Galactic Axion Factories: Stellar Populations and X-Ray Signals for Axion Searches

Axions in Stockholm, July 4, 2025

Orion Ning

University of California, Berkeley

Lawrence Berkeley National Laboratory

Based on works: 2404.14476, 2503.09682, 2507.XXXXX+ ongoing

Berkeley UNIVERSITY OF CALIFORNIA BERKELEY LAB

Image: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Key Highlights

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II. Use of Stellar Populations (*Galaxies*) as a Powerful Technique
III. *A Diverse Playground for Axion Physics*
   A. *Looking Ahead and Future Work*
   B. *Chat with me at this conference!*

I. Why Search For Axions with Astrophysics?

Axions?

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$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \sum_f \frac{g_{aff}}{2m_f} (\partial_\mu a) \bar{f} \gamma^\mu \gamma_5 f$$

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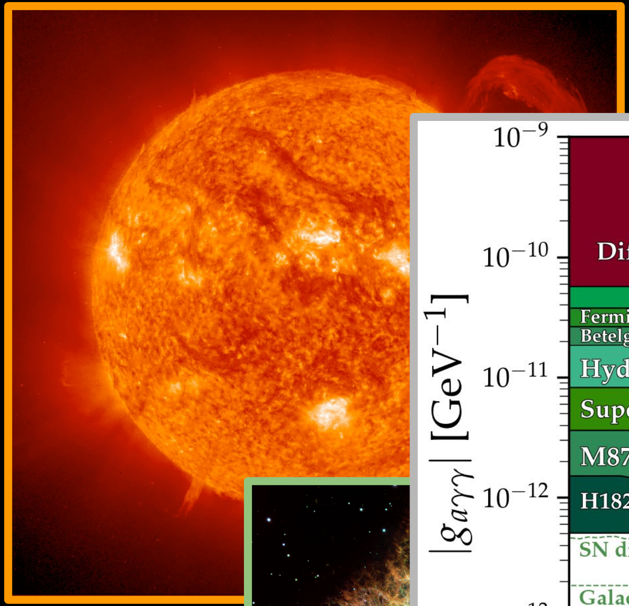
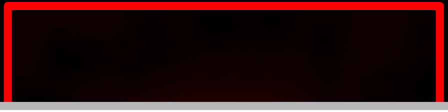
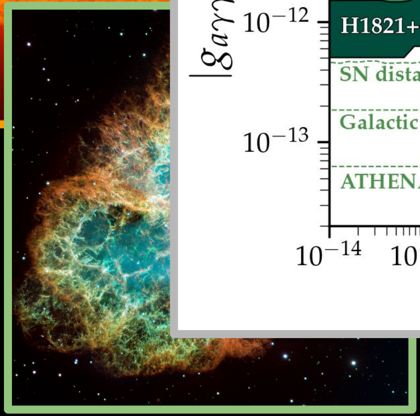
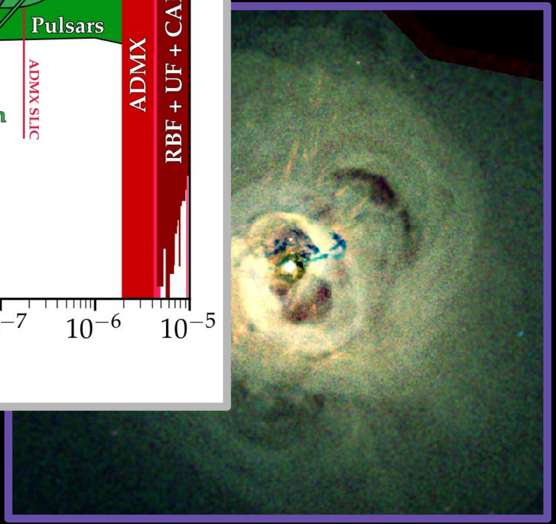
Couplings can be *magnified* in extreme astrophysical environments!

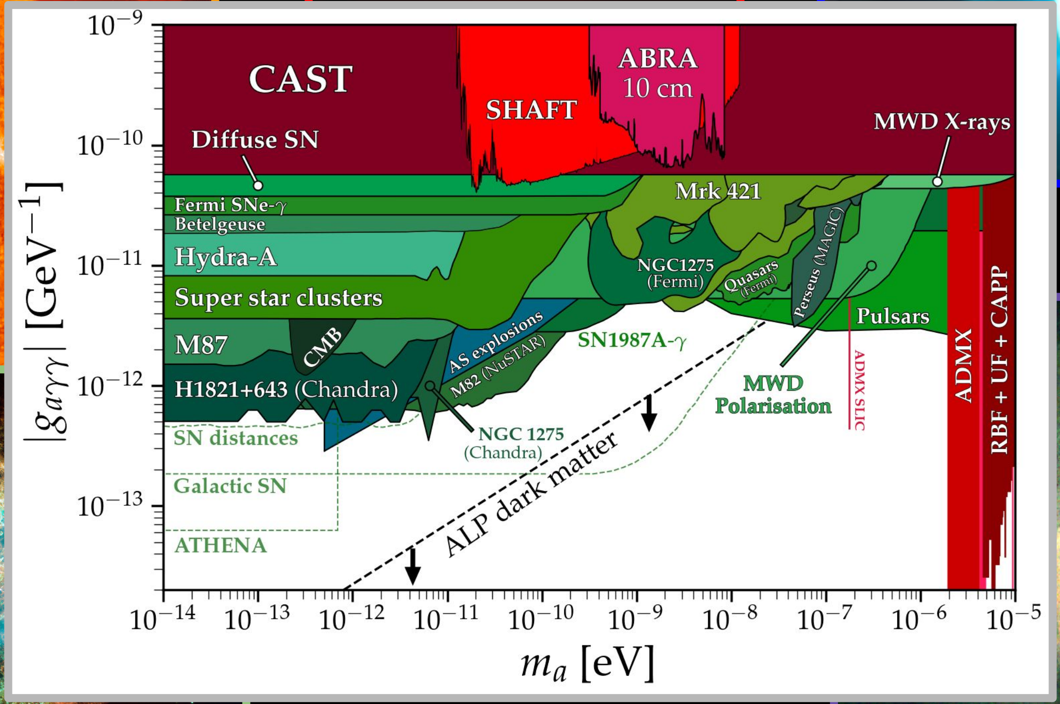
The search is on for Astrophysics + Axions !











Credits: C. O'Hare

Images: NASA, or artists' renditions

II. Stellar Populations (Galaxies) as a Powerful Technique

ON, B. Safdi: 2404.14476, 2503.09682

Note: not necessarily chronological

Leveraging stellar populations

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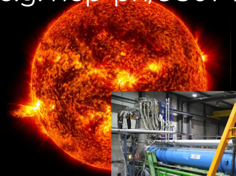
Leveraging stellar populations

The Sun

- Helioseismology, CAST

e.g. hep-ph/9807476, 1705.02290



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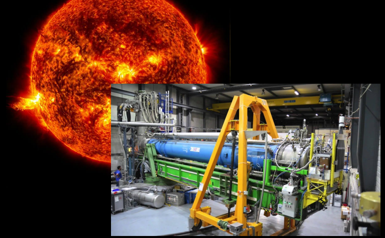
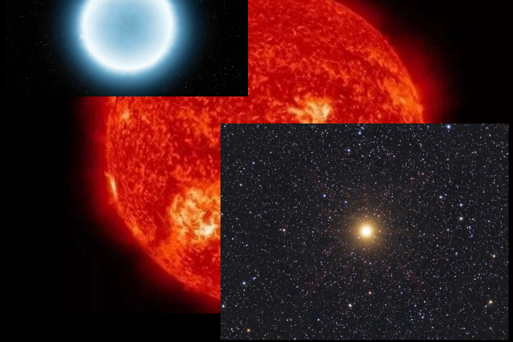


Special Stars
- Red Giant
- White Dwarf
- Supergiant star (e.g. Betelgeuse)

e.g. hep-ph/9410205, 1211.3389, 1605.06458, 2204.03121



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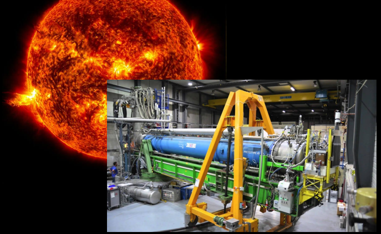

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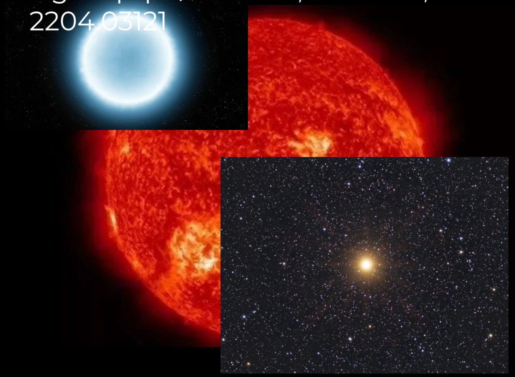
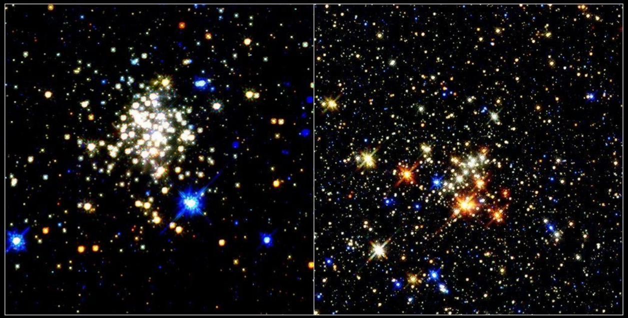


Clusters and Collections
- Globular Clusters; TRGB, R Parameter
- WD Luminosity Fn
- Super Star Clusters

e.g. 1406.6053, 2207.03102, 2007.03694, 1406.7712, 2008.03305



Leveraging stellar populations

Our Story: Galaxies and Whole Stellar Populations

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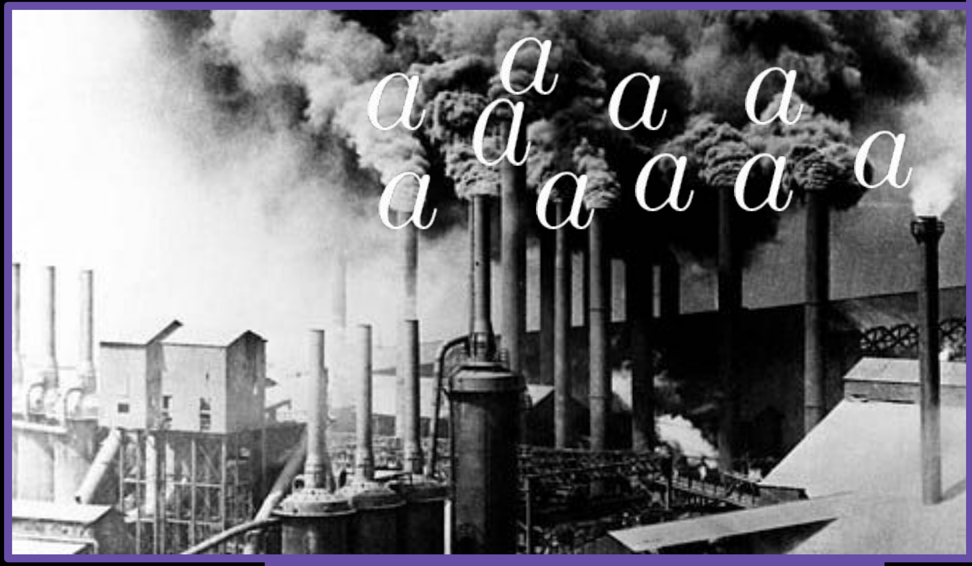
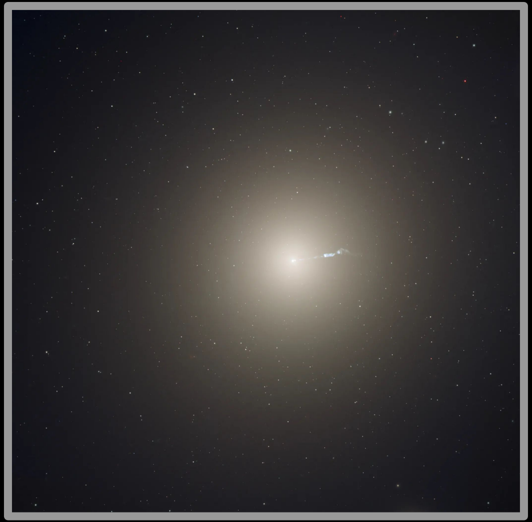


Galaxies as Axion Factories

Our Tale of Two Galaxies (2404.14476)

