

# On the origin of high-energy cosmic ray breaks

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UHE Gamma Rays @ Yerevan

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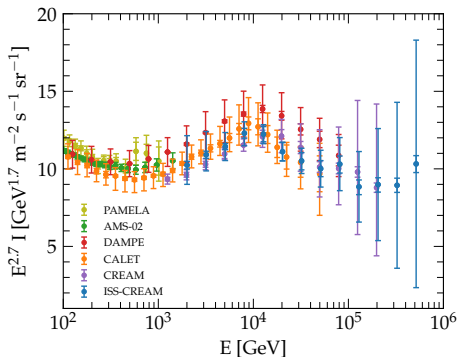


- ▶ Unprecedented measurements of CR flux and composition below the knee
- ▶ Changing paradigm: the abandonment of the universal (and single) power-law assumption
- ▶ What are we learning from these new measurements?
- ▶ Galactic cosmic-ray propagation at high-energy in a nutshell:

$$\Phi \propto Q(E)\tau(E) \propto \frac{Q(E)}{D(E)}$$

# The proton high-energy spectrum

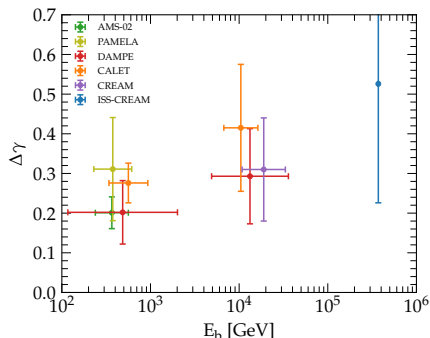
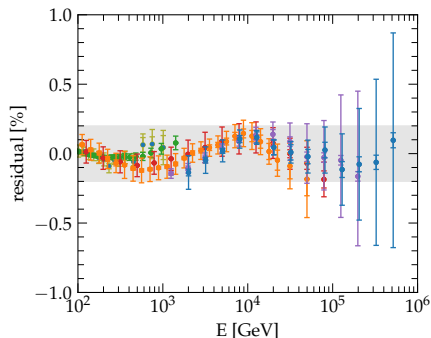
Adriani+, Science, 332, 2011; Yoon+, ApJ, 839, 2017; An+, Science Adv., 5, 2019; Aguilar+, Phys.Rep., 894, 2021; Adriani+, PRL, 129, 2022; Choi+, ApJ, 940, 2022



- ▶ Cosmic-ray proton flux measurements from **direct** experiments.
- ▶ Similar patterns also observed in the **Helium** spectrum [Alemanno+, PRL, 126, 2021]
- ▶ The standard halo model predicts a power-law behaviour for  $E \gg 10$  GeV [CE & Dupletsa, arXiv:2309.00298]:

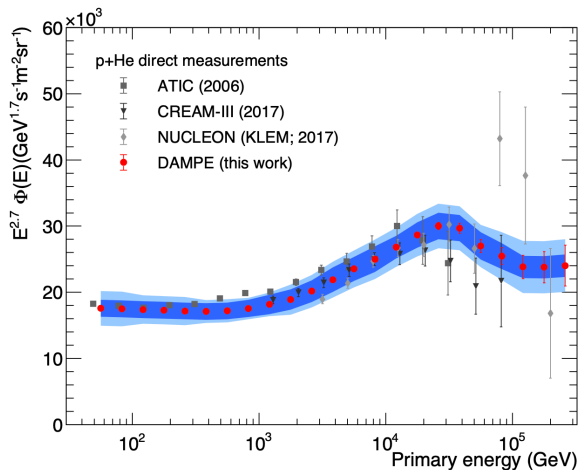
$$\sim Q(E)/D(E) \propto E^{-\alpha-\delta}$$

# The proton high-energy spectrum



- ▷ Residuals (left panel) calculated relative to single power-law fits for each experiment.
- ▷ Deviations observed at approximately 10-20% level.
- ▷ Consistent slope changes with  $\Delta\gamma \sim 0.2 - 0.3$
- ▷ Are there **too many breaks**? Several physical scales!
- ▷ Currently there is no explanation for the high-energy ones.

