UNIVERSITÉ DE GENÈVE

ERC PeVSPACE

Direct Detection of TeV—PeV Cosmic Rays in Space

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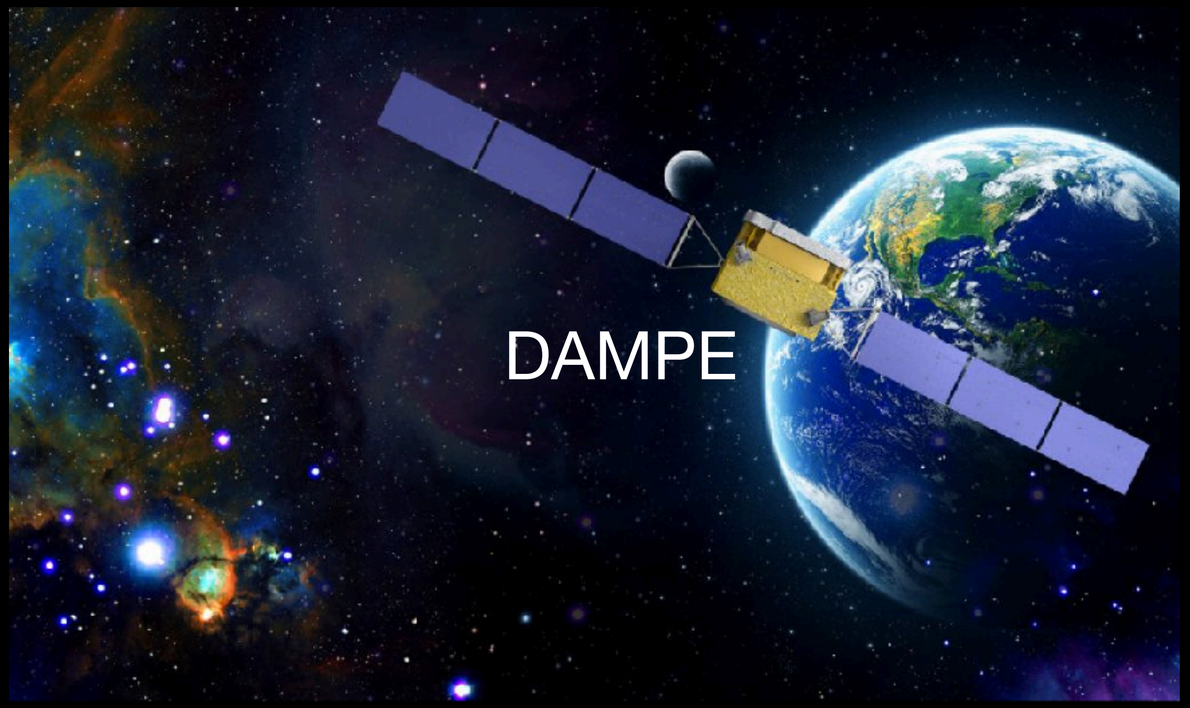
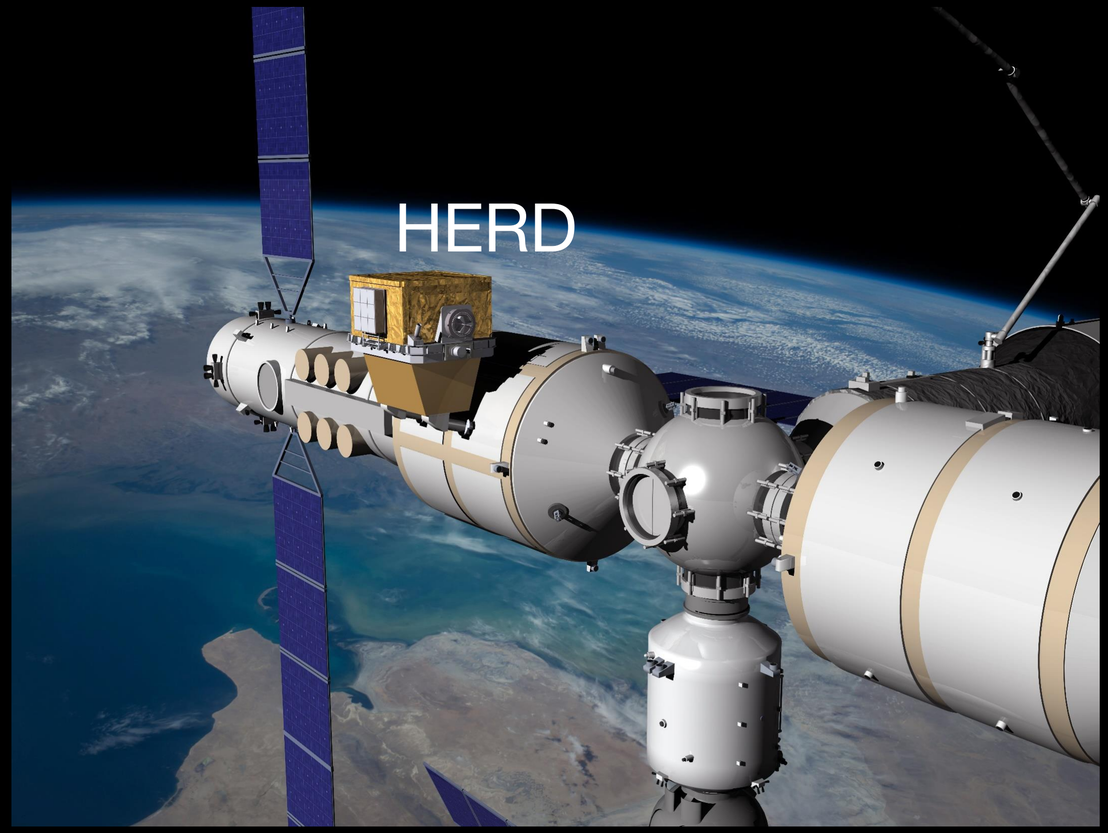
Chapter I
Instruments



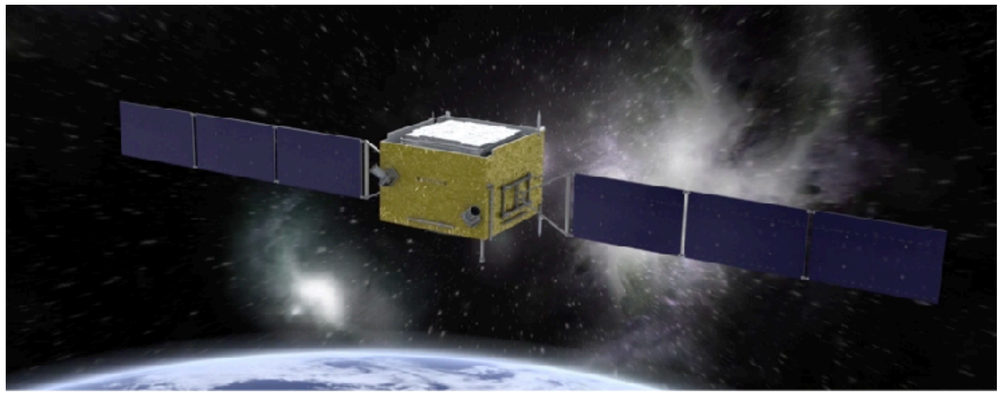
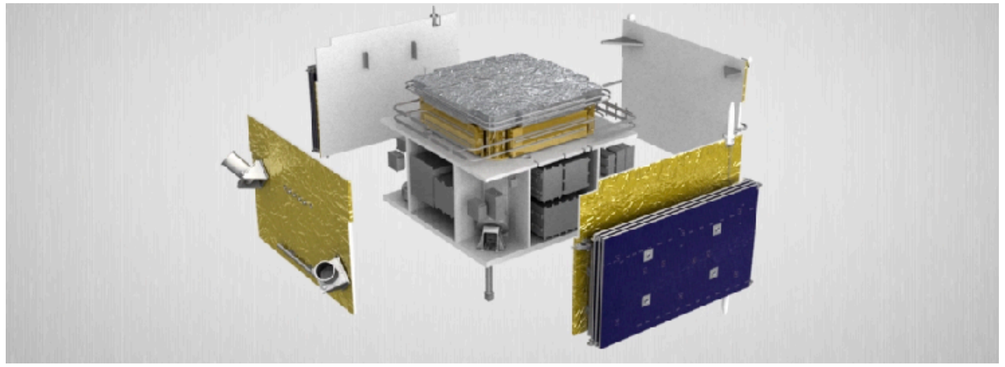


DArk Matter Particle Explorer (DAMPE)

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

Collaboration



DArk Matter Particle Explorer (DAMPE)

BGO

- 31 X_0 — thickest in space
- e/γ detection up to ***10 TeV***
- *p*/ions up to ***50 GeV — 500 TeV***

STK

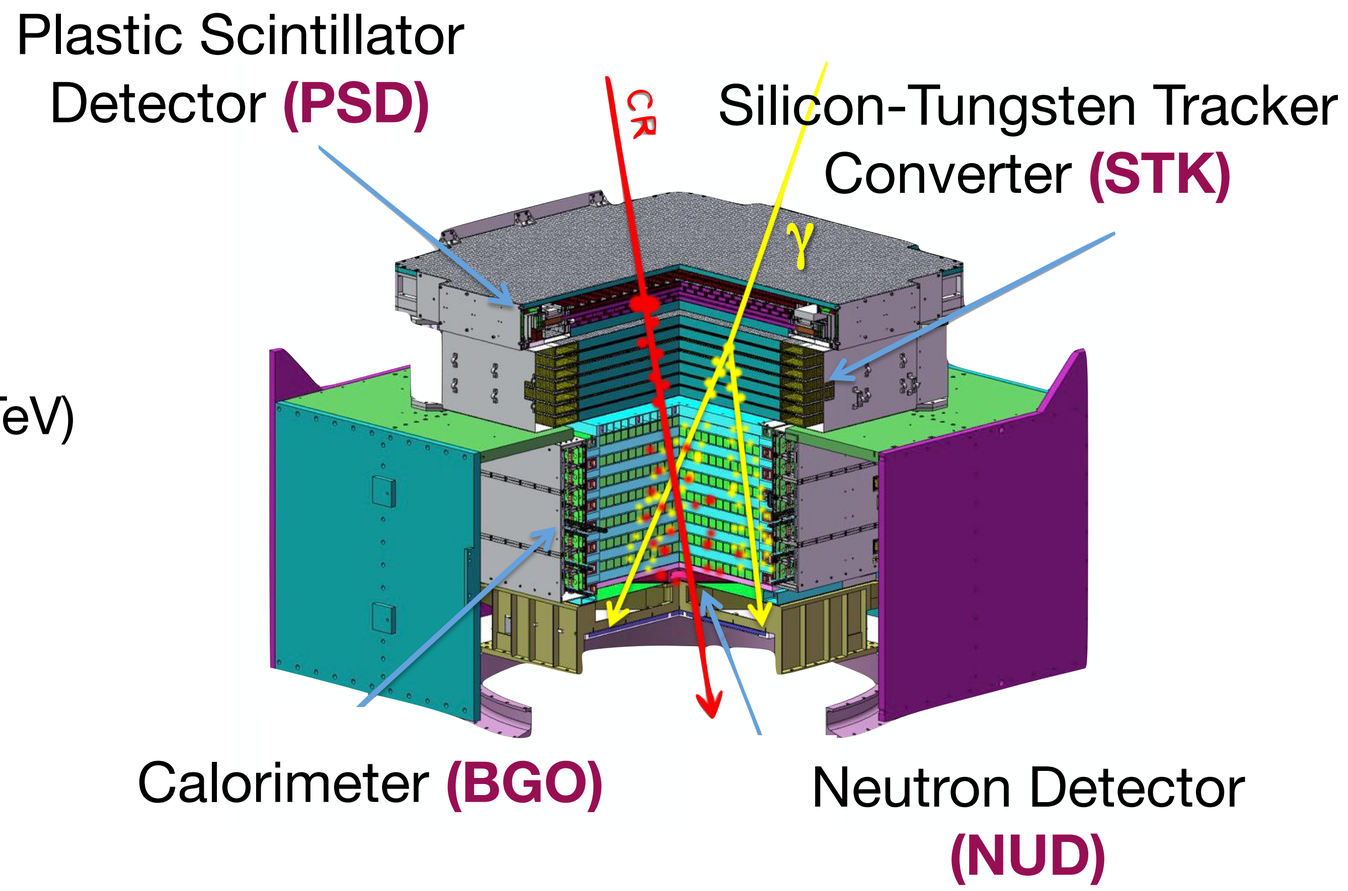
- Position solution ***~50 micron***
- γ angular resolution ***0.5°—0.1°*** (GeV— TeV)
- Absolute Charge (Z) identification

