Implications of IceCube Observation for Gamma-ray Bursts

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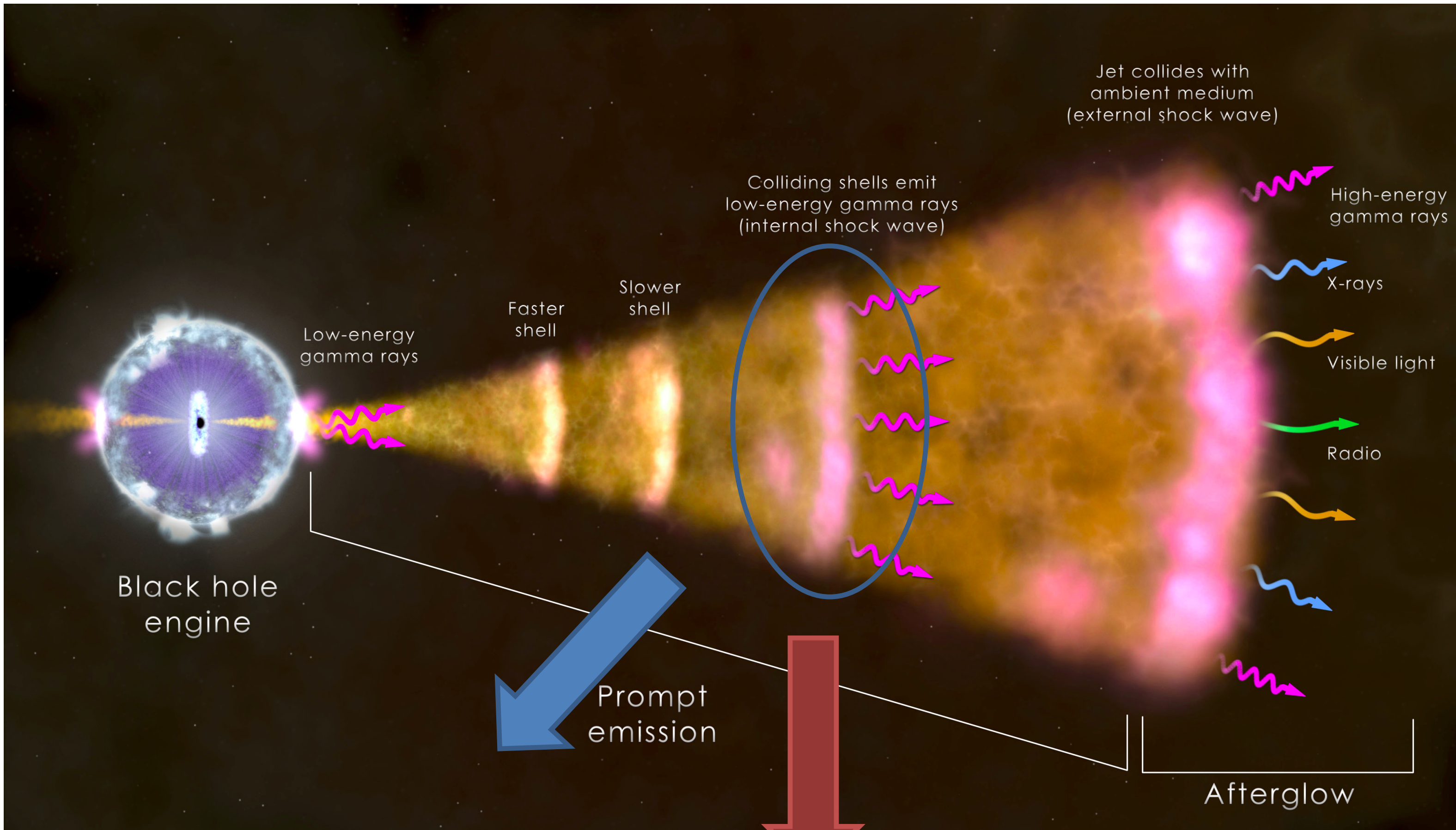
Outline

- A brief introduction to gamma-ray burst (GRBs) neutrinos
  - Theory
  - Observation
- Implications
  - GRB as the sources of UHECRs
  - Hadronic Origin of High-energy emission from GRBs
- Other populations of GRBs
- Summary

A general picture of gamma-ray burst



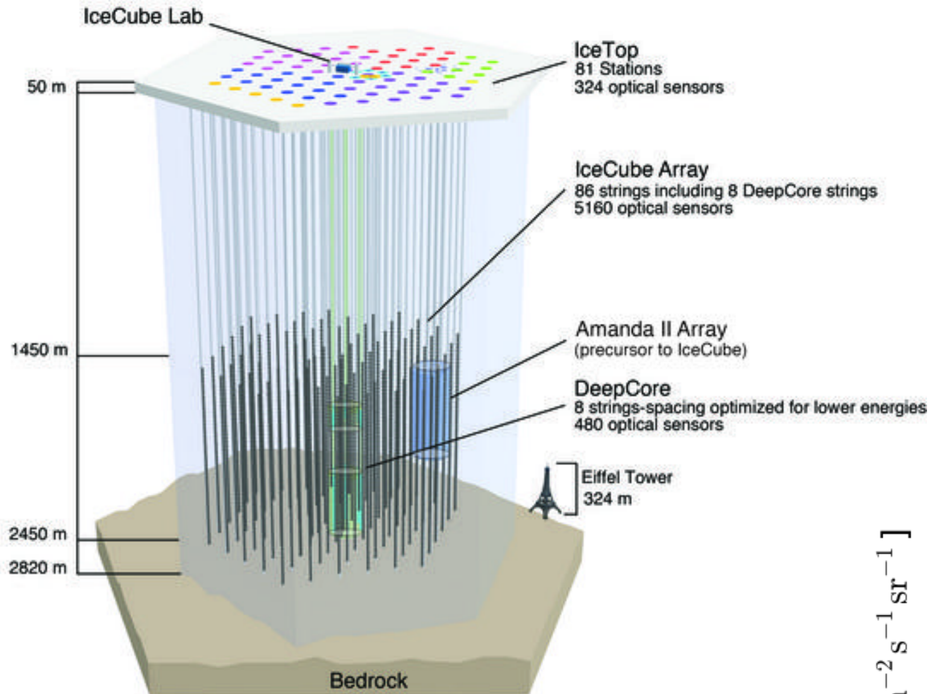
Cosmic ray accelerator → pγ interactions → Neutrino emitter

Waxman 1995, PRL
Vietri 1995, ApJ

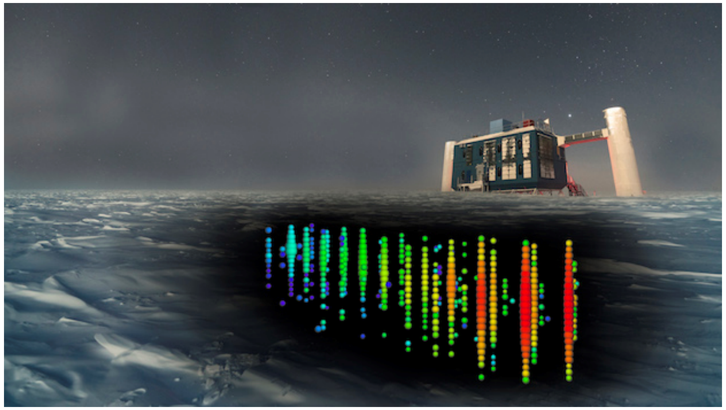
$P+\gamma \rightarrow p/n+\pi^{0/\pm}$
$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$
$\mu^{\pm} \rightarrow e^{\pm} + \nu_{\mu} + \nu_{e}$

