Cosmic ray hadronic interaction models & the Forward Physics Facility

4th Forward physics facility meeting
February 1st 2022
Felix Riehn

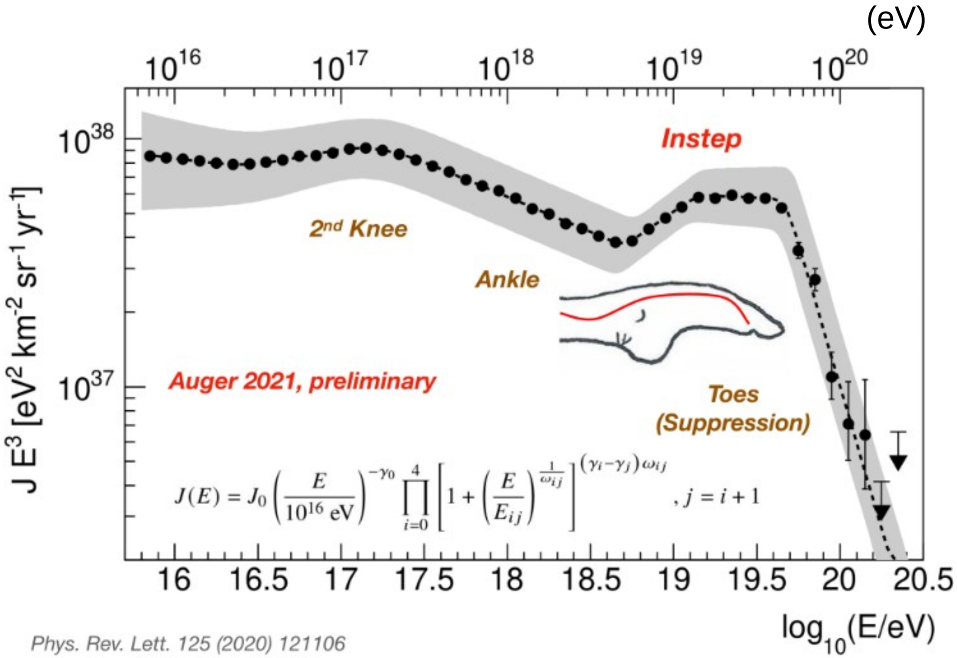
Take home message:

* UHE astroparticle physics limited by (unknown) uncertainty due to hadronic models

* FPF can test solutions to muon-puzzle, significantly decreasing the uncertainty

Ultra High Energy Cosmic Rays

1eV ~ 10**-19 J !

