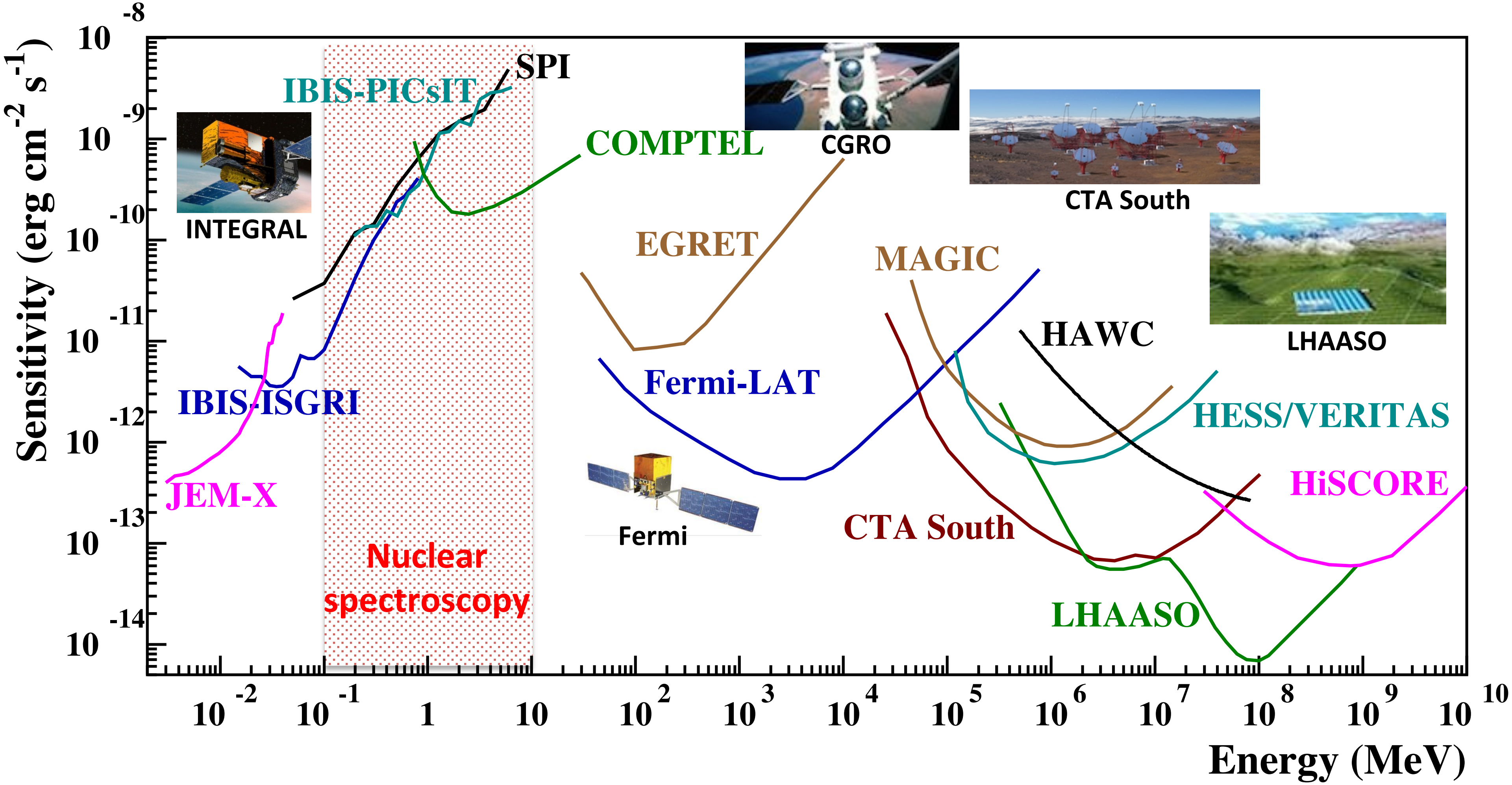
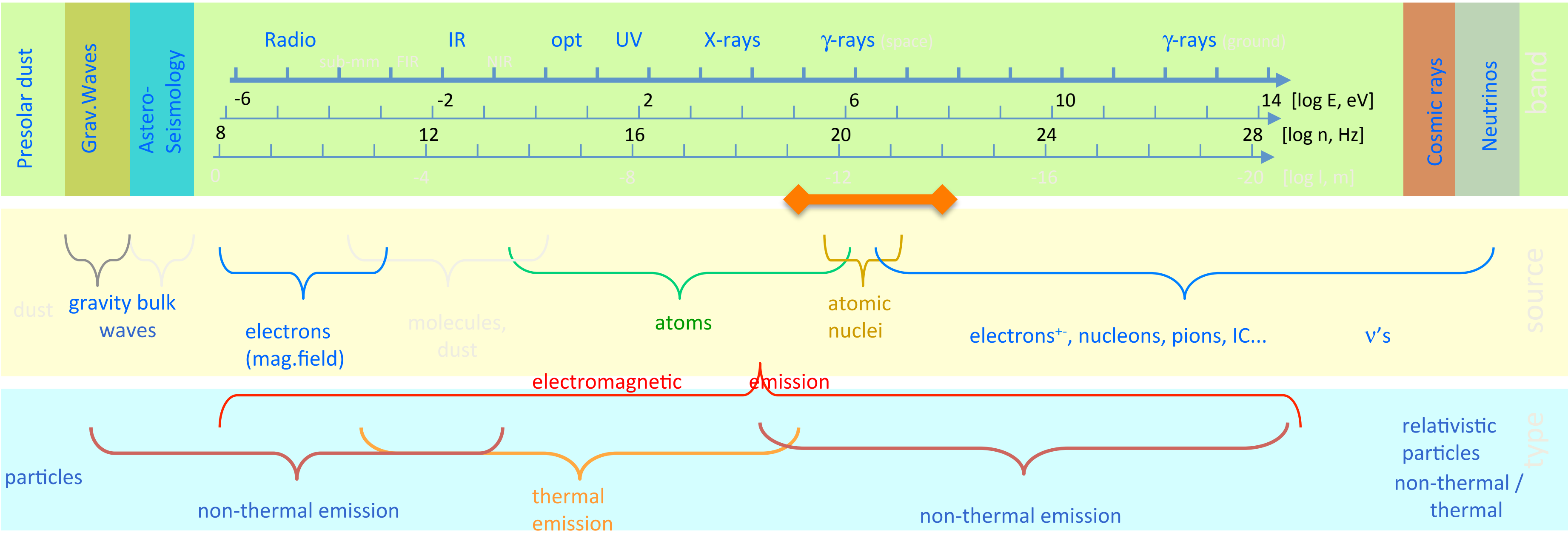
Gamma-ray astronomy

Vincent Tatischeff
CSNSM, Orsay, France

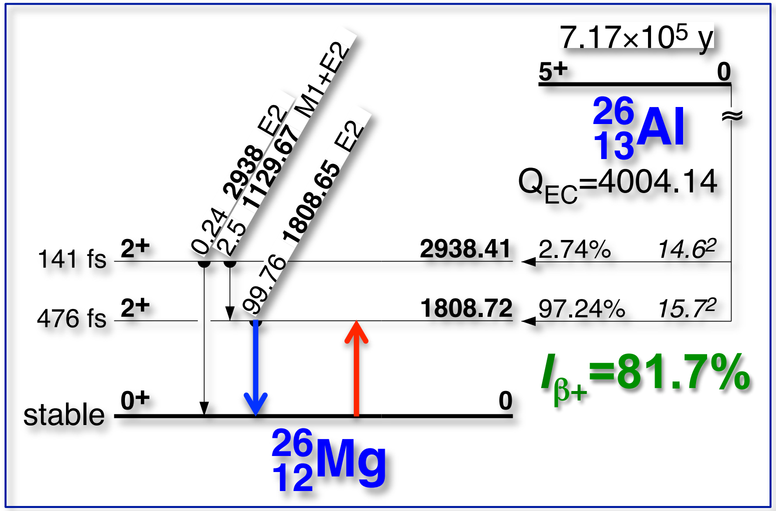


Nuclear spectroscopy in the EM spectrum



Gamma-ray line production from:

- Radioactivity
- Nuclear collisions
- Positron annihilation (511 keV)
- Neutron capture (2.2 MeV from n + H)



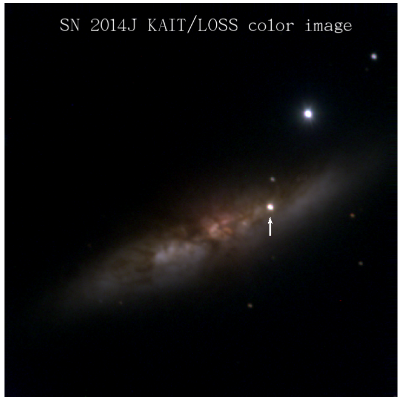
Astronomy with radioactivities

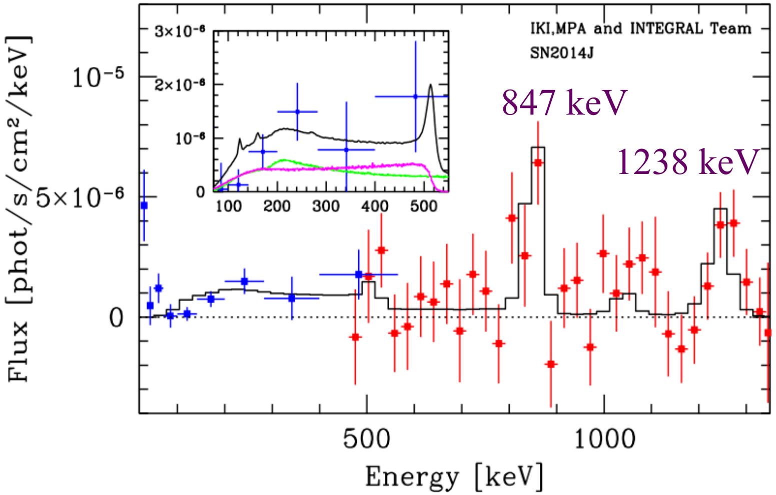
Isotope	Production site[a]	Decay chain[b]	Half-life[c]	γ-ray energy (keV) and intensity[d]
^{7}Be	Novae	$^{7}\mathrm{Be} \xrightarrow{\epsilon} {}^{7}\mathrm{Li}^*$	53.2 d	478 (0.10)
^{56}Ni	Type Ia SNe, Core-collapse SNe	$^{56}\mathrm{Ni} \xrightarrow{\epsilon} {}^{56}\mathrm{Co}^*$ $^{56}\mathrm{Co} \xrightarrow{\epsilon(0.81)} {}^{56}\mathrm{Fe}^*$	6.075 d 77.2 d	158 (0.99), 812 (0.86) 847 (1), 1238 (0.66)
^{57}Ni	Type Ia SNe, Core-collapse SNe	$^{57}\mathrm{Ni} \xrightarrow{\epsilon(0.56)} {}^{57}\mathrm{Co}^*$ $^{57}\mathrm{Co} \xrightarrow{\epsilon} {}^{57}\mathrm{Fe}^*$	1.48 d 272 d	1378 (0.82) 122 (0.86), 136 (0.11)
^{22}Na	Novae	$^{22}\mathrm{Na} \xrightarrow{\beta^+(0.90)} {}^{22}\mathrm{Ne}^*$	2.60 y	1275 (1)
^{44}Ti	Core-collapse SNe, Type Ia SNe	$^{44}\mathrm{Ti} \xrightarrow{\epsilon} {}^{44}\mathrm{Sc}^*$ $^{44}\mathrm{Sc} \xrightarrow{\beta^+(0.94)} {}^{44}\mathrm{Ca}^*$	60.0 y 3.97 h	68 (0.93), 78 (0.96) 1157 (1)
^{26}Al	Core-collapse SNe, WR stars AGB stars, Novae	$^{26}\mathrm{Al} \xrightarrow{\beta^+(0.82)} {}^{26}\mathrm{Mg}^*$	$7.2 \cdot 10^5$ y	1809 (1)
^{60}Fe	Core-collapse SNe	$^{60}\mathrm{Fe} \xrightarrow{\beta^-} {}^{60}\mathrm{Co}^*$ $^{60}\mathrm{Co} \xrightarrow{\beta^-} {}^{60}\mathrm{Ni}^*$	$2.6 \cdot 10^6$ y 5.27 y	59 (0.02) 1173 (1), 1332 (1)
r-process nuclei	Neutron star mergers	β decay, α decay fission	$\sim$ day	$\sim 0.1 - 2$ MeV

