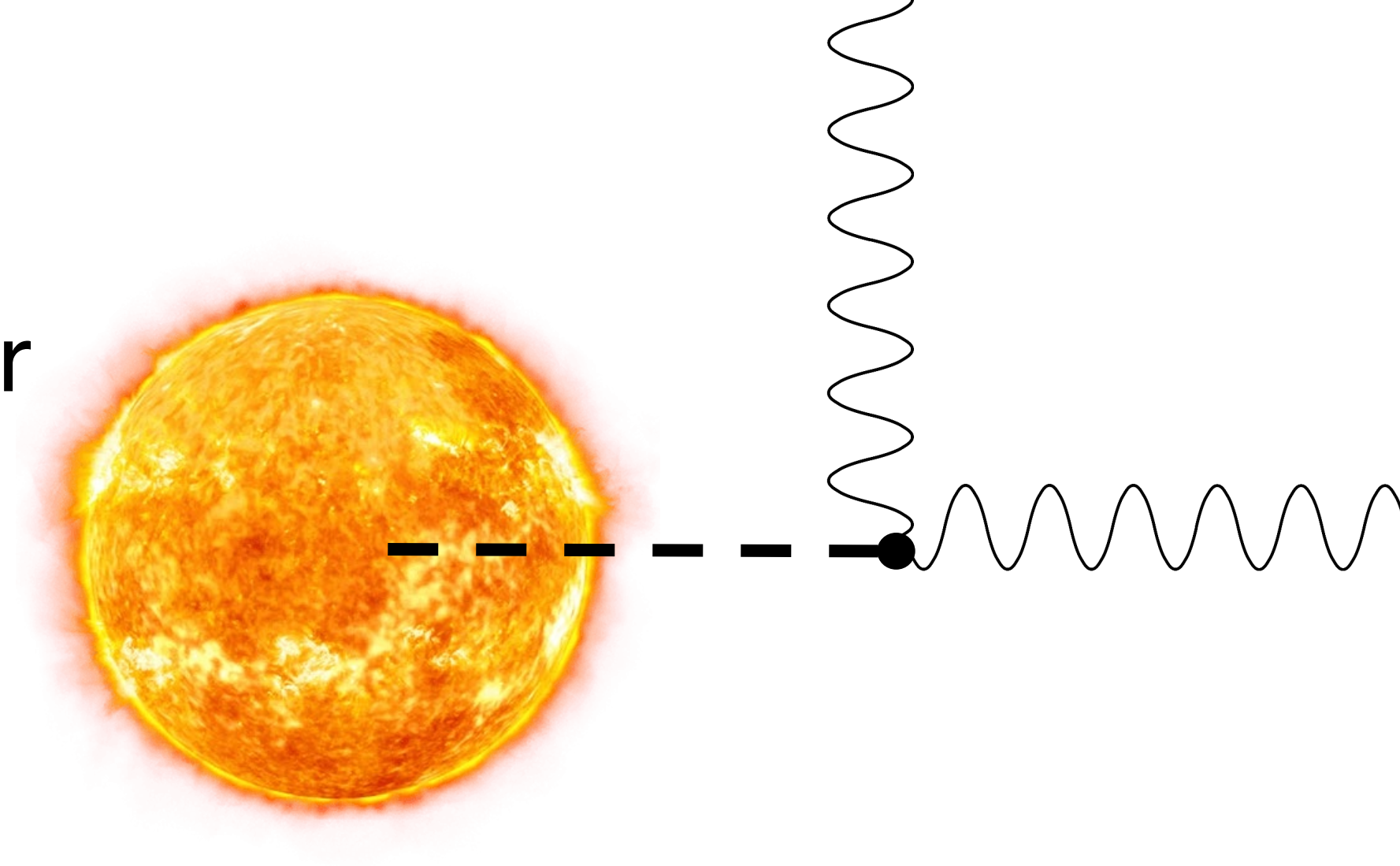
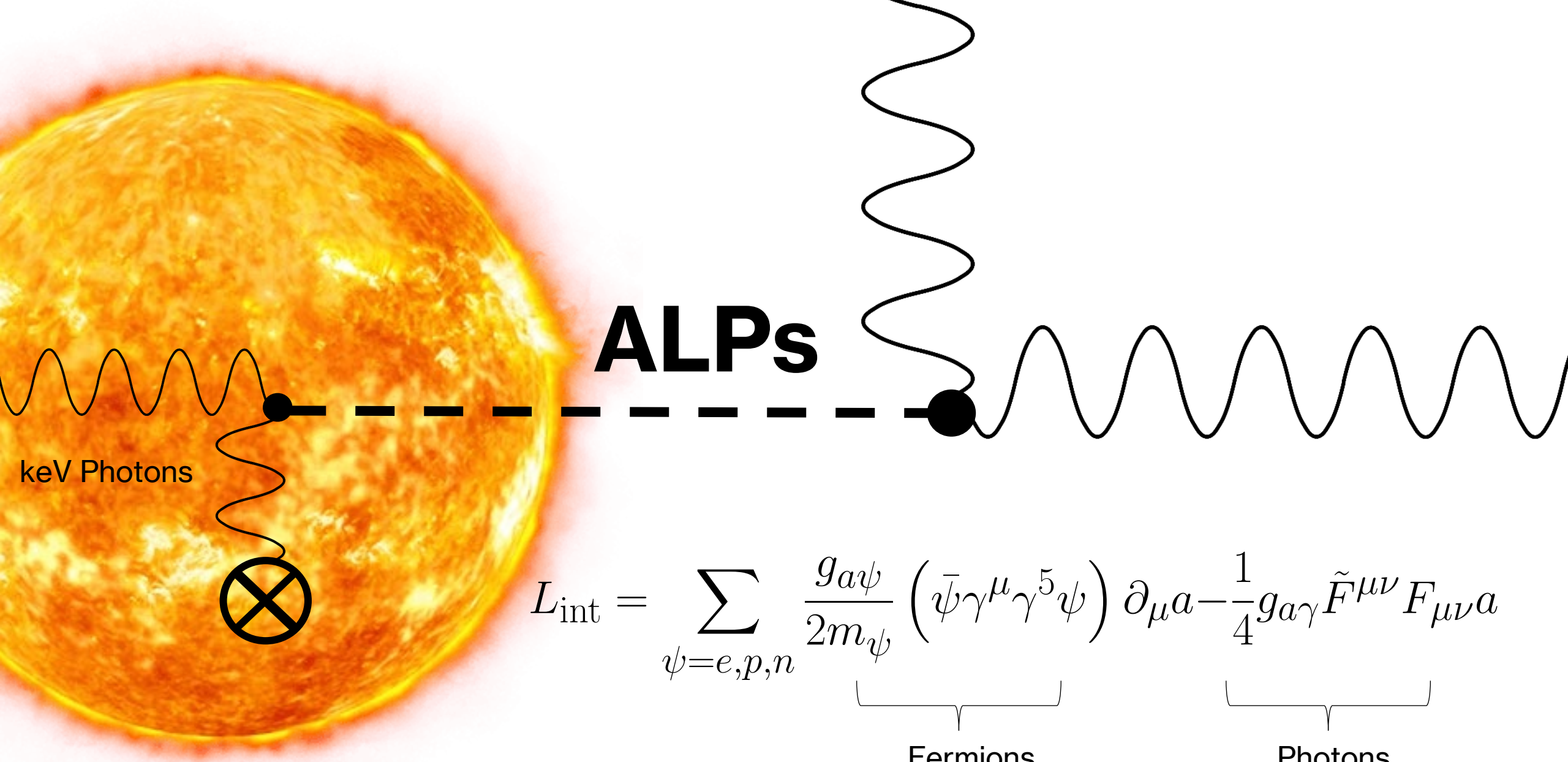
X-ray Searches for **Axions:**

