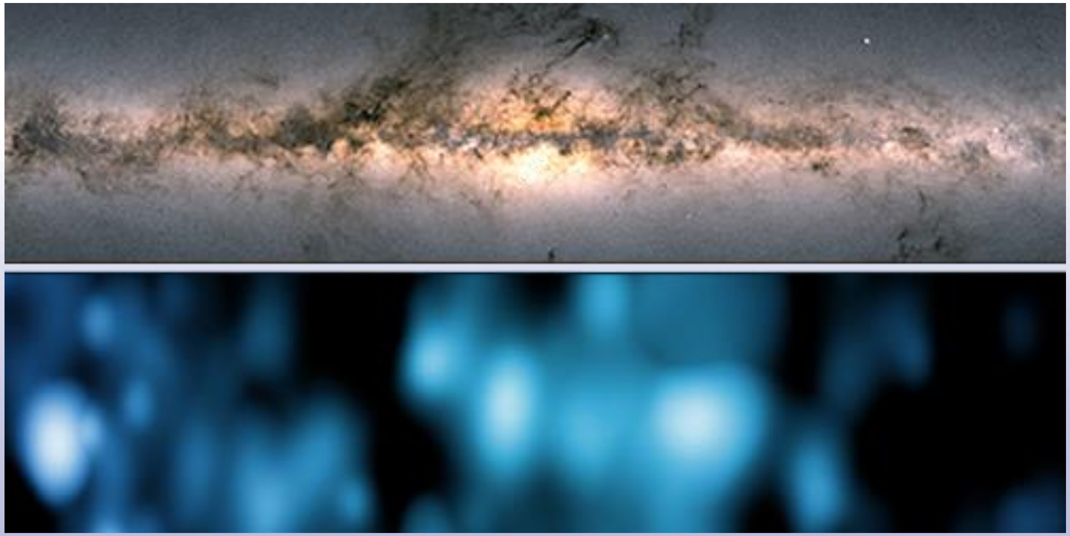
Calibrating Molecular Cloud Density Tracers using Neutrino emission from the Galactic Centre

8th July 2025 – National Astronomy Meeting, Durham, UK



Neutrinos from the Galactic Plane; IceCube Collab. (2023)

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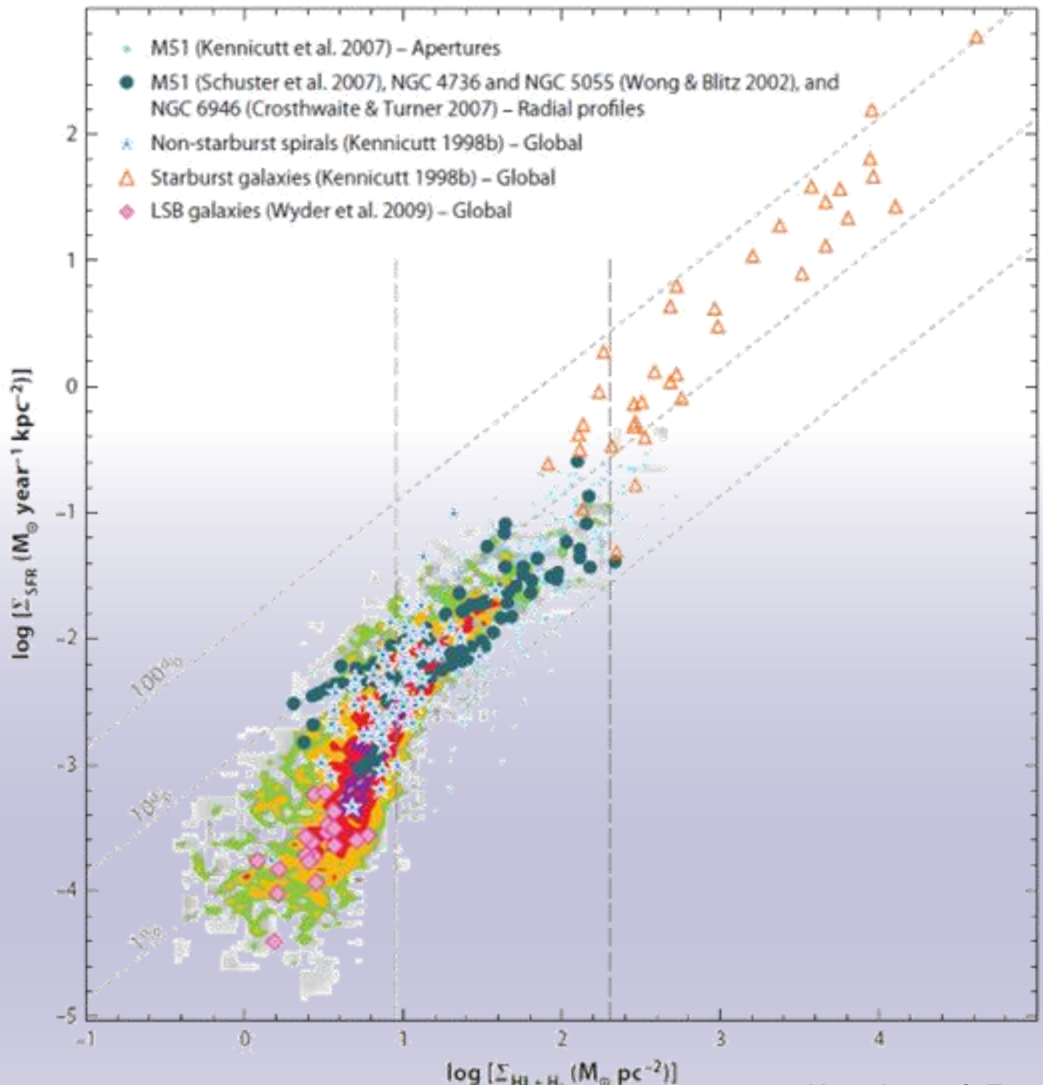
Outline

