Neutrinos from Gamma-Ray Bursts ...

... and tests of the UHECR paradigm

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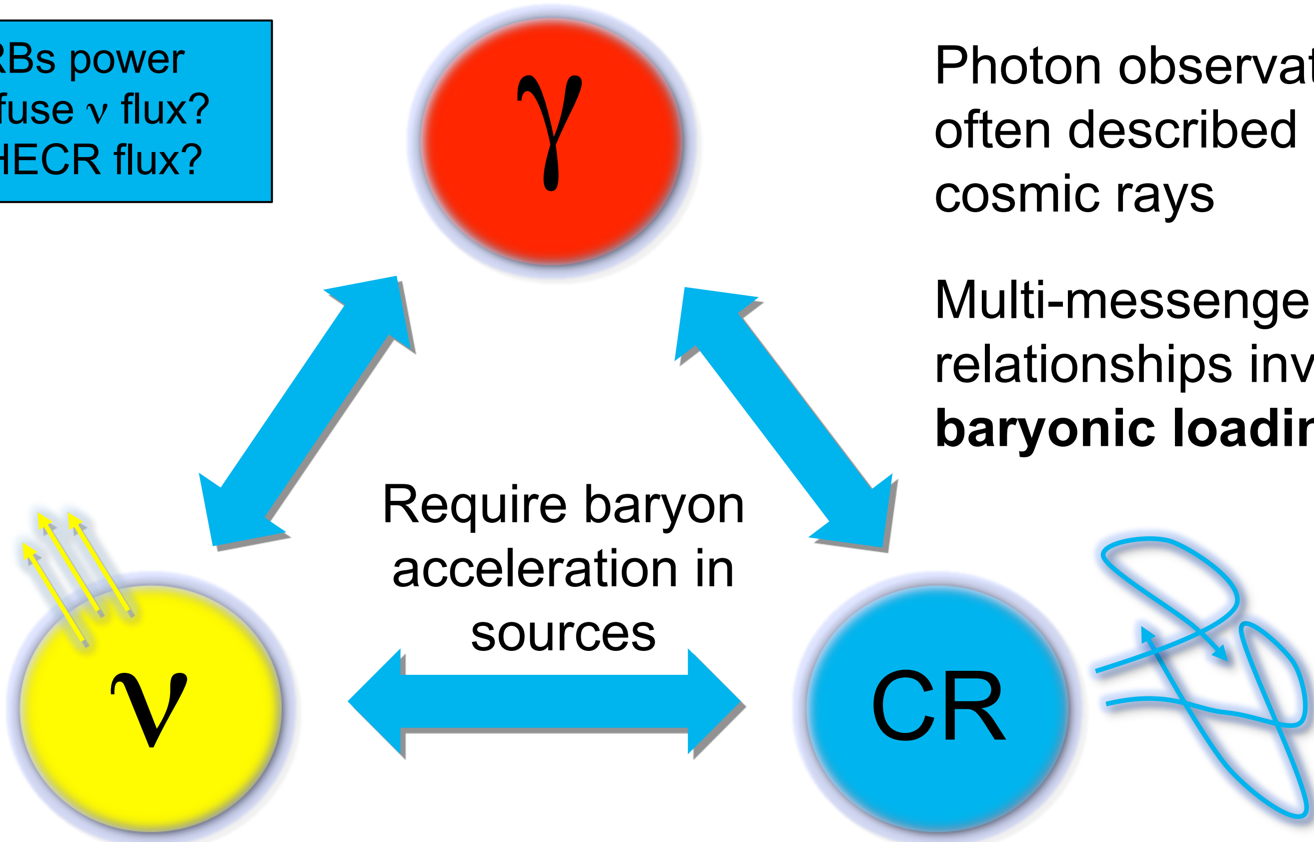
Multi-messenger astrophysics

Can GRBs power
- the diffuse ν flux?
- the UHECR flux?



Photon observations can be often described without cosmic rays

Multi-messenger relationships involve **baryonic loading**

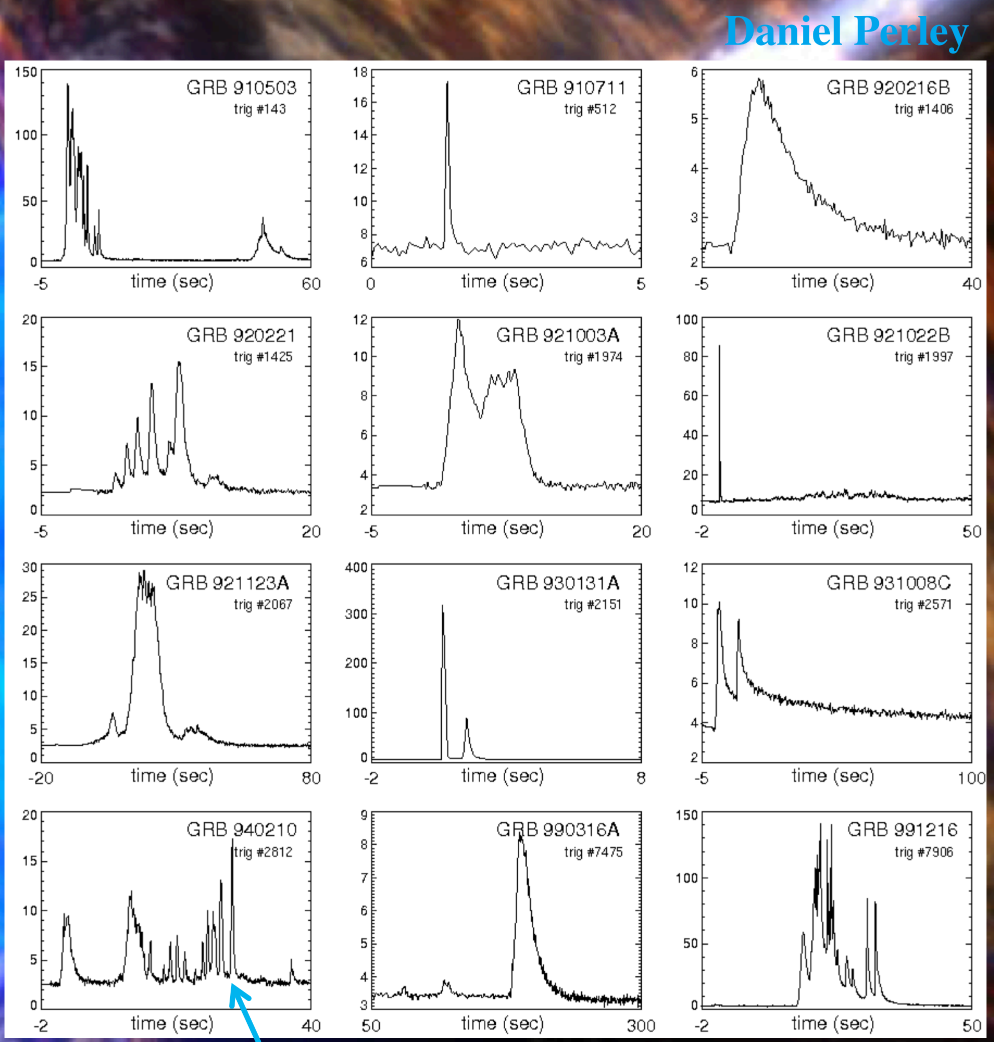
Mostly extragalactic origin?

