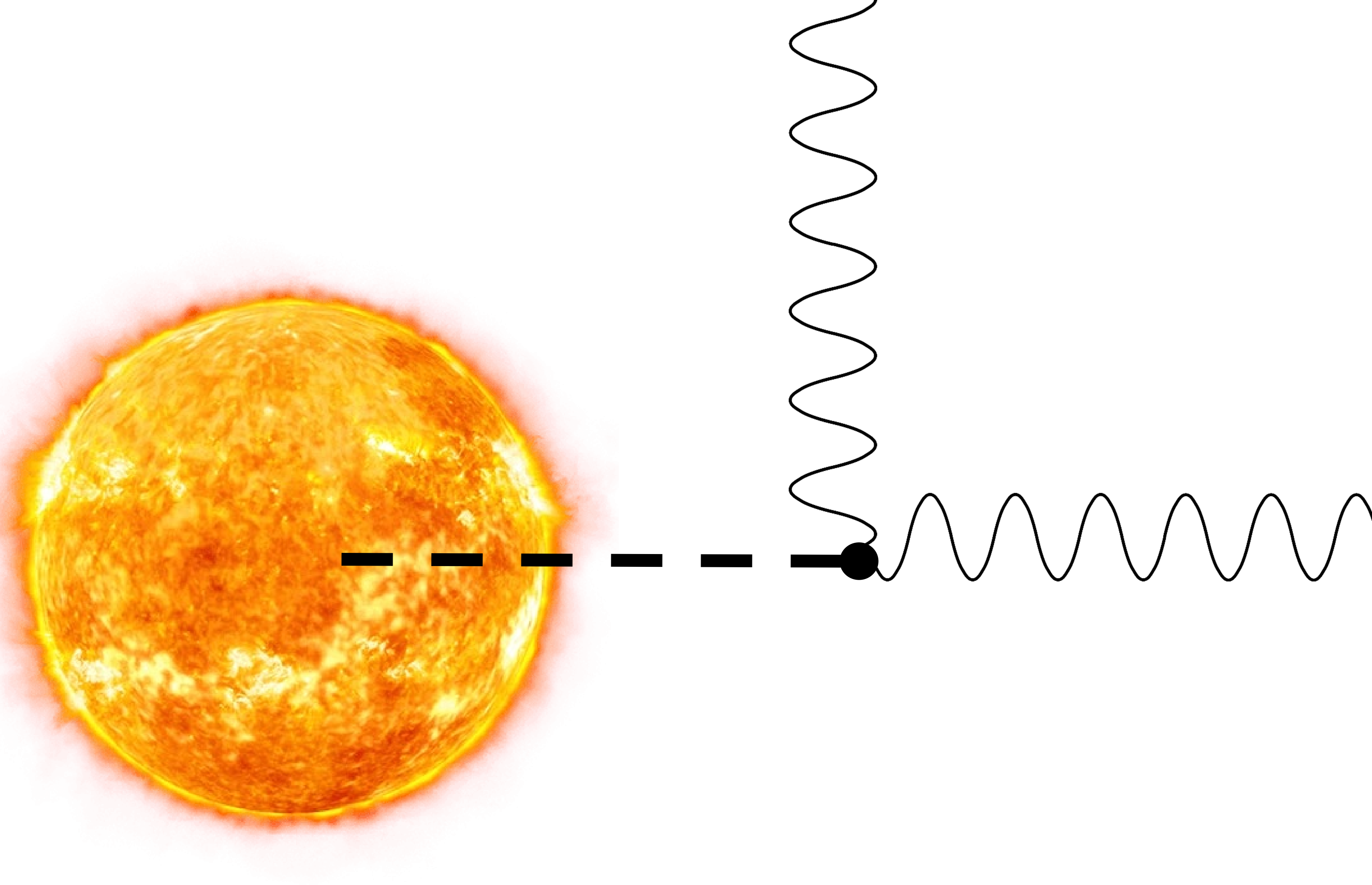
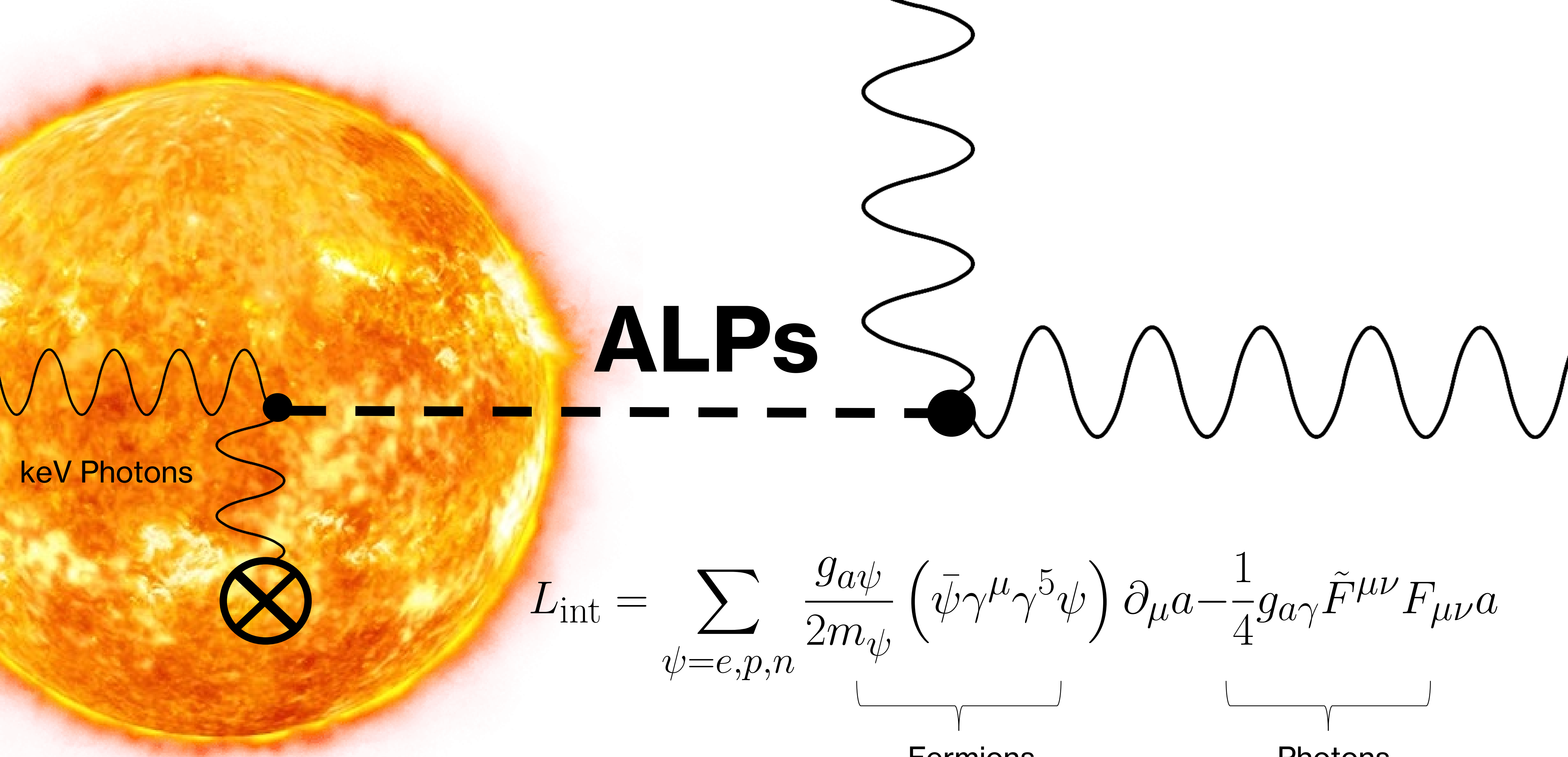
X-ray Searches for **Axions:**

