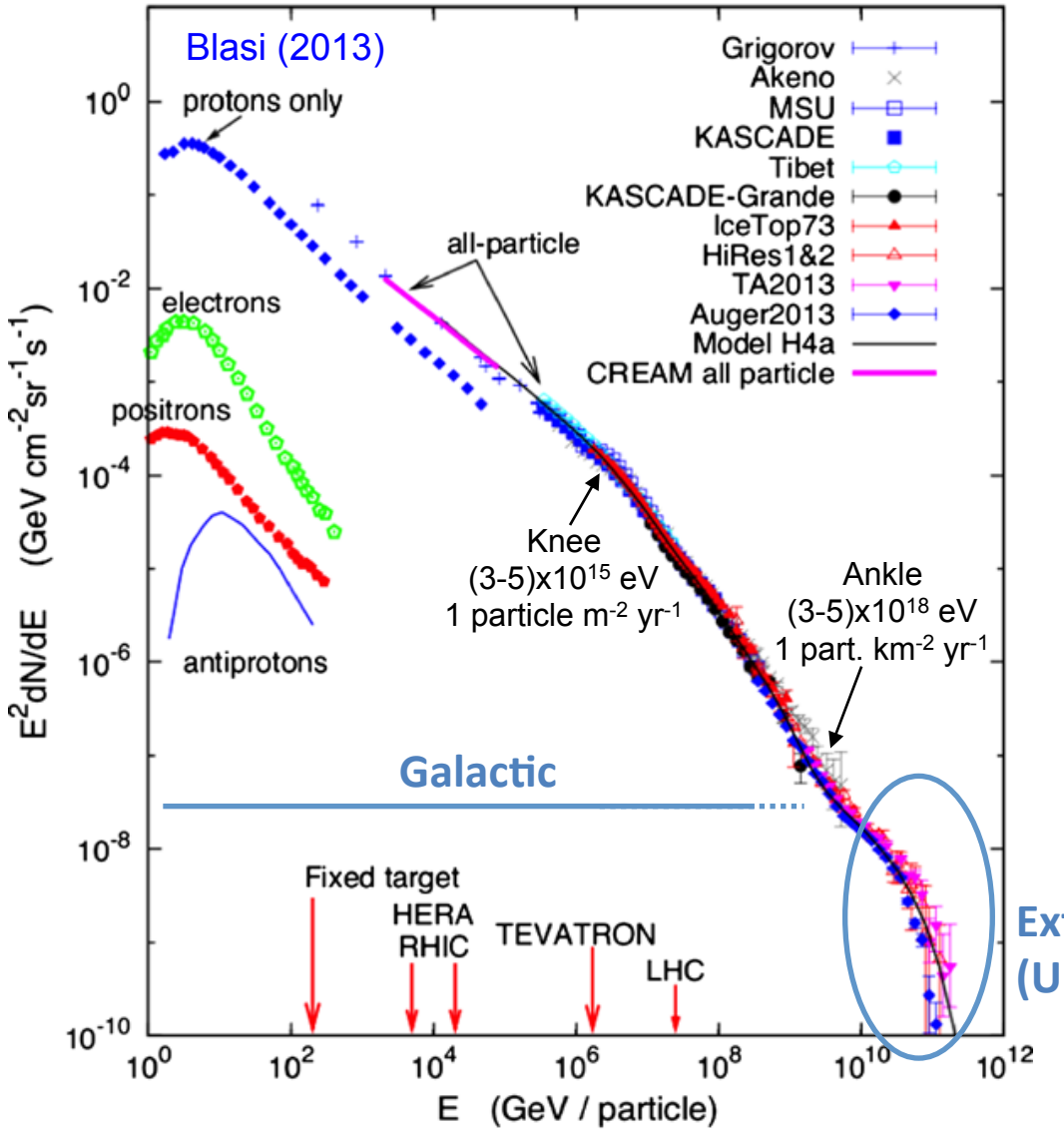
Nuclear Physics for Cosmic-ray Physics



Some needs of nuclear physics for cosmic ray physics

1 Propagation of Galactic cosmic-rays in the AMS-02 era

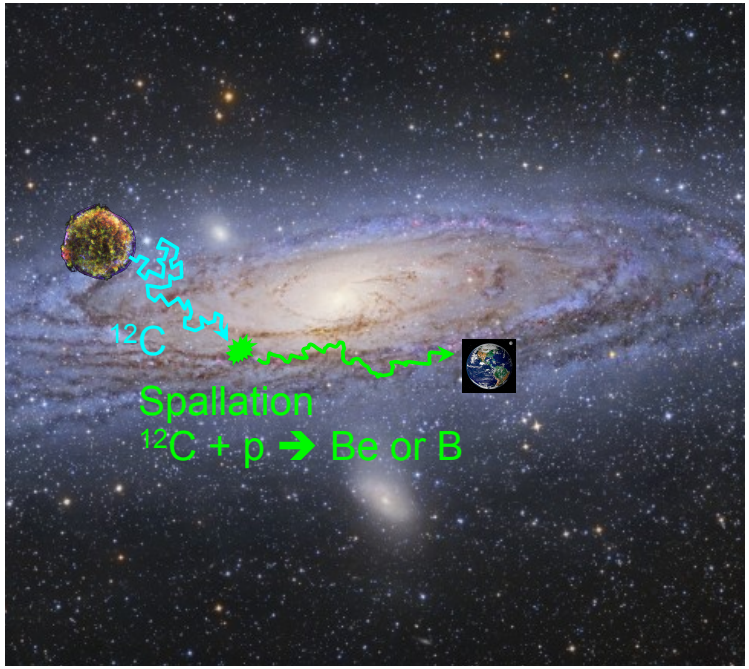
