Galactic Plane Results

NBIA Summer School: Neutrinos – here, there & everywhere

Ludwig Neste on behalf of the IceCube Collaboration

2025-07-08

Galactic Neutrinos:

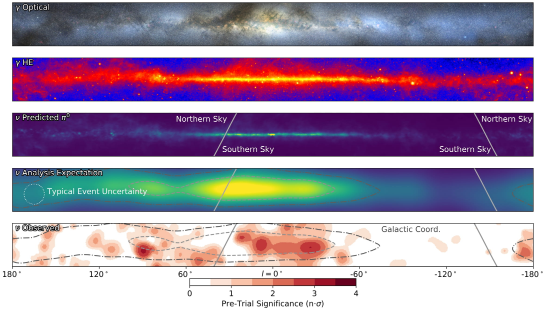
CR+ISM: π^+, π^-, π^0 ($\sim 1 : 1 : 1$) from hadronic p-p interactions

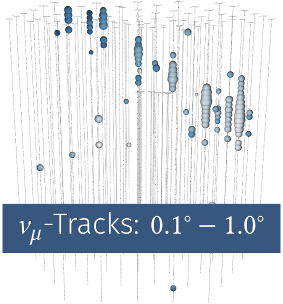
$$\pi^0 \to \gamma\gamma$$

$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_\mu \bar{\nu}_\mu \nu_e$$

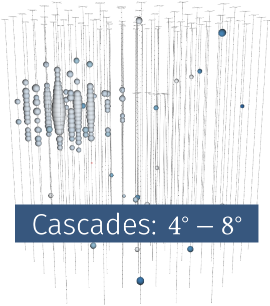
$$\Rightarrow E_\gamma = 2E_\nu$$

$$\Rightarrow E_\nu^2 \frac{\mathrm{d}N_\nu^{\text{All-Flavor}}}{\mathrm{d}E_\nu} = \frac{3}{2} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$



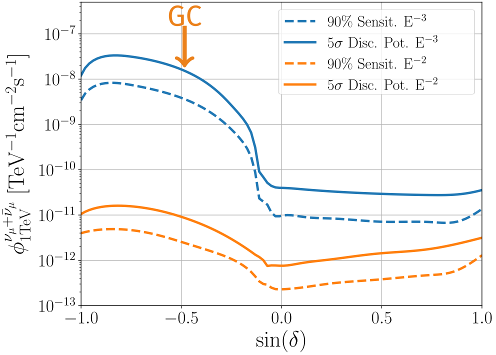


ν_μ-Tracks: $0.1^\circ - 1.0^\circ$



Cascades: $4^\circ - 8^\circ$

The Galactic Plane is Challenging for IceCube



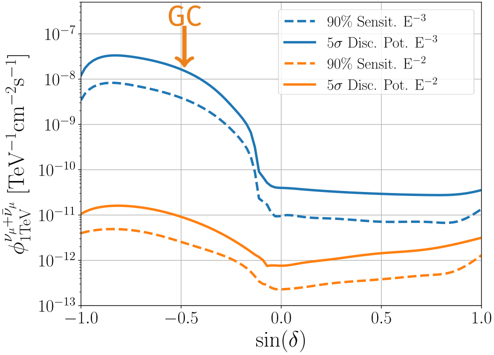
← Track point source sensitivity (2020, doi:10.1103/PhysRevLett.124.051103)

Galactic plane is mainly in the south

Center is at $\delta = -29°$

⇒ Challenging observation for IceCube

The Galactic Plane is Challenging for IceCube



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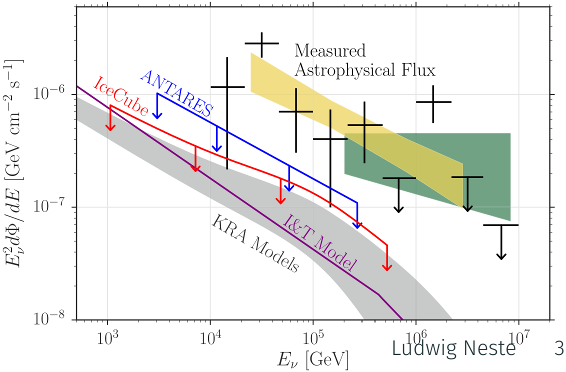
⇒ Challenging observation for IceCube

First IC GP results using tracks → (1.5σ 2017, doi:10.3847/1538-4357/aa8dfb)



