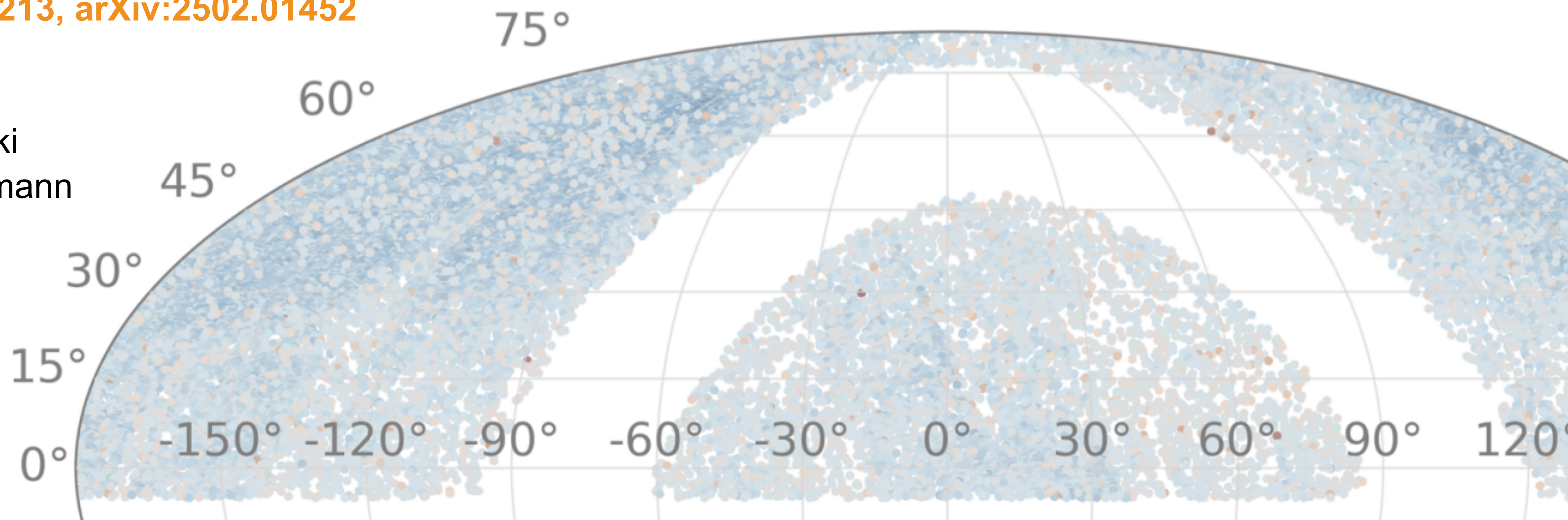


Promise and perils of neutrino source stacking

arXiv:2501.10213, arXiv:2502.01452

Marek Kowalski
Markus Ackermann
Imre Bartos

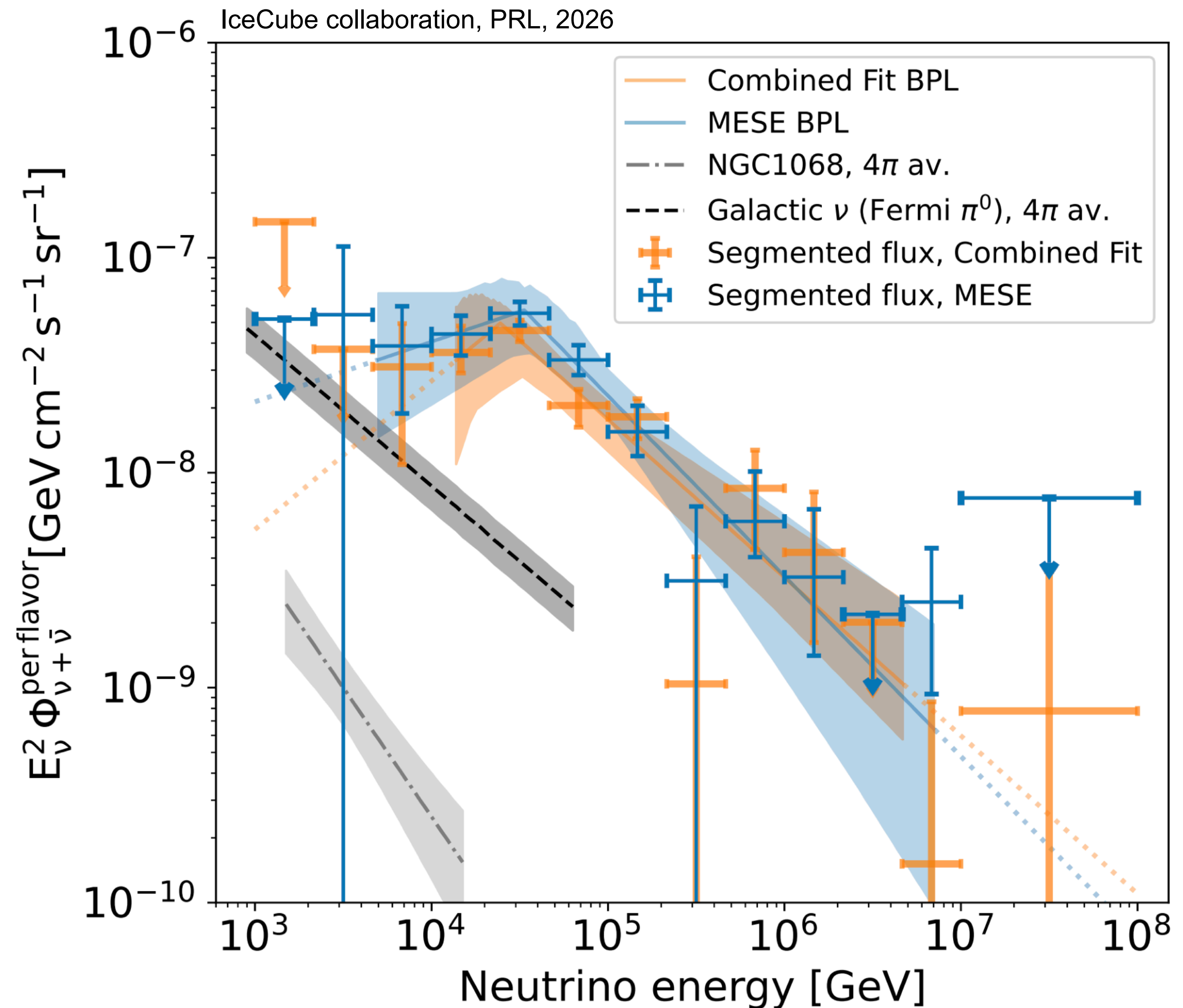
IPA, Madison
Oct 15, 2026



From point source to stacking analysis

Which source populations are responsible for the astrophysical neutrino flux ?

