Constraints on Axion-Like Particles from a Hard X-ray Observation of Betelgeuse

Mengjiao Xiao, MIT

APS April Meeting (online)

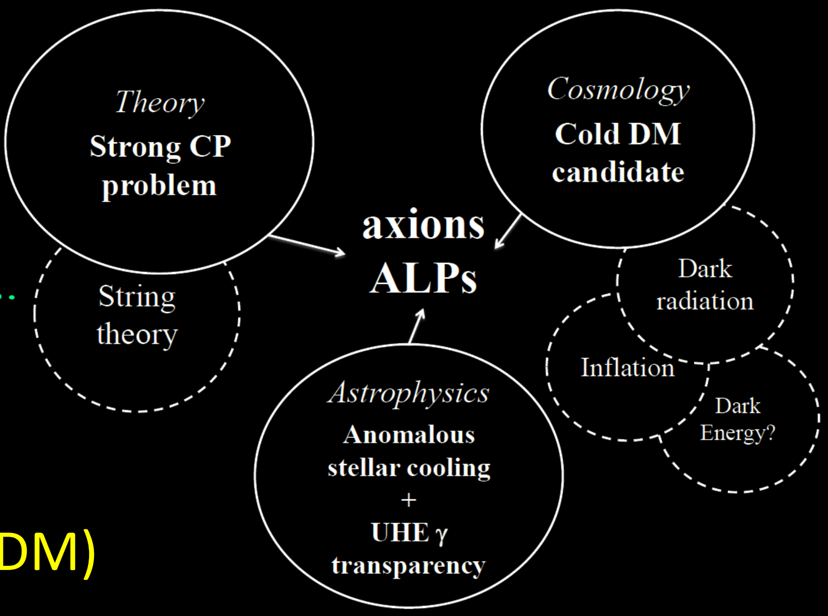
2021-04-19

Based on the work: M. Xiao, K. Perez, M. Giannotti, O. Straniero, A. Mirizzi, B. Grefenstette, B. Roach, M. Nynka. *Phys. Rev. Letts 126, 031101 (2021)*

Axions & Axion-Like Particles

❑Strongly motivated to solve strong CP problem of the Standard Model.

$$L = \ldots + \boxed{\frac{a}{f_a}} \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \ldots$$



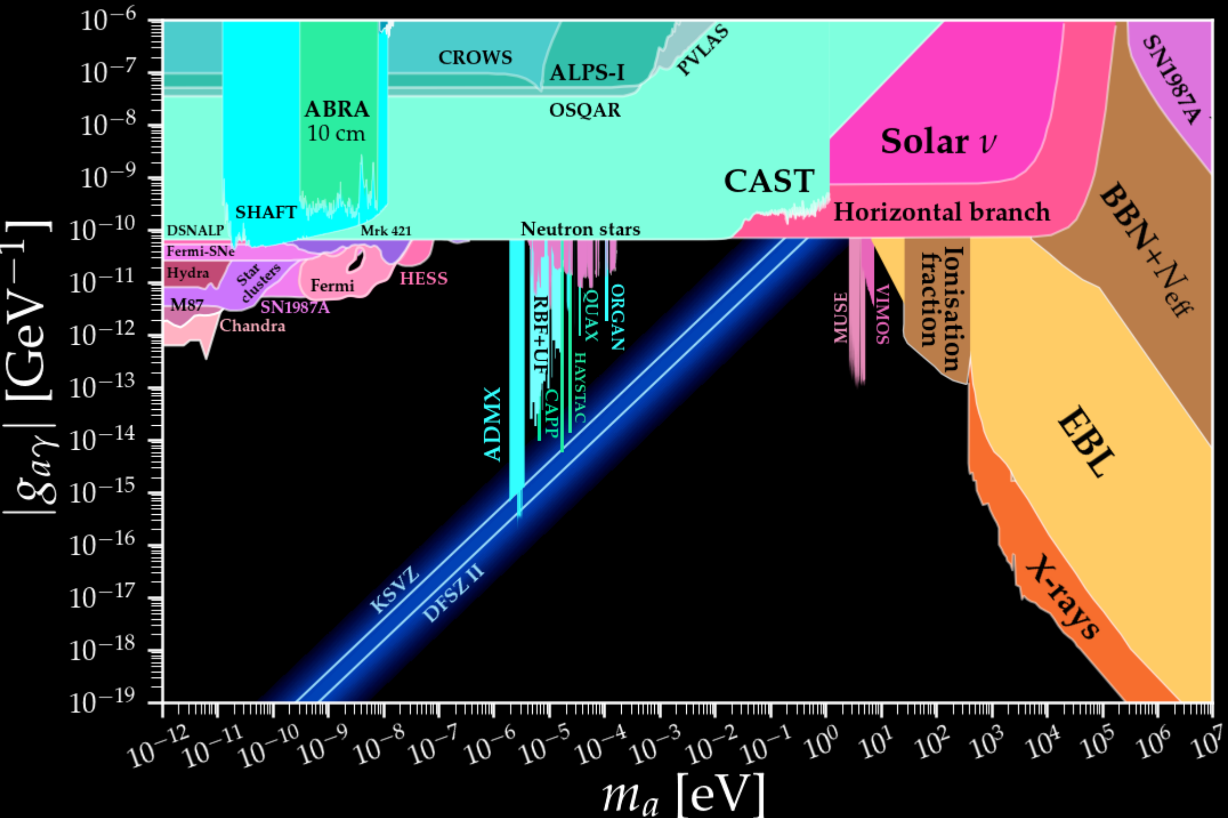
$\theta = \frac{a}{f_a}$ → relaxes to zero ($|\theta| < 10^{-10}$ from neutron EDM)

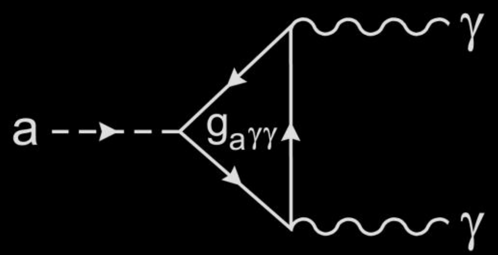
❑Axion-like particles (ALPs): predicted by many extensions of the Standard Model (e.g. string theory)

❖May solve the dark matter problem for free.

Searches for Axion/ALPs

- ❑ May weakly couple to many particles in SM (gluons/quarks, and photons)
  - ALP-photon coupling promising (naturally) for detection



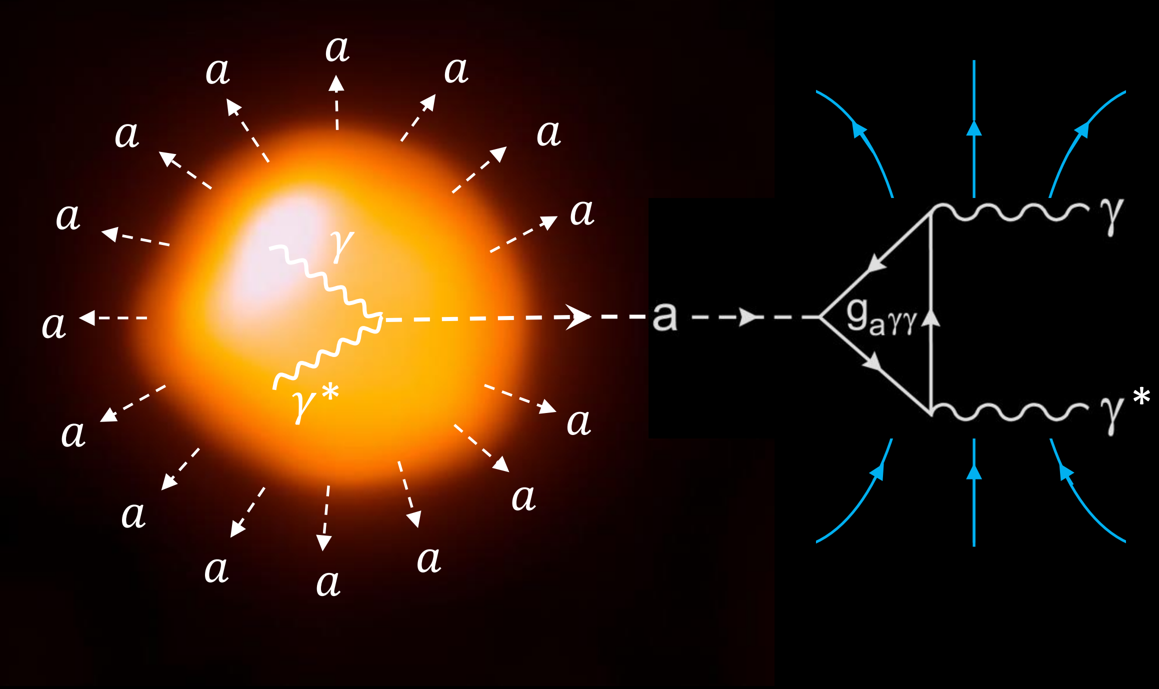


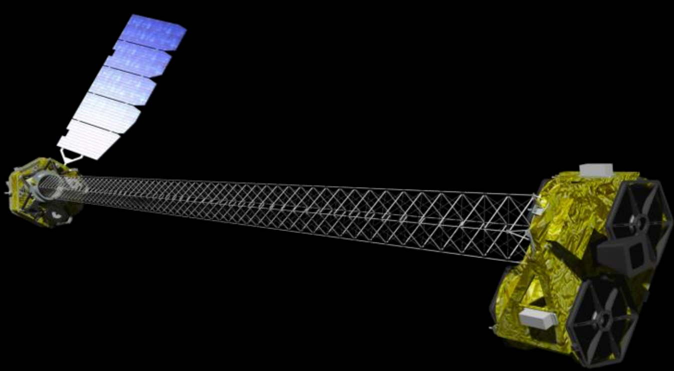
- ❑ *Significant unexplored parameter space, experimental efforts growing fast!*

