Probing the Cross Correlation of IceCube Neutrinos with Tracers of Large Scale Structure

David Guevel and Ke Fang on Behalf of the IceCube Collaboration

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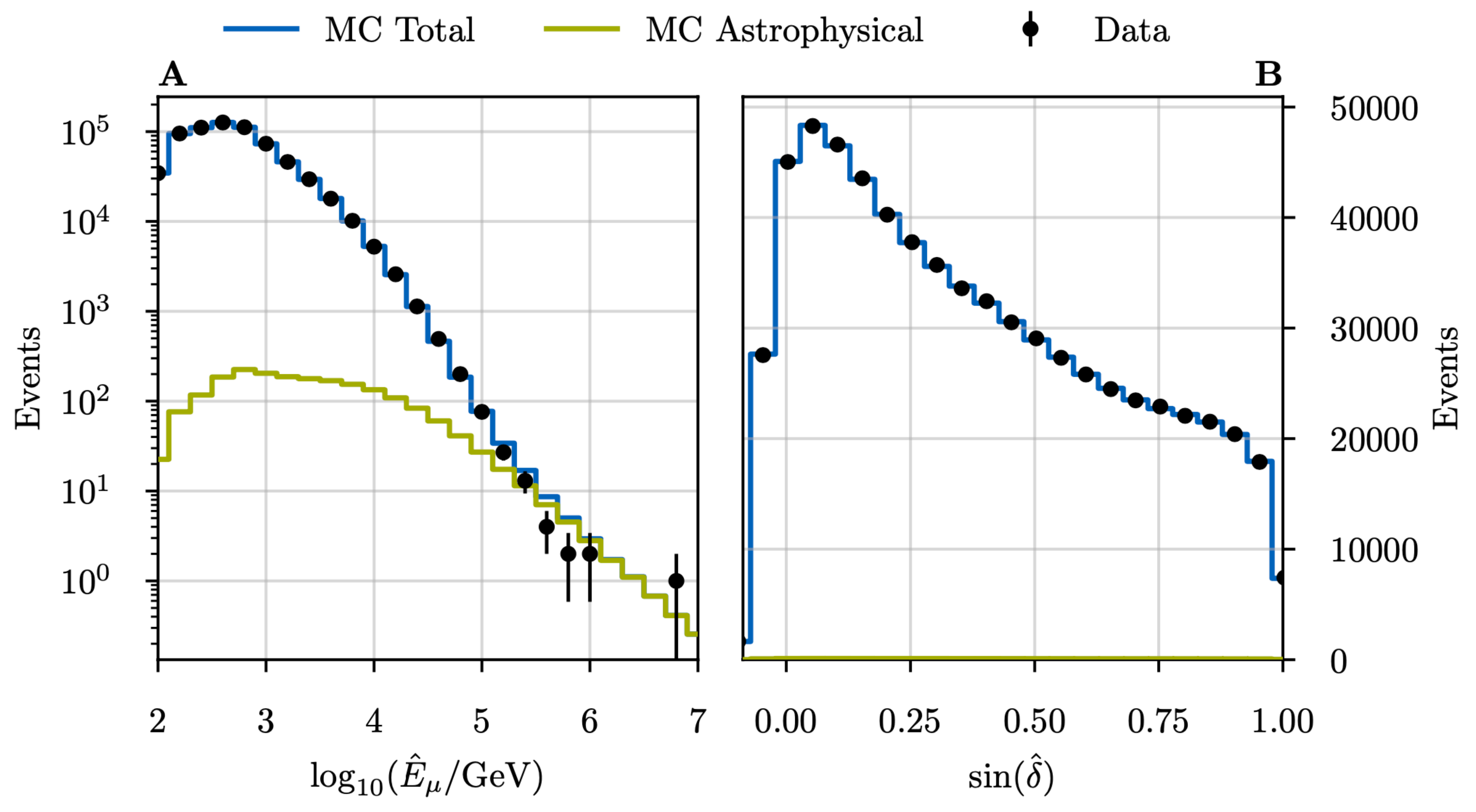
Overview

- Introduction
- Data sets:
  - IceCube track-like events
  - unWISE-2MASS galaxies
- Cross Correlation
- Outlook

IceCube Neutrinos

- Track-like northern sky events
- Minimimal atmospheric muon contamination.



