

# Discussion: Particle Physics in the Context of GCOS

GCOS Workshop 2022

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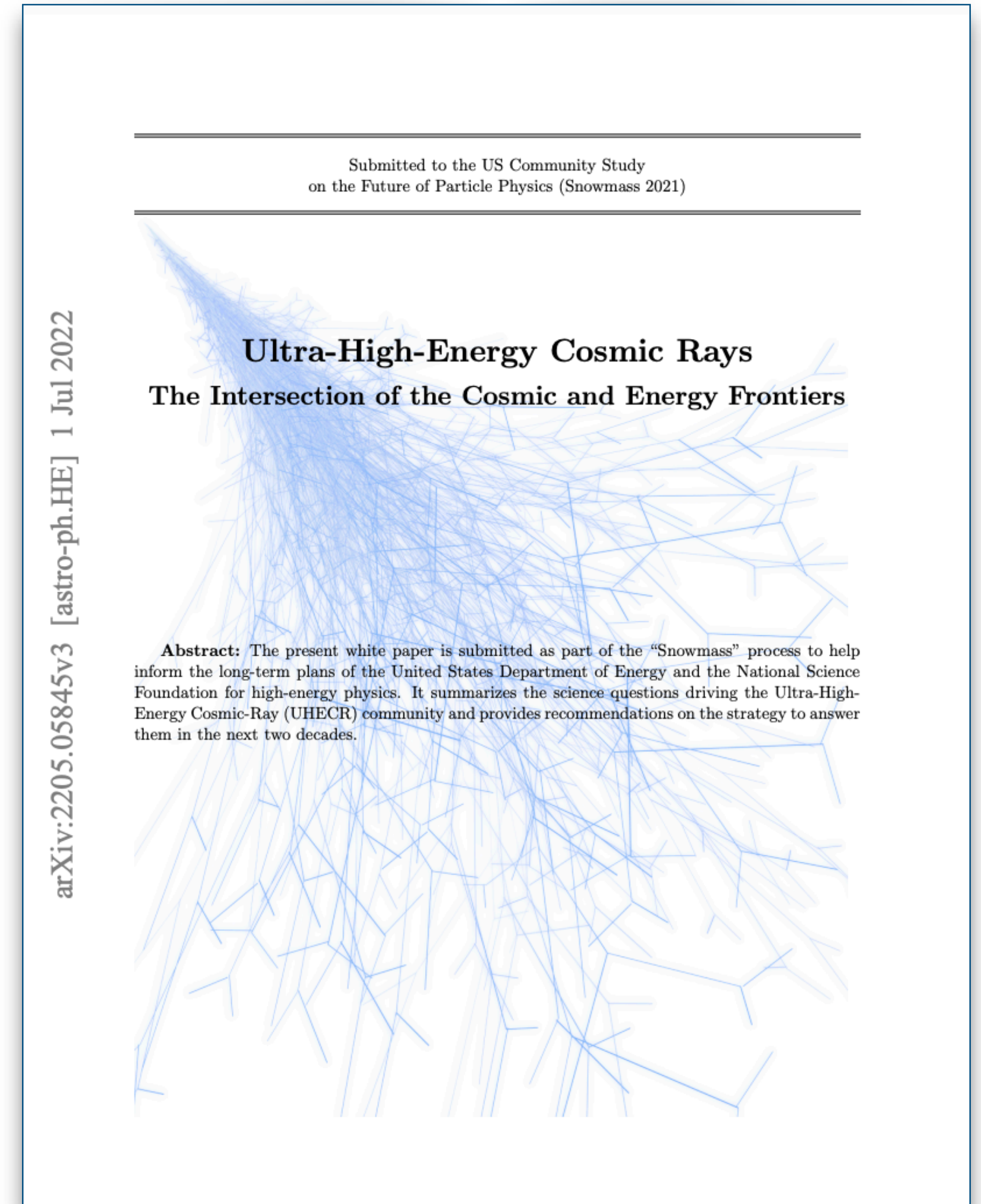


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# Outline

- ▶ Particle Physics with Cosmic Rays
- ▶ Overview: Current Status
- ▶ The Next 10 Years
- ▶ Particle Physics with GCOS
- ▶ Discussion





# Snowmass 2022 White Paper

► This talk: summary & discussion of the Snowmass White Paper's particle physics sections

[arXiv:2205.05845]

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# Particle Physics with Cosmic Rays

▶ EAS measurements probe particle physics at the highest energies

▶ Example: proton-air cross-section

▶ Complementary to collider measurements:

▶ EAS particles: Nuclei, mesons, ...

▶ CM energies: GeV to hundreds of TeV

▶ Forward direction

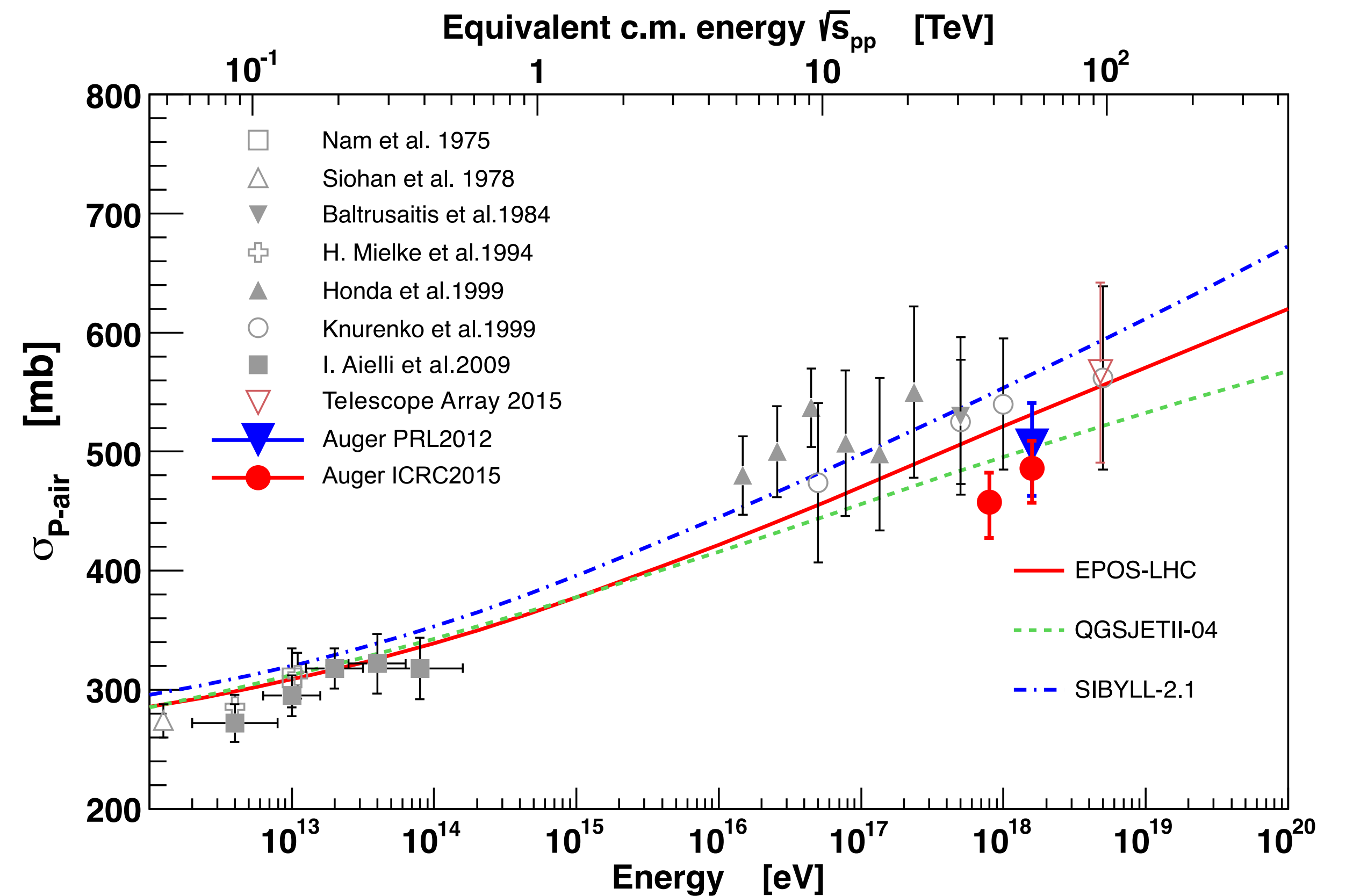
▶ Non-perturbative regime

▶ Crisis for high-energy physics?

▶ No new particles found at LHC

▶ Nature of Dark Matter is still unknown

▶ Opportunity for cosmic ray physics?



[R. Ulrich (Pierre Auger Collaboration), PoS(ICRC2015)401 (2016)]