PSD

- Z identification up to *Ni* (Z=28)
- γ anti-coincidence signal

NUD

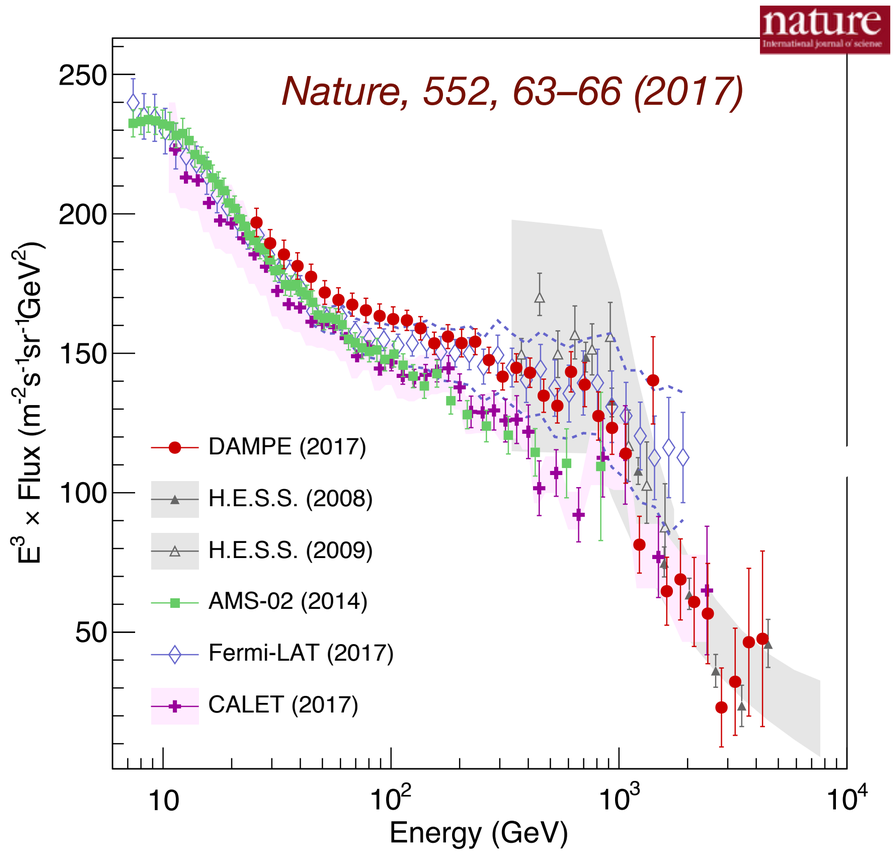
- Additional e/p rejection capability



Cosmic Rays (CR) @ DAMPE

Electrons (+ positrons)

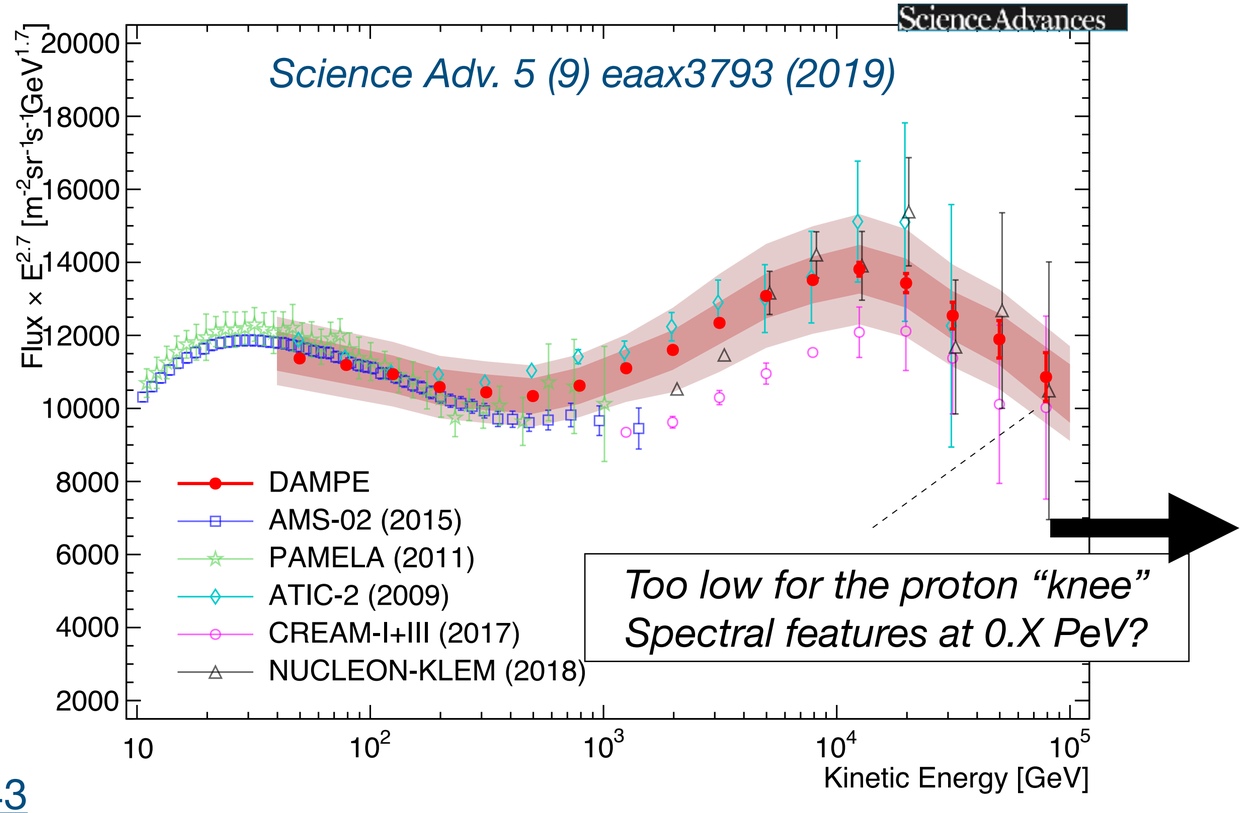
- Direct observation of spectral break



Also solar physics with $e^+ + e^-$, *see* Astro.J.Lett. 920 (2021) 2, L43

Protons

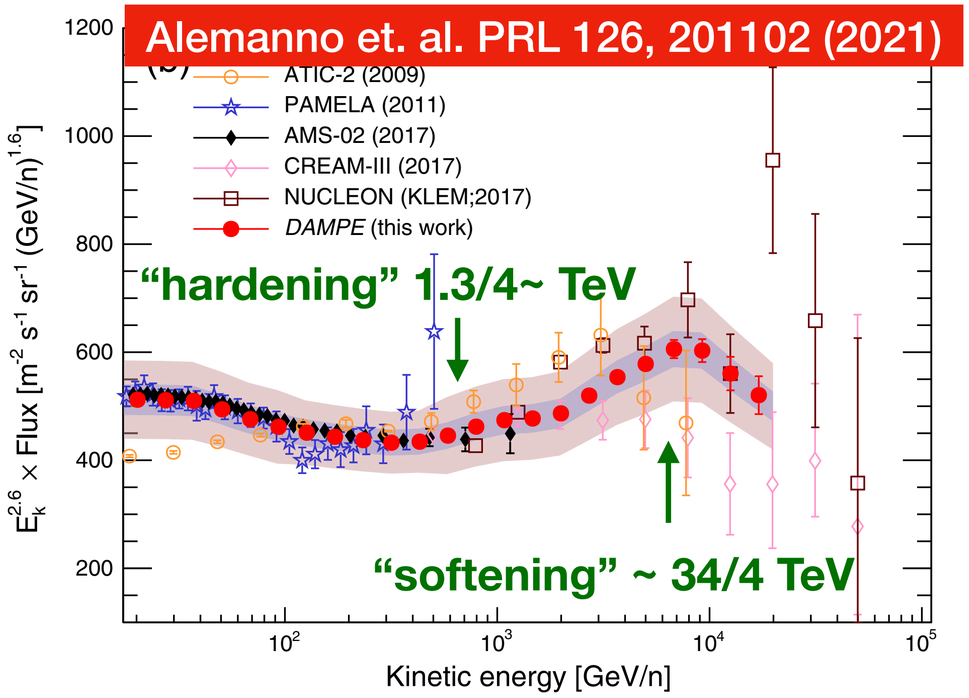
- First direct measurement up to 100 TeV
- Reveals new spectral feature at ~13 TeV



Cosmic Rays (CR) @ DAMPE

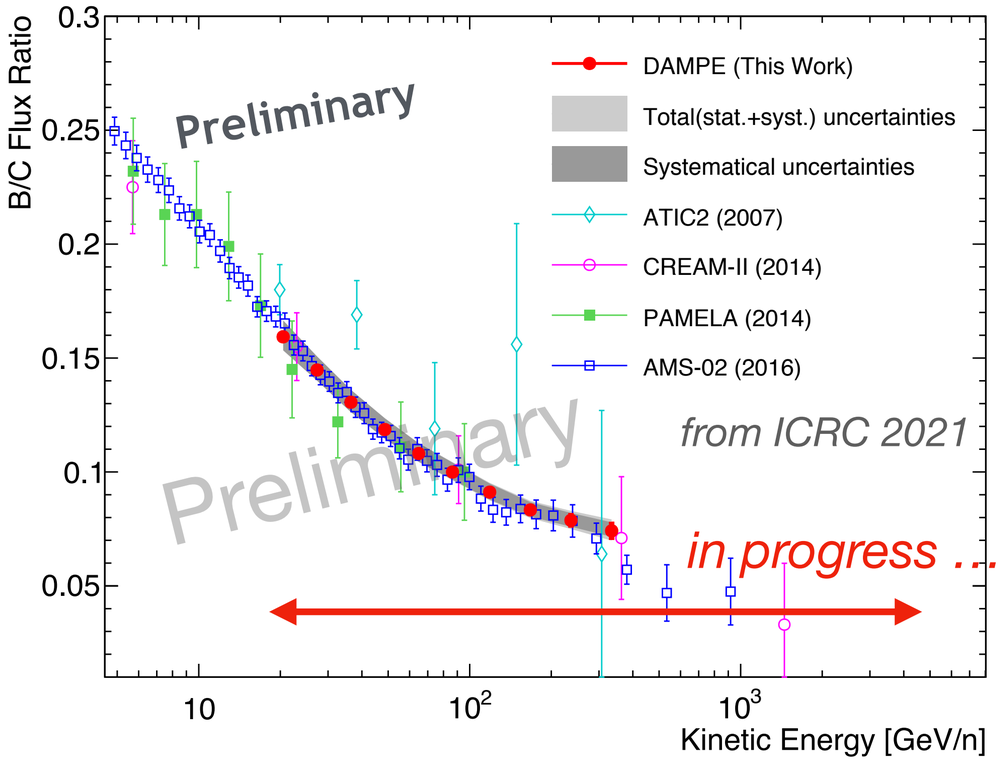
He

- Indication of Z-dependent acceleration source of CR ?



B/C ratio

- CR propagation at TeV ?



