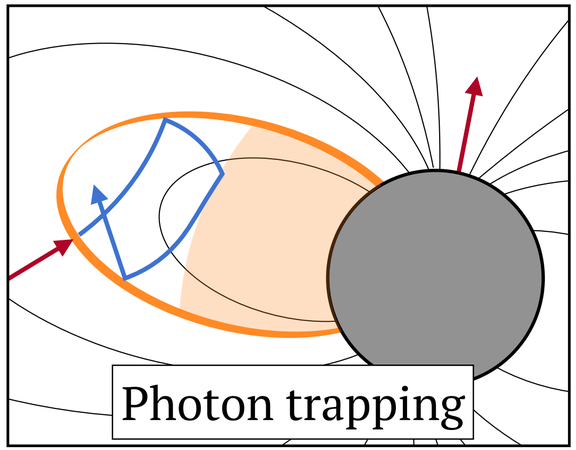
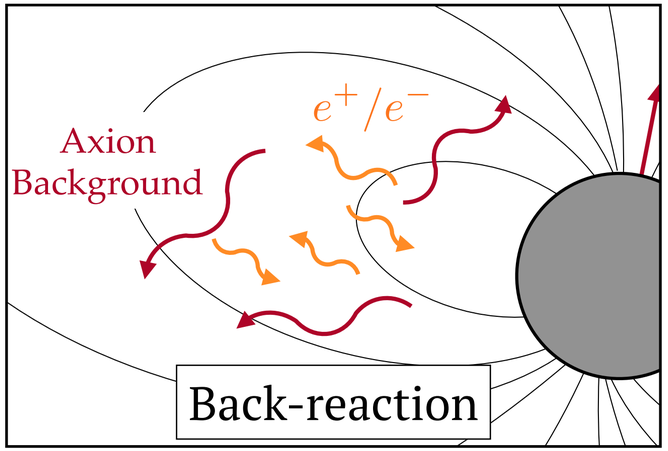
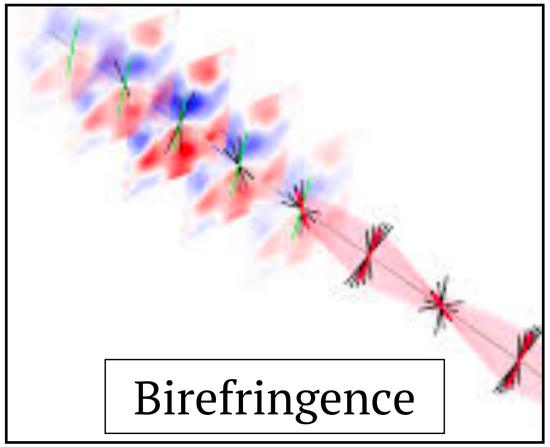


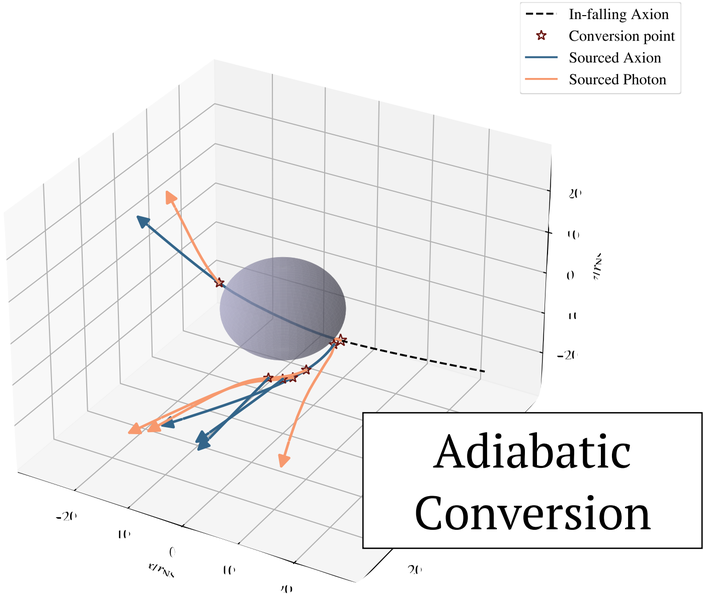
Image credit:
Bransgrove & Beloborodov

Novel Observables

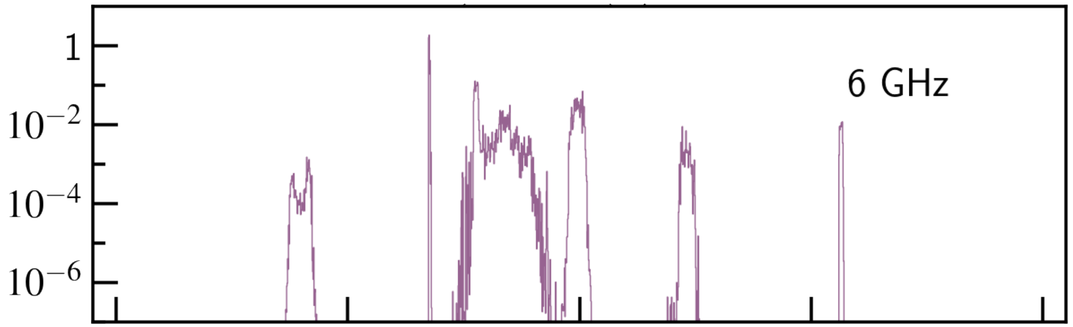




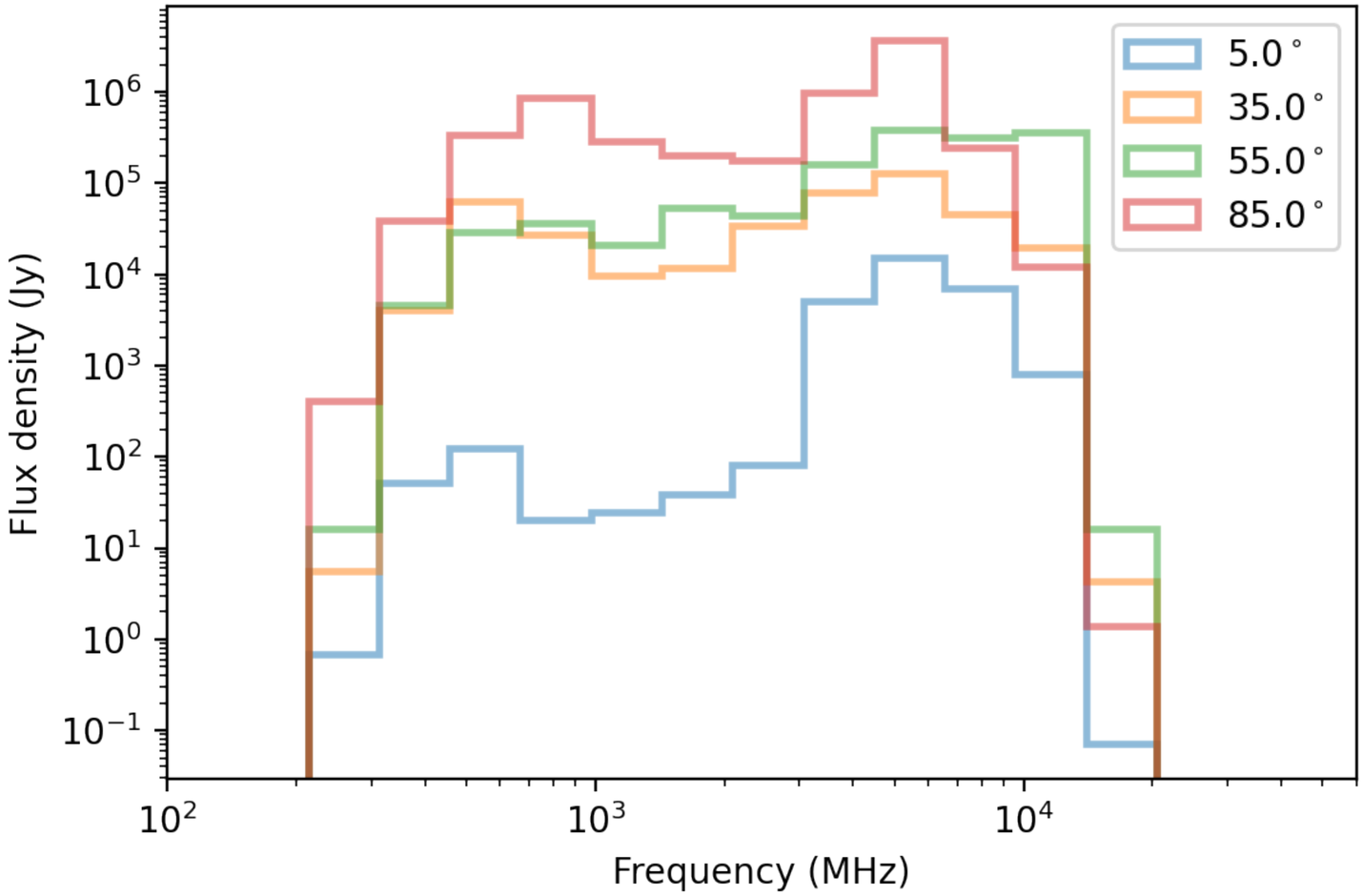




More Data



Currently analyzing: MWA, GBT
Future: FAST, Meerkat, HERA, SKA


5.0°
35.0°
55.0°
85.0°
Flux density (Jy)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{2}
10^{3}
10^{4}
Frequency (MHz)

The strong CP problem

Why does QCD seem to conserve charge-parity (CP) symmetry?

CP violating term in QCD Lagrangian:

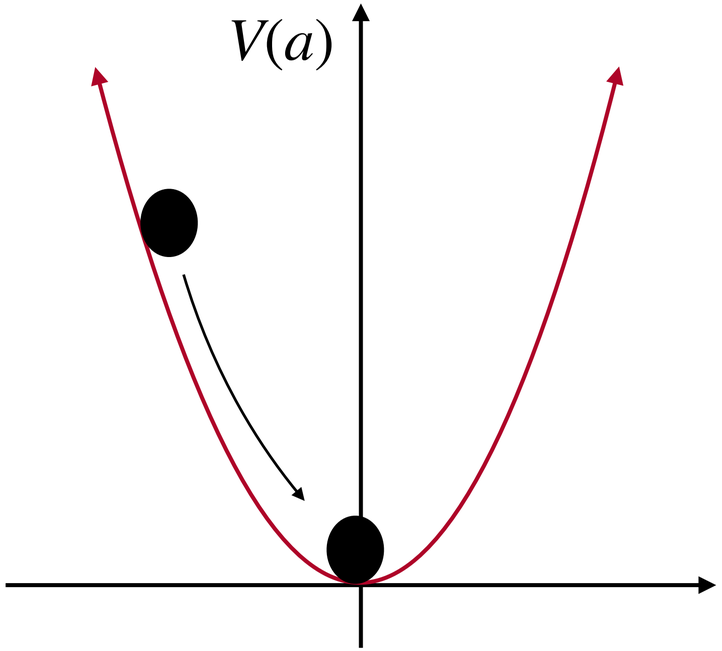
$$\mathcal{L}_{CPV} \supset \overline{\theta} \, \frac{g_s^2}{32\pi^2} \, G \, \tilde{G}$$

Neutron electric dipole moment (eDM) $\propto \overline{\theta}$

Current limit: $\overline{\theta} \leq 5 \times 10^{-11}$ Abel et al (2020)

A solution to the strong CP problem: axions

Solution: Introduce goldstone boson a with parameter f_a to make theta term dynamical



Neutron eDM ~ 0

$$\mathcal{L}_\theta = -\left(\overline{\theta} + \frac{a}{f_a}\right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

QCD generates a potential for the axion:

$$V(a) \sim \Lambda_{QCD}^4 \left(\overline{\theta} + \frac{a}{f_a}\right)^2$$

Peccei & Quinn (1977), Weinberg (1978), Wilczek (1978)

Properties of the QCD axion

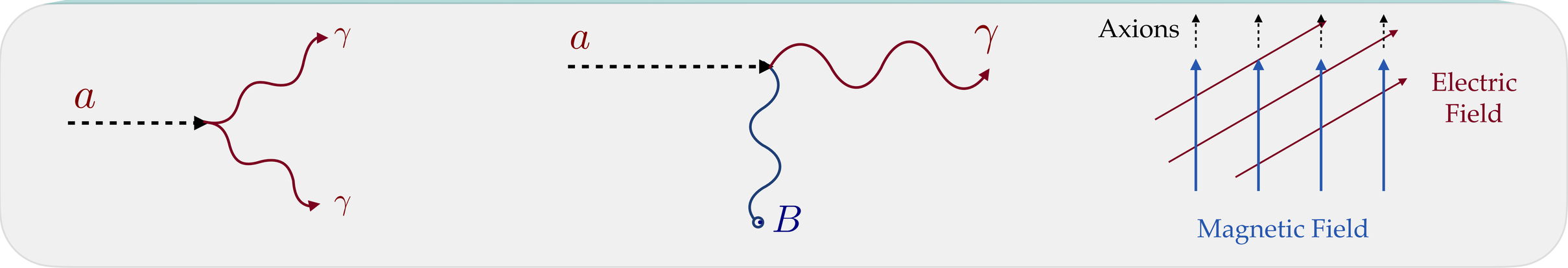
Axion Mass: $$m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$$

Axion Couplings: $$\mathcal{L} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \sum_f \frac{1}{f_a}\partial_\mu a\, \bar{f}\gamma^\mu\gamma_5 f$$

(Slight model dependence in couplings)

(Term for Strong CP Problem) (Electro-Mag) (Fermions)

$$a\,\vec{E}\cdot\vec{B}$$



Axion-like particles (ALPs)

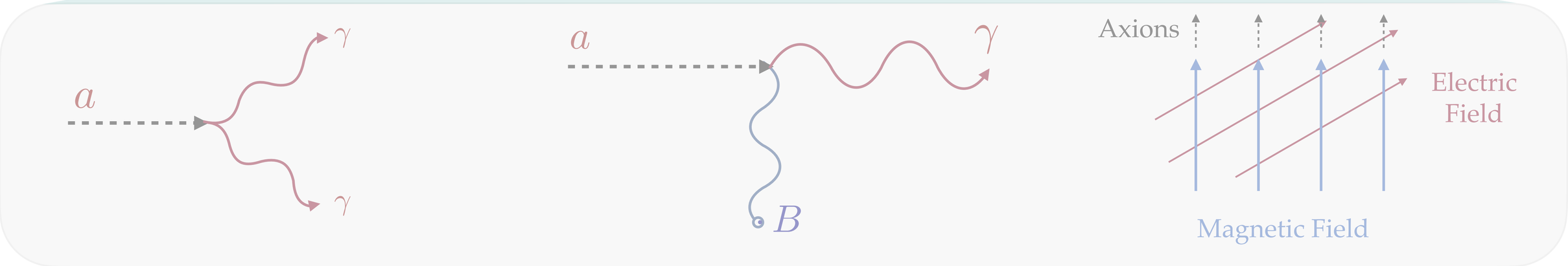
ALPs do not solve strong CP problem, but naturally emerge in String Theory from compactification

Axion Couplings: $\mathcal{L} \supset$ No Coupling $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ $\cdots$ + other terms

(Electro-Mag)

Axion mass m_a and decay constant f_a uncorrelated

$a\,\vec{E}\cdot\vec{B}$

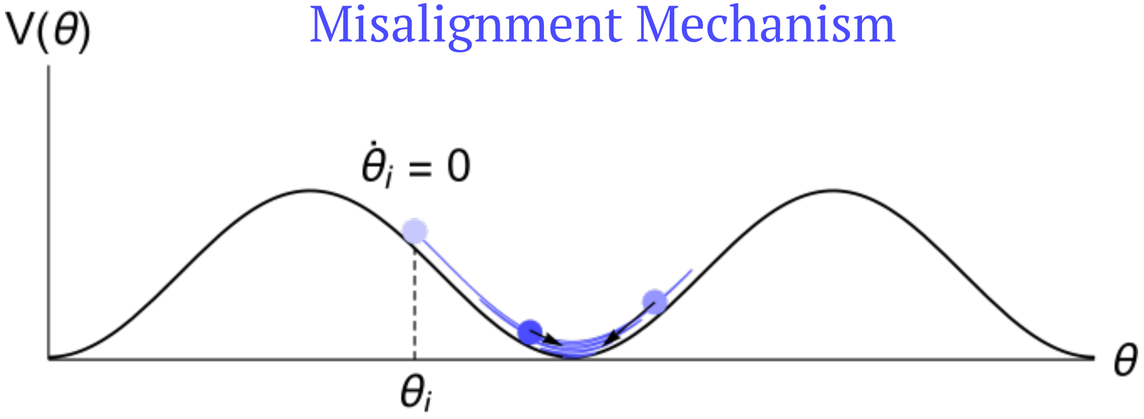


Axion dark matter

Requirements for dark matter:

- Cosmologically stable ⟶ *True for all light (viable) axions*
- Production mechanism *(cold / pressureless)*

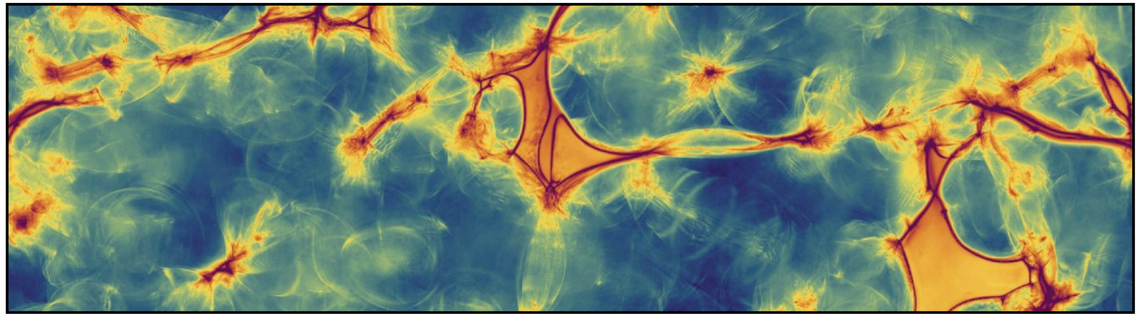
Misalignment Mechanism



$$\Omega_{cdm} \sim 0.4 \left(\frac{\theta_i}{\pi/2}\right)^2 \left(\frac{m_a}{10^{-17}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)^2$$