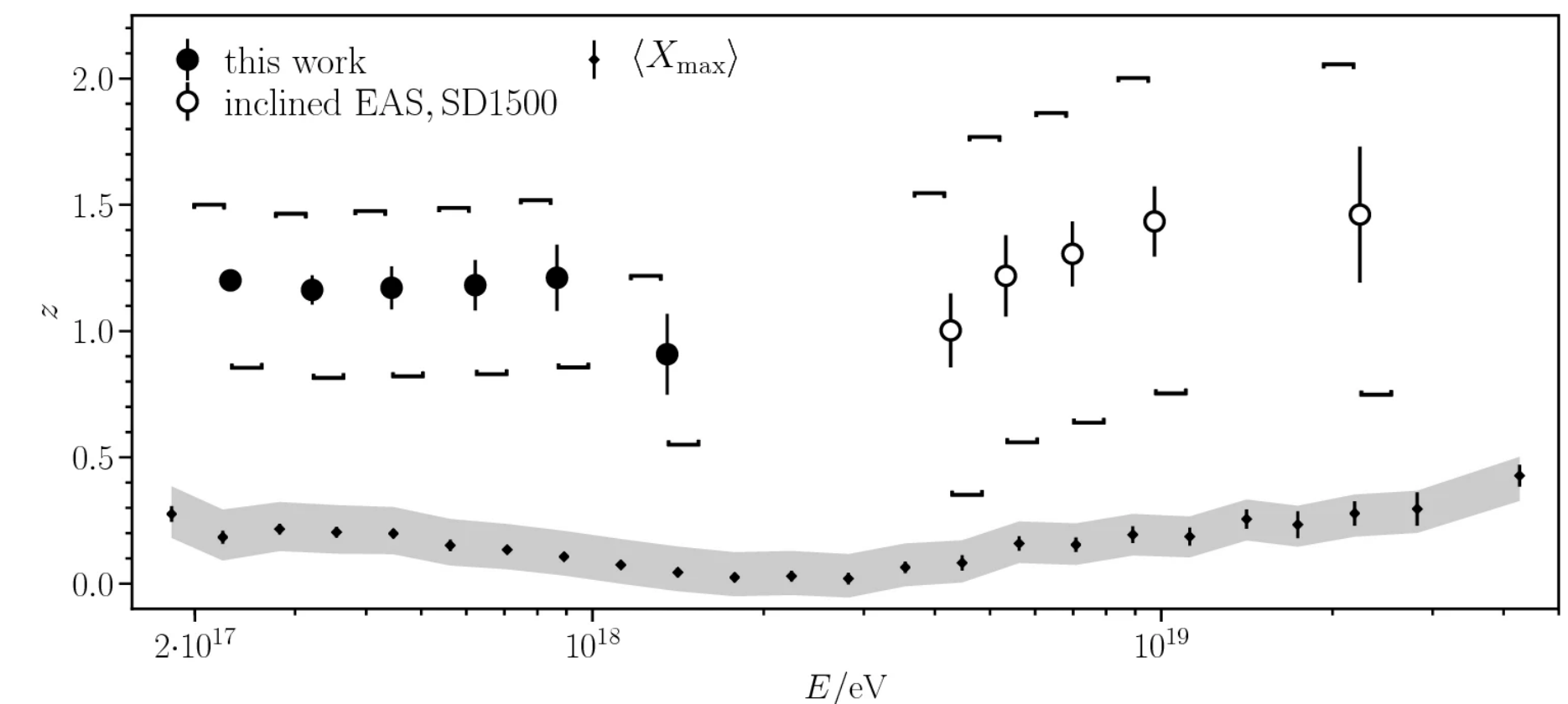
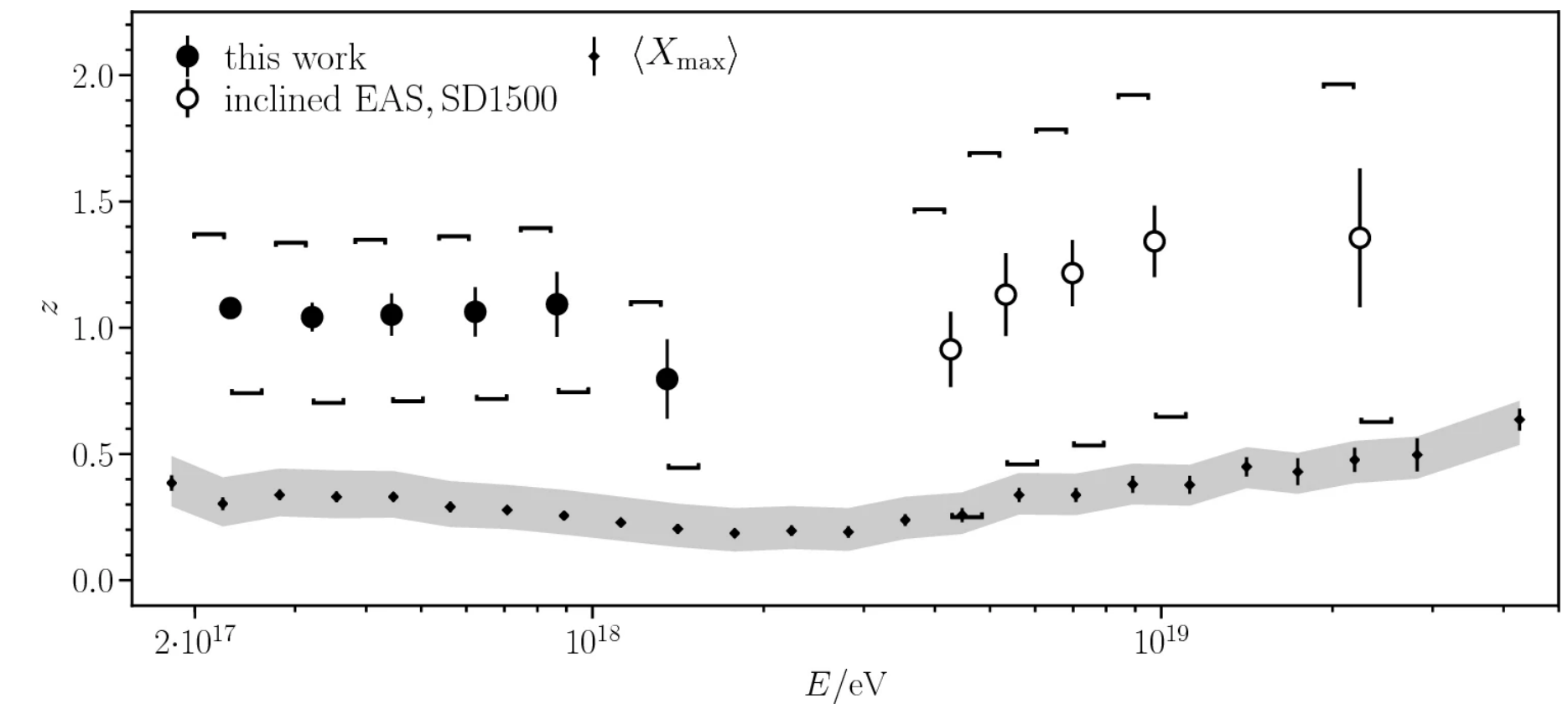
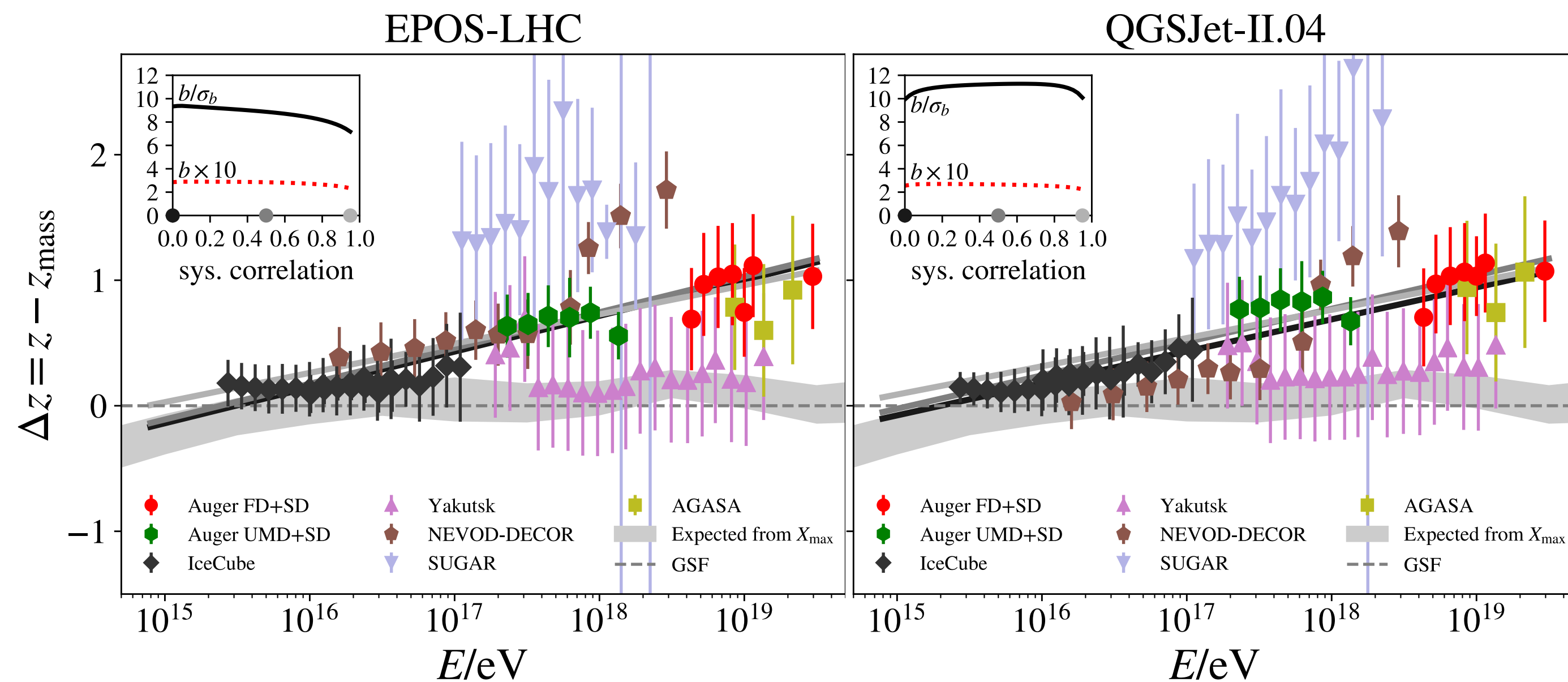
# What is the current status of the field?

- ▶ Significant discrepancies in the number of muons in EAS observed between MC and data for all recent hadronic interaction models!

- ▶ z-value:

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,p})}{\ln(\rho_{\mu,Fe}) - \ln(\rho_{\mu,p})}$$

$z = 0$ : proton ,  $z = 1$ : iron



[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. D91 (2015)]

[A. Aab et al. (Pierre Auger Collaboration), Eur. Phys. J. C 80 (2020)]

[D. Soldin et al. (WHISP), PoS(ICRC2021)349 (2021)]

# What is the current status of the field?

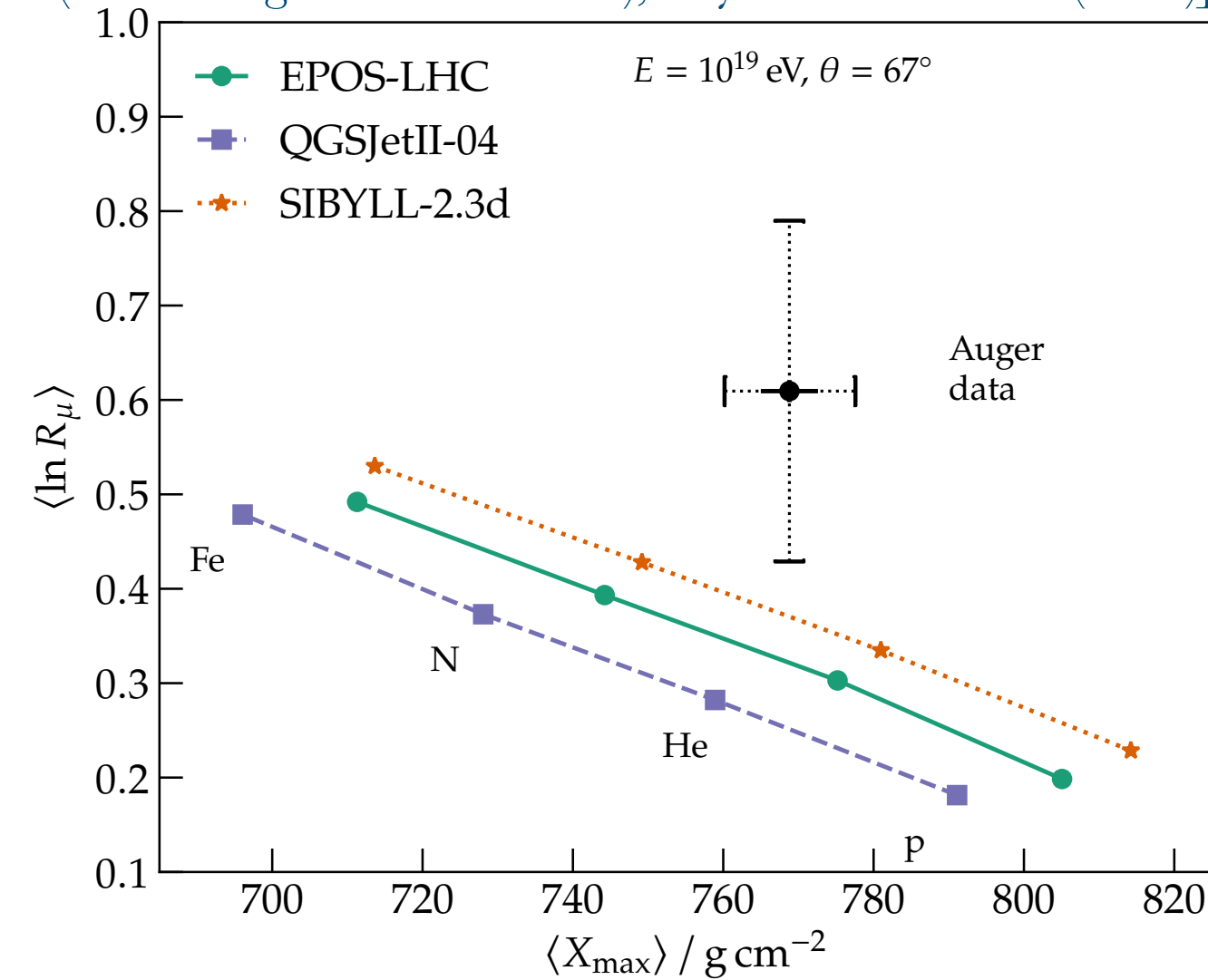
## ► Muon Puzzle:

- Up to  $\sim 30\%$  discrepancies in  $N_\mu$
- $N_\mu$  vs.  $X_{\max}$  and  $X_{\mu,\max}$  vs.  $X_{\max}$
- WHISP: excess towards high energies
  - slope in  $z - z_{\text{mass}}$  significant at  $\sim 8\sigma$
- Origin remains unknown!

