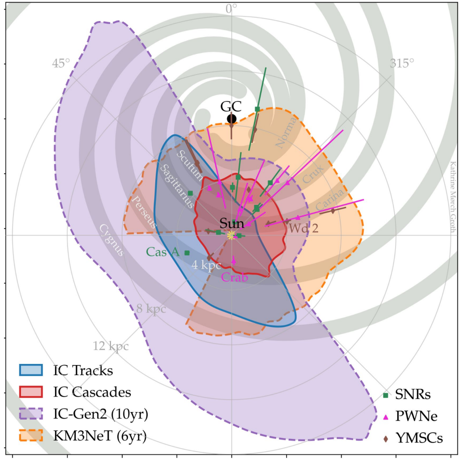
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Diffuse Emission of Neutrino Sources beyond the Discovery Horizon

arXiv:2306.17285



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Astrophysical neutrino sources

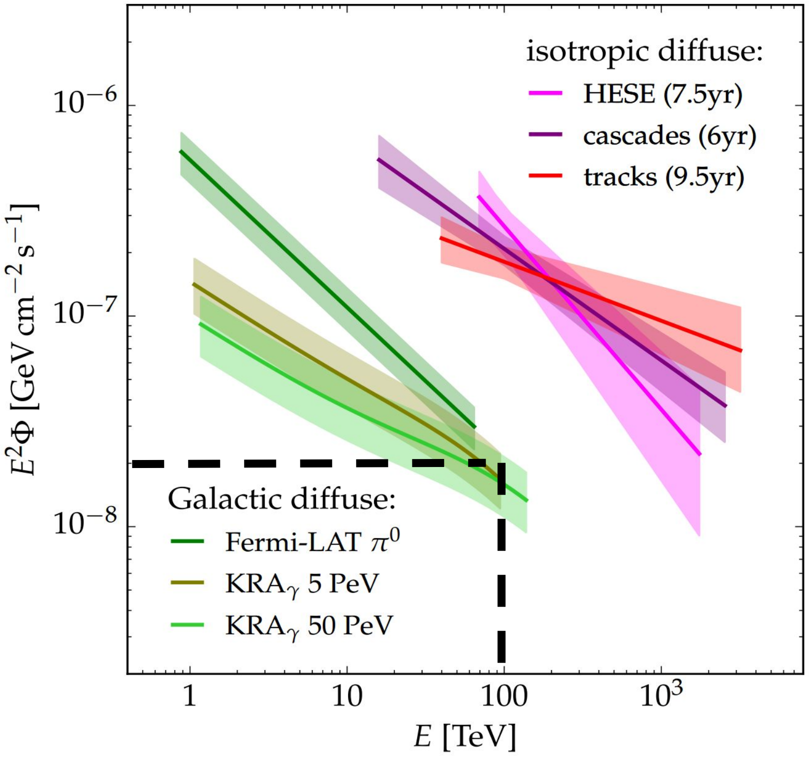
AA+**KMG**+EP+MA arXiv:2306.17285

IceCube has observed astrophysical neutrinos:

- ➢ Isotropic diffuse flux
- ➢ Galactic diffuse flux

Galactic plane neutrino emission:

- ➢ Consistent with CR diffusion models
  [Fermi-LAT Collab. '15, Gaggero et al. '15]
- ➢ Hidden Galactic sources?

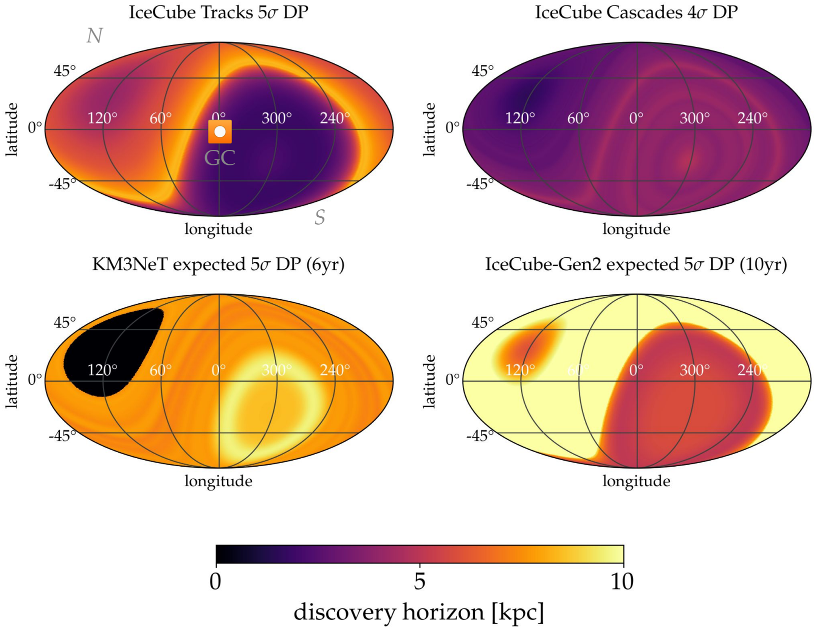


IceCube Collaboration '23

See also talks by Mirco Hünnefeld and Lisa Schumacher

The Discovery Horizon

- From a choice of luminosity, $L_{100\,\mathrm{TeV}} \equiv \left[E^2\, Q_\nu\right]_{E=100\,\mathrm{TeV}}$ we can convert the Discovery Potential to a maximal distance



DP's from: IC Tracks [1] IceCube Collab '20, IC Cascades [2] IceCube Collab. '23, KM3NeT Collab. '19 [3] and IceCube-Gen2 Collab. '23 [4]