M82 and **Betelgeuse**

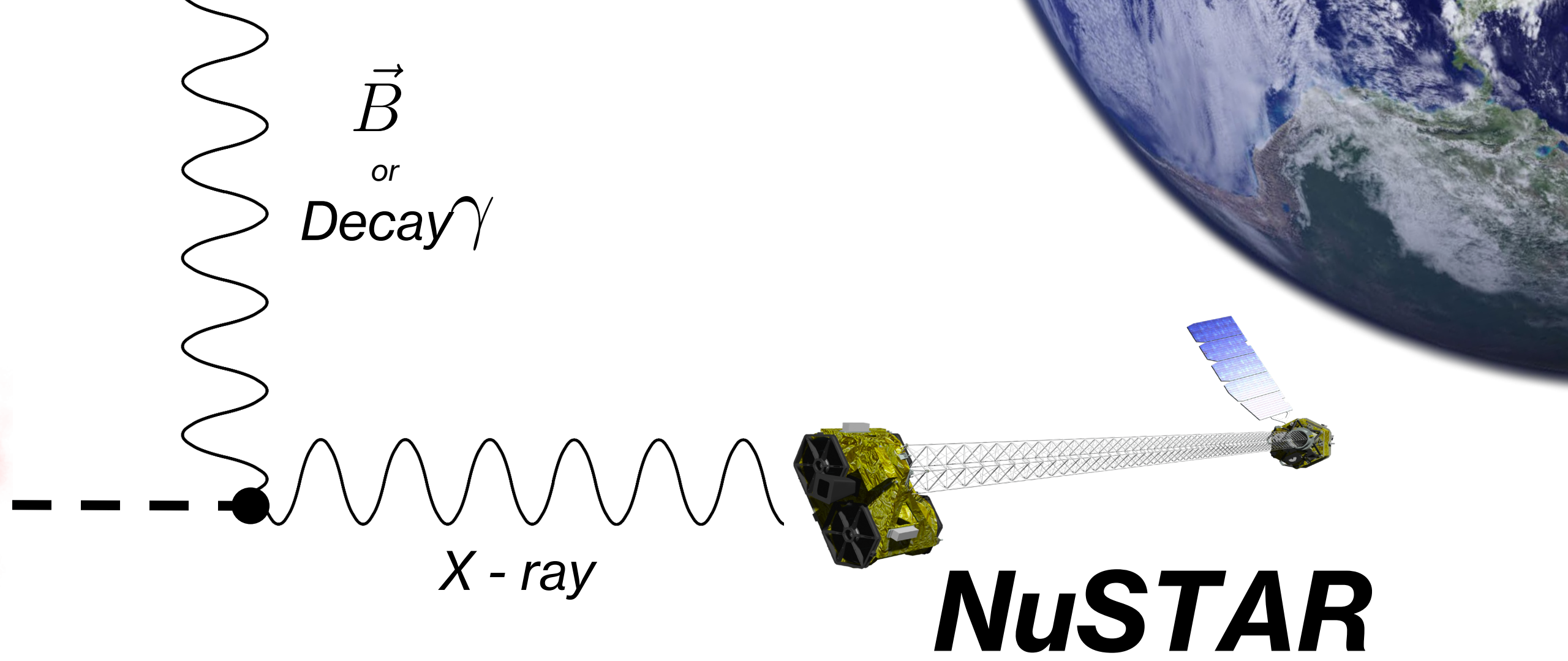


Francisco Rodríguez Candón

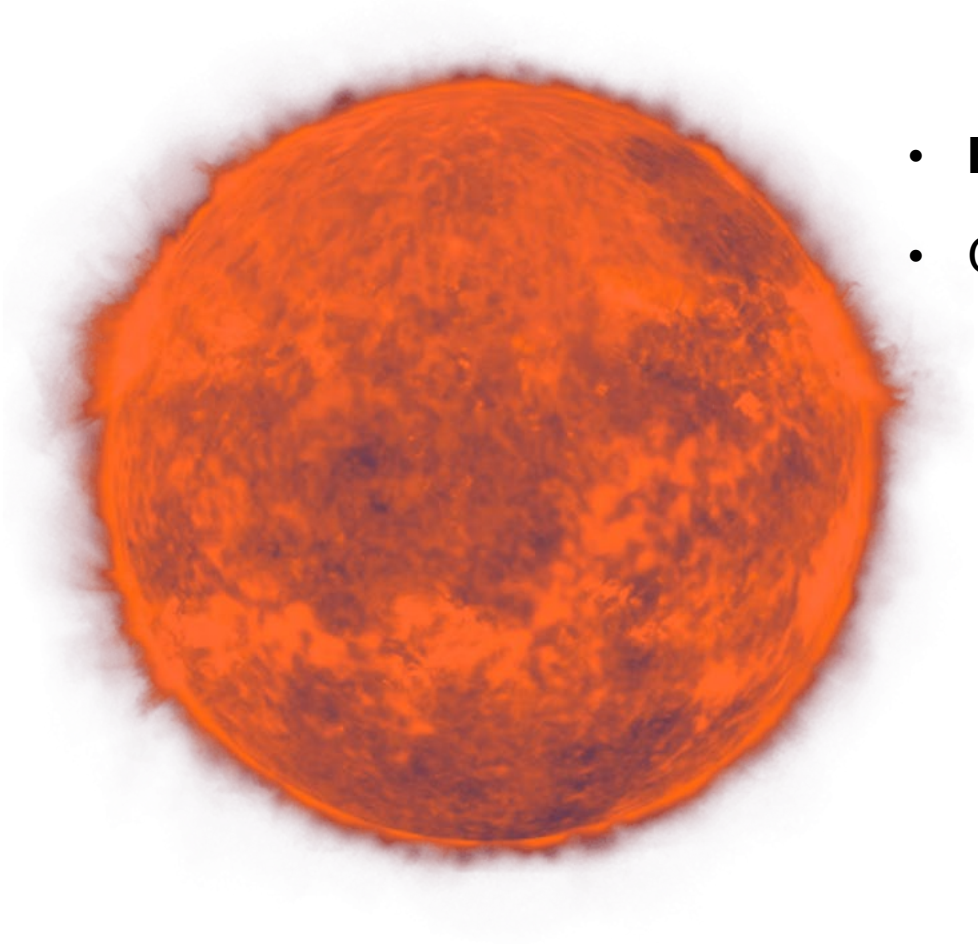
Annecy, September 2025



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

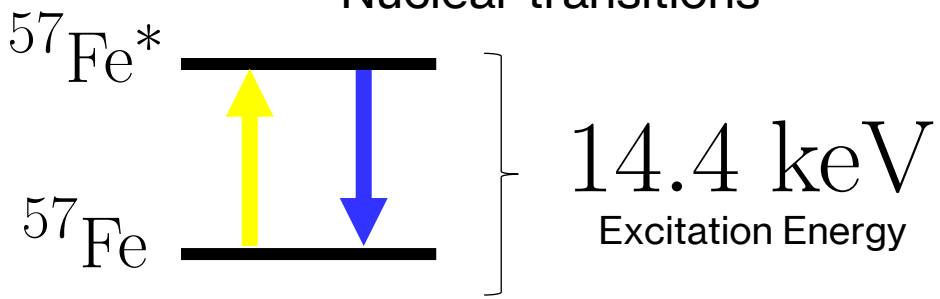

$\vec{B}$
or
Decay
γ
X - ray
NuSTAR

The **Betelgeuse** case



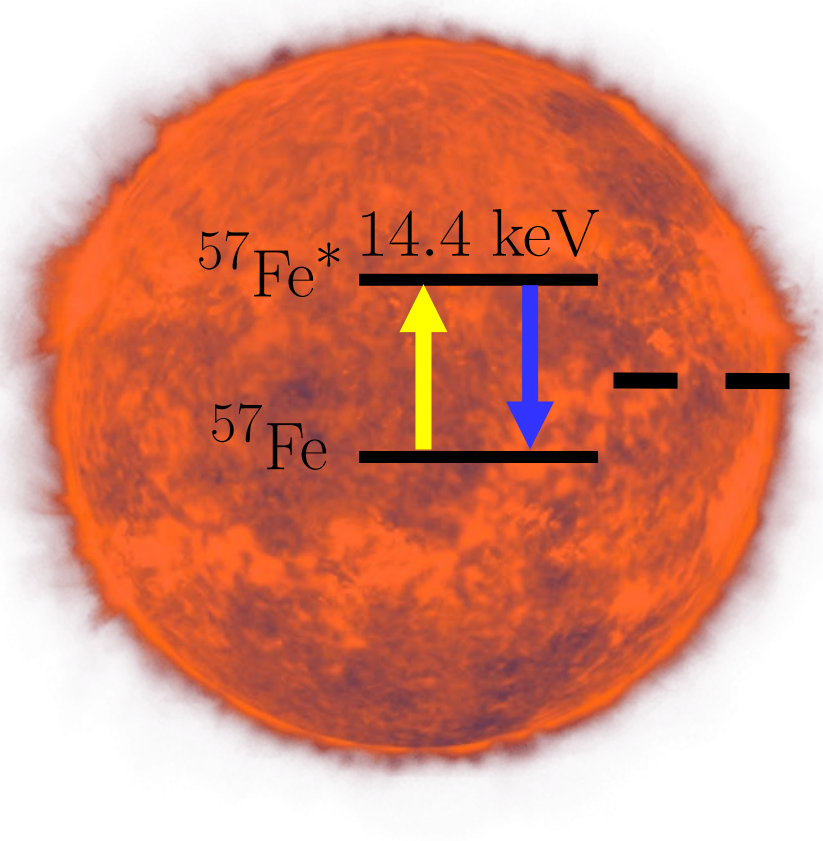
- **Betelgeuse**, a red supergiant star of about 20 $M_\odot$ at 197 pc
- Core temperatures higher tan **14.4 keV**

