Astrophysical Messengers: cosmic rays and neutrinos

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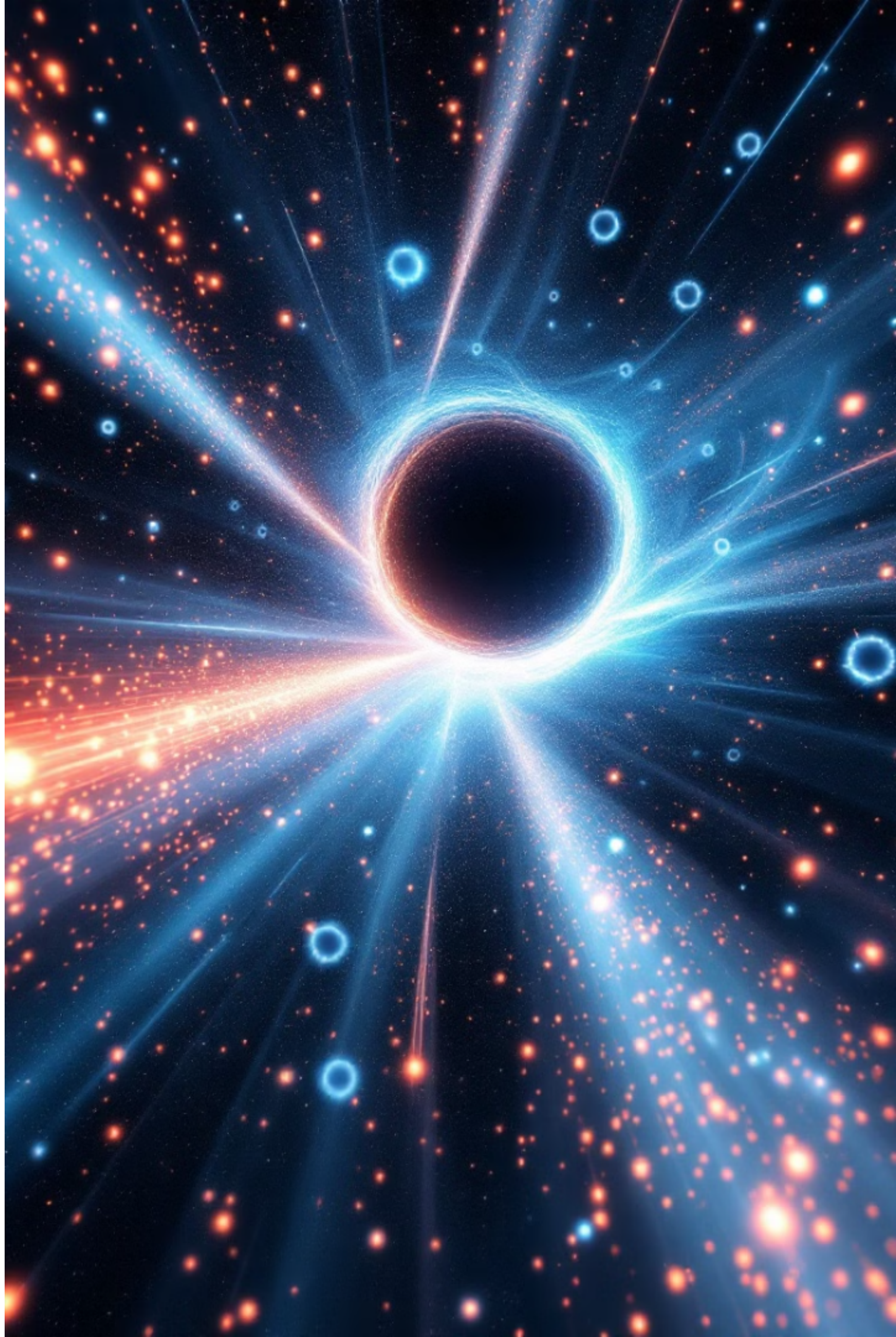
Max Planck Institute for Physics
Project Review 2024

SFB 1258 Neutrinos Dark Matter Messengers

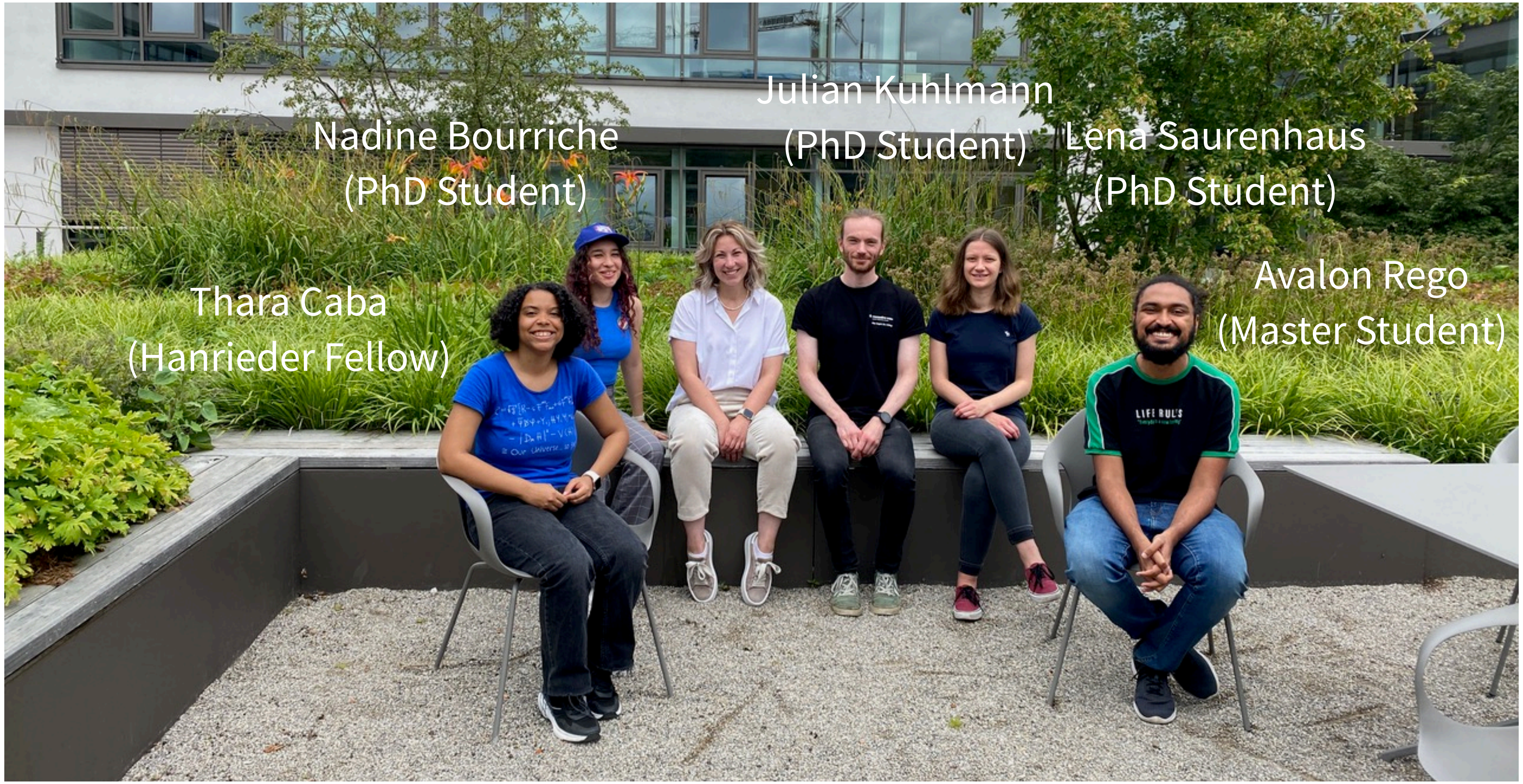
ODSL ORIGINS Data Science Lab

MAX-PLANCK-INSTITUT FÜR PHYSIK

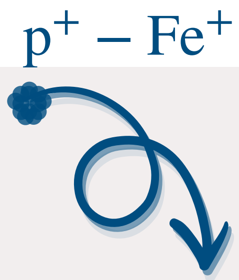


The group

Minerva Fast-Track group funded by the Max Planck Society, ORIGINS Excellence Cluster and SFB 1258
Started in 2022 with full house since January 2023