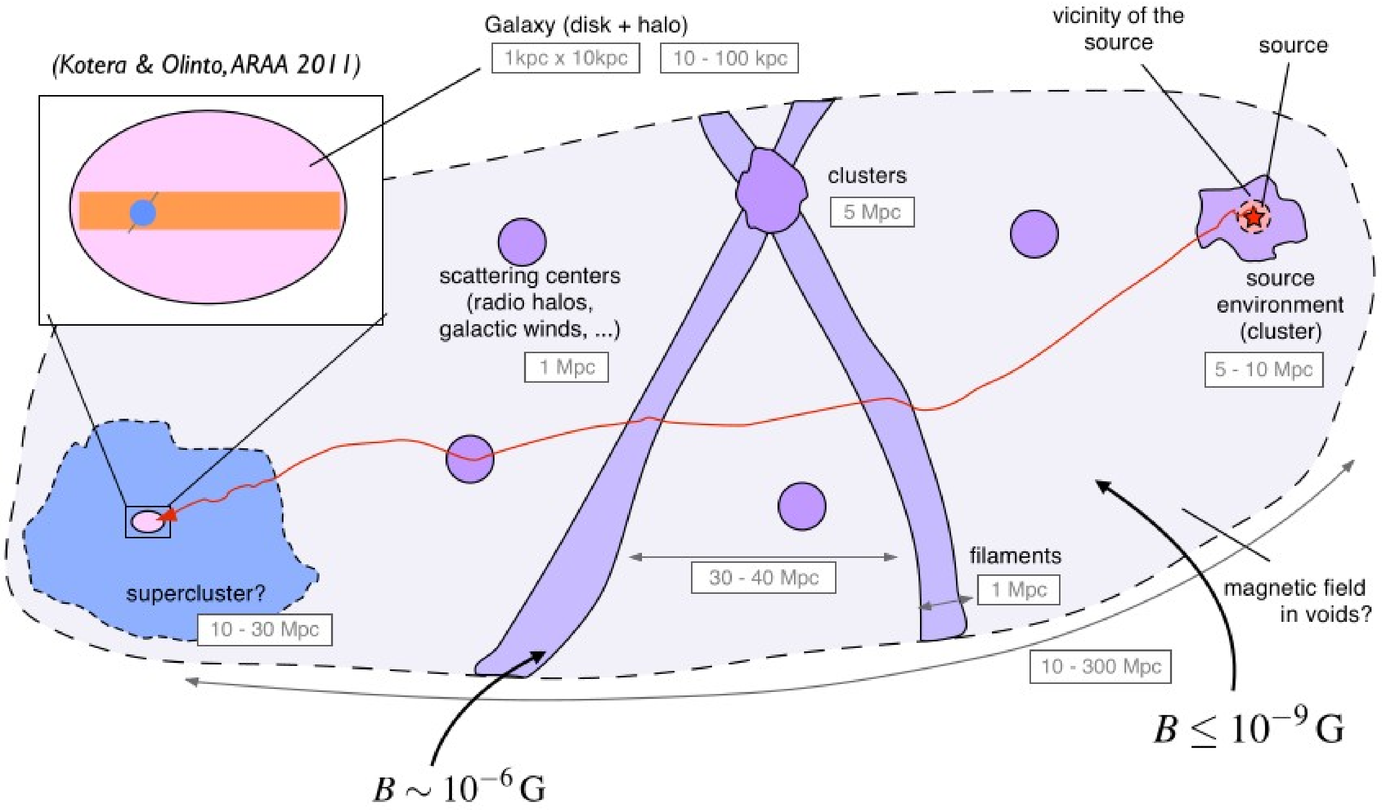


Phys. Rev. Lett. 125 (2020) 121106

LHC technology

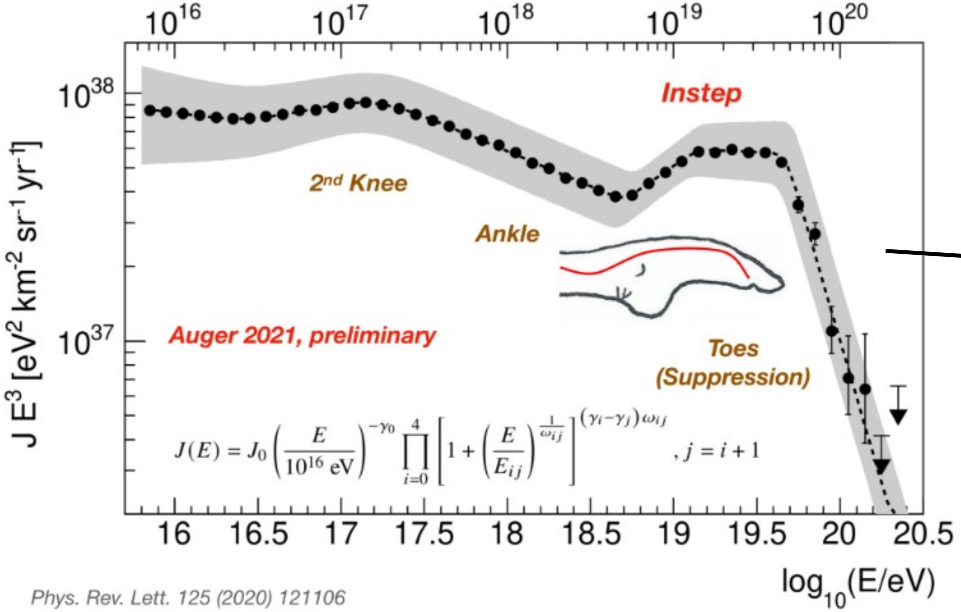
Where ?
How accelerated?
What are these accelerators?

Ultra High Energy Cosmic Rays



CR astronomy? → account for deflection → need mass/charge !

UHE protons ?



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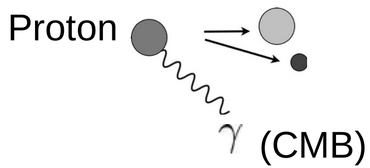
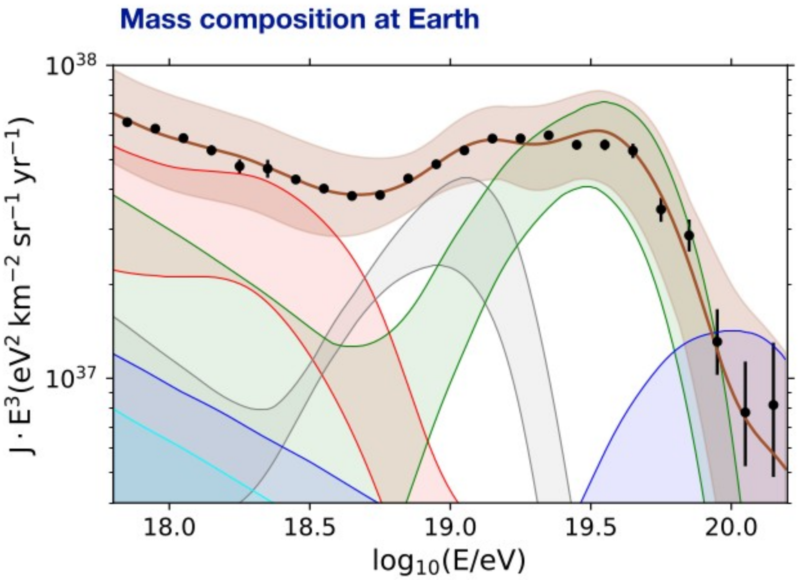
Flux suppressed! Protons?

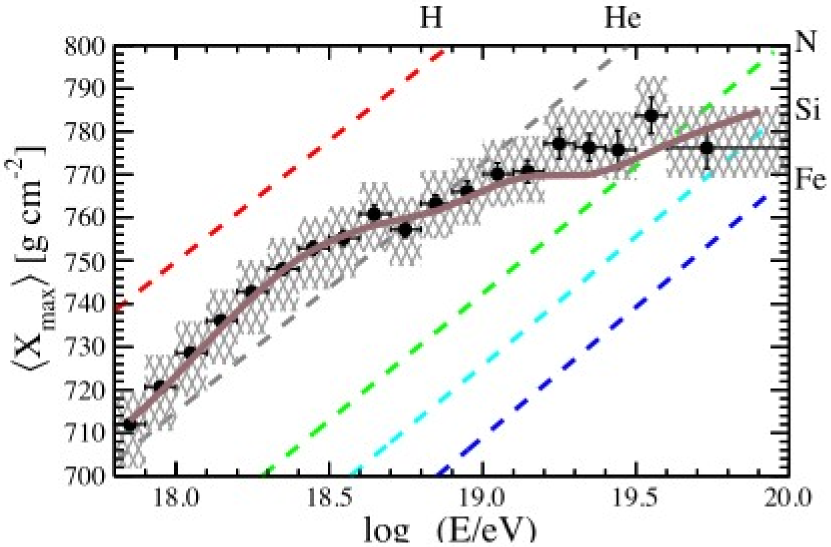
(Greisen-Zatsepin-Kuzmin, 1966)