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

Focus on GRB origin of cosmic rays at extremest energies

Gamma-ray bursts (GRBs)

- Most energetic electromagnetic (gamma-ray) outburst class
- Several populations, such as
  - **Long-duration bursts** (~10 – 100s), from collapses of massive stars?
  - Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers?
- Typical redshift ~ 1-3 (cosmological distances)
- Observed light curves come in large variety →



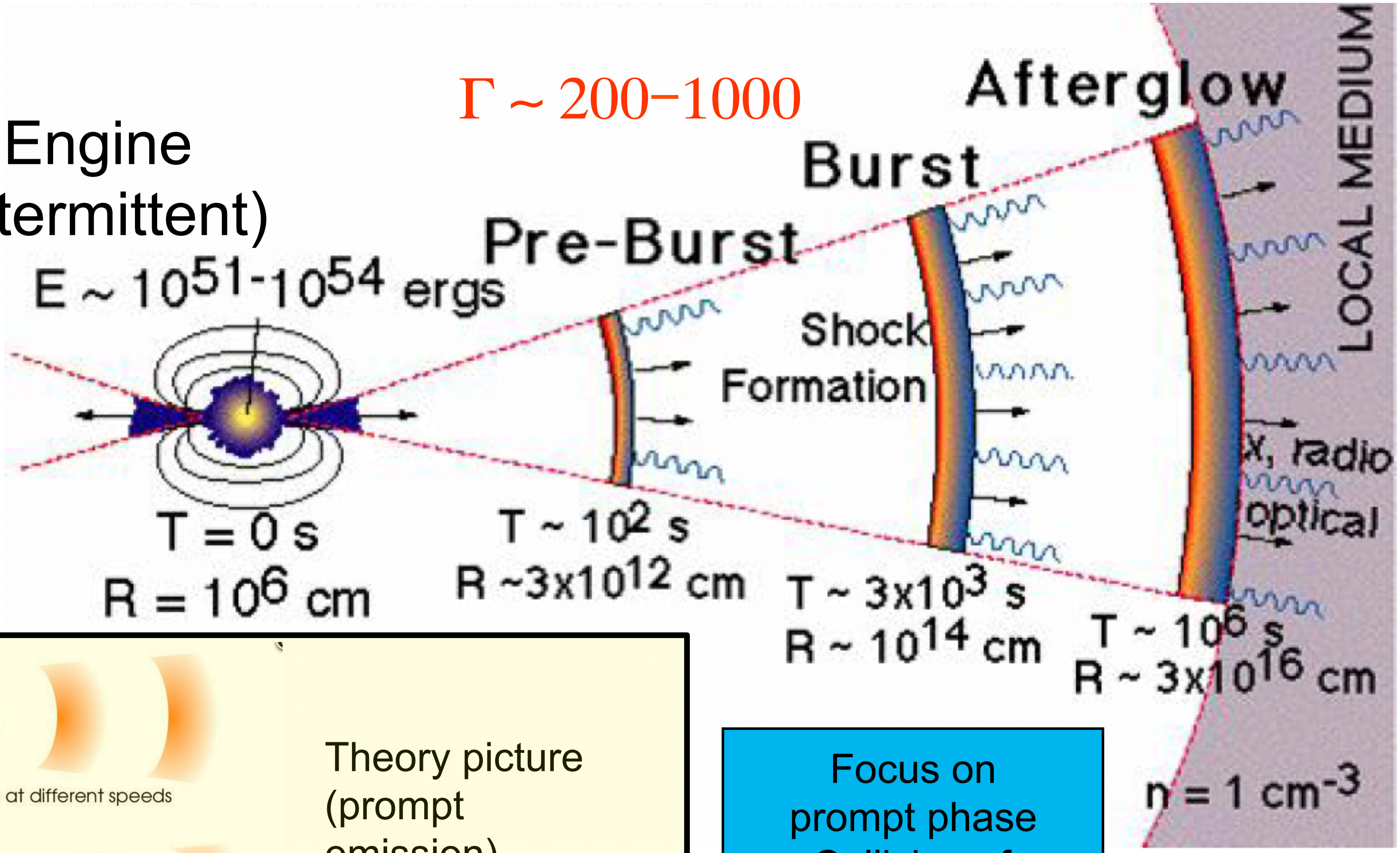
t_v: variability timescale

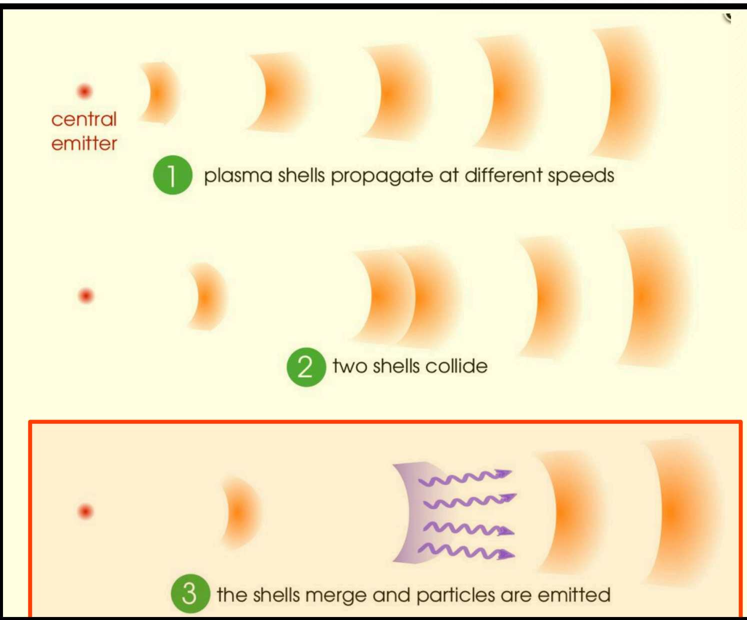
Source: NASA

GRB - Internal shock model

(Source: SWIFT)

"Isotropic equivalent energy" [extremly high]





Theory picture (prompt emission)

Simplest theory: all collisions alike, **one zone model**

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

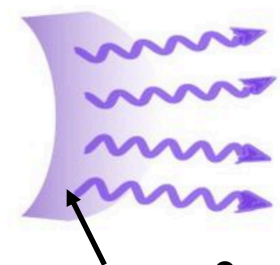
Neutrino production efficiency in GRBs ... from geometry estimators

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

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

L'_γ

$\Delta d'$



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

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

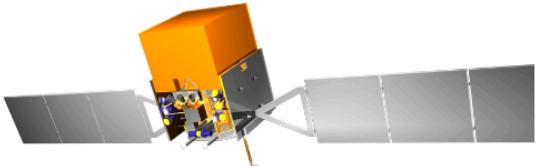
$$R \simeq 2\Gamma^2 \frac{c\, t_v}{1+z} \qquad \Delta d' \simeq \Gamma \frac{c t_v}{1+z} \quad \Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\mathrm{br}})$$

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

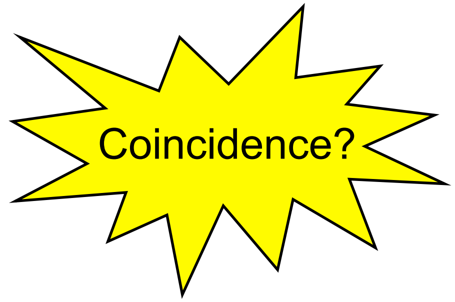
- *Magnetic re-connection models*: est. for *R* from pulse timescale (larger)
- *Photospheric emission*: *R* corresponds to photospheric radius
- *Multi-zone models*: *R* and Δd' individually calculated for each collision
- **Production radius R and luminosity L$_\gamma$ are the main control parameters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

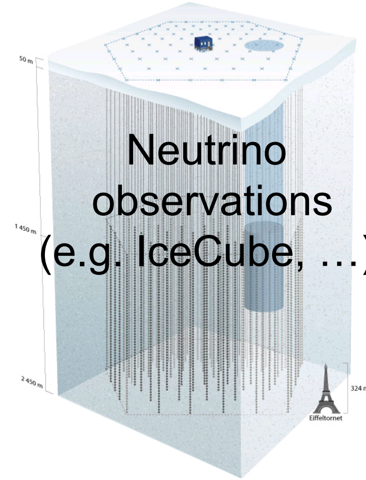
e.g. He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5) for details

Multimessenger stacking bounds

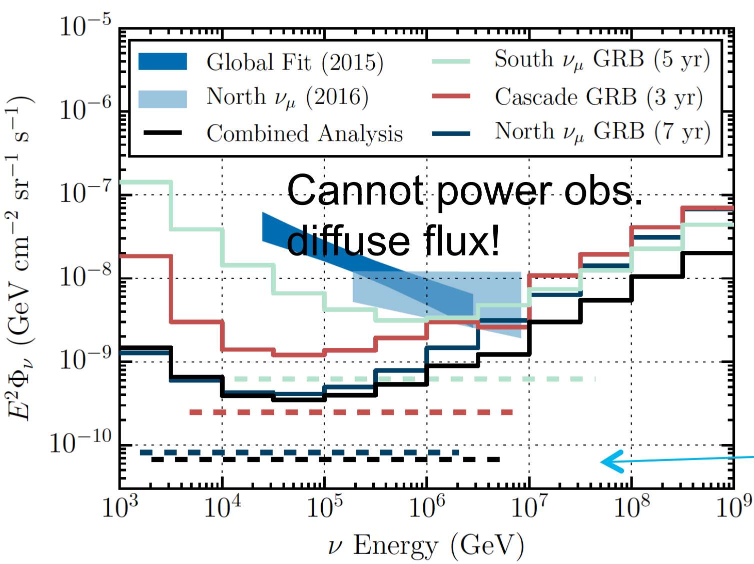


Gamma-ray observations (e.g. Fermi, Swift, etc)