- Introduction
  - Gas tracers in astronomy
  - Cosmic rays and neutrino production
- Using neutrinos to improve traditional gas tracers
  - Calibration in the Galactic Centre region
- Timescales and prospects
- Summary

Gas density measurement in astronomy



Kennicutt & Evans (2012)

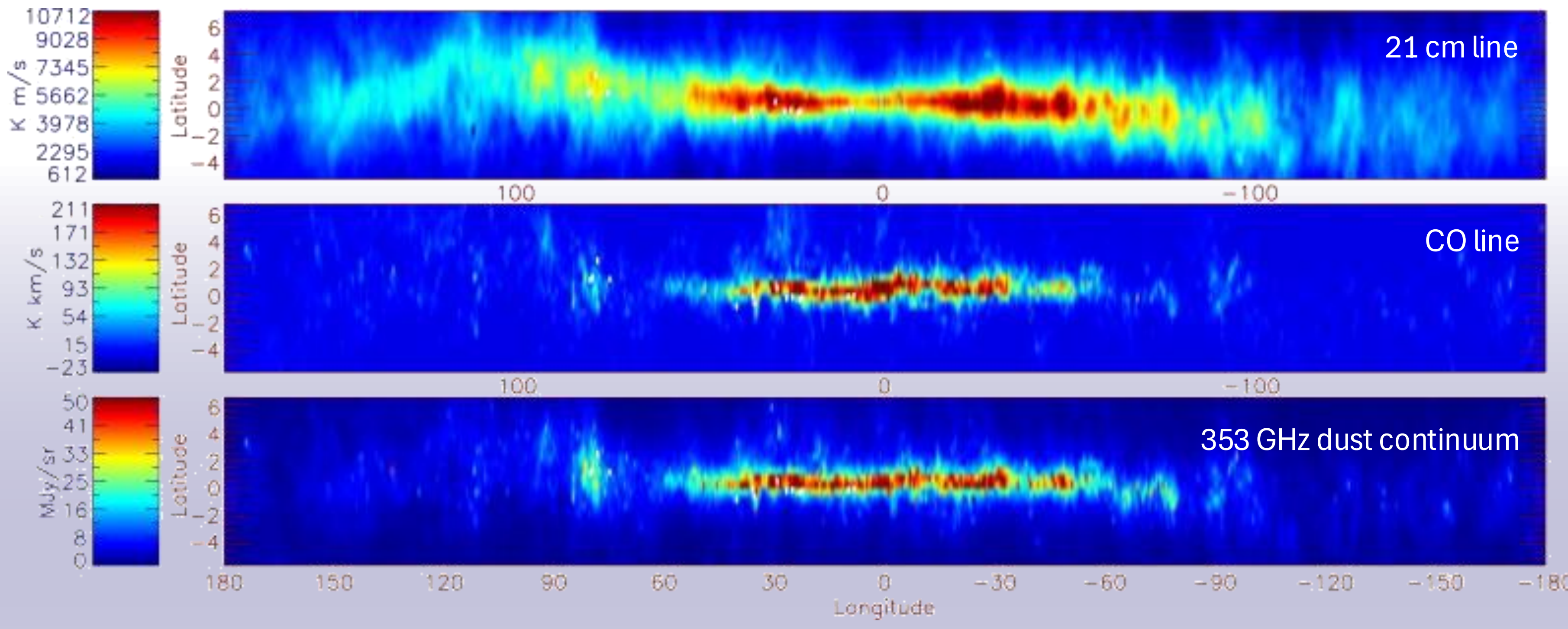
Improving our confidence in gas density and distribution measurement tools is critical for advancing galaxy formation/evolution

E.g. deviations from the KS relation in galaxy types/regions

But relies on a robust determination of gas mass/surface density

Gas density measurement in astronomy

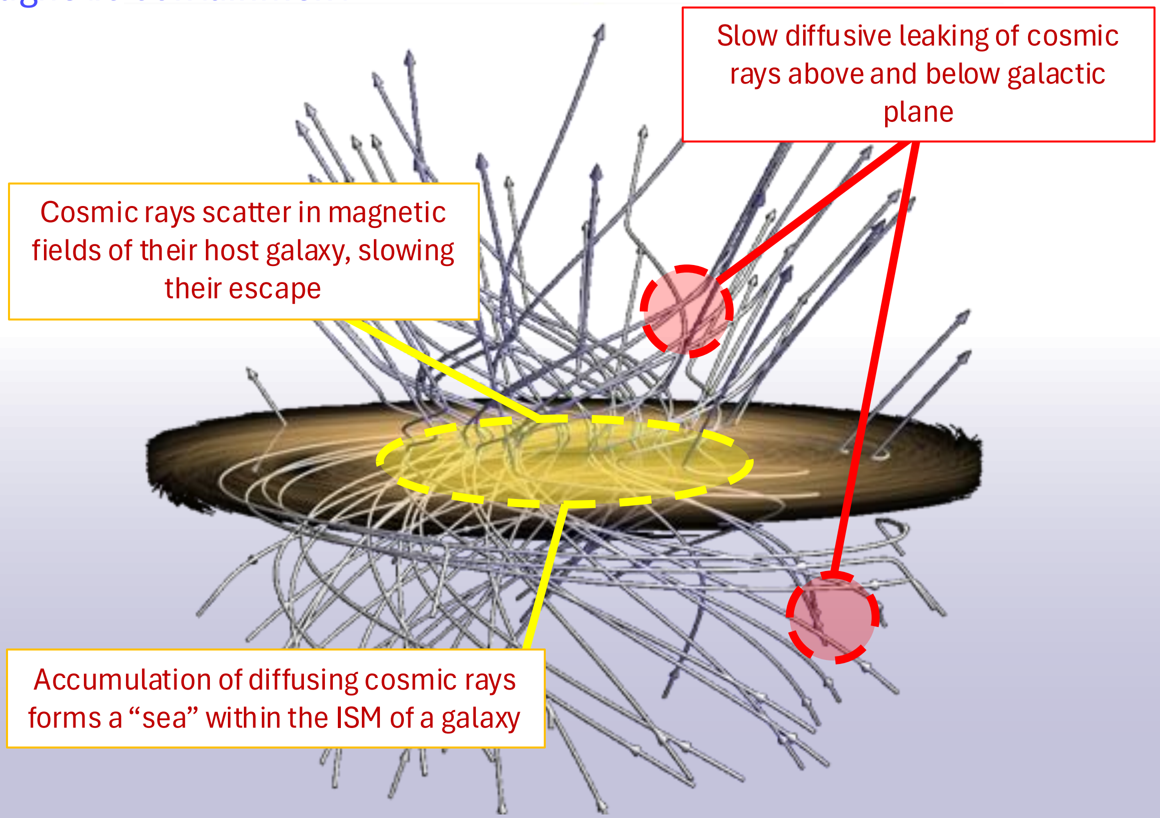
- Determinations of gas density within galaxies relies on tracers
- Can be inconsistent