See e.g. Turner (1986)

Decays of Topological Defects



(Defects only produced when $T_{\not{PQ}} \ll T_{Reheat}$*)*

- $\Omega_{cdm} \sim$??
- Seeds of axion miniclusters

See e.g. Buschmann et al (2021), Gorghetto et al (2020)

Photon production

Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2021)

Tjemsland, **SJW**, McDonald (To appear)

Non-adiabatic limit
(Inefficient conversion)

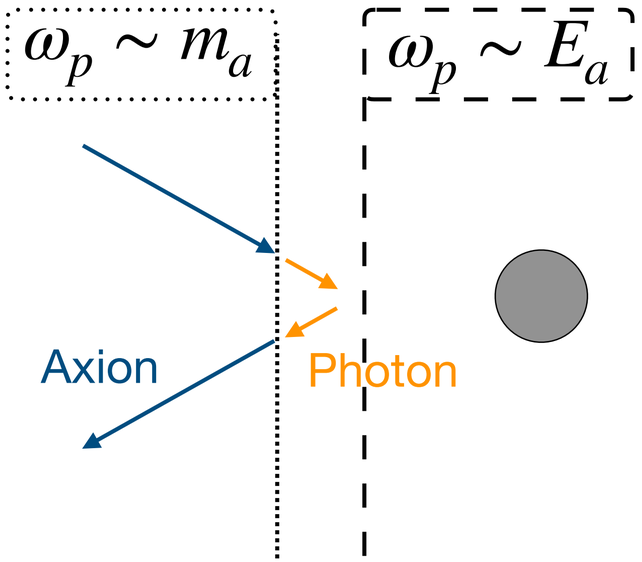
$p_{a\to a} \sim 1$

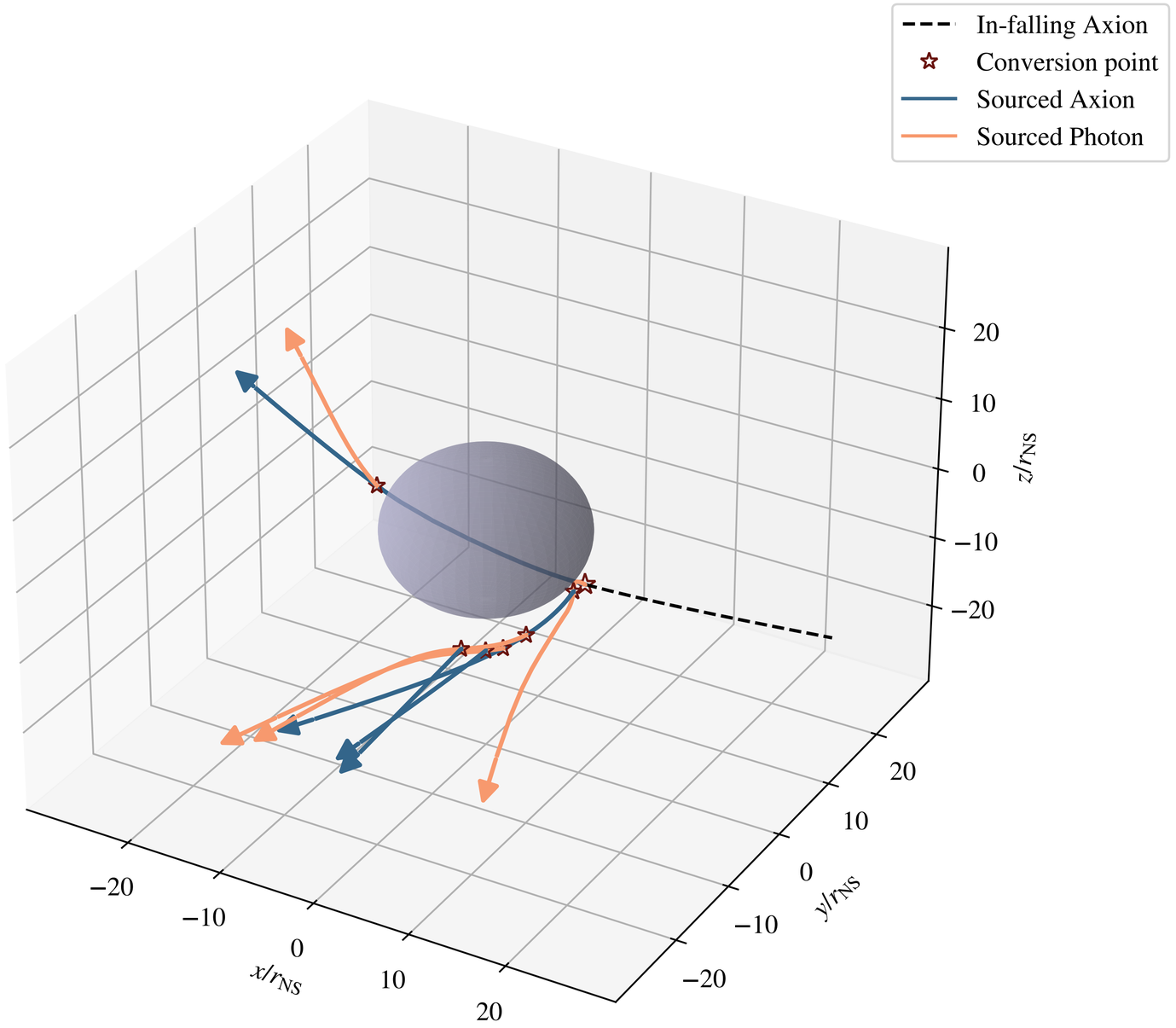
$p_{a\to\gamma} \sim \epsilon$

Adiabatic limit:
(Efficient conversion)

$p_{a\to a} \sim e^{-x}, \quad x \gg 1$

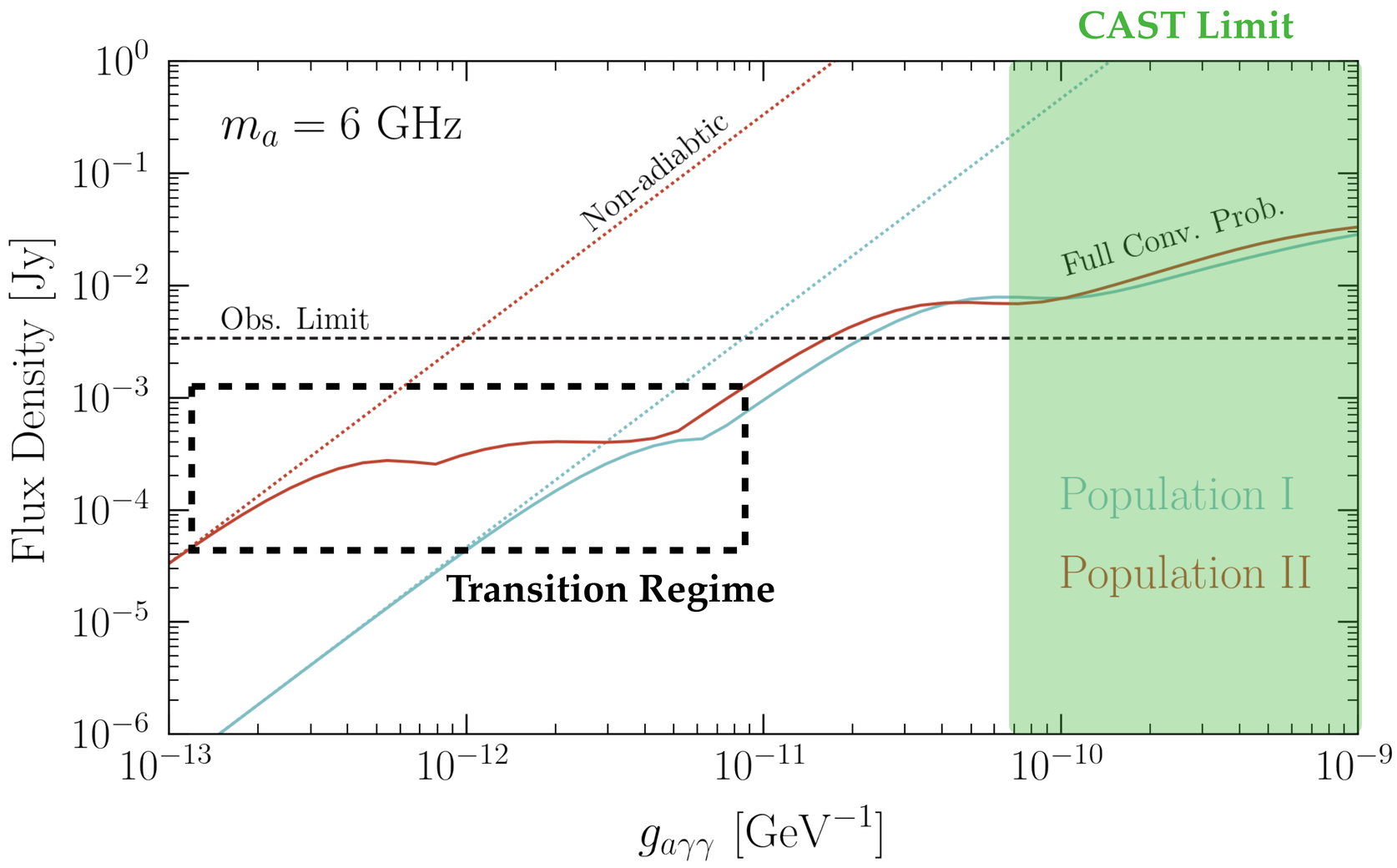
$p_{a\to\gamma} \sim 1$





Thjemsland, **SJW**, McDonald (To appear)

Adiabatic Conversion

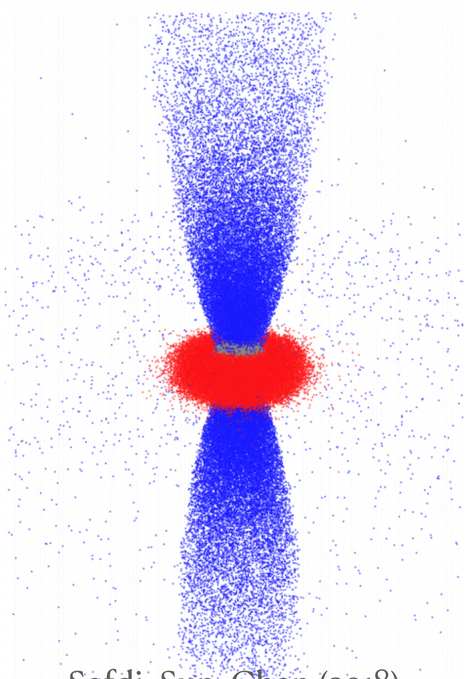


Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Plasma Distribution in Magnetospheres

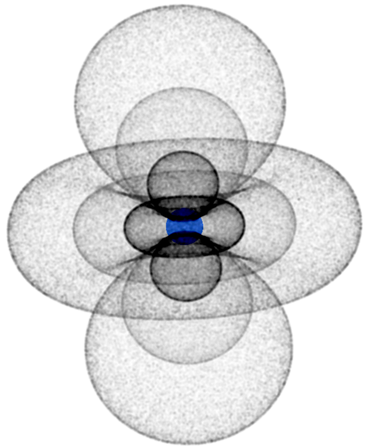
Electrosphere Model

(GJ-ish at small distances)

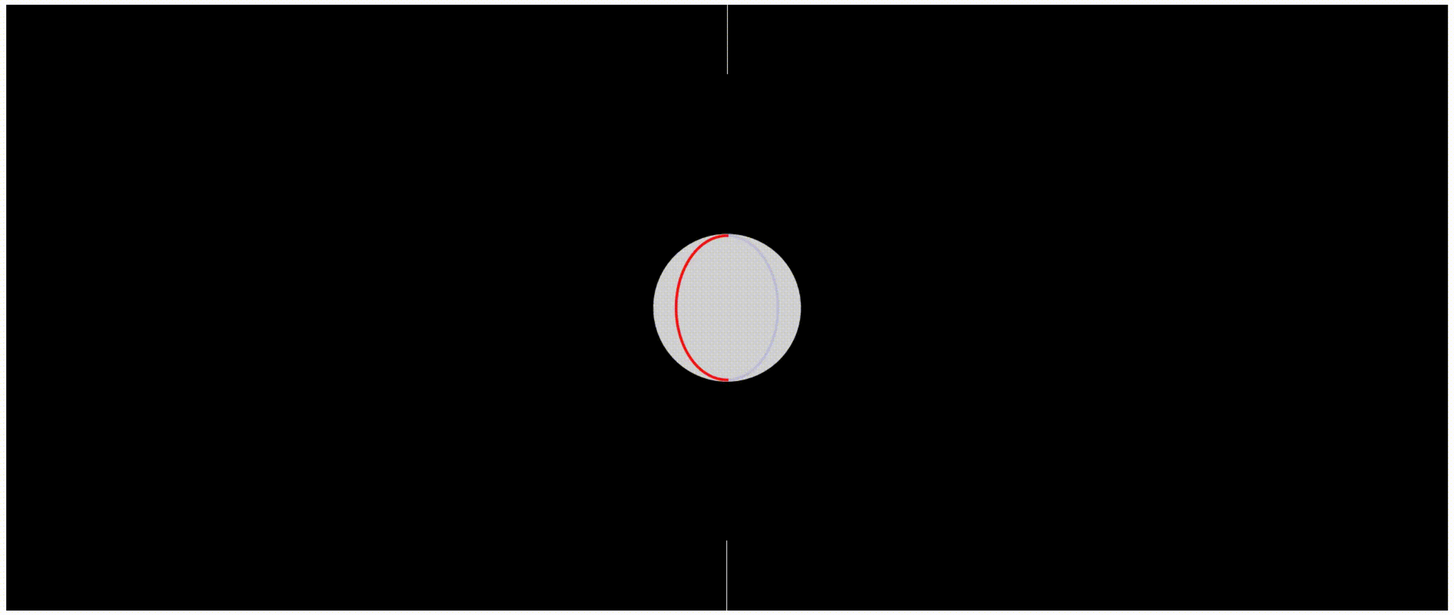


Safdi, Sun, Chen (2018)

Goldreich-Julian



Weak Pular (particle-in-cell simulations)



Credit: Rui Hu, Pigeon code, https://github.com/hoorayphyer/Pigeon

(Dead Neutron Stars) → Particle production efficiency / activity → (Active Pulsars)

