The cosmic diffuse high-energy *Neutrino* and *Gamma-ray* background: Challenges for astrophysical models

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(collabs. with Nicholas Senno, Di Xiao, Kohta Murase, Zigao Dai & colleagues)

PMO, December 2016

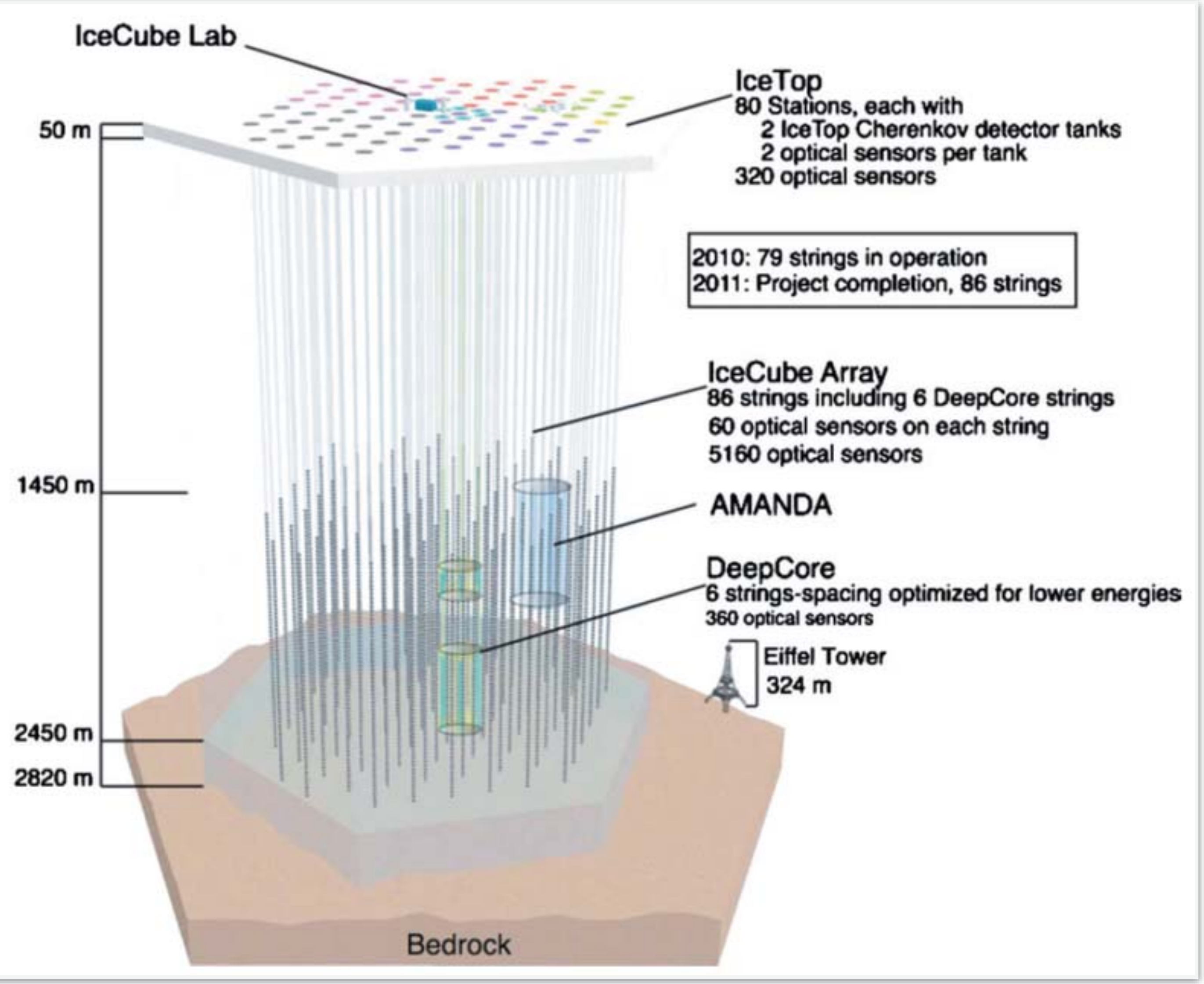
what causes
HENUs
at < few PeV?

or rather:

What causes
HECRs,
at < 100 PeV?

Multi-messenger traces: VHE neutrinos

IceCube



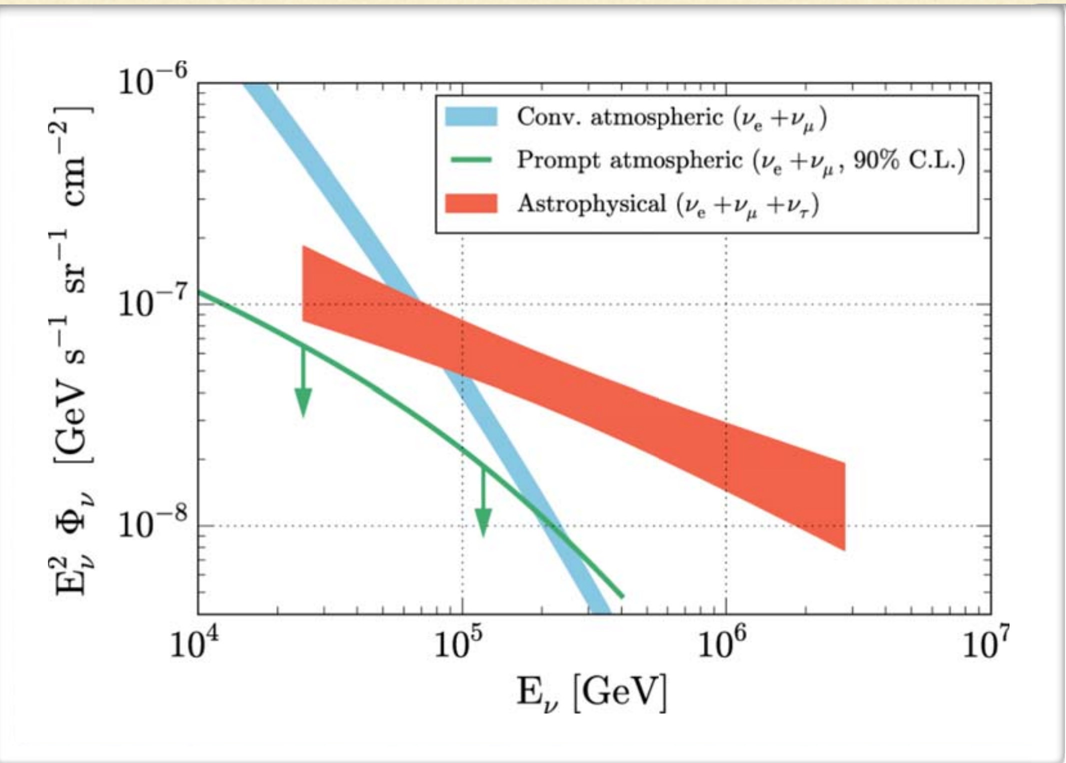
- The IceCube (IC) neutrino observatory is located at the Antarctic pole and has been at full operating capacity since 2011.
- Neutrinos produce charged particles when they interact with ice molecules. The Cherenkov radiation from these particles are observed by the optical sensors.
- Sensitive to two types of signals:
    - Charged current (CC) muon interactions are seen as track-like events
    - CC electron and tau interactions, and all neutral current (NC) interactions are seen as cascades

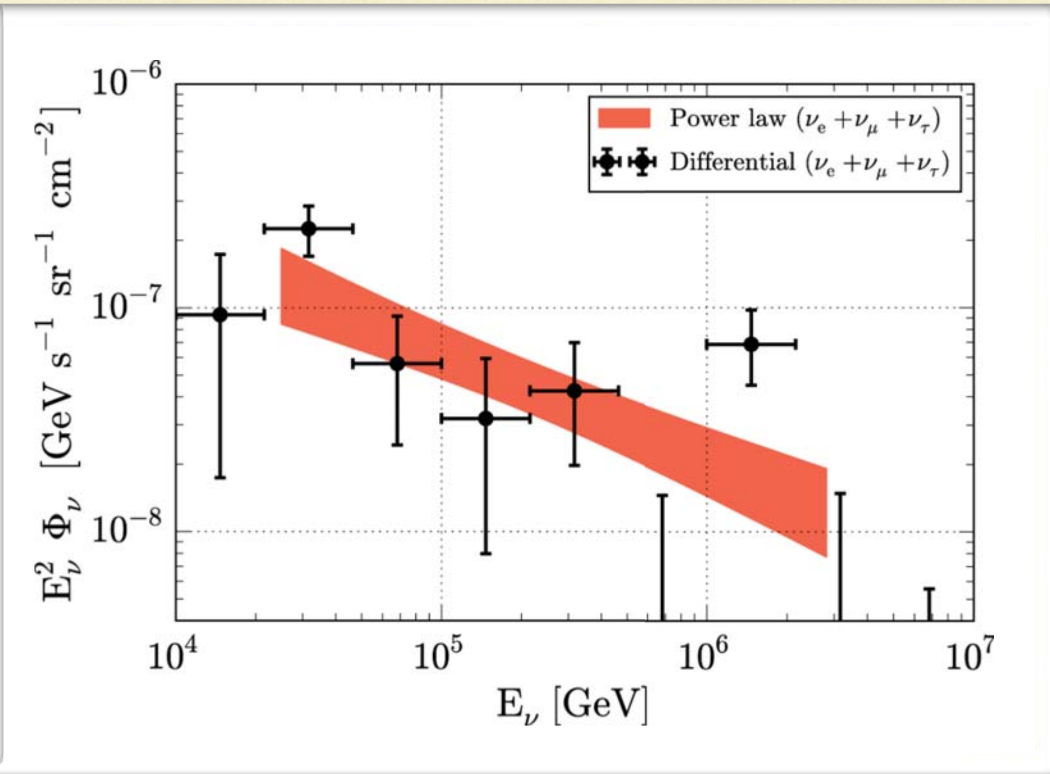
1 GTon instrumented volume, US$ 300M (30c/Ton)

- There is strong evidence for a diffuse, astrophysical flux of neutrinos with energies between 25 TeV and 2.8 PeV.

- The measured flux is well fit (at the 3.8σ level) by a soft power-law with index -2.50 ± 0.09 and an all-flavor flux of ~ 7×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV.

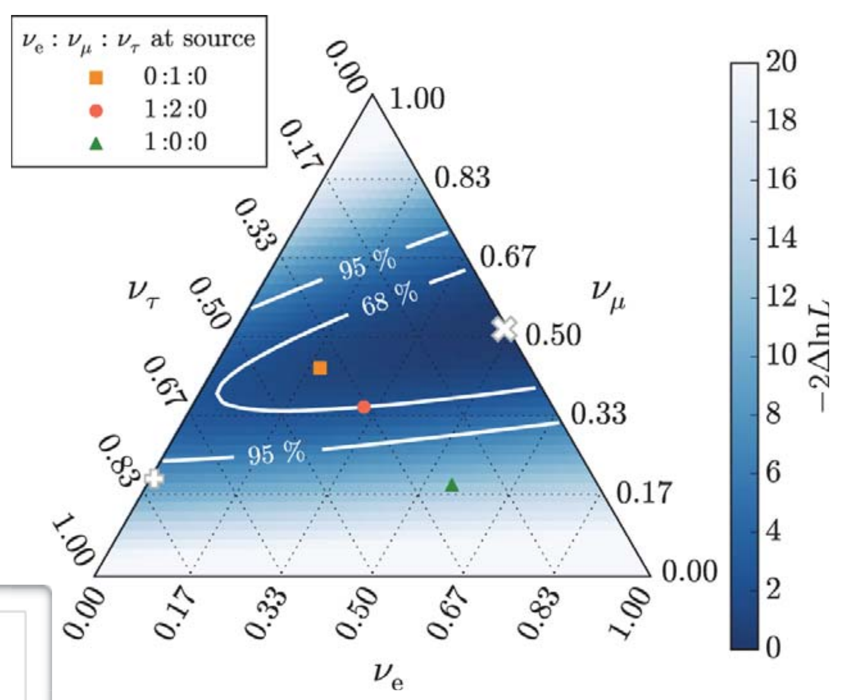
- Sources of the neutrino flux are unknown.

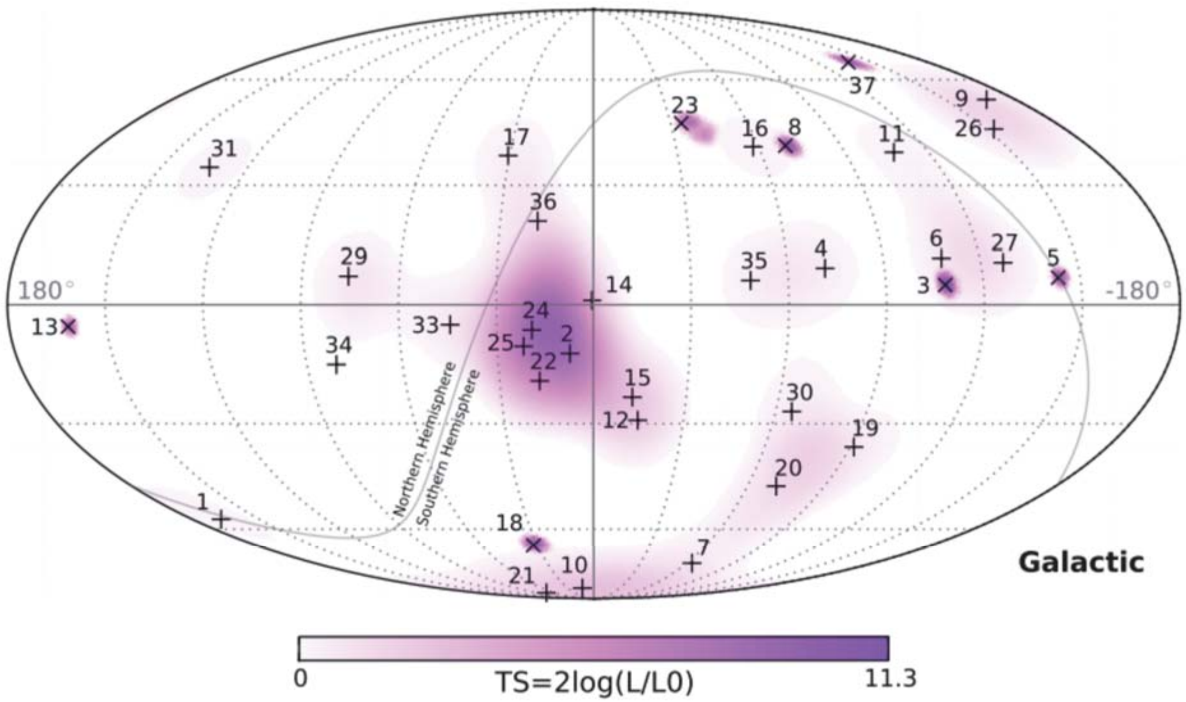




Aartsen, M.G. et al. ApJ 809, 98 (2015)

- There is increasing evidence for an extra-galactic origin for the observed neutrinos
- The measured flavor ratio (ν_e:ν_μ:ν_τ) is consistent with oscillation over cosmological distances (>100 Mpc)





- The neutrino arrival directions are consistent with isotropically distributed sources

→No obvious sources!

NEUTRINO PRODUCTION

- Astrophysical neutrinos are produced by CR interactions with ambient light or matter (pγ or pp interactions, respectively)
- VHE neutrinos and γ-rays are produced with ~0.05% and ~0.1% of the initial CR energy respectfully.
- For neutrinos with energy 25 TeV–5 PeV, CRs with energy ~50–100 PeV are needed
- To find the maximum CR energy achievable in our source models, we compare the acceleration time with the various energy-loss (cooling) timescales

$$p + p/\gamma \to N + \pi^{\pm} + \pi^{0} + \ldots$$

(Tan-background slides credit: Nick Senno)

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + \ldots$$

$$\begin{aligned} \pi^{+} &\rightarrow \mu^{+} + \nu_{\mu}\ , \\ & \quad \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} \end{aligned}$$

$$K^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

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

$$\begin{aligned} \pi^{-} &\rightarrow \mu^{-} + \bar{\nu}_{\mu}\ , \\ & \quad \mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} \end{aligned}$$

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

- Both ν_e and ν_μ are produced by charged pion decay,
- γ-ray photons are produced by neutral pion decay
- Secondary leptonic pairs also up-scatter ambient photons to GeV–TeV energies

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + ...$$

$$\begin{aligned} \pi^{+} &\rightarrow \mu^{+} + \nu_{\mu}, \\ & \quad \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} \end{aligned}$$

$$\begin{aligned} \pi^{-} &\rightarrow \mu^{-} + \bar{\nu}_{\mu}, \\ & \quad \mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} \end{aligned}$$

$$\begin{aligned} K^{+} &\rightarrow \mu^{+} + \nu_{\mu} \\ n &\rightarrow p + e^{-} + \bar{\nu}_{e} \\ \pi^{0} &\rightarrow \gamma + \gamma \end{aligned}$$

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$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + \dots$$

$$\begin{aligned} \pi^{+} &\rightarrow \mu^{+} + \nu_{\mu} \ , \\ & \quad \mu^{+} \rightarrow \boxed{e^{+}} + \nu_{e} + \bar{\nu}_{\mu} \end{aligned}$$

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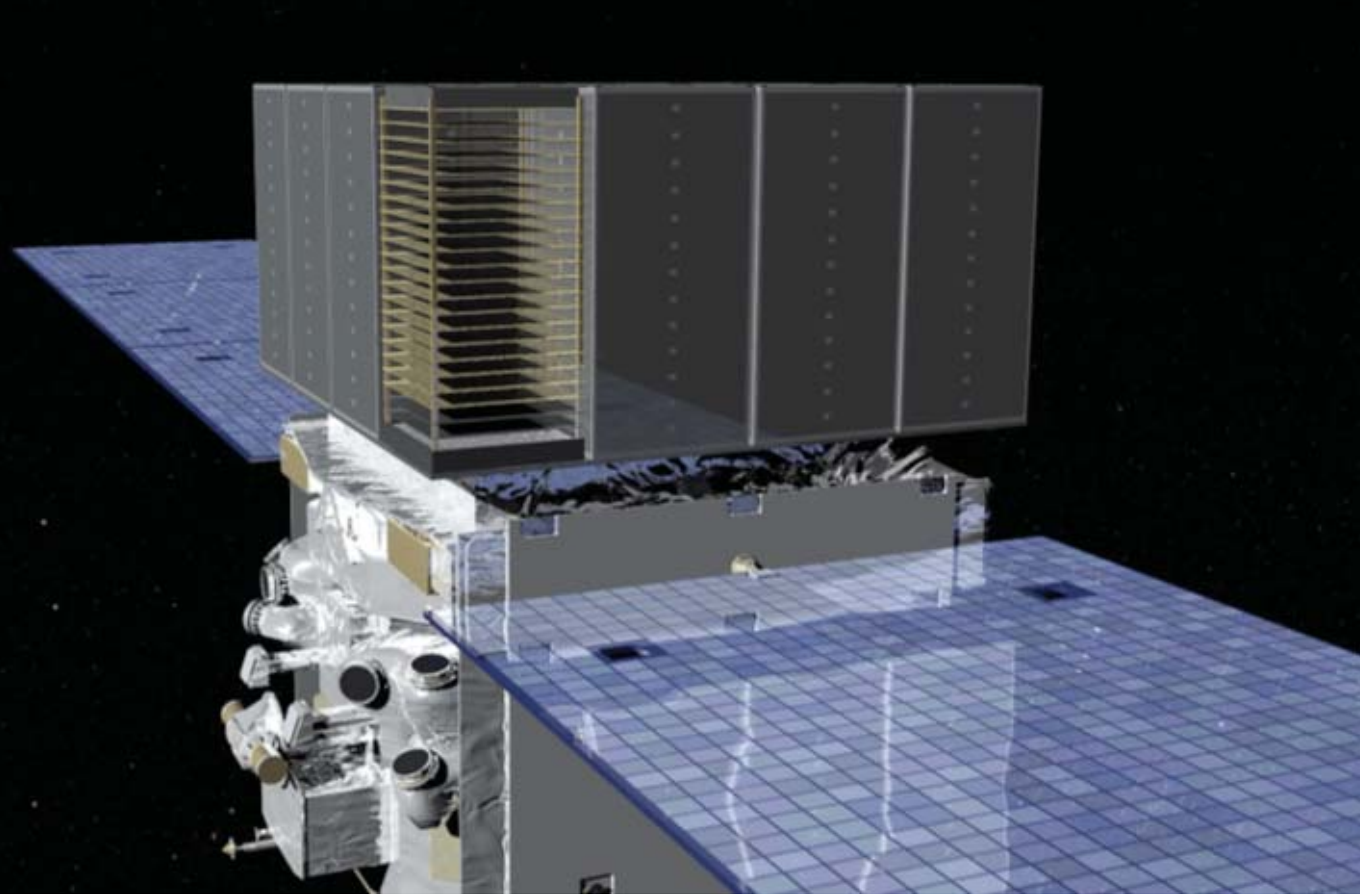
$$\pi^{0} \rightarrow \boxed{\gamma} + \boxed{\gamma}$$