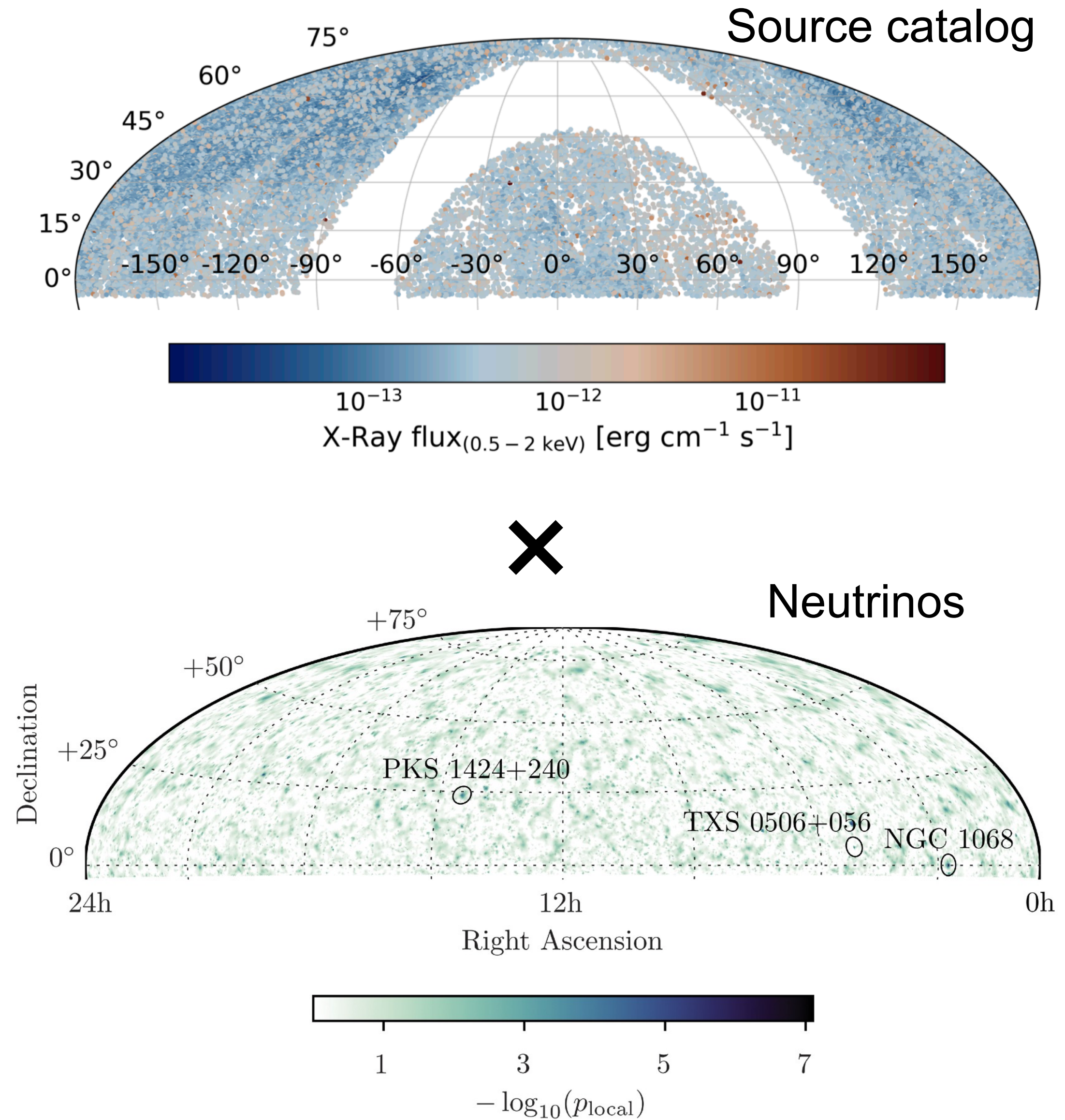
- Astrophysical neutrino flux is dominated by **extragalactic sources**
- The most prominent extragalactic source candidate (NGC 1068) represents a **tiny fraction of the total intensity**
- **Low flux, high abundance source populations** are generating most of the astrophysical emission
- **Stacking multiple sources** can be a powerful method to detect a source population even if individual sources are weak, **deep-stacking** is what we call stacking using complete & deep catalogs
- **What are the limits / benefits of stacking sources?**
- **How to stack sources optimally?**



From point source to stacking analysis

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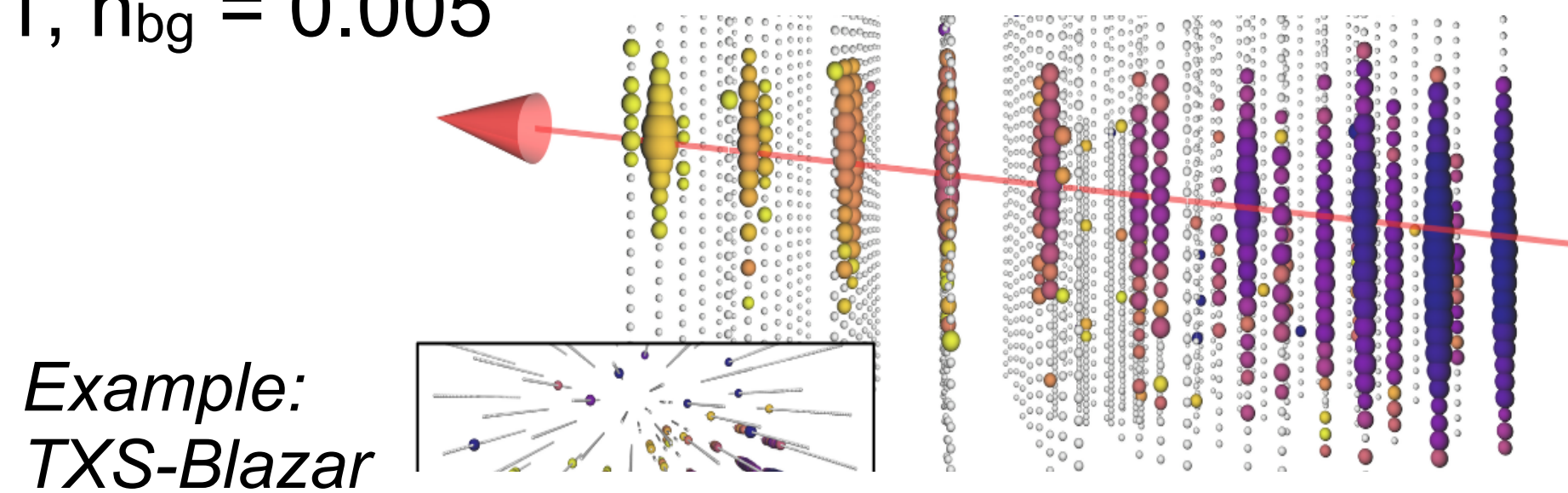


From point source to stacking analysis

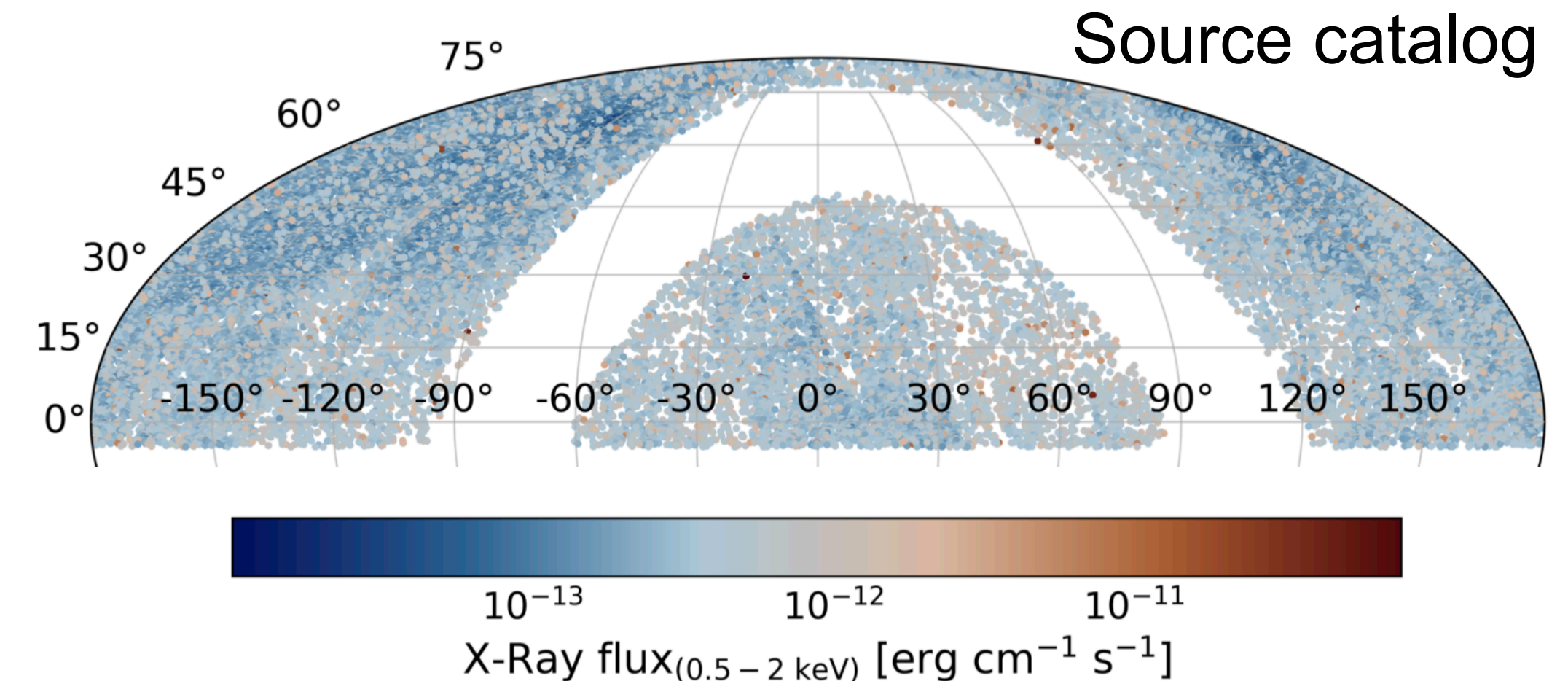
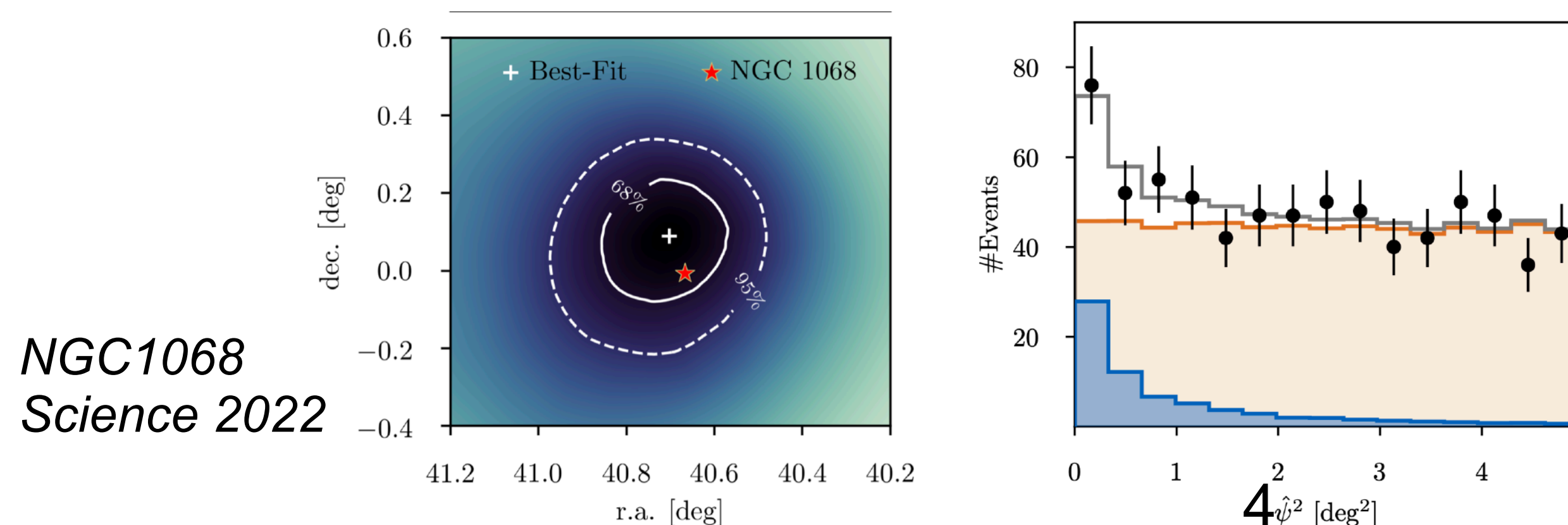
Which source populations are responsible for the astrophysical neutrino flux ?

