Title: TBA

Speakers: Joshua Foster

Series: Particle Physics

Date: September 15, 2020 - 1:00 PM

URL: http://pirsa.org/20090015

Abstract: Abstract TBD

Based on:

- *Dessert, **J.F.**, and Safdi. 2008.03305 [hep-ph]. Submitted to PRL*
- ***J.F.** et al. 2004.00011 [astro-ph.CO]. Submitted to PRL*
- *Dessert, **J.F.**, and Safdi. 1910.02956 [astro-ph.HE]. ApJ.*

And ongoing work

ASTROPHYSICAL SEARCHES FOR AXIONS

Joshua W. Foster

AXION MOTIVATIONS: THE STRONG CP PROBLEM AND THE QCD AXION

$$\mathcal{L}_{\rm QCD}^{\mathcal{CP}} = -\frac{\bar{\theta} g^2}{32\pi^2} G\tilde{G}$$

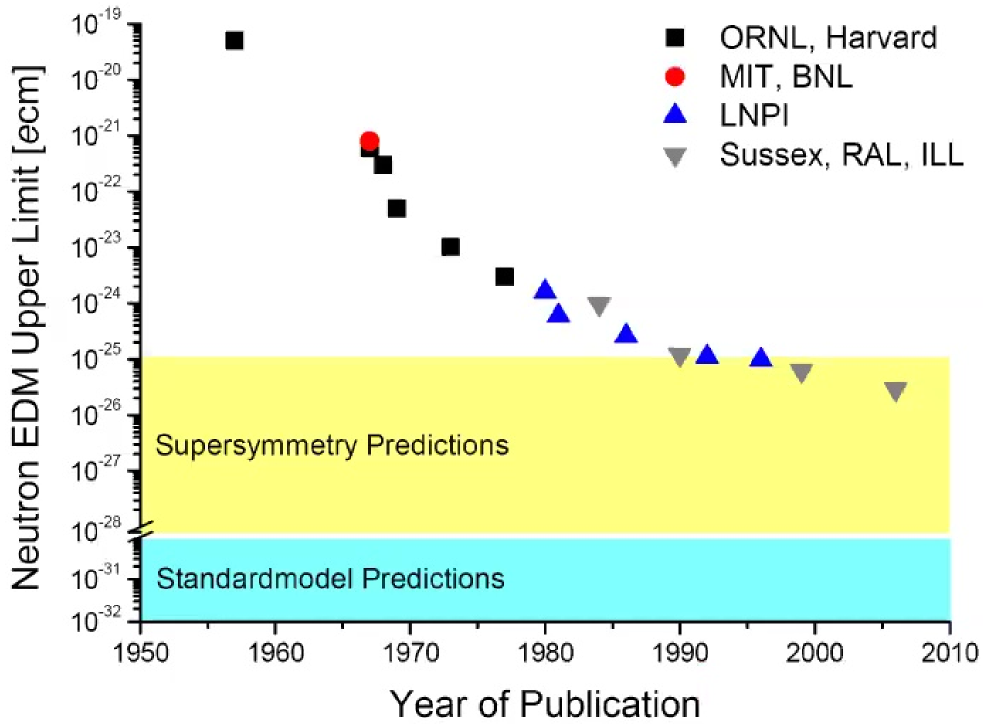
- QCD lagrangian can contain CP violating terms
- Contributes to neutron electric dipole moment
  - Theory:

$$d_n \approx 10^{-16} \times \bar{\theta} \ \mathrm{e \cdot cm}$$

  - Experiment:

$$|\bar{\theta}| < 10^{-10}$$

AXION MOTIVATIONS: THE STRONG CP PROBLEM



AXION MOTIVATIONS: THE STRONG CP PROBLEM

$$\mathcal{L}_{\text{axion}} = -\left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}G\tilde{G}$$

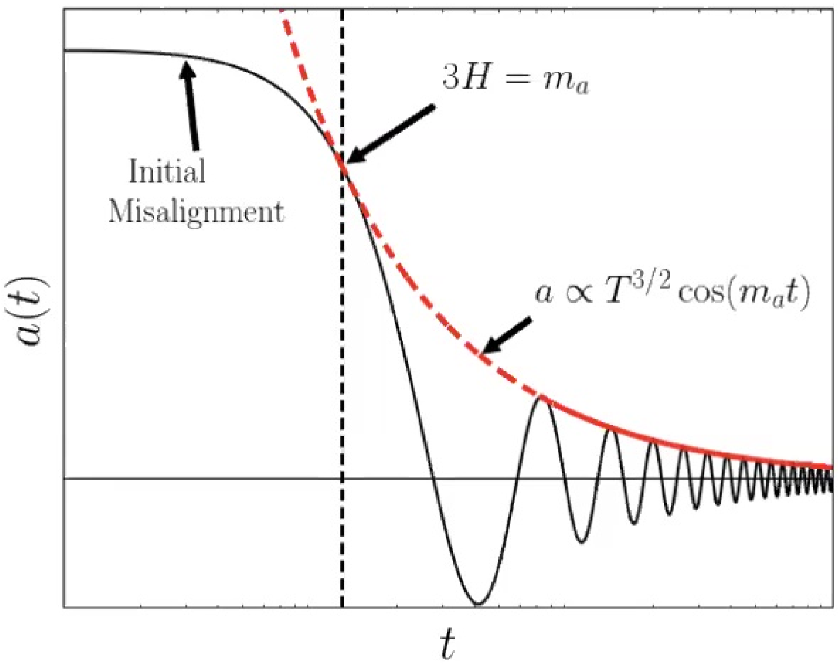
- Peccei-Quinn Mechanism: new degree of freedom coupled to CP violating term

$$V(a) = m_a^2 f_a^2 \left[1 - \cos(\bar{\theta} + a/f_a)\right]$$

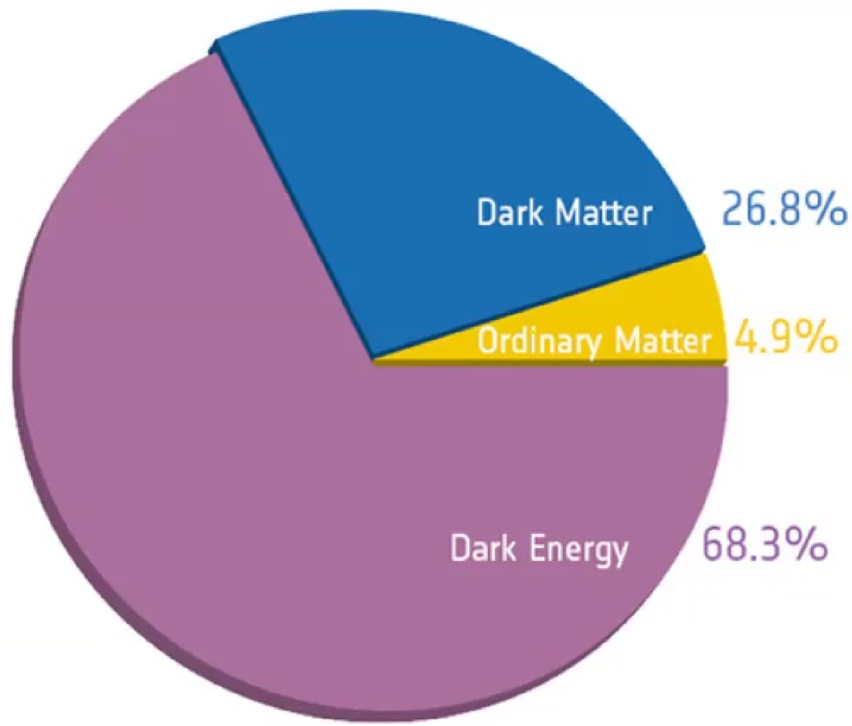
- Topological effects produce effective potential with an axion mass
- Axion minimizes potential, dynamically eliminates CP violation

AXION MOTIVATIONS: DARK MATTER

- Dark matter is out there
- Relic abundance naturally obtained in QCD axion scenario

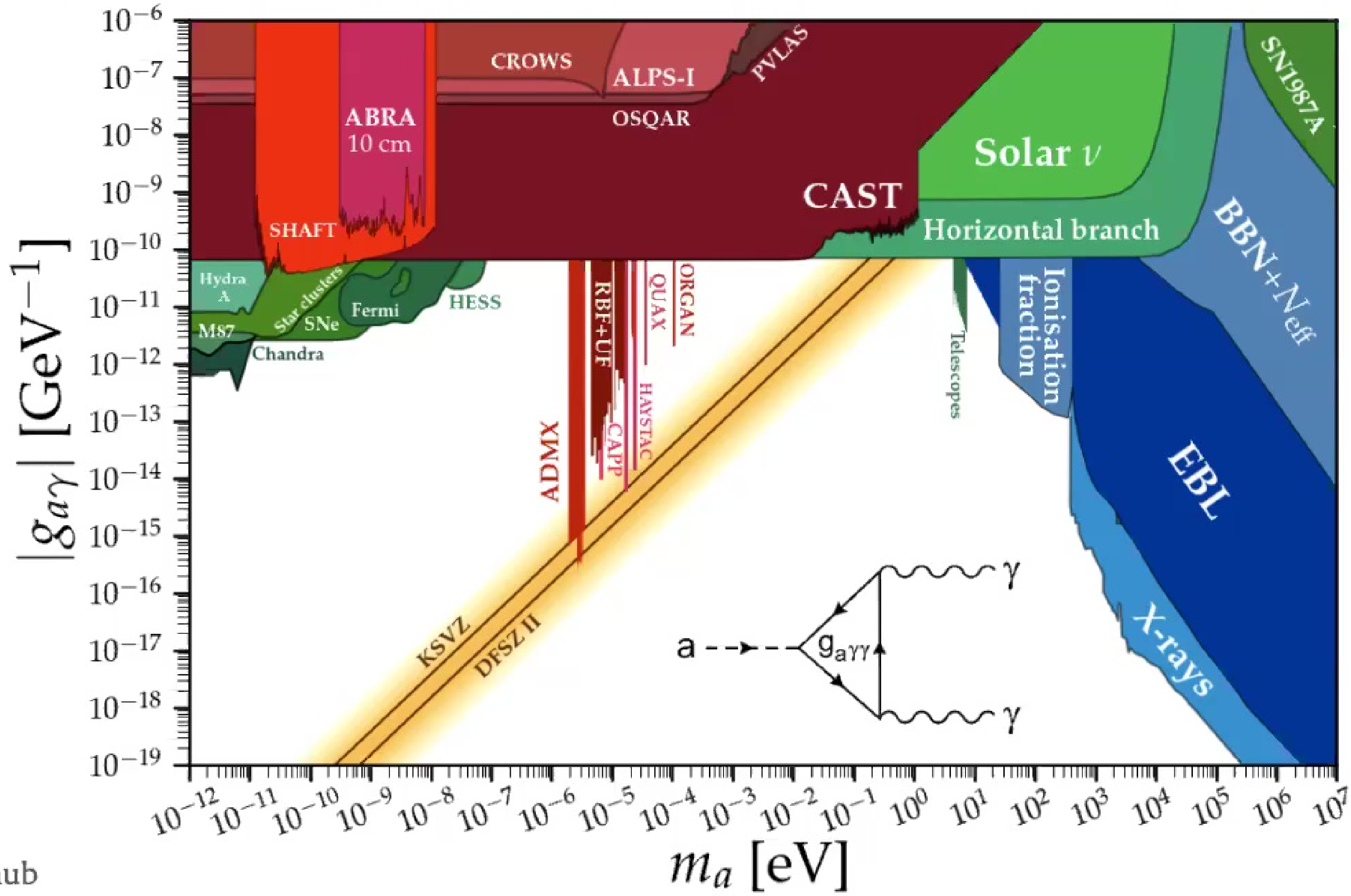


Planck 2015



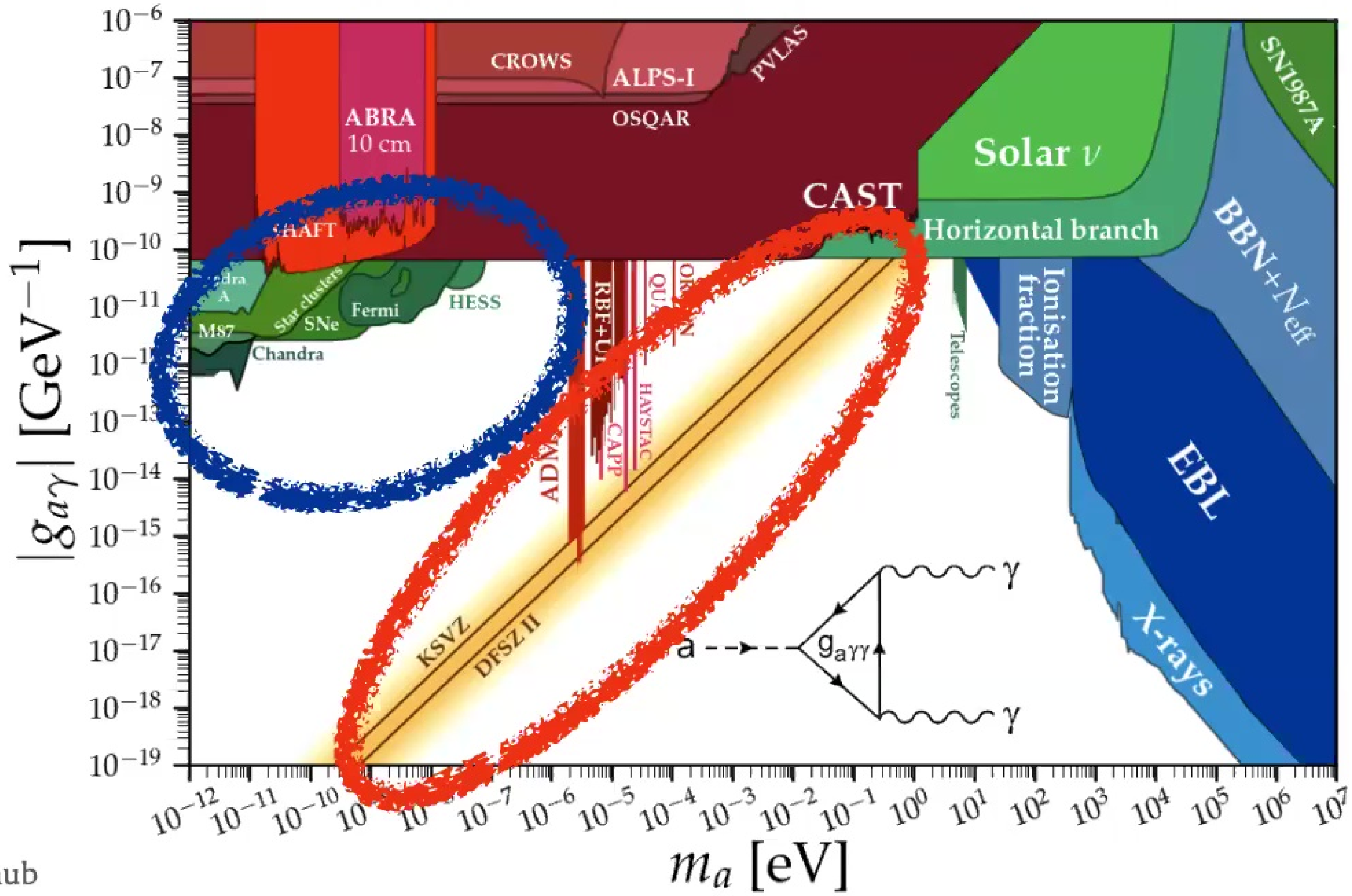
- Relaxation process can be complicated:
  - Buschmann, J.F. and Safdi. 1906.00967 [astro-ph.CO]. *PRL*

WHERE DO WE LOOK FOR AXIONS?



Ciaran O'Hare. Github

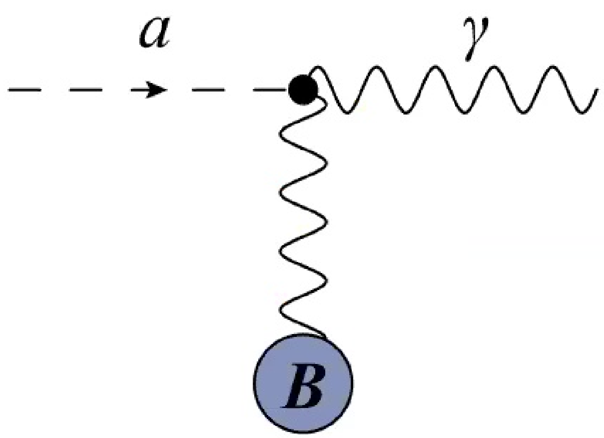
WHERE DO WE LOOK FOR AXIONS?



Ciaran O'Hare. Github

HOW DO WE LOOK FOR AXIONS: DIRECT DETECTION

- Precision direct detection experiments:
  - ADMX, HAYSTAC, MADMAX, ABRACADABRA/DM-Radio, …
  - CAST, IAXO, JURA…
- Most (not all) search for axion through its photon coupling
- In practice, large B-field in controlled environment



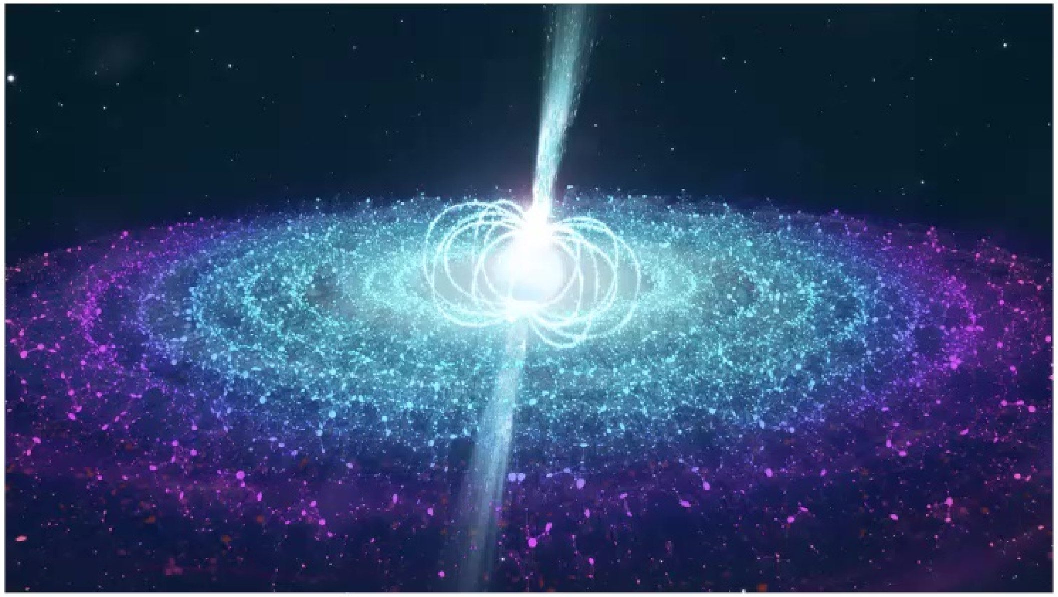
Ouellet, Salemi, J.F. et al. 1901.10652 [physics.ins-det]. Phys Rev. ***D***
Ouellet, Salemi, J.F. et al. 1810.12257 [hep-ex]. PRL
J.F. et al. 1711.10489 [astro-ph.CO]. Phys. Rev. ***D***
+ More to come!

