Recent Results on MeV Dark Matter Candidates

Matterhorn

Antimatterhorn
Darkmatterhorn
?

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5/11, Würzburg Dark Matter Workshop, Würzburg

Light Dark Matter — Overview

- Classically: everything on the mass scale below WIMPs (~GeV—TeV)
  - *MeV scale dark matter*
  - *MeV signatures of dark matter: primary, secondary, tertiary*
- Light dark matter (LDM) particles
  - *Decay into standard model particles*
  - *Annihilation into standard model particles*
- Primordial black holes (PBHs)
  - *Hawking radiation of evaporating black holes into standard model particles*
- Axion-like particles (ALPs)
  - *Conversion into standard model particles via magnetic or electric fields*

→ **Standard model particle products are key to indirect searches!**

Light Dark Matter — Overview

- Measurements:
  - *Photon emission*
  - *Particles (cosmic rays)*
- Light dark matter (LDM) particles
  - *Photon channels: Gamma-ray lines*
  - *Particle channels: Final state radiation (FSR = internal bremsstrahlung)*
- Primordial black holes (PBHs)
  - *Hawking radiation (quasi blackbody plus FSR)*
- Axion-like particles (ALPs)
  - *Secondary interactions! → see WIMPs*
- Weakly Interacting Massive Particles (WIMPs)
  - ***Secondary interactions** of produced electrons/positrons:*
    - *Inverse Compton scattering with CMB, ISRF*
    - *Bremsstrahlung*
    - *Synchrotron radiation*
  - ***Tertiary interactions** of produced electrons/positrons: annihilation! → 511 keV*

Dark Matter Halos

Spatial profile of (Milky Way) halo not (entirely) known:

- *Navarro-Frenk-White (NFW)*
- *Isothermal sphere (ISO)*
- *Einasto profile (EIN)*
- *Burkert profile (BUR)*

General double power law profile

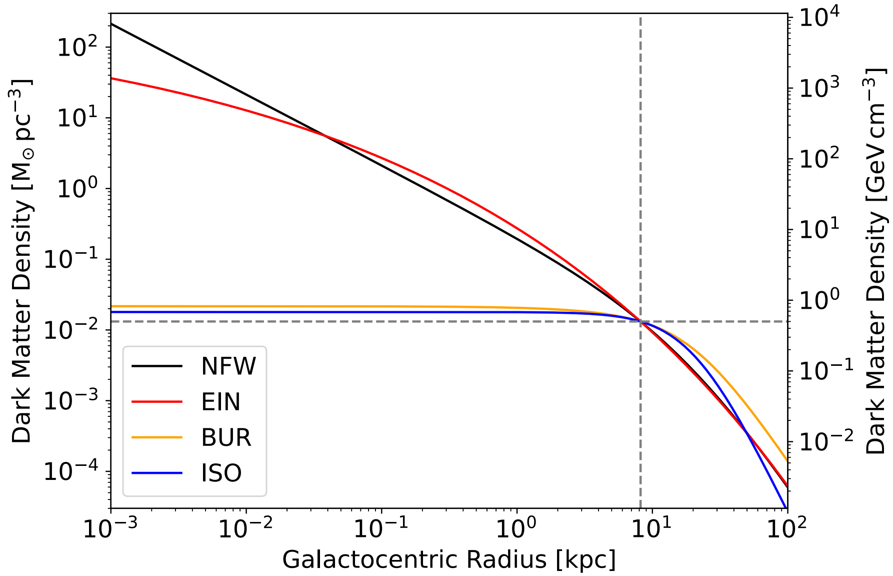
$$\rho_{\text{halo}}(r;\rho_0,r_s,\alpha,\beta,\gamma) = \frac{\rho_0}{\left(r/r_s\right)^{\gamma}\left[1+\left(r/r_s\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

$$\rho_{\text{NFW}}(r;\rho_0,r_s,\alpha=1,\beta=3,\gamma=1) = \frac{\rho_0}{\left(r/r_s\right)\left[1+\left(r/r_s\right)\right]^{2}}$$

$$\rho_{\text{ISO}}(r;\rho_0,r_s,\alpha=2,\beta=4,\gamma=0) = \frac{\rho_0}{\left[1+\left(r/r_s\right)^{2}\right]^{2}}$$

$$\rho_{\text{EIN}}(r;\rho_0,r_s,\alpha) = \rho_0 \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right)$$

$$\rho_{\text{BUR}}(r;\rho_0,r_s) = \frac{\rho_0 r_s^3}{\left(r_s+r\right)\left(r_s^2+r^2\right)}$$



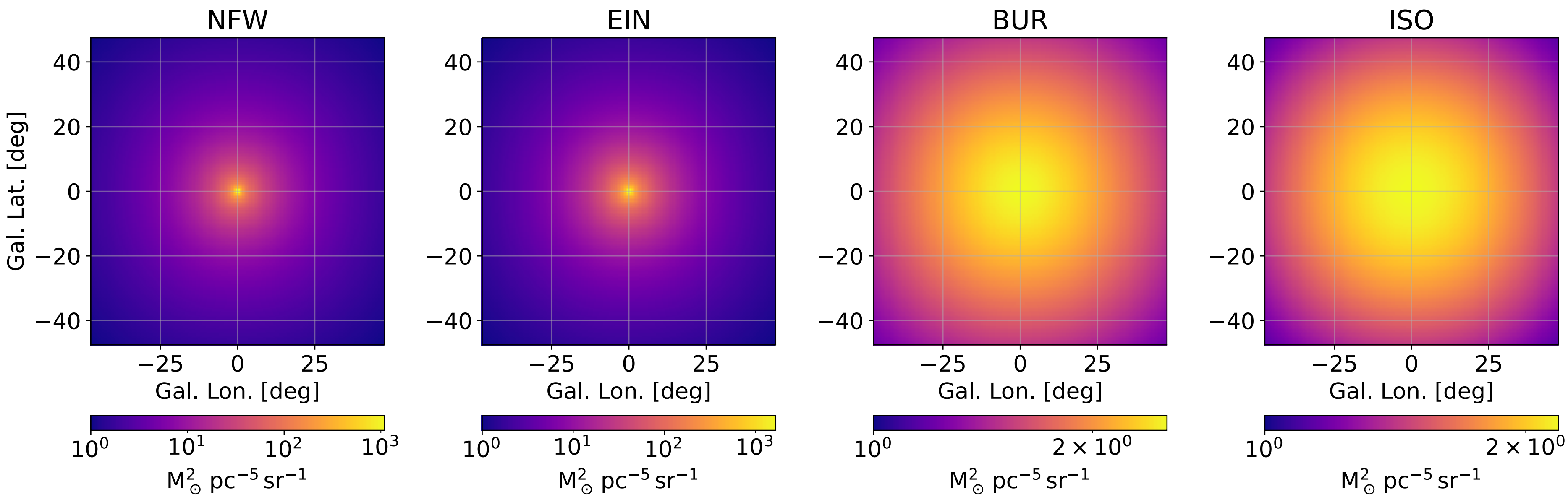
Dark Matter Halos

Spatial profile of (Milky Way) halo not (entirely) known:

- *Navarro-Frenk-White (NFW)*
- *Isothermal sphere (ISO)*
- *Einasto profile (EIN)*
- *Burkert profile (BUR)*

Line of sight integration (J-factor):
n=1: decay / evaporation
n=2: annihilation / de-excitation

$$J = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{0}^{+\infty} \rho^n(s)\, ds\, d\Omega$$



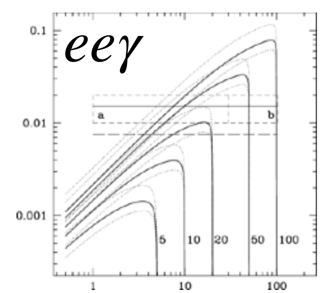
Dark Matter Spectra — Primary emission

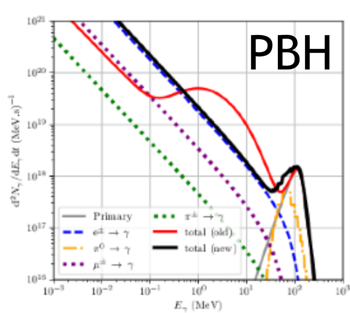
- Spectral shapes of decaying/annihilating/evaporating/de-exciting assumed to be known (calculated from theory): **primary emission**
  - ***Photon-photon*** *($\gamma\gamma$, also photon-Y) final state (gamma-ray line)*
  - *Any standard model particles*
    (goes to pions, electrons, positrons, neutrinos(!))
    - *pion bump (photon spectrum peak ~1/20 m_{DM})*
    - ***internal bremsstrahlung*** *($ee\gamma$, cut off around m_{DM})*
  - ***Hawking radiation*** *(BH, any standard model particle)*
    - *quasi-thermal spectrum peaking according to temperature of black hole*
    - *similar spectrum of each particle (modulo rest mass)*

$$\left(\frac{dN}{dE}\right)_{\gamma\gamma} = \delta(E - m_{\rm DM})$$

$$\left(\frac{dN}{dE}\right)_{ee\gamma} = \frac{\alpha}{\pi}\left[\frac{(2m_{\rm DM})^2 + (2m_{\rm DM} - E)^2}{(2m_{\rm DM})^2 E}\ln\left(\frac{2m_{\rm DM}(2m_{\rm DM} - E)}{m_e^2}\right)\right]$$

$$\left(\frac{dN}{dE}\right)_{\rm BH} = \frac{1}{2\pi}\frac{\Gamma_i(E_i, M_{\rm BH})}{\exp\left(\frac{E_i}{T_{\rm BH}}\right) - (-1)^{2s_i}}$$

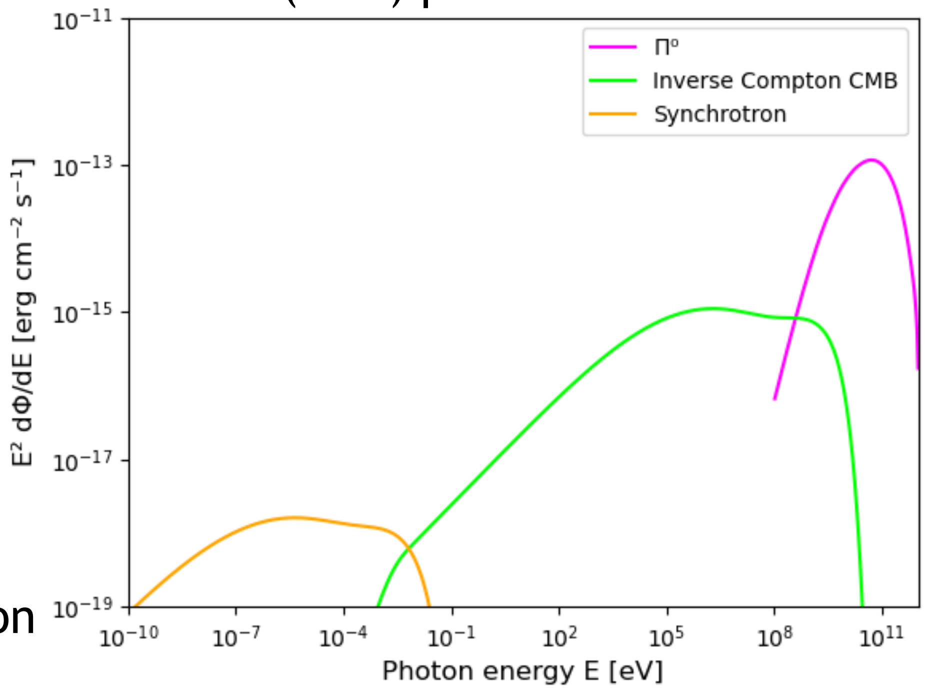




Dark Matter Spectra — Secondary emission

- Spectral shapes of decaying/annihilating/evaporating/de-exciting assumed to be known (calculated from theory): **secondary emission**
  - ***Inverse Compton scattering*** *of produced electrons/positrons*
    - *Interaction with CMB and ISRF*
  - ***Synchrotron radiation***
    - *Interaction with magnetic field*
  - *Bremsstrahlung*
    - *Interaction with (dense) gas and electrons*

m_{DM} = 1.1 TeV
IC (CMB) peaks at 1–10 MeV!