2 Propagation of extragalactic cosmic-rays (see Olivier's talk)

3 Tracing low-energy cosmic-rays by nuclear gamma-ray lines

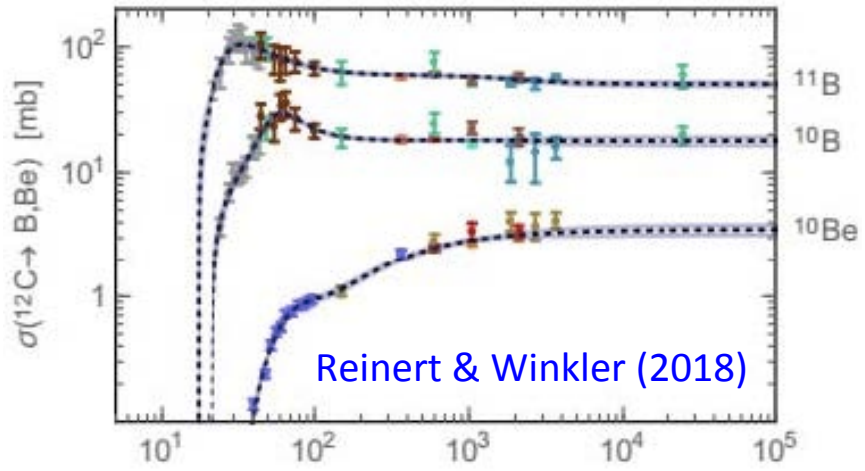
4 On the origin of ^{60}Fe in the GCRs from a local source

Extragalactic (Ultra-High-Energy Cosmic Rays)