HOW DO WE LOOK FOR AXIONS: DIRECT DETECTION

CAST Experiment

$$p_{a\to\gamma} \sim g^2_{a\gamma\gamma} B^2 L^2$$

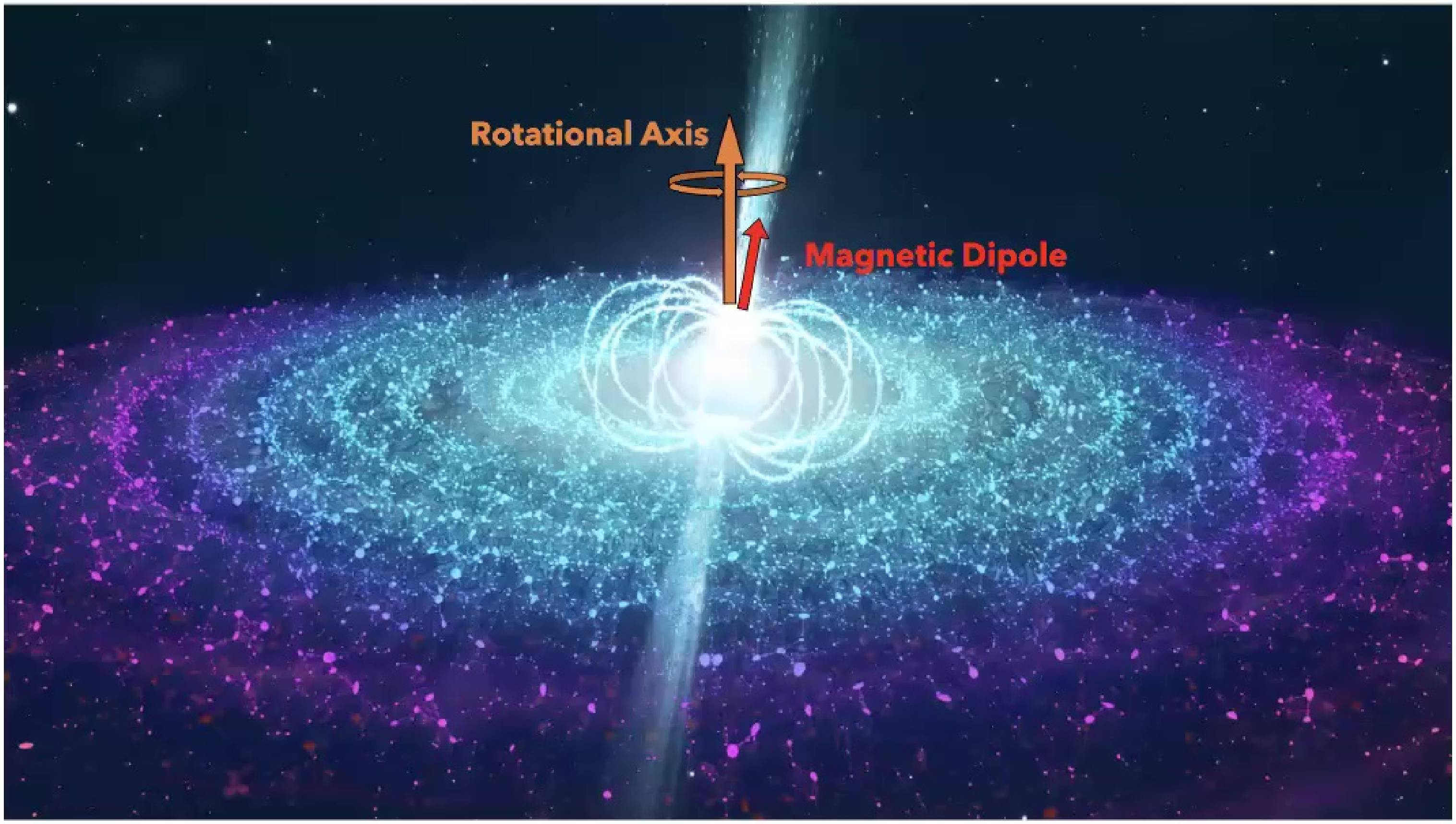
HOW DO WE LOOK FOR AXIONS: INDIRECT DETECTION AT NEUTRON STARS



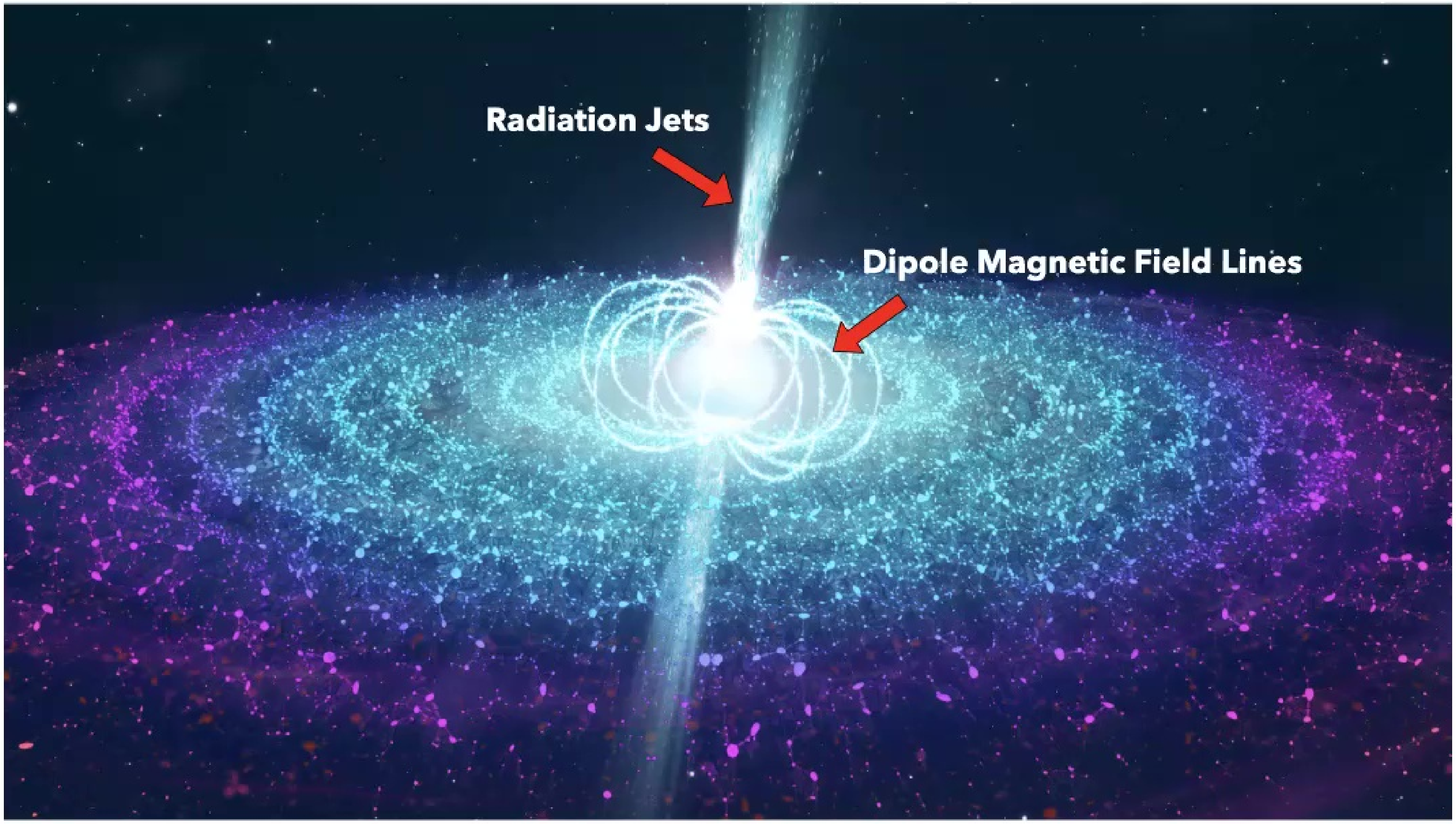
- Intrinsic trade-off:
  - Observational targets are bigger, more extreme astrophysical environments
  - Observational targets are further away, weak signal, background uncertainty, etc.