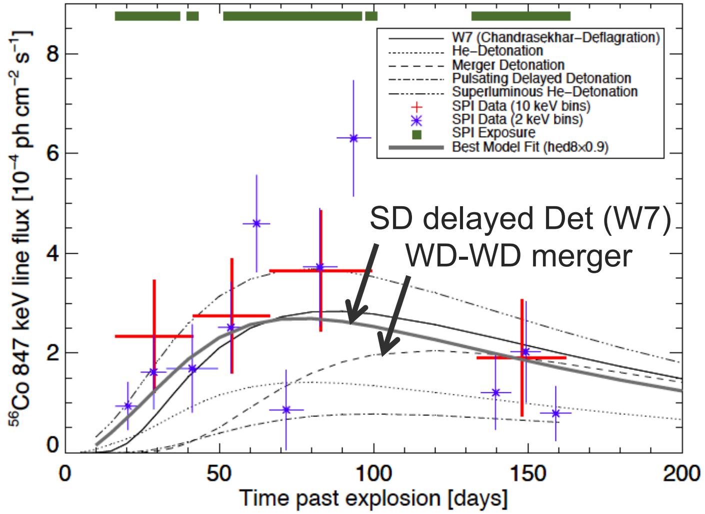
Highlights:

- ^{56}Ni decay chain detected from SN 1987A (core-collapse) and SN 2014J (thermonuclear)
- ^{44}Ti detected from 2 SNRs, Cas A and SN 1987A, no other source found in γ-ray surveys
- ^{26}Al and ^{60}Fe diffuse radioactivities (flux ratio of 15%) => hot ISM properties

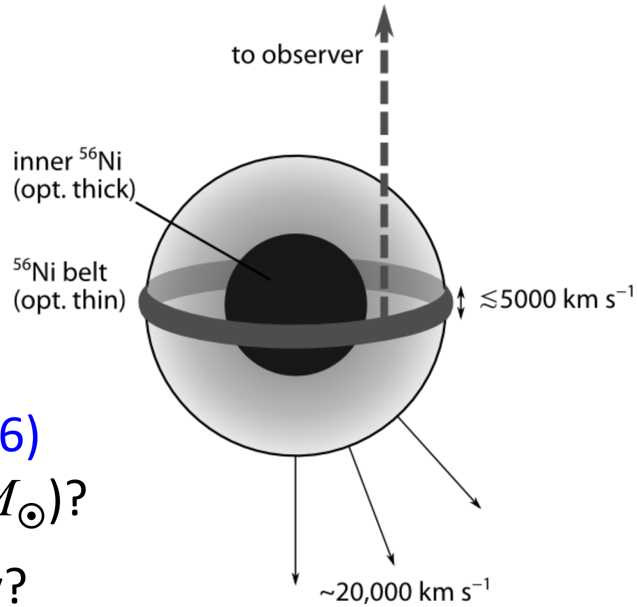
SN 2014J: first SN Ia detected in γ rays



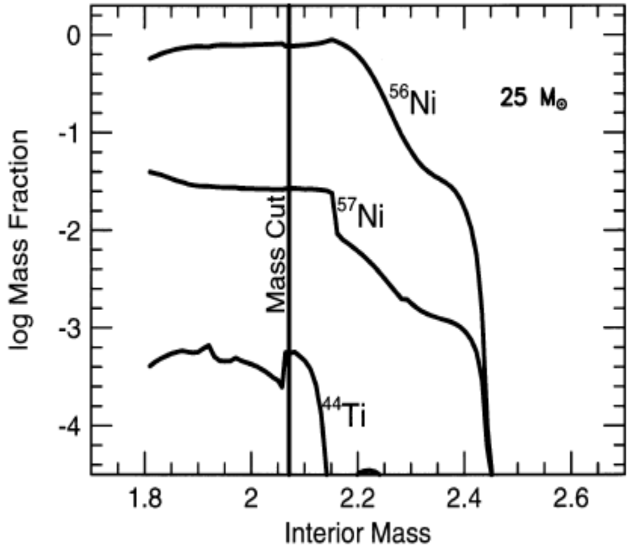


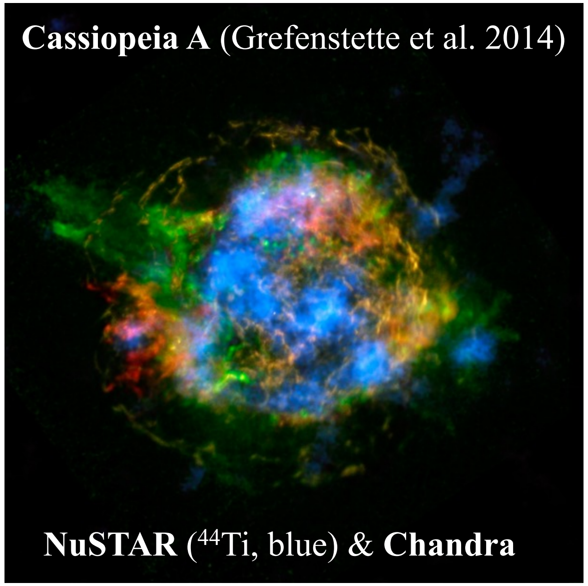


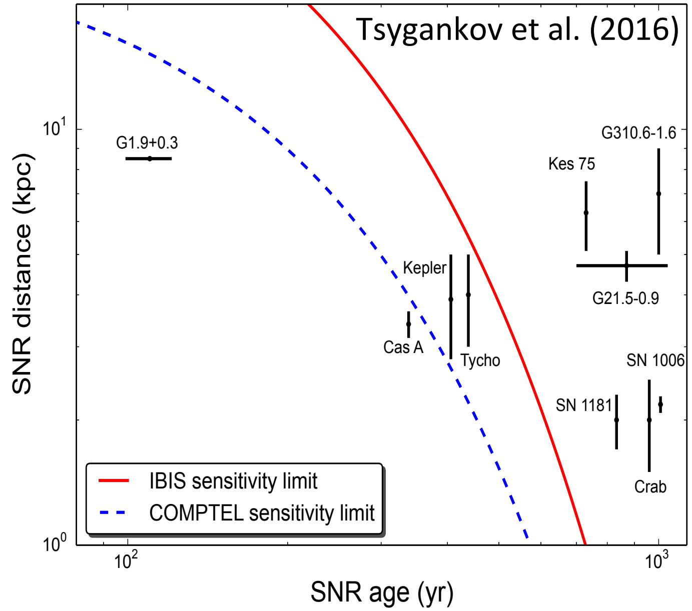
- Nearest type Ia (thermonuclear) SN in last 50 years, occurred in the starburst galaxy M82 at $D = 3.5$ Mpc
- *INTEGRAL* detection of the ^{56}Co ($T_{1/2}$=77 d) γ-ray lines ⇒ synthesis of 0.6 ± 0.1 $M_\odot$ of ^{56}Ni in the explosion (Churazov et al. 2014, 2015; see also Diehl et al. 2015)
- Unexpected detection of the ^{56}Ni ($T_{1/2}$=6.1 d) γ-ray lines ~ 20 d after the explosion (Diehl et al. 2014; Isern et 2016) ⇒ Surface explosion? High-speed plume of ^{56}Ni (~0.05 $M_\odot$)?
- Are SN Ia good standard candles for *precision* cosmology?



^{44}Ti supernova in core-collapse SNe

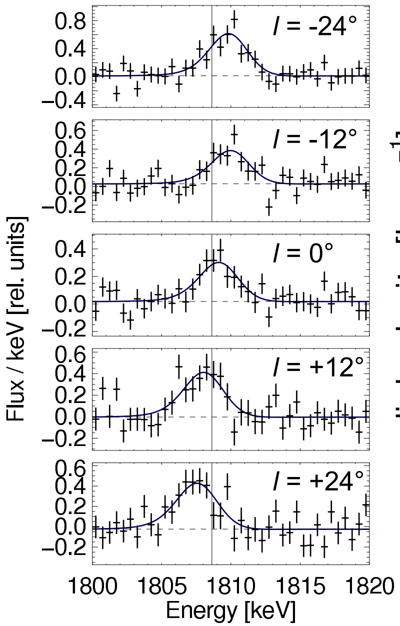


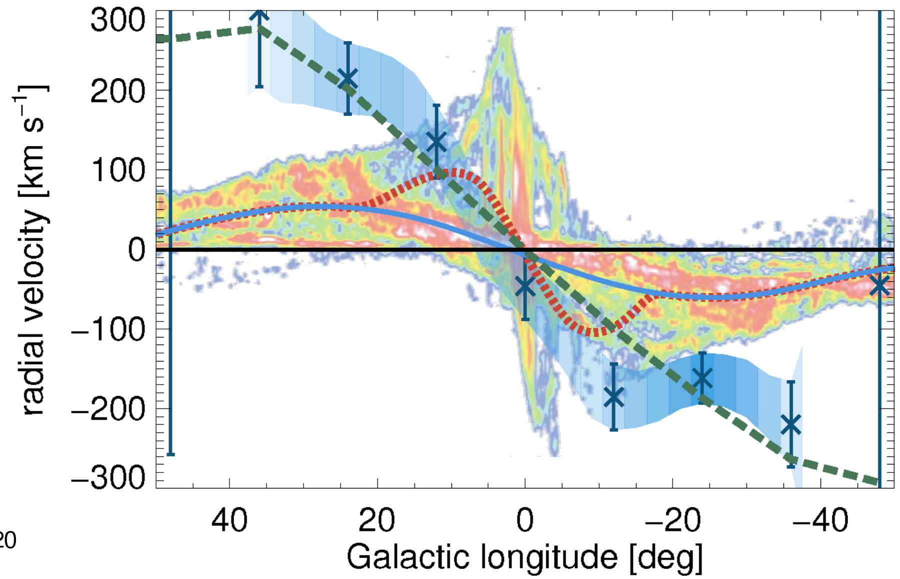


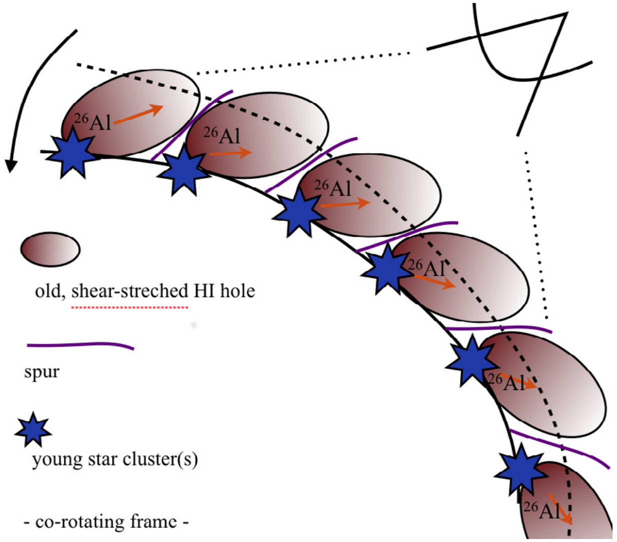


- ^{44}Ti produced close to the "mass cut", at r < 10^3 km from α-rich freeze out $\Rightarrow$ unique probe of the explosion mechanism
- ^{44}Ti decay detected from Cas A (*COMPTEL*, *INTEGRAL*, *NuSTAR*...) and SN 1987A (*INTEGRAL*, *NuSTAR*) $\Rightarrow$ ^{44}Ti ejected mass: ~ (1.2 − 2) × 10^{-4} $M_\odot$
- *NuSTAR's* mapping of radioactivity in Cas A SNR: explosion asymmetries probably caused by low-mode convective instabilities (Grefenstette et al. 2014, 2017)
- Only Cas A detected in the Galaxy: abundant synthesis of ^{44}Ti in a rare class of SNe (see Tsygankov et al. 2016)

