# Axion-like particle constraints from preSN in future experiments

## 2nd General Meeting of COST Action COSMIC WISPers (CA21106)

on going work with Alessandro Mirizzi, Maurizio Giannotti, Francesca Calore, Giuseppe Lucente, Pierluca Carenza, Aldo Morselli e Gonzalo Fernandez-Perez

INFN ROMA TOR VERGATA

Fermi Gamma-ray Space Telescope

asi agenzia spaziale italiana

**Federica Giacchino (ROMA2-INFN & SSDC), 03/09/2024, Istinye University - Istanbul (Turkey)**

# Outline of this talk

- Which relation between ALP and preSN?
- Review of the proposal and future MeV experiments
- Results: extension of a previous work *Xiao, Giannotti et al. ‘22* with NuSTAR

# Axion-Like Particle (ALP) in Nutshell

## Generalisation of QCD axion

SM gauge symmetries + extra approximate global symmetry. When the symmetry is explicitly broken pseudo-Goldstone bosons can be produced and the Axion-Like Particle is one of them: for example the breaking of $U_{PQ}(1)$ symmetry produces the QCD axion, familion (Wilczek '82), majoron (Gelmini '81).

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**Quick ID 👣:**

- The couplings are totally unrelated to the ALP mass $m_a$
- The mass spans a wide range of values
- ALP as Feebly Interacting Particle (FIP): light particle of subGeV masses, extremely suppressed interactions between new particles and SM bosons and/or fermions (*hidden sector*)
- ALP could be dark matter (from $10^{-22}$ eV to few keV scale) or in MeV scale a portal (bridge particle between visible and hidden sector)
- ALP has an impact in particle physics, cosmology, astrophysics

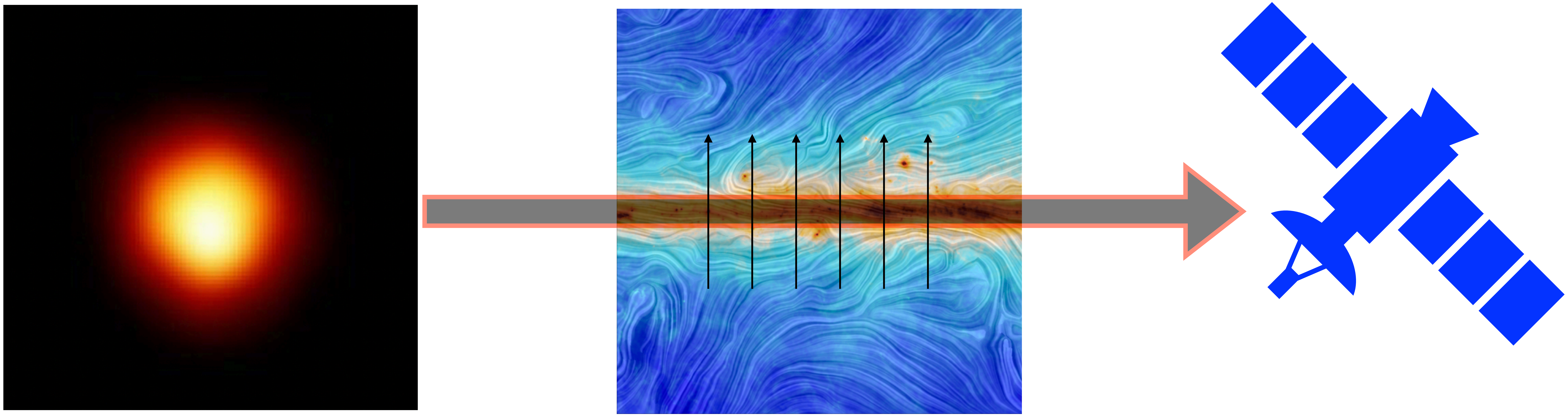
# Axion-Like Particle (ALP) in Nutshell

## Recent reviews

- I.Irastorza, J. Redondo, *New experimental approaches in the search for axion-like particles*, Prog.Part.Nucl.Phys.102 (2018)
- L. di Luzio et al., *The landscape of QCD axion models*, Phys. Rept. 870 (2020)
- P. Sikivie, Invisible Axion Search Methods, Rev. Mod. Phys. 93 (2021)
- A. Caputo, G. Raffelt, *Astrophysical Axion Bounds*, Pos COSMICWISPers (2024)
- …

