Cosmic neutrinos in the Fermi context

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7th International Fermi symposium
Garmisch–Partenkirchen, Germany

October 15-20, 2017

HELMHOLTZ ASSOCIATION

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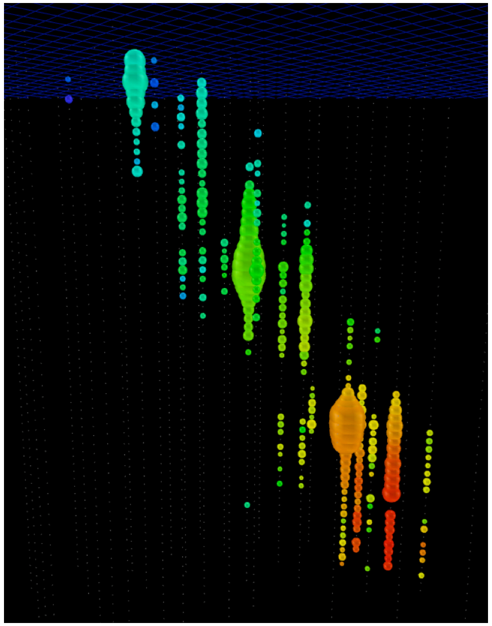
- Introduction
- Observations and (some of) their implications
- Generic multi-messenger relationships
- Neutrinos and the origin of cosmic rays?
  Example: Multi-messenger models for Gamma-Ray Bursts
- Conclusions

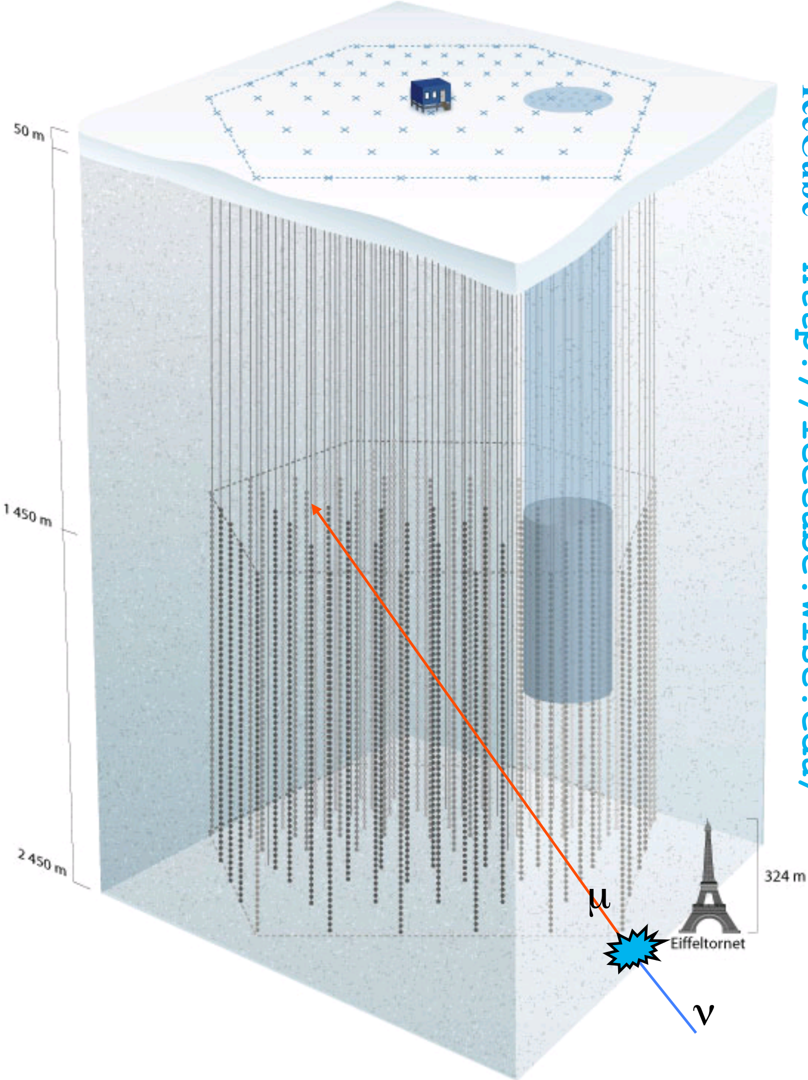
Observing TeV-PeV neutrinos with IceCube

Muon track:

- From ν_μ (mostly)



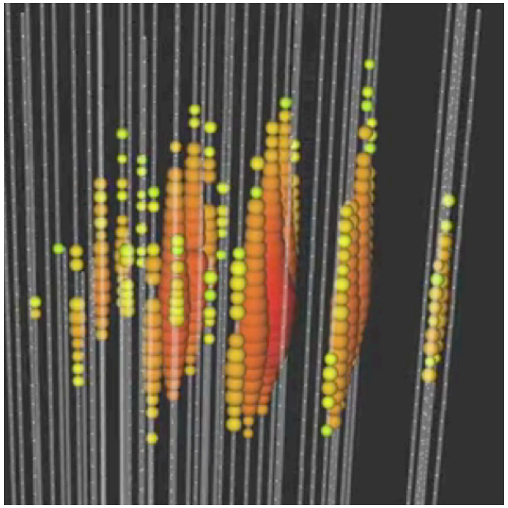
Better directional info



IceCube http://icecube.wisc.edu/

Cascade (shower):

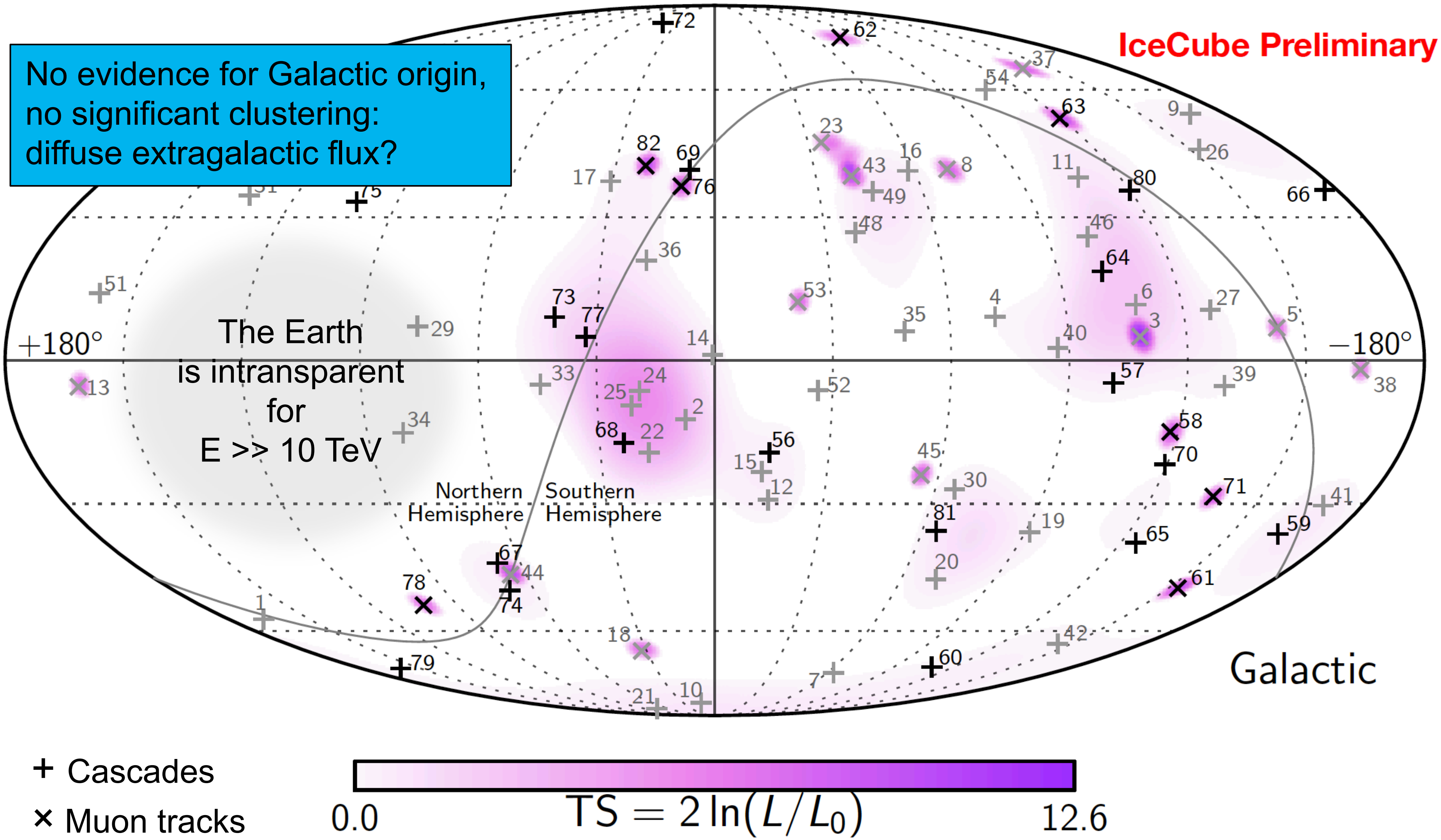
- From ν_e
- From ν_τ
- [From ν_e, ν_μ, ν_τ neutral current interactions]



Better energy info

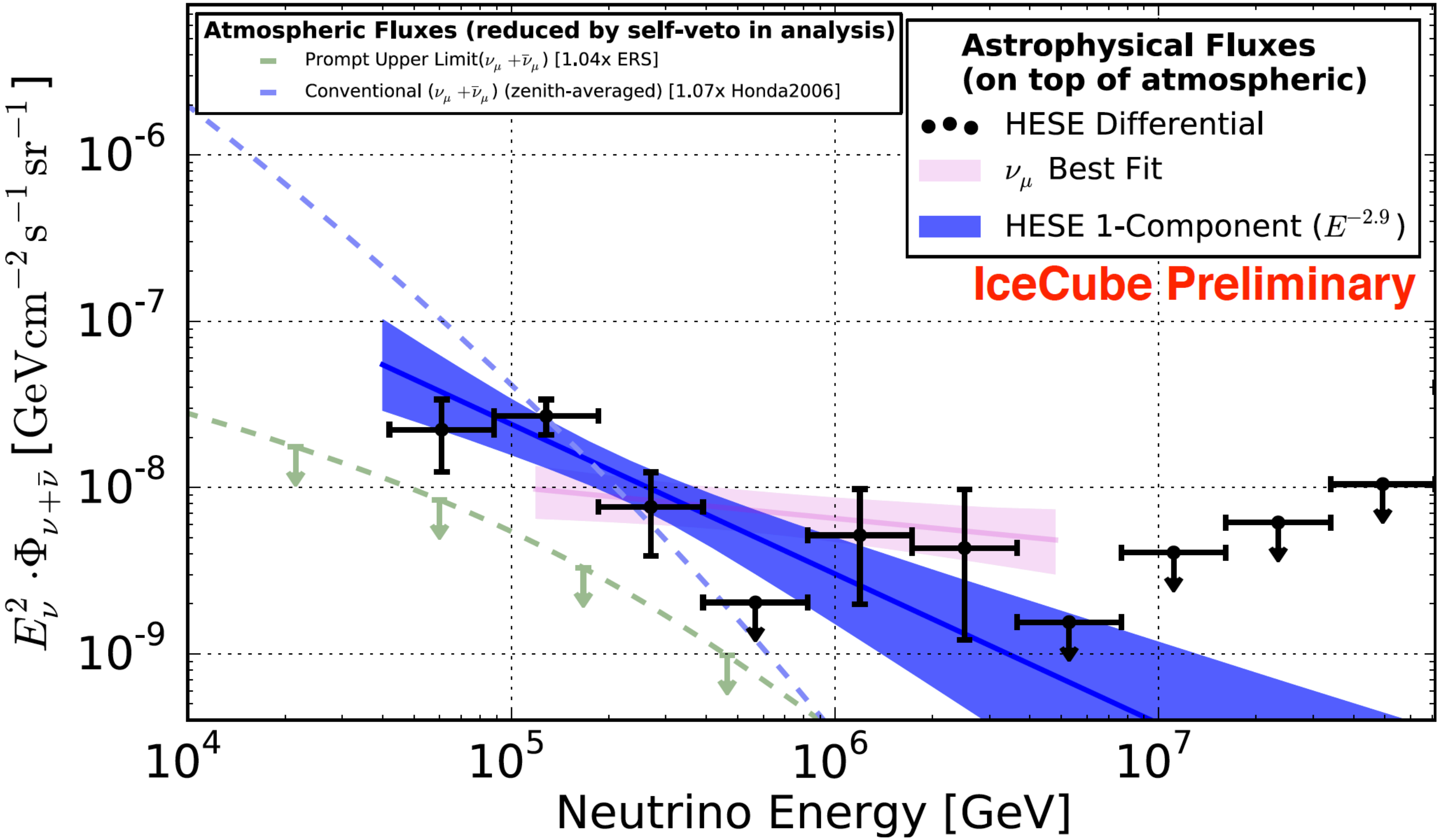
A flux of high energy cosmic neutrinos

No evidence for Galactic origin,
no significant clustering:
diffuse extragalactic flux?



IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014);
update from Kopper at ICRC 2017

Observed neutrino flux

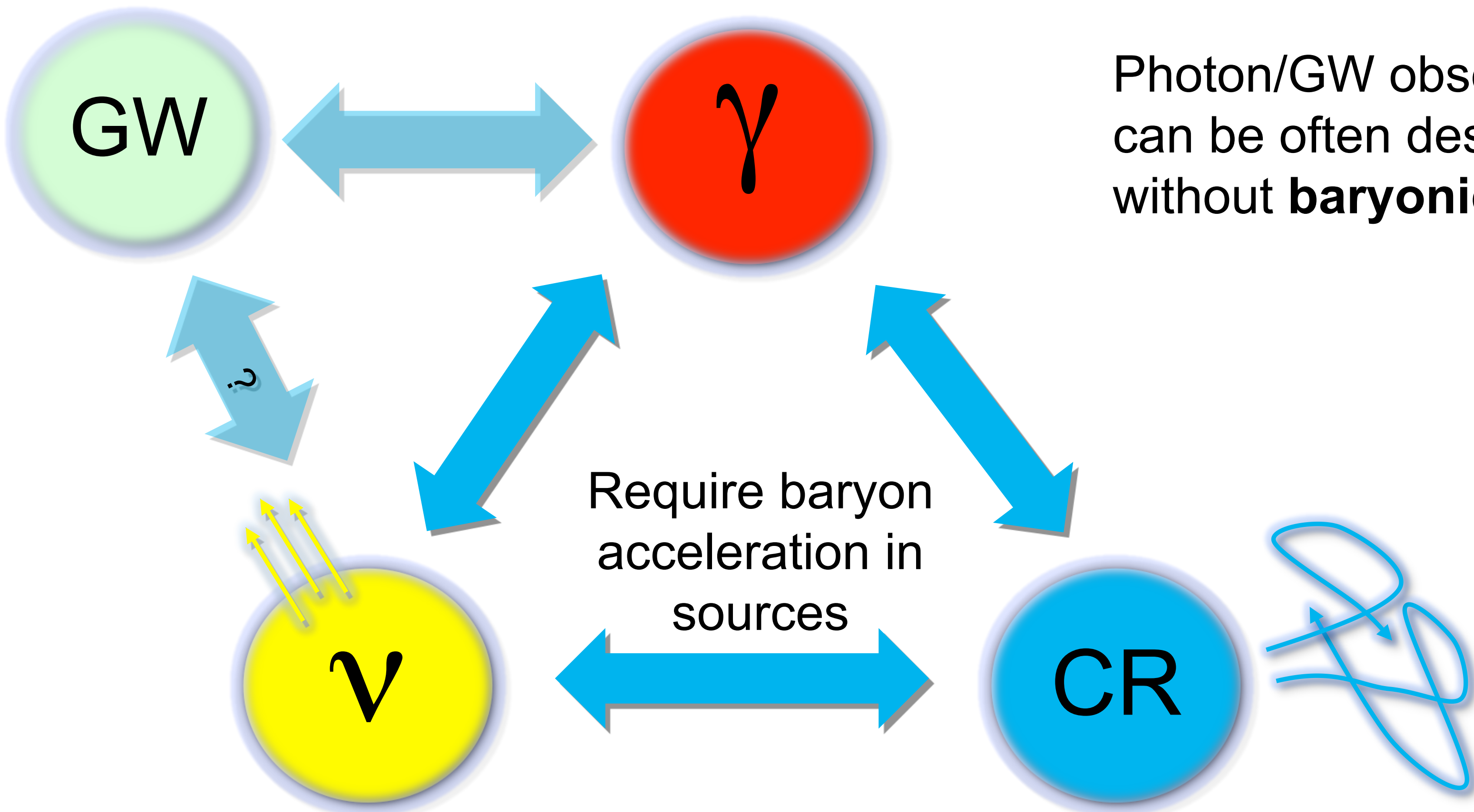


- Could be a two-component flux, but not yet statistically evident

IceCube/Claudio Kopper at ICRC 2017

Multi-messenger astrophysics with neutrinos

Photon/GW observations can be often described without **baryonic loading**



What do the neutrinos tell us?

Extragalactic origin?
- Beyond ankle: Yes! **Auger, Science 2017**
- Beyond 10^{18} eV: Probably
- Between knee and ankle: Maybe

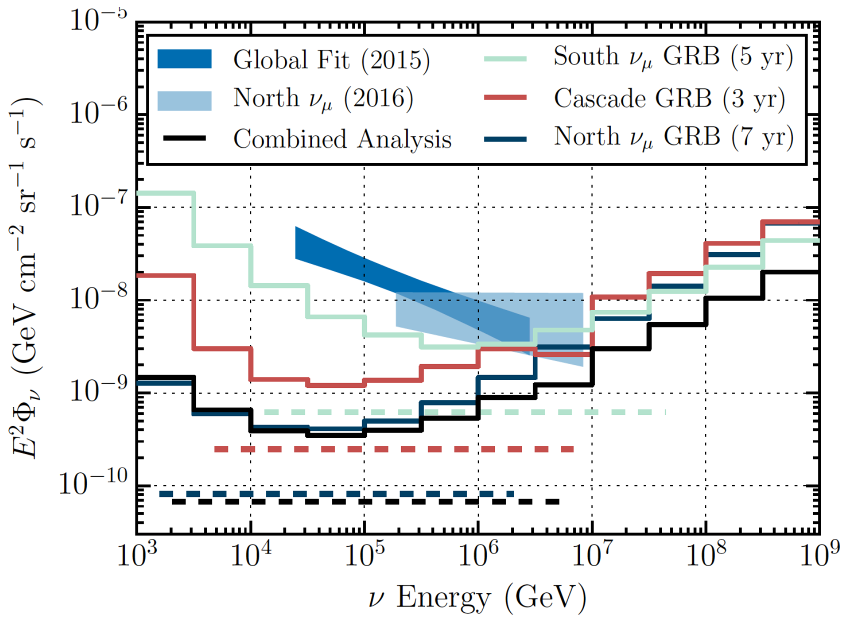
Focus on origin of neutrinos and cosmic rays at highest energies

The prime candidate classes for the νs?

Neutrino telescopes are users of Fermi catalogues

Gamma-Ray Bursts (LGRBs)

- Transients
  (e.g. from explosion of massive star)
- High luminosity over short time

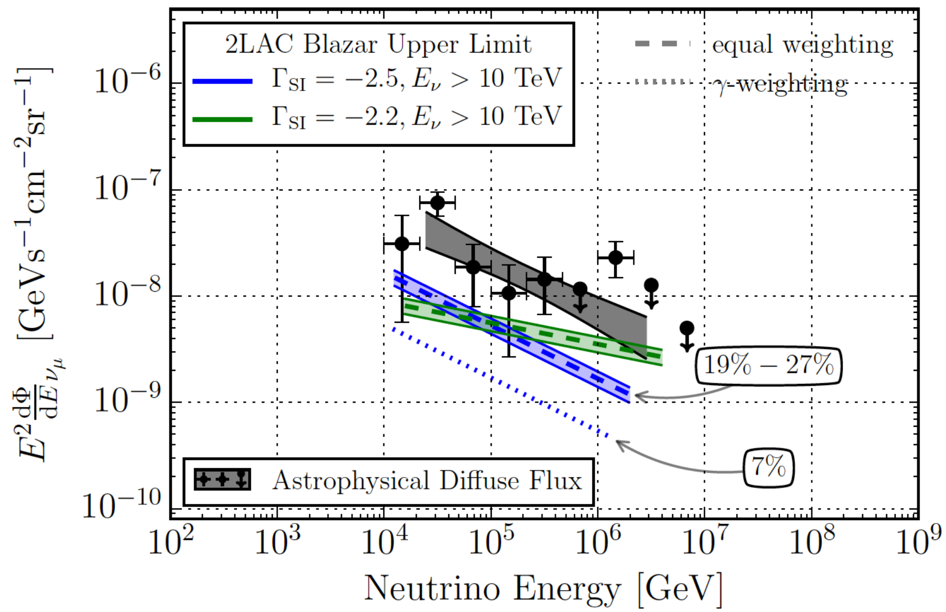


- Less than ~1% of observed ν flux

IceCube, Nature 484 (2012) 351;
Newest update: arXiv:1702.06868

Active Galactic Nuclei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



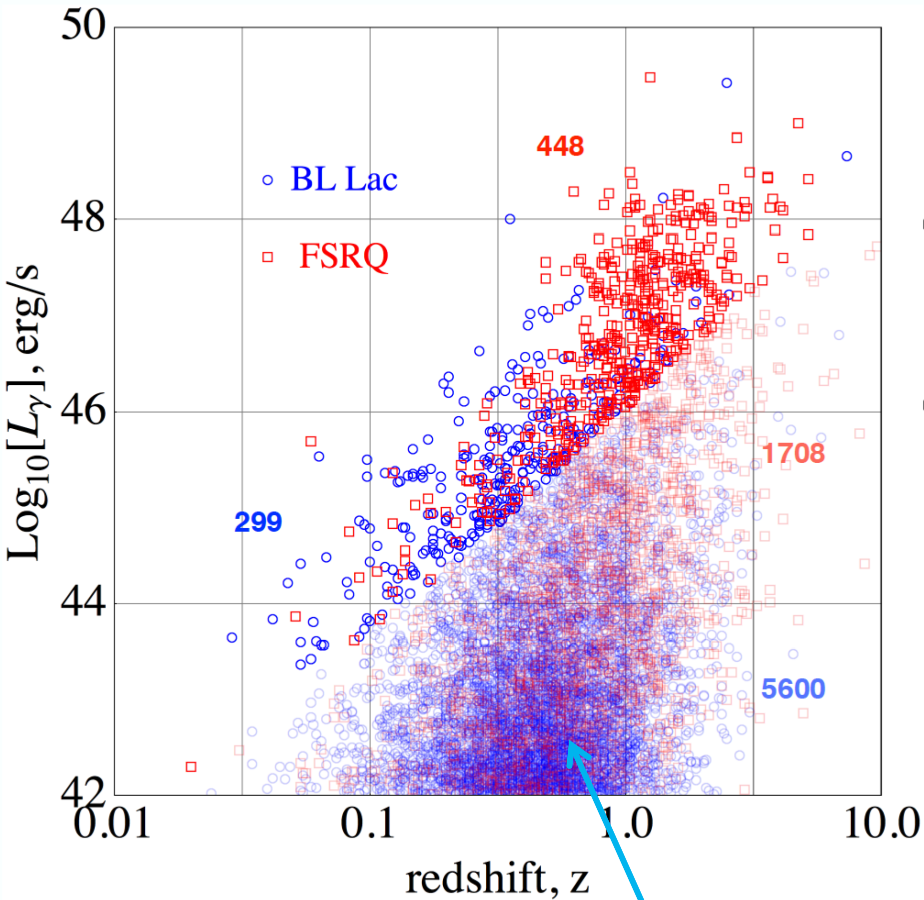
- Less than ~10% of observed ν flux

IceCube, Astrophys. J. 835 (2017) 45
(see proceedings of ICRC 2017 for updates)

Interpretation???? Implications?

