Multi-messenger physics of astrophysical *Neutrino* and *Cosmic-ray* sources

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(collabs. with Kohta Murase, Shigeo Kimura & colleagues)

Neutrino 2018, Heidelberg

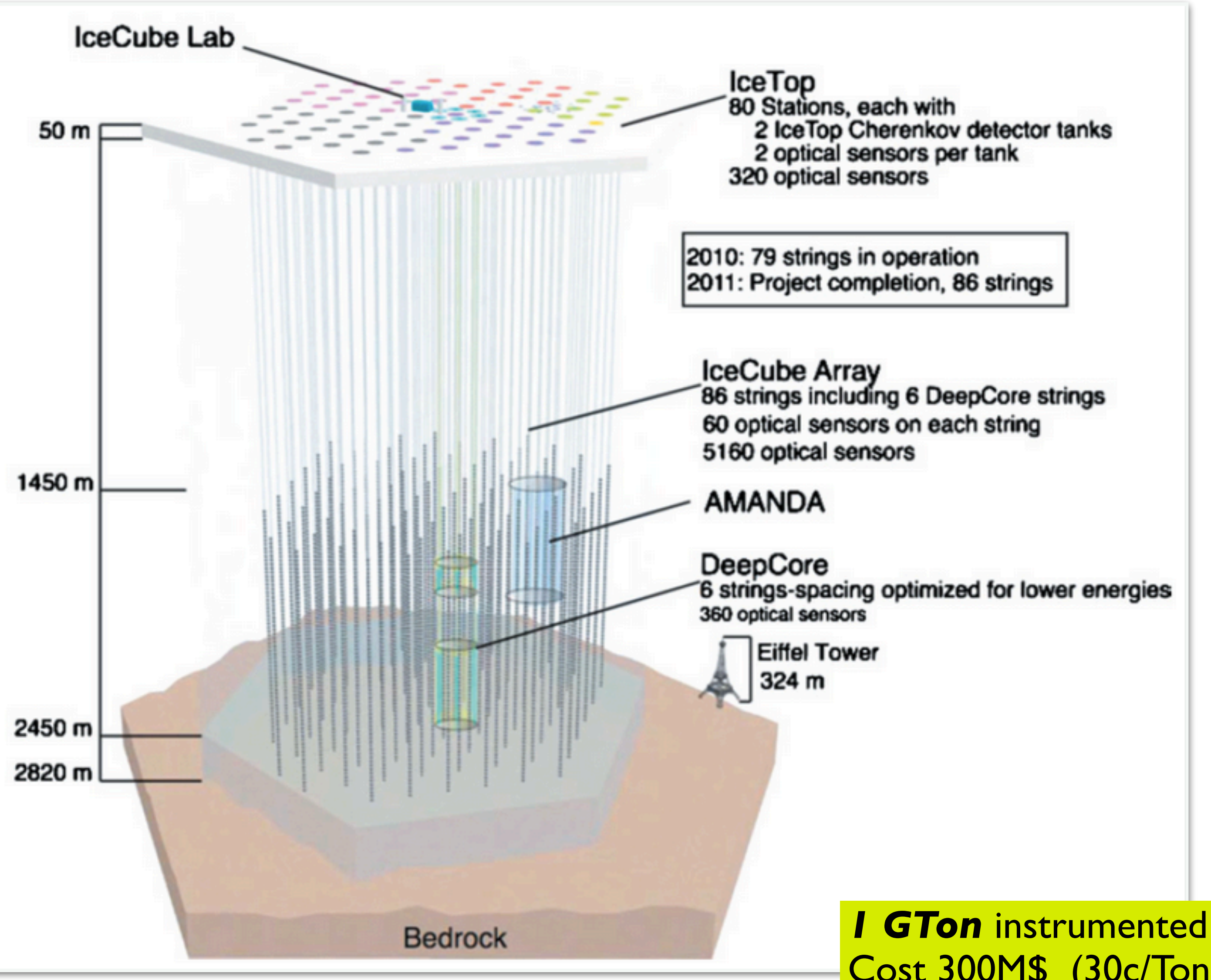
what causes HENUs at < few PeV?

or rather:

What causes HECRs, at < 100 PeV?

Multi-messenger traces:
VHE neutrinos

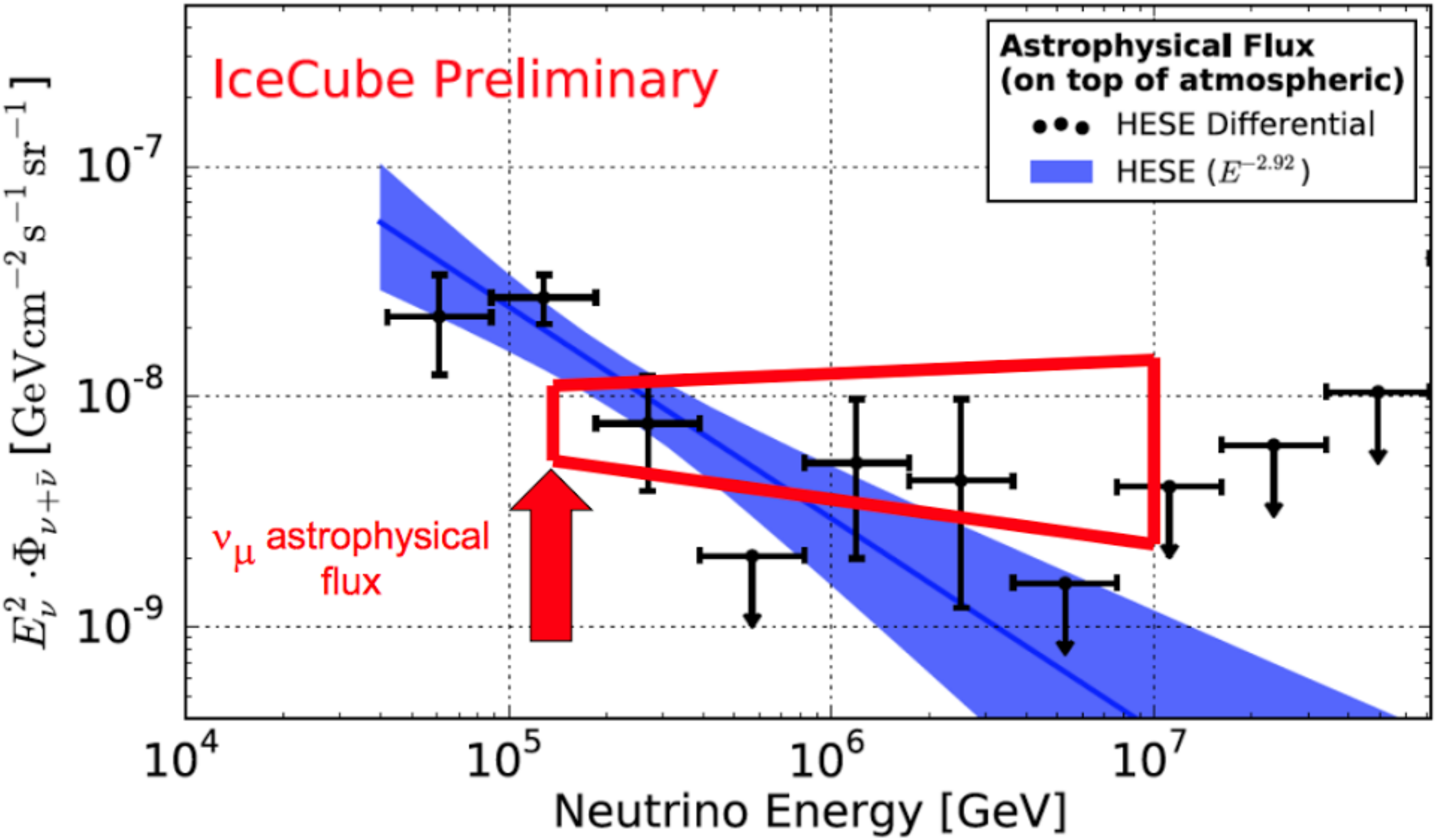
IceCube



- 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

I GTon instrumented volume,
Cost 300M$ (30c/Ton)

