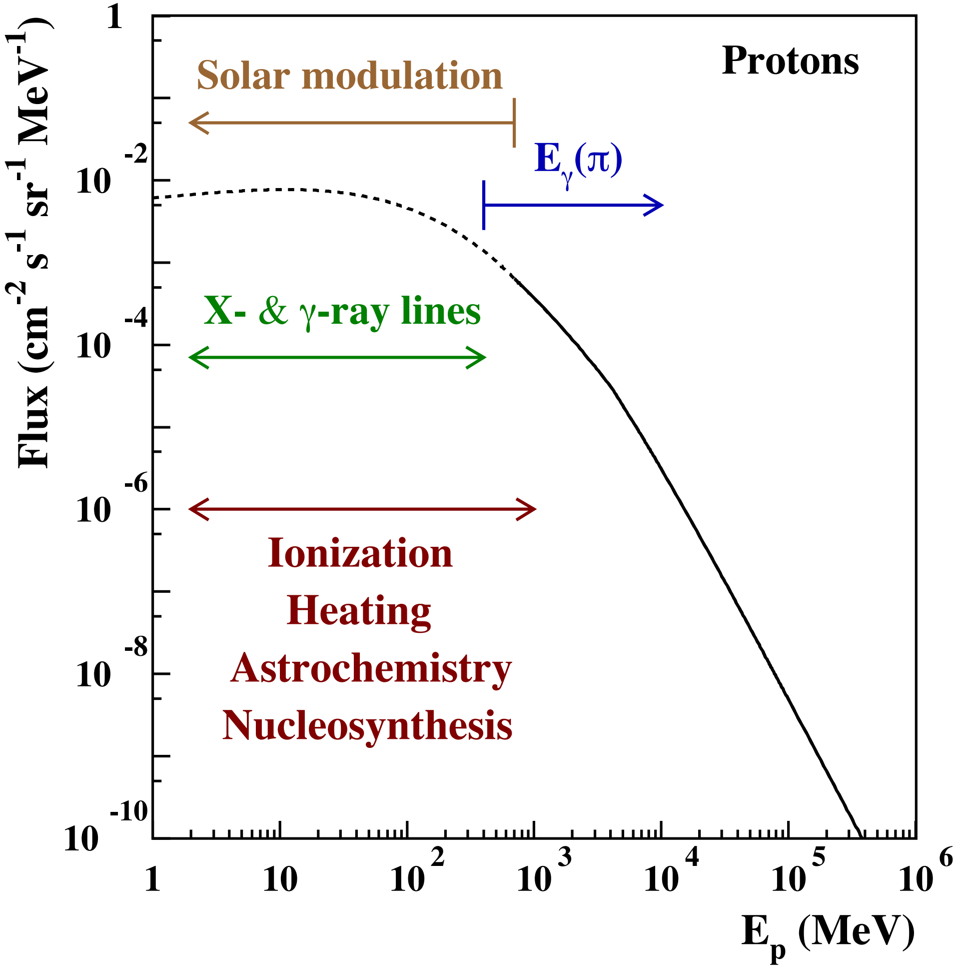
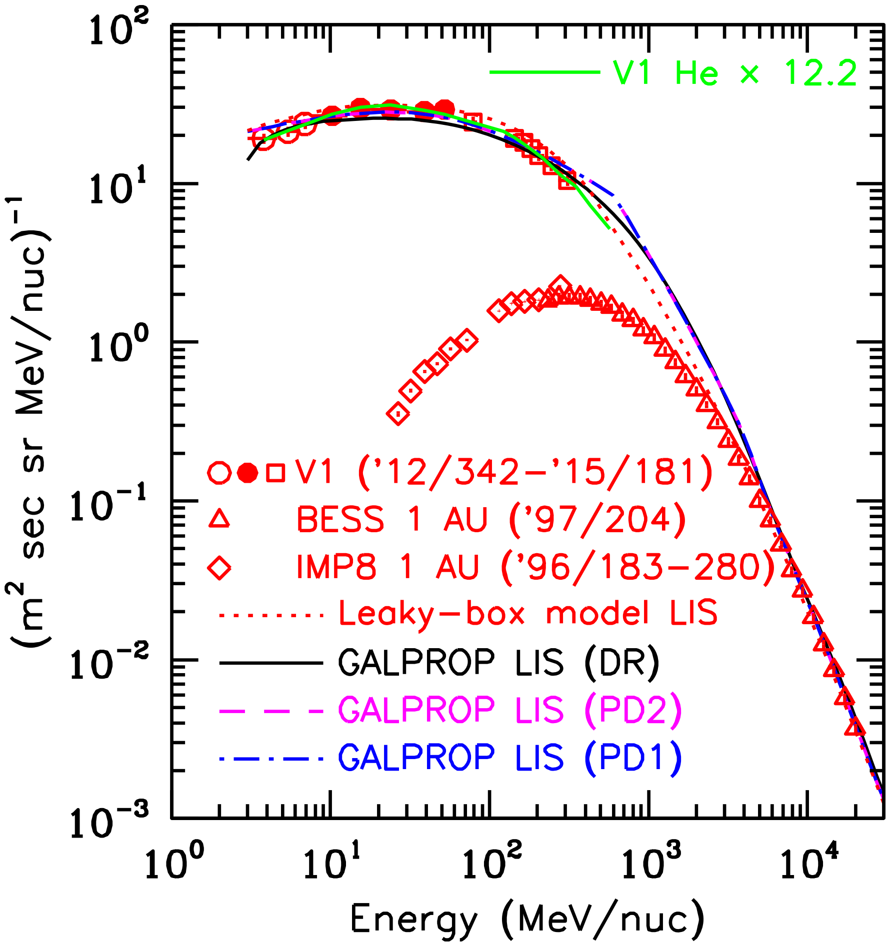
A la recherche des rayons cosmiques de basse énergie

Vincent Tatischeff (CSNSM, Orsay)



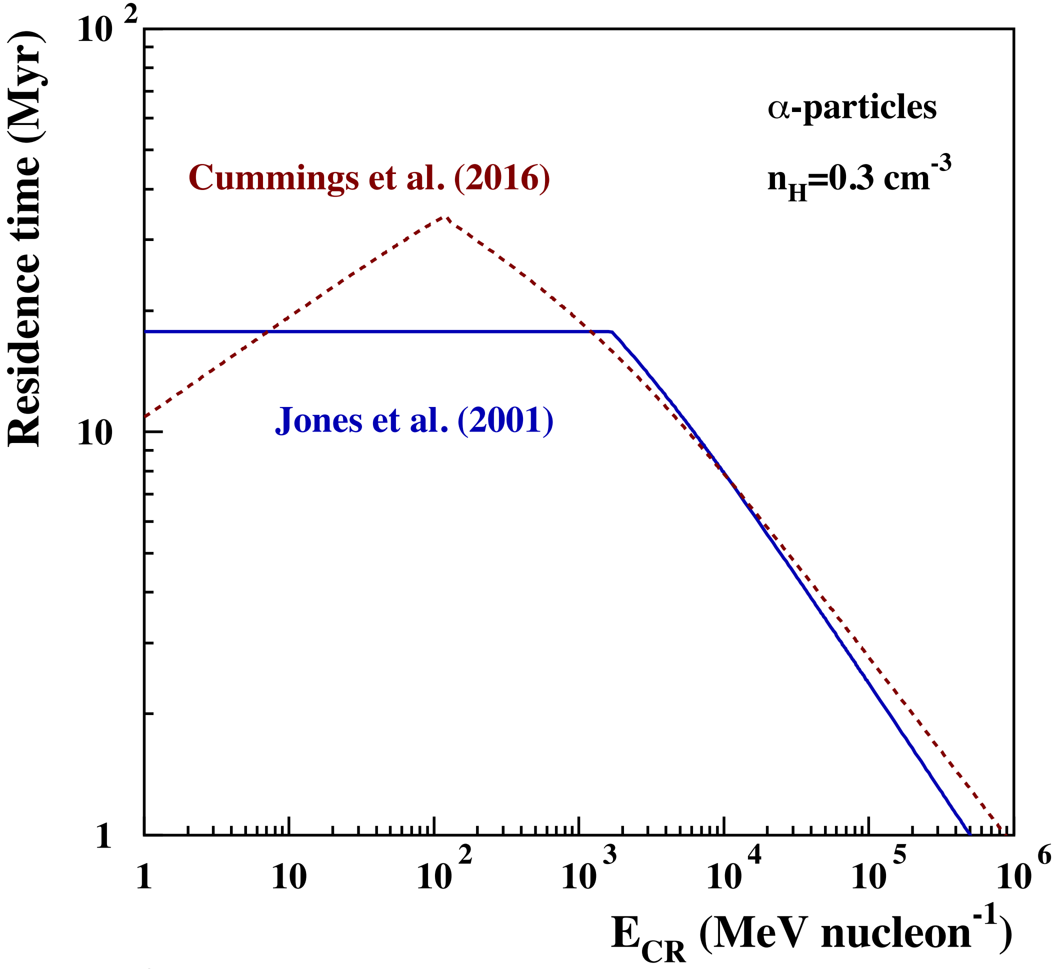
Voyager 1 probe (Cummings et al. 2016)



Model fitting to *Voyager 1* data

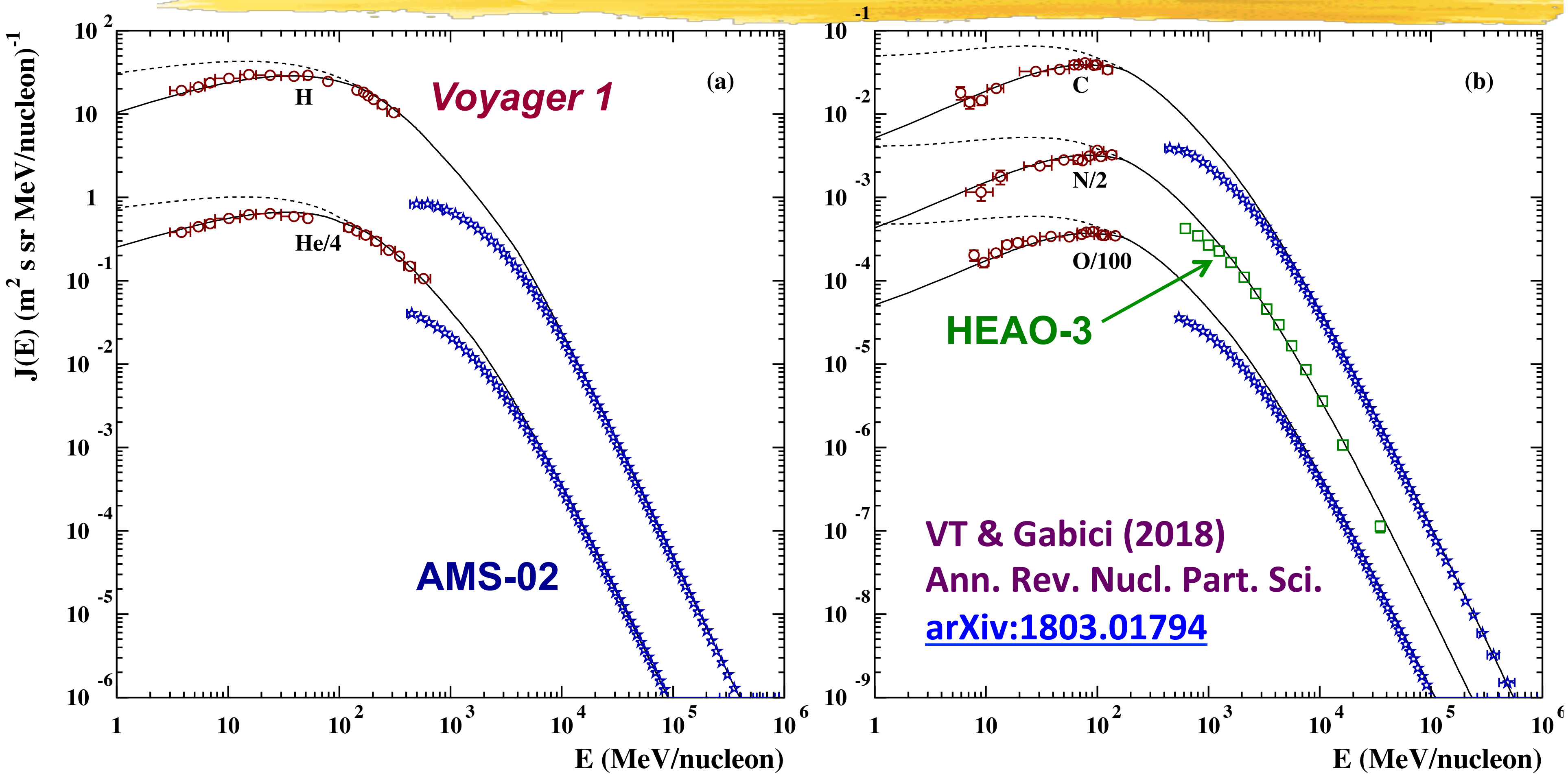
Cummings et al.(2016)

- ☐ GALPROP models:
  - Diffusive Reacceleration & Plain Diffusion models
  - Source spectra: double broken power laws in rigidity (two breaks)
  - Spatial diffusion coefficient: broken power law in rigidity
  - More than 20 free parameters per model (≠ for p, α and Z >2)!



