Abstract

IceCube has provided the first measurements of the extragalactic high energy astrophysical neutrino flux. The sources of these neutrinos remains unknown. I will first discuss the possibility that they are of galactic origin and show that they are dominantly extragalactic. The most luminous events in the universe are Gamma ray bursts (GRBs) which are relativistic jetted outflows resulting from some supernovae (SNe). GRBs are a promising candidate of high energy cosmic rays and neutrinos despite no direct evidence of a correlation between events and known sources. Some GRBs may be electromagnetically choked emitting only neutrinos. To constrain the properties of GRBs, we assume that choked GRBs are a natural continuation of visible GRBs. This allows for constraints on GRB properties and the fraction of SNe that form jets from IceCube's data.

Gamma Ray Bursts, Supernovae, Neutrinos, and IceCube

Peter B. Denton

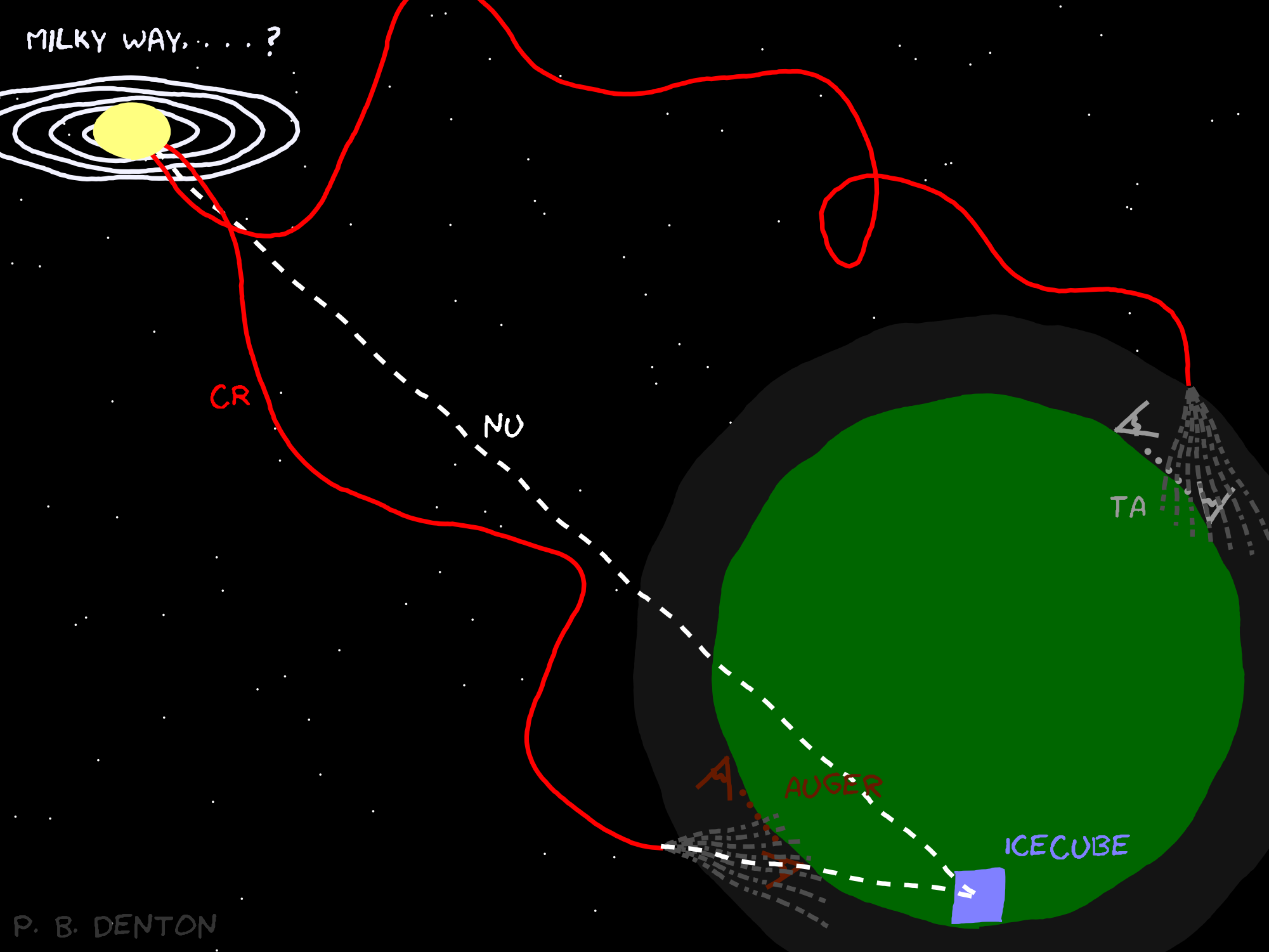
IIHE

April 4, 2018

1703.09721 with Danny Marfatia and Tom Weiler
1711.00470 and 1802.10098 with Irene Tamborra

The Niels Bohr International Academy

VILLUM FONDEN


MILKY WAY. . . . ?
CR
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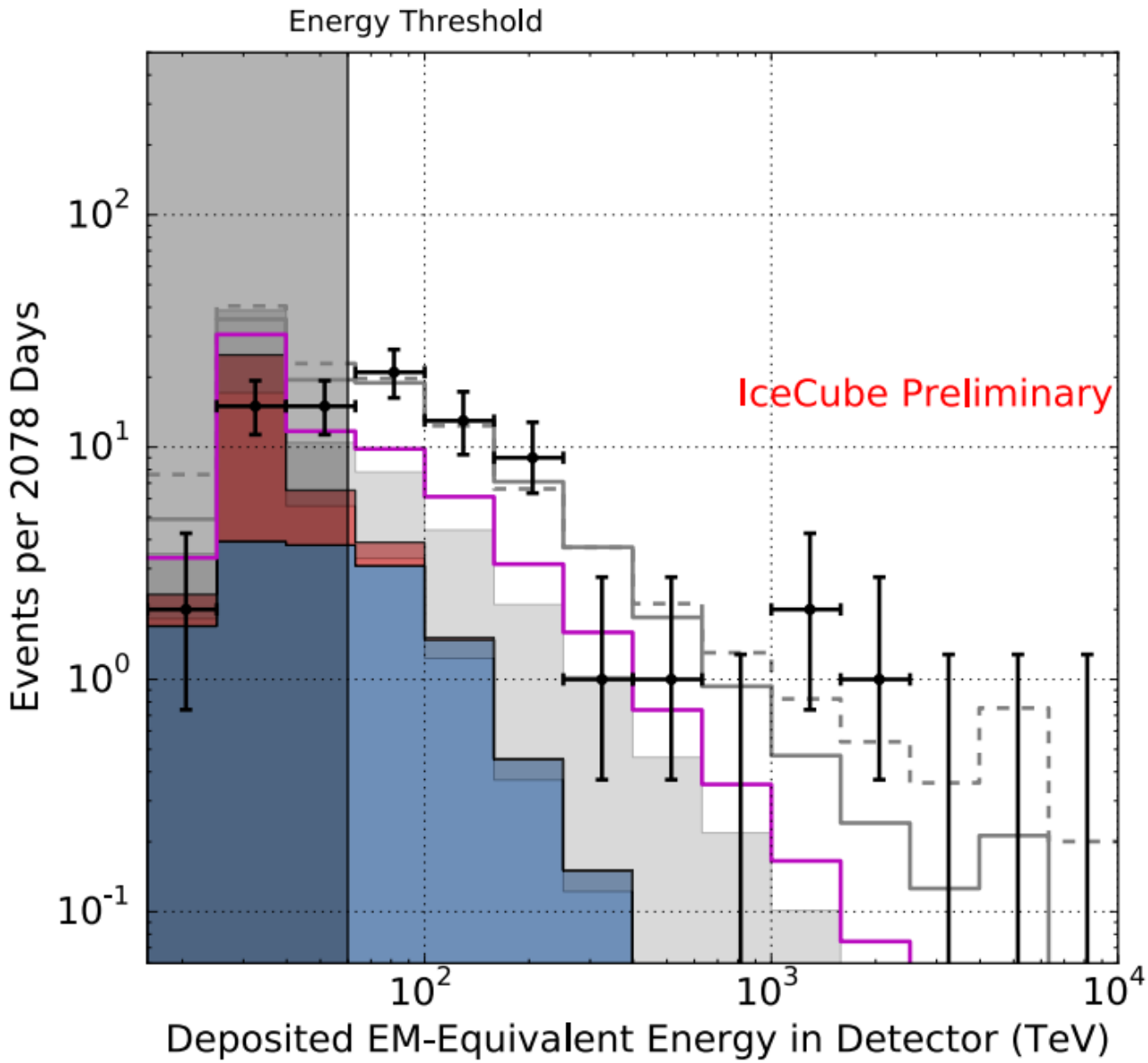
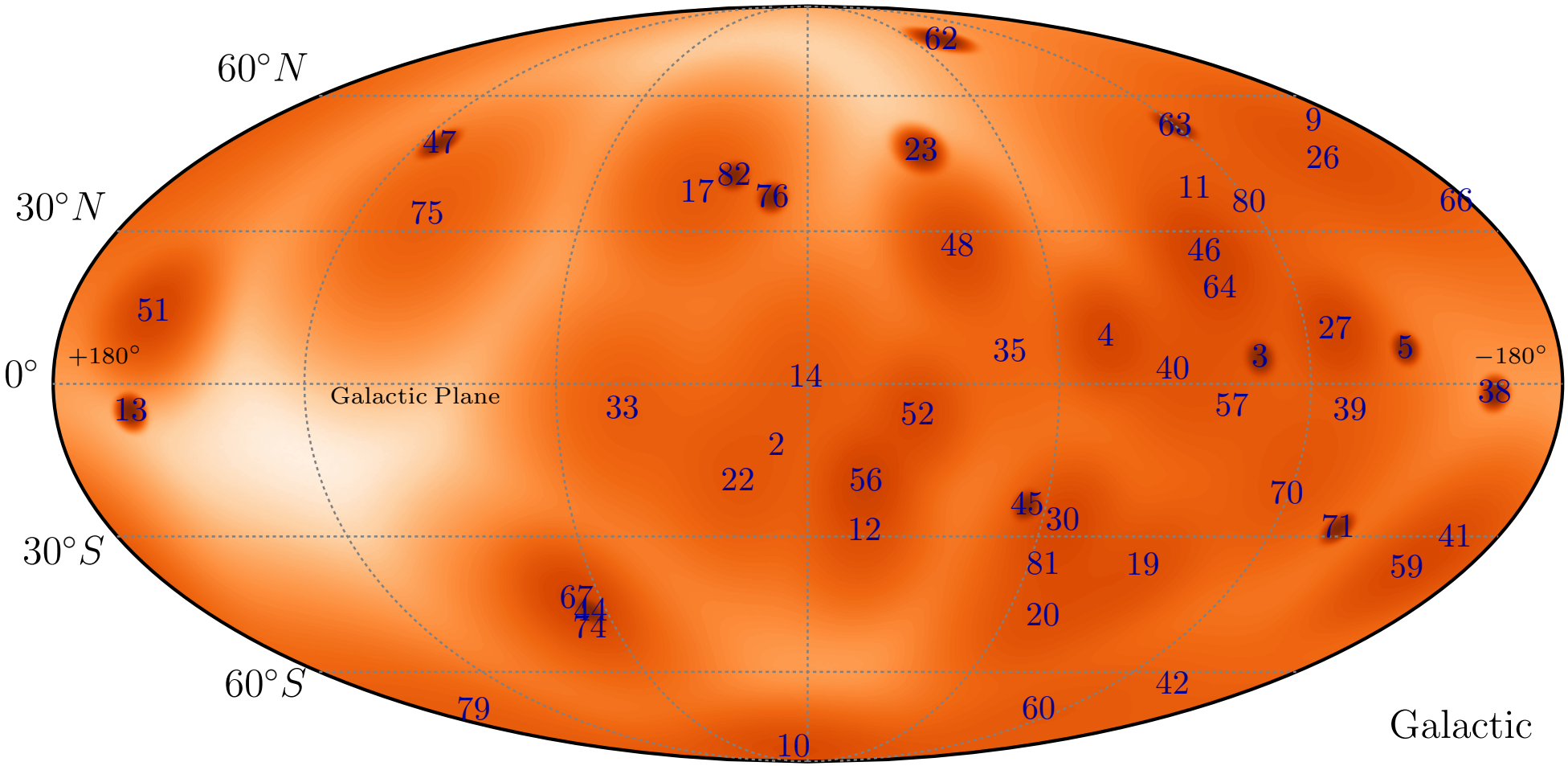
P. B. DENTON