IceCube diffuse astrophysical neutrino background

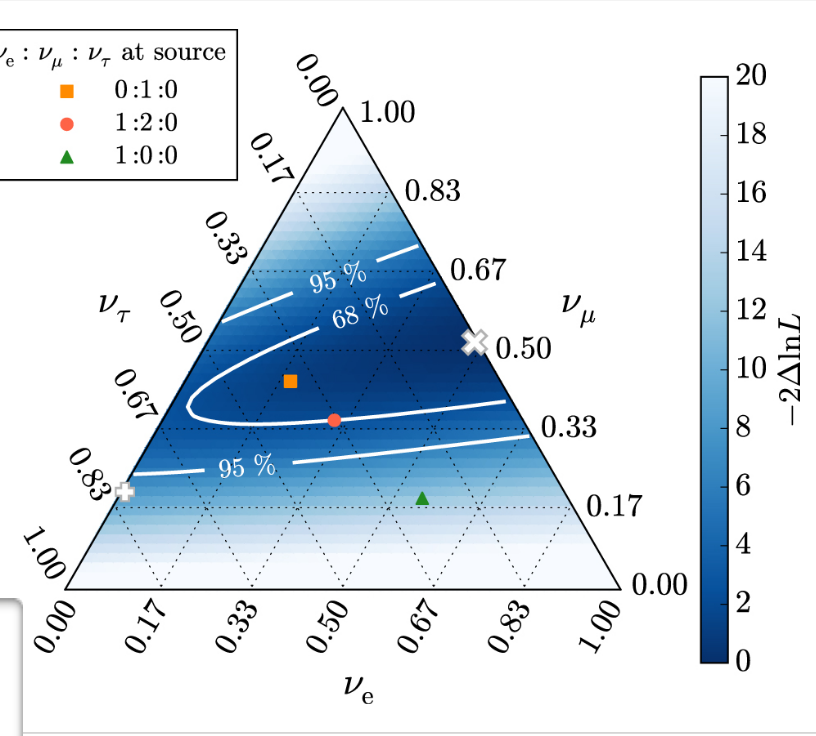


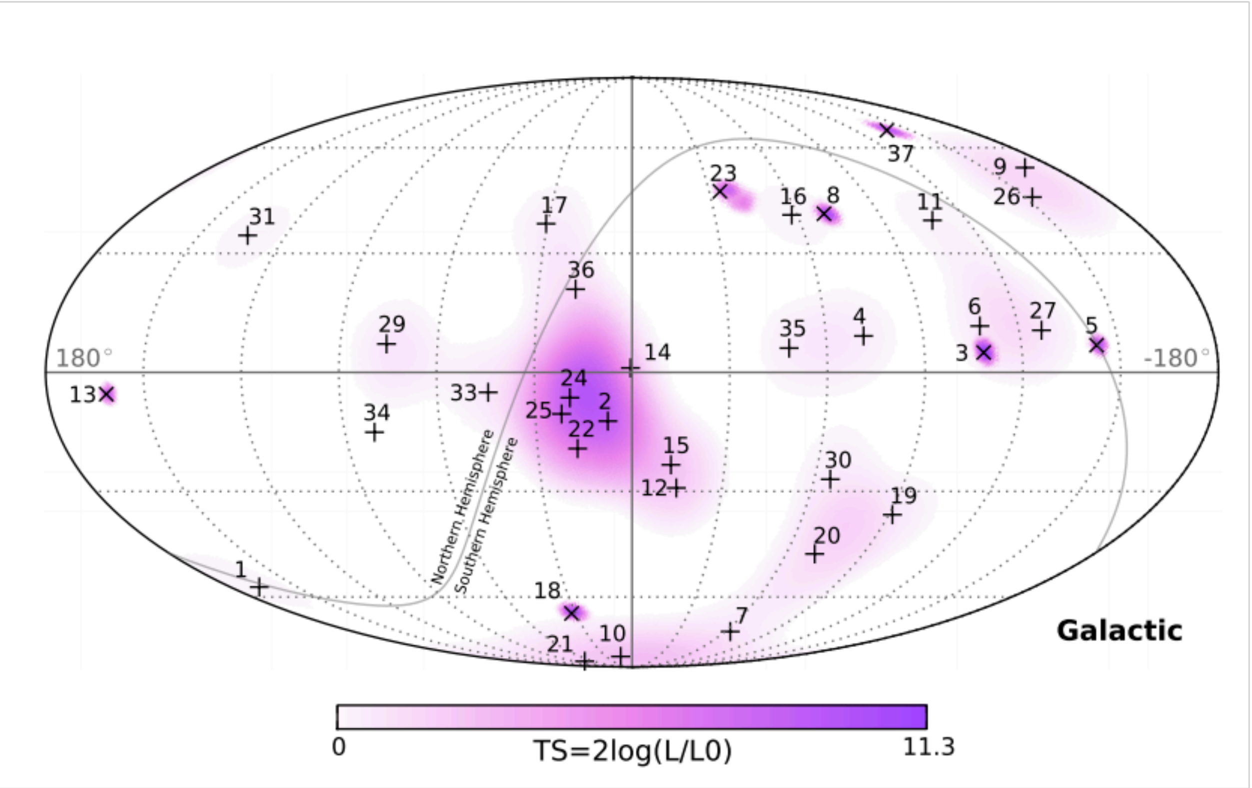
(maybe two components?)

(Halzen, 2017, TeVPA)

- 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!**

(possible exception: later)

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

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

(Tan-background slides credit: Nick Senno)

