# A minimal two-population model of cosmic ray spectra at GeV-PeV energies

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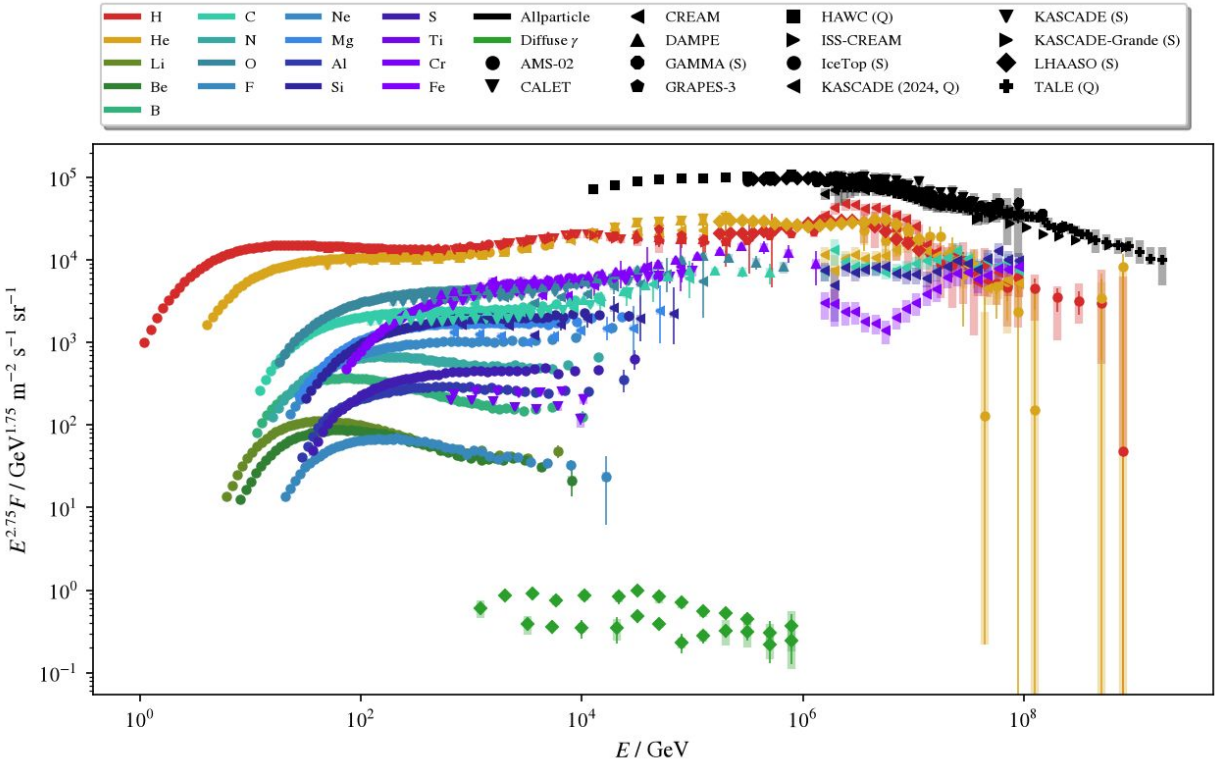
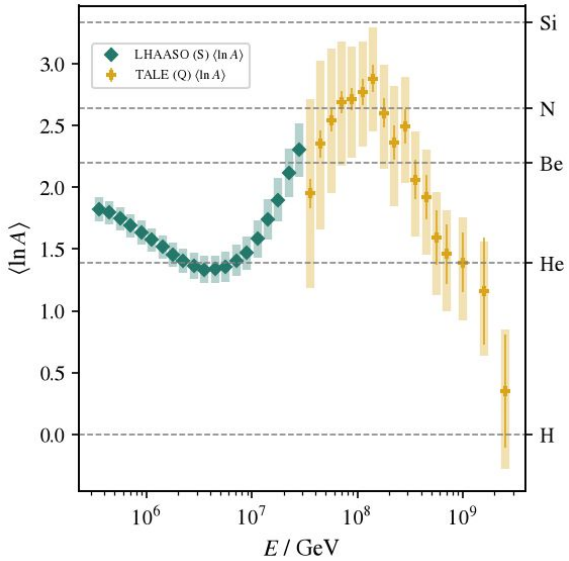
# Cosmic ray landscape from GeV to PeV



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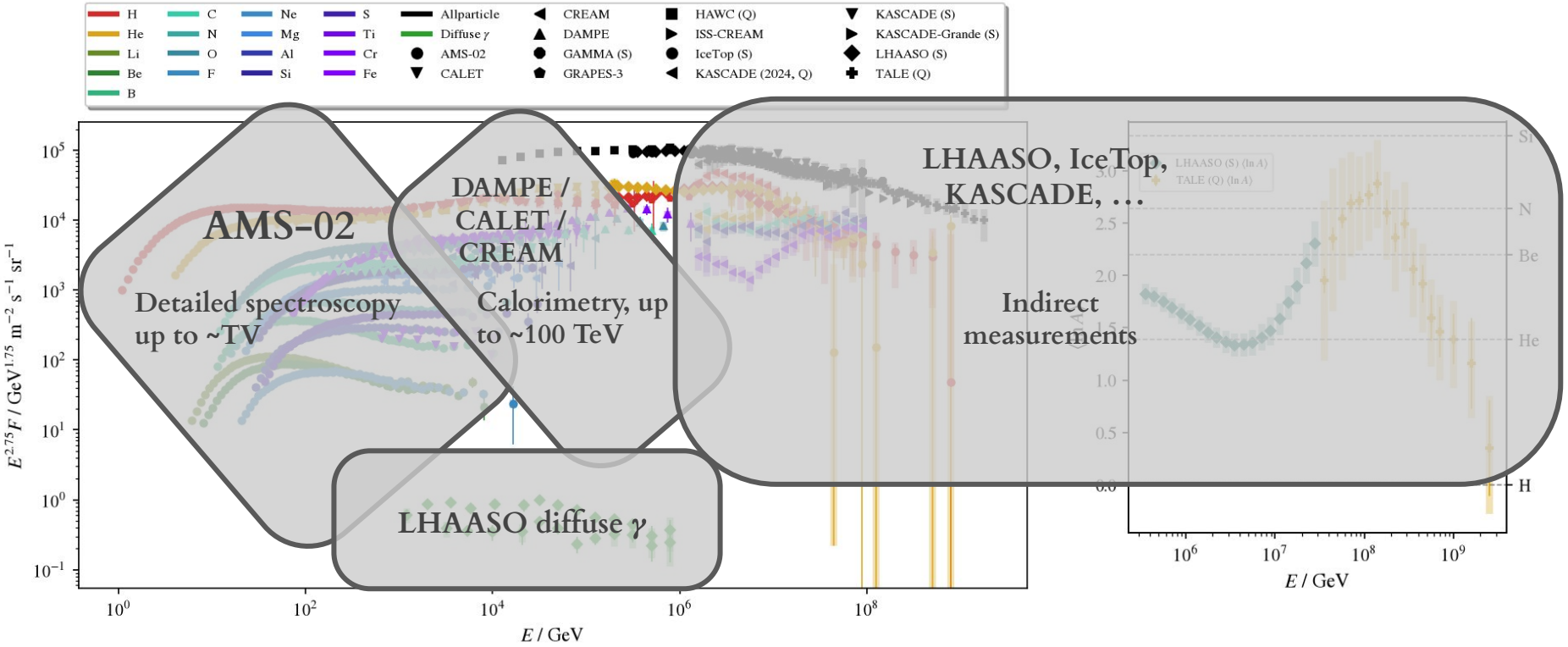

