ERC PeVSPACE

Catching TeV—PeV particles in Space

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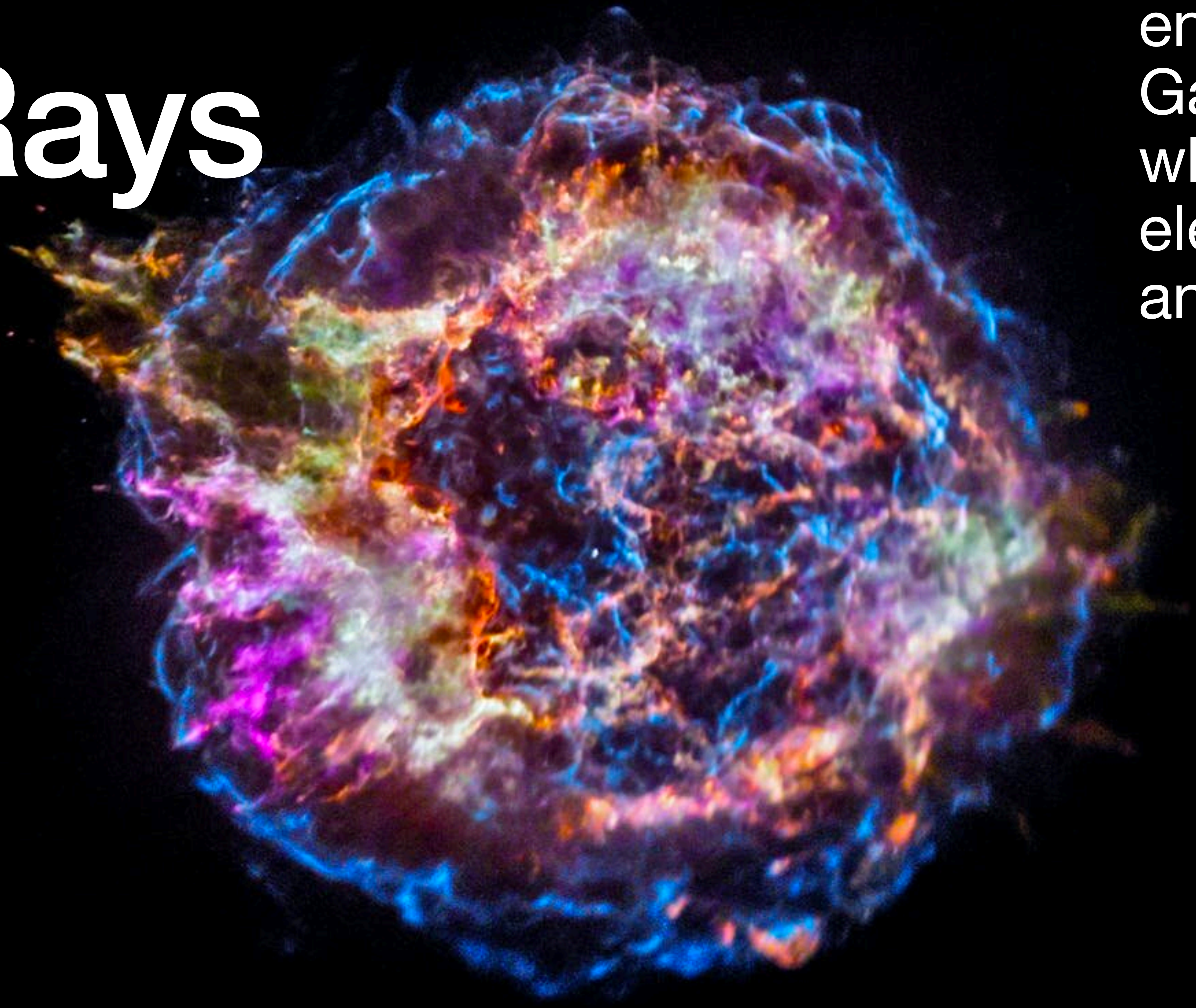
Ljubljana, March 30, 2022

Chapter I: Cosmic Rays

Cosmic Rays — direct messengers of the most energetic events in the Galaxy and beyond, which impact Galactic element composition and evolution



Supernova remnant: Cassiopea A (credit: Credit: NASA/CXC/SAO CC BY)

Historical remark

First hints of already in 18th century

- Coulomb observed spontaneous discharge of electroscope

1912 Discovery by Victor Hess in ballon flight

- Conclusive proof of increasing penetrating radiation with altitude

1920 Millikan called them “cosmic rays”

- Believed them to be energetic photons

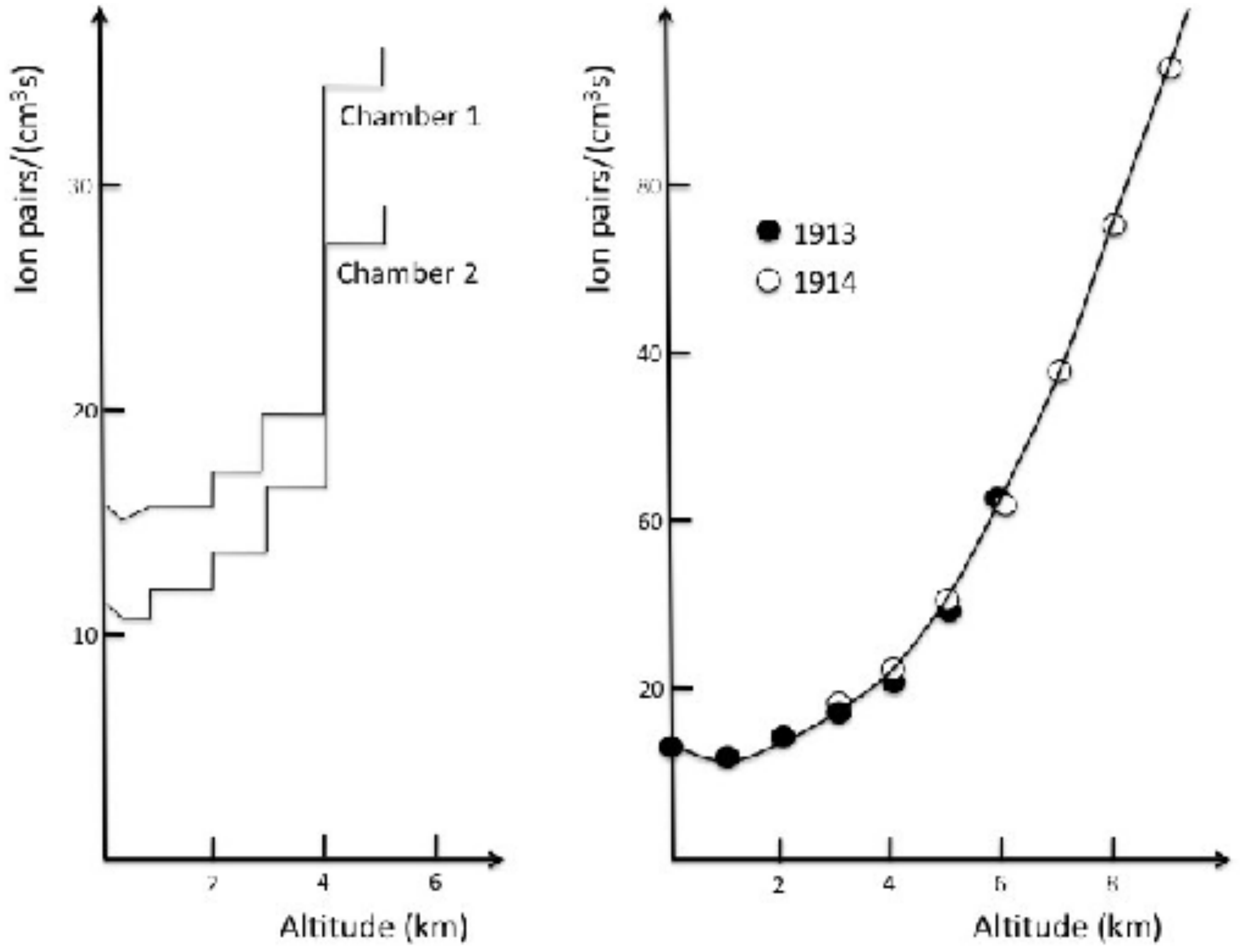
1927 J. Clay discovered the latitude dependence of cosmic ray intensity

- Geomagnetic effect proves that cosmic rays are charge particles

Particle physics emerges from cosmic rays

- Discovery of μ, π, e+, K, Λ
- Proof of special relativity (atmospheric muons)

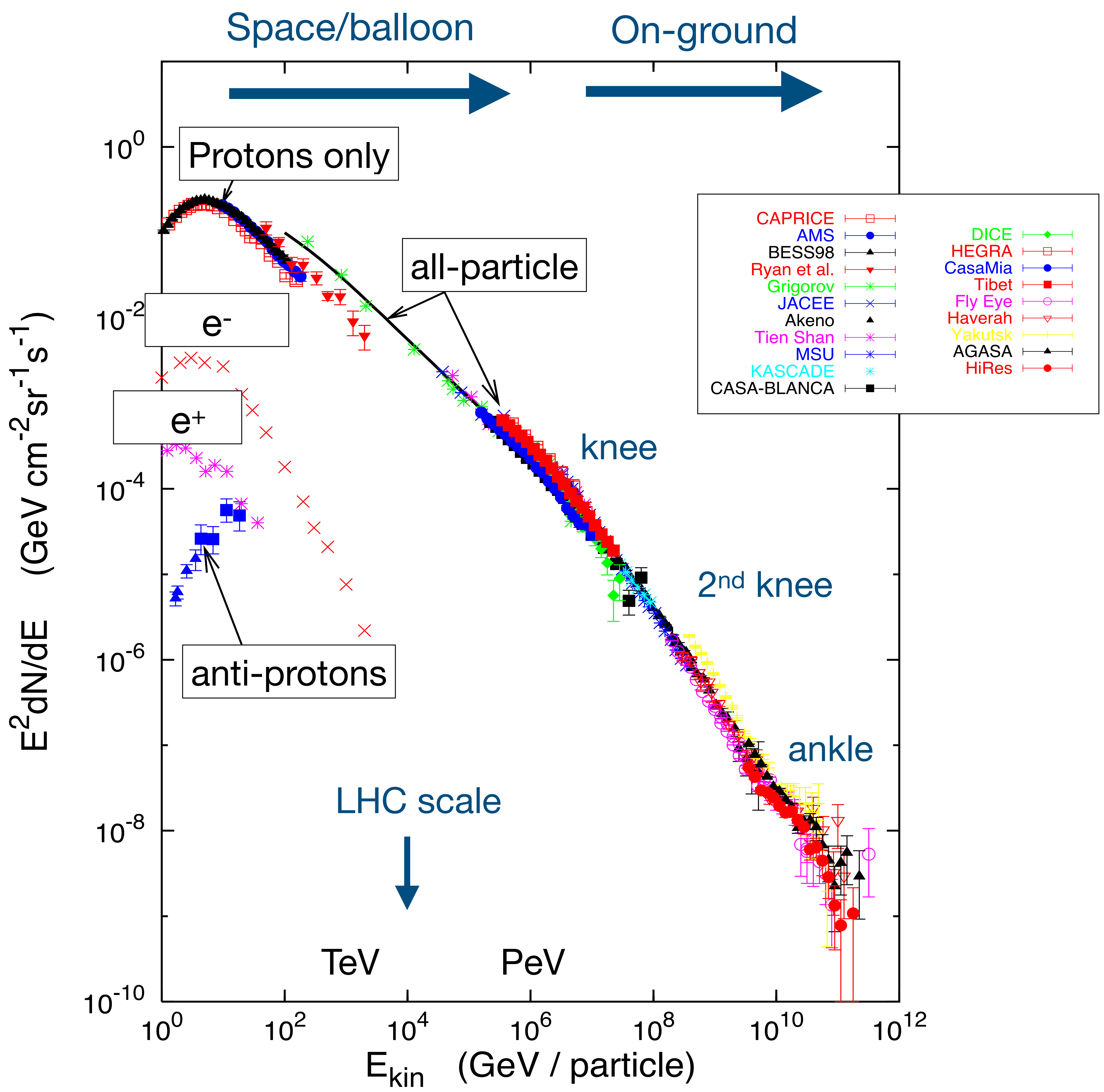
Nowadays Cosmic Rays represent a laboratory for the Universe study ….



Victor Hess’ flight

Cosmic Rays (CR)

- 85—90% ***p***, 10% ***He***, few **%** ***ions***, <1% ***e***
- Maximum energy up to ~10^{20} eV (GZK cutoff*)
- Spectrum consists of different power-laws
  - dN/dE ∝ ~ $E^{-2.7}$ up to the "knee"
- **The "knee" (region around few PeV)**
  - Galactic sources "work" up to ~PeV scale
  - Likely change of chemical composition
- **Direct measurements (Space/balloon flights)**
  - Precise, relatively small size/energy acceptance
- **On-ground (air-shower/Cherenkov)**
  - Large acceptance, limited identification capacity of CR composition



* limit due to interaction of cosmic rays with cosmic microwave background

Power law in CR

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

$$\Delta E = k * E$$

("rich get richer")

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

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

- Energy after N interactions:

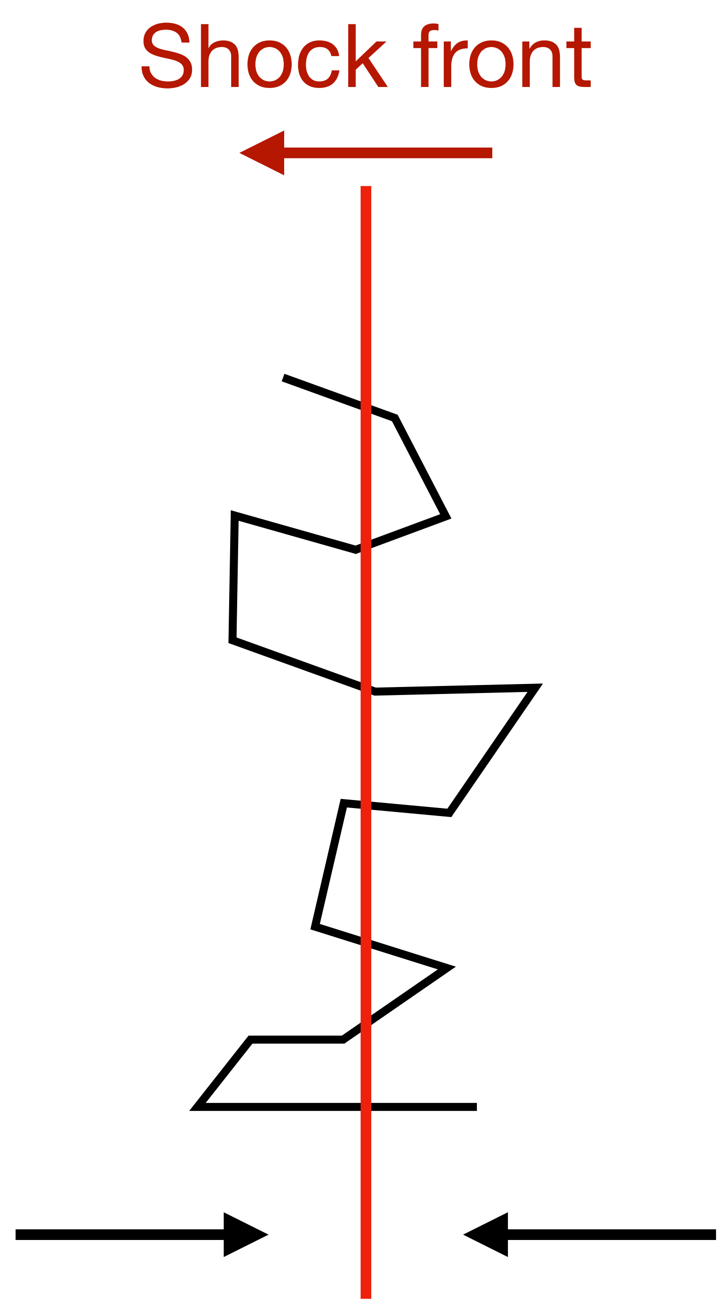
$$E = (1+k)^N * E_0$$

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

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

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

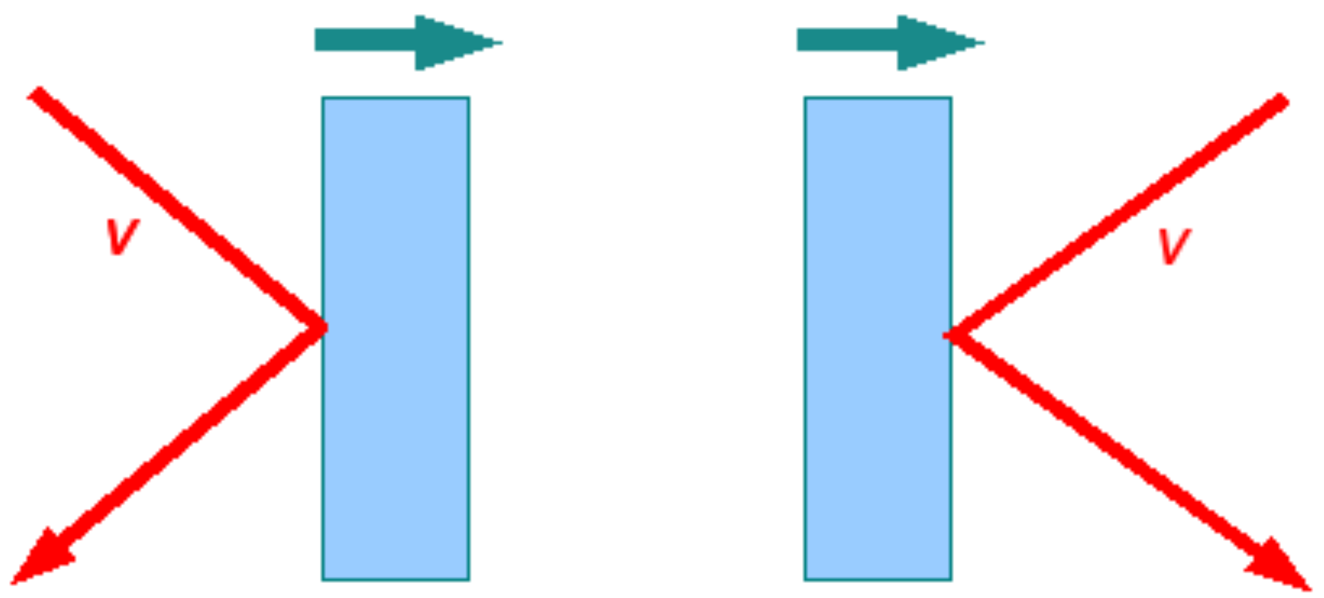
— *probability distribution function of gained CR energy*



Accelerated particle going back and forth until it escapes the front

Fermi acceleration mechanism

- **Fermi 2-nd order: dE / E ~ $\sqrt{V / C}$**
  - "Reflection" from magnetic "mirror"
  - Energy loss at following collision
  - Energy gain at heads-on collision
  - Not efficient enough to explain CR spectra

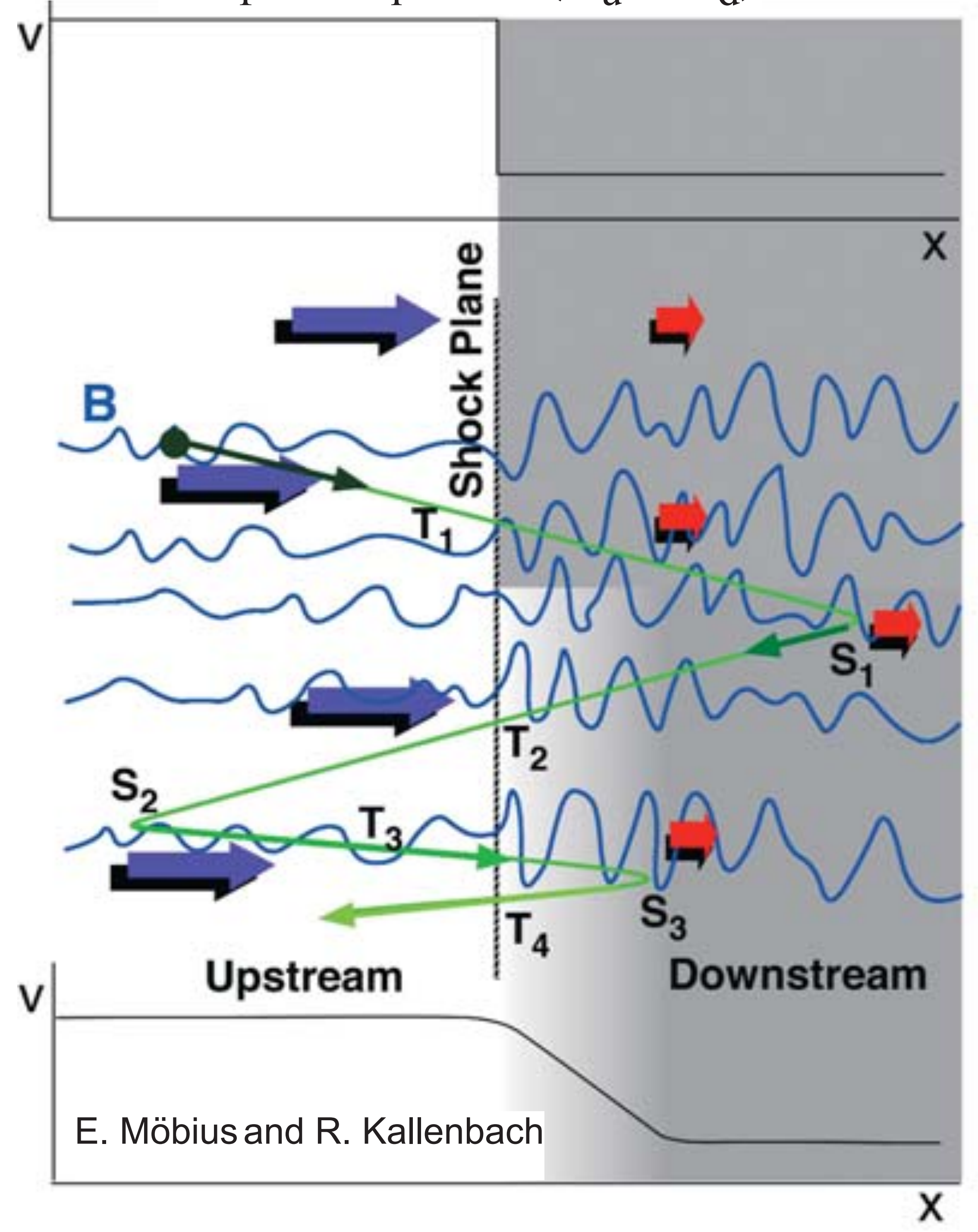


- **Fermi 1-st order: dE / E ~ V / C**
  - Acceleration when crossing shock wave front
  - Energy gain both upstream and downstream
  - Yields spectral index ~ 2
  - ***<u>Efficient</u>***

    … can produce galactic CR in supernovae

    … at least least up to ~ 0.x PeV

$$mv_f = mv_i + 2m(V_u - V_d)$$



(Image credit: M. Bustamante et al.)

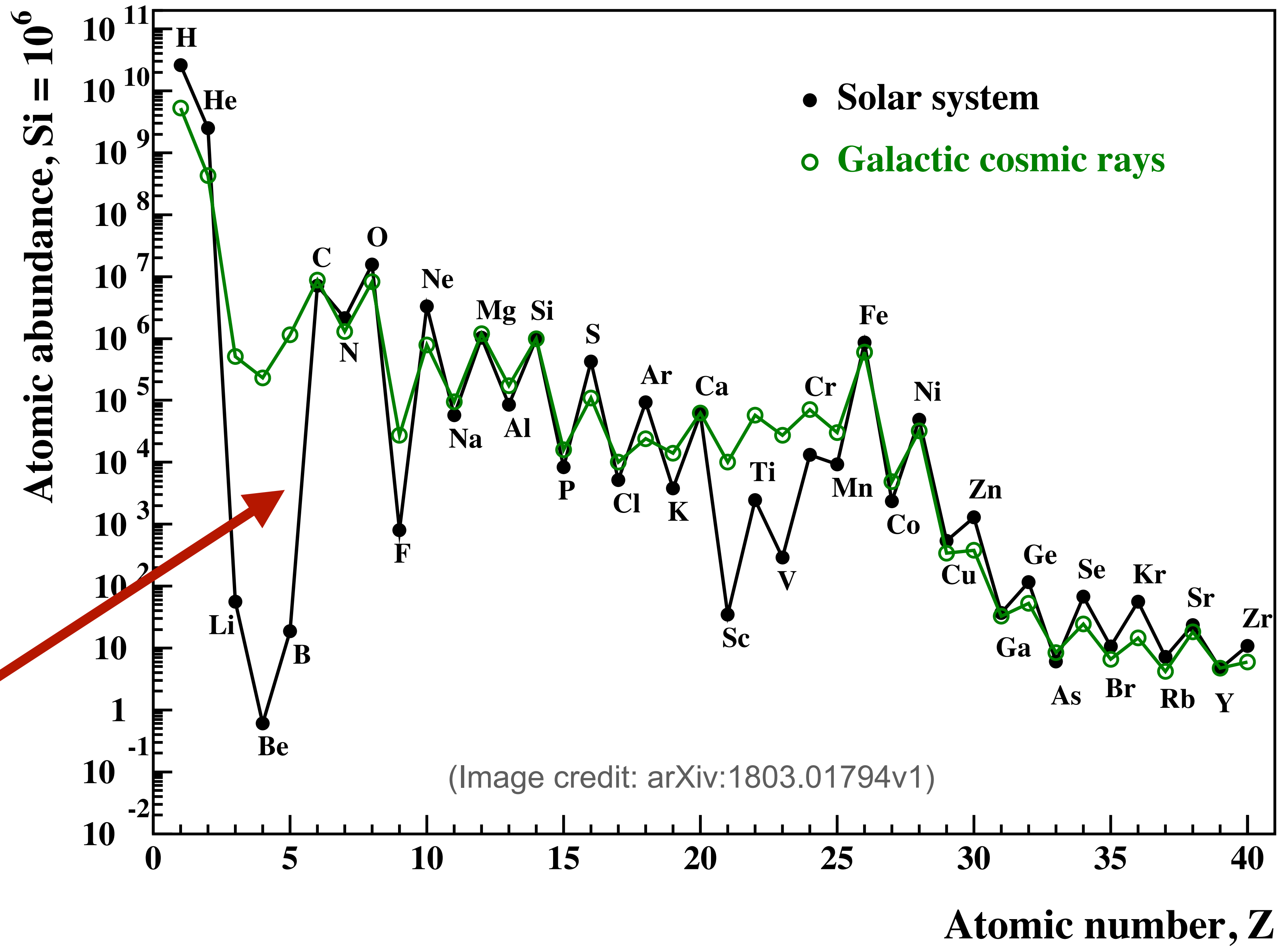
Cosmic ray propagation

Cosmic rays propagate though Interstellar Medium (ISM) before reaching us

- Diffusive confinement of CRs in the Galaxy
  - → leaky box model
- Traverse on average ~ 10 g/cm²
- Crossing multiple turbulent magnetic fields
  - → isotropic CR direction
- Power law spectrum modified

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

- Secondary cosmic rays produced



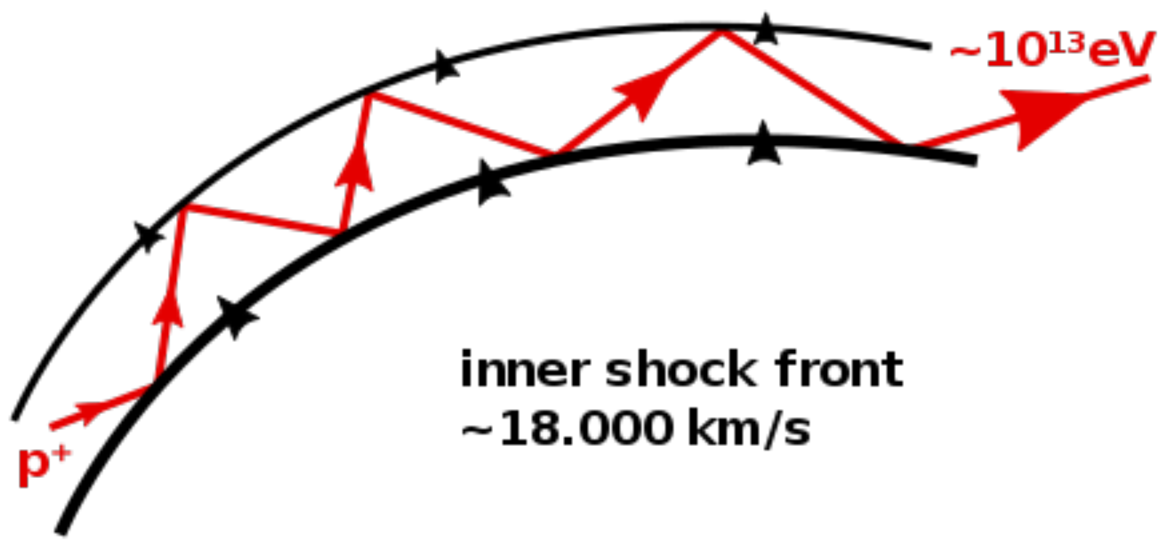
- Ratio of primary/secondary CRs (e.g. B/C) carries crucial information about ISM!

Supernovae remnants (SNRs)

SNRs — most likely source of CRs below the "knee"

Only known Galactic source with sufficient energy to power CRs

Even for SNRs, the mechanism has to be highly efficient!



CR composition → source injecting material from entire galaxy

Old not freshly synthesised material including low-mass stars

Non-thermal emission observed in SNRs

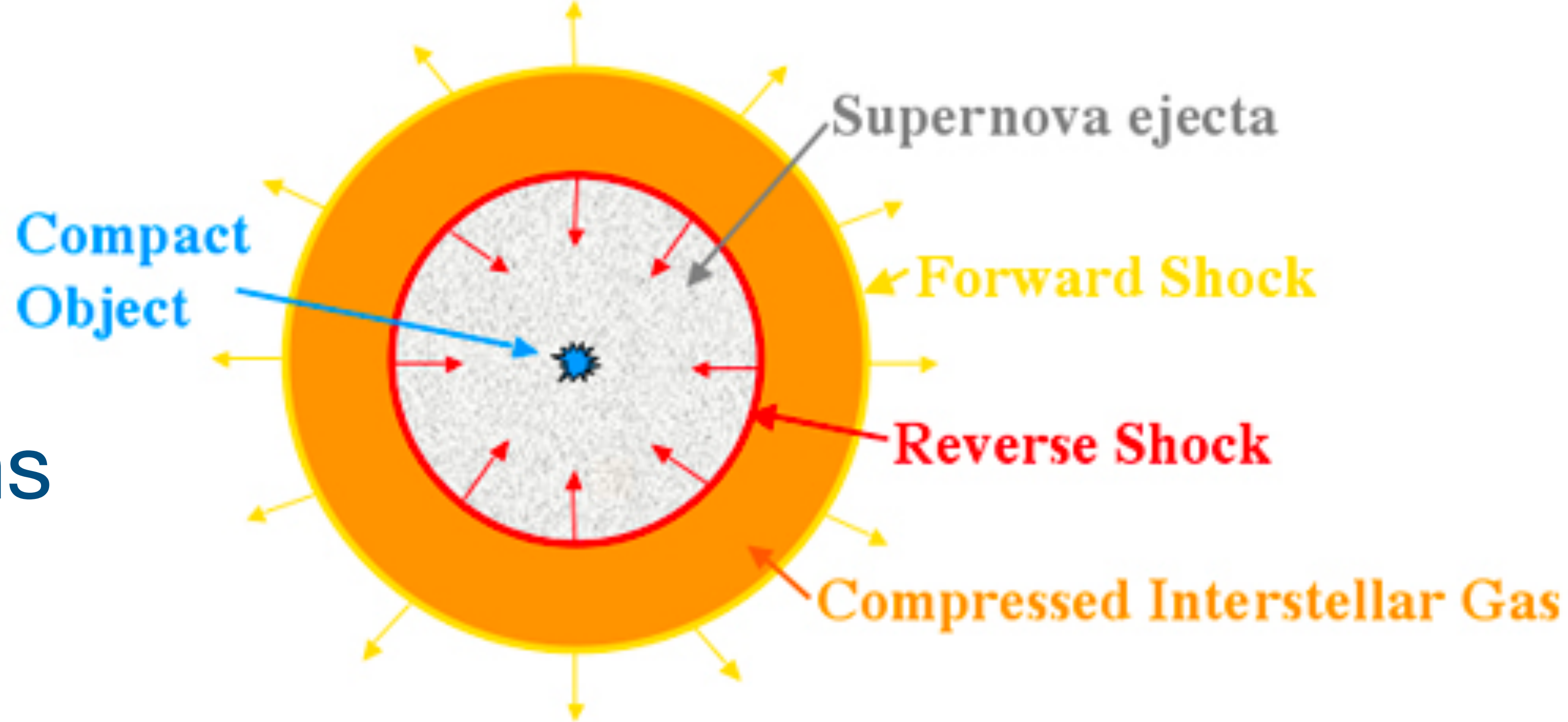
Radiation by ultra relativistic electrons & ions

In-situ footprint of CR production!

