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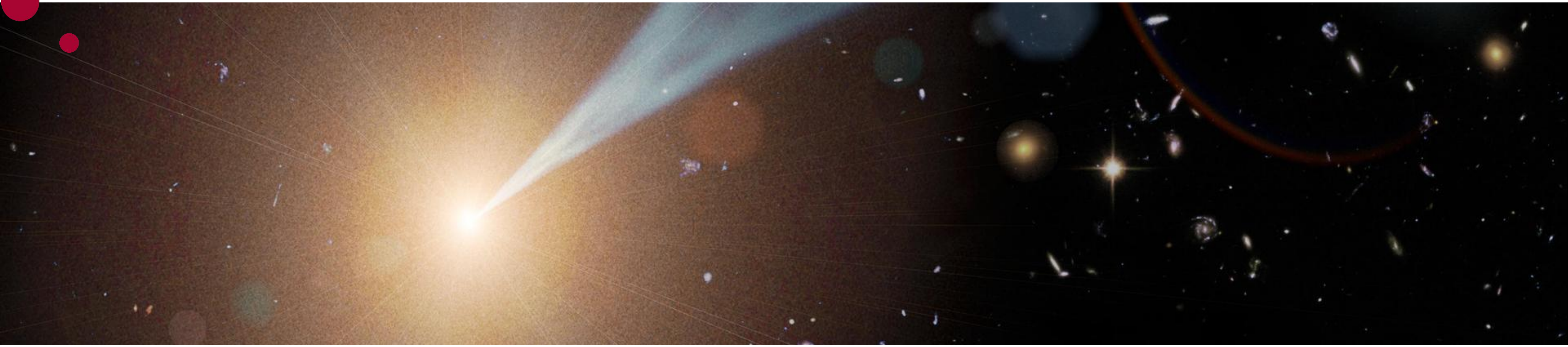


Deciphering cosmic neutrinos

Kathrine Mørch Groth

Niels Bohr Institute, University of Copenhagen, Denmark
Supervisor: Markus Ahlers