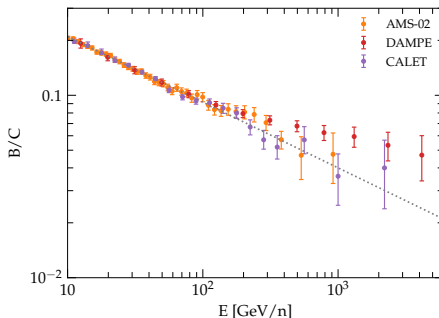
# The proton+He high-energy spectrum



- DAMPE p+He measurements suggest the same hardening at  $\sim 100$  TeV [Alemanno et al., arXiv:2304.00137]

# An old story: secondary-over-primary ratios

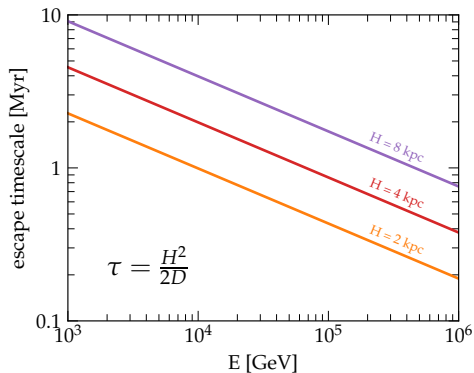
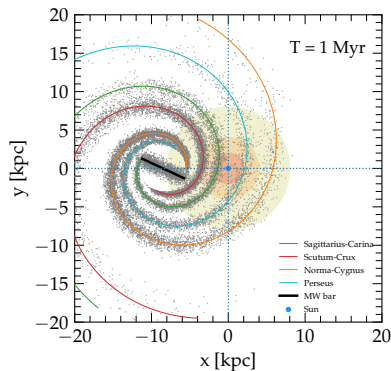
AMS-02, PRL, 2019; DAMPE, Science Bulletin 67, 2022



- ▶ At 300 GV the same break in the secondary/primary ratio  $\rightarrow$  grammage
- ▶ Something new is happening in terms of CR **transport** in the Galaxy
- ▶ At present two physical interpretations are at hand:
  - ▶ The transition marks the energy at which the self-generation of turbulence by the CR themselves runs out of steam [Blasi+, PRL 2012]
  - ▶ The transition is due to different turbulence conditions in the disk and in the halo [Tomassetti, A&A 2012]
- ▶ Problematic in terms of sharpness of the feature

# Galactic cosmic-ray transport at VHE

CE+, PRD, 104, 2021



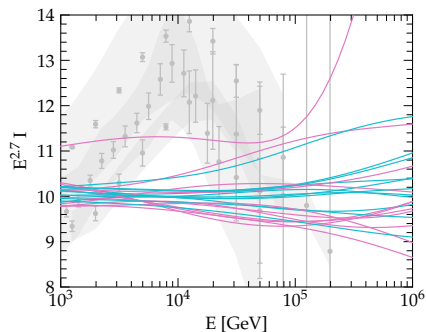
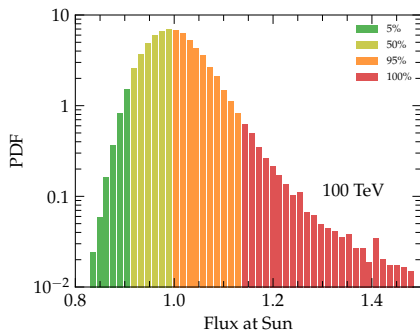
- ▶ Modelling burst-like injection  $\tau_{\text{snr}} \ll \tau_e$  from discrete sources
- ▶ Grammage indicators provide [Schroer et al., PRD, 103, 2021]

$$\frac{D(E)}{H} = 0.42 \left( \frac{E}{\text{TeV}} \right)^{0.36} \text{ kpc Myr}^{-1}$$

- ▶ Radioactive CR species sets the halo size to be larger  $H \gtrsim 2 \text{ kpc}$  CE+, PRD, 2020; Weinrich+, A&A, 2020

