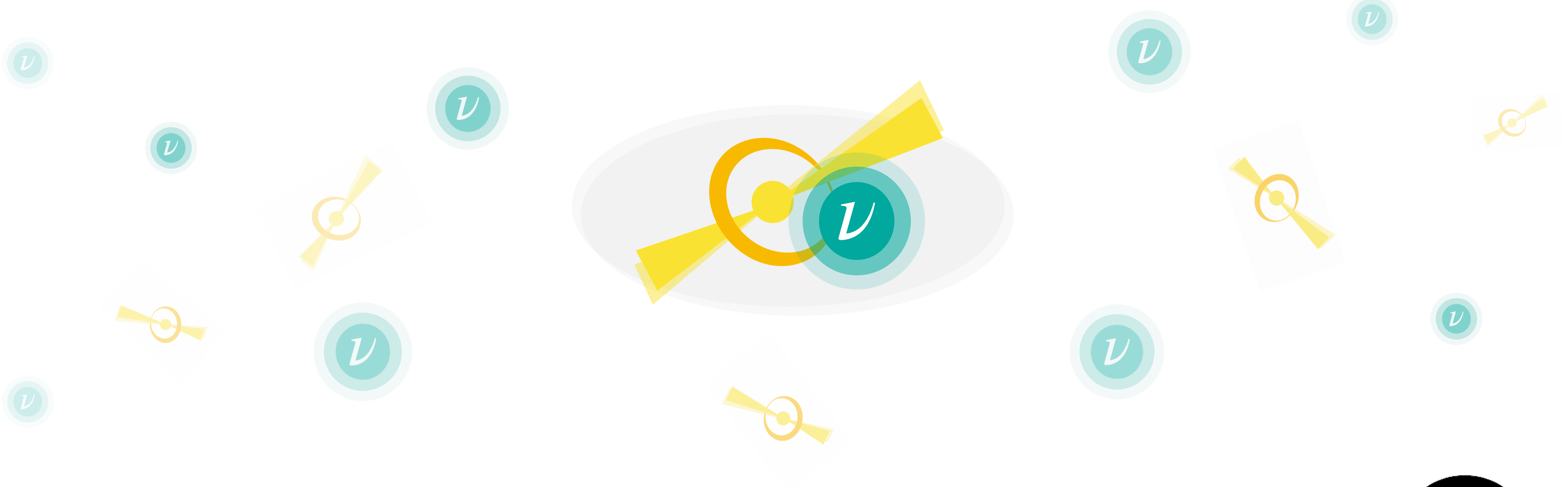
EVALUATING COSMIC COINCIDENCES



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TUM ORIGINS Excellence Cluster

MOTIVATION

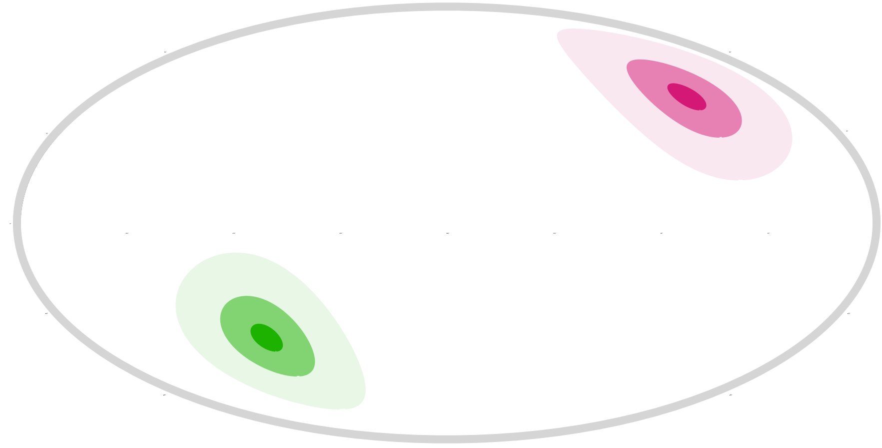
- Multi-messenger data gives new insights into astrophysical sources
- As the amount of data increases, so do chance coincidences

TXS 0506+056 and IceCube 170922A

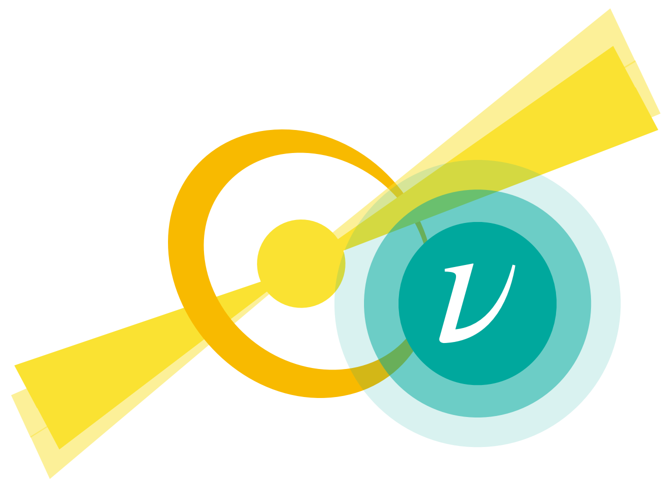
- 3σ significance
- "Signalness" of ν is ~ 0.6
- Blazars are relatively common
- Blazar flare duration of ~ 6 months
- ν-γ connection is still unclear

IceCube Collaboration et al. (2018)