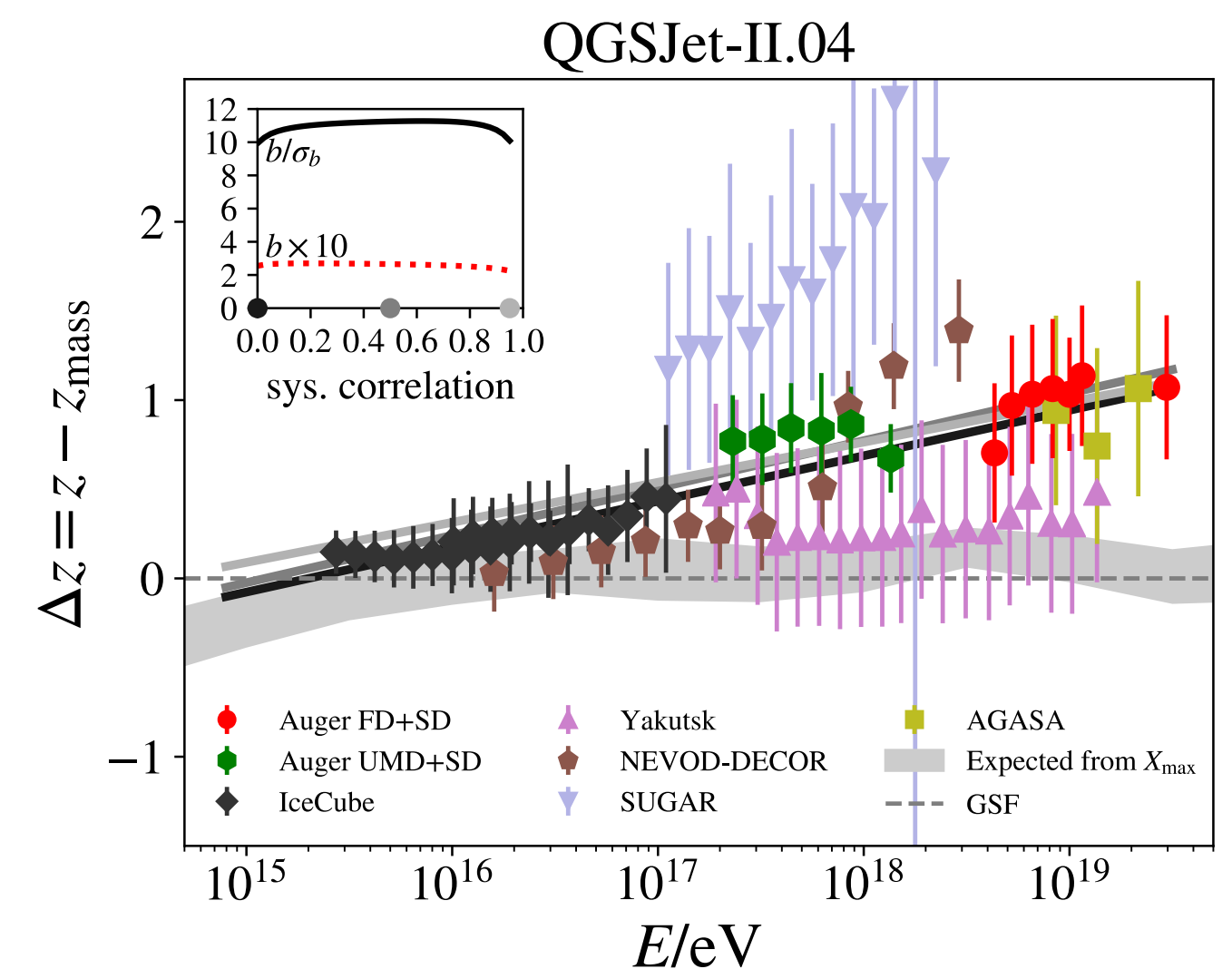
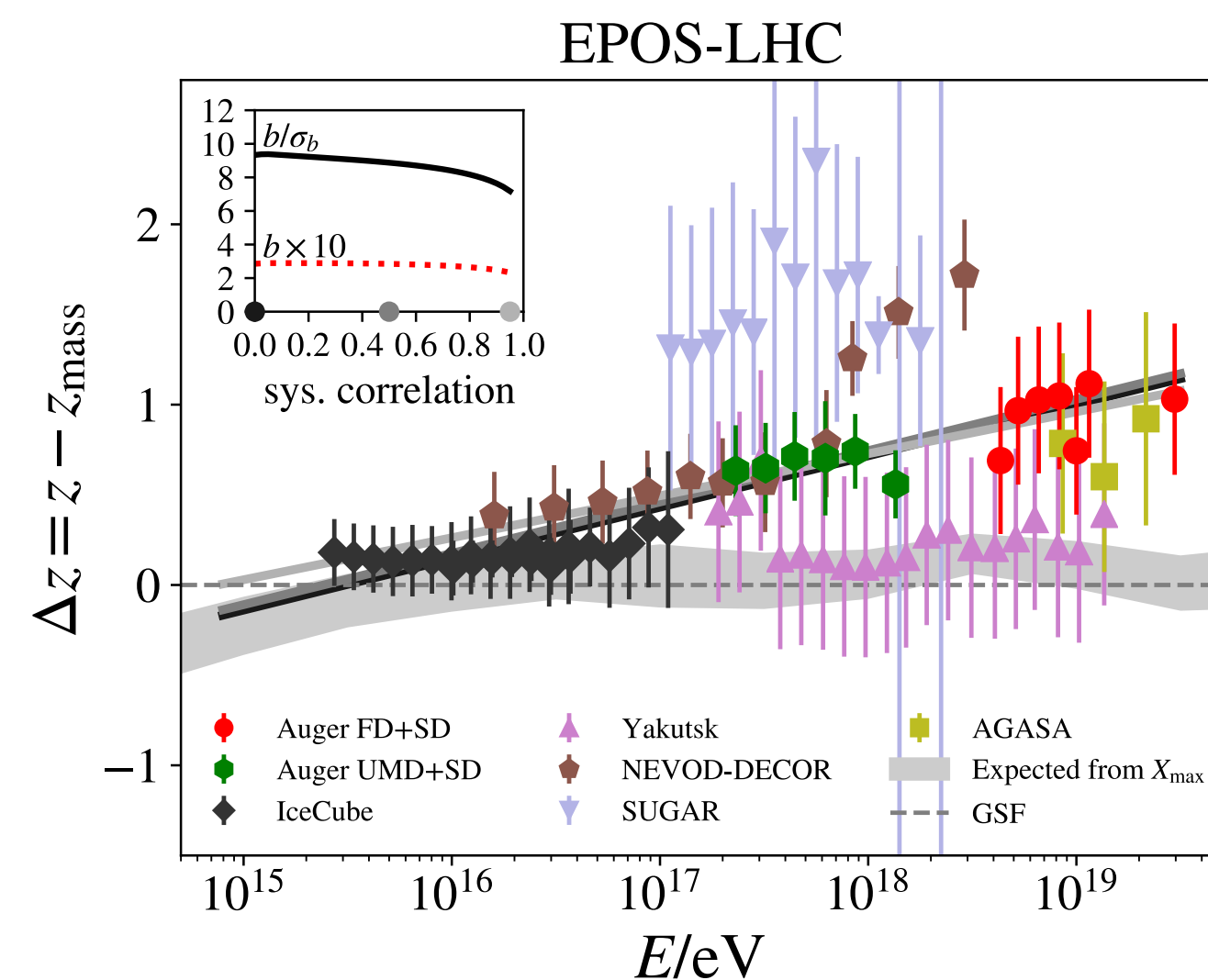
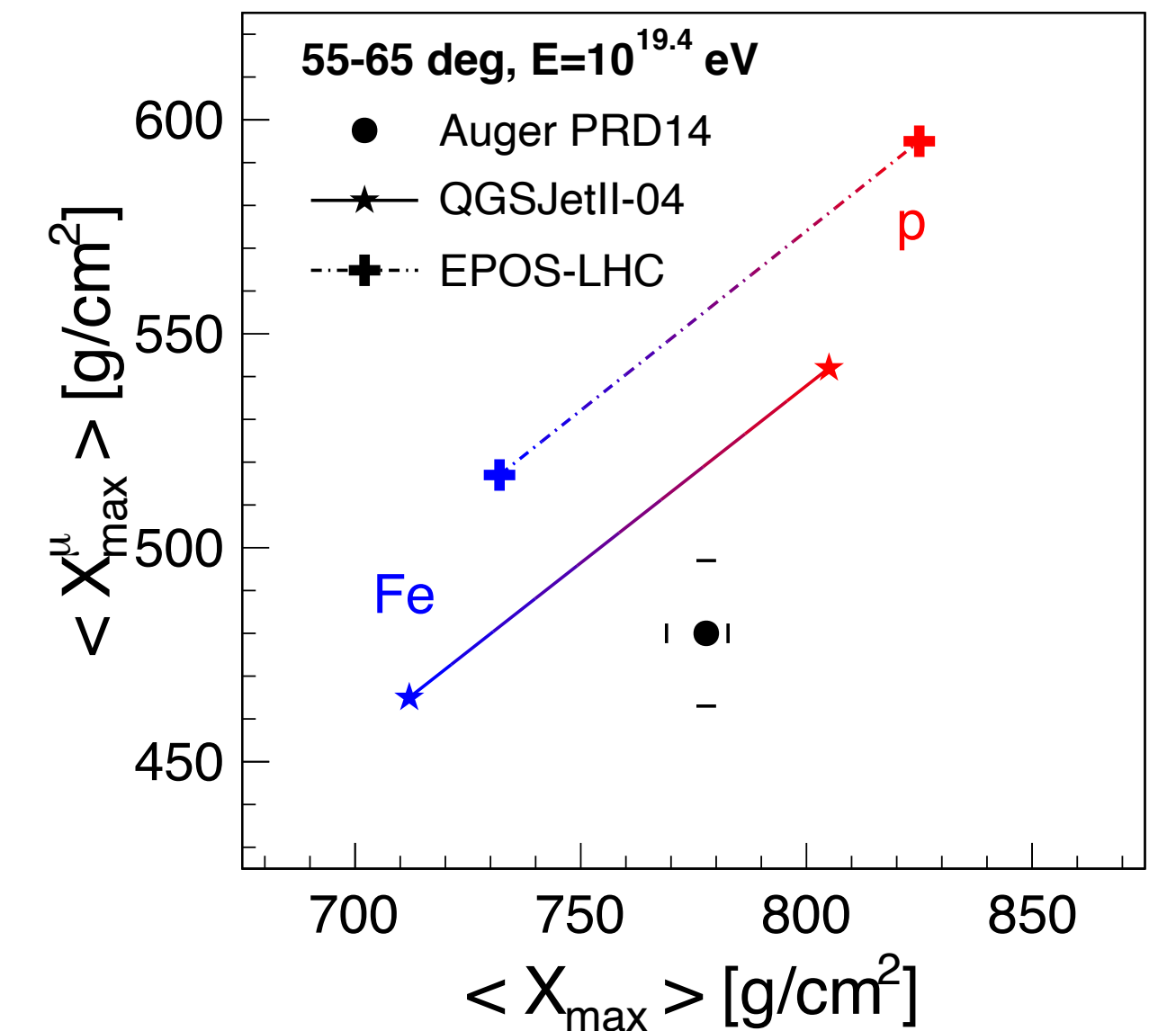
## ► Challenge for accelerators:

- Interactions of EAS particles
- CM energies: GeV to hundreds of TeV
- Forward direction

[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 126 (2021)]



[L. Cazon, PoS(ICRC2019)005 (2020)]



[D. Soldin et al. (WHISP), PoS(ICRC2021)349 (2021)]

# What is the current status of the field?

## ▶ Accelerator measurements:

▶ ALICE, CMS/CASTOR, LHCf, LHCb/SMOG, NA61/SHINE

▶ Inelastic cross-sections

▶ Hadron multiplicity

▶ Elasticity

▶ Hadron composition  
(ratio e.m. to hadr. energy flow)