See talk by **Laura Eisenberger** (Friday)!

$$\frac{d\Phi_{\mathrm{IC}\gamma}}{dE_\gamma\, d\Omega} = \frac{1}{E_\gamma} \int_{\mathrm{l.o.s.}} ds\, \frac{j(E_\gamma, r(s,\theta))}{4\pi}$$

$$j(E_\gamma, r) = 2 \int_{m_e}^{M_{\mathrm{DM}}(/2)} dE_e\, \mathcal{P}_{\mathrm{IC}}(E_\gamma, E_e, r)\, \frac{dn_{e^\pm}}{dE_e}(r, E_e)$$

Includes assumptions / approximations on cosmic-ray electron propagation!

Dark Matter Spectra — Tertiary emission

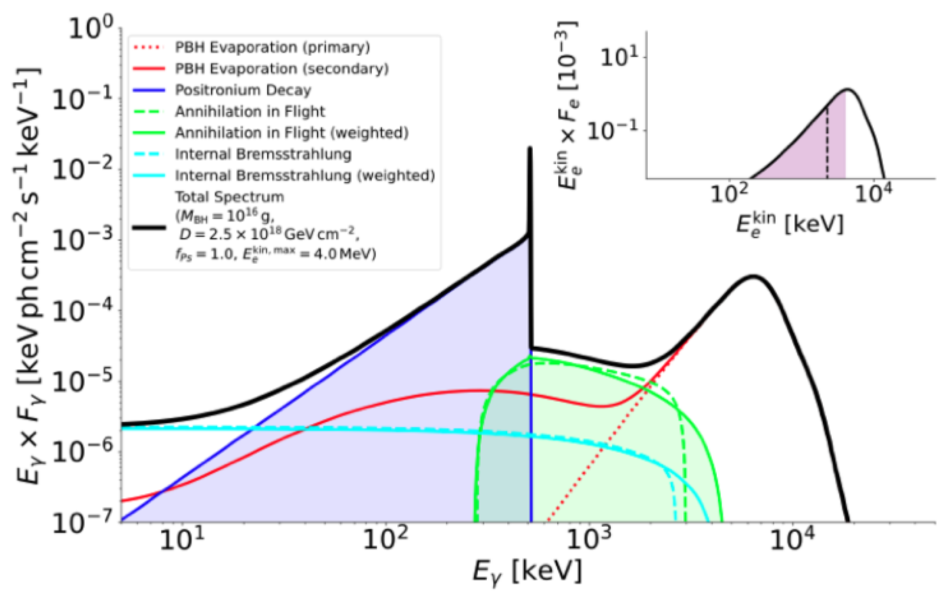
- Spectral shapes of decaying/annihilating/evaporating/de-exciting assumed to be known (calculated from theory): **tertiary emission**
  - ***Positron annihilation*** *of produced electrons/positrons*
    - *In-flight annihilation (cutoff around mDM)*
    - *Positronium formation (511 keV line and ortho-Ps continuum)*
  - *Applies to all(!) dark matter candidates*

Requires strong assumptions on low-energy cosmic-ray electron/positrons propagation!

The details for this are unknown.

→ 511 keV line serves as bound to dark matter models (and many many other things)!

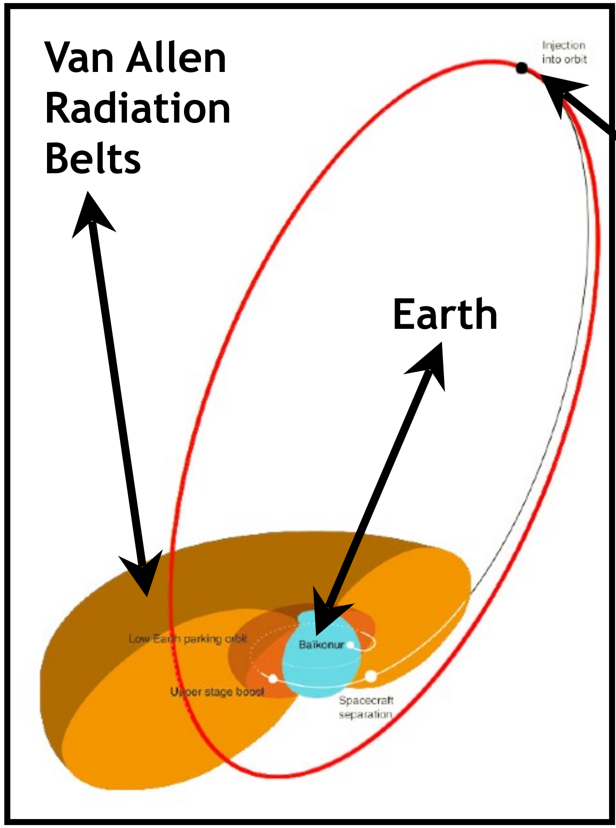
Primary and tertiary emission from PBH evaporation in Reticulum (Siegert et al. 2021)

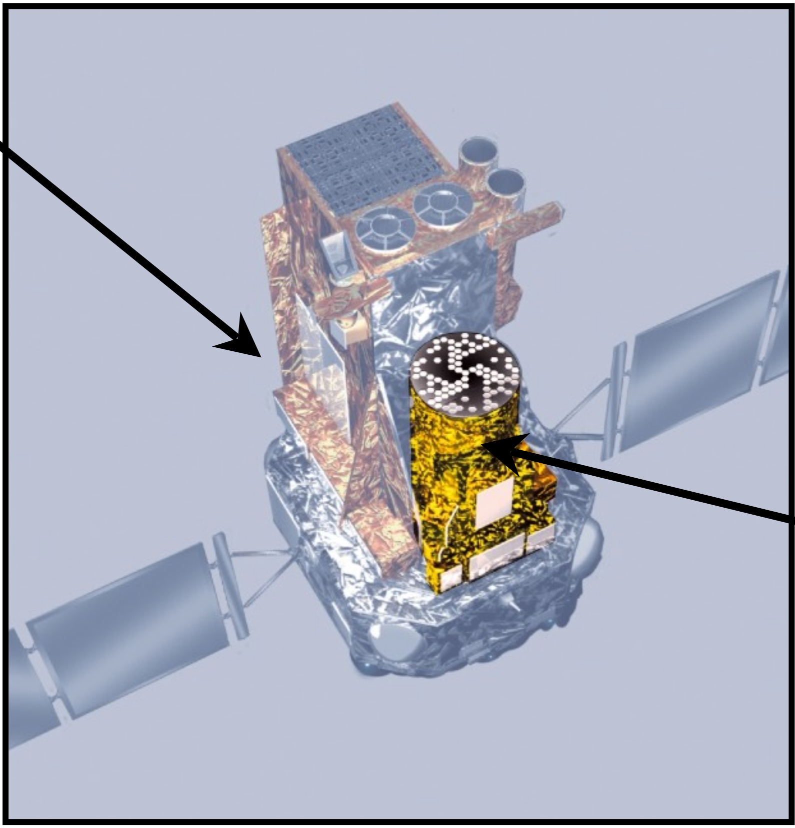


INTEGRAL Mission and Orbit

SPI on INTEGRAL (2002–2029)

INTErnational Gamma-Ray Astrophysics Laboratory





Mission:

2002 – still active!

Orbit:

3 days

High inclination

High eccentricity

Payload:

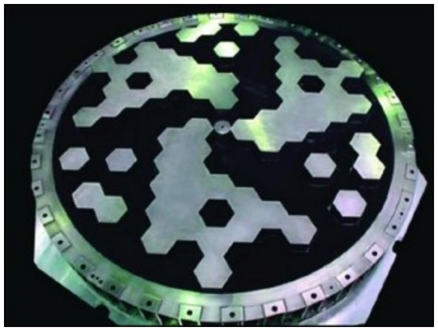
4 instruments:

- **SPI**
- IBIS
- JEM-X
- OMC

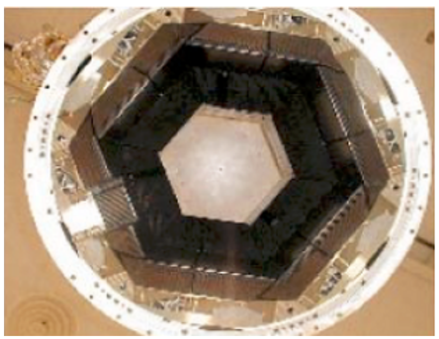
Measuring Gamma-Rays with SPI/INTEGRAL

Coded-mask spectrometer telescope

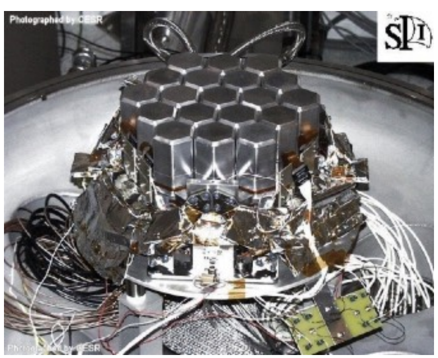
W Mask



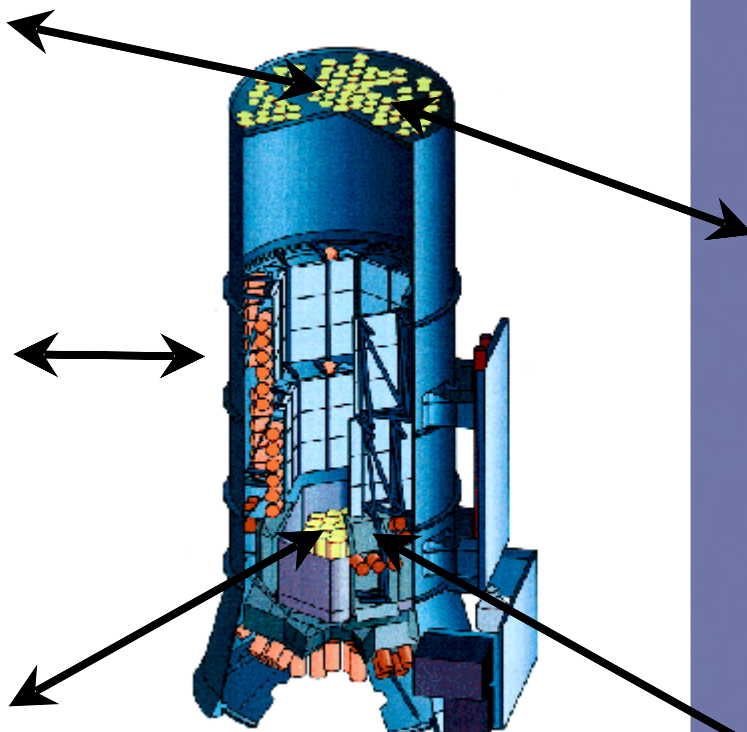
BGO Antico-incidence shield

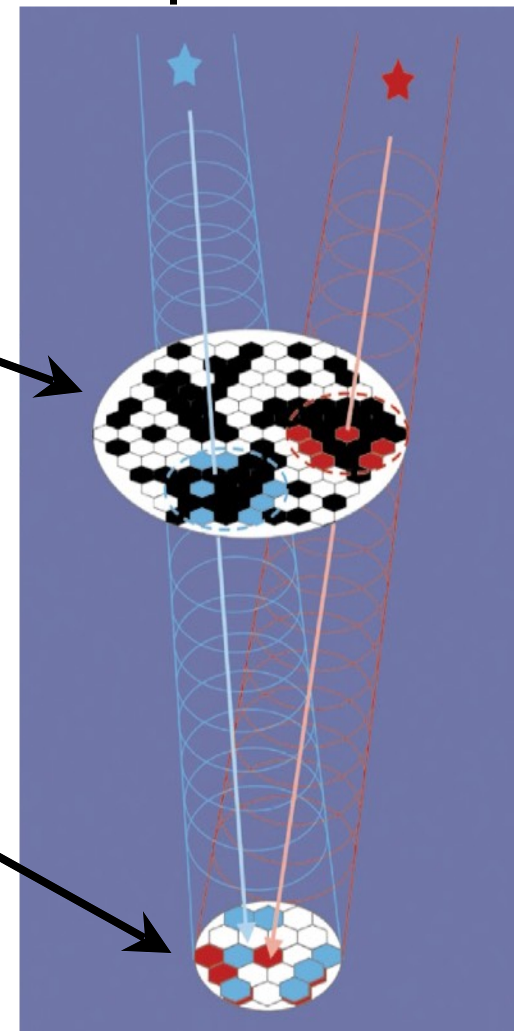


HPGe detectors



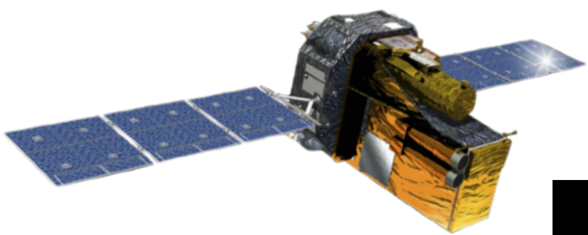
SPI

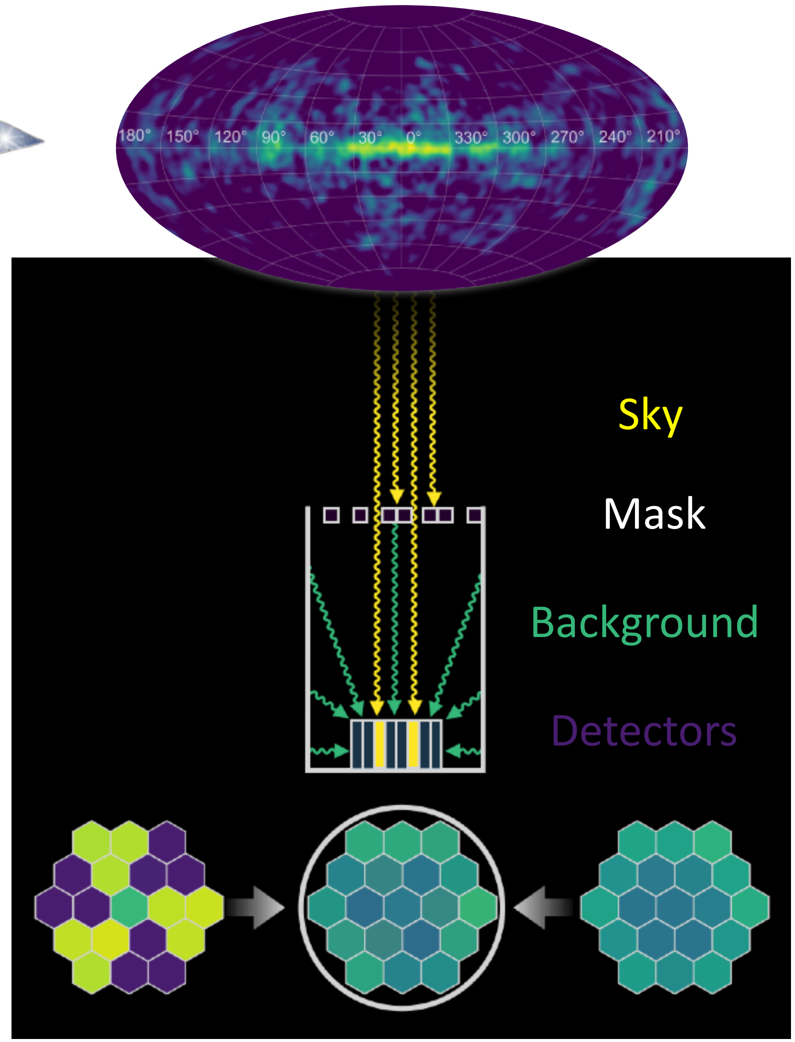


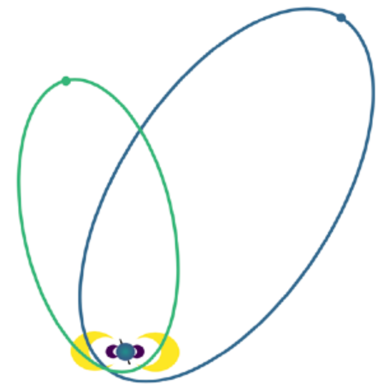


How to Measure MeV Gamma-Rays?

Example: Coded-Mask Telescope INTEGRAL/SPI





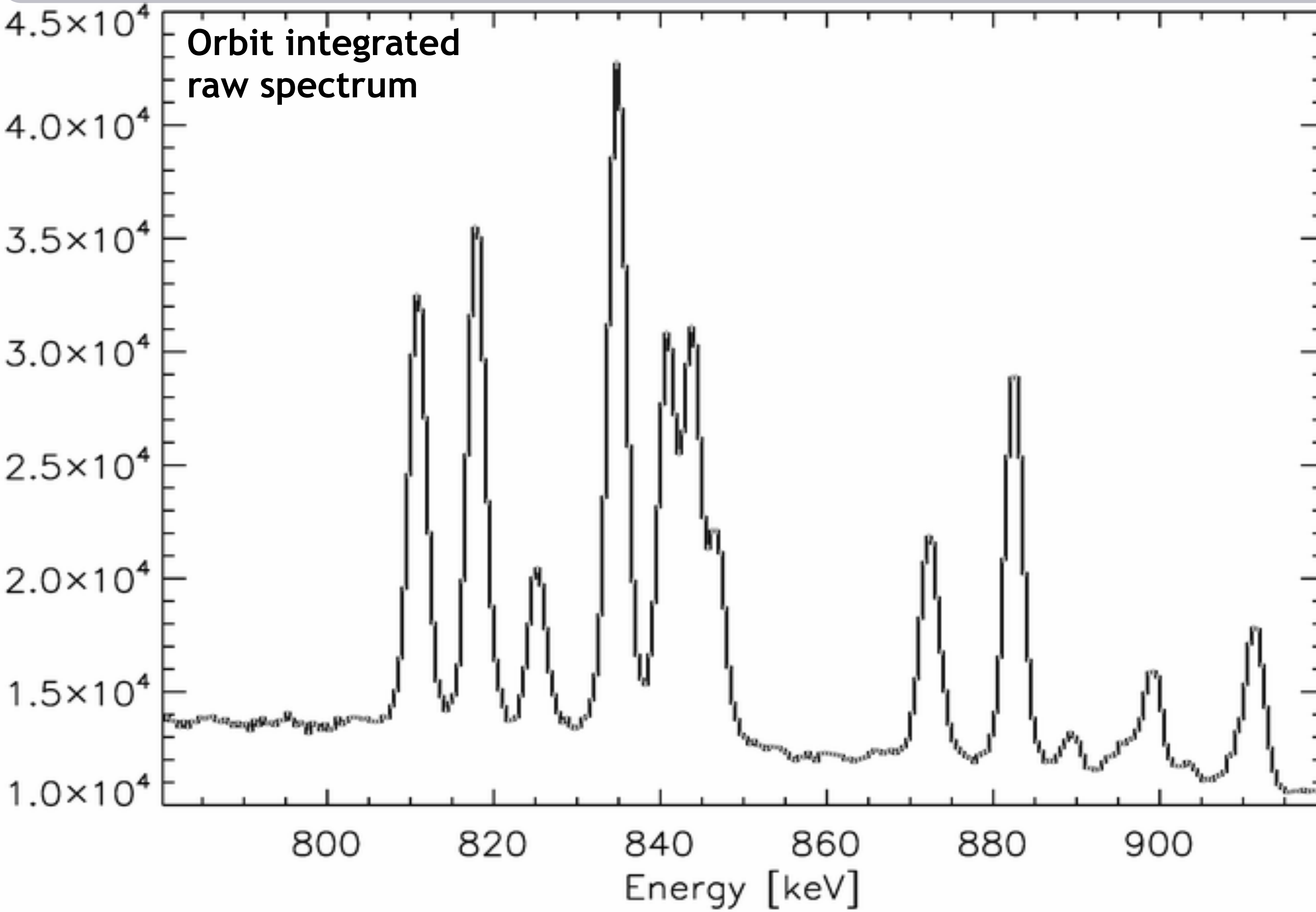


INTEGRAL/SPI:
20–8000 keV
3.1 keV FWHM @ 1.8 MeV
2.7 deg resolution
2002–2029
lots (lots!) of background

Patterns from the sky

Patterns from the background

How to treat large background?