Waxman & Bahcall 1997, PRL

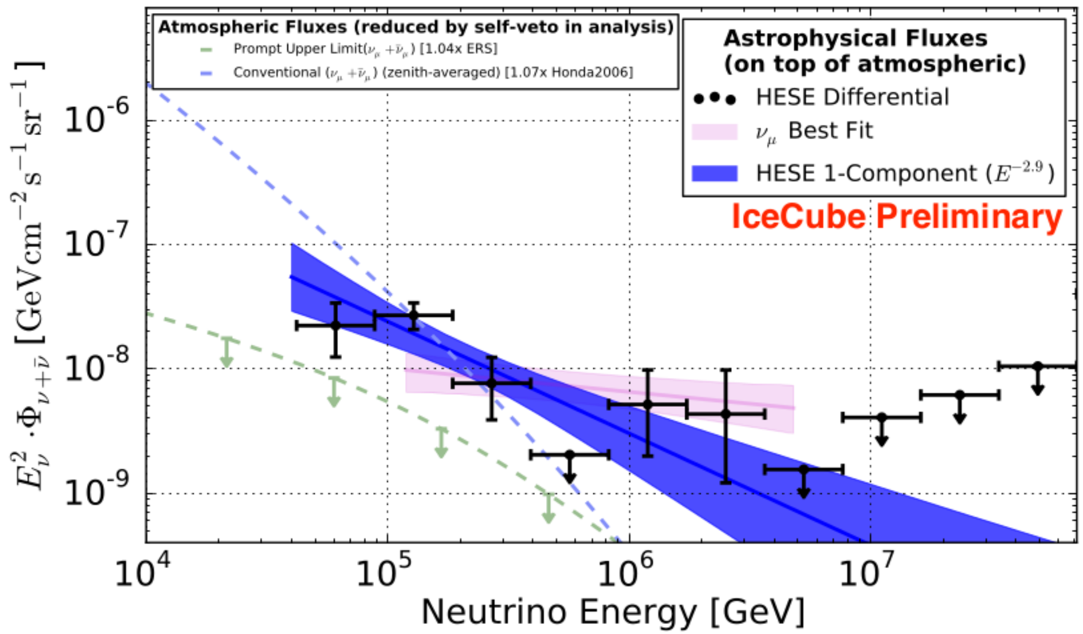
IceCube neutrino telescope



Credit: IceCube Collaboration



Diffuse neutrino background (>60TeV)

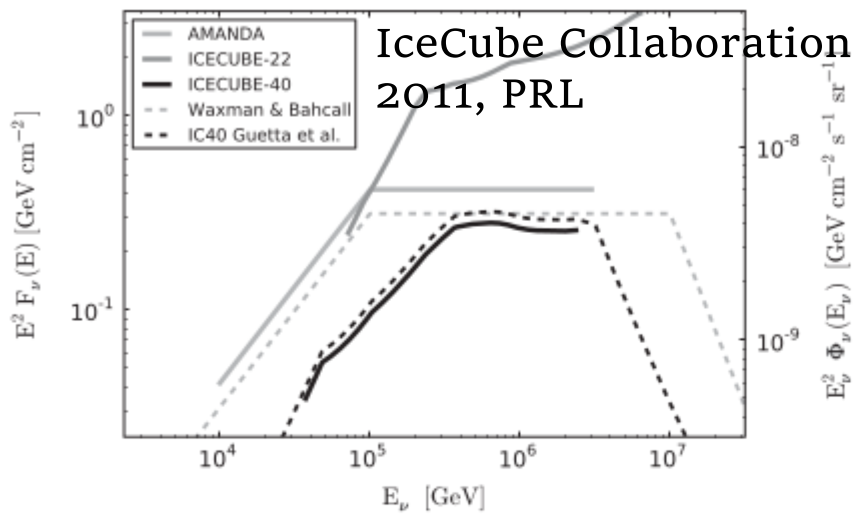


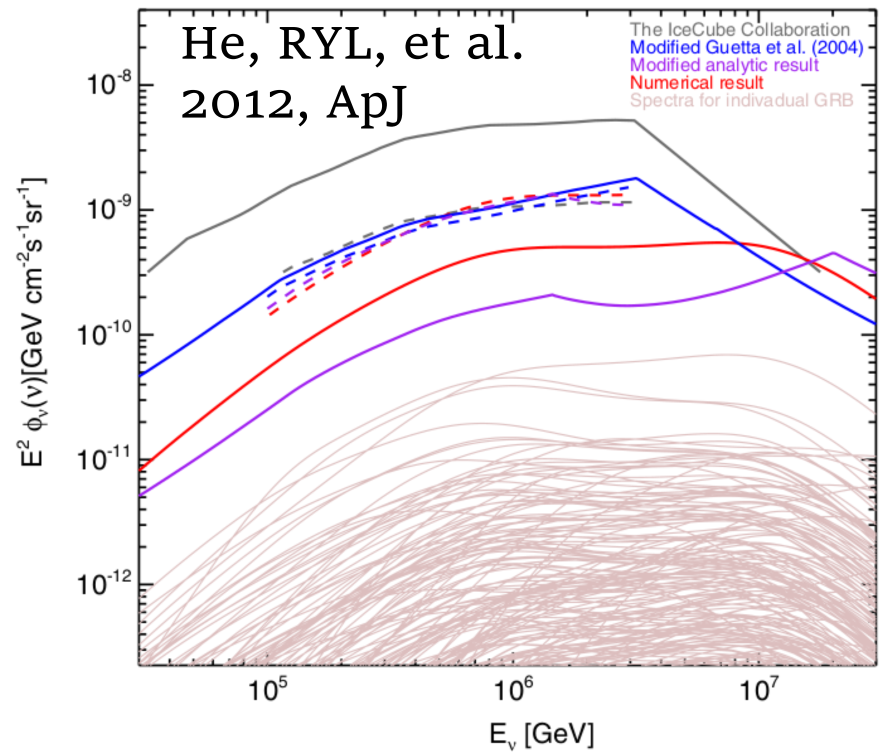
GRB: background almost free
Position + time window

No correlation between GRBs and neutrino events

Milestone: IceCube-40

Neutrino observation starts to constrain jet parameters!





Stacking observation on 117 GRBs
Aggregated theoretical fluence exceeds observation upper limit

See also
Li 2012, PRD
Hümmer et al. 2012, PRL

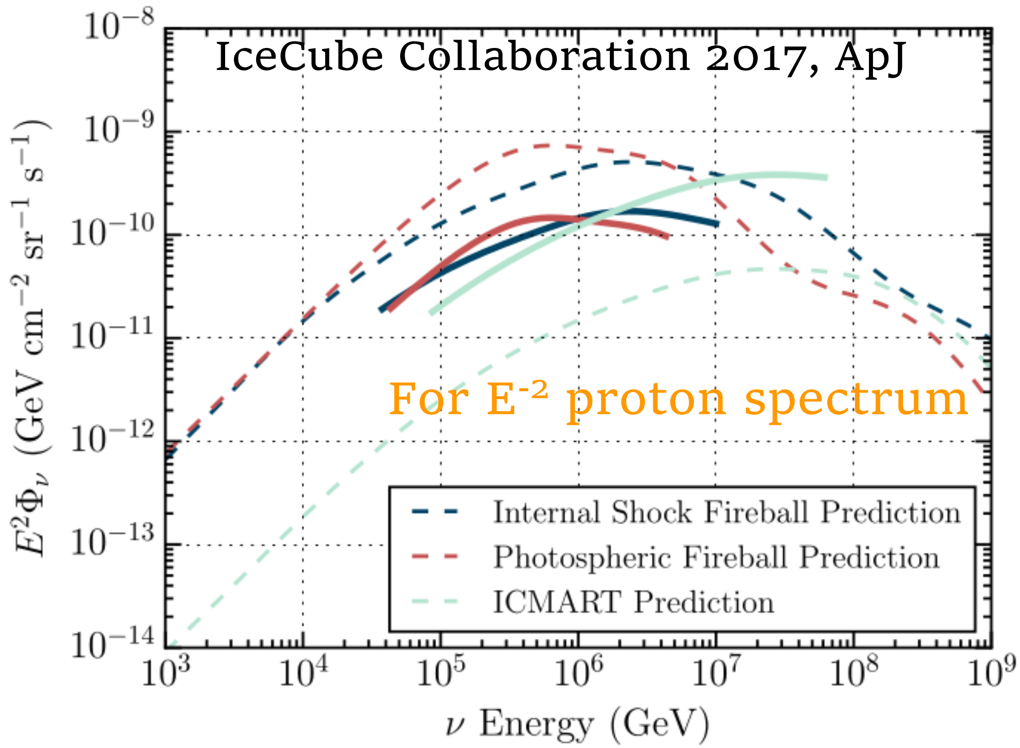
Either a low baryon loading factor (ratio of energy in protons in the entire energy range to that in keV-MeV photons) or low interaction efficiency (large dissipation radius or large bulk Lorentz factor)