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

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

$$K^+ \to \mu^+ + \nu_\mu$$

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

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

$$\pi^0 \to \gamma + \gamma$$

- 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

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

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

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

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

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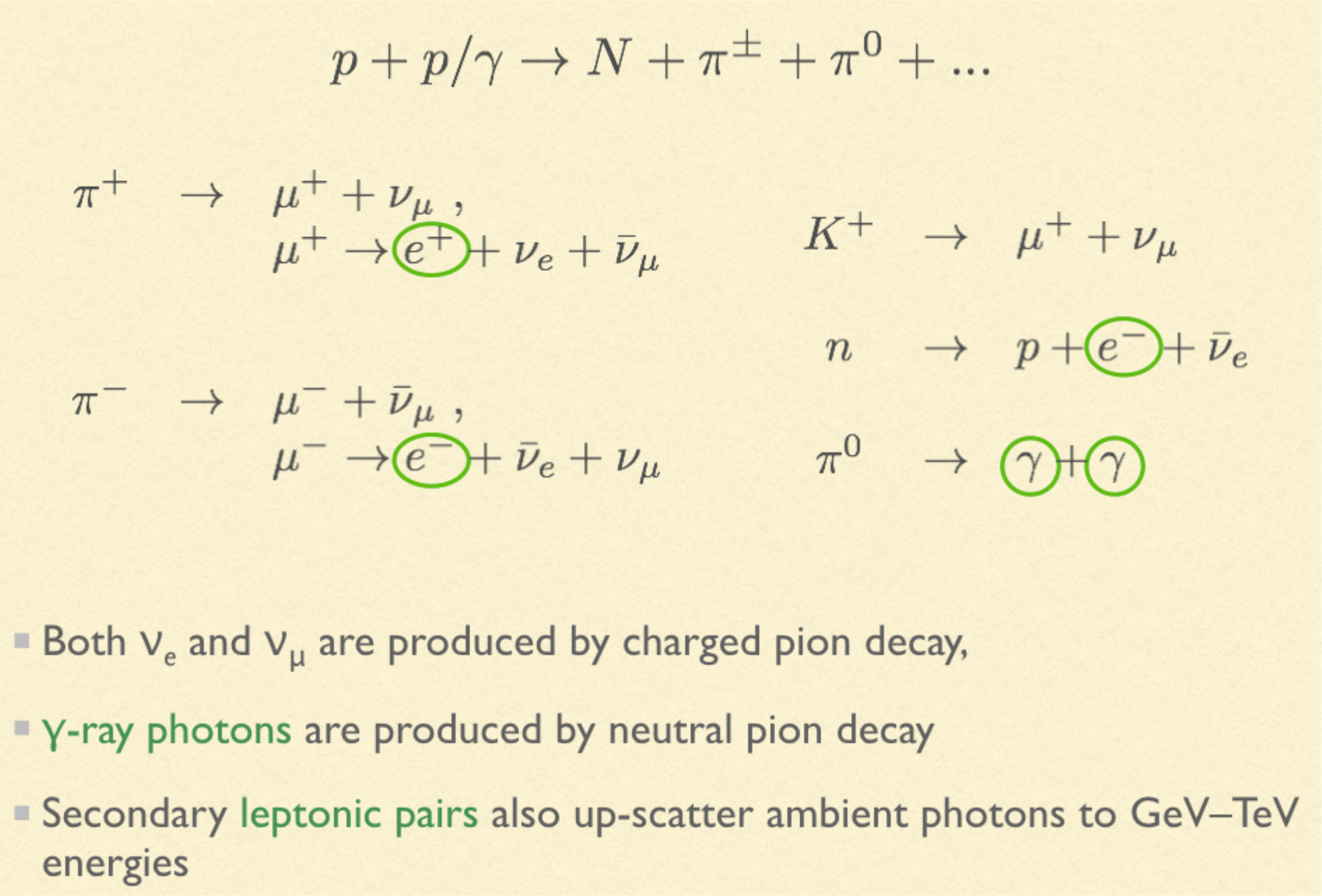

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + \ldots$$

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

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

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

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

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

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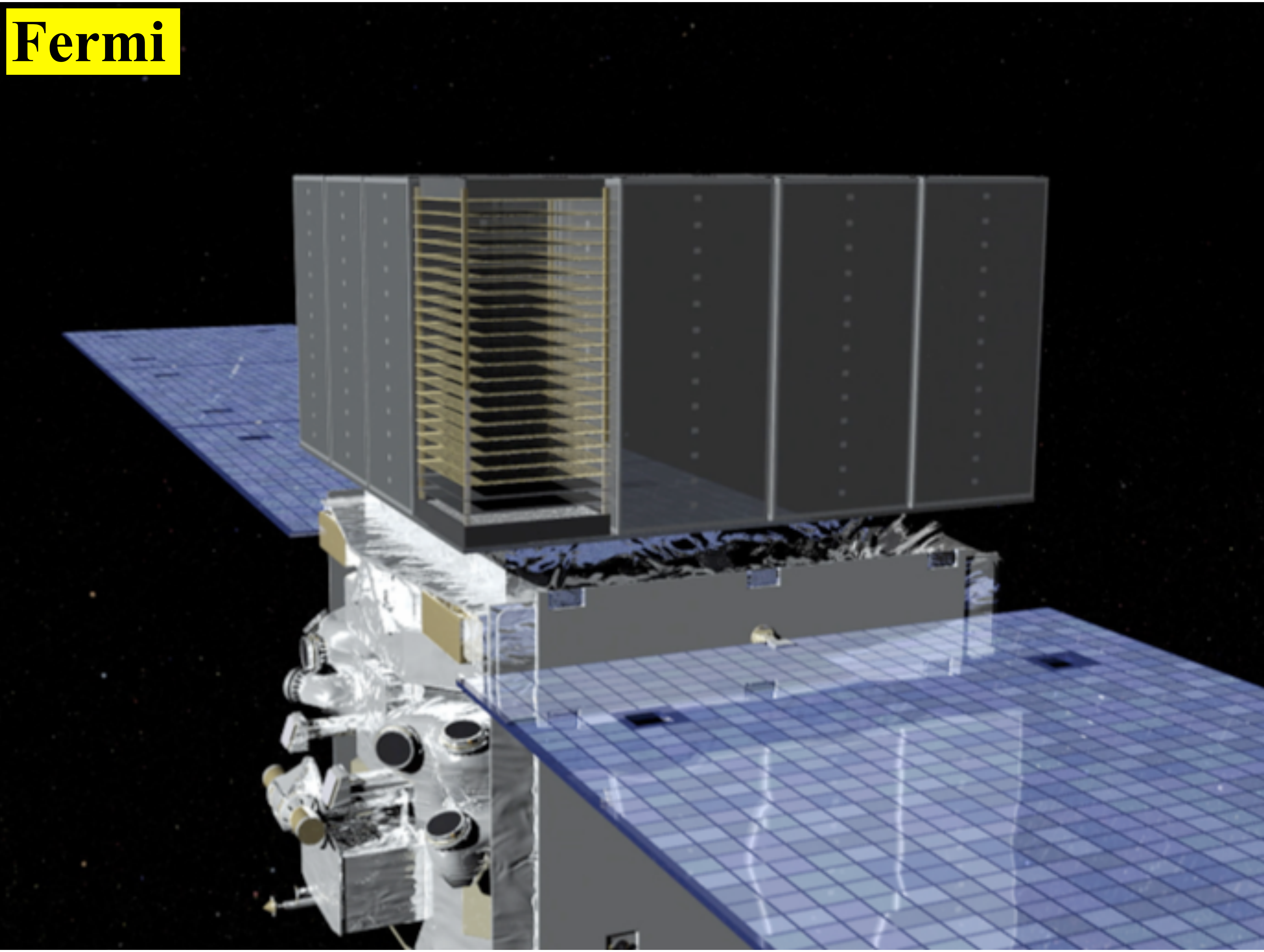
- Secondary leptonic pairs also up-scatter ambient photons to GeV–TeV energies