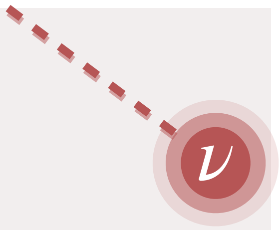


Probes of energetic particle acceleration



Cosmic Rays

Accelerated charged particles can escape their sources and be detected

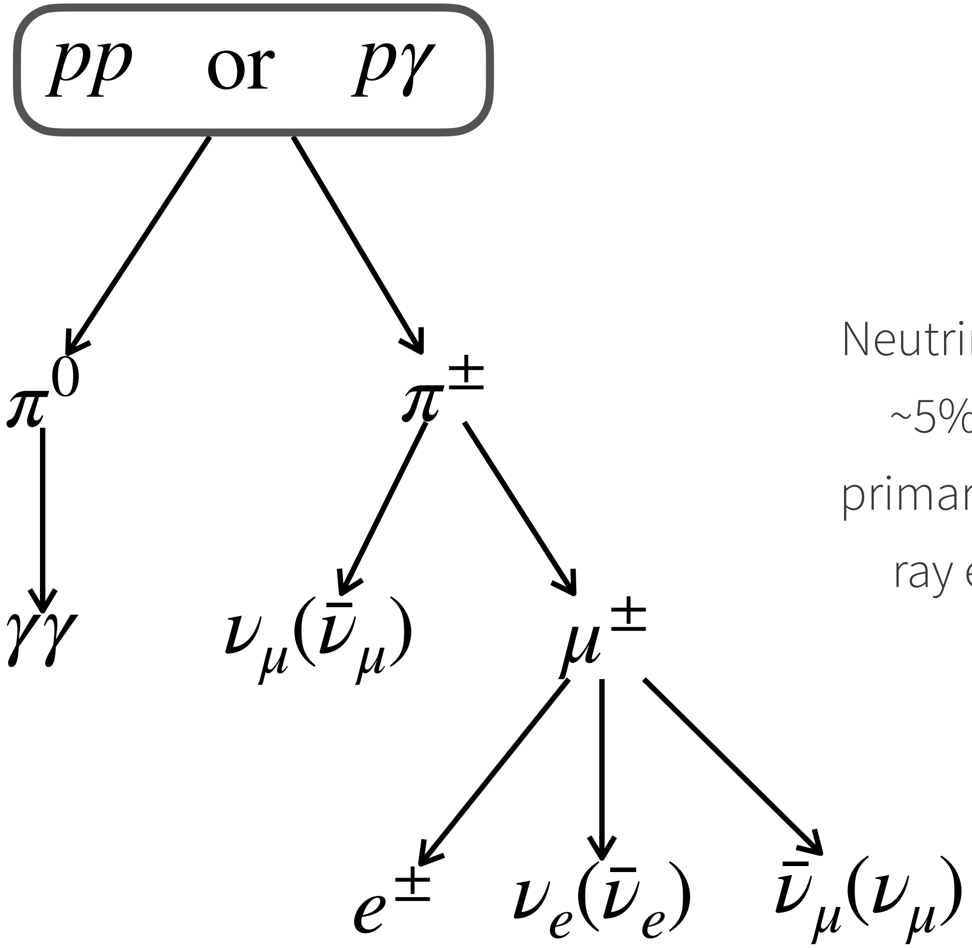


Neutrinos

Neutrinos are only produced in hadronic interactions
⇒ clear signal

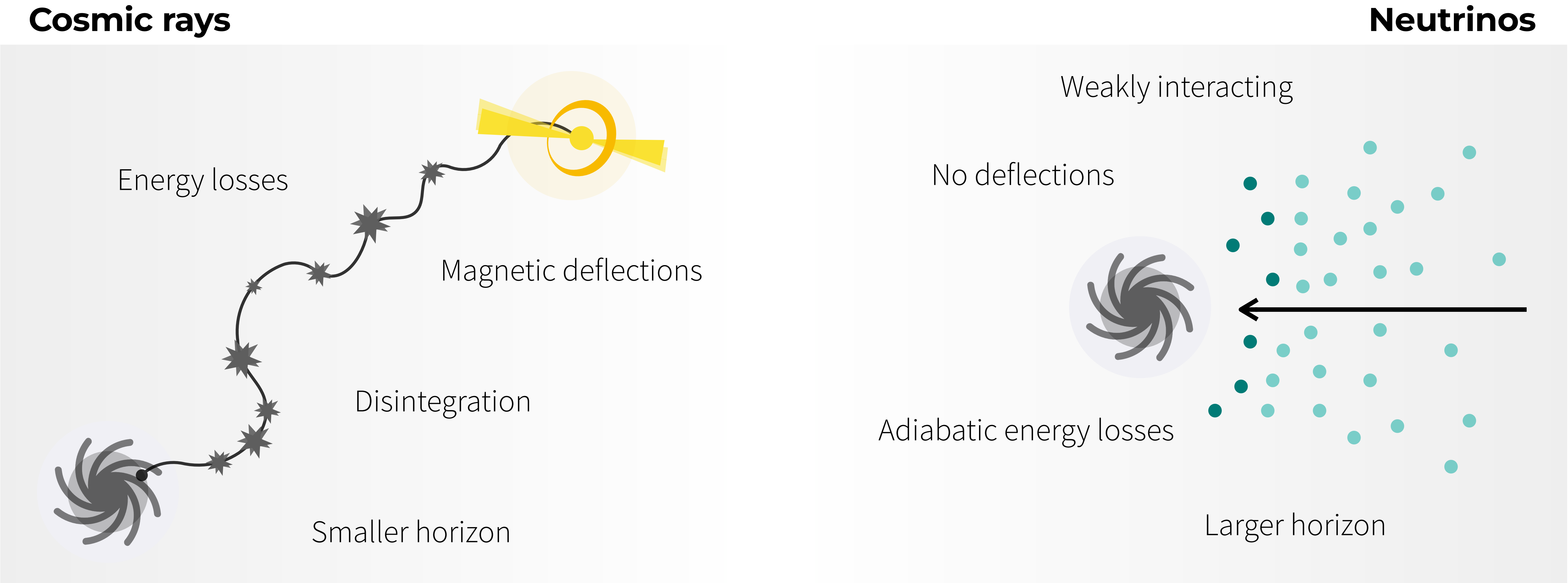
Photohadronic and Hadronuclear reactions

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

Ultra-high-energy cosmic rays (UHECRs)

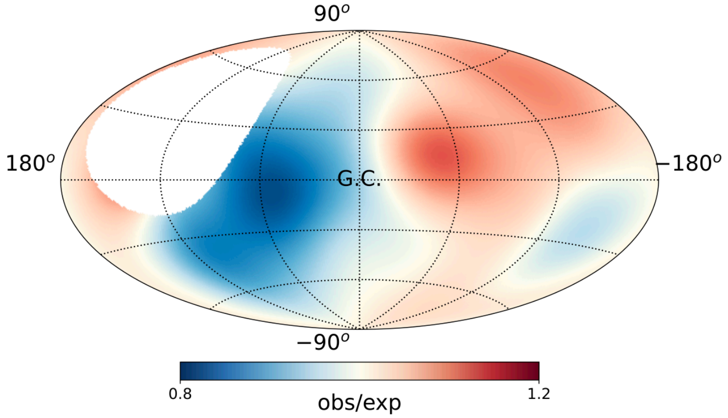
Key experiments: Pierre Auger & Telescope Array

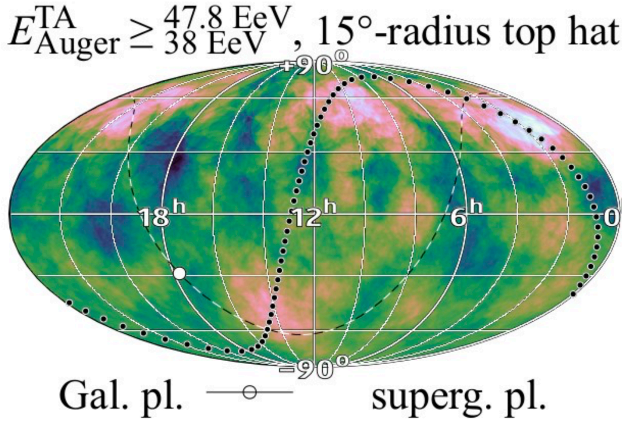
The arrival directions are not isotropic

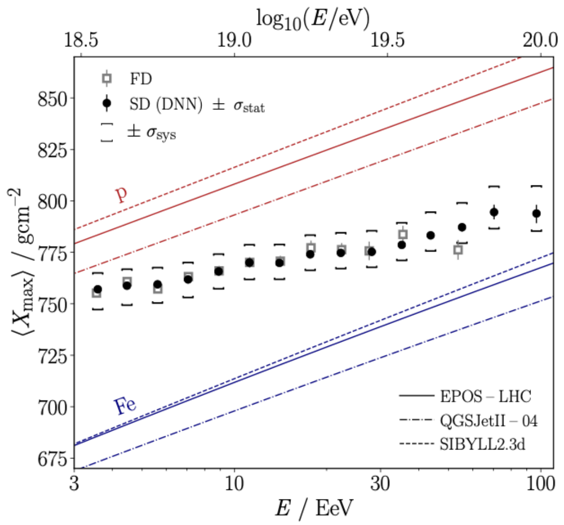
Cosmic rays get heavier towards the highest energies

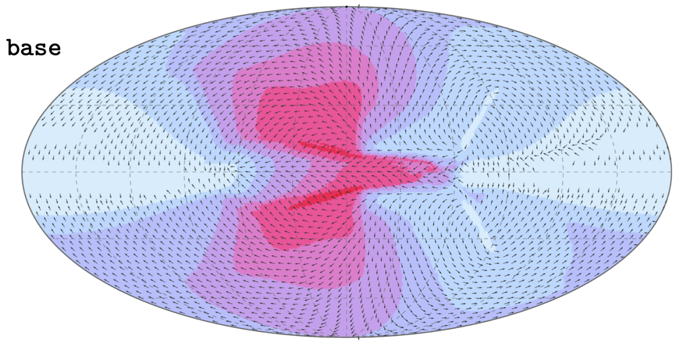
Recent updates in modelling the Galactic magnetic field

Planned upgrades will improve measurements of the particle type (AugerPrime) and increase the sample size (TAx4)









[Pierre Auger Collaboration (2024); Rubtsov+ (UHECR 2024); Fitoussi+ (UHECR 2024); Unger+Farrar (2023)]

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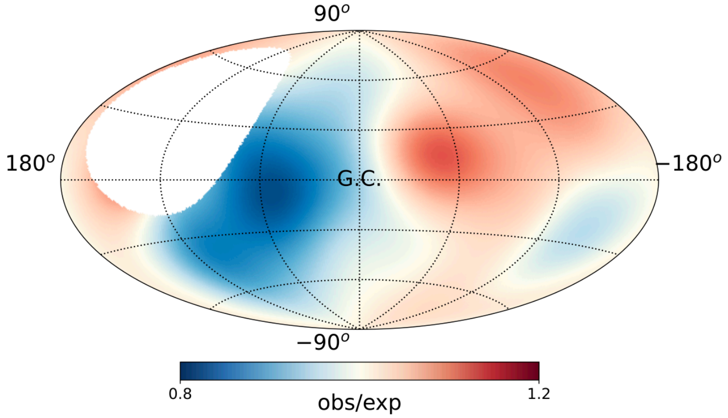
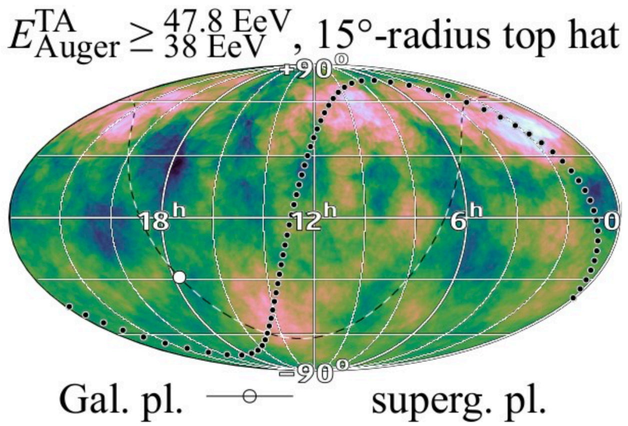
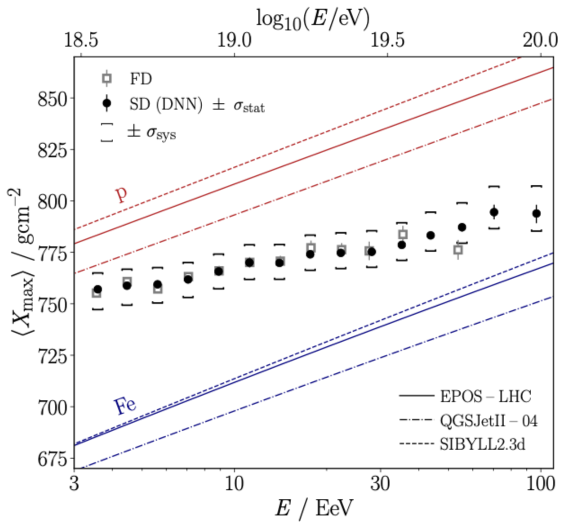
Challenges:

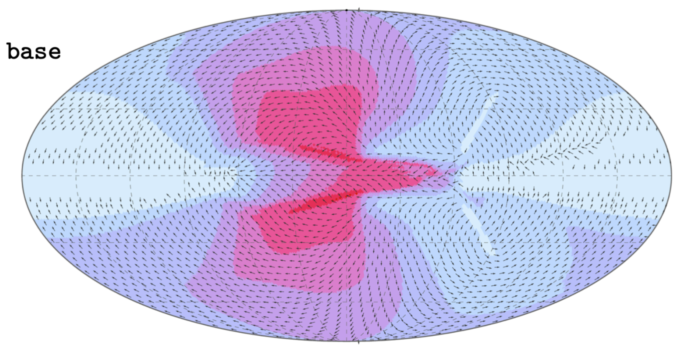
Rejecting isotropy → explaining the data

Combining information from theory and observations









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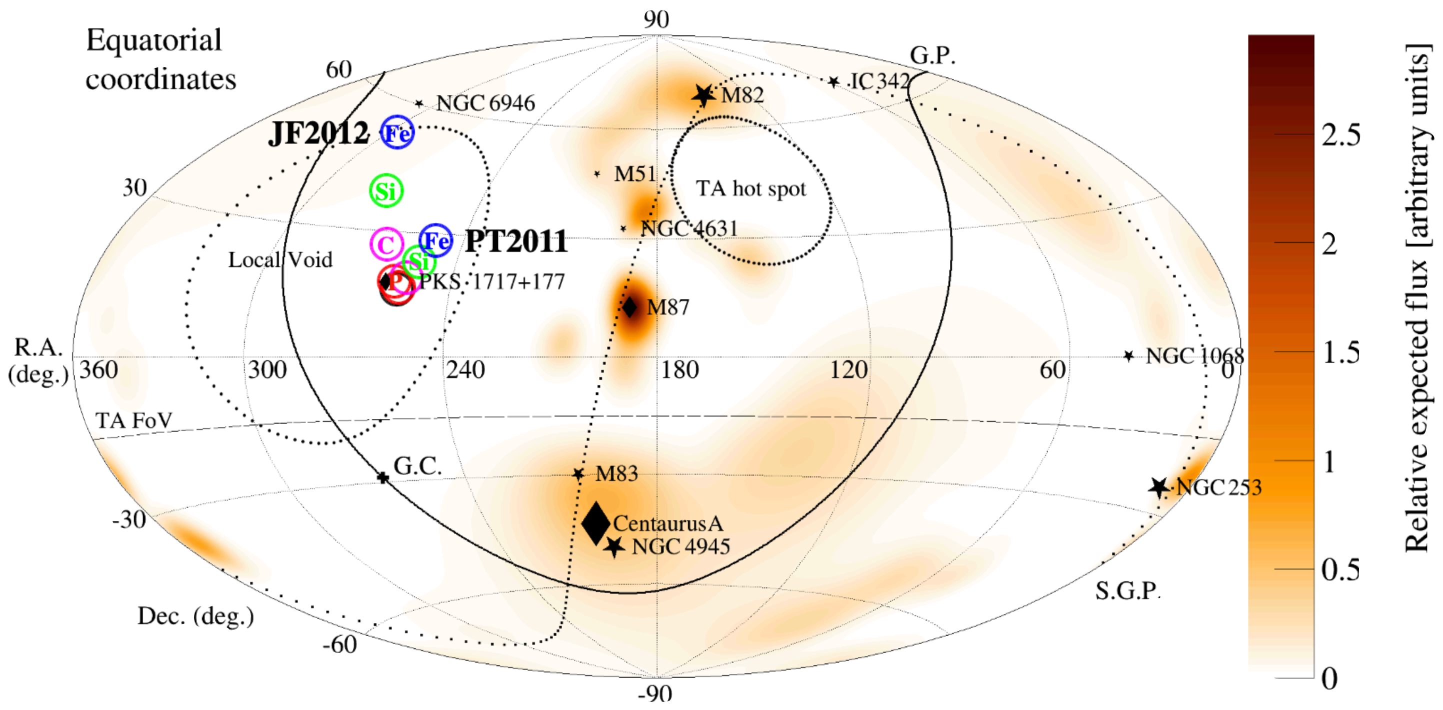
UHECR Astronomy at the highest energies

Work by PhD student Nadine Bourriche (MPP)

Higher energy ⇒
Less deflected by magnetic fields
Must come from nearby (limited interactions)

Recent observation of the “Amaterasu” particle
Second highest energy event ever detected
It seems to come from within the “Local Void” ⇒
No obvious astrophysical counterpart?



$$E = 244 \pm 29(\text{stat.})^{+51}_{-76}(\text{syst.})\ \text{EeV}$$

[Telescope Array Collaboration (2023)]

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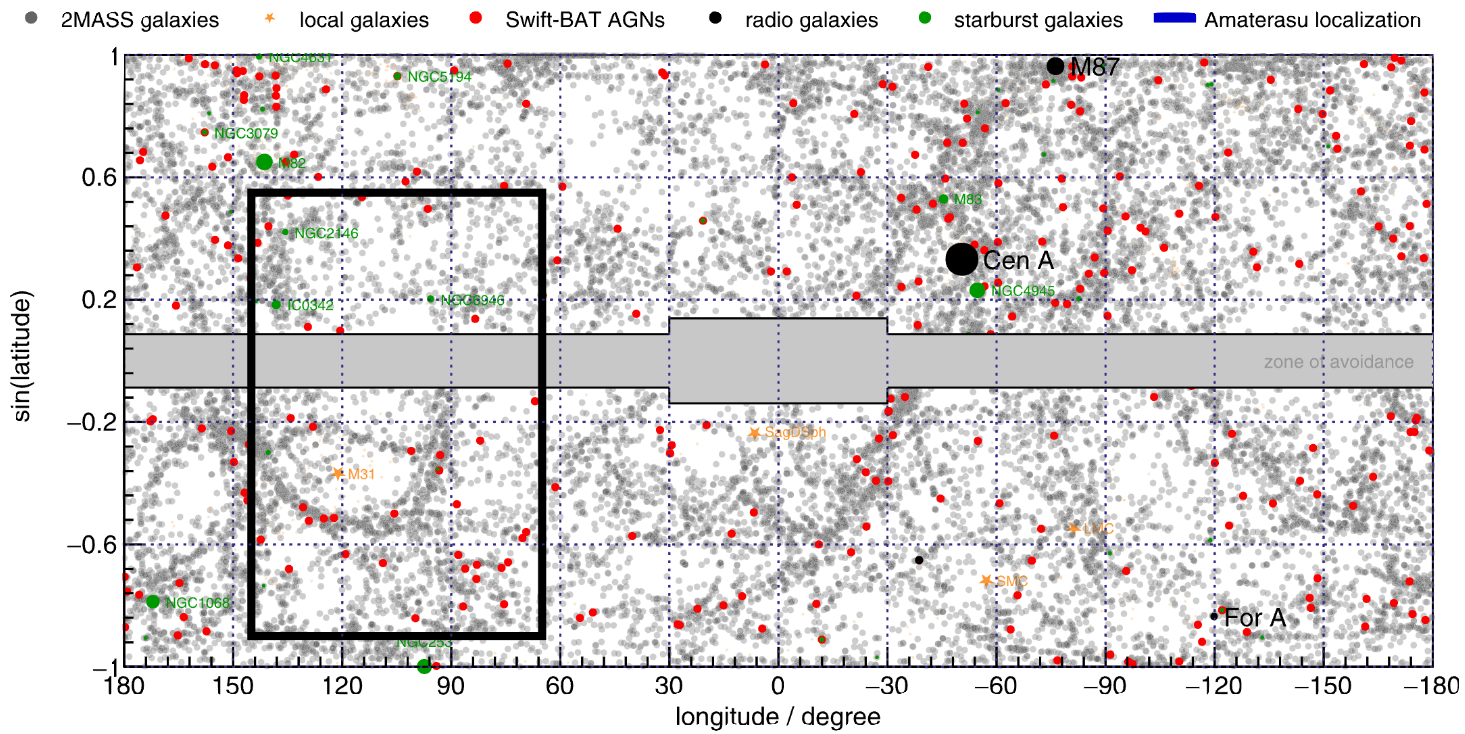

[Unger & Farrar (2024); See also Kuznetsov (2023)]

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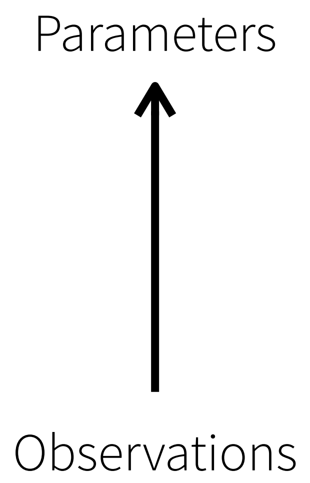

Previous approaches:

- “Backtrack” - trace back possible origins by making assumption about arrival particle mass
- Separate treatment of particle interactions and deflections
- Ignore the possible contribution of extra-Galactic magnetic fields, focus on Galactic field

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Our novel simulation-based approach via Approximate Bayesian Computation:
- Forward model the full problem - no assumption of arrival particle mass
- Consider particle interactions and deflections together
- Inclusion of Galactic and extra-Galactic magnetic fields
- Consistent combination of relevant uncertainties

Parameters

↓

Observations

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How?
1. Sample from prior: source position, direction, particle energy, magnetic field parameters
2. Simulation UHECR propagation with CRPropa3 [https://github.com/CRPropa/CRPropa3]
3. Does this simulation result in a detected particle which looks like Amaterasu?
4. Accept if yes, reject if no, repeat until many accepted samples