Many more ongoing analyses: *B—C—N—O, Fe,* γ-ray physics

High Energy Radiation Detector (HERD)

Next-gen Calorimetric detector in Space

- 5-side tracking & absolute charge ID
- 3D imaging LYSO calorimeter
- Target size ~ $55X_0$, $3\lambda_i$
- On board CSS ~ 2027

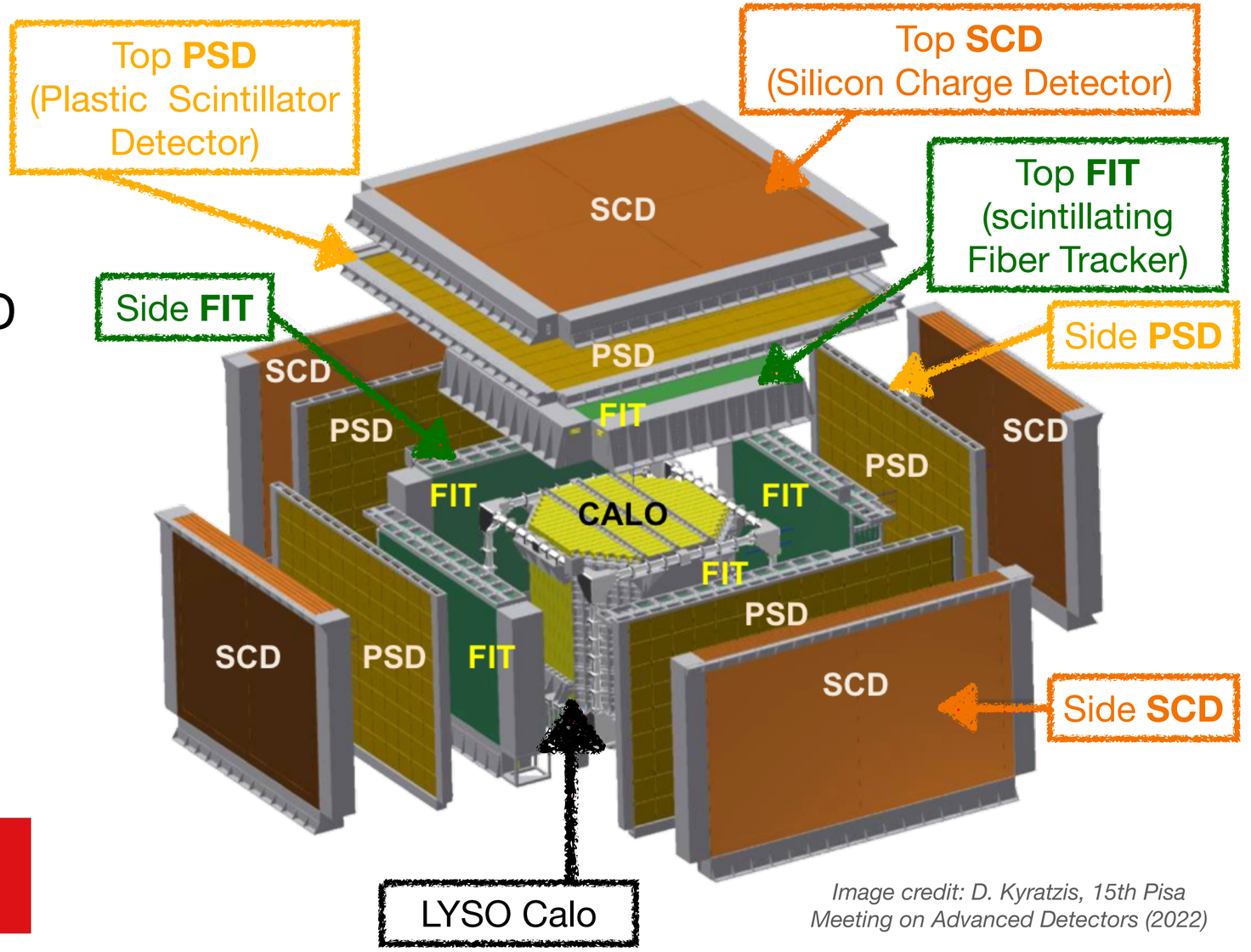
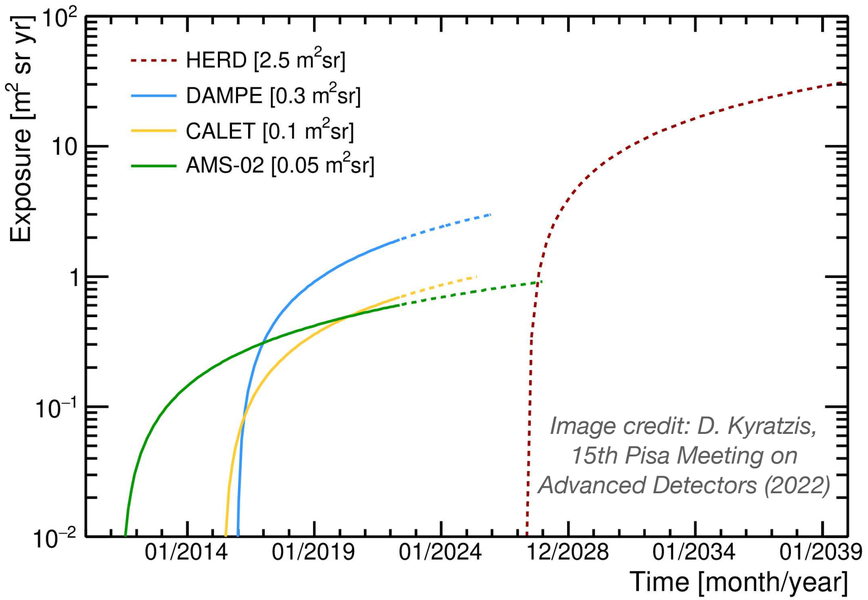


Image credit: D. Kyratzis, 15th Pisa Meeting on Advanced Detectors (2022)

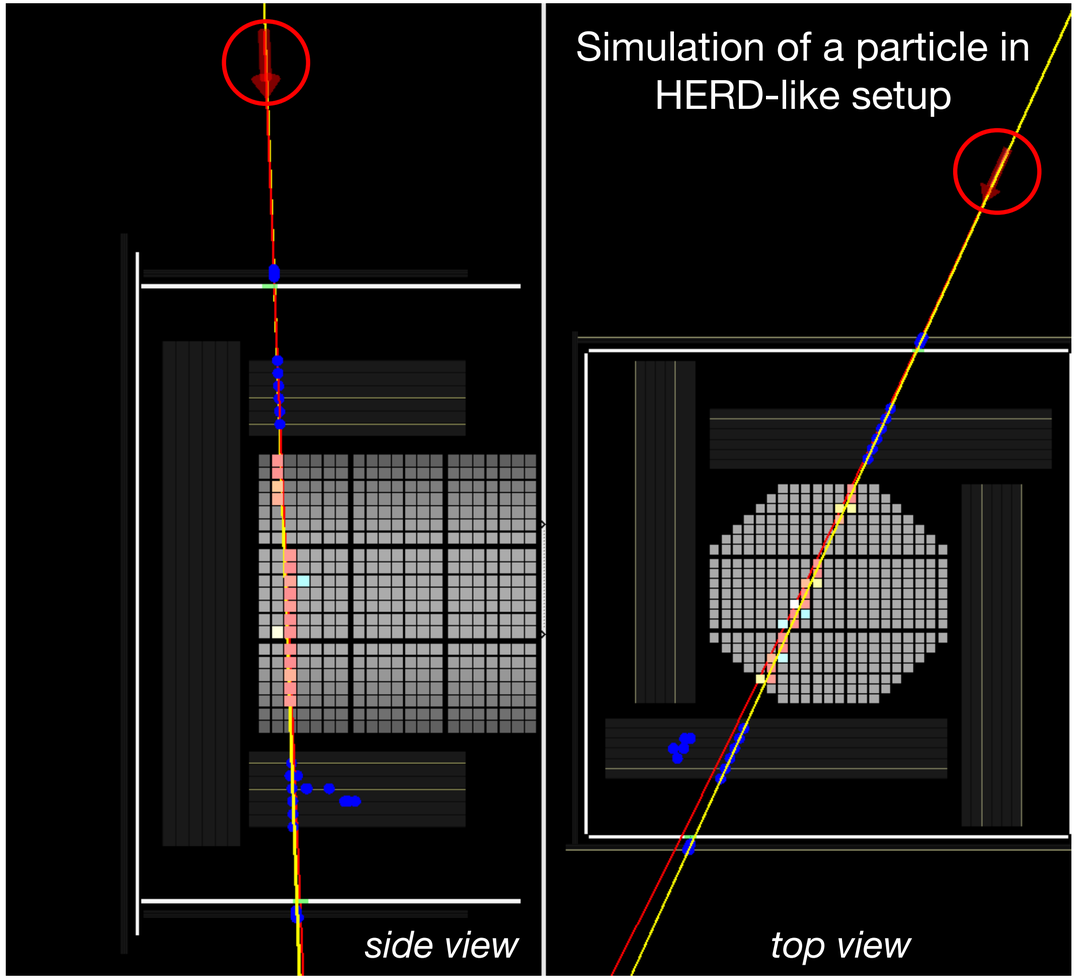
Collaboration

High Energy Radiation Detector (HERD)

- *e/γ* 10 GeV — 10s TeV
- p/ions 10s GeV — few PeV
- Lifetime ~ 10 years

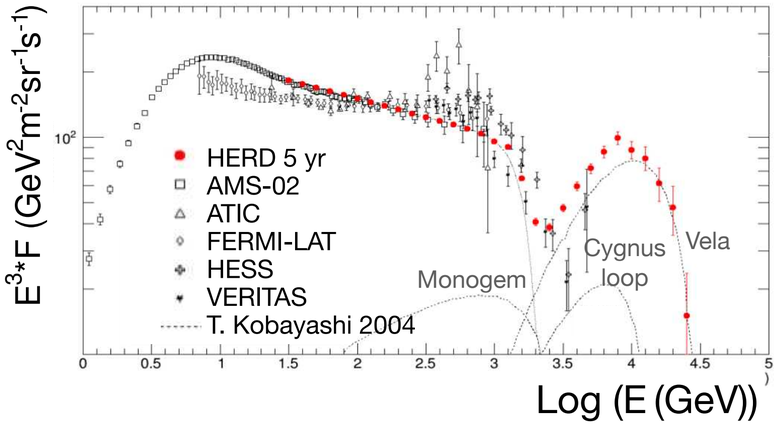


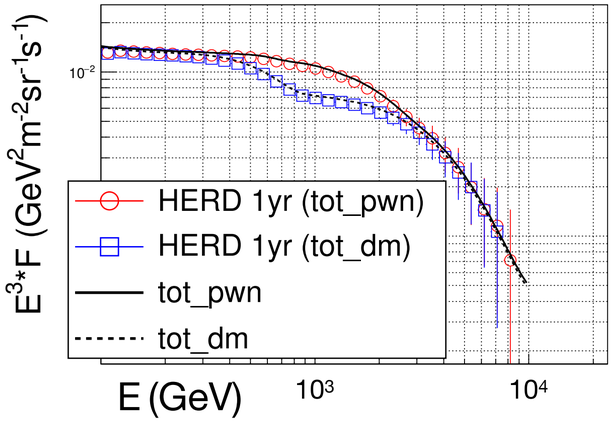
15 — 20 m² sr yr
Order of magnitude higher exposure compared to previous experiments



High Energy Radiation Detector (HERD)

