UNIVERSITÉ DE GENÈVE

erc

Recent observations in Galactic Cosmic Rays

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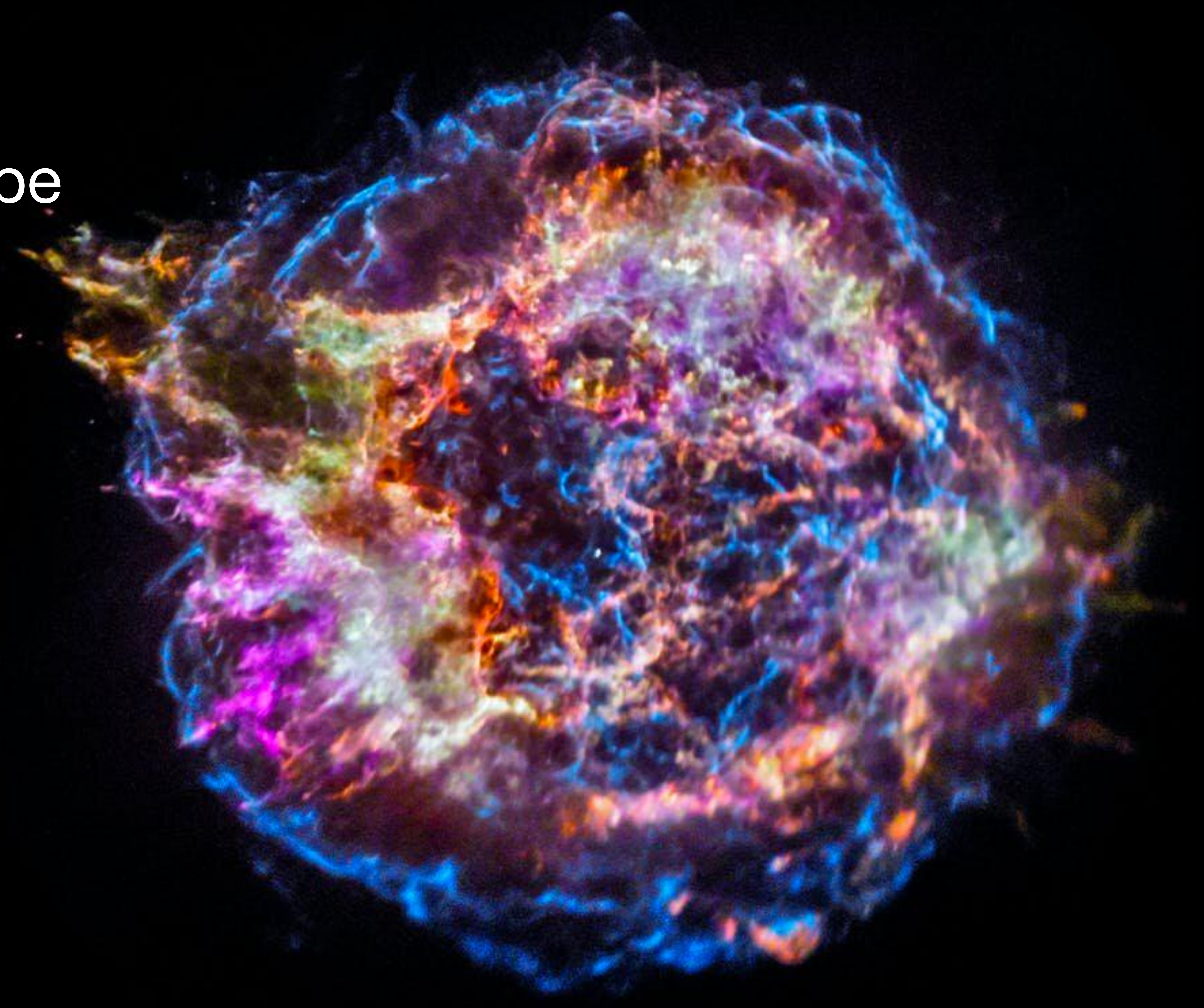
Geneva, March 20, 2024

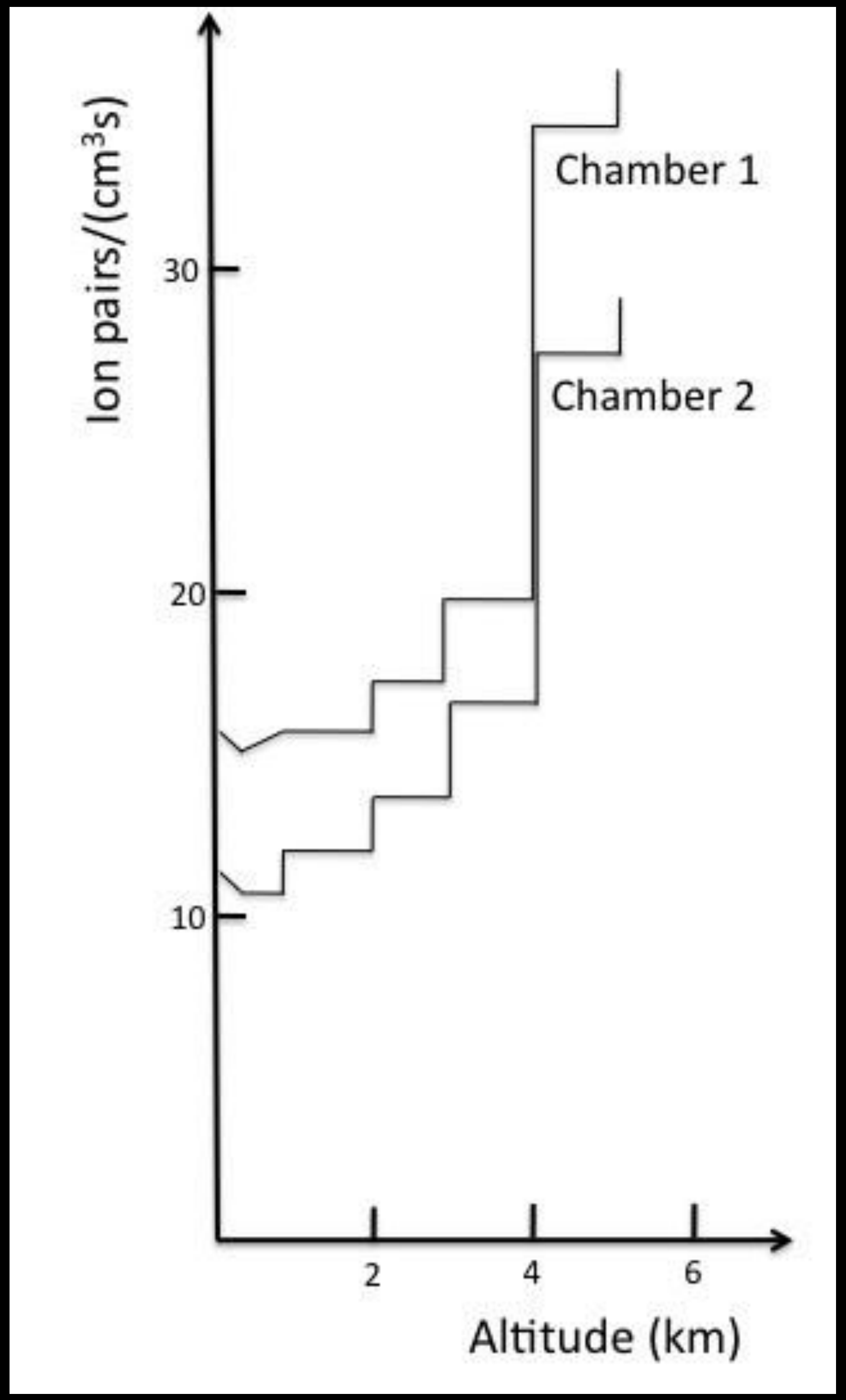
Outline

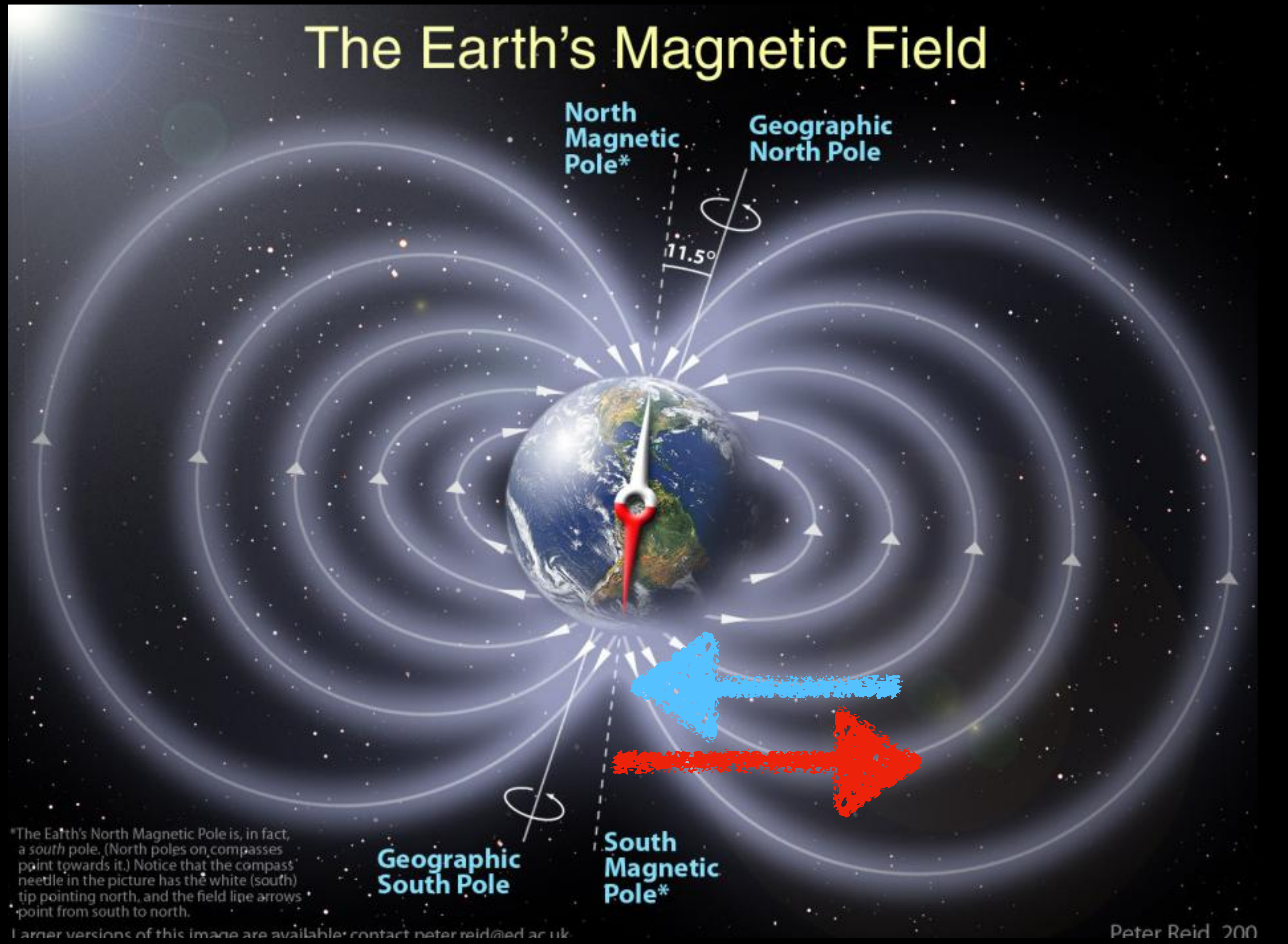
- Cosmic ray history and current landscape
- Space experiments & results
    - Protons, ions
    - Electrons, positrons
- Ground-based experiments & results
    - Spectrum & composition
    - Anisotropy



First hints of already in 18th century (Coulomb)

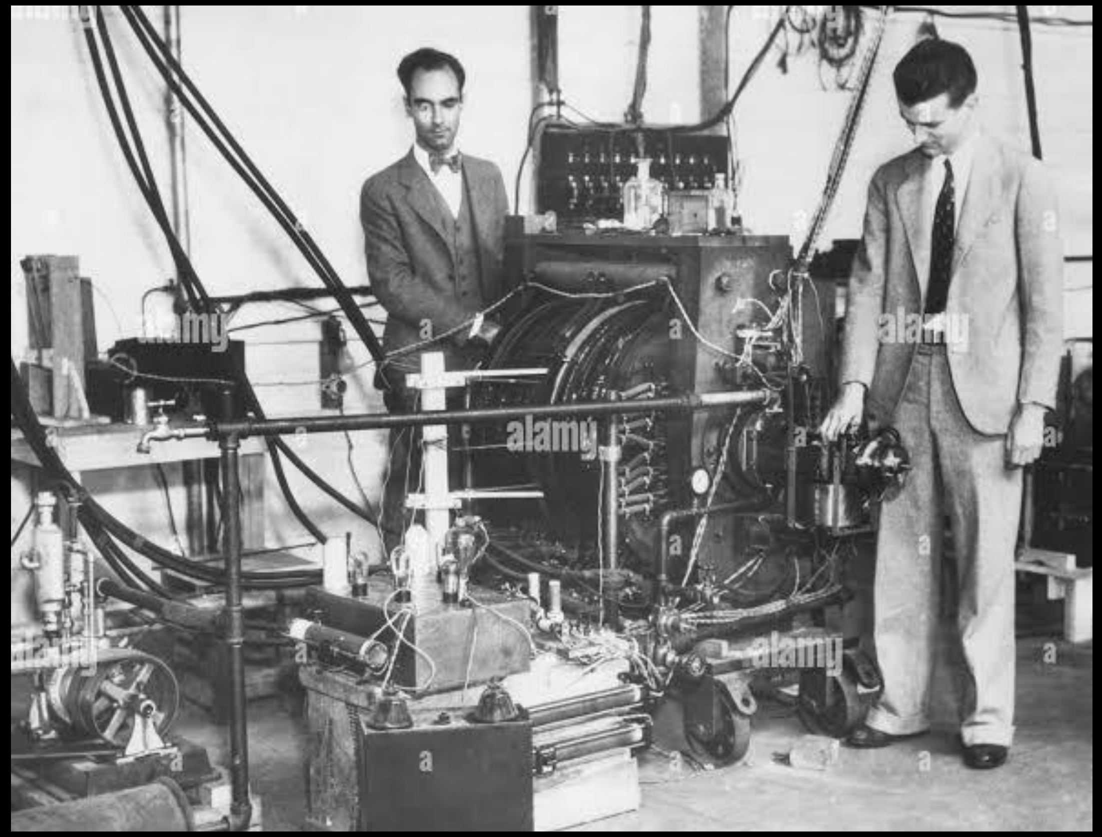
1912 — Discovery of Cosmic Rays in ballon flight (Victor Hess)





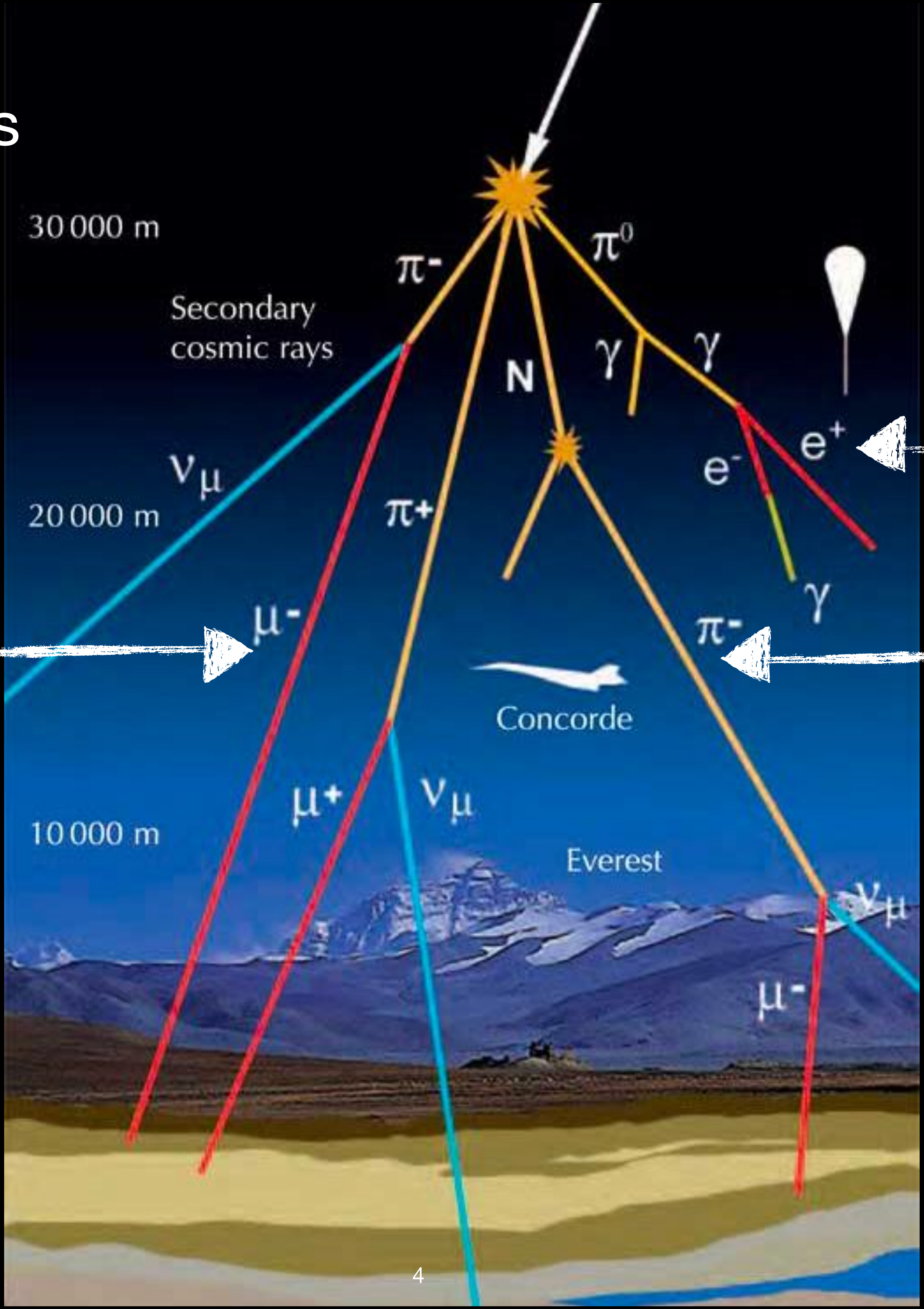
B. Rossi: due to earth magnetic field, flux of cosmic rays is different between east and west directions — cosmic rays are charged!

First particle physics discoveries in cosmic rays (before accelerators era)



Seth Neddermeyer and Carl Anderson

1936



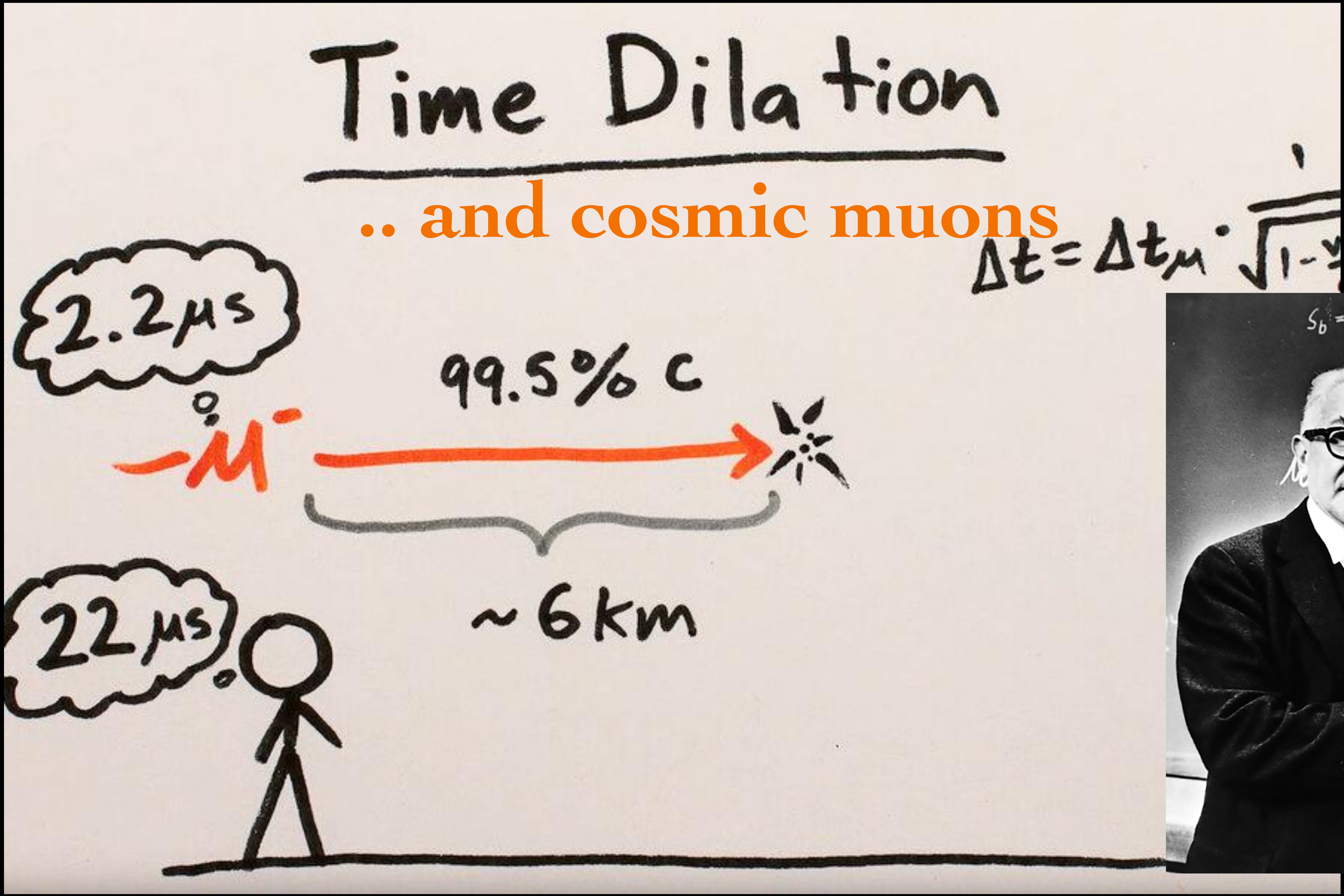
Carl David Anderson

1932

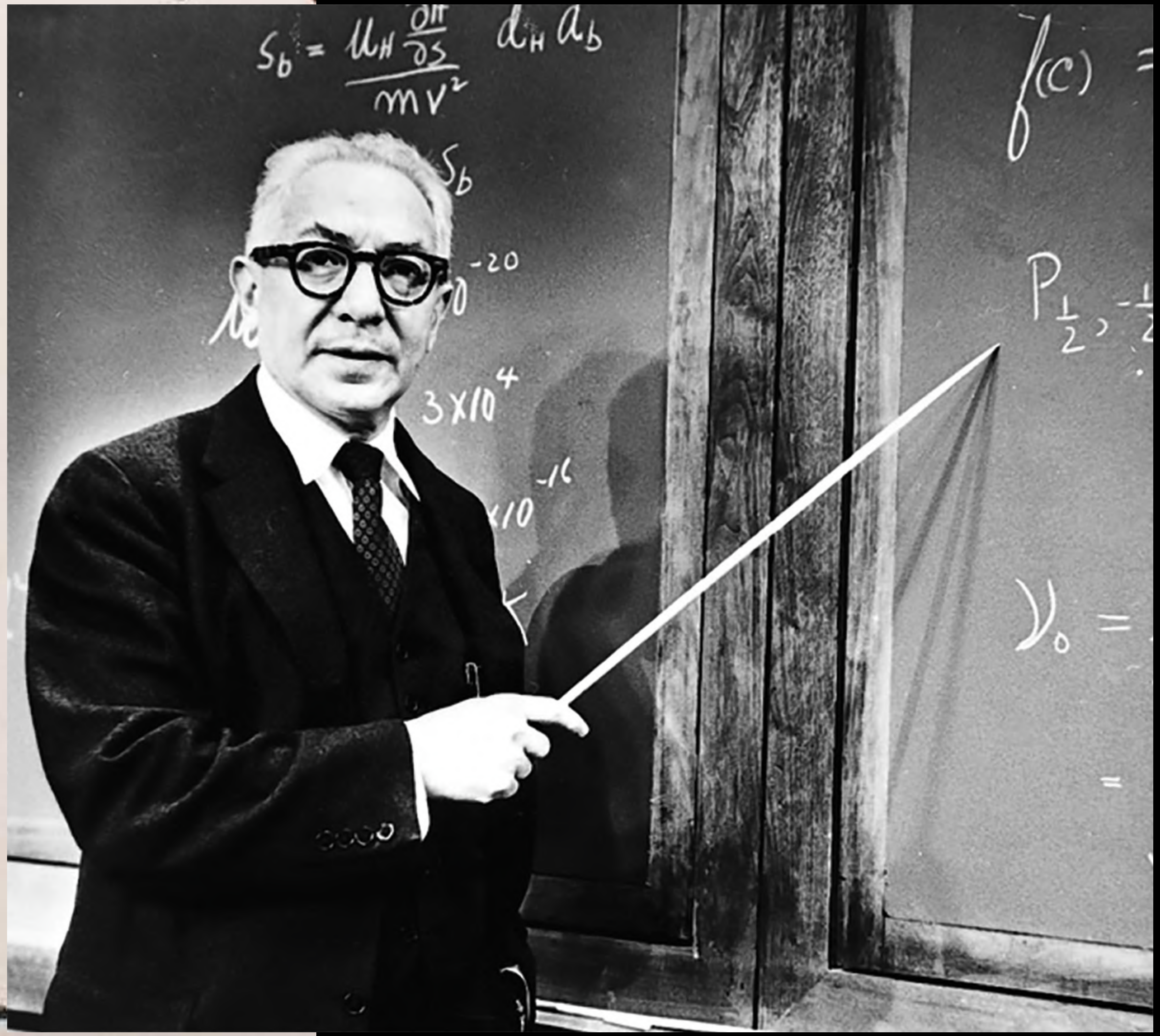
1947

Cecil Powell

Many more discoveries, K, Λ ..

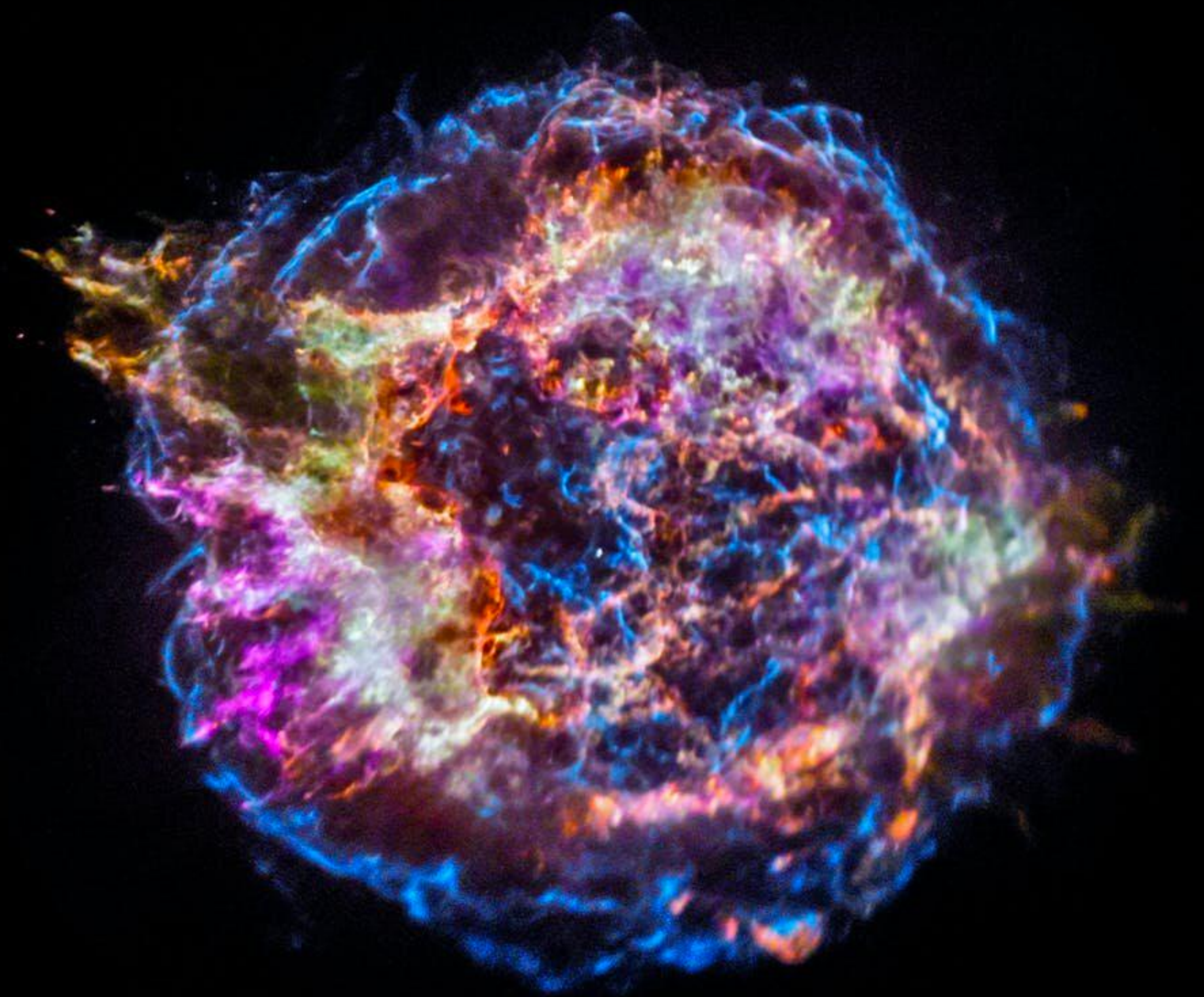


.. and cosmic muons

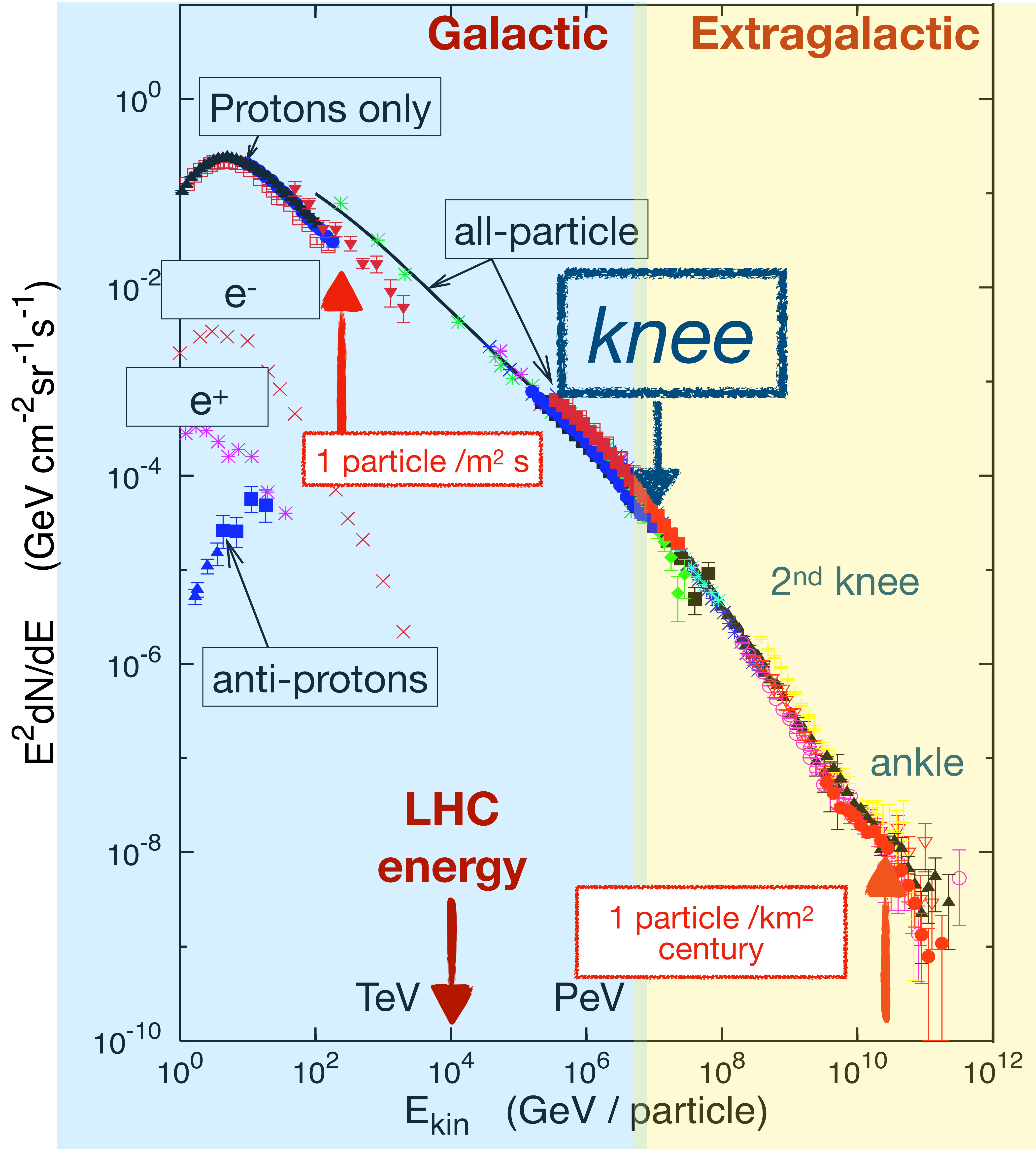


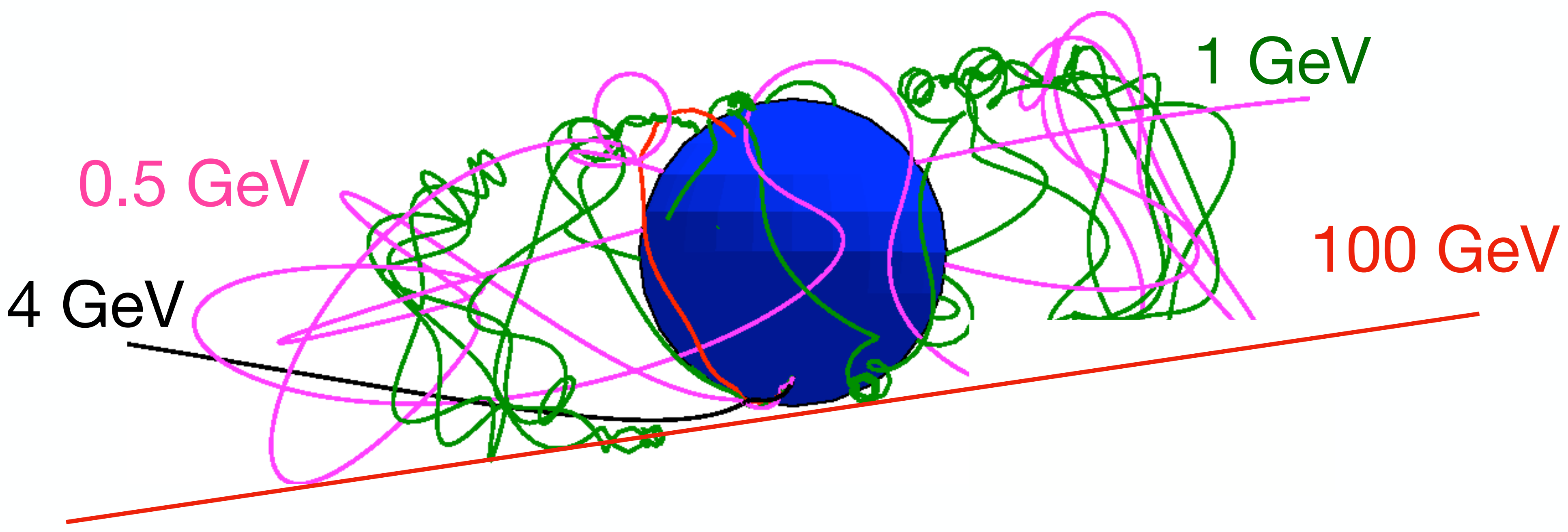
Isidor Isaac Rabi:
"who ordered that?"

Cosmic Ray landscape



Cosmic Ray composition and spectrum





- Composition:

  85—90% ***p***, 10% ***He***, few ***% ions***, <1% ***e***

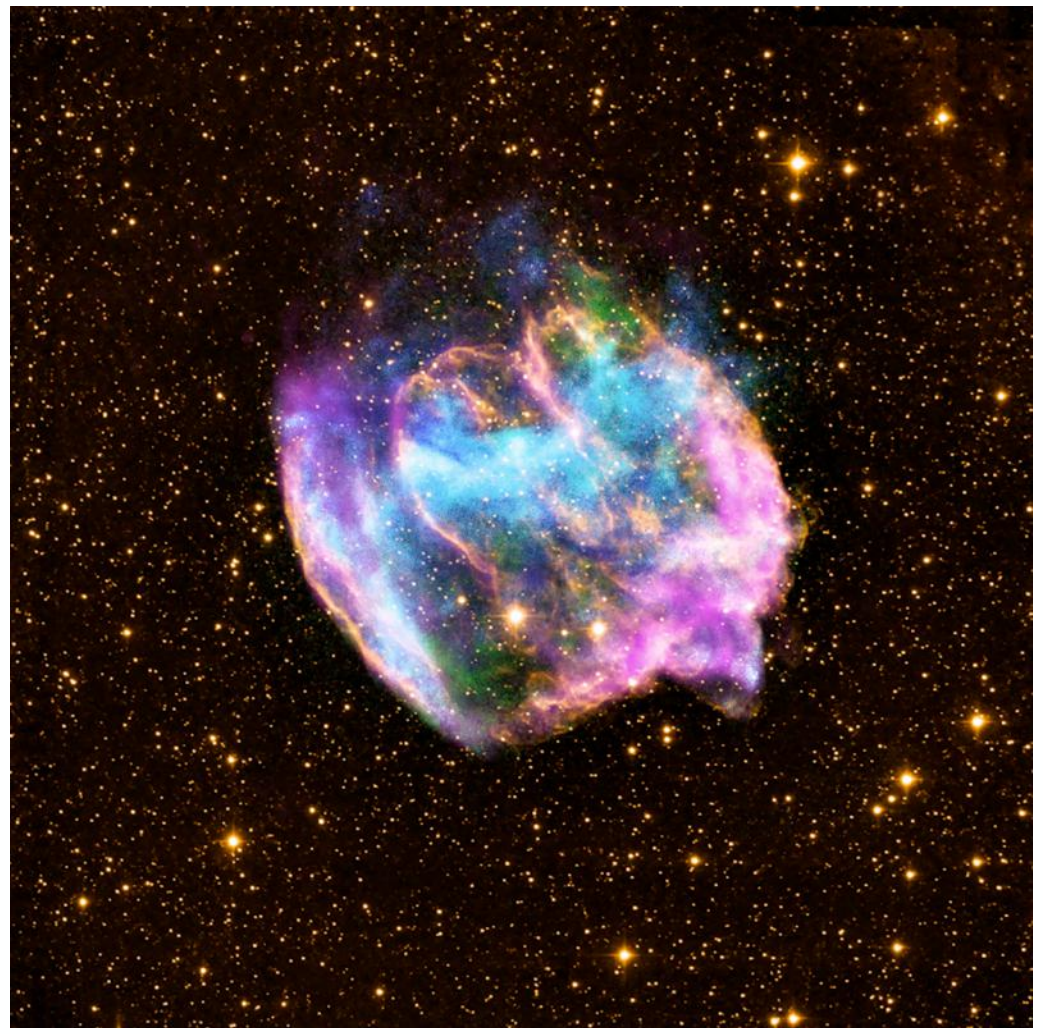
- Maximum energy **~10^{20} eV** (GZK cutoff)

  Limited by interaction with cosmic microwave background

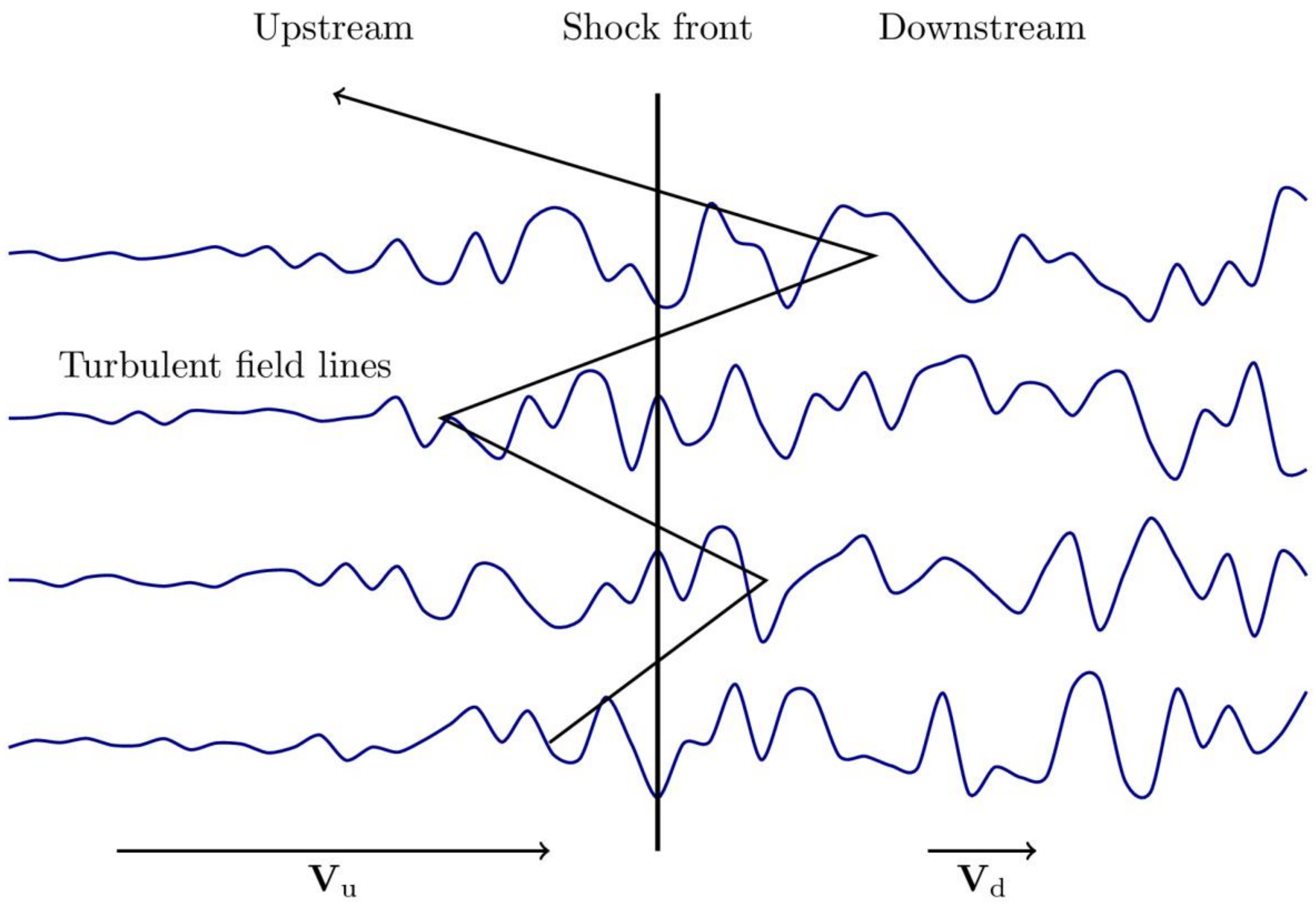
- Spectrum consists of different power-laws
  - $dN/dE \propto \sim E^{-2.7}$ up to the "knee"

- **The "knee" (region around few PeV)**
  - Galactic sources "work" up to ~PeV scale