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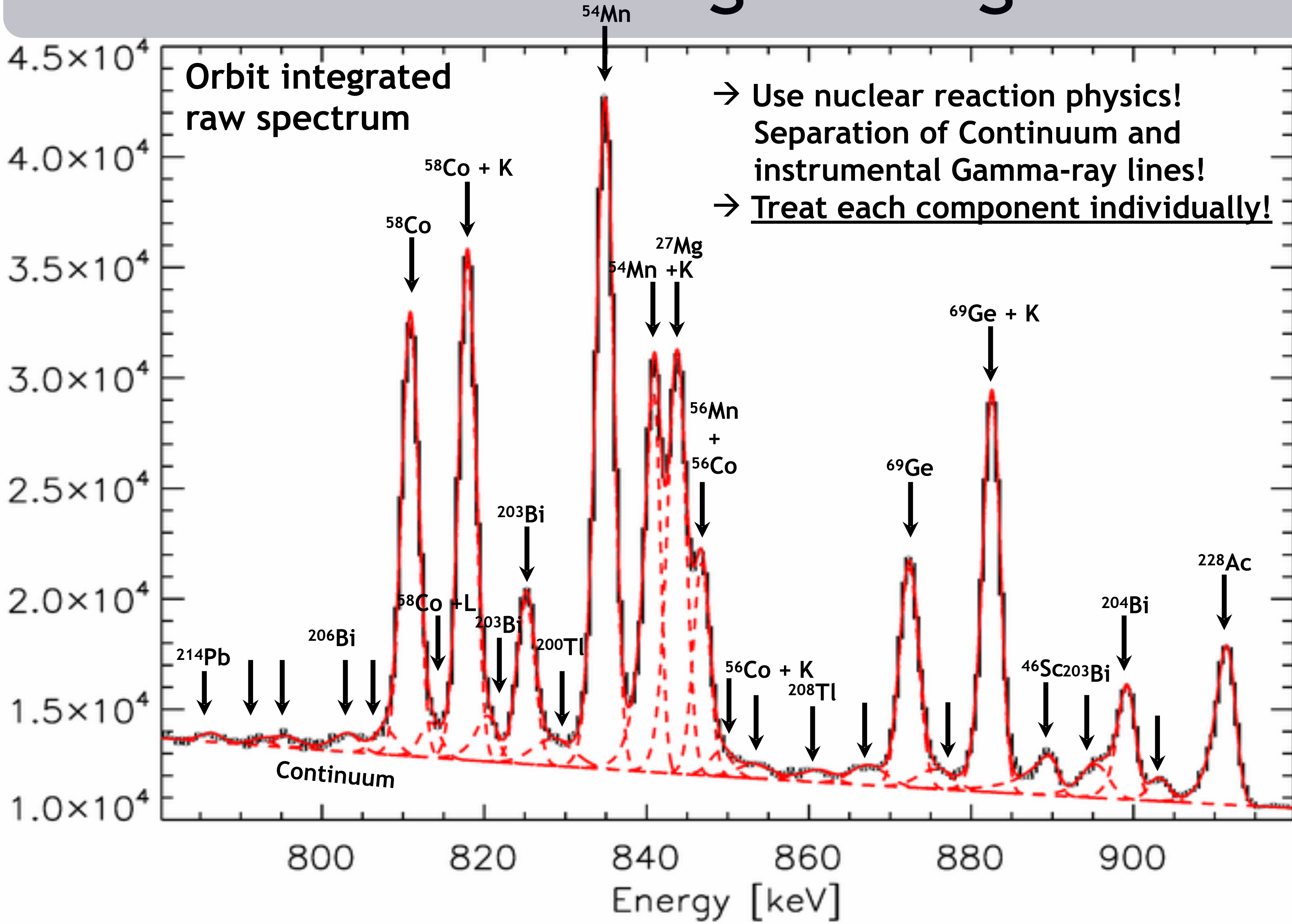
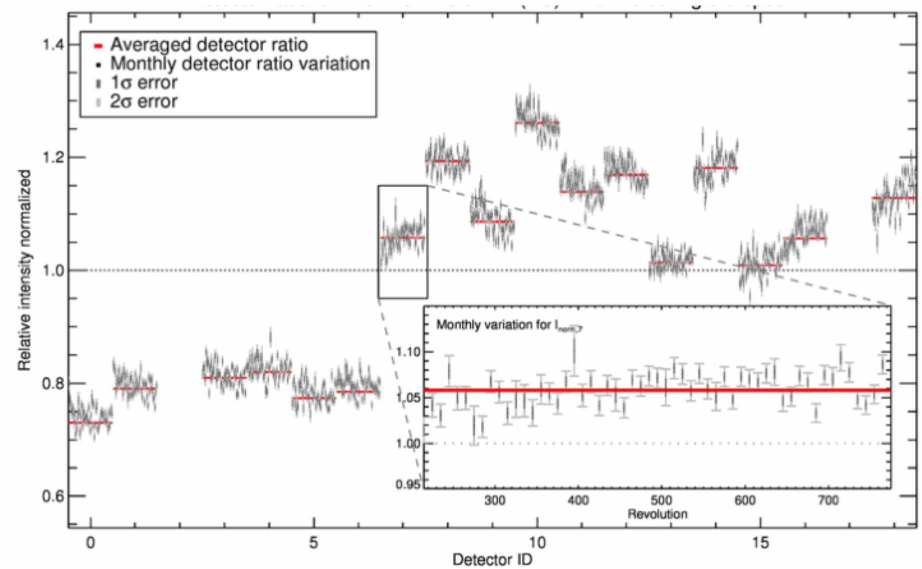


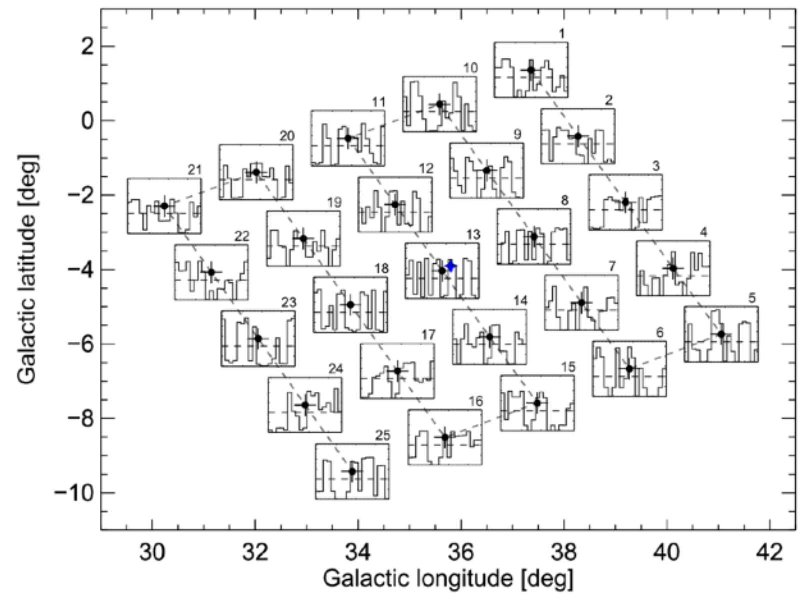
How to measure celestial gamma-rays?

Difference between background and sky: detector pattern!

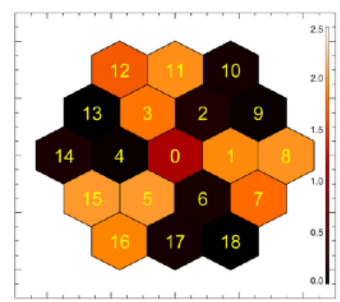
Background pattern Siegert et al. (2018)

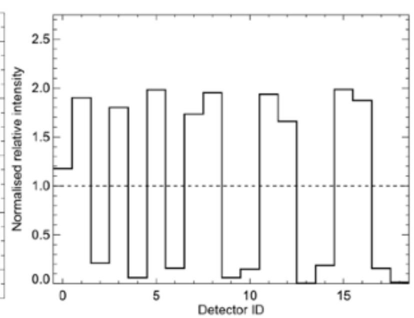


Patterns in the sky …



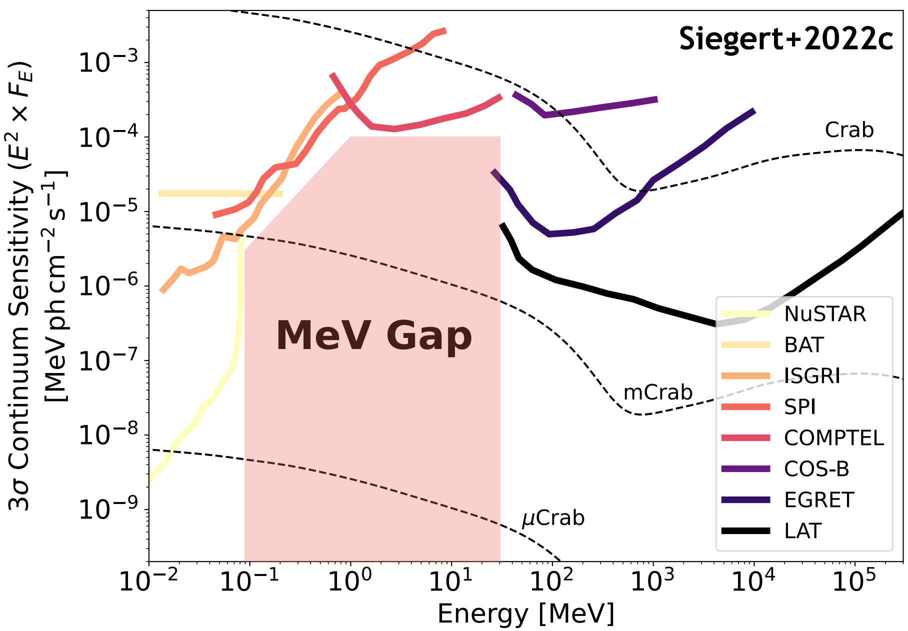
Use constancy (BG) / variation (SKY) of detector patterns to discriminate and determine intensities!