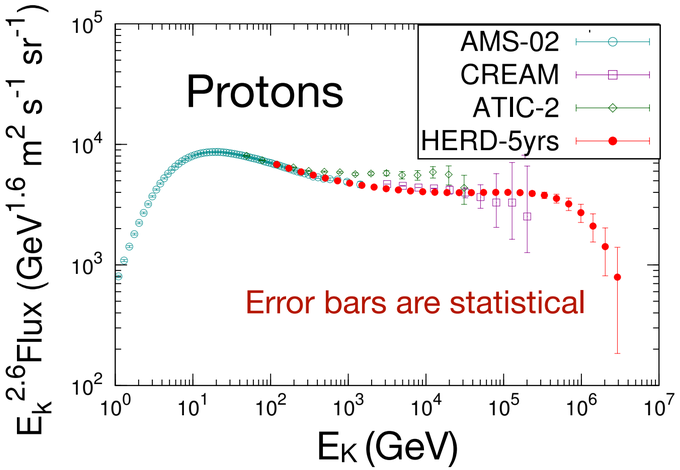
$e^- + e^+$

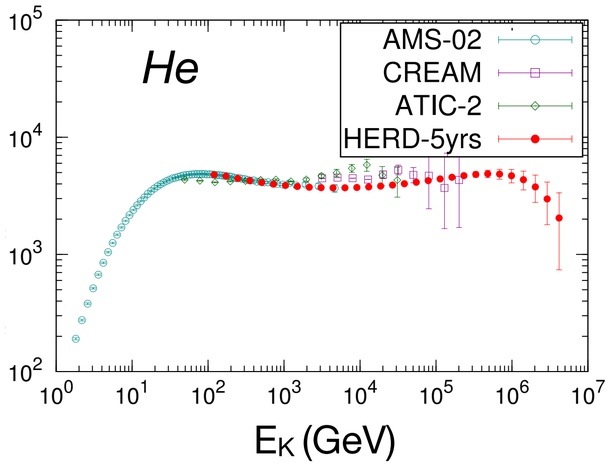




- Measure spectral cutoff, direct observation of local sources, anisotropy …
- Discriminate Astrophysical sources from ***Dark Matter*** contribution

p & ions

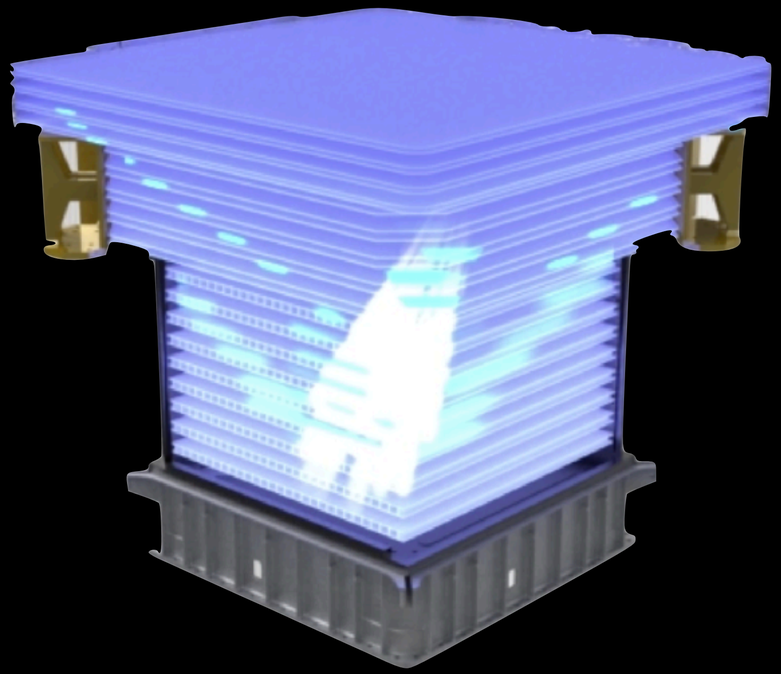


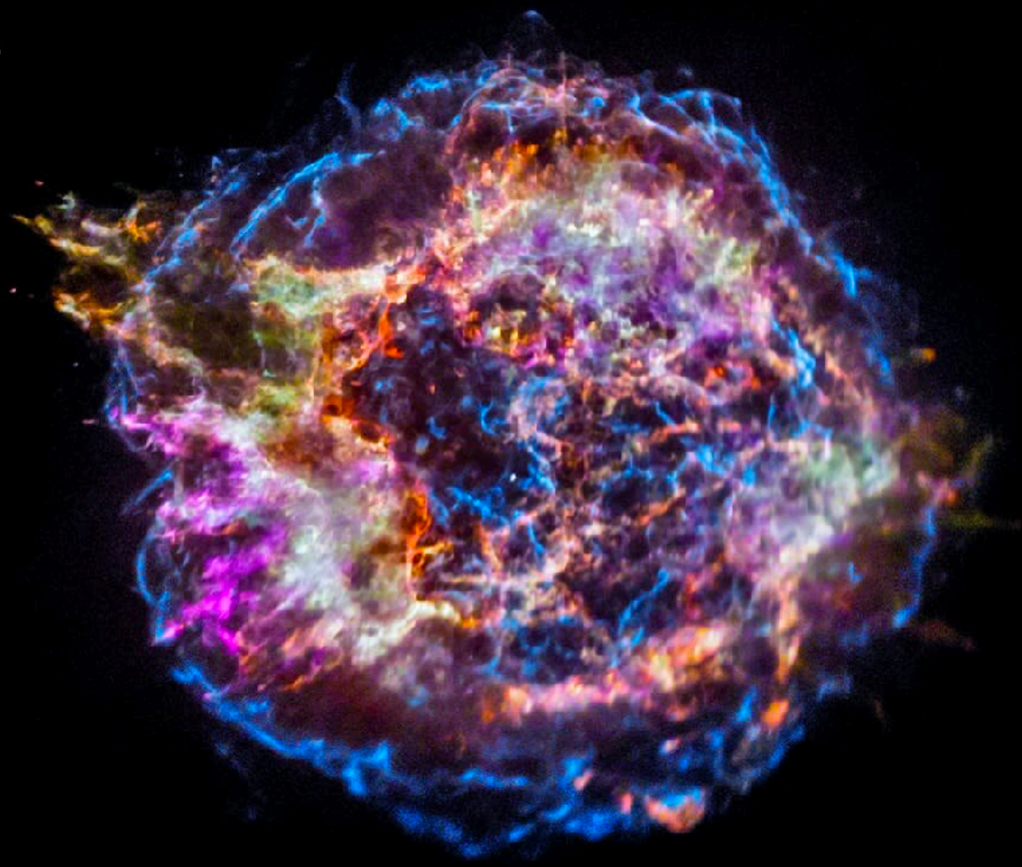


- First direct probe of ***knee structures*** and ***acceleration limit*** for *p* and *He*
- Further insights into ***propagation mechanisms*** (*B/C* @ 10s TeV/n , *Li,..*)

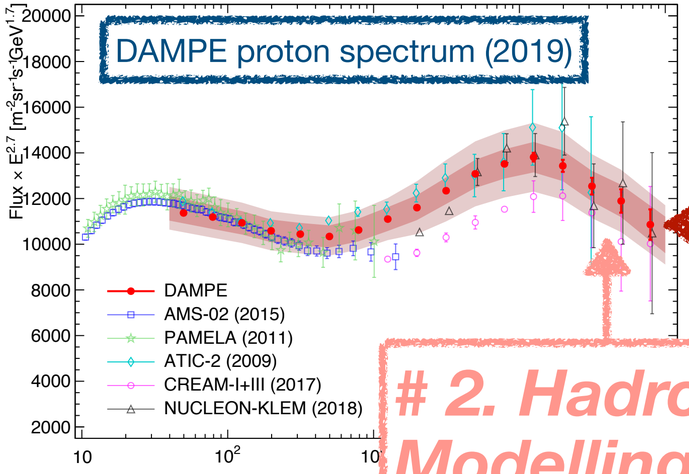
Chapter II

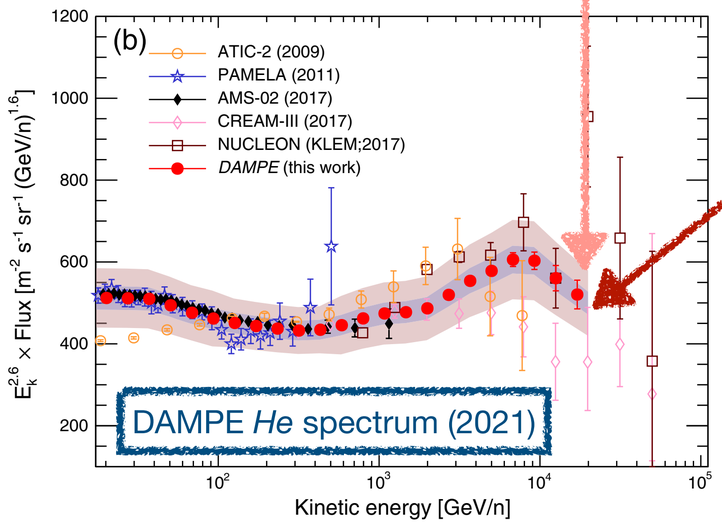
TeV—PeV Cosmic Rays: Analysis & Challenges





TeV—PeV CR detection in Space: key systematics



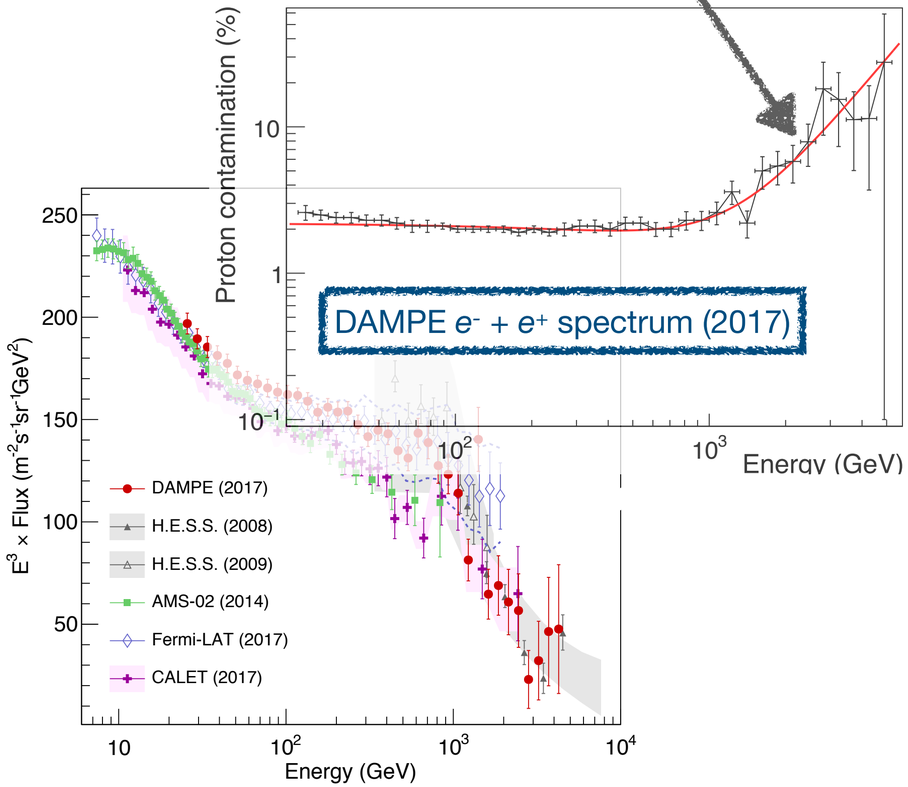


 # 1. Tracking & Particle ID

 # 2. Hadronic Modelling

…. also deteriorate analyses of B-C-N-O, Fe etc.

 # 3. Electron / Proton discrimnation



Relevant for both DAMPE and HERD !