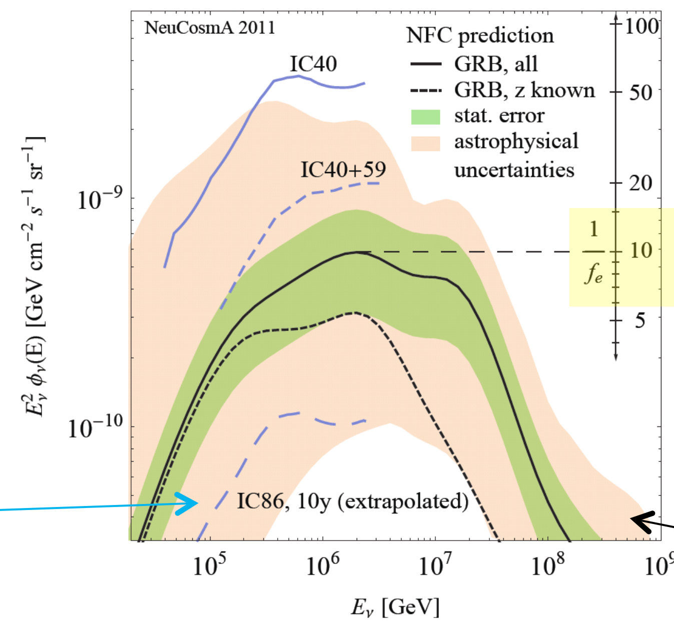




- Use timing, directional and energy inform. to reduce BG
- Current result vs. one zone prediction from γ-rays:



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



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

Geometry estimators

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

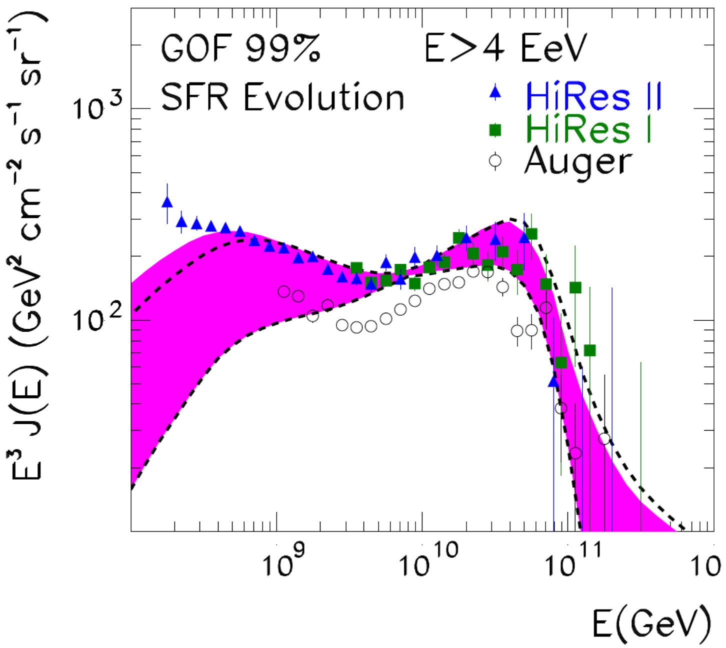
Generic constraints: Neutron model

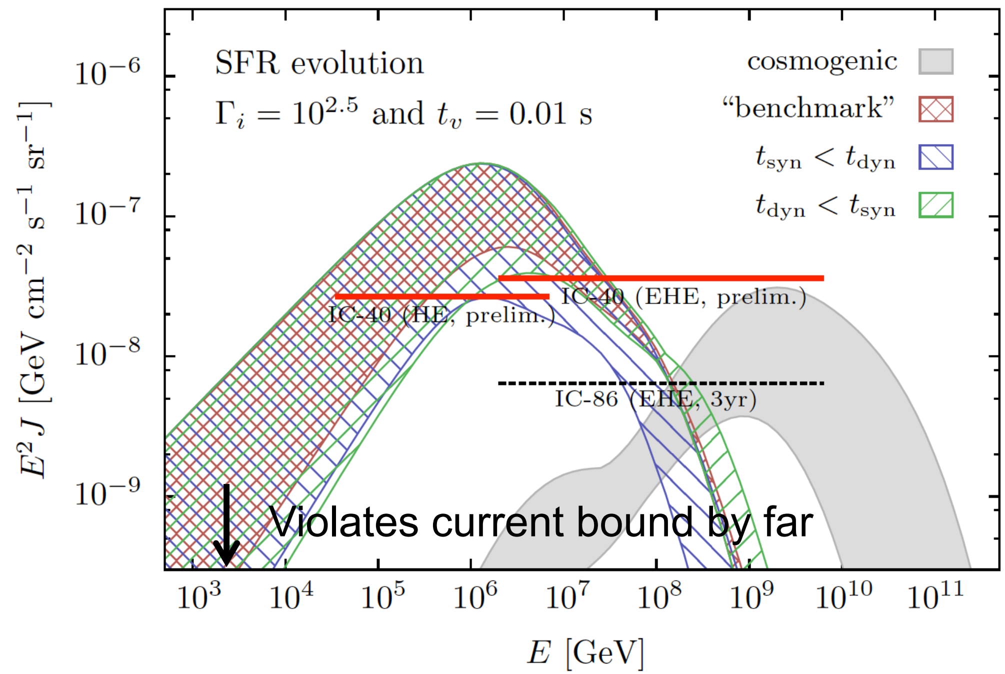
ν ⟷ CR

- Δ-resonance picture: (simplified)

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

- Assume that these neutrons escape and are the UHECRs: Fit to UHECR data (implies high baryonic loading)





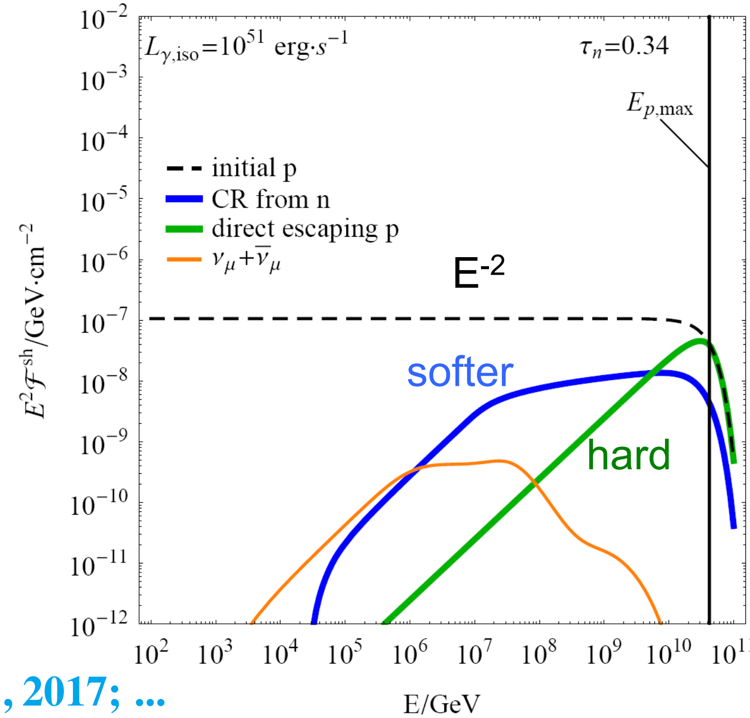
Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

Challenge: How do cosmic rays escape from the source?