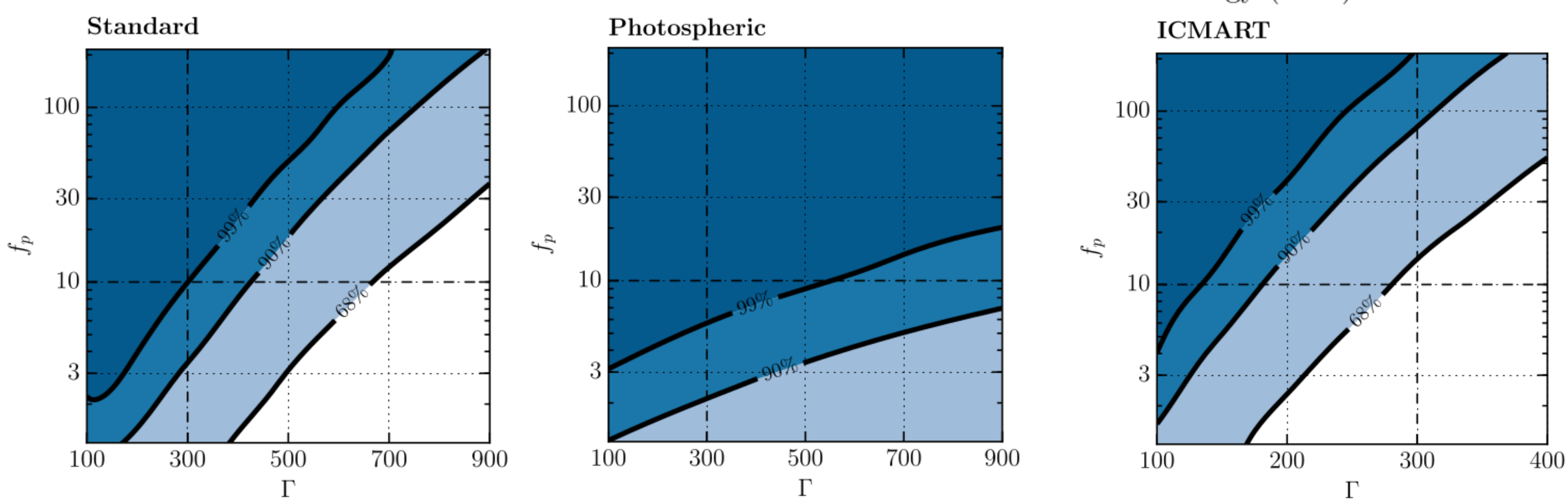
Result with larger statistics… still no detection

Stacking observation on 1172 GRBs from southern hemisphere in 5 years

No significant correlation between neutrino events and observed GRBs

<1% contribution of the astrophysical neutrino flux





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Implications – can GRBs still be sources of UHECRs?

GRB energy production rate in photons: ~10^{43}ergMpc^{-3}yr^{-1}

CR energy production required to explain >30EeV UHECRs ~ 5×10^{43}ergMpc^{-3}yr^{-1} (~10^{45}ergMpc^{-3}yr^{-1} in all energy range)

For proton composition Katz et al. 2009, JCAP

Require baryon loading factor: ~100

GRBs as the source of UHECRs is
Excluded in PS
Disfavored in IS
Remain possible in ICMART

See also e.g., Baerwald et al. 2015, APh

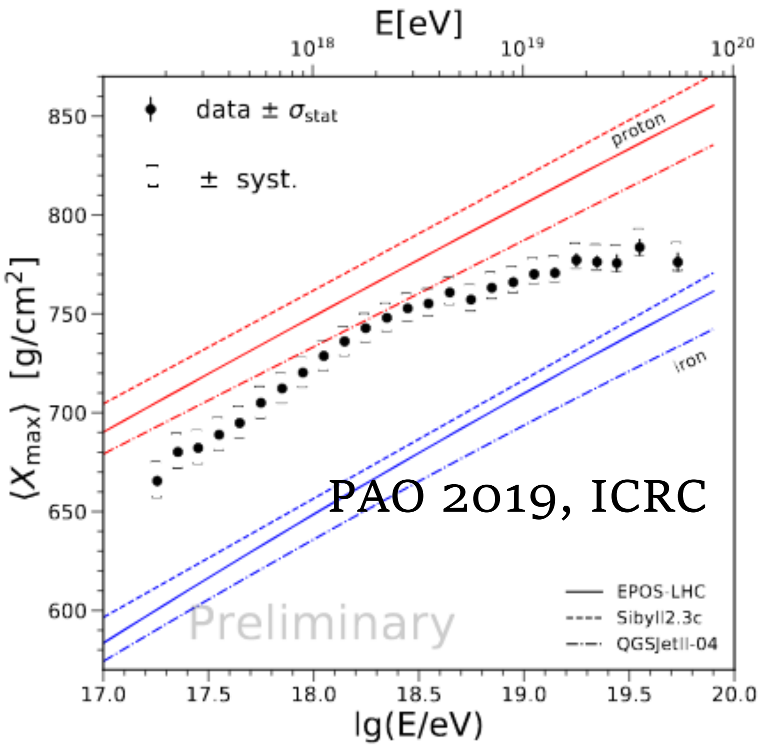
Uncertainty in CR spectrum

A hard CR spectrum from GRB :
TeV-PeV flux will be reduced
Required baryon loading factor is reduced

See e.g. Asano & Meszaros 2016, PRD

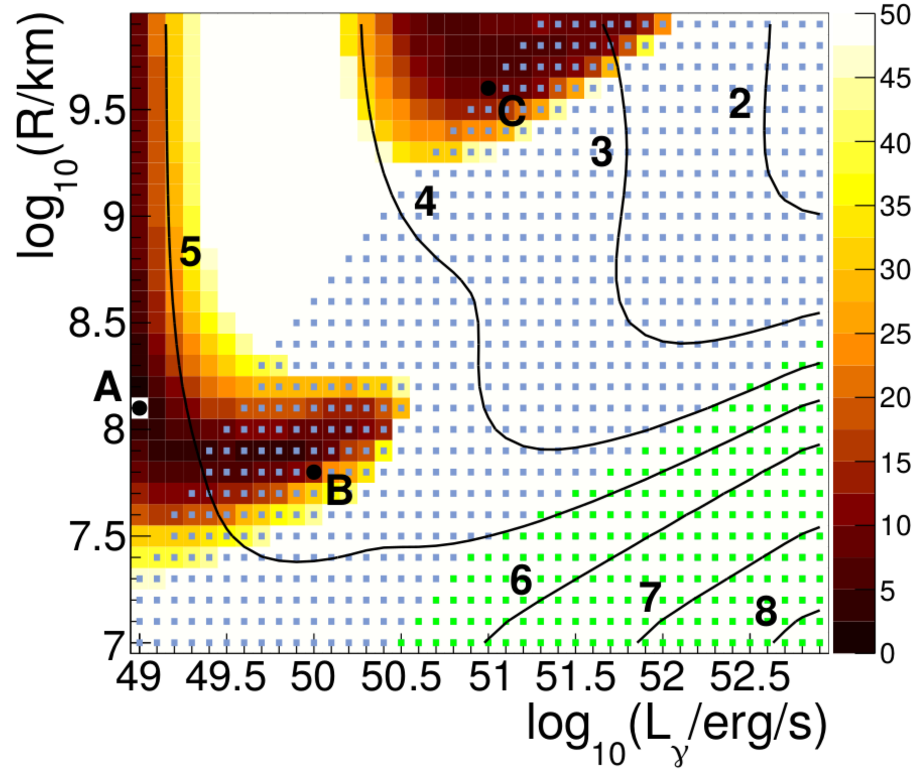
Nuclei composition of UHECRs

CR shower maximum



PAO 2019, ICRC

(jet's Lorentz factor Γ=300 is fixed)