Track reconstruction @ DAMPE

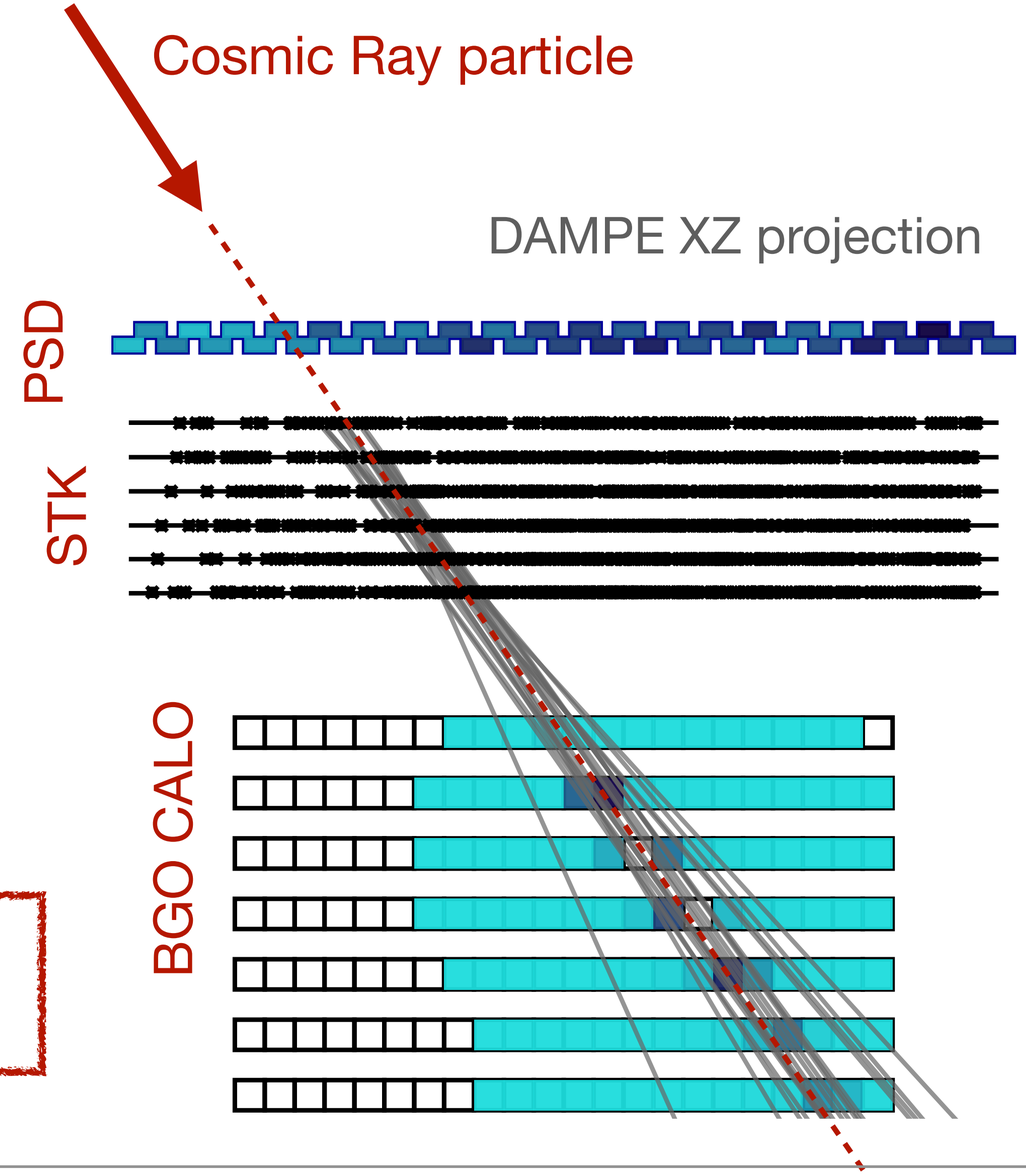
Conventional track reconstruction:

- Shower axis from CALO as a seed
- Kalman fitting
- Combinatorial track finding
- XZ and YZ fitted separately,
- … then combined in 3D tracks

Problems:

- Selection needed to find **the ONLY track**
- Efficiency drops at high hit multiplicity

At TeV— PeV hit multiplicity increases dramatically —>
Track reconstruction & identification is a key challenge!

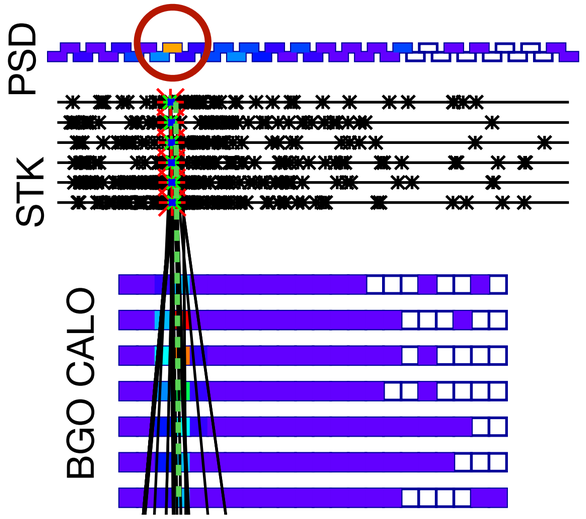


Charge identification @ DAMPE

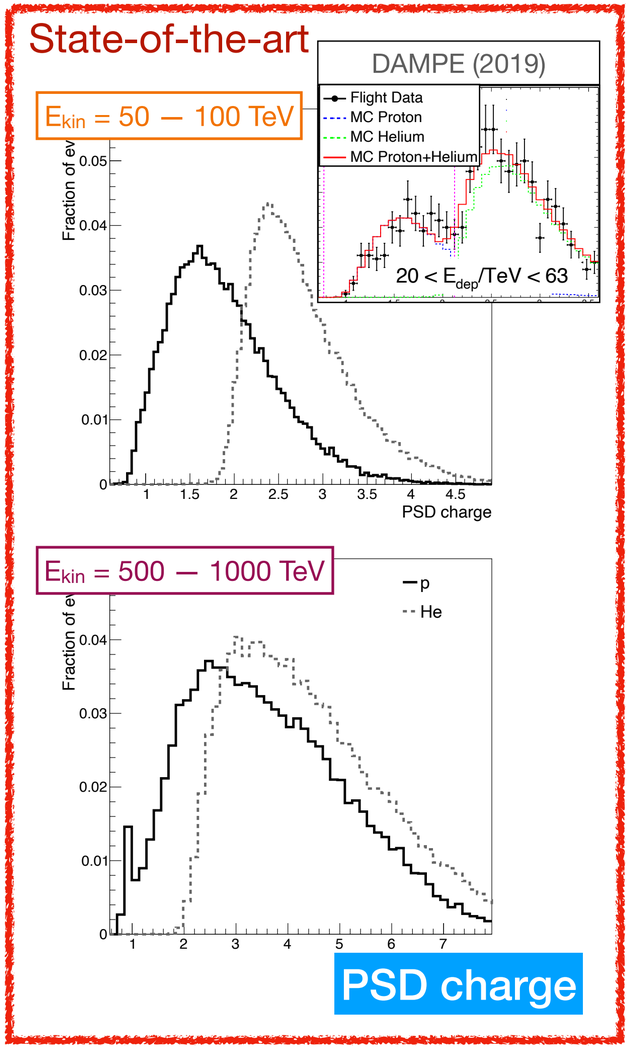
- Normally done in PSD
- Track used as a pointer to PSD
- Tolerant to track mis-identification, however:

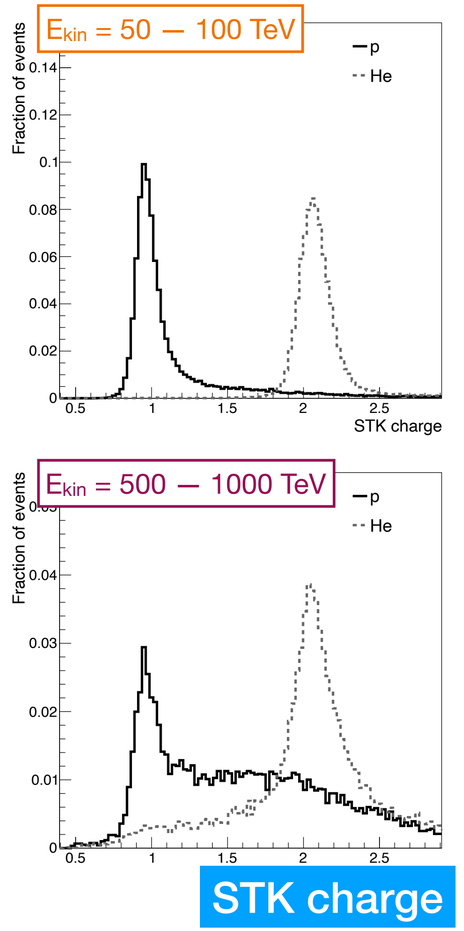
***p* and *He* peaks washed out**

Gets worse at high energies!

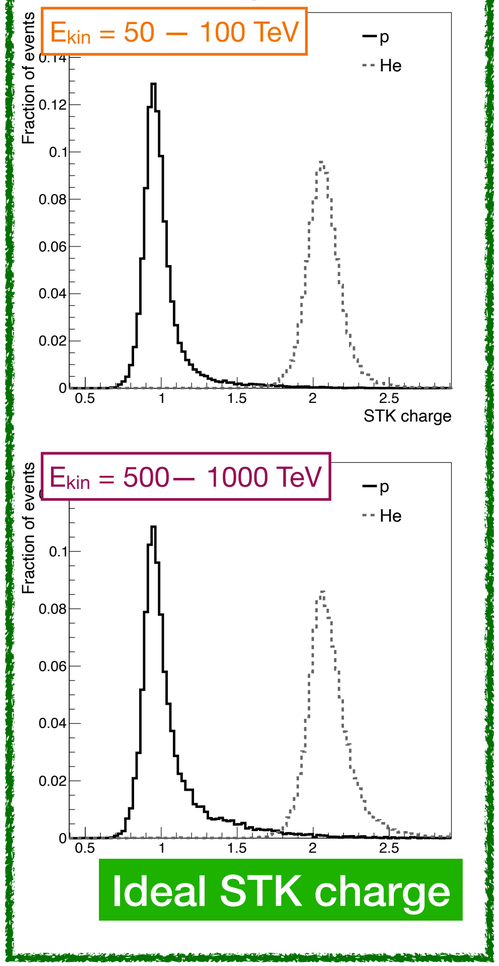


State-of-the-art



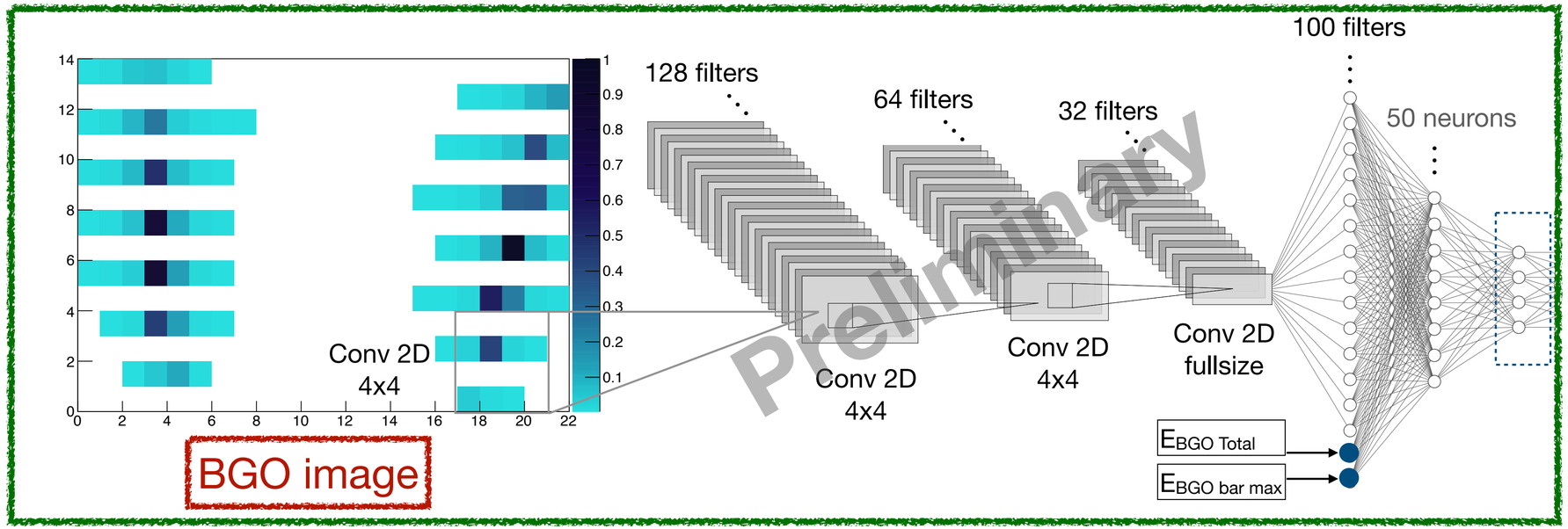


Our goal!

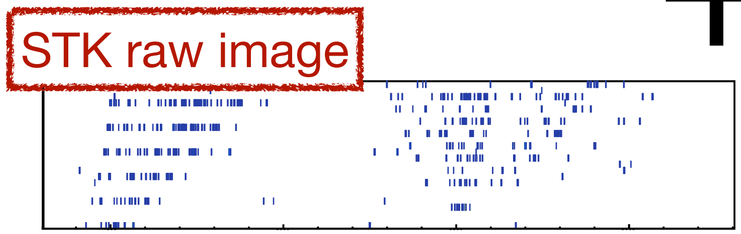


New tracking algorithm required for ~ PeV measurements!