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

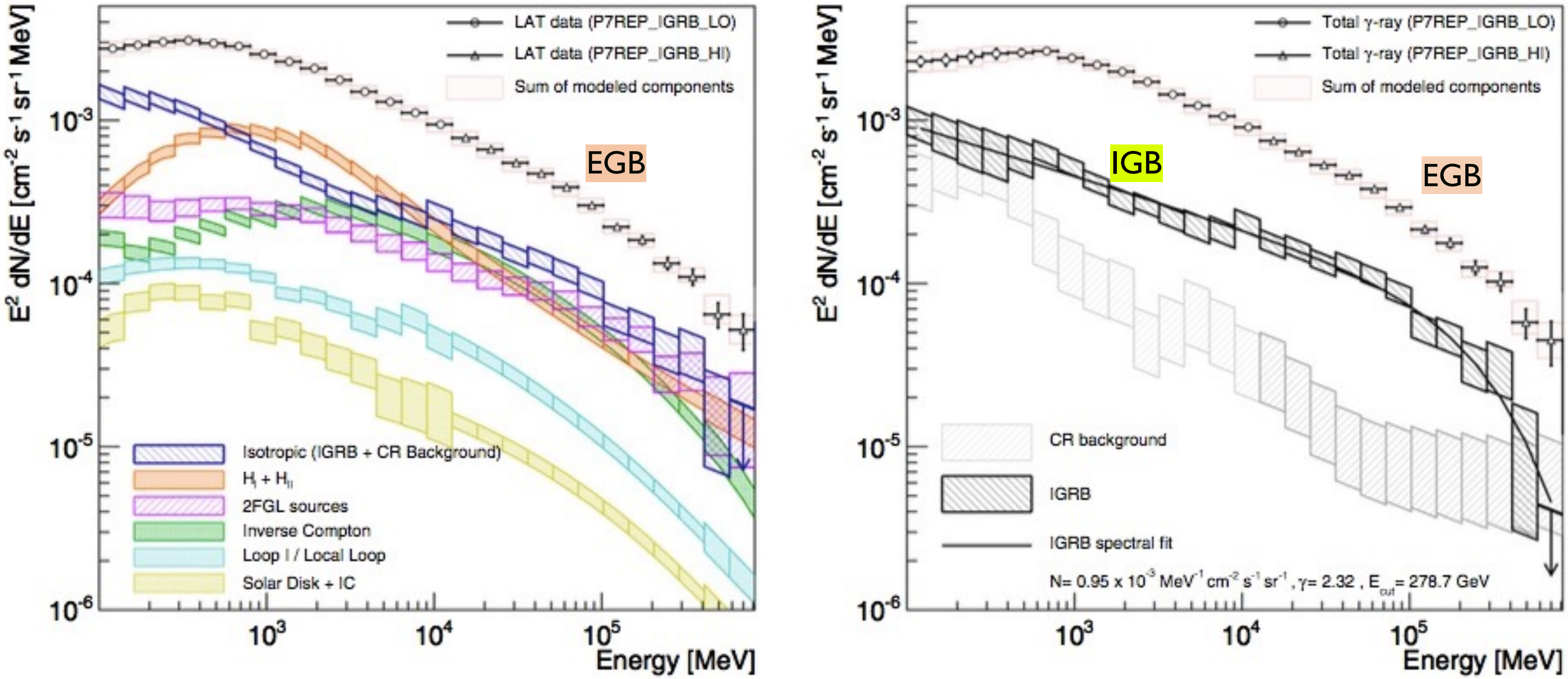
Fermi



Observed:

Fermi EGB & IGB

(Fermi coll.; Ackermann+15)



- EGRB: Extragalactic "gamma-ray" background (incl. everything, incl, point sources, etc)
- IGRB: Isotropic gamma-ray bkg. (incl. unresolved sources, or truly diffuse) : ~14% of EGB

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

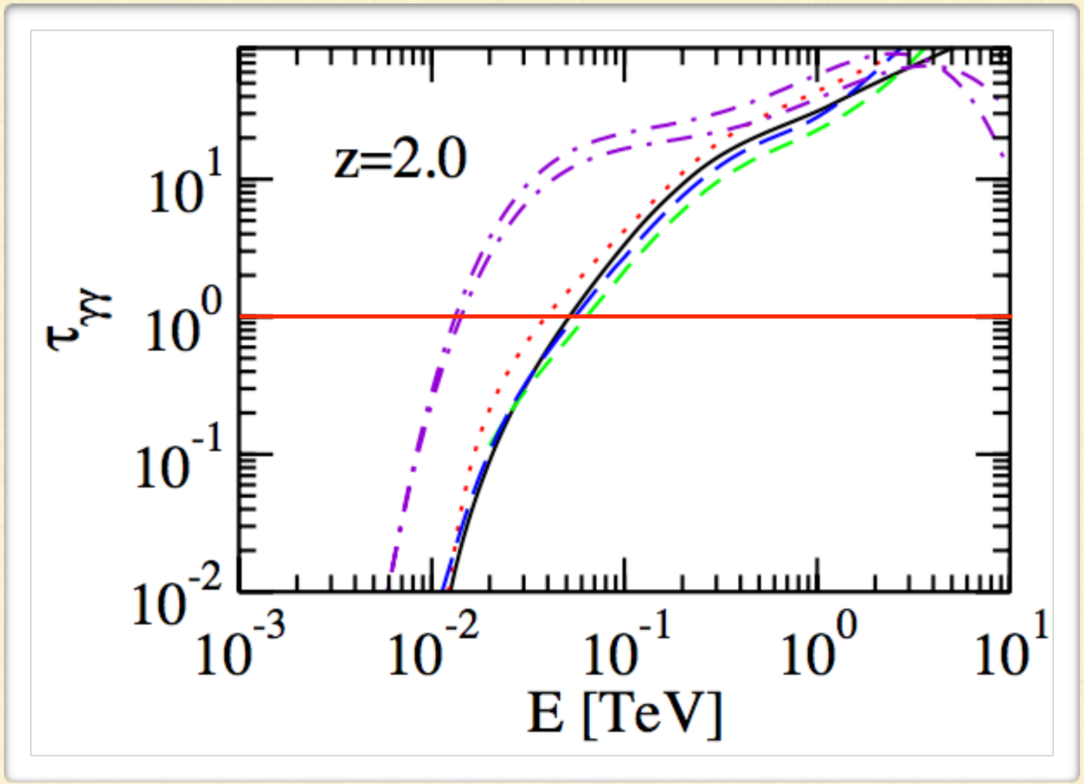
$$\epsilon_\gamma^2\Phi_\epsilon \simeq 2^{s-1}\varepsilon_\nu\Phi_\varepsilon\Big|_{\varepsilon_\nu=0.5\epsilon_\gamma}$$

(injection spectrum similar)

BUT:

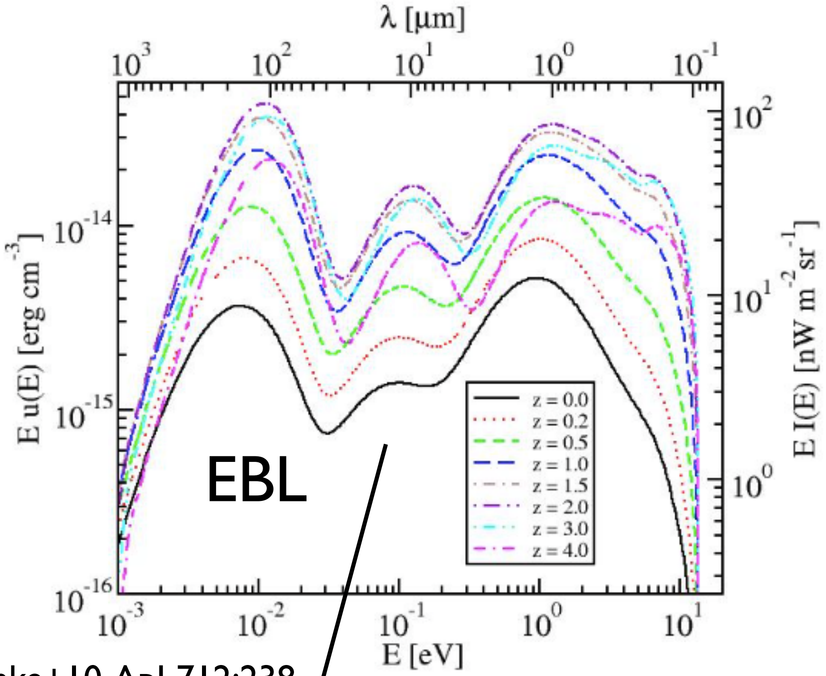
- A fraction $\sim 1-e^{-\tau_{\gamma\gamma}}$ of γ–rays are attenuated by extra-galactic background light (EBL)
- The resulting spectrum is universal for large distances

