What's Nu?:
Status of neutrino astrophysics and the UHECR connection

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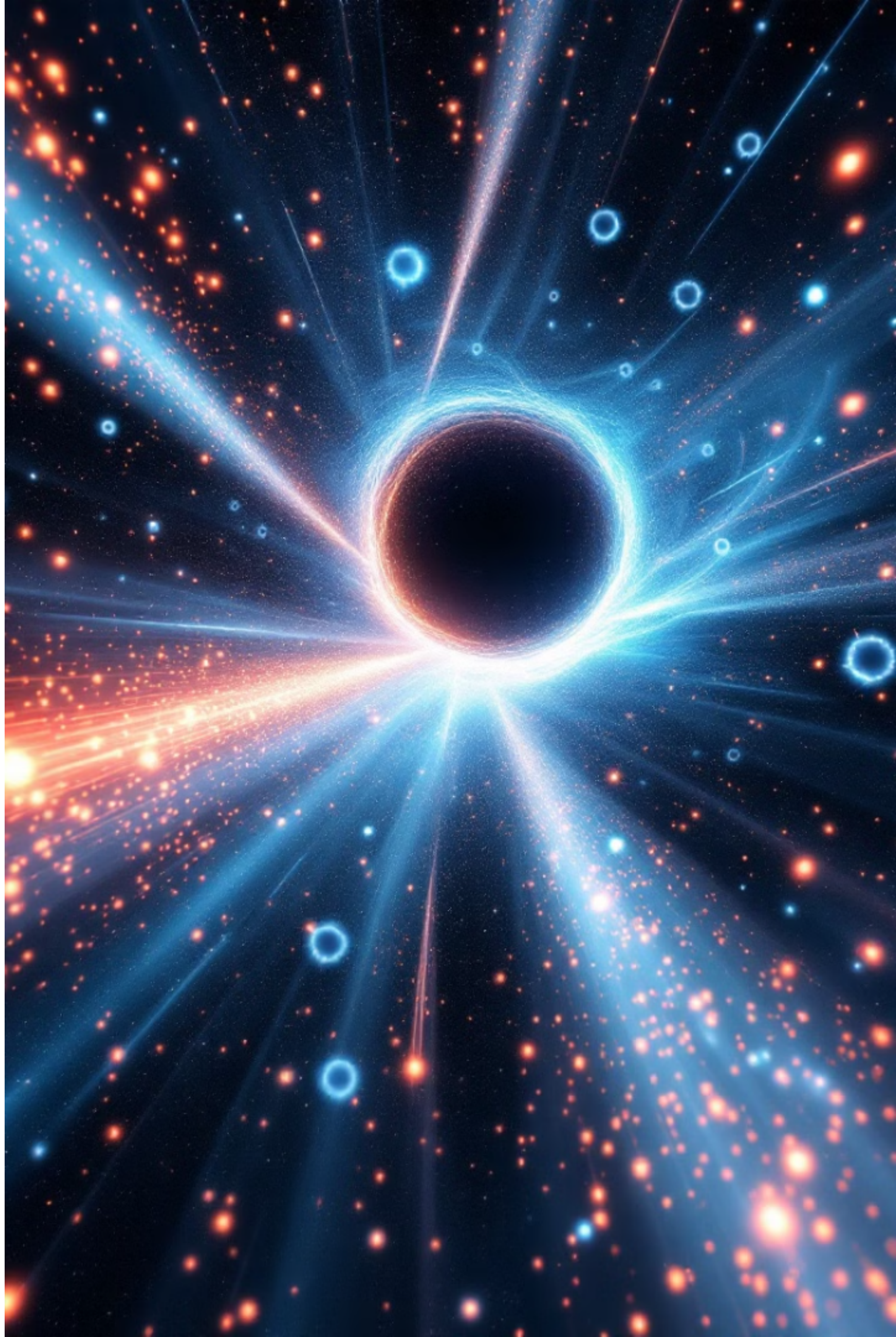
7th International Symposium on Ultra-High-Energy Cosmic Rays
Malargüe, 19th November 2024

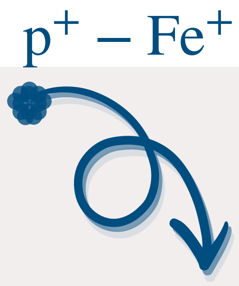
SFB 1258 Neutrinos Dark Matter Messengers

ODSL ORIGINS Data Science Lab

MAX-PLANCK-INSTITUT FÜR PHYSIK

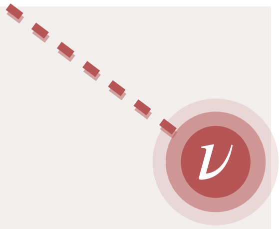


Probes of energetic particle acceleration



Cosmic Rays

Accelerated charged particles can escape their sources and be detected

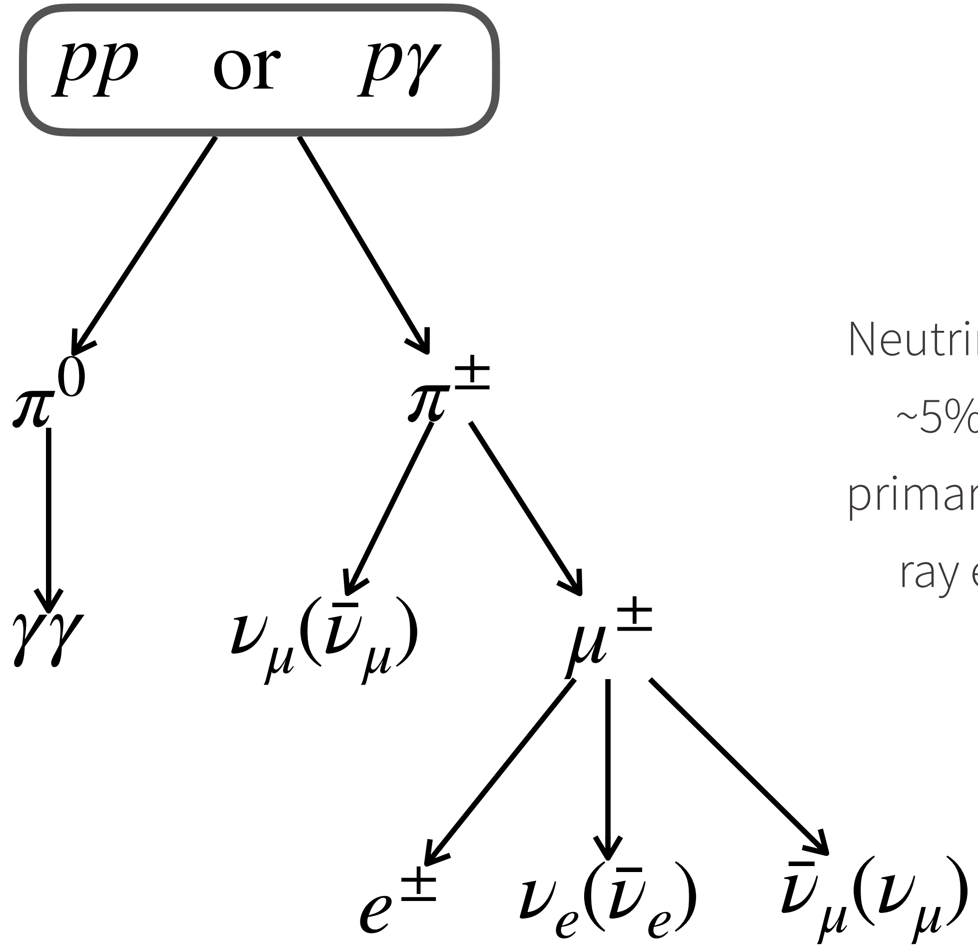


Neutrinos

Neutrinos are only produced in hadronic interactions
⇒ clear signal

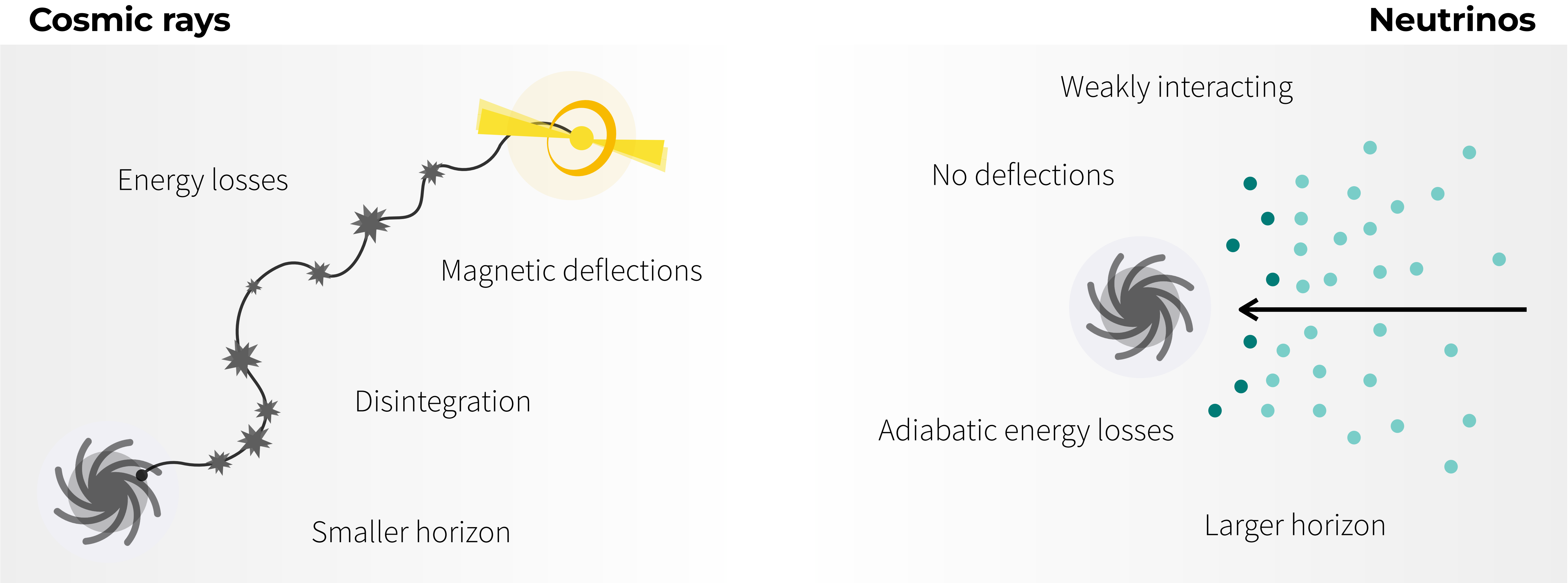
Photohadronic and Hadronuclear reactions

Gamma-rays can have leptonic or hadronic origin, may be absorbed



Neutrinos carry ~5% of the primary cosmic ray energy

The cosmic ray—neutrino connection



Complementary information from each messenger

The UHECR—neutrino connection

UHECRs: ~EeV scale

Magnetic deflections ⇒
Astronomy only at highest rigidities

Interactions ⇒
Local sources

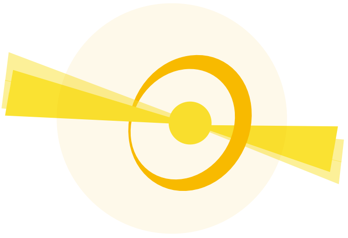
HE ν: TeV—PeV scales; UHE ν: ~EeV scale

$E_\nu \sim 0.05\ E_{CR}$

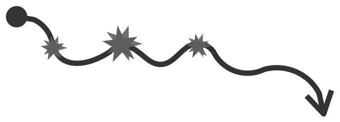
HE neutrinos produced by lower energy cosmic rays
UHE neutrino connection clearer

Local and distant sources

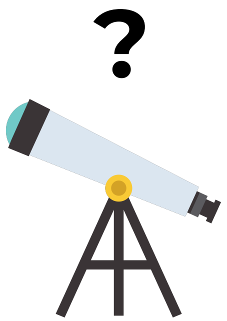
Possible sites of neutrino production



Source environment
HE, UHE ν



UHECR propagation
UHE ν, “cosmogenic”



Challenges in connecting current observations

This talk:

High-energy (~TeV—PeV) neutrinos

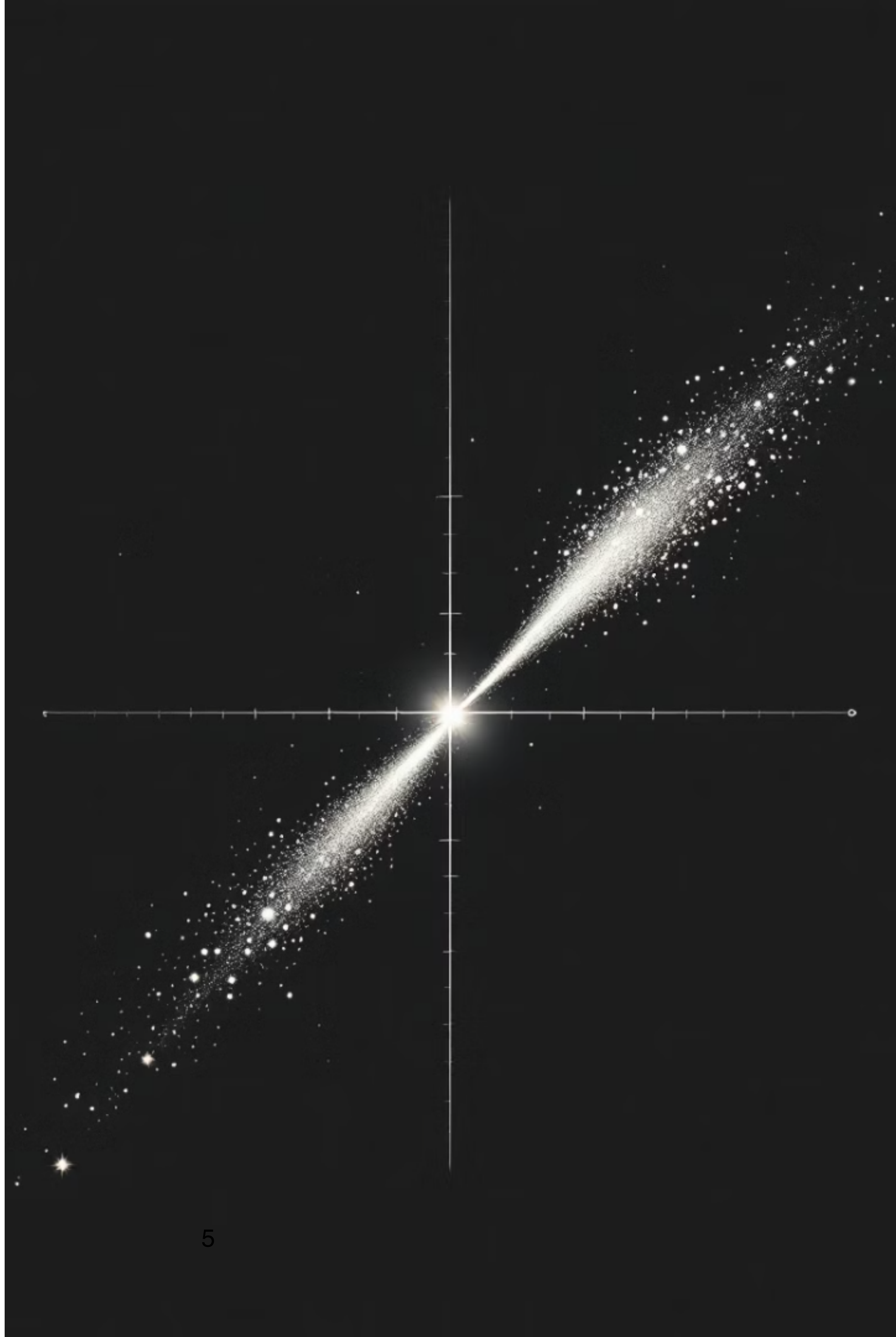
First sources emerging, many observations