M82

- Starburst Galaxy
- Indications of Strong B-fields

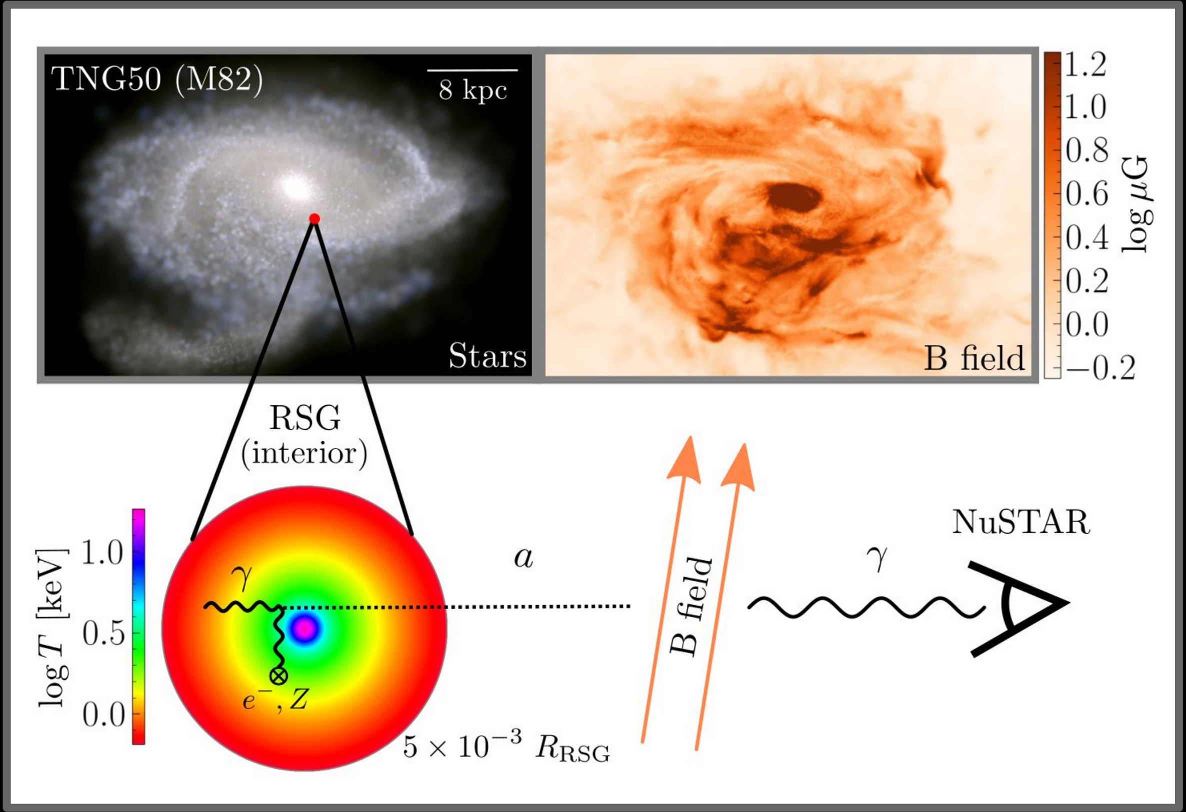


M87

- Massive Elliptical
- Extended Virgo Cluster B-fields

Images: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Searching for Axions with NuSTAR:



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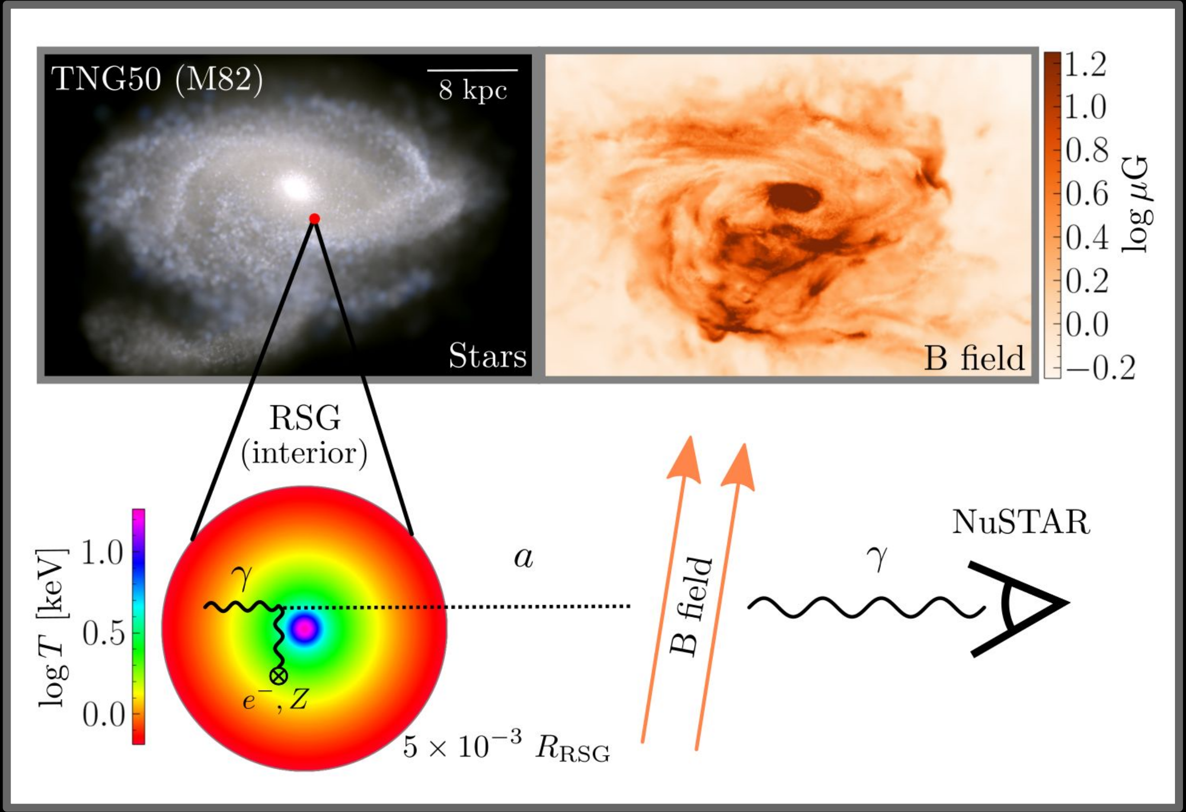

Axions produced via Primakoff in stellar interiors

$$g_{a\gamma\gamma}$$

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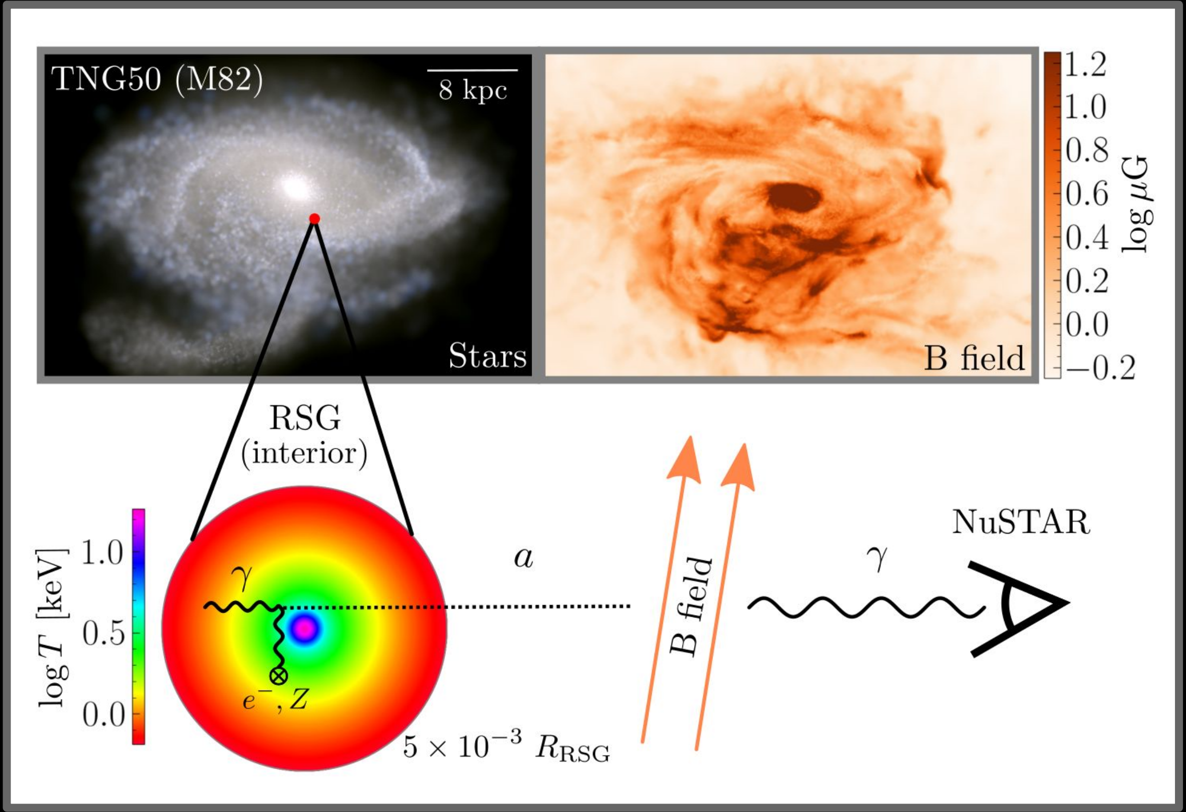

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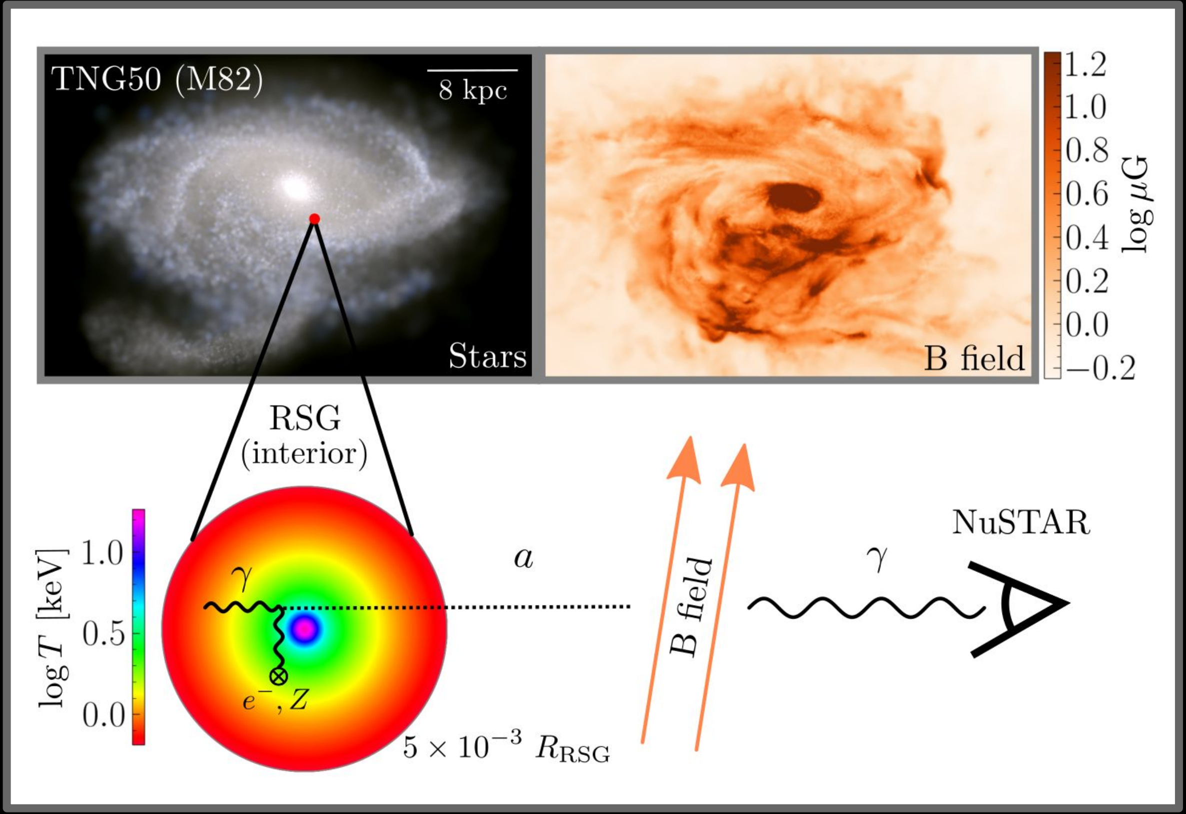

Observed by the NuSTAR telescope

Convert to hard X-rays in galactic/cluster magnetic fields

Axion Signal Model Ingredients

$$\frac{dF}{dE}(E) = P_{a\to\gamma}(E)\frac{1}{4\pi d^2}\frac{dL_a(E)}{dE}$$

Axion-Photon Conversion Probability

Distance

Total Axion Luminosity from Stars

Signal Model Ingredients (1/2)

Axion Luminosity from Stellar Populations of M82/M87

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Primakoff Process $$\frac{dL_a(E)}{dE}$$

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Primakoff Process

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Stellar Profiles (MESA)

$$\frac{dL_a(E)}{dE}$$

- Temperature
- Density
- Abundances

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- Temperature
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Stellar Population Models (Obs.)

- Metallicity
- SFH
- IMF
- # of Stars

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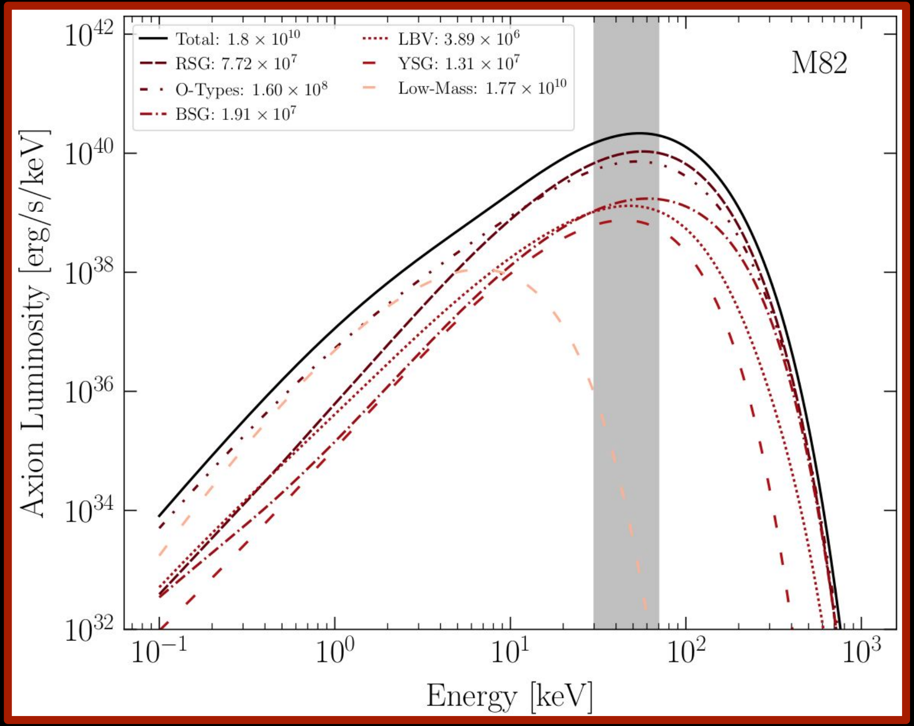

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Axion Luminosity from Stellar Populations of M82/M87

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Stellar Profiles (MESA)

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Stellar Population Models (Obs.)