Using unbinned maximum $\mathscr{L}$ template fit

Upper limits (KRA$_\gamma$, red) above modeled flux

2023: Observation of high-energy ν from the Galactic plane

Stockholm University

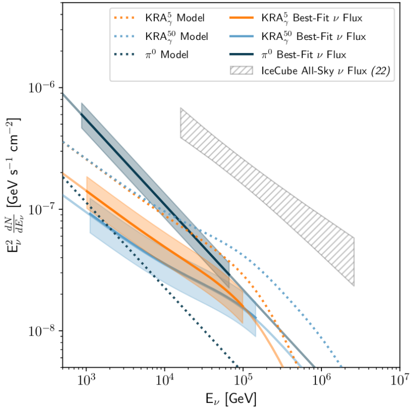
Model	n_s	Flux	Significance
Fermi-LAT π^0	748	$21.8^{+5.3}_{-4.9}$*	4.71σ
$\mathrm{KRA}_\gamma^{5\,\mathrm{PeV}}$	276	$0.55^{+0.18}_{-0.15} \times \mathrm{MF}$	4.37σ
$\mathrm{KRA}_\gamma^{50\,\mathrm{PeV}}$	211	$0.37^{+0.13}_{-0.11} \times \mathrm{MF}$	3.96σ

→ Trials-corrected significance:

4.48σ ν **observation of the Milky Way**

→ GP flux contributes approx. $10\,\%$ to astrophysical flux

→ Partial contribution from unresolved sources in the GP can not be excluded



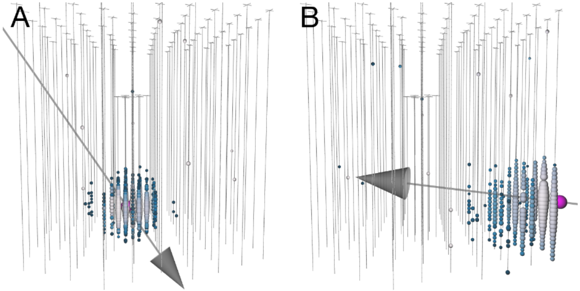
Analysis by

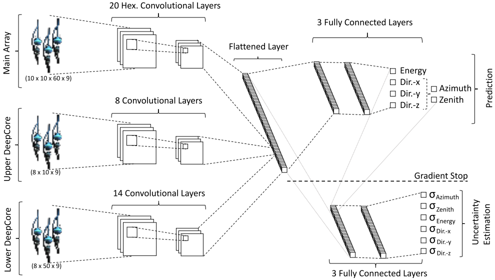
Steve Sclafani

Mirco Hünnefeld

*$E^2\Phi$ at 100 TeV assuming SPL $\gamma = 2.7$ in 10^{-12} TeV/cm^{2}s

Downgoing cascades are easier to differentiate from muons, but hard to filter out





2023 Machine Learning based event-selection increased dataset by a factor of 20:

~60 000 cascade events

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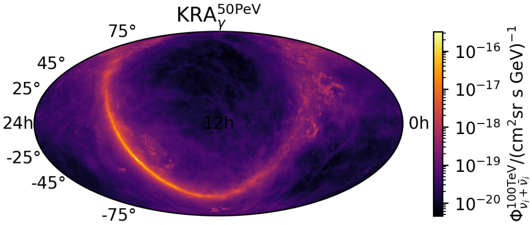

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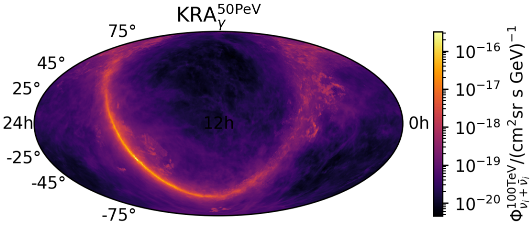
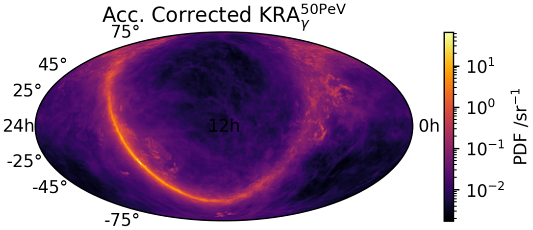


2. Account for detector acceptance



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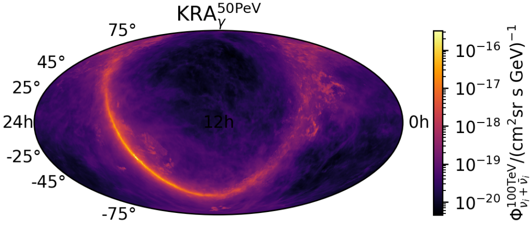

