

Search for the common sources of high-energy cosmic neutrinos and ultra-high-energy cosmic rays

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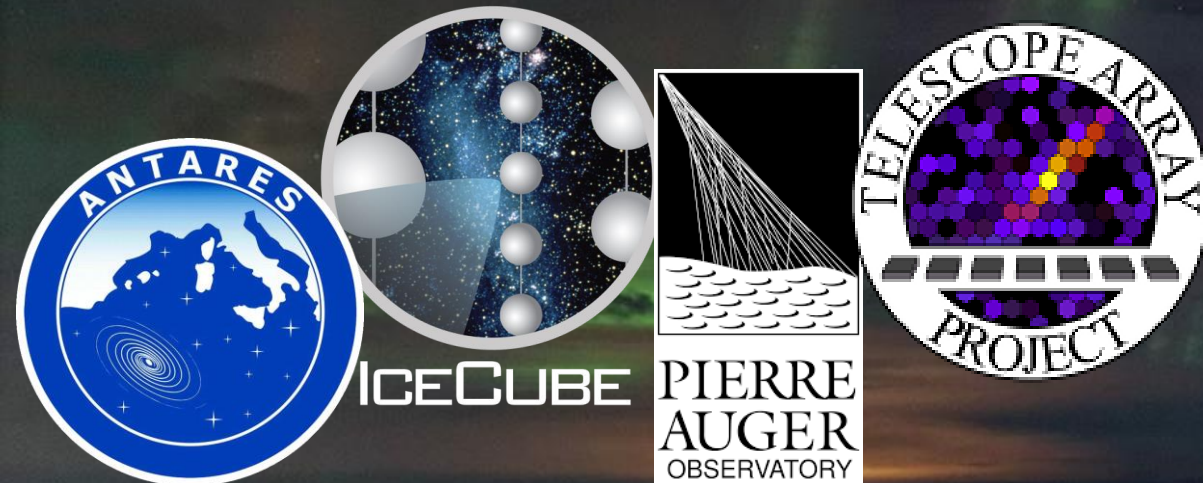
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Outline:

- Multimessenger puzzle:
The connection of highest-energy extragalactic particles
- Challenges:
Finding the sources of highest-energy neutrinos and ultra-high-energy cosmic rays
- Results

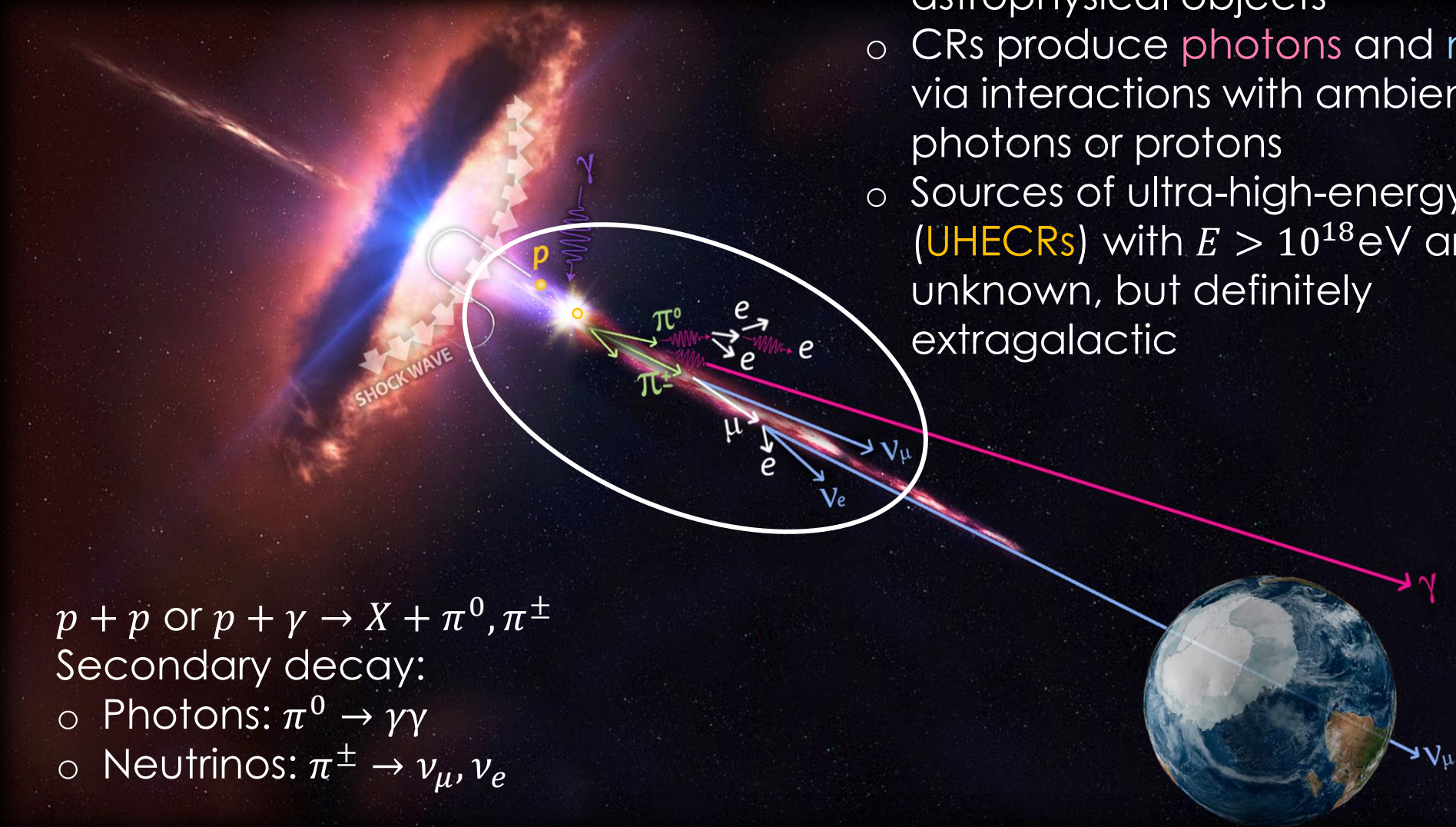
Pre-print: arXiv:2201.07313, Accepted by ApJ

Multimessenger puzzle

- Protons and nuclei (charged **CRs**) accelerated by central engine of astrophysical objects
- CRs produce **photons** and **neutrinos** via interactions with ambient photons or protons
- Sources of ultra-high-energy CRs (**UHECRs**) with $E > 10^{18}$ eV are unknown, but definitely extragalactic

$p + p$ or $p + \gamma \rightarrow X + \pi^0, \pi^\pm$
Secondary decay:

- Photons: $\pi^0 \rightarrow \gamma\gamma$
- Neutrinos: $\pi^\pm \rightarrow \nu_\mu, \nu_e$