Collisionless shock in SNRs → 1st order Fermi acceleration

Effective for accelerating of ions & electrons

Most naturally explains similar spectral shapes of leptons and hadrons

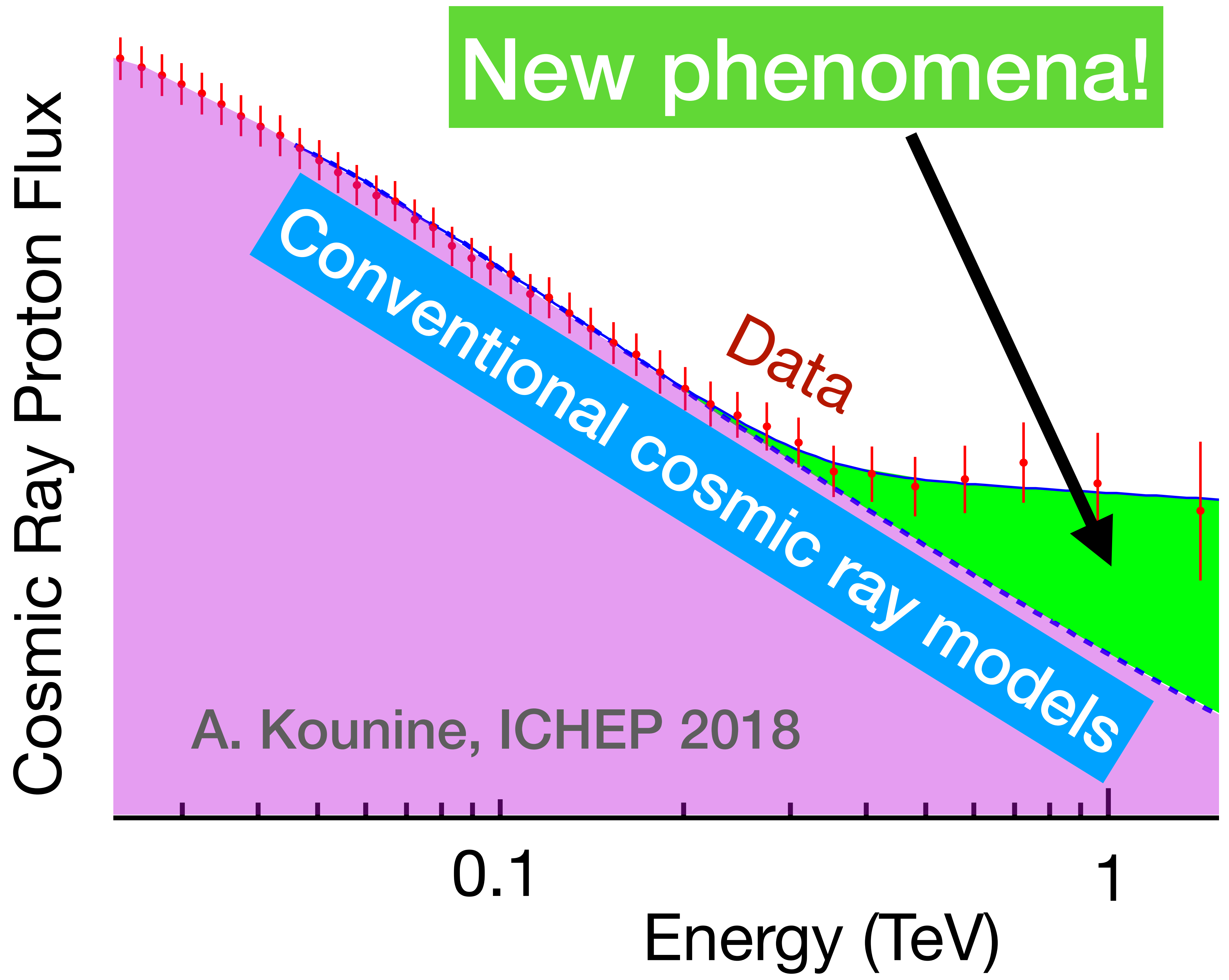


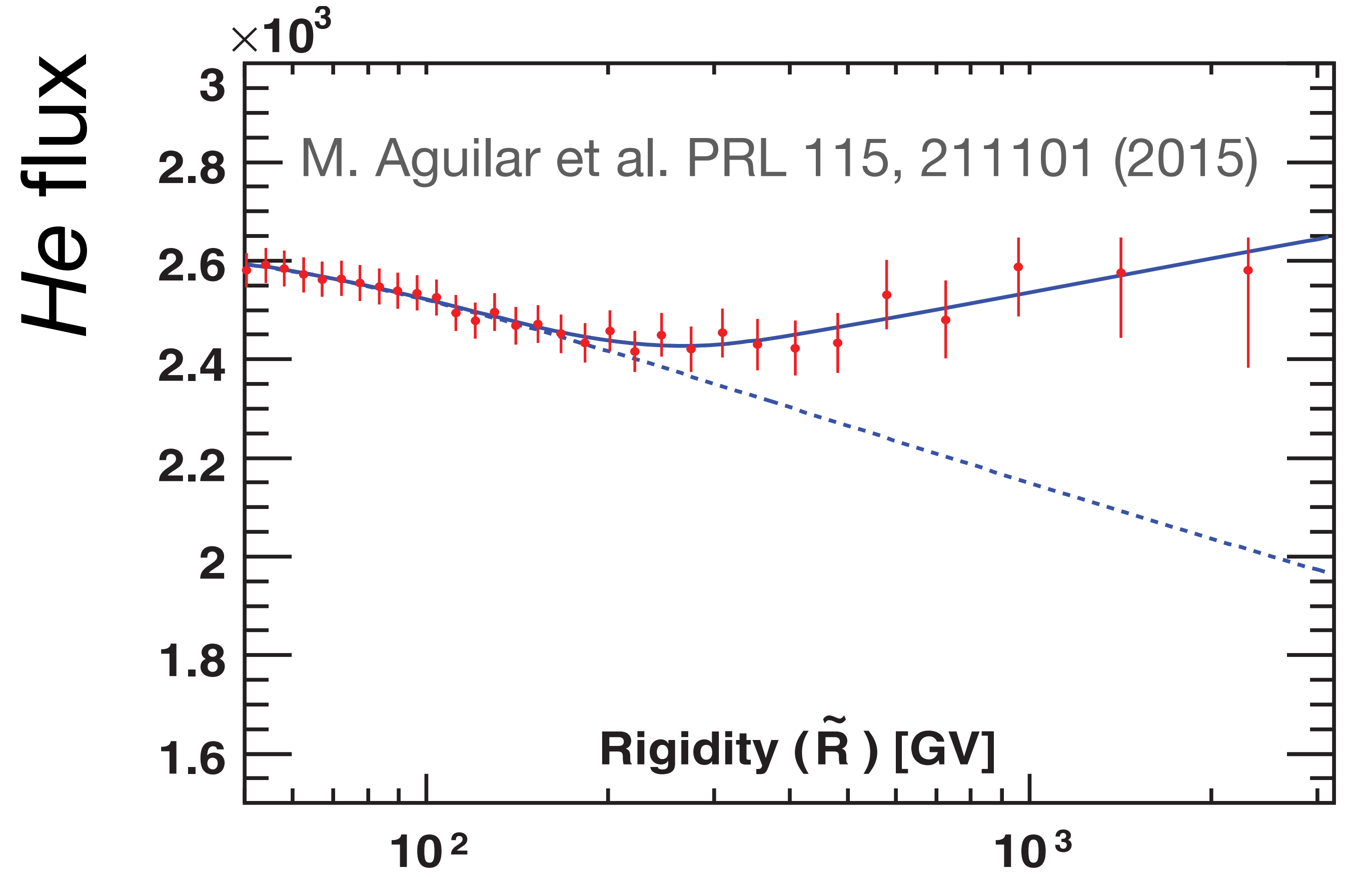
(Image credit: https://astronomy.swin.edu.au/)

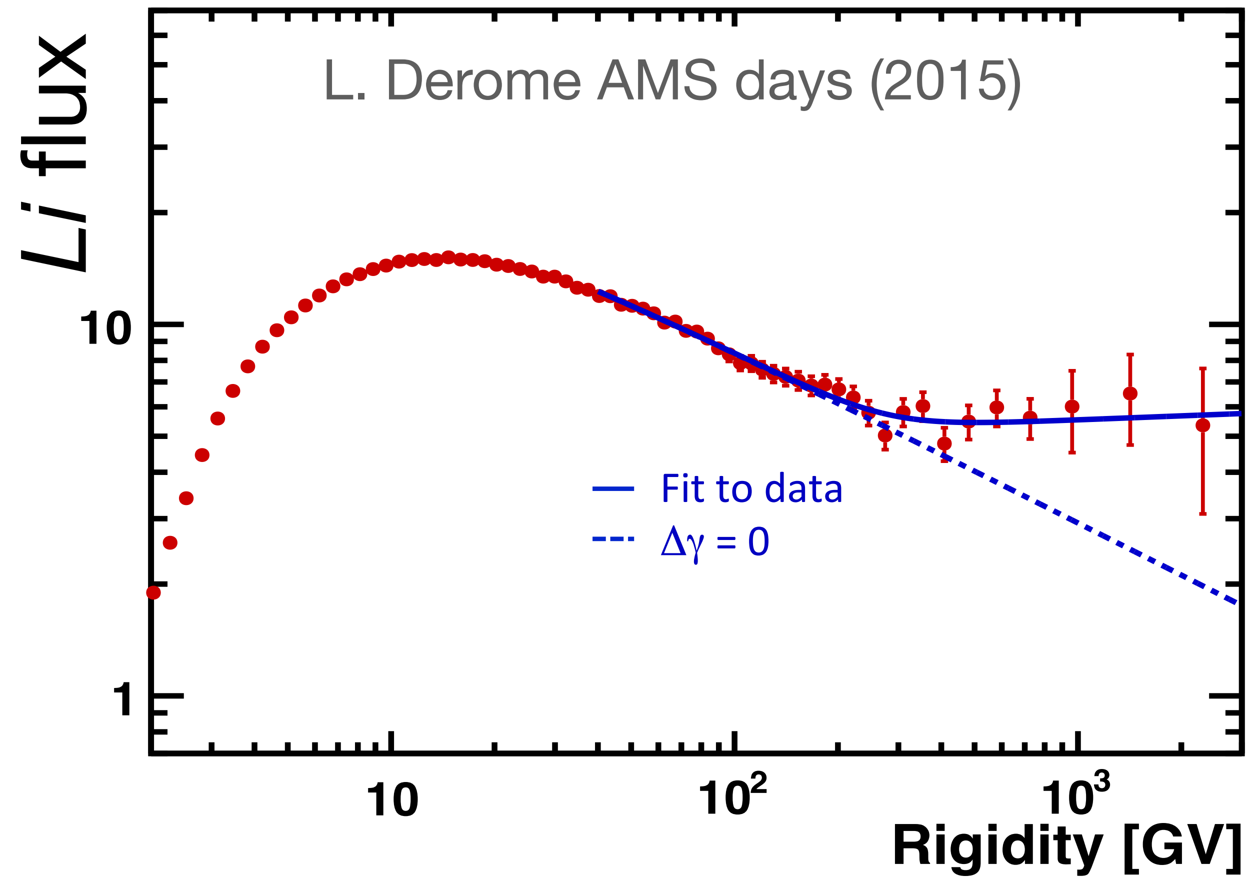
(See e.g. Bykov et al. arxiv.org/abs/1801.08890v1 Bell et al. doi.org/10.1016/j.astropartphys.2012.05.022)

Problems with SNRs (< TeV scale)

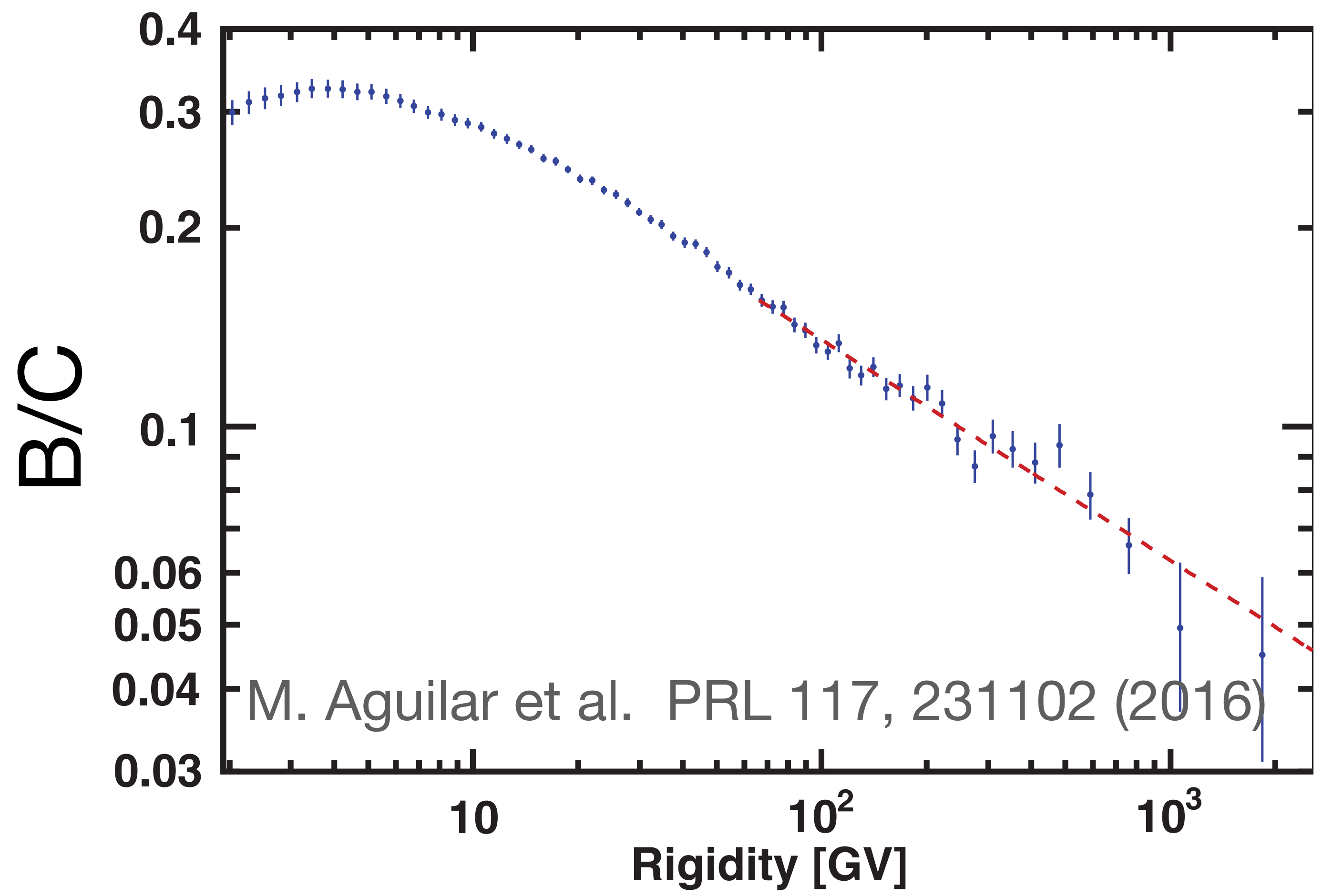
- Recent Cosmic Ray data question conventional SNR models
- Spectral break confirmed in major CR species







- No structure in B/C ratio !



- New source?
- New propagation mechanism?
  self-generated waves (Blasi et al), superbubbles …

Problems with SNRs (PeV scale)

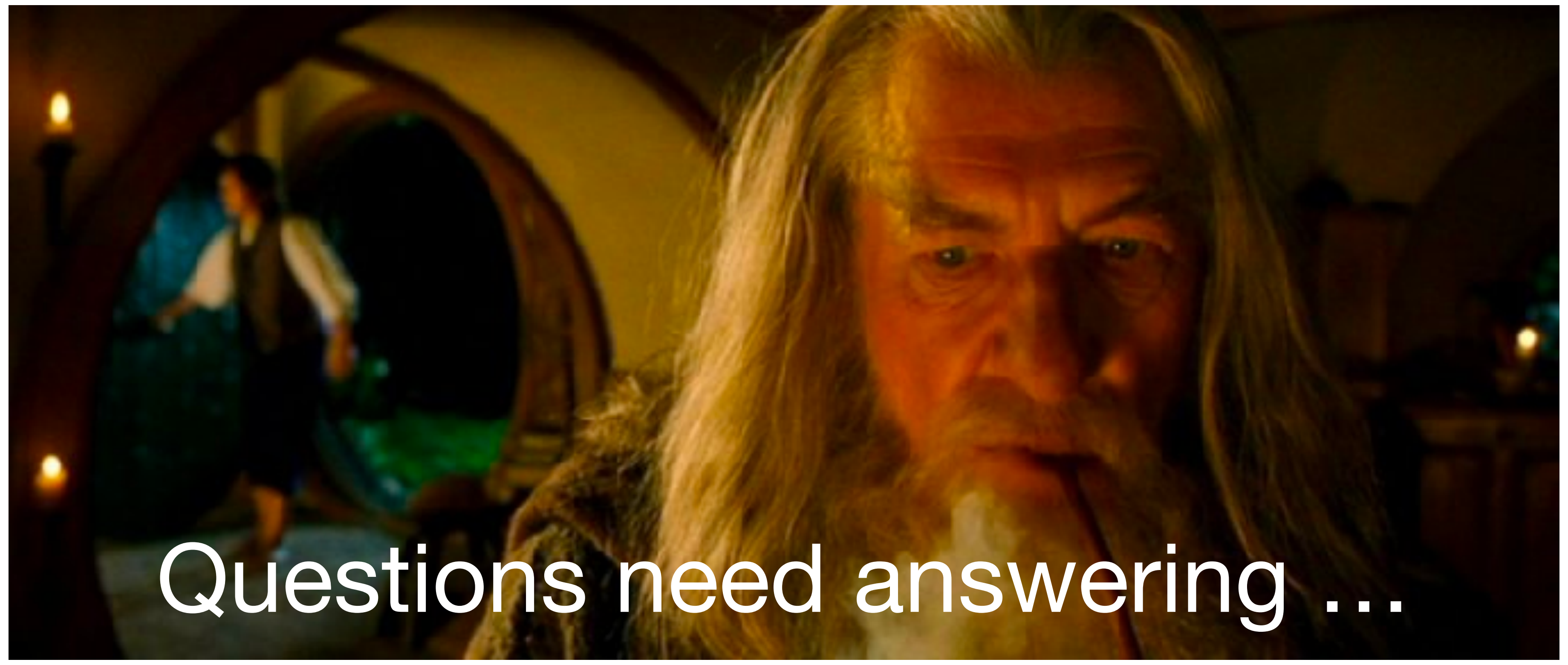
Challenging to explain CR acceleration to PeV by classic SNR paradigm

- Maximum CR energy in observed SNRs does reach into the "knee"
- Requires strong magnetic field amplification above typical interstellar values
- How particles escape from the accelerator without experiencing strong adiabatic losses ?

Are there CRs beyond PeV produced in SNRs?

- Acceleration in early years after supernovae explosion?
- Explosion of Wolf-Rayet stars? (Thoudam et al.)
- Re-acceleration of CRs in Superbubbles?

Origin of cosmic rays close to the knee and above remains an enigma!
Observational data at TeV—PeV is a key to crack it!



Cosmic Rays beyond the "knee"

Mostly extragalactic, even more uncertain origin, various hypotheses exist

Objects with strong rotating magnetic fields

- **Binaries** with neutron star or a pulsar

  Mergers accompanied by Gamma-Ray Burst &

  Gravitational Waves

- **Pulsars** — fast spinning highly-magnetised neutron star

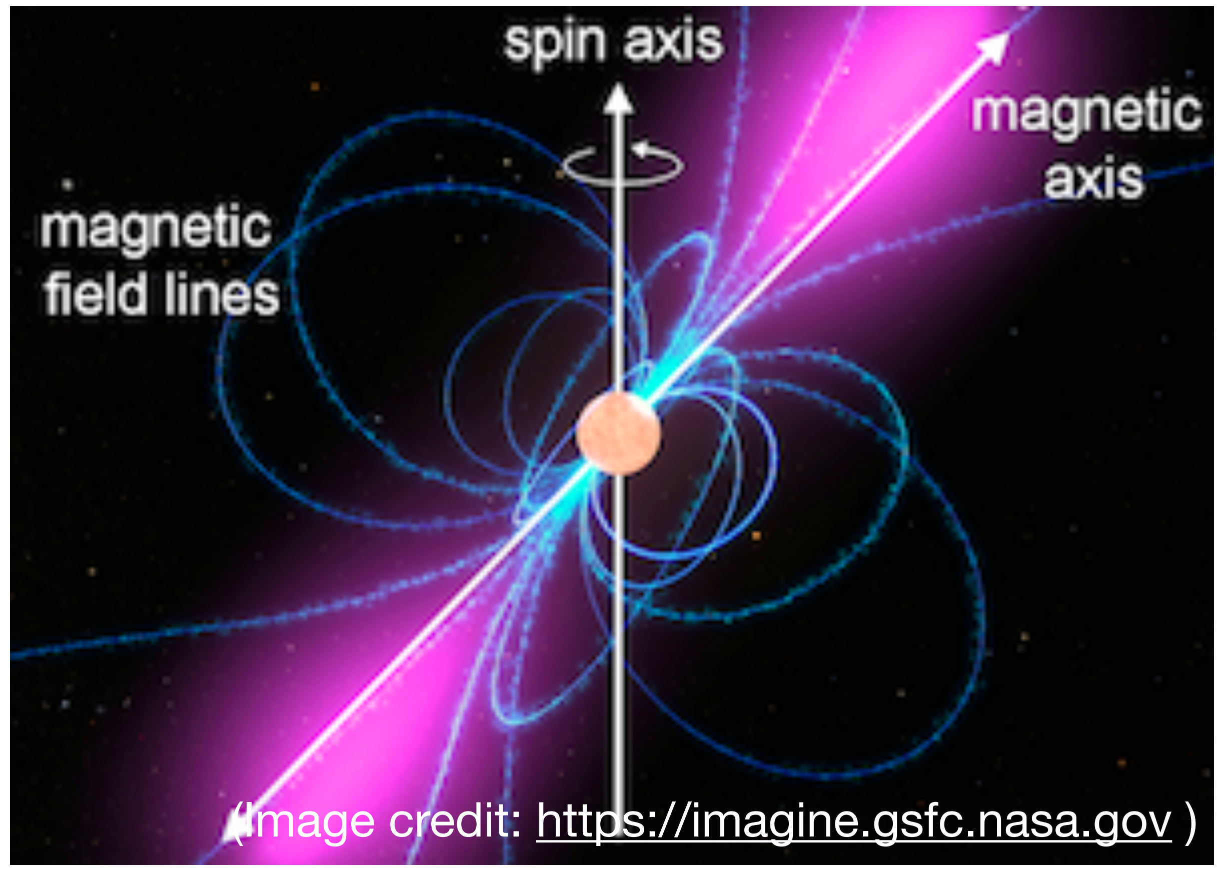
  Appears as a result of Supernovae explosion

Accretion to supermassive black hole

- Tidal Disruption Events
- Active Galactic Nuclei, …

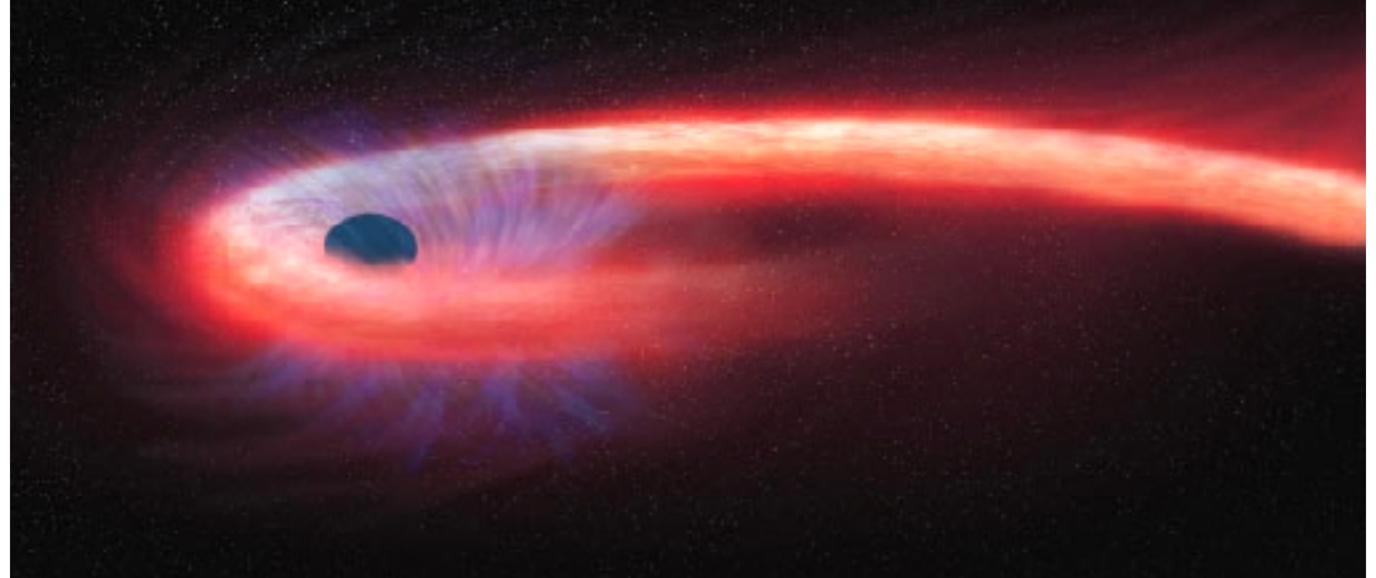
***Starburst galaxies**, etc.*

Pulsar magnetic & spin axes do not coincide
→ appear "flickering" (pulsating)



(Image credit: https://imagine.gsfc.nasa.gov)

Artist representation of tidal disruption event: a star is shredded by a supermassive black hole



(Adapted from: NASA/CXC/M. Weiss)

Cosmic ray electrons & positrons (CRE)

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

- Sensitive to new physics

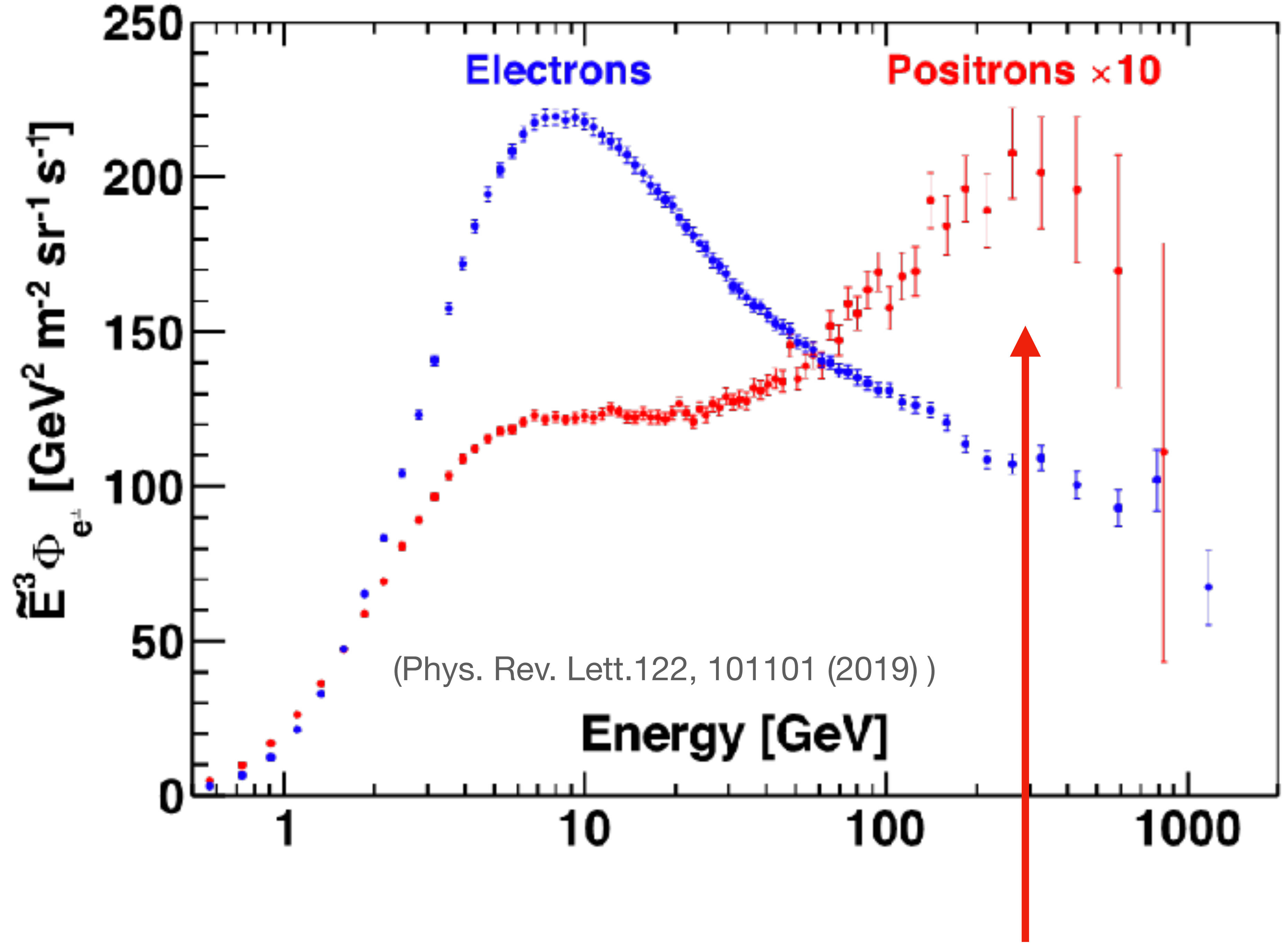
Rapidly loose their energy during propagation