Biehl et al. 2018, A&A

Above "ankle" (4EeV):
CR composition becomes heavier and heavier

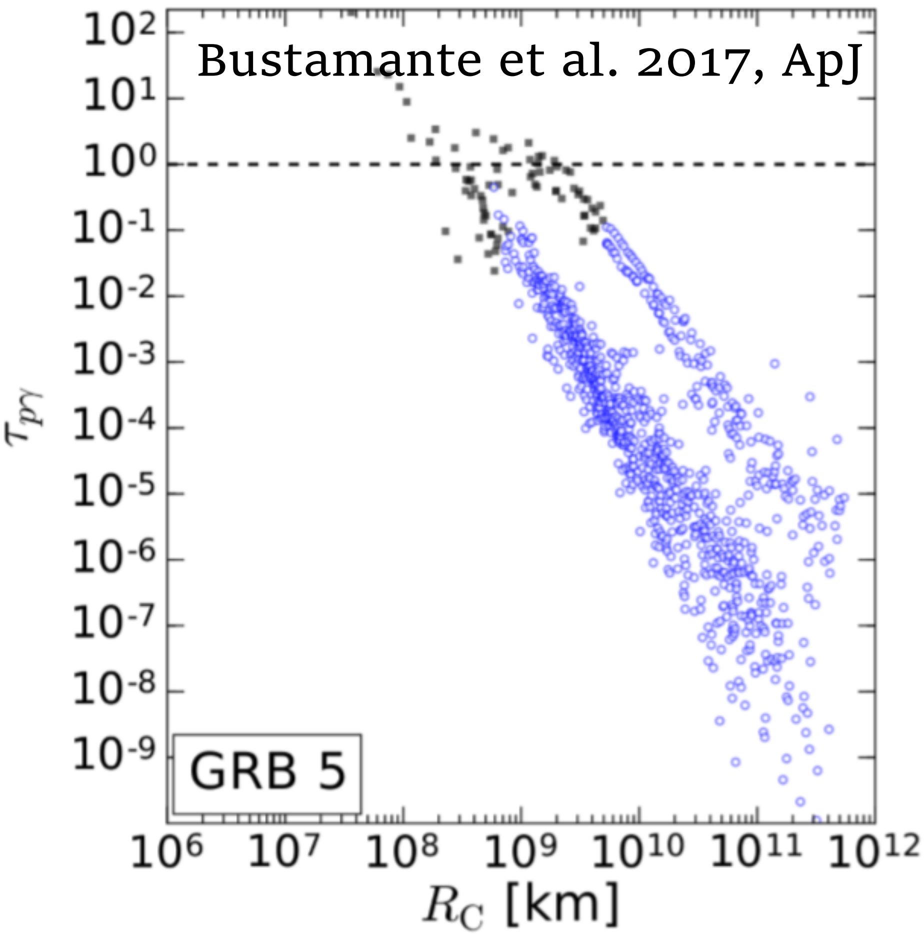
Multi-zone model for GRB

Multiple dissipation zones

From sub-photospheric radius
to super-photospheric radius

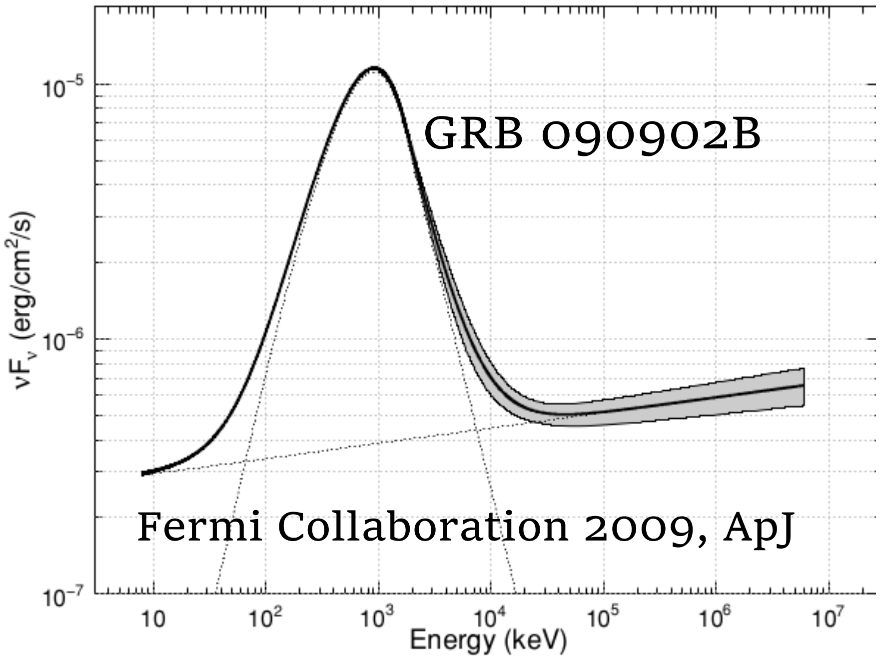
Dissipations happens at different radius, physical parameters evolves with time (radius)

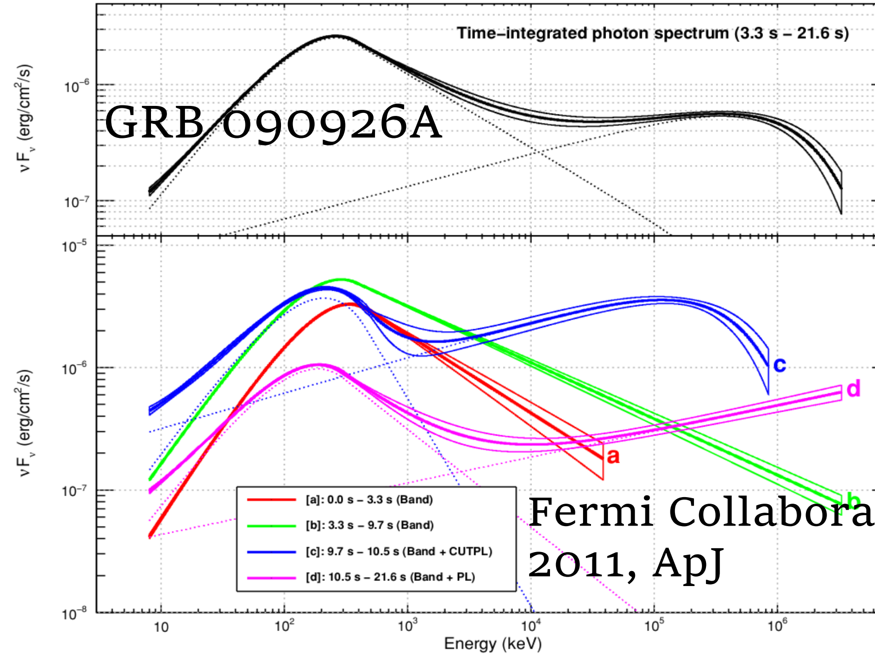
Not all accelerated CRs can produce neutrinos efficiently



See also, e.g, Globus et al. 2015, MNRAS

Implication – does the hadronic model work for high-energy gamma-ray emissions (>0.1GeV)?