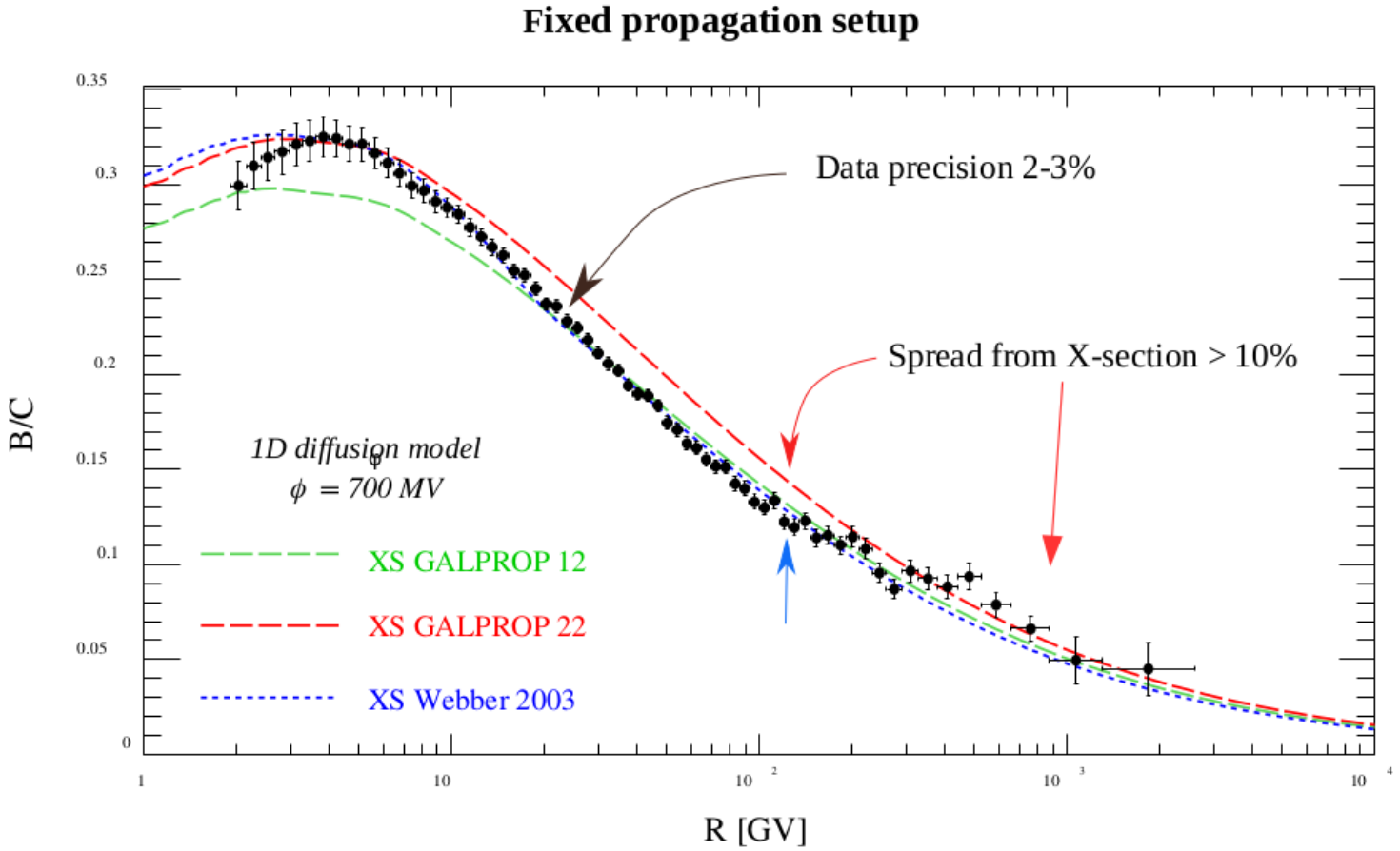
1- Cross sections for Galactic cosmic-ray propagation



- **AMS-02 experiment**:
  - Installed on ISS in May 2011
  - ~ 60 millions particles detected per day, ~ **200 billions CR events** so far
- Uncertainties in CR flux data (a few % with AMS-02) are now well below those in **cross sections of spallation reactions above 100 MeV/nucleon** (10-15%)



1- Cross sections for Galactic cosmic-ray propagation



References:

- Maurin, Putze & Derome (2010)
- Génolini, Maurin, Moskalenko & Unger (2018) (*arXiv:1803.04686*)
- See also *https://lpsc.in2p3.fr/usine*

- "**Need support for nuclear physics** and high energy physics communities
  - Few % accuracy required on key channels (100 MeV/n to multi-GeV/n
  - Improve model if possible..."