- ☐ Leaky box model:
  - Source spectra: power laws in rigidity
  - Non standard path length $\propto \beta^{3/2}$ at low rigidities

New fits to *Voyager 1* and AMS-02 data



VT & Gabici (2018)
Ann. Rev. Nucl. Part. Sci.
arXiv:1803.01794

- CR path length from Jones et al. (2001) (disk-halo diffusion ≡ leaky-box model)
- Fits to AMS-02 data with a power-law in momentum per nucleon: $q_{\mathrm{h.e.}}=4.3$
- Break for all species $E_{\mathrm{break}} = 200$ MeV/nucleon, with: $q_{\mathrm{l.e.}}=3.75$ for H-He, 3.0 for CNO

Spectrum of CRs released in the ISM

☐ **Isolated supernova remnants:**

- During the **Sedov phase**, the spectrum of escaping particle has the **same shape** than that found at SNR shock
- **At the end of the Sedov phase**, hardening of the spectrum below $E_{\mathrm{break}}=E_{\mathrm{max}}(t_{\mathrm{rad}})$ due to (i) the radiative energy losses, (ii) the increase of the shock compression factor, (iii) the decline of the acceleration efficiency, (iv) the Coulomb losses of the CRs trapped in the SNR

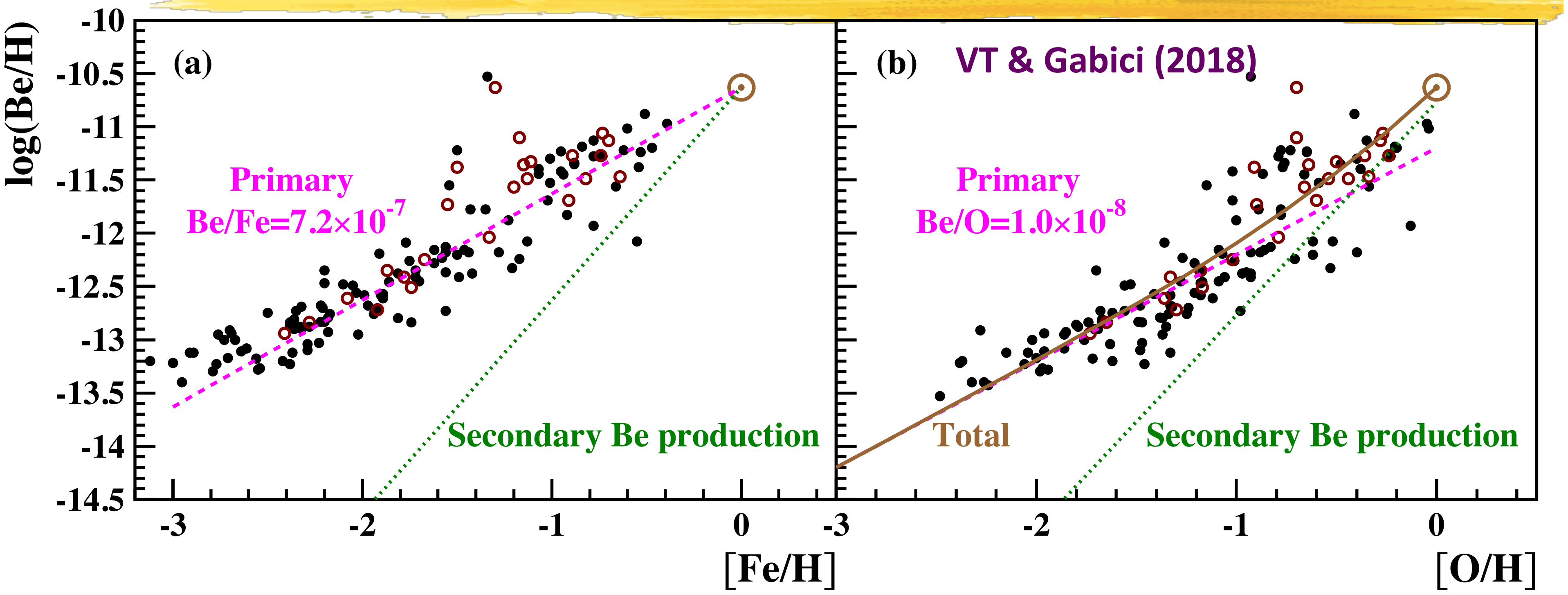
☐ **Cosmic-ray acceleration in superbubbles:**

- At high energies, diffusive shock acceleration at individual SNRs
- Hardening of the spectrum at low energies due to the diffusion of CRs through multiple shocks (see Bykov & Fleishman 1992)

$$f_0(p) = \frac{q\,Q_0}{4\pi p_{\mathrm{inj}}^3 u_s}\left(\frac{p}{p_{\mathrm{inj}}}\right)^{-q} \quad \text{where} \quad q = 3 + \frac{P_{\mathrm{esc}}}{\beta_{\mathrm{acc}}} = \frac{3r}{r-1}$$

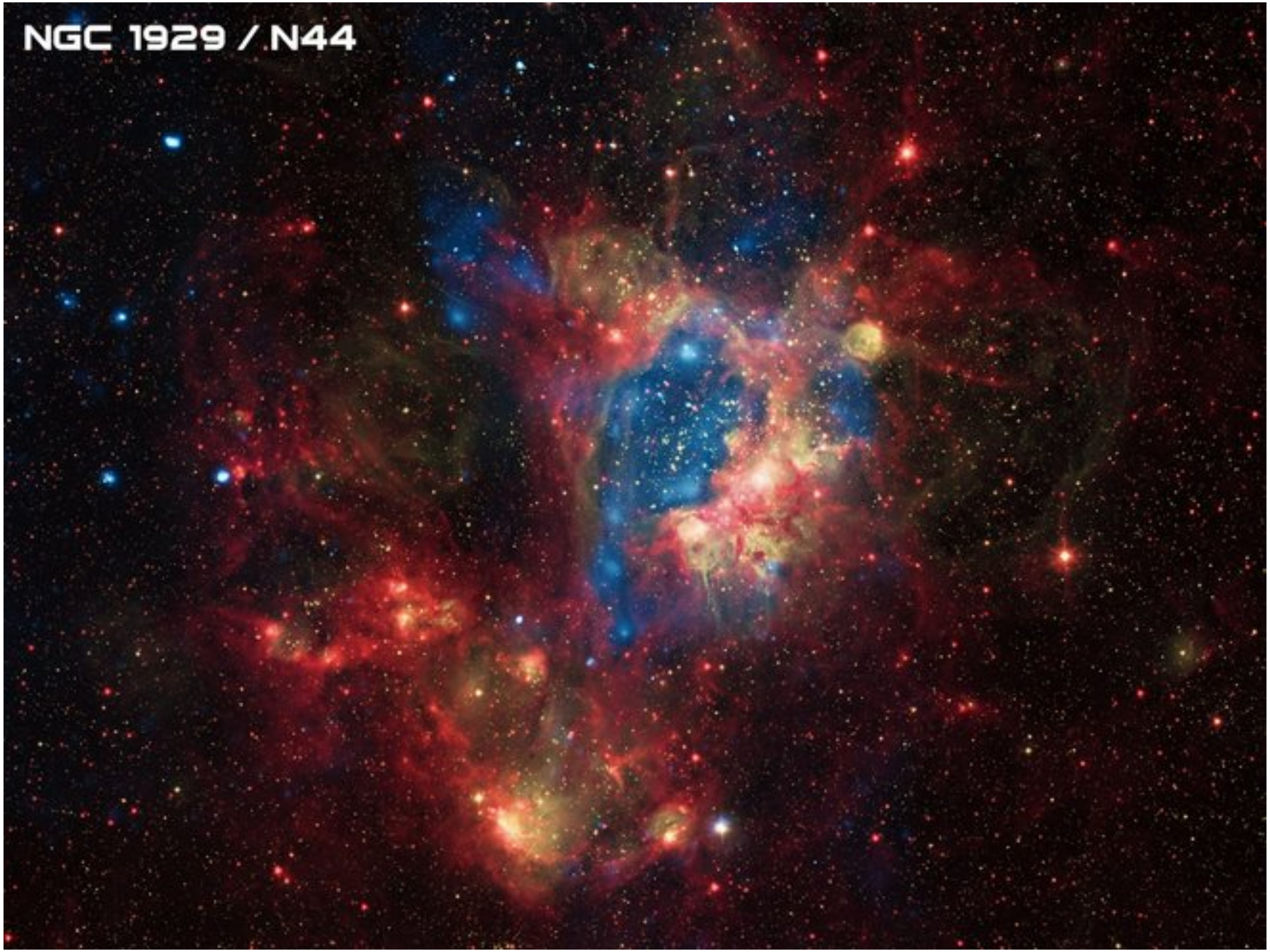
⇒ $f_0(p) \propto p^{-q}$ with $q = 3$ (i.e. $Q(E) \propto E^{-1}$) when $P_{\mathrm{esc}} \rightarrow 0$