M82 and **Betelgeuse**

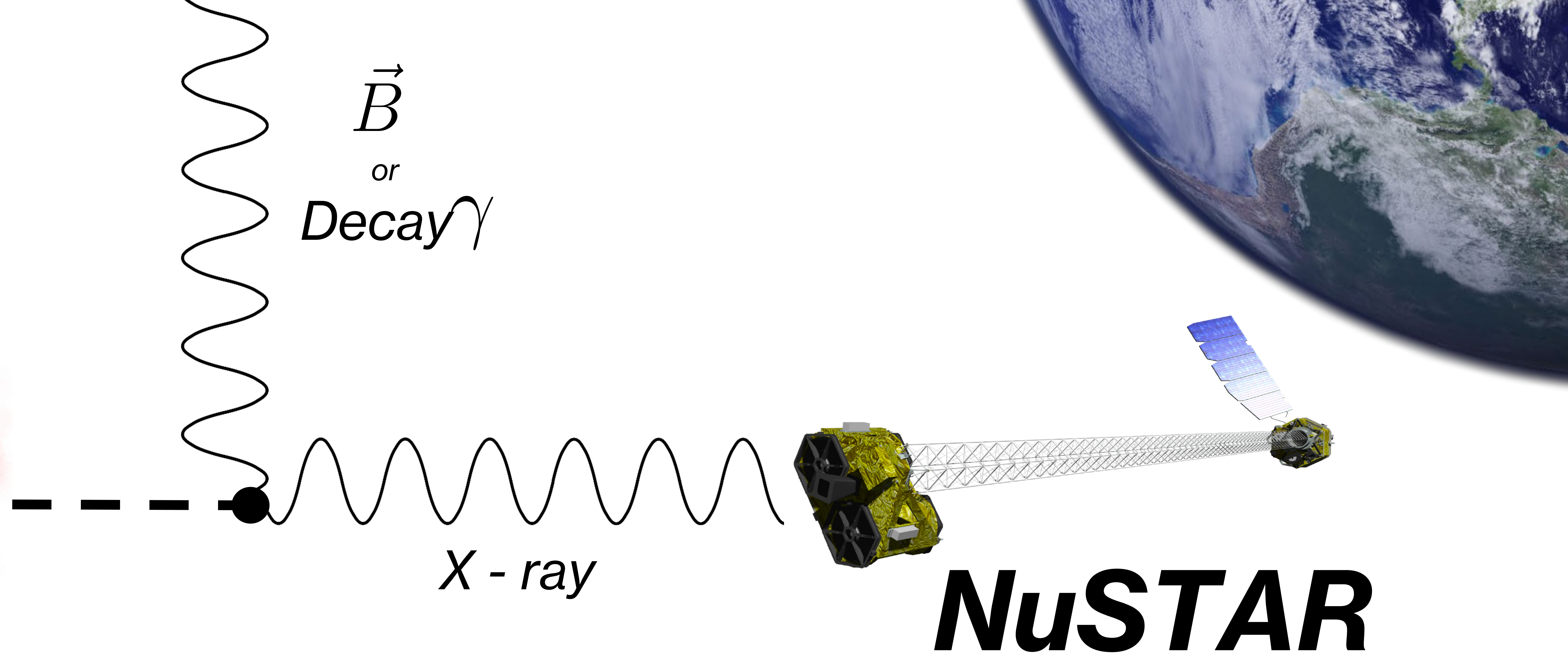


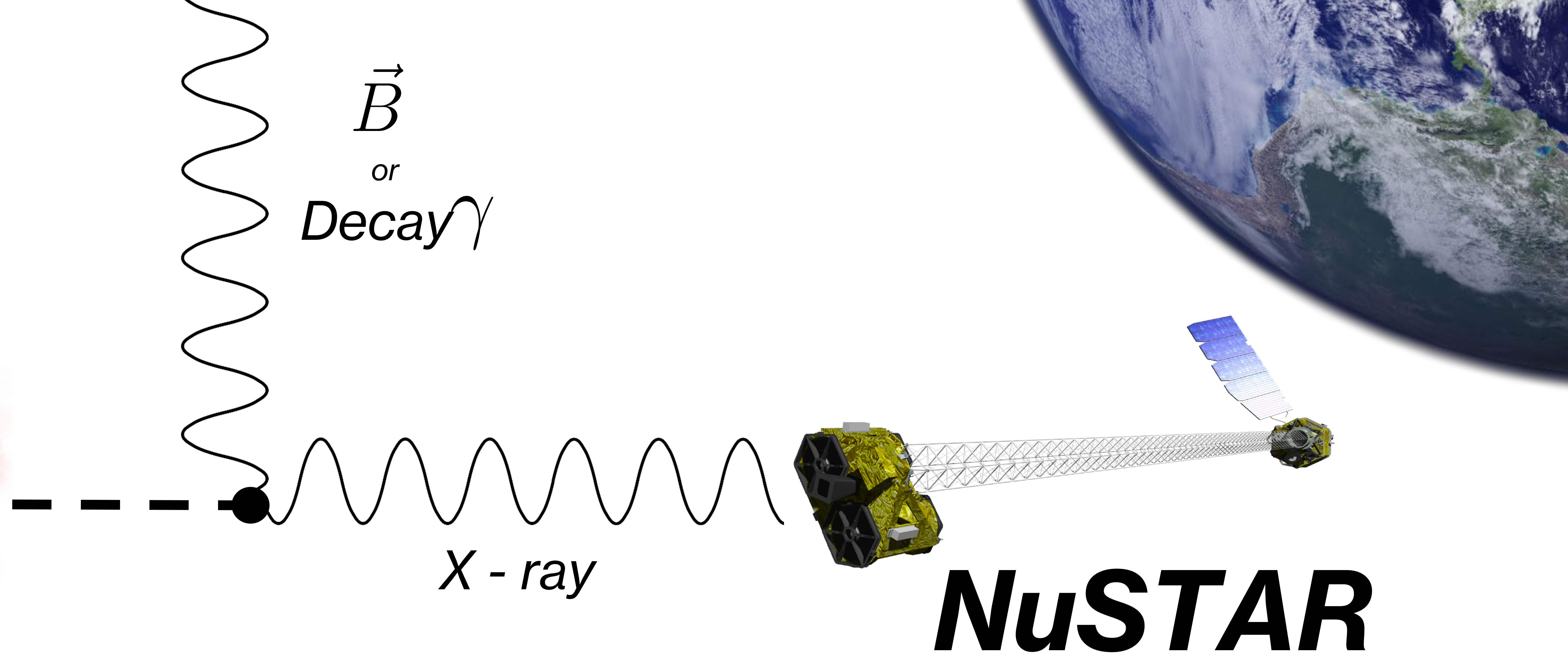
Francisco Rodríguez Candón

Sofia, September 2025



$$L_{\rm int} = \sum_{\psi=e,p,n} \frac{g_{a\psi}}{2m_\psi} \underbrace{\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)\partial_\mu a}_{\text{Fermions}} - \frac{1}{4}\underbrace{g_{a\gamma}\tilde{F}^{\mu\nu}F_{\mu\nu}a}_{\text{Photons}}$$


$\vec{B}$
or
Decay γ
X - ray
NuSTAR


$\vec{B}$
or
Decay γ
X - ray
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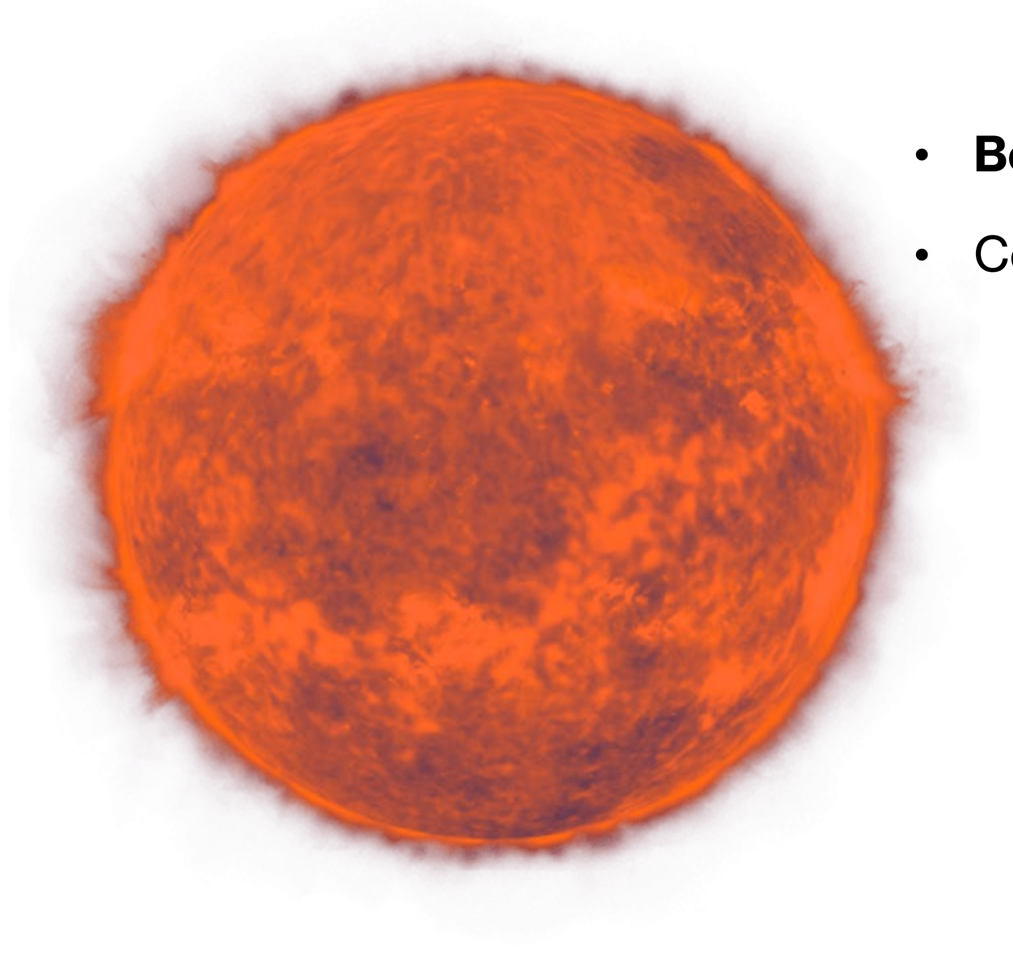
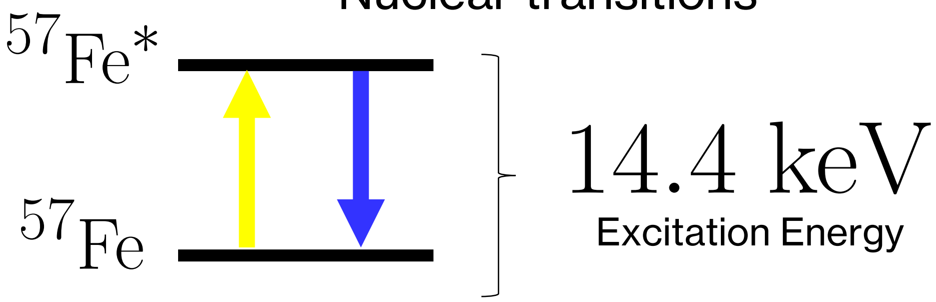
The **Betelgeuse** case



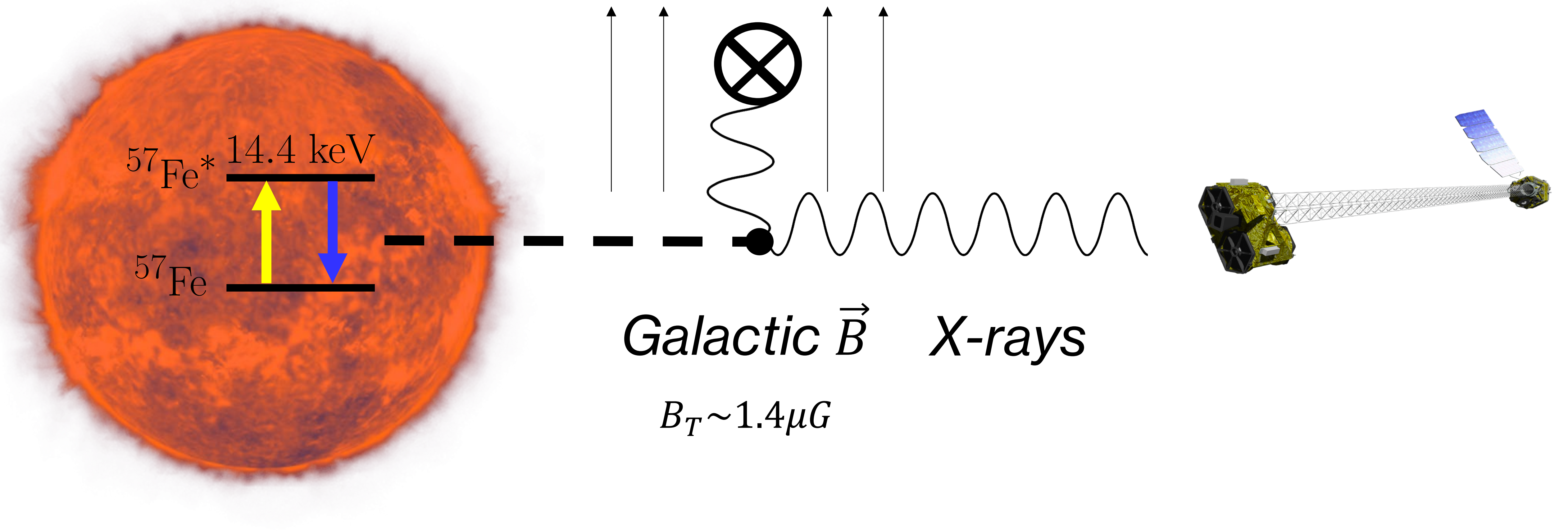
- **Betelgeuse**, a red supergiant star of about 20 $M_\odot$ at 197 pc
- Core temperatures higher tan **14.4 keV**