Ultra-high-energy (~EeV) neutrinos

Many planned experiments

The UHECR connection

How we can use this data to pinpoint UHECR sources



The high-energy neutrino sky

1 Diffuse flux

2 Galactic plane

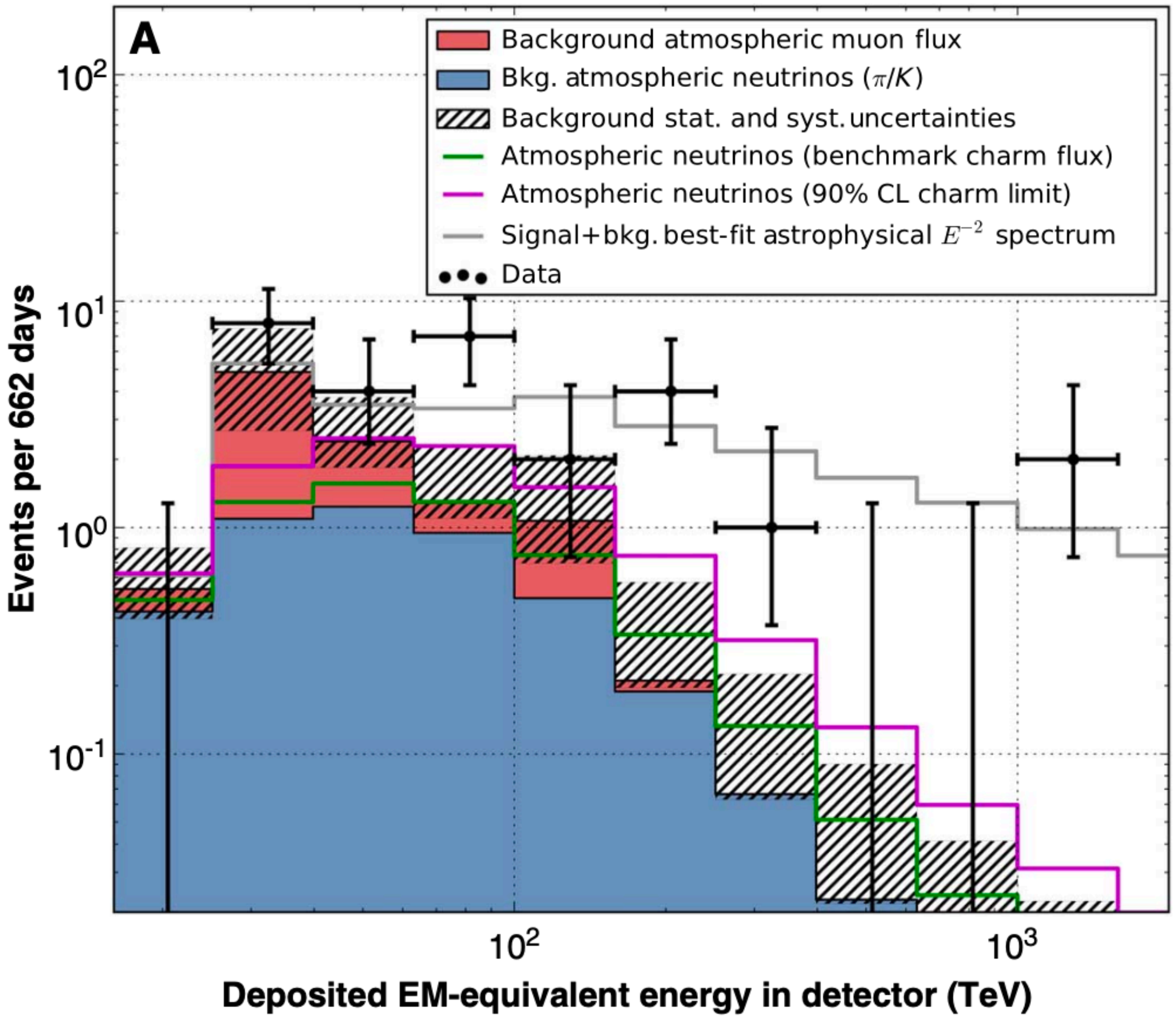
3 Point sources

4 High-energy events

Diffuse flux

Discovery in 2013

First detection of astrophysical neutrinos with a significance of 4σ using starting events in IceCube [Aartsen+ Science (2013)]



Diffuse flux

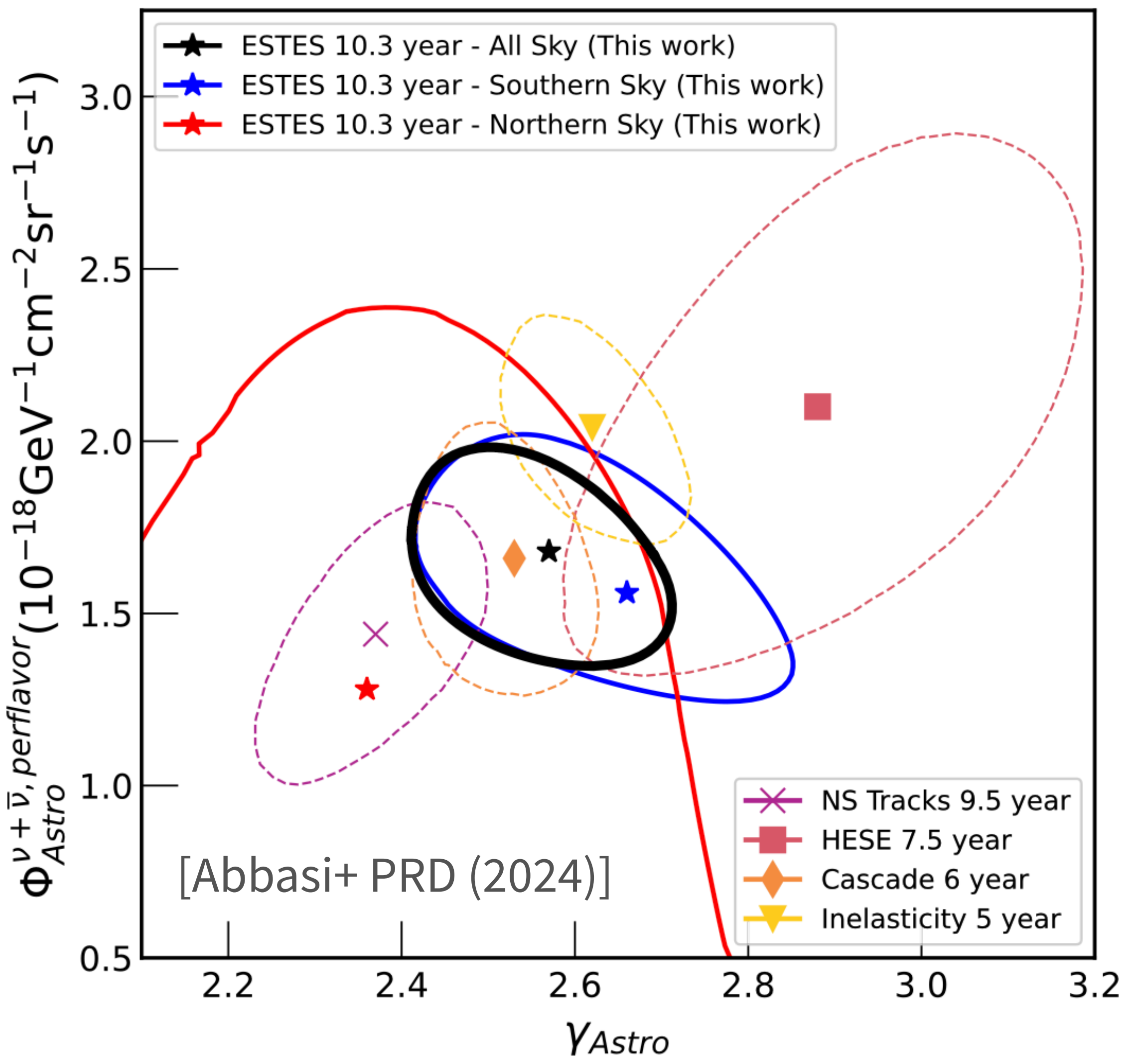
Characterisation in various channels

Cascades [Aartsen+ PRL (2020)]

HESE: High-energy starting events [Abbasi+ PRD (2021)]

Through-going muon tracks [Abbasi+ ApJ (2022)]

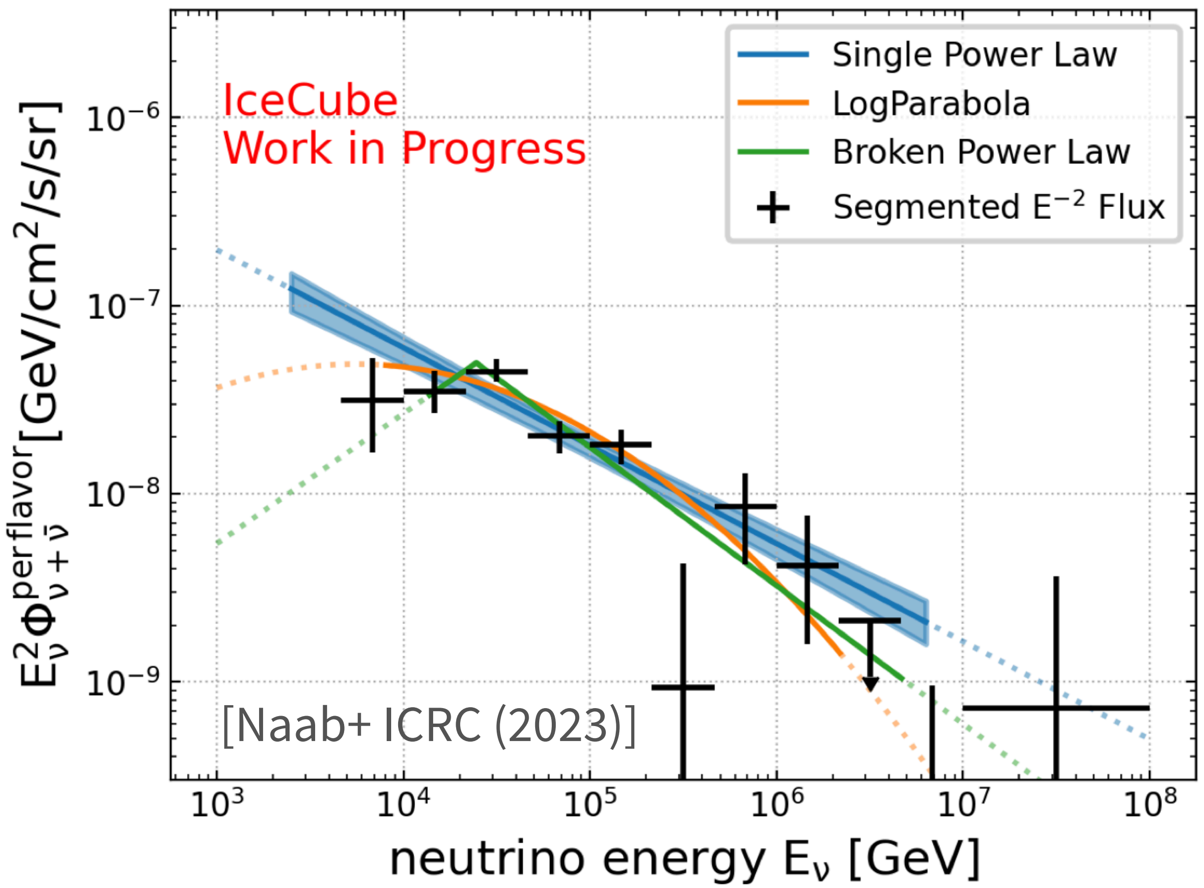
ESTES: Enhanced starting track event selection [Abbasi+ PRD (2024)]



Well-described by a power law

Hints of substructure from tracks and cascades

Diffuse flux



Combined analyses

Make the most of different event selections!

[Aartsen+ ApJ (2015); Naab+ ICRC (2023); Rechav+ TeVPA (2024)]

Stronger constraints and indication of spectral break

Diffuse flux

Status

Clear astrophysical signal

Flavour composition consistent with equal ratio

Possible spectral break (2σ significance)

Source constraints

Should not overproduce gamma-rays

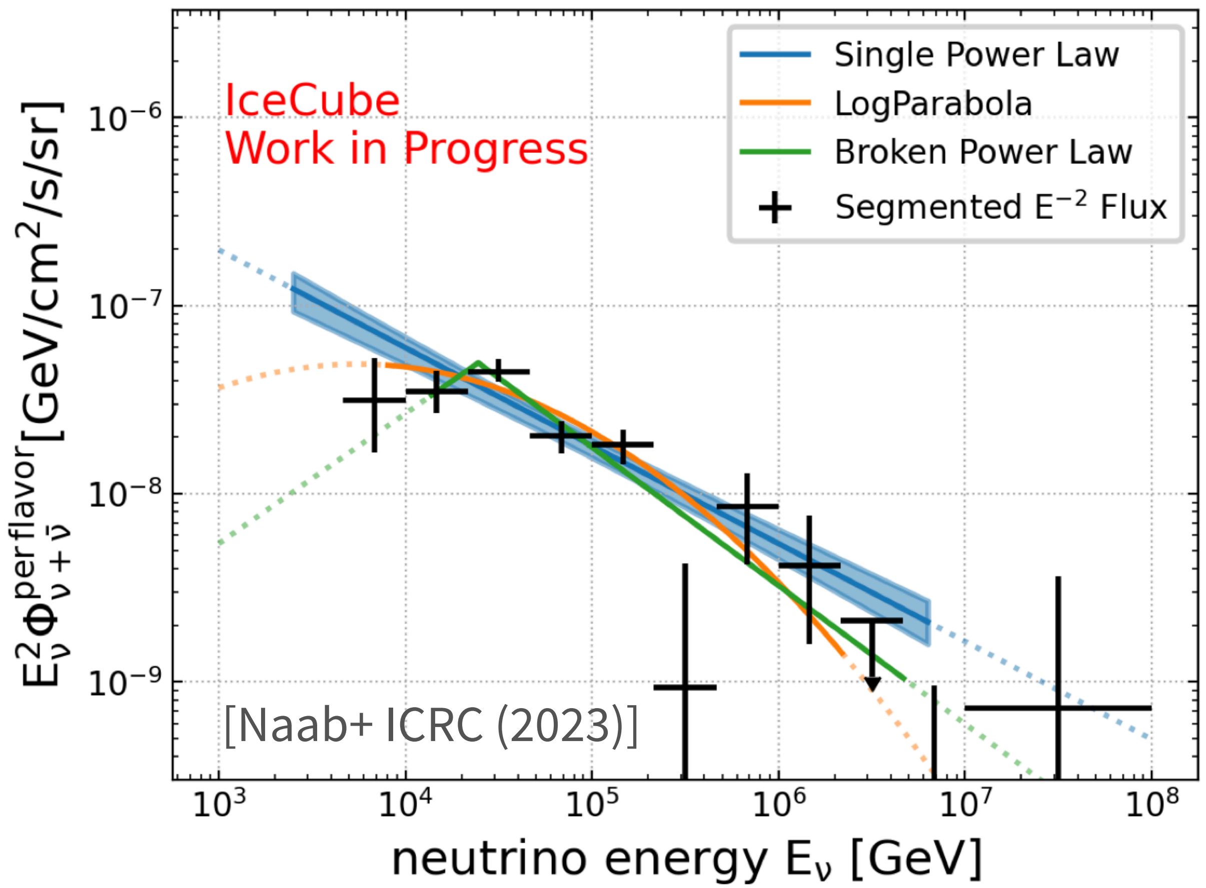
[Bechtol+ ApJ (2017); Murase+ PRL (2016)]