(γγ→e+e- cascades)



Finke et al. ApJ 712, 238 (2010)

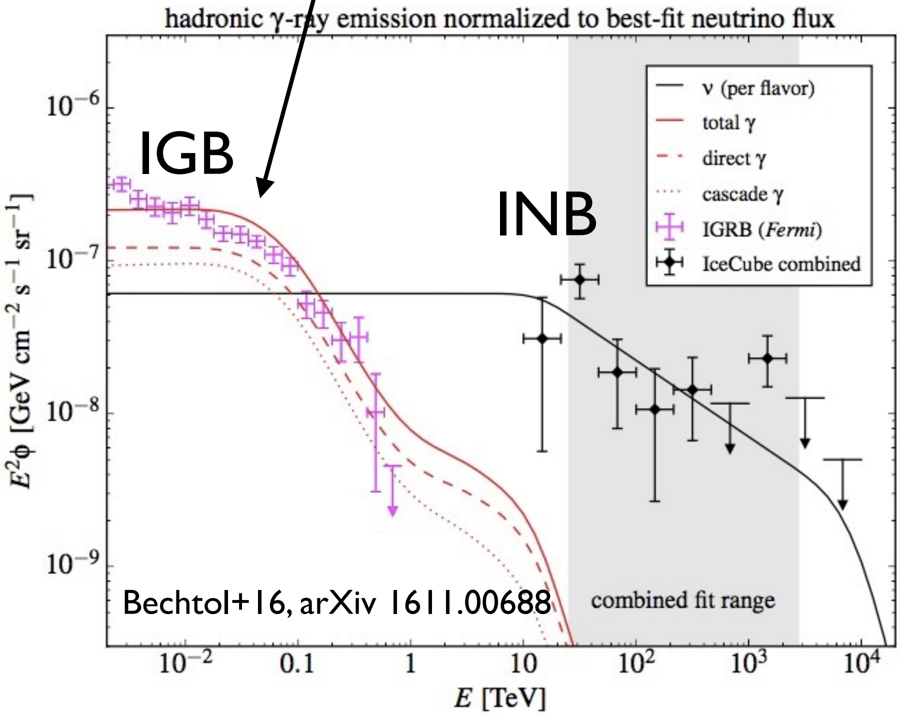
High energy γ-ray propagation in intergalactic space



Finke+10, ApJ 712:238

γγ cascades of injected HE γ on EBL γ

hadronic γ-ray emission normalized to best-fit neutrino flux



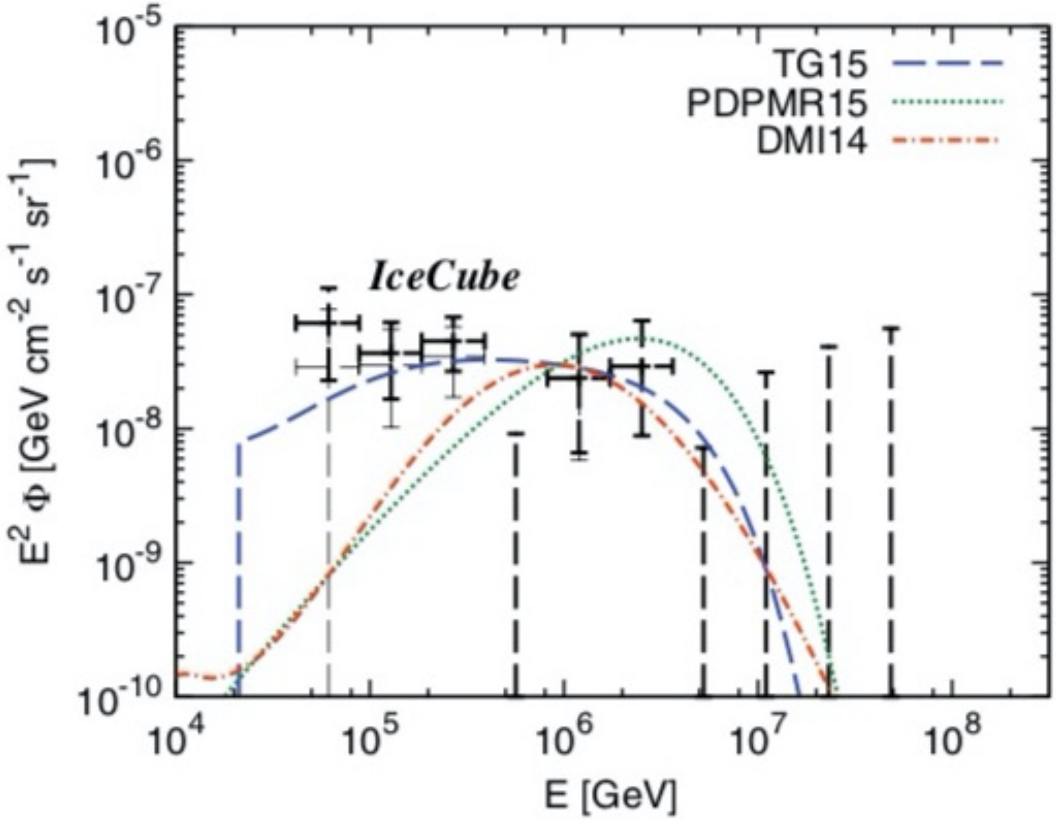
Bechtol+16, arXiv 1611.00688

- $\gamma_h + \gamma_s \rightarrow e^+ + e^-$
- 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

Origin of the diffuse neutrino, related CR and γ-ray backgrounds

- AGNs? Ideal since make most of IGB, but..
- Clusters of galaxies?
- Starburst galaxies? (SNe & HNe in them?)
- GRBs? (or choked/low-luminosity GRBs?)
- Galaxy & Galaxy Cluster mergers, LSS?
- Or: other suspects?

AGNs



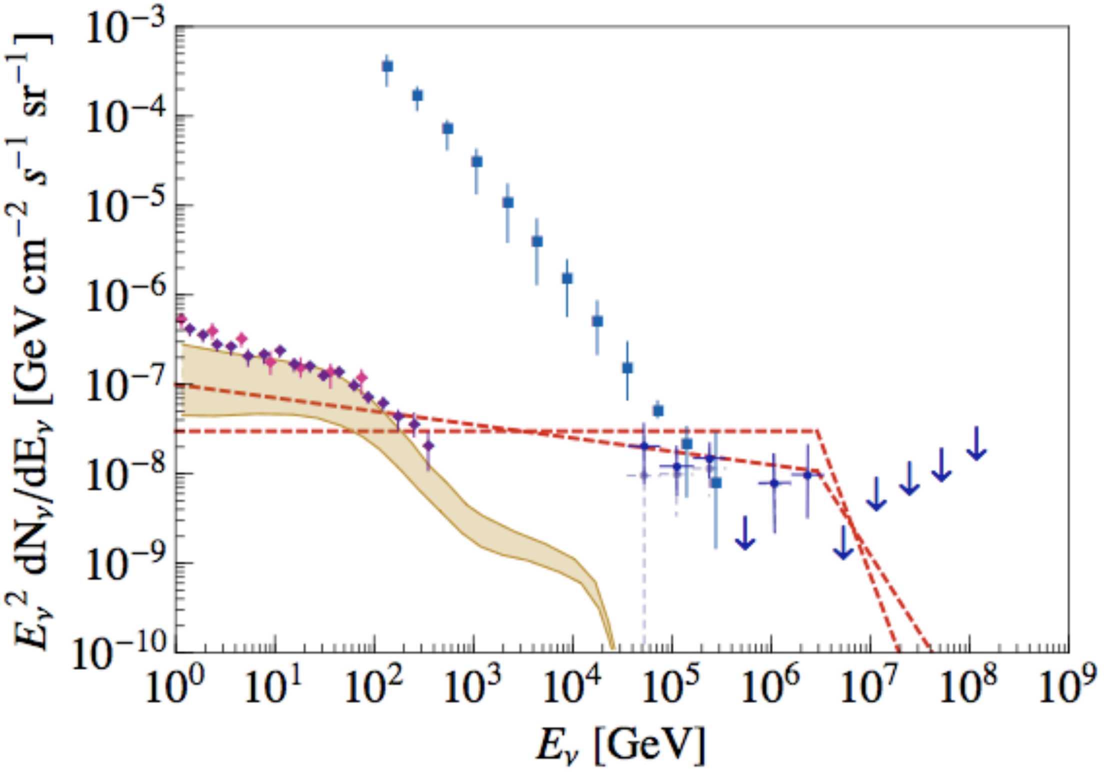
Diffuse neutrino background (all-flavor) from various AGN jet and AGN core models from various authors