- Both ν_e and ν_μ are produced by charged pion decay,
- γ-ray photons are produced by neutral pion decay (plus $e^{\pm}$ interactions)
- Secondary leptonic pairs also up-scatter ambient photons to GeV–TeV energies

→ ***expect a corresponding γ-ray background !***

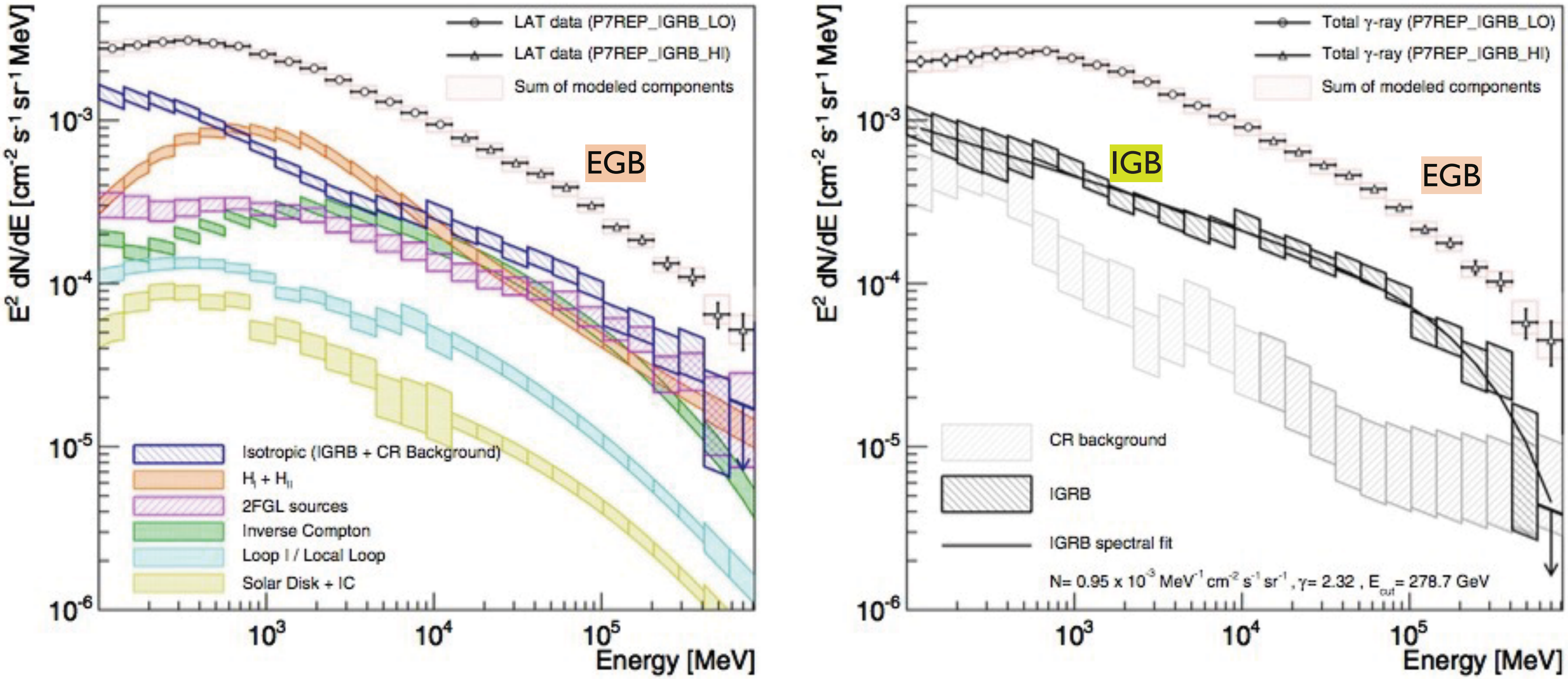
Other multimessenger traces: VHE gammas, **Fermi**



Observed:

Fermi EGB & IGB

Ackermann+15, ApJ 799:86



- ***EGB:*** Extragalactic “gamma-ray” background (everything, incl, point sources, CRs, etc)
- ***IGB:*** Isotropic gamma-ray bkg. (minus extrapol. unresolved blazars :→ ~14% of EGB)

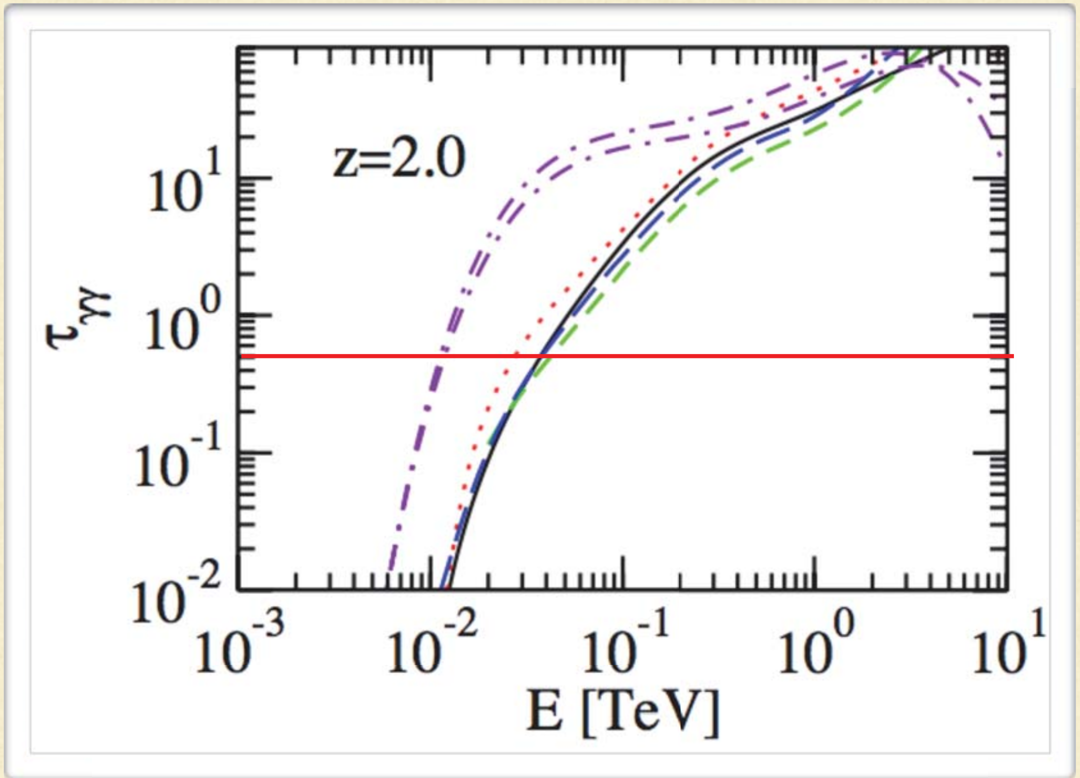
VHE γ–rays are expected to accompany neutrinos.
They are related via:

$$\epsilon_\gamma^2 \Phi_\epsilon \simeq 2^{s-1} \varepsilon_\nu \Phi_\varepsilon \Big|_{\varepsilon_\nu = 0.5\epsilon_\gamma}$$

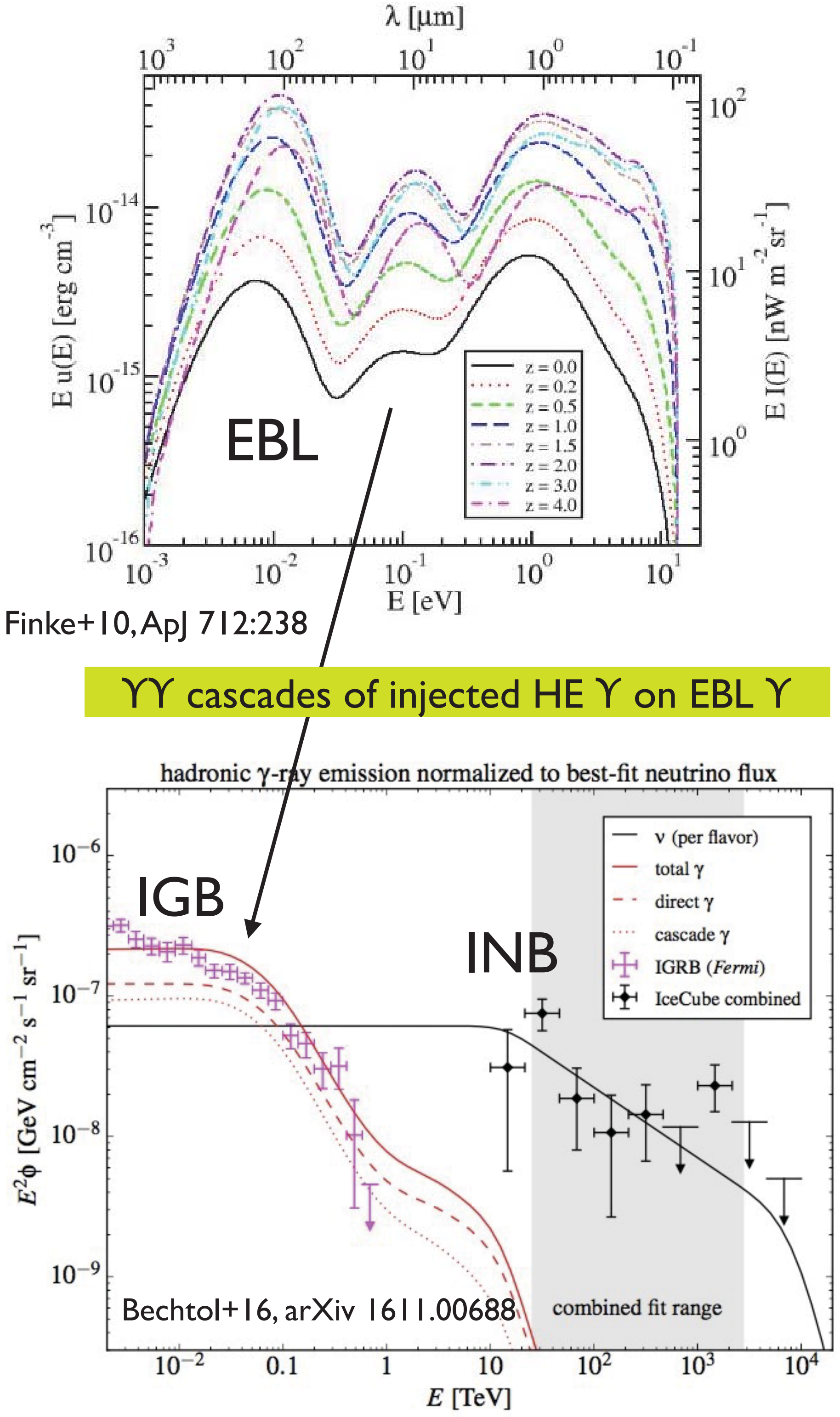
(injection spectrum similar)

BUT:

- A fraction $\sim 1 - e^{-\tau_{\gamma\gamma}}$ of γ–rays are attenuated by extra-galactic background light (EBL)
- The resulting spectrum is universal for large distances
(γγ→e+e- cascades)



Finke et al. ApJ 712, 238 (2010)



Finke+10, ApJ 712:238

ϒϒ cascades of injected HE ϒ on EBL ϒ

Bechtol+16, arXiv 1611.00688

High energy γ-ray propagation in intergalactic space

- $\gamma_h + \gamma_s \rightarrow e^+ + e^-$
- Threshold: $E_{\gamma h} > (m_e c^2)/E_{\gamma s}$
- Target photons $E_{\gamma s}$: diffuse IR bkg, from starlight + CMB
- Multiple γγ cascades until below threshold
- MC simulations, or kinetic equ's →universal final spectrum

(Berezinsky+ 75, Coppi, Aharonian 97, etc….)

Some possible pp scenarios

Need: enough CR energy budget, pp efficiency

- ***Radio Galaxies***: CRs 10-100 EeV, escape into cluster IGM, where produce ***pp nus*** in the LSS ~✔?
- ***IGS*** (cluster accretion shocks): CRs @ 100PeV, then ***pp nu*** in IGM , & $t_{diff} \sim t_{inj}$ → sp. break ~✔?
- ***SBGs*** (starburst gals): may expect higher B_{ISM}, both SNe, HNe → CRs @ 100PeV, → ***pp nus*** ~✔?

Murase, Ahlers, Lacki 2013, PRD, 88:121301

Some early specific attempts

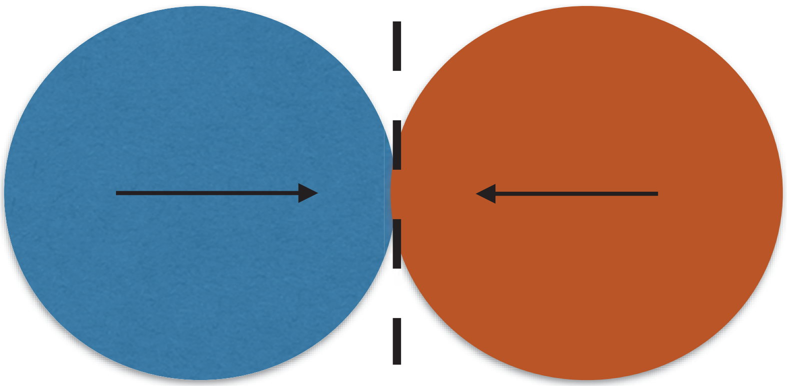
(assuming data status @ 2013-14)

(i) Galaxy mergers

Galaxy mergers

- They occur!
- Their gas components will undergo a strong shock
- Shock →particles will be Fermi accelerated→CRs
- Dense gas →ample targets for pp

Galaxy merger shocks



$M_\star \sim 10^{11}\ M_\odot$, $M_{gas} \sim 10^{10}\ M_\odot$

$v_s \sim 3\text{-}5 \times 10^7$ km/s

$$\overline{E}_{gms} \approx M_{gas} v_s^2, \text{ or}$$

$$\overline{E}_{gms} \sim 3.2 \times 10^{58}\ M_{gas,10} v_{s,7.6}{}^2 \text{ erg.}$$

$$t_{dyn} \approx R_{gal}/v_s \sim 25\ R_{gal,22.5} v_{s,7.6}{}^{-1} \text{ Myr,}$$

$$\mathcal{R}_{gms} \gtrsim 10^{-4} \quad \text{Mpc}^{-3}\ \text{Gyr}^{-1}$$

$$L_{gms} \sim 4.0 \times 10^{43}\ \overline{E}_{gms,58.5} v_{s,7.6} R_{gal,22.5}{}^{-1} \text{ erg s}^{-1}$$

Cosmic ray energy input into Universe:

$$Q_{cr,gms} \sim 3.2 \times 10^{44} \text{ erg Mpc}^{-3}\ \text{yr}^{-1} \times \xi_{cr,-1} \overline{E}_{gms,58.5} \mathcal{R}_{gms,-4}$$

Shock CR acceleration in gal. merg. shock

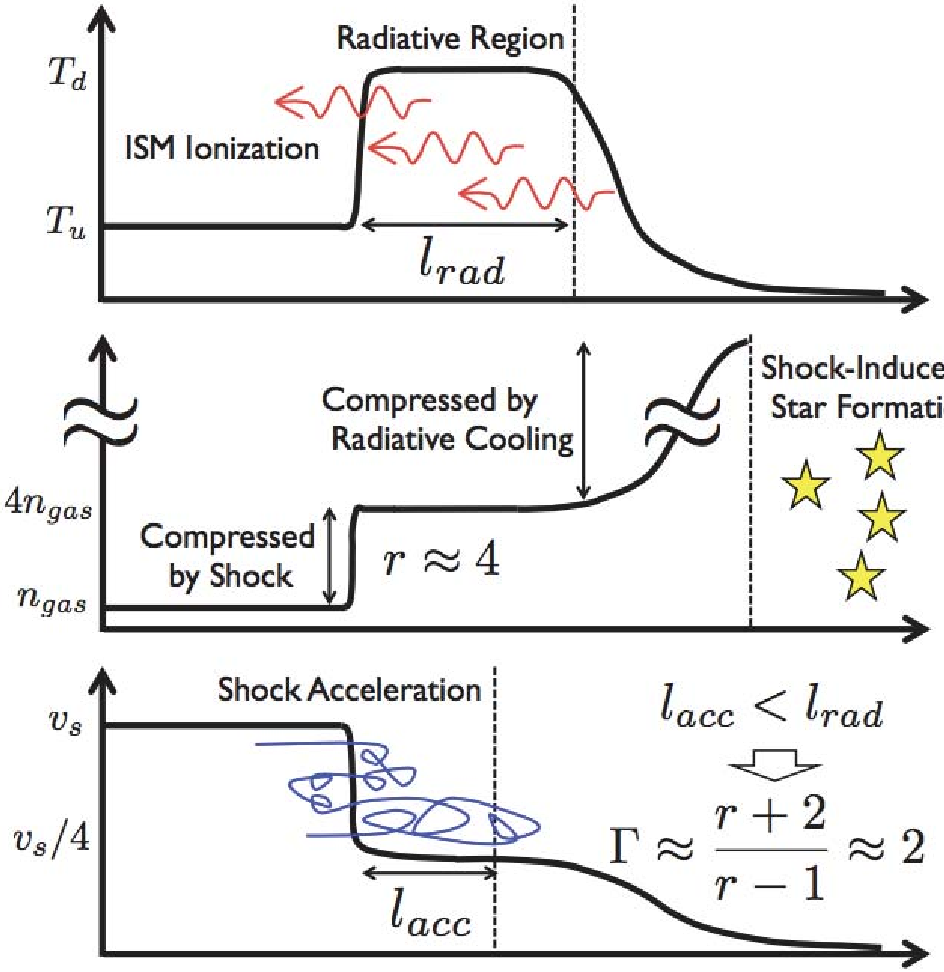


FIG. 1.— The schematic picture of GMS and the DSA in-situ; temperature (top), density (middle), and velocity in the shock rest frame (bottom).