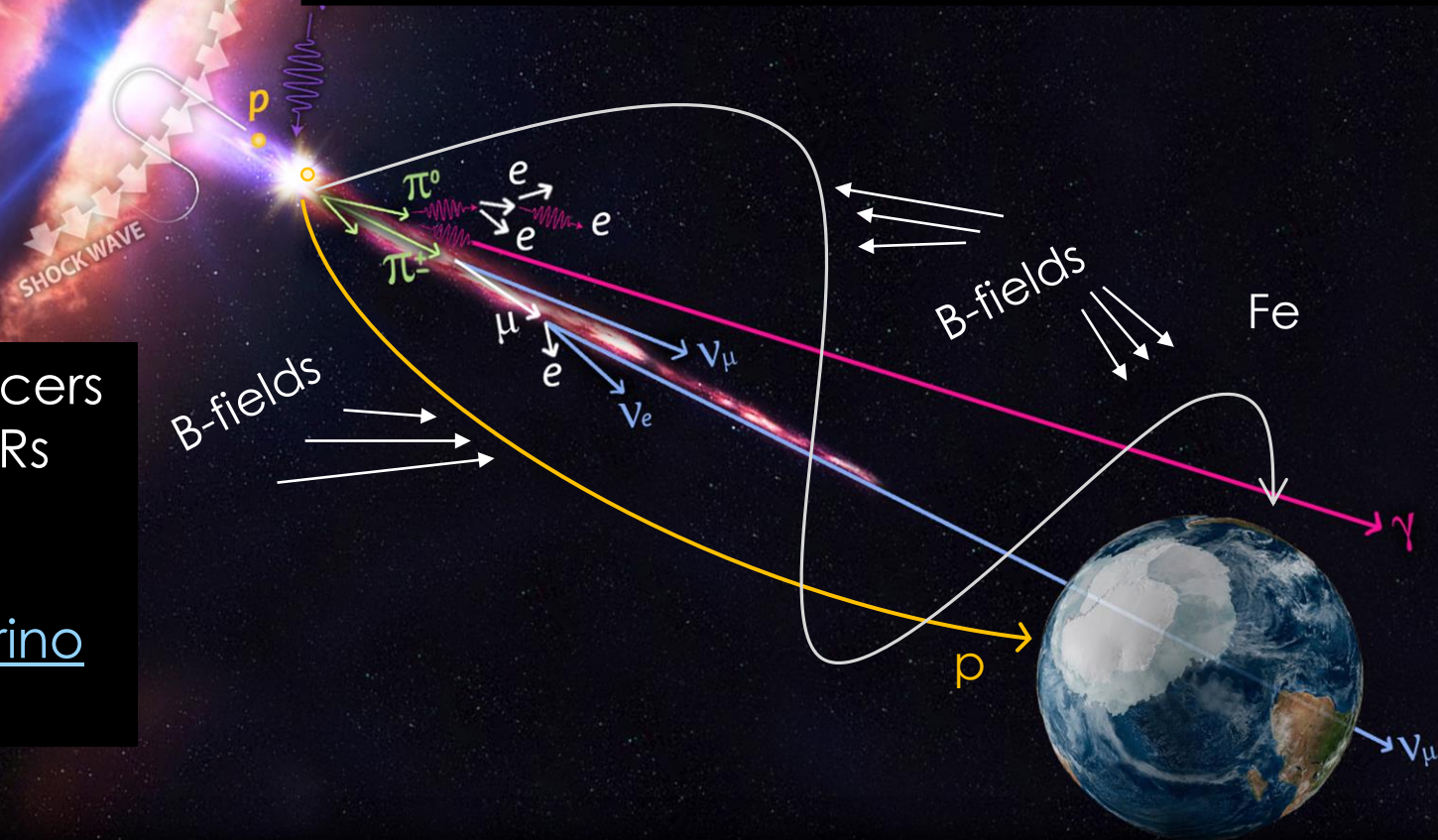


Challenges

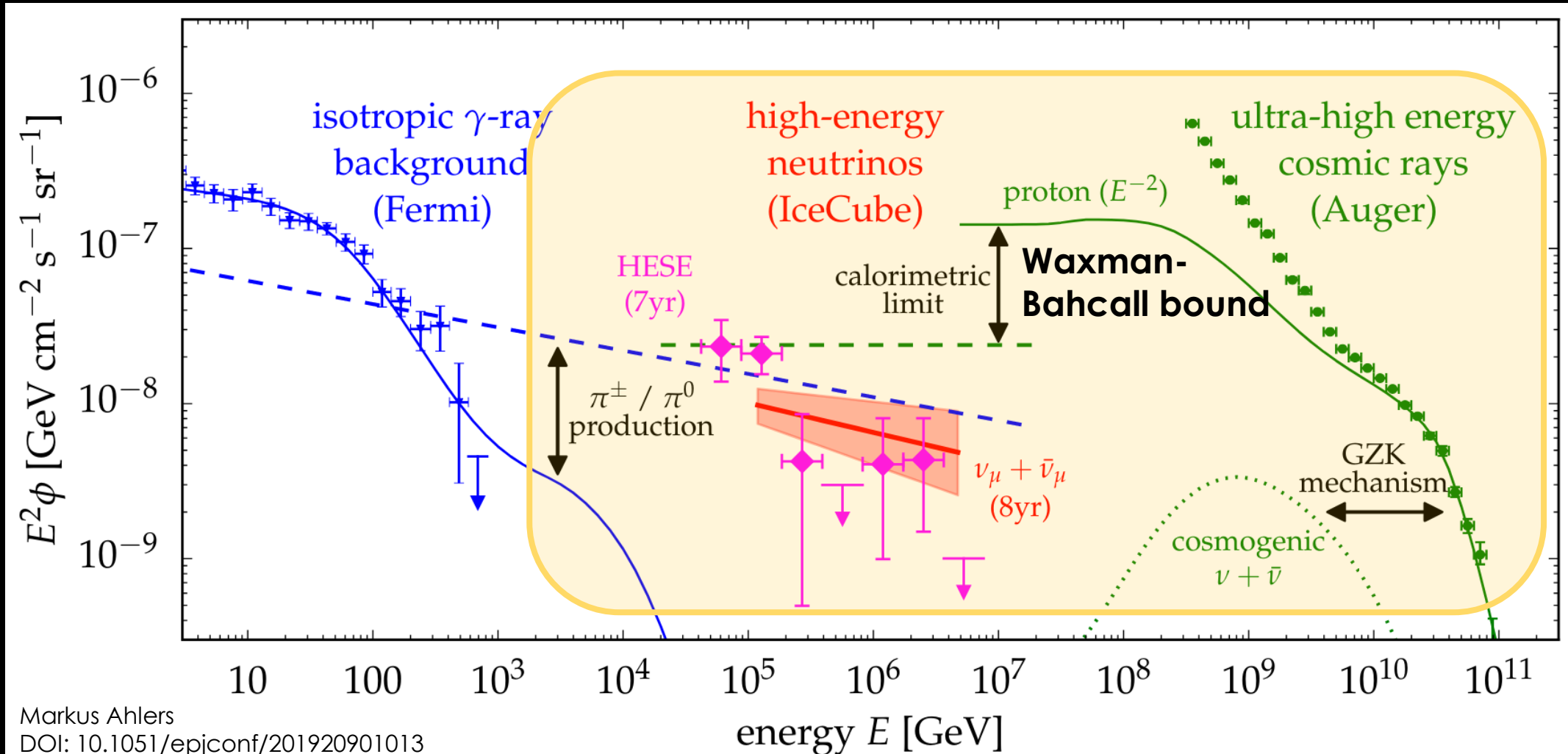
Difficulties in finding hadronic sources:

- CRs deflected by magnetic fields
- Charge of highest-energy CRs unknown on event-by-event basis
- Photons may originate from leptonic processes
- TeV photons quickly absorbed

- Neutrinos unambiguous tracers of hadronic processes of CRs
- Neither deflected, nor absorbed on way to Earth
- Combine UHECR and neutrino information to find sources



Multimessenger puzzle: Energy density of extra-galactic particles



Experimental Motivation

1) Astrophysical neutrino flux closely below Waxman-Bahcall bound at $E^2 \frac{d\Phi}{dE} \sim 10^{-8} \text{ GeV/cm}^2 \text{ s sr}$, eg.

<https://doi.org/10.3847/1538-4357/ac4d29>

2) Initial indication of UHECR-neutrino correlation at 3σ level, <https://doi.org/10.1088/1475-7516/2016/01/037>

2) UHECR anisotropy in correlation with extragalactic γ -sources (Starburst galaxies and γ -AGN) at 4σ level,

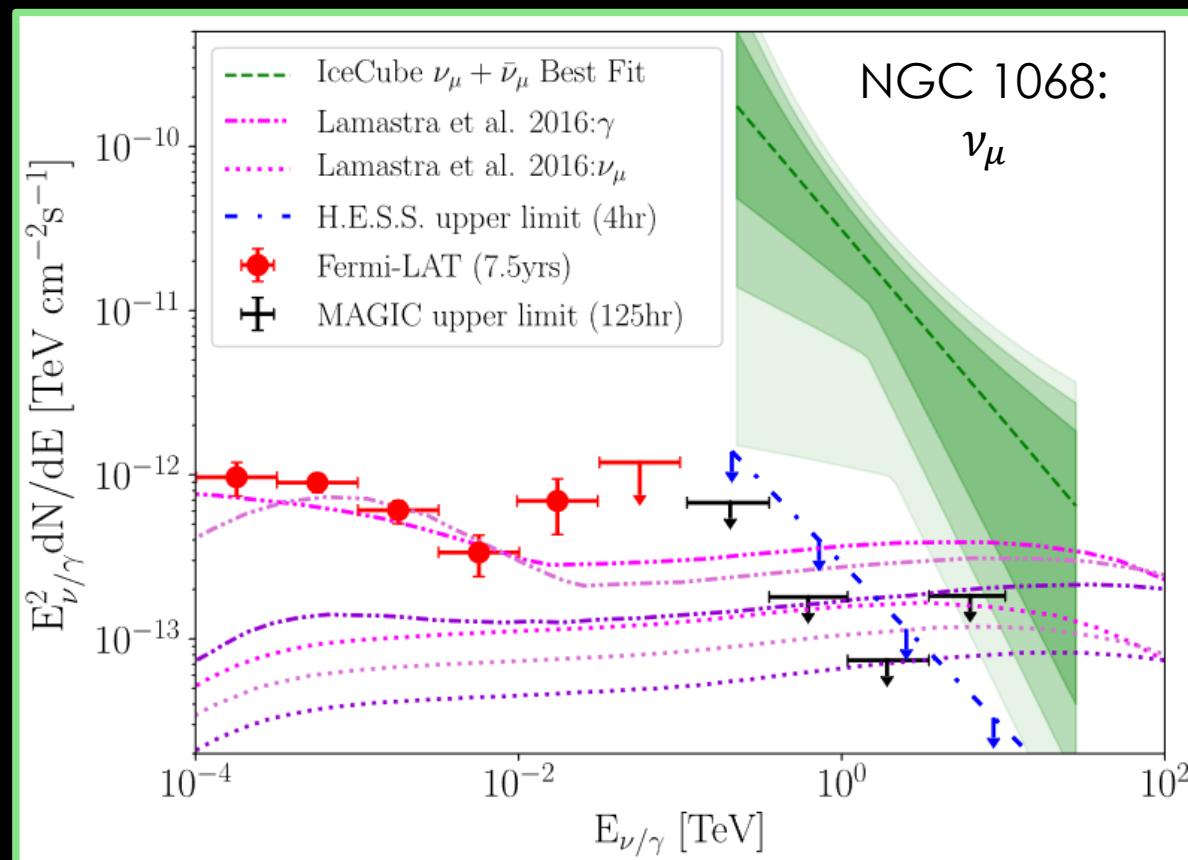
<https://doi.org/10.3847/2041-8213/aaa66d>