Combined density and luminosity of proposed source classes must not overshoot

[E.g. Murase+Waxman PRD (2016); Capel+ PRD (2020)]

Expect high-energy "bump" imprint of pγ processes

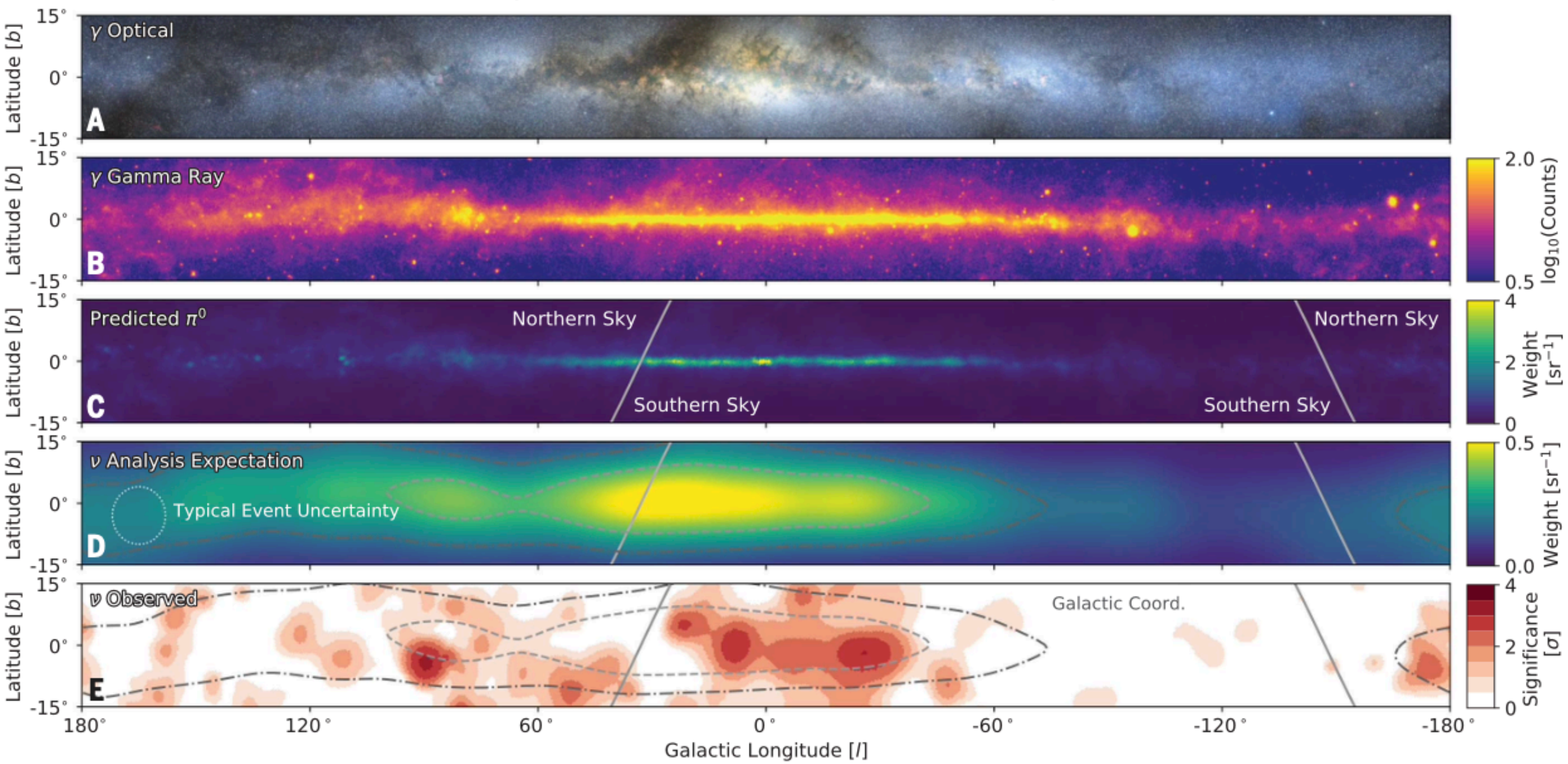
[Fiorillo+Bustamente PRD (2022)]



Galactic plane

Connection to lower-energy Galactic cosmic rays

Search based on gamma-ray predictions finds 4.5σ significance



[Abbasi+ Science (2023)]

Extra-Galactic sources are more powerful

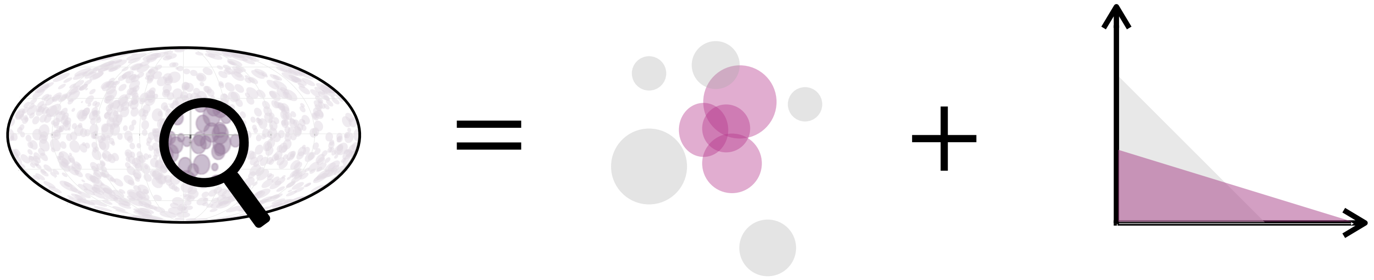
We can still learn about higher-energy particle acceleration from nearby lower-energy systems

[E.g. Fang+ Nat. Astron (2024); Fang+Murase ApJL (2024); Desai+ ApJ (2024); Ambrosone+ PRD (2024); Allakhverdyan+ (arXiv:2411.05608)]

Point sources

How to search for sources in the diffuse sky?

1. Excess/clustering of neutrino directions
2. Excess of neutrinos at higher energies



[Braun+ Astropart. Phys. (2008); Wolf+ ICRC (2019); Bellenghi+ ICRC (2023); SkyLLH code]

Test points across the sky

Unbiased way to look for “hotspots”

Many points tested ⇒ large trial correction factor

Not very sensitive

Use information on known sources

Test a fixed list ⇒ small trial correction factor

“Stacking” of similar sources to increase signal

Multi-messenger selection or weighting

Some examples (incomplete)

Active Galactic Nuclei & Blazars

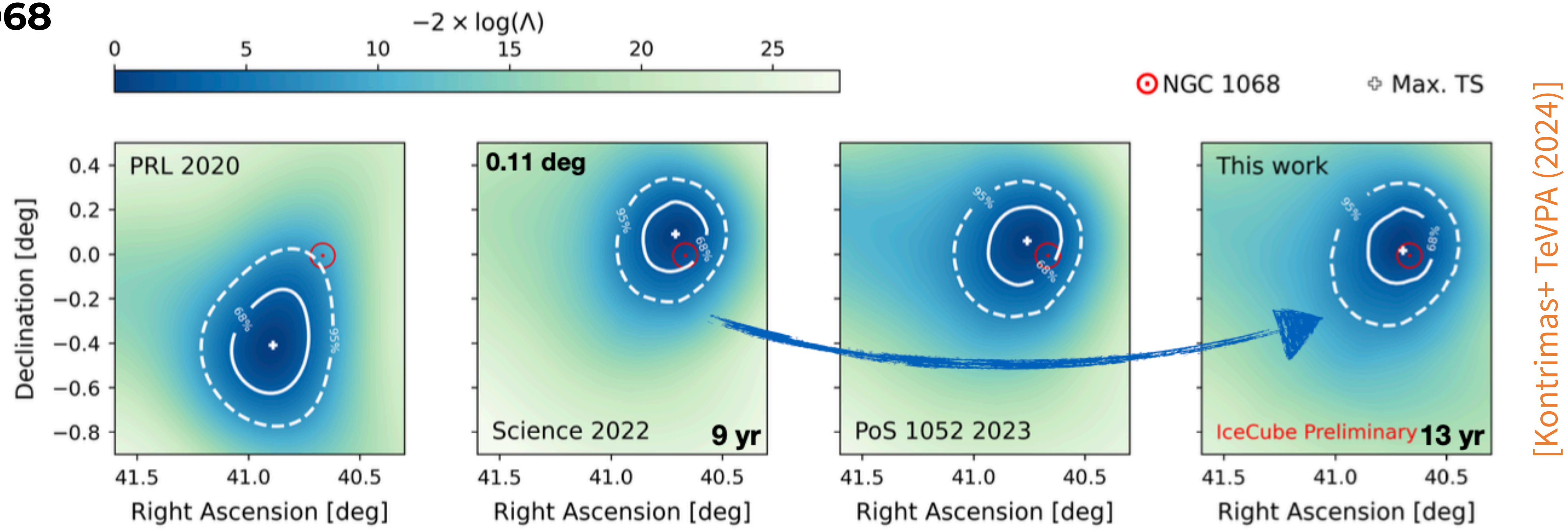
[IceCube+ (2018a, 2018b); Plavin+ (2020); Giommi+Padovani (2021); Buson+ (2022/23); Bellenghi+ (2023); Rodrigues+ (2024)]

NGC 1068 & Seyfert galaxies

[Abbasi+ (2022); Neronov+ (2023), Abbasi+ (2024a,b)]

Point sources

NGC 1068



Including more data:

Moves the hotspot closer to NGC 1068

Softens the spectral index to γ ~ 3.4

Lowers the significance slightly to 4σ

[Aartsen+ PRL (2020); Abbasi+ Science (2022); Glauch+ ICRC (2023)]

Point sources

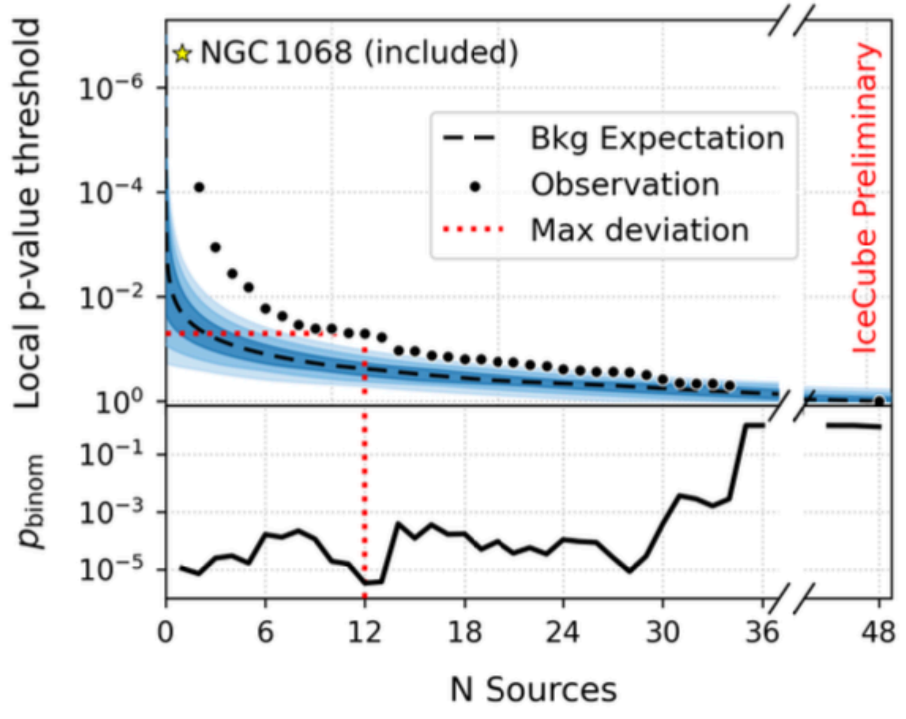
NGC 1068 & Seyfert galaxies

Search for X-ray bright Seyfert galaxies (Northern sky) [Abbasi+ (arXiv:2406.07601)]
2.7σ from binomial analysis due to 2 sources: NGC 4151 and CGCG 420-015

ESTES Southern sky Seyfert search [Yu+ TeVPA (2024)]
3.0 σ from stacking of 13 Southern Seyfert galaxies