$$t_{rad} \sim 0.77\, {n_{gas,0}}^{-1} {v_{s,7.6}}^{3.4}\ \mathrm{Myr},$$

$$l_{rad} \approx v_s/4 \times t_{rad} \sim 78\, {n_{gas,0}}^{-1} {v_{s,7.6}}^{4.4}\ \mathrm{pc}$$

$$t_{diff} \approx 16D/cv_s \sim 0.14\, \varepsilon_{cr,17} {B_{-5}}^{-1} {v_{s,7.6}}^{-1}\ \mathrm{Myr}$$

$$l_{acc} \approx v_s/4 \times t_{diff} \sim 17\, \varepsilon_{cr,17} {B_{-5}}^{-1}\ \mathrm{pc}$$

$l_{acc} < l_{rad}$ → $M >> 1$, $r \sim 4$

i.e. strong shock

$$\longrightarrow \varepsilon_{cr,max} \approx \eta Z e B R_{gal} v_s / c,$$

$$\boxed{\varepsilon_{cr,max} \sim 1.3 \times 10^{17}\ \eta Z B_{-5} v_{s,7.6} R_{gal,22.5}\ \mathrm{eV}}$$

pp →π+ →ν from gal. merger shock

$$t_{pp} \approx 1/\kappa_{pp} n_{gas} \sigma_{pp} c \sim 26\ n_{gas,0}{}^{-1}\ \mathrm{Myr},$$

$$f_{pp} = t_{dyn}/t_{pp}, \qquad f_{pp} \sim 0.96\ R_{gal,22.5} v_{s,7.6}{}^{-1} n_{gas,0}.$$

$$\varepsilon_{\nu_i,max} \sim 0.05 \times \varepsilon_{p,max}/(1+z) \sim 4\ (1+z)^{-1} \varepsilon_{p,max,17}\ \mathrm{PeV}$$

$$\varepsilon_{cr} Q_{\varepsilon_{cr}} = Q_{cr}/\mathcal{C}.$$

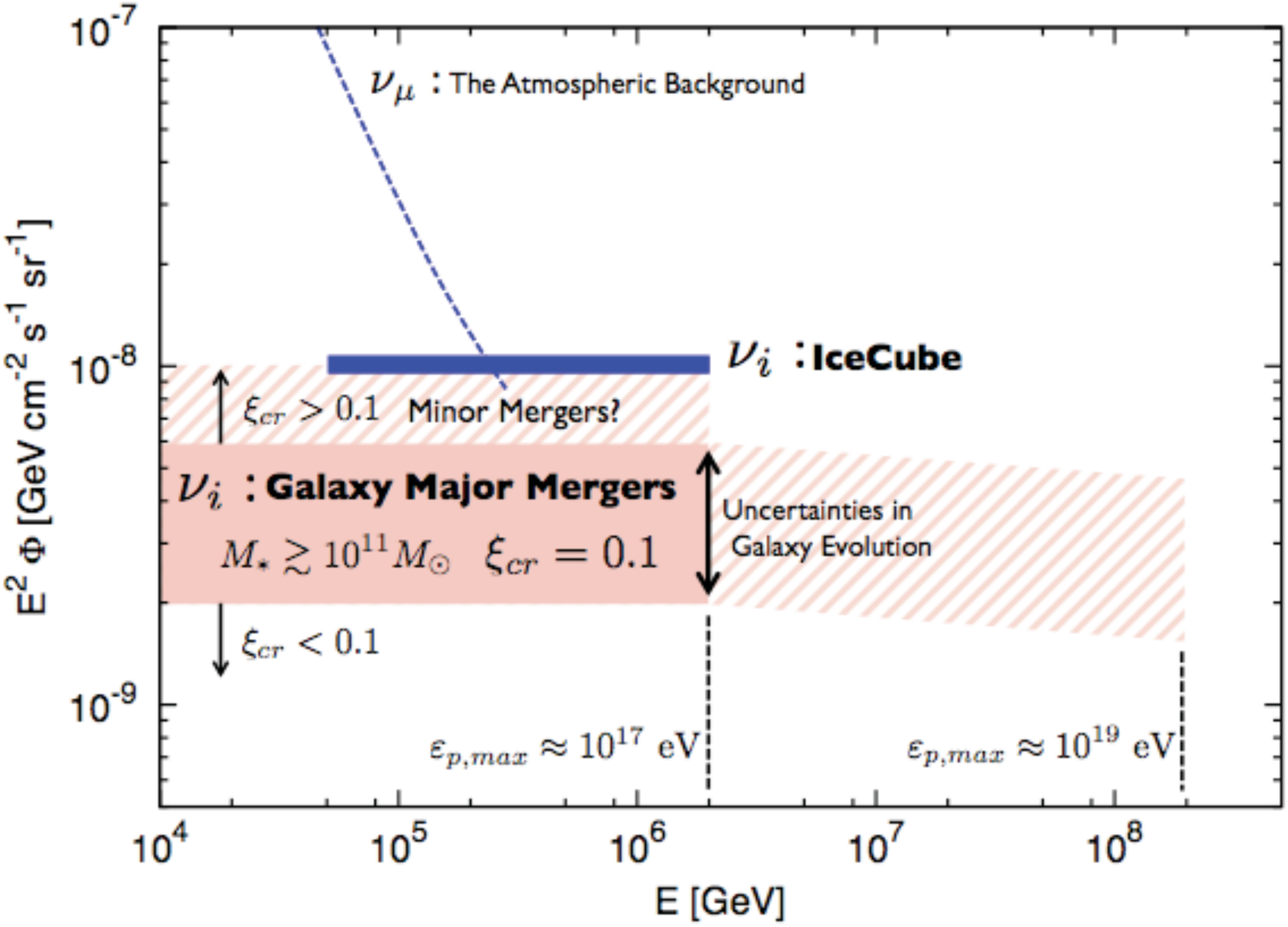
$$\varepsilon_{\nu_i}^2 \Phi_{\nu_i} \approx \frac{c t_H \xi_z}{4\pi} \frac{1}{6} \min[1, f_{pp}] (\varepsilon_{cr} Q_{\varepsilon_{cr}}).$$

$$\varepsilon_{\nu_i}^2 \Phi_{\nu_i} \sim 0.59 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} (\xi_z/3)(18/\mathcal{C}) \times f_{pp} \xi_{cr,-1} \overline{E}_{gms,58.5} \mathcal{R}_{gms,-4}$$

$$\varepsilon_{\gamma}^2 \Phi_{\gamma} \approx 2 \times \varepsilon_{\nu}^2 \Phi_{\nu}|_{\varepsilon_\nu = 0.5 \varepsilon_\gamma}.$$

Galaxy mergers, INB & IGB

Kashiyama & Mészáros '14, ApJL 790:L14



- ***Every galaxy*** merged at least ***once*** in the last ***Hubble time***
- ***Major mergers*** → E_{gms}~$10^{58.5}$ erg, R~10^{-4} Mpc^{-3} Gyr^{-1} v_s~$10^{7.7}$ cm/s $Q_{cr,gms}$~3×10^{44} erg Mpc^{-3} yr^{-1} $\varepsilon_{cr,max}$ ~$10^{18.5}$ Z eV
- ***pp*** → PeV **ν**s, 100 GeV **γ**s
- **ν:** Individual GMS: 10^{-2} μ/yr, INB: ***20-60%*** IC3 obs.flux
- γ: Individual GMS flux: ~3.10^{-13} erg/cm2/s→CTA? ***IGB*** ~10^{-8} GeV/cm^2/s/sr , about ***10-30%*** Fermi IGB (too much?)
- Minor mergers: uncertain, could add up to 70-100%
- Good, at least for ***PeV nus*** (but not for TeV nus, if p=-2)

Another candidate:

(ii) Supernovae
& Hypernovae
@ z <4-5

STARBURST GALAXIES

The Antennae Galaxies
Credit: NASA/ESA

- Starburst galaxies (SBGs) have high star formation activity and a significant amount of free gas.
- They can be triggered by the collision or interaction of two galaxies.
- Some typical values:

$n_p \sim 10 - 100 \text{ cm}^{-3}$ $B_g \sim 200\ \mu\text{G}$

$H_{sbg} \sim 30 - 300 \text{ pc}$ $l_{c,g} \sim 10 \text{ pc}$

- Compare with typical Milky Way Galaxy:

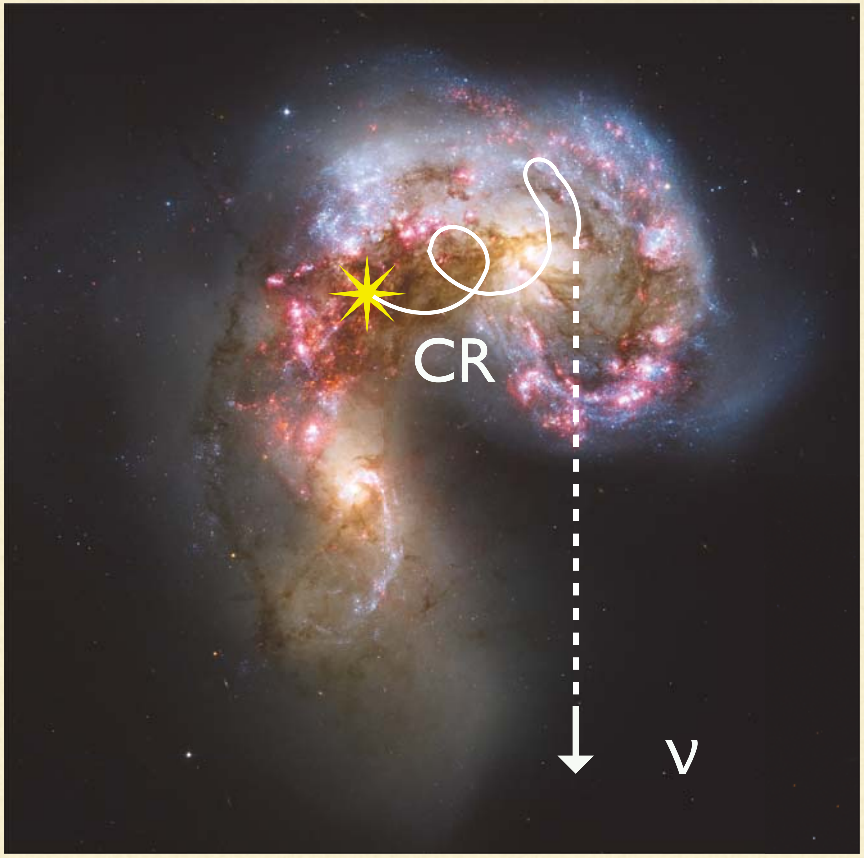
$n_p \sim 1 \text{ cm}^{-3}$ $B_g \sim 6\ \mu\text{G}$

$H_{sbg} \sim 1000 \text{ pc}$

CR

STARBURST GALAXIES

(Loeb & Waxman 06, …)



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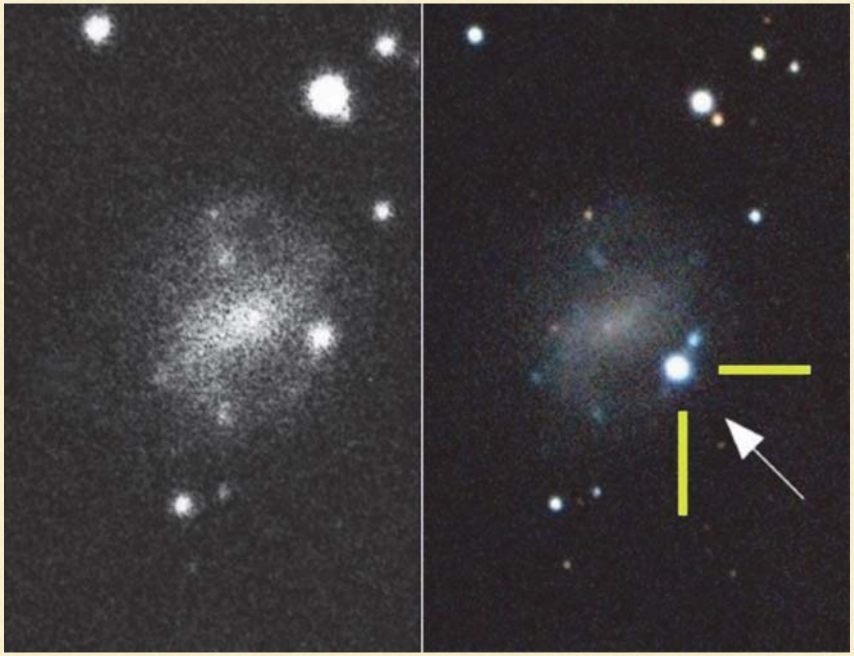
HYPERNOVAE

→are found more plentifully in SBGs; and accelerate CRs!

- Hypernovae (HNe) are a class of Type Ibc core collapse supernovae (ccSNe) that release up to 10x more energy in their ejecta (~10^{52} ergs).
- They have fast trans-relativistic ejecta, possibly from a stalled jet.
- SNe are presumed CR accelerators up to ~ PeV energies. HNe should be capable of producing 100 PeV protons.



ESO 184-G82
May 15, 1985

SN 1998bw
May 4, 1998

European Southern Observatory
Galama et al. Nature 395, 670 (1998)

HN/SN Energetics & pp rate

(Wang+ 07, Budnik+07,…, Senno+15)

$$\mathcal{R}_{\rm hn} \sim 4 \times 10^{-6} \xi_{{\rm hn},-1.4} \ {\rm Mpc}^{-3} \ {\rm yr}^{-1}$$

$$\boxed{\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\rm hn} \simeq 6.4 \times 10^{44} \ \xi_{{\rm hn},-1.4} \ \mathcal{C}_{18}^{-1} E_{{\rm cr,hn},51.4} \quad {\rm erg} \ \ {\rm Mpc}^{-3} \ \ {\rm yr}^{-1},}$$

$$\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\rm sn} = \frac{(1-\xi_{\rm hn})}{\xi_{\rm hn}} \frac{\mathcal{C}_{\rm hn}}{\mathcal{C}_{\rm sn}} \frac{E_{\rm cr,sn}}{E_{\rm cr,hn}} \left(\varepsilon_p Q_{\varepsilon_p}\right)_{\rm hn}$$

$$\varepsilon_{p,\rm max} \simeq (3/20) Ze B_s R_{\rm dec} \beta_{\rm ej} \ \simeq 10^{17} Z n_{g,2.3}^{1/6} E_{k,{\rm hn},52} \ M_{{\rm ej},0.5}^{-2/3} \ {\rm eV}$$

$$D(\varepsilon_p) = D_* \left[(\varepsilon_p/\varepsilon_{p,*})^{\alpha} + (\varepsilon_p/\varepsilon_{p,*})^2 \right] \qquad r_L(\varepsilon_{p*}) = \ell_c/5$$

(Propagation in ISM and IGM)

$$t_{d,g} = H_g^2/6D_g \simeq 1.5 \times 10^{12} H_{g,21}^2 \ell_{g,20} B_{g,-3.7}^2 \varepsilon_{p,17.2}^{-1/3} \ {\rm s} \qquad t_{w,g} = H_g/V_w \simeq 6.2 \times 10^{12} H_{g,21} V_{w,3.2}^{-1} \ {\rm s}$$

$$\boxed{\tau_{pp,g} \simeq n_g \kappa \sigma_{pp} c \ \ \min[t_{d,g}, \ t_{w,g}]}$$

(optical depth for nu-production)

HN/SN diffuse nu-bkg

(Senno+ ’15)

$$f_{pp,\mathrm{sbg}} = \xi_{\mathrm{sbg}}\left(1 - e^{-\tau_{pp,g,\mathrm{sbg}}}\right)$$

$$f_{pp,\mathrm{sfg}} = \xi_{\mathrm{sfg}}\left(1 - e^{-\tau_{pp,g,\mathrm{sfg}}}\right) \quad ; \quad \xi_{\mathrm{sfg}} = 1 - \xi_{\mathrm{sbg}}$$

$$f_{pp,\mathrm{cl}} = \left(1 - e^{-\tau_{pp,\mathrm{cl}}}\right) \times \left[\xi_{\mathrm{sbg}} e^{-\tau_{pp,g,\mathrm{sbg}}} + \xi_{\mathrm{sfg}} e^{-\tau_{pp,g,\mathrm{sfg}}}\right]$$

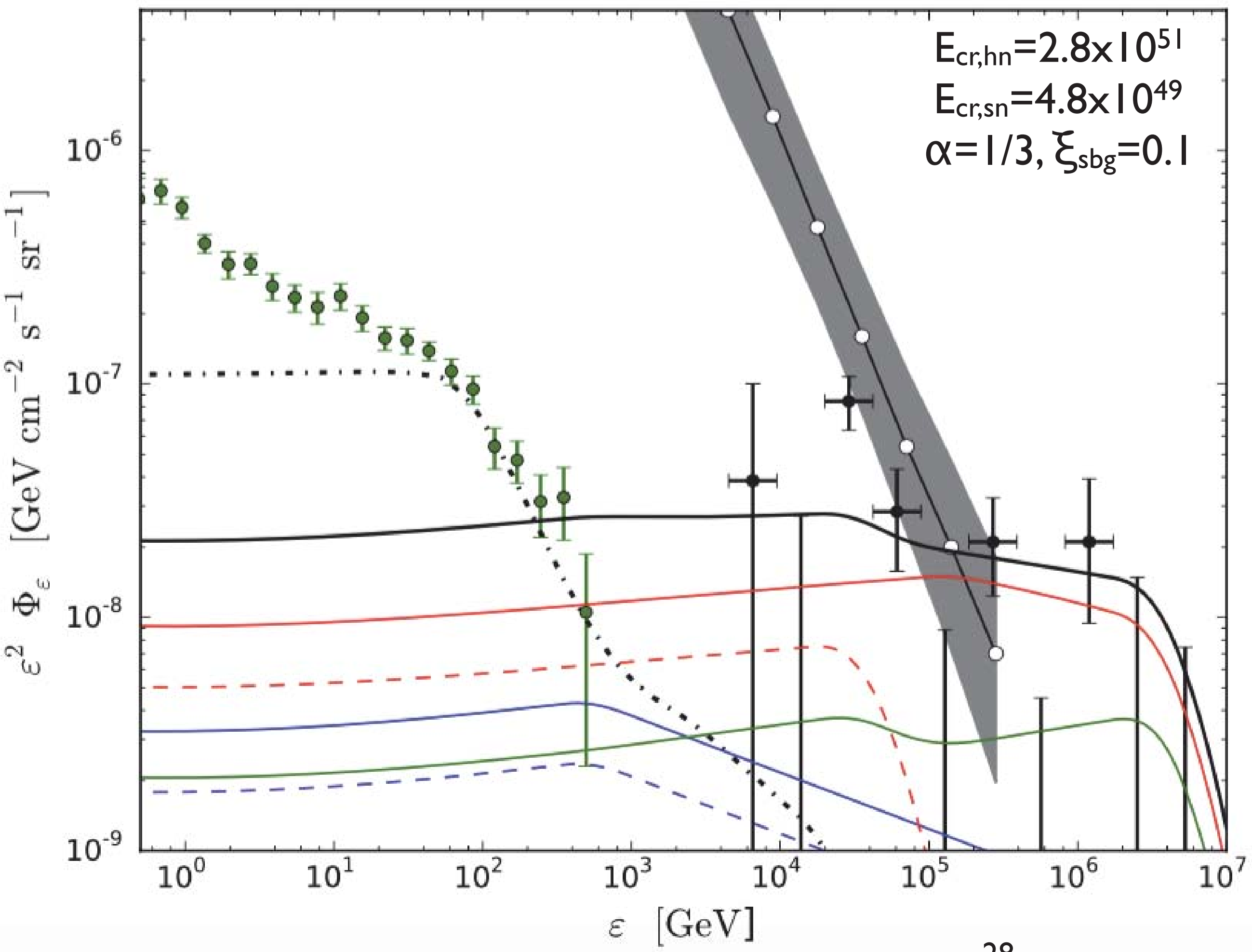
$$\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{phys}}(z) = \left[\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{hn}} + \left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{sn}}\right](1+z)^3 S(z)$$

$$S(z) = \left[(1+z)^{a\eta} + \left(\frac{1+z}{B}\right)^{b\eta} + \left(\frac{1+z}{C}\right)^{c\eta}\right]^{1/\eta},$$

$$\boxed{\varepsilon_\nu^2 \Phi_{\varepsilon_\nu} = \frac{c}{4\pi}\int_0^z \sum_i \frac{f_{i,pp}}{6}\frac{\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{phys}}}{(1+z')^4}\left|\frac{dt}{dz'}\right| dz',}$$

HNe & SNe in SBG, SFG

Senno, Mészáros, Murase, Baerwald & Rees, 2015, ApJ, 806:24



- HNe, SNe accelerate CRs with spectrum $N(E) \sim E^{-2}$, Emax $\sim 10^{15}$ eV (SNe) Emax $\sim 10^{17}$ eV (HNe)

Blue: SFG, HN solid, SN dashed;
Red: SBG, HN solid, SN dashed;
Green solid: Cluster total contrib
Black crosses: IceCube neutrinos
Green points: Fermi diff. gammas
Shaded: atmospheric nu-backgr'd

- CRs diffuse and undergo pp both in host galaxy & in cluster before they escape

- the t_{diff} at low energies is limited by t_{esc}, t_{wind} , t_{Hubble}
→ spectrum flattens at low E

- Looks fair, ***provided*** that assume this INB mechanism is responsible for ***all the IGB -*** but this is NOT warranted.

