Astrophysical interpretation of small-scale neutrino angular correlation searches with IceCube

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Abstract

IceCube, a cubic-kilometer sized neutrino detector at the Geographic South Pole, has recently discovered a diffuse all-flavor flux of astrophysical neutrinos [1]. However, the corresponding astrophysical sources have not yet been identified in current IceCube analyses. We present a method to interpret the results of an angular correlation analysis in IceCube searching for spatial clustering of muon neutrino events [2] in terms of astrophysical models (given by an arbitrary source count distribution). We exemplarily show the resulting limits on the parameters of a class of source count distributions motivated by Fermi-LAT observations of resolved blazars [3].

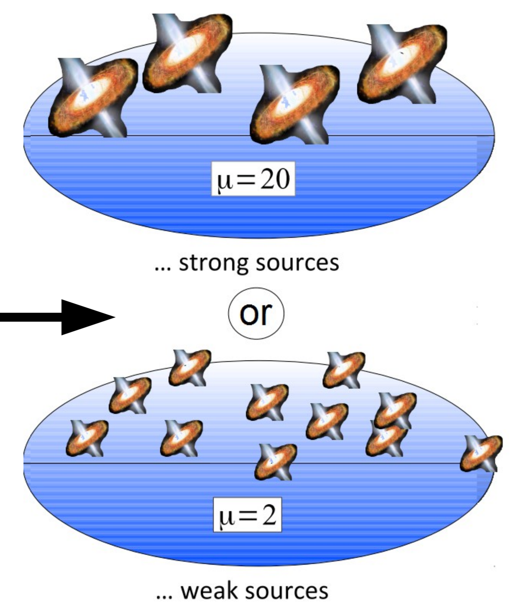
Input

1) IceCube angular correlation analysis [2]

The analysis tests *signal hypotheses*, characterized by *fixed* parameters:

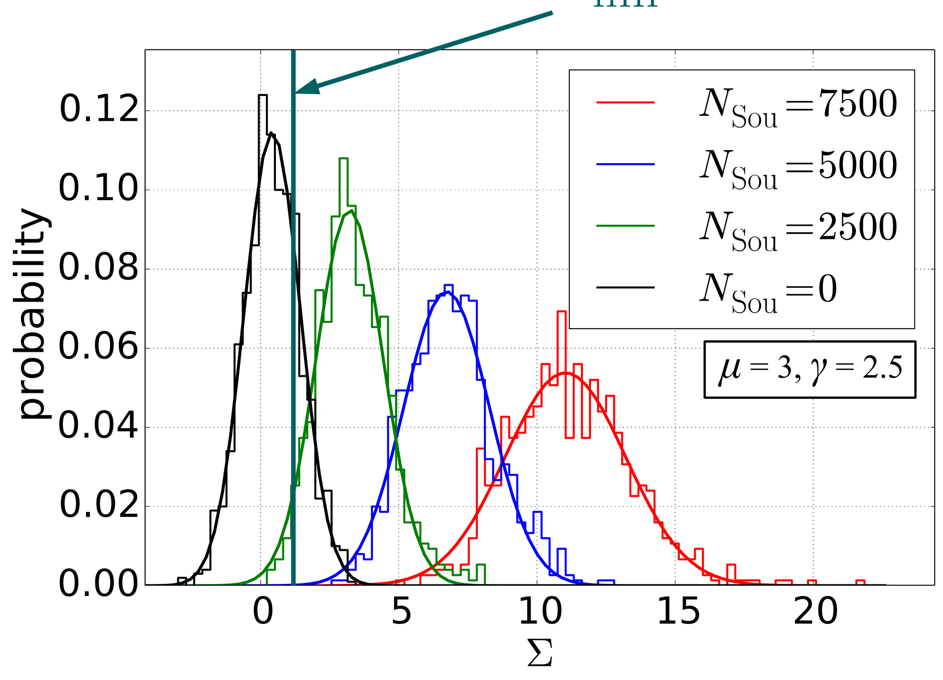
- Number of sources N_{Sou}
- Mean number of neutrinos per source μ (source strength)
- Astrophysical spectral index γ