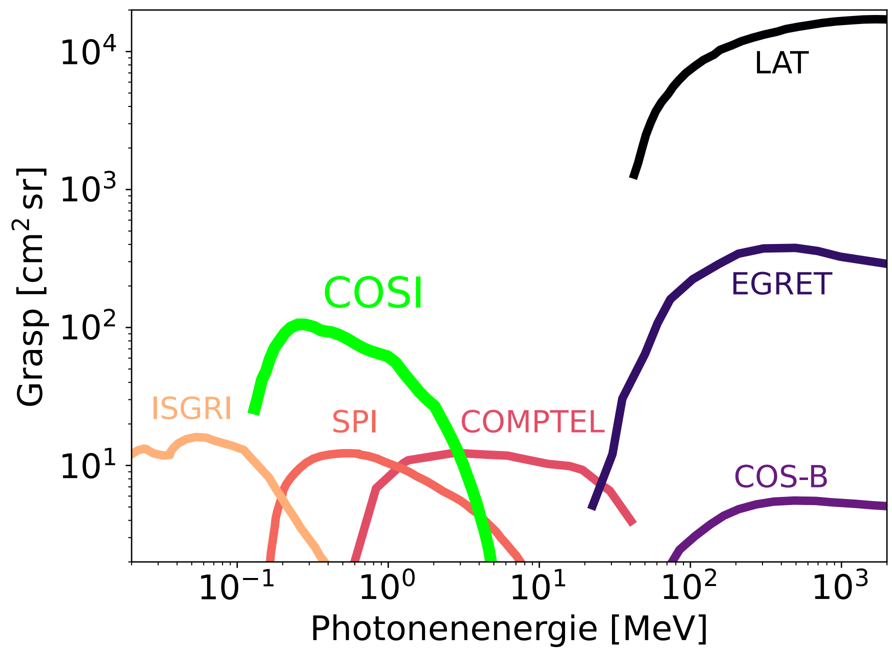


The Future of MeV Astrophysics

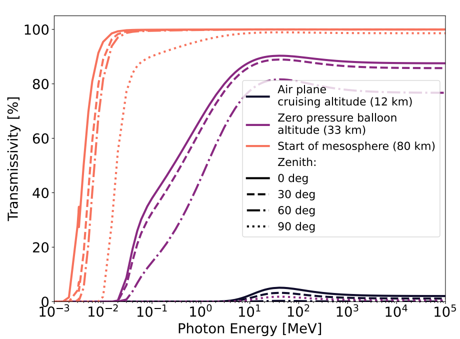
MeV sensitivity gap now



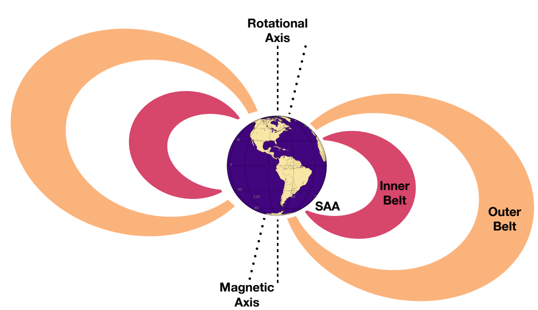
Capabilities of future (2027!)



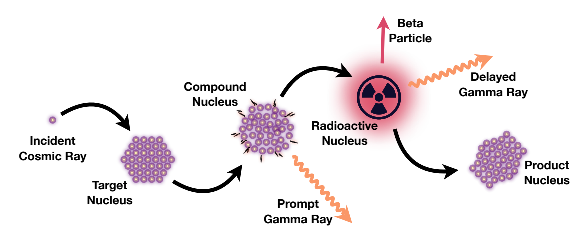
Atmospheric transmissivity



Van-All radiation belts



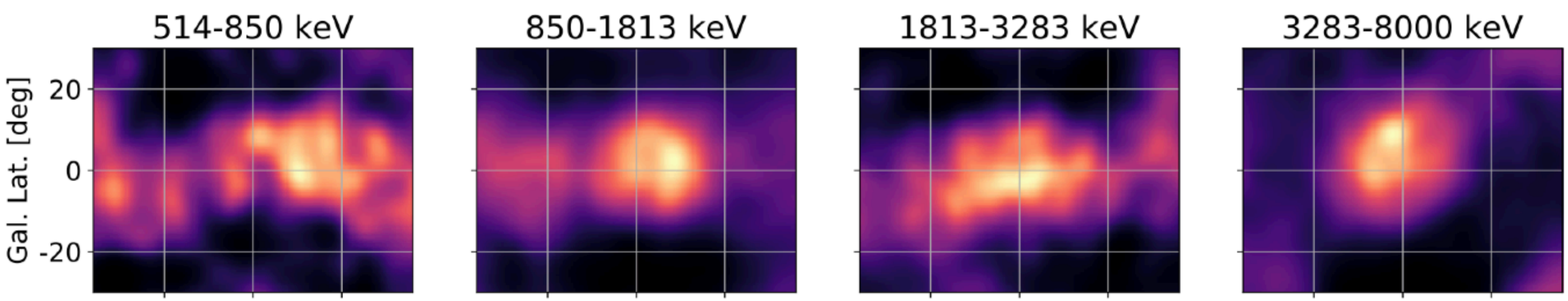
Nuclear excitation



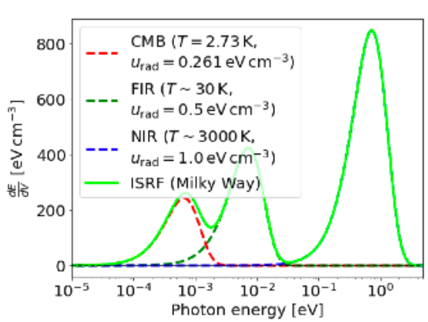
Astrophysical Back- and Foreground

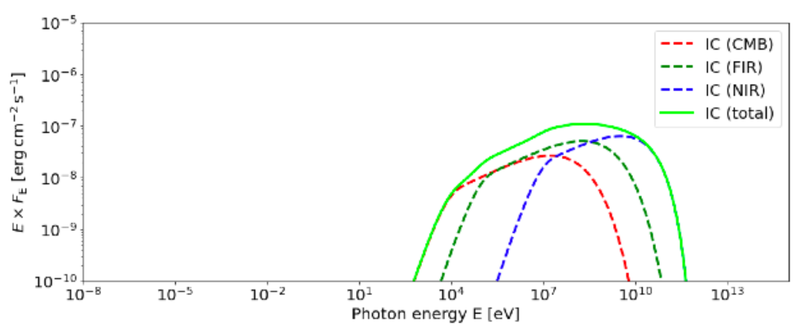
- Dark matter is probably hidden in a multitude of "astrophysical", i.e. "understood", emission components: **MeV range**
  - ***Inverse Compton*** *scattering: electrons + ISRF (CMB, stars, …) → IC*

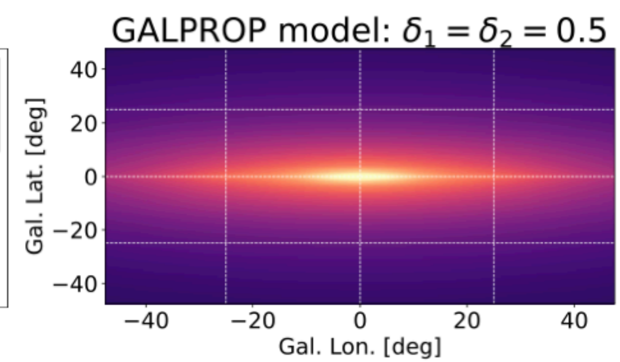
Measurements with INTEGRAL/SPI (Siegert et al. 2022)



Modelling IC emission







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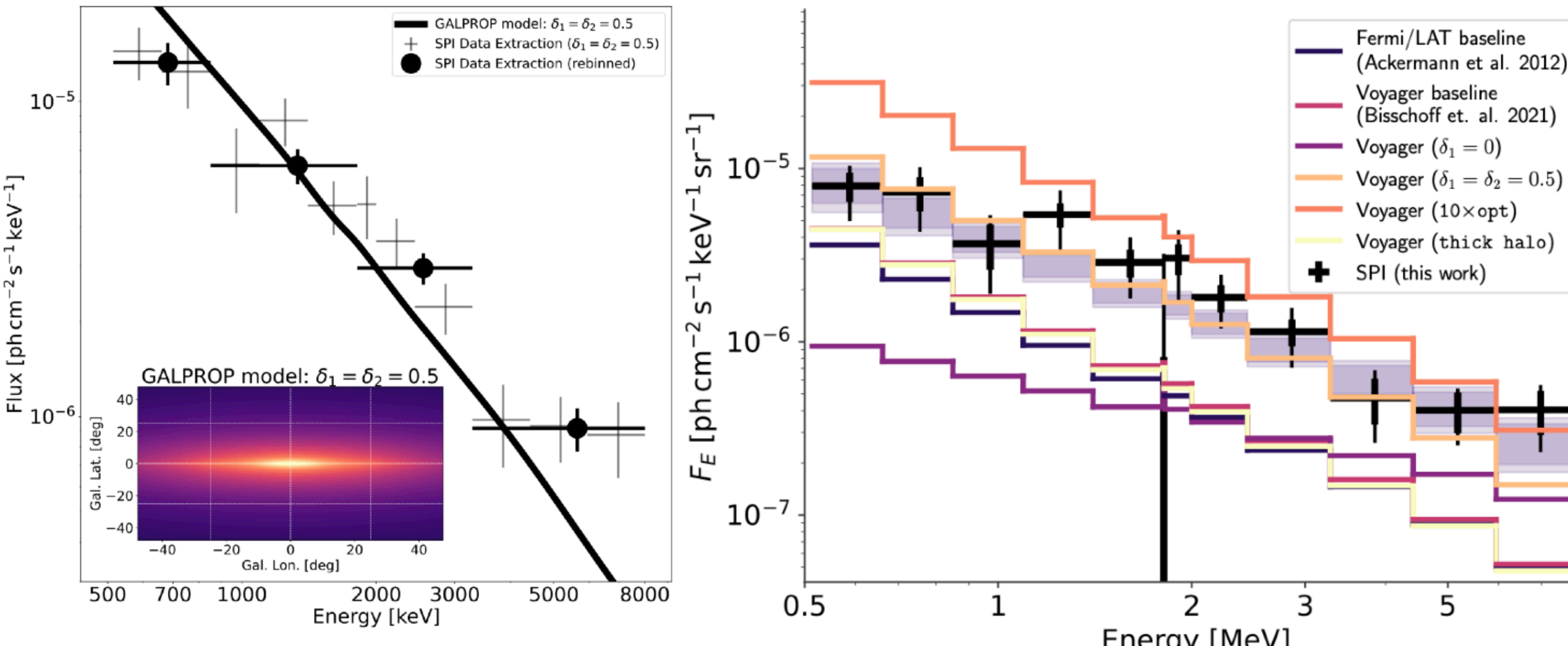