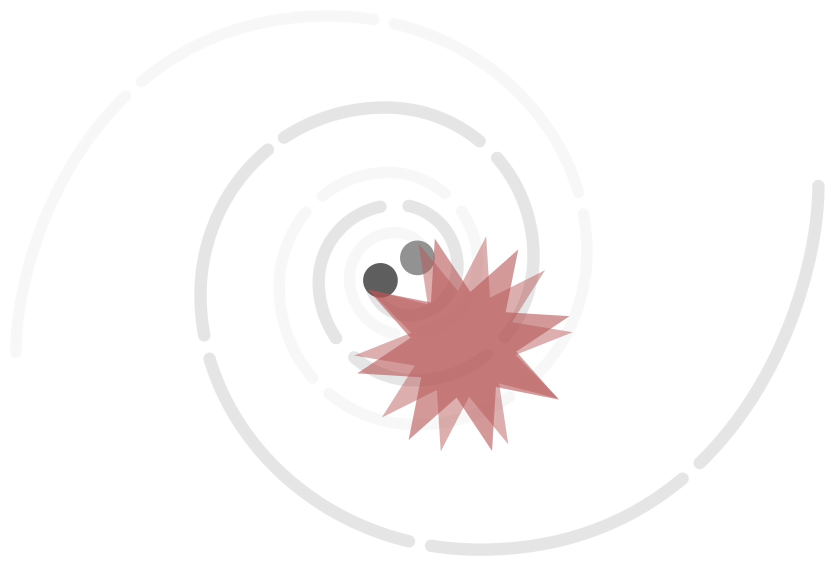
Signals from different directions



Flaring blazar and a high-energy neutrino



GW170817 and GRB 170817A



Definitely not connected

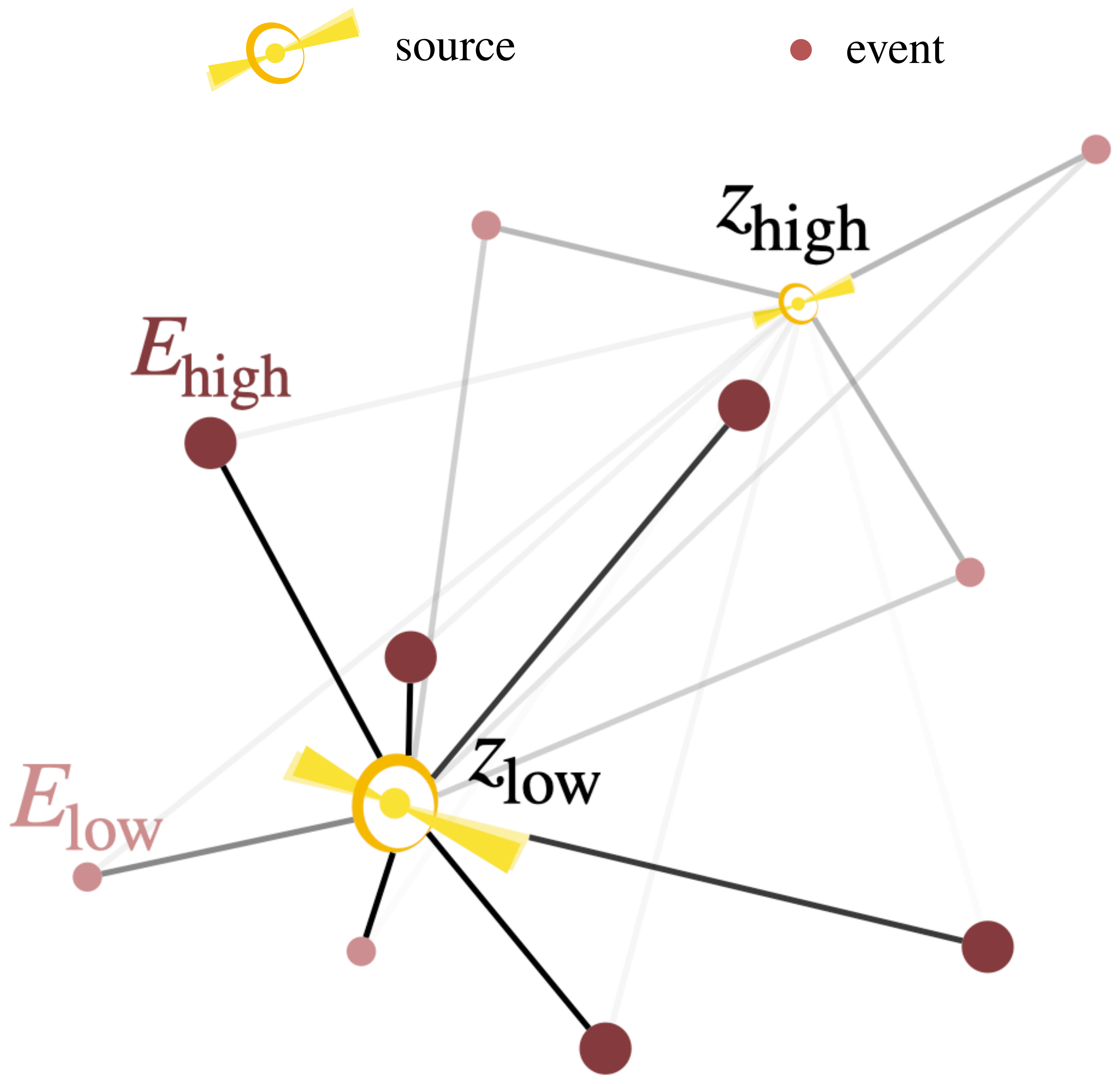
Definitely connected

INDIVIDUAL ASSOCIATIONS

Idea

Decide if individual observations are connected based on **all available information**

- Directions
- Energies
- Distances
- Fluxes
- Spectra
- Uncertainties
- Physical connections
- ...



