EUROPEAN AI FOR FUNDAMENTAL PHYSICS CONFERENCE
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AI for cosmic ray direct detection in space with the DAMPE mission

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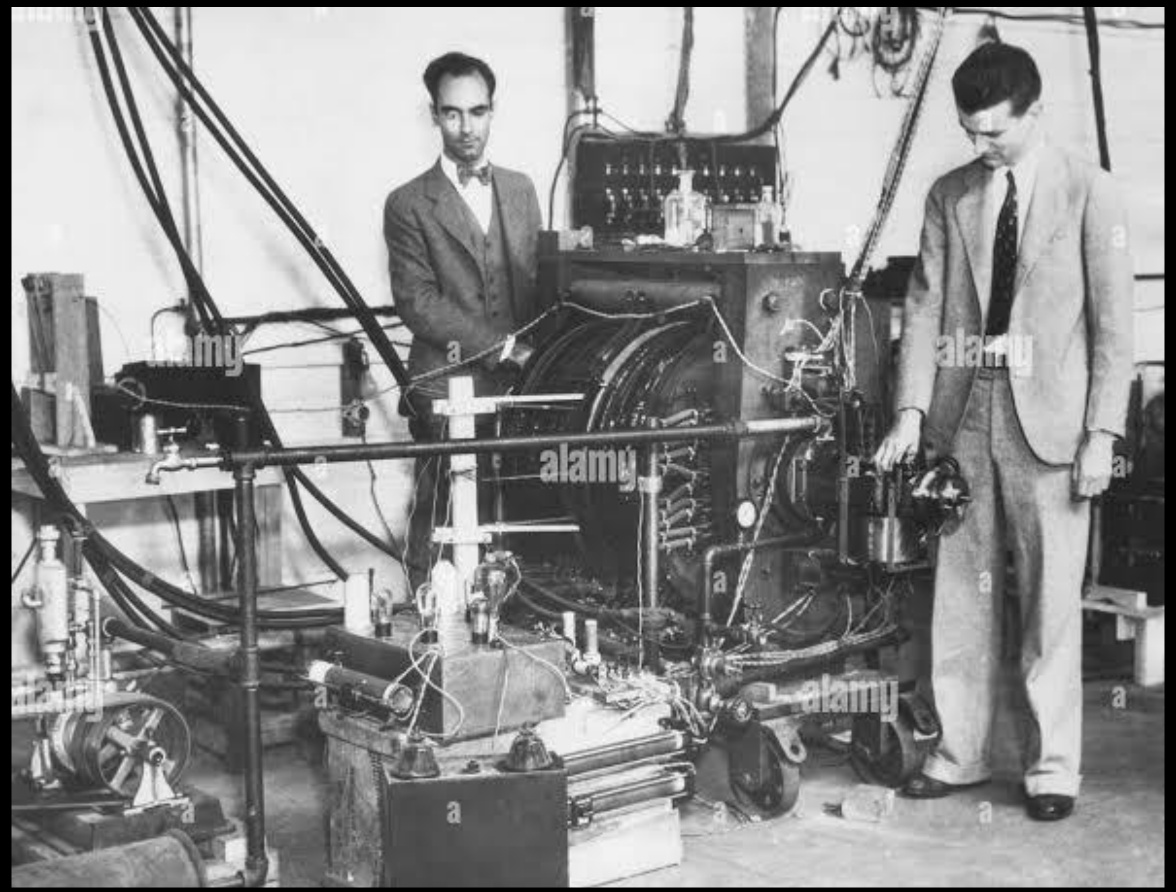
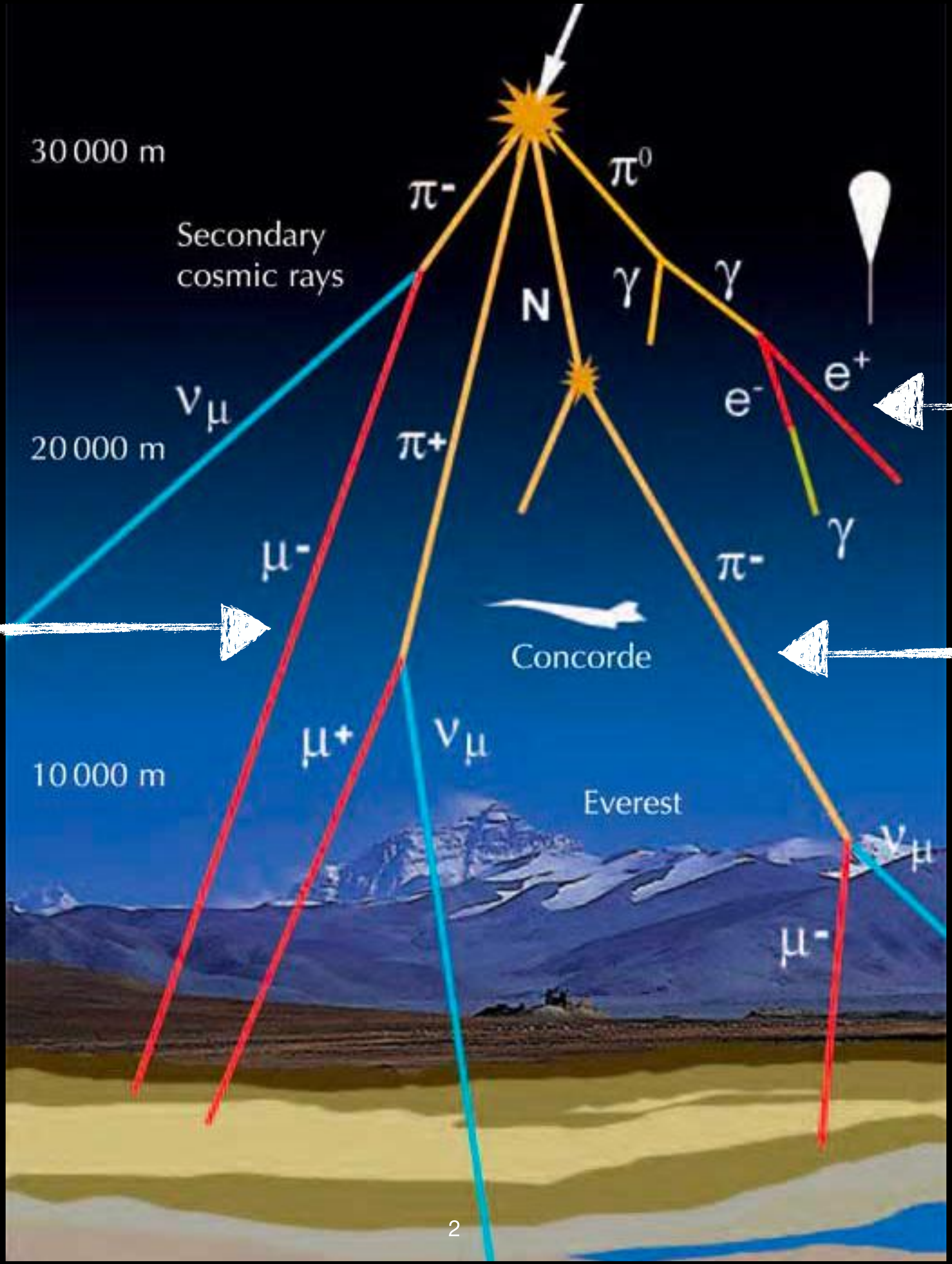
erc European Research Council
UNIVERSITÉ DE GENÈVE

Cosmic Rays - First Particle Physics Lab

Cosmic rays discovered by Victor Hess (1912, Nobel prize in 1936)



Seth Neddermeyer and Carl Anderson (1936)



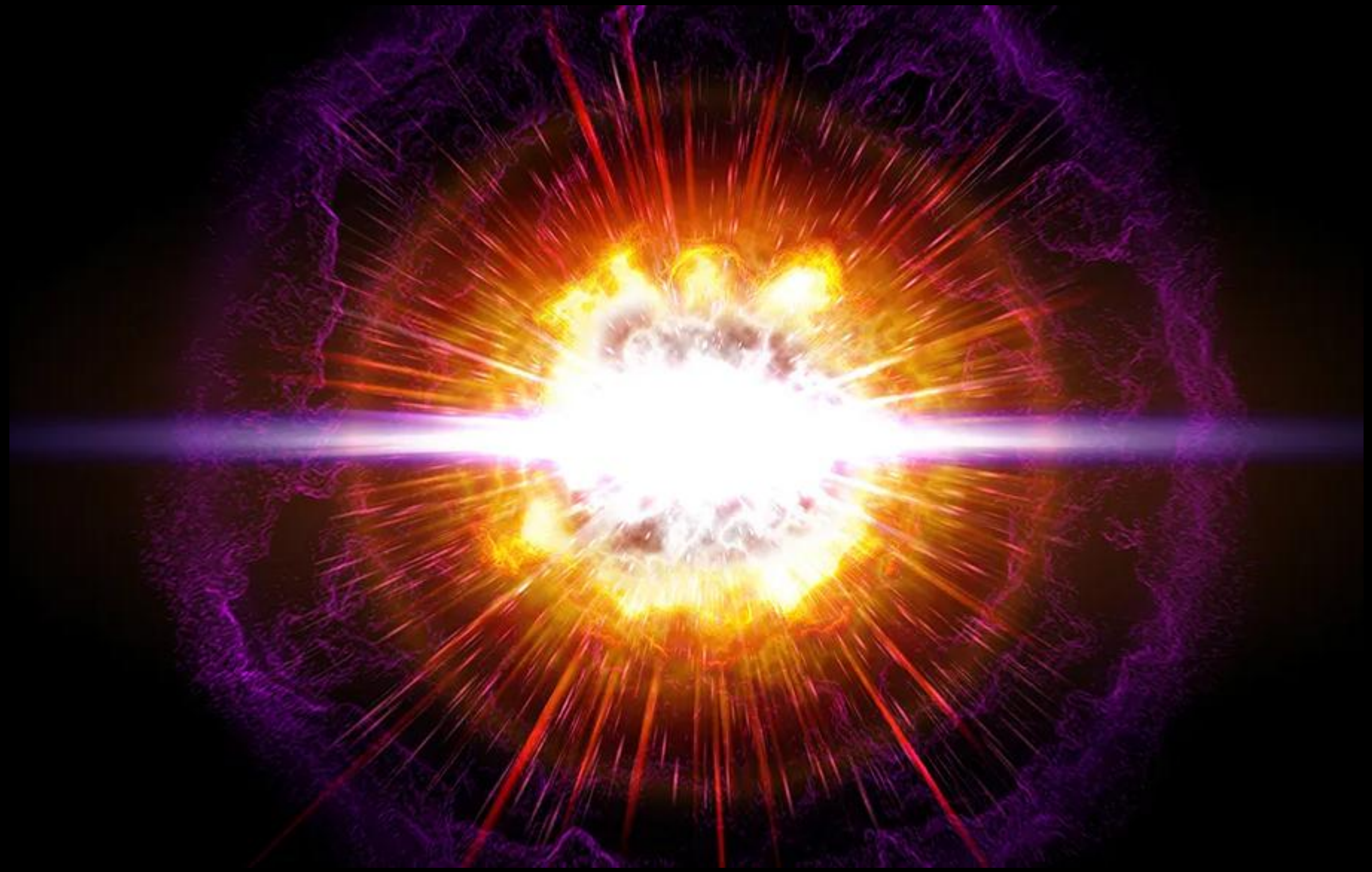
Carl David Anderson (1932)

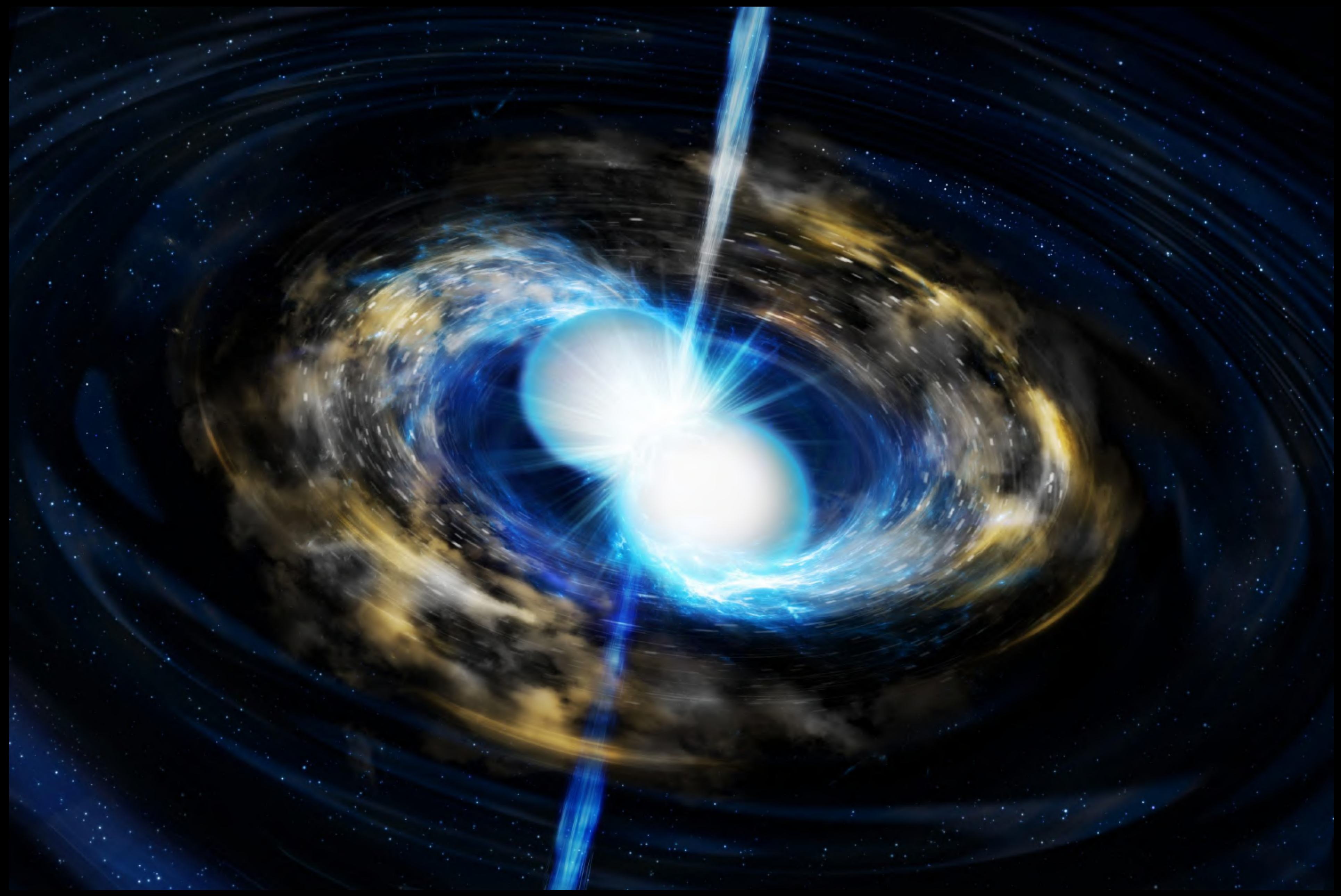
Cecil Powell (1947)

Cosmic Rays: messengers of highest-energy process in Universe

Particles (98% are protons and helium ions) accelerated in the most intense shock processes in our Galaxy and beyond: supernovae, neutron star mergers, accretion to supermassive black hole in a center of a galaxy

Not just messengers — cosmic rays constitute significant fraction of energy in the astrophysical environment, ionize neutral interstellar gas, affect star formation and contribute to gravitational balance of the Galaxy





Cosmic Ray detection

Space *(satellites, ISS, balloons)*

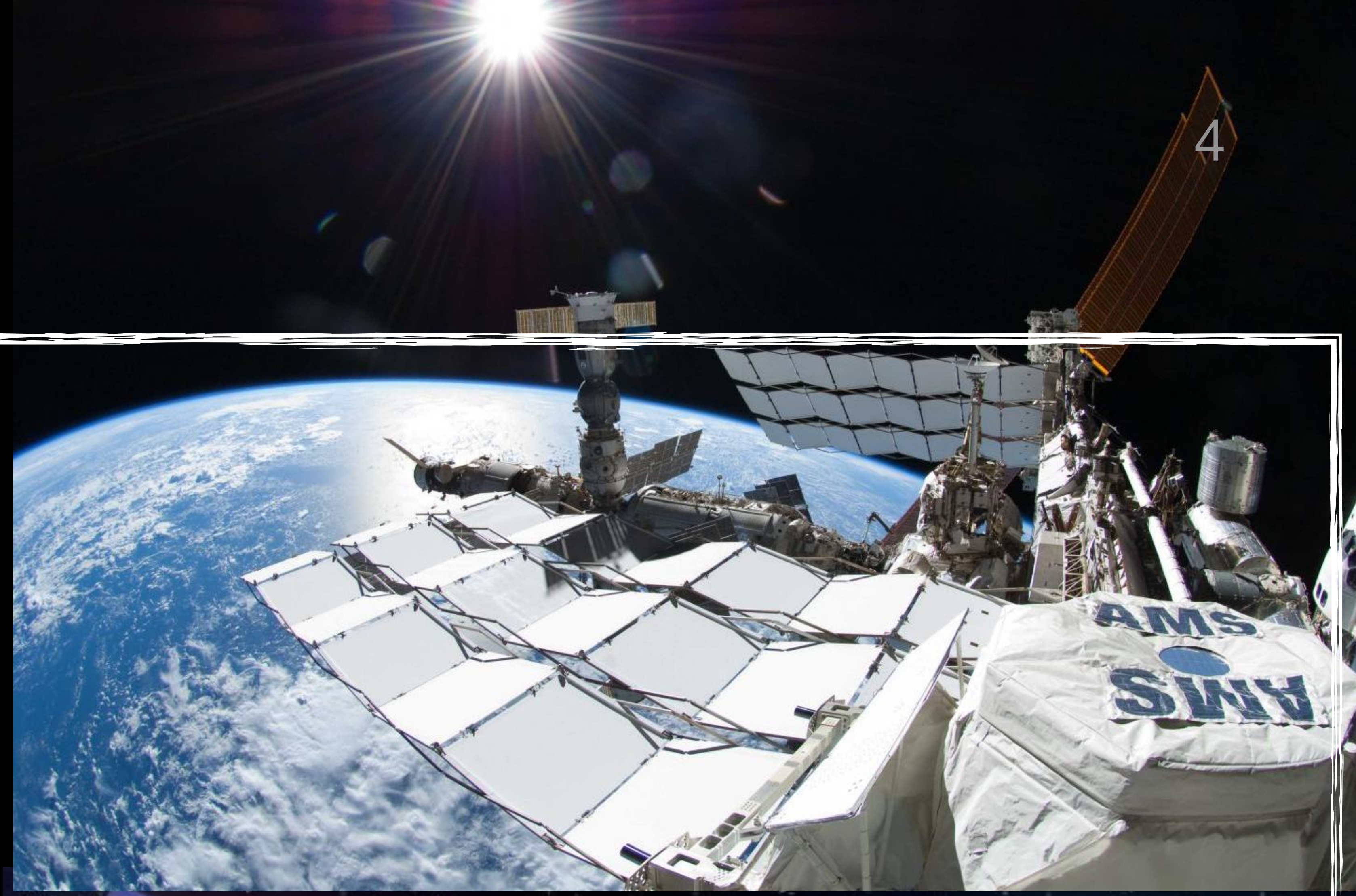
Very precise — measurement errors reaching 1% level