Be evolution and cosmic-ray origin



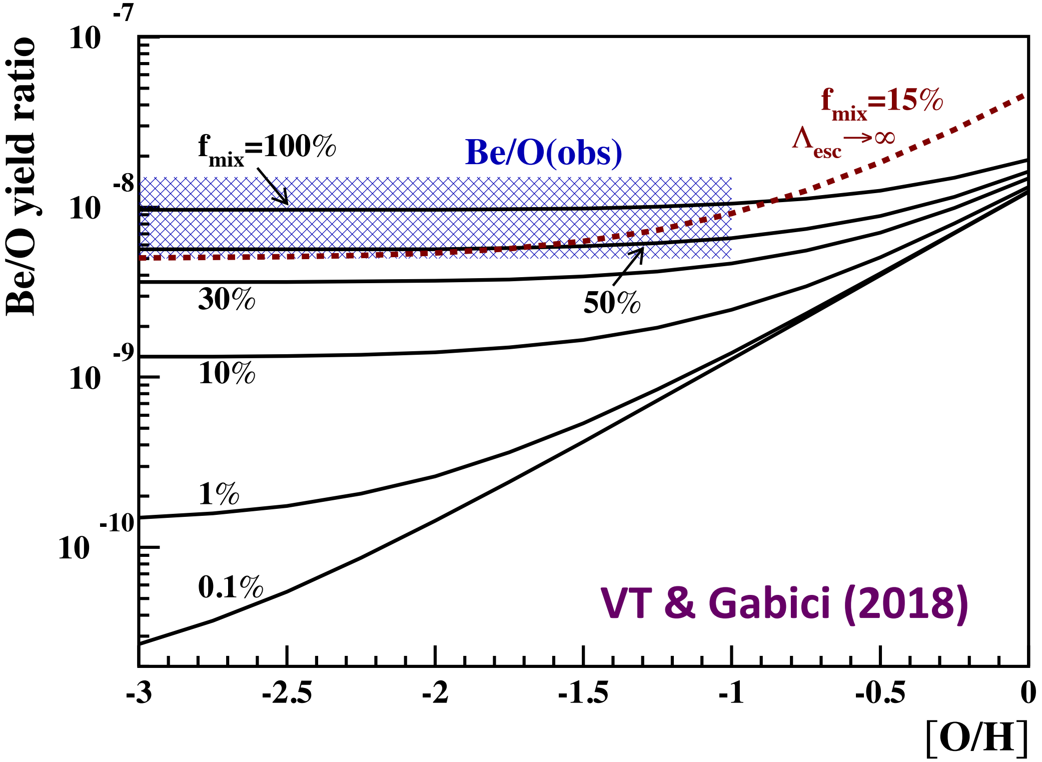
- Oxygen is a better indicator of Be nucleosynthesis (CNO spallation) than Fe
- Primary Be production up to [O/H] ~ -0.5, i.e. during the Galactic halo phase
- With the best fit ratio Be/O = 1.0 x 10^{-8} and the mean O yield of $1.2\ M_{\rm sol}$ per core-collapse SN: $Q_{\rm Be} \sim 10^{48}$ atoms per SN in the early Galaxy
- With current-epoch GCR (compo. + *Voyager* spect.): $Q_{\rm Be}/W \sim 10^{-2}$ Be/erg
- **Required CR energetics with present GCR: $W_{\rm SN} \sim 10^{50}$ erg per SN**

Cosmic-ray acceleration in superbubbles?



Cosmic-ray acceleration in superbubbles?

- In the early Galaxy, Be was mainly produced by spallation of fast CNO that were much more abundant in the GCR than in the average ISM at that time
- In the superbubble model, CRs are accelerated out of a mix of fresh ejecta from massive stars / SNe with average ISM material ($f_{\mathrm{mix}} \sim 20\%$ according to Lingenfelter & Higdon 2007; Binns et al. 2008; Murphy et al. 2016)



- The superbubble model could explain the observed Be/O ratio if (i) the GCRs were **more confined in the halo phase of the Milky Way** (closed-Galaxy model) and (ii) $f_{\mathrm{mix}} > \sim 15\%$
- But it cannot explain the GCR ^{22}Ne / ^{20}Ne ratio of (5.3 ± 0.3) times solar (Prantzos 2012)

Low-energy cosmic rays in the ISM

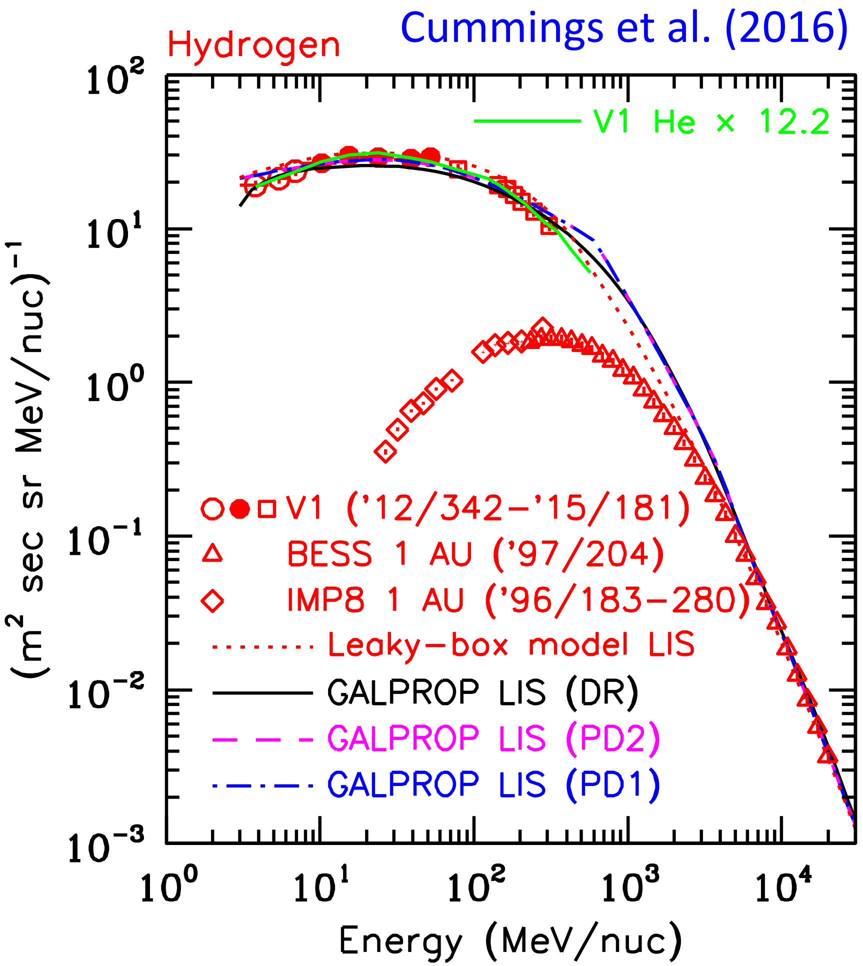
- Production of Be by a distinct component of low-energy cosmic rays?

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

⇒ CR ioni. rate: $\zeta_H=(1.51-1.64)\times10^{-17}\,\mathrm{s}^{-1}$, 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?



Cummings et al. (2016)

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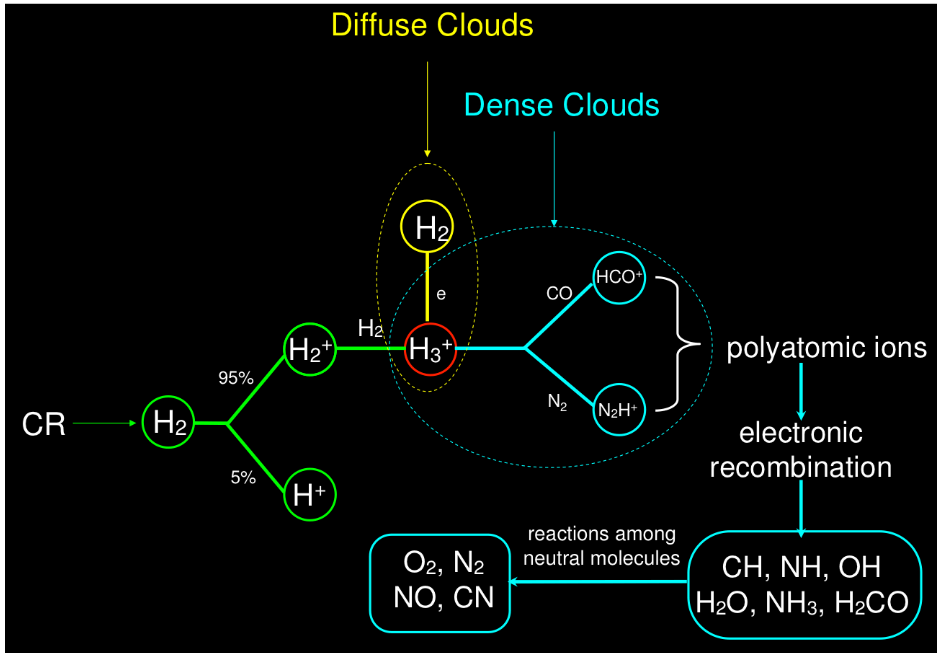
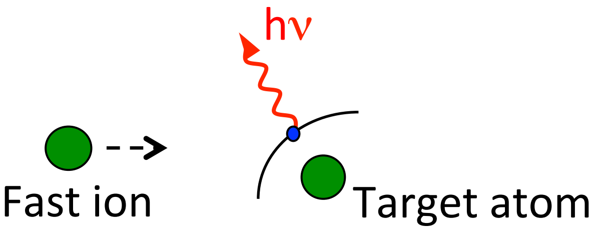
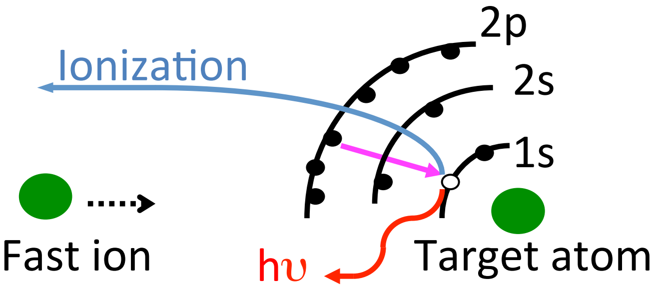


Non-thermal X-ray emission

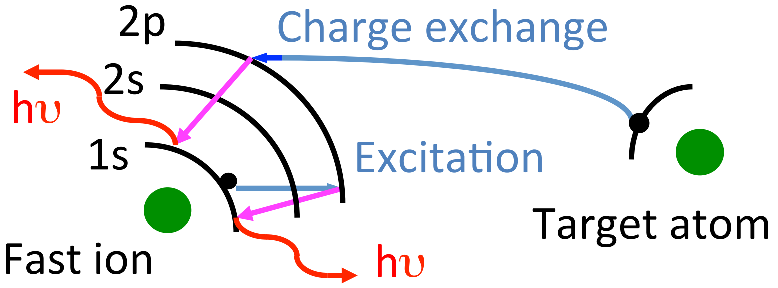
- Continuum: Inverse Bremsstrahlung (+ Bremsstrahlung from secondary e$^-$)



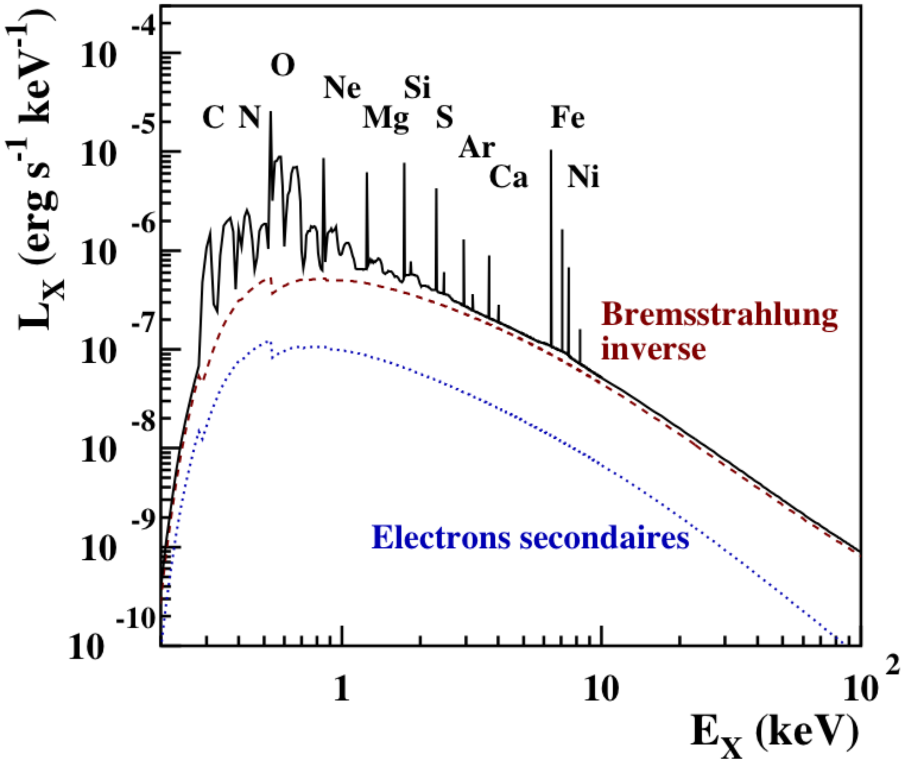
- Narrow lines: collisional inner-shell ionization