# How to probe the ALP?

## Looking for signatures from the space



NASA/HUBBLE SPACE TELESCOPE collaboration

ESA/Planck collaboration

**PRODUCTION SOURCES**

$$\frac{d\dot{N}_a}{dE}$$

**MAGNETIC FIELD ALONG GALACTIC PLANE FOR ALP-PHOTON CONVERSION**

$$P_{a\gamma}$$

**DETECTOR FOR CATCHING PHOTONS FROM ALP CONVERSION**

$$\frac{dN_\gamma}{dE\,dS\,dt}$$

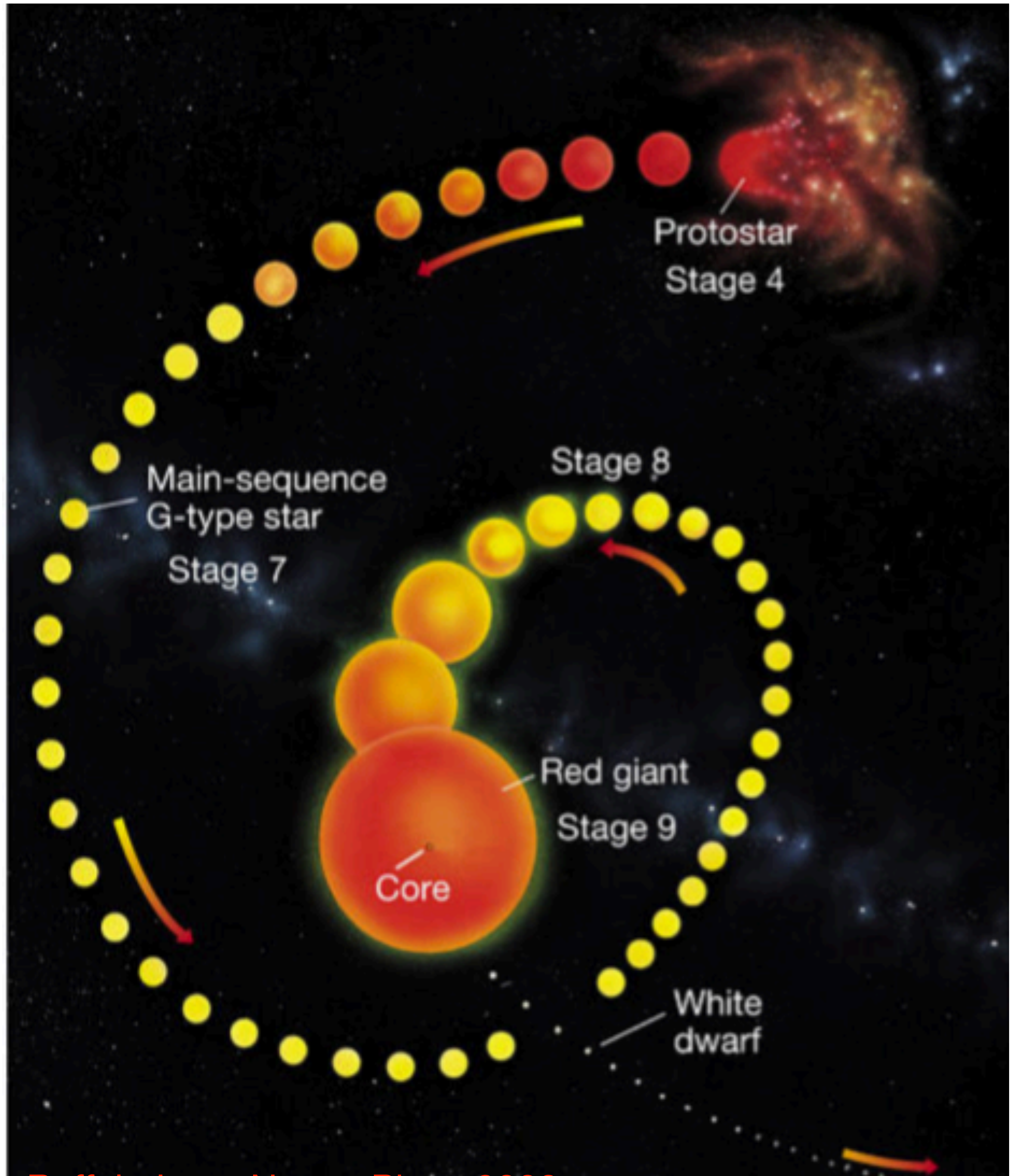
# How to probe the ALP?

## Looking for signatures from the space

$$\mathscr{L}_{ALP} = \frac{1}{2}(\partial^\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - i\sum_f g_{af}\, m_f\, a\, \bar{\psi}_f \gamma_5 \psi_f$$

Stars are good factories of FIPs, *i.e.* ALP as in our case. According to the stage of the star, there is a more dominant **production** $\left(\frac{d\dot{N}_a}{dE}\right)$ process:

- Primakoff $\gamma + Z_e \rightarrow Z_e + a$ (MS stars as Sun or HB stars)
- Compton $\gamma + e \rightarrow e + a$ (Contribution for HB stars)
- Bremsstrahlung $e + Ze \rightarrow e + Ze + a$ (helium-burning RGB and white dwarfs)
- Nuclear Bremsstrahlung $N_1 + N_2 \rightarrow N_3 + N_4 + a$ (dominant for neutron stars and SN)
- Pion Induced $\pi^- + N \rightarrow a + N$ (dominant in SN)



Raffelt, Lect. Notes. Phys. 2008

# SuperGiant Stars

## Astro environment to search ALP signature

Galactic SNe would produce an enormous ALP flux. However they are rare events. What about massive stars?

There are 21 supergiants within 1 *kpc* from the Sun. Some of them in advanced stage which could produce a large ALP flux. One is Betelgeuse.

### Betelgeuse ID 👣 (Graham et al. ’08, Harper et al. ’17, Luo et al. '22)

- $d \sim 200$ pc
- Red supergiant star with spectral type M2Iab
- $M \sim 15 - 24\, M_{\odot}$

# SuperGiant Stars: Betelgeuse

## Astro environment to search ALP signature

$$\frac{d\dot{N}_a}{dE} = \text{Primakoff} + \text{Compton} + \text{Bremsstrahlung}$$

*Carlson 1995* — *Raffelt 1996* — *Carenza and Lucent '21*

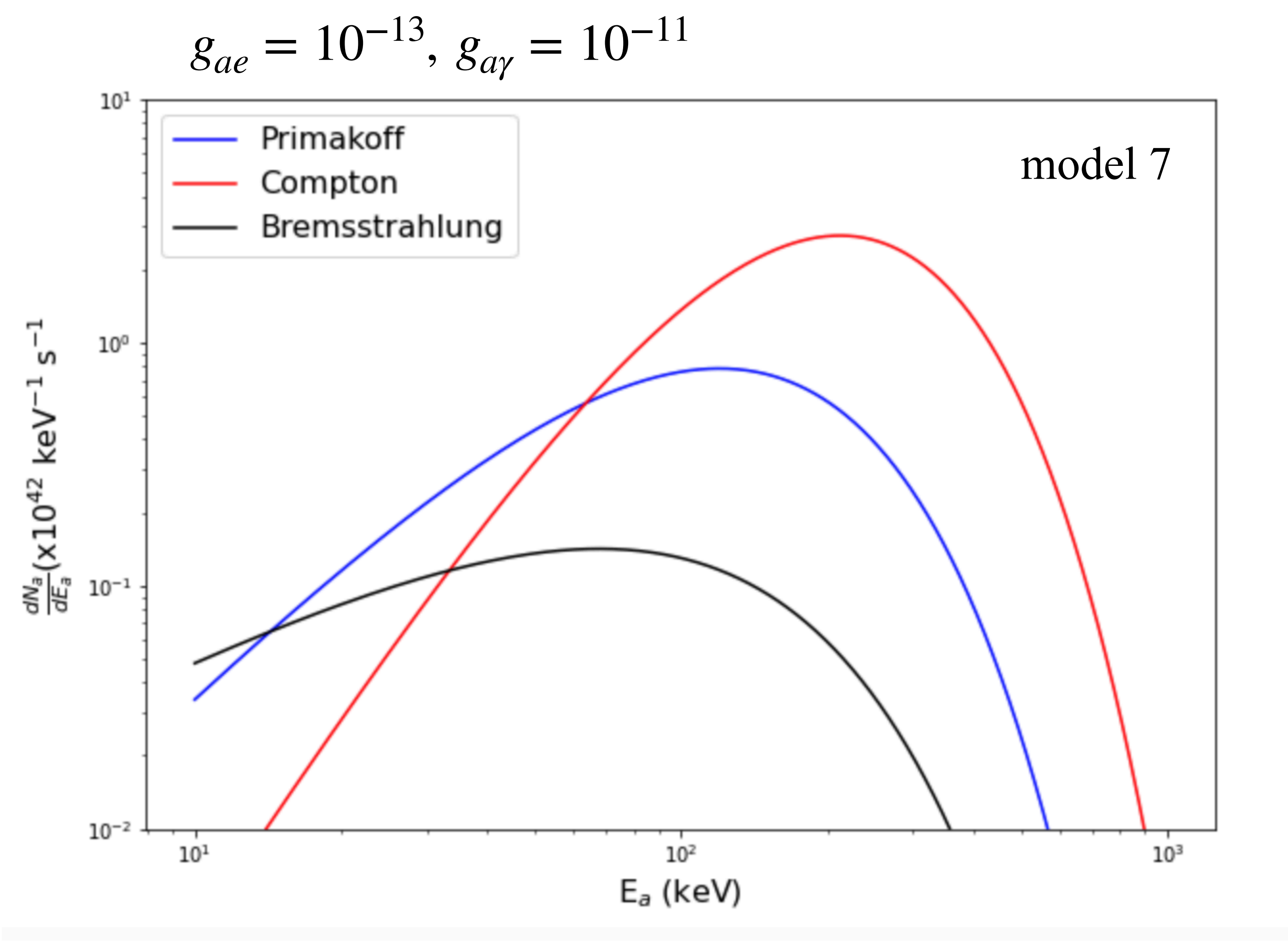
$$C^P\left(\frac{g_{a\gamma}^2}{10^{-11}}\right)\text{GeV}^{-1}\left(\frac{E}{E_0^P}\right)^{\beta^P} e^{-(\beta^P+1)E/E_0^P}$$