# Consequences of the Stochastic Nature of Cosmic-Ray Sources

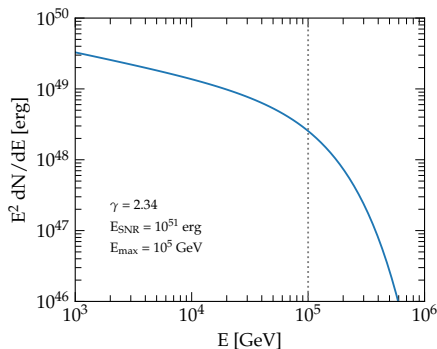
CE+, PRD, 104, 2021



- ▶ The CR flux at Earth is inherently **stochastic**, characterized by a heavy-tail PDF Lee, ApJ, 1979; Bernard+, A&A, 2012
- ▶ Individual realizations show **deviations** from a pure power-law at varying levels
- ▶ Averaging these realizations leads to the textbook result,  $\propto E^{-2.7}$ , in the **mean field limit**



# The Injection Spectrum from a Single Source



$$\frac{dN}{dE}(E) \propto E_{\text{SN}} \left( \frac{E}{\text{GeV}} \right)^{-\gamma} \exp \left( -\frac{E}{E_{\text{max}}} \right)$$

- ▶ Typical Monte Carlo simulations are performed assuming **identical** sources
- ▶ Although variance in these parameters (both from theoretical and observational perspectives) is expected

# Addressing model variance

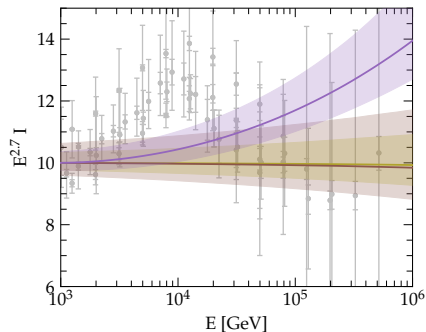
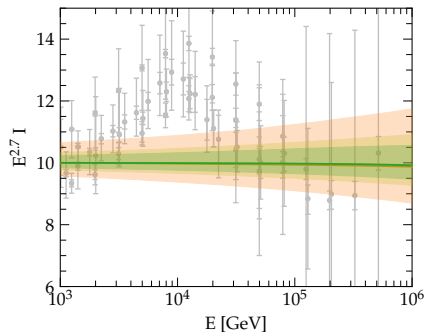
## Identical sources

- ▷  $H = 4$  kpc, fixed source parameters
- ▷  $H = 2$  kpc
- ▷  $H = 8$  kpc

## Source variance

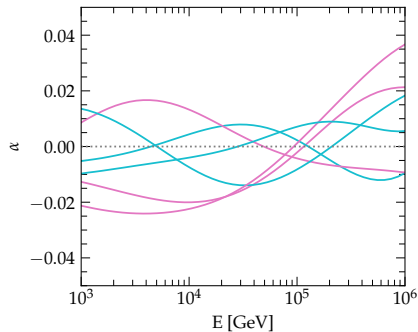
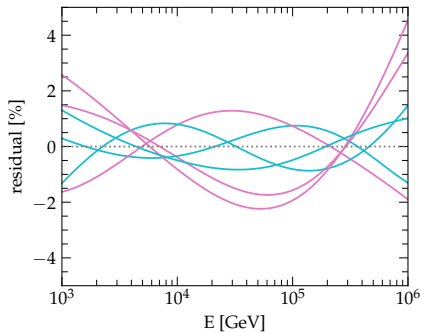
- ▷  $H = 4$  kpc, fixed source parameters
- ▷  $H = 4$  kpc, log-normal distribution for  $E_{\text{SN}} \sigma_{\log E} \sim 0.3$  [Leahy et al., ApJS 248, 2020]
- ▷  $H = 4$  kpc, gaussian distributed  $\sigma_{\alpha} \sim 0.15$  (see also SNR radio X-observations [Green, 2019])

## On the CR spectrum variance

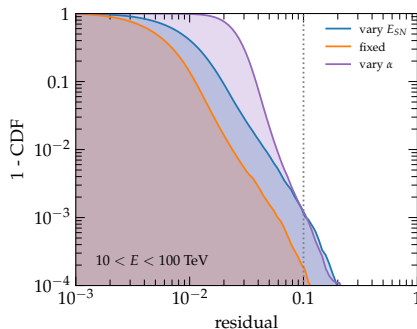
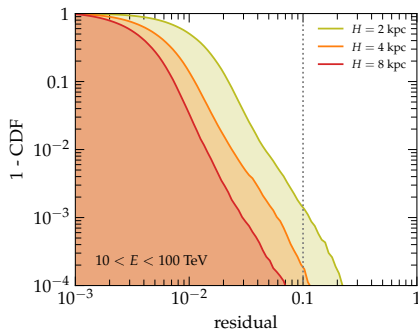