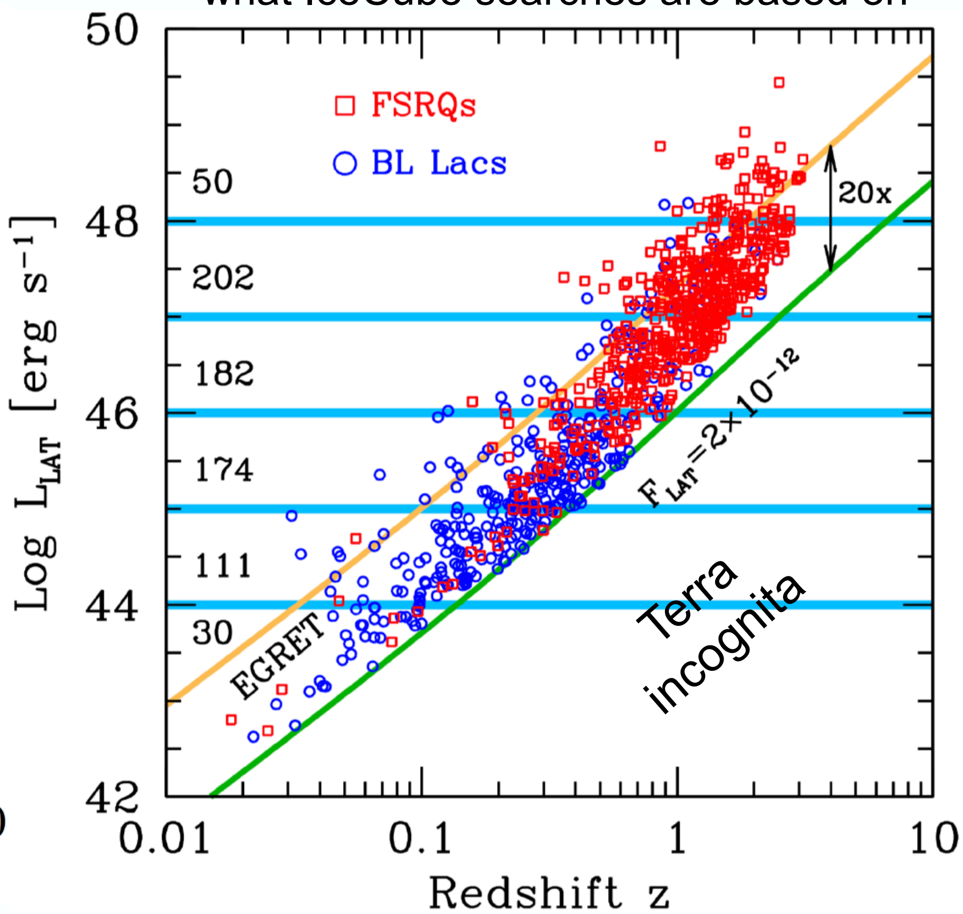
Can AGN blazars power the diffuse neutrino flux?

Simulated



Observed

~ what IceCube searches are based on



Shan Gao et al, in prep.

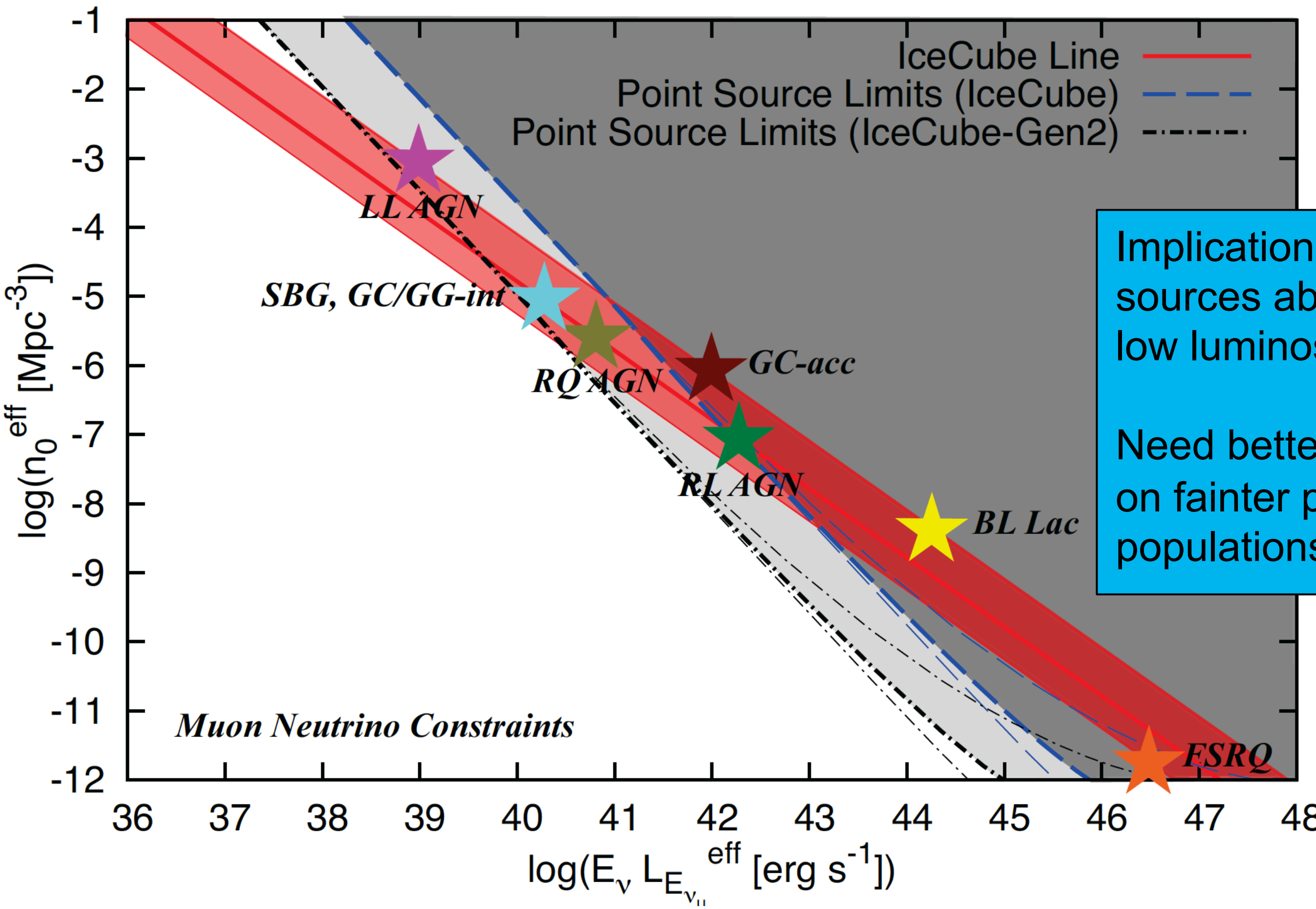
How many unobserved low-luminosity objects?

Ghisellini et al, MNRAS 469(2017), arXiv: 1702.02571

DESY

Neutrino multiplet constraints

> Limits on source density of powerful sources by non-observation of neutrino multiplets from these (here steady sources)



Implications? Neutrino sources abundant, but at low luminosity?

Need better knowledge on fainter part of source populations?

Kowalski, 2014; Ahlers, Halzen, 2014; Fig. from Murase, Waxman, 2016

A simple multi-messenger toy model for the source

If neutrons can escape:
Source of cosmic rays

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutrinos produced in ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic messengers

Δ-resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

2) Interactions in known environments (e.g. CMB)

3) Interactions in guesstimated densities (e.g. in sources)

1) Generic relationships among secondaries

Levels of technical "sophistication" (no of parameters)

$$\pi^0 \rightarrow \gamma + \gamma$$

High energetic gamma-rays; typically cascade down to lower E

Generic multi-messenger relationships

Generic relationships: pp versus pγ interactions

- **pp interactions**

$$p + p \rightarrow \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

Spectrum: $E^{-\alpha}$ non-rel. $E^{-\alpha}$

(Branchings actually not exactly 1/3; see JCAP 1701 (2017) 033)

- Generic relationship (if γ-rays can escape from source)

$$E_\gamma^2 \Phi_\gamma \approx 2(E_\nu^2 \Phi_{\nu_i})|_{E_\nu = 0.5 E_\gamma}$$

- **pγ interactions**: more sophisticated, as relativistic target

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

$E^{-\alpha}$ $E^{-\beta}$ $E^{-\alpha+\beta-1}$

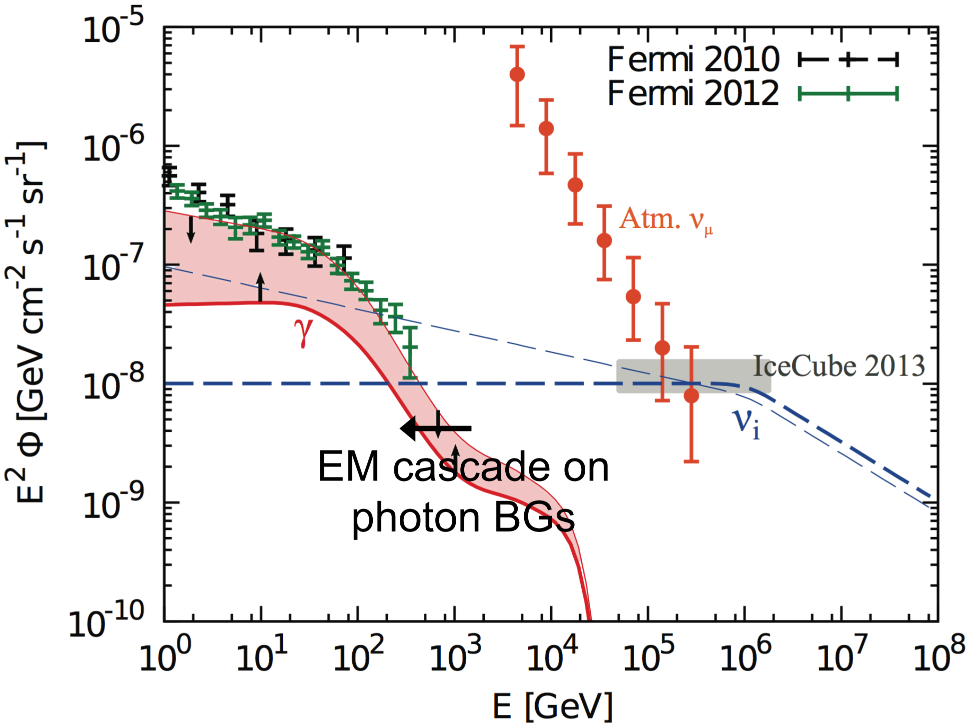
$E^{-\alpha}$ only if β=1! Often "ad hoc" implied assumption. Not for AGN!