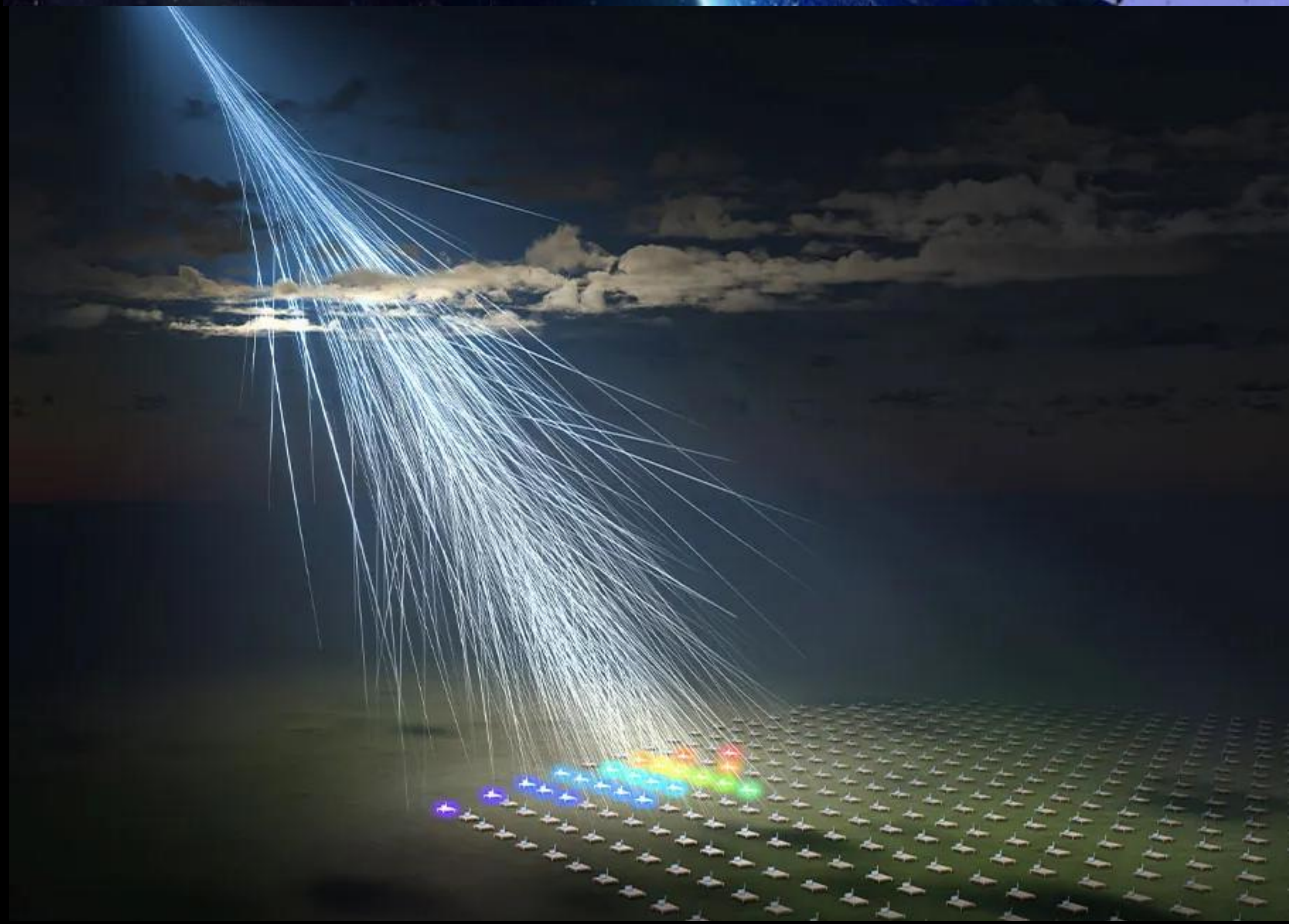
Limited in energy up to ~hundreds of TeV

Ground-based

Cover very large ares ~O(100) km^2 and reach maximum possible energies — up to 10^{19} eV (~millions of TeV)

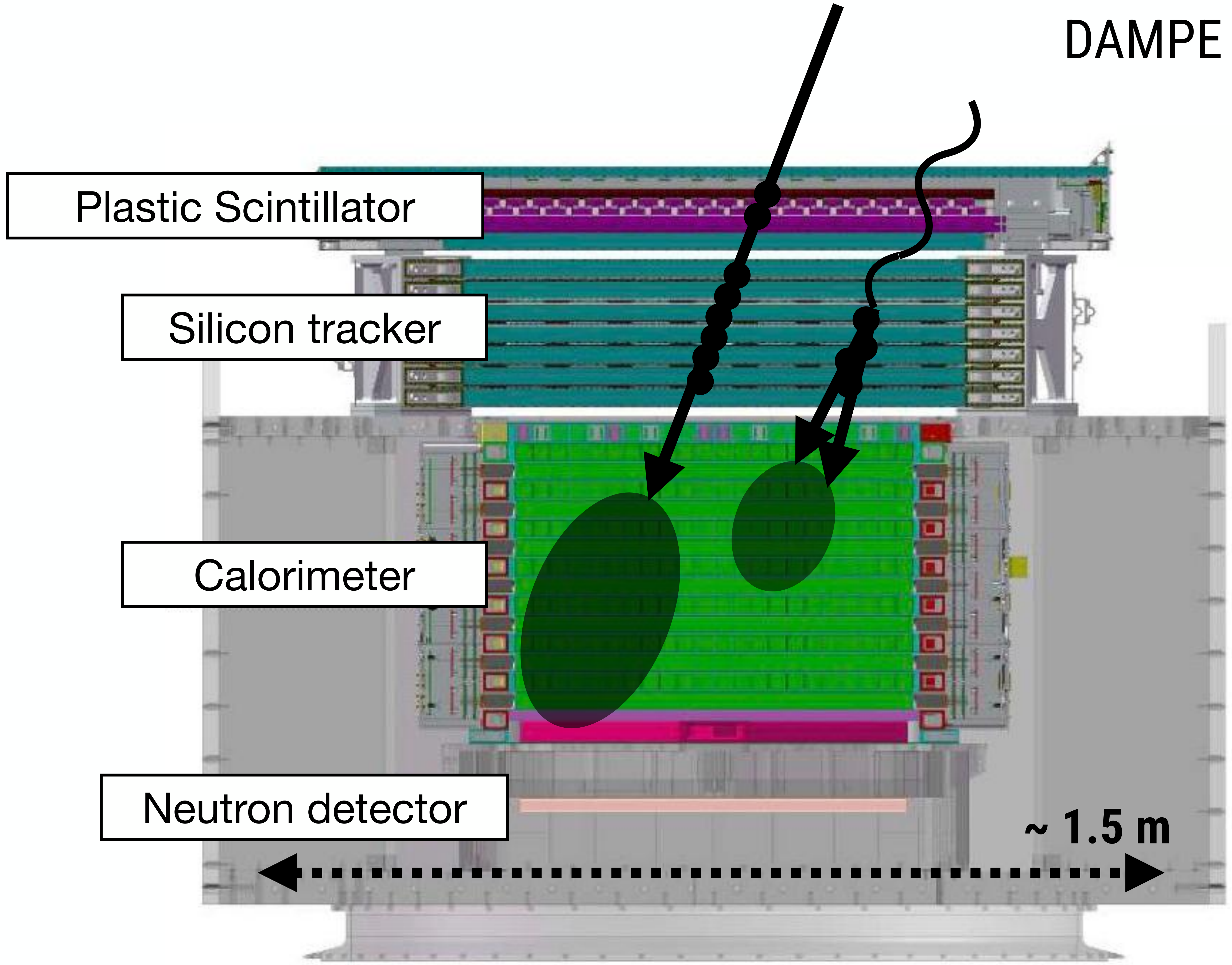
Not very precise — measurement errors more than 100%!



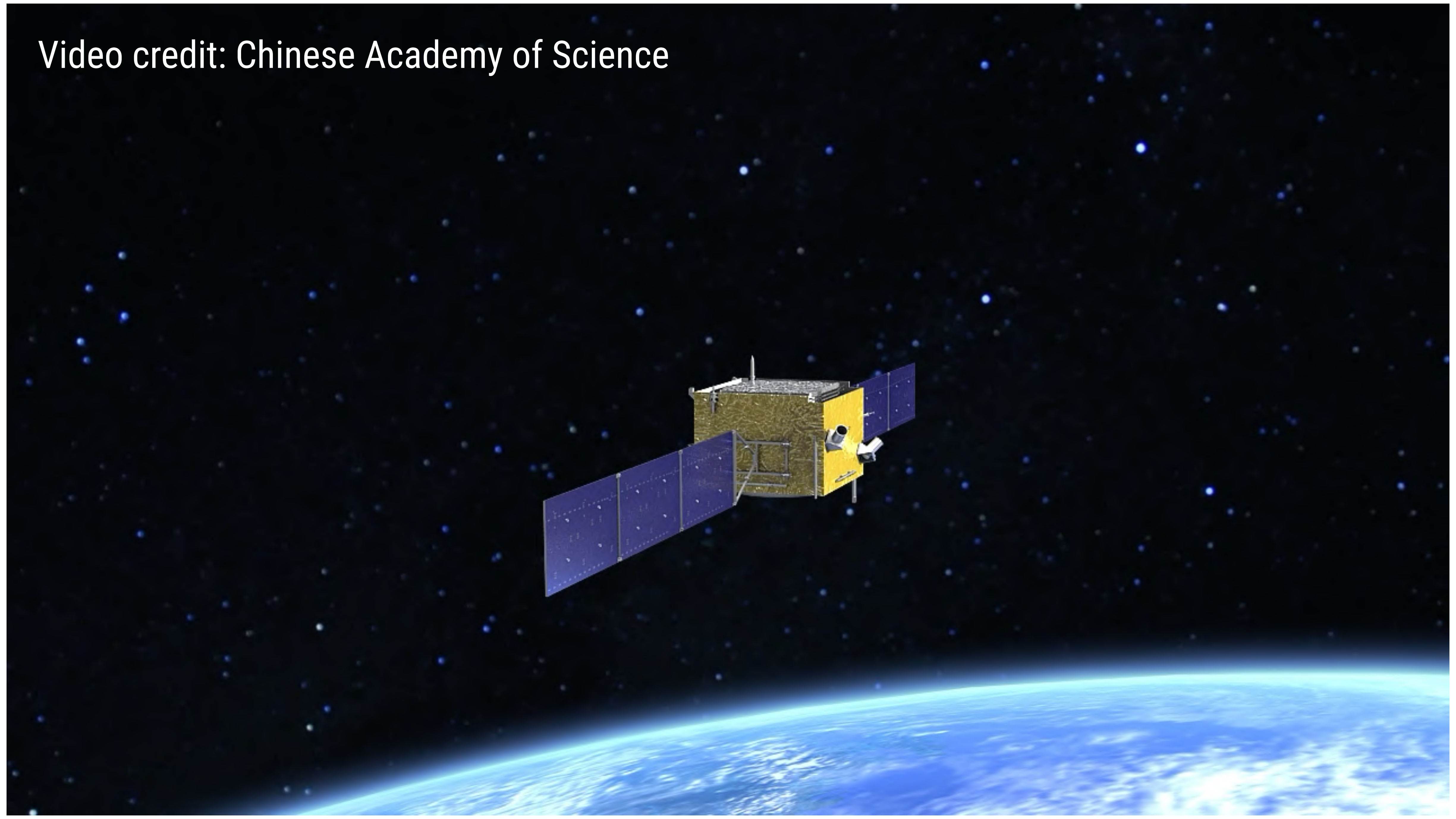


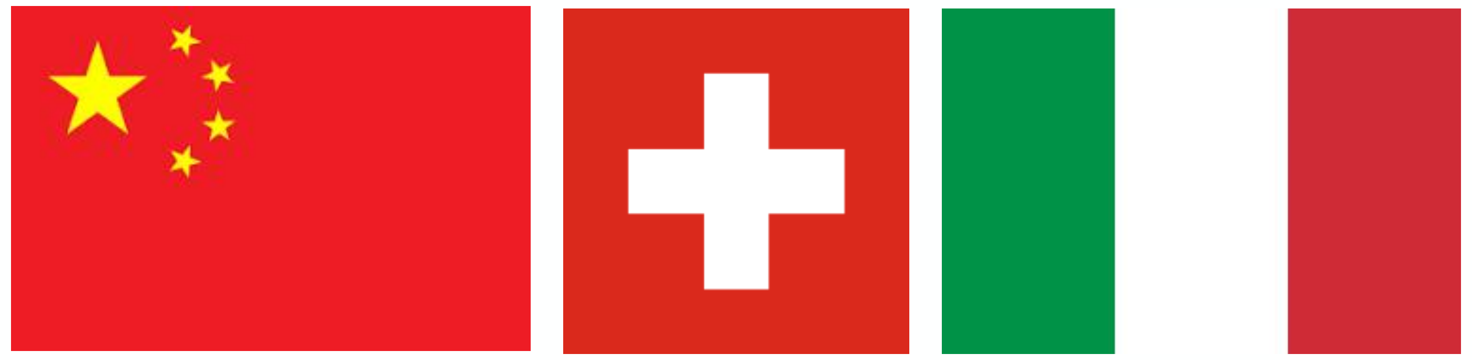
DAMPE (DArk Matter Particle Explorer)

DAMPE - a particle detector in space



Example of a typical cosmic ray (left particle)
gamma ray (right particle) interaction in DAMPE

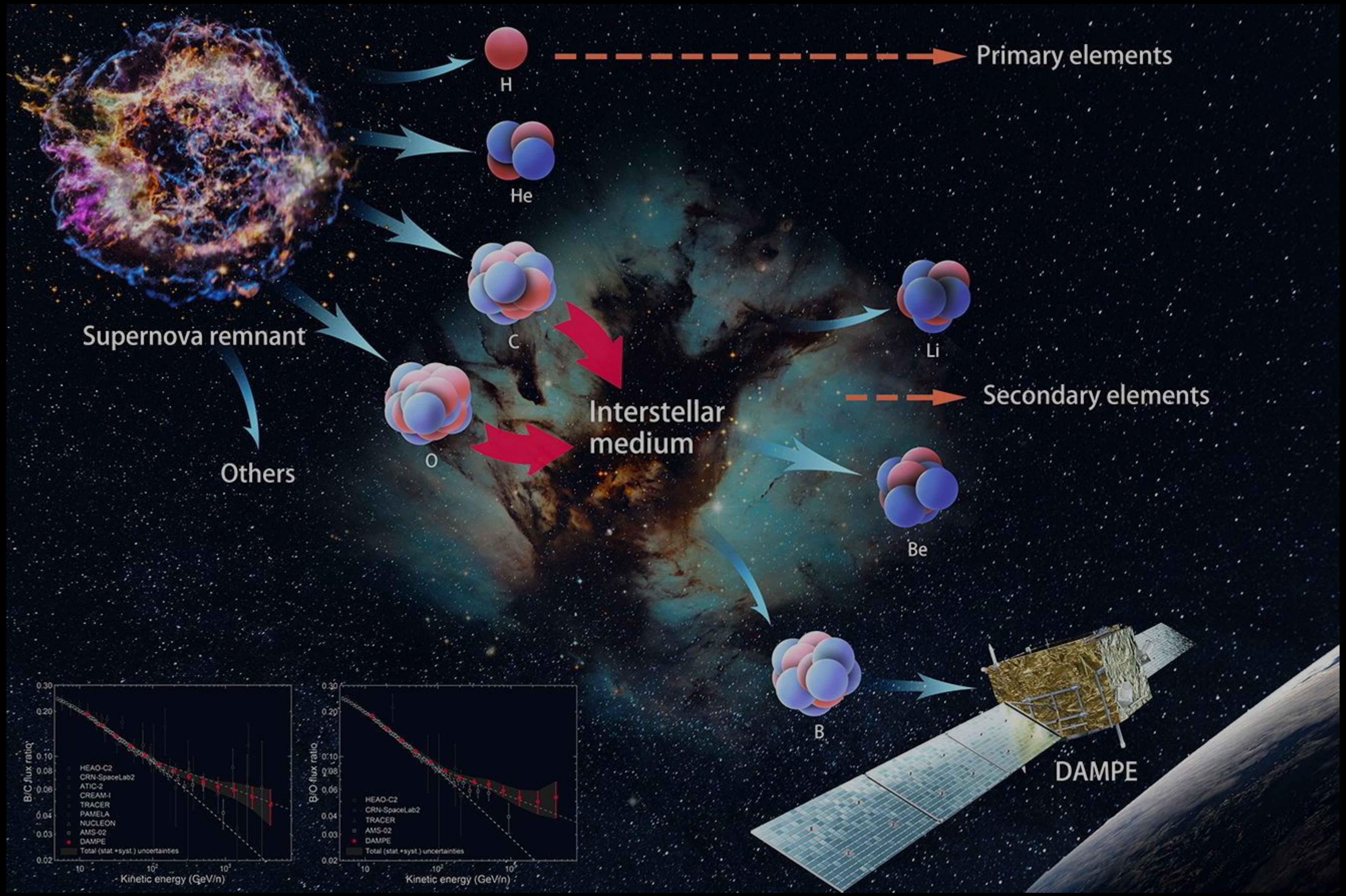


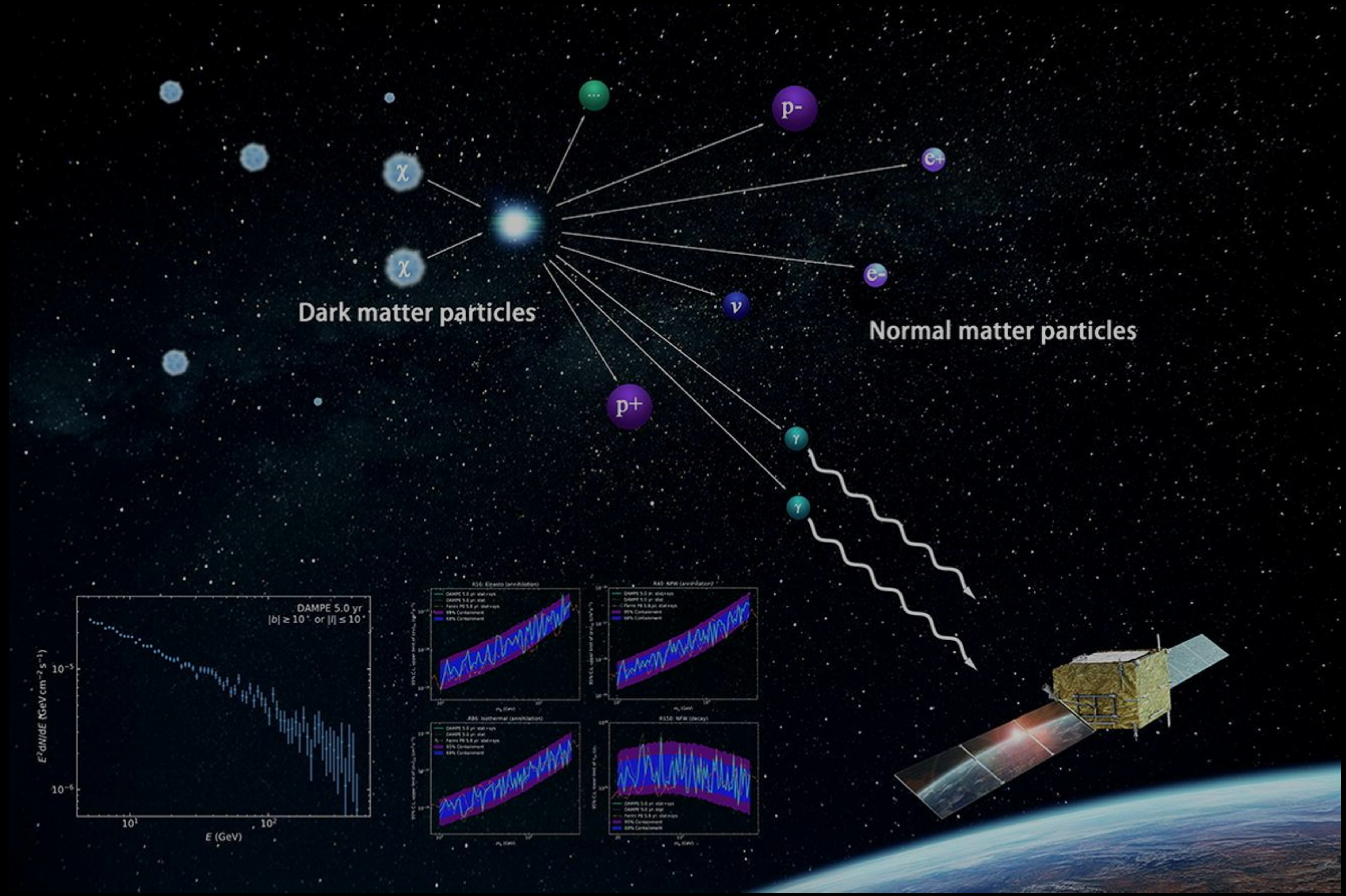


Joined project of China, Switzerland and Italy (launched in 2015)