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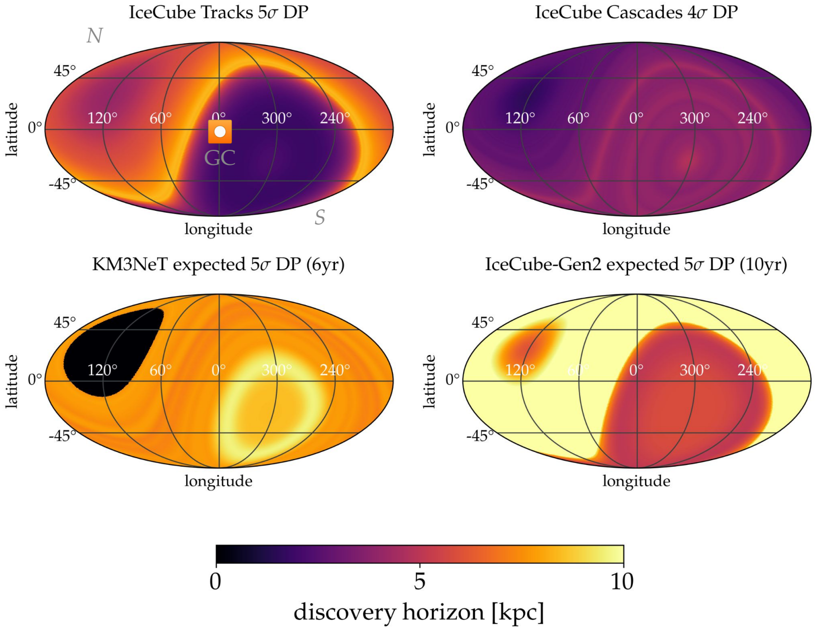

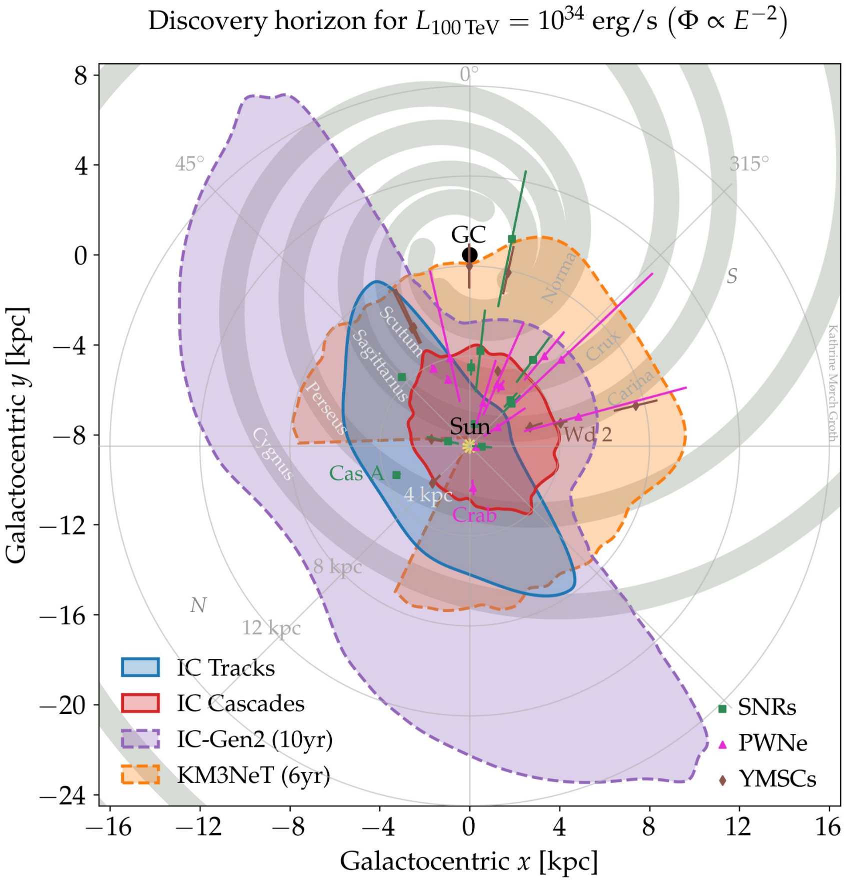

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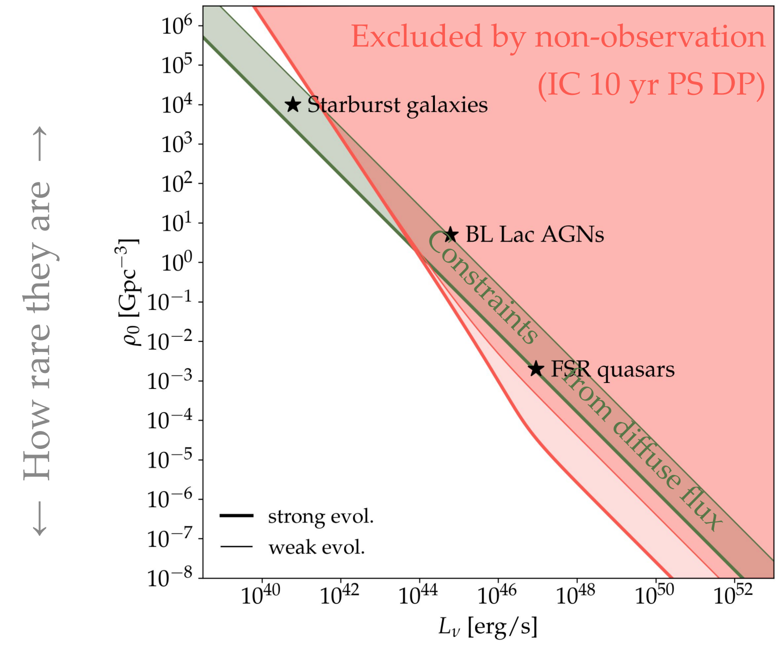
Updated from AA+**KMG**+EP+MA arXiv:2306.17285

Neutrino populations

➢ Extragalactic version:



➢ Galactic version:

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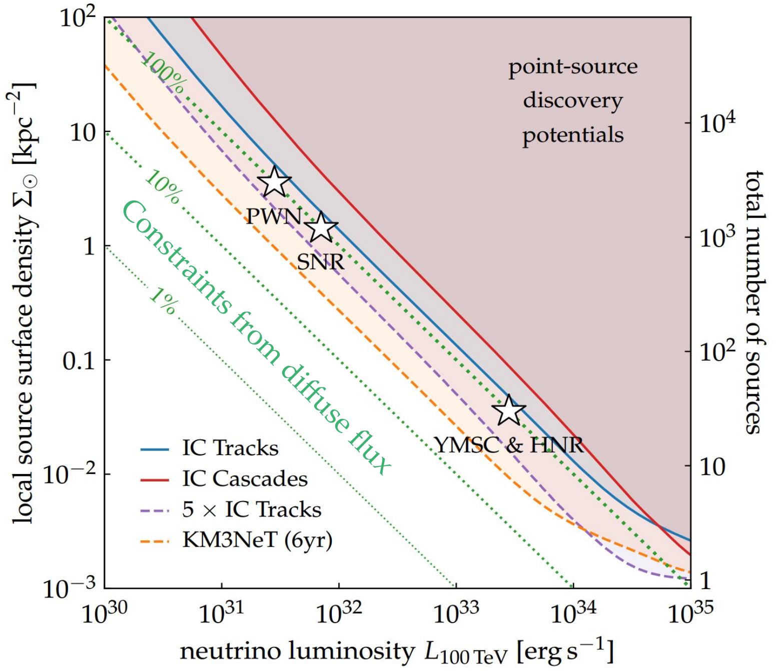
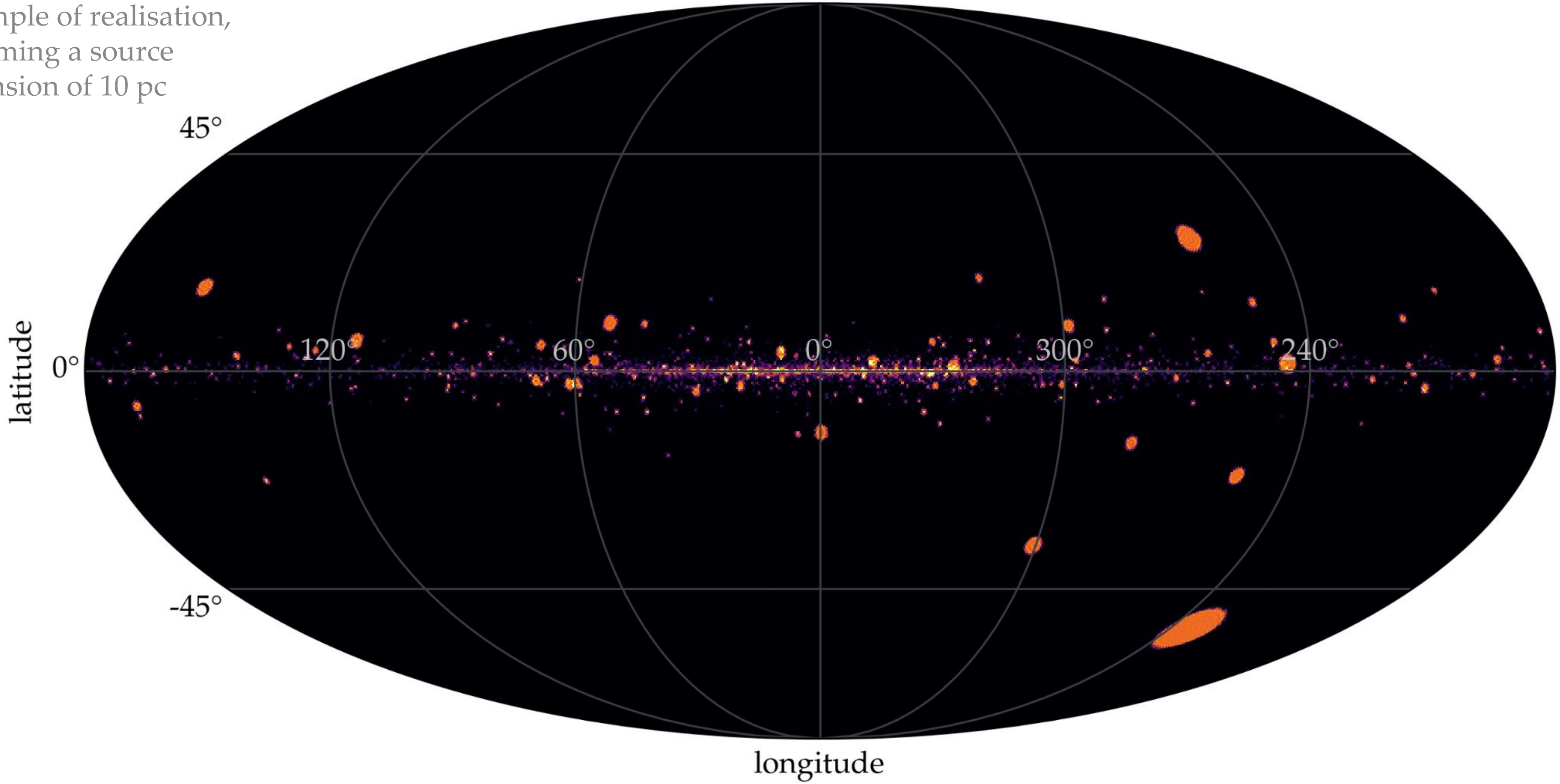


See e.g. Murase & Waxman '16, Ahlers & Halzen '18, IceCube Collab. '19, Capel et al. '20, Fiorillo et al. '22