C. O'Hare. Github

ALP Telescope Principle

Massive Stars as ALP Factories | *Galactic Magnetic Field* | **Space Telescopes**





ALP Production Rate (Primakoff process) ⊗ ALP-Photon Conversion Probability ($P_{a\gamma}$) ⊗ Detector Response = Observed Signal Rate

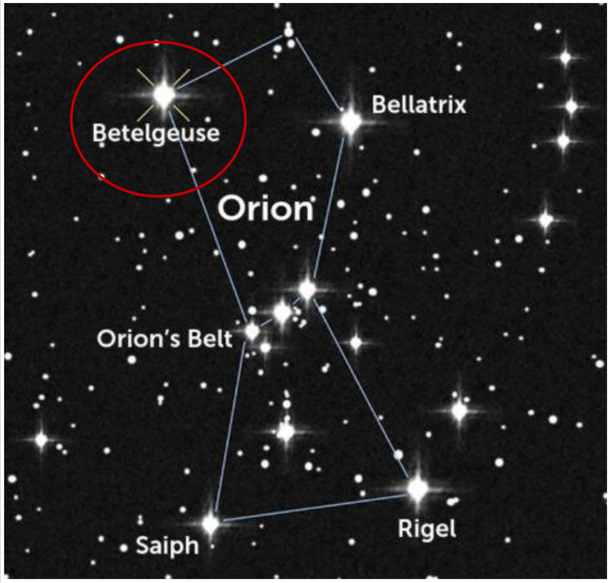
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a = \mathbf{E}\cdot\mathbf{B}a$$

Betelgeuse as ALP Factory

Alpha Orionis (Betelgeuse): red supergiant in the constellation of Orion.

❑ Well studied:

- $\log L/L_{\odot}$ = 5.10 ± 0.22 *T. Le Bertre et al. (2012)*
- T_{eff} = 3641 ± 53 K *G. Perrin et al. (2004) , E. Levesque & P. Massey (2020)*
- M ~ 20 $M_{\odot}$ *M. Dolan et al, Astro- phys. J. 819, 7 (2016)*



❑ Advanced stage

❑ Near (200 pc) *G. Harper et al. (2008) (2017)*

❑ No solar-like corona that could emit X-rays *J. Posson-Brown et al. arXiv:astro-ph/0606387*

❑ There are no bright sources within 5°, ensuring no significant stray light contamination

❑ Other observations (Chandra, soft X-rays) exist *J. Posson-Brown et al. arXiv:astro-ph/0606387*

Betelgeuse: ALP-photon Production

- ❑ *ALP production rate:*

$$\frac{d\dot{N}_a}{dE} = \frac{10^{64}\, C\, g_{a\gamma}^2}{keV\ s} \cdot \left(\frac{E}{E_0}\right)^{\beta} \cdot e^{-\frac{(\beta+1)E}{E_0}}$$

Parameterized by stellar model

Model	Phase	t_{cc} [yr]	$\log_{10}(L_{eff}/L_{\odot})$	$\log_{10}(T_{eff}/K)$
0	He burning	155000	4.90	3.572
1	before C burning	23000	5.06	3.552
2	before C burning	13000	5.06	3.552
3	before C burning	10000	5.09	3.549
4	before C burning	6900	5.12	3.546
5	in C burning	3700	5.14	3.544
6	in C burning	730	5.16	3.542
7	in C burning	480	5.16	3.542
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10	between C/Ne burning	7.2	5.16	3.542
11	in Ne burning	3.6	5.16	3.542
12	beginning of O burning	1.4	5.16	3.542

- ➢ *t_{cc}: time until core collapse for Betelgeuse, modeled from 1.4 yr to 1.55×10^5 yr*

- ❑ *ALP-photon conversion probability :*

$$P_{a\gamma} = 8.7\times 10^{-6}\left(\frac{g_{a\gamma}}{10^{-11}}\right)^2 \left(\frac{B_T}{1\ \mu G}\right)^2 \left(\frac{d}{197\ pc}\right)^2 \frac{\sin^2 q}{q^2}$$

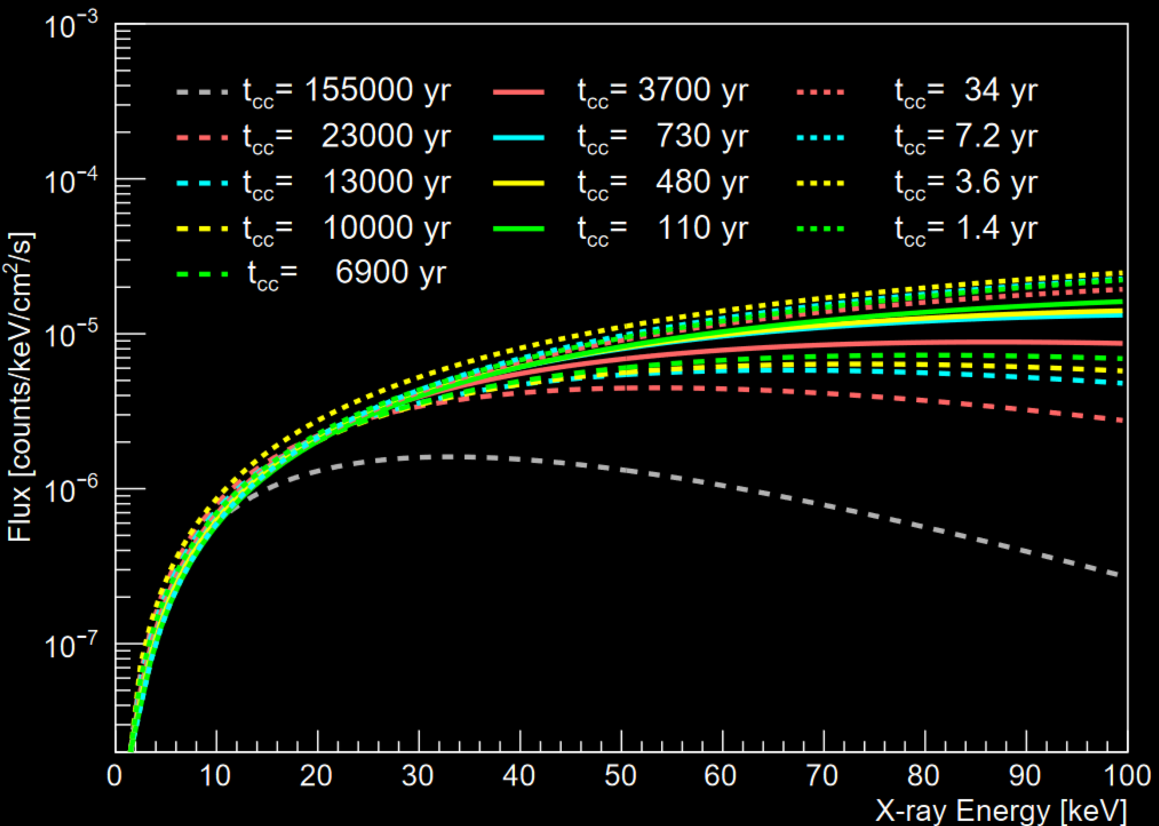
$$q = \left[77\left(\frac{m_a}{10^{-10}\ eV}\right)^2 - 0.14\left(\frac{n_e}{0.013\ cm^{-3}}\right)\right] \times \left(\frac{d}{197\ pc}\right)\left(\frac{E}{1\ keV}\right)^{-1}$$

- ➢ *B_T : Assuming homogeneous regular , 0.4~3.0 μG*

R. Jansson et al. (2012)
J. Xu et al. (2019)
L. Harvey-Smith et al. (2011)

Betelgeuse: ALP-photon Production

- *Predicted ALP-photon Flux :* $\frac{d\dot{N}_a}{dE} \times P_{a\gamma} \propto {B_T}^2 \cdot g_{a\gamma}^4$