NEW Track reconstruction @ DAMPE



We employ **Convolutional Neural Networks (CNNs)** to boost the accuracy of track reconstruction & identification @ DAMPE



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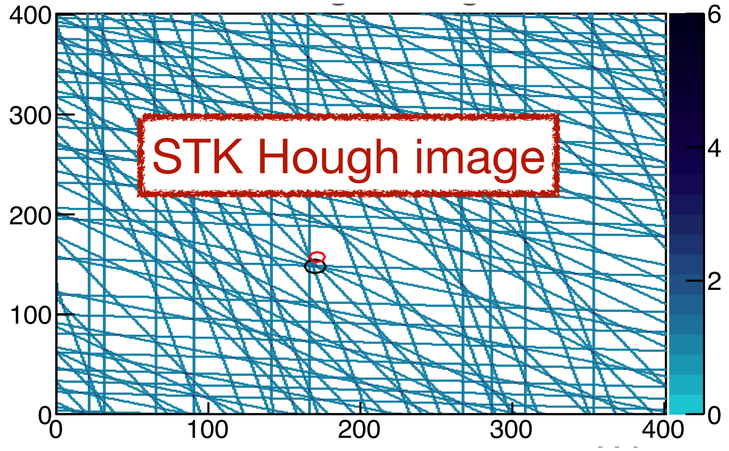
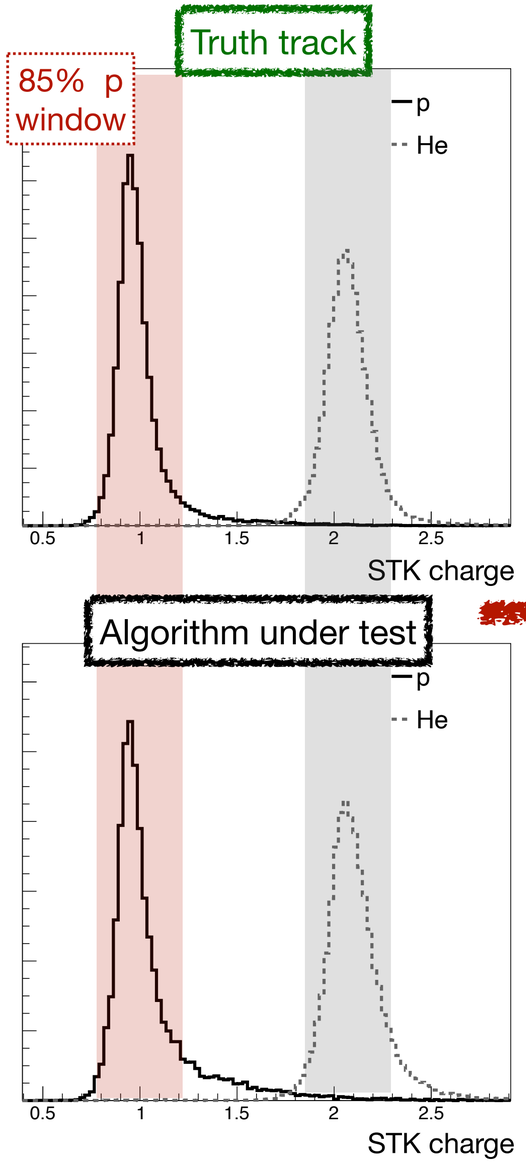


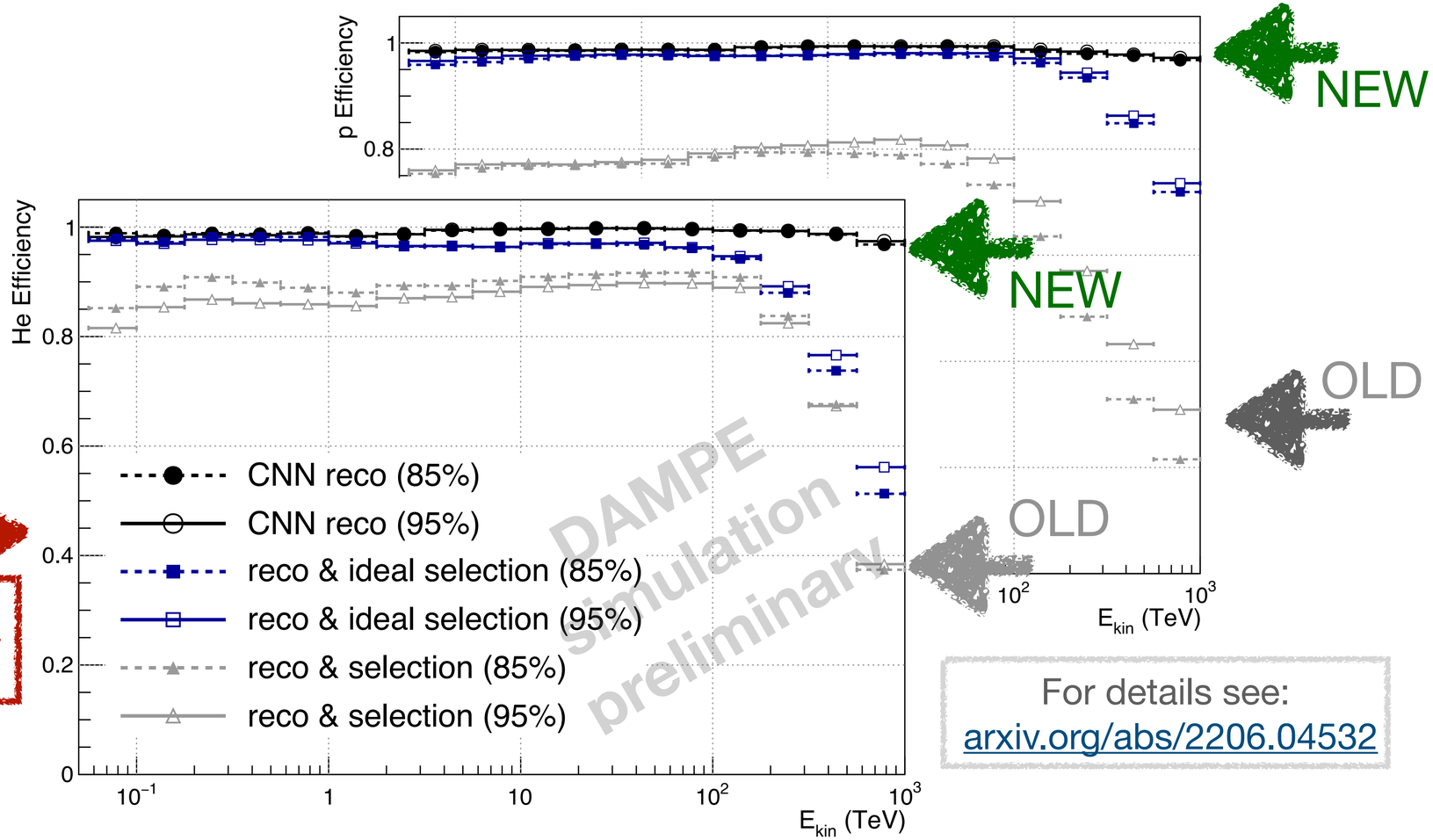
For details see:
arxiv.org/abs/2206.04532

CALO & Tracker "images" used as input, regression type of problem — returns particle direction as an output (no track selection needed)

Charge identification & NEW tracking



$$\text{Eff} = \frac{N_{\text{algorithm}}}{N_{\text{true}}}$$



For details see:
arxiv.org/abs/2206.04532

CNN tracking efficiency = **98-99%** up to 500 TeV (> **96%** @ PeV)

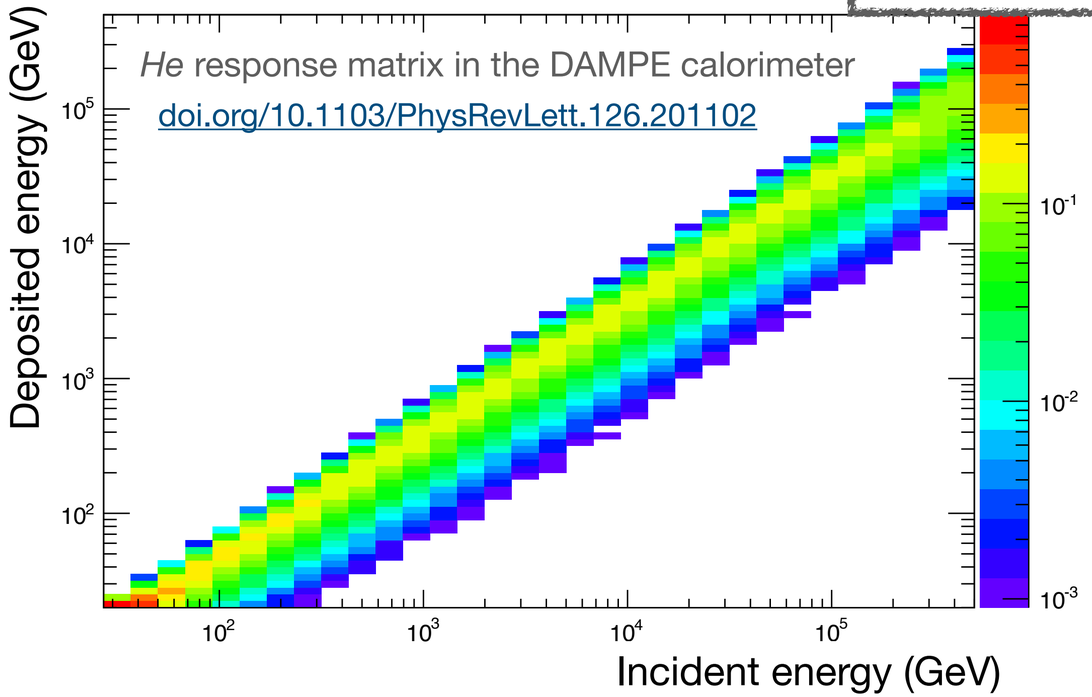
Hadronic models & cross-sections

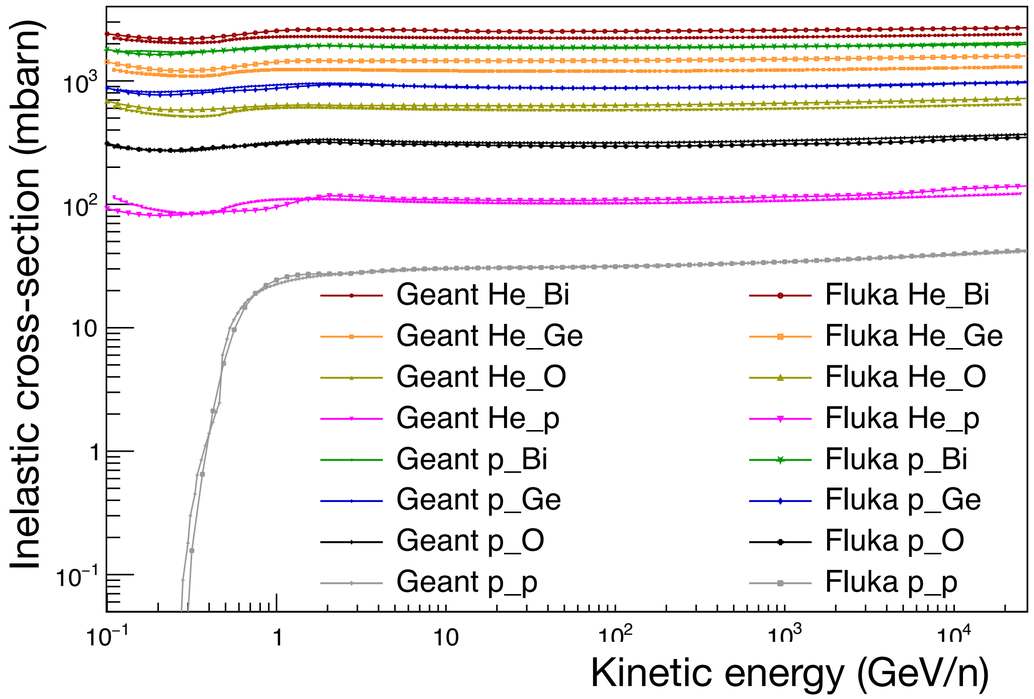
Protons & ions leave ~1/3 of energy in calorimeter