- ▶ Smaller halo size increases the variance  $\rightarrow$  for  $H = 2$  kpc, I found  $\lesssim 15\%$  at 1 PeV
- ▶ Comparable effect by allowing source parameters to vary individually
- ▶ Spreading of the injection slope corresponds to an **hardening** of the propagated spectrum

## A sample of Galactic realizations

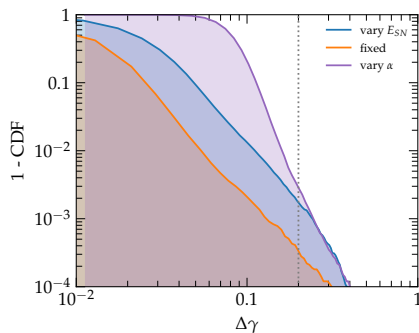
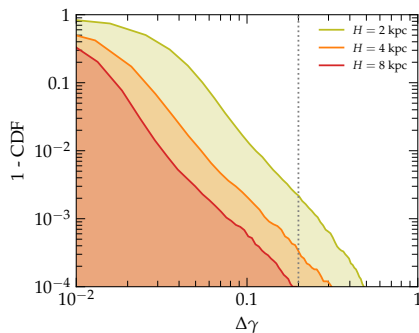


# Residual probabilities



- It shows the fraction of Galaxy to have a residual larger than a given value over the energy range 10 GeV - 100 TeV
- It is certainly an upper limit to the actual probability quite agnostic on the properties of the residual
- The probability is smaller than 0.1%

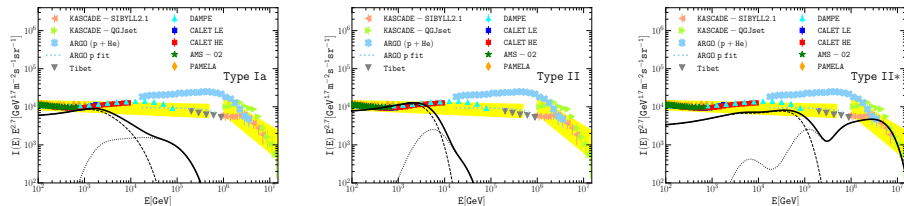
## Slope variation probabilities



- The fraction of galaxies with a slope excursion larger than a given  $\Delta\gamma$
- Again the probability is smaller than 0.1%

# The SNR escape spectrum

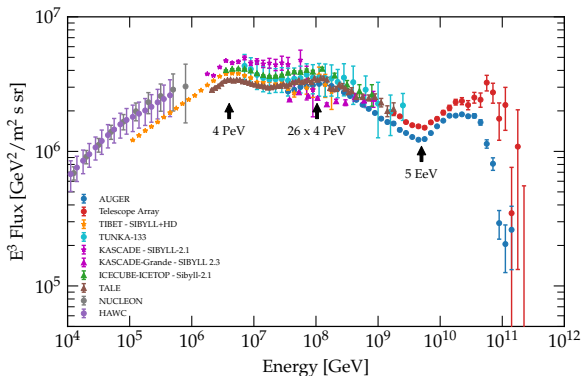
Cristofari+, Astroparticle Physics, 123, 2020



- ▶ There are different populations of SNR with different  $E_{\text{max}} \rightarrow$  expected features associated with Type Ia SNe, or dips in the spectra of core collapse SNe [Cristofari+, APH 2020; Diesing, arXiv:2305.07697]
- ▶ However, all these features must have large variance  $\rightarrow$  how ends up in having only one feature? [Lipari & Vernetto, APH 2020]
- ▶ Can it be the 10 TeV softening due to the transition between two populations?
- ▶ Fine tuned explanation: (efficiency  $\times$  rate  $\times$  energetic) very close to each other.

# Galactic-Extragalactic transition

Aloisio+, JCAP 2014; Globus+, PRD 2015; Thoudam+, A&A 2016; Evoli & Boncioli, in prep.