← How bright they are →

Simulation of Galactic sources

Example of realisation, assuming a source extension of 10 pc



Galactic SNR distribution from Green '15

Extended sources

- Scaling: $\Phi_{\rm DP}(E_\nu, \delta, \sigma_{\rm src}) \simeq \sqrt{\frac{\sigma^2_{\rm PSF} + \sigma^2_{\rm src}}{\sigma^2_{\rm PSF}}}\, \Phi_{\rm DP}(E_\nu, \delta)$
- Exclusion limits degrade for increasing source extensions → strong contributions permitted
- For 10 pc source extension:
  Rare but powerful Galactic sources within future reach if they dominate (> 50%) the diffuse emission at 100 TeV

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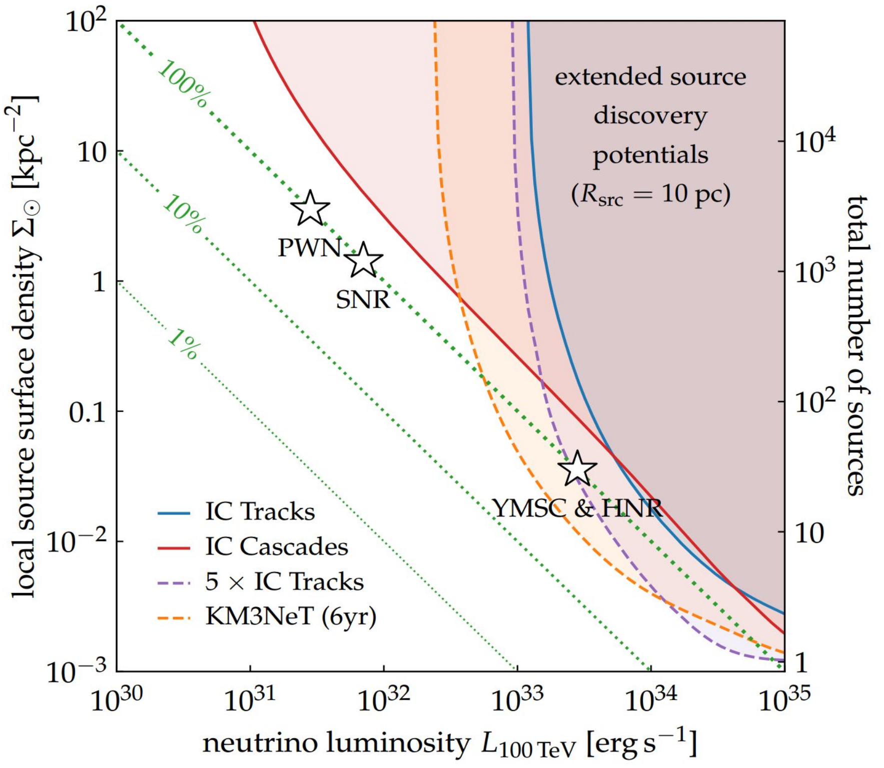

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Extended sources

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- Exclusion limits degrade for increasing source extensions → strong contributions permitted
- For 10 pc source extension:
  Rare but powerful Galactic sources within future reach if they dominate ($> 50\%$) the diffuse emission at 100 TeV
- For 50 pc:
  Even future detectors lose sensitivity

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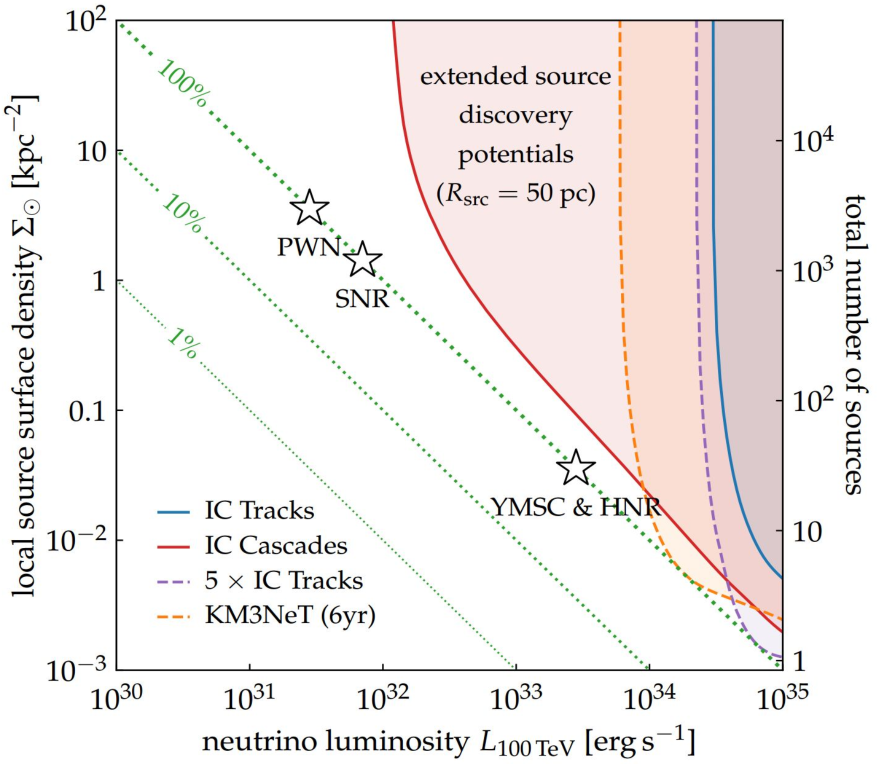


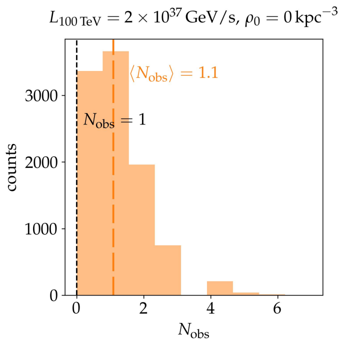
DP's from: IC Tracks [1] IceCube Collab '20, IC Cascades [2] IceCube Collab. '23, KM3NeT Collab. '19 [3]