Search for hard X-ray AGN [Abbasi+ (arXiv:2406.06684)]
2.9σ from NGC 4151

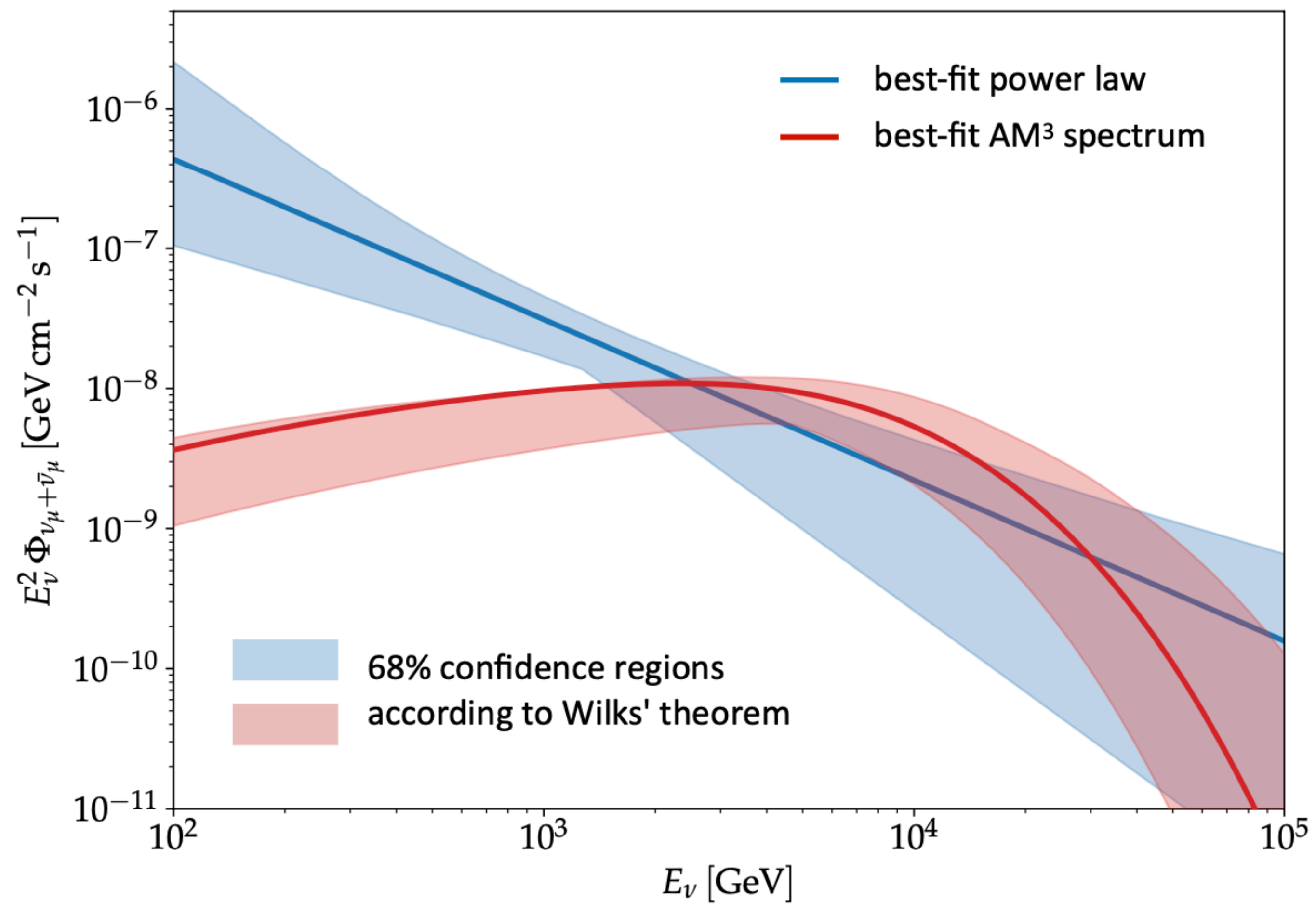
Update to 13 years of data [Kontrimas+ (2024)]
3.3σ from binomial analysis due to 11 X-ray bright Seyferts



[Kontrimas+ TeVPA (2024)]

Point sources

NGC 1068 & Seyfert galaxies



[Saurenhaus+ RICAP (2024); See also Carpio+ TeVPA (2024)]

Hidden sources: not seen in gamma-rays

So far analyses have focused on background rejection

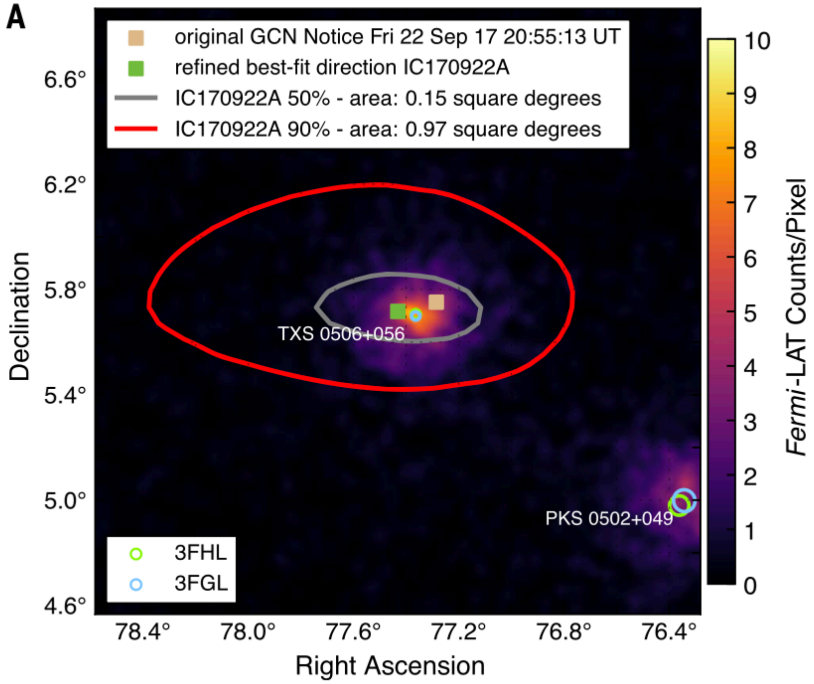
To move beyond discovery to characterisation, physical modelling is important

[Inoue+ (2019,2020); Murase+ (2020); Kheirandish+ (2021); Eichmann+ (2022); Padovani+ (2024)]

High-energy events

Follow-up of individual energetic events that have a higher probability of being astrophysical

Blazar TXS 0506+056



[IceCube+ Science (2018)]

E =~290 TeV, P_{astro} ~ 56%

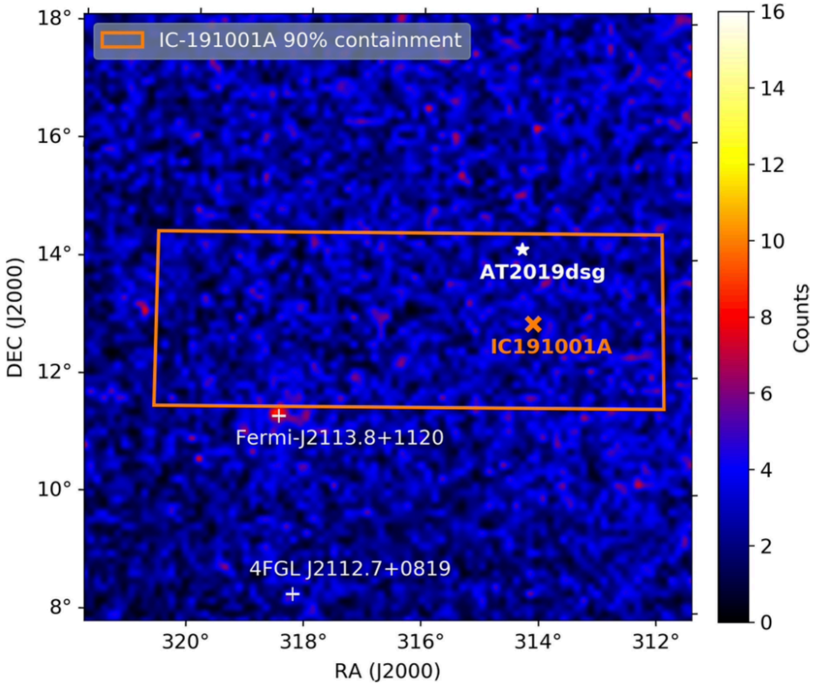
Coincident with ~6 month flare

3σ significance

Gamma-ray—neutrino connection unclear

[IceCube Science (2018)]

TDE AT2019dsg



[Stein+ Nat. Astron. (2021)]

E ~ 200 TeV, P_{astro} ~ 59%

Within ~6 months of TDE onset

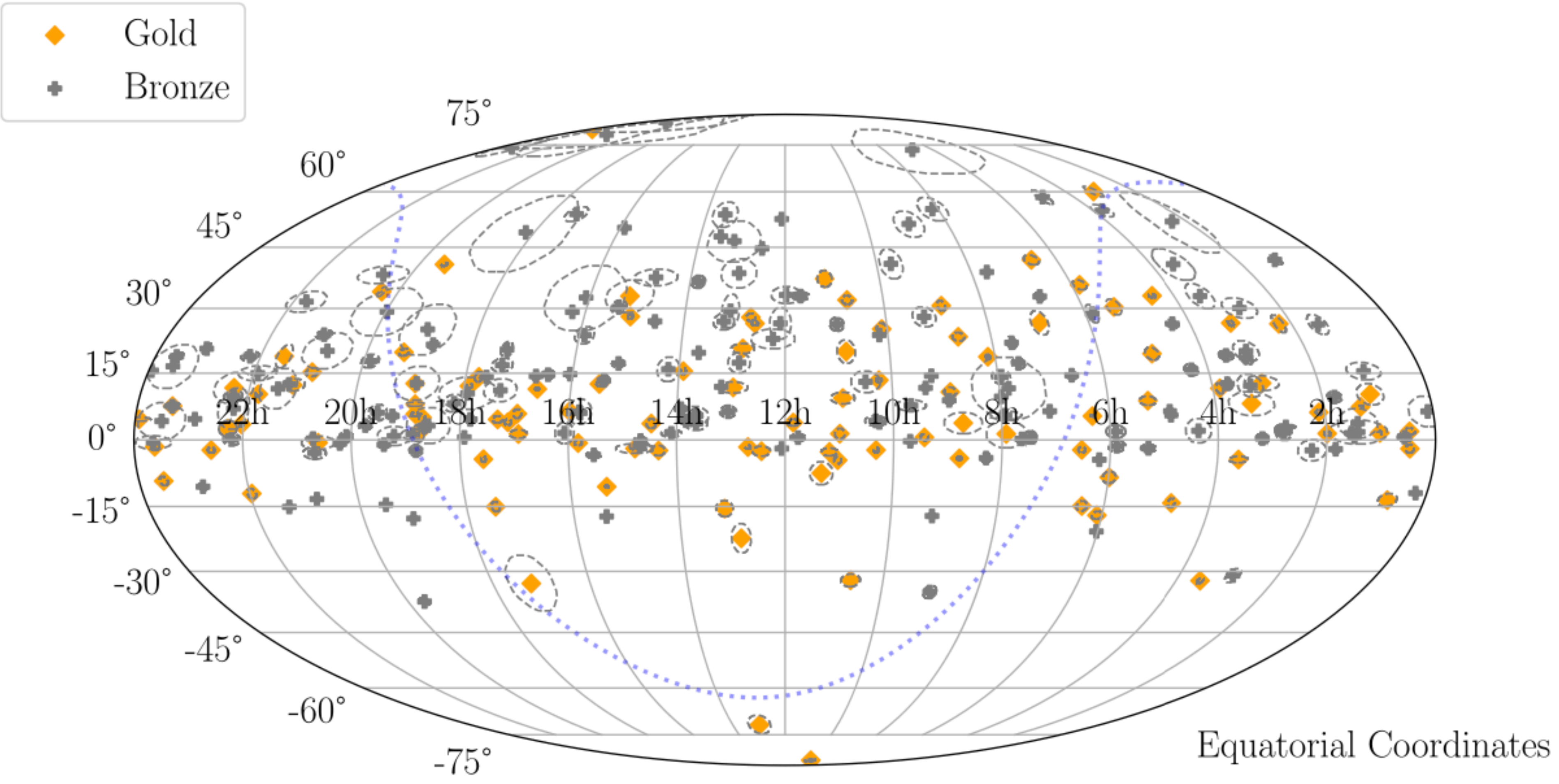
Two other candidates found ⇒ 3.7σ significance

Electromagnetic connection unclear

[Reusch+ PRL (2022); Van Velzen+ MNRAS (2024)]

High-energy events

IceCat-I



Chance coincidence rate is only getting larger as we survey the sky

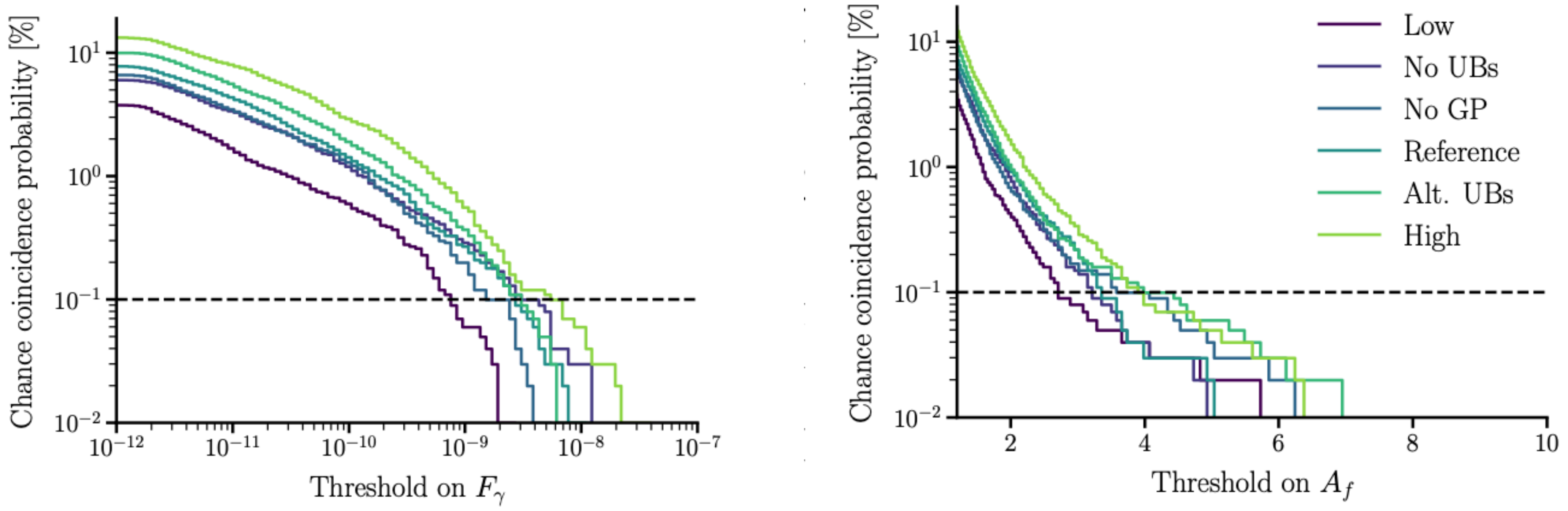
Transient sources and/or physical connections needed for meaningful associations

[Abbasi+ ApJS (2023)]

High-energy events

E.g. Blazar flares

[Capel+ A&A (2022)]

