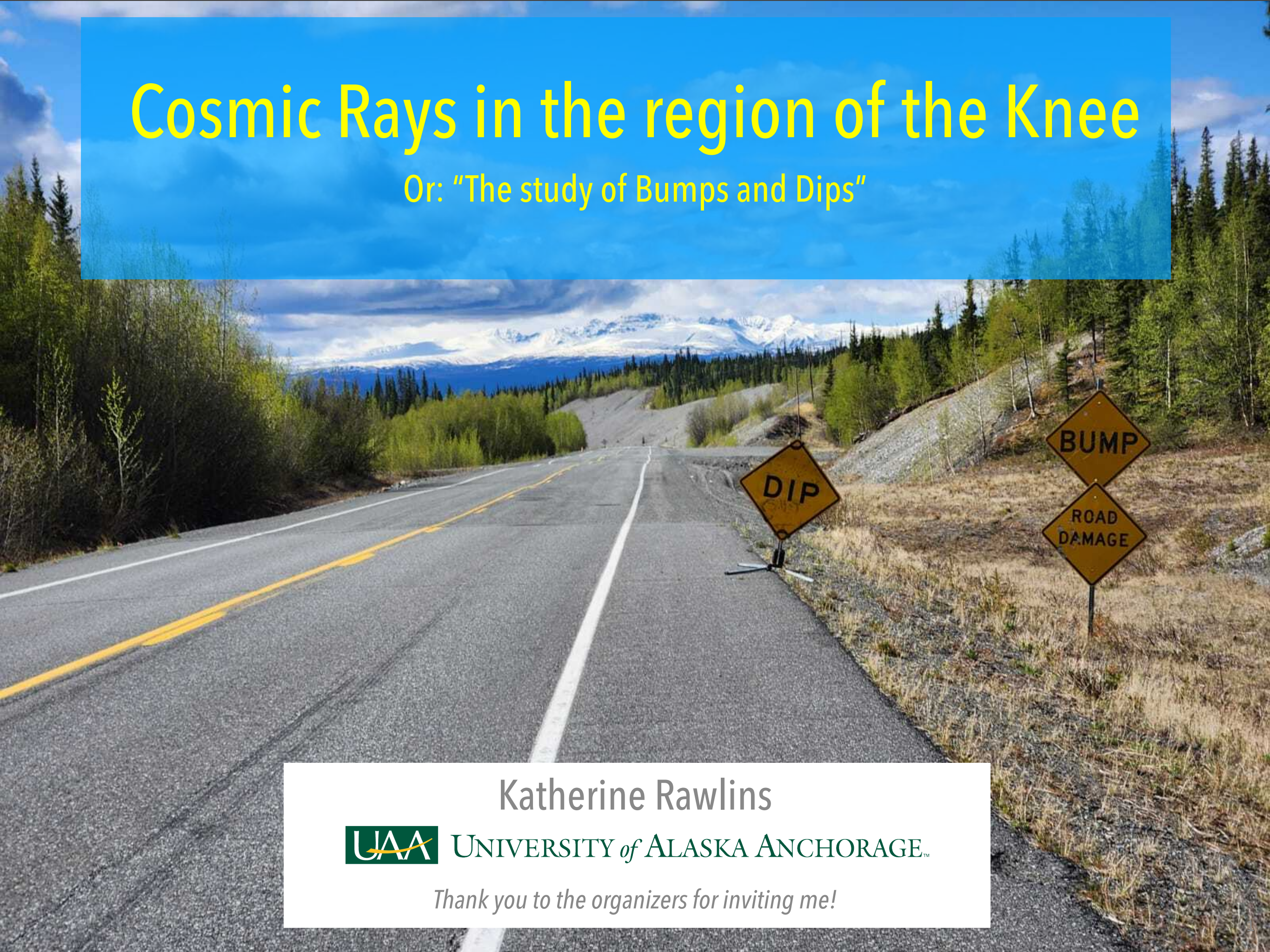


Cosmic Rays in the region of the Knee

Or: "The study of Bumps and Dips"



Katherine Rawlins



UNIVERSITY of ALASKA ANCHORAGE™

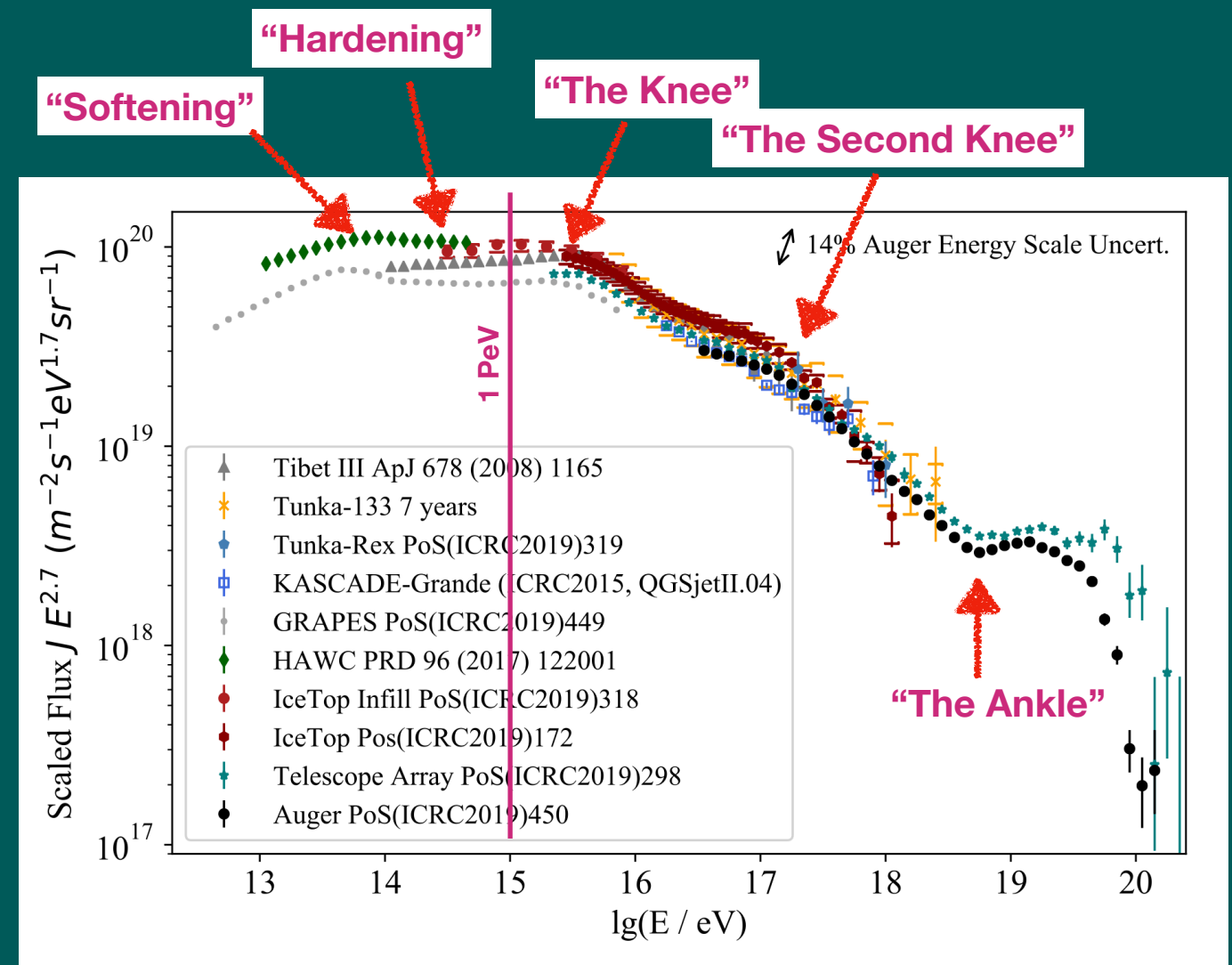
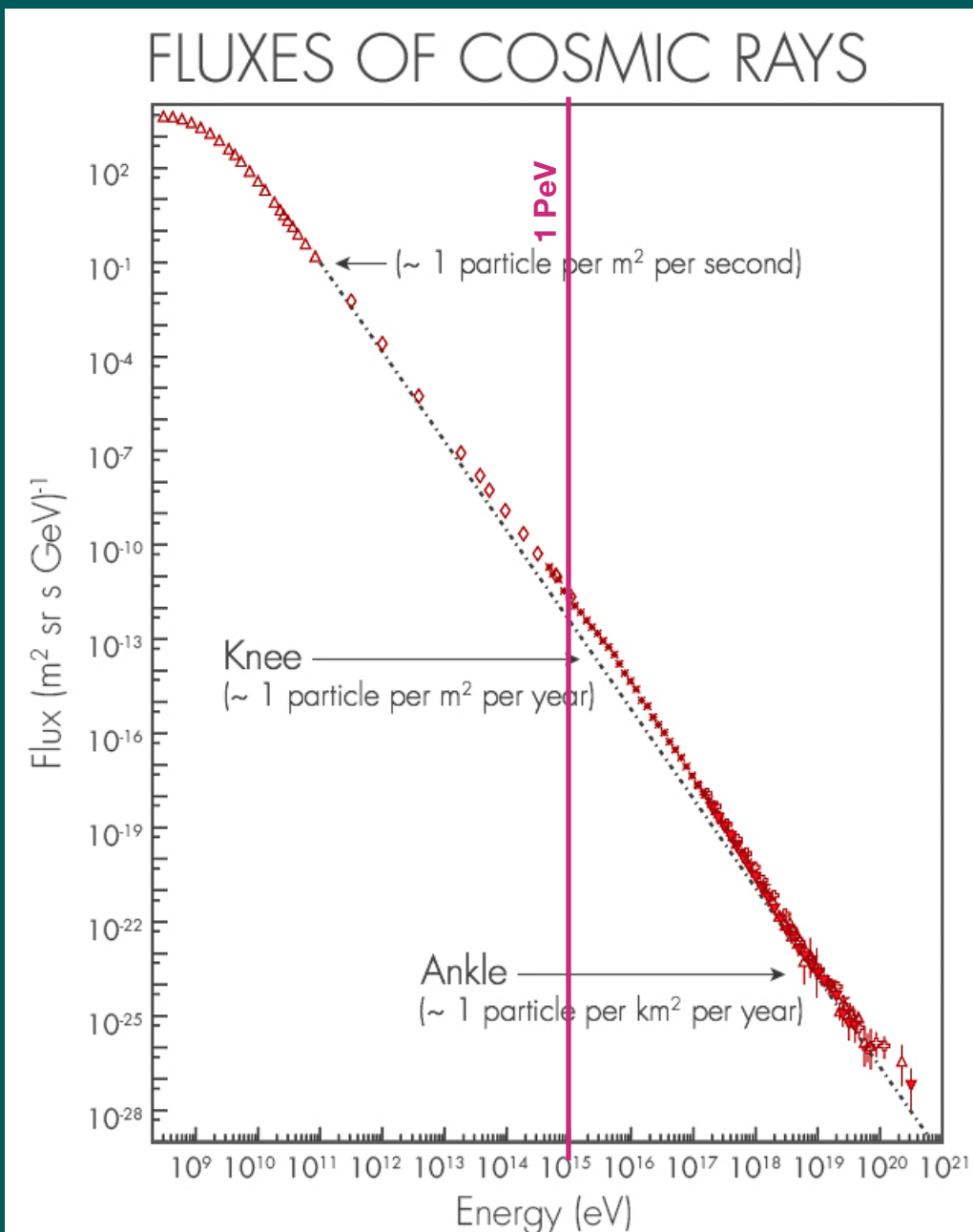
Thank you to the organizers for inviting me!

The Backstory

Energy Spectra

- Cosmic rays follow a steeply-falling power law*:
 - * actually, a complicated structure with bumps and wiggles and different power indices
 - A very old plot...

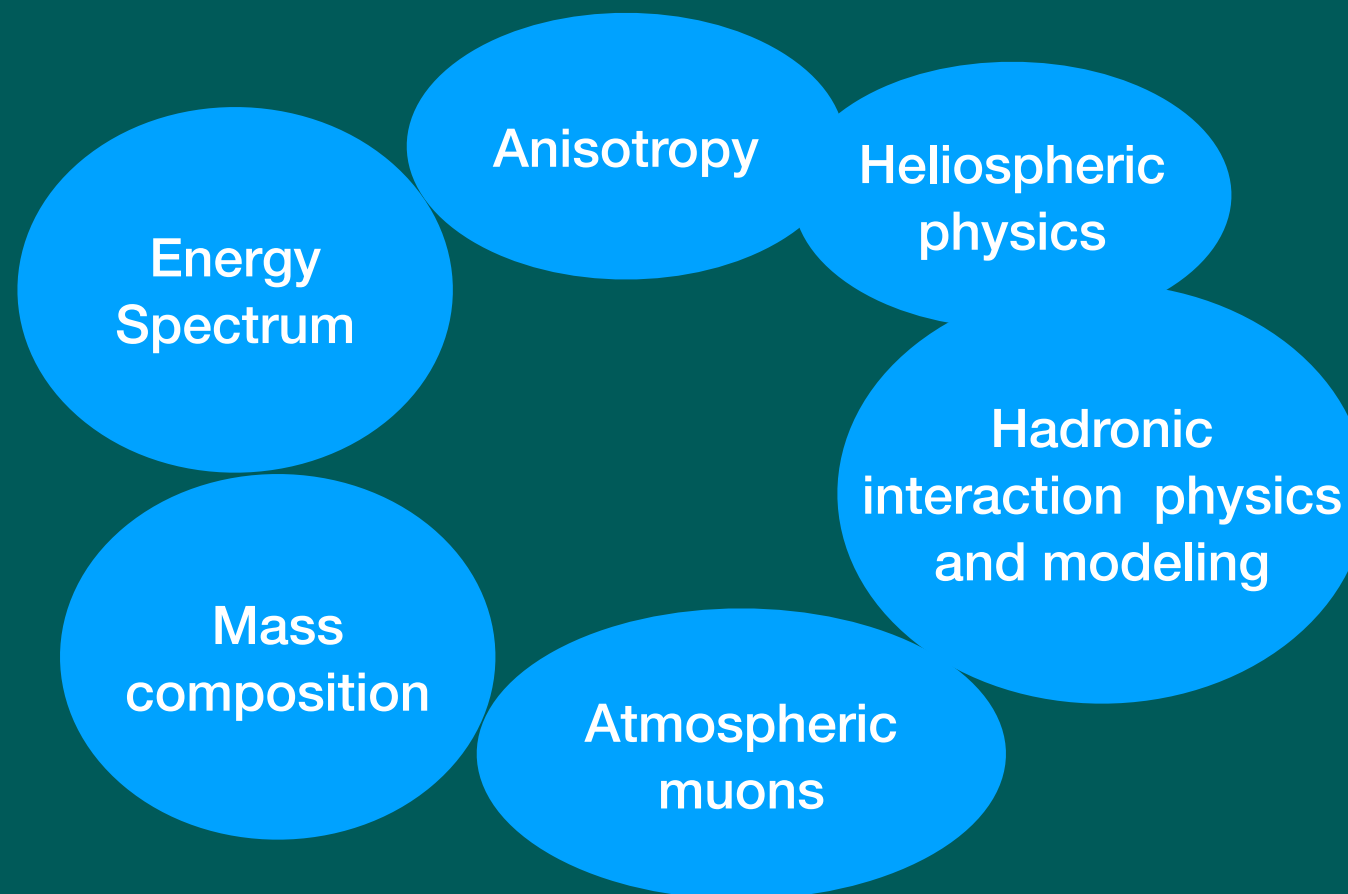
...some years later (2019)...



F. Schroeder,
CRI Rapporteur (ICRC2019)
arXiv:1910.03721

The interesting questions

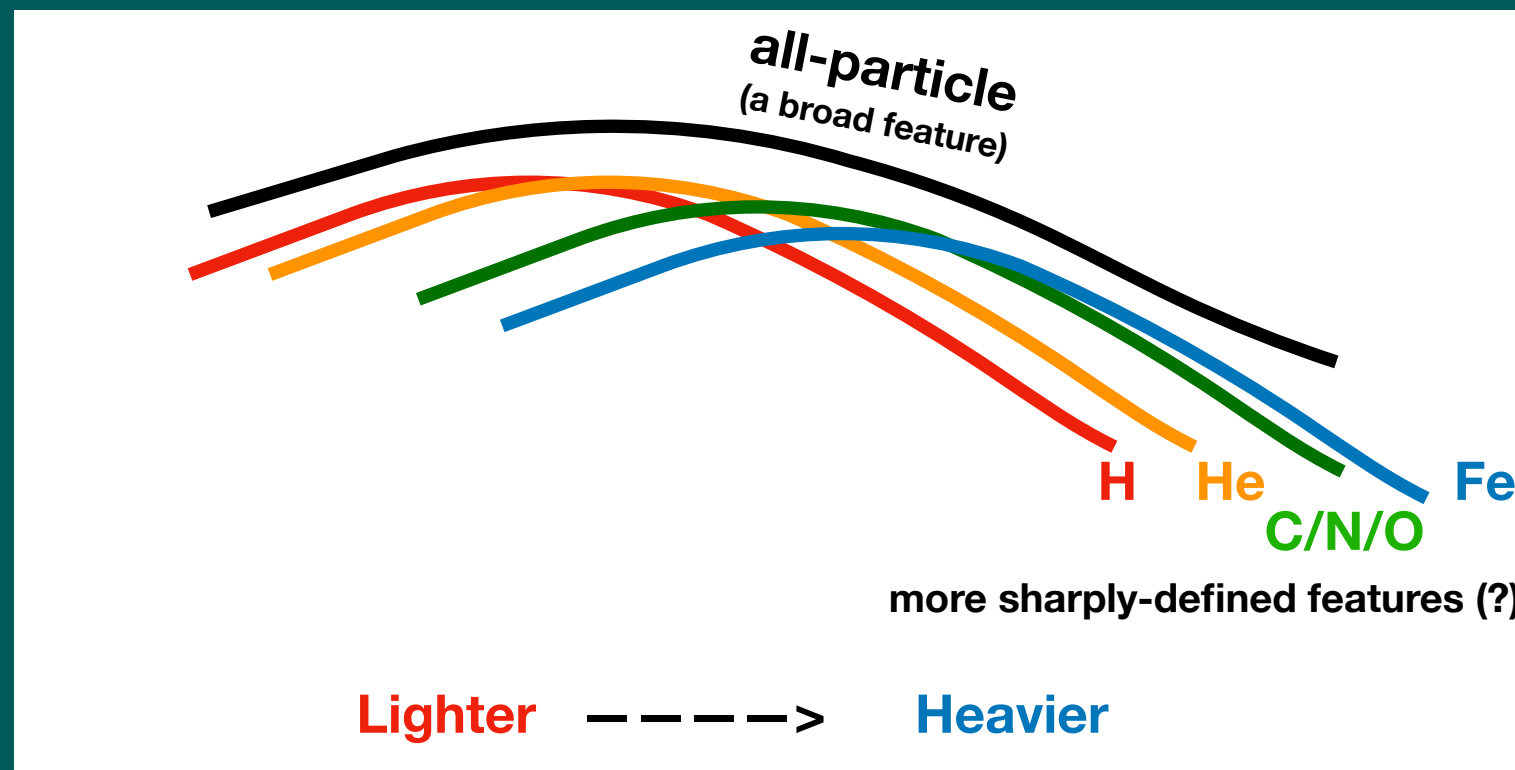
- The features in the all-particle spectrum are a probe of...
 - How the particles are produced (acceleration)
 - Their propagation
 - Interactions with other particles



- Where do they come from?

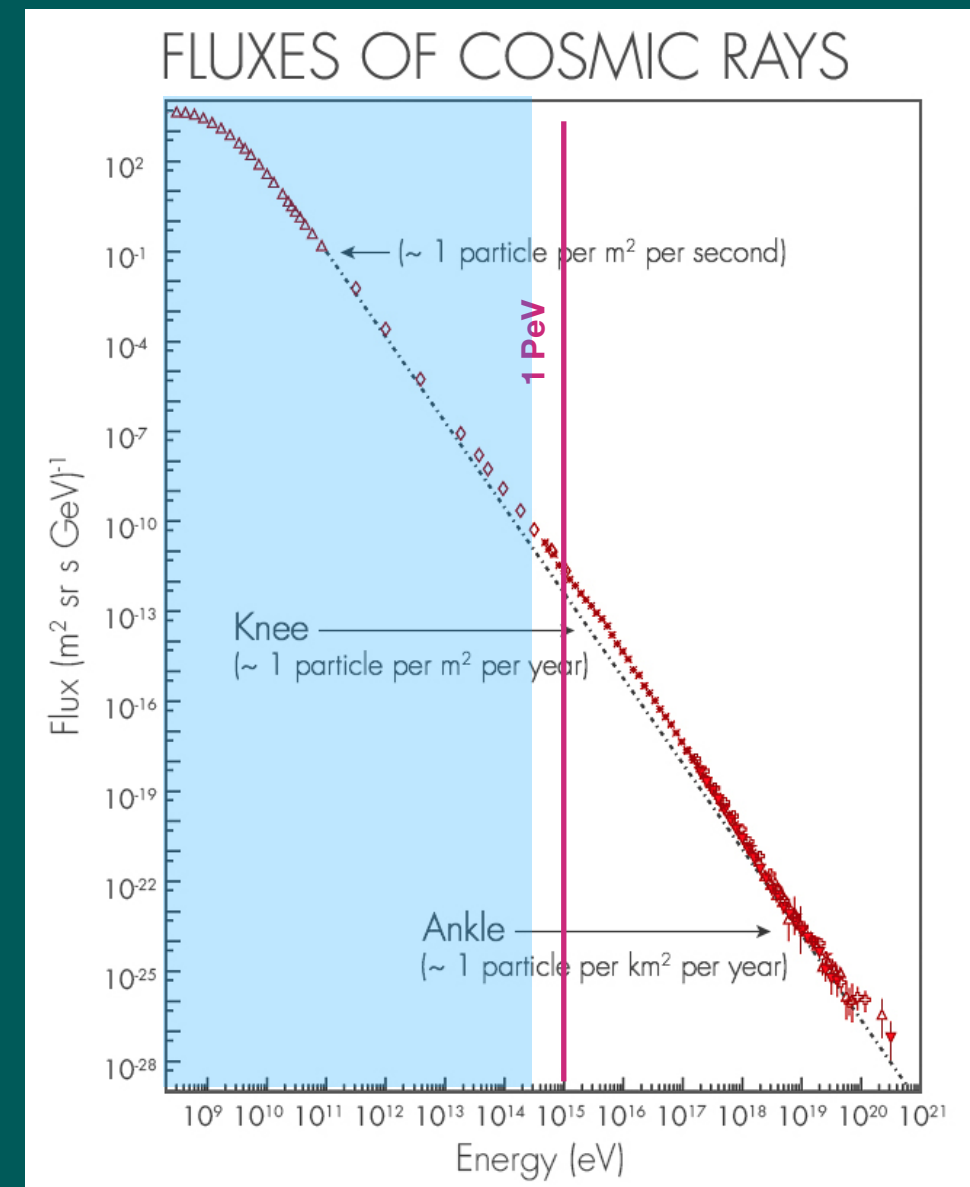
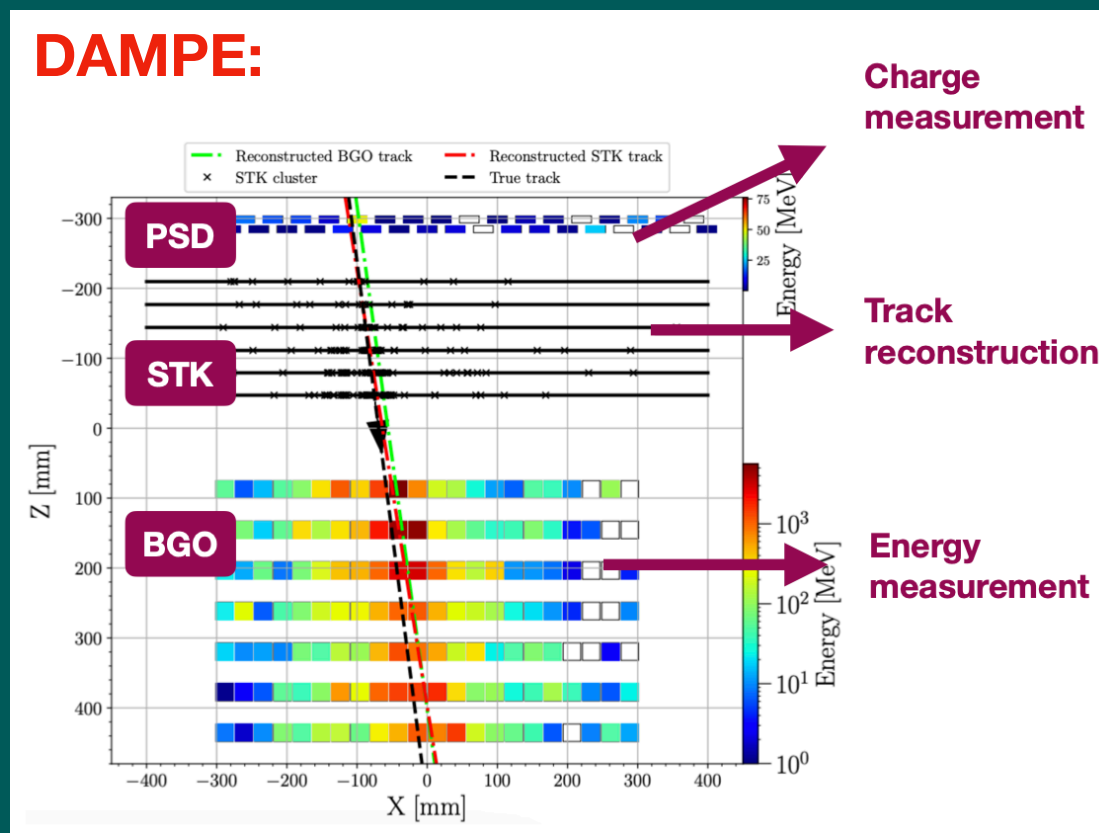
The interesting questions

- What are the spectra of individual nuclei?
 - What is the chemical composition of the cosmic rays? As a function of energy, does it get heavier or lighter?
 - If the bumps and wiggles are an indication of (say) a cutoff or limit in one of the things listed above, then does the behavior depend on the charge (and rigidity), or the mass?