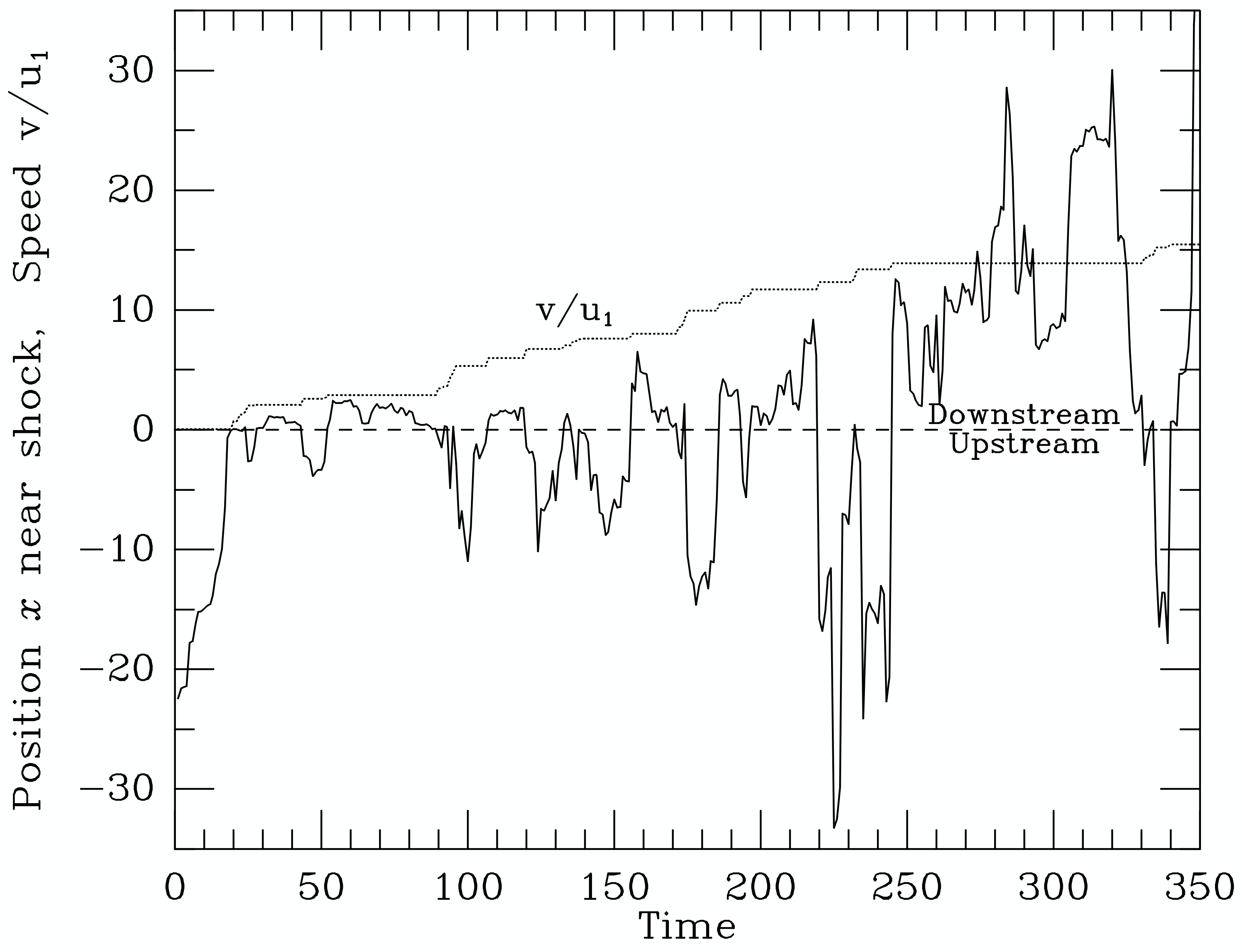
Cosmic Ray acceleration



Supernova explosion
(a few per century)



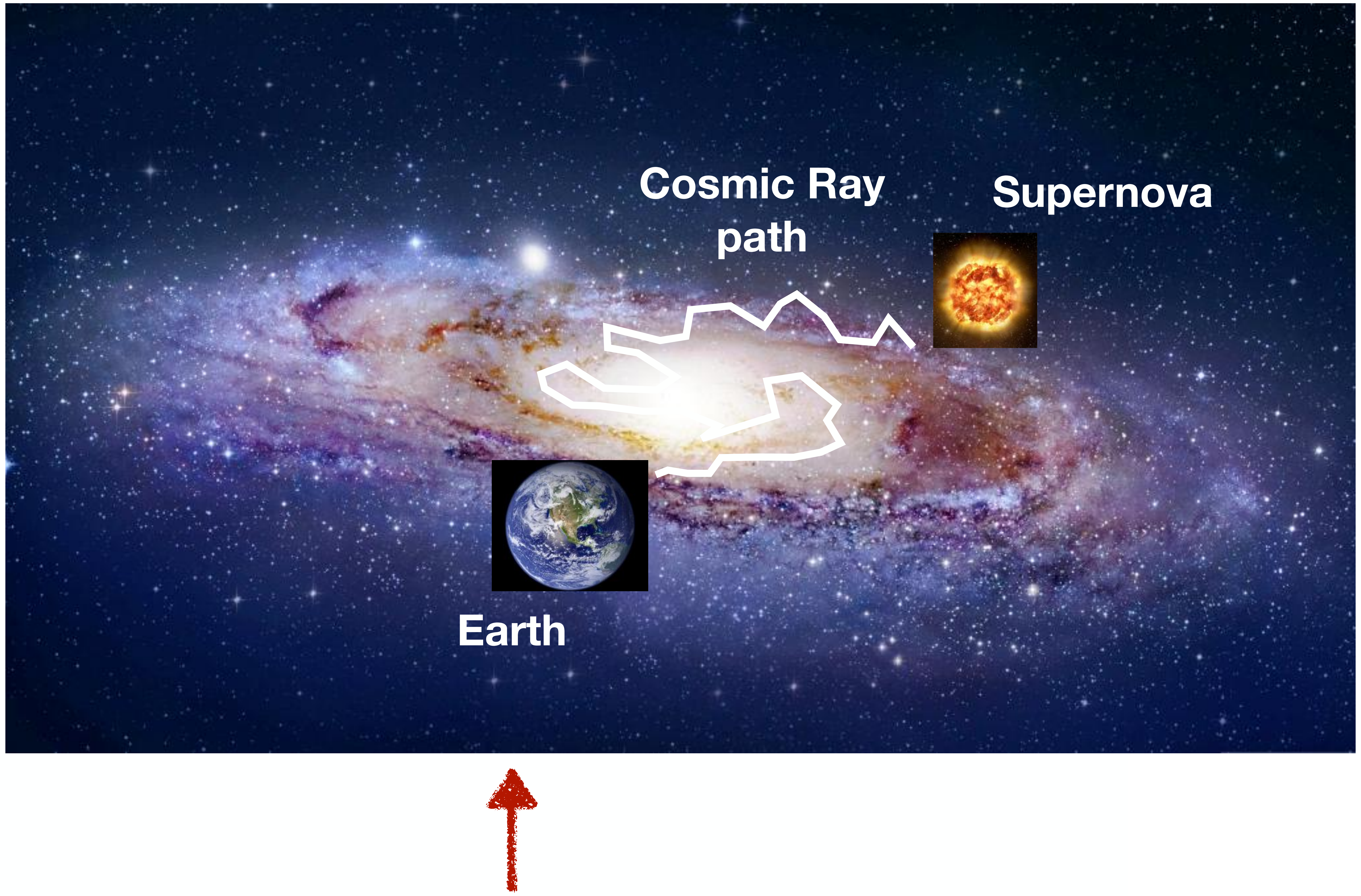
Propagating shock wave front

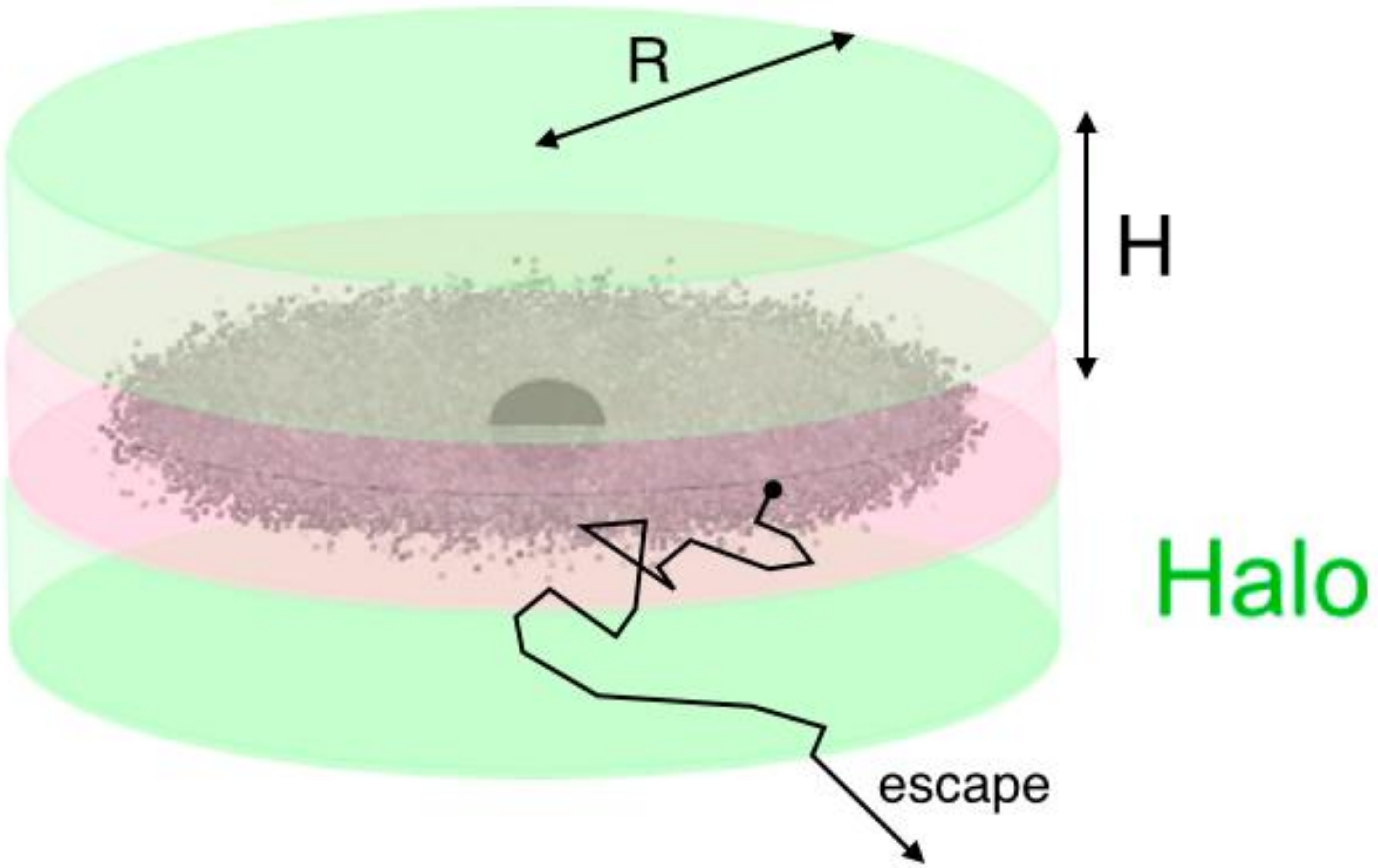


Particle gaining energy each time crossing the shock front

Diffusive Shock Acceleration mechanism suggested by Fermi: **Flux ~ E^{-2}**

Cosmic Ray propagation





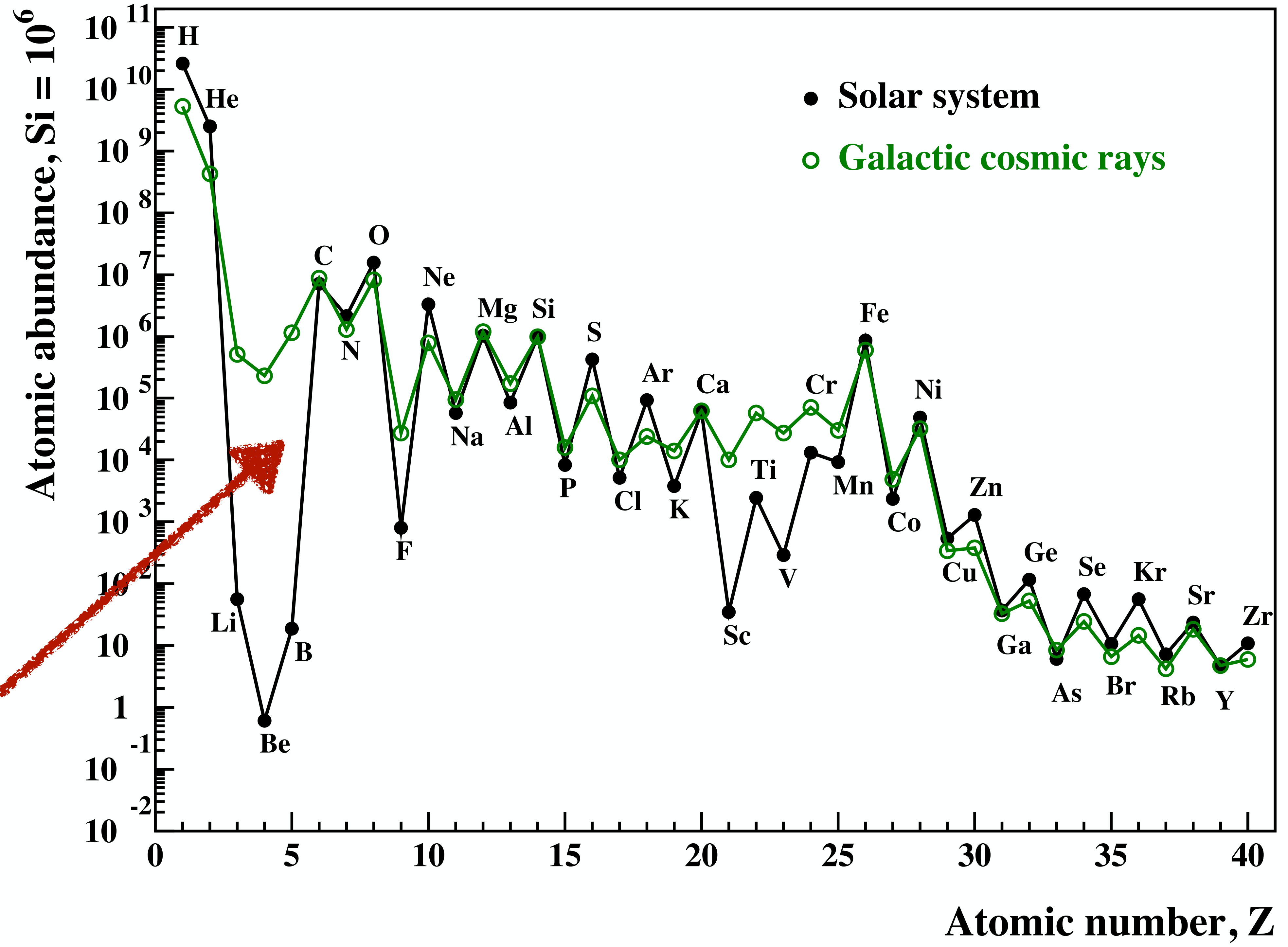
- Cosmic rays “scatter” diffusively in turbulent magnetic fields (in analogy to heat transfer)
  - Travel (confined) in Galaxy for **millions of years**, before reaching us
  - Part of them escape from the surface of the galaxy disk (“leaky box” model)
  - Direction becomes isotropic

Cosmic Rays: Primaries & Secondaries

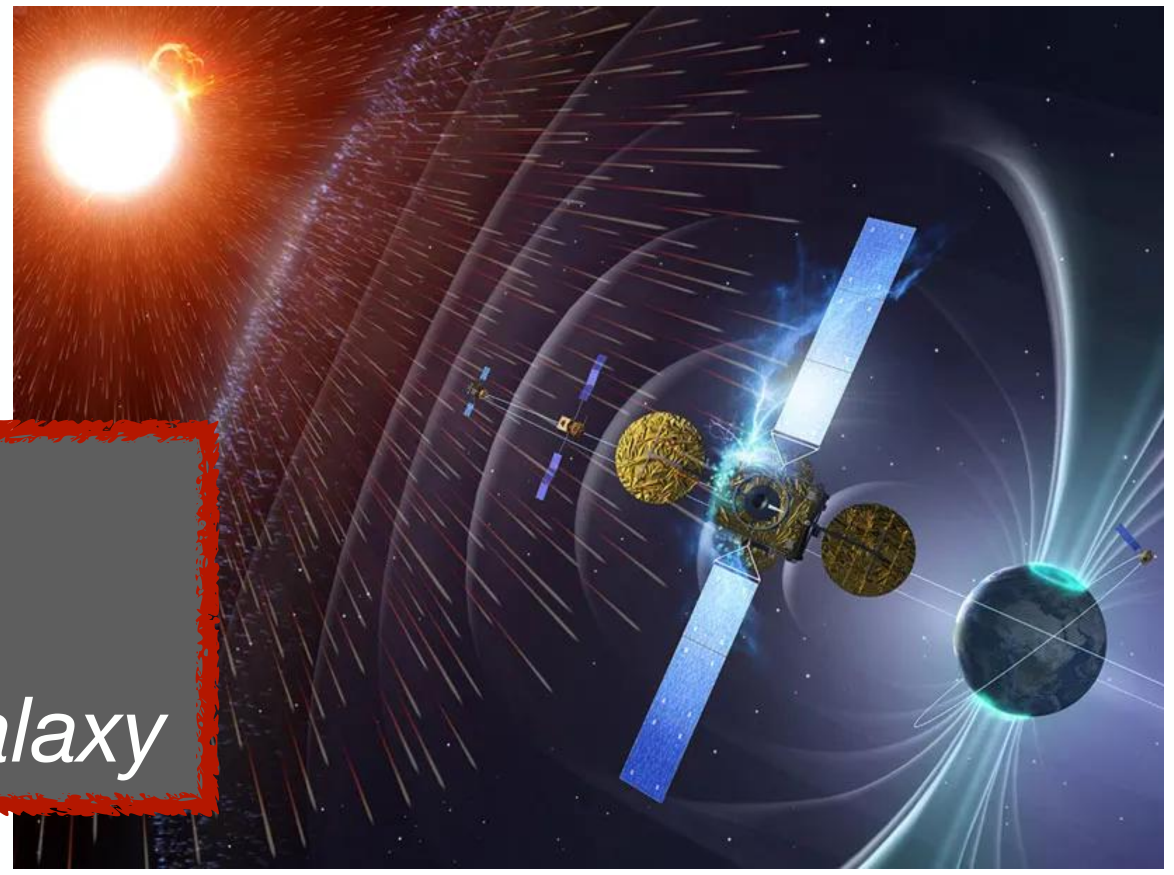
Primary Cosmic Rays: *p, e⁻, He, C, O, Fe*

- Create secondaries during propagation and interaction with interstellar medium
- Traverse on average ~ 10 g/cm^2
- Propagation modifies spectral index:

$$P(E) \propto E^{-2-\Delta}$$

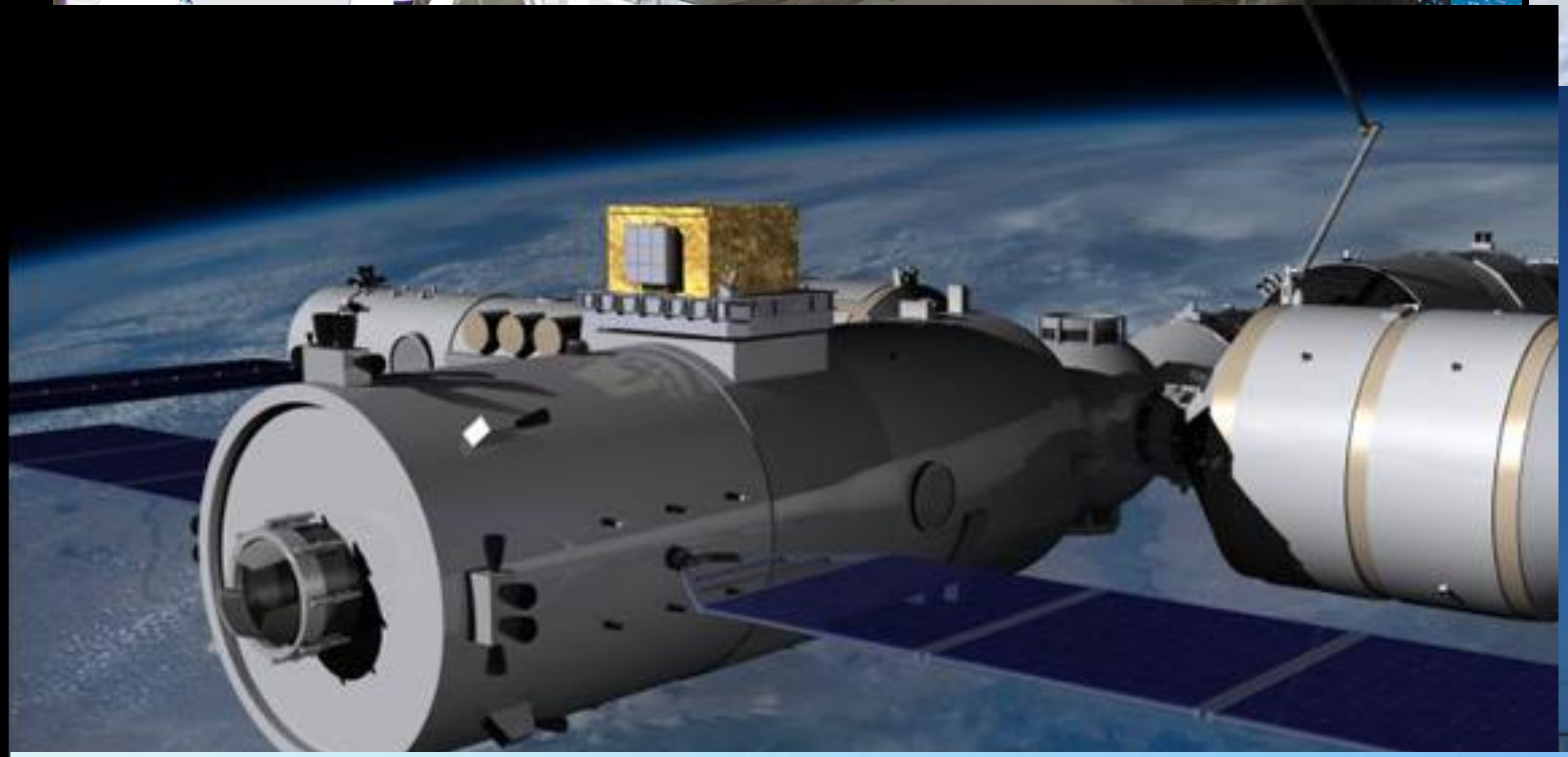


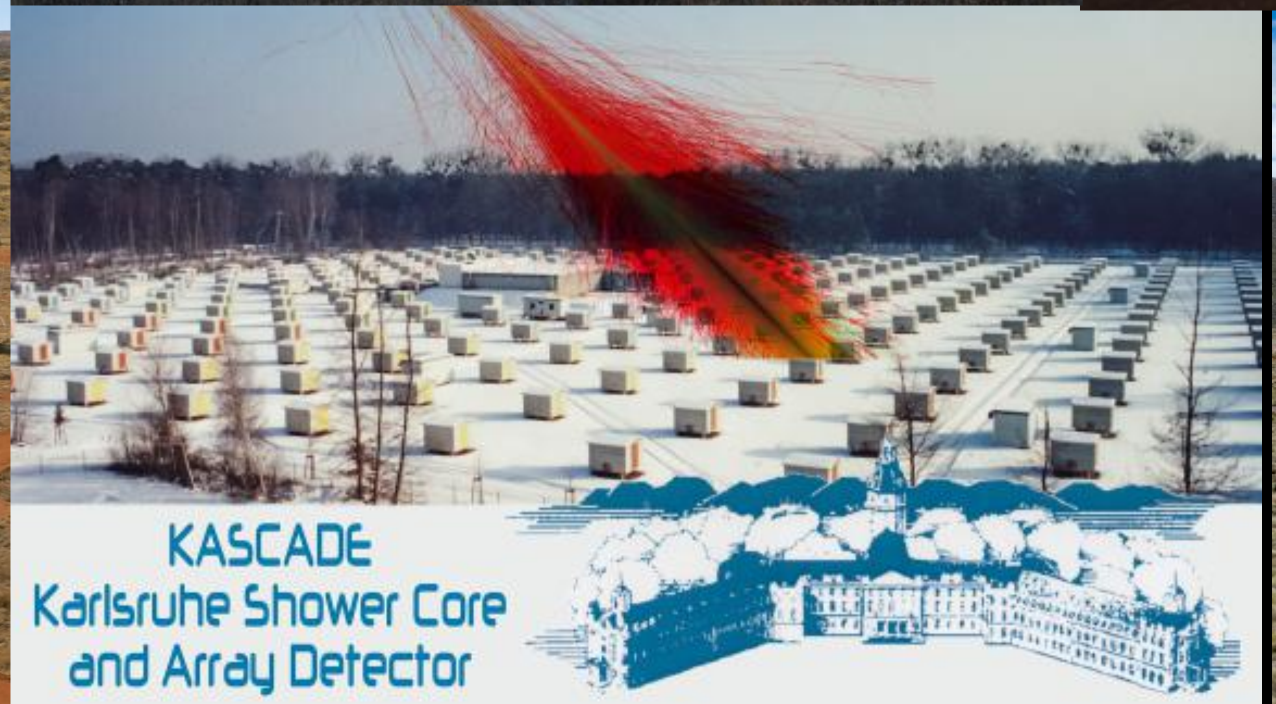
Secondary cosmic rays: *e⁺, $\bar{p}$, Li, Be, B,…*



Cosmic rays constitute significant fraction of energy in typical astrophysics environments
*→ **comparable to energy of magnetic fields, radiation fields or the turbulent gas***
Cosmic rays ionise neutral interstellar gas and also contribute to gravitational balance of the Galaxy

Experiments





Space vs Ground

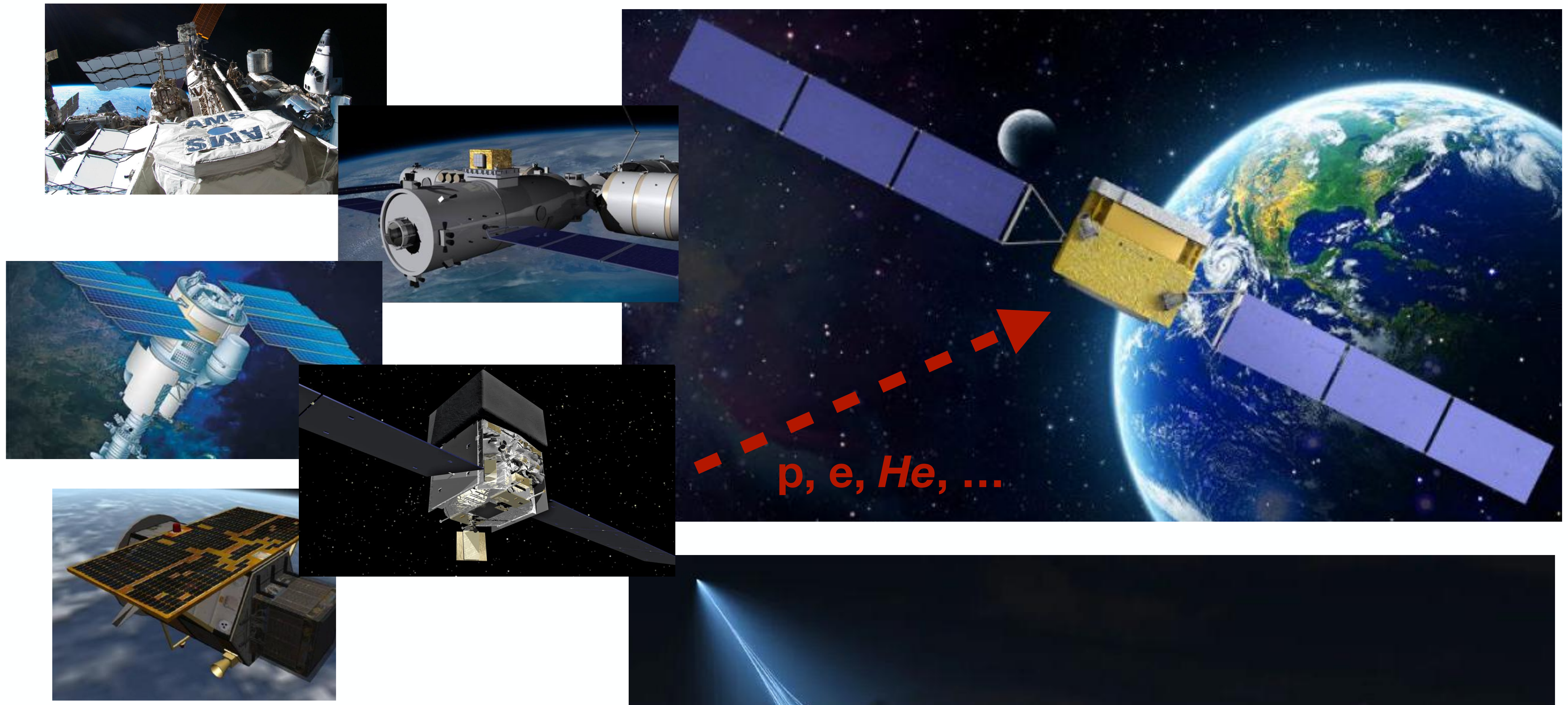
Space

+ Direct detection — very precise

Energy spectrum and composition

– Relatively small size (~m^2)

Limited in energy ~ hundreds TeV



Ground-based

+ Large (~km^2) — reaching highest energies (up to GZK)

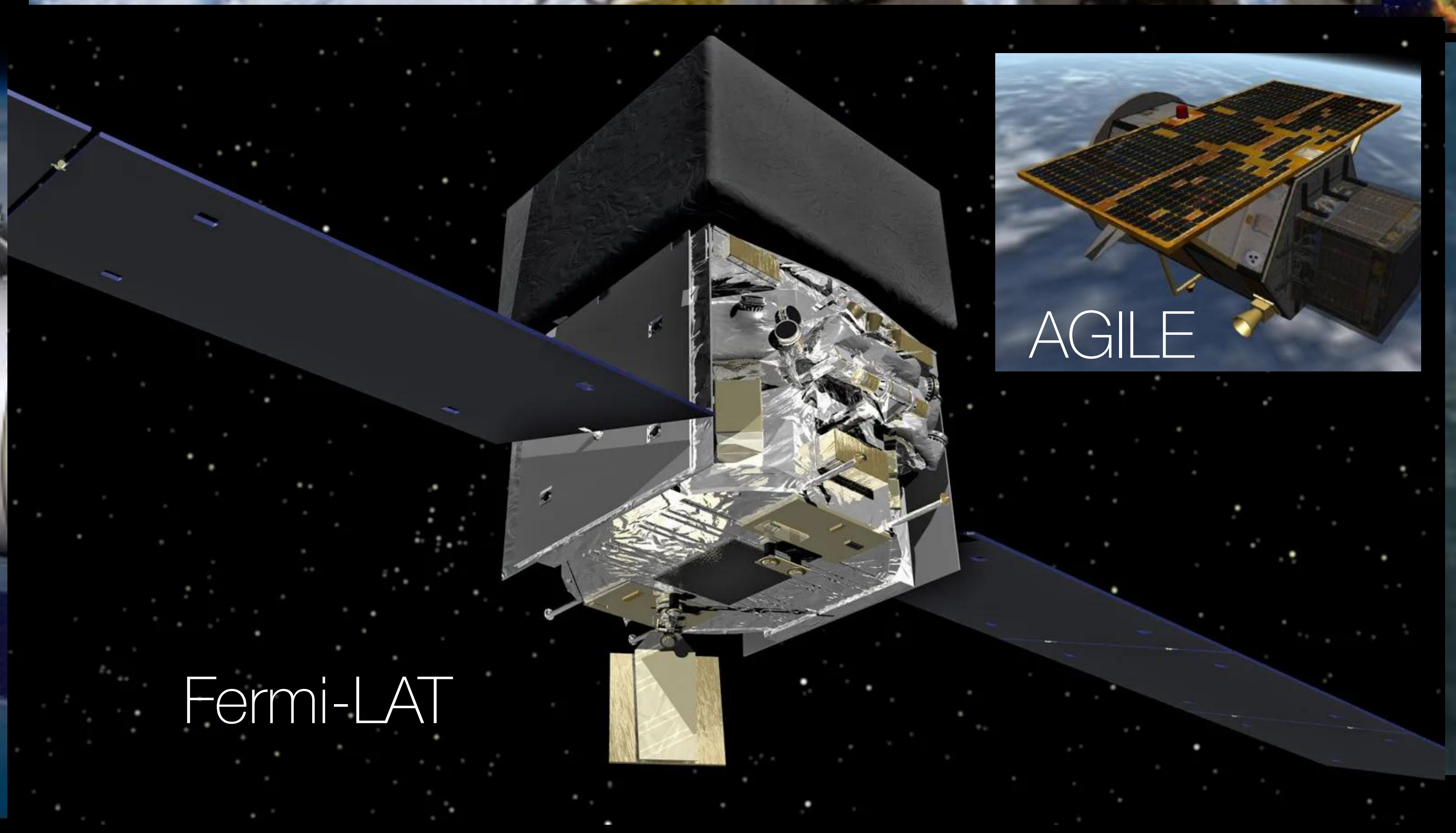
Wide field of view (important for γ-ray physics)

– Indirect detection:

Low sensitivity to composition

Large uncertainty of energy scale

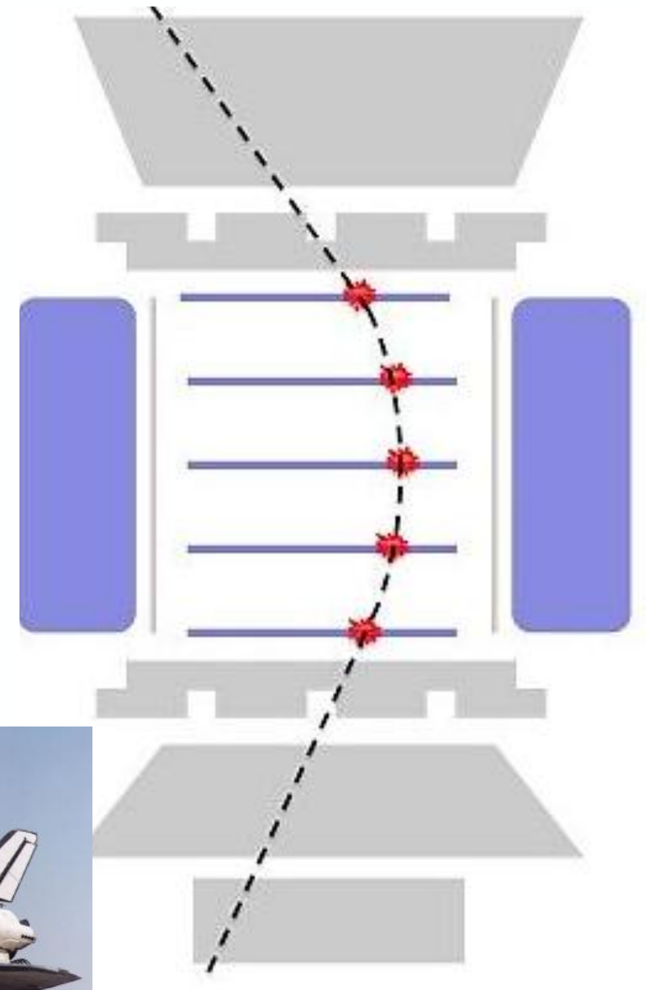
Experiments in space



Space: from spectrometers to calorimeters

Magnetic spectrometers

- **PAMELA**: Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (2006)
- **AMS-02**: Alpha Magnetic Spectrometer (launch to ISS **2011**)



Measuring rigidity (momentum divided by particle charge)

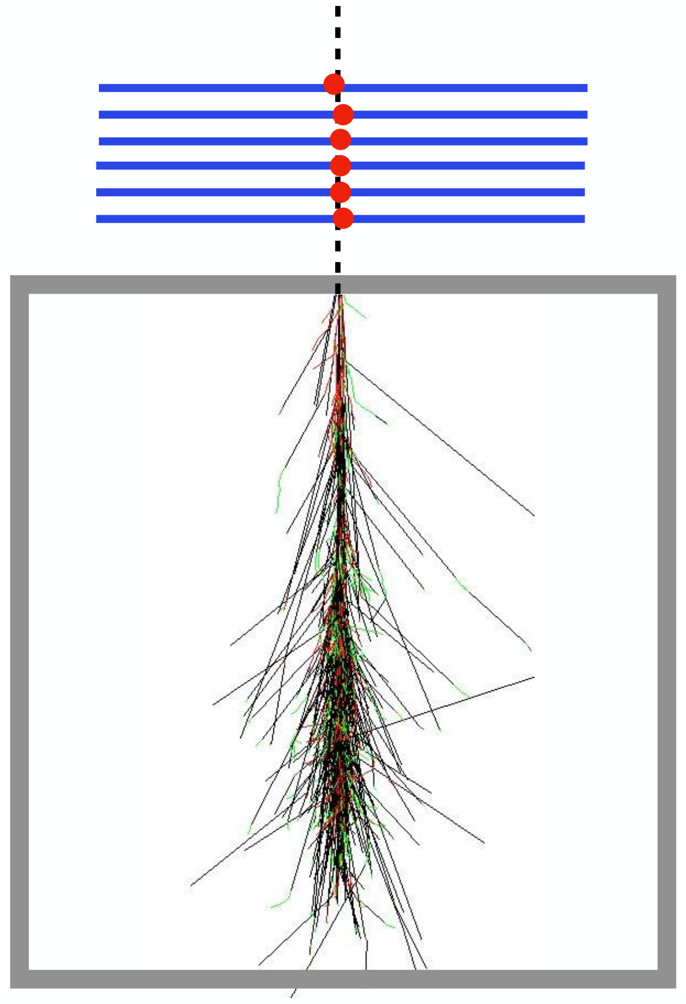
Provide most precise comic ray measurements up to ~TeV scale

… difficult to go beyond few TeV with spectrometers

Covered in this talk

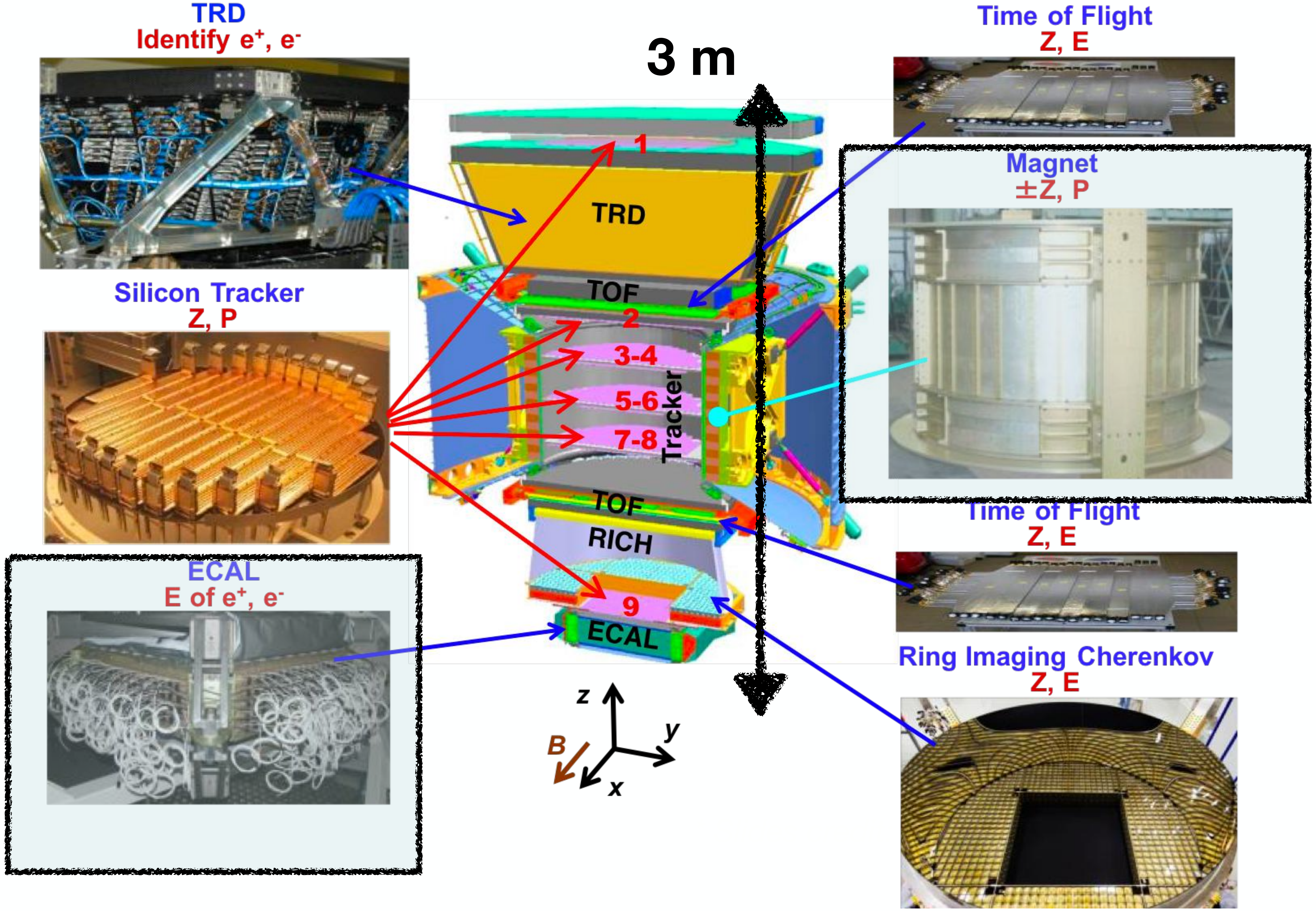
Calorimetric experiments

- **AGILE, Fermi-LAT** (2007, 2008) — relatively small calorimeters
- **CALET**: Calorimetric Electron Telescope (launch **2015**)
- **DAMPE**: DArk Matter Particle Explorer (launch **2015**)
- **HERD**: High Energy cosmic Radiation Detection experiment (~2028)



* Active contribution of UNIGE to experiment R&D, including the **tracker** sub-detector construction

Alpha Magnetic Spectrometer (AMS-02)

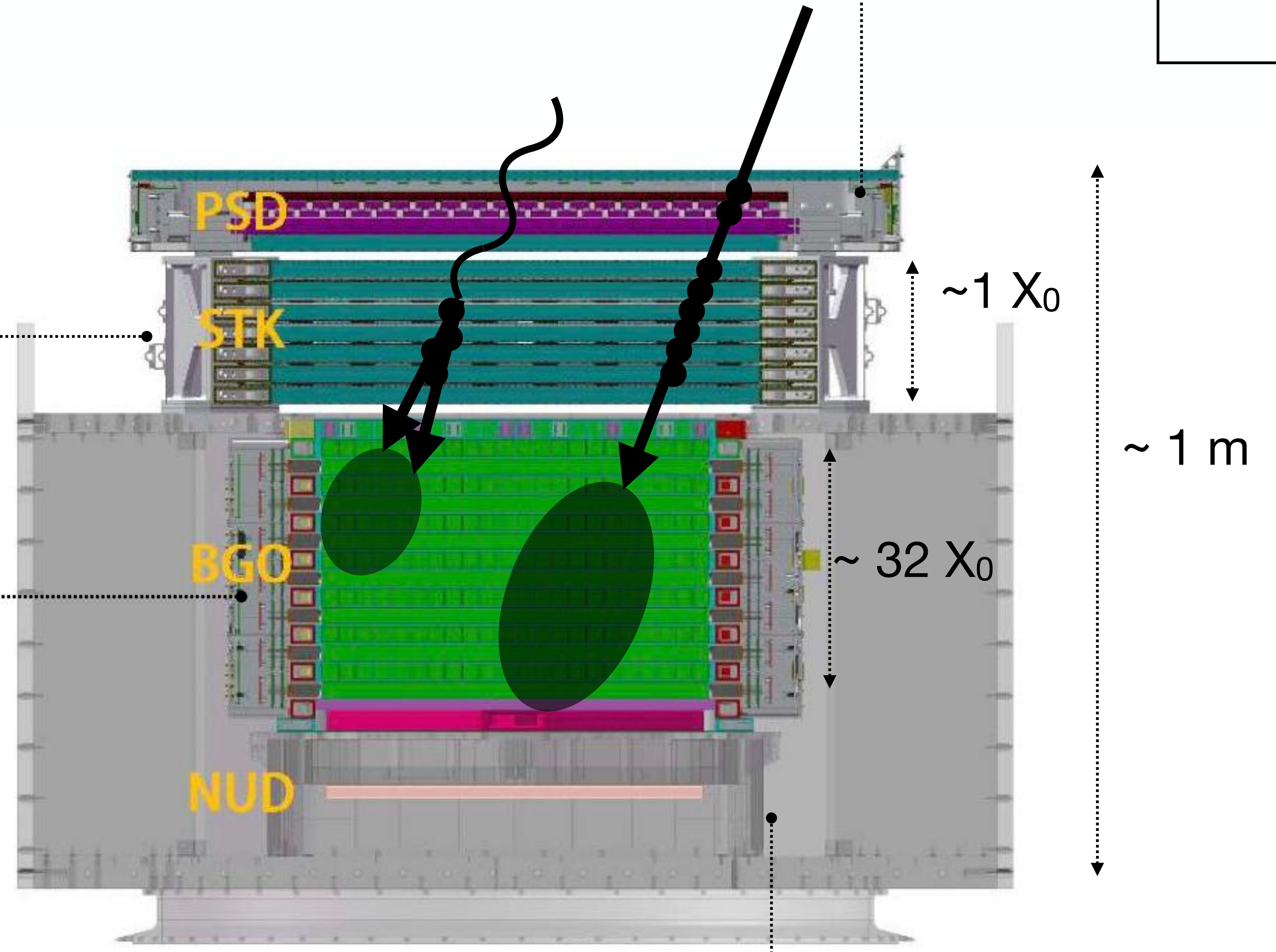


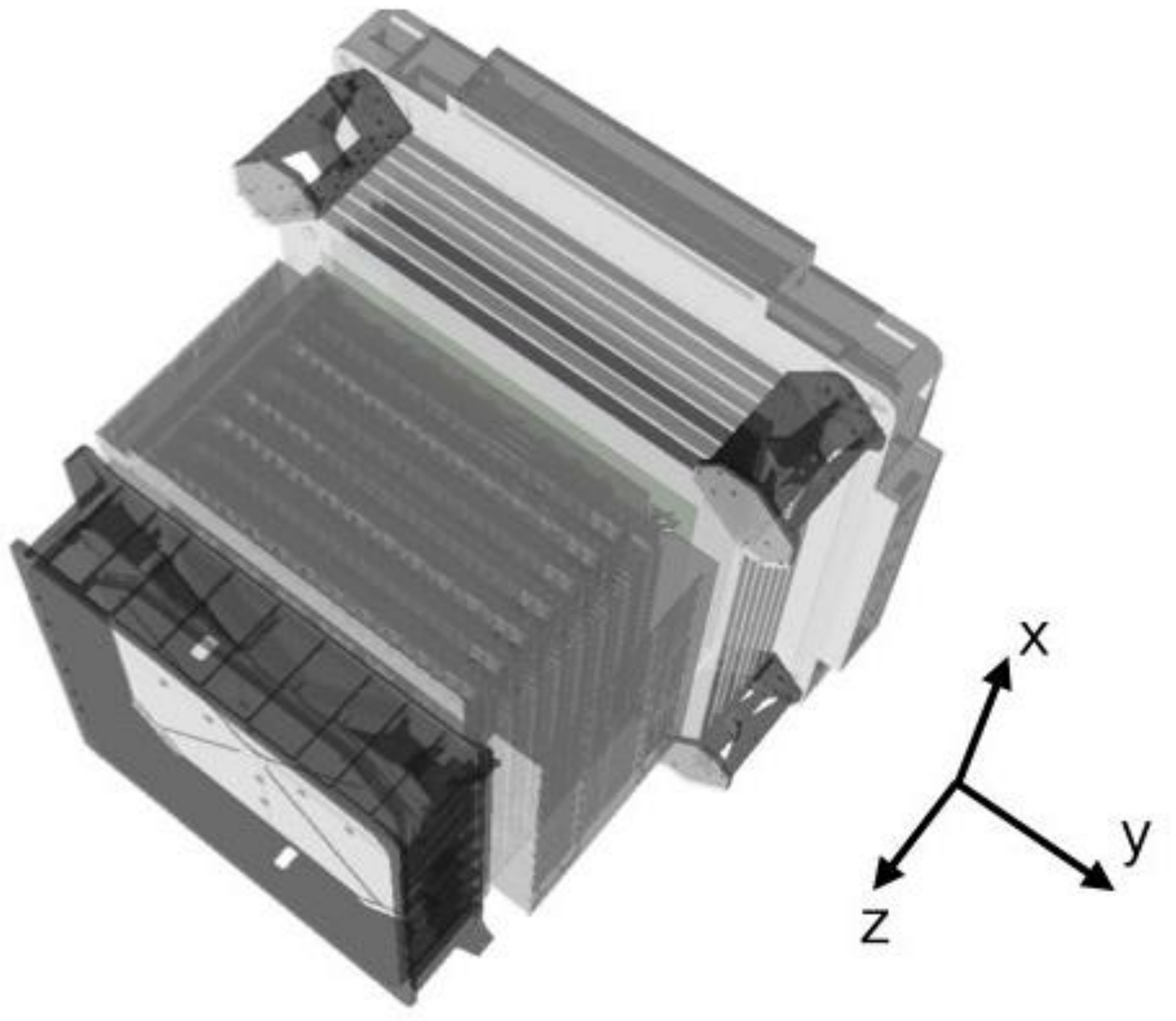
Magnetic spectromenter for hadronic cosmic rays