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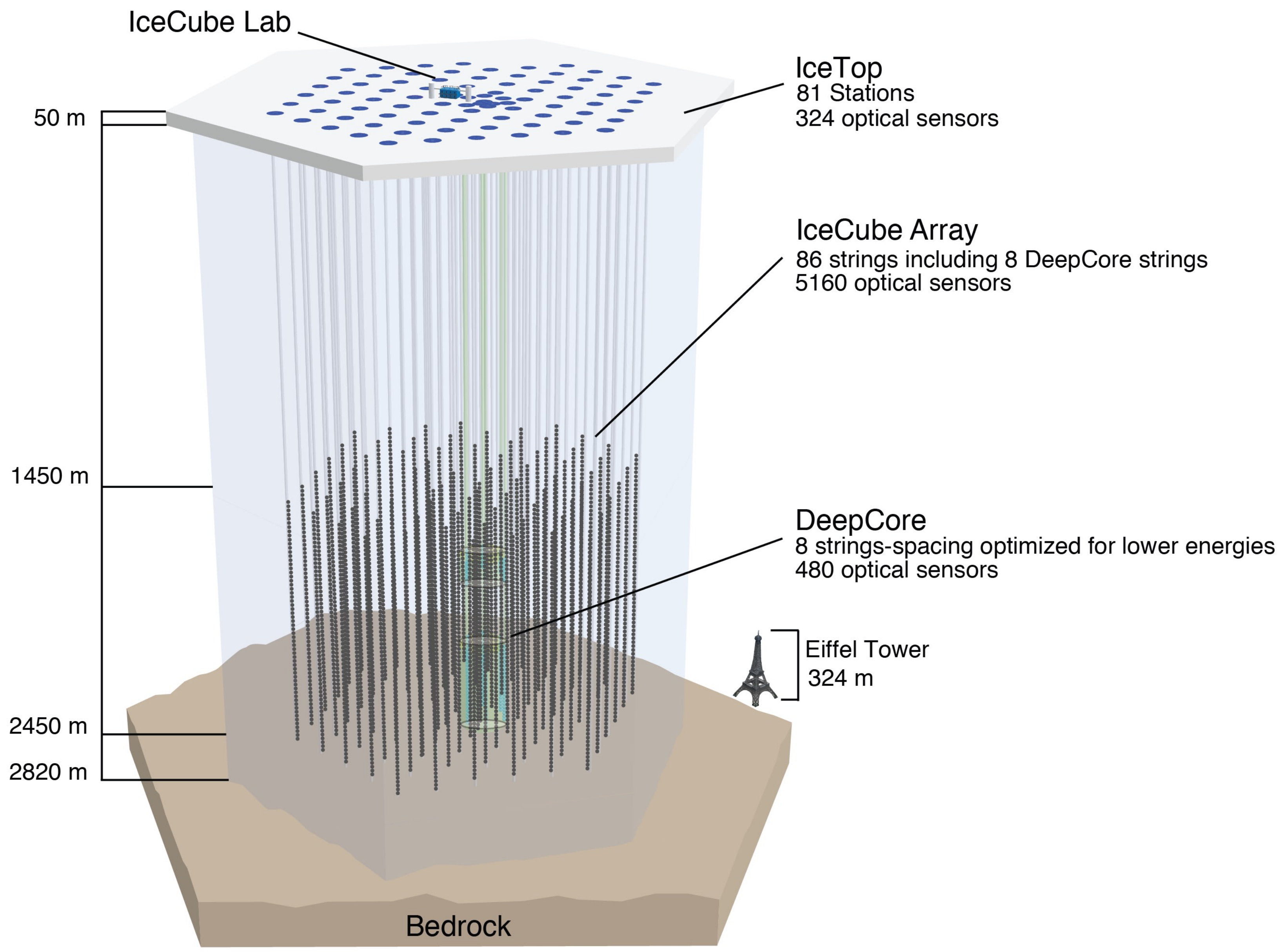