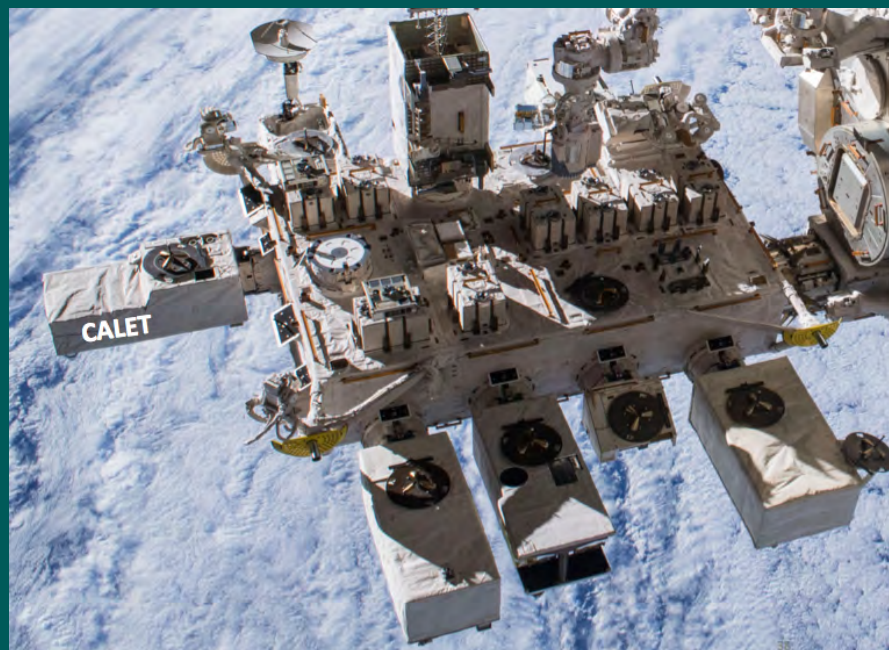
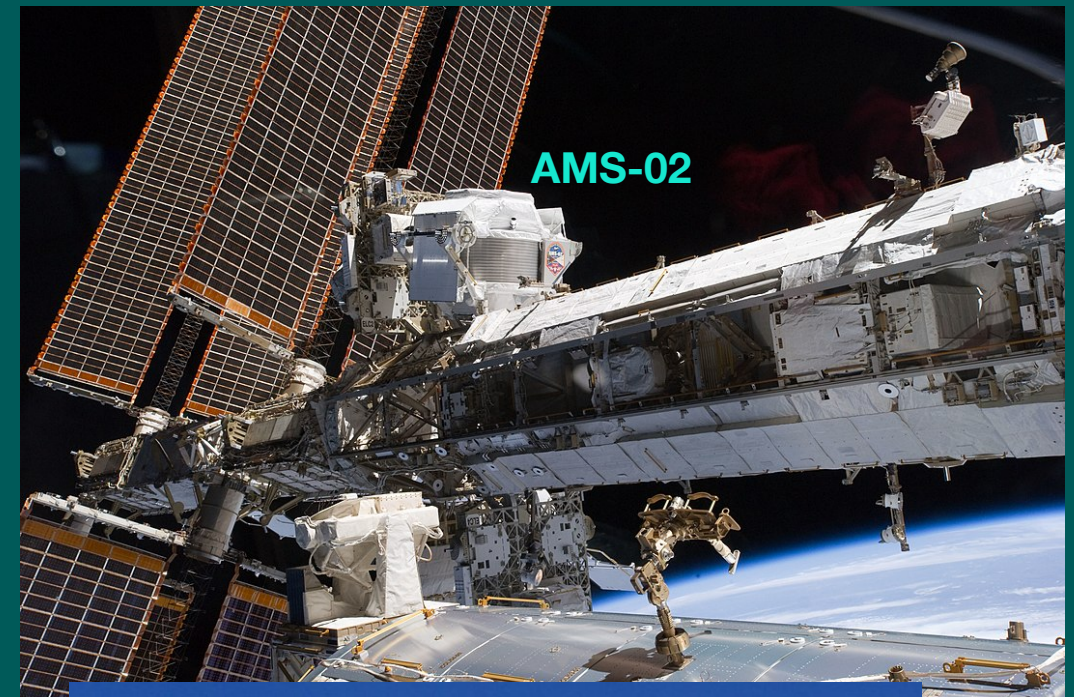


The “how” of measurement

- To catch cosmic rays directly, you must put a detector in space
 - Can measure particles directly, but...
 - Limited collecting area
 - Expensive

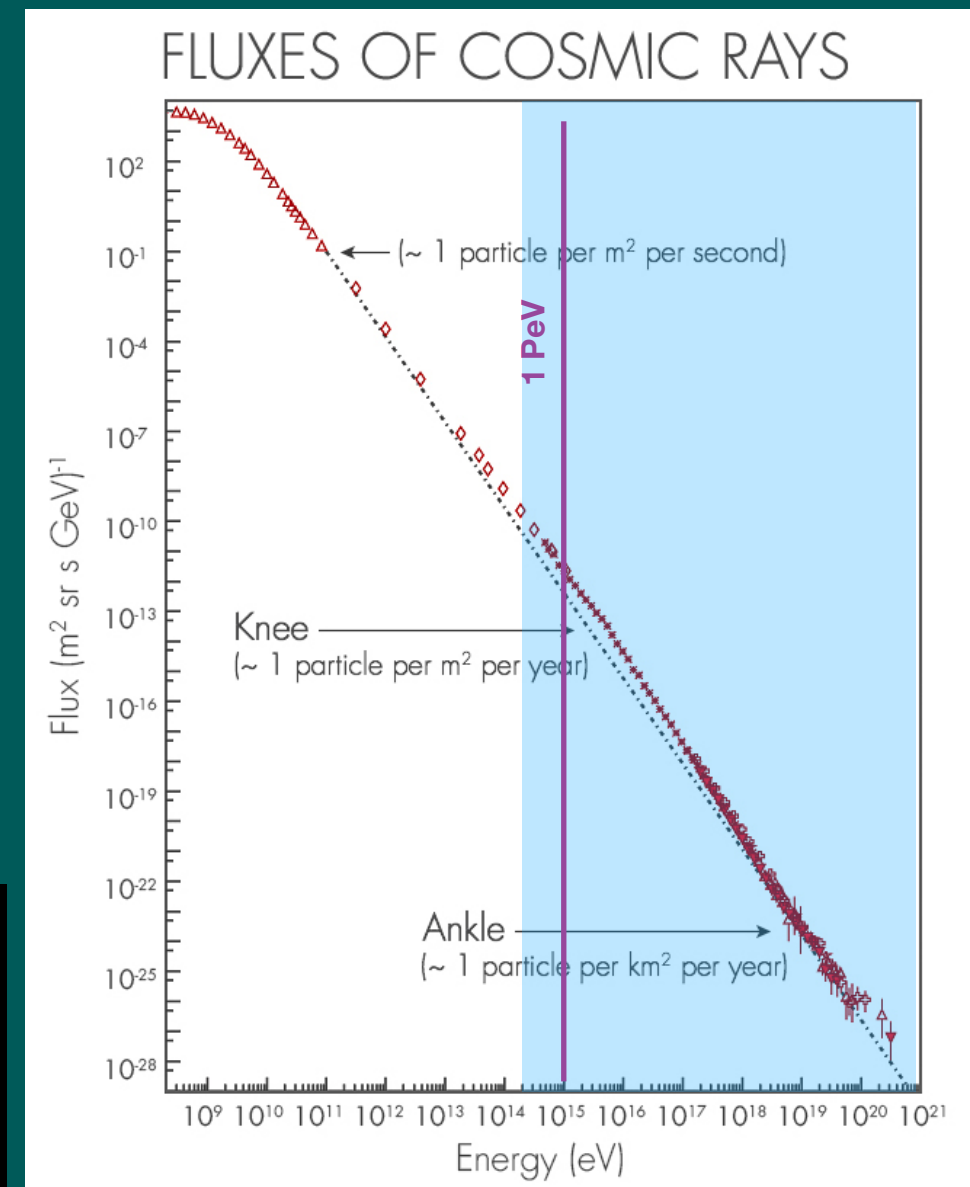
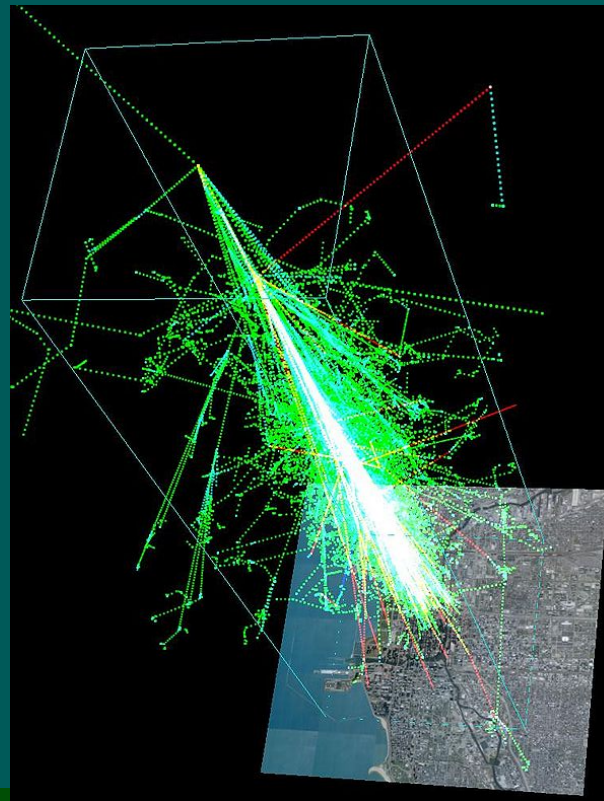


Space- and balloon-based detectors



The “how” of measurement

- Ground-based detector arrays
 - Detect the *extensive air shower* caused by a CR interaction in the atmosphere. Can cover a large area, but...
 - Must infer properties of the primary cosmic ray indirectly
 - Depends on simulations and modeling
 - Difficult to calibrate



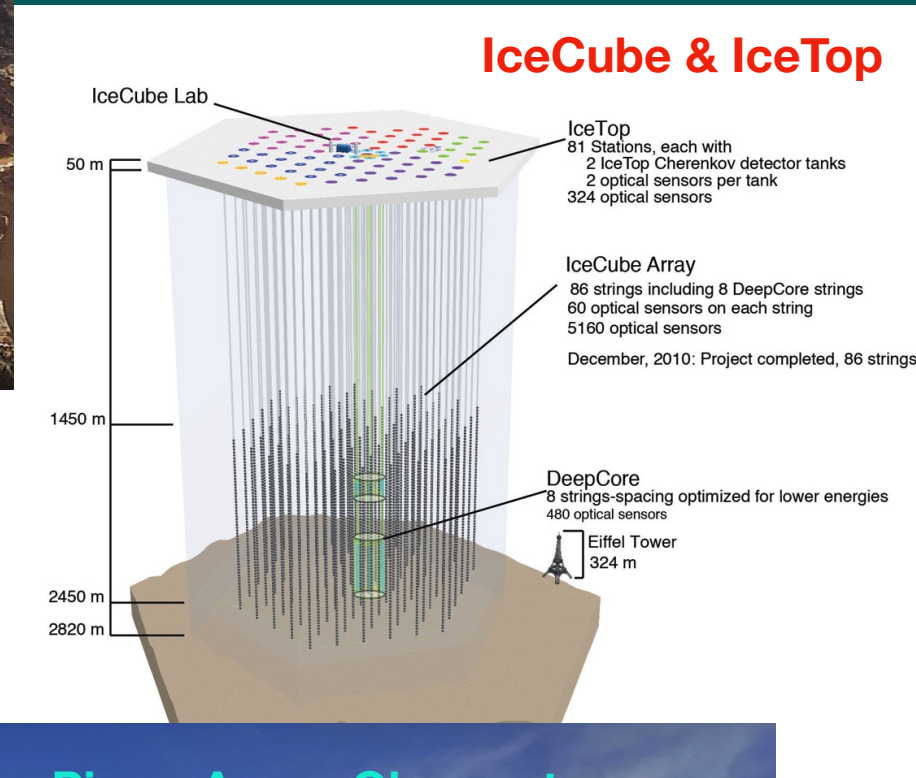
Extensive air shower detectors



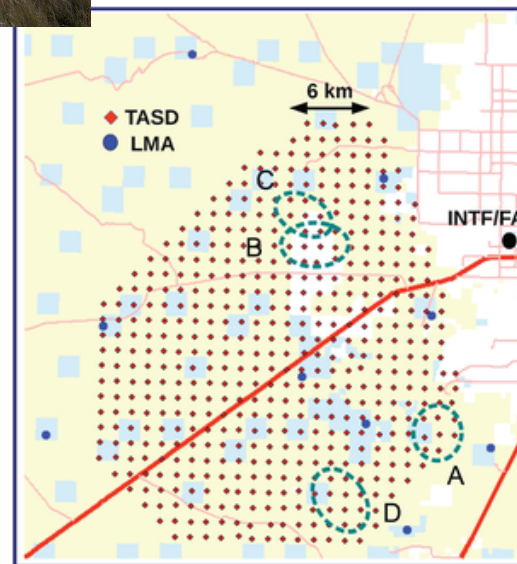
LHAASO



HAWC



Telescope Array



Pierre Auger Observatory

How I explain it to non-physicists

I'm trying to determine the *populations* of various species of bugs, and how fast they are flying! But all I can do is drive around and collect splatters on the windshield.

They're all different, and each only contains a small bit of the original bug.



Entomologist

That sounds hard!
Isn't there anything you can do to make this easier?

A bigger windshield?

With better resolution!

Why it's hard

- In general, we want to determine both the primary energy and the mass (“composition”). But it is hard to disentangle the two from air shower data.



11

Is this a big splatter because the energy is high, or because it's a heavy iron nucleus?

Shower forensics: heavy vs. light

10 TeV proton

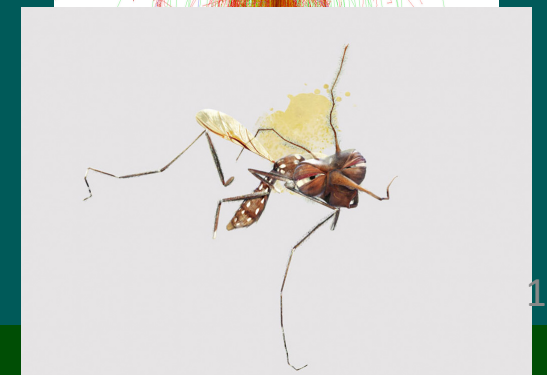
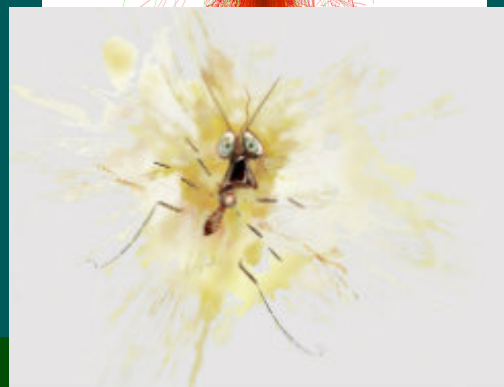
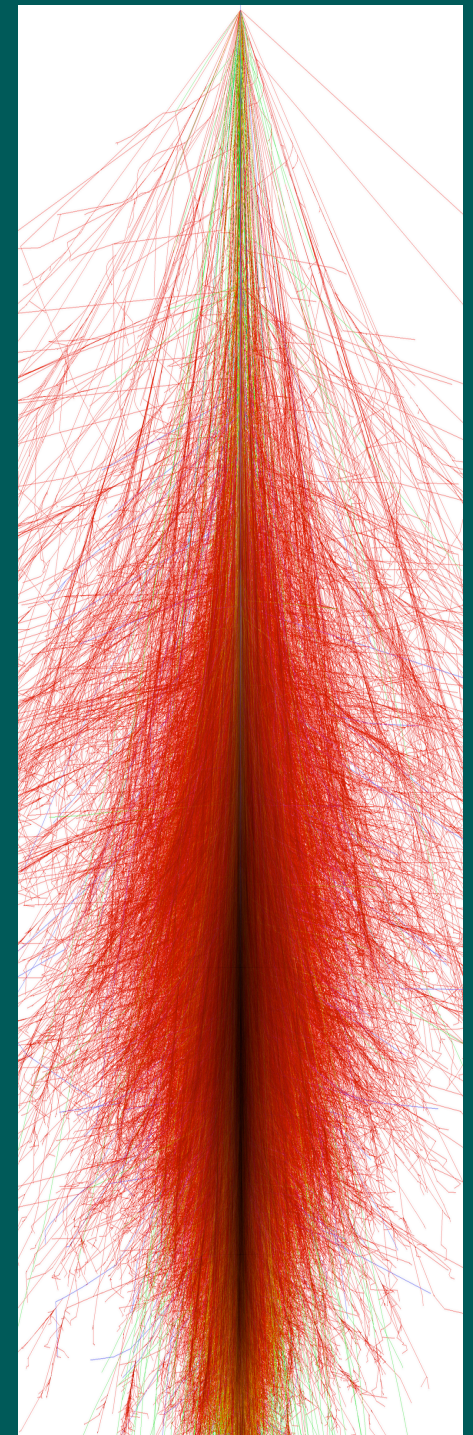
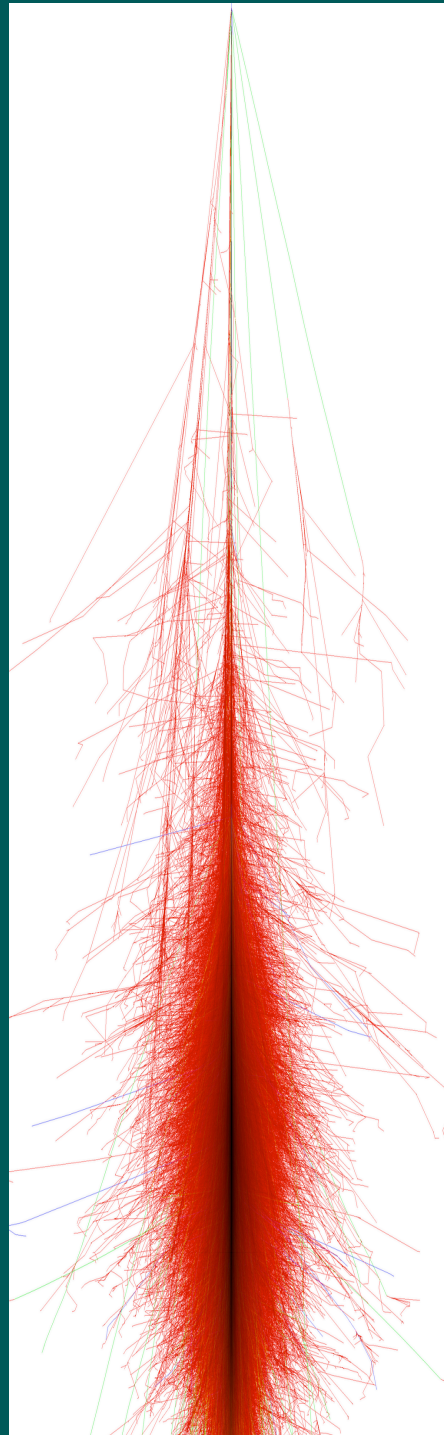
10 TeV iron

Height of interaction in the atmosphere is different

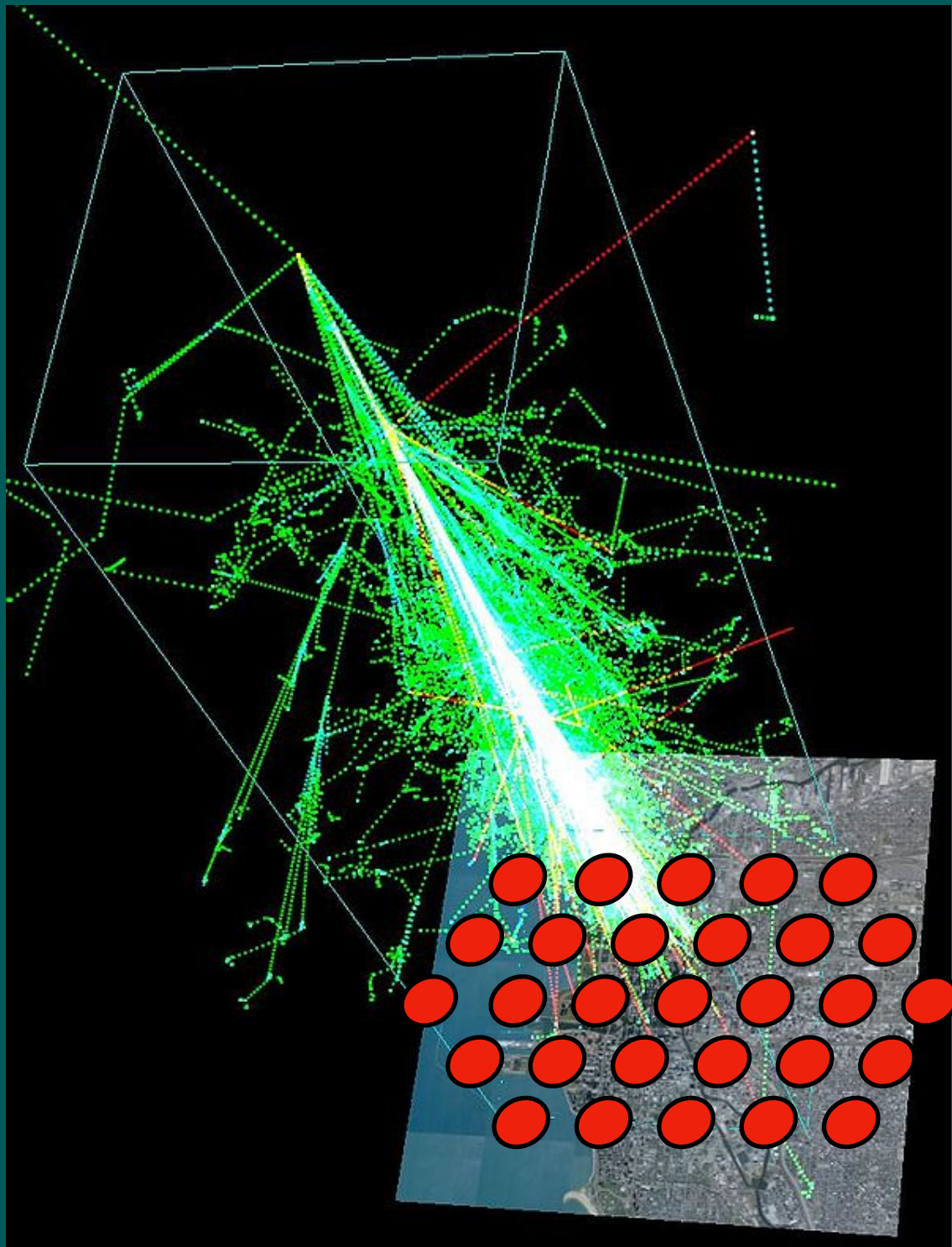
“Xmax” is different

Shower-to-shower fluctuations are different

Iron showers are more “muon-rich”