$P(\text{associated} \mid \text{data})$

Statistical methods

Likelihood-based

- Mixture models
- Poisson processes
- Bayesian hierarchical models

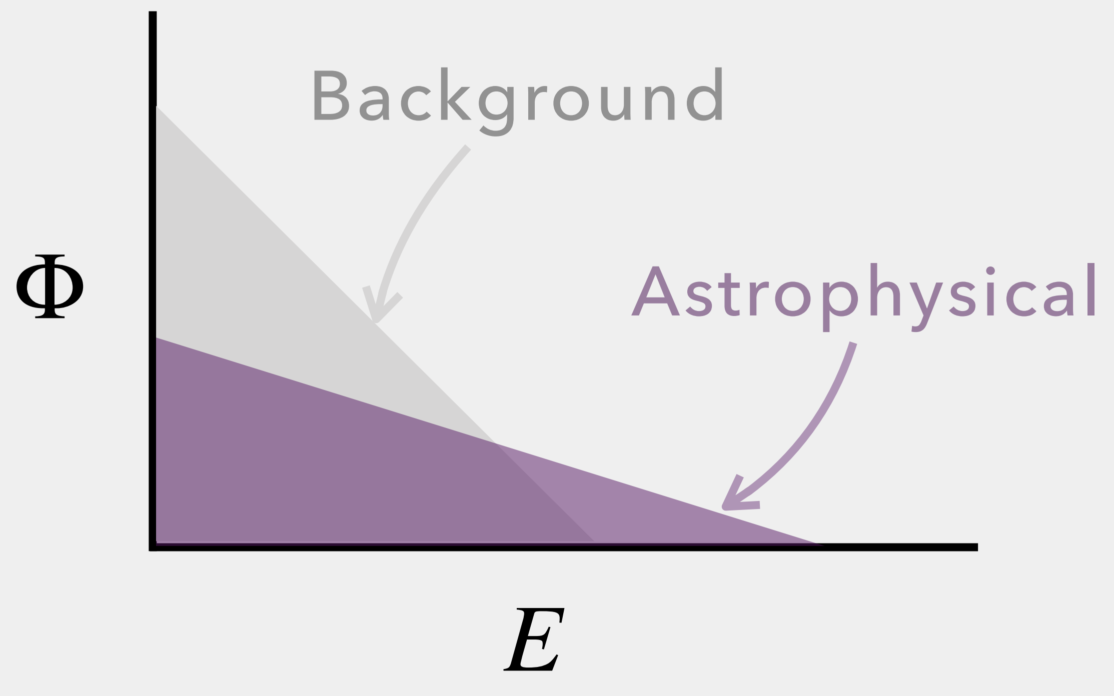
Some examples

- Braun et al. 2008 and 2010
- Budavári & Loredo 2016
- Ashton et al. 2018
- Bartos et al. 2019
- Capel & Mortlock 2019

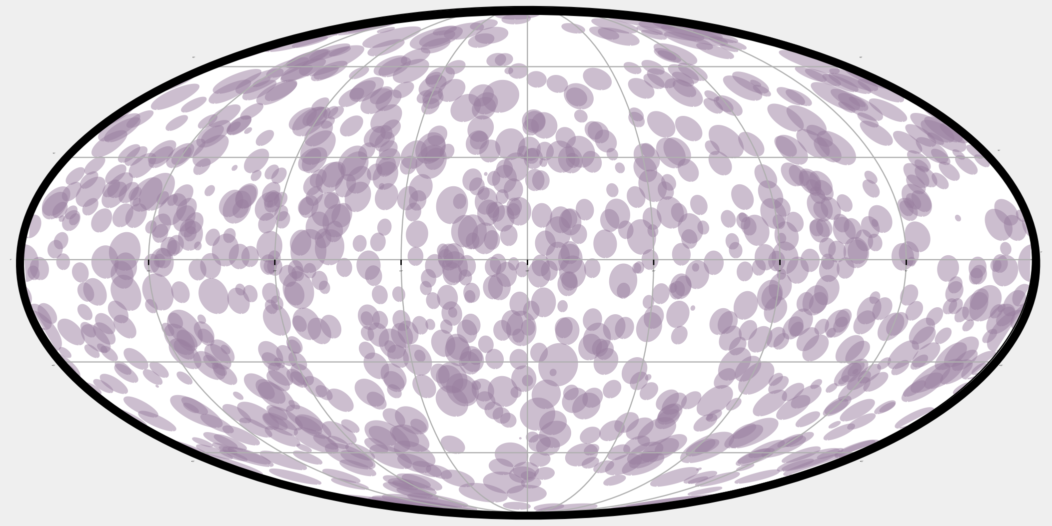
SOURCE POPULATIONS

- Sources are part of an astrophysical population
- Individual associations must also make sense in this bigger picture