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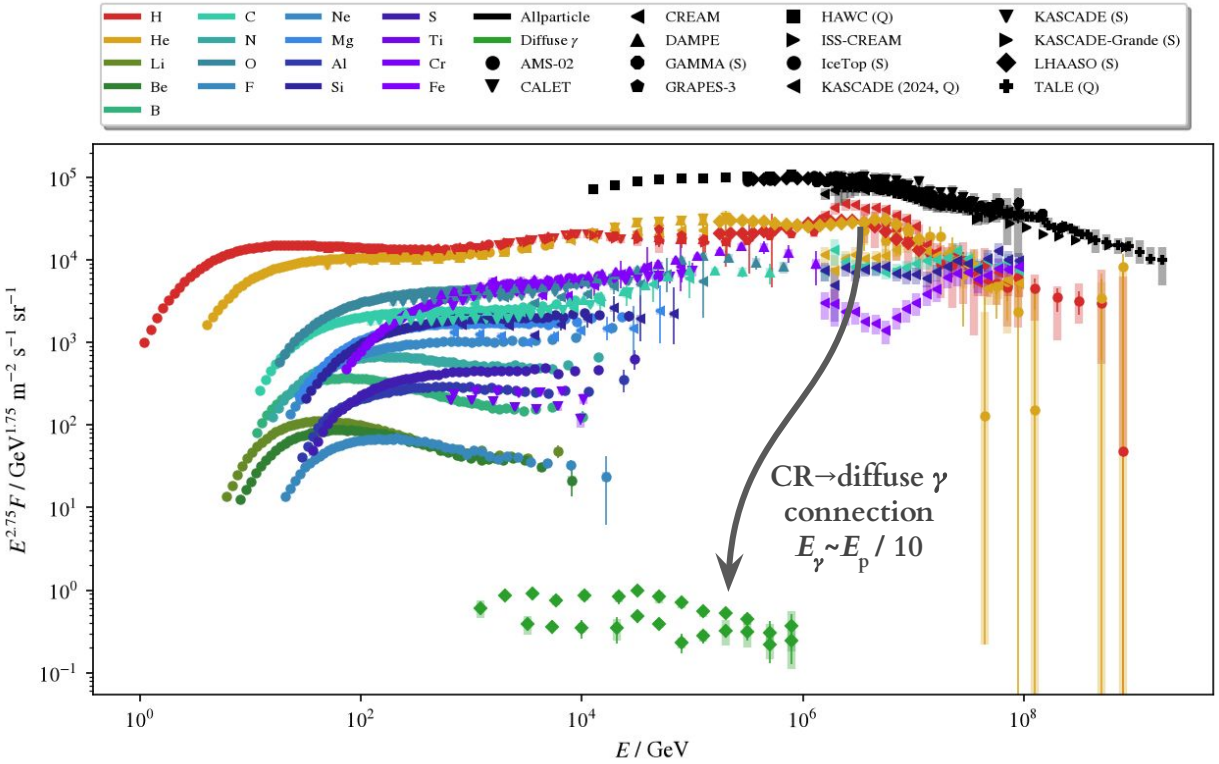
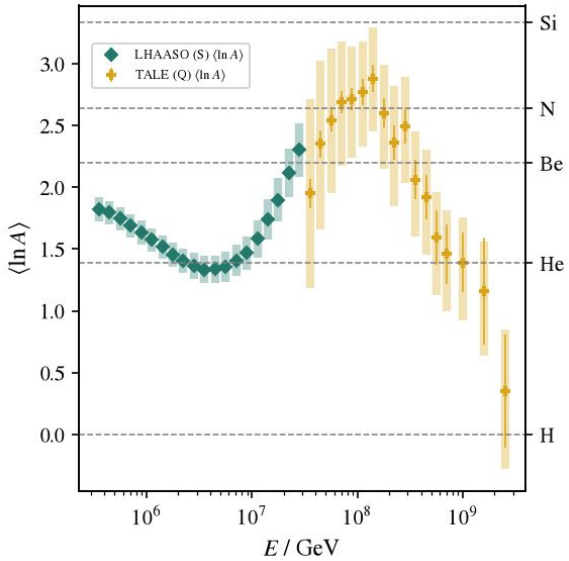


# Building a minimal model

**What is the simplest self-consistent description of the CR data in GeV-PeV range?**

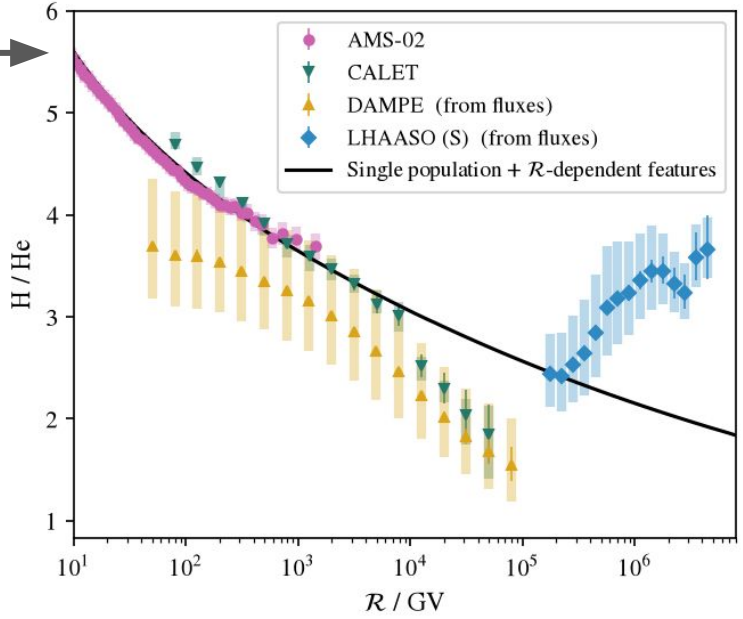
Fewest number of parameters, physical assumptions, etc

Concordant between elemental spectra (e.g. R-scaling of features), elemental and all-particle data, CR and $\gamma$-rays

# Building a minimal model

**What is the simplest self-consistent description of the CR data in GeV-PeV range?**

- Single population models are firmly excluded →

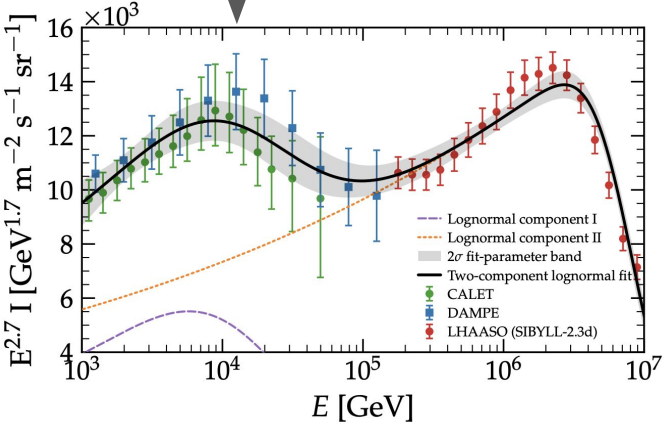


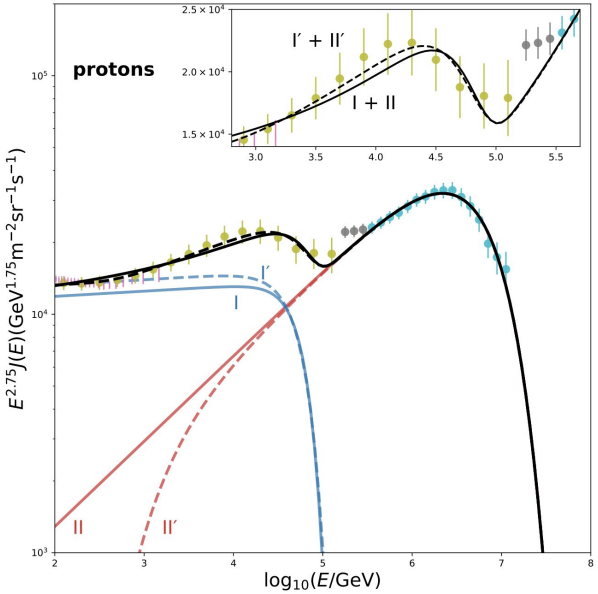

📖 Prevotat, C. et al. arXiv:2507.10823 (2025)
📖 **IV**, Evoli, C. & Espinosa Castro, L. E. PoS(ICRC2025) 148 (2025)

# Building a minimal model

**What is the simplest self-consistent description of the CR data in GeV–PeV range?**

- Single population models are firmly excluded
- Two-population models are viable at least for elemental spectra (p & He) in isolation



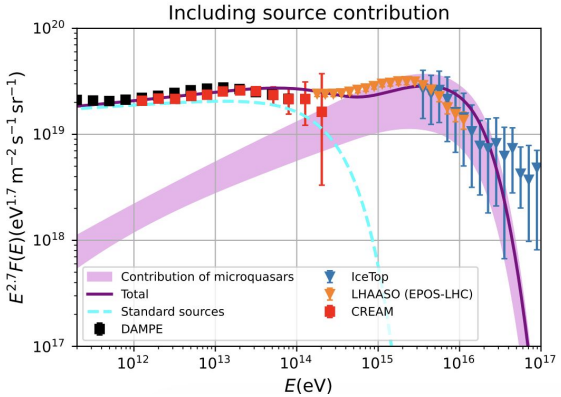


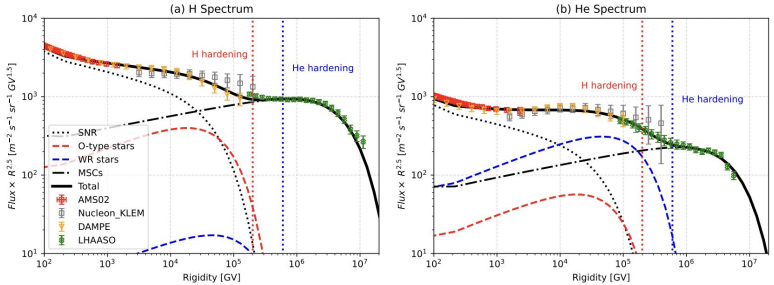
📖 Aharonian, F. & Zhang, B. T. arXiv:2602.08223
📖 Evoli, C. Physics and the Cosmos 1, (2026)