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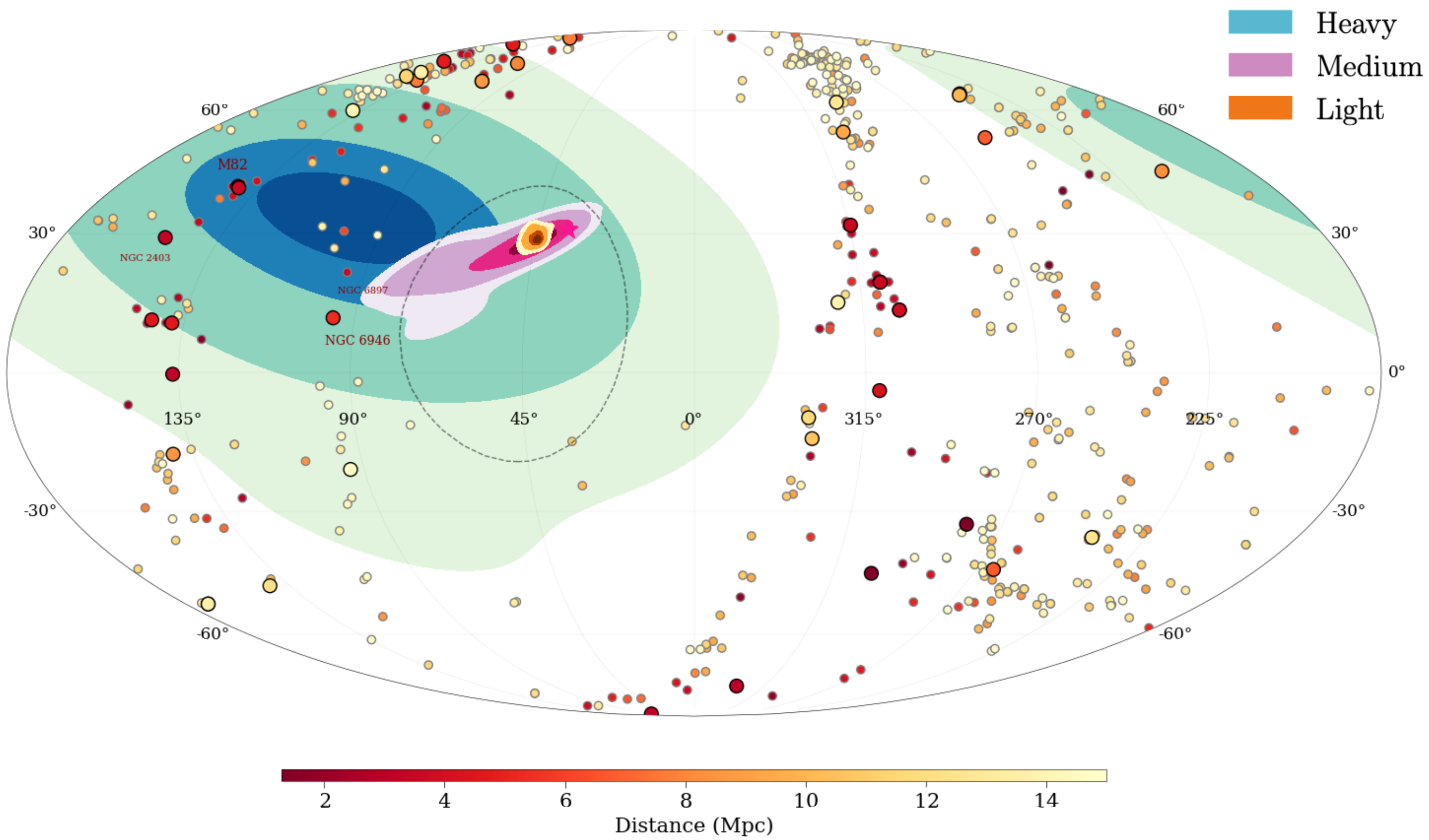

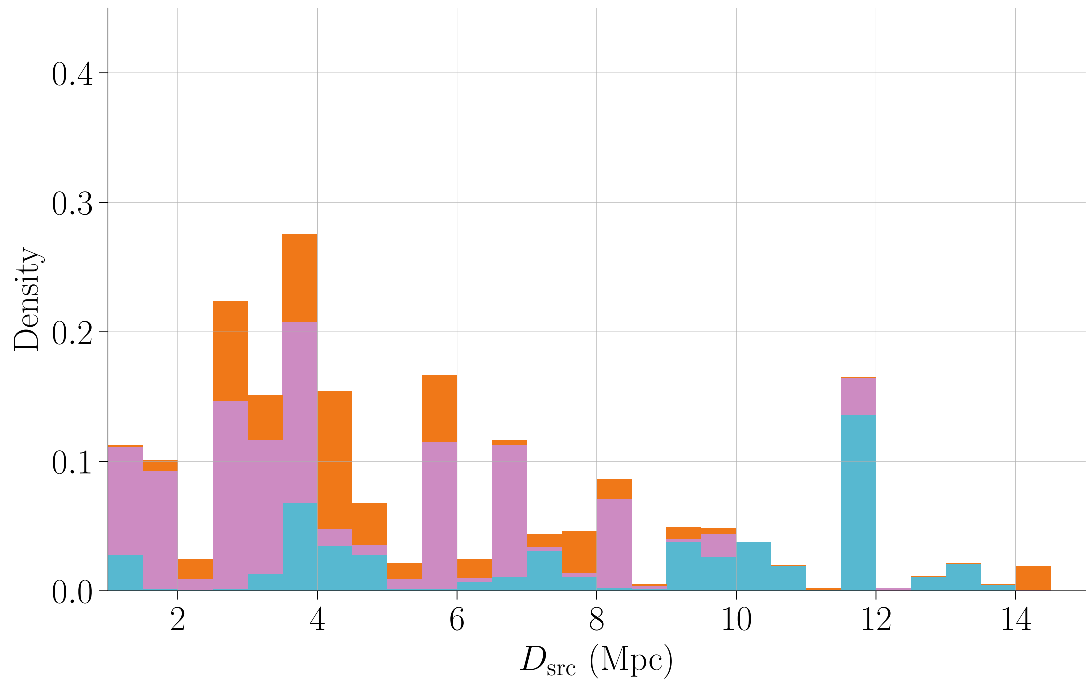

[Bourriche & Capel (2024) - arXiv:2406.16483 under review at ApJL]

We find possible origins consistent with known astrophysical sources

We also demonstrate the important of UHECR mass measurements for individual events

See also: Application to highest-energy events from the Pierre Auger Observatory [Bourriche & Capel (ICRC 2023)]

UHECRs: Larger samples

Work by PhD Student Keito Watanabe (KIT; previously MPP summer student)

We now have thousands of UHECR events above ~EeV energies

We want a complementary way to use these larger samples despite the higher uncertainties

Simplify the model to make it fast/scalable while keeping key physics

UHECRs: Larger samples

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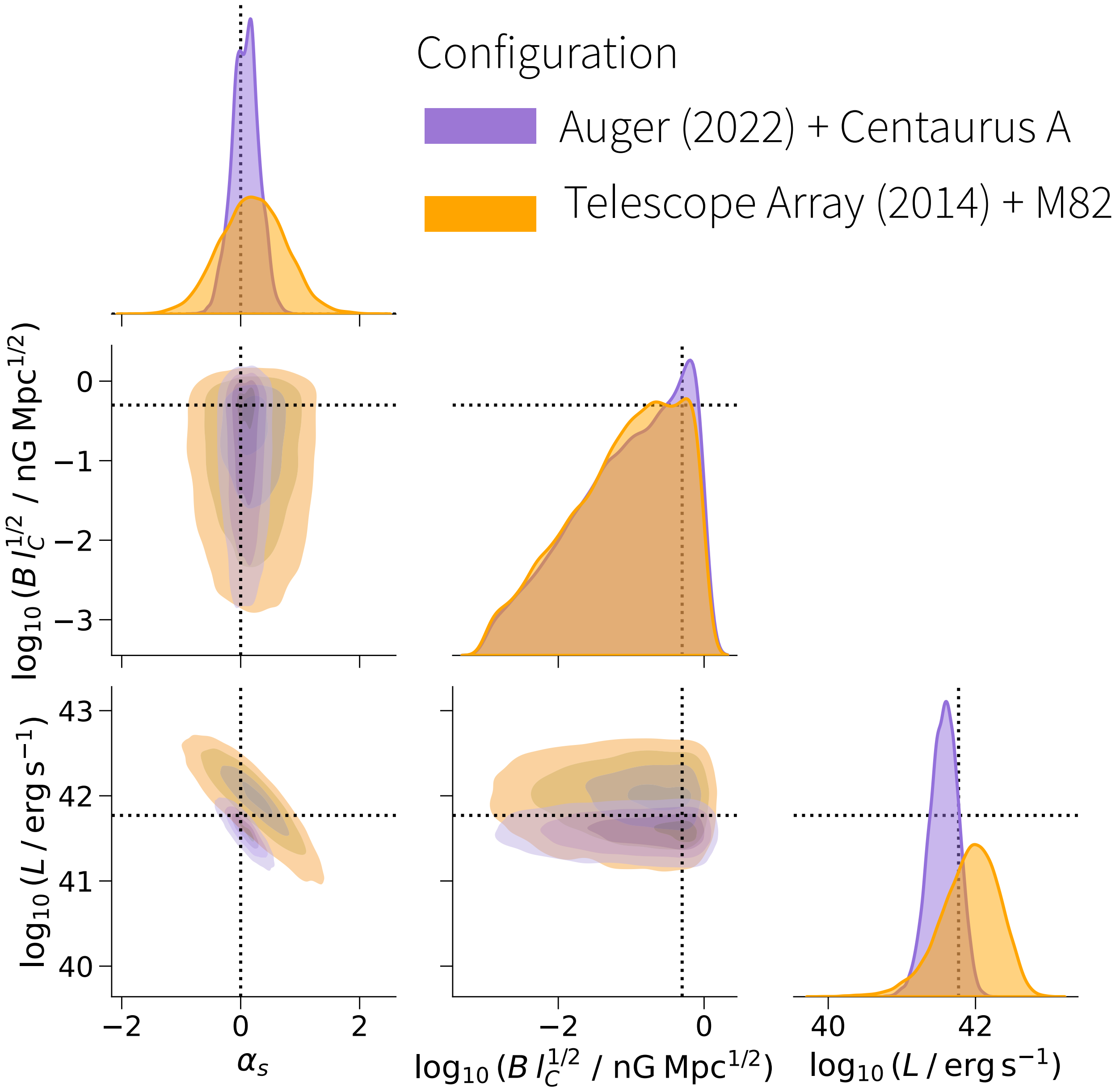