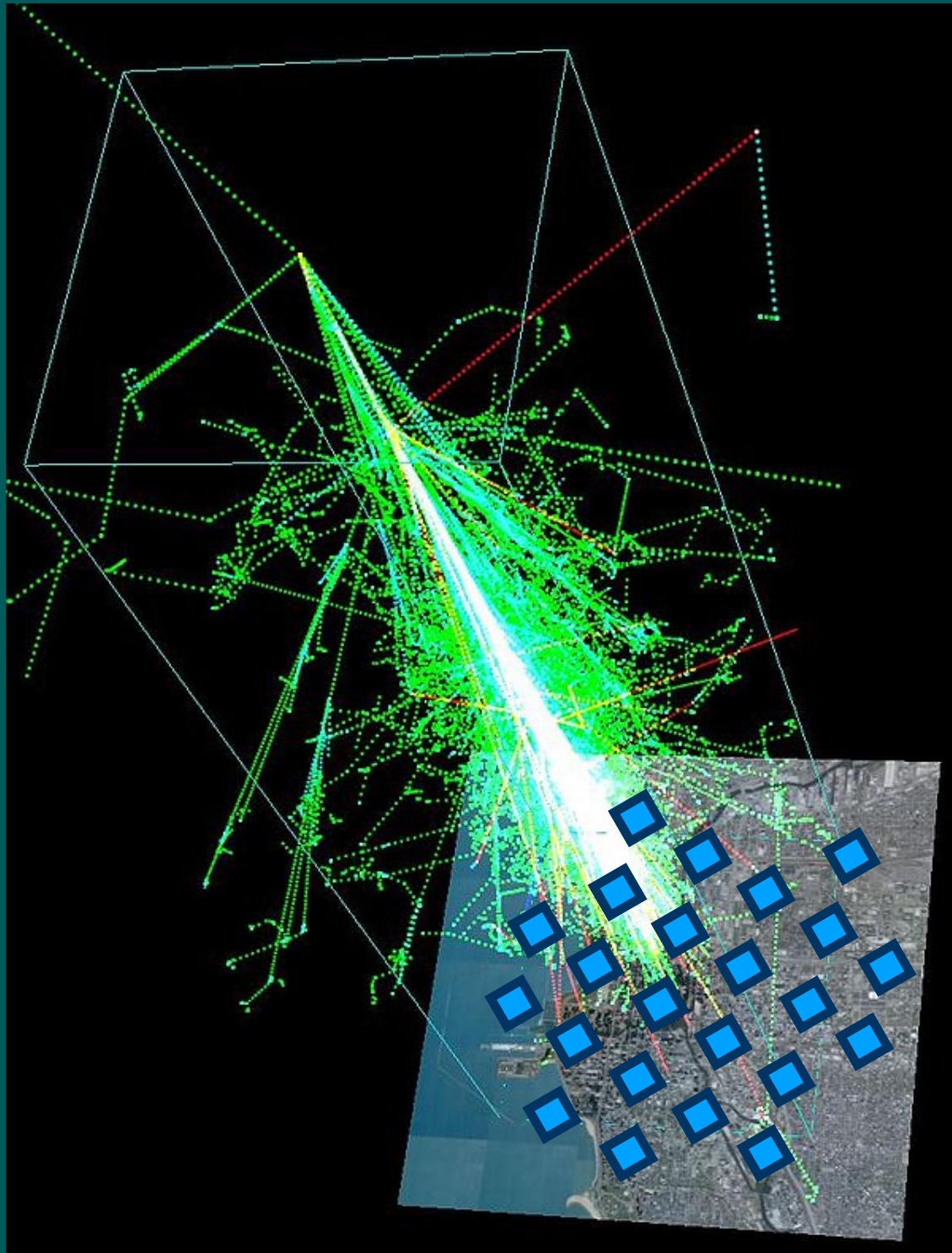


What ground-based detectors can do



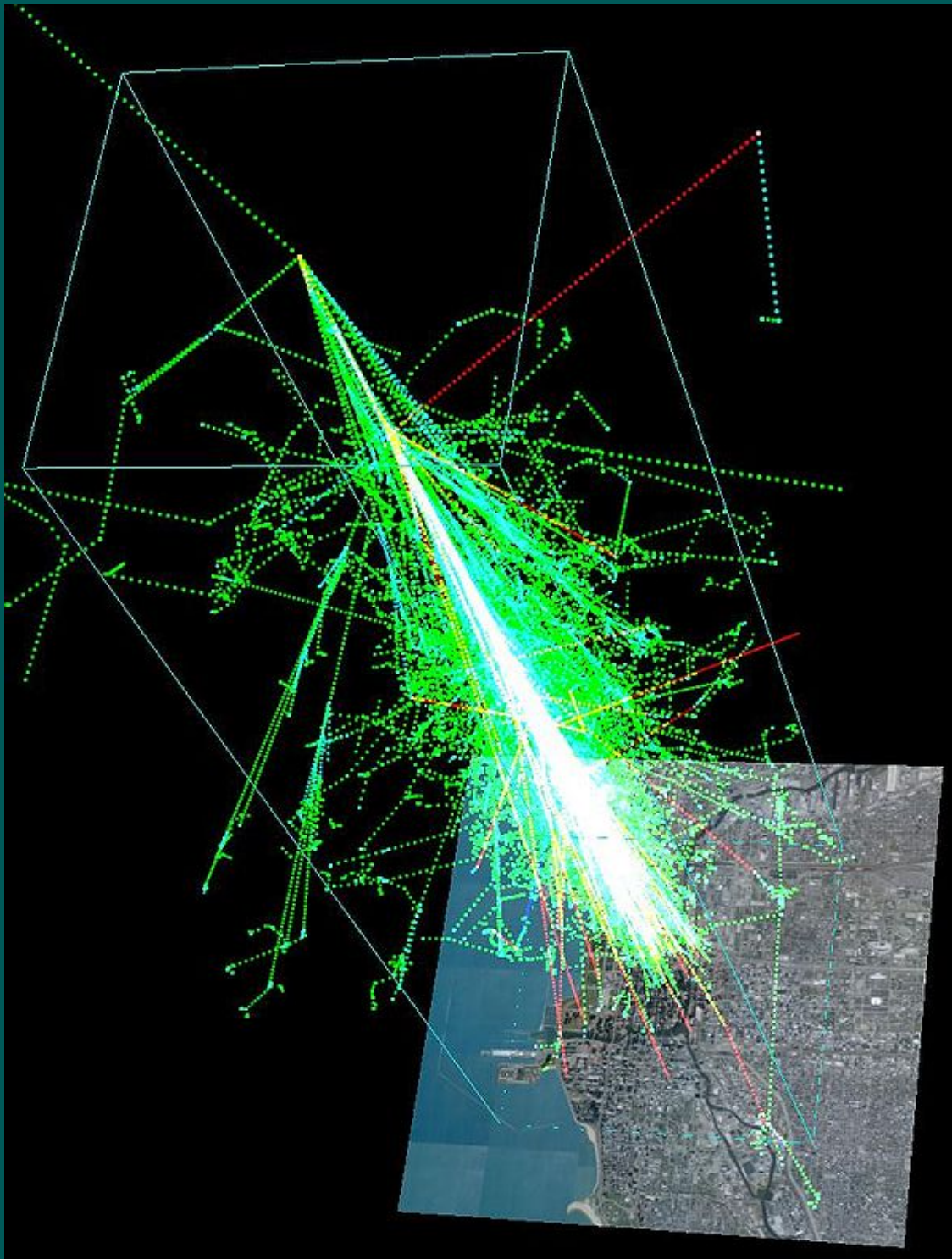
Water tanks or scintillator panels at ground level: Can measure the overall shape and size of the particle cascade

What ground-based detectors can do



Muon detectors: Can measure the muon content of the shower, which adds composition sensitivity

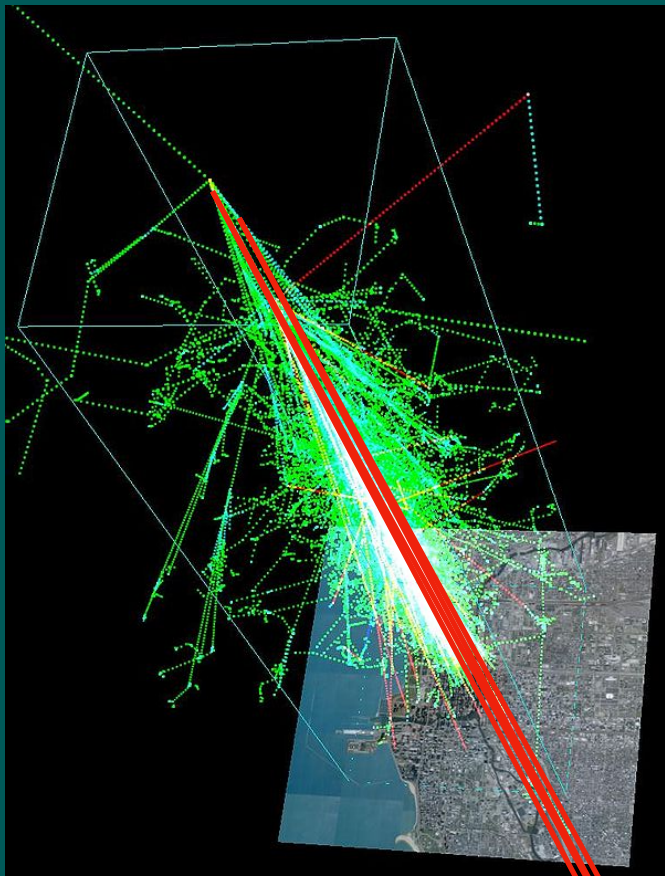
What ground-based detectors can do



Air Cherenkov or fluorescence telescopes: Can measure properties of the shower as it develops longitudinally through the atmosphere (X_{max} , energy)



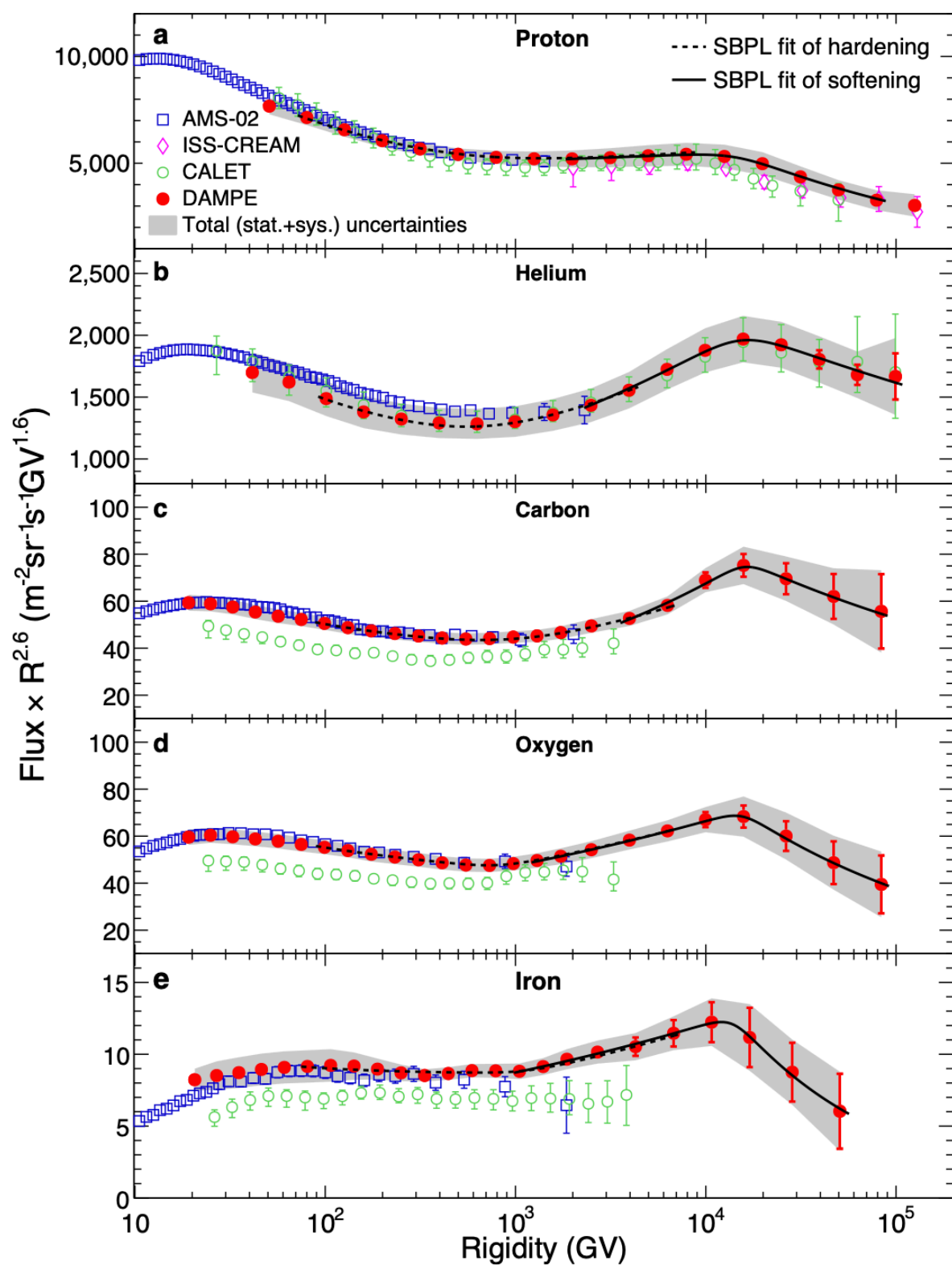
What ground-based detectors can do



A deep muon detector: Can measure the TeV muon content from the first interactions of the primary, which also adds composition sensitivity

Some measurements

Below the knee



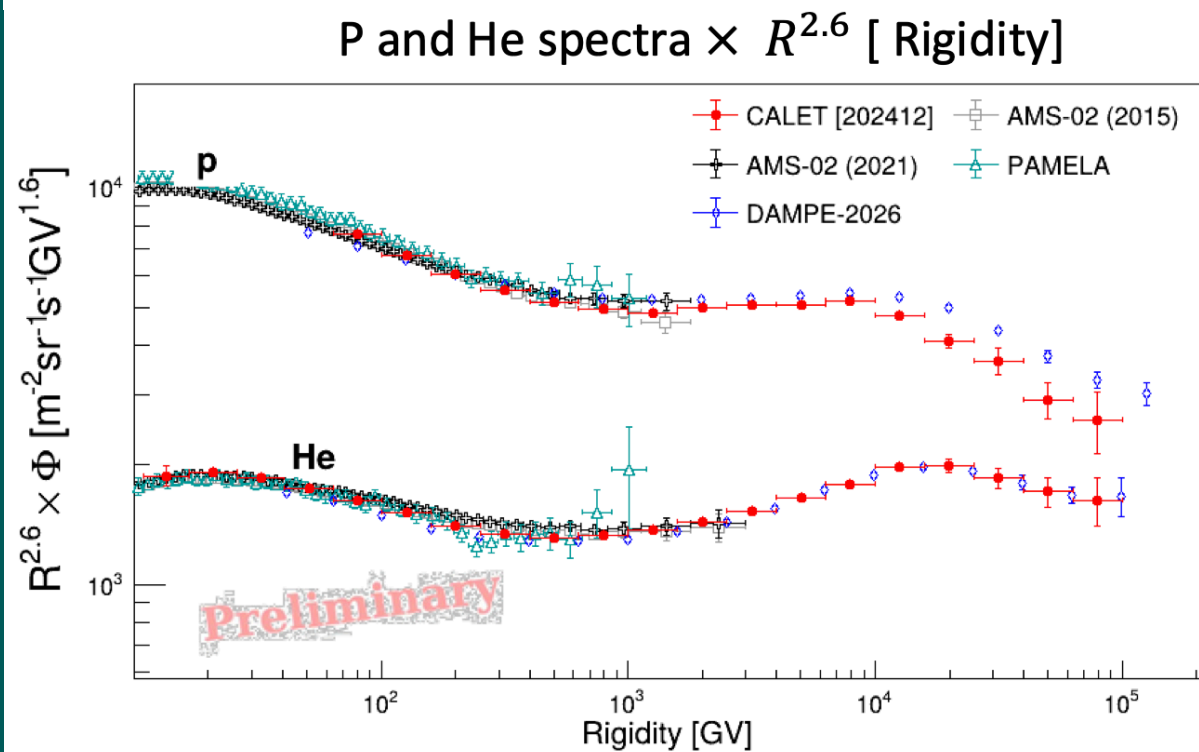
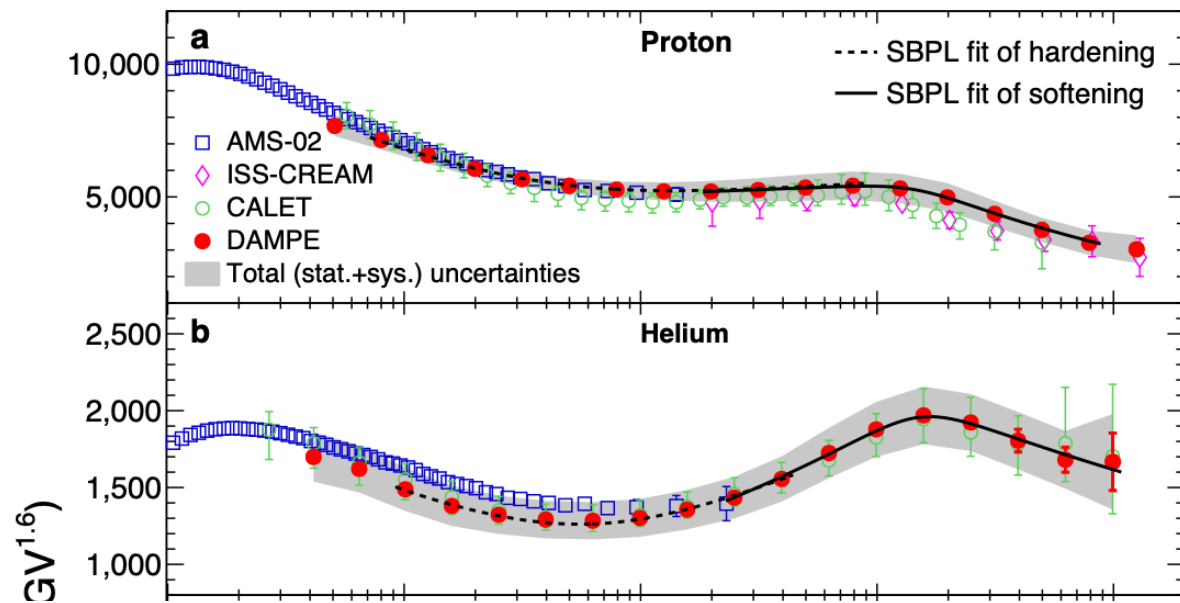
DAMPE sees the GeV hardening and TeV softening in all nuclei

*F. Alemanno et al. (DAMPE Collaboration)
Charge-dependent spectral softenings of
primary cosmic rays below the knee
Nature, volume 653, pages 52–55 (2026)*

← Note: this is not an *energy* spectrum, it's a *rigidity* spectrum.