IceCube detects astrophysical neutrinos

IC's 6 yr HESE: ICRC 2017

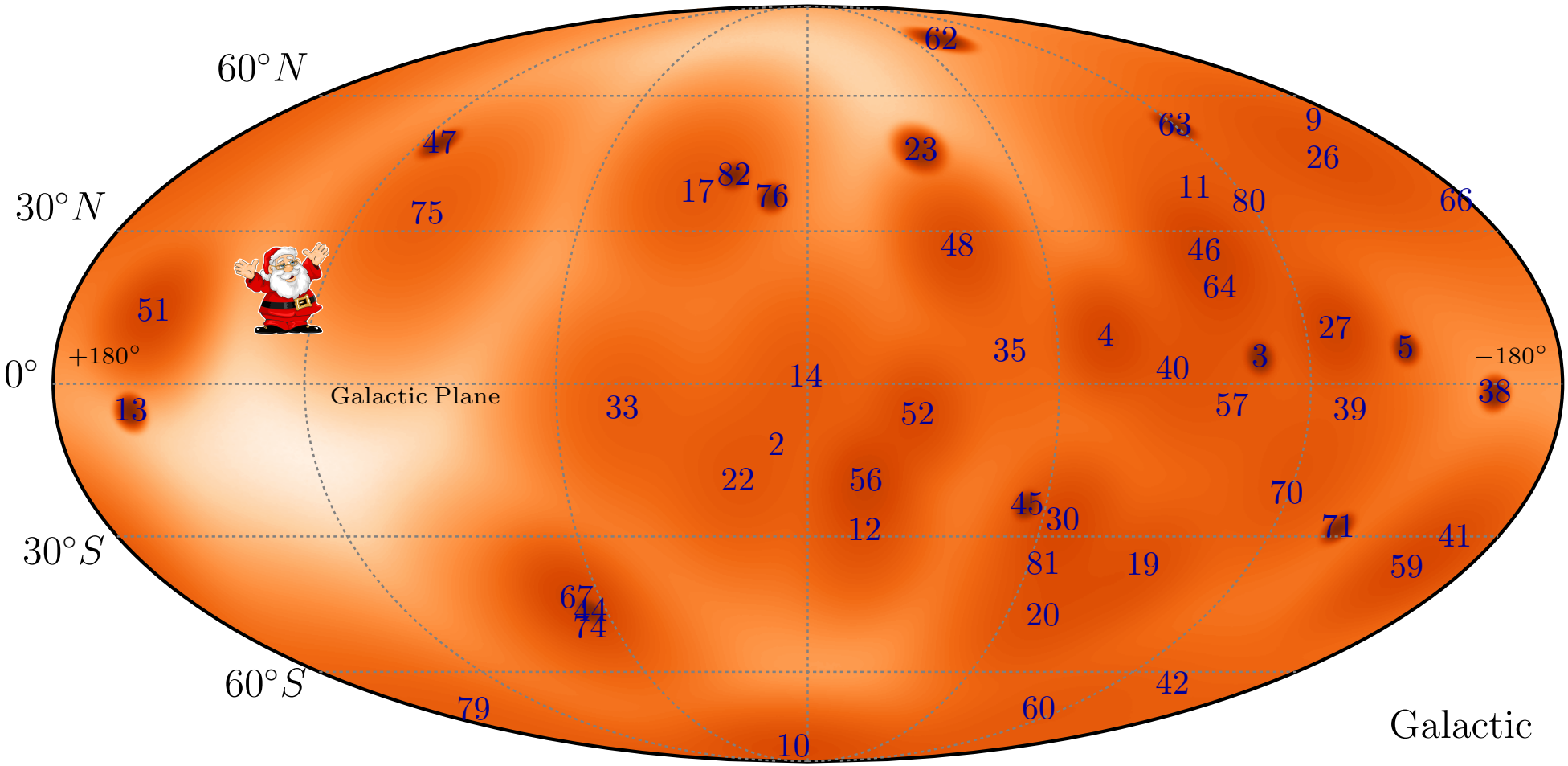


IceCube detects isotropic flux of astrophysical neutrinos



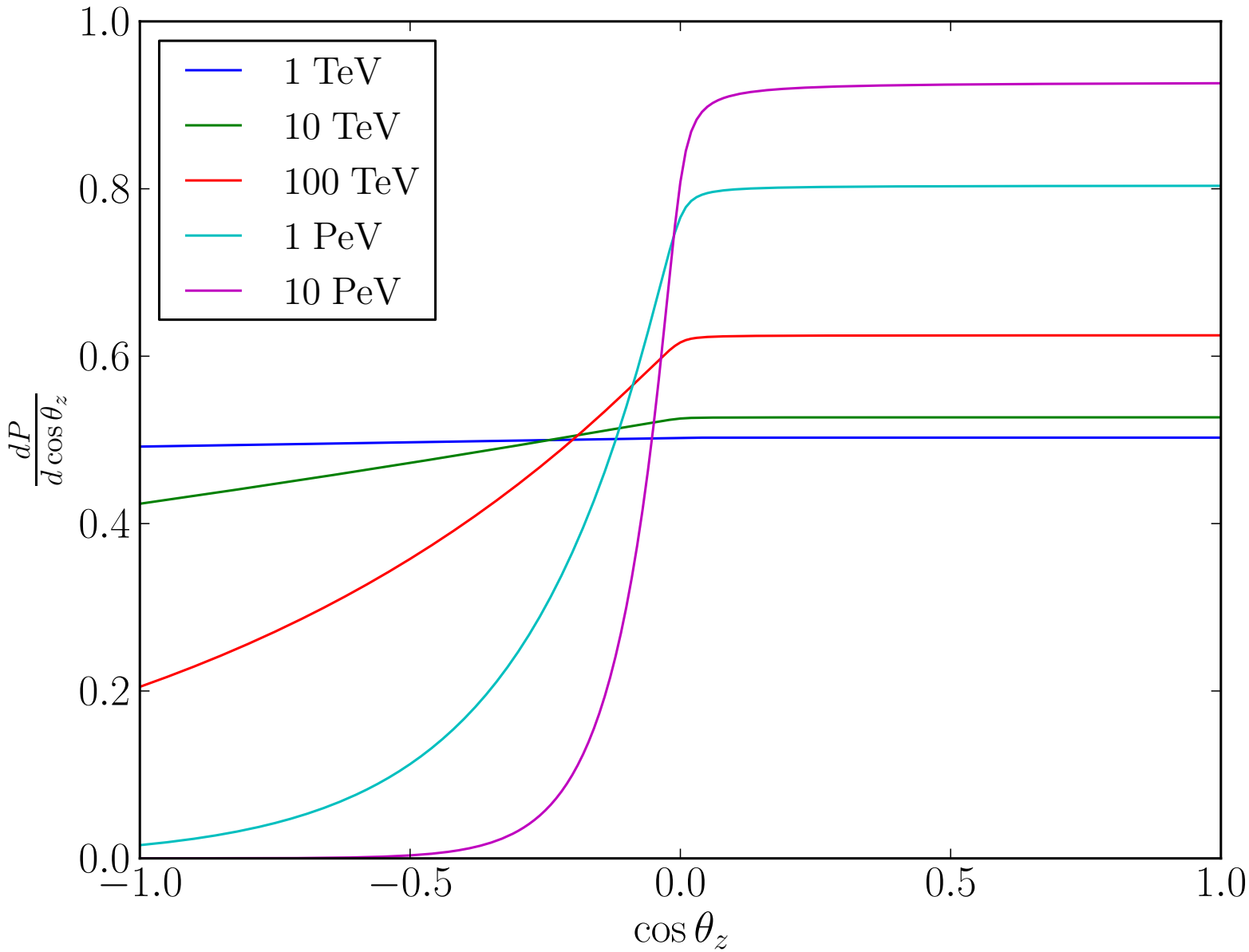
50 events with $E_{\text{dep}} > 60$ TeV from IC 6 year HESE

IceCube detects isotropic flux of astrophysical neutrinos

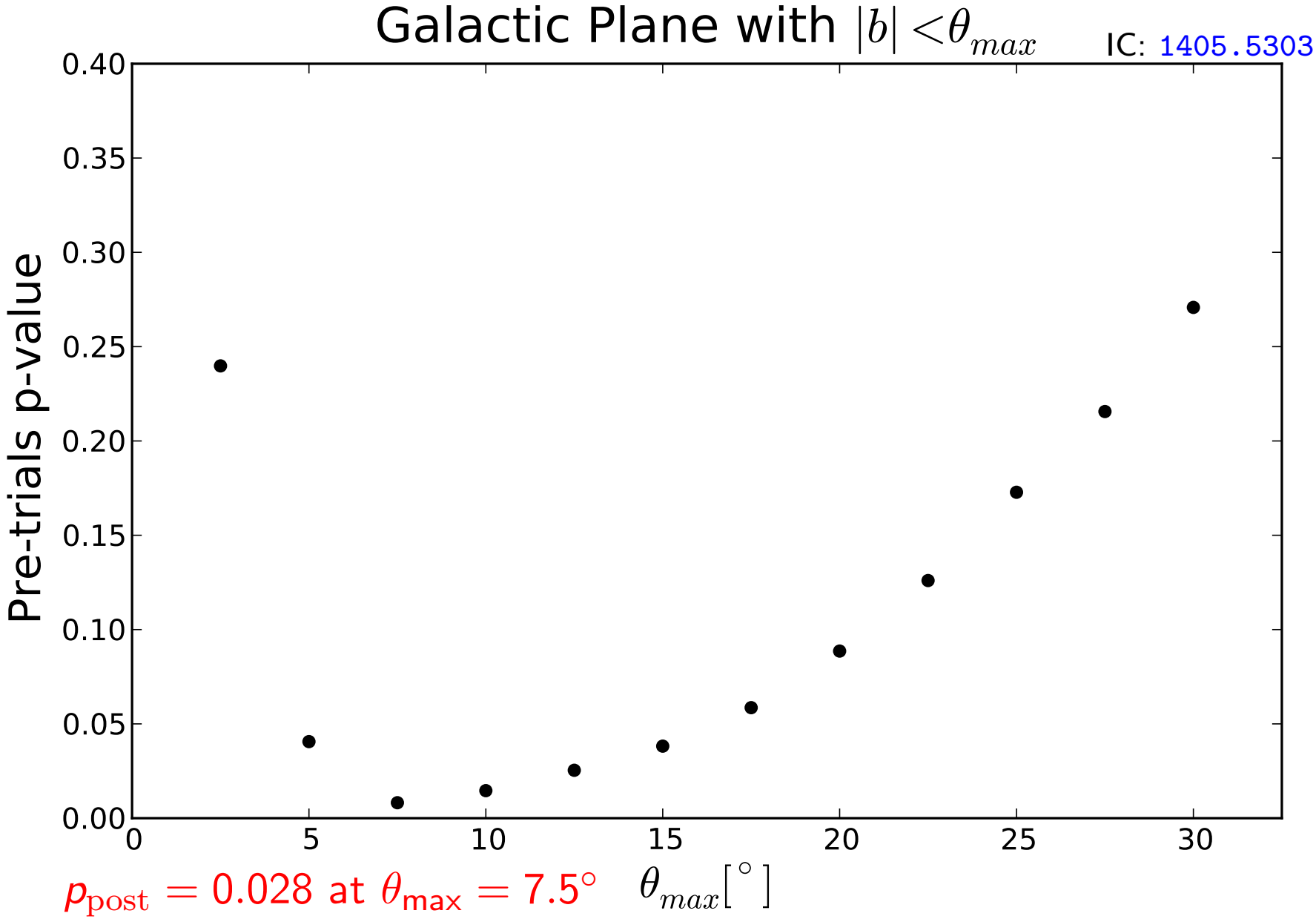


50 events with $E_{\mathrm{dep}} > 60$ TeV from IC 6 year HESE

High energy neutrinos are absorbed by the Earth



Significance of the galaxy as the source



Galactic or extragalactic?

Various methods to search for anisotropies:

- Windowed search around the Galactic center/plane.

  IC: 1311.5238, 1405.5303

  Ahlers, Murase: 1309.4077

  Anchordoqui, et al.: 1410.0348

  Palladino, Winter: 1801.07277

- Known Galactic sources:
  CRs, γ-ray correlations, GC, Fermi bubbles, misc. Galactic catalogs, ...

  IC: 1406.6757 + 1707.03416

  Ahlers, et al.: 1505.03156

  Celli, Palladino, Vissani: 1604.08791

- Known extragalactic sources: AGNs, blazars, SFGs, GRBs, ...