Fermi Collaboration 2011, ApJ

pγ interactions → γ/e$^{\pm}$→ GeV emission (e.g., Gupta & Zhang 2007, MNRAS; Asano et al. 2009, ApJ; Asano & Meszaros 2012, ApJ)

Neutrino production in this scenario is unavoidable!

A rough estimation of all-sky neutrino flux

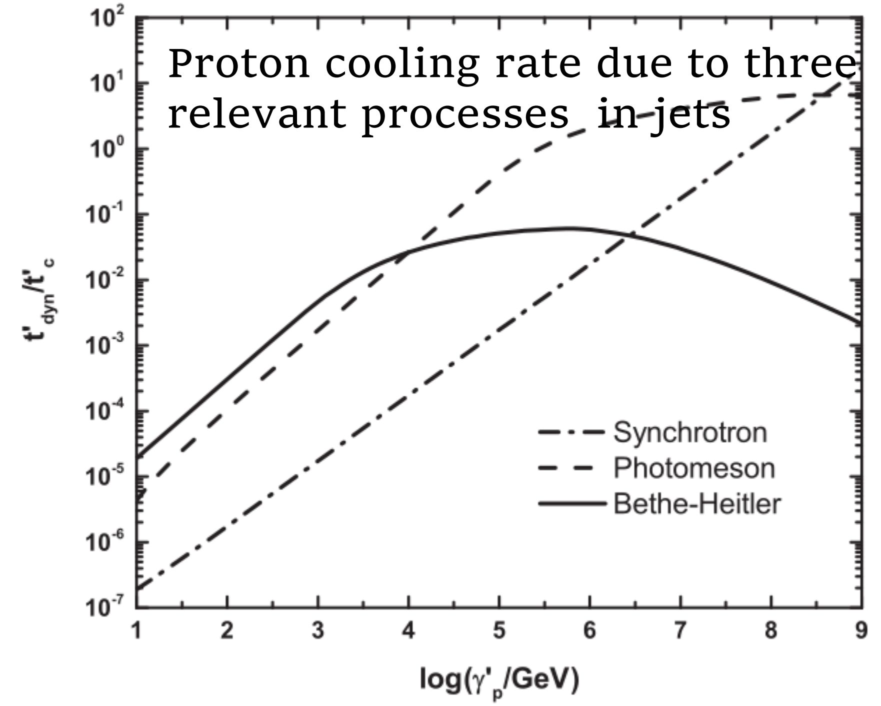
Typical GBM GRB fluence: 10^{-5}erg/cm^2 (10-1000 keV), peak at 100keV
GeV & neutrino fluence : (1GeV/100keV)^(2-β) → 1%GBM (for β=2.3)
neutrino fluence → 10^{-7}erg/cm^2
All-sky diffuse neutrino flux: 10^{-10}GeVcm^{-2}sr^{-1}s^{-1}
(assume 667 GRBs per year, only marginally consistent with the current limit)

Two possible solutions

1. Not all GRBs have the same properties as those with the extra component

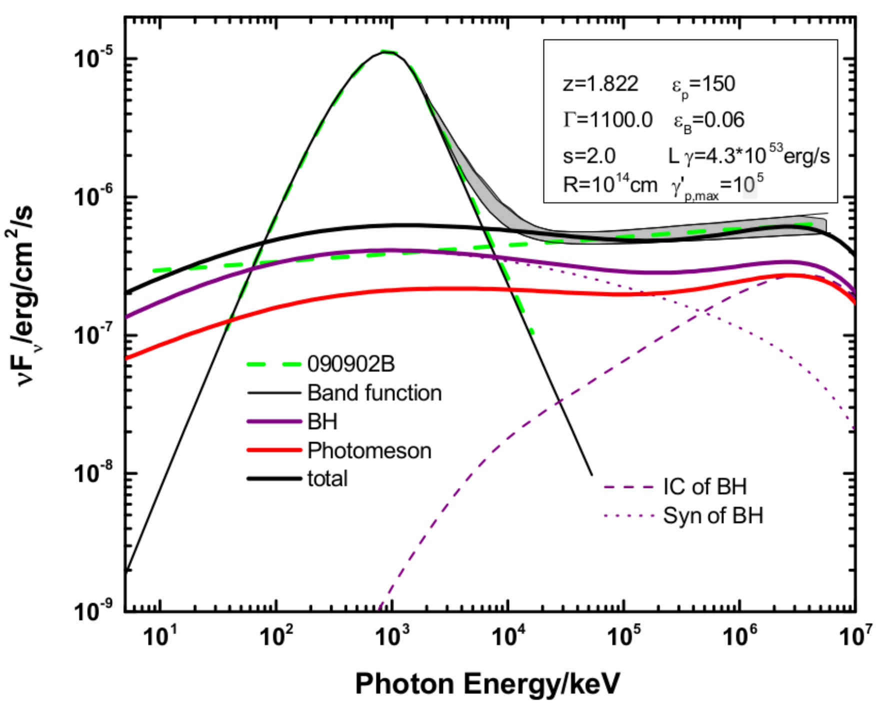
2. The maximum CR energy is not necessarily so high

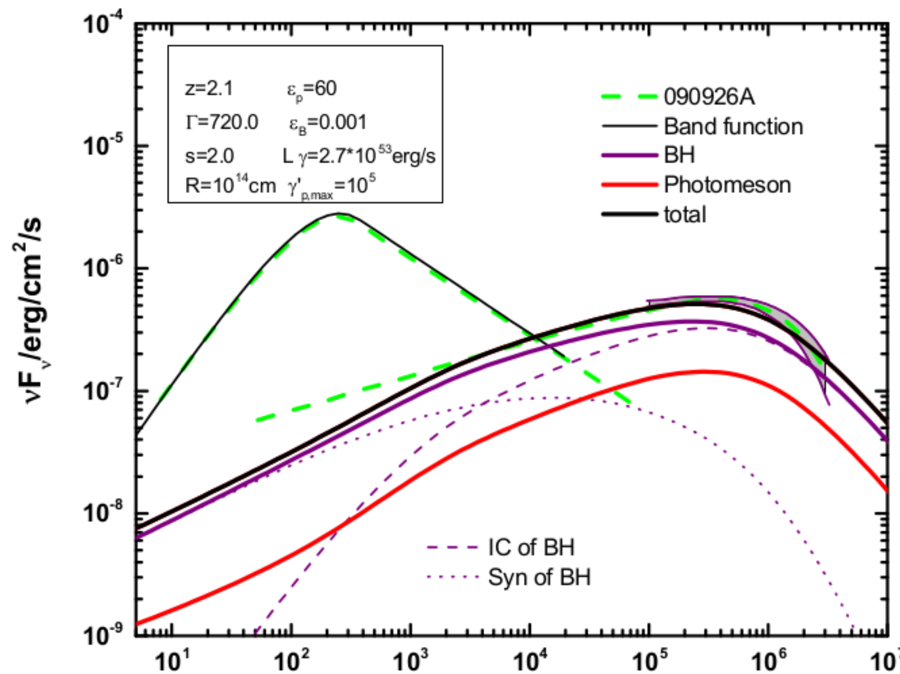
Proton cooling rate due to three relevant processes in jets