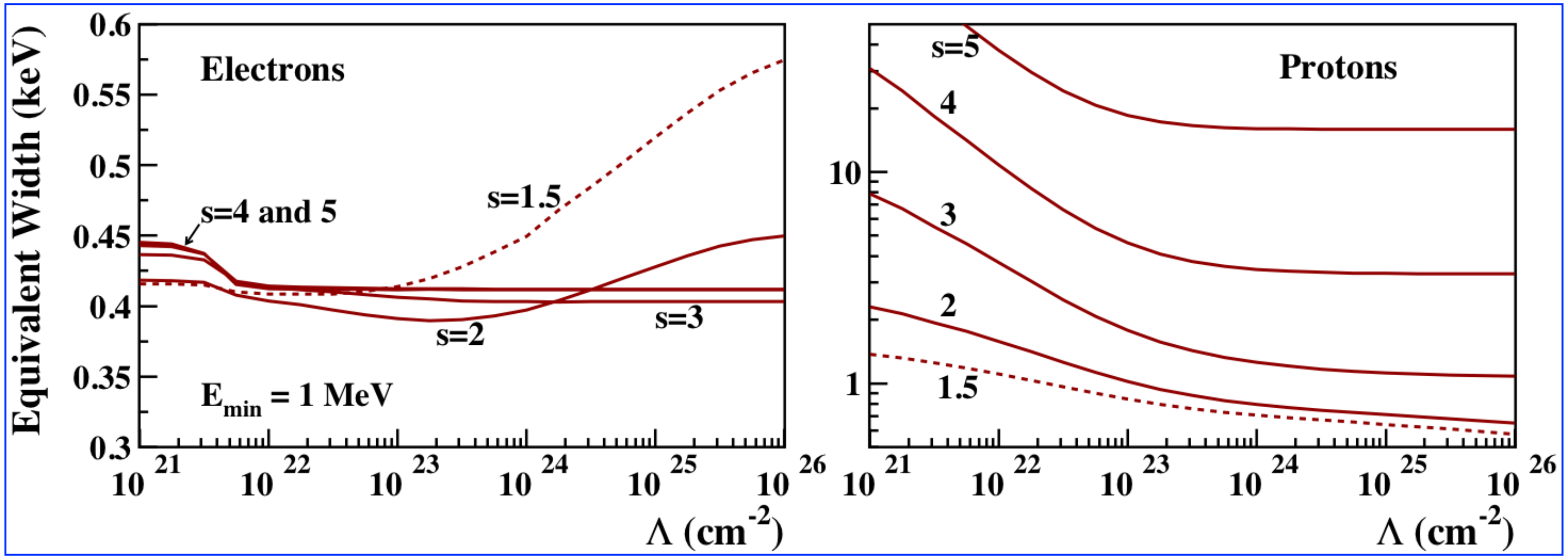
- Broad lines: charge exchange

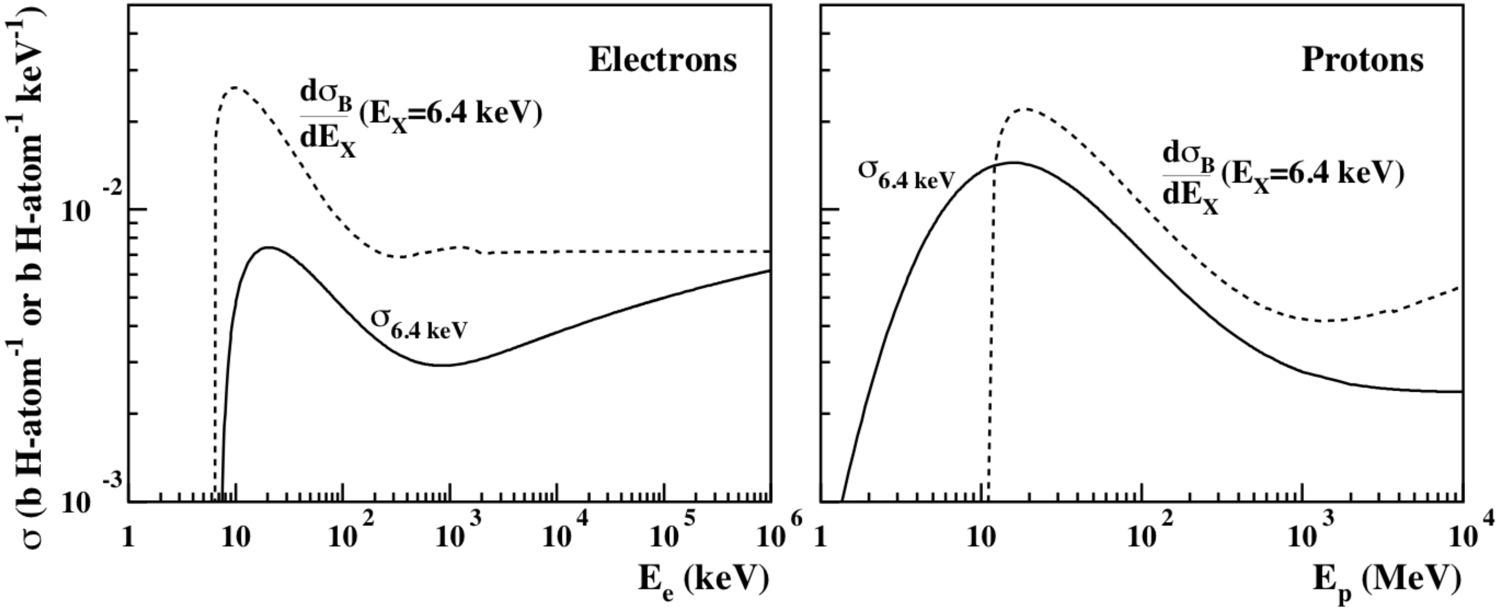


⇒ Generic, steady-sate, slab models for CR ions and e$^-$ in XSPEC (VT et al. 1998, 2012)



6.4 keV line from LECR protons / electrons



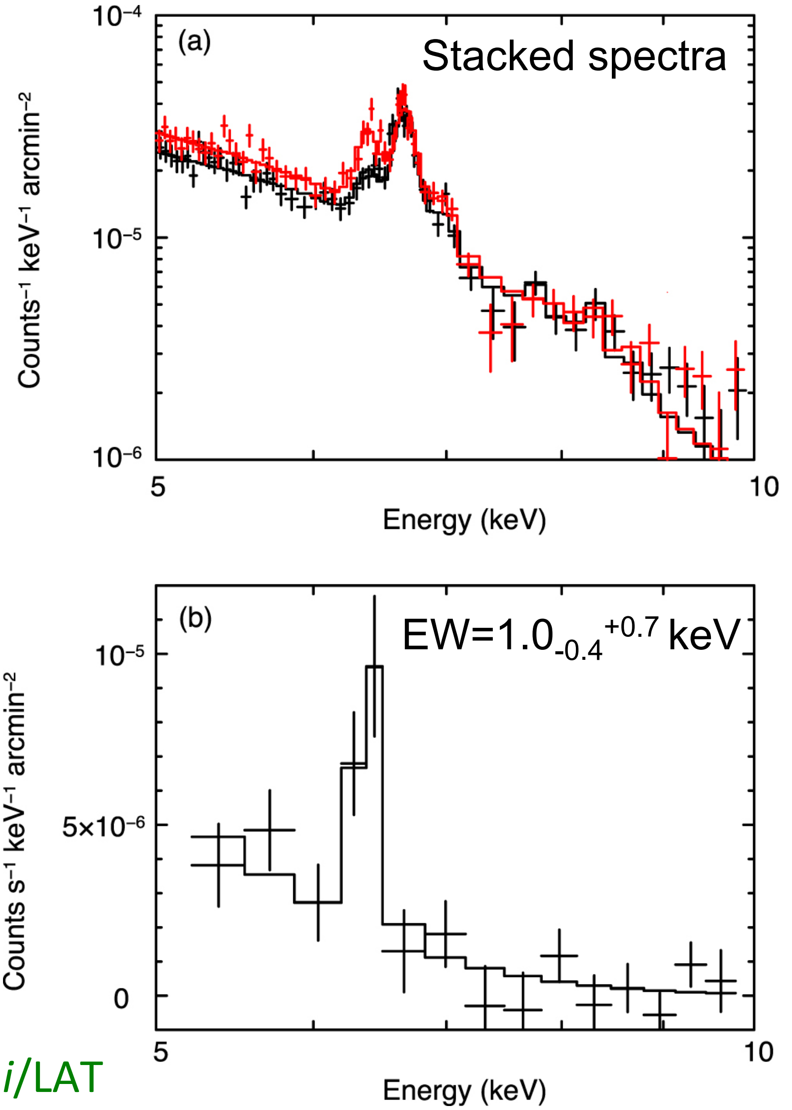


Contrary to e^-, LECR protons can produce large EW of the 6.4 keV line for soft source spectra

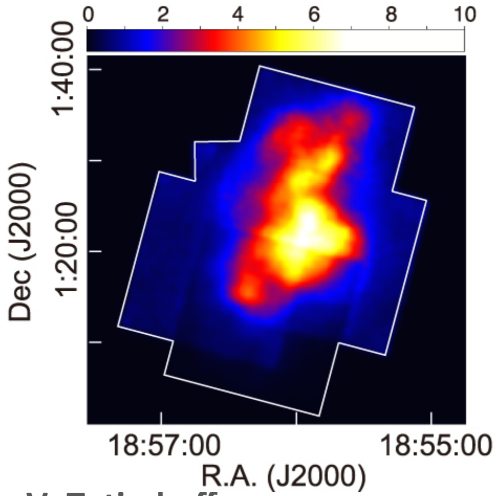
6.4 keV line from supernova remnants

Nobukawa et al. (2018, ApJ 854:87)

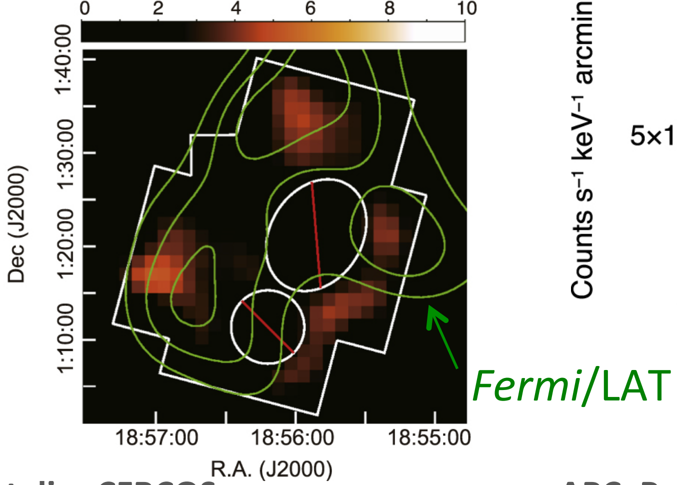
- From *Suzaku* archive, **Fe I Kα line** found in **five SNRs** interacting with molecular clouds: W28, Kes 67, Kes 69, Kes 78 and W44
- Spectra and morphologies suggest the line is produced by LECRp, with an estimated proton energy density $\gtrsim 10 - 100$ eV cm^{-3}
- Should be checked with *XMM-Newton*