PROBLEMS with the above:

- ***Both*** the above galaxy merger & SNe/HNe shock acceleration + pp have this problem
- They addressed the ***PeV*** neutrinos only (the more recent ***TeV*** nu-flux is higher)
- But, more recent higher nu-flux @ TeV & the more recent lower Fermi flux @ 600 GeV impose ***stricter constraints***
- Also, need substract from Fermi EGB the ~86% attributable to resolved and unresolved **blazars**
- If above models satisfy this ***residual*** Fermi IGB, they ***overproduce*** by x2-3 the IceCube INB flux

⇒ Need “hidden” neutrino sources ?

- Hidden in the sense of “low or no EM”
- E.g., high optical depth ***(Thomson hides)?***
- Or, e.g., high distances ***(redshift hides)?***

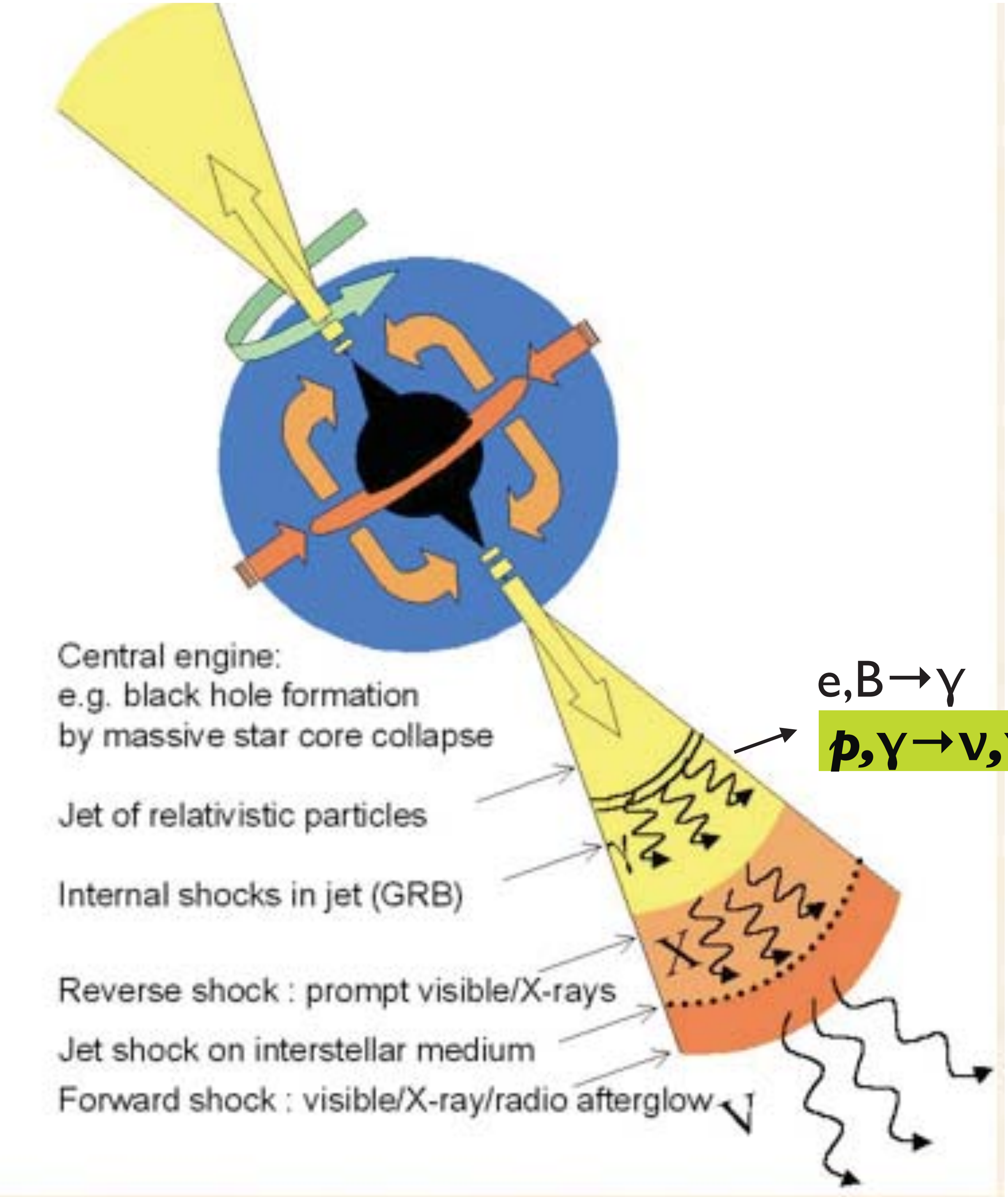
Possibility I (Thomson)

Hide EM? → high optical depth!

Normal GRBs?

- Yes, but IceCube finds that <1% of "classical" EM-observed GRBs can be contributing to this observed neutrino flux (e.g. arrival times)
- Classical GRBs are associated with core-collapse SNe Ic; the classical model is that relativistic jet penetrates expanding stellar envelope
- Jet undergoes shocks outside envelope, Fermi accelerates both electrons (synchrotron→MeV γ-rays) and protons (p,γ→π+ →ν @ TeV energies)

Conventional collapsar GRB model



e,B→γ

p,γ→ν,γ

- If $L_p/L_\gamma \sim 10$, expect that $L_\nu/L_\gamma \sim 1$,
- ***but*** IC3 observ.: → such high L_ν seems ***disproven***

That is, for standard internal shock model where γ and CR produced in same IS shocks

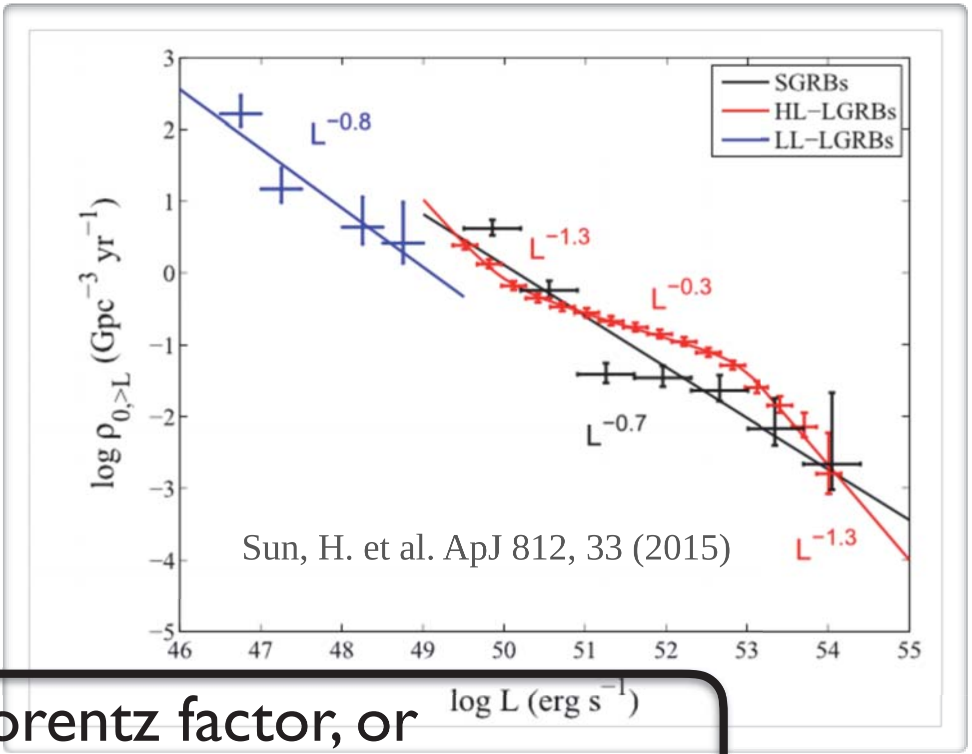
(IC3 team, 2015, ApJL, 805: L5)

Low optical depth →no hiding!

[A]: Alternatively: **LLGRBs**?

- Low luminosity GRBs (LLGRBs) have $L_\gamma \sim 10^{-2}$ -10^{-3} ***smaller,*** but are are ~100x more ***numerous***

- Prompt emission can be up to 10^3 s, with smooth light curves



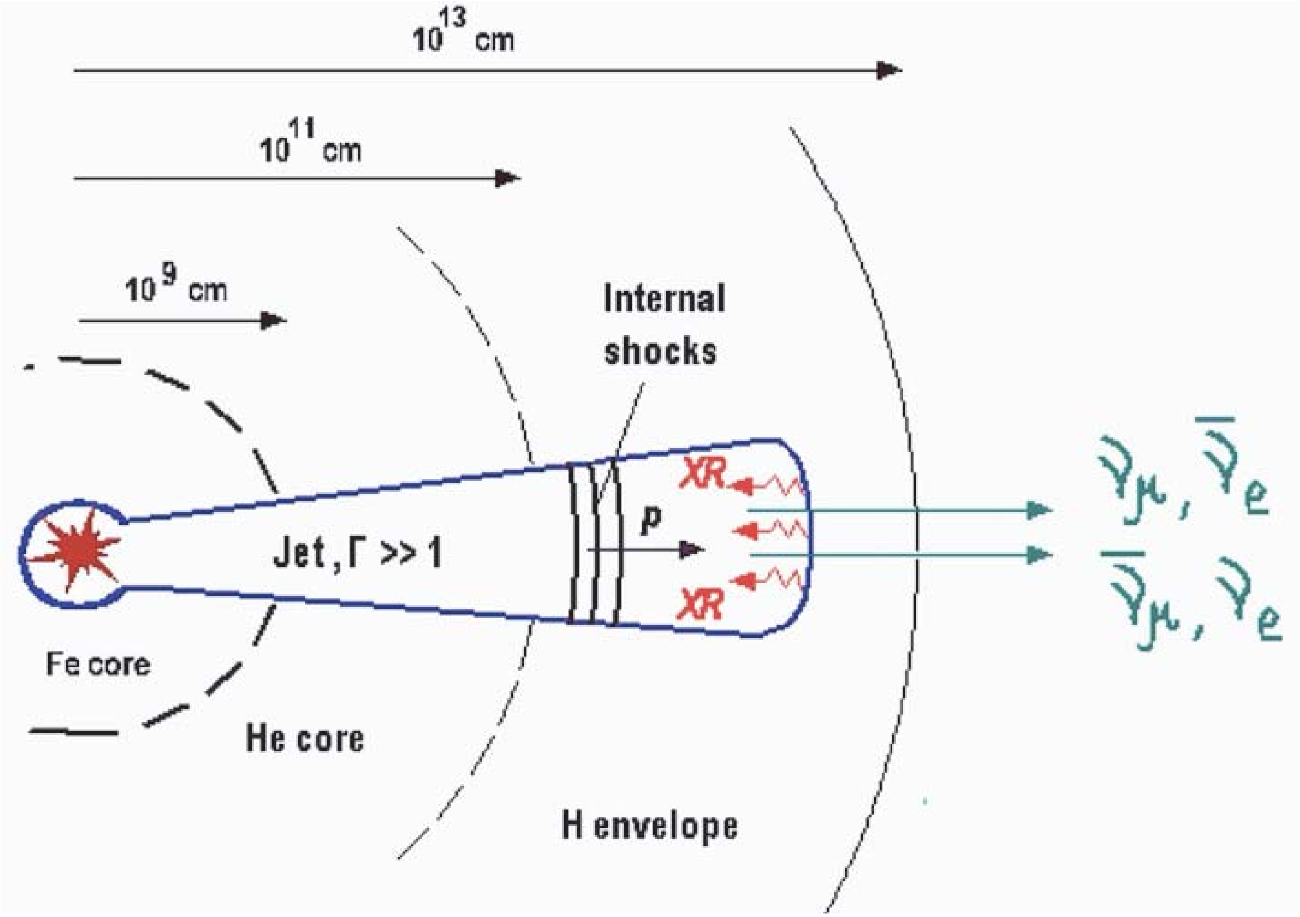
Sun, H. et al. ApJ 812, 33 (2015)

These may be:

- (a) emergent jets (***EJ***) of lower Lorentz factor, or
  (b) jets barely emerging - shock breakout (***SB***), or
  (c) choked jets (***CJ***) which did not emerge…
  ….jet kinetic luminosity may be ~ comparable in all 3 cases

- All 3 cases: expect ***low*** L_γ, do not trigger EM detector unless nearby

→EM hidden, or inconspicuous

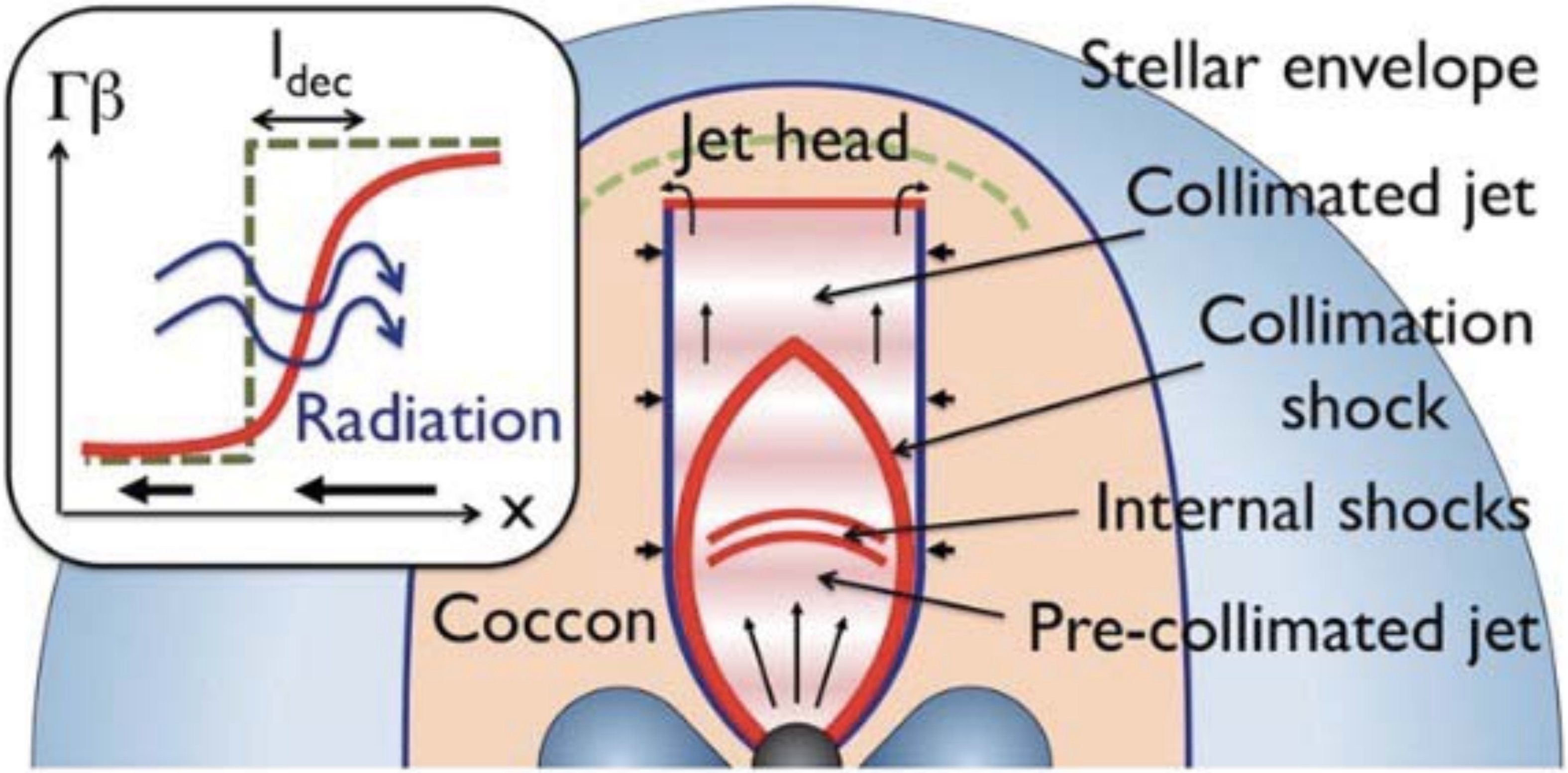


Choked, or buried and later emergent jets

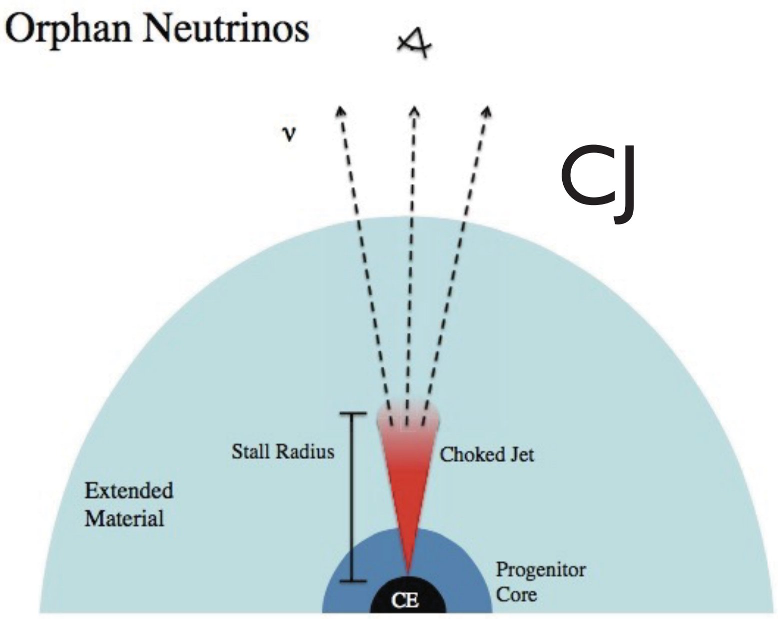
(Mészáros &Waxman, 2001, …..)