▶ Different

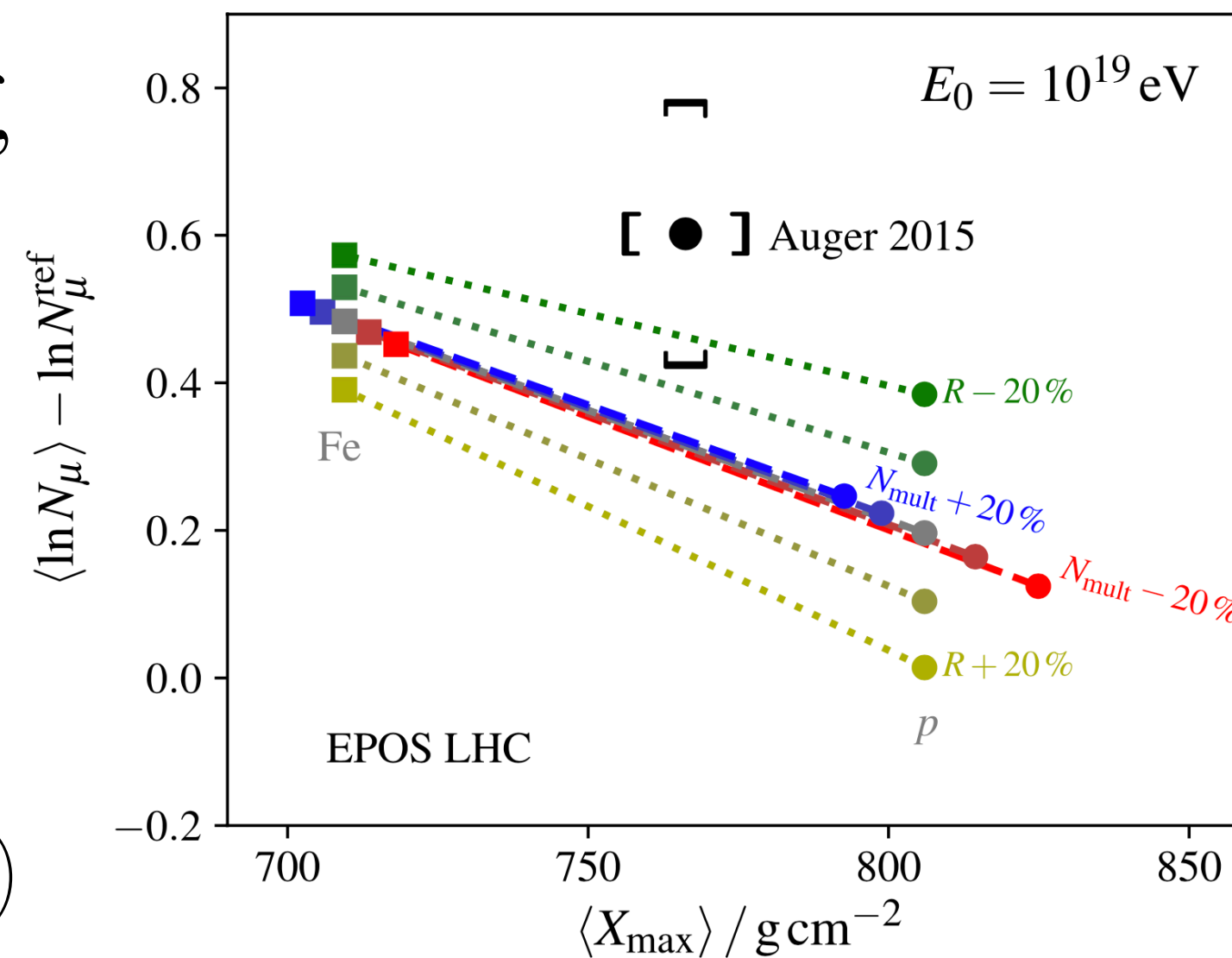
▶ energies

▶ rapidity ranges

▶ particle types

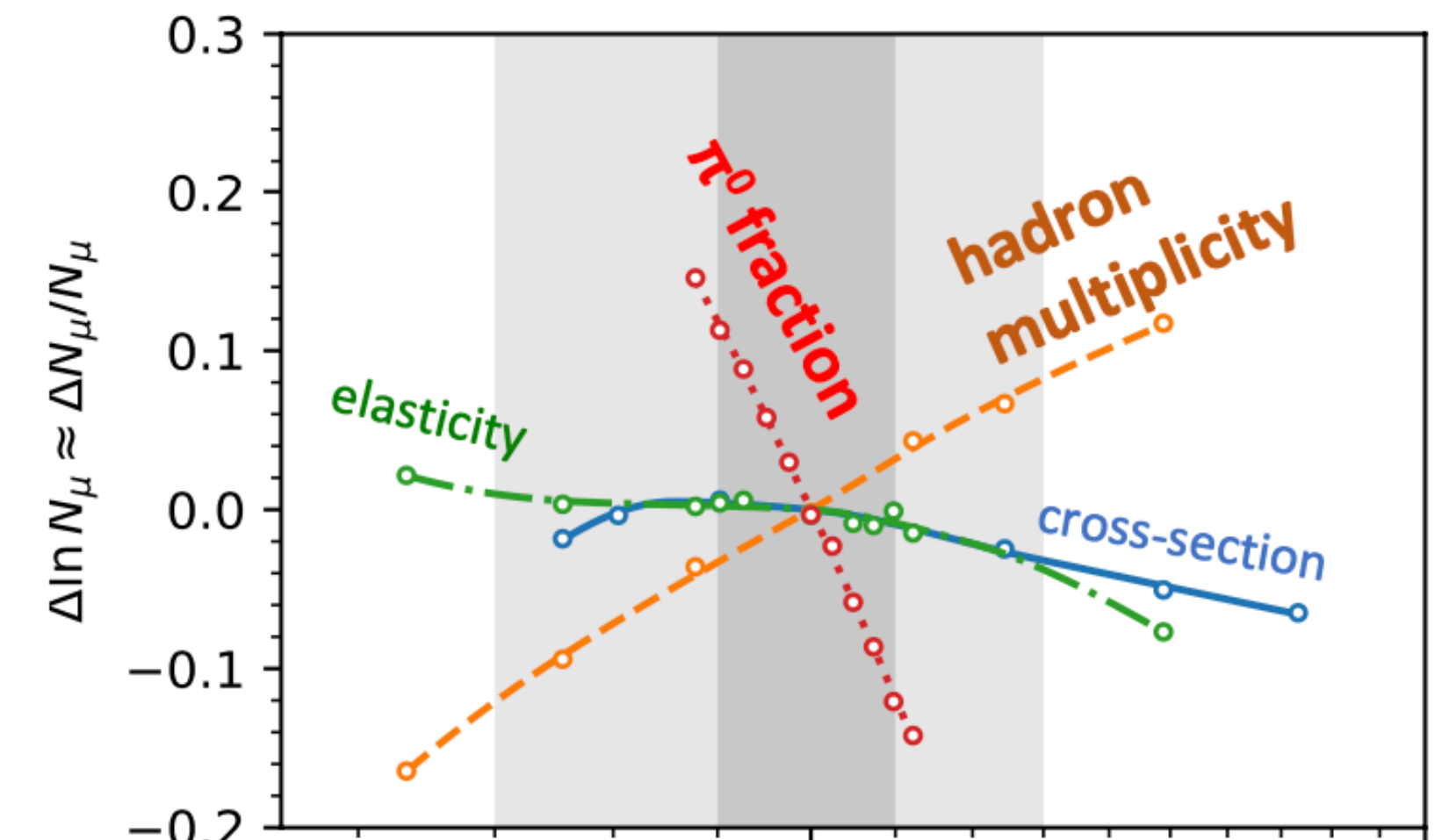
▶ EAS data needed!

[S. Baur et al., arXiv:1902.09265 (2019)]



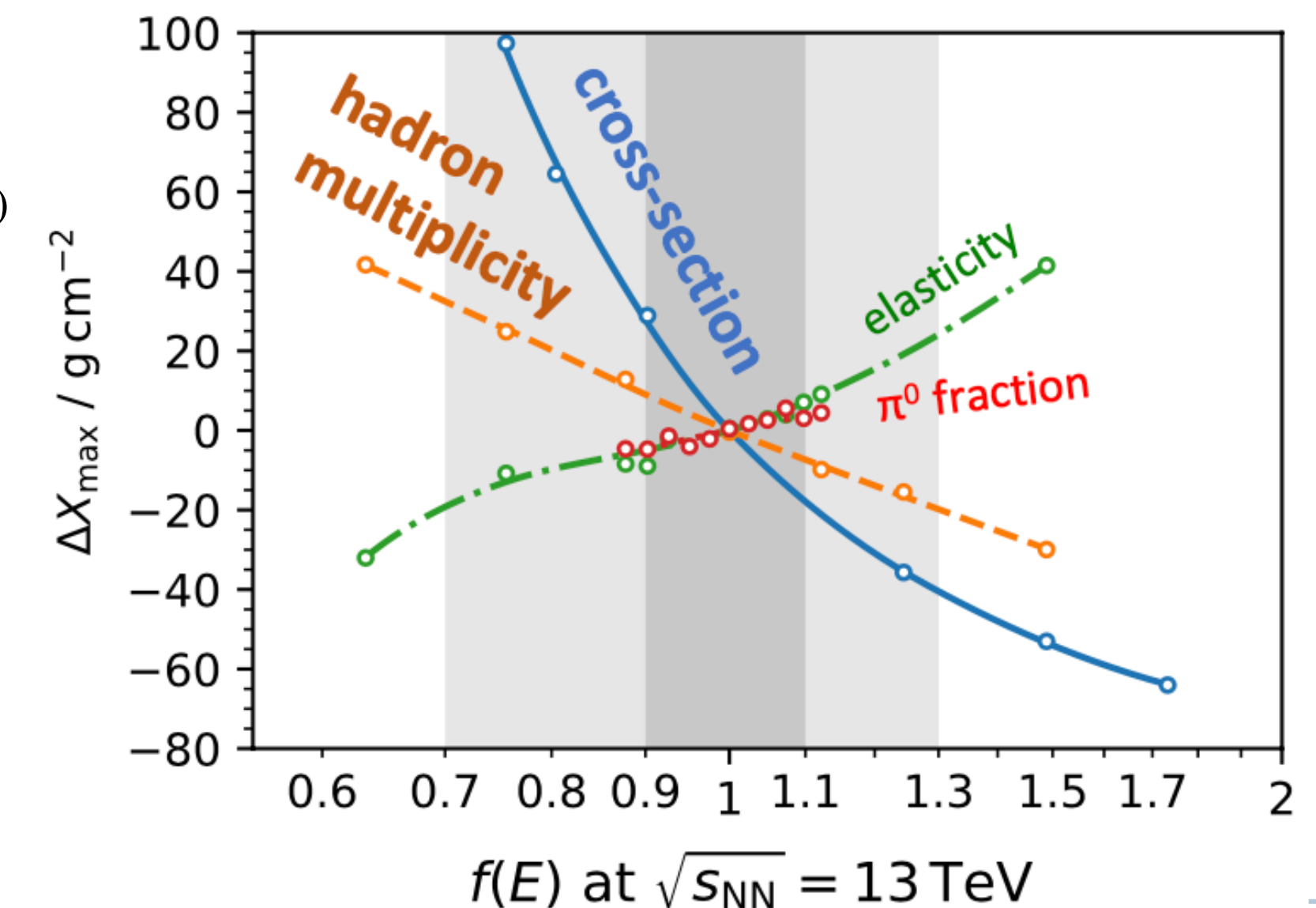
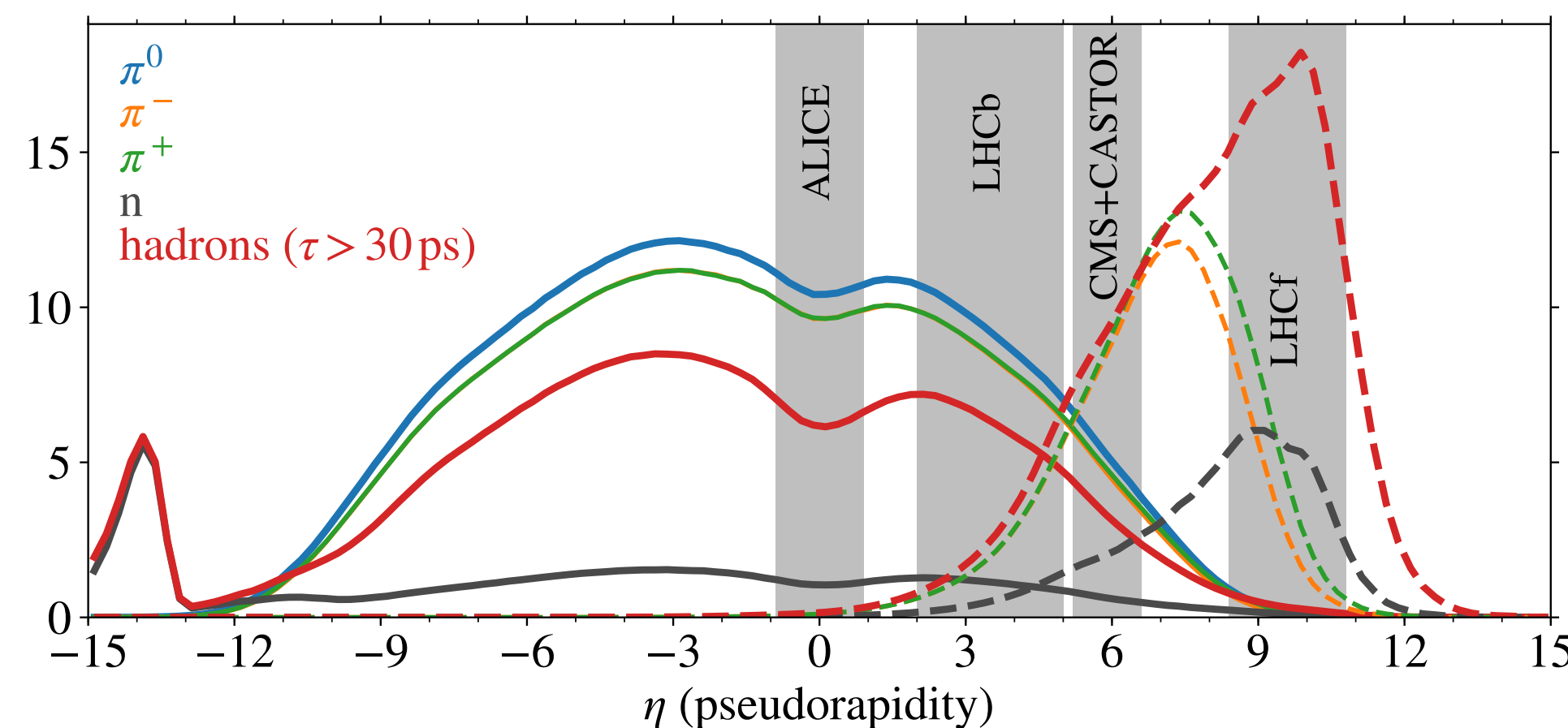
[R. Ulrich, R. Engel, M. Unger, Phys. Rev. D 83 (2011)]

CONEX, SIBYLL-2.1 p @  $10^{19.5} \text{ eV}$



[J. Albrecht et al., Astrophys.Space Sci. 367 (2022)]