← Age

Magnetosphere Axisymmetric Rotator

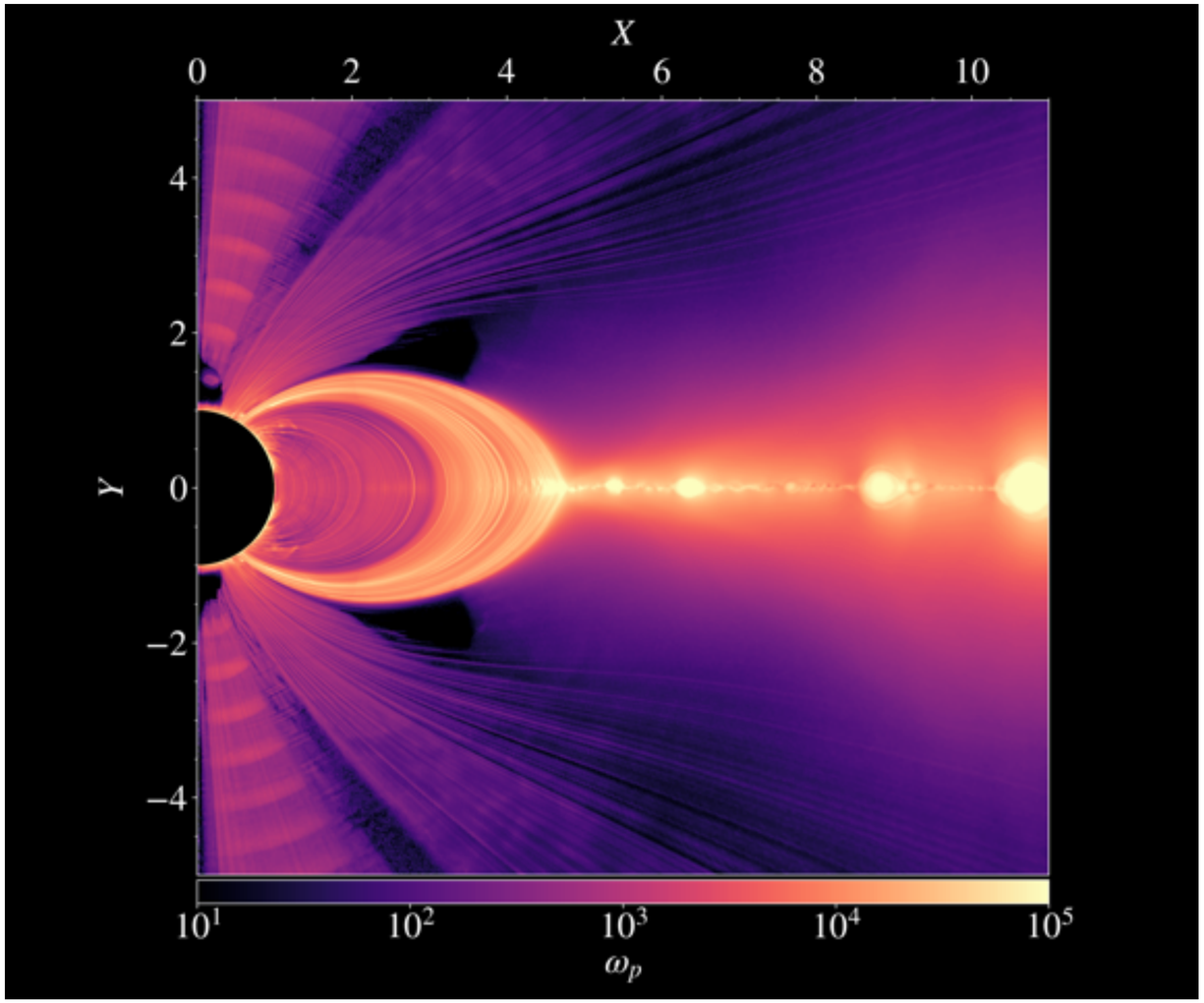
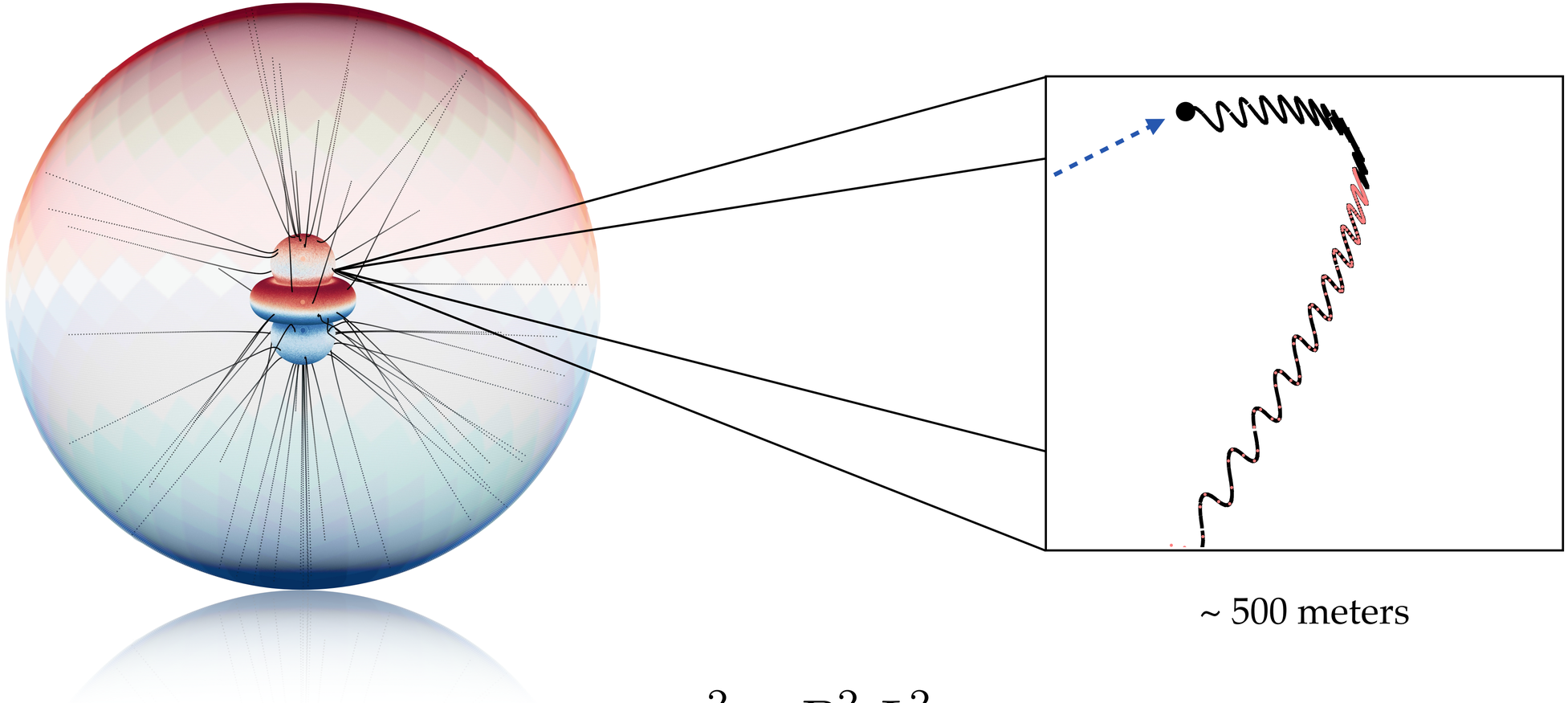


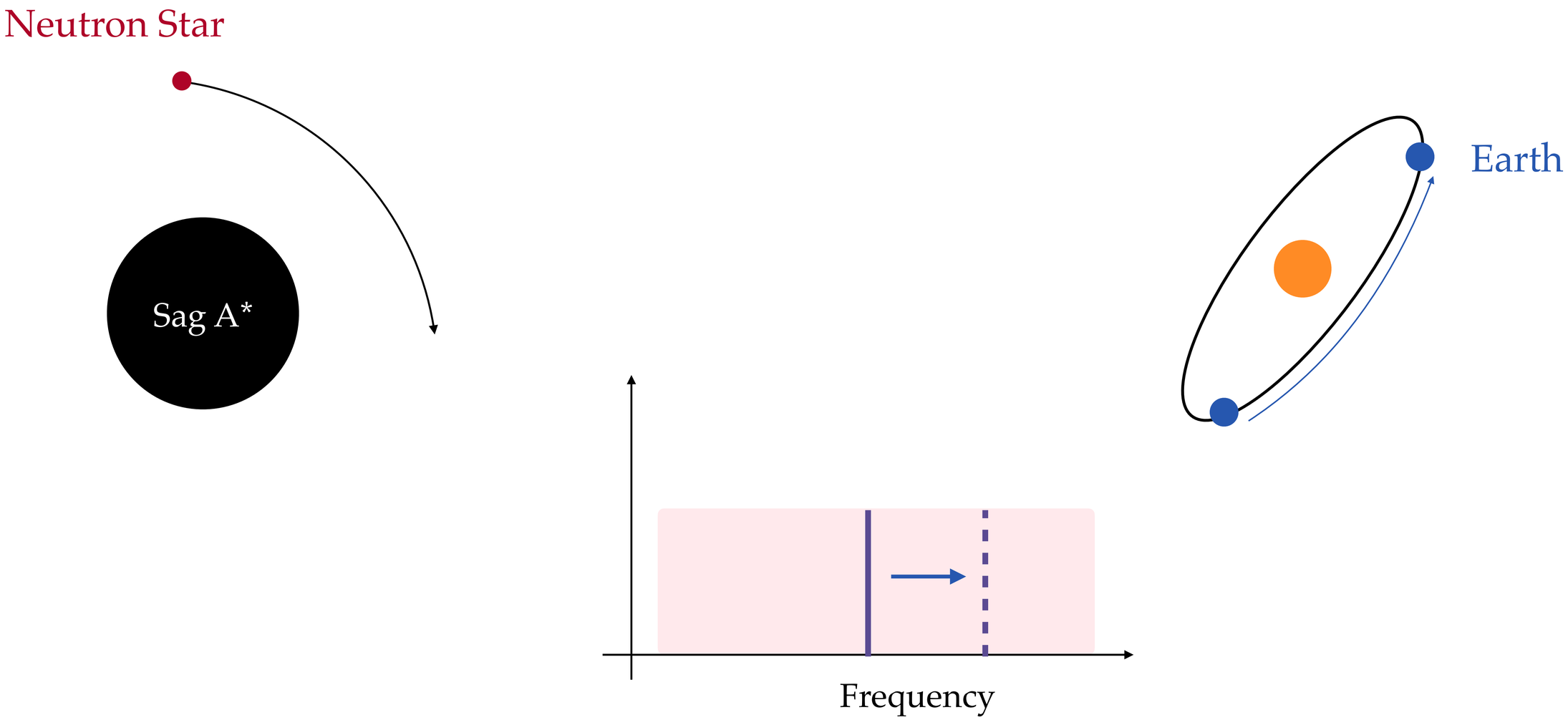
Image credit: Bransgrove & Beloborodov



$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 \, B^2 \, L^2$$

Analytic estimates of L ~ 100 m

The Problem of Time…



Neutron star population modeling

How are they distributed?

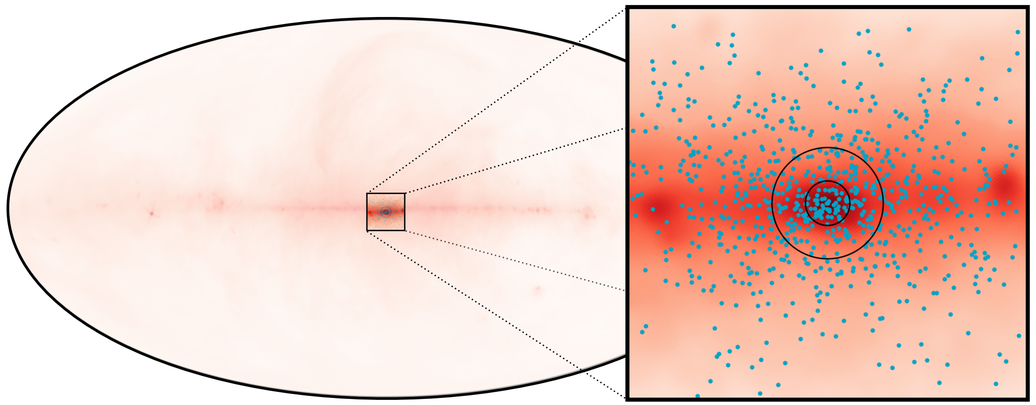
Young population:

- Stellar distribution

Old population:

- Numerical simulations of the dynamics, in-fall, and capture

Generozov et al (2018)



How many are there?

Young population:

- Star formation + stellar mass distribution

Old population:

- Globular cluster infall, mass segregation, *in situ* star formation

How do we view each NS?

- Marginalize

What are their properties?

- Use models to spin-down each pulsar and decay magnetic field
- Fit initial distributions to observed populations

Radio Telescope Sensitivity

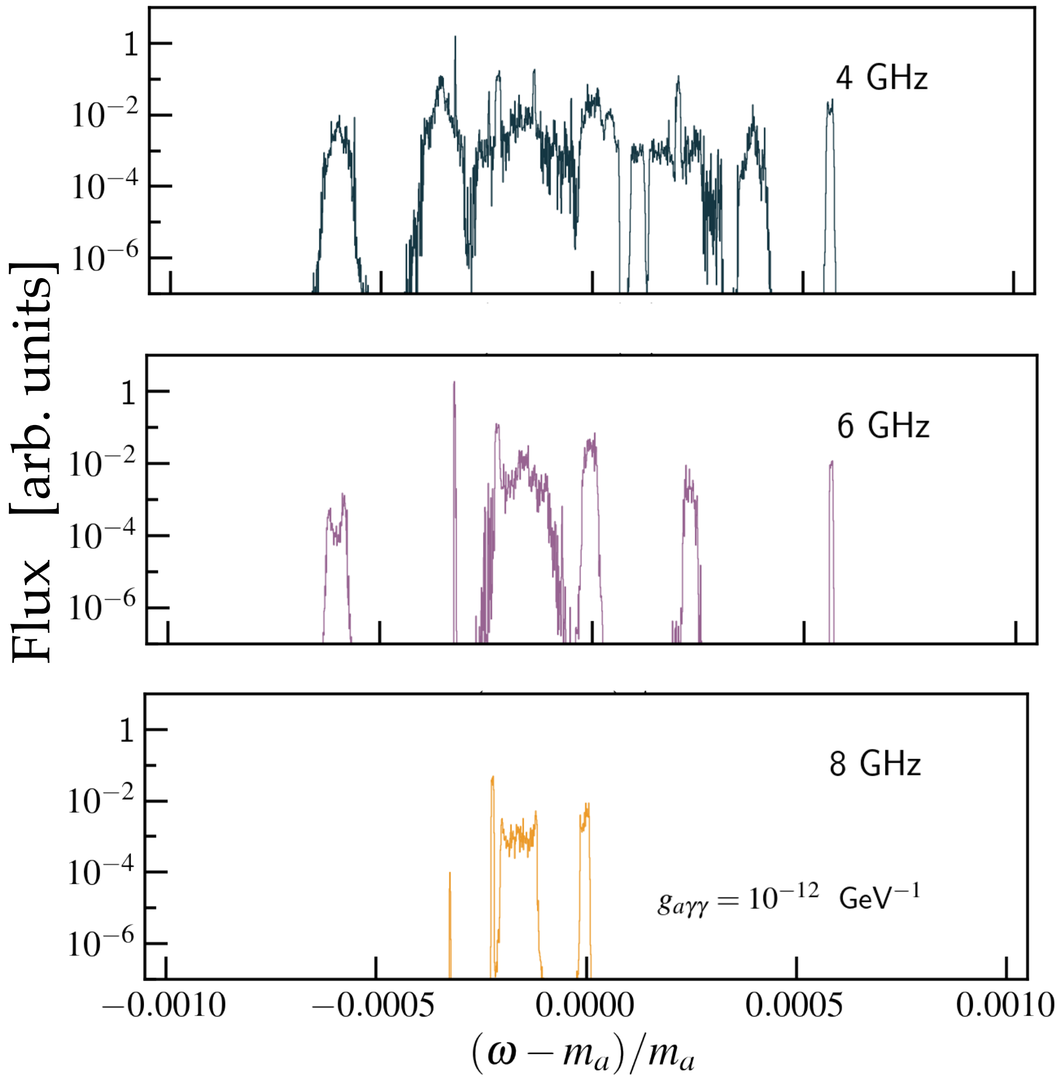
Radiometer Equation:

$$S/N \propto \sqrt{\Delta t / \Delta f}$$

Idealized Searches:

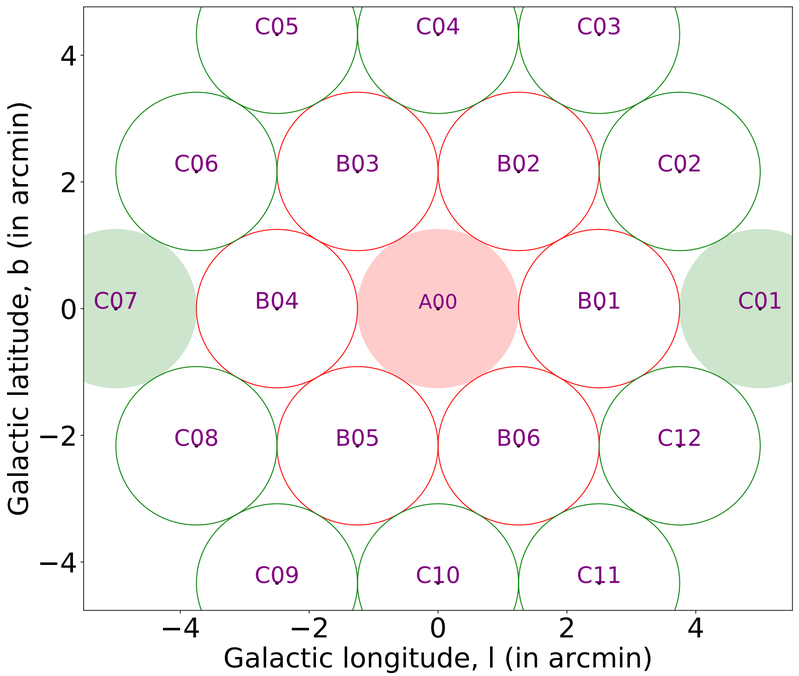
- More Time
- Narrower Line

Tradeoff between looking for brightest neutron star and exploiting the entirety of the signal



GBT Observations

Start MJD	Fields	Calibrator	Test pulsars	Total On Source Time (min)
58702.20313657	A00,C01,C07	3C295	B0355+54, J1744–1134	40
58704.99252314	A00,B01–B06,C01–C12	3C286	B1133+16, J1744–1134	285
58733.98109953	A00	3C286	B2021+51	28
58734.95761574	A00	–	–	60
58737.95781249	A00	3C286	B2021+51	258