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

> **Neutron model**
Only neutrons can escape

> **Direct escape** (aka "high pass filter", "leakage", …)
Charged *cosmic rays can efficiently escape if Larmor radius reaches size of region*
(conservative escape contribution, green curve, hard)
(predicted in: Baerwald et al, ApJ 768 (2013) 186) →



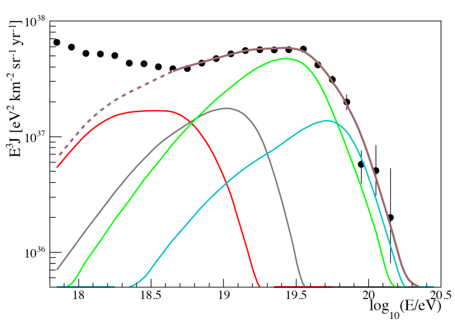
(GRB, protons, without propagation effects)

> **All escape**, advective/free-streaming escape
(most aggressive scenario, dashed curve, ~ E^{-2})

> **Diffusive escape:** e. g. Escape rate ~ $(R_L)^\alpha$
(compromise, but highly assumption dependent)

e.g. Unger et al, 2015; Kachelrieß et al, 2017; Fang, Murase, 2017; …

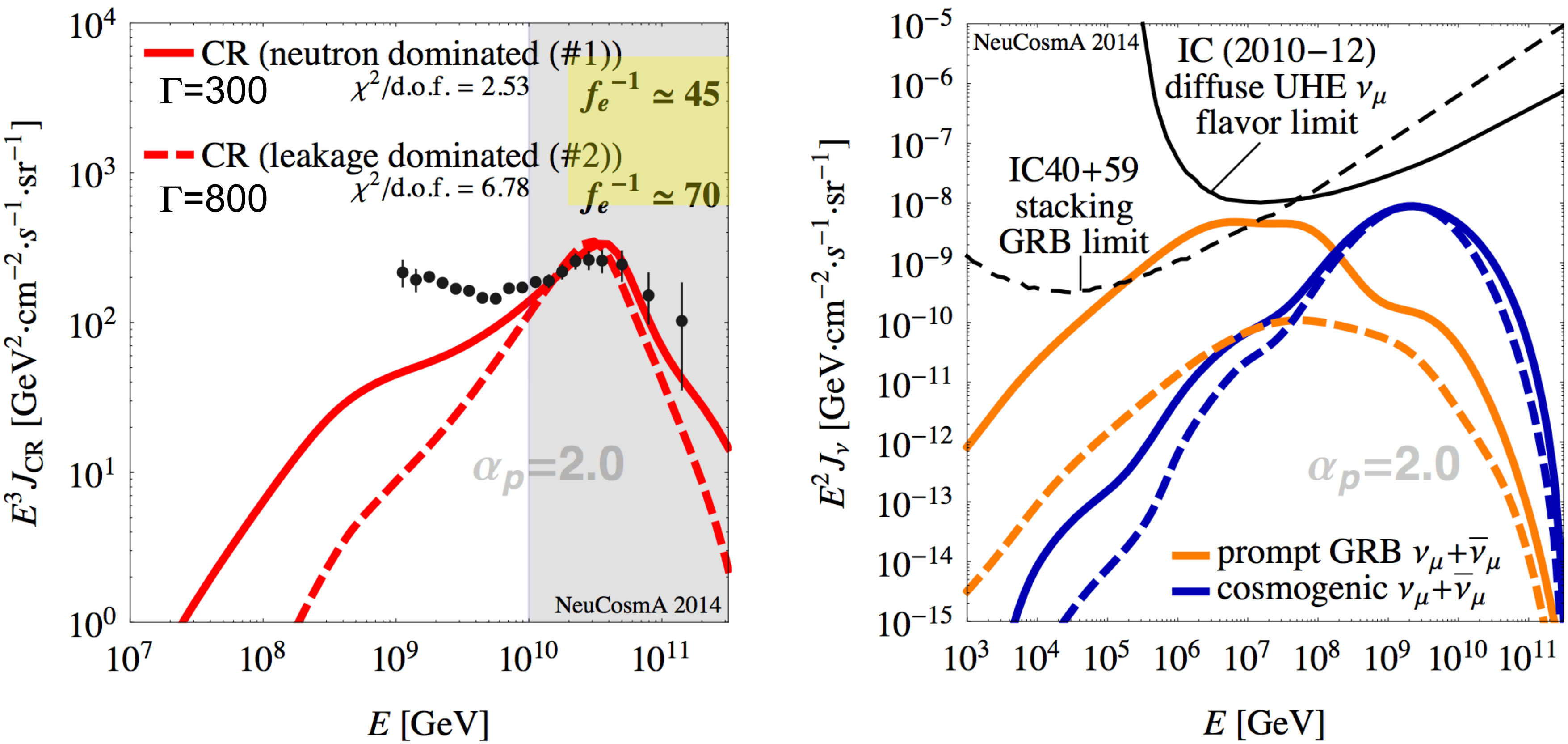
> Current Auger best-fit supports direct escape hypothesis
(requires E^{-1} from sources);
possibly neutrons below ankle?
(e. g. Unger, Farrar, Anchordoqui, 2015)



Auger

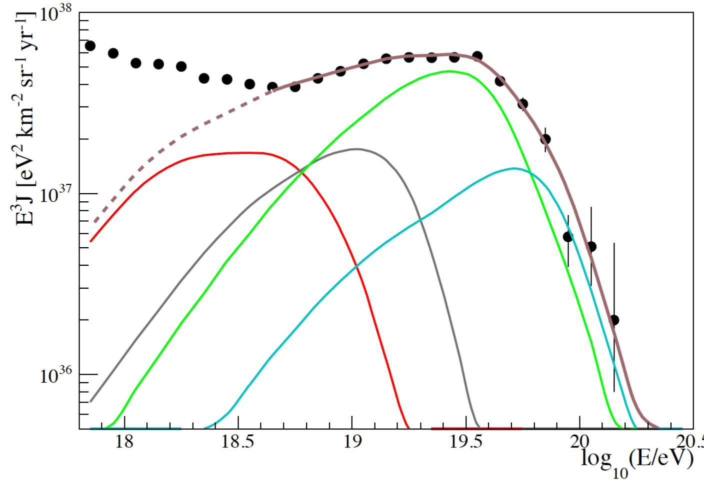
Combined source-propagation model

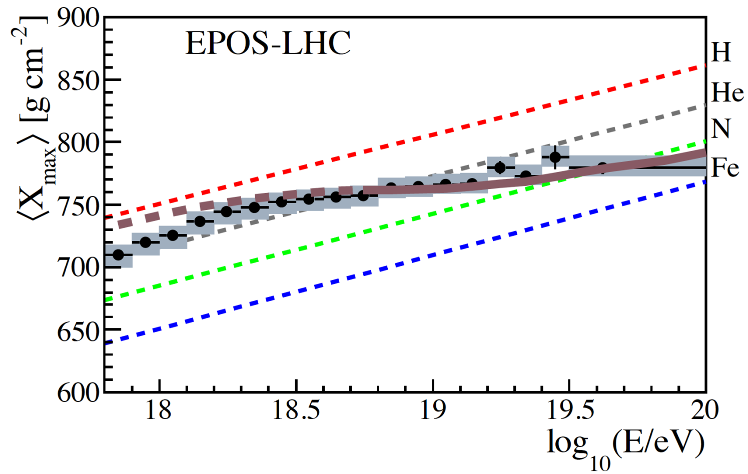
- Baryonic loading (f_e^{-1}) is obtained by the fit to UHECR data (no input!)
- GRBs can be the sources of the UHECRs depending on parameters
- Neutrino bounds translate into parameter space constraints (e.g. R, L_{iso})



Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66; here figures with TA data