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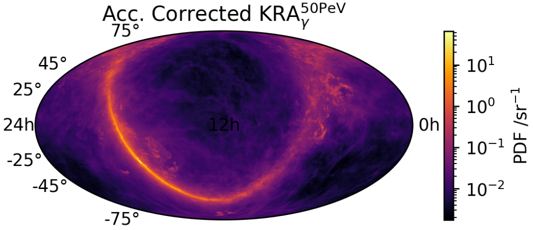
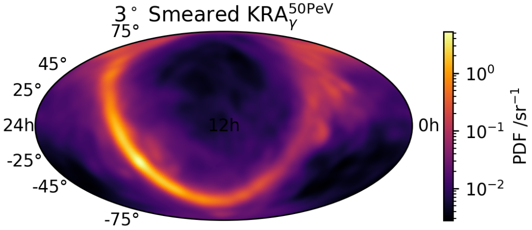


3. Account for per-event angular unc. σ_i



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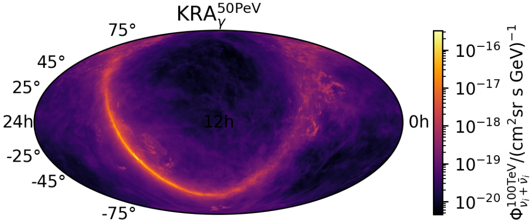

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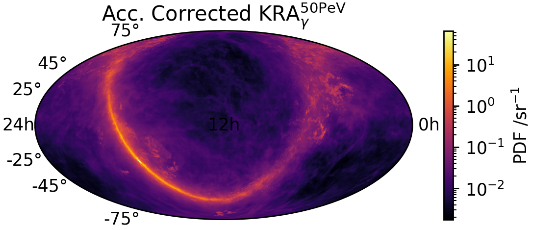

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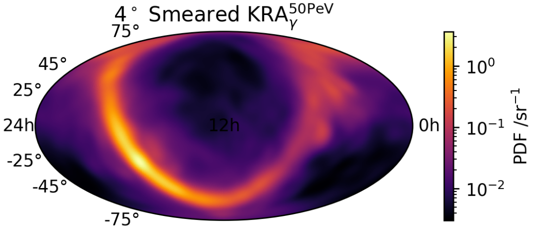

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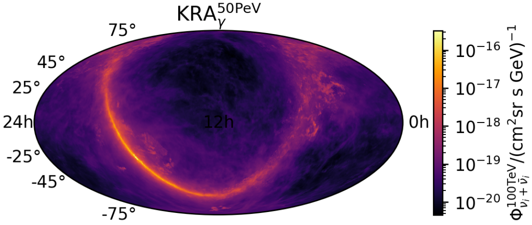

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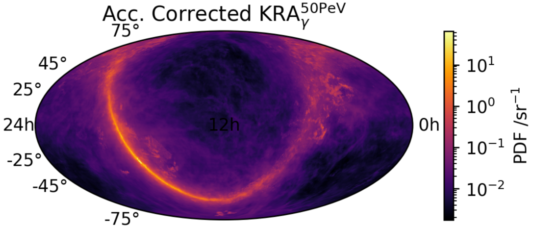

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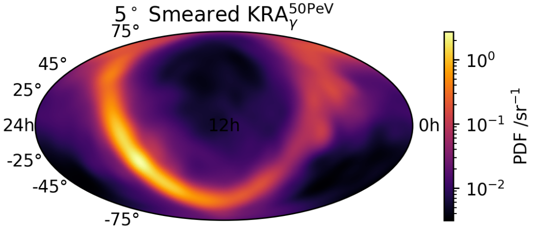

Spatial Templates Signal PDF

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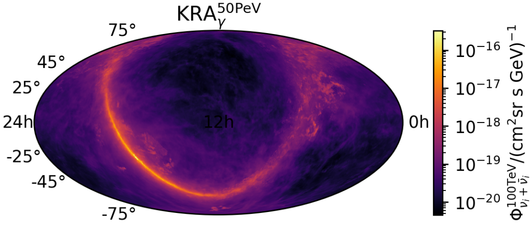

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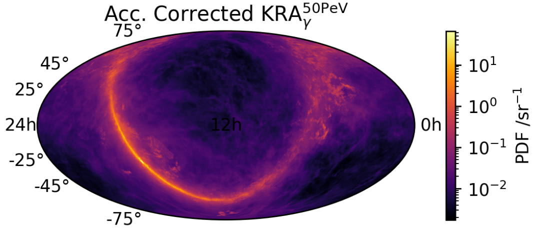

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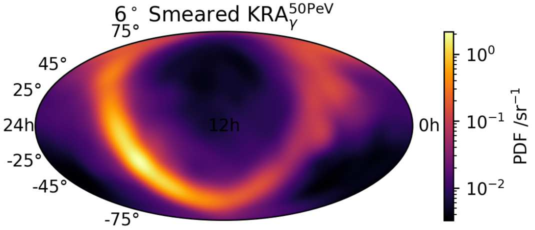