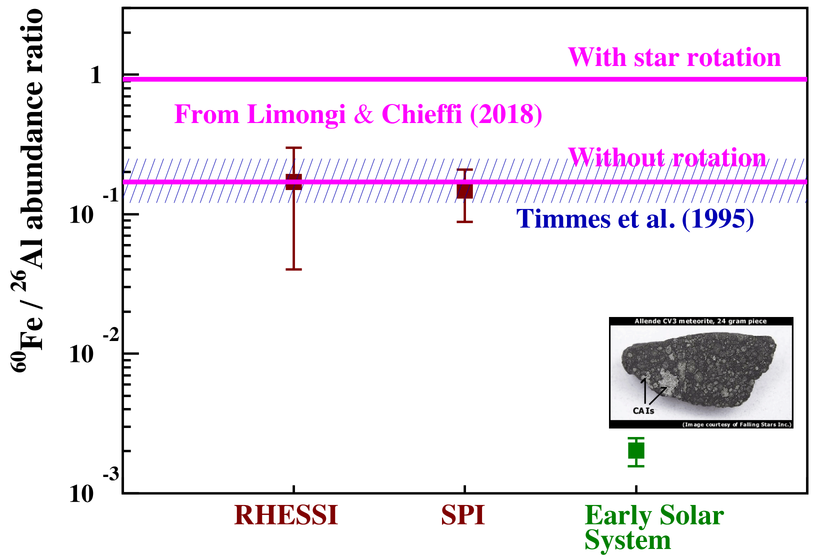
^{26}Al (and ^{60}Fe): tracing the hot ISM



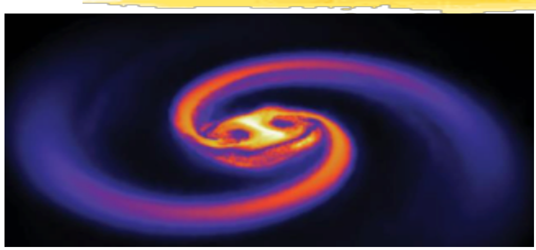


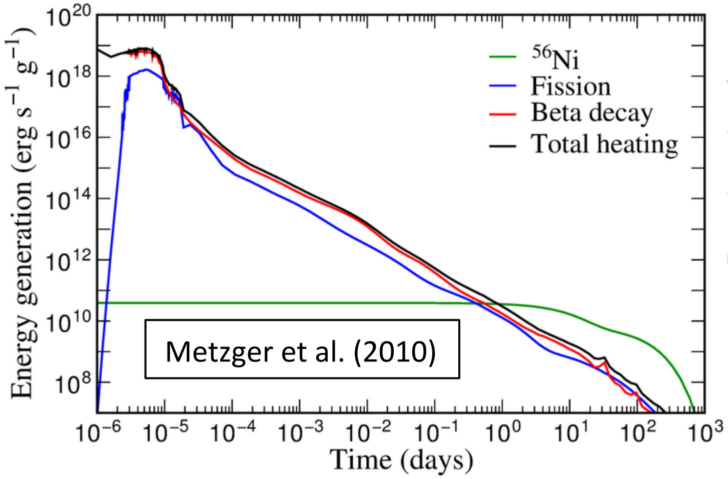


- Measured Doppler shifts of ^{26}Al 1.8 MeV line exceed expectations from Galactic rotation (e.g. CO data) => ^{26}Al ejected from massive stars and SNe into hot gas superbubbles expanding towards the leading edge of spiral arms (Kretschmer et al. 2013, Krause et al. 2015)
- ^{60}Fe-to-^{26}Al source abundance ratio of 15%

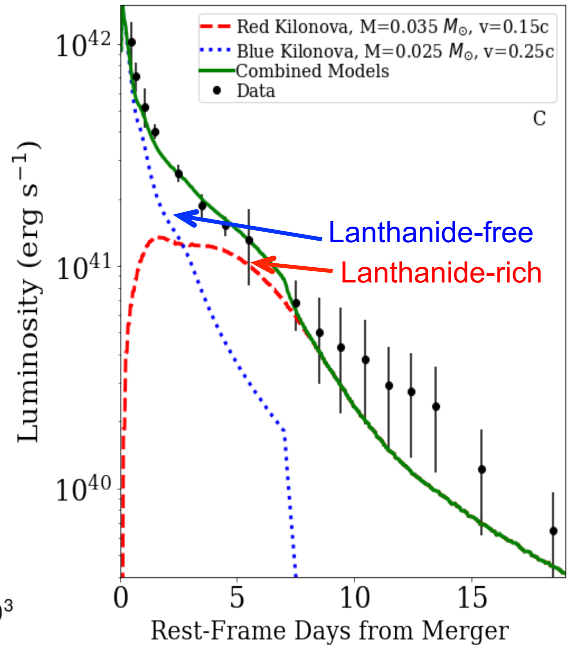


Neutron star mergers and kilonovae

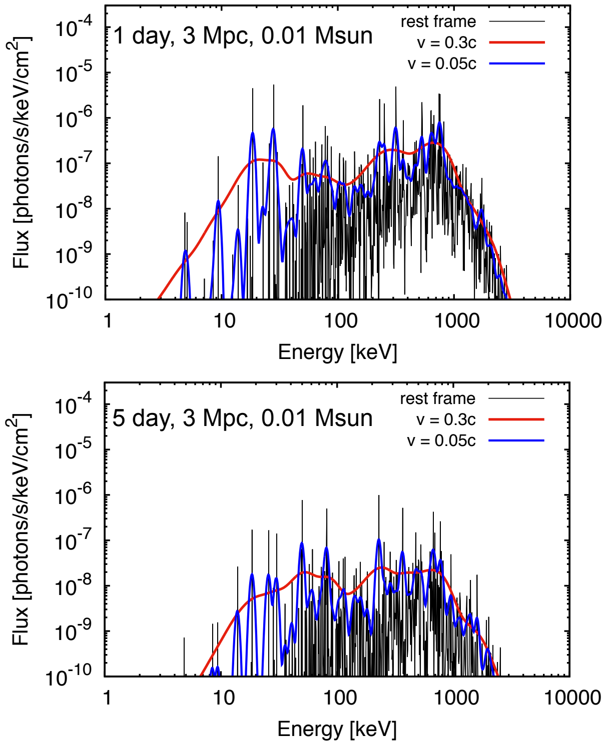




SSS17a (Kilpatrick et al. 2017)

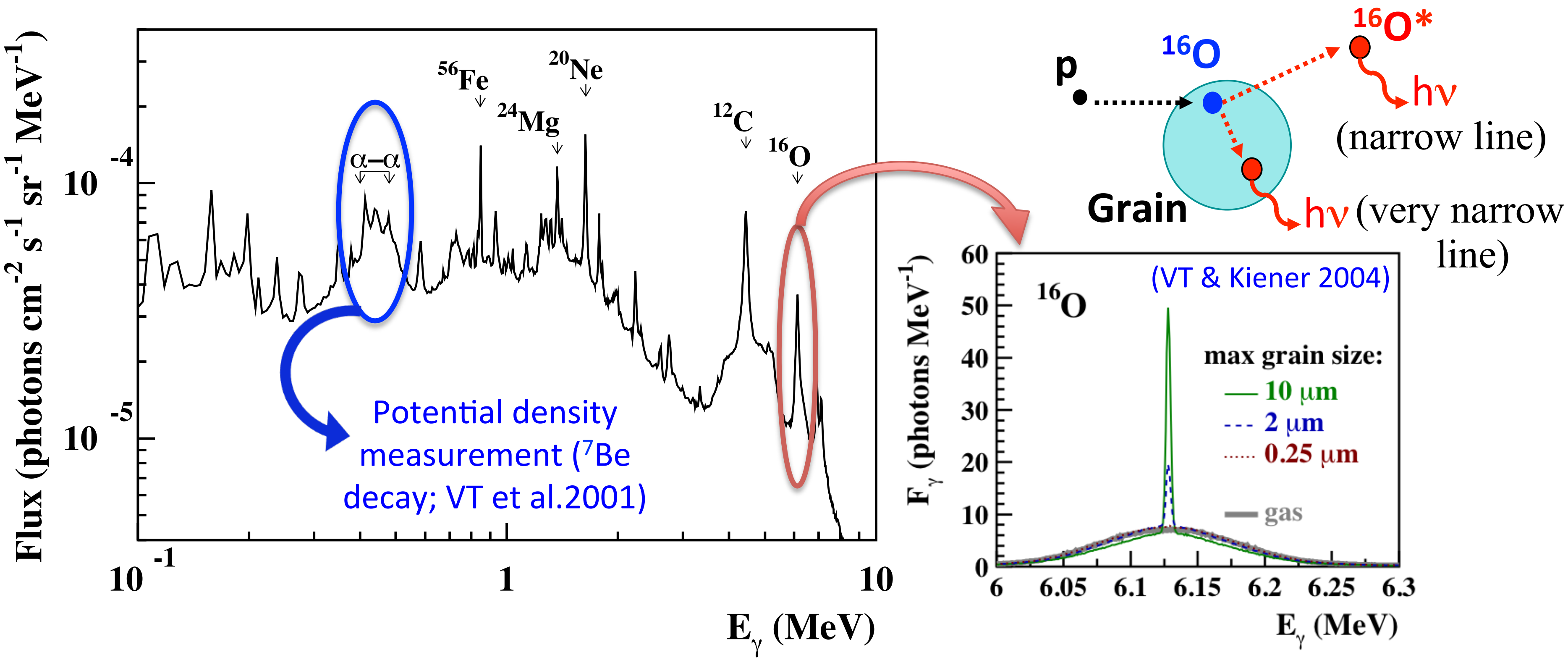


Hotokezaka et al. (2016)