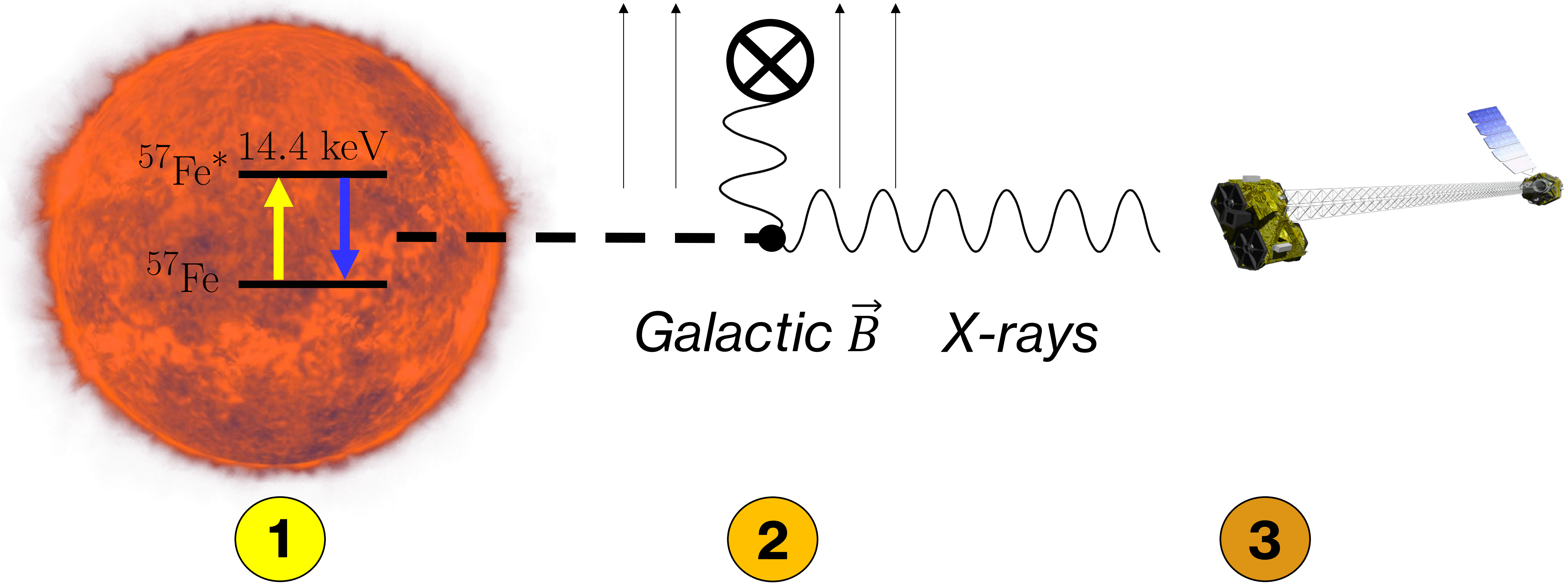
Magnetic dipole (M1)
Nuclear transitions



FRC, P. Casaseca, M. Giannotti,
M. Kaltschmidt, J. Ruz, J. K. Vogel
arXiv:2504.21107

The **Betelgeuse** case



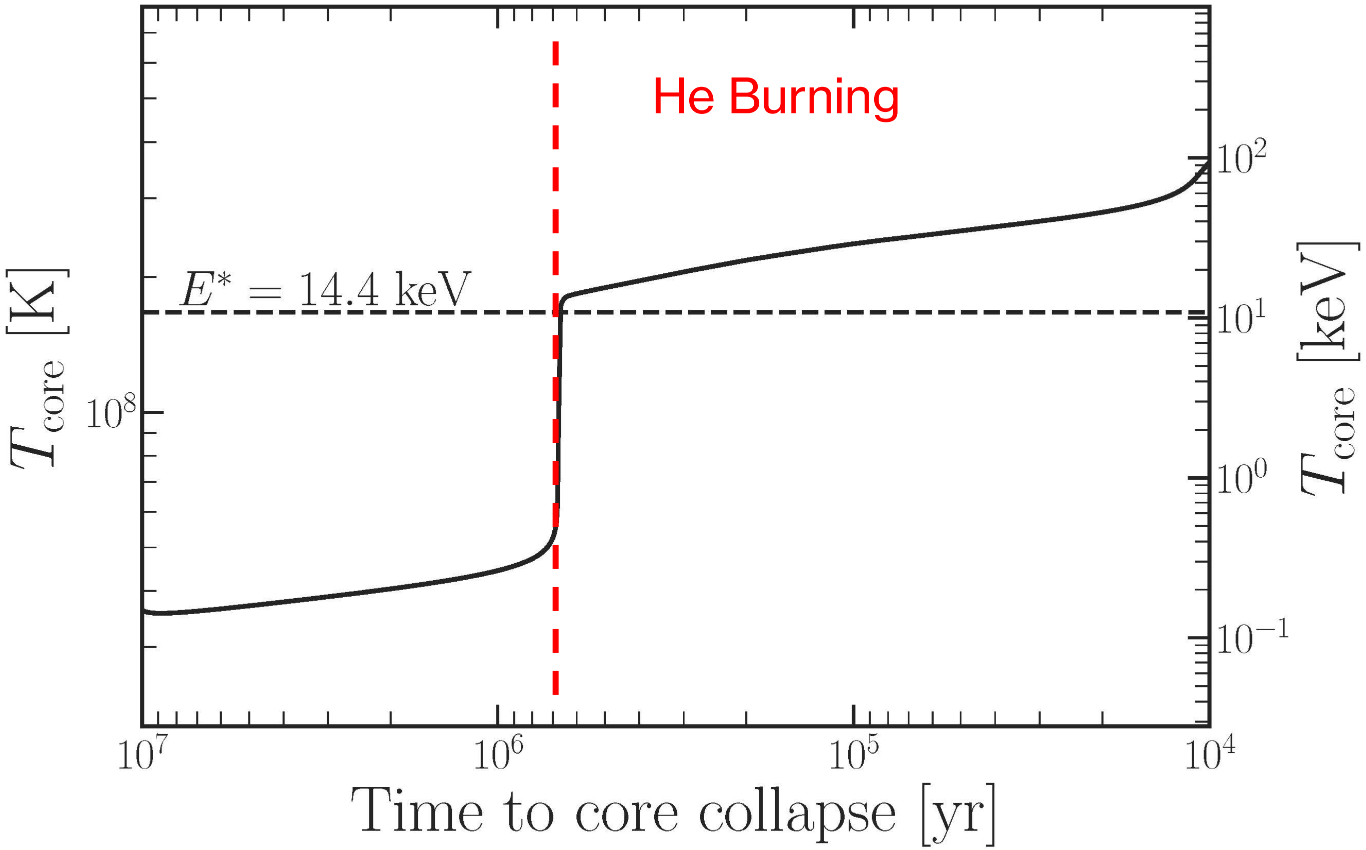


1. **Simulations** of the Star interior *(MESA).*
2. Total produced **axion flux.**

3. **B field and conversion.**
4. **Axion-photon flux** at Earth.