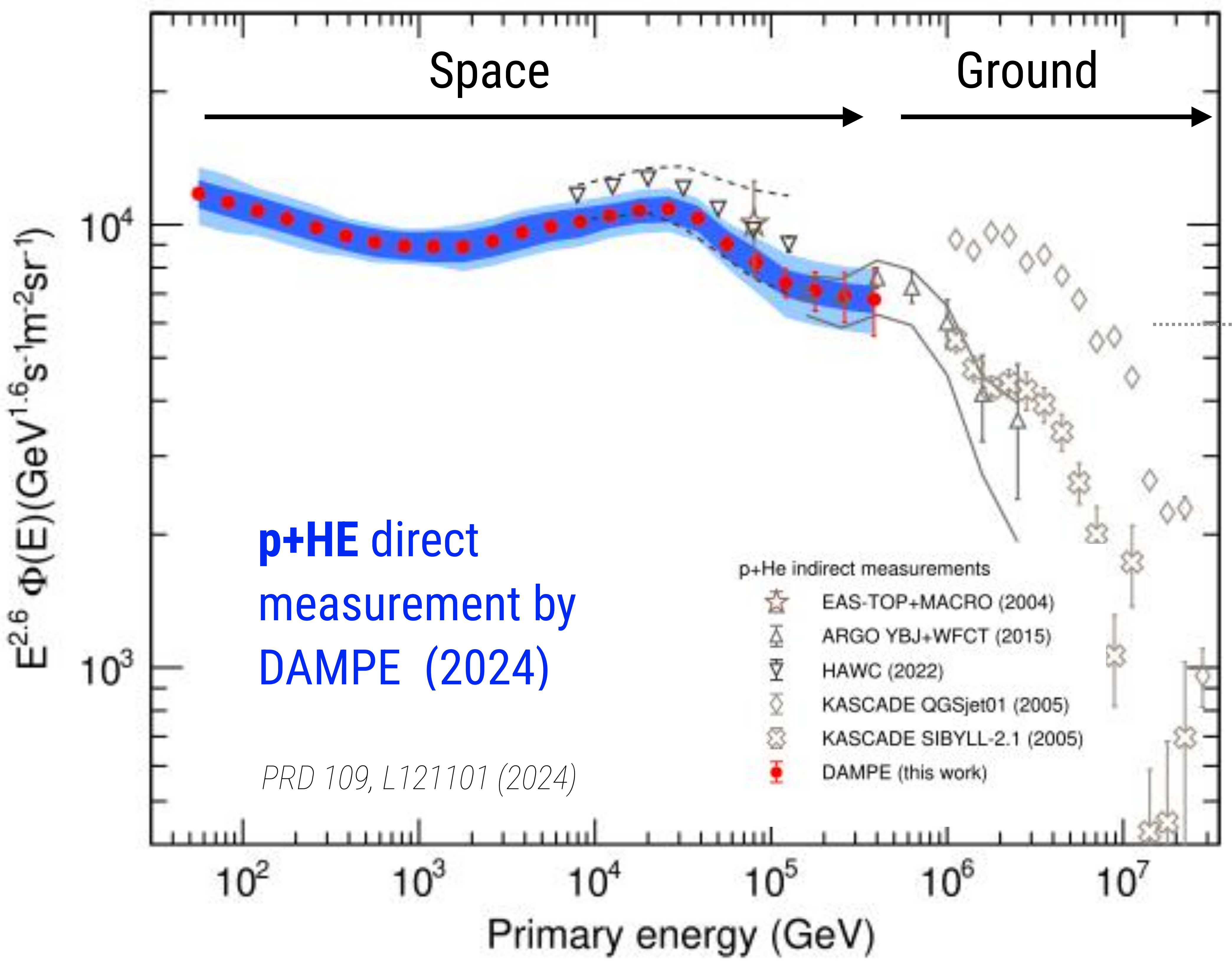
DAMPE on orbit

- Many exciting cosmic ray (and gamma ray) measurements published since 2015:
  ➡ electrons, protons, helium, B/C and B/O, dark matter search with γ-rays, solar physics
- More in progress (C,O, Ne-Mg-Si, Fe)





Motivation - exploring TeV - PeV energy domain



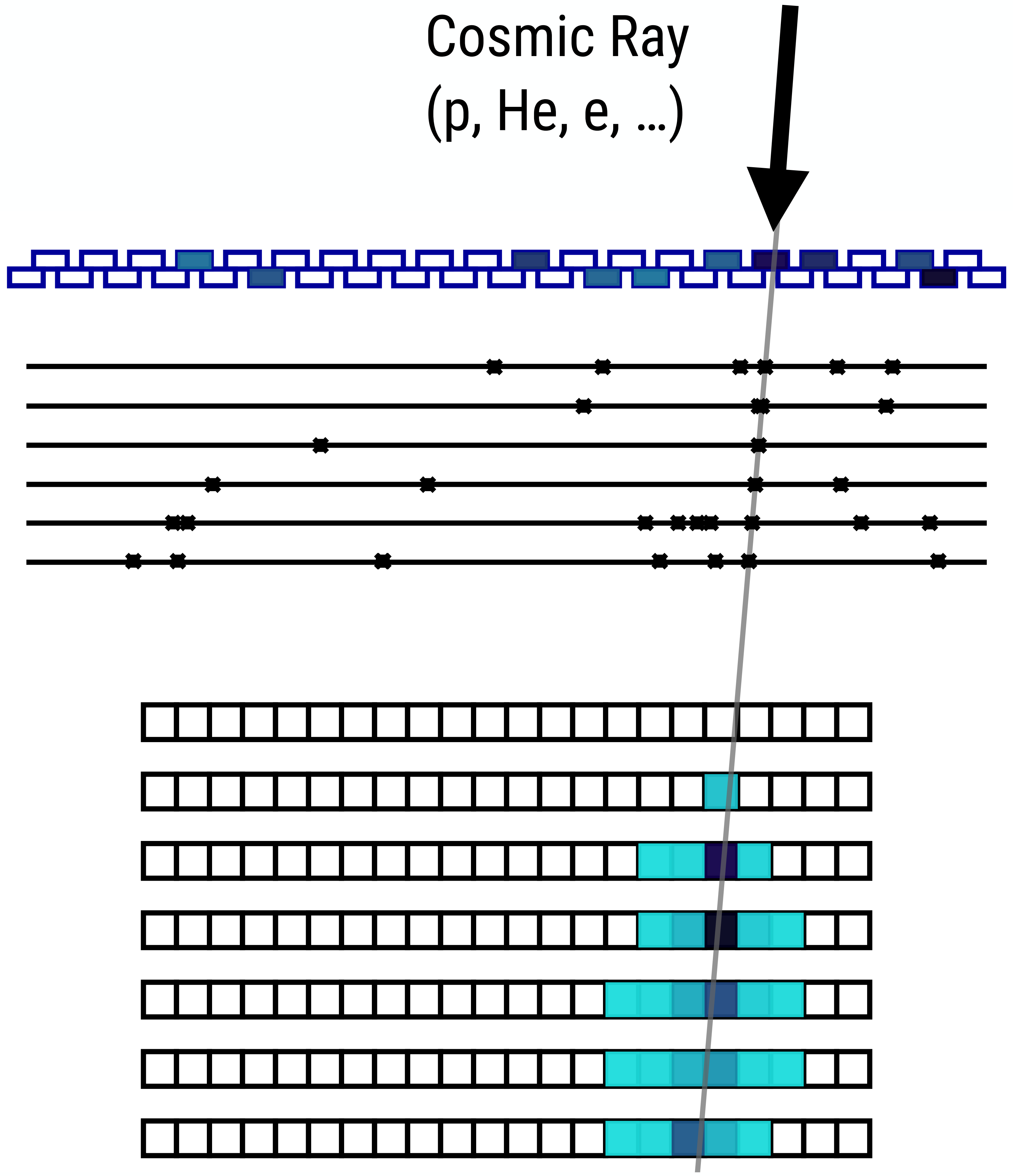
Why space measurements are important? Just look at the uncertainty range / discrepancy between ground experiment data - it reaches more than 100%!

- We can already measure combined spectrum (p+He) at up to ~0.5 TeV, but ...

  → **We need individual p and He measurements towards PeV - crucial for understanding the origin of Galactic CR!**

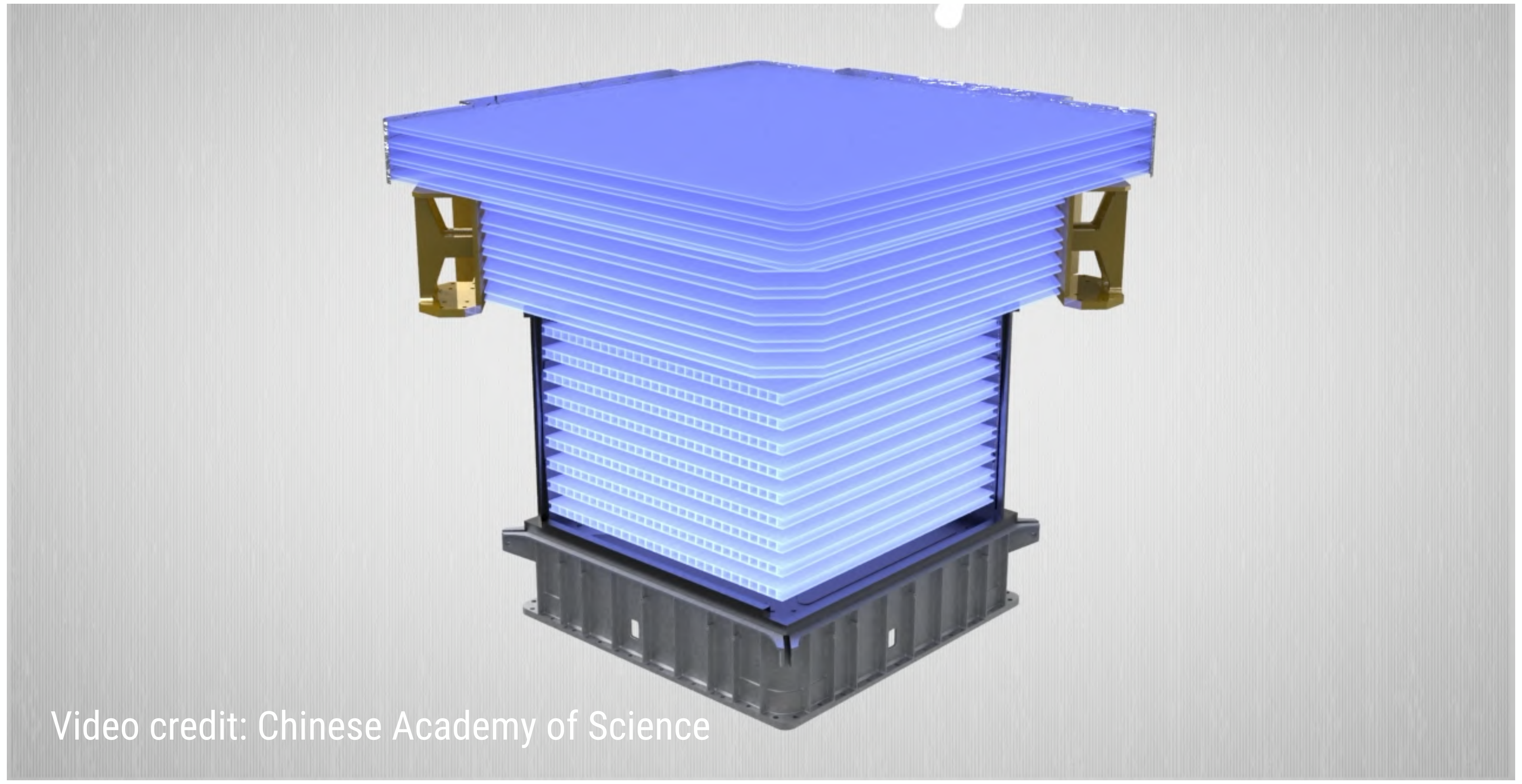
  ... but here comes the key data analysis challenge (see next slides)

Particle interaction in DAMPE at < TeV is ~ relatively simple

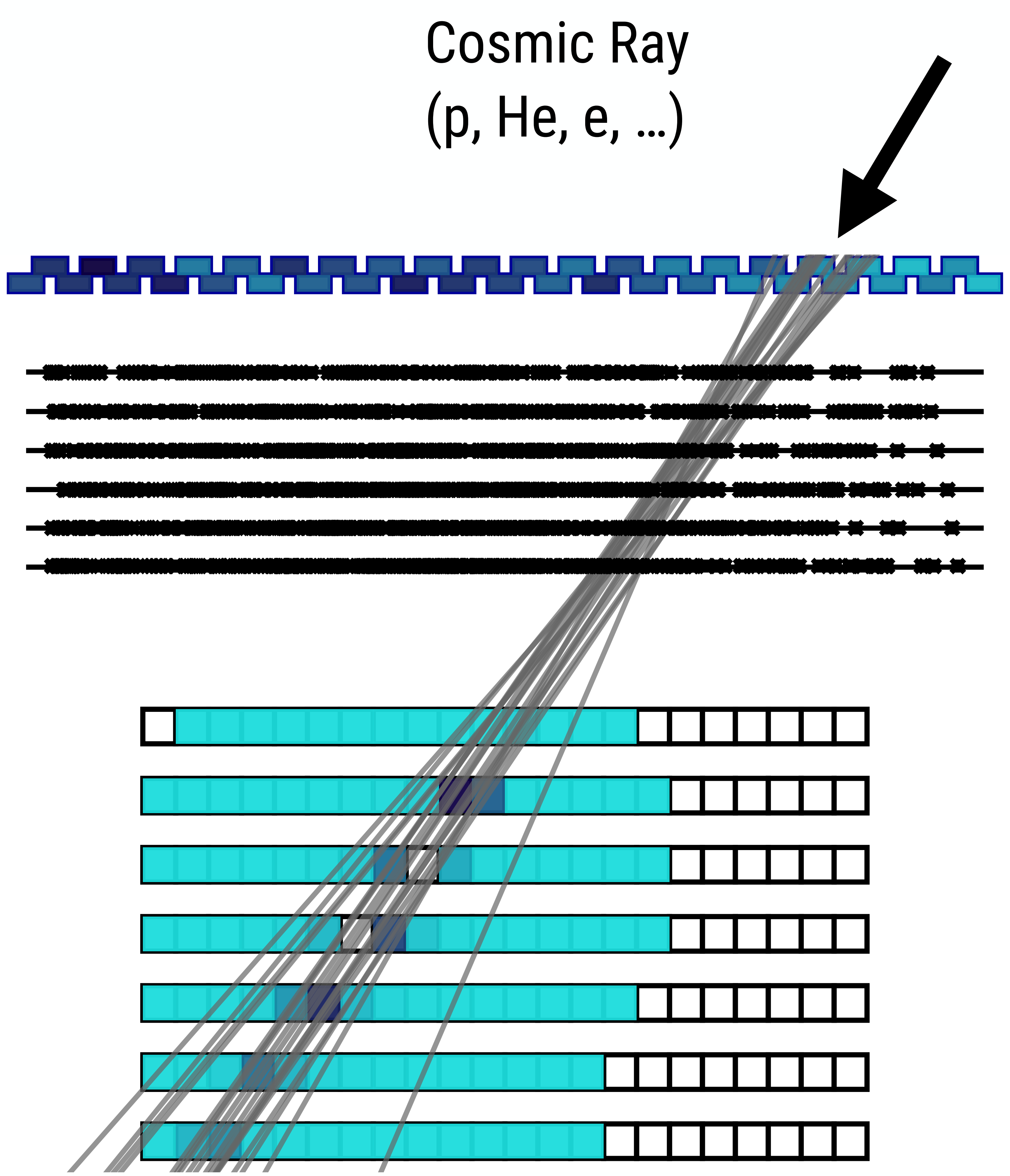


Example of a typical interaction in DAMPE (one projection) for a ~ 1 TeV cosmic ray

As a baseline for data analysis, classical well-understood techniques are use: Kalman filter for reconstructing particle track, linear regression for calorimeter image processing, etc.



Challenge: cosmic ray track reconstruction at TeV - PeV



Example of a typical interaction in DAMPE (one projection) for a ~ 100 TeV cosmic ray

Analysis becomes challenging at > ~ 100 TeV due to back-scattering of secondaries particle from calorimeter.

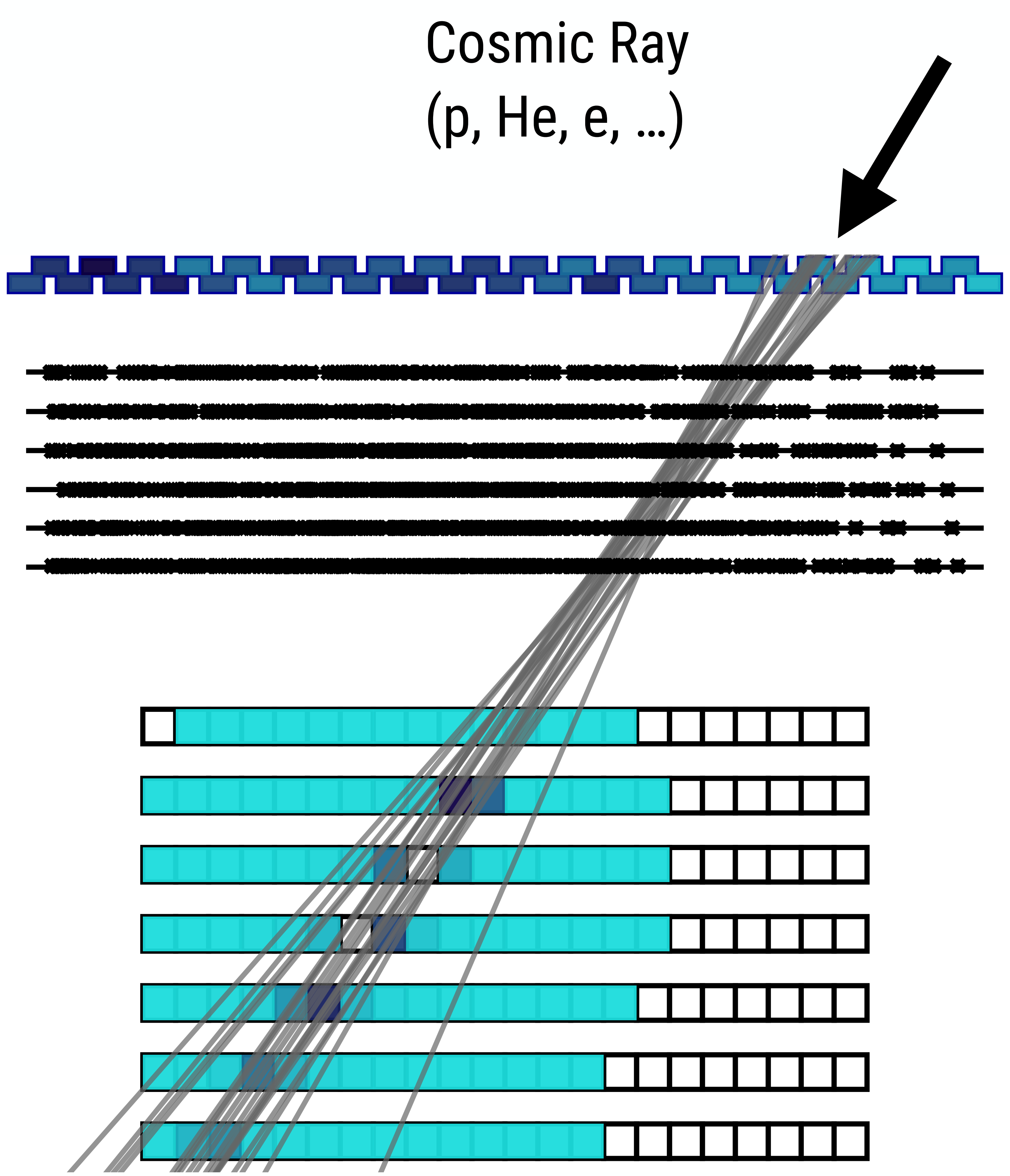
Identifying a track of a Cosmic Ray in a vast noise of secondary tracks is a **search for a needle in a haystack!**

Q: Why it is essential to precisely identify a track of a cosmic ray?