We consider **two idealized scenarios**, each with flux **normalized to 3-sigma for the nearest source**

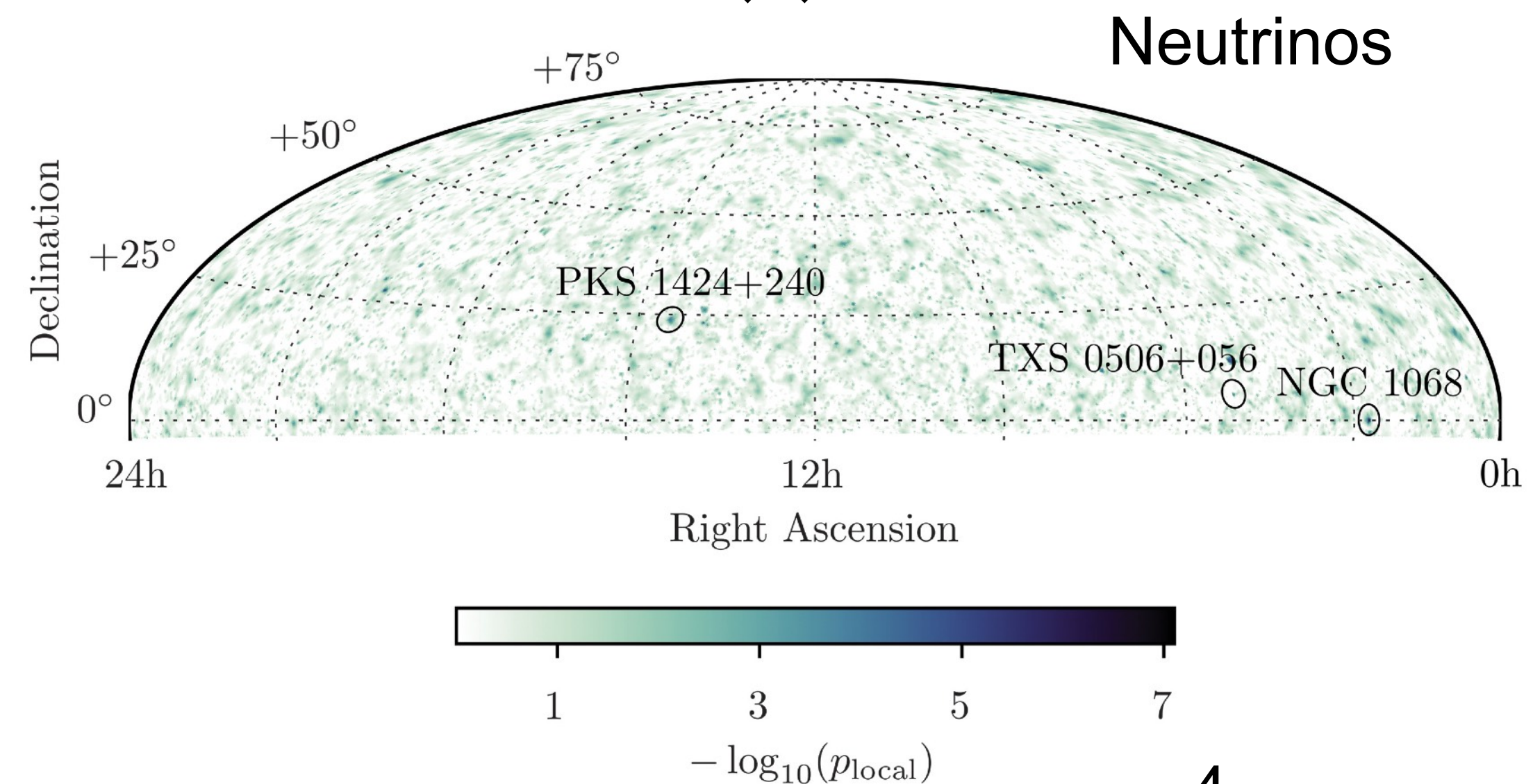
- Low background (e.g. based on alerts coincidence):
 $n_{s,closest} = 1, n_{bg} = 0.005$



- High background (e.g. based on all neutrinos):
 $n_{s,closest} = 30, n_{bg} = 100$



×



From point sources to deep-stacking analyses

Conclusions of the talk, up-front

- Deep-stacking provides gain of up to factor 3-5 in sensitivity
- Stacking of alert-like / low-background neutrinos works best
- High-background stacking works poorly due to the nature of correlation and source luminosity variance
- Potential to measure the redshift evolution of source density and luminosity, resolve the diffuse flux into populations, and link neutrino sources to history of CR production
- Complete and deep catalogs of prospective sources required (up to the source confusion limit)
- Bayesian analyses best suited for implication