RADIO SEARCHES FOR AXION DM

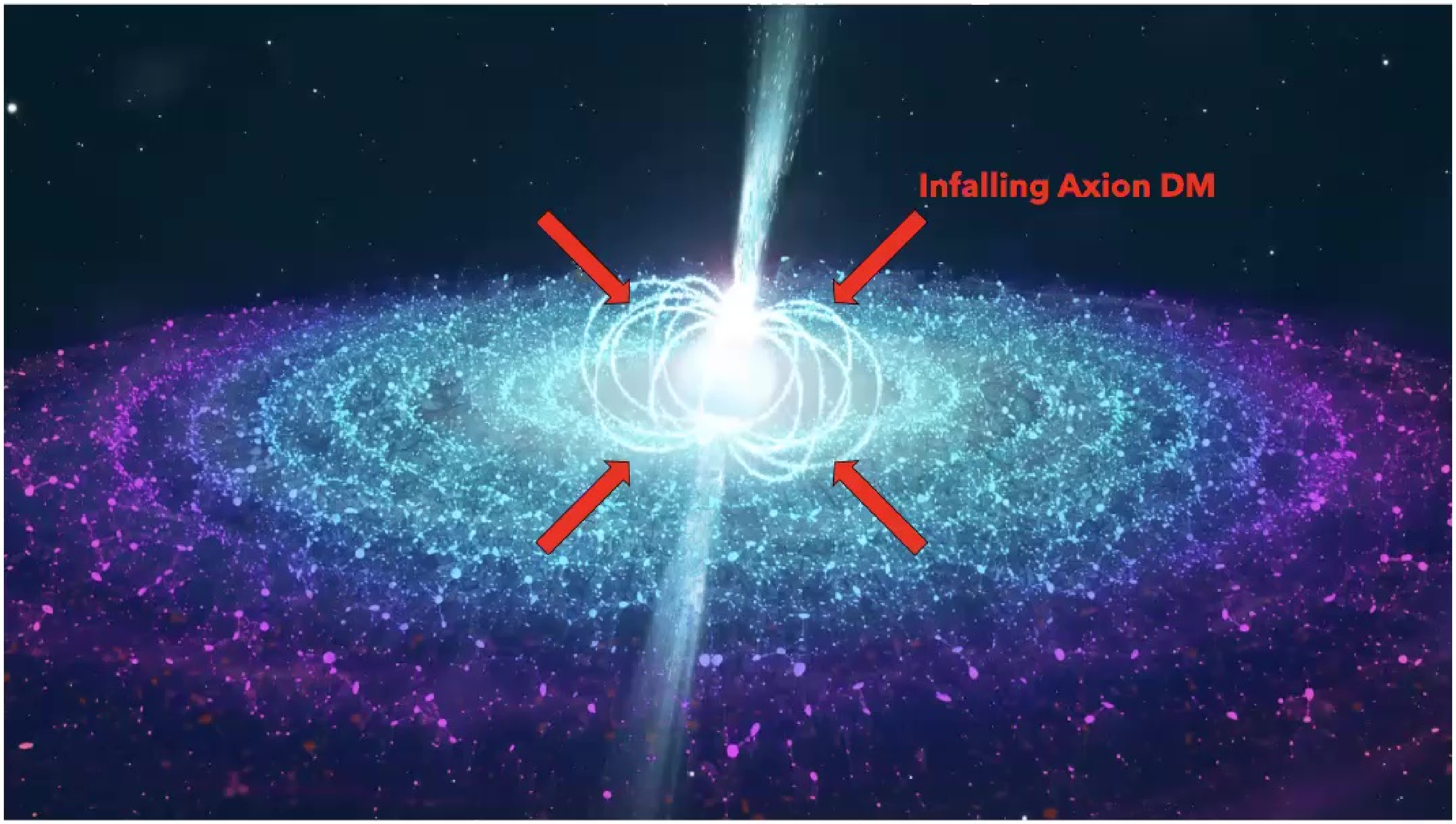
RADIO SEARCHES: SIGNAL PHENOMENOLOGY



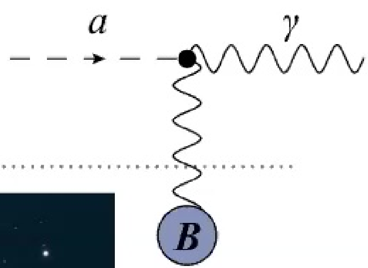
RADIO SEARCHES: SIGNAL PHENOMENOLOGY

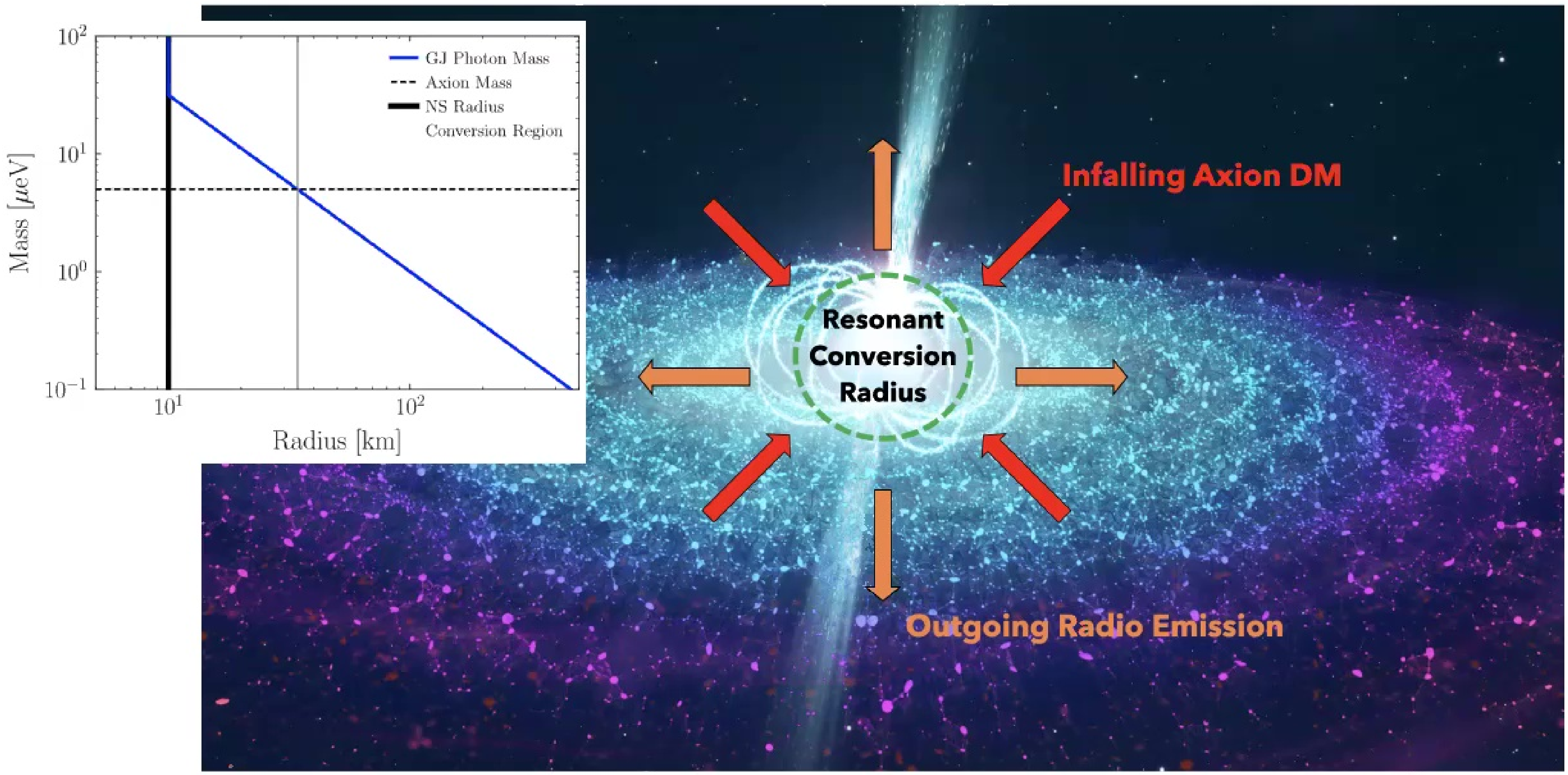


RADIO SEARCHES: SIGNAL PHENOMENOLOGY



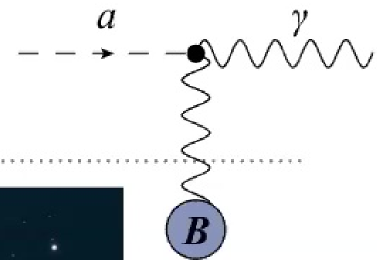
RADIO SEARCHES: SIGNAL PHENOMENOLOGY

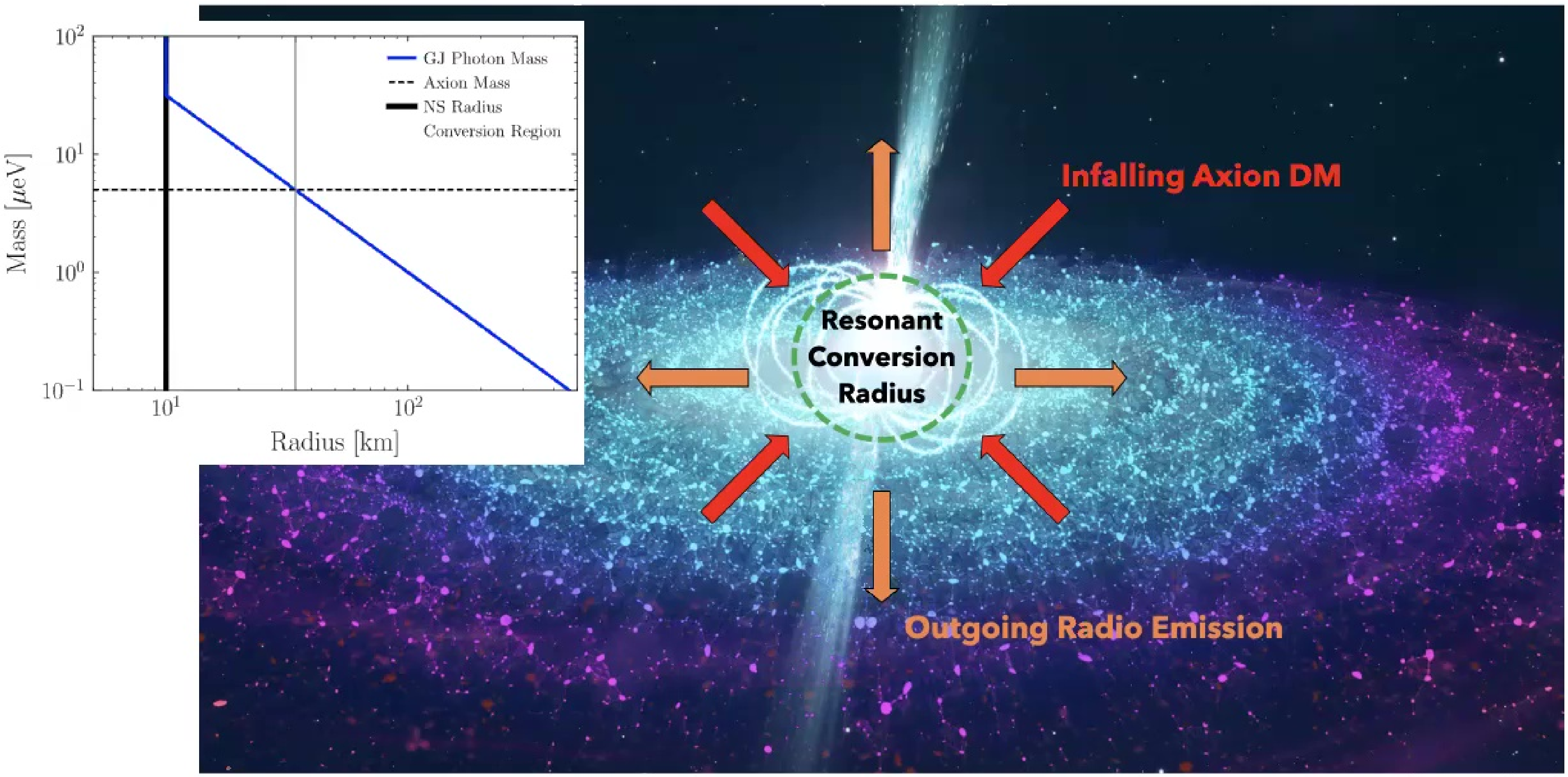




$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 L^2$$

RADIO SEARCHES: SIGNAL PHENOMENOLOGY





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

RADIO SEARCHES: SIGNAL PHENOMENOLOGY

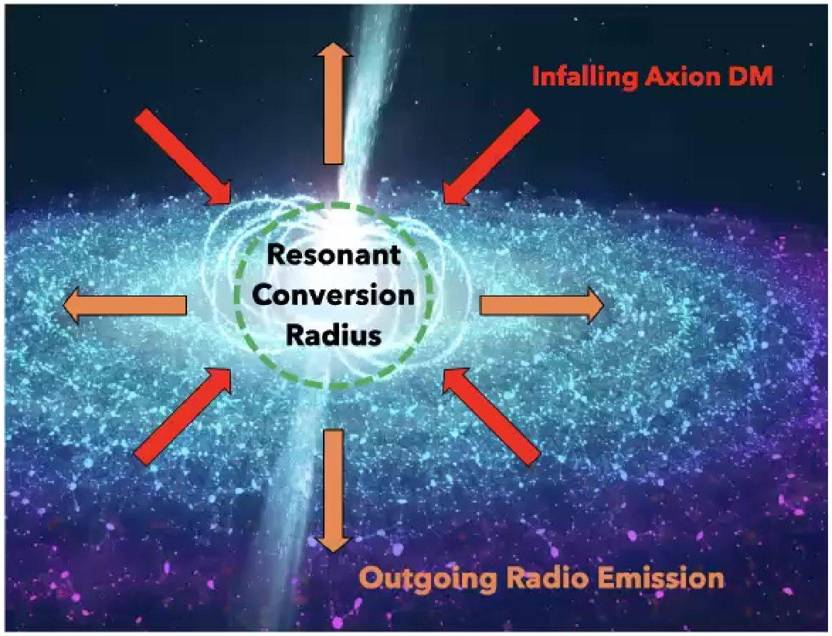
- Radio flux from conversion determined by:
  - axion particle properties
  - astrophysical axion distribution
  - NS properties

$$\mathcal{P} \sim \frac{g_{a\gamma\gamma}^2}{m_a^{2/3}} \times \frac{\rho_a(d_{NS})}{v_a d_{NS}^2} \times (B_{NS}^2 P_{NS}^4)^{1/3}$$

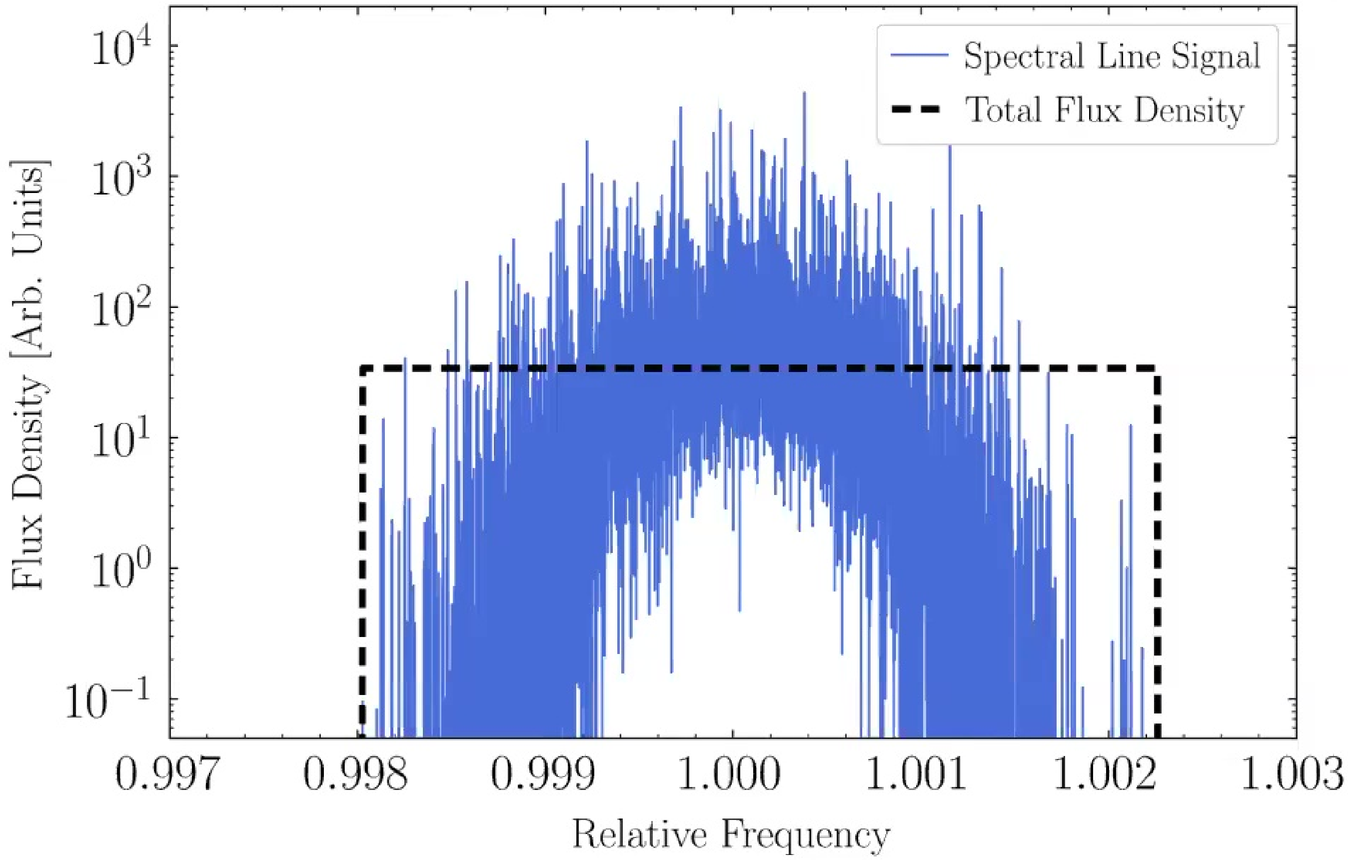
- Expected spectral morphology

$$f \sim m_a(1 + \mathcal{O}(v^2))/2\pi$$

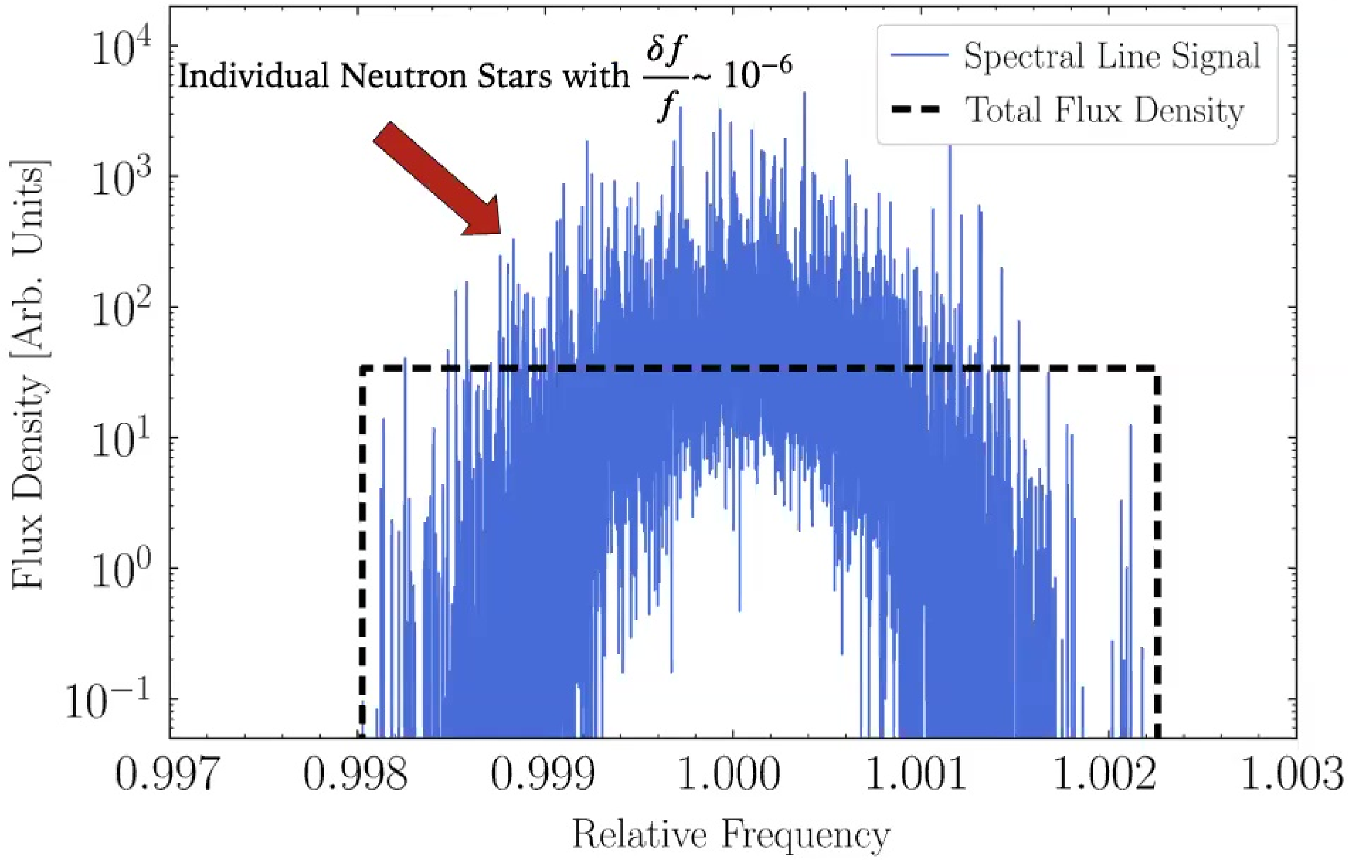
  - Quasi-monochromatic, broadened by astrophysical velocity distribution, medium effects