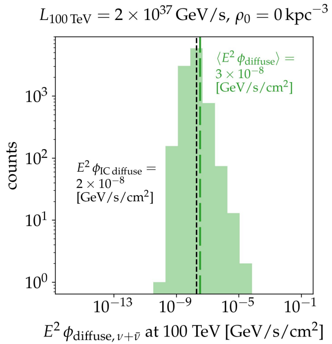
Simulation of Galactic sources

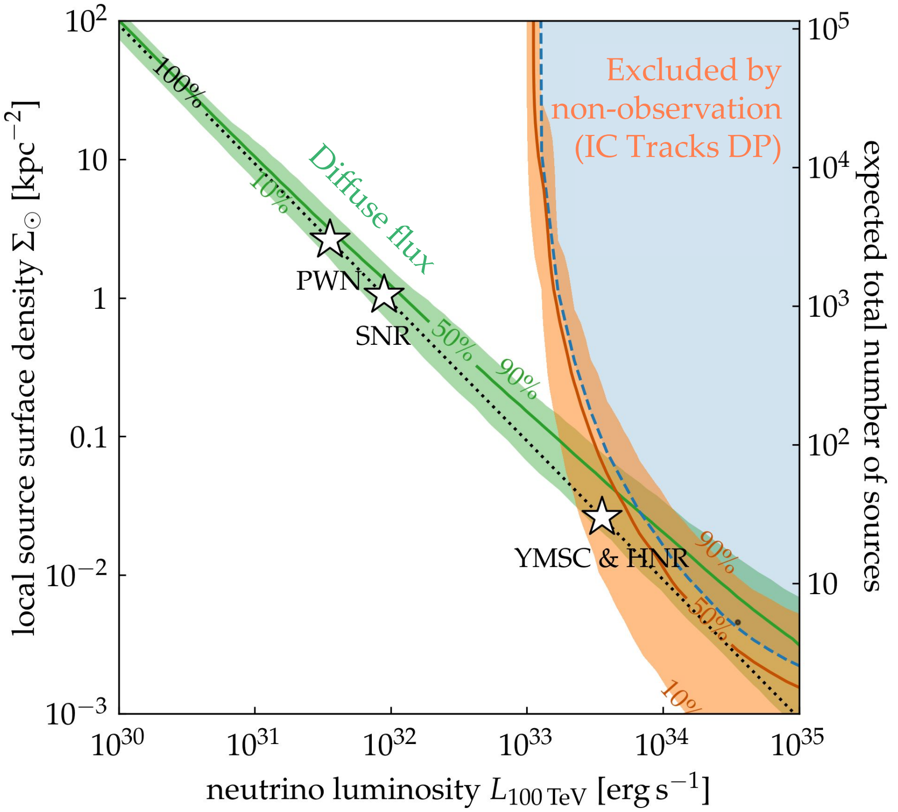
- Simple MC simulation to Poisson sample Galactic sources
- Contours show:

  How much of the resulting flux is above the observed level?

  How many sources do we detect, when including the DP and source extension [10 pc]?







See also: Desai et al. ‘23

Work in progress!

IC Tracks DP IceCube Collab ‘20

Simulation of Galactic sources

- Simple MC simulation to Poisson sample Galactic sources
- Contours show:

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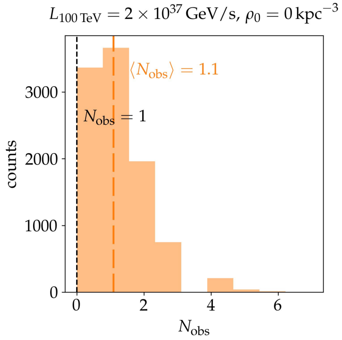
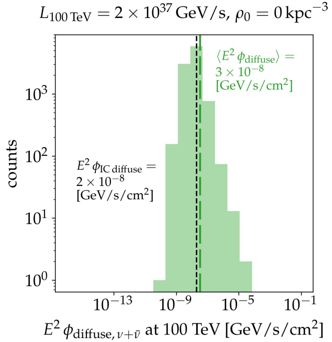
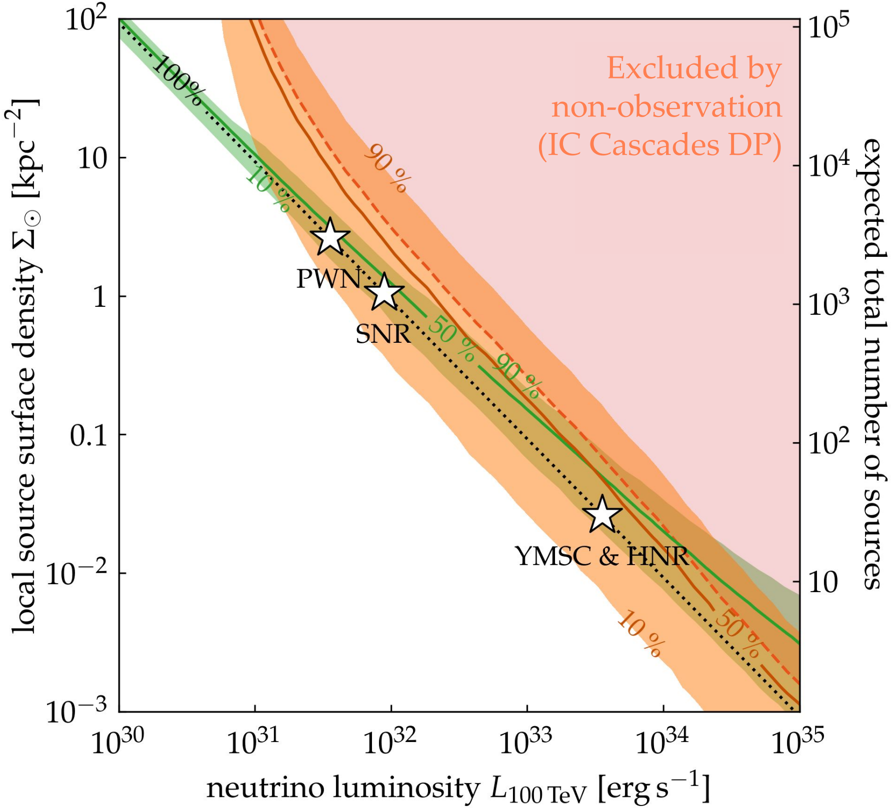






See also: Desai et al. '23

Work in progress!