Neutrinos in the multi-messenger view

Multi-messenger astrophysics

- **Unsolved mystery**

  Looking for high-energy neutrino sources – origin still unknown

- **Neutrinos**

  From cosmic ray interactions; neutrinos a telltale sign

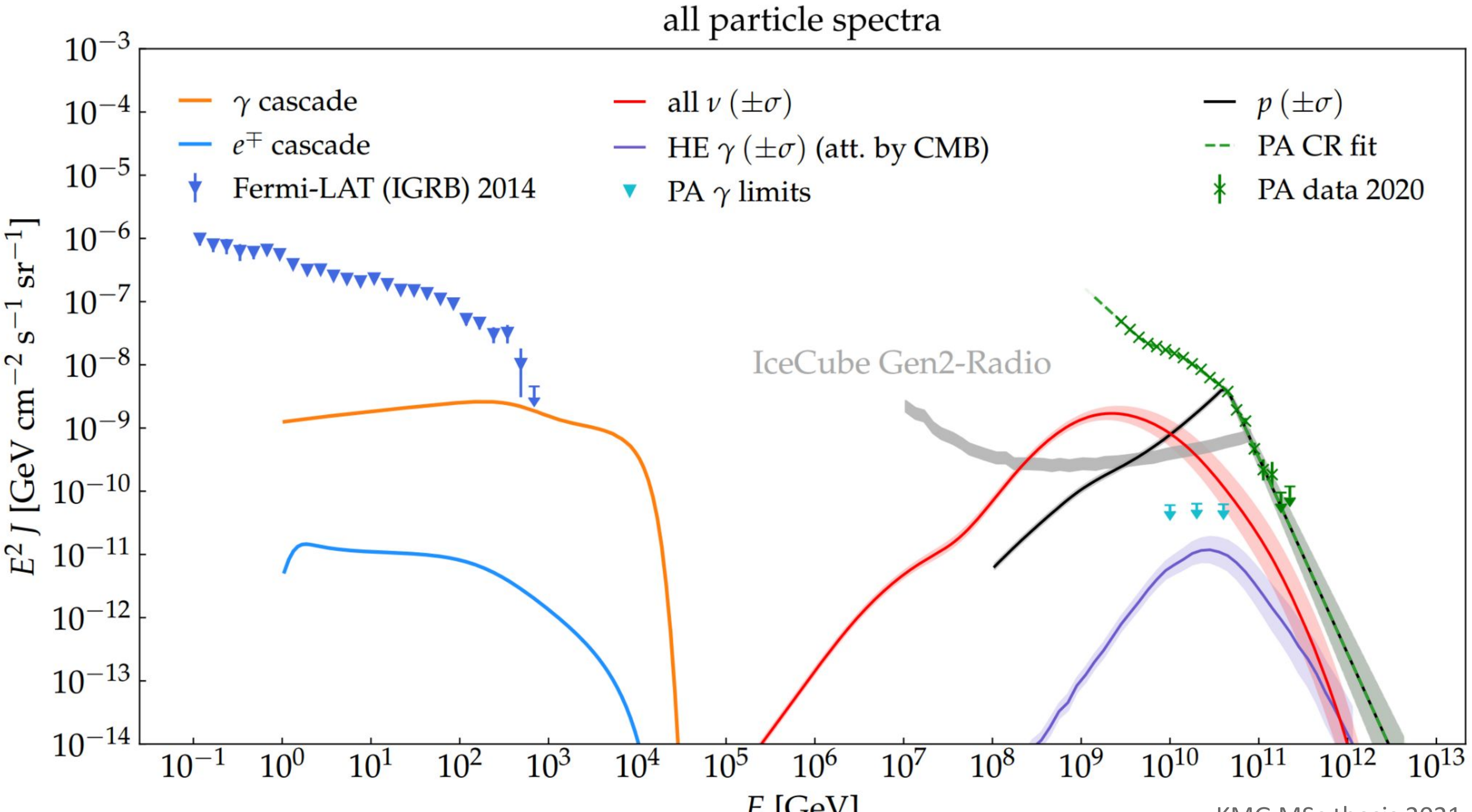
- **Squeezing the signals:**

  Take advantage of the closely associated emission of cosmic rays, γ-rays and neutrinos