Pedaletti et al. (2015)

Cosmic rays in galaxies

Cosmic ray magnetic containment



Adapted from Farrar et al. (2016)

Cosmic rays and multimessenger astronomy

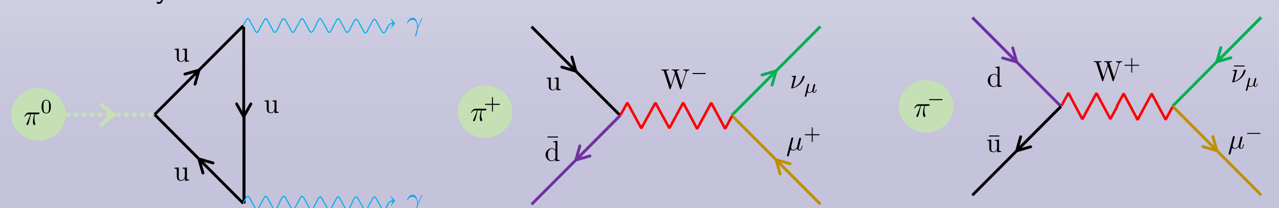
- Cosmic rays as a **driver** of neutrino astronomy

pp-pion production

$$\mathrm{p} + \mathrm{p} \rightarrow \begin{matrix} \mathrm{p} + \cdots \\ \mathrm{n} + \cdots \end{matrix} + \zeta_0 \left(\pi^0\right) + \zeta_\pm \left(\pi^+ \; \pi^-\right)$$

Pion multiplicities

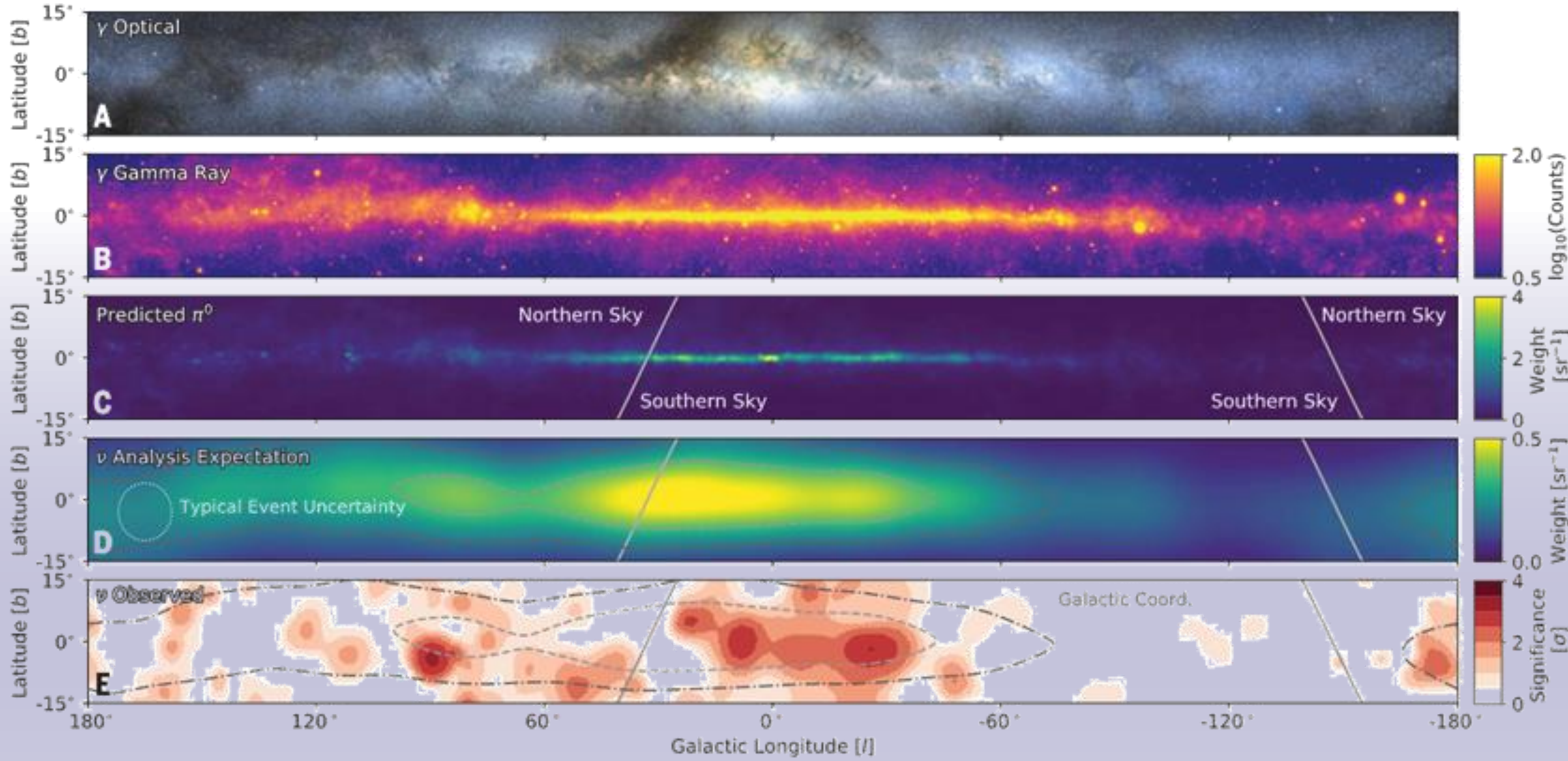
Pion decays



Figures adapted from Owen 2023 (A&G)