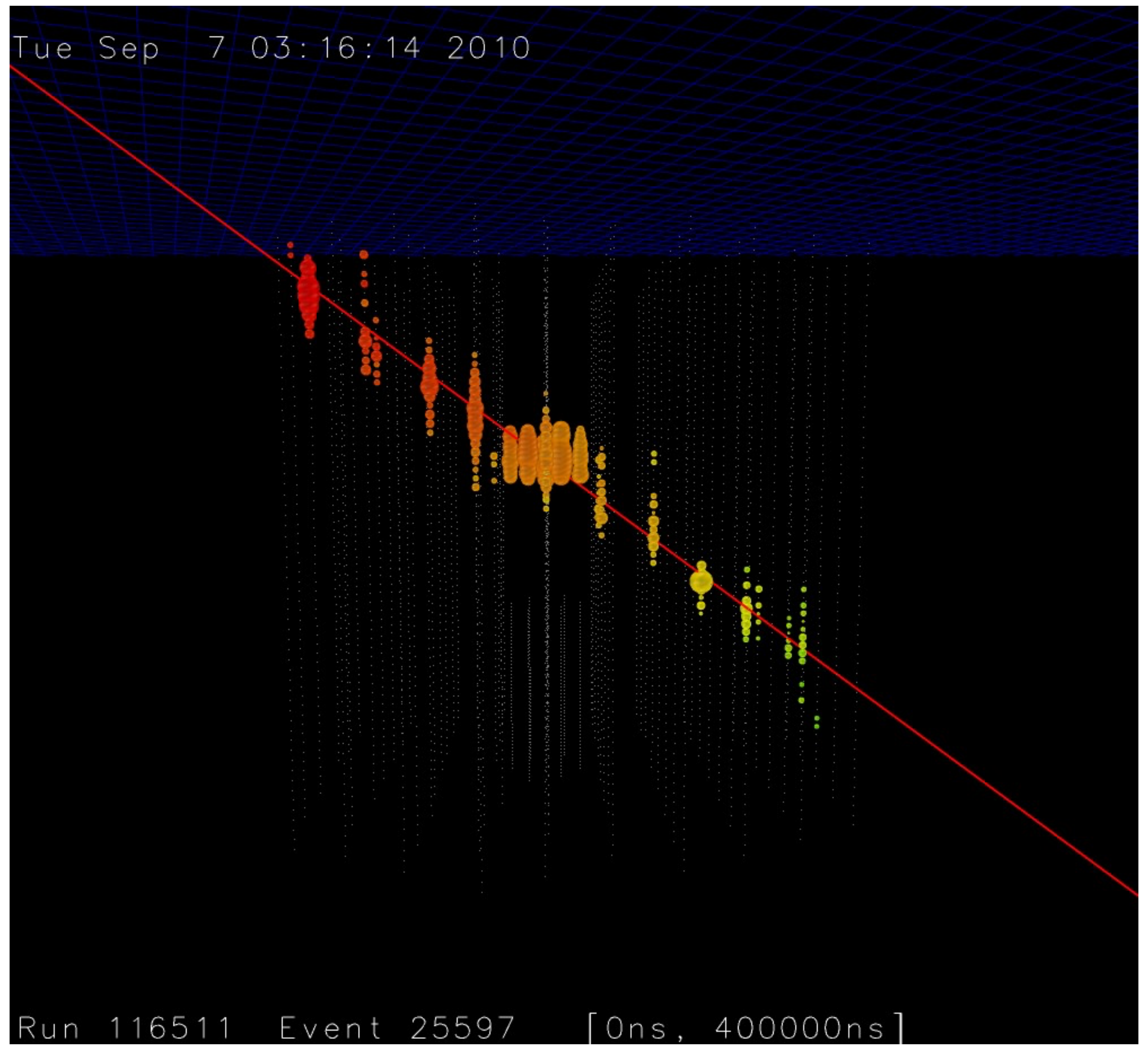
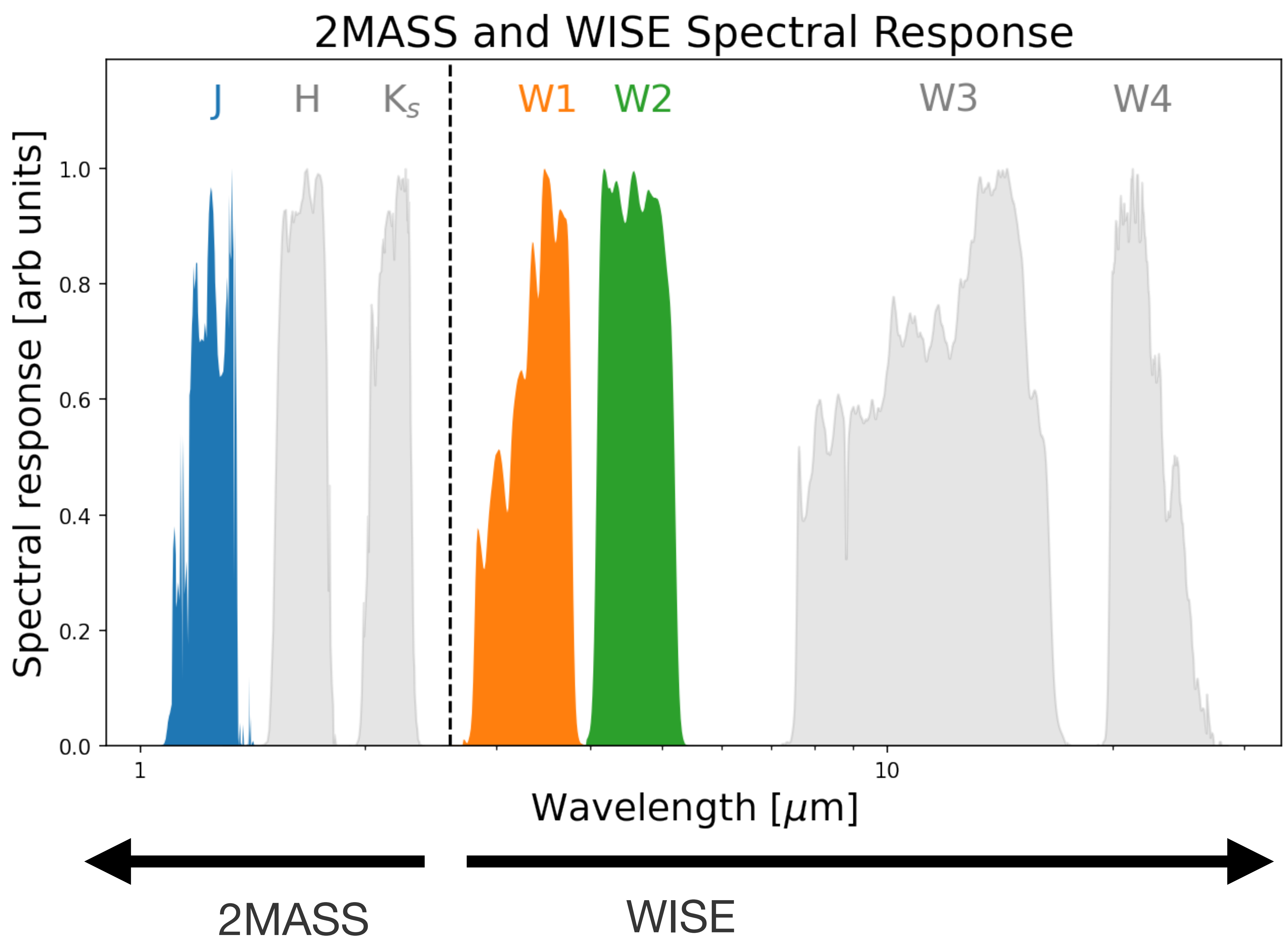
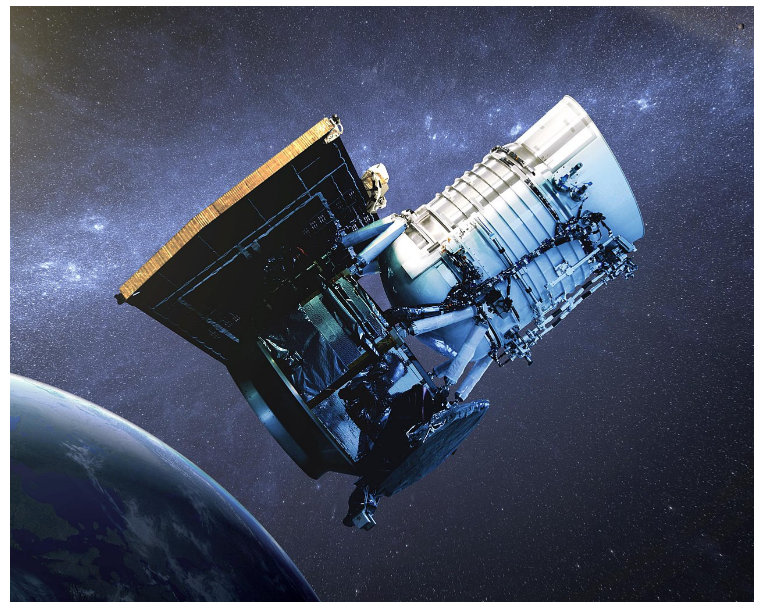