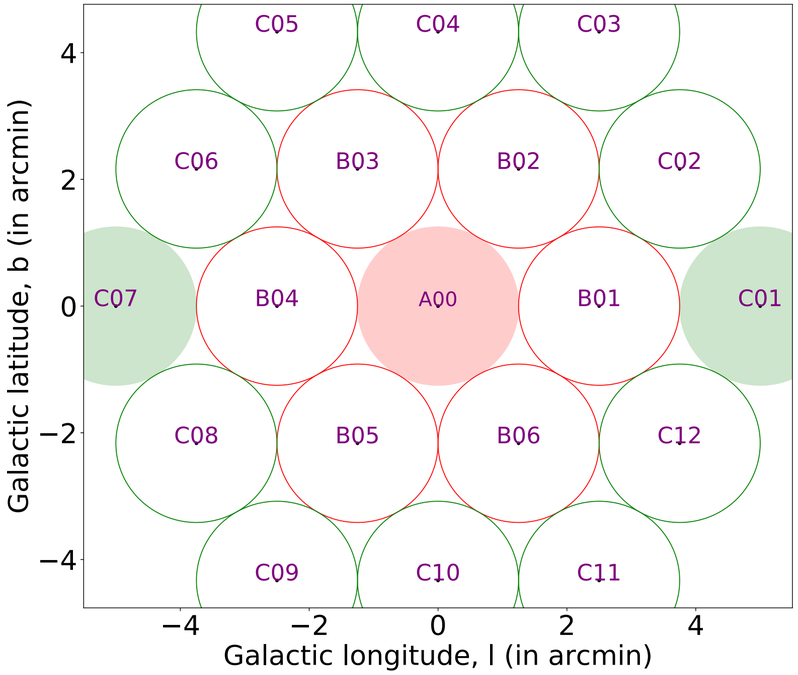


GBT Observations

Frequency drift

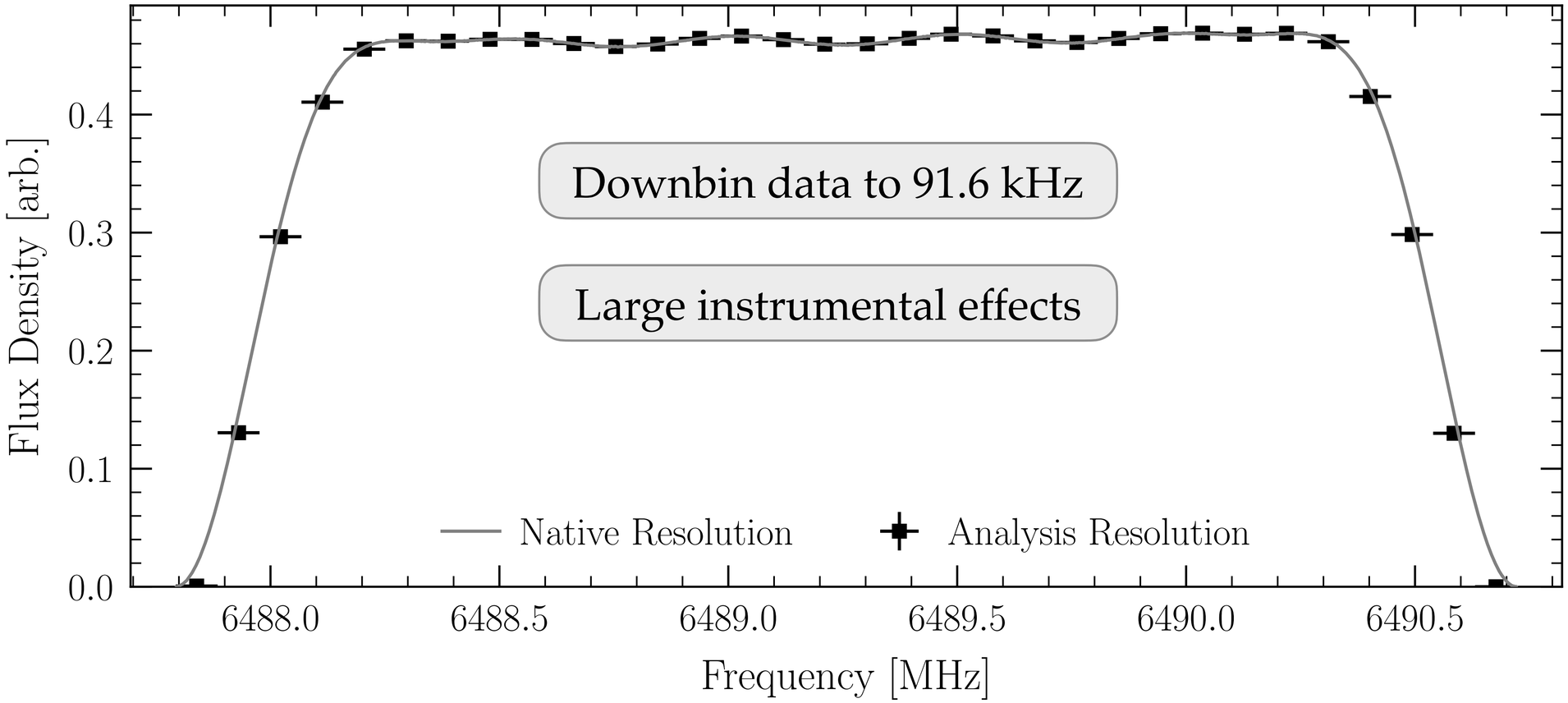
No controls

Start MJD	Fields	Calibrator	Test pulsars	Total On Source Time (min)
58702.20313657	A00,C01,C07	3C295	B0355+54, J1744–1134	40
58704.99252314	A00,B01–B06,C01–C12	3C286	B1133+16, J1744–1134	285
58733.98109953	A00	3C286	B2021+51	28
58734.95761574	A00	–	–	60
58737.95781249	A00	3C286	B2021+51	258



GBT Observations

Single "coarse channel"



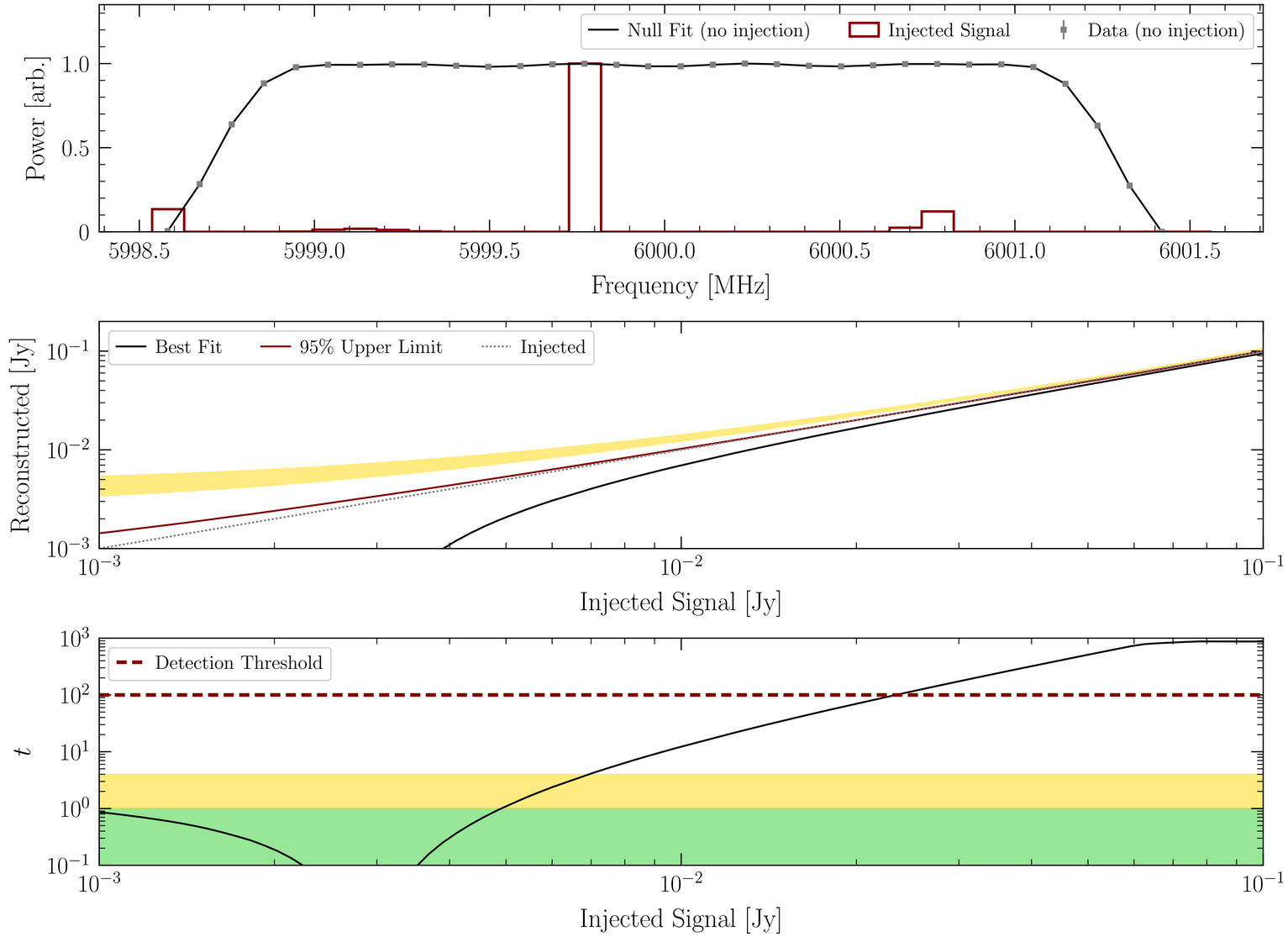
Use parametric modeling and Gaussian processes to model smooth background

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

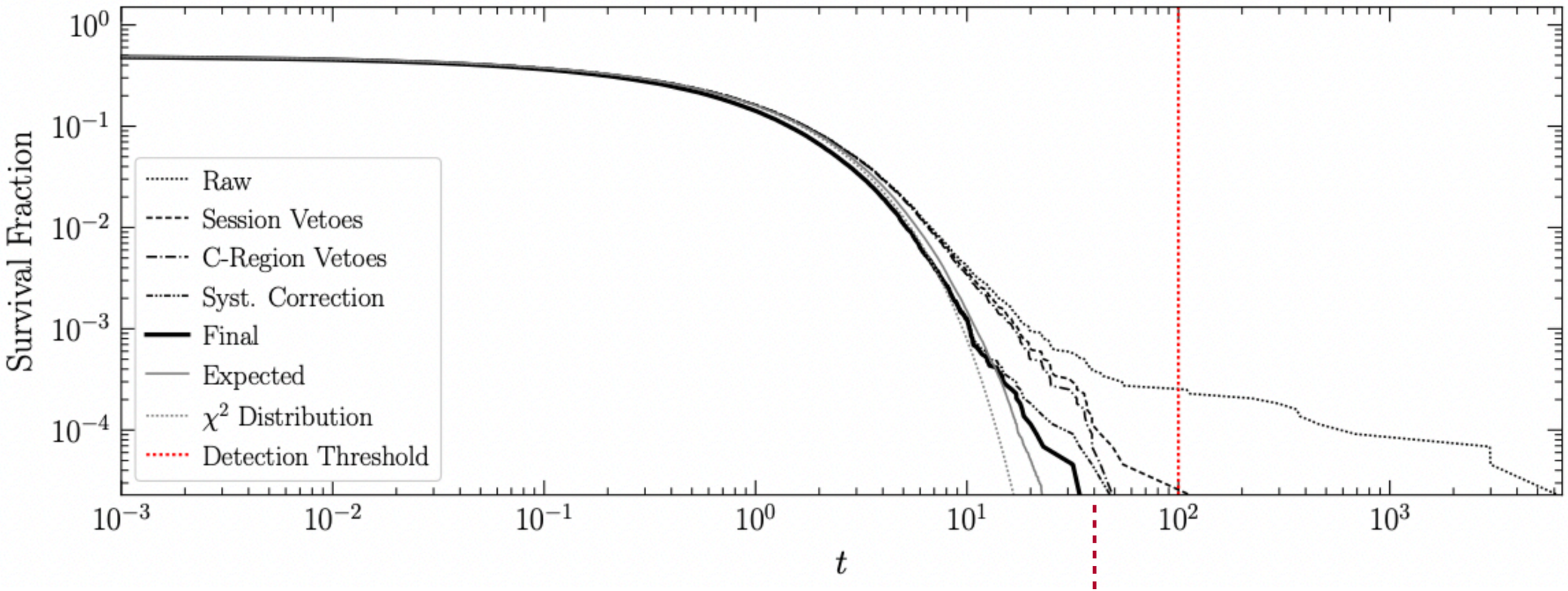
Signal Injection Tests

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Analysis framework leads limits with proper coverage and can recover injected signals



GBT Observations

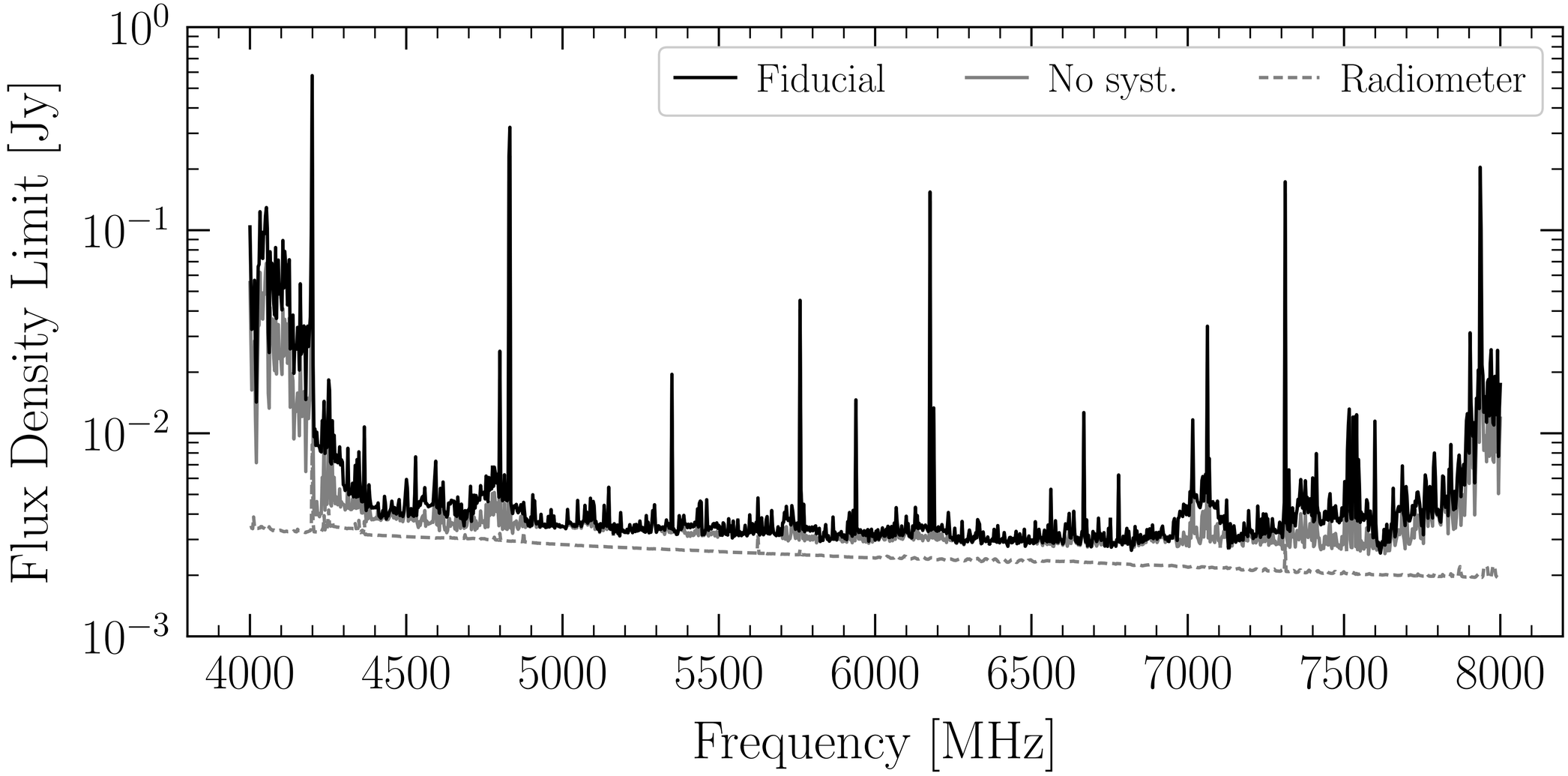


17 distinct excesses with t > 25

4.7σ Local significance
1.7σ Global significance

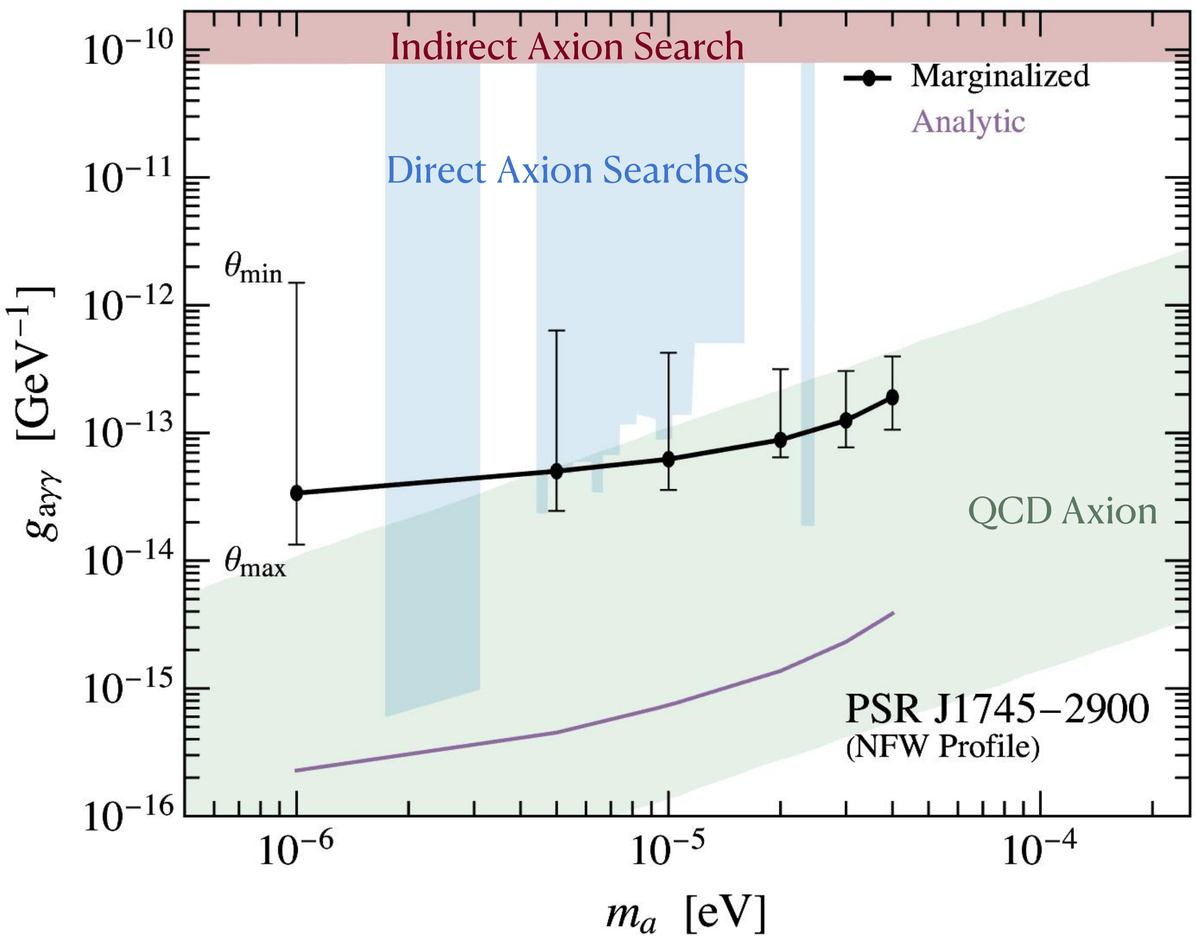
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