5. **Observational data analysis.**
6. **Unbinned likelihood analysis.**

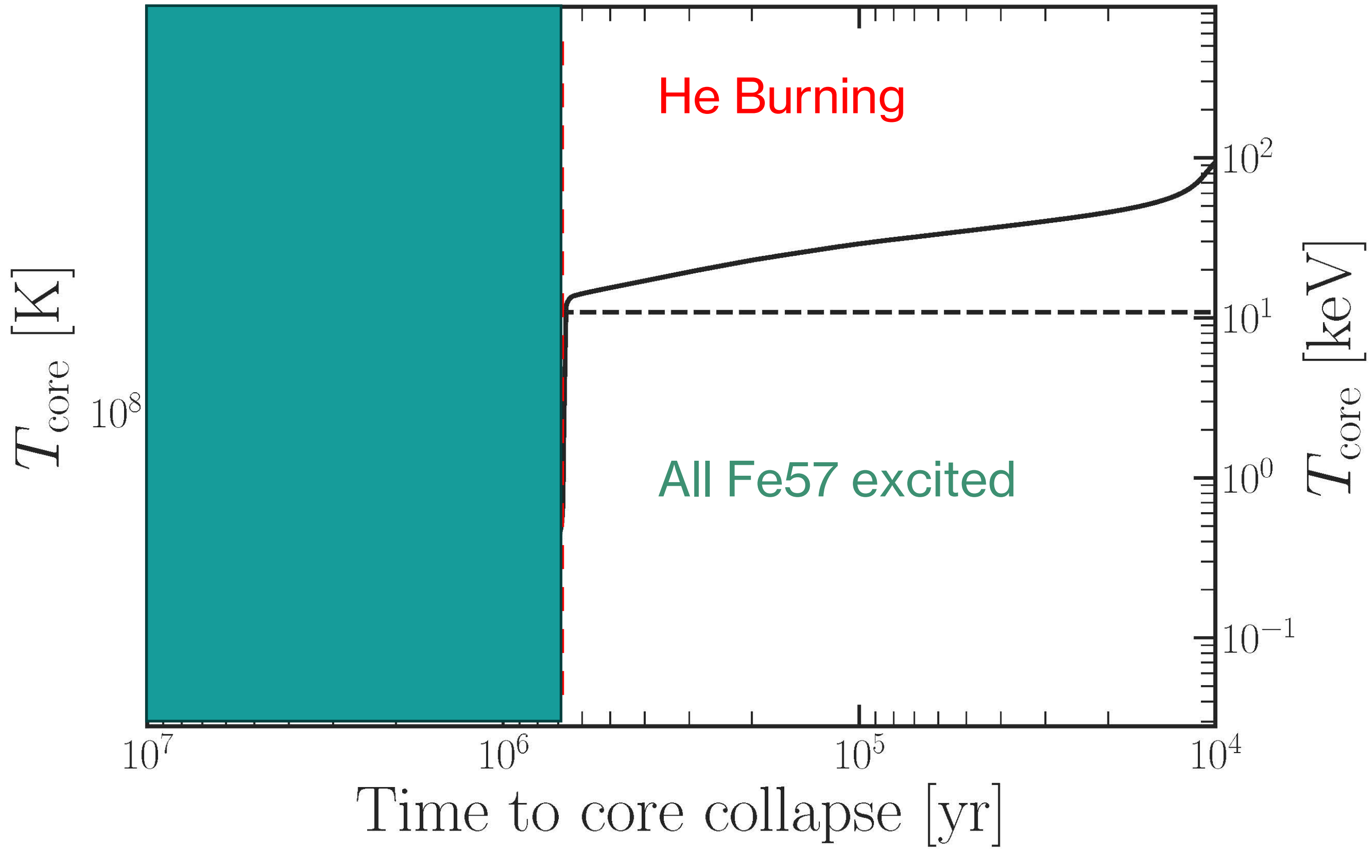
Stellar Simulations



MESA

Modules for Experiments in **Stellar Astrophysics**

Stellar Simulations



MESA

Modules for Experiments in **Stellar Astrophysics**

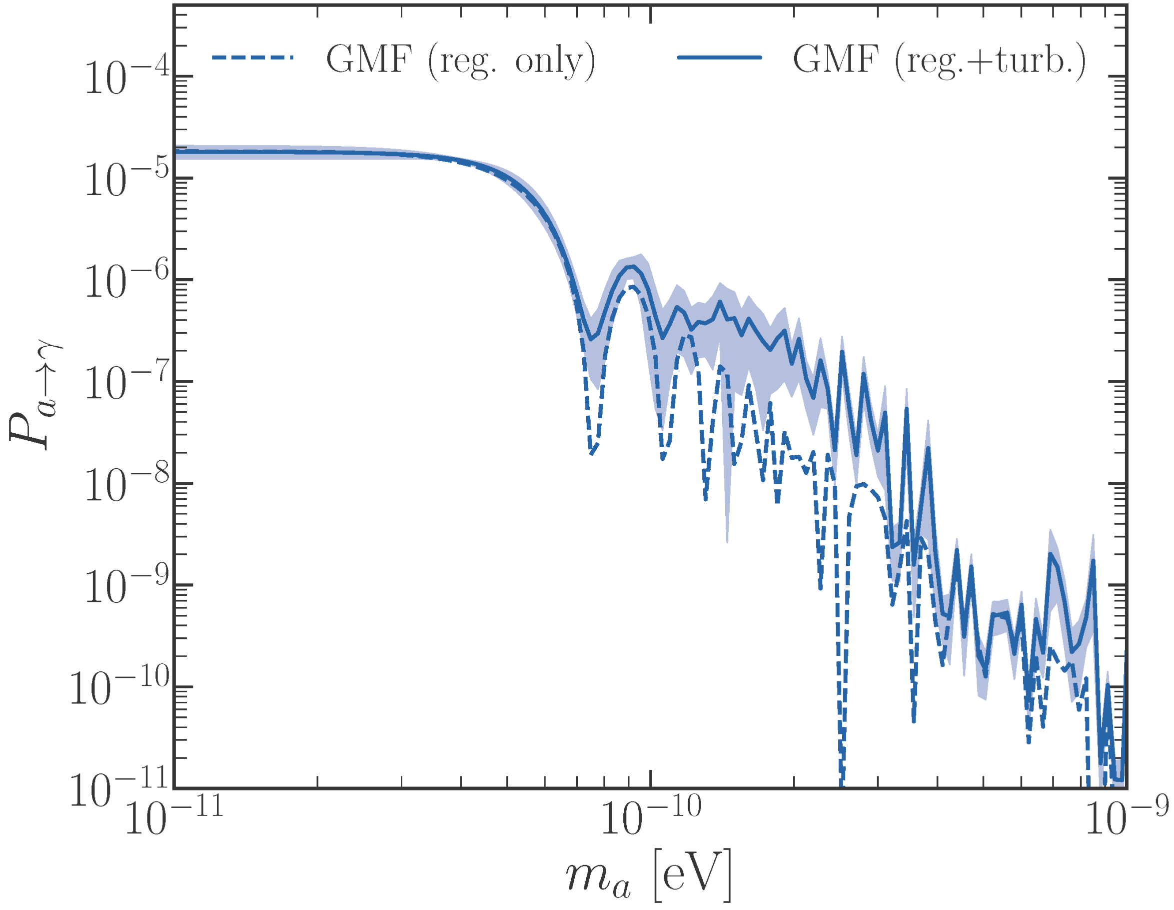
Axion flux

$$\frac{\mathrm{d}N_a(E)}{\mathrm{d}E} = \frac{1}{4\pi d^2} \int_0^{R_{\mathrm{star}}} \mathcal{N}_a(r) \mathcal{G}(E, \sigma(r)) \rho(r) 4\pi r^2$$

Where $\mathcal{N}_a$ is the axion rate that depends on the Fe57 number density, the occupation of the first excited state and the branching factor ratio

$$\frac{\Gamma_a}{\Gamma_\gamma} = 2.32 \left(\underbrace{0.16 g_{ap} + 1.16 g_{an}}_{g_{aN}^{\mathrm{eff}}}\right)^2$$

Probability conversion



Galactic Magnetic Field

Regular + Turbulent

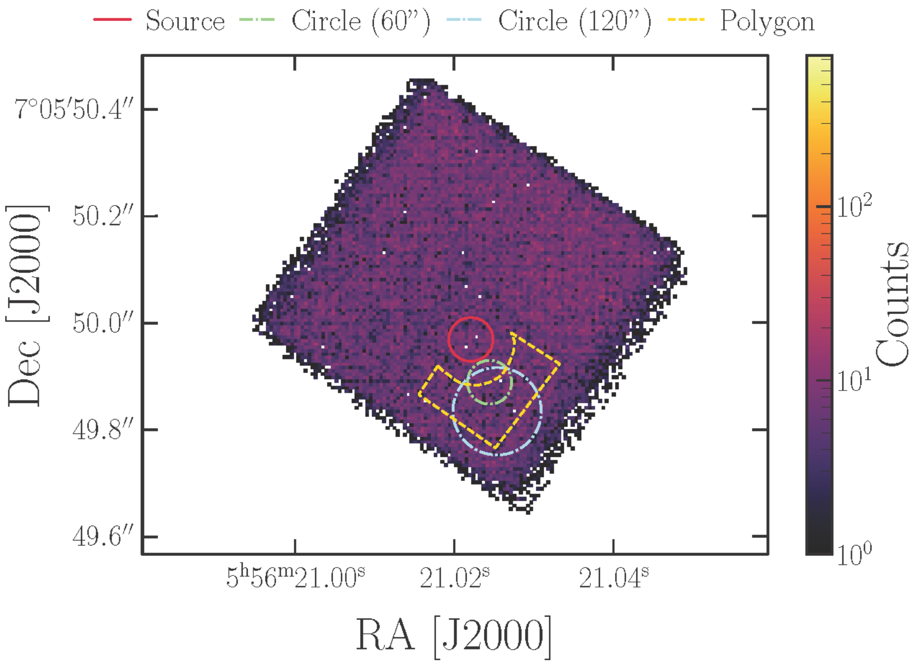
$$P_{a\gamma} = 8.7\times10^{-6} g_{11}^2 \left(\frac{B_{\rm T}}{1\mu{\rm G}}\right)^2 \left(\frac{d}{197{\rm pc}}\right)^2 \frac{\sin^2(qd)}{(qd)^2}$$

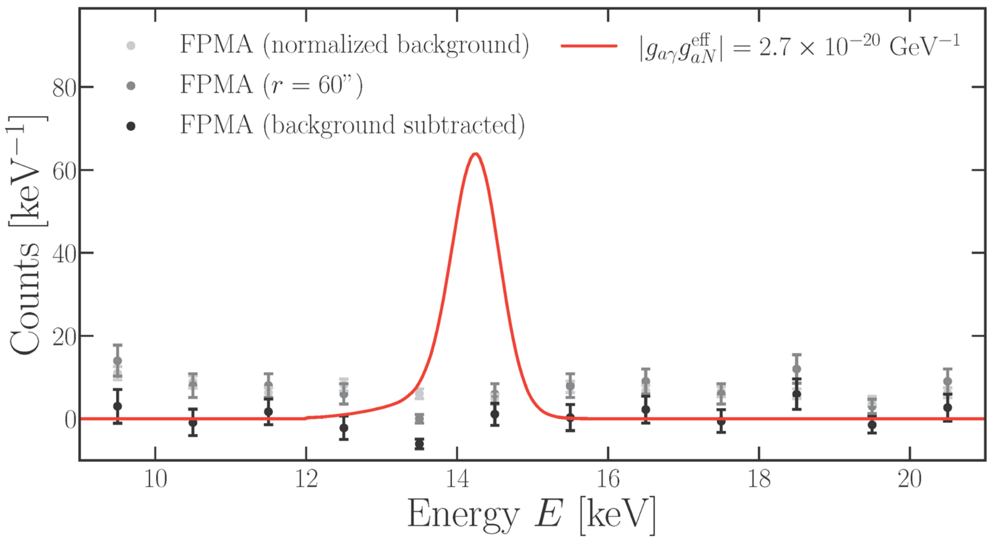
$$g_{11} = (g_{a\gamma}/10^{11}\,{\rm GeV}^{-1})$$

$$qd \simeq \left[77\left(\frac{m_a}{10^{-10}\ {\rm eV}}\right)^2 - 0.14\left(\frac{n_e}{0.013\ {\rm cm}^{-3}}\right)\right] \times \left(\frac{d}{197\ {\rm pc}}\right)\left(\frac{E}{1\ {\rm keV}}\right)^{-1}$$