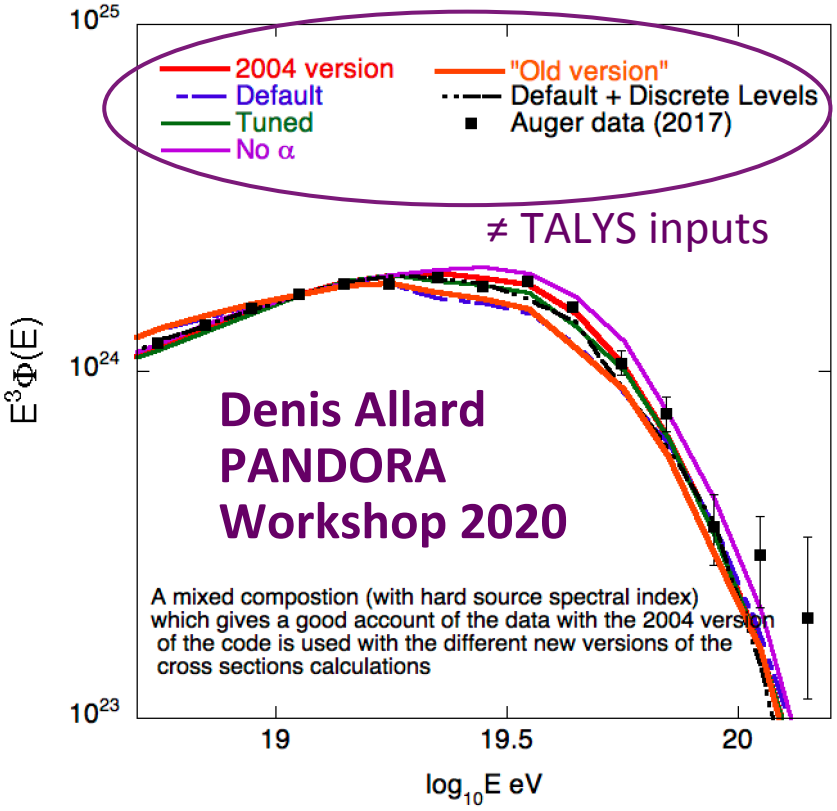
https://indico.in2p3.fr/event/17759/contributions/65127/attachments/49868/63495/Maurin.pdf

2- Cross sections for propagation of UHECRs

- UHECR composition becomes **increasingly heavier with energy** (Pierre Auger coll.) see Olivier's talk
- UHECR spectrum and composition are modified **by interactions with the CMB** (~1 meV) + IR, optical and UV backgrounds (excitation of the giant dipole resonance)

⇒ **Need of total photo-absorption cross sections and n-, p-, α-, γ- decay branching ratios for ^{4}He, ^{12}C, ^{16}O..., ^{28}Si... ^{56}Fe**

- Predicted GDR peak energies and cross sections vary significantly between nuclear models (e.g. TALYS)



- **PANDORA**: ***Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics*** Project initiated by **D. Allard** (APC) (see also Khan, Goriely, Allard et al. 2005) and led by **A. Tamii** (RCNP, JP), **L. Pellegri** (iThemba LABS, SA), **P.-A. Söderström** (ELI-NP, RO) (about 60 scientists from institutes in 8 countries)