➡ Cosmic ray energy spectrum measurement rely significantly on hadronic simulations

➡ Largest **source of large systematics!**

- Inelastic Cross-sections uncertainty ~ 10 — 20%
- Different generators (GEANT4, FLUKA) and models (DPMJET, EPOS, FTFP)

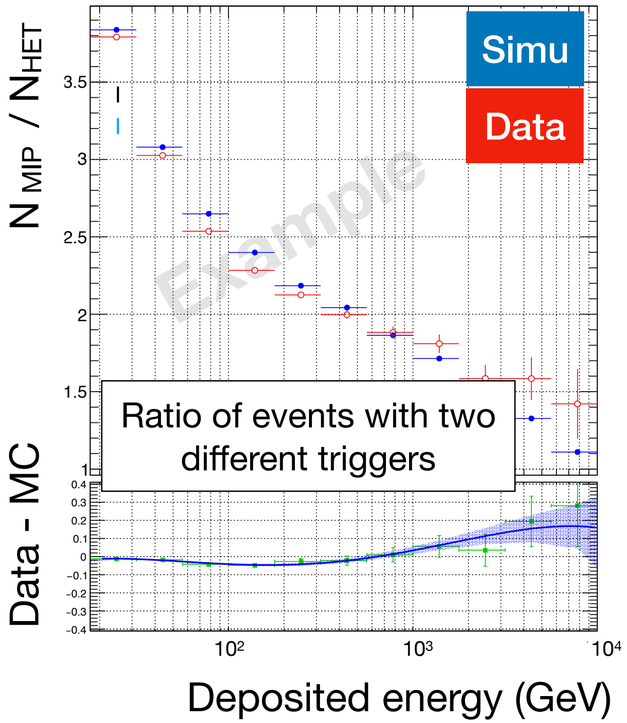


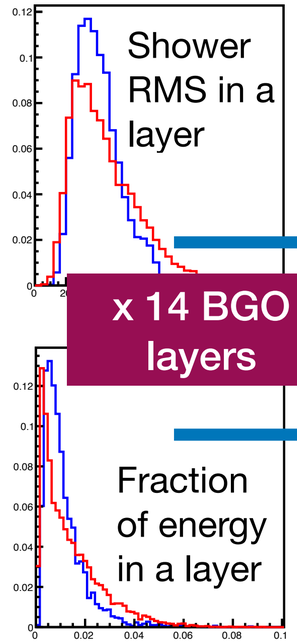


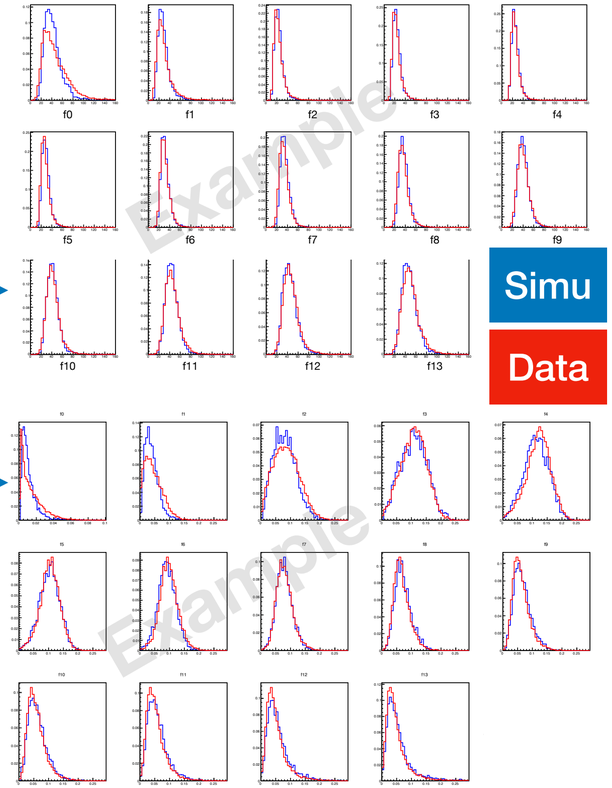
Hadronic models & cross-sections

Profit of **TeV—PeV data and fine granularity of CALO to "tune" models & cross-sections?**

- ➡ Precise CNN tracking helps to perform clean particle ID
- ➡ Use shower-shape characteristics to constrain model parameters etc.





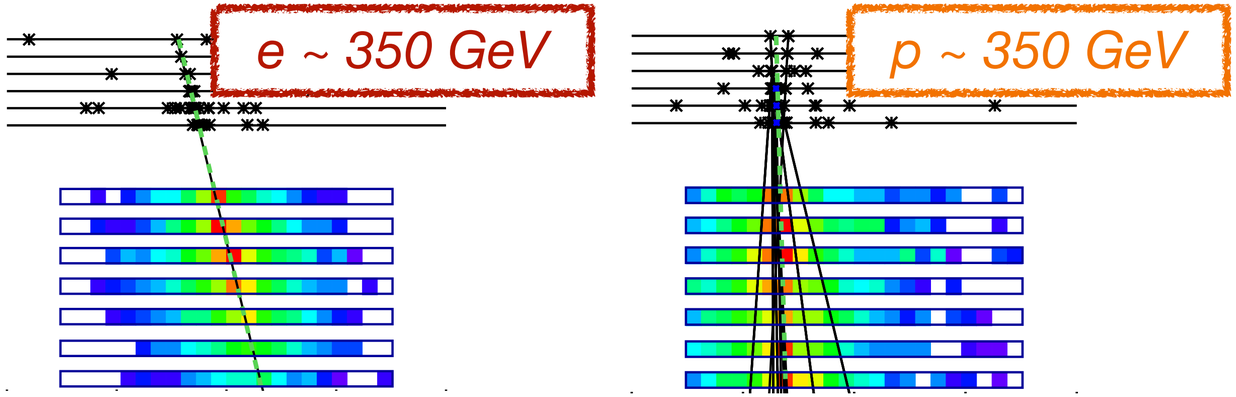


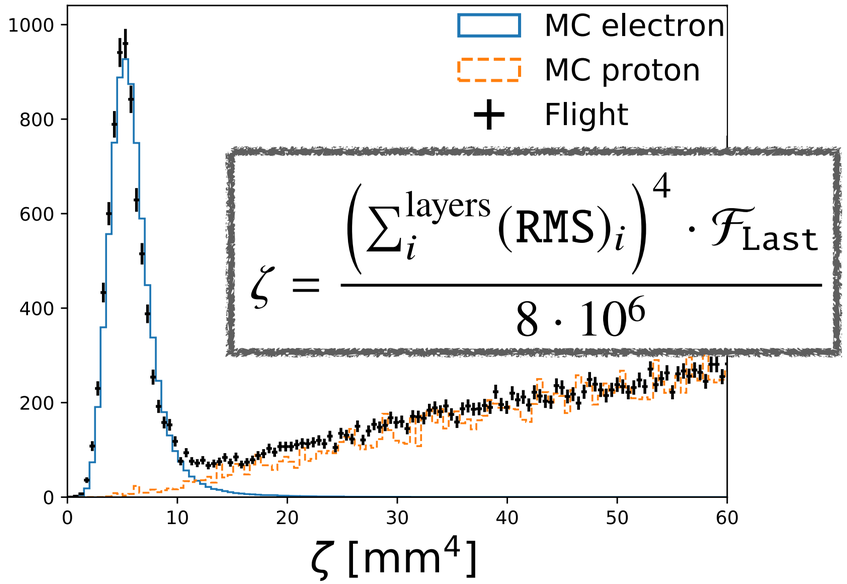
Not trivial since primary energy is not known!

… work in progress

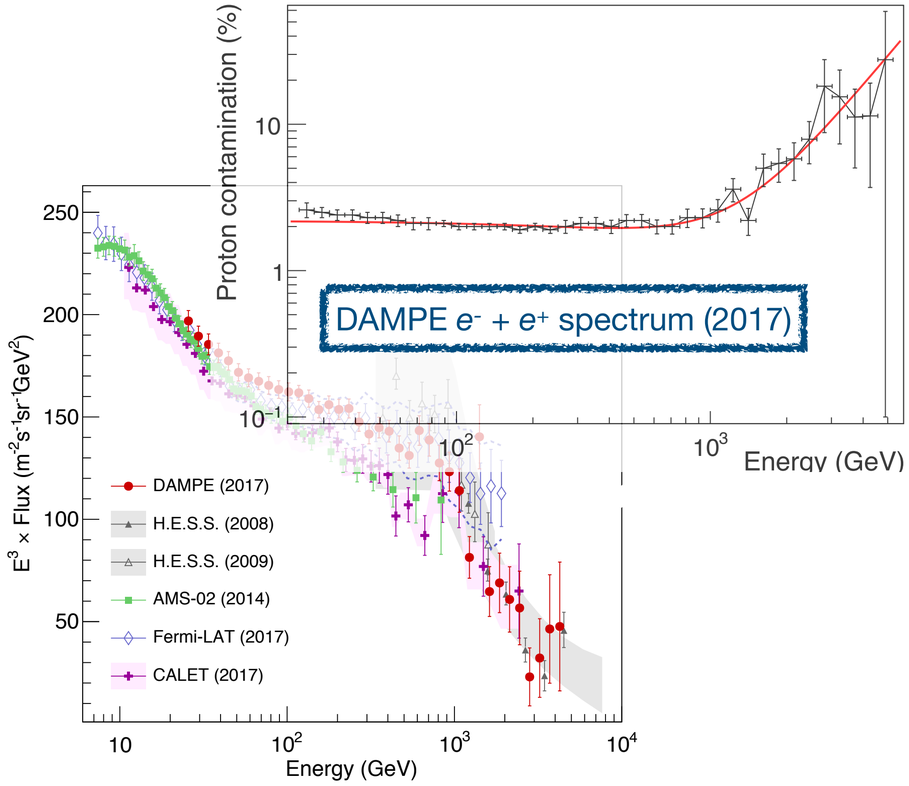
Electron / Proton discrimination

Classical e/p discrimination based on shower shape: EM showers are “slimmer” & “shorter”





$$\zeta = \frac{\left(\sum_i^{\text{layers}} (\text{RMS})_i\right)^4 \cdot \mathcal{F}_{\text{Last}}}{8 \cdot 10^6}$$

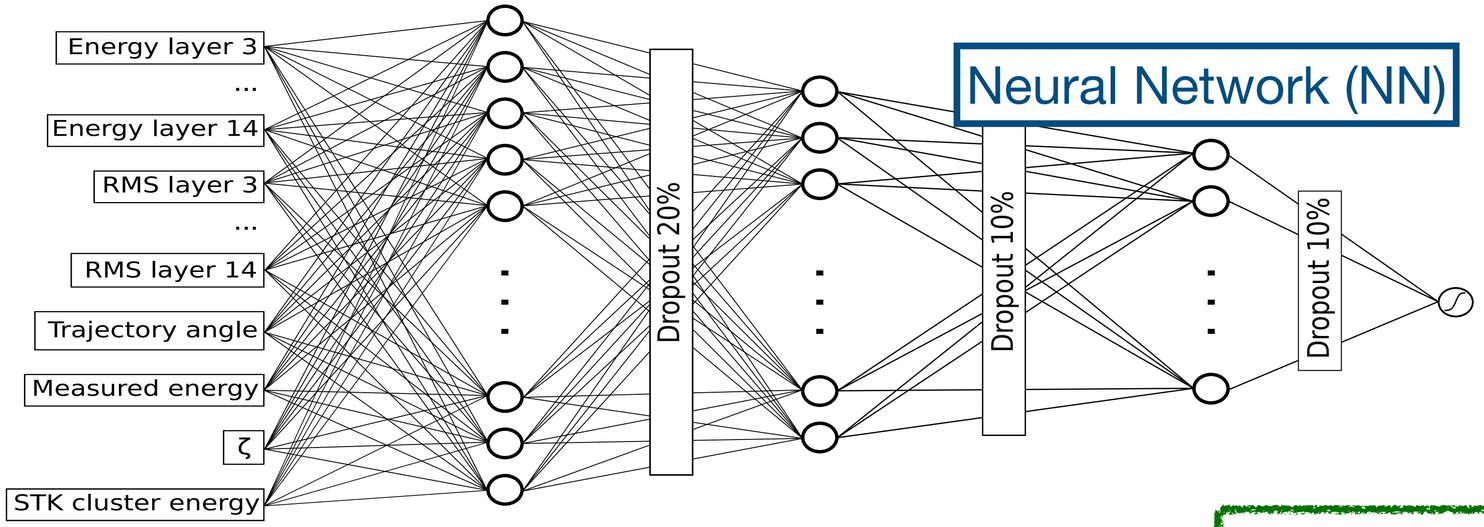


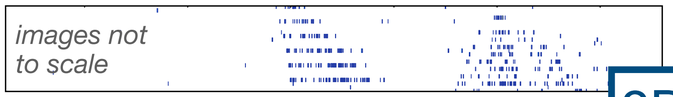
At TeVs, EM showers penetrate deeper — harder to discriminate from hadronic showers → at 10 TeV proton background dominates! ***New classifier is needed …***