A universal softening at around 15 TV

Below the knee



CALET's latest version of this same plot, for p and He

*Yosui Akaike's talk from this meeting
Extending Cosmic-Ray Measurements over a Decade with CALET*

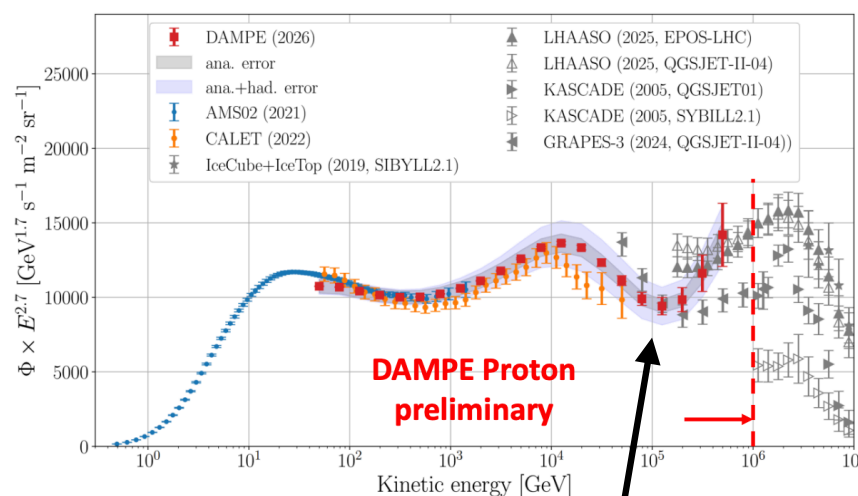
- Space-based experiments are closing in on the PeV mark, and the start of the knee

Proton and Helium (update towards PeV)

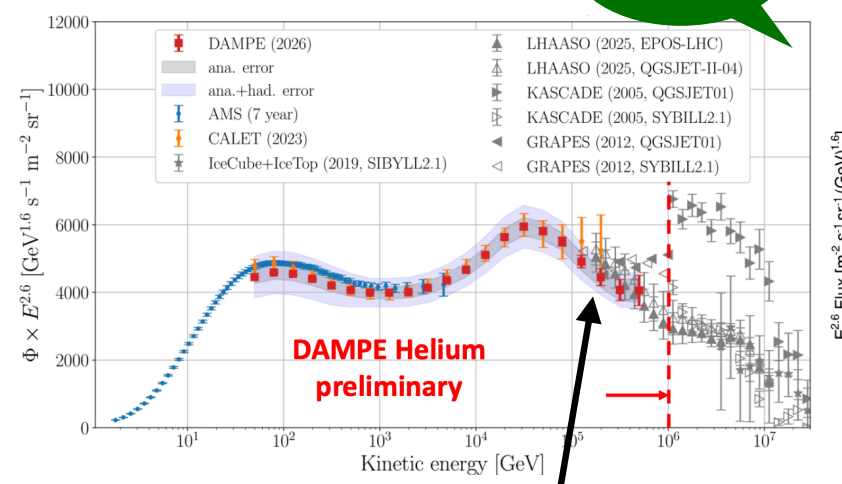
- Update proton and helium spectra:

- ➡ 10 years of data
- ➡ Novel particle ID using AI cosmic ray track reconstruction (+30% increased acceptance)
- ➡ Improved hadronic model (using DAMPE-measured cross sections)

*Andrii Tykhonov's talk from this meeting
DAMPE results after the first 10 years of operation*



Proton flux shows a hardening at ~150 TeV



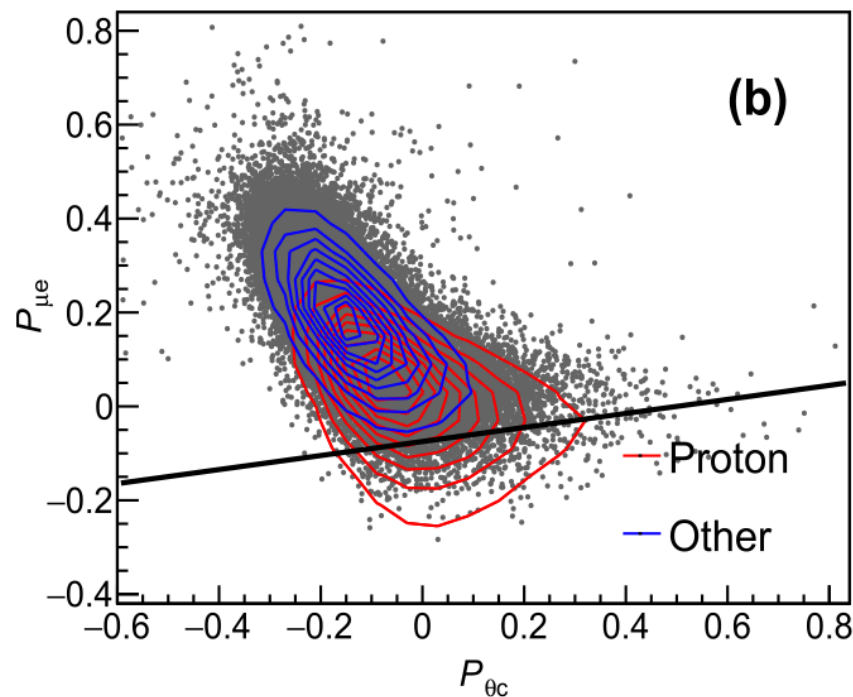
Not enough statistics above 300 TeV to check for a new hardening for He

- Why this matters for knee people: direct measurements *anchor* the models that EAS detectors need

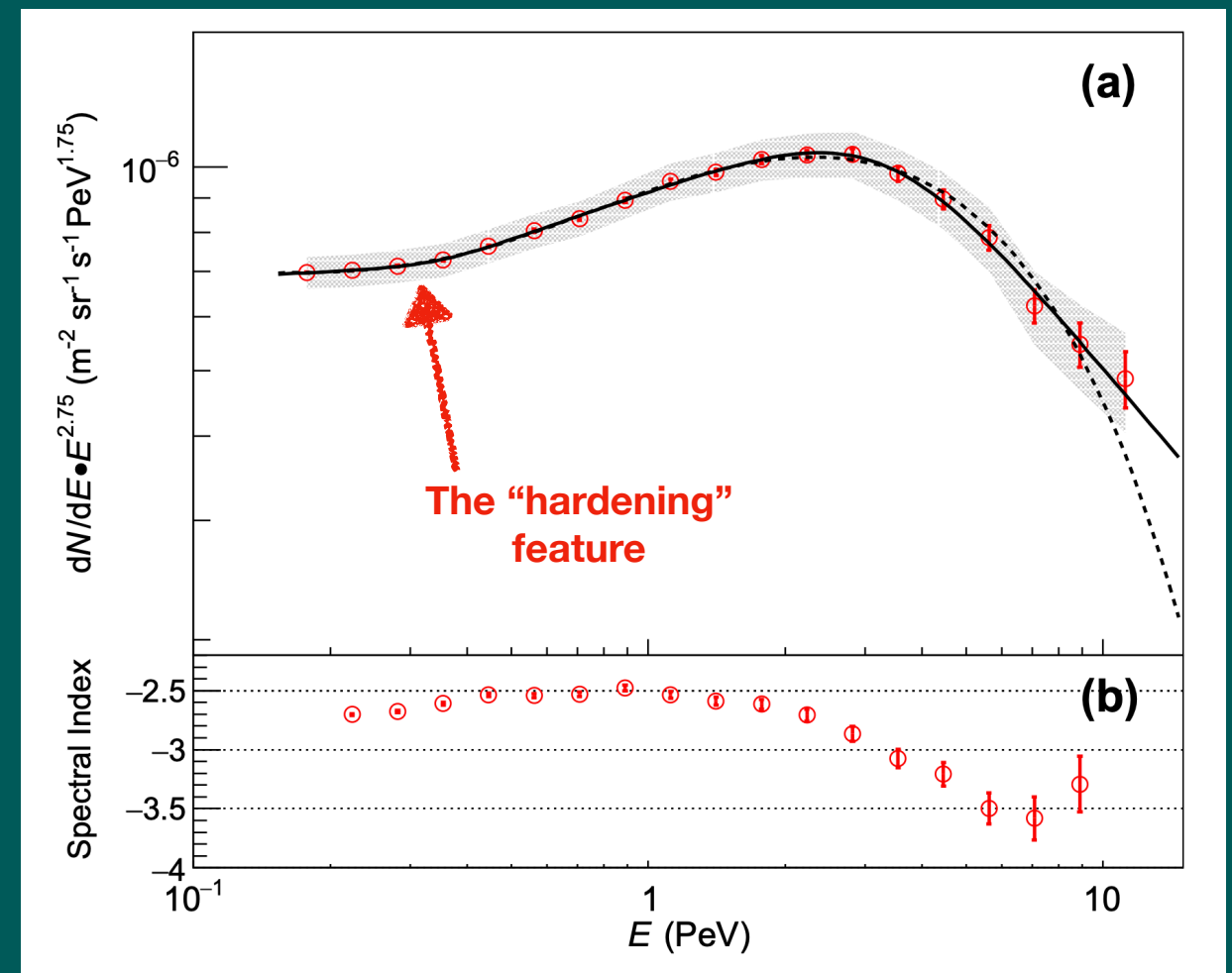
LHAASO: the proton knee

- Analysis of ~900 hours of time (October '21 -> April '22)
- Aperture of 75,000 m²sr above a couple hundred TeV
- Hybrid between KM2A and WFCTA
- How it's done:

$$P_{\mu e} = \log_{10}(N_{\mu}/N_e^{0.82})$$



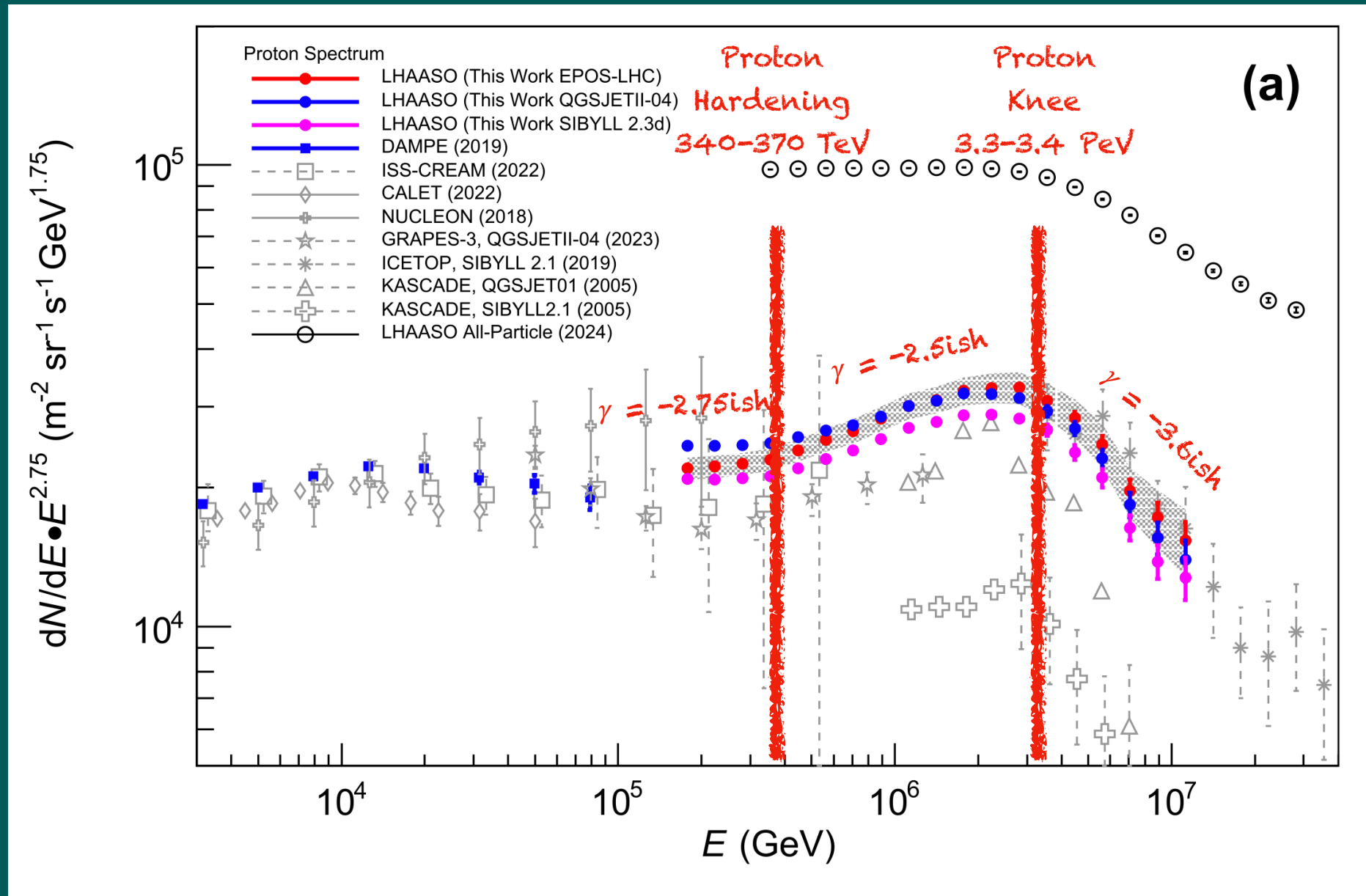
Cherenkov light parameter



Z. Cao, et al (LHAASO Collaboration)
 Precise measurements of the cosmic ray proton energy spectrum in the "knee" region
 Science Bulletin, Volume 70, Issue 24, Pages: 4173-4180 (2025)

LHAASO: the proton knee

Compared to other experiments:



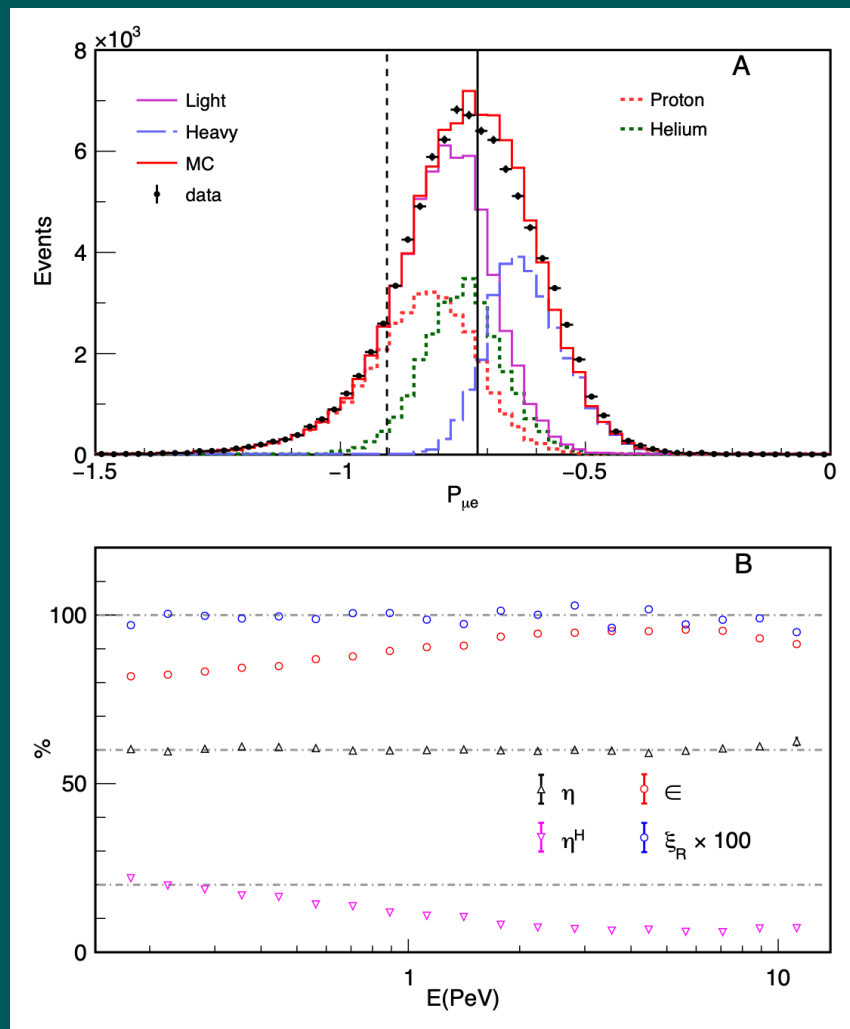
Z. Cao, et al (LHAASO Collaboration)

Precise measurements of the cosmic ray proton energy spectrum in the "knee" region

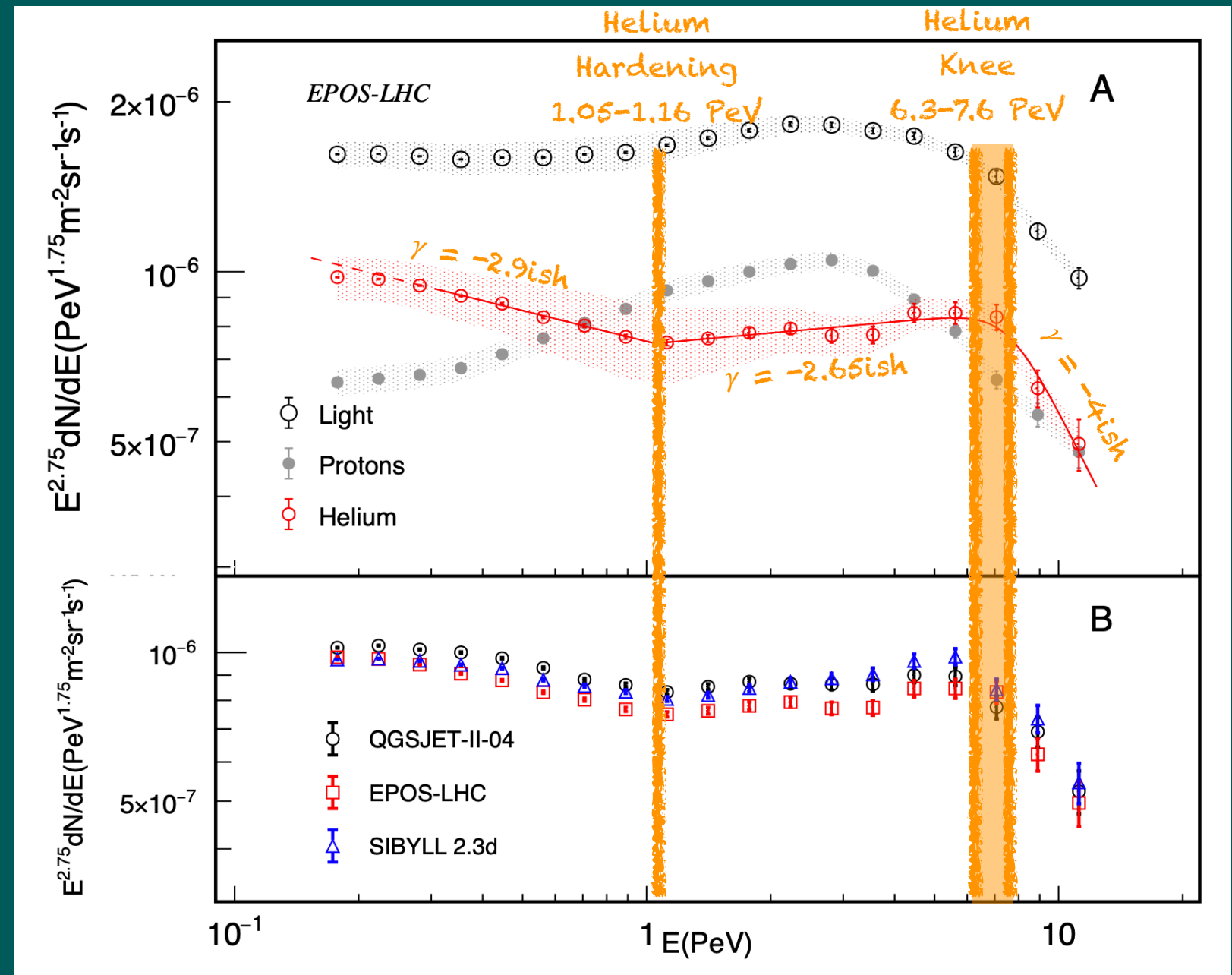
Science Bulletin, Volume 70, Issue 24, Pages: 4173-4180 (2025)

LHAASO: the helium knee

- Measure a “light” group (protons + He), and subtract the contribution from protons
 - Do your best to make sure that your procedure, quality cuts, etc. affect protons and He equally



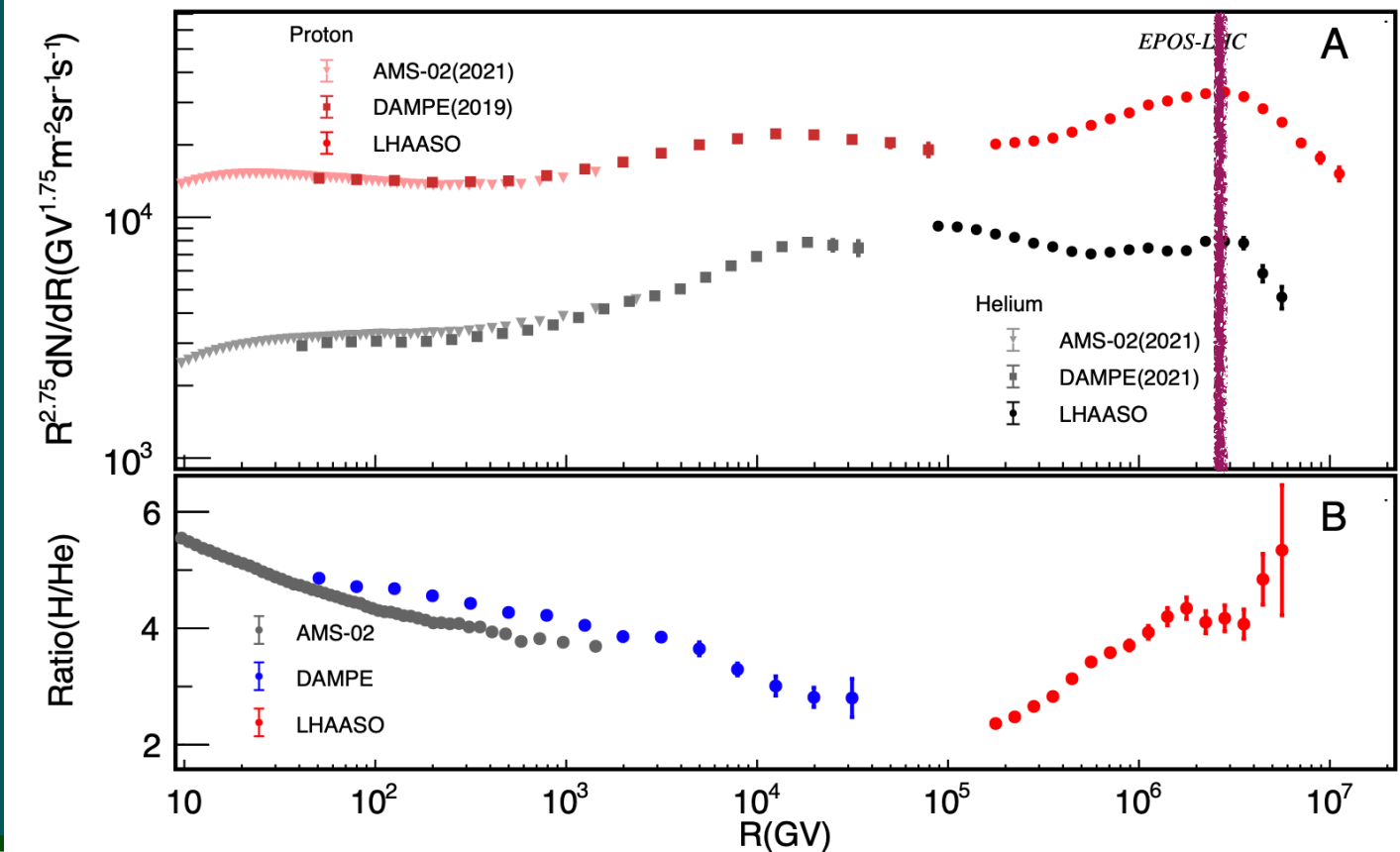
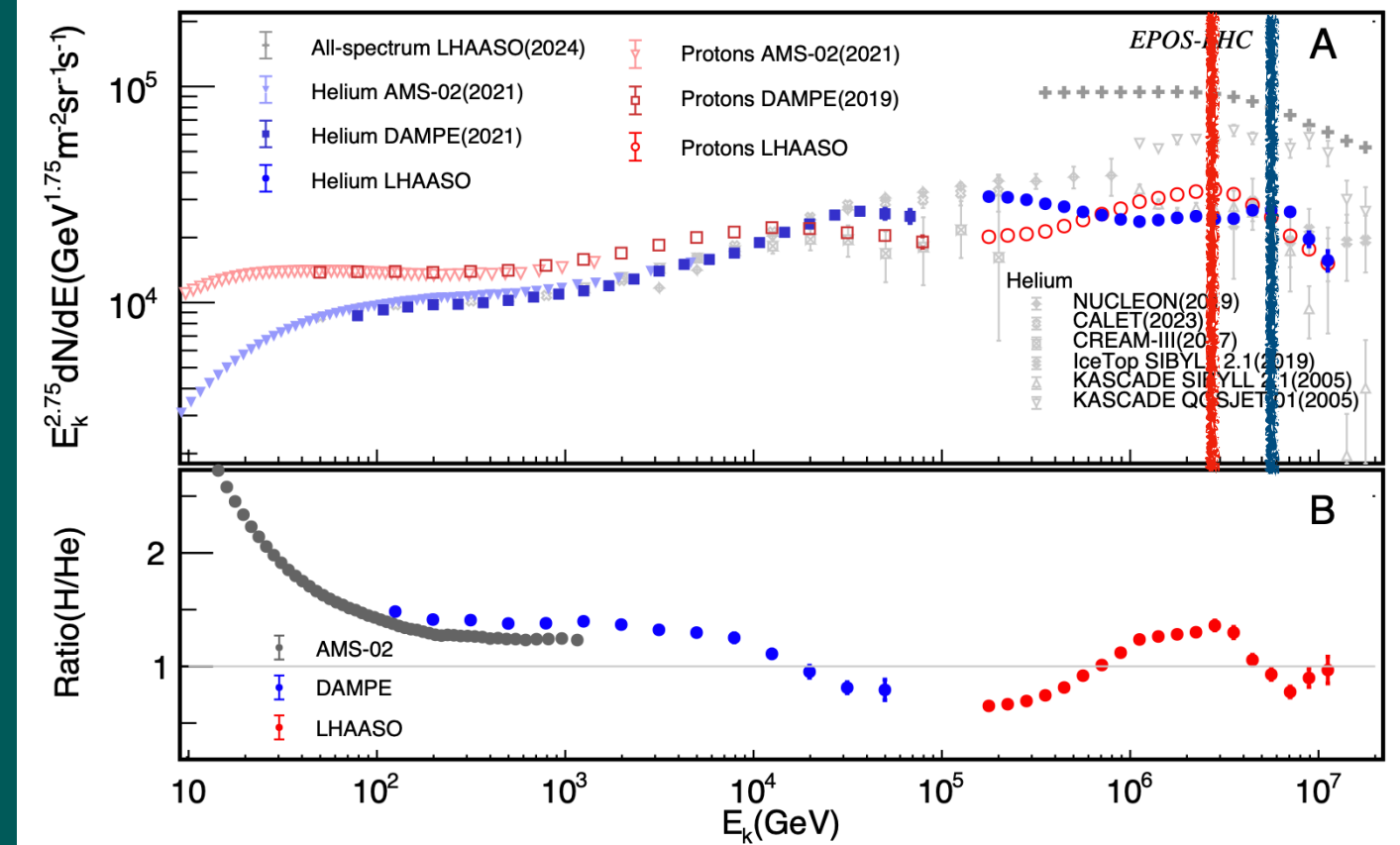
Z. Cao, et al (LHAASO Collaboration)
 Precise Measurement of the Cosmic Ray
 Helium Spectrum above 0.1 PeV
 Phys. Rev. Lett. 136, 121001 (2026)