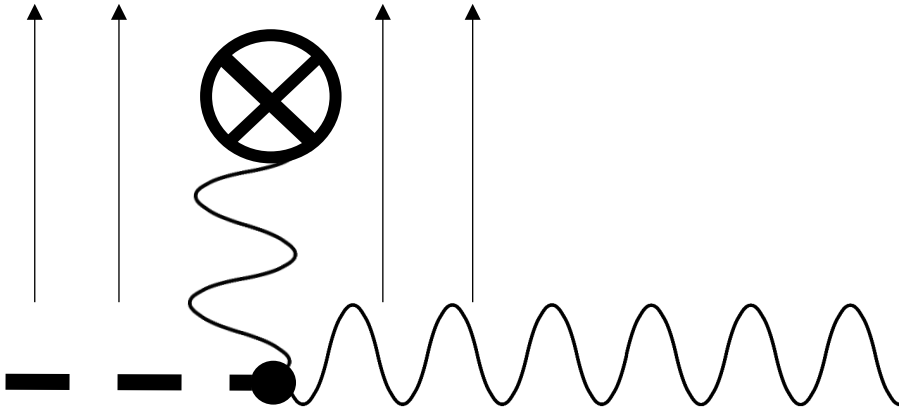
Magnetic dipole (M1)
Nuclear transitions

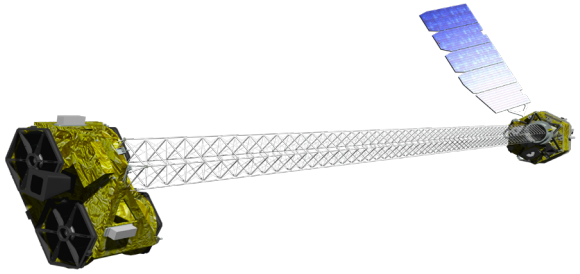


FRC, P. Casaseca, M. Giannotti,
M. Kaltschmidt, J. Ruz, J. K. Vogel
arXiv:2504.21107