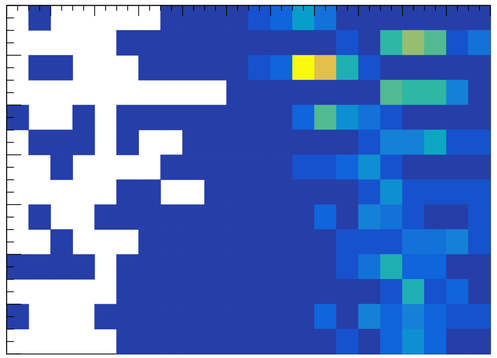
Electron / Proton discrimination — NEW method

Different Deep Learning techniques tested (NN, CNN) — the most optimal solution found with a classical NN

For details, see arxiv.org/abs/2102.05534

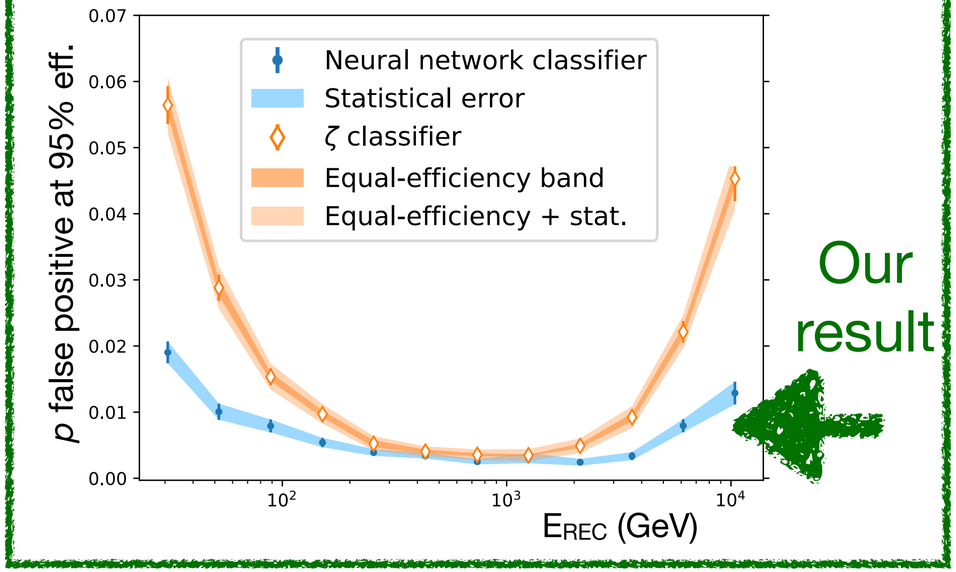


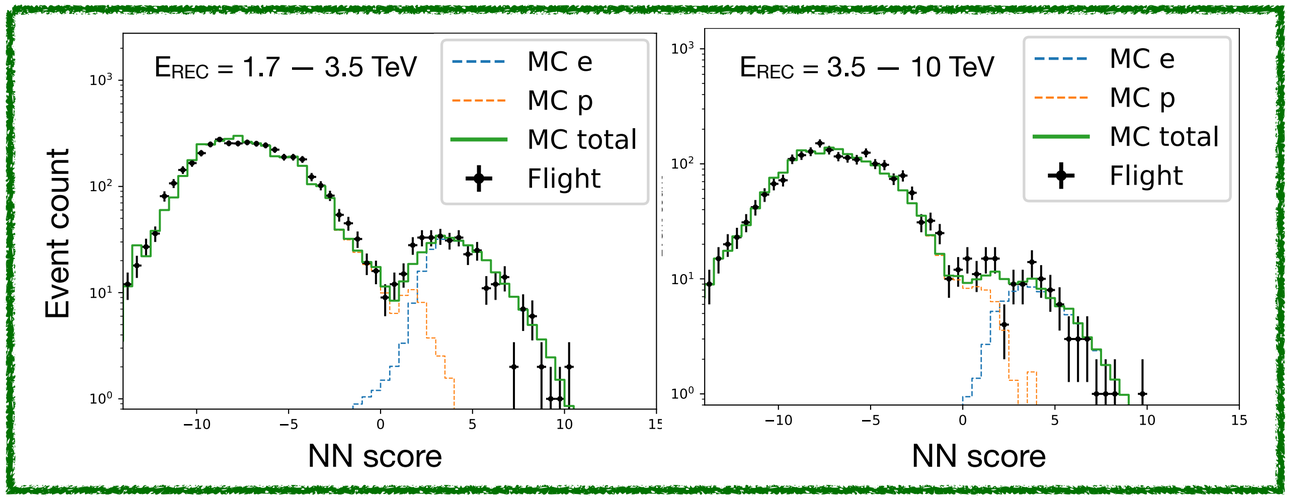




2D CNN

Future studies:
3D CNN @ HERD?





Summary

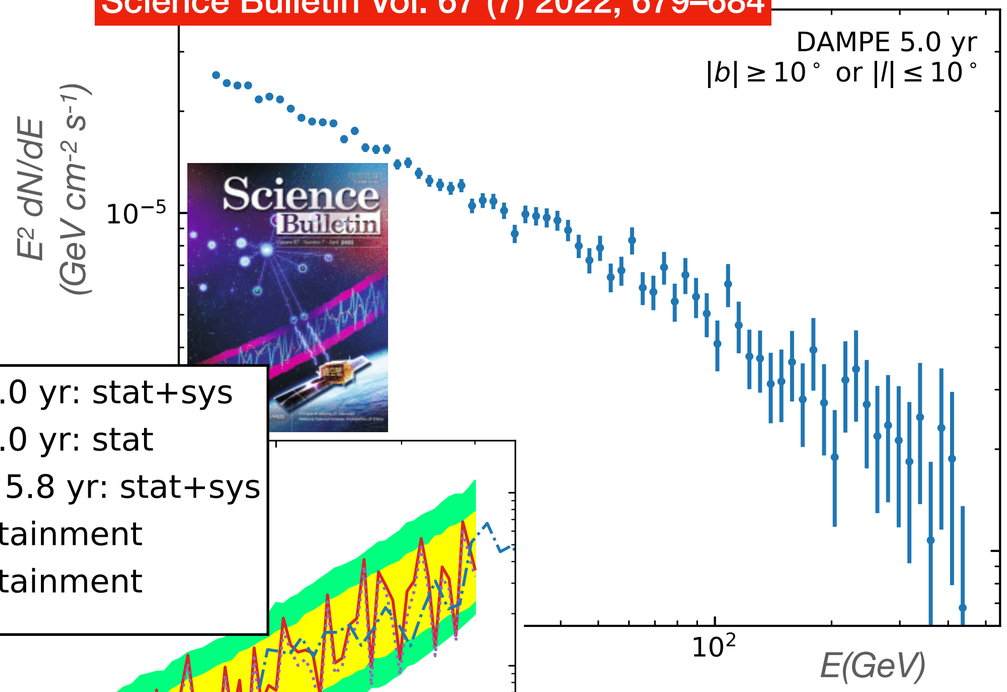
- **Raise of Calorimetric Experiments in Space**
  - **DAMPE** — ***present***, **HERD** - ***future***
  - Bridge gap between Space and ground-based
  - The tool for TeV—PeV CR measurements
  - Systematics dominated by hadronic modelling, track reconstruction, particle ID
- **Goal: tackle major systematics using ML and improved hadronic modelling**
  - Neural—Net electron/hadron classifier developed: 3—4 better background rejection
  - CNN tracking algorithm developed: > ~ 96% tracking efficiency up to PeV energies
  - Hadronic modelling optimisation & implementation in analysis will follow— *stay tuned!*

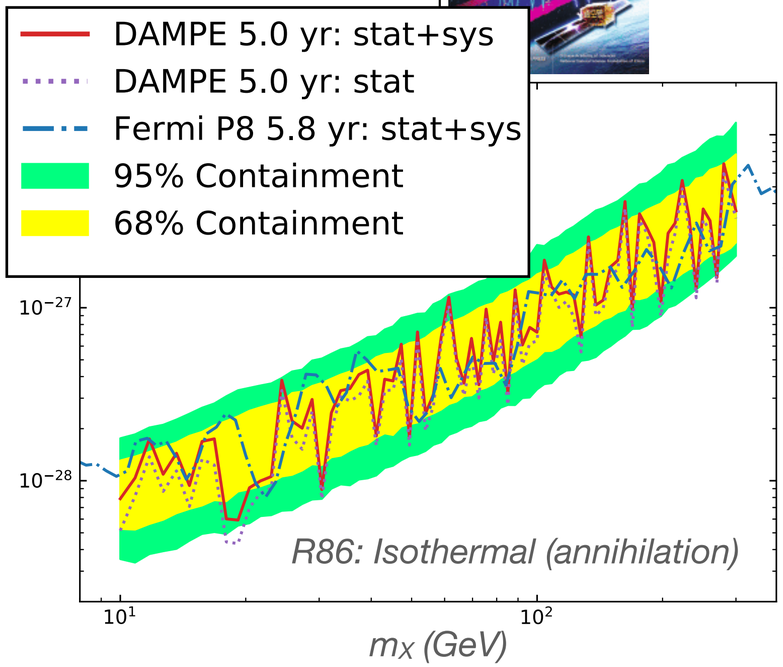
Backup slides

Gamma Rays with DAMPE

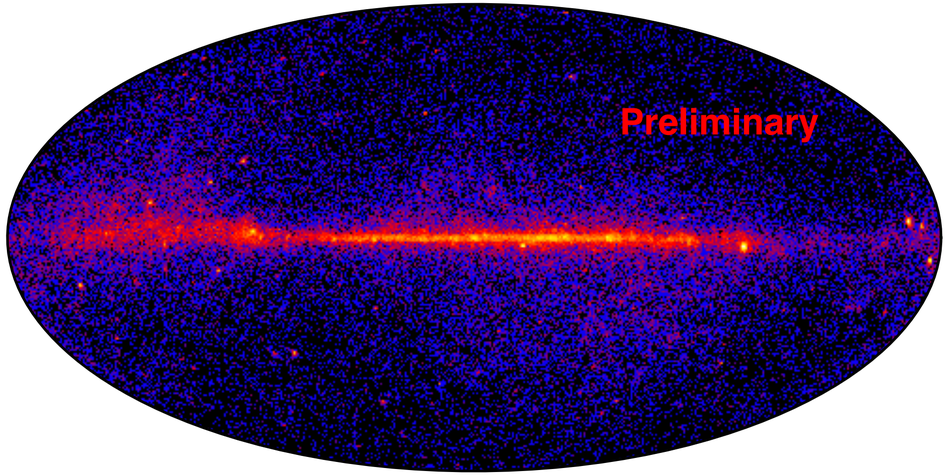
New constraints on Dark Matter density profiles

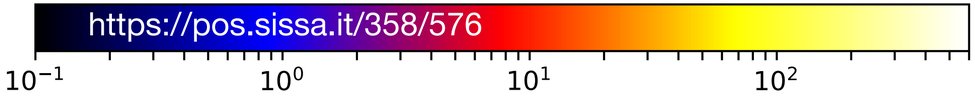
Science Bulletin Vol. 67 (7) 2022, 679–684





Rich catalog of sources





Type	AGN	Pulsar	SNR and/or PWN	binary	globular cluster
Number	163	44	7	3	1

(5 years)