RADIO SEARCHES: SIGNAL PHENOMENOLOGY



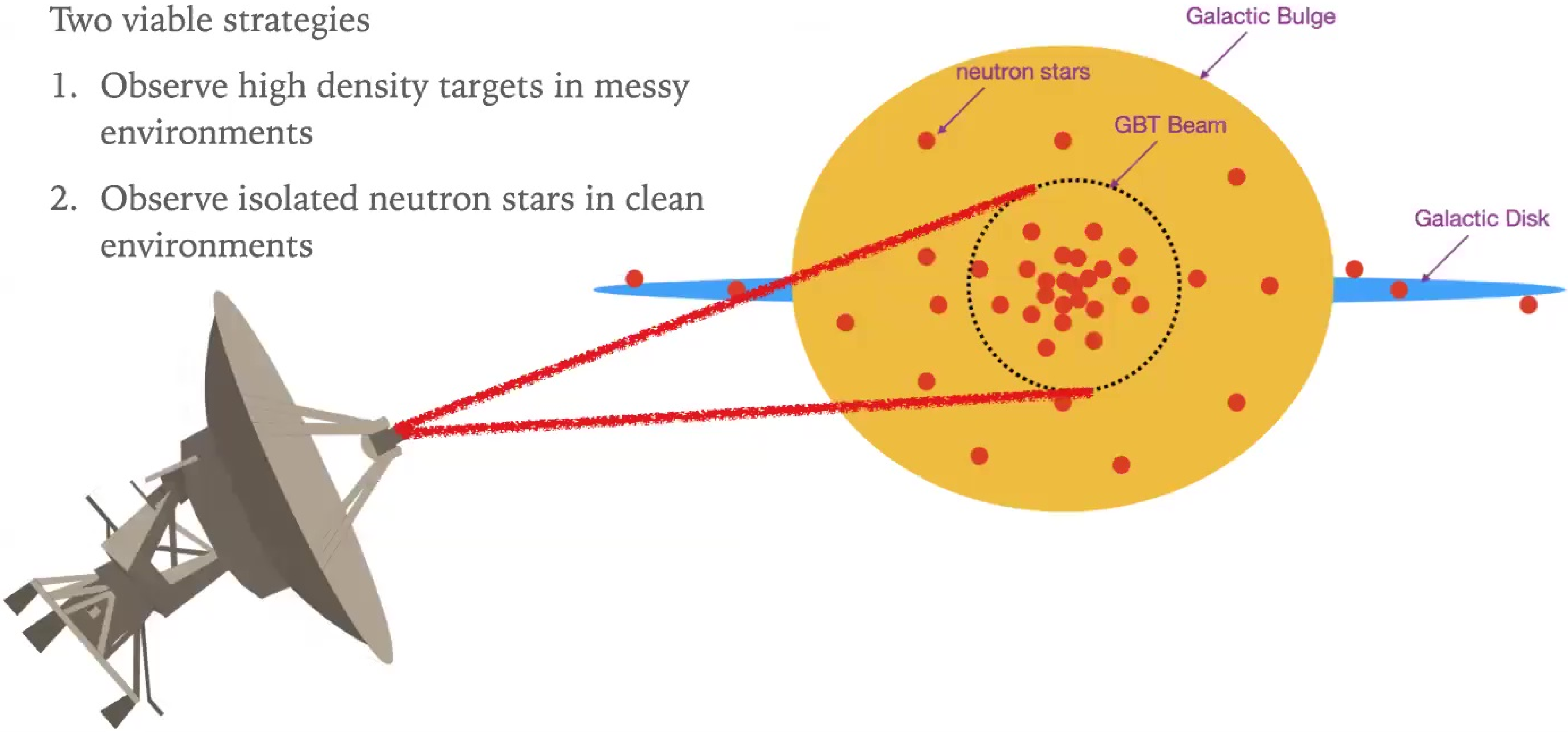
RADIO SEARCHES: SIGNAL PHENOMENOLOGY



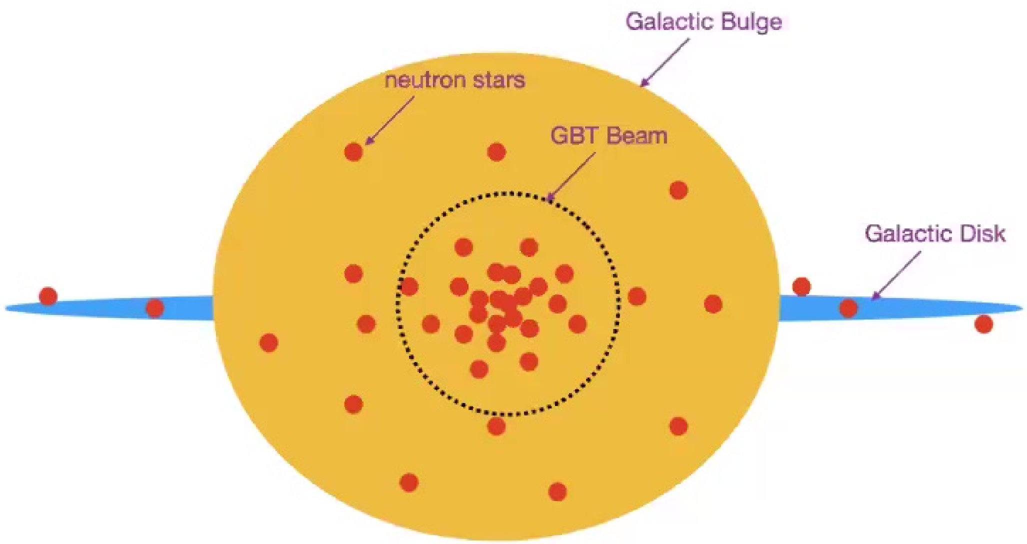
RADIO SEARCHES: OBSERVING STRATEGIES

Two viable strategies

1. Observe high density targets in messy environments
2. Observe isolated neutron stars in clean environments

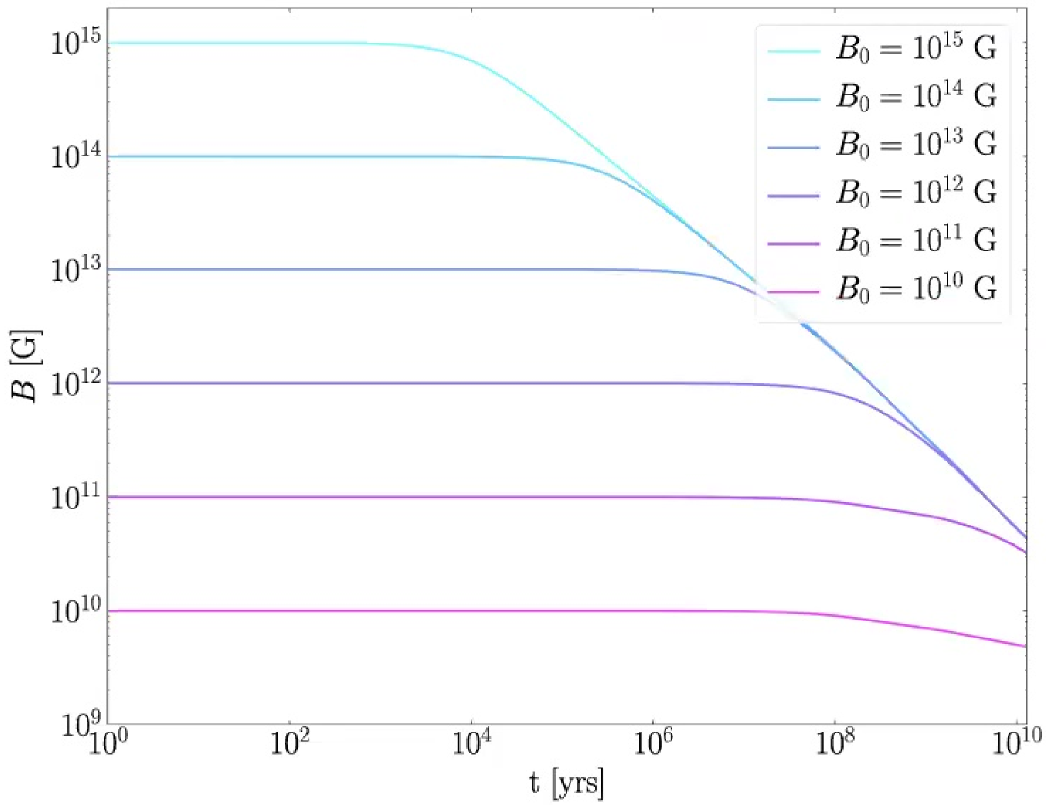


RADIO SEARCHES: POPULATION OBSERVATIONS

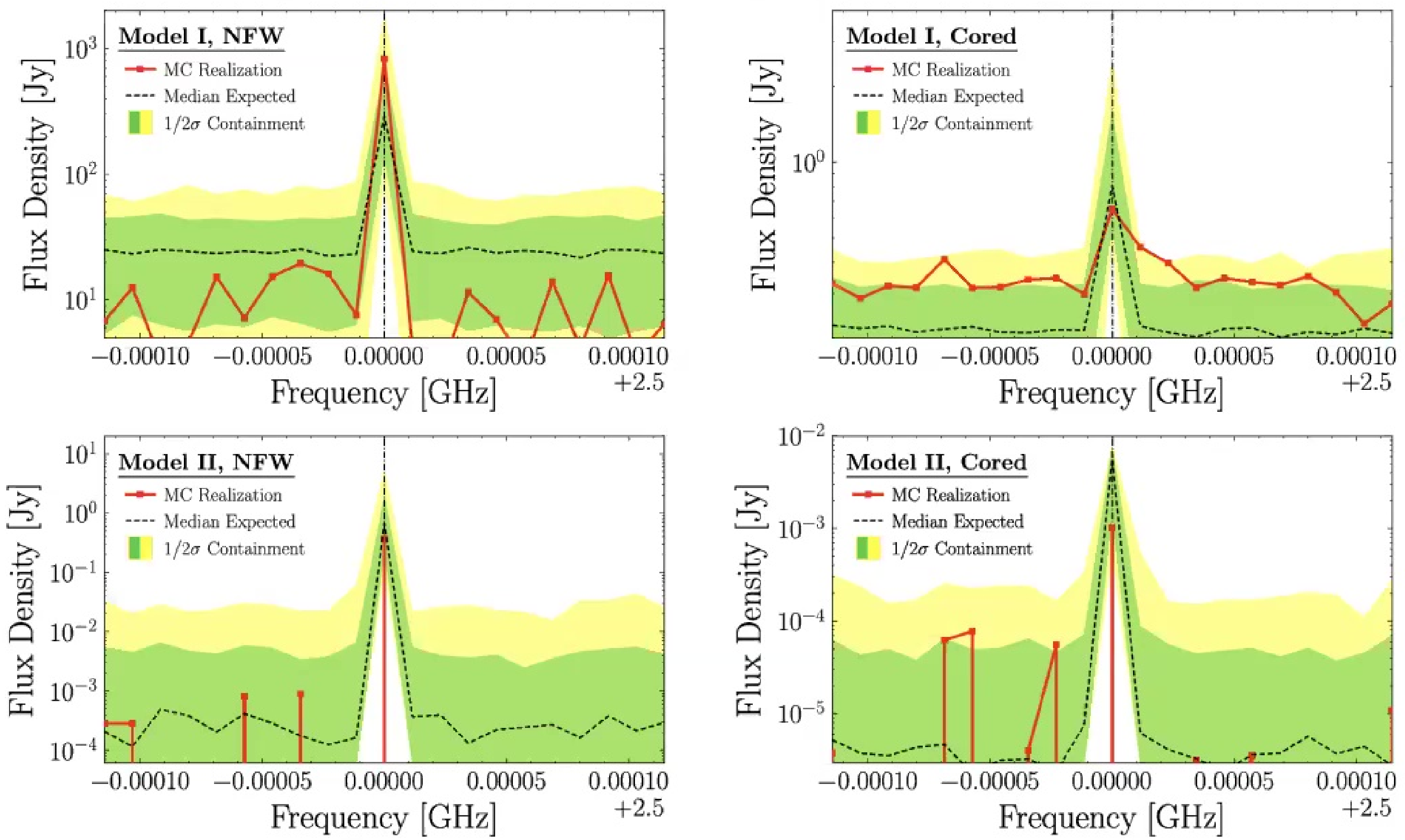


- Most neutron stars in galaxy haven't been directly detected, properties unknown
- Depend on population models for neutron star properties, spatial distribution, etc.
  - Modeling assumptions on neutron star evolution from birth to present day
- Expected signal only characterized statistically

RADIO SEARCHES: POPULATION MODELING



RADIO SEARCHES: POPULATION OBSERVATIONS



RADIO SEARCHES: ISOLATED NEUTRON STARS

- Seven nearby isolated neutron stars
  - Radio-quiet
  - No detected non-thermal emission
  - Nearby, d ~ 100-1000 pc
- B ~ 1e13-1e14 Gauss
- P ~ 1-10 seconds

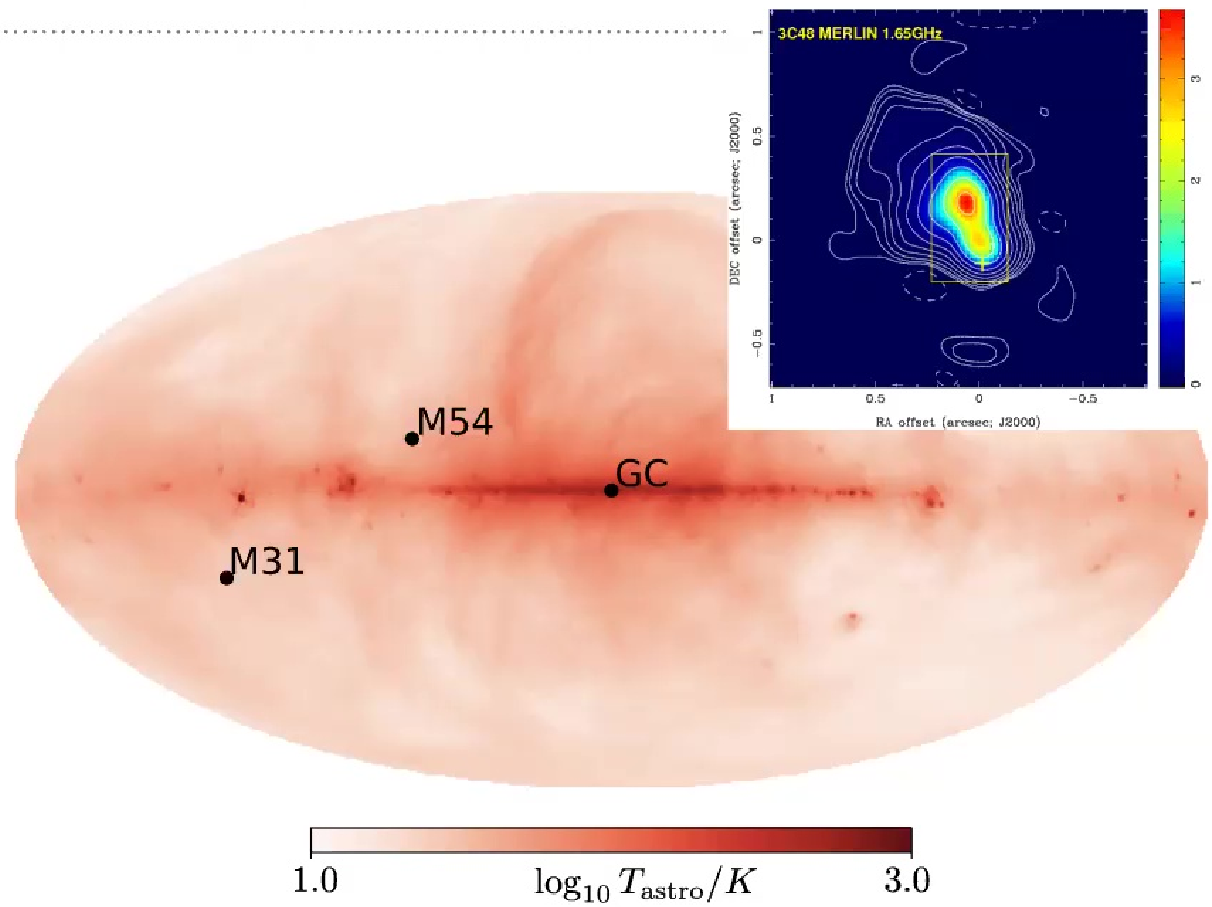
$$\mathcal{P} \sim \frac{g^2_{a\gamma\gamma}}{m_a^{2/3}} \times \frac{\rho_a(d_{NS})}{v_a d^2_{NS}} \times (B^2_{NS} P^4_{NS})^{1/3}$$

- Limited mass reach as conversion turns off ~ 7 GHz

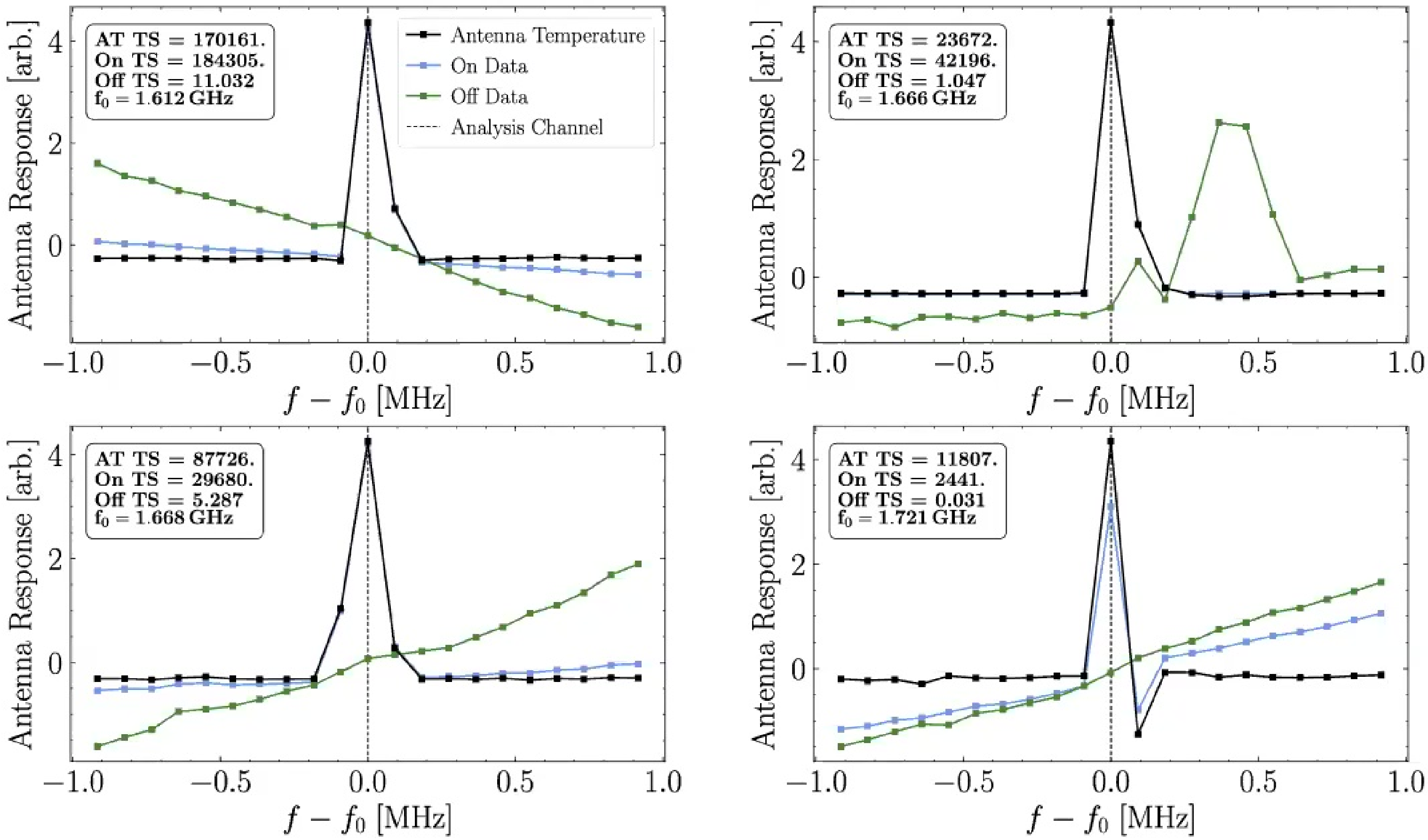
M7 Name	$\log(B_0/\mathrm{G})$	P [s]	d [pc]
RX J0806.4-4123	13.40 ± 0.13	11.37	240 ± 25
RX J1856.6-3754	13.18 ± 0.05	7.05	123 ± 13
RX J0420.0-5022	13.00 ± 0.06	3.45	345 ± 200
RX J1308.6+2127	13.68 ± 0.04	10.31	663 ± 137
RX J0720.4-3125	13.53 ± 0.05	8.39	361 ± 130
RX J1605.3+3249	13.00 ± 0.20	6.88	393 ± 219
RX J2143.0+0654	13.30 ± 0.10	9.44	430 ± 200

RADIO SEARCHES: OBSERVING STRATEGIES AND CALIBRATION

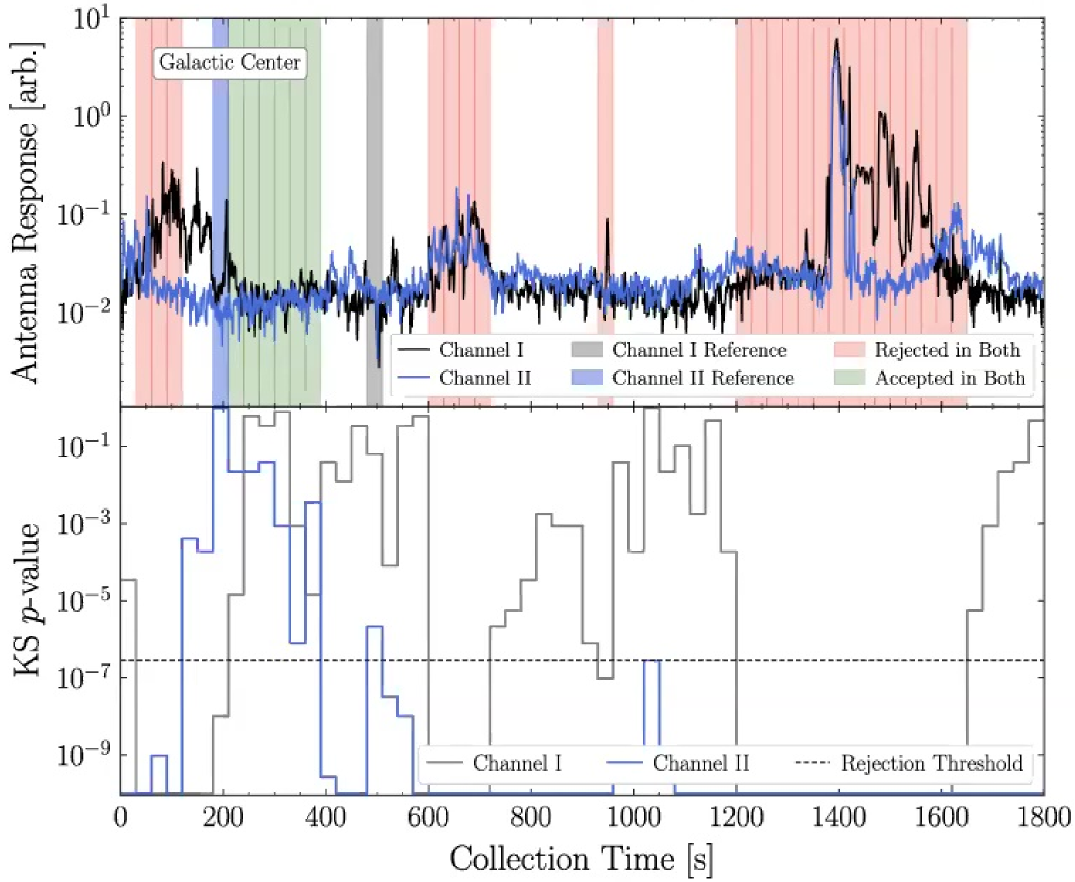
- Position switched measurements with calibration noise diode
  - Noise diode calibrates system temperature
  - Off measurement removes backgrounds
  - Calibration measurement of known source to convert to flux density
- Dual polarizations, high frequency resolution
- Collected with GBT and Effelsberg