Approximation: Consider all UHECRs in a given energy range belong to one “mass group” (MG)

Verification with simulations: correct reconstruction of key physics parameters

Can also demonstrate impact of wrong mass group assumptions

[Watanabe, Fedynitch, Capel & Sagawa (UHECR 2024)]

High-energy Neutrinos

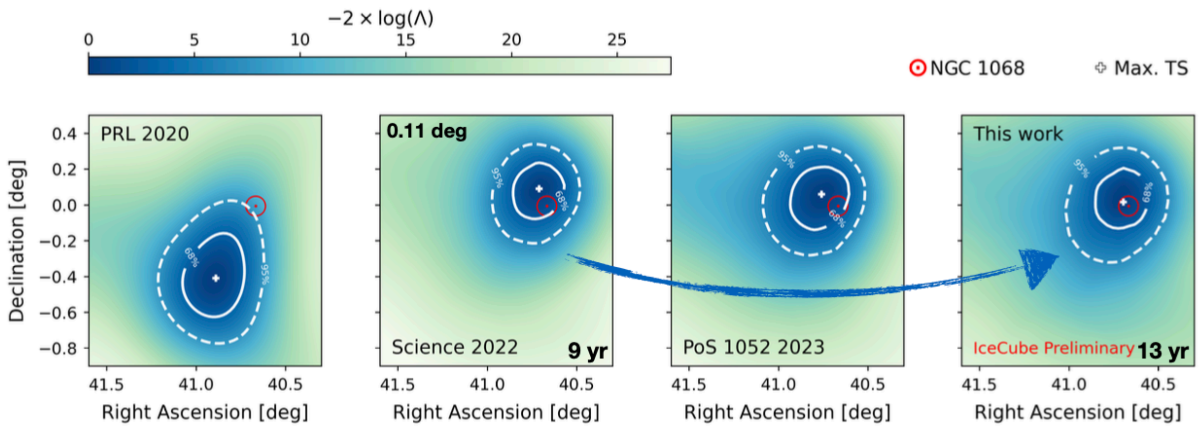
Key experiments: IceCube, KM3Net

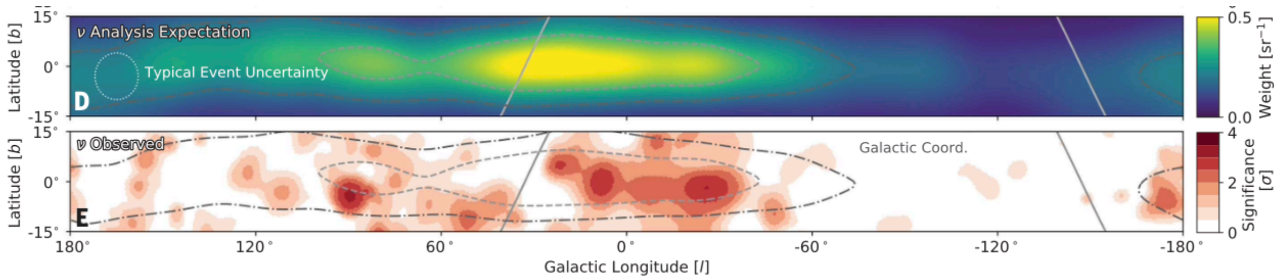
First point sources emerging (~4σ)

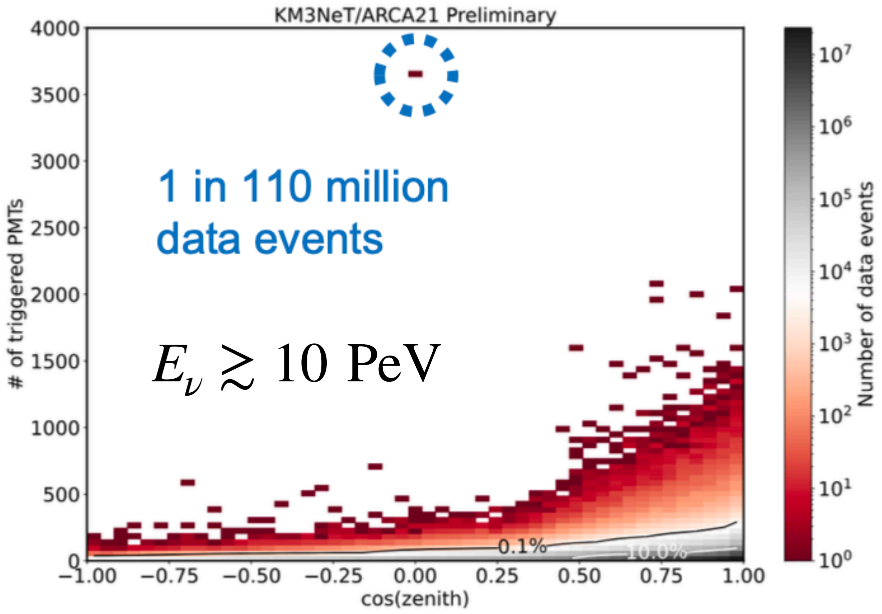
Galactic plane contribution (4.5σ)

Very high energy events

The IceCube upgrade (2025) will improve the angular resolution and future larger experiments will increase the effective area







[Kontrimas+ (TeVPA 2024); IceCube Collaboration (2023); Coelho+ (Neutrino 2024)]

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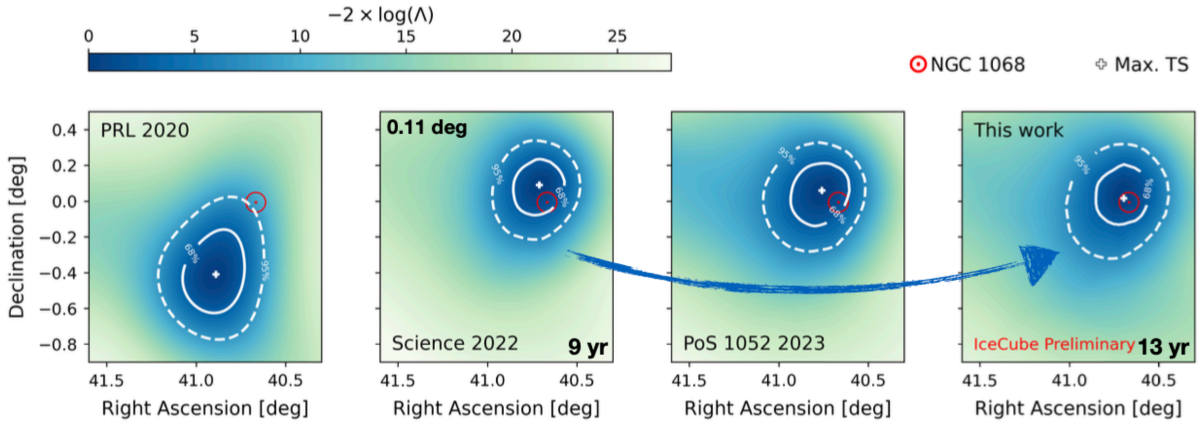

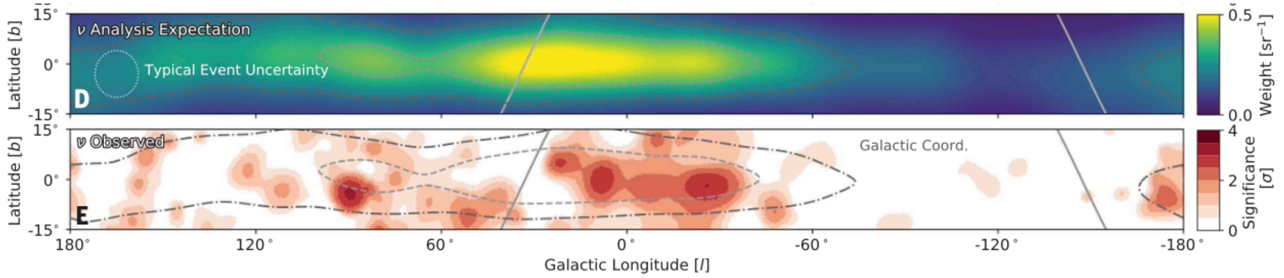

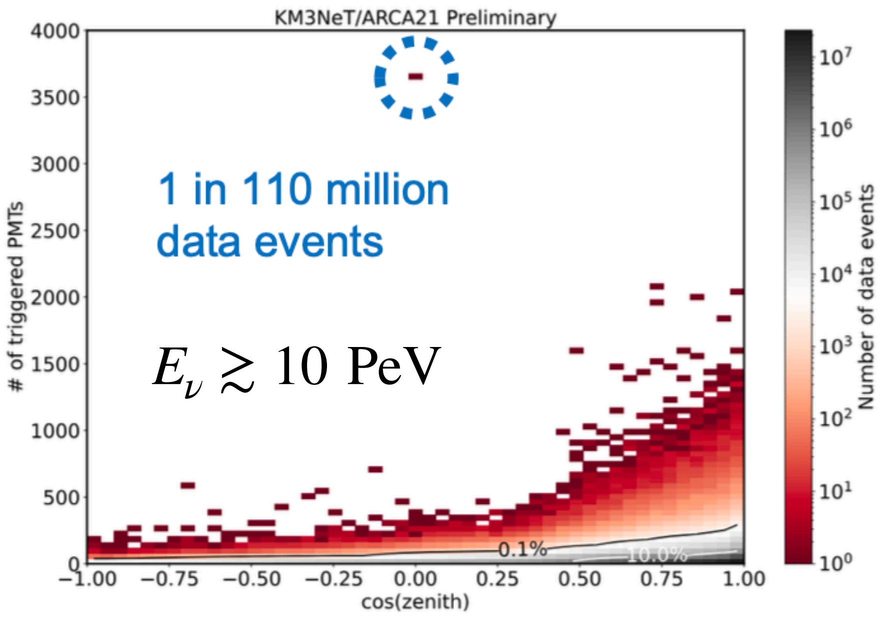

[Kontrimas+ (TeVPA 2024); IceCube Collaboration (2023); Coelho+ (Neutrino 2024)]