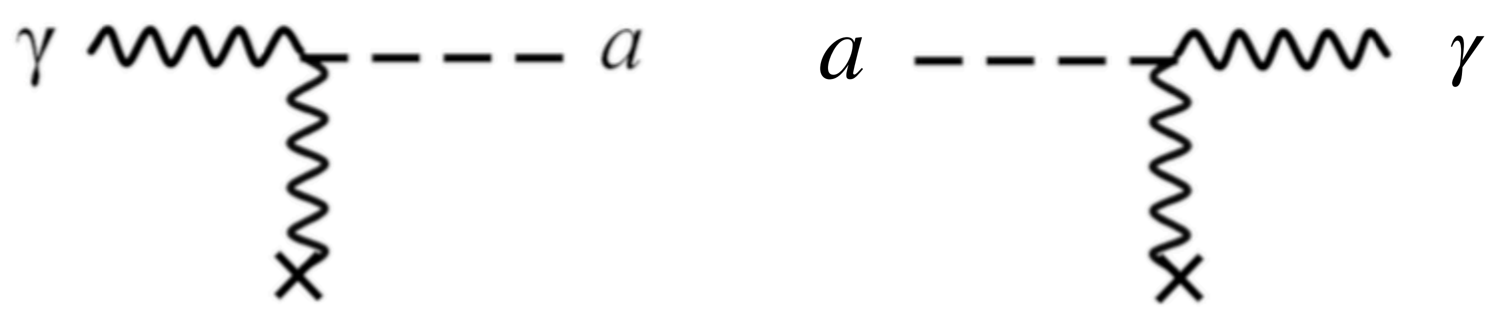
$$C^C\left(\frac{g_{ae}^2}{10^{-13}}\right)\text{GeV}^{-1}\left(\frac{E}{E_0^C}\right)^{\beta^C} e^{-(\beta^C+1)E/E_0^C}$$

$$C^B\left(\frac{g_{ae}^2}{10^{-13}}\right)\text{GeV}^{-1}\left(\frac{E}{E_0^B}\right)^{\beta^B} e^{-(\beta^B+1)E/E_0^B}$$

| Model | Phase | $t_{cc}$ [yr] | $\log_{10}\frac{L_{\rm eff}}{L_\odot}$ | $\log_{10}\frac{T_{\rm eff}}{\rm K}$ | Primakoff | | | Bremsstrahlung | | | Compton | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $C^P$ | $E_0^P$ [keV] | $\beta^P$ | $C^B$ | $E_0^B$ [keV] | $\beta^B$ | $C^C$ | $E_0^C$ [keV] | $\beta^C$ |
| 0 | He burning | 155000 | 4.90 | 3.572 | 1.36 | 50 | 1.95 | 1.3E-3 | 35.26 | 1.16 | 1.39 | 77.86 | 3.15 |
| 1 | before C burning | 23000 | 5.06 | 3.552 | 4.0 | 80 | 2.0 | 2.3E-2 | 56.57 | 1.16 | 8.55 | 125.8 | 3.12 |
| 2 | before C burning | 13000 | 5.06 | 3.552 | 5.2 | 99 | 2.0 | 6.4E-2 | 70.77 | 1.09 | 17.39 | 156.9 | 3.09 |
| 3 | before C burning | 10000 | 5.09 | 3.549 | 5.7 | 110 | 2.0 | 8.9E-2 | 76.65 | 1.08 | 22.49 | 169.2 | 3.09 |
| 4 | before C burning | 6900 | 5.12 | 3.546 | 6.5 | 120 | 2.0 | 0.136 | 85.15 | 1.06 | 31.81 | 186.4 | 3.09 |
| 5 | in C burning | 3700 | 5.14 | 3.544 | 7.9 | 130 | 2.0 | 0.249 | 97.44 | 1.04 | 50.62 | 210.4 | 3.11 |
| 6 | in C burning | 730 | 5.16 | 3.542 | 12 | 170 | 2.0 | 0.827 | 129.17 | 1.02 | 138.6 | 269.1 | 3.17 |
| 7 | in C burning | 480 | 5.16 | 3.542 | 13 | 180 | 2.0 | 0.789 | 134.54 | 1.02 | 153.2 | 279.9 | 3.15 |
| 8 | in C burning | 110 | 5.16 | 3.542 | 16 | 210 | 2.0 | 1.79 | 151.46 | 1.02 | 252.7 | 316.8 | 3.17 |
| 9 | in C burning | 34 | 5.16 | 3.542 | 21 | 240 | 2.0 | 2.82 | 181.74 | 1.00 | 447.5 | 363.3 | 3.22 |
| 10 | between C/Ne burning | 7.2 | 5.16 | 3.542 | 28 | 280 | 2.0 | 3.77 | 207.84 | 0.99 | 729.2 | 415.7 | 3.23 |
| 11 | in Ne burning | 3.6 | 5.16 | 3.542 | 26 | 320 | 1.8 | 3.86 | 224.45 | 0.98 | 856.4 | 481.2 | 3.11 |

TABLE of parameters for 12 numerical models of Betelgeuse obtained by the Full Network Stellar evolution code (Straniero et al. '19 and Xiao et al. '22)






# ALP-photon conversion

## Astro environment to search ALP signature

A monochromatic ALP/photon beam of energy E propagating along $z$-axis in the presence of an external magnetic field $\overrightarrow{B}$ can convert due to the mixing matrix of ALP photon interaction. Approximation: regime $E >> m$ and $B_T$ component of magnetic field is homogeneous.