RADIO SEARCHES: OBSERVING STRATEGIES AND CALIBRATION

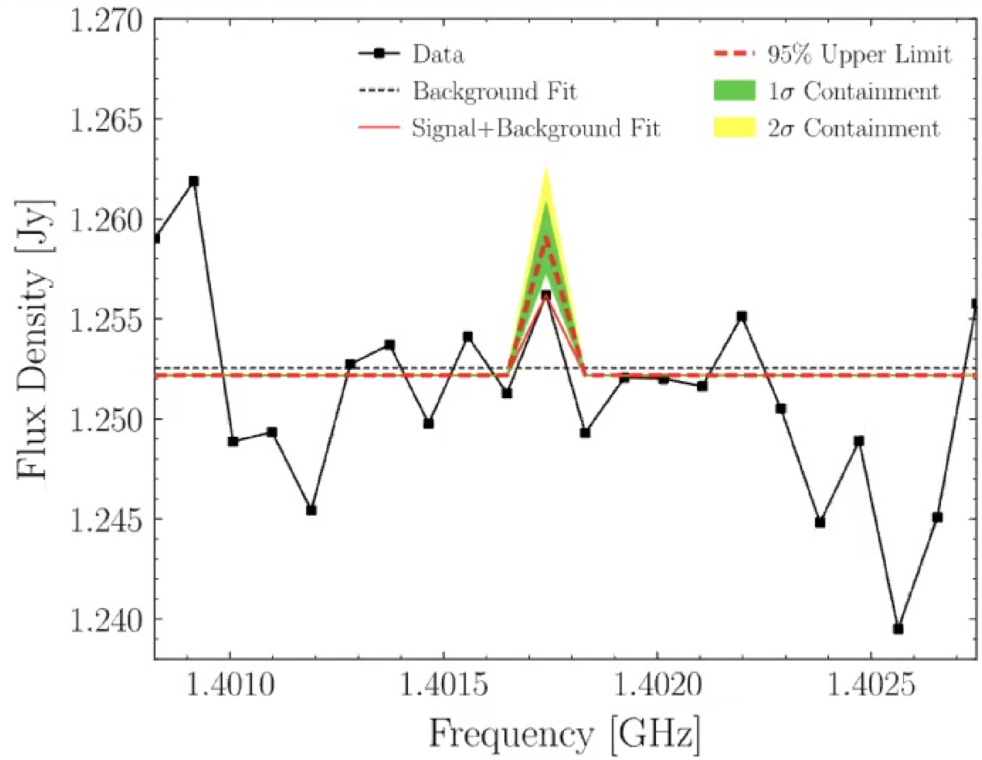


RADIO SEARCHES: DATA CLEANING AND CALIBRATION



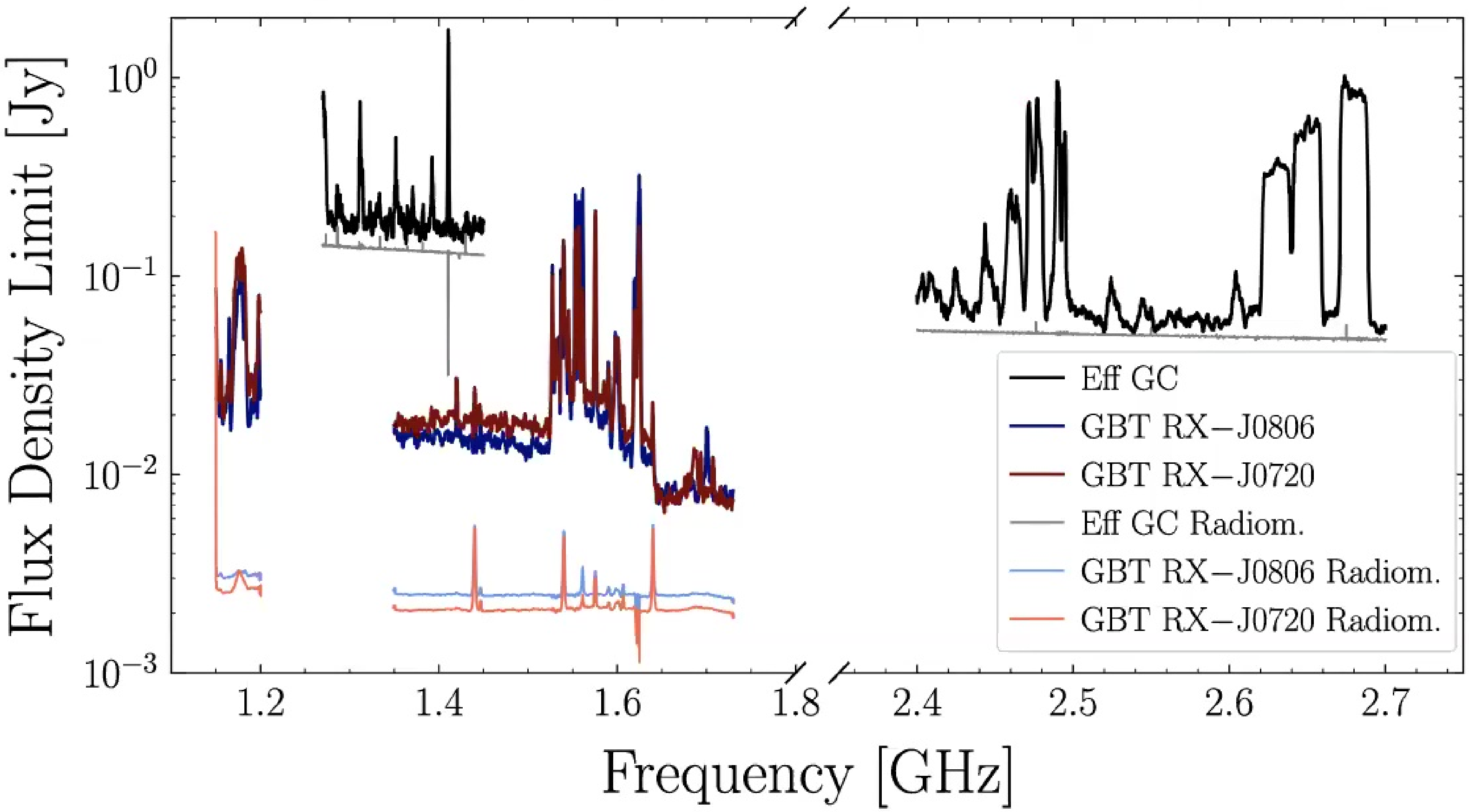
RADIO SEARCHES: DATA ANALYSIS

- Line search in windowed data
  - Quadratic background +spectral line signal model
- Frequentist limits set using profiled gaussian likelihoods
- Power-constrained limits for downward fluctuations
- Assumed statistics require *a posteriori* check

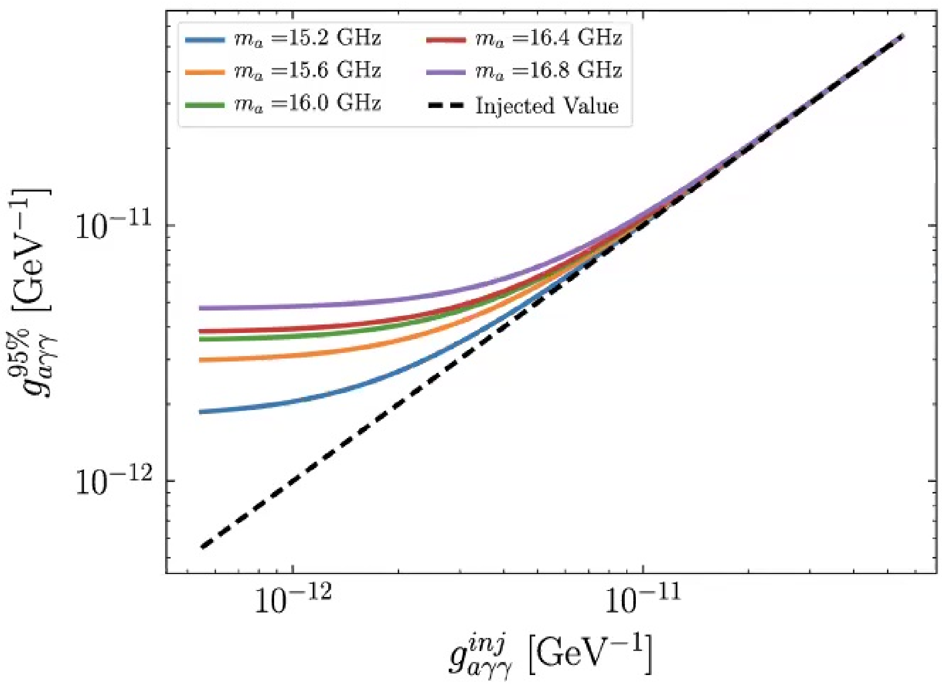


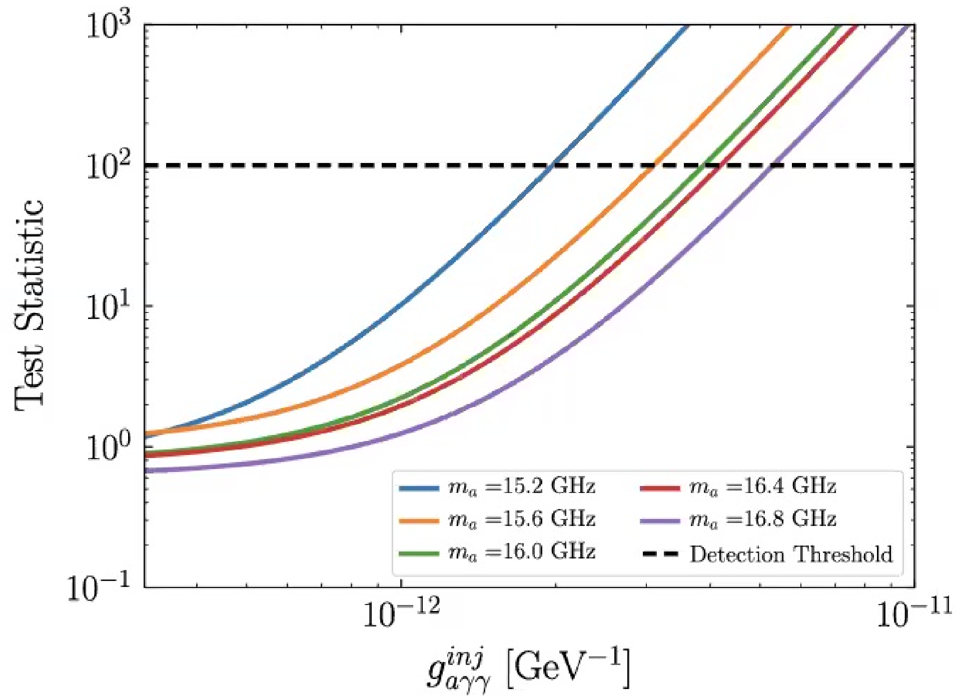
$$\mathcal{L}(d|m_a, A; \mathbf{a}, \sigma) = \prod_k \frac{1}{\sqrt{2\pi\sigma_k^2}} \exp\left[-\frac{(d_k - As_k - \mu_k(\mathbf{a}))^2}{2\sigma_k^2}\right]$$