  Bechtol, et al.: 1511.00688

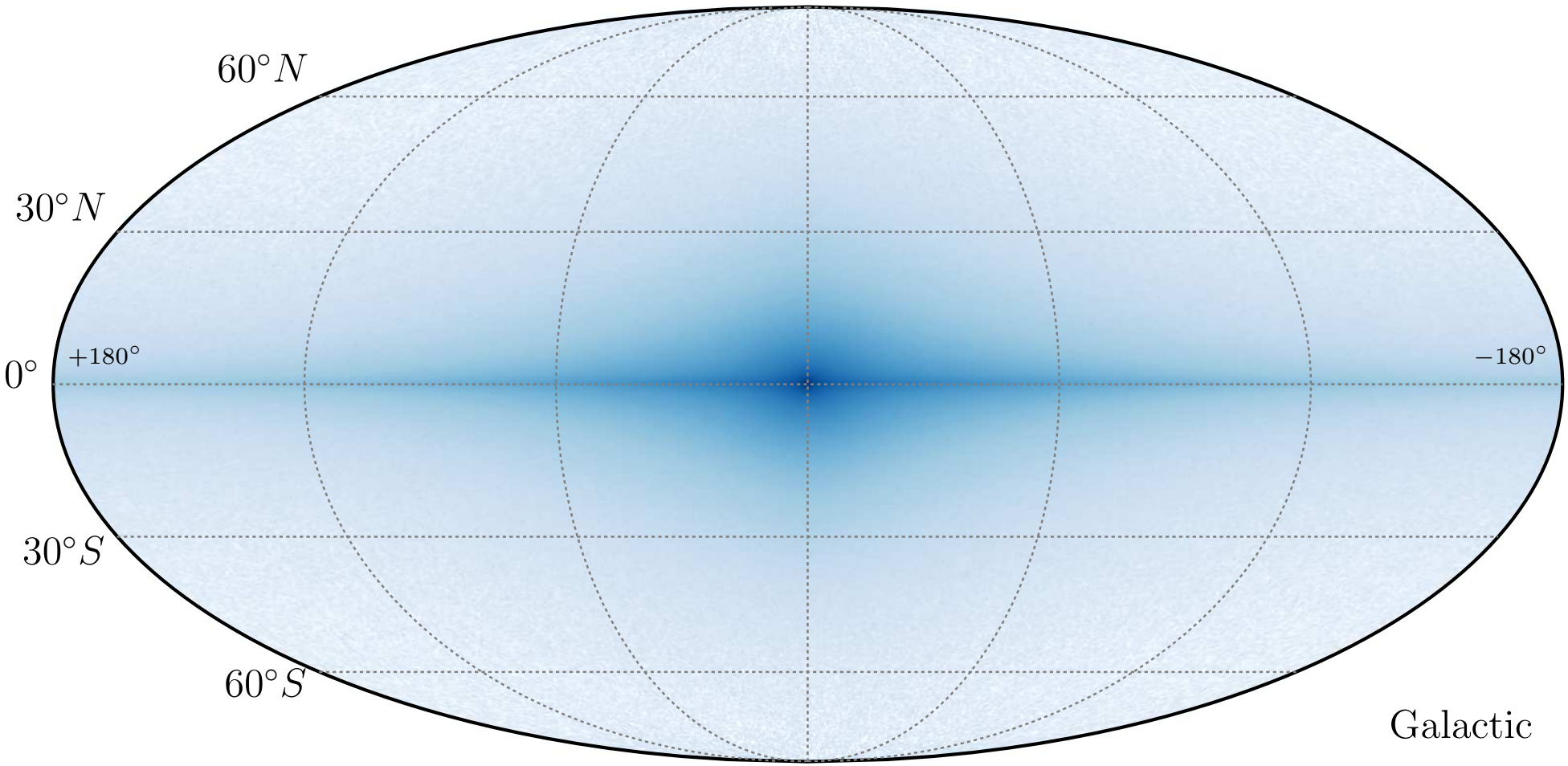
  IC: 1601.06484

  Padovani, et al.: 1601.06550

  Lunardini, Winter: 1612.03160

  Biehl, et al.: 1711.03555, 1705.08909

Expected distribution from the galaxy



Mass distribution in MW

McMillan: 1102.4340

Galactic or extragalactic?

Given that an event is astrophysical, the conditional likelihoods are,

$$\mathcal{L}_{\mathrm{gal|astro},i}(f_{\mathrm{gal}}) = f_{\mathrm{gal}} \int d\Omega\, \Phi_{\mathrm{gal}}(\Omega) f_{\mathrm{vMF}}(\theta, \kappa_i)\,, \qquad \leftarrow \text{IC's psf}$$

$$\mathcal{L}_{\mathrm{exgal|astro},i}(f_{\mathrm{gal}}) = (1 - f_{\mathrm{gal}}) \frac{1}{4\pi}\,.$$

The likelihood that event i is described by this model is,

$$\mathcal{L}_i(f_{\mathrm{gal}}) = \mathcal{L}_{\mathrm{bkg},i} \frac{1}{4\pi} + \mathcal{L}_{\mathrm{astro},i} \left[\mathcal{L}_{\mathrm{gal|astro},i}(f_{\mathrm{gal}}) + \mathcal{L}_{\mathrm{exgal|astro},i}(f_{\mathrm{gal}})\right]\,,$$

and the total likelihood is the product,

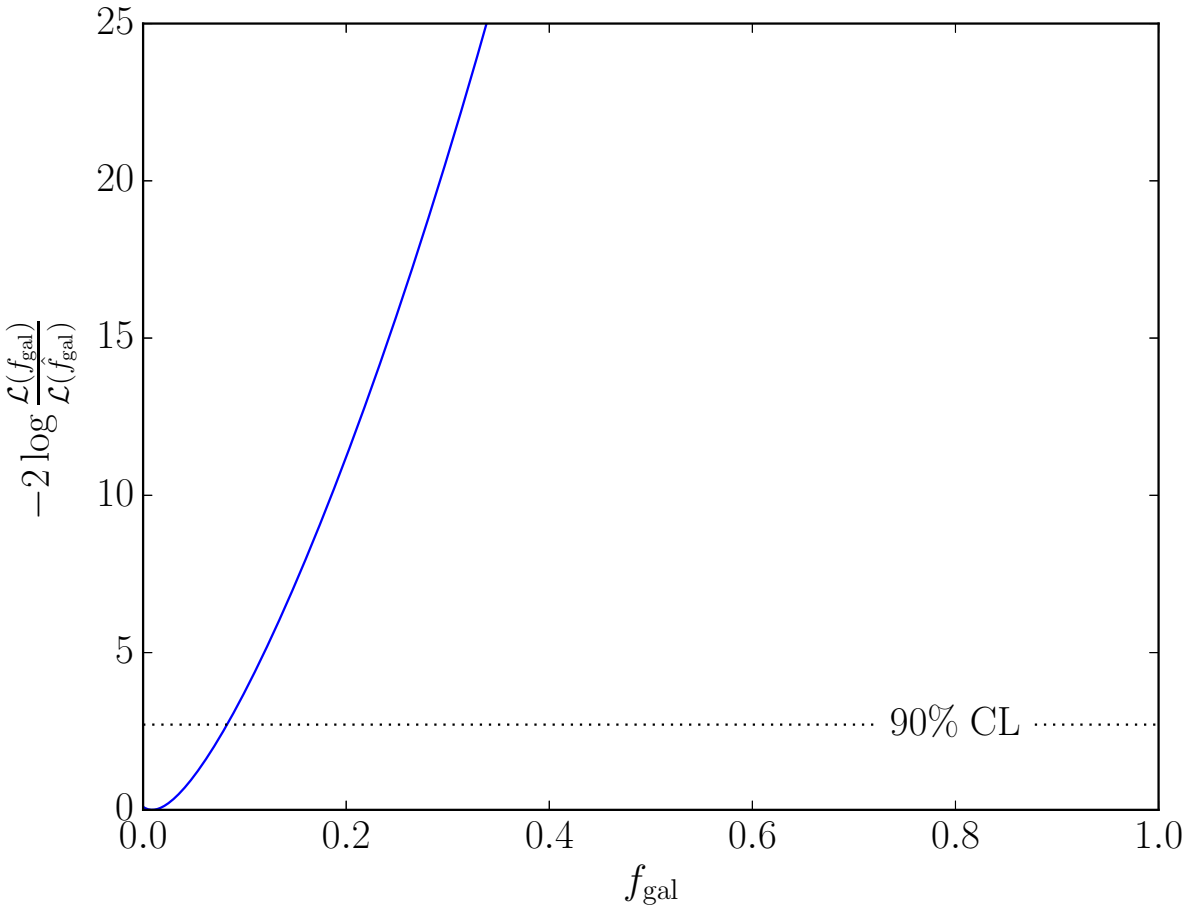
$$\mathcal{L}(f_{\mathrm{gal}}) = \prod_i \mathcal{L}_i(f_{\mathrm{gal}})\,.$$

- For $E_{\mathrm{dep}} > 60$ TeV, we expect < 6 events from backgrounds.

  IC: 1405.5303

- Results independent of spectral fit, use data directly.

Galactic fraction: results



$\hat{f}_{\rm gal} = 0.013$

$f_{\rm gal} = 0$ consistent at $< 1\sigma$

CL	$f_{\rm gal}$
1σ	< 0.057
90%	< 0.095
3σ	< 0.2

PBD, D. Marfatia, Weiler: 1703.09721

Other possible sources

- Other galactic sources such as the Crab, Fermi bubbles: nothing found.

  IC: 1106.3484

  Ahlers, Murase: 1309.4077

  Ahlers, et al.: 1505.03156

- Cosmogenics from UHECR energy loss: wrong energy.

  Berezinsky, Zatsepin: PLB '69

- Point source searches: nothing found.

  IC: 1406.6757

- Catalog correlations: nothing (significant) found.

  Moharana, Britto, Razzaque: 1602.03694

- UHECR correlation: nothing (significant) found.

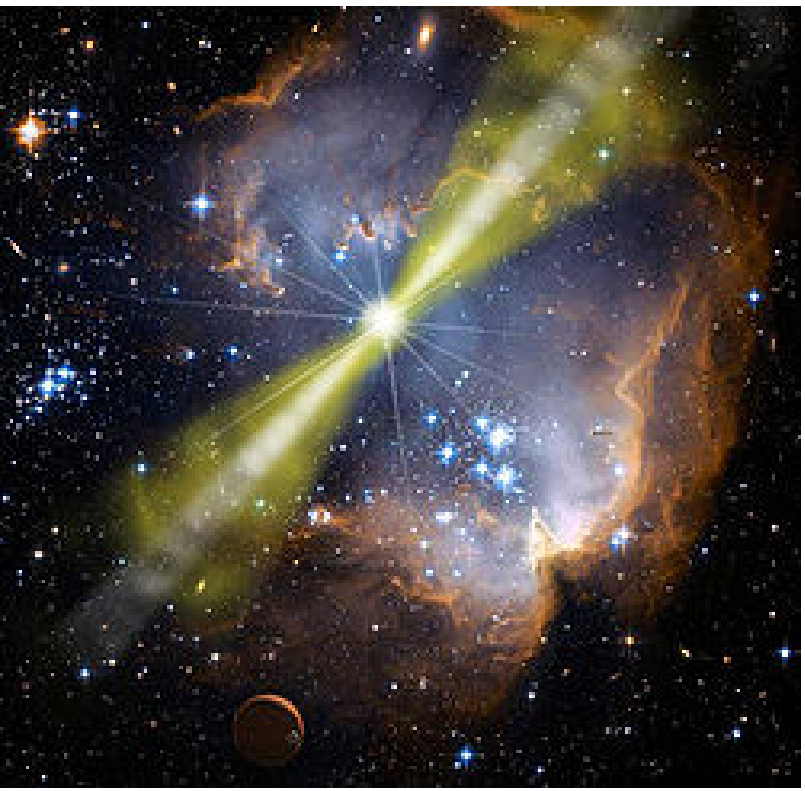
  IC, Auger, TA: 1511.09408

Seem to be running out of source catalogs to check.

$\therefore$ Move to diffuse intensities and use spectral information to constrain source properties.

Gamma ray bursts

GRBs are potential UHECR and HEν sources.



- Most luminous events observed.
- Have observed ~ 1000 GRBs.
- Photon measurements $\Rightarrow$ high Γ outflow.

  Excellent HE particle production candidate.
- Central engine?
  - CCSN.
  - Binary mergers, . . . ?
- IceCube has strong constraints from spatial + timing correlations.

IC: 1601.06484

CCSN–GRB connection

Mounting evidence that some or all long duration GRBs are associated with CCSNe.

- Theoretical:

  Lazzati, Morsony, Blackwell, Begelman: 1111.0970

  Sobacchi, Granot, Bromberg, Sormani: 1705.00281

- Observational:

  Paczyński: astro-ph/9710086

  Hjorth, Bloom: 1104.2274

  Modjaz: 1105.5297

  Hjorth: 1304.7736

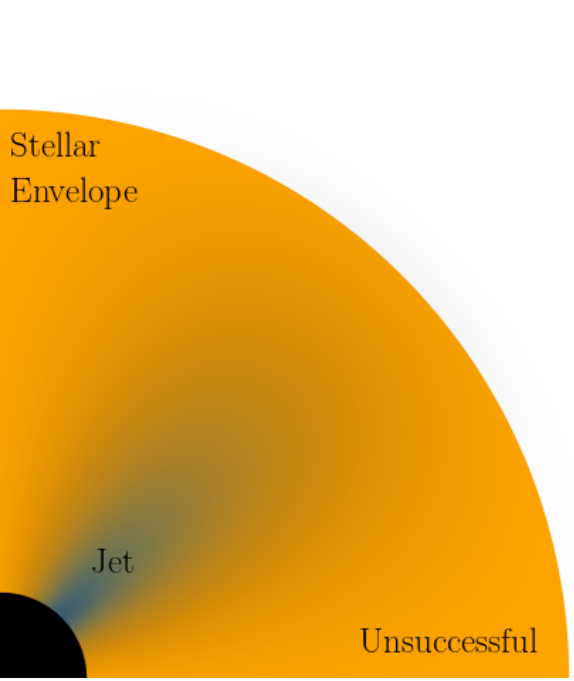
  Margutti, et al.: 1402.6344

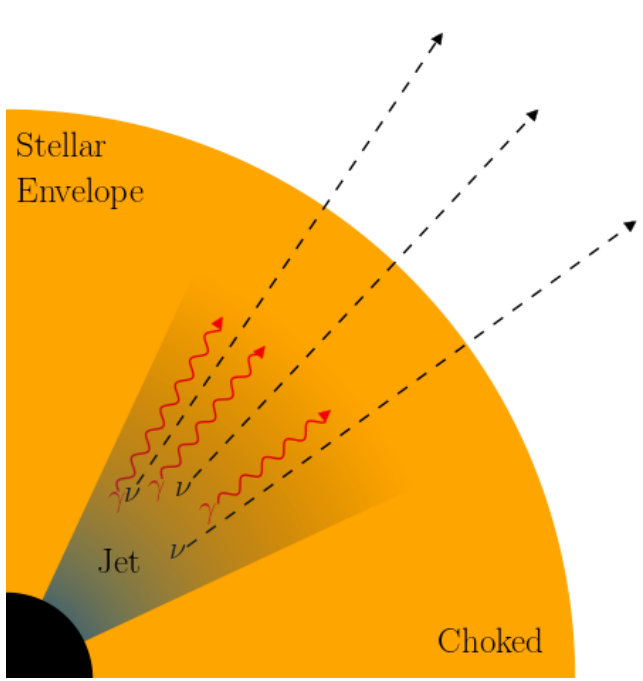
CCSN + (rotation, B field) $\Rightarrow$ jet.