(Murase, Waxman'16, PRD 94:103006).

- AGNs are among oldest suspected HECR sources, and as such are "natural suspects" for HENU sources ✔
- Ideal, since they are responsible for ~85% of the diffuse gamma-bkg ✔
- ***However***, successive IceCube and other group's attempts at correlations between HENU events and AGN catalogs have shown ***no significant correlation*** ✘

(BUT: see TXS 0506+056)

Galaxy clusters

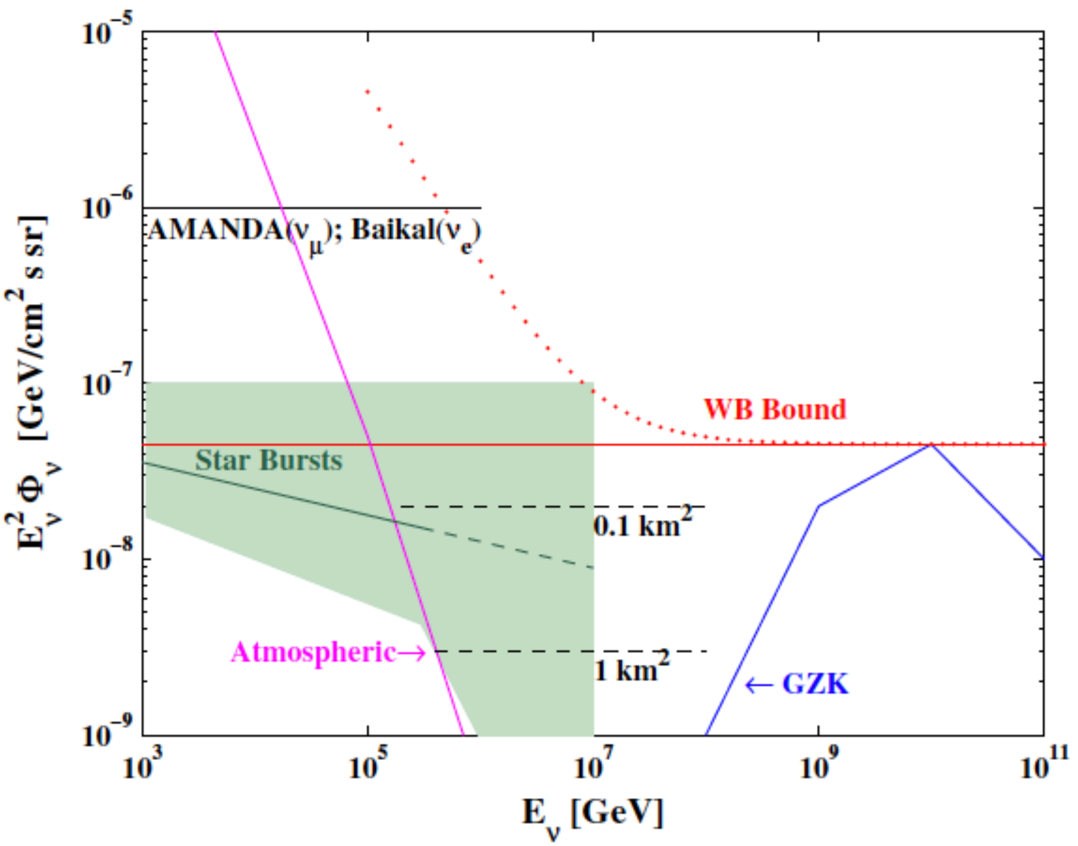


(e.g. generic source pp spectrum, Anchordoqui'14)

- Accretion shocks onto cluster lead to HECR acceleration
- Can also lead to HENU and γ-rays

- **However**, if fit $E_\nu F_\nu$ to observed IceCube flux, from $\pi^\pm/\pi^0$ branching ratio expect $E_\gamma F_\gamma \sim E_\nu F_\nu$, ≈ to full Fermi IGB
- Clusters mainly at $z \lesssim 1$, intervening $\boxed{\tau_{\gamma\gamma} \leq 1}$, no $\gamma\gamma$ absorption
- Thus, if explain IceCube, ***violate*** the non-blazar Fermi IGB ✗

(However: for AGNs in clusters, see Fang & Murase, 2018 NatPh 14:3961)



(accelerators in) **Starburst Galaxies**

- The relativistic electron spectra deduced from the SBG radio emission suggests the injection of **>multi-PeV protons** (Loeb & Waxman'06)

- The inferred SBG CR energy budget and SBG luminosity function indicates a cosmological energy input comparable to the GZK bound

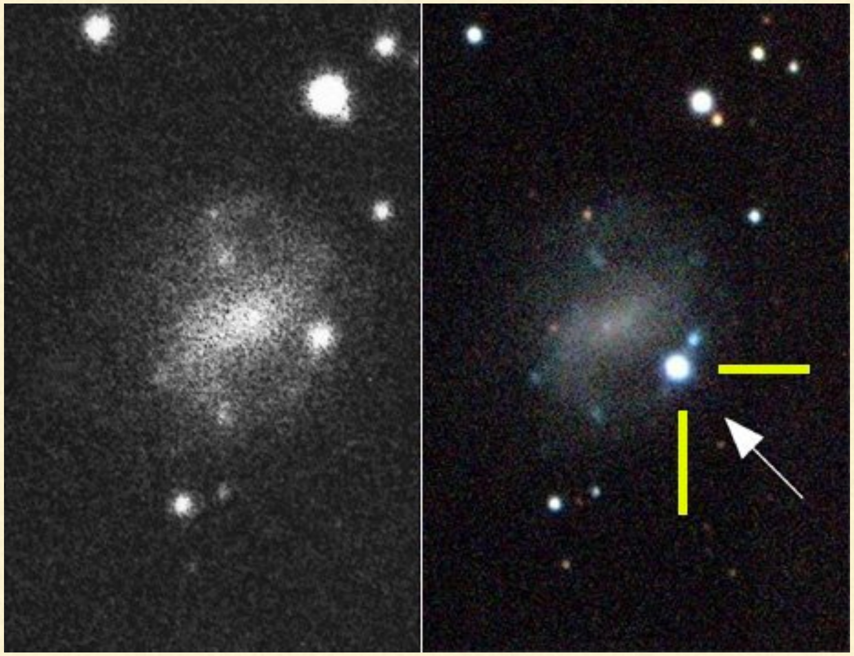
- Under calorimetric conditions, this leads to an IceCube-compatible diffuse neutrino flux level - might work!