LHAASO: the helium knee

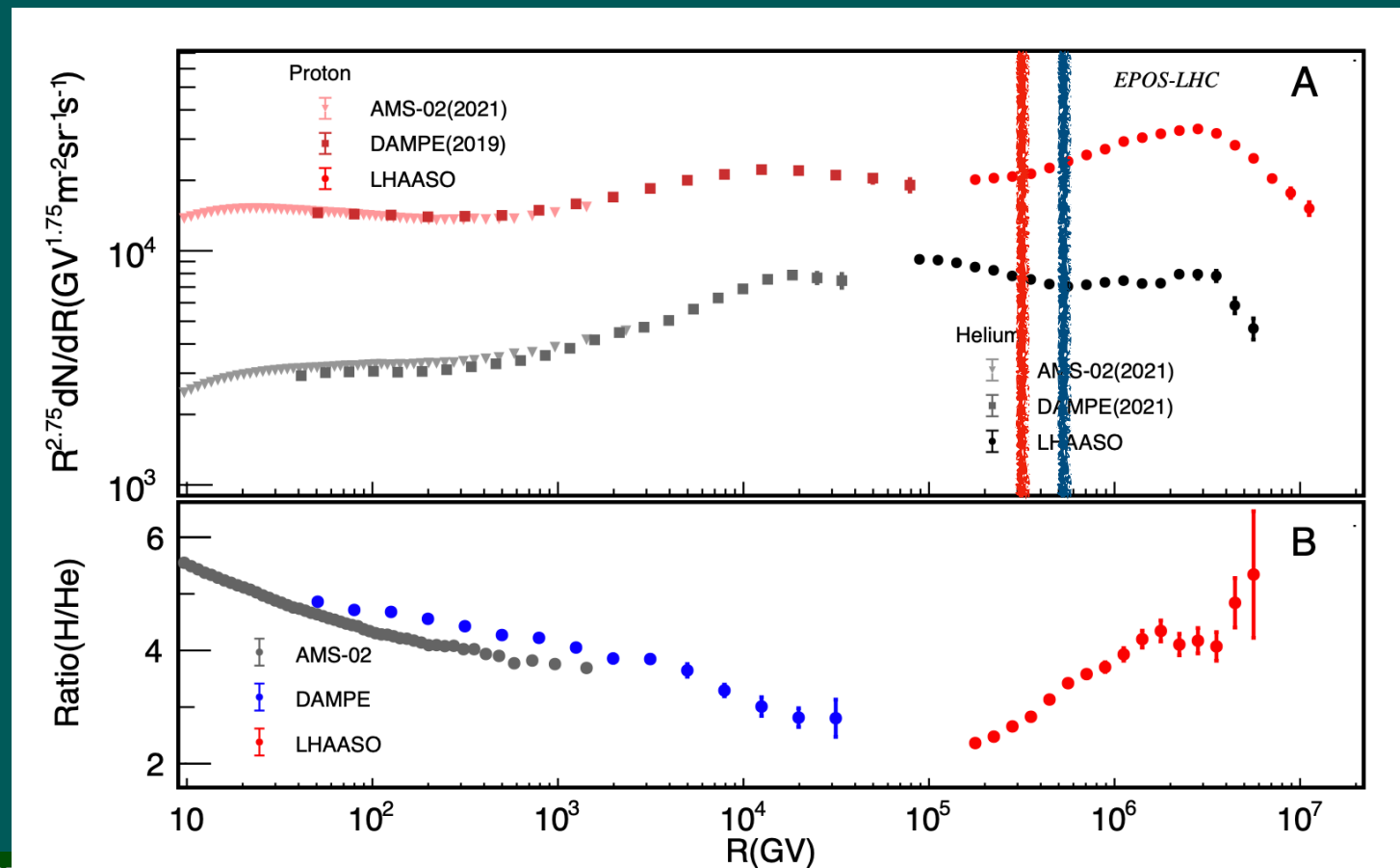
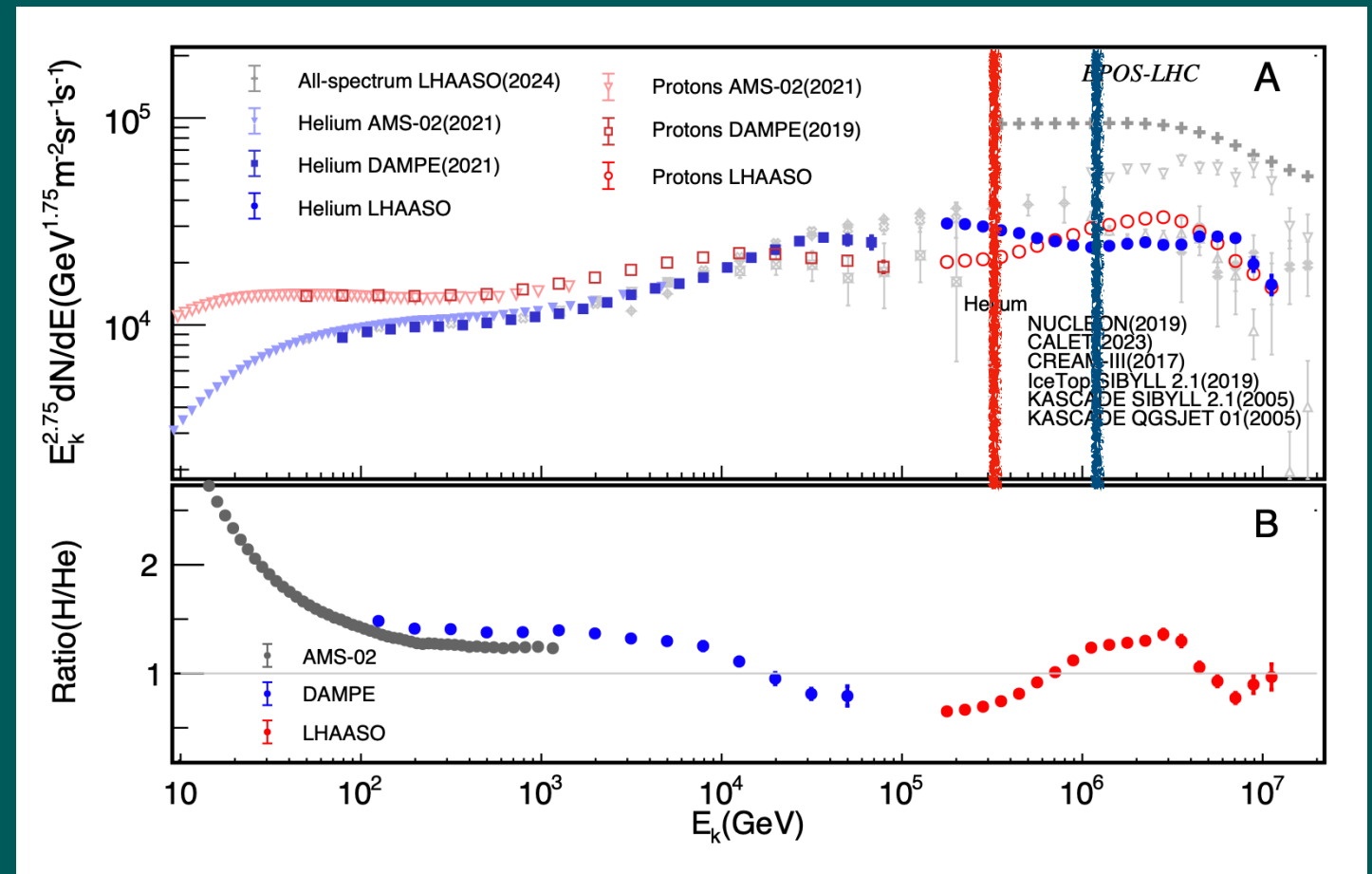
- An energy spectrum plot:
 - Knees at different energies
- A version using rigidity instead
 - The two knees are at the same rigidity

Z. Cao, et al (LHAASO Collaboration)
 Precise Measurement of the Cosmic Ray
 Helium Spectrum above 0.1 PeV
 Phys. Rev. Lett. 136, 121001 (2026)



LHAASO: the helium knee

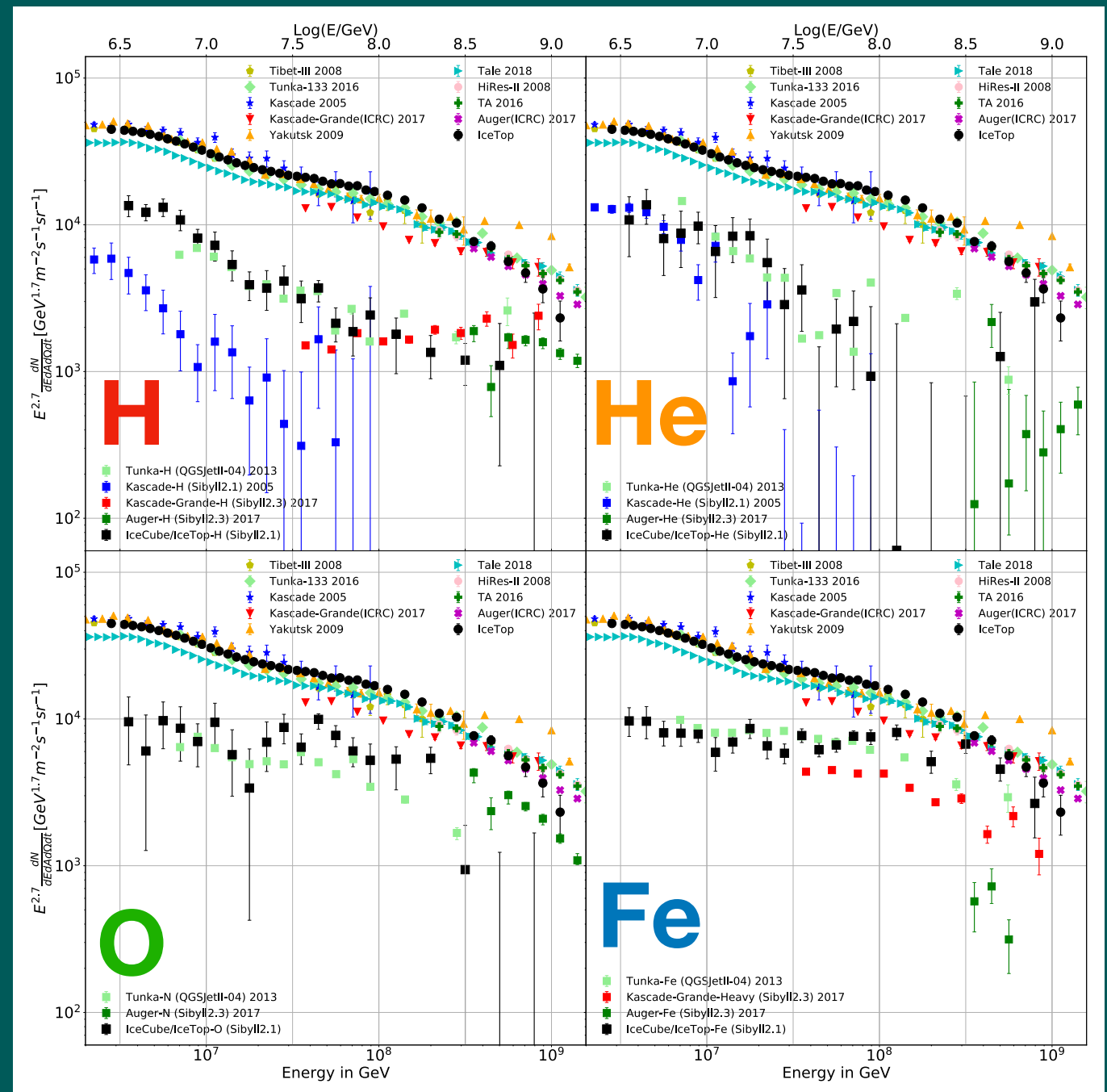
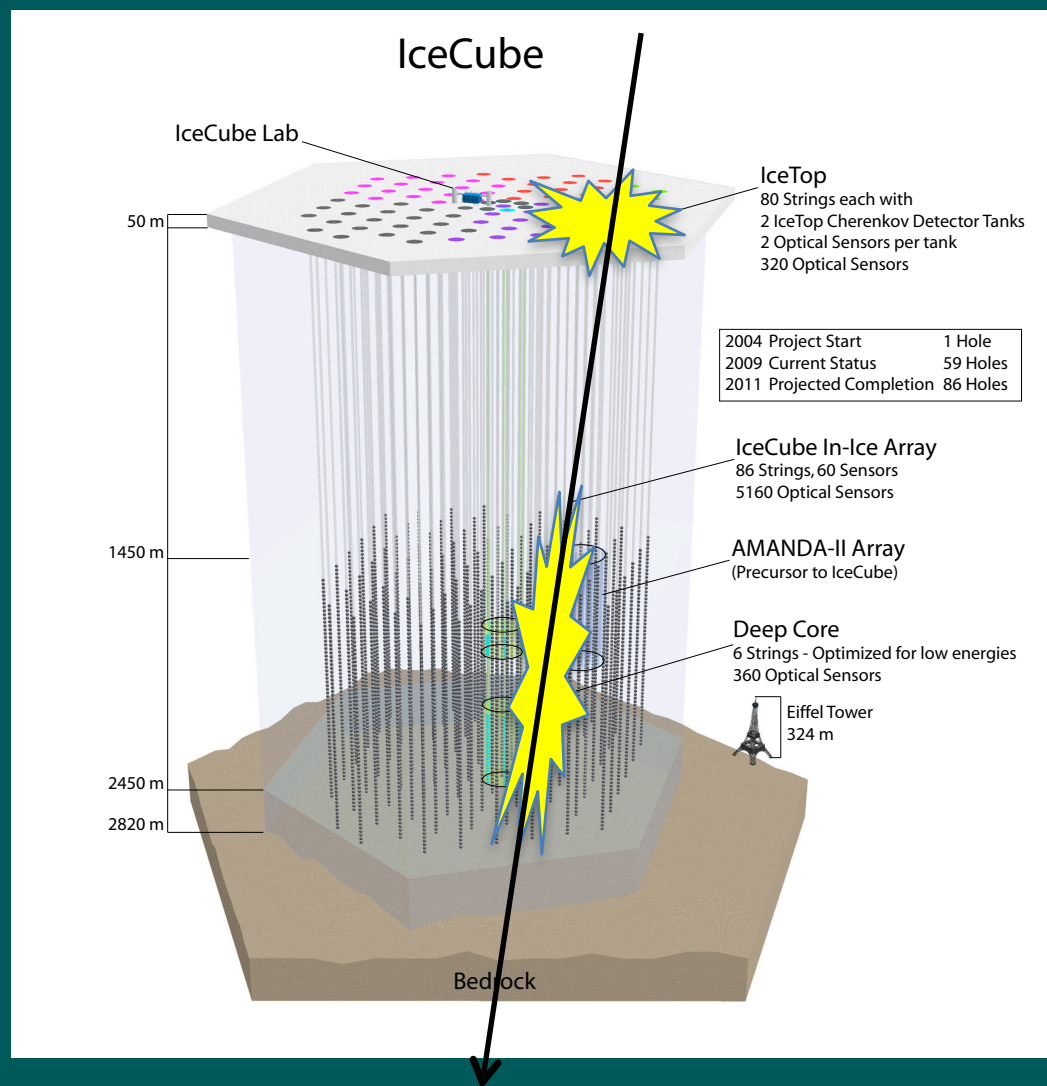
Note: cannot say the same thing for the “hardening” feature below the knee.



Z. Cao, et al (LHAASO Collaboration)
Precise Measurement of the Cosmic Ray
Helium Spectrum above 0.1 PeV
Phys. Rev. Lett. 136, 121001 (2026)

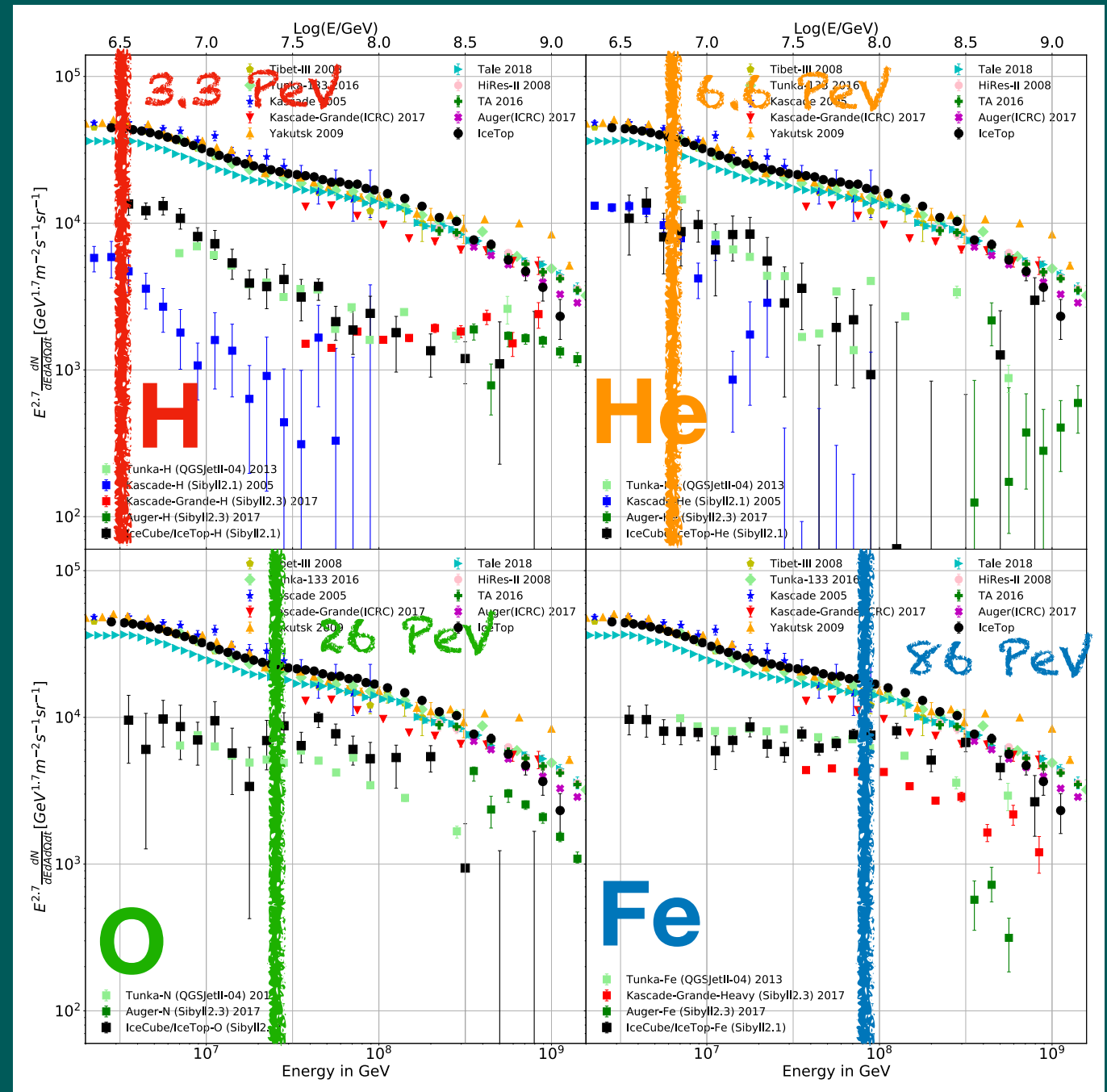
IceCube+IceTop: past the knee

- IceCube + IceTop:
- Uses tanks at the surface + energy loss profile of high-energy muons in the deep ice
- Limited number of events, but composition sensitivity



IceCube+IceTop: past the knee

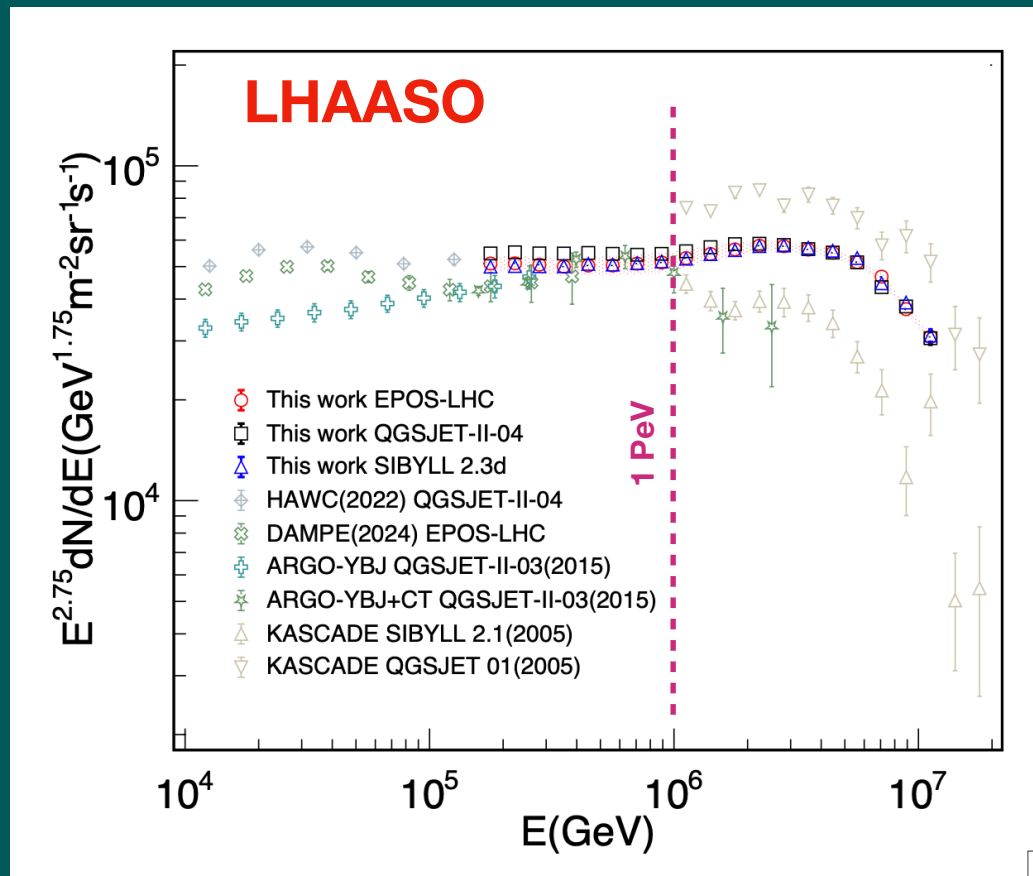
- Heavier nuclei have harder spectra in this regime (composition is getting heavier)
- Good match to the H4a composition model
- This measurement doesn't have the precision to measure exactly where knees are
 - Lines represent $3.3 \times Z$ PeV to guide the eye
 - Remember, though, that heavy elements here are really “groups”