3) Indication of neutrino emission from NGC 1068 (Starburst/ Seyfert galaxy) measured by IceCube, also found in UHECR anisotropy study

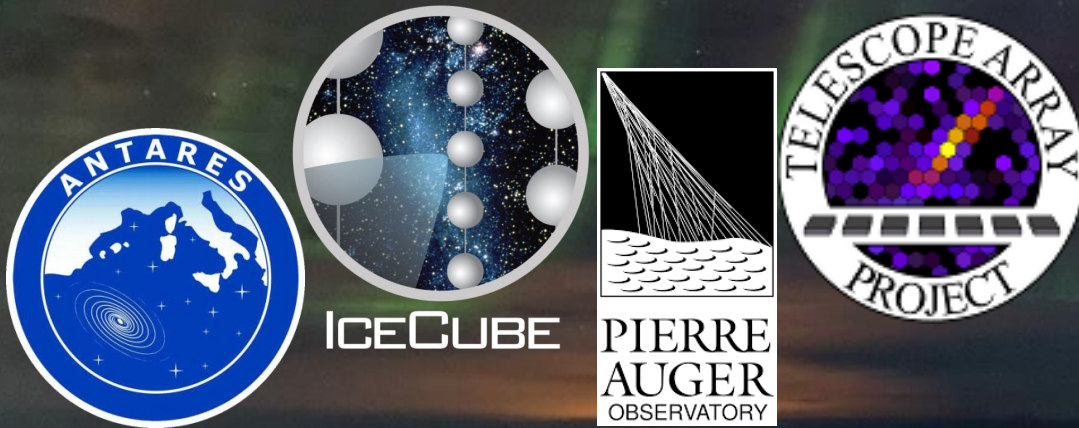
<https://doi.org/10.1103/PhysRevLett.124.051103>

Table 2. Populations investigated

SBGs	l [°]	b [°]	Distance ^a [Mpc]	Flux weight [%]	Attenuated weight: A / B / C [%]	% contribution ^b : A / B / C [%]
NGC 253	97.4	-88	2.7	13.6	20.7 / 18.0 / 16.6	35.9 / 32.2 / 30.2
M82	141.4	40.6	3.6	18.6	24.0 / 22.3 / 21.4	0.2 / 0.1 / 0.1
NGC 4945	305.3	13.3	4	16	19.2 / 18.3 / 17.9	39.0 / 38.4 / 38.3
M83	314.6	32	4	6.3	7.6 / 7.2 / 7.1	13.1 / 12.9 / 12.9
...						
NGC 1068	172.1	-51.9	17.9	12.1	5.6 / 7.9 / 9.0	6.4 / 9.4 / 10.9



Detecting highest-energy cosmic particles at Earth: ANTARES, IceCube, Pierre-Auger, and Telescope Array Observatories



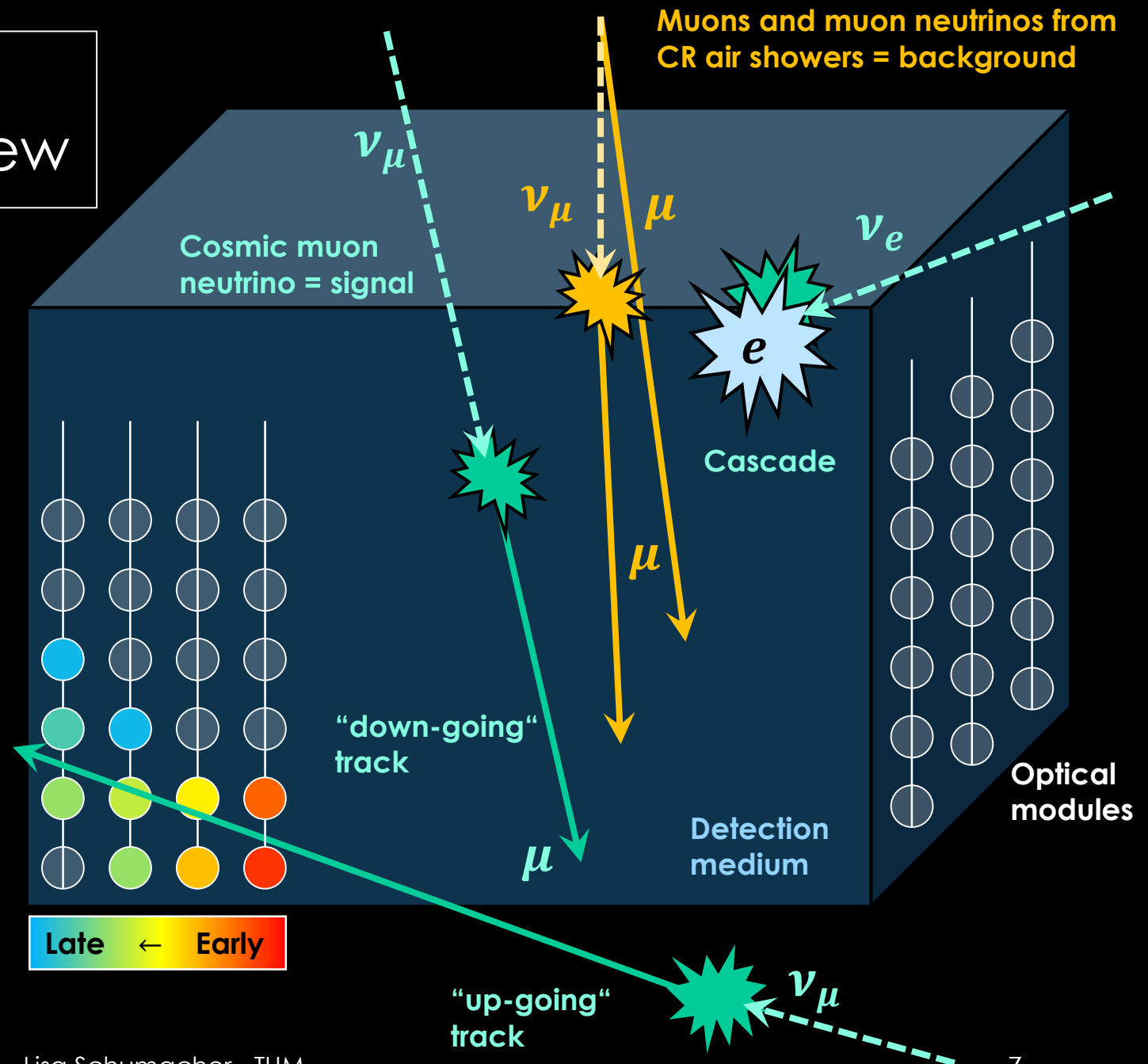
ANTARES & IceCube: Complementary field of view

ANTARES:

- Water-cherenkov neutrino detector in the Mediterranean Sea near France
- $0.1\text{km}^2 \times 350\text{m}$ volume instrumented with 12×75 optical modules in depth of 2500m

IceCube:

- Ice-Cherenkov neutrino detector deep in the glacial ice at the geographical South Pole
- 1km^3 volume instrumented with 86×60 digital optical modules in depth of 1450–2450m



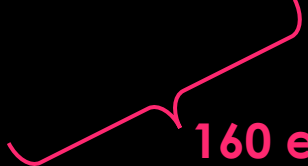
ANTARES & IceCube: event selections

Focused on high-energy/purity (all flavor)

IceCube:

- **102** High-energy events starting inside the detection volume, all flavor, $E > 60$ TeV
- **35** High-energy muon tracks, $E > 200$ TeV
- **20** Extremely-high-energy muon tracks, $E > 500$ TeV

ANTARES:

- **3** muon tracks, $> 40\%$ purity  **160 events**

Backgrounds: atmospheric muons and neutrinos

HE- ν in the following!