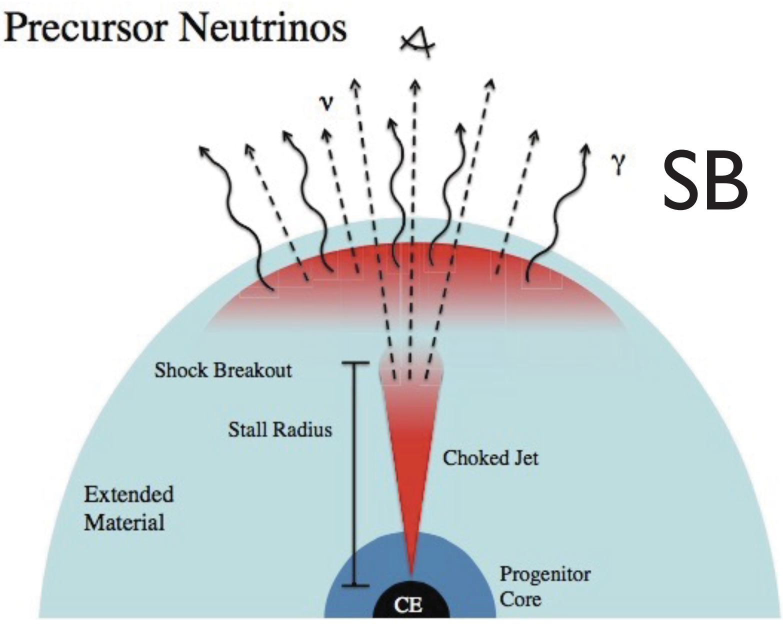
Star-penetrating jets

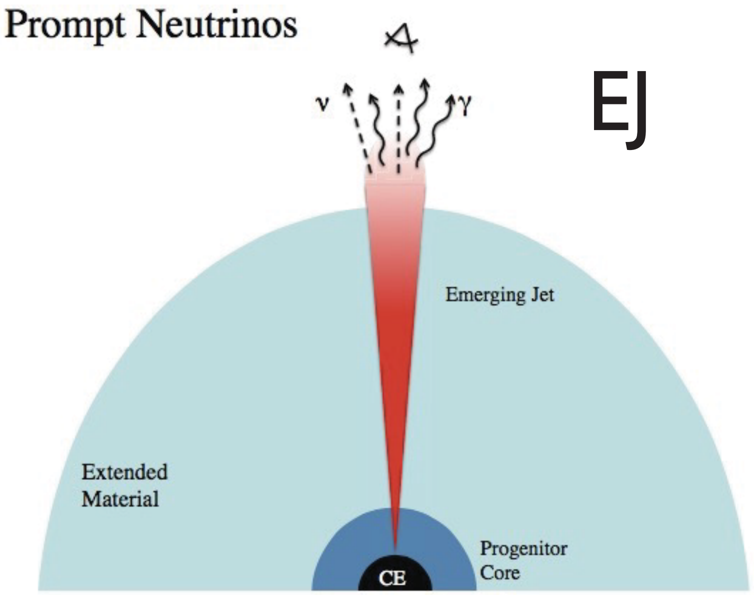
Mizuta & Ioka '13, ApJ, 777:162
Bromberg+, '11, ApJ, 740:100
Mészáros, Rees'01, ApJL 556:L37



From Choked to Emergent Jets as Hidden Neutrino Sources







Senno, Murase, Mészáros,
(2016) PRD, 93, 083003

Other previous work on choked GRBs:

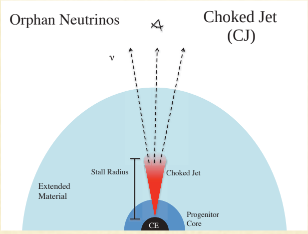
Mészáros &Waxman 2001, PRL 87, 171102

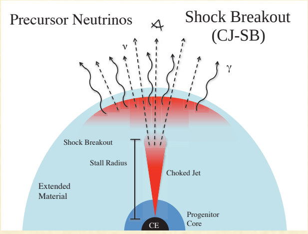
Waxman, Campana & PM 2006, ApJ 667, 351

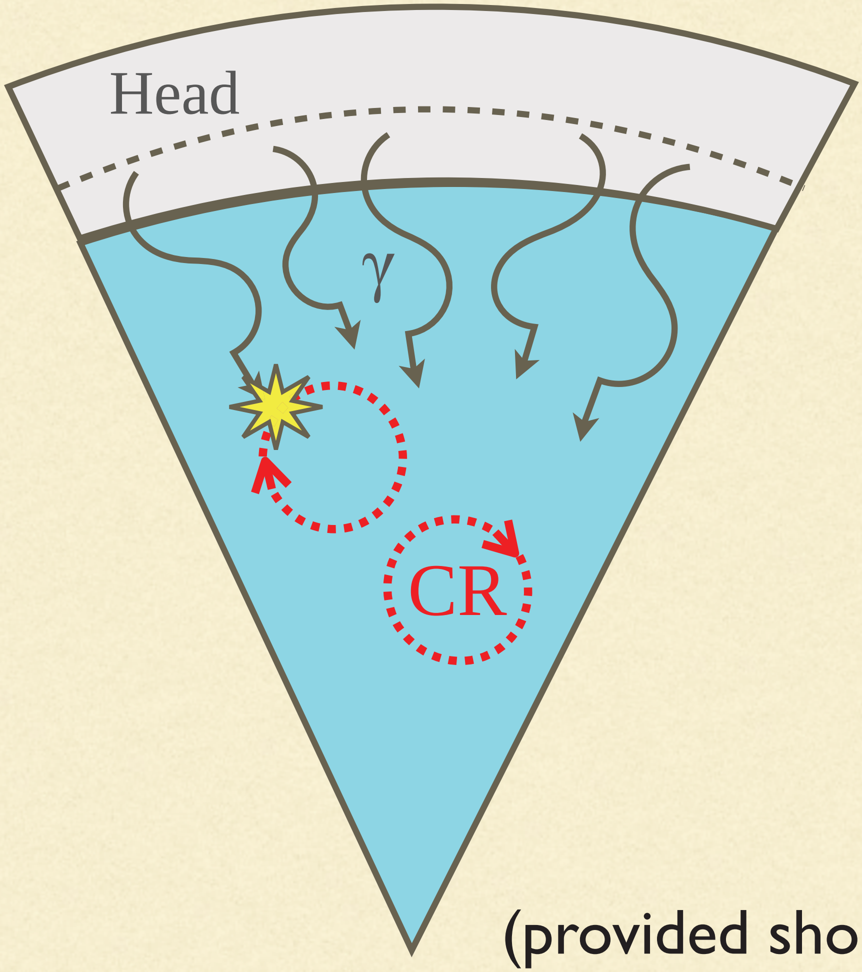
Murase & Ioka, 2013, PRL 111, 121102

Nakar, 2015, ApJ 807, 172, etc.

CJ NEUTRINOS FROM pγ INTERACTIONS







- The plasma surrounding the jet is optically thick

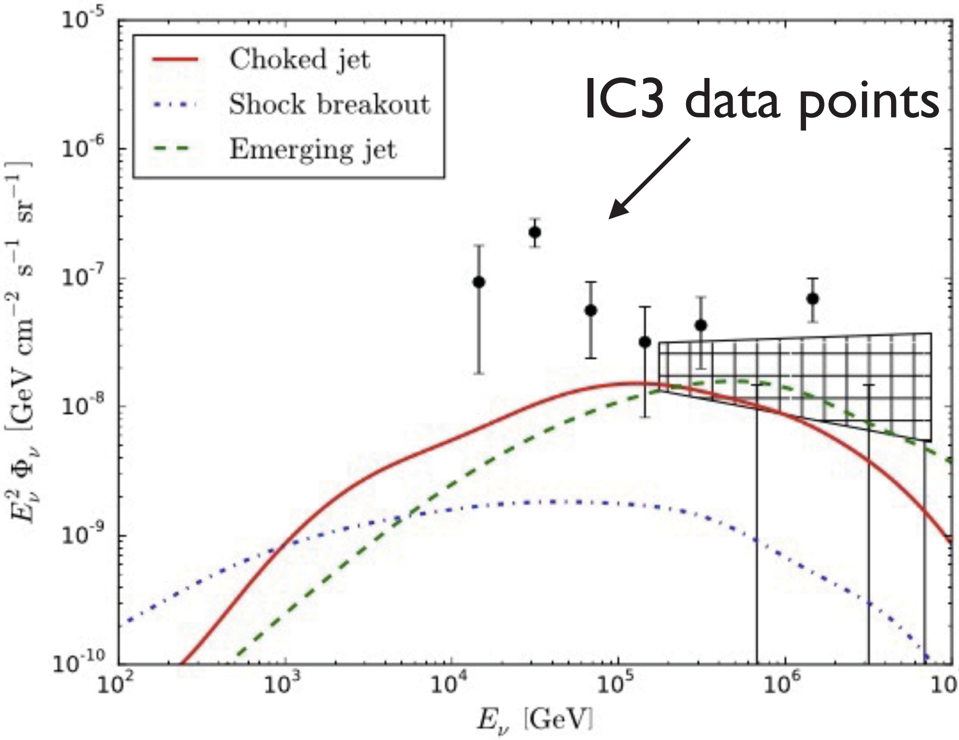
- The dominant photon field for pγ interactions is from photons generated in the jet head

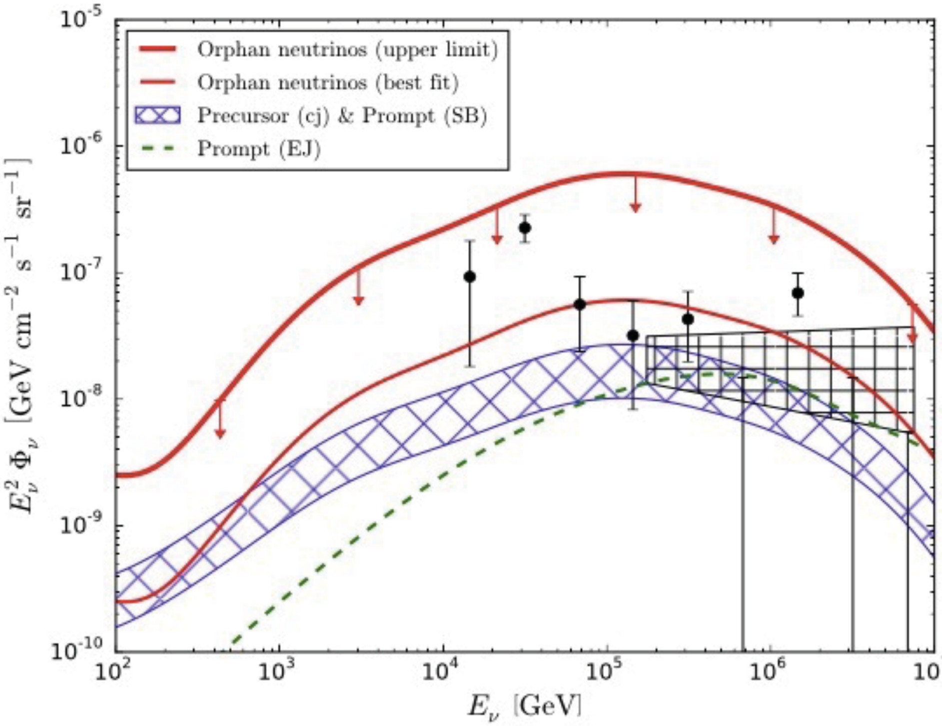
$$kT_j \simeq 5.3\ \mathrm{keV}\ \Gamma_{\mathrm{rel},1.2}$$

$$U_{\gamma,j} \sim \Gamma_{\mathrm{rel}}^2 U_{\gamma,h}$$

(provided shocks NOT radiation dominated, i.e. LLGRBs)

[A] Choked jet, shock breakout & emergent jet ν-spectra





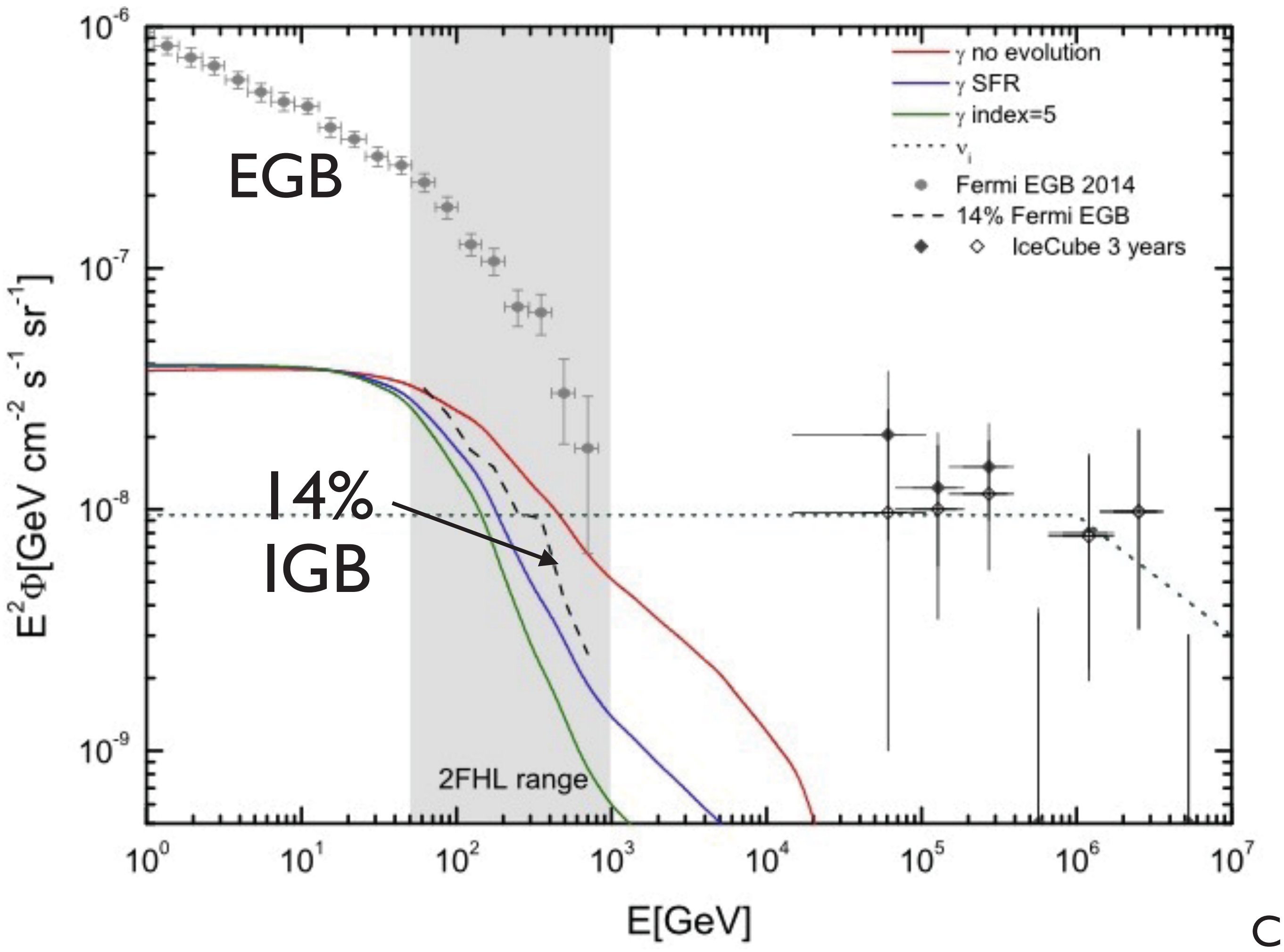
May do the job - LLGRBs produce practically no IGB ⇒ hidden ✔

Senno, Murase, Mészáros, PRD, 93, 083003

Possibility II
(redshift)

another way to hide is

Generic sources @ high redshift



From high redshift, γ-rays have more distance to undergo γγ cascades that degrade their energy to below the Fermi constraints ✔

Chang, Liu & Wang, 1602.06625

Possibility II++ (SN/HN + redshift)

[B]: Revisit the role of **SNe/HNe & consider them also @ high z**

Xiao, Mészáros, Murase, Dai,
arXiv: 1604.08131 (ApJ in press)

- Include two significant new aspects:
- Consider effects of time-evolution of SNR in the Sedov-Taylor phase
- Consider Pop. III SNR/HNR @ $4<z<10$

First:

Pop. I/II SNe/HNe (only)

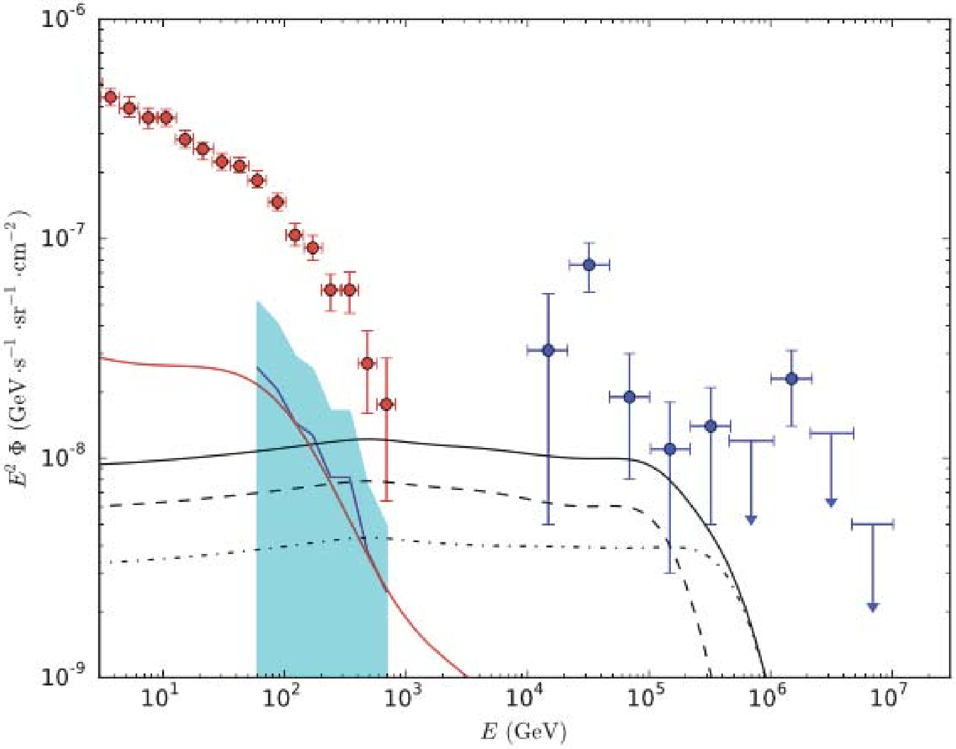


FIG. 1.— Combined fit of diffuse neutrino flux and gamma-ray flux for the case $\alpha = -1$ for the conventional case. The IceCube neutrino and the Fermi-LAT extragalactic gamma-ray background observations are shown by blue and red data points respectively (Ackermann et al. 2015; Aartsen et al. 2015). The cyan area shows the allowed region for the non-blazar gamma-ray flux in Fermi Collaboration (2016) and the best-fit 14% residual of the Fermi EGB is marked by the purple solid line. Black dashed and dotted lines represent the calculated contribution to the neutrino flux from SNe and HNe respectively, from the range $z \leq 4$. The black solid line is the predicted total diffuse neutrino flux and the red solid line is the predicted gamma-ray flux. The main parameters are $\mathcal{E}_{\rm SNe} = 5\times10^{50}$erg, $\mathcal{E}_{\rm HNe} = 10^{52}$erg, $\eta = 0.1$, $n_0 = 1\rm cm^{-3}$, $\mathcal{R}_{\rm HNe} = 3\%\mathcal{R}_{\rm CCSNe}$. The SBG magnetic field is set to $B = 1$ mG.