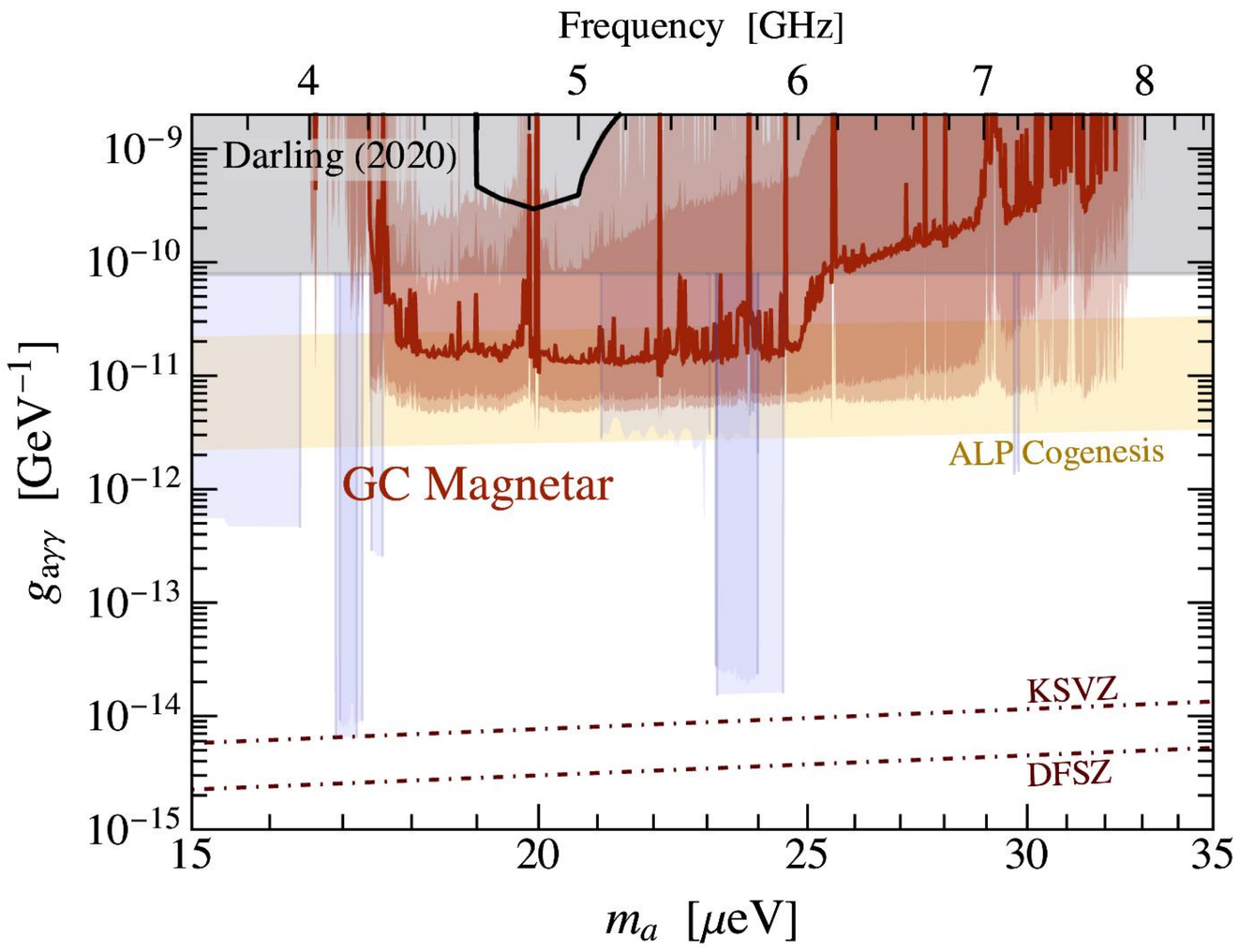
Fiducial Limits



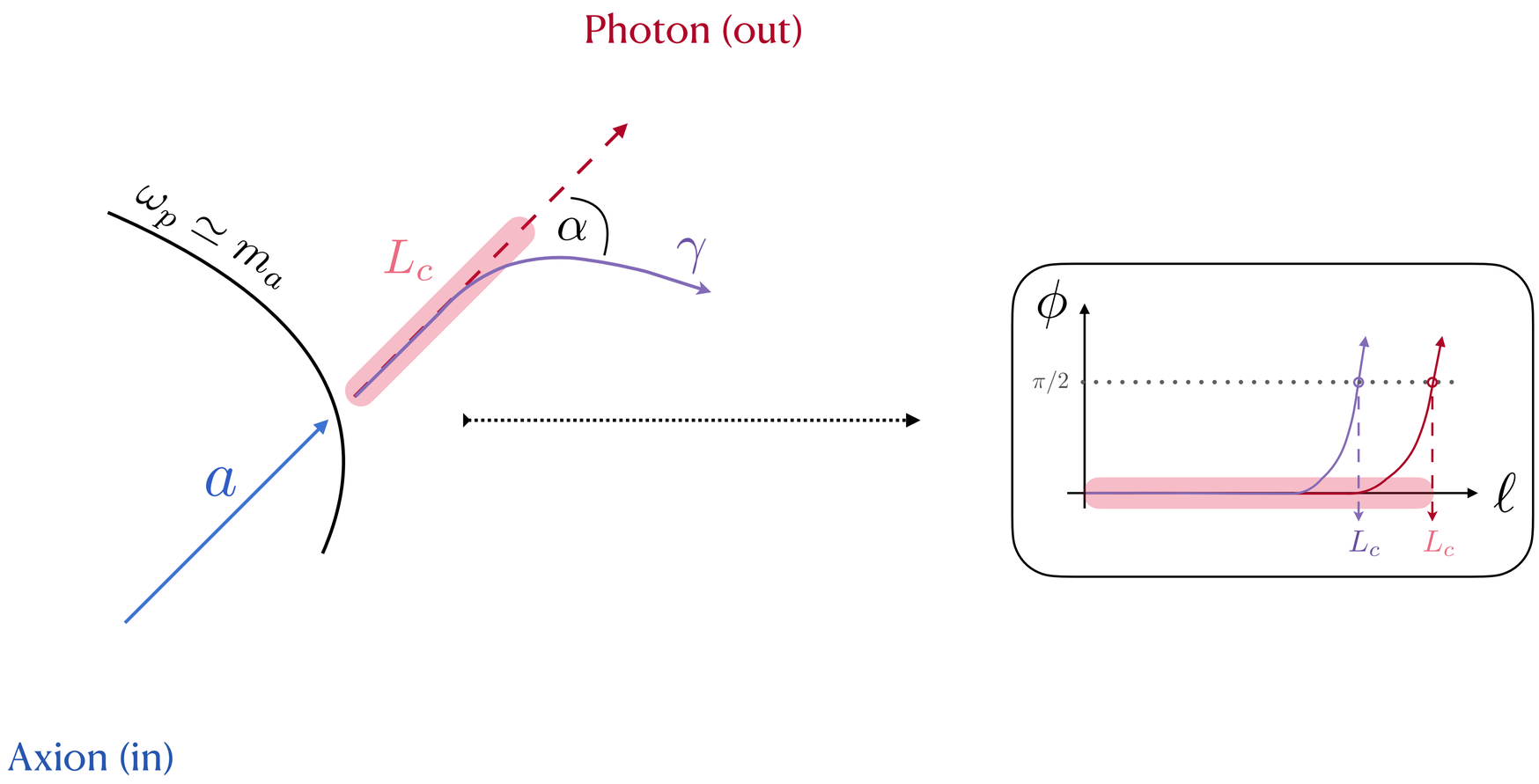
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

SJW, Noordhuis, Edwards, Weniger (2021)




Frequency [GHz]
4
5
6
7
8
Darling (2020)
GC Magnetar
ALP Cogenesis
KSVZ
DFSZ
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$g_{a\gamma\gamma}$ [GeV^{-1}]
15
20
25
30
35
m_a [μeV]

Axion-Photon Conversion (2D)

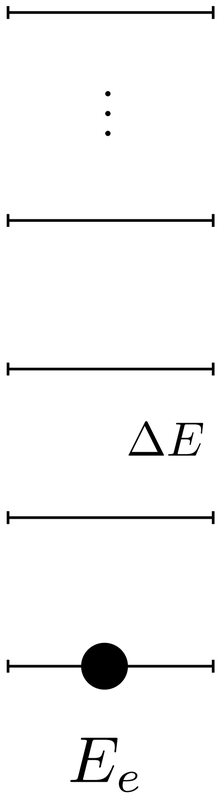


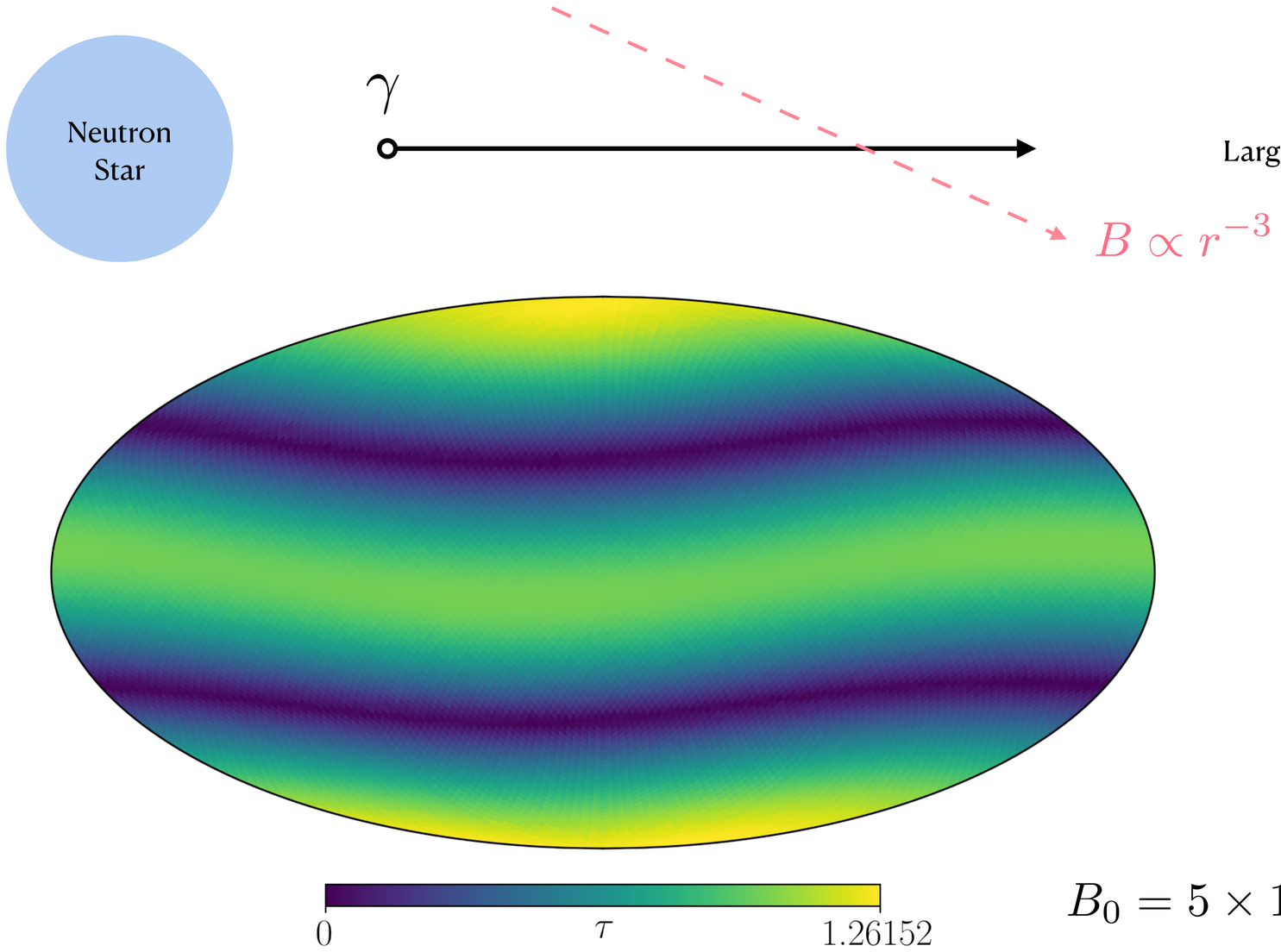
SJW, Noordhuis, Edwards, Weniger (2021)

Photon Absorption

SJW, Noordhuis, Edwards, Weniger (2021)