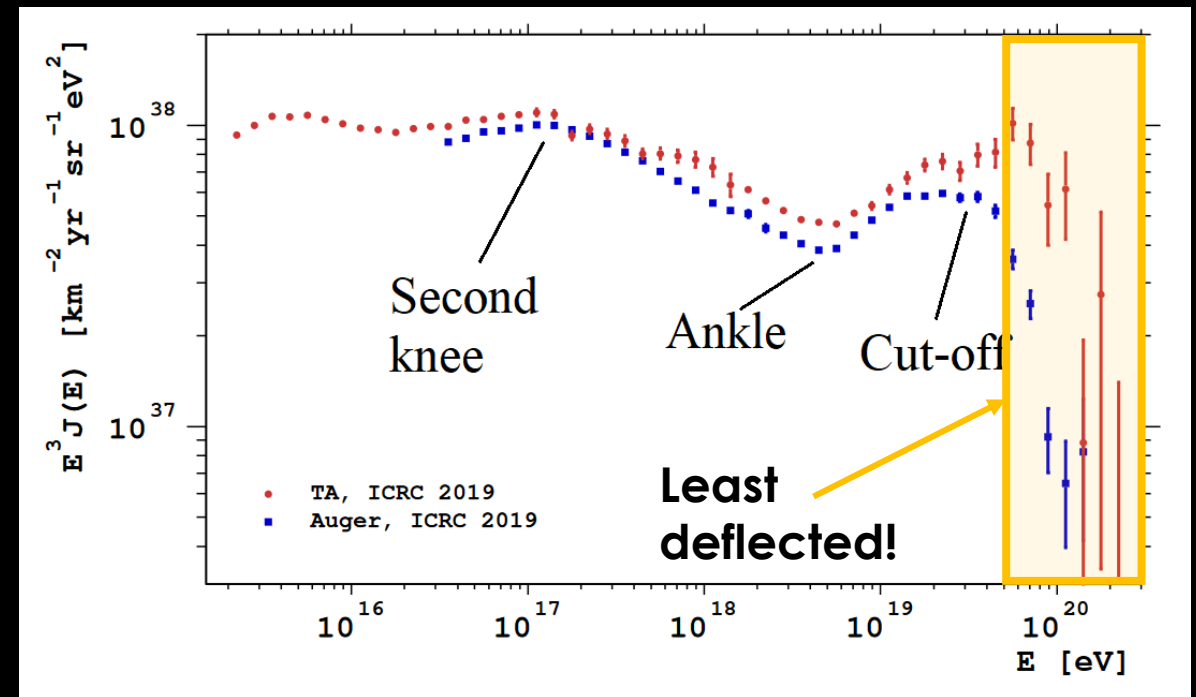
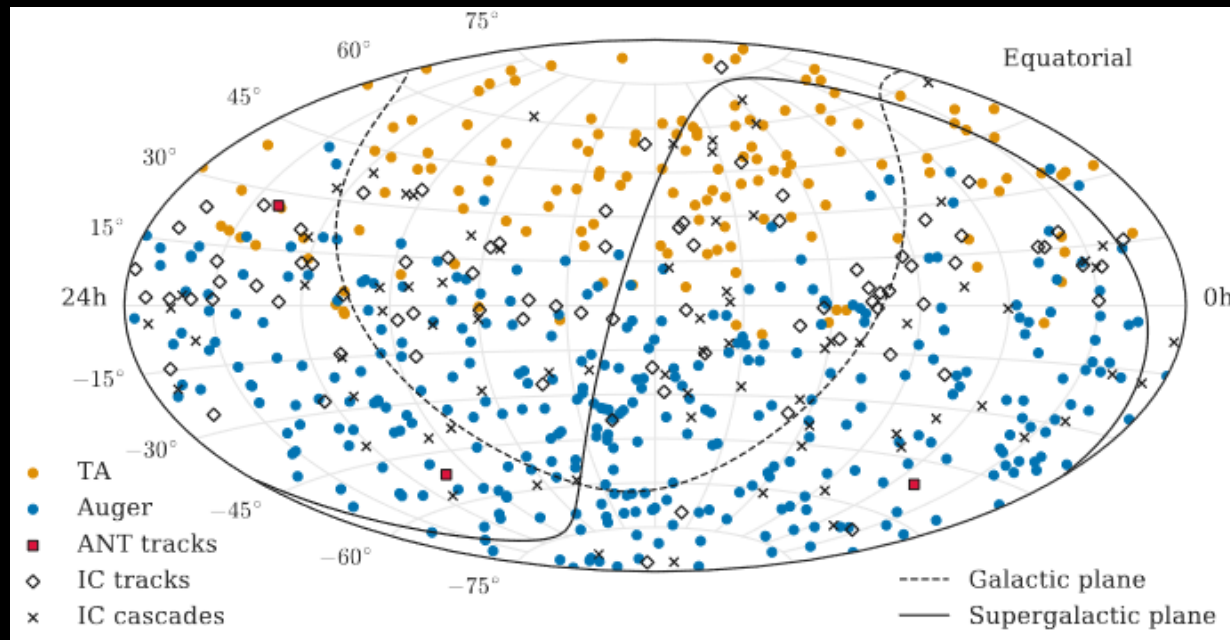
Focused on signal-efficiency/pointing (ν_μ)

- IceCube: Combined data set of 10.5 years of muon tracks from 2007-2018 = **1.4 Million events** (all arrival directions)
- ANTARES: 11 years of muon tracks recorded between 2007-2017 = **8754 events** mainly from Southern Hemisphere (up-going and horizontal arrival directions)
- Backgrounds: atmospheric muons and neutrinos
- **$\sim 1\%$ purity, but absolute larger signal efficiency $\rightarrow$ O(1000) astrophysical neutrinos**
- Energy threshold: > 100 GeV

PS- ν in the following!

Pierre-Auger Observatory & Telescope Array

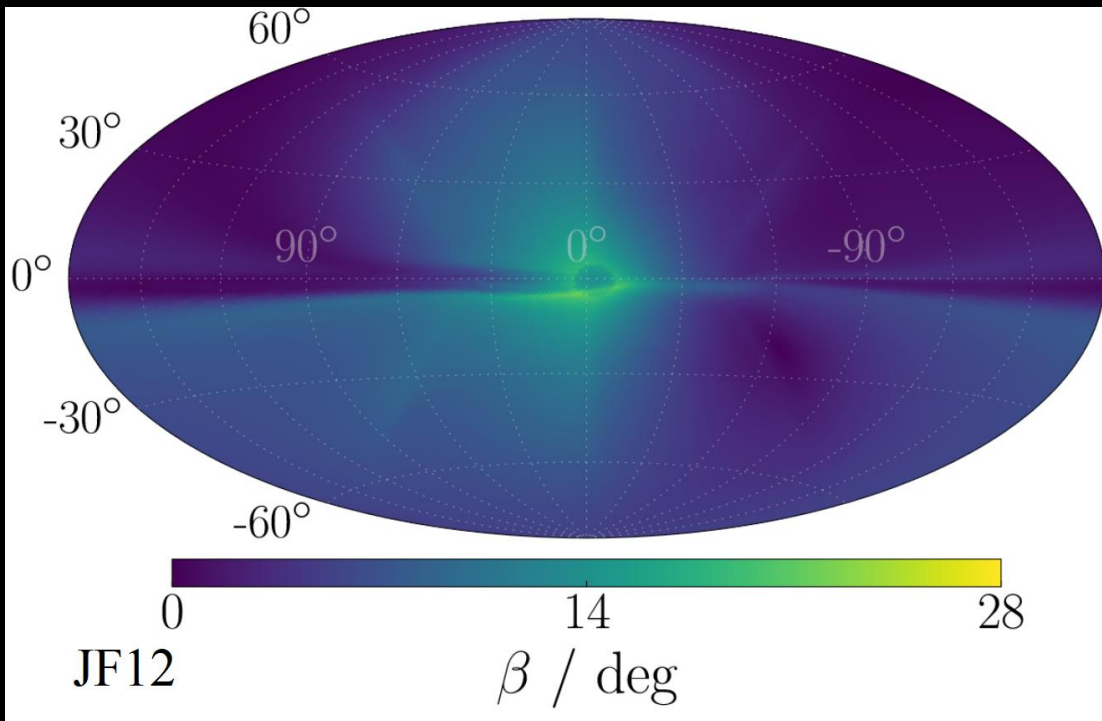
- 3000km² cosmic-ray observatory in Argentina, with water-Cherenkov tanks (SD) and fluorescence telescopes (FD)
- Data: **324 cosmic-ray events** recorded by SD from 2004 to 2017 mainly from Southern Hemisphere; Reconstructed energies **>52EeV**, angular resolution <0.9°
- 700 km² array of scintillation detectors (SD) and fluorescence telescopes (FT) in Utah, USA
- Data: **143 cosmic-ray events** recorded by SD from 2008 to 2017 mainly from Northern Hemisphere; Reconstructed energies **>57EeV**, angular resolution < 1.5°