Proton @ 100 EeV –> little deflection

CR mass composition not trivial

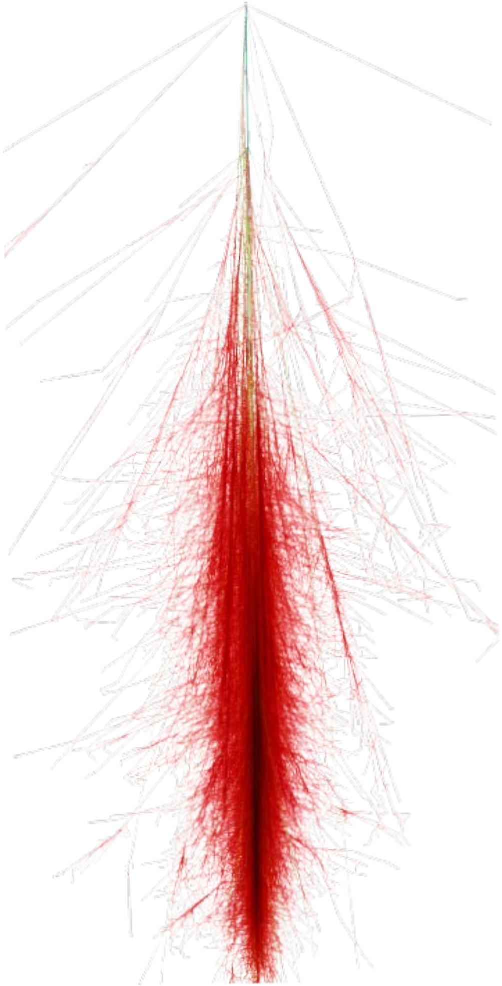


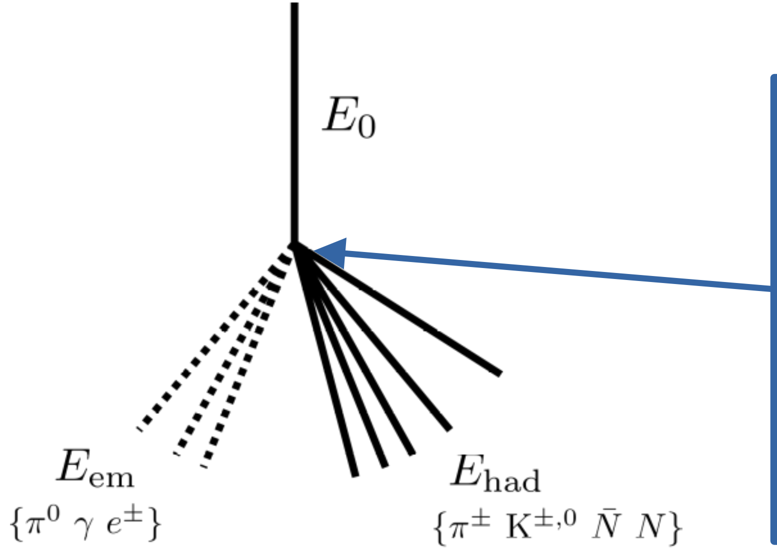


Only average mass! CR astronomy needs PID!

Where do hadronic interactions enter ?