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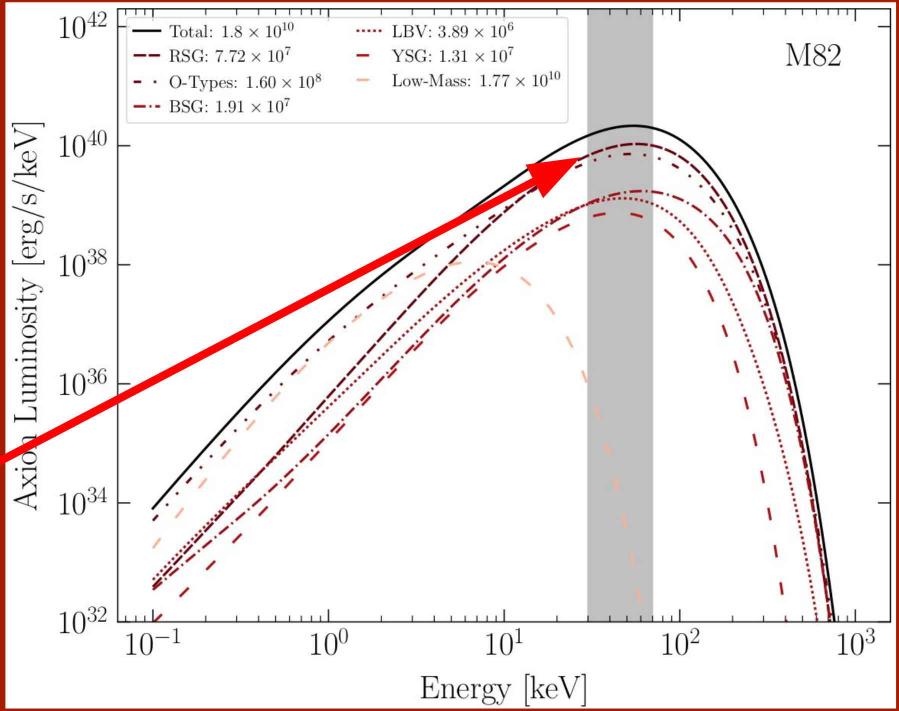
=

Total Axion Luminosity Spectra

$$\frac{dL_a(E)}{dE}$$

- Dominated by Supergiants and O-Types, generally
- M82: starburst = excellent for axions!



Signal Model Ingredients (2/2)

Conversion Probability for Axion-Photon Conversion

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Axion Mass m_a

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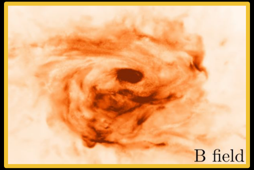
Magnetic Fields



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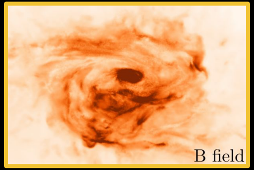

+

Free-electron Densities n_e

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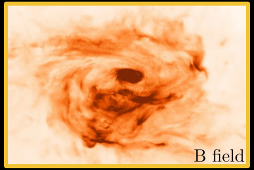

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Conversion Probabilities $P_{a \to \gamma} \sim g_{a\gamma\gamma}^2 B^2 L^2$

Signal Model Ingredients (2/2)

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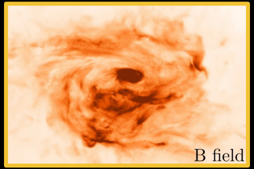

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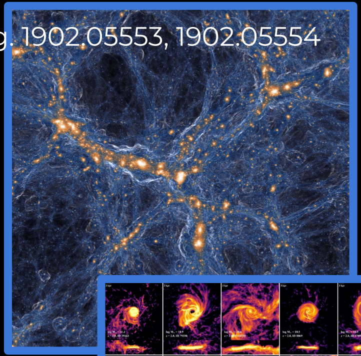
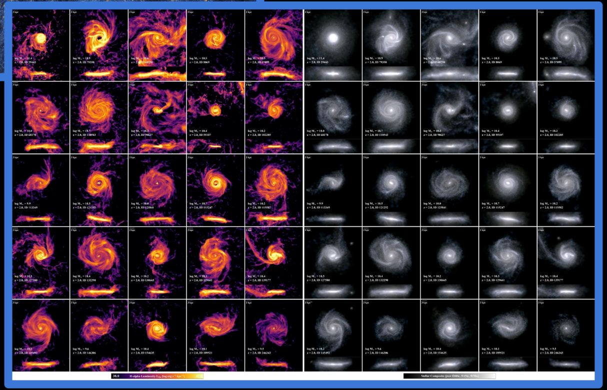
IllustrisTNG TNG50/300 Simulations

e.g. 1902.05553, 1902.05554





Credit: IllustrisTNG

Signal Model Ingredients (2/2)

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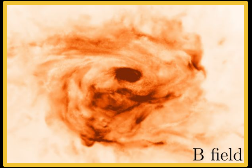
Magnetic Fields



+

Free-electron Densities n_e

=

Conversion Probabilities

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

The variability in galaxy candidates and magnetic fields = largest source of uncertainty in our analysis

IllustrisTNG TNG50/300 Simulations

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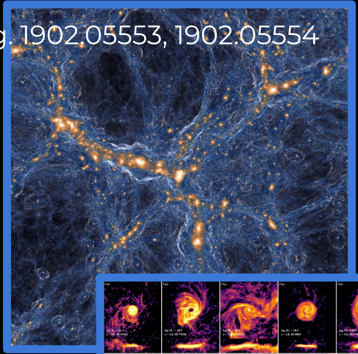
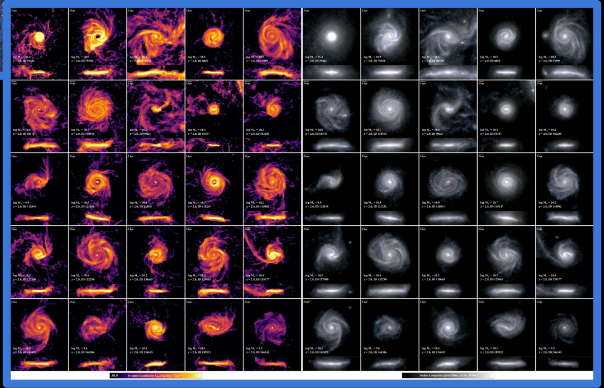
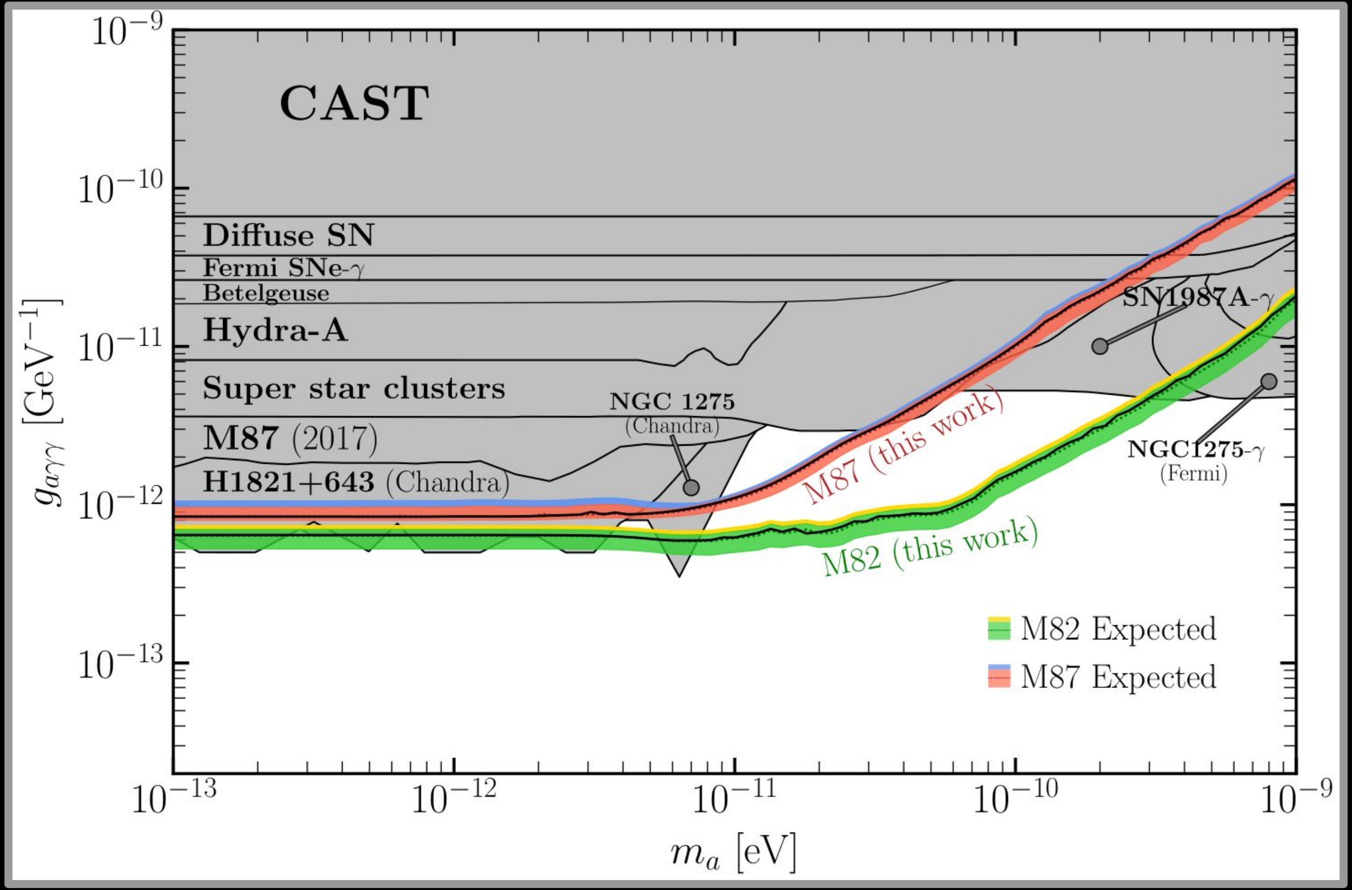




Credit: IllustrisTNG

No evidence for axions from NuSTAR = Upper limits on coupling



Previous Limits: C. O'Hare

Opens up many possibilities for extensions and follow-ups!

Introducing: The Axion-Electron Coupling (2503.09682)

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aee}}{2m_e} (\partial_\mu a) \bar{e} \gamma^\mu \gamma_5 e$$

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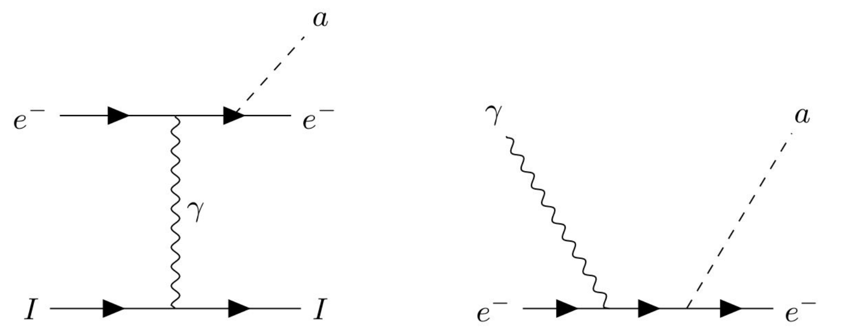

(a) Bremsstrahlung (b) Compton

We can thus probe the combined axion-electron and axion -photon coupling $g_{aee} \times g_{a\gamma\gamma}$

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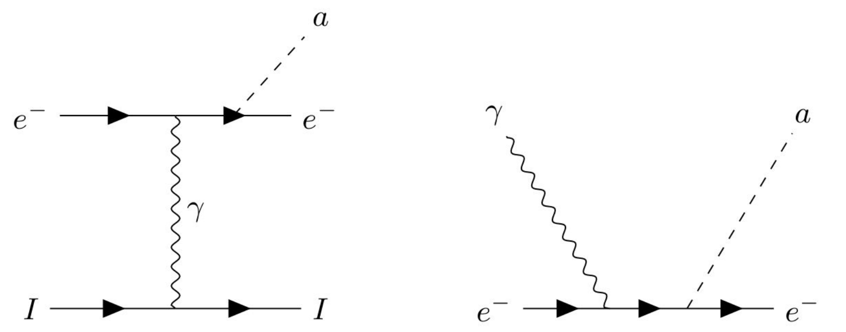

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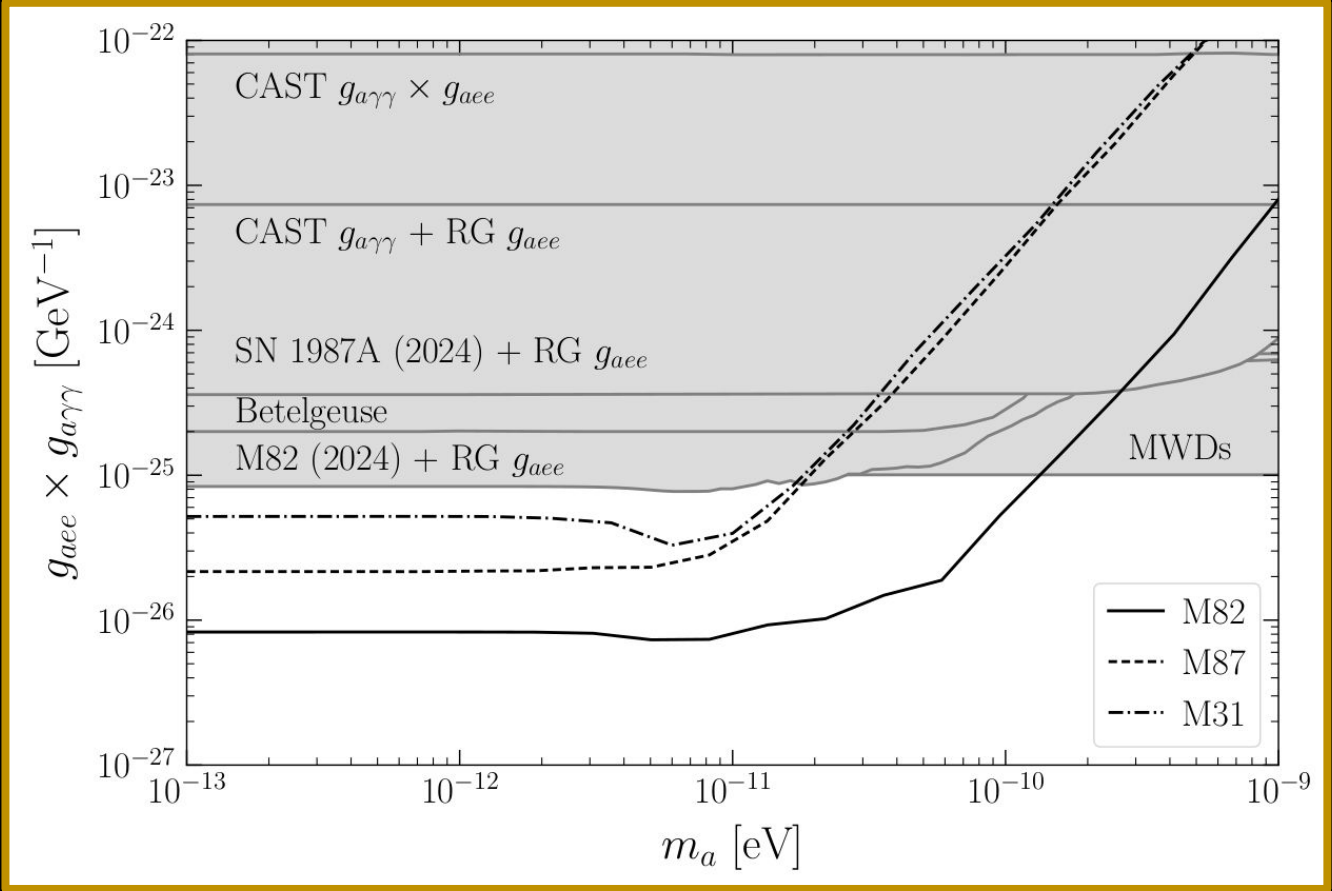
$$g_{aee} \times g_{a\gamma\gamma}$$