The challenges

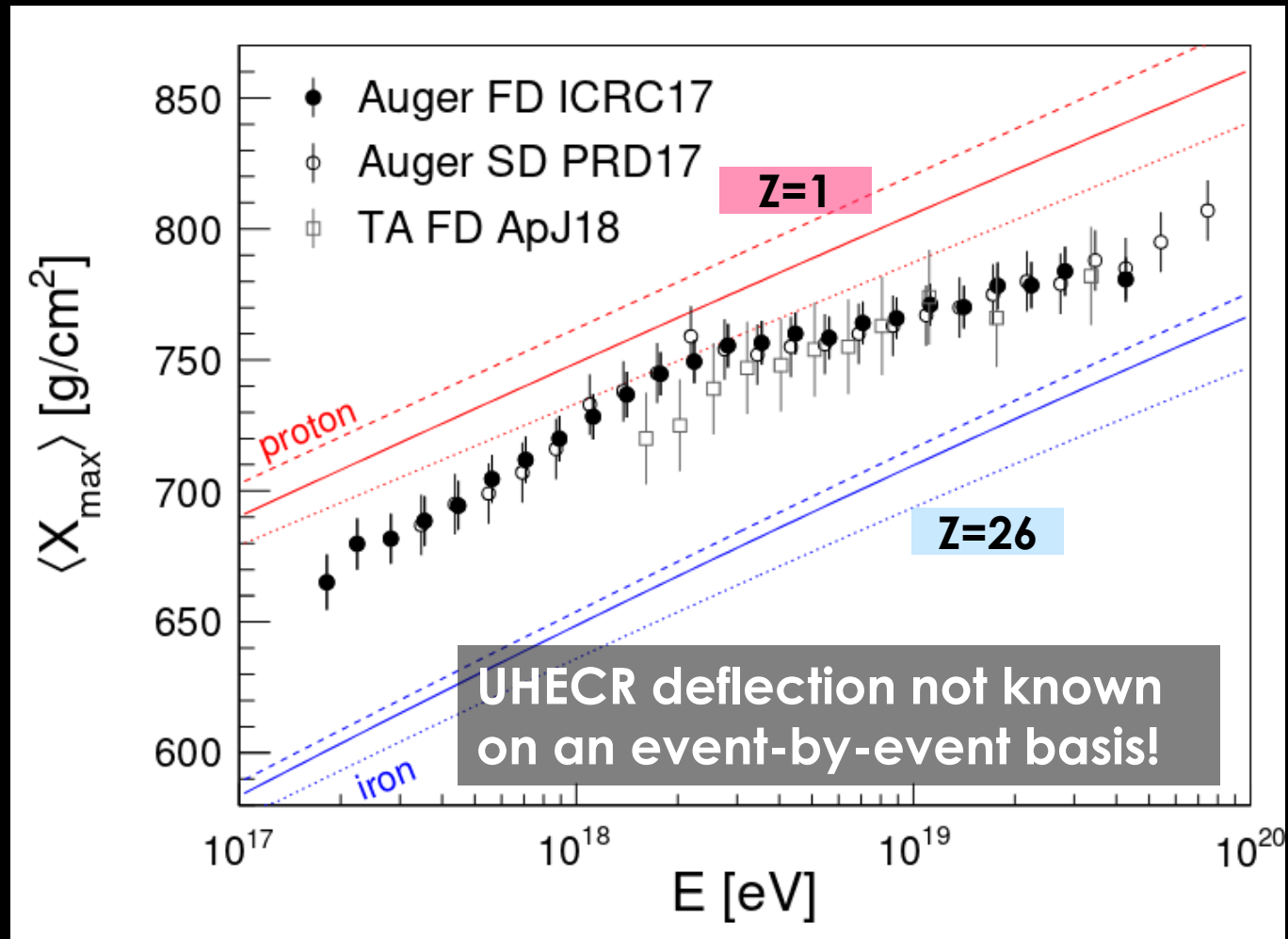
UHECR deflection

Simulated deflection for a proton (100 EeV) in Galactic Magnetic Field (GMF) with the Jansson-Farrar (JF12) model.



<https://doi.org/10.1016/j.astropartphys.2016.10.002>

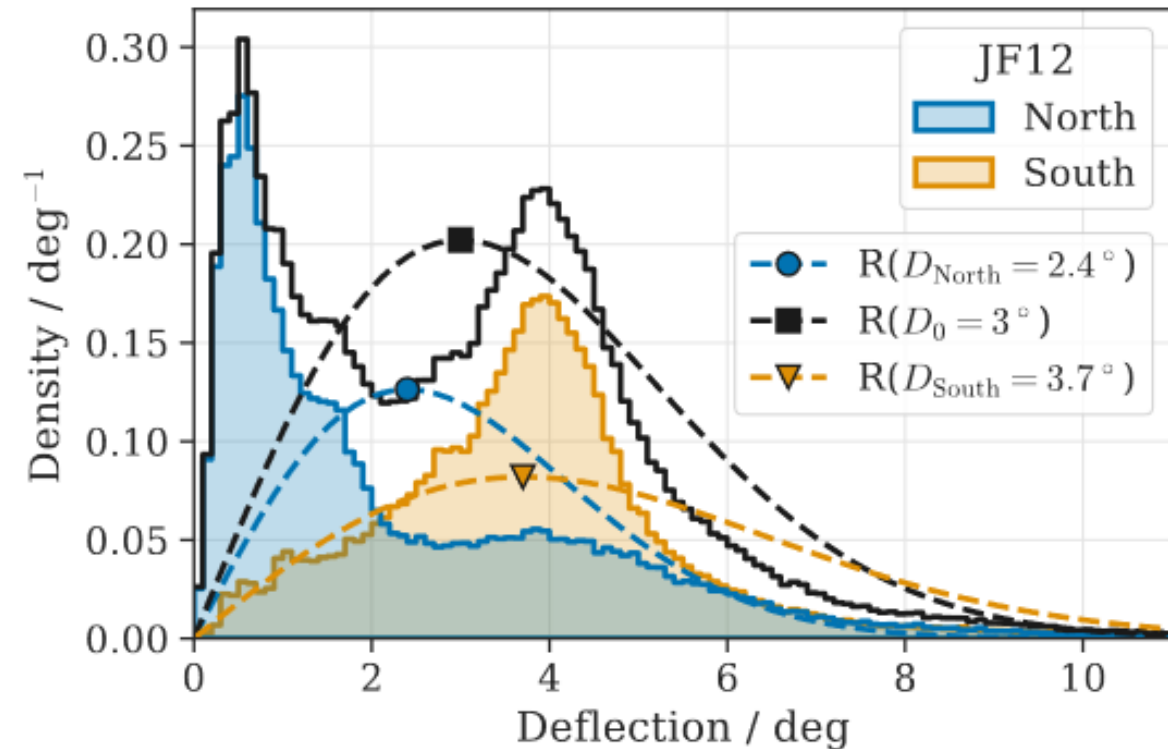
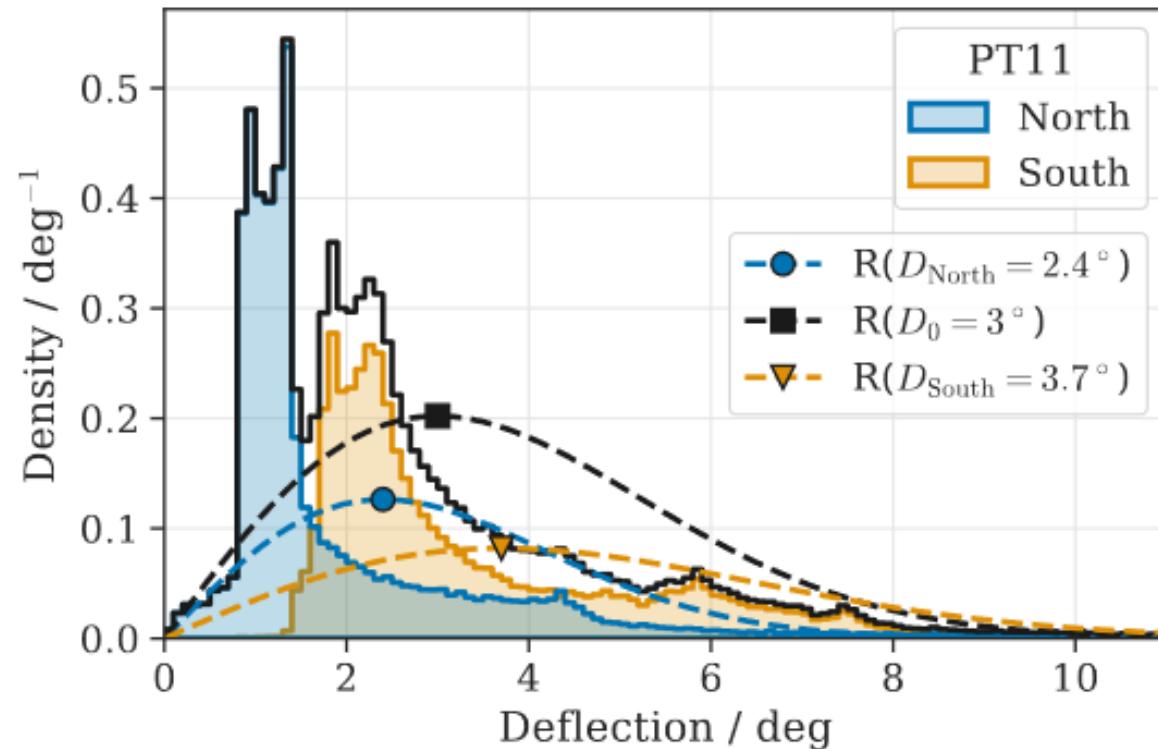
UHECR **composition** measurements compared to proton (**red**) and iron (**blue**) expectation up to ~ 70 EeV



UHECR deflection approximation

Simulated deflection for a proton (100 EeV) in Galactic Magnetic Field (GMF) with the Pshirkov-Tinyakov (PT11) and Jansson-Farrar (JF12) models.