IC Cascades DP IceCube Collab '23

Summary

- The **flux of unresolved Galactic neutrino sources can contribute significantly** to the observed Galactic diffuse emission at 100 TeV, consistent with current non-observations of individual Galactic neutrino sources
- **Extended sources are especially permitted** by the limited discovery horizons
- The upcoming detectors (KM3NeT ARCA & IceCube-Gen2) will be able to **probe rare but powerful Galactic sources** if they dominate the diffuse emission at 100 TeV
- Fluctuations could bring us observations of the 1st Galactic neutrino source sooner

Backup

Backup: Comparison of the diffuse emission and source populations

- Galactic diffuse emission:

$$\boxed{\Phi_{\rm QD}(E_\nu) \equiv \int d\Omega \boxed{\phi_{\rm QD}(E_\nu,\Omega)} = Q_\nu(E_\nu)\Sigma_\odot \boxed{\xi_{\rm gal}}}$$

$$\phi_{\rm QD}(E_\nu,\Omega) = \frac{Q_\nu(E_\nu)}{4\pi}\int_0^\infty dD\rho(\mathbf{r}_\odot + D\mathbf{n}(\Omega))$$

$$\xi_{\rm gal} \equiv \frac{1}{4\pi\Sigma_\odot}\int d\Omega \int_0^\infty dD\rho(\mathbf{r}_\odot + D\mathbf{n}(\Omega))$$

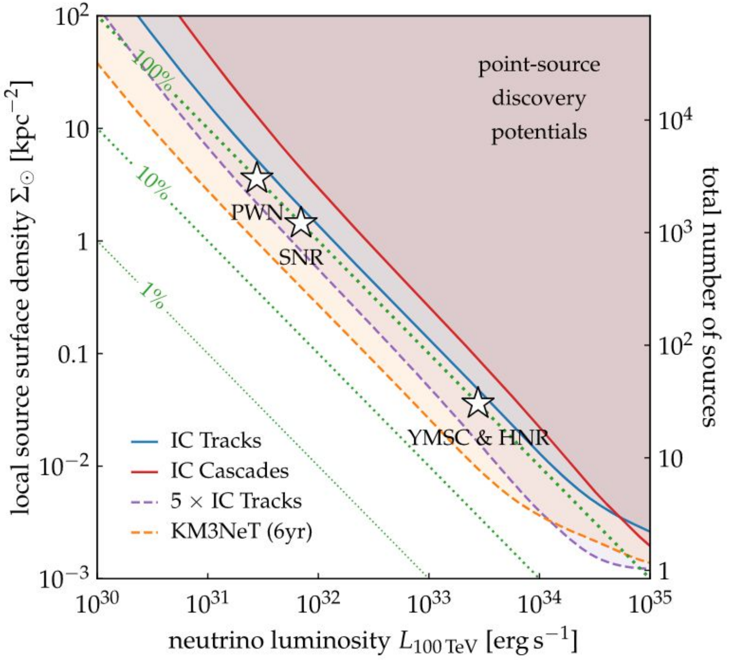
- Point-source discovery potentials:

$$\boxed{N_{\rm obs} = \int d\Omega \int_{R_{\rm src}}^{\boxed{D_{\rm max}(\delta)}} dD D^2\rho(\mathbf{r}_\odot + D\mathbf{n}(\Omega))}$$

$$D_{\rm max}(\delta) \equiv \sqrt{\frac{L_{100\,\rm TeV}}{4\pi[E_\nu^2 \boxed{\Phi_{\rm DP}(E_\nu,\delta)}]_{E_\nu=100\,\rm TeV}}}$$

$$\Phi_{\rm DP}(E_\nu,\delta,\sigma_{\rm src}) \simeq \sqrt{\frac{\sigma^2_{\rm PSF}+\sigma^2_{\rm src}}{\sigma^2_{\rm PSF}}}\,\Phi_{\rm DP}(E_\nu,\delta)$$

$$\Sigma_\odot \equiv 2\lambda\rho(r_\odot)$$



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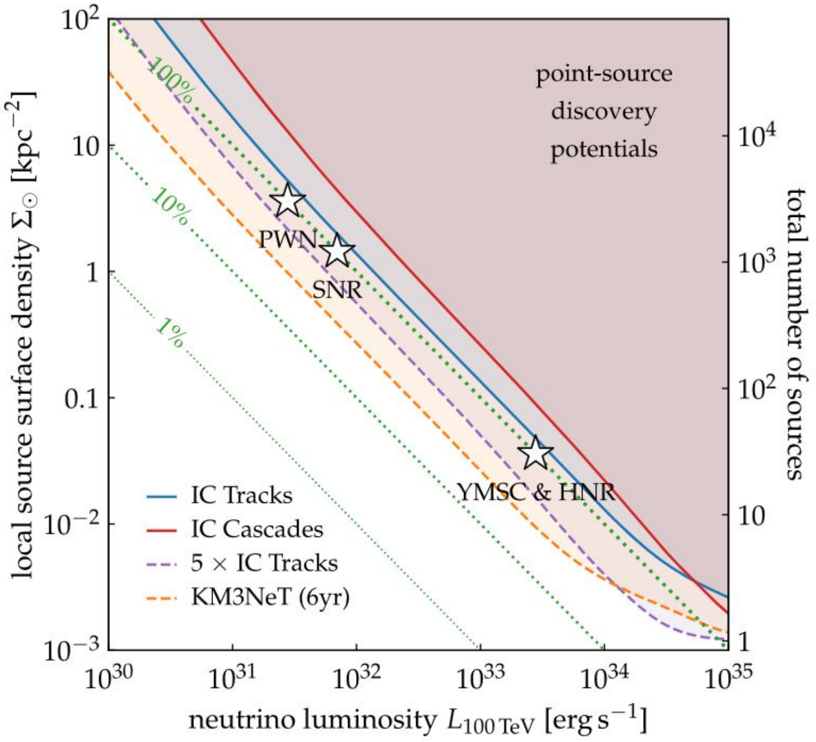
Backup: Estimates for source populations