A: To extract information about the particle type (if it is p, He or other ion)!

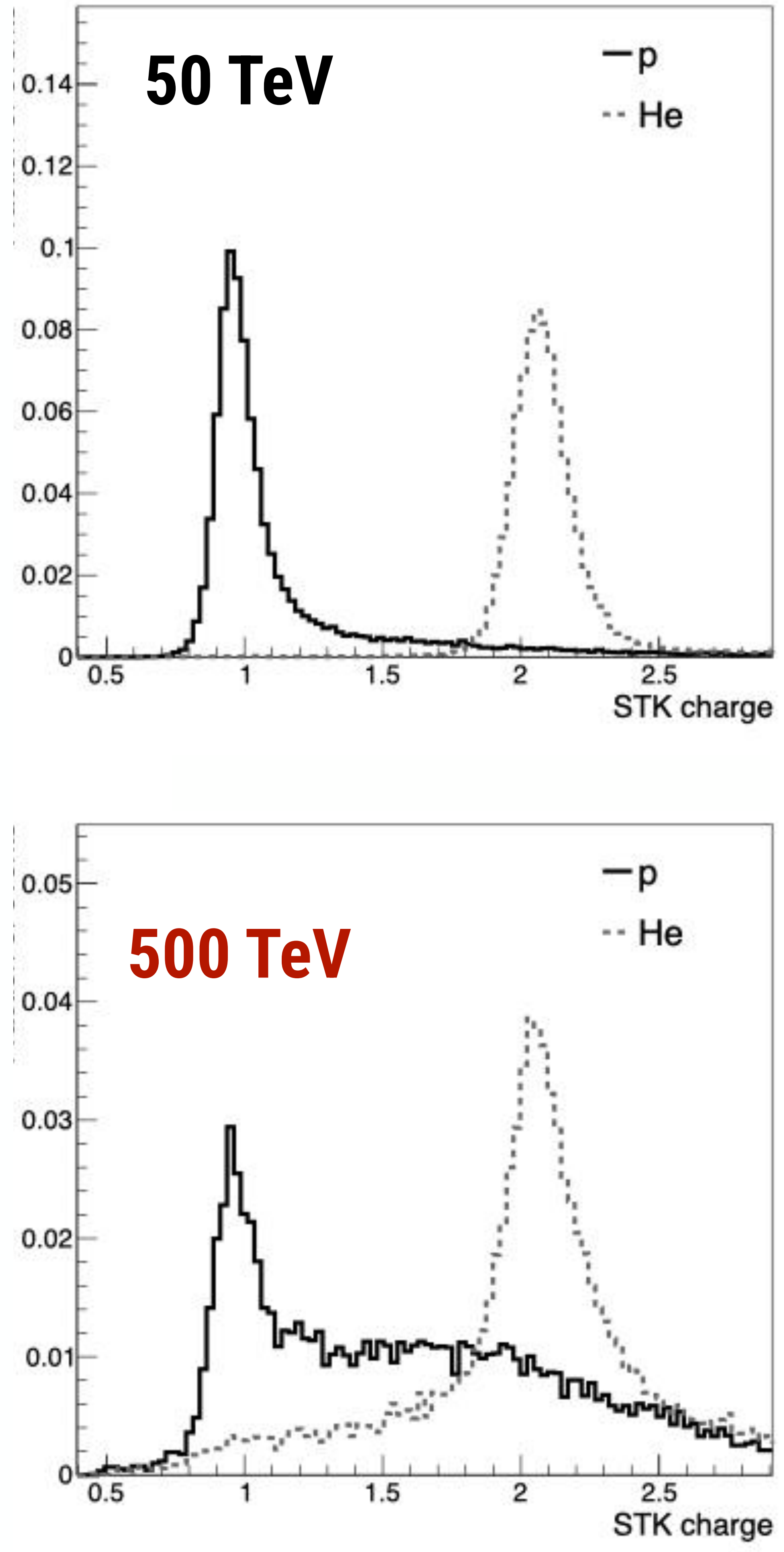
$$\left\langle -\frac{dE}{dx} \right\rangle \sim K z^2 \frac{Z}{A} \frac{1}{\beta^2}$$

Challenge: cosmic ray track reconstruction at TeV - PeV



Example of a typical interaction in DAMPE (one projection) for a ~ 100 TeV cosmic ray

Reconstructed proton and helium charge distribution at 50 TeV (top) and 500 TeV (bottom)



Still OK...

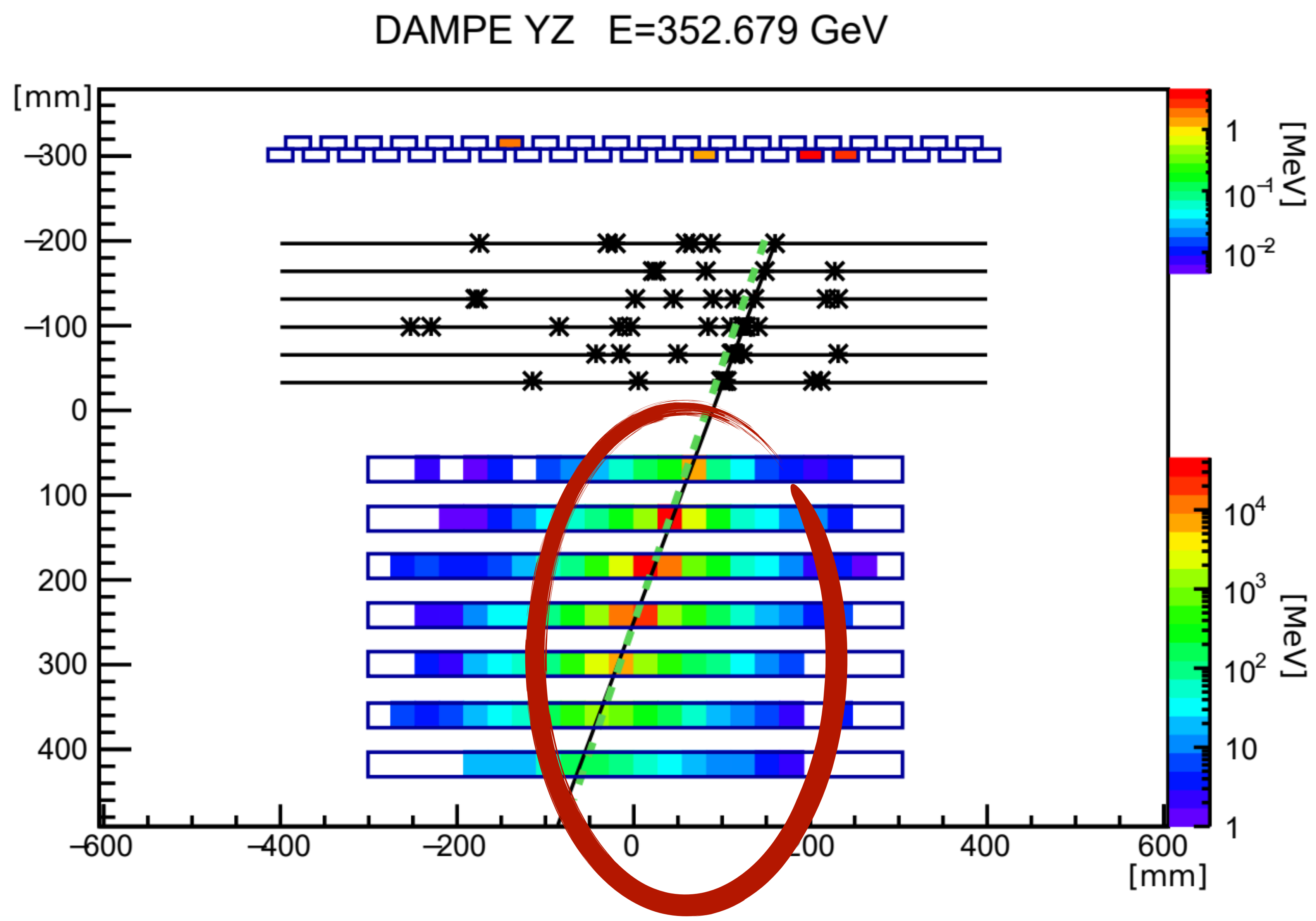
Not sustainable for reliable analysis

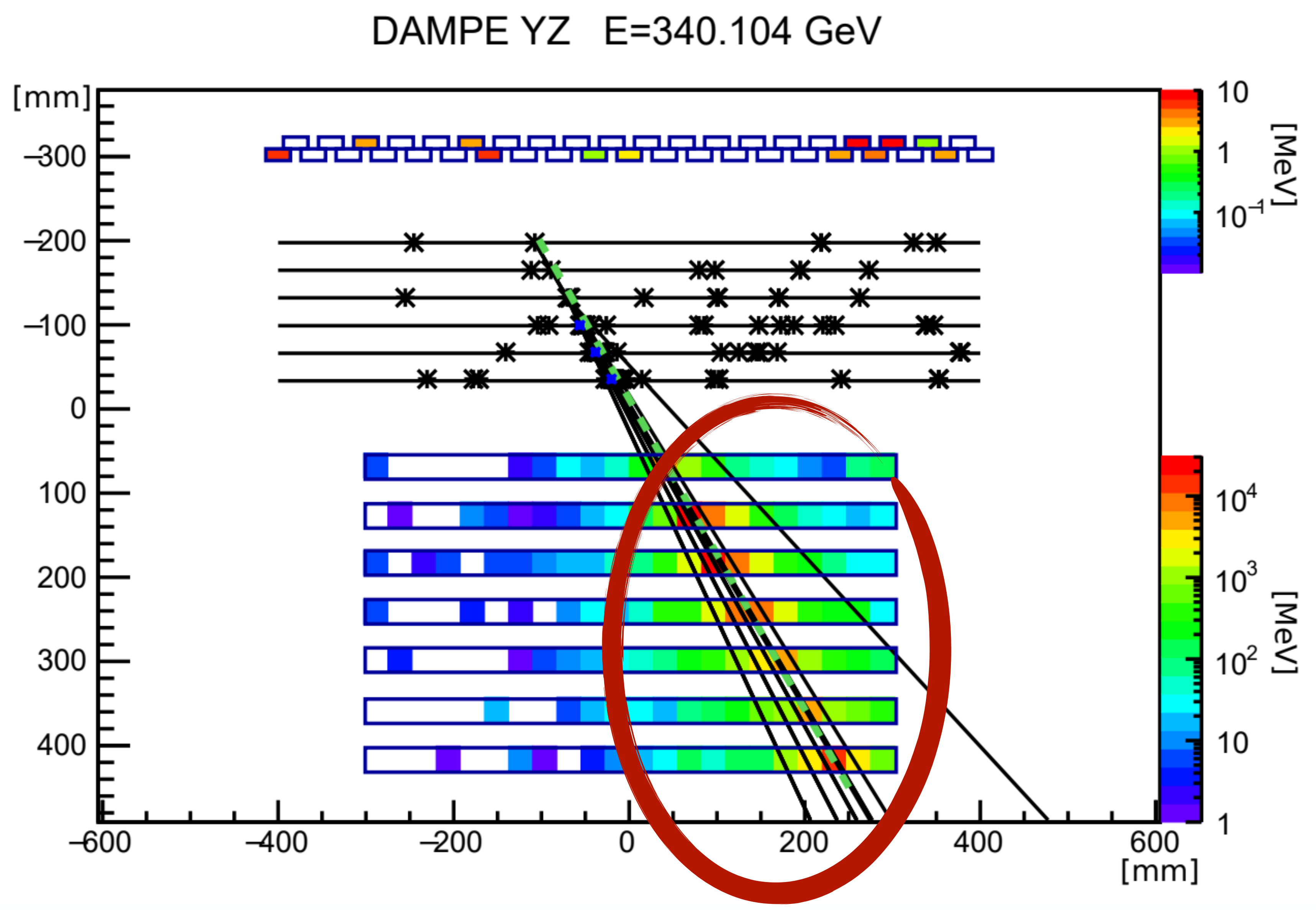
We need a new algorithm to reconstruct particle track with ultimately better precision! (regression problem)

Challenge: particle identification (electrons VS protons)

- Protons are $10^4 – 10^5$ more abundant than electrons at > TeV energies
- Electron VS proton discrimination is one of the major challenges in calorimetric-type measurements (including DAMPE, AMS, CALET and other space experiments)

Typical **electron** interaction in DAMPE

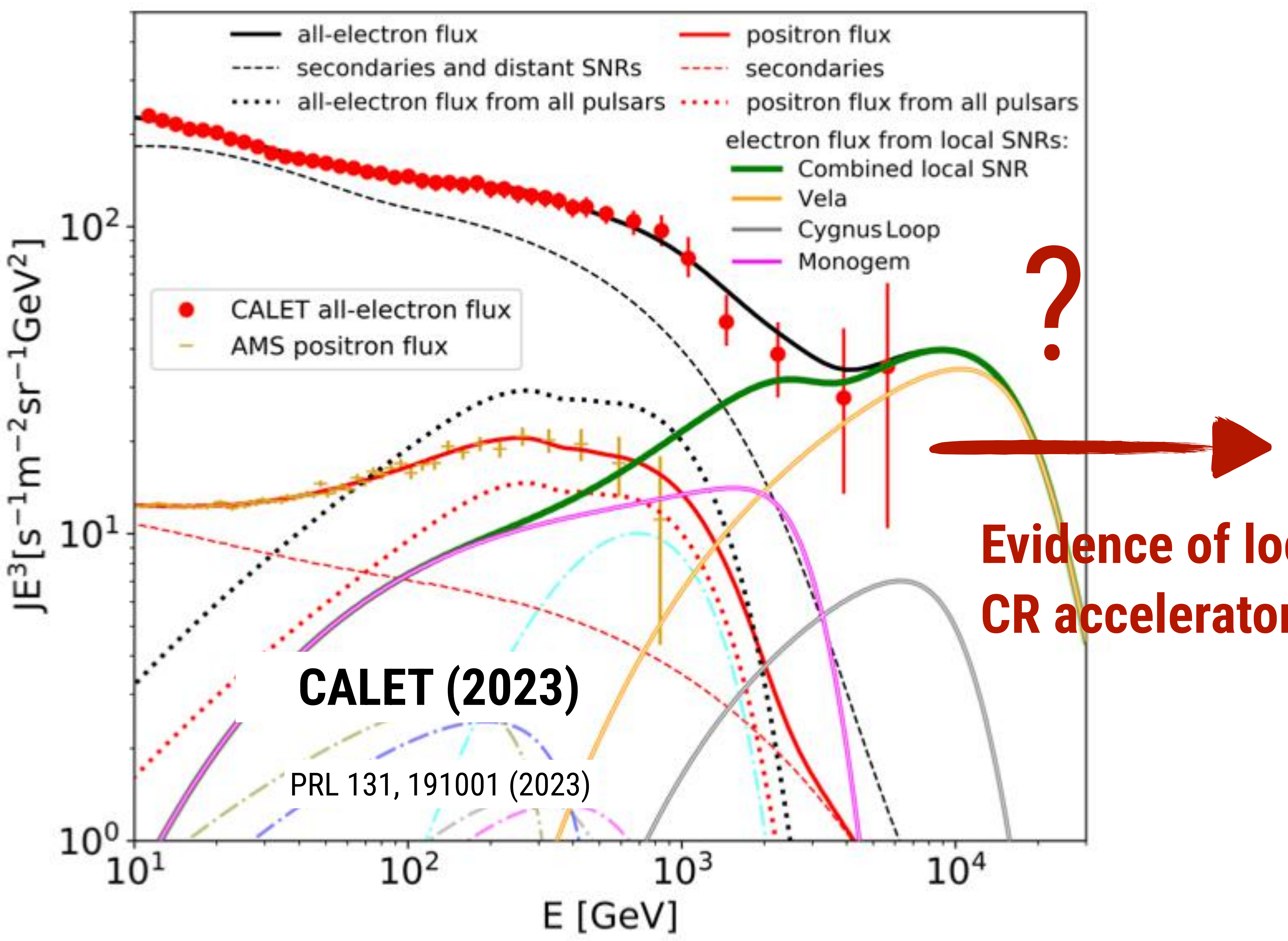




Typical **proton** interaction in DAMPE

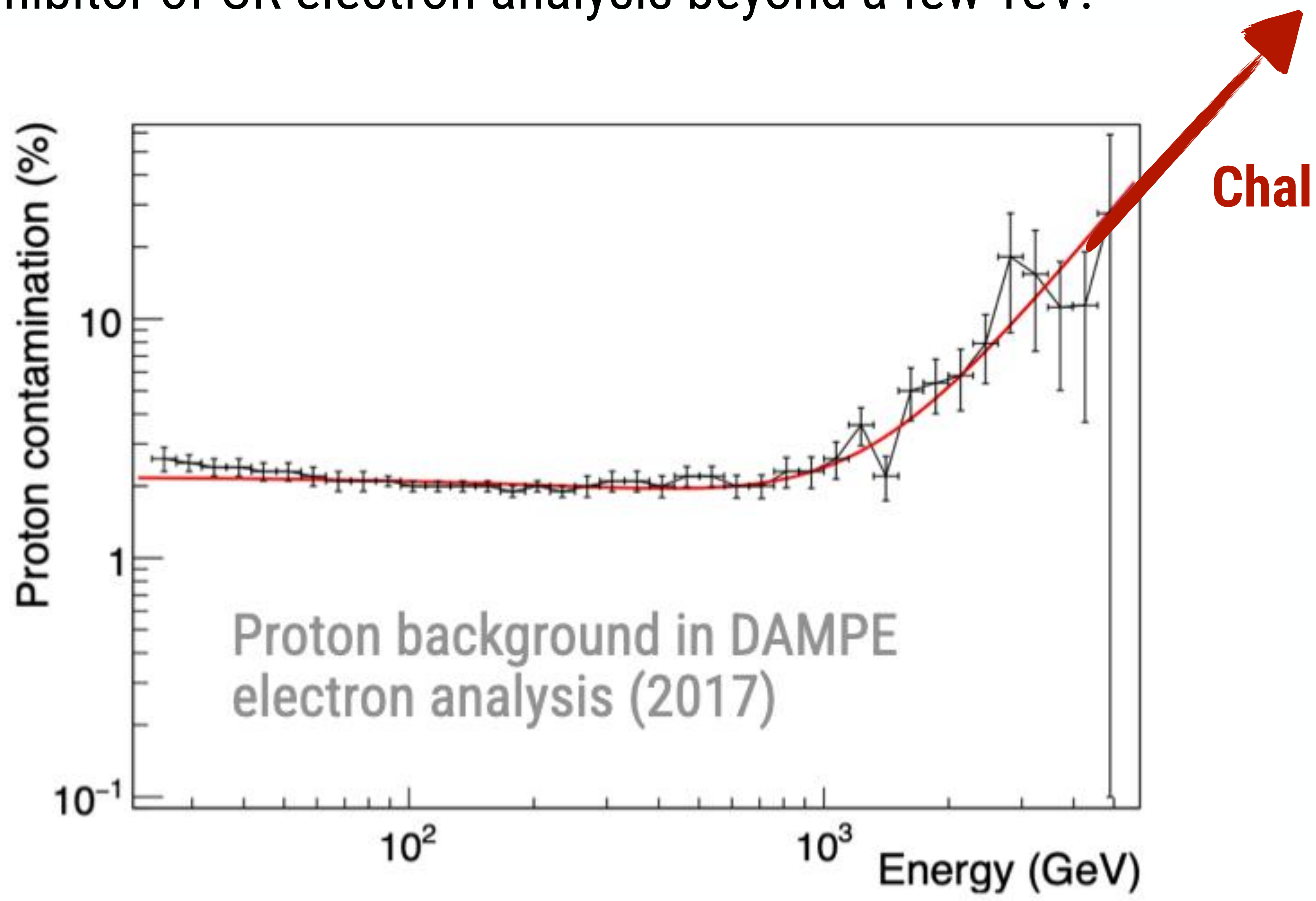
<u>We need very powerful e/p separation technique!</u>
(classification problem)

Challenge: particle identification (electrons VS protons)



Evidence of local CR accelerator?