Auger global fit





Auger global fit, 1612.07155

Caveat 1: UHECRs are not dominated by protons …

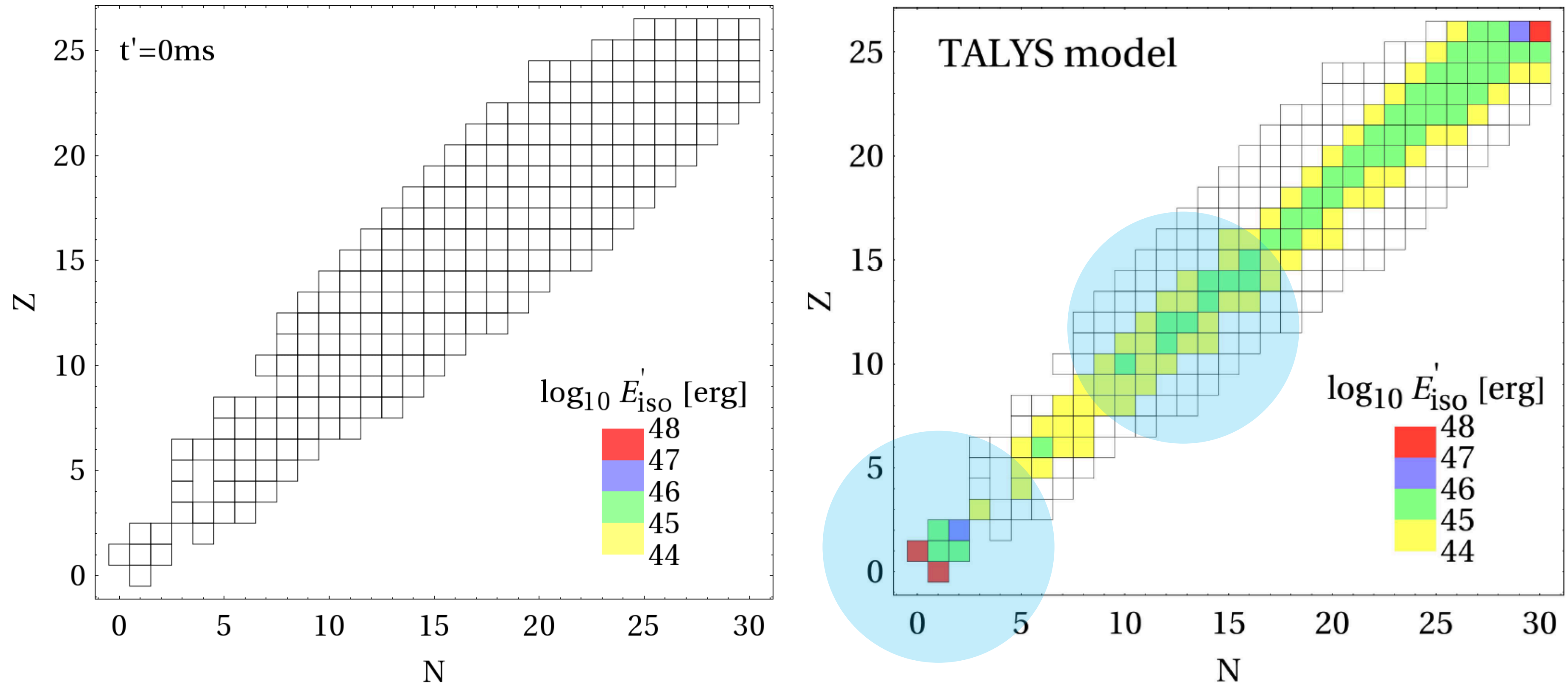
Hard spectra from sources $\gamma \sim 1$ (best-fit).

Elements up to silicon from sources

Development of nuclear cascade: disintegration models

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

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

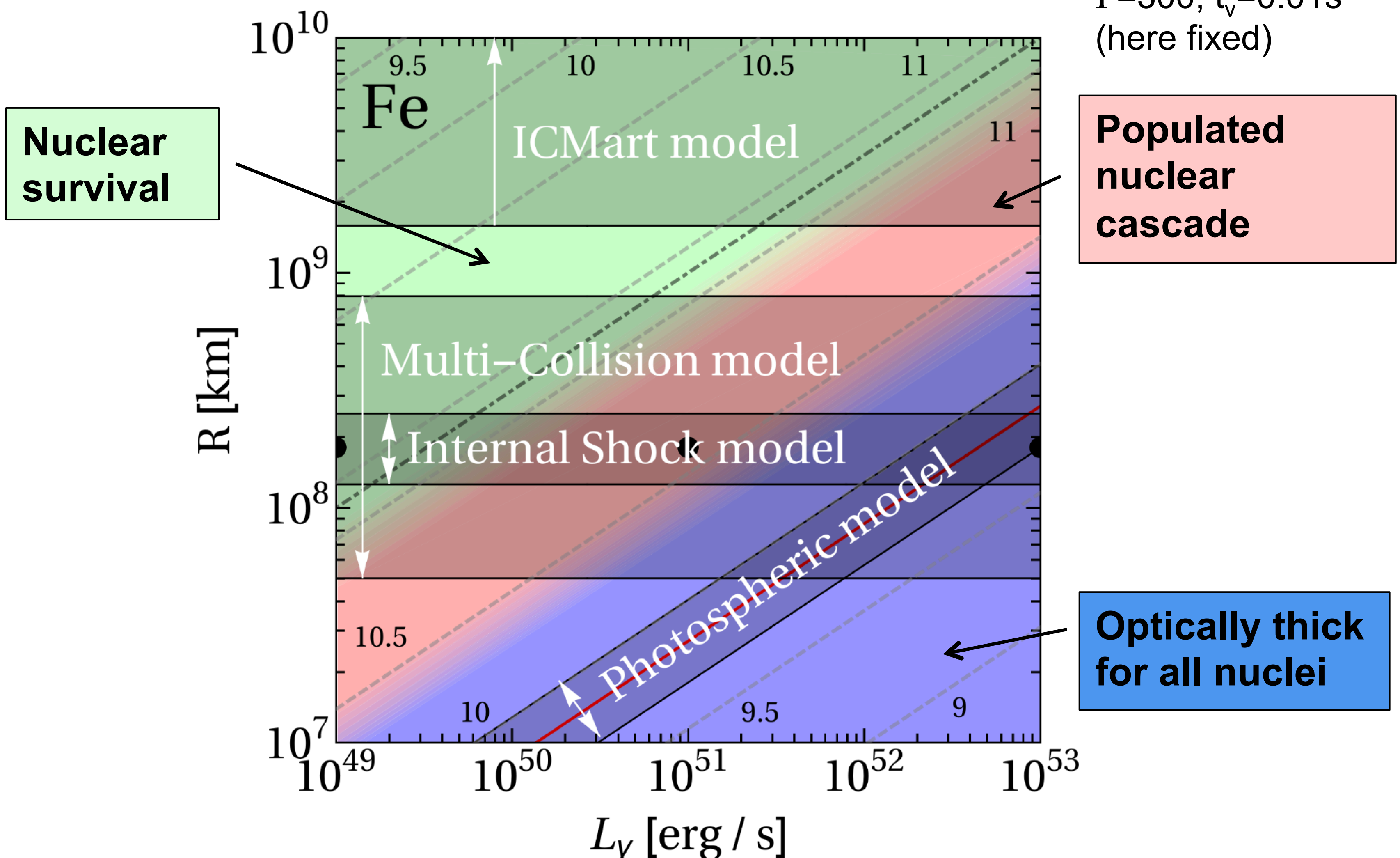


TALYS 1.8, CRPropa 2 (low mass isotopes)

- Abundant production of nucleons, α particles, light nuclei (consequences for UHECR composition, neutrinos)

Nuclear cascade: Dependence on "control" parameters

Γ=300, t_v=0.01s (here fixed)

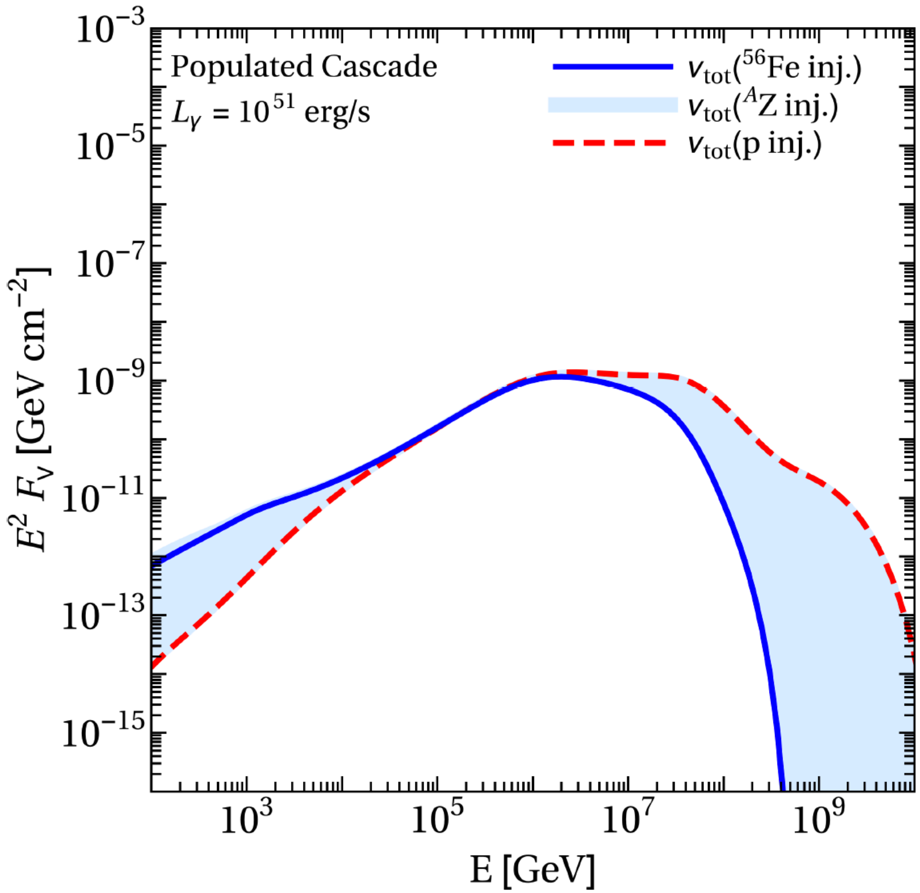


From: Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909; see also Murase et al, 2008; Anchordoqui et al, 2008