The **Betelgeuse** case



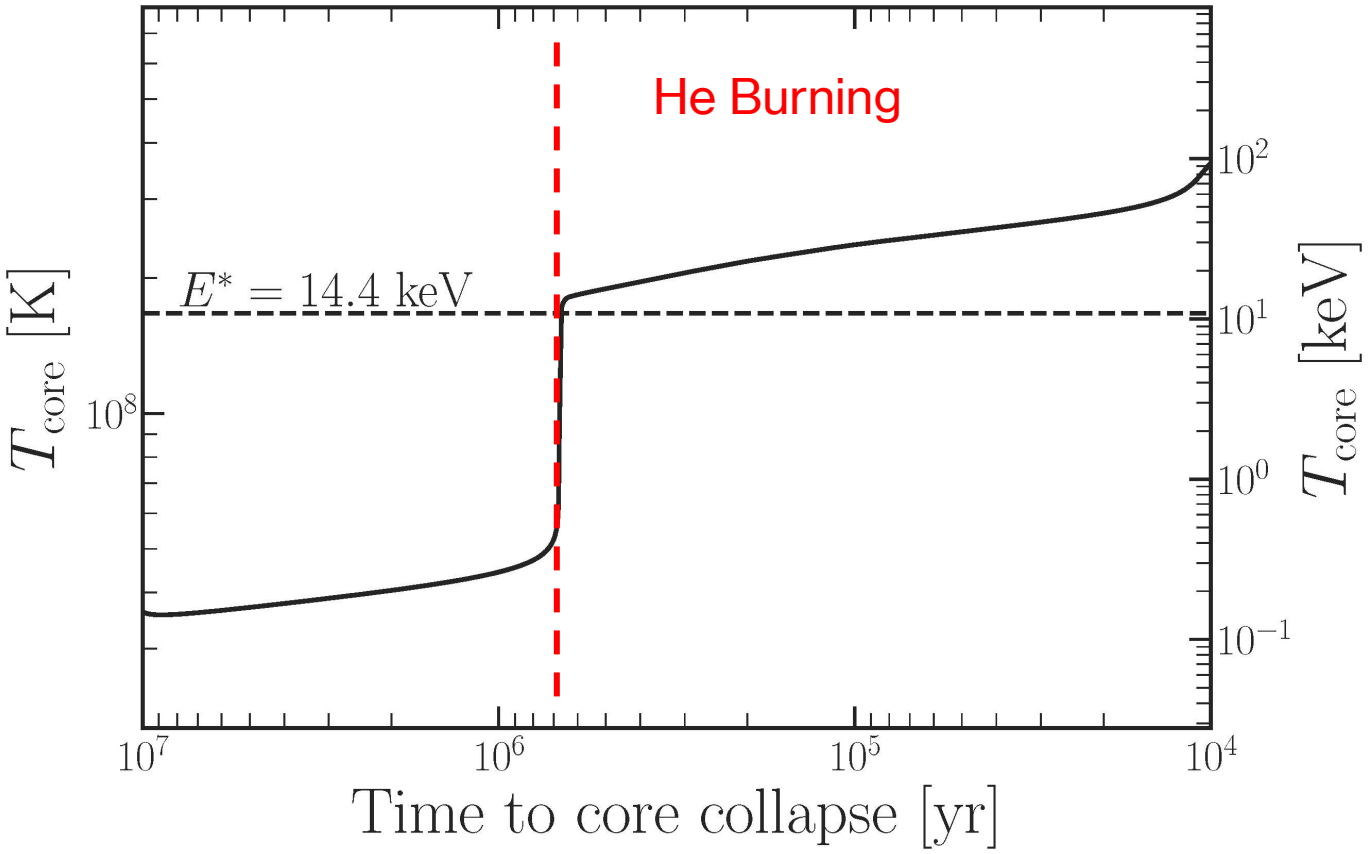




Galactic $\vec{B}$ *X-rays*

$B_T \sim 1.4 \mu G$

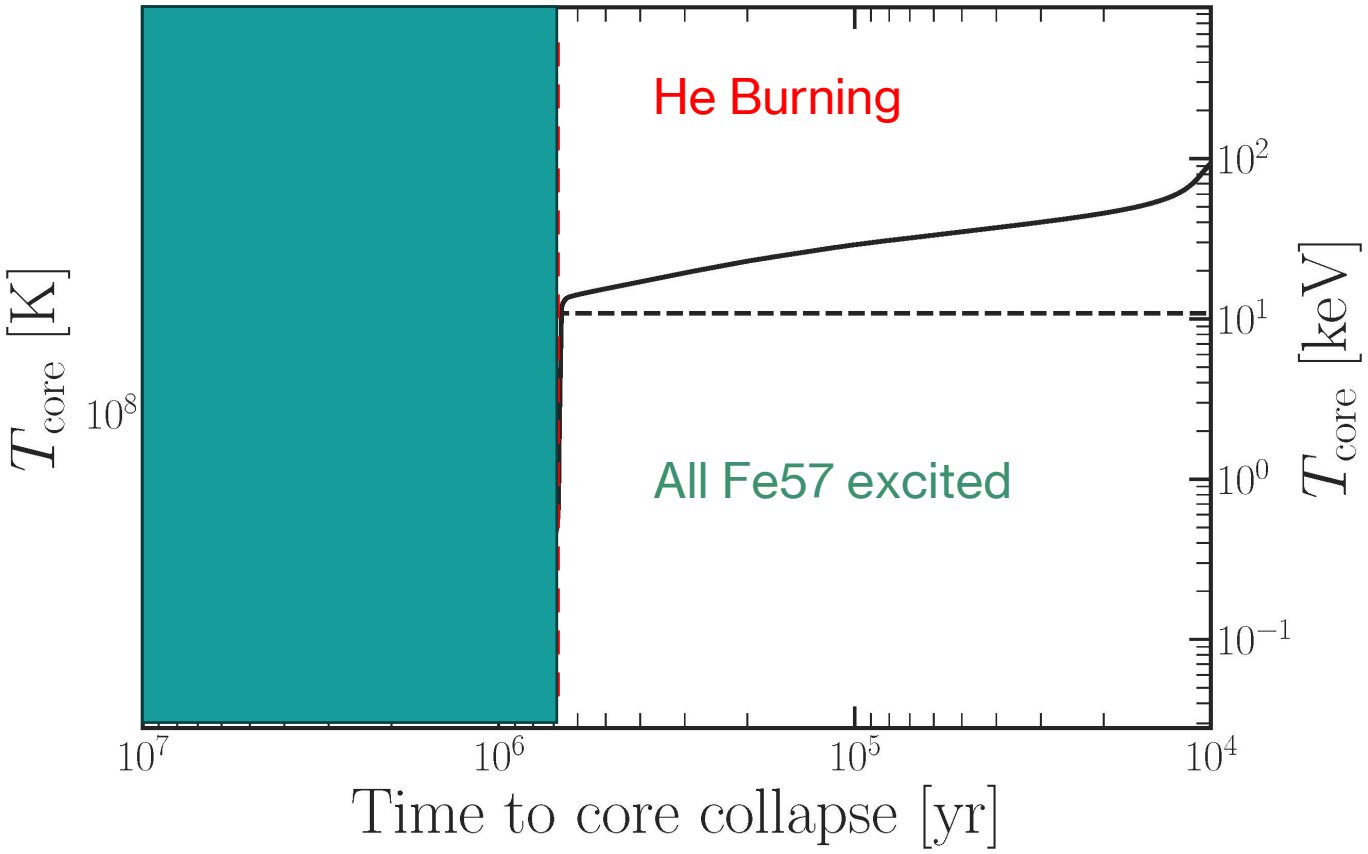
Stellar Simulations



MESA

Modules for Experiments in **Stellar Astrophysics**

Stellar Simulations