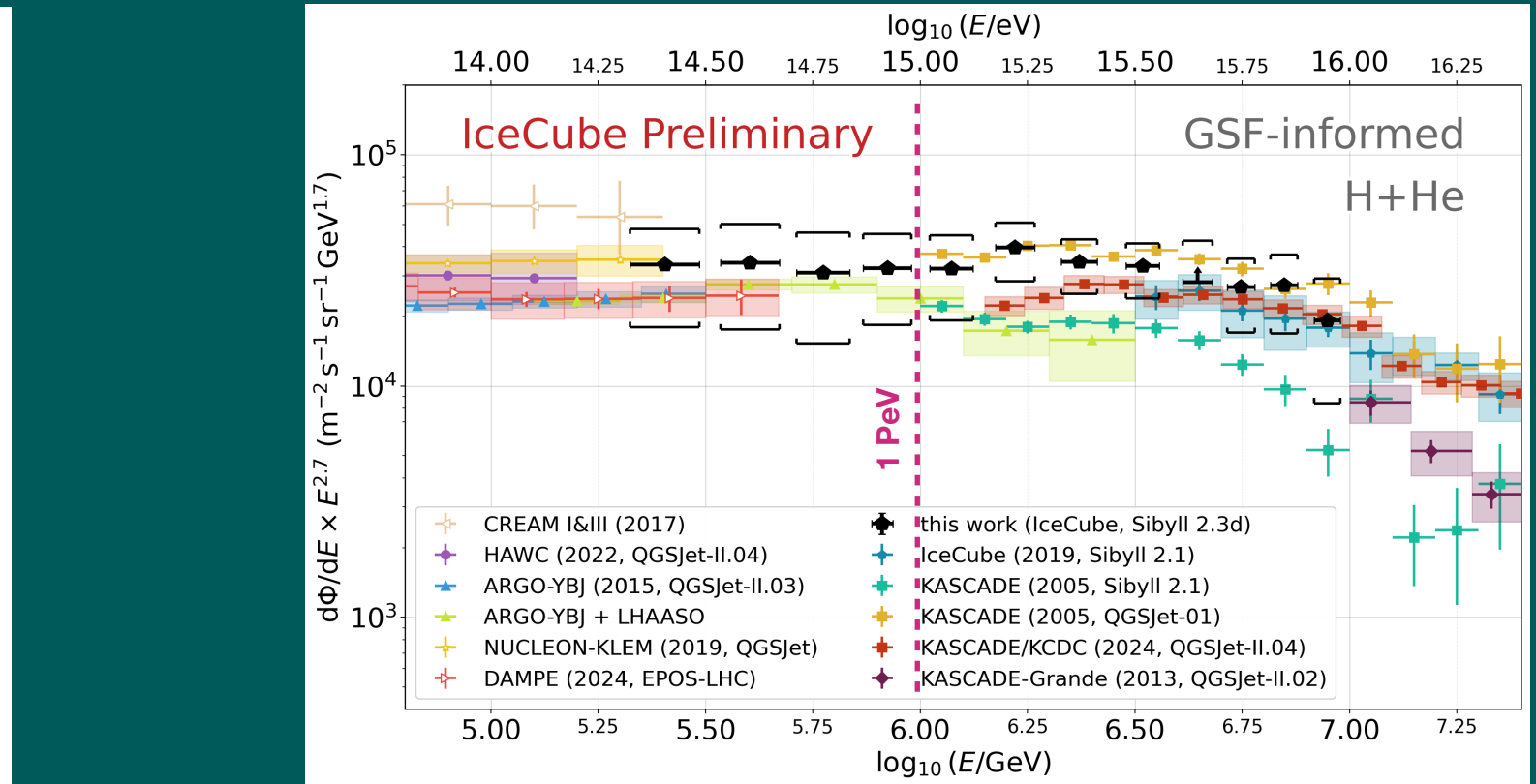
*M. G. Aartsen et al. (IceCube Collaboration)
Cosmic Ray Spectrum and Composition from PeV - EeV
Using 3 Years of Data From IceTop and IceCube
Phys. Rev. D 100, 082002 2019*

The “light group” = protons + He

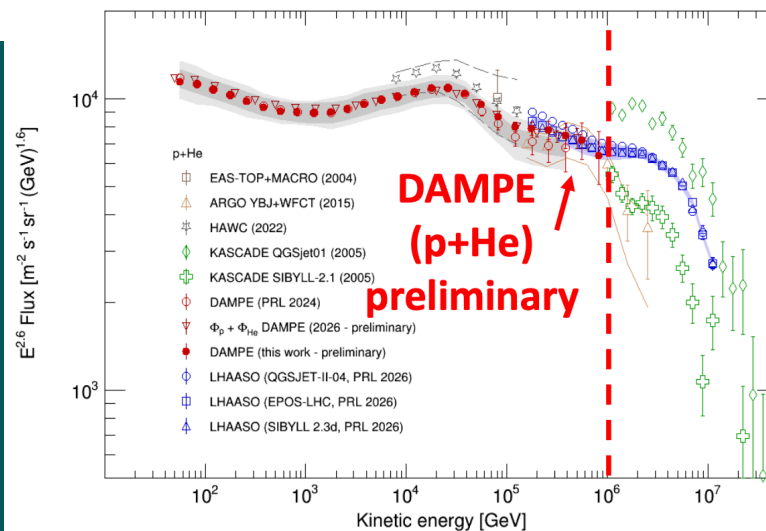
This is an easier measurement, and can still be enlightening



Z. Cao, et al (LHAASO Collaboration)
Precise Measurement of the Cosmic Ray
Helium Spectrum above 0.1 PeV
Phys. Rev. Lett. 136, 121001 (2026)



J. Saffer et al. (IceCube),
Spectrum of PeV Cosmic-Ray Protons and
Helium Nuclei with IceCube,
PoS ICRC2025, 376 (2025), 2511.05284.



Independent (p+He) measurement
is consistent with the sum of the
individual p and He fluxes

Andrii Tykhonov's talk from this meeting
DAMPE results after the first 10 years of operation

What makes all of this hard

- “If all this sounds tricky to do, that’s because it is.”
- Analysis depends crucially on comparing data to simulations, and simulations depend crucially on the *hadronic interaction model*, which describes the first (highest-energy) interaction of the primary cosmic ray with the atmosphere.
- Simulations can be made of various primary nuclei (protons, He, C/N/O, Fe, etc.). However, using these simulations to represent reality involves making an assumption about the composition. This “you have to know the composition to measure the composition” catch-22: analyses may be iterative, or account for this as a source of systematic uncertainty.
- Additional systematics from things like atmospheric conditions, detector efficiencies and calibration, etc.

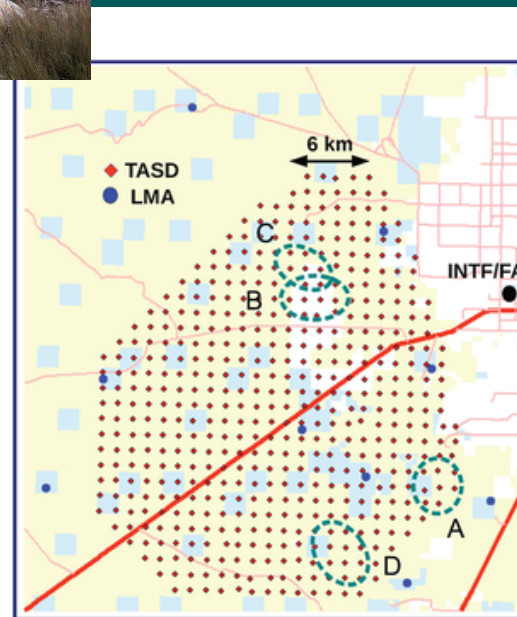
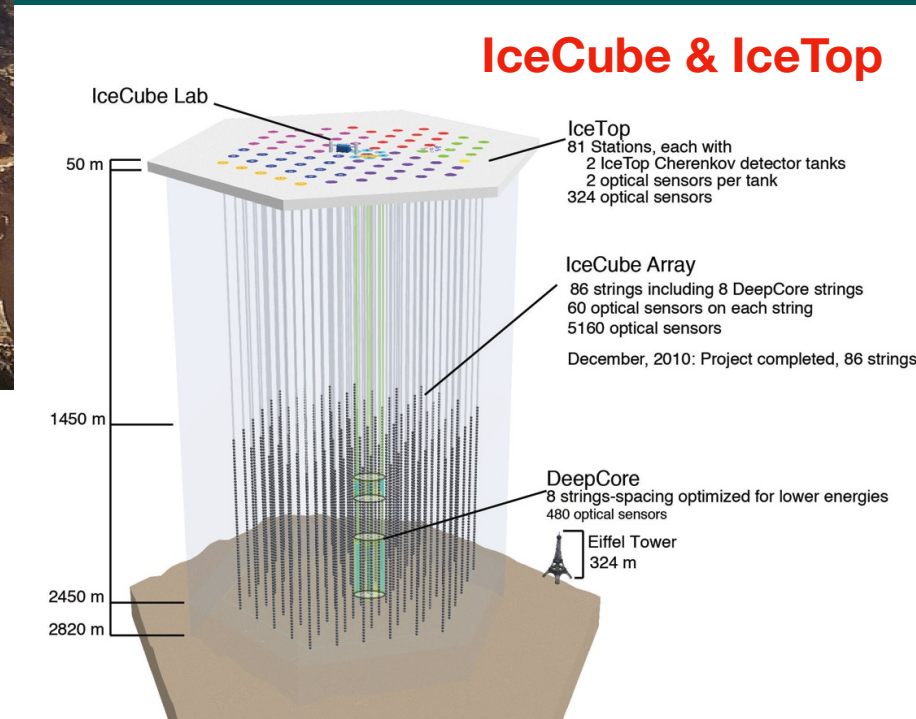


Fight against the sadness, Artax!

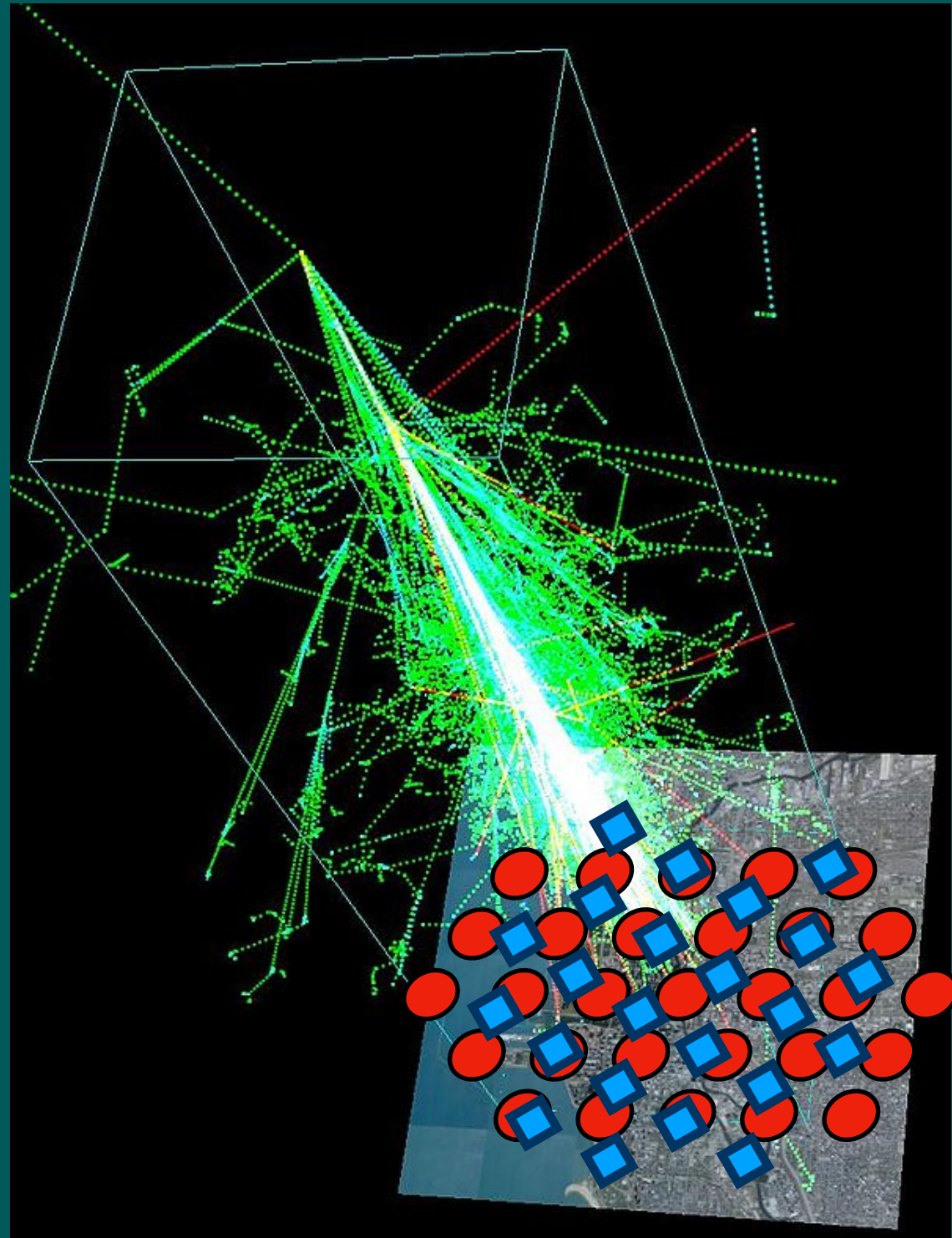
New: Multimessenger

Extensive air shower detectors

Gamma Ray Observatories Neutrino Detectors



A cosmic ray observatory = A gamma-ray observatory

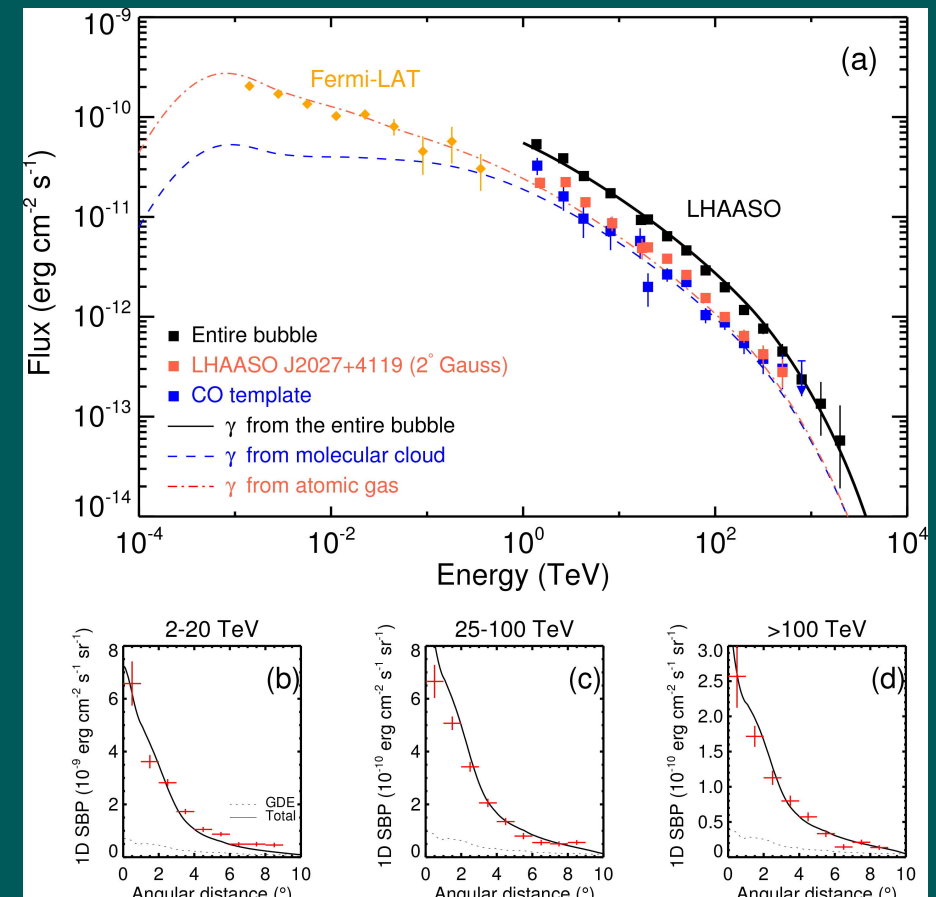
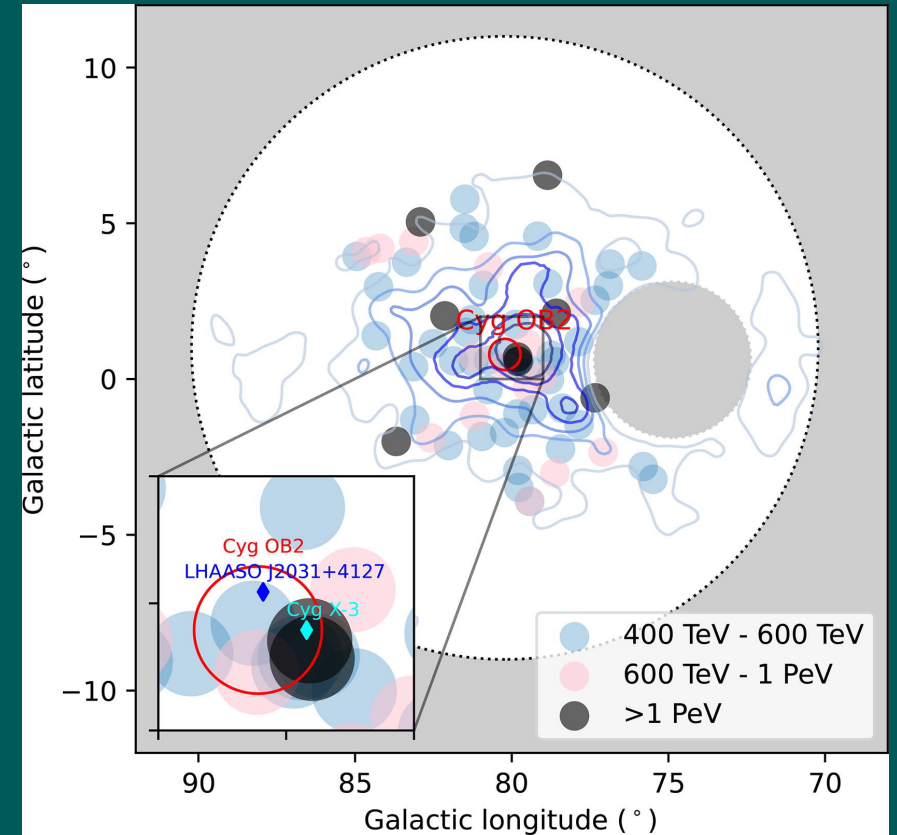


Gamma rays will produce an electromagnetic air shower... but absent of the muons.

“Gamma-hadron separation”:
select events that are muon-poor

LHAASO's PeVatrons

- LHAASO sees PeV gamma rays!
- We've been hearing about them all week
- *Friday morning plenary talk...*
- SNR's have always been a candidate for Galactic cosmic rays, but it was hard to get them accelerating cosmic rays to $> 100\text{TeV}$... Now, there are more candidates to consider, that can produce cosmic rays in the knee region.



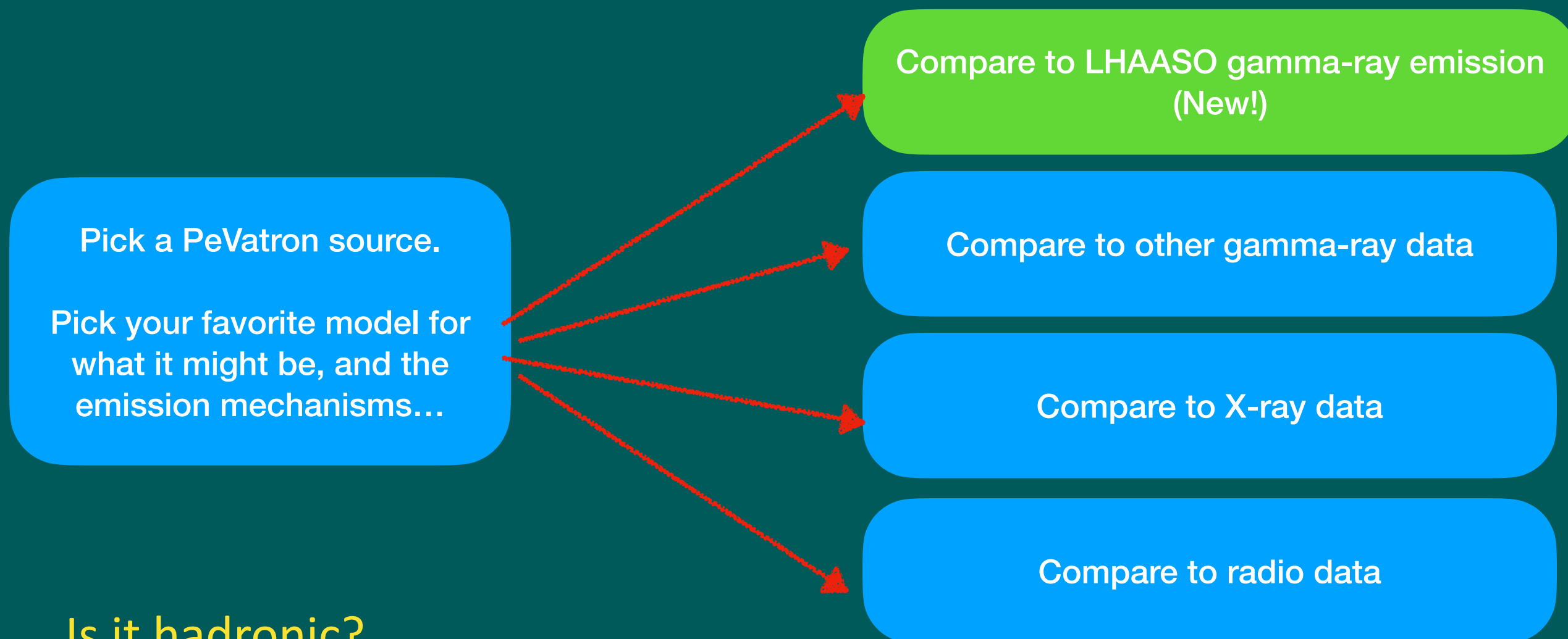
LHAASO Collaboration
 "An ultrahigh-energy gamma-ray bubble powered
 by a super PeVatron"
 Science Bulletin 69 (2024) 449–457

Theories and Modeling

"So, Galactic PeVatrons are a thing!"

Now what?