Based on angular correlations of neutrino directions, a test statistic, called 'signalness' Σ, is calculated



→ Simulations [4]: $\Sigma \propto N_{Sou} \cdot \mu^2$

Limit from experimental data: $\Sigma_{lim} = 1.38$



2) Observed astrophysical neutrino flux by IceCube [1]

Energy spectra E^{γ} with $\gamma = 2.0$ and $\gamma = 2.5$ are tested. Used best-fit fluxes:

$$\frac{d\Phi}{dE} = \frac{9.9 \cdot 10^{-19}}{\mathrm{GeV\,cm^2\,sr\,s}} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.0} \qquad \frac{d\Phi}{dE} = \frac{2.0 \cdot 10^{-18}}{\mathrm{GeV\,cm^2\,sr\,s}} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.5}$$

3) Fermi-LAT high-latitude source count distribution [3]

Fermi-LAT measured the source count distribution of *photons* from resolved blazars in dependence of the particle flux S:

$$\frac{dN_{Sou}}{dS} = \begin{cases} AS^{-\beta_1}, & S \geq S_b \\ AS_b^{-\beta_1+\beta_2} S^{-\beta_2}, & S < S_b \end{cases}$$

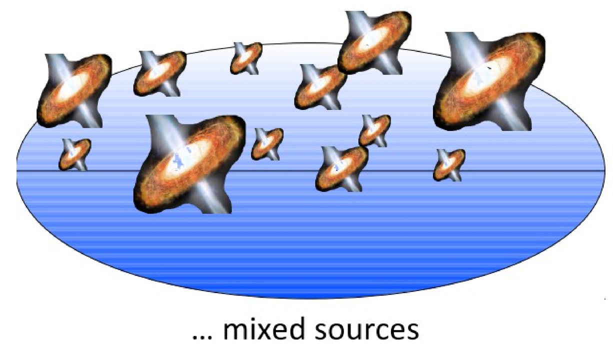
Best-fit values used:

$\beta_1 = 2.49 \pm 0.12$ $\quad A = 16.46 \cdot 10^{-14}\,\mathrm{cm^2\,s\,deg^{-2}}$

$\beta_2 = 1.58 \pm 0.08$ $\quad S_b = 6.60 \cdot 10^{-8}\,\mathrm{cm^{-2}\,s^{-1}}$

Idea

Realistic source populations: Sources with *varying* source strengths



⇒ use source count distribution $\frac{dN_{Sou}}{d\mu}$

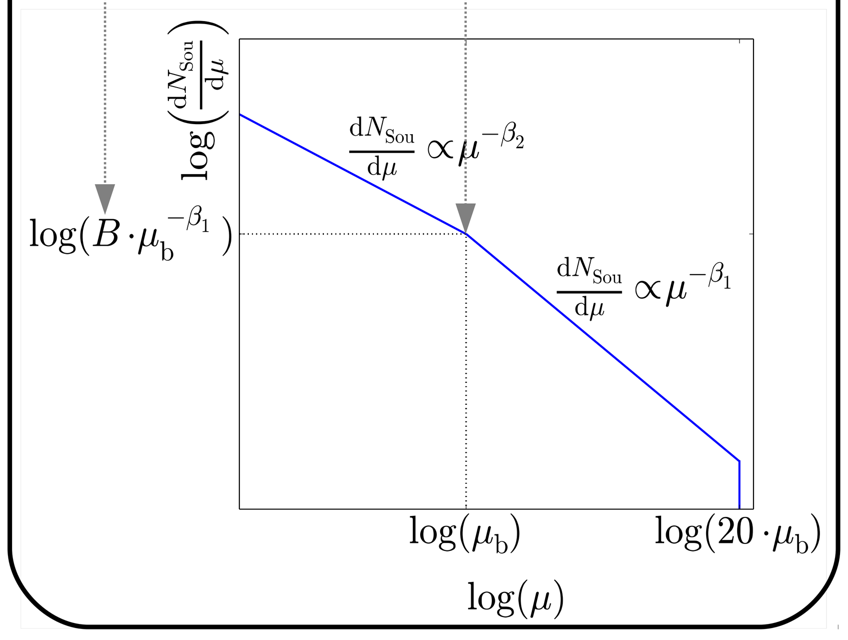
Source count distribution adopted from Fermi-LAT