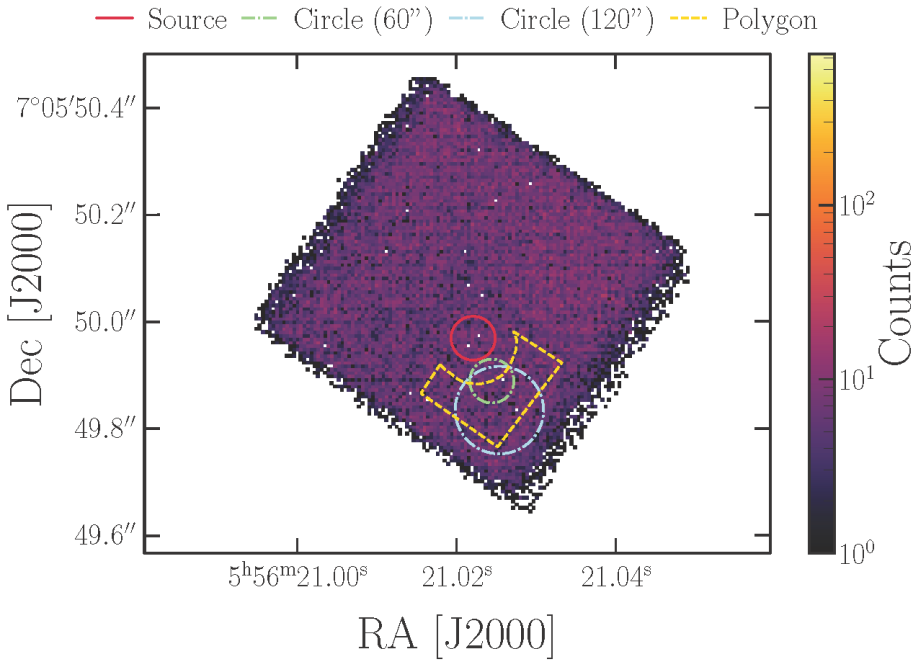


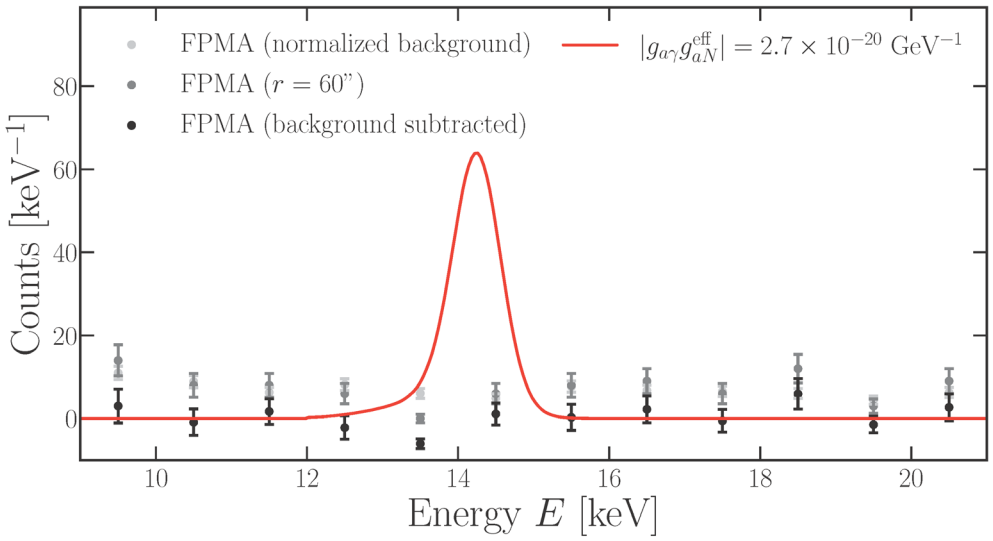
MESA

Modules for Experiments in **Stellar Astrophysics**

Observational data analysis

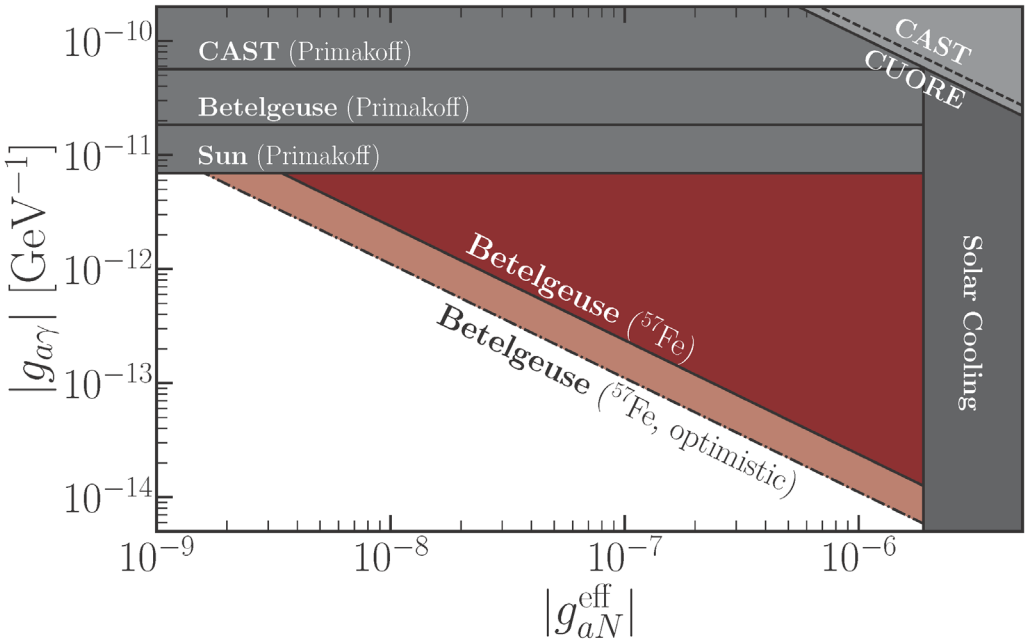
- **NASA** data analysis tools: HEASOFT, NuSTARdas, XSPEC