RADIO SEARCHES: DATA ANALYSIS

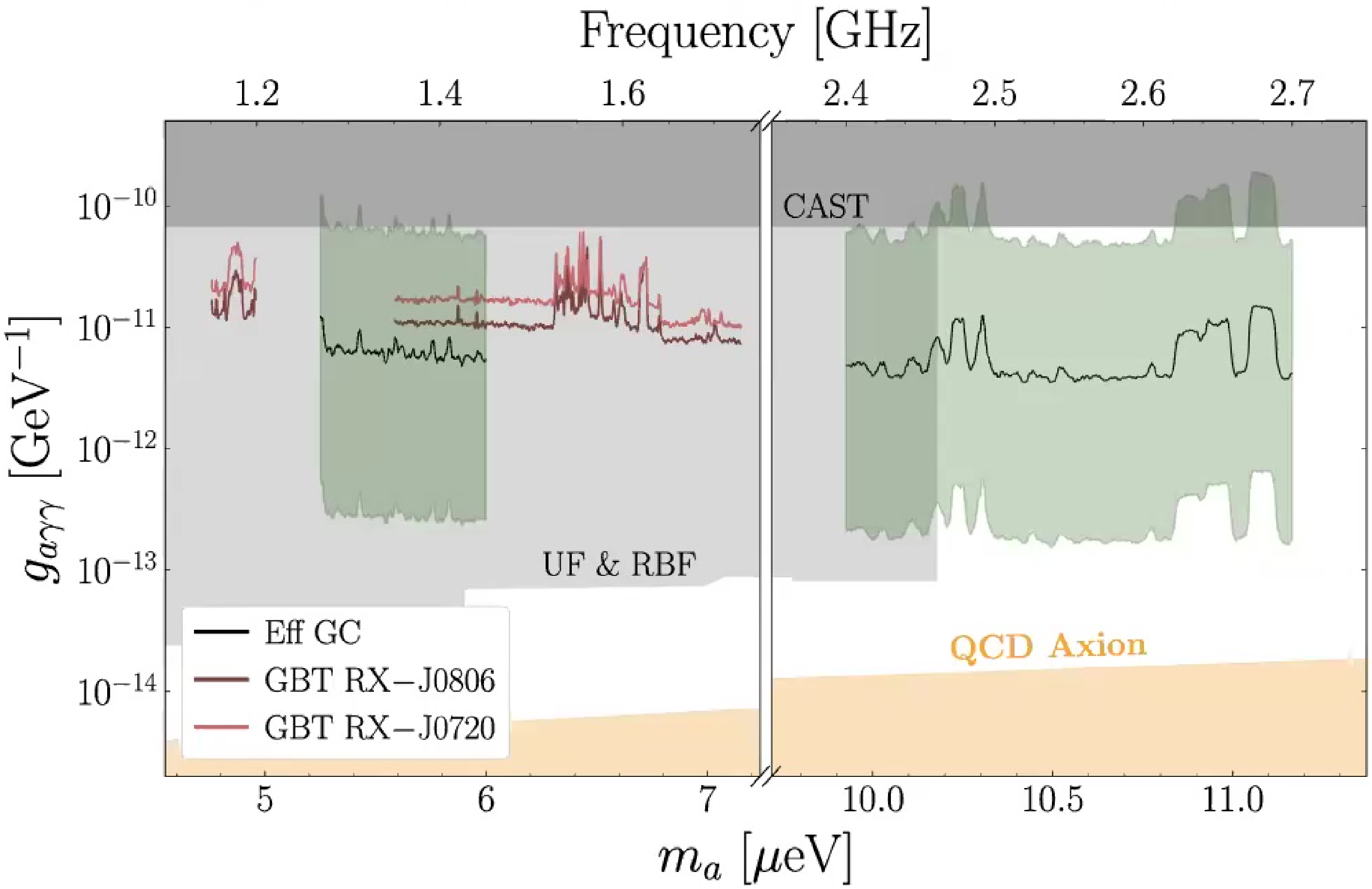


RADIO SEARCHES: DATA ANALYSIS

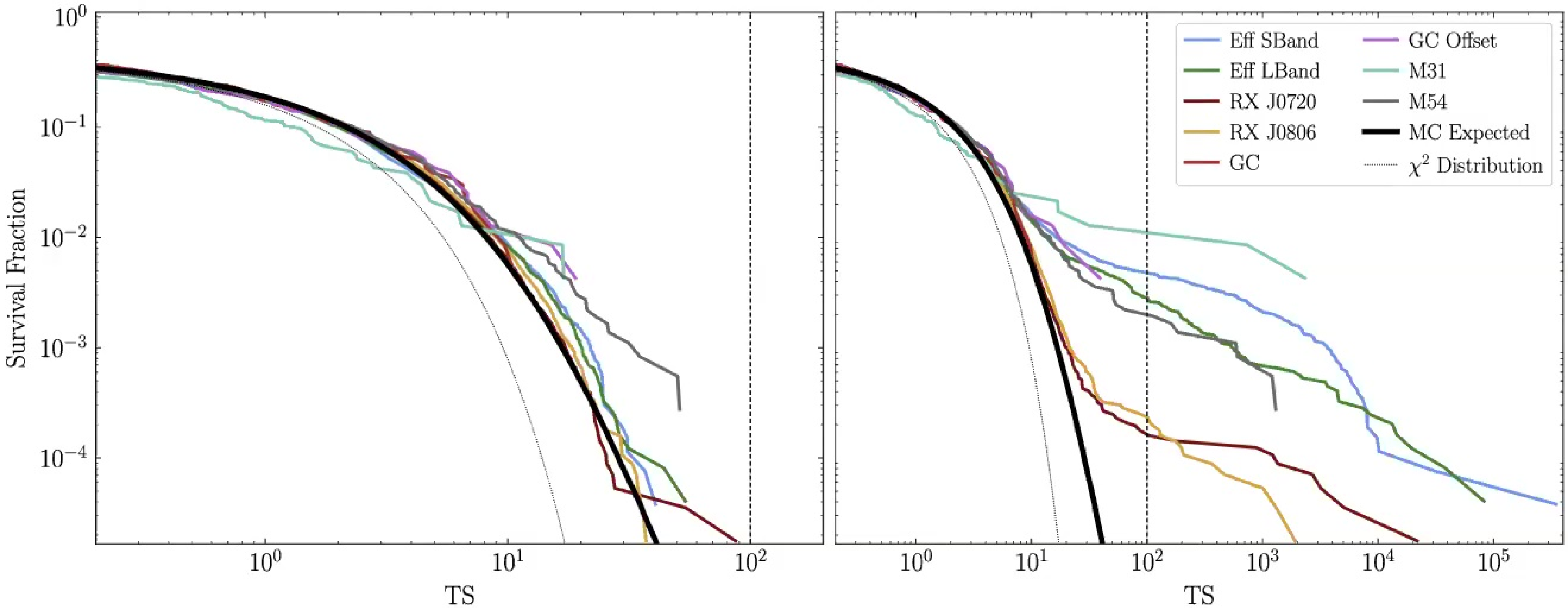




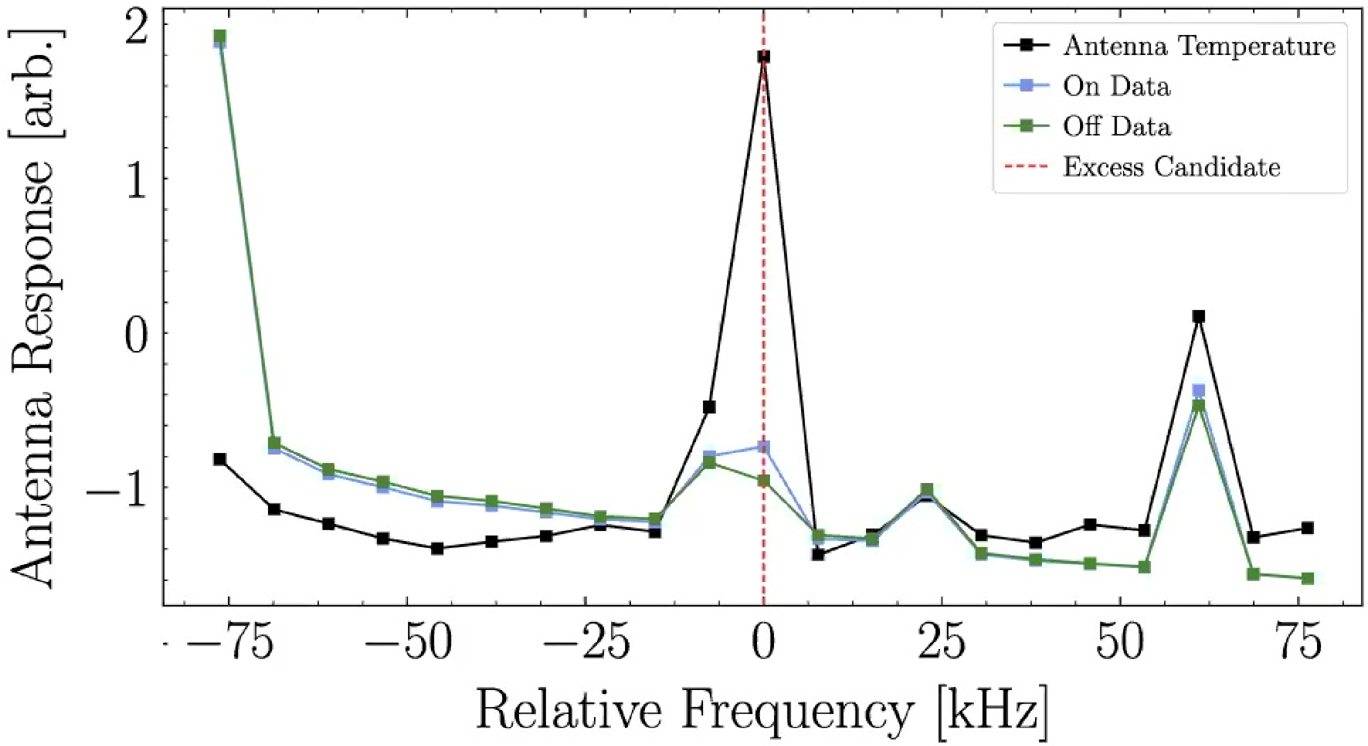
RADIO SEARCHES: AXION CONSTRAINTS



RADIO SEARCHES: SIGNIFICANCE DISTRIBUTION

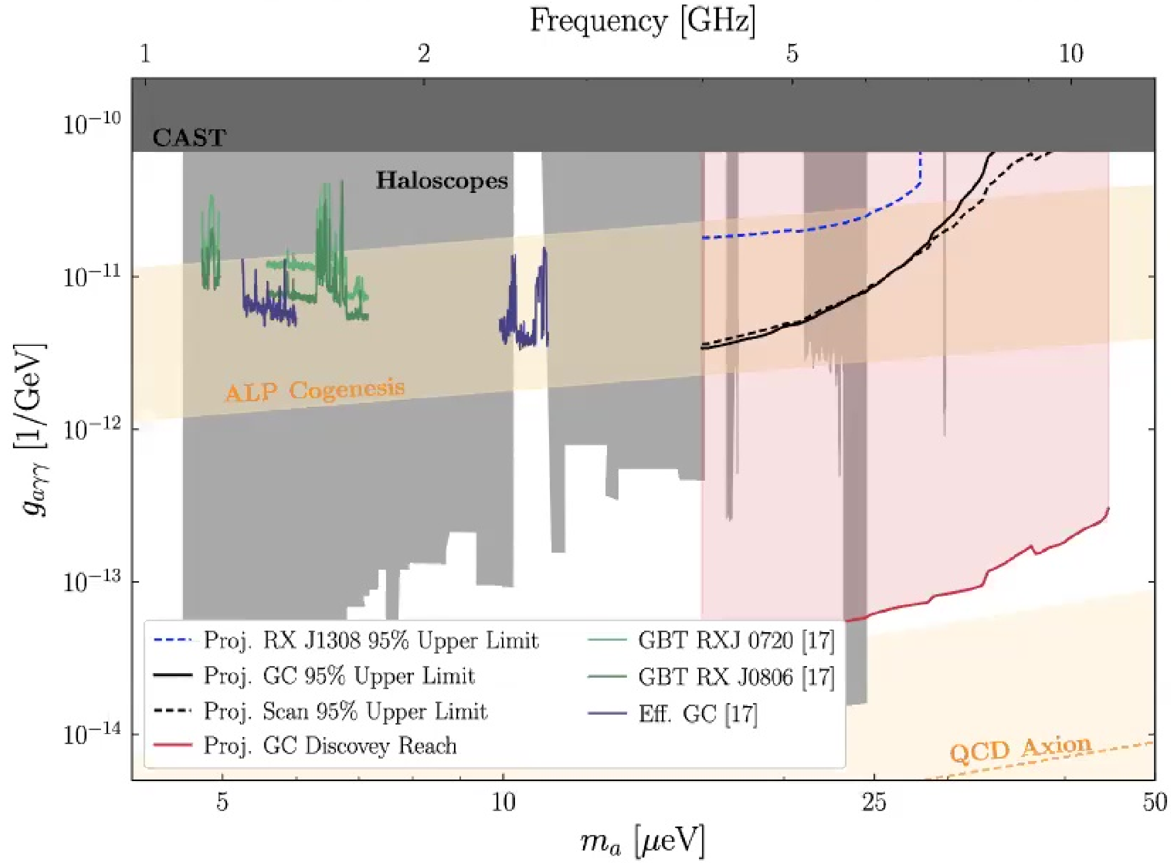


RADIO SEARCHES: EXCESS CANDIDATE

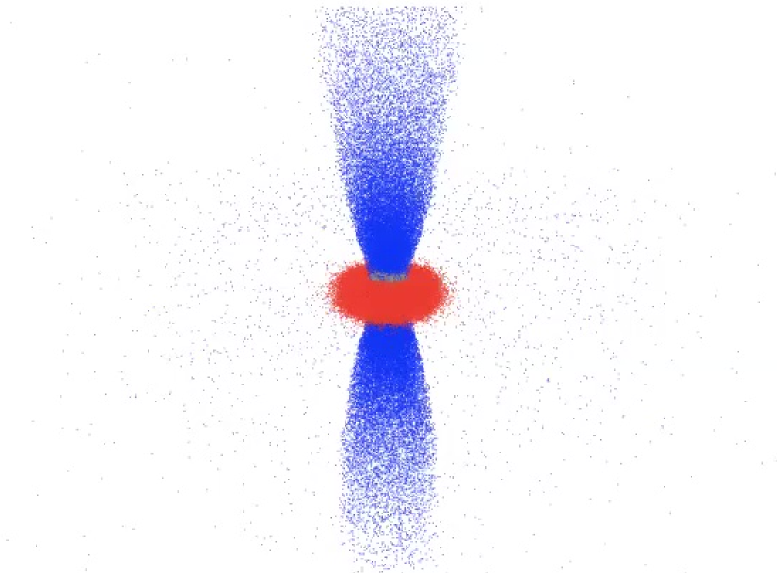


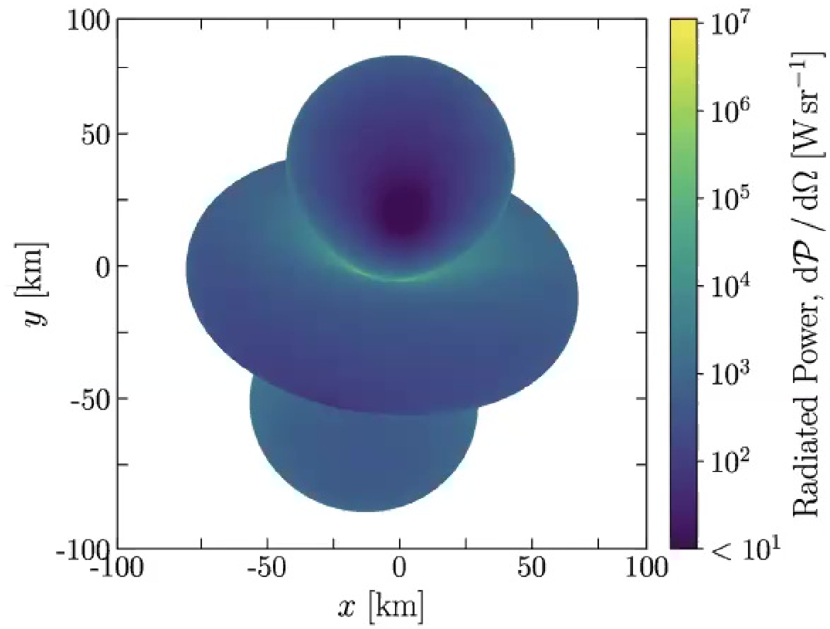
RADIO SEARCHES: FUTURE SEARCHES AND OBJECTIVES

- Archival data from the Breakthrough Listen Project
- Surveys with the Murchison Widefield Array
- Newly proposed dedicated observing with GBT
  - 24 hours covering 4-10 GHz
- A number of instruments, ongoing work to find optimal search strategy



RADIO SEARCHES: FUTURE SEARCHES AND OBJECTIVES

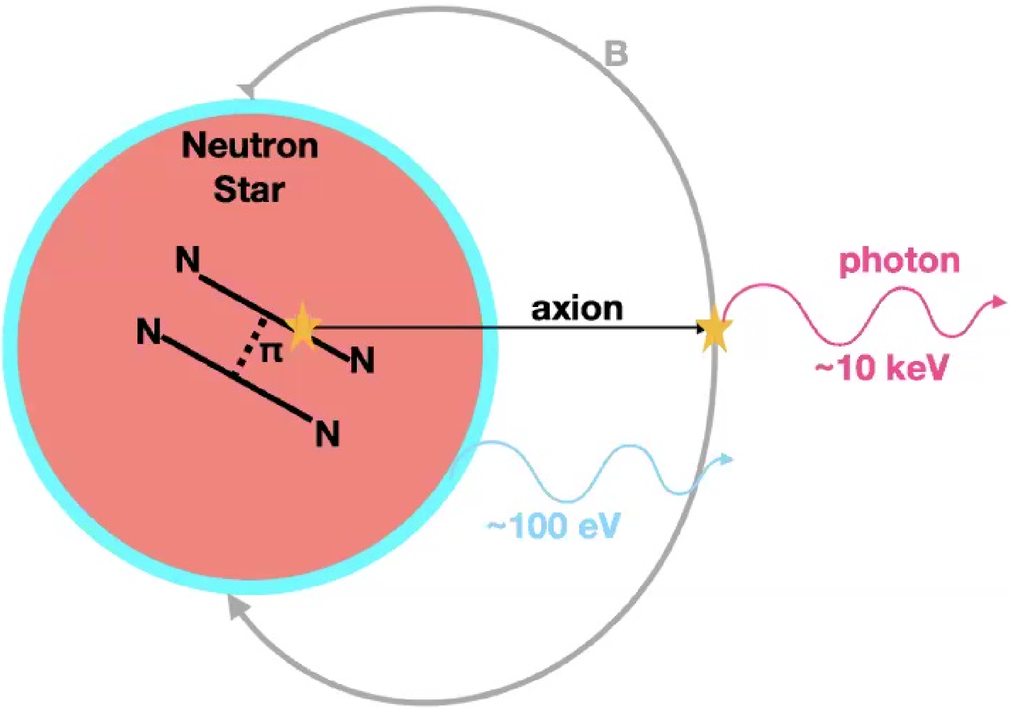




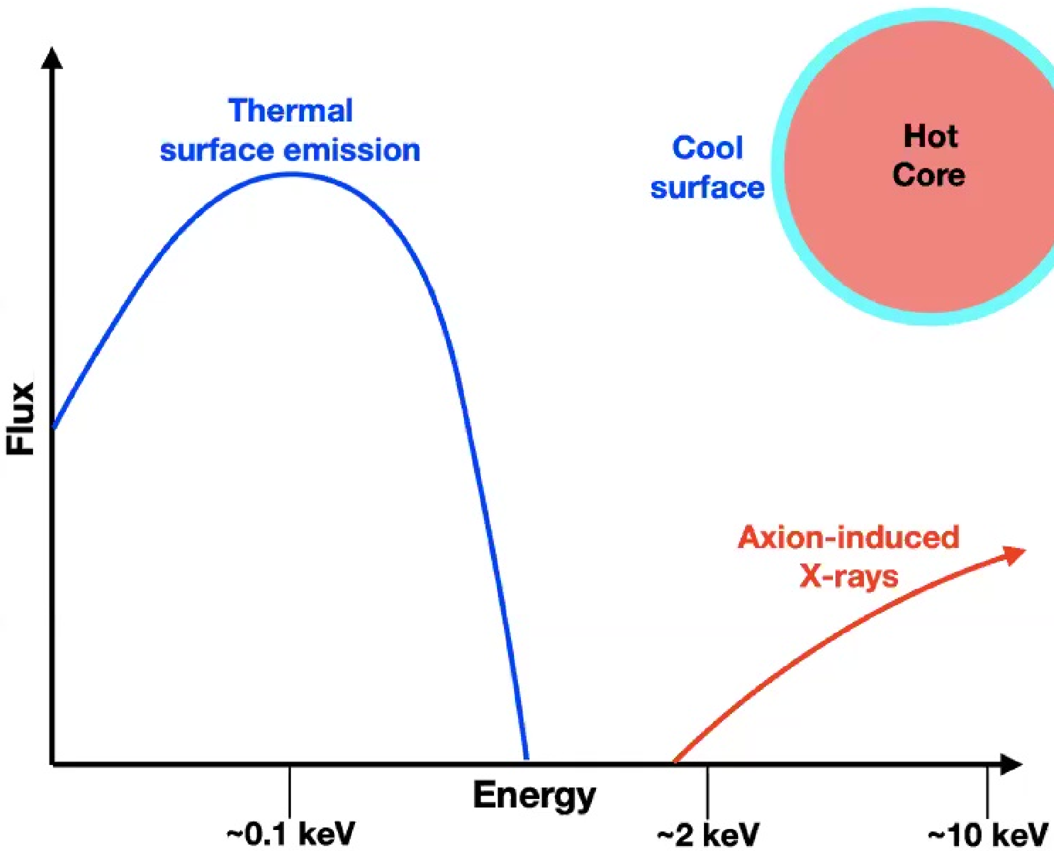
- Theory wishlist:
  - Full 3D simulations of magnetosphere + axion conversion
  - Consistent propagation of outgoing photons
  - Improved NS population models
  - Calculation for active pulsars

Safdi et al. 1811.01020, Leroy et al. 1912.08815, Battye et al. 1910.11907

THERMAL PRODUCTION OF AXIONS IN NEUTRON STAR CORES

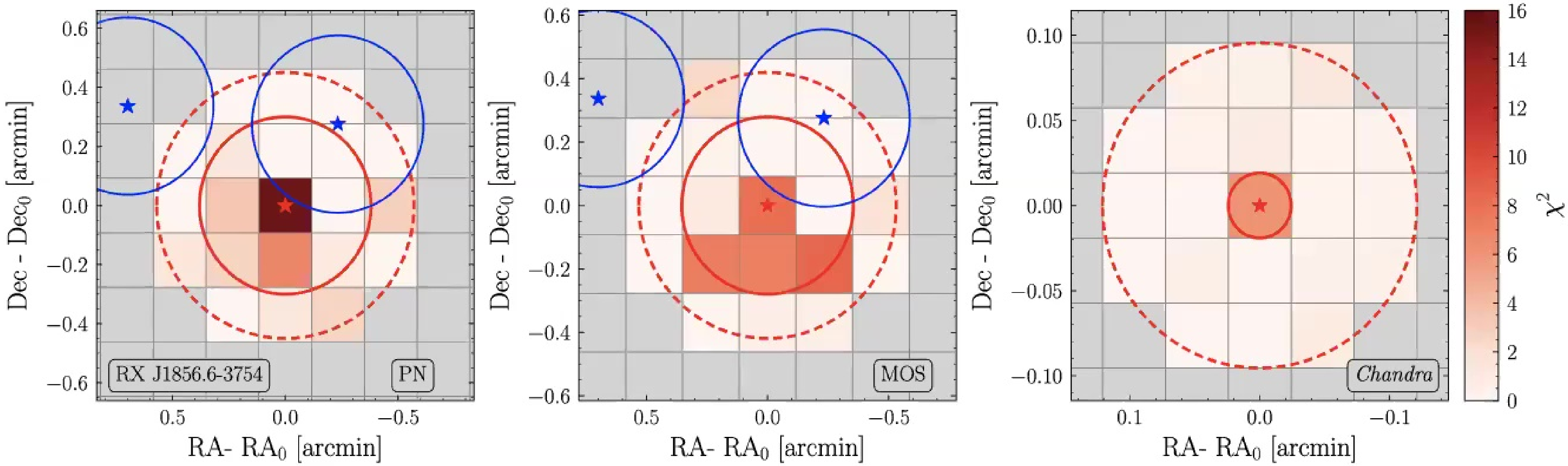


LIGHT SHINING THROUGH NEUTRON STAR CORES

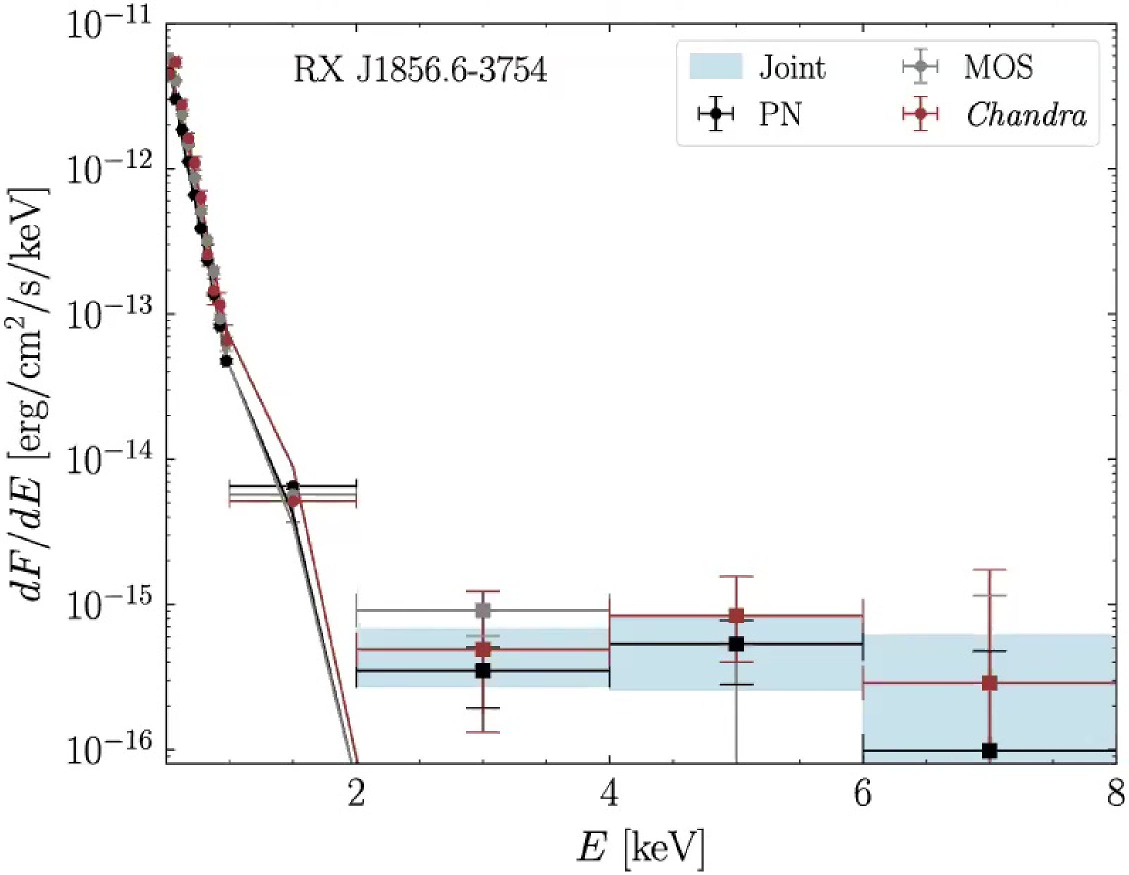


- Same isolated neutron stars relevant for radio searches
- Archival data at all seven from XMM-Newton, *Chandra* telescopes
- Different systematics, good complementarity