unWISE and 2MASS

- unWISE (Schafley et al 2019):
  - $W1$ and $W2$ magnitudes for 8 billion sources
  - 99% complete for $W2 < 15.5$
- 2MASS (Skrutskie et al 2006):
  - J, H, and K_s magnitudes for 471 million sources
  - 99% complete for $J < 16$

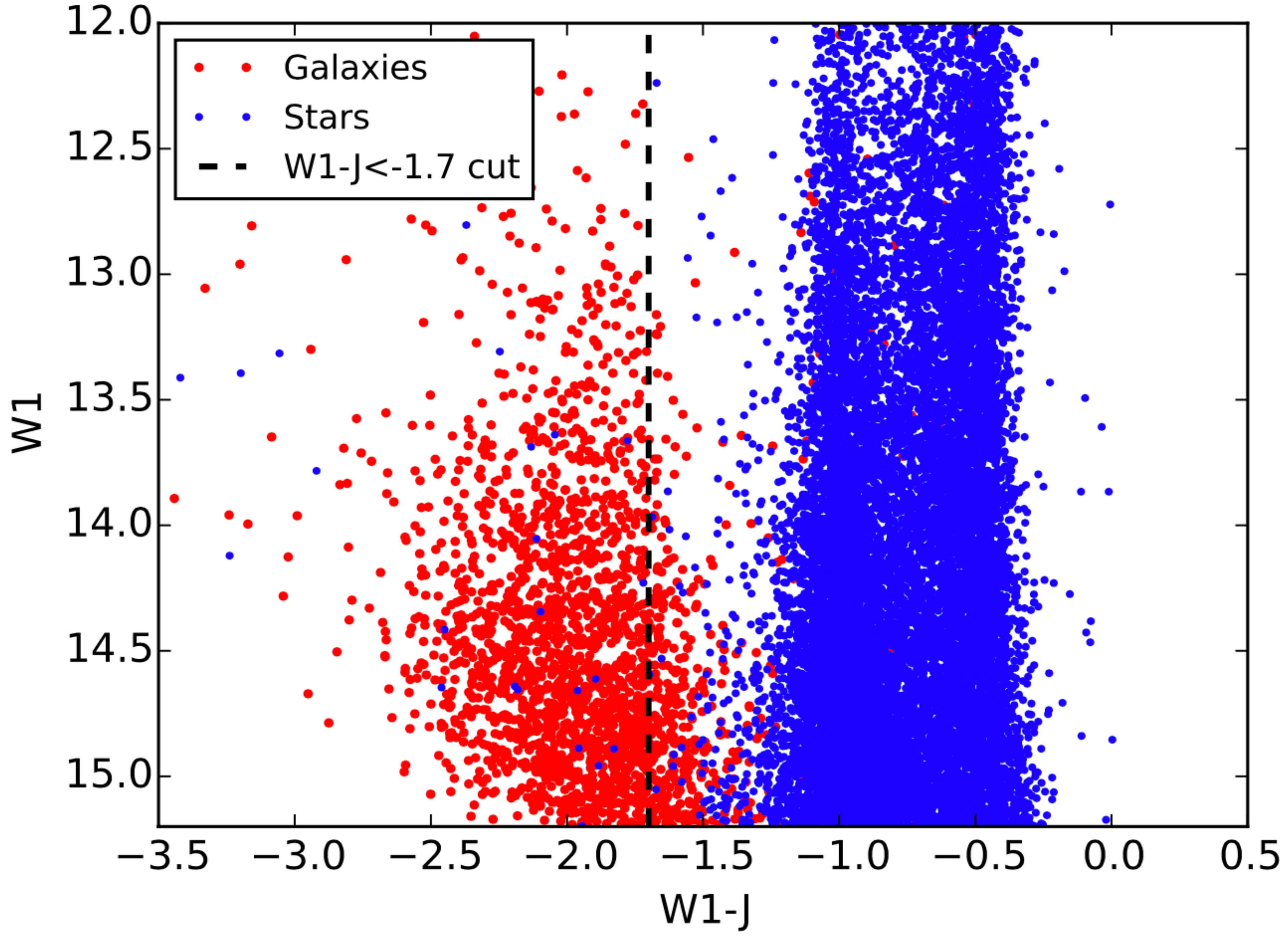


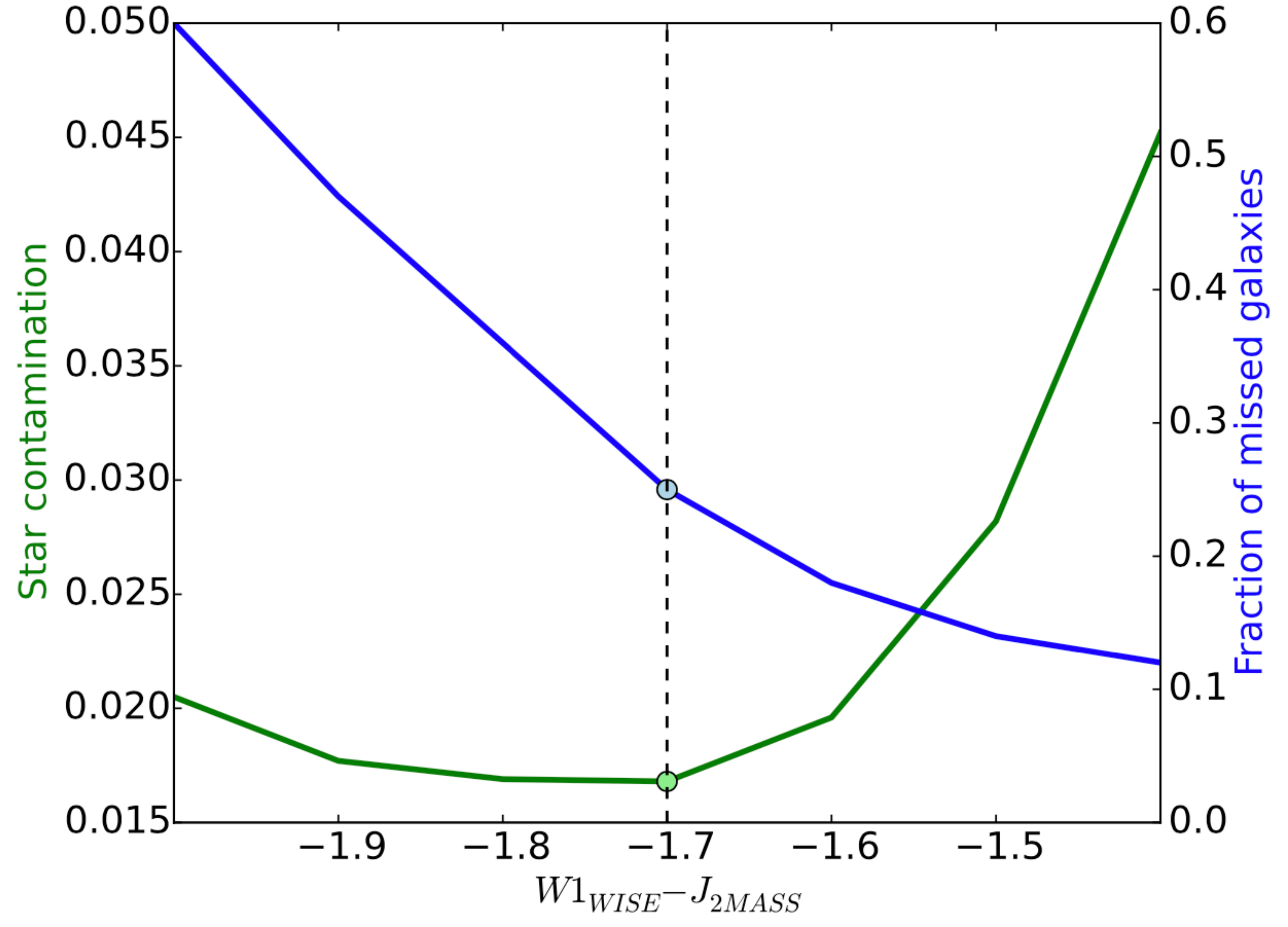


unWISE-2MASS Catalog

- Three color and brightness cuts from Kovacs & Szapudi (2015):
  1. $W1 - J < -1.7$
  2. $W2 < 15.5$
  3. $J < 16.5$