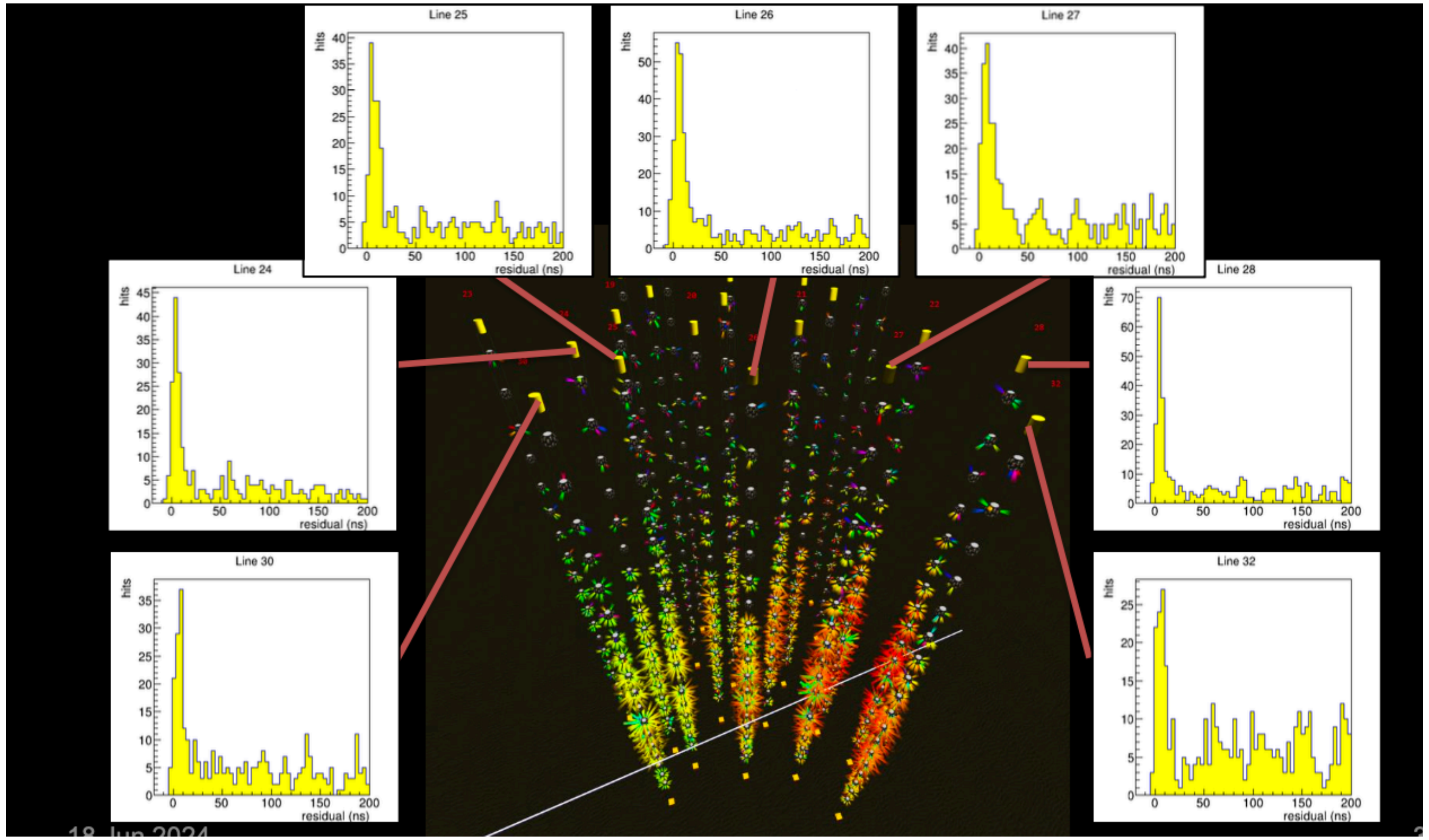


Chance coincidence rate is only getting larger as we survey the sky

Transient sources and/or physical connections needed for meaningful associations

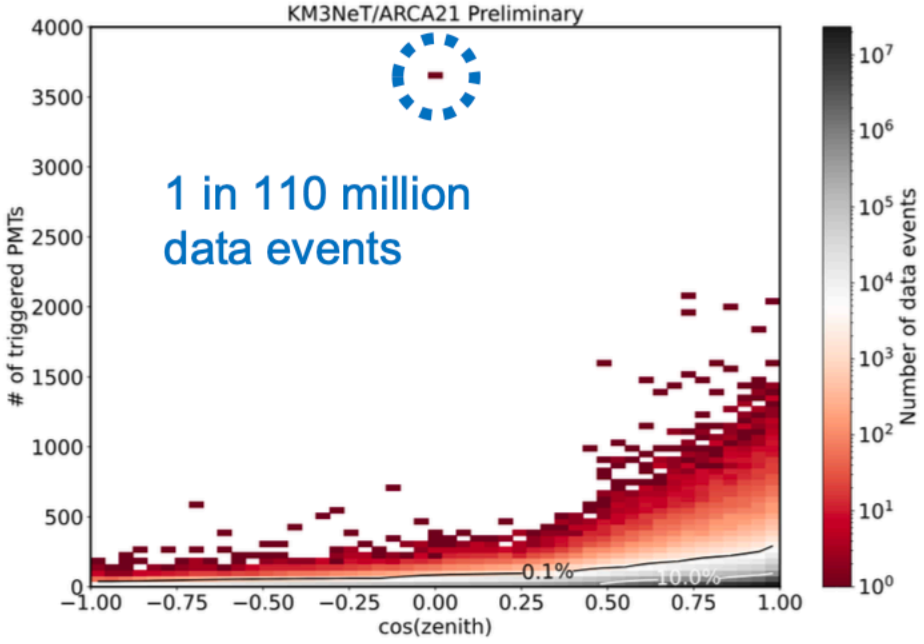
(Ultra?)-high-energy events

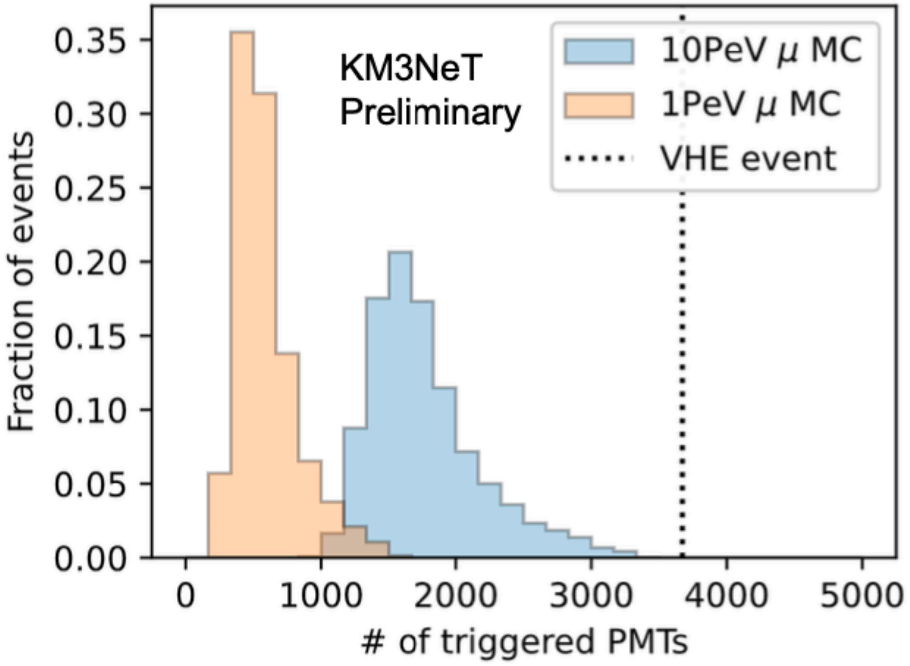
KM3Net ARCA Observation



[Coelho+ Neutrino (2024)]

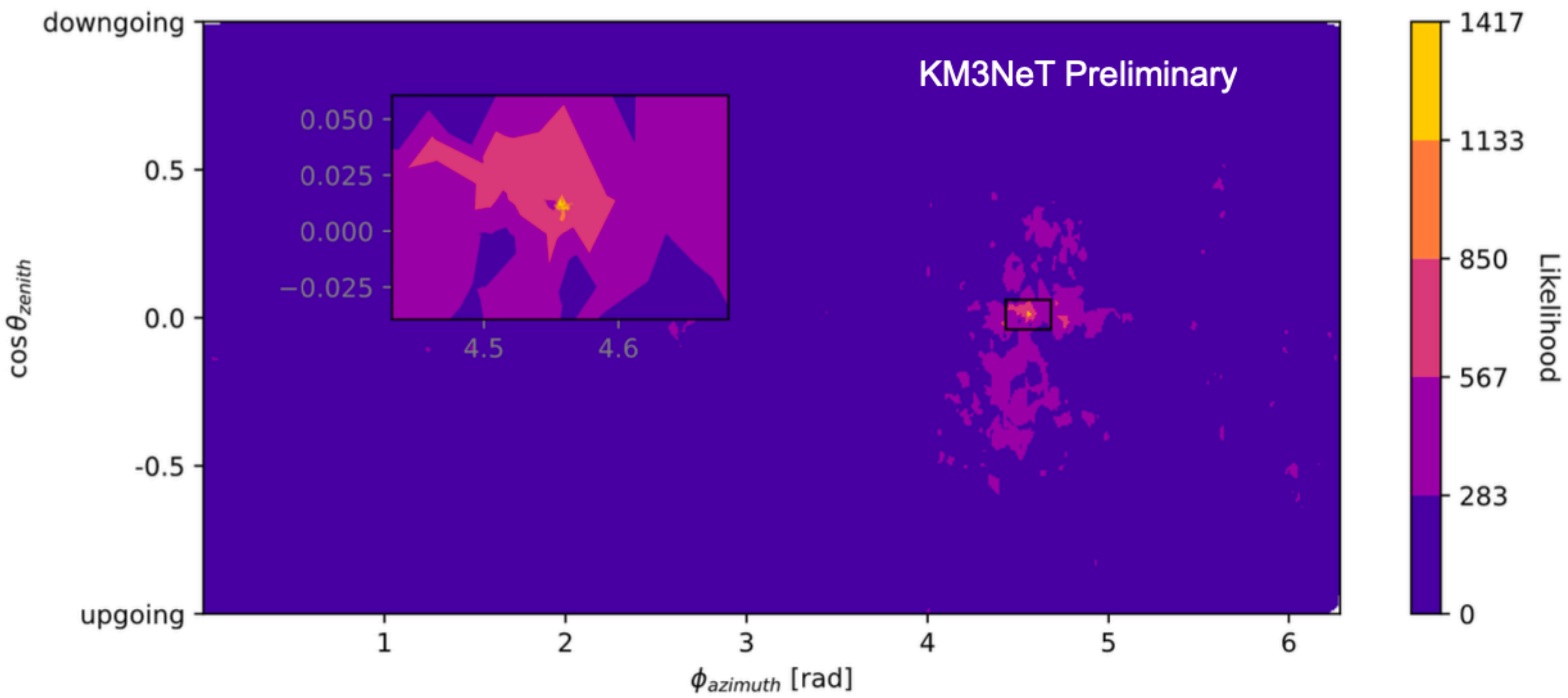
$E_\nu \gtrsim$ 10s PeV ⇒ $E_p \gtrsim$ 100s PeV
High angular resolution