Imaging Calorimeter for electrons & positrons

Momentum uncertainty 3.4% at 1 TeV

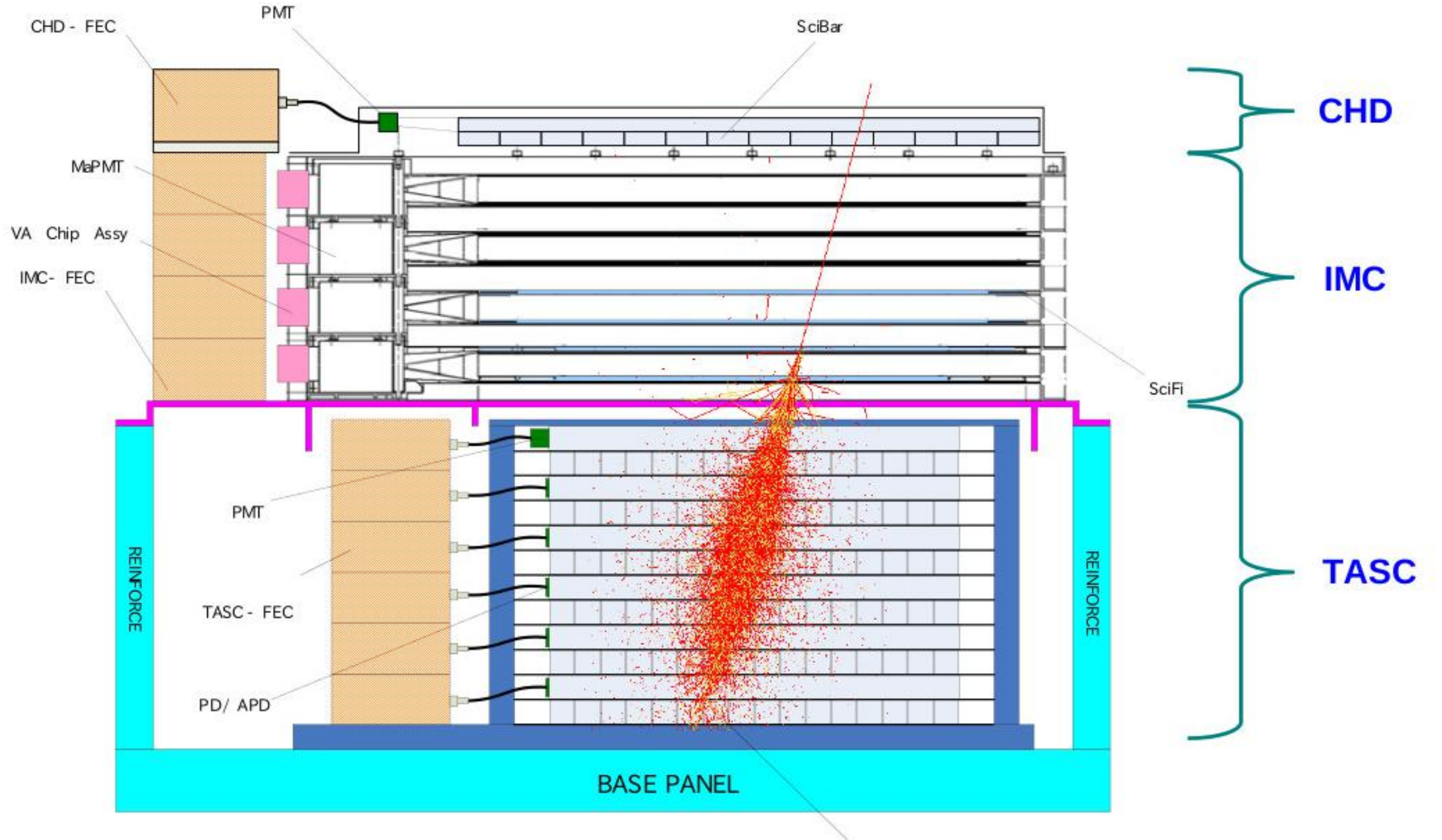
DArk Matter Particle Explorer (DAMPE)





DAMPE collab., Astropart. Phys. 95 (2017) 6-24

CALorimetric Electron Telescope (CALET)



Charge Detector
lastic scintillator array

Imaging Calorimeter ($3X_0$)
$1mm^2$ scintillating fibers interleaved with tungsten

Total Absorption Calorimeter ($30X_0$)
12 layers of Lead Tungstate (PWO) logs

DAMPE and CALET can be considered "ATLAS/CMS" of astroparticle physics world

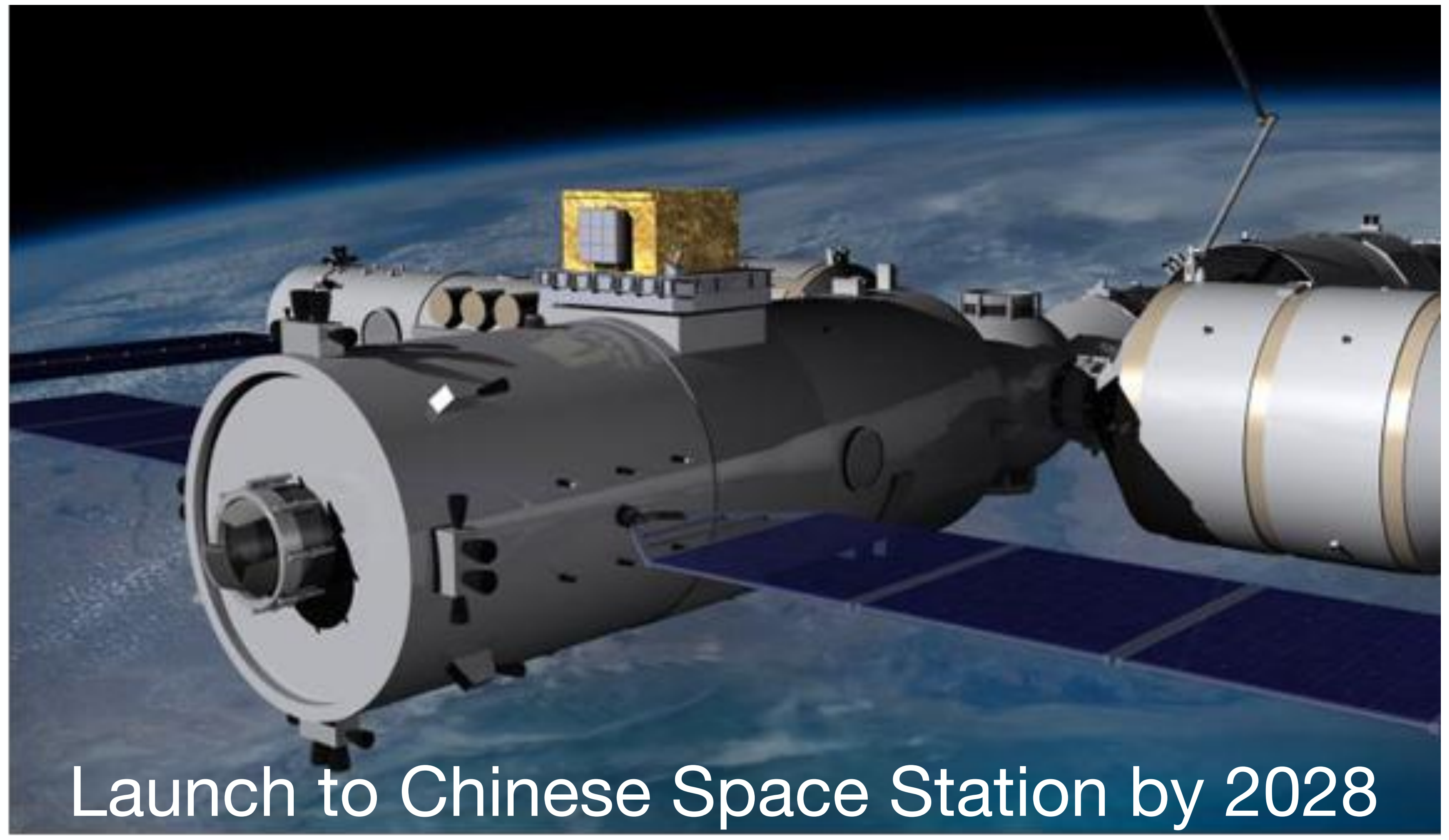
- same physics goals & detection principle, different instrumentation philosophy

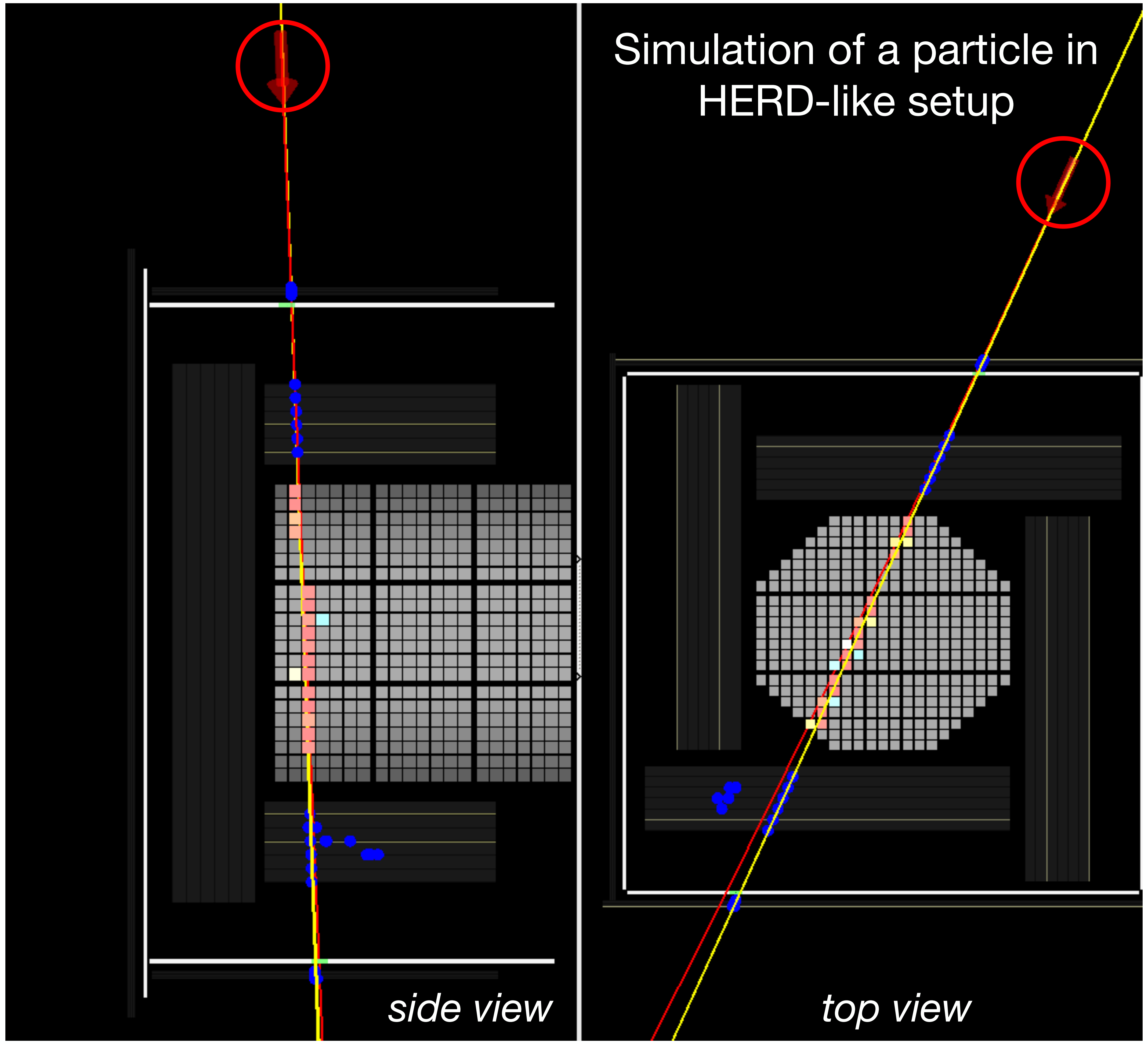
High Energy cosmic Radiation Detection facility (HERD)

3D calorimeter of 55X_0 (3Λ) + 5-side tracker

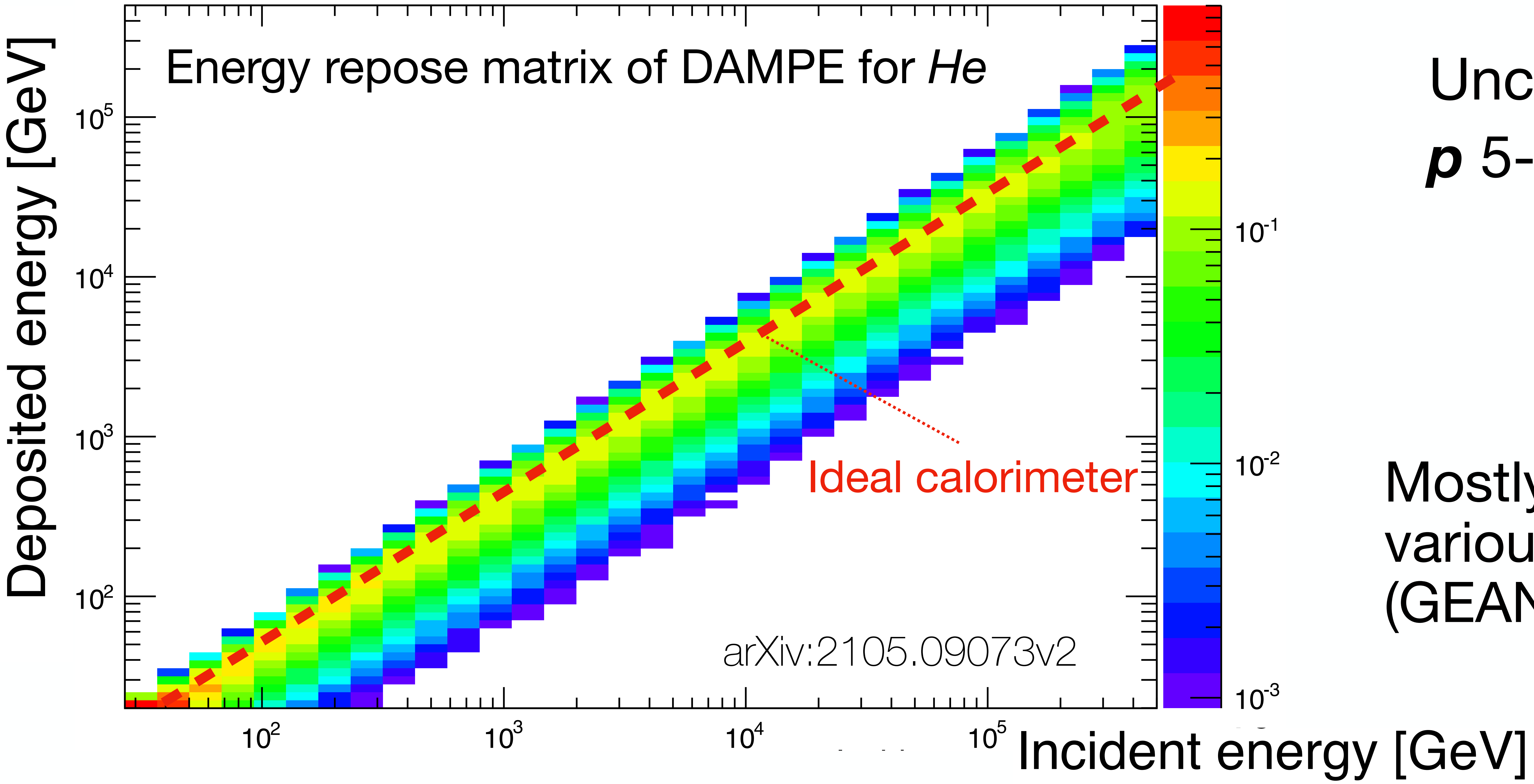
- CR electrons up to 100 TeV
- CR p/ions up to PeVs
- x 10 acceptance compared to DAMPE

→ hundreds of PeV cosmic rays / year





Calorimeters (DAMPE, CALET)



Uncertainties (DAMPE):
p 5-10%, ***ions*** (10-20%)

Mostly evaluated by comparing various models & cross-section sets (GEANT4, FLUKA, EPICS, CORSIKA)

- Excellent for *e* and *γ*: **1-2% resolution**, almost total energy absorption
- Excellent for *e*/*p* discrimination: **10^4—10^5 *p* rejection**
- *p* and ions: ~1.6 Λ, shower absorption ~ 30-40%

  → **rely significantly on hadronic simulations for the energy reconstruction**

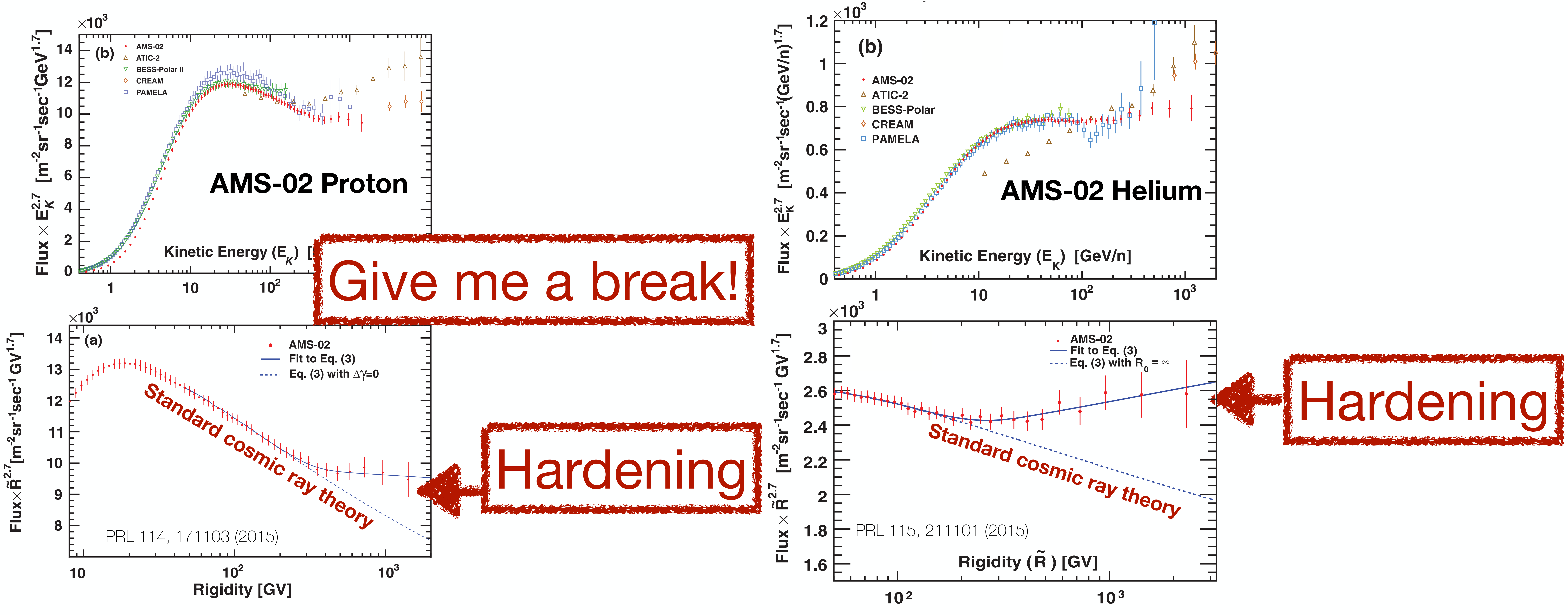
Experiments in space

Primaries: *p, He* (AMS-02)

- Spectrum measurement of cosmic ray protons and helium reported by AMS-02 in 2015

  New feature discovered — break (hardening) at few hundred GV

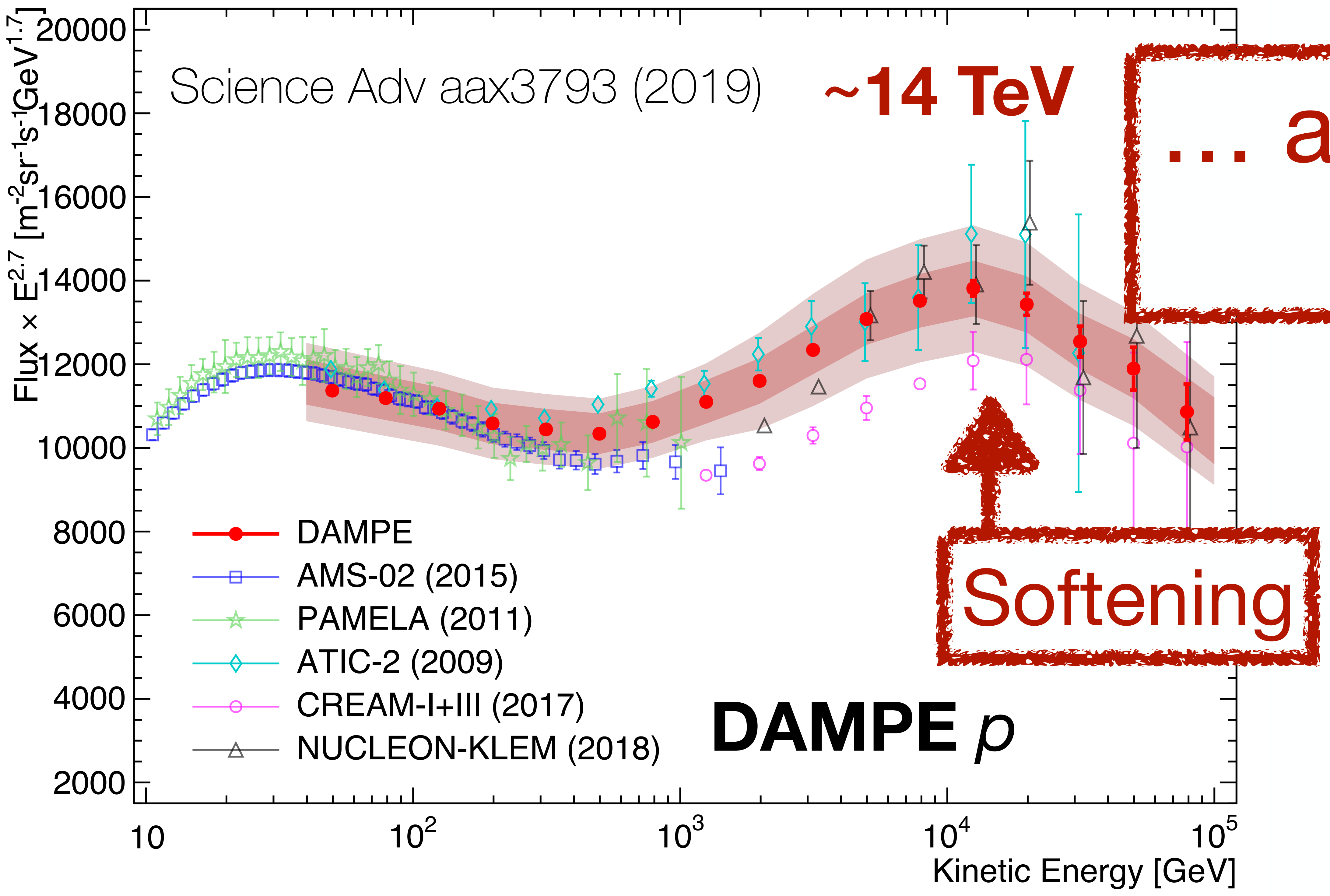
  Not expected within the standard shock acceleration + diffusive propagation theory



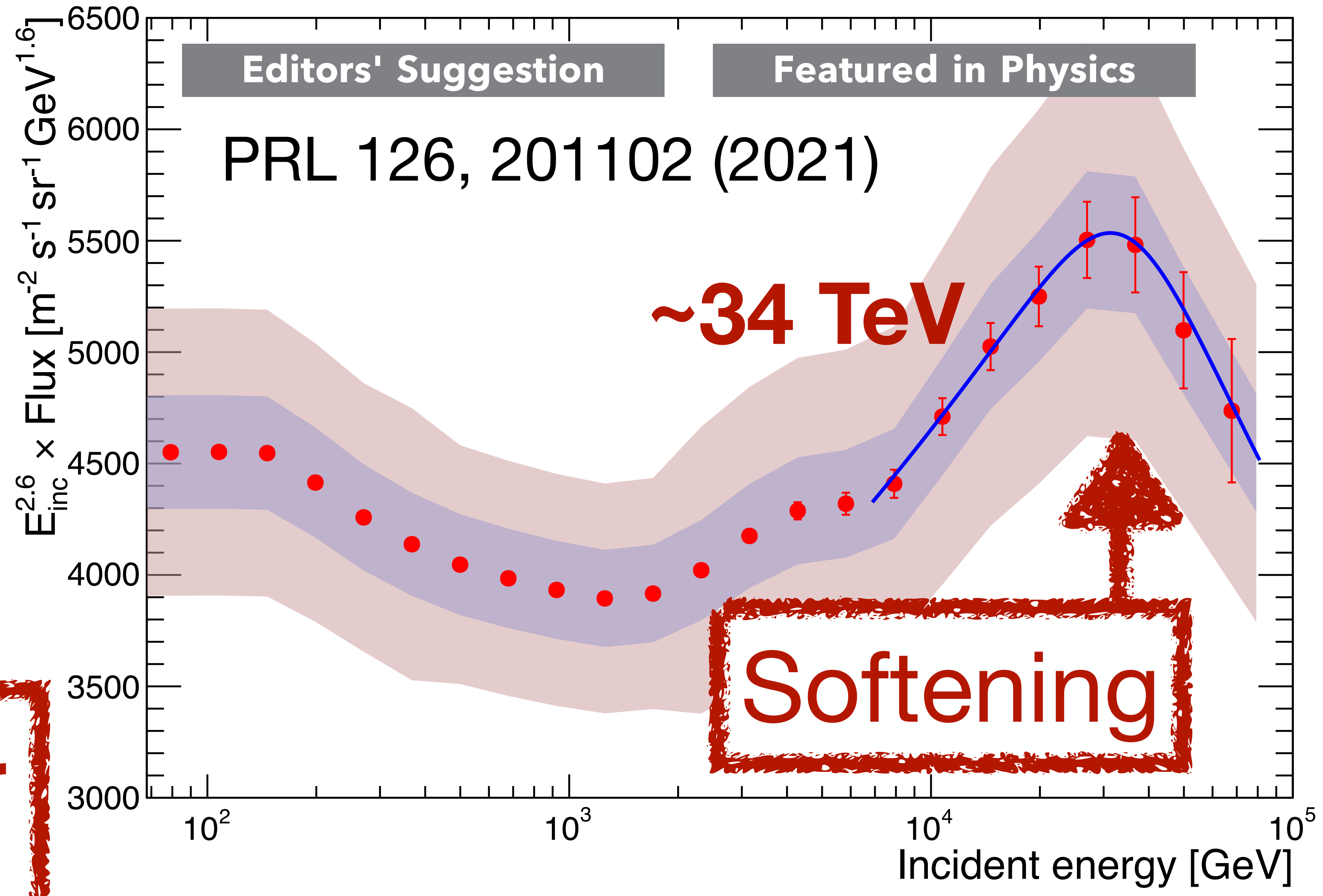
Primaries: *p, He* (DAMPE)

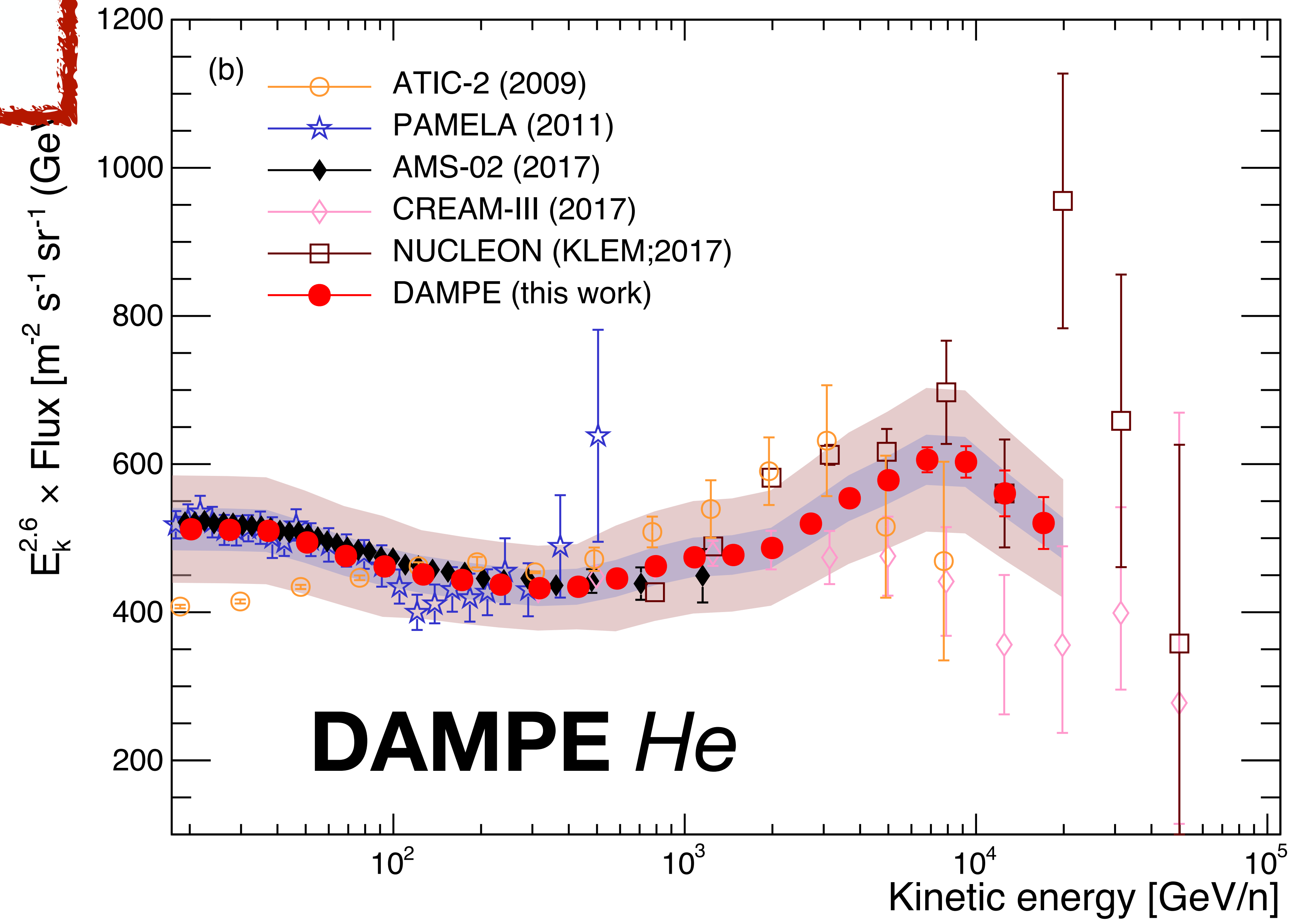
DAMPE:

- Confirms the hardening observed previously by AMS
- Observation of another break: **~10 TeV softening** (significance: **proton** ~ 4.7σ, **helium** ~ 4.3σ)



… and another break!





Primaries: *p, He* (DAMPE)

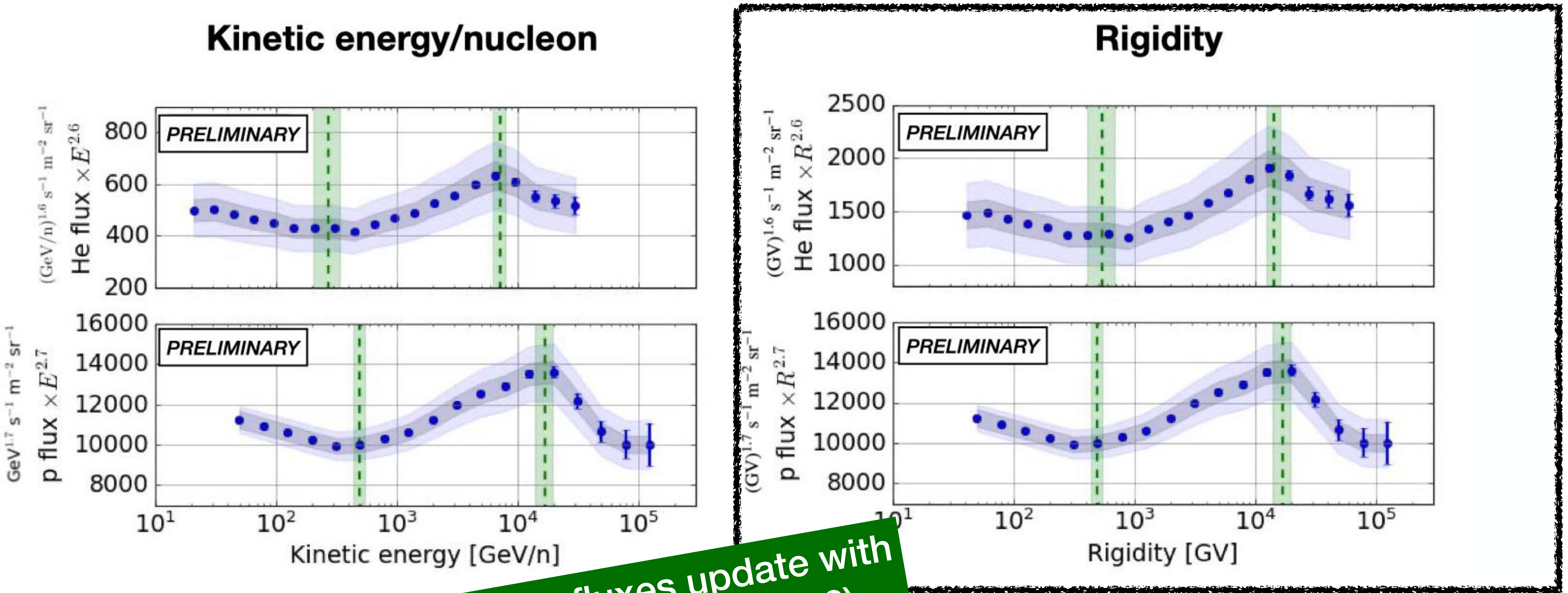
NEW! 2023

Precise identification of the break positions

→ answers if underlying CR mechanisms are mass (velocity) or charge (rigidity) dependant

Helium flux

Proton flux



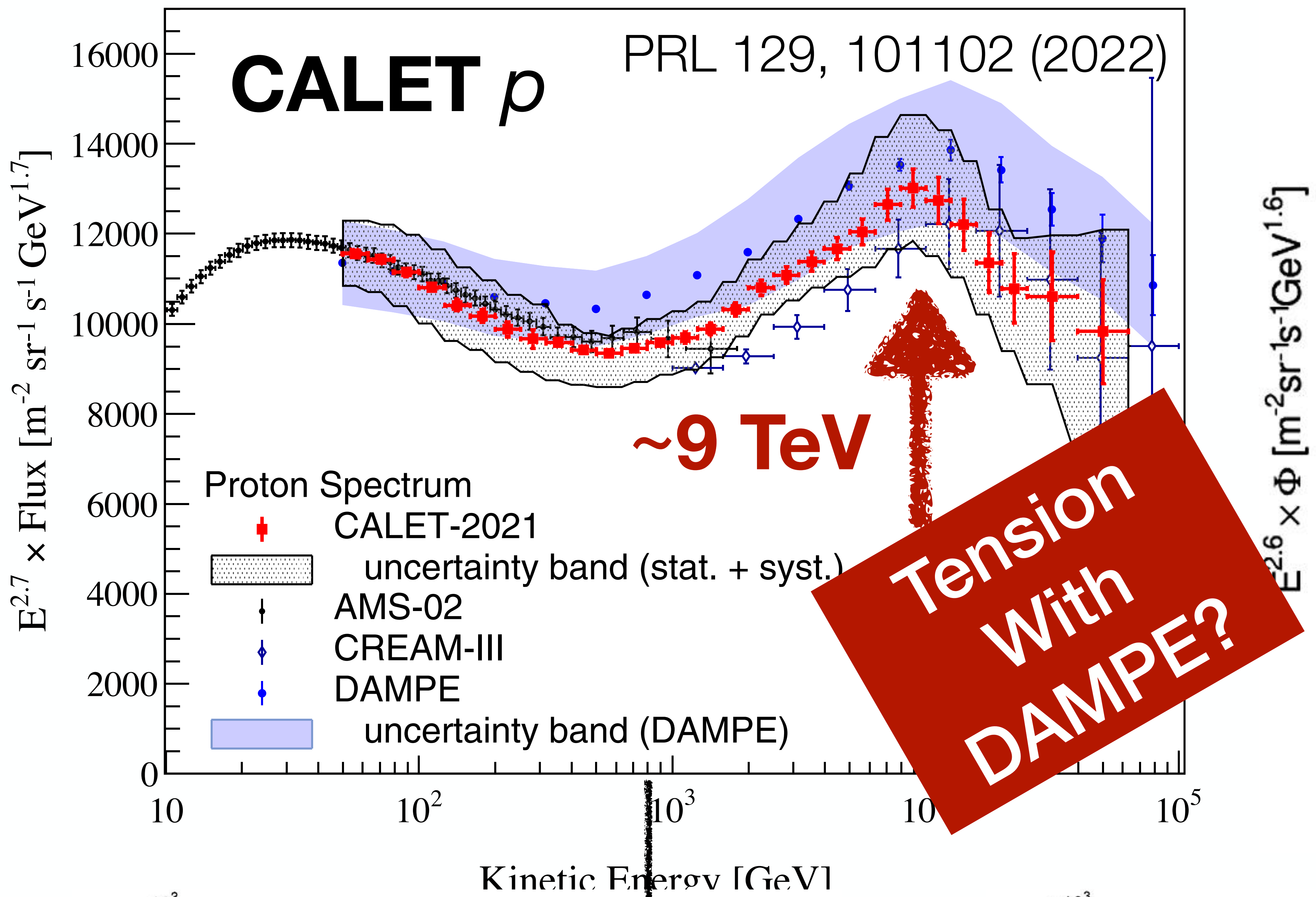
A. Ruina, A Kotenko ICRC2023

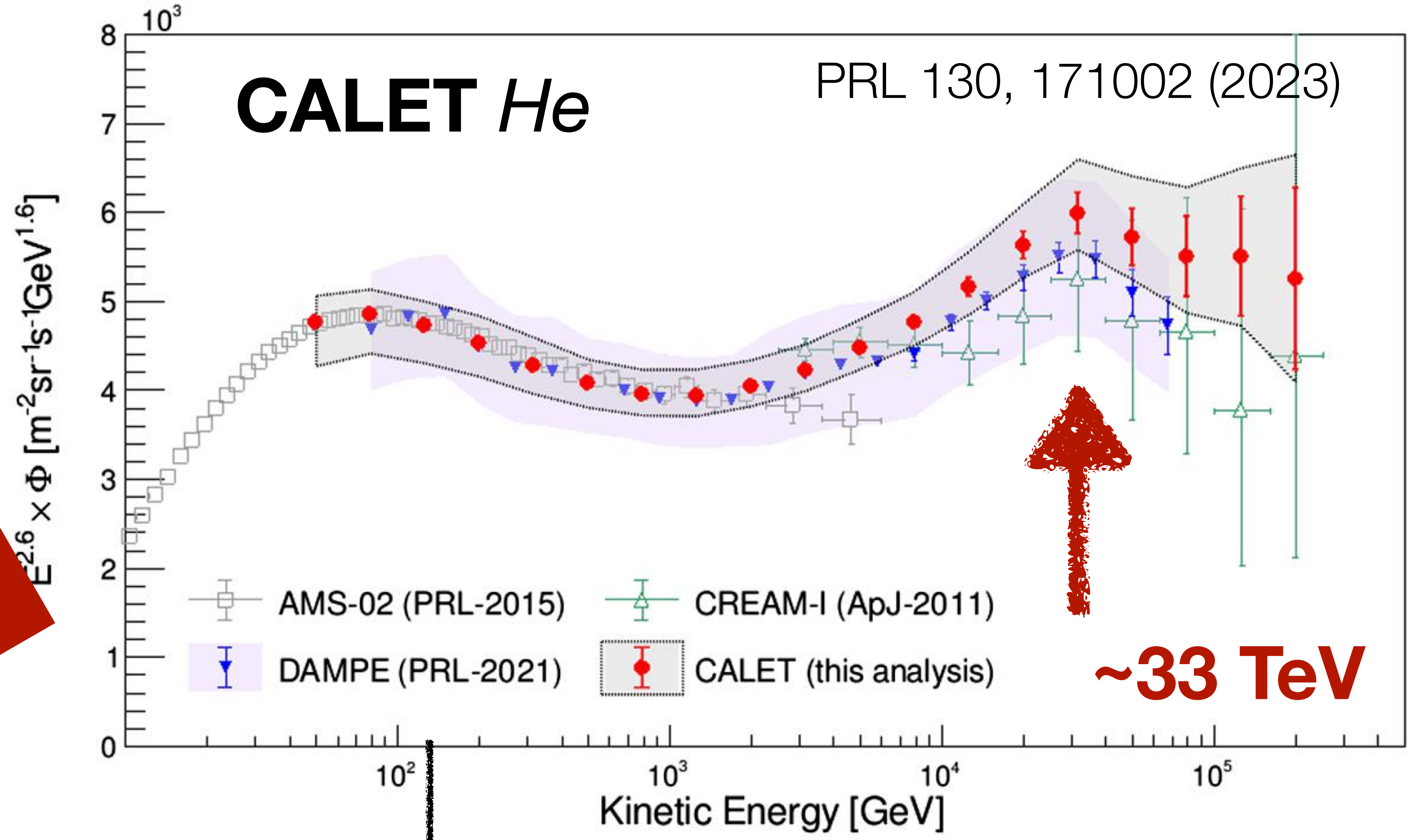
Proton & helium fluxes update with 7 years of DAMPE data (2023)