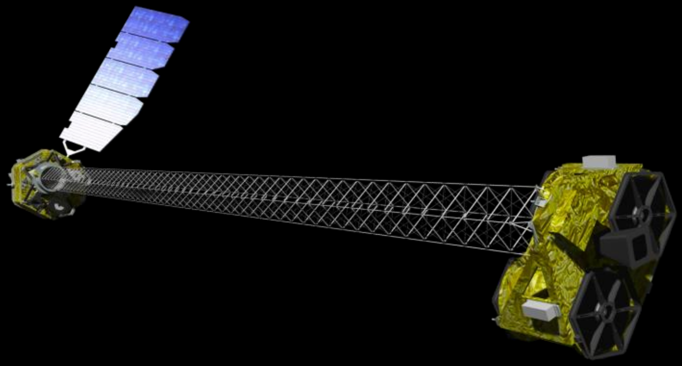


- Expected event counts from ALP-photon conversion from Betelgeuse for 13 stellar models
  - $m_a = 10^{-11}\ eV$
  - $B_T = 1.4\ \mu G$
  - $g_{a\gamma} = 1.5\times 10^{-11}\ GeV^{-1}$

➡ *Hard X-ray range!*

NuSTAR Satellite Telescope

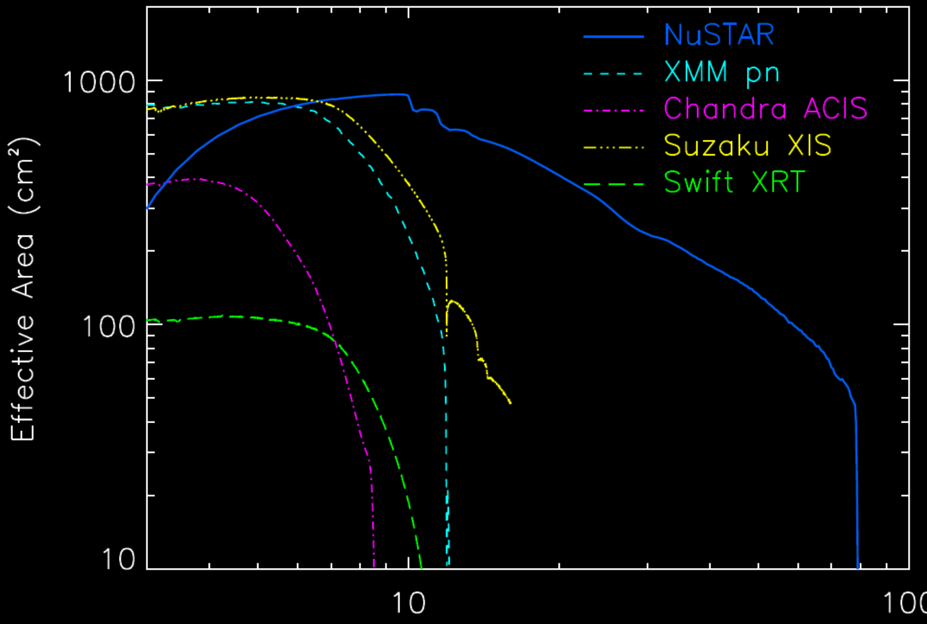
- ❑ ***NuSTAR***: NUclear Spectroscopic Telescope Array, launched in 2012.



F.A. Harrison et al. ApJ, 770, 103 (2013)

- ❑ Two identical telescopes, independent optic and focal-plane detector (FPMA/FPMB)
  - Each FOV 13′×13′, with a half-power diameter of ~60′′ for a point source near the optical axis.

- ❑ Best existing instrument to detect the ***hard X-rays*** (3-79 keV) in space!

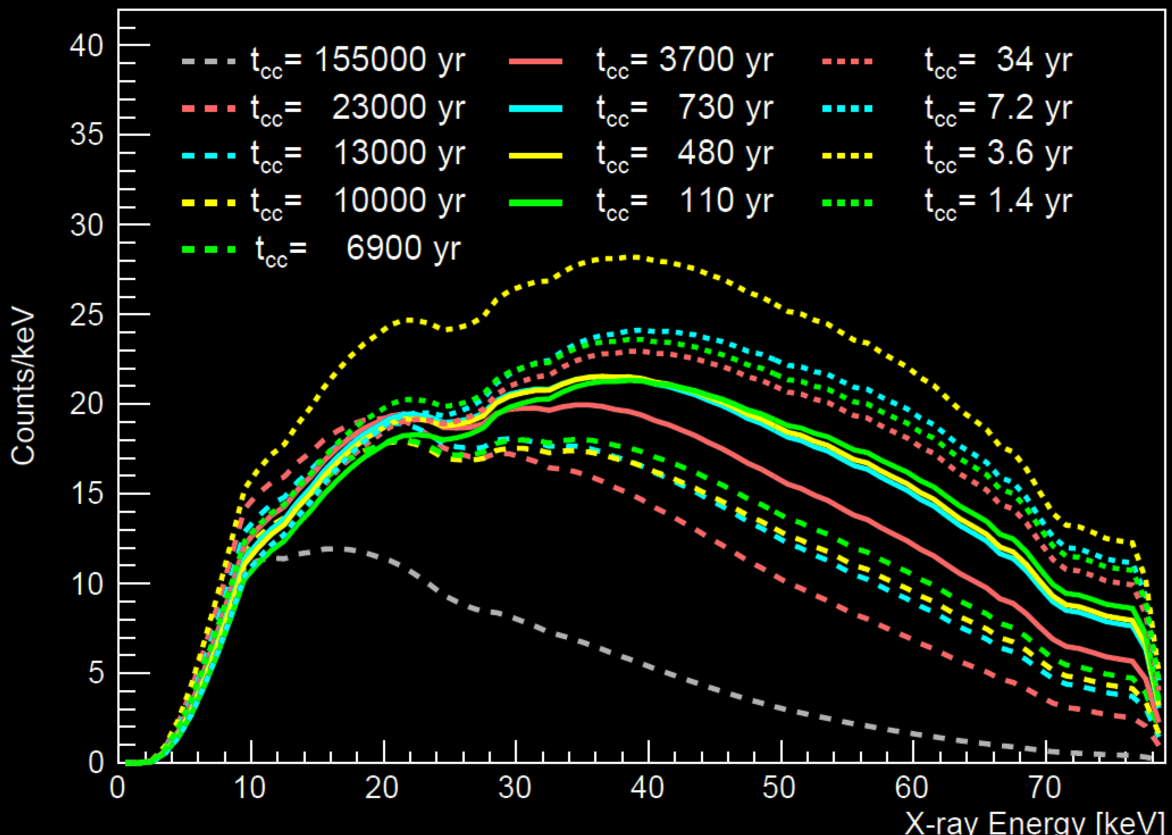


Betelgeuse Observation with NuSTAR

X-ray Spectrum Prediction = ALP Production ($d\dot{N}_a/\mathrm{dE}$) ⊗ ALP-Photon Conversion ($P_{a\gamma}$) ⊗ NuSTAR Response

- Expected event counts in NuSTAR for 13 stellar models of Betelgeuse
  - *Instrument response files were extracted from source region (see later)*

- $m_a = 10^{-11}\ eV$
- $B_T = 1.4\ \mu G$
- $g_{a\gamma} = 1.5 \times 10^{-11}\ GeV^{-1}$

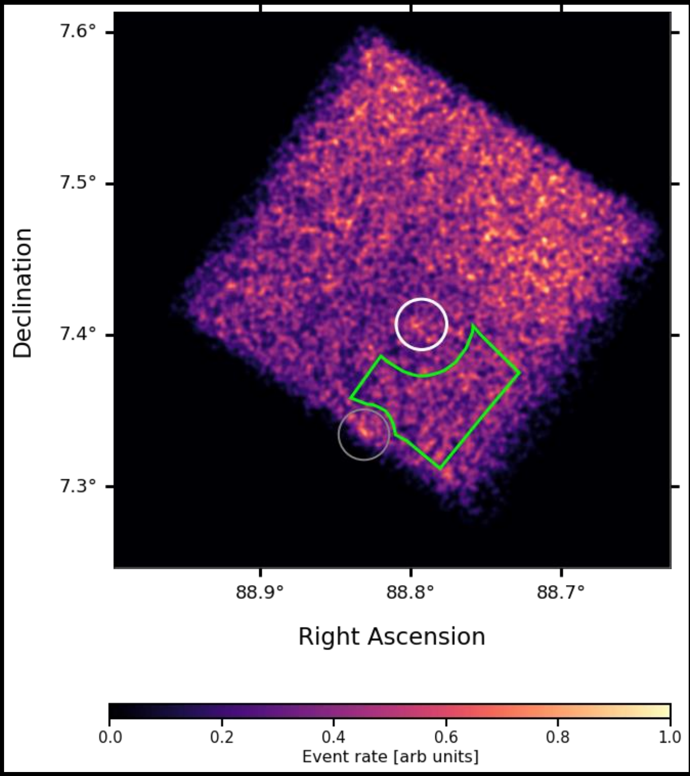


Betelgeuse Observation with NuSTAR

- ❑First hard X-ray observations of Betelgeuse, using NuSTAR (~50 ks, taken on Aug. 23, 2019, ObsID 30501012002)
  - NASA Grant No. 80NSSC20K0031