- For these cuts:
  - Stellar contamination: 1.7%
  - Missed galaxies: 2.5%

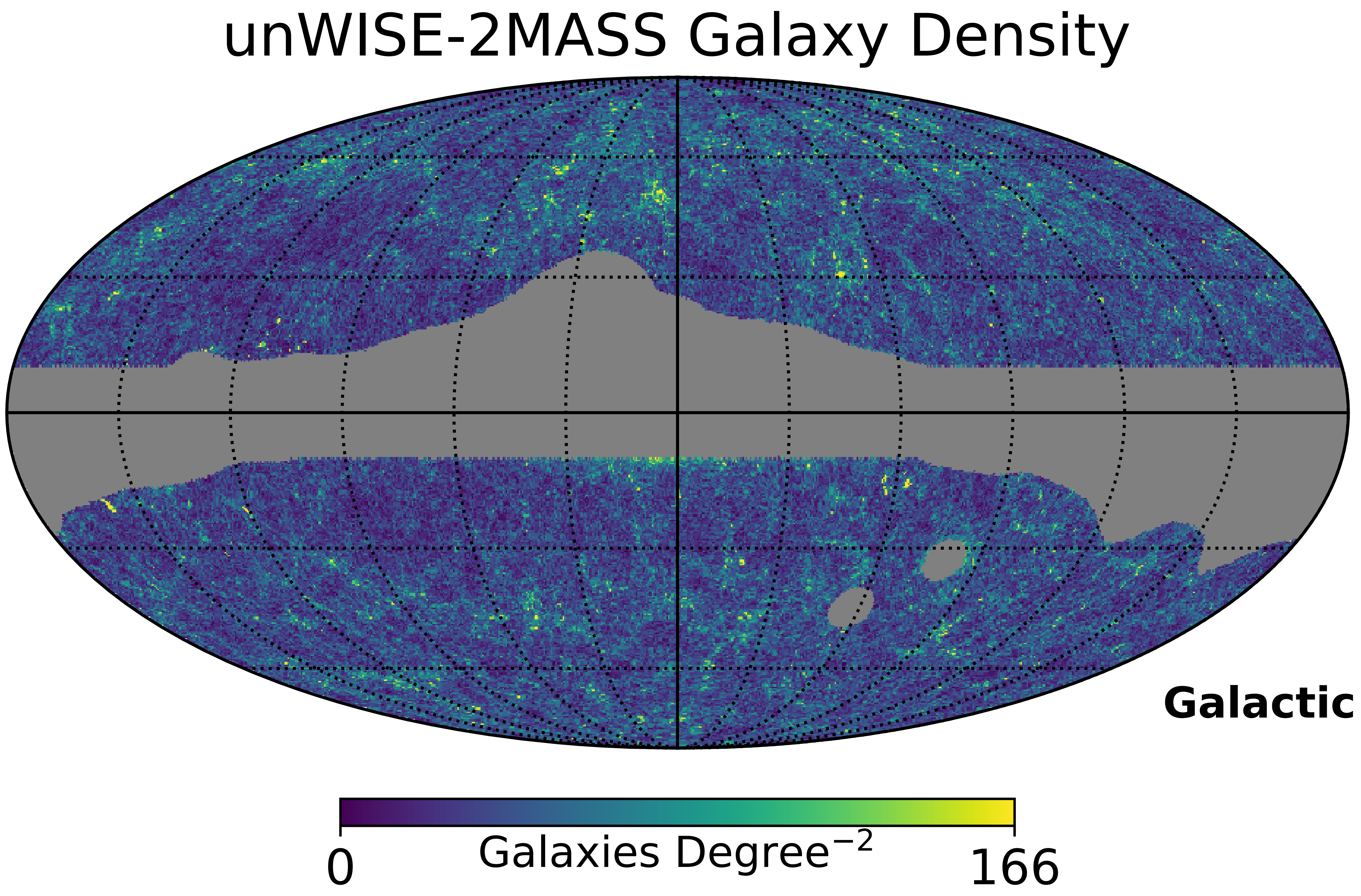




DOI:10.1093/mnras/stv063

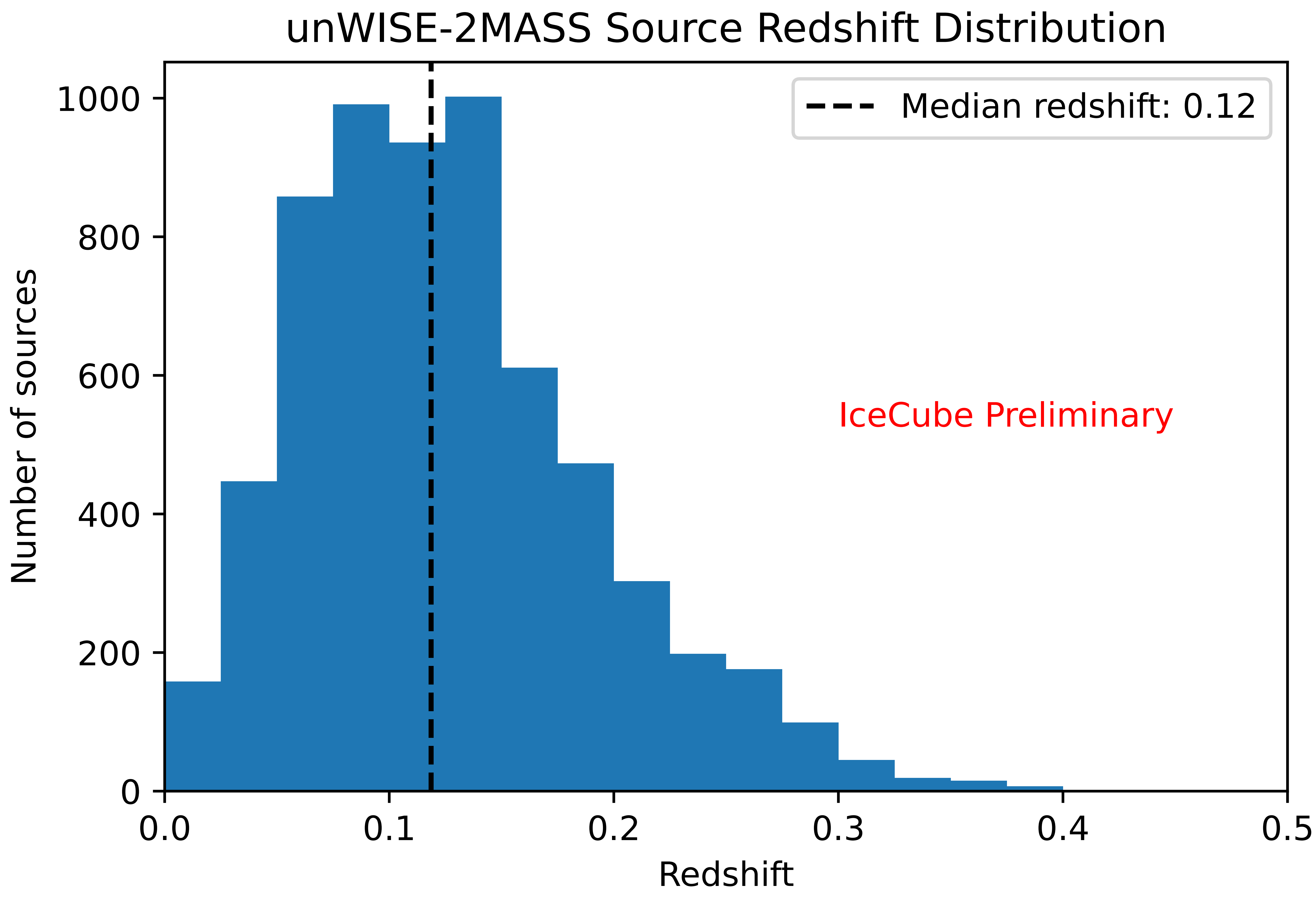
unWISE-2MASS Catalog

- 1.2 million sources after masking.
- Gray mask is the combination of:
  - Planck 90% dust map (Aghanim 2020).
  - 5 deg around galactic plane.
  - Large and Small Magellanic Clouds
- Redshift distribution by cross matching with GAMA Survey



unWISE-2MASS Redshift Distribution

- 3'' cross-match unWISE-2MASS source locations with the GAMA redshift survey.
- Redshifts of matched sources are shown in the figure.



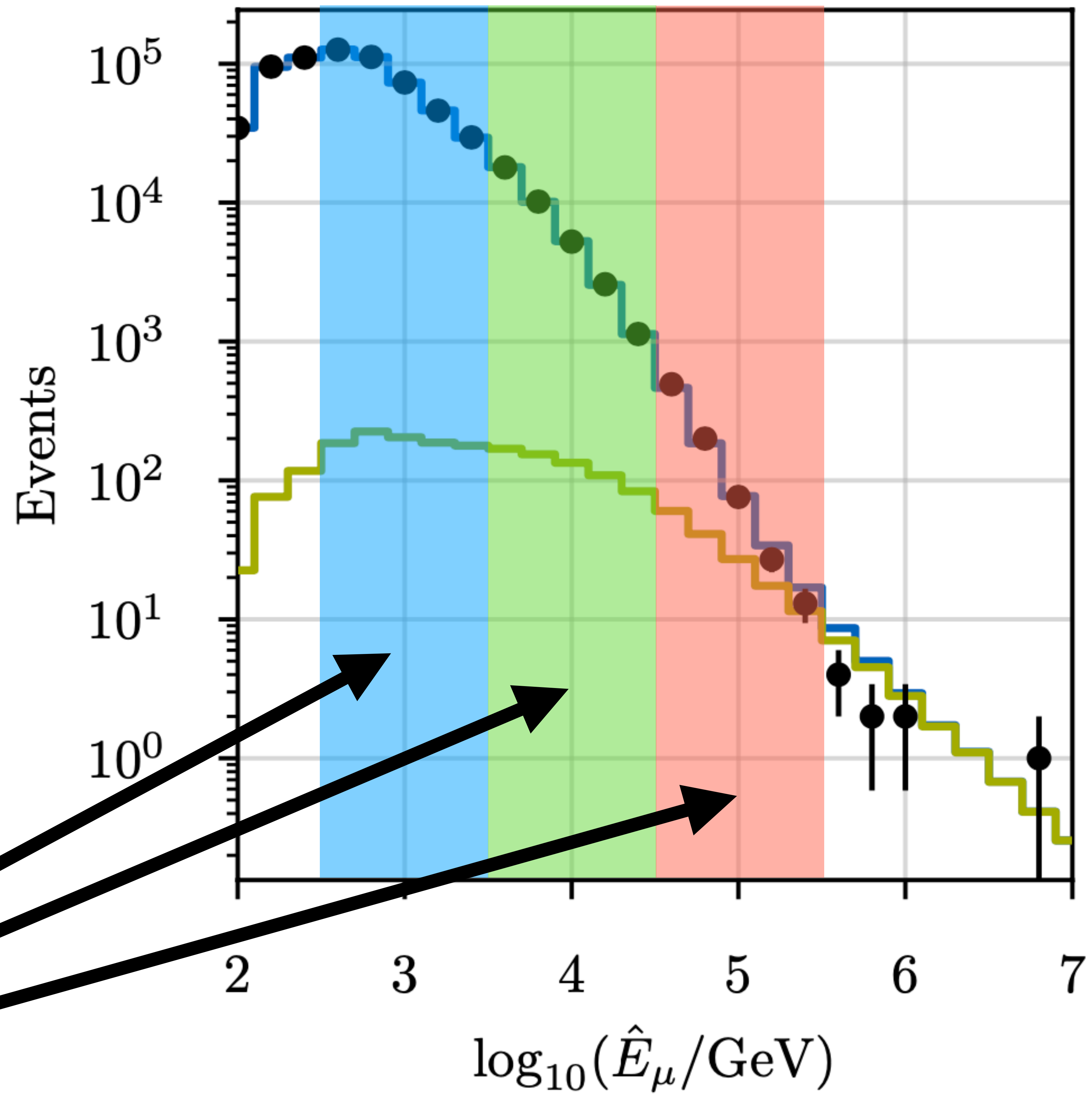
Cross Correlation: Overview

- The cross-power spectrum defined as

$$C_{\ell,i}^{g\nu} = \frac{1}{f_{\text{sky}}(2\ell+1)} \sum_{\ell} a_{\ell m}^{g*} a_{\ell m,i}^{\nu}$$

  $a_{\ell m,i}^{\nu}$ and $a_{\ell m,i}^{g}$ are the multipole representations of the galaxy and neutrino over-density of events in energy bin i.

- Calculate $C_{\ell,i}^{g\nu}$ in **three energy bins** centered at 1, 10 and 100 TeV



Cross Correlation: Modeling

- The cross-power spectrum in energy bin i can be decomposed into signal and atmospheric components:

$$C^{g\nu}_{\ell,i} = f\,\kappa_i(\gamma)\;C^{\nu,\text{signal}}_{\ell,i} + f_{isotropic,i}\;\cancel{C^{g,\text{isotropic}}_{\ell,i}} + f_{atm,i}\;C^{\nu,\text{atm}}_{\ell,i}$$

Correlation strength:
$f = \frac{b_s}{b_g}\frac{n_s}{n_{total}}$

b_s and b_ν are the $\mathcal{O}(1)$ linear bias parameters describing the clustering strength relative to the true mass density power spectrum.