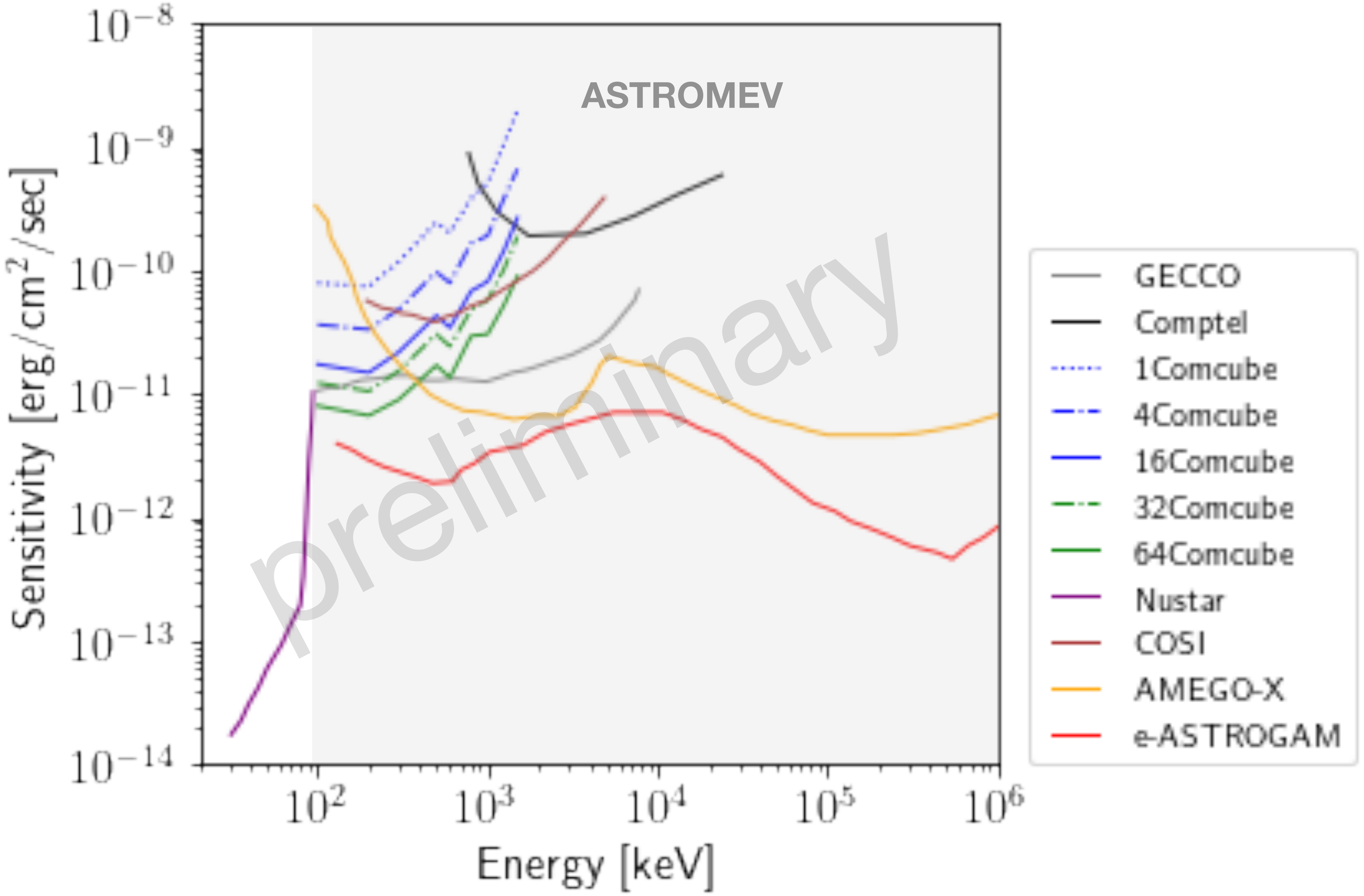
$$P_{a\gamma} = 8.7 \times 10^{-6} \left( \frac{g_{a\gamma}}{10^{-11}} \text{GeV}^{-1} \right)^2 \left( \frac{B_T}{1\mu\text{G}} \right)^2 \left( \frac{d}{197\,\text{pc}} \right)^2 \frac{\sin^2(qd)}{(qd)^2}$$

with $qd$ the product of the momentum transfer and the magnetic field length which depends on ALP mass, electron density and photon energy.

# Differential photon flux

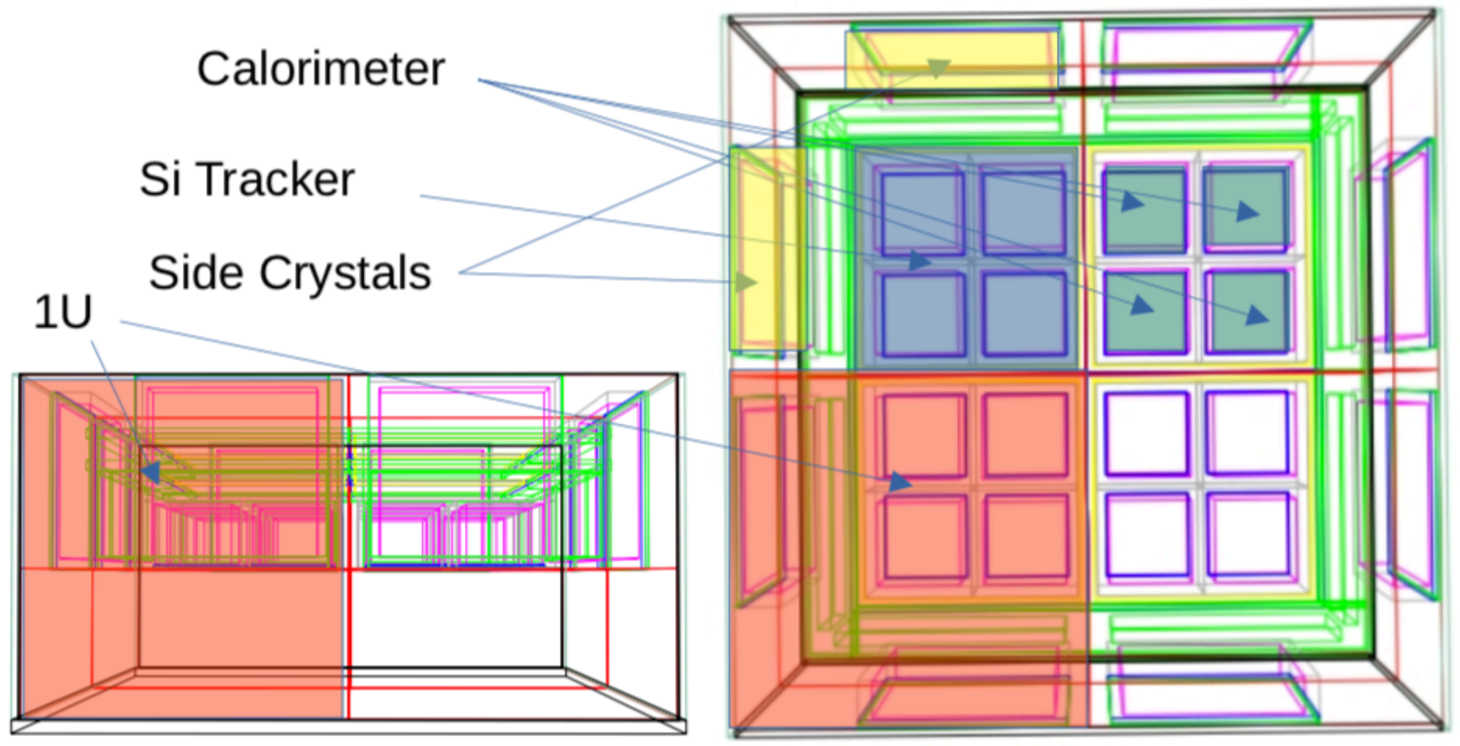
## Astro environment to search ALP signature