# Building a minimal model

**What is the simplest self-consistent description of the CR data in GeV–PeV range?**

- Single population models are firmly excluded
- Two-population models are viable at least for elemental spectra (p & He) in isolation
- Regular galactic SNR seem to have trouble accelerating CRs to the knee, and another kind of sources is required: microquasars, massive star clusters, superbubbles, rare powerful SNRs, …



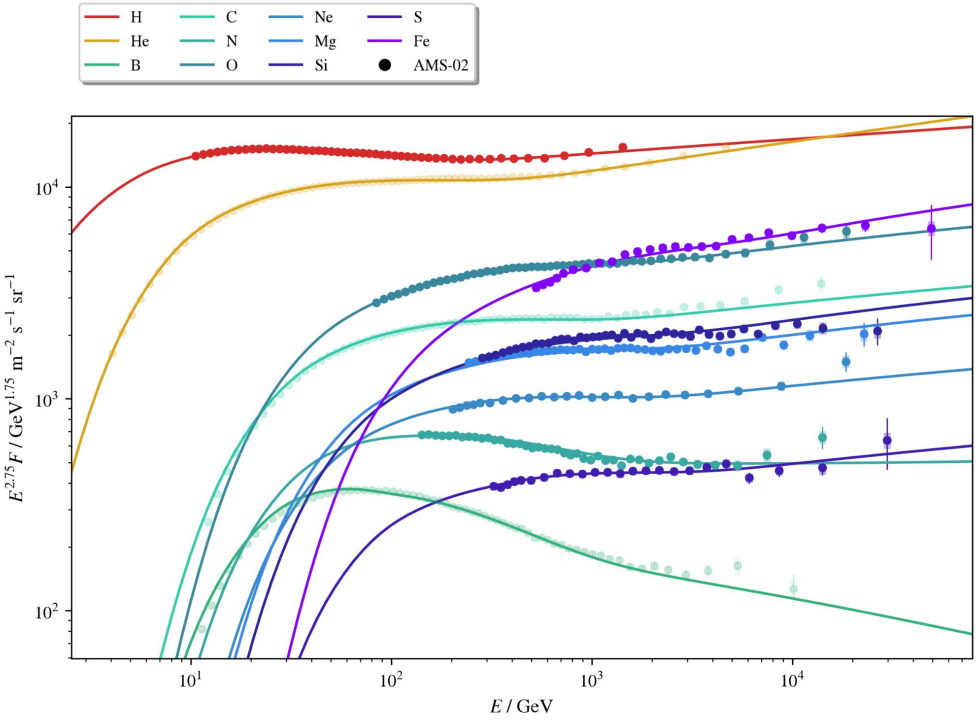





📖 Diesing, R. ApJ 958, 3 (2023)
📖 Zhang, B. T. & Yu, S. arXiv:2602.08940 (2026)
📖 Kaci, S., Giacinti, G., Aharonian, F. & Wang, J.-S. arXiv:2510.01369 (2025)
📖 Qiu, Z., Lin, S. & Yang, L. arXiv:2605.31362 (2026)

# Low-energy population (≲100 TV)

- Diffusive propagation is modeled with **CRAMS**, 1D transport equation code, modelling a full nuclear matrix
- Injection parameters are constrained by AMS-02 elemental fluxes; 3 independent injection indices are needed for H, He & nuclei
- Break in the diffusion coefficient around ~300 GV, constrained by sec./prim. data
- Spectrum cutoff is naturally introduced in the injection as a result of $R_{max}$ variability

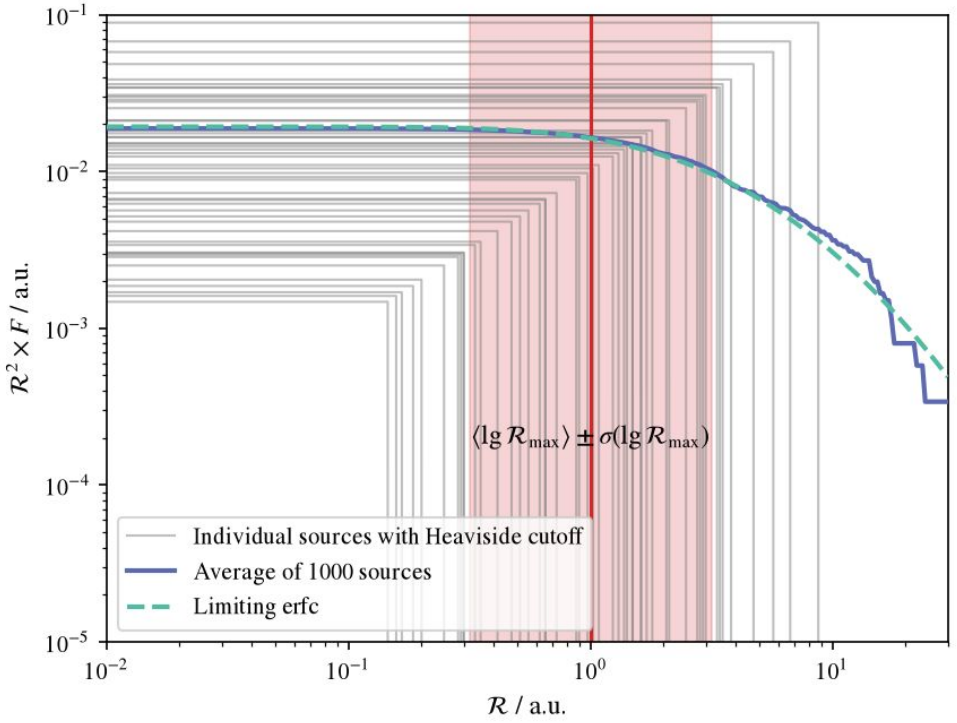




📖 Evoli, C., Morlino, G., Blasi, P. & Aloisio, R. Phys. Rev. D 101, (2020)
📖 Evoli, C., Aloisio, R. & Blasi, P. Phys. Rev. D 99, (2019)

# Spectral cutoff as a population effect

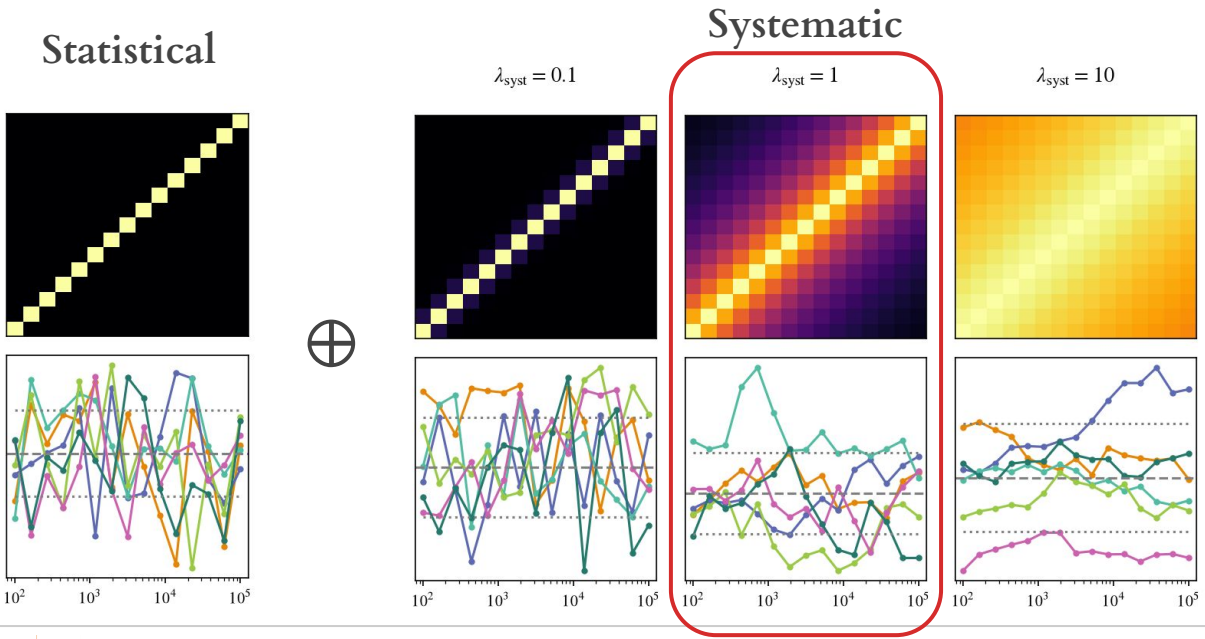
- Assume individual sources to have sharp cutoffs distributed lognormally
- Then, effective injection has a erf-shaped cutoff
- Sharpness of the cutoff is connected to the variability of sources
- For Galactic SNR $\sigma \simeq 0.5$-$0.6$, dominated by variance of $E_{SN}$
- Naive $\exp(-R/R_{max})$ cutoff corresponds roughly to $\sigma \simeq 0.3$-$0.4$