A simple analytic model based on count statistics

arXiv:2501.10213

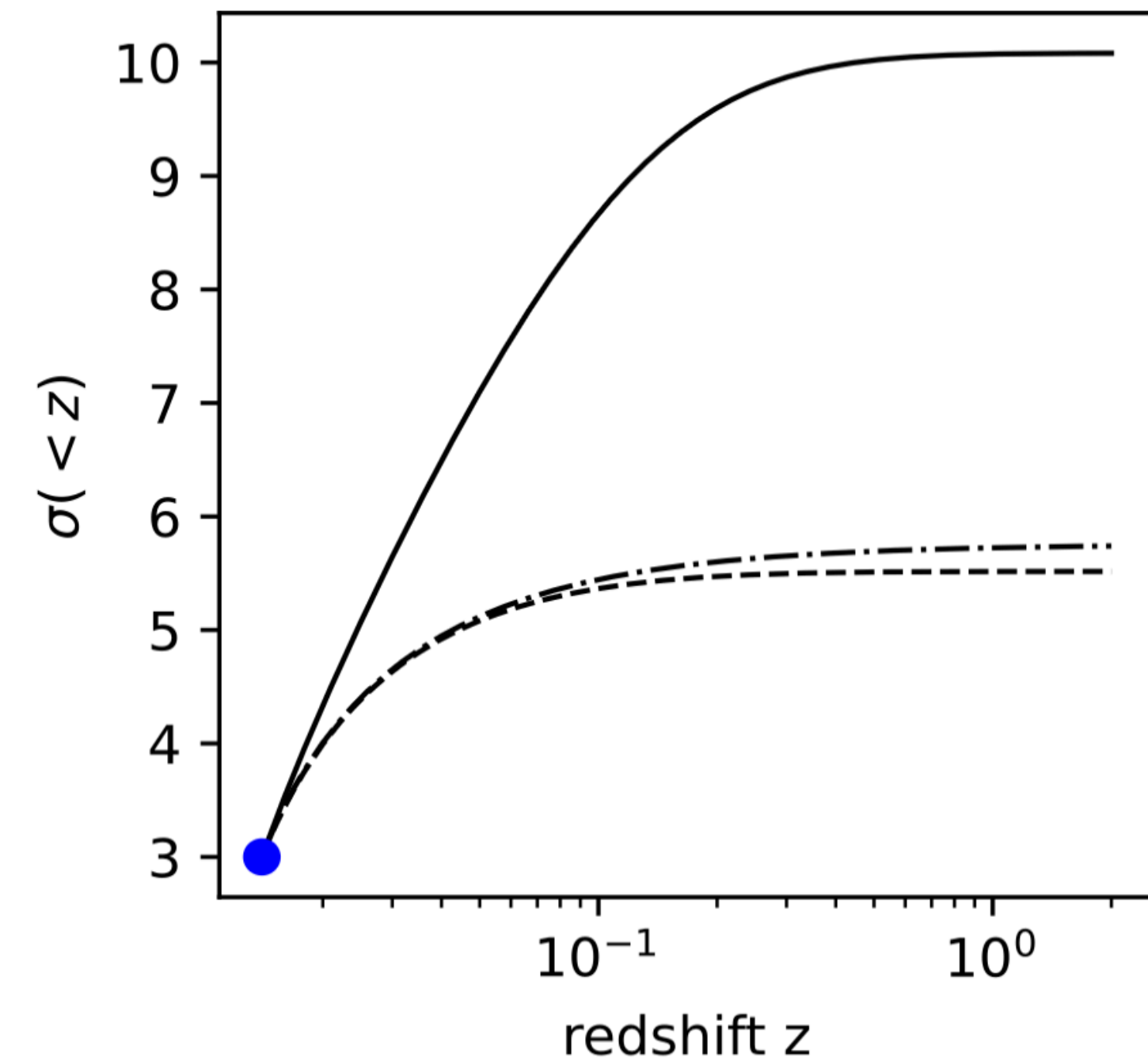
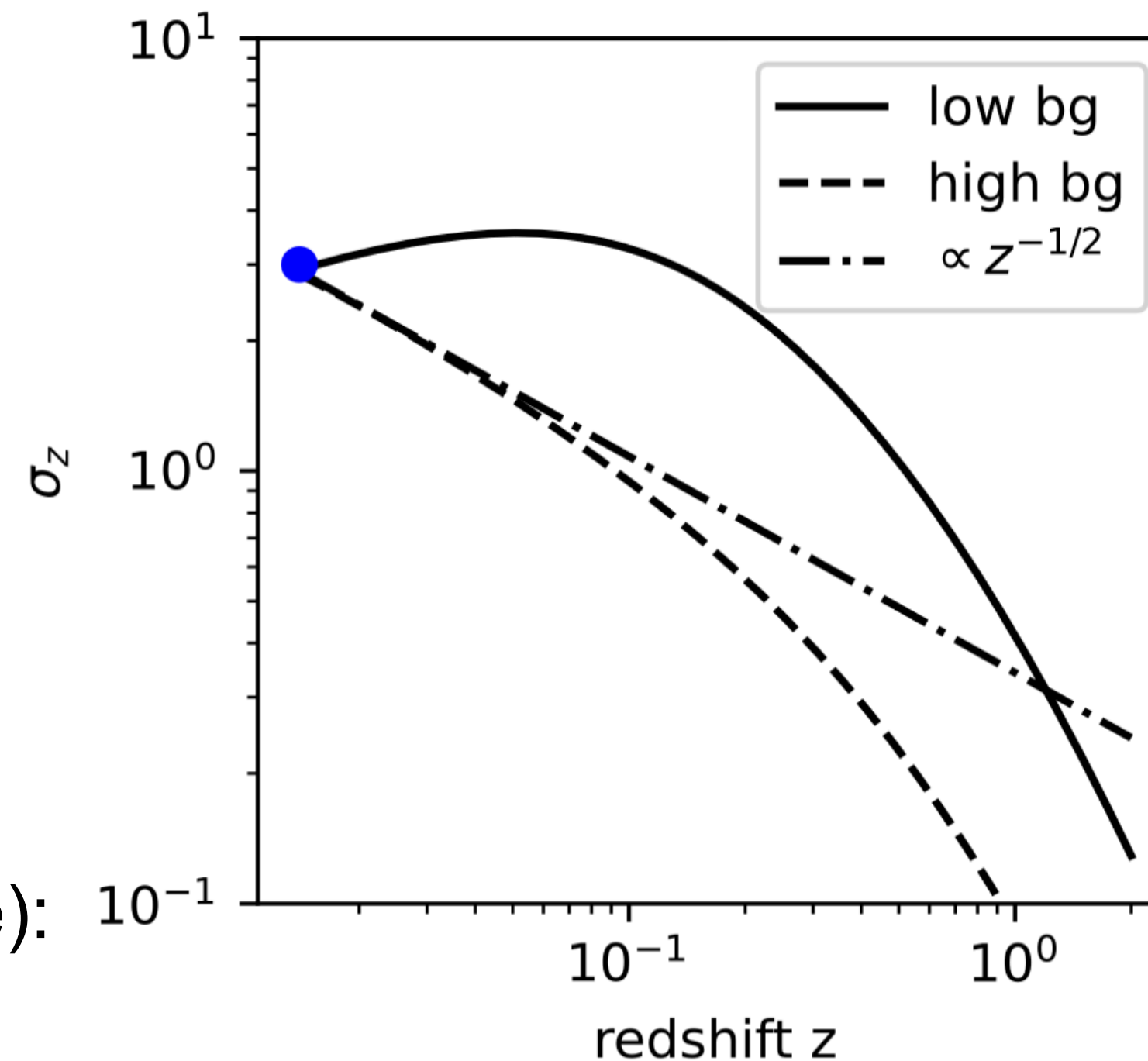
- A stacking analysis with an **idealized counting experiment**
- Sources in the population are **standard candles** ($L_v = \text{const.}$, local density ρ_0)
- Sources can have **redshift evolution of density and luminosity**
- **Brightest/closest source** detected at 3σ
- **Background** per source $n_{\text{bg}} = \text{const.}$
- **Significance** evaluated using ‘Asimov’ sample statistics (needed for low-bg case):

$$\sigma_j = \sqrt{-2 \ln \left(\frac{L(n_s = 0, \hat{n}_b)}{L(\hat{n}_s, \hat{n}_b)} \right)}$$

$$= \sqrt{2 \cdot [(\hat{n}_s + \hat{n}_b) \ln(1 + \hat{n}_s/\hat{n}_b) - \hat{n}_s]}$$

$$\sigma_z := \left[z \frac{d\sigma_{\text{tot}}^2}{dz} \right]^{1/2}$$

$$\sigma(< z) := \int_0^z \frac{d\sigma_{\text{tot}}^2}{dz'} dz'$$



Low background case profits strongly from stacking a large number of sources (here up to $z \sim 0.3$, for local density $\rho_0 = 10^3 \text{ Gpc}^{-1}$ and no redshift evol)