Overwhelming proton contamination is the major inhibitor of CR electron analysis beyond a few TeV:



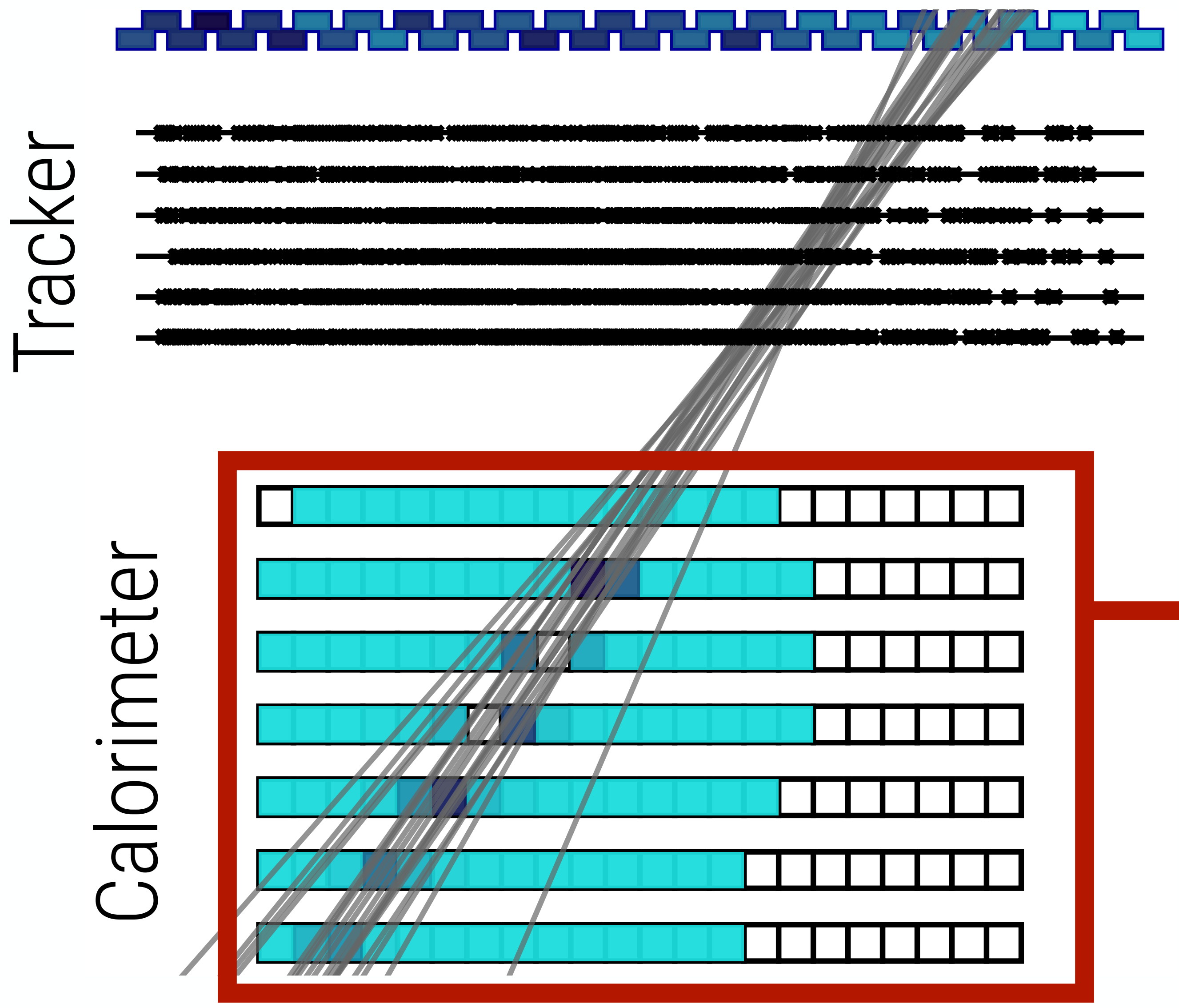
Challenge!

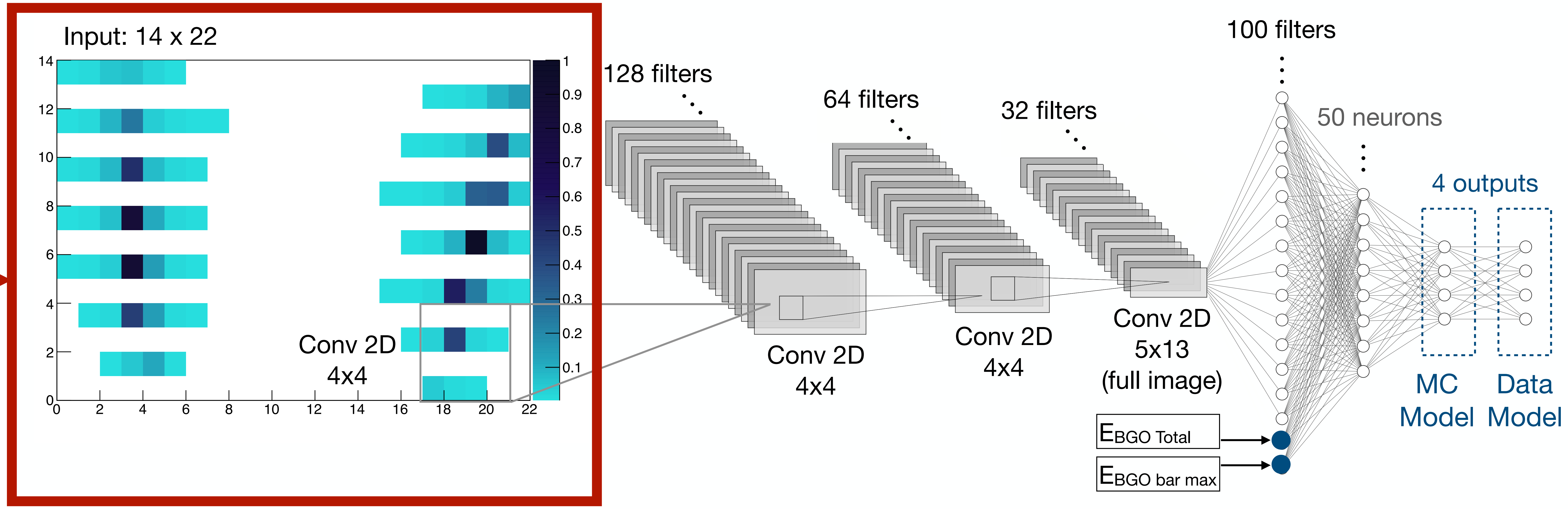
<u>We need very powerful e/p separation technique!</u>

(classification problem)

AI in DAMPE
(CNNs or fully-connected NNs)

Particle tracking (regression): CNN (calorimeter)



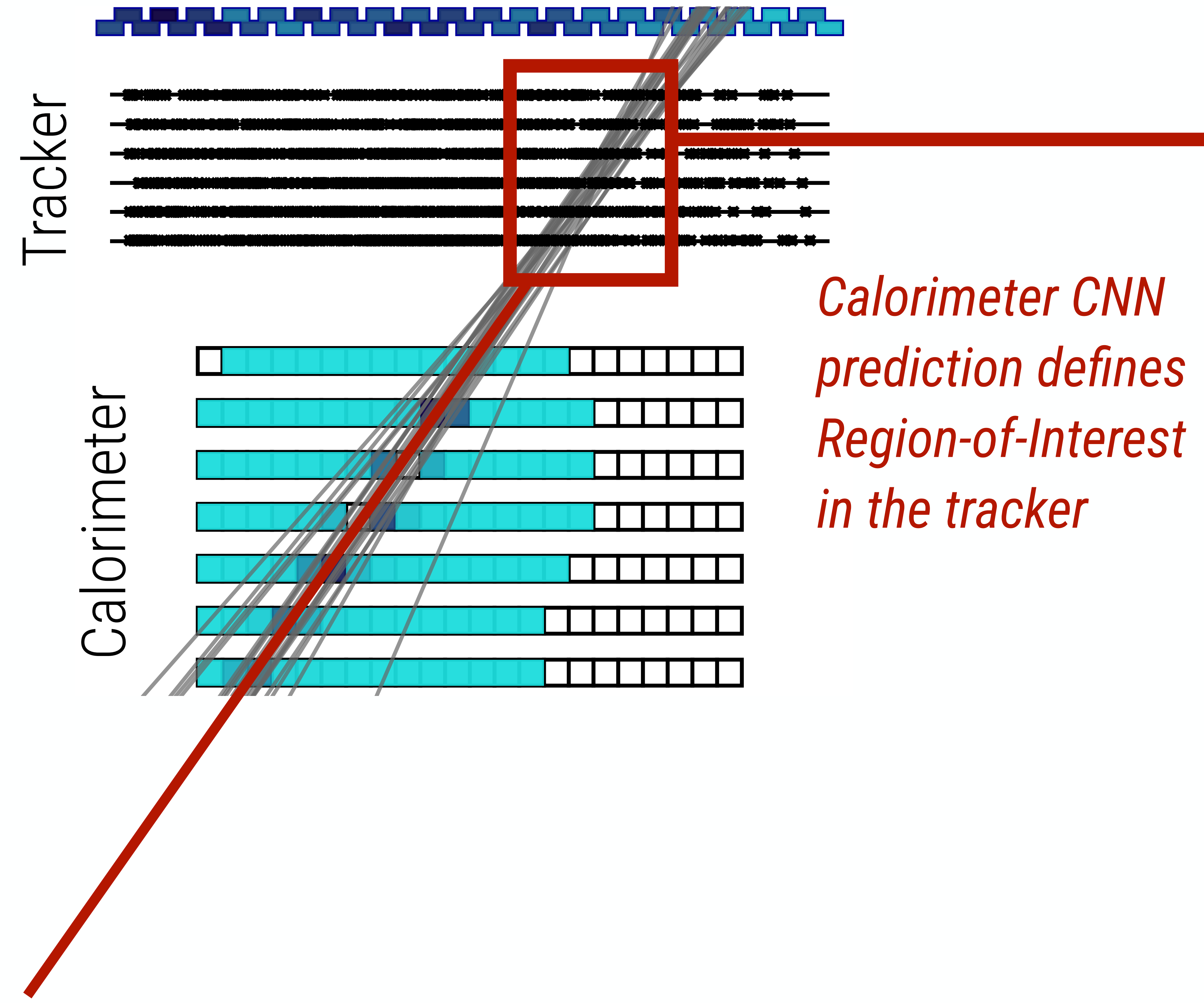


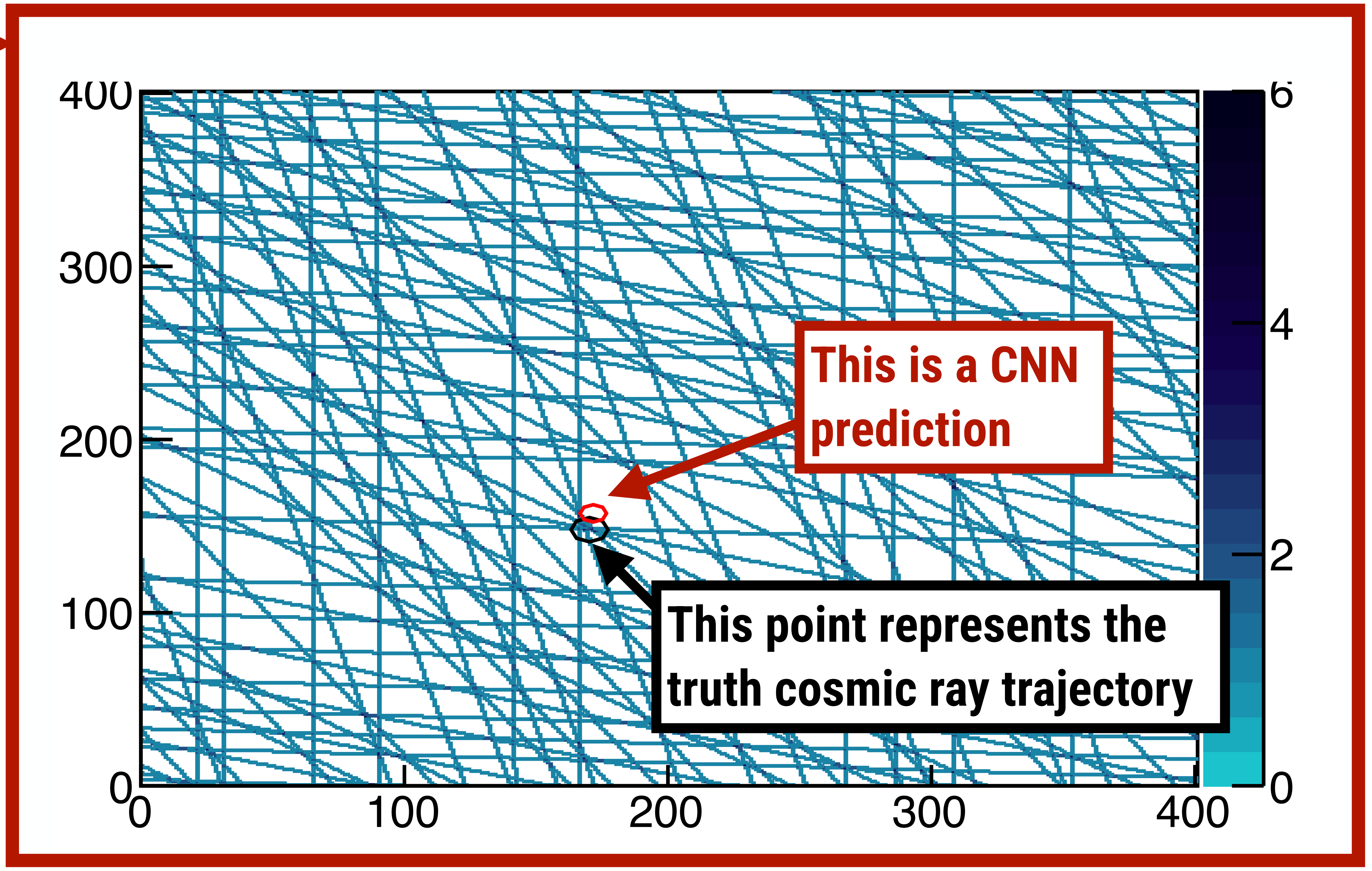
- Combined calorimeter image (two projections merged in one image)
- Processed by a CNN to predict a particle direction (intercept and slope in 2 projections)

We start with the analysis of calorimeter data to get a first "rough" prediction of particle trajectory:

Particle tracking (regression): CNN (tracker)

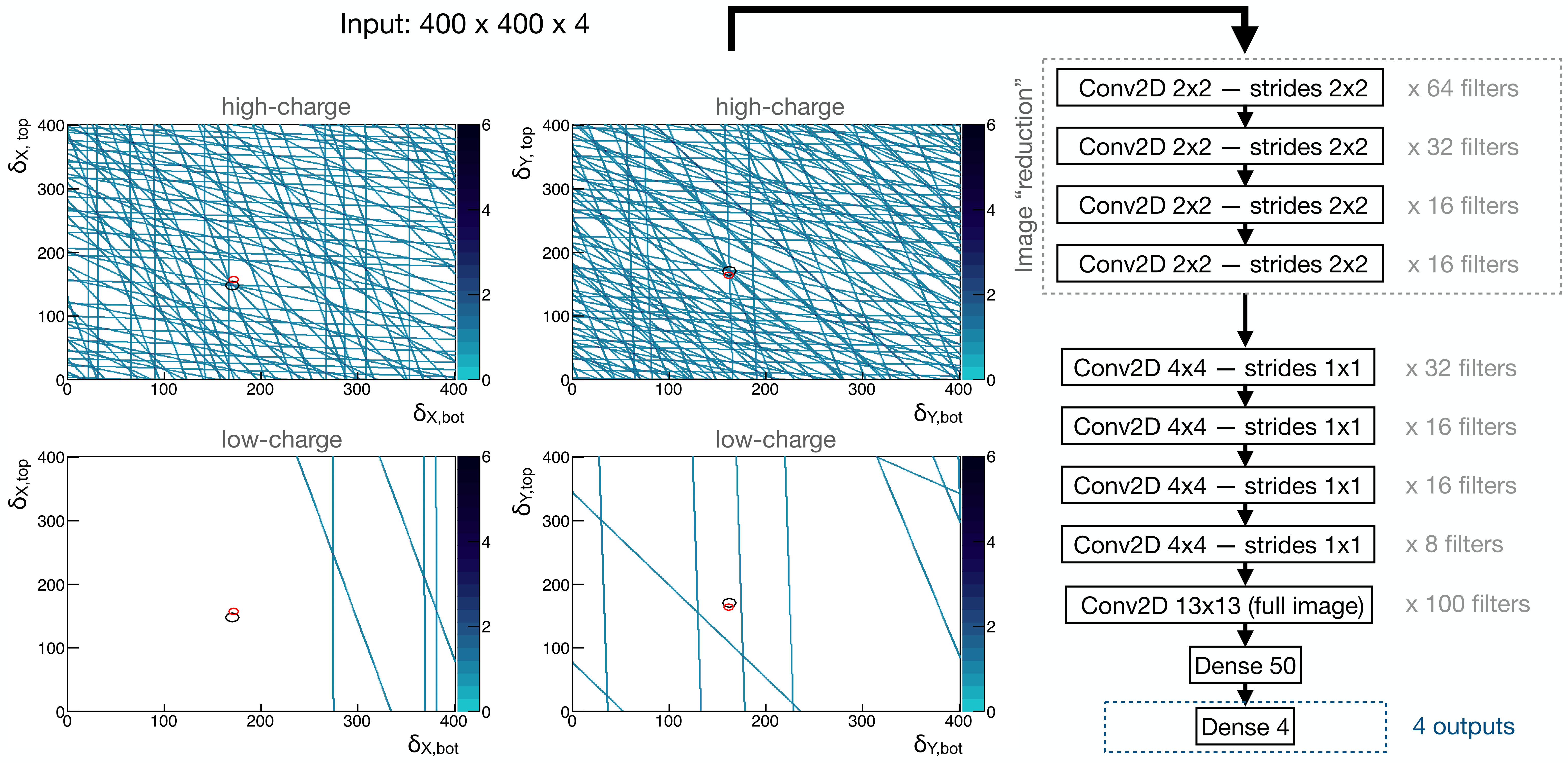
Before applying an CNN algorithm to the tracker data, we convert tracker signals (points on the left image into lines using the Hough transform)





Particle tracking (regression): CNN (tracker)