Astrophysical Back- and Foreground

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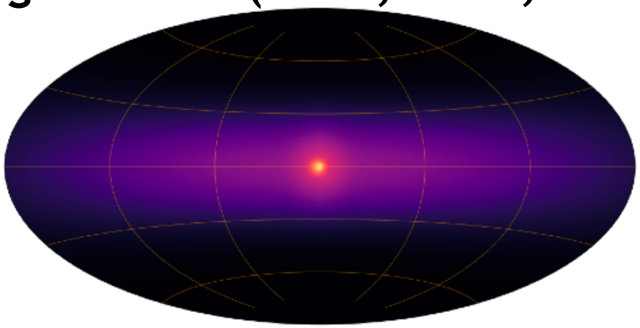
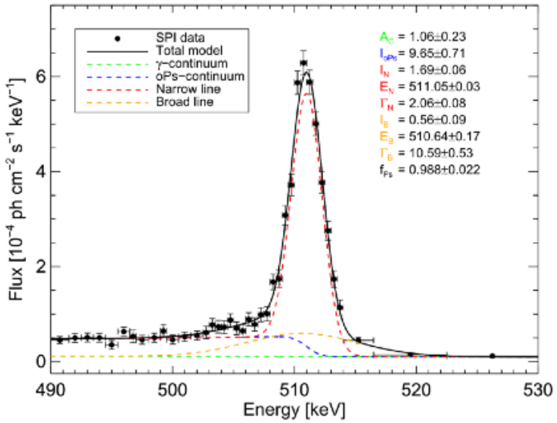
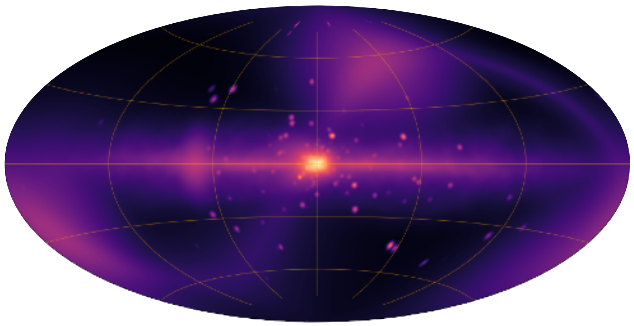
  - ***Positron annihilation:*** *electrons + positrons → ≥ 2 photons*

Measurements with INTEGRAL/SPI
Siegert et al. (2016, 2019, 2022)





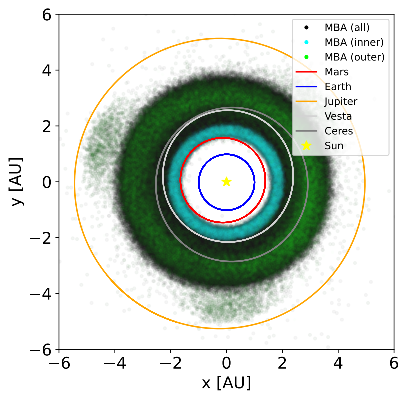
Modelling 511 keV emission

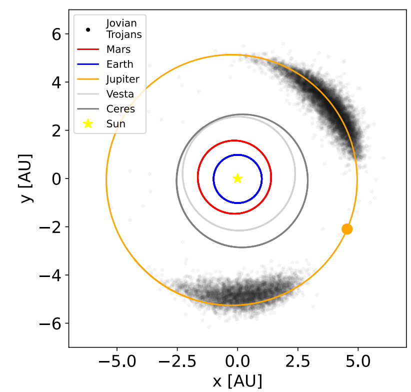


Sources:
Nucleosynthesis
XRBs / Microquasars
Stellar flares
Asteroids
…
Propagation:
Generic (needs refinement!)

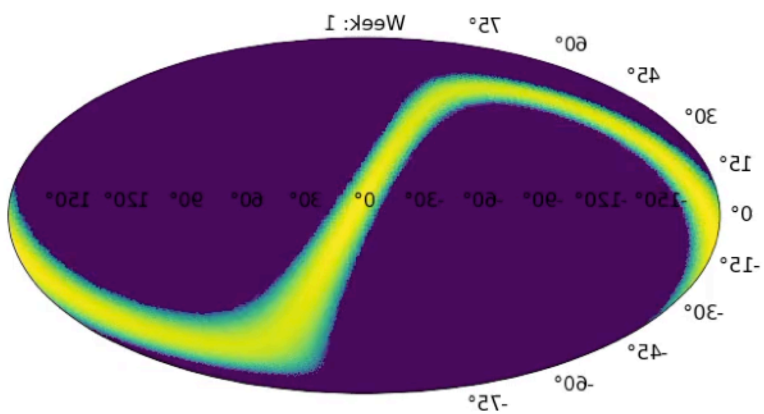
Astrophysical Back- and Foreground

- Dark matter is probably hidden in a multitude of "astrophysical", i.e. "understood", emission components: **MeV range**
  - *Cosmic-ray excitation (example: solar system): CR + anything → photons*

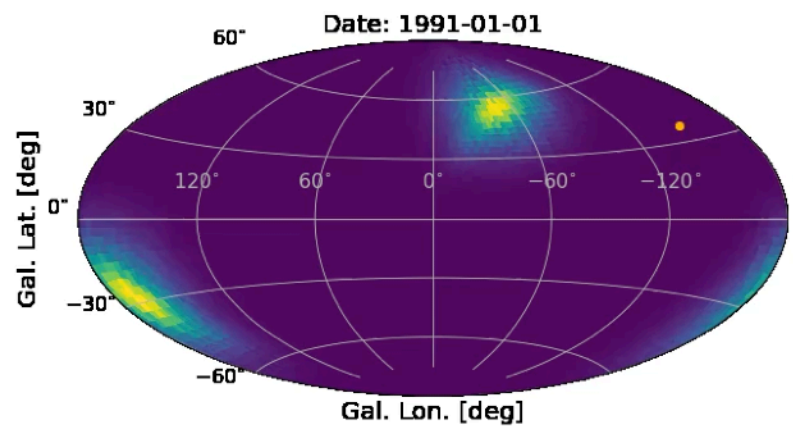




Main Belt Asteroids: variation in 1 yr



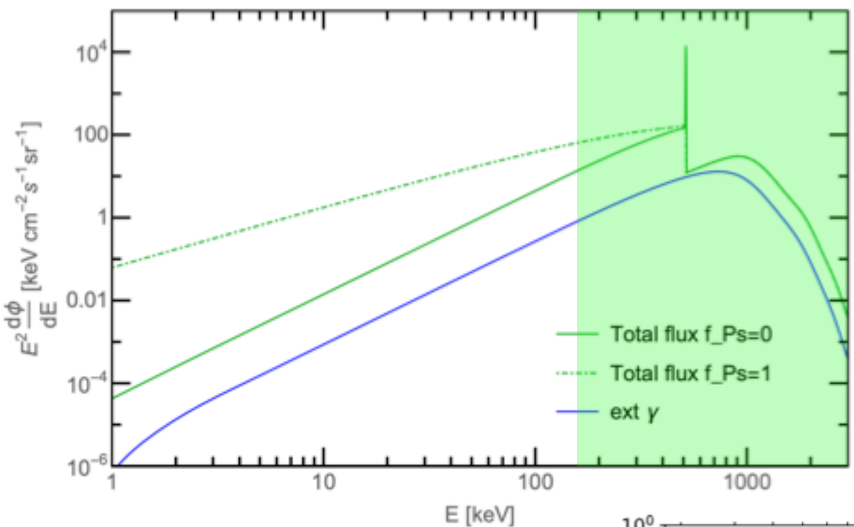
Jovian Trojans: variation in 7 yr



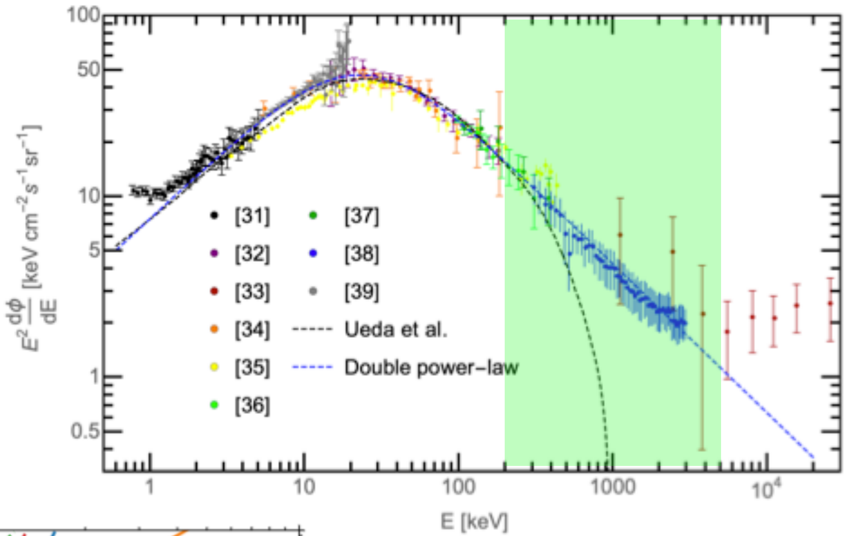
Primordial Black Hole Dark Matter

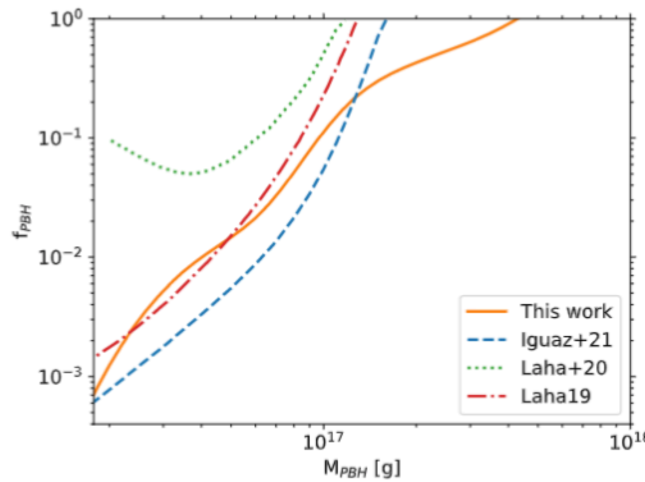
Cosmic Gamma-ray Background (Iguaz, Serpico, Siegert 2021)