Observational data analysis

- **NASA** data analysis tools: HEASOFT, NuSTARdas, XSPEC





Likelihood analysis

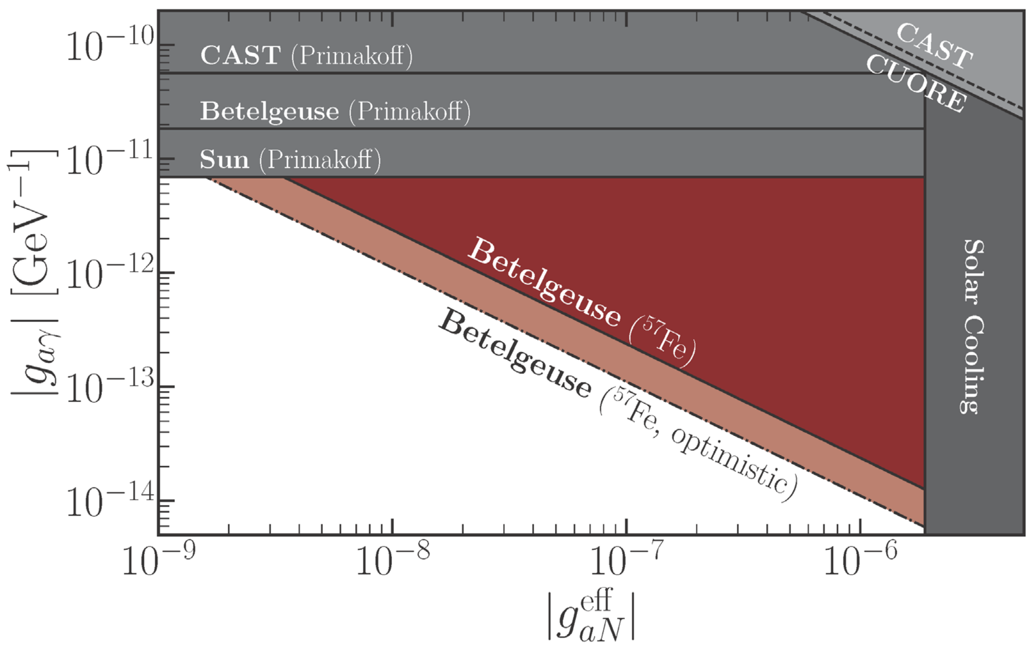
Unbinned likelihood and Bayesian analysis. The 95% C.L are obtained by integrating the **posterior probability**

$$\int_0^{(g_{a\gamma}^2 g_{aN}^2)_{as\%}} P\left(g_{a\gamma}^2 g_{aN}^2\right) \mathrm{d}\left(g_{a\gamma}^2 g_{aN}^2\right) = 0.95$$

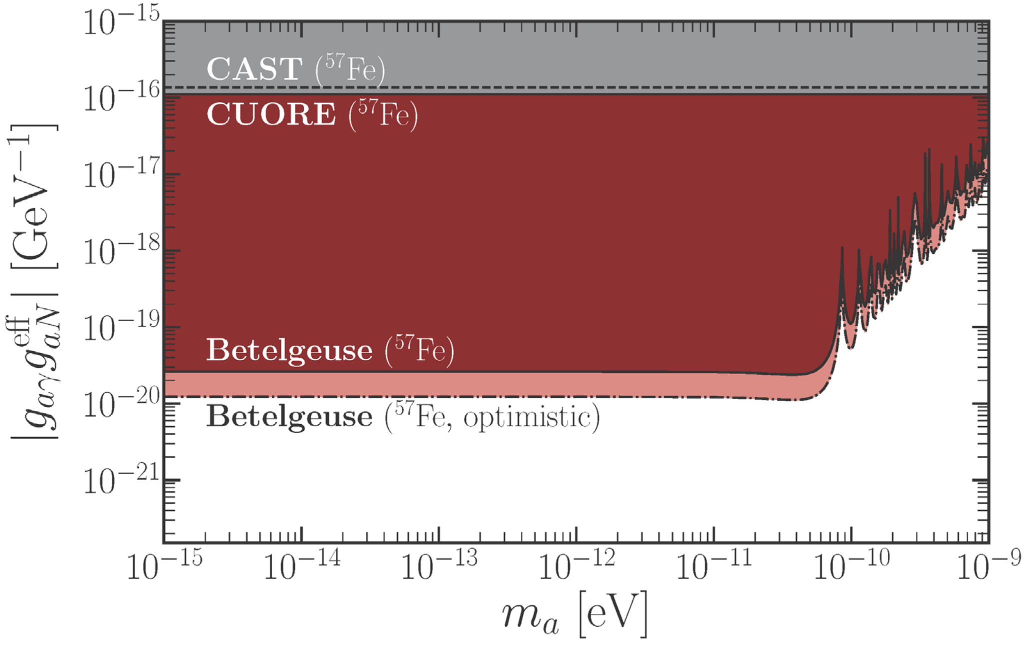
$$\Downarrow$$

$$\left|g_{a\gamma} g_{aN}^{\mathrm{eff}}\right| \leq (1.2 - 2.7) \times 10^{-20} \mathrm{GeV}^{-1}$$

Likelihood analysis



Massless Case



Masive Case

SMM photon observations from SN1987 $\left|g_{a\gamma} g_{aN}^{\rm eff}\right| \lesssim 3 \times 10^{-24} \mathrm{GeV}^{-1}$

The **M82** case

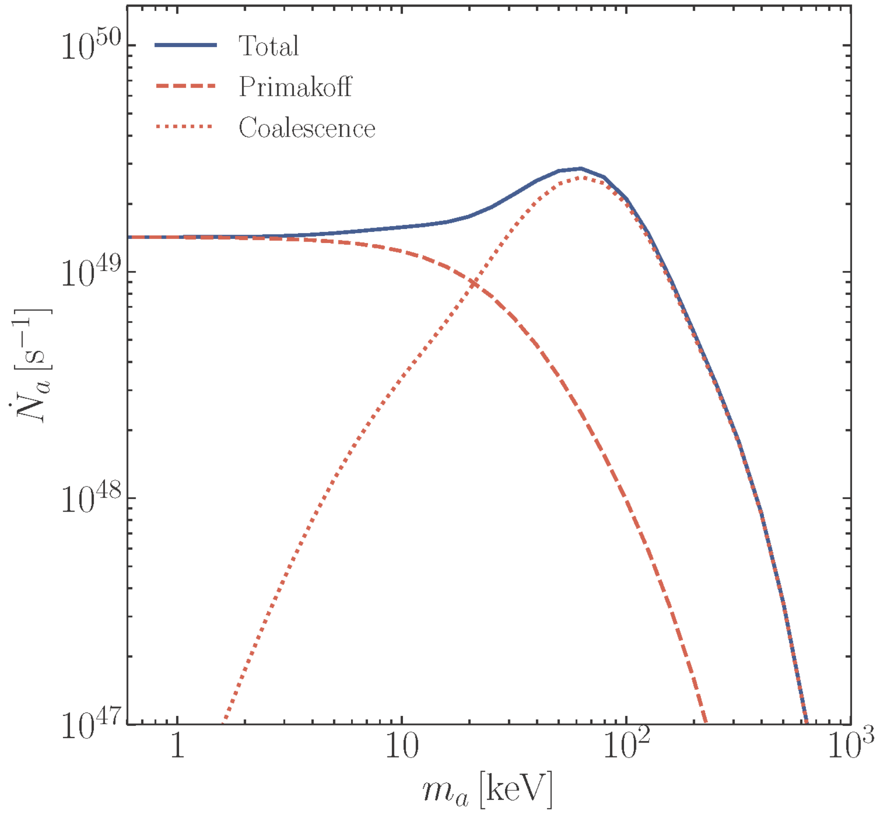
The **M82** case

- **M82** is a starburst Galaxy at 3.8 Mpc.
- Heavy Axion emission dominated by young massive stars