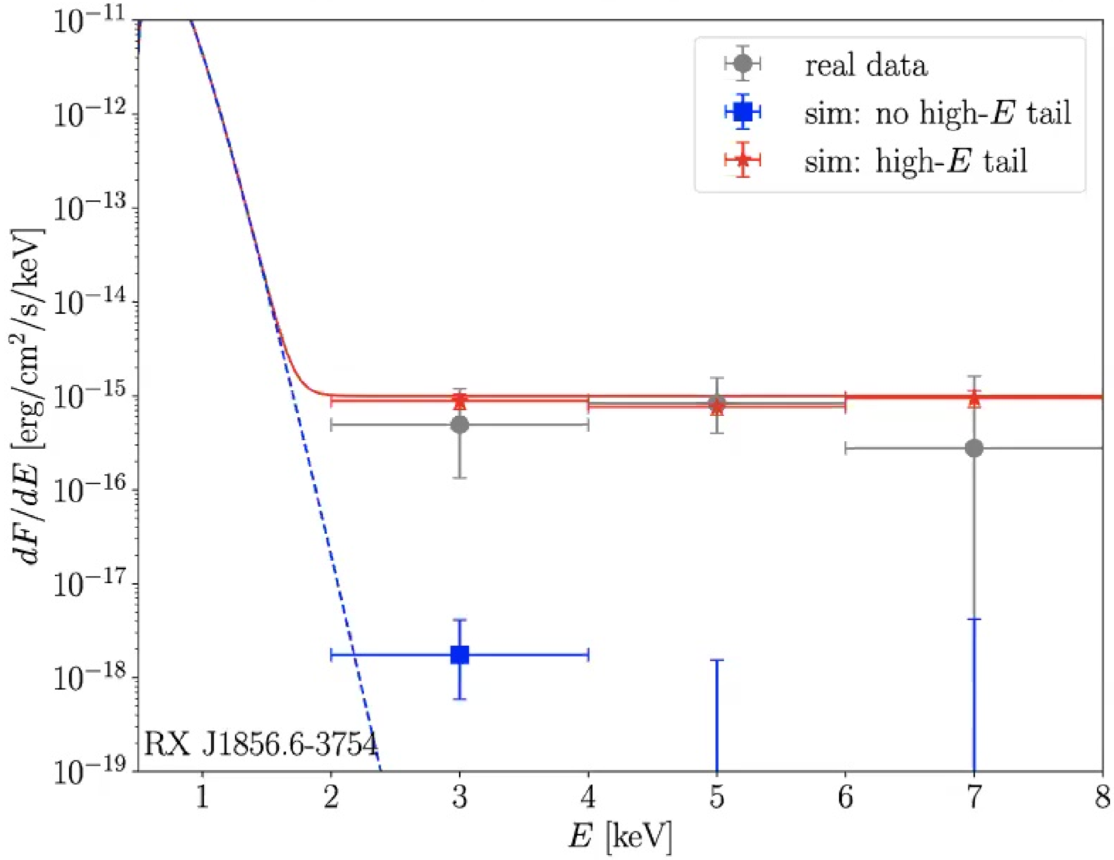
HARD X-RAY EXCESSES IN THE M7



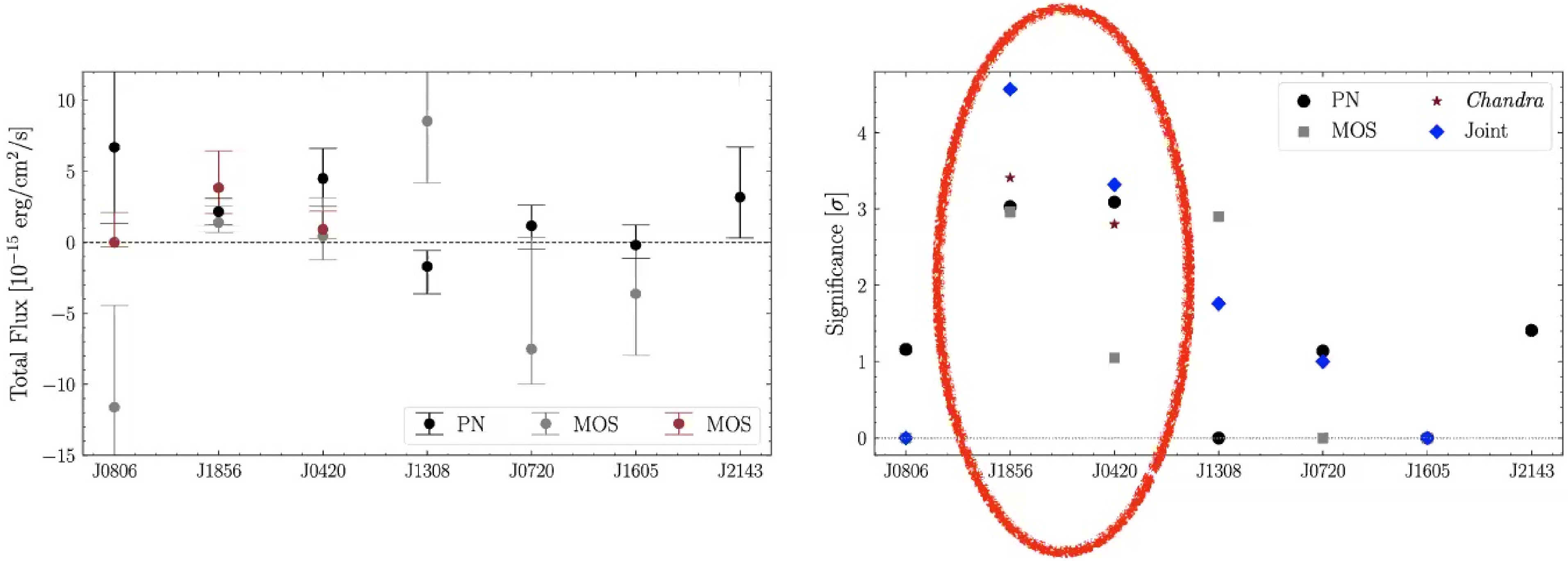
HARD X-RAY EXCESSES IN THE M7



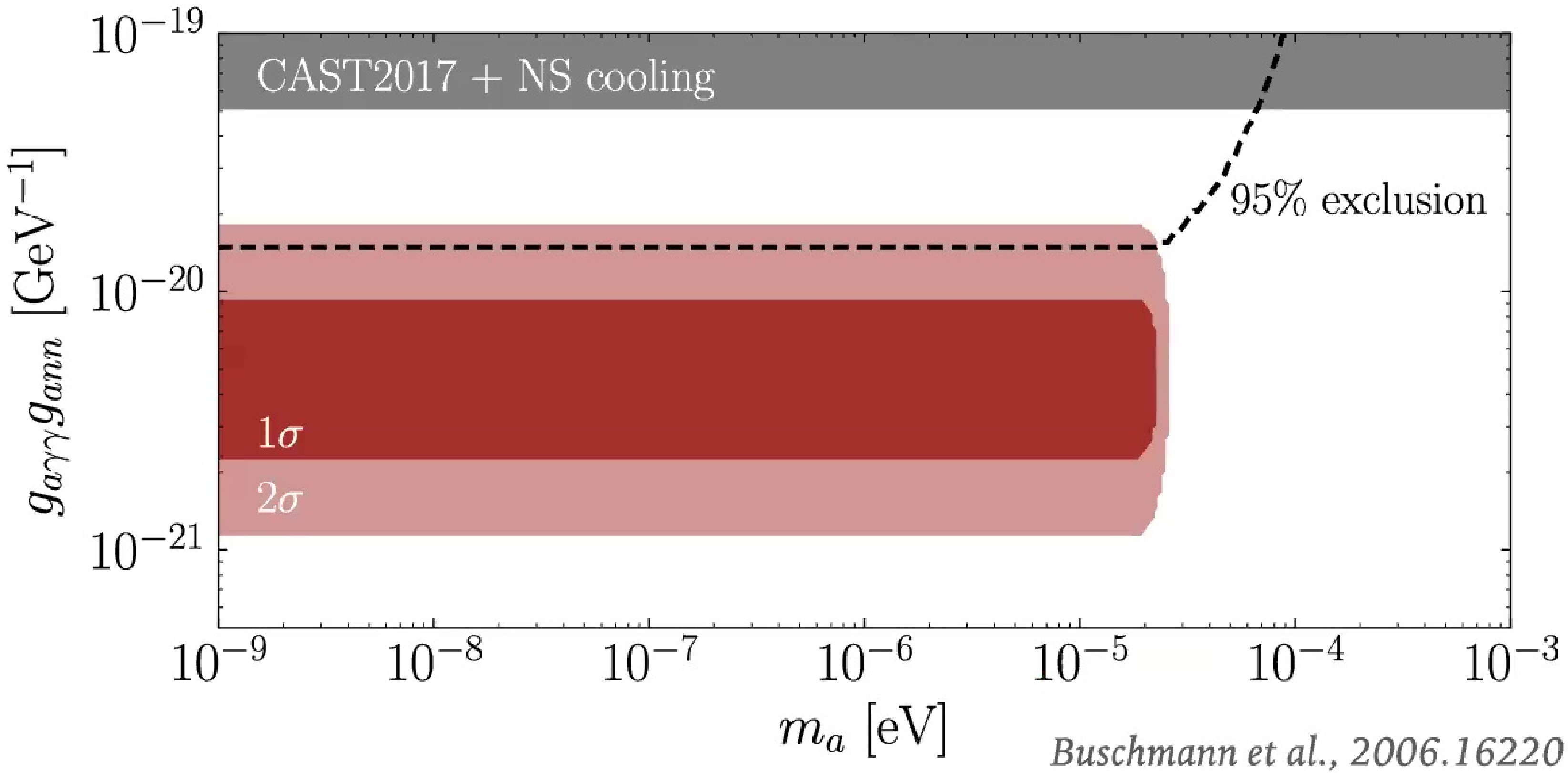
HARD X-RAY EXCESSES IN THE M7



HARD X-RAY EXCESSES IN THE M7

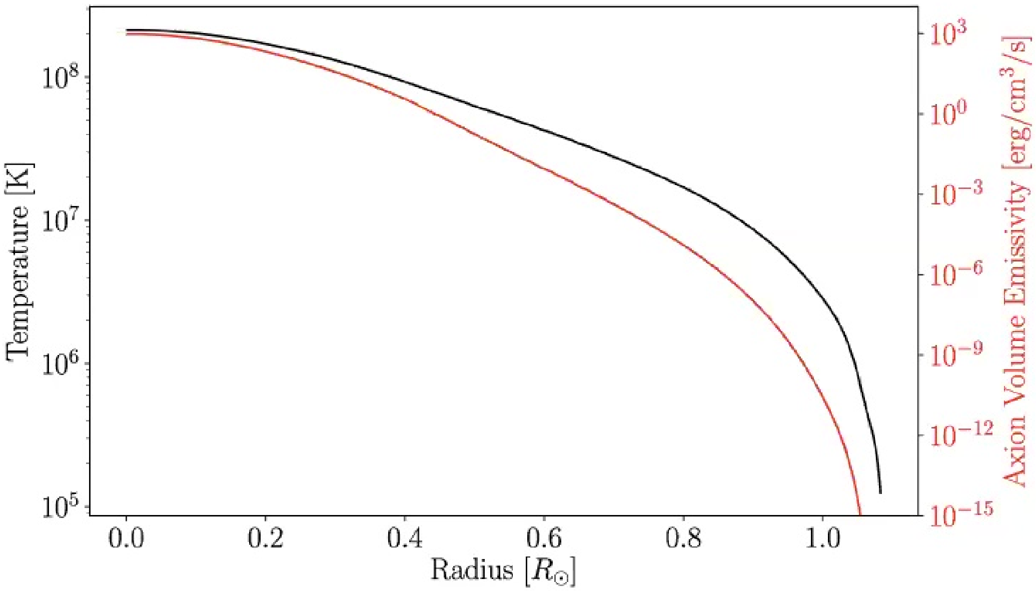


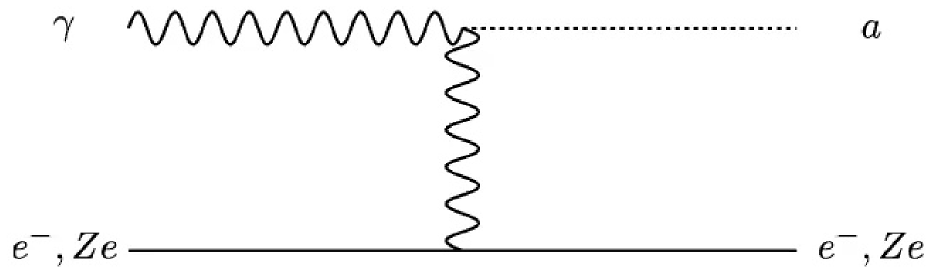
AXION INTERPRETATION OF THE HARD X-RAY EXCESS



Buschmann et al., 2006.16220 [hep-ph]

THERMAL PRODUCTION OF AXIONS IN HOT YOUNG STARS





G. Raffelt. Phys. Rev. D **33**, 897, 1986

G. Raffelt. Phys. Rev. D **37**, 1356,1988

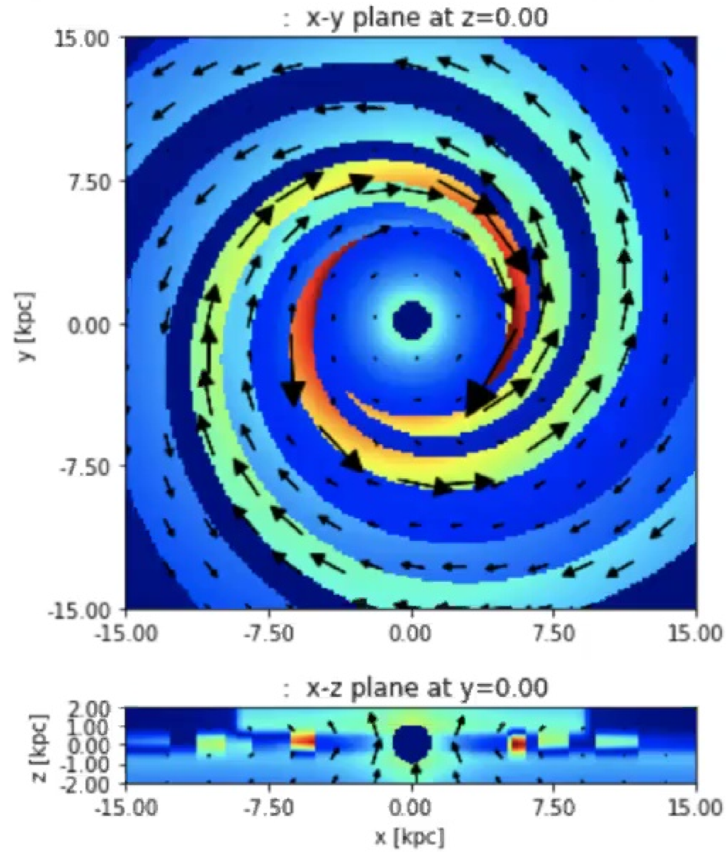
$$\mathcal{L}_a \sim T^4 - T^7$$

AXION CONVERSION IN GALACTIC MAGNETIC FIELD

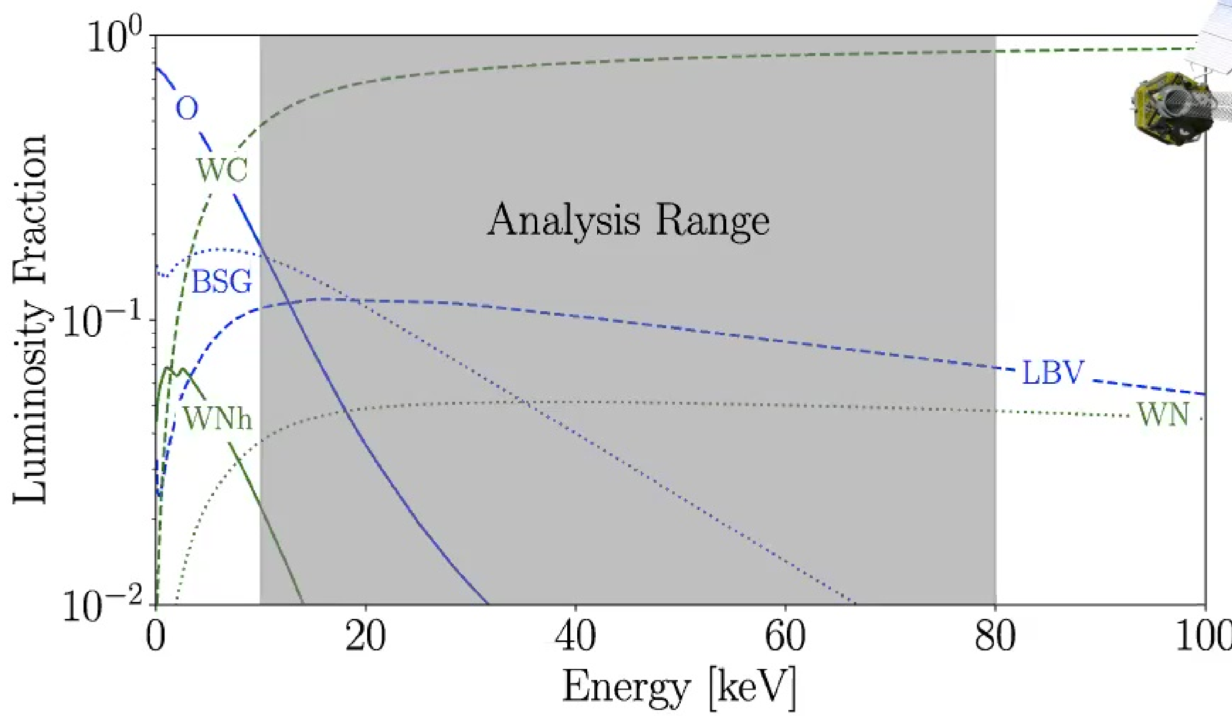
- Restrict to the coherent component of the galactic magnetic field
- Conversion probabilities computed from a line-of-sight integral