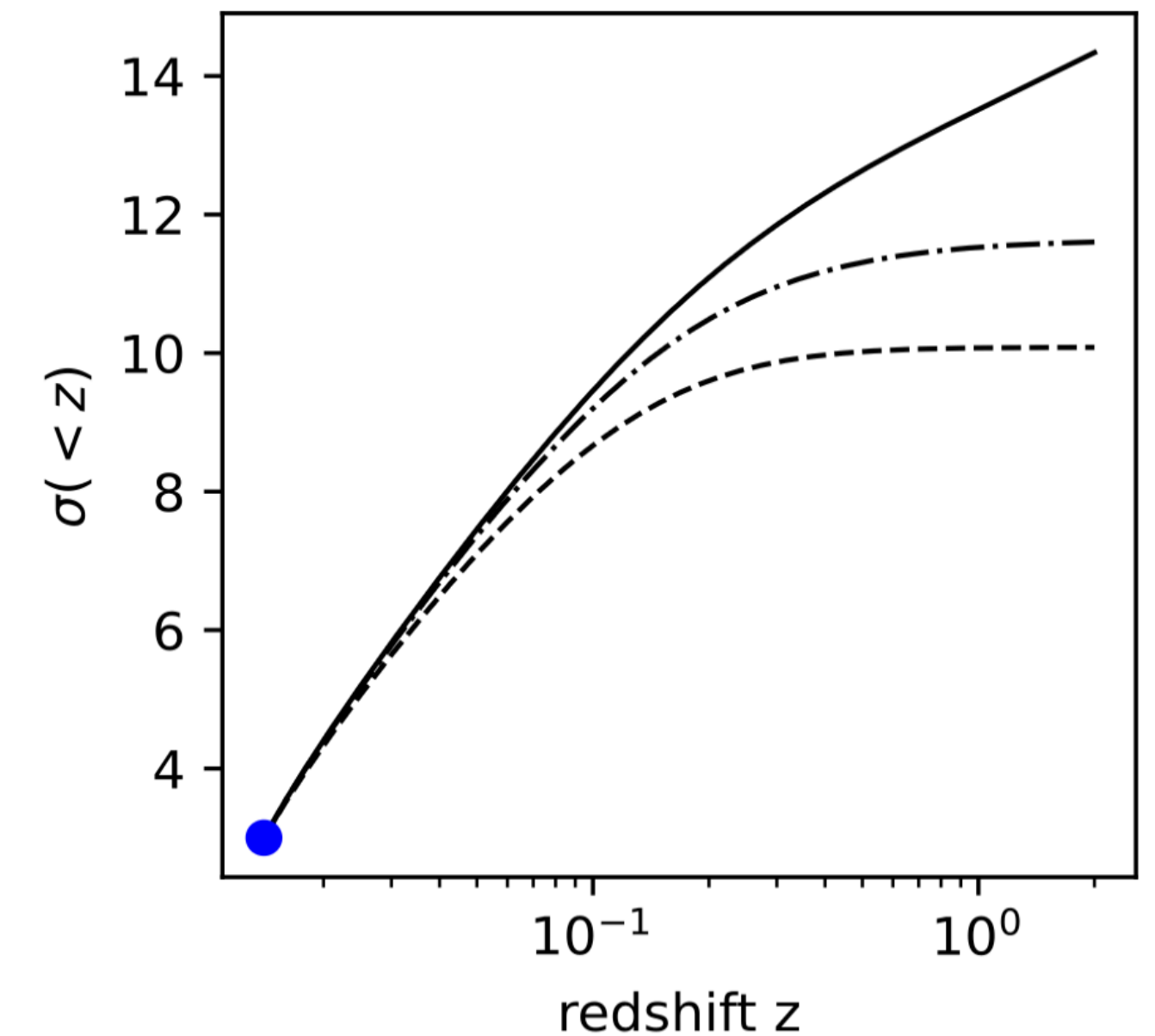
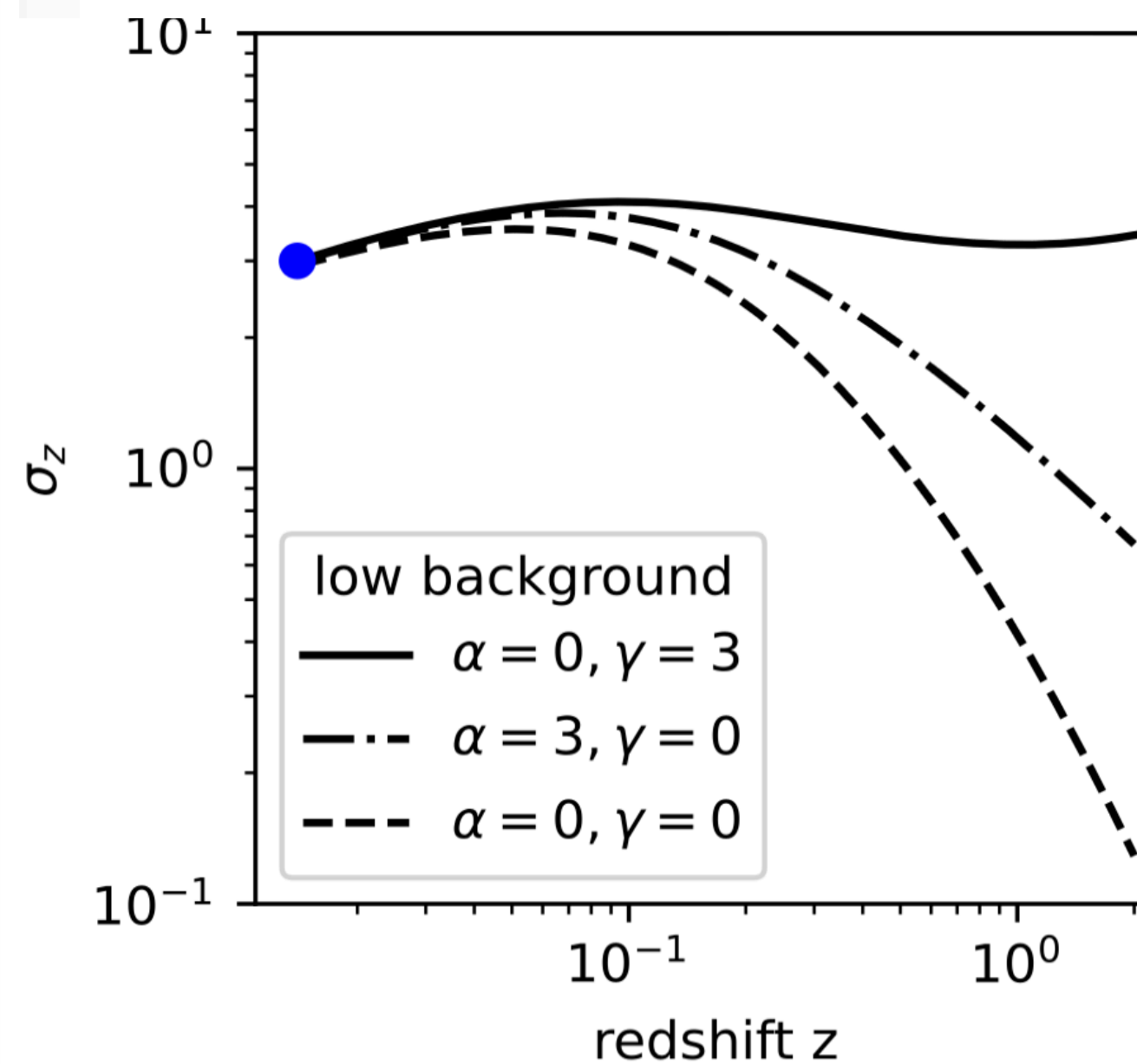
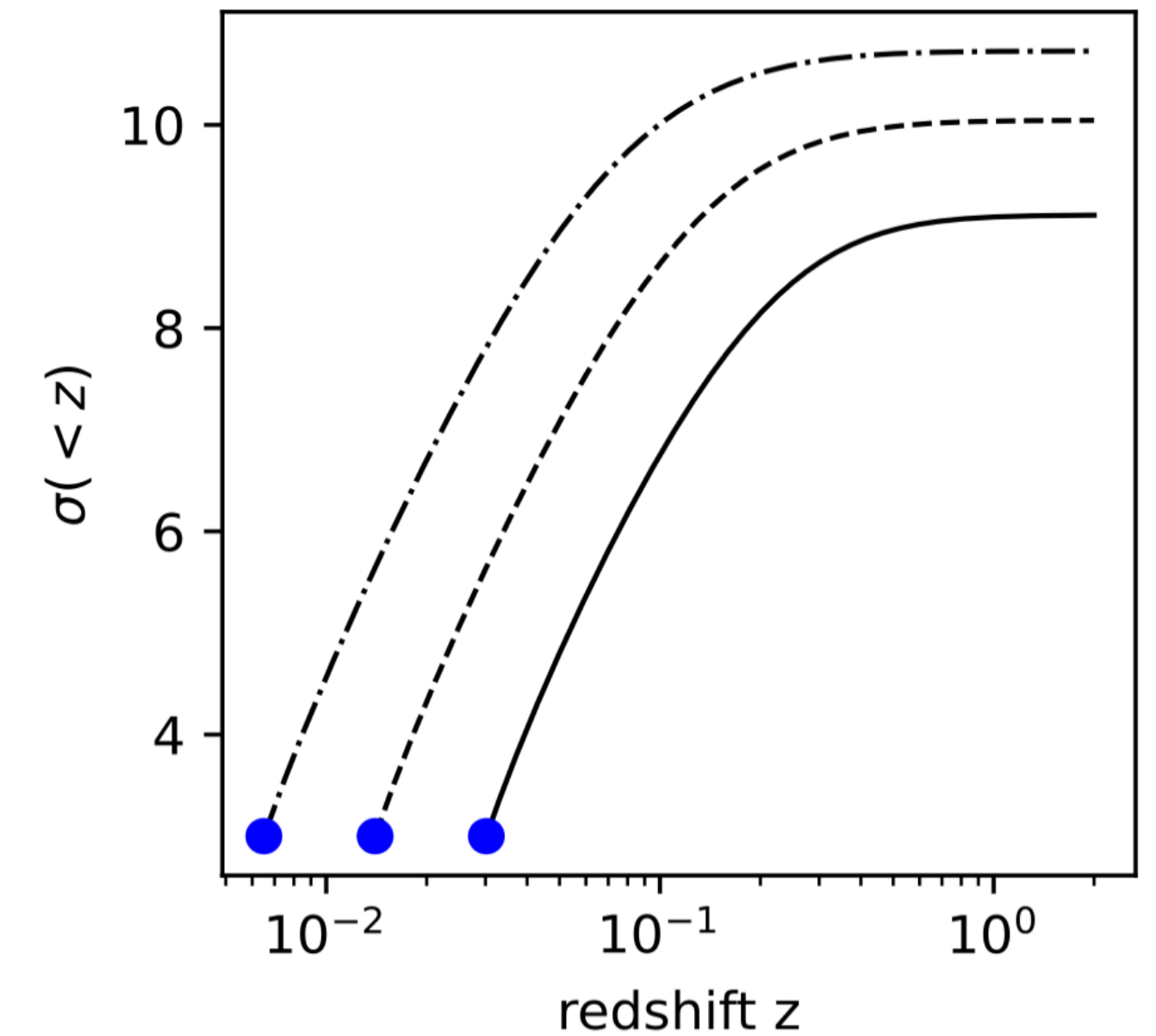
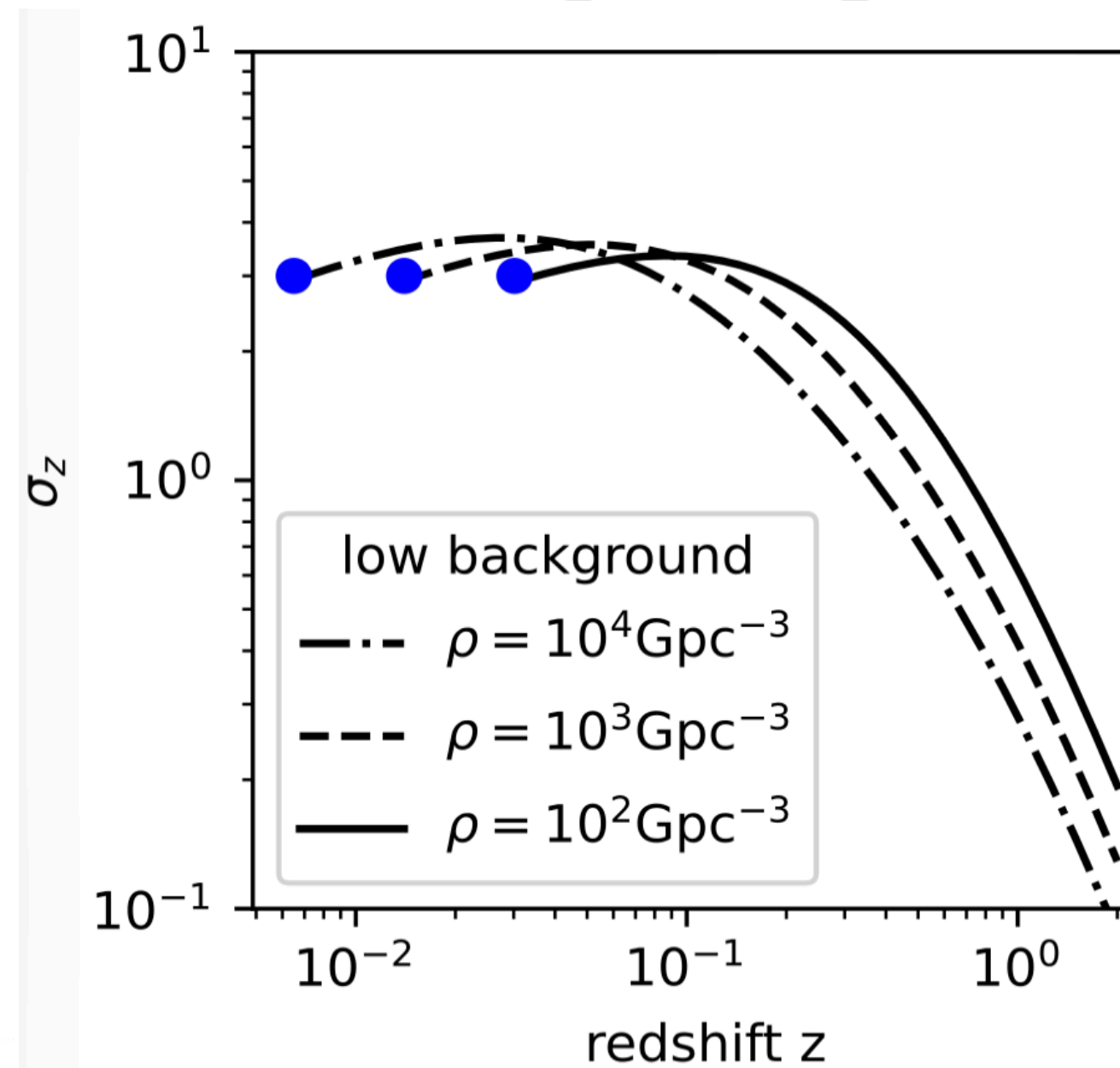
A simple analytic model