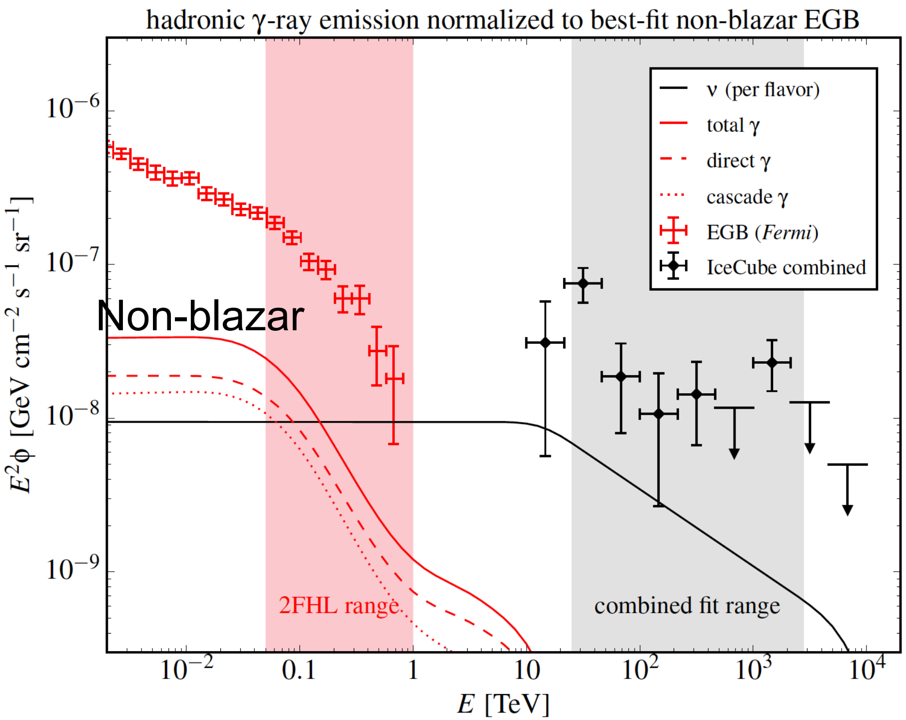
- Generic multi-messenger relationships more assumption-dependent
(e.g. Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87; Murase, Guetta, Ahlers, PRL 116 (2016) 071101; ...)

Constraints from diffuse γ-ray background

$$p + p \to \begin{cases} \pi^+ \\ \pi^- \\ \pi^0 \end{cases}$$

- Limits any pp source class with a neutrino spectrum much softer than ~ $E^{-2.2}$





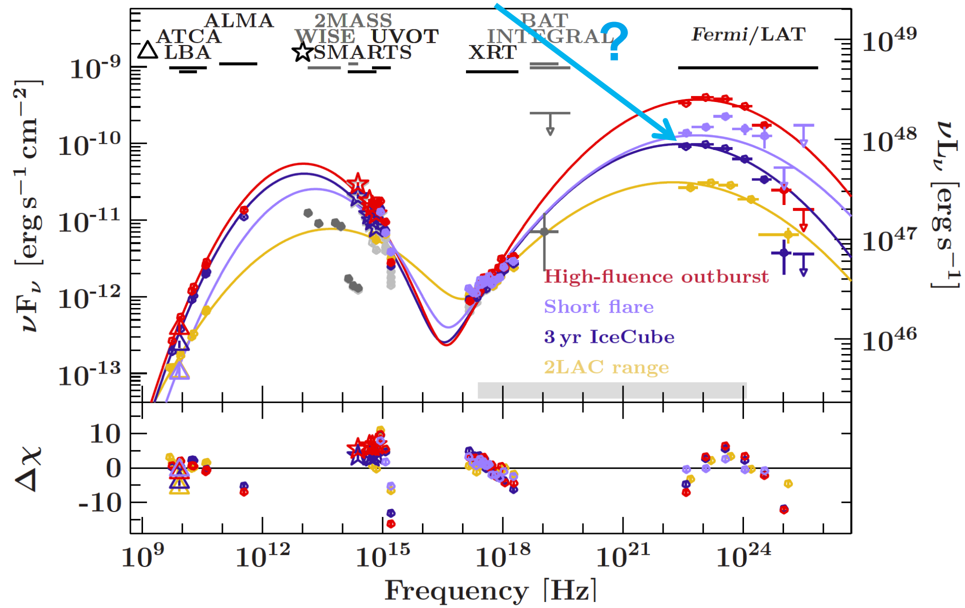
Murase, Ahlers, Lacki, 2013 **Bechtol, Ahlers, di Mauro, Ajello, Vandenbroucke, 2017**

- The constraints may be even stronger if the non-blazar contribution to the extragalactic γ-ray background is small; challenges e.g. starburst galaxies as dominant neutrino sources?

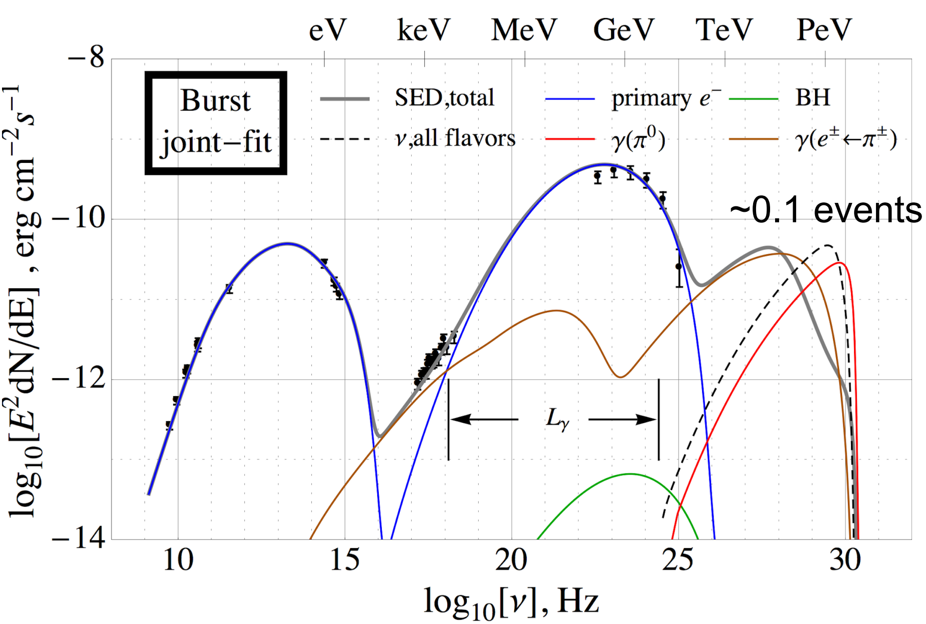
Example: Neutrino production in AGN blazar flares

- Assume that 2nd peak from hadronic γ-rays
- One neutrino event from blazar PKS B1424-418?
- Limitation: hadronic processes are sub-dominant in 2nd peak in SED for this object (self-consist. rad. model):

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$



Kadler et al, arXiv:1602.02012, Nature Physics



Multi-messenger – multi-wavelength models

Blue: leptonic origin
Red/brown: hadronic origin

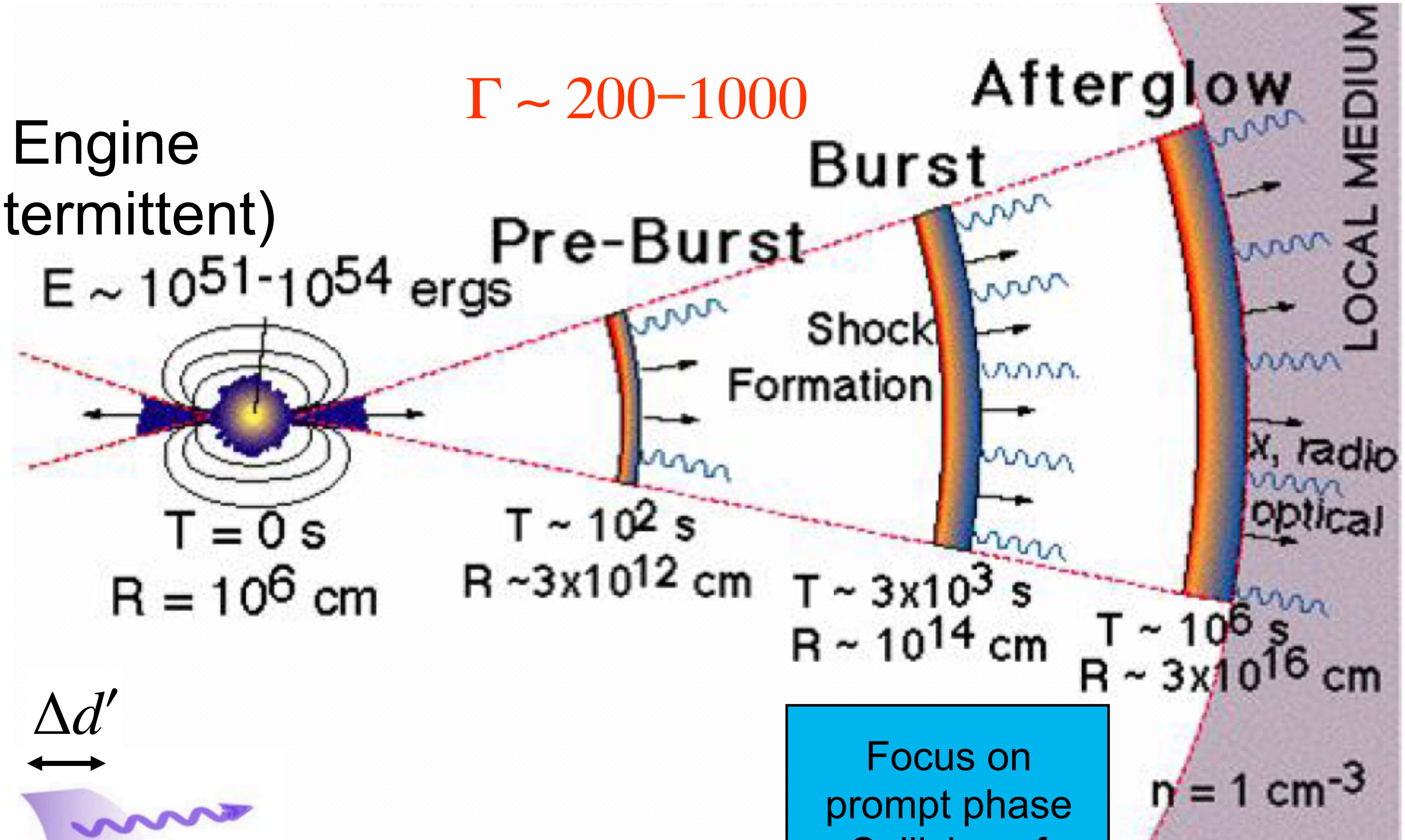
Gao, Pohl, Winter, ApJ, 2017

Neutrinos and the origin of cosmic rays?
Example: Multi-messenger models for GRBs

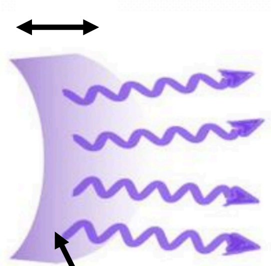
Gamma-Ray Bursts (here long GRBs)

(Source: SWIFT)

Isotropic (equivalent) energy



Isotropic (equivalent) emission region



$$V'_{\mathrm{iso}} = 4\pi R^2 \cdot \Delta d'$$

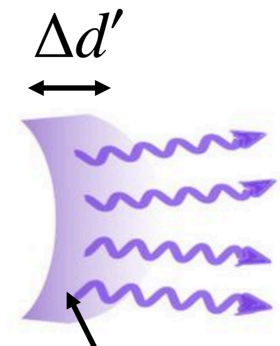
Focus on prompt phase
Collision of shells
⇨ Shocks
⇨ Particle acc.