Galactic Center Neutrinos

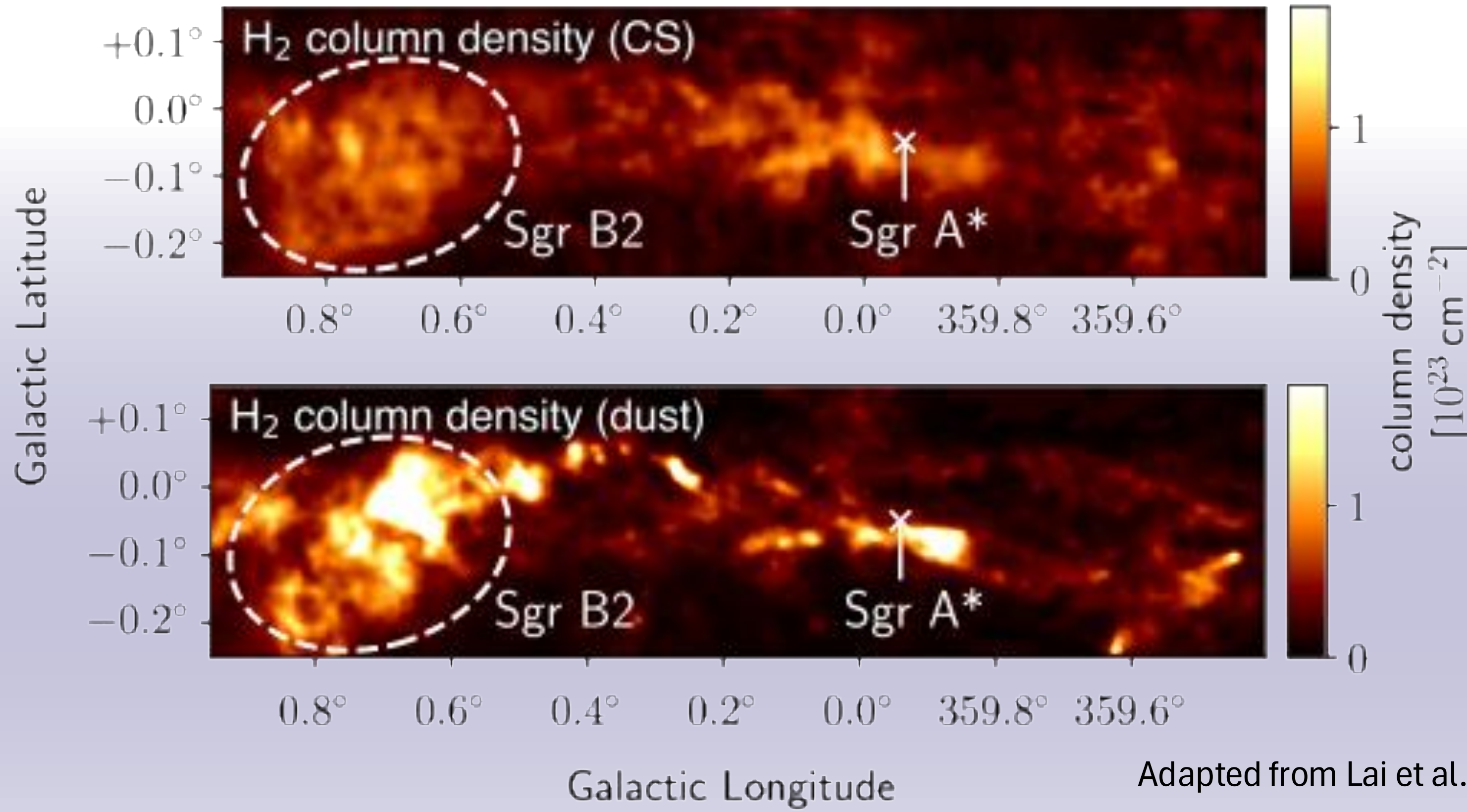
- Confirmation of the Milky Way as a neutrino source (pp interactions)



IceCube Collab. (2023)

Galactic Center region gas maps

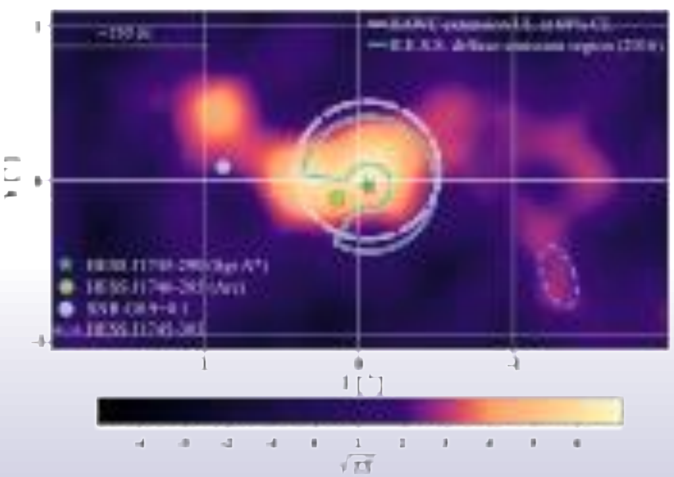
- Typical tracers yield very different views of the of the region around the GC
- Which is the most "correct"?
- As neutrinos have been detected, can use them to calibrate