Source density and evolution effects

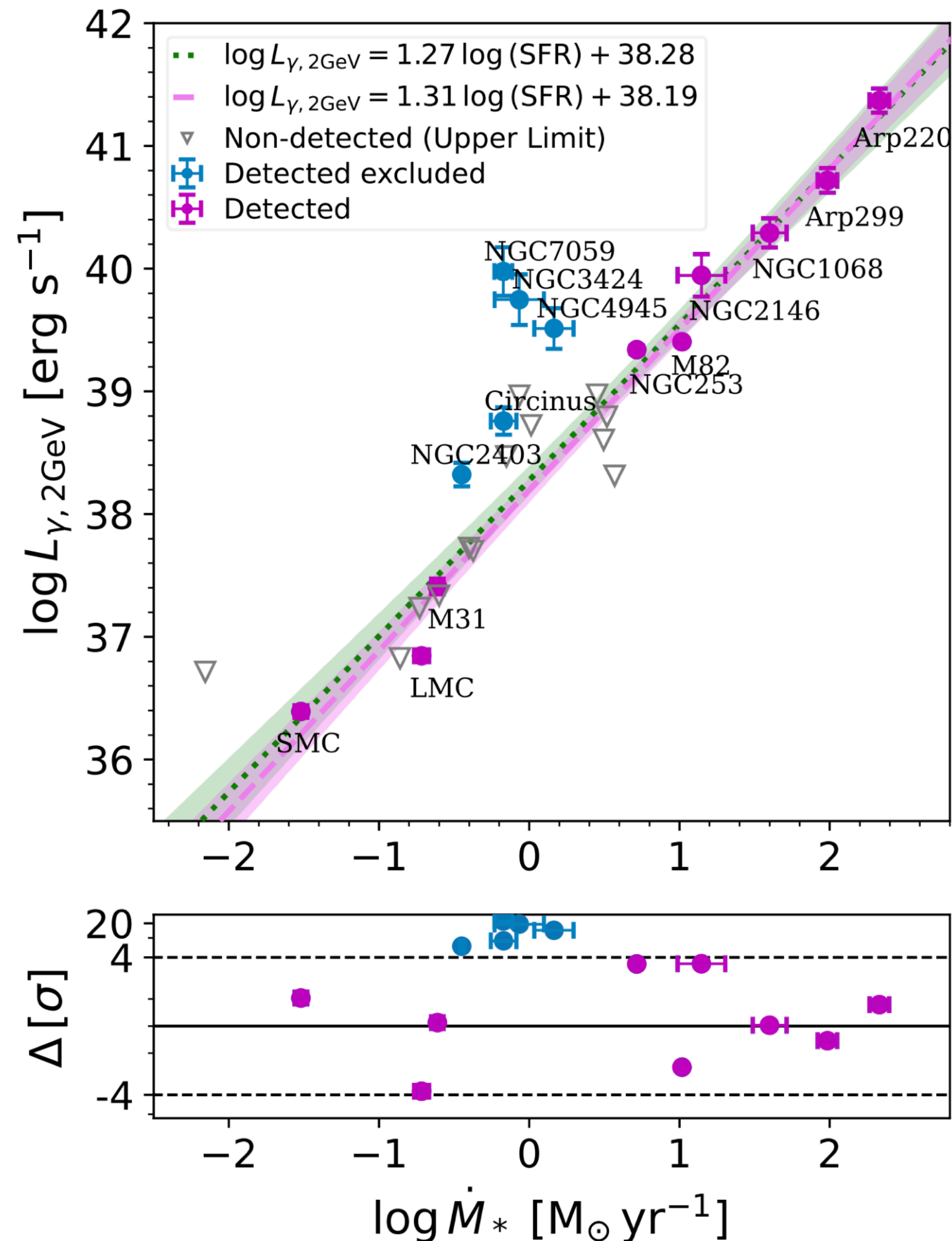
- Source density and evolution have a significant impact on the optimal stacking 'depth'
- Density and luminosity evolution scenarios shown in lower panels
 - $L = L_0 \times (1+z)^\gamma$
 - $\rho = \rho_0 \times (1+z)^\alpha$
- Far less potential gain and differences in high-background case
- Typical low background searches: short transients, hard / high-peaked source spectra