Extensive air showers

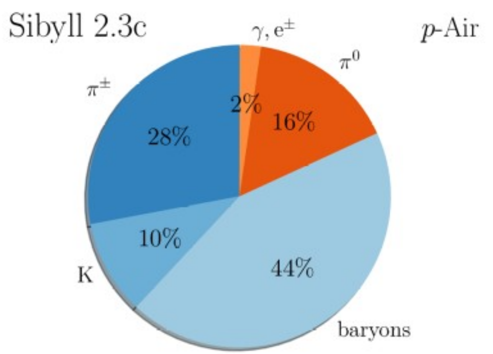




EM cascade **hadronic cascade**

Energy flow

Energies of secondaries



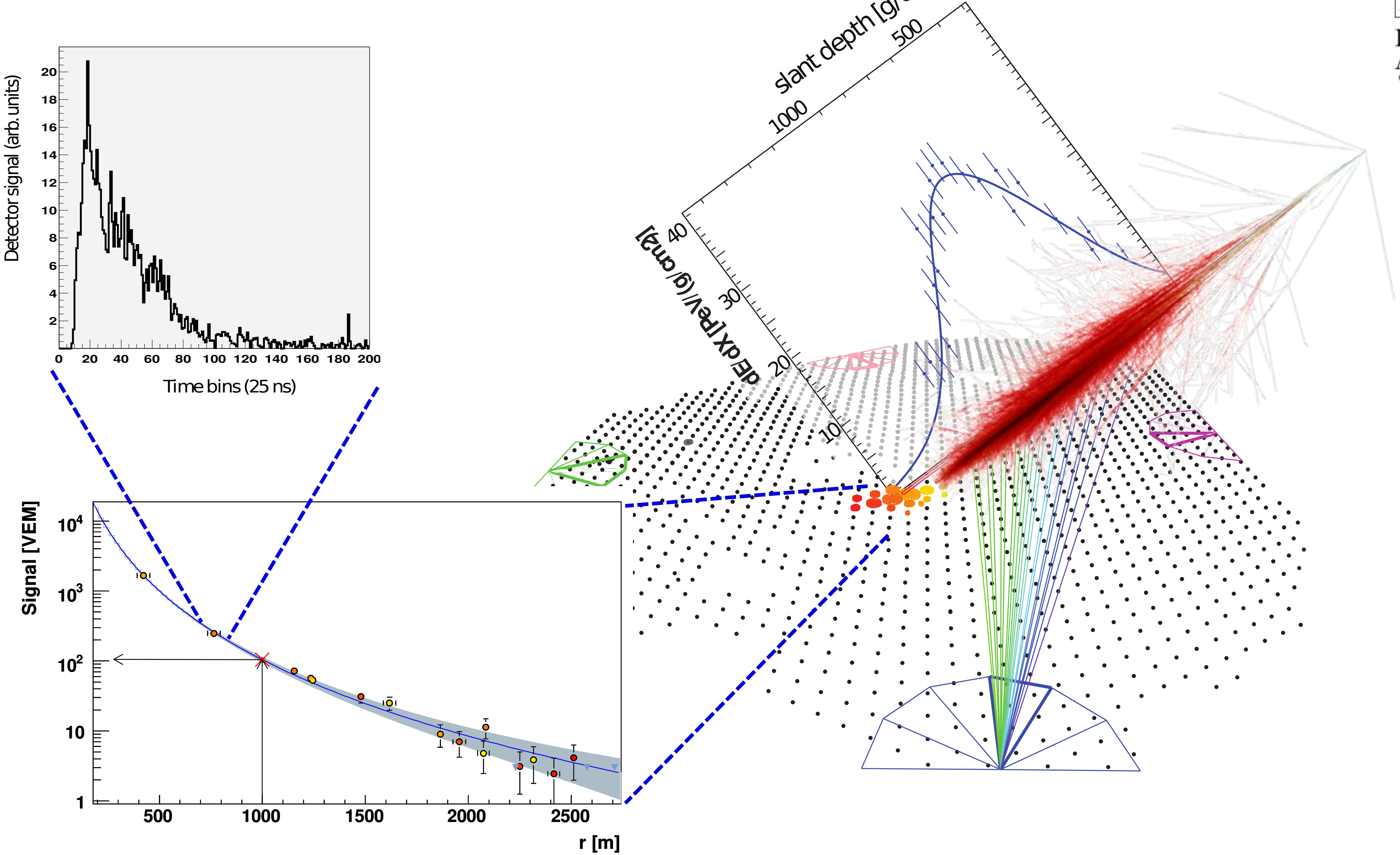
Only 80% energy remains in hadrons ..

After n steps:

$$E_n^{\mathrm{had}} = 0.8^n\, E_0$$

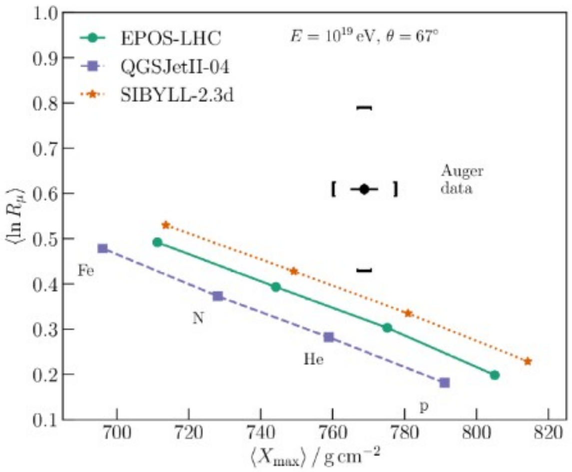
$$E_n^{\mathrm{EM}} = (1 - 0.8^n)\, E_0$$

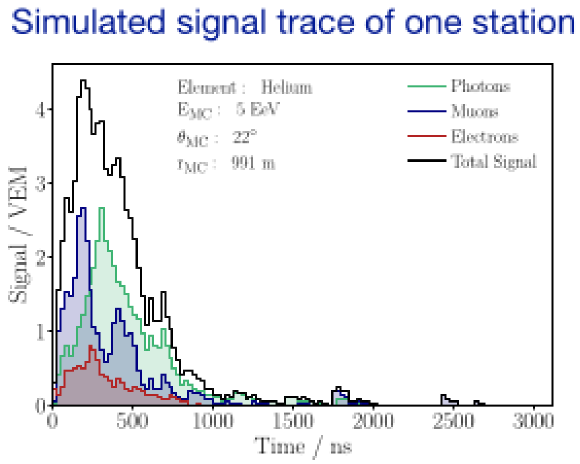
Hybrid detection of UHECR

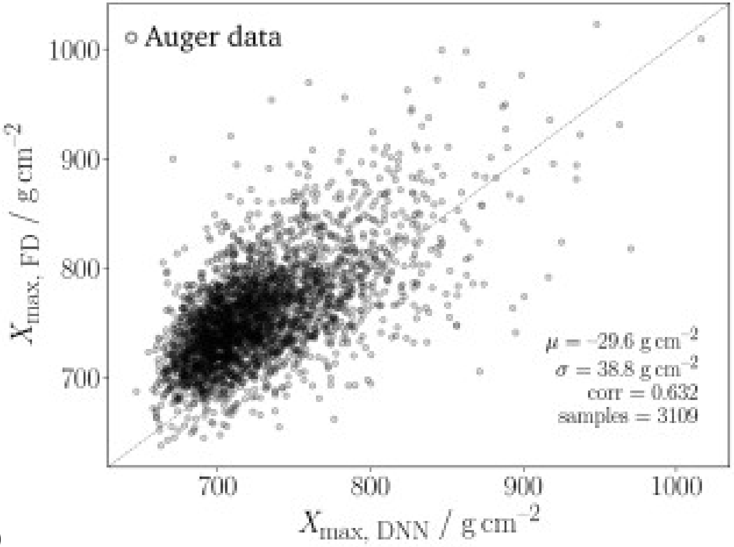


Impact of the muon puzzle on UHECR

Cannot trust EAS simulations! → No ML, no detailed analysis of time structure







(Auger 2021)

→ No event-by-event PID with Auger Phase 1 (2004-2020) data !
Unless muon puzzle is fixed