Wang, **RYL** et al. 2018 ApJ

E_{max}'=10^{14}eV, BH dominates energy loss of protons





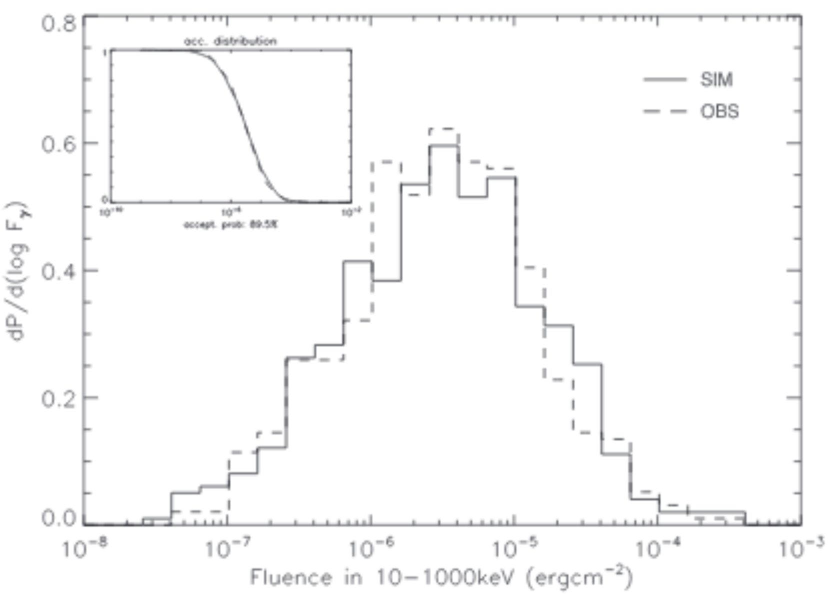
Diversities of GRBs

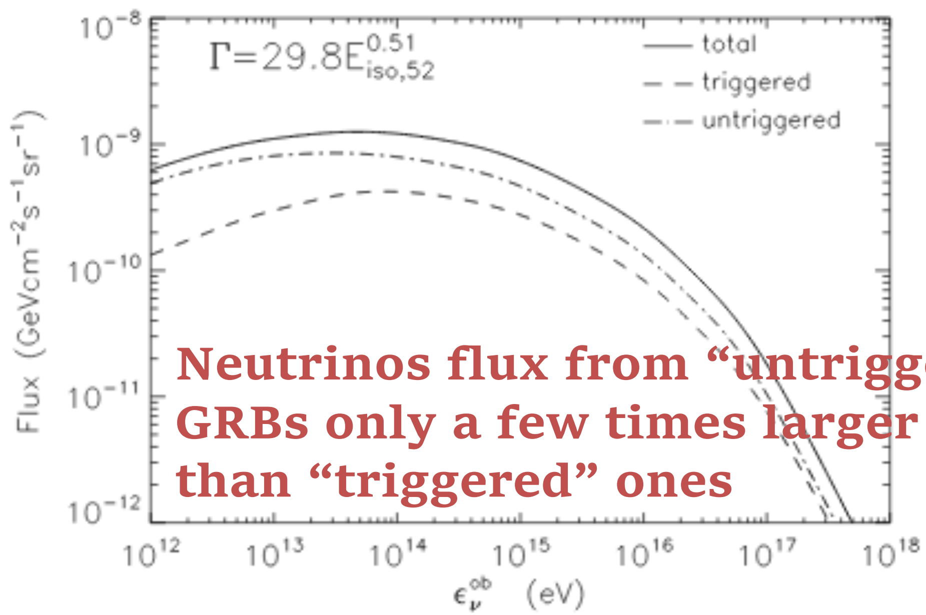
- Dim "untriggered" GRB
  - ordinary GRBs but with comparatively low luminosity and/or locate at comparatively high-redshift, do not trigger GRB detector
  - More numerous
- Low-Luminosity GRBs
  - a distinct population of GRBs (prototype: GRB 980425)
  - Lower energy input from single event, higher event rate
  - Smaller bulk Lorentz factor of jets
- Failed GRBs/Choked jets inside stellar envelop
  - Probably due to thick envelop
  - comparable energy input, higher event rate
  - Technically, not a GRB

No constraints on those GRBs from neutrino observation
Could they be the sources of diffuse neutrinos/UHECRs?

"untriggered" GRB

Step 1: simulate a GRB sample following LF, $E_{\gamma,iso}$-$L_{\gamma,iso}$, ε_{peak}-L_{γ} ...
Step 2: distinguishing "untriggered" GRBs from "triggered GRBs" in the simulated sample based on the performance of detector (i.e., GBM)
Step 3: make the "triggered GRB" sample is statistically consistent with observed GRB sample, so that we regard "untriggered GRB" sample represents the reality
Step 4: calculate neutrino flux from both samples, adjusting parameters to let neutrinos from "triggered" GRBs lower than limit

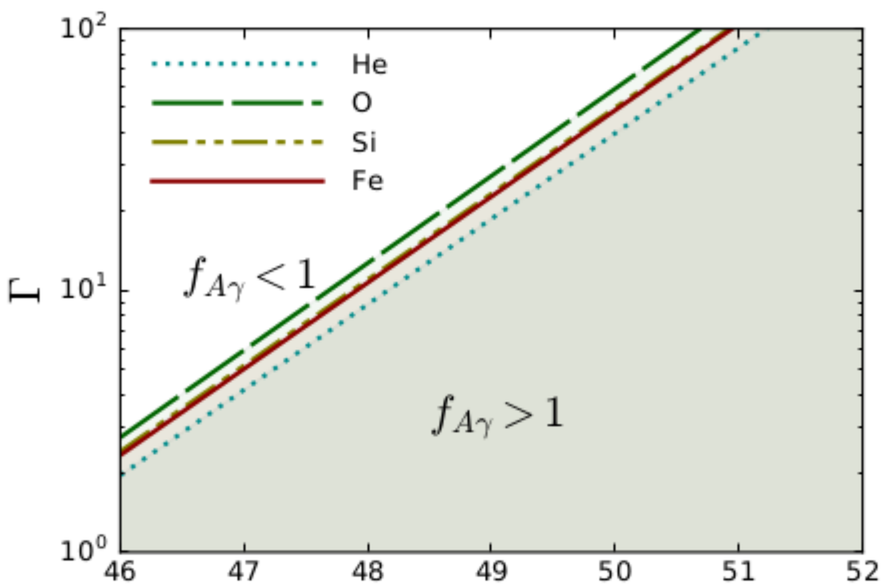




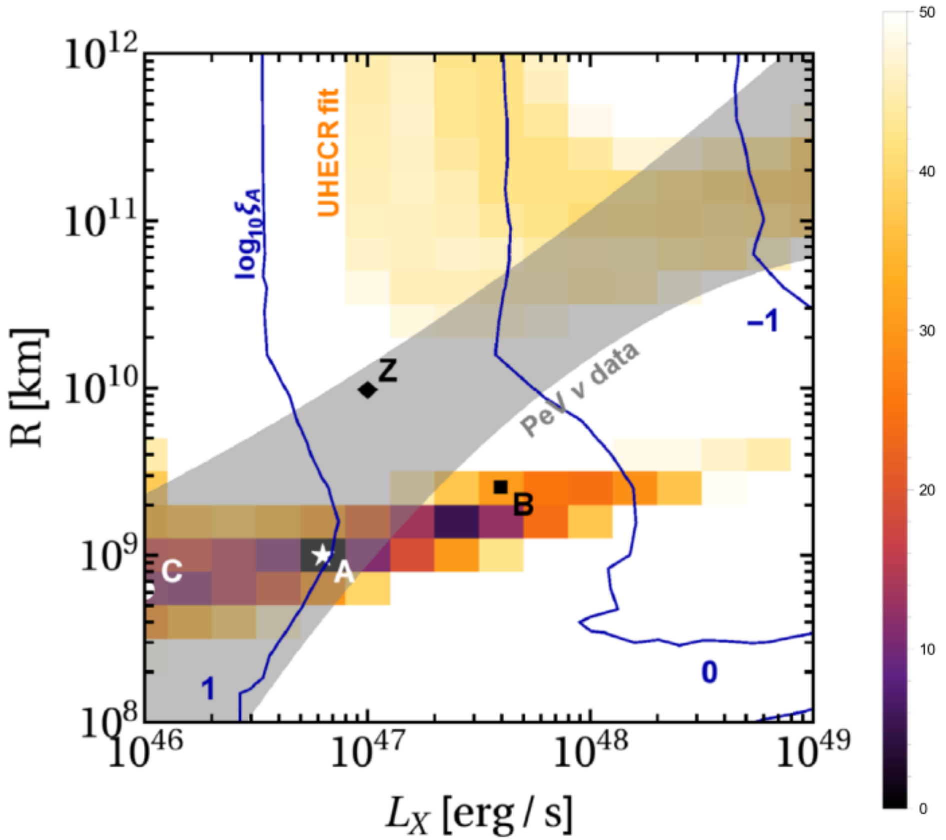
Neutrinos flux from "untrigger" GRBs only a few times larger than "triggered" ones