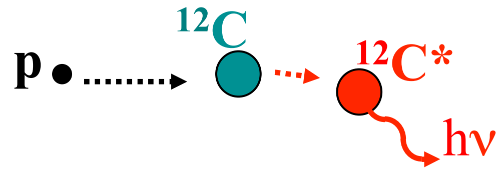
- Kilonova: UV-Optical-NIR transient powered by the radioactive decay of r-process nuclei (Metzger et al. 2010)
- GW170817 (advanced LIGO and Virgo) associated with the short GRB 170817A (*Fermi* and *INTEGRAL*) and the optical/NIR transient SSS17a/AT2017gfo => kilonova
- Previous kilonovae suspected in GRBs 050709, 060614, 130603B
- Gamma-ray line emission detectable with the next-generation γ-ray observatories (e.g. e-ASTROGAM) to a distance <~12 Mpc (Li 2018) => ≈ 0.05 - 0.5 NS merger per century

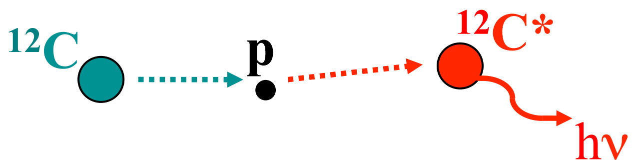
γ-ray line spectrum from energetic collisions



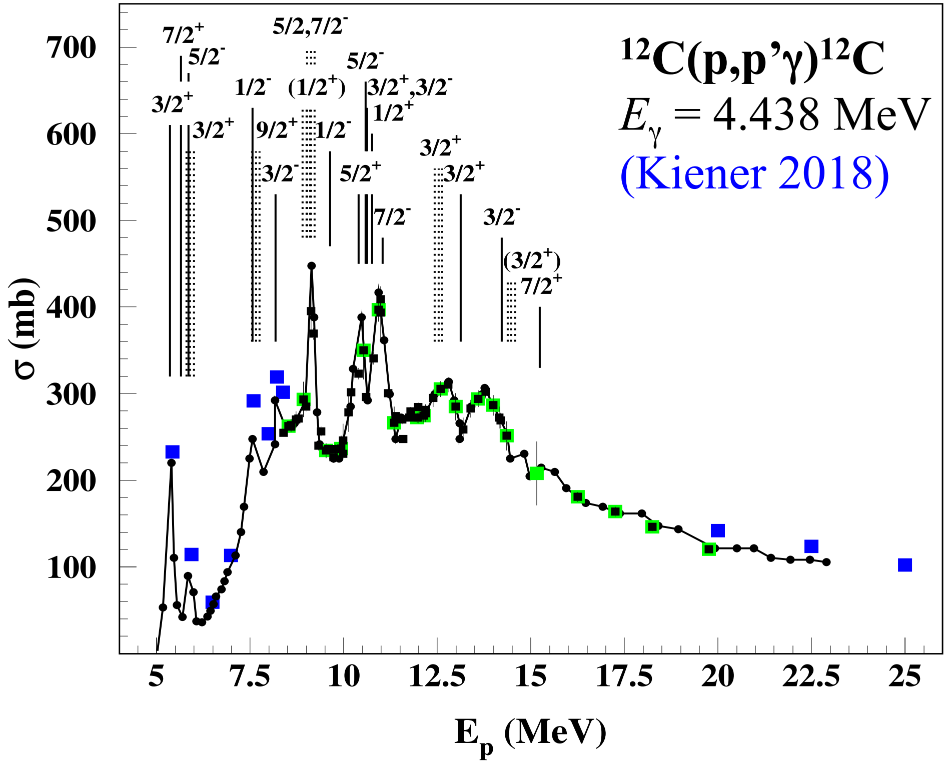
- Narrow lines: e.g. ^{12}C(p,p')^{12}C$^*_{4.439}$, ^{12}C(p,2pn)^{10}B$^*_{0.718}$
- Broad lines: e.g. ^{1}H(^{12}C,^{12}C$^*_{4.439}$)^{1}H
- α-α line: ^{4}He(α,n)^{7}Be$^*_{0.429}$ and ^{4}He(α,p)^{7}Li$^*_{0.478}$

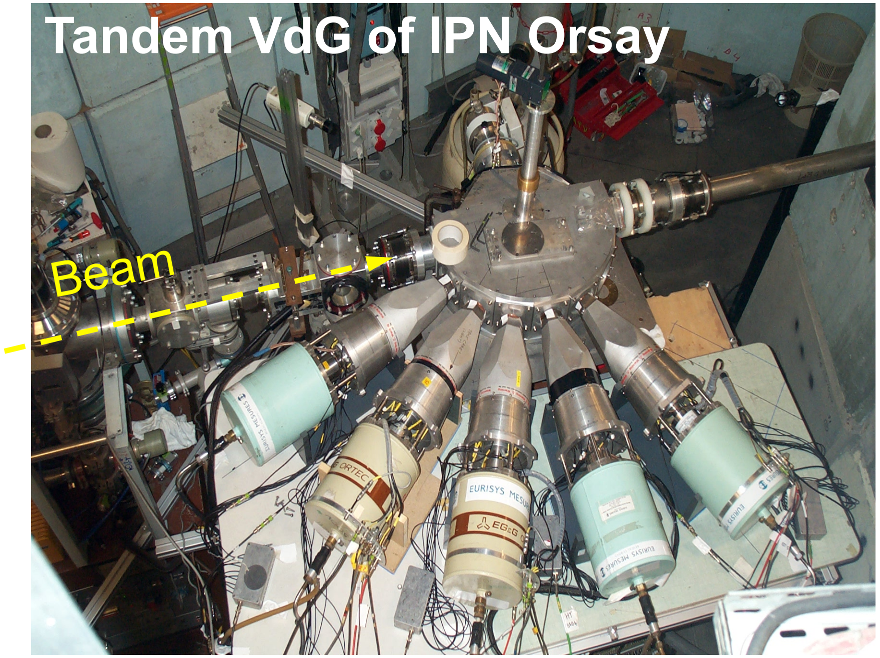
\+ the 511 keV line (not shown)





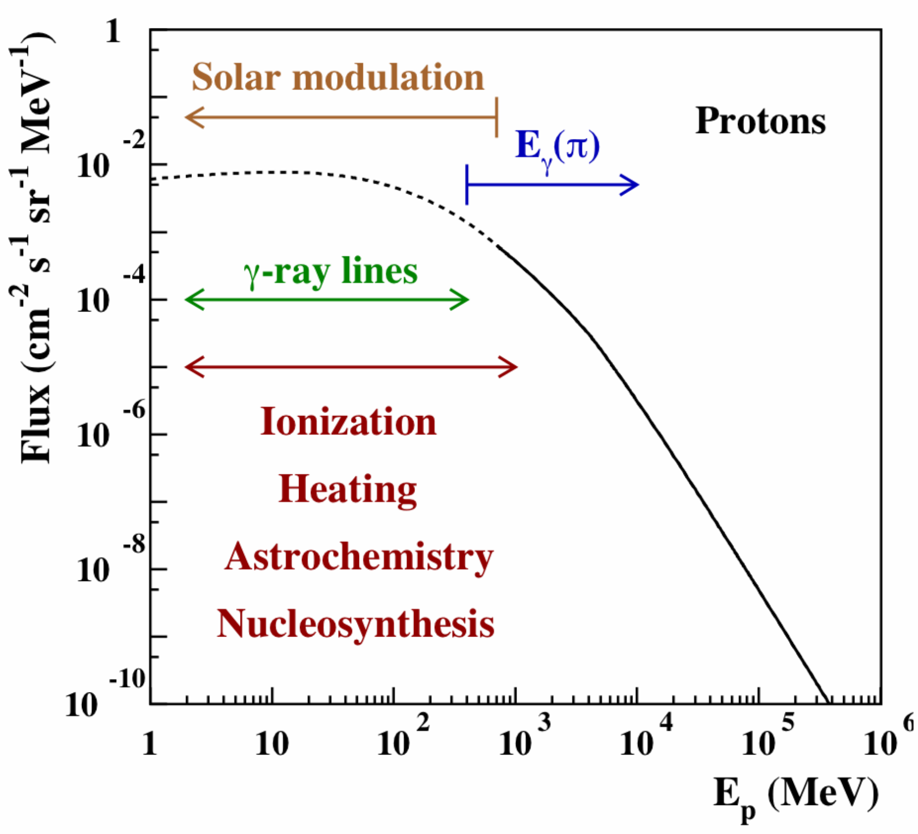
Nuclear excitation cross sections

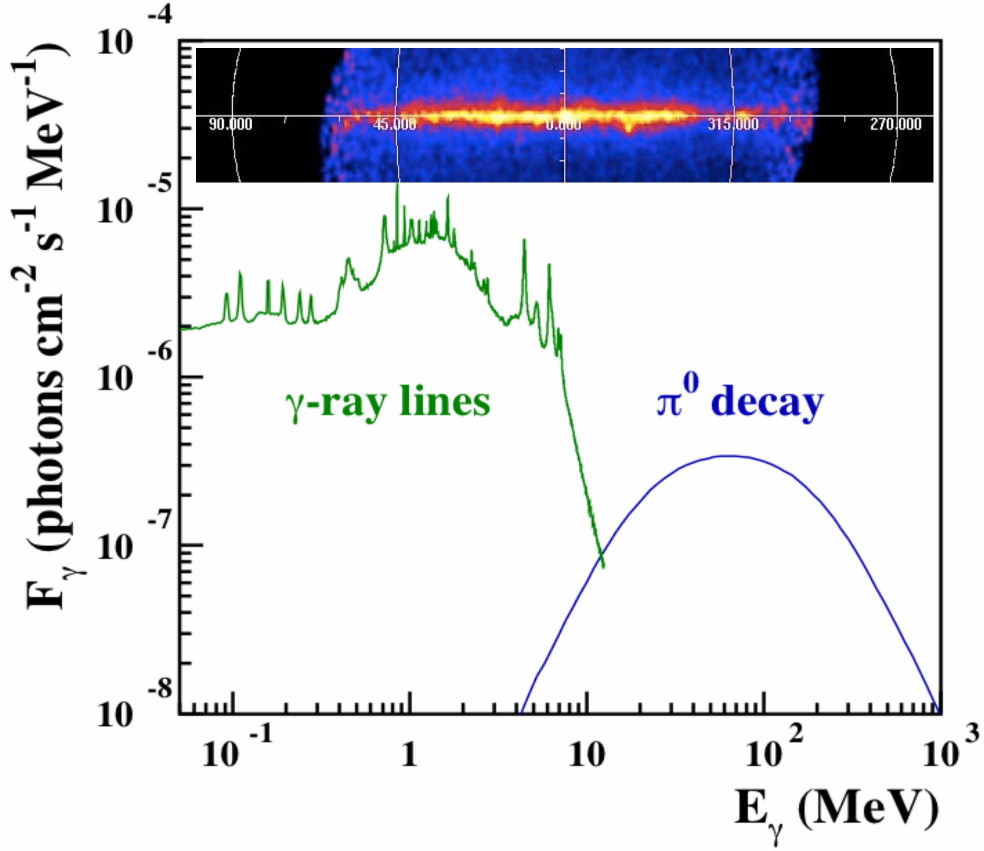




- Inelastic nuclear collisions: p, ^{3}He, α + C, N, O, Ne, Al, Mg, Si, Ca & Fe
- **Accelerator experiments** at ALTO-IPNO (p < 25 MeV, α < 40 MeV), iThemba LABS (30 – 200 MeV protons) and HZ Berlin (50 – 90 MeV α) (+ Talys nuclear code): 82+ lines in p reactions, 73+ lines in α reactions (Kiener et al. 2012)
- Data evaluation/compilation: Murphy et al. (2009); Benhabiles-Mezhoud et al. (2013)