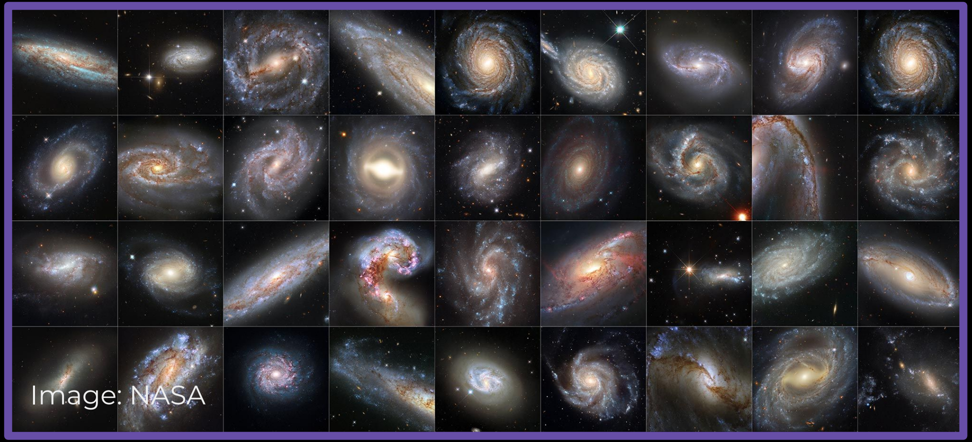
No evidence for axions = upper limits on combined coupling

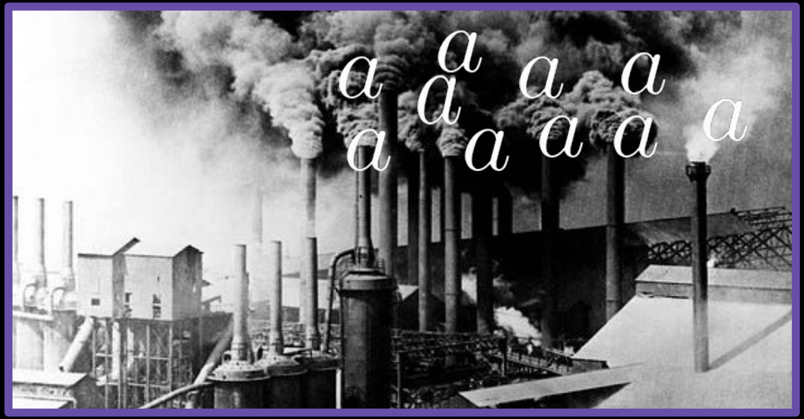


III. A Diverse Playground for Axion Physics

- Work-in-progress with collaborators toward other promising directions
- Axion-Nucleon coupling can be probed as well
  - Nucleon bremsstrahlung in NS's – for conversion off magnetospheres → can reach higher axion masses (Buschmann et al. 1910.04164)
  - Axions from Nuclear Isotope De-excitations (see, e.g. CAST 0906.4488, Candón et al. 2504.21107) → ON, A. Ray, B. Safdi: 2507.XXXXX
- Heavy Axions (e.g. Candón et al. 2412.03660)
- The list goes on!

Conclusion and Outlook





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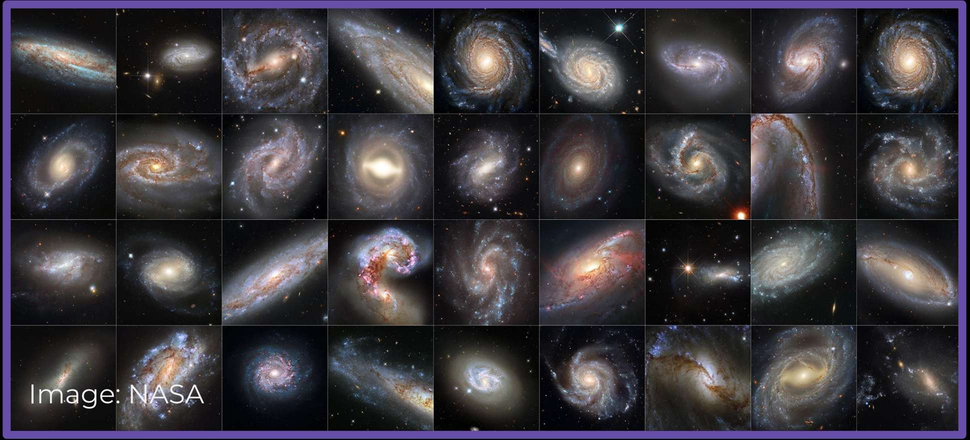
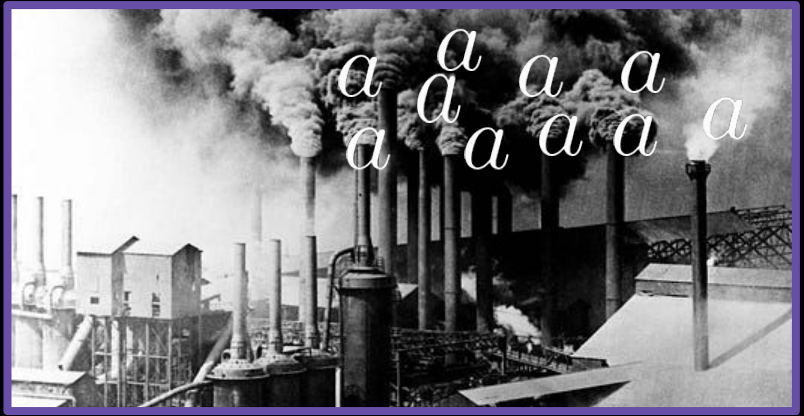
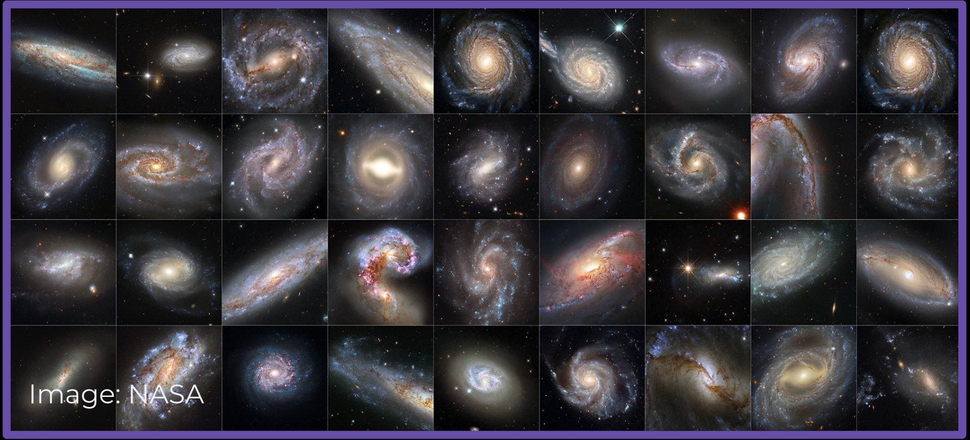
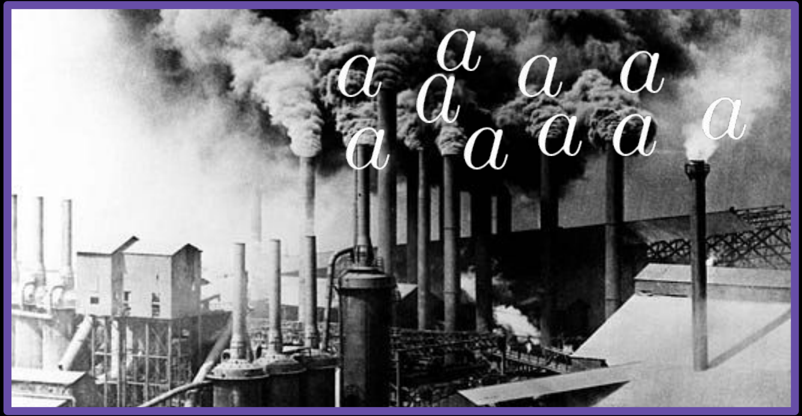




- (Galactic) Stellar populations as axion factories → powerful probes of axion physics

Conclusion and Outlook





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- Clearly demonstrated with X-ray studies using M82, M87, searching for various axion-SM couplings

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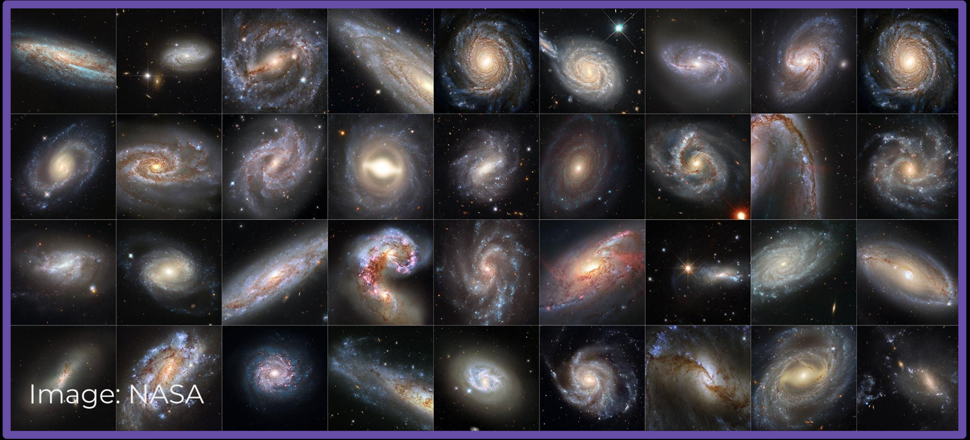

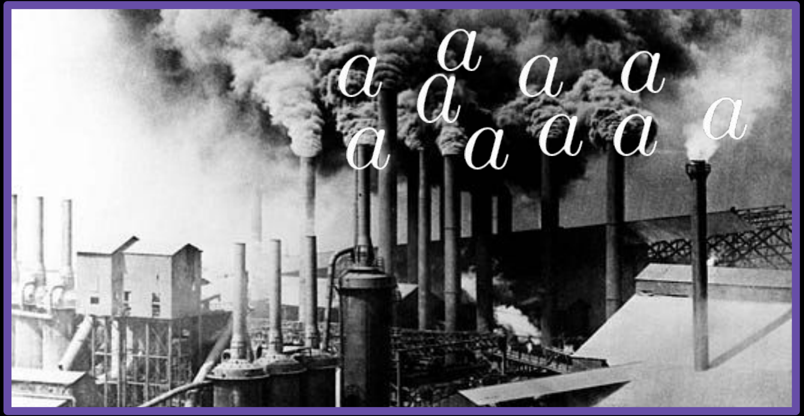

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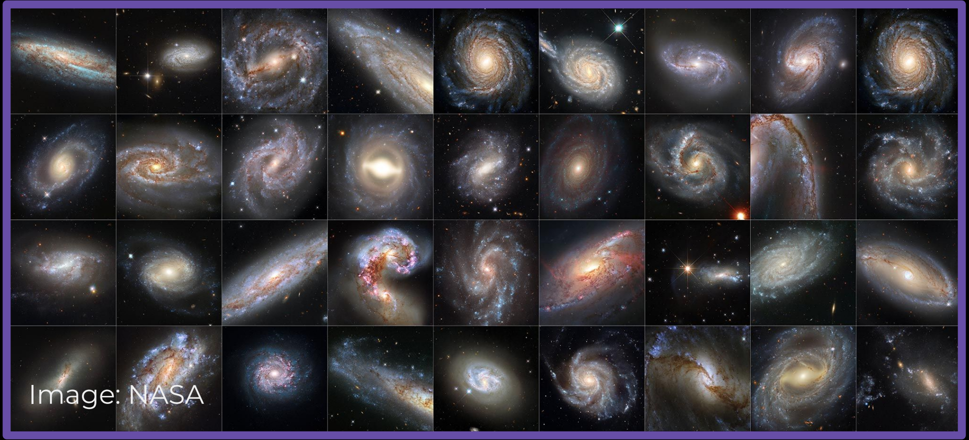