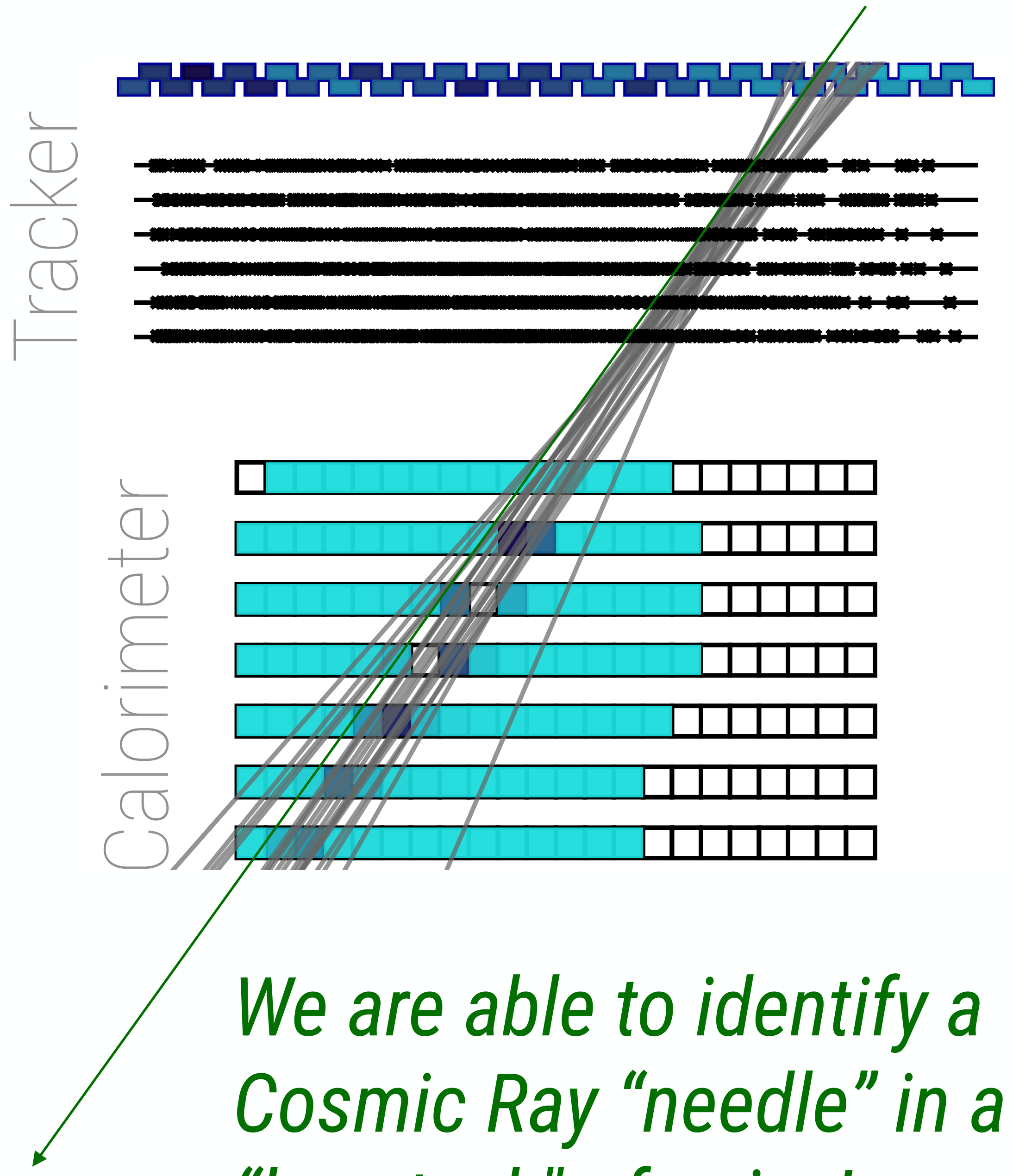
- From the Region-of-Interest inferred by a calorimeter CNN we create a 400 x 400 x 4 image of the tracker
- Similar to calorimeter CNN, the tracker CNN predicts 4 numbers (particle intercept and slope on 2 projections)



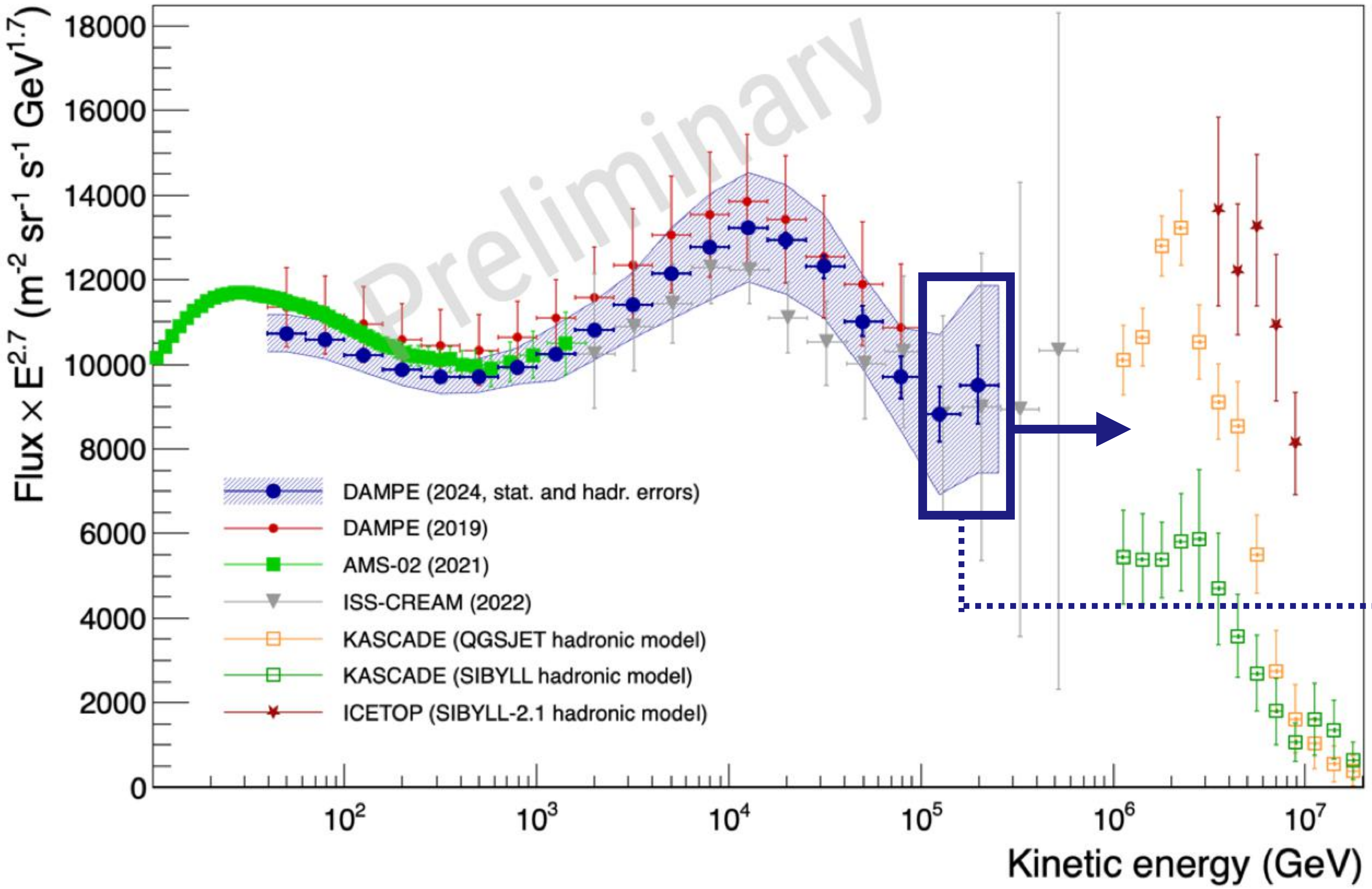
Particle tracking (regression): CNN (tracker + calorimeter)

Q: Why this is important/exciting for physics?

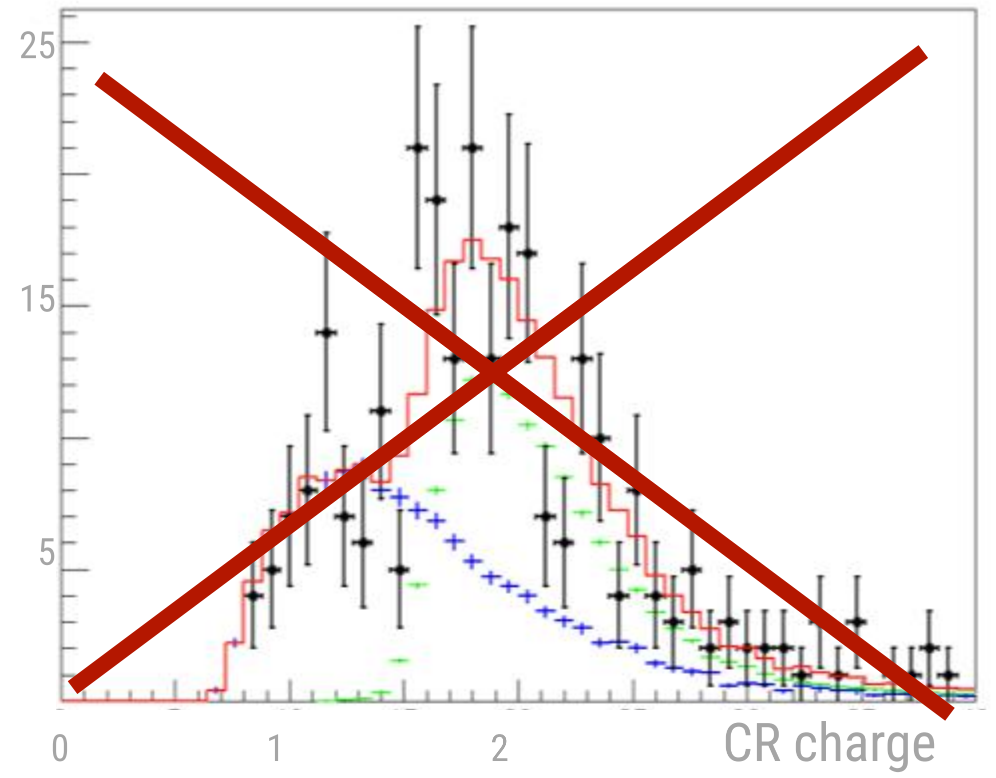
A: Enables most precise CR measurement towards PeV!



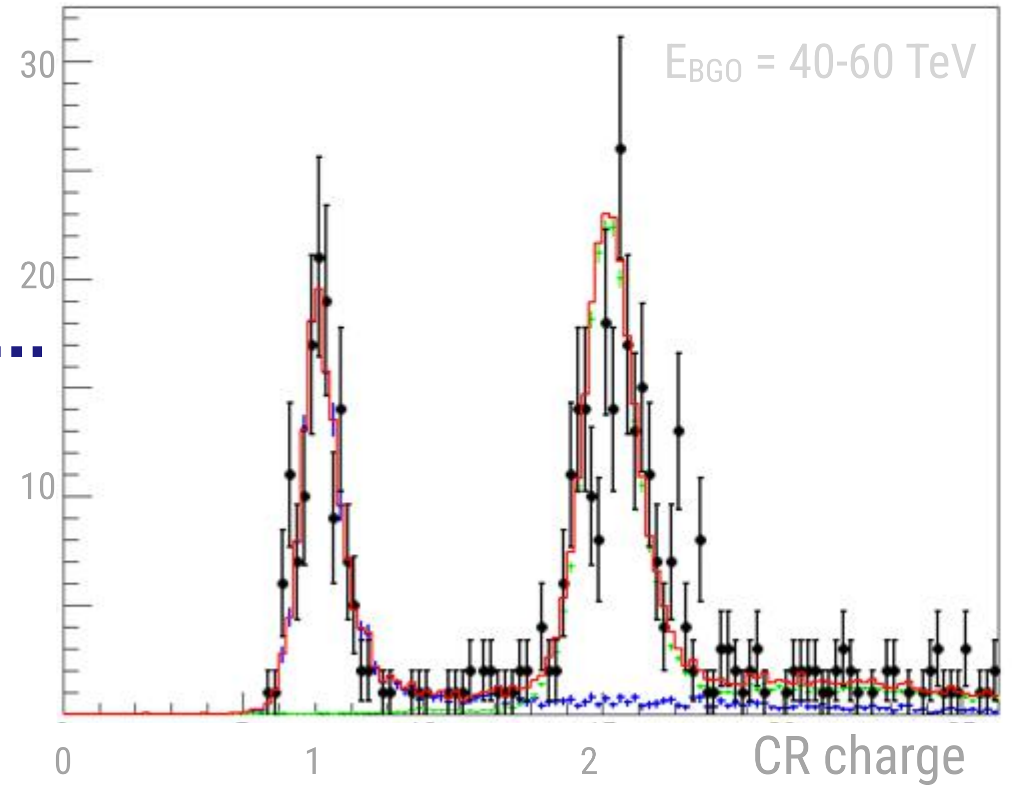
We are able to identify a Cosmic Ray "needle" in a "haystack" of noise!



Before (Kalman):

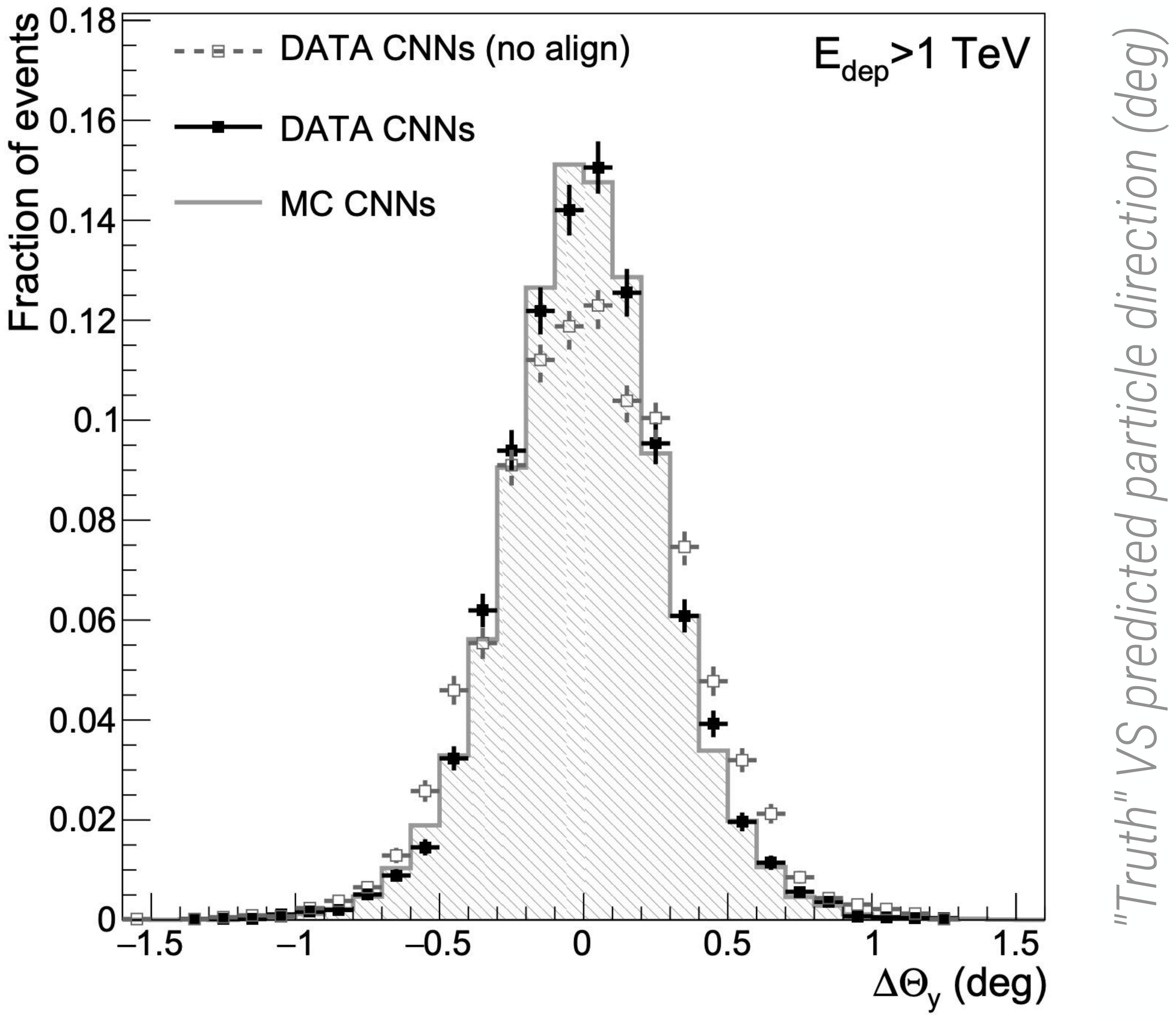


Now (CNNs):



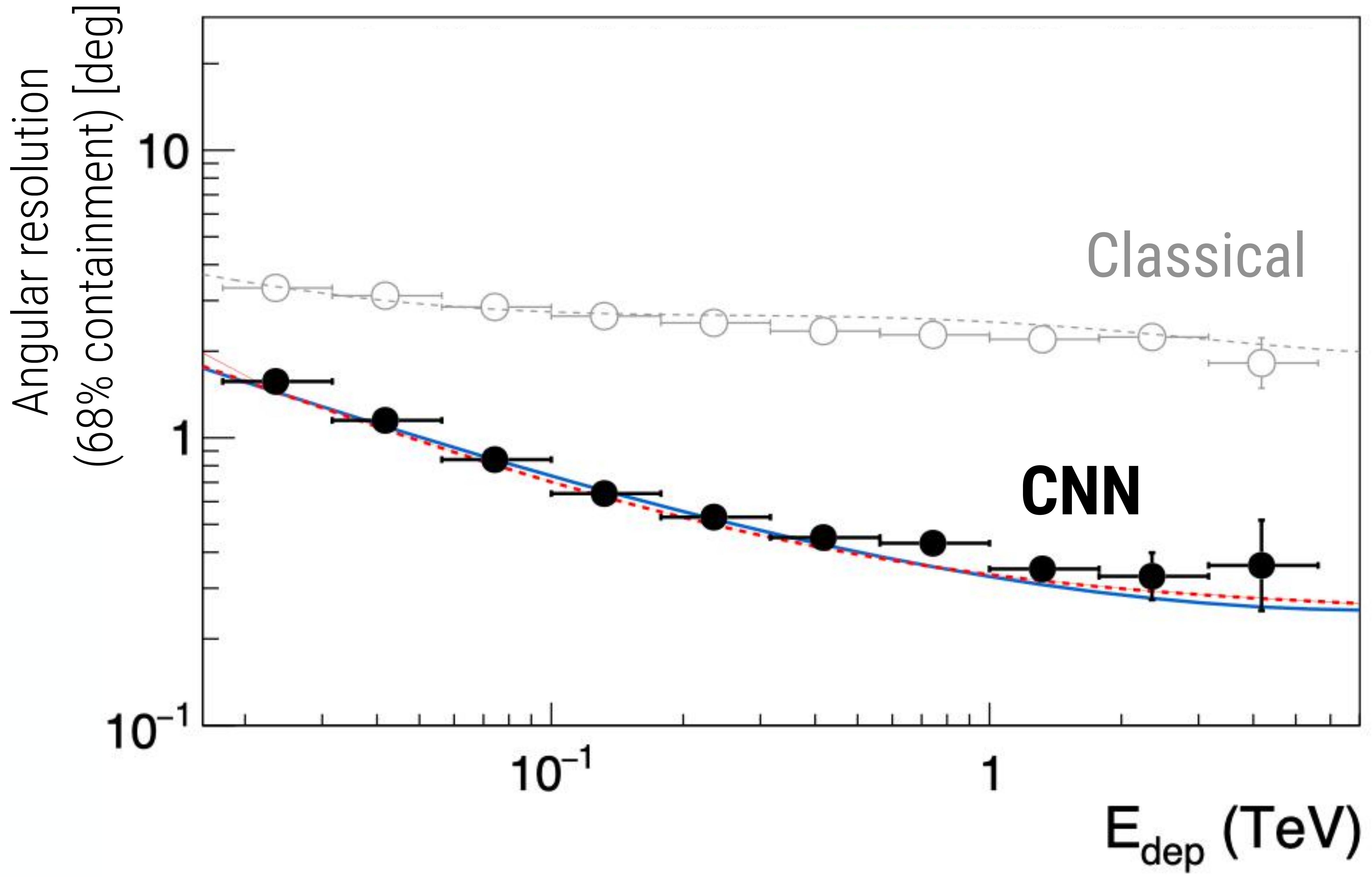
On the domain shift ...