Gamma-ray lines from low-energy cosmic rays





- MeV gamma-ray astronomy is the only direct way of studying the various effects of hadronic **low-energy cosmic rays** (E < 1 GeV nucleon^{-1}) in the ISM: ionization, heating – important for star formation –, astrochemistry, large-scale MHD turbulence, nucleosynthesis (LiBeB)

Low-energy cosmic rays in the ISM

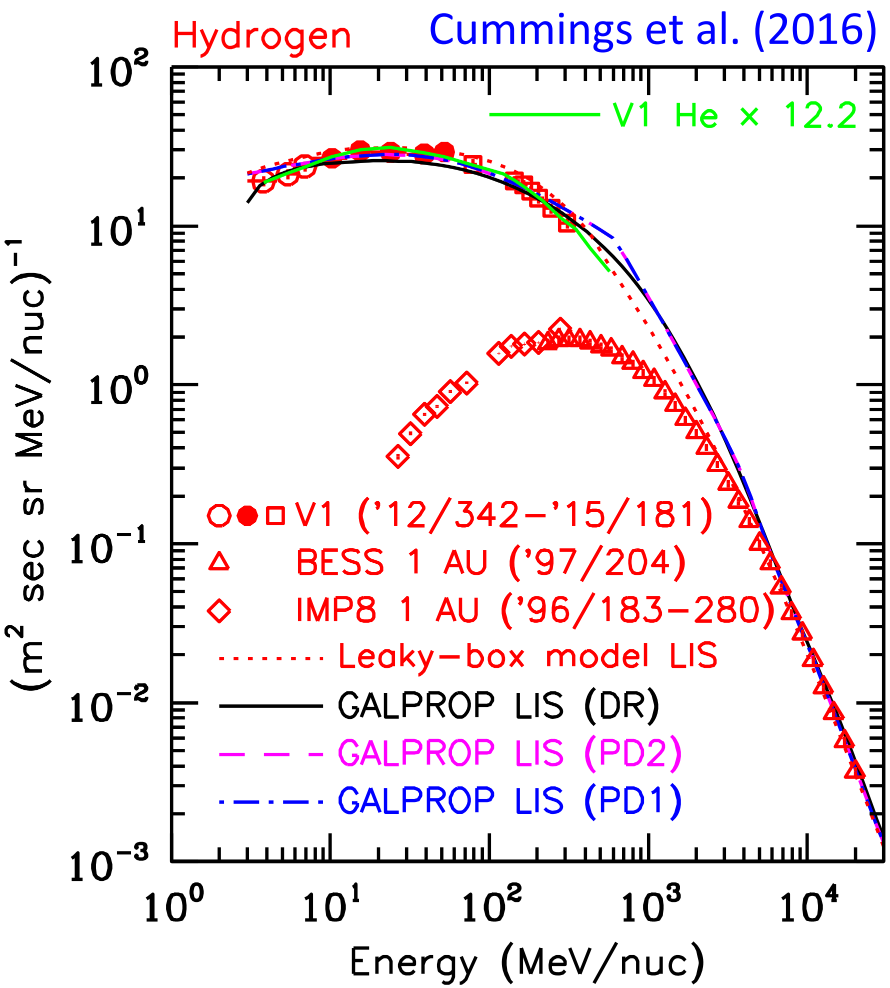
- ***Voyager 1*** measurements of LECR spectra down to 3 MeV nucleon^{-1}

⇒ CR ionization rate: $\zeta_H = (1.51 - 1.64) \times 10^{-17}\,\mathrm{s}^{-1}$, a factor >10 lower than the mean CR ionization rate measured in diffuse clouds, $\zeta_H = 1.78 \times 10^{-16}\,\mathrm{s}^{-1}$ (Indriolo et al. 2015, Neufeld et al. 2017)

- H_3^+ observations show that the density of LECRs strongly varies from one region to another in the Galaxy

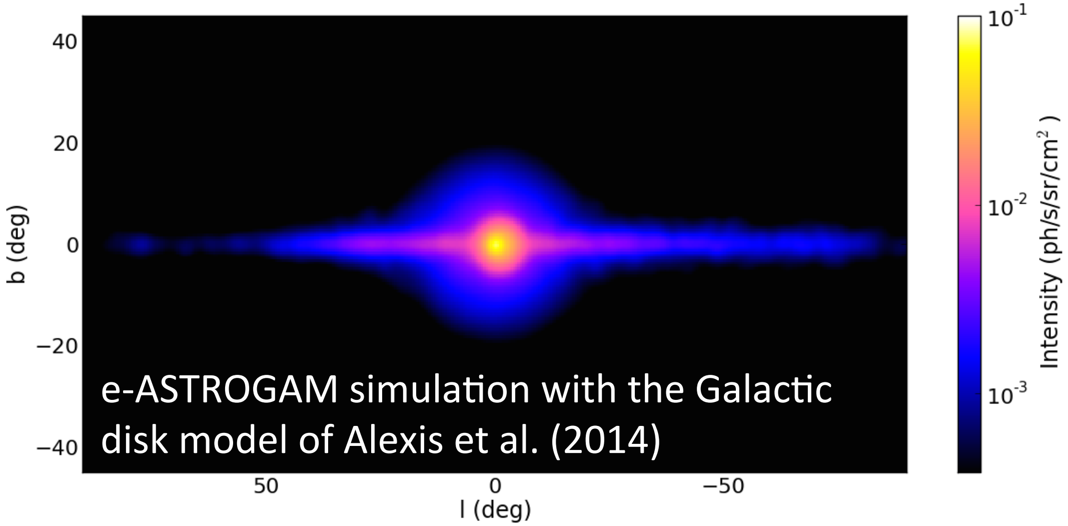
⇒ Other sources of LECRs (<1 GeV/n) besides SNRs, e.g. OB associations (Parizot et al. 2004), microquasars (Heinz & Sunyaev 2002), anomalous CRs (Scherer et al. 2008) ?

⇒ γ-ray line flux from CR in the inner Galaxy detectable with foreseen observatories (Benhabiles-Mezhoud et al. 2013)

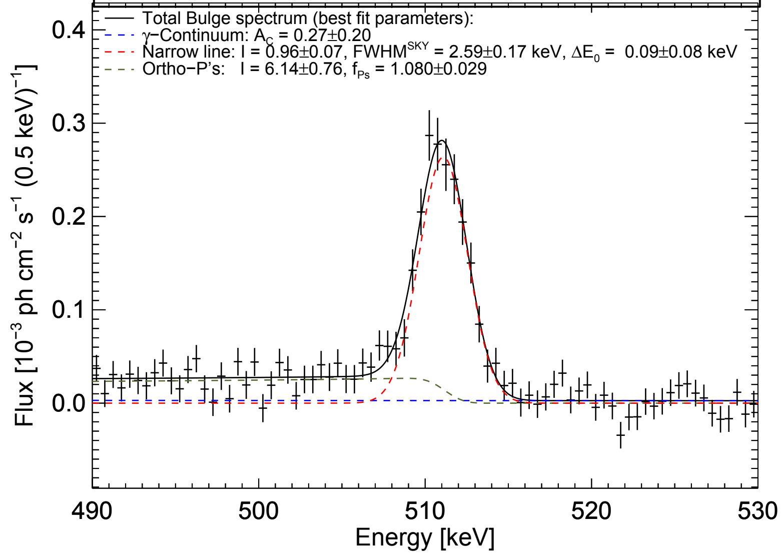


511 keV line from positron annihilation

- First (& brightest) γ-ray line detected from outside the solar system (Johnson et al. 1972; Leventhal et al. 1978) => Galactic positron annihilation rate of $\sim 5 \times 10^{43}\ s^{-1}$
- Three distinct annihilation regions in the Galaxy: disc, bulge and center (nucleus) (Skinner et al. 2014, Siegert et al. 2016)
- **What are the positron sources**: β+ decay (^{26}Al, ^{44}Ti, ^{56}Ni), p-p interaction by CRs, γ-γ in LMXRBs and/or microquasars, dark matter annihilation...?
- How do positrons **propagate** from their sources (B-field, ISM turbulence...) and **annihilate** (ISM morphology, cloud penetration...)

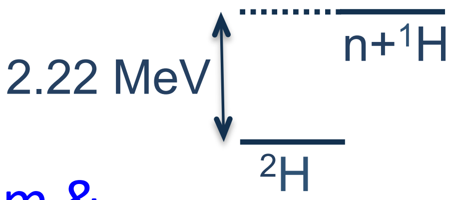


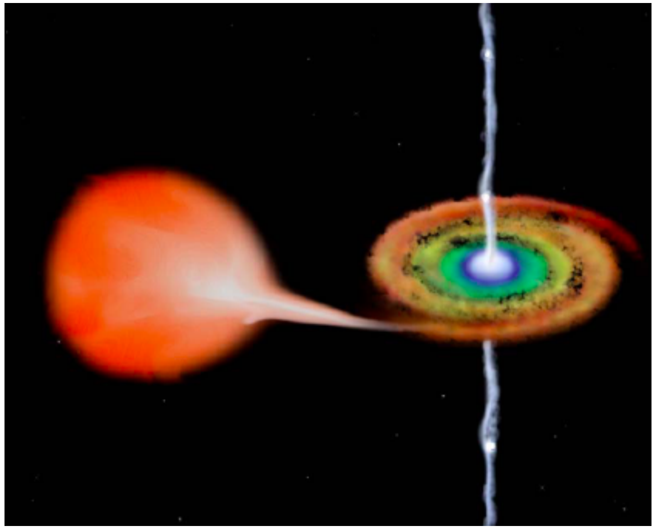
INTEGRAL/SPI – Siegert et al. (2016)

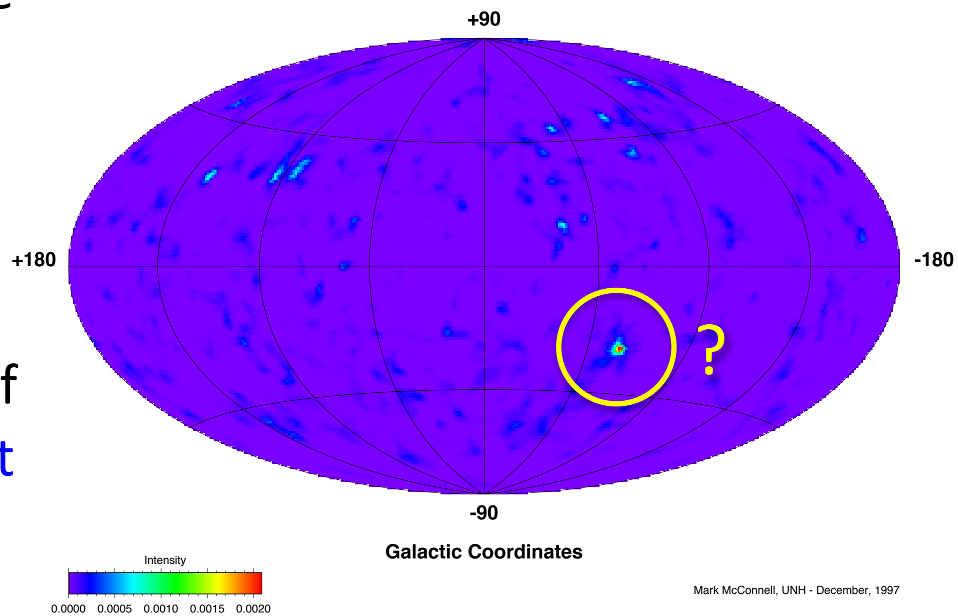


2.22 MeV line from X-ray binaries

- Neutron production by breakup of ^4He and heavier nuclei **accreted onto a compact object**
- Recombination with H in the companion star (e.g. Guessoum & Jean 2002) or in neutron star atmosphere (e.g. Bildsten et al. 1993)
- Energy and width of the 2.2 MeV line $\Longrightarrow$ nuclear equation of state
- Searched for with SPI from the Be/X-ray binary A0535+262 in outburst (May-June 2005; Çaliskan et al. 2009)
- However, COMPTEL 3.7σ detection of a 2.2 MeV point source (McConnell et al. 1997) is still not explained