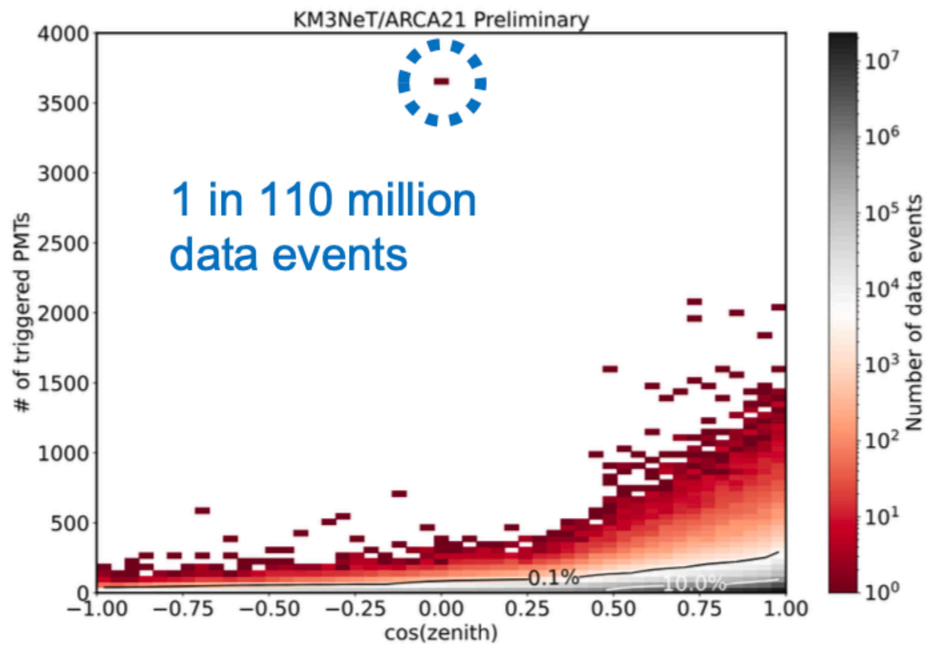


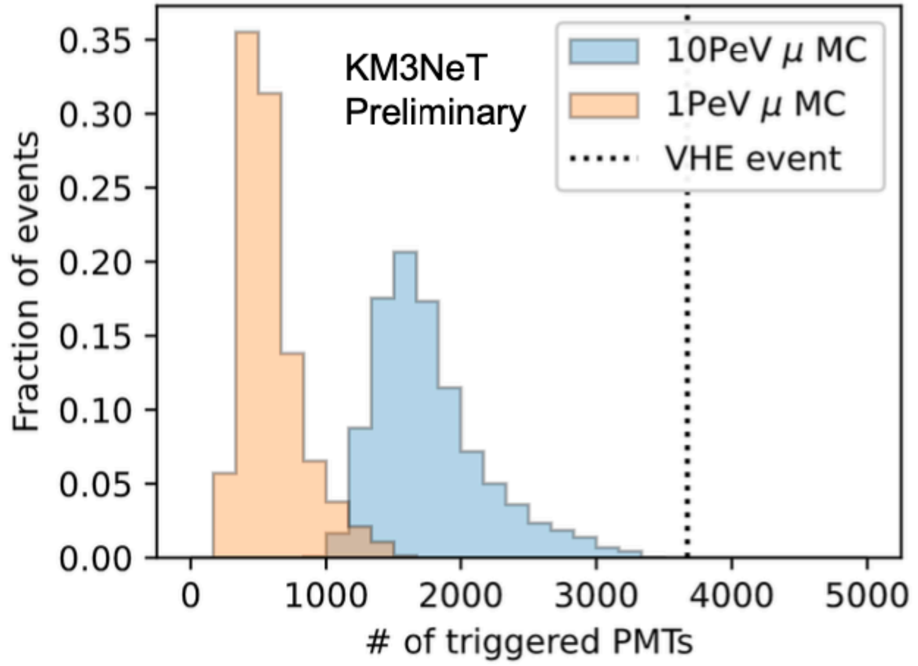


(Ultra?)-high-energy events

KM3Net Observation





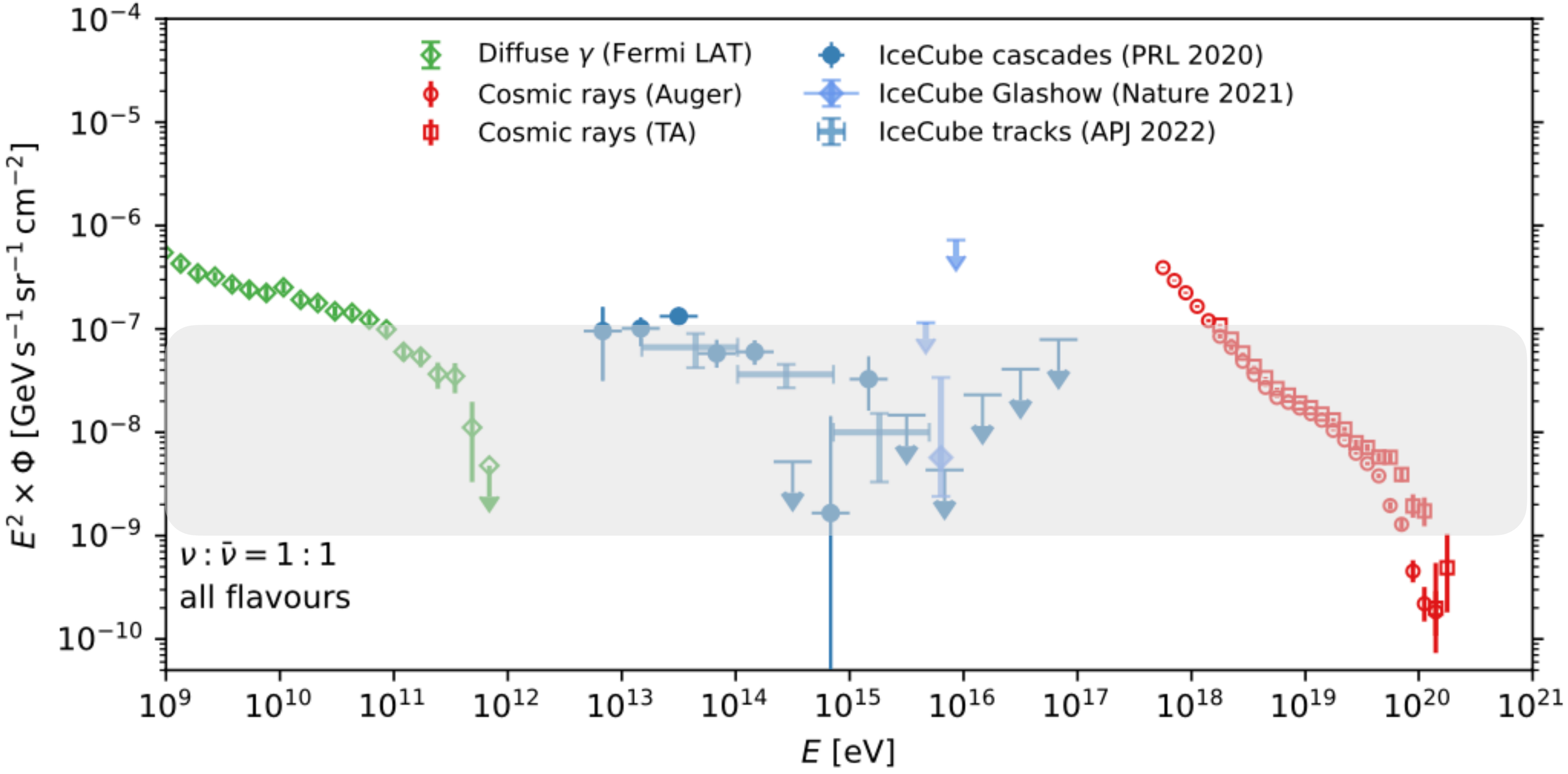


[Coelho+ Neutrino (2024)]

$E_\nu \gtrsim$ 10s PeV $\Rightarrow E_p \gtrsim$ 100s PeV
High angular resolution

High-energy neutrinos & UHECRs

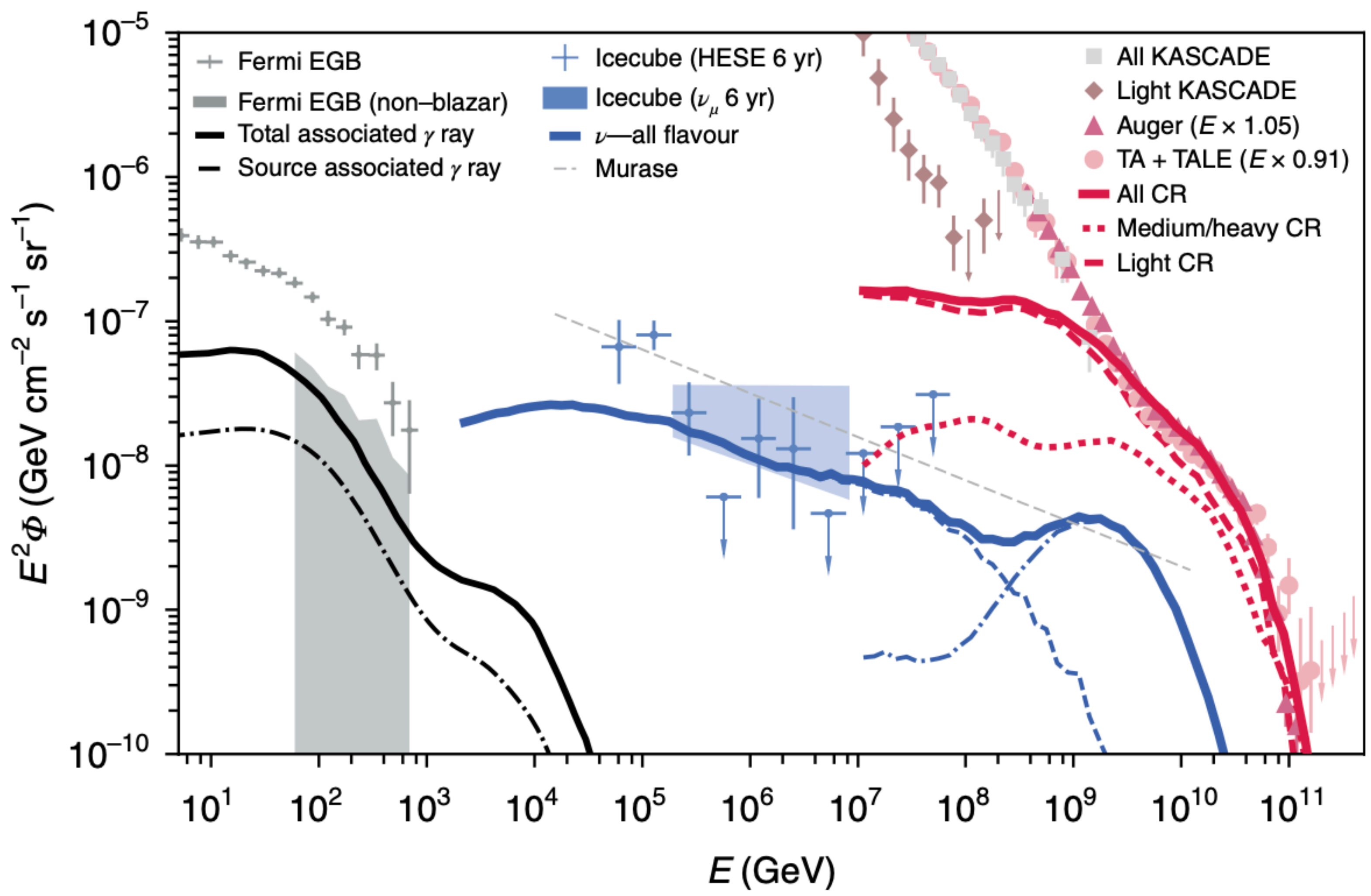
Similar energy density ⇒ unified origins?



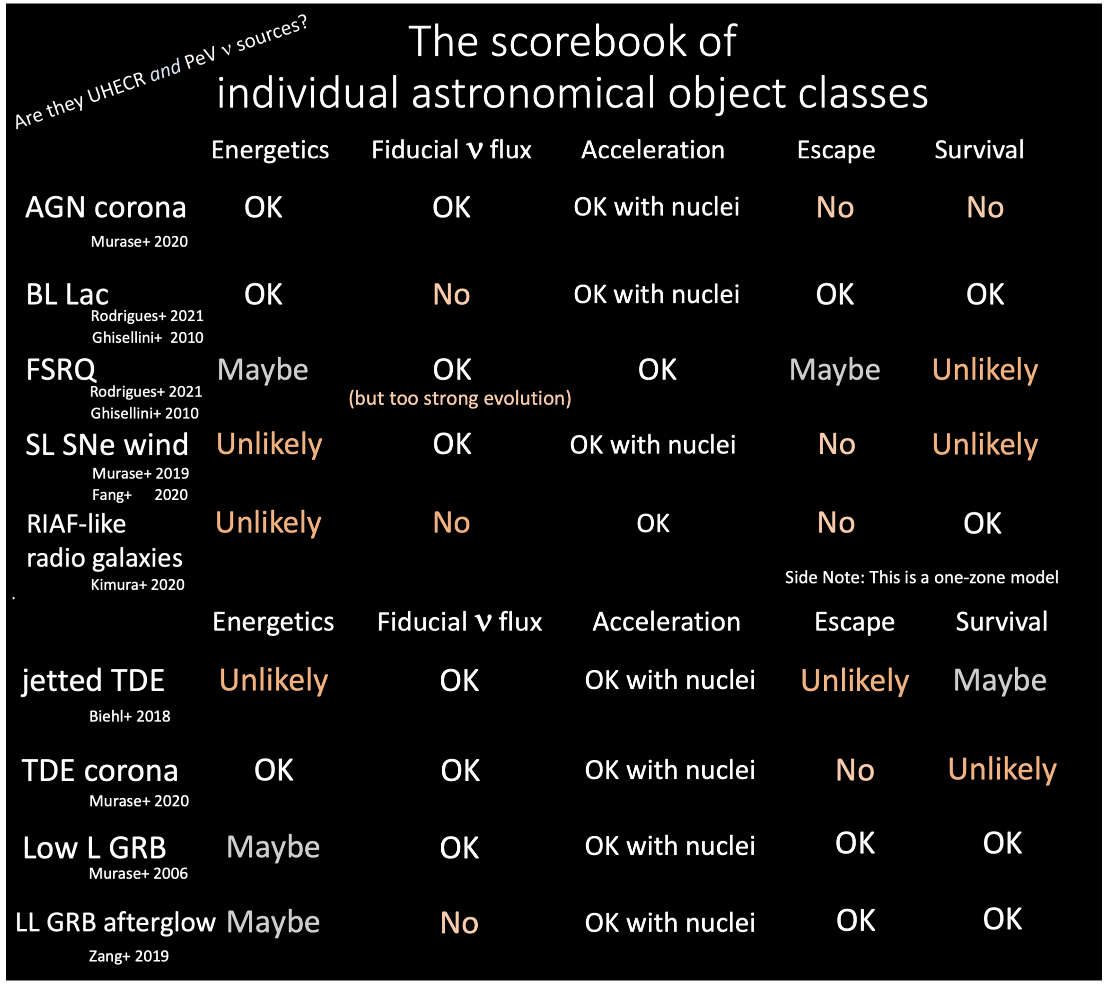
[Ackermann+ JHEA (2024)]

High-energy neutrinos & UHECRs

Connected models are possible



[Fang+Murase Nature (2018)]



	Energetics	Fiducial ν flux	Acceleration	Escape	Survival
AGN corona (Murase+ 2020)	OK	OK	OK with nuclei	No	No
BL Lac (Rodrigues+ 2021, Ghisellini+ 2010)	OK	No	OK with nuclei	OK	OK
FSRQ (Rodrigues+ 2021, Ghisellini+ 2010)	Maybe	OK (but too strong evolution)	OK	Maybe	Unlikely
SL SNe wind (Murase+ 2019, Fang+ 2020)	Unlikely	OK	OK with nuclei	No	Unlikely
RIAF-like radio galaxies (Kimura+ 2020)	Unlikely	No	OK	No	OK

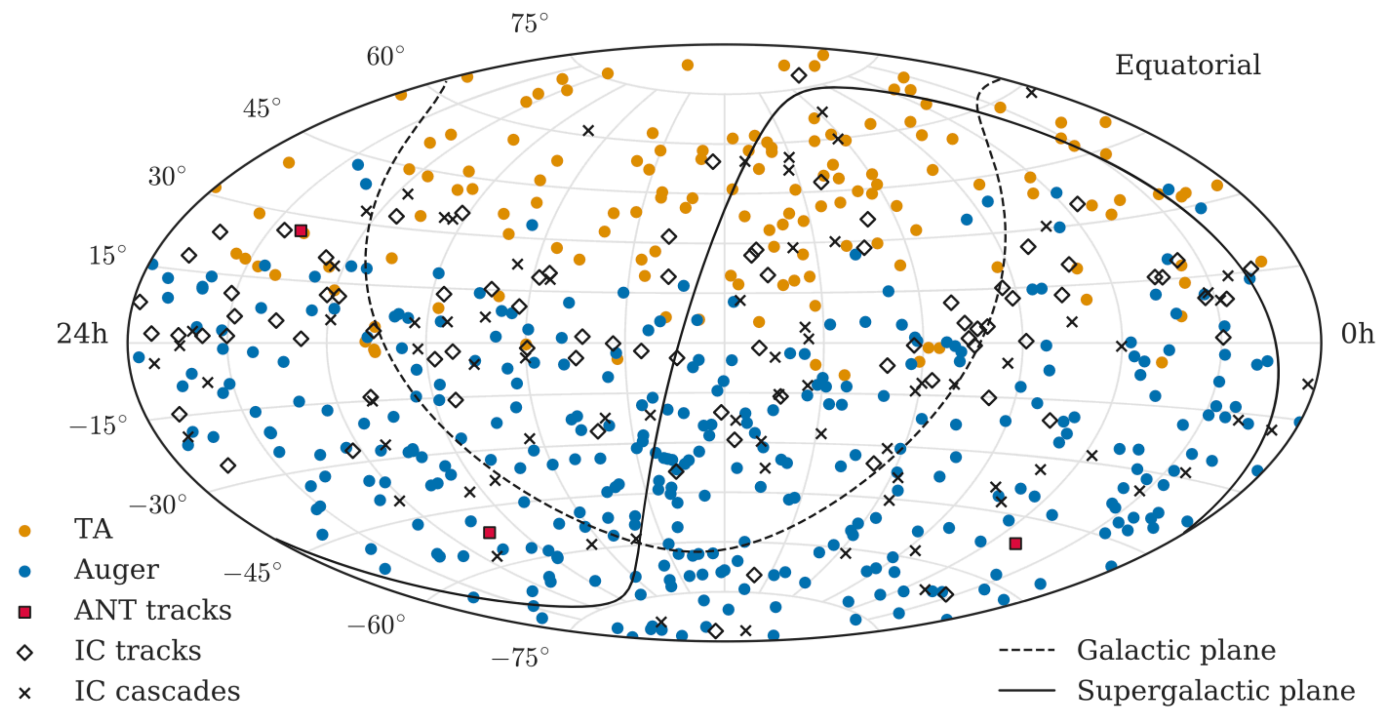
	Energetics	Fiducial ν flux	Acceleration	Escape	Survival
jetted TDE (Biehl+ 2018)	Unlikely	OK	OK with nuclei	Unlikely	Maybe
TDE corona (Murase+ 2020)	OK	OK	OK with nuclei	No	Unlikely
Low L GRB (Murase+ 2006)	Maybe	OK	OK with nuclei	OK	OK
LL GRB afterglow (Zang+ 2019)	Maybe	No	OK with nuclei	OK	OK