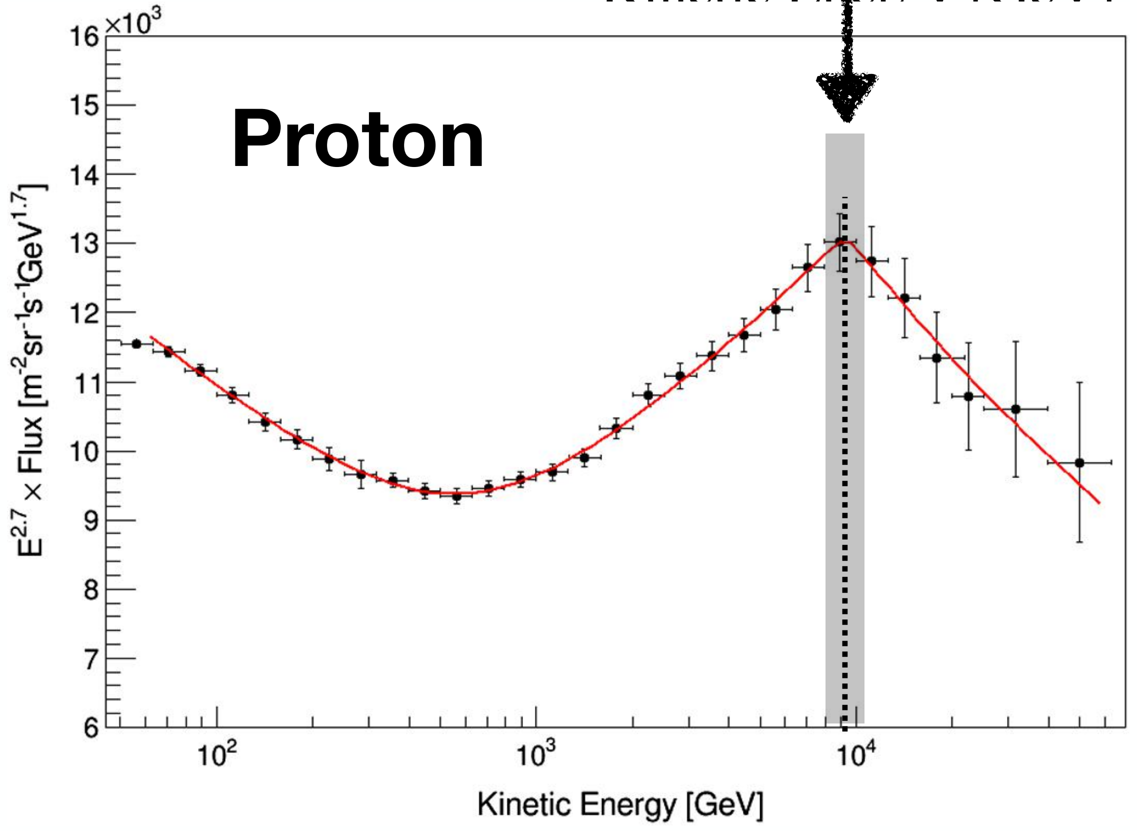
P & He hardening/softening: **charge dependence favoured**

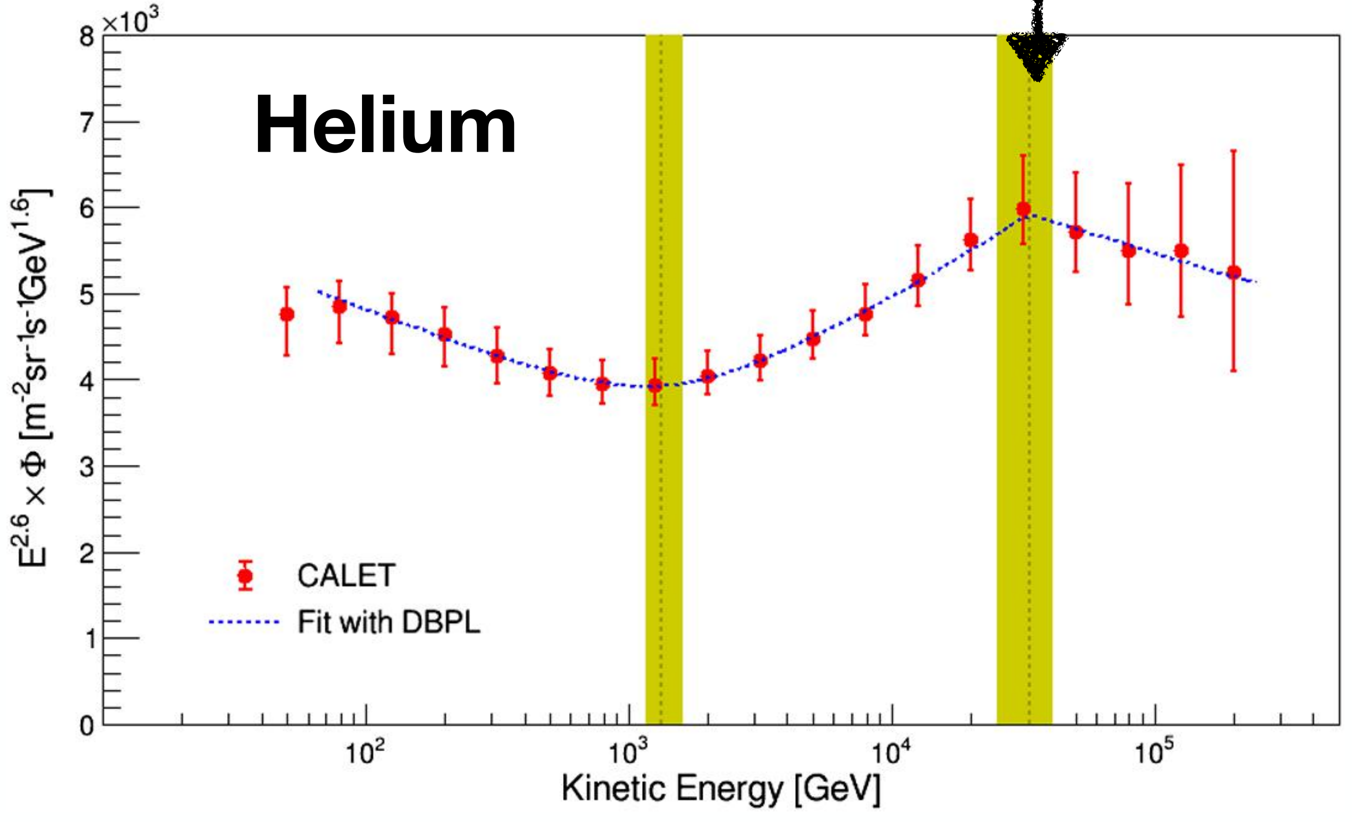
Primaries: *p, He* (CALET)

- **CALET**: *He* softening consistent with DAMPE, *proton* softening is lower (favours A dependence)





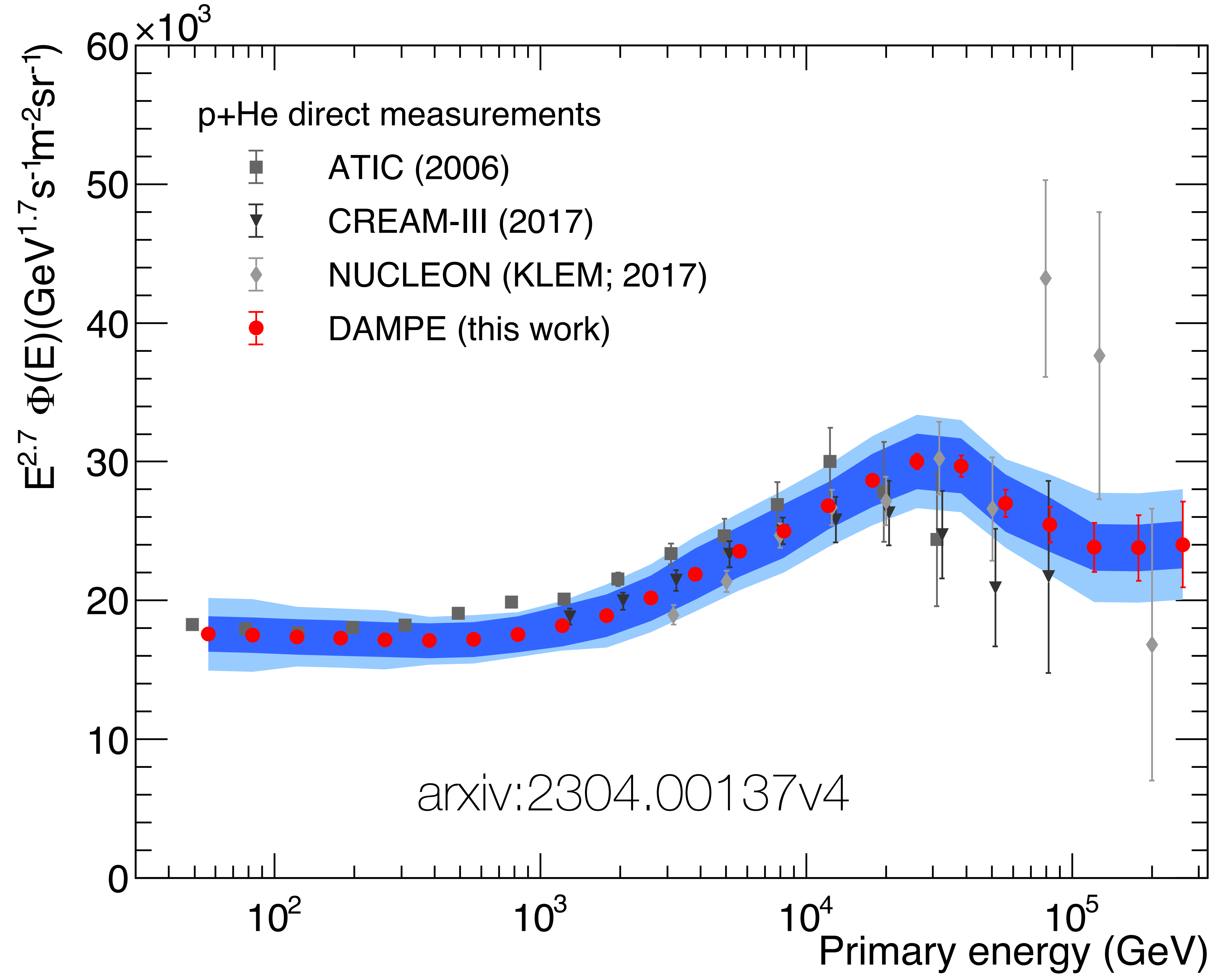


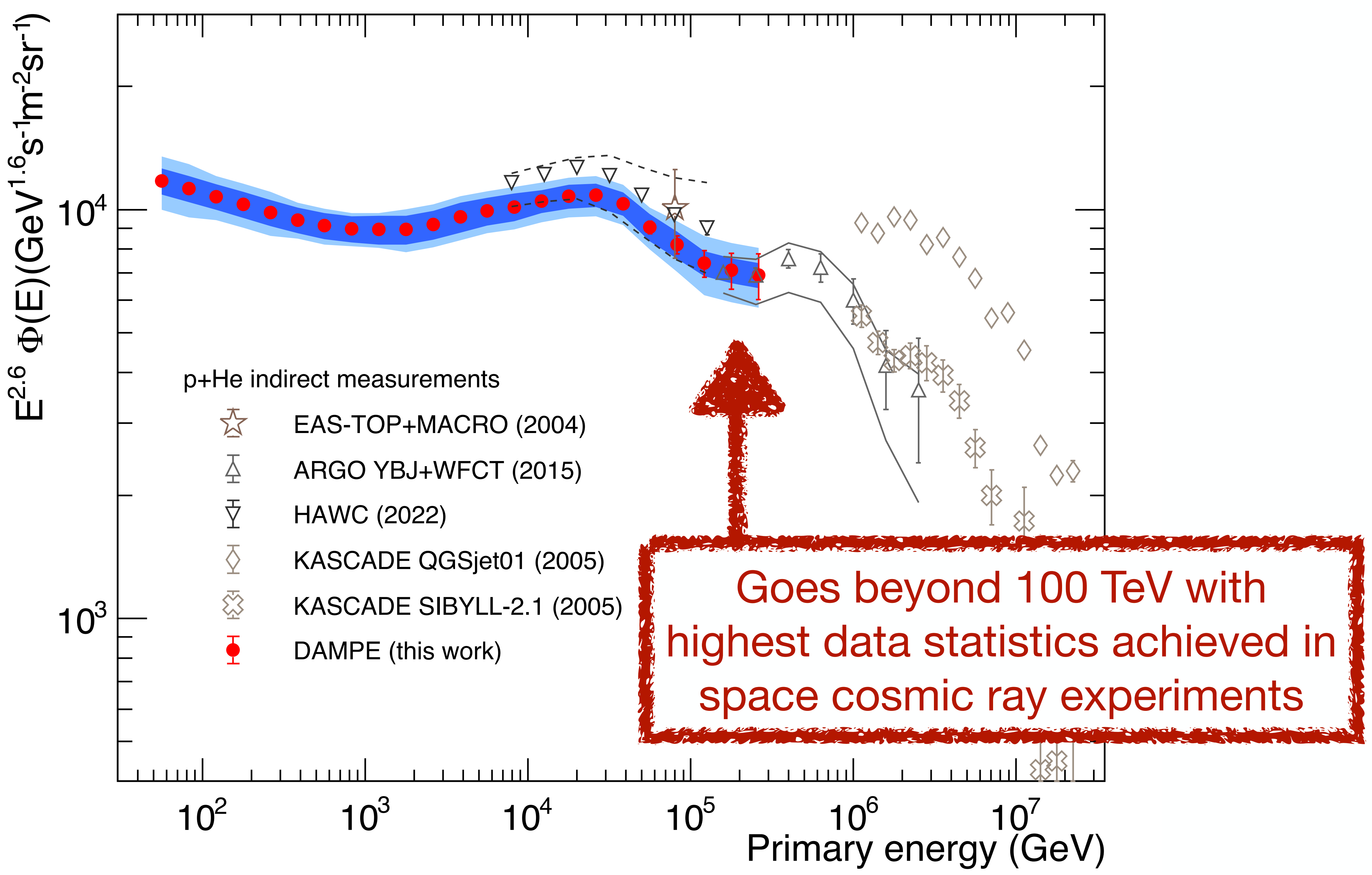


CREAM data: softening consistent with DAMPE

Primaries: *p + He*

- DAMPE measurement of proton+helium spectrum:
  - profit of larger statistics (compared to individual proton or helium spectrum)
  - lower uncertainties of particle identification
  - **connection with ground based experiments**

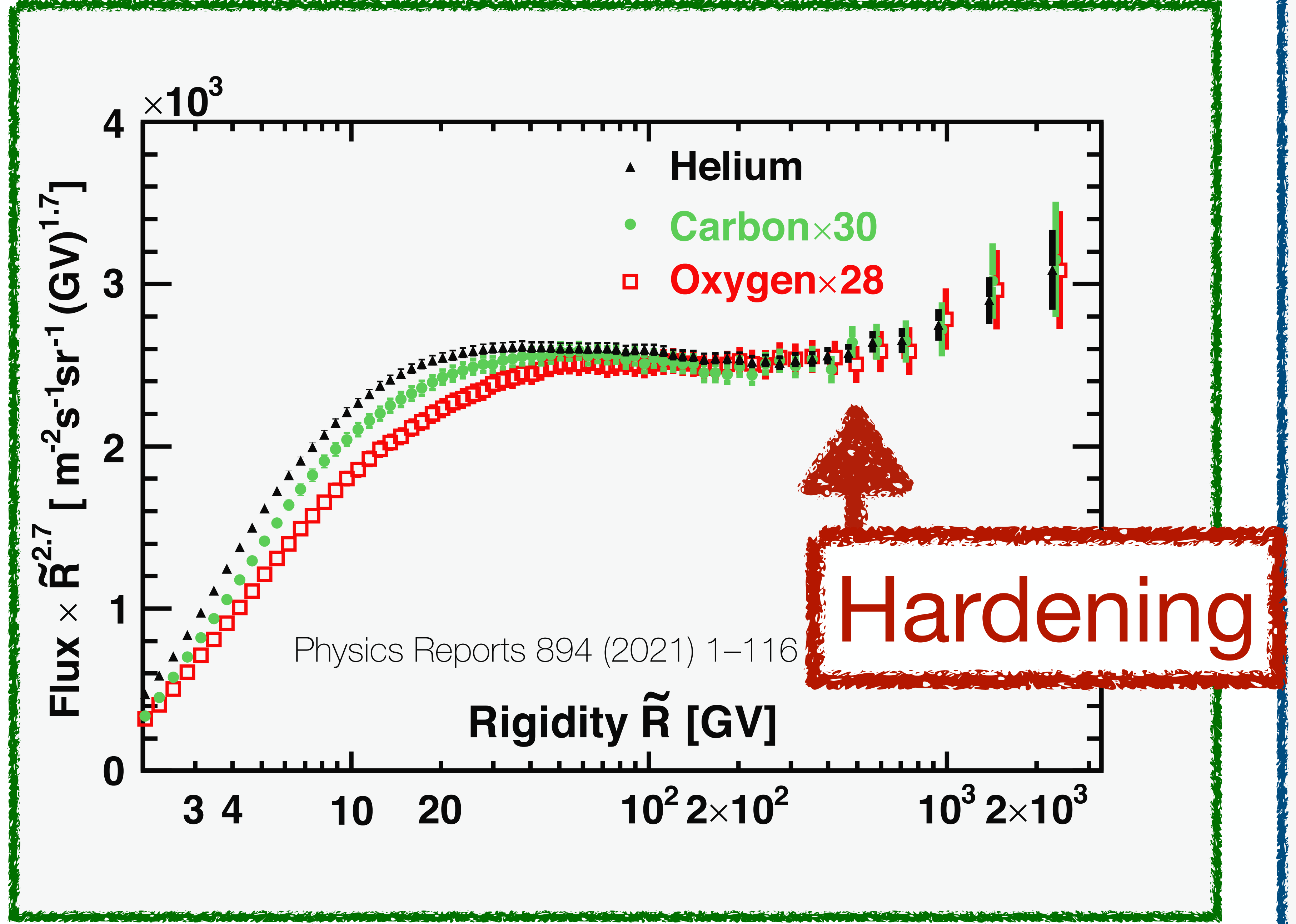




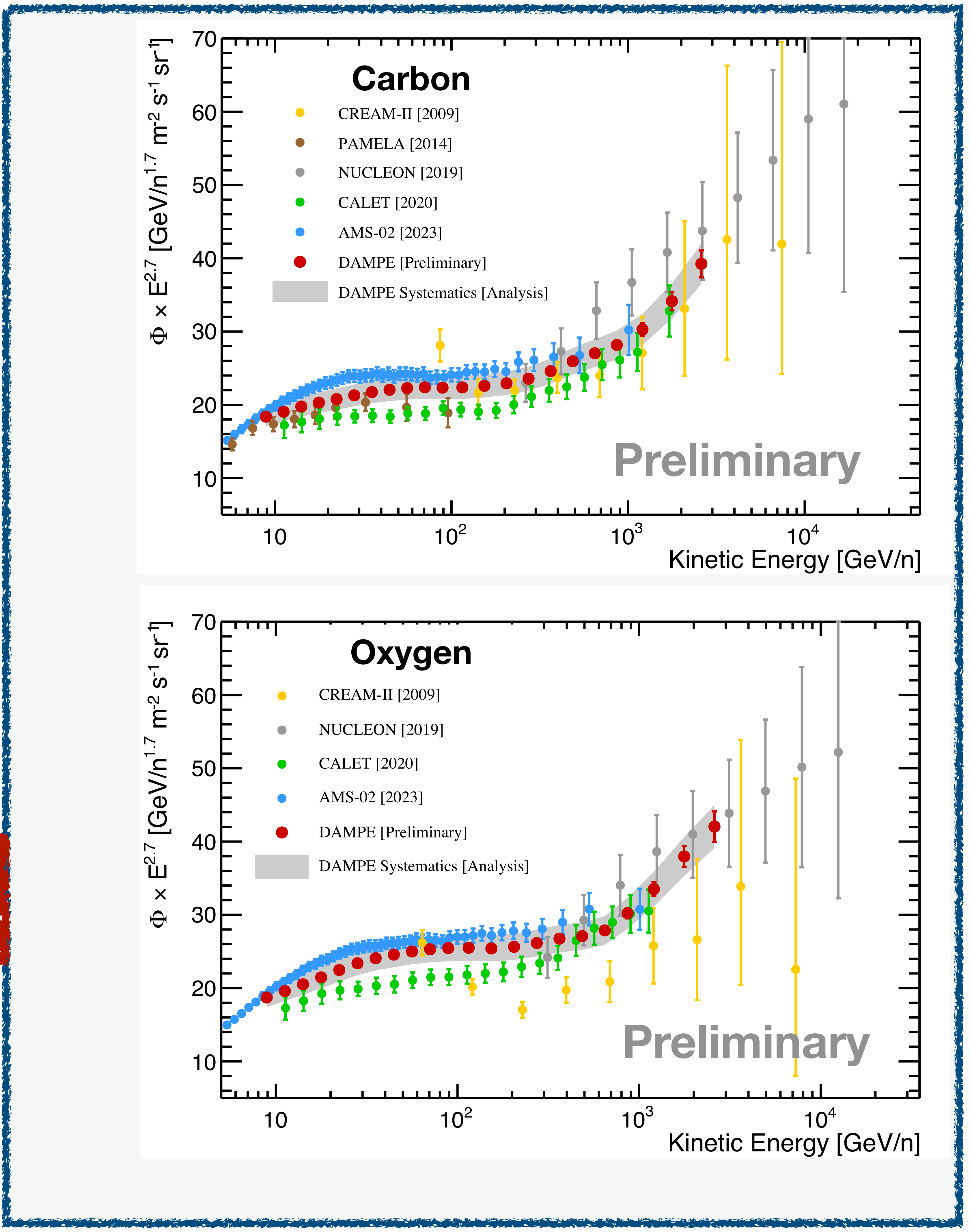
Primaries: *C, O*

- Intermediate-mass primaries like **carbon** and **oxygen** also confirm spectral **hardening**

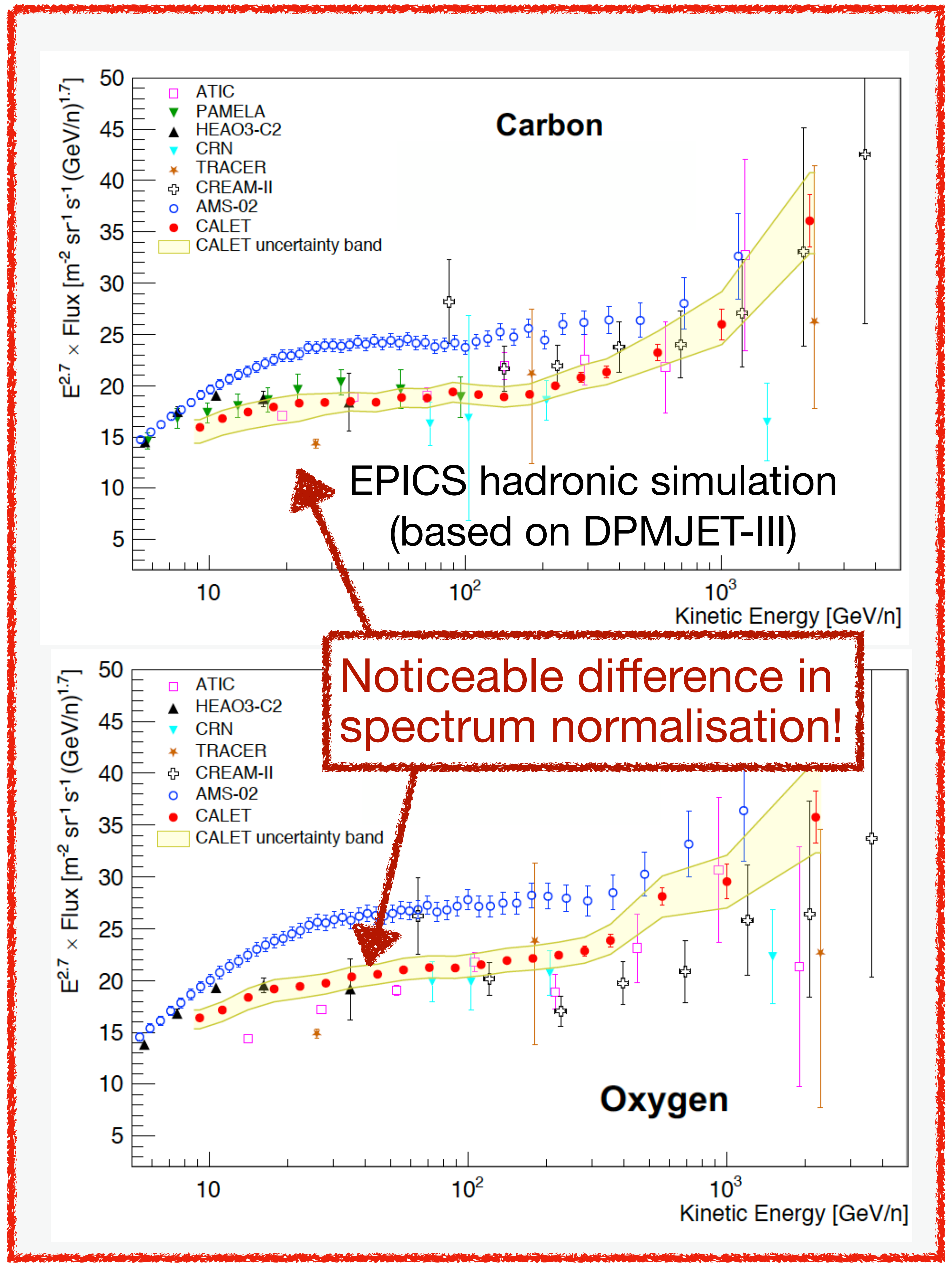
AMS-02



DAMPE



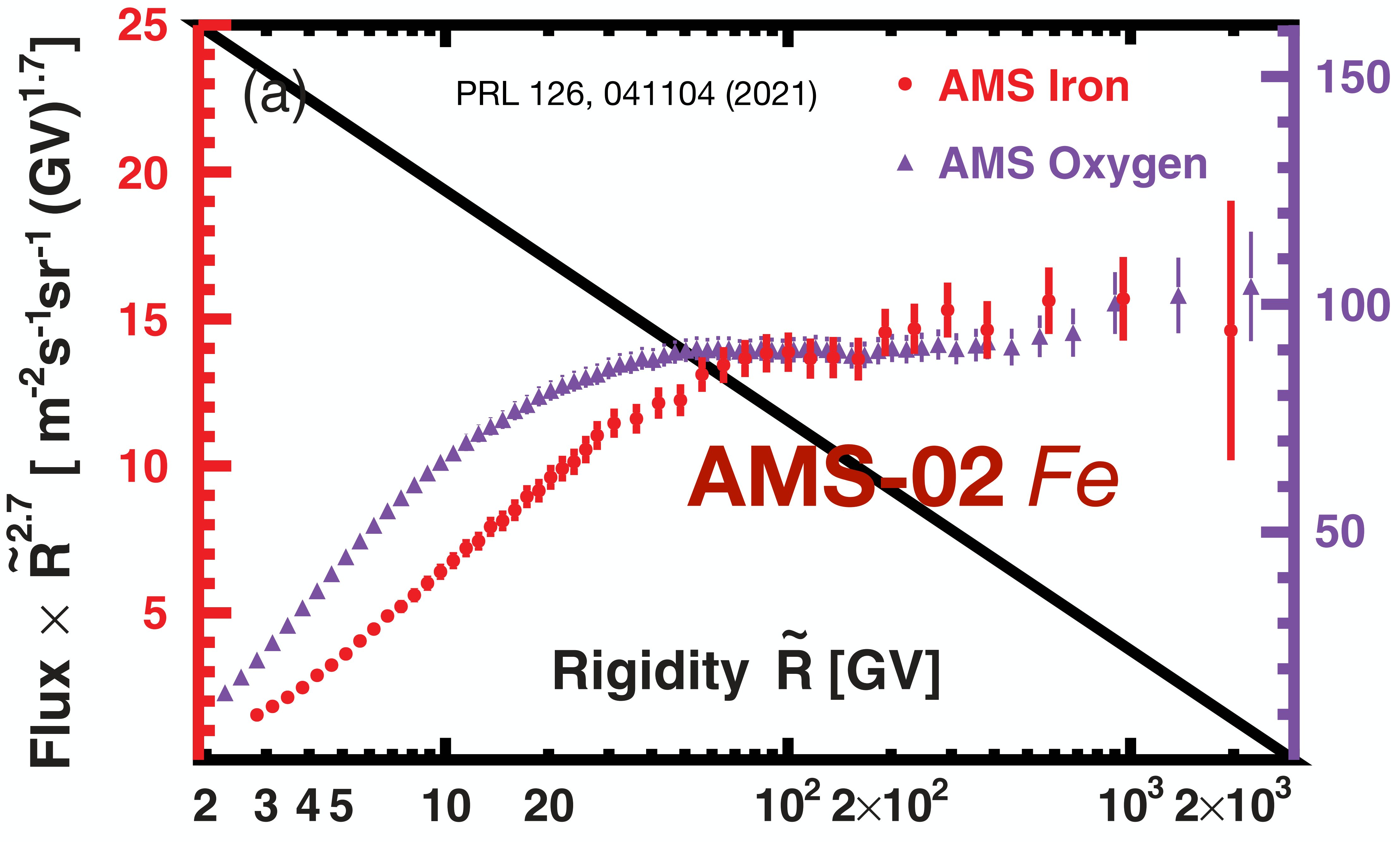
CALET

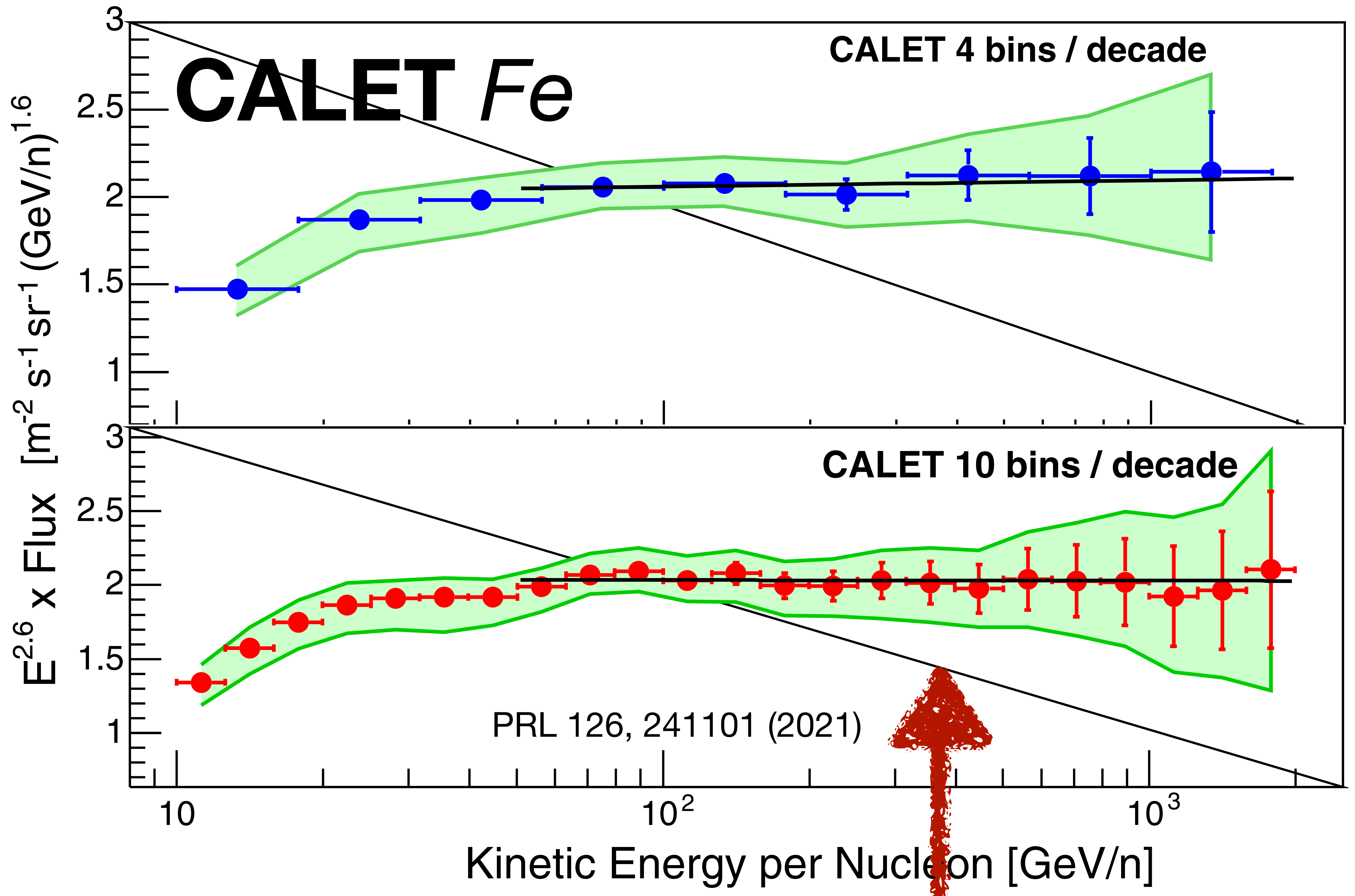


Primaries: *Fe*

Iron is the third most abundant CR after proton and helium at ~TeV (total kinetic energy)

- No hardening in Iron spectrum observed in AMS-02 data
- CALET data reaching same energise with comparable (to AMS) statistics — still no hardening



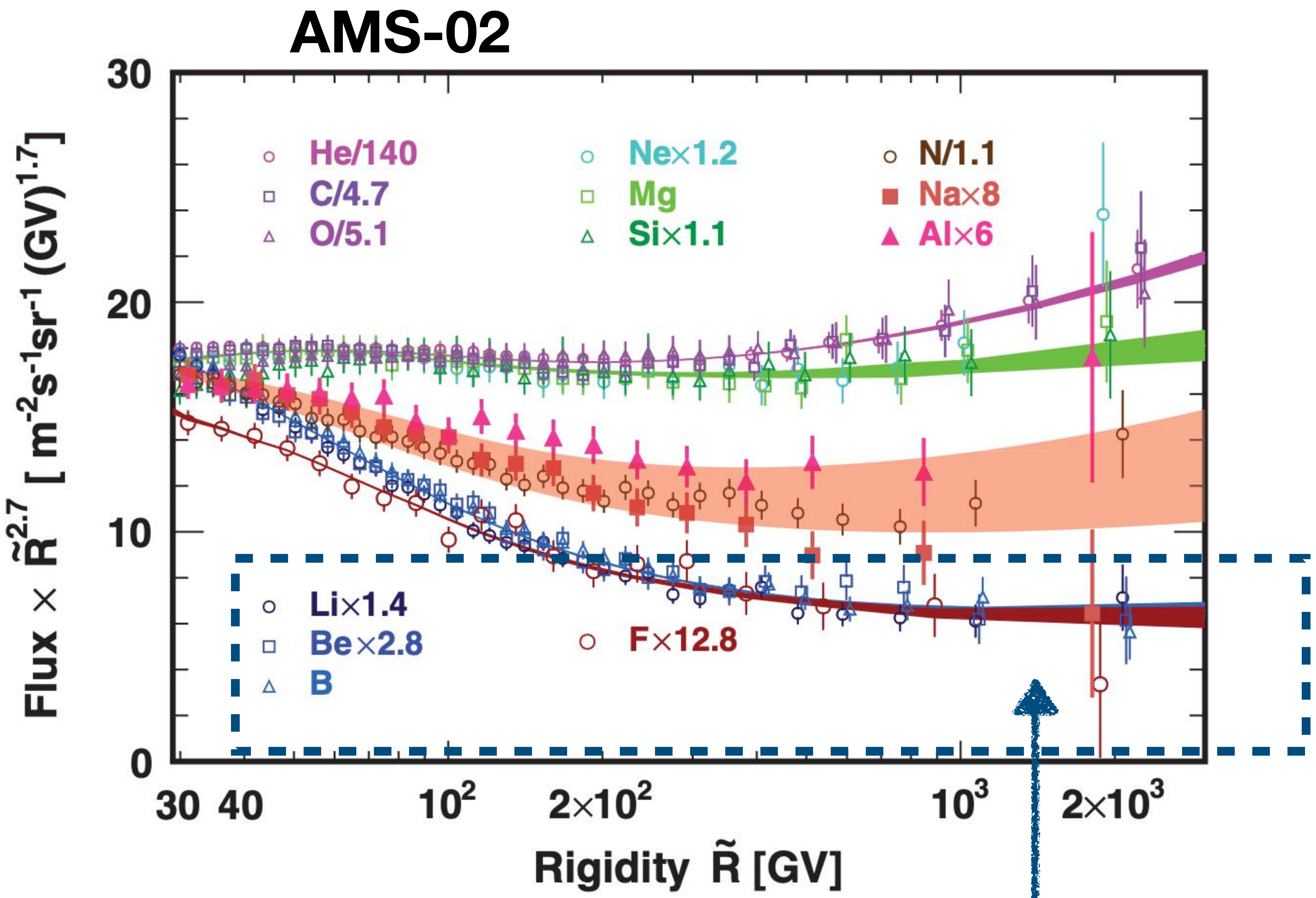


What about DAMPE ? (stay tuned …)

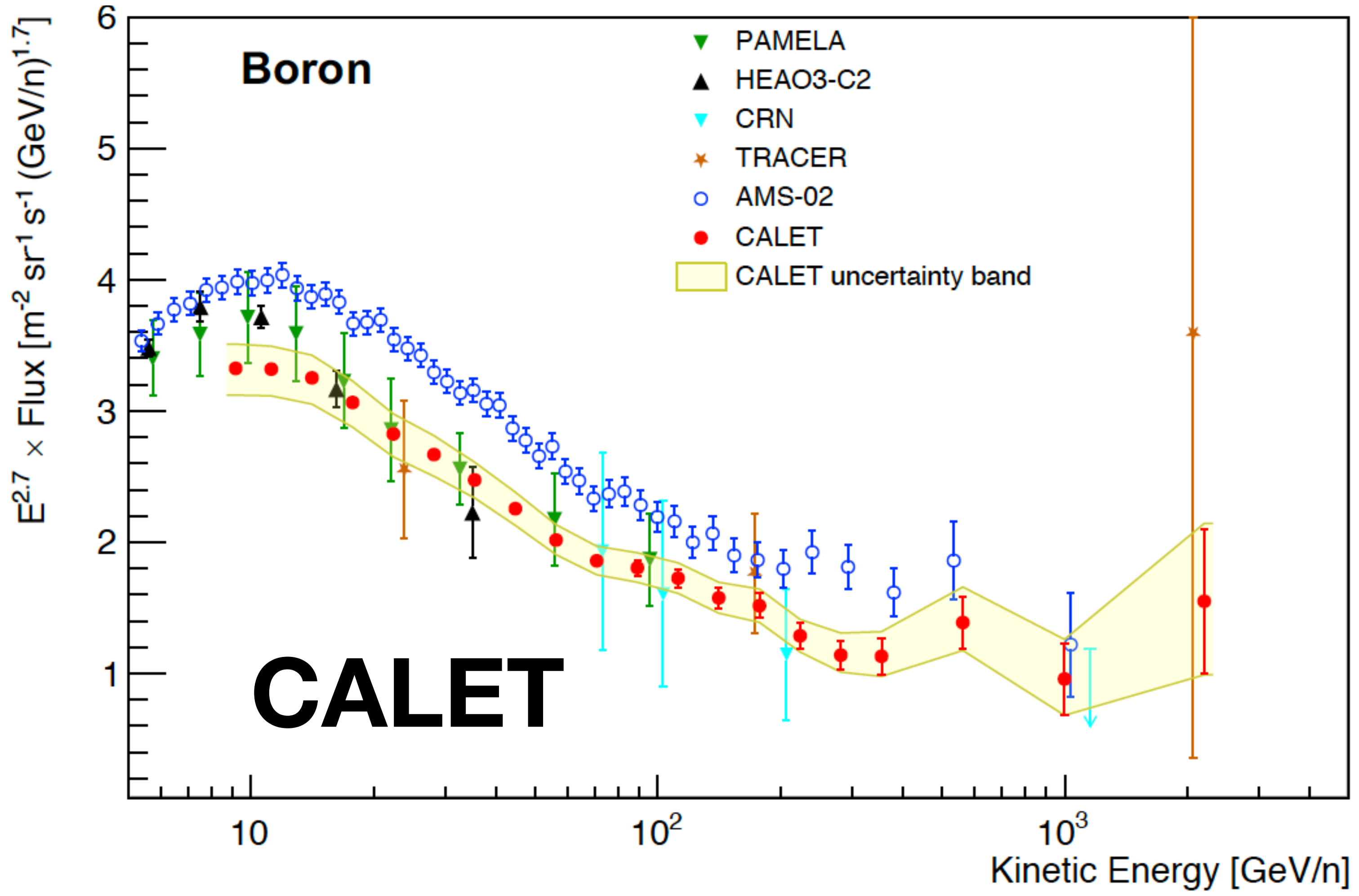
No hardening in Fe spectrum!

Secondaries: *Li, Be, B*

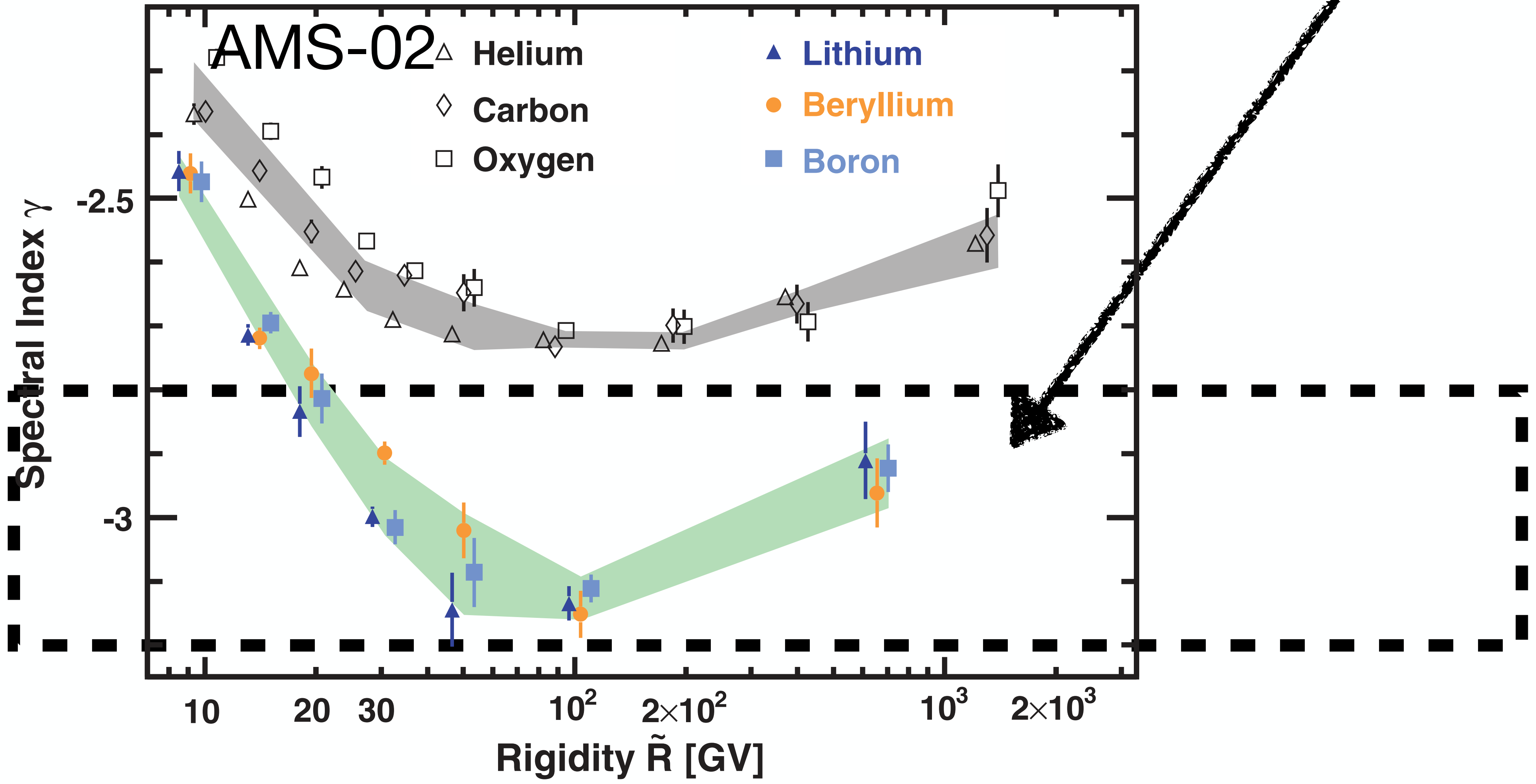
- What about spectral features in secondary cosmic rays



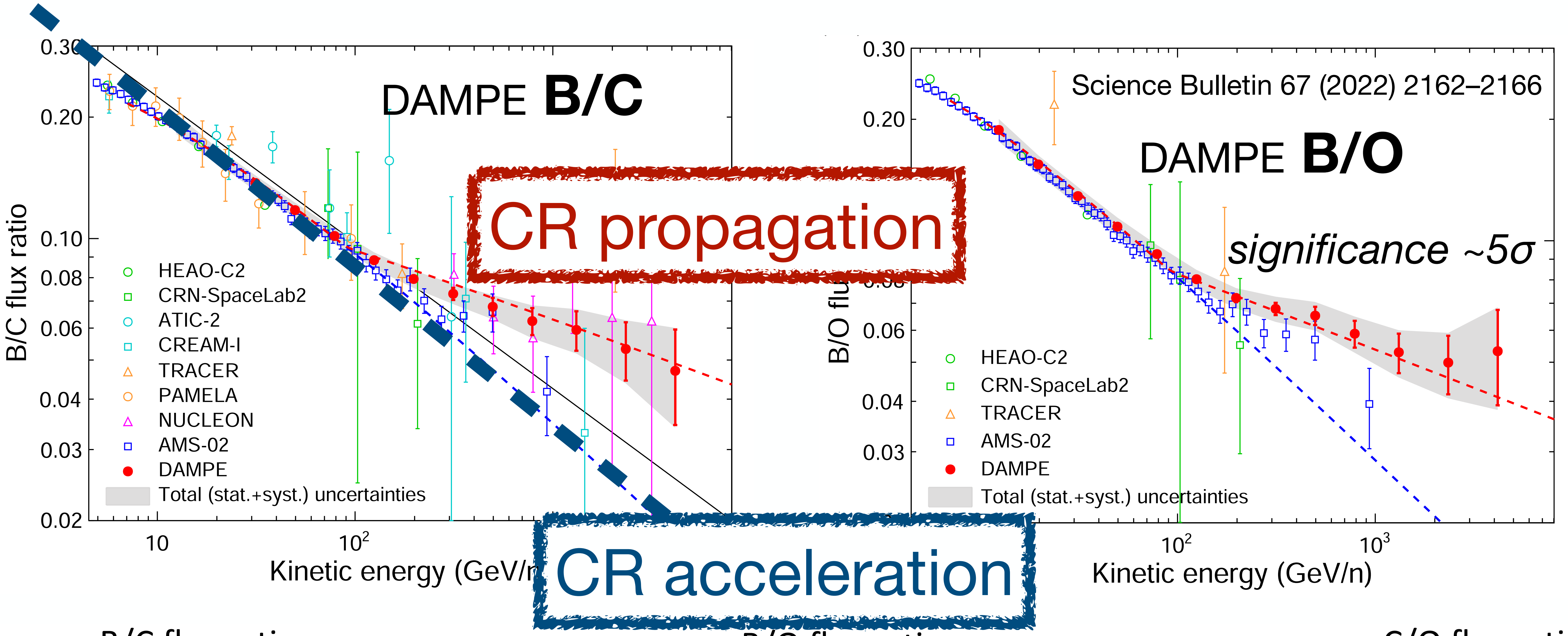
Hardening also observed secondaries



Secondaries are hardening more than primaries?