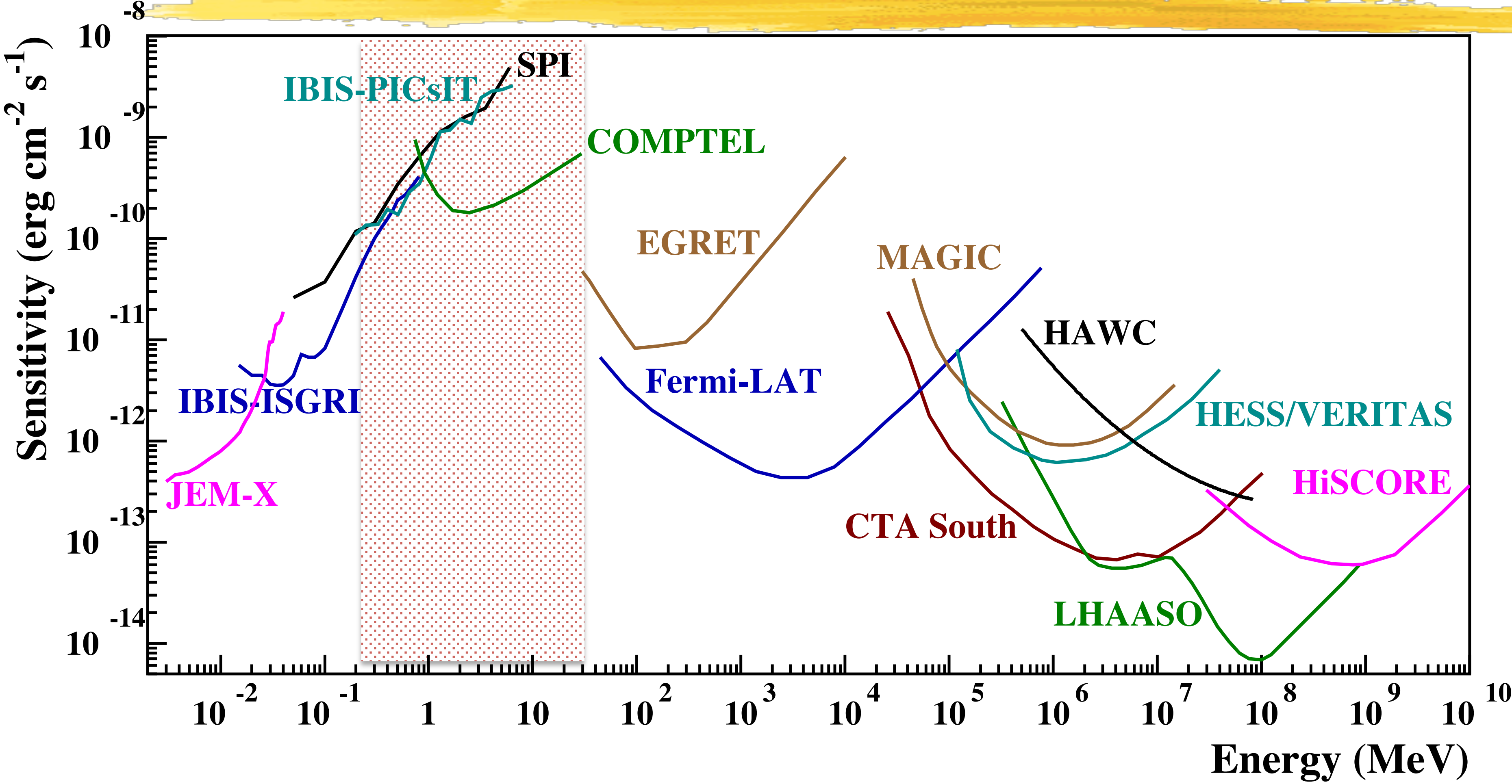




γ-ray line astrophysics: science objectives

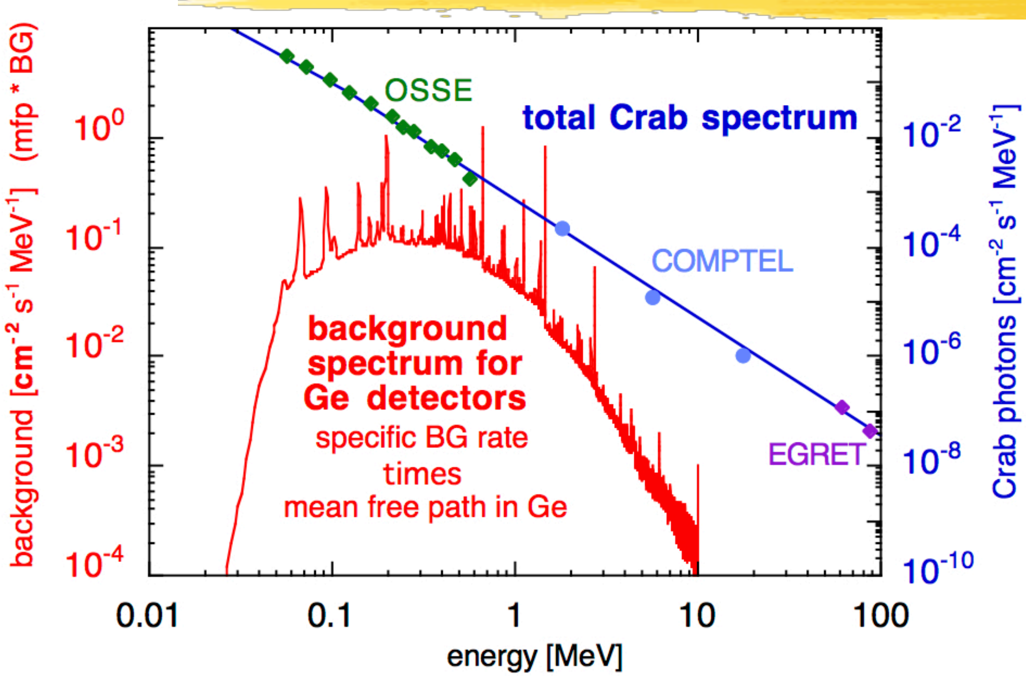
- Understand the progenitor system(s) and explosion mechanism(s) of **thermonuclear SNe** (^{56}Ni, ^{56}Co)
- Study the dynamics of **core collapse** in massive star explosions (^{56}Co, ^{44}Ti) and the recent **SN history** in the Milky Way (^{44}Ti)
- Constrain the mixing between accreted matter and white dwarf core in **nova explosions** (^{7}Be, ^{22}Na) and the nova contribution to Galactic **^{7}Li** (^{7}Be)
- Study the dynamic interstellar medium and the **cycle of matter** (^{26}Al, ^{60}Fe)
- Understand the origin of the **positrons** annihilating in the Galactic bulge
- Probe the distribution of **low-energy cosmic rays** in different environment and study the role of these particle in the Galactic ecosystem
- Constrain the accretion physics and the **nuclear equation of state** from the 2.22 MeV line produced in X-ray binaries
- Study the acceleration of particles and the mixing processes in the solar outer convection zone **from solar flare radioactivity**

Gamma-ray astronomy in the MeV domain

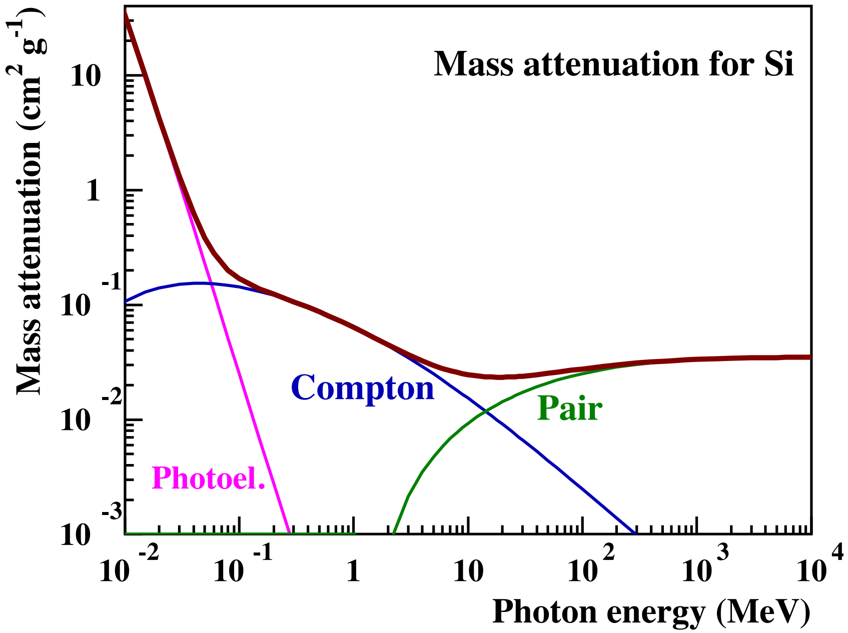


- Worst covered part of the EM spectrum (only a few tens of known steady sources so far between 0.5 and 30 MeV vs. 5500+ sources in the current Fermi/LAT catalog)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)