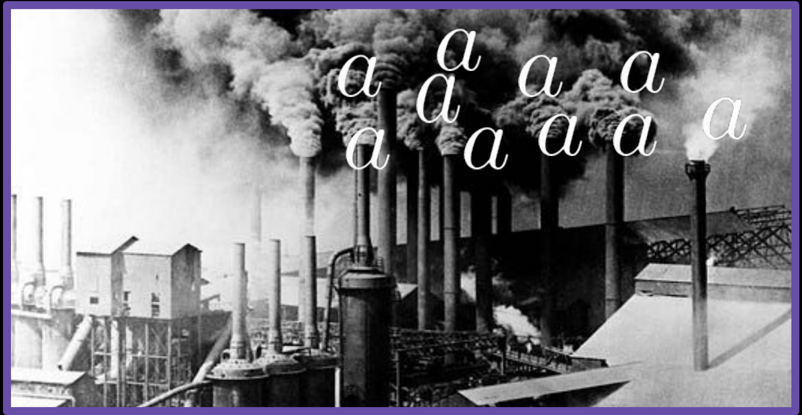

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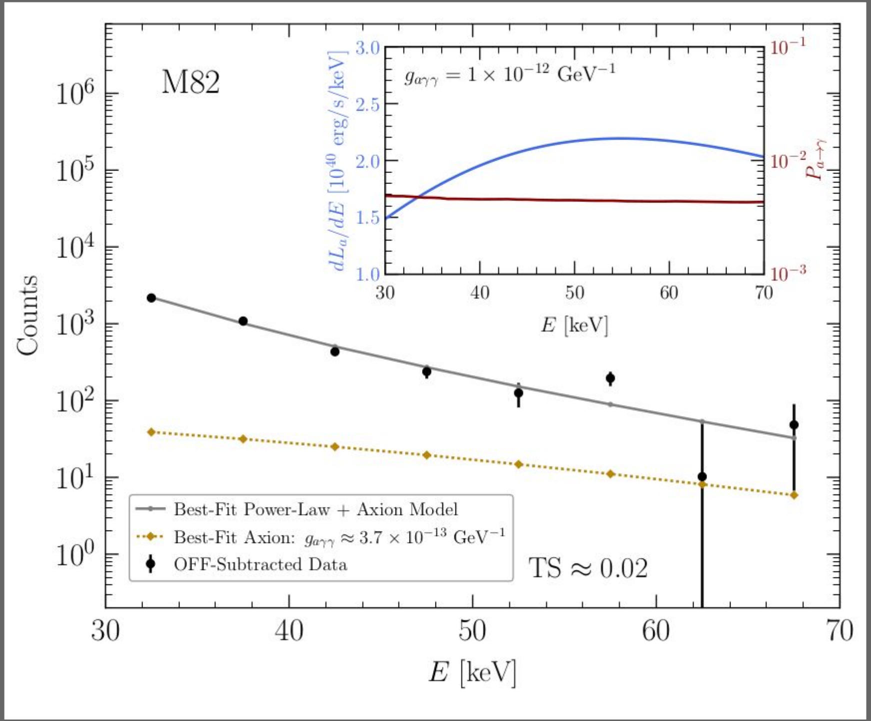
- Clearly demonstrated with X-ray studies using M82, M87, searching for various axion-SM couplings
- No evidence for axions → stringent constraints
- The search continues, and a plethora of possibilities to explore

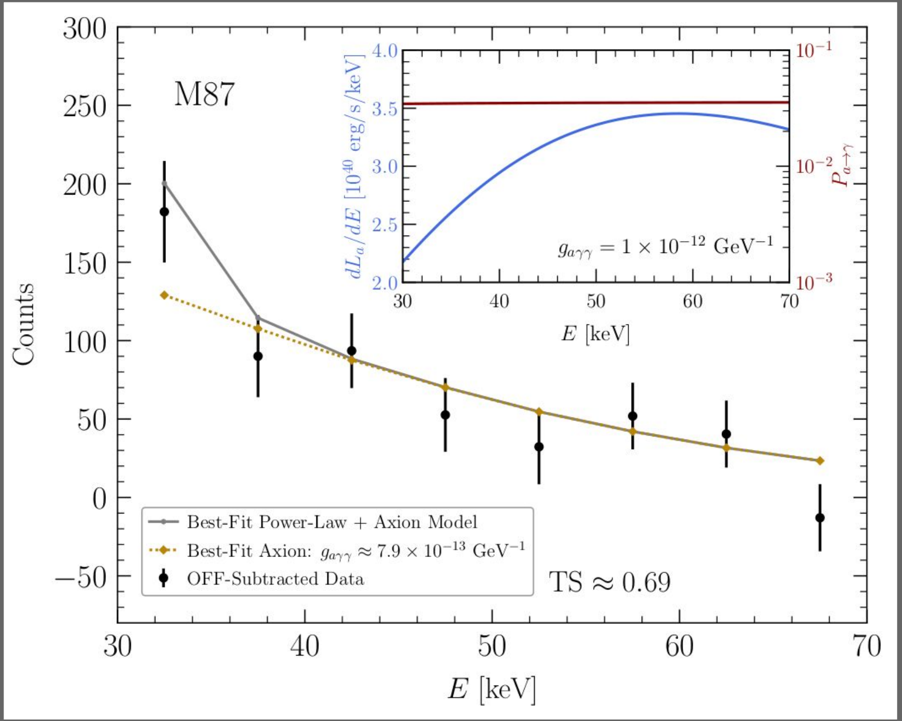
Thanks for listening!

Appendix

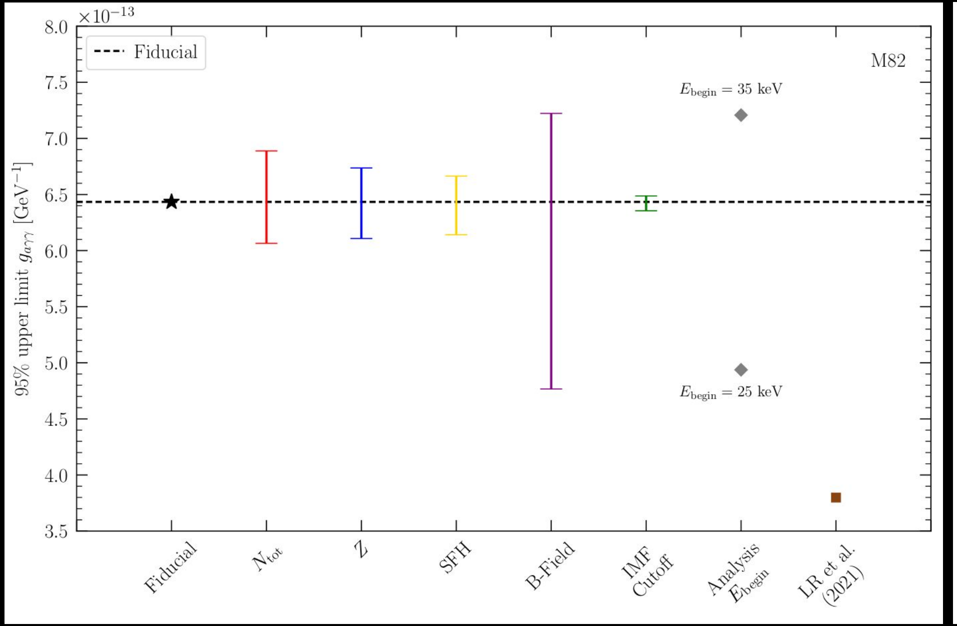
Axion-Photon 2404.14476

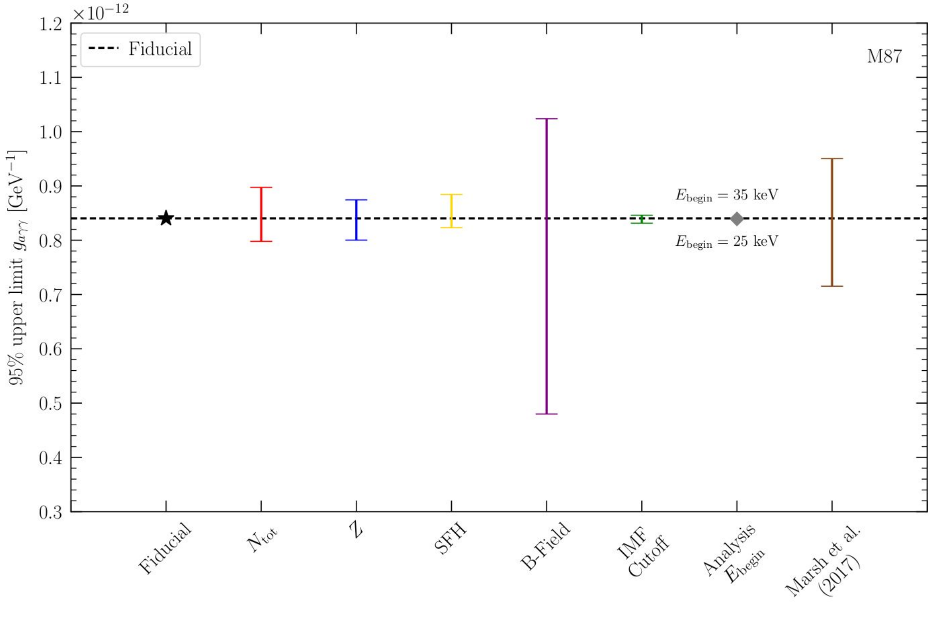
Signal Model + NuSTAR Data Constrains Axion-Photon Coupling