A new method to search for point sources

Work by PhD student Julian Kuhlmann (MPP)

Previous approaches:

- Null hypothesis significance testing → p-value, background rejection
- Simple minimisers → 2 free parameters

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Our `HierarchicalNu` approach:

- Bayesian framework → quantify probability of neutrino—source connection
- Hamiltonian Monte Carlo with ~1000s of free parameters
- Goal: Go beyond source discovery to characterisation

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How?
Bayesian hierarchical model
Implemented in the Stan probabilistic programming framework via a Python interface
Publicly available: 10.5281/zenodo.13760503

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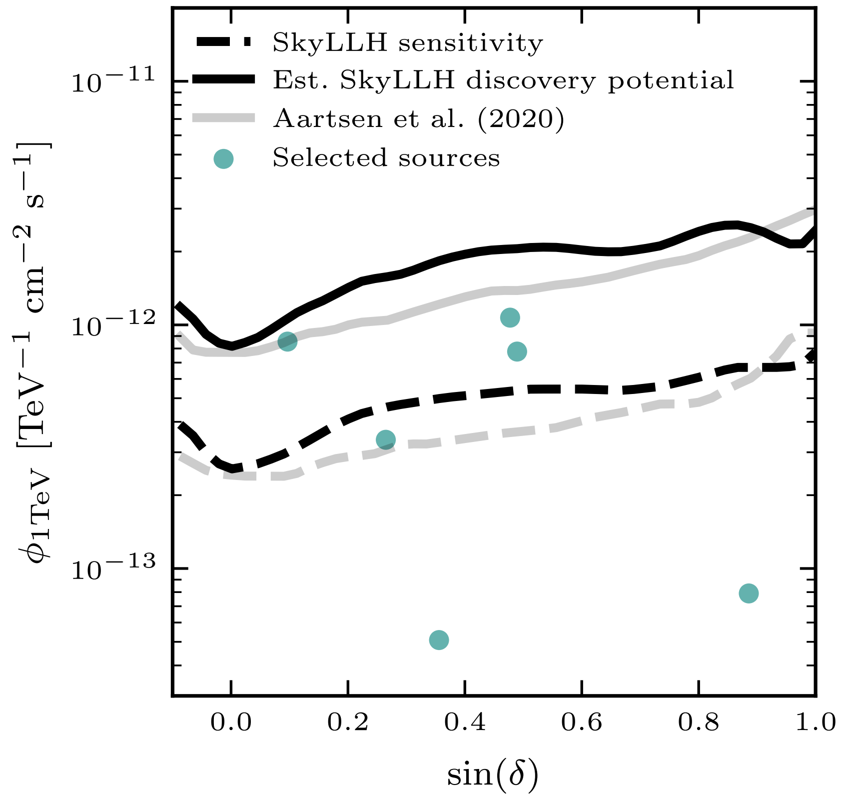
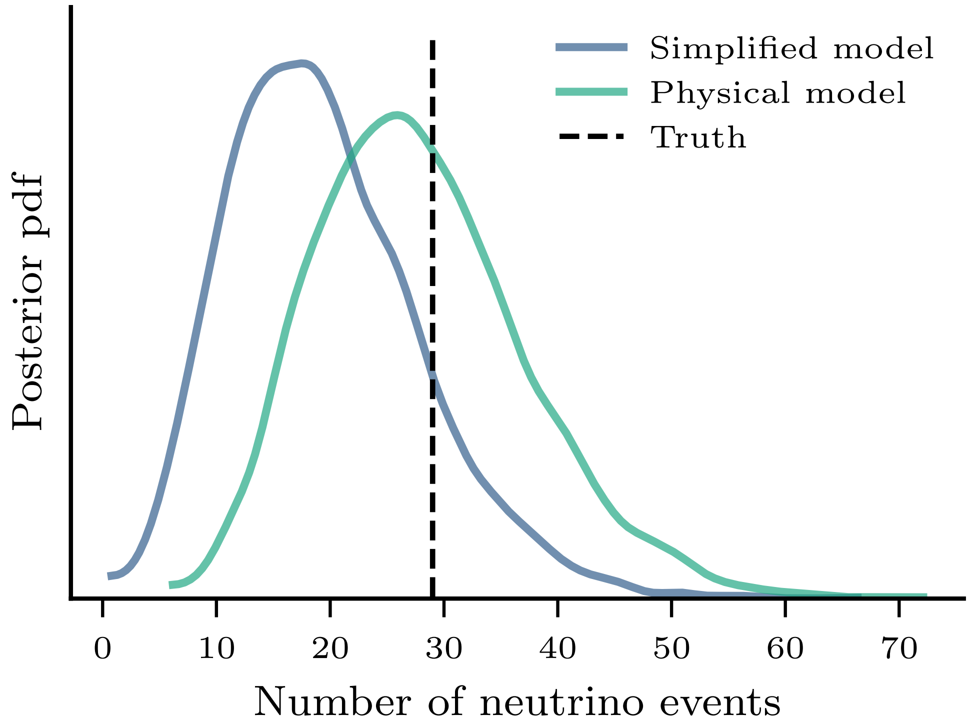
Simulate weak sources below the detection threshold of existing methods



Demonstrate how including more information on the source spectra helps to recover these sources



[Capel, Kuhlmann, Haack, Ha Minh, Niederhausen & Schumacher ApJ (2024)]

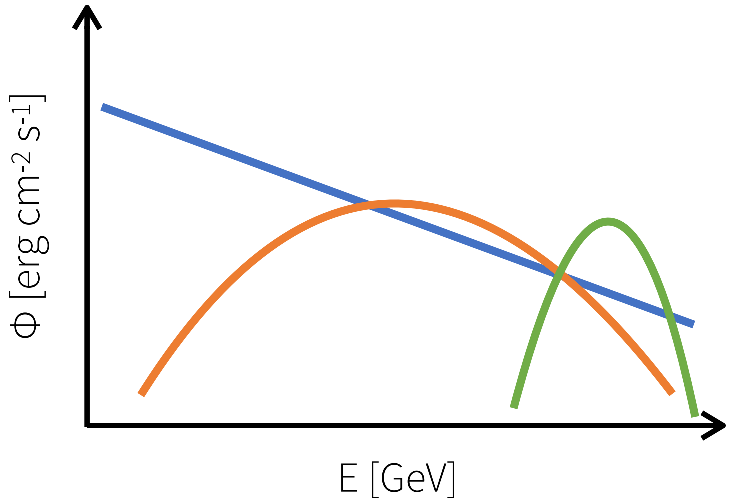
A new method to search for point sources

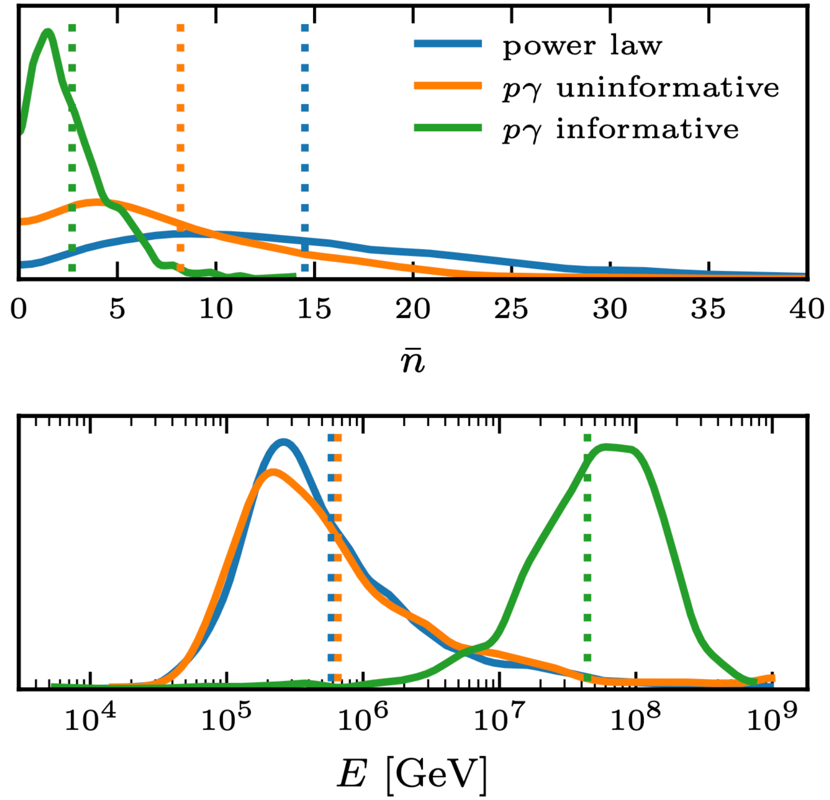
Work by PhD student Julian Kuhlmann (MPP) & Hanrieder Fellow Thara Caba

Application to public IceCube data: TXS 0506+056

Lots of multi-wavelength information, challenge to understand neutrino connection (pγ model)

[E.g. IceCube Collaboration (2018a, 2018b); Capel, Mortlock & Finley (2020); Capel+ (2022); Buson+(2023,2024); Bellenghi+ (2023); Rodrigues+ (2024)]





Impact of physical modelling:

- Less neutrinos associated
- Stronger high-energy associations

[Kuhlmann & Capel (in prep., for submission to ApJ)]

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Application to public IceCube data: Blazars spatially associated with high-energy "alert" events

4FGL	4FGL Alt. name	Alert event ID	Fit #1	Fit #2
J0158.8+0101*	5BZU J0158+0101	II.1	0.89	0.94
J0509.4+0542*	TXS 0506+056	IC170922A	0.97	0.96
J1117.0+2013	3HSP J111706.2+20140	IC130408A	0.00	0.00
J1314.7+2348	5BZB J1314+2348	IC151017A	0.00	0.00
J1321.9+3219	5BZB J1322+3216	IC120515A	0.00	0.00
J1528.4+2004	3HSP J152835.7+20042	II.10	0.00	0.00
J1808.2+3500*	CRATESJ180812+350104	IC110610A	0.29	0.43
J2030.9+1935	3HSP J203057.1+19361	II.4	0.00	0.00
J2227.9+0036	5BZB J2227+0037	IC140114A	0.00	0.00
J2326.2+0113	CRATESJ232625+011147	IC160510A	0.00	0.00

$$P(\text{alert event from source} \,|\, \text{data})$$

[Kuhlmann (RICAP 2024); Kuhlmann & Capel (in prep., for submission to ApJ)]