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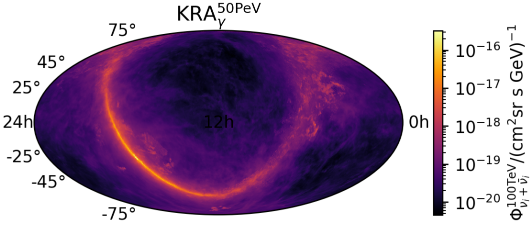

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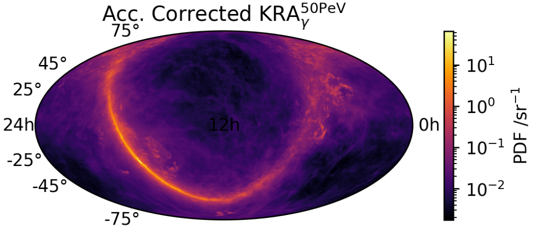

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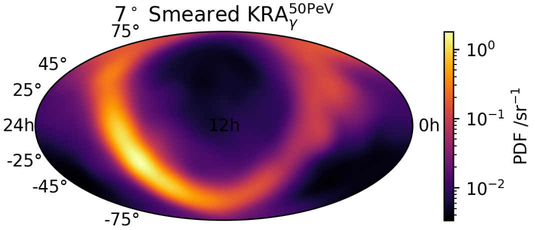

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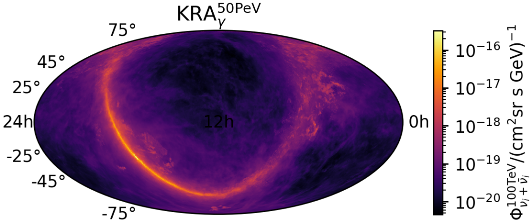

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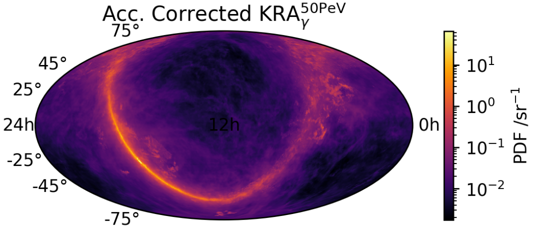

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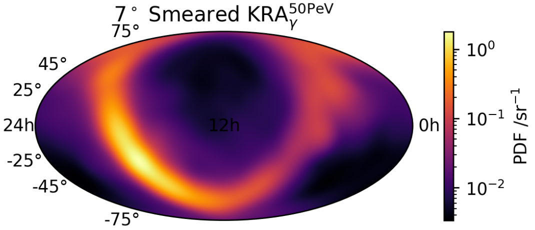
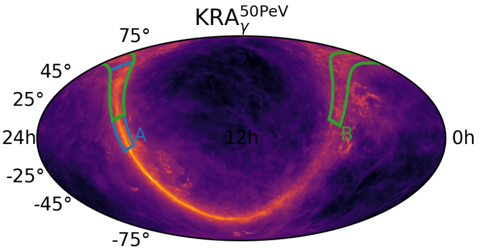


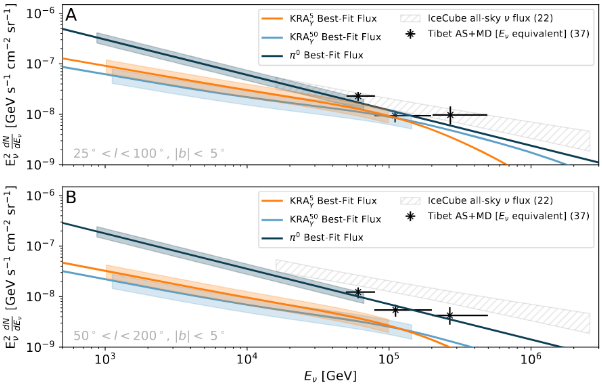
$\Rightarrow$ Use diffuse ν prediction as spatial PDF:

$$\mathcal{S}(\alpha,\delta|\sigma) = \mathcal{T}(\alpha,\delta|\sigma)$$

Don't forget to account for the large signal contamination in the scrambled background-PDF! (Signal substraction)

Comparison to High Energy γ Rays





← Compare IC GP results from high energy γ-ray observatories

- Scale IC GP result to Tibet AS-γ analysis region
- Convert γ-flux to ν flux assuming pure π^0-decay

⇒ Consistent with high energy γ-rays
But: Best fit π^0 is $\sim 5\times$ higher than simple extrapolation