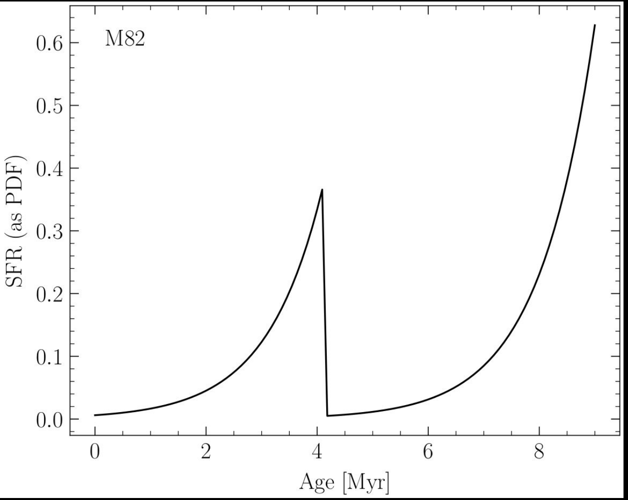


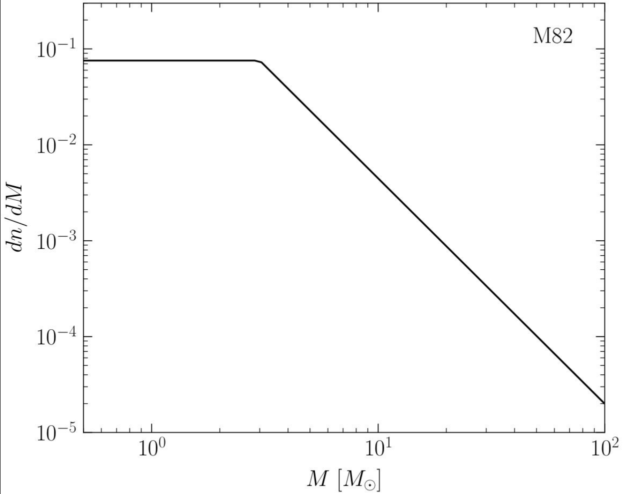
Systematics

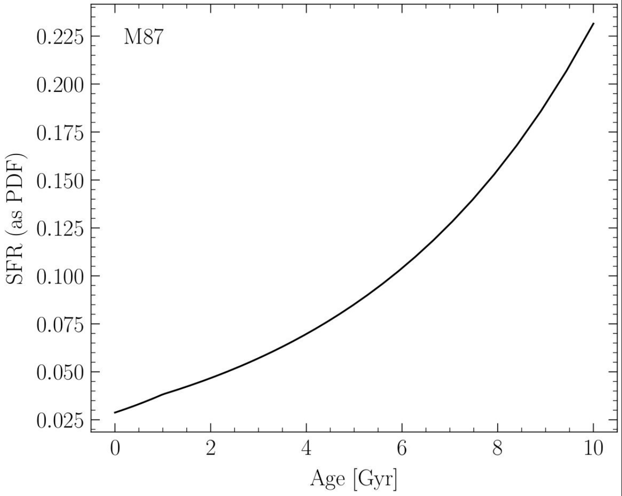


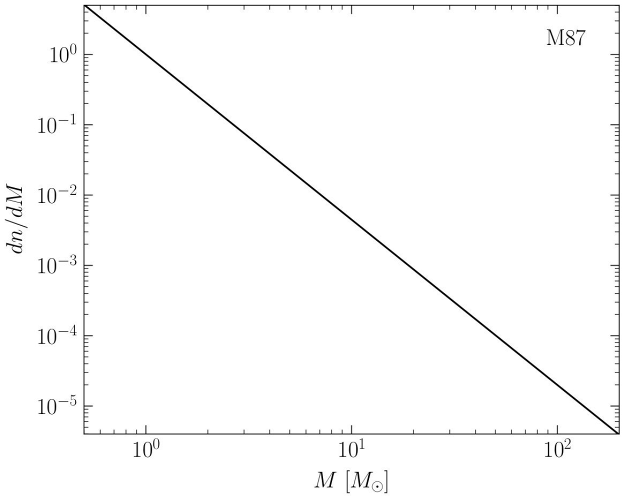


Stellar Population Modeling

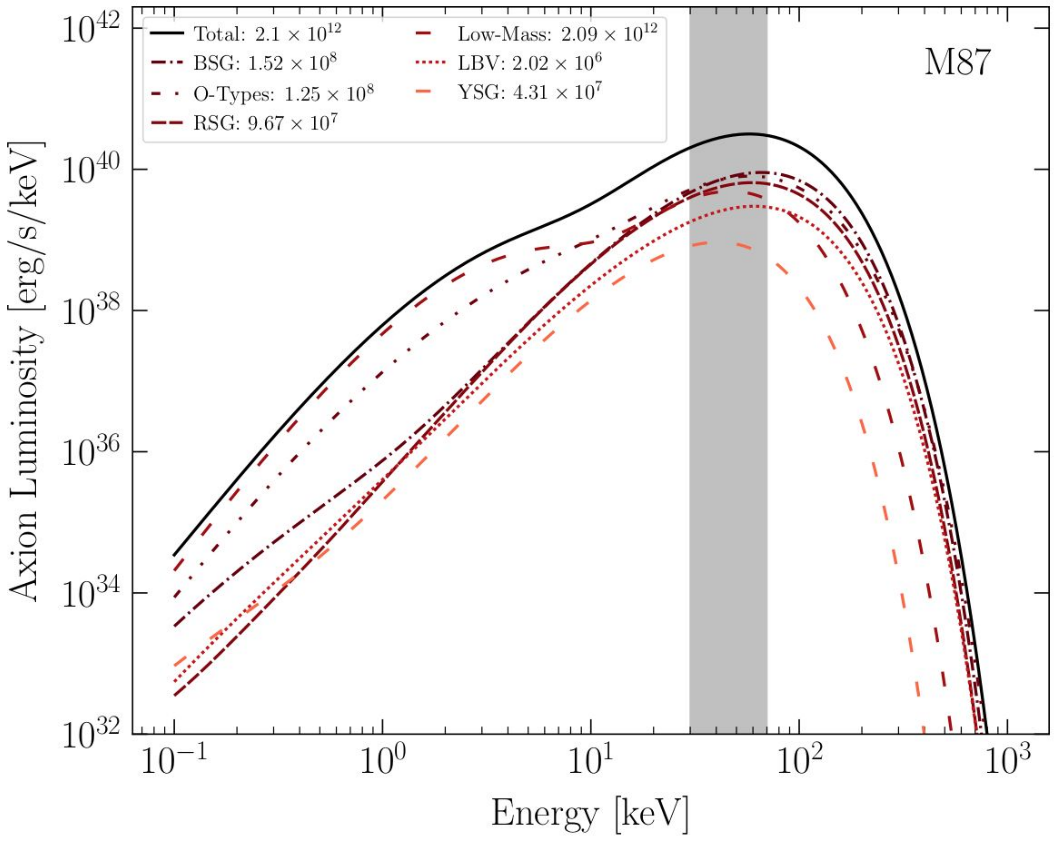




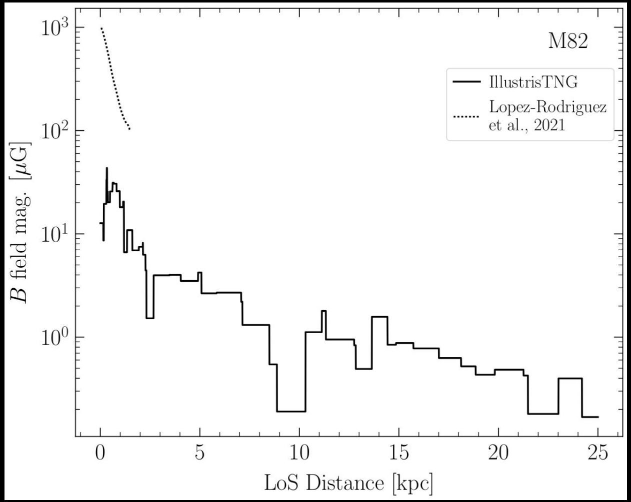


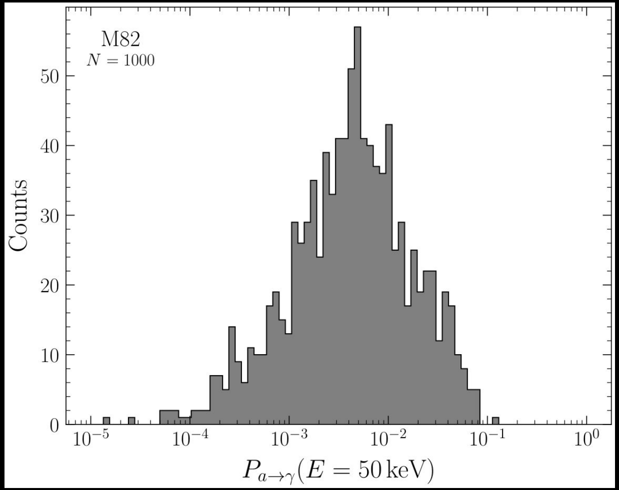


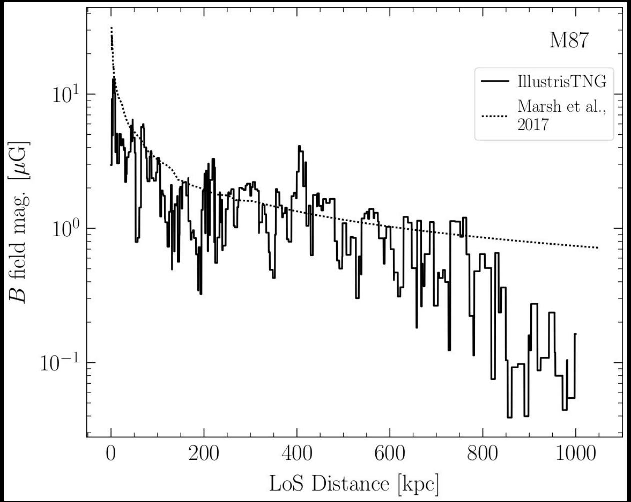
Axion Luminosity for M87

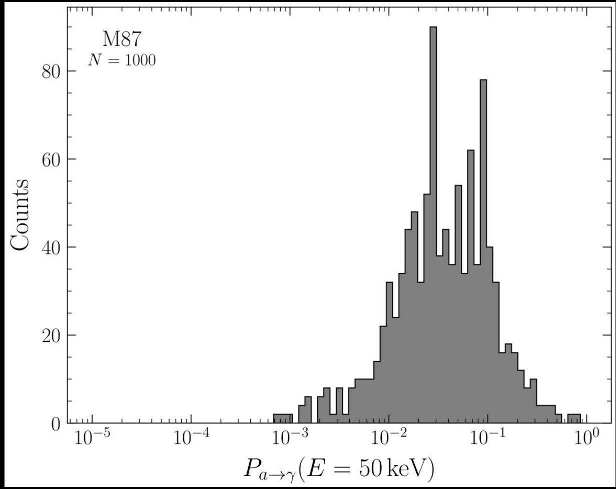


Conversion Probabilities

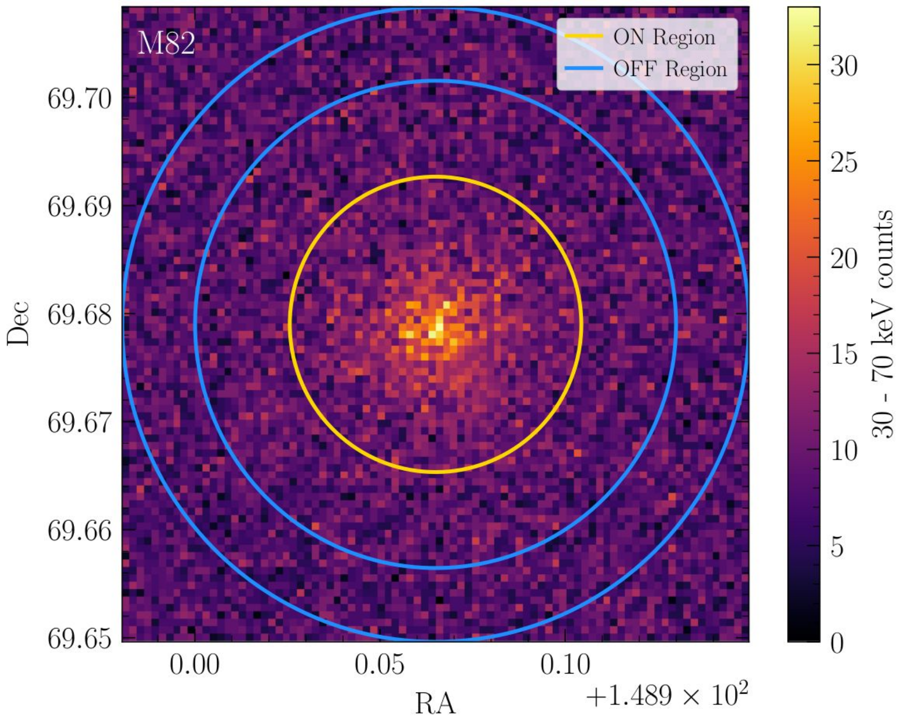


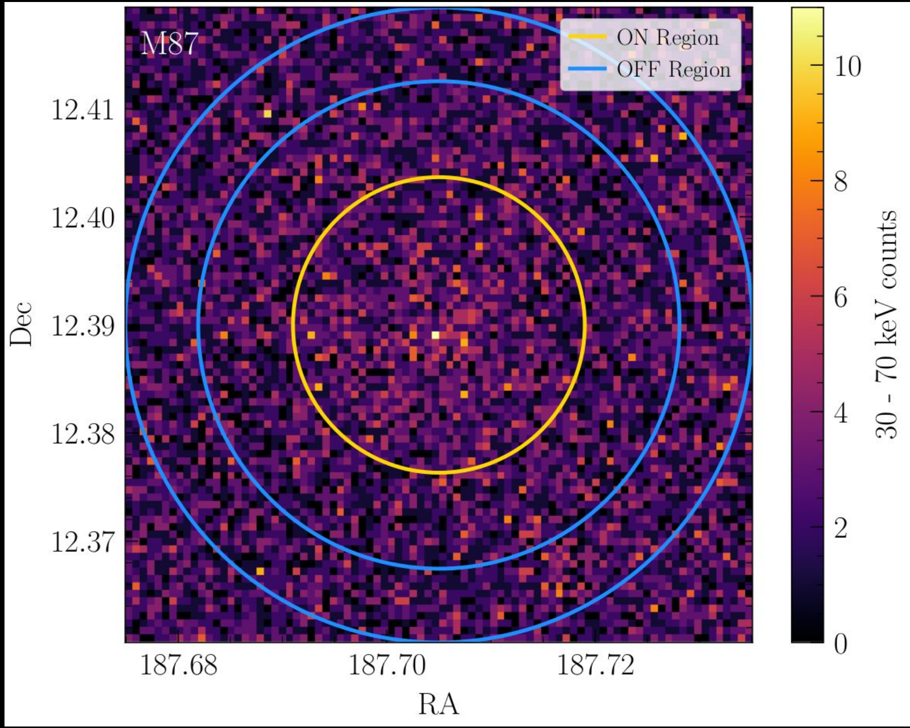




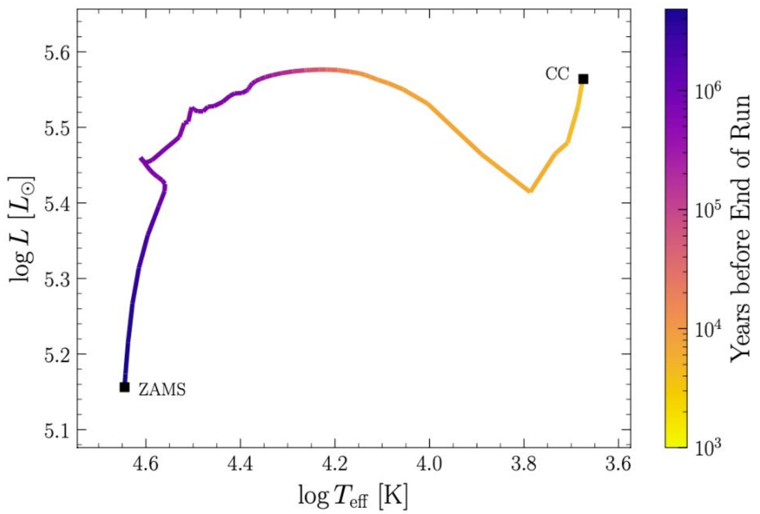


Spatial Maps

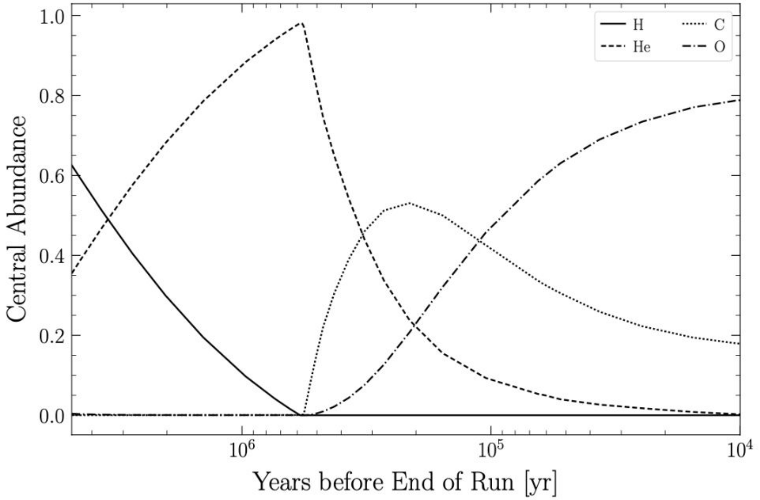




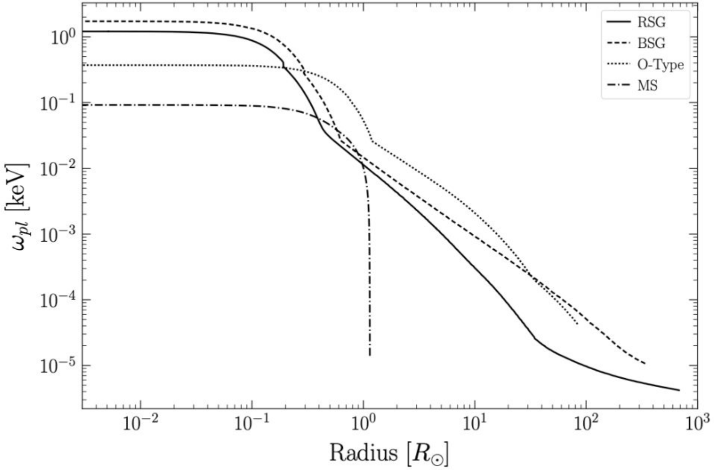
MESA



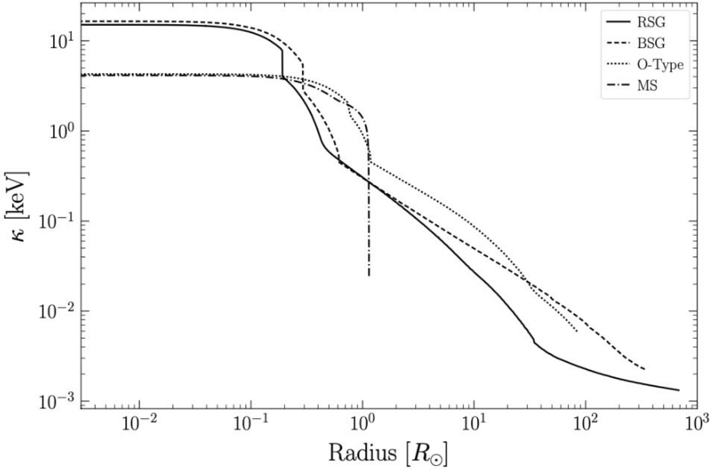
CC
ZAMS
log L [$L_\odot$]
log $T_{\rm eff}$ [K]
Years before End of Run