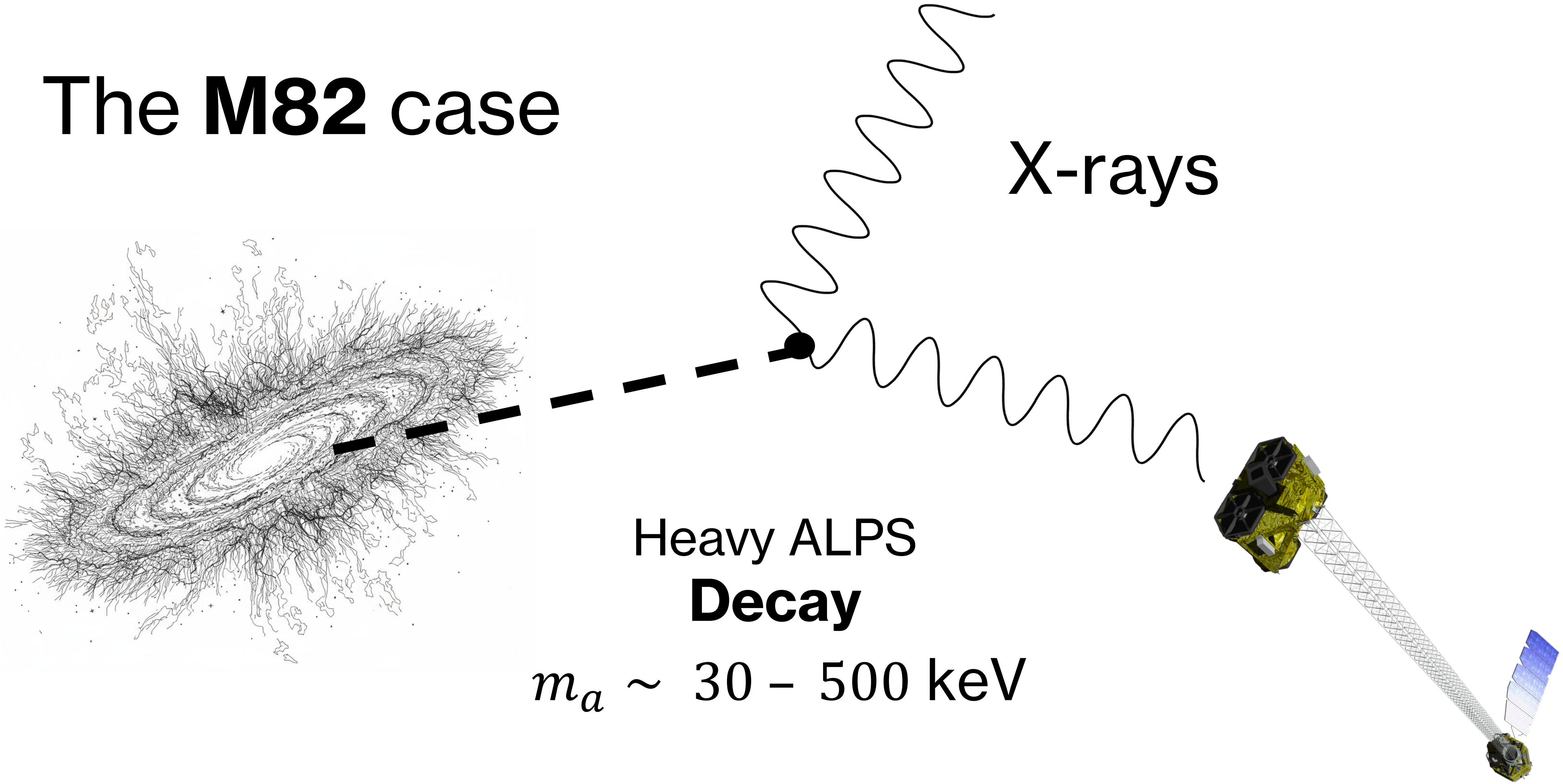
Two dominant processes

$$\gamma + Ze \to Ze + a$$
$$\gamma + \gamma \Rightarrow a$$

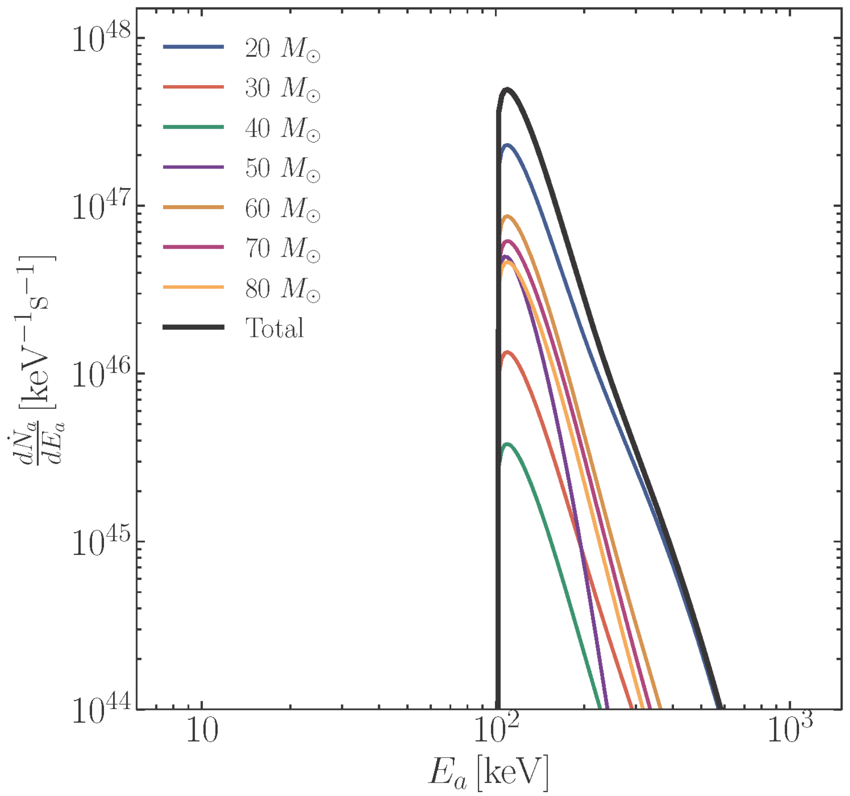
FRC, D.F.G. Fiorillo, G.L. Lucente, E. Vitagliano, J.Vogel
PhysRevLett.134.171004



The **M82** case

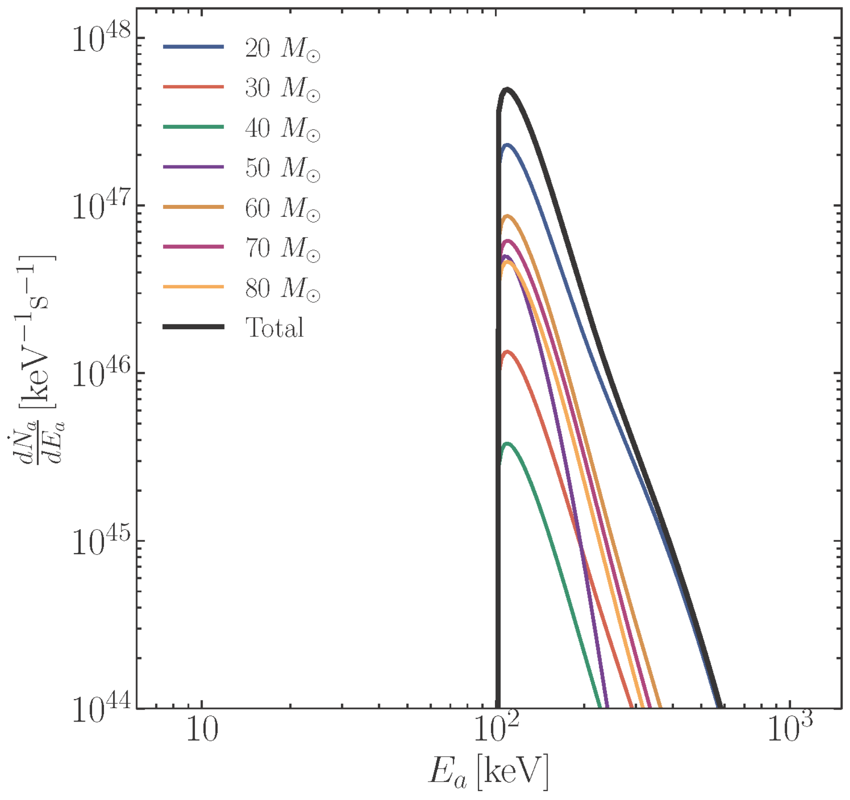


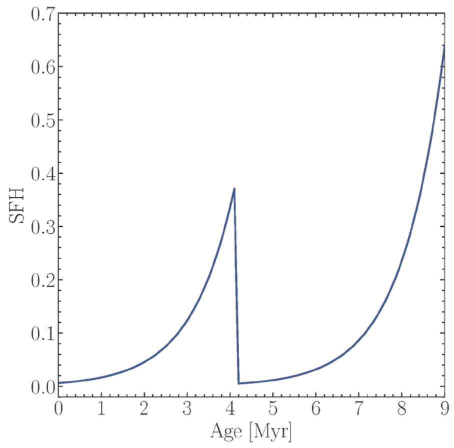
Total **Axion** Flux



$$\frac{d\dot{N}_a}{dE_a} = N_{\mathrm{tot}} \int dM_s dt_s\, \mathrm{IMF}\left(M_s\right) \mathrm{SFH}\left(t_s\right) \frac{d\dot{N}_a^s}{dE_a}$$

Total **Axion** Flux

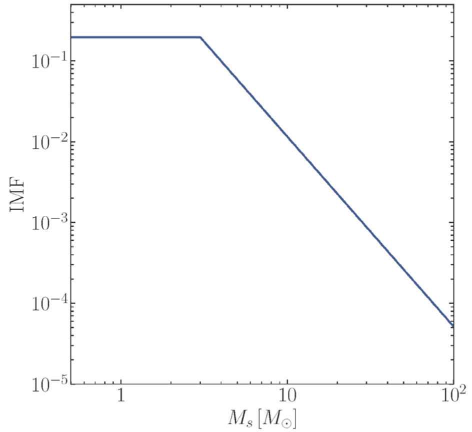




Star Formation History

$$\frac{d\dot{N}_a}{dE_a} = N_{\text{tot}} \int dM_s dt_s \,\text{IMF}\,(M_s)\,\text{SFH}\,(t_s)\,\frac{d\dot{N}_a^s}{dE_a}$$