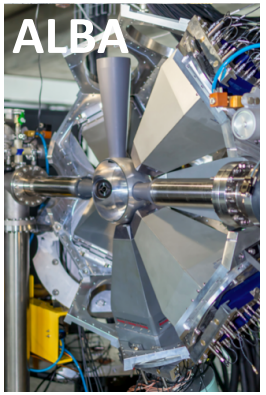
⇒ Coulomb excitation meas. at **iThemba** and **RCNP** + photodissociation at **ELI-NP**

2- Cross sections for propagation of UHECRs

facility	iThemba LABS	RCNP	ELI-NP
beam	p at 200 MeV	p at 392 MeV	LCS γ
photon	virtual	virtual	real
E_x range	8-24	7-32	0.2-19.5
total strength	yes	yes	no
polarized photon	no	no	yes
polarization transfer	no	yes	no
decay detection	p, α, γ	$p, \alpha, (\gamma)$	n, xn, p, α, γ

- **First PANDORA experiment at iThemba LABS scheduled in 2022** (approved in 2019; 6 days): photo-absorption cross sections and p, α and γ decay of ^{12}C (uncertain (γ,xα) channels) and ^{27}Al (reference)
  - Photo-absorption: (p,p') @ 200 MeV, with the magnetic spectrometer **K600**, at 0° and 4°
  - Proton and alpha decay: **CAKE** (Si DSSSDs)
  - Gamma-ray decay: **ALBA** ($LaBr_3$)

CAKE



- **Next PANDORA experiment at RCNP** approved in 2021 (8 days): photo-nuclear reactions of B, C, Al and Mg nuclei, with the **Grand Raiden** spectrometer, **SAKRA** Si detector array and $LaBr_3$ detectors

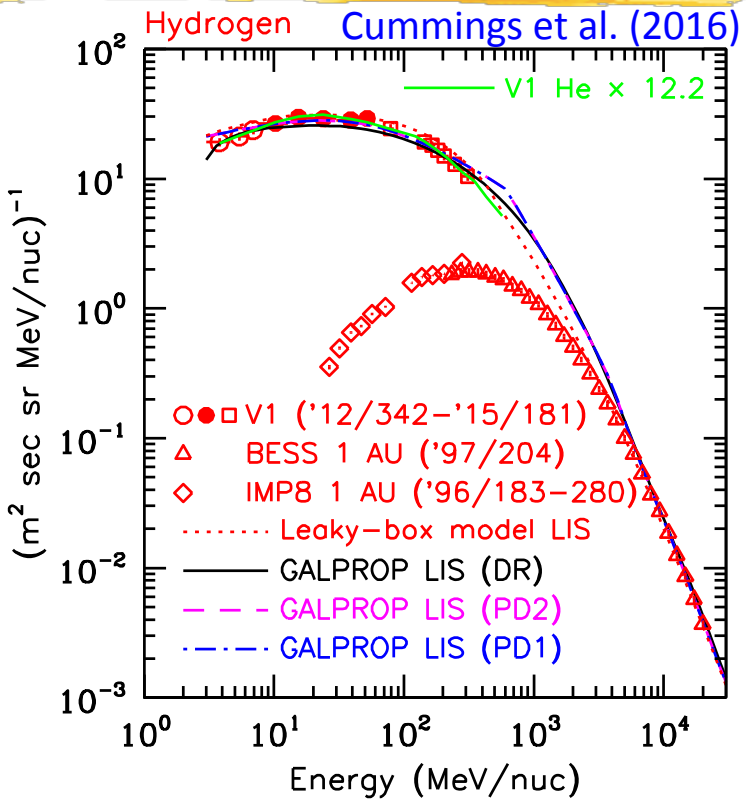
3- Gamma-ray line production by low-energy cosmic-rays