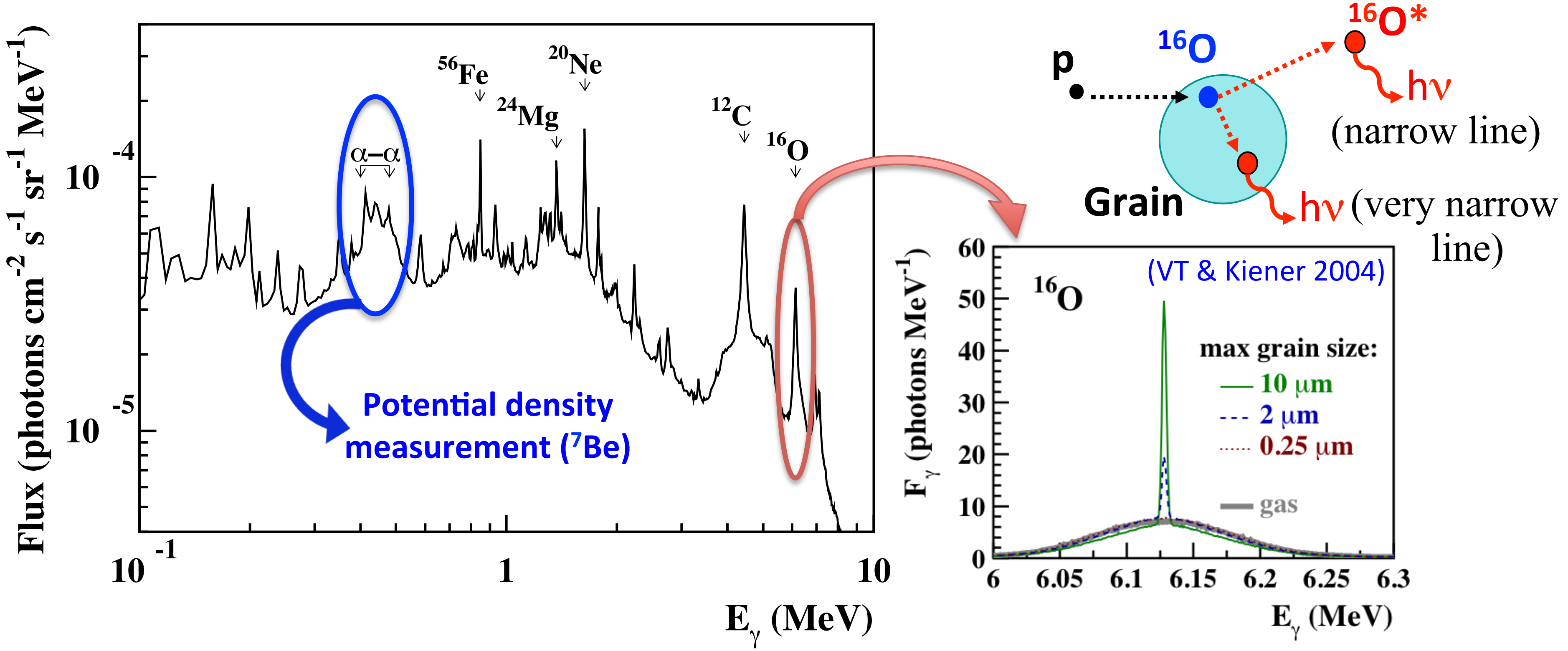
W44 (0.5 – 2 keV)



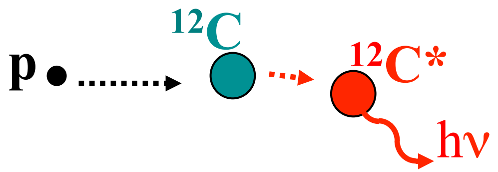
W44 (6.2 – 6.5 keV)



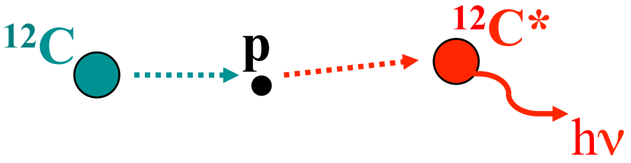
γ-ray line spectrum from energetic collisions



- Narrow lines: e.g. $^{12}\mathrm{C}(p,p')^{12}\mathrm{C}^*_{4,439}$, $^{12}\mathrm{C}(p,2pn)^{10}\mathrm{B}^*_{0,718}$

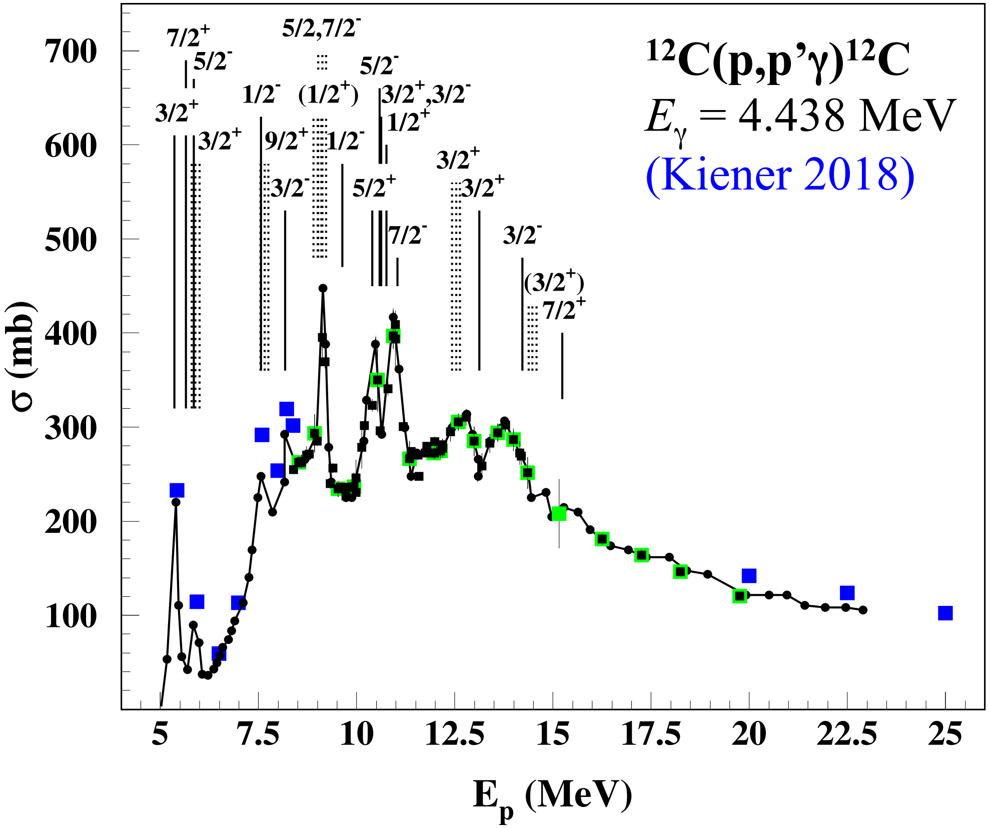


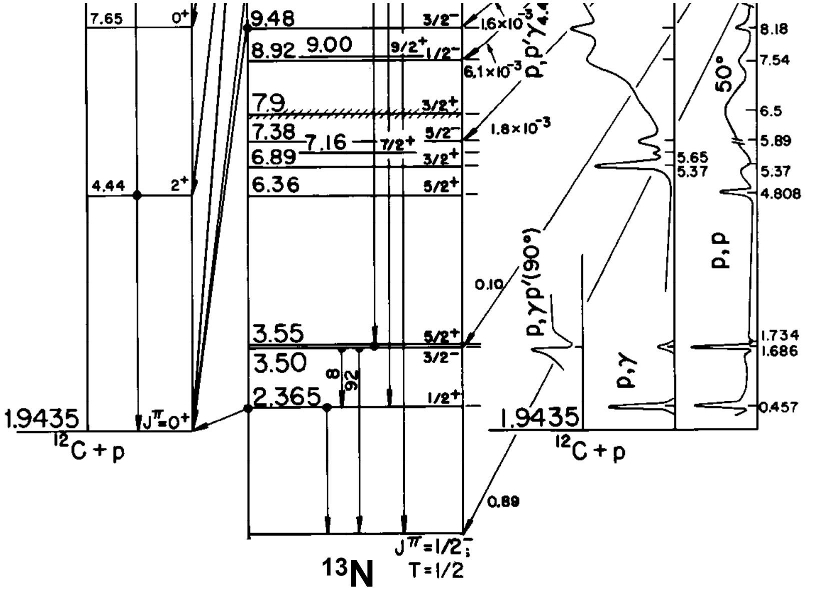
- Broad lines: e.g. $^{1}\mathrm{H}(^{12}\mathrm{C},^{12}\mathrm{C}^*_{4.439})^{1}\mathrm{H}$
- α-α line: $^{4}\mathrm{He}(\alpha,n)^{7}\mathrm{Be}^*_{0,429}$ and $^{4}\mathrm{He}(\alpha,p)^{7}\mathrm{Li}^*_{0,478}$



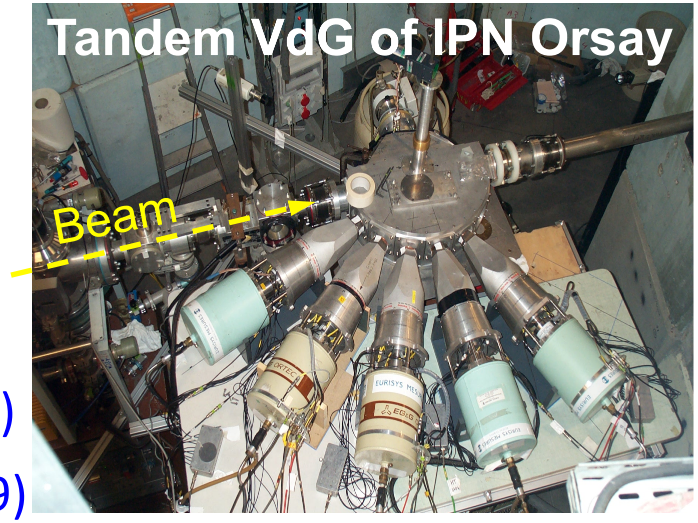
\+ the 511 keV line (not shown)

Nuclear excitation cross sections





- Inelastic nuclear collisions: p, α + He, C, O, Ne…, Fe
- **Orsay experiments** (+TALYS and EMPIRE): 82 lines in p reactions, 73 lines in α reactions (Kiener et al. 2012)
- Data evaluation and compilation: Murphy et al. (2009)