$$\frac{dN_\gamma}{dE\,dS\,dt} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}$$



# Review of the proposal and future experiments

## Astro environment to search ALP signature

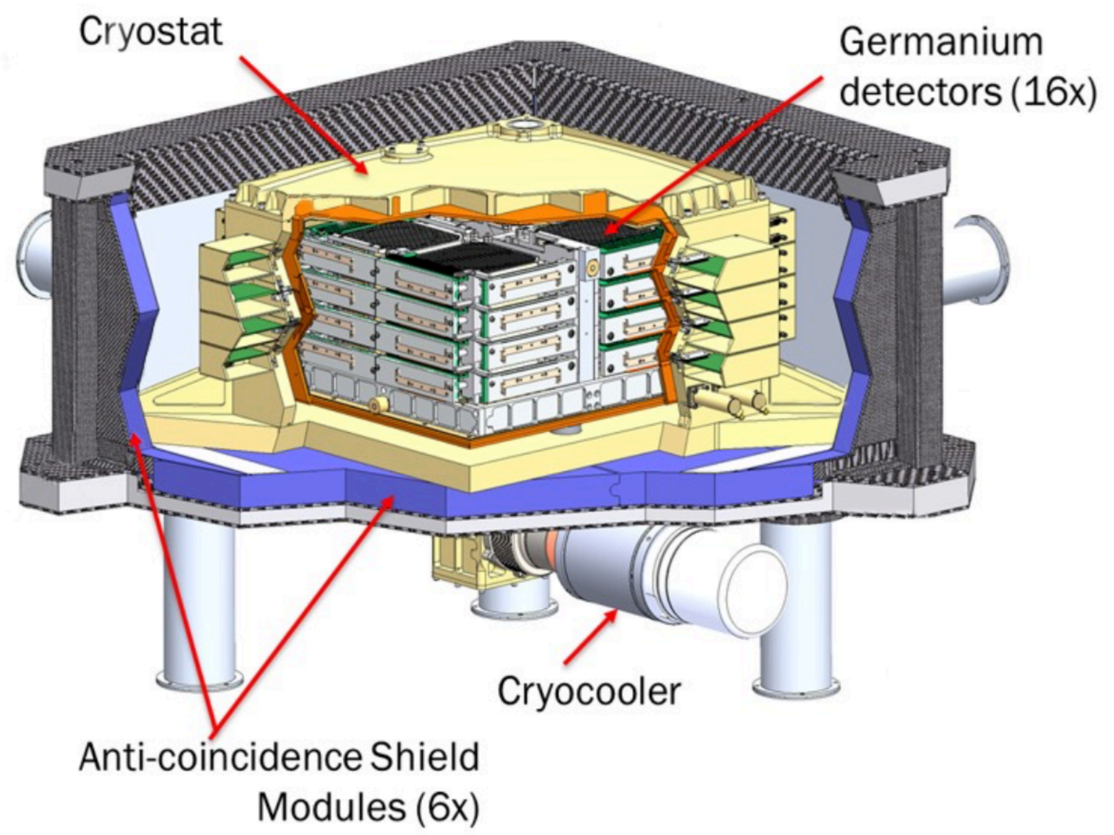



**COMCUBE ID:**

- European programme AHEAD2020, a COMpton polarimeter CUBEsat mission
- Launched prototype in ballon in winter 2024
- cheap solution and extendable number
- $(100 < E < 1500)$ keV, angular resolution (> 200 keV) ~ 20deg, energy resolution (3 -13)%
- 1Unit = $10 \times 10 \times 10\,\text{cm}^3$ and 1.3 kg.
- tracker: Two layers of four double-sided silicon stripped detectors + calorimeter: cerium bromide (CeBr3) + 1 p-Terphenyl plastic scintillator
- 1 COMcube = 4U + CeBr3 in side part
- energy and direction of an incoming photon by reconstructing a Compton interaction

# Review of the proposal and future experiments

## Astro environment to search ALP signature




**COSI ID https://cosi.ssl.berkeley.edu/ and arXiV 1908.04334:**

- NASA SMEX MISSION, COmpton Spectrometer and Imager
- Approved and it will be launched ~2027
- (0.2 < E < 5) MeV, angular resolution < 4deg, $\Delta E/E \sim 0.2 - 1\,\%$
- Gamma-ray detector - tracker: 16 arrays of crossed-strip cryogenic GeDetectors + housed cryostat (cryocooler) + readout ASIC + Anti-coincidence: BGO scintillator
- BGO shield box is $41 \times 41 \times 14$ cm$^3$
- energy and direction of an incoming photon by reconstructing a Compton process