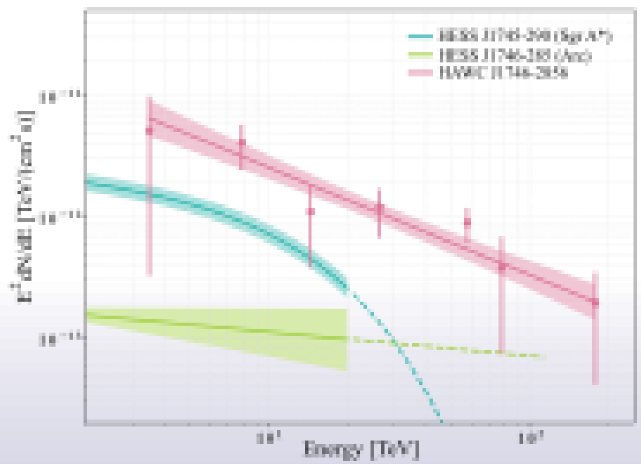


Adapted from Lai et al. (2025)

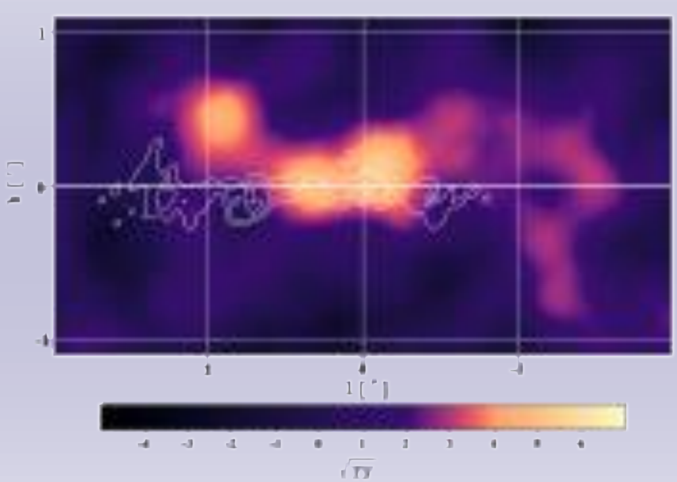
The Galactic Center in Gamma-Rays

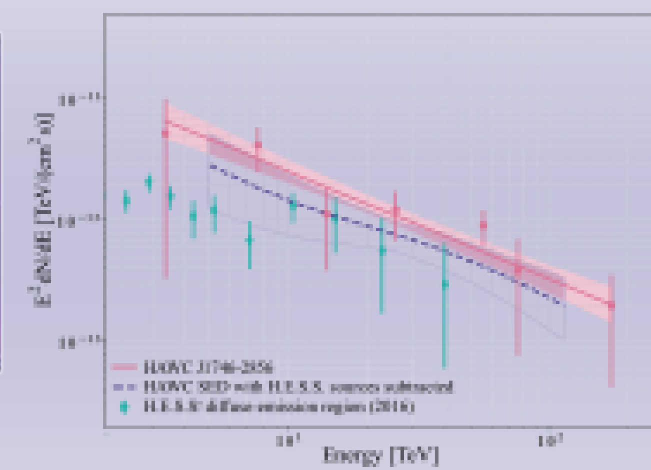
Use gamma-ray observations of the region (sources subtracted) to estimate diffuse emission, and obtain a CR spectrum through Galactic Center region





Position & spectrum of the three main point sources and one extended source in the GC region as measured by H.E.S.S.

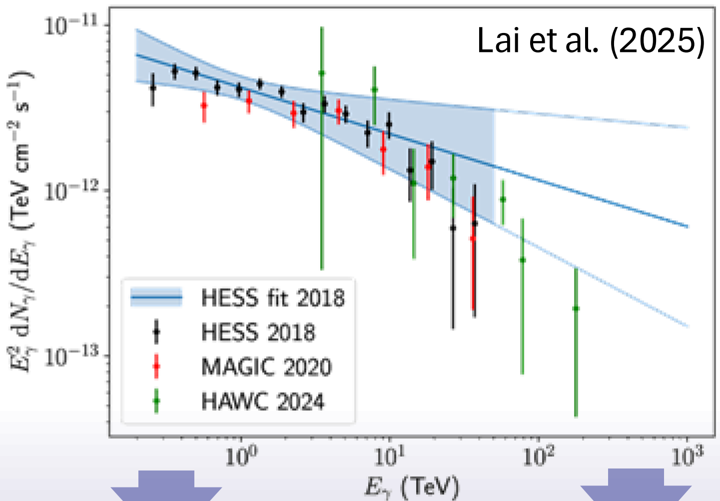


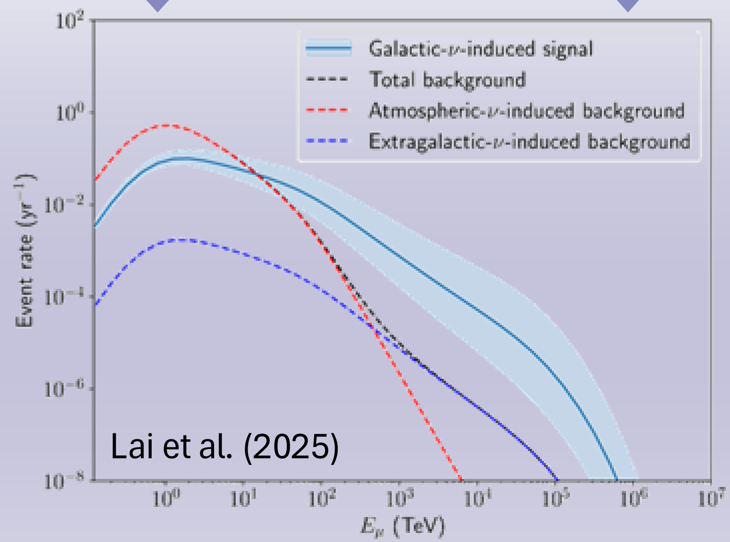


Region with H.E.S.S. sources subtracted, leaving some GC source to generate a synthetic CR spectrum for our analysis