- First, low redshift only, $z \lesssim 4$ SNe & HNe
- Nominal kin. en., CR effic., $B_{\rm ext}$, $n_{\rm ext}$
- To fit residual 14% of IGB, can get only 50% of INB

Xiao, Mészáros, Murase, Dai, 1604.08131

Then:

Pop. III SNe (only)

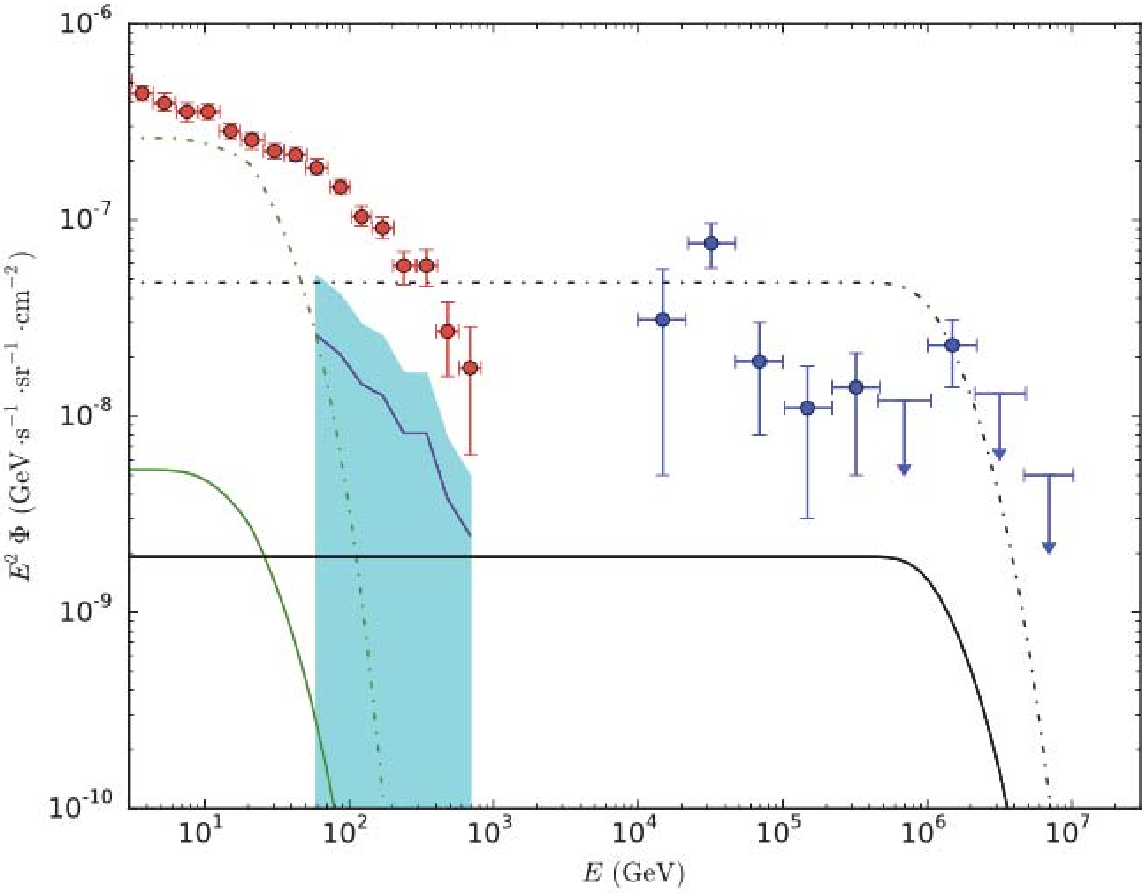
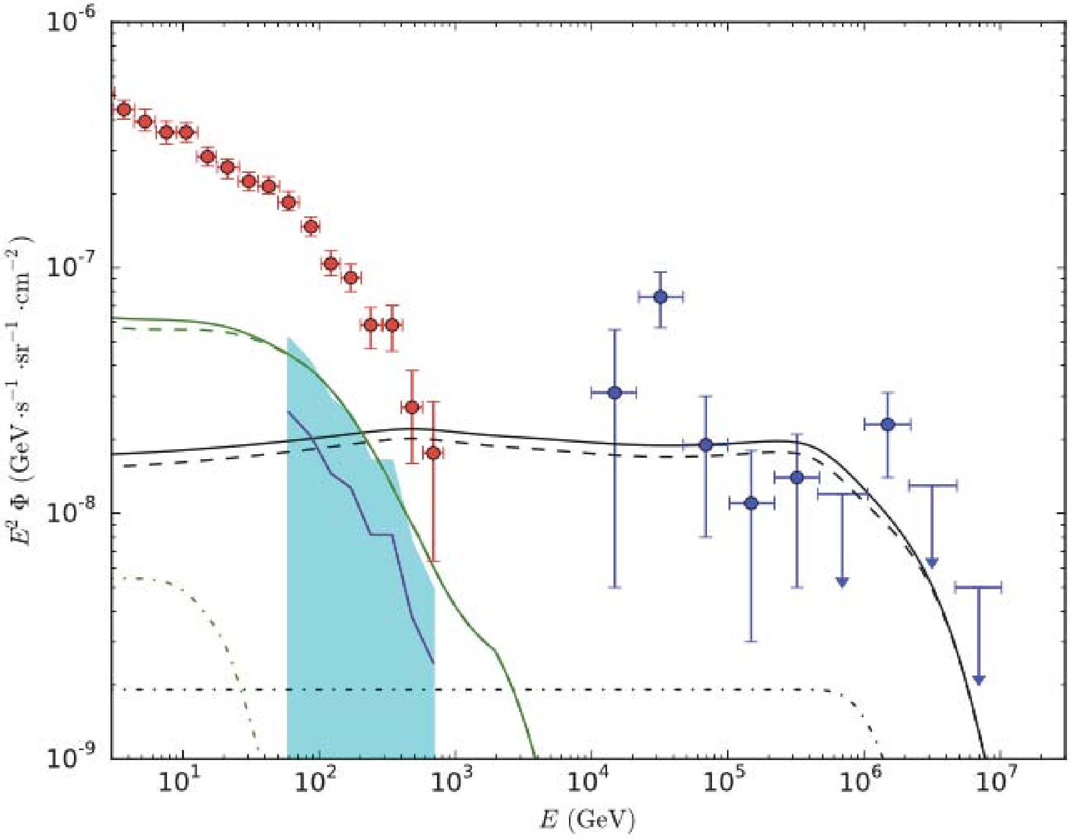


FIG. 5.— Possible contribution from Pop-III HNRs with $4 \leq z \leq 10$ by themselves. Black and green lines represent the predicted diffuse neutrino and gamma-ray fluxes respectively. For the solid lines the efficiency η is 0.1 and the kinetic energy is $\mathcal{E}_{\rm kin} = 10^{52.5}$ erg. For the dotted-dashed lines, the value of $\eta\mathcal{E}_{\rm kin}$ (i.e. the flux) is multiplied by a factor 25. These dotted-dashed lines serve as an upper bound for the Pop-III contribution.

High z only:
$4 \leq z \leq 10$

Xiao, Mészáros, Murase, Dai, 1604.08131

finally: Pop I/II+Pop. III comb.



Low and high z:

$0 \leq z \leq 10$

Does the job ✔

+1σ of IGB &

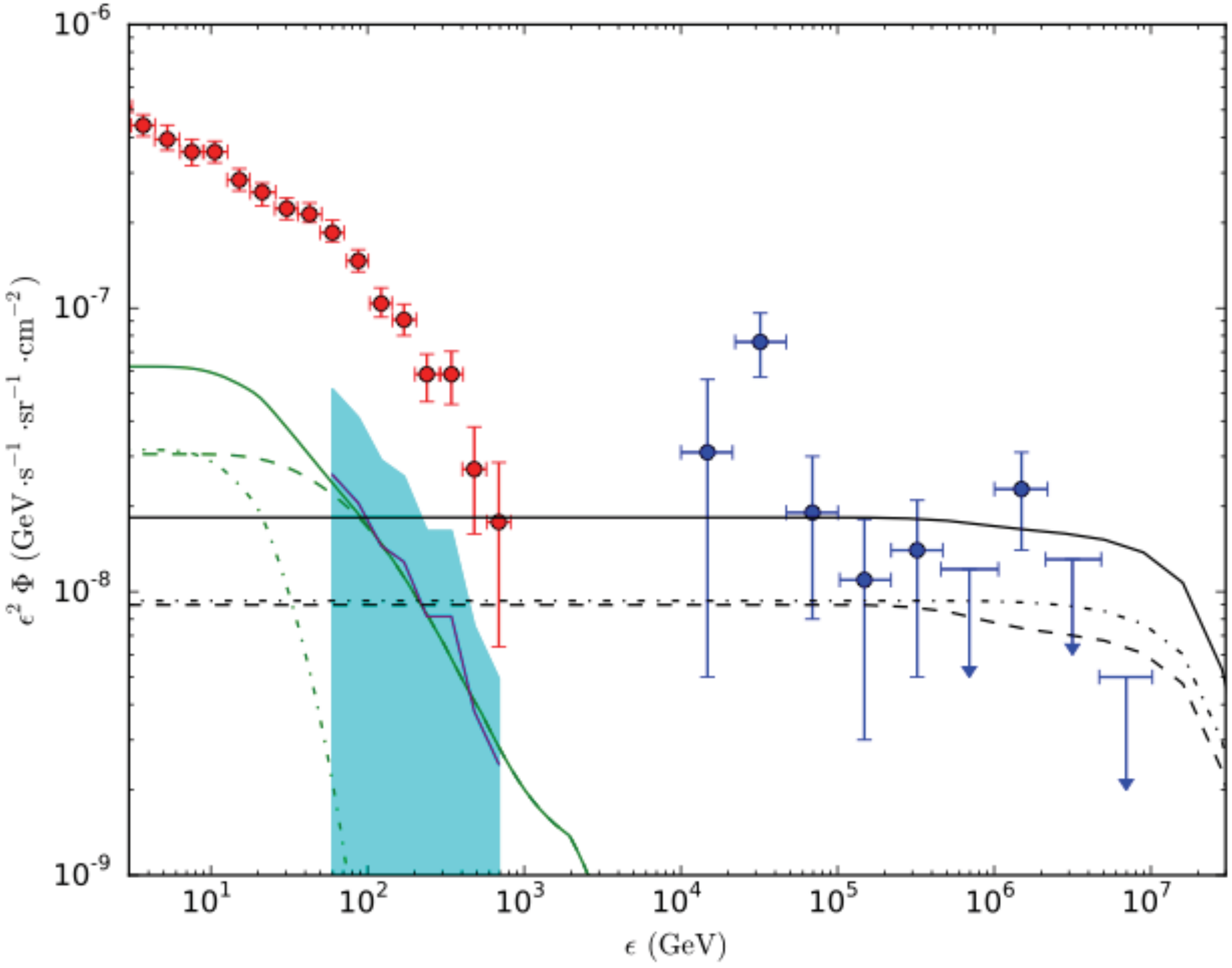
INB (- 30 TeV ν)

Xiao, Mészáros, Murase, Dai, 1604.08131

FIG. 7.— An example for two component (low and high redshift) contribution. Black and green solid lines represent the total diffuse neutrino flux and gamma-ray flux, while the dashed lines are the $z \leq 4$ SNe/HNe and the dotted lines are the Pop. III SNe. The CR contribution of the Pop. III is instrumental in making this fit more complete and reasonable, with a fiducial CR efficiency $\eta = 0.1$ for both populations.

Also varying parameters:

[B] Pop. I-II + Pop. III, with $\neq\eta$



Low and high z,
$0 \leq z \leq 10$,
plus
I/II lower CR effic
III higher CR effic

Does the job ✔ on nominal IGB & INB (- 30 TeV ν)

Xiao, Mészáros, Murase, Dai, 1604.08131

Fig. 10 An example for two component contribution. Black and green solid line represent the total diffuse neutrino flux and gamma-ray flux, while dashed lines are the $z \leq 4$ SNe/HNe and the dotted lines are the Pop. III SNe. The CR contribution of the Pop.III/Pop.I-II ratio is 1 : 1, with CR efficiencies $\eta_{\rm III} = 0.1$, $\eta_{\rm I-IIHNe} = 5\times10^{-3}$, $\eta_{\rm I-IISNe} = 1\times10^{-3}$.

[C] Another possibility

MBH TDEs

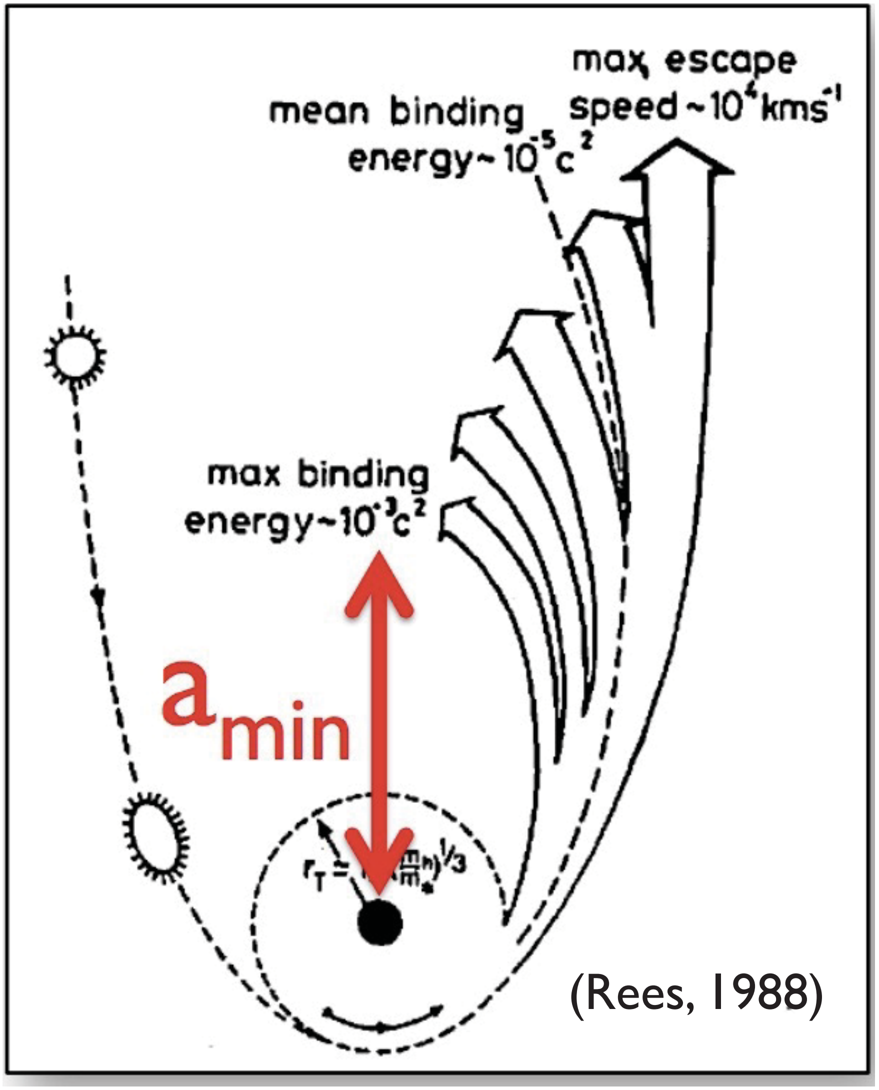
i.e.