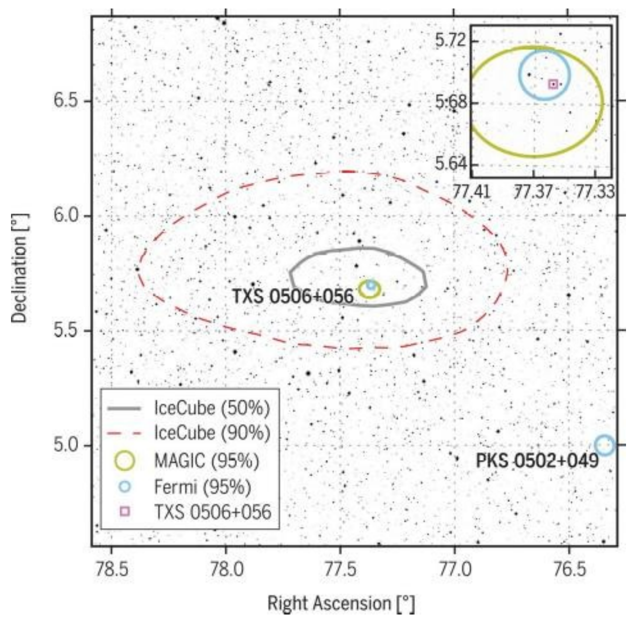
Forget charged CRs, neutrinos !

Interaction of UHECRs in source environment will produce HE neutrinos.

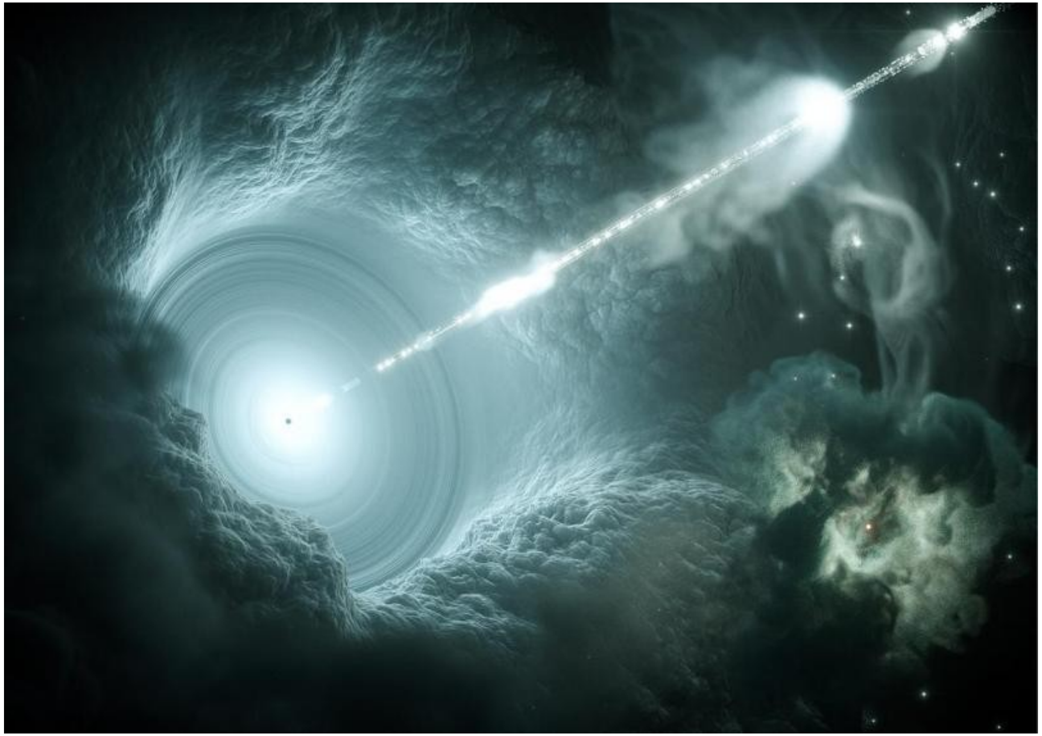
HE neutrinos will reveal CR sources!

Yes, ..

Multimessenger observation of blazar



(Science 361, eaat1378 (2018))