- Study candidate neutrino sources in the context of multi-messenger observations, to answer:

What is the origin of the high-energy neutrino flux observed with IceCube?

Multi-messenger studies



KMG MSc thesis 2021

PA data 2020: arXiv:2008.06486

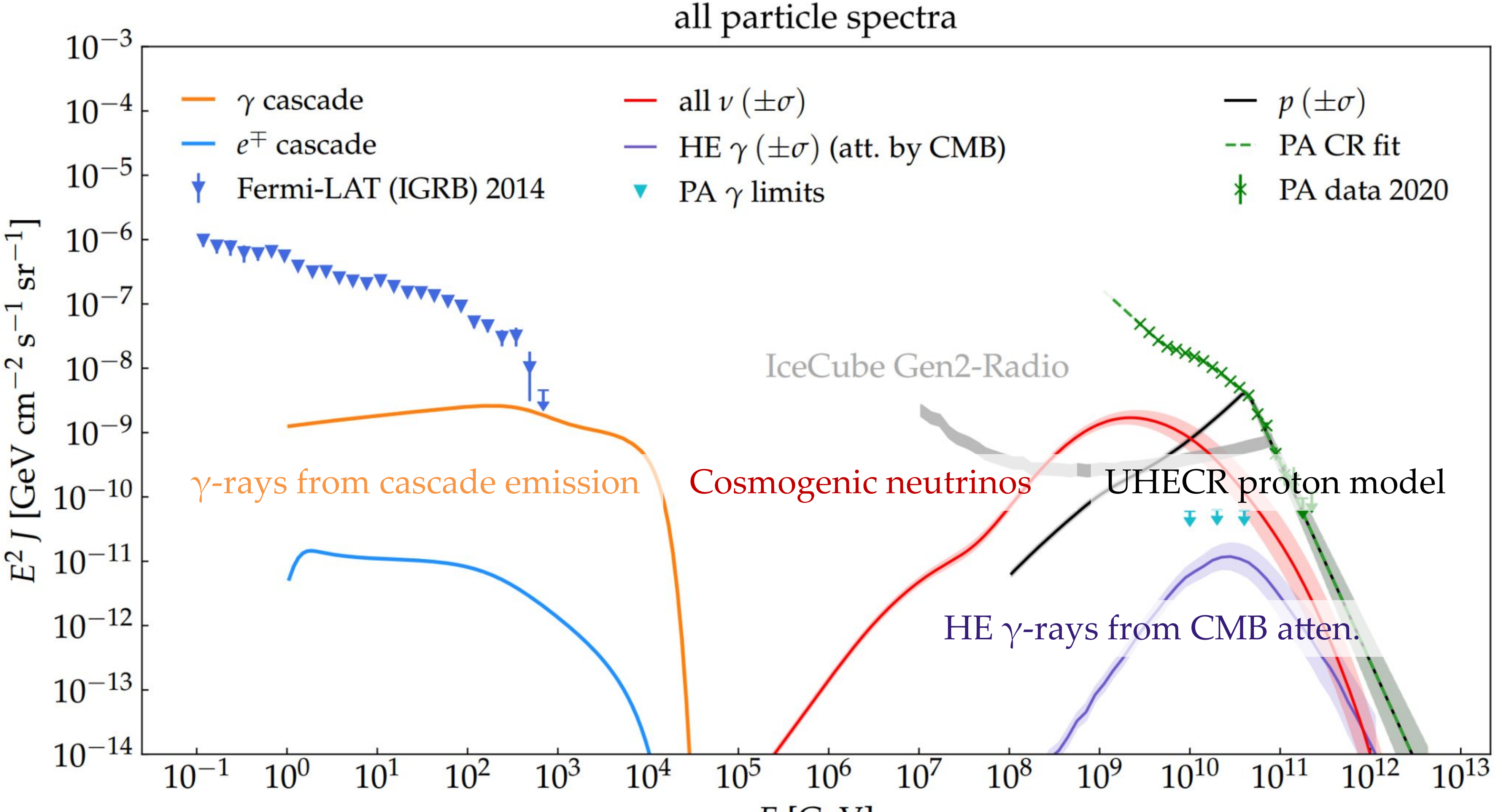
PA photon limits: PoS(ICRC2015) 236 (2016) 1103