Landau Levels

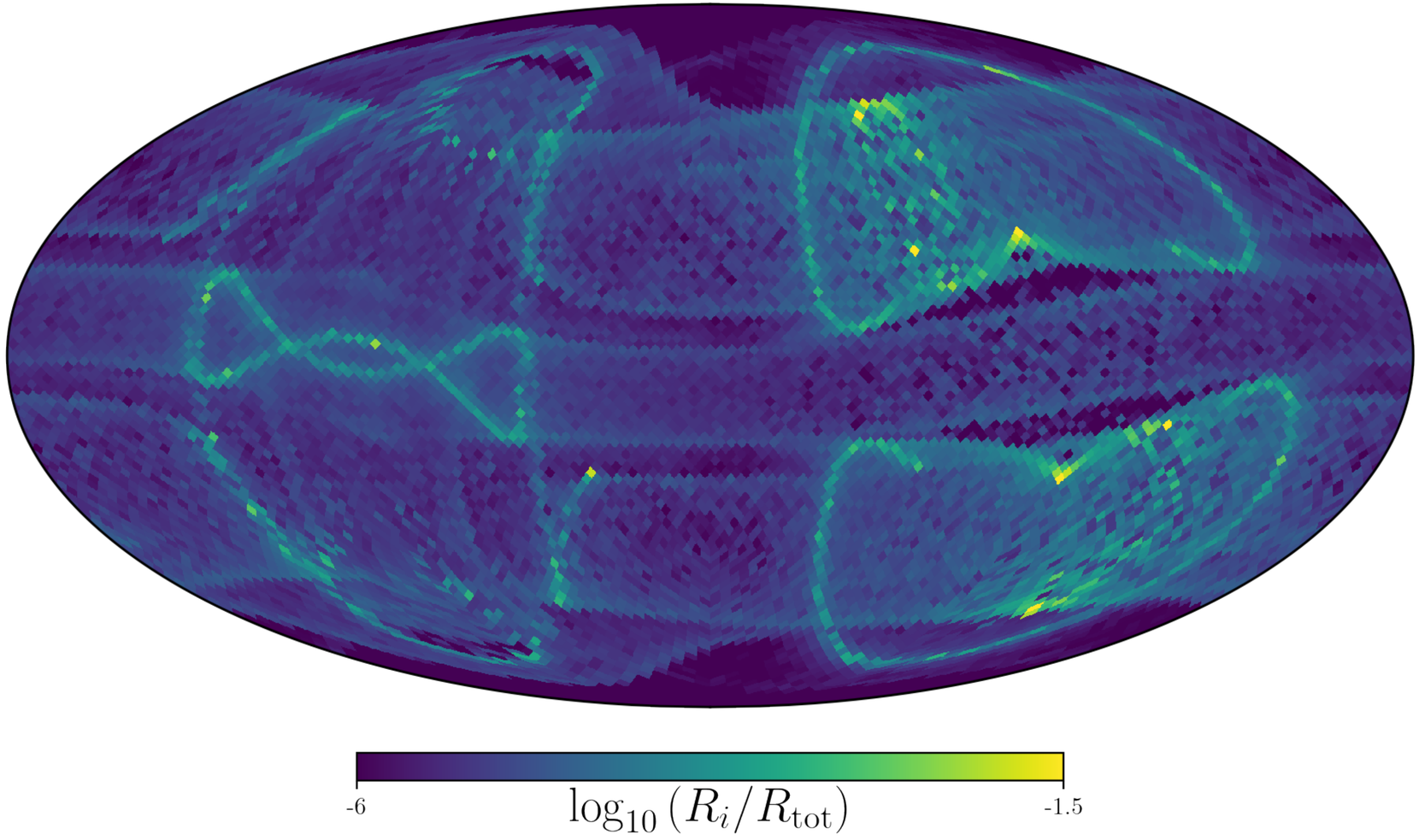




Larger B leads to more absorption**

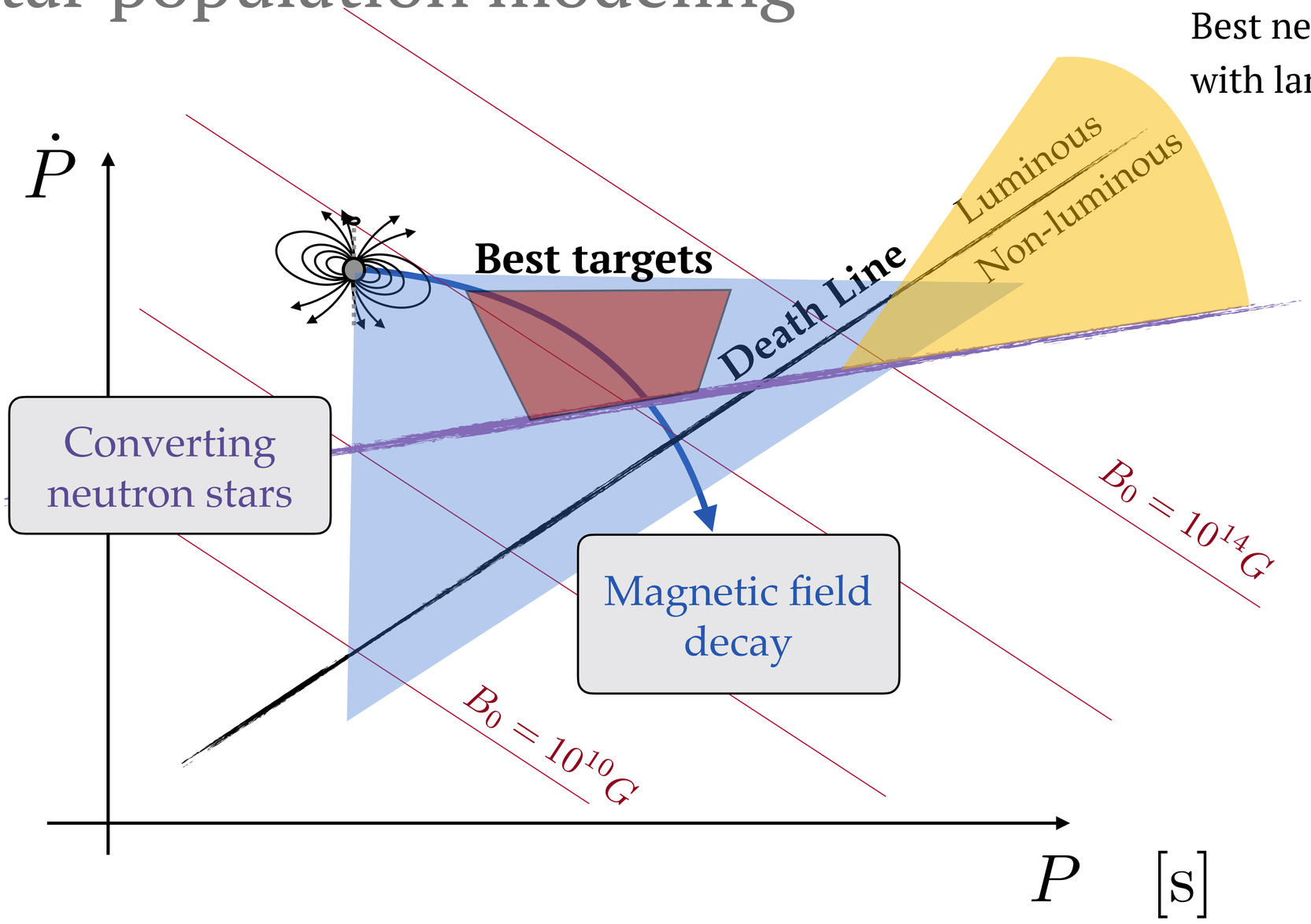
$B_0 = 5 \times 10^{14} G$

Minicluster Infall



Neutron star population modeling

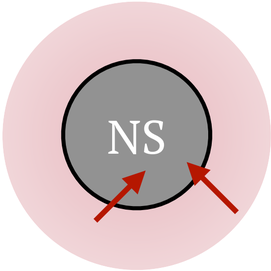
Naive expectation:
Best neutron stars those with large $|\vec{B}(r_c)|$



Quenching of bound state growth

Absorption in Neutron Star:

Noordhuis, Prabhu, **SJW** (To appear)



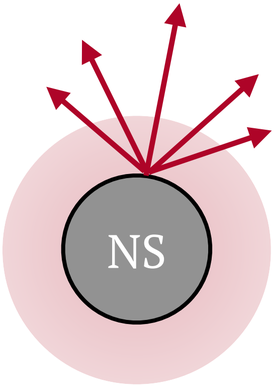
$$aNN \to NN$$

$$\Gamma_{\rm abs,eff} = \Gamma_{\rm abs}\left(1 - e^{-E/T}\right) \sim \left(\frac{E}{T}\right)\Gamma_{\rm abs}$$

Absorption heavily suppressed in low energy limit

Back-reaction on vacuum gap:

Caputo, **SJW**, Phillipov (In progress)

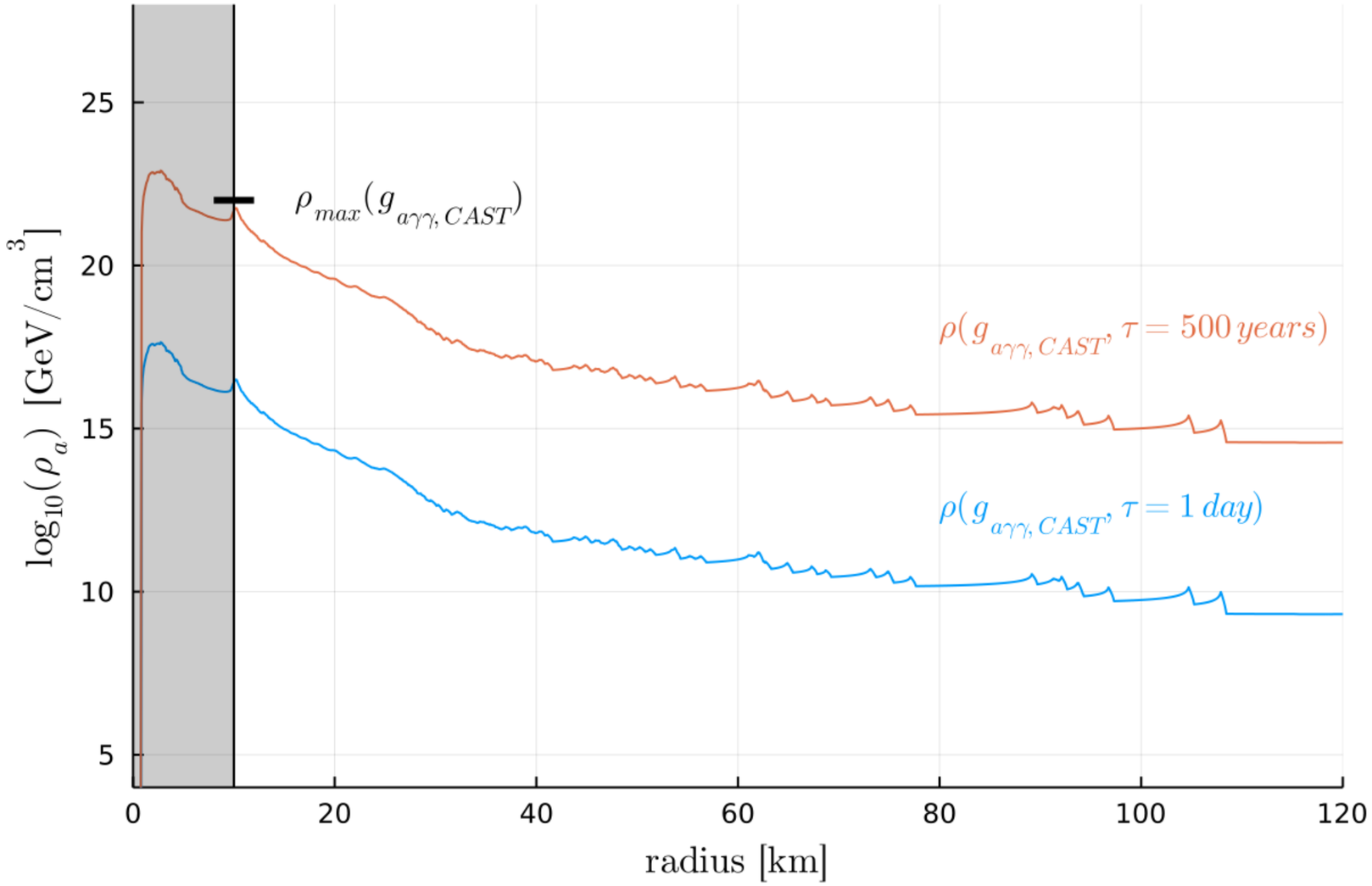


$$\nabla \cdot \vec{E} = \rho - g_{a\gamma\gamma}\vec{B} \cdot \nabla a$$

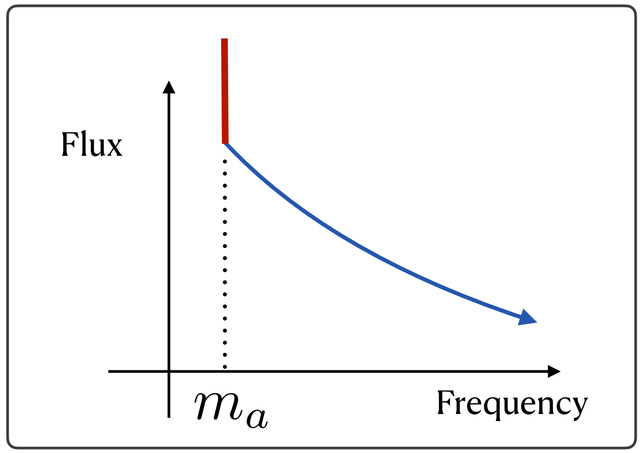
Large axion cloud can modify the plasma dynamics that drive production

$$\rho^{br}_{\rm max}(g_{a\gamma\gamma}, z = R_{\rm NS})$$

Bound state profiles

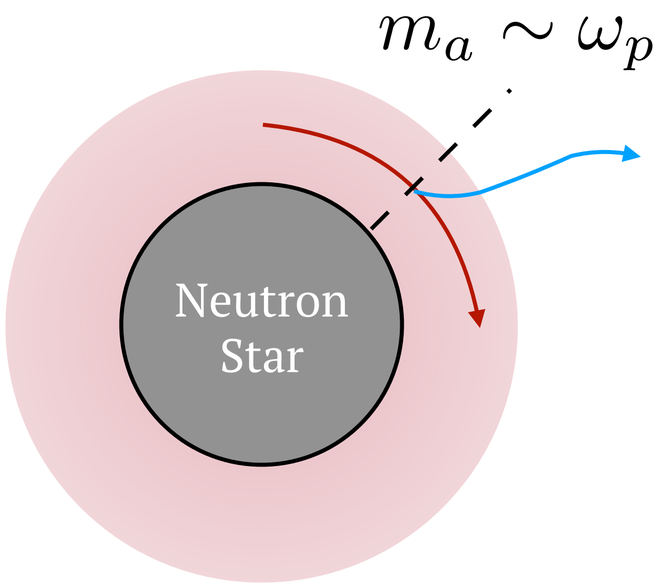


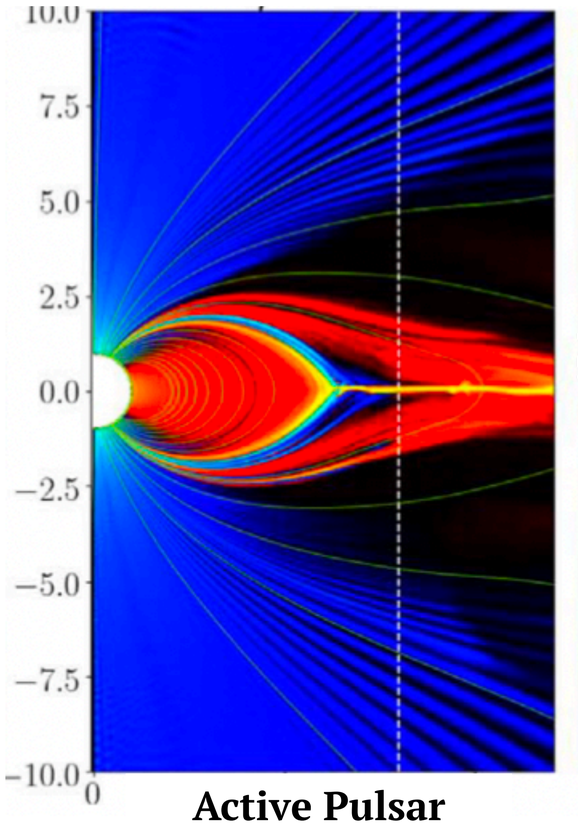
Noordhuis, Prabhu, **SJW**(To appear)



Quenching of bound state growth

Resonant Conversion:



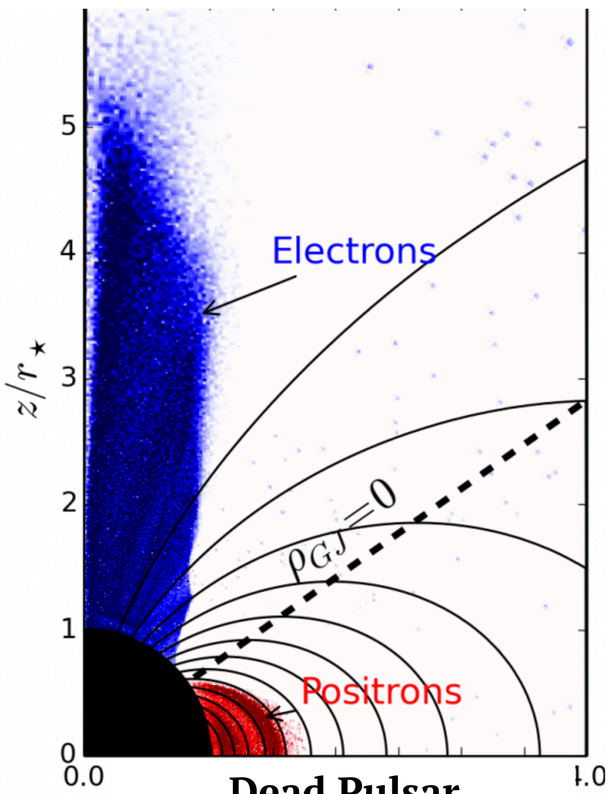


Active Pulsar

Do we hit resonance?

Age

$$\frac{d\rho_{inj}}{dt} \sim \frac{d\rho_{diss}}{dt}$$



Dead Pulsar

Noordhuis, Prabhu, **SJW** (To appear)

Image credit: Chen, Cruz, Spitskovski

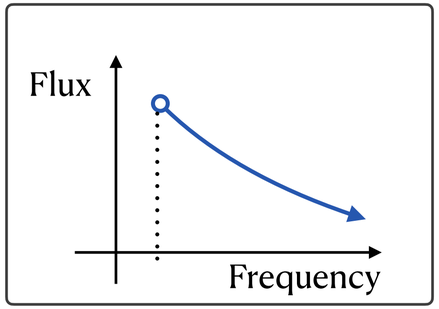
Image credit: Cerutti & Beloborodov

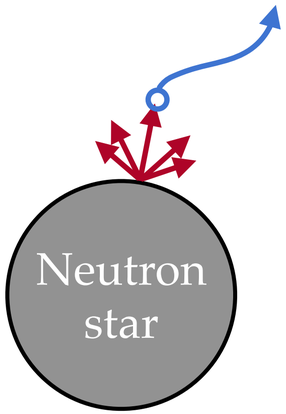
Radio signals

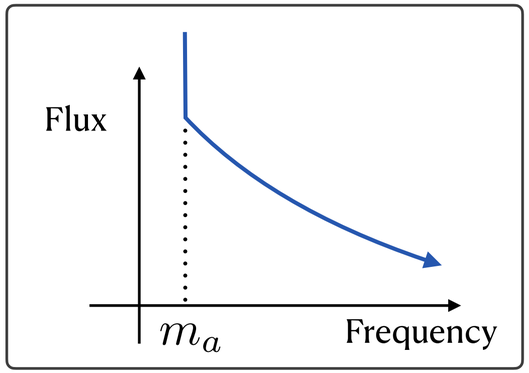
Noordhuis, Prabhu, **SJW,** Chen, Cruz (To appear)

Noordhuis, Prabhu, **SJW** (To appear)

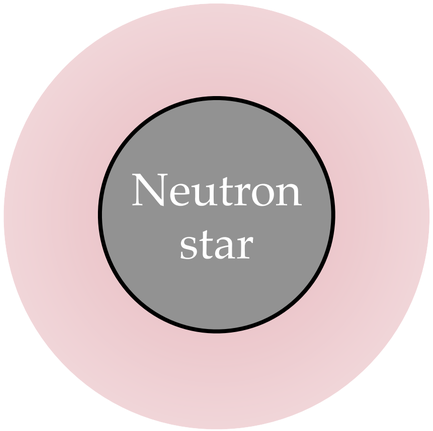
Relativistic axions

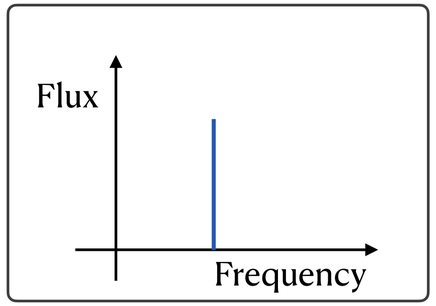






Bound state axions





Has the axion cloud modified production?