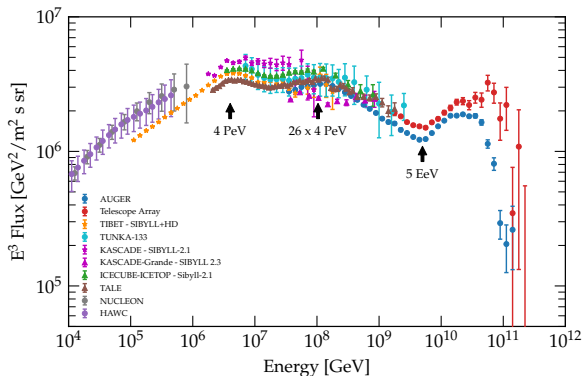
## Well-known facts

- ▷ The two knees are distinctly separated by a factor of approximately 26  $\rightarrow$  the first knee is primarily attributed to **protons**, while the second knee is associated with **Iron** nuclei.
- ▷ The origin of the knee can be attributed to one of two factors: (a) A transition from diffusive to ballistic cosmic ray propagation in the **Galactic escape**, (b) a **cutoff**-like in the Galactic source spectrum.



# Galactic-Extragalactic transition

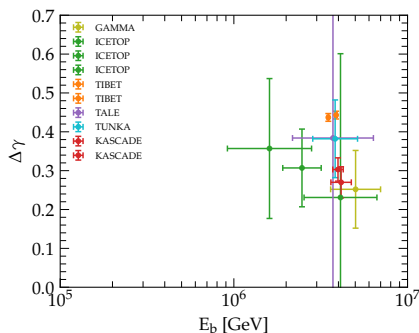
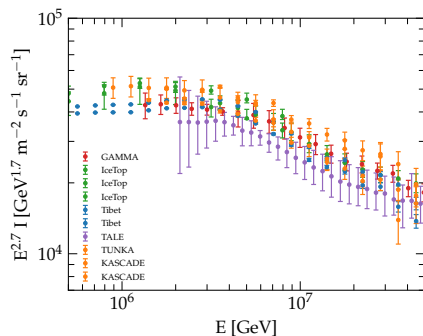
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## Well-known facts

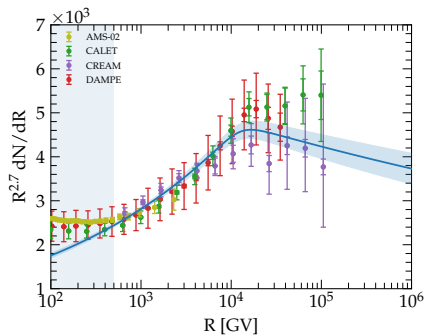
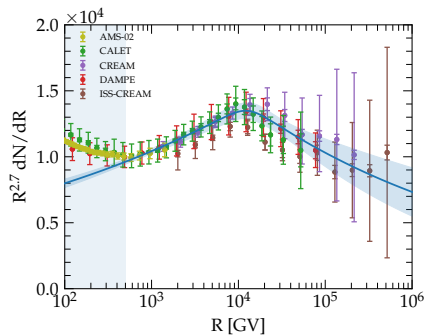
- ▶ The two knees are distinctly separated by a factor of approximately 26 → the first knee is primarily attributed to protons, while the second knee is associated with Iron nuclei.
- ▶ The origin of the knee can be attributed to one of two factors: (a) A transition from diffusive to ballistic cosmic ray propagation in the Galactic escape, (b) a cutoff-like in the Galactic source spectrum.

## Toward the knee



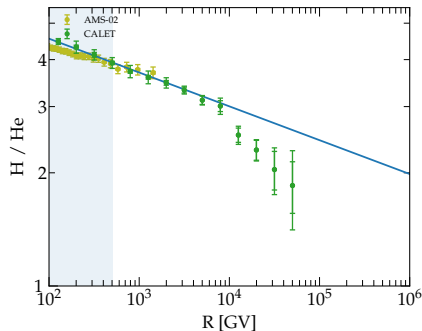
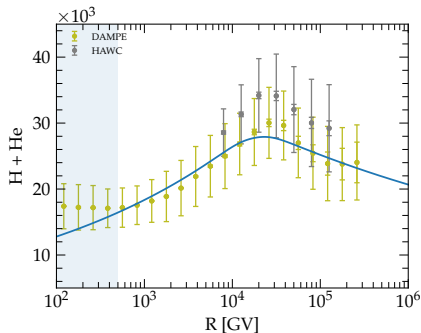
- Consistent features in the **all-particle spectrum** above  $\simeq 1$  PeV
- The knee is identified at  $\sim 4$  PeV
- Still unclear composition, large uncertainties  $\rightarrow$  waiting for LHAASO findings