[Yoshida ICRC (2023)]

[See also Plotko+ (arXiv:2410.19047, TDEs; talks by Antonio Ambrosone (SBGs) and Foteini Oikonomou (UFOs)]

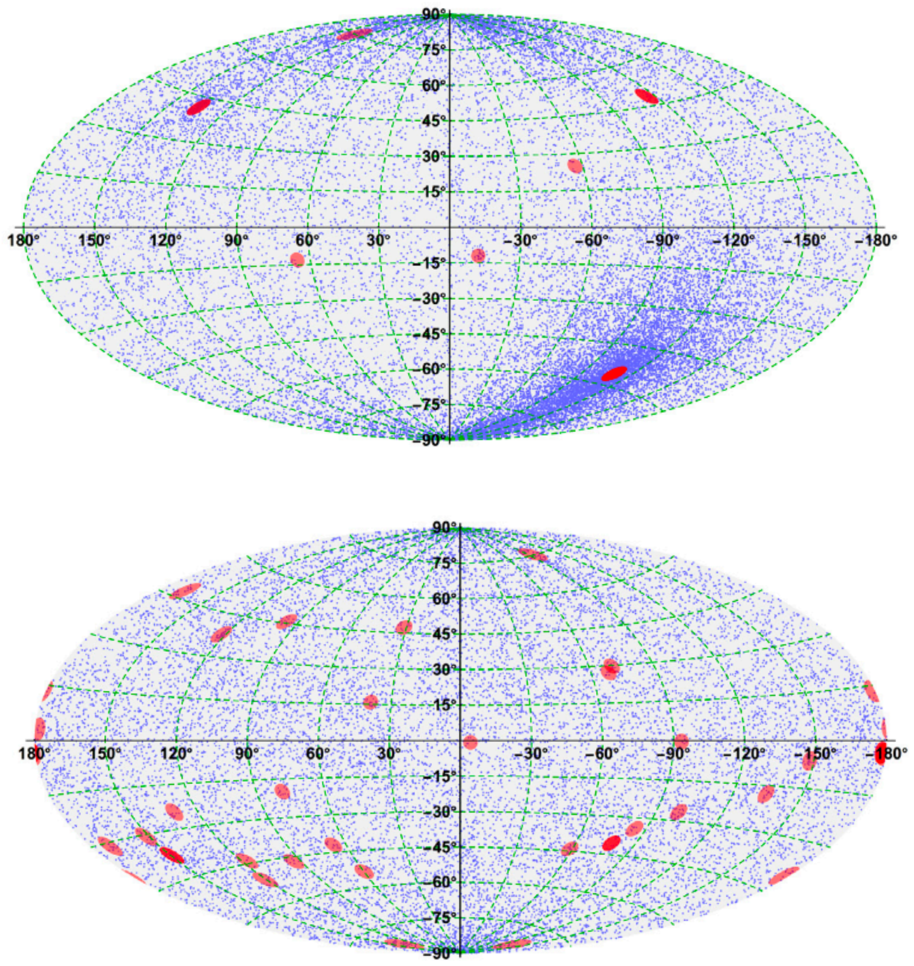
High-energy neutrinos & UHECRs

Difficult to observe direct correlations



UHECR and HE neutrino sample

[Albert+ (2022)]



Neutrino flux too clustered, negative source evolution required

[Palladino+ MNRAS (2019)]

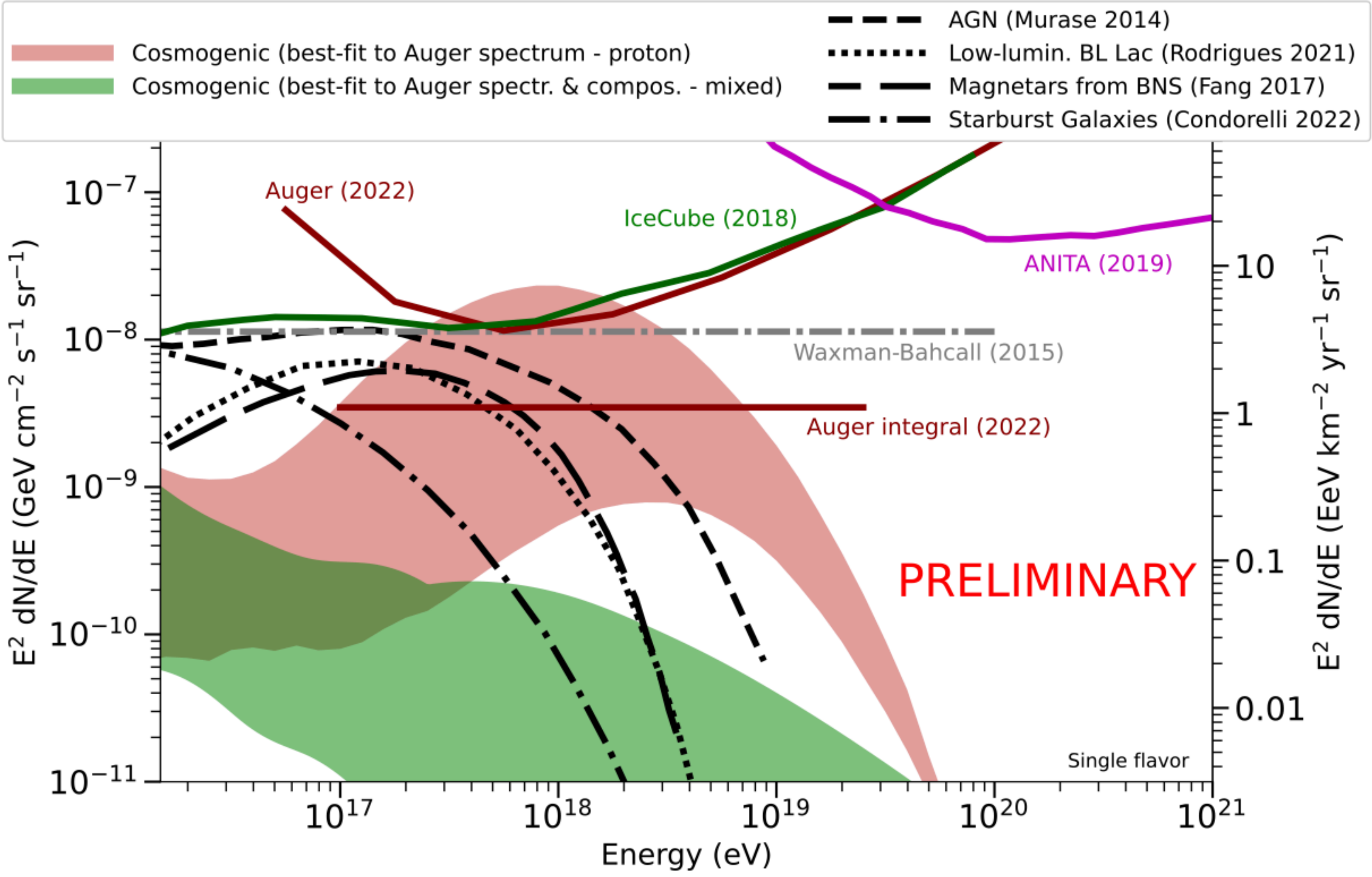
Ultra-high-energy neutrinos

Current status

Clear connection to UHECRs

Light compositions constrained
Proton fraction ≲ 20%

Strong evolutions constrained
E.g. FSRQs (FRII)
Even for subdominant protons



[Alosio+ Astropart. Phys (2011); Aartsen+ PRL (2016); Ackermann+ JHEA (2022); Ehlert+ JCAP (2024)]

[Niechciol+ ICRC (2023); Talk by B. T. Zhang]
[Also talks later by Alvarez-Muniz & Takahashi]

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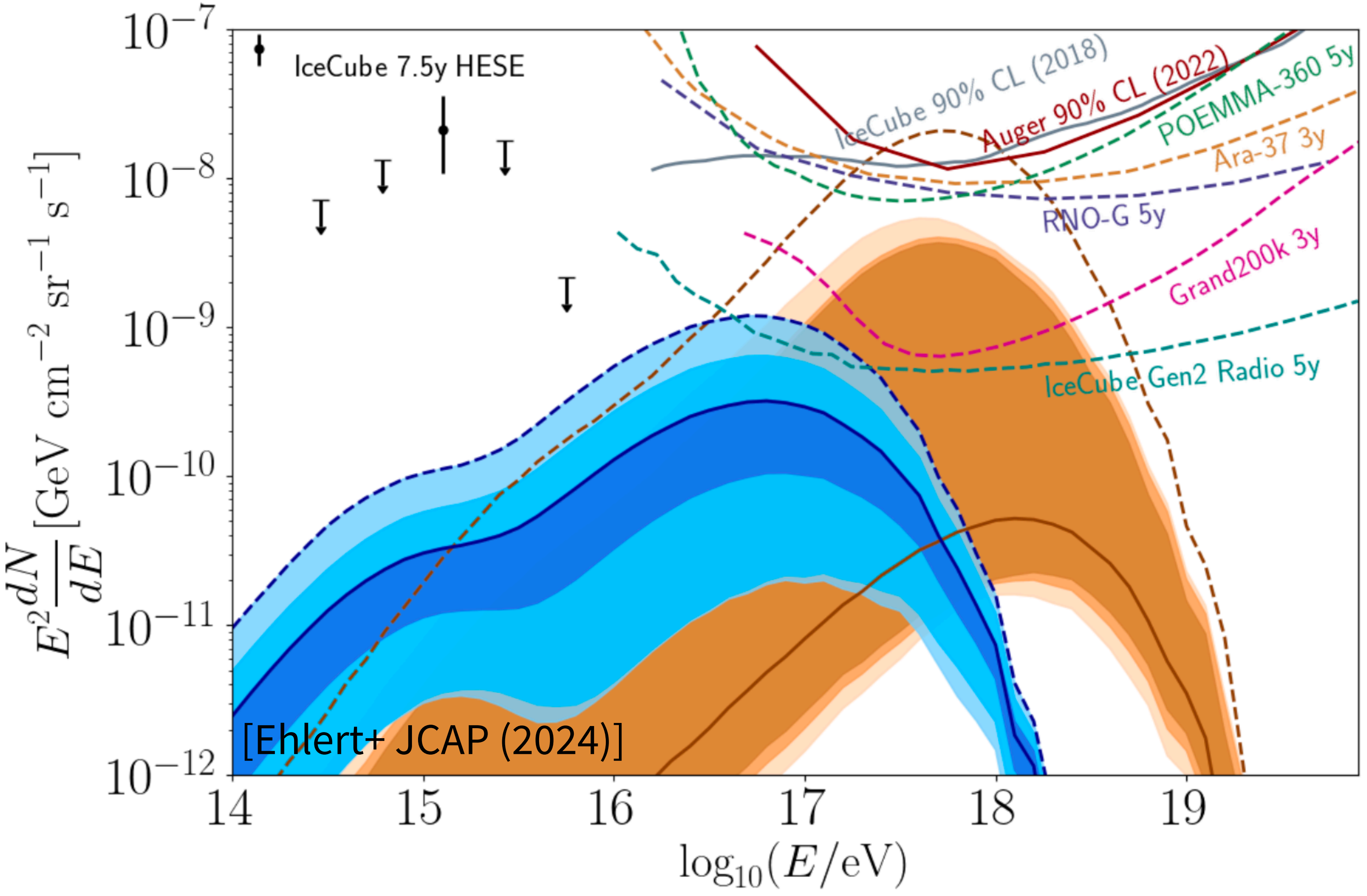


[Alosio+ Astropart. Phys (2011); Aartsen+ PRL (2016); Ackermann+ JHEA (2022); Ehlert+ JCAP (2024)]

Ultra-high-energy neutrinos

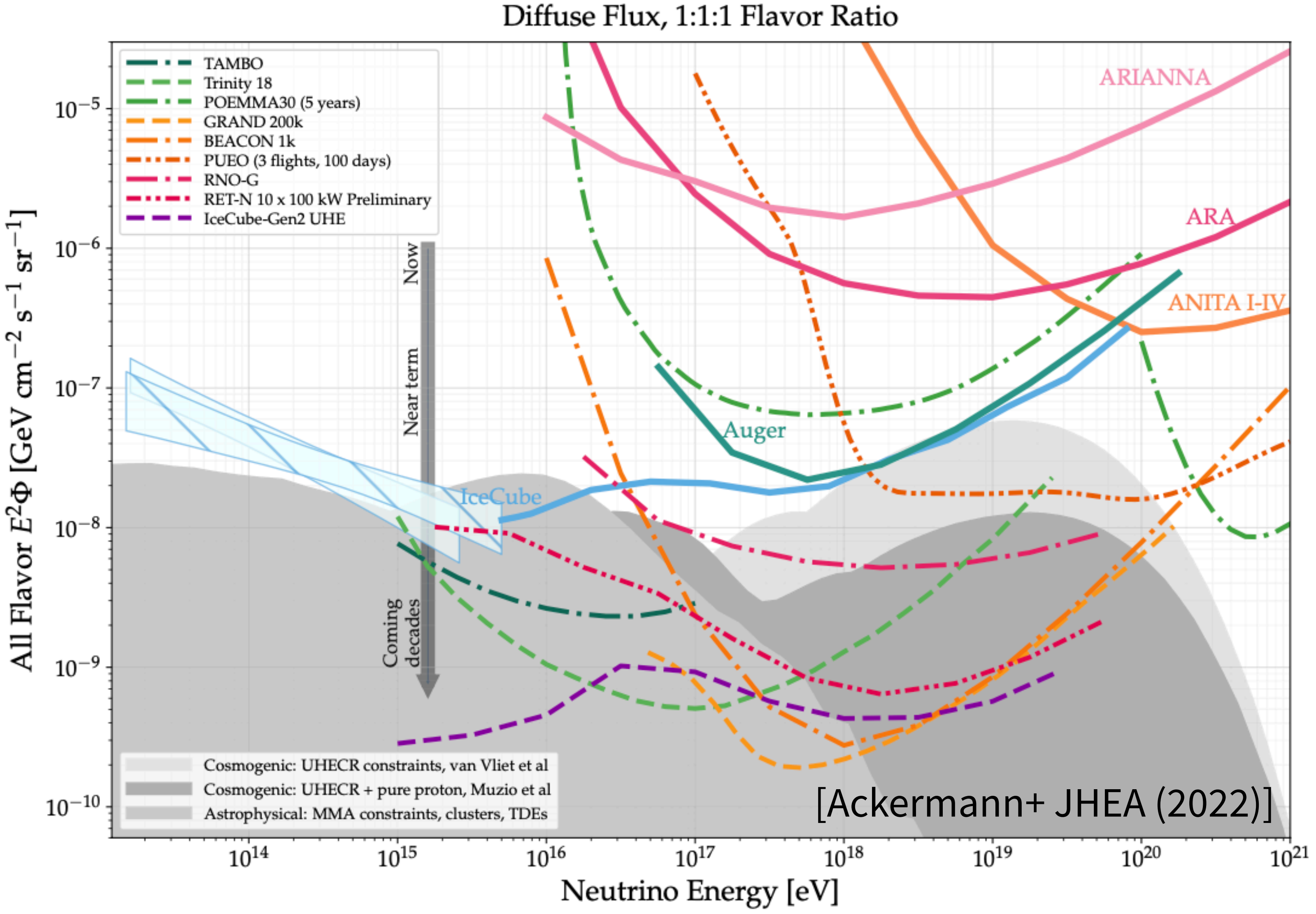
Challenges

Clear connection to UHECRs

Degeneracies in constraints

UHE neutrinos can also be produced in UHECR sources

Flux may be low in pessimistic case
Target sensitivity: 10^{-10} GeV cm^{-2} sr^{-1} s^{-1}



[Alosio+ Astropart. Phys (2011); Aartsen+ PRL (2016); van Vliet+ PRD (2019); Ackermann+ JHEA (2022); Ehlert+ JCAP (2024)]

[See also talks by Alessandro Cermenati & Jon Paul Lundquist]

The bigger picture: a complex astrophysical landscape

1

TeV—EeV Neutrinos

Complementary constraints
Larger horizons
Probing dense environments

2

UHECRs

TeV—PeV connection possible (unclear)
Clearer for future UHE detection

3

Multi-messenger connection

How can we make the most of this data and prepare for the future?