- (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
  - Mostly originate from π decays,
  - photons above e^+e^- production threshold (pulsars) ?
- (**Secondary**) interaction of CR with interstellar medium

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

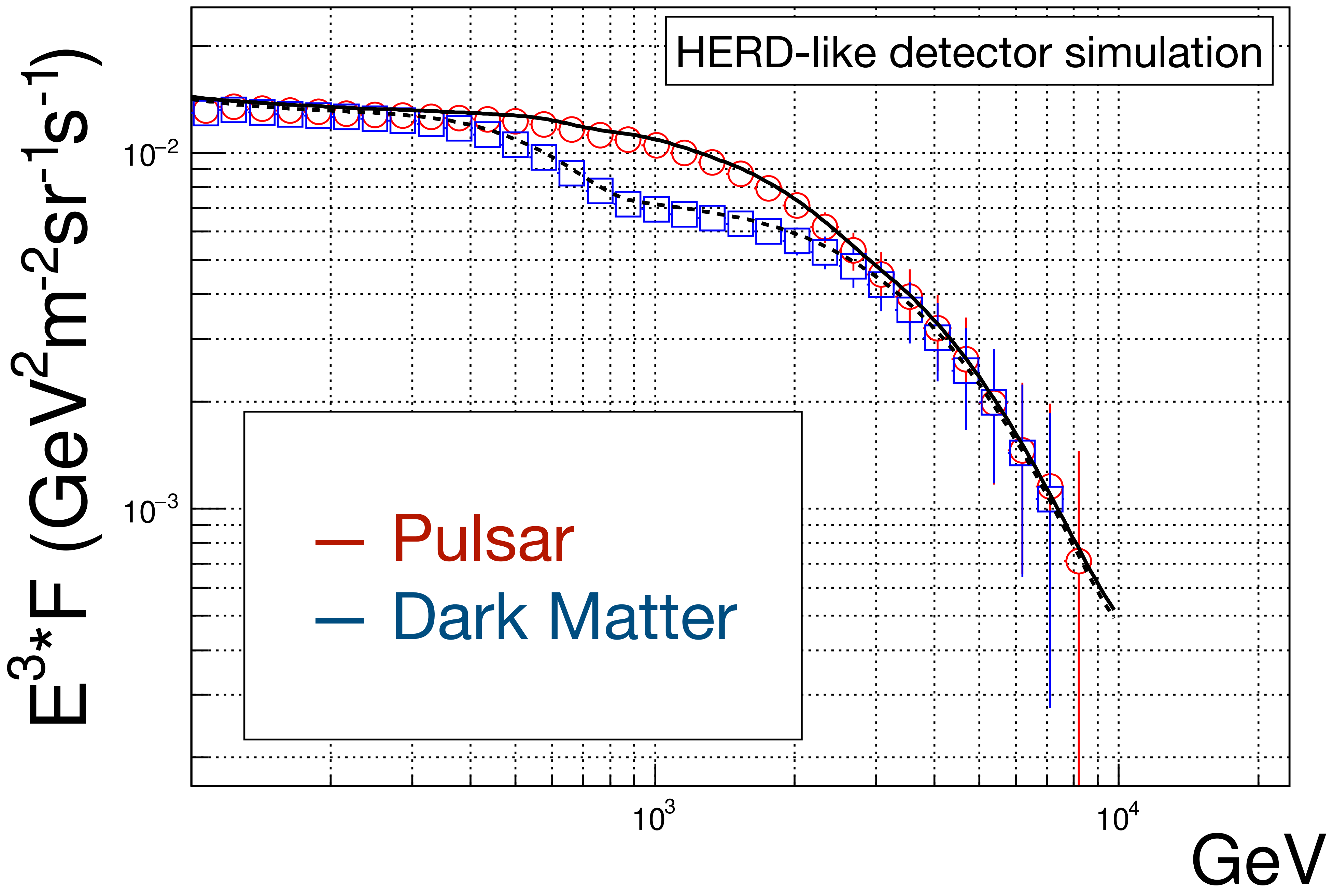


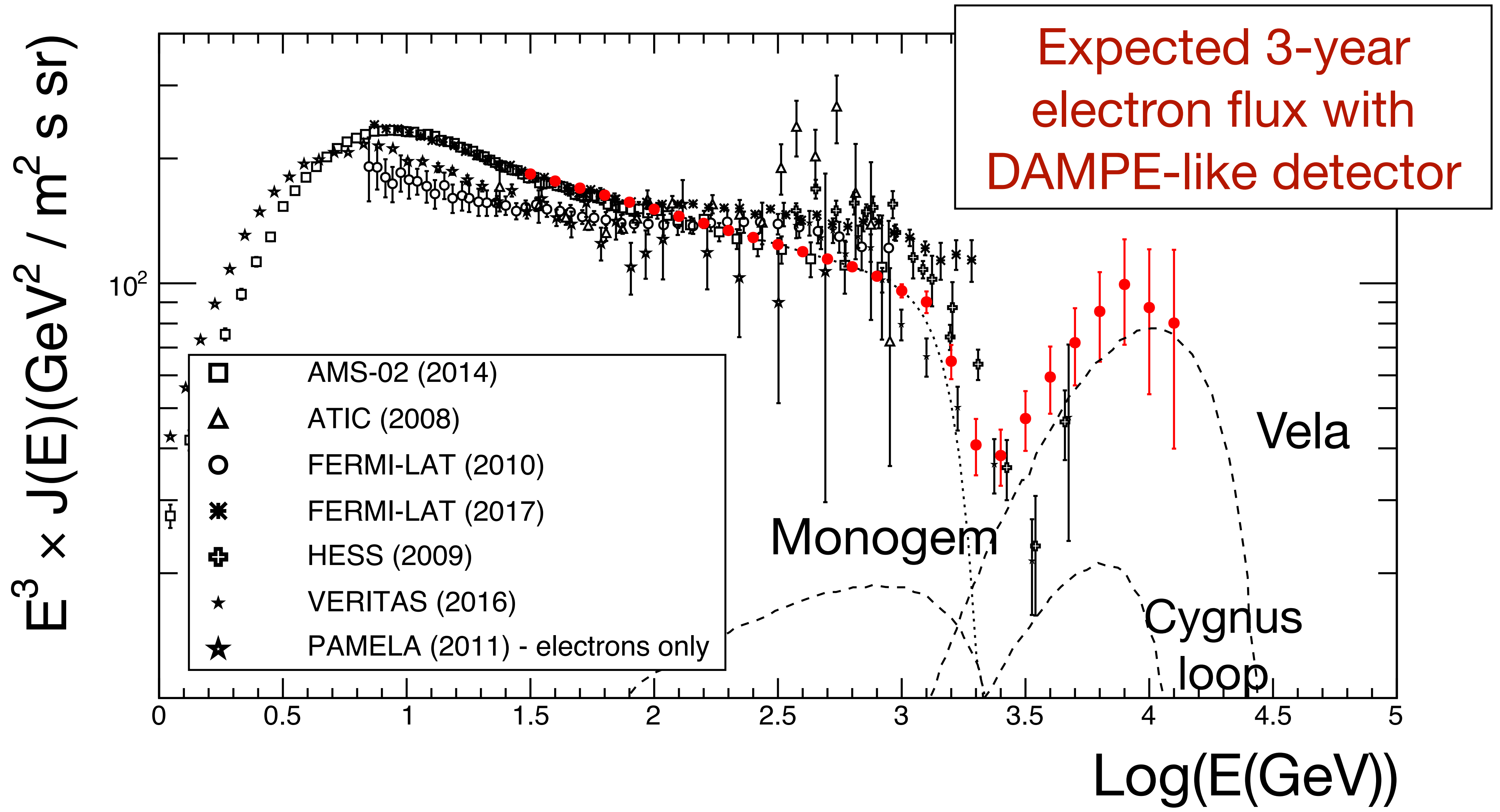
Positron spectrum incompatible with purely secondary origin: DM, pulsar ?

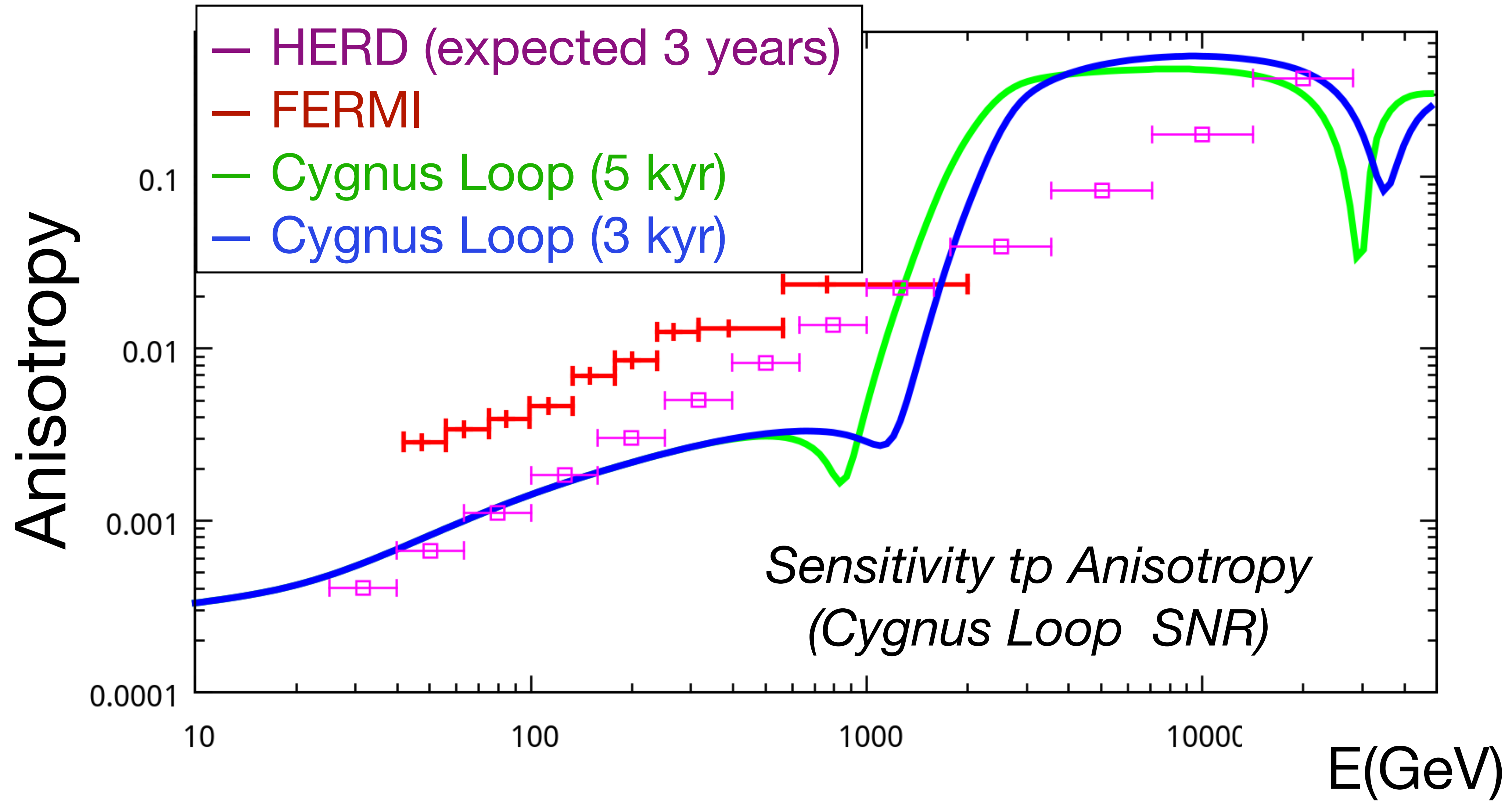
Cosmic ray electrons & positrons (CRE)

Can be produced in annihilation\decay of Dark Matter (DM)

- Distinct spectral features, isotropic

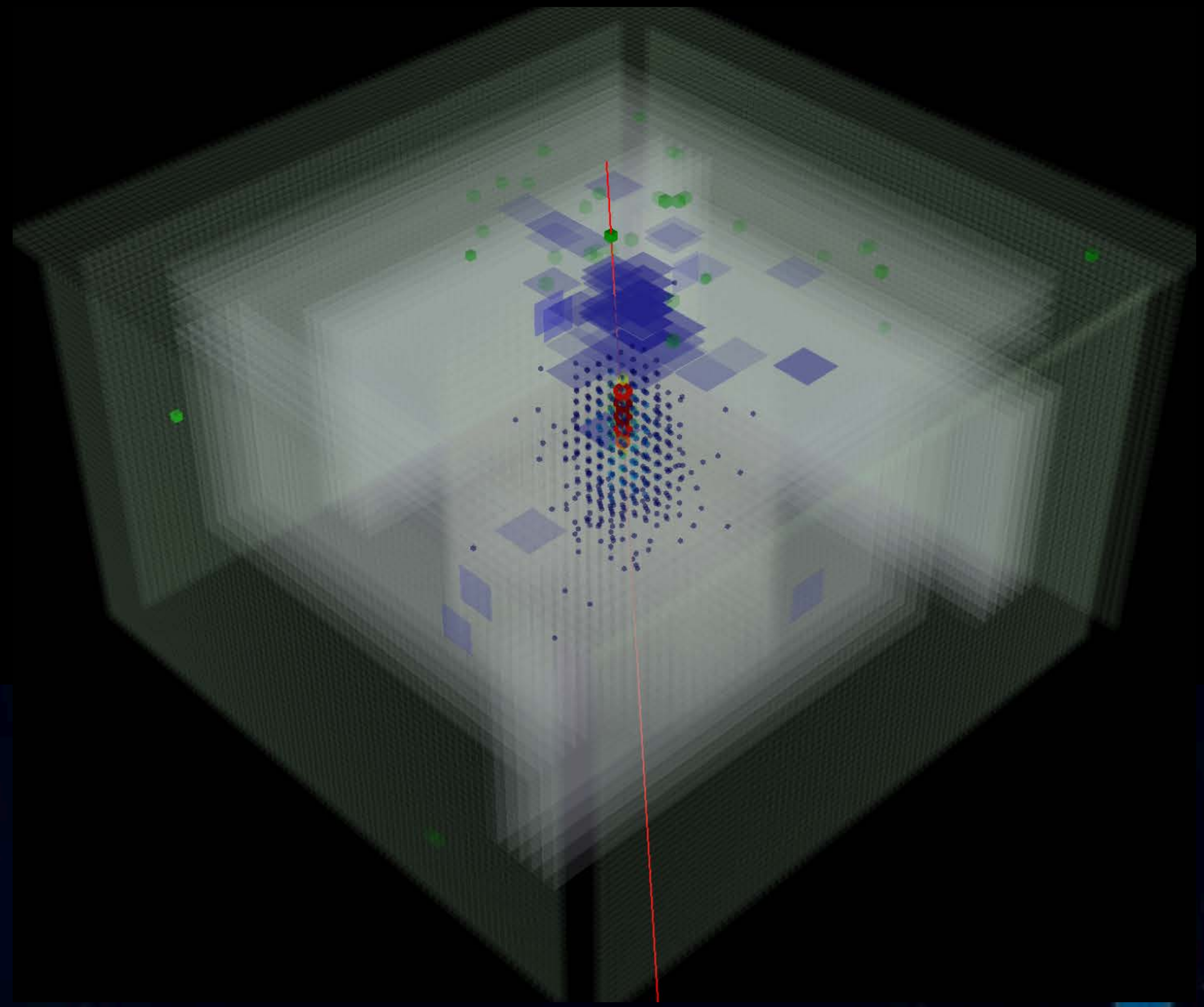




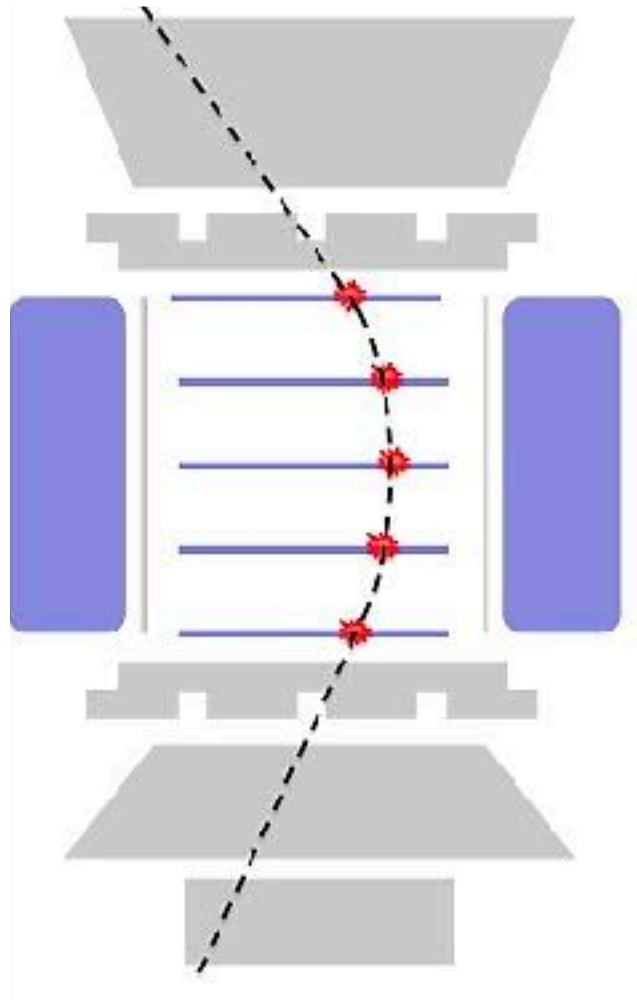


Future precise CRE spectrum & anisotropy measurement at TeVs — key to disentangle Dark Matter signatures from local sources

Chapter II: Instruments

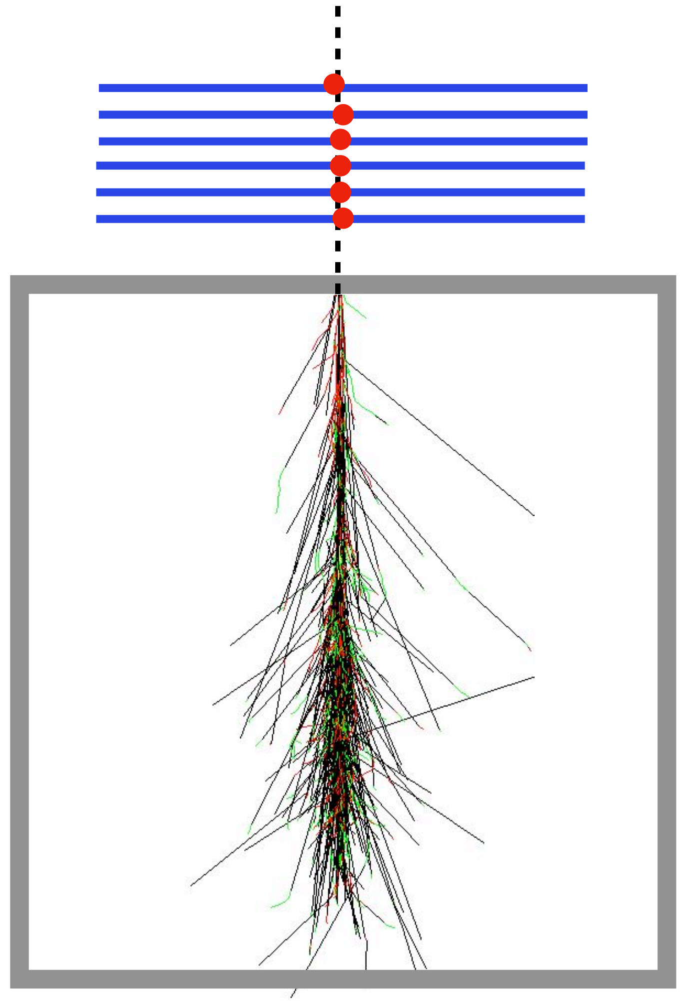


From spectrometers to calorimeters



Alpha Magnetic Spectrometer (AMS-02)

- Launched to ISS in 2011
- Utmost precise CR measurements up to ~ TeV
- Difficult to go beyond few TeV with spectrometers



Calorimetric space experiments

- **AGILE, FERMI** (2007, 2008) — relatively thin calorimeters
- **CALET**: Calorimetric Electron Telescope (launch 2015)
- **DAMPE**: DArk Matter Particle Explorer (launch 2015)
- **HERD**: High Energy Radiation Detection mission (next-gen)

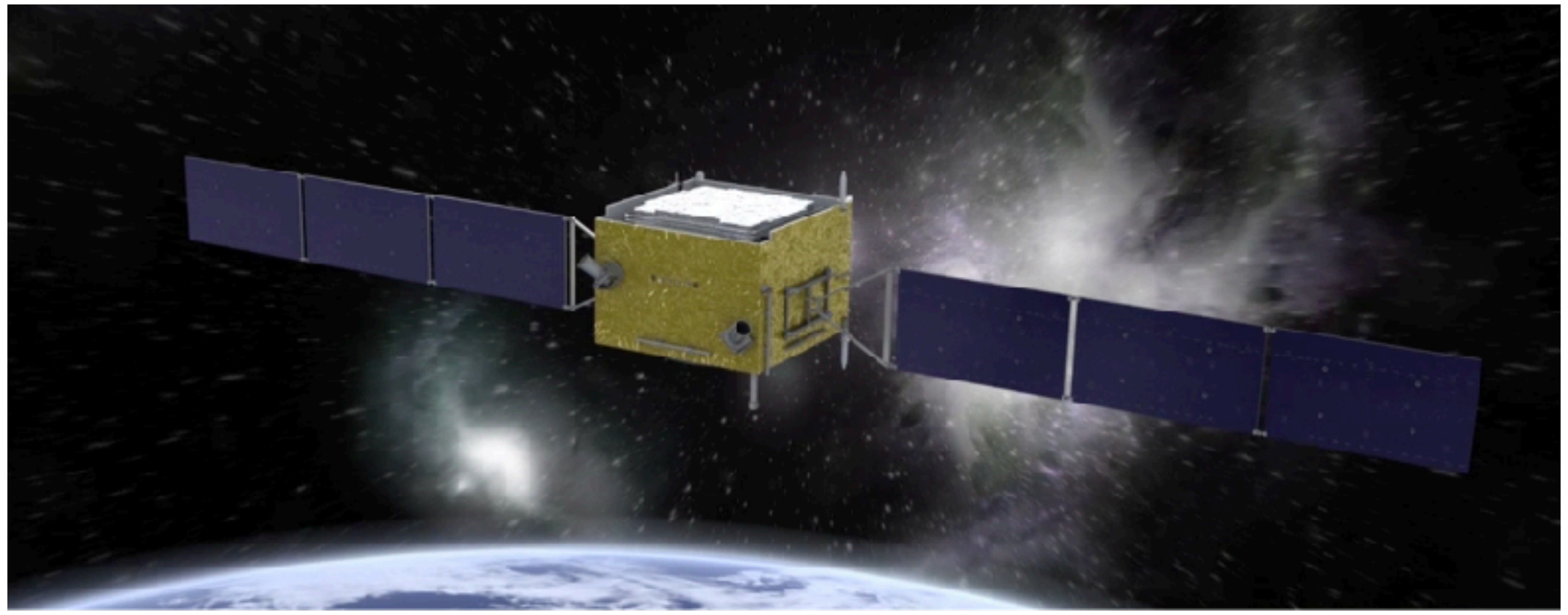
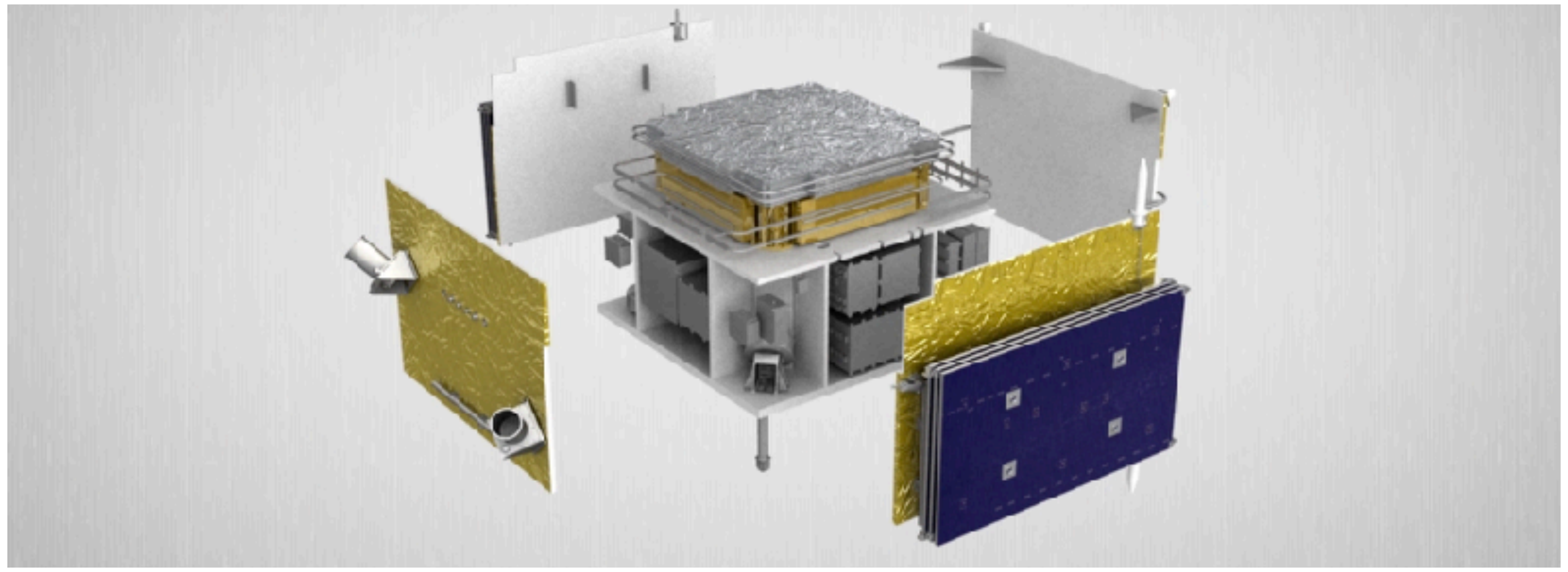
DArk Matter Particle Explorer (DAMPE)

- Launched in **Dec 2015**
- Orbit: sun-synchronous, **500 km**
- Period: **95 min**
- Payload: **1.4 Tonn**
- Power: ~ **400 W**
- Data: ~ **12 GByte / day**

Collaboration



University of Geneva

DArk Matter Particle Explorer (DAMPE)

Thick calorimeter ~ 32 X_0 (biggest in Space)

- e/γ detection up to ***10 TeV***
- CR *p*/ions ***50 GeV — 500 TeV***
- e/γ energy resolution ***1% at TeVs***
- e/p rejection factor ~ ***10^4 — 10^5***

Precise Silicon-Tungsten tracker-converter

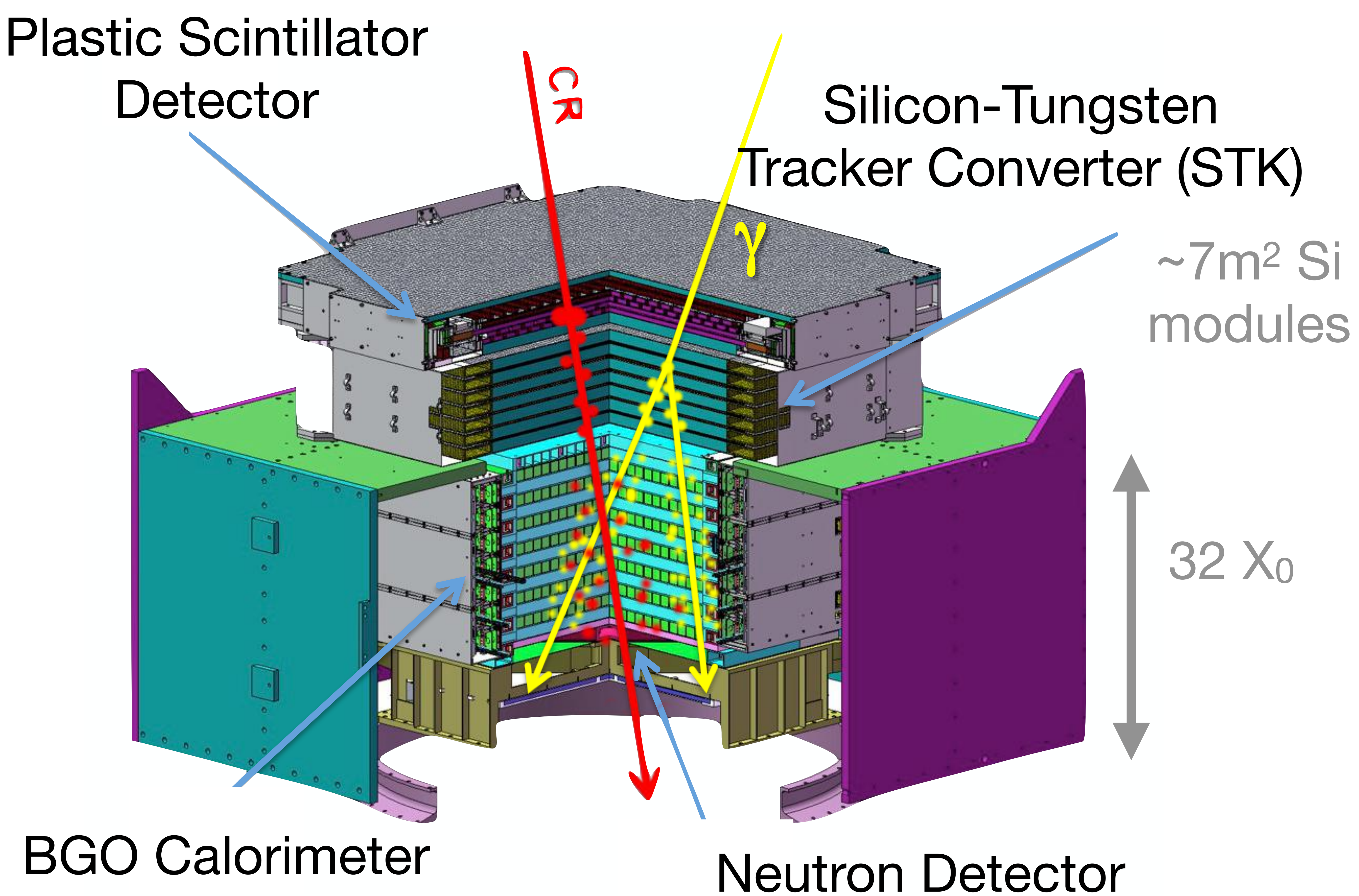
- Position resolution ***~50 micron***
- Charge Z identification up to *Fe*
- γ pointing ***0.5°*** **—** ***0.1°*** (GeVs — TeV)