HAWC Collab. (2024)

Galactic Center Neutrinos as an astrophysical tool





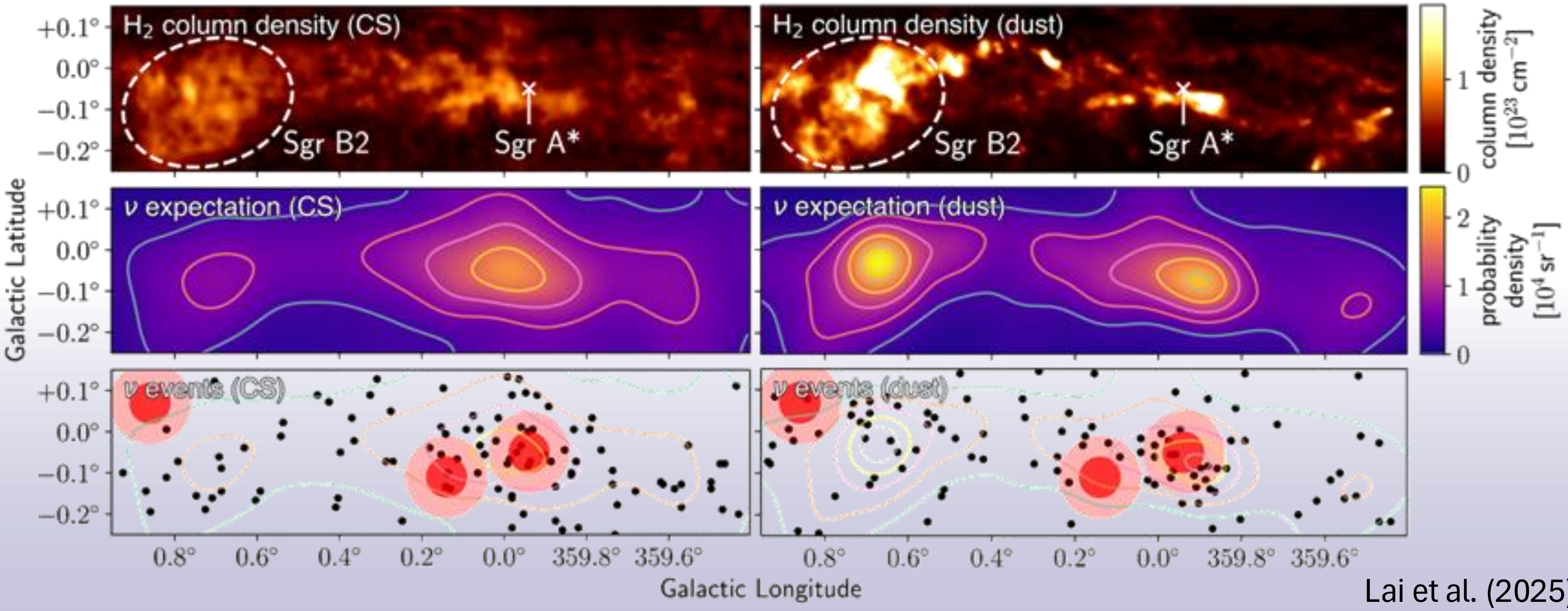
Scale down gamma-ray flux to empirically gauge the CR distribution, and then predict neutrino spectrum

- Hadronic interaction & secondary production
- Instrument response (IceCube)

Expected annual detection rate of muon neutrino events from the CMZ by a neutrino telescope with the same detection efficiency as IceCube (but located in the Northern Hemisphere at the site of KM3NeT).

Galactic Center Neutrinos as an astrophysical tool

Expected neutrino picture of the Milky Way's Galactic Center region



Lai et al. (2025)

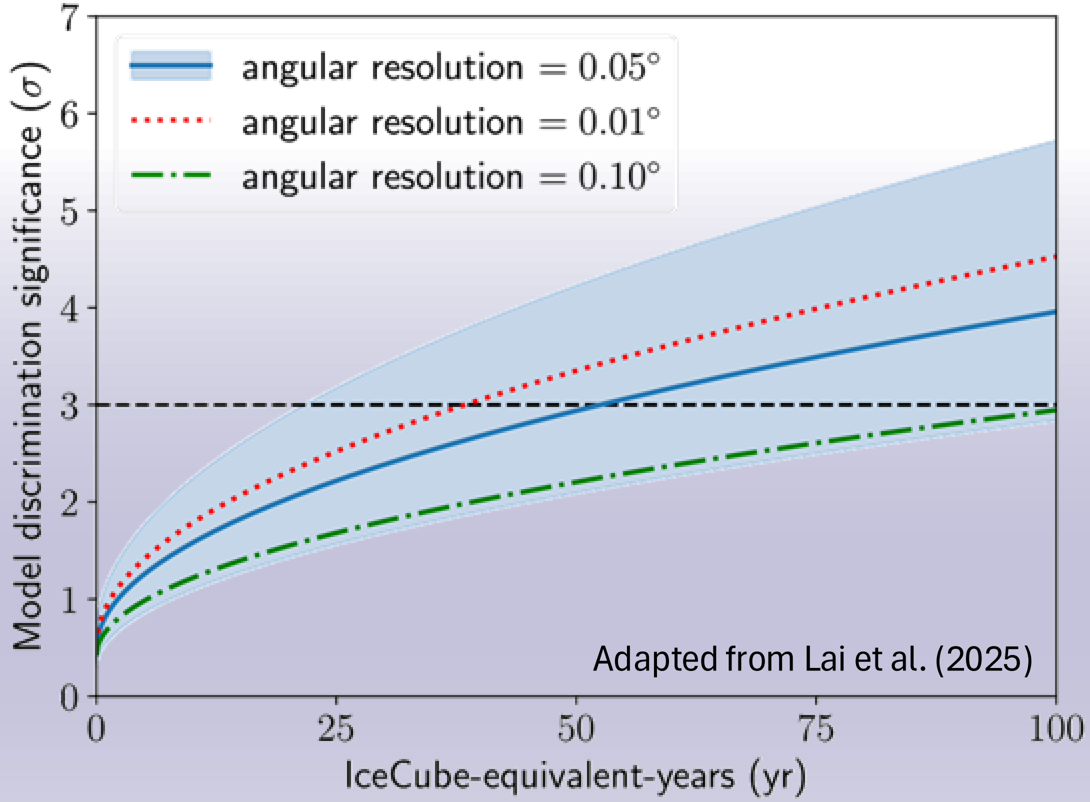
Middle: probability of neutrino emission, based on the corresponding gas maps and smoothed with a Gaussian kernel to emulate an angular resolution of next-gen instruments (0.05 degrees)