**AMEGO-X ID arXiv:2208.04990:**

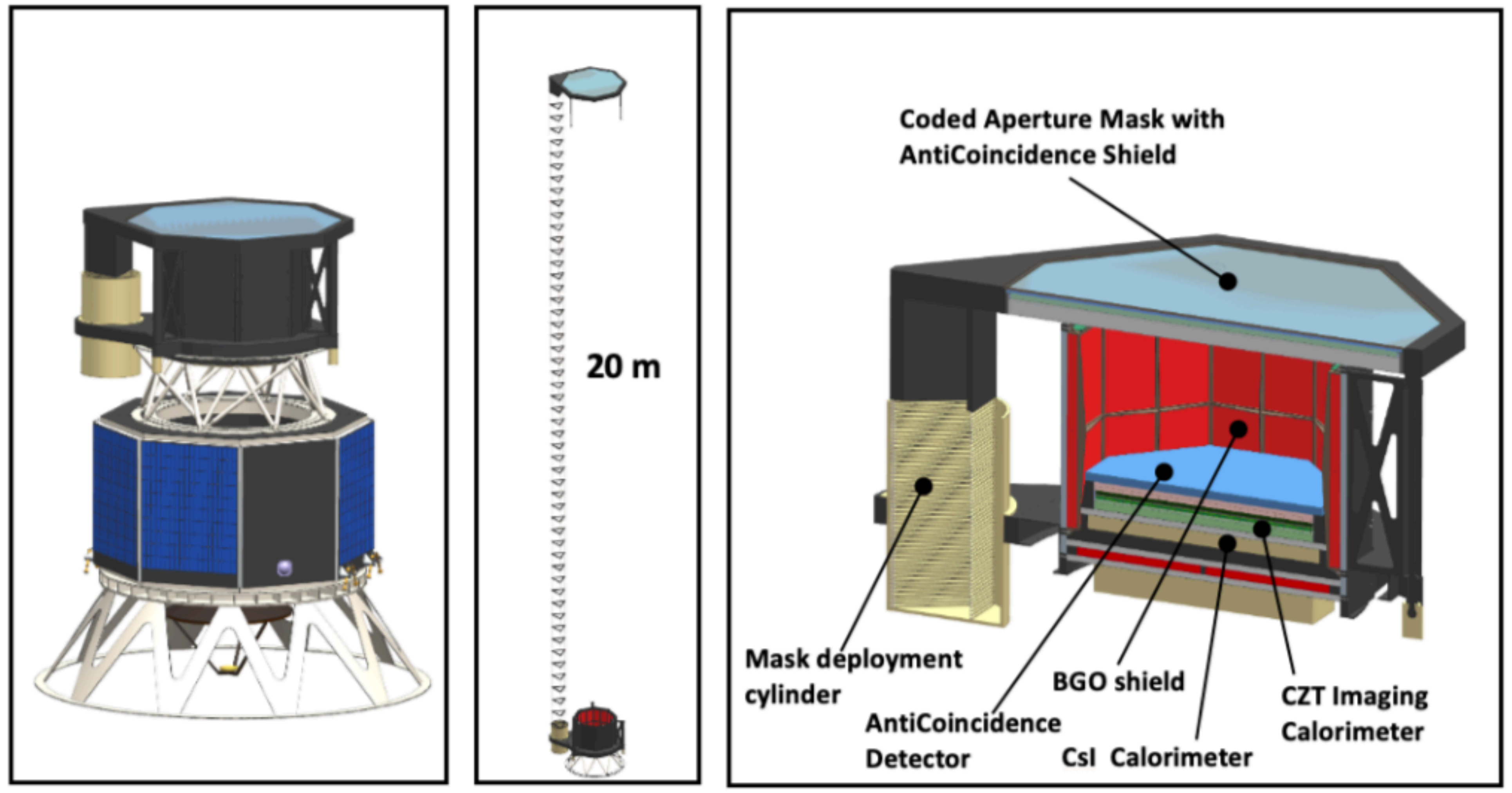
- NASA MISSION, All-sky Medium Energy Gamma-ray Observatory
- Resubmit in the next MIDEX round (~2027)
- (0.025 < E < 1000) MeV, angular resolution ~ COMPTEL, energy resolution 5% in FWHM
- Gamma-ray detector in 4 towers - tracker: 40 layers of silicon CMOS monolithic active pixel sensors + calorimeter: 4 layers of Cesium iodide scintillators + anti-coincidence + covered by micro-meteoroid shield
- effective area $\sim (500 - 1000)$ cm$^2$
- energy and direction of an incoming photon by reconstructing a Compton + Pair + Photoelectric processes

# Review of the proposal and future experiments

## Astro environment to search ALP signature

**e-ASTROGAM ID:**

- proposal ESA mission
- an idea to propose a smaller one with ASI collaboration
- tracker: 70 silicon layers of 6x6 DSS strip + read out with ASICS + calorimeter: high-Z scintillator material + anti-coincidence of plastic scintillators
- $(0.1 < E < 1000)$ MeV, angular resolution < 1.5deg, $\Delta E/E \sim 3 - 30\,\%$
- effective area $(120 - 1000)$ cm$^2$, ~ 400 kg
- events from Compton and Pair production