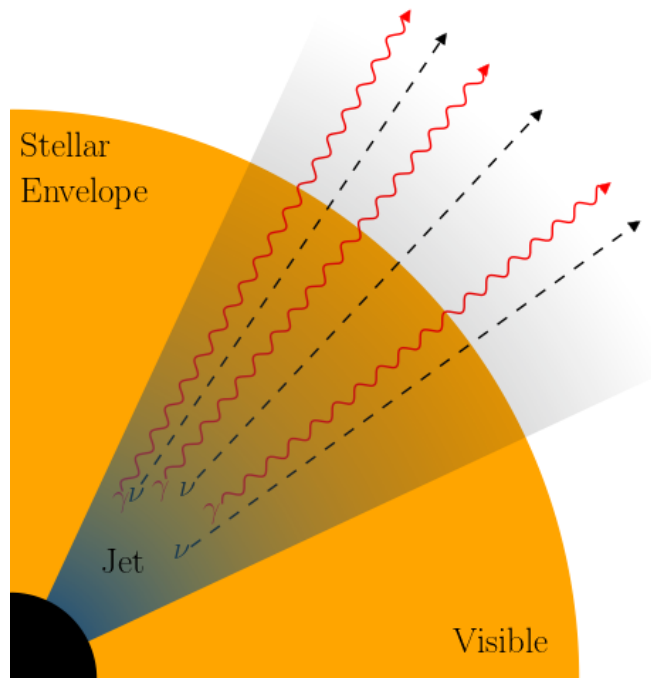
Three kinds of jets

The type of the jet determines the particle output:

- Unsuccessful $\Rightarrow \emptyset$.
- Successful but choked $\Rightarrow \nu$'s.
- Successful and visible $\Rightarrow \nu$'s and γ's.







Choked GRBs

- Without EM observations, it is possible to write down anything for a choked source.
- We assume that all jets are drawn from the same distribution.
- We match the high luminosity jets to observations.
- One extra parameter $\zeta_{\rm SN}$: fraction of CCSNe that harbor jets.

GRB model: properties

- Protons accelerated by the central engine following Fermi acceleration.
- Photons are measured to have a non-thermal spectrum.

Band, et al.: ApJ, 413, 281

Amati, et al.: astro-ph/0205230

- Magnetic fields carry $\sim 10\%$ of the total jet energy.
- Jet opening angle is related to the Lorentz boost factor: $\theta_j = 1/\Gamma$ for $\Gamma \leq 100$, $\theta_j = 30/\Gamma$ else.

Goldstein, et al.: 1512.04464

- Variability time t_v scales with Γ: ~ 100 s for small Γ down to ~ 0.001 s for $\Gamma \sim 1000$.

Sonbas, et al.: 1408.3042

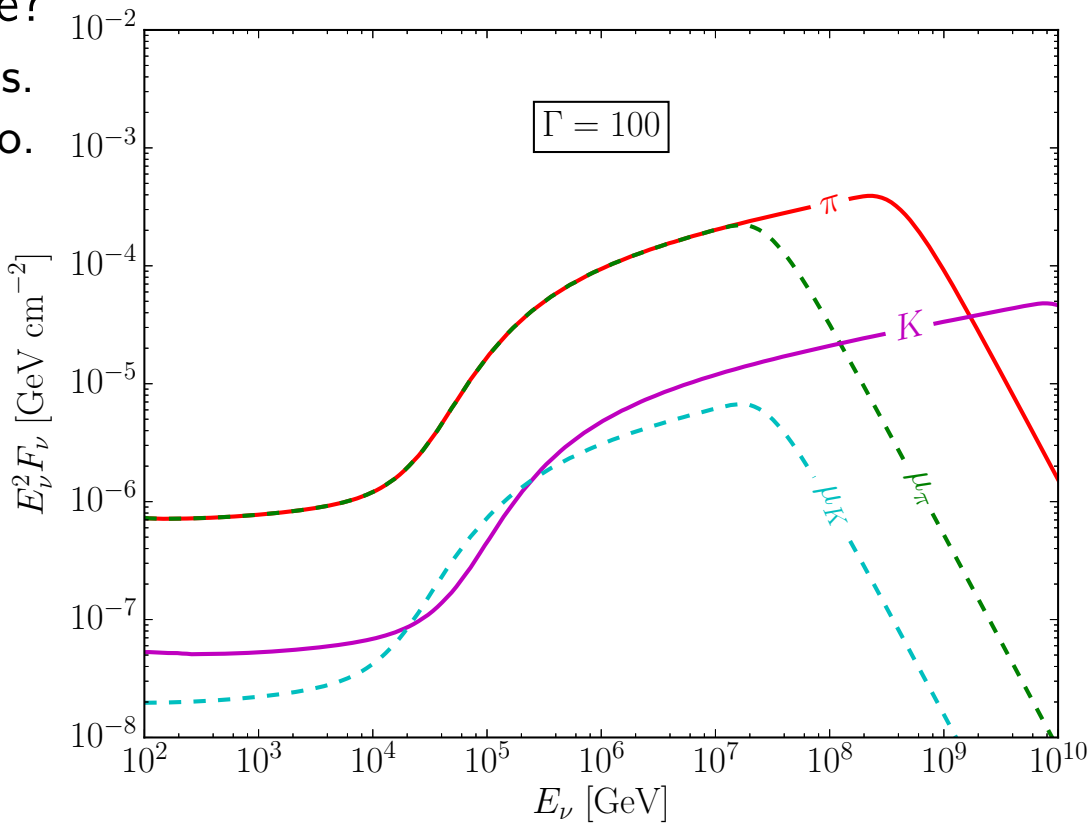
Campana, et al.: astro-ph/0603279

Gupta, Zhang: astro-ph/0606744

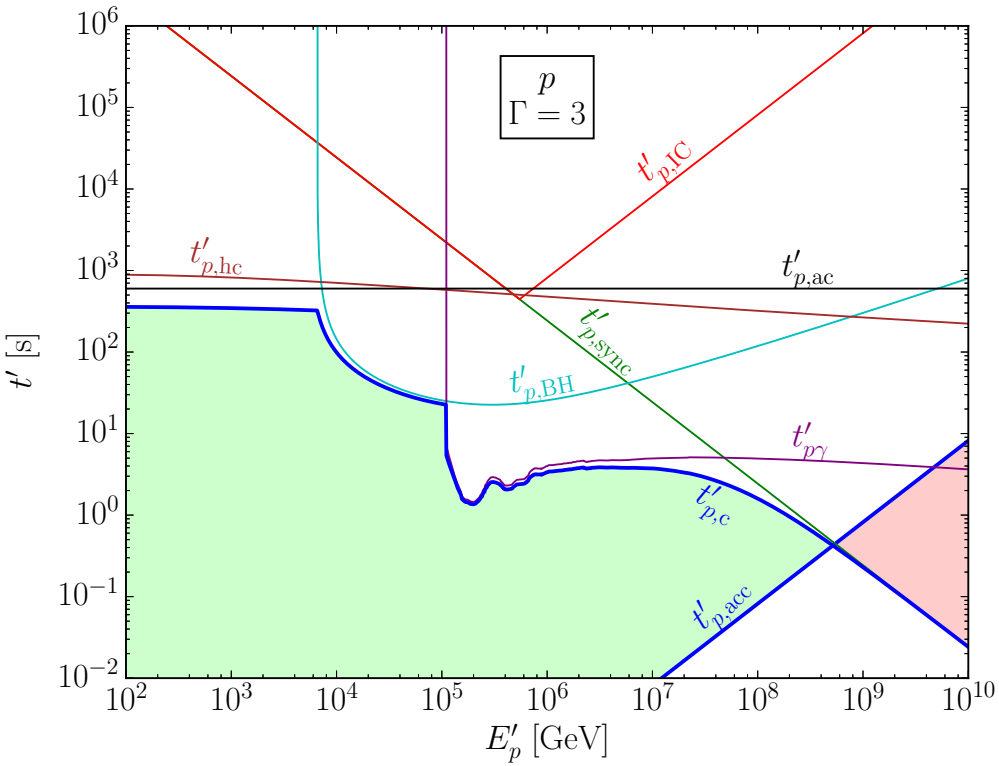
- The shock radius of acceleration follows the internal shock model and is $r_{\mathrm{IS}} \propto t_v$.

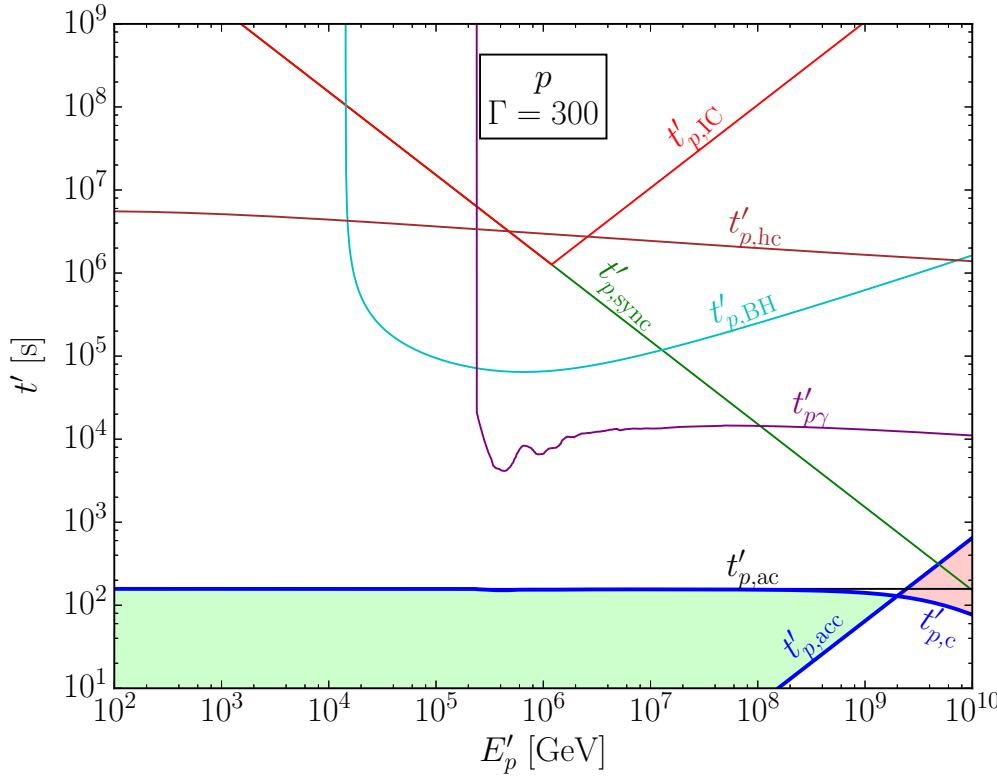
Particle physics in jets

- $p\gamma$ interactions lead to pions and kaons.
- Pions and kaons quickly decay to muons and neutrinos.
- Muons decay to more neutrinos.
- Protons, pions, kaons, and muons lose energy in the jet,
  - Do they decay in time?
    - Low energy $\Rightarrow$ yes.
    - High energy $\Rightarrow$ no.



Proton cooling





Similarly for π's, μ's, and K's.

Distribution of jets: the Simple model

Each jet has one Γ value sampled from a power law $\propto \Gamma^{\alpha_\Gamma}$.