- **SuperNova Remnants:**
  CR acceleration (via DSA), active until ~ radiative phase:
  $t_{RP} \simeq 4 \cdot 10^4$ yr $(\mathcal{E}_{ej} / 10^{51}$ erg$)^{4/17}(n_{gas}/n_{ISM})^{-9/17}$
  Local no. of active SNR:
  $N_{SNR} \simeq t_{RP} R_{SN} \simeq 1200$
  This gives a local surface source density: $\Sigma_\odot \simeq 1.6$ kpc^{-2}
  Leads to estimate of luminosity to saturate diffuse flux:
  $L_{100\,TeV} \simeq 6 \cdot 10^{31}$ erg s^{-1}
- **HyperNova Remnants:**
  1–2% of SN rate
  $N_{HNR} \simeq 30$, $\mathcal{E}_{ej} \sim 10^{52}$ erg, $\Sigma_\odot \simeq 0.04$ kpc^{-2}, $L_{100\,TeV} \simeq 2.5 \cdot 10^{33}$ erg s^{-1}
- **Pulsar Wind Nebulae:**
  though leptonic, protons could be confined in TeV halos:
  $N_{PWN} \simeq t_{PWN} R_{SN} \simeq 3000$
  $\Sigma_\odot \simeq 3.6$ kpc^{-2}, $L_{100\,TeV} \simeq 2.8 \cdot 10^{31}$ erg s^{-1}
- **Young Massive Star Clusters:**
  CR acceleration via DSA at wind termination shock
  No. density estimated from local SFR density
  Hereof 10% → clusters, hereof 10% → YMSCs
  $\Sigma_\odot \simeq 0.04$ kpc^{-2}, $L_{100\,TeV} \simeq 2.5 \cdot 10^{33}$ erg s^{-1}



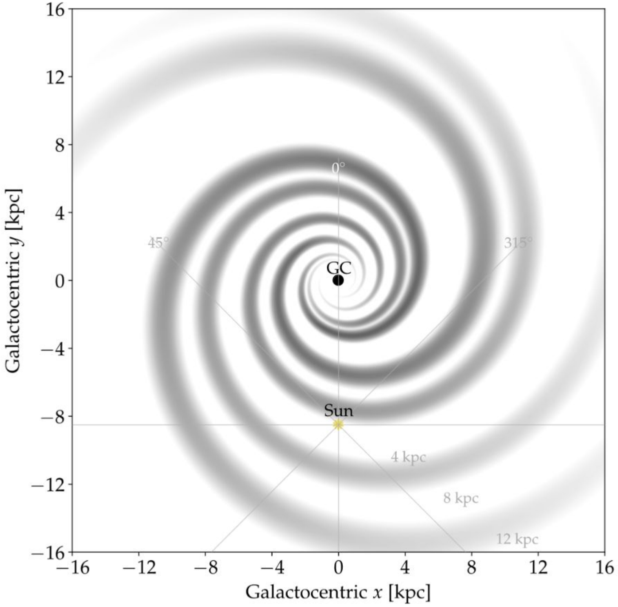
See more details in AA+**KMG**+EP+MA arXiv:2306.17285 and refs therein

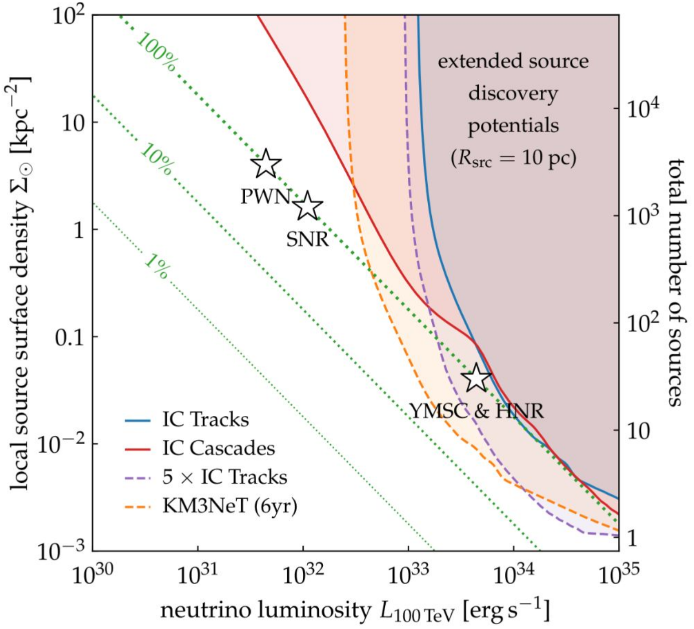
Backup: Galactic arm structure

- Robust against variations of distribution. Using a source distribution following the Galactic arm structure:

- Galactic form factor:
  - Benchmark:
    $\xi_{\text{gal}} \simeq 3$
  - Varying SNR model:
    $2.6 \lesssim \xi_{\text{gal}} \lesssim 4.1$
  - 4-arms:
    $1.3 \lesssim \xi_{\text{gal}} \lesssim 2.9$

$$\xi_{\text{gal}} \equiv \frac{1}{4\pi\Sigma_\odot}\int d\Omega \int_0^\infty dD\rho(\mathbf{r}_\odot + D\mathbf{n}(\Omega))$$