H
He
C
O
Central Abundance
Years before End of Run [yr]



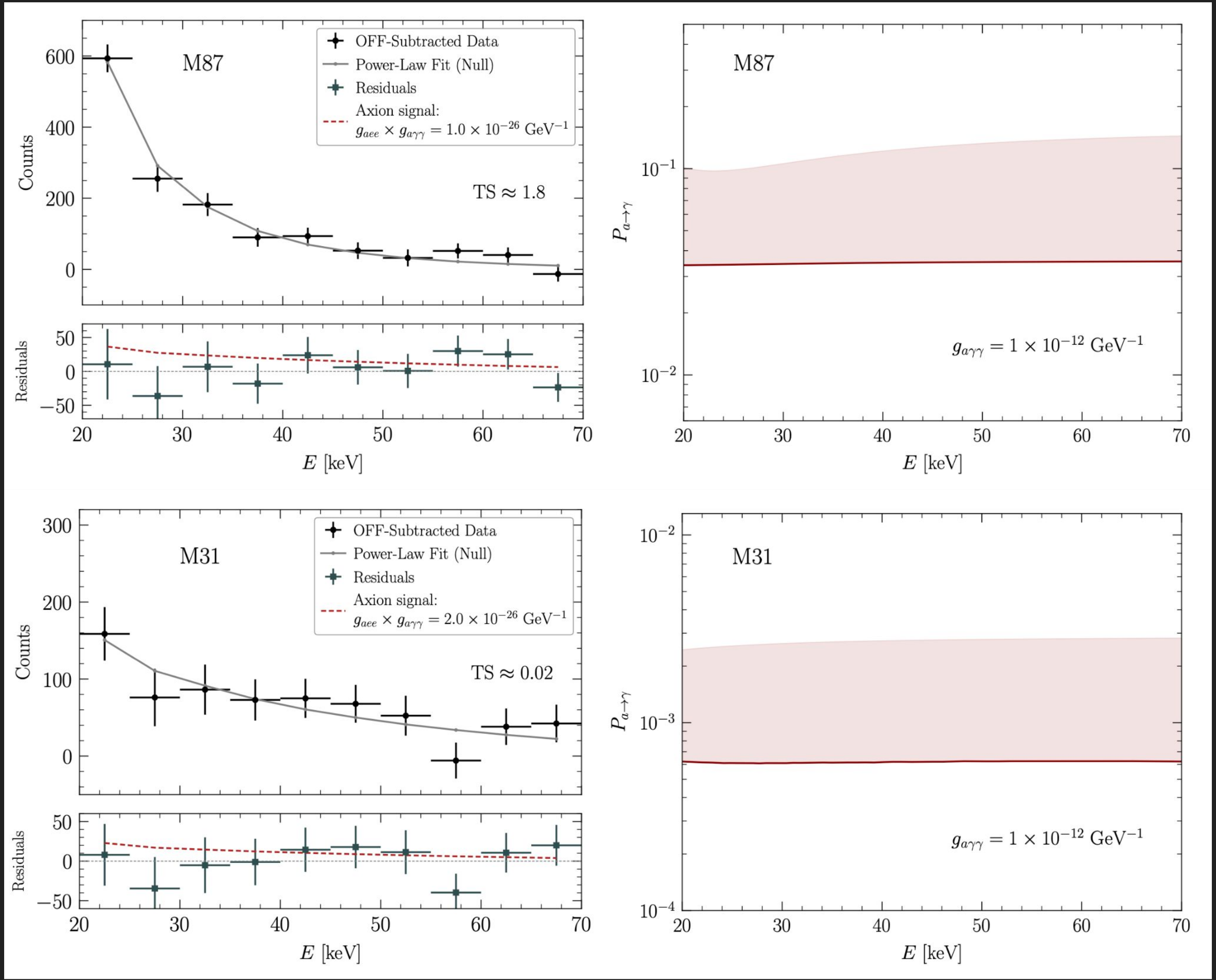
RSG
BSG
O-Type
MS
ω_{pl} [keV]
Radius [$R_\odot$]



RSG
BSG
O-Type
MS
κ [keV]
Radius [$R_\odot$]

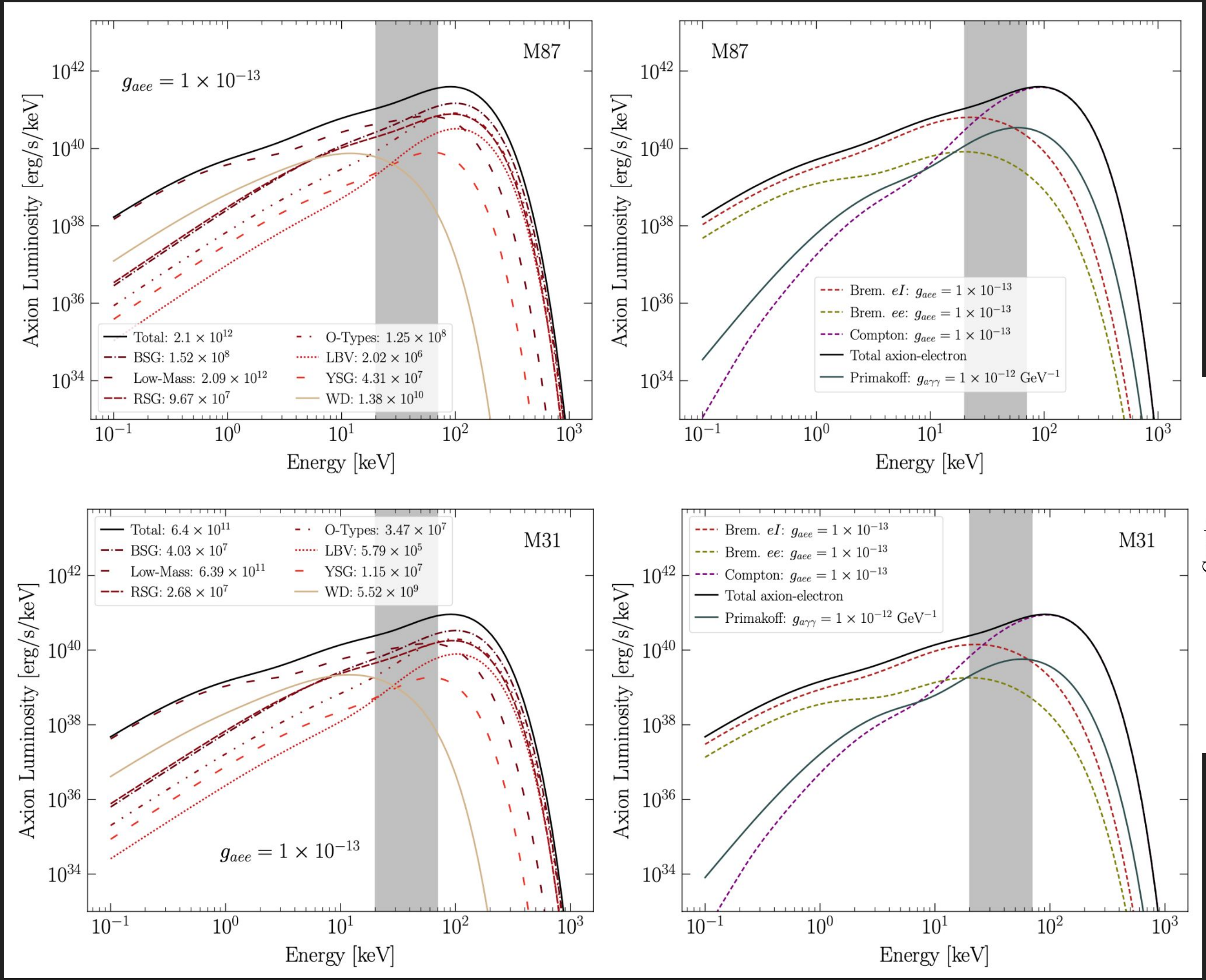
Axion-Electron 2503.09682

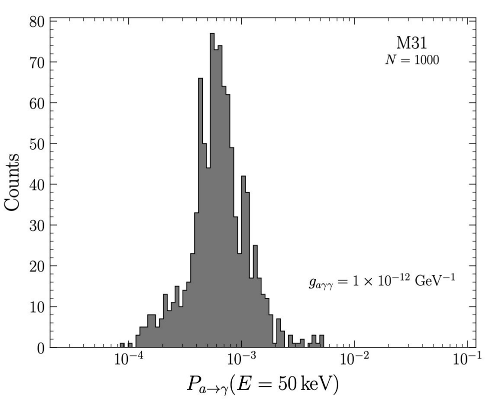
M87 and M31



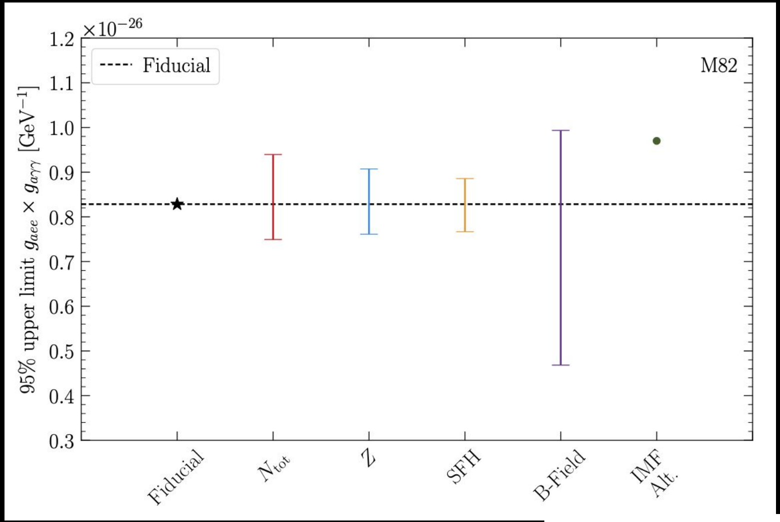
M87
OFF-Subtracted Data
Power-Law Fit (Null)
Residuals
Axion signal:
$g_{aee} \times g_{a\gamma\gamma} = 1.0 \times 10^{-26}$ GeV^{-1}
TS ≈ 1.8
Counts
Residuals
E [keV]
$P_{a\to\gamma}$
$g_{a\gamma\gamma} = 1 \times 10^{-12}$ GeV^{-1}
M31
OFF-Subtracted Data
Power-Law Fit (Null)
Residuals
Axion signal:
$g_{aee} \times g_{a\gamma\gamma} = 2.0 \times 10^{-26}$ GeV^{-1}
TS ≈ 0.02
Counts
Residuals
E [keV]
$P_{a\to\gamma}$
$g_{a\gamma\gamma} = 1 \times 10^{-12}$ GeV^{-1}

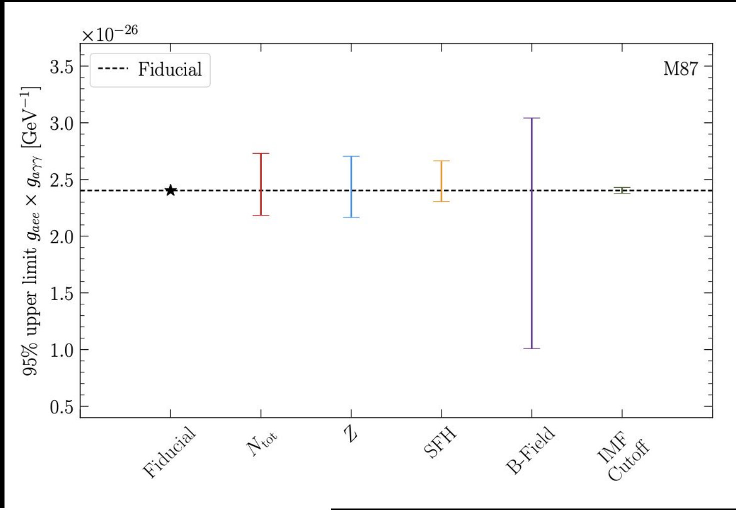
M87 and M31

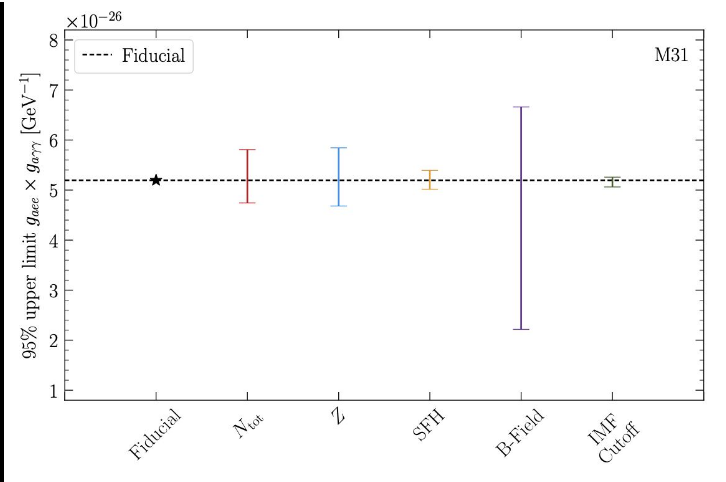

M87
$g_{aee} = 1 \times 10^{-13}$
Total: 2.1×10^{12}
BSG: 1.52×10^{8}
Low-Mass: 2.09×10^{12}
RSG: 9.67×10^{7}
O-Types: 1.25×10^{8}
LBV: 2.02×10^{6}
YSG: 4.31×10^{7}
WD: 1.38×10^{10}
Brem. eI: $g_{aee} = 1 \times 10^{-13}$
Brem. ee: $g_{aee} = 1 \times 10^{-13}$
Compton: $g_{aee} = 1 \times 10^{-13}$
Total axion-electron
Primakoff: $g_{a\gamma\gamma} = 1 \times 10^{-12}$ GeV^{-1}
M31
Total: 6.4×10^{11}
BSG: 4.03×10^{7}
Low-Mass: 6.39×10^{11}
RSG: 2.68×10^{7}
O-Types: 3.47×10^{7}
LBV: 5.79×10^{5}
YSG: 1.15×10^{7}
WD: 5.52×10^{9}
$g_{aee} = 1 \times 10^{-13}$
Axion Luminosity [erg/s/keV]
Energy [keV]