$$\sigma_z := \left[z \frac{d\sigma_{\text{tot}}^2}{dz} \right]^{1/2}$$

$$\sigma(< z) := \int_0^z \frac{d\sigma_{\text{tot}}^2}{dz'} dz'$$



Impact of source luminosity variance in typical stacking



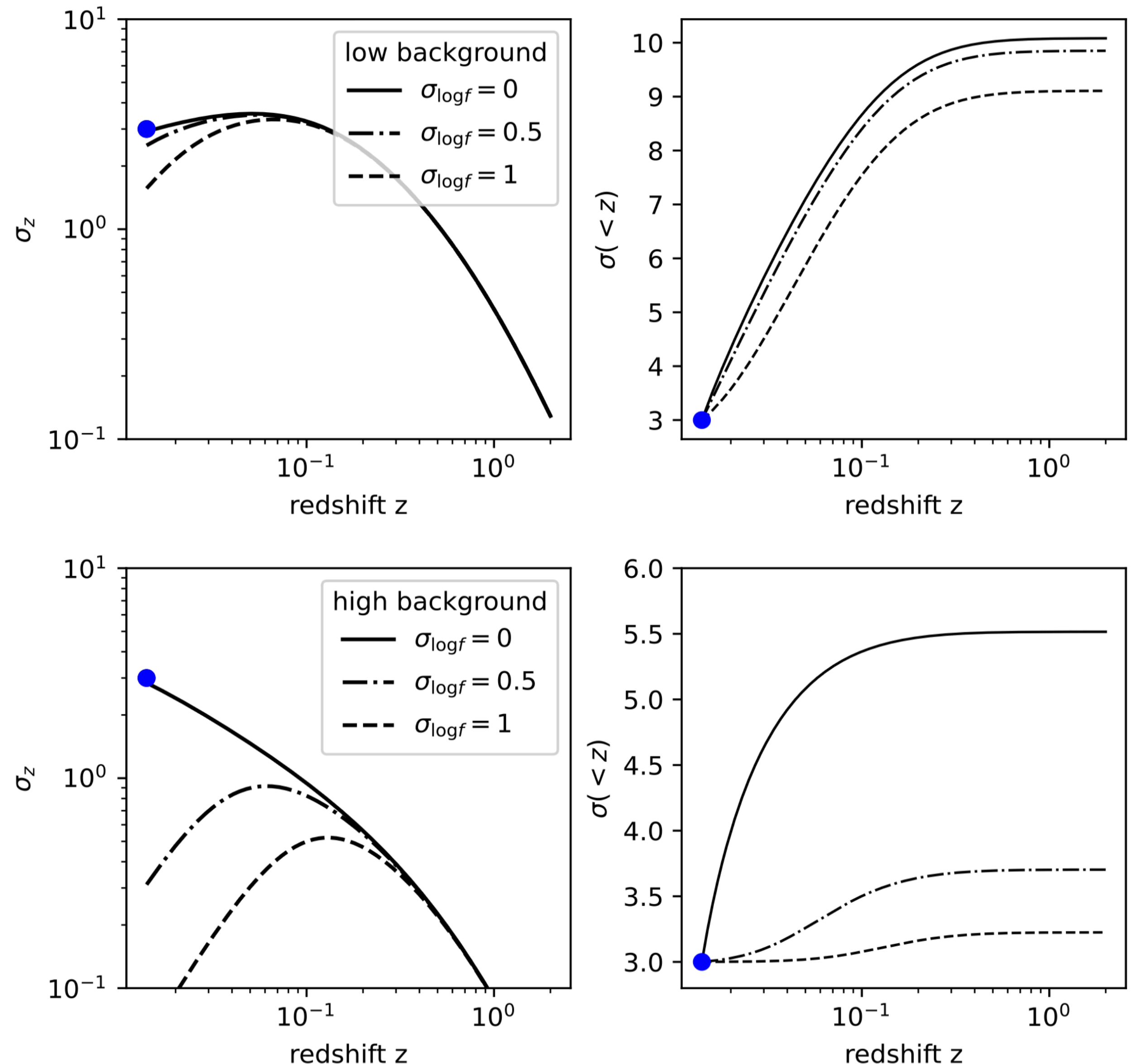
Example of a “very good” correlation: Gamma-ray emission of galaxies vs star-formation rate

- **Typical stacking searches** start with a catalog of sources from a candidate population, as well as weight/flux model
- **Weight/flux model** is chosen that predicts the neutrino luminosity of these sources, e.g., $L_v = \xi \times L_\gamma$.
- **A single scaling parameter** ξ is fitted, together with spectral parameters that are assumed universal over the population (e.g., spectral index γ)
- **Luminosities scatter substantially** around the values predicted by the correlation function (factors ranging from 2 to >10)
- Would introduce N_{src} additional parameters $L_{v,i} = \xi \times \xi_i \times L_\gamma$ (ξ_i with range priors according to assumed quality of correlation)
- **What happens to the discovery potential if the neutrino luminosity model prediction is not exact?**
And Is there a better method for this more realistic case?

Impact of source variance / neutrino luminosity model

- **Source variance** (scatter between actual and modeled luminosity distribution) parametrized as $\sigma_{\log f}$
- $\sigma_{\log f} = 1$: factor 10 scatter between observed and expected luminosity
- Source variance only **important if larger than Poisson variance** ($n_s = 0.6$ for $\sigma_{\log f} = 1$)
- **Severely limits benefits** of stacking searches in high-background case

Many previous and current stacking analyses are high-background! Source variance needs to be addressed by stacking method!



A better approach: Bayesian deep stacking

arXiv:2502.01452, “Proof of principle” Monte Carlo simulation

- **Standard unbinned likelihood for point source searches** in neutrino telescopes
- Gaussian PSF, fixed spectral index, simple effective area approximation, partial sky field-of-view
- Source populations with or without redshift evolution

Three methods:

Likelihood / Sample normalization

- **“Classic” stacking analysis** with a single luminosity parameter for the entire source sample (e.g., $L_v = \xi \times L_y$).
- Parameter estimation by likelihood maximization.

Likelihood / source normalization

- **“Classic” stacking analysis plus nuisance parameters** for source variance (e.g., $L_{v,i} = \xi \times \xi_i \times L_y$).
- Parameter estimation by likelihood maximization, including log-normal penalties to constrain values of ξ_i .

Bayesian deep stacking

- **Calculate posterior** from likelihood marginalizing over nuisance parameters.
- **Compare odds ratio** between background only model and model with source contribution.