Plastic scintillator

- Z identification
- γ anti-coincidence signal

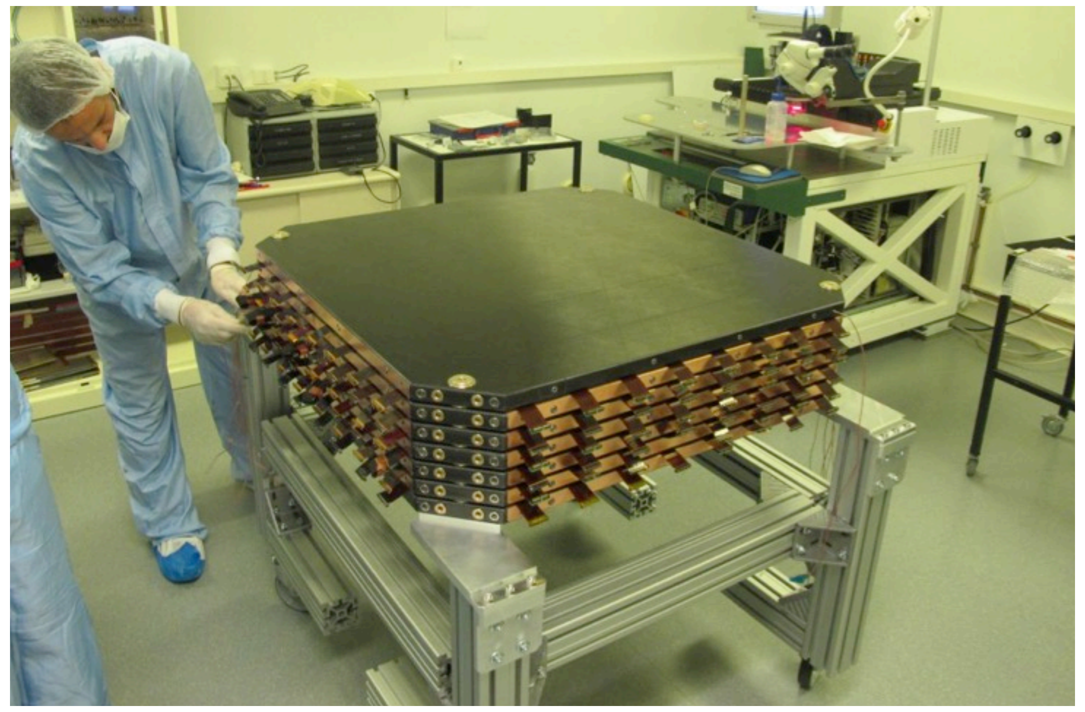
Netron detector

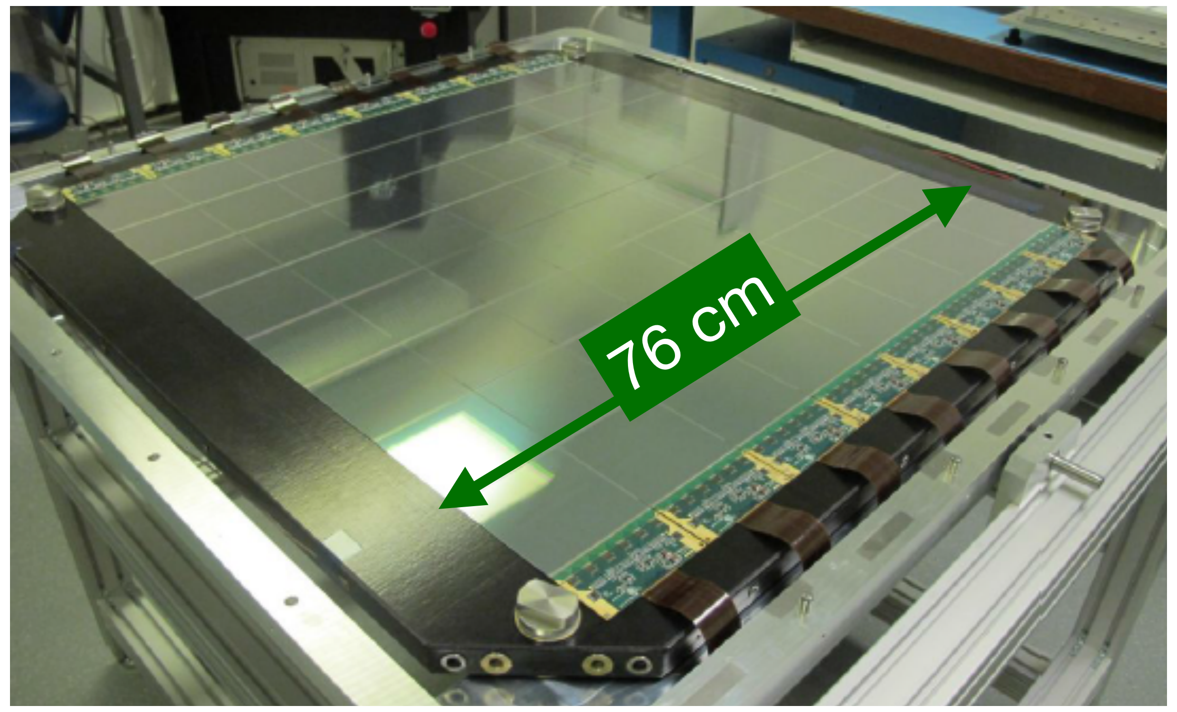
- Additional e/p rejection capability



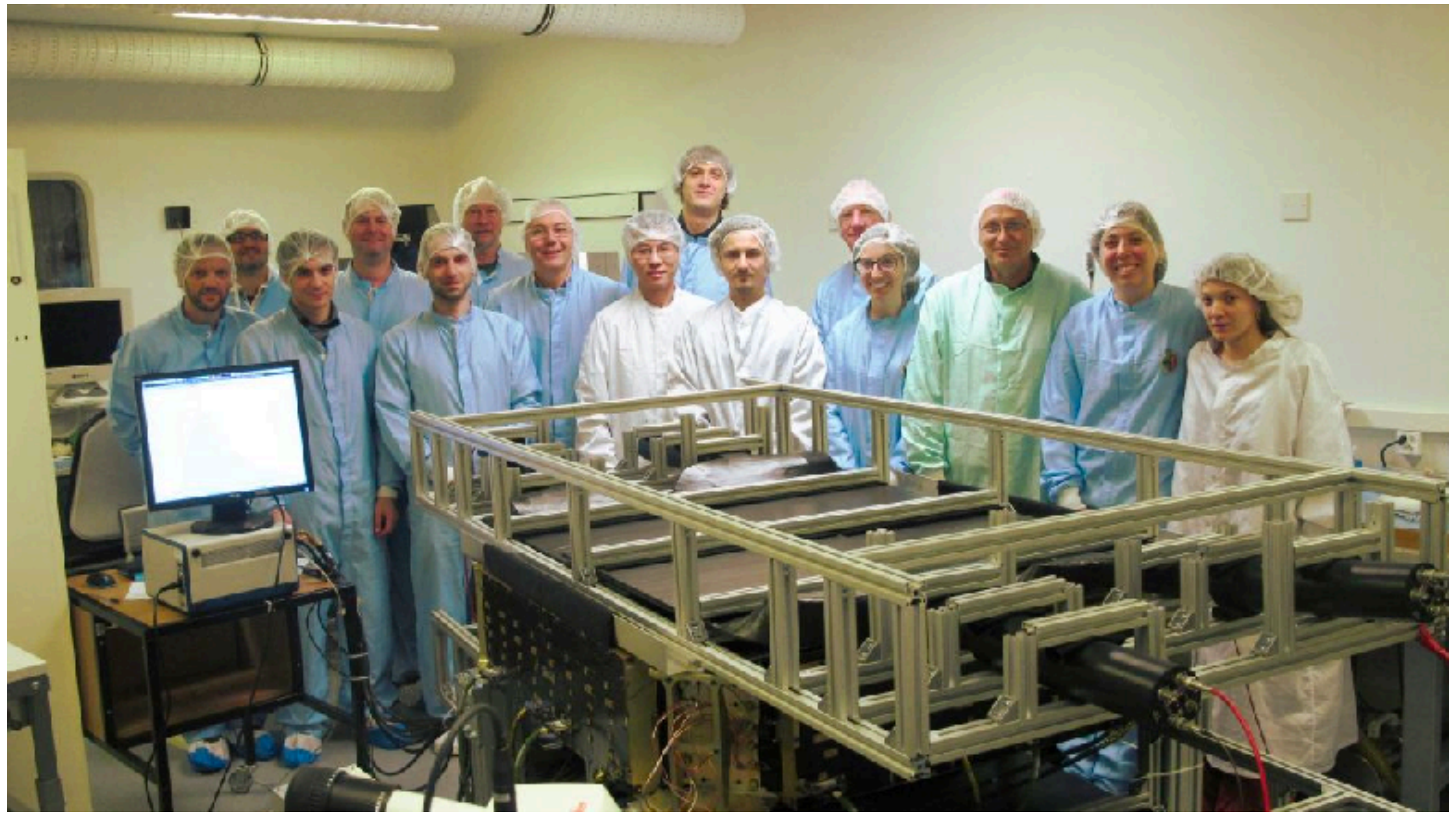
DAMPE Tracker detector (STK) & DPNC

R&D Construction (2013–2015)

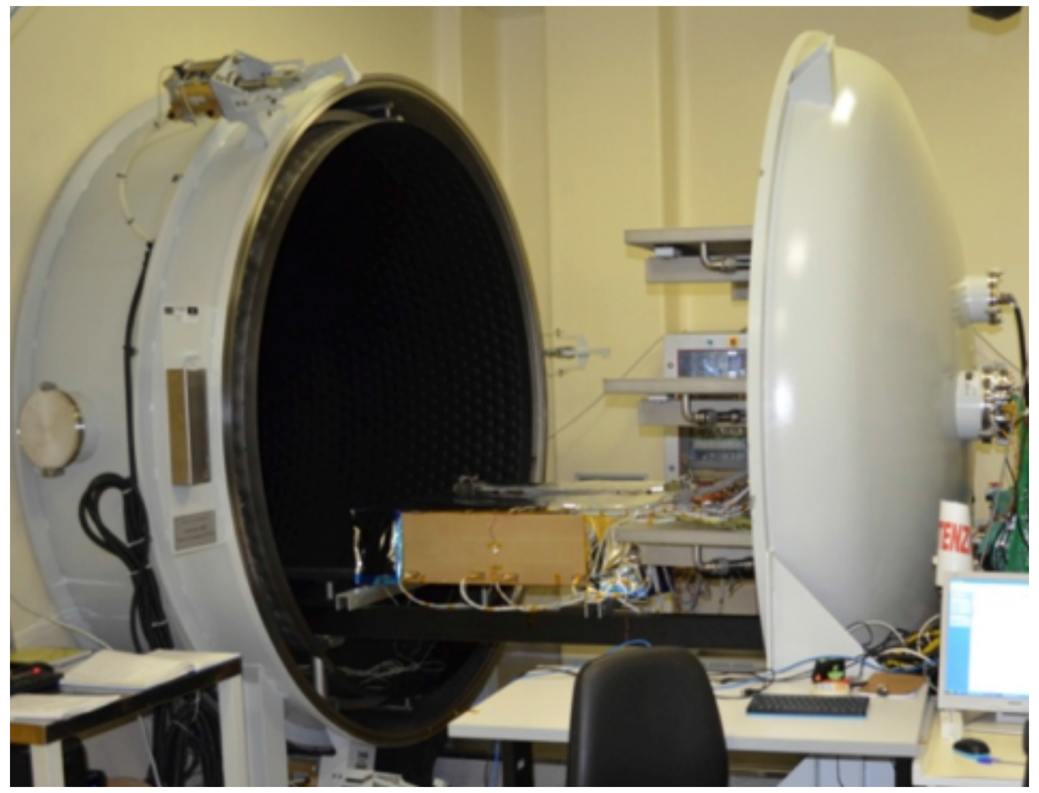




University of Geneva (DPNC) &
INFN Perugia groups
DAMPE Silicon Tracker tests with cosmic muons (April 2015)



Space qualification (2014–2015)



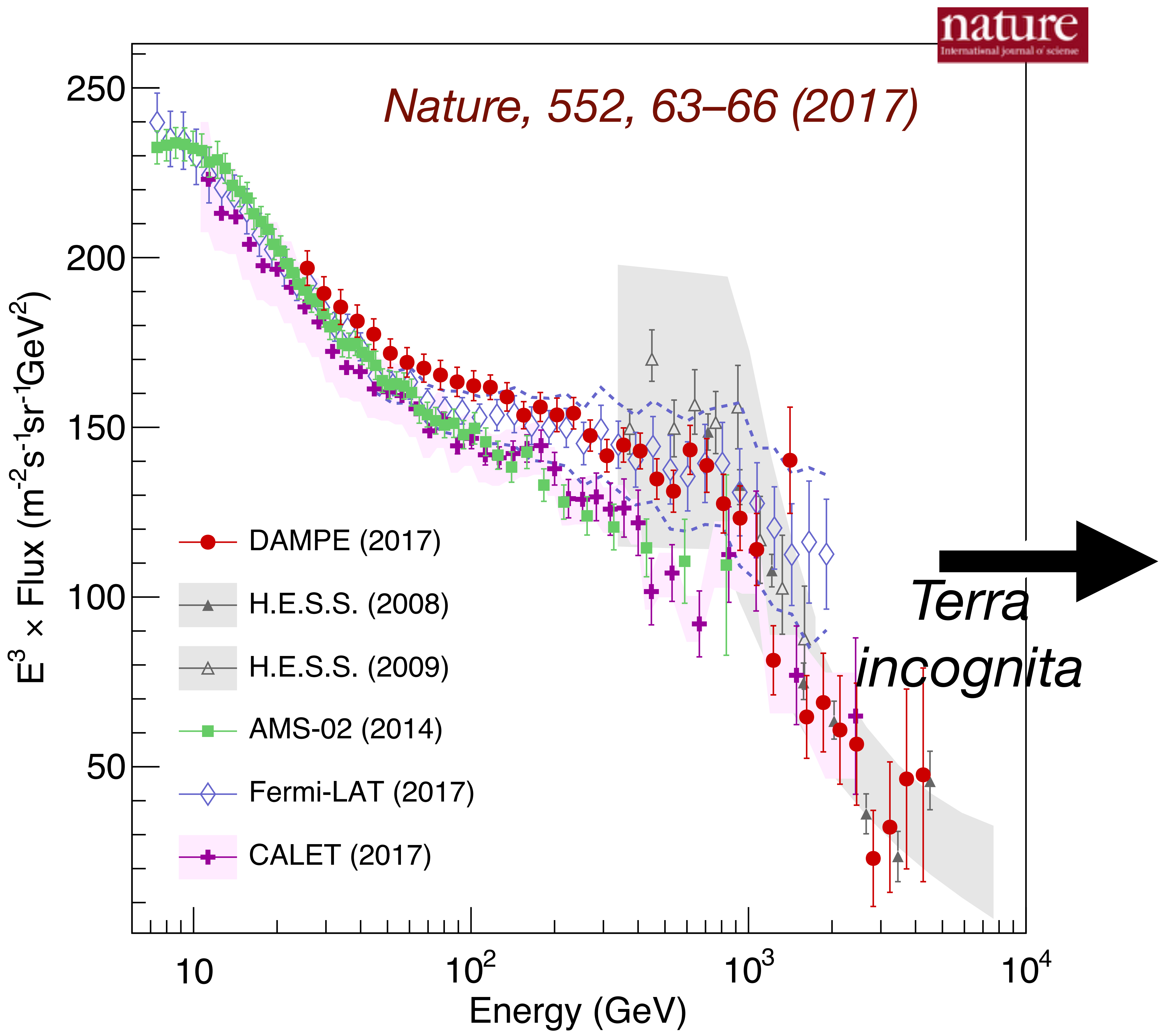
Vibration, shock, thermal cycling,..

Beam tests @ CERN (2014–2015)

DAMPE Cosmic Rays Measurements

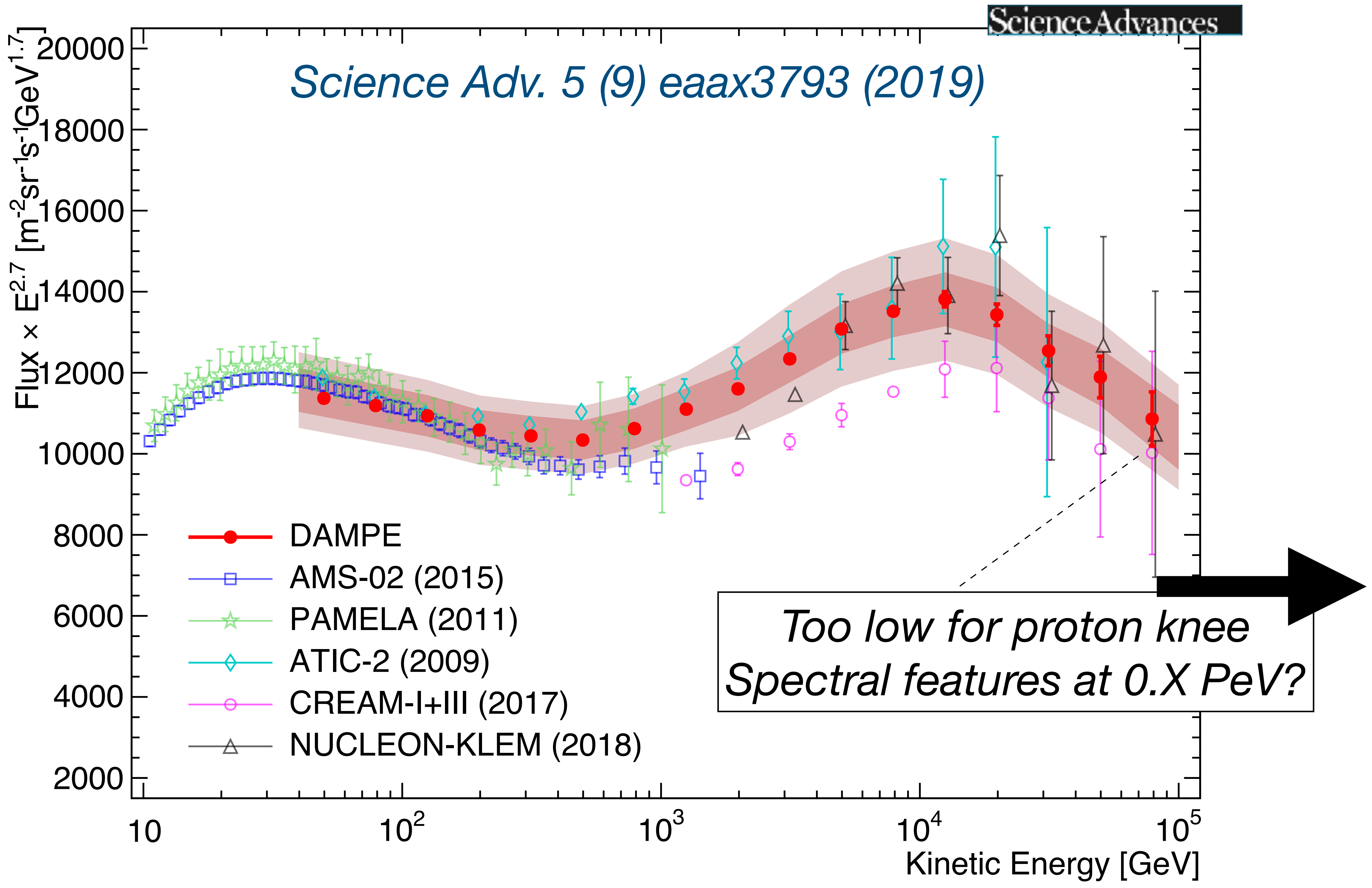
Electron—positron spectrum

- Energy span 3 orders of magnitude!
- Direct observation of spectral break



Proton spectrum

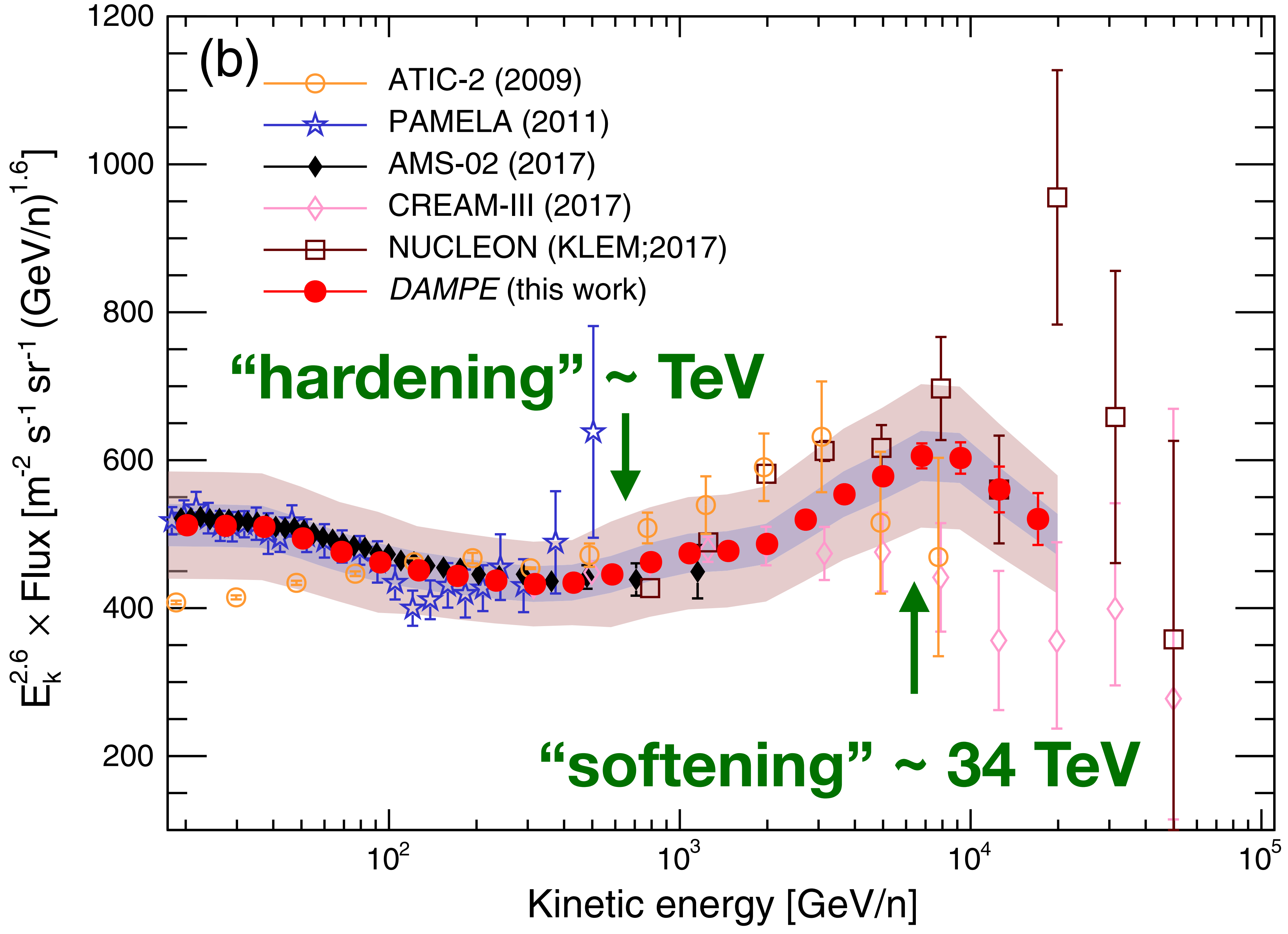
- First direct measurement up to 100 TeV
- Reveals new spectral feature at ~13 TeV



DAMPE Cosmic Rays Measurements

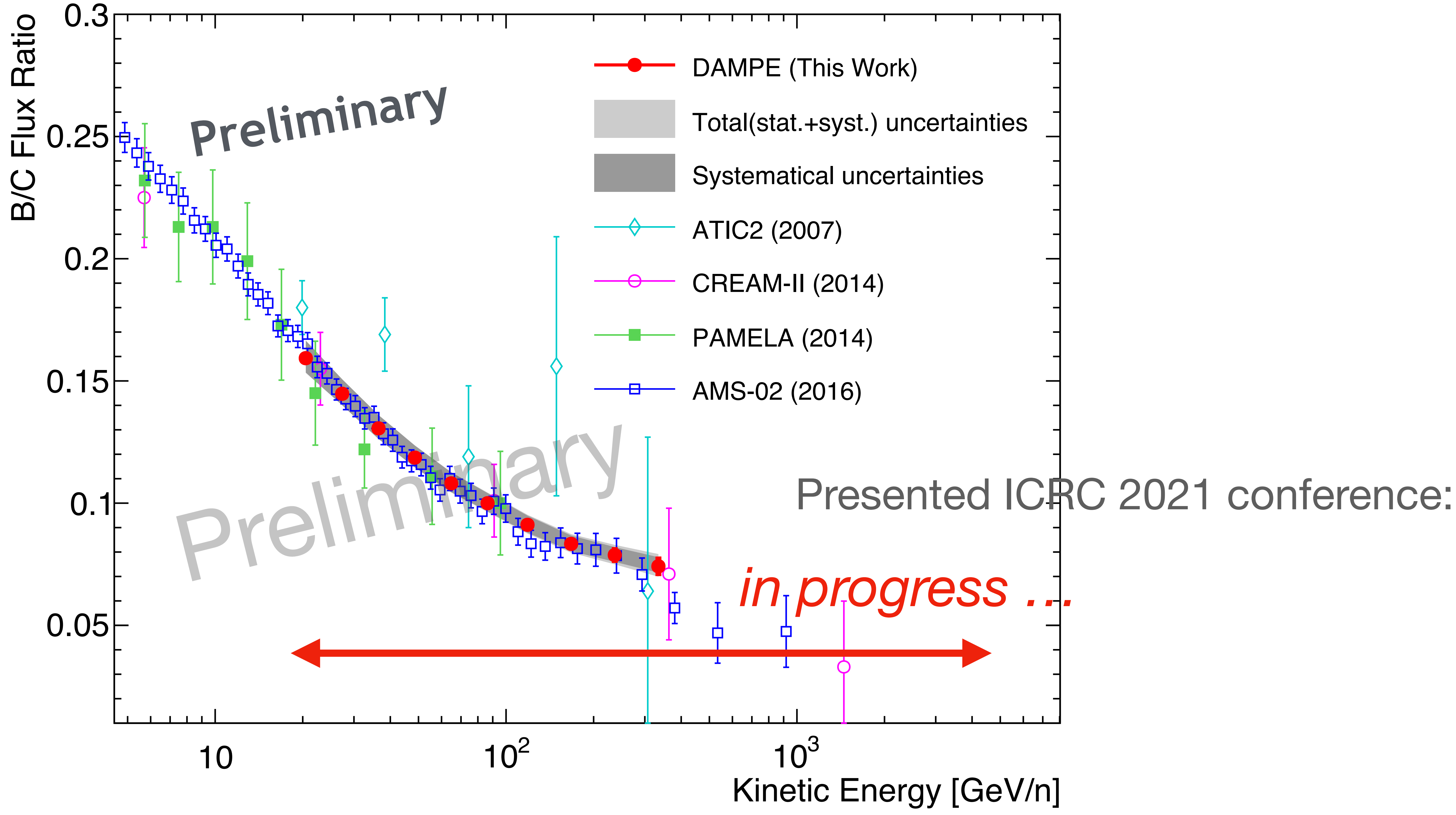
Alemanno et. al. PRL 126, 201102 (2021)

CR *He* spectrum



… *indicates of Z-dependent source*

B/C ratio



… partial cancellation of systematics

Many more ongoing analyses — not covered in this talk (*C, O, Fe,* Anisotropy, Gamma Rays ..)