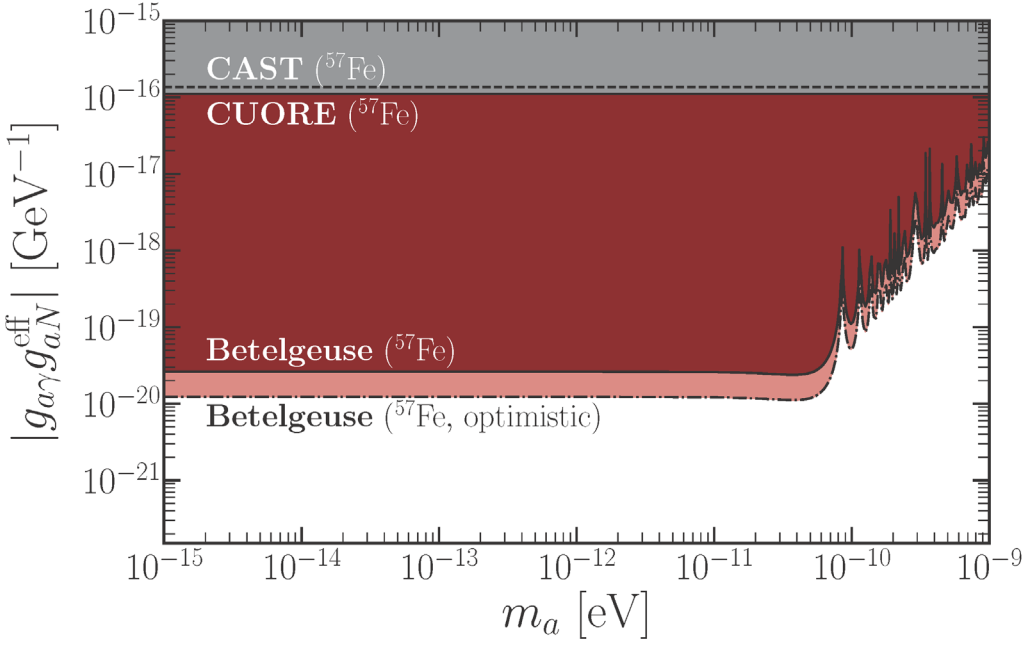


Likelihood analysis

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



Massless Case



Masive Case

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

The **M82** case

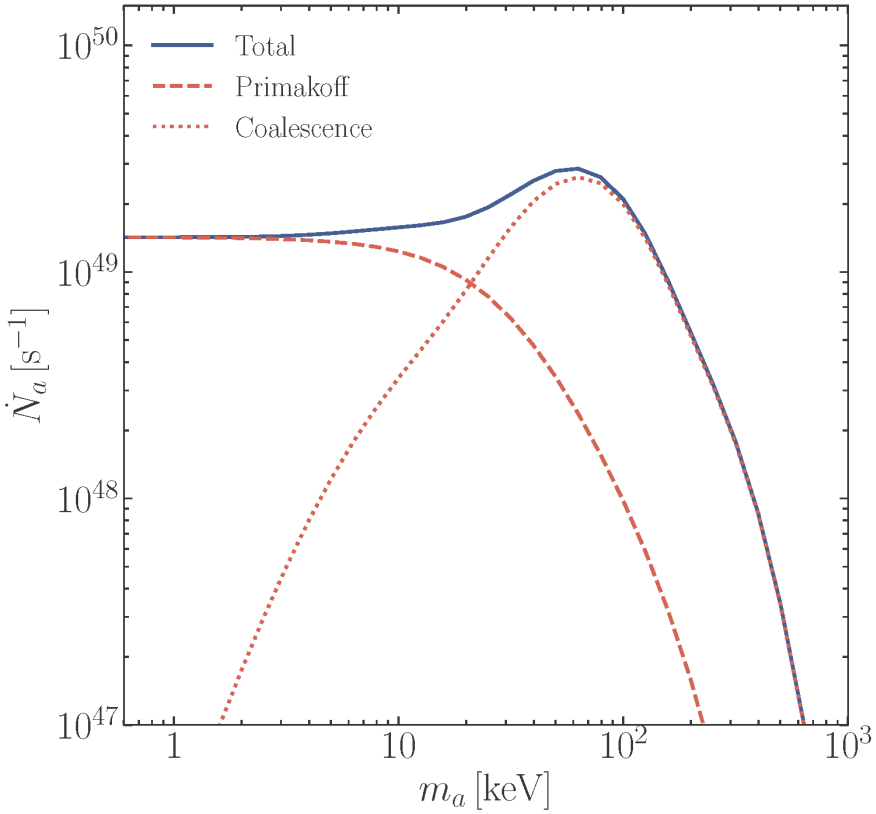
The **M82** case

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

Two dominant processes

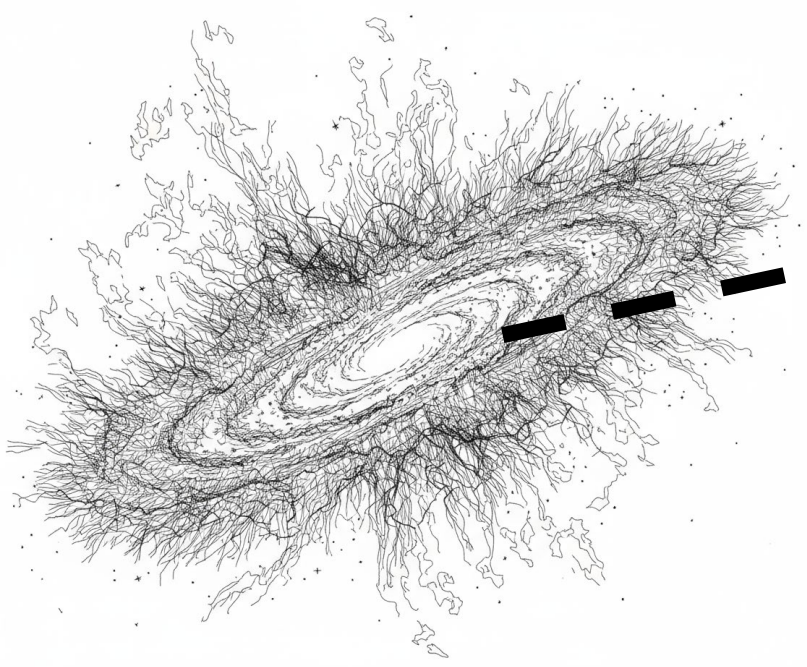
$$\gamma + Ze \rightarrow Ze + a$$

$$\gamma + \gamma \Rightarrow a$$



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

The **M82** case

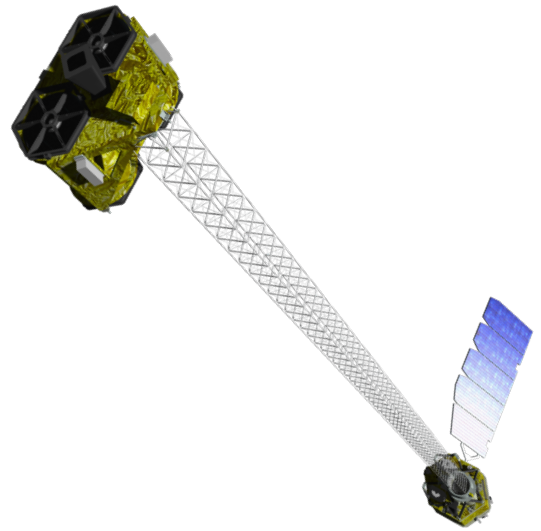


X-rays

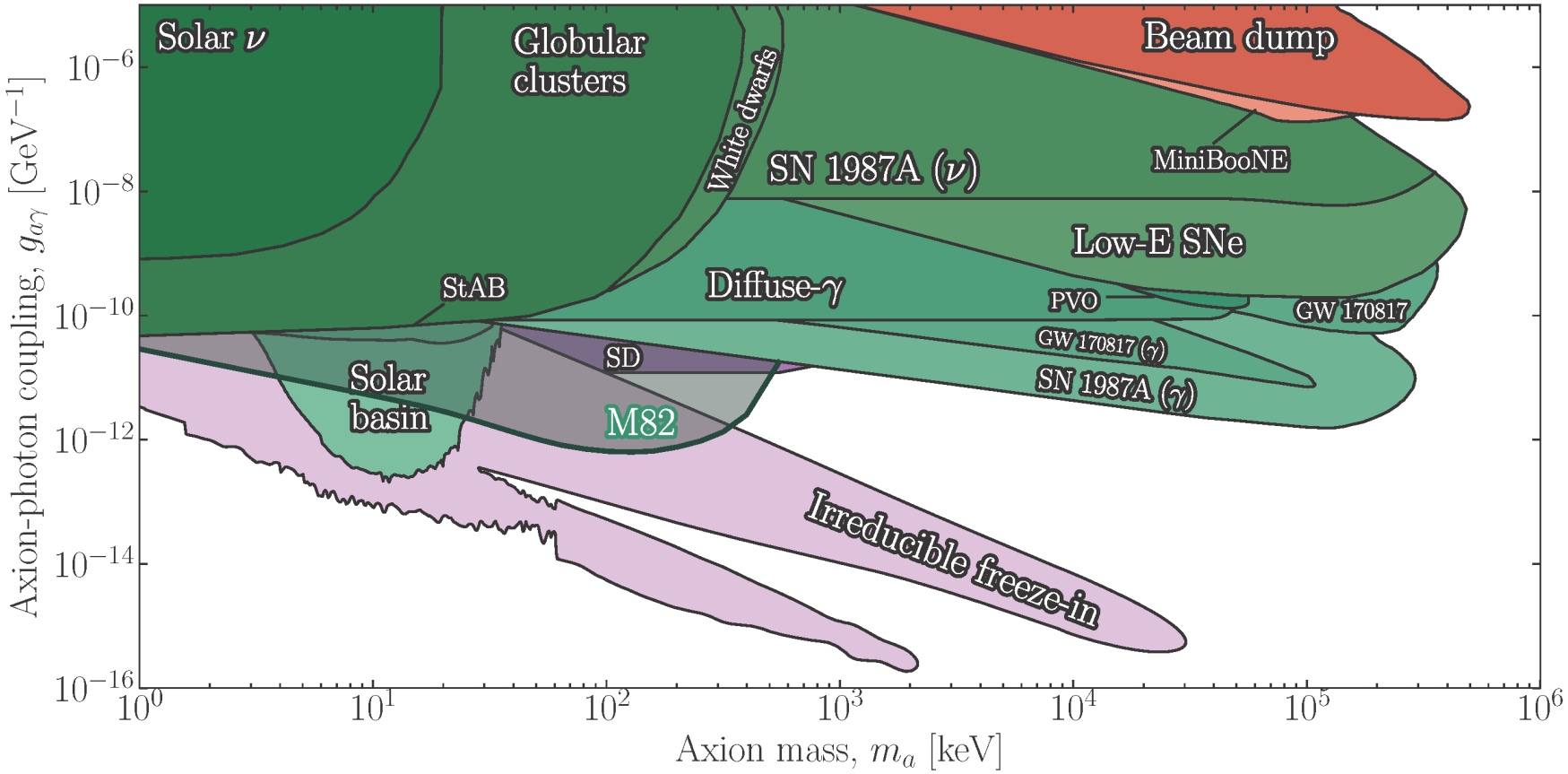
Heavy ALPS

Decay

$m_a \sim 30 - 500$ keV

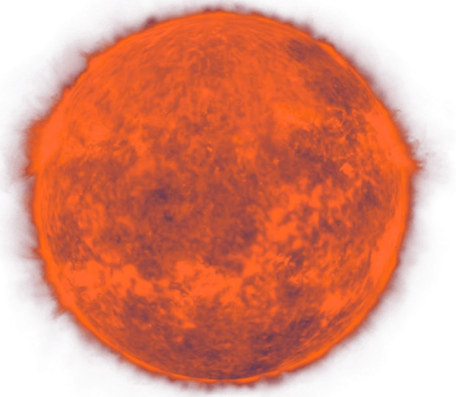


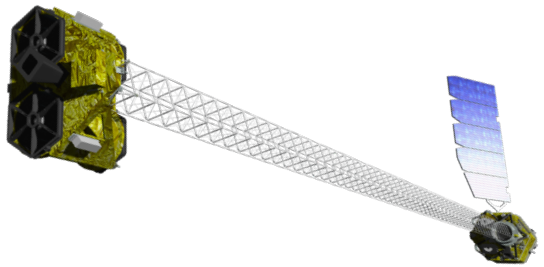
The **M82** case

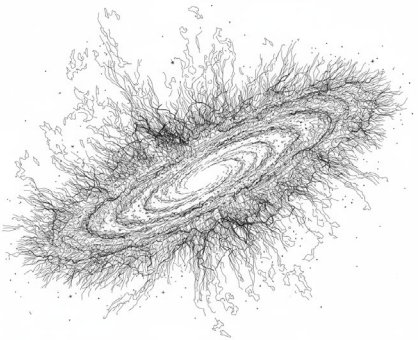

Solar ν
Globular clusters
White dwarfs
Beam dump
SN 1987A (ν)
MiniBooNE
Low-E SNe
StAB
Diffuse-γ
PVO
GW 170817
GW 170817 (γ)
SD
Solar basin
M82
SN 1987A (γ)
Irreducible freeze-in
Axion-photon coupling, $g_{a\gamma}$ [GeV^{-1}]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{0}
10^{1}
10^{2}
10^{3}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