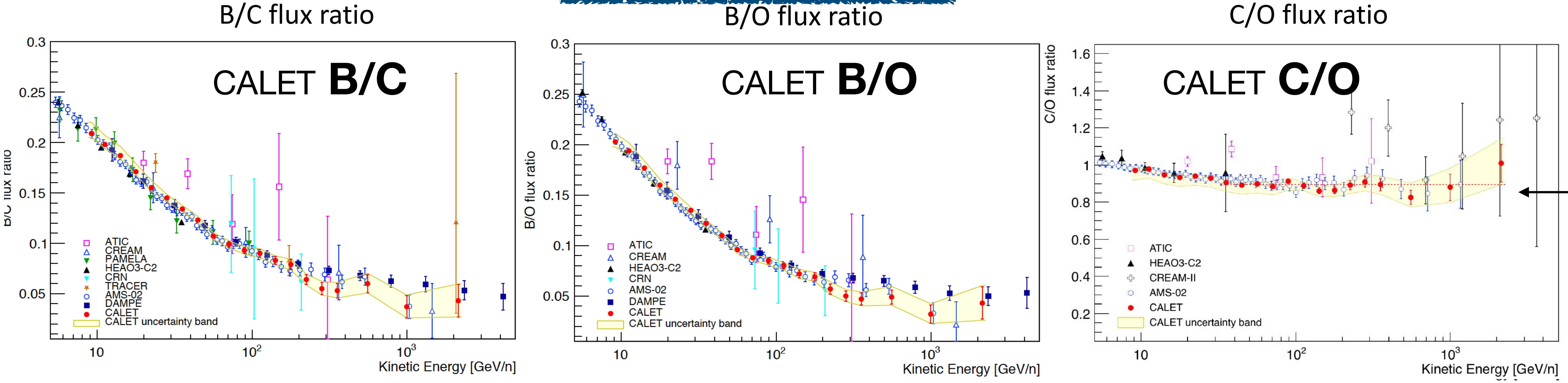


Secondary-to-primary ratios: *B/C, B/O*



Secondaries harden ~ twice more than primaries

→Hardening is NOT related to the cosmic ray source!

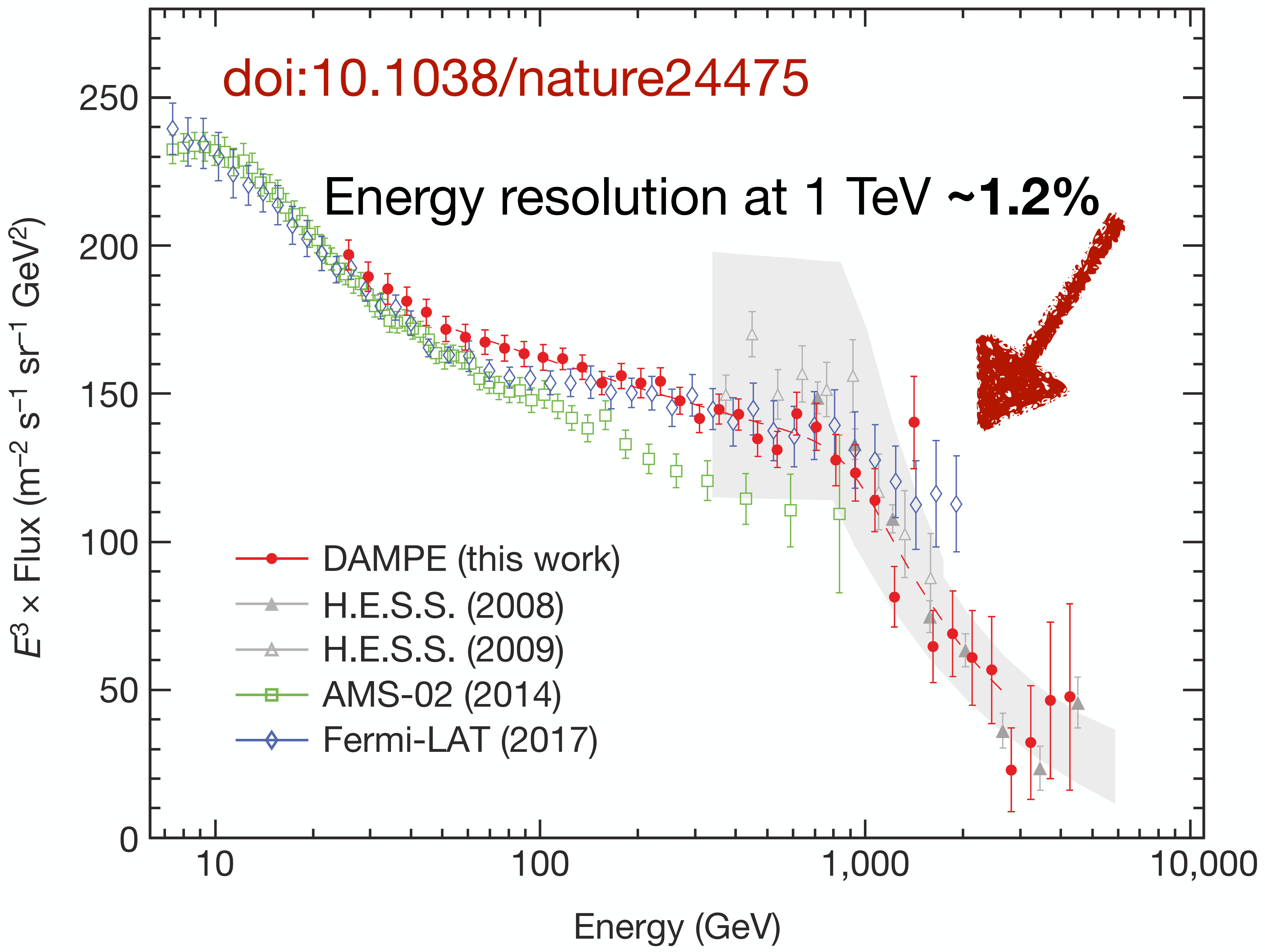


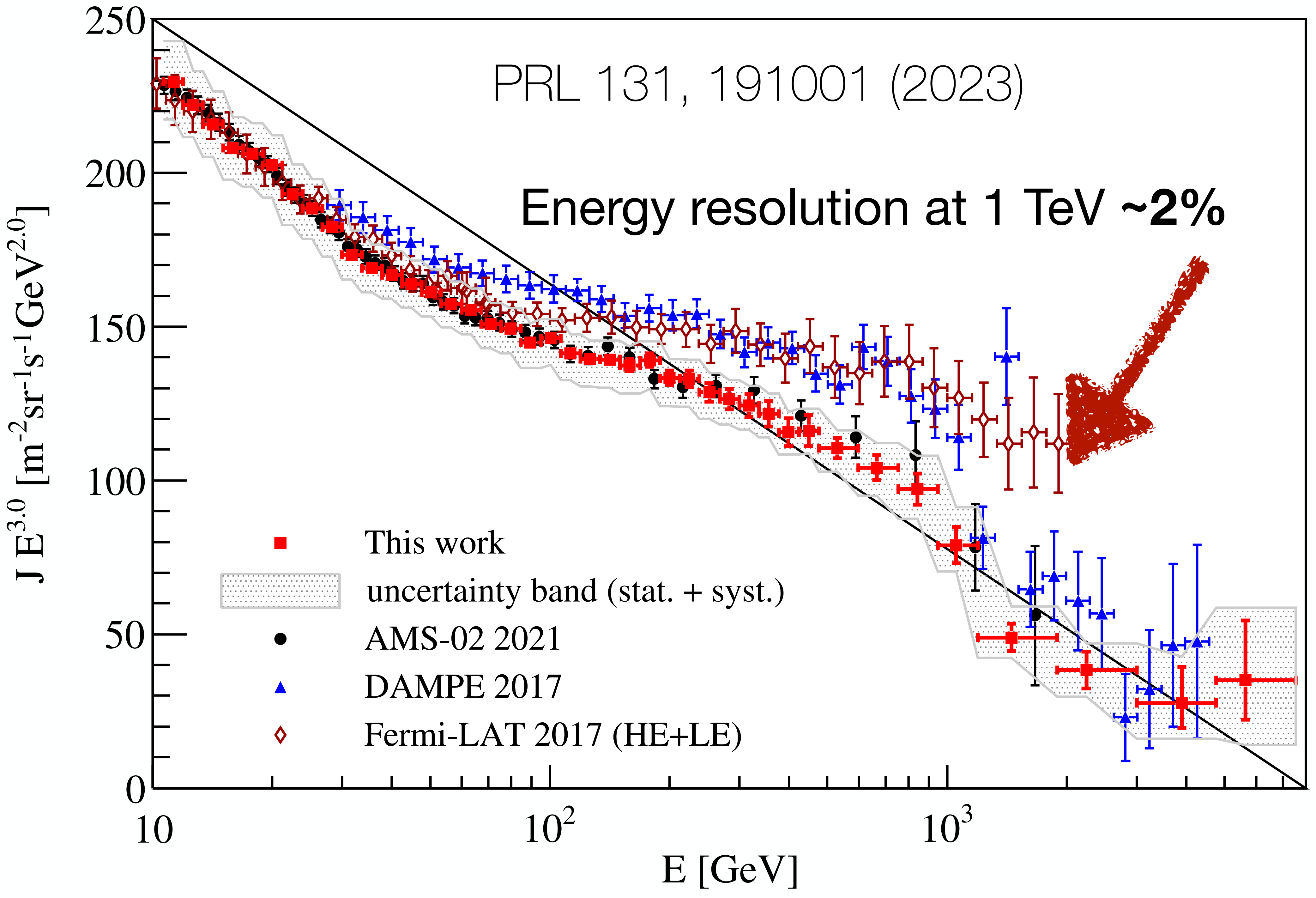
No break in primary-primary (C/O) ratio, as expected

Ratios are powerful observable since majority of systematic uncertainties cancel out!

e^-+e^+

- Hints of spectral by break previously seen H.E.S.S
  - Large systematics due hadronic interaction modelling in the atmosphere
- **Spectral break at 1 TeV first directly observed by DAMPE and CALET**
  - Excellent energy resolution ~1—2%*, major systematic - **p background rejection**

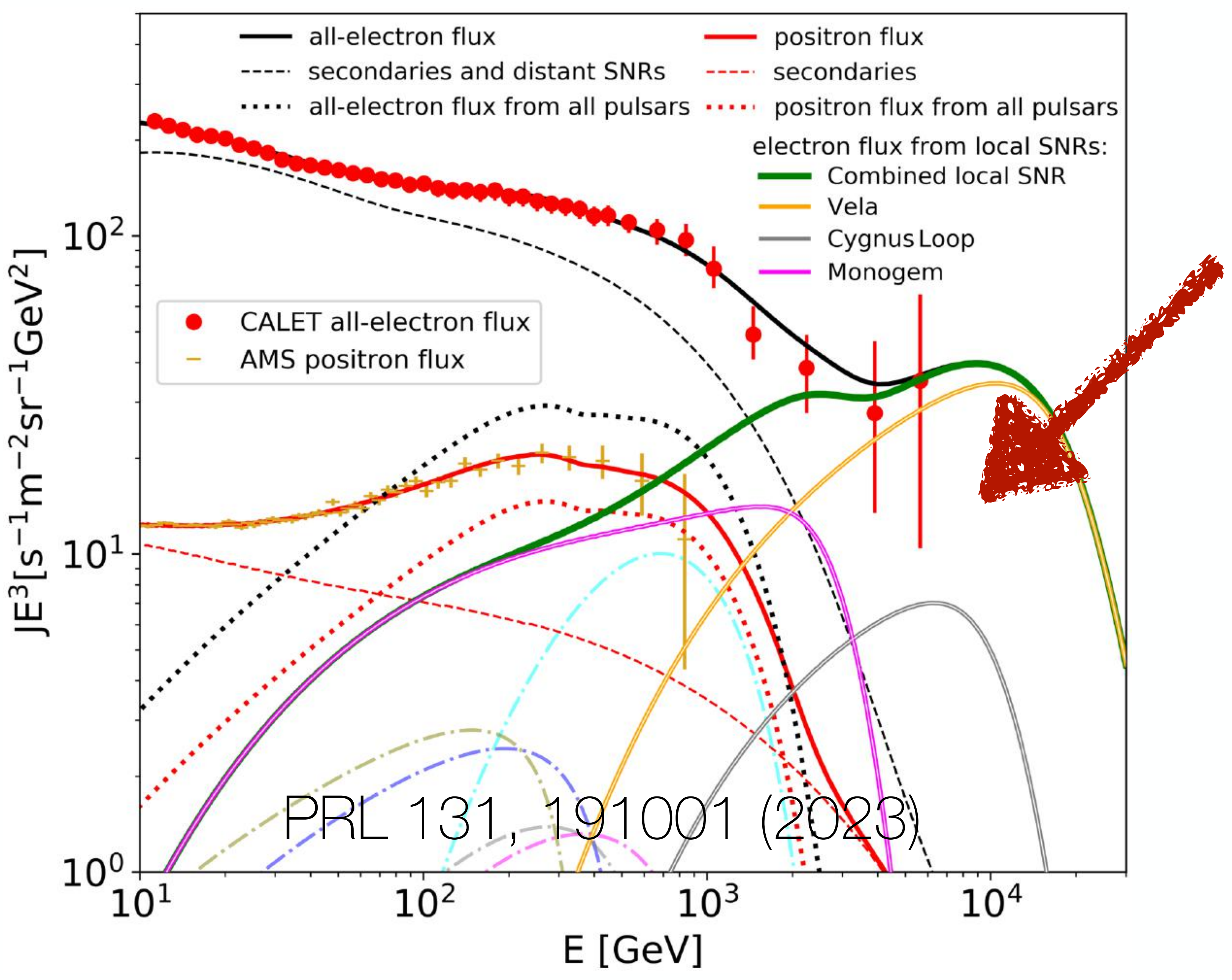


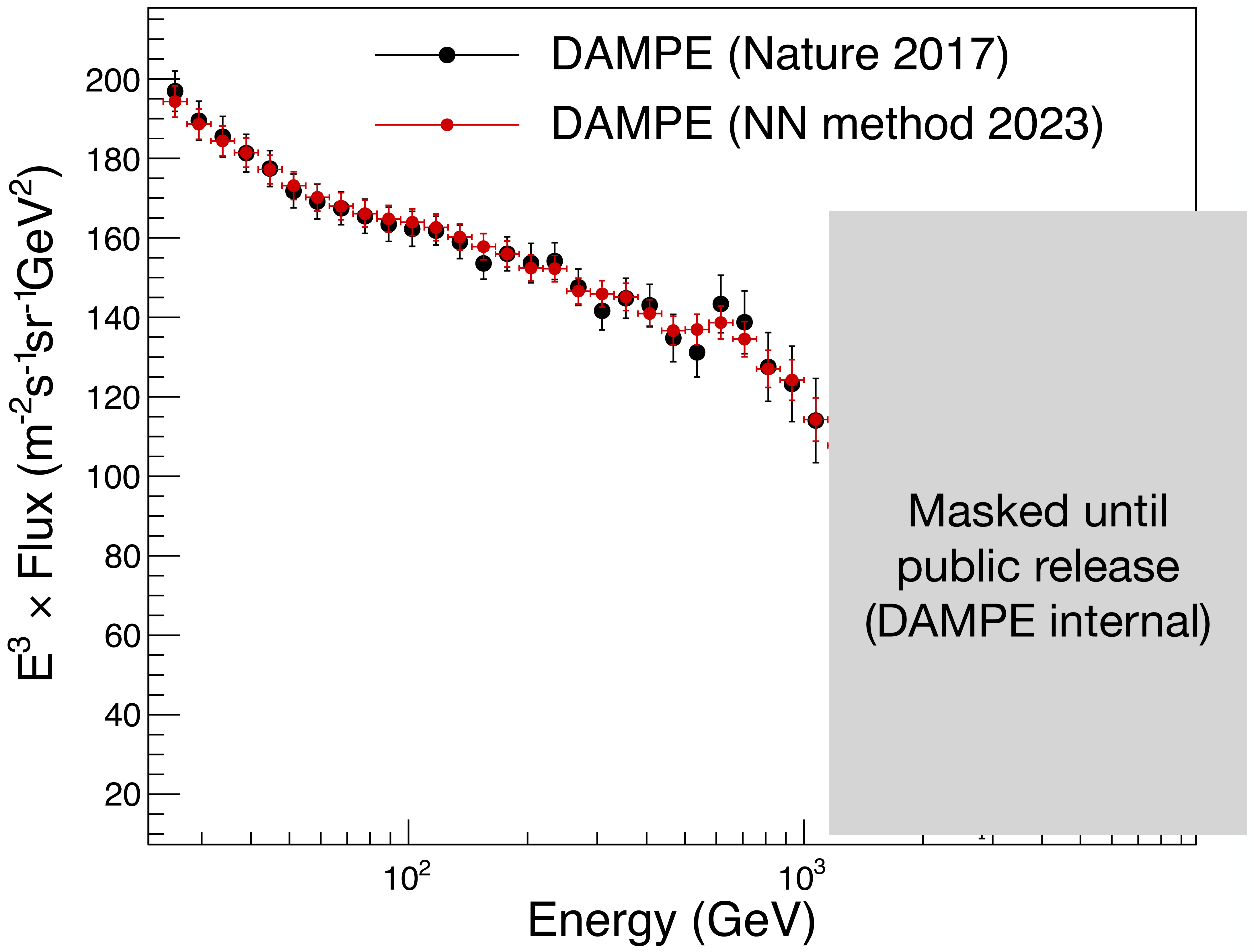


* for comparison, AMS resolution at 1 TeV O(10)%

$e^{-}+e^{+}$

- ~TeV spectrum becomes sensitive to age/distance of young nearby sources
  - Manifest in bumps in spectrum — **use spectrum to search for sources!**

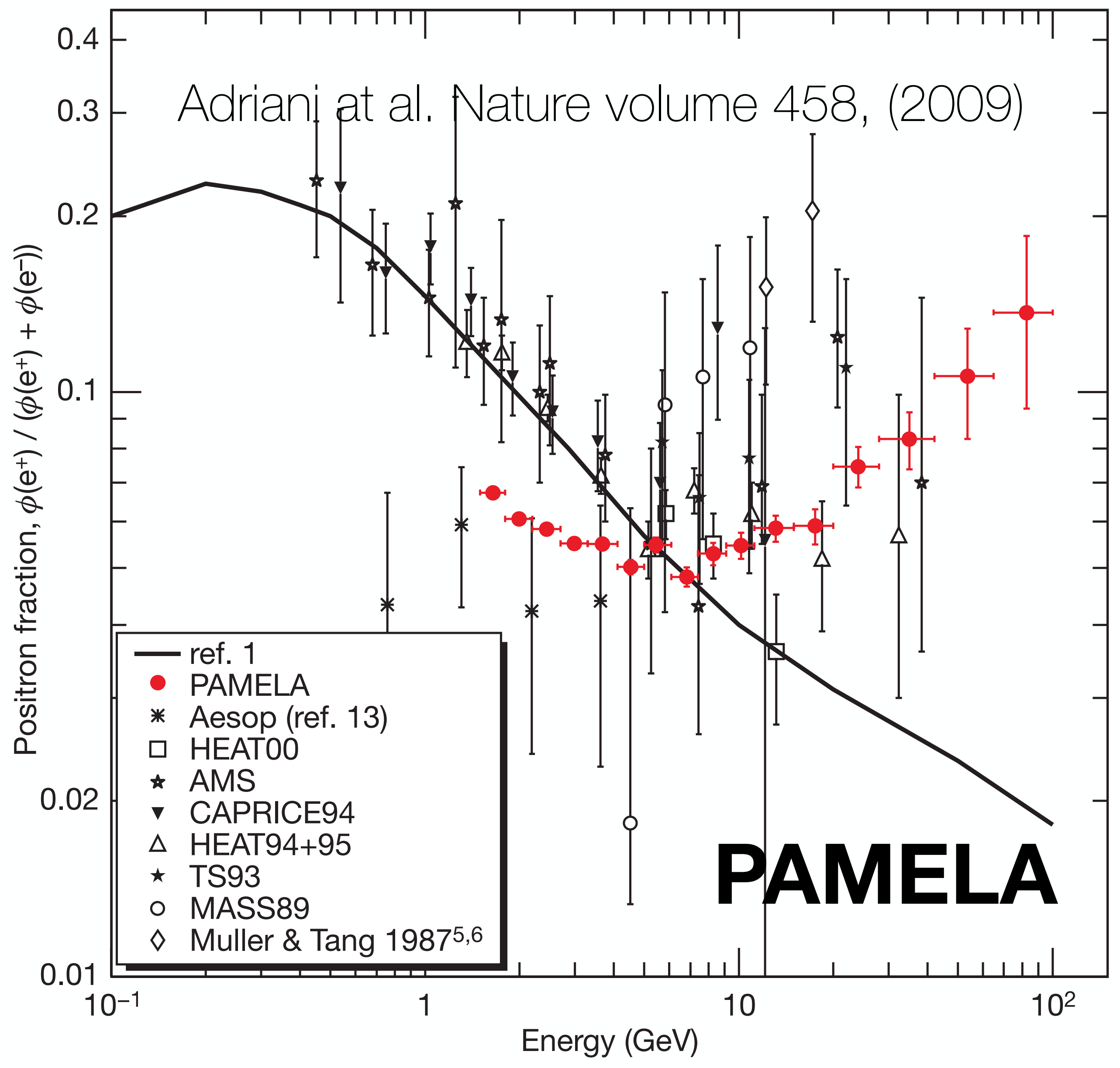


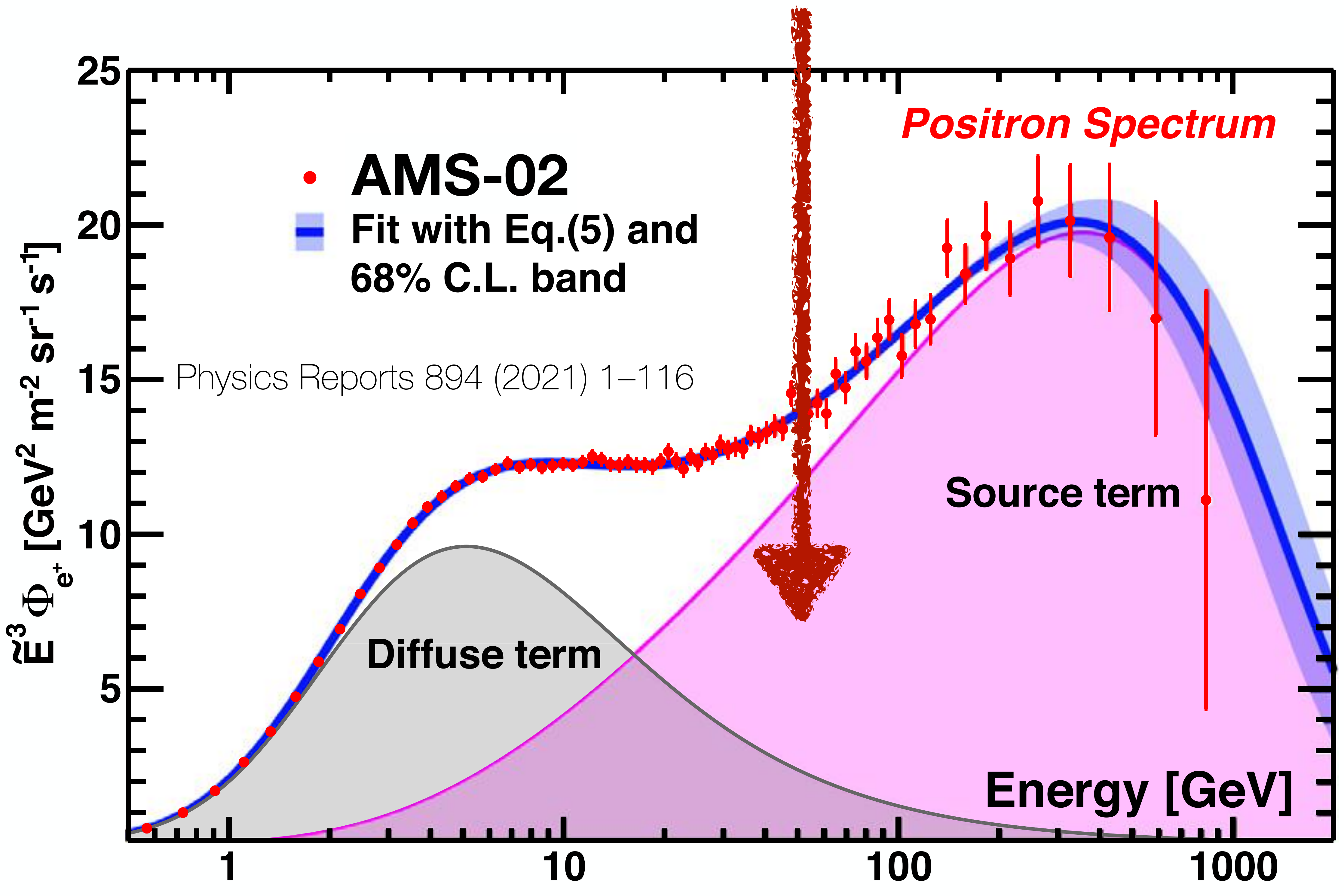


NN method:
D. Droz et al 2021 JINST 16 P07036

e^+

- Hardening in e^+ spectrum first observed by PAMELA, origin unclear until now



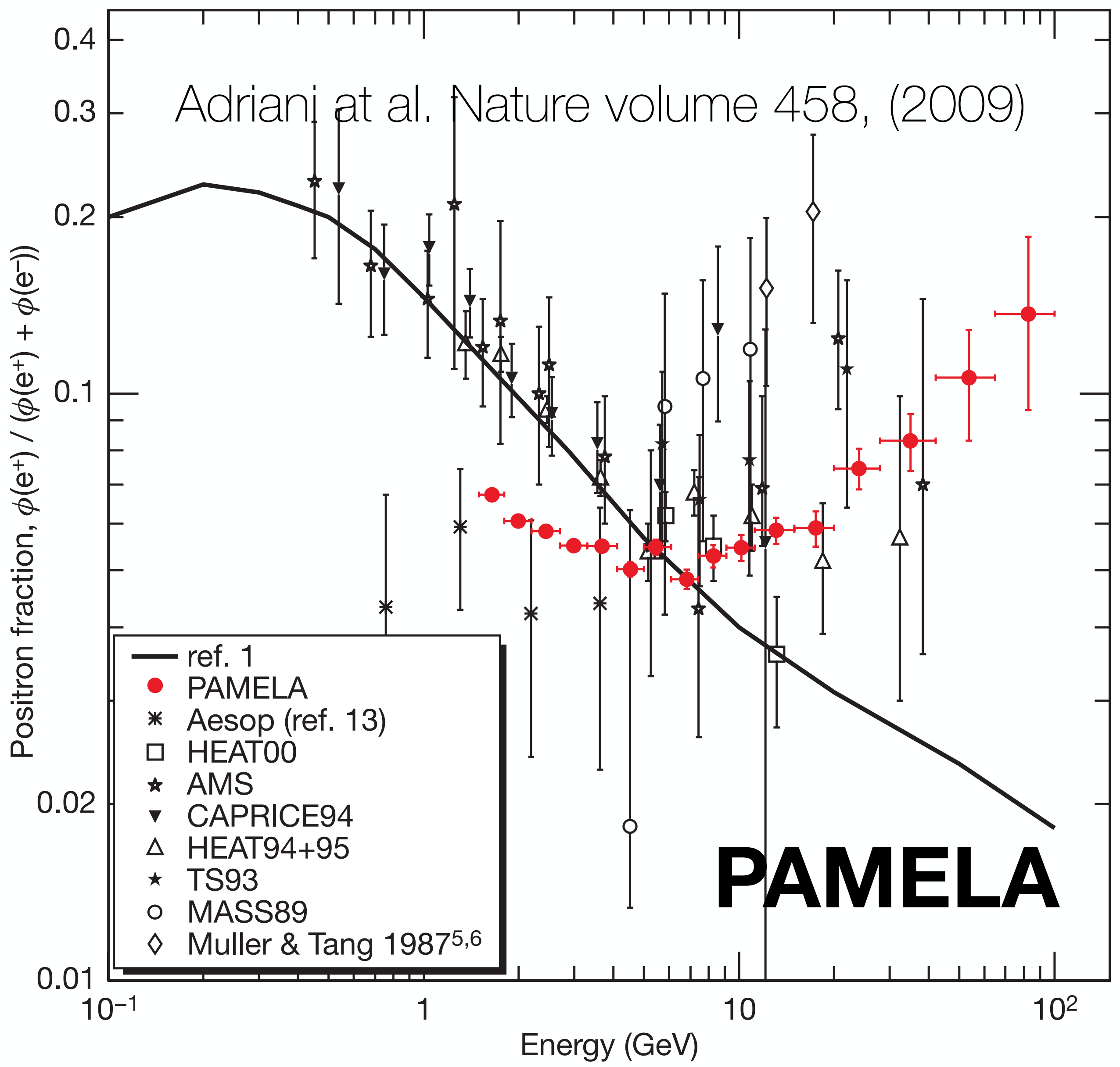


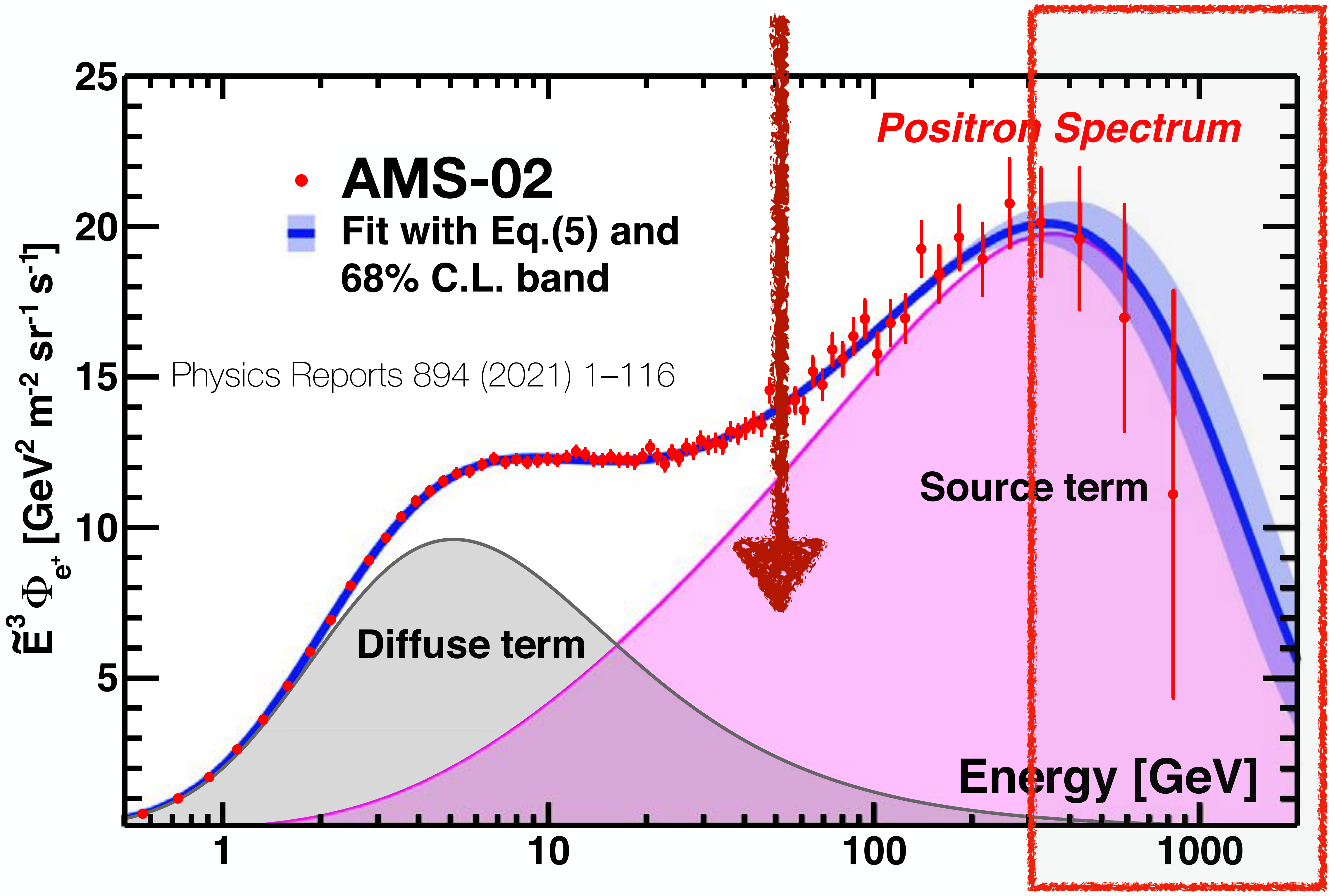
- HAWC: γ-ray halos around pulsar wind nebulae (PWNs)*
  → indication towards astrophysical origin of positron excess

* [10.1126/science.aan4880]

e^+

- Hardening in e^+ spectrum first observed by PAMELA, origin unclear until now





pulsar

Is it *break* or *cutoff*?

dark matter

- HAWC: γ-ray halos around pulsar wind nebulae (PWNs)*
  → indication towards astrophysical origin of positron excess

* [10.1126/science.aan4880]

Ground

Image credit : T. Lohse PoS(HEP2005)411

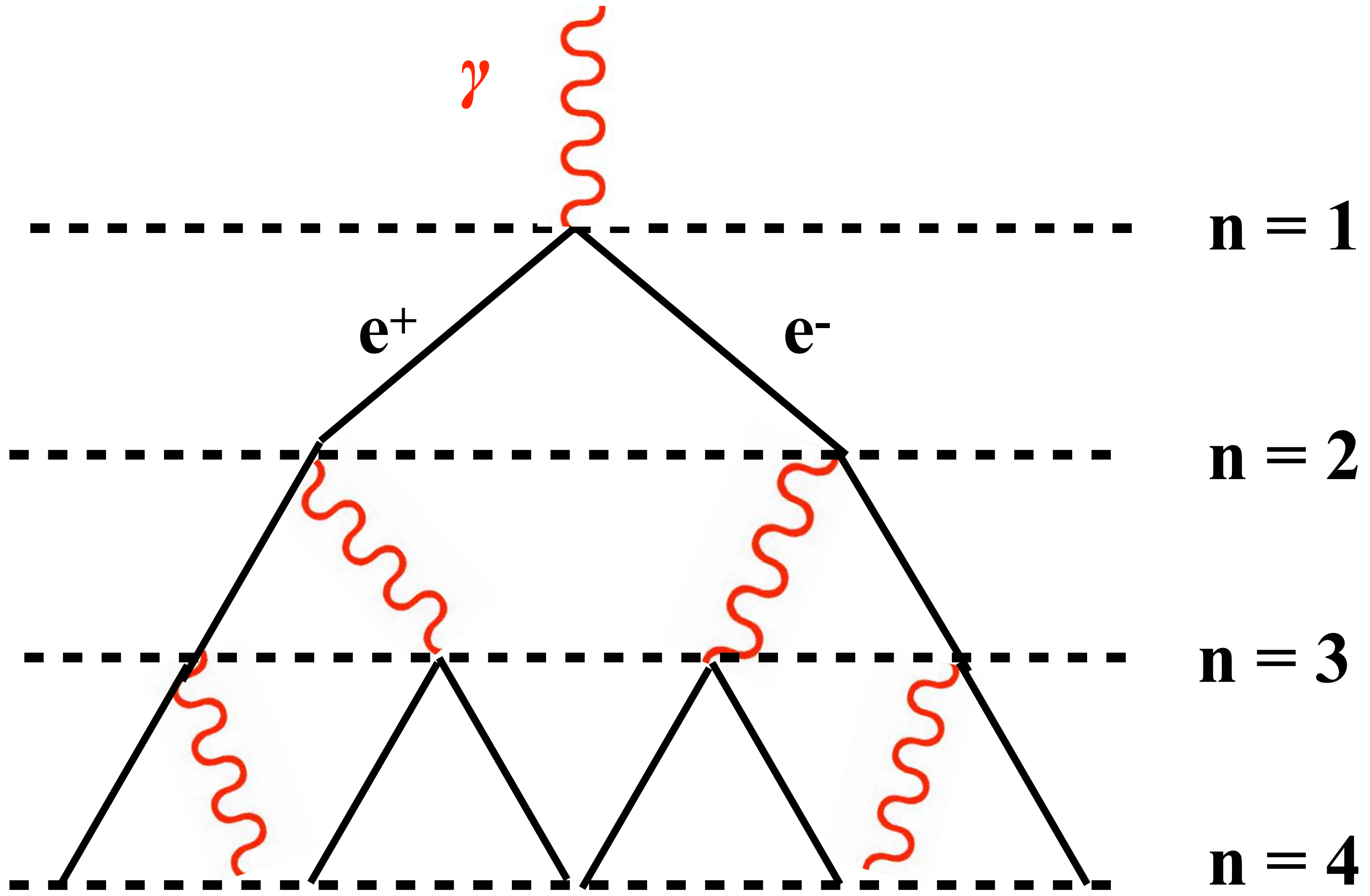
Extensive Air Shower (EAS) detectors

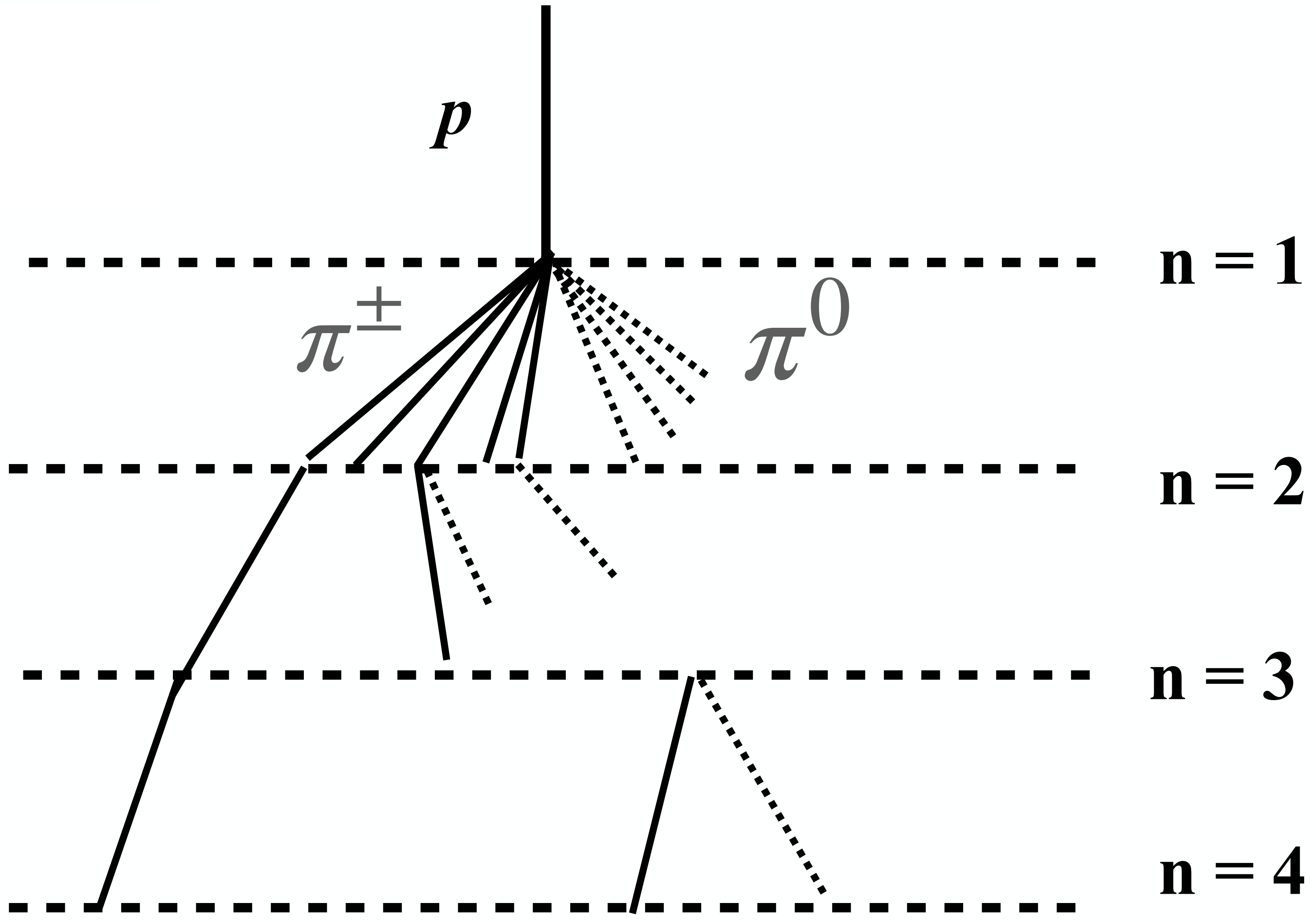
At ~ PeV and higher energies, flux of CR is not sufficient to observe them directly.
Instead, interactions in the atmosphere are observed.