Neutrino production efficiency in GRBs ... from geometry estimators

- Need photon density, which can be obtained from energy density. Rather model-independently:

$$u'_\gamma \equiv \int \varepsilon' \, N'_\gamma(\varepsilon') \mathrm{d}\varepsilon' = \frac{\boxed{L_\gamma} \, \Delta d'/c}{\boxed{\Gamma^2} \, V'_{\mathrm{iso}}} = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

L'_γ



$$V'_{\mathrm{iso}} = 4\pi \, R^2 \cdot \Delta d'$$

- Scales ~1/R^2 from simple geometry arguments
- *Internal shock scenario*: e.g. Guetta et al, 2004

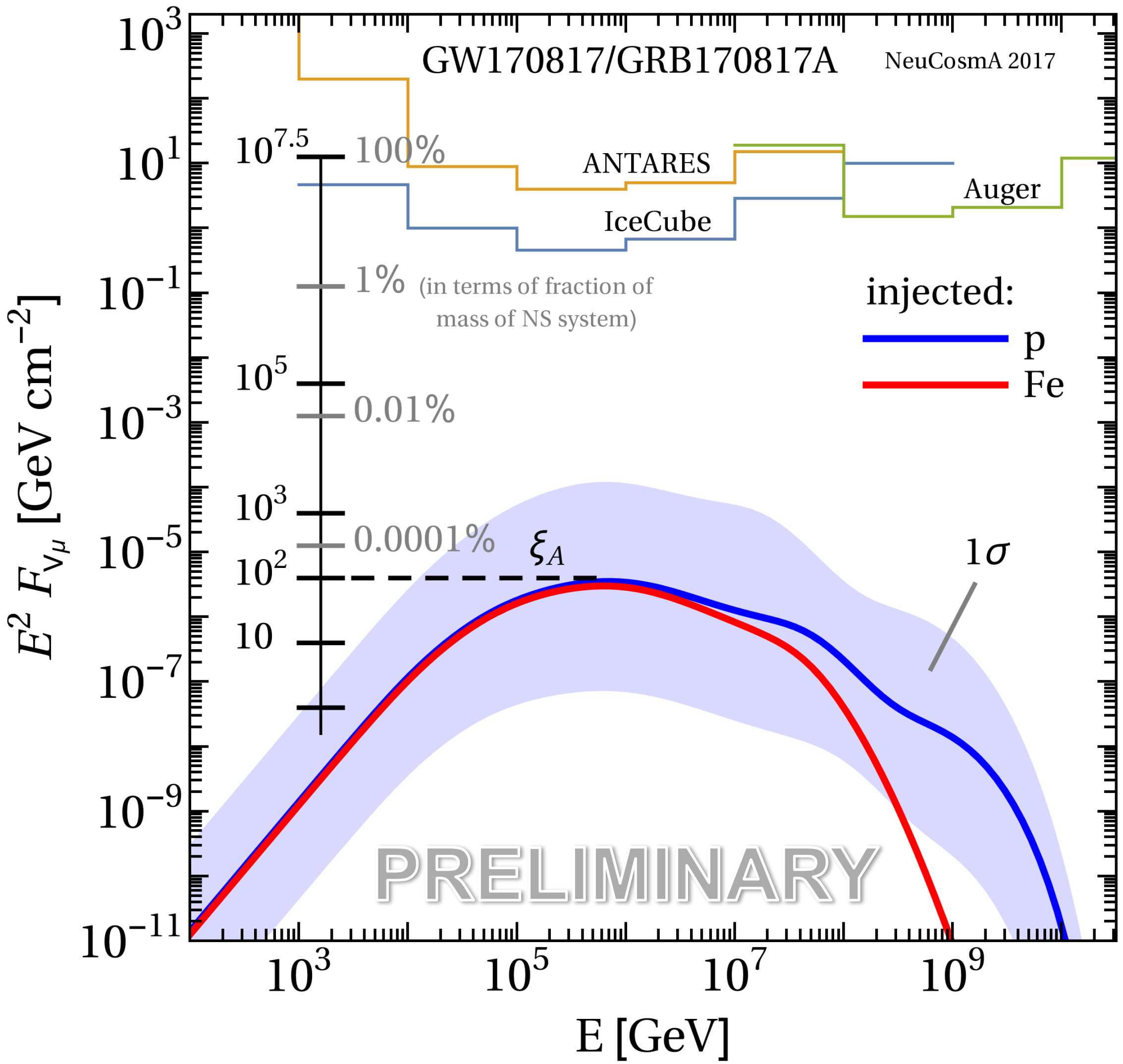
$$R \simeq 2\,\Gamma^2 \, \frac{c\, t_v}{1+z} \qquad \Delta d' \simeq \Gamma \frac{c t_v}{1+z} \quad \Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\mathrm{br}})$$

$$\left(f_{p\gamma} \propto \Delta d' / \lambda'_{\mathrm{mfp}} \sim \Delta d' \, \sigma_{p\gamma} u'_\gamma / (\epsilon_{\gamma,\mathrm{br}}/\Gamma) \right)$$

- *Magnetic re-connection models*: est. for *R* from pulse timescale (larger)
- *Photospheric emission*: *R* corresponds to photospheric radius
- *Multi-zone models*: *R* and Δd' individually calculated for each collision
- **Production radius R and luminosity L_γ are the main control parameters for the neutrino production** [t_v does not vary as much as L_γ]

e.g. He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5) for details

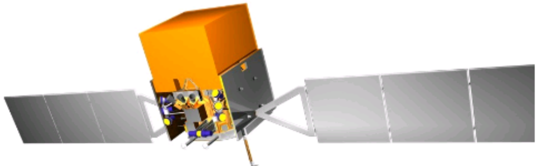
Example: Expected neutrino fluence from SGRB 170817A



- Expectation yields ~10^{-4} events for a baryonic loading (energy baryons/γ-rays in jet) ξ_A = 100 (scales with ξ_A)
- Based on Fermi-GBM SED and flux
  Goldstein et al, 1710.05446
- Structured jet model calculation;
  R optimistic close to photosphere ~ 10^{13} cm
  Abbott et al, ApJ 747 (2017) L13
- Uncertainty region (1σ) includes SED, break energy, z, γ-ray flux, t_v, T_{90}

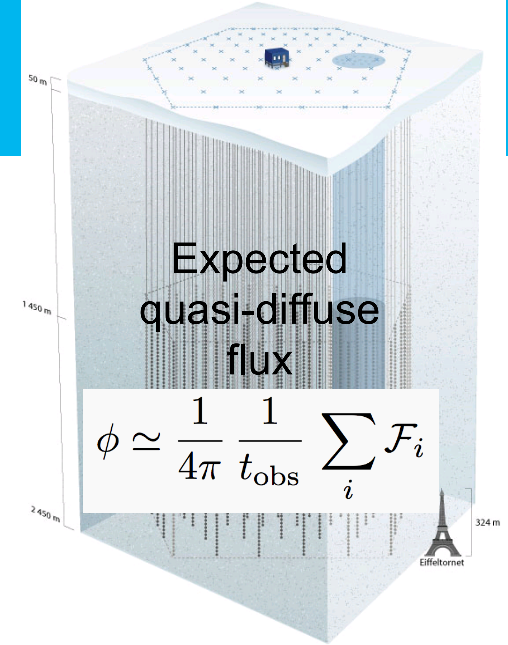
Biehl et al, in prep.;
neutrino bounds from arXiv:1710.05839

GRB stacking bounds



Gamma-ray observations
(e.g. Fermi, Swift, etc)

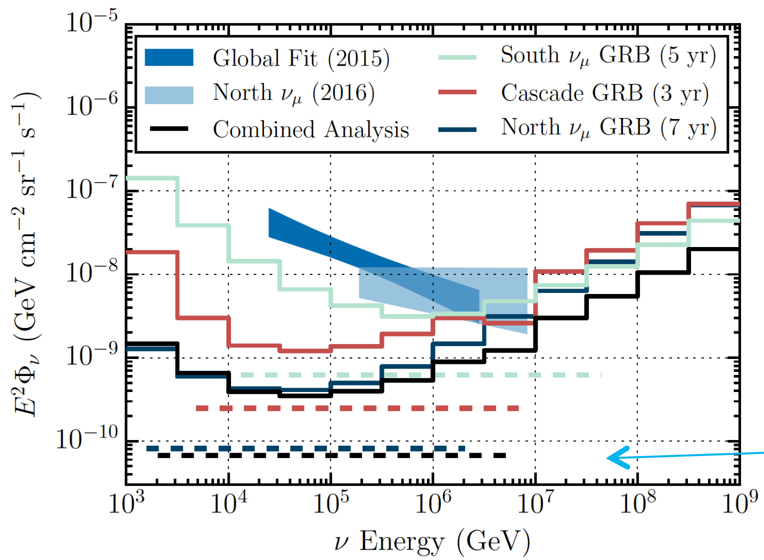
Use information on individal GRBs to compute expected neutrino fluence F_i

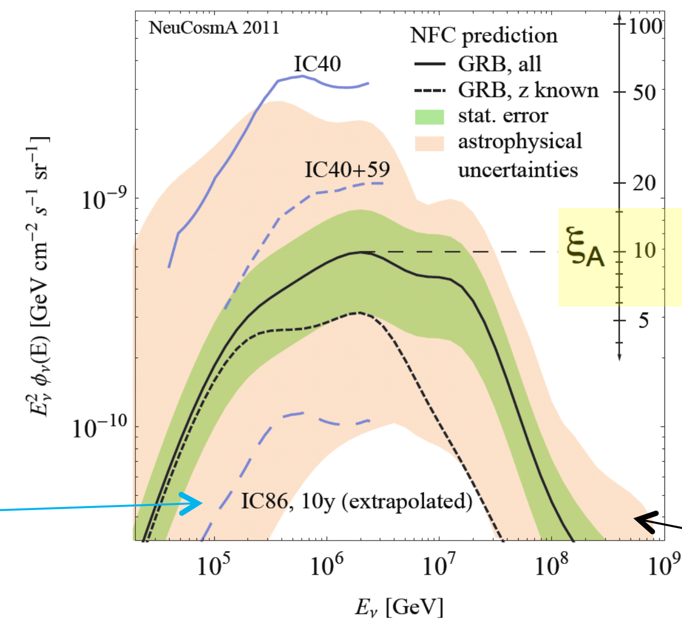


Expected quasi-diffuse flux

$$\phi \simeq \frac{1}{4\pi} \frac{1}{t_{\rm obs}} \sum_i \mathcal{F}_i$$

- Current result vs. one zone prediction from γ-rays: Exclude GRBs as UHECR sources? But what is exactly the required ξ_A?





!