IceCube neutrino observations

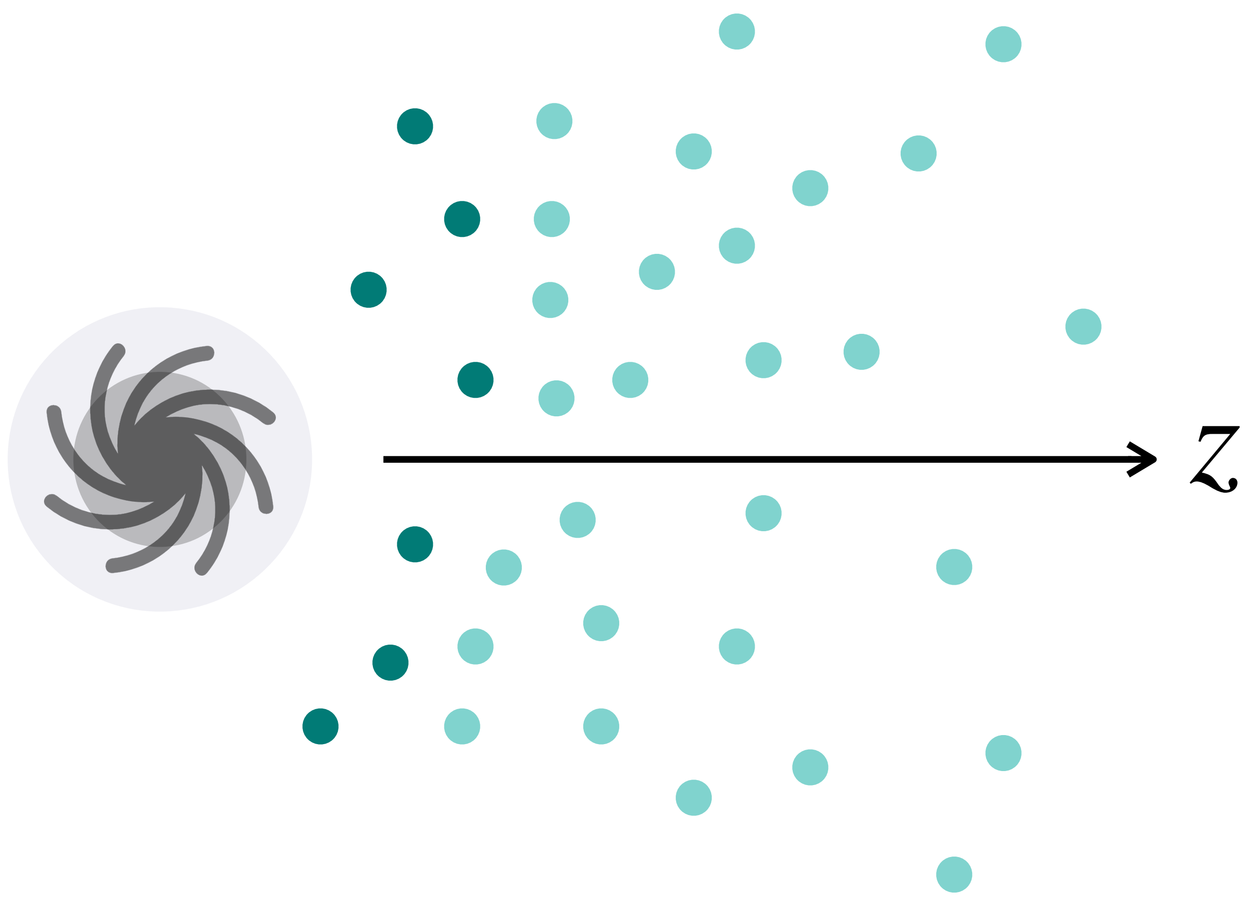


An astrophysical flux...



...but no obvious point sources

Physical picture



Extragalactic sources characterised by a **density, luminosity and cosmological evolution**

GENERAL CONSTRAINTS

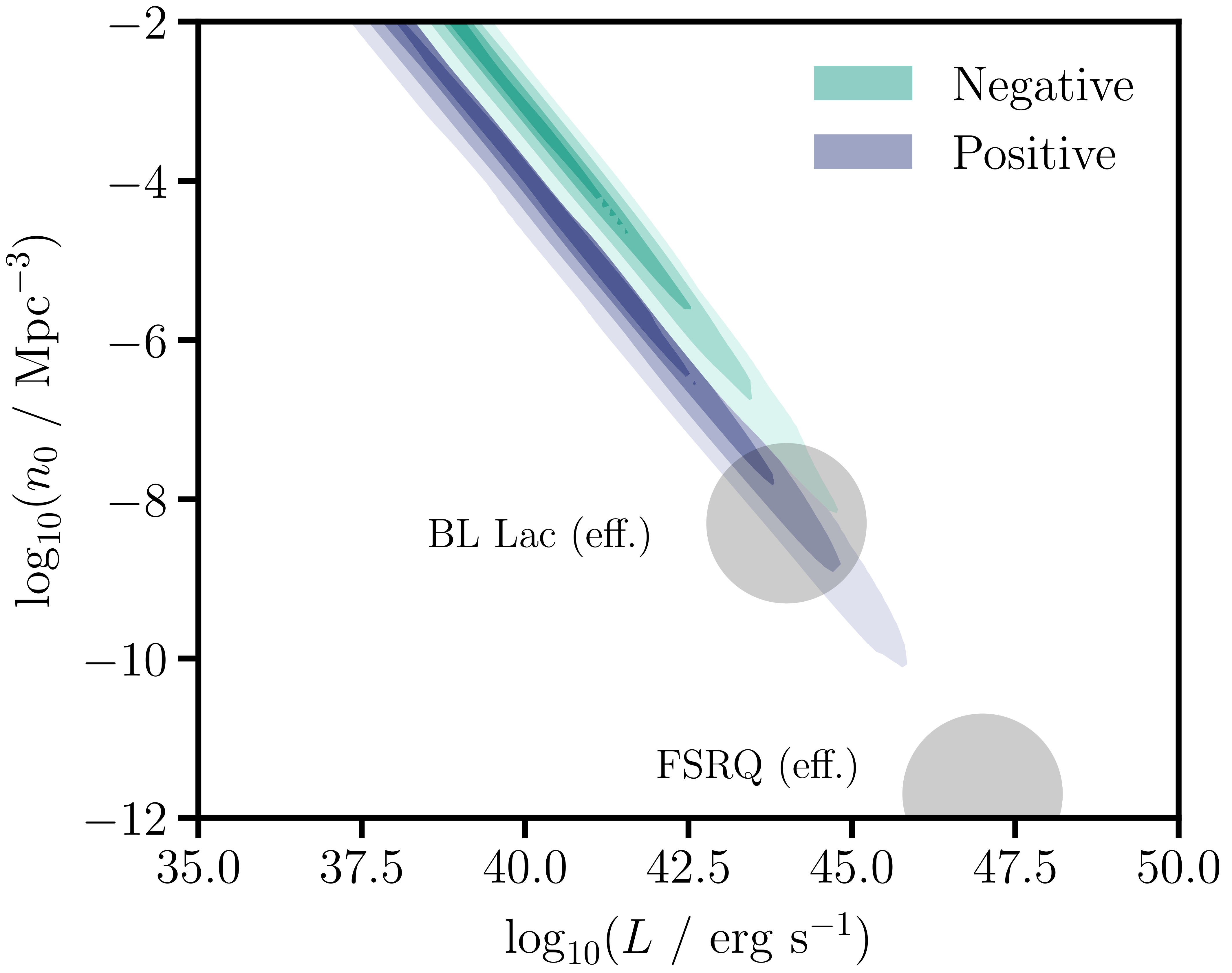
If blazars are the main neutrino sources:

- They must be numerous and powerful enough to produce the observed astrophysical flux
- They cannot be too rare or bright, as then point sources would be detected

We used a Bayesian hierarchical model to find the constraints on the **density** and **luminosity** of neutrino sources

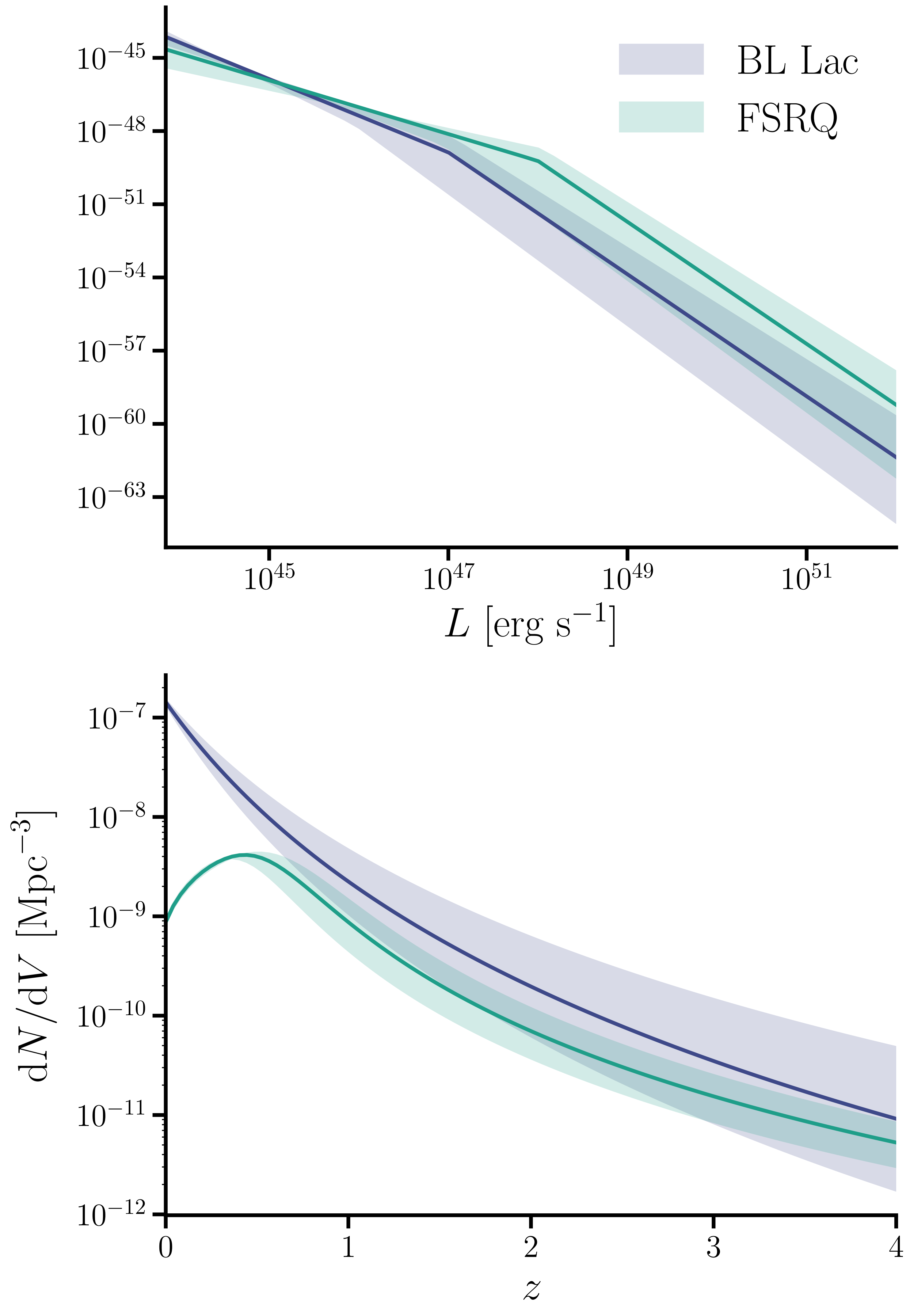
- TXS 0506+056 is either a BL Lac or FSRQ blazar (e.g. Padovani et al. 2019)
- In both cases sources are **strongly constrained**