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→ Spatial association with alert events is not the best way to select interesting blazars/sources

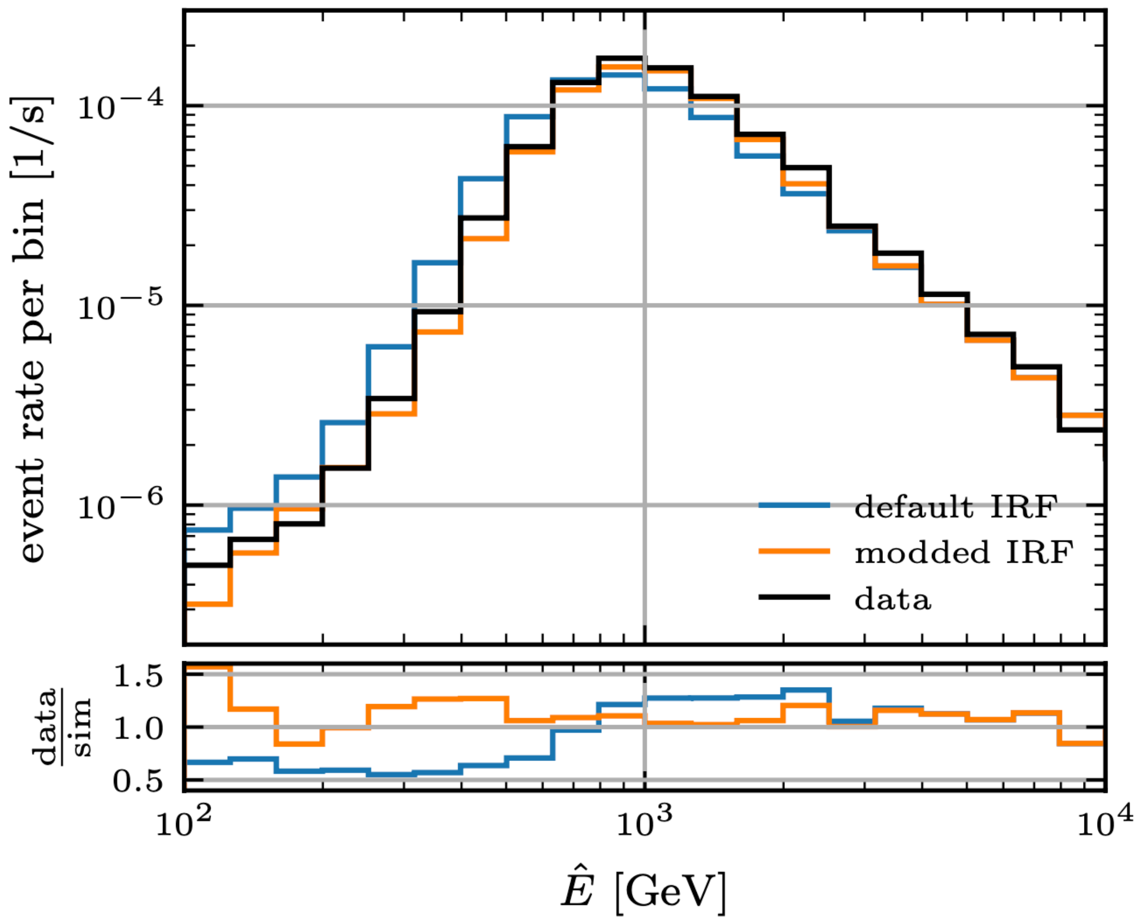
[Kuhlmann (RICAP 2024); Kuhlmann & Capel (in prep., for submission to ApJ)]

A new method to search for point sources

Work by PhD student Julian Kuhlmann (MPP)

Challenges of working with public data: Instrument response function doesn't align with data

Difficult to reproduce published results at lower energies (e.g. NGC 1068)



[Kuhlmann (RICAP 2024); Kuhlmann & Capel (in prep., for submission to ApJ)]

The source—population connection

Work by PhD student Lena Saurenhaus (MPP)

NGC 1068 is seen in neutrinos but not gamma-rays ⇒ core-corona model (implemented in **AM³** software)

[Murase+ (2020); Klinger+ (2020); https://gitlab.desy.de/am3]

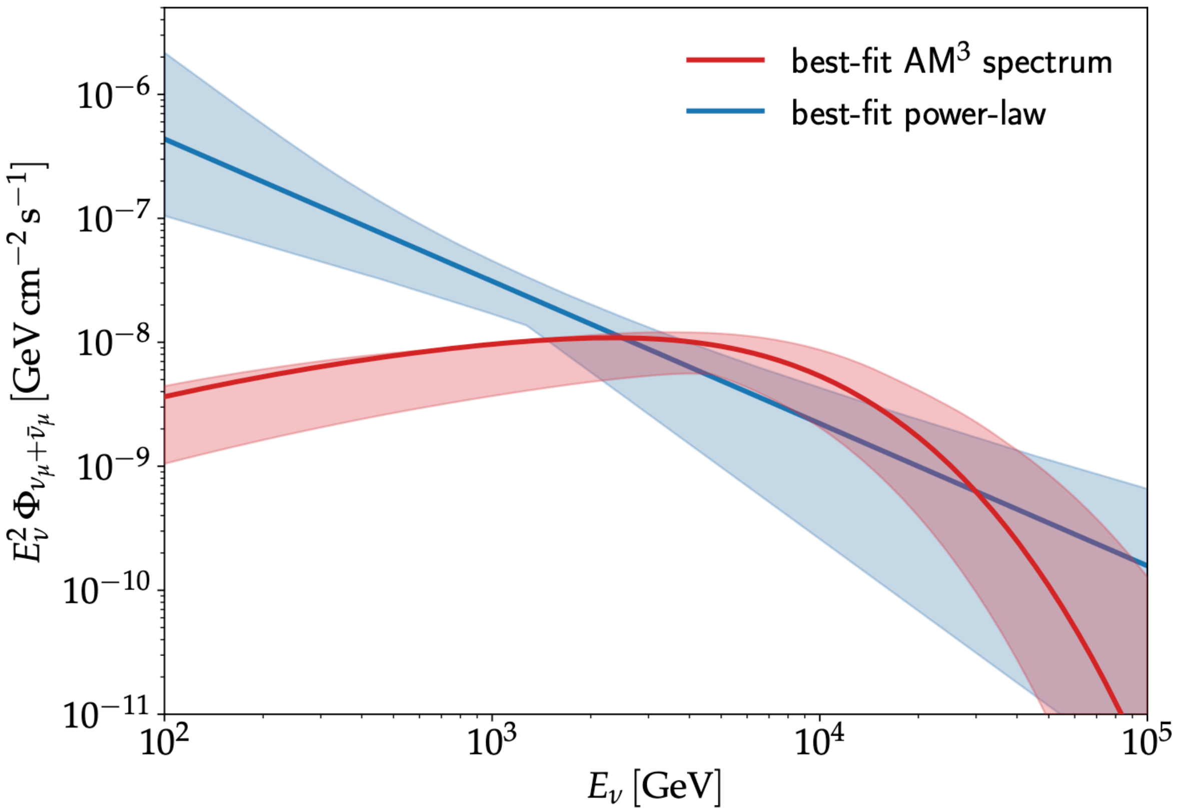
[Developed in collaboration with Foteini Oikonomou at NTNU]

Fit the model to the public IceCube data with **SkyLLH**

[https://github.com/icecube/skyllh/tree/new_flux_spectrum]

Free parameters

- P_{CR}/P_{th}: normalisation of the proton spectrum (<0.5)
- η: Inverse turbulence strength of coronal magnetic field



[Saurenhaus, Capel & Oikonomou (RICAP 2024)]