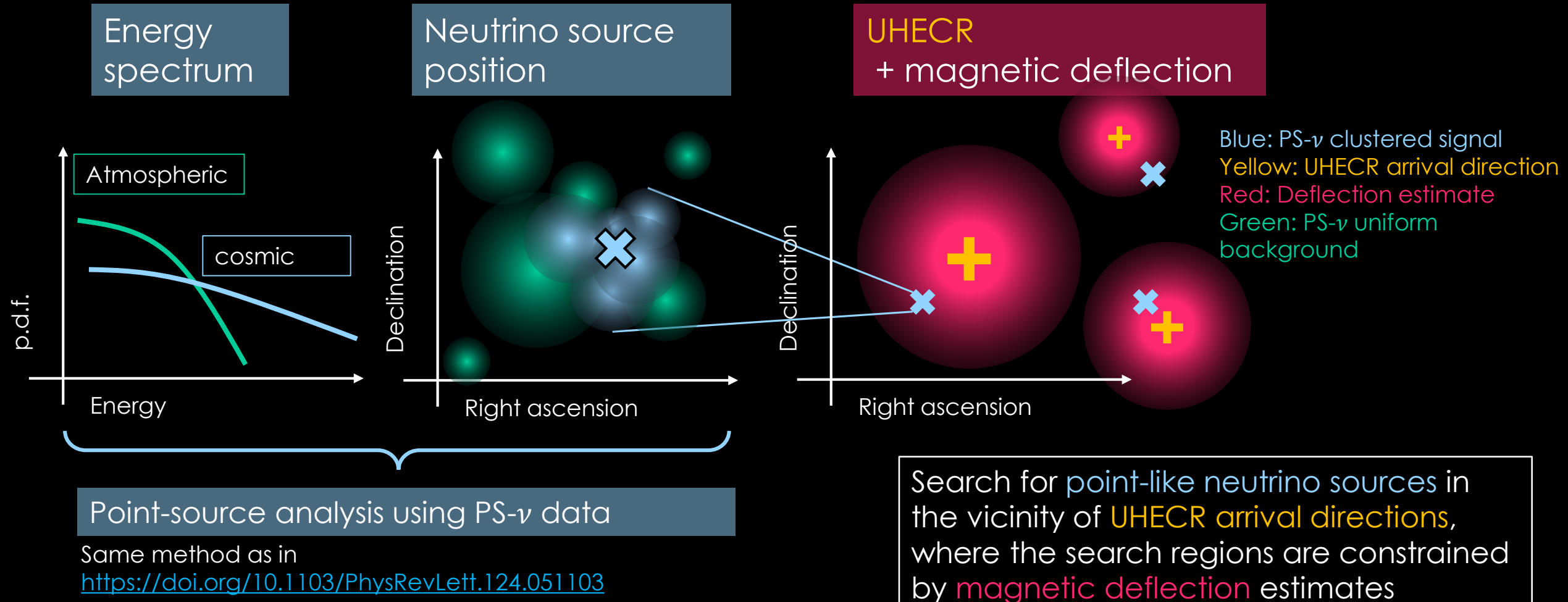
Dashed lines:
Random-walk approximation



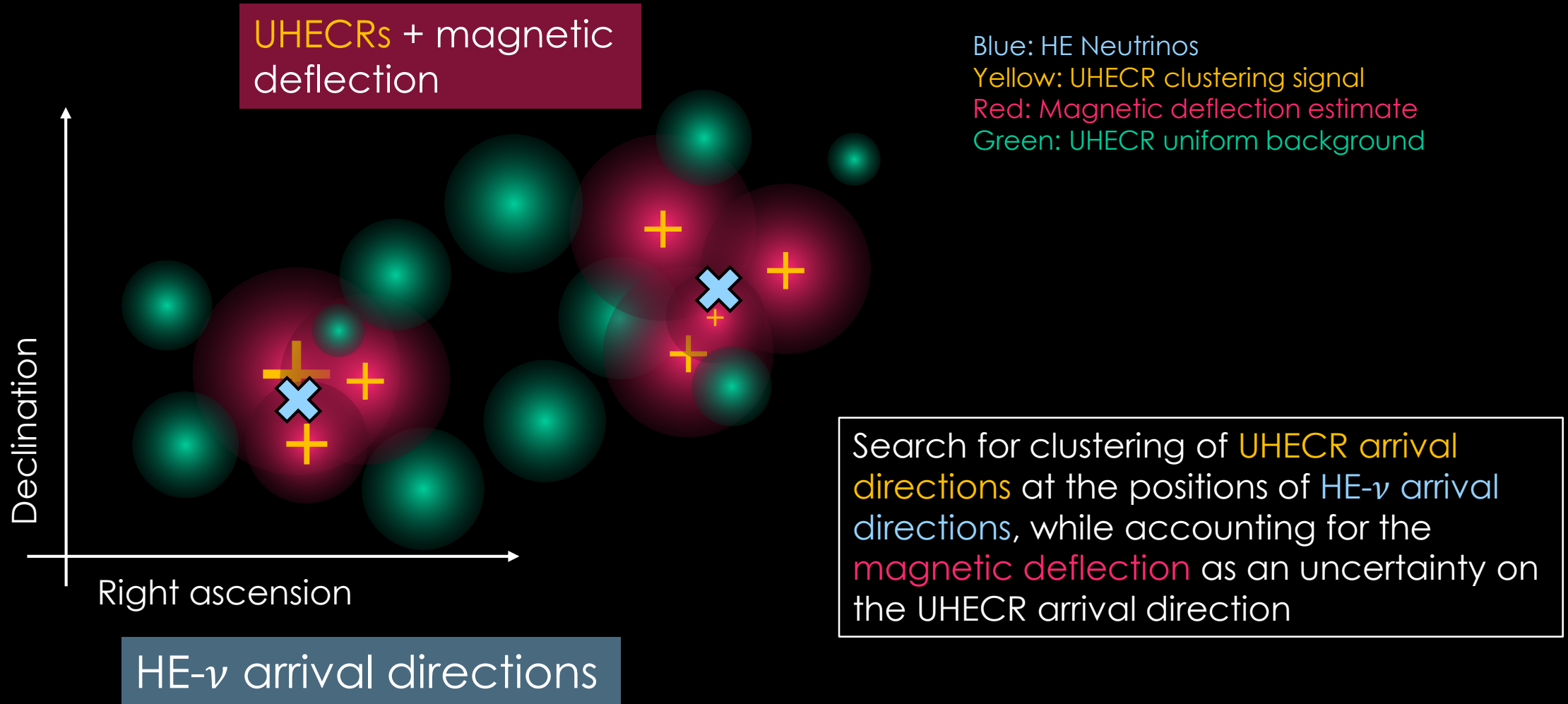
Three approaches: Combining data of different particle types and observatories

Preprint: arXiv:2201.07313
Accepted by ApJ

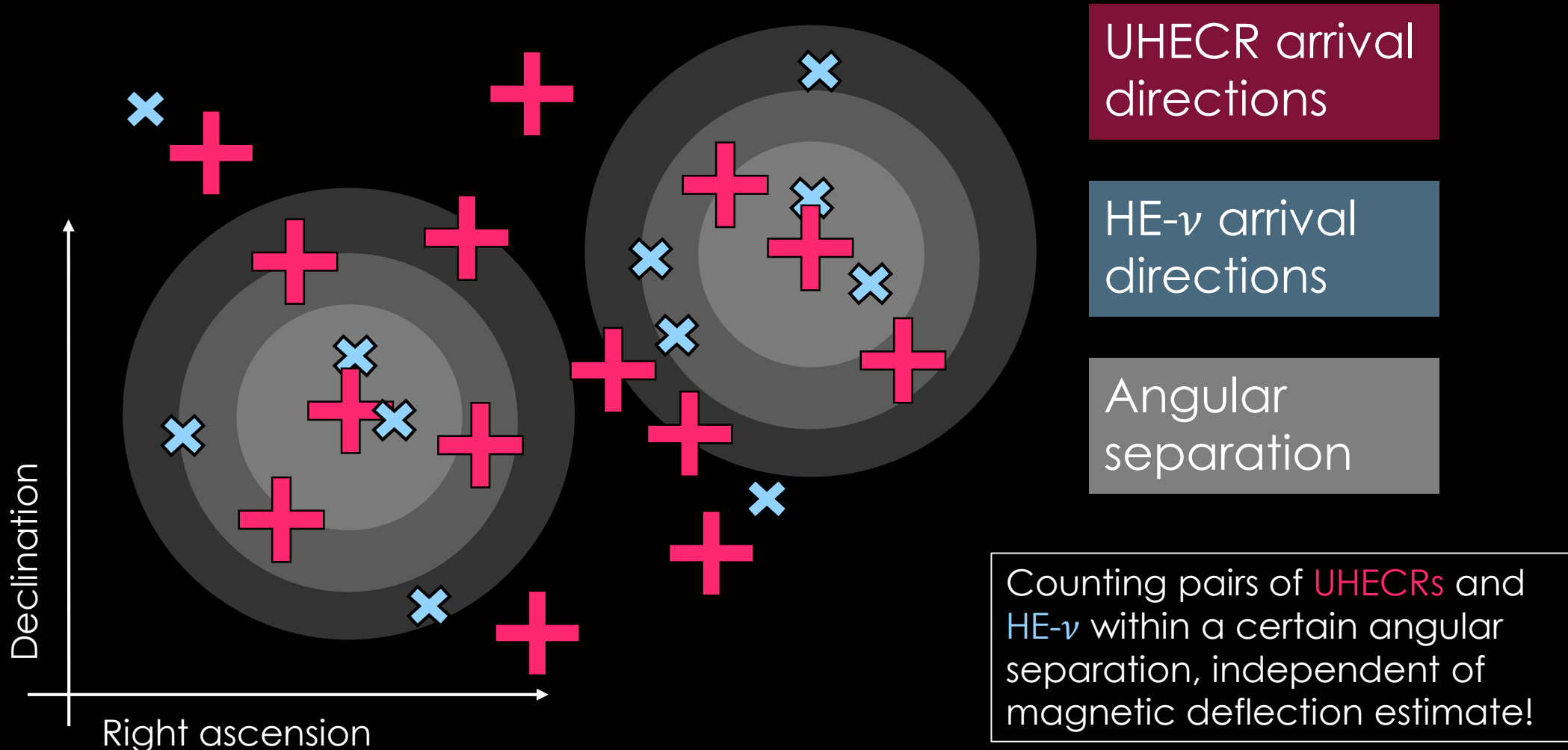
1) Point-source analysis of neutrinos with additional UHECR and deflection information