- **What are the accelerators** in SBGs?

Hypernovae & supernovae

→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)

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

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

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

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

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

(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)

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

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

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

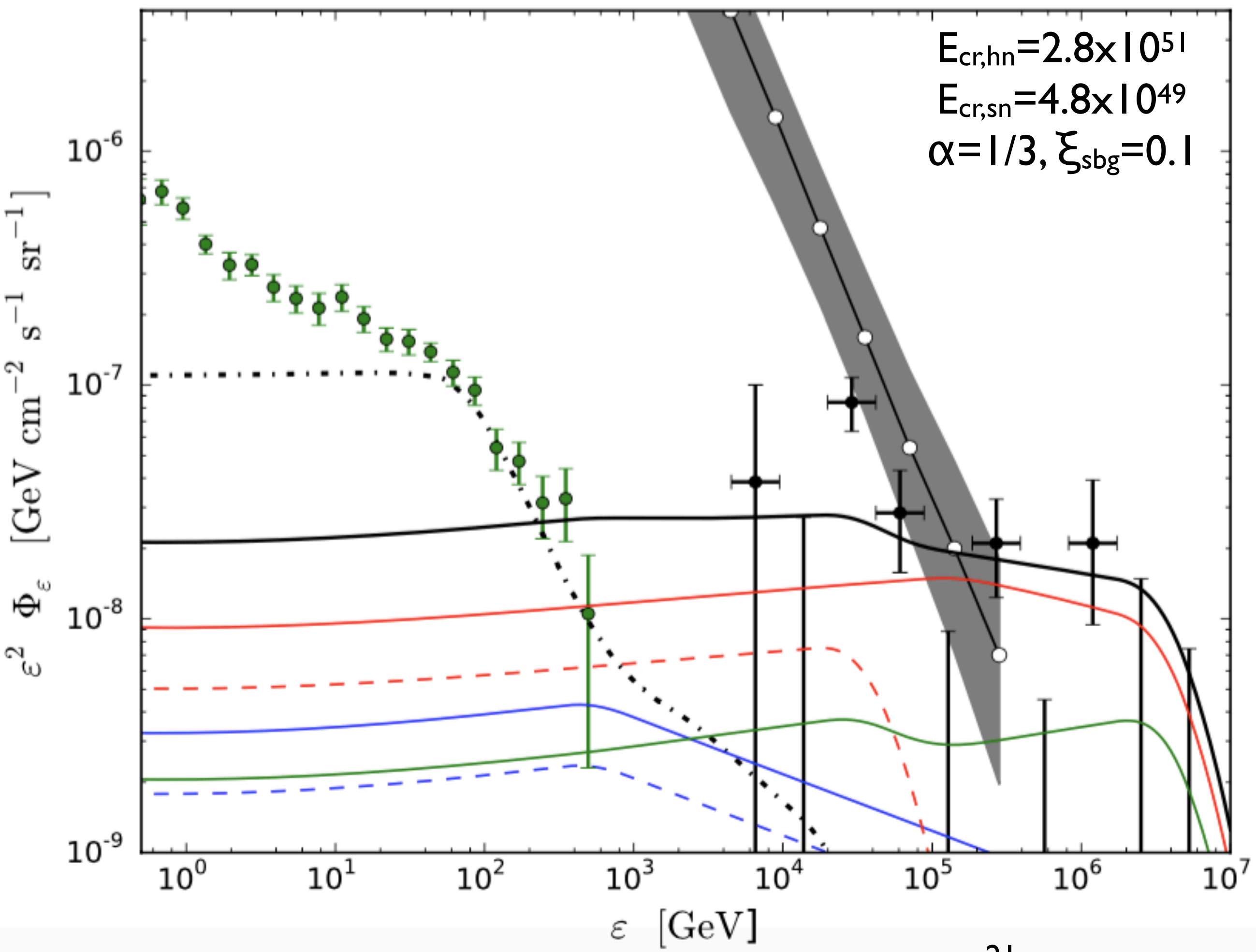
$$\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{phys}}(z) = \left[\left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{hn}} + \left(\varepsilon_p Q_{\varepsilon_p}\right)_{\mathrm{sn}}\right](1+z)^3 S(z)$$

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

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

HNe & SNe in SBG, SFG

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



- HNe, SNe accelerate CRs with spectrum N(E)~E^{-2}, Emax ~10^{15} eV (SNe) Emax ~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 both Cluster models & z≲4 Starburst SNe/HNe

- They can address mainly the ***PeV*** neutrinos, whereas the more recent ***TeV*** nu-flux is higher
- One need ***substract*** from Fermi EGB the ~86% attributable to resolved and unresolved **blazars**
- Also, the more recent Fermi flux @ 600 GeV imposes ***stricter constraints***
- If above models satisfy this ***residual*** Fermi IGB, they ***overproduce*** by x2-3 the IceCube INB flux

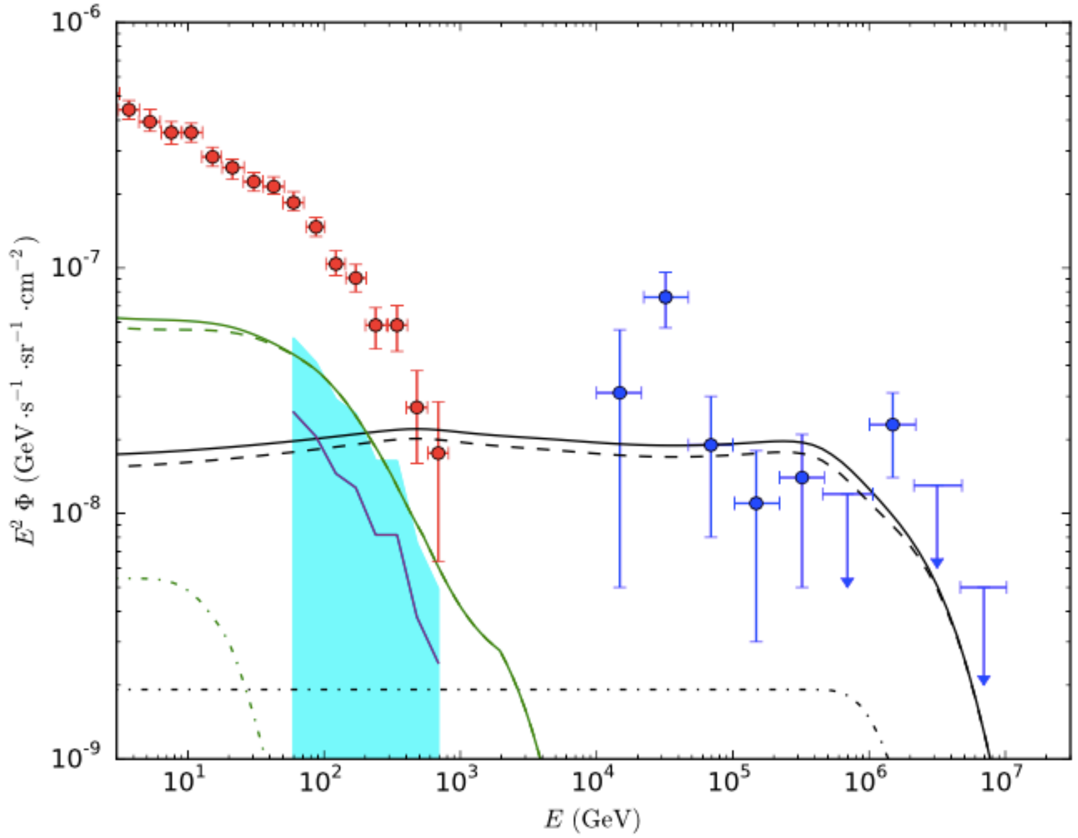
SNe/HNe revisited:
consider also @ high z

Xiao, Mészáros, Murase, Dai ’16, ApJ 826:133

- 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
- From high-z, more γγ absorption !

adding

Pop I/II+Pop III combined



Low and high z,
$0 \le z \le 10$:

Does better job ✔
(+1σ of IGB & INB)

(except 30 TeV nu)

Xiao, Mészáros, Murase, Dai,
2016, ApJ 826:133

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 $z \le 4$ 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.