Composition dependence of neutrino fluence from GRBs

- The neutrino fluence (per shell) hardly depends on the injection composition

[Consequence of E^{-2} injection, conserved energy per nucleon in the disintegration chain, magnetic field effects on secondaries, and interaction rate flat in energy above threshold]

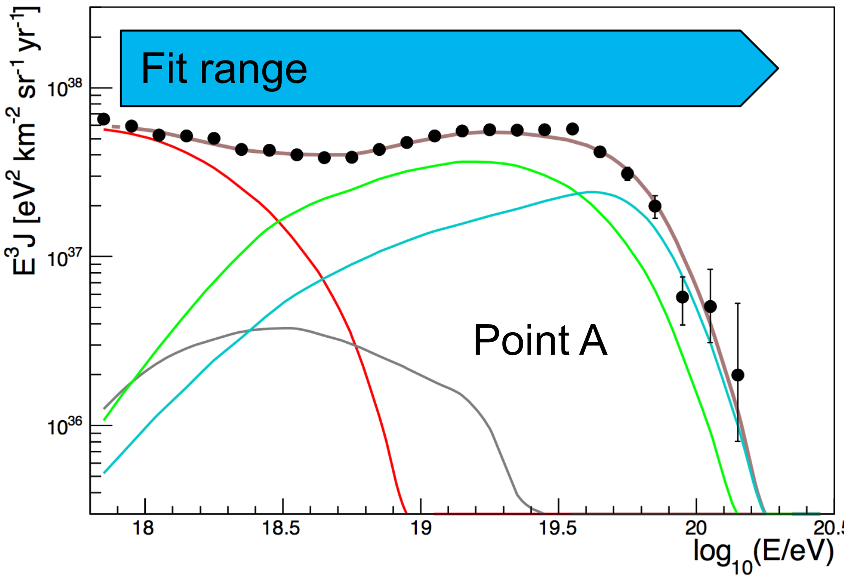


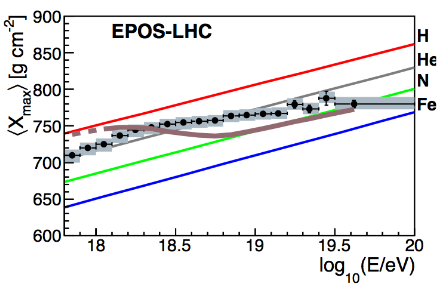
- The neutrino bounds on GRBs will roughly apply if UHECRs are nuclei (propagation effects modify required injection rate, though …)

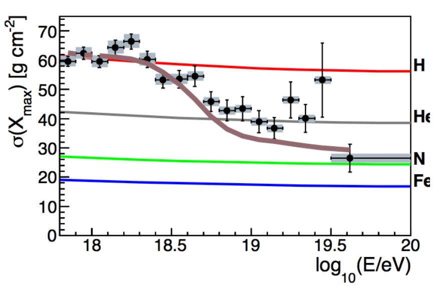
Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909

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

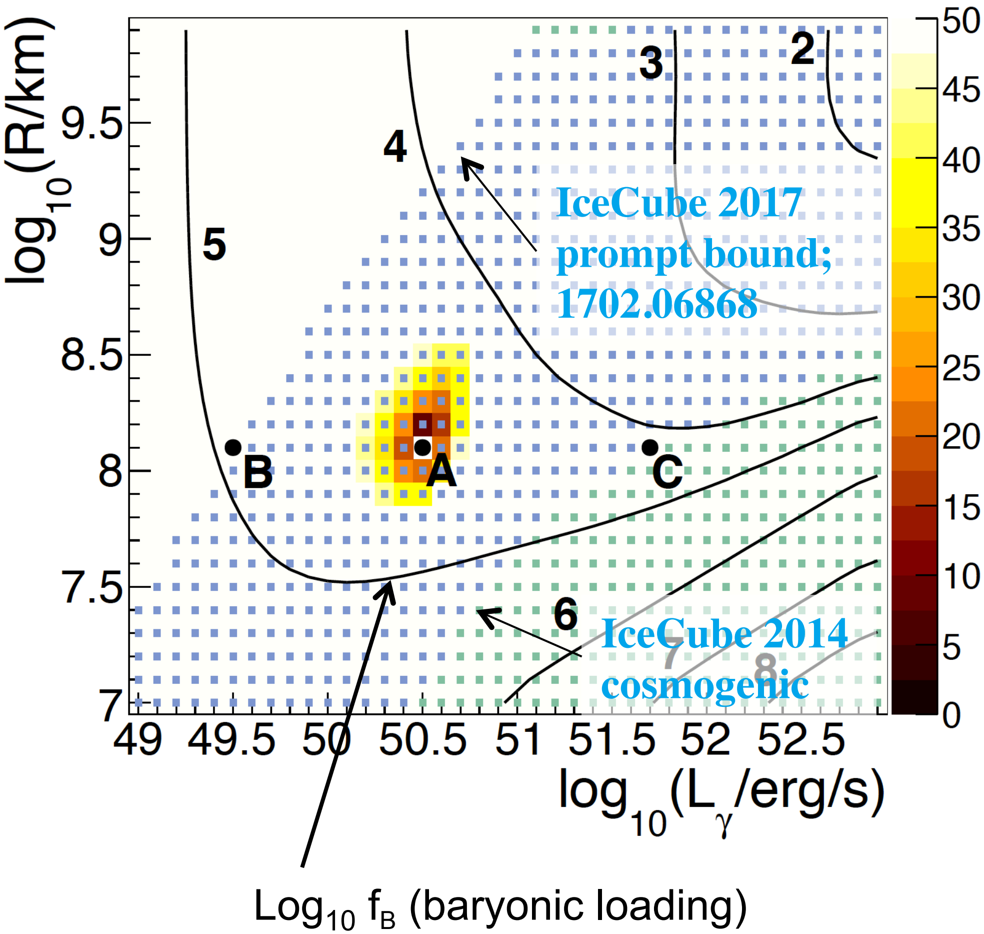
> Mixed composition dip model







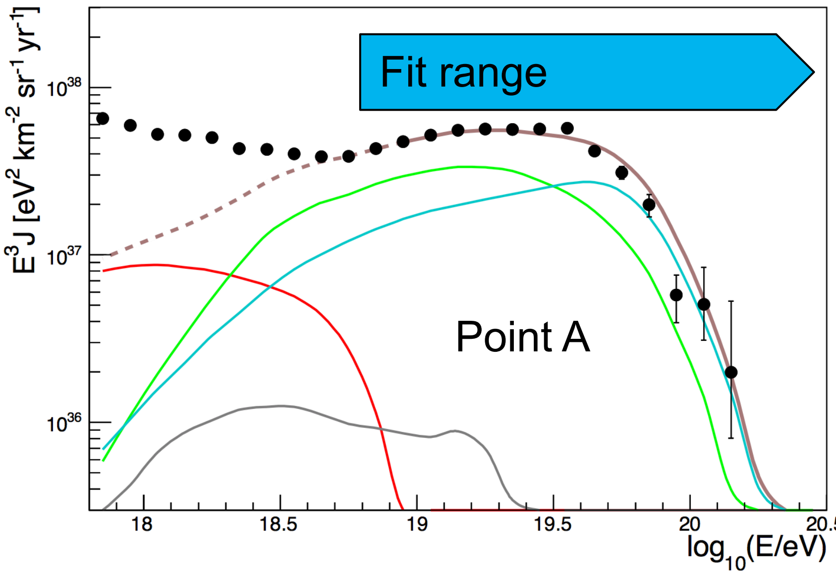
The neutrino bounds are powerful!