Capel, Mortlock & Finley 2020
https://github.com/cescalara/nu_pop



See also: Lipari et al. 2008, Silvestri & Barwick 2010, Ahlers & Halzen 2014, Kowalski 2015, Murase & Waxman 2016, Palladino et al. 2020

BLAZAR POPULATION



More details are needed to examine a blazar-neutrino coincidence

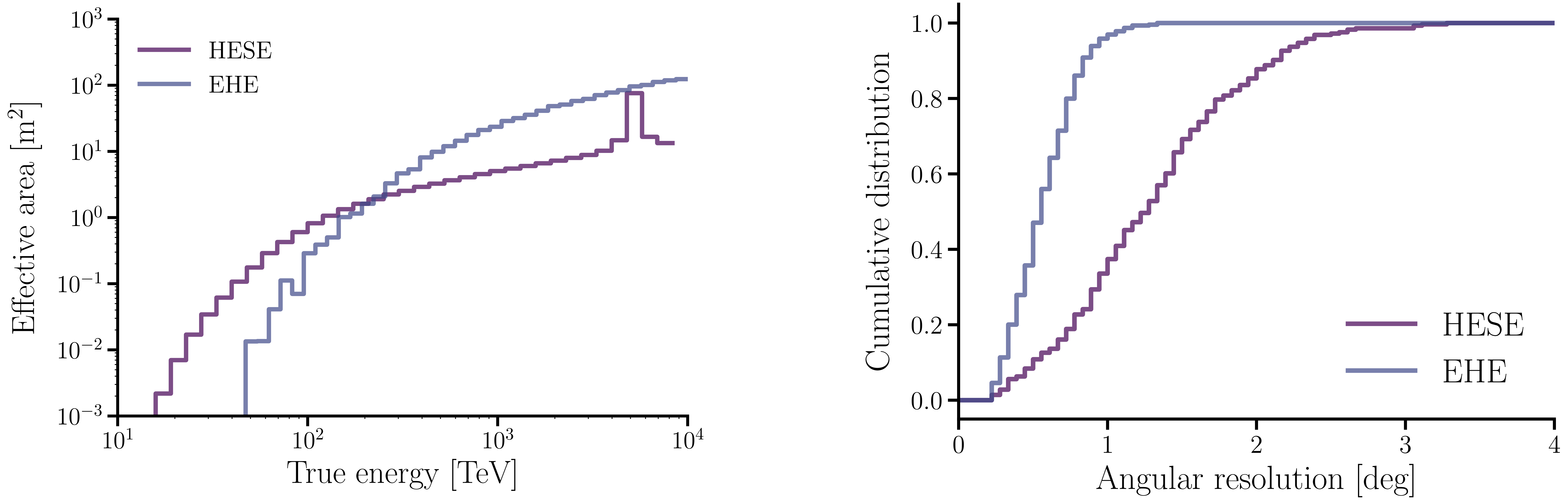
A gamma-ray connection is necessary for the 3σ significance

We can use what we know from **gamma-ray observations** to model the blazar population

- BL Lacs and FSRQs
- Luminosity function and cosmological evolution
- Variability
- Selection effects

FSRQs (Ajello et al. 2012), BL Lacs (Ajello et al. 2014), 2nd FAVA (Abdollahi et al. 2017)

BLAZAR-NEUTRINO CONNECTION



IceCube HESE/EHE alerts (Aartsen et al. 2017), IceCube Alert Catalog (Aartsen et al. 2018)

For high-energy neutrino alerts, model HESE and EHE alerts detected by IceCube

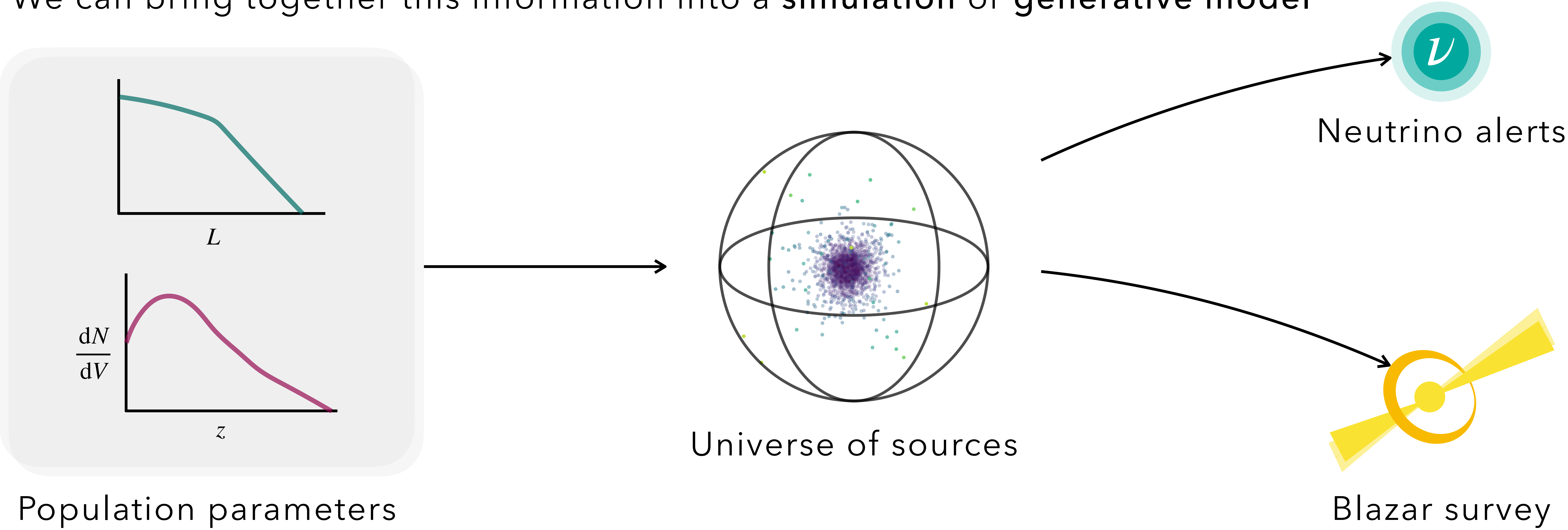
Two options for neutrino production: **isotropic** diffuse flux or **connected** to blazars