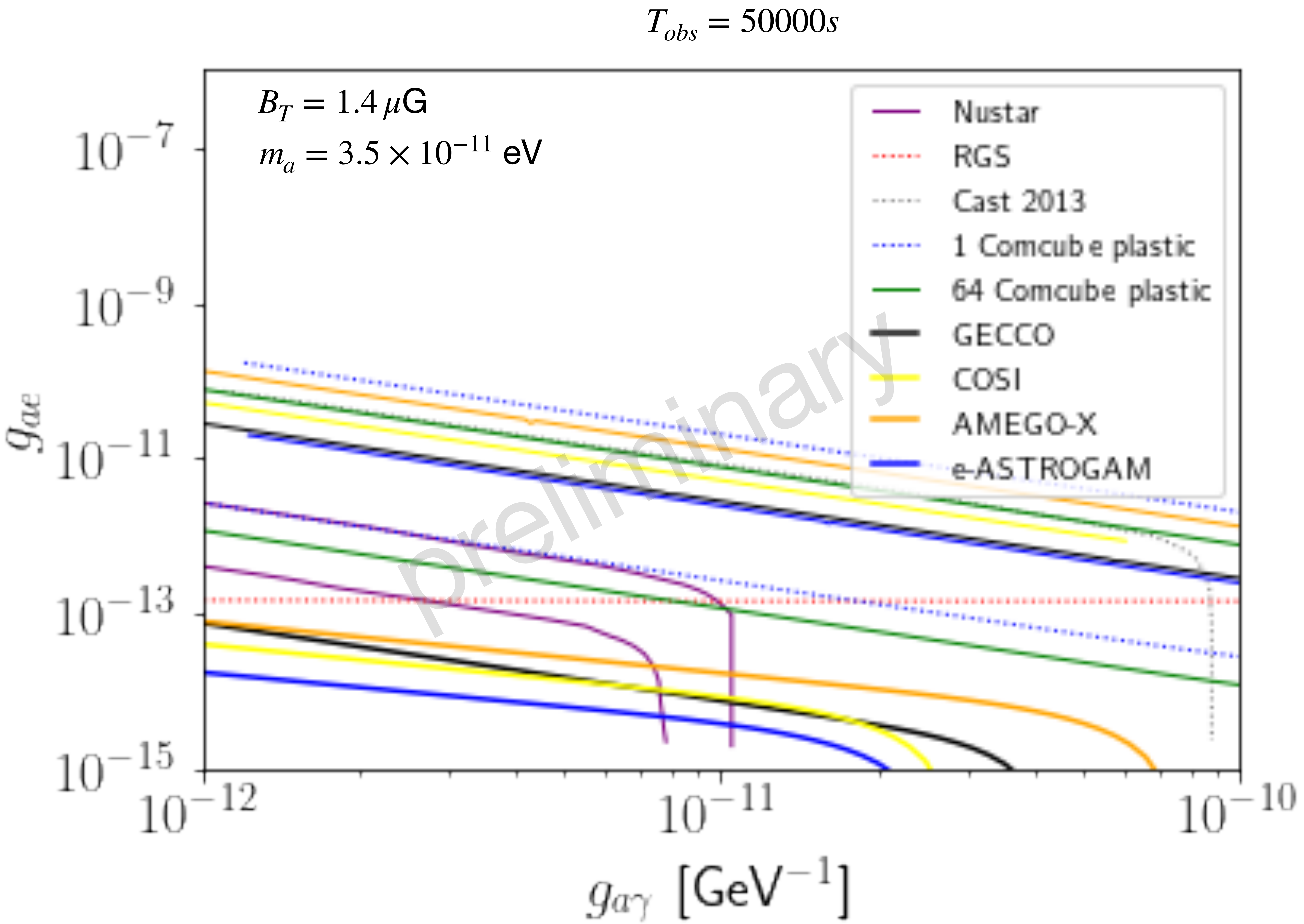



**GECCO ID:**

- proposal NASA mission, Galactic Explorer with a Coded Aperture Mask Compton Telescope
- Compton Telescope + coded aperture mask for photoelectric regime
- $(0.2 < E < 10)$ MeV, angular resolution 1-2 arcmins, $\Delta E/E < 1\,\%$
- effective area $1200$ cm$^2$