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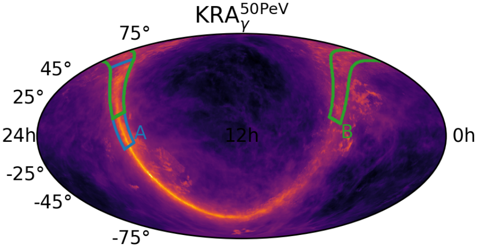

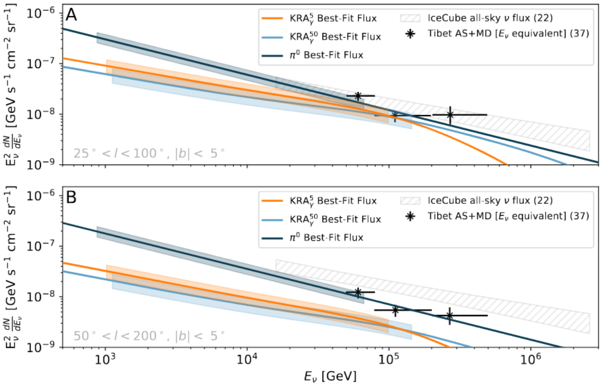

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⇒ Consistent with high energy γ-rays
But: Best fit π^0 is $\sim 5\times$ higher than simple extrapolation

⇒ It's difficult to compare subregions and spectral indices of the result

New Analysis Method: Segmented Templates

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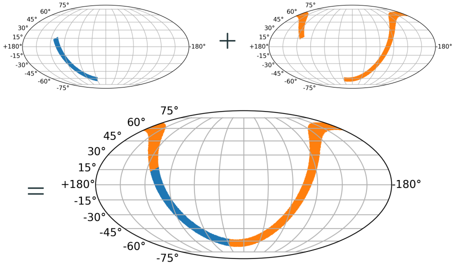
$$\mathcal{L}(\gamma, n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i(\gamma) + \frac{N - n_s}{N} B_i \right]$$

New Features

$$S = \sum_{k=1}^{M} w_k \cdot \mathscr{E}(E \mid \delta, \gamma_k) \cdot \mathscr{T}_k(\alpha, \delta \mid \sigma)$$

$2M$ free parameters:

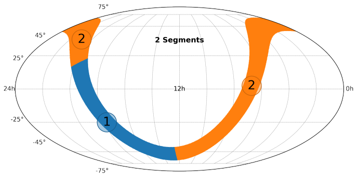
$n_1, \dots, n_M, \gamma_1, \dots, \gamma_M$

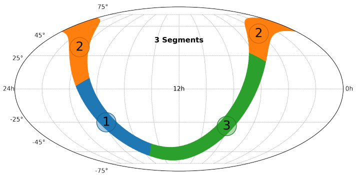


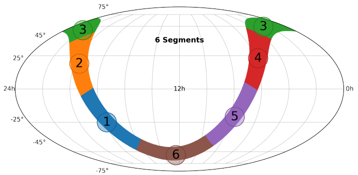
Segmented Template Analysis

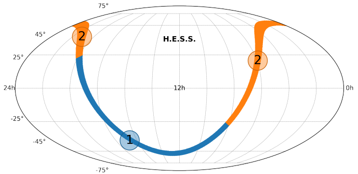
- Spectral index γ for each segment
- Flux normalization Φ for each segment
- Not dependent on neutrino emission models
- Independent result for each segment

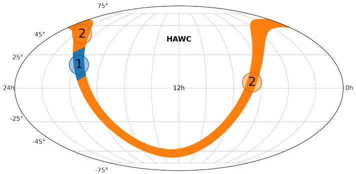
Outlook: Gamma Ray Inspired Segmentations Schemes

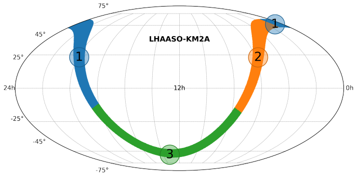


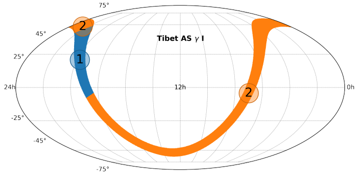


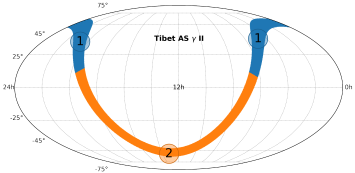








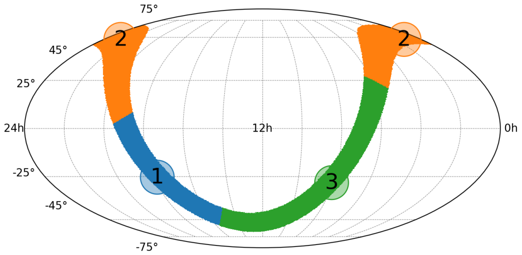




Conclusion: IceCube is not done with the Galaxy, yet

My work: Segmented fit of the GP

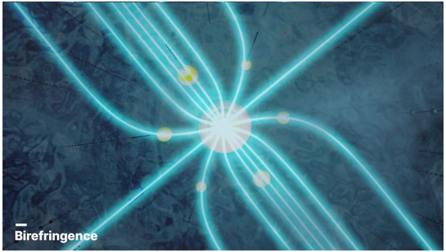
Segmented GP flux and γ measurement



Matthias Thiesmeyer (PhD student, Madison):