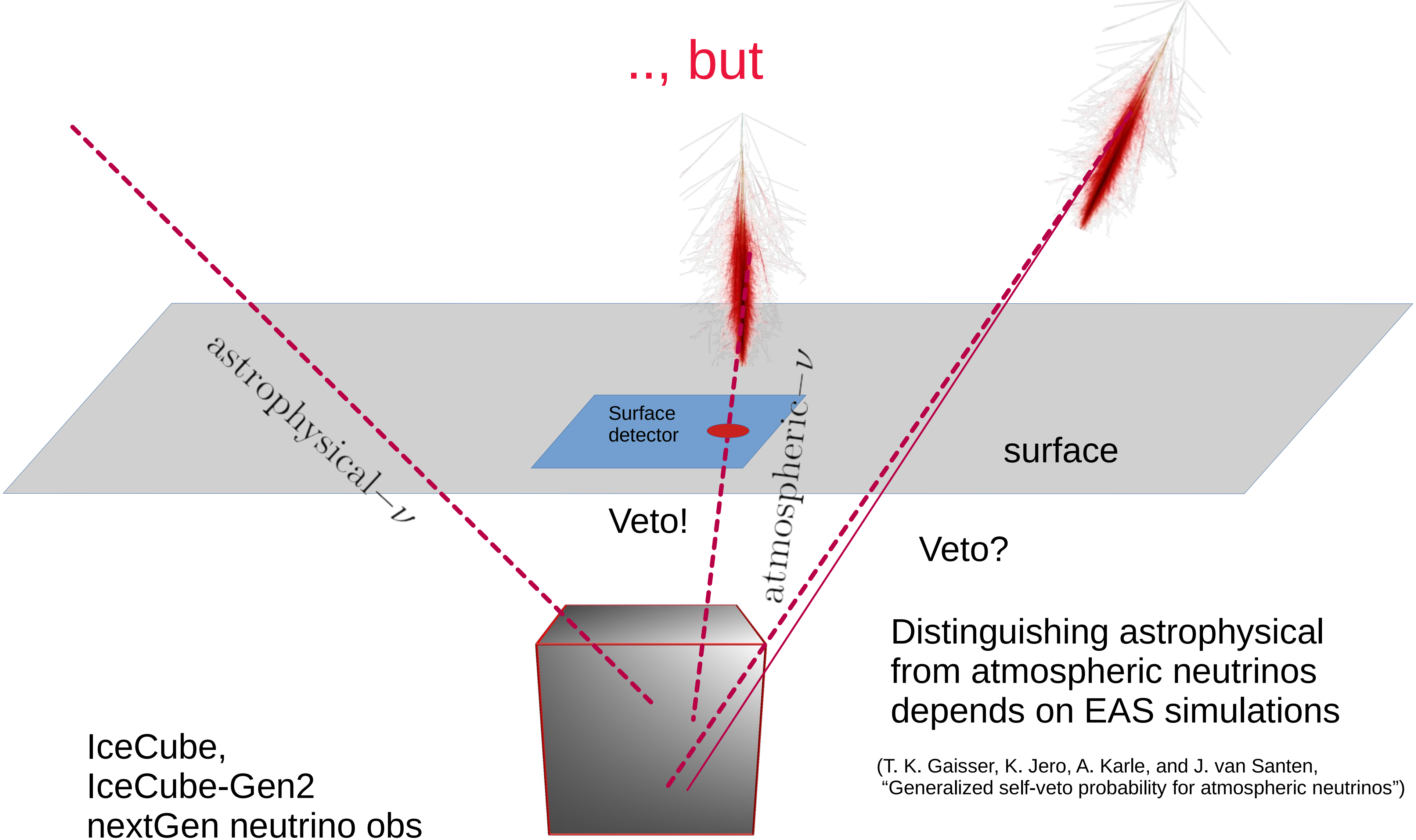


(DESY 2018)

But..

… The vast majority of neutrinos detected by IceCube arise from cosmic-ray interactions within Earth's atmosphere. Although atmospheric neutrinos are dominant at energies below 100 TeV, their spectrum falls steeply with energy, allowing astrophysical neutrinos to be more easily identified at higher energies. The muon-neutrino astrophysical spectrum, together with simulated data, was used to calculate the **probability that a neutrino at the observed track energy and zenith angle in IceCube is of astrophysical origin. This probability, the so-called signalness of the event (14), was reported to be 56.5% (17)**. Although IceCube can robustly identify astrophysical neutrinos at PeV energies, for individual neutrinos at several hundred TeV, an atmospheric origin cannot be excluded. ...

.., but



IceCube,
IceCube-Gen2
nextGen neutrino obs

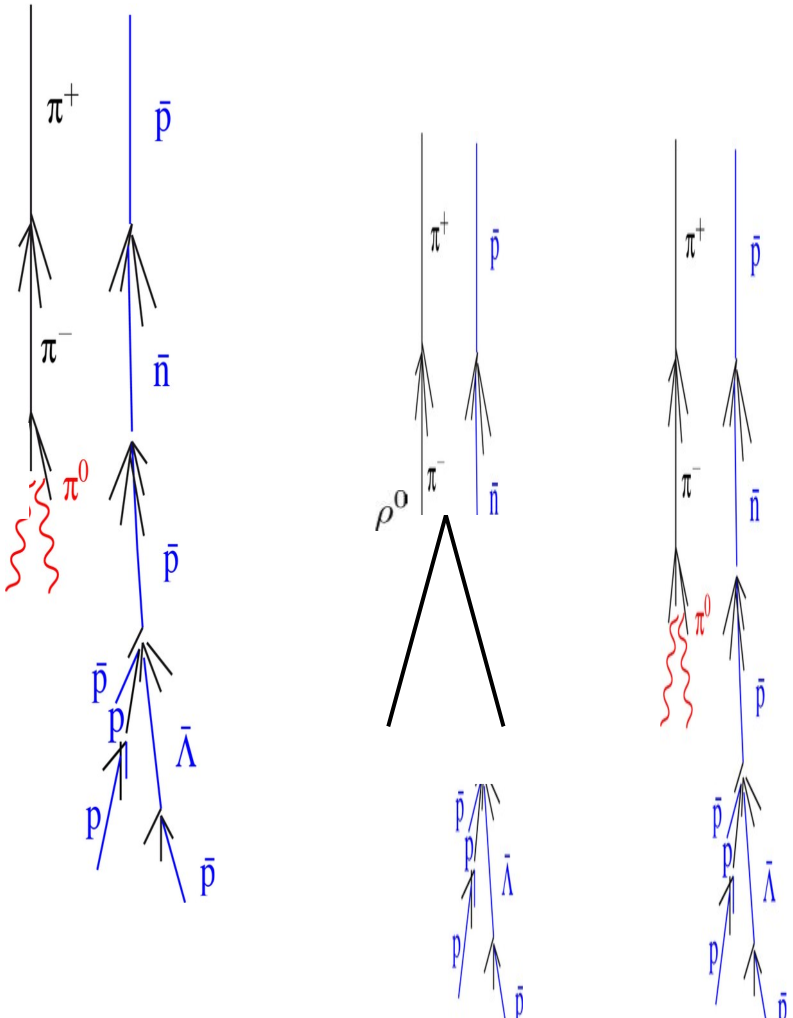
Distinguishing astrophysical from atmospheric neutrinos depends on EAS simulations

(T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, "Generalized self-veto probability for atmospheric neutrinos")

FPF snowmass, S. Klein et al.