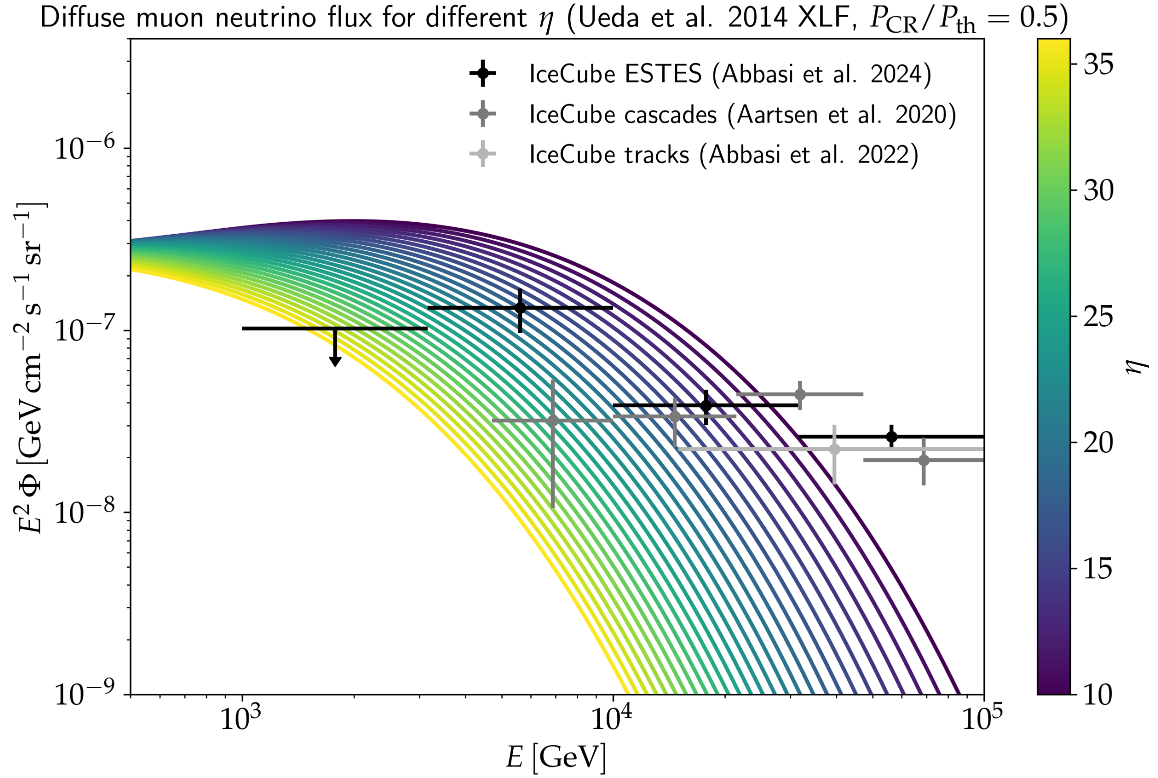
The source—population connection

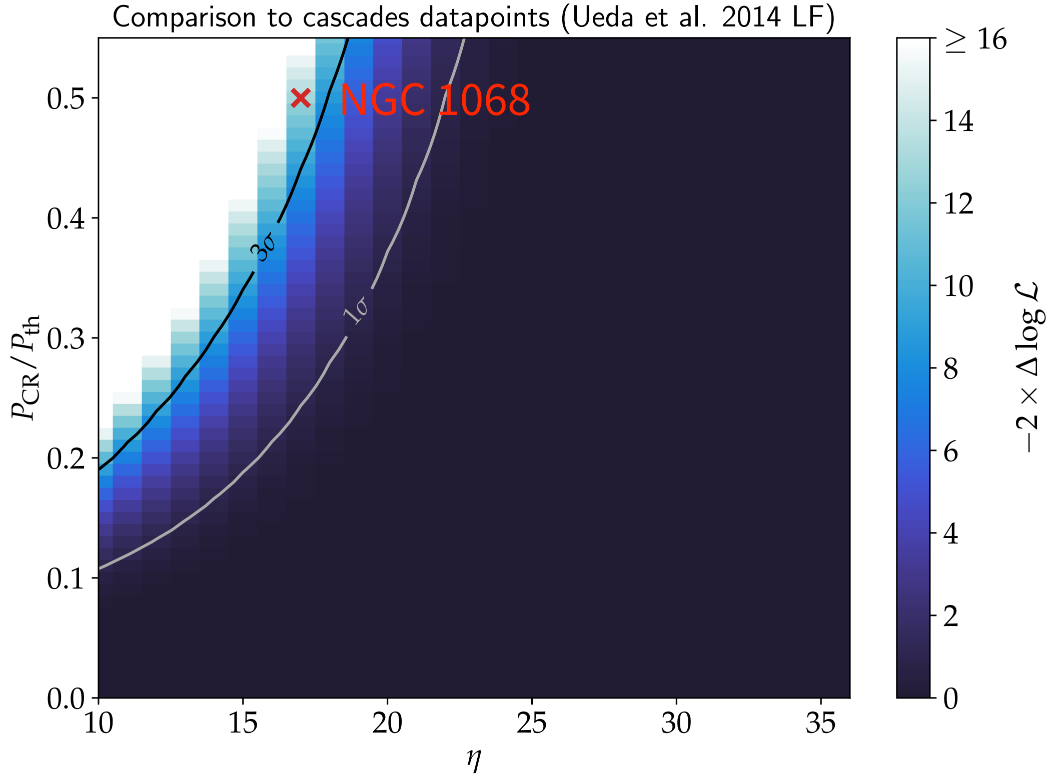
Work by PhD student Lena Saurenhaus (MPP)

Extrapolate to the entire Seyfert population using the X-ray luminosity function and `popsynth`

[Ueda+ (2014); Buchner+ (2015); Capel & Burgess (2021); https://github.com/cescalara/popsynth]

Constrain free parameters from comparison with the diffuse flux ⇒ NGC 1068 is on the threshold





[Saurenhaus, Capel & Oikonomou (in prep. paper #1)]

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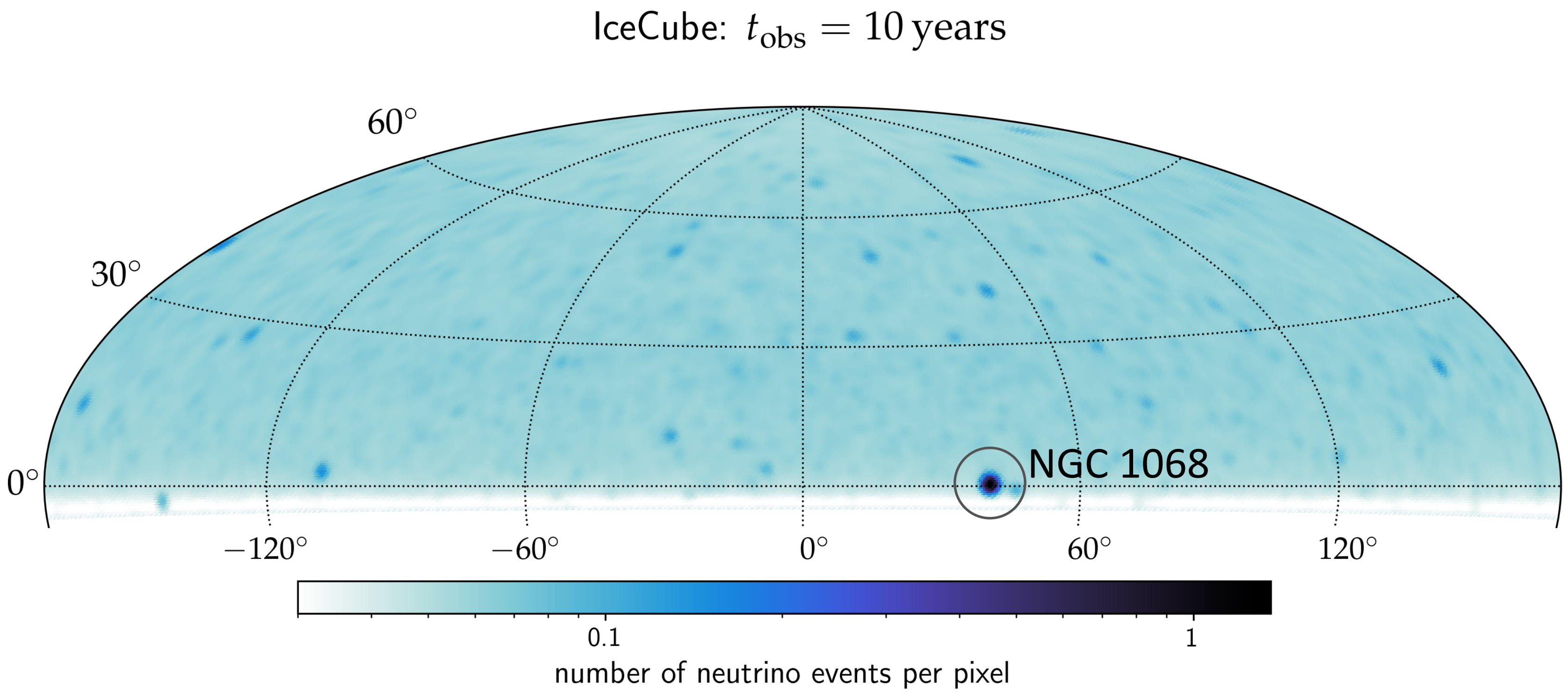
Detailed template for future point source searches



[Saurenhaus, Capel & Oikonomou (in prep. paper #2)]

Preparation for future experiments

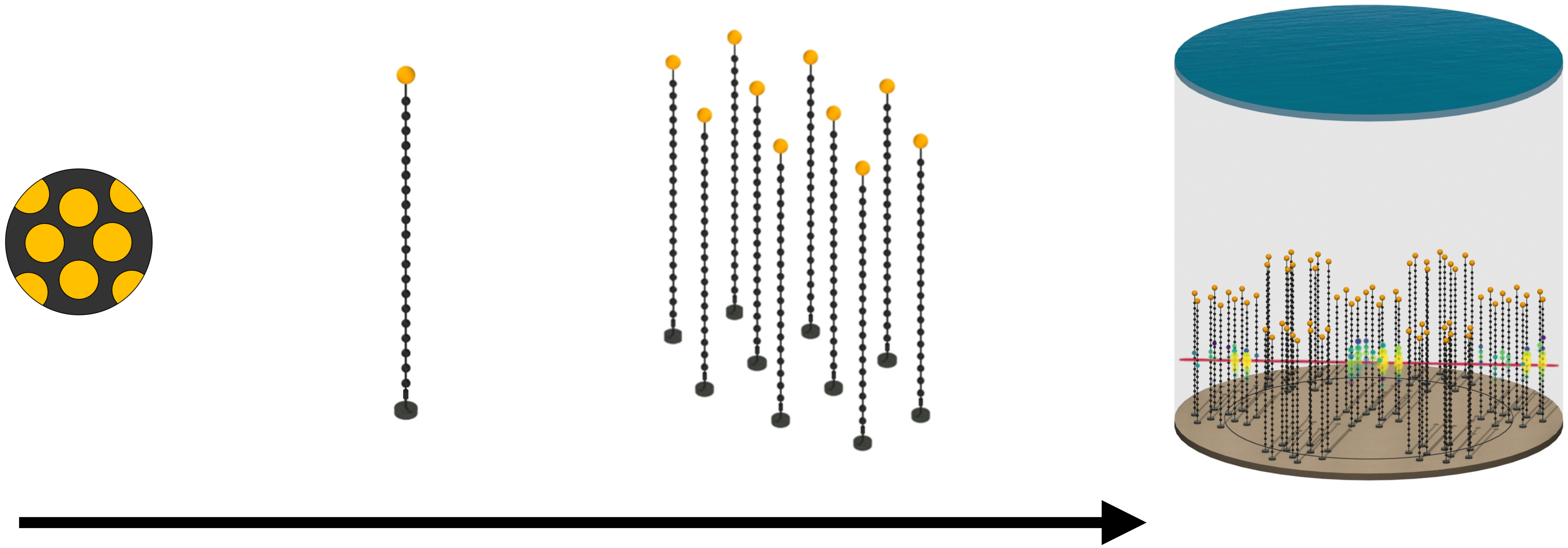
Work by Master Student Avalon Rego (LMU)

FPGA-based fast machine learning triggers for application to underwater neutrino telescopes (e.g. P-ONE)

Goal: Handle complex bioluminescence signals ⇒ lower energy threshold with fixed telescope design

How: Using Graph-based neural networks implemented in `GraphNet`

Status: Scaling from single detector line to groups of lines, expect improved performance (WIP)



Summary

We set out to address these challenges

Challenges:

Rejecting isotropy → explaining the data

Combining information from theory and observations

Ultra-high-energy cosmic rays

- Two new methods presented to the community to search for sources
- Complementary analyses at different energy scales

High-energy neutrinos

- New approach to point source searches presented to the community
- Tools for connecting the individual sources to their populations

Thank you for your support!