- ❑**Source Region:** r=60" around the star's equatorial coordinates (RA=88.79293°, Dec.=7.40706°)

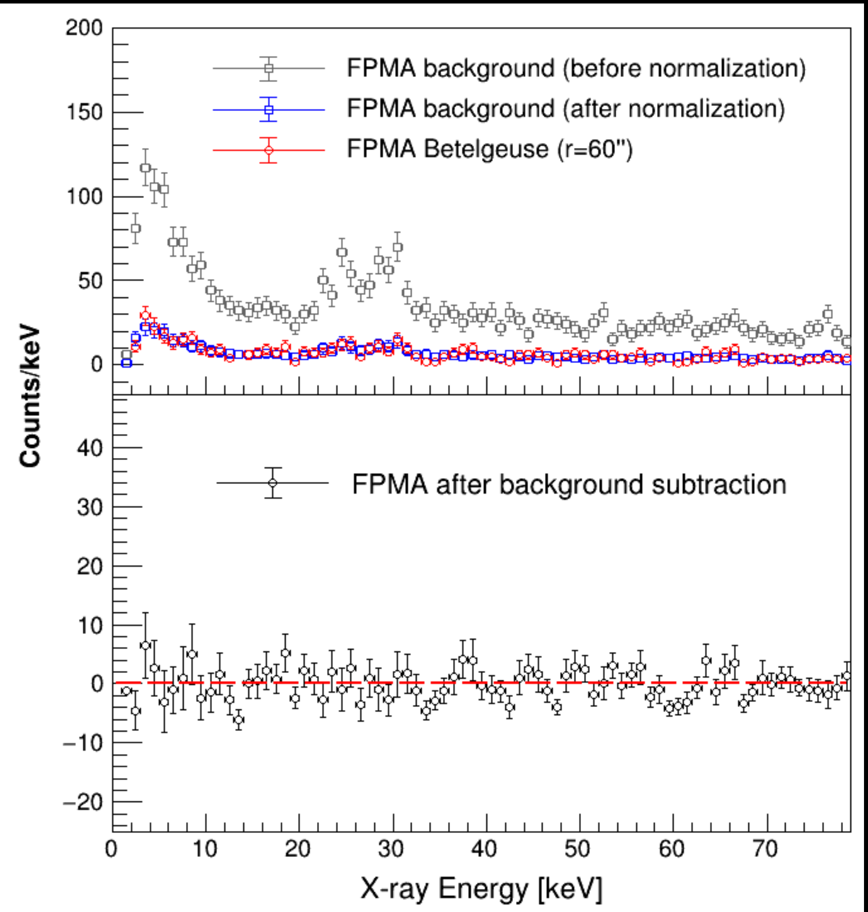
- ❑Background Region:
  - On the same detector chip as the source region (to properly describe spatially-varying backgrounds).
  - Separated from source region center by at least 120" and at least 60" from one point source (Chandra source CXOJ055520:2+072002).



- *FPMA image of NuSTAR observation regions in the energy range 3-79 keV*

Data Analysis

- Data were processed with the standard NuSTAR data reduction pipeline
- *Source spectrum:* extracted from the source region with NUPRODUCTS
  - *Instrument response files (ARF/RMF) were extracted simultaneously*



- *Background (N_{bkg}):* normalized the background spectrum to source region size

Data Analysis

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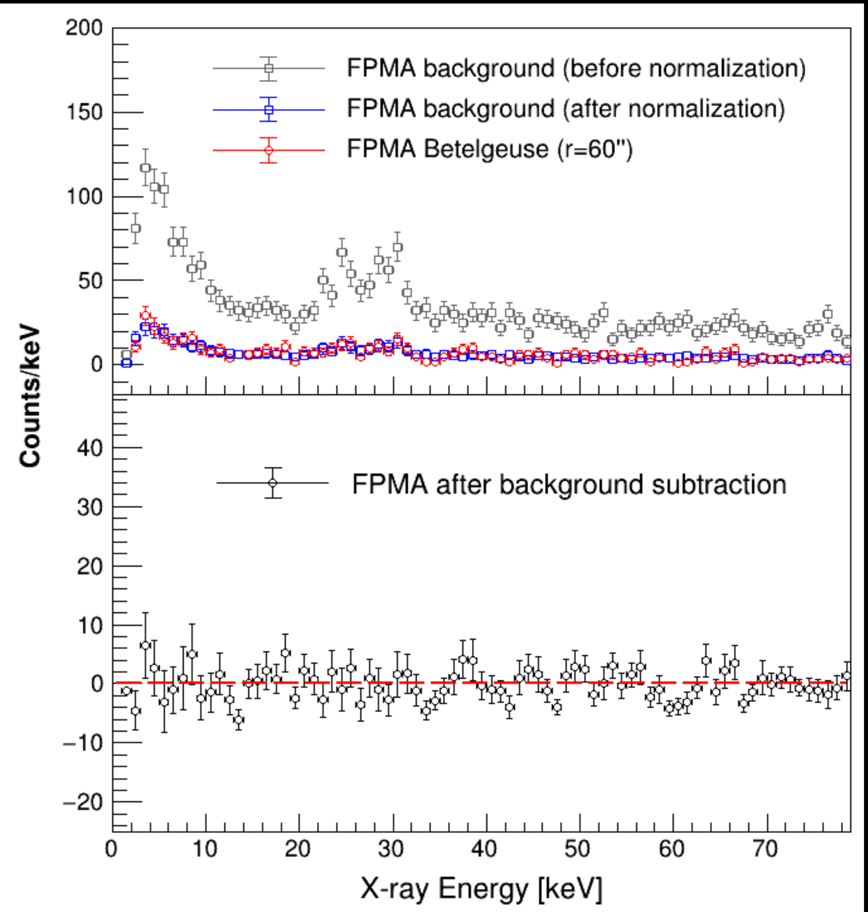


- *Background (N_{bkg}):* normalized the background spectrum to source region size

Photon Energy	FPMA		FPMB	
	$N_{\rm obs}$	$N_{\rm bkg}$	$N_{\rm obs}$	$N_{\rm bkg}$
10—60 keV	313	315.8	352	362.7
10—70 keV	354	359.8	397	406.4
10—79 keV	384	392.7	433	441.2

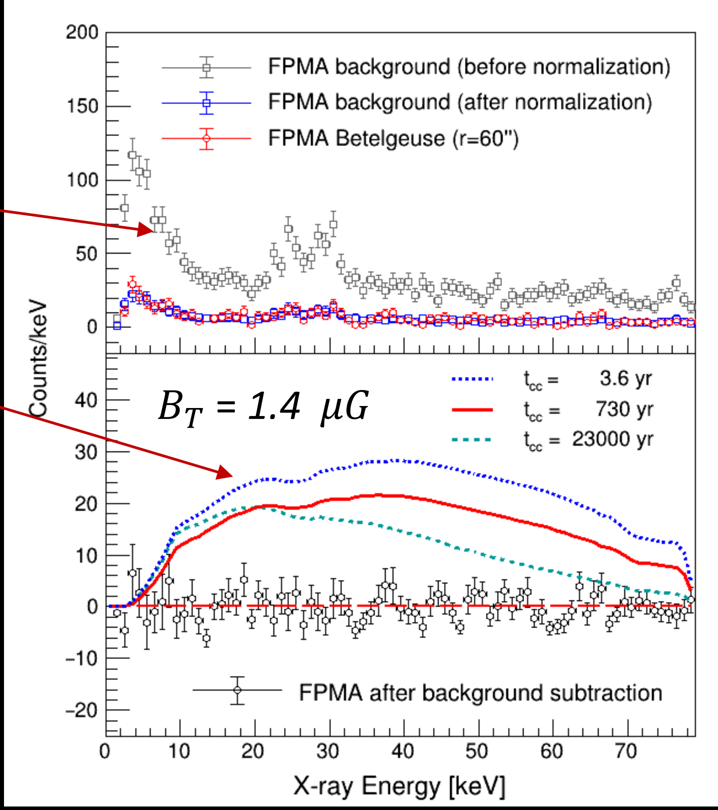
- *No significant excess of events above the expected background was found!*

Data Fitting

- Profile likelihood analysis approach was performed to fit the data.