Bottom: Picture of 100 neutrinos (future neutrino telescope with 10x IceCube exposure). Red circles can't be used for analysis, as they are nearby sources

Calibration timescale for gas tracers

Projected maps are clearly different, allowing tracers to be discriminated as integration time increases, and clear gas tracer calibration to be obtained

- Milky Way is used for calibration, so neutrinos not needed for other targets



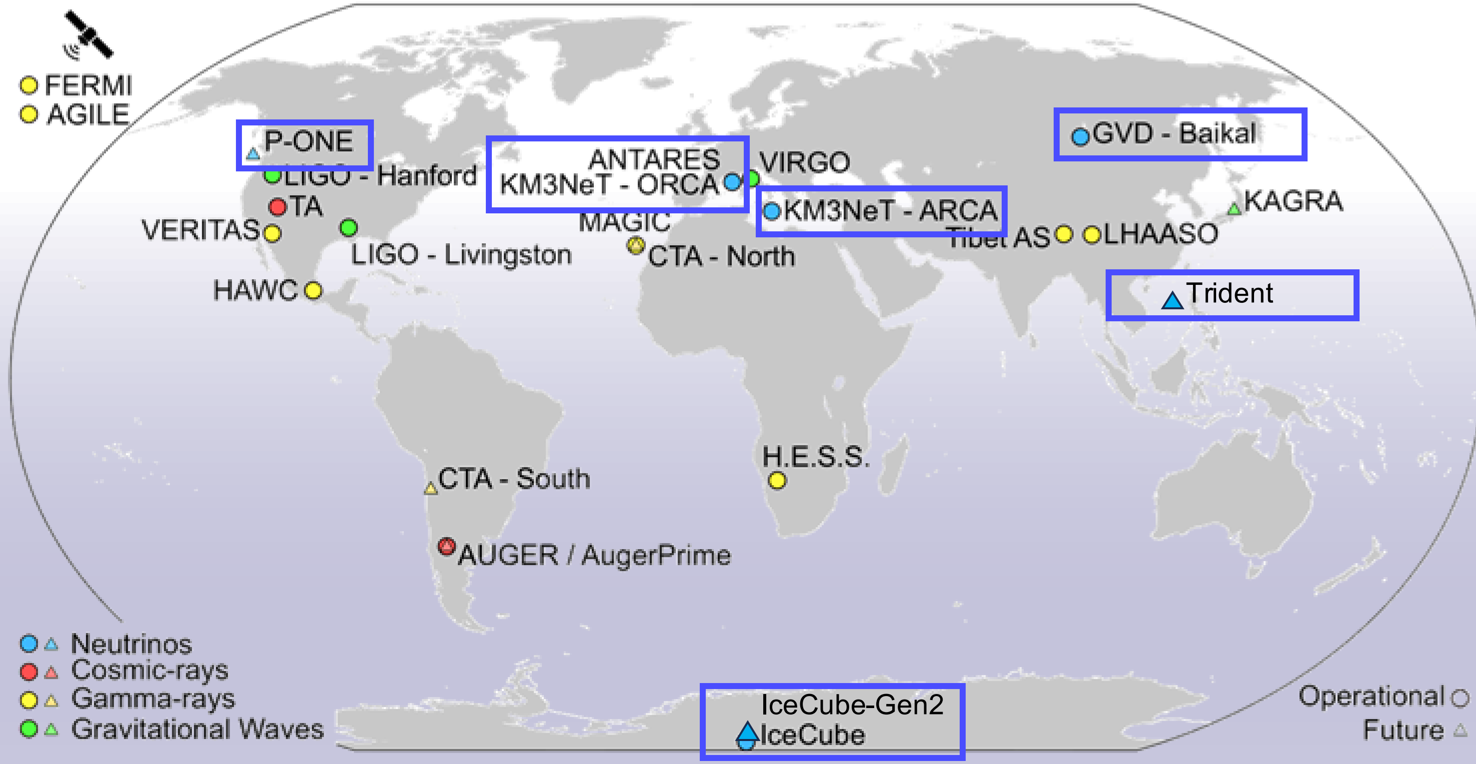
Lai et al. (2025)

Requires about 30 years with current instruments

High-energy multimessenger outlook

Neutrinos: *IceCube-Gen2, KM3NeT, P-ONE, Trinity, Trident, Baikal GVD…*

Upcoming new facilities will reduce the 30 yr timescale considerably (~decade)



Adapted from Greus & Losa (2021)