Model



Measurements

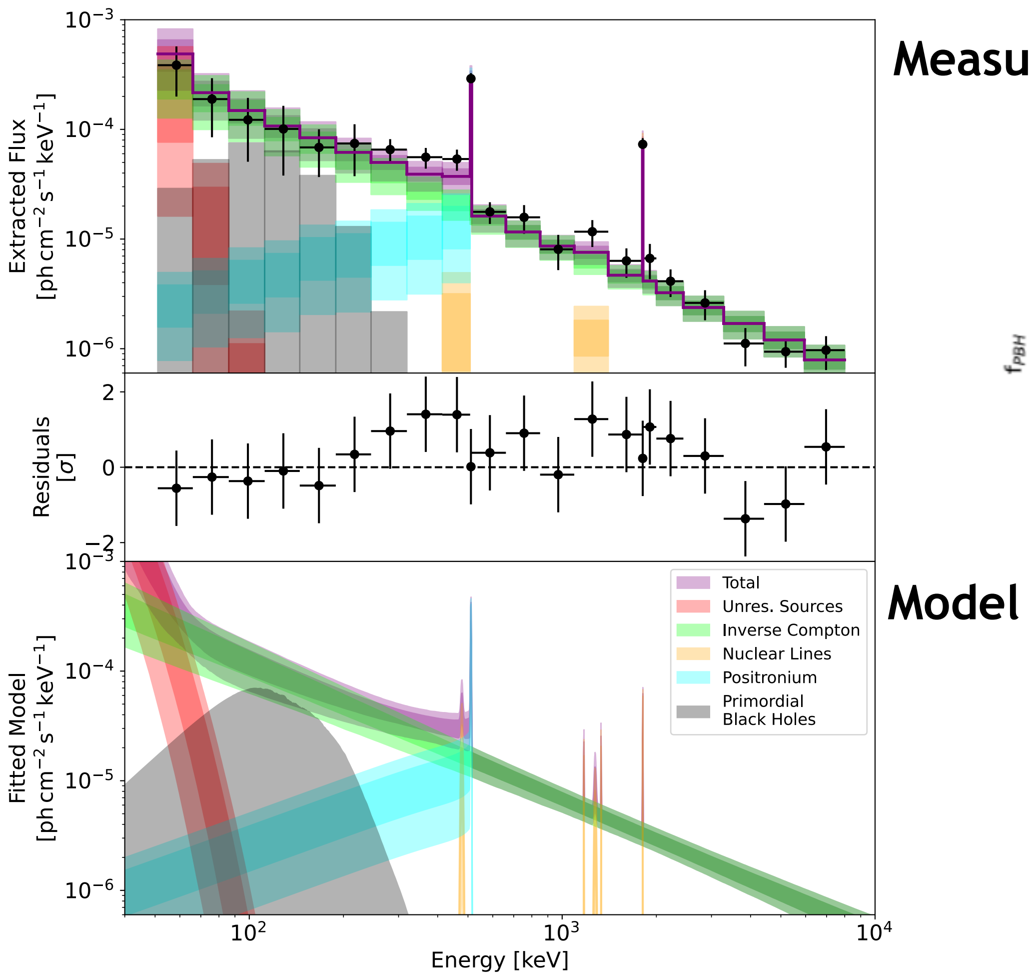


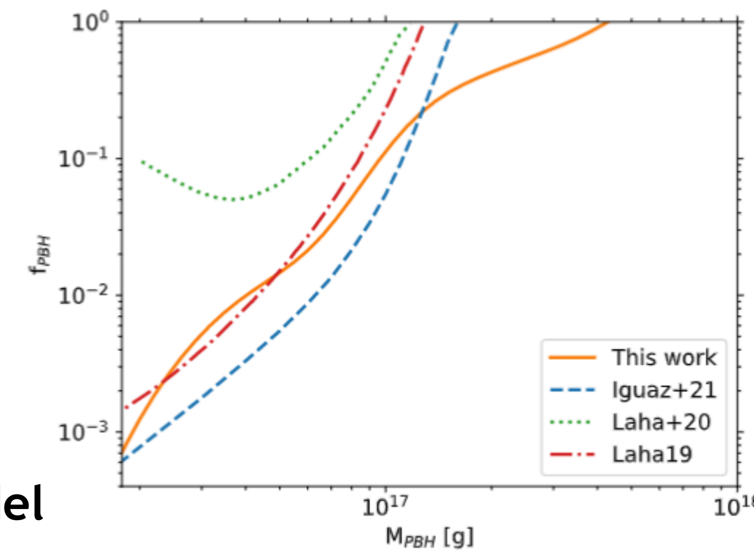


Can exclude PBH masses up to ~2×10^{17} g to explain 100% of dark matter!

Primordial Black Hole Dark Matter

Milky Way Halo (Berteaud, Calore, Siegert, et al. 2022)

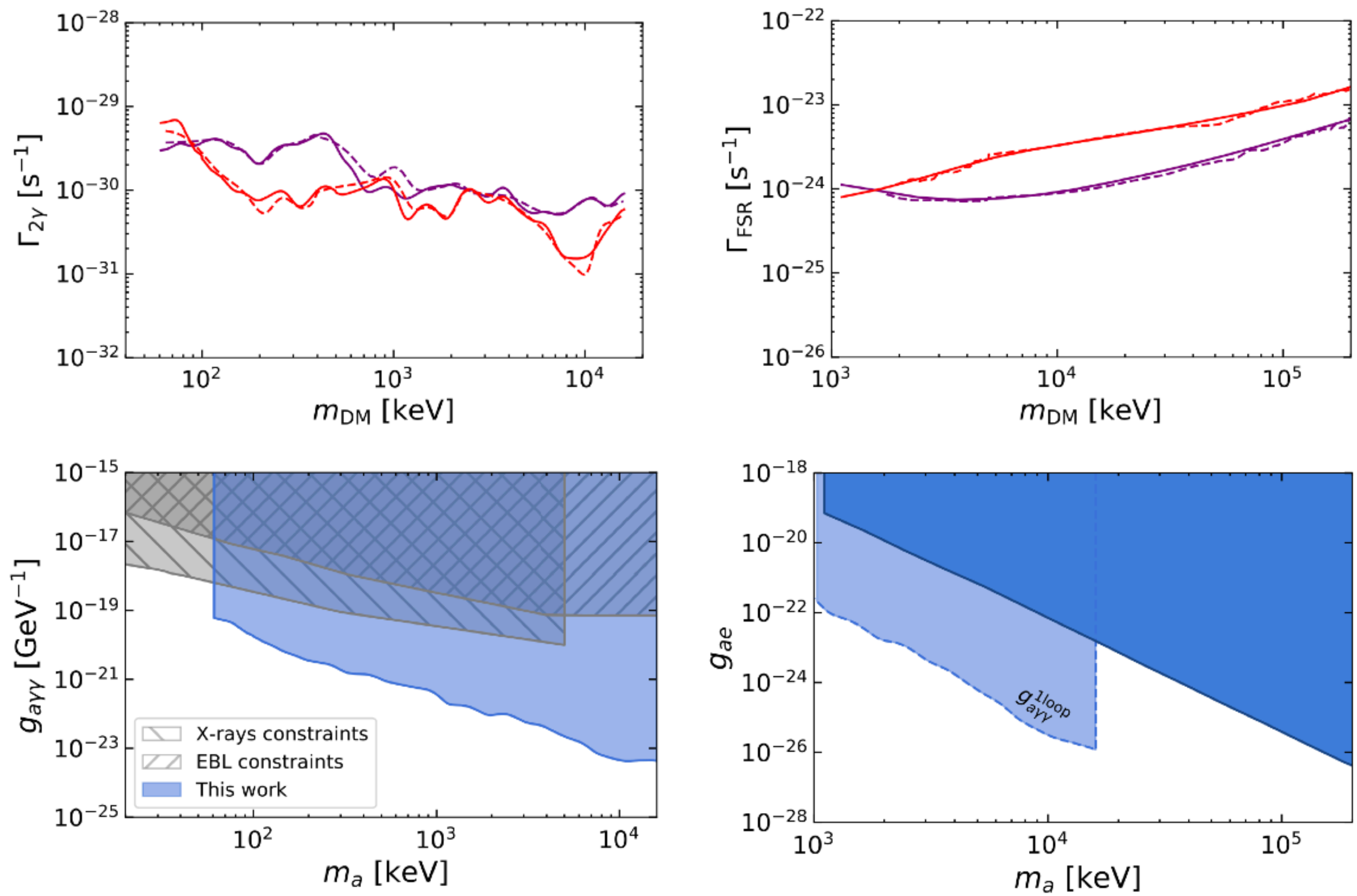




Can exclude PBH masses up to ~4×10^{17} g to explain 100% of dark matter!

Light Particle Dark Matter Decay

Milky Way Halo (Calore, Dekker, Siegert, et al. 2023)

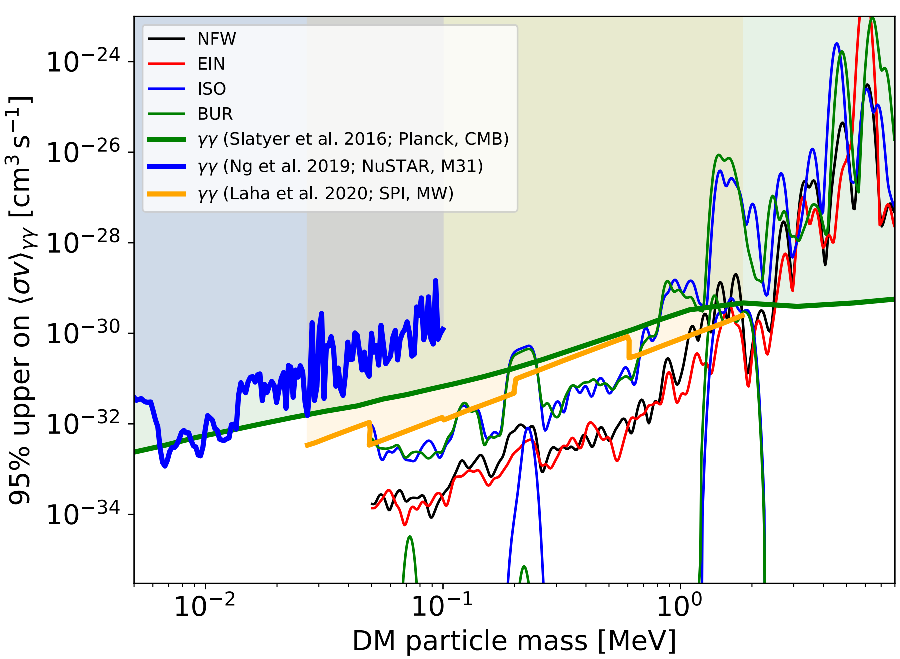


Strongest bounds on decaying light dark matter to date!