2) Stacking analysis of UHECRs at neutrino arrival directions



3) Angular-separation count of UHECR and neutrino pairs



Results

1) Neutrino PS

- Six hypotheses tested: smallest p-value 9% (24% after multiple testing correction)
→ Background compatible
- 90% U.L. on ν_μ -flux per source
$$\frac{d\Phi}{dE} \sim 1 \dots 10 \cdot 10^{-10} / \text{GeV cm}^2 \text{ s} \cdot \left(\frac{E}{1 \text{ GeV}} \right)^{-2}$$
depending on assumed deflection strength, UHECR energy threshold and ν -correlation fraction

2) UHECR stacking

- Six hypotheses tested: smallest p-value 26%
→ Background compatible
- 90% U.L. on number of UHECRs correlated with HE- ν events:
 - <10 correlated with ν tracks
 - < 50...100 correlated with ν cascades(out of 324+143 UHECRs)
 - Depending on assumed deflection strength

3) Angular separation

- Four hypotheses tested: smallest p-value 15% (corrected for angular-separation scan $1^\circ \dots 30^\circ$)
→ Background compatible
- Depending on ν -tracks/cascade separation and isotropic UHECR/ ν background hypothesis

Results

1) Neutrino PS

- Six hypotheses tested: smallest p-value 9% (24% after multiple testing correction)
→ **Background compatible**
- 90% U.L. on ν_μ -flux per source

$$\frac{d\Phi}{dE} \sim 1 \dots 10 \cdot 10^{-10} \text{ (GeV)}^{-2}$$

$$\cdot \left(\frac{E}{1 \text{ GeV}} \right)^{-2}$$

depending on
deflection strength
energy threshold
correlation from

2) UHECR stacking

- Six hypotheses tested: smallest p-value 26%
→ **Background compatible**
- 90% U.L. on number of UHECRs correlated with HE- ν events:
 - <10 correlated with ν

3) Angular separation

- Four hypotheses tested: smallest p-value 15% (corrected for angular-separation scan $1^\circ \dots 30^\circ$)
→ **Background compatible**

Initial indication of UHECR-neutrino correlation at 3σ level could not be confirmed with significantly enlarged data sets and improved methods

<https://doi.org/10.1088/1475-7516/2016/01/037>

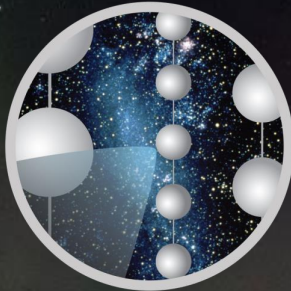
ν -
e
isotropic
ground

Why haven't we detected any sources?

- Efficient UHECR sources could be less efficient neutrino sources and vice versa
- UHECR horizon:
 - Too few strong* neutrino sources within ~ 200 Mpc, compared to neutrino horizon of $\sim$ Gpc
 - Example:
Distance to blazar TXS 0506+056: 1.3 Gpc
Distance to NGC 1068: 16 Mpc
- Deflection is underestimated:
 - Too few protons at highest energies, magnetic deflection leads to spatially uncorrelated heavy UHECRs and neutrinos
 - Galactic and intergalactic magnetic fields are stronger than assumed
- Sources are transient: due to magnetic deflection, UHECRs and neutrinos arrive at significantly different times

*detectable with
ANTARES/IceCube

Exploring the cosmos, together!



ICECUBE



Thanks for your attention!

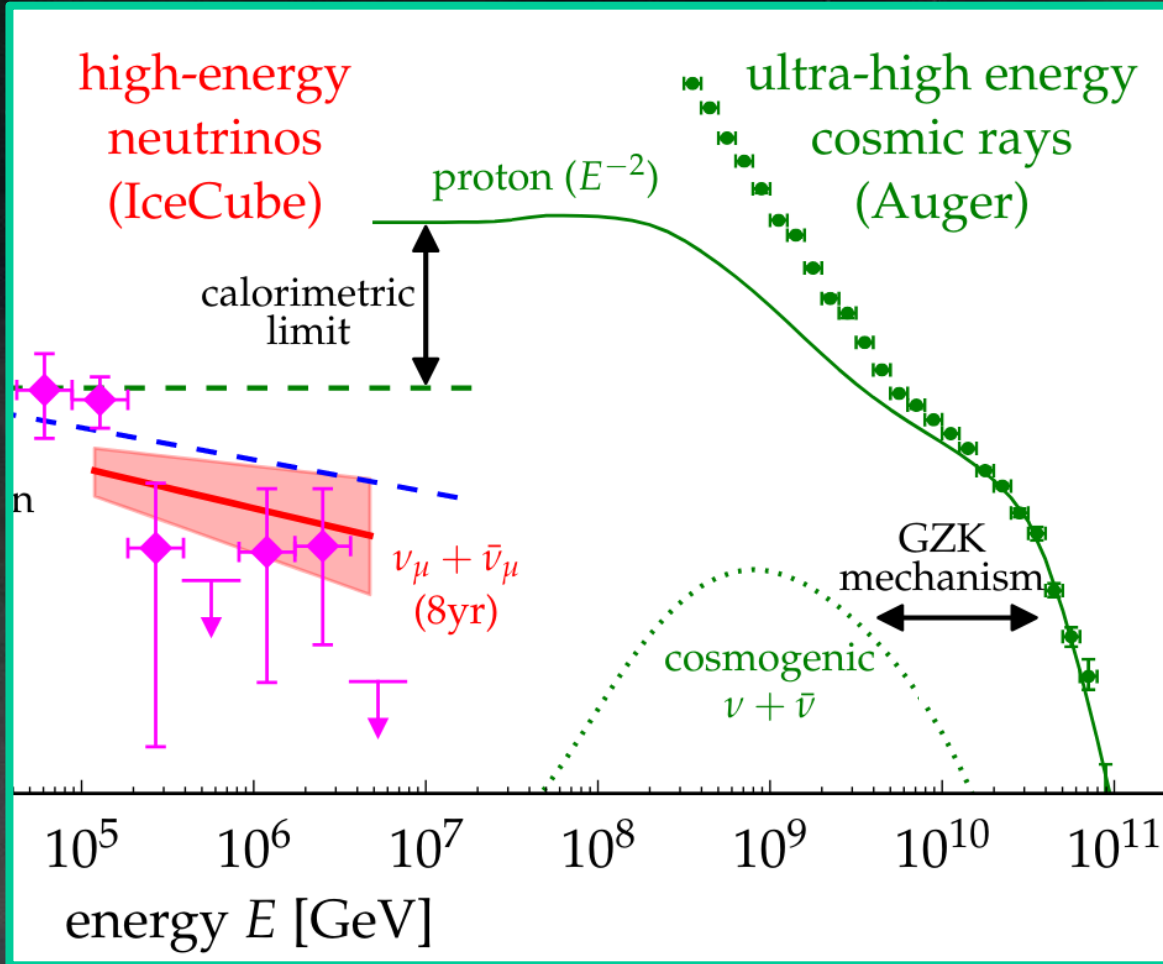
Summary:

- Search for common sources of UHECRs and neutrinos is motivated by similar energy density and potentially similar source candidates
- Unknown UHECR charge and complicated galactic magnetic fields are currently the largest uncertainties
- No excess over background expectation was found
- Pre-Print on arXiv (arXiv:2201.07313) and in last stage of publication processing by ApJ!

A photograph of the Aurora Borealis (Northern Lights) over a snowy, mountainous landscape at night. The sky is dark with numerous stars visible. The aurora displays vibrant green and red light curtains. The ground is covered in snow, and the horizon shows dark silhouettes of mountains and trees.