RYL & Wang 2013, ApJ
See also, Chen, **RYL** & Wang 2018, MNRAS

Low-Luminosity GRBs



Zhang et al. 2018, PRD

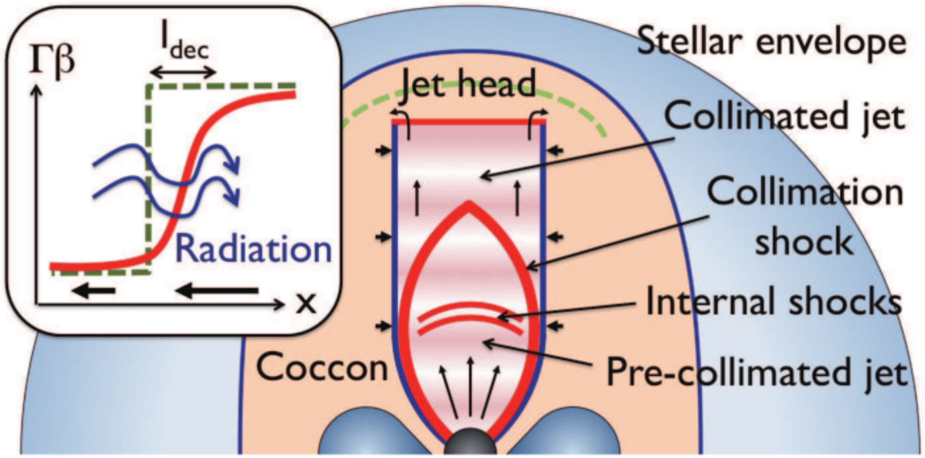


Boncioli et al. 2019, ApJ

Either UHECRs or neutrino (>100TeV) can be explained
fine tuning of parameters is needed to explain both simultaneously

earlier study: e.g., Murase et al. 2006, ApJ
Gupta & Zhang 2007, Aph
RYL et al. 2011, MNRAS
Senno et al. 2016, PRD

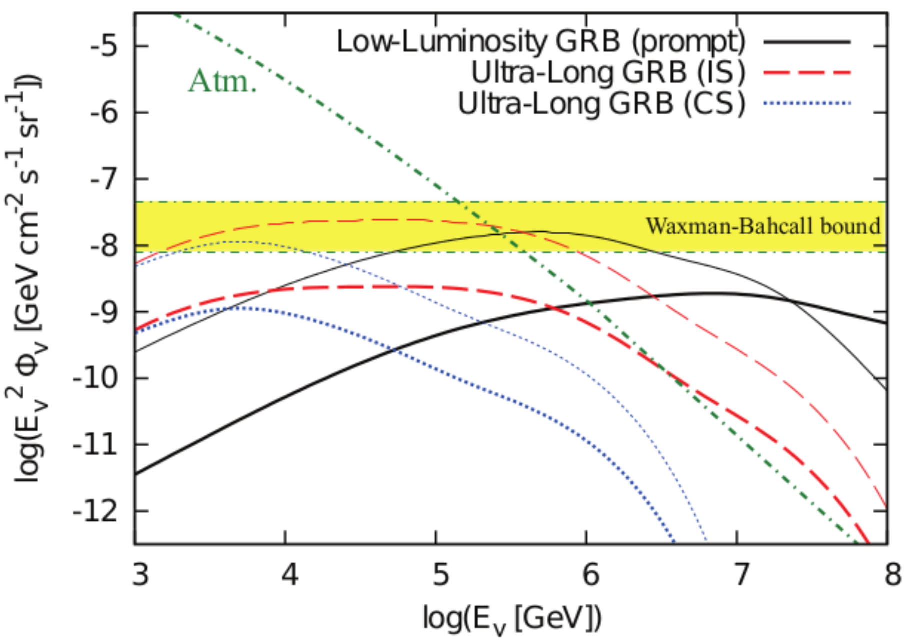
Choked jets (failed GRBs)

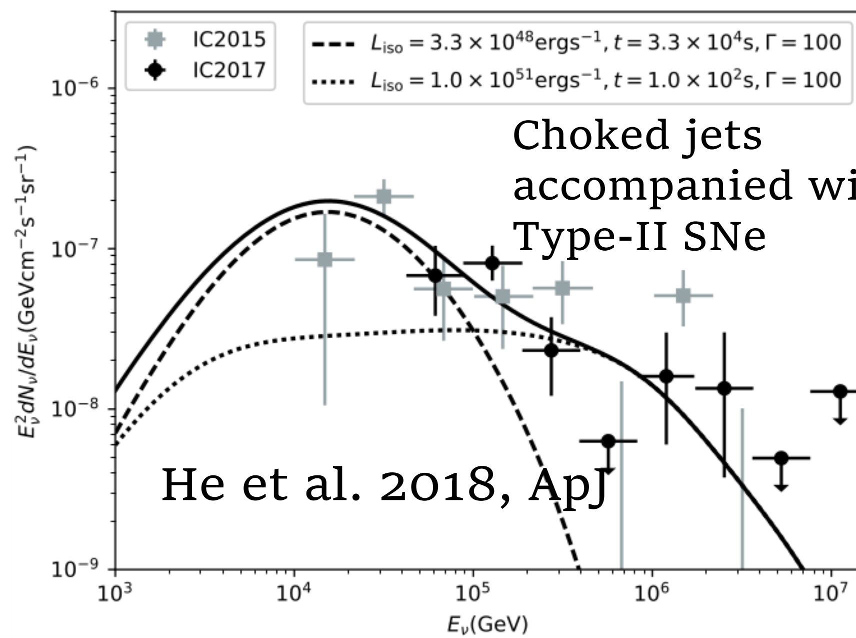


Murase & Ioka 2013, PRL

Shock produced during the propagation of jet inside the stellar envelop

Preferably occurs in low-power jet (e.g. low-luminosity GRB and ultralong GRB) case in which the shock is radiation-unmediated so CR acceleration is efficient.