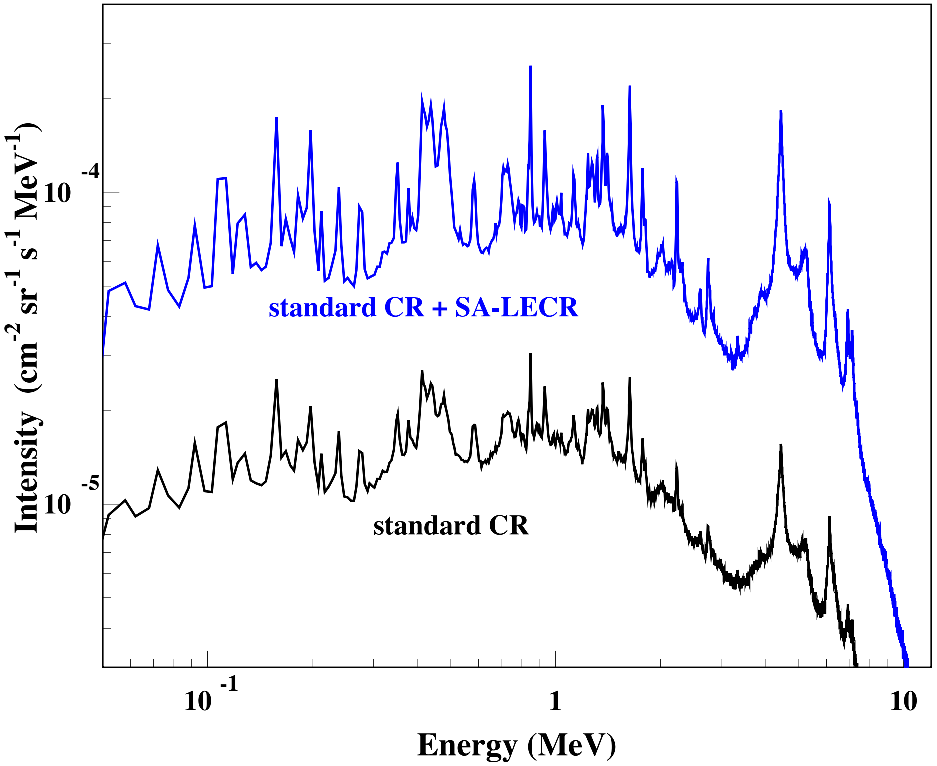


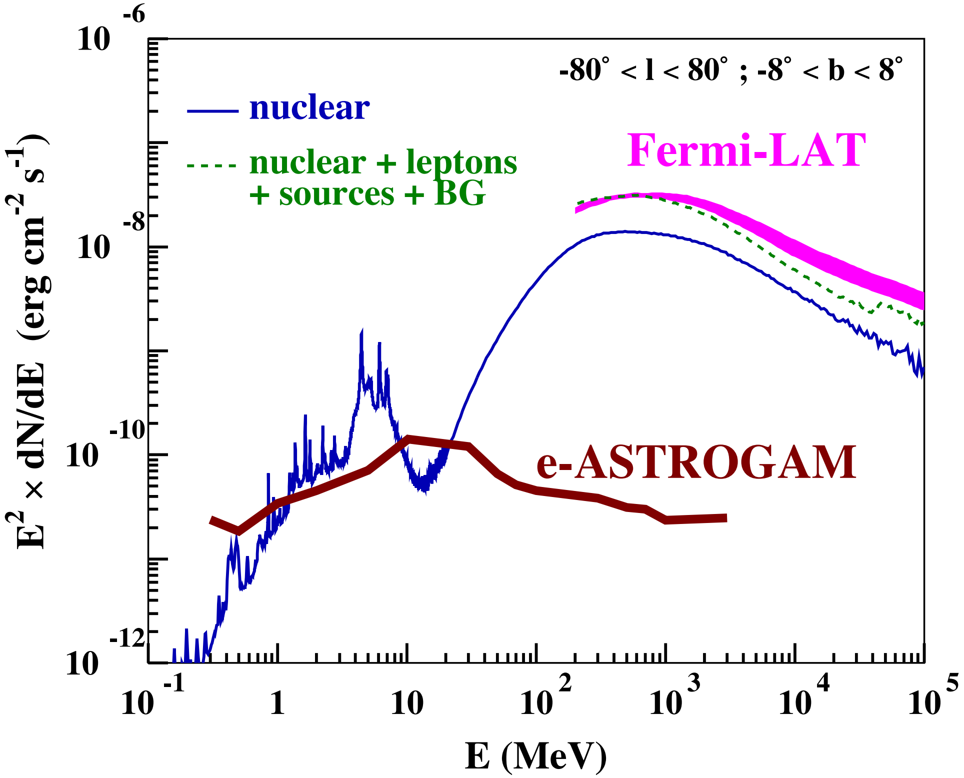
Gamma-ray lines from LECRs - Prediction

- Benhabiles-Mezhoud et al. (2013): CR spectrum with a low-energy component accounting for the observed mean **CR ionization rate** and the **Fermi-LAT data** (i.e. independent of the ambient medium column density)

⇒ Predicted fluxes from the inner Galaxy ($|l| \leq 80°$; $|b| \leq 8°$):

$F_\gamma(4.4\ \mathrm{MeV}) = (0.1 - 2.0) \times 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$; $F_\gamma(3 - 8\ \mathrm{MeV}) = (0.3 - 2.1) \times 10^{-4}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

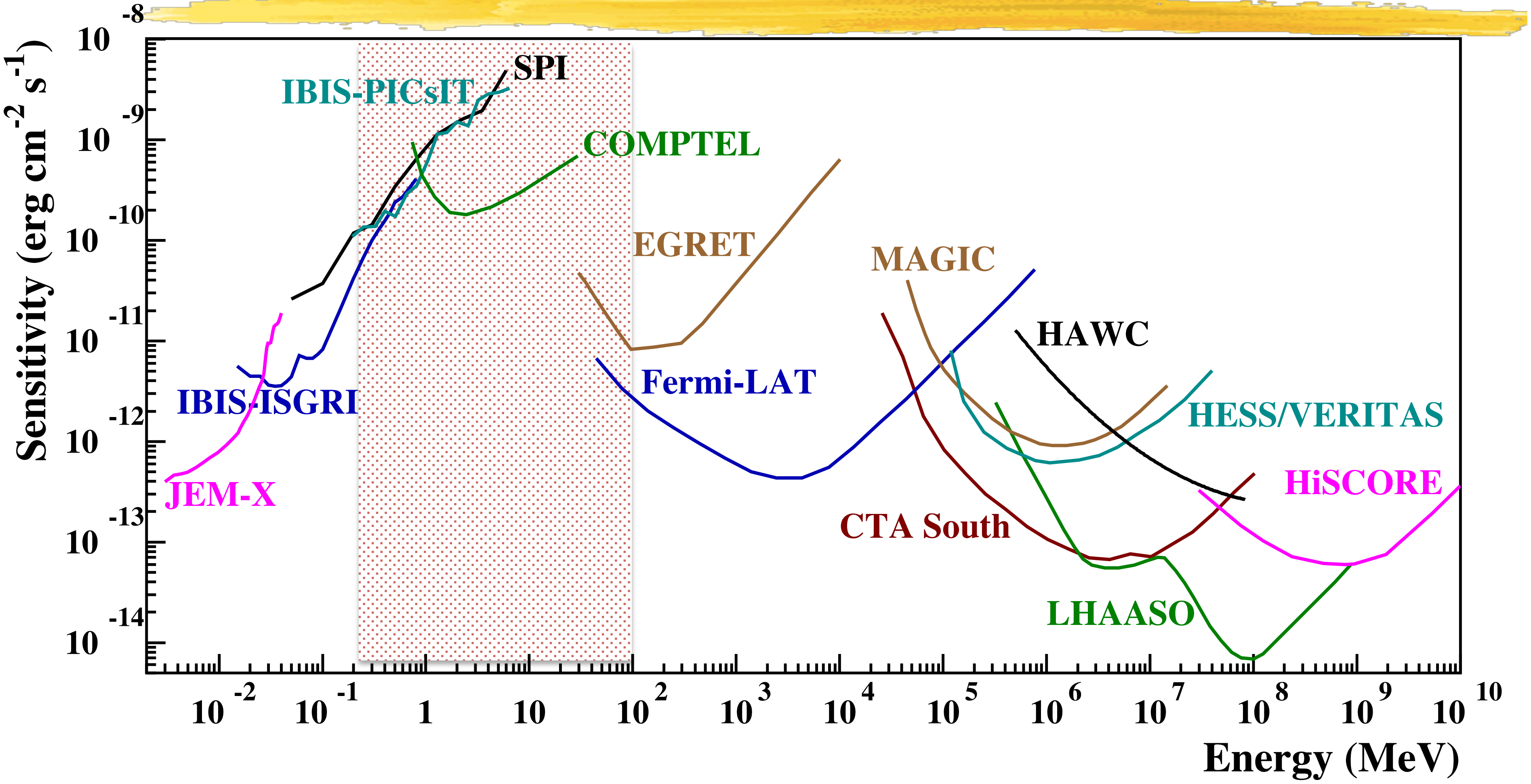




e-ASTROGAM

- ESA M5 proposal
- Passed the technical down-selection to 13 best candidates
- 3 missions to be selected for a phase A (decision next May)
- Launch in 2030…

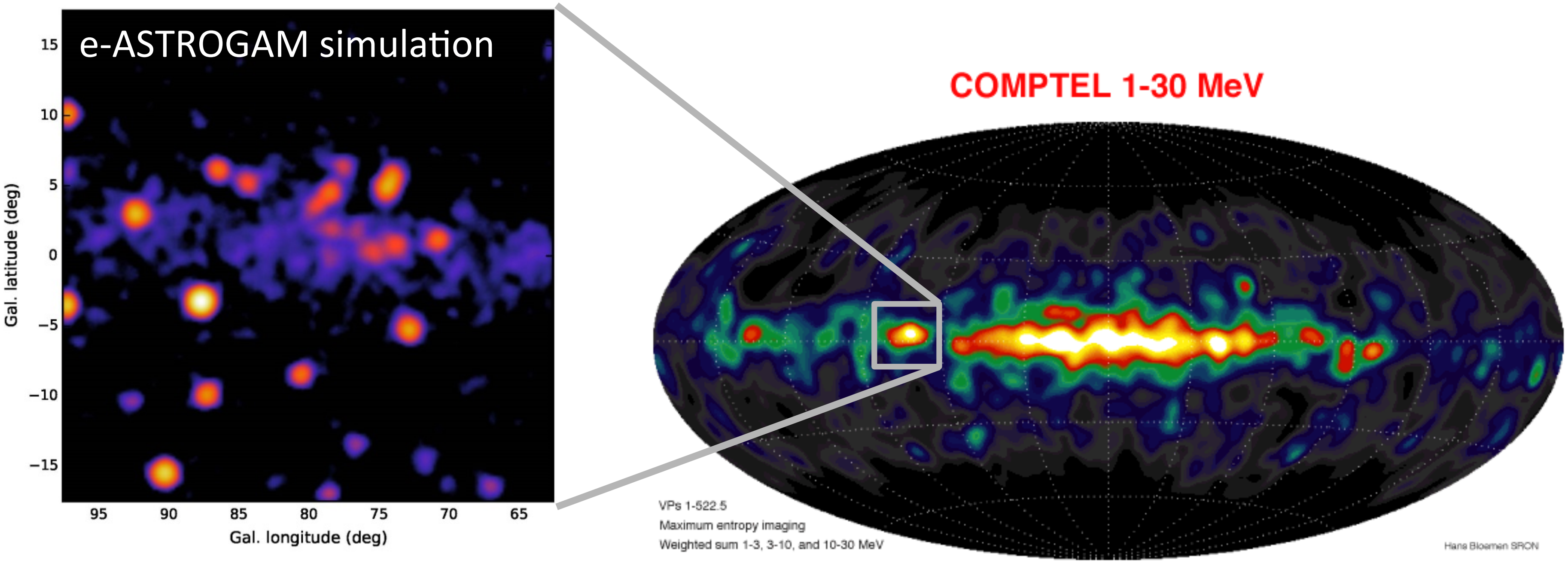
The MeV/sub-GeV γ-ray astronomy domain



- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have peak emissivity in this range (GRBs, FSRQs, some pulsars...)