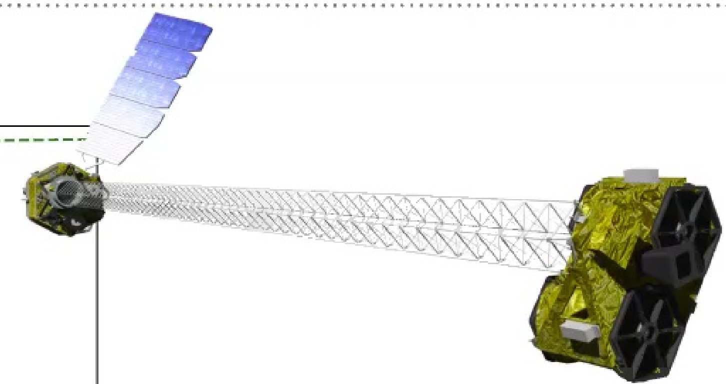
$$p_{a\to\gamma} = \frac{g_{a\gamma\gamma}^2}{4} \sum_{i=1,2} \left| \int_0^d dr' B_i(r') e^{i\Delta_a r' - i\int_0^{r'} dr'' \Delta_{||}(r'')} \right|^2$$

- Galactic certain magnetic field currently uncertain, make conservative underestimates



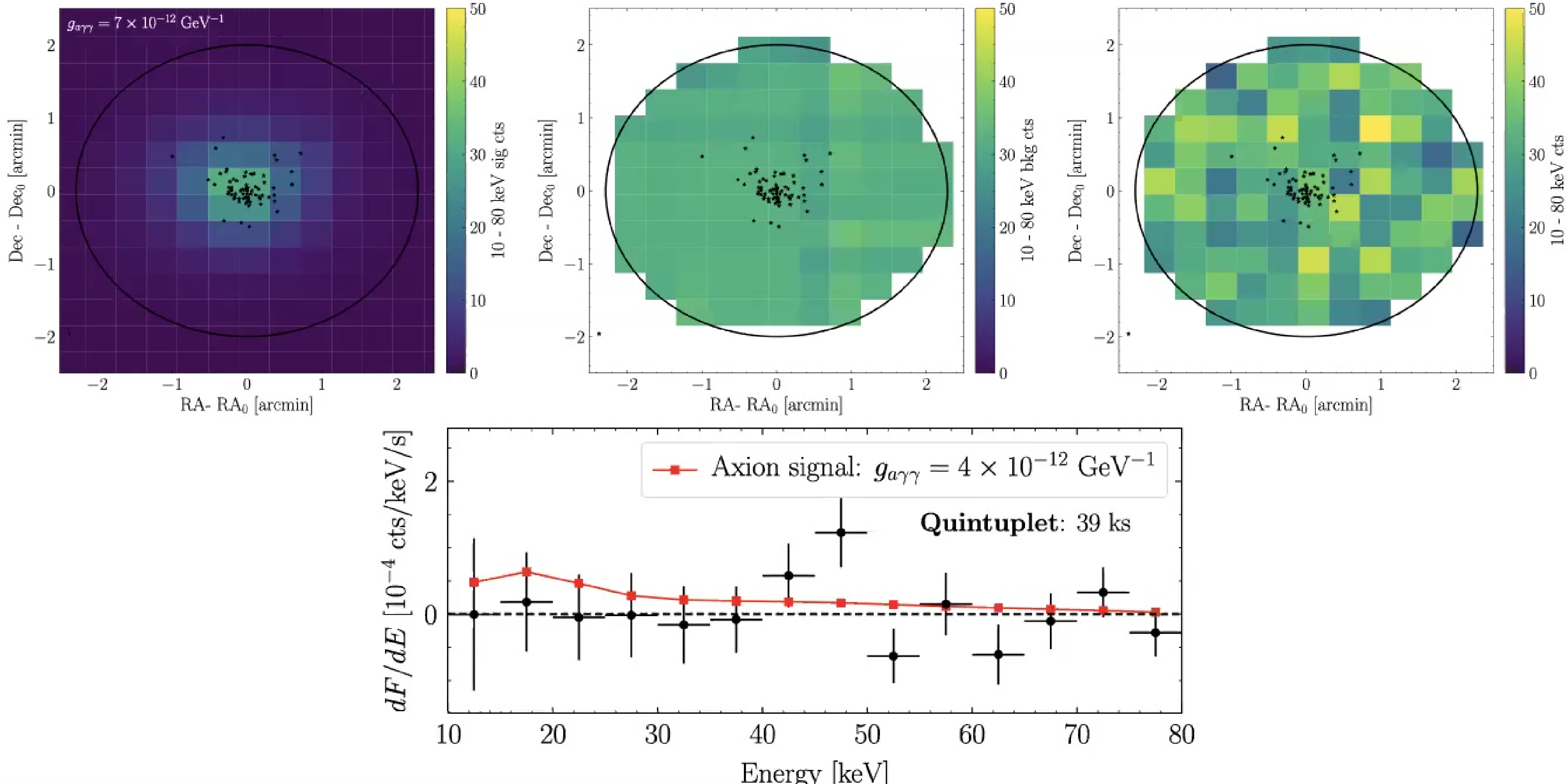
NUSTAR OBSERVATIONS OF SUPER STAR CLUSTERS



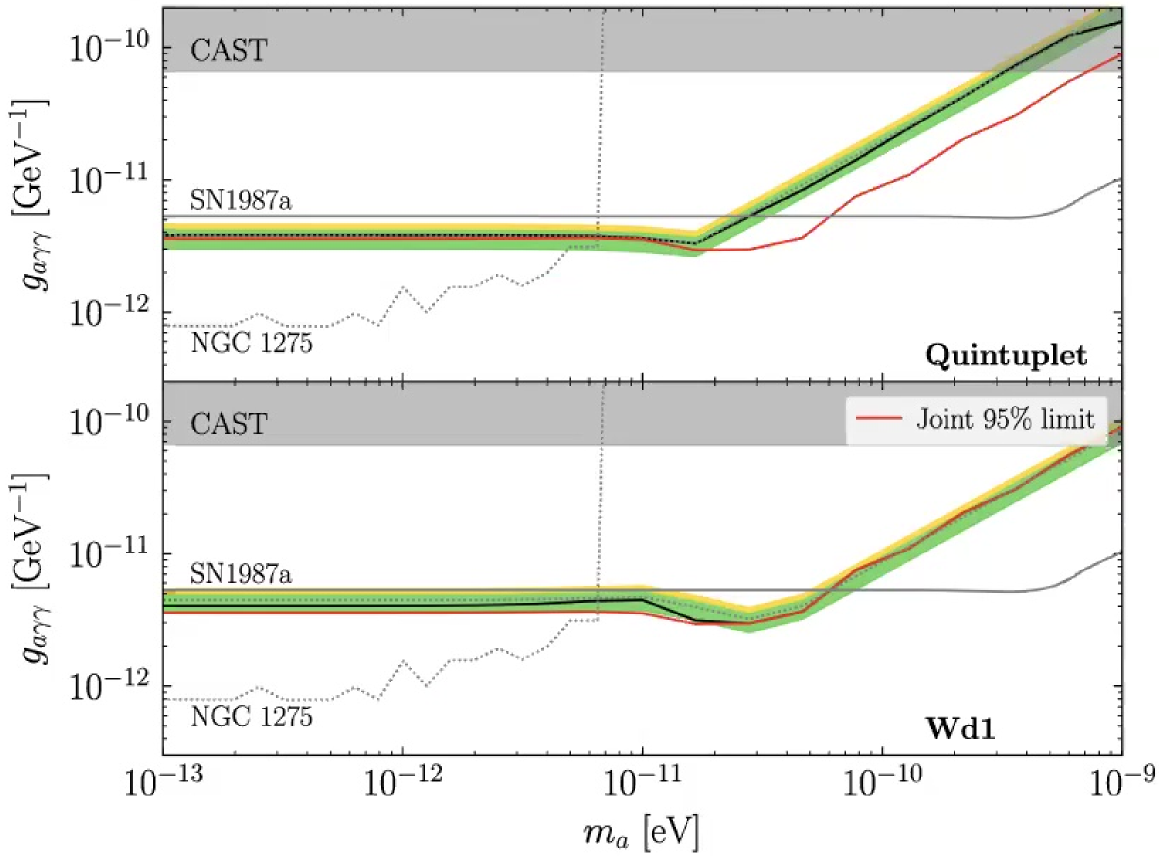


NuSTAR

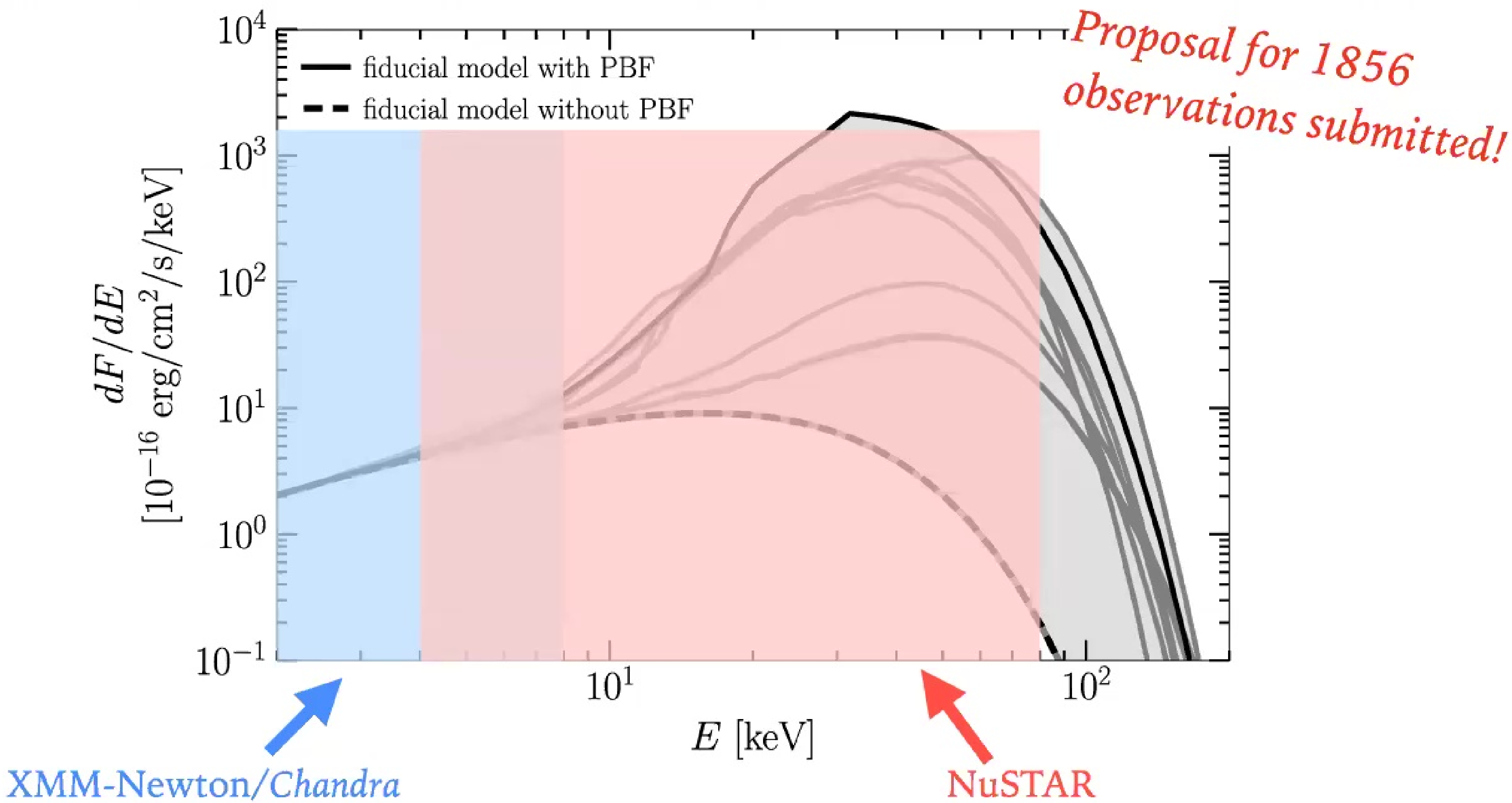
NUSTAR OBSERVATIONS OF QUINTUPLET



AXION CONSTRAINTS



FUTURE PROSPECTS AND OBSERVATIONS



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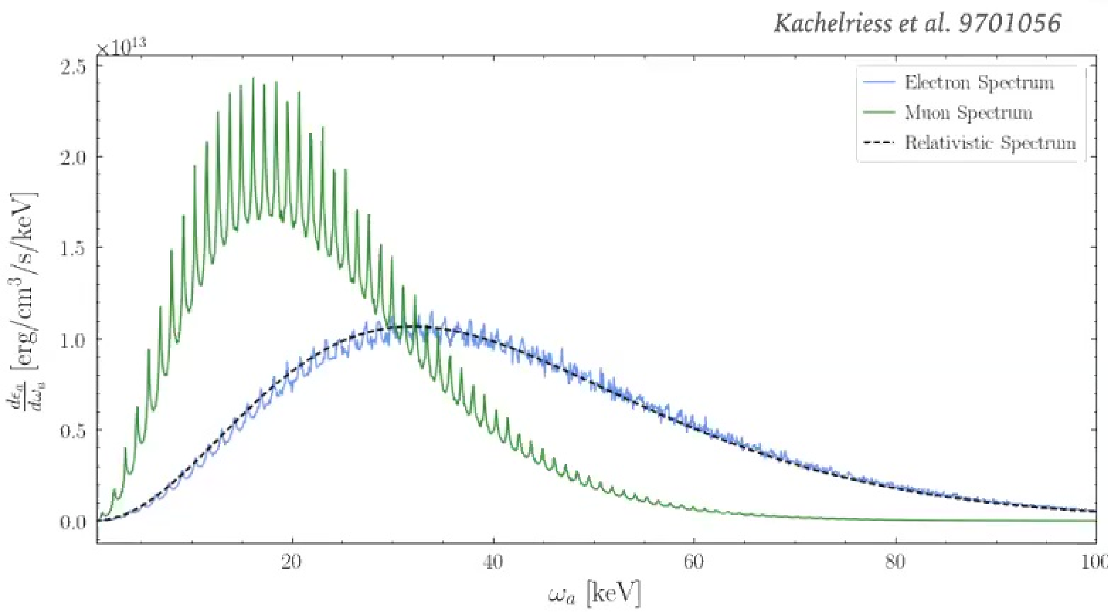

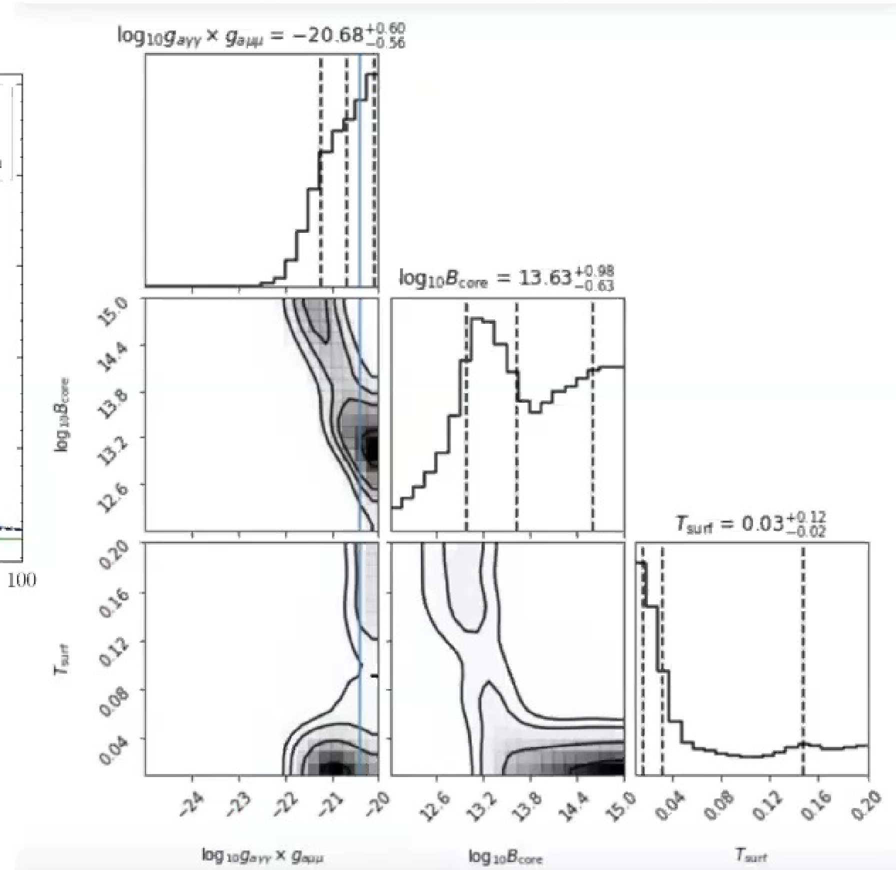

- ➤ New production mechanisms for the NS excess: electrons, muons, protons
- ➤ NS cooling implications?

BACKUP SLIDES