We use a *modified parametrization* for *neutrinos* with only dimensionless parameters:

$$\frac{dN_{Sou}}{d\mu} = \begin{cases} 0, & \mu \geq 20\mu_b \\ B\mu^{-\beta_1}, & 20\mu_b > \mu \geq \mu_b \\ B\mu_b^{-\beta_1+\beta_2}\mu^{-\beta_2}, & \mu < \mu_b \end{cases}$$

B: scale factor ∝ normalization

μ_b: source strength at the breaking point



Limit conversion

$$\Sigma = \int_0^\infty d\mu \frac{d\Sigma}{d\mu}(\mu) = \int_0^\infty d\mu \frac{dN_{Sou}}{d\mu}(\mu) \frac{d\Sigma}{dN_{Sou}}(\mu)$$

Solve for parameters of the source count distribution (here: B, μ_b)

→ obtain limits on these parameters

Observed astrophysical neutrino flux by IceCube

#(ν) from astrophysical neutrino flux → $n(\mathrm{astroph.}) \stackrel{!}{=} n(\mathrm{scd})$ ← #(ν) from source count distribution

$$n(\mathrm{astroph.}) = \sum_{IC} T^{IC} \int_0^\infty dE\, A_{eff}^{IC} \frac{d\Phi}{dE}$$

IC: IceCube configurations IC40, IC59, IC79

$$n(\mathrm{scd}) = \int_0^\infty d\mu \frac{dN_{Sou}(B, \mu_b)}{d\mu} \cdot \mu$$