Baryonic loading:
Ad hoc assumption (est. from UHECRs)

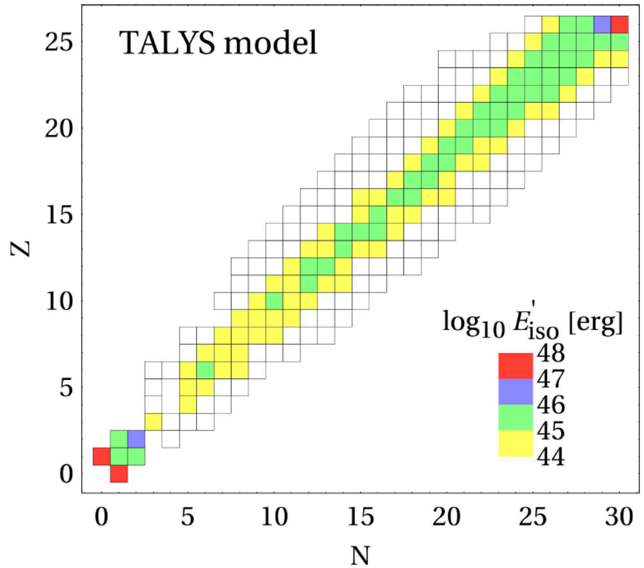
Geometry estimators (int. shock)

IceCube, Nature 484 (2012) 351;
Fig. from update: arXiv:1702.06868

Hümmer et al PRL 108 (2012) 231101;
Waxman, Bahcall, 1997; Guetta et al, 2003

Caveat 1: UHECR composition

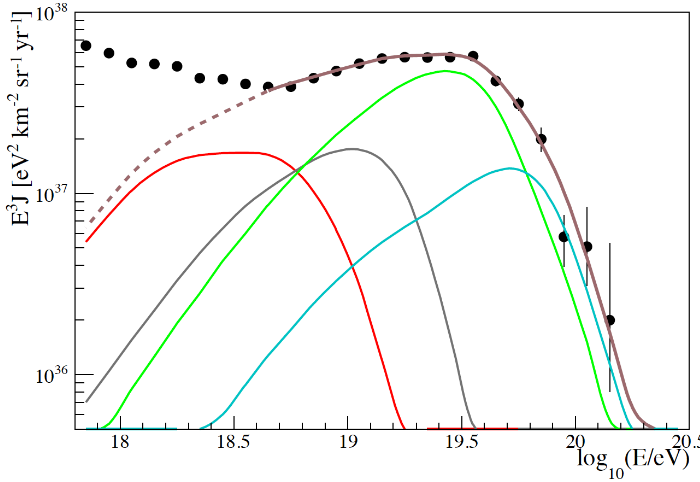
- UHECR composition is heavy. Baryonic loading can be obtained from UHECR fit →
- Need to compute the nuclear cascade in the emission zone
  (otherwise same logic as proton model)

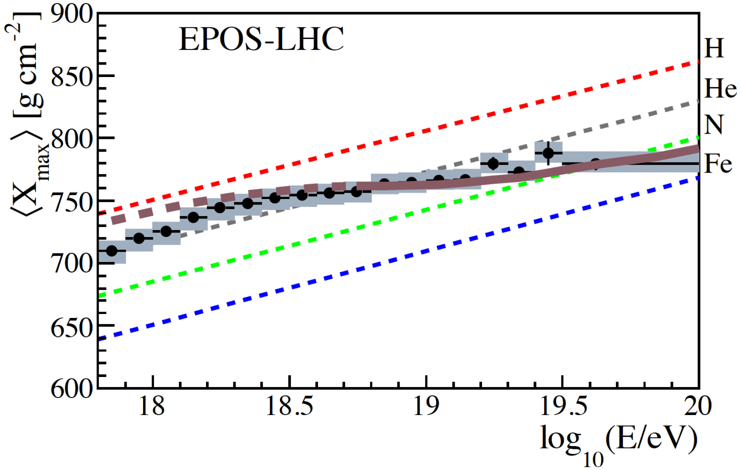


Disintegration of ^{56}Fe ***within*** a GRB shell
($L_\gamma = 10^{52}$ erg/s)

Boncioli, Fedynitch, Winter, Scientific Reports, 7 (2017) 4882

Auger global fit

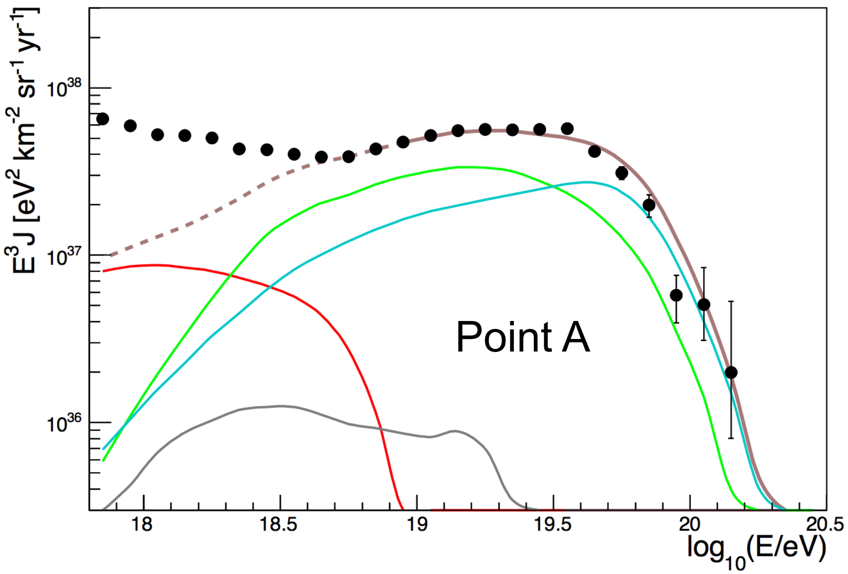


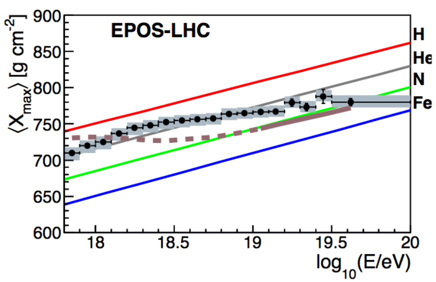


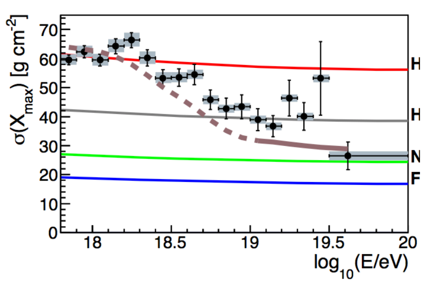
Auger global fit, 1612.07155

Neutrino data constrain the prompt emission mechanism

… if GRBs are to be the sources of the UHECRs

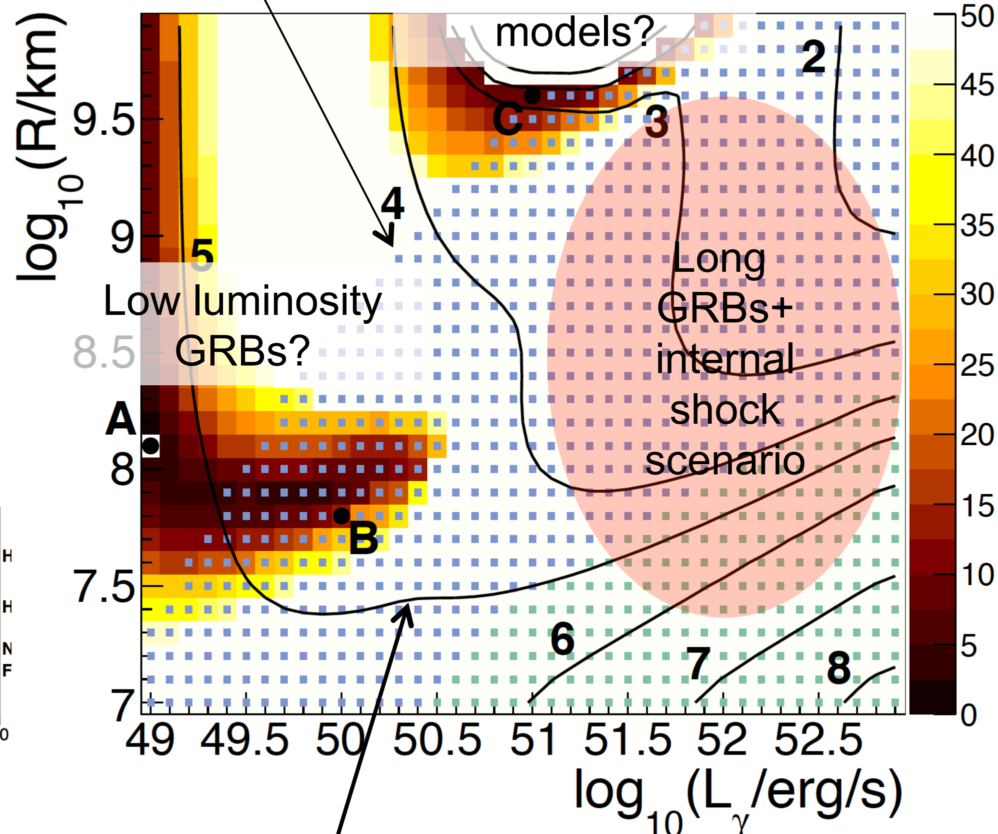






Combined (one zone) source-propagation model (internal shock scenario): Description of Auger data with pure ^{28}Si injection into radiation zone

IceCube 2017 prompt bound; 1702.06868

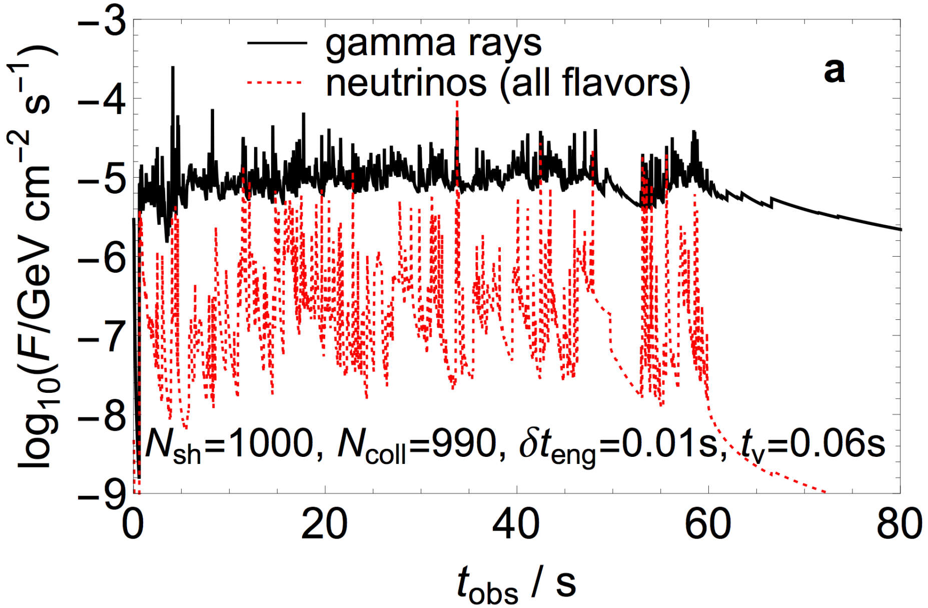


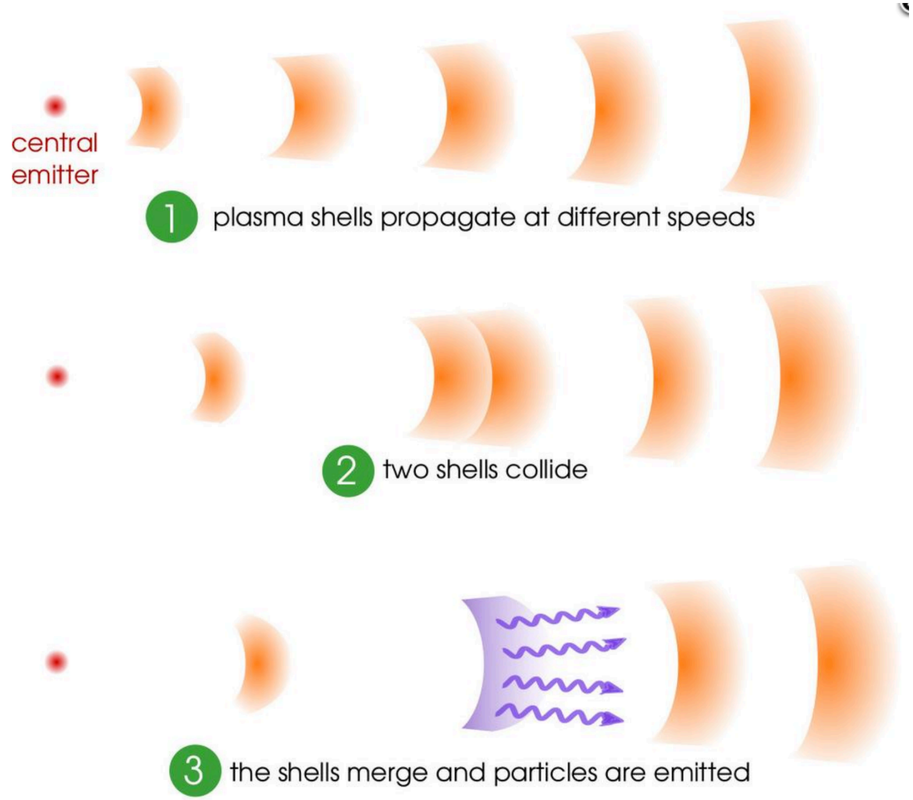
Log$_{10}$ f_B (baryonic loading)