If connected, integrated gamma-ray and neutrino fluxes are proportional:

$$\Phi_\nu = \epsilon_{\gamma\nu}\Phi_\gamma$$

SIMULATIONS

We can bring together this information into a **simulation** or **generative model**



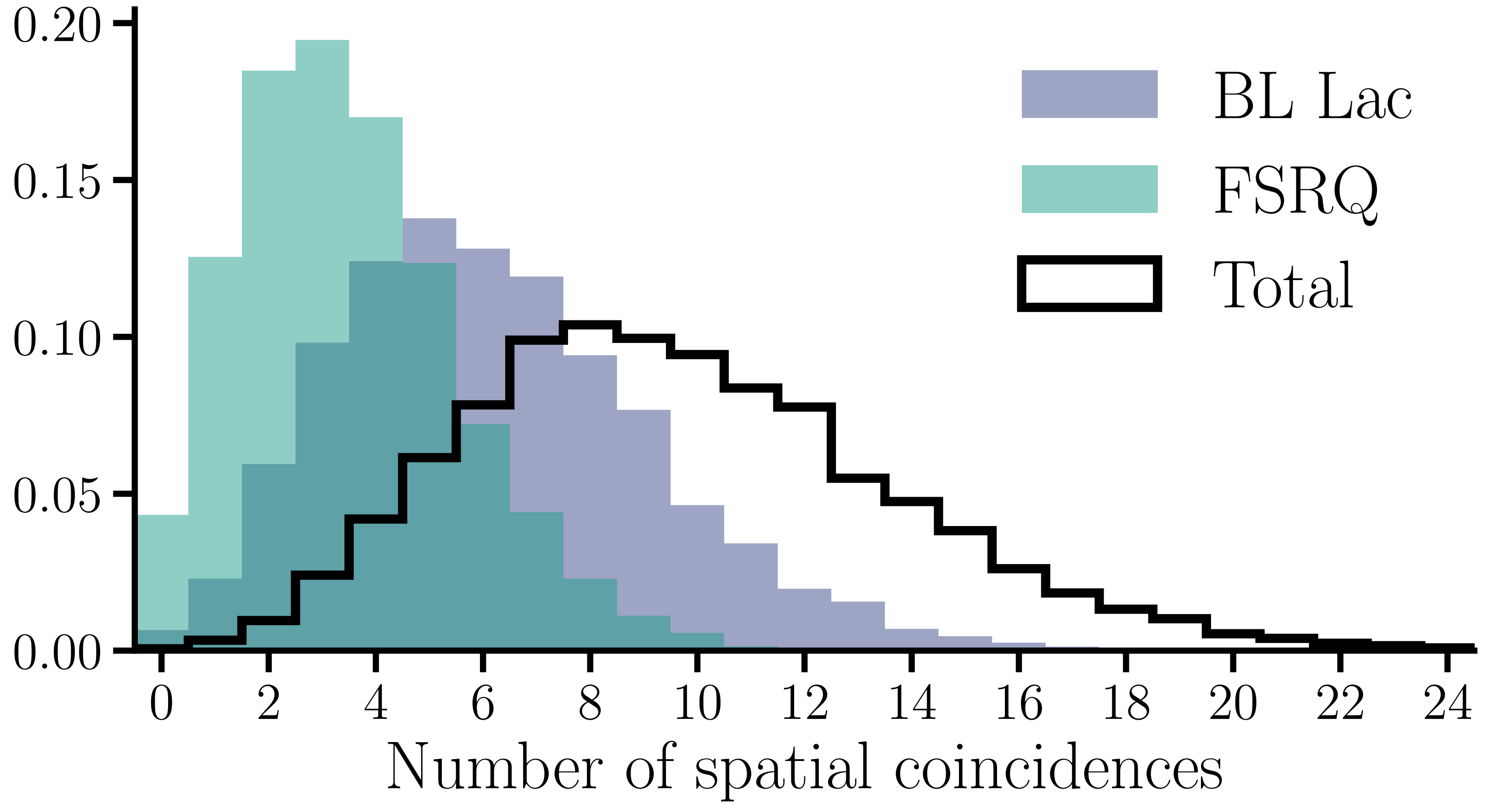
The implementation makes use of the **popsynth** and **icecube_tools** python packages, and we verify that our "reference model" input parameters can reproduce the results of the Fermi 4FGL, FAVA and IceCube alert catalog.

https://github.com/grburgess/popsynth, https://github.com/cescalara/icecube_tools,
Fermi 4FGL (Abdollahi et al. 2020), 2nd FAVA (Abdollahi et al. 2017) IceCube alerts (Aartsen et al. 2018)

CHANCE COINCIDENCES

~5%

Chance coincidence rate for neutrino alerts and flaring blazars



Capel et al., 2021 (in prep.)