Observational challenges for γ-ray astronomy

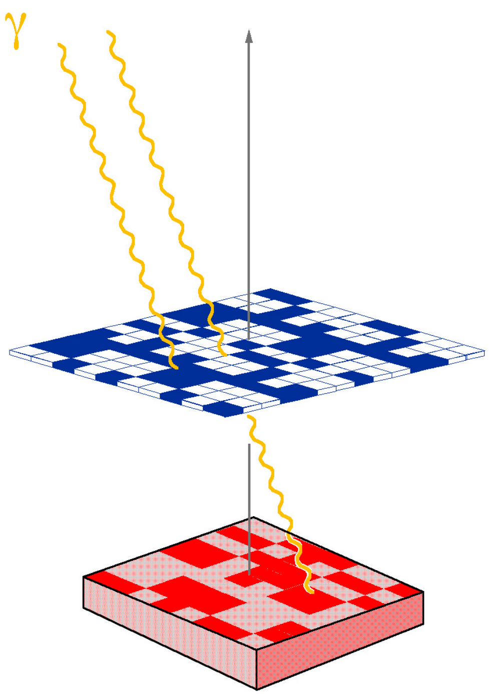
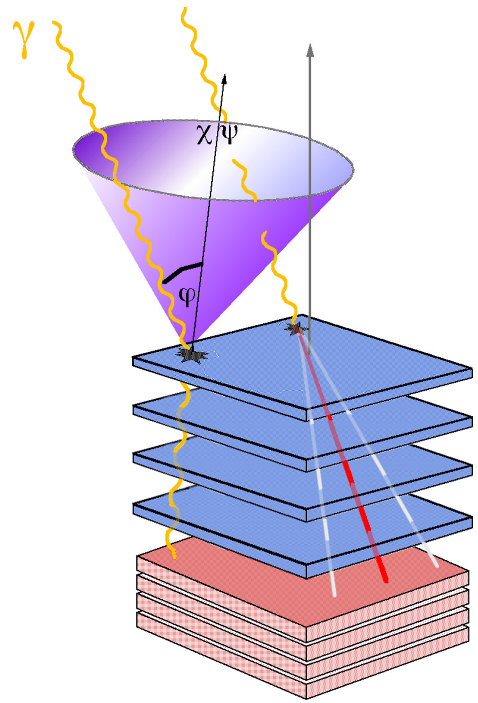
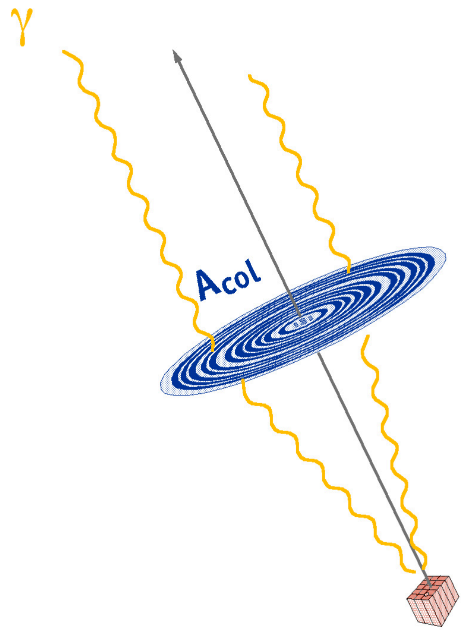


- ☺ The MeV range is the domain of nuclear γ-ray lines (radioactivity, nuclear collision, positron annihilation, neutron capture)
- ☹ Strong instrumental background from activation of space-irradiated materials



- ☹ Photon interaction probability reaches a minimum at ~ 10 MeV
- ☹ Three competing processes of interaction, Compton scattering being dominant around 1 MeV
  ⇒ complicated event reconstruction

Instrument concepts in γ-ray astronomy

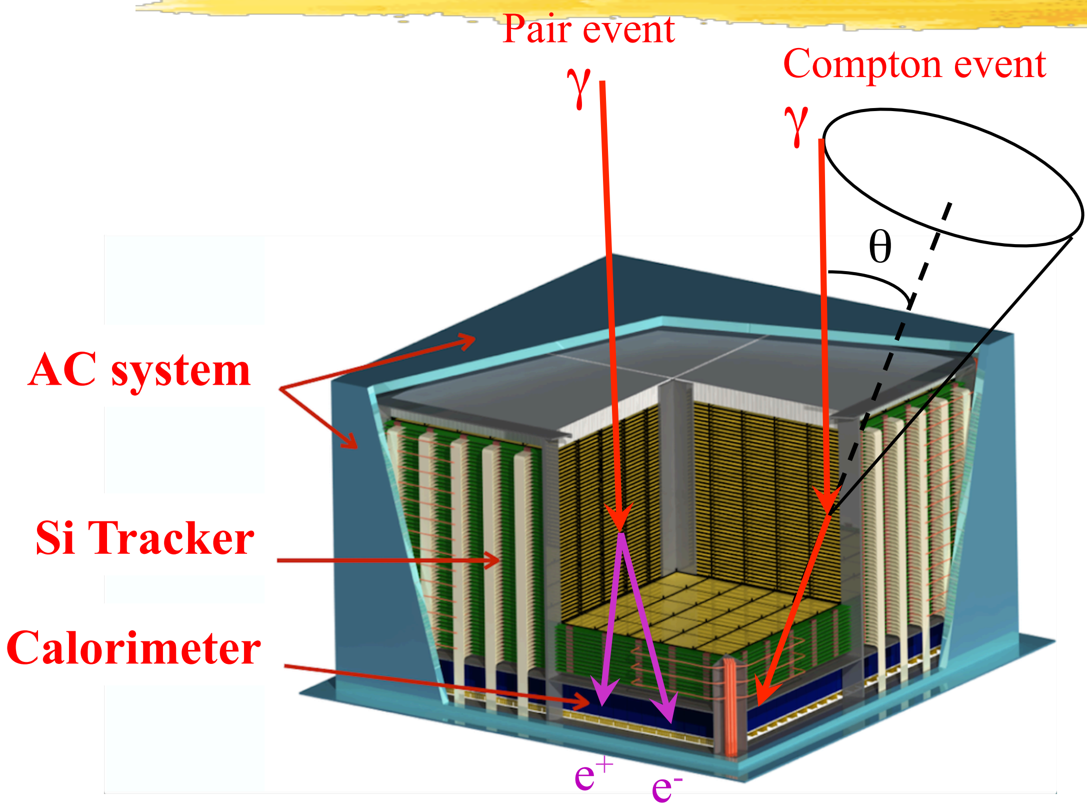
	geometric optics absorption	**quantum optics** incoherent scattering	**wave optics** coherent scattering
aperture detector			
	ex. coded masks "on-off" collimators	ex. Compton telescopes tracking chambers	ex. Laue lenses Fresnel lenses

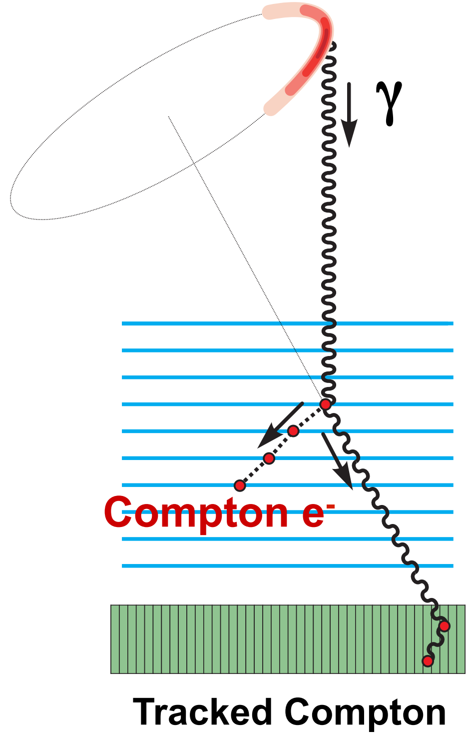
Ex: *INTEGRAL*/SPI and IBIS
☹ Background + ΔE range

Ex: *CGRO*/COMPTEL
☹ Limited angular resolution

Ex: CLAIRE (IRAP)
☹ Small field-of-view + ΔE range

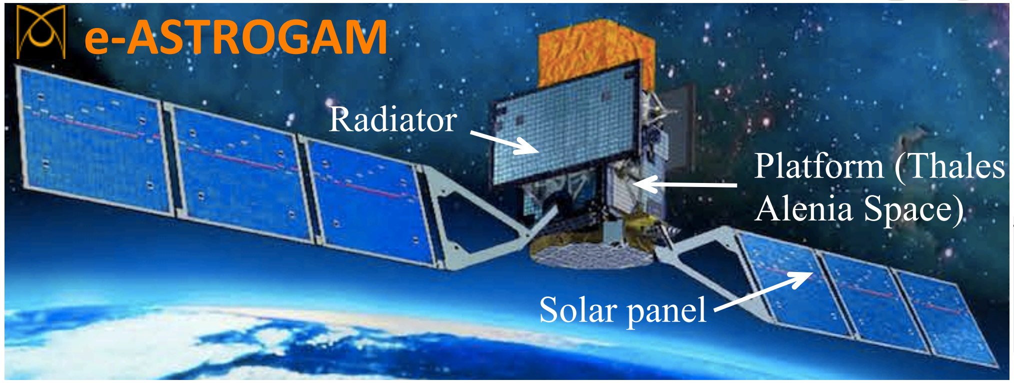
Compton and pair-creation telescope

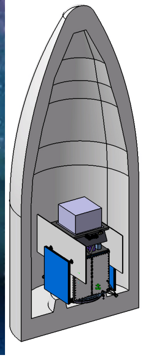


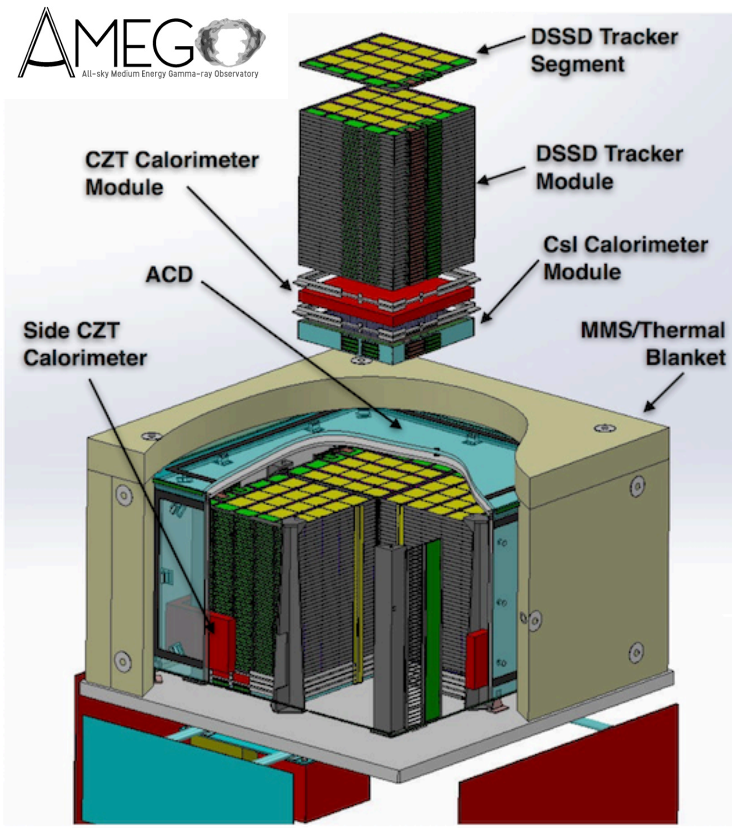


- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si Drift Diodes for better energy resolution
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by Si photomultipliers