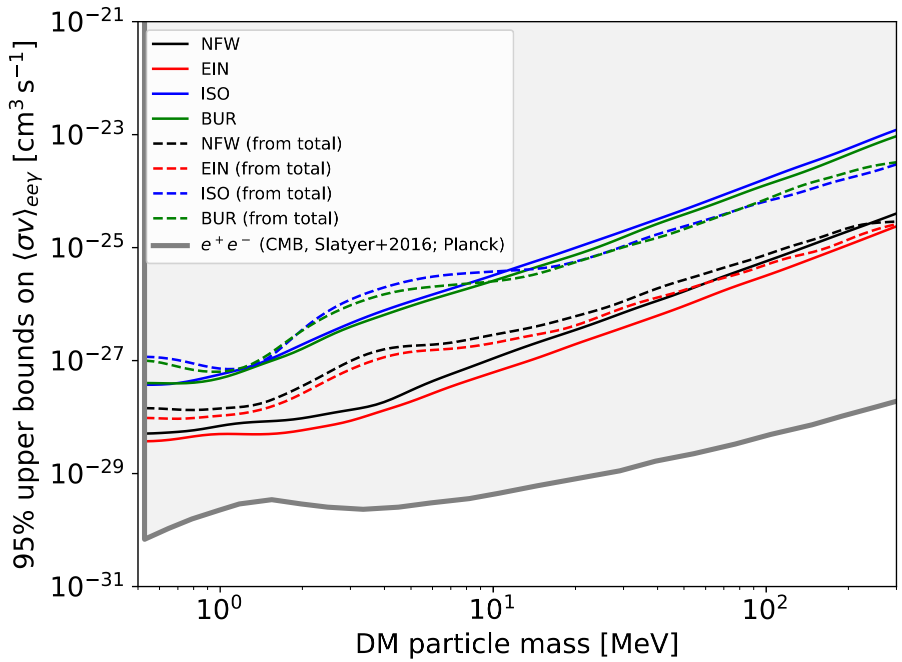
Light Particle Dark Matter Annihilation

Milky Way Halo (Siegert, Calore, et al. 2023, in prep.)

γγ Channel (different halo models)



e^+e^- Channel (FSR) (different halo models)

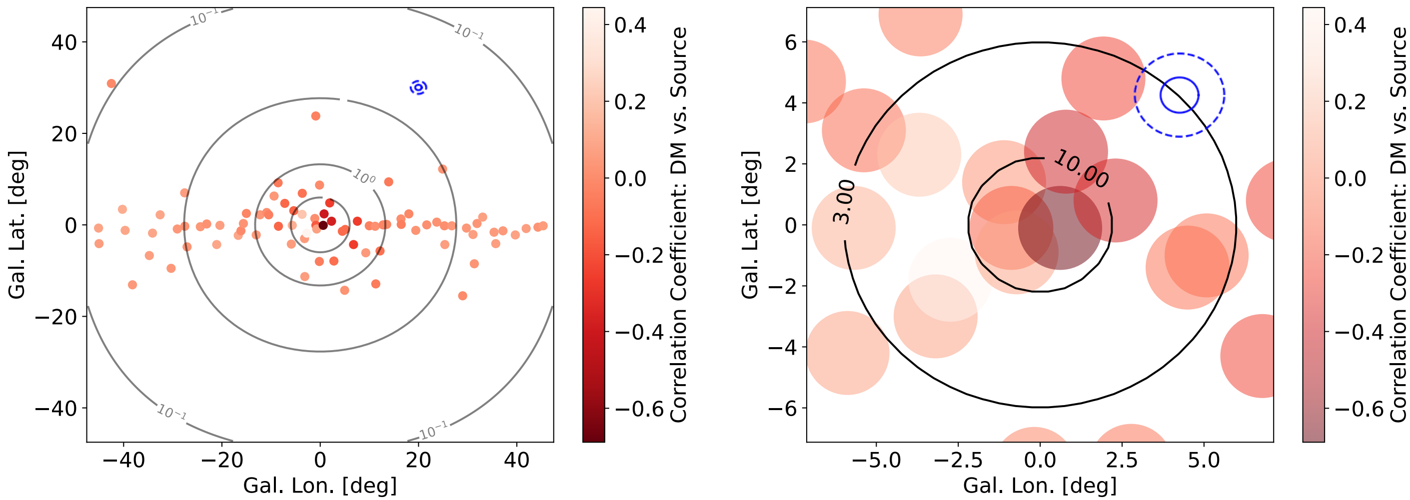


Strongest bounds on annihilating light dark matter for γγ channel!

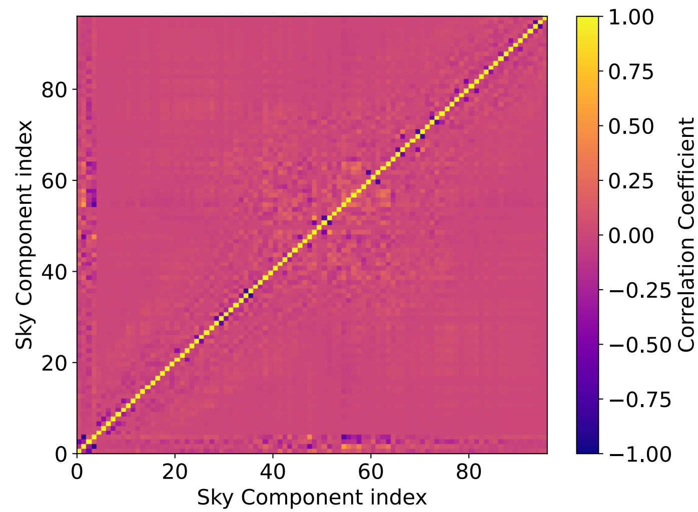
Almost strongest bounds on annihilating light dark matter for e^+e^- (FSR) channel! Only CMB limits stronger!

Covariance between components

Milky Way Halo (Siegert, Calore, et al. 2023, in prep.)



Strong correlation with resolved point sources and dark matter halo profiles!



Need to have good constraints from other instruments to fix point source spectra!

Light Dark Matter (ALPs) in Stars

Betelgeuse (Xiao et al. 2022; soon to be updated by Calore, Siegert et al.)

ALP (a) production via:

→ **Primakoff process:** $\gamma + Ze \rightarrow a + Ze$

→ **Compton scattering:** $\gamma + e \rightarrow e + a$

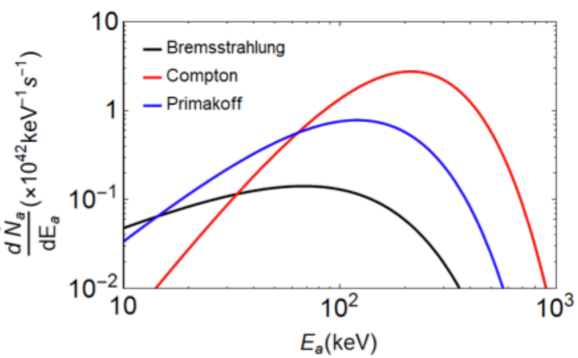
→ **Bremsstrahlung:** $e + Ze \rightarrow e + Ze + a$

→ Total ALP spectrum is obtained by integrating reaction rates over the volume of a star.

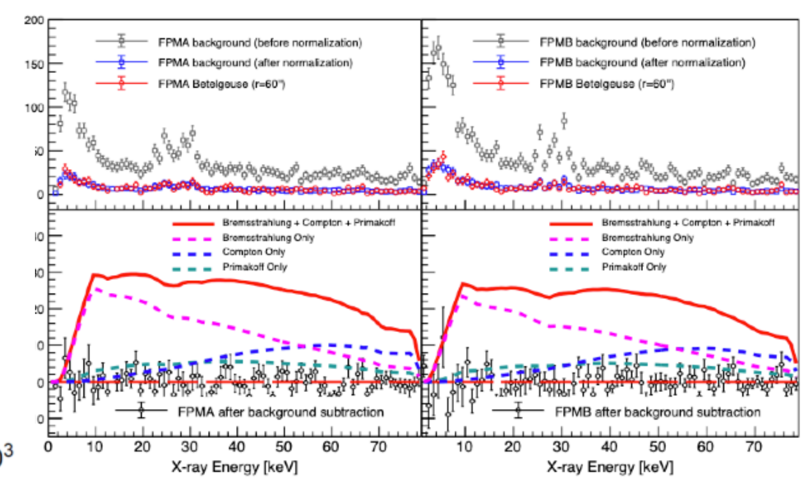
→ **Use nearby massive star!**
Here: Betelgeuse

Model

$$\frac{d\dot{N}_a}{dE} = \frac{10^{42}}{\text{keV s}}\left[C^B g_{13}^2 \left(\frac{E}{E_0^B}\right)^{\beta^B} e^{-(\beta^B+1)E/E_0^B} + C^C g_{13}^2 \left(\frac{E}{E_0^C}\right)^{\beta^C} e^{-(\beta^C+1)E/E_0^C} + C^P g_{11}^2 \left(\frac{E}{E_0^P}\right)^{\beta^P} e^{-(\beta^P+1)E/E_0^P}\right],$$

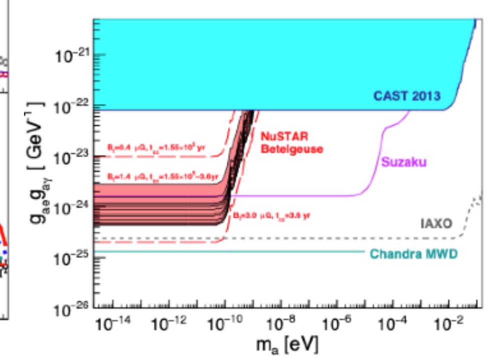


Measurements (NuSTAR)



Limits

Coupling constants
vs.
ALP mass



Summary

- The **MeV range is unique** to detecting (light) dark matter indirectly
  - *MeV scale dark matter (light particles)*
  - *MeV signatures of dark matter: primary, secondary, tertiary*
  - *Primordial black hole evaporation of asteroid mass scale (10^{14}–10^{18} g)*
- **INTEGRAL** set the strongest bounds on light dark matter
  - *Decay (Calore+2023, Xiao+2022)*
  - *Annihilation (Siegert+2023)*
  - *PBH (Berteaud+2022)*
  - *CGB (Iguaz+2021)*
  - *DM into standard model particles with subsequent photon emission*
- With **COSI** launching in 2027, the search for MeV scale dark matter with **primary** channels (γγ and eeγ), **secondary** (IC scattering) and **tertiary** (positron annihilation) emission will boost the topic thanks to its large field of view, unique imaging capabilities and spectral resolution