Updated GP analysis using combined datasets

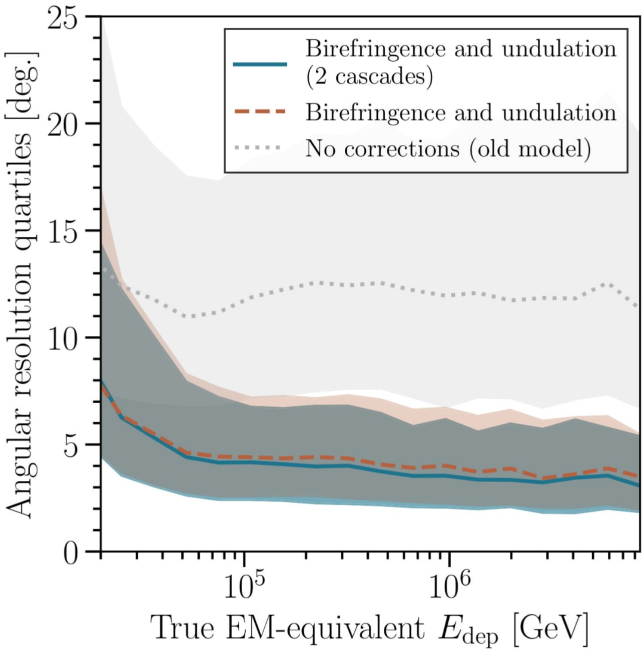
- Cascades+Through-going Tracks+Starting Tracks
- More data
- Improved ice models