- **Hadronic showers** — most of energy carried away by π^0 and $\pi^\pm$

  $\pi^0 \to \gamma\gamma$ (electromagnetic component)

  $\pi^\pm \to \mu^\pm\nu$ (muons, neutrino carry away 10—20% — *invisible* energy)





arXiv:2202.11618v1

Appl. Sci. 2022, 12, 705

Extensive Air Shower (EAS) detectors

Secondary observables used to determine shower energy (E) and cosmic ray particle mass (A)

- N_{max} — **shower size (total number of particles) — most direct probe of energy**
- X_{max} —shower depth in the atmosphere

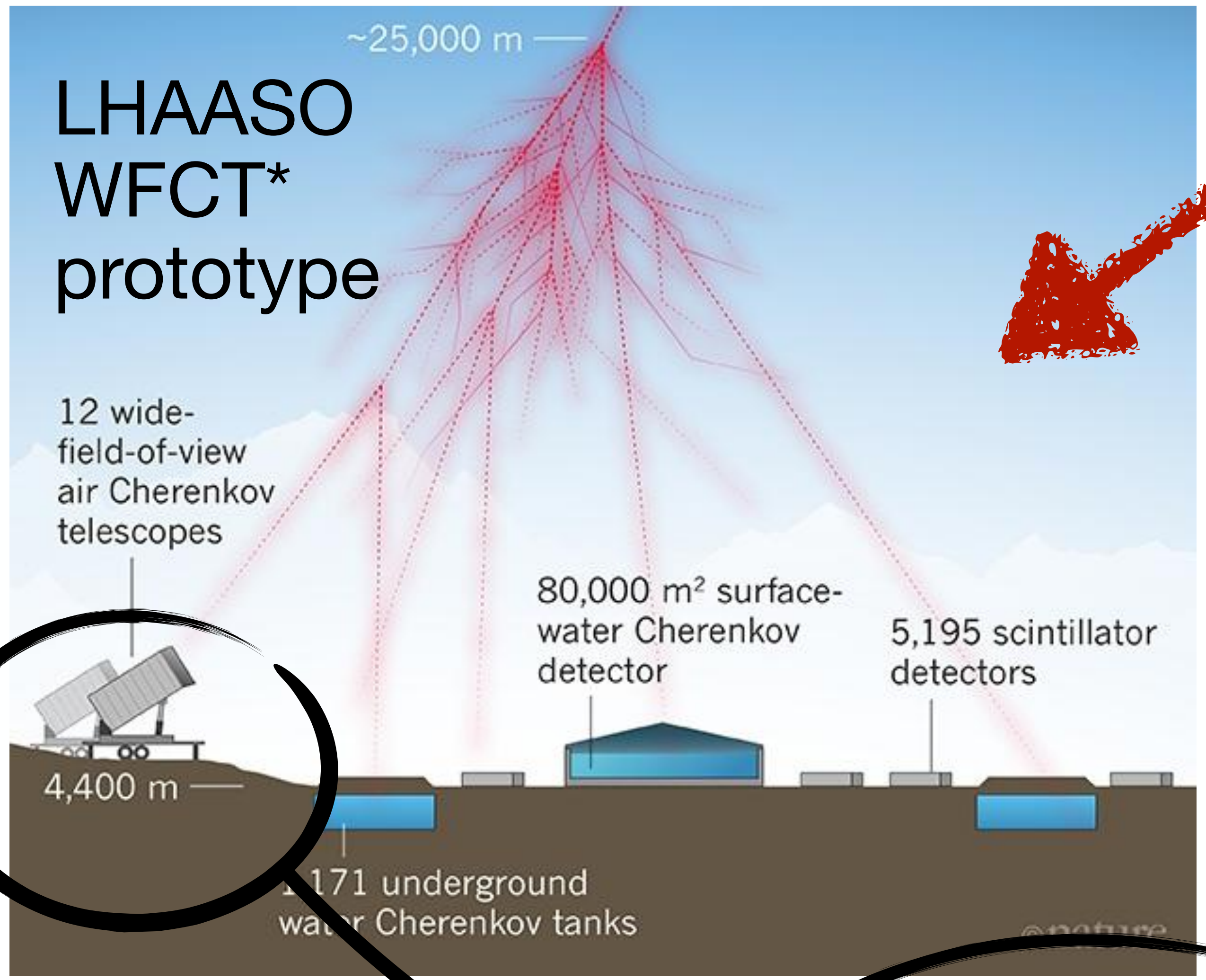
$$N_{\max} \propto E$$

$$X_{\max} \propto \log E$$

$$X_{\max} \propto \log A^{-1}$$

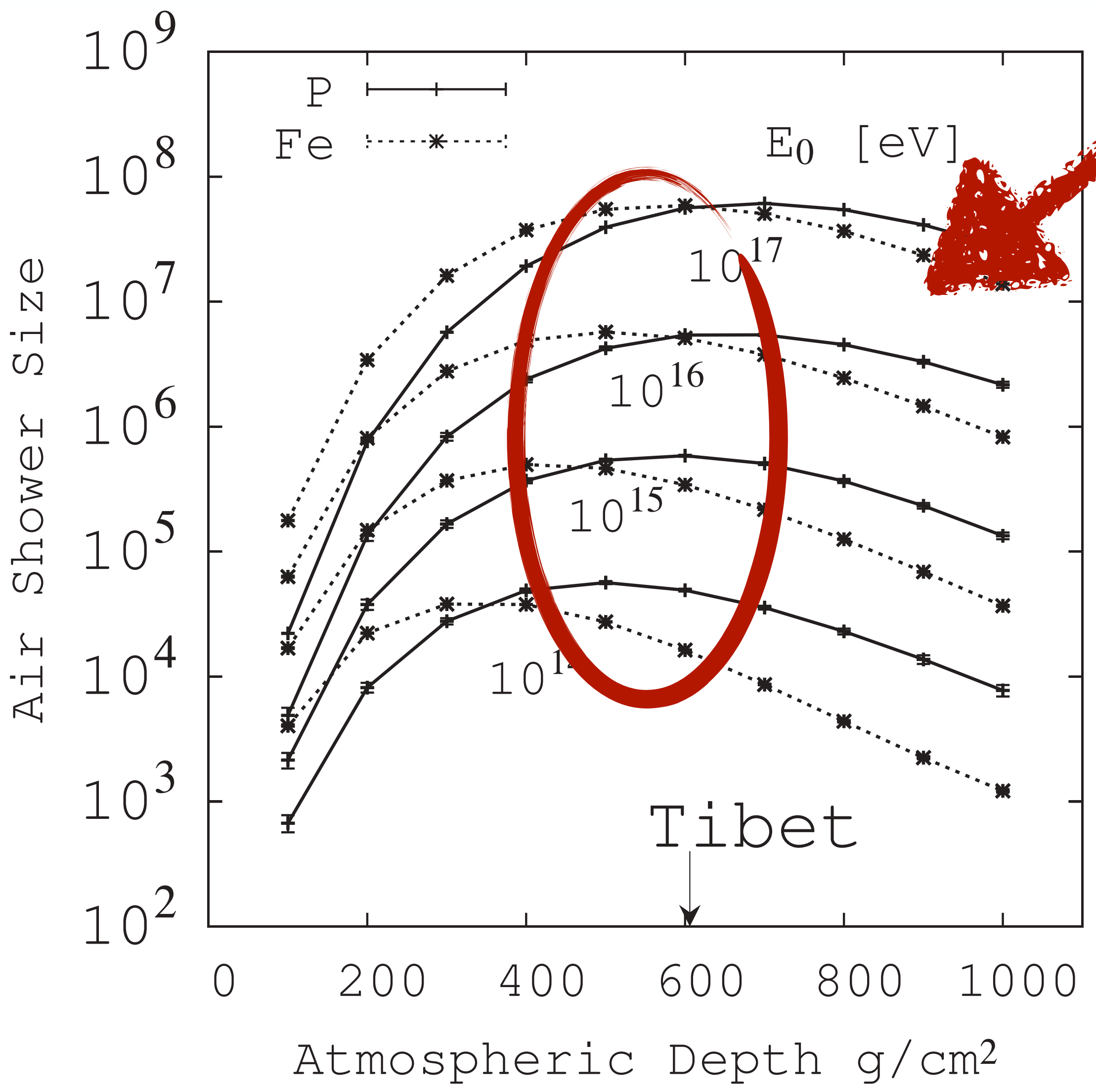
$$N_{\mu} \propto A^{(1-\beta)} E^{\beta}$$

$$\beta \simeq 0.85 \ldots 0.95$$



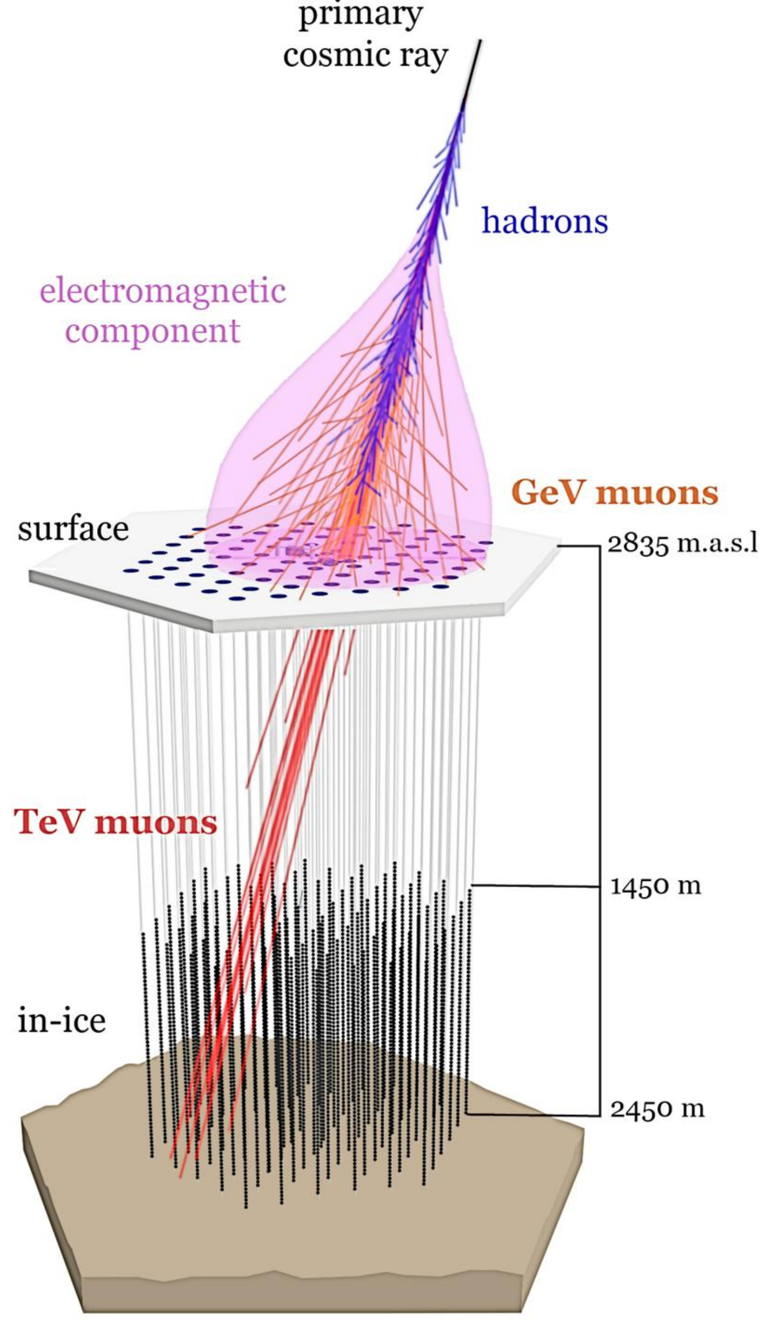
ARGO-YBG
RPCs array

- Combine ground-level observations (hadronic) with Cherenkov (electromagnetic) part
- Higher altitudes — probing showers close to the core — resolving *E* & *A* degeneracy

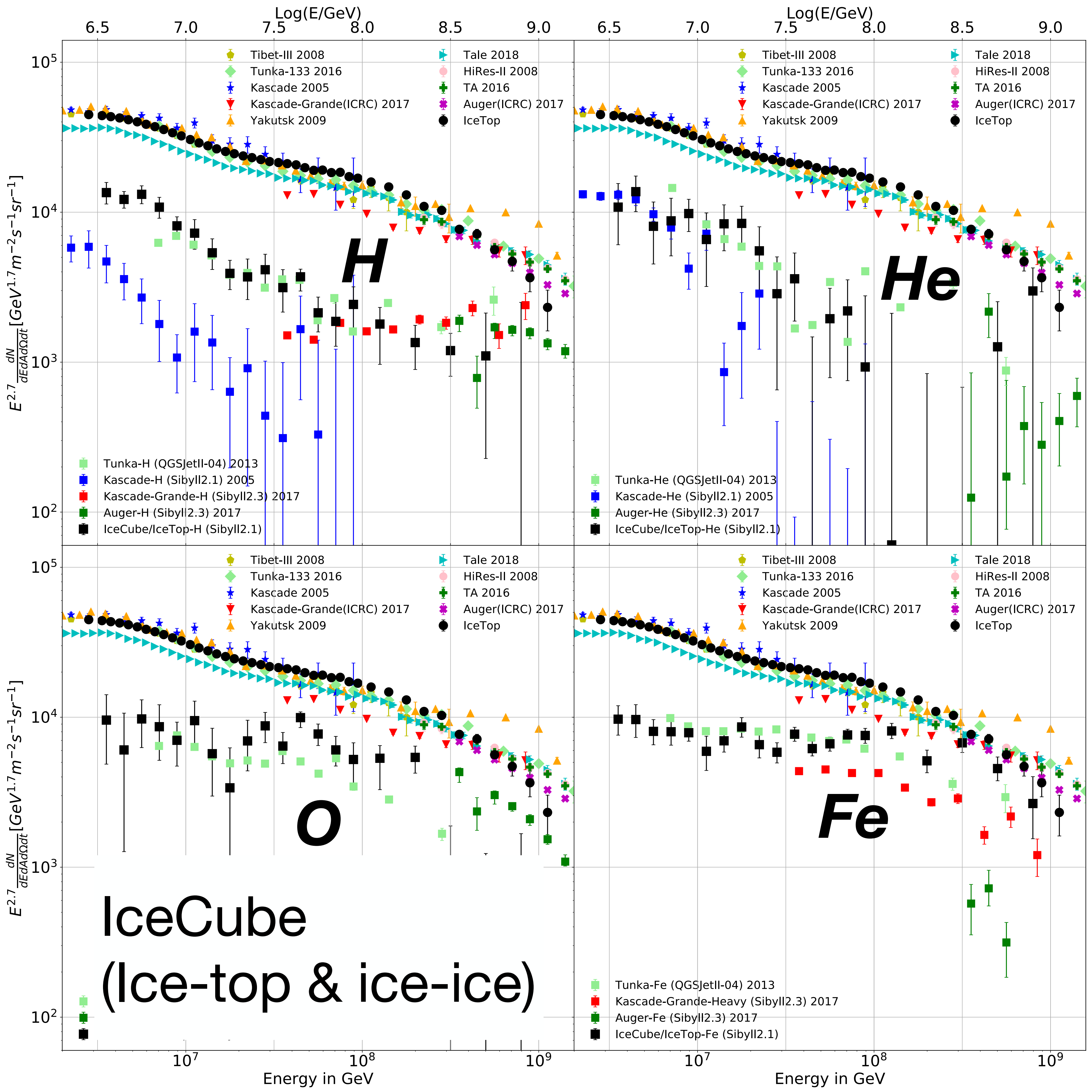


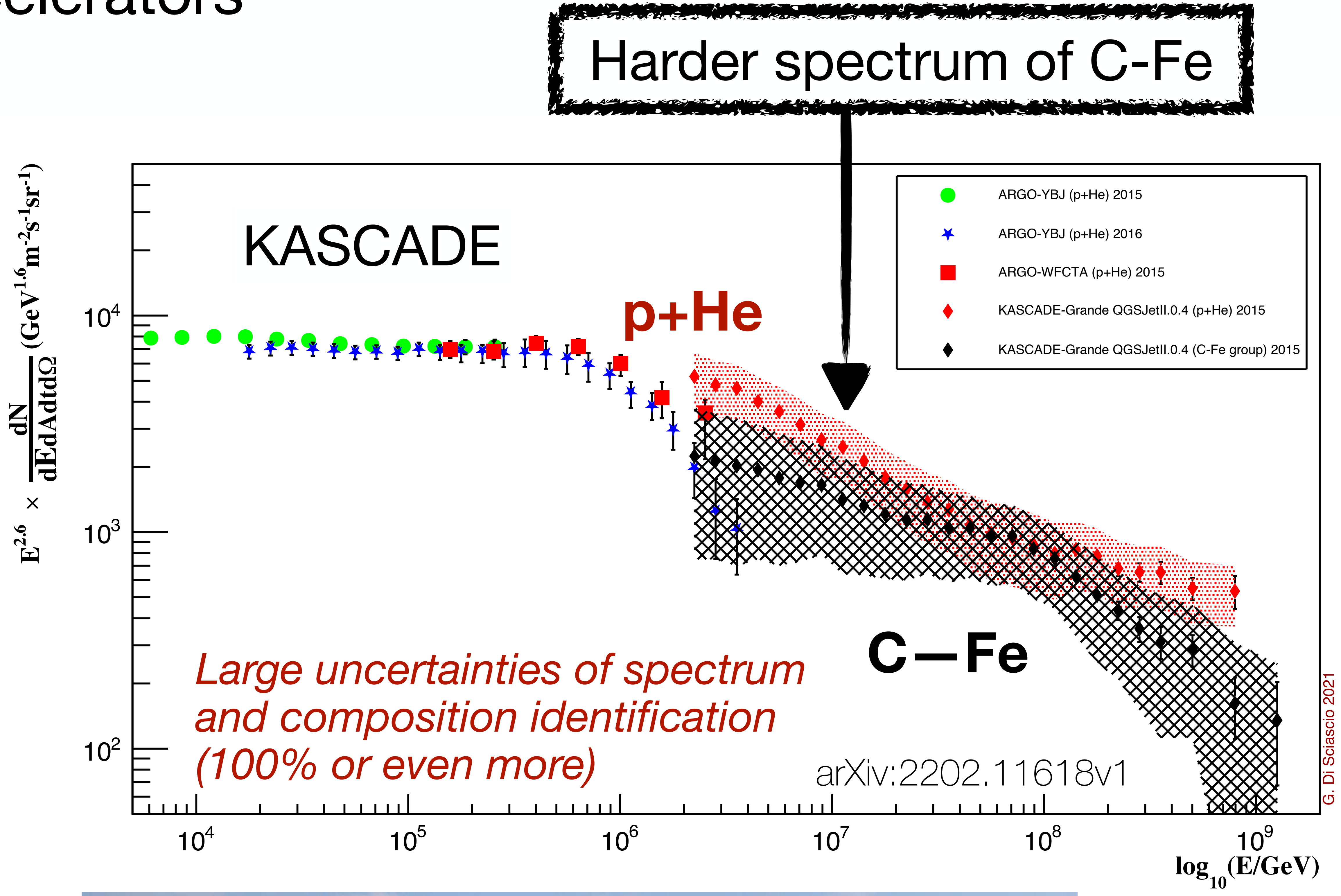
EAS results: ~PeV *knee*

- Increasing contribution of heavy cosmic rays (C-Fe) after few PeV (IceCube, KASCADE)
  - Indicates exhaustion of galactic cosmic-ray accelerators



IceCube





EAS results: 100 PeV — 2nd *knee*

- After 100 PeV, the composition becomes lighter indicating of Extragalactic origin

Model	X_0^{H}	D_0^{H}	D_1^{H}	X_0^{Fe}	D_0^{Fe}	D_1^{Fe}
Sibyll 2.3	$7[illegible]2.6 \pm 0.6$	58.1 ± 0.3	-0.5 ± 0.2	659.3 ± 0.7	63.2 ± 0.4	-2.8 ± 0.2
EPOS-LHC	748.5 ± 0.6	57.4 ± 0.3	-0.9 ± 0.2	649.9 ± 0.5	63.3 ± 0.3	-2.6 ± 0.1
QGSJet II-04	733.1 ± 0.5	54.9 ± 0.2	-0.2 ± 0.1	637.9 ± 0.7	59.8 ± 0.4	-2.9 ± 0.2

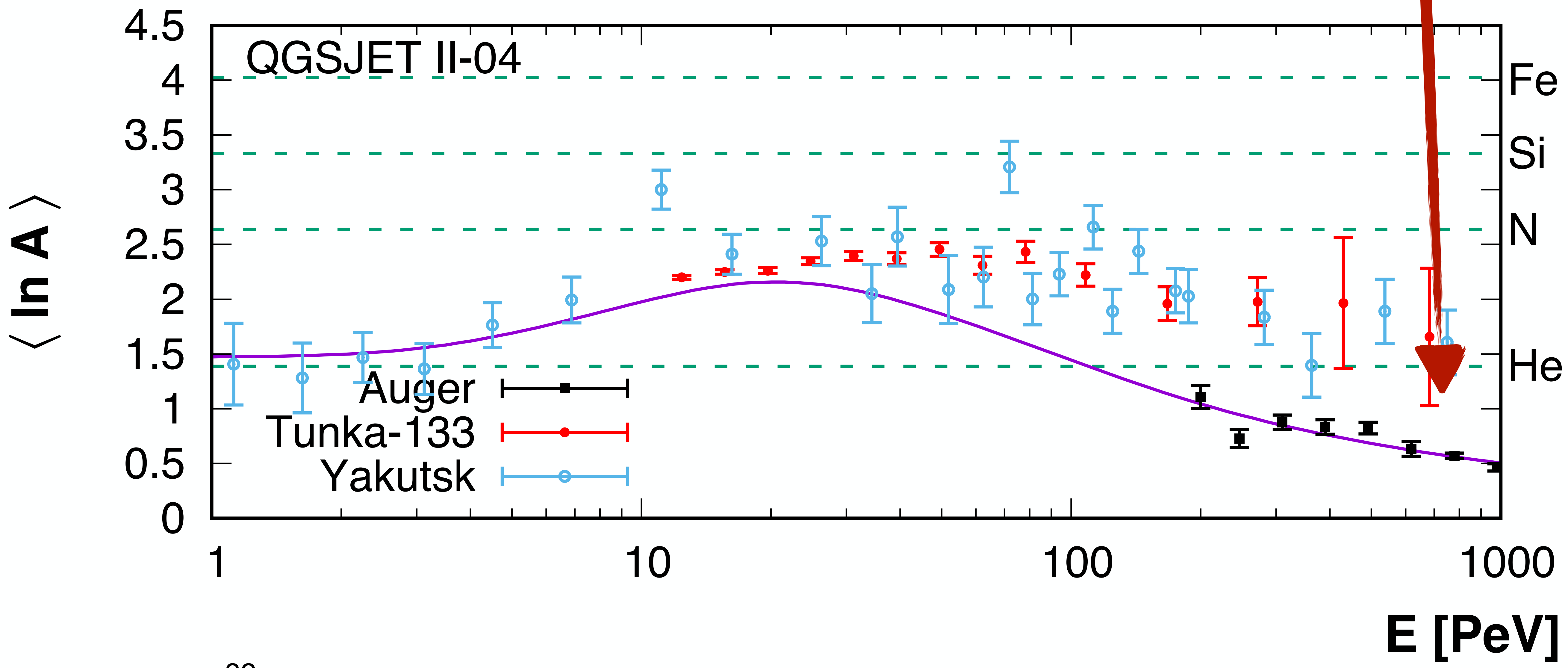
$$X_{\max}^{A} = X_0^{A} + D^{A}(E)\log(E/\mathrm{EeV}),$$

$$D^{A}(E) = D_0^{A} + D_1^{A}\log(E/\mathrm{EeV}).$$

$$\langle \ln A \rangle \simeq \ln 56 \, \frac{X_{\max}^{\mathrm{H}}(E) - \langle X_{\max} \rangle}{X_{\max}^{\mathrm{H}}(E) - X_{\max}^{\mathrm{Fe}}(E)}$$

Detectors in the Pierre Auger observatory on the Argentina pampas

Average CR mass (<lnA>) decreases towards p-He group



https://arxiv.org/abs/1812.04026

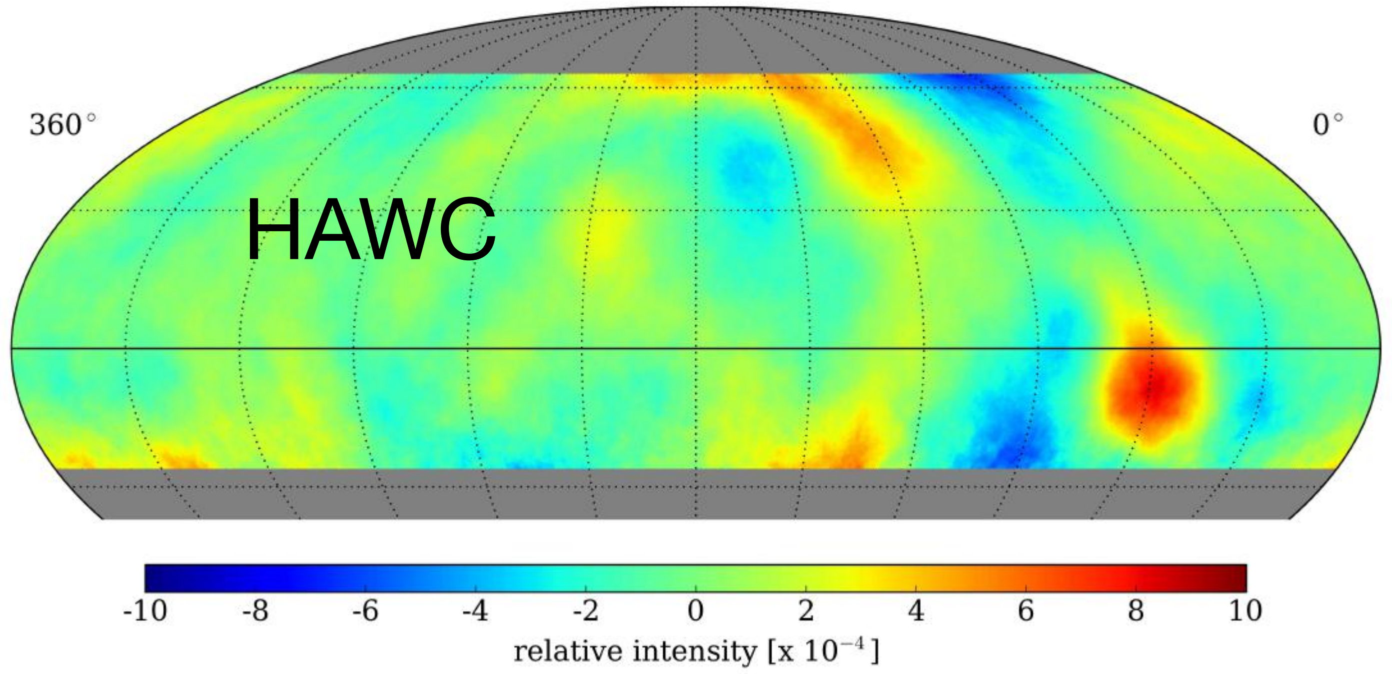
Cosmic Ray anisotropy

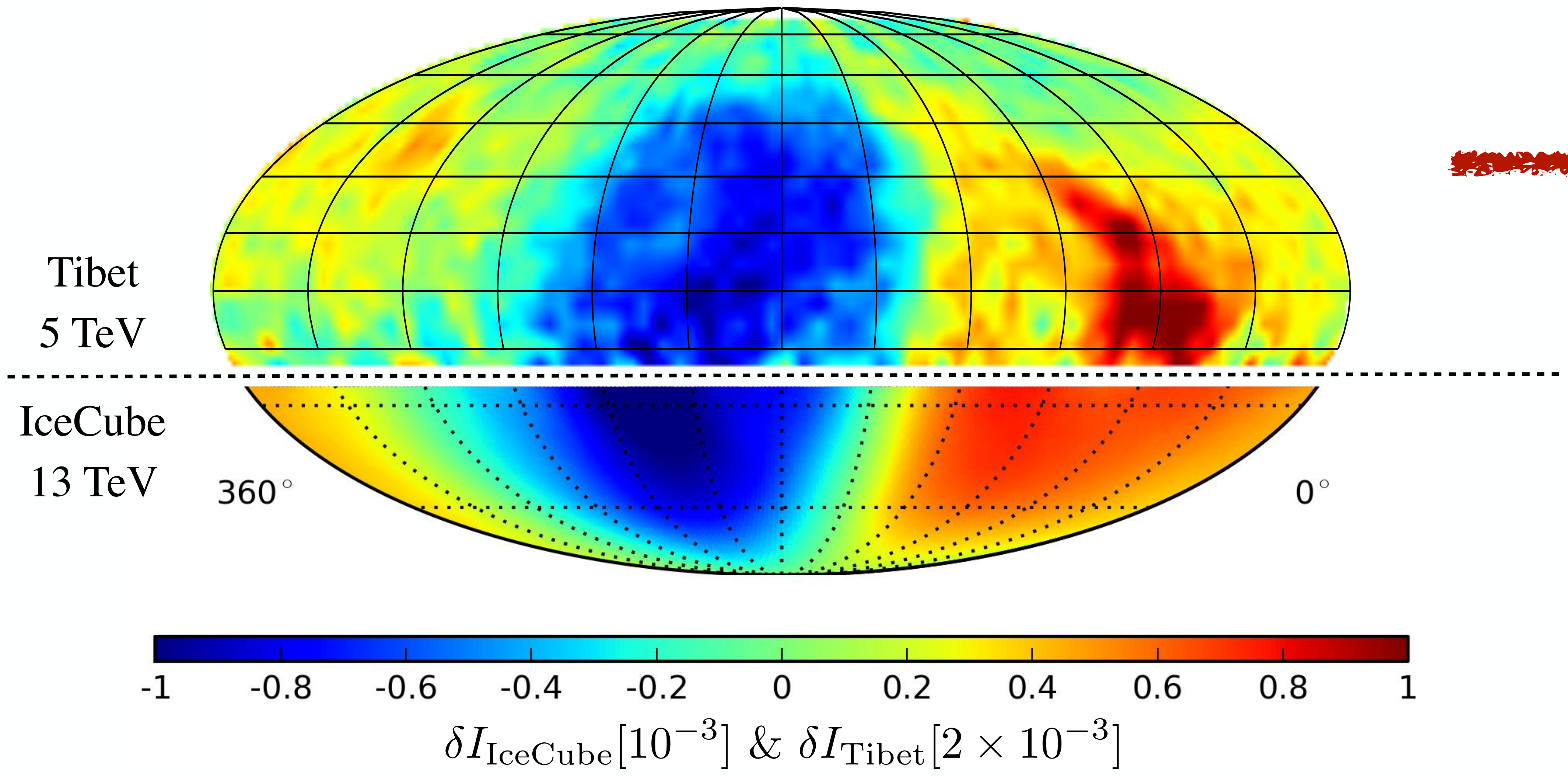
- CR are mostly isotropic, anisotropies are 10^{-3} to 10^{-4}
- Large-scale (dipole) expected from diffusive propagation: **gradient due to CR source variation**
- Small-scale anisotropies (~10°) NOT predicted by standard diffusive theory

  → Likely attributed to specific realisation of the turbulent magnetic field in our Galactic neighbourhood.

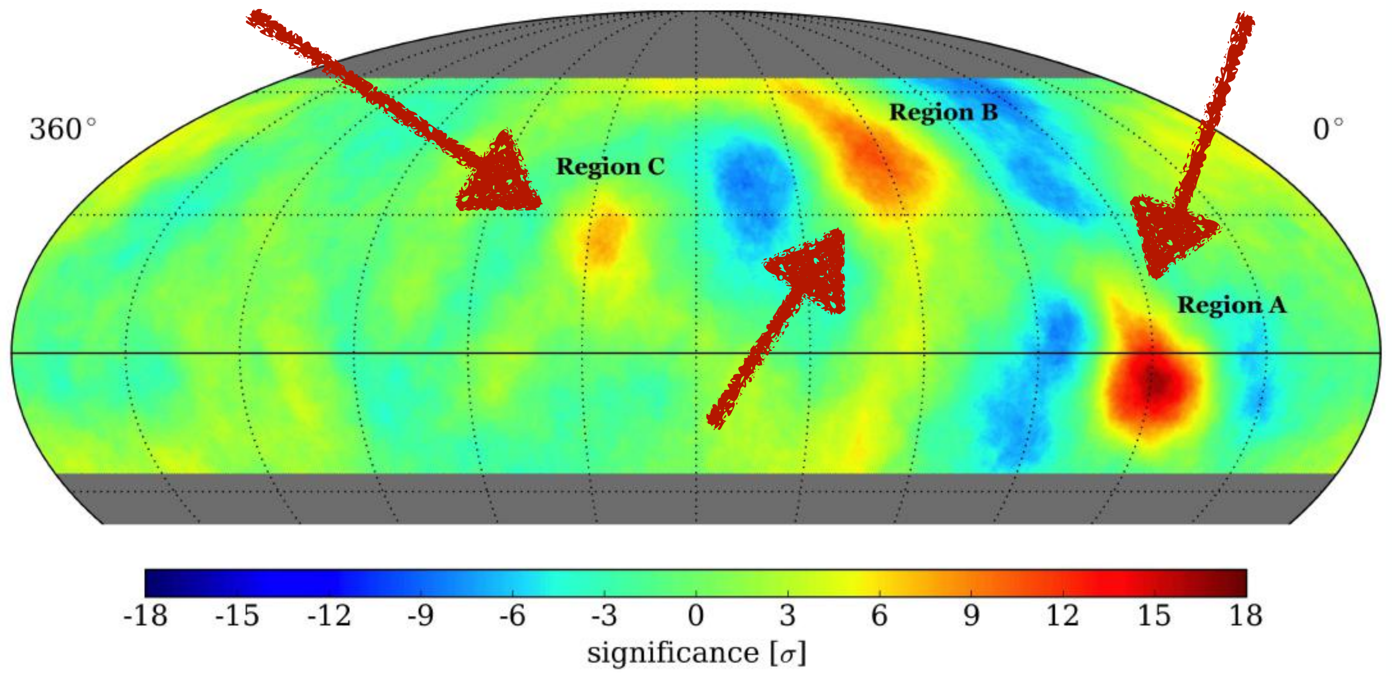
$$I(\mathbf{n}) \equiv \frac{\phi(\mathbf{n})}{\phi^{\mathrm{iso}}} \equiv 1 + \delta I(\mathbf{n})$$

Harmonic/Fourier decomposition: donated by leading harmonics (dipole, quadrupole,..)





Small-scale (after subtracting dipole)



arXiv:1612.01873v1

Conclusions …

Cosmic Rays - very broad and active field!

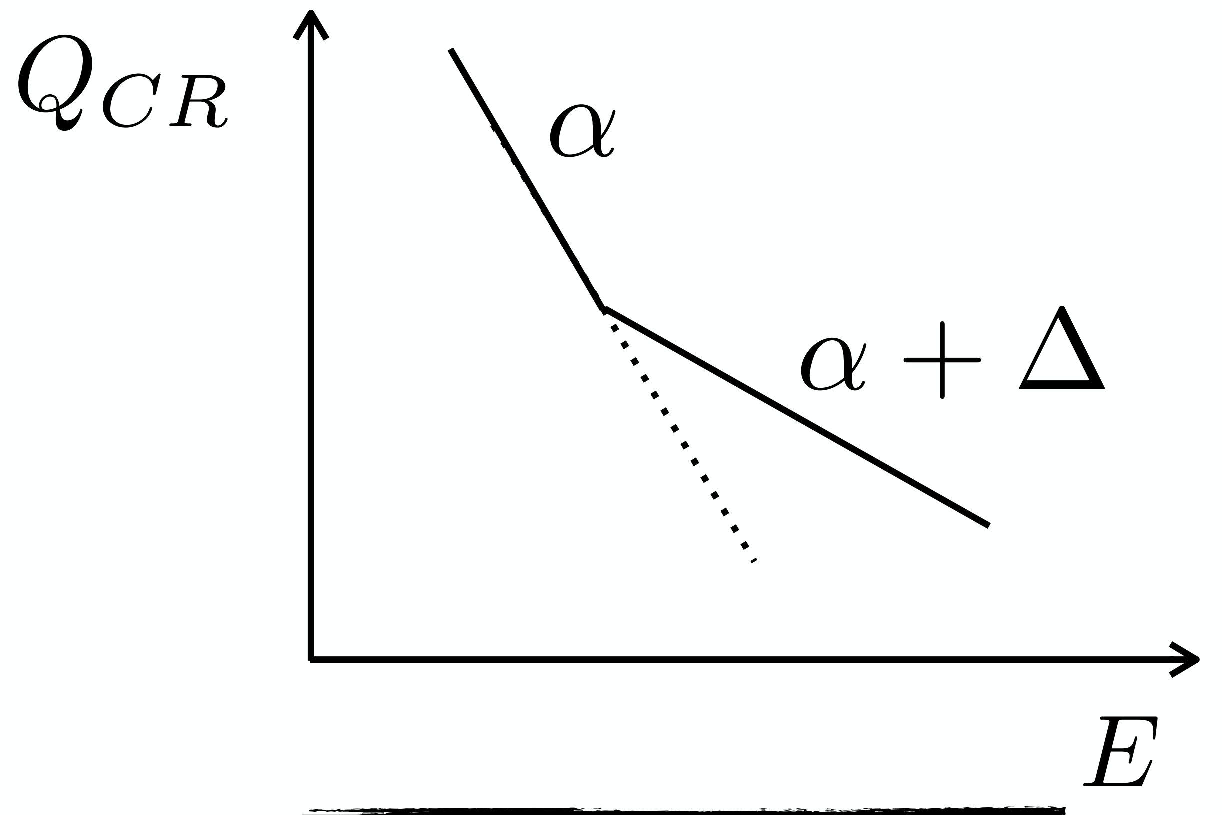
Impossible to summarise here, some (biased) thoughts:

- Space:
  - Things because complicated with the raise of direct measurements
  - Breaks as an indication of “new” physics in cosmic rays
    - — non-linear plasma effects
    - — era of first probes of individual accelerators!
    - — tantalising features in anti-matter
  - Direct measurements approach PeV frontier — highest CR energies in the Galaxy

- Ground:
  - Large uncertainties (energy, tentative composition)
  - Knee — shift of CR composition towards heavy elements
  - Light elements taking over after 100 PeV — second knee
  - Small-scale anisotropies — new beast!

Backu-ups

What does theory say about the hardening?

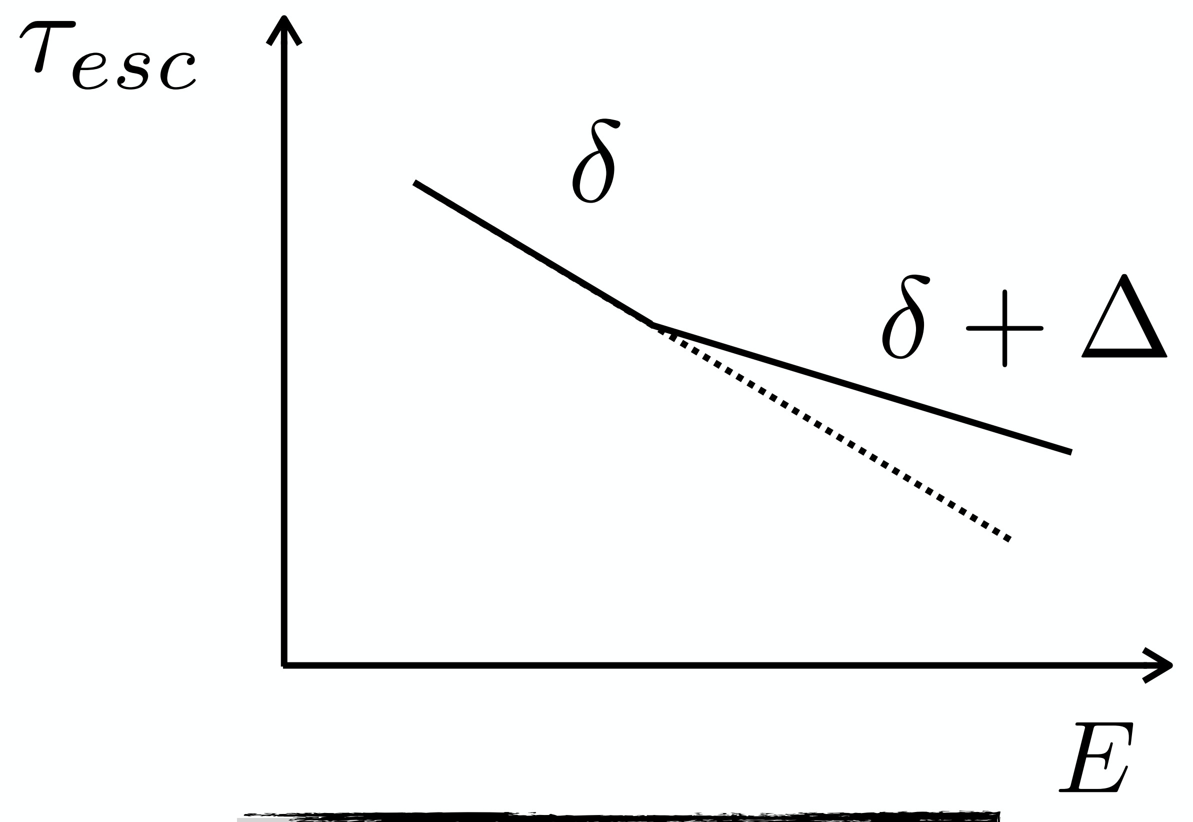


SOURCES

$$N_{CR} = Q_{CR}\tau_{esc}$$

$$Q_{sec} \sim N_{CR}$$

$$N_{sec} = Q_{sec}\tau_{esc}$$



PROPAGATION

$$N_{CR} = Q_{CR}\tau_{esc}$$

$$Q_{sec} \sim N_{CR}$$

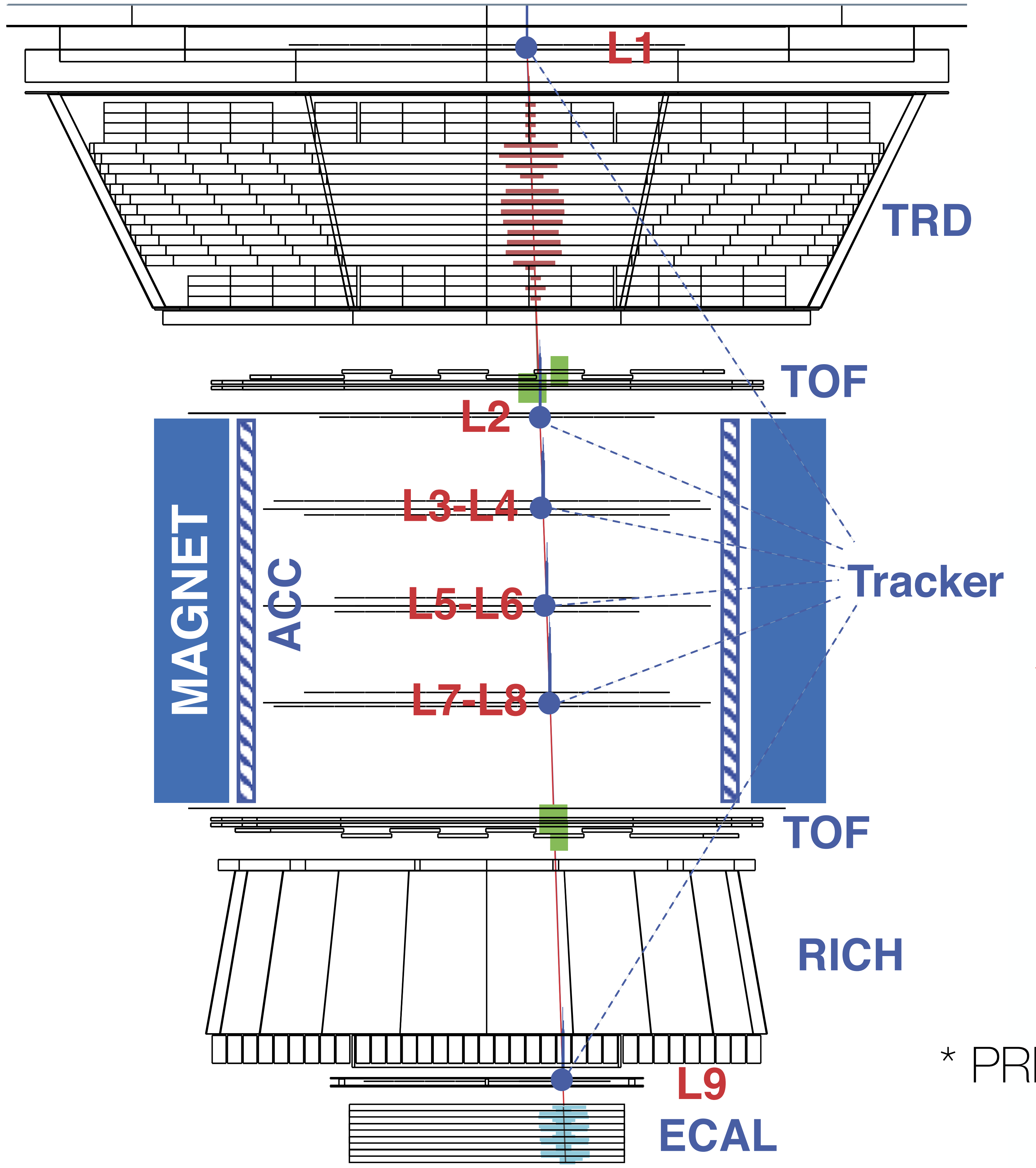
$$N_{sec} = Q_{sec}\tau_{esc}$$

In fact, if the spectral break is due to ***propagation****, the change of power-law index for secondaries will be* ***twice*** *that of primaries!*

Image credit to: *S. Gabici, ICRC 2023*

Hadronic Cross Sections & Cosmic Rays

- For AMS-02, Cosmic Ray charge selection is affected by **survival probability**



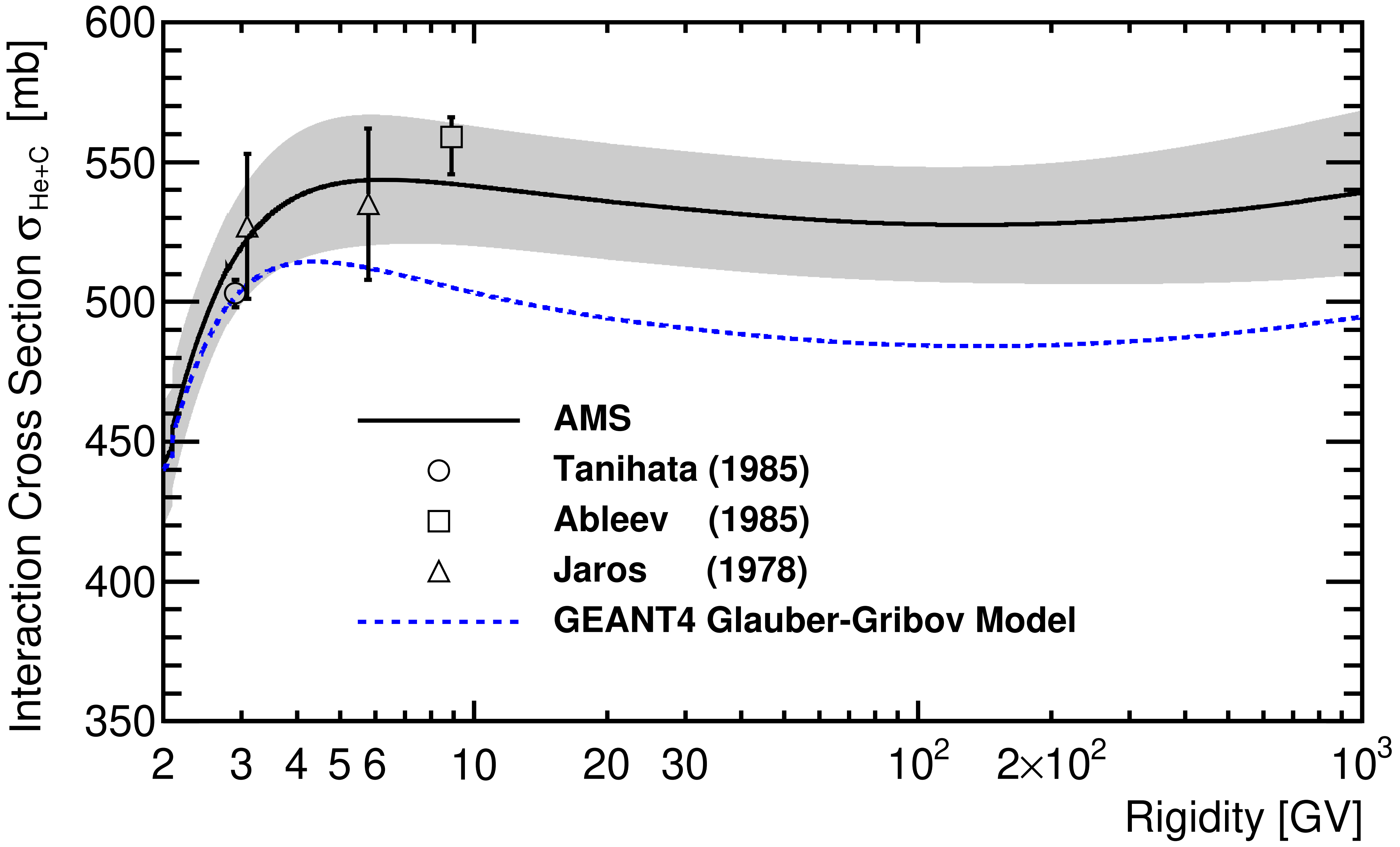
***He* flux:**

1.7 < Z < 2.5

up to layer L8*

* PRL 115, 211101 (2015)