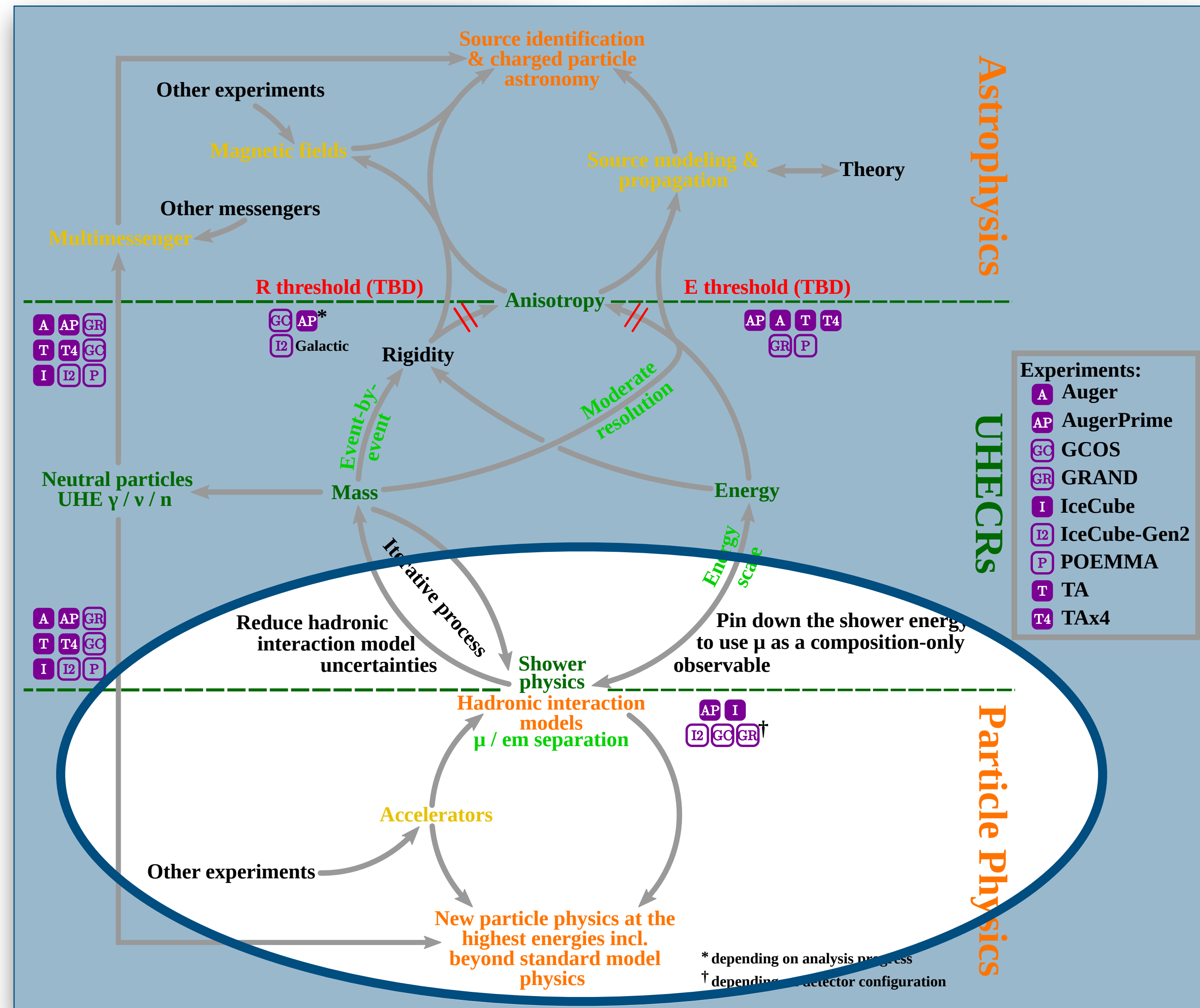
EPOS-LHC: pO 10 TeV —  $N_{\text{inel}}^{-1} dn/d\eta$  ----  $d(\sum E_{\text{lab}}^{0.93})/d\eta$  (a.u.)





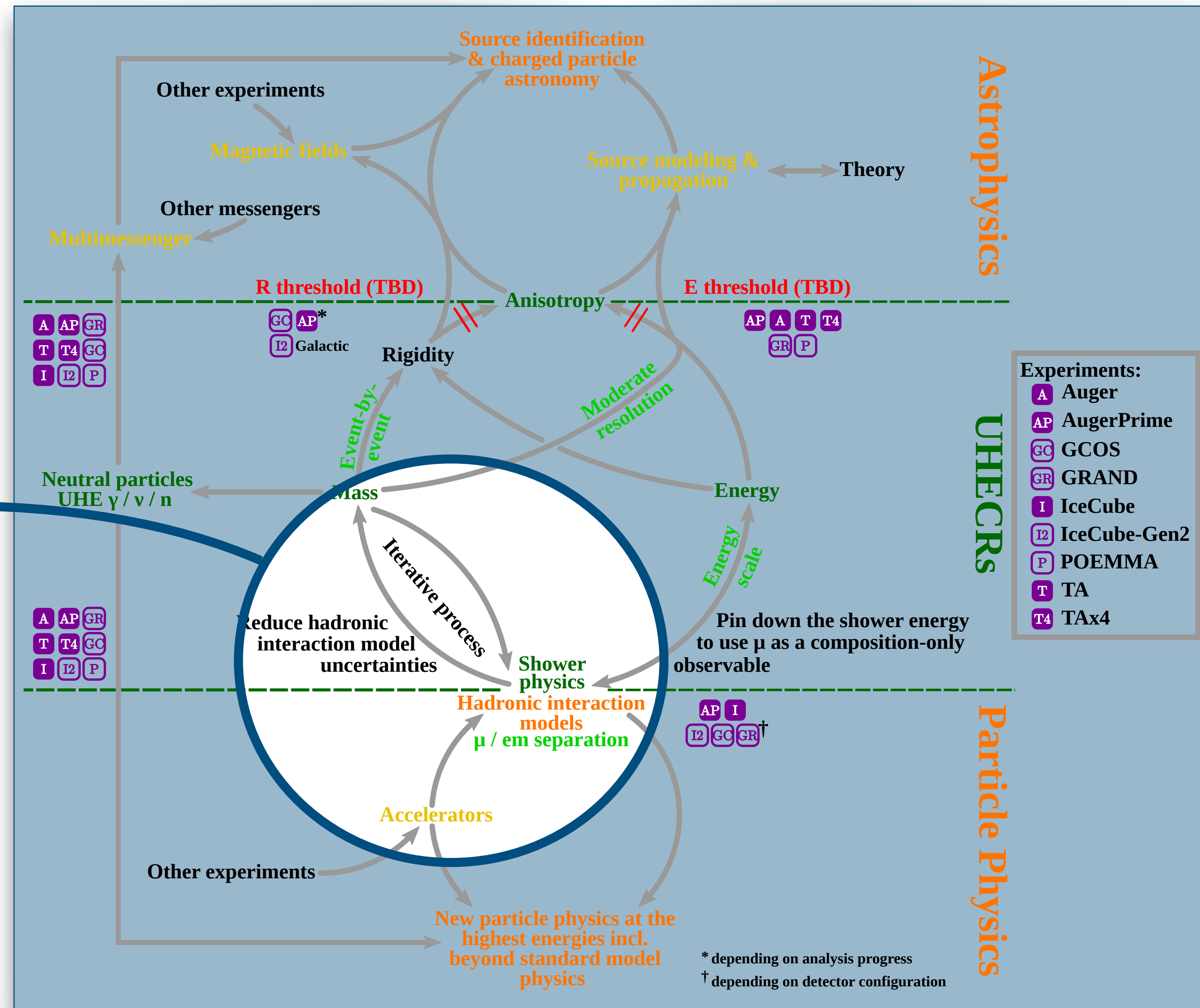
# Where are we going to be 10 years from now?

- ▶ Current uncertainties of muon measurements:  $\sim 15\text{-}20\%$
- ▶ Proton EAS: fluctuations of same order
- ▶ Iron EAS:  $\sim 5\%$  fluctuations
- ▶ Uncertainties of muon measurements will be reduced in the next decade:
  - ▶ New detectors
  - ▶ Measurements close to shower axis
  - ▶ Larger statistics
  - ▶ Improved calibration
  - ▶ New analysis techniques (ML)
- ▶ Smaller uncertainties, better resolution ( $\sim 10\text{-}15\%$ )



# Where are we going to be 10 years from now?

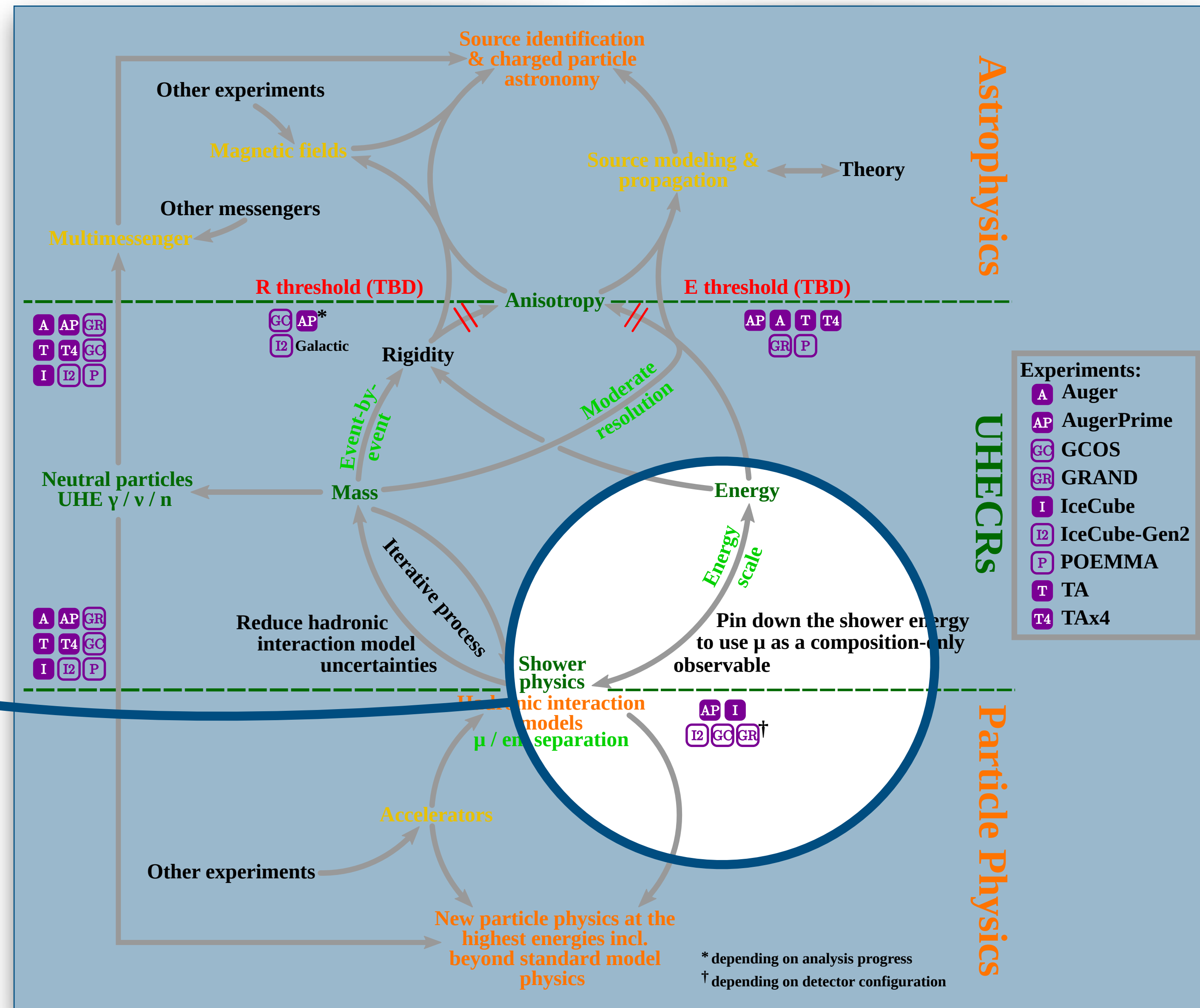
- ▶ Multi-hybrid measurements (Auger)!
  - ▶ EAS energy:  
Fluorescence Detectors (FD)
  - ▶ Muon number:  
Surface Detectors (SD)  
+ Scintillators (SSD)  
+ Muon Detectors (MD)
- ▶ Event-to-event muon distributions
- ▶ Studies of the observed discrepancies in a non-degenerated way
- ▶ Radio extension (RD): mass & energy, resolves bias from single technology
- ▶ Simultaneous measurement:  $X_{\max}$ ,  $X_{\mu, \max}$
- ▶ Zenith angle evolution: muon spectrum!
- ▶ Machine learning techniques