Summary

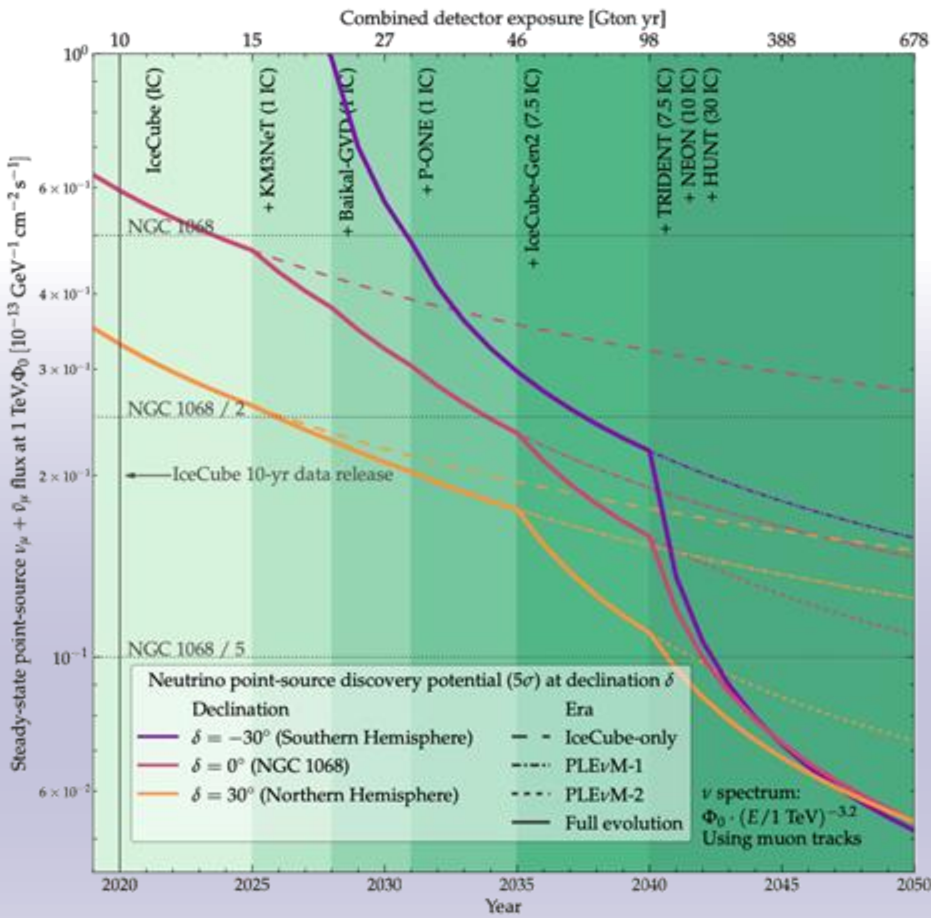
- **Robust** measures of **gas density** are required for reliable tests of galaxy evolution and star-formation
- Traditional tracers can be **inconsistent** and dependent on local conditions
- **Neutrinos** can be used to calibrate traditional tracers for gas density in galaxies
- Achievable on decade timescales with the combined sensitivity of upcoming generation of neutrino observatories

Backup: Future neutrino observatories

Gas tracers could be calibrated with 3-sigma significance within 10-15 yr timescale

Combined detector exposure

1 TeV source flux

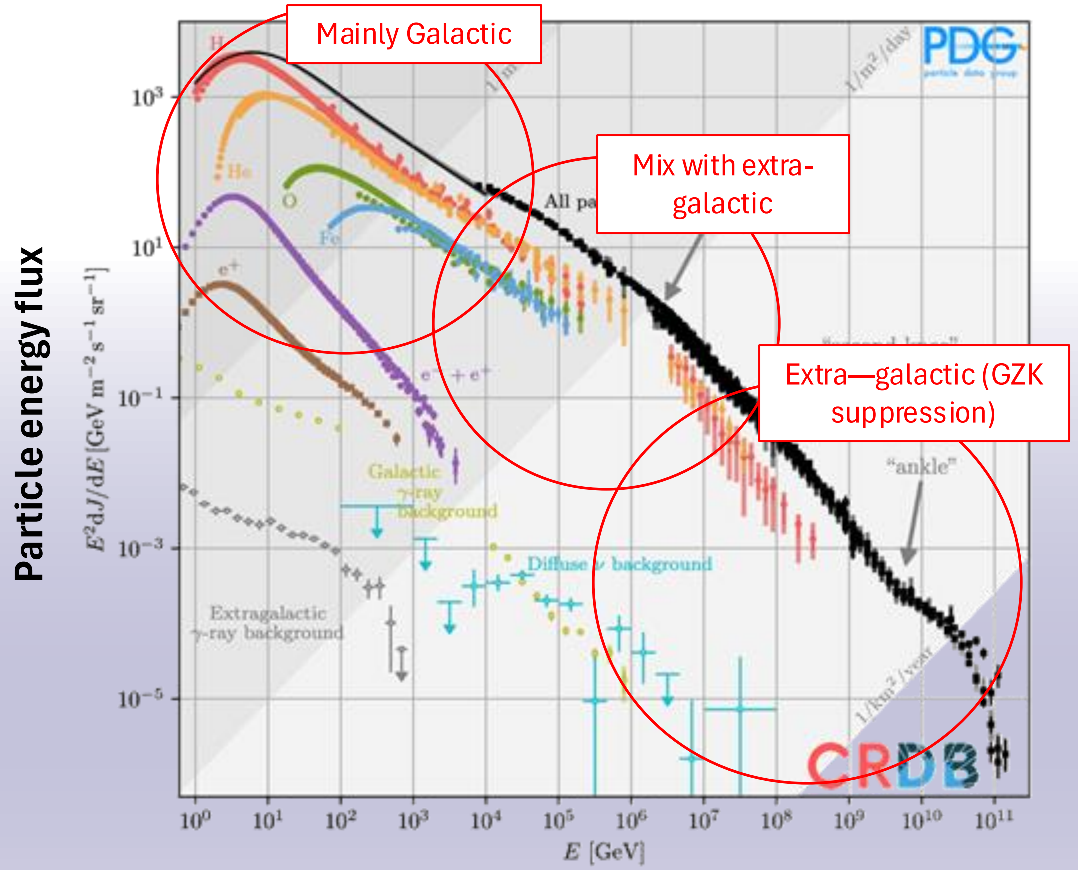


Schumacher et al. (2025)

Backup: Cosmic rays

- Cosmic rays are nucleons (mainly protons, He, O…) and electrons

Cosmic ray spectrum measured around Earth



Navas et al., Particle Data Group (2024)