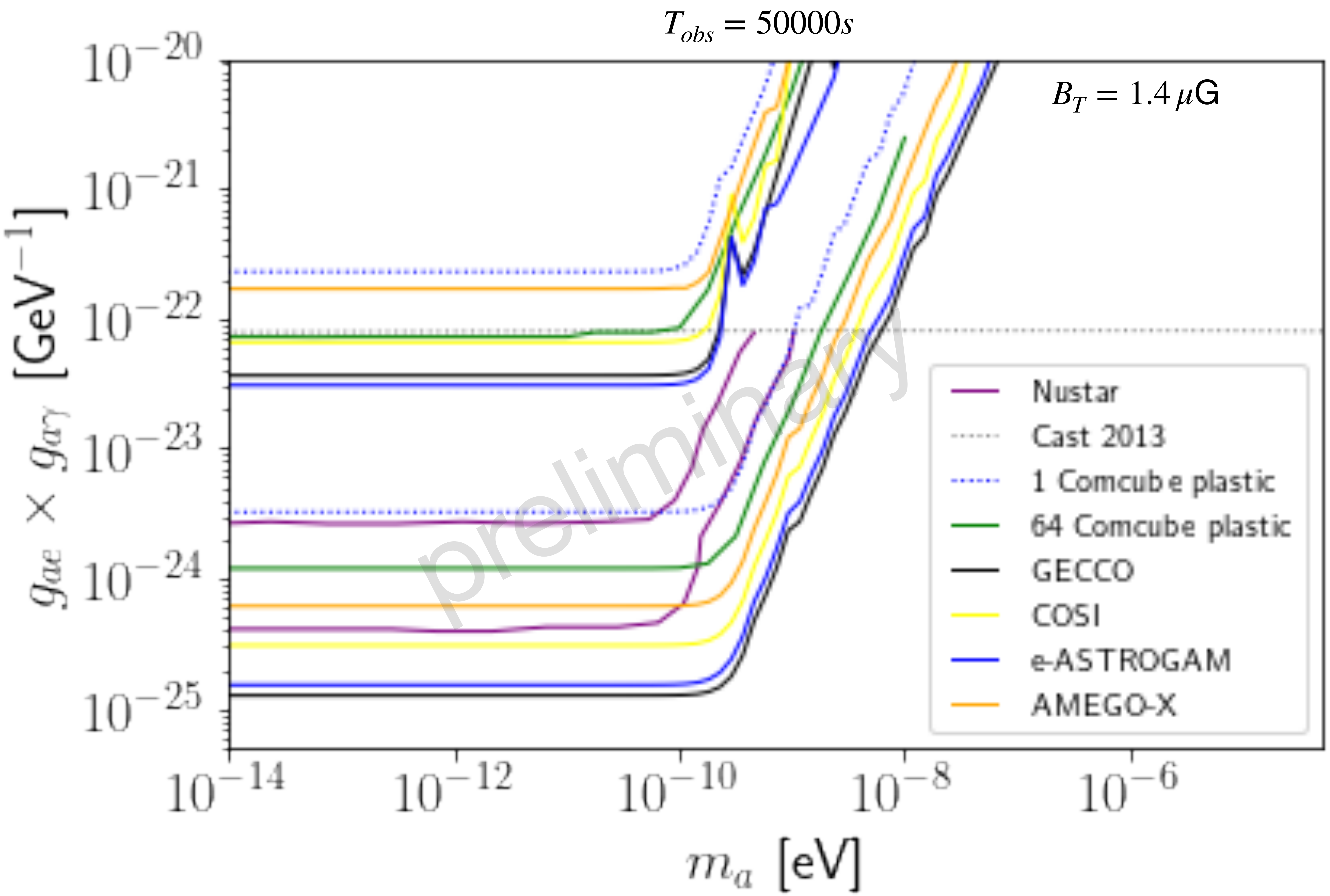
# Constraints and Results

## Astro environment to search ALP signature



# Constraints and Results

## Astro environment to search ALP signature



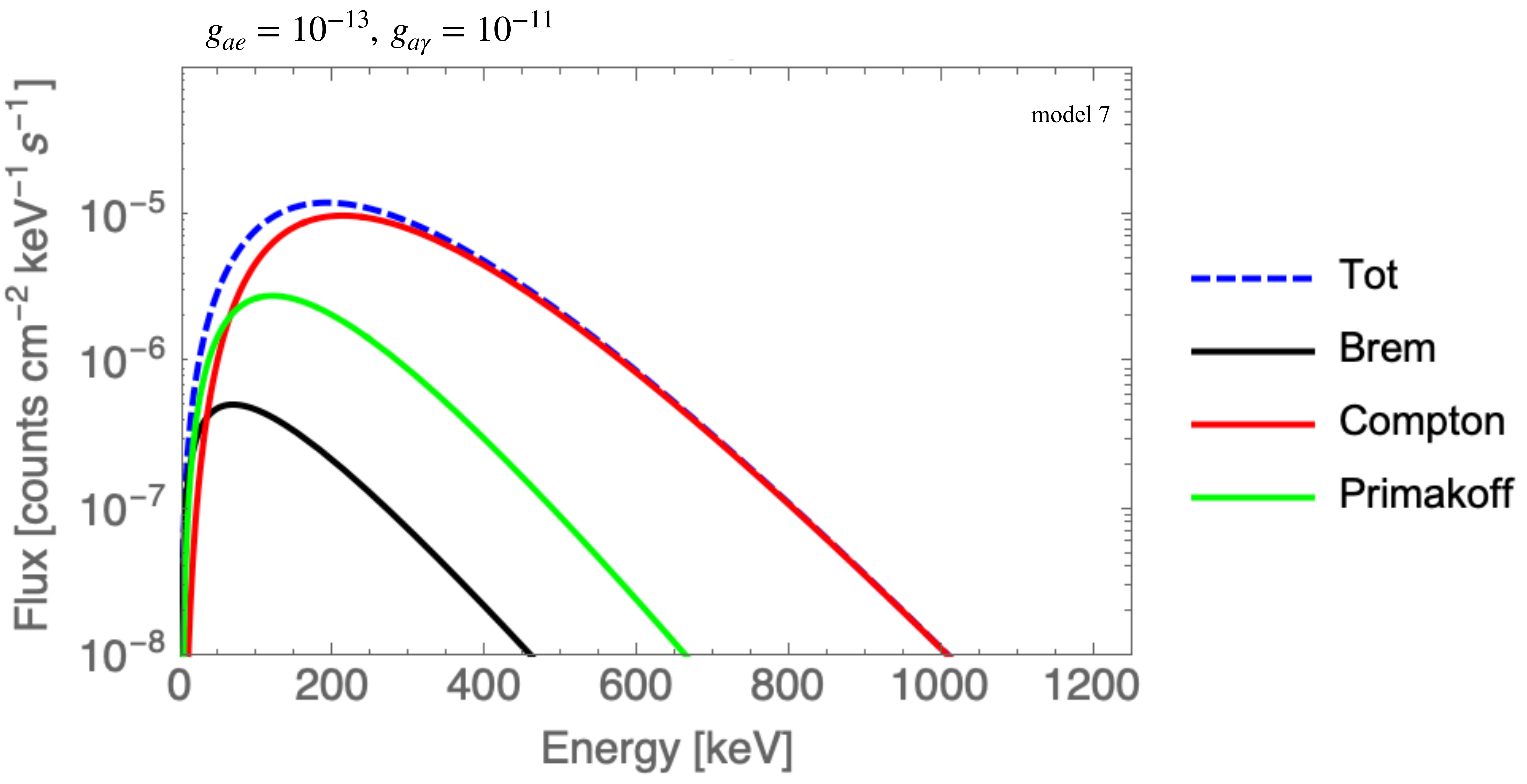
# CONCLUSION

## Astro environment to search ALP signature

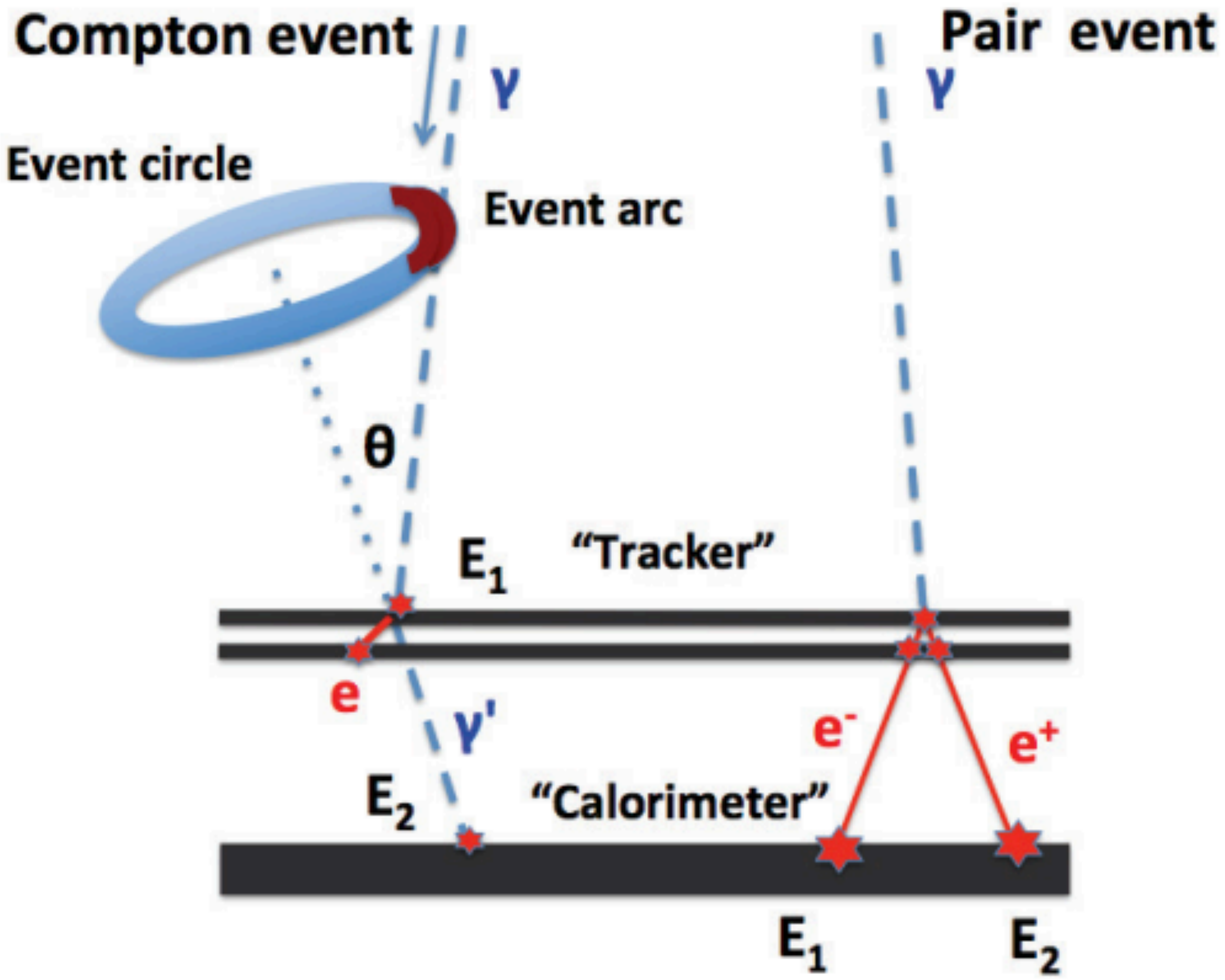
- Stars produce a lot of ALP flux and a several signatures can be detected
- The ALP signal detection could give us informations about the evolutionary stage of Betelgeuse
- What we can learn from our results concerning the best characteristics of an experiment for testing small couplings?
- We really **<u>need</u>** future space-based experiments in MeV range
- *Stay tuned for a space signal*

# BACKUP SLIDES

# Differential Photon flux from ALP conversion



# Compton and Pair production events



# COMCUBE

## Simulation with MEGALib