Biehl, Boncioli, Fedynitch, WW, A&A accepted, arXiv:1705.08909

Caveat 2: The emission comes from multiple zones

- Set out a number of shells with a (stochastic) Γ *factor distribution*
- Shells collide, merge and cool by radiation of energy
- Light curve predictable (see below)
- Efficient energy dissipation (e. g. into gamma-rays) requires broad Γ factor distribution

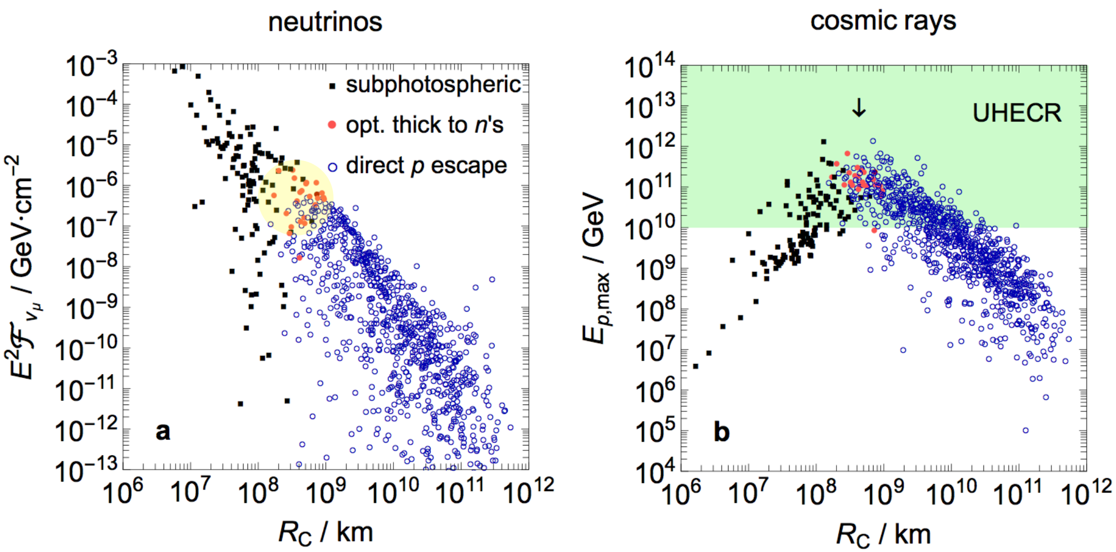




Bustamante, Baerwald/Heinze, Murase, Winter, Nature Commun. 6, 6783 (2015) + ApJ 837 (2017) 33;

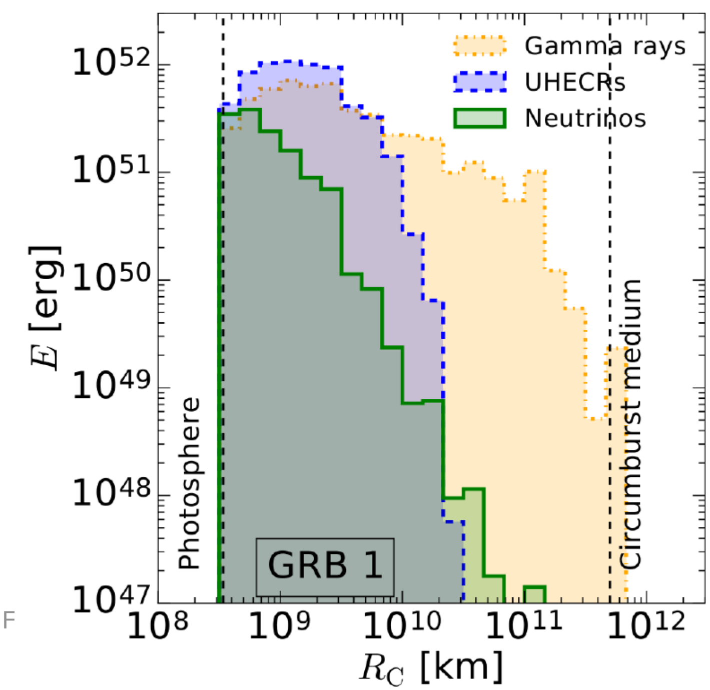
based on Kobayashi, Piran, Sari, 1997; see also Globus et al, 2014+2015

Production of different messengers



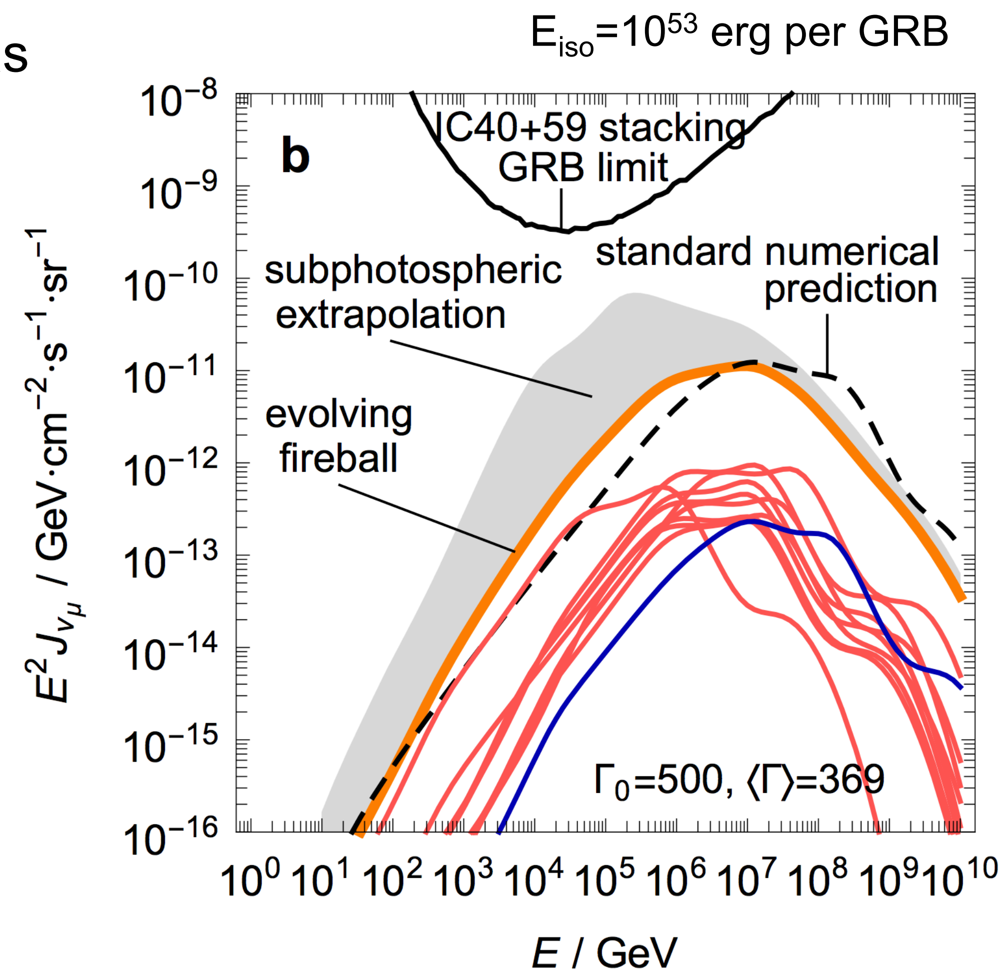
Bustamante et al
Nature Commun. 6, 6783 (2015) +
ApJ 837 (2017) 33

- The different messengers originate from → different regimes of the GRB *where the photon densities are very different*
- More fundamental implications?
  - Quantities inferred from γ-ray observations not representative for neutrinos and UHECRs? Especially high-E γ-rays need low densities!
  - Neutrinos and cosmic rays come from different regions or objects? (e. g. AGNs over blazar sequence)



Consequences for neutrino production

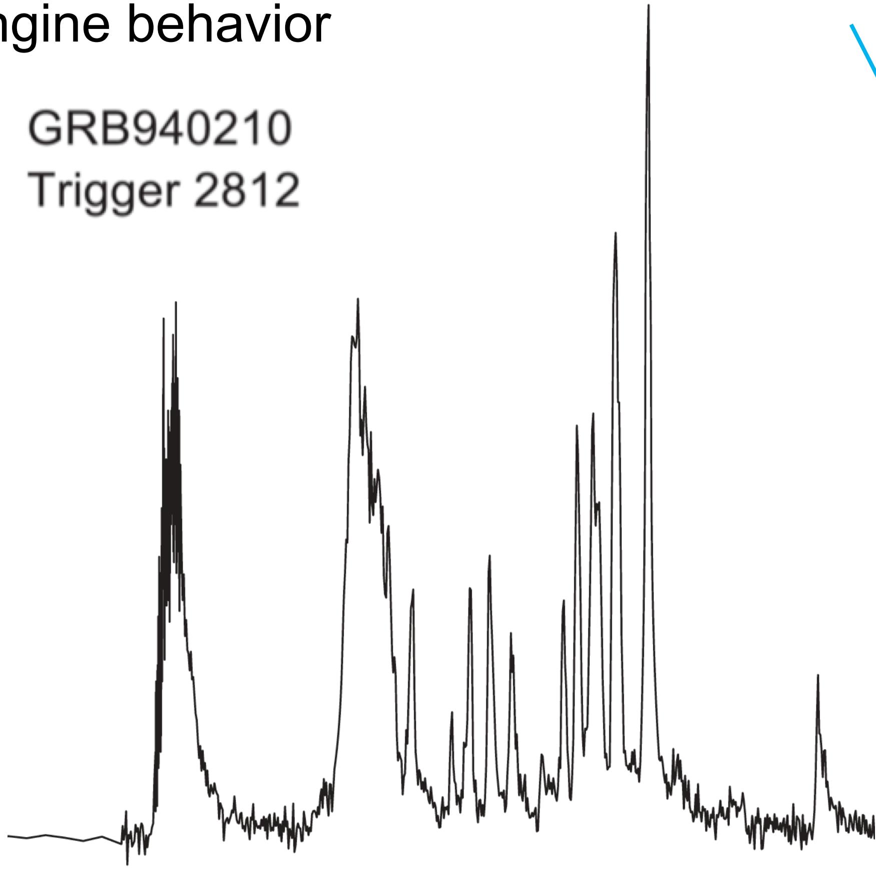
- This model: Take observed flux as input for target photon spectrum
- Sub-photospheric contribution is an extrapolation (speculation?)
- Neutrino flux is dominated by a few collisions with high densities beyond photosphere
- Can be used to predict a "minimal" (and **robust** wrt. geometry estimators) super-photospheric neutrino flux ➔ IceCube-Gen2?
  $E^2\,\phi \sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}