- For FPMA/FPMB, an unbinned likelihood function was constructed:

$$\mathcal{L}_i = \text{Poisson}(N_{\text{obs}}|N_{\text{exp}}) \times \prod_{j=1}^{N_{\text{obs}}} \left[\frac{N_{\text{ax}} P_{\text{ax}}(E_\gamma^j)}{N_{\text{exp}}} + \frac{N_{\text{bkg}}(1+\delta_{\text{bkg}}) P_{\text{bkg}}(E_\gamma^j)}{N_{\text{exp}}} \right]$$

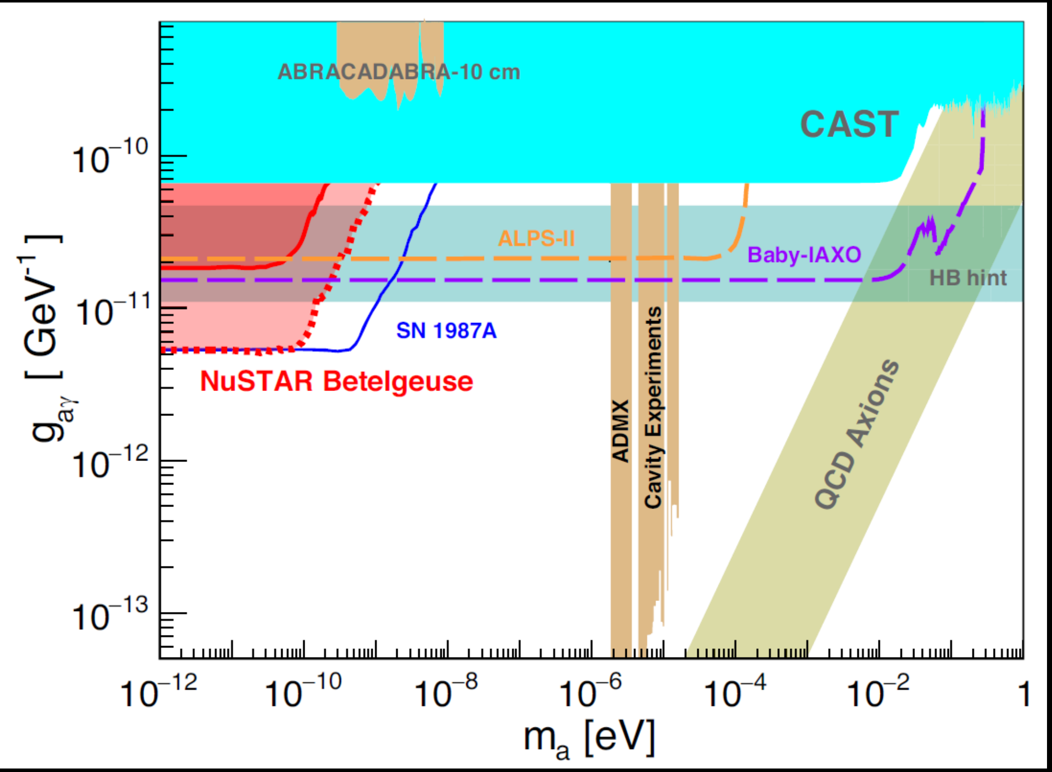


- Combined data sets from FPMA and FPMB were fitted to set the final upper limit on $g_{a\gamma}$ *(for an assumed* B_T *and* t_{cc}*)*.

$$\mathcal{L} = \prod_{i=1}^{n} \mathcal{L}_i \times \prod_{i=1}^{n} \text{Gauss}(\delta_{\text{bkg}}^i, \sigma_{\text{bkg}}^i)$$

Constraints on the ALPs

- ❑ A new competitive bound (95% C.L.) from the hard X-ray observation of Betelgeuse with NuSTAR, a factor of ~3x stronger than CAST at low mass.

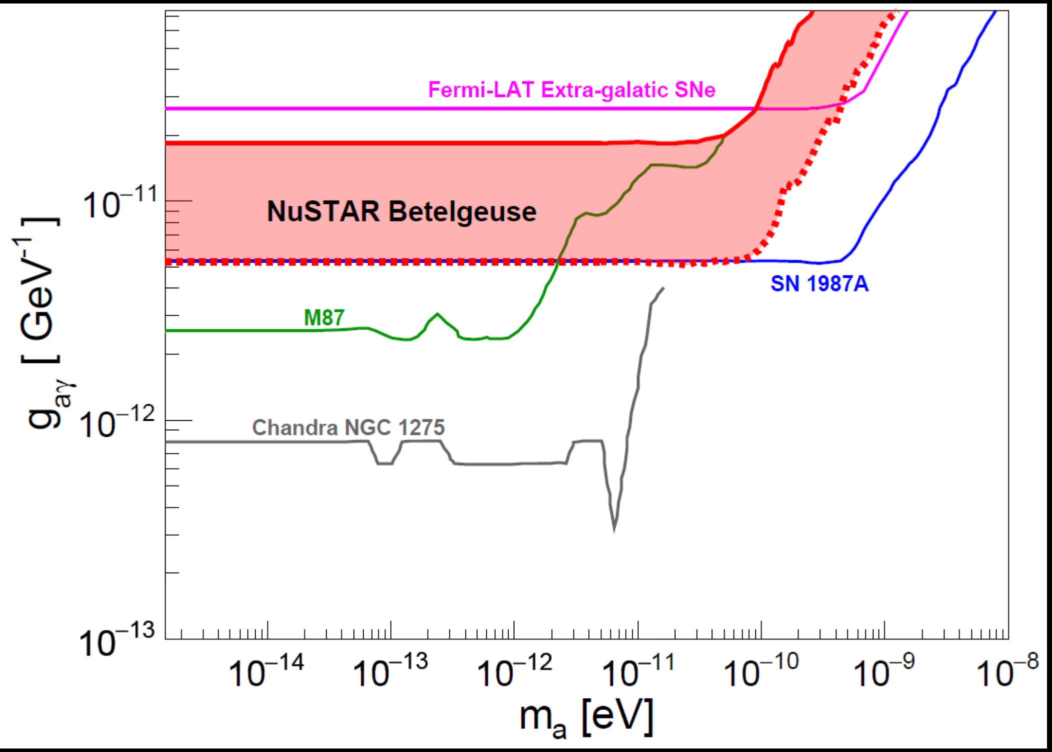


- *$0.4\ \mu G \leq B_T \leq 3.0\ \mu G$*
- *$1.4\ yr \leq t_{cc} \leq 1.55 \times 10^5\ yr$*
- *$g_{a\gamma}$ < (0.5–1.8)$\times 10^{-11}\ GeV^{-1}$ (depending on magnetic field and Betelgeuse stellar model) for ALP masses m_a<(5.5–3.5) $\times 10^{-11}$ eV*

**Similar study with other stellar objects: C. Dessert et al. (2020)*

Constraints on the ALPs

- Compare to other astrophysical constraints in the low-mass ALP regime.
  - Each constraint has unique sources of systematic errors.