In the specific example of the DAMPE calorimeter CNN, something which is trained purely on simulated data (Geant4, FLUKA) matches real data extremely well:



This is not always the case!

Somewhat unexpected result: our calorimeter CNN outperforms classical shower-shape fitting up to 6 times!

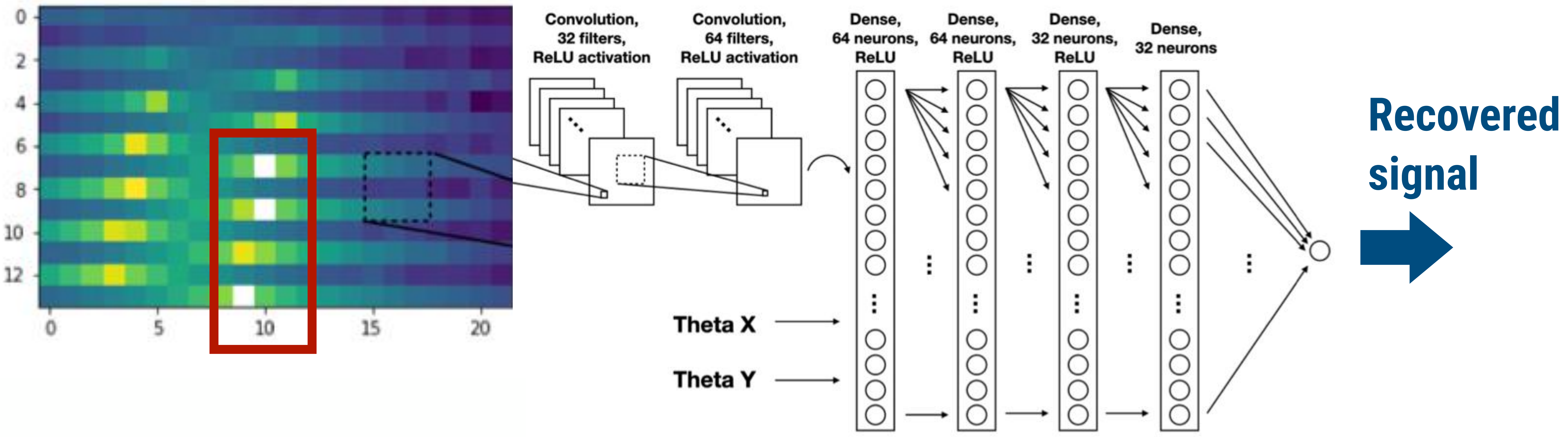


More CNN applications: recovery of lost signal (regression)

Important instrumentation implications ...

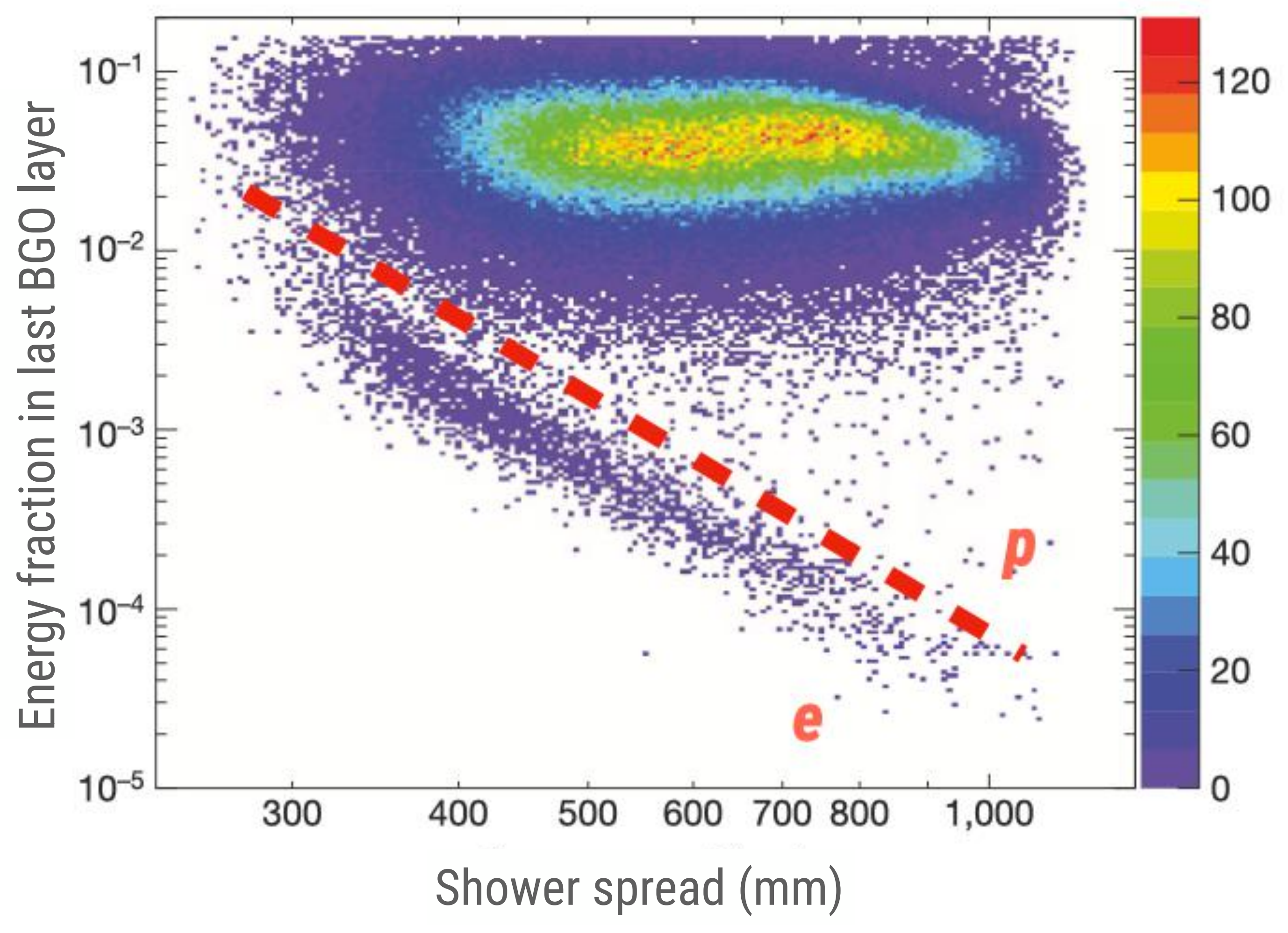
PROBLEM: Lost signal - happens at very high energies (> 100 TeV) due to the detector saturation
➡ Up to 50% of information lost...

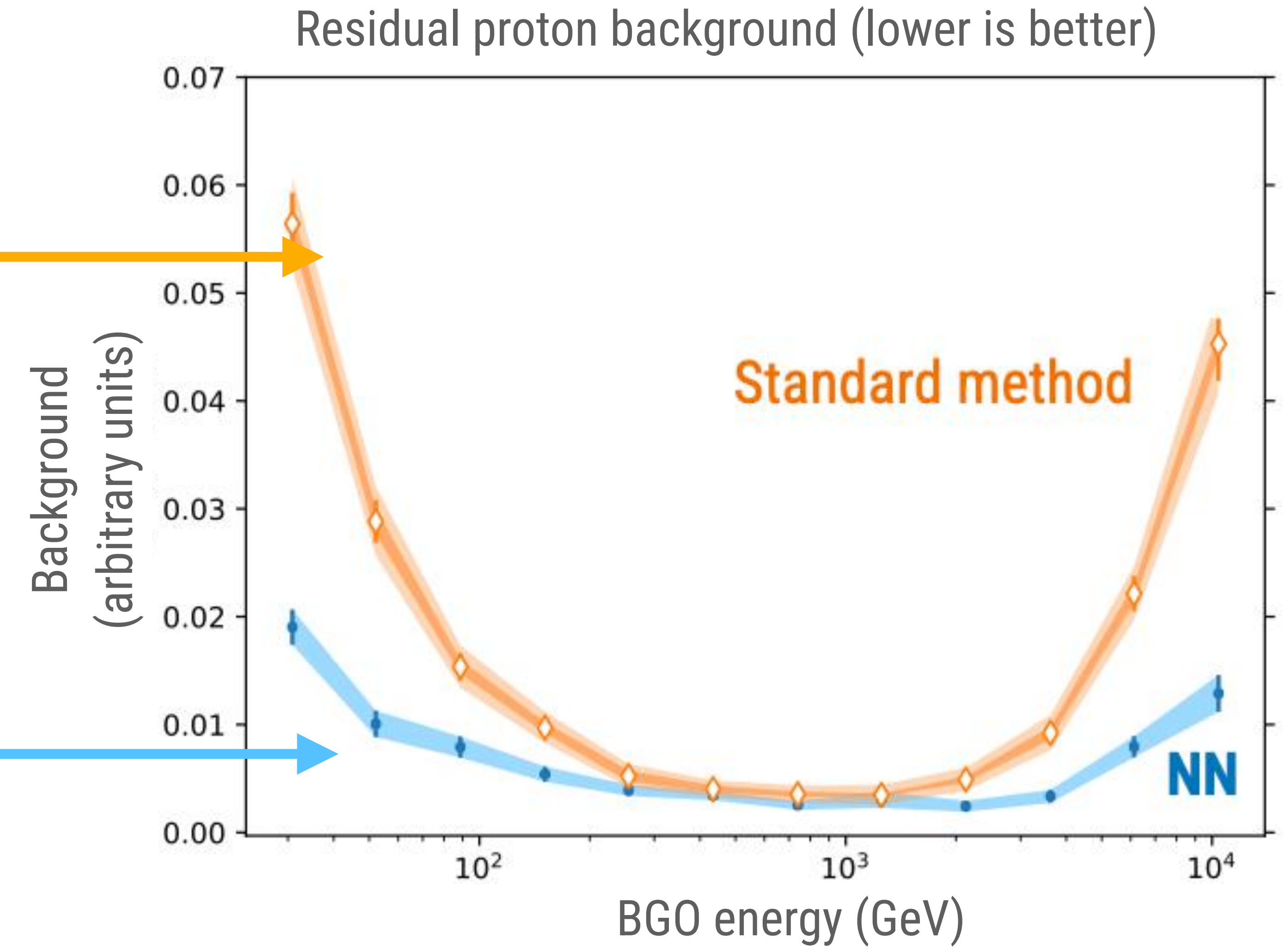
SOLUTION: We employ CNNs to recover the missing “pixels” using the image of the calorimeter
➡ recovered profiting of the information of surrounding pixels



Electrons VS protons (classification): a fully-connected NN

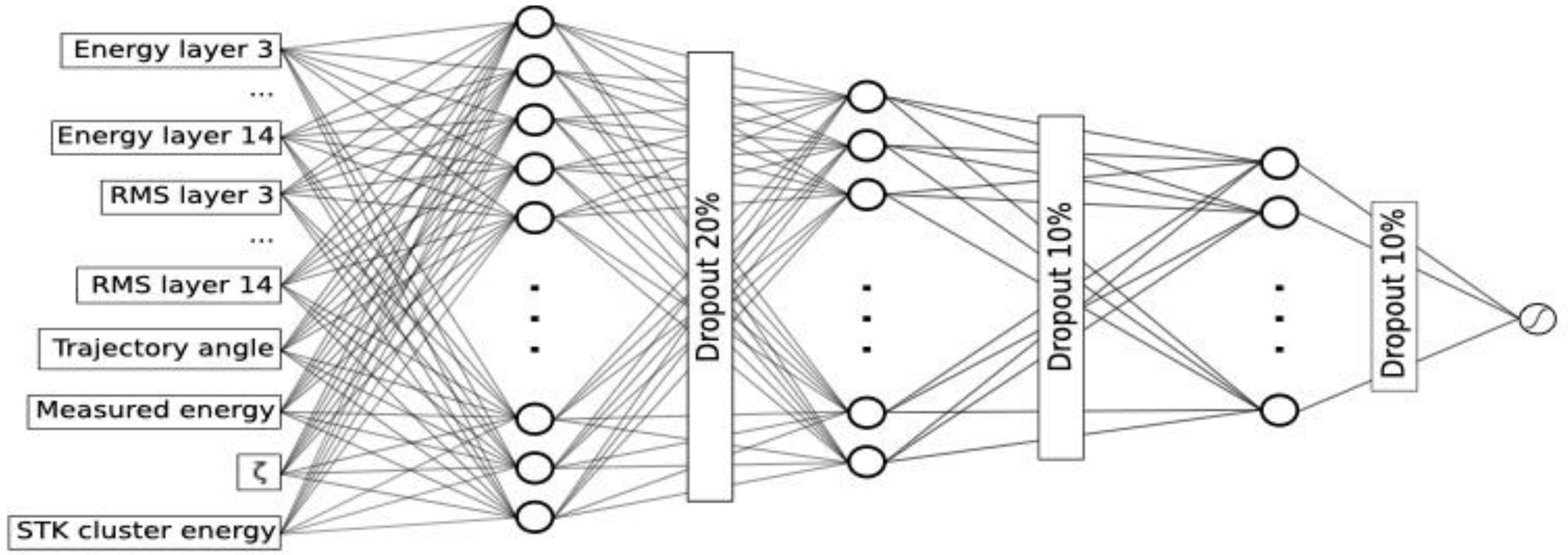
Standard method (shower-shape):





x4 better proton background rejection at > 10 TeV compared to classical methods!

Neural Network classifier:



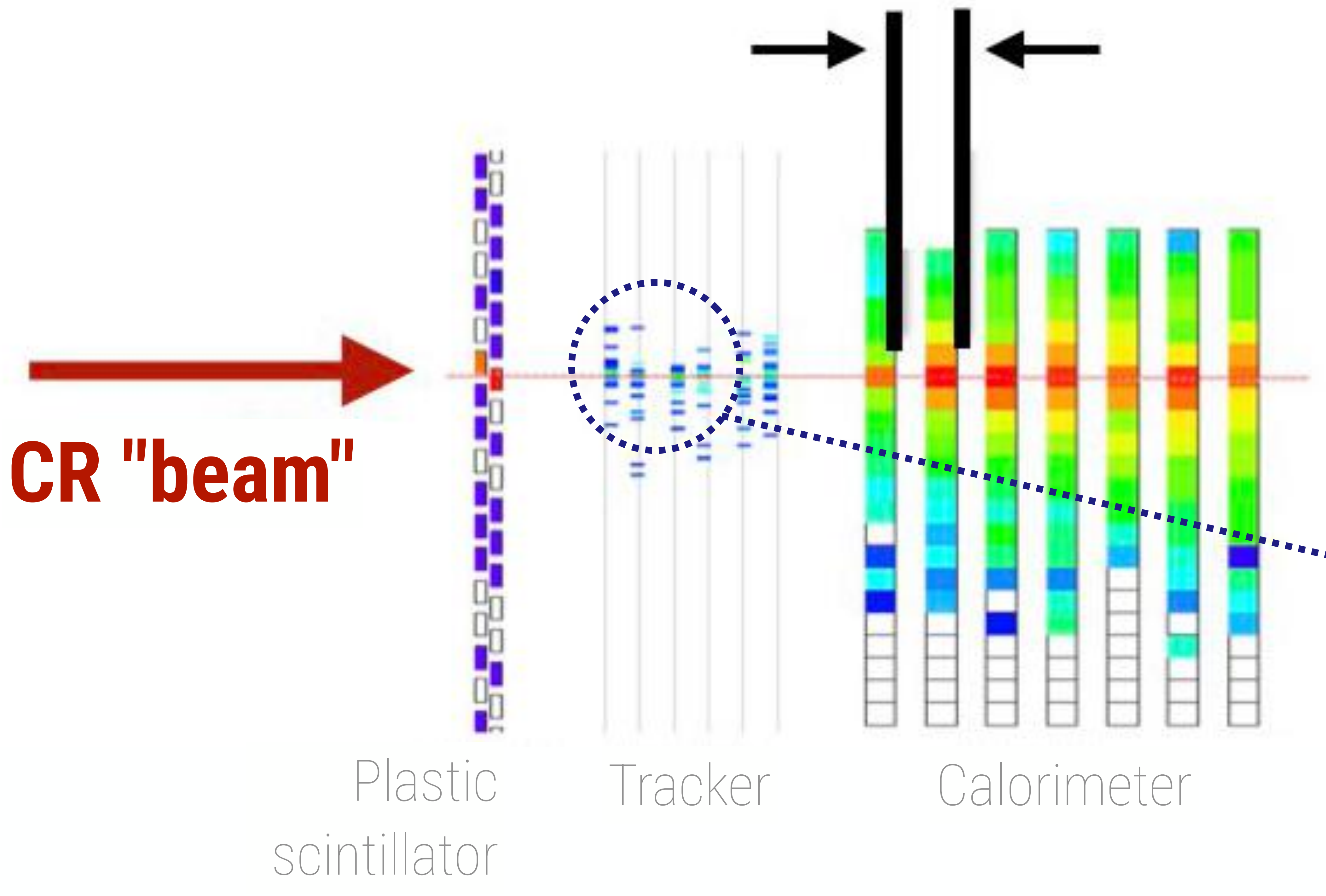
This is a perfect example of a simpler NN performing better on a real data (compared to CNN)

Droz et al. JINST 16 P07036 (2021)

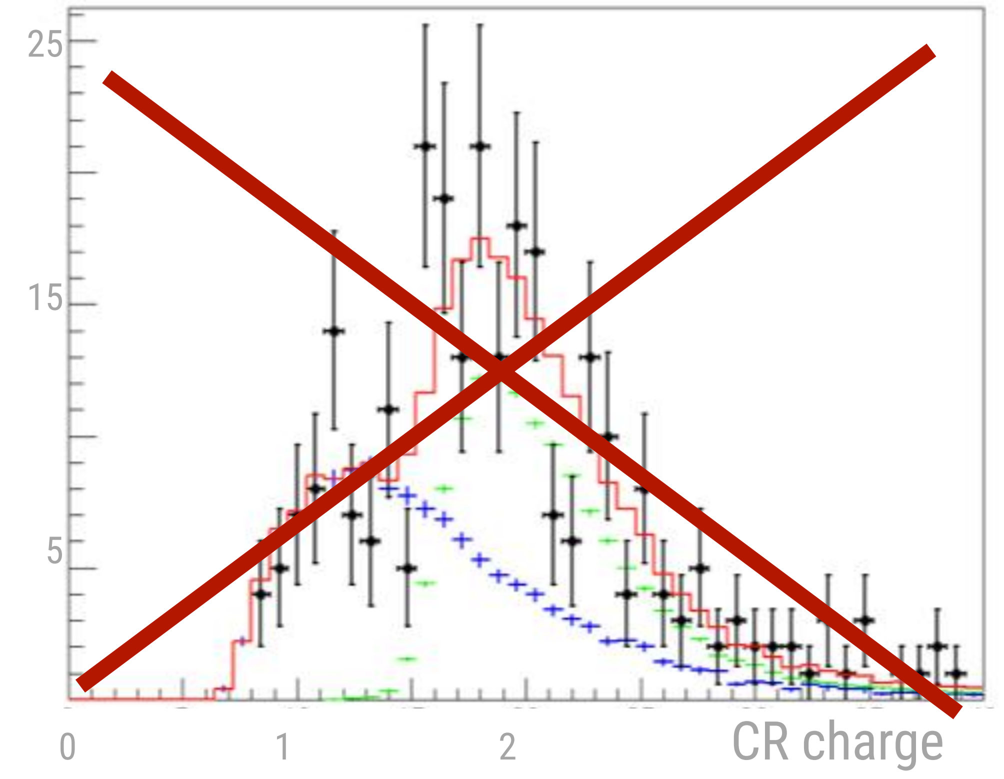
Back to particle physics with Cosmic Rays thanks to AI!