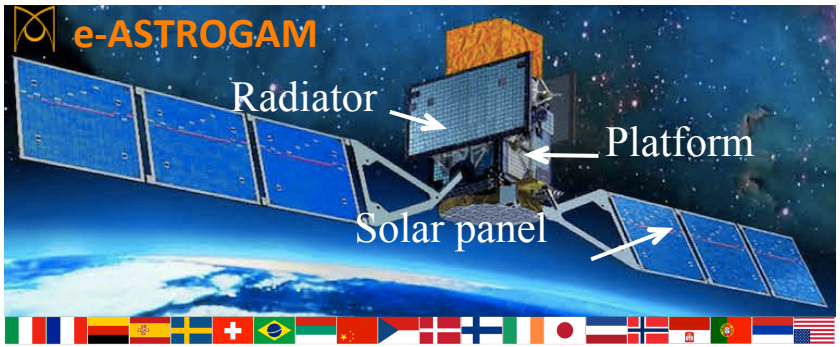
- ***Voyager 1*** measurements of low-energy cosmic-ray spectra down to 3 MeV nucleon^{-1}

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

- **H_3^+ observations** show that the density of LECRs strongly varies from one region to another and suggest the existence of **various sources of LECRs** in the Galaxy (SNRs, microquasars, anomalous CRs...?)

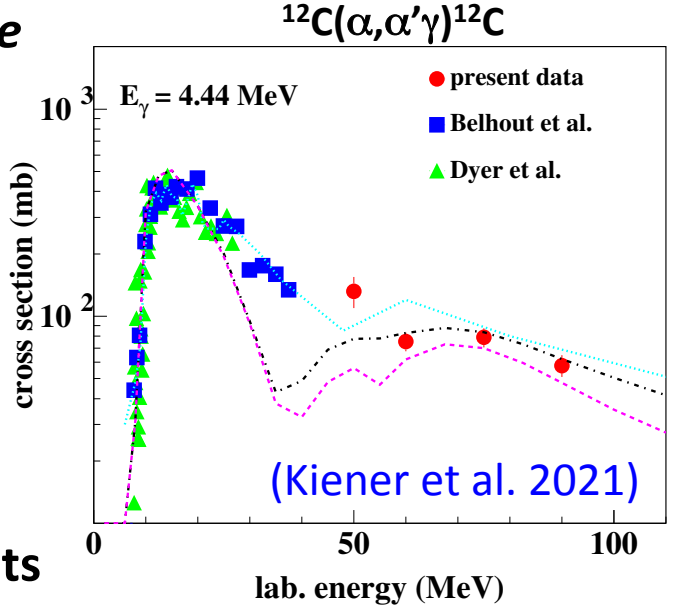
- **MeV gamma-ray astronomy**: **only direct way** of studying the effects of **hadronic LECRs** (E < 1 GeV nucleon^{-1}) in the ISM: **ionization**, **heating** (important for star formation), **astrochemistry**, large-scale **MHD turbulence**, **nucleosynthesis** (LiBeB)