📖 Evoli, C. Physics and the Cosmos 1, (2026)

# How to fit the data?

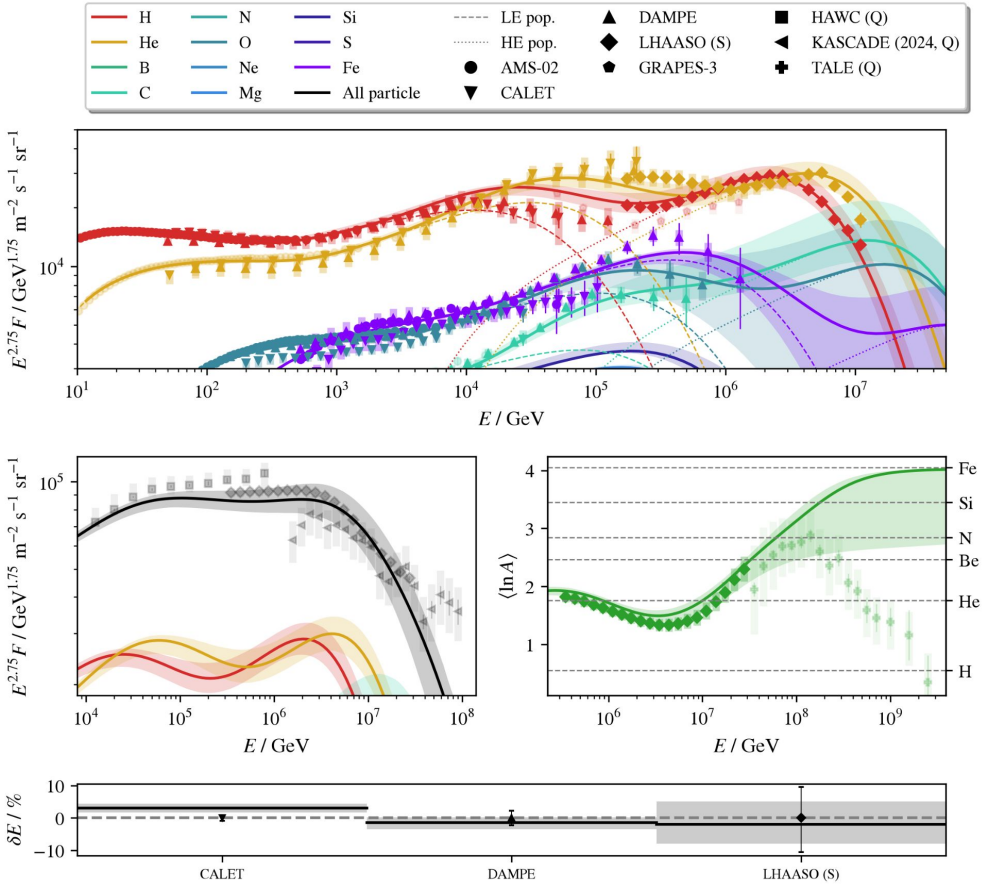
- The usual naive $\chi^2$ wrongly assumes systematics to be uncorrelated between bins
- No correlation matrices are published by experiments :(




- We assume exponentially decaying correlation with characteristic $\lambda_{syst}$ measured in decades
- Fiducial value is $\lambda_{syst}$=1 for all experiments, roughly matching DAMPE's assumption
- Correlation between datasets is neglected

# The minimal model

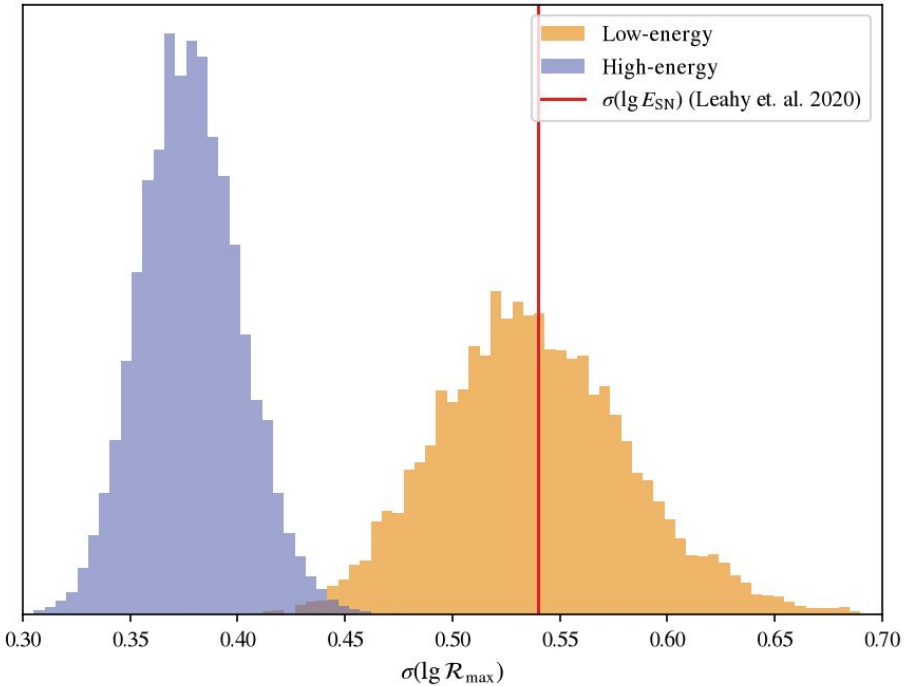
- Two-population model reproduces all data in GeV-PeV range reasonably well
- Low-energy population is constrained in the GeV range by AMS-02 and extrapolated up with the population cutoff
- High-energy population enters at ~100 TeV and dominates the knee
- Allparticle observables are not included in the fit, but reproduced quite well up to ~30 PeV



# **The minimal model:** implications

**Cutoff shape → $R_{max}$ variance**

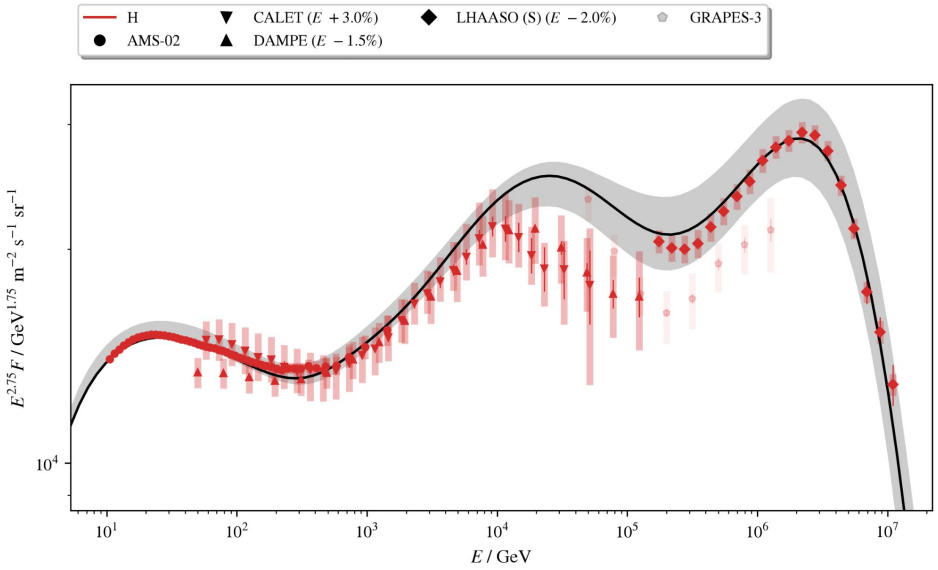
- HE: quite uniform sources, e.g. a few powerful accelerators
- LE: consistent with $E_{SN}$ variance, although intrinsic cutoff shape and environment variance need to be taken into account