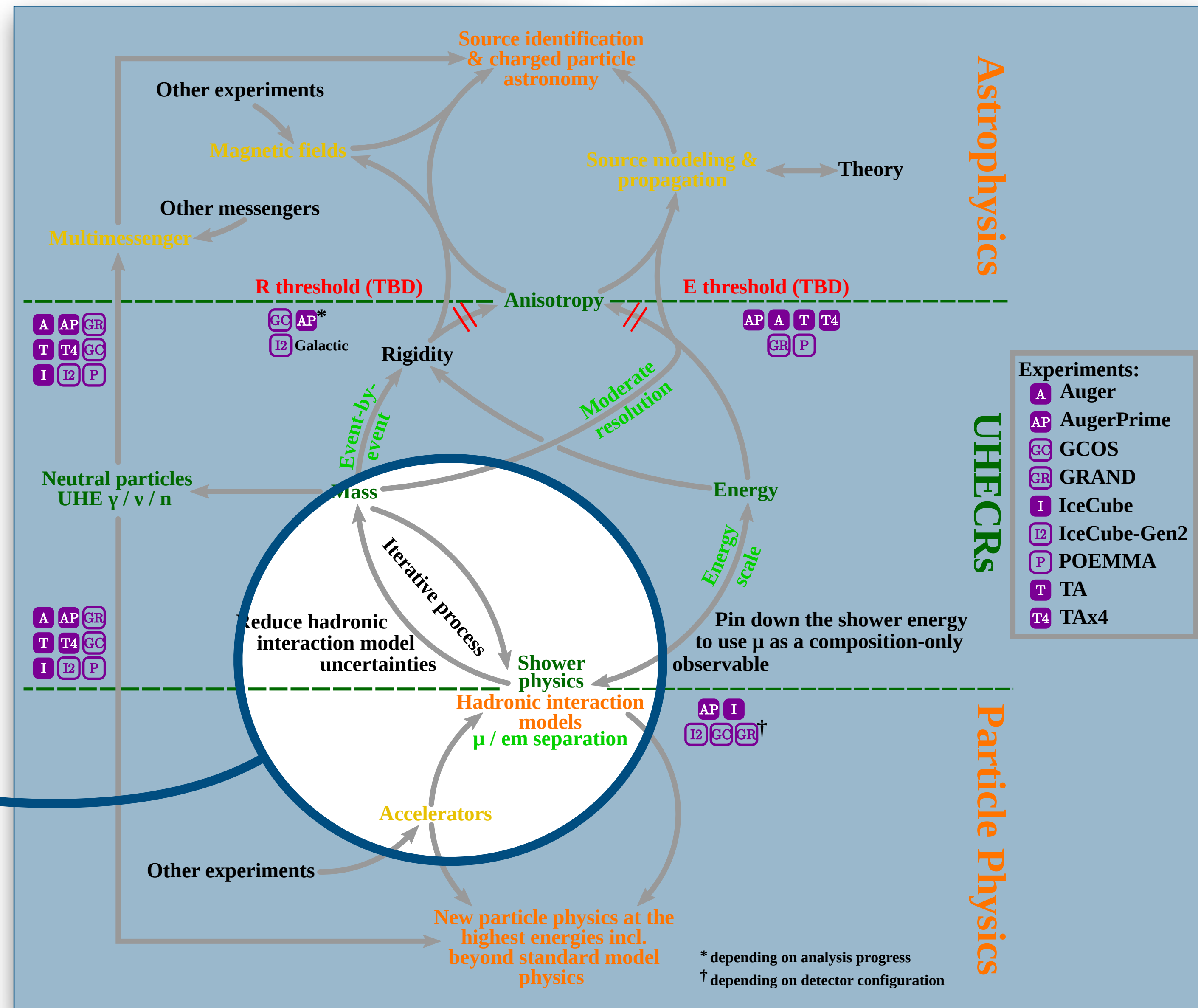
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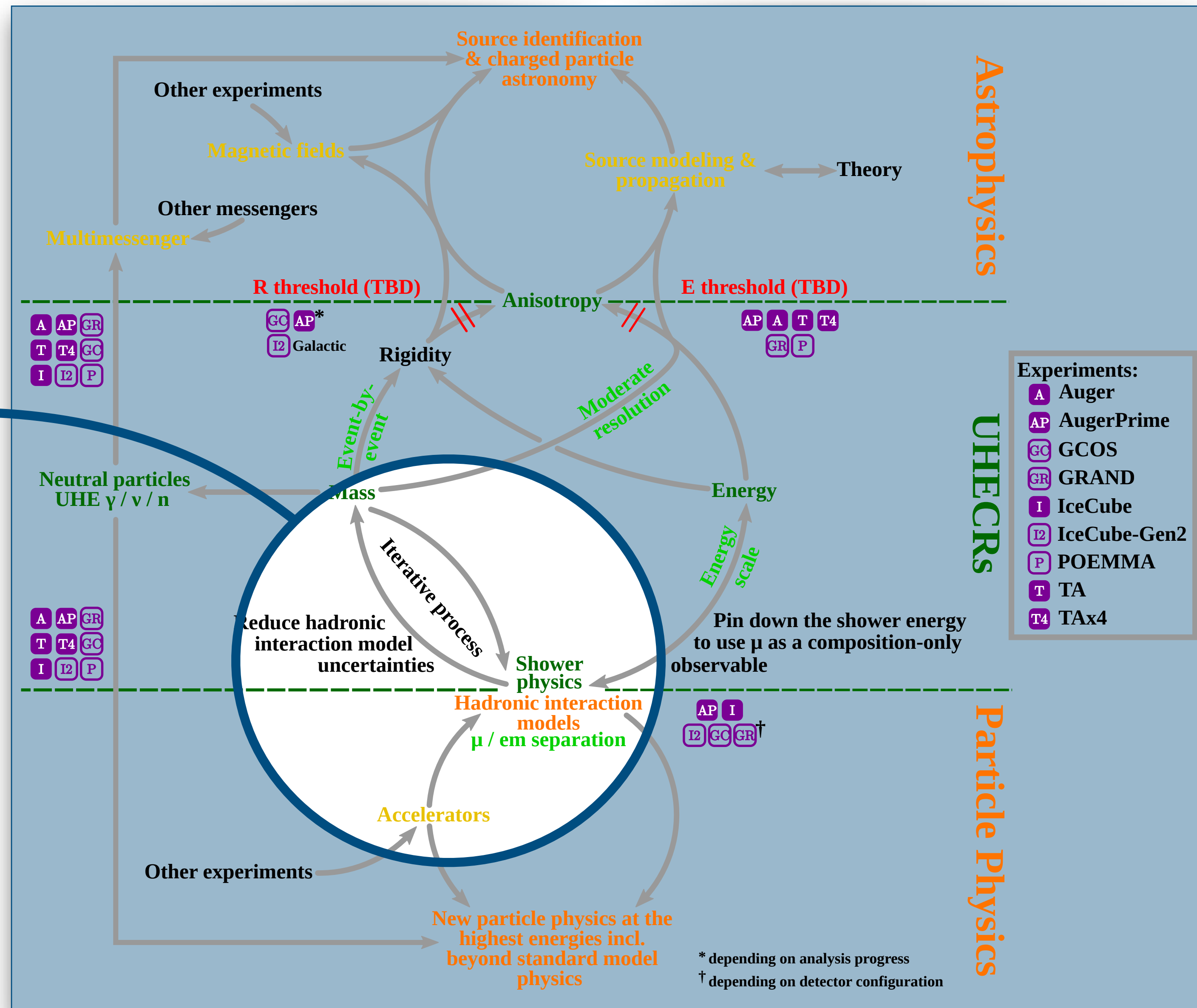
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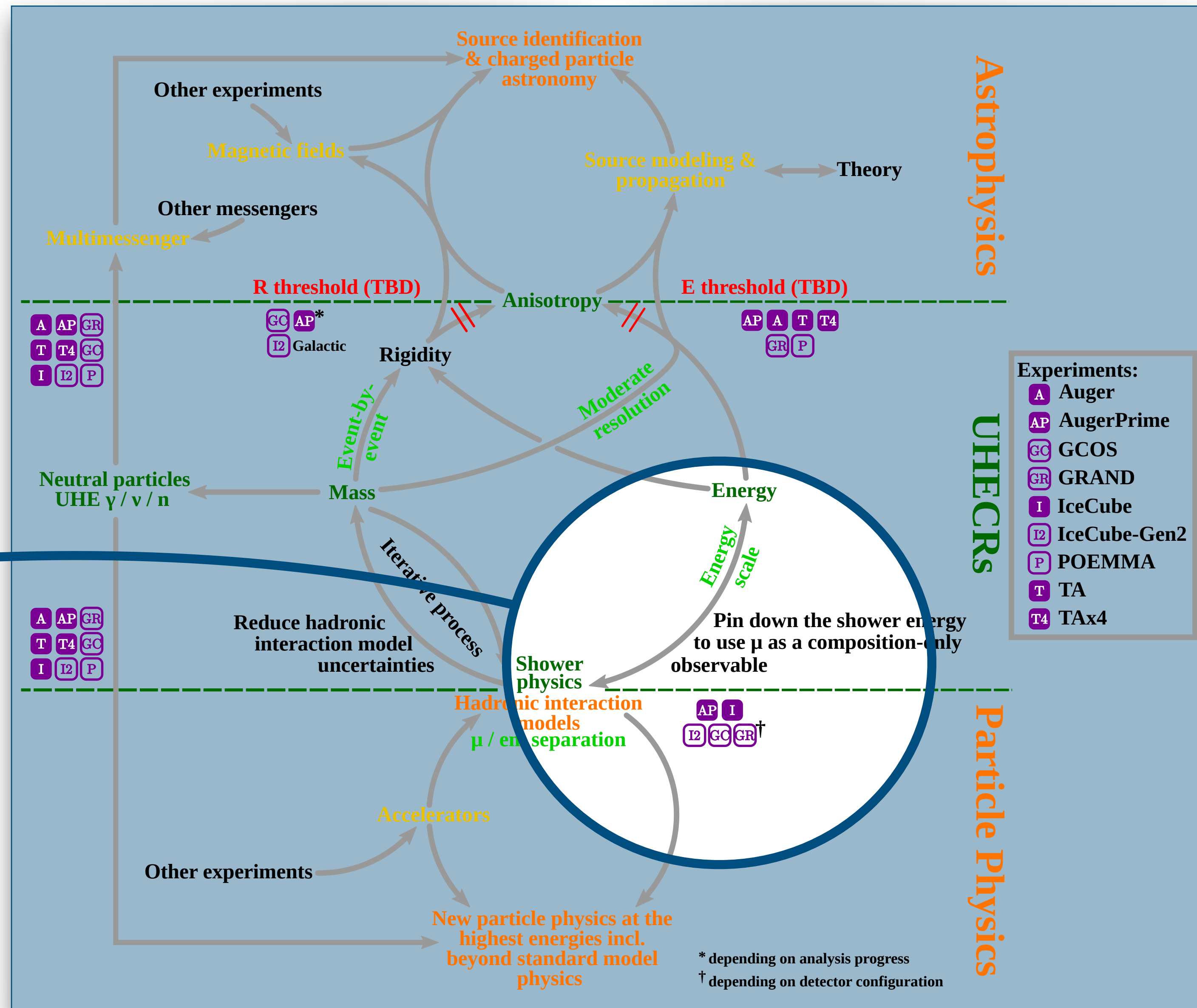
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- ▶ Multi-hybrid measurements (IceCube)!
  - ▶ EAS energy:  
Surface detectors (IceTop+upgrade)
  - ▶ Muon number:  
IceTop (GeV muons)  
+ in-ice array (TeV muons)
  - ▶ Two vastly different energy regimes
  - ▶ Spectral information!
- ▶ Radio extension (RD): mass & energy, resolves bias from single technology
- ▶ Measurement of prompt (PeV) muons?
- ▶ Seasonal muon flux as a probe for pion/kaon ratio (lower EAS energies)
- ▶ Machine learning techniques