How FPF can help ?

Model scenarios to enhance muons



Established:

* baryon anti-baryon production (Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

* leading pion effect (Drescher 2007, Ostapchenko 2016)

New:

* enhanced strangeness (Pheno/Fireball - S. Sciutto et al. **(FPF snowmass)**, QGP - Pierog et al. 2019)

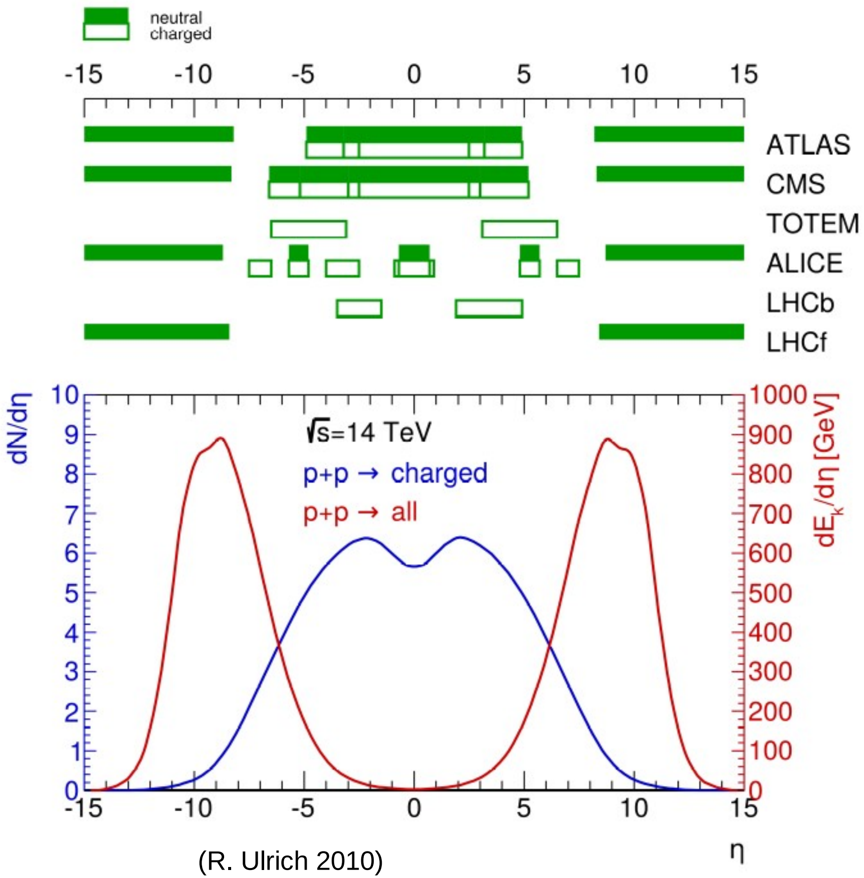
* chiral symmetry restoration (Farrar, Allen 2012)

* ...

FPF will increase coverage

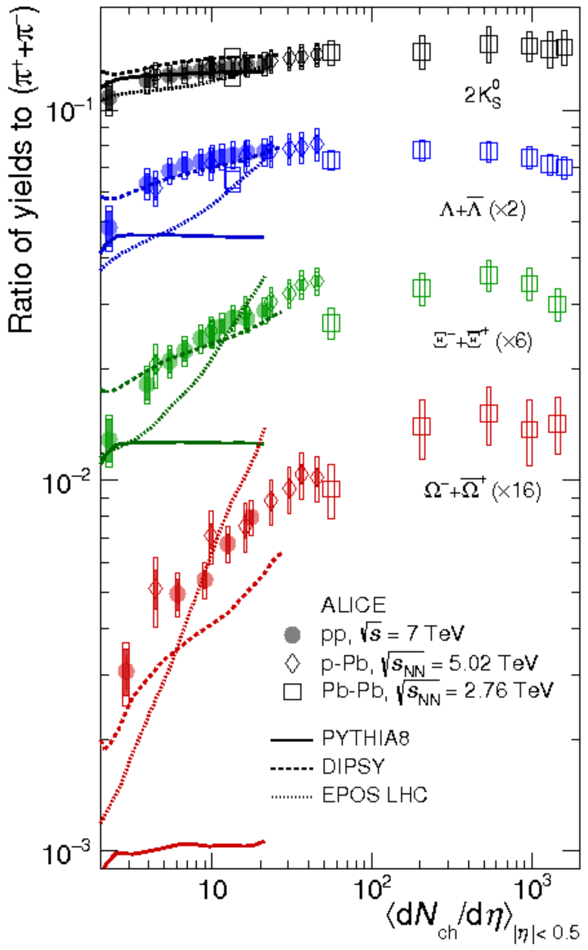
* so far no particle id for charged in very forward phase space

* pion – kaon ratio



(R. Ulrich 2010)

strangeness enhancement through QGP



(ALICE,Nature Physics volume 13, pages535-539 (2017))

* already in pp enhancement of strange production

* same behavior as pPb and PbPb

→ large parton density ?