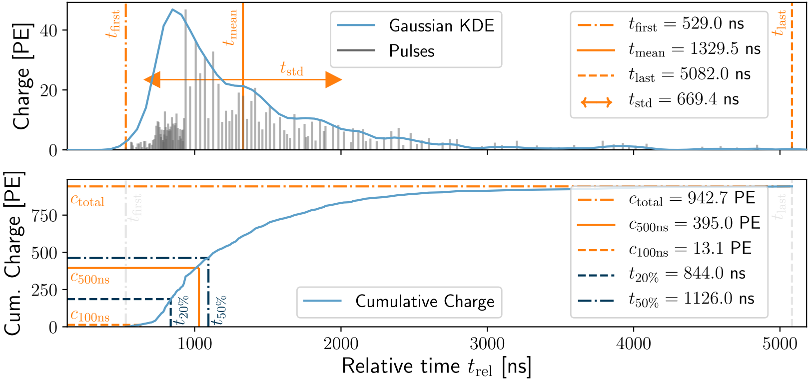
Stay tuned for ICRC! 😁

Backup

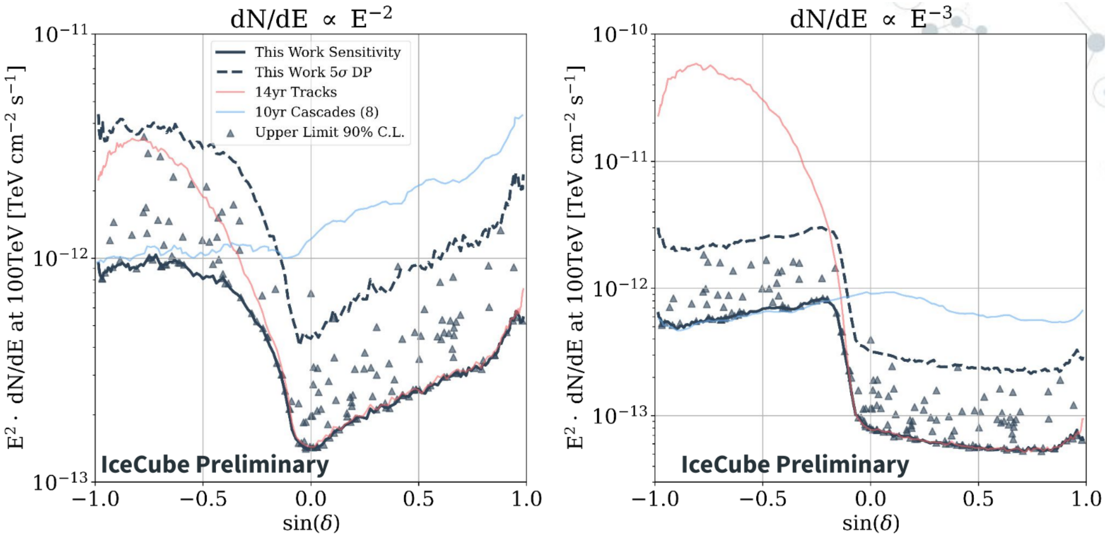
Current Cascade Reconstructions



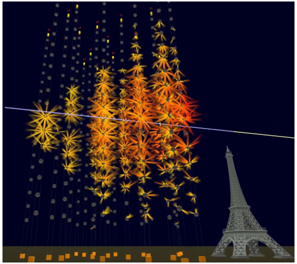
DNN per-DOM Input



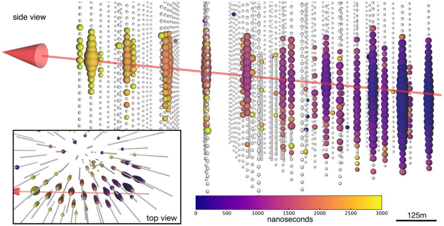
Updated PS Sensitivities (2025)



Key Differences between KM3Net and IceCube



⬇️ Scattering	⇒	Better pointing
⬆️ Absorption	⇒	Denser layout
≈ Homogeneous	⇒	No depth-dependency
🌊 Dynamic	⇒	Changing geometry
📍 North	⇒	Optimal for southern sky



⬆️ Scattering	⇒	Poorer pointing
⬇️ Absorption	⇒	Sparser layout
Inhomogeneous	⇒	Depth-dependency
🧊 Static	⇒	Fixed geometry
📍 South Pole	⇒	Optimal for northern sky

The Leap: Deep Neural Networks (DNNs)

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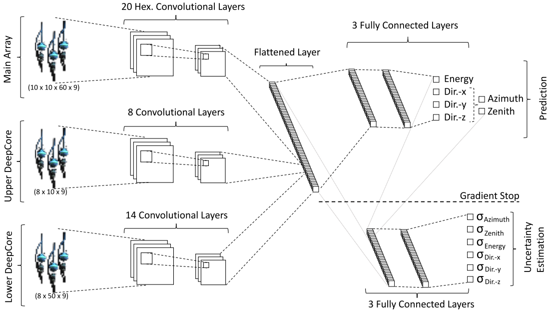
- Convolutional & fully connected layers
- DNNs optimized for (hexagonal) layout
- Built-in uncertainty estimation
- Arbitrary labels (e.g. event-type)
- Fast reconstruction $\mathcal{O}(\mathrm{ms})$



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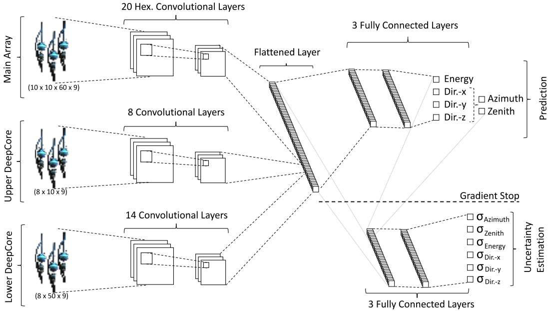
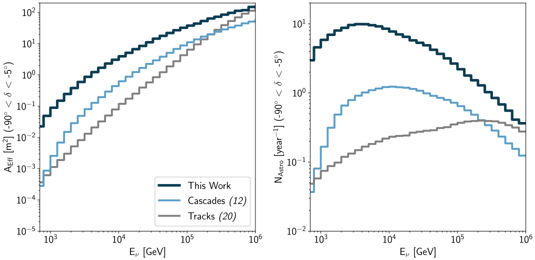
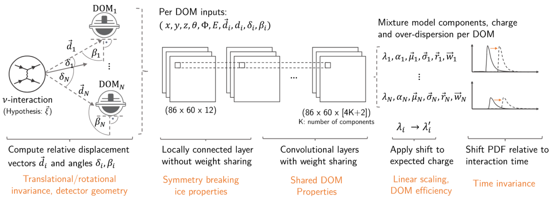




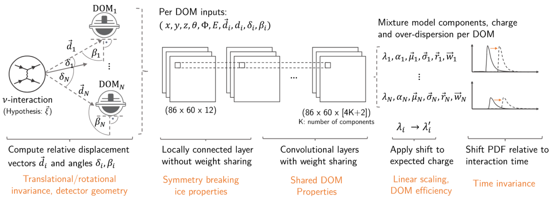
- Previous cascade selection:
  $\sim$ 2000 events
- DNN-based cascade selection:
  $\sim$ 60 000 events