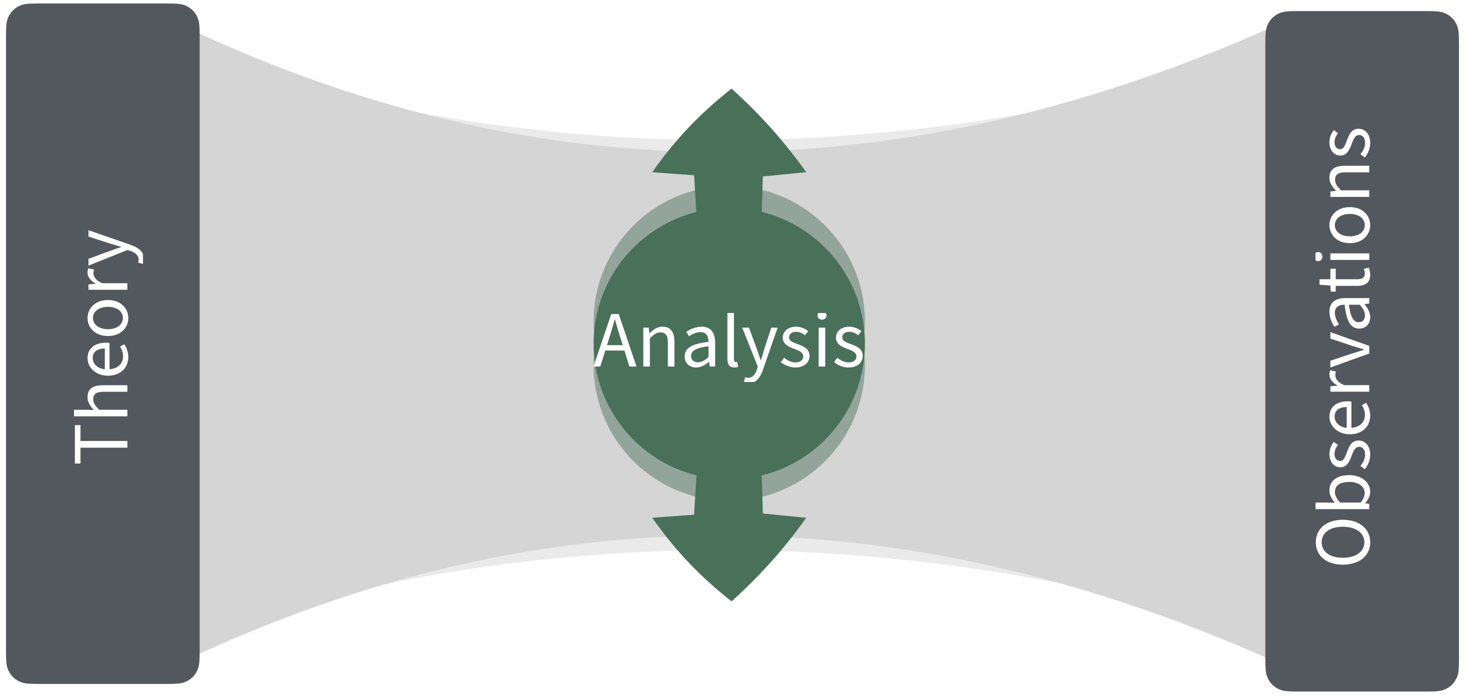
Challenges

Complex physical models

UHECR acceleration

TeV—EeV neutrino production

UHECR propagation



Diverse relevant datasets

UHECRs

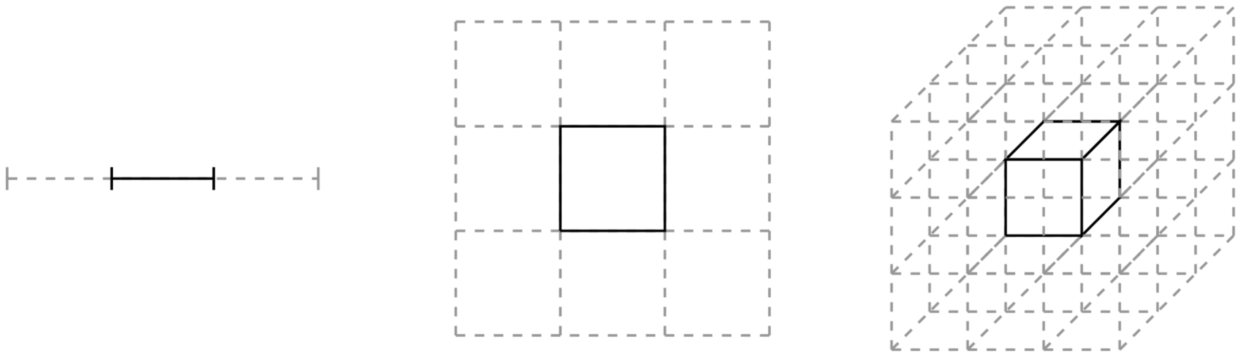
TeV—EeV neutrinos

Multi-wavelength data
Astronomical catalogues

Challenges

Computational aspects

- Number of free model parameters
- Complexity in theoretical and data models
- Determination of uncertainties in best-fit parameters

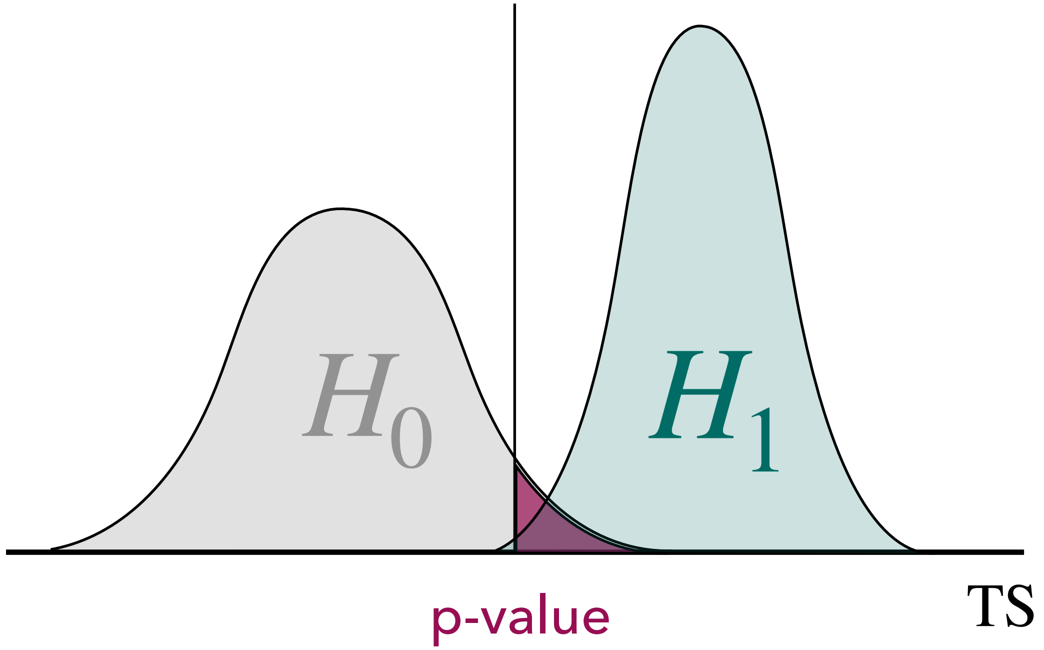


[Betancourt (arxiv:2017)]

Hypothesis testing & p-values

- Interpretation always in relation to null hypothesis (indirect question)
- Analysis choices and sensitivity driven by trial-factor corrections
- Impossible to calculate trial factors across separate analyses
- Data should not be re-used to investigate interesting results

[Gigerenzer et al. (2004); Wasserstein & Lazar (2016); Kowalski (2021)]



Ways forward

High-dimensional analyses
More free parameters ⇒ include more physics
Markov chain Monte Carlo, simulation-based inference etc…

[Capel+Mortlock MNRAS (2019); Capel+ ApJ (2024)]

Interpretable analyses
Not just background rejection, try to describe the data
Generative modelling, Goodness-of-fit, Bayesian approaches

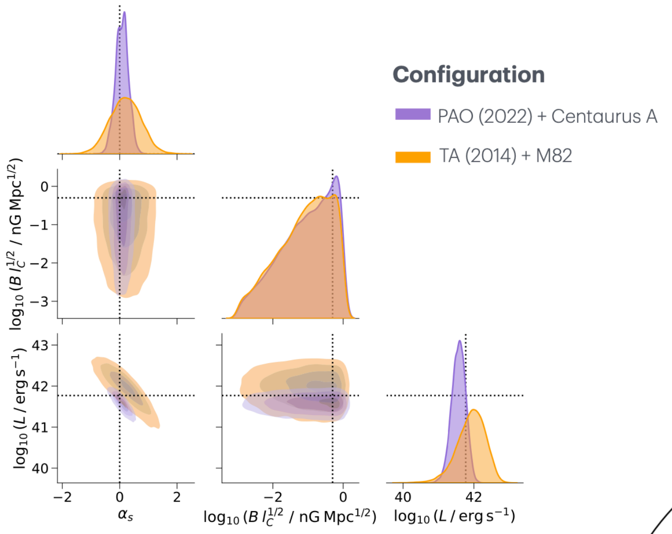
[Talk by Etienne Parizot, Talk by Teresa Bister]

Open analyses
Loss of information in comparing analysis results with predictions
Open source simulations and analysis frameworks

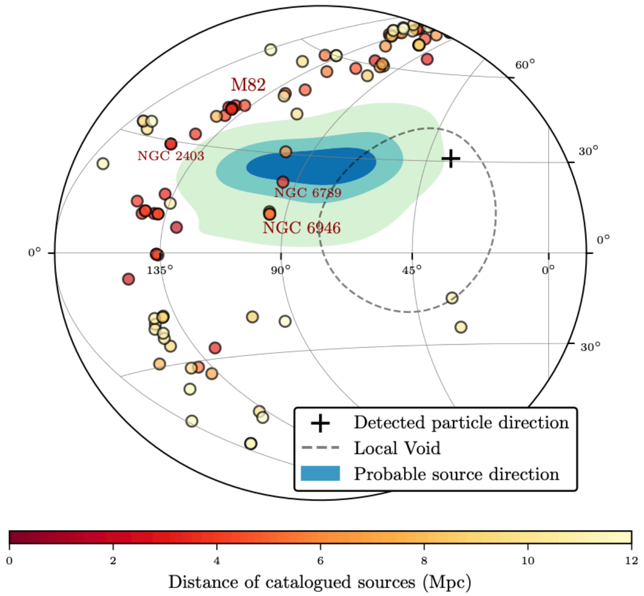
[Coleman+ Asrtopart. Phys. (2023)]

Ways forward

UHECR sources



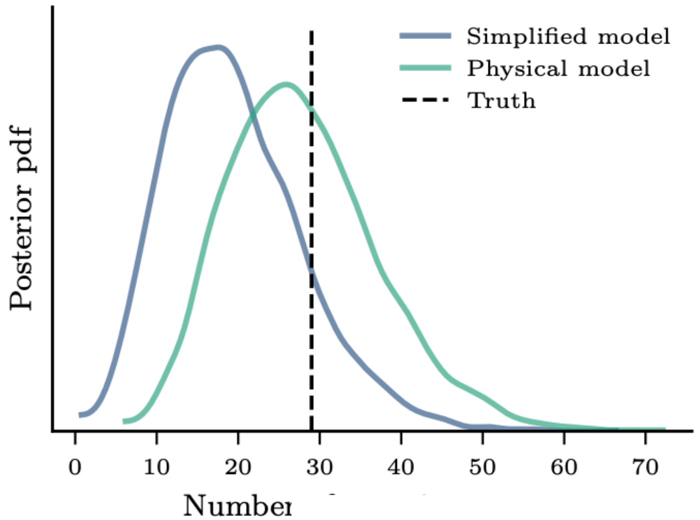
[Talk by Keito Watanabe]

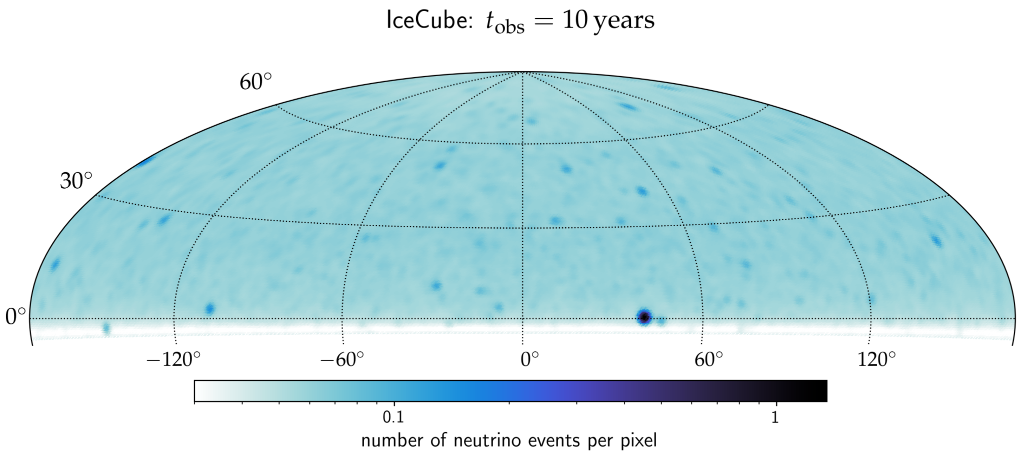


[Poster by Nadine Bourriche]

HE neutrino sources

[Capel+ ApJ (2024); Kuhlmann+ RICAP (2024)]





[Saurenhaus+ (RICAP) 2024]

The future is (neutrino-) bright…

Future UHECR detectors are also neutrino detectors

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

[Coleman+ Astopart. Phys. (2024)]

…lighting the path to UHECR sources!