We normalize with the SN and HL-GRB rates,

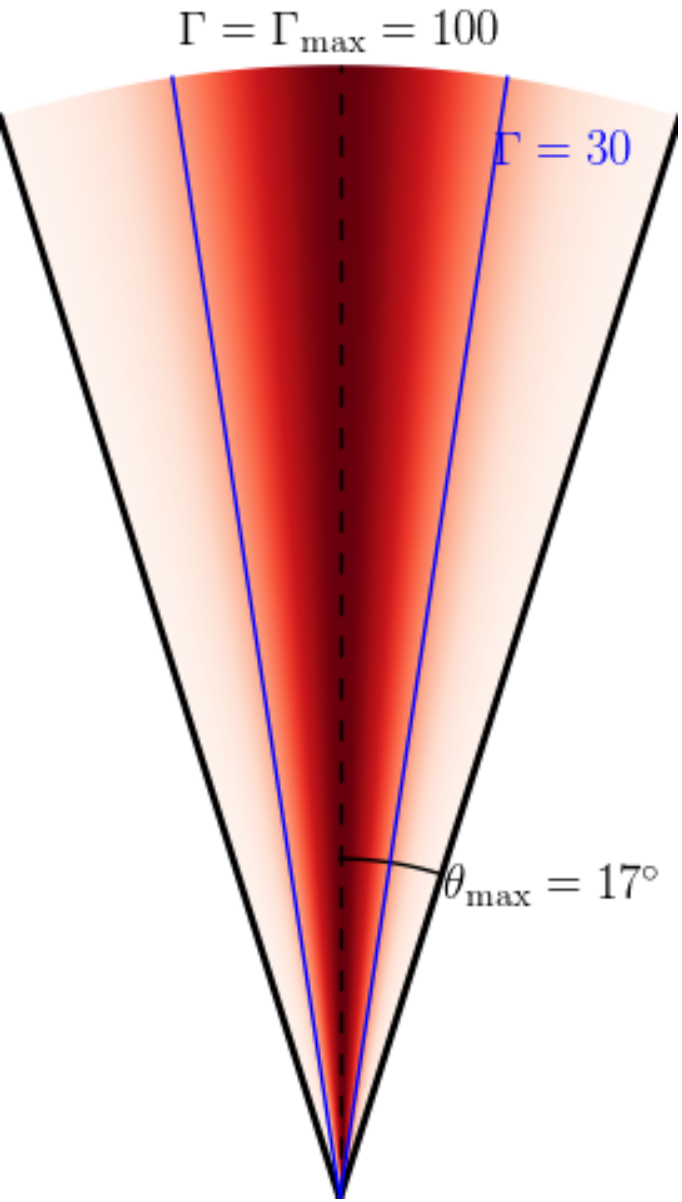
- All jets are equal to the fraction of SNe $\zeta_{\rm SN}$ that form jets and point at us.
- Relativistic jets ($\Gamma > 200$) forms the observed HL-GRB data set.

This leads to exponents $\alpha_\Gamma \sim [-1, -3]$ depending on $\zeta_{\rm SN}$.

Then the redshift evolution follows that of star formation rate not that of GRBs.

Yuksel, et al.: 0804.4008

Structured jets: the Advanced model



Multiple shocks $\rightarrow$ random walk.

Distribution of jets drawn from a power law.
In each jet:

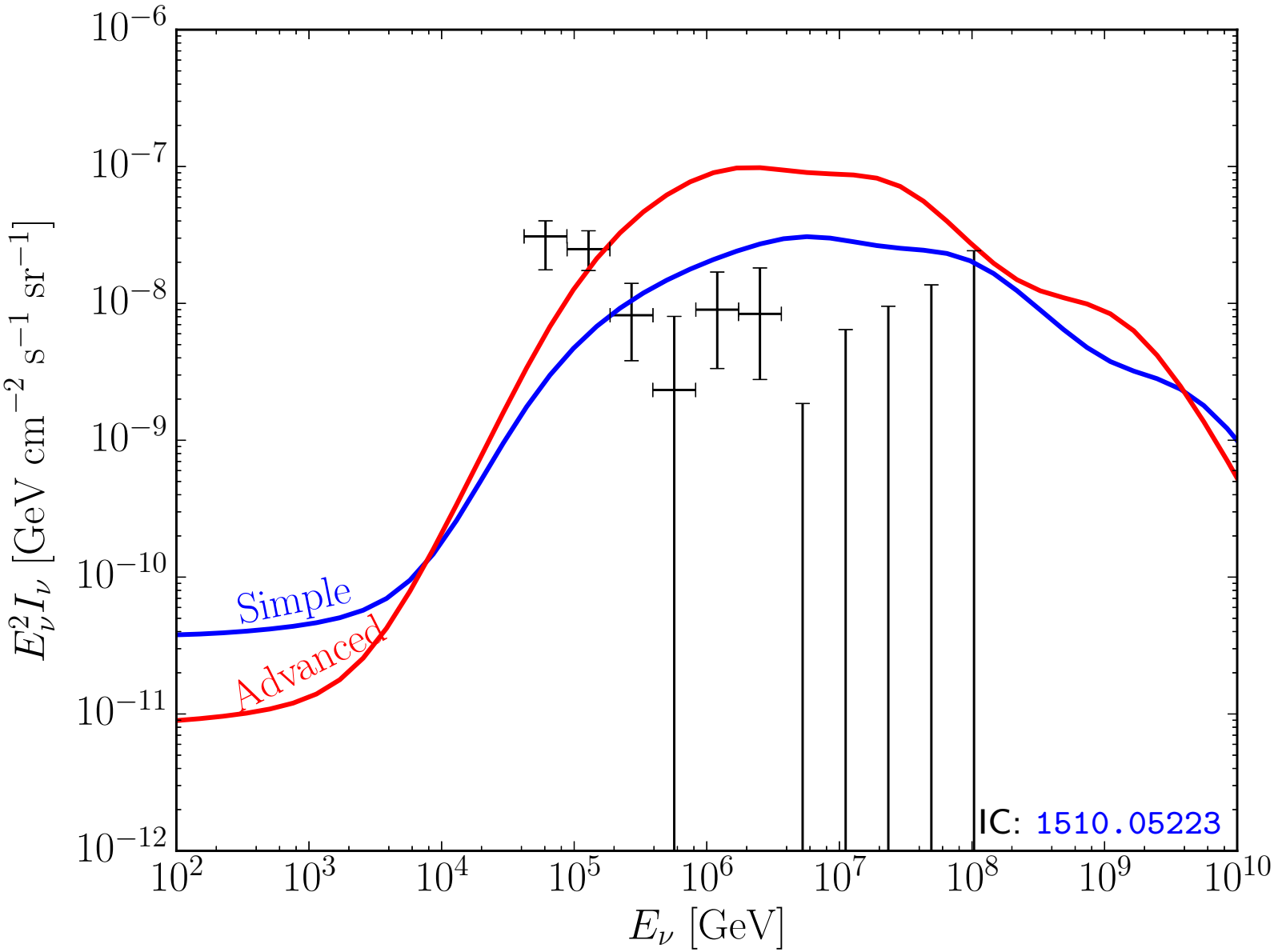
- $\Gamma = \Gamma_{\rm max}$ along the jet axis.
- Γ falls off as the angle increases with characteristic width $\sigma = 1/\sqrt{\Gamma_{\rm max}}$.
- The total jet opening angle contains all $\Gamma > 1$.

The observed distribution in Γ's comes from both:

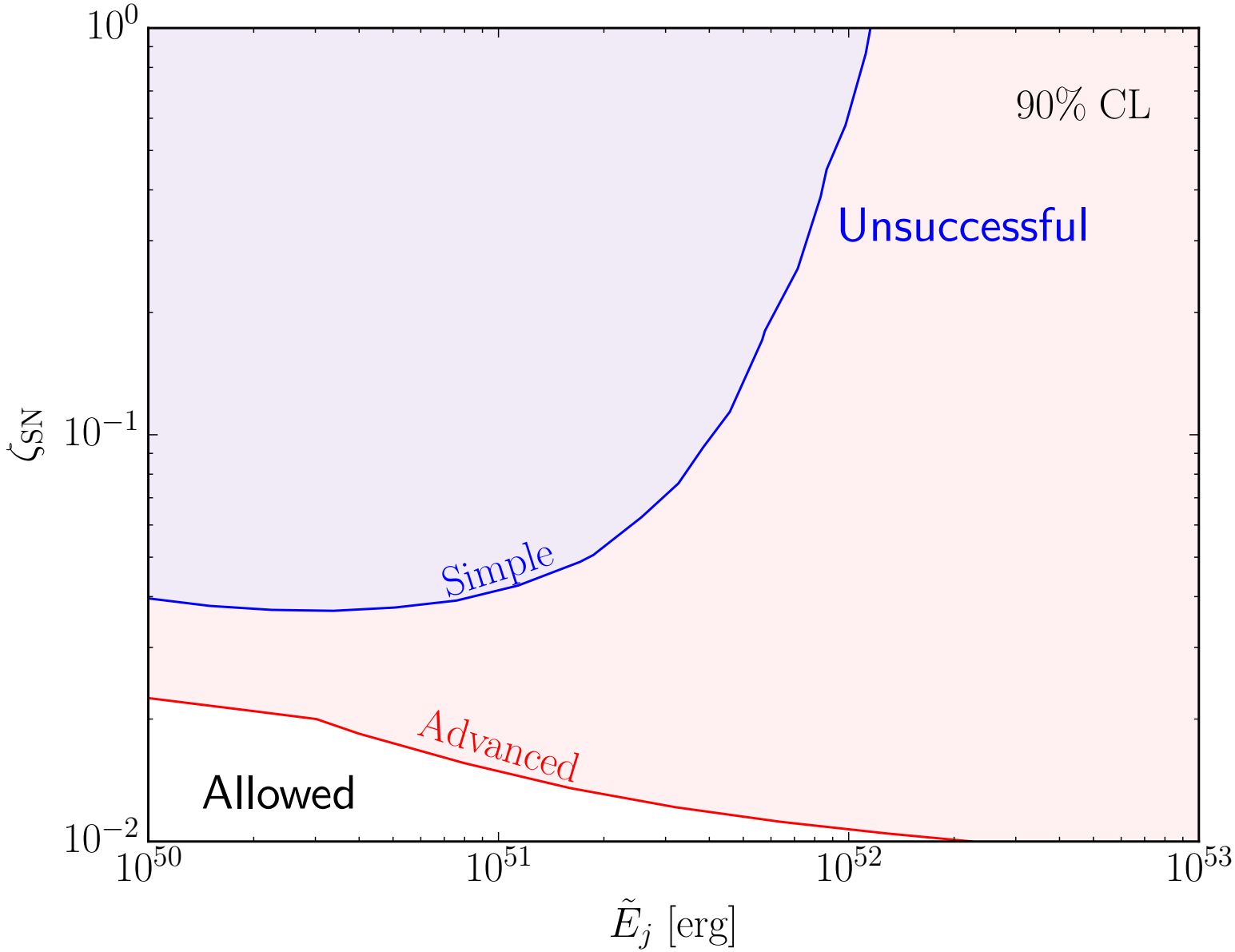
- Distribution of jets: power law in $\Gamma_{\rm max}$, and
- Angle of the jets relative to the Earth.

Diffuse intensities

At $\zeta_{\rm SN} = 0.1$ and $\tilde{E}_j = 10^{51}$ erg.



Source parameter exclusion limits



GRB–Supernovae in the literature

- If all Ibc's form a jet, $\lesssim 10\%$ are visible.

  Soderberg, Frail, Wieringa: astro-ph/0402163

  Soderberg, Nakar, Kulkarni: astro-ph/0507147

  Sobacchi, Granot, Bromberg, Sormani: 1705.00281

- $R_{\rm GRB}(0)/R_{\rm Ibc}(0) \sim 0.1 - 1\%$, and Ibc's are $\sim 10\%$ of all CCSNe.

  Grieco, et al.: 1204.2417

- The subclass broadlined CCSNe linked to GRBs sans gamma rays.