M31
$N = 1000$
$g_{a\gamma\gamma} = 1 \times 10^{-12}$ GeV^{-1}
Counts
$P_{a\to\gamma}(E = 50\,\mathrm{keV})$

Systematics





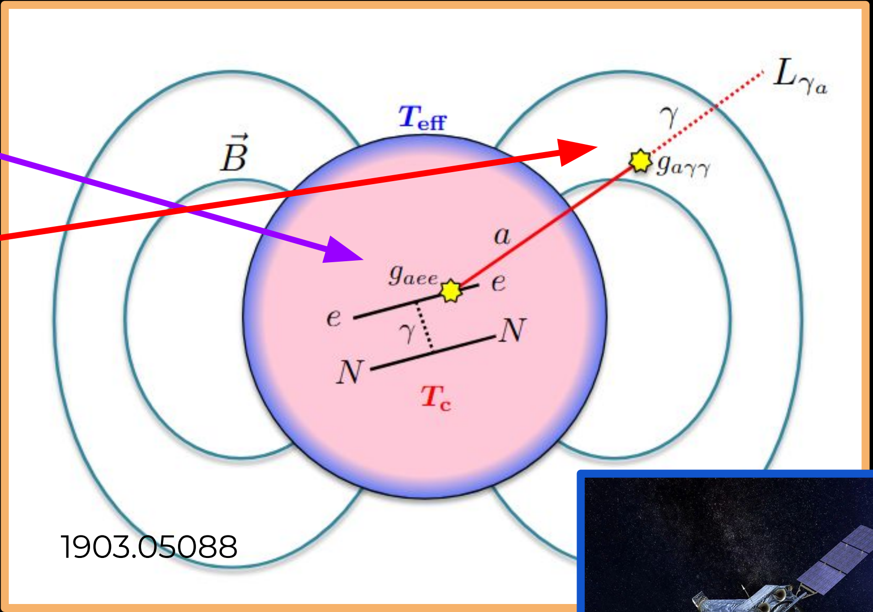


MWDs 2411.05041

Can look for compact objects as well:

Prelude: Axion Signatures from MWDs (2411.05041)

- Axions thermally produced through electron bremsstrahlung in degenerate WD cores (*T* ~ keV)
- Convert to X-ray photons in magnetospheres, which can be strong for MWDs (*B* ~ hundreds of MG)
- Examine multiple MWDs with *Chandra* to probe $g_{aee} \times g_{a\gamma\gamma}$



$$\frac{m_a^2}{2E} L \sim 1$$

Lower scale L → can probe higher axion masses!

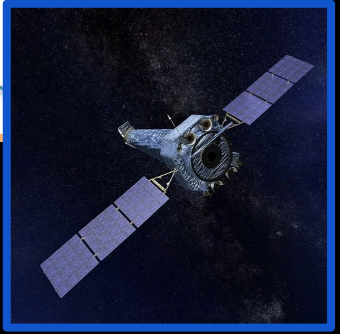
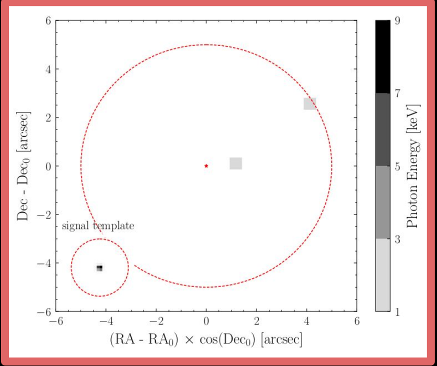
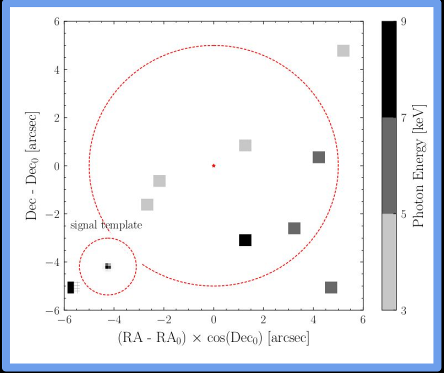


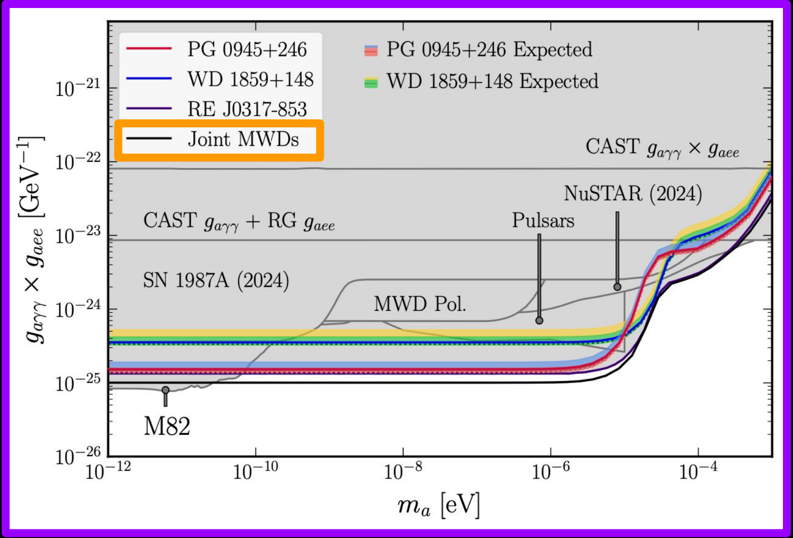
Image: NASA

We observed PG 0945+246 and WD 1859+148 with *Chandra* for ~40 ks each, in 2022 and 2023

- Generally high core temps
- Strong magnetospheres



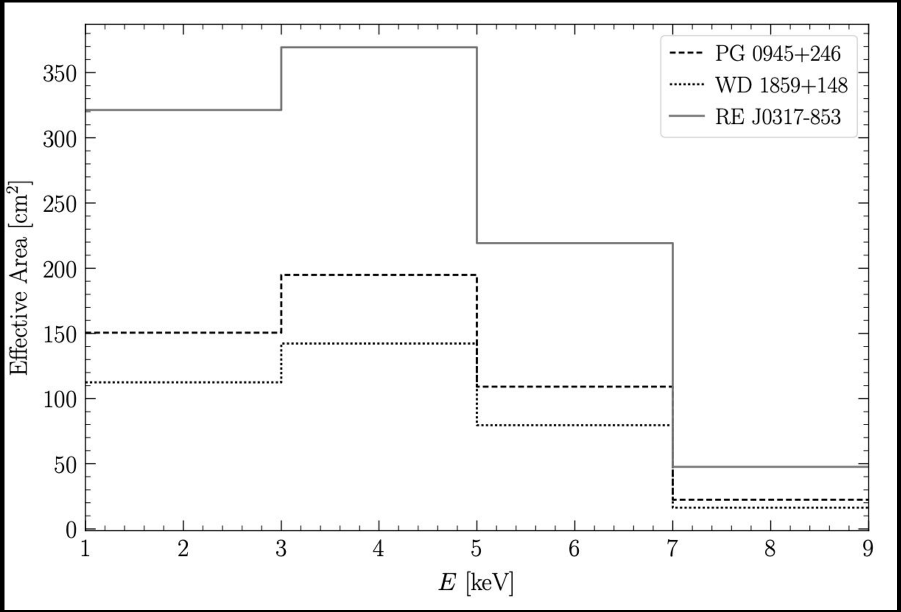


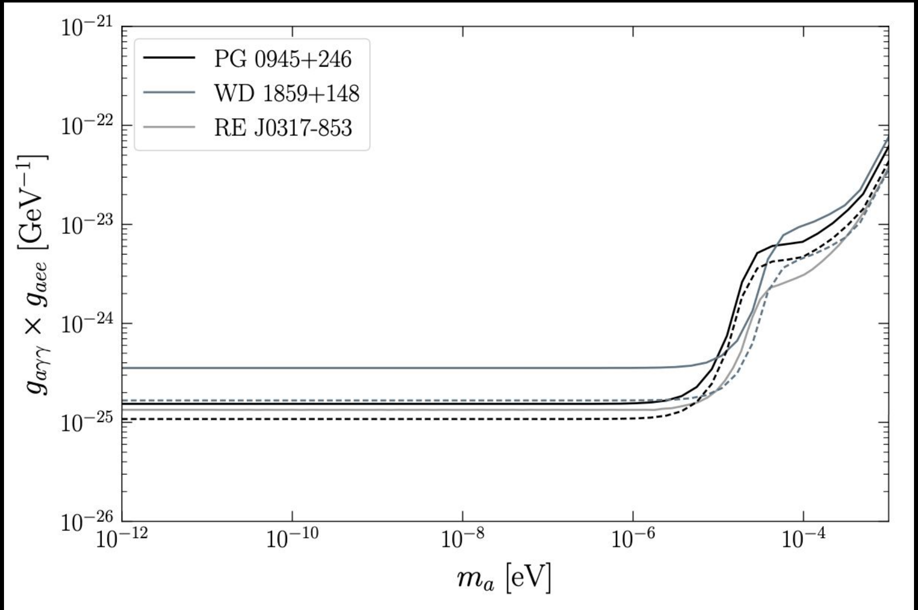


No evidence for axions → higher mass constraints on couplings

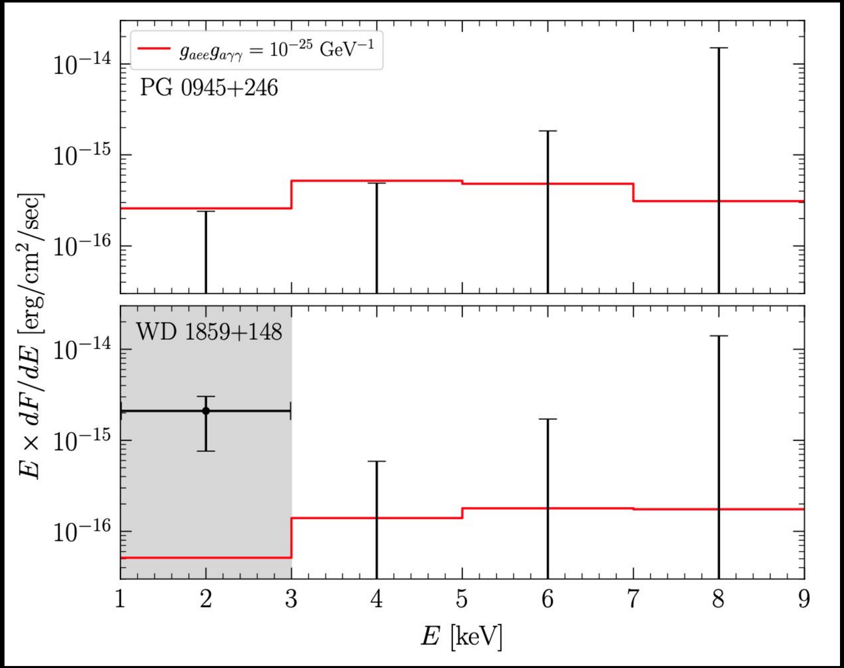
Imagine looking at many MWDs...

The Tragedy of Chandra

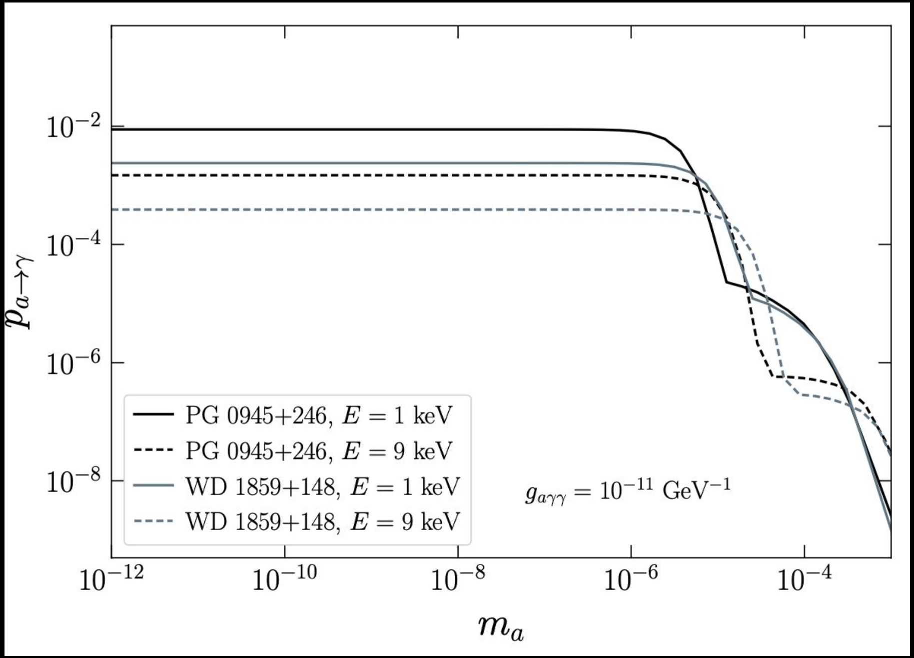




Misc. Plots



$g_{aee}g_{a\gamma\gamma} = 10^{-25}$ GeV^{-1}
PG 0945+246
WD 1859+148
$E \times dF/dE$ [erg/cm^2/sec]
E [keV]



$p_{a\to\gamma}$
PG 0945+246, $E = 1$ keV
PG 0945+246, $E = 9$ keV
WD 1859+148, $E = 1$ keV
WD 1859+148, $E = 9$ keV
$g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}
m_a