Solve for $B(\mu_b)$ → obtain the colored lines

Fermi-LAT best-fit variation

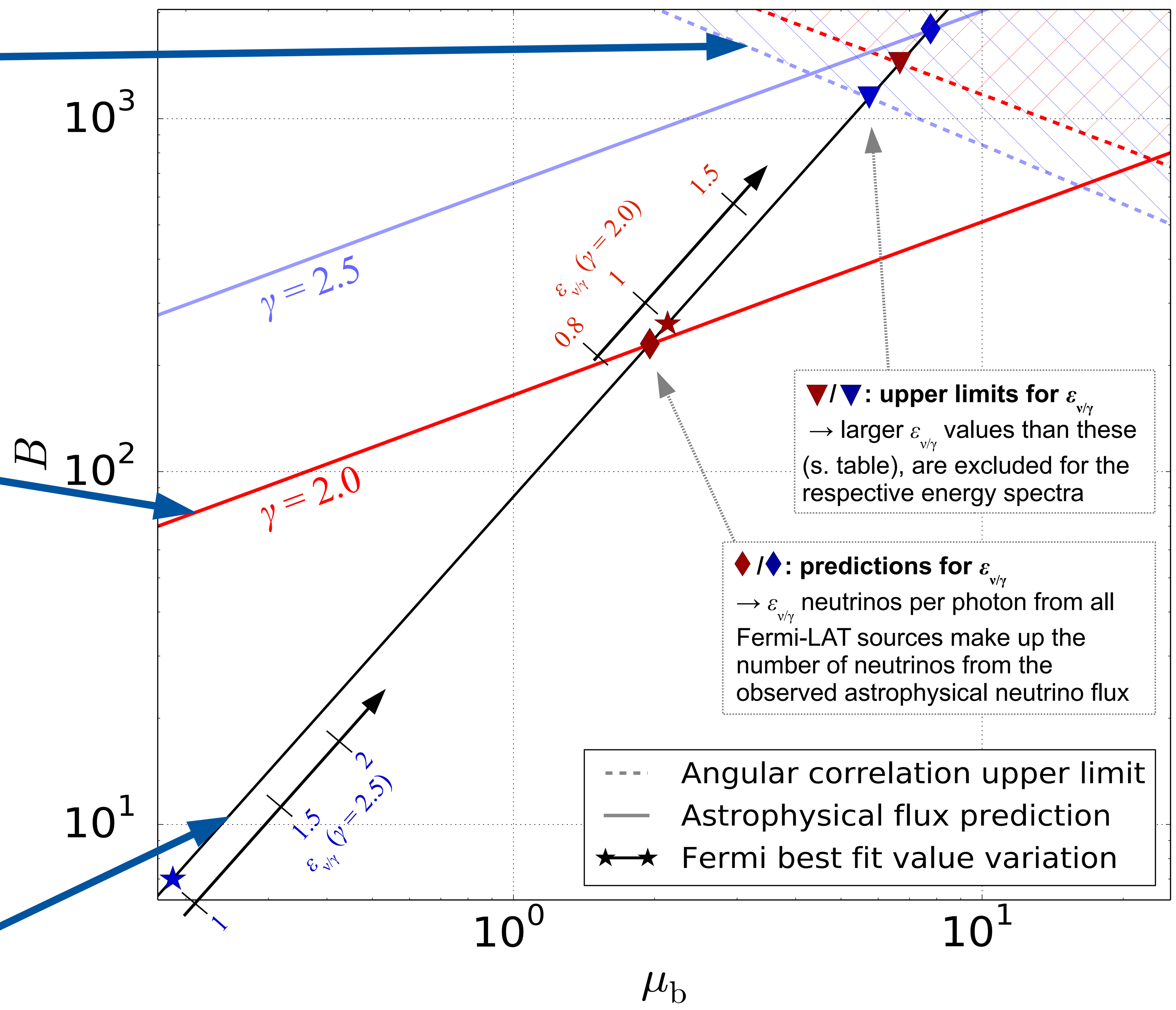
Assumption:

Each source emits $\varepsilon_{\nu/\gamma}$ times as many neutrinos as photons in each energy range

★/★ ($\varepsilon_{\nu/\gamma}$=1): Fermi-LAT best fit values (B, μ_b) (extrapolated to IceCube's energy range)

Black line: solution for variations of $\varepsilon_{\nu/\gamma}$:

$$B = \varepsilon_{\nu/\gamma}^{\beta_1 - 1} \cdot B_{Fermi} \qquad \mu_b = \varepsilon_{\nu/\gamma} \cdot \mu_{b,Fermi}$$



Conclusions

If sources measured by Fermi-LAT make up *all* neutrino sources with *universal* ν-γ ratio, the corresponding limits and predictions are:

γ	$\varepsilon_{\nu/\gamma}$ upper limit	$\varepsilon_{\nu/\gamma}$ flux prediction
2.0	3.13	0.92
2.5	30.6	41.4

The Fermi-LAT sources are *excluded* to be the only origin of the discovered flux for spectral index $\gamma = 2.5$ but *not excluded* for $\gamma = 2.0$