No → Look for smooth radio signal

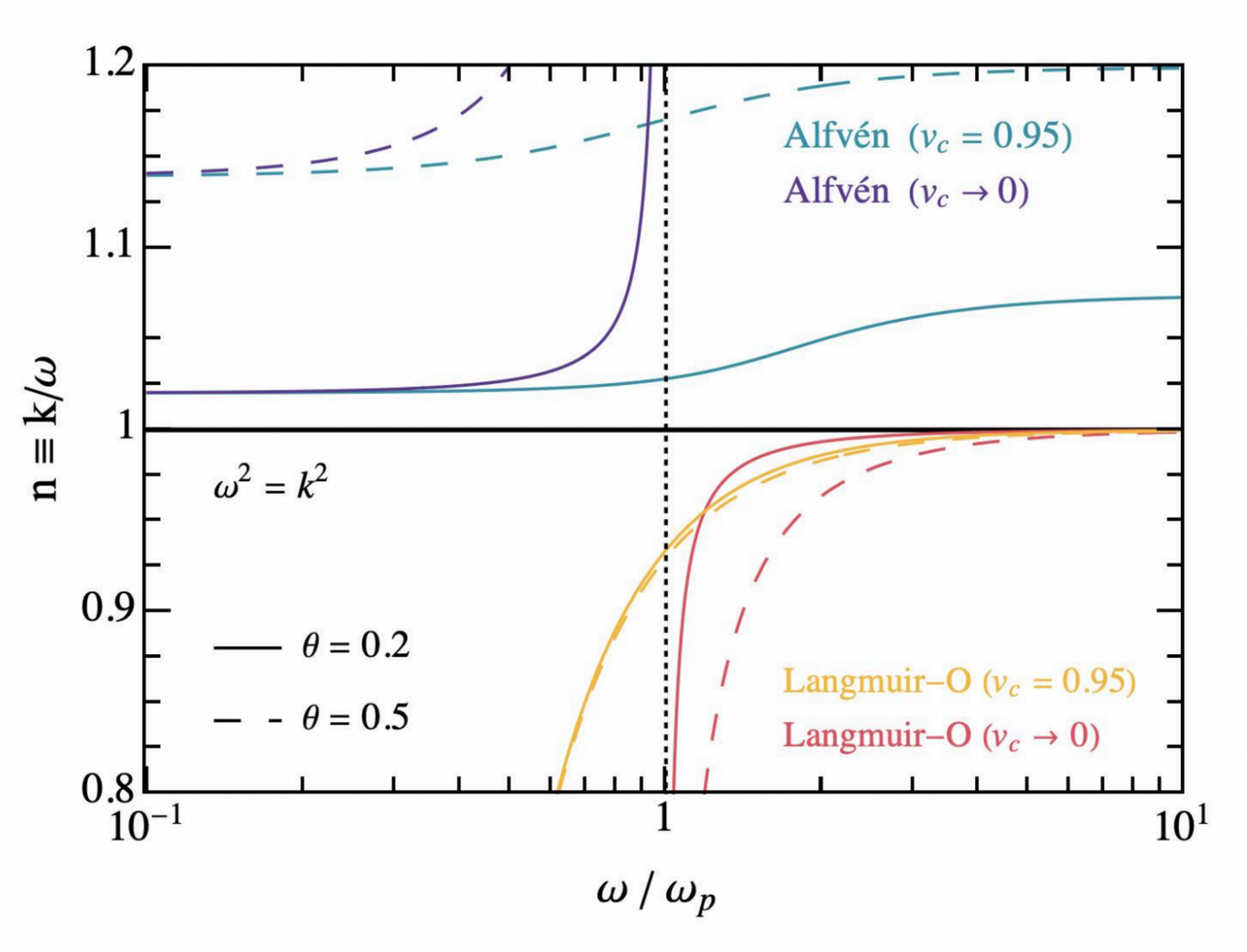
Yes → We must have a **very** dense axion cloud!

Can bound axions resonantly convert?

Yes → Look for narrow radio lines

No → Look for *rare* radio lines that decay!

EM Modes


1.2
1.1
1
0.9
0.8
$n \equiv k/\omega$
10^{-1}
1
10^{1}
ω / ω_p
Alfvén ($v_c = 0.95$)
Alfvén ($v_c \to 0$)
$\omega^2 = k^2$
$\theta = 0.2$
$\theta = 0.5$
Langmuir–O ($v_c = 0.95$)
Langmuir–O ($v_c \to 0$)

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Fast Magnetic Field Decay

Dominated by young neutron stars

"Data driven approach"

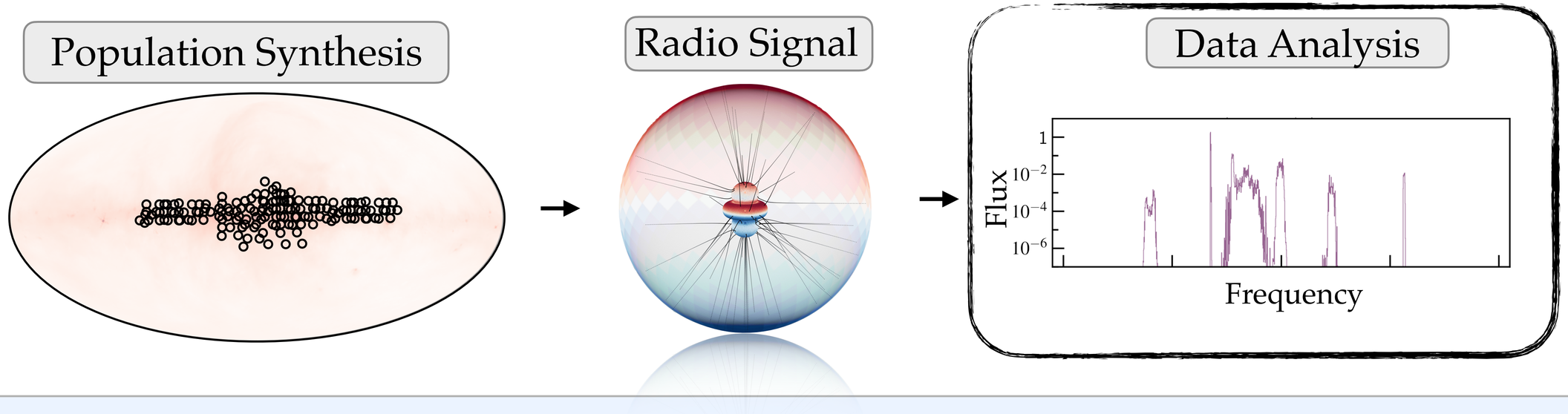
~1500 NSs [Age < 30 Myr in inner pc]

Slow Magnetic Field Decay

Both young and old neutron stars contribute

Population Modeling

300,000 NSs inner few pcs



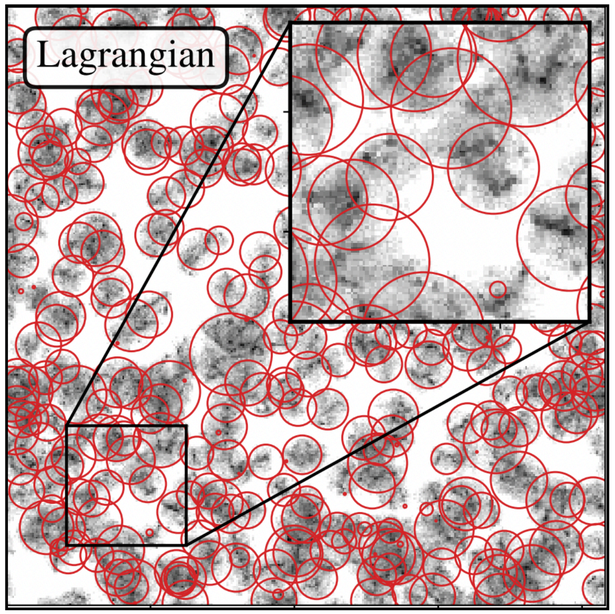
Transient radio lines

- Axion miniclusters (axion stars) form in post-inflationary scenario
- Periodic encounters of miniclusters/stars with neutron stars generate transient radio lines

Reference properties: $M_{\rm AMC} \sim 10^{-12}\, M_\odot,\ R_{\rm AMC} \sim 10^9\,{\rm km}, \tau \sim [{\rm hours} - {\rm years}]$

Reference properties: $M_{\rm AS} \sim 10^{-13}\, M_\odot,\quad R_{\rm AS} \sim 10^4\,{\rm km}, \tau \sim {\rm seconds}$

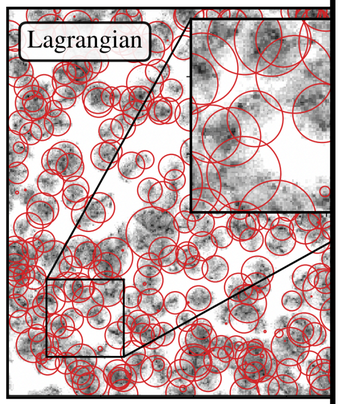
Density field at matter-radiation equality



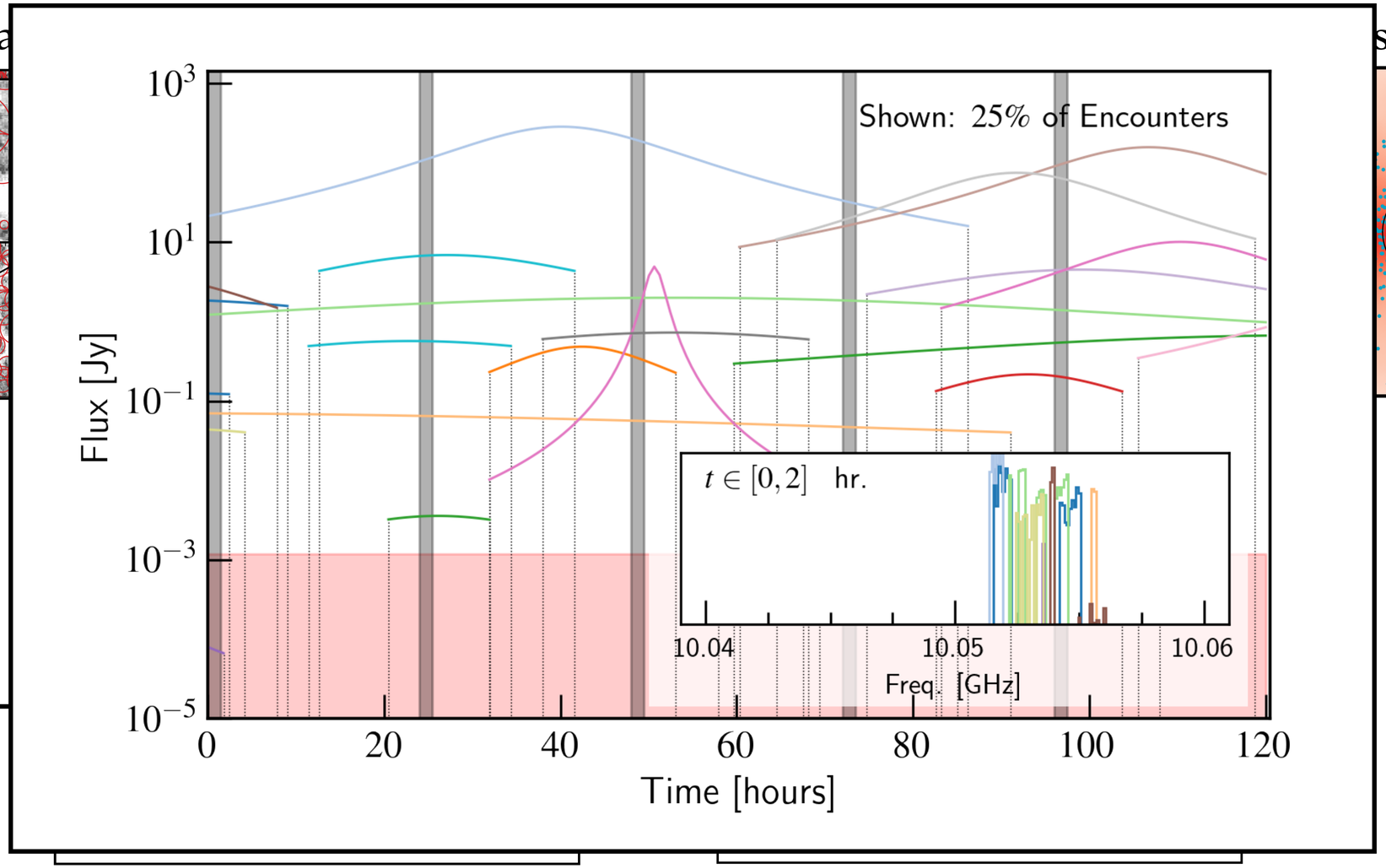
Ellis et al (2022)

Transient radio lines (Pipeline)

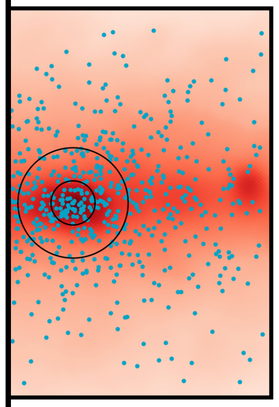
Minicluster forma



Ellis et al (2022)



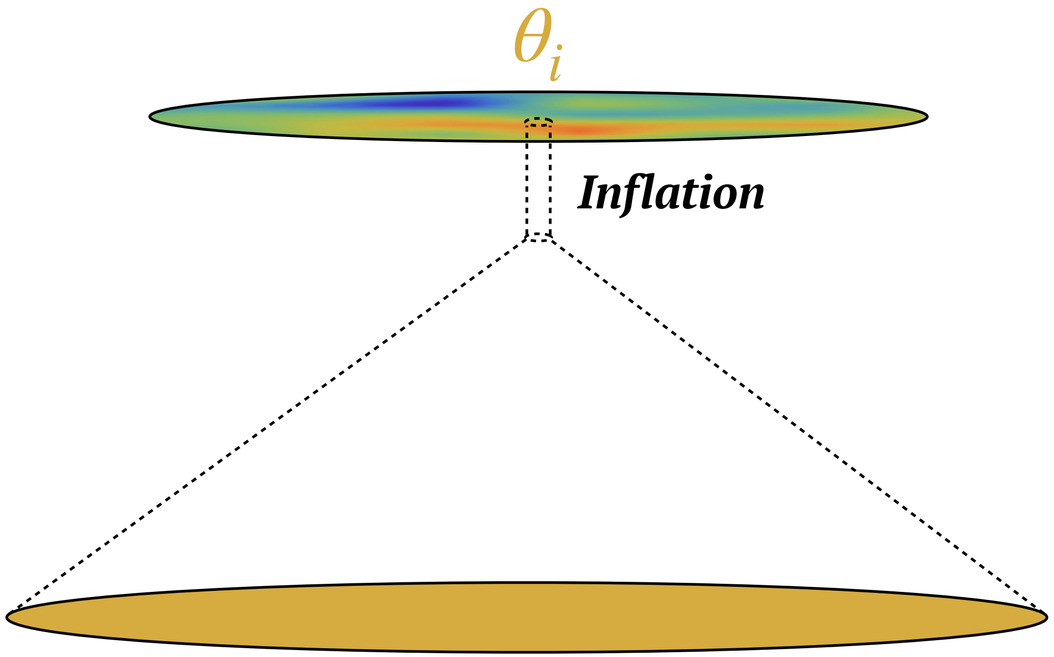
star population



SJW, Salinas, Baum, Lawson, Millar, Marsh, Weniger (To appear)
Agrawal, Johsnon, Edwards, Kavanaguh, Marsh, Ransom, Shroyer, Visinelli, **SJW**, Weniger (Data analysis ongoing)

Axion dark matter

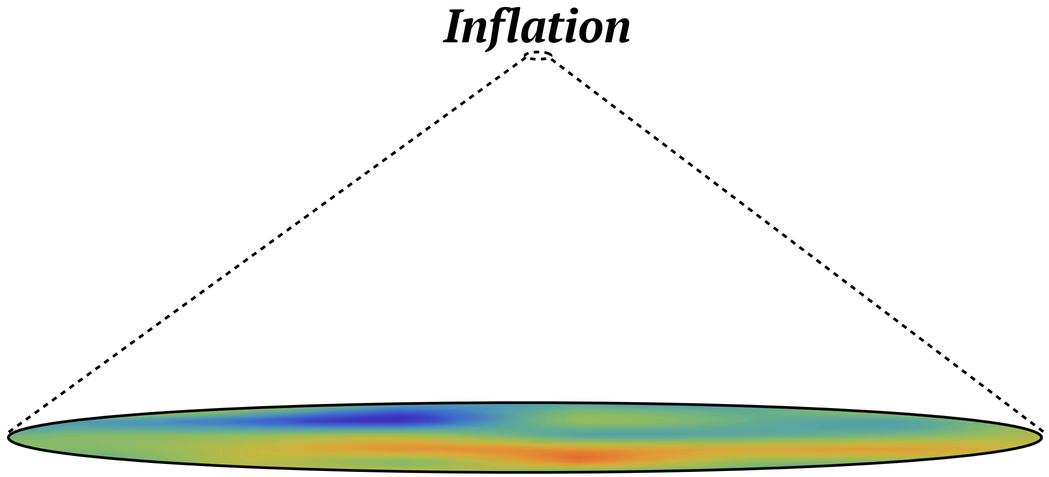
Pre-Inflationary Scenario $[f_a \gg H_I]$