  Podsiadlowski, et al.: astro-ph/0403399

  Mazzali, et al.: astro-ph/0505199

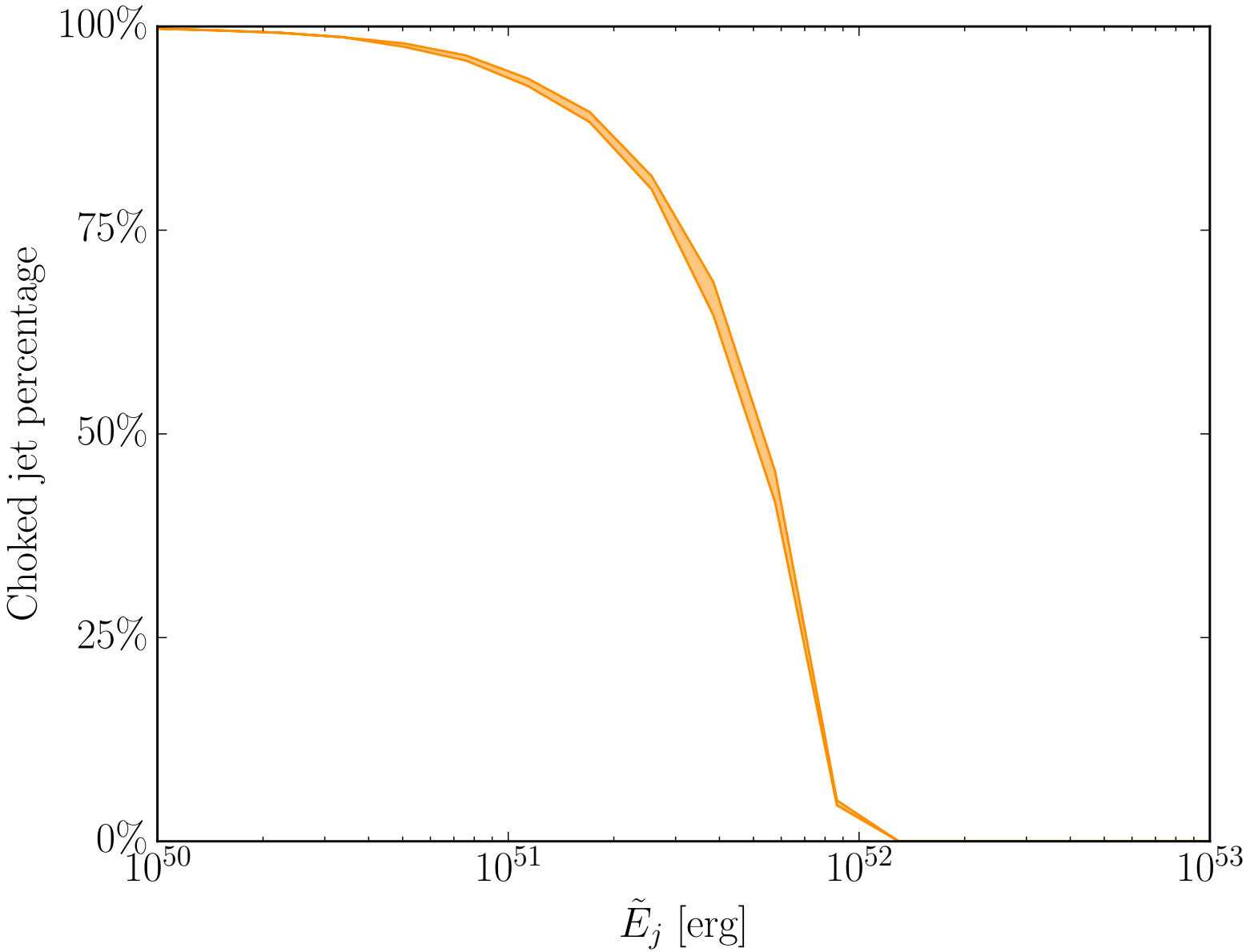
  Soderberg, Nakar, Kulkarni: astro-ph/0507147

  Soderberg: astro-ph/0601693

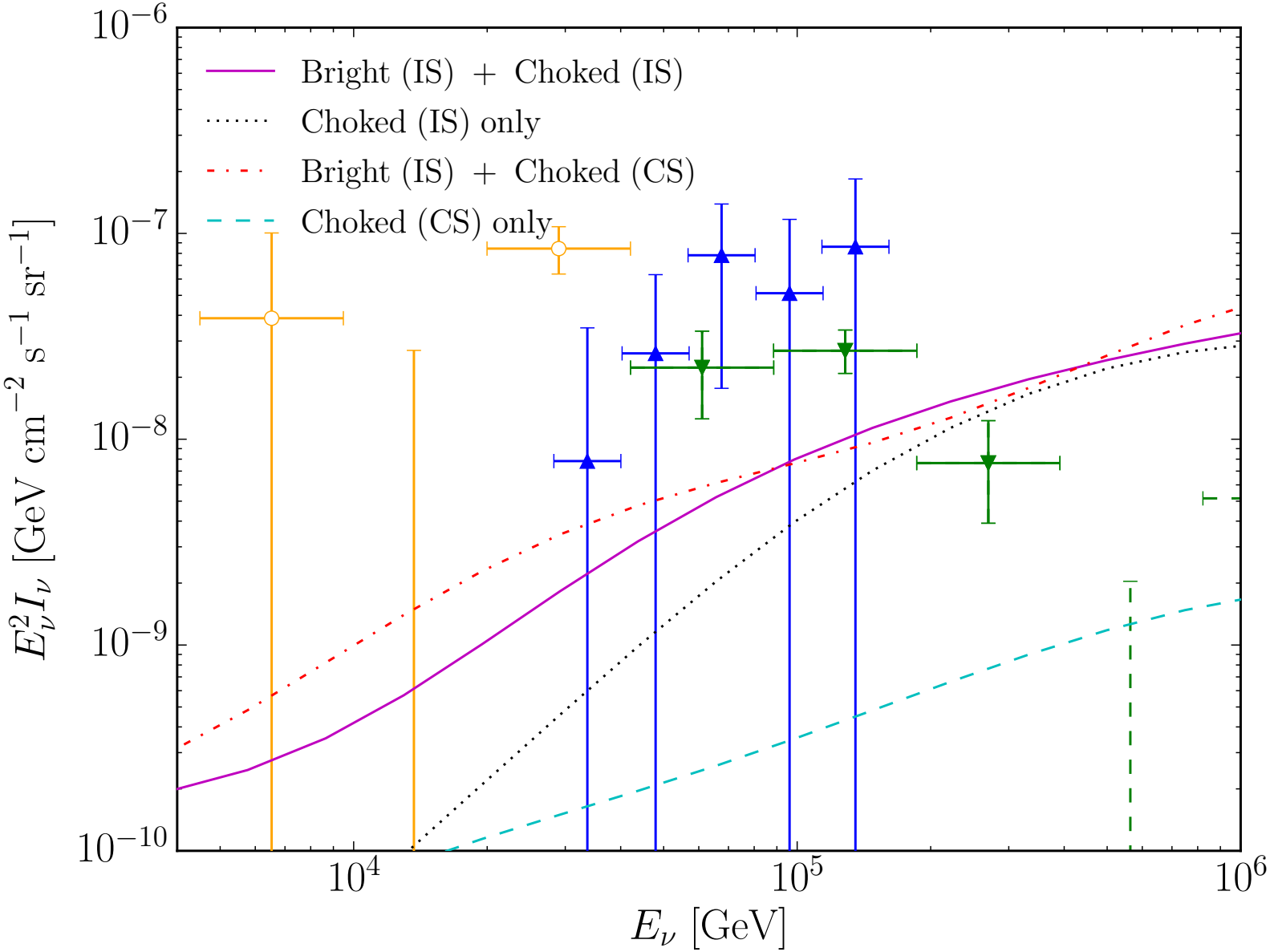
- Example: SN2002ap (Ic) had a jet 90° from observer, $\tilde{E}_j = 5 \times 10^{50}$ erg.

  Totani: astro-ph/0303621

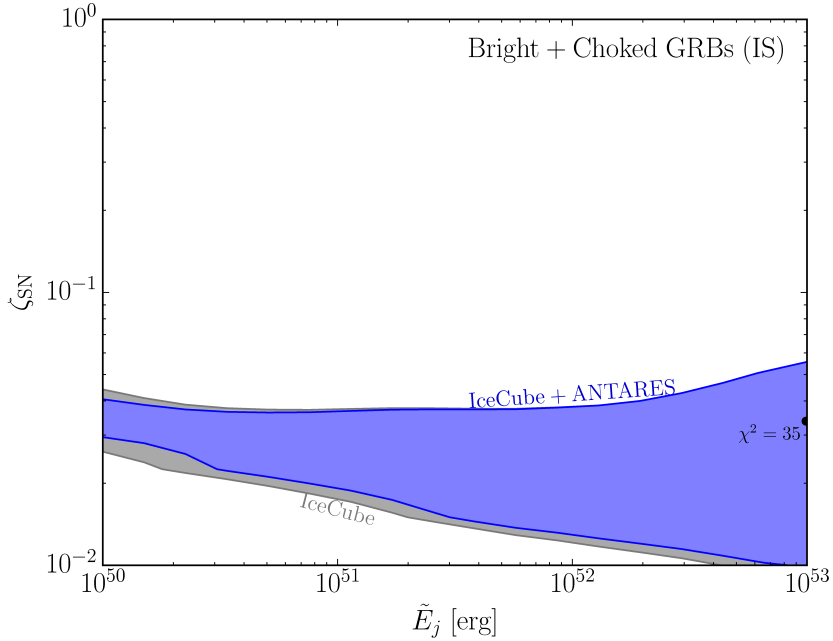
Choked fraction

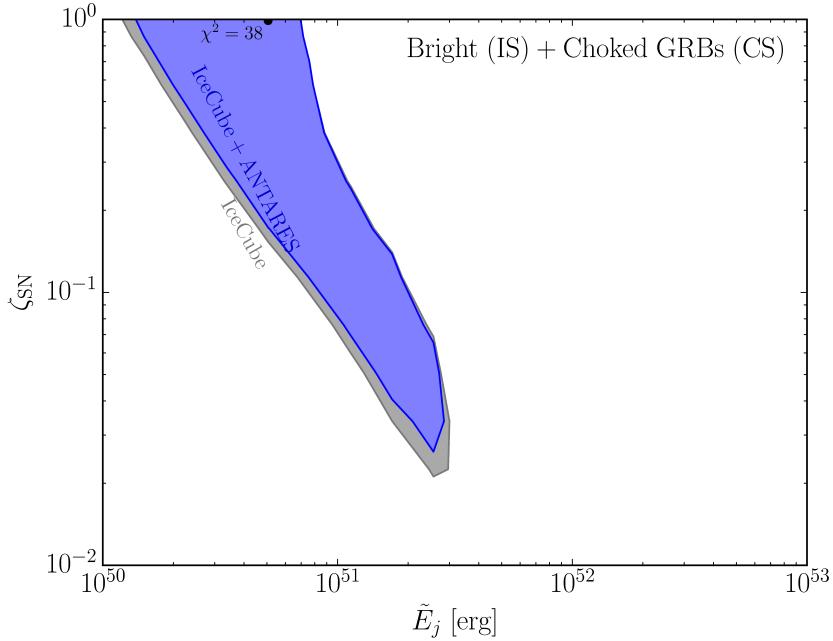


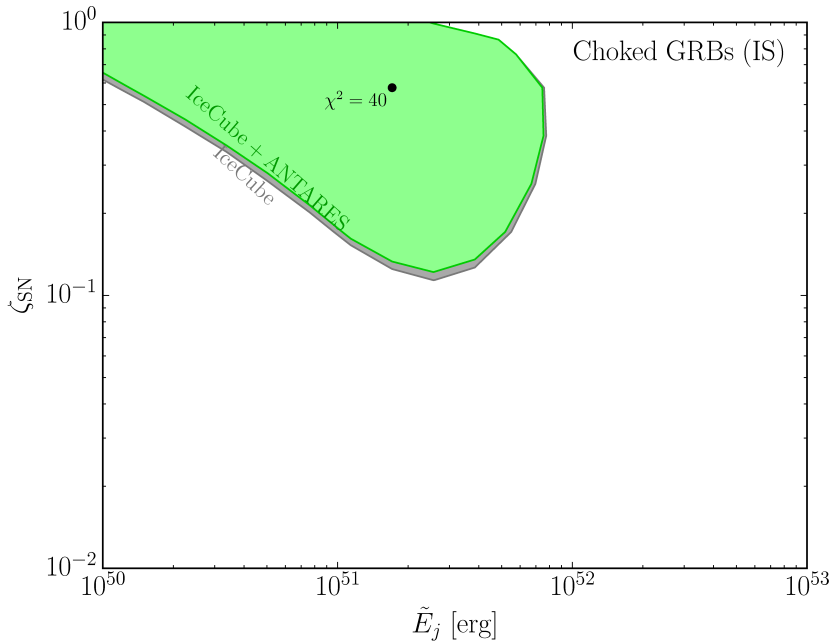
Low energy GRB diffuse intensity: choked jets?



Choked jets constraints







Conclusions

- IceCube has measured the HE astrophysical neutrino flux.
- The astrophysical neutrino flux is extragalactic and isotropic.
- GRBs naturally lead to a high neutrino flux.
- Need to consider different classes of jets.
- CCSNe-GRB connection allows for physical constraints on choked GRBs.
- $\lesssim 1\%$ of CCSNe form jets, the majority of which will be choked.
- These could be type Ibc SNe forming jets: unsuccessful, choked, off/on-axis.
- Choked jets don't explain the low energy excess.