# Extrapolating composition from TeV to PeV



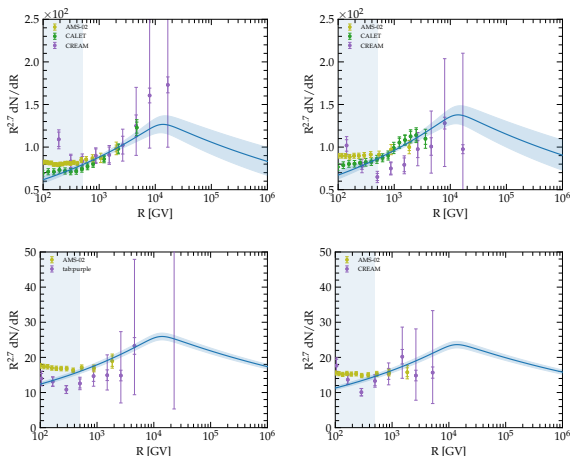
- Fit based only on direct measurements: H (left) and He (right)
- Helium spectrum persisting harder than H up to 100 TeV

# Extrapolating composition from TeV to PeV



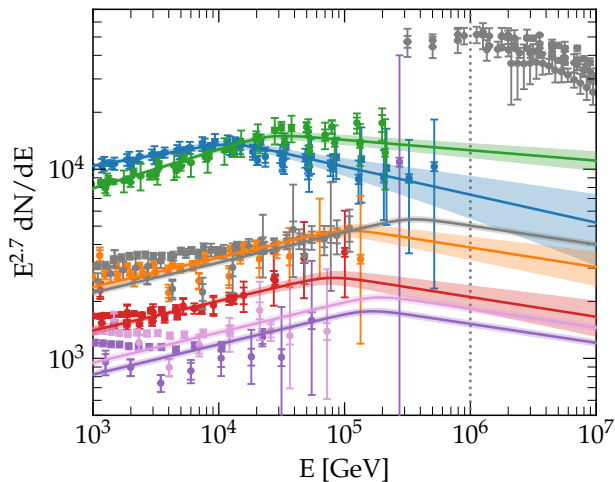
- ▷ Differences between the proton and helium spectra measured up to  $\sim 60$  TeV/n [Adriani et al., PRL 130, 2023]
- ▷ At odds with what one would expect in the case of **pure rigidity dependent acceleration** [Caprioli, Varenna Lecture Notes 2022]
- ▷ H is **softer** than nuclei, while He is **harder**:  $\Delta\gamma \sim \pm 0.05$
- ▷ Problematic even for models of the difference between H and He injection based on the different  $A/Z$  at shocks [Hanusch+, Apj 2019]

# Extrapolating composition from TeV to PeV



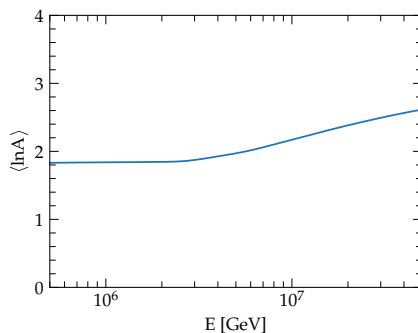
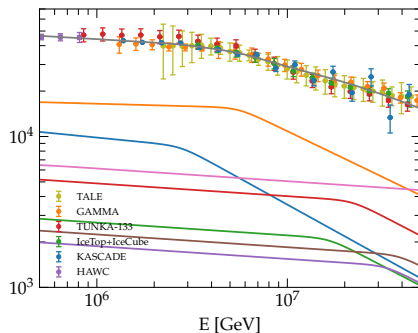
- ▶ Intermediate-mass nuclei well fitted with the same slope
- ▶ Measurements are compatible within  $\sim 5\%$  energy-scale shift

## Extrapolating composition from TeV to PeV



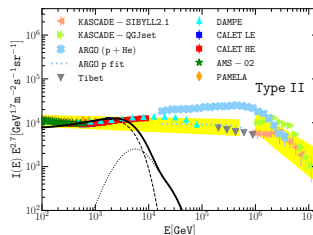
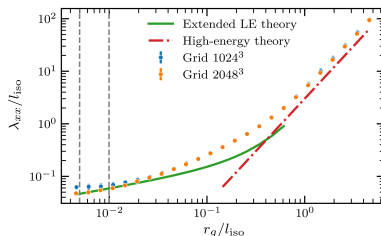
At 1 PeV in order: He, H, Fe, C, O, Mg, ...