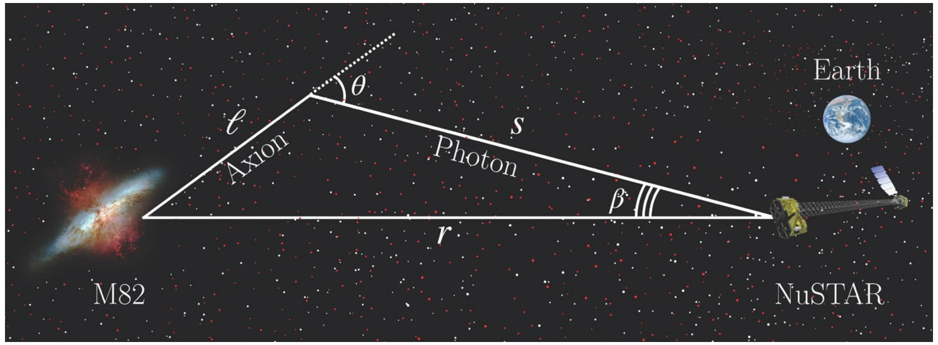
Initial Mass function

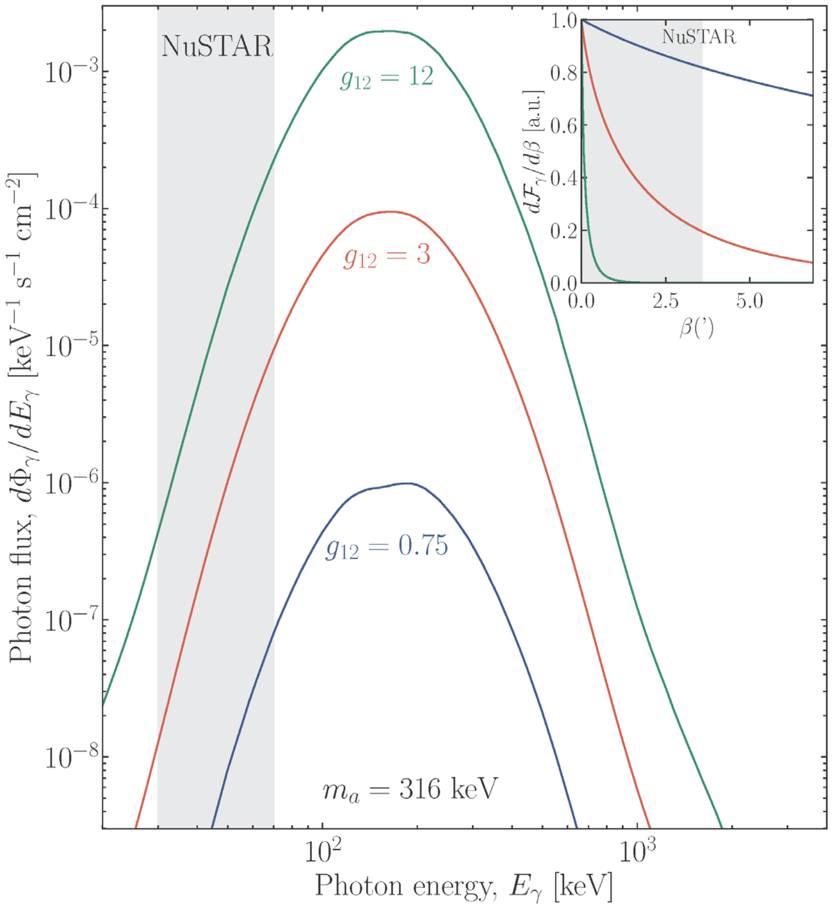


Total **Photon** Flux

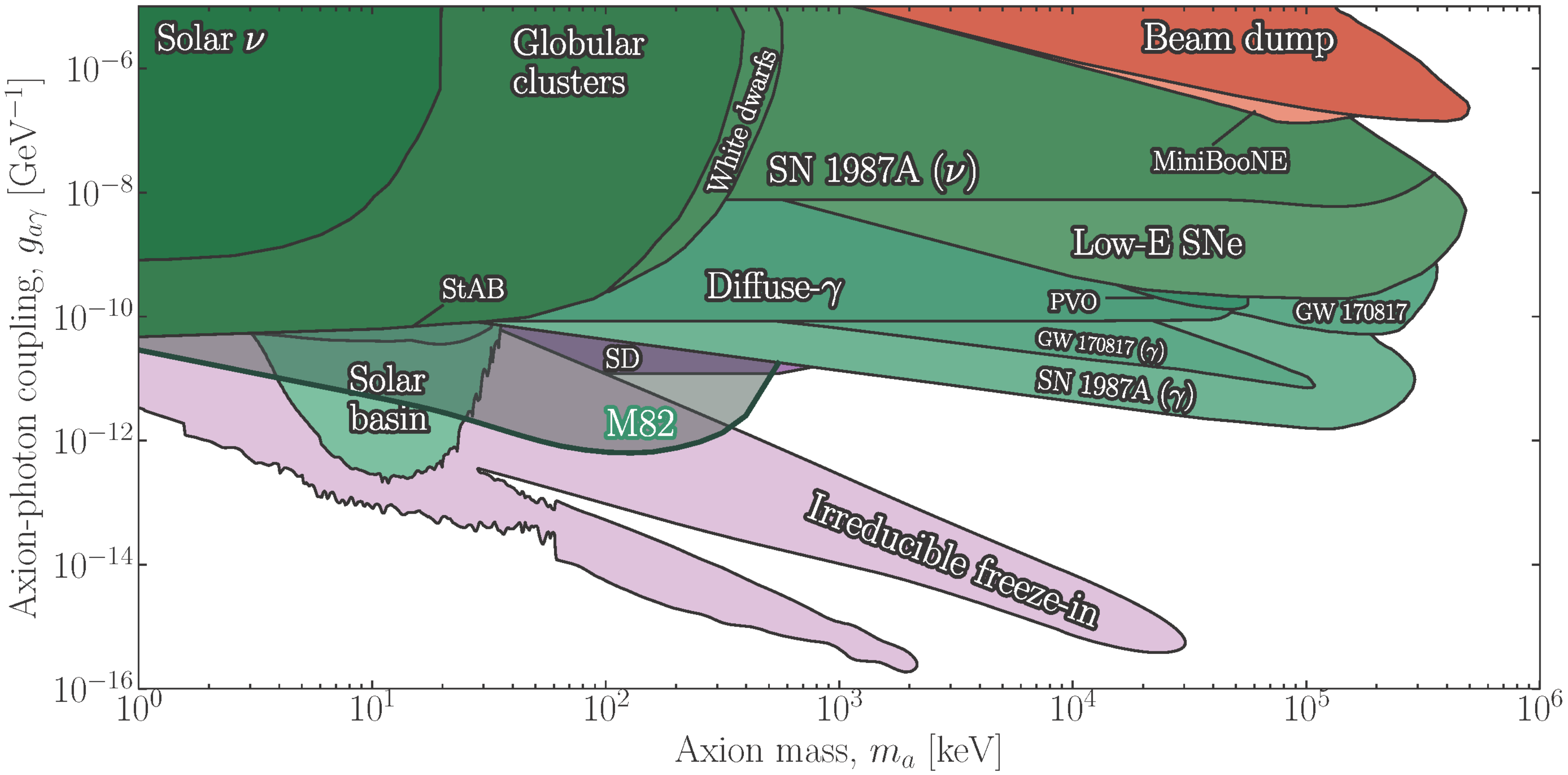
$$\frac{d\Phi_\gamma}{dE_\gamma d\beta} = \int_{E_{a,\mathrm{min}}}^{+\infty} \frac{2dE_a \cos\beta}{p_a} \frac{d\dot{N}_a/dE_a}{4\pi r}$$

$$\Theta(\cos\beta - \cos\theta)\exp\left[-\frac{\Gamma_a m_a r \sin\beta}{p_a \sin\theta}\right]\frac{\Gamma_a m_a}{p_a \sin\theta}$$





The **M82** case



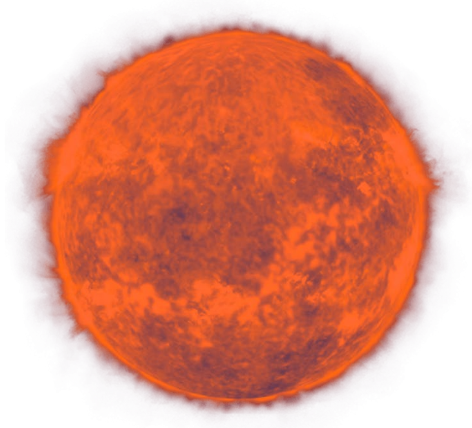
Solar ν
Globular clusters
White dwarfs
Beam dump
SN 1987A (ν)
MiniBooNE
Low-E SNe
StAB
Diffuse-γ
PVO
GW 170817
GW 170817 (γ)
SD
SN 1987A (γ)
Solar basin
M82
Irreducible freeze-in
Axion-photon coupling, $g_{a\gamma}$ [GeV^{-1}]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Axion mass, m_a [keV]

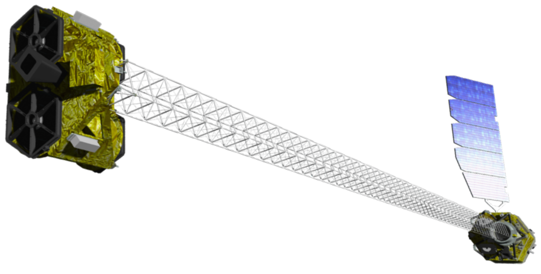
Conclusions

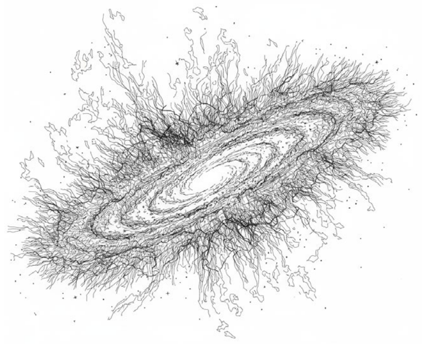
- 14.4 keV Transition of Fe57 provides a stable, narrow line-like X-ray signature.

- The decay of slow axions from starburst Galaxies leads to a peculiar X-ray flux observable by NuSTAR

- X-ray Telescopes like NuSTAR, Chandra, and future missions like Athena and HEX-P, are key in the quest of the QCD Axion and ALPS







GRACIAS!!

BACKUPS

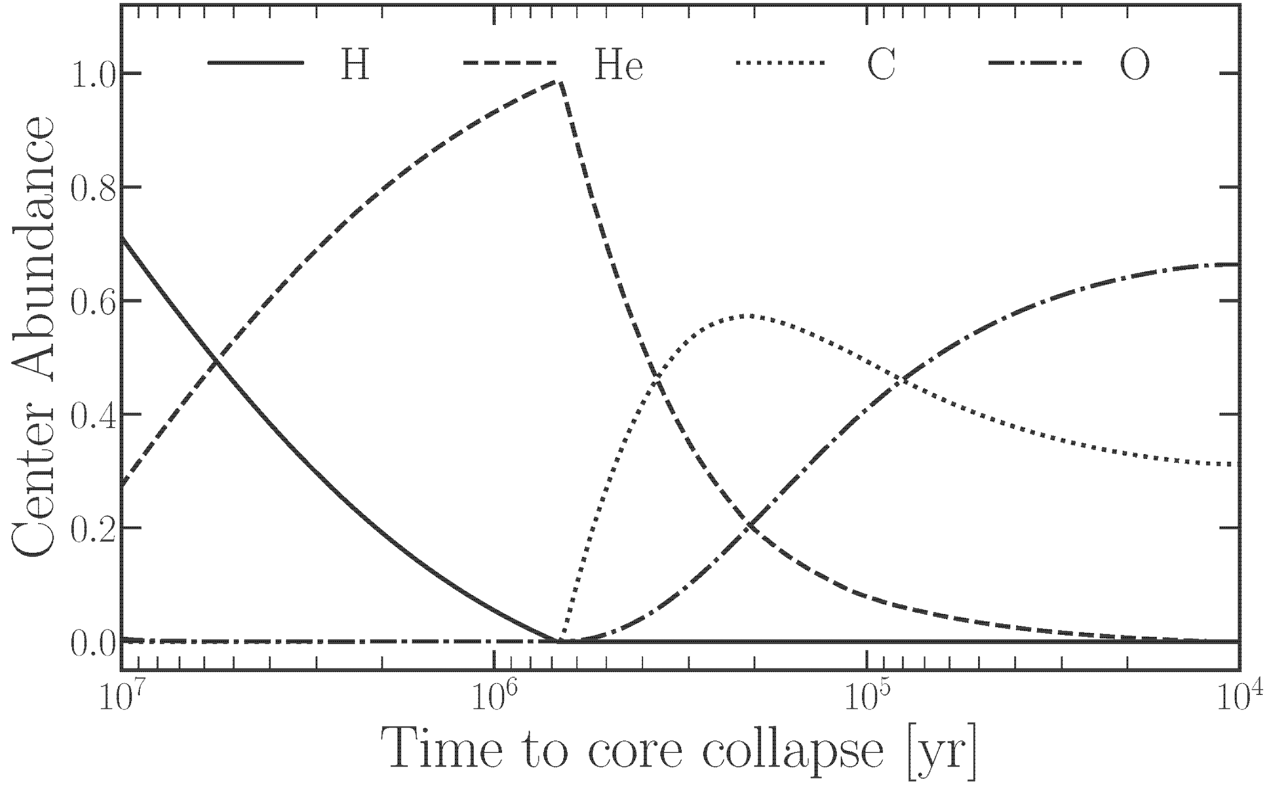
Likelihood analysis

Unbinned likelihood $\mathcal{L} = \prod_{i=\{\mathrm{A,B}\}} \mathcal{L}_i \times \prod_{i=\{\mathrm{A,B}\}} \mathcal{G}\left(\delta^i_{\mathrm{bkg}} \sigma^i_{\mathrm{bkg}}\right)$