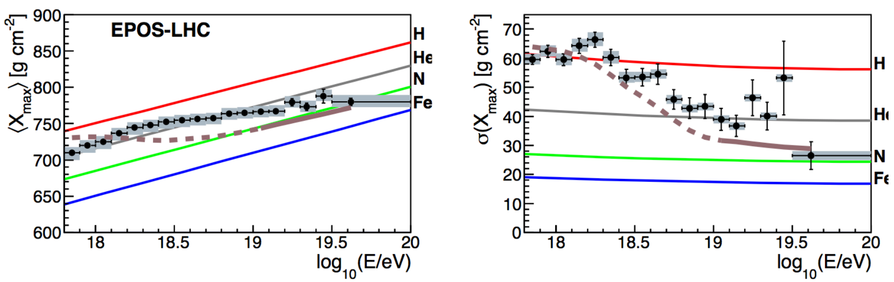


Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909

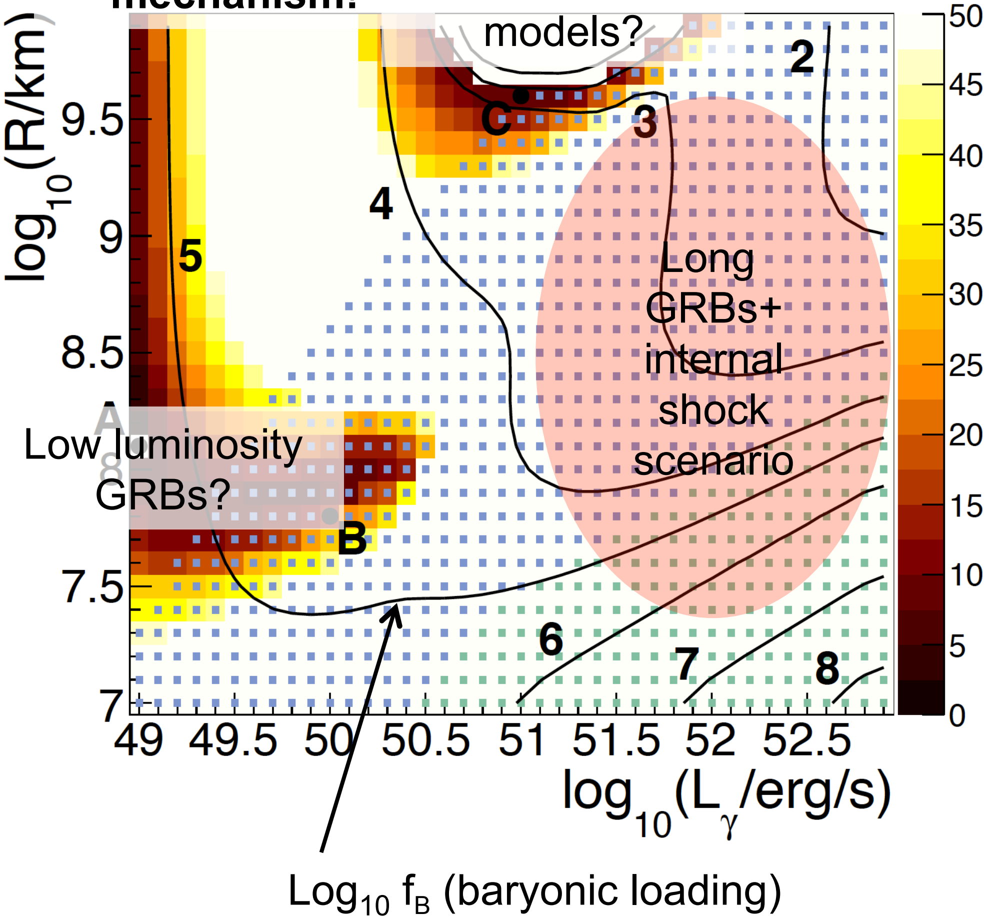
Combined (one zone) source-propagation model (internal shock scenario): Description of Auger data with ^{28}Si injection into GRB only

> **Mixed composition ankle model**





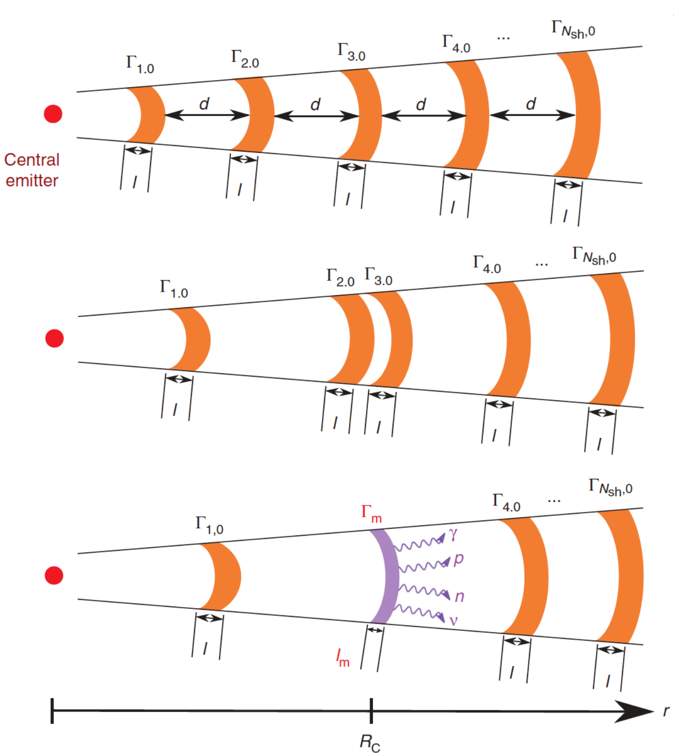
Constrains prompt emission mechanism!

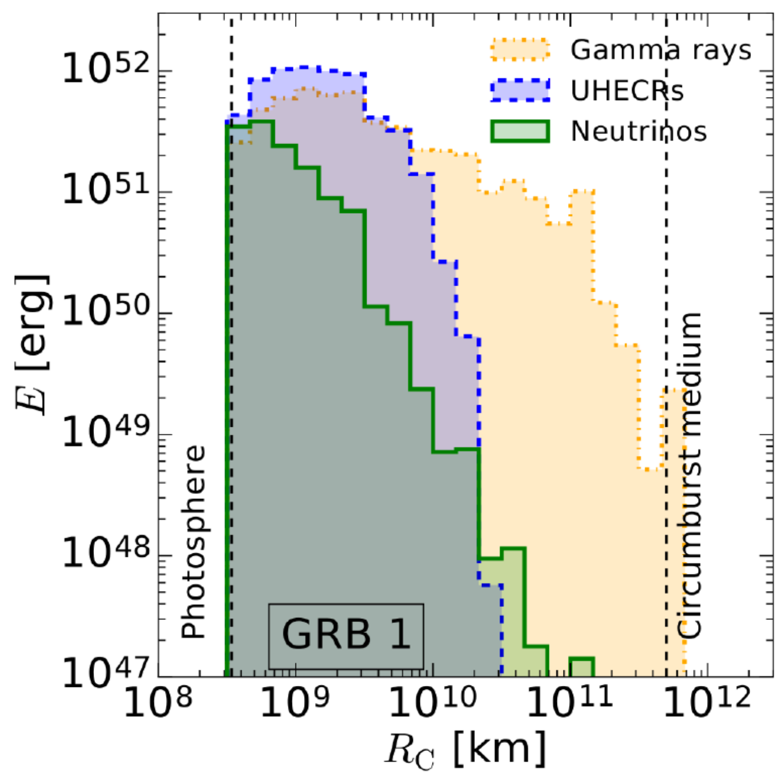


Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909

Caveat 2: The one zone assumption is possibly too simplistic

The GRB emission comes from multiple zones





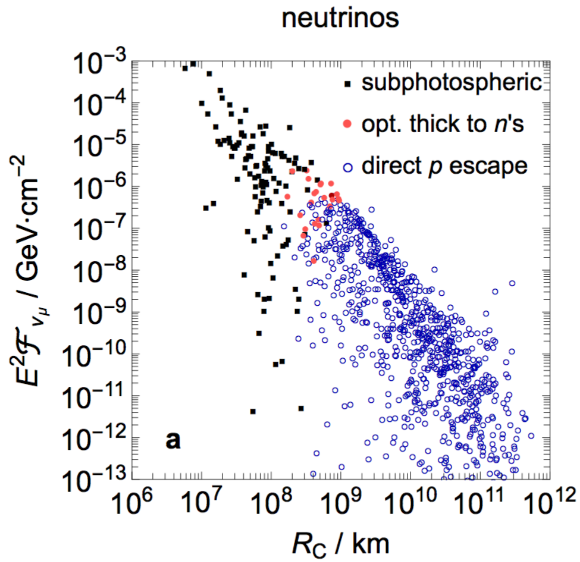
Bustamante, Baerwald/ Heinze, Murase, Winter, Nature Commun. 6, 6783 (2015) + ApJ 837 (2017) 33;

see also Globus et al, 2014+2015; earlier works e.g. Guetta, Spada, Waxman, 2001 x 2