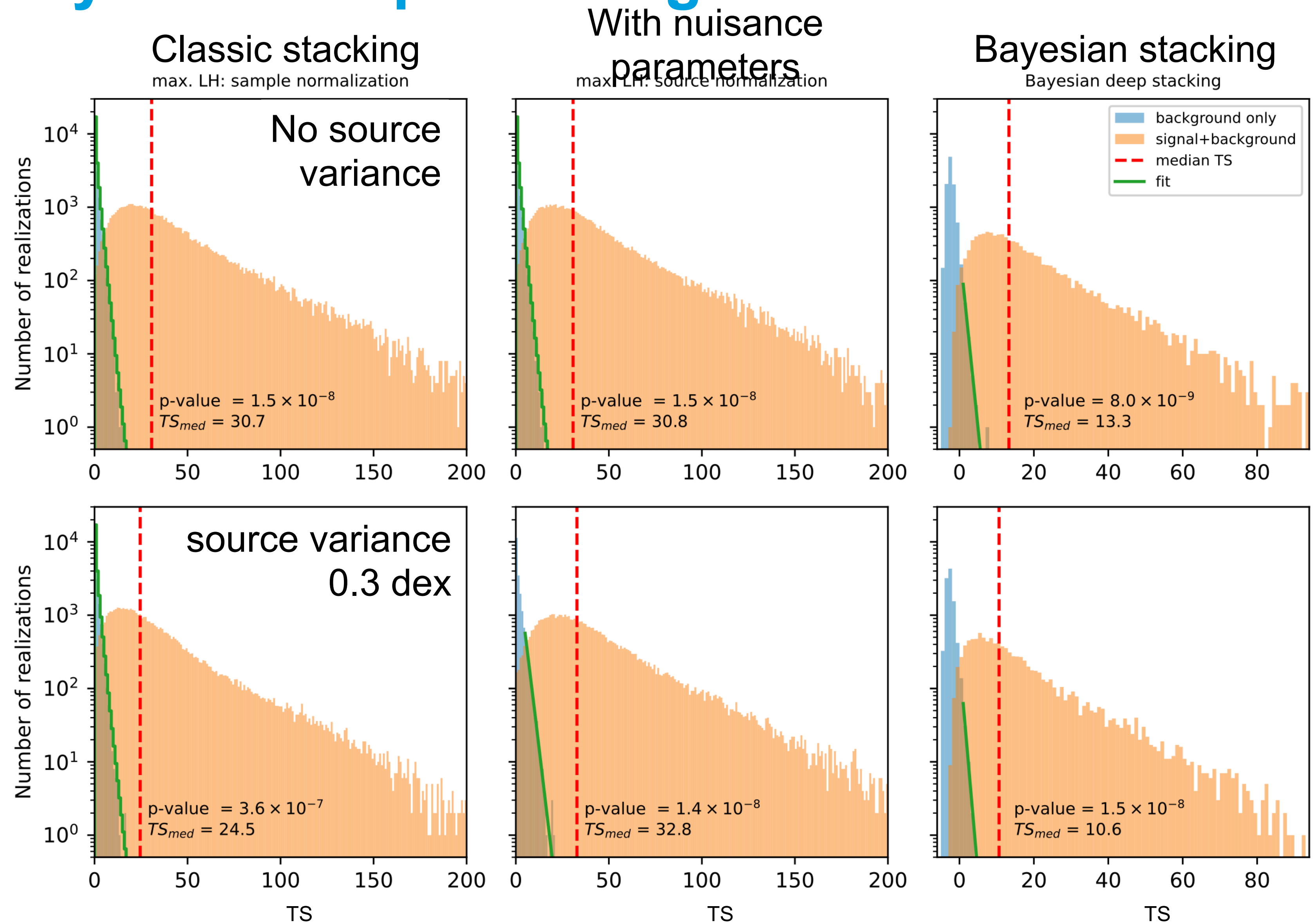
A better approach: Bayesian deep stacking

Results

- Odds ratio and frequentist significance metrics not directly comparable
- Possible, if odds ratio is used as a test statistic (TS)
- p-values are derived by comparing TS distributions for background only / signal simulations

Panels:

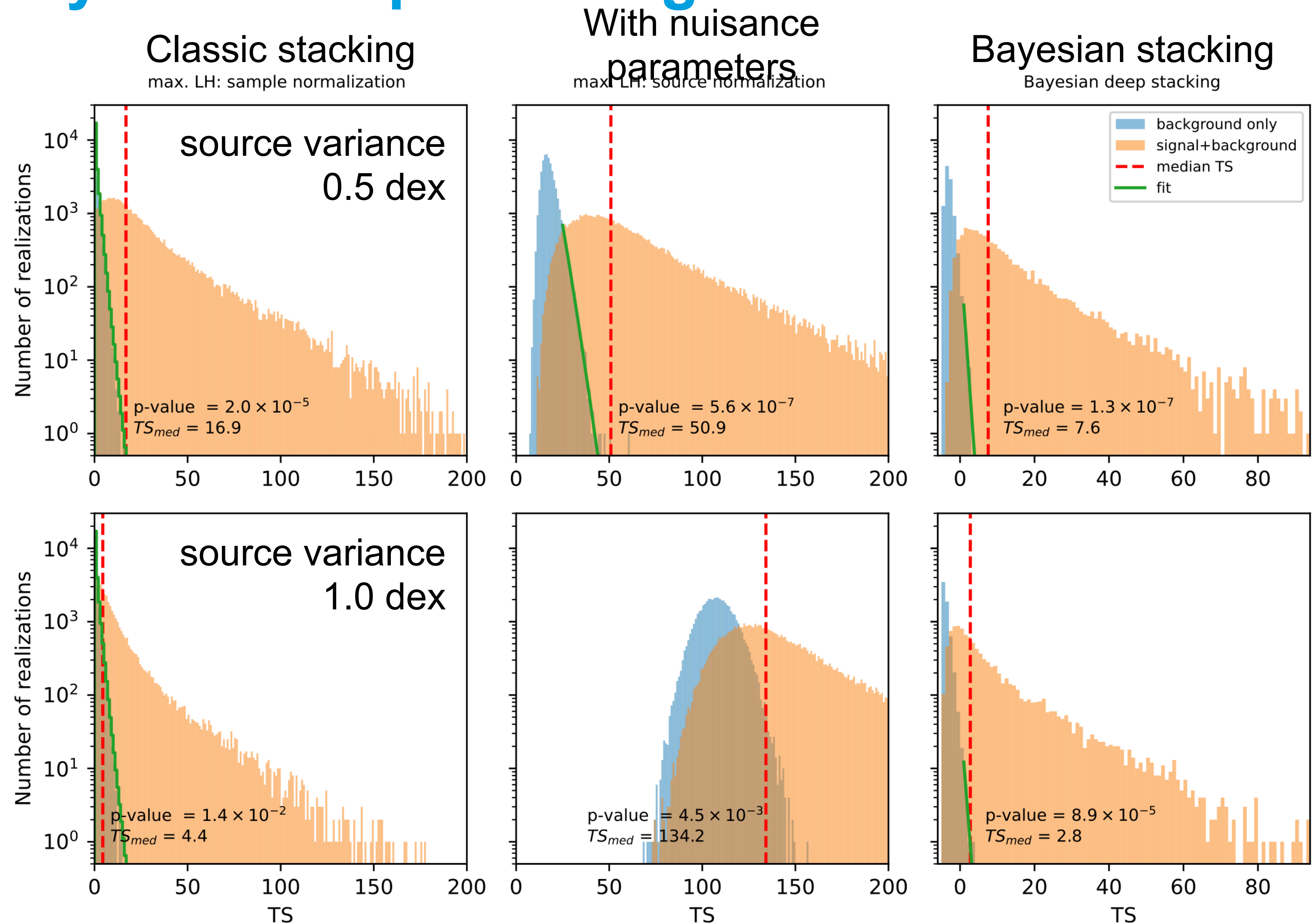
- Stacking of ~120 sources in field-of-view.
- Brightest source not individually detectable
- Spectral index $\gamma = -2.5$



A better approach: Bayesian deep stacking

Results

- Classic stacking shows severe deterioration of discovery potential at larger source variances
- Maximum likelihood analysis with nuisance parameters increasingly suffers from added degrees of freedom
- Using the odds ratio as test statistic delivers lowest p-value for high source variance setups
- Bayesian stacking more performant (lower p-values)



Outlook

Resolving the diffuse flux allows us to check for completeness and study relation to cosmic rays

This is what we measure

$$I_\nu(E_\nu) = \frac{c}{4\pi} \int_0^{z_{\max}} \frac{1}{E(z)} \frac{d\dot{N}_\nu}{dE_\nu} dz$$

↑
Diffuse flux

Known from cosmology

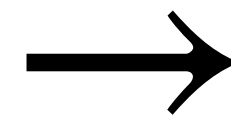
Neutrino emission
across redshift

Outlook

Resolving the diffuse flux allows us to check for completeness and study relation to cosmic rays

$$I_\nu(E_\nu) = \frac{c}{4\pi} \int_0^{z_{\max}} \frac{1}{E(z)} \frac{d\dot{N}_\nu}{dE_\nu} dz \approx \underset{\substack{\uparrow \\ \text{Neutrino conversion /} \\ \text{production efficiency}}}{\epsilon} \frac{c}{4\pi} \int_{t(z_{\max})}^{t_0} \frac{d\dot{N}_{\text{CR}}}{dE_{\text{CR}}} dt = \epsilon I_{\text{CR}}(E_{\text{CR}})$$

Neutrino emission
across redshift



Cosmic ray flux
on Earth today

Conclusion

We could be sitting on 15 sigma strong signal

- Deep-stacking provides gain of up to factor 3-5 in sensitivity
- Stacking of alert-like / low-background neutrinos works best
- High-background stacking works poorly due to the nature of correlation and source luminosity variance
- Potential to measure the redshift evolution of source density and luminosity, resolve the diffuse flux into populations, and link neutrino sources to history of CR production
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