$\kappa_i(\gamma)$ is the relative correlation strength in energy bin i.

It is equal to the ratio of acceptance in bin i to the acceptance over the full energy range.

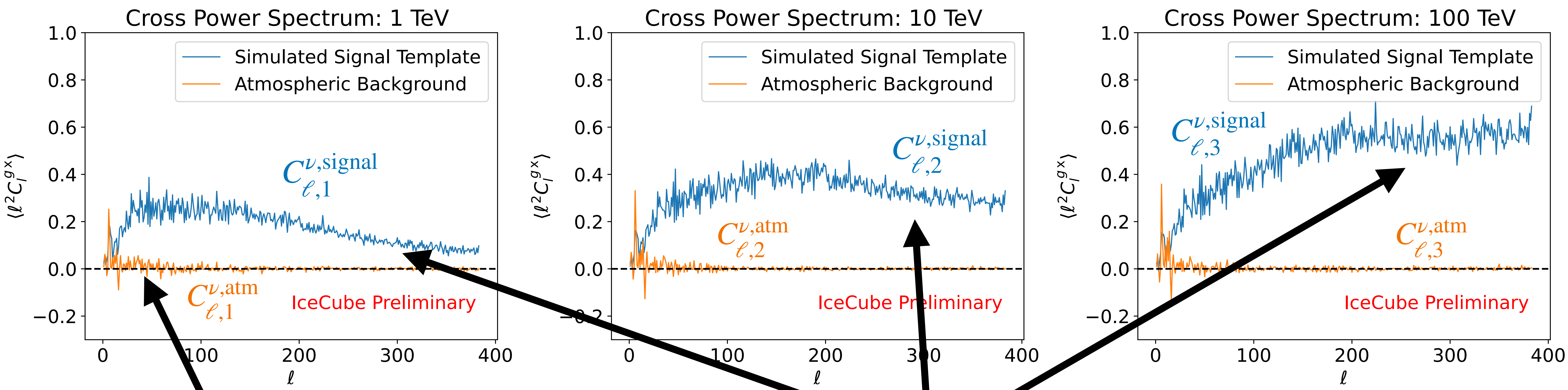
Cross power spectrum for a purely correlated sample.

$C^{g,\text{isotropic}}_{\ell,i} = 0$ by the design of the weighting scheme.

Atmospheric correlation strength in bin i: $f_{atm,i} = \frac{n_{atm,i}}{n_{total,i}}$

Cross power spectrum for a purely atmospheric sample.

Statistical Formulation



Higher energy → better angular resolution → more power at larger ℓ

Declination dependence of atmospheric neutrinos is important at small ℓ

Cross Correlation: Likelihood

- The cross-power spectra are **normally distributed**.

$$\mathscr{L}(\{C^{g\nu}_{\ell,i}\}\,|f,\,\gamma,\,f_{atm,1},\,f_{atm,2},\,f_{atm,3}) = \sum_{i=1}^{3}(C^{g\nu}_{\ell,i} - \langle C^{g\nu}_{\ell,i}(f,\gamma,f_{atm,i})\rangle)^{T}\Sigma^{-1}(C^{g\nu}_{\ell,i} - \langle C^{g\nu}_{\ell,i}(f,\gamma,f_{atm,i})\rangle) + \text{constant}$$

Energy bins are independent, so the log-likelihoods sum.

Data

Model

Multipoles are *not* independent because of the masking.

We estimate the covariance matrix with MC simulations.

Normal distribution normalization constant

Statistical Details

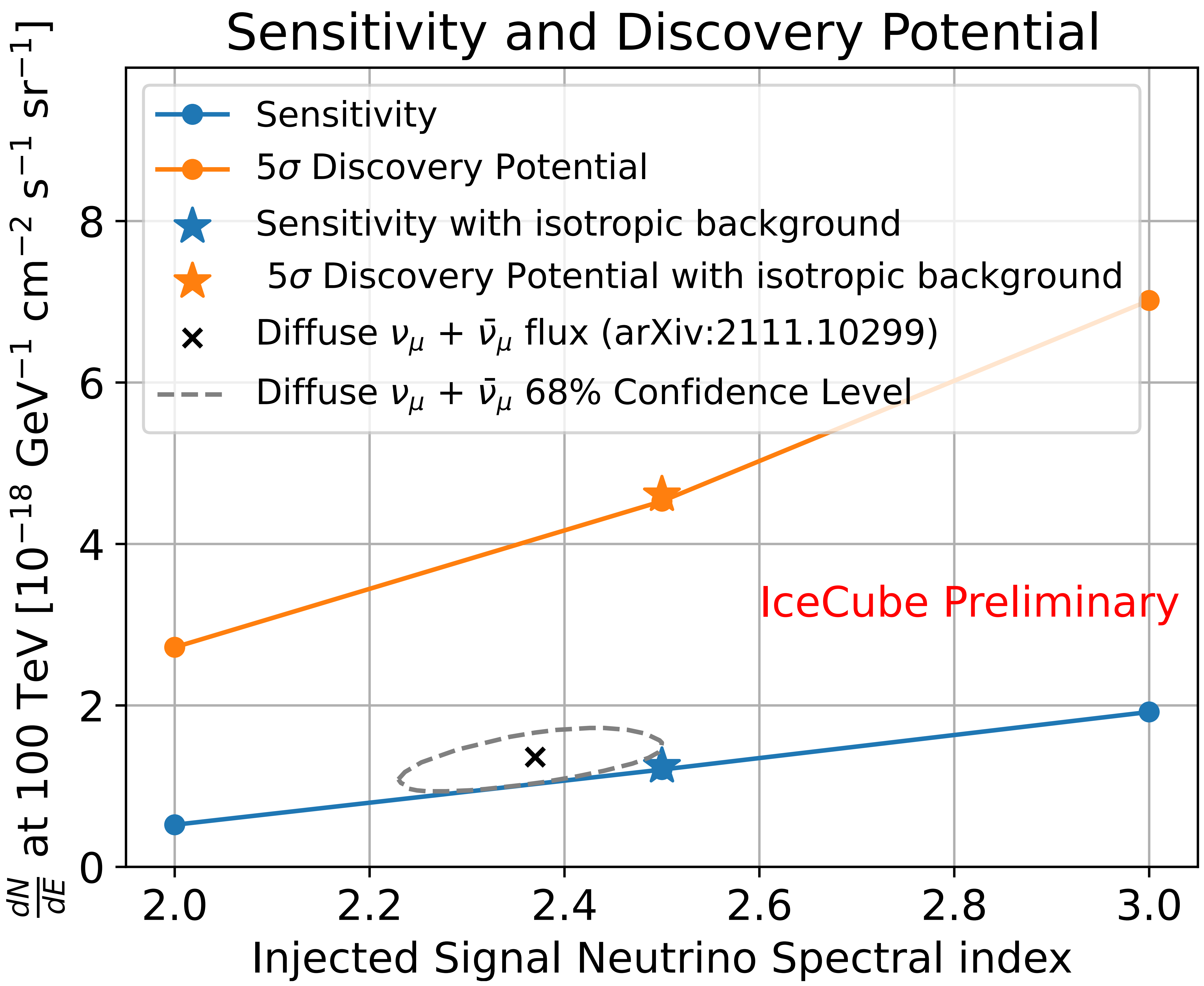
- Test statistic is the **log-likelihood ratio**
  $TS = 2\left(\log \mathscr{L}(\{C_{\ell i}^{g\nu}\}\,|f, \gamma, f_{atm,1}, f_{atm,2}, f_{atm,3}) - \log \mathscr{L}(\{C_{\ell i}^{g\nu}\}\,|0,\ 0, f_{atm,1}, f_{atm,2}, f_{atm,3})\right)$