- Model your gamma-rays and X-rays



- Is it hadronic?
- Time variation?
- Inner part of the object vs. outer part of the object?
- Cruise the GR sessions for many examples

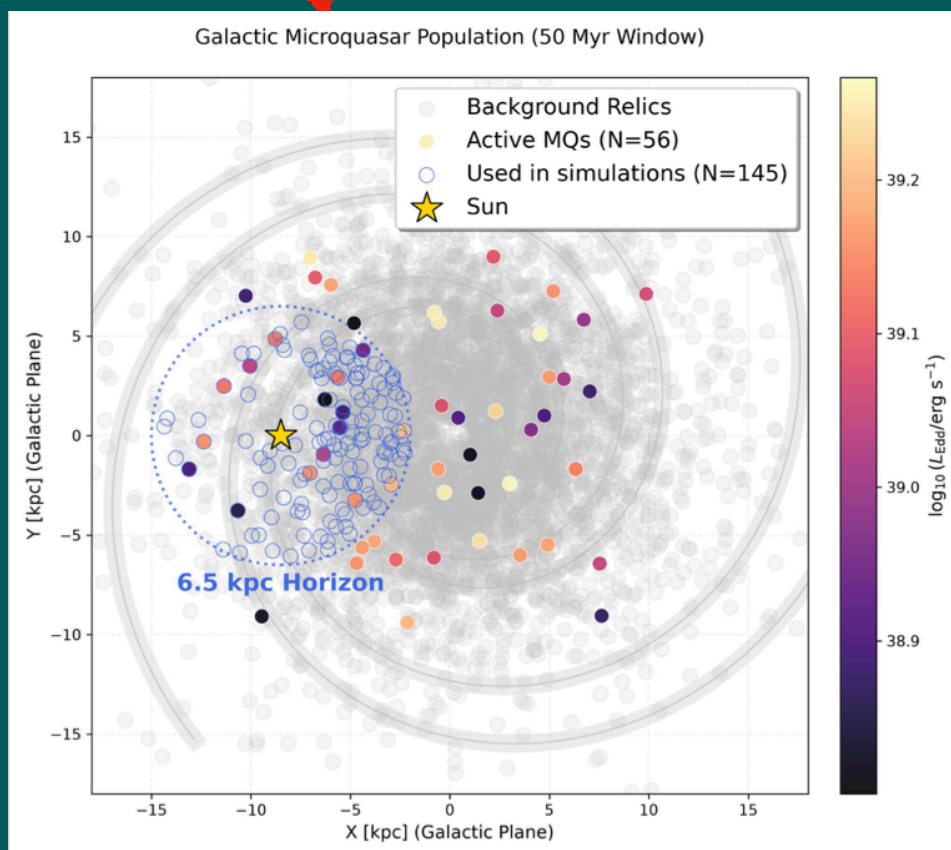
Go for it, modelers!

Model your knee protons (or other diffuse galactic stuff)

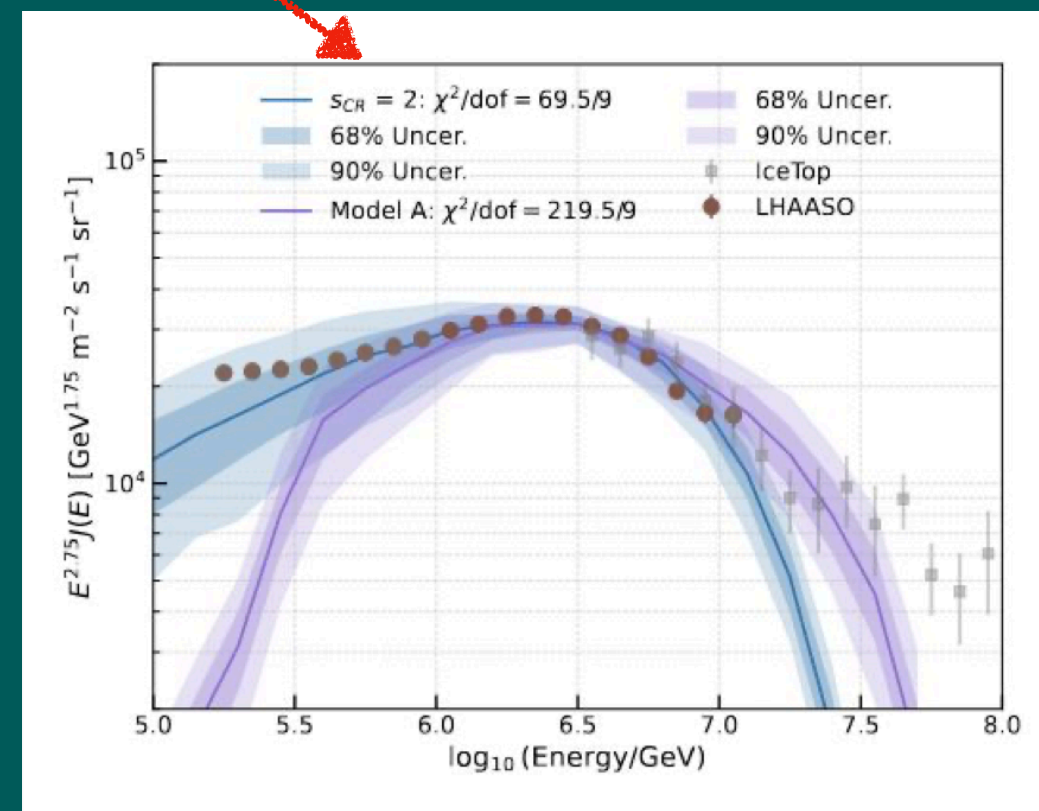
Pick a PeVatron source or source class(s)

Inject their protons and model their propagation

Model a galaxy full of them



Shiqi Yu's talk at this conference
Microquasar Origin of PeV Cosmic Rays
and Constraints on the Diffuse Neutrino
Sky



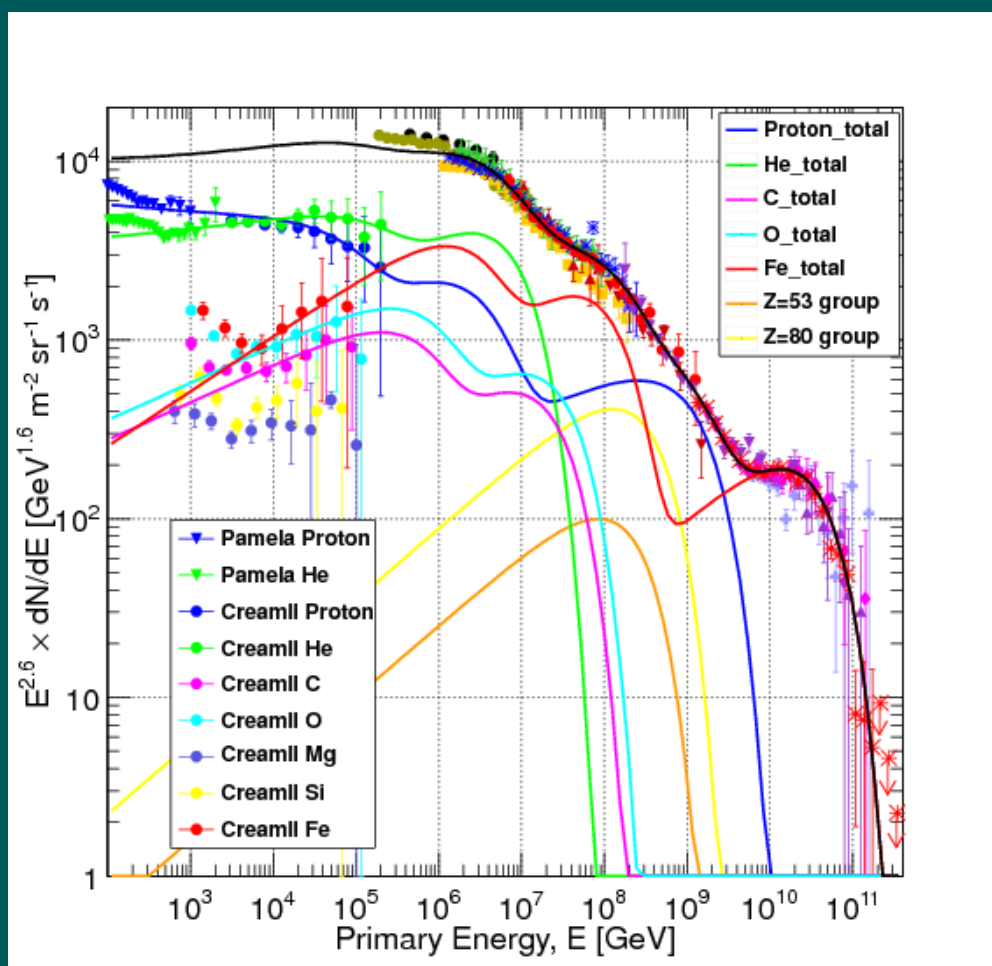
Compare to the cosmic ray proton spectrum from various experiments (DAMPE, LHAASO, IceTop, etc.) (New!)

Note: it's not that nobody could do this before, it's just that the precision has gotten so much better.

Data-driven models: “bumps and wiggles”

- Theory: Assume some populations (two galactic, one extragalactic, for instance) that produce cosmic rays... whatever they are.
- Assume that each population’s process has a rigidity-dependent cutoff (Pc/Ze)... so protons disappear first, and iron last
- Mess around with the parameters of each population (turn-on, cutoff, spectral index, etc.) until things seem to match the global data

- The GST fit:

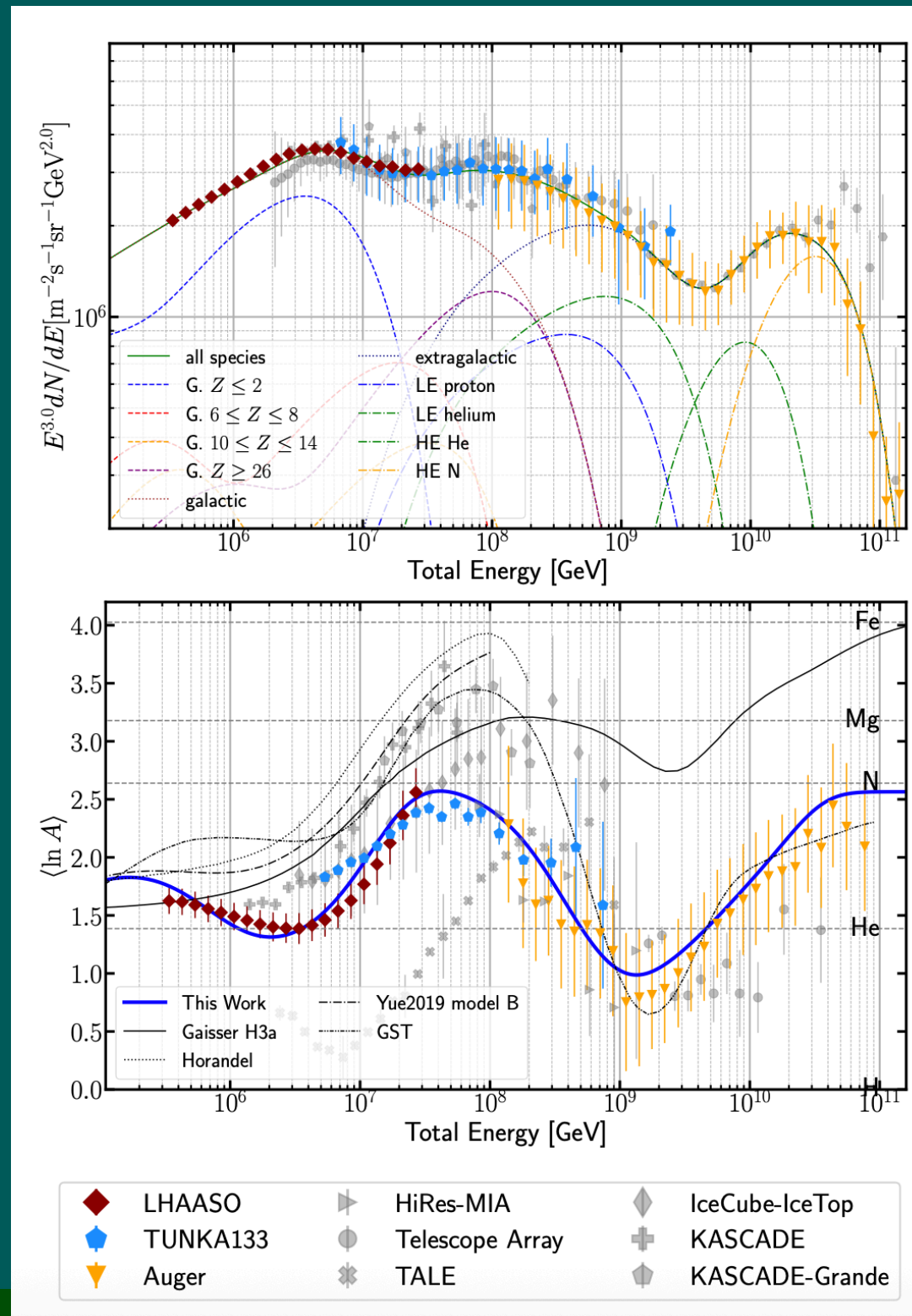


Notice: these models also predict, How the *mass composition* should be changing through these transitions

*T. K. Gaisser, T. Stanev, and S. Tilav,
Front. Phys.(Beijing) 8 (2013)
arXiv:1303.3565v1*

Data-driven models: “bumps and wiggles”

- This recent “LHAASO-anchored” model uses three galactic populations, and two extragalactic populations:

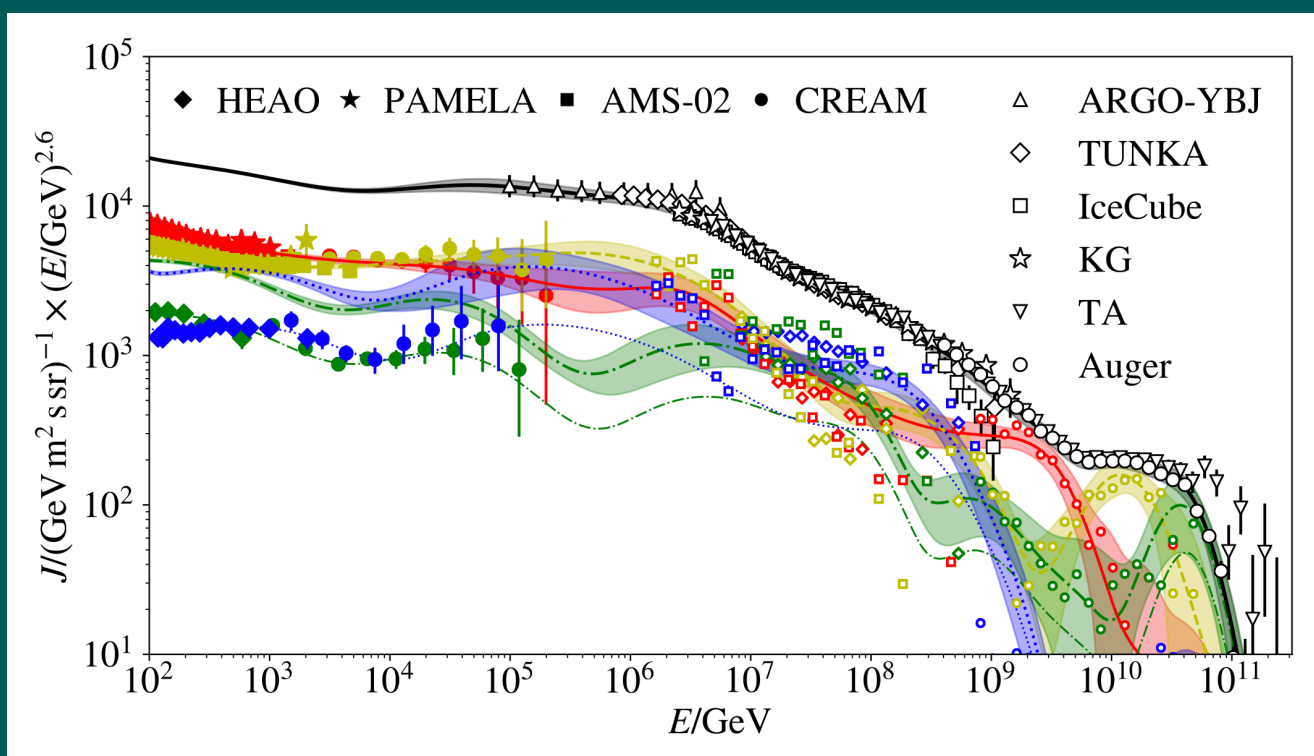


*Lv et al.
Precise measurement of the cosmic-ray
spectrum and $\langle \ln A \rangle$ by LHAASO —
connecting the Galactic to the
extragalactic components
Astrophys. J. 979, 225 (2025)*

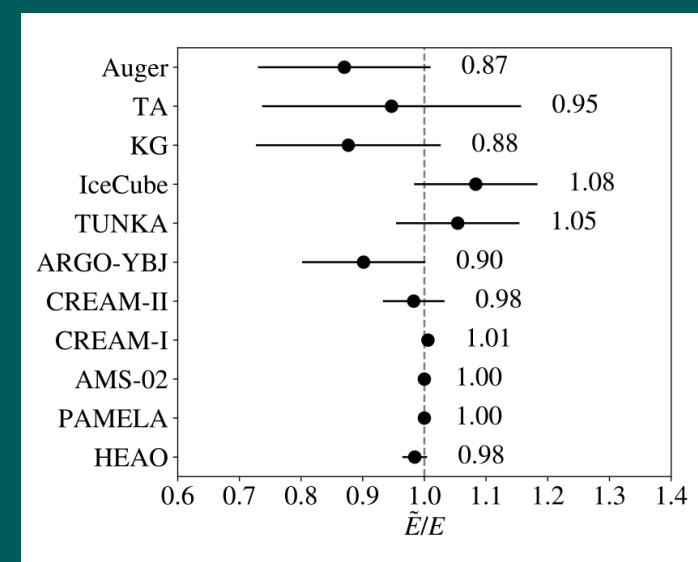
Data-driven models: “bumps and wiggles”

Another strategy: just try to find the shape of the spectrum, with its changing composition, irrespective of models of origin.

The Global Spline Fit (GSF):



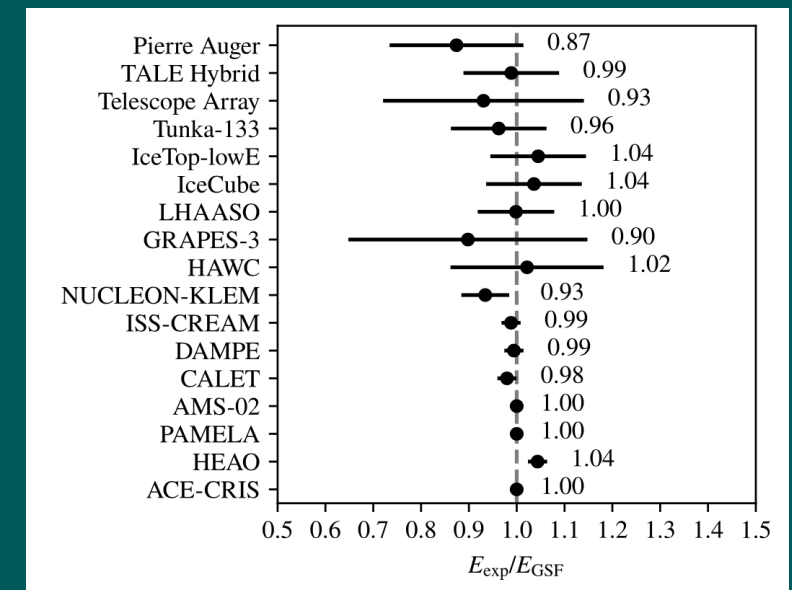
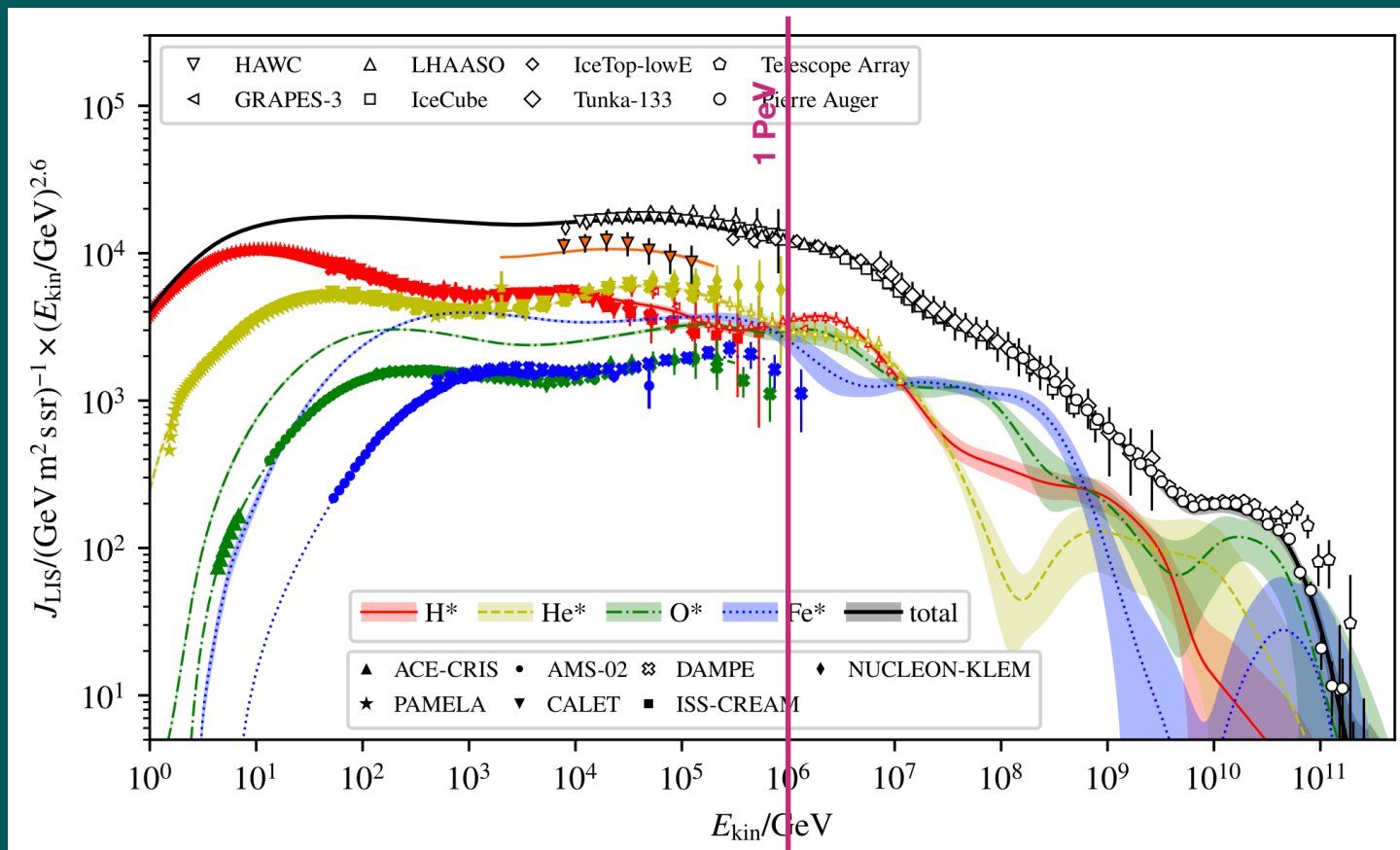
“GSF”: *H. Dembinski et al., PoS(ICRC2017) 533*



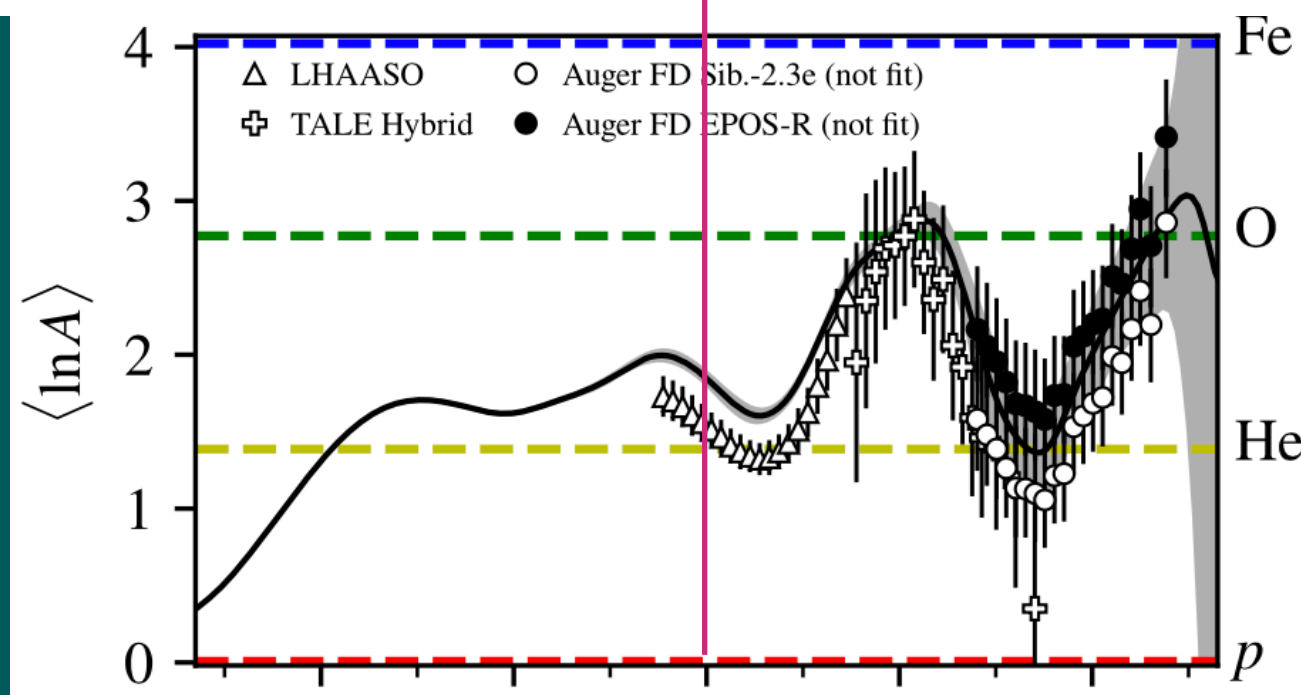
One must do some tweaking of the energy scales of different detectors to make this work

Data-driven models: “bumps and wiggles”

A new “GSF 2026” model is under review and should be available soon: anchored in the latest direct measurements, includes the latest from LHAASO, etc.