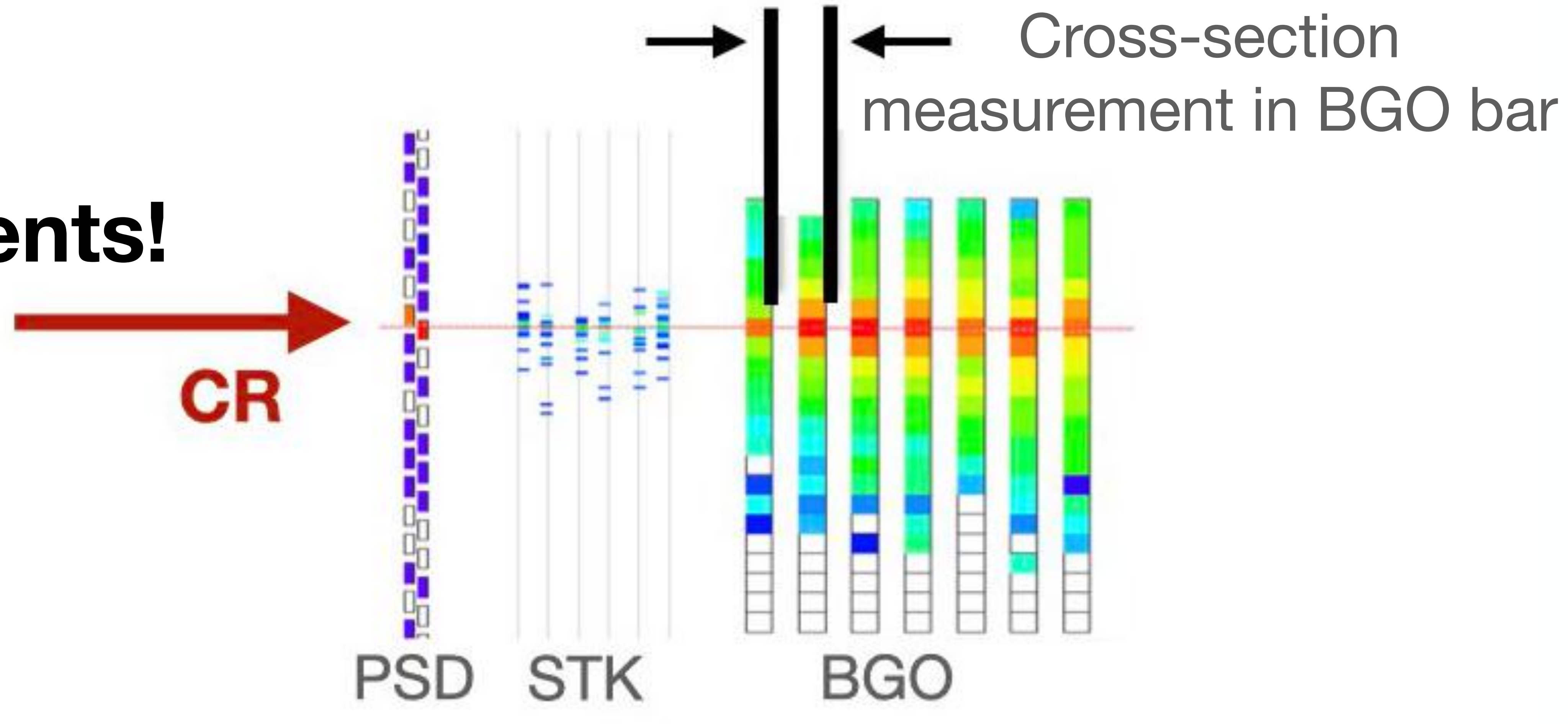
He — C interaction cross section measurement by AMS



Q. Yan Nuclear Physics A 996 (2020) 121712

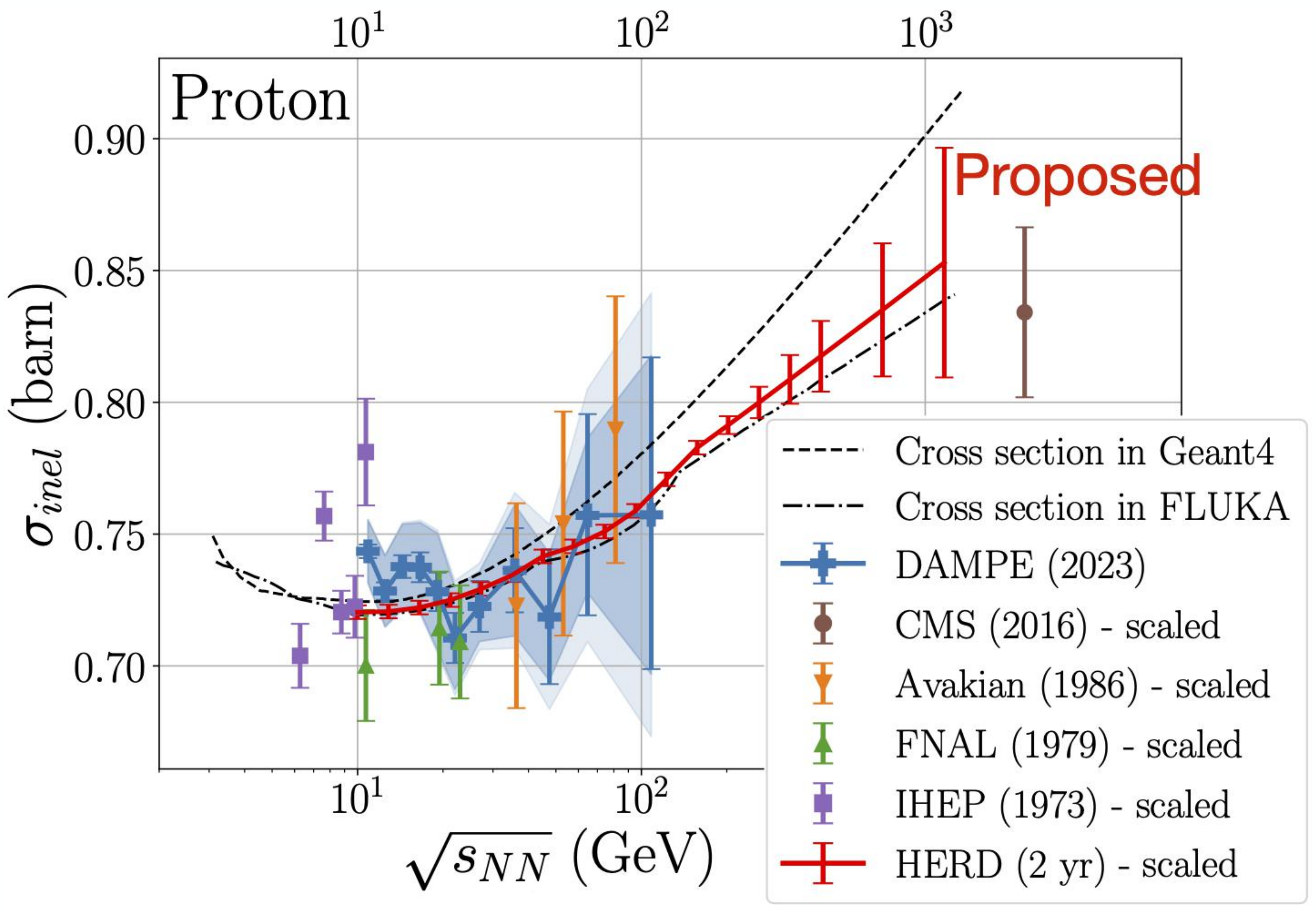
Hadronic Cross Sections & Cosmic Rays

- Good segmentation of DAMPE BGO calorimeter
  → **Use DAMPE/HERD for cross-section measurements!**

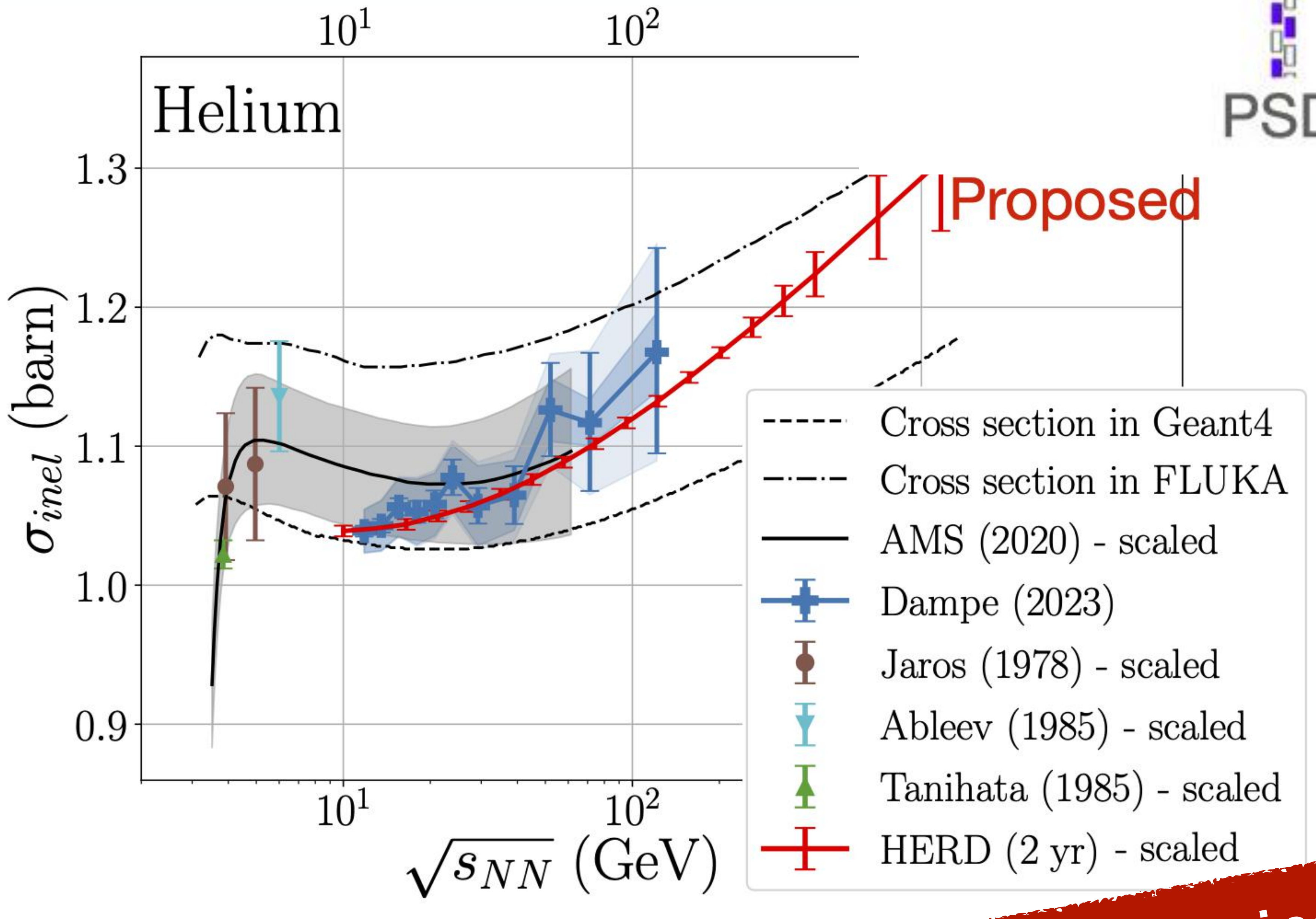


Adapted from
P. Coppin el al. ICRC 2023
https://pos.sissa.it/444/142

p—**BGO**



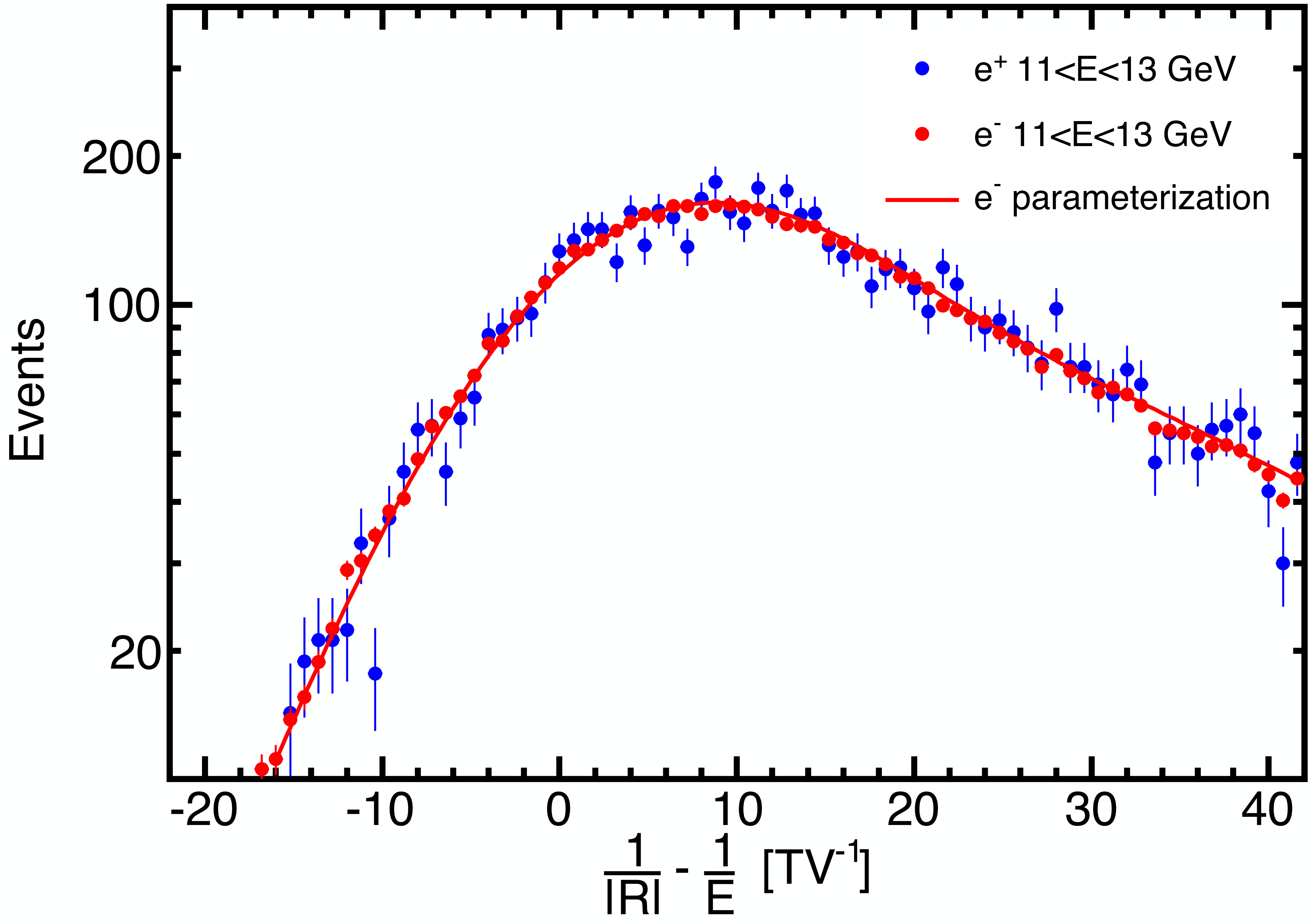
He—**BGO**

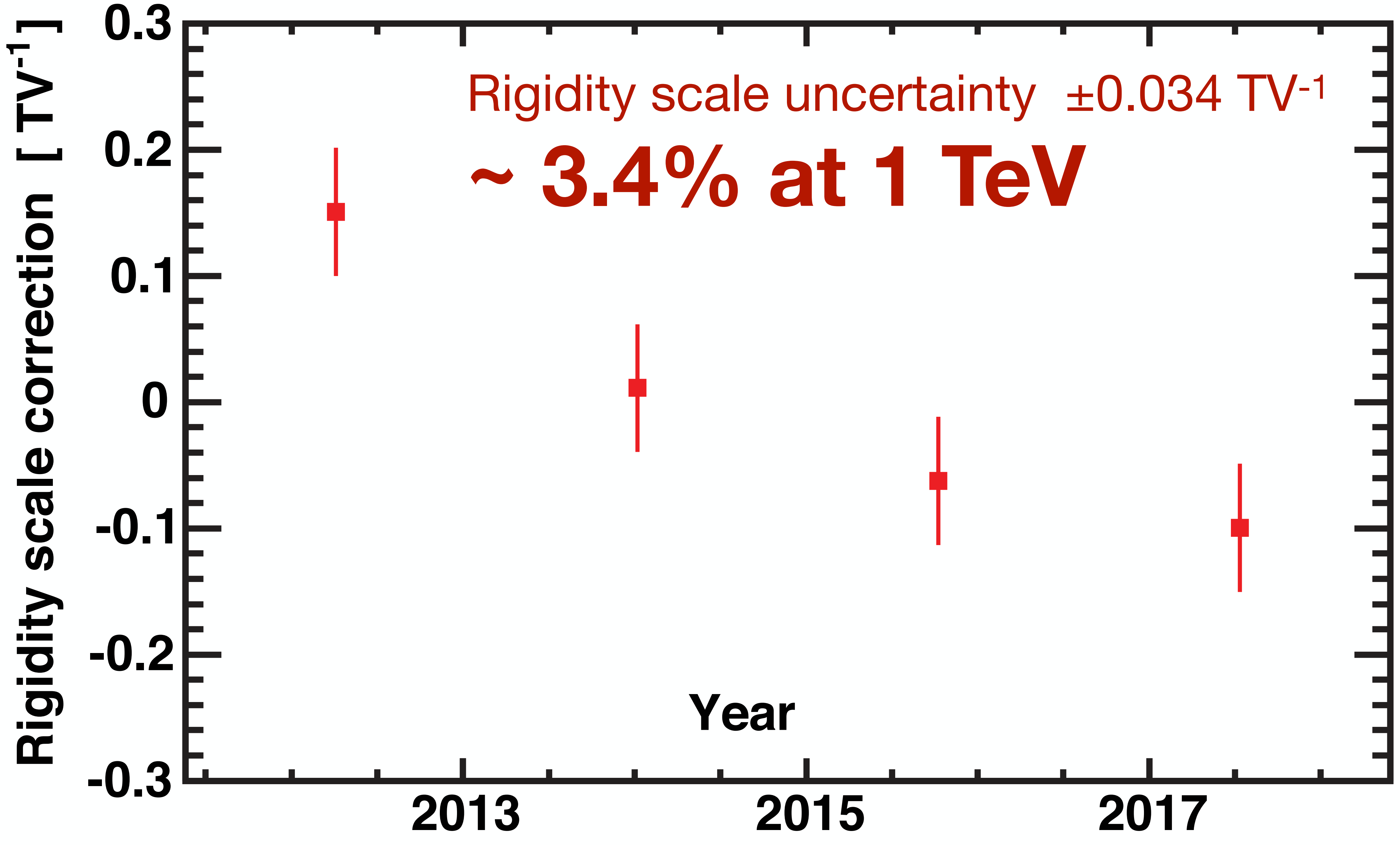


Important for reducing the uncertainty of hadronic cosmic ray measurements with calorimetric experiments

Alpha Magnetic Spectrometer (AMS-02)

- **Largest systematic uncertainty is due to absolute rigidity scale**
  - Calibrated on-ground with tests beams (up to 400 GV)
  - Rigidity scale shift determined by e^+/e^- cross-calibration with calorimeter





PRL 114, Physics Reports 894 (2021) 1–116

Cosmic Ray electrons & positrons

Rare: 1/10000 cosmic rays at 1 TeV is an e^- or e^+

- Sensitive to new physics

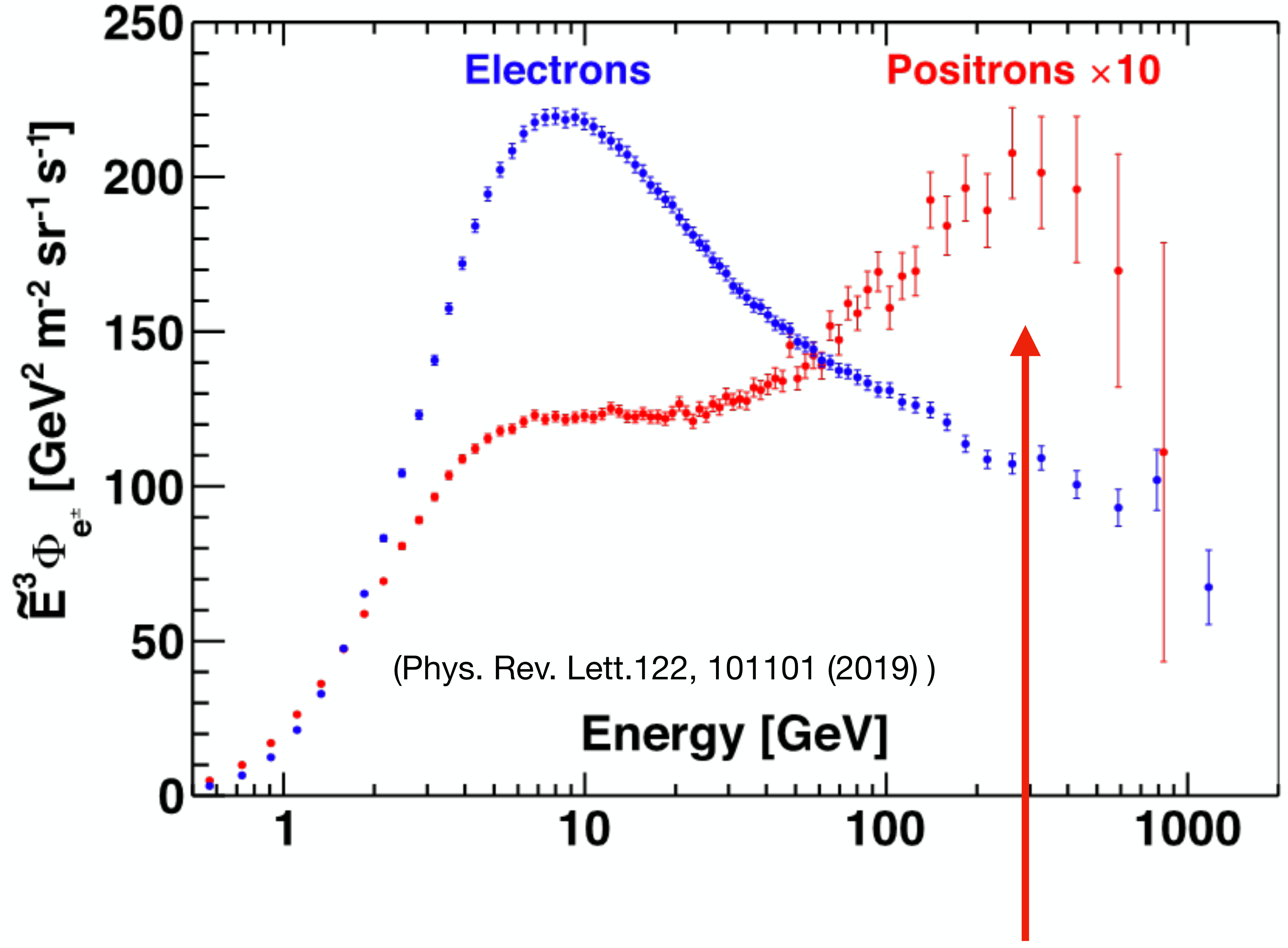
Rapidly loose their energy during propagation

- (synchrotron radiation & inverse Compton)
- Only nearby sources (1 kpc) at TeVs

Can be of primary or secondary nature

- (**Primary**) Pulsars & Supernovae
  - Same acceleration mechanism as CR *p*/ions
  - Photons above e^+e^- production threshold (pulsars) ?
- (**Secondary**) interaction of CR with interstellar medium
  - Mostly originate from π decays,

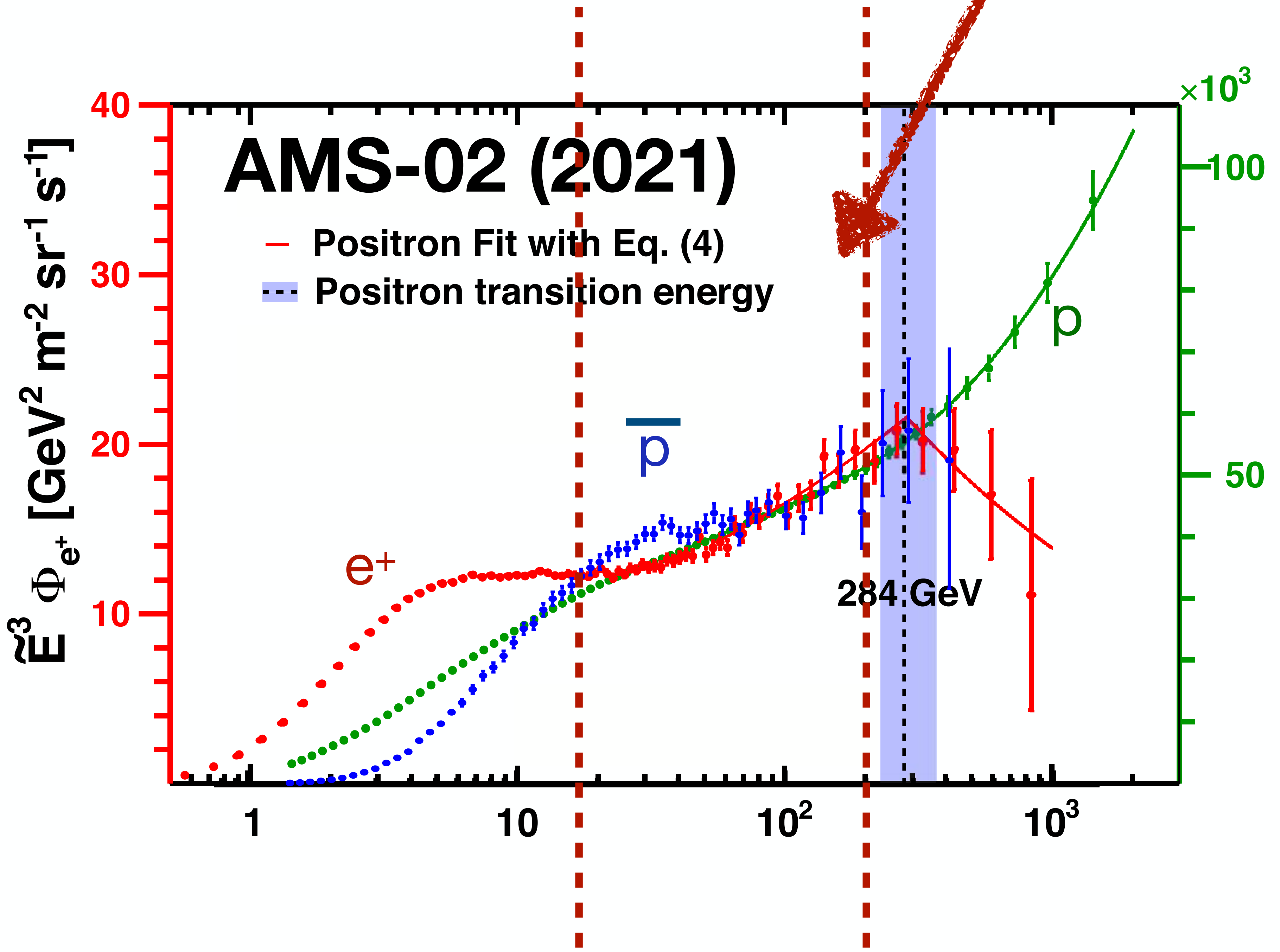
CR electron and positron spectrum up to 1 TeV measured by AMS-02 mission

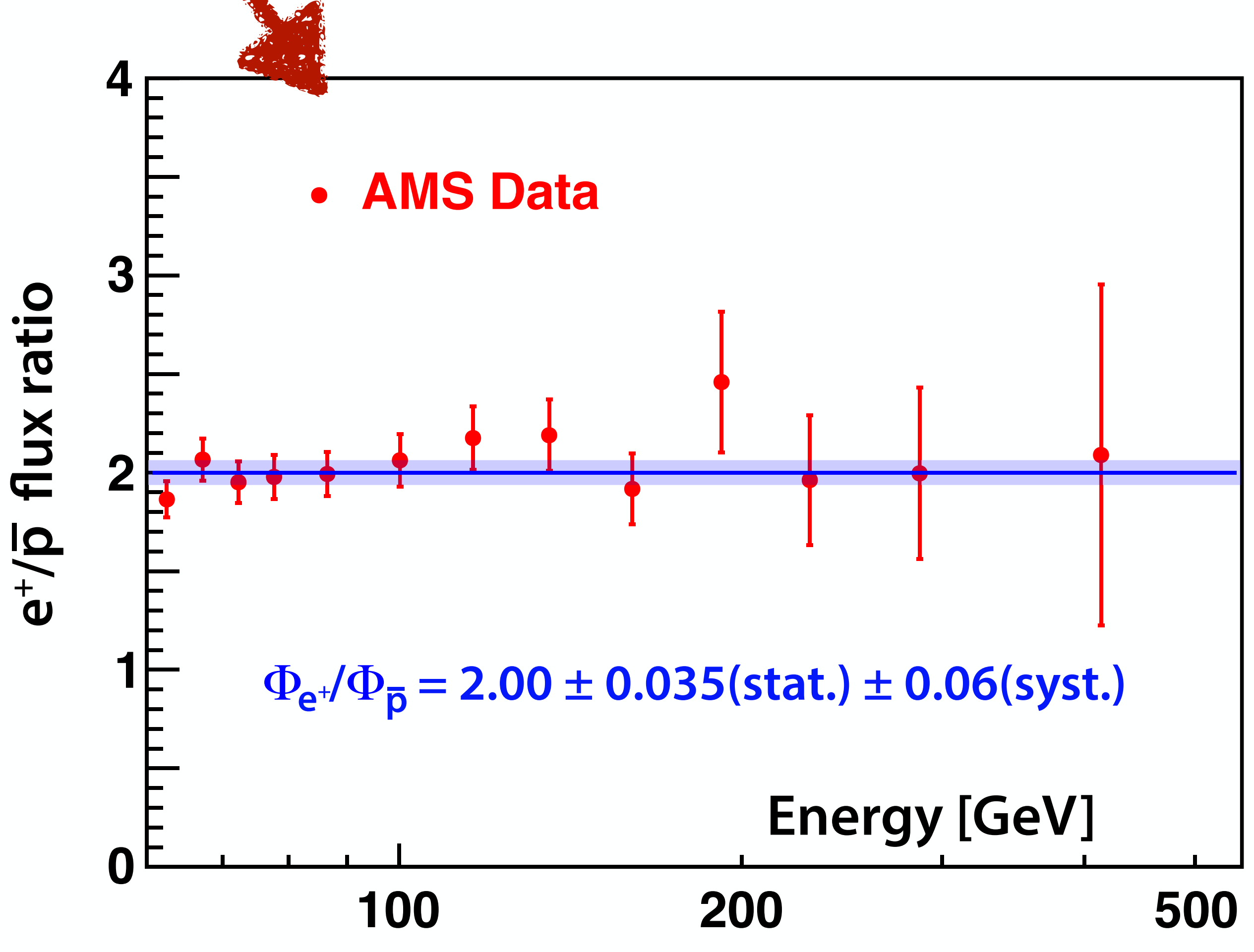


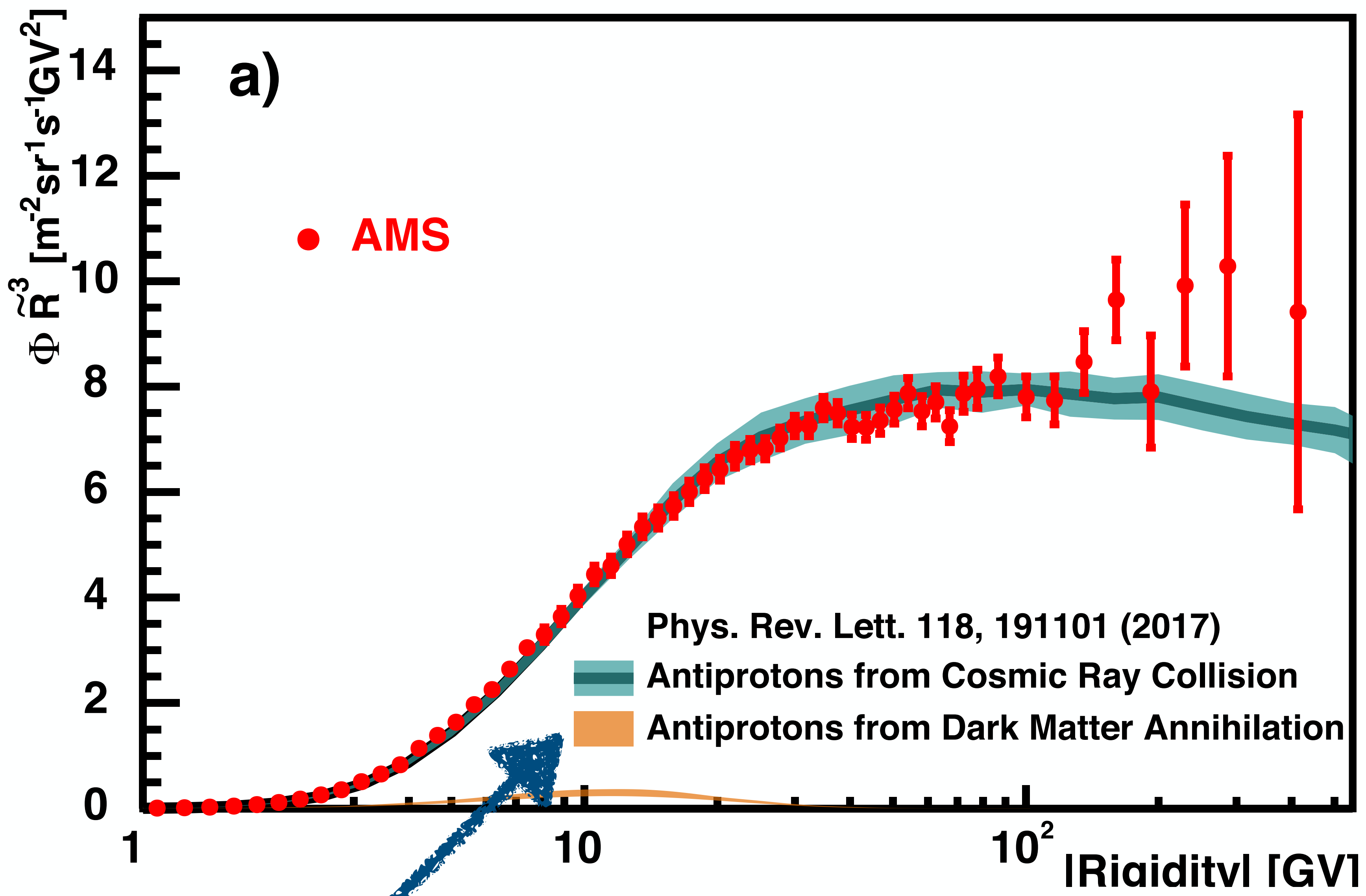
Positron spectrum incompatible with purely secondary origin: DM, pulsar ?

$\bar{p}$ (antiprotons)

- Mostly of secondary origin, unlike positrons: <u>not produced in pulsars</u>
- Surprisingly, spectrum similar to (primary) protons and positrons at 10—300 GV





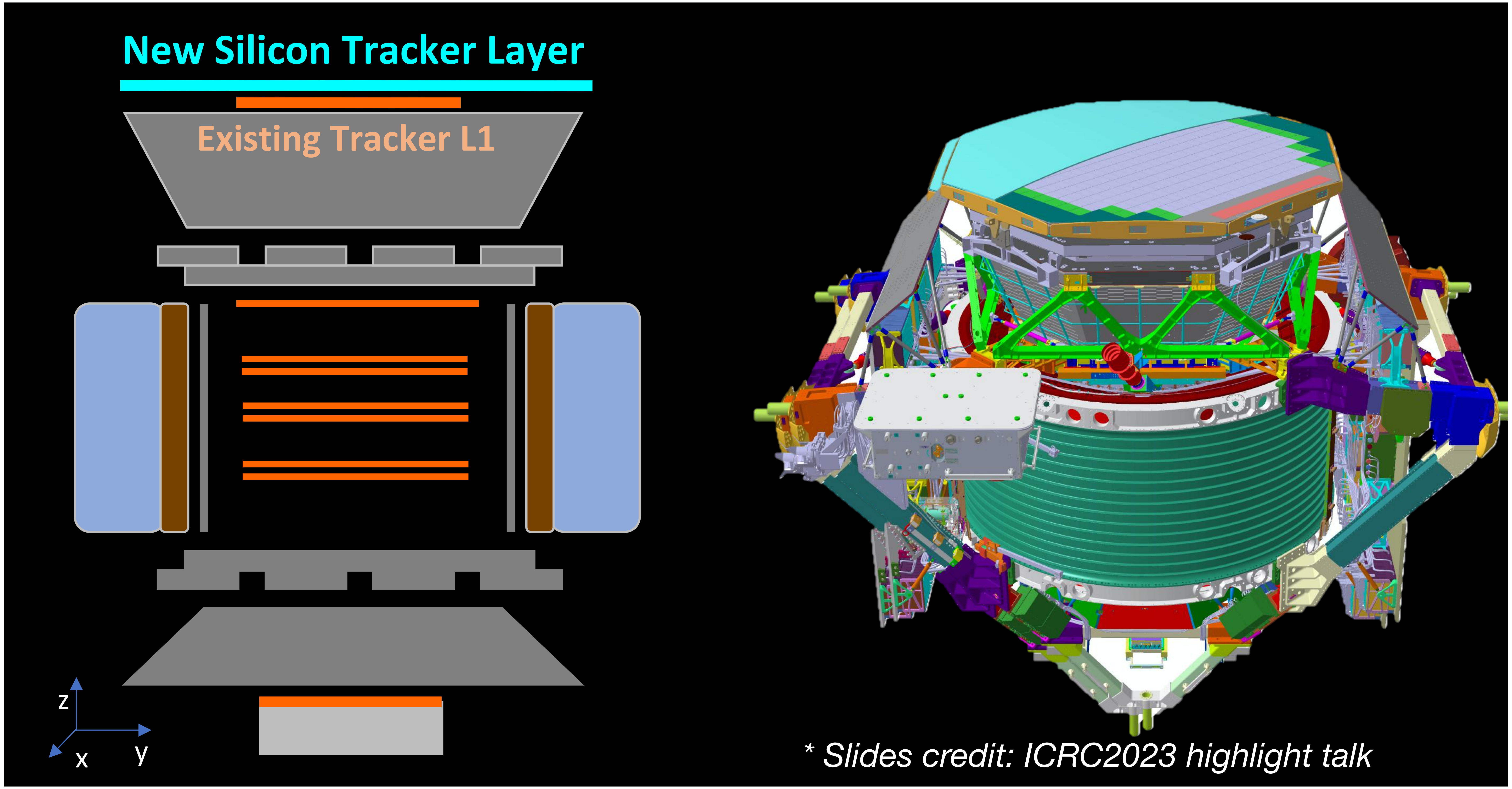


Still compatible with CR collisions with interstellar medium

PRL 114, Physics Reports 894 (2021) 1–116
PRL 117, 091103 (2016)

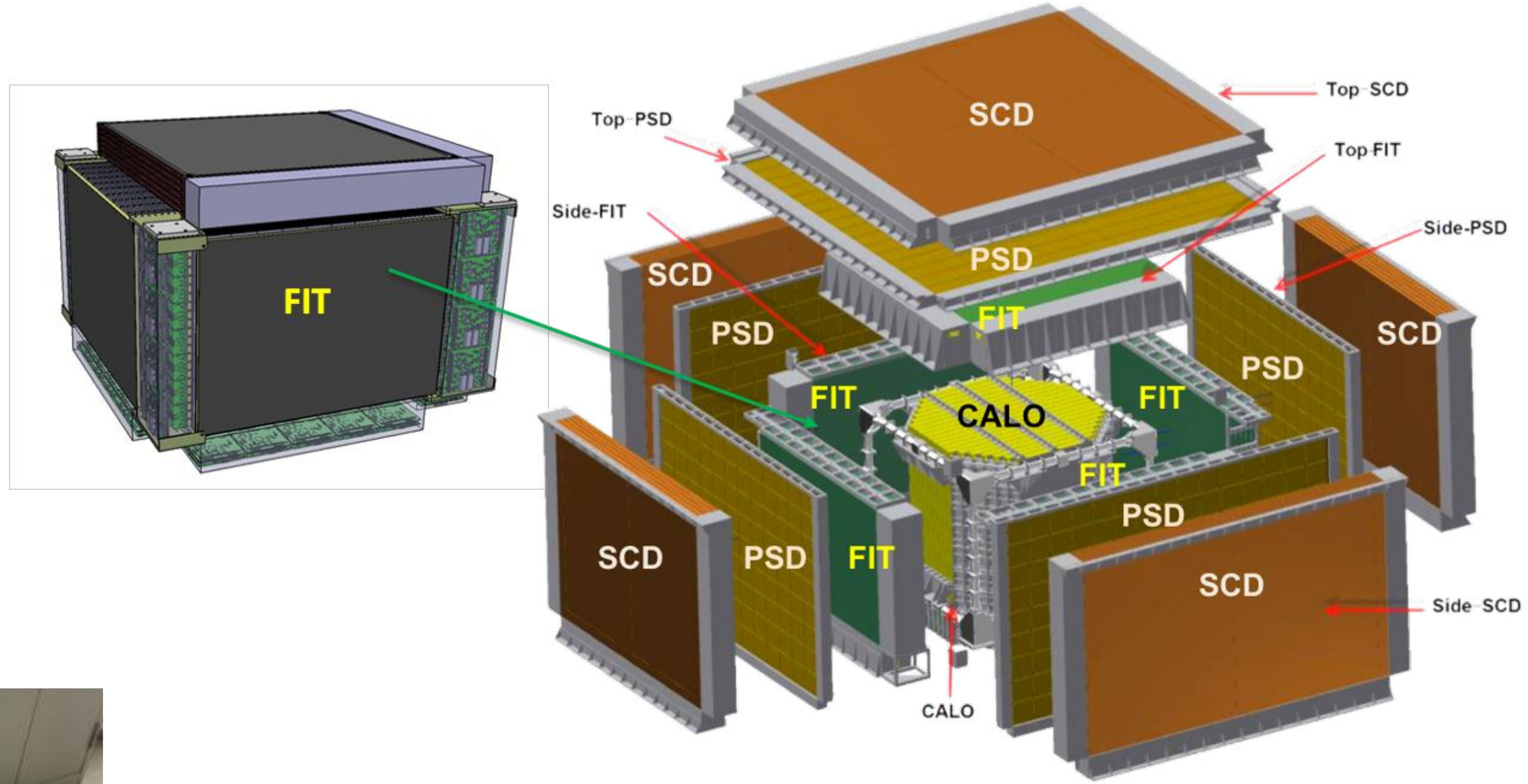
AMS-02 L0 Upgrade

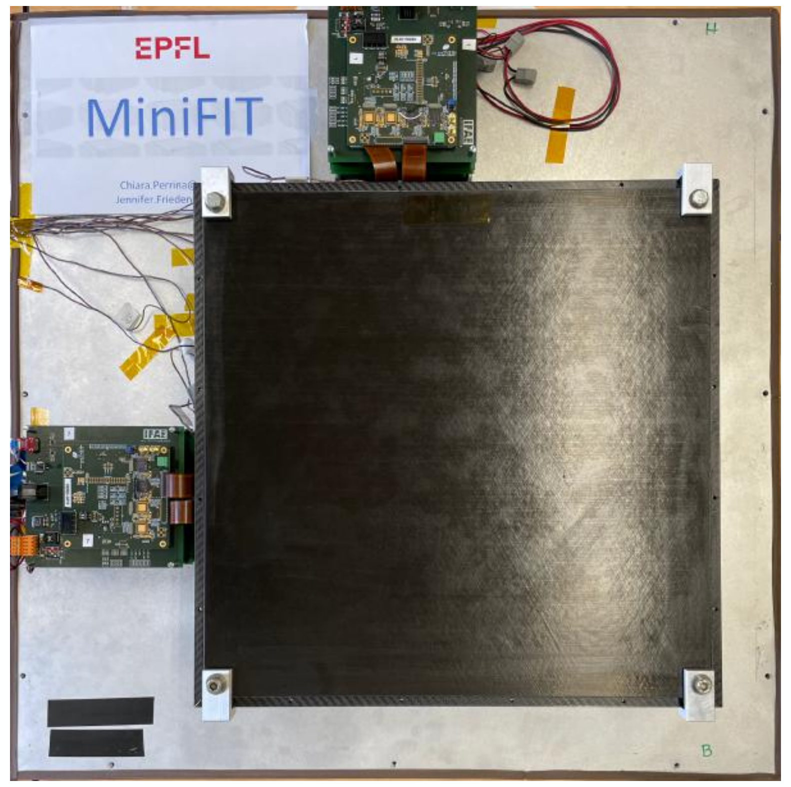
- Upgrade of AMS-02 silicon tracker in 2025 — 3 times more acceptance