Fermi-LAT (IGRB) 2014: arXiv:1410.3696

IceCube Gen2-Radio: arXiv:2008.04323

CRPropa3 code: arXiv:1603.07142

Multi-messenger studies



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IceCube Neutrino Observatory

A sense of the scale of the IceCube detector

Map data ©2021 Google

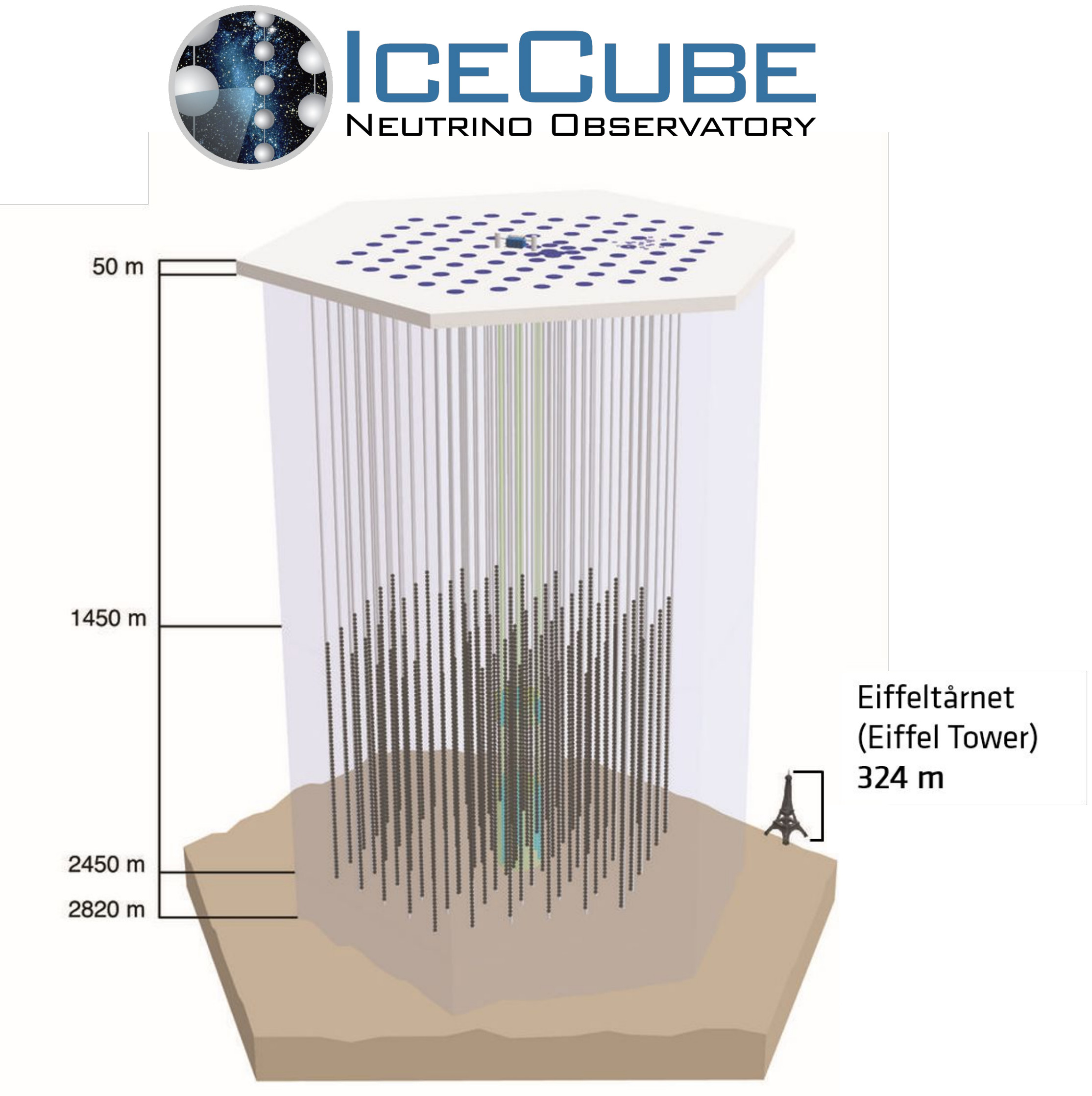

Illustration: IceCube/NSF

IceCube Neutrino Observatory

A sense of the scale of the IceCube detector

Map data ©2021 Google

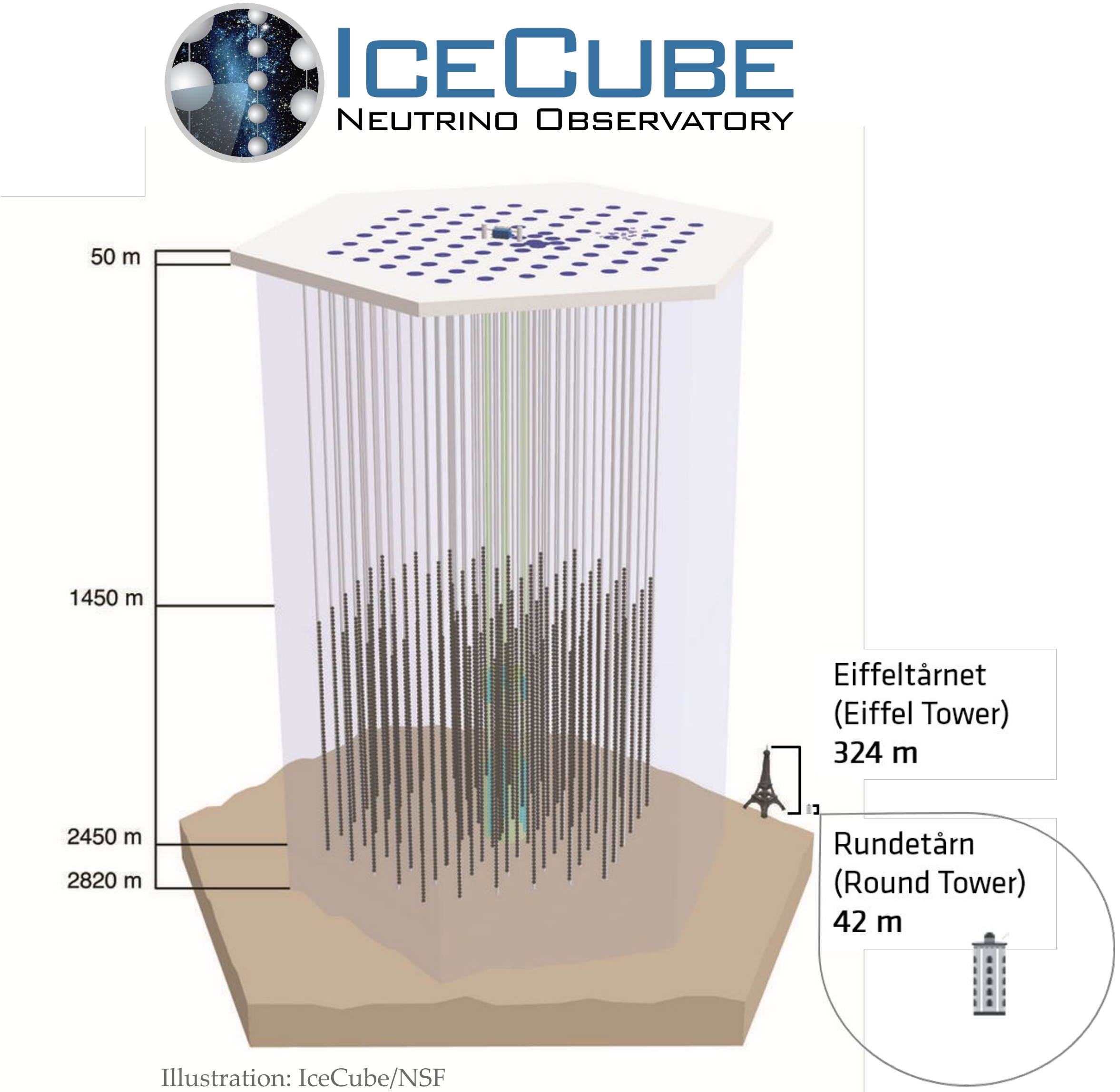

Illustration: IceCube/NSF

Identifying HE neutrino sources

Conditions for neutrino source candidates