Assuming **no blazar-neutrino connection**, how often do we see chance coincidences in 10 year surveys?

Roughly 5% of surveys, ranging between 3% and 8% when changing the blazar reference model within uncertainties

FSRQs account for ~4%, and BL Lacs for ~1%

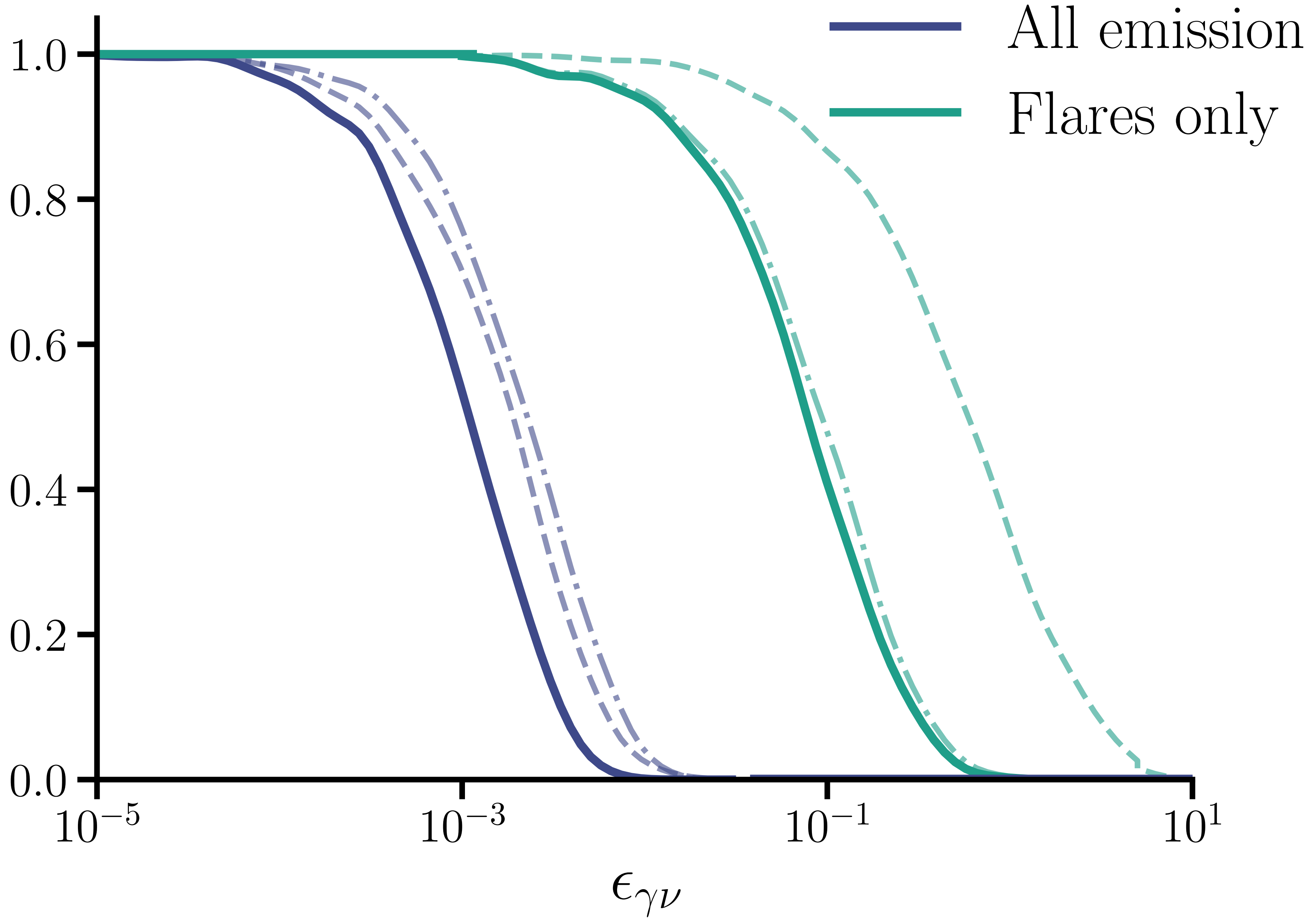
NB: Not exactly the same analysis as original work resulting in 3σ (i.e. 0.1%) result

We can also investigate the number of spatial coincidences, and how this compares with the observed values

IMPLICATIONS

$$\Phi_\nu = \epsilon_{\gamma\nu}\Phi_\gamma$$

Fraction satisfying $N_\nu^a \leq 51$ and $N_\nu^m \leq 1$



Capel et al., 2021 (in prep.)

Assuming that **blazar gamma-ray emission is connected to neutrino production, we** can place constraints on the gamma-ray – neutrino connection

We consider the gamma-ray flux in the 0.1 – 100 GeV range and the neutrino flux in the 10 TeV – 100 PeV range, and 7.5 years of observations

Simple constraints:

N_ν^a Number of neutrino alerts

N_ν^m Multiplicity of each source

Could be extended to constraints on the hadronic component with more careful spectral modelling

CONCLUSIONS

- We can use source populations to better understand potential coincidences

- Future work:
  - Using the generative model for likelihood-free inference
  - Applications to other source – event associations

THANK YOU!