Backups

Likelihoods to Probabilities

$$p_{\mathrm{gal},i} = \frac{\mathcal{L}_{\mathrm{gal|astro},i}(\hat{f}_{\mathrm{gal}})\mathcal{L}_{\mathrm{astro},i}}{\mathcal{L}_i(\hat{f}_{\mathrm{gal}})}\,,$$

$$p_{\mathrm{exgal},i} = \frac{\mathcal{L}_{\mathrm{exgal|astro},i}(\hat{f}_{\mathrm{gal}})\mathcal{L}_{\mathrm{astro},i}}{\mathcal{L}_i(\hat{f}_{\mathrm{gal}})}\,,$$

$$p_{\mathrm{bkg},i} = \frac{\frac{1}{4\pi}\mathcal{L}_{\mathrm{bkg},i}}{\mathcal{L}_i(\hat{f}_{\mathrm{gal}})}\,.$$

$$\sum_i p_{\mathrm{gal},i} = 0.6\,, \qquad \sum_i p_{\mathrm{exgal},i} = 45.3\,, \qquad \sum_i p_{\mathrm{bkg},i} = 4.1\,.$$

50 Event-By-Event Probabilities at $\hat{f}_{\rm gal} = 0.013$

E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$
2003	35	0.0096	0.99	0
1140	20	2e-5	1	0
1040	14	0.36	0.64	0
885	45	1.2e-4	1	0
512	13	1.8e-4	1	8.6e-4
404	38	3.8e-4	0.87	0.13
384	33	0.012	0.98	0.0045
318	82	2.7e-5	0.56	0.44
249	76	6.8e-5	0.7	0.3
219	22	0.046	0.93	0.021
210	26	0	0.88	0.12
199	17	1.9e-4	0.84	0.16
190	63	1.1e-5	0.75	0.25
165	67	0	0.47	0.53
165	4	0.0017	1	0
164	44	1.4e-5	0.84	0.16
164	75	4.2e-5	1	0
159	23	2.8e-5	0.94	0.06
158	79	0	0.81	0.19
158	52	0.043	0.96	0
158	46	4.2e-5	0.94	0.057
157	40	0.0014	1	0
152	3	4.7e-4	0.95	0.046
151	81	1.2e-4	1	0
146	62	0	0.89	0.11

E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$
143	47	0	0.96	0.041
141	71	1.6e-5	0.92	0.079
137	5	1.3e-4	0.81	0.19
132	57	6.9e-4	1	0
128	30	1e-4	1	0
124	59	0	0.81	0.19
117	2	0.12	0.87	9.5e-4
104	48	3.2e-4	1	0.0032
104	56	0.0046	1	0
104	12	0.002	1	0
101	39	2.8e-4	0.96	0.04
98	70	9.9e-5	0.99	0.0064
97	10	0	0.99	0.0074
93	60	0	1	0
88	11	3.9e-5	0.9	0.095
87	41	1.4e-5	0.78	0.22
85	80	3.5e-5	0.91	0.091
84	66	2.5e-5	0.95	0.054
76	42	0	0.98	0.017
71	19	2.6e-5	1	0
71	74	1.6e-5	0.77	0.23
70	64	1.9e-4	0.98	0.016
66	51	6.3e-5	0.96	0.044
63	9	0	0.91	0.092
60	27	1.8e-4	0.89	0.11

Muon energy correction

The energy deposited in tracks is not the true neutrino energy because the muon carries some of the energy out of the detector.

- Muon energy loss rate: $\frac{dE_\mu}{d\ell} = -(a + bE_\mu)$.
- Inelasticity parameter $y \equiv E_{\rm had}/E_\nu$.
- For a finite sized detector $\ell_{\rm max} = 1$ km, we can relate the deposited and neutrino energies by,

$$\frac{E_{\rm dep}}{E_\nu} \approx \langle y \rangle + (1 - \langle y \rangle) b \ell_{\rm max} \,,$$

  which is valid in the region of interest.

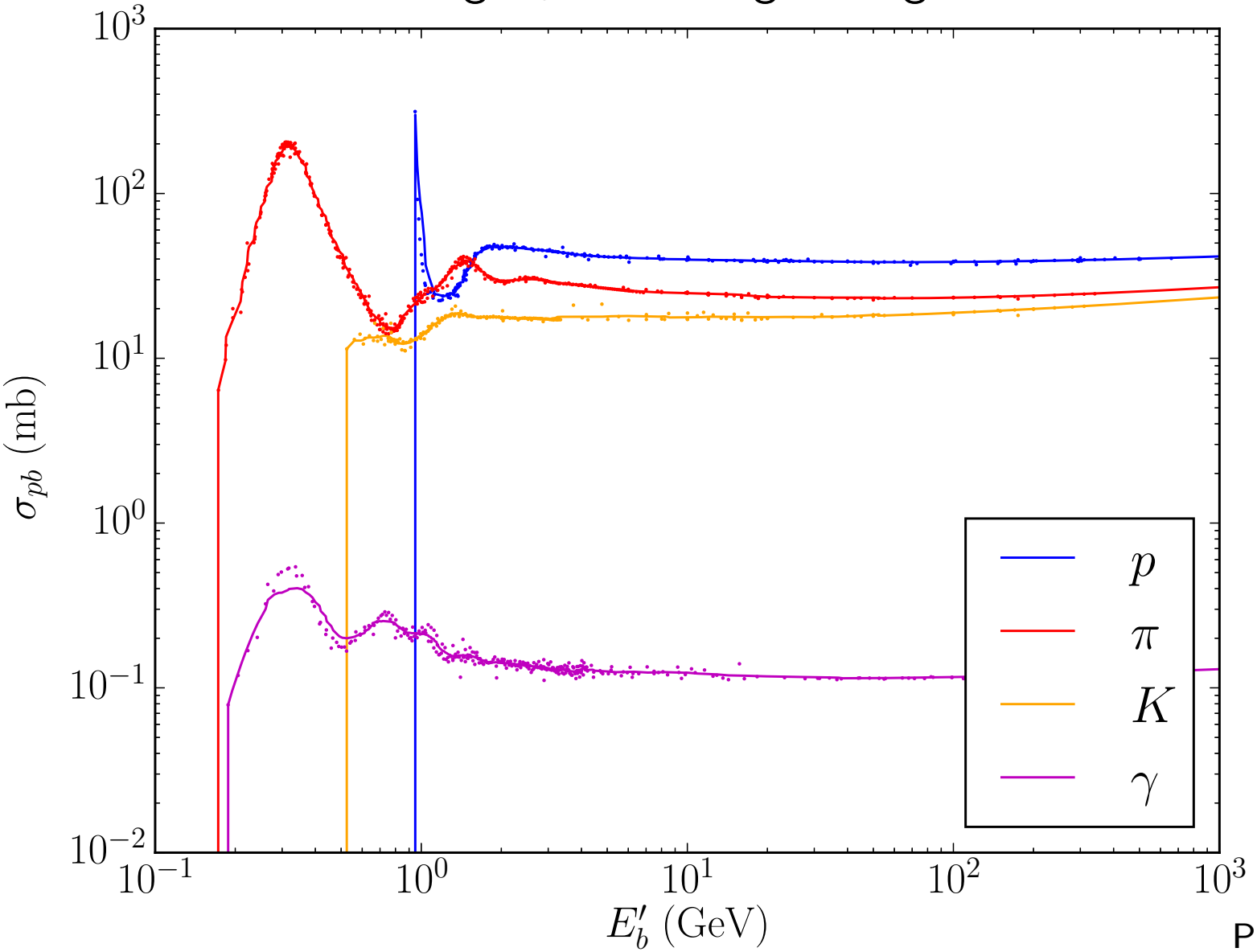
  Anchordoqui, Weiler, et al.: 1611.07905

- $\langle y \rangle \in [0.25, 0.55]$ for relevant energies.

  Gandhi, Quigg, Reno, Sarcevic: hep-ph/9512364

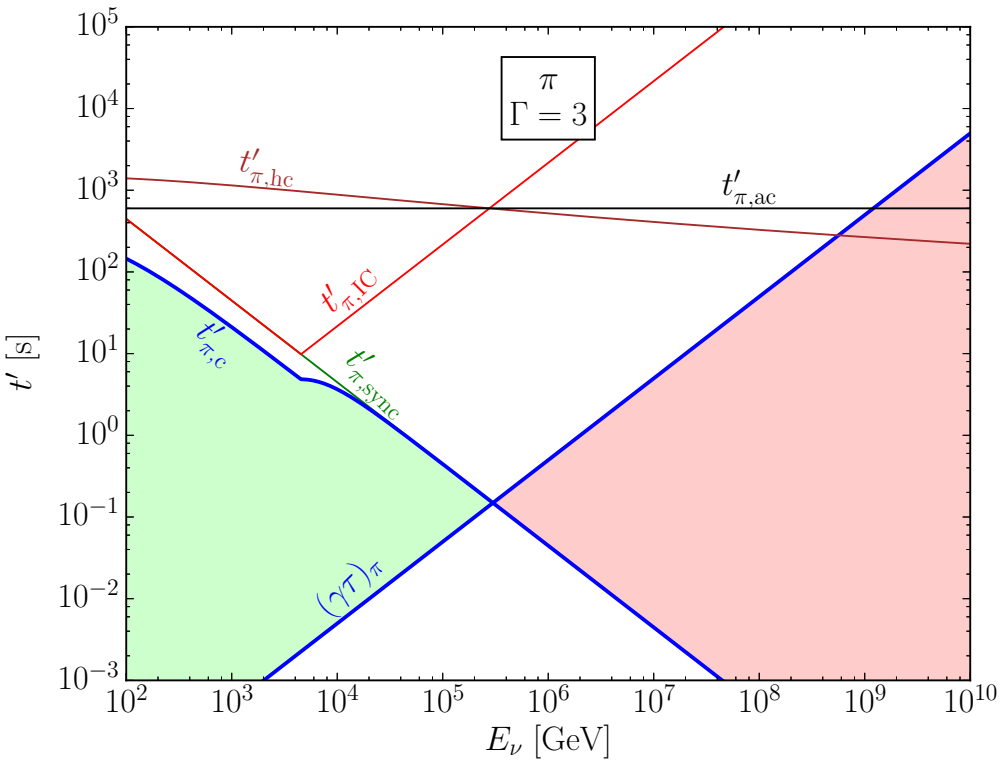
Cross sections

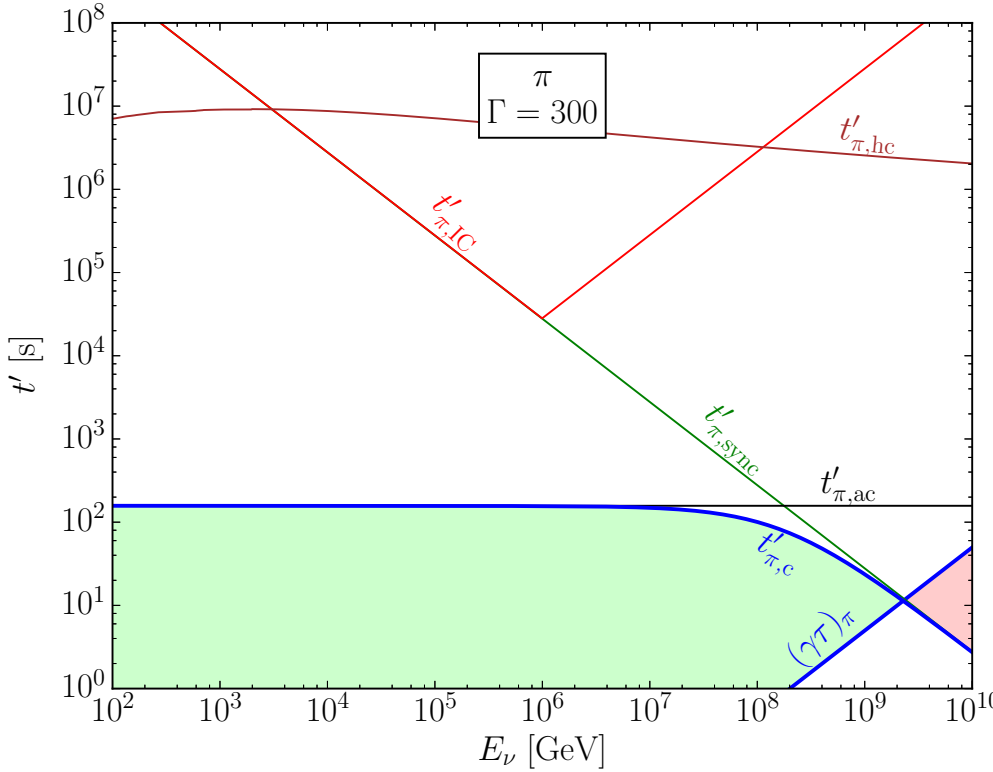
Use the data for low energies, fits for high energies.