e-ASTROGAM & AMEGO







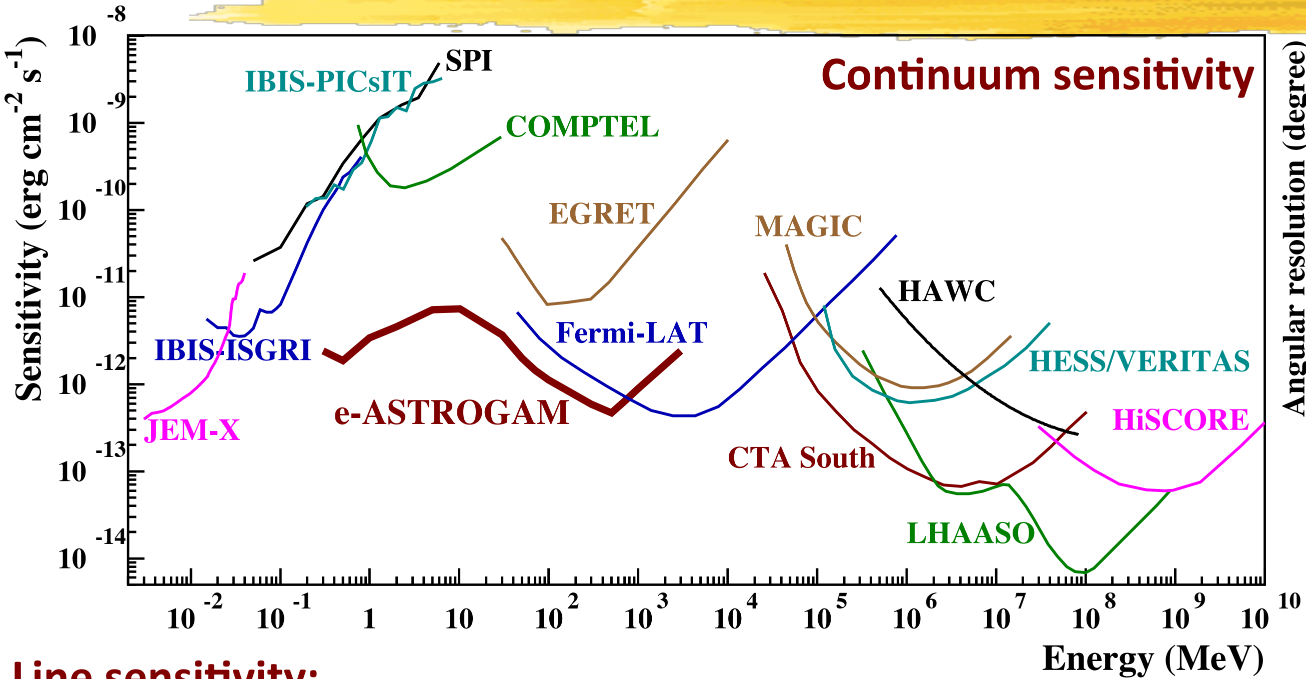
- **e-ASTROGAM Instrument**
  - **Tracker**: 56 layers of 4 times (4 towers) 5×5 DSSDs of 500 μm thickness and 240 μm pitch
  - **Calorimeter**: 33 856 CsI(Tl) bars coupled at both ends to low-noise Silicon Drift Detectors
  - **Anti-coincidence detector**: segmented plastic scintillators coupled to SiPM by optical fibers
- **Orbit** - Equatorial (inclination i < 2.5°) low-Earth orbit (altitude in the range 550 - 600 km)
- **Observation modes** - (i) zenith-pointing sky-scanning mode, (ii) nearly inertial pointing, (iii) fast repointing

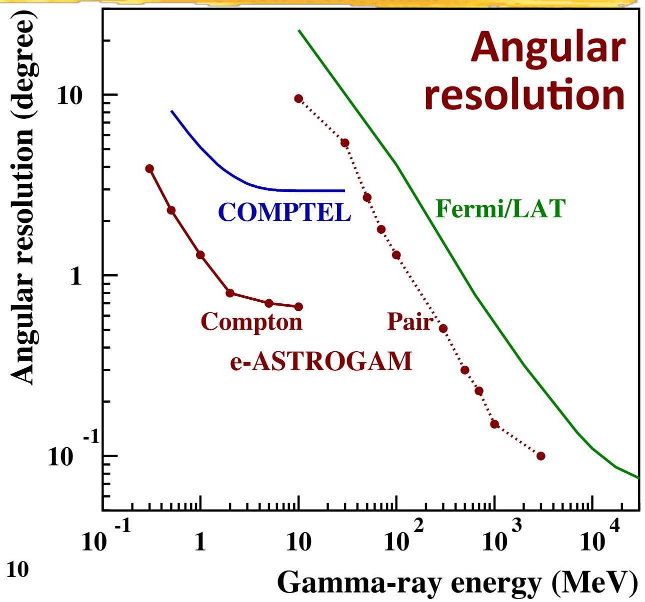
✓ **e-ASTROGAM** designed for an ESA M-size mission

✓ **AMEGO** - **A**ll-sky **M**edium **E**nergy **G**amma-ray **O**bservatory (large coll. lead by NASA/GSFC)

✓ Designed for a NASA Probe mission

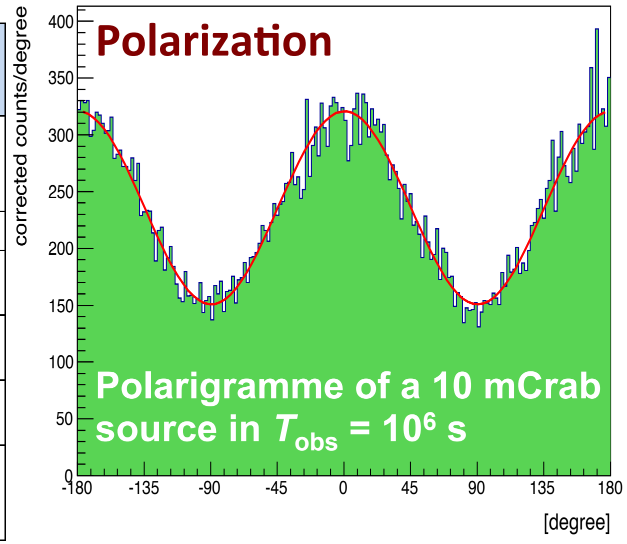
e-ASTROGAM expected performance



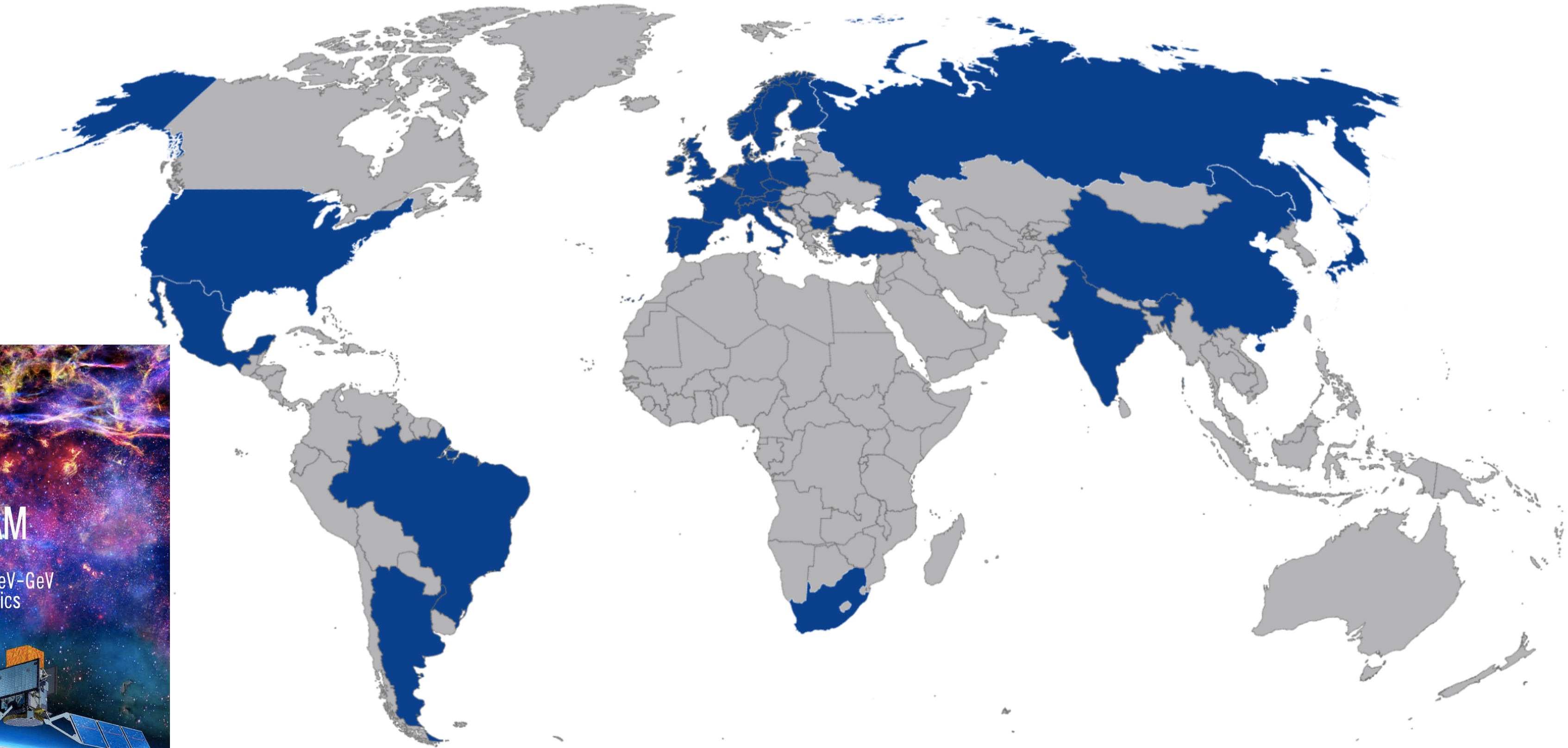


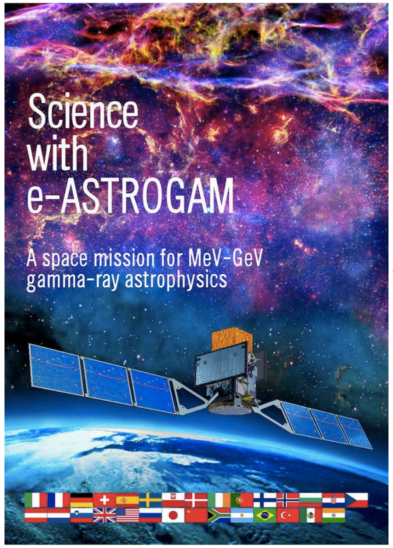
Line sensitivity:

E (keV)	FWHM (keV)	Origin	SPI sensitivity (ph cm^{-2} s^{-1})	e-ASTROGAM sensitivity (ph cm^{-2} s^{-1})	Improvement factor
511	1.3	Narrow line component of the e+/e- annihilation radiation from the Galactic center region	5.2×10^{-5}	4.1×10^{-6}	13
847	35	^{56}Co line from thermonuclear SN	2.3×10^{-4}	3.5×10^{-6}	66
1157	15	^{44}Ti line from core-collapse SN remnants	9.6×10^{-5}	3.6×10^{-6}	27
1275	20	^{22}Na line from classical novae of the ONe type	1.1×10^{-4}	3.8×10^{-6}	29
2223	20	Neutron capture line from accreting neutron stars	1.1×10^{-4}	2.1×10^{-6}	52
4438	100	^{12}C line produced by low-energy Galactic cosmic-ray in the interstellar medium	1.1×10^{-4}	1.7×10^{-6}	65



e-ASTROGAM Collaboration





- More than **400 collaborators** from institutions in 29 countries
- **Lead proposer**: A. De Angelis (INFN, It.); **Co-lead proposer**: V.T. (CNRS, Fr.)
- **Instrument paper**: Exp. Astronomy 2017, 44, 25 – https://arxiv.org/abs/1611.02232
- **Science White Book** (245 authors; 216 pages), see https://arxiv.org/abs/1711.01265