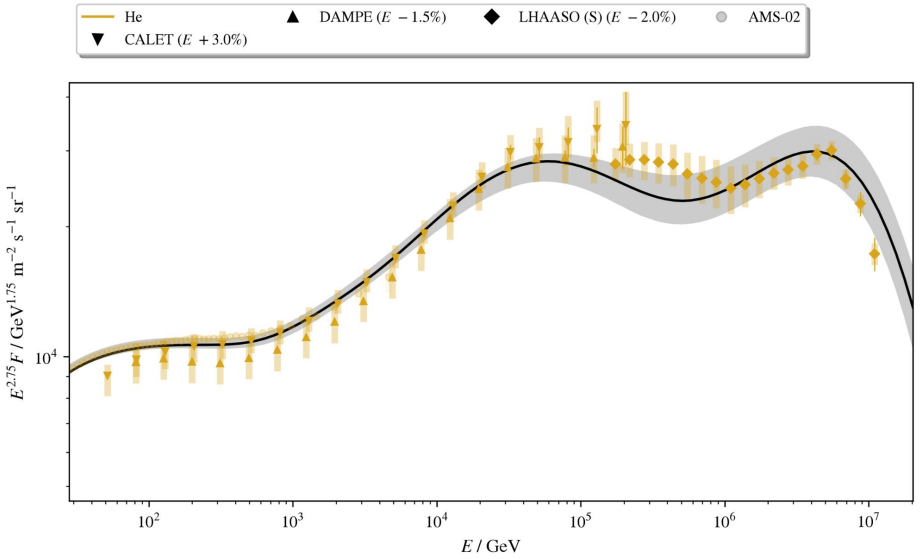



📖 Leahy, D. A., Ranasinghe, S. & Gelowitz, M. ApJS 248, 16 (2020)

# **The minimal model:** shortcomings

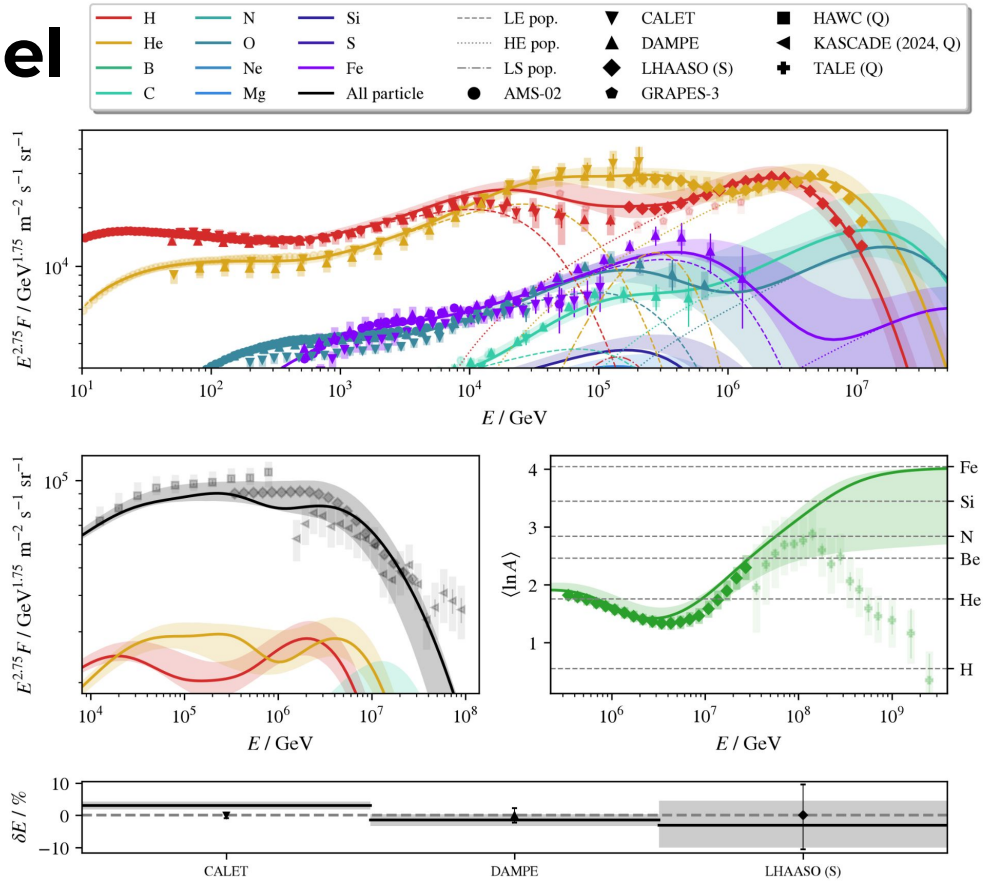
- In 10–100 TeV range, H and He are over- and underprediced, although within (correlated) systematics
- If true physical effect, this requires another population to provide non-$R$-scaling features in that range



# The post-minimal model

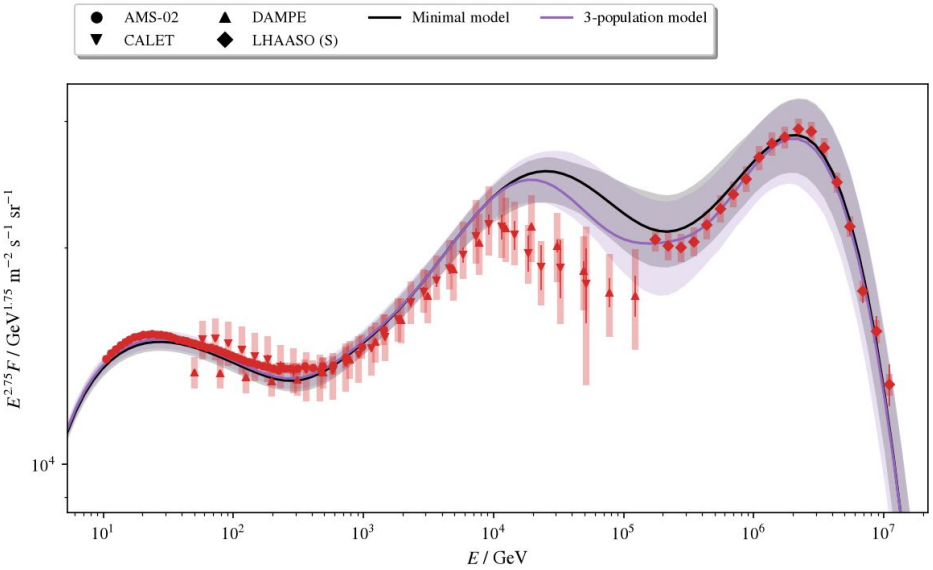
- Three-population model includes an additional component to break *R*-scaling in 10-100 TeV range
- Could be a genuine population or a local source (however, see probabilistic criticism)
- Significance of the third population is ~2.8$\sigma$
- Problematic dip in the all-particle spectrum (not included in the fit)

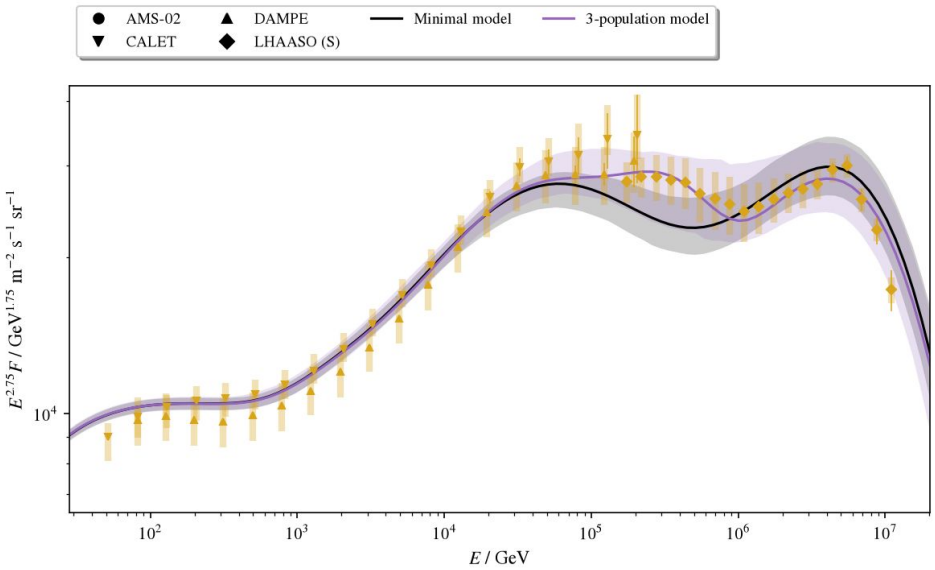



📖 Evoli, C., Amato, E., Blasi, P. & Aloisio, R. Phys. Rev. D 104, (2021)