# Fitting the knee



- Composition at the knee **fixed** by direct measurements
- Incompatible with rigidity dependent exponential cutoff
- Rigidity dependent break at  $E_p \sim 2$  PeV
- Fit to the **all-particle** gives a change of slope for each species of about  $\Delta\gamma \sim 0.4 - 0.5$
- Predictions for composition across the knees

# The end of the Galactic spectrum



- ▶ Explanations in terms of escape predict a transition between **diffusion** dominated escape timescale  $\tau \propto E^{-1/3}$  to **small pitch-angle scattering**  $\tau \propto E^{-2} \rightarrow \Delta\gamma \sim 1.7$  [Dundovic+, PRD, 102, 2020]
- ▶ Even larger in terms of source "cutoff"
- ▶ Source maximum energy variance? [Kachelriess+, Phys. Lett. B 634, 2006; Ehlert+, PRD 107, 2023]

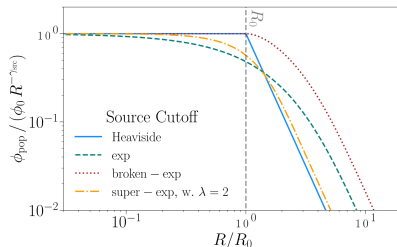
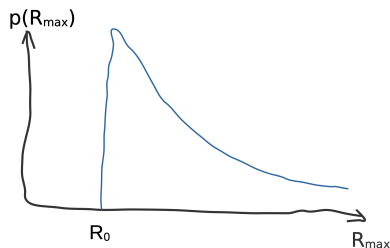
$$\frac{dN}{dE}(E) \propto E_{\text{SN}} \left( \frac{E}{\text{GeV}} \right)^{-\gamma} \exp \left( -\frac{E}{E_{\text{max}}} \right)$$

- ▶ Is this physically motivated?
- ▶ Or, an additional Galactic population from the first to the second knee?



# The end of the Galactic spectrum

From Domenik Ehlert's slides at CrPropa workshop



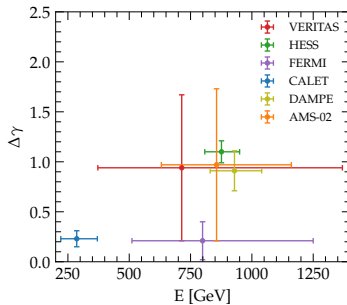
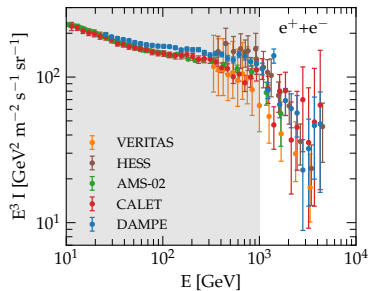
- Distribution of maximum rigidities

$$p(R_{\max}) = \begin{cases} 0 & R_{\max} < R_0 \\ \frac{\beta-1}{R_0} \left( \frac{R_{\max}}{R_0} \right)^{-\beta} & R_{\max} \geq R_0 \end{cases}$$

- Population Spectrum

$$\phi = \int_0^\infty dR_{\max} \phi_s(R, R_{\max}) p(R_{\max}, R_0) = \phi_0 R^{-\gamma_s} \begin{cases} 1 & R < R_0 \\ \left( \frac{R}{R_0} \right)^{-\beta+1} & R \geq R_0 \end{cases}$$

# The end of the Galactic spectrum



- Consistent sharp break at  $\sim 1$  TeV with  $\Delta\gamma \sim 1$

# Conclusions

- ▶ Data in the latest two decades have been forcing us to revisit most (if not all) of our ideas after the founding era → extremely dynamic field
- ▶ The standard model certainly needs modifications
- ▶ Whether such modifications are small adjustments or cracking of the pillars it must be critically assessed in the next years!

# Thank you!

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