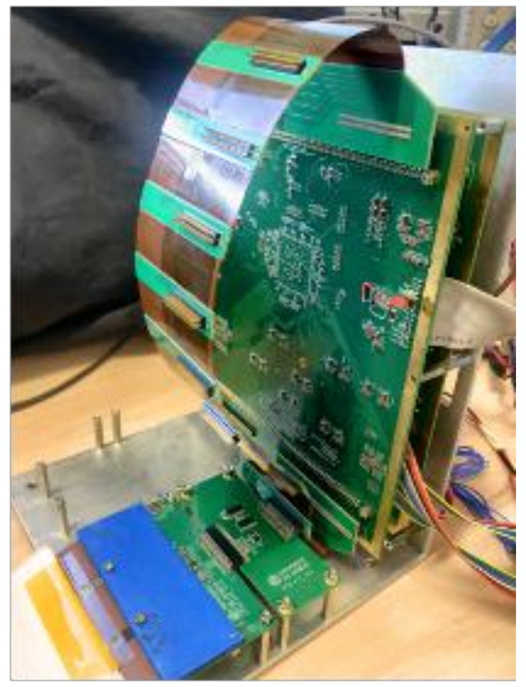


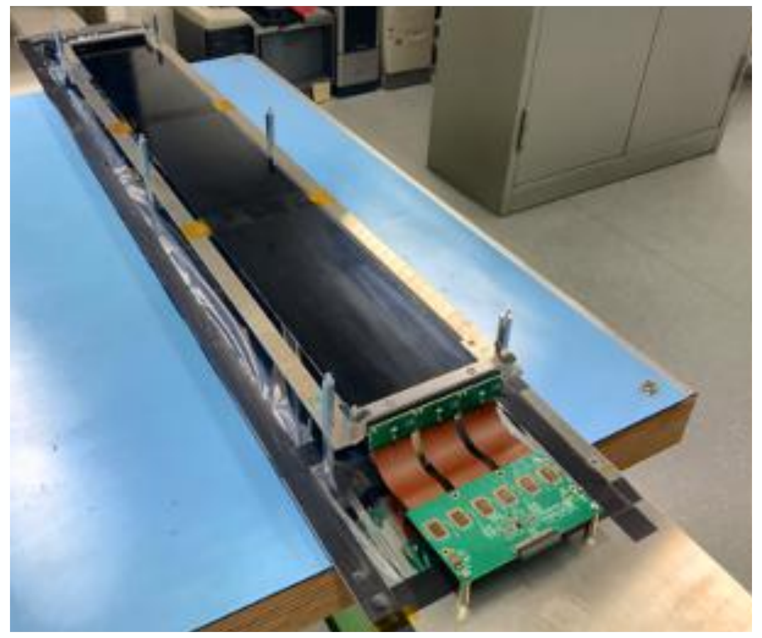
High Energy Radiation Detection facility (HERD)

- **UNIGE and EPFL in charge of the FIber Tracker (FIT)**
  - Phase B R&D completed
  - Test beam activities on-going
  - Update of FEB with new ASIC
  - Simulation studies ongoing





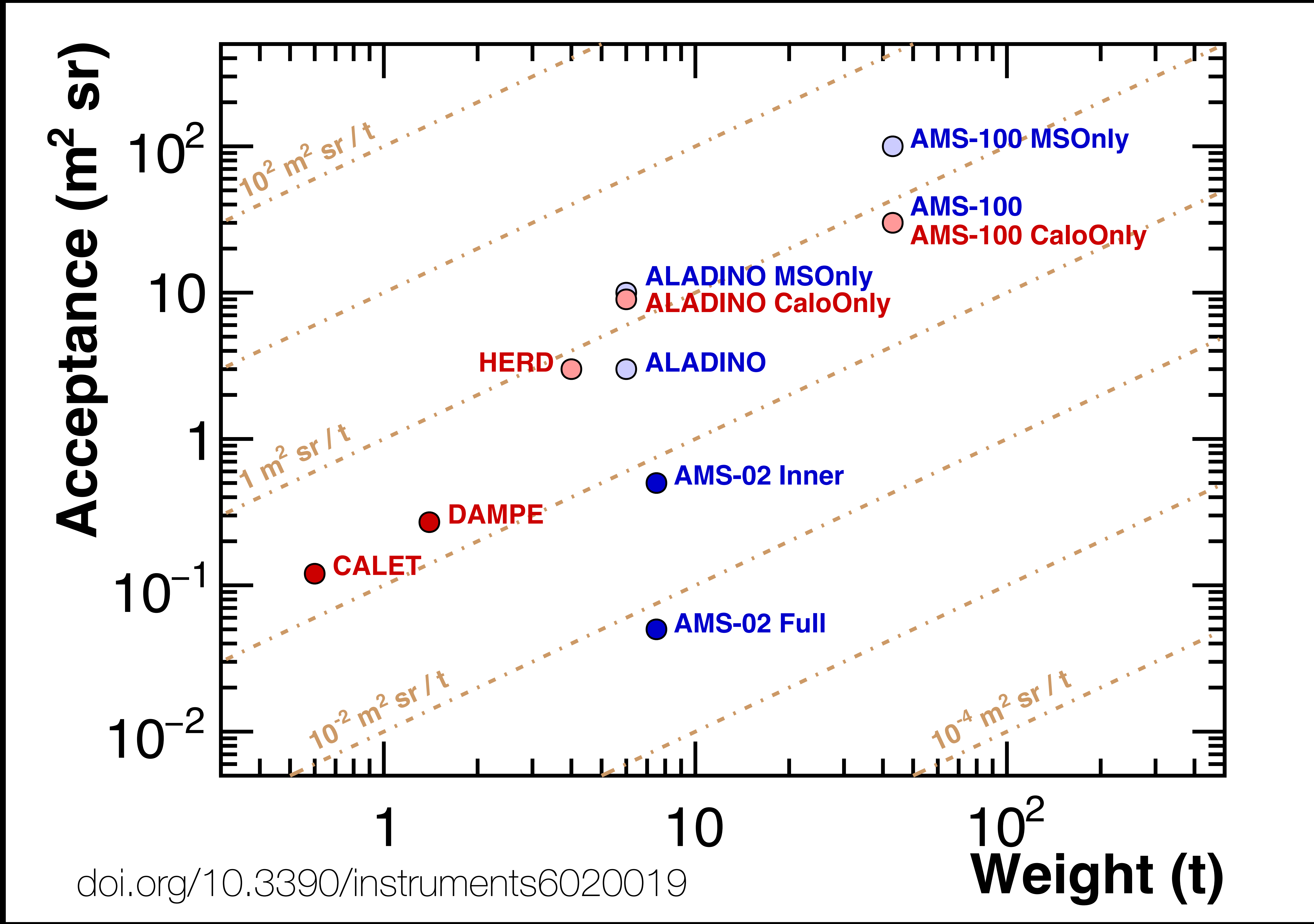




UNIVERSITÉ DE GENÈVE

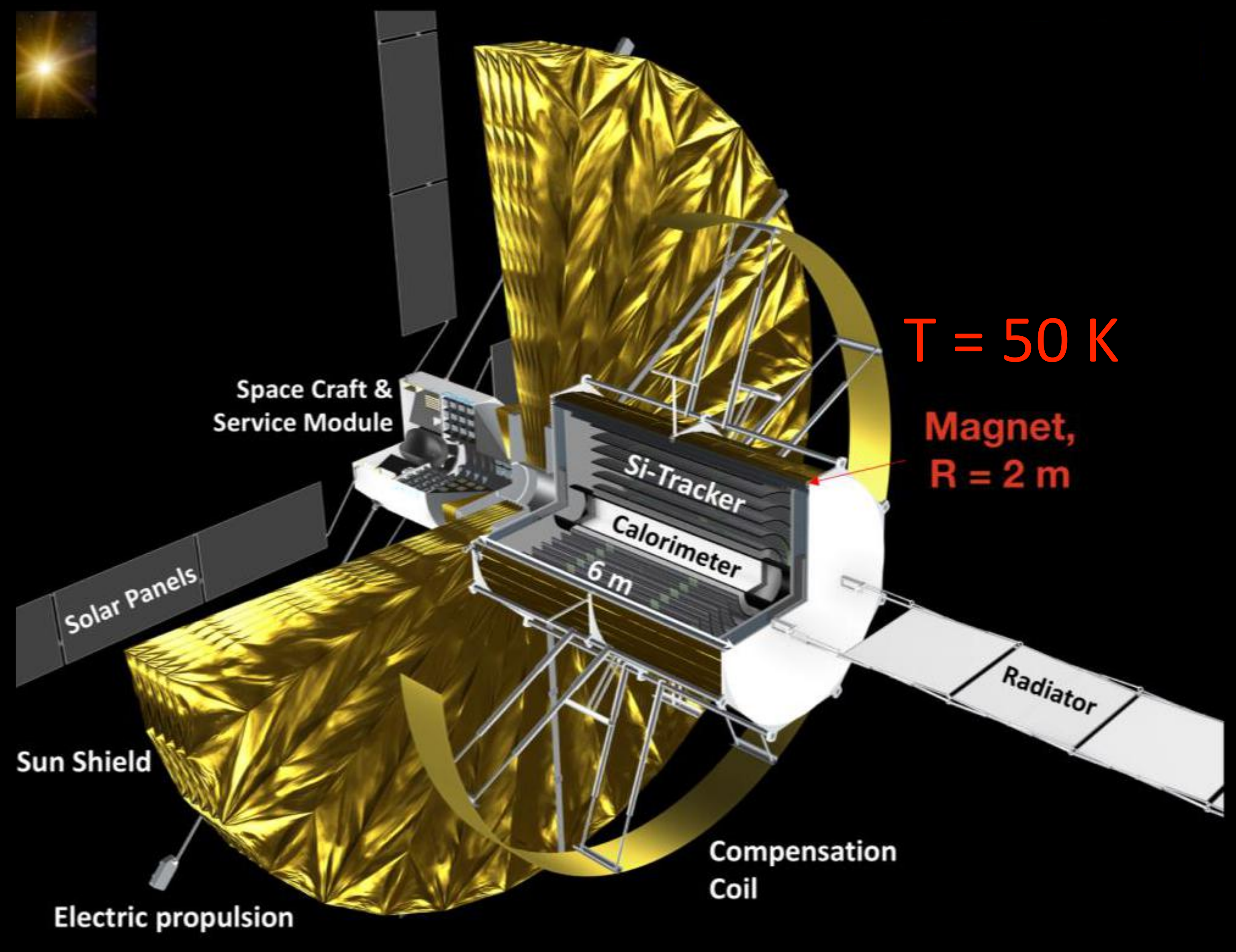
EPFL

Future spectrometers in space



AMS-100 / ALLADINO*

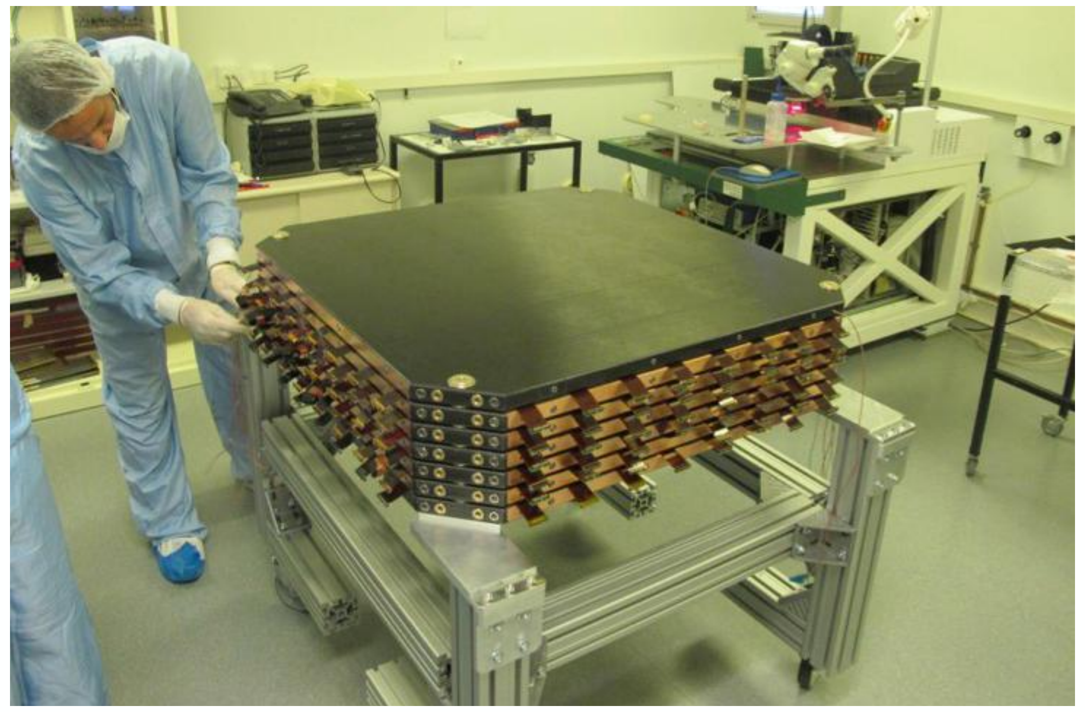
- High-temperature superconducting magnet
- solenoid (toroid)
- 100 / 10 m^2 sr acceptance
- Placed in Lagrange point 2

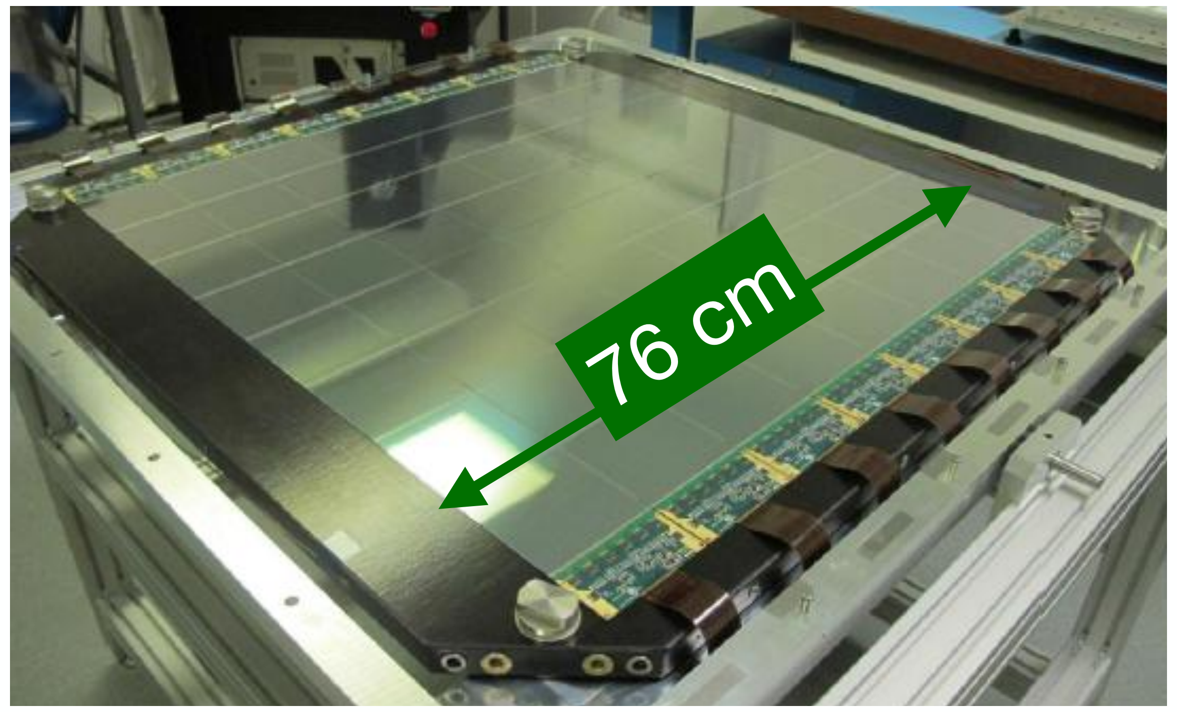


* Antimatter Large Acceptance Detector In Orbit (ALADInO)

DAMPE Tracker detector (STK) & DPNC

R&D Construction (2013–2015)





University of Geneva (DPNC) & INFN Perugia groups DAMPE Silicon Tracker tests with cosmic muons (April 2015)

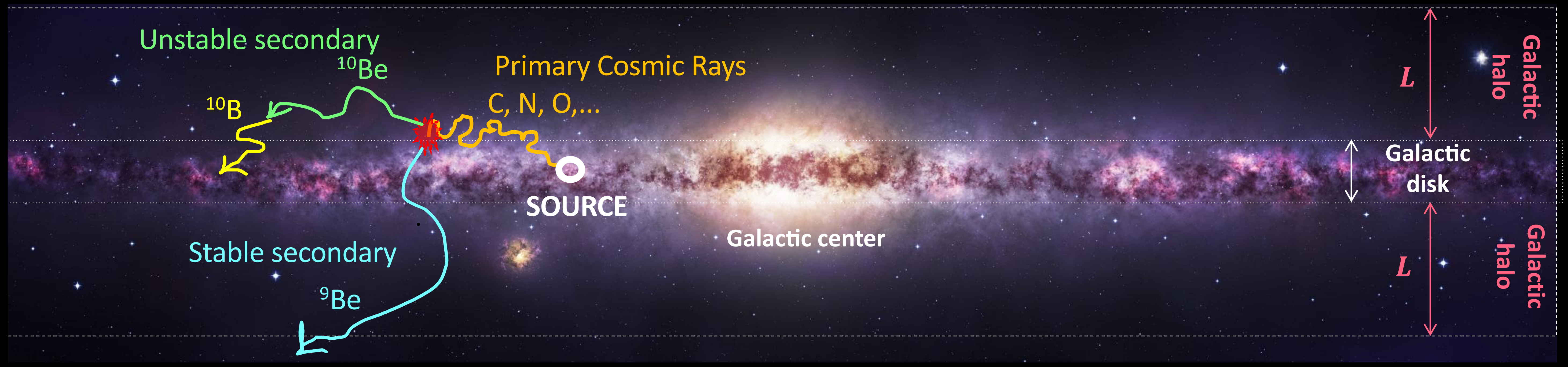
Space qualification (2014–2015)

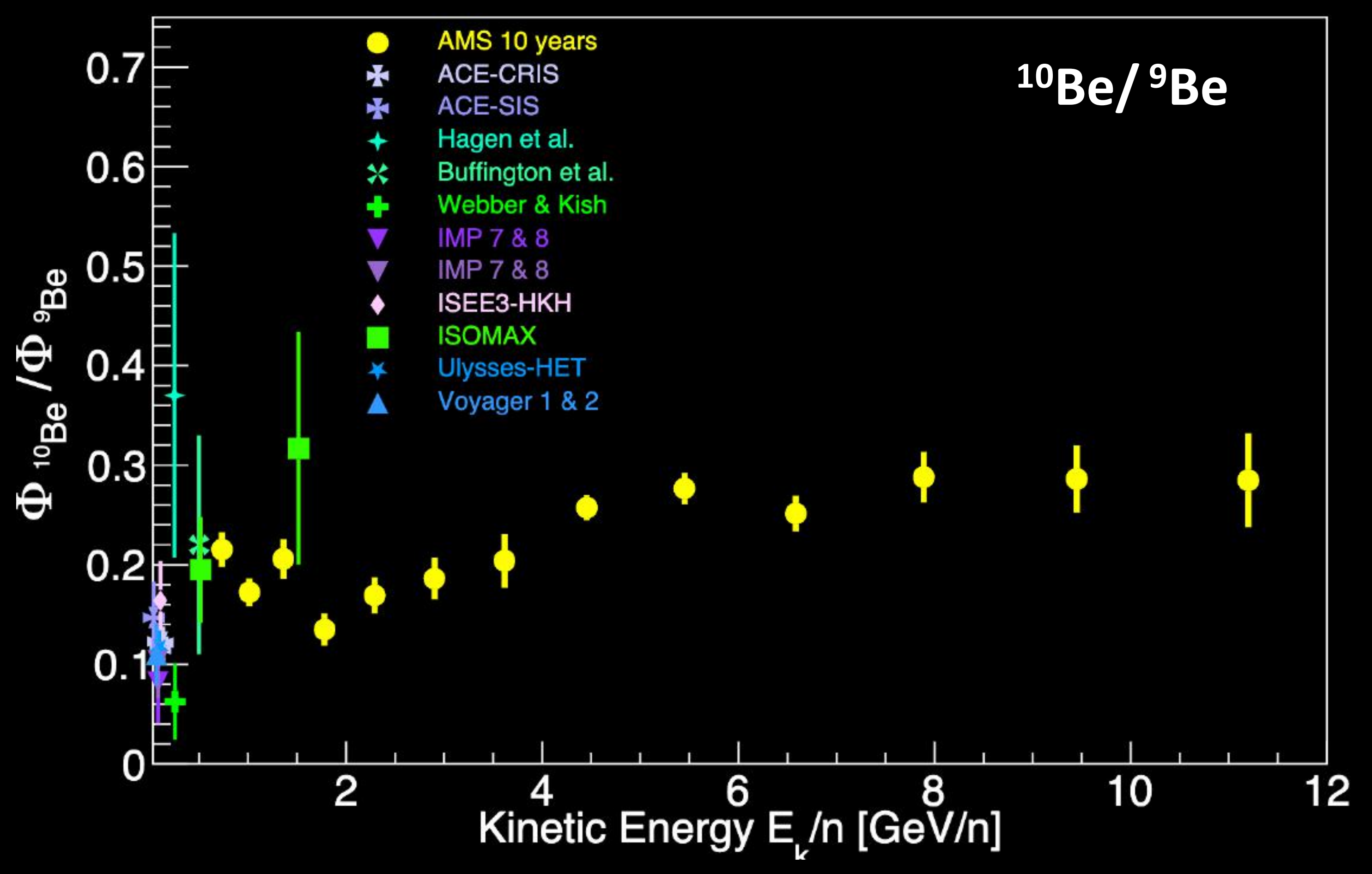
Vibration, shock, thermal cycling,..

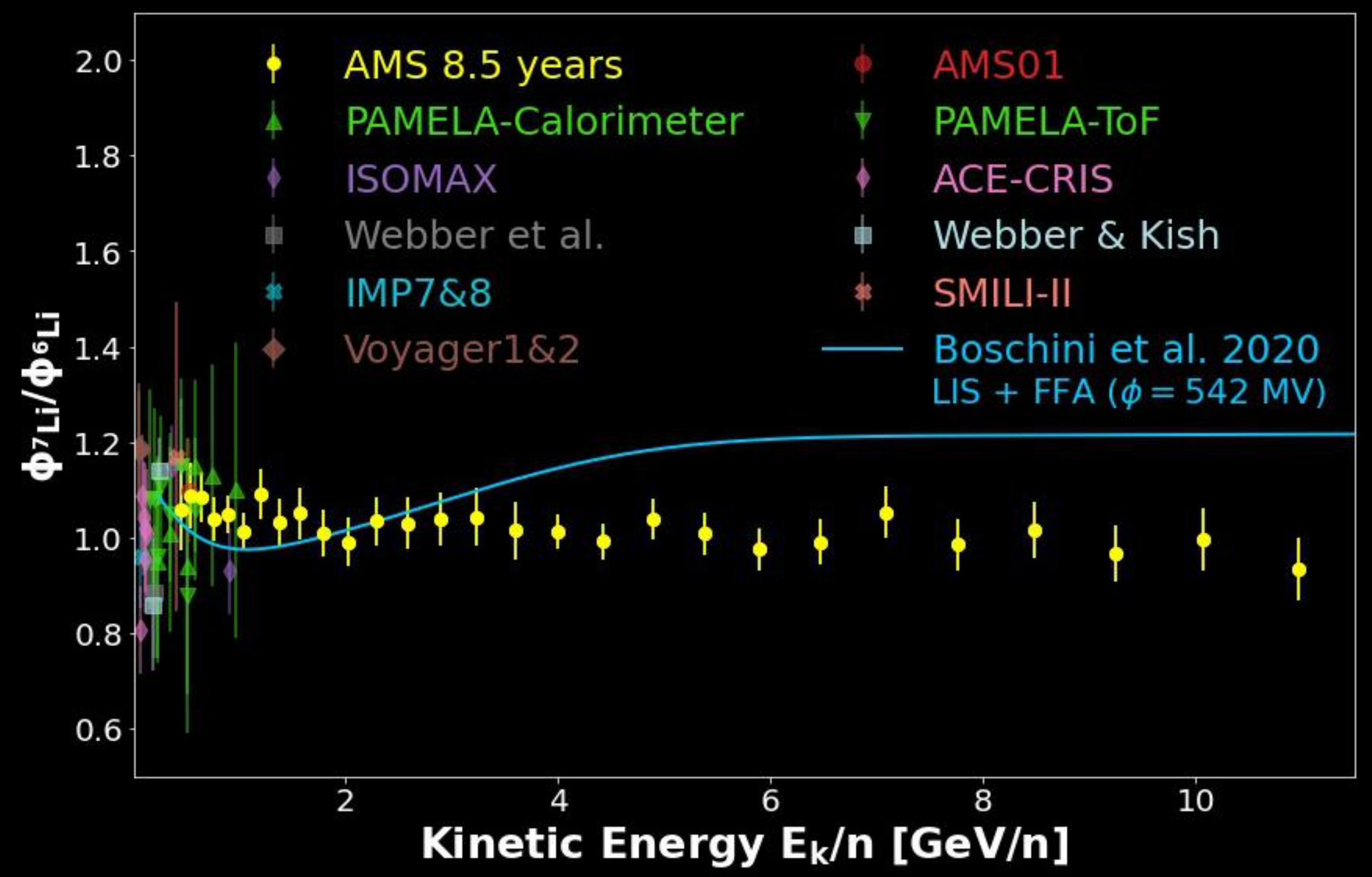
Beam tests @ CERN (2014–2015)

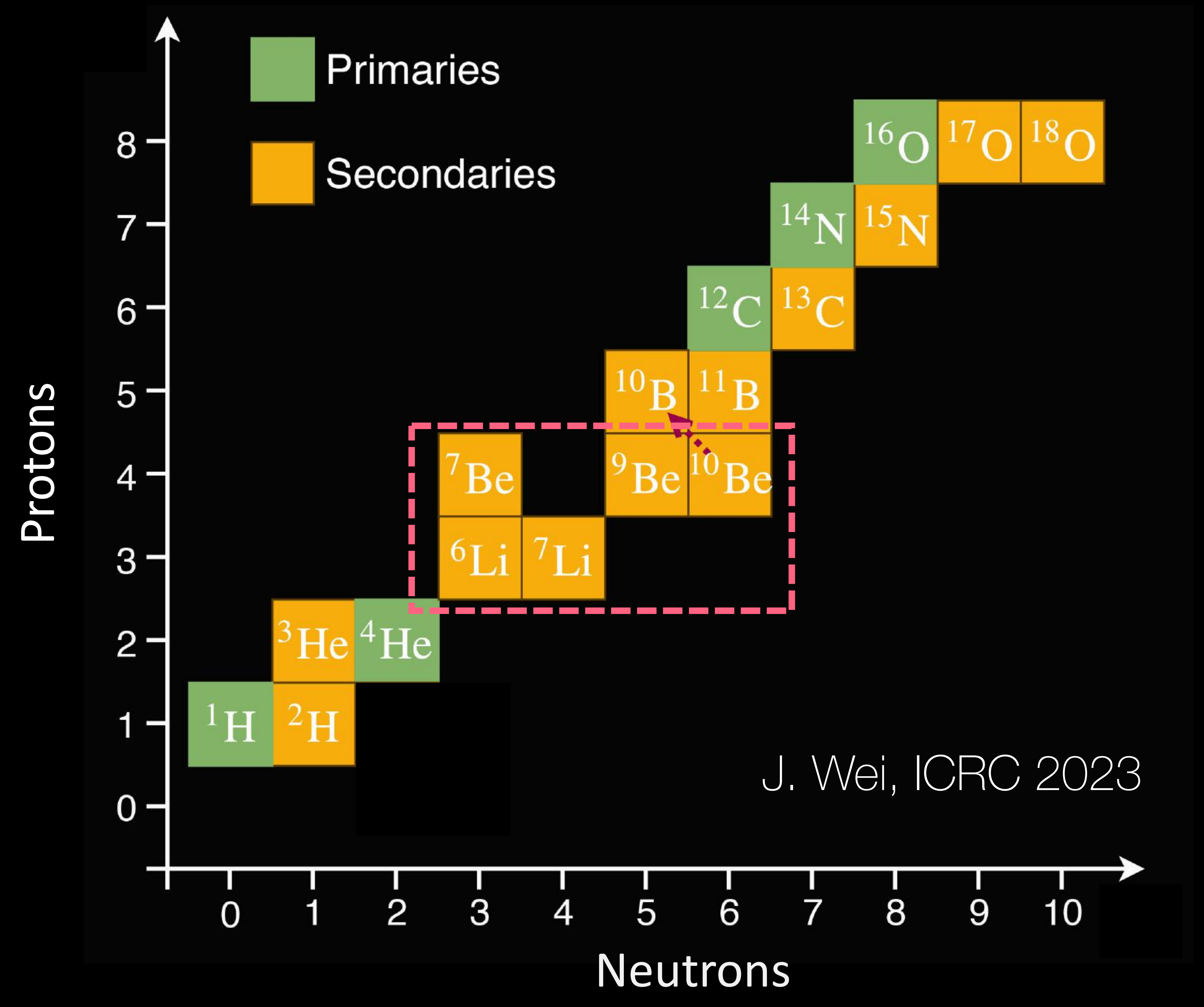
AMS-02: isotopes

- AMS-02: simultaneous charge & velocity measurement: allows detecting isotopes!
  - Information on propagation medium/mechanism, galactic halo size (cosmic ray “clock”)



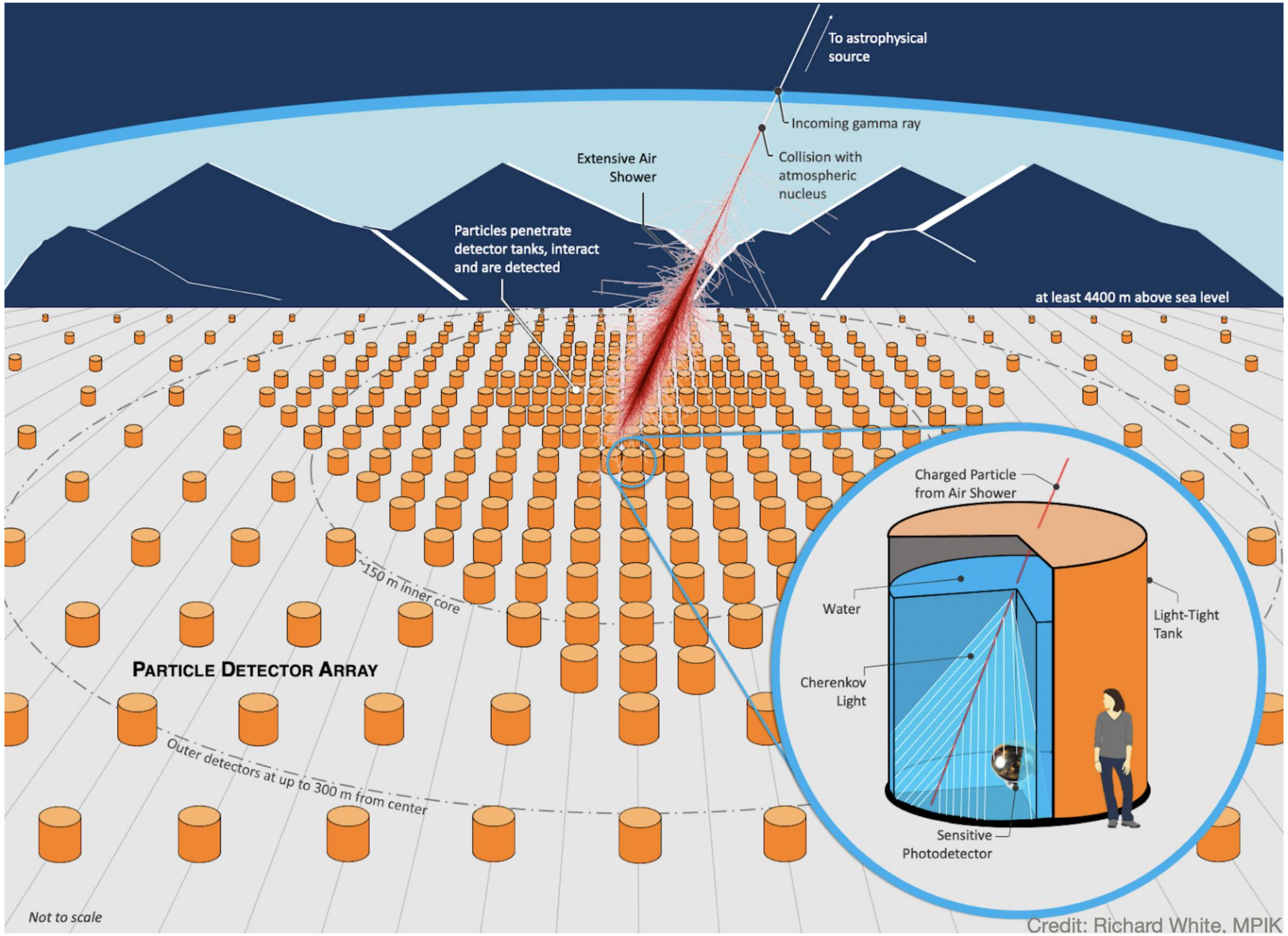






For details see theory review: arXiv:2204.13085

Water cherenkov



https://ecap.nat.fau.de/wp-content/uploads/2022/10/Bachelorarbeit_Scharrer.pdf
https://www.swgo.org/SWGOWiki/doku.php

Power law in Cosmic Rays

- <u>Gain/loss at each acceleration proportional to energy:</u>

$$\Delta E = k * E$$

- Given ***p*** — escape probability at each acceleration, probability to stay within acceleration region after ***N*** interactions:

$$P = (1-p)^N$$

- Energy after ***N*** interactions:

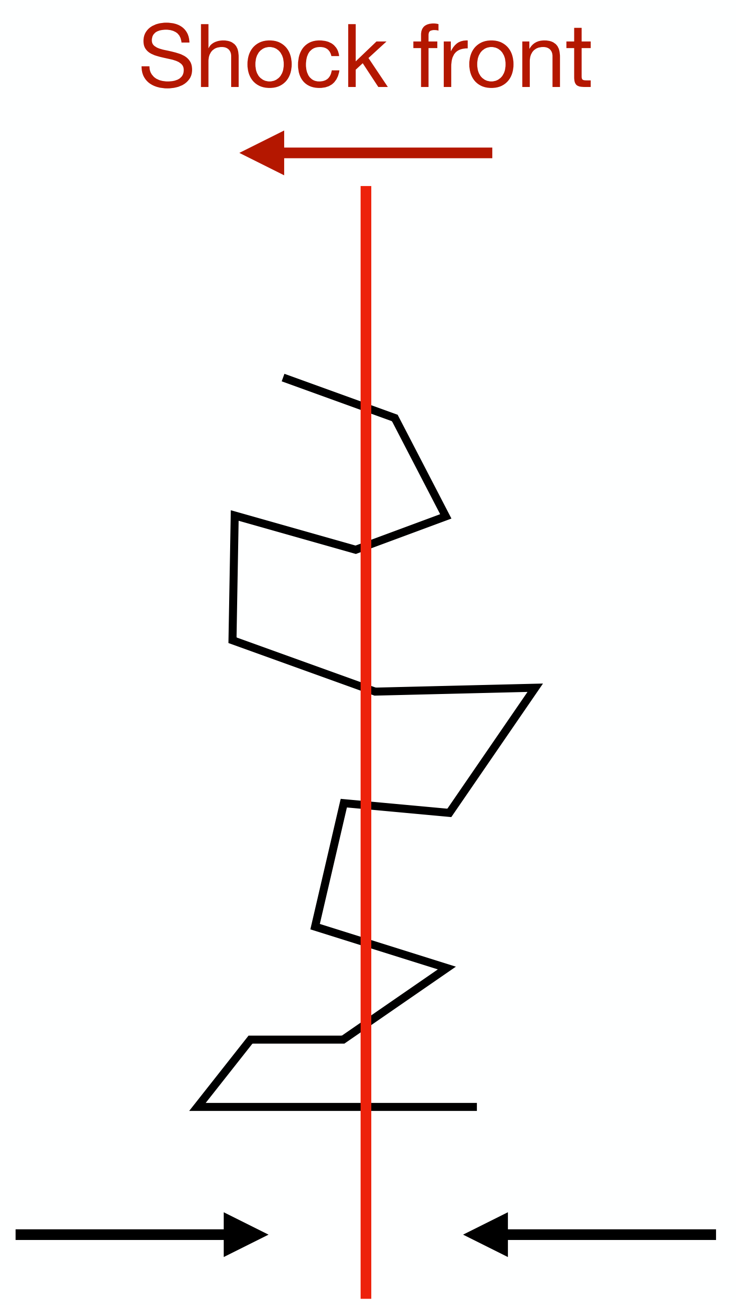
$$E = (1+k)^N * E_0$$

$$\Longrightarrow \quad \log(E/E_0) / \log(1+k) = \log(P) / \log(1-p) \quad \Longrightarrow \quad P(E) \propto E^{-\gamma}$$

… where $\gamma = -\log(1-p) / \log(1+k)$. In differential form:

$$dP/dE \propto E^{-\gamma-1}$$

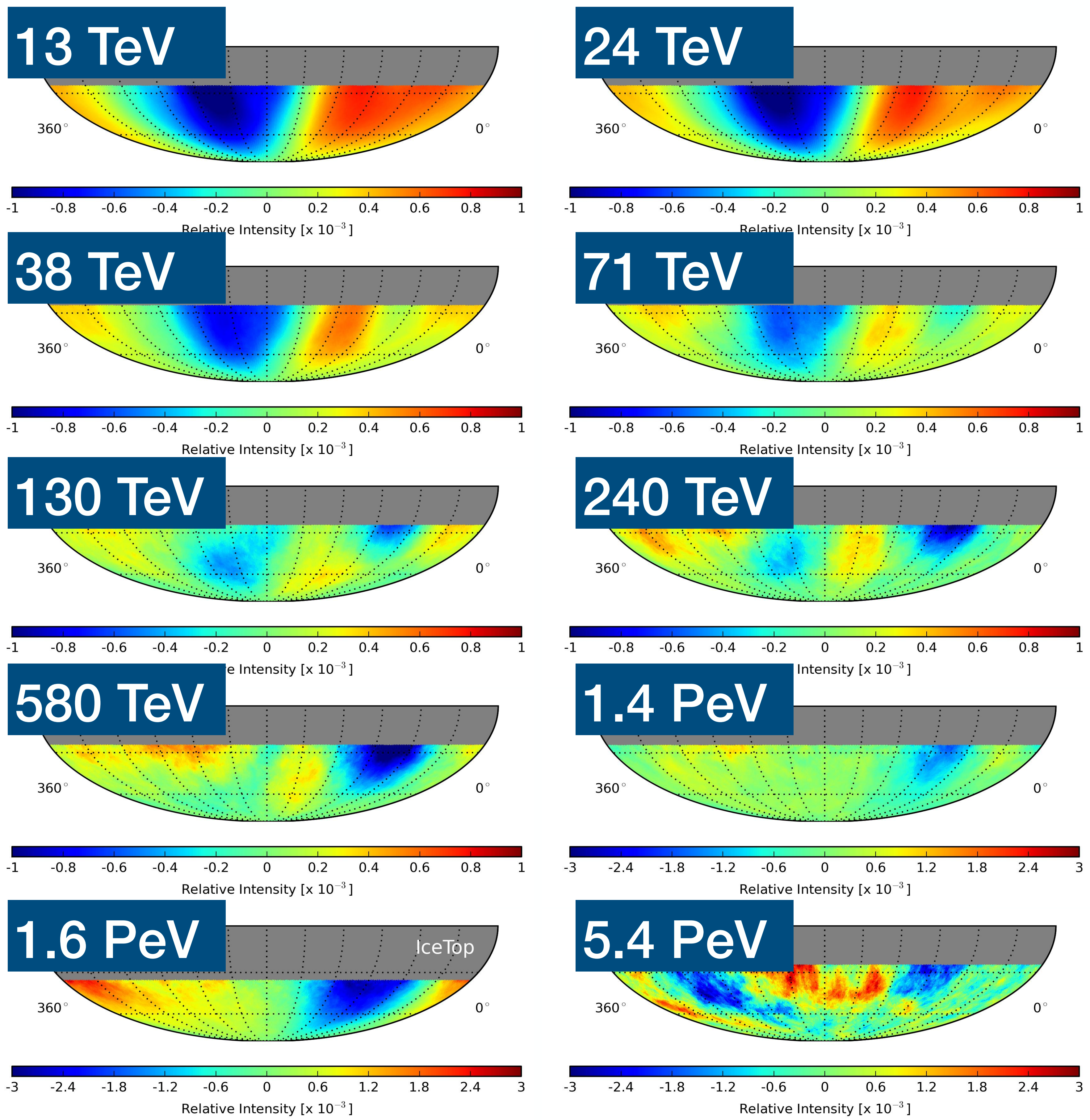
— *probability distribution function of gained CR energy*

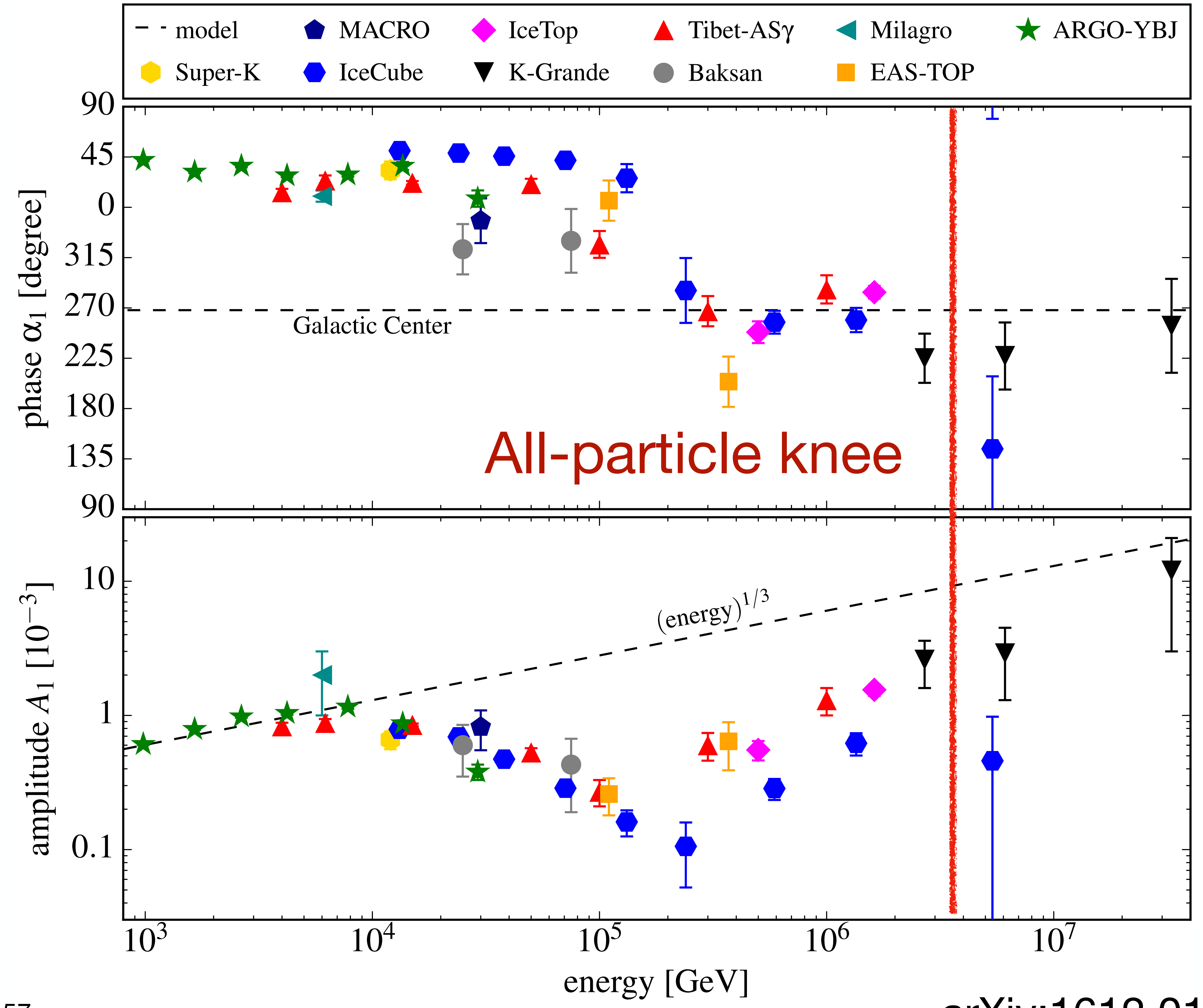


Accelerated particle going back and forth until it escapes the front

Cosmic Ray anisotropy

- Phase flip of 180° at ~100TeV towards galactic plane
  - Anisotropy for CR of different rigidities formed over different distances — non-trivial energy dependance
  - Can be described by Vela SNR — one of the strongest contributors to the CR anisotropy





arXiv:1612.01873v1