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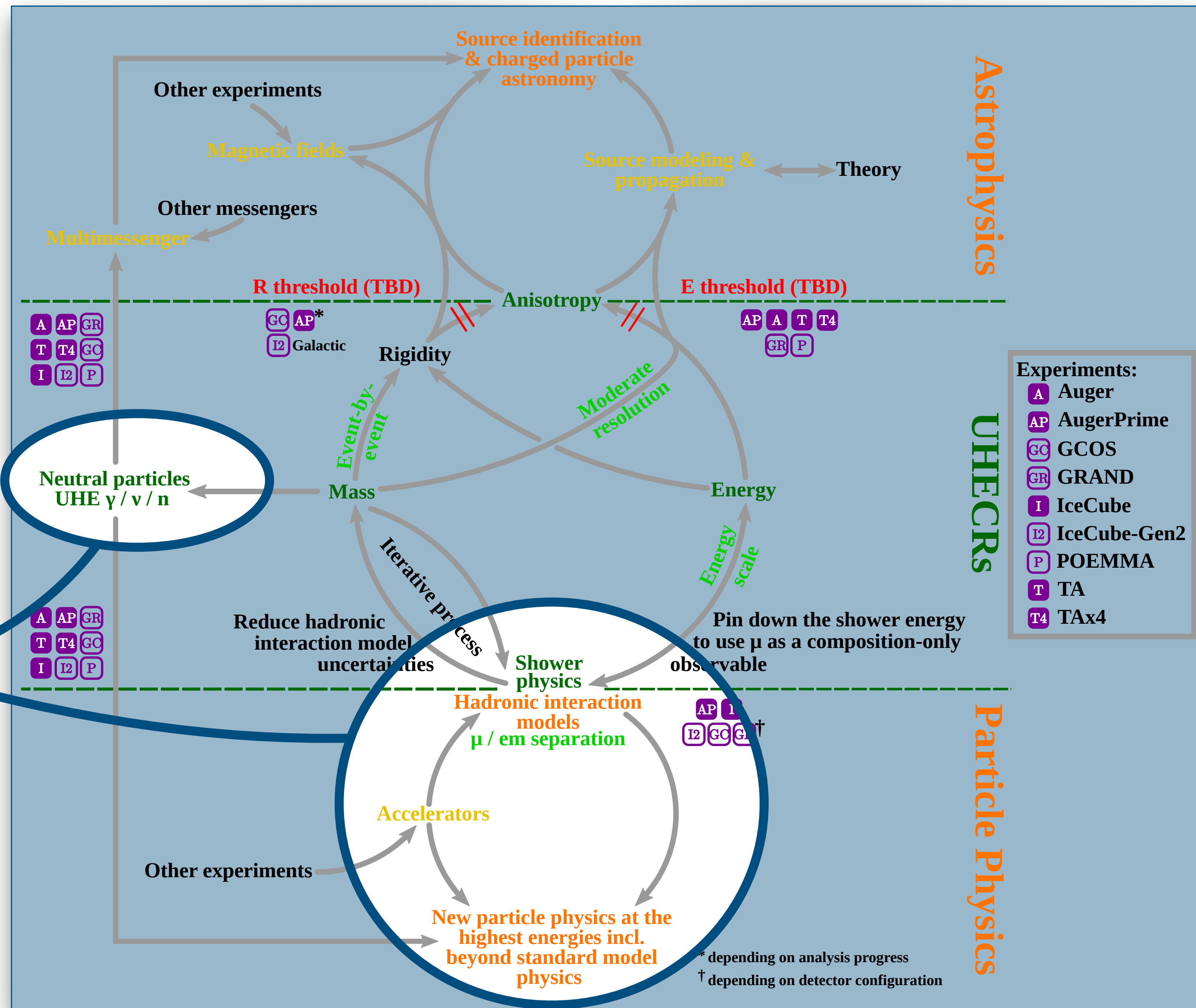
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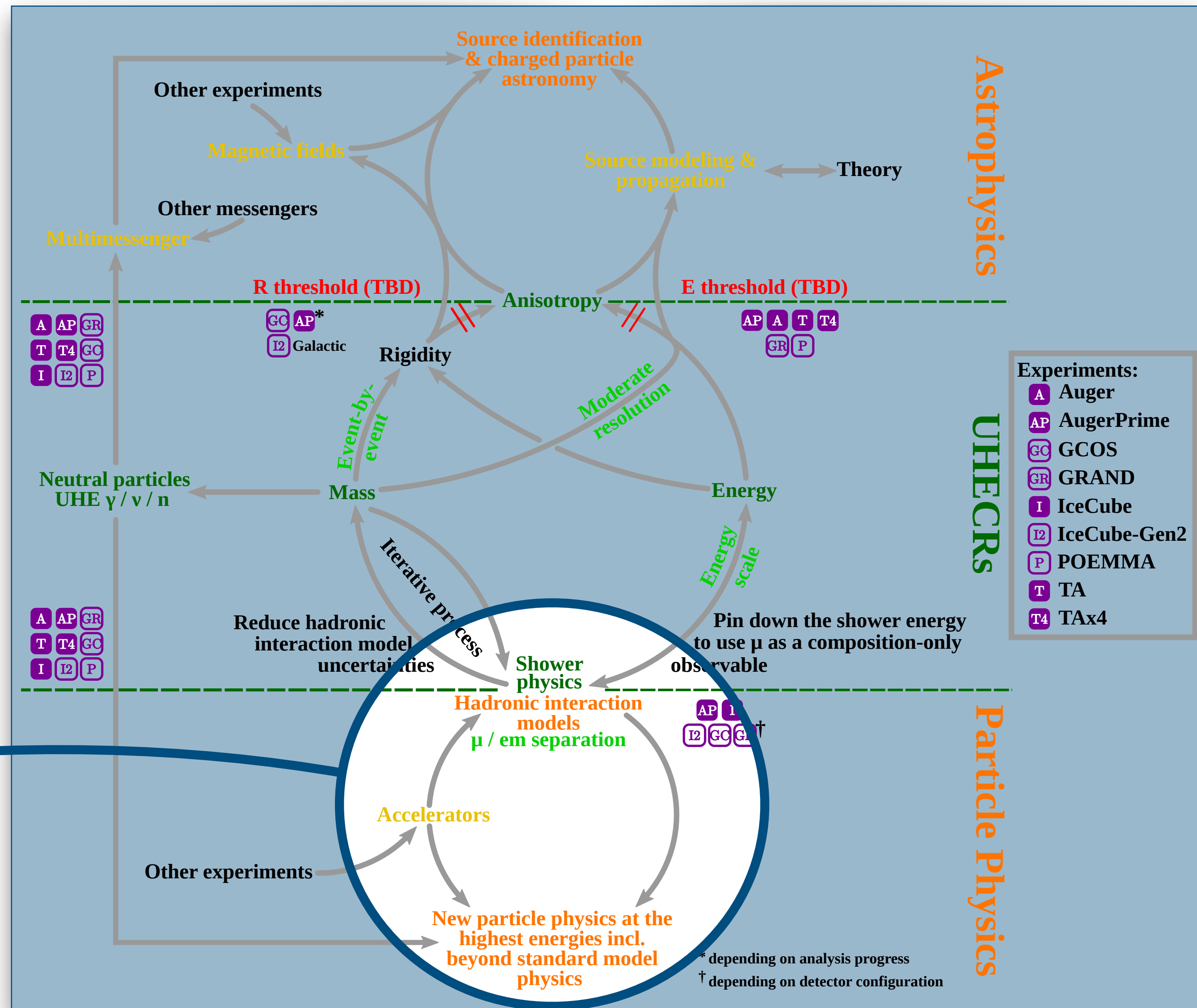
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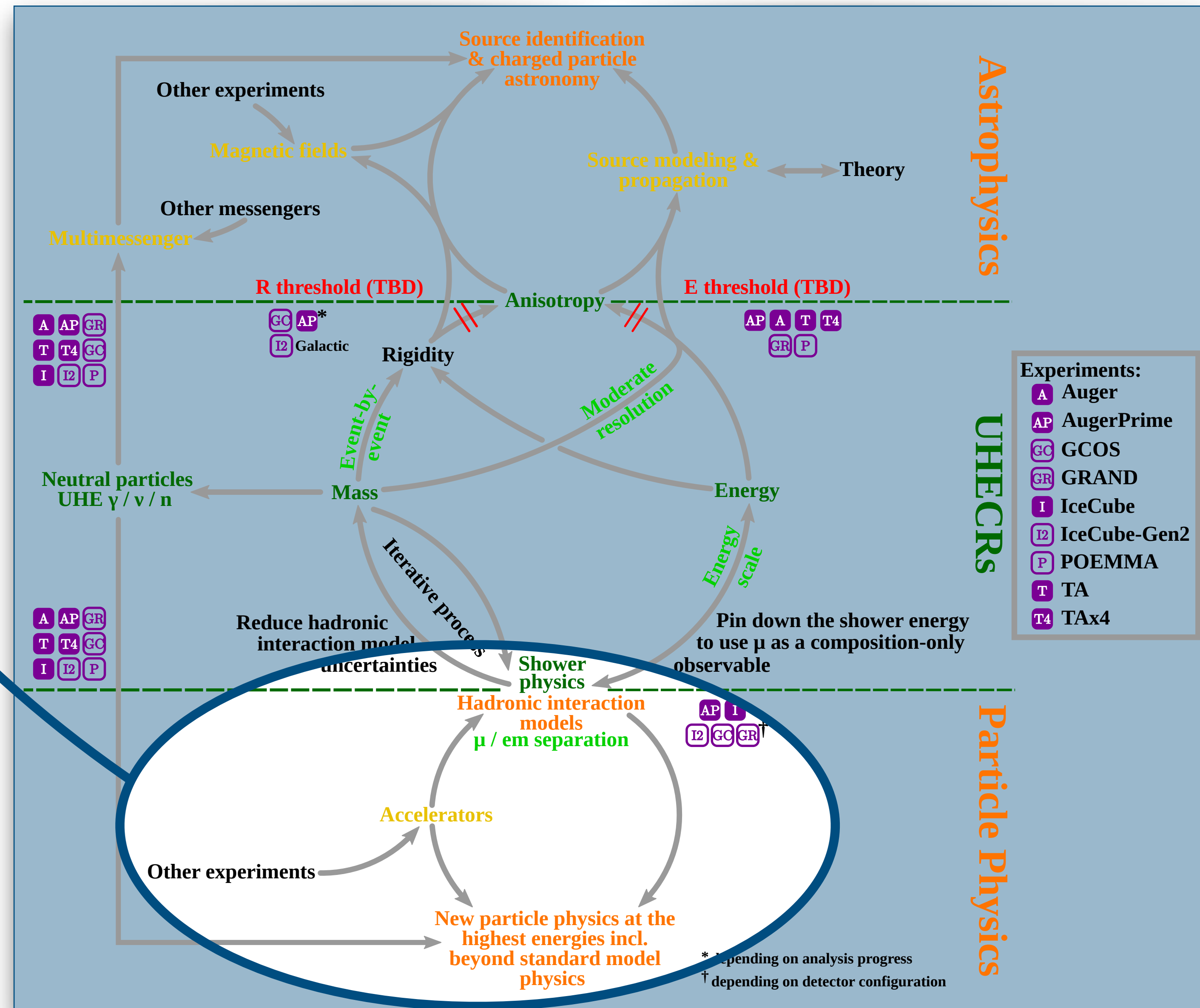
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# Where are we going to be 10 years from now?

- ▶ Accelerator measurements (LHC)!
- ▶ Proton-Oxygen collisions in Run 3 (2023)
- ▶ Importance for EAS physics
- ▶ High-Luminosity LHC!
- ▶ Forward experiments
- ▶ See later slides...



# Expectation for the next decade

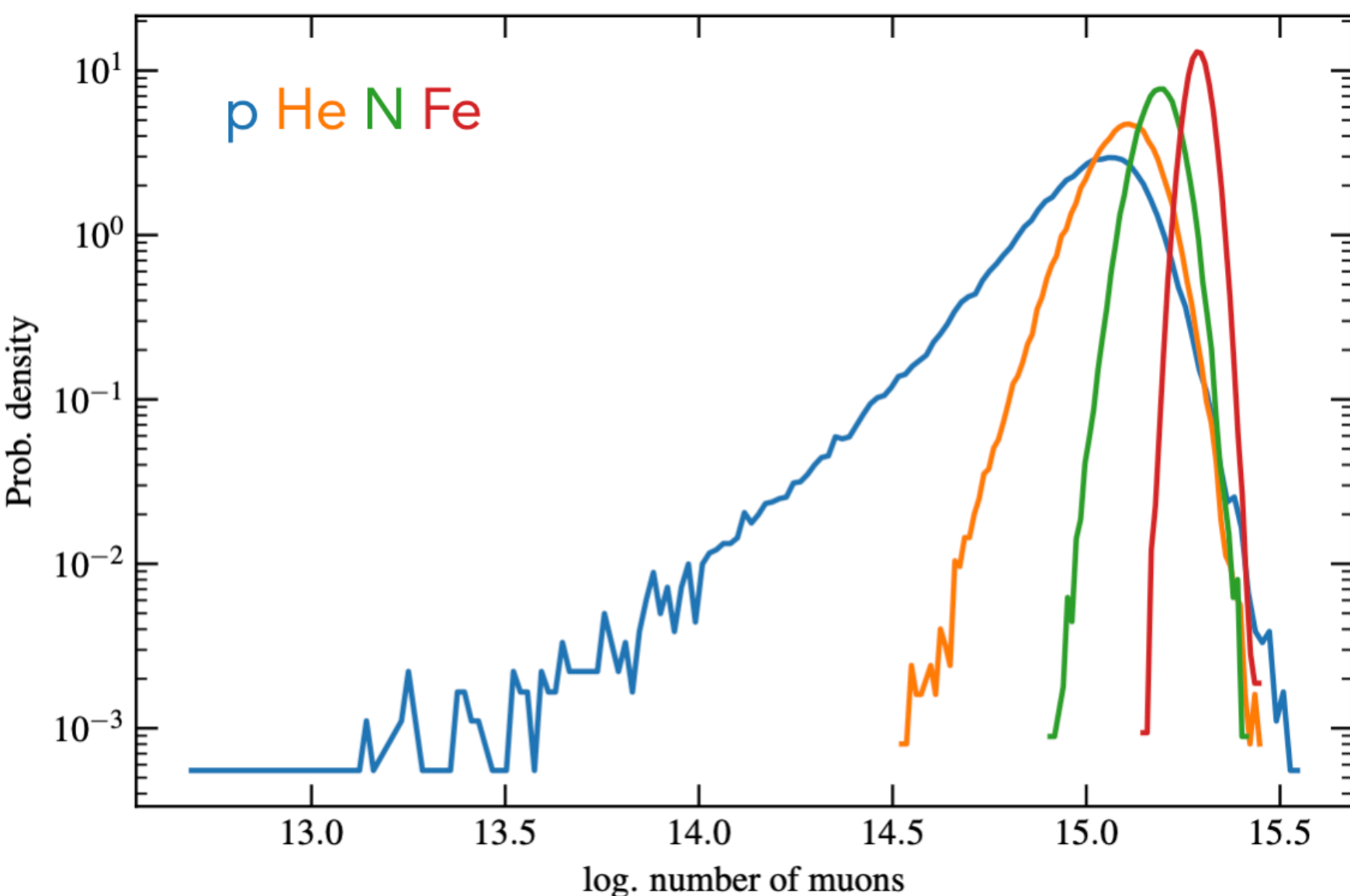
- ▶ Large variety of new high-precision data:
  - ▶ EAS detector upgrades will become fully operational, e.g. AugerPrime, IceCube upgrade
  - ▶ Precise muon measurements of multiple observables by multiple EAS experiments
  - ▶ New accelerator data, e.g. Run 3 at LHC (Oxygen data)
- ▶ Strong constraints on hadronic interaction models (muon enhancement models)
  - ▶ Precise characterization (solution?) of the Muon Puzzle within the next decade expected!