Model of Galactic arm structure based on T. Y. Steiman-Cameron et al. Astrophys. J. 722 (2010) 1460–1473

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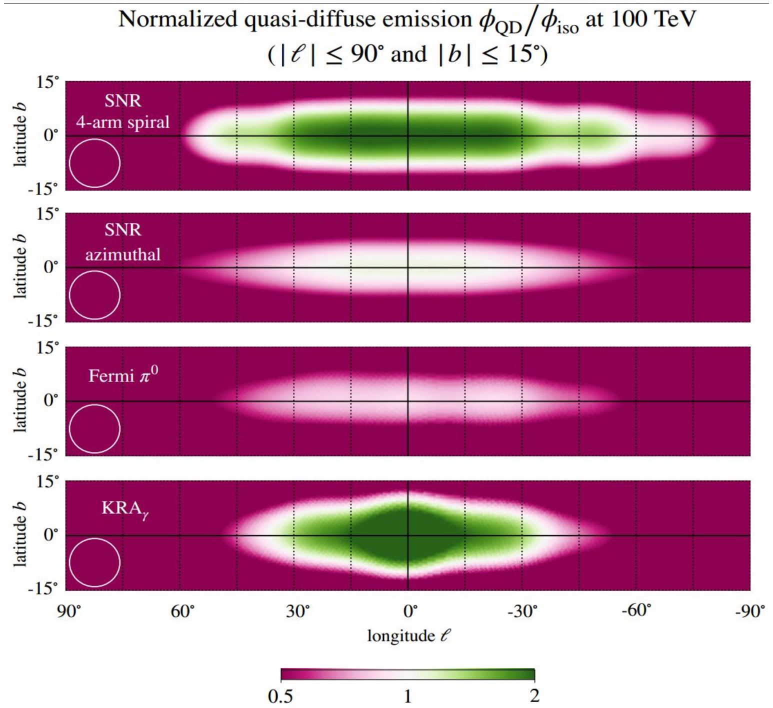
Backup: Diffuse and quasi-diffuse emission templates



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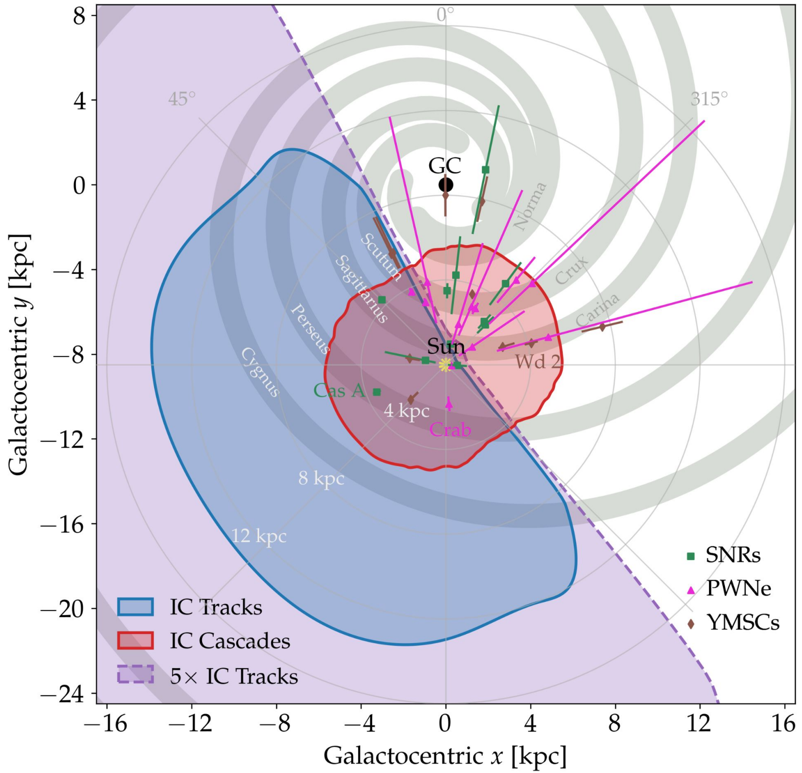
Backup: Spectral index

- Changing from a spectral index of $\gamma = 2$ to $\gamma = 3$ gives broadened discovery horizons
- For IC track analysis, drastically reduced for declinations above ~5°

Discovery horizon for $L_{100\,\mathrm{TeV}} = 10^{34}$ erg/s $(\Phi \propto E^{-3})$



DP's from: IC Cascades [1] and IC Tracks [2]

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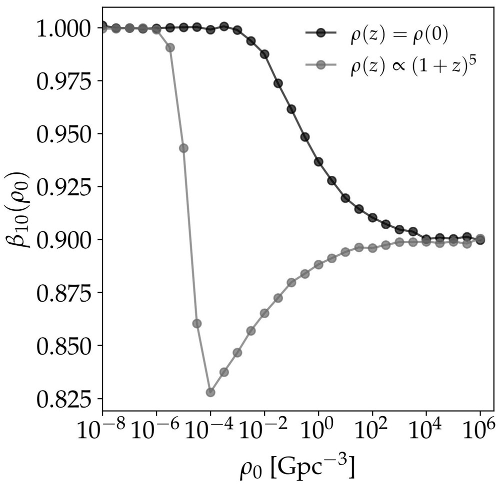
Backup: Extragalactic case

- Avenues for improvements for neutrino constraints: Including more than the brightest source
- Comparing original case of only the brightest source ($k = 1$) with **combination of 10 brightest neutrino sources**:

$$\beta_k(\rho_0) \equiv \left.\frac{\phi_1(5\sigma)^{k\text{ sources}}}{\phi_1(5\sigma)^{1\text{ source}}}\right|_{\rho_0}$$

lowest β_k	
no evol. $m = 0$	0.90
strong evol. $m = 5$	0.83



More to come!

- Results for $k = 10$, for two cases of redshift evolution of sources, show **~10-20% effect**