Scientific requirements for a new γ-ray mission

1. Broad spectral range (~ 100 keV – few GeV) with excellent sensitivity in the 1-30 MeV energy domain (better than CGRO/COMPTEL by a factor of 50 - 100)
2. Gamma-ray polarization for both transient and steady sources
3. Improve angular resolution close to the physical limit (Doppler broadening)
4. Large field of view (e.g. ~ 2.5 sr) for an efficient monitoring of the γ-ray sky
5. Sub-millisecond trigger and alert capability for transients (e.g. GW events)

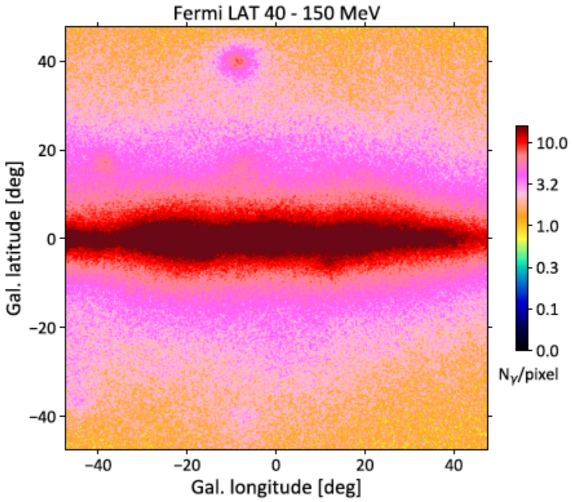


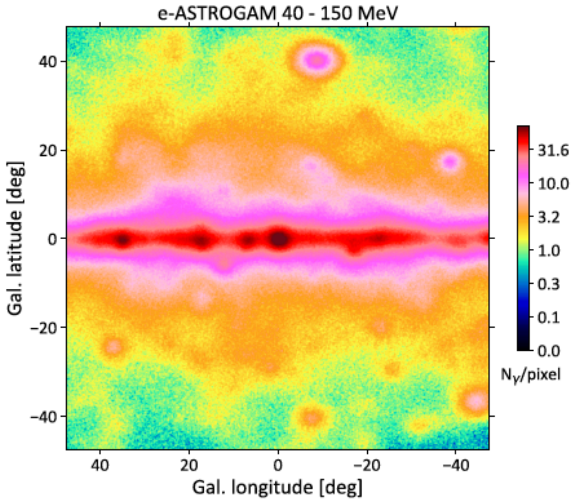
e-ASTROGAM: Core science motivation

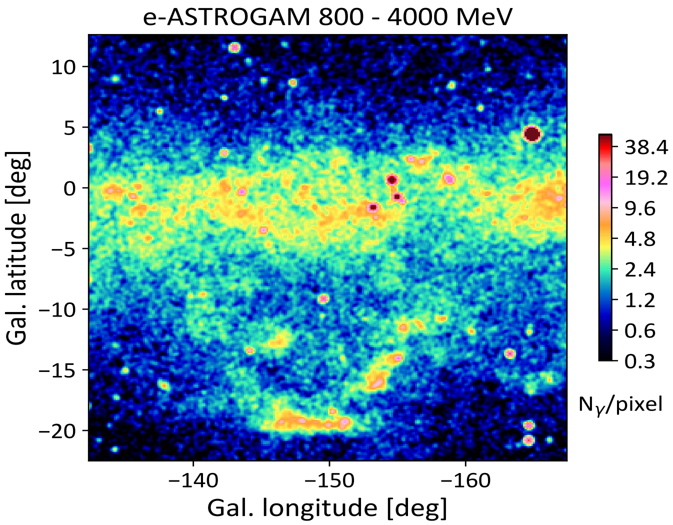
1. **Extreme extragalactic Universe** (active galactic nuclei, gamma-ray bursts) and the link to **new messenger astronomies** (gravitational waves, neutrinos, ultra-high energy cosmic rays)

2. Origin & impact of **cosmic-ray particles** on **Galaxy evolution**

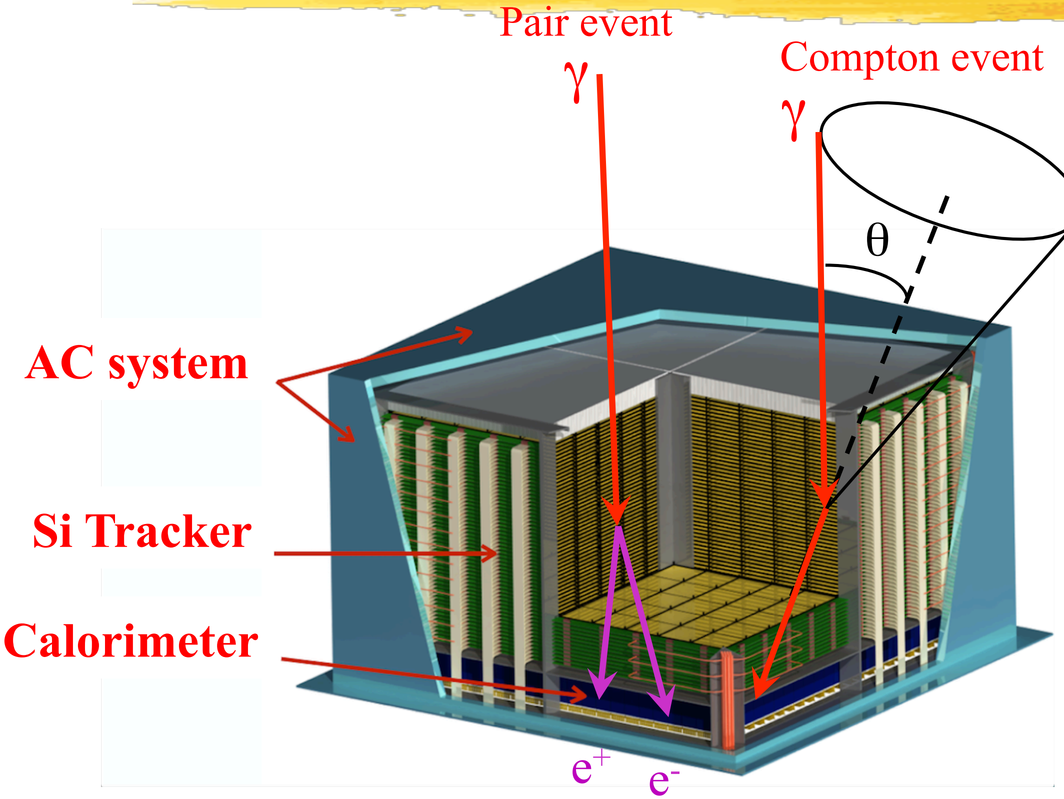
3. **Supernovae, nucleosynthesis** & **cosmic evolution** of matter

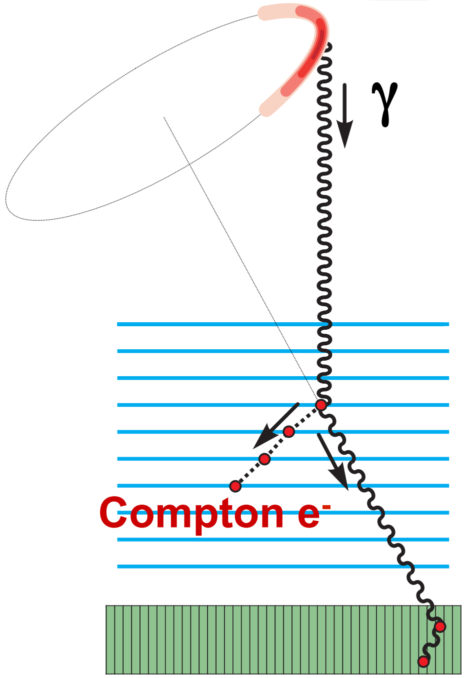






Compton and pair-creation telescope

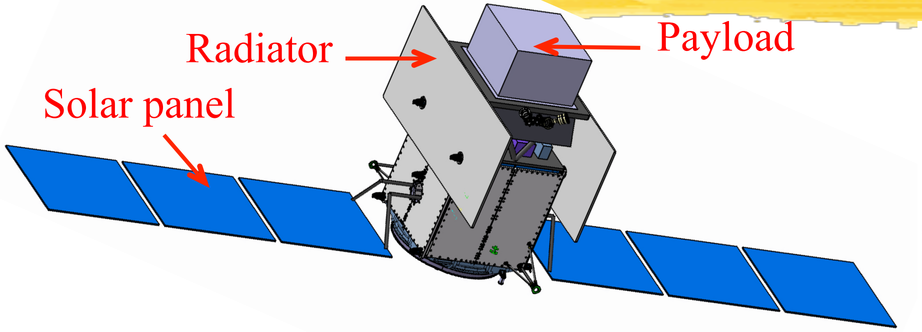


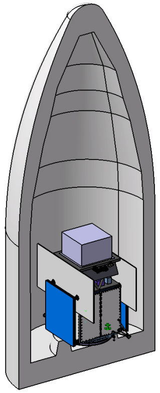


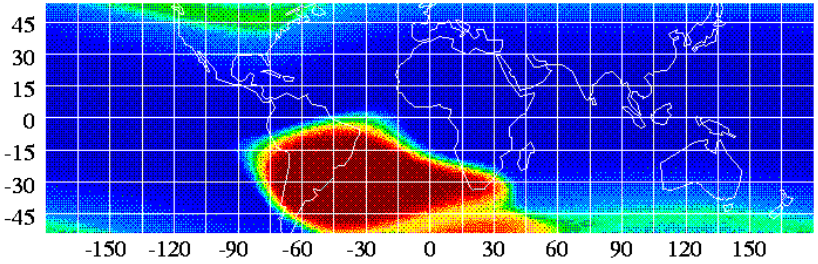
Tracked Compton

- **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

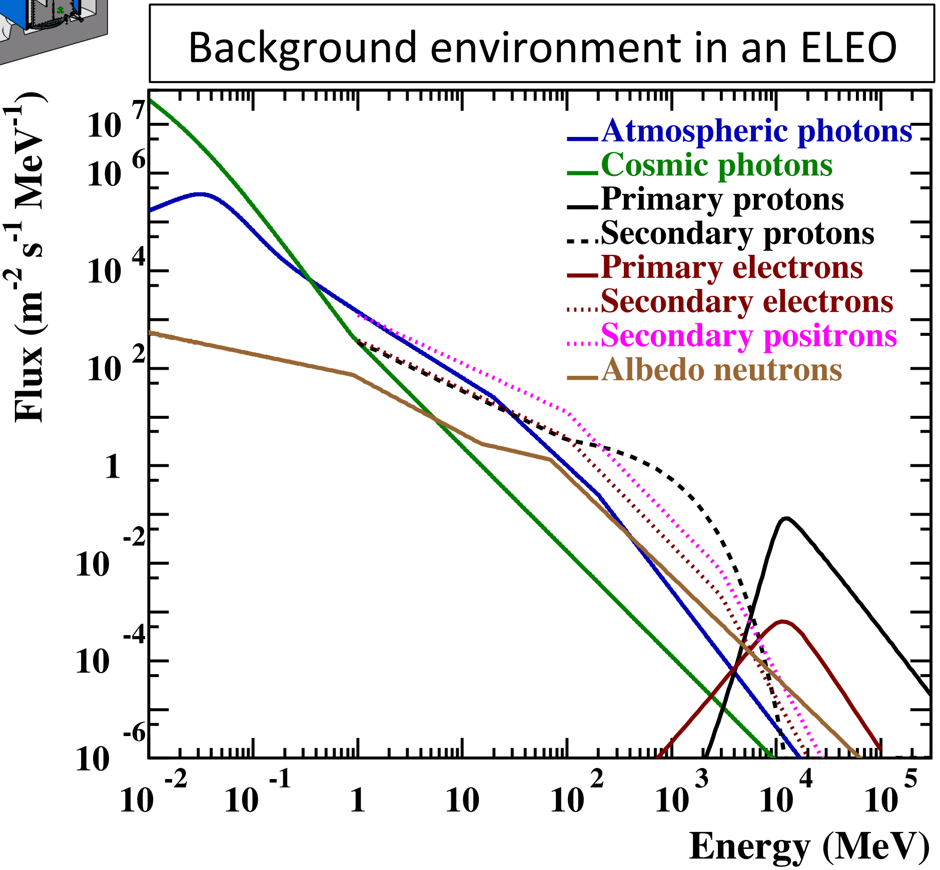
e-ASTROGAM satellite and mission profile