Choked jets accompanied with Type-II SNe

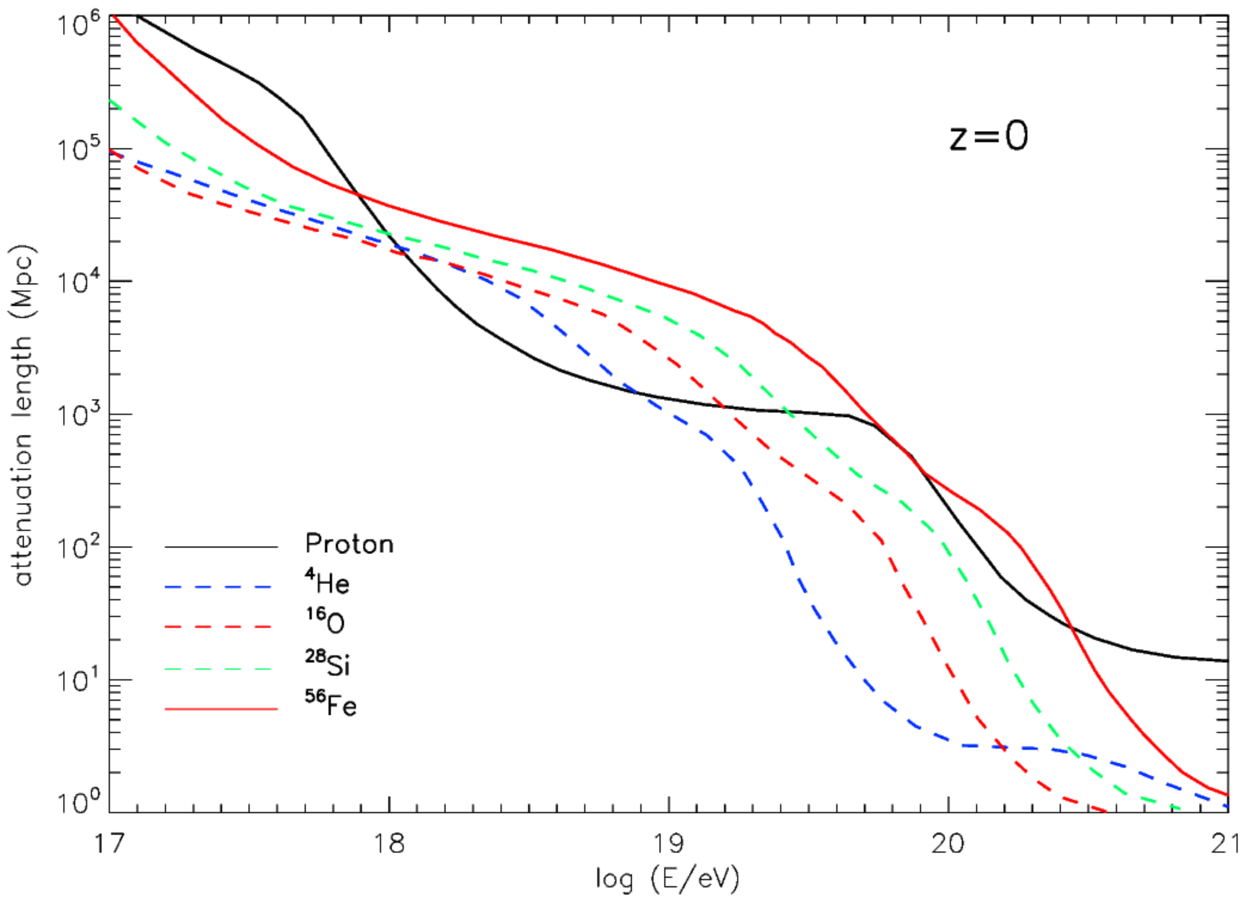
He et al. 2018, ApJ

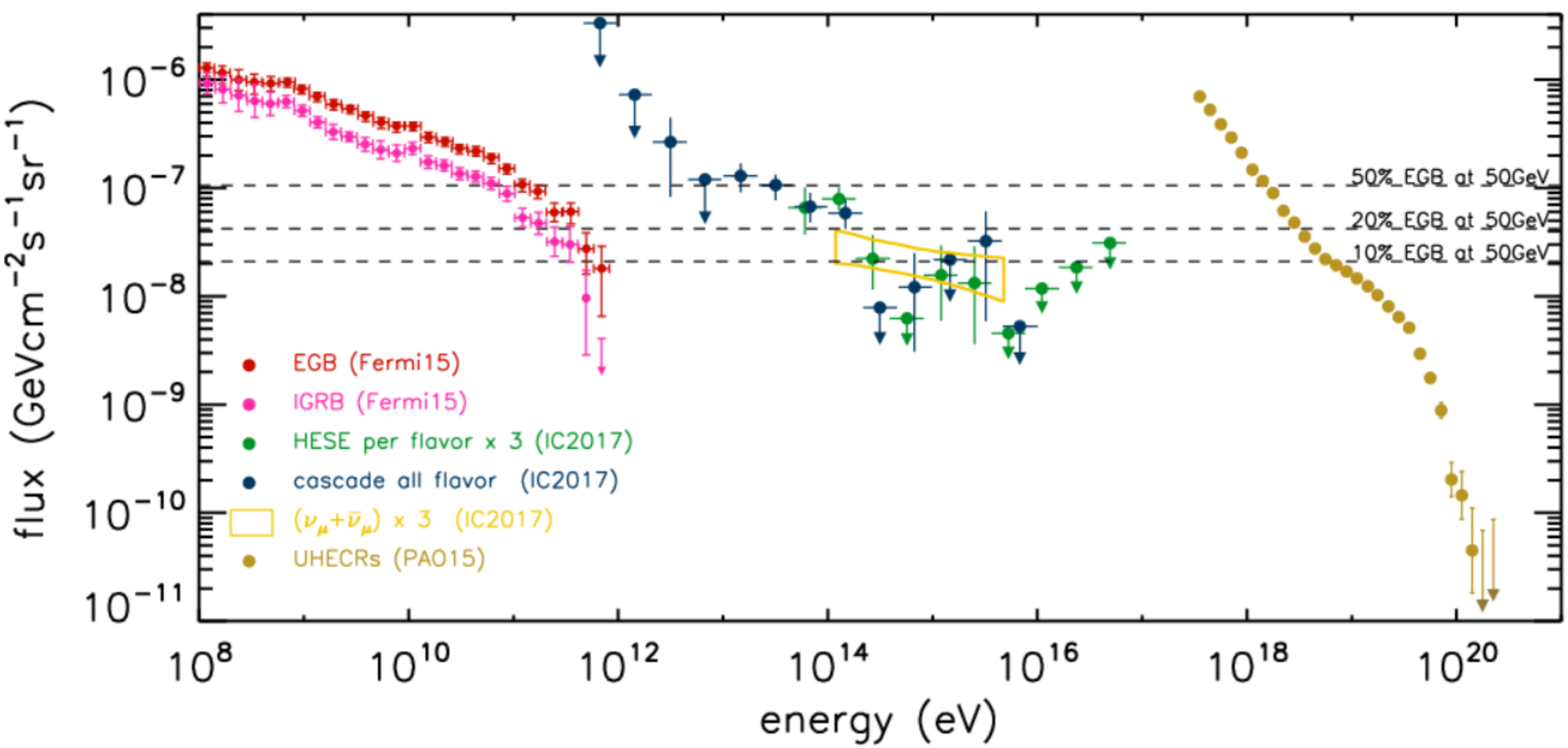
See also, e.g., Xiao & Dai 2014, ApJ; Senno et al. 2016, PRD

Summary

- GRBs do not make a significant contribution to diffuse neutrino background
- GRBs can still be sources of UHECRs from the point of view of neutrino observation
- Hadronic model for GeV prompt emission needs further tests (2^{nd} LAT catalogue)
- The possibilities of other populations of GRBs as the origins of diffuse neutrino background are not constrained

Backup slides


z=0
attenuation length (Mpc)
log (E/eV)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
17
18
19
20
21
Proton
^{4}He
^{16}O
^{28}Si
^{56}Fe



EGB (Fermi15)
IGRB (Fermi15)
HESE per flavor x 3 (IC2017)
cascade all flavor (IC2017)
$(\nu_\mu+\bar{\nu}_\mu)$ x 3 (IC2017)
UHECRs (PAO15)
50% EGB at 50GeV
20% EGB at 50GeV
10% EGB at 50GeV
flux (GeVcm^{-2}s^{-1}sr^{-1})
energy (eV)