- IceCube has detected cosmic neutrinos (10 TeV – 10 PeV energies) – why do we not see point sources?
- Constraints on extragalactic neutrino source populations in terms of local **density** & **luminosity**

➡ Expect weak, extragalactic sources

Identifying HE neutrino sources

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Deriving the expectation value for the brightest source

METHOD

- Expected flux from brightest source:

probability distribution of brightest source

$$\langle \phi \rangle = \int d\phi \, \overbrace{p_1(\phi)} \, \phi$$

$$= \int dz \, \frac{dN}{dz} \, \frac{L_\nu}{4\pi \, d_L^2(z)} \, e^{-N(z)}.$$

- Distribution of sources:
  - *Simple case*
    standard candle luminosity function
    + redshift evolution of sources

standard candle luminosity function

$$\frac{d^2 N(L,z)}{dL \, dz} = \overbrace{\delta(L - L_0)} \, \underbrace{\rho(z)} \, \frac{d}{dz} V_c(z)$$

density per co-moving volume

Identifying HE neutrino sources

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Blue regions: Excluded by non-observation

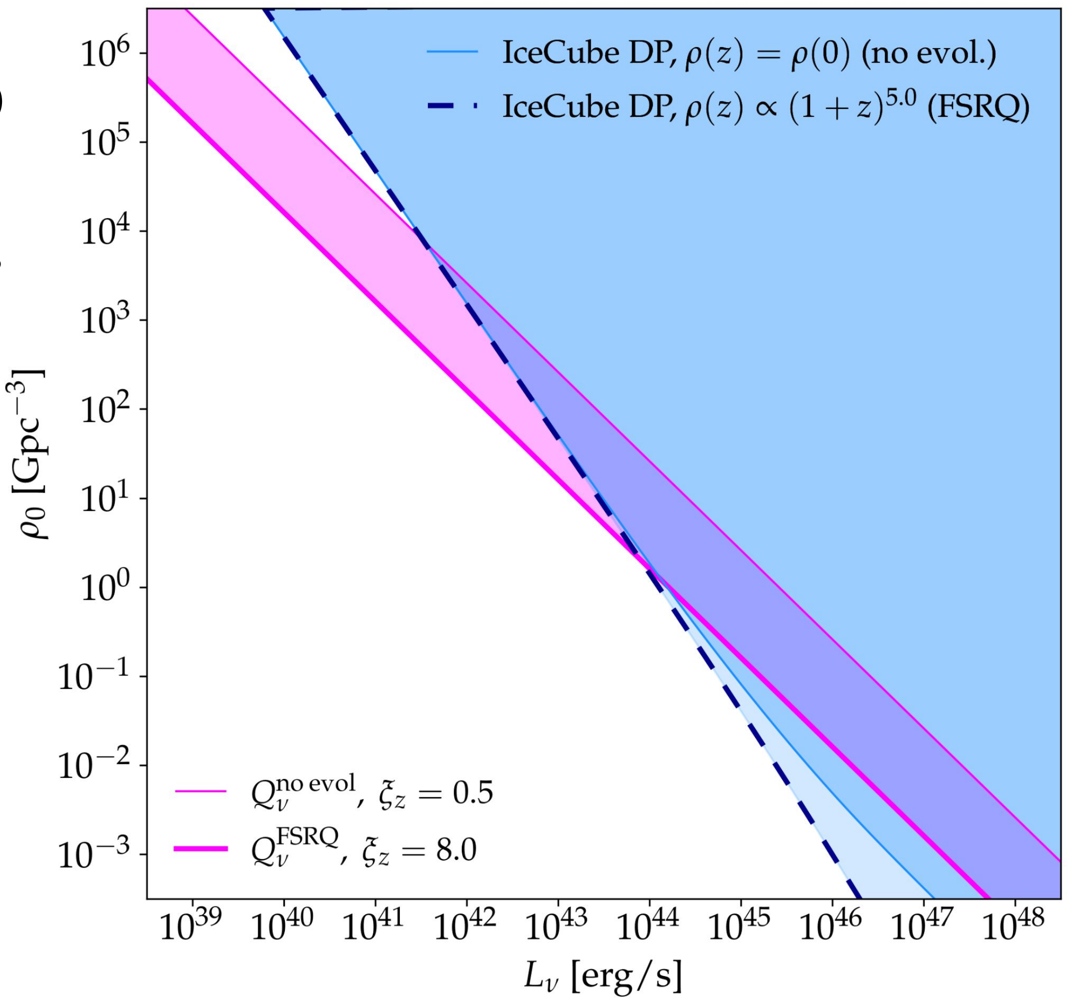
- IceCube 10-year PS discovery potential