...after some tweaking of the energy scales



Thank you to Anatoli Fedynitch for a sneak peek at these plots!

Outlook

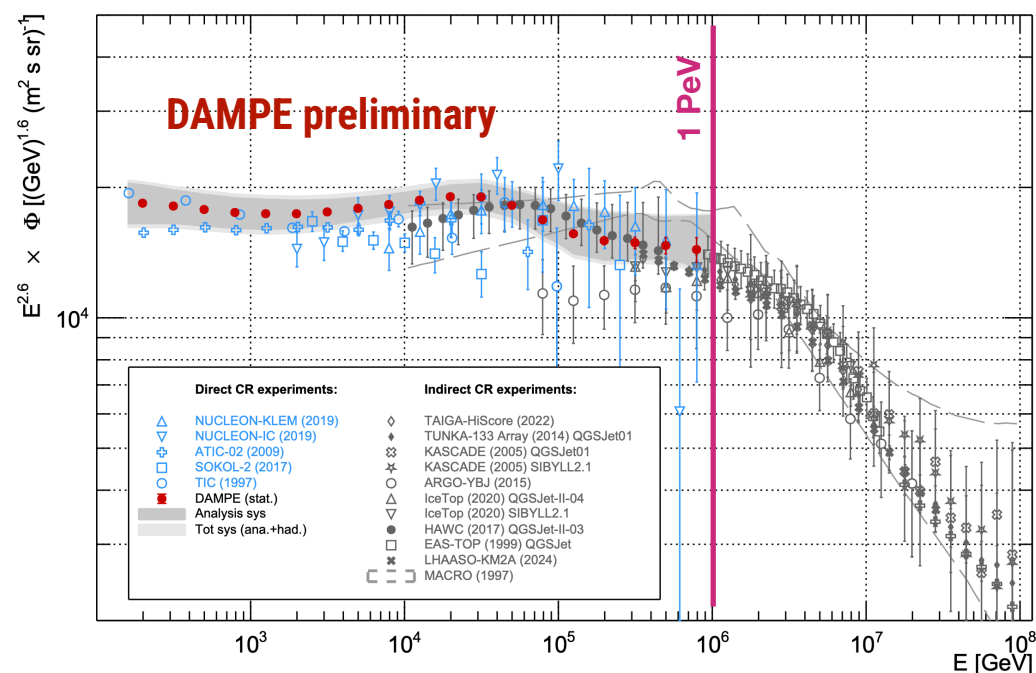
Closing the gap

Space-based experiments are nearing the PeV mark and the start of the knee, closing the gap between direct and indirect measurements

Push exposure

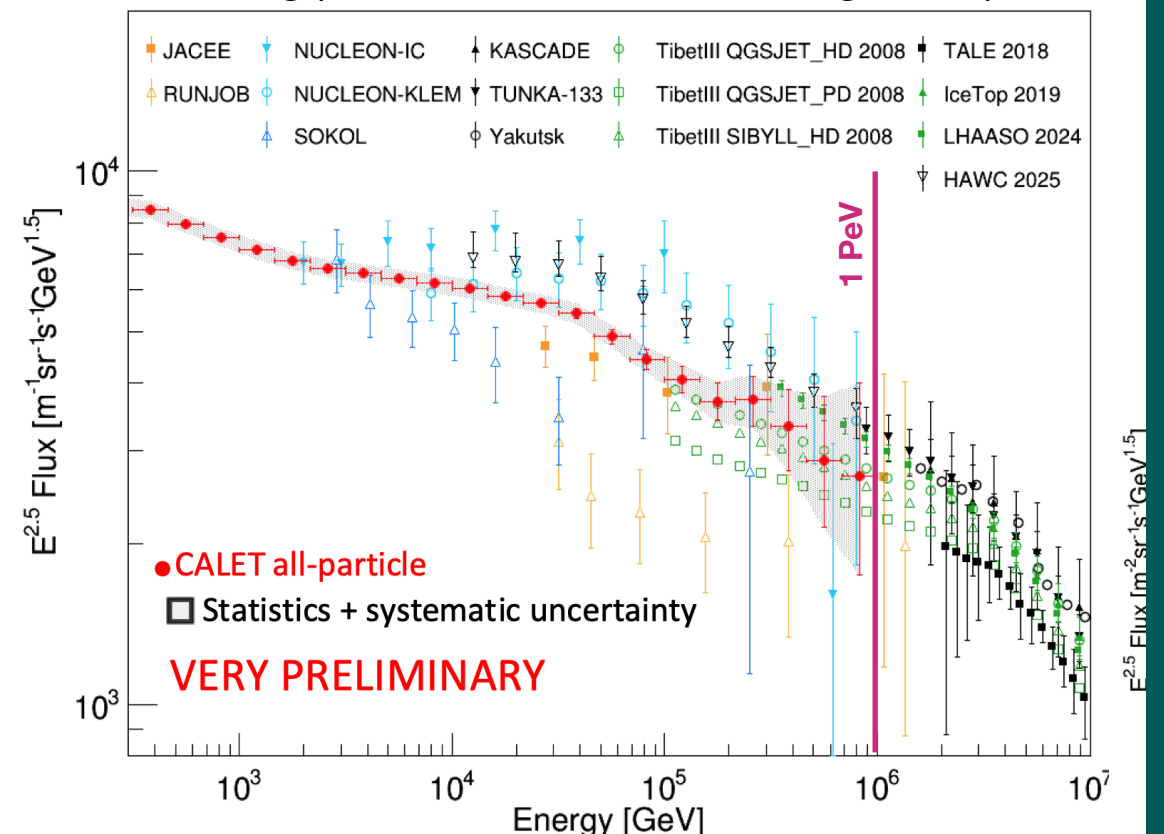
Push exposure

- All-particle spectrum measurement spanning 4 orders of magnitude in energy!



Andrii Tykhonov's talk from this meeting
DAMPE results after the first 10 years of operation

CALET closes the gap with indirect measurements from ground experiments

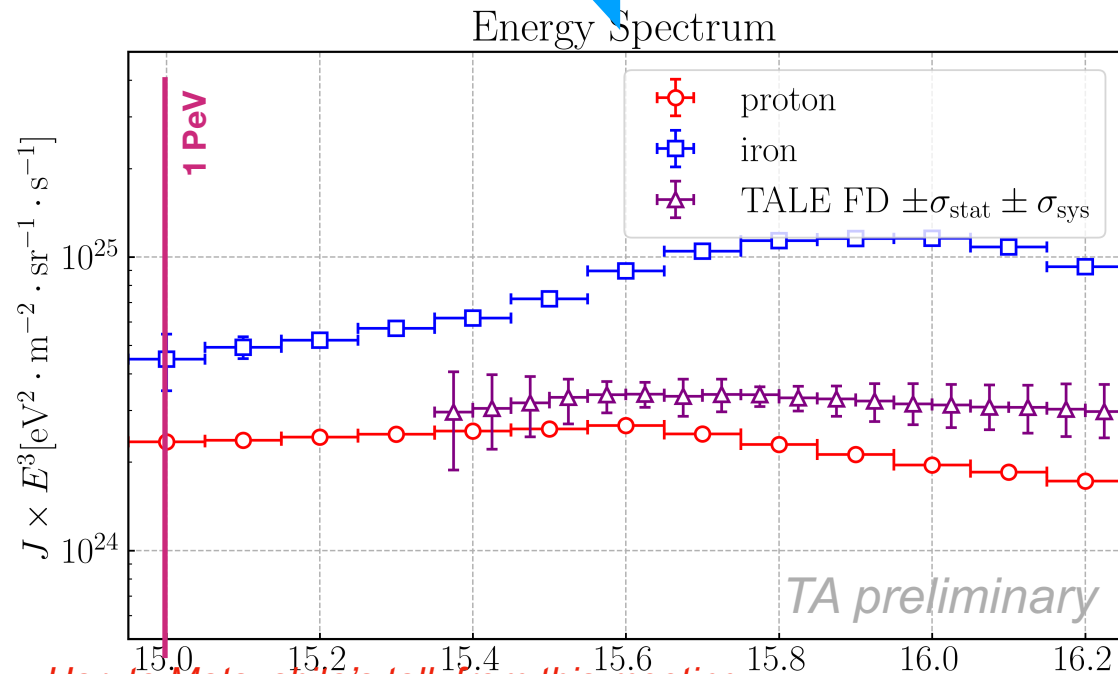


Yosui Akaike's talk from this meeting
Extending Cosmic-Ray Measurements over a Decade with CALET

Closing the gap

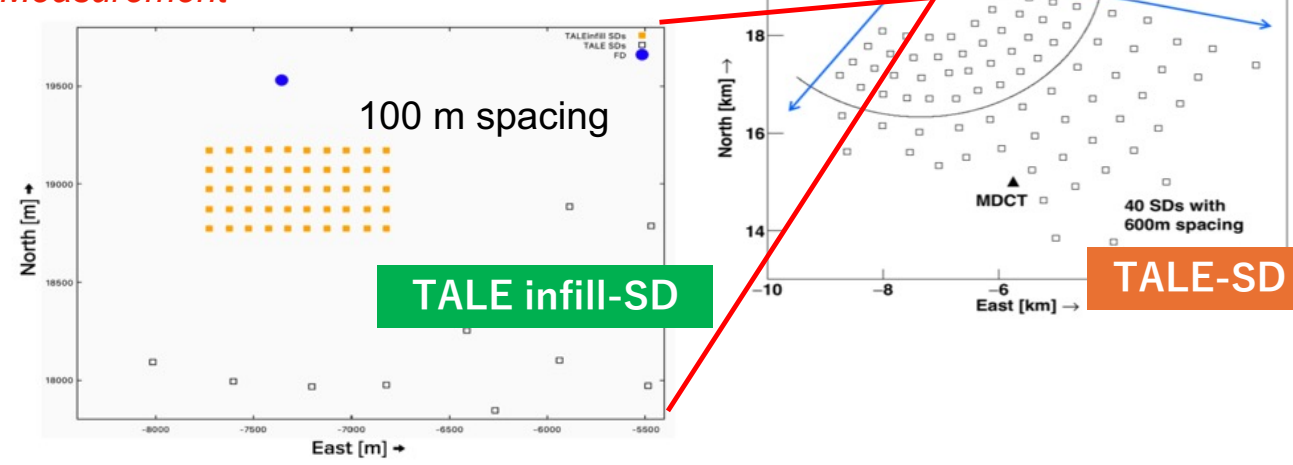
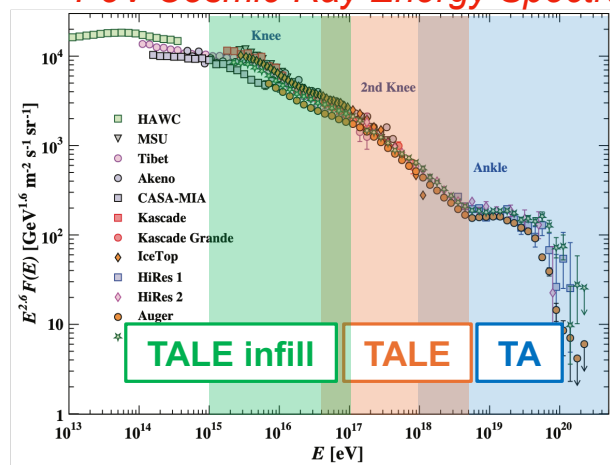
Meanwhile, ground-based experiments are pushing their thresholds lower, using “infill” arrays

Push threshold

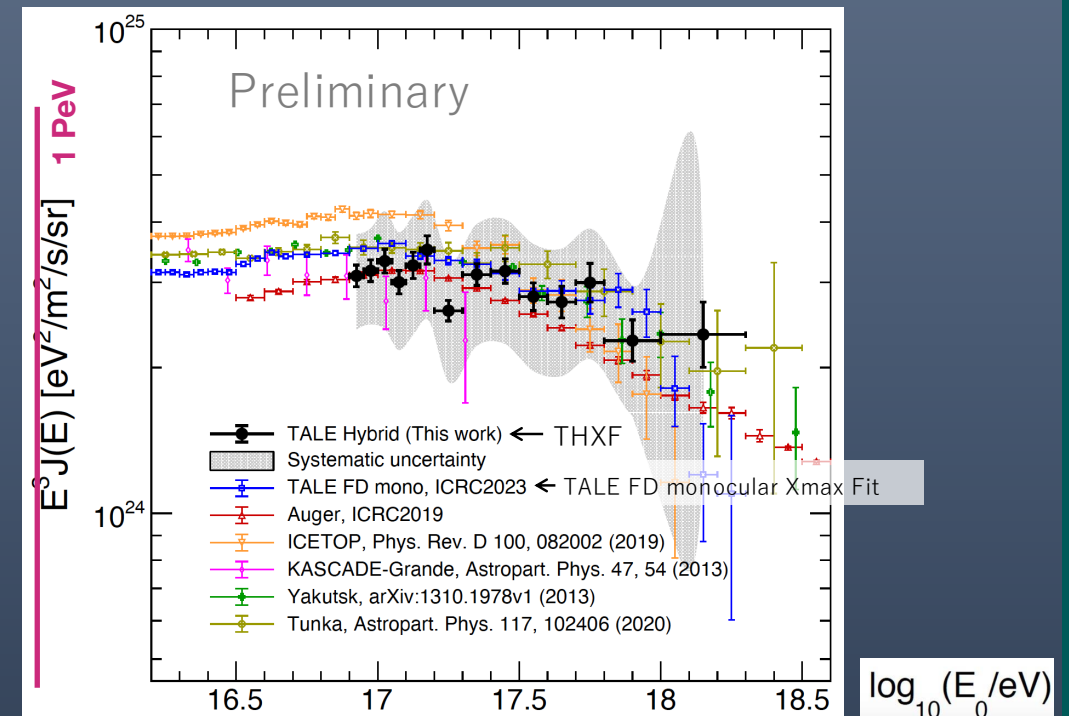


Haruto Matsushita's talk from this meeting
First Results with the TALE infill array for a
PeV Cosmic-Ray Energy Spectrum Measurement

R. U. Abbasi et al. (Telescope Array Collaboration), *ApJ* 865, 74 (2018).

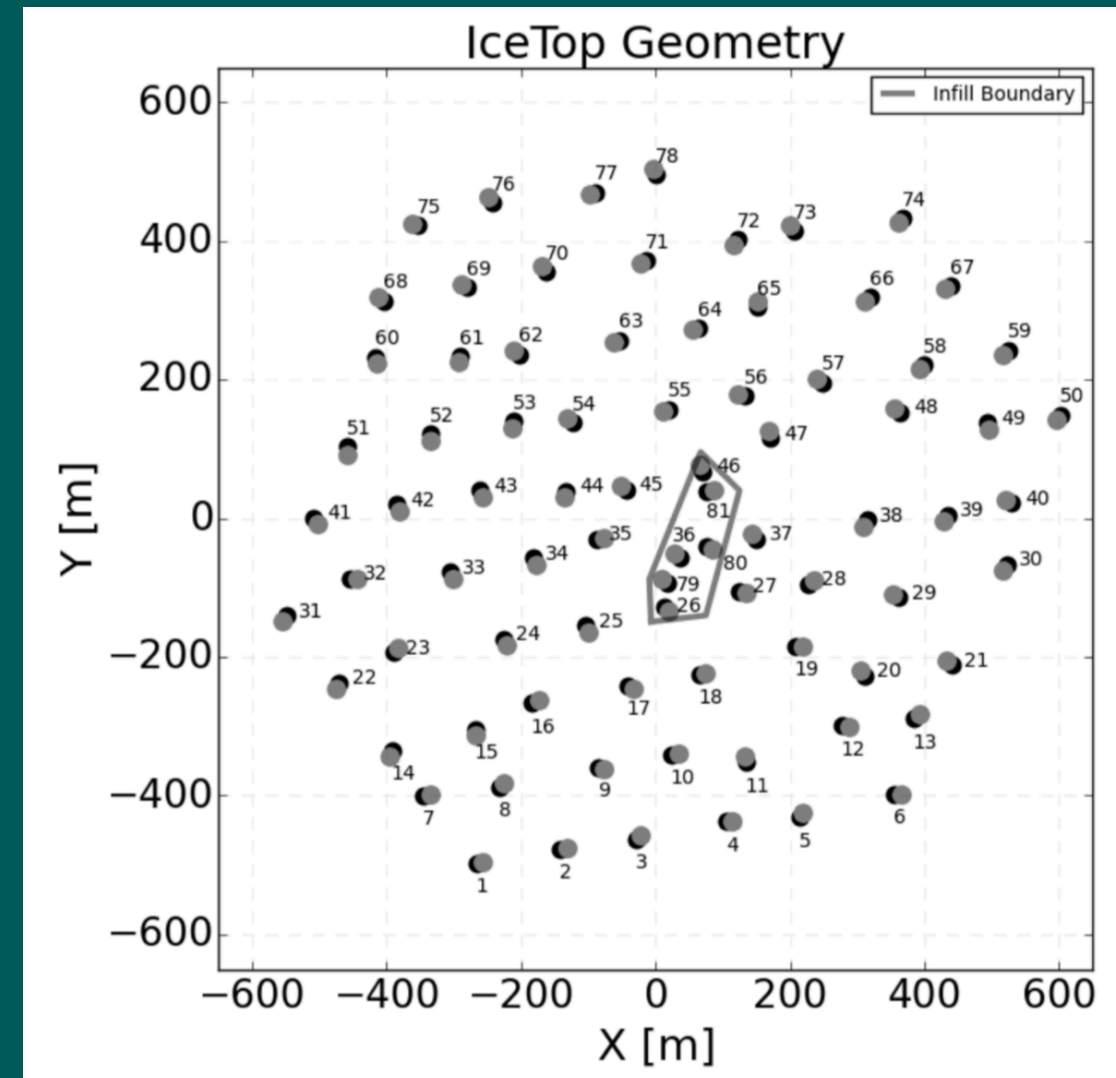
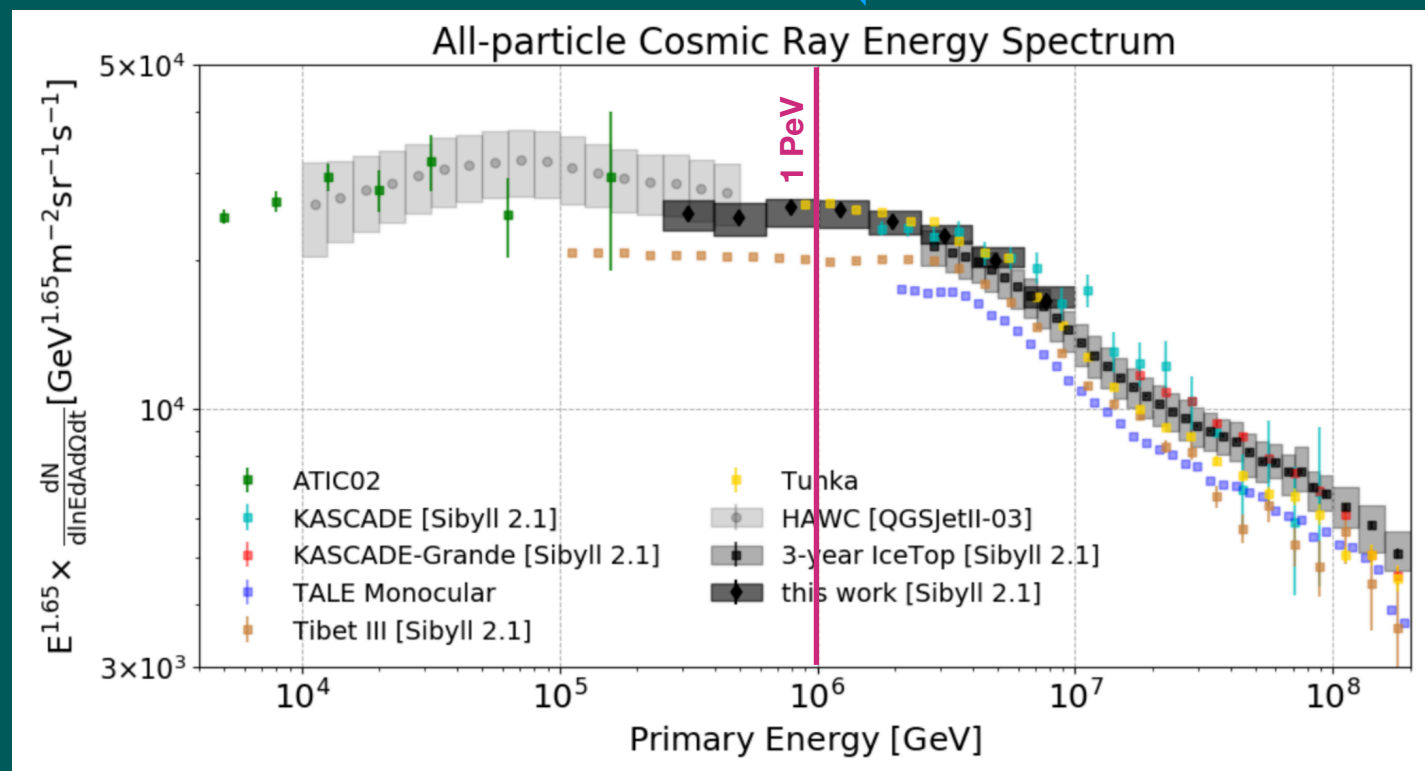
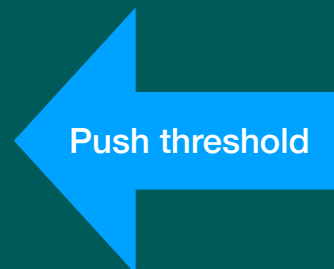


Result: Energy Spectrum



Hitoshi Oshima's talk from this meeting
Measurement of the cosmic-ray energy
spectrum with the TALE detector in hybrid mode

Meanwhile, ground-based experiments are pushing their thresholds lower, using “infill” arrays



*M. G. Aartsen et al. (IceCube Collaboration)
Cosmic Ray Spectrum from 250 TeV to 10 PeV Using IceTop
Physical Review D102 (2020) 122001*

- This field is craving — and is getting — *precision*.



- Precision allows modelers to do what they do best.
- Hard work goes into understanding systematic errors in these kinds of measurements, and it is an ongoing challenge.

BACKUP