# The post-minimal model

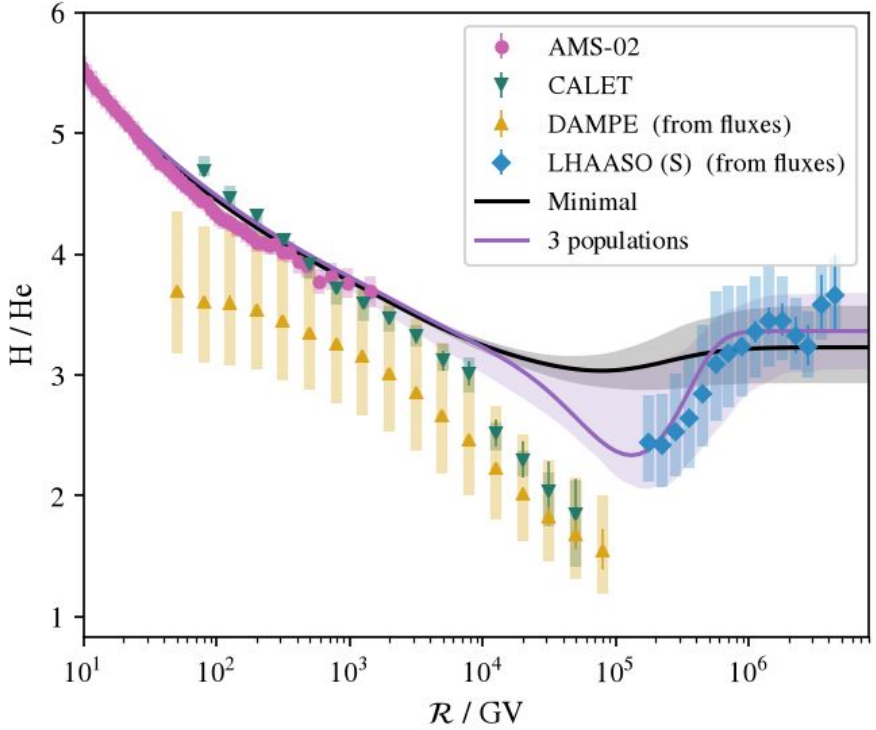
- H and He spectra are less problematic with an extra component
- Some mild tension remains — is there a better way?



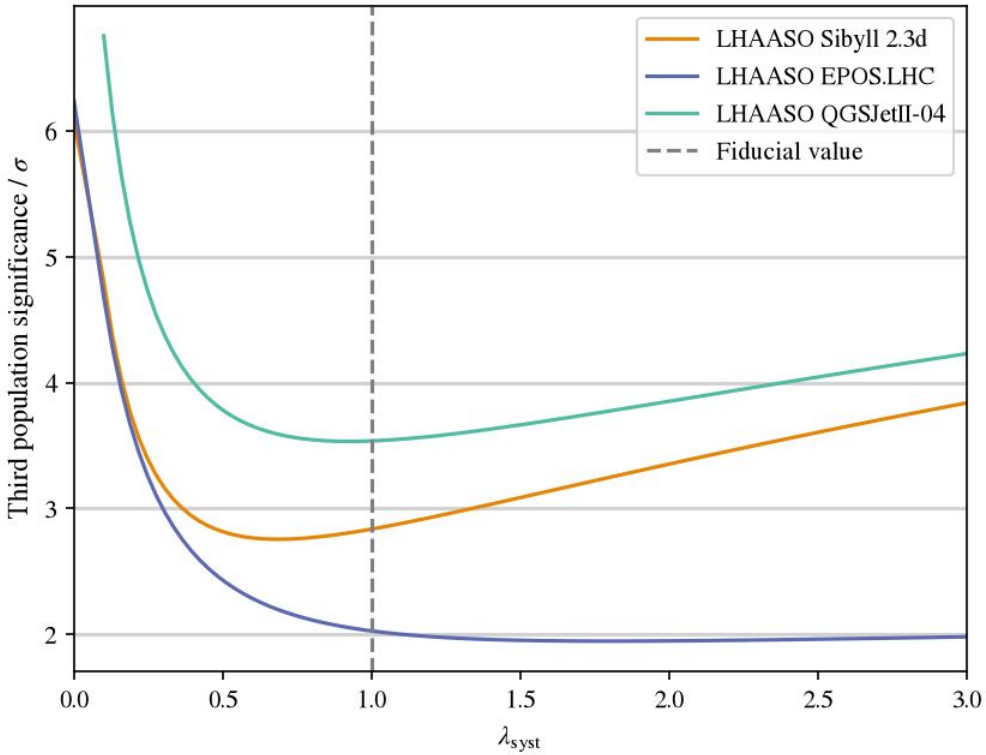
# The post-minimal model

- The benefit of the 3-population model is best illustrated by the H/He ratio
- Data for DAMPE and LHAASO here are crudely reconstructed from reported fluxes – most likely there's possibility to have greatly reduced systematics!
- 10-100 TV dip in the H/He ratio is indicative of the third population contributing there



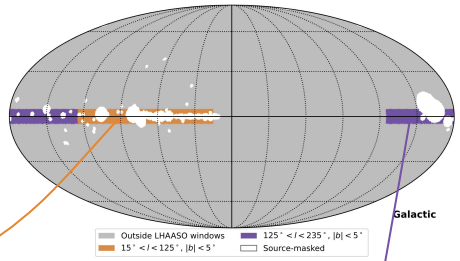
# **The post-minimal model** and correlations

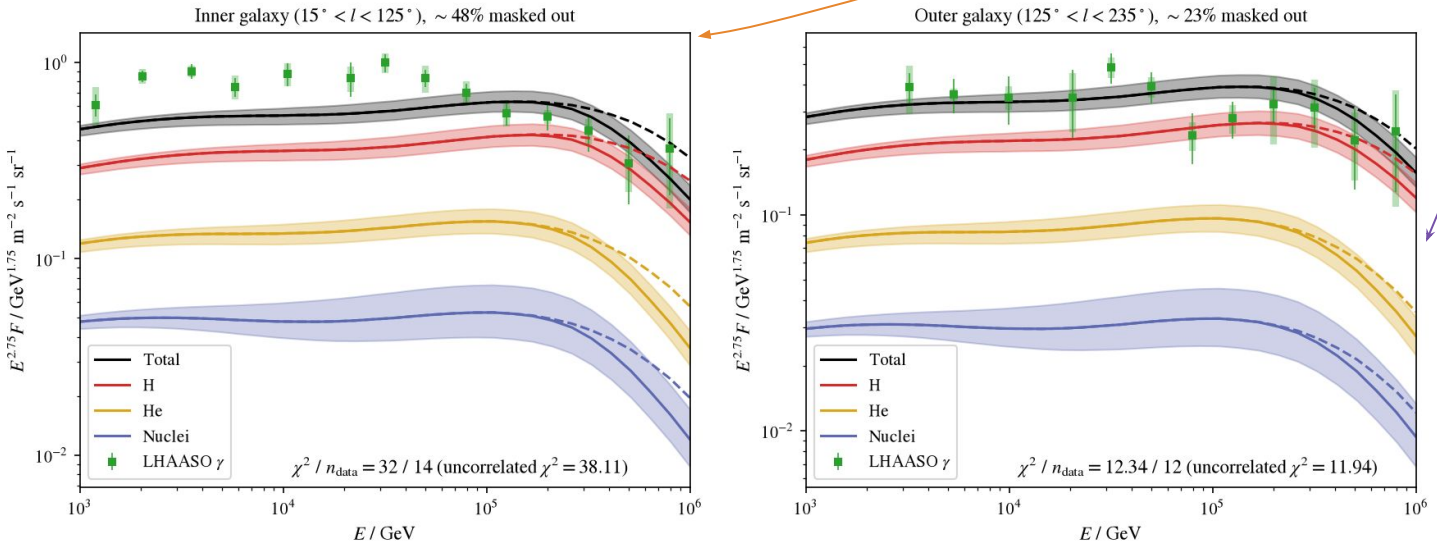
- Quoted 2.8$\sigma$ significance is for LHAASO with Sibyll 2.3d and the fiducial $\lambda_{syst}$=1
- **The significance very sensitively depends on $\lambda_{syst}$ → we need better account of systematics' correlations**
- Naive uncorrelated $\chi^2$ would yield >6$\sigma$



# Diffuse $\gamma$-rays implication

- We use **HERMES** code to LOS-integrate $\gamma$-ray emissivity from CR-gas interactions and produce diffuse $\gamma$-ray spectrum, assuming homogeneous CR density
- Outer galaxy is well reproduced, while there's clear discrepancy in the inner one, not explainable by a simple rescaling