$$E^2\,\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}\ \mathrm{TeV/cm^2/s} = \int \mathrm{d}z\,\frac{L_\nu/3}{4\pi d_L^2(z)}\,\frac{\mathrm{d}N}{\mathrm{d}z}\,e^{-N(z)}$$

Magenta band: Constraints from observations

- Measured diffuse flux $E^2\,\phi_\nu \simeq 10^{-8}\ \mathrm{GeV/cm^2/s/sr}$

$$\frac{1}{3}\sum_\alpha E_\nu^2\,Q_{\nu_\alpha}(E_\nu) = \frac{4\pi}{c}\,\frac{H_0}{\xi_z}\,\frac{1}{\rho_0}\,\frac{1}{3}\sum_\alpha E_\nu^2\,\phi_{\nu_\alpha}(E_\nu)$$



FSRQ evol. from A.Neronov, D.Semikoz [arXiv:1811.06356]

Population studies

From the simple case to a more realistic description

- Consider not just brightest source, but second brightest, third brightest .. *k* brightest

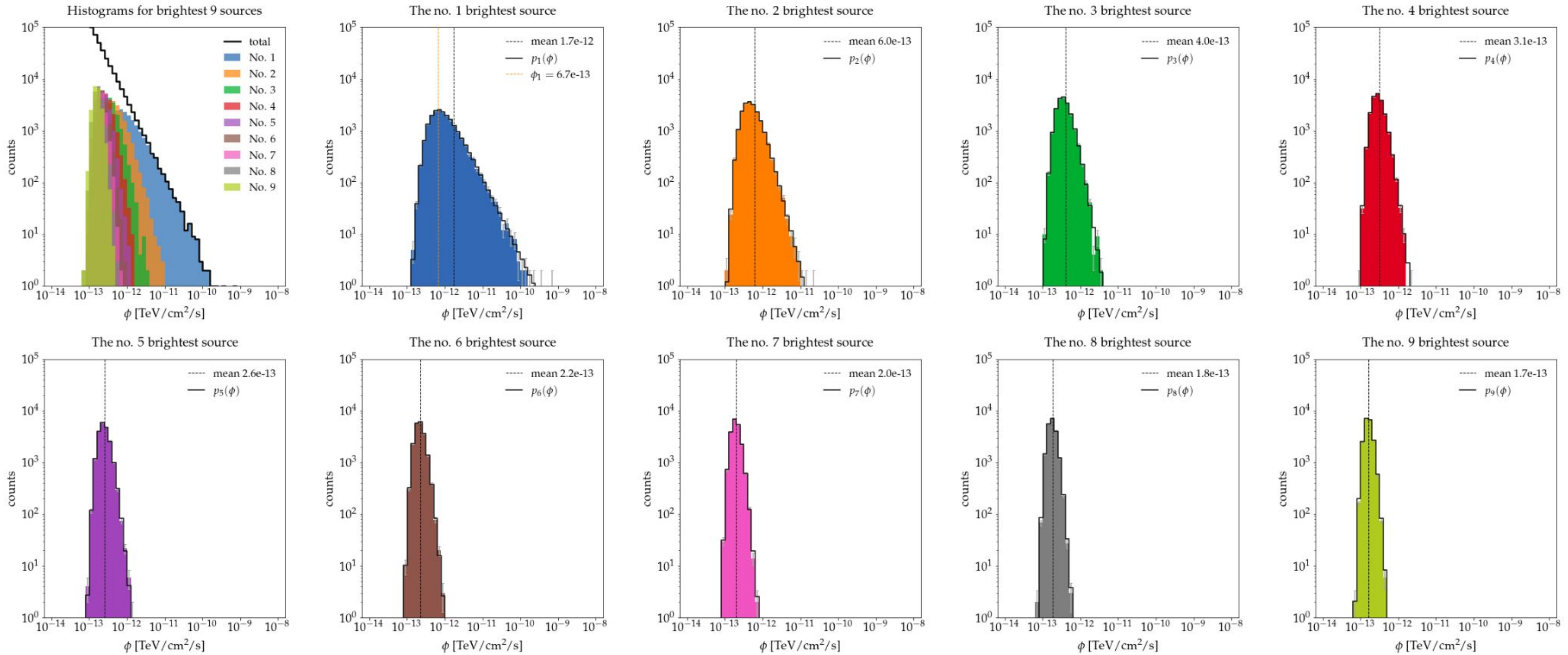
$$p_k(\phi) \simeq \frac{1}{(k-1)!} \frac{3}{2} \frac{1}{\phi} \left(\frac{\phi_1}{\phi}\right)^{3k/2} e^{-\left(\frac{\phi_1}{\phi}\right)^{3/2}},$$

1) Simulate a collection of individual point sources (sample fluxes uniformly from random distribution)
2) Gather *k* brightest
3) Compare to derived probability distribution

Population studies

Histograms of flux counts from simulated sources compared to predicted distribution $p_k(\phi)$:

$$p_k(\phi) \simeq \frac{1}{(k-1)!}\,\frac{3}{2}\,\frac{1}{\phi}\left(\frac{\phi_1}{\phi}\right)^{3k/2} e^{-\left(\frac{\phi_1}{\phi}\right)^{3/2}},$$

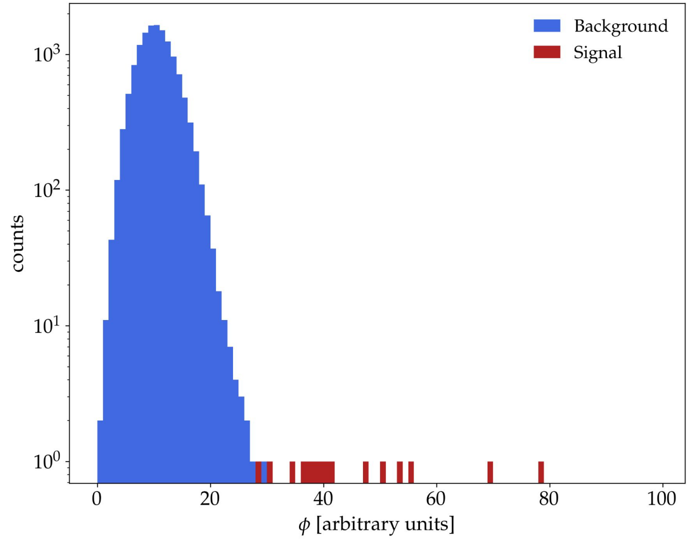


Population studies

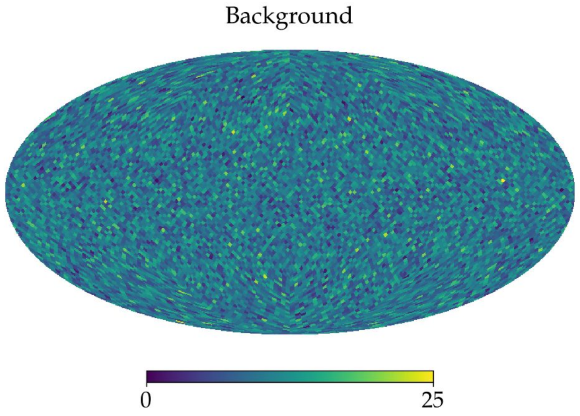
From the simple case to a more realistic description (*continued*)