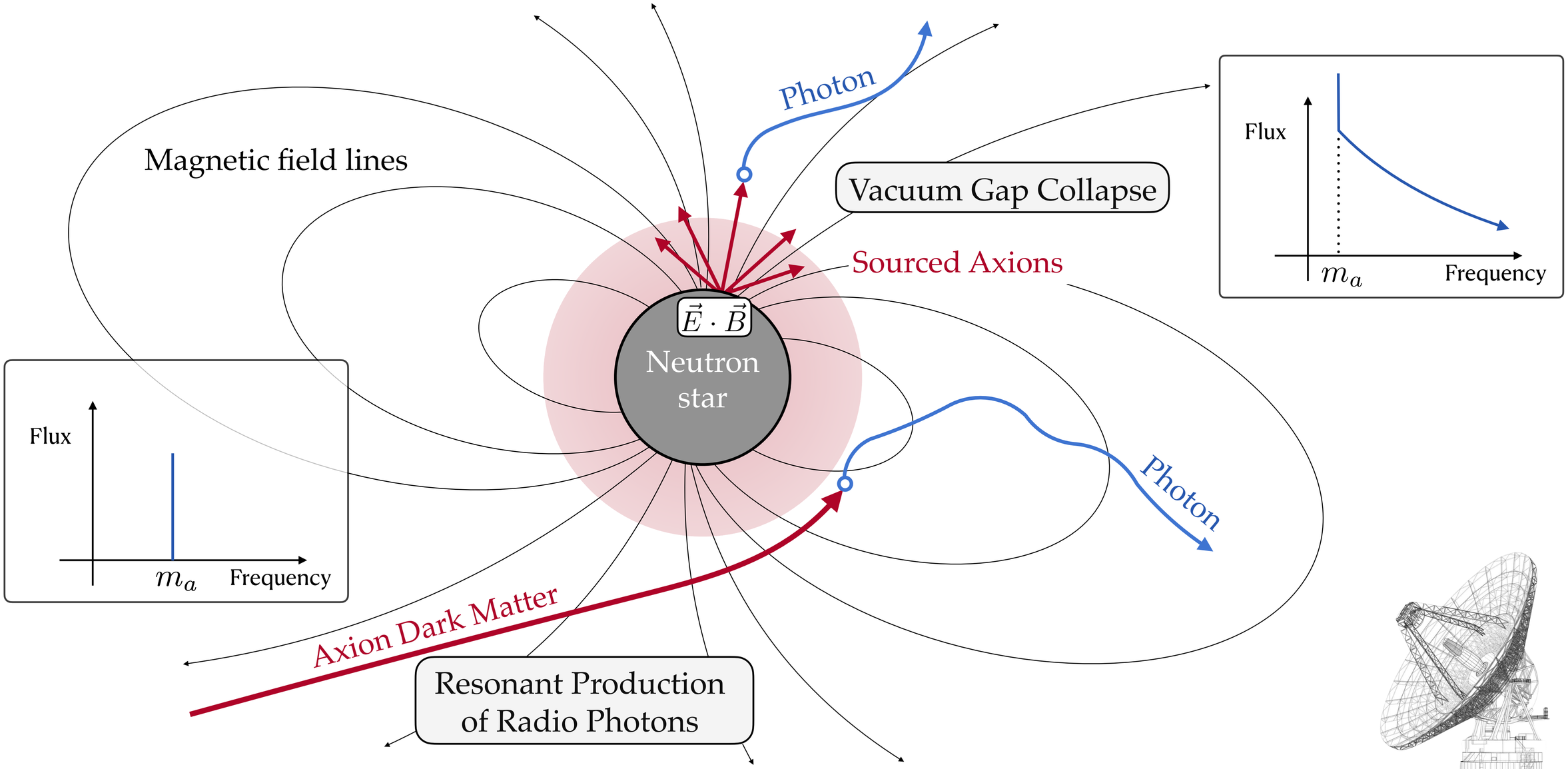
Heuristic argument (QCD axion):

$$10^{-7}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$$

Post-Inflationary Scenario $[f_a \ll H_I]$



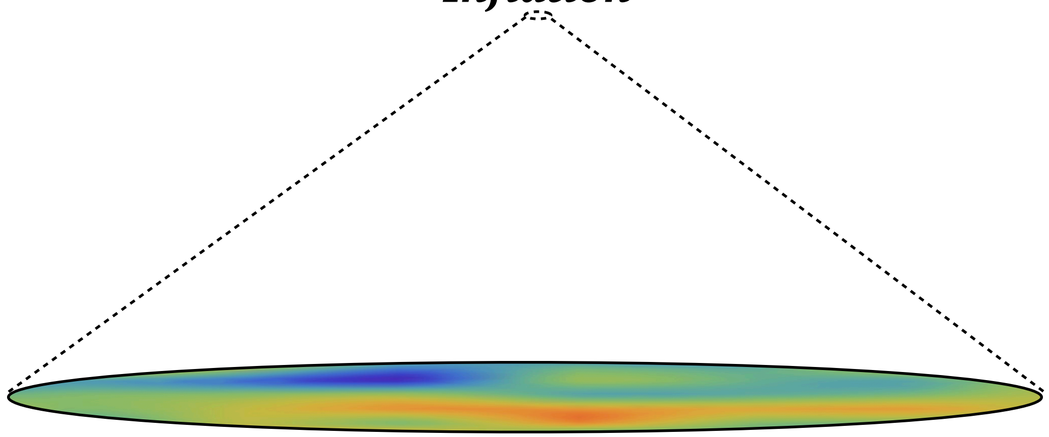
Neutron stars as axion labs



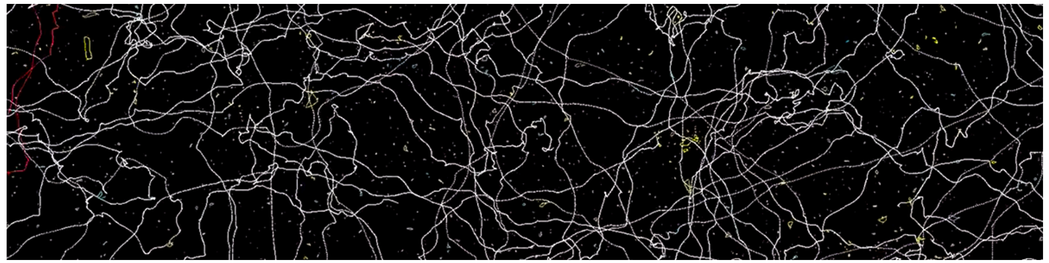
Axion dark matter

Post-Inflationary Scenario $[f_a \ll H_I]$

Inflation



Topological Defects



$$\Omega_{cdm} = \Omega_{mis-mech} + \Omega_{strings} + \Omega_{DW}$$

Can be calculated exactly

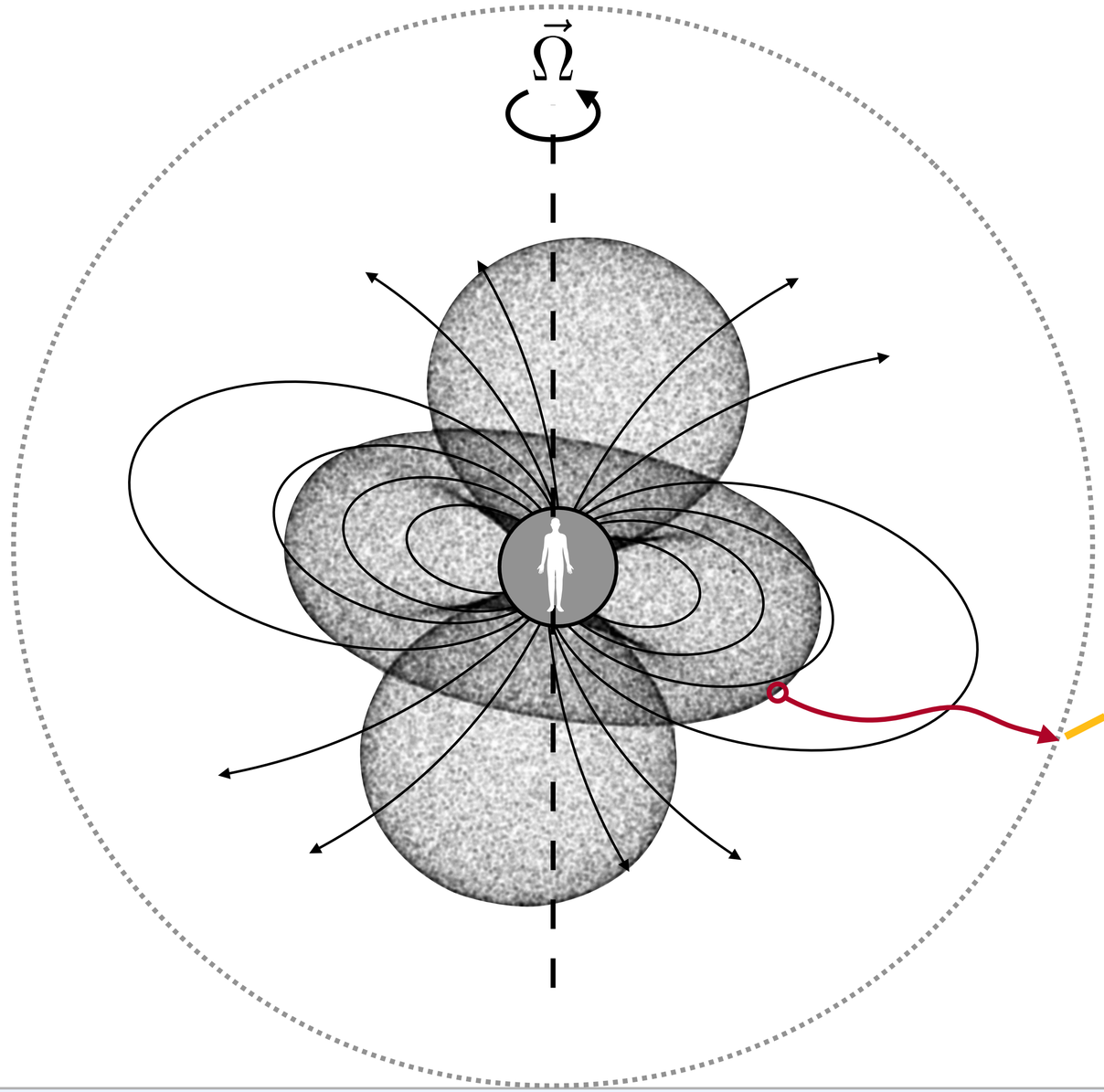
Industry of computationally expensive simulations

See e.g. Buschmann et al (2021), Gorghetto et al (2020)

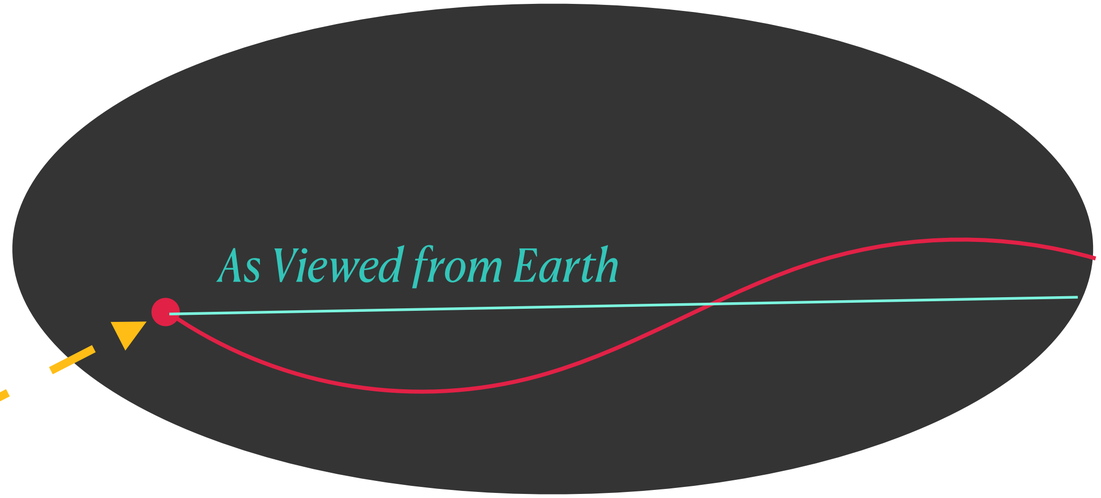
Current Expectation for QCD axion:

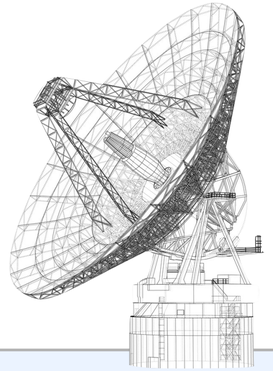
$$26\,\mu\text{eV} \lesssim m_a \lesssim 10^{-3}\,\text{eV}$$

$\mathcal{O}(1)$ density perturbations seeds axion miniclusters

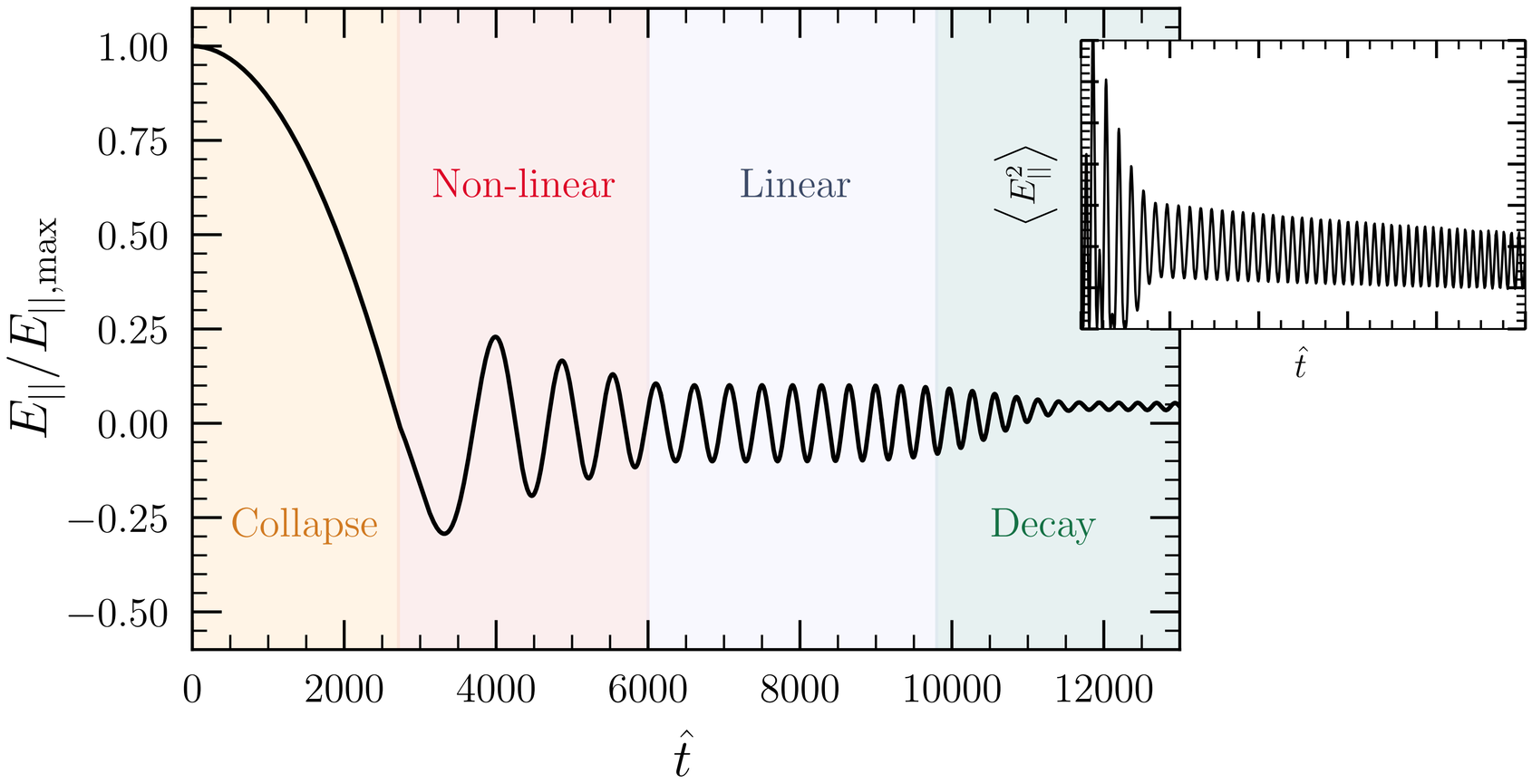


Observational signature



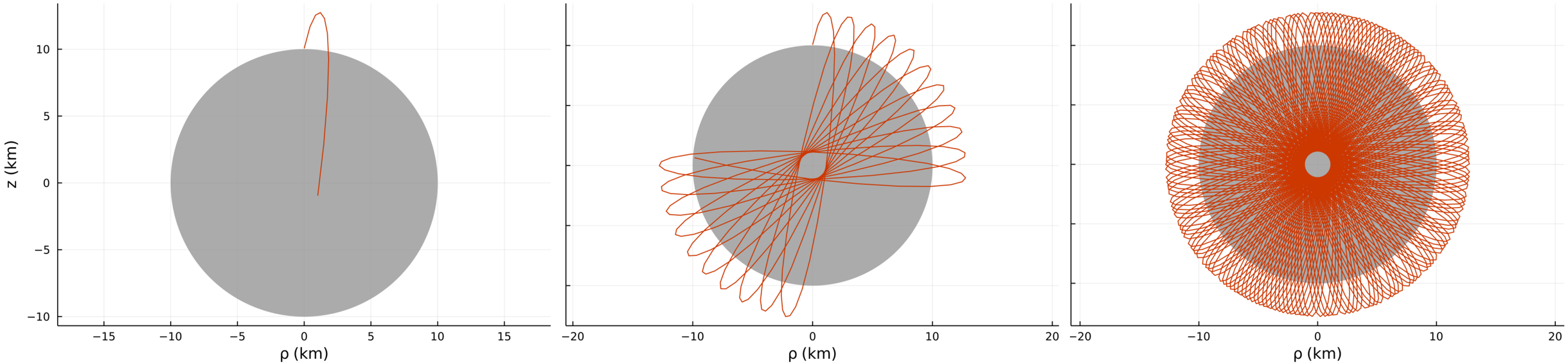


Neutron star rotation changes location of photon over time


1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
$E_{\|}/E_{\|,\mathrm{max}}$
0
2000
4000
6000
8000
10000
12000
$\hat{t}$
Collapse
Non-linear
Linear
Decay
$\langle E_{\|}^2 \rangle$
$\hat{t}$

Bound states

Time: 0.0002 seconds 0.006 seconds 0.05 seconds



Axion production rate constant over ~ Myr timescales

(Assuming one can neglect axion cloud)

Noordhuis, Prabhu, **SJW** (To appear)