High Energy Radiation Detection facility (HERD)

Next-gen Calorimetric detector in Space

- 5-side tracking & charge (Z) detectors
- 3D imaging LYSO calorimeter
- Target size ~ 55 X_0
- Estimated launch timeline ~ 2027

Collaboration

University of Geneva
EPFL Lausanne

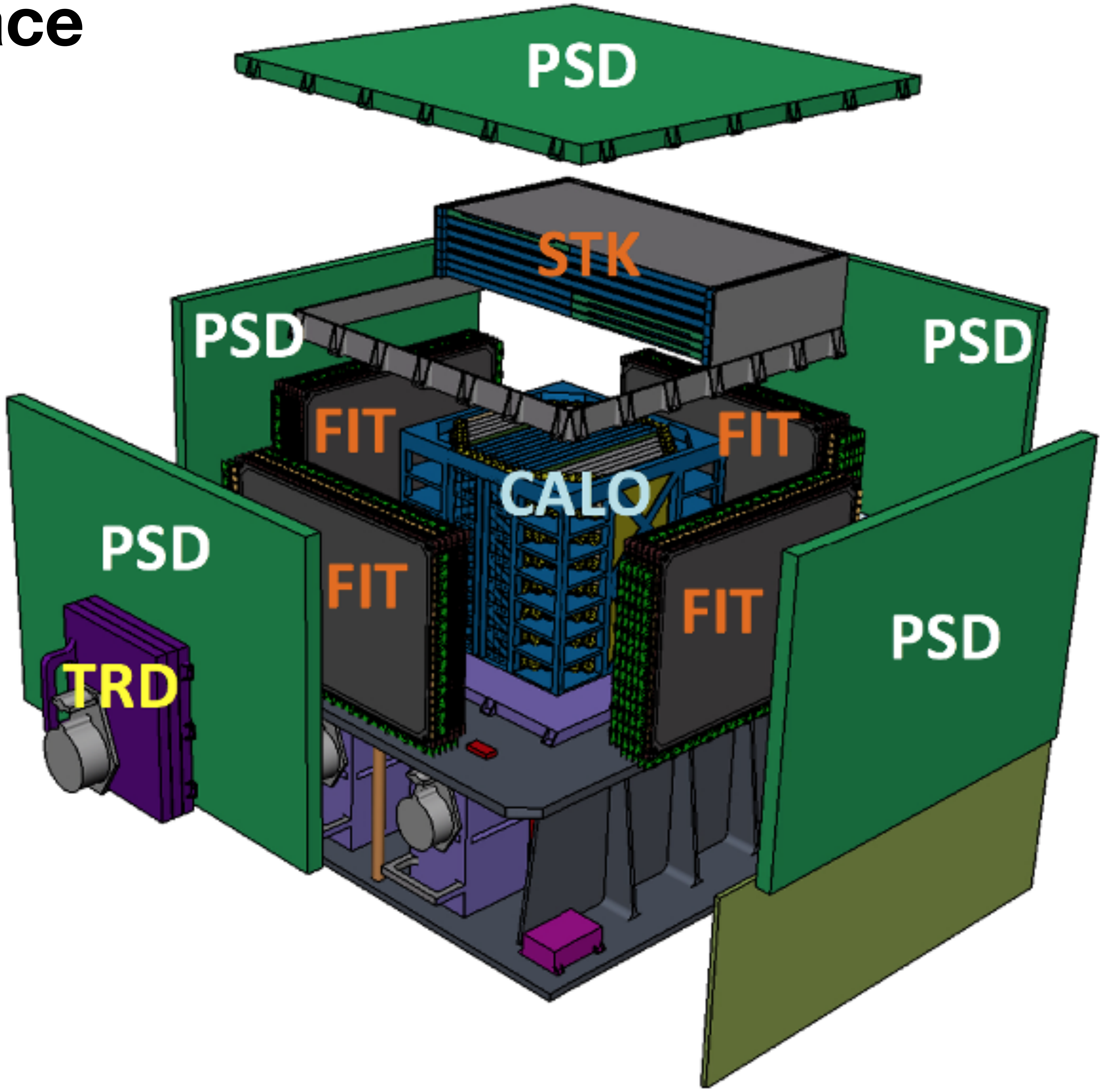


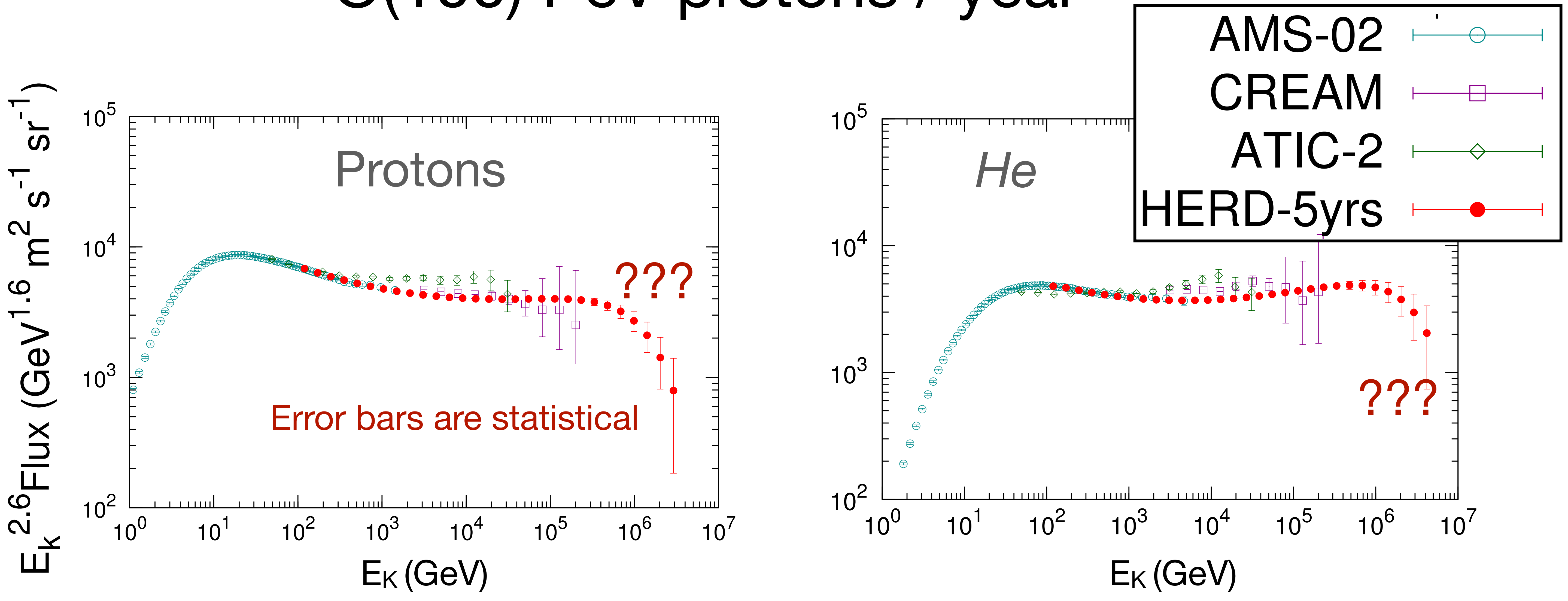
Image credit: C. Perrina, EPJ Web of Conferences, 2019 (RICAP-18)

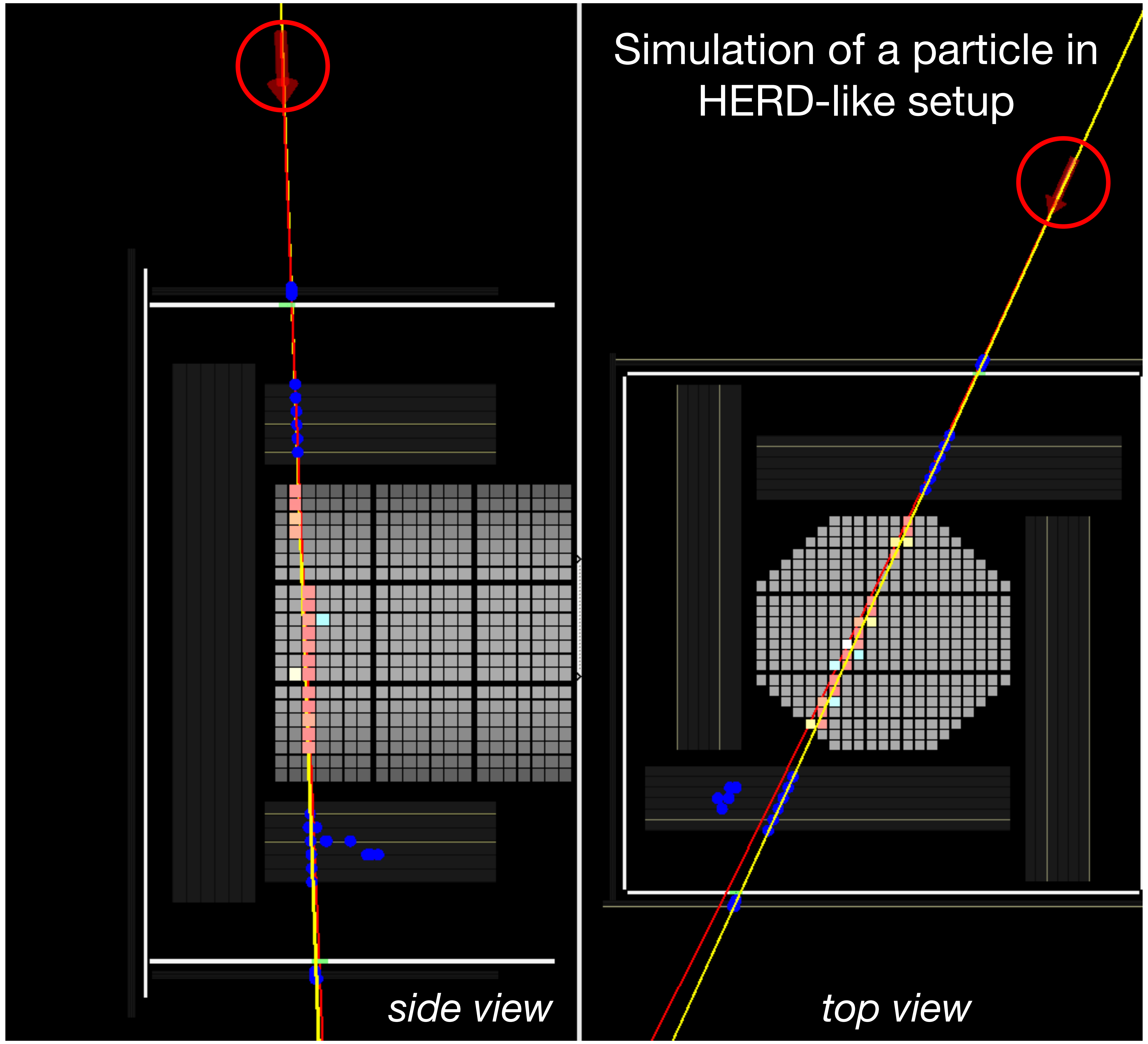
High Energy Radiation Detection facility (HERD)

BIG 3D calorimeter + 5-side tracker =

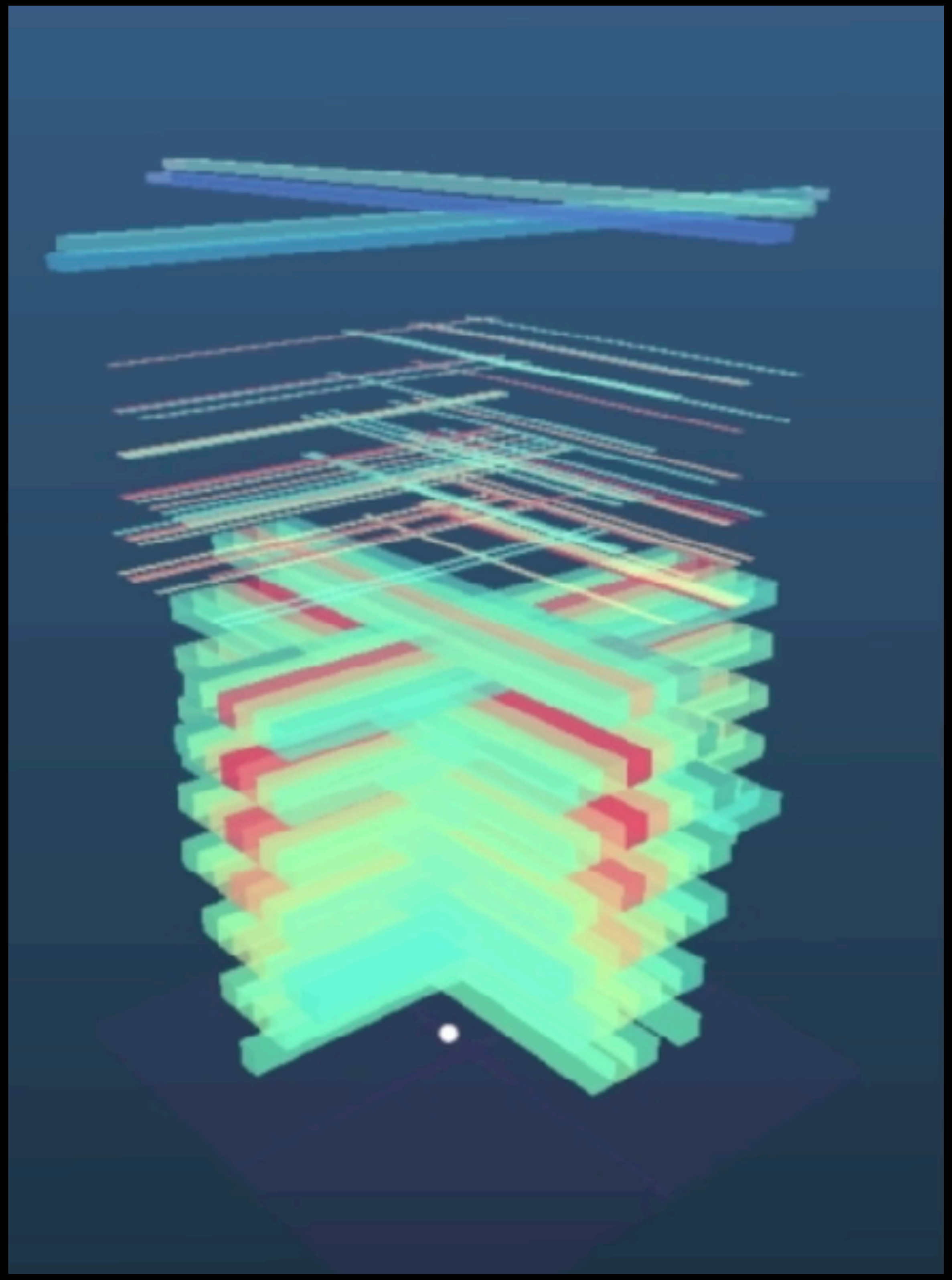
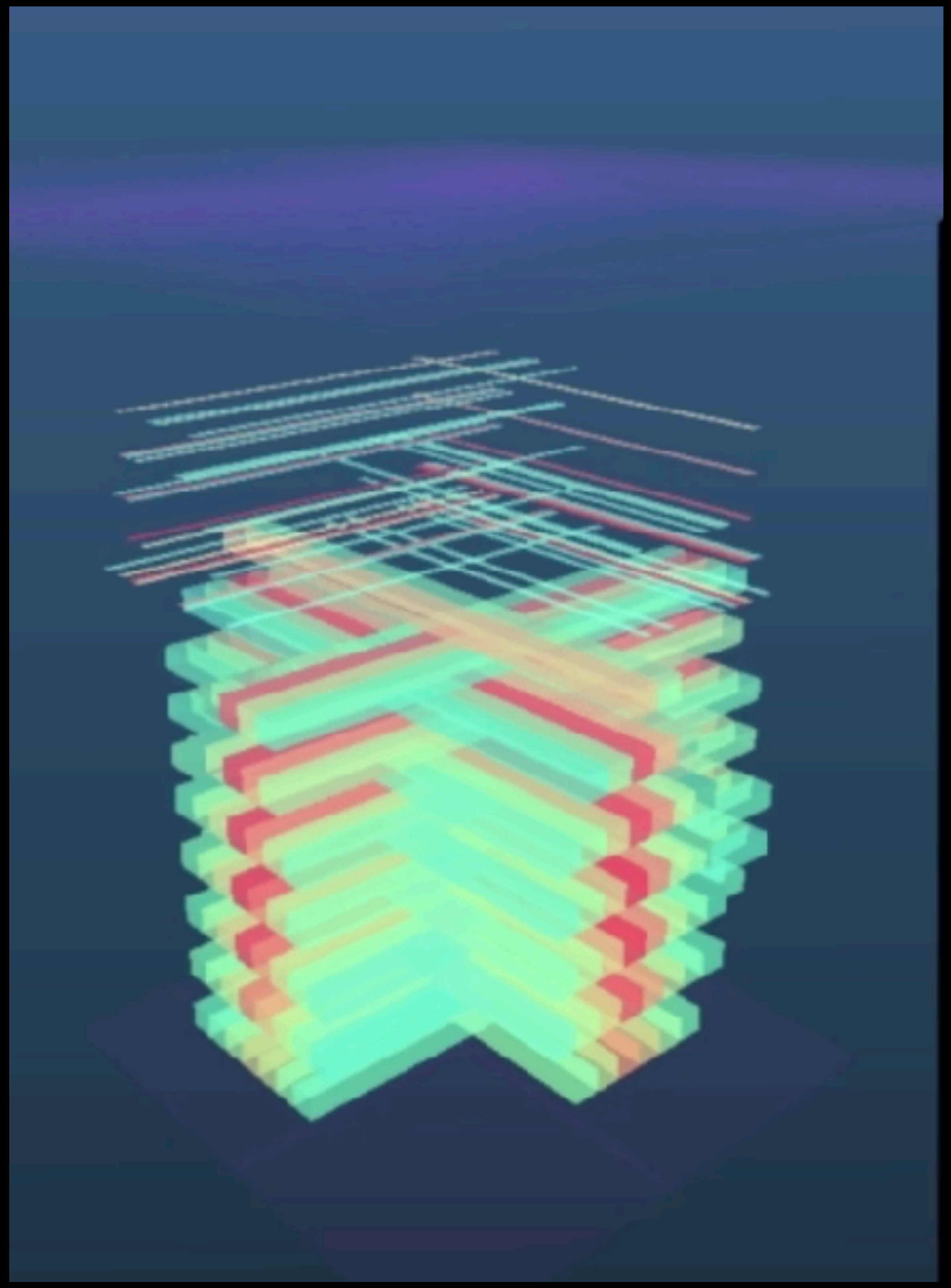
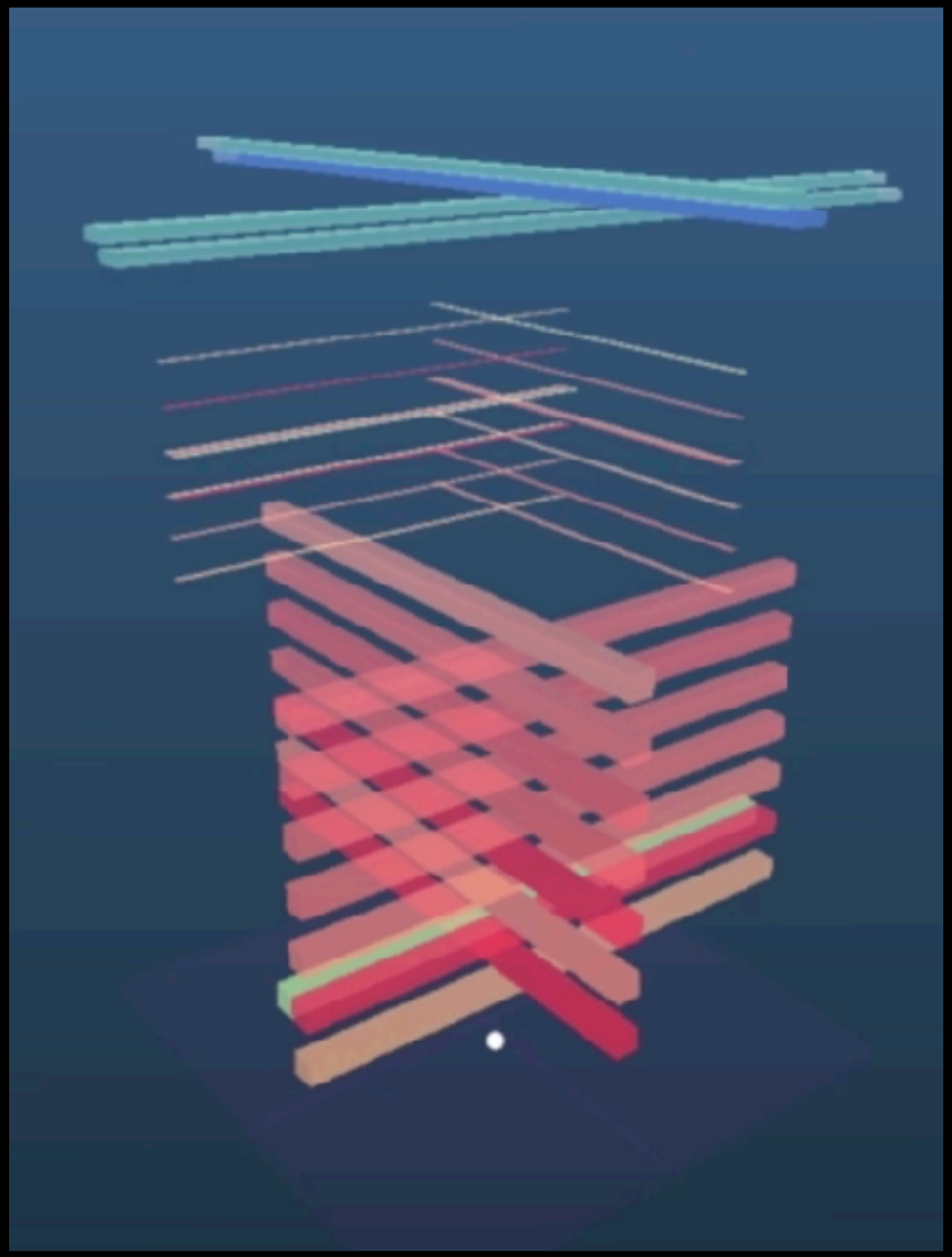
- CR electrons up to 100 TeV
- CR p/ions detection up to PeVs
- > order of magnitude higher acceptance (compared to DAMPE)

→ O(100) PeV protons / year



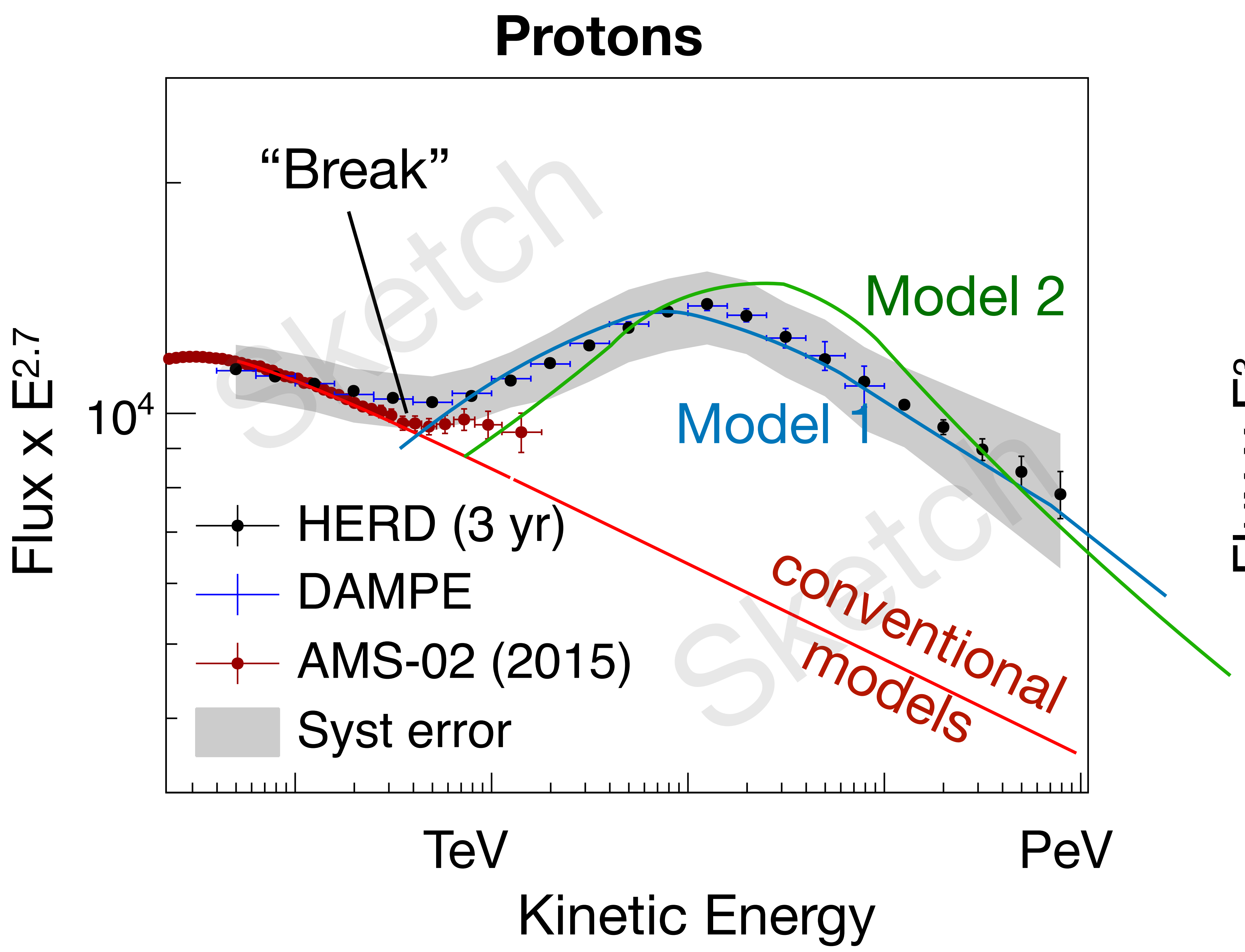


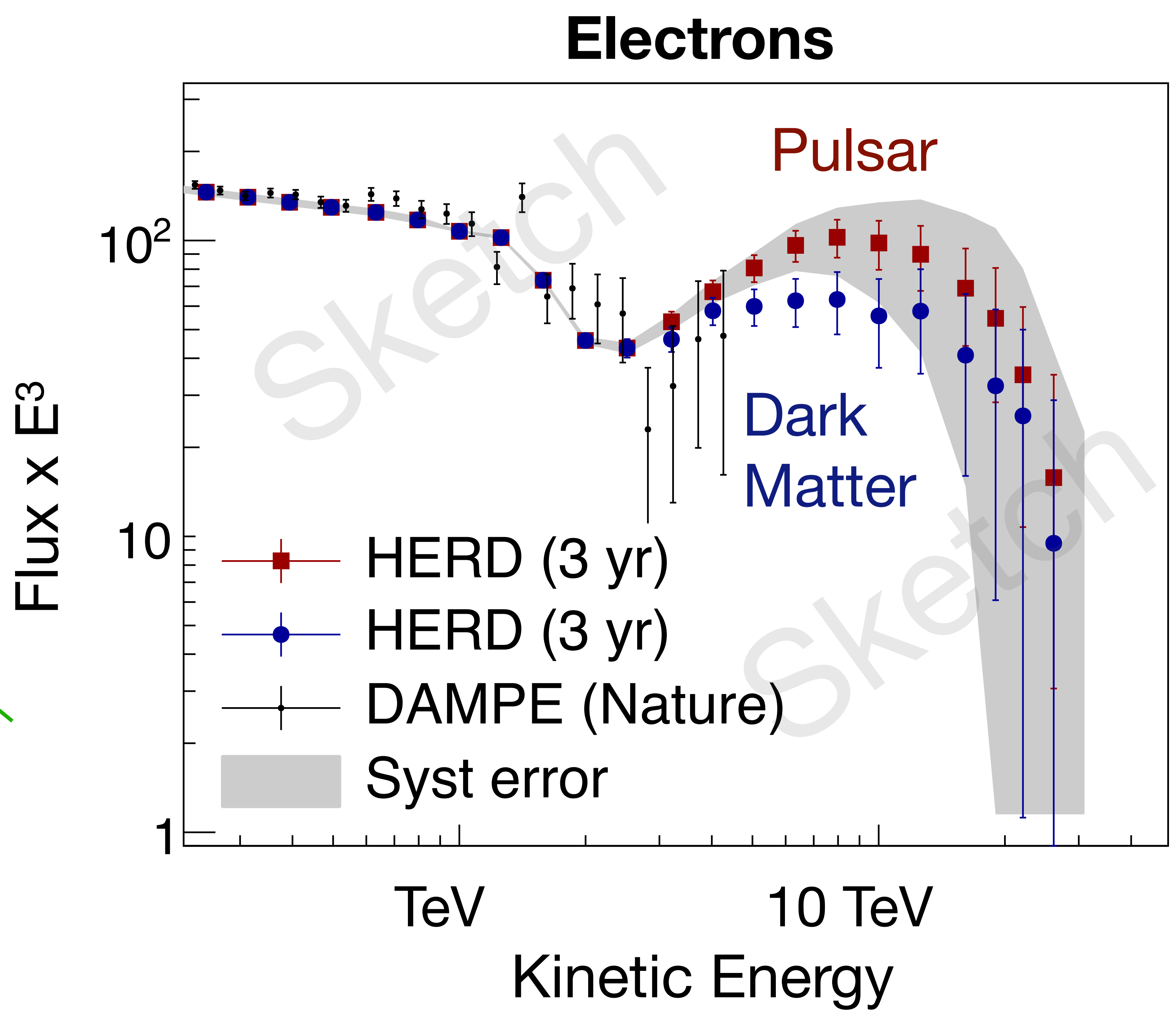
Chapter III:
Data Analysis & Challenges

Problems of TeV—PeV CR detection in Space

- Instruments“big enough” to collect good data statistics at TeV—PeV, but ….

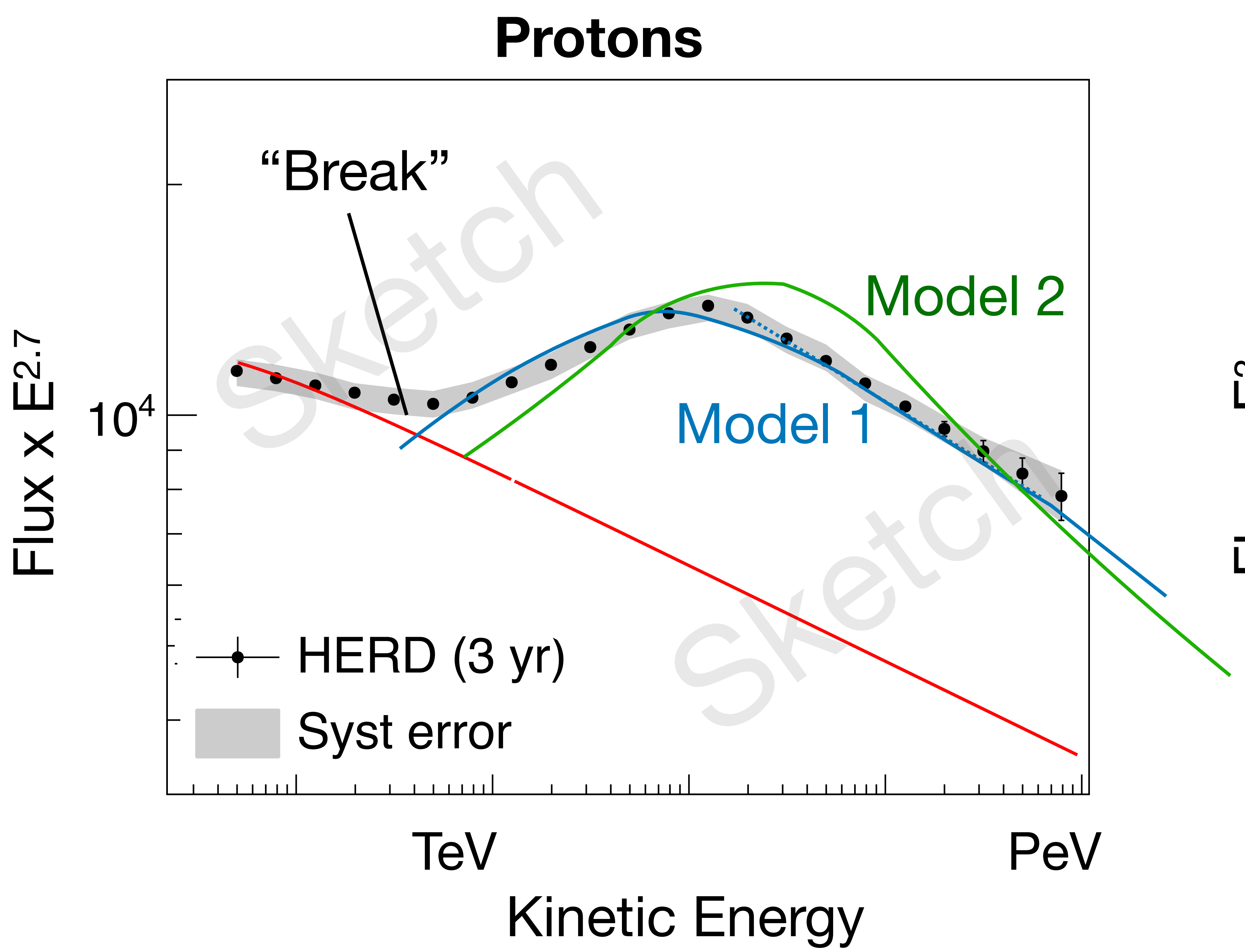


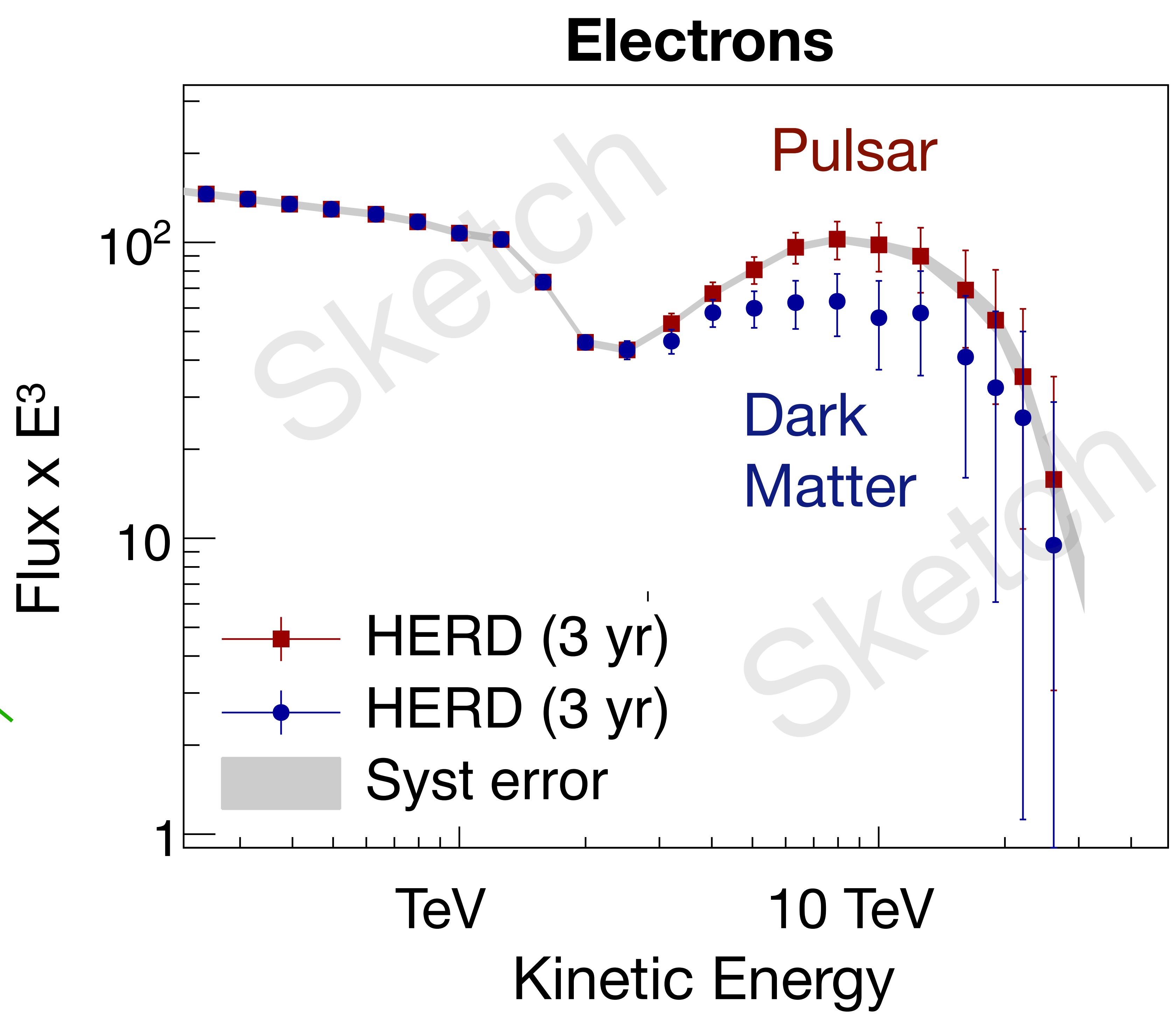


- **Systematic errors dominate!**
  Particle Identification & tracking, hadronic interaction modelling