- Consider not just brightest source, but second brightest, third brightest .. *k* brightest
- Replace standard candle by more realistic luminosity function
- Point sources as non-Poissonian statistical fluctuations

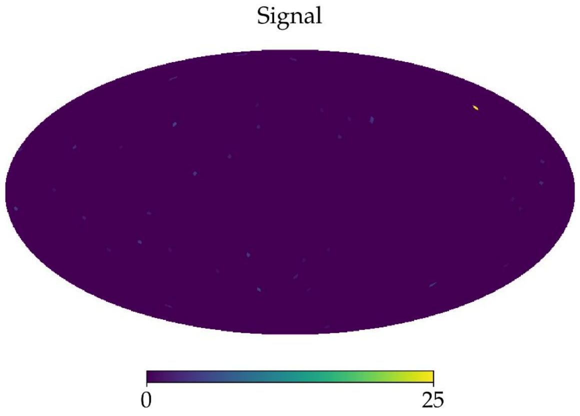
Characterise and test neutrino source populations



Poissonian:
Background and diffuse contribution



Non-Poissonian:
Point-source contribution



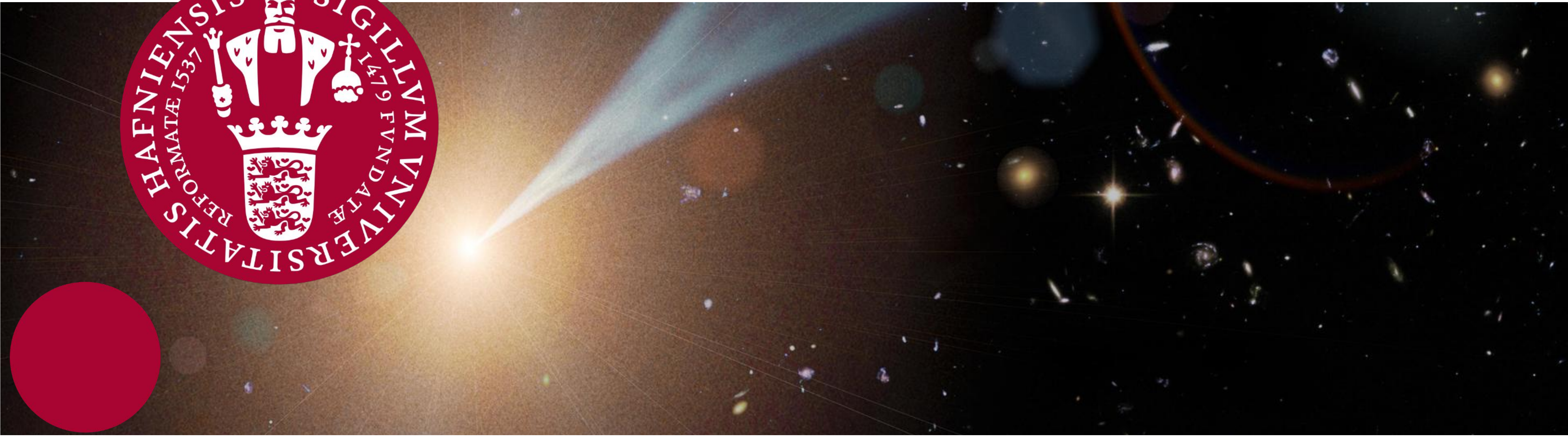
Outlook

Testing the neutrino source populations:

- ➢ IceCube analysis proposal
- ➢ Multi-messenger: what does this mean for the γ-ray flux?

References & further reading:

- ❖ M.Ackermann, M.Ahlers et al. [arXiv:1903.04334]
- ❖ M.Ahlers & F.Halzen [arXiv:1406.2160]
- ❖ M.G.Aartsen, M.Ackermann et al. [arXiv:1909.08623]



Thank you!

Kathrine Mørch Groth (kathrine.groth@nbi.ku.dk)

Image credit: NASA/JPL-Caltech