Stockholm University



- Hybrid: DNNs & Likelihood
- Utilizes physical symmetries
- Predicts per-DOM PDF parameters $\vec{p}_i$ given an event hypothesis $\vec{x}, \Phi, \Theta, E, t$
- Maximize $\mathcal{L}(\vec{x}, \Phi, \Theta, E, t | \text{data})$

The Leap Part 2: A new Cascade Reconstruction



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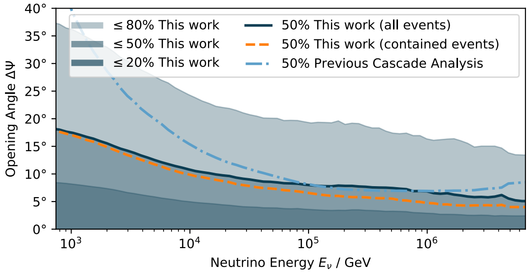
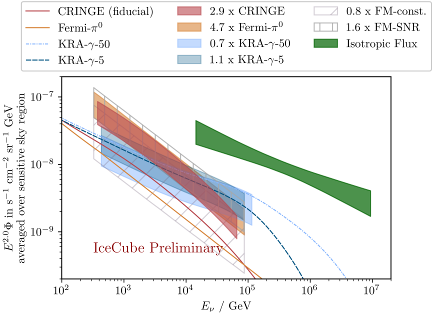
- Enhances directional reconstruction in all energy regions
- ~5° median resolution at high energies

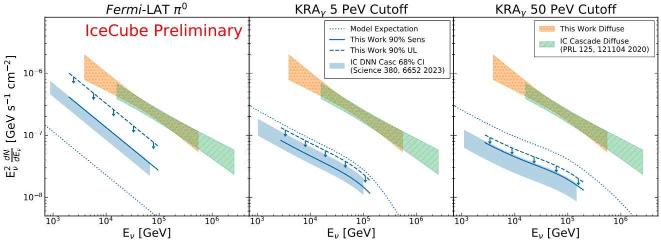


The GP in Tracks (ICRC 2023)

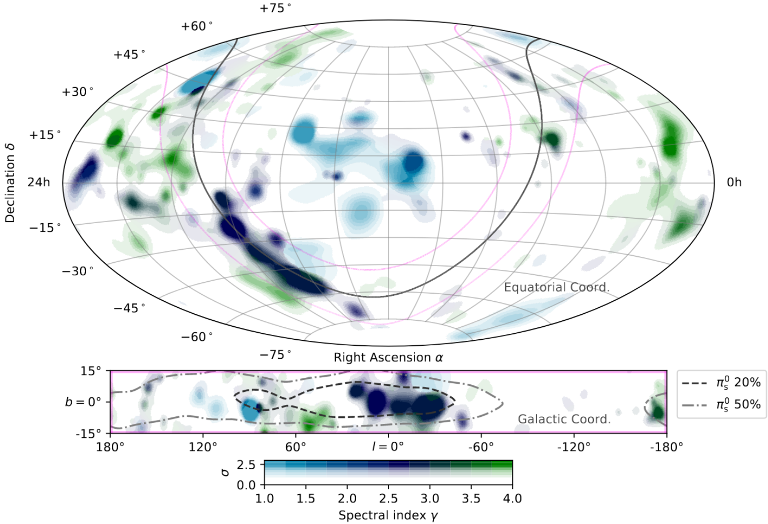
Through-going northern tracks:
CRINGE with 2.7σ
arXiv:2308.08233



Starting tracks:
Fermi π^0 with 1.5σ
arXiv:2308.04582



DNN Cascades Skyscan



- Assume a point source at every "pixel" in the sky
- Compute significance and fit γ

⇒ Galactic plane emerges visually among the fluctuations

Unbinned maximum Likelihood approach: $\mathscr{L}(n_s, \theta) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S(\mathbf{x}_i|\theta) + \frac{N - n_s}{N} B(\mathbf{x}_i) \right]$

- Background PDF B is obtained from data via RA scrambling
- Distribution of test statistic $\Lambda = 2 \log \frac{\mathscr{L}(n_s = \hat{n}_s)}{\mathscr{L}(n_s = 0)}$ evaluated on randomized data

$\Rightarrow$ p-values are robust against systematic uncertainty

- Signal PDF S uses spatial and energy information: $S = \mathscr{E}(E|\delta) \cdot \mathscr{S}(\alpha, \delta|\sigma)$
- For large signals: When using data-driven background-PDF, subtract the signal from it!