📖 Dundovic, A. et. al. A&A 653, A18 (2021) 📖 Espinosa Castro, L. E. et. al. MNRAS: Letters 543, L20–L26 (2025) 📖 Prevotat, C. et al. arXiv:2507.10823 (2025)

# Summary

- CR spectra measurements demand at least two populations in GeV-PeV range
- At present, the minimal two-population model is sufficient to describe the data
- There are good candidates for both populations; CR spectrum carries information about both their intrinsic and population properties
- However, it has shortcomings in 10-100 TeV range; a third component is preferred at ~2.8$\sigma$; H/He ratio is the clearest probe
- CR data are systematics-limited, and their usual treatment is flawed; release the matrices!
- Diffuse $\gamma$-ray data probe possible non-local features of the CR spectrum

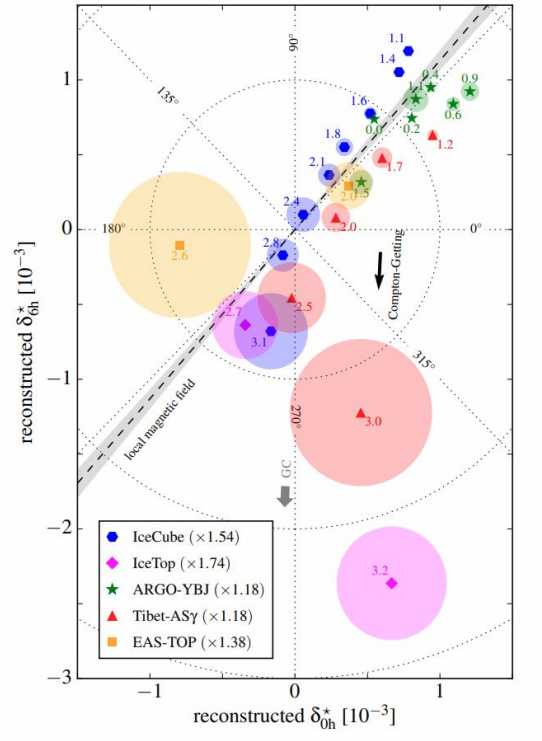
# Thank you!

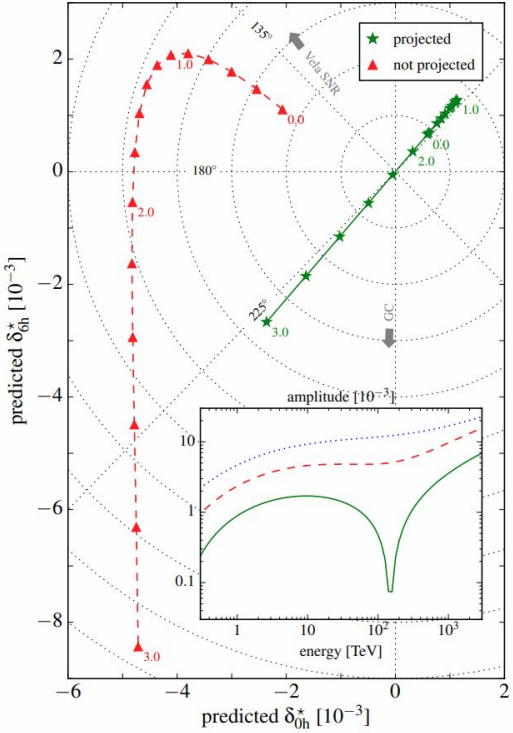
# A note on anisotropy

In some recent works, anisotropy data is fitted along with spectra, however…

- It requires strong assumptions on propagation (spatial dependency, anisotropic diffusion, etc)
- The observed anisotropy is projected along the local GMF → does not necessarily point to sources
- Dominant contributors to the anisotropy might be negligible for the flux

This effectively decouples descriptions of spectrum and anisotropy; we limit ourselves to the former

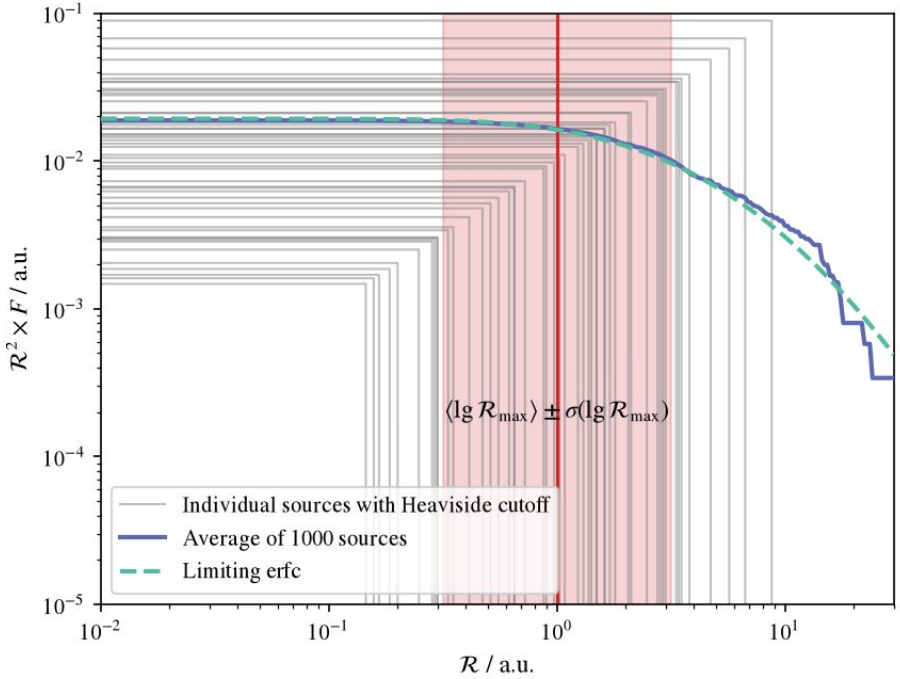


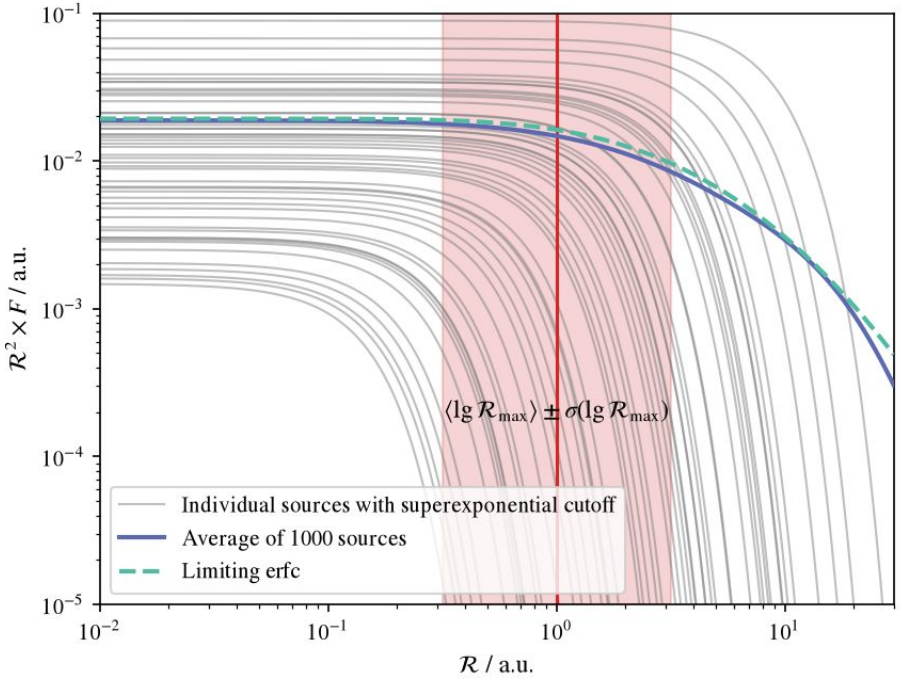





📖 Ahlers, M. & Mertsch, P. PPNP 94, 184–216 (2017)
📖 Ahlers, M. PRL 117, (2016)