Consider DAMPE detector as your typical particle detector (fixed-target experiment) but exposed to a "free" beam of particle with **energies higher than LHC!**

→ To perform particle-physics type measurement, we need to select particles in the CR "beam" in a clean **unbiased** way



Before (Kalman):



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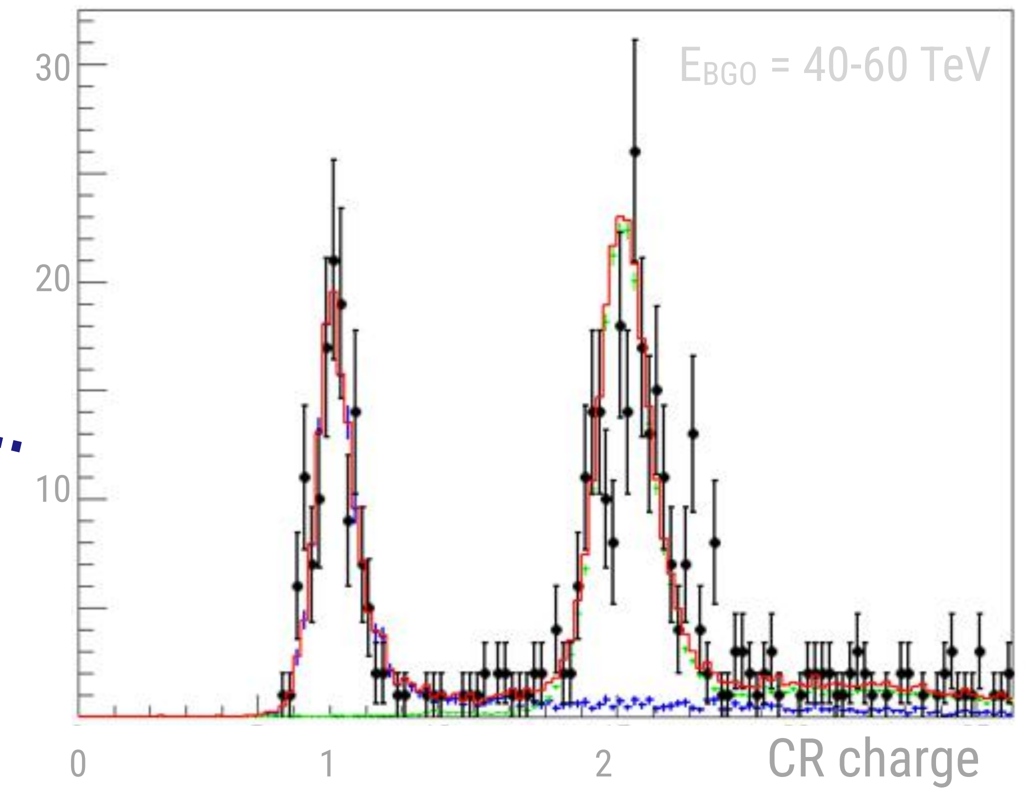
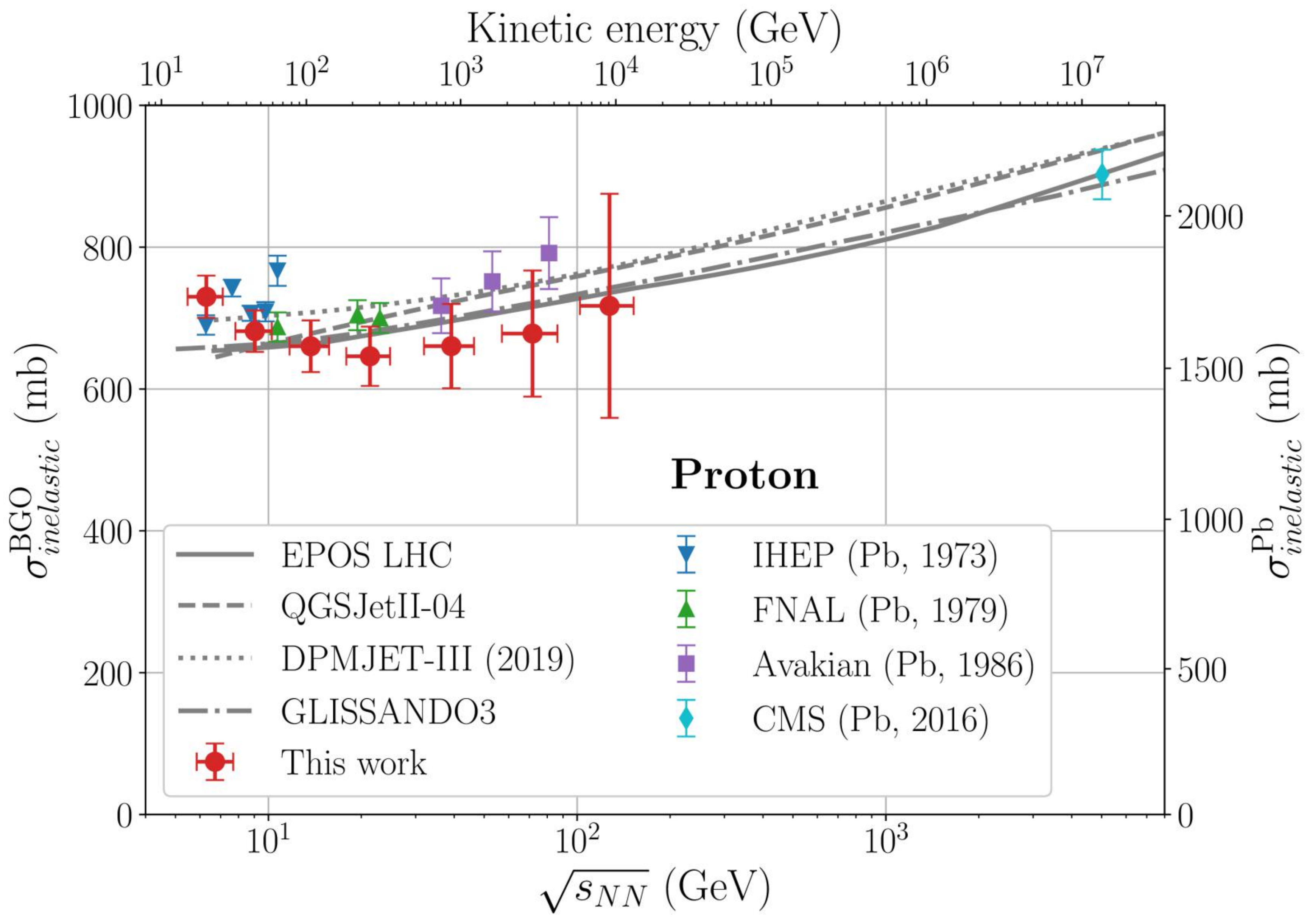
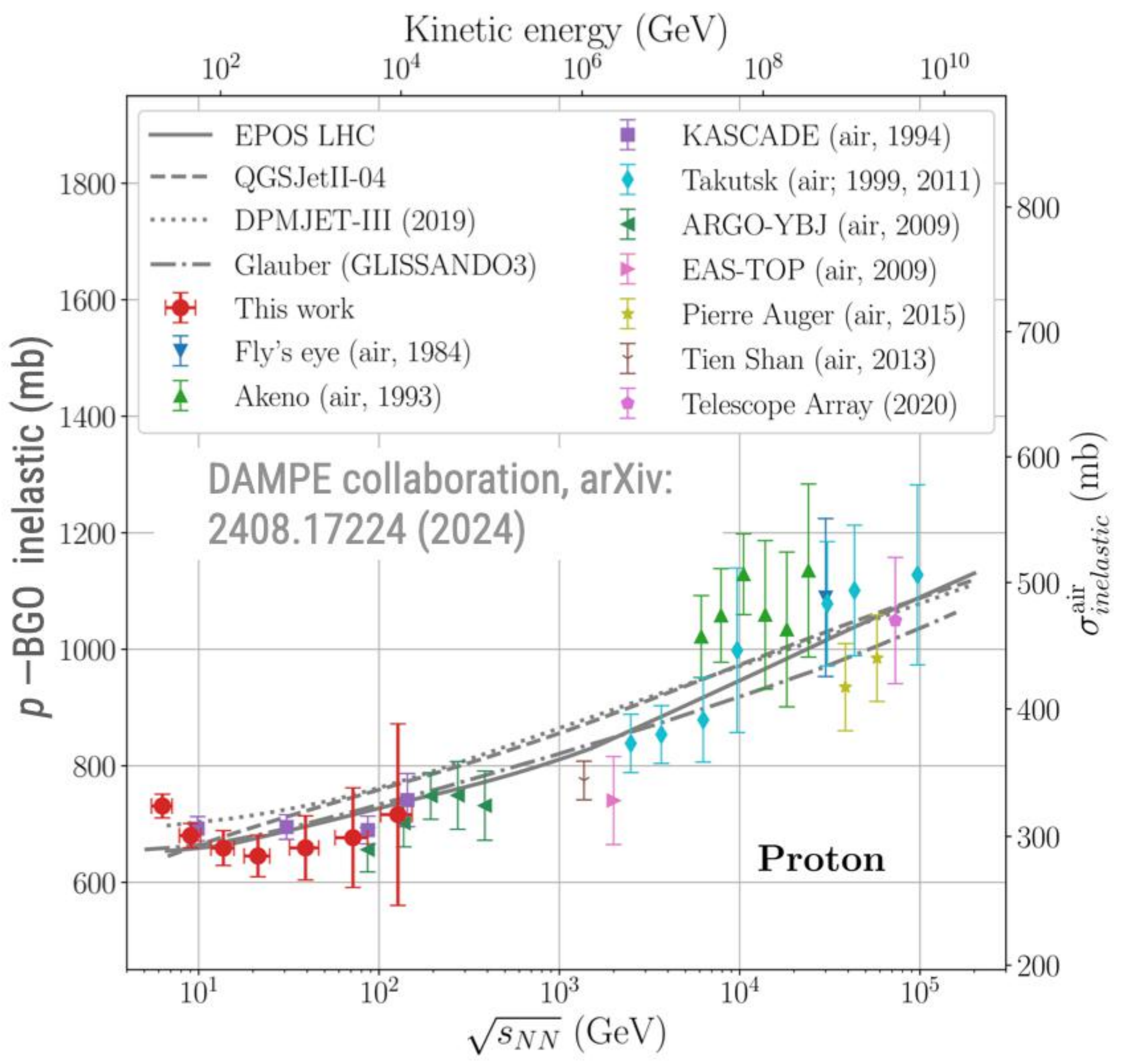


Back to particle physics with Cosmic Rays thanks to AI!

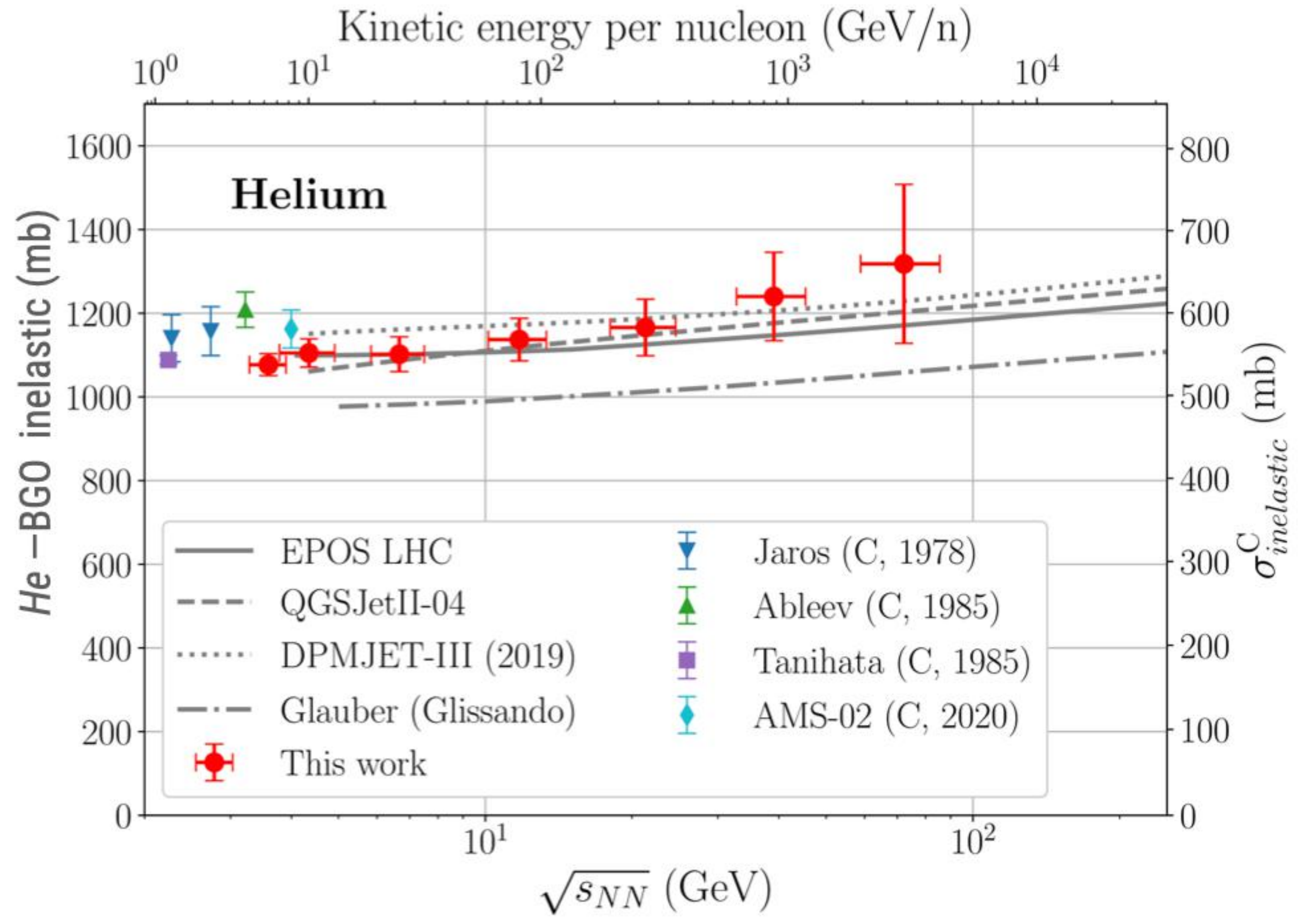
CNN-based tracking enabled the measurement of proton and helium inelastic hadronic cross sections, otherwise unachievable at that level of precision!



First proton cross section measurement spanning almost 2 order of magnitude in c.m.s. energy by a single experiment



Complementary to accelerator and air-shower results



First measurement of helium cross section at such high energies

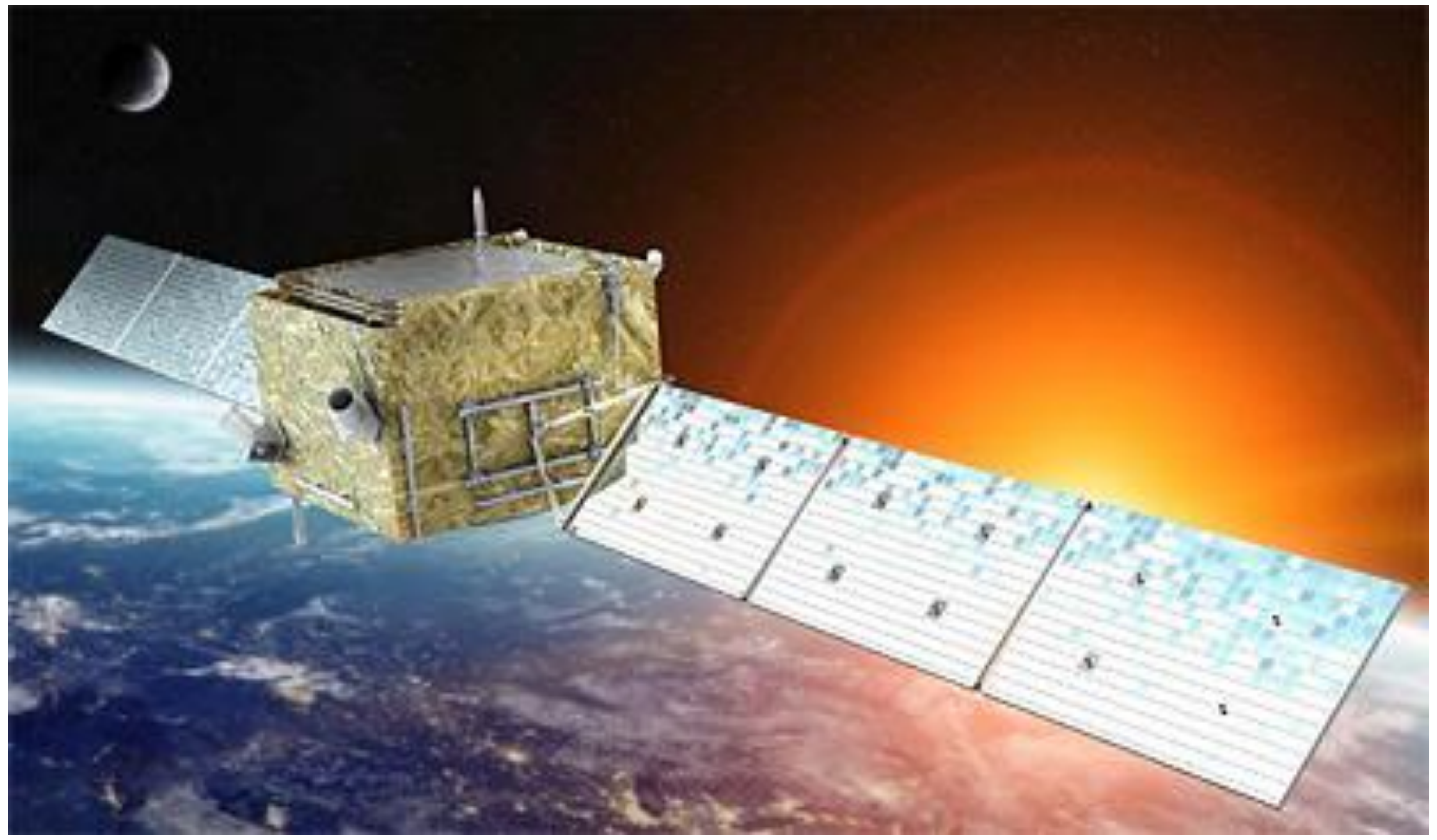
Phys. Rev. D 111, 012002 (2025) arxiv:2408.17224
(work lead by Dr. Paul Coppin at UniGeneva)

Conclusions

- DAMPE a state-of-the art particle detector in space pioneering TeV-PeV frontier
- DAMPE physics goals naturally push for deep learning to replace conventional methods (Kalman etc.)
  - ➡ Enables precise TeV-PeV particle detection
  - ➡ Helps/enables particle physics with cosmic rays
  - ➡ CNNs and NNs do the job so far, but we look beyond...

Papers/results already integrated in data analysis pipeline of DAMPE:
- Track reconstruction with CNNs (regression): https://arxiv.org/abs/2206.04532
- Electron VS Proton classification with NNs (classification): https://arxiv.org/abs/2102.05534
- Recovery of lost signal / saturation correction (regression): https://arxiv.org/abs/2201.12185

Work in progress: https://arxiv.org/abs/2503.10521 and a few more in preparation ...



DARK MATTER DAMPE PARTICLE EXPLORER
erc
Swiss National Science Foundation

To be continued, stay tuned ….

Thank You!