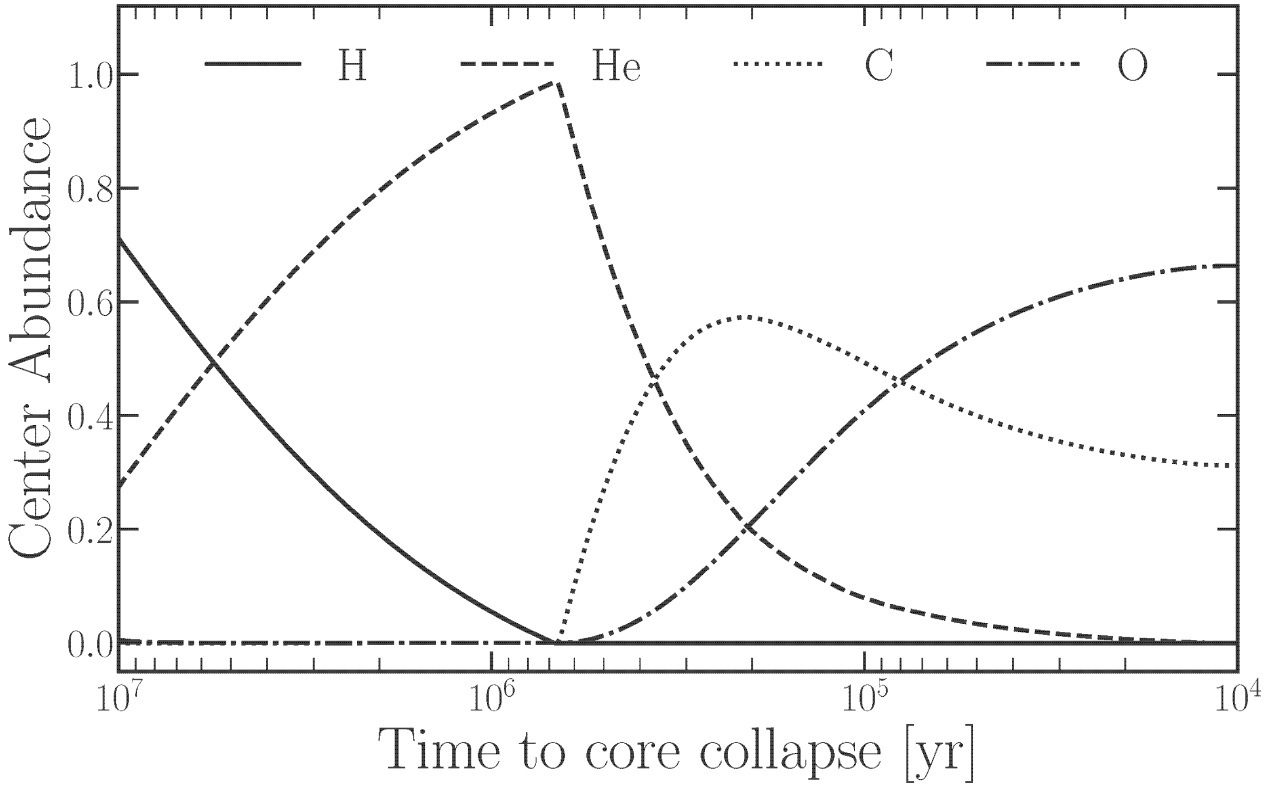
Likelihood analysis

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

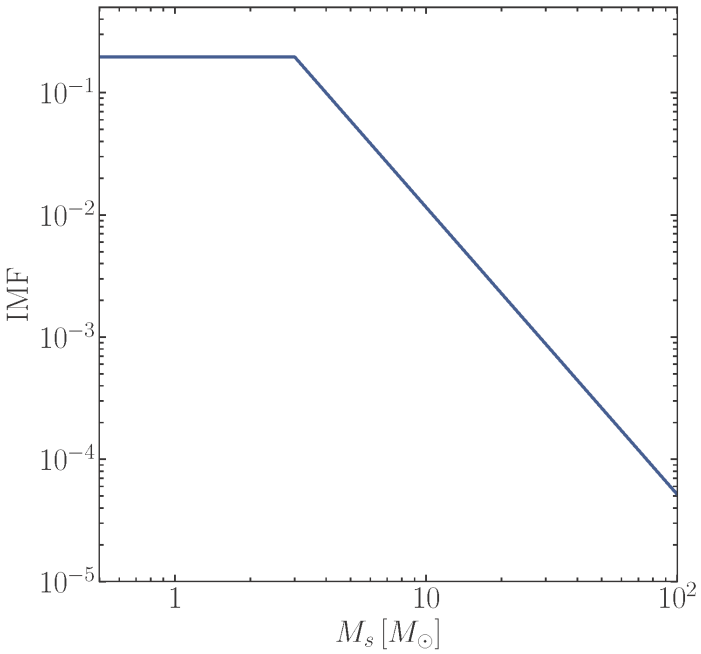
$$\mathcal{L}_i = \mathrm{Poisson}\left(N_{\mathrm{obs},i} \mid N_{\mathrm{exp},i}\right) \times \prod_{j=1}^{N_{\mathrm{obm},i}} \left[\frac{N_{\mathrm{ax},i} P_{\mathrm{ax}}\left(E'_j\right)}{N_{\mathrm{cxp},i}} + \frac{N_{\mathrm{bkg},i}\left(1+\delta^i_{\mathrm{bkg}}\right) P_{\mathrm{bkg}}\left(E'_j\right)}{N_{\mathrm{exp},i}}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

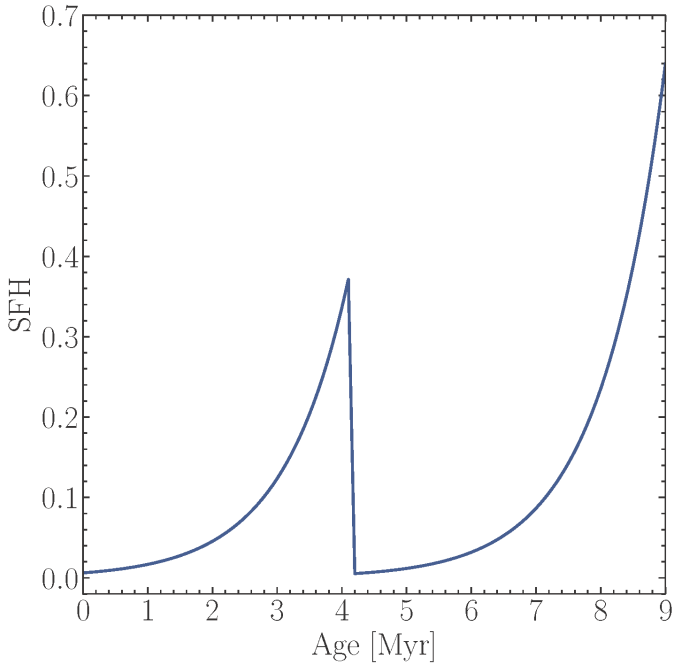
$$P(\theta) = \frac{\mathcal{L}(\theta)}{\int \mathcal{L}\left(\theta'\right) \mathrm{d}\theta'} \qquad \int_0^{\left(g^2_{a\gamma} g^2_{aN}\right)_{as\%}} P\left(g^2_{a\gamma} g^2_{aN}\right) \mathrm{d}\left(g^2_{a\gamma} g^2_{aN}\right) = 0.95$$