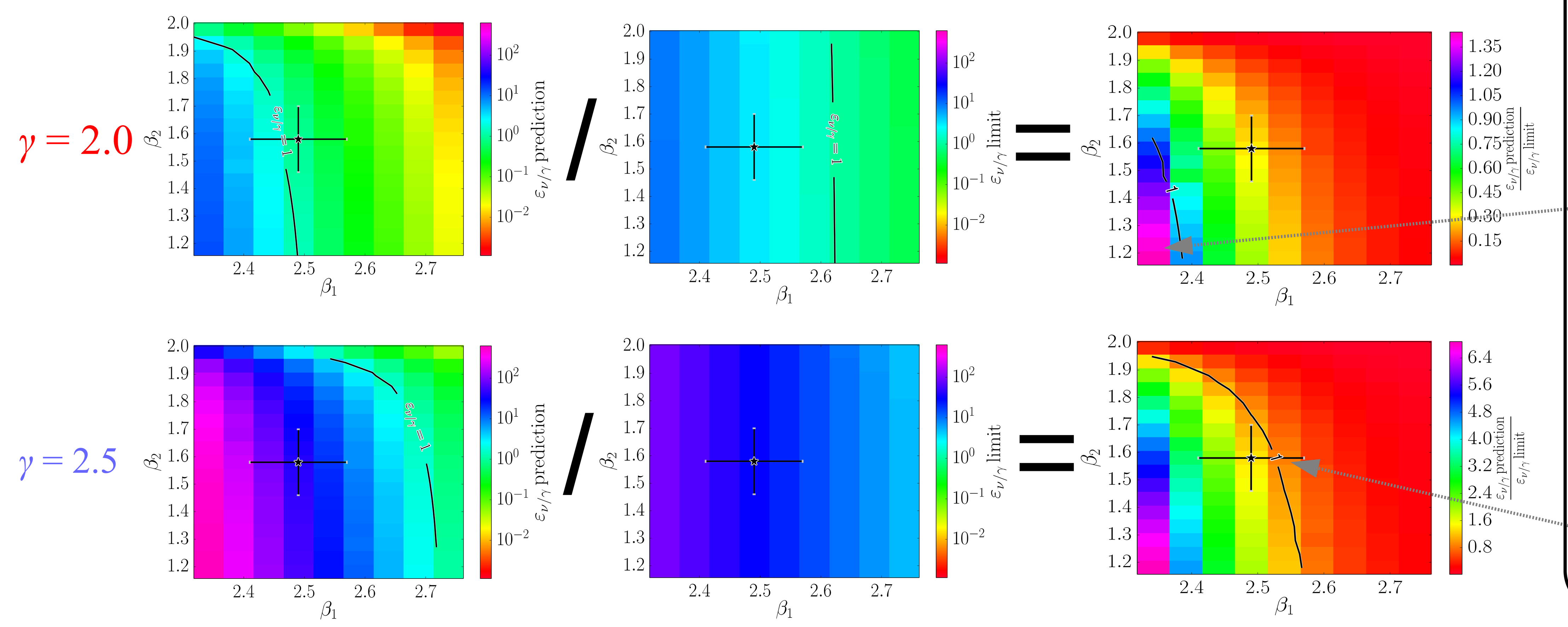
Changing parameter space

Repeat above procedure, varying β_1, β_2

Depending on β_1 and β_2 and the tested energy spectra, figures show:

- 1st column: *prediction* for $\varepsilon_{\nu/\gamma}$ corresponding to the astrophysical neutrino flux
- 2nd column: *limit* on $\varepsilon_{\nu/\gamma}$
- 3rd column: *ratio* between prediction and limit
  - predicted $\varepsilon_{\nu/\gamma}$ excluded to be larger than the $\varepsilon_{\nu/\gamma}$ limit
    ⇒ ratios > 1 are *excluded*

✛: Fermi-LAT best-fit values for β_1, β_2 with uncertainties



Conclusions

$\gamma = 2.0$: For the best-fit values the hypothesis of a universal ν-γ ratio with a source count distribution parametrization from Fermi-LAT is not excluded. The lowest values for β_1 and β_2 are excluded (lower left)

$\gamma = 2.5$: For the best-fit values the hypothesis of a universal ν-γ ratio with a source count distribution parametrization from Fermi-LAT is excluded. However, the uncertainty interval of β_1 reaches into the allowed region

References

[1] Phys. Rev. Lett. 113, 101101 (2014)

[2] Astroparticle Physics 66, 39 (2015)

[3] ApJ 720, 435 (2010)

[4] M. Leuermann, Search for diffuse neutrino point sources using a Mulipole analysis in IceCube, RWTH Aachen, Master Thesis (2014)

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