Massive Black Hole (MBH) +

Tidal Disruption Event (TDE)

MBH TDE

Wang, X.-Y., & Liu, R.-Y.
2016, PRD, 93, 083005



(Rees, 1988)

- Jets also from TDE of stars by MBH in galactic centers
- Some TDEs show a relatvistic jet (e.g. Sw J1644+57)
- If galacti center environment very dense, jet could be choked
- If jet has internal shocks and accelerated CRs, get pp nus
- If so, this would also be “hidden” nu source (envelope may be optically thick to gamma-rays, but not to nus)

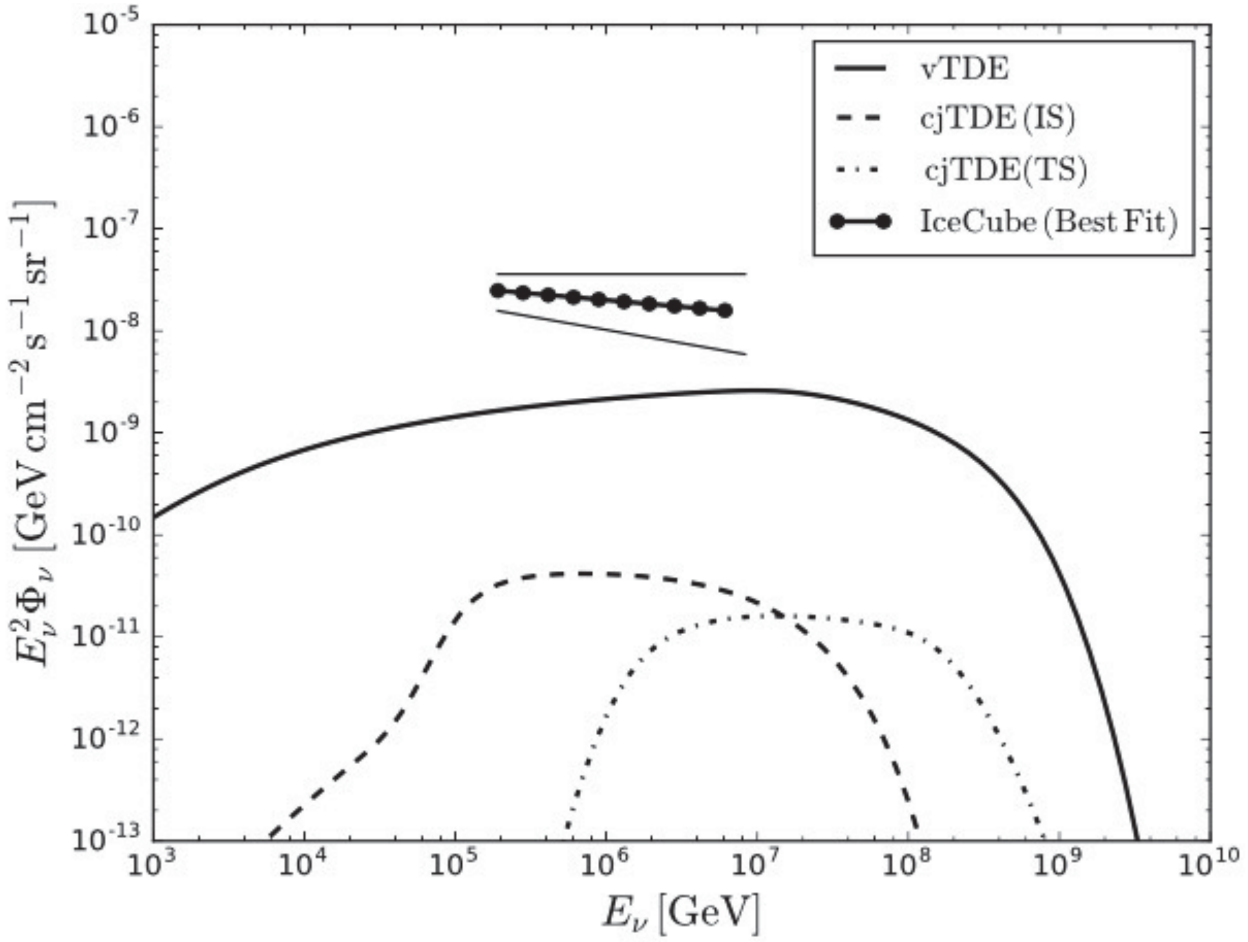


FIG. 7.— Contributions to the diffuse neutrino background due to $p\gamma$ interactions from X-ray bright visible jets and possible choked jets. For successful jets leading to X-ray bright TDEs, the cosmic-ray luminosity is given by $\xi_{\rm cr} = L_{\rm cr}/L_\gamma = 1-3$. For choked jets, the internal shock and termination shock scenarios are considered, and the cosmic-ray luminosity is assumed to be comparable to the total luminosity L. For the diffuse neutrino data, we use the muon neutrino data obtained by IceCube with the multiplication by a factor of 3 (IceCube Collaboration et al. 2016b).

(Senno, Murase, Mészáros, 1612.00918)

(see also Dai,Fang16, Lunardini,Winter16)

However…

[C]
MBH TDE:

yes, but more careful calcul. shows shortfall

-Including bright jets, shock breakouts and choked jets:

-At most can explain ***10-30%*** of observed IceCube diffuse flux

Conclusions

- At least ***two*** possible interpretations for the ***IceCube INB*** & the ***Fermi IGB***
- One are ***LLGRBs*** (act as "hidden sources") ***[A]***
- The other is ***HNe/SNe*** (they are "hidden" if their strongest contribution is at ***high z***) ***[B]***
- No need for blazars (they would not be "hidden")
- MBH TDEs: can contribute, but $\lesssim$ 10-30% **[C]**

A different question:

[D]

Could GRBs explain GZK UHECRs?

There have been

3 main objections:

- (1) If spectral index is ***p*=2** (Fermi 1st order) ⇒GRB CR energy budget >10^{52} -10^{53} , too high
- (2) If ***assume same*** shocks accelerate ***CRs*** (and do p,γ→ν) as those producing obs. γ-***rays***: ⇒GRBs in Swift time windows ***over-produce ν's***
- (3) IceCube stacking analysis: ≤ ***1%*** of UHENUs can be coming from Swift EM-triggered GRBs

[C]

A way to address some objections raised about GRBs explaining UHECRs

Consider objection (1):

- (1) If spectral index is ***p*=2** (Fermi 1st order) ⇒GRB CR energy budget >10^{52} -10^{53} too high

Possible solution to (1): harder slope

(Asano & Mészáros, 2016, PRD 94, 023005)

Consider Fermi **2nd** : stochastic acceleration

- May be expected in turbulence in relativistic jet outflow, induced by:
- E.g., RT in decelerating outflow (ext. shock), or KH in shear flow (say boundary of jet-cocoon), or Richtmyer-Meshkov in IS, etc.
- Also, turbulence can enhance mag. reconn., which also can lead to Fermi 2nd

Energy diff. coefficient:

$$D(\varepsilon) \equiv \frac{1}{2}\left\langle \frac{\Delta\varepsilon\Delta\varepsilon}{dt} \right\rangle$$

$$D(\varepsilon) \sim \varepsilon^2 \frac{v_{\mathrm{W}}^2}{c\ell} \frac{\delta B^2}{B^2} \int_1^{\ell k_{\mathrm{max}}} d(\ell k)(\ell k)^{1-q}$$

where v_w = wave phase velocity, ℓ = eddy scale,
and q = is the index of turbulence power spectrum

- q=2 is frequent result from MHD turbulent simulations,

⇒ leads to ***D(ε) ~ ε²*** (hard sphere approximation)

Thus, consider

$$D(\varepsilon) \sim \varepsilon^2 \beta_{\mathrm{W}}^2 \zeta \frac{c}{\ell} \quad \sim 3\varepsilon^2 \zeta \frac{c\xi_{0.1}\Gamma}{R}$$

where ζ is dimensionless factor (for uncertainties in $\Delta B/B$, k_{max}, q), and ξ is fudge factor for eddy scale

denote $D(\varepsilon) = K\,\varepsilon^2$,
where $K=3\,c\,\zeta\,\xi_{0.1}\,\Gamma/R$, and

$$t_{\mathrm{acc}} \sim 1/K \gtrsim t_{\mathrm{dyn}}/(3\zeta) \approx (R/c\Gamma 3\zeta)$$

Maximum CR Energy:

Maximum energy: Larmor radius < eddy scale ℓ

then, using

$$B^2/(8\pi) = f_B U_{\rm ph} \qquad U_{\rm ph} = \frac{L_\gamma}{4\pi c R^2 \Gamma^2}$$

$$\varepsilon_{\rm max} = \Gamma \ell e B/(1+z)$$

➡

$$\varepsilon_{\rm max} = \frac{\xi e}{(1+z)\Gamma}\sqrt{\frac{2 f_B L_\gamma}{c}}$$

$$\simeq 8.2 \times 10^{19} \xi_{0.1} (1+z)^{-1} \Gamma_{300}^{-1} f_B^{1/2} L_{52}^{1/2}\ {\rm eV}$$

Evol. of proton en.distr.(i)

$$\frac{\partial N(\varepsilon,t)}{\partial t} = \frac{\partial}{\partial \varepsilon}\left[D(\varepsilon)\frac{\partial N(\varepsilon,t)}{\partial \varepsilon}\right] - \frac{\partial}{\partial \varepsilon}\left[\frac{2D(\varepsilon)}{\varepsilon}N(\varepsilon,t)\right] + \dot{N}_{\rm inj}(\varepsilon,t),$$

$$\text{at } t = 0 \text{ with } \dot{N}_{\rm inj}(\varepsilon,t) \equiv N_0\delta(\varepsilon-\varepsilon_0)\delta(t)$$ (impulsive)

$$N_{\rm G}(\varepsilon,t) = \frac{N_0}{2\varepsilon_0\sqrt{\pi K t}}\sqrt{\frac{\varepsilon}{\varepsilon_0}}\exp\left(-\frac{9}{4}Kt - \frac{(\ln\frac{\varepsilon}{\varepsilon_0})^2}{4Kt}\right)$$

Evol. of proton en.distr.(ii)

or if consider

constant injection with $\dot{N}_{\rm inj}(\varepsilon) \equiv \dot{N}_0 \delta(\varepsilon - \varepsilon_0)$ for $t \geq 0$,

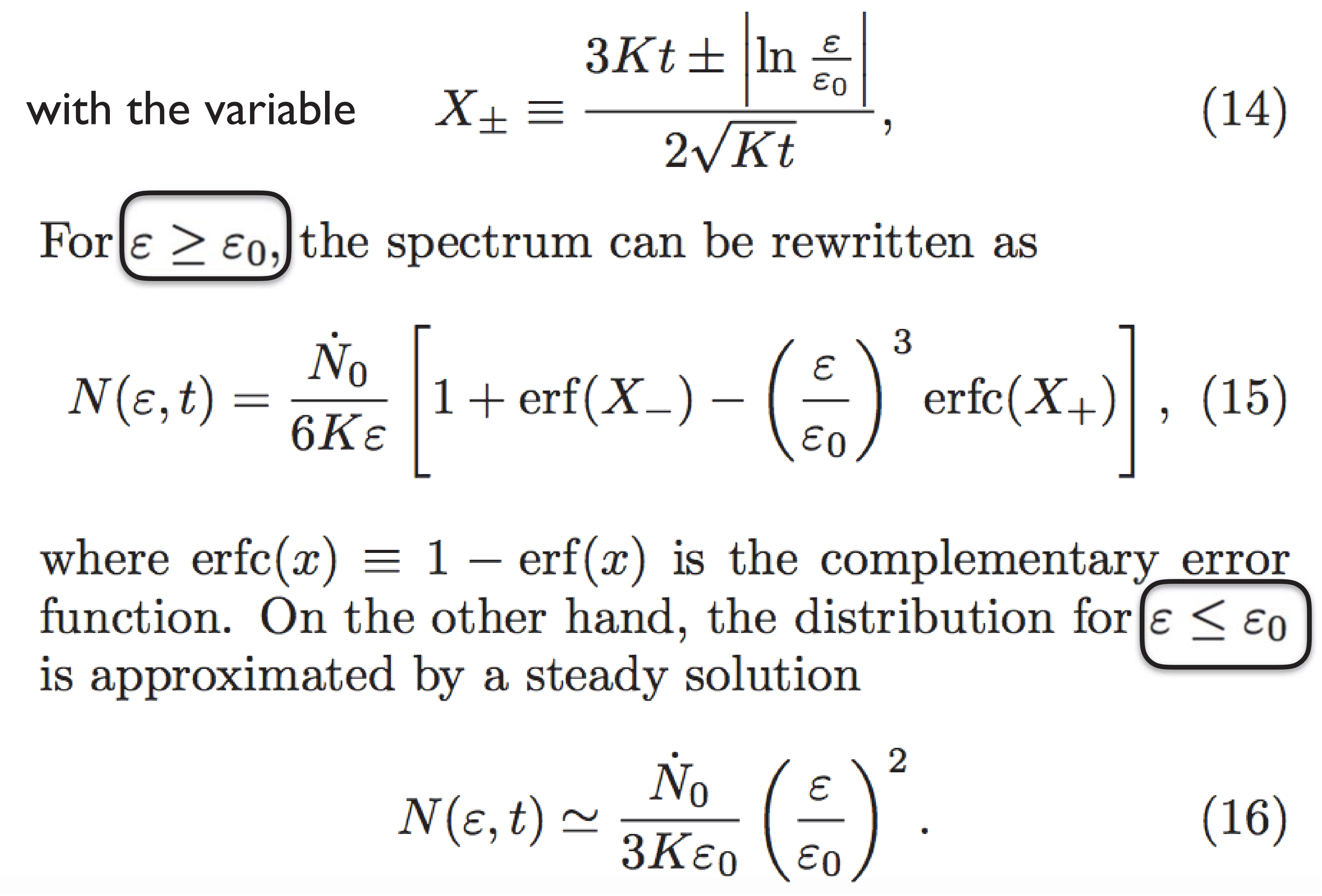
$$N(\varepsilon, t) = \frac{\dot{N}_0}{N_0} \int_0^t dt' N_{\rm G}(\varepsilon, t')$$

$$= \frac{\dot{N}_0}{2\varepsilon_0} \sqrt{\frac{\varepsilon}{\varepsilon_0}} \int_0^t dt' \frac{\exp\left(-\frac{9}{4}Kt' - \frac{(\ln \frac{\varepsilon}{\varepsilon_0})^2}{4Kt'}\right)}{\sqrt{\pi K t'}}$$

which has an analytical solution,

$$N(\varepsilon, t) = \frac{\dot{N}_0}{6K\varepsilon_0} \sqrt{\frac{\varepsilon}{\varepsilon_0}} \left[\exp\left(-\frac{3}{2}\left|\ln \frac{\varepsilon}{\varepsilon_0}\right|\right)(1 + \mathrm{erf}(X_-)) + \exp\left(\frac{3}{2}\left|\ln \frac{\varepsilon}{\varepsilon_0}\right|\right)(-1 + \mathrm{erf}(X_+)) \right],$$

Evol. of proton en.distr.(iii)



with the variable $$X_{\pm} \equiv \frac{3Kt \pm \left|\ln \frac{\varepsilon}{\varepsilon_0}\right|}{2\sqrt{Kt}}, \tag{14}$$

For $\boxed{\varepsilon \geq \varepsilon_0,}$ the spectrum can be rewritten as

$$N(\varepsilon, t) = \frac{\dot{N}_0}{6K\varepsilon}\left[1 + \mathrm{erf}(X_-) - \left(\frac{\varepsilon}{\varepsilon_0}\right)^3 \mathrm{erfc}(X_+)\right], \tag{15}$$

where $\mathrm{erfc}(x) \equiv 1 - \mathrm{erf}(x)$ is the complementary error function. On the other hand, the distribution for $\boxed{\varepsilon \leq \varepsilon_0}$ is approximated by a steady solution

$$N(\varepsilon, t) \simeq \frac{\dot{N}_0}{3K\varepsilon_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^2. \tag{16}$$

Model CR spectra (i)

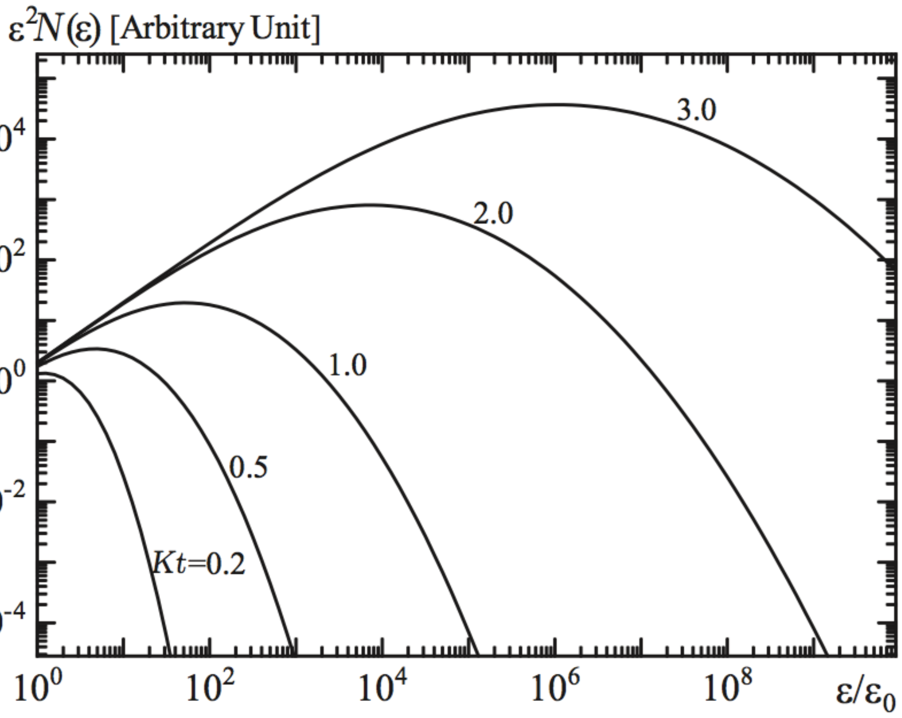


FIG. 1. Evolution of the particle energy distribution expressed by Eq. (15).

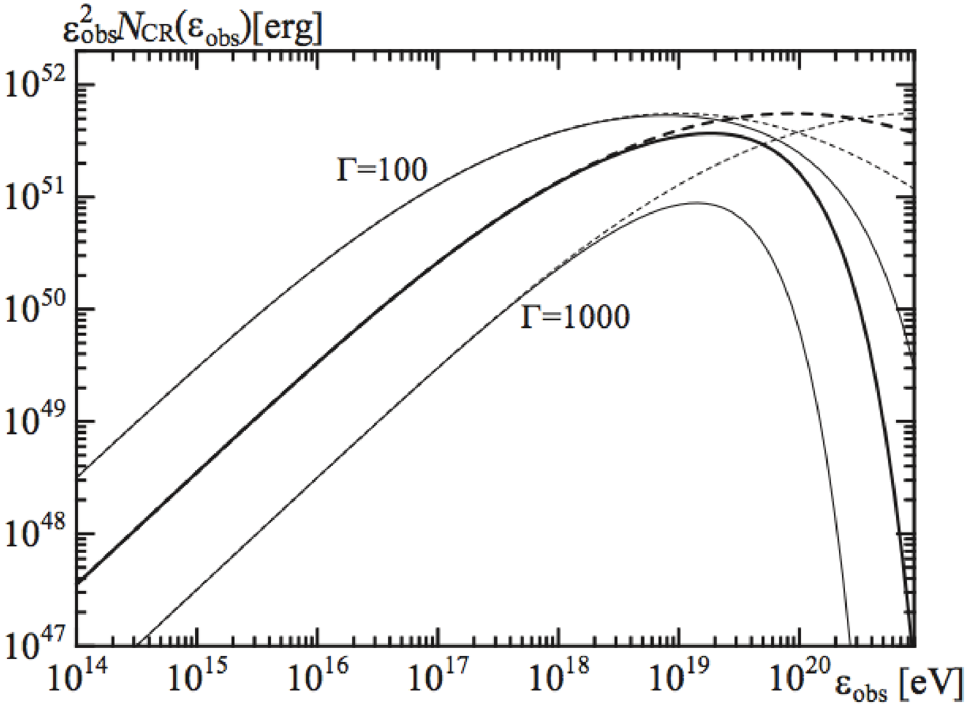


FIG. 2. Model spectra of the UHECRs escaping from a GRB. The thick lines are the spectrum for the parameters $L_{52} = \Gamma_{300} = f_B = f_{\rm CR} = \xi_{0.1} = 1$, while the thin lines show the spectra with the same parameters but for different values of Γ. The dashed lines are the spectra neglecting the exponential cut-off due to the maximum energy determined by the eddy size.

so that

- Below ε_{max} this Fermi 2nd order gives a ***much harder*** spectrum than the usual one of p=2 for Fermi 1st.

- Total energy needed down to ε_{min} is ***much less*** than with p=2

(Harder e^- spectra from Fermi 2nd, see, e.g,
Bykov & Mészáros, 1996, ApJ(Lett)461, L37;
or Murase, et al, 2013, ApJ, 746, 164)

Model CR spectra (ii)

$$\phi(L_\gamma) \propto \begin{cases} \left(\frac{L_\gamma}{L_*}\right)^{-0.17} & \text{for } L_\gamma \le L_* \\ \left(\frac{L_\gamma}{L_*}\right)^{-1.44} & \text{for } L_\gamma > L_* \end{cases}$$

TABLE I. Model parameters.