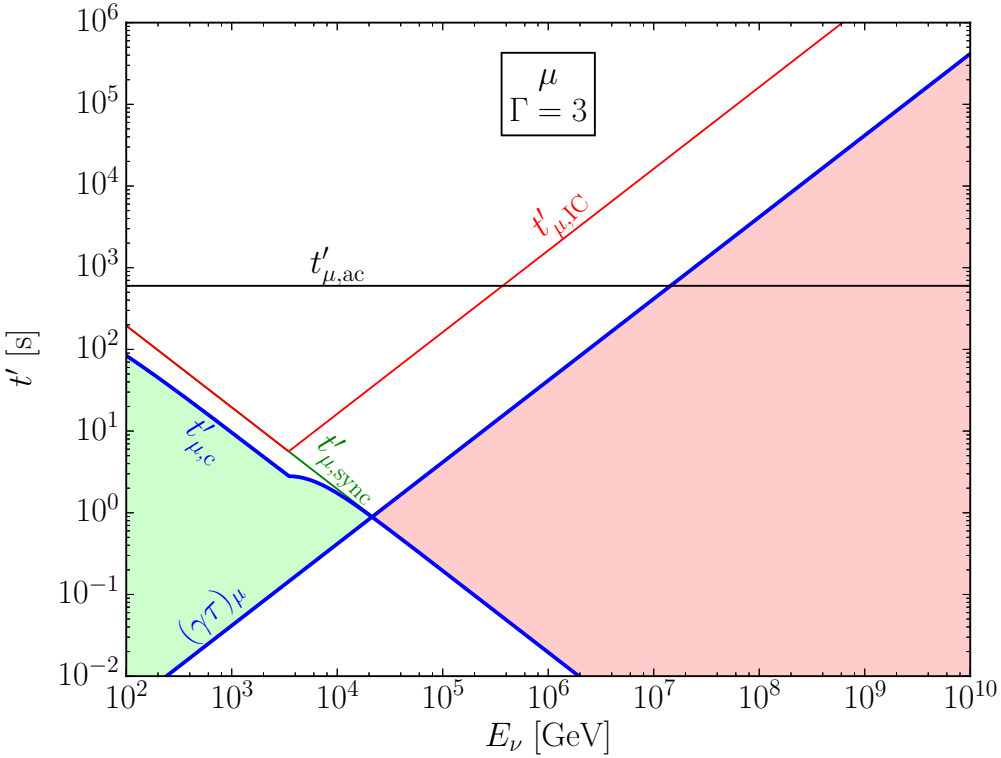
PDG

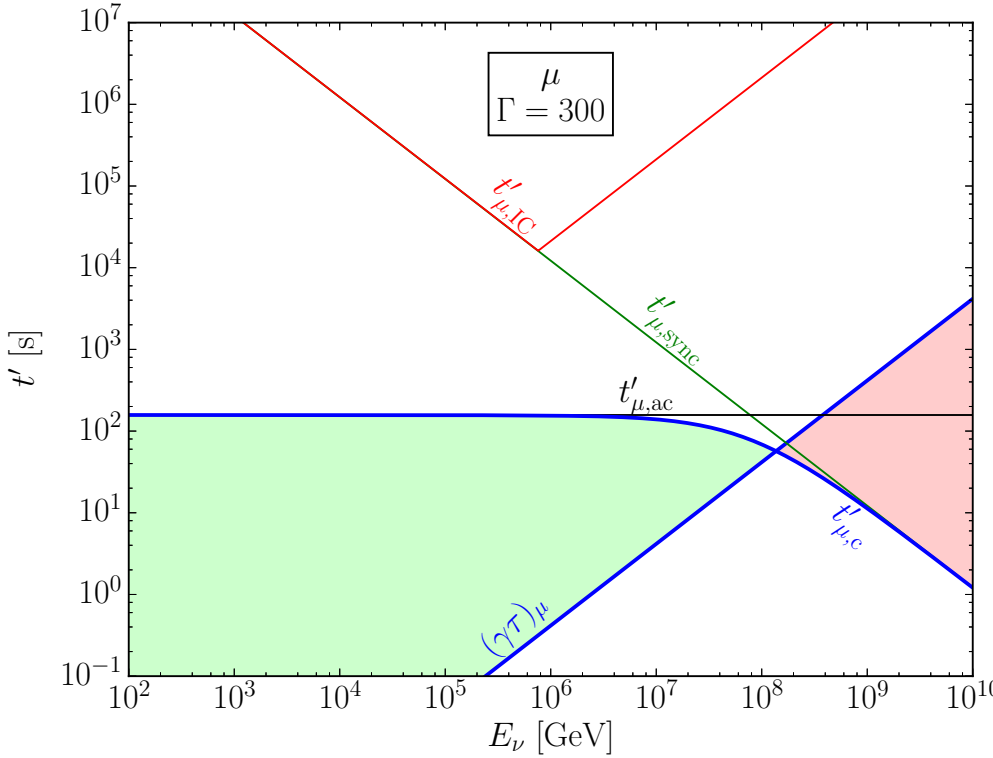
Pion cooling



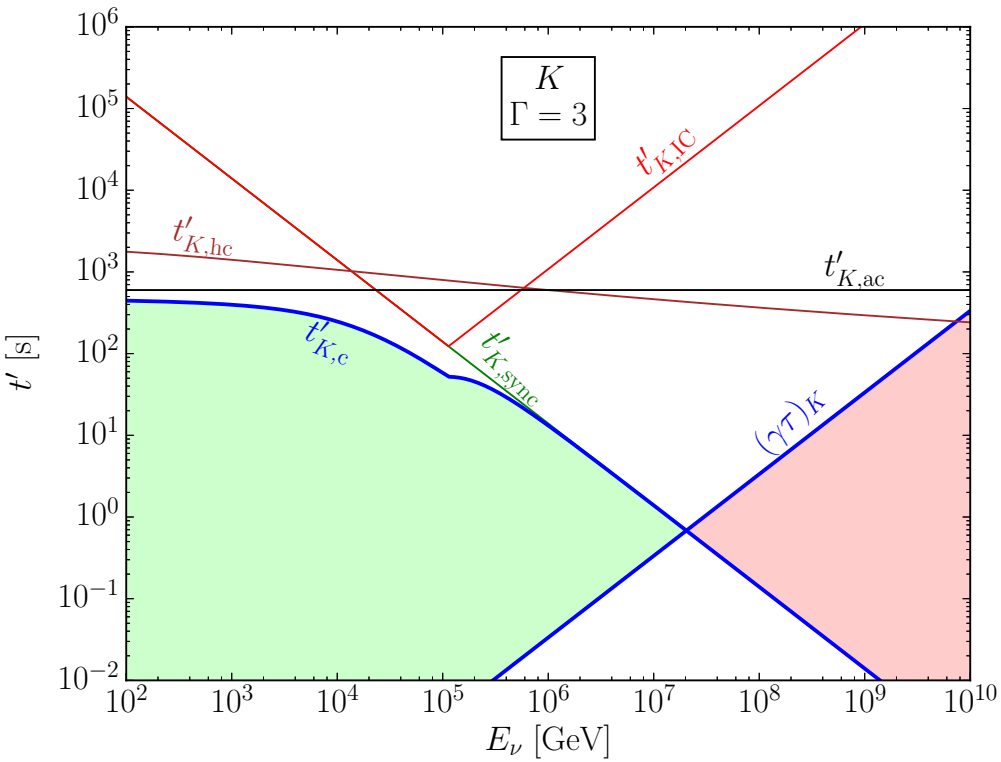


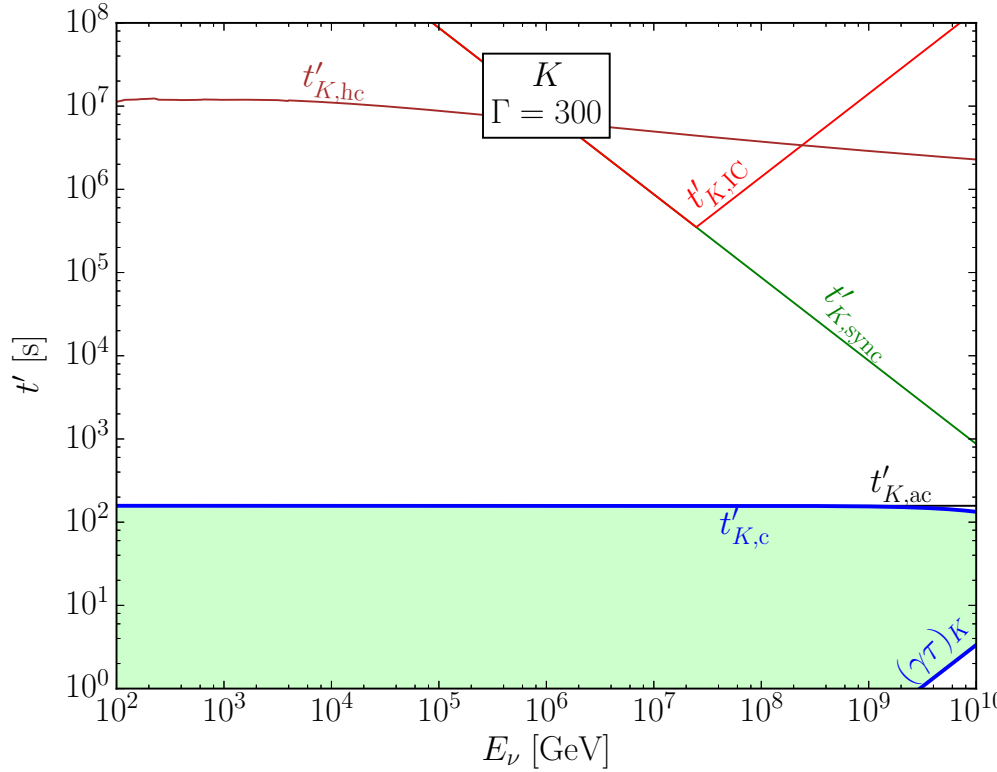
Muon cooling





Kaon cooling



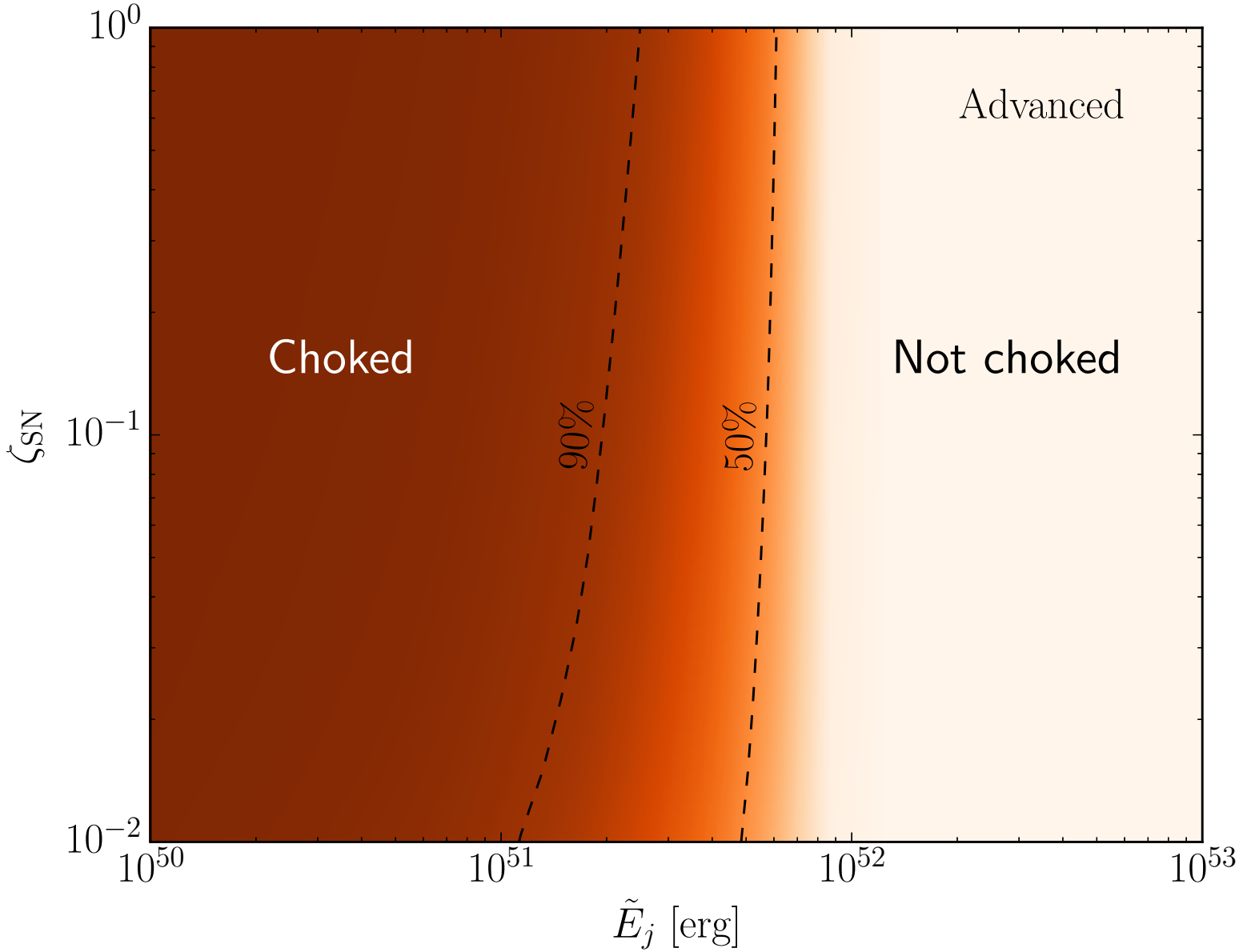


Normalization

Normalize to GRB and CCSNe rates based on Γ along line of sight:

- The CCSNe rate times the fraction ($\zeta_{\rm SN}$) that forms jets normalizes all the jets.
- The HL-GRB rate normalizes the highly relativistic jets ($\Gamma > 200$).

This leads to exponents $\alpha_\Gamma \sim [-1, -3]$ depending on $\zeta_{\rm SN}$.

The redshift evolution follows that of star formation rate not that of GRBs.

Choked fraction