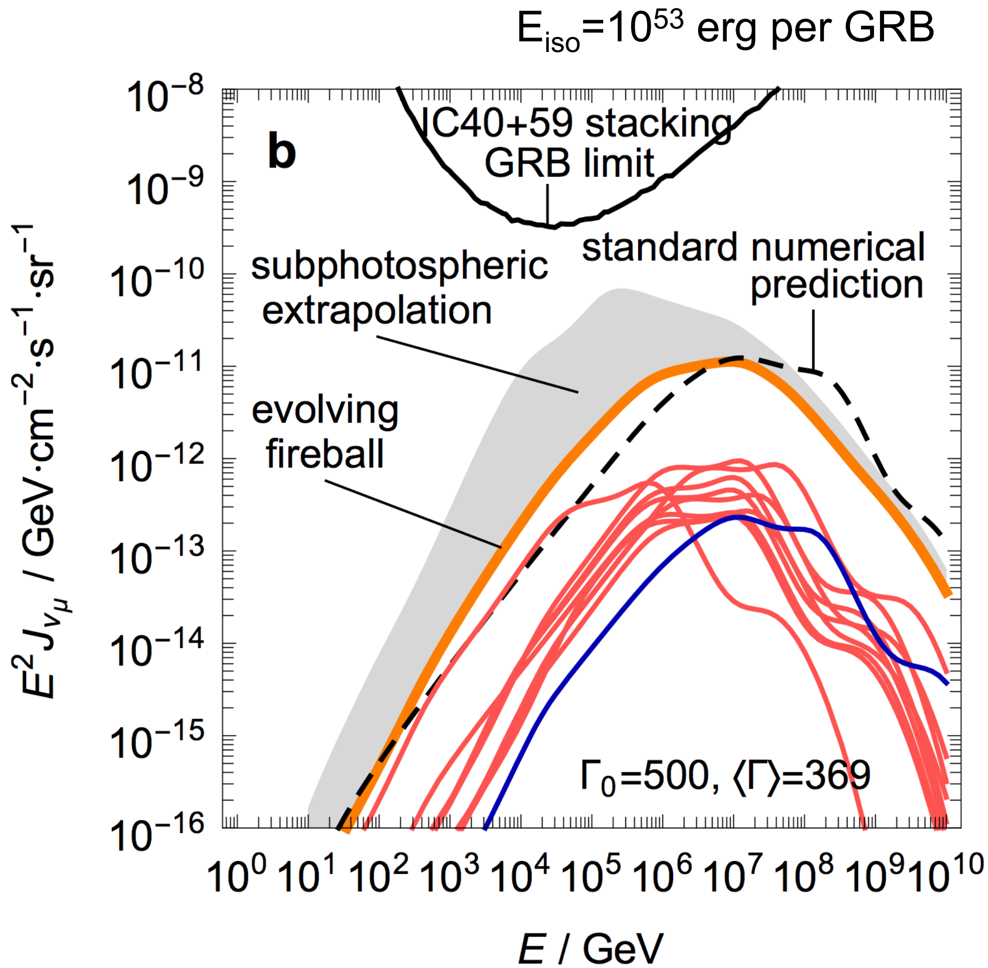
- The different messengers originate from different regimes of the same GRB *where the photon densities are very different*
- More fundamental problems implies?
  - Quantities inferred from γ-ray observations not representative for neutrinos and UHECRs?
  - Neutrinos and cosmic rays come from different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

Consequences for neutrino production

- Neutrino flux is dominated by a few collisions with high densities



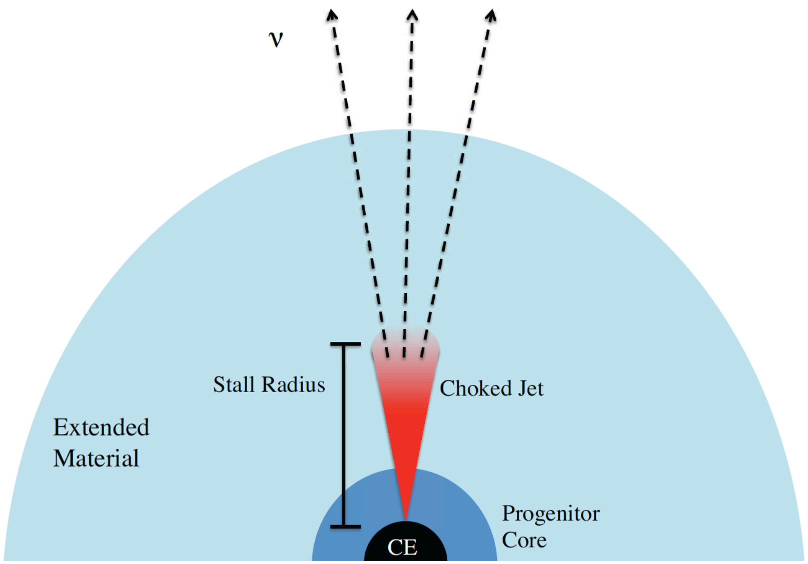
- Can be used to predict a "minimal" (+**robust** wrt. geometry estimators) super-photospheric neutrino flux ➔ IceCube-Gen2? **$E^2\,\phi \sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}** →
- Sub-photospheric contribution is extrapolation



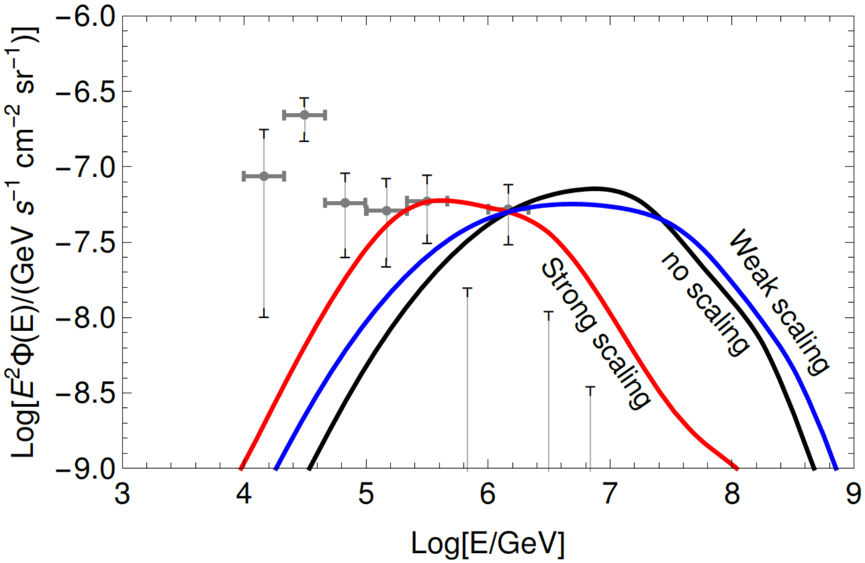
Bustamante, Baerwald/Heinze, Murase, Winter, Nature Commun. 6, 6783 (2015) + ApJ 837 (2017) 33

But: can GRBs power the diffuse neutrino flux?

- Sources invisible in photons?
  Example: Choked jets
  e. g. Senno, Murase, Meszaros, 2016



- Abundant, low luminosity sources?
  Example: Low luminosity GRBs
  e. g. Murase, Ioka, 2013; Tamborra, Ando, 2015
- Other source class with internal shocks? Example: Tidal Disruption Events



From Lunardini, Winter, 2017;
see also Wang, Liu, Dai, Cheng, 2011; Wang, Liu, 2016; Dai, Fang, 2017; Senno, Murase, Meszaros, 2017; Batista, Silk, 2017; Zhang, Murase, Oikonomou, Li, 2017

Conclusions

- GRB neutrino searches are promising from the neutrino perspective: highest sensitivity among all source classes
- Conventional GRBs cannot power the observed diffuse neutrino flux; may contribute at ~ 1% level
- GRBs could be, however, sources of the UHECR **nuclei**
- In that case, neutrinos constrain the prompt emission mechanism of GRBs (e.g. the collision radii are expected to be high in the one zone model)
- Caveat: different messengers may originate from different regions of the same object class (multi-collision model)
- Multi-collision prediction, which is hardly sensitive to the geometry estimators, is potentially within reach of IceCube-Gen2