Model	A	B	C	D
$f_{\rm CR}$	10	10	U.M.[a]	U.M.
Γ	300	$72.1L_{52}^{0.49}$	300	$72.1L_{52}^{0.49}$
LLC[b]	30.0%	45.8%	92.3%	100%

[a] Universal CR luminosity model expressed in Eq. (24)

[b] The UHECR contribution from GRBs with $L \le L_*$ at $10^{18.5}$ eV (Low Luminosity Contribution).

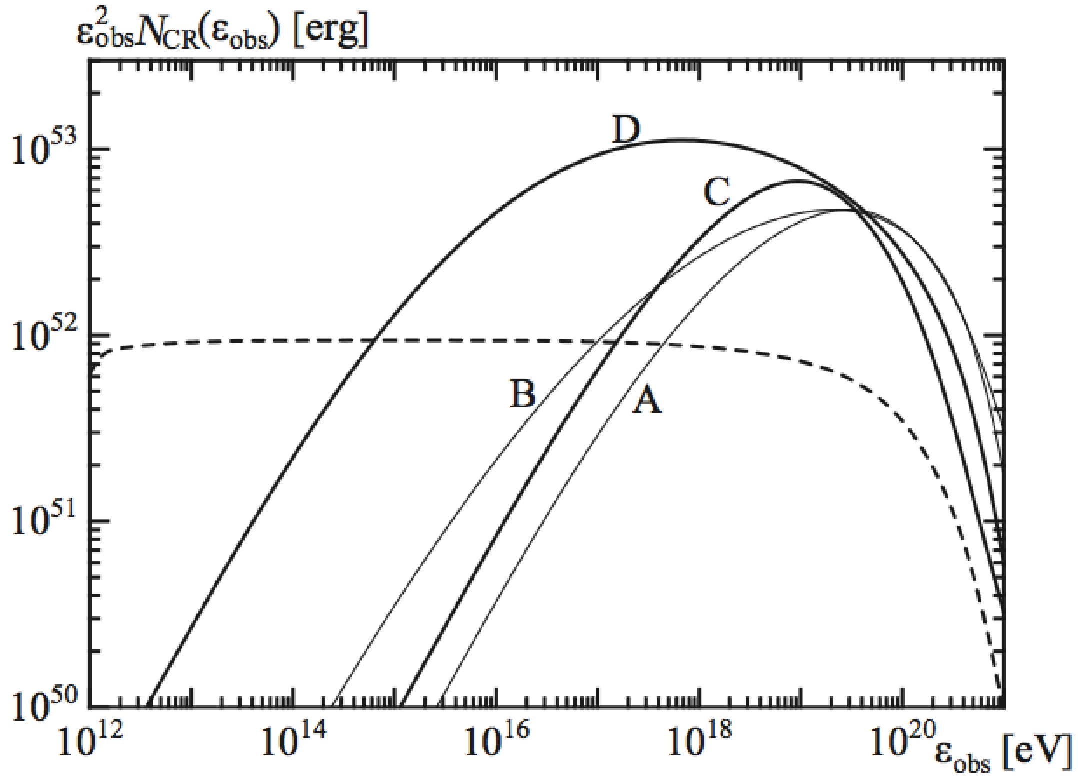


FIG. 3. The average UHECR spectra per burst for the parameter sets shown in Table I. The thin lines are for the models A and B, while the thick lines are for the models C and D. The dashed line is the average UHECR spectrum for the shock acceleration model adopted in Asano and Mészáros [22], in which $f_{\rm CR} = 10$, $f_B = 0.1$, and $\Gamma_{300} = 1$ with the same luminosity function.

Diffuse CR-NU spectrum

$$R_{\mathrm{GRB}}(z) \propto (1+z)^{2.1} \text{ for } z \leq 3.0 \text{ and } \propto (1+z)^{-1.4} \quad \text{for } z > 3.0$$

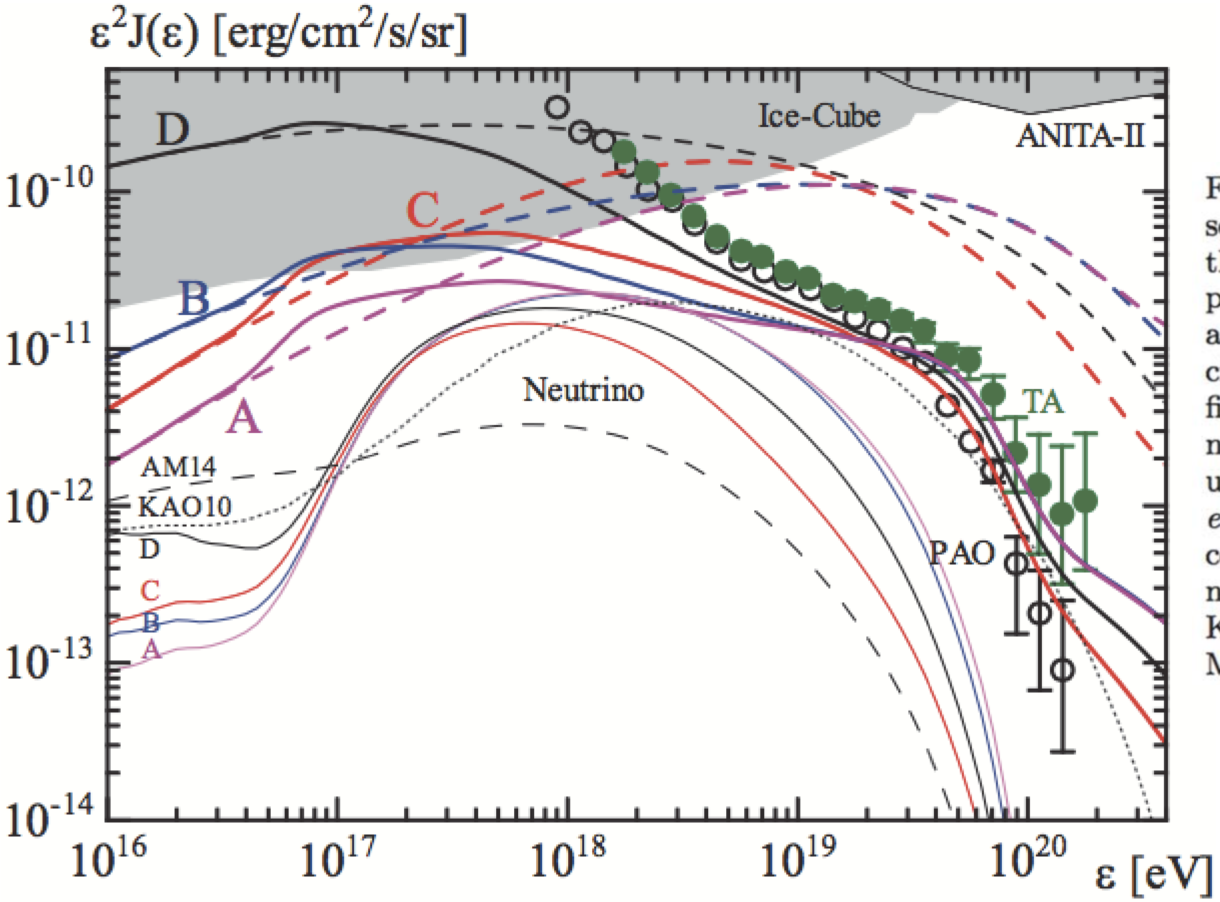


FIG. 4. The diffuse UHECR spectra for models A–D (thick solid lines). The thick dashed lines are spectra neglecting the effects of photomeson production and Bethe–Heitler pair production. The observed data for the UHECR intensities are taken from Schulz [78] for Pierre Auger observatory (open circles) and Abu-Zayyad *et al.* [79] for Telescope Array (green filled circles). The thin lines show the all-flavour cosmogenic neutrino intensities for the models A–D, which are below the upper limits (grey shaded area) by IceCube taken from Heinze *et al.* [80] based on Ishihara [81], and ANITA-II [82]. For comparison, we also plot the model spectra of the cosmogenic neutrinos by Kotera *et al.* [83] (thin dotted line, denoted as KAO10) and prompt plus cosmogenic neutrinos by Asano and Mészáros [22] (thin dashed line, denoted as AM14).

(Asano & Mészáros, 2016, PRD 94, 023005)

What about the other objections?

- (2) If ***assume same*** shocks accelerate ***CRs*** (and do p,γ→ν) as those which produce the γ-***rays***: ⇒GRBs in Swift time windows ***over-produce ν's***(2)

- (3) IceCube stacking analysis: ≤ ***1%*** of UHENUs can be coming from Swift EM-triggered GRBs

Possible solution to (2,3) :

≠ CR & γ regions

(Asano & Mészáros, 2016, PRD 94, 023005)

Accel. site & ν-production

- The **accelerating shock** (***CRs, νs)*** could be, e.g., external shock:

$$R_{\rm dec} = \left(\frac{3E_{\rm tot}}{4\pi n m_{\rm p} c^2 \Gamma^2}\right)^{1/3}$$
$$\simeq 1.46 \times 10^{17} n_0 \left(\frac{E_{\rm tot}}{10^{53.5}\ {\rm erg}}\right)^{1/3} \left(\frac{\Gamma}{127}\right)^{-2/3} \ {\rm cm},$$

Or could be a larger radius internal shock, e.g.

$$R_{is} = 2\, c\, \Gamma^2\, \Delta t \gtrsim 10^{16} (\Gamma/127)^2 (\Delta t/10s)\ \ {\rm cm}$$

- ***But*** the bulk of ***photon radiation (γs)*** could be from a ≠ **region,** e.g. from a **photosphere**,

$$R_{ph} = (dM/dt)\kappa/4\pi c \Gamma^2) \sim 6{\rm x}10^{12} L_{52} (\Gamma/127)^{-3}\ \ {\rm cm},$$

(i.e., way below the CR, ν production region)

then…

Neutrino efficiency is reduced

- First, if γ emission is short, photons may have escaped before outer shocks occur ⇒ no pγ

- Even if duration is longer than $(R/c\Gamma^2)$, photon density will be much diluted, and ⇒ pγ efficiency is significantly reduced

CR-nu-ph. spectrum single GRB

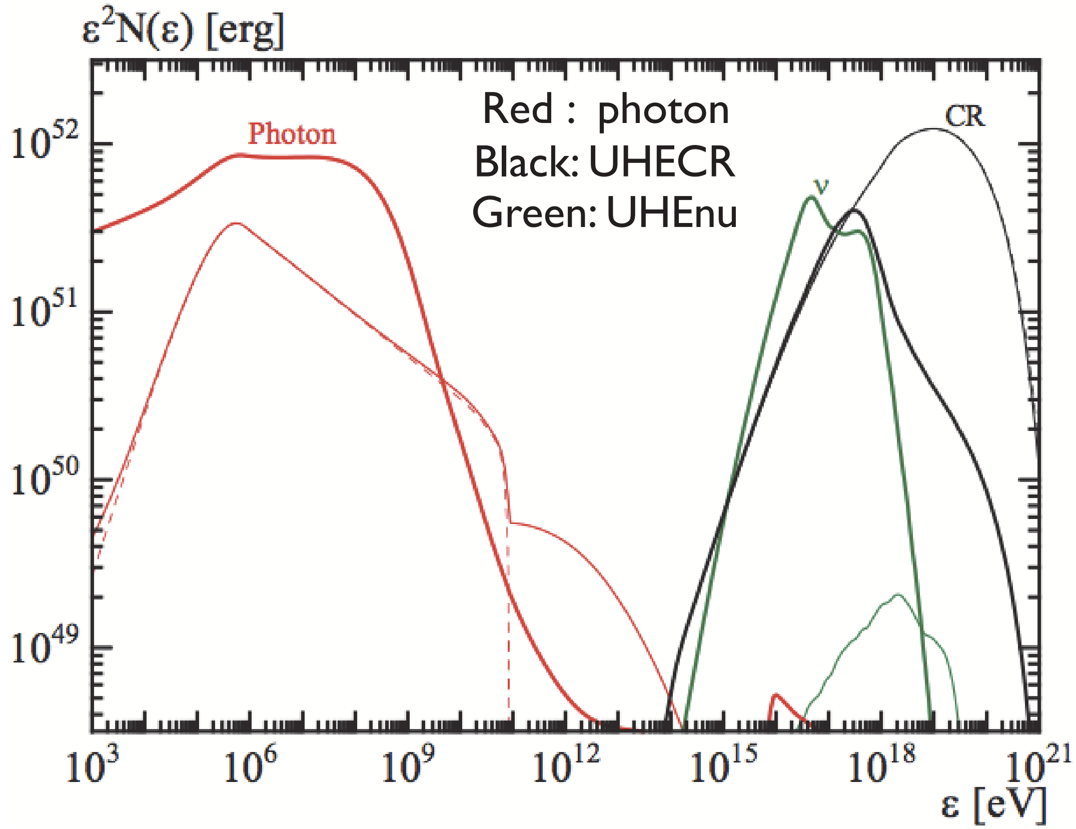


FIG. 5. The final photon (red), cosmic-ray (black), and neutrino (green) spectra from a GRB with $E_\gamma = 2 \times 10^{52}$ erg and $\Gamma = 127$. The assumed radii of the UHECR acceleration site are 10^{15} cm (thick line), 10^{16} cm (thin line), and 10^{17} cm (dashed line), respectively. The dashed lines for photon and cosmic-ray mostly overlap with the thin lines. The photon spectrum for 10^{17} cm is almost the input shape of the Band function. The dashed line for neutrino is far below the plot range of this figure.

(Asano & Mészáros, 2016, PRD 94, 023005)

- $R_{CR}=10^{15}$ (thick),
  10^{16} (thin),
  10^{17} (dashed)
- $R_{CR}=10^{15}$ (thick) can be ruled out, because: (1) RCR photons overwhelm input Band and wrong shape, and (2) too much neutrino
- $R_{CR}=,10^{16}$ (thin), and 10^{17} (dashed) satisfy all constraints ✔✔

so:

CONCLUSION for GRB UHECRs

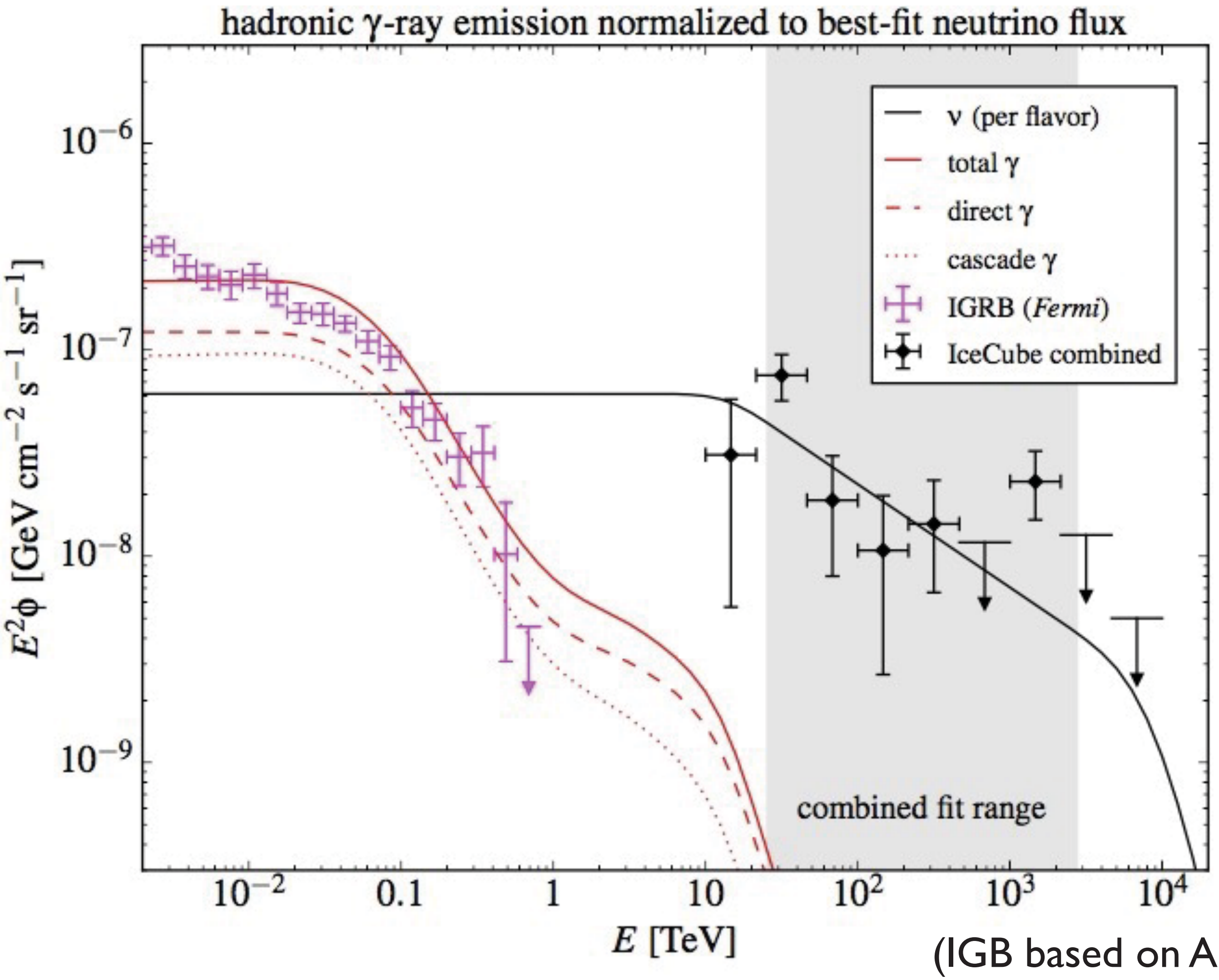
- *One way to resolve objections for GRBs to:*
- Provide the 10^{18}-10^{20} eV UHECR flux
- Not require excessive energy $(L_p/L_\gamma) \leq 10$
- Maintain observed γ-ray (Band) spectrum
- Satisfy (amply) the IceCube neutrino limits

Overall Conclusions

- At least ***two*** possible interpretations for the ***IceCube INB*** & the ***Fermi IGB***
- One are ***LLGRBs*** (act as "hidden sources") ***[A]***
- The other is ***HNe/SNe*** (they are "hidden" if their strongest contribution is at ***high z***) ***[B]***
- No need for blazars (the would not be "hidden")
- MBH TDEs: may explain ≤ 10-30% of INB **[C]**
- Normal luminosity ***GRB***s with Fermi 2nd CRs in ≠ shocks than the γs : can be GZK ***UHECR*** sources ***without*** violation of IceCube limits ***[D]***

Thanks!

Generic argument for pp→π^+,π^0 : SBGs may make ***too many*** γs?



- More recent neutrino data down 10 ***TeV:***
- Now need steeper spectrum ~$E^{-2.5}$
- More recent FERMI IGB data > ***600 GeV:***
- Single -2.5 PL makes too much gamma-rays; even broken PL has ***trouble***

(Bechtol+16, 1511.00688)

(IGB based on Ackermann et al 2016, to be pub.)