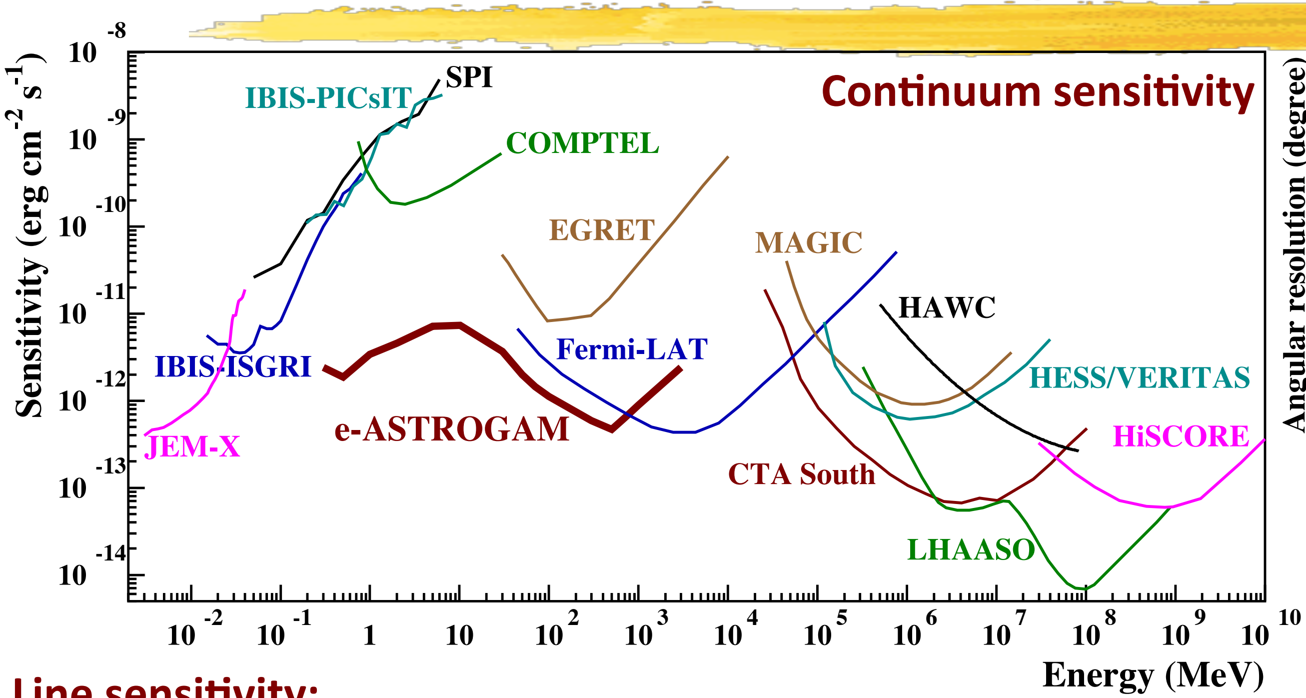


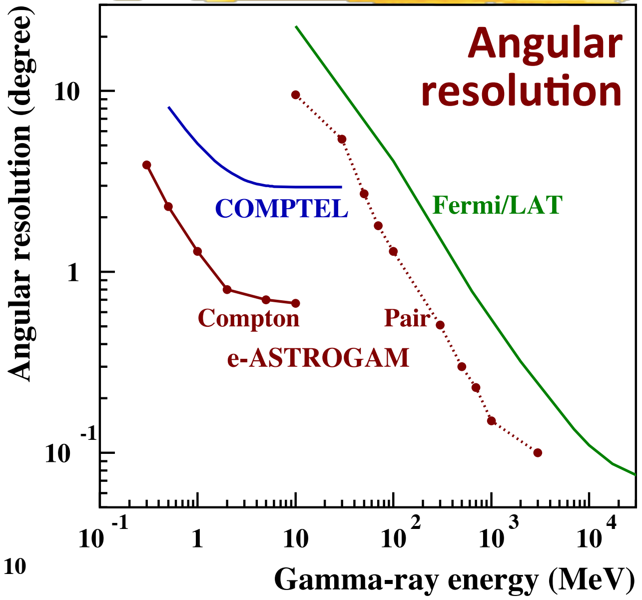


- **Platform** – Thales Alenia Space PROTEUS 800 (SWOT CNES/NASA)
- **Orbit** – Equatorial (inclination *i* < 2.5°, eccentricity *e* < 0.01) low-Earth orbit (altitude in the range 550 - 600 km)
- **Launcher** – Ariane 6.2
- **Observation modes** – (i) zenith-pointing sky-scanning mode, (ii) nearly inertial pointing, and (iii) fast repointing to avoid the Earth in the field of view
- **In-orbit operation** – 3 years duration + provisions for a 2+ year extension


Background environment in an ELEO

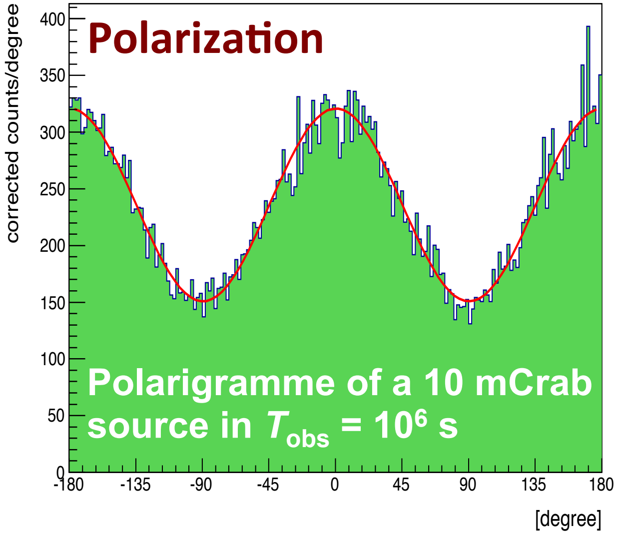
e-ASTROGAM performance


Continuum sensitivity


Angular resolution

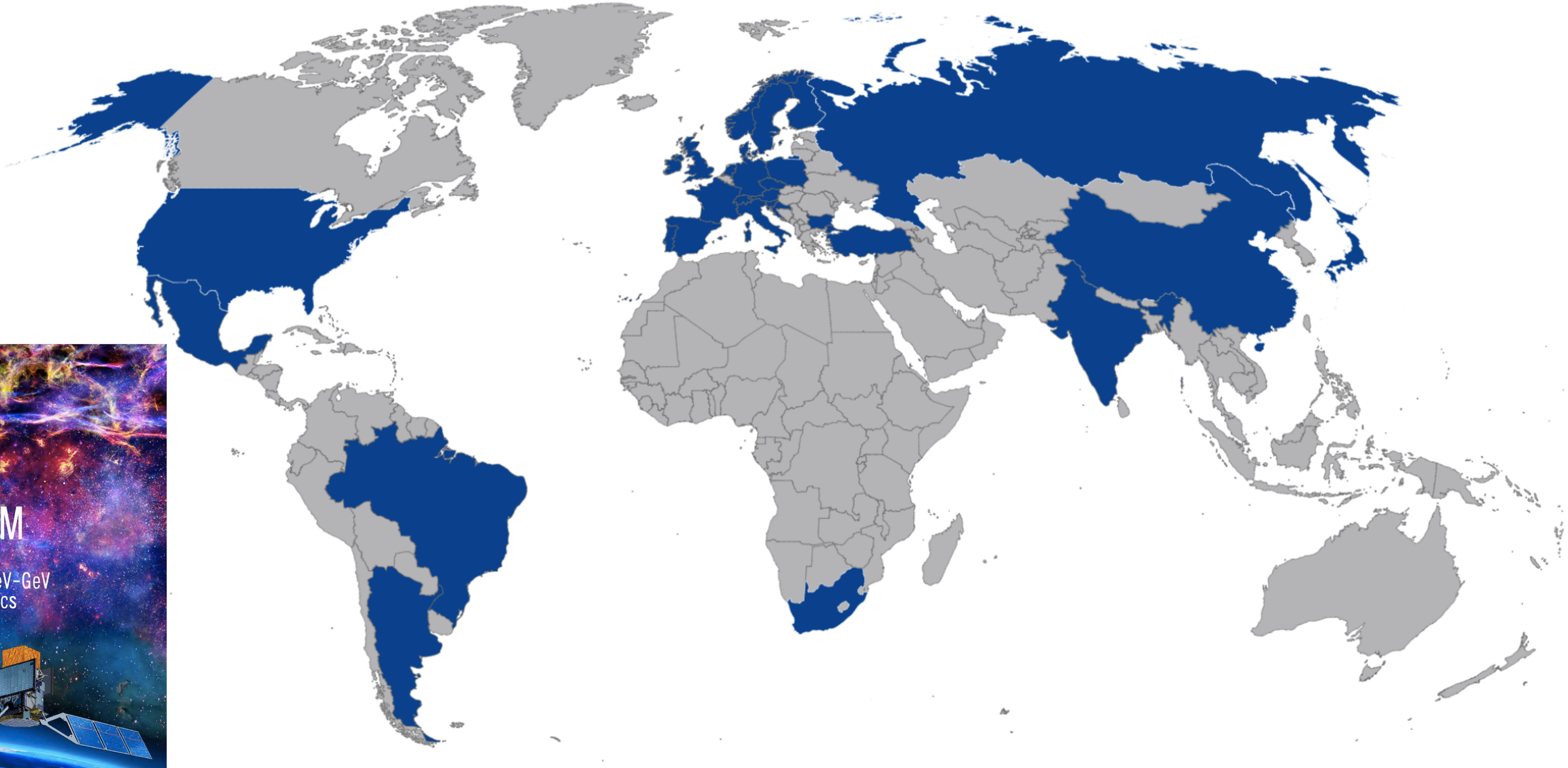
Line sensitivity:

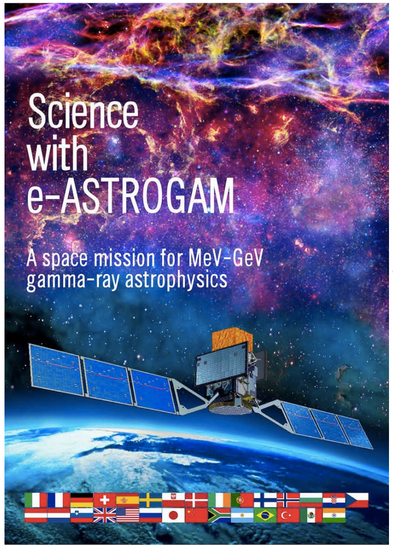
E (keV)	FWHM (keV)	Origin	SPI sensitivity (ph cm^{-2} s^{-1})	e-ASTROGAM sensitivity (ph cm^{-2} s^{-1})	Improvement factor
511	1.3	Narrow line component of the e+/e- annihilation radiation from the Galactic center region	5.2×10^{-5}	4.1×10^{-6}	13
847	35	^{56}Co line from thermonuclear SN	2.3×10^{-4}	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


Polarization

Polarigramme of a 10 mCrab source in $T_{obs} = 10^6$ s

e-ASTROGAM Collaboration





Science with e-ASTROGAM

A space mission for MeV-GeV gamma-ray astrophysics

- More than **400 collaborators** from institutions in 29 countries
- **Lead proposer**: A. De Angelis (INFN, It.); **Co-lead proposer**: VT (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