Problems of TeV—PeV CR detection in Space

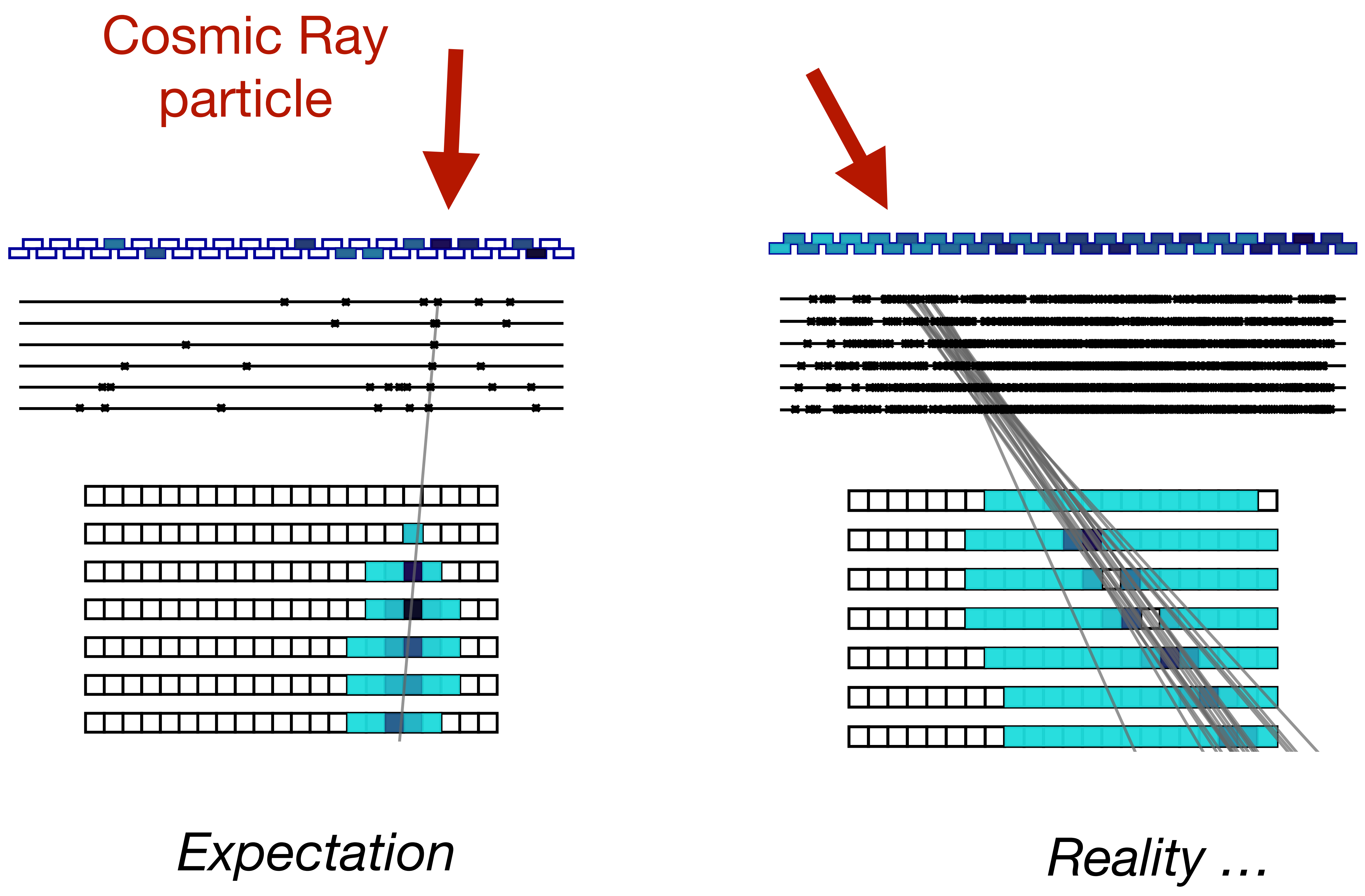
Goal — reduce the systematics and fundamentally improve the accuracy of direct Cosmic Ray measurements at TeV—PeV





Use **state-of-the-art Artificial Intelligence** techniques and improved **hadronic simulations** to minimise the key uncertainties

Particle Tracking



Primary CR track drawn in the sea of secondary-particle hits

- Pre-showering before the calorimeter
- Back-splash from calorimeter
- Majority of events affected
- Gets worse at higher energies

Similar to LHC particle tracking problem?
— … not exactly

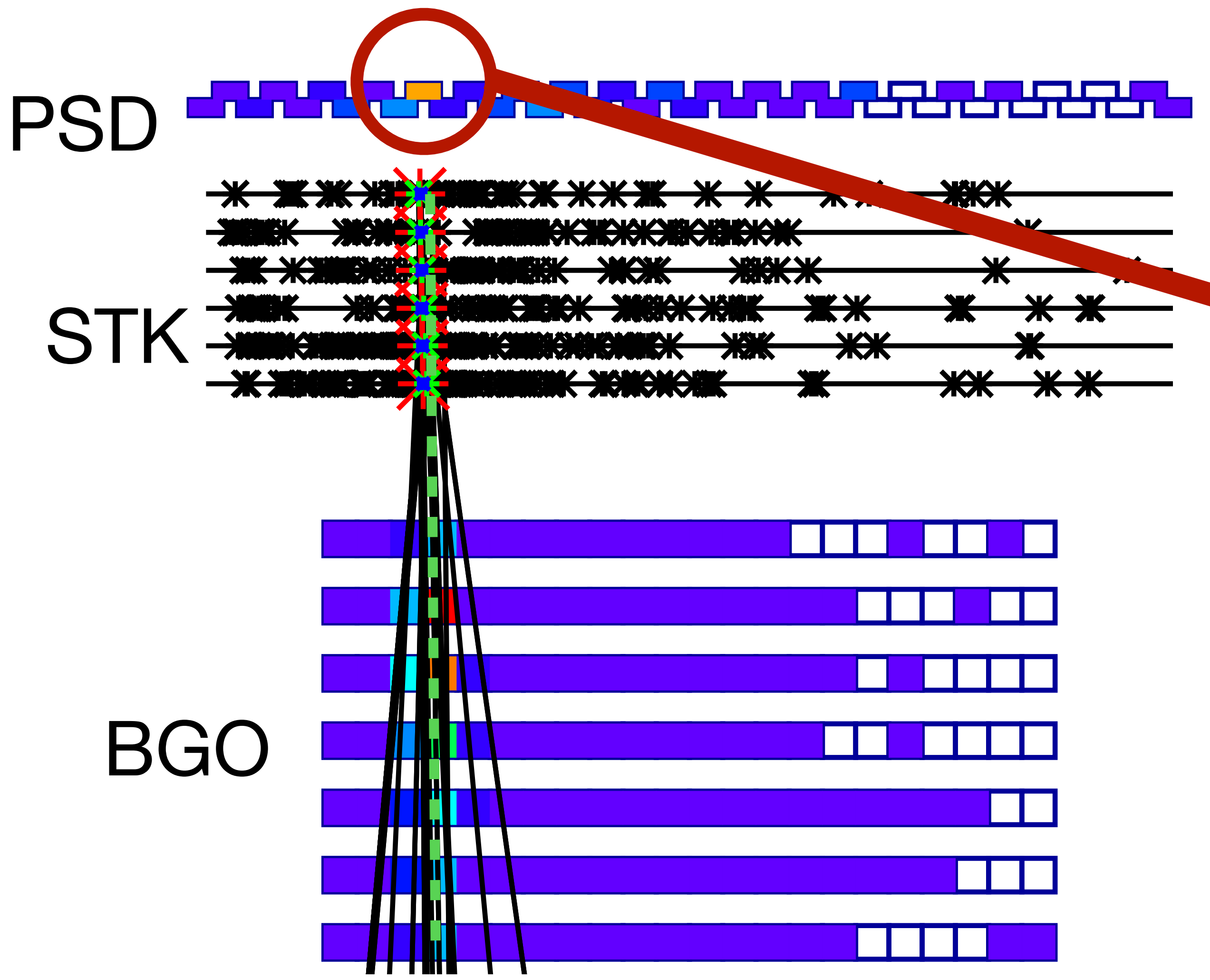
- No magnetic field
- Interaction point (axis) unknown
- Way higher energies …
- More passive material in/around tracker

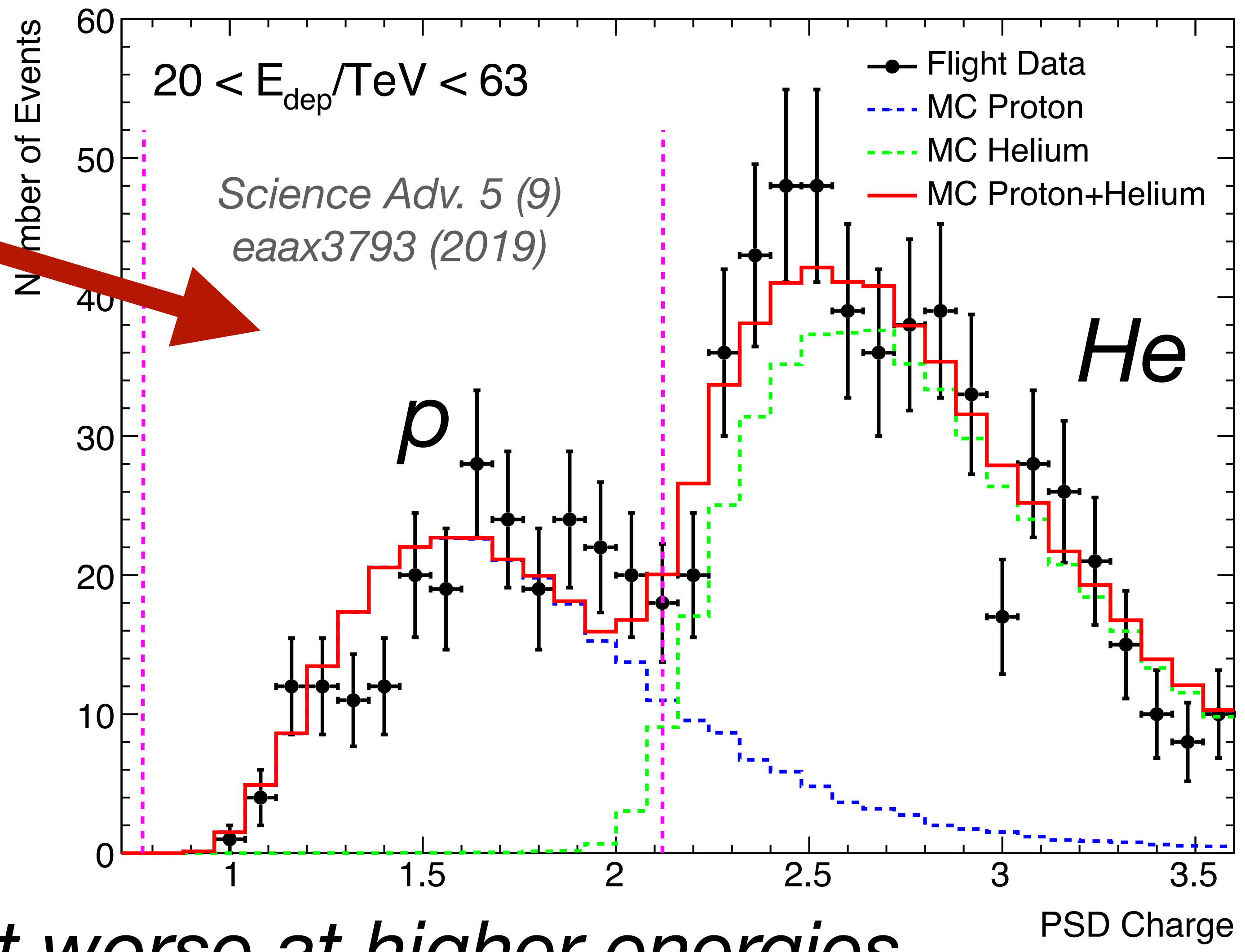
Conventional pattern recognition not capable of disentangling the primary particle track

→ **give a shot to AI & Machine Learning**

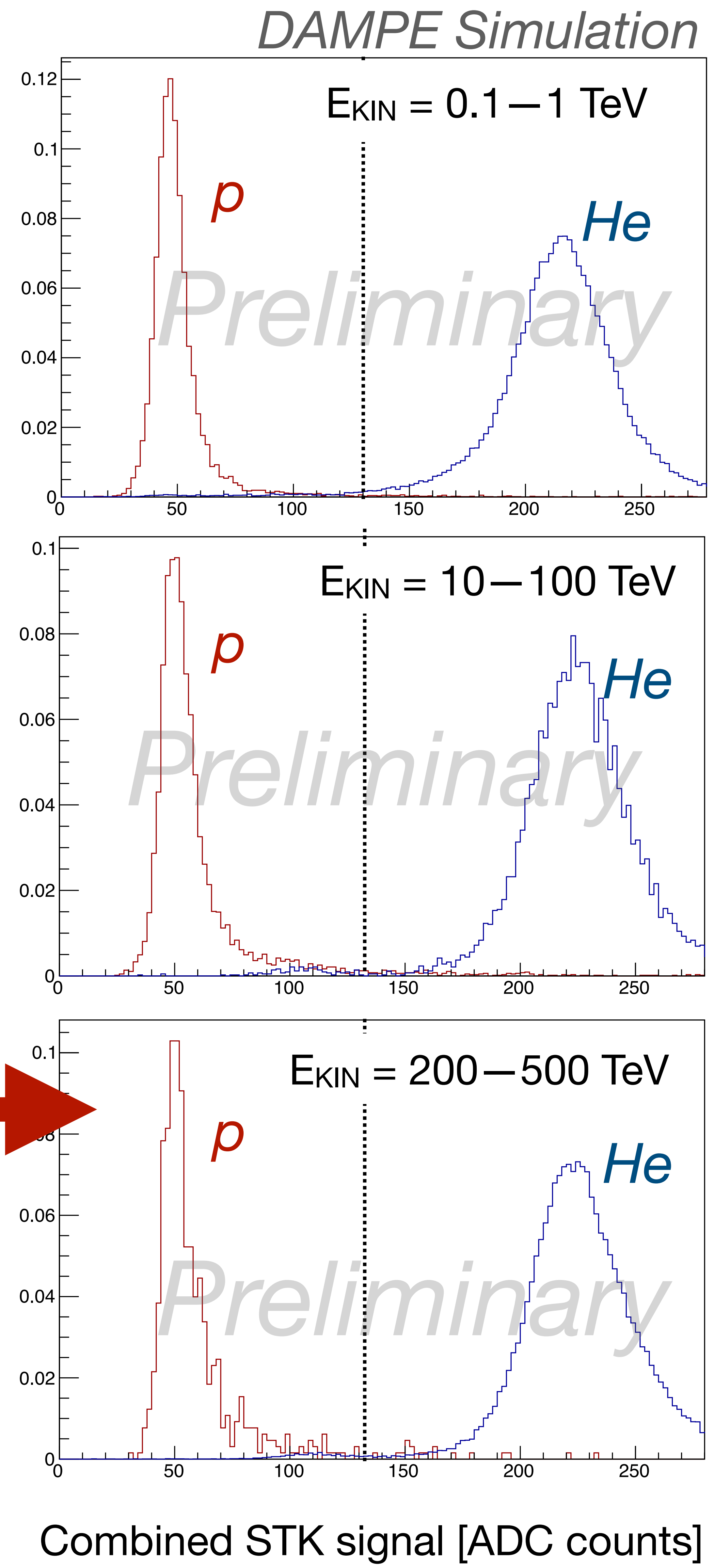
Particle Tracking & Z identification

At present, Z measured in Plastic Scintillator (PSD):





Gets event worse at higher energies …



Here we assume the primary track is reconstructed & identified

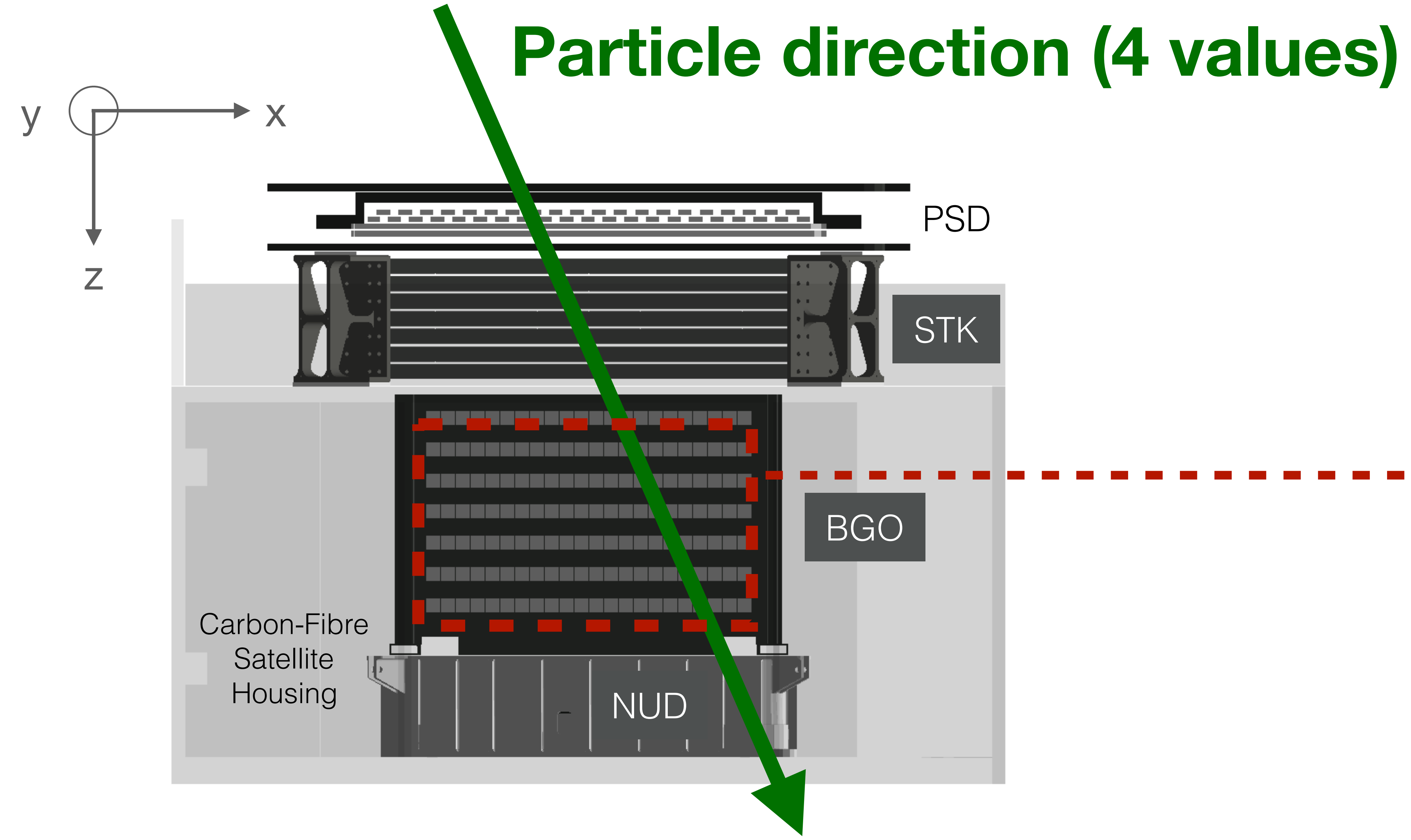
Why precise tracking is important for CR?

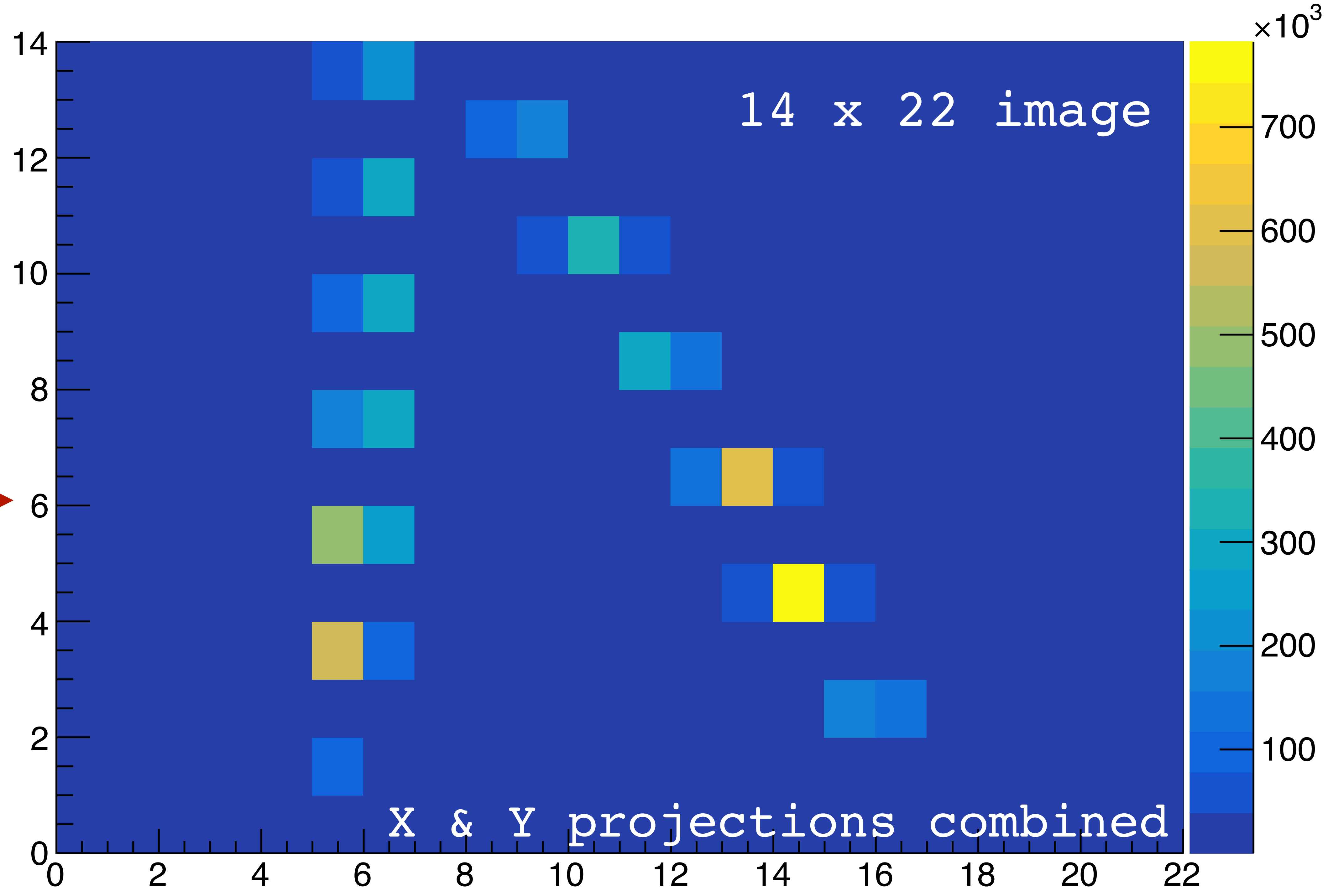
- **Enables STK-based Z identification!**
- Not affected (almost) by secondary particles (unlike PSD)
- Provide up to 12 independent Z measurements
- High accuracy at all energies

Tracking & Machine Learning — ConvNet

Many ides for ML application … Let us start with the **seed:**

- **Initial / rough guess** of a particle direction, provided by either
  A. Combinatorial guess (e.g. 3–point combinations from the tracker)
  B. External detector (calorimeter) → ***Used in DAMPE***

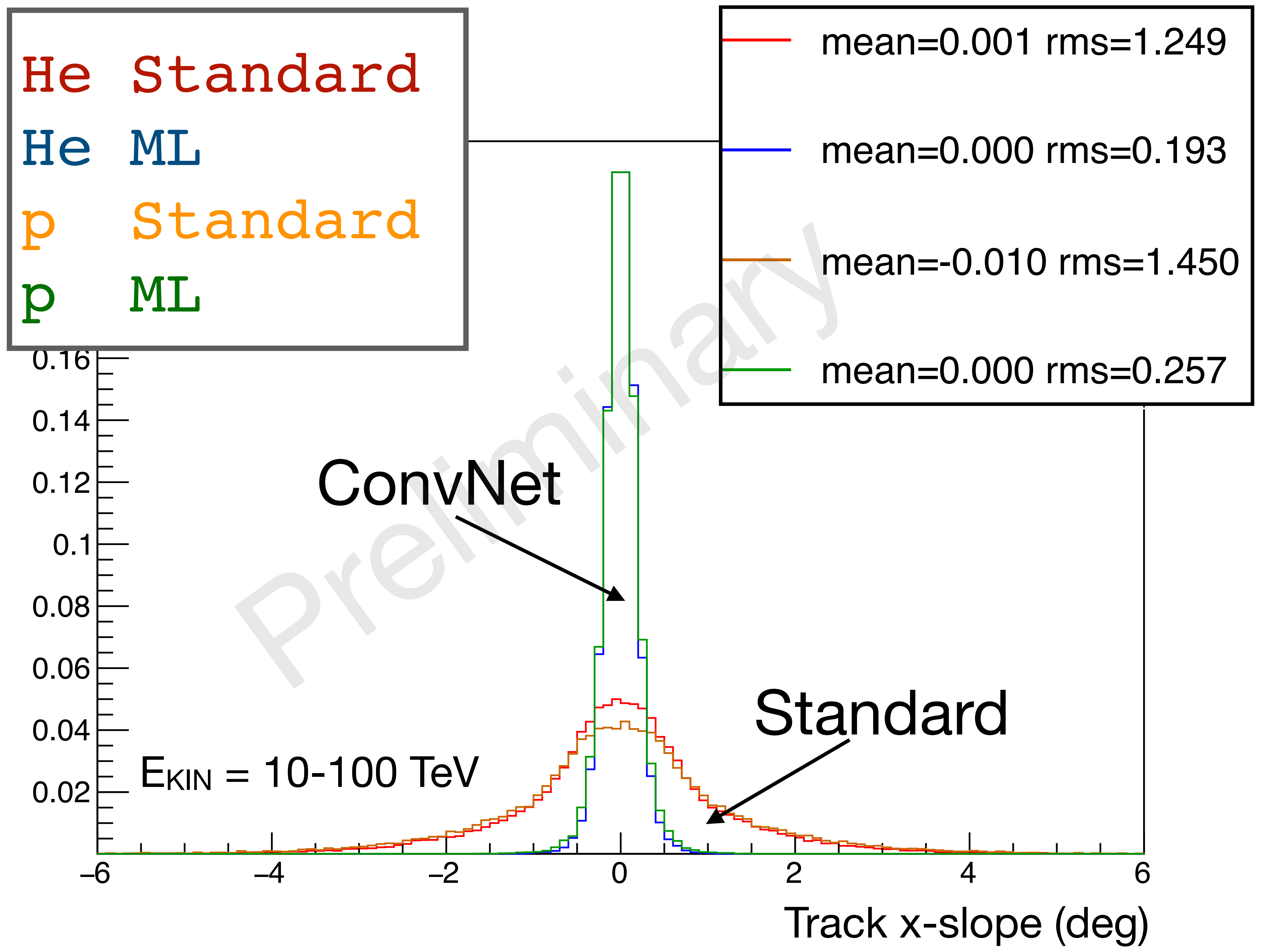


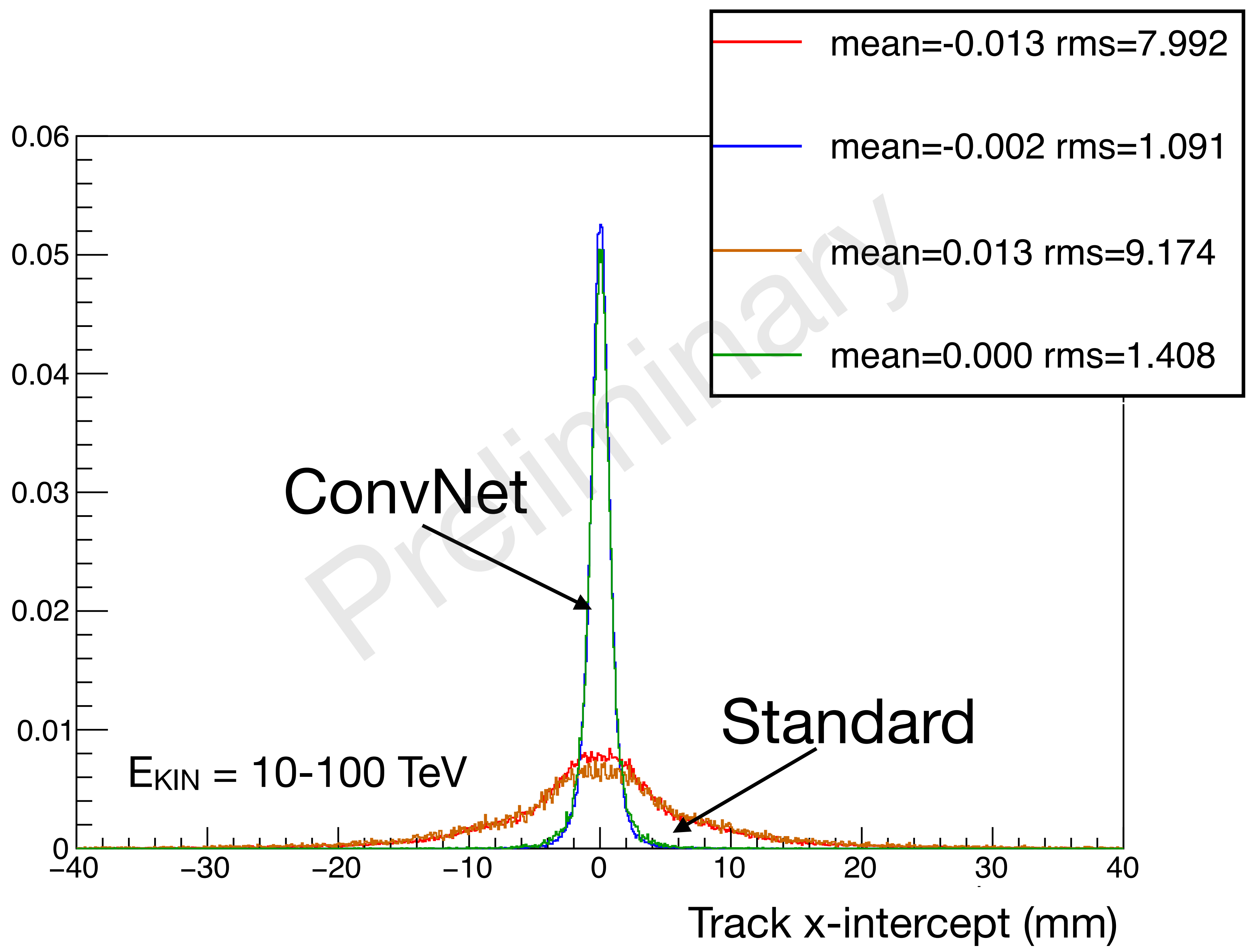


*Try regression with **Convolutional Neural Net** based on BGO "image" to predict the seed*