# Spectral cutoff as a population effect



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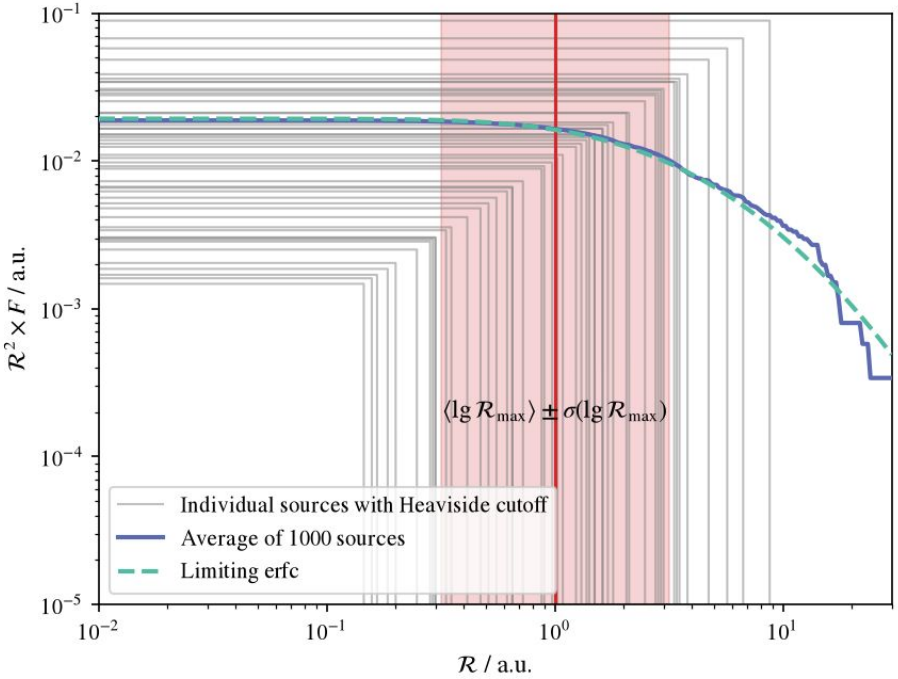
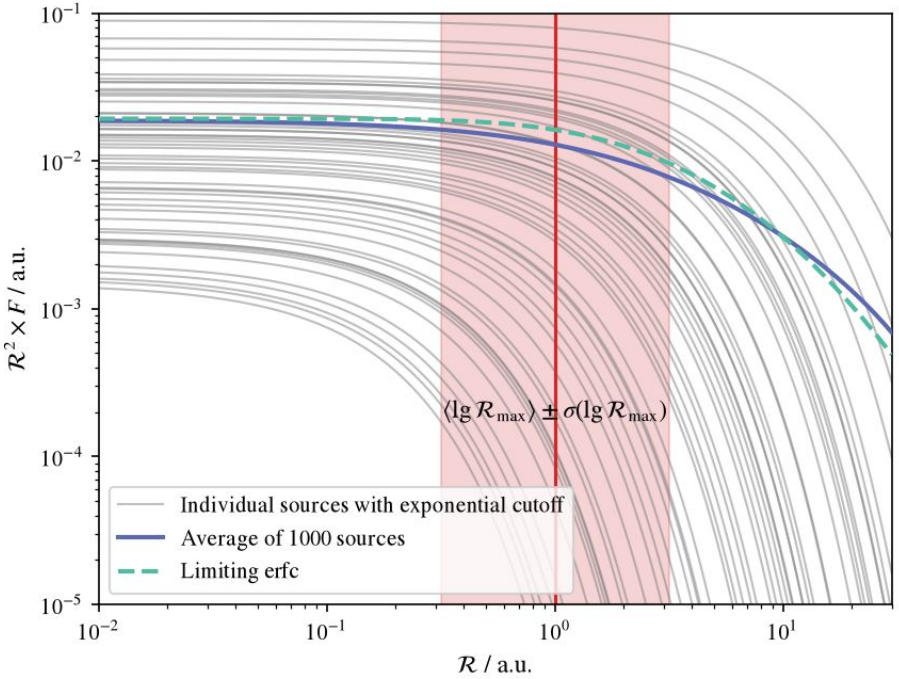
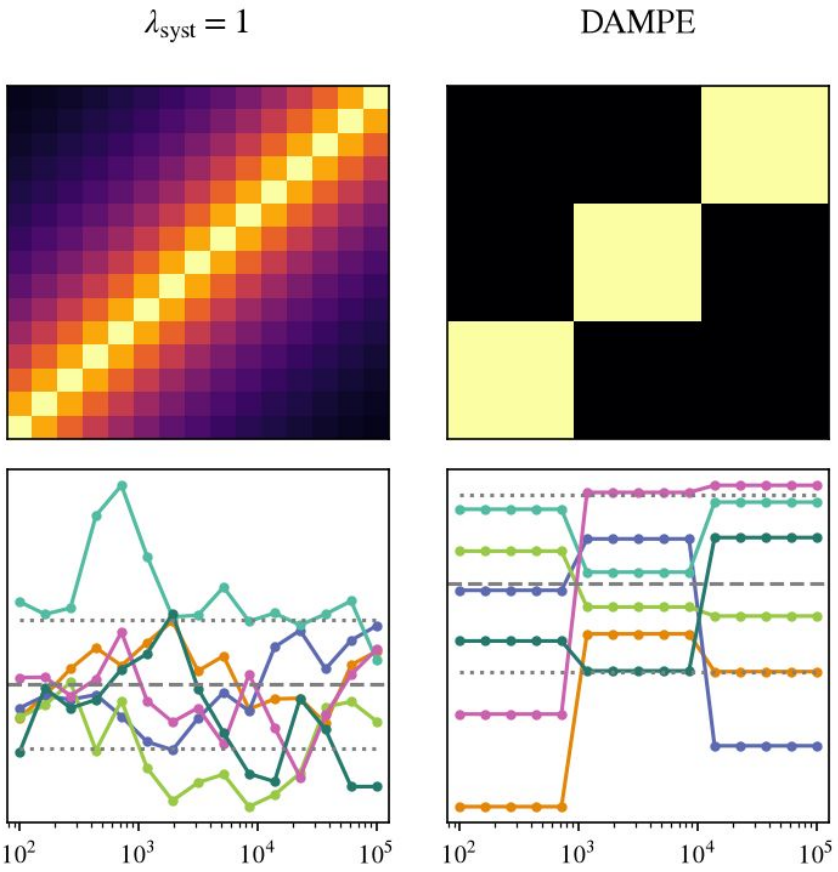


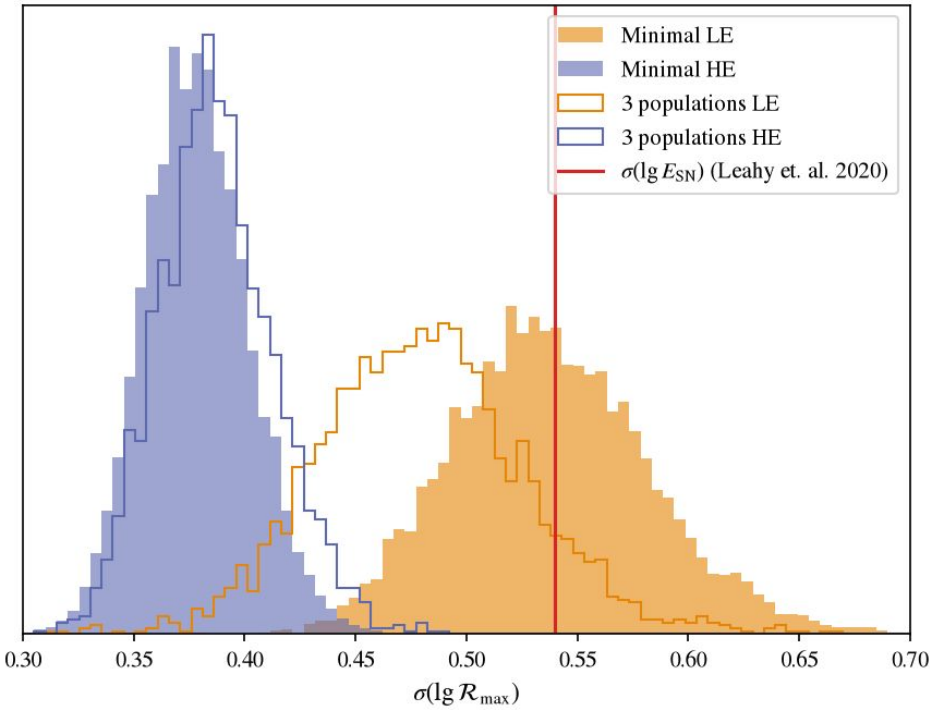
# DAMPE systematics

- DAMPE analysis doesn't use correlation matrix explicitly, but introduces nuisance parameter per ~decade, constrained by systematics
- This corresponds to a block correlation matrix
- Is this a realistic description or the error generating process? Could be for DAMPE, but too entropic to be used generically



# Population variances with minimal & post-minimal models

- Adding 3rd component reduces the LE population variance → tension with SNR expectations

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