Back up slides

Production of high-energy neutrinos



Energy:

- $E_\nu = E_{CR} \cdot \frac{0.05}{A}$

- 30 TeV (10 PeV) neutrinos originate from 600 TeV (200 PeV) CR protons

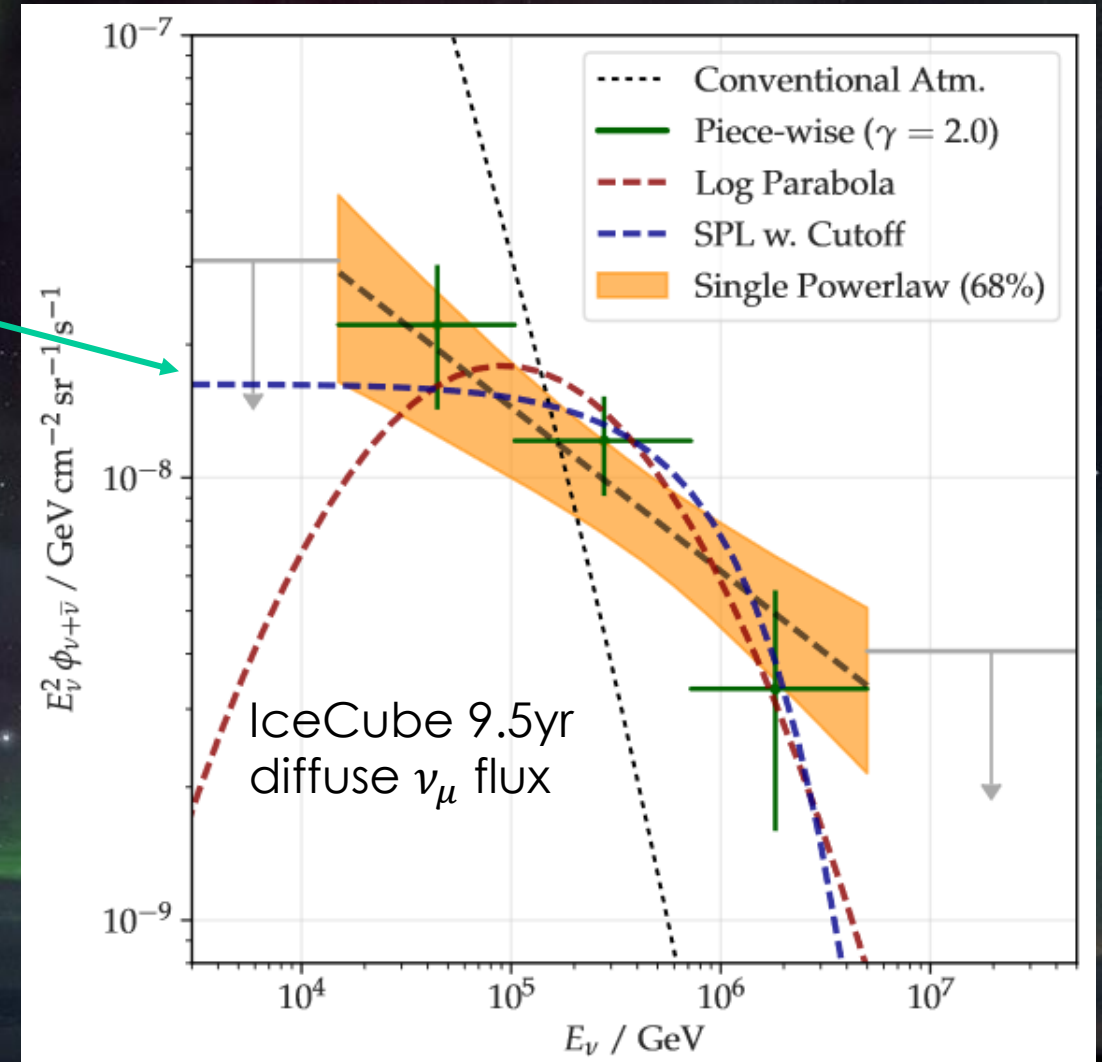
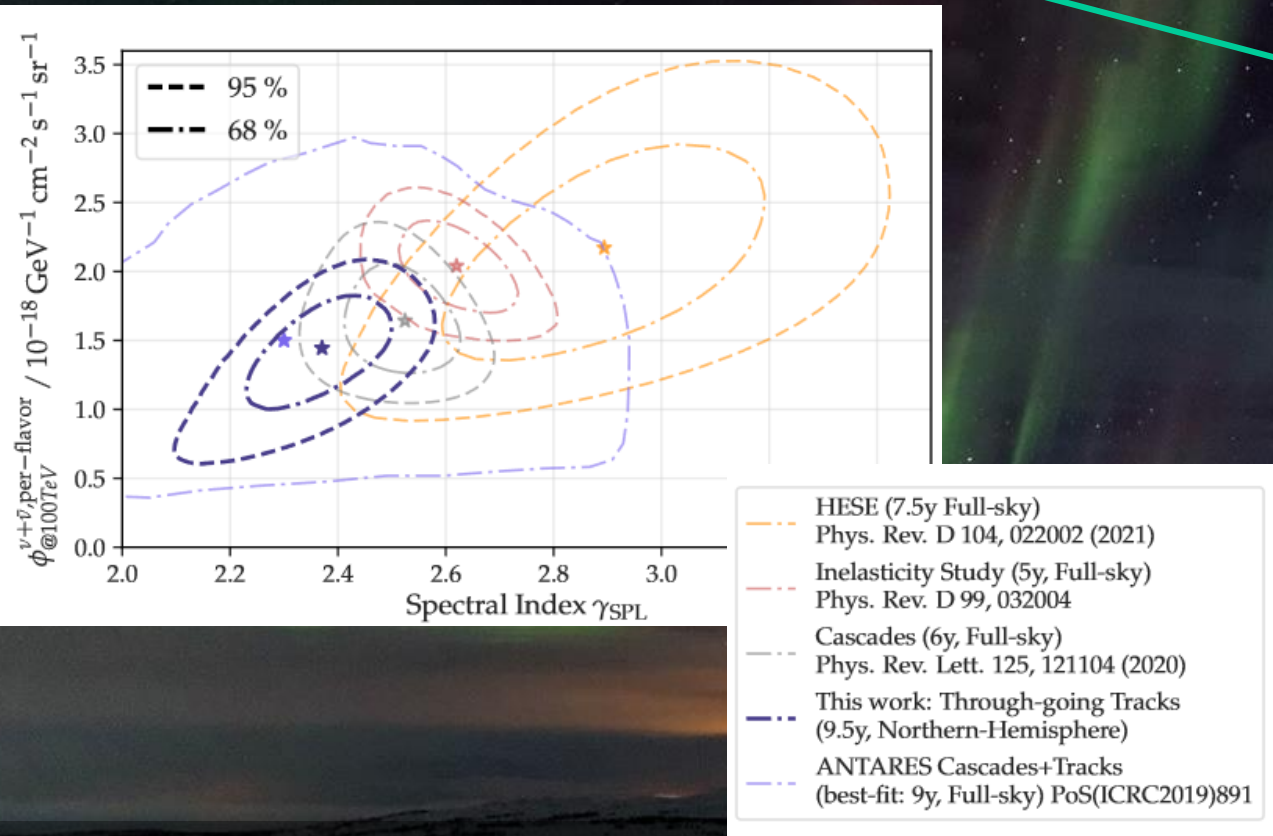
How does this fit with UHECR energies above $10^3 - 10^5$ PeV?

- Lower-energy CRs with flux $\propto E^{-2}$ produce neutrinos, while UHECRs leave the source

- Calorimetric environment for lower-energy CRs + partial acceleration and escape of UHECRs

Diffuse Flux ν_μ measurement

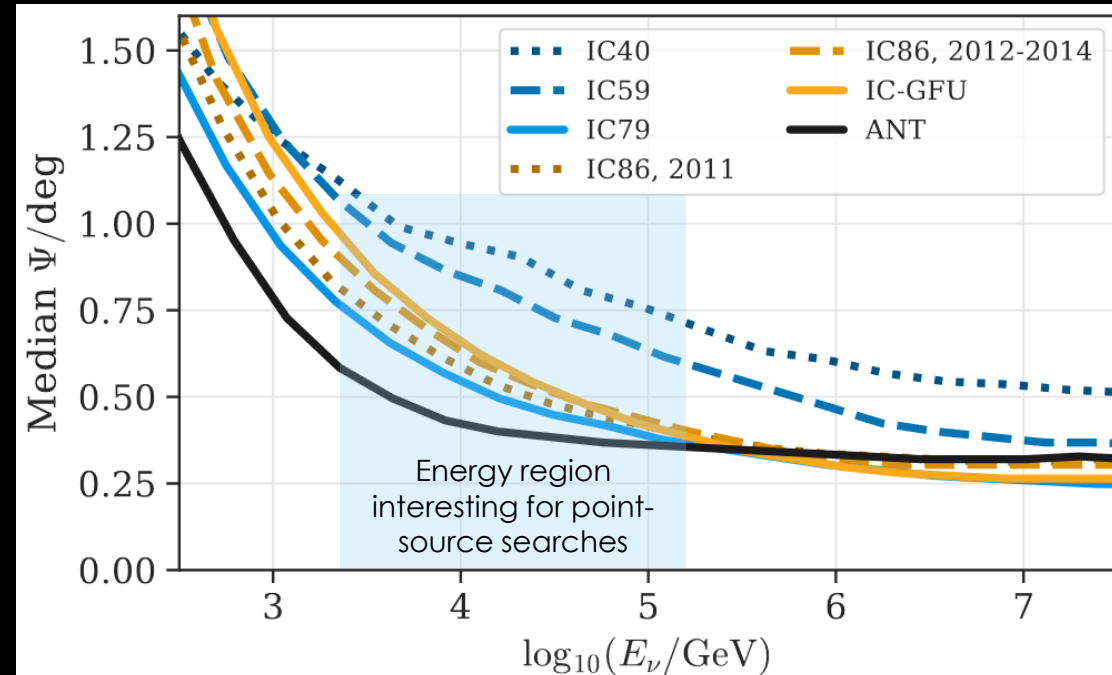
1) Waxman-Bahcall bound
at $E^2 \frac{d\Phi}{dE} \sim 10^{-8} \text{ GeV/cm}^2 \text{ s sr}$



Angular resolution and signal acceptance for muon neutrinos

Why combine ANTARES and IceCube data?

ANTARES reaches good angular resolution of $<0.5^\circ$ at lower energies than IceCube



ANTARES contributes significant signal to Southern Hemisphere, especially for soft spectral indices