- *The combination of various astrophysical constraints*

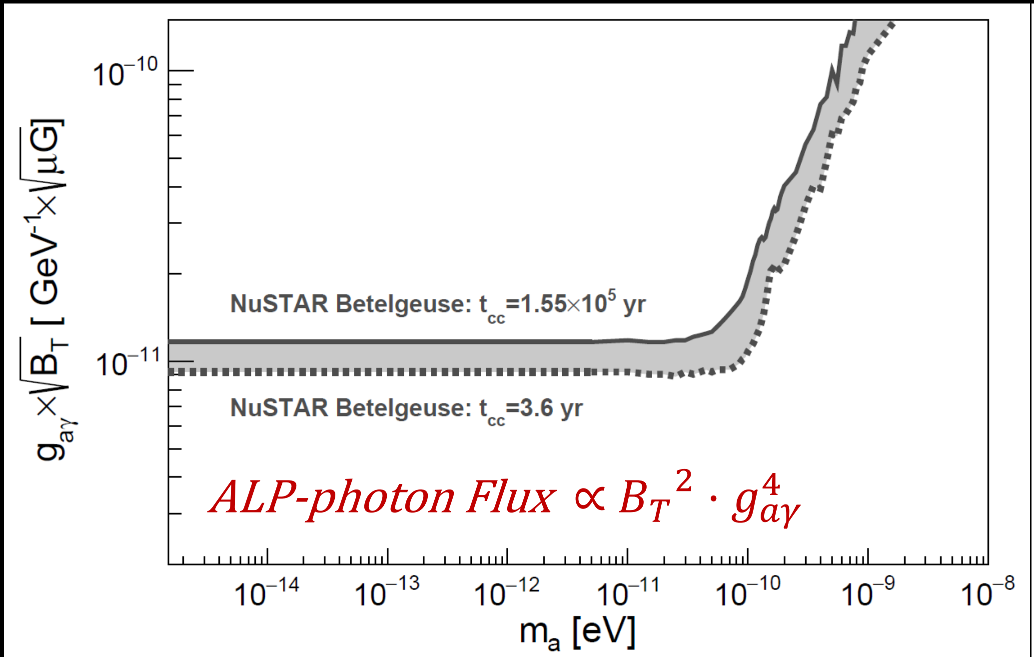
⇩

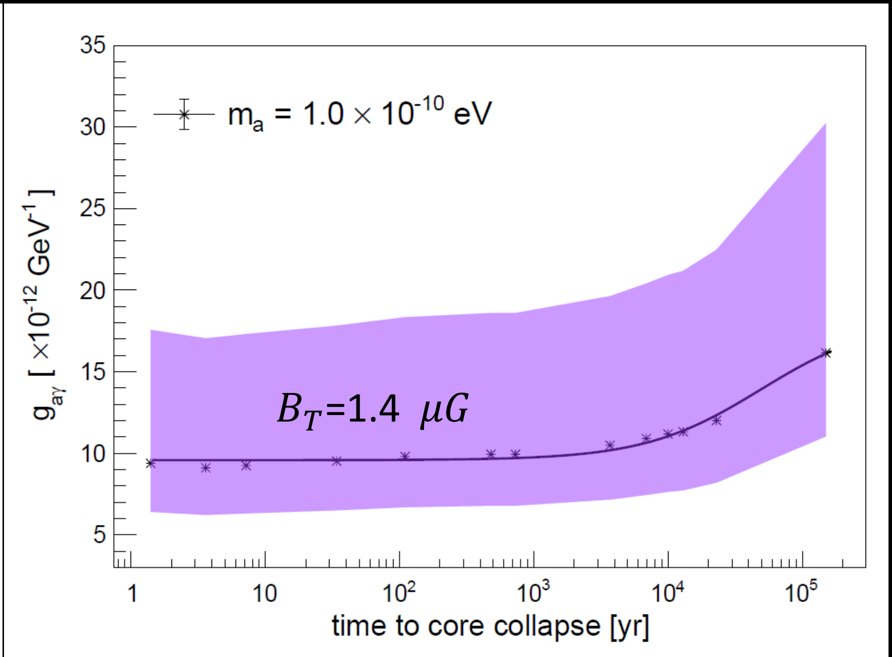
Builds confidence in the robustness of the exclusion!

**Similar study with other stellar objects: C. Dessert et al. (2020)*

More Discussion

- Evolution of $g_{a\gamma}$ with the remaining time until the core-collapse (t_{cc}) for Betelgeuse.

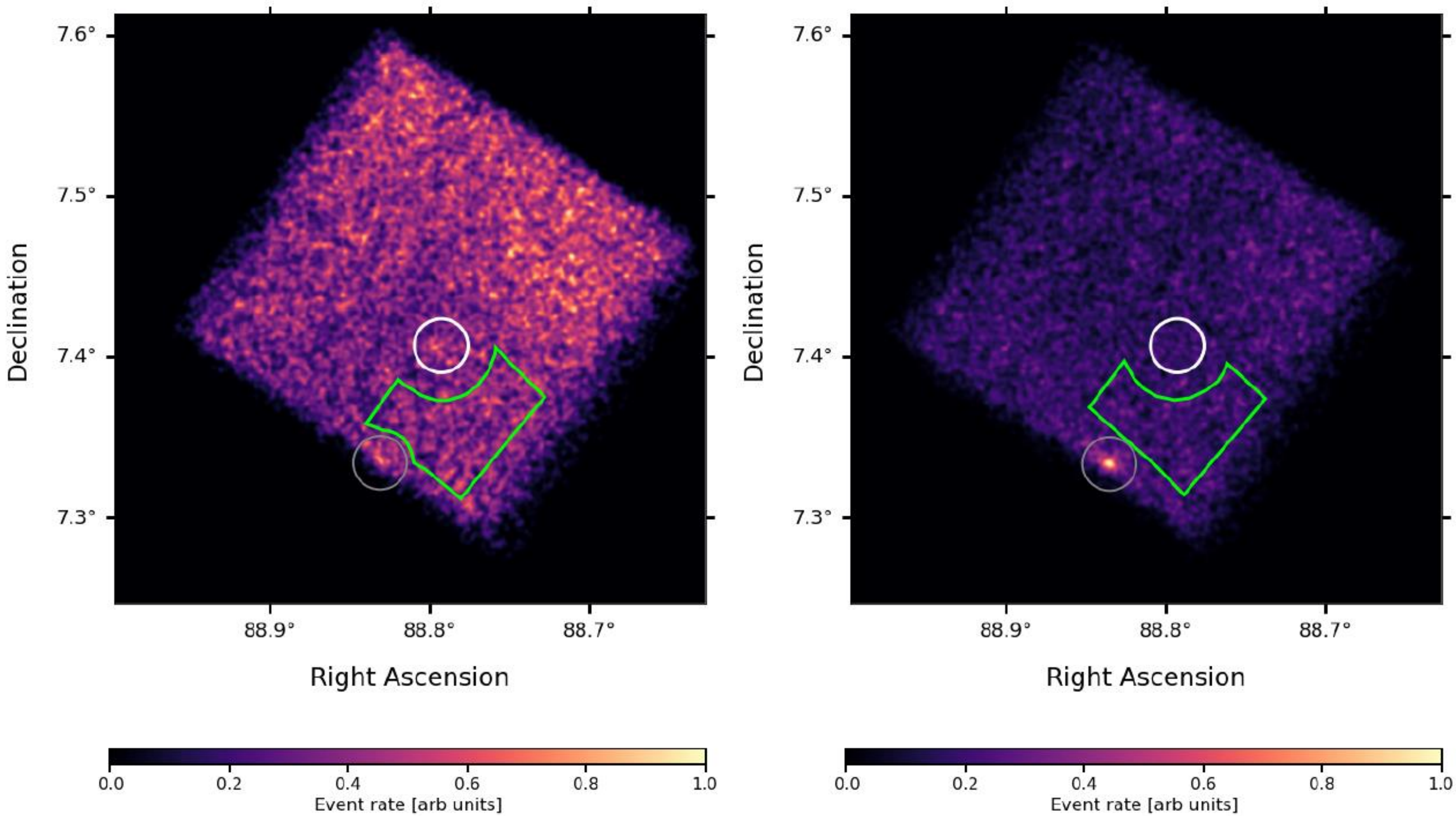




- *Benefit:* if future ALP experiments discover ALPs in the region our optimistic case excludes, we would set a lower limit on t_{cc} for Betelgeuse

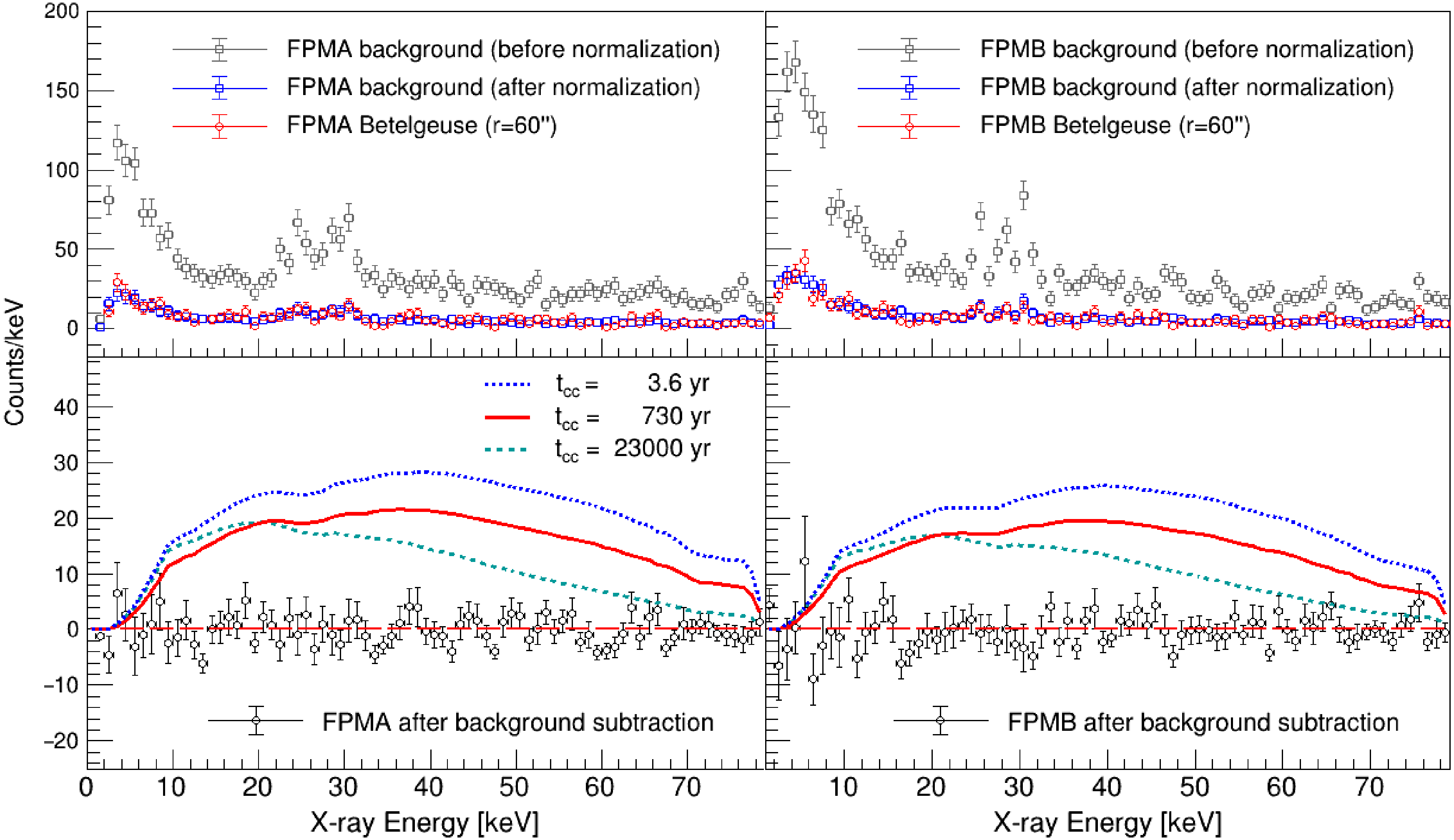
Thank You!