- **Null hypothesis:** Atmospheric neutrinos and possibly astrophysical neutrinos from an uncorrelated source ie. $f = 0$.

- **Test hypothesis:** Additional astrophysical events from a correlated source distribution with energy distribution following a power law distribution; maximum likelihood estimate for f and γ.

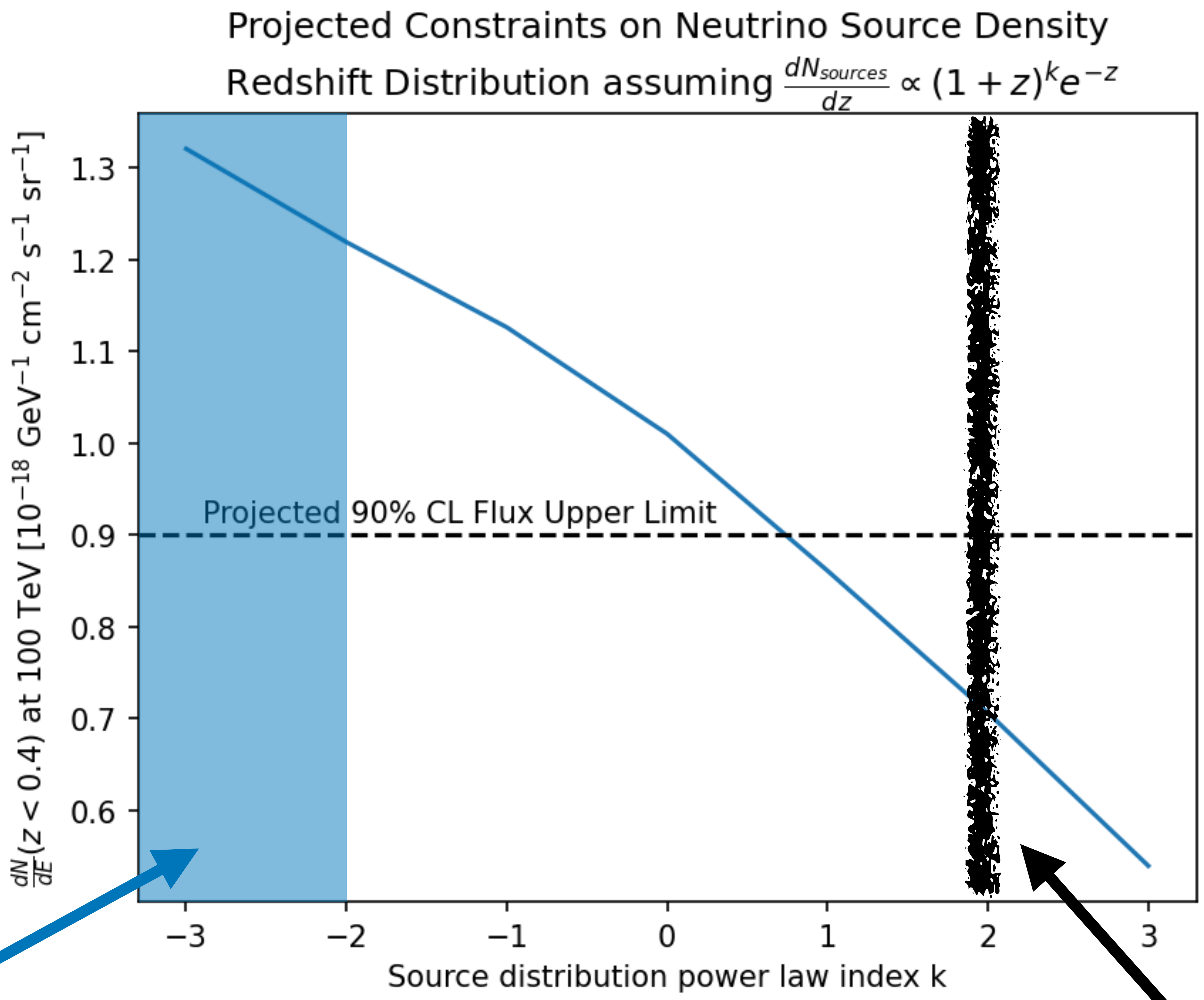
Sensitivity and Discovery Potential

- If equal bias, ie $b_s = b_g$, the projected 90% CL upper limit is less than the measured diffuse $\nu_\mu + \bar{\nu}_\mu$ flux.



Neutrino Source Population Constraints

- If the co-moving source density follows a cutoff power law redshift evolution, we may be able to exclude very nearby distributions.



Some tidal disruption event models, eg DOI: 10.1093/mnras/stw1290

Approximate star formation rate evolution

Summary

- We have developed a cross-correlation of IceCube neutrinos with tracers of large-scale structure.
- The sensitivity of the analysis is less than the diffuse $\nu_\mu + \bar{\nu}_\mu$ flux possibly allowing a constraint on a $z < 0.4$ origin of IceCube diffuse neutrinos the sources follow the large-scale structure.