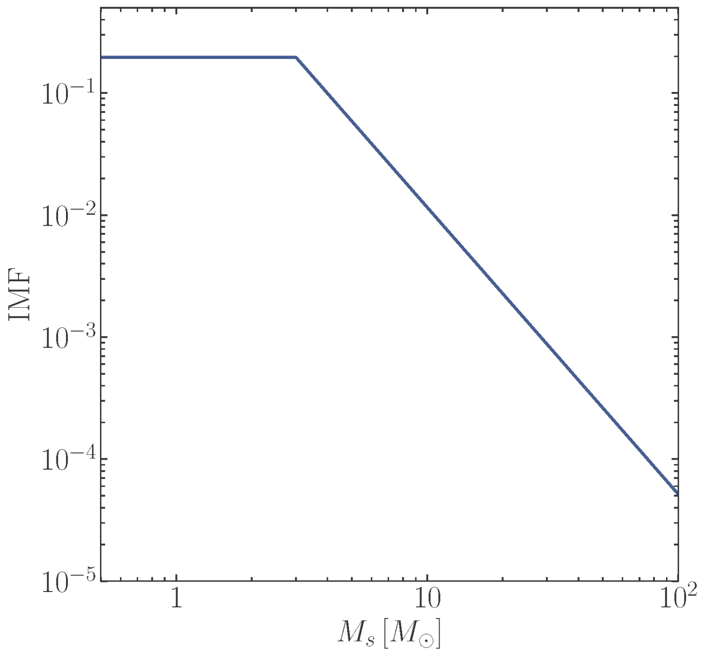
$$\mathcal{L}_i = \mathrm{Poisson}\left(N_{\mathrm{obs},i} \mid N_{\exp,i}\right) \times \prod_{j=1}^{N_{\mathrm{obm},i}} \left[\frac{N_{\mathrm{ax},i} P_{\mathrm{ax}}\left(E'_j\right)}{N_{\mathrm{cxp},i}} + \frac{N_{\mathrm{bkg},i}\left(1+\delta^i_{\mathrm{bkg}}\right) P_{\mathrm{bkg}}\left(E'_j\right)}{N_{\exp,i}}\right]$$

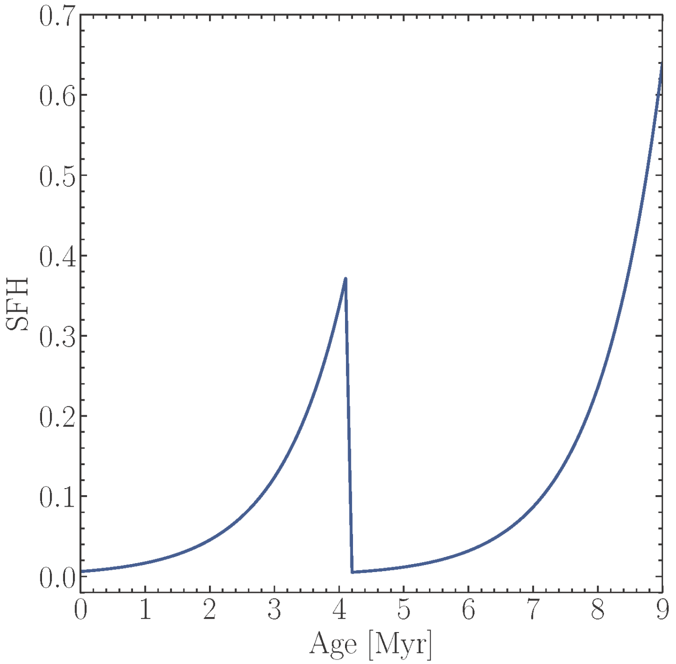
$$P(\theta) = \frac{\mathcal{L}(\theta)}{\int \mathcal{L}\left(\theta'\right) \mathrm{d}\theta'} \qquad \int_0^{\left(g^2_{a\gamma} g^2_{aN}\right)_{as\%}} P\left(g^2_{a\gamma} g^2_{aN}\right) \mathrm{d}\left(g^2_{a\gamma} g^2_{aN}\right) = 0.95$$

Betelgeuse Simulations



Betelgeuse Simulations





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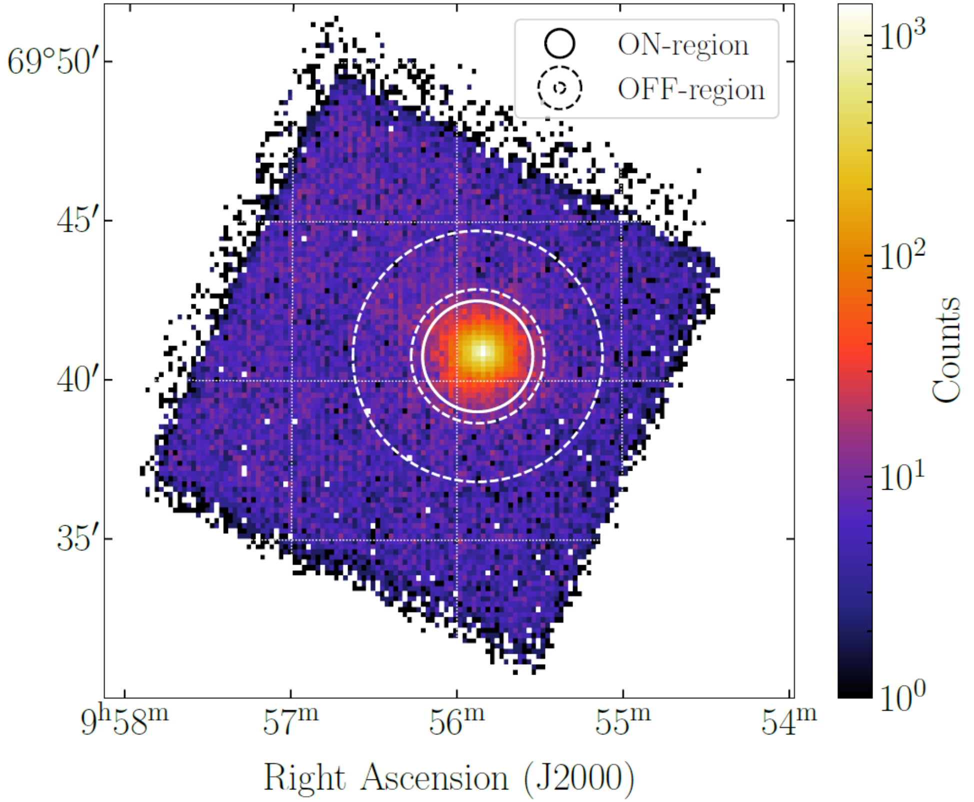
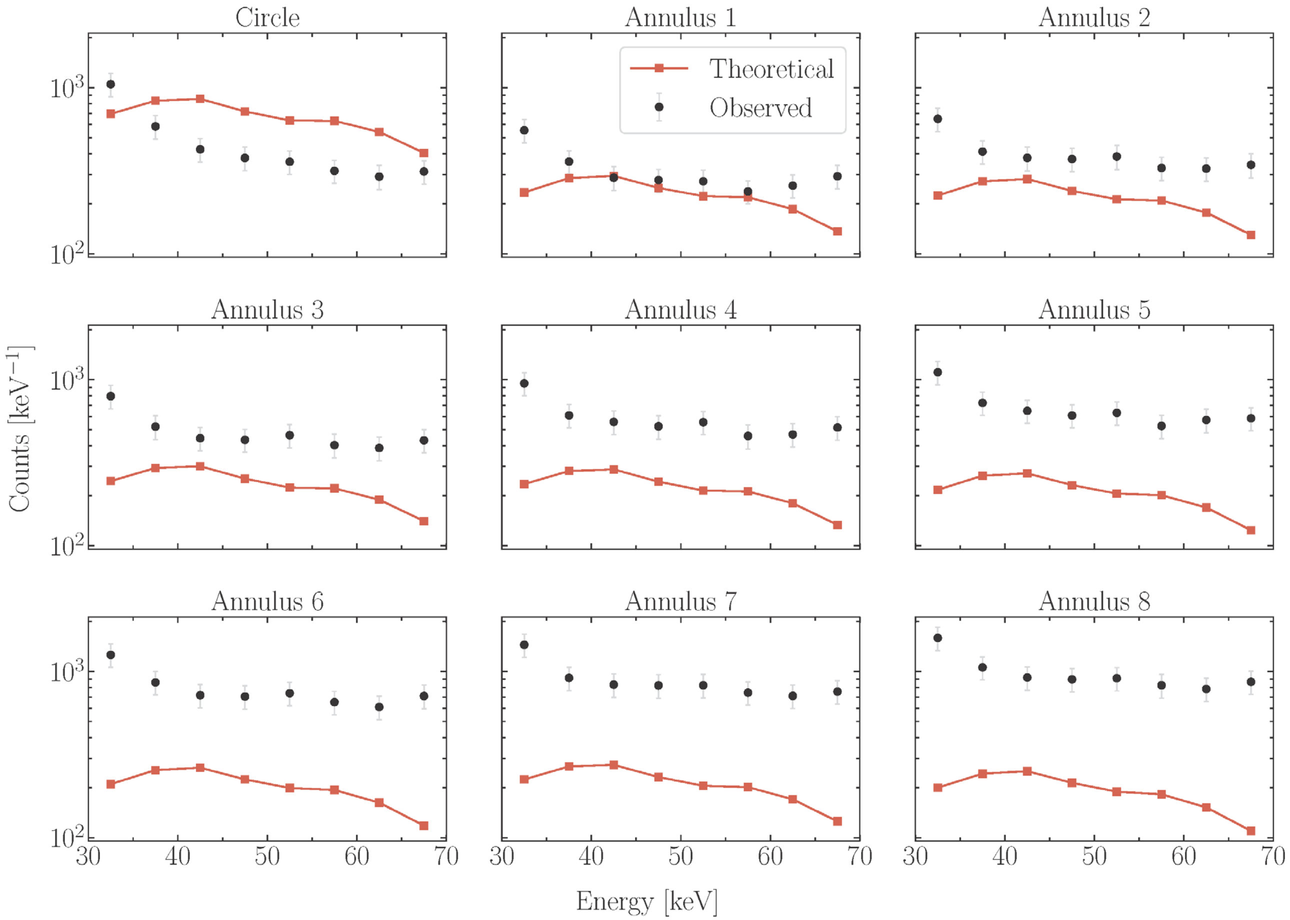
M82 FOV



$$N^{a}_{c,i,\alpha}\left(g_{a\gamma}, m_a\right) = t^{c} \int dE' \, \mathrm{RMF}^{c}_{i,\alpha}\left(E_i, E'\right) \mathrm{ARF}^{c}_{\alpha}\left(E'\right) S_{\alpha}\left(E' \mid g_{a\gamma}, m_a\right)$$

M82 FOV



Circle
Annulus 1
Annulus 2
Annulus 3
Annulus 4
Annulus 5
Annulus 6
Annulus 7
Annulus 8
Theoretical
Observed
Counts [keV^{-1}]
Energy [keV]
10^3
10^2
30
40
50
60
70

Betelgeuse Simulations