Backup Slide: observation images

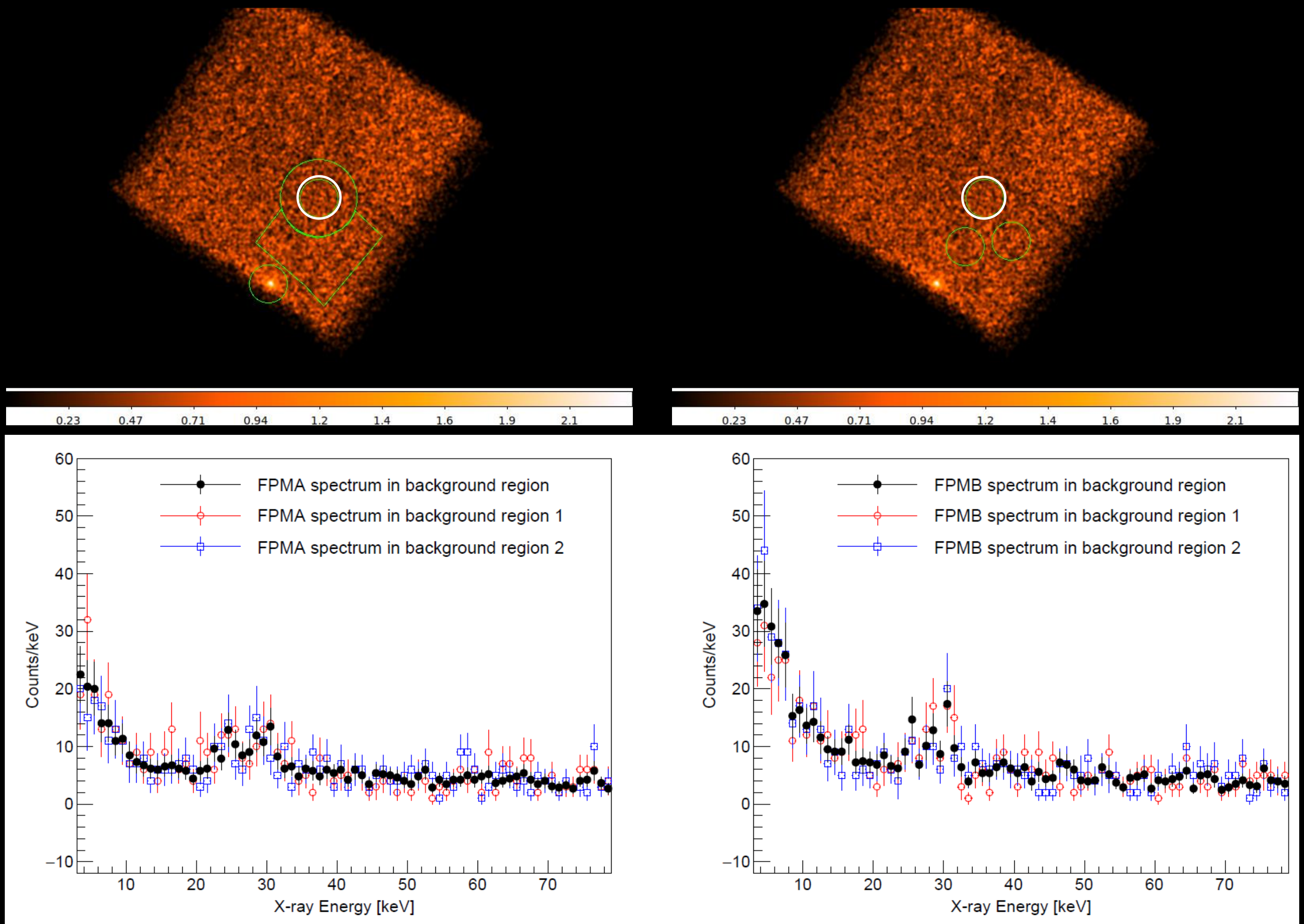


(a)FPMA (b)FPMB

Backup Slide: observation data

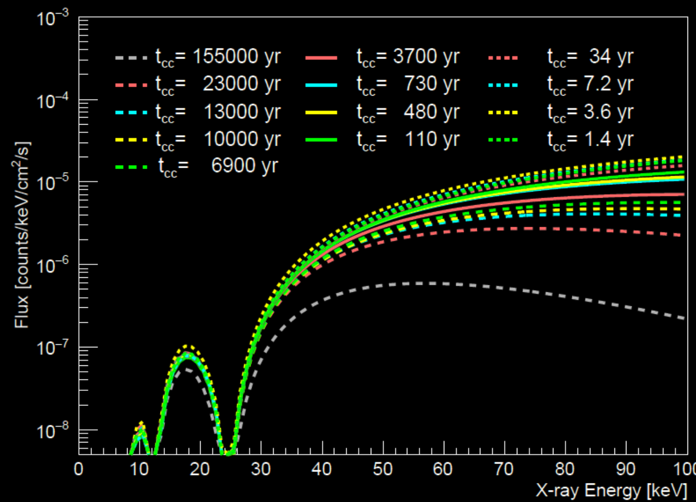


Backup Slide: background regions

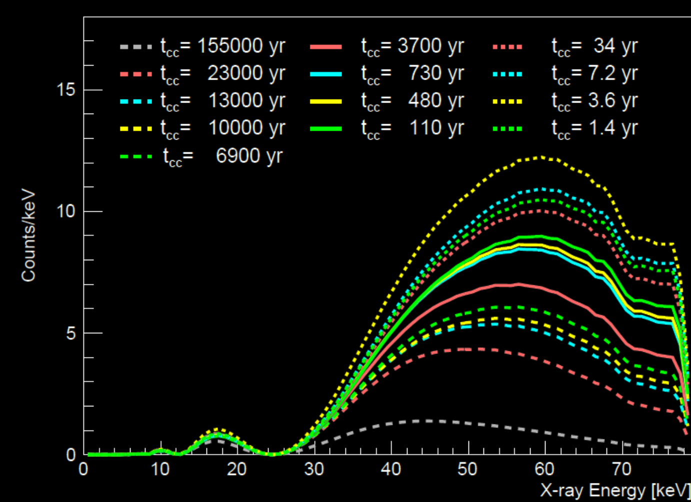


(a)FPMA (b)FPMB

Backup Slide: more ALP-photon flux



$m_a = 1.0 \times 10^{-10}$ eV (before $NuSTAR$)



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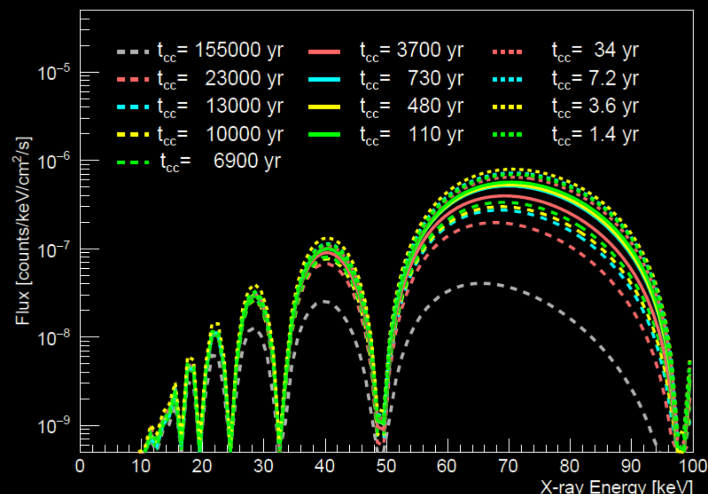
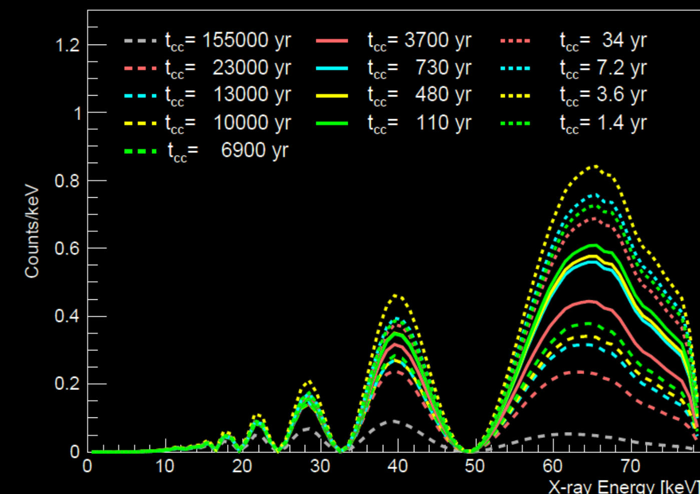