Tracking & Machine Learning — ConvNet

Preliminary ConvNet at multi-TeV significantly beats the standard algorithm:

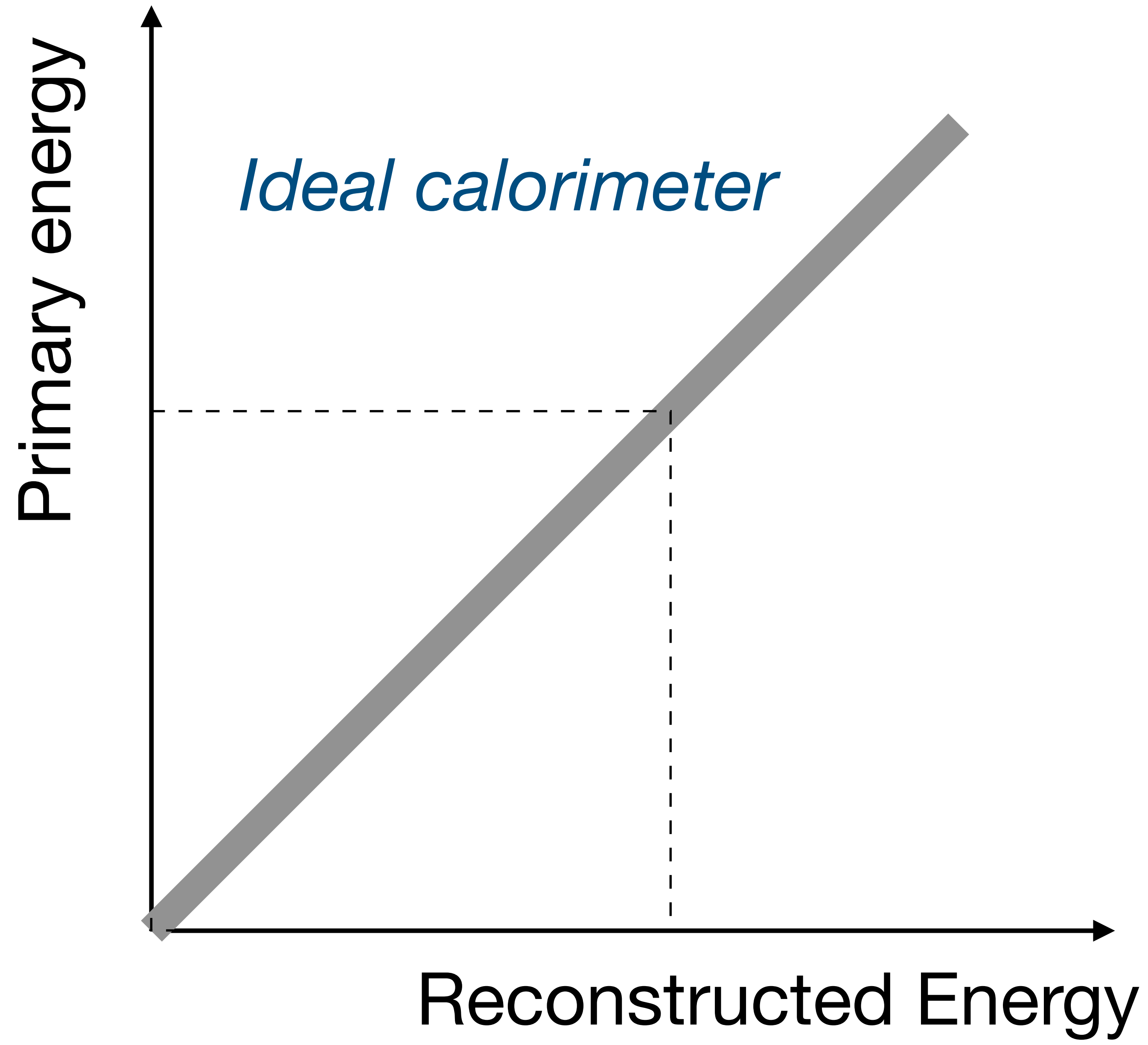


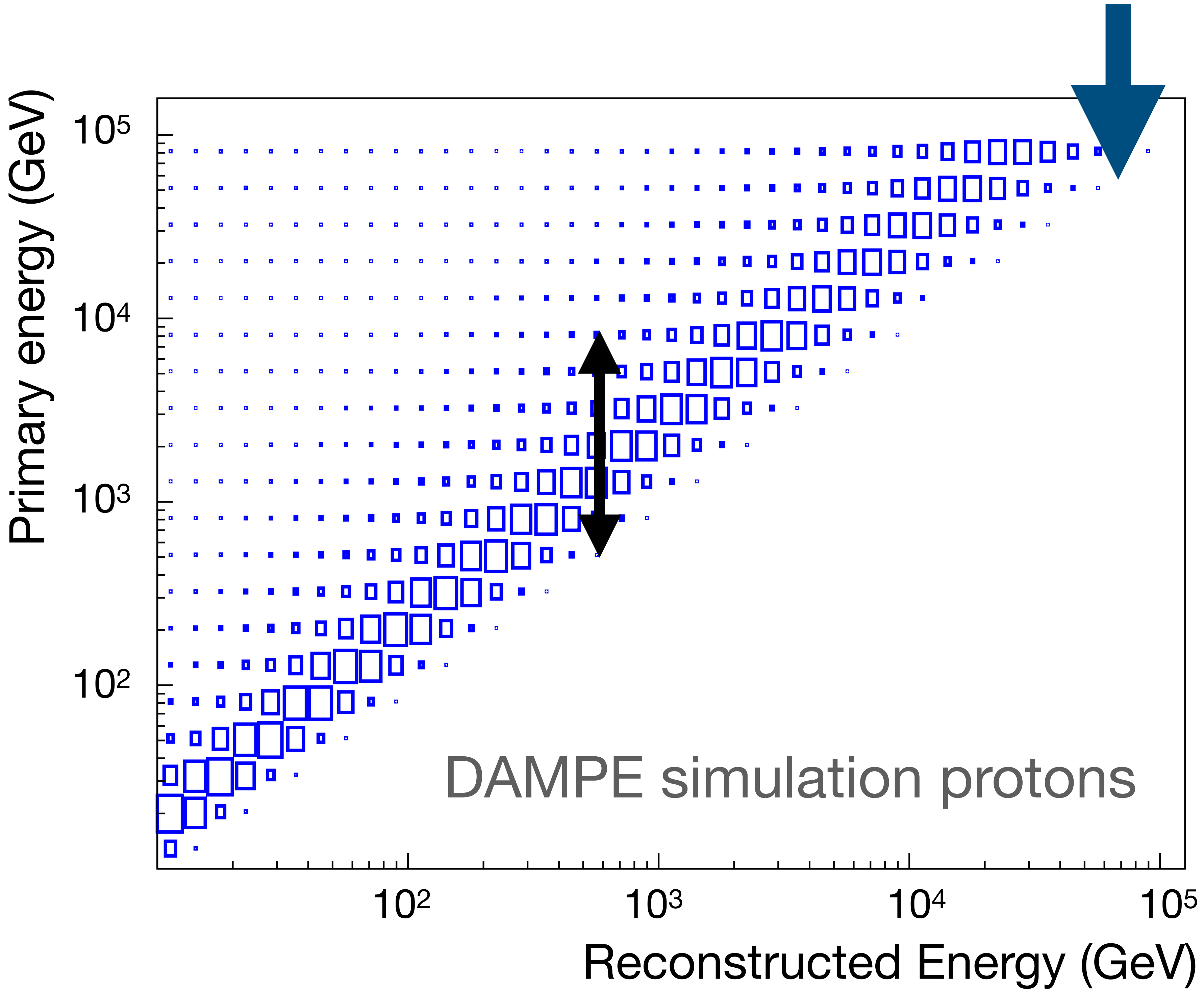


- Position resolution of ~1mm — not bad! (given that STK silicon strip readout pitch is ~0.2mm)
- Allows pre-selecting small sub-set of candidate hits for tracking
- Next steps (tracker ConvNet + Hugh approach, etc), etc.

Hadronic Interaction Modelling

- DAMPE — thickest calorimeter in space, HERD will be even bigger
  - Excellent e/γ energy reconstruction, $E_{primary} = \sim E_{reco}$, uncertainty 1% (at TeVs)
  - *p/ions* leave only ~1/3 of energy in calorimeter, response matrix is not diagonal

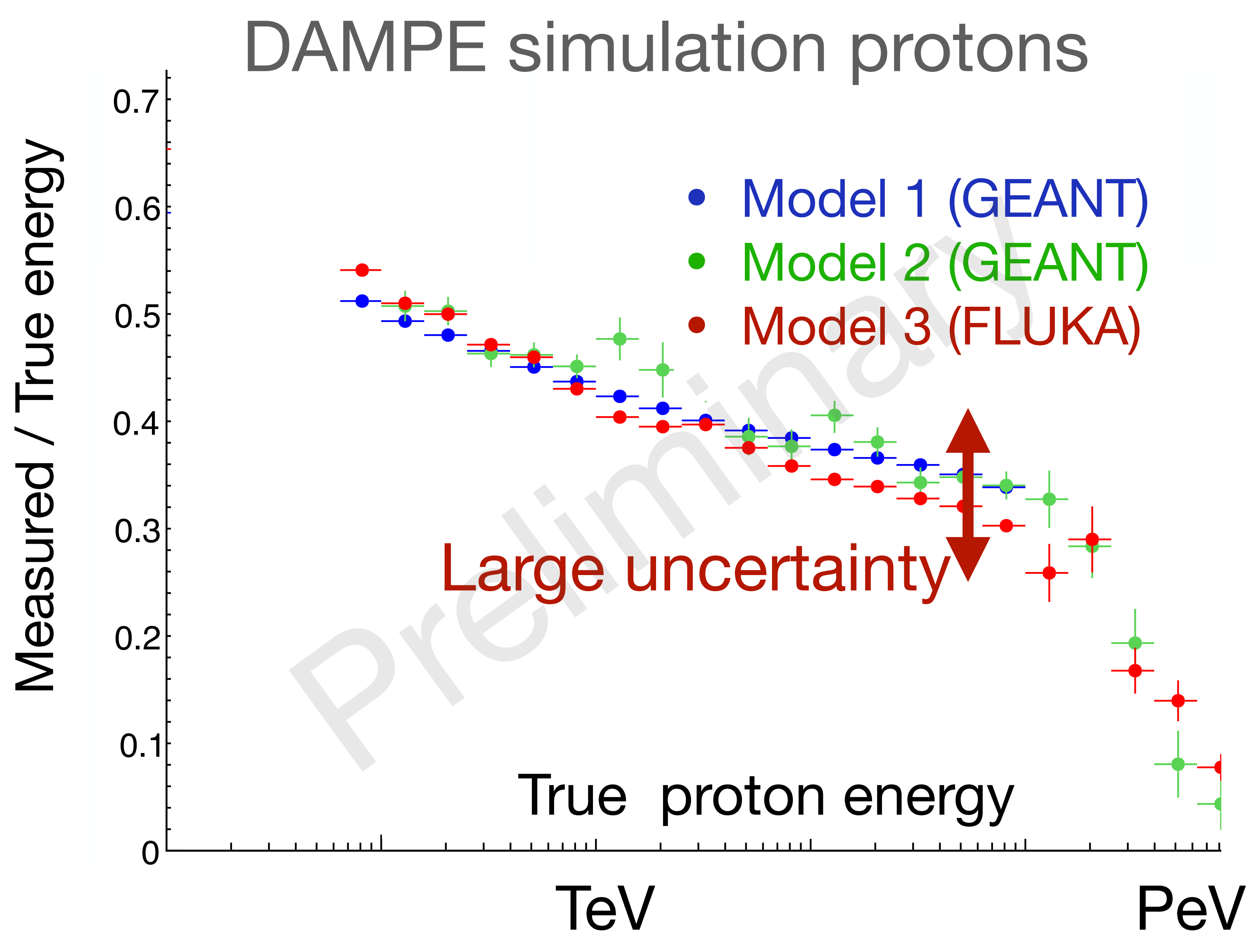




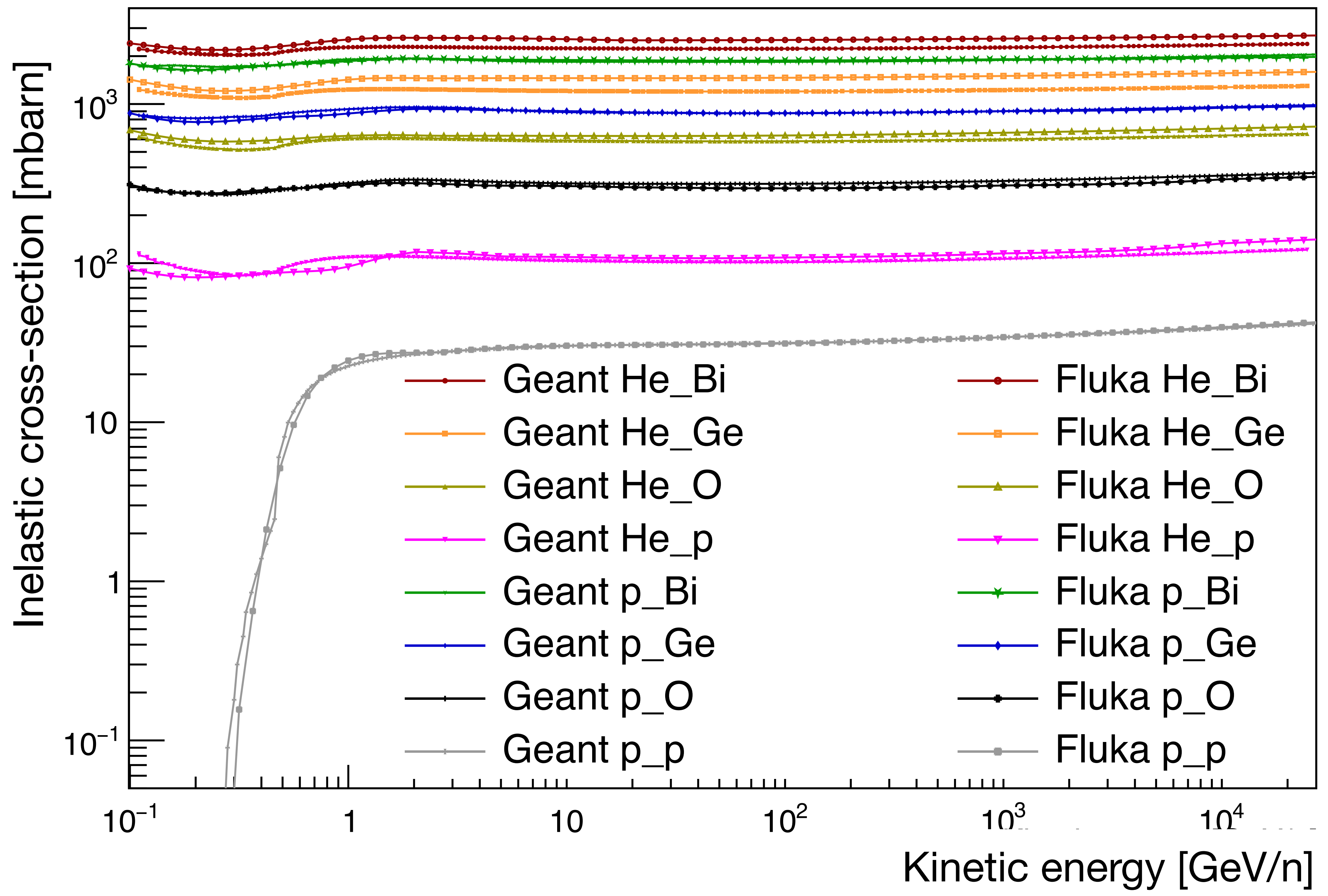
- Energy of incident *p/ion* can be identified only with limited accuracy
- Primary spectrum obtained from “visible” spectrum through unfolding (e.g. D’Augustini)

Hadronic Interaction Modelling

- CR p/ion energy spectrum measurement rely significantly on hadrons simulations
- Limited accuracy of inelastic cross-sections & hadronic models (differential cross-sections)
  - → not constrained above LHC energies
  - → **source of large systematics!**

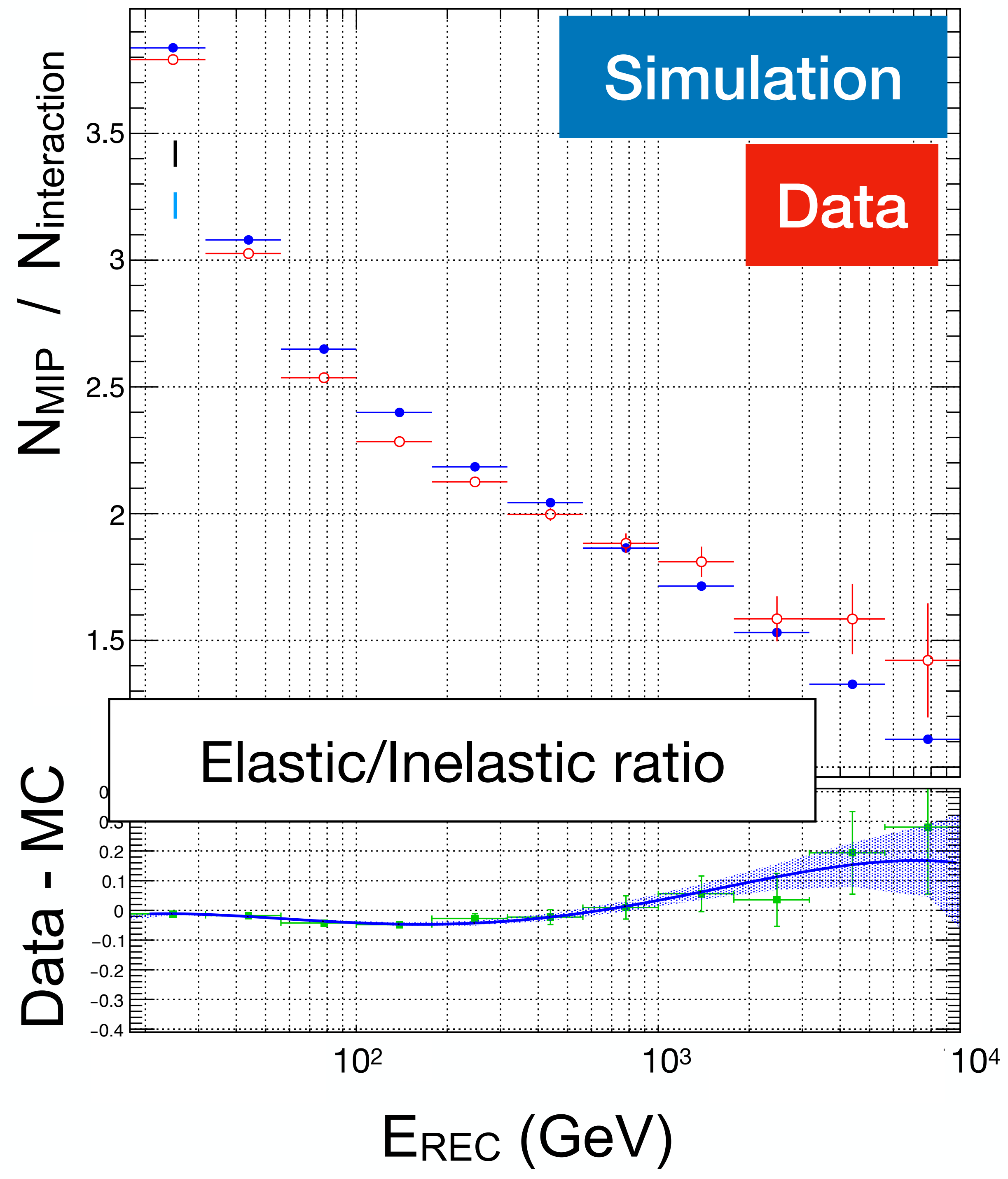


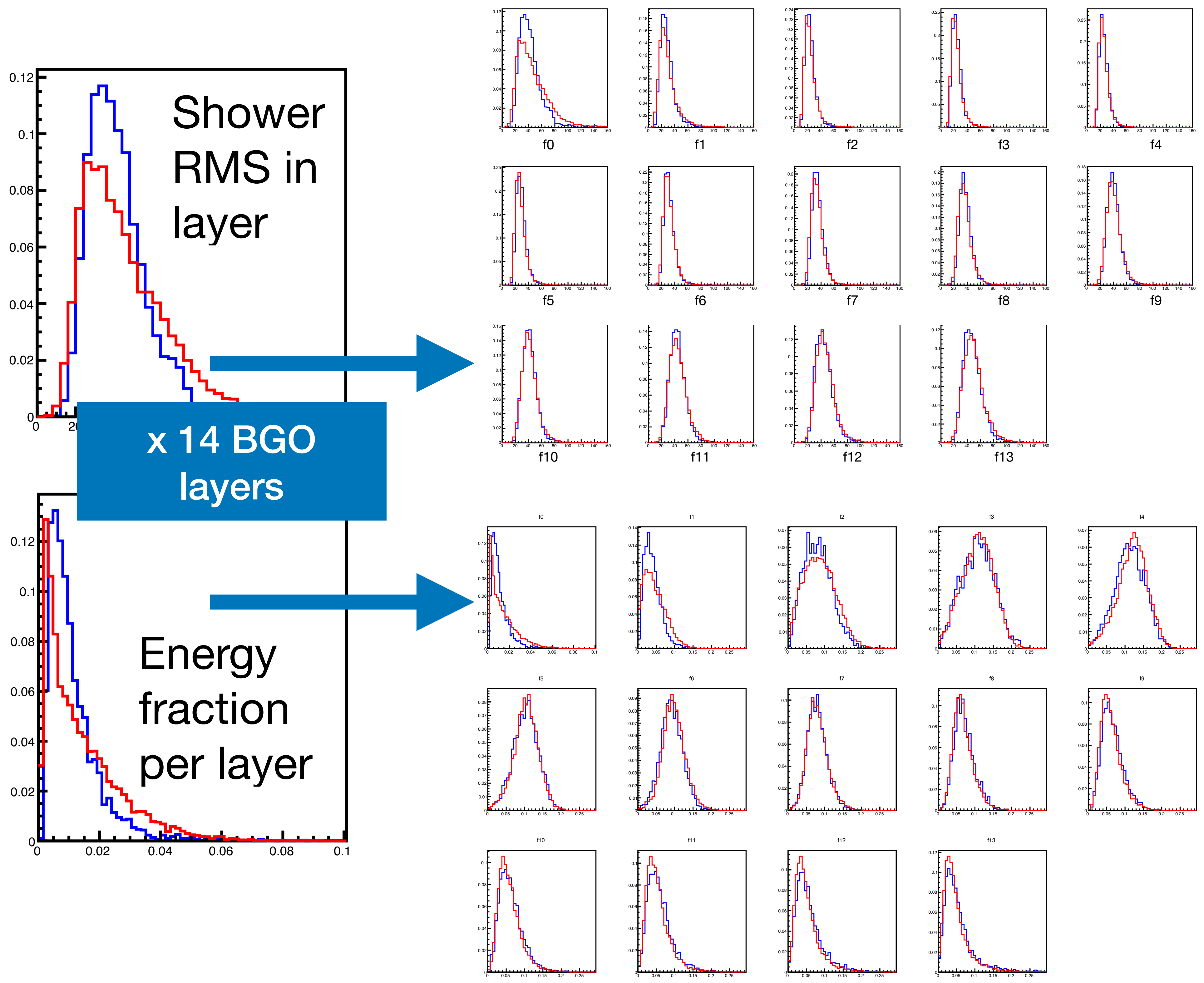
Cross-section uncertainty ~ 10%



Hadronic Interaction & Simulation Tuning

- DAMPE (HERD) feature **highly granular calorimeter** and **unique data at multi-TeV**
- Use these data to constrain/tune cross-sections & hadronic models
  - elastic/Inelastic ratio, shower shape characteristics (lateral, longitudinal, etc.)

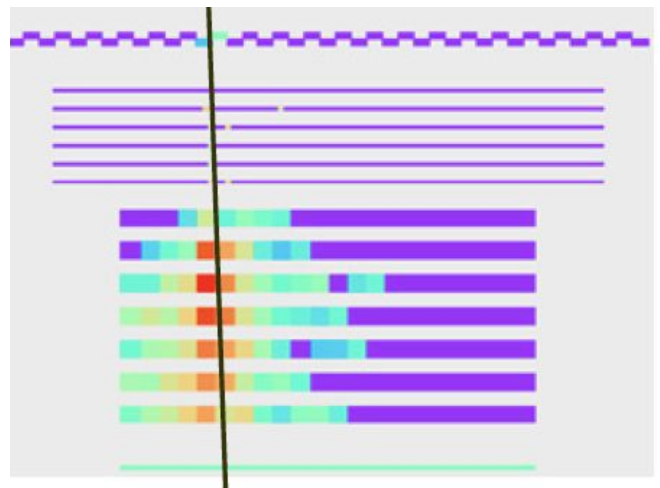


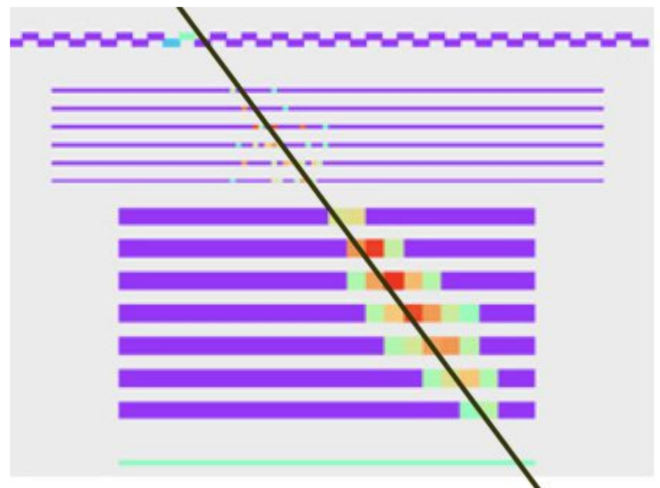


- Needs reliable **Z identification** and **vertex reconstruction** → connection to ML tracking

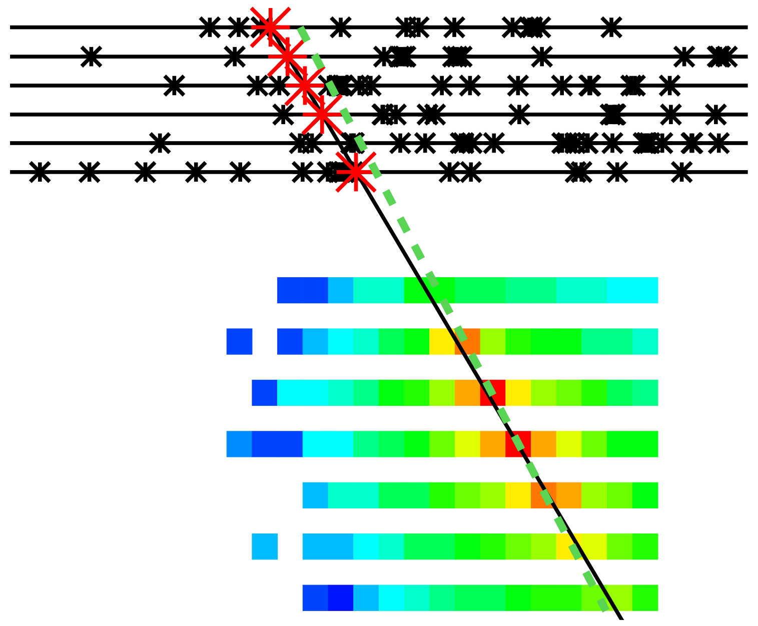
e/p discrimnation

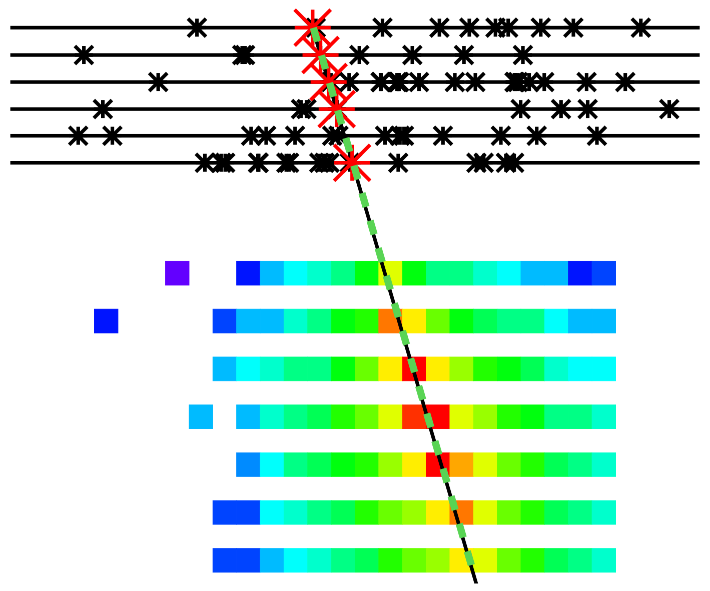
- Tiny fraction e^-+e^+ in CR → gets even smaller with energy
  → electron signal buried under proton background


typical *p* interaction


typical *e* interaction

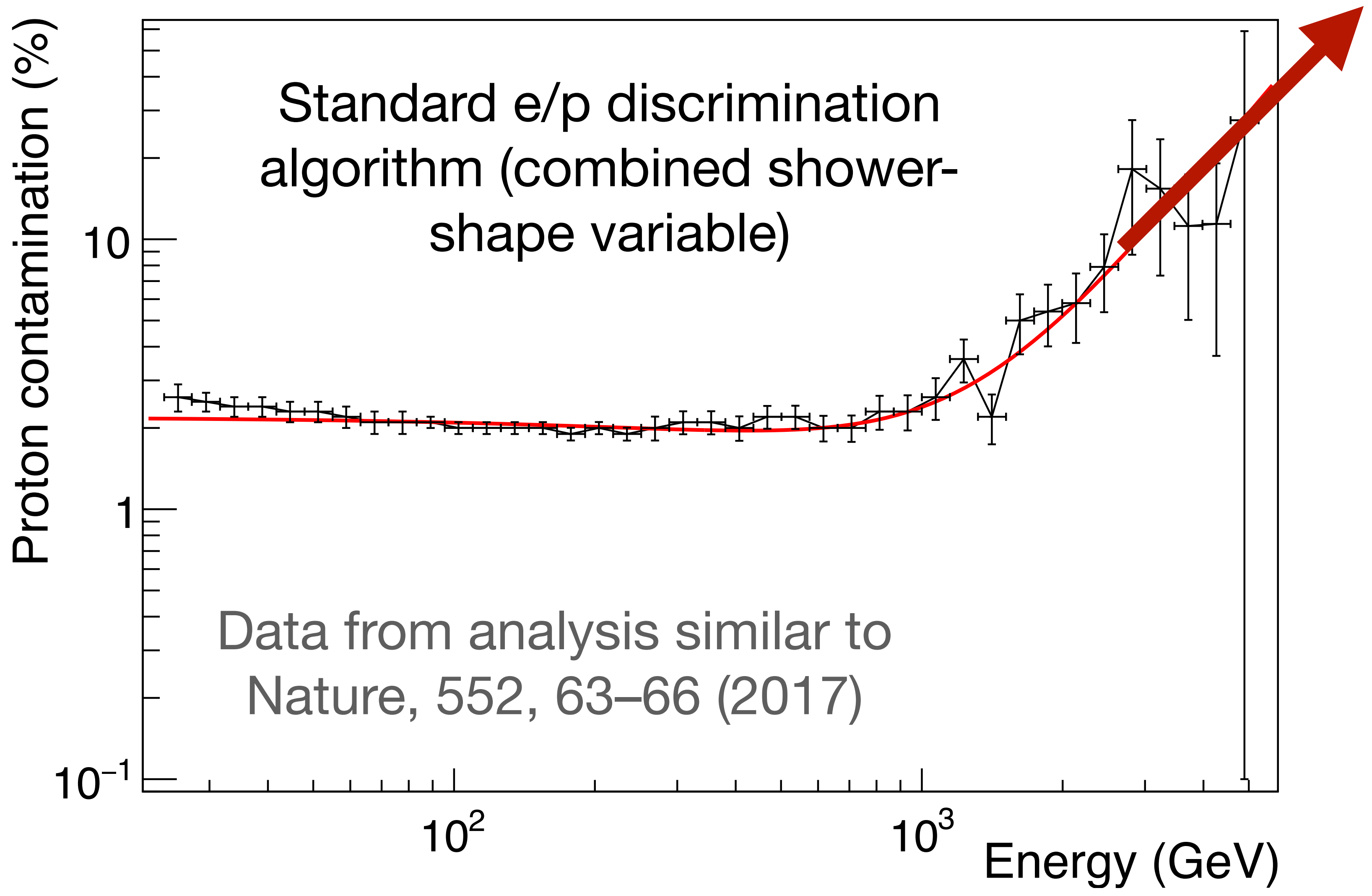
Normally proton showers are thick & long, while electron showers are narrow and well contained


p candidate (~10TeV)


e candidate (~10TeV)