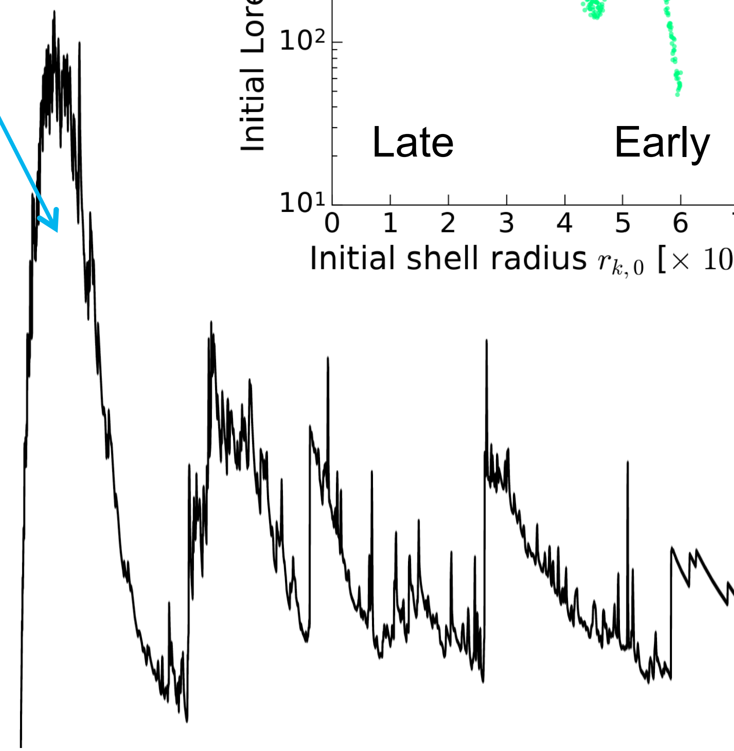
Bustamante, Baerwald/Heinze, Murase, Winter, Nature Commun. 6, 6783 (2015) + ApJ 837 (2017) 33

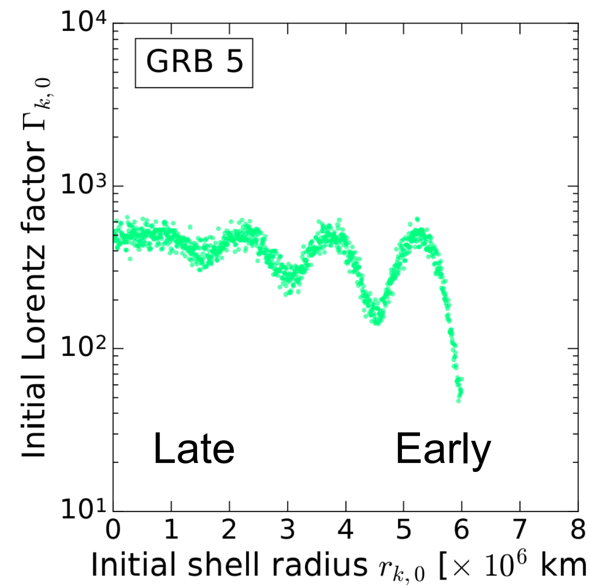
Non-trivial light curves: observed vs. synthetic

- Can be produced from the engine behavior:
  Longer pulses require “disciplined” (non-stochastic) engine behavior



BATSE

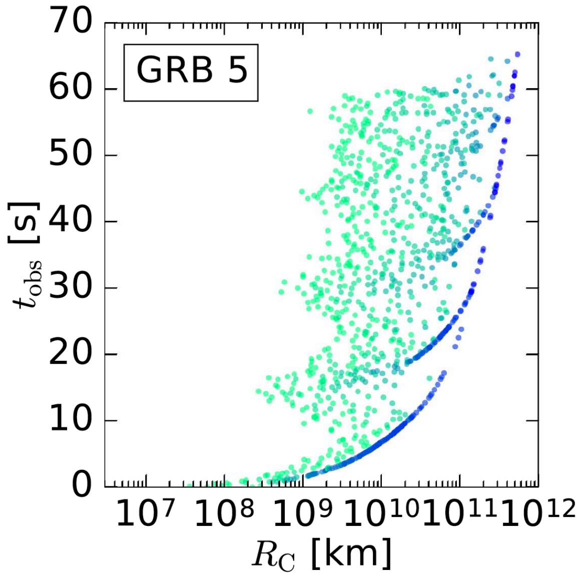


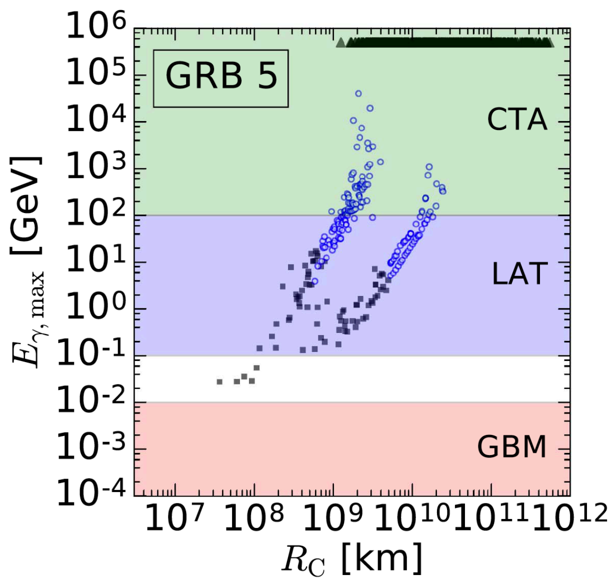


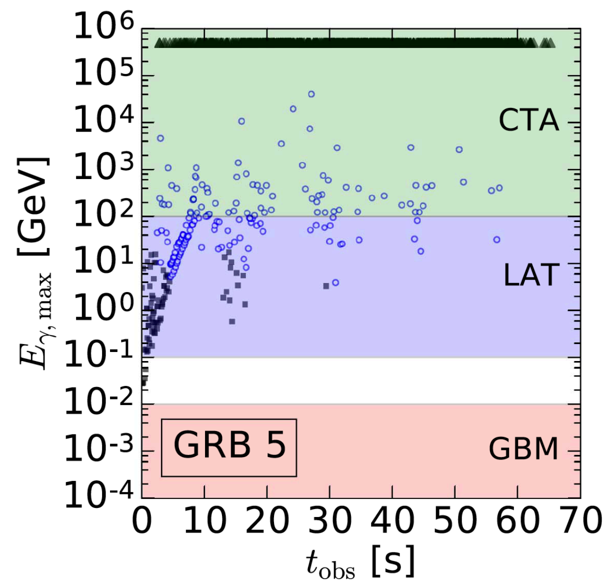
Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33

Features of non-stochastic engine behavior

> There is a correlation between observation time and R_C:





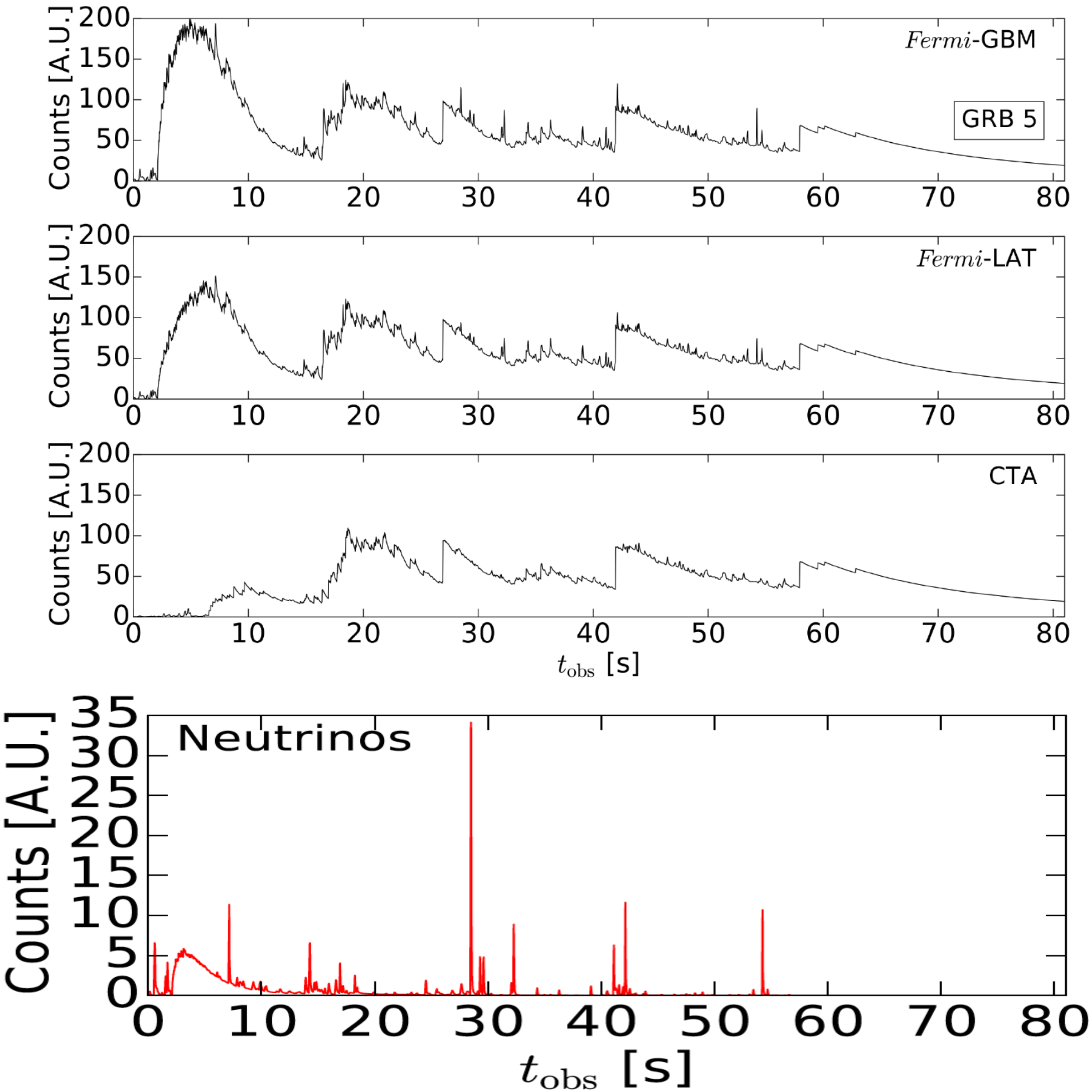


> Consequences:

- There is an early suppression of high-E γ-ray production (which may be interpreted as delay)
- Overall neutrino production can be lower in these sources

Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33

Multi-messenger-multi-wavelength light curves



- Delay a few seconds in Fermi-LAT, order ten seconds in CTA (similar to GRB 080916C, Abdo et al, Science, 2009)
- Neutrino emission efficiency high in suppression region + uncorrelated contributions
- Future perspectives for more sophisticated source diagnostics?

Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33

Conclusions and future prospects

- Neutrino telescopes are heavy “users” of Fermi catalogue data, such as in stacking searches
- The extragalatic background light measurements of Fermi constrain the production mechanism for neutrinos at a very fundamental level (pp vs. pγ)
- From the neutrino (and GW?) perspective, one would like to have a better understanding of the fainter parts of the source populations, since the neutrino flux may be dominated by these; prospects in Fermi? Threshold?
- The different messengers do not necessarily come from the same objects or even production regions within the same objects; sometimes there are “anti-correlations” (e.g. neutrinos – high-E gamma-rays)
  (see also Murase, Guetta, Ahlers, PRL 116 (2016) 071101)
- Consequence: Multi-messenger interpretations have to rely on theoretical models, which need improvement
- IceCube-Gen2 will possibly identify neutrinos from specific sources (e.g. GRBs), constrain source populations by multiplet searches, and disentangle different components (e.g. Galactic versus extragalactic) statistically