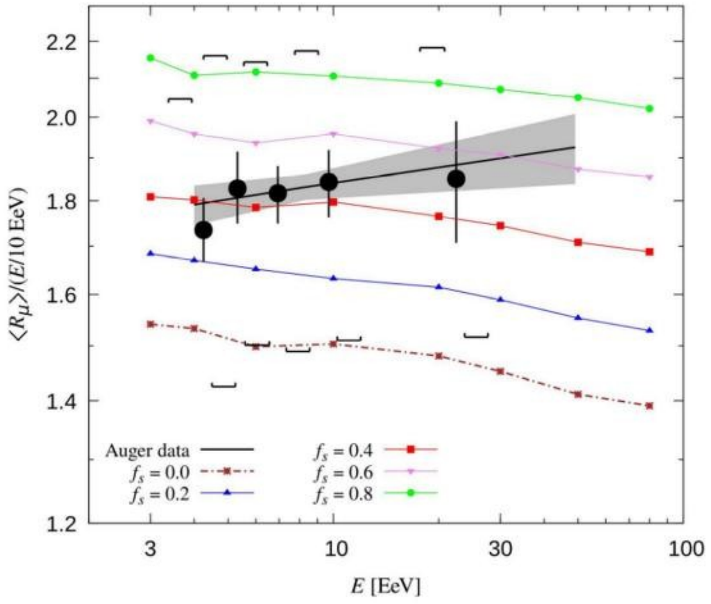
* extends to forward?

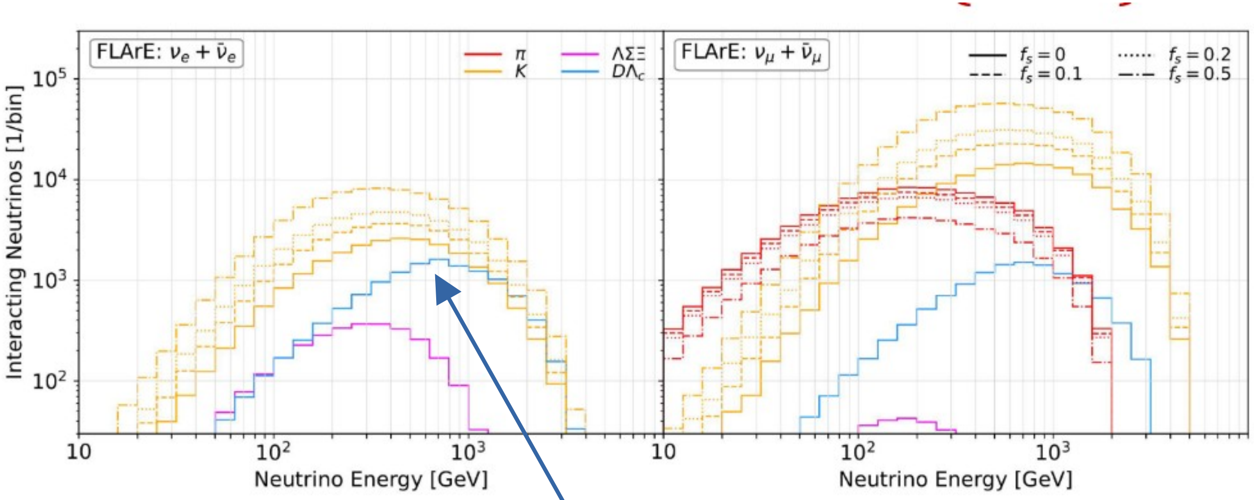
* confirmation in pO? (Run planned this year?)

* confirmation from LHCb & **FPF** (interm. and large xF)?

FPF can test strangeness enhancement

FPF snowmass: Sciutto et al.





Fs: Pi→K swapping
Could resolve muon puzzle

test forward charm! → neutrino observatories
→ see talk by R. Enberg

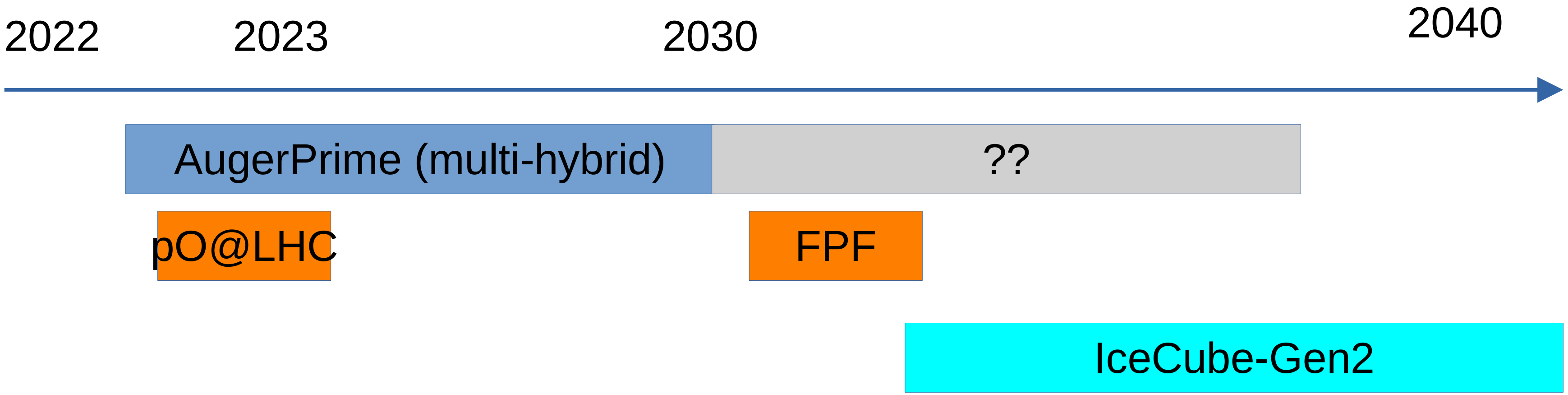
FPF snowmass: Bhattacharya et al., T. Ruhe, & S. Klein

Summary

* hadronic uncertainties severely limit physics opportunities of UHECR observatories

* FPF can test scenarios for muon puzzle, complementing pOxygen run at LHC!
  & Auger multi-hybrid data!

* reduce hadronic uncertainties both for current & future charged CR and neutrino observatories



Multi-hybrid in AugerPrime