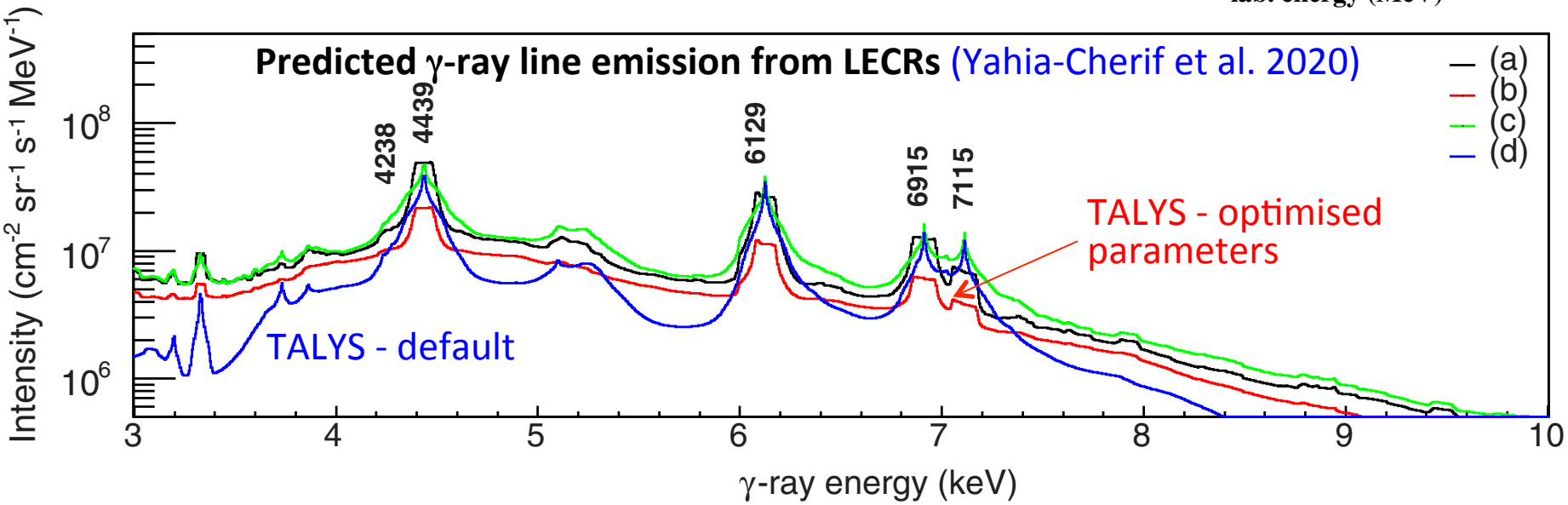




3- Gamma-ray line production by low-energy cosmic-rays

- **GRAPE**: ***Gamma-Ray emission in Accelerated Particle Environments*** (Coll. **IJCLab**, South Africa, Algeria, Germany; PI: **J. Kiener**)
  - p => C, O, Mg, Al, Si, Ca, Fe E = 30 – 180 MeV
    2013-2017 **iThemba LABS**, South Africa
  - α => C, Mg, Si, Fe E = 50 – 90 MeV
    2015-2016 **HMI Berlin**, Germany
- Nuclear model parameters (optical model potentials, level structure) must be **adjusted from measurements**