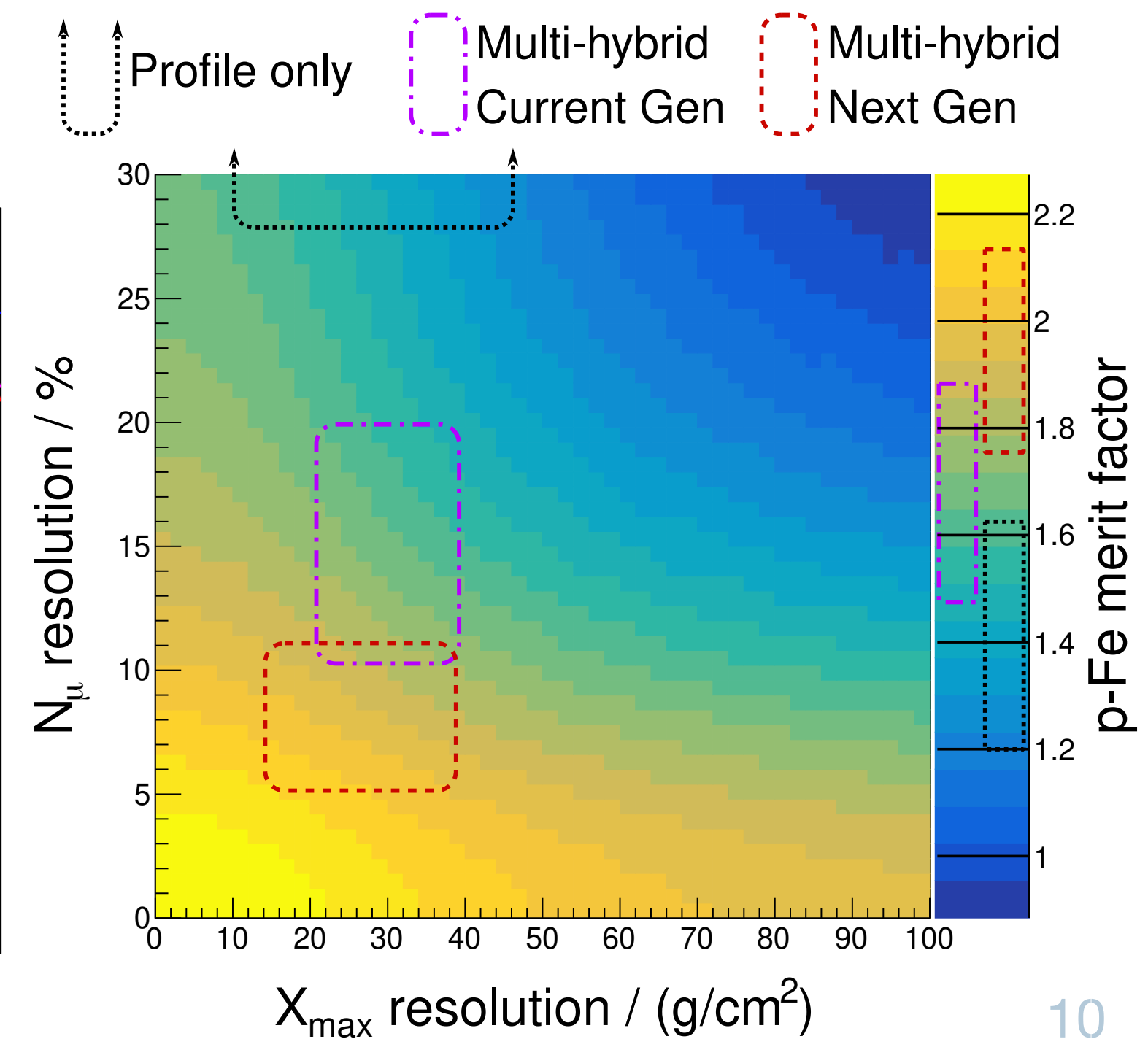
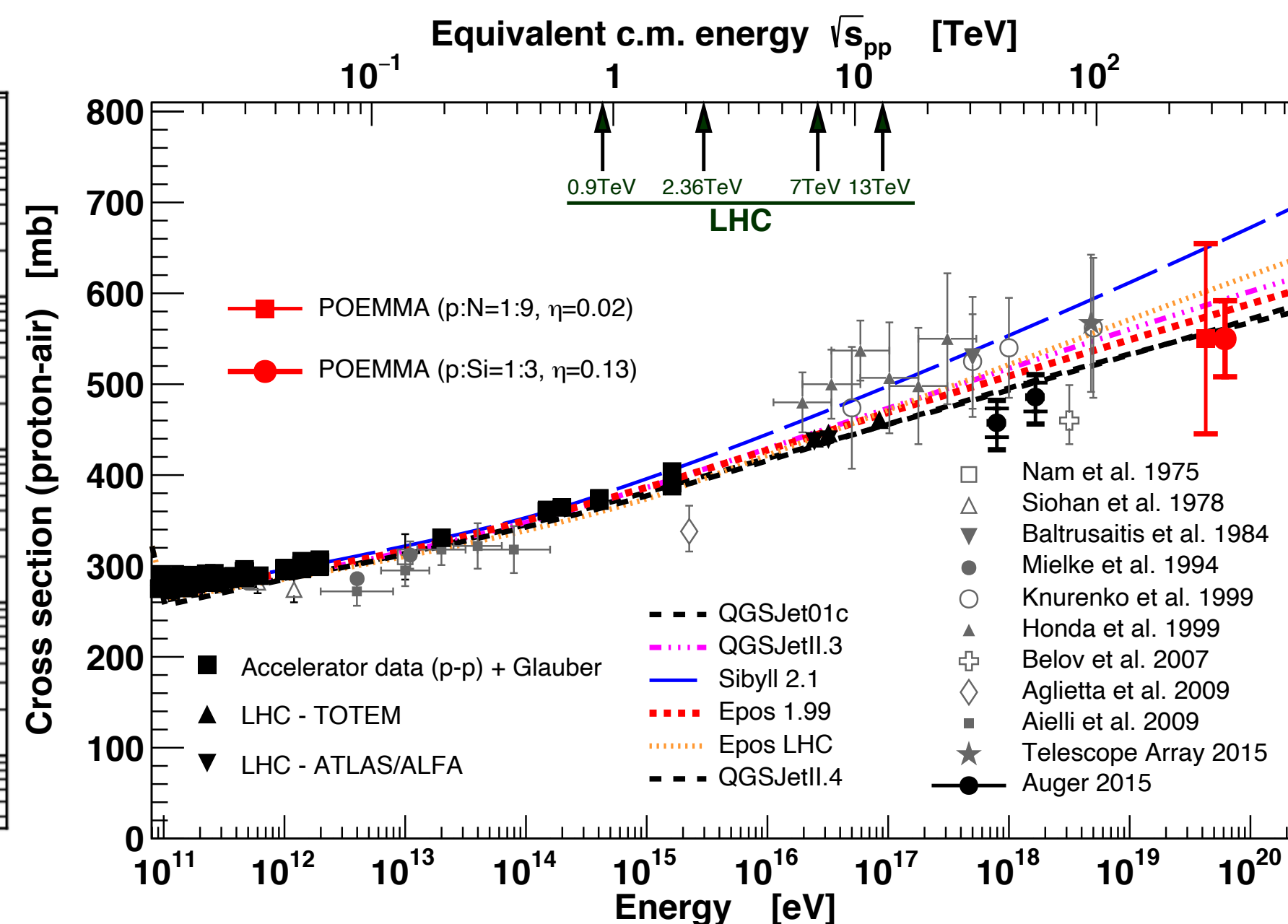
# Open questions for the new generation of UHECR observatories

- ▶ New large-scale EAS observatories with particle detectors (GCOS, IceCube-Gen2, GRAND?) will provide large aperture and thus unprecedented event statistics
- ▶ Possibly new EAS observables and analysis techniques to test hadronic interaction models
- ▶ New era of high-precision measurements with EAS!

[L. Cazon, R. Conceicao, F. Riehn, Phys. Lett. B 784 (2018)]



[L. A. Anchordoqui et al., Phys. Rev. D 101 (2020)]



# Open questions for the new generation of UHECR observatories

- ▶ Precise measurements in the forward region at the High-Luminosity LHC (including new proposed experiments, e.g. Forward Physics Facility, Very Forward Hadron Spectrometer) will further constrain hadronic models
- ▶ Hadronic models have to describe both EAS and LHC measurements
  - ▶ Tests of SM predictions at energies much higher than the LHC (far-forward region)!
- ▶ Once the hadronic interaction models can successfully describe all details they will become reliable tools for the development of the proposed Future Circular Collider (FCC)
  - ▶ Validation of EAS models at the (HL-)LHC / FPF / FCC



# Open questions for the new generation of UHECR observatories

▶ If LHC data is reproduced but Muon Puzzle remains:

▶ Tests of beyond SM physics / exotic scenarios, e.g.

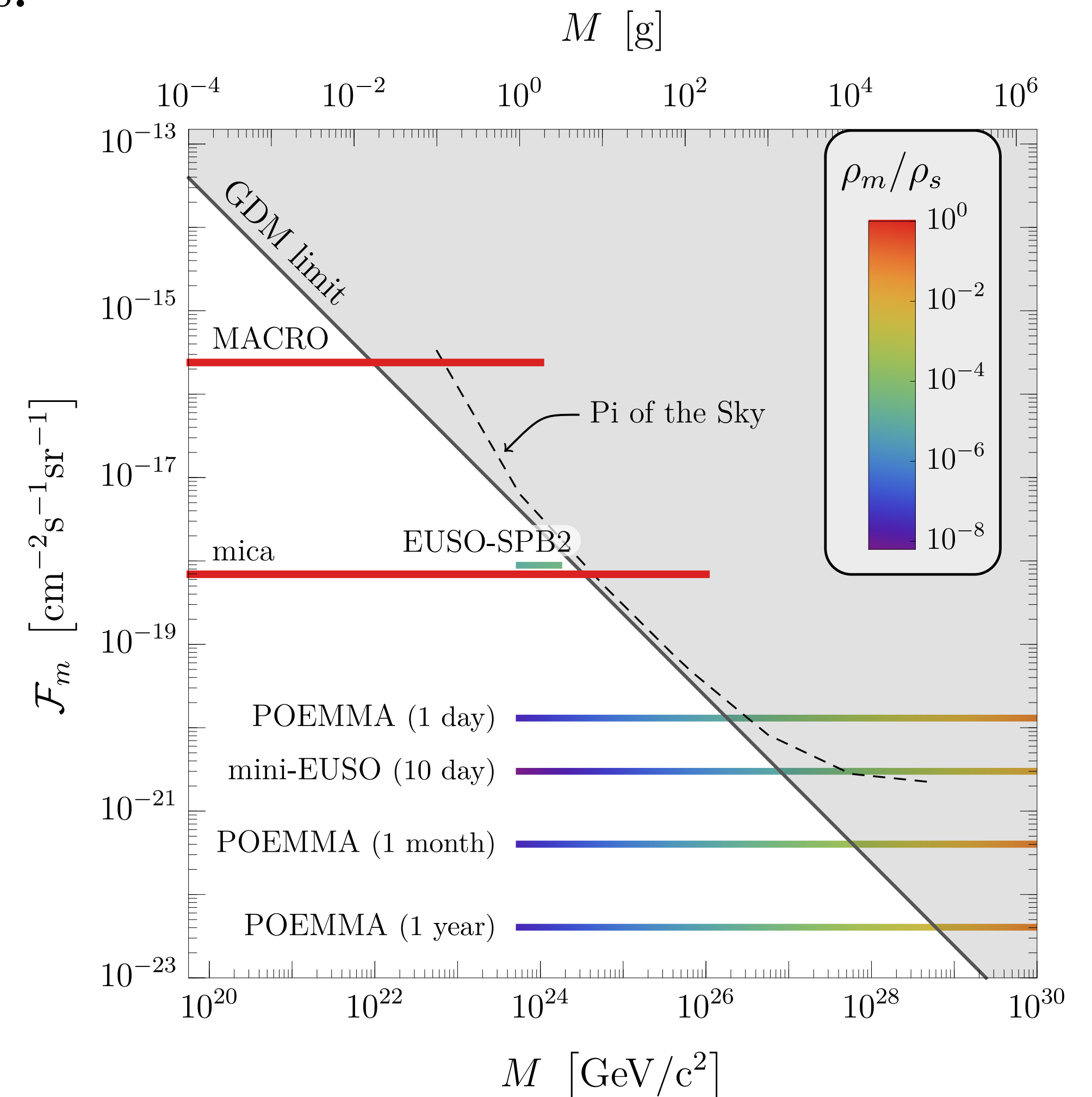
▶ Lorentz-invariance violation

▶ Super-heavy Dark Matter

▶ Macroscopic Dark Matter

▶ Nuclearites

▶ ...





# Summary & Discussion

- ▶ Expectation:
  - ▶ Muon Puzzle precisely characterized (solved?)
    - ▶ High-precision particle measurements with EAS!
    - ▶ Tests of SM predictions at energies much higher than the LHC
    - ▶ Provides event generators for future collider experiments, e.g. FPF / FCC
  - ▶ If the Muon Puzzle remains unsolved
    - ▶ Tests of beyond SM physics / exotic scenarios!
- ▶ Main focus / needs of the GCOS community?
- ▶ Requirements for GCOS design?
- ▶ Probably many further questions / comments / additions...