$m_a = 2.0 \times 10^{-10}$ eV (before $NuSTAR$)



$m_a = 2.0 \times 10^{-10}$ eV (after $NuSTAR$)

Backup Slide: Data Analysis

- Data were processed with the standard NuSTAR data reduction pipeline
  - NuSTARDAS v1.8.1 distributed in HEASOFT v6.24
  - Latest calibration package (CALDB.indx20191219)
  - SAAMODE=OPTIMIZED and TENTACLE=YES
- *Source spectrum:* extracted from the source region with NUPRODUCTS
  - Instrument response files (ARF/RMF) were extracted simultaneously
- *Background (N_{bkg}):* normalized the background spectrum to source region size

Photon Energy	FPMA		FPMB	
	N_{obs}	N_{bkg}	N_{obs}	N_{bkg}
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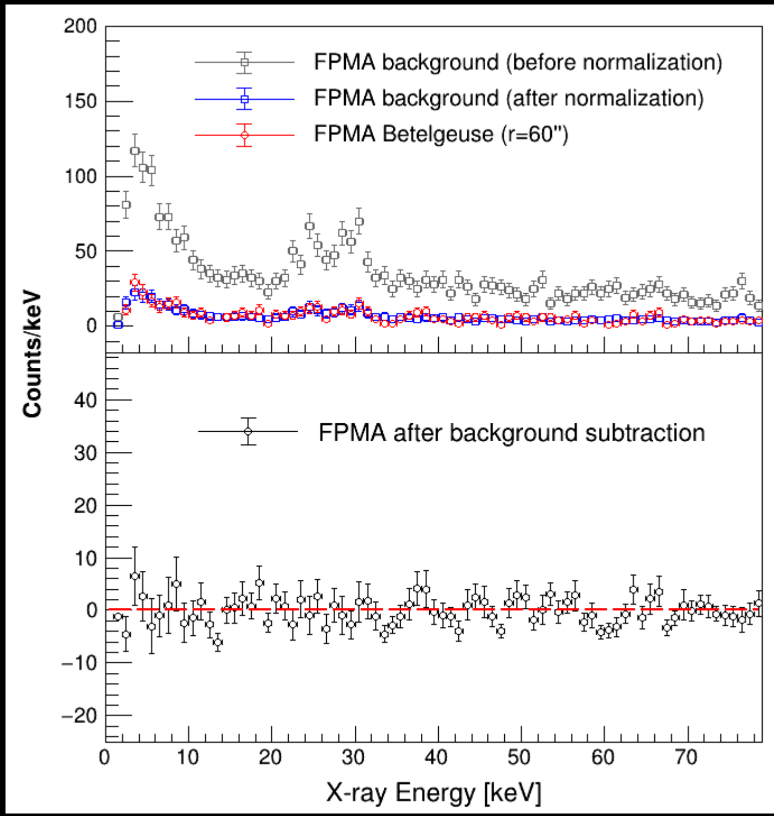

- ***No significant excess of events above the expected background was found!***

Backup Slide: NuSTAR Satellite Telescope

F.A. Harrison et al. ApJ, 770, 103 (2013)

Parameter	Value
Energy range	3–78.4 keV
Angular resolution (HPD)	58″
Angular resolution (FWHM)	18″
FoV (50% resp.) at 10 keV	10′
FoV (50% resp.) at 68 keV	6′
Sensitivity (6–10 keV) (10^6 s, 3σ, $\Delta E/E = 0.5$)	2×10^{-15} erg cm^{-2} s^{-1}
Sensitivity (10–30 keV) (10^6 s, 3σ, $\Delta E/E = 0.5$)	1×10^{-14} erg cm^{-2} s^{-1}
Background in HPD (10–30 keV)	1.1×10^{-3} counts s^{-1}
Background in HPD (30–60 keV)	8.4×10^{-4} counts s^{-1}
Energy resolution (FWHM)	400 eV at 10 keV, 900 eV at 68 keV
Strong source ($>10\sigma$) positioning	1″.5 (1σ)
Temporal resolution	2 μs
Target of opportunity response	<24 hr
Slew rate	0°.06 s^{-1}
Settling time	200 s (typ)

Focal Plane Parameter	Value	Focal Plane Parameter	Value
Pixel size	0.6 mm/12″.3	Max. processing rate	400 events s^{-1} module^{-1}
Focal plane size	12′ × 12′	Max. flux meas. rate	10^4 counts s^{-1}
Hybrid format	32 pix × 32 pix	Time resolution (relative)	2 μs
Energy threshold	2 keV	Dead time fraction (at threshold)	5%

Backup Slide: ALP-photon Production

ALP production rate:

$$\frac{d\dot{N}_a}{dE} = \frac{10^{64}\, C\, g_{a\gamma}^2}{keV\ s} \cdot \left(\frac{E}{E_0}\right)^{\beta} \cdot e^{-\frac{(\beta+1)E}{E_0}}$$

Parameterized by stellar model

ALP-photon conversion probability :

$$P_{a\gamma} = 8.7\times 10^{-6}\left(\frac{g_{a\gamma}}{10^{-11}}\right)^2 \left(\frac{B_T}{1\ \mu G}\right)^2 \left(\frac{d}{197\ pc}\right)^2 \frac{\sin^2 q}{q^2}$$

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

(Assuming homogeneous regular B field)

Model	Phase	t_{cc} [yr]	$\log_{10}(L_{eff}/L_{\odot})$	$\log_{10}(T_{eff}/K)$	C	E_0 [keV]	β
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8	in C burning	110	5.16	3.542	16	210	2.0
9	in C burning	34	5.16	3.542	21	240	2.0
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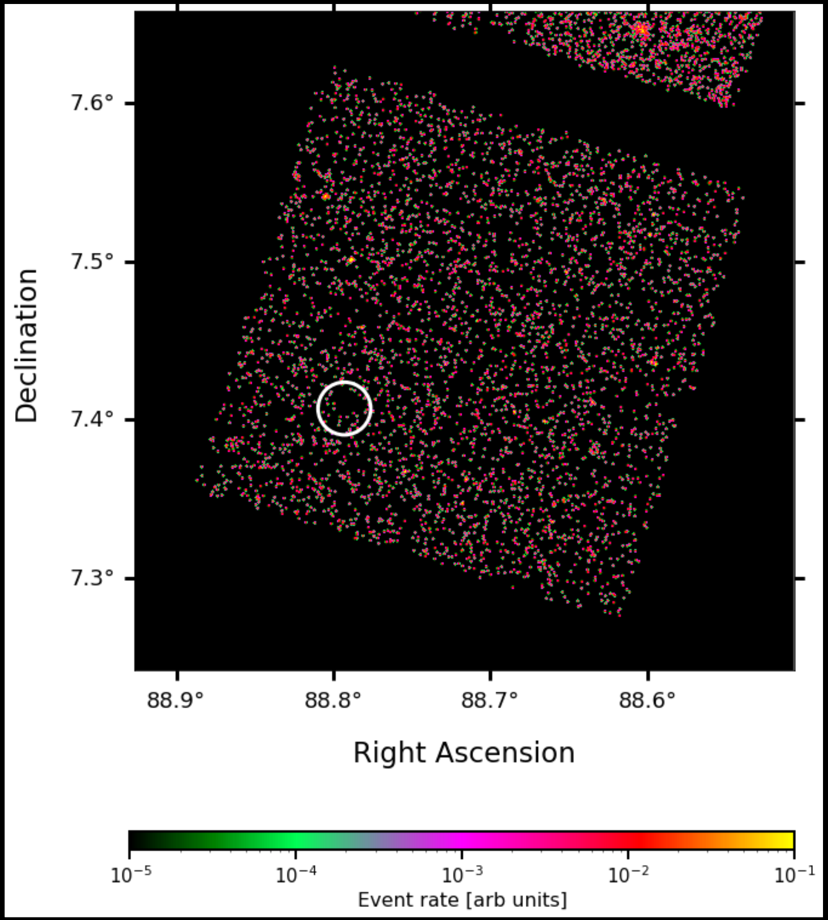
11	in Ne burning	3.6	5.16	3.542	26	320	1.8
12	beginning of O burning	1.4	5.16	3.542	27	370	1.8

- ***t_{cc}: time until core collapse for Betelgeuse***

Backup Slide: Betelgeuse-Chandra



- ObsID: 3365
- Energy range: 0.3-8 keV
- Exposure time: 4.899 ks