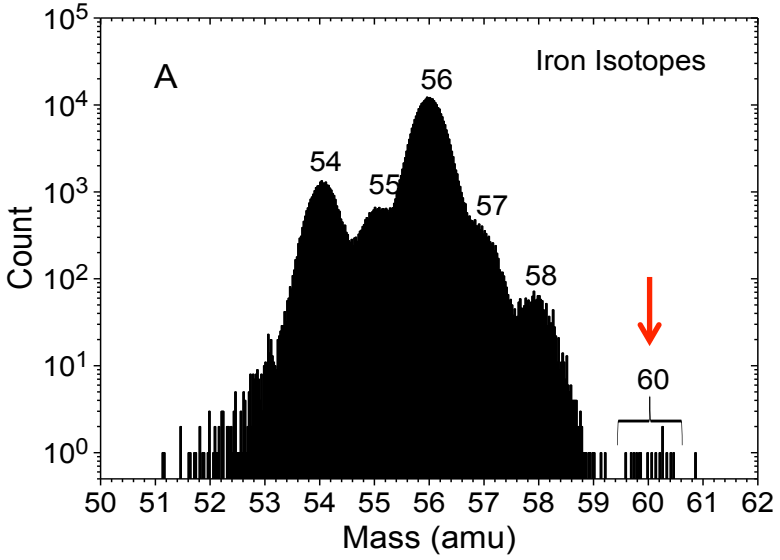


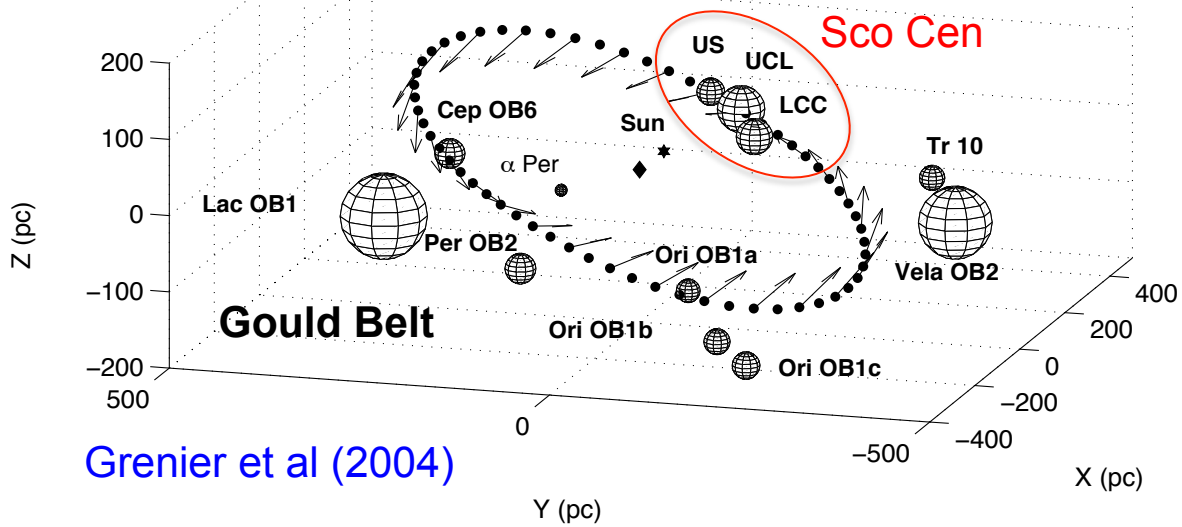


4- On the origin of ^{60}Fe in the Galactic cosmic rays

- Detection with **16.8 years of data of ACE/CRIS** of **15 nuclei of ^{60}Fe (lifetime τ_{60}=3.8 Myr)** and 2.95×10^5 ^{56}Fe (in ~50 - 500 MeV/nucl.) (Binns et al. 2016)

- Approximate maximum distance to the source: $L \sim (D\,\gamma\,\tau_{60})^{1/2} \sim 400 \div 700$ **pc (i.e. local)** where $D \sim (1 \div 3) \times 10^{28}$ cm^2 s^{-1} is the CR diffusion coefficient at ~300 MeV/nucl (e.g. Evoli et al. 2019) and $\gamma = 1.3$ the Lorentz factor





Grenier et al (2004)

- **Nearest young OB association**: **Scorpius-Centaurus** (subgroups **LCC**: 17 Myr, 118 pc; **UCL**: 16 Myr, 140 pc; **US**: 11±3 Myr, 145 pc), at the origin of the **Local Hot Bubble** surrounding the Sun from the explosion of ~ **15 supernovae** (Zucker et al. 2022, Nature)

4- On the origin of ^{60}Fe in the Galactic cosmic rays

- **^{60}Fe detected in deep-sea crusts** suggest **two nearby** (< 100 pc) and **recent SNe**: 6.5 - 8.7 Myr and **1.5 - 3.2 Myr** ago (Wallner et al. 2016)
- **Do ^{60}Fe in GCRs come from acceleration of material in the Local Hot Bubble by a recent supernovae?** (De Séréville, VT, Gabici & Cristofari, in prep)
- **Stochastic model of local chemical enrichment**
  - Stellar masses generated **randomly** from the known stellar populations of the Sco-Cen subgroups and the **Initial Mass Function** of Kroupa et al. (1993)
    ⇒ about **15±5 supernovae**
  - **Supernova yields** and massive star **wind composition** from Limongi & Chieffi (2018) and references therein

⇒ **Calculated enrichment of the Local Hot Bubble** consistent with the measured ^{60}Fe/^{56}Fe ratio in GCRs

⇒ Other isotopic signatures of this local CR source?