At multi-TeV, a chances to get a proton which looks like an electron become very high

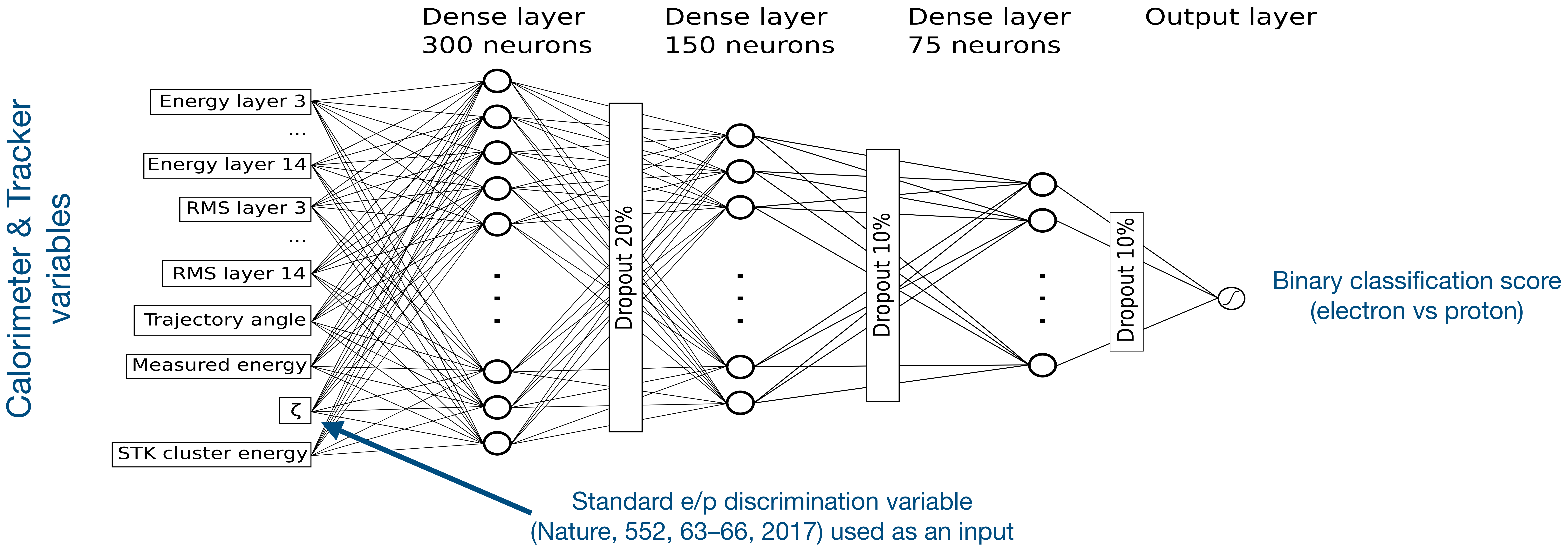
Proton contamination after electron selection



- Standard e/p discrimination method not efficient at > few TeV; background-related systematics “explodes”!
- Let’s try something new …

e/p discrimination: MLP

- Neural Net — Multi Layer Perceptron (MLP)



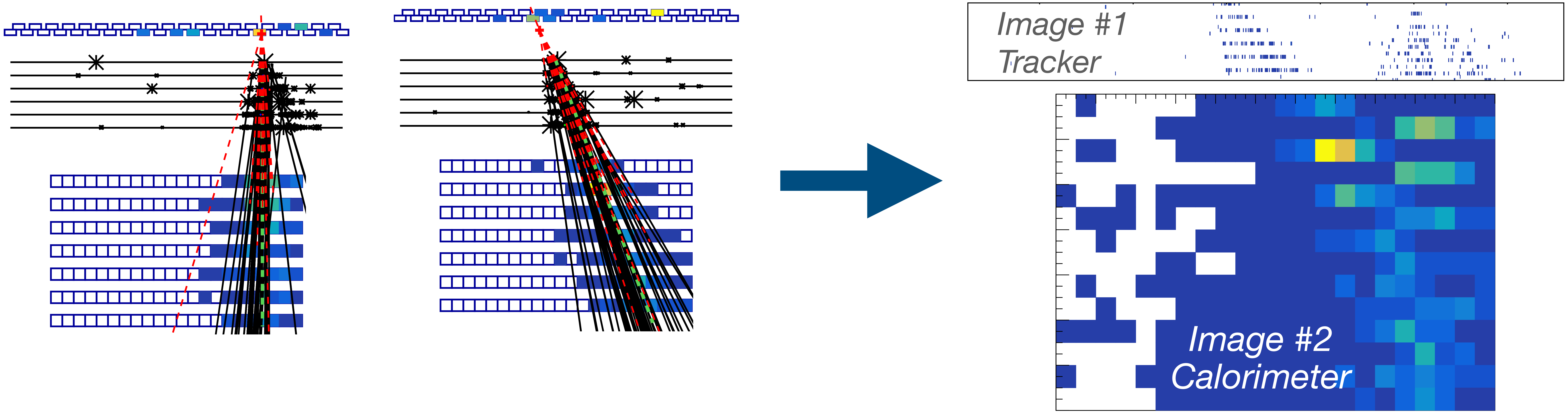
- Multiple models tested (grid search) to optimise a set of hyper-parameters (number of layers, neutrons, dropout, etc.)

D. Droz, A. Tykhonov et al. JINST, 16(07): P07036, 2021

e/p discrimination: ConvNet

- Alternative option — ConvNet
- Consider both tracker and calorimeter as images

DAMPE XZ view   DAMPE YZ view   *(images not to scale)*

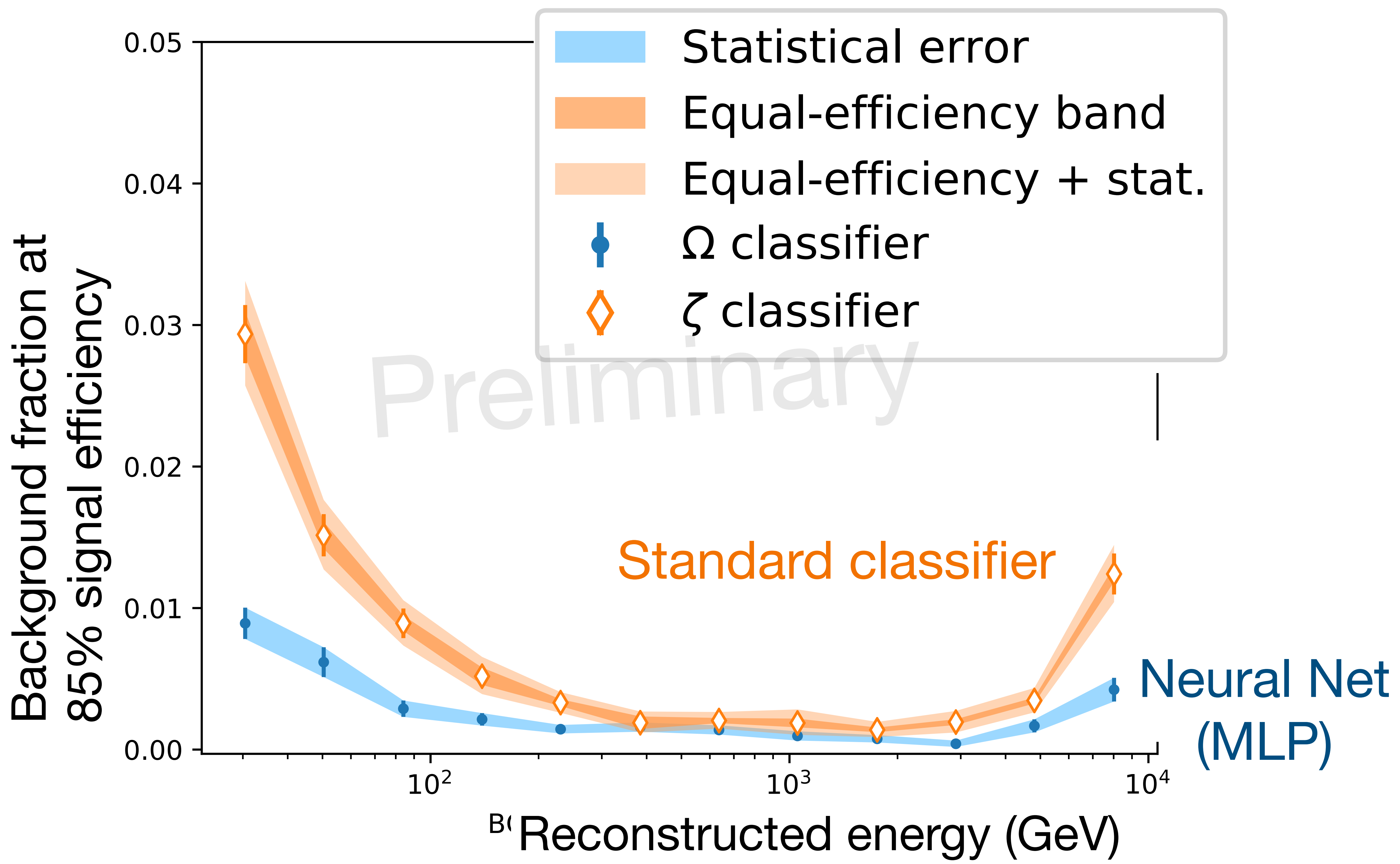


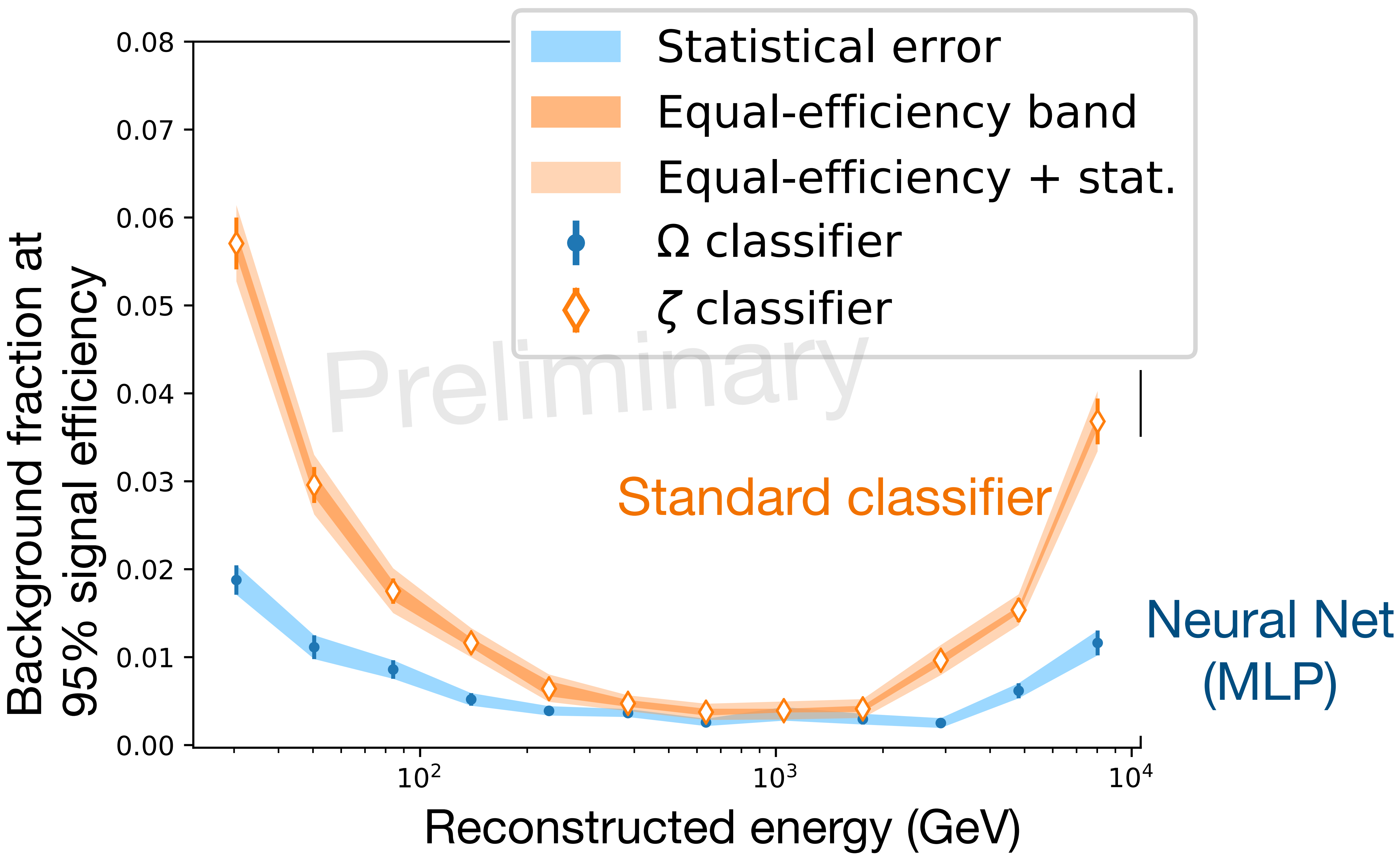
- Outputs of two ConvNets concatenated, followed by a standard MLP network
- Extensive optimisation campaign — network architecture, impact of data selection, etc.

  (lots of technical details beyond the scope of this talk) …

e/p discrimination: ML performance

- Neural Net classifier (MLP): 3—4 times better *p* rejection at highest energies (10 TeV)





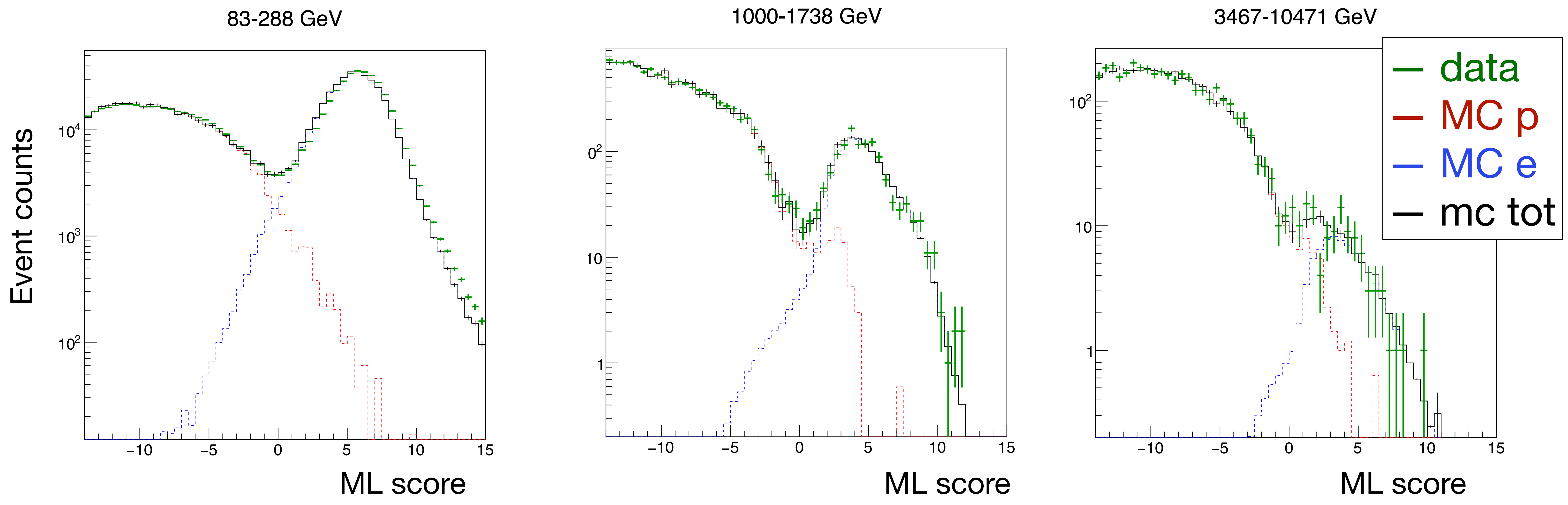
- MLP classifier with even better performance was developed → requires further data/simu optimisation
- ConvNet performance usually marginally better than MLPs, but requires more optimisation with the data

Machine Learning — data vs simulation

- Optimisation and training of Machine Learning usually done with **simulated data**
- Performance of ML algorithm is important — yes, however
- **Equally important is a good correspondence between simulation and real data!**

  Quite specific to particle physics!

electron / proton discrimination with MLP classifier, data vs simulation:

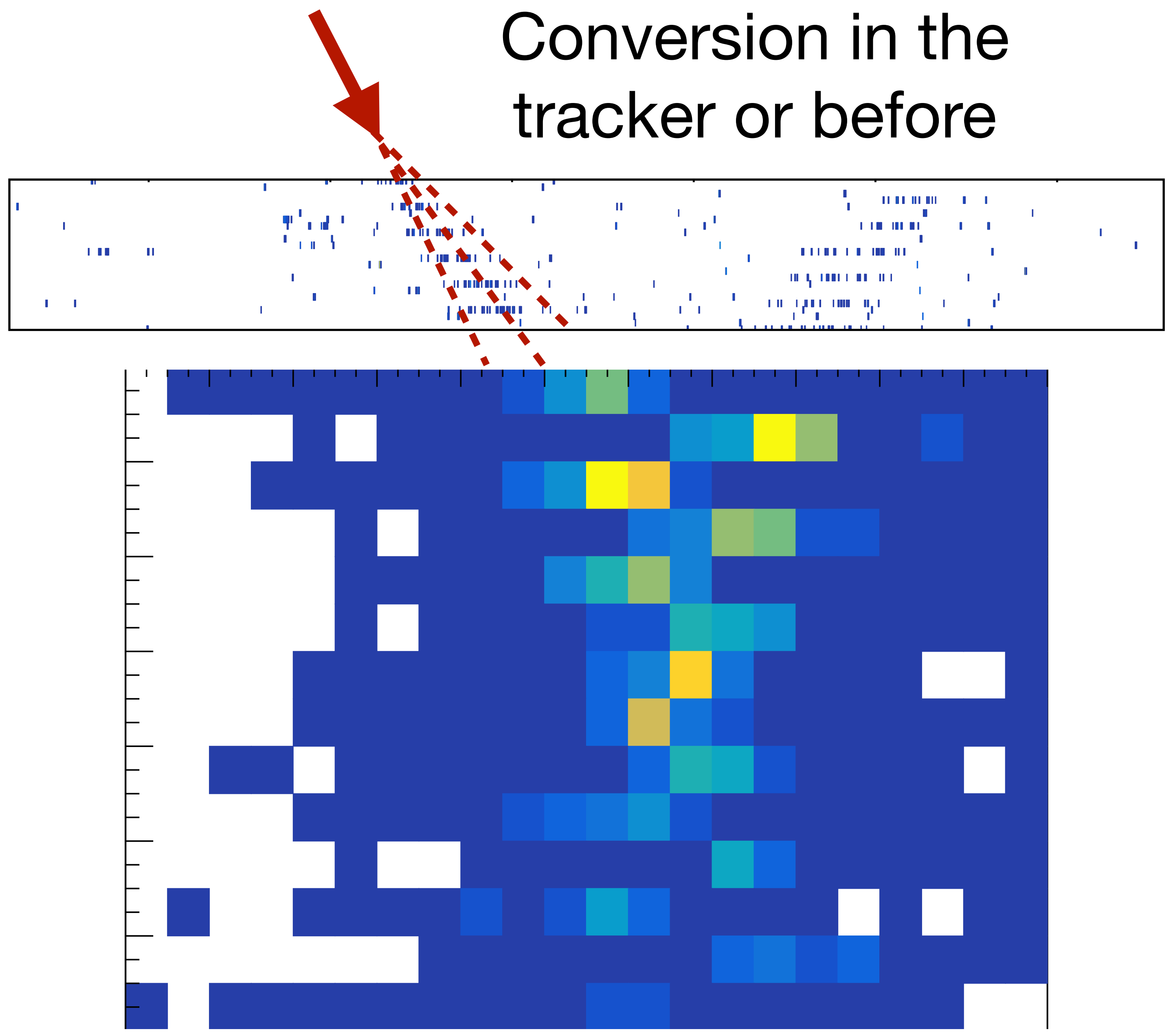


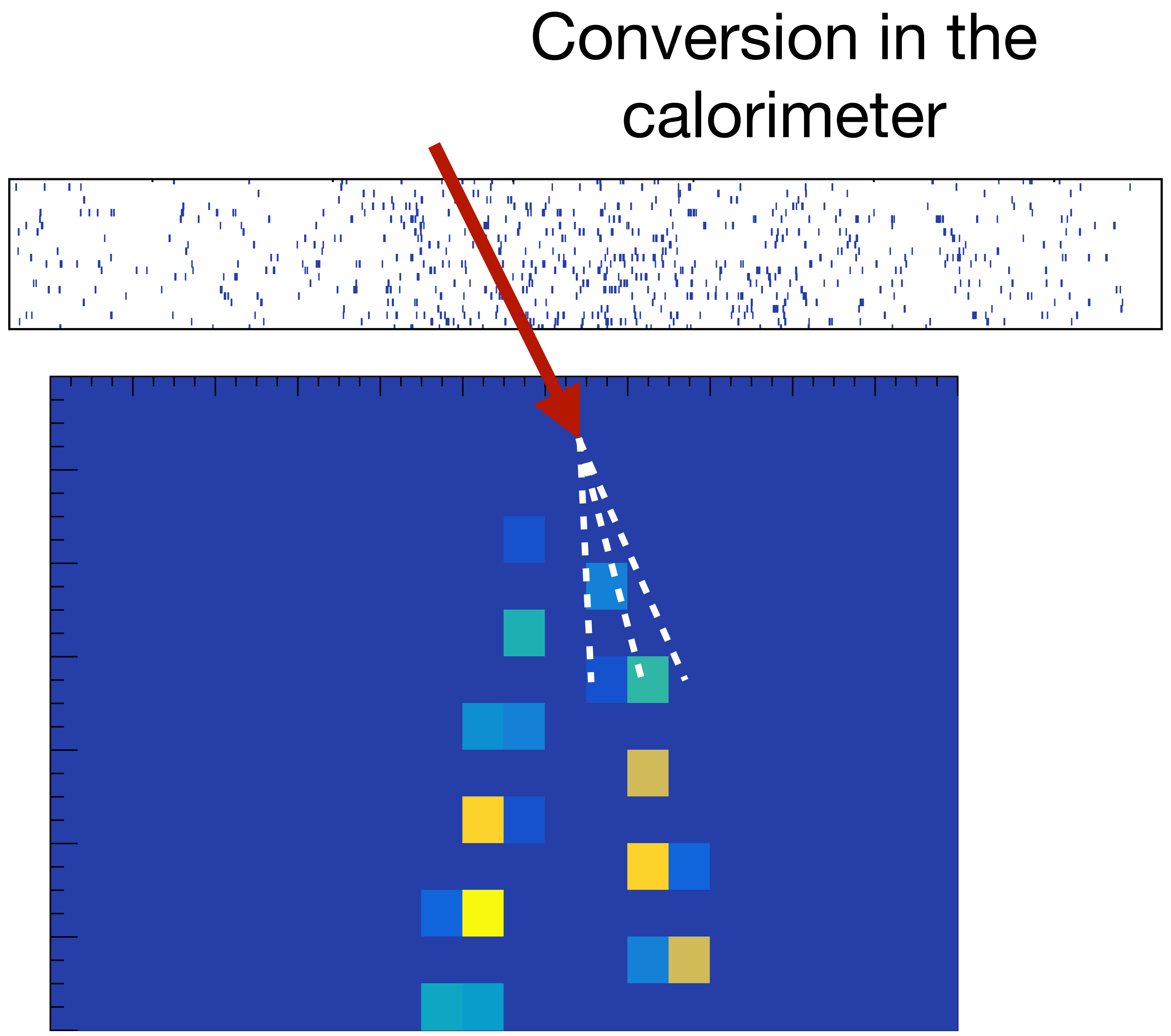
Good data / MC agreement achieved — reliable classifier!

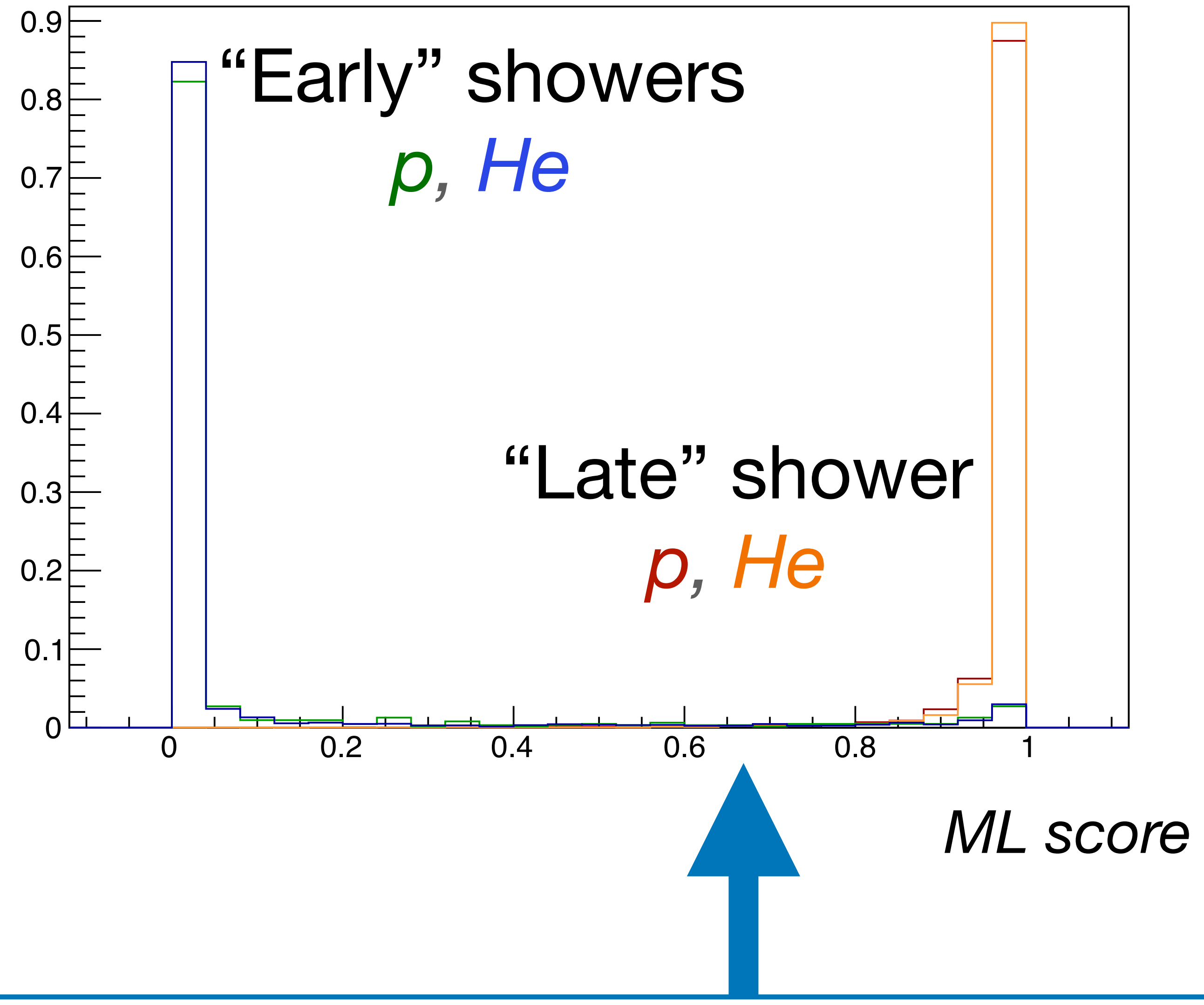
Machine Learning — vertex finding

Inelastic interaction Vertex reconstruction (CR measurements, hadronic physics, etc.)

- Regression problem (predict vertex position) — yes, seems “easy” in the Tracker
  → not good precision in reality → majority of events convert in Calorimeter







- First, a classification problem to solve: does conversion happen before calorimeter?
  → **Developed ConvNet calssifier — very good (per cent level) accuracy!**

Wrap-up

- **Cosmic Rays (CR) — the laboratory for the Universe study**
  - **TeV—PeV** is at borderline of our present CR understanding
  - after there are many theories / models
  - direct CR measurements are crucial to clarify the picture

- **Calorimetric experiments in space (DAMPE, HERD)**
  - Unique capability to directly measure CR at TeV—PeV
  - Data analysis bottleneck (hadronic models, particle identification)
  - Solution provided with modear AI techniques — first results very promising — ***stay tuned!***