Betelgeuse Simulations



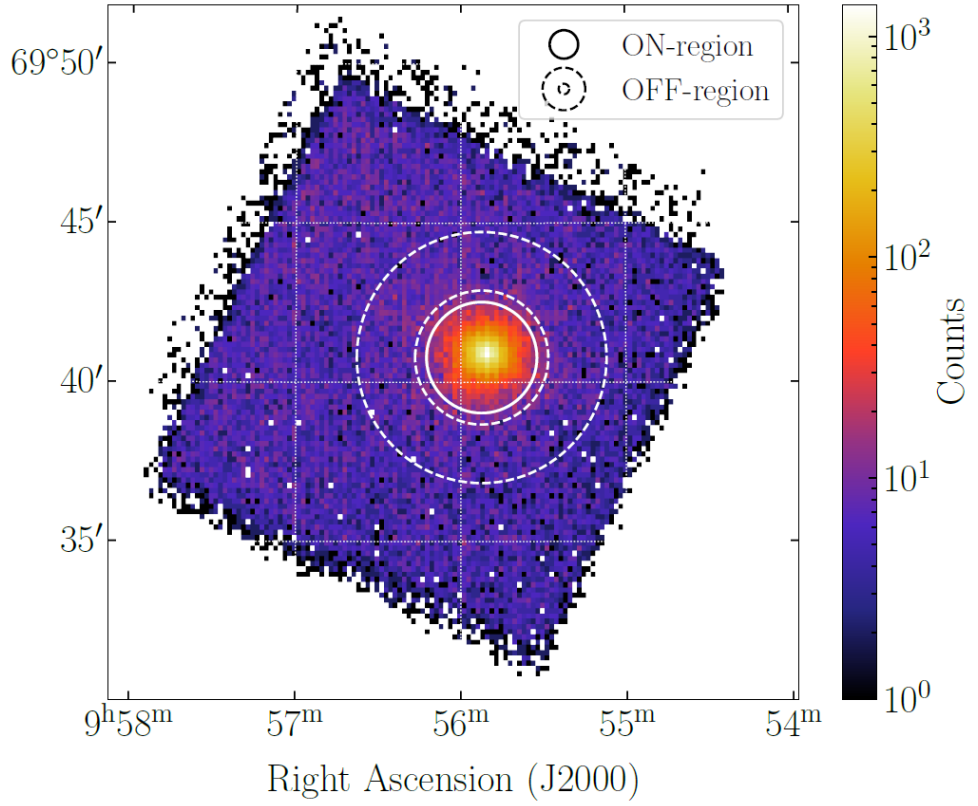
Betelgeuse Simulations





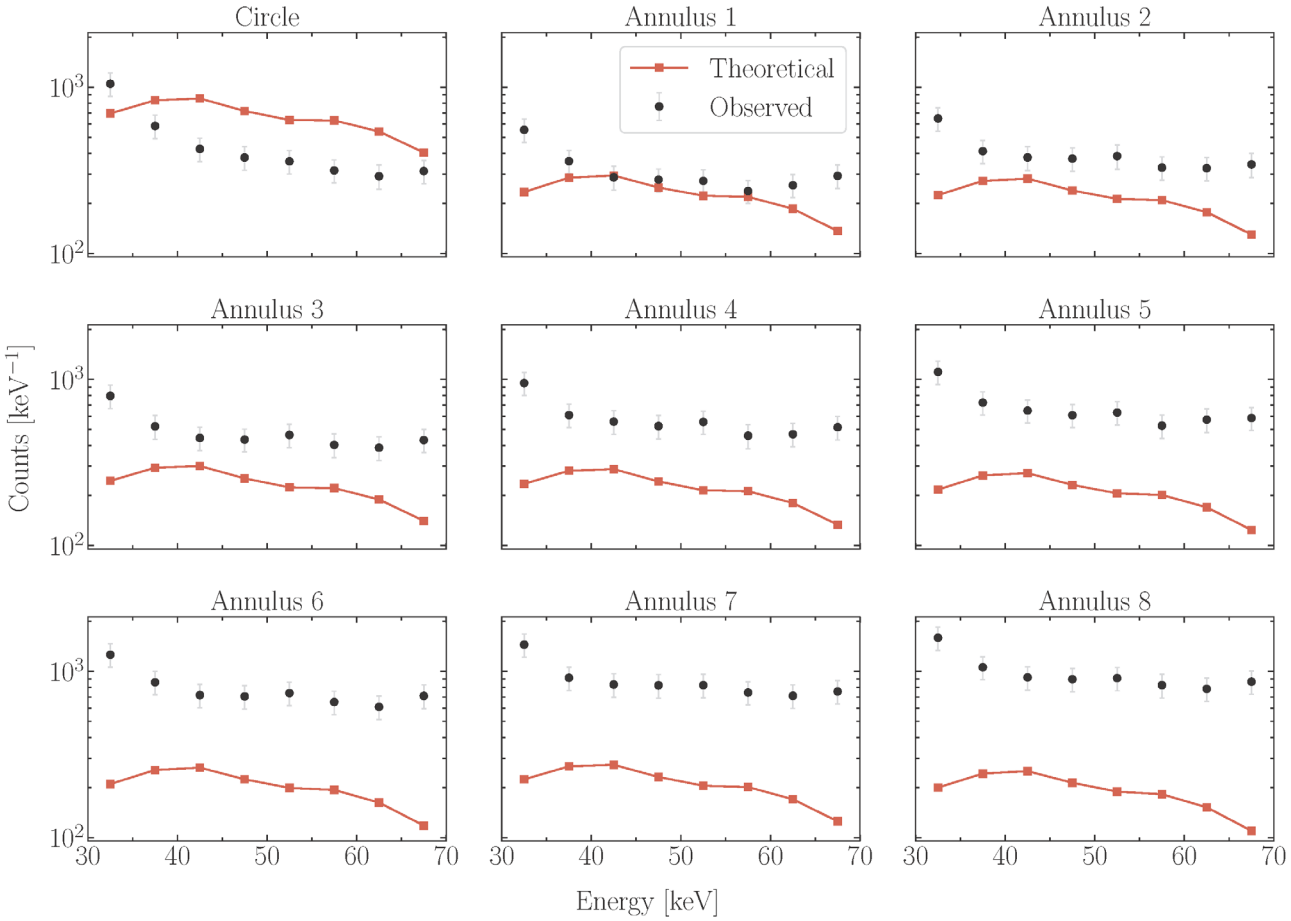
$$\frac{d\dot{N}_a}{dE_a} = N_{\rm tot} \int dM_s dt_s \,{\rm IMF}\,(M_s)\,{\rm SFH}\,(t_s)\,\frac{d\dot{N}_a^s}{dE_a}$$

M82 FOV

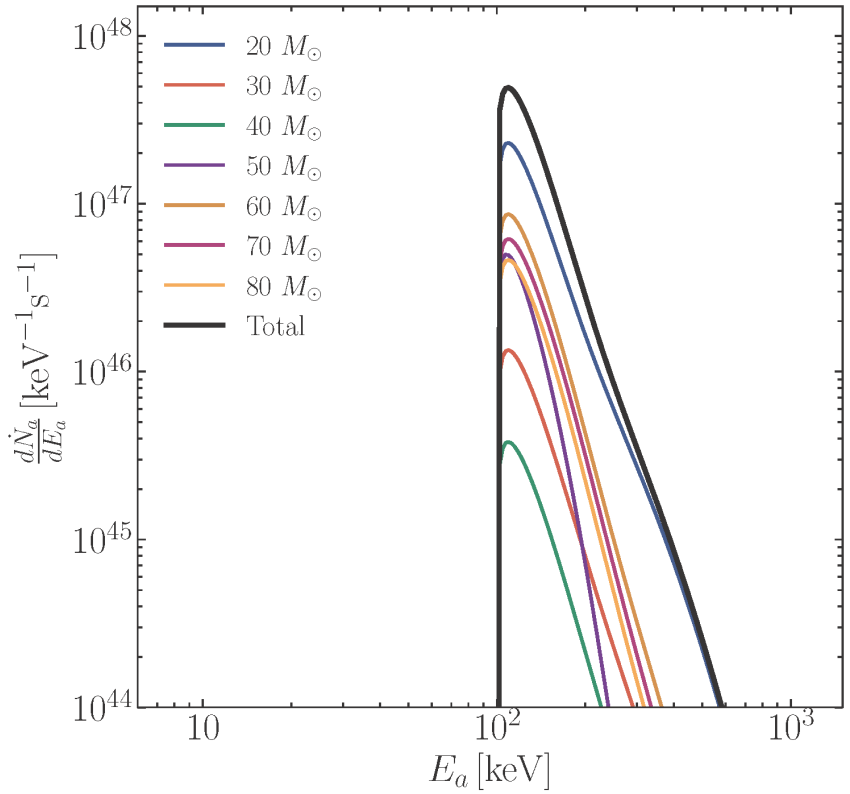


$$N^{a}_{c,i,\alpha}\left(g_{a\gamma}, m_a\right) = t^{c} \int dE' \, \mathrm{RMF}^{c}_{i,\alpha}\left(E_i, E'\right) \mathrm{ARF}^{c}_{\alpha}\left(E'\right) S_{\alpha}\left(E' \mid g_{a\gamma}, m_a\right)$$

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

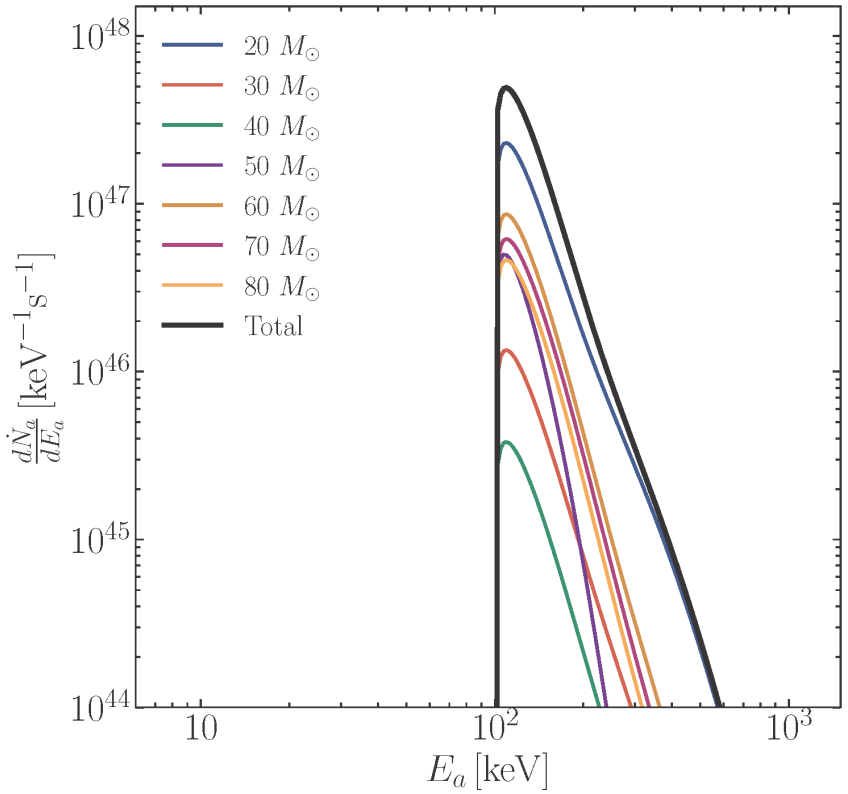
Total **Axion** Flux

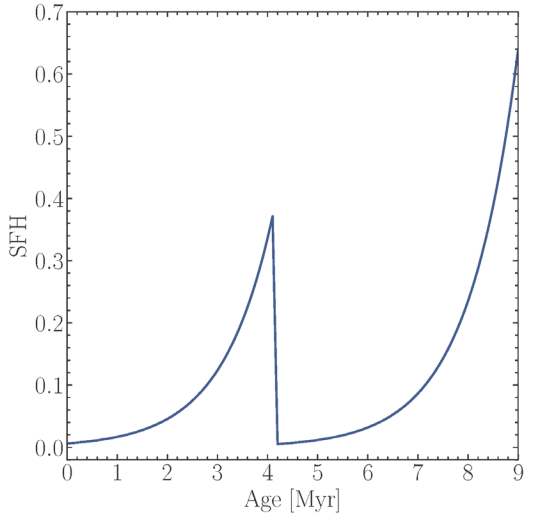


$$\frac{d\dot{N}_a}{dE_a} = N_{\rm tot} \int dM_s dt_s \, {\rm IMF}\,(M_s)\, {\rm SFH}\,(t_s)\, \frac{d\dot{N}_a^s}{dE_a}$$

Betelgeuse Simulations

Total **Axion** Flux





Star Formation History

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

Initial Mass function