A way to look at it is:

⇒ Need "hidden" neutrino sources

- Hidden in the sense of "low or no EM"
- This could be if @ high z (***redshift hides***)
- Or, high optical depth ***(Thomson hides)?***

Could they be

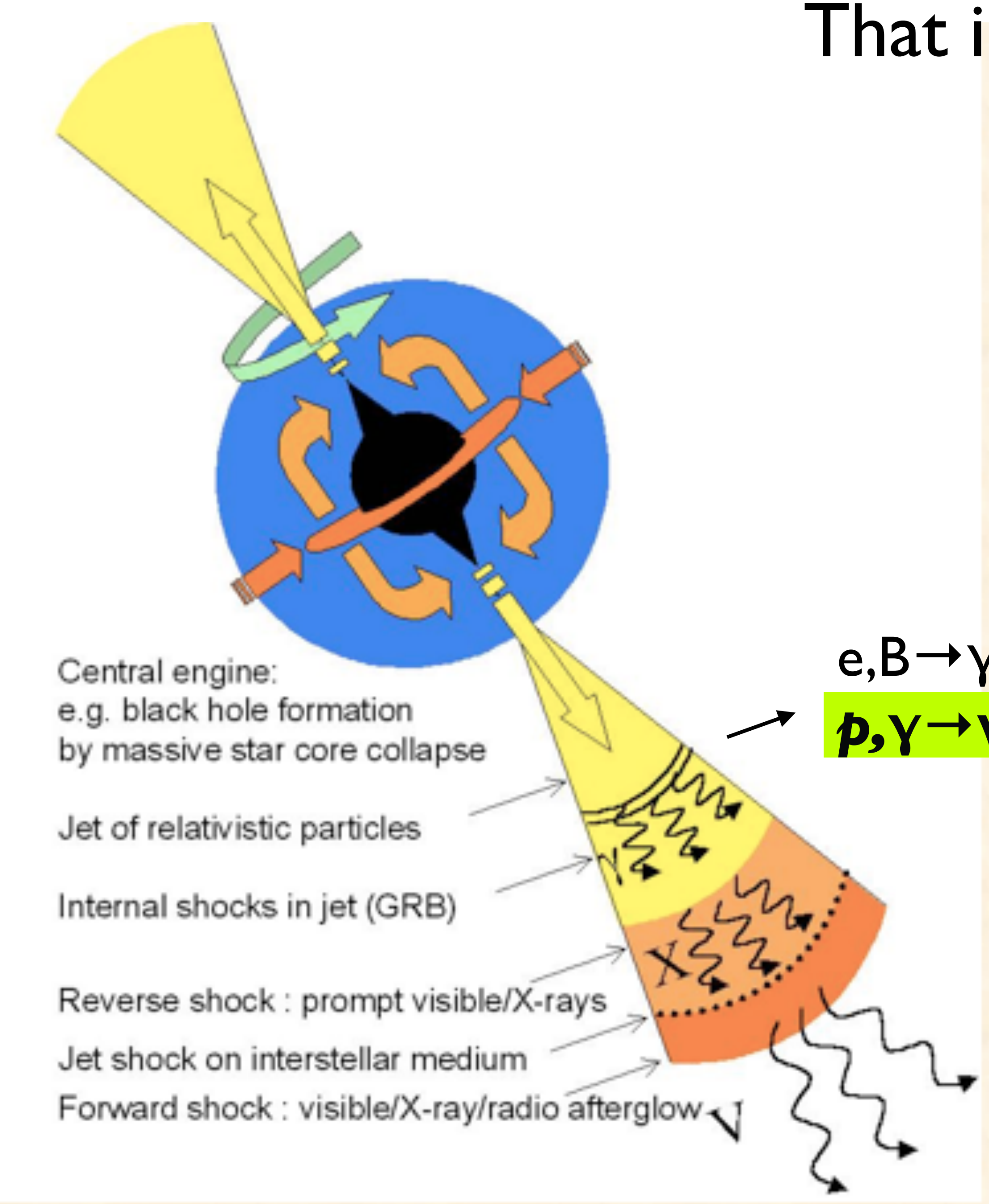
Normal GRBs?

Problematic :

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

That is,

Classical collapsar GRB model



e,B→γ

p,γ→ν,γ

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

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

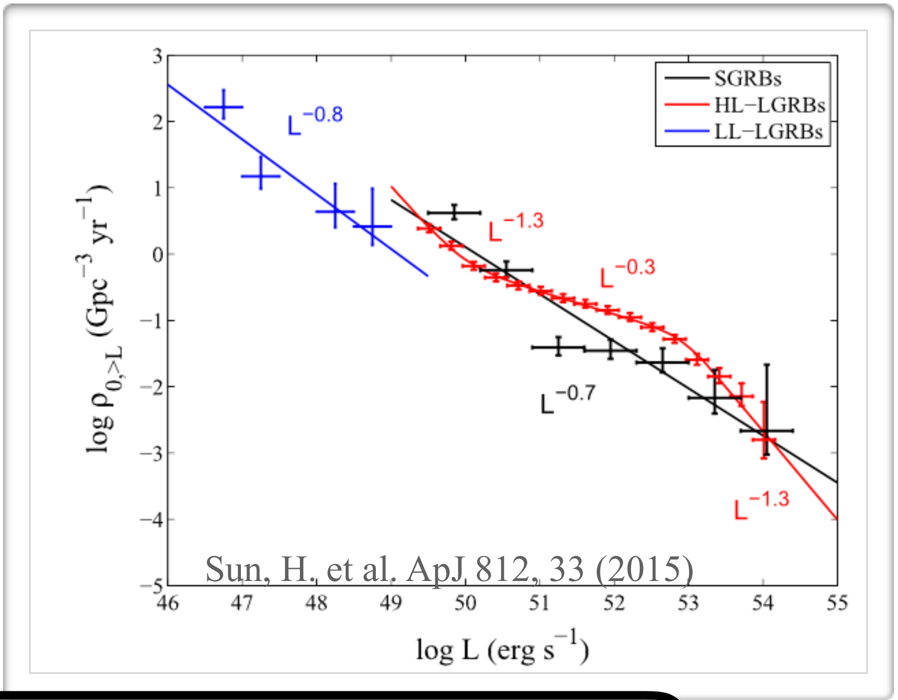
(IC3 team, 2015, ApJL, 805: L5)

Low optical depth →no hiding → Not classical GRBs!

An alternative : **LLGRBs?**

- Low luminosity GRBs (LLGRBs) have $L_\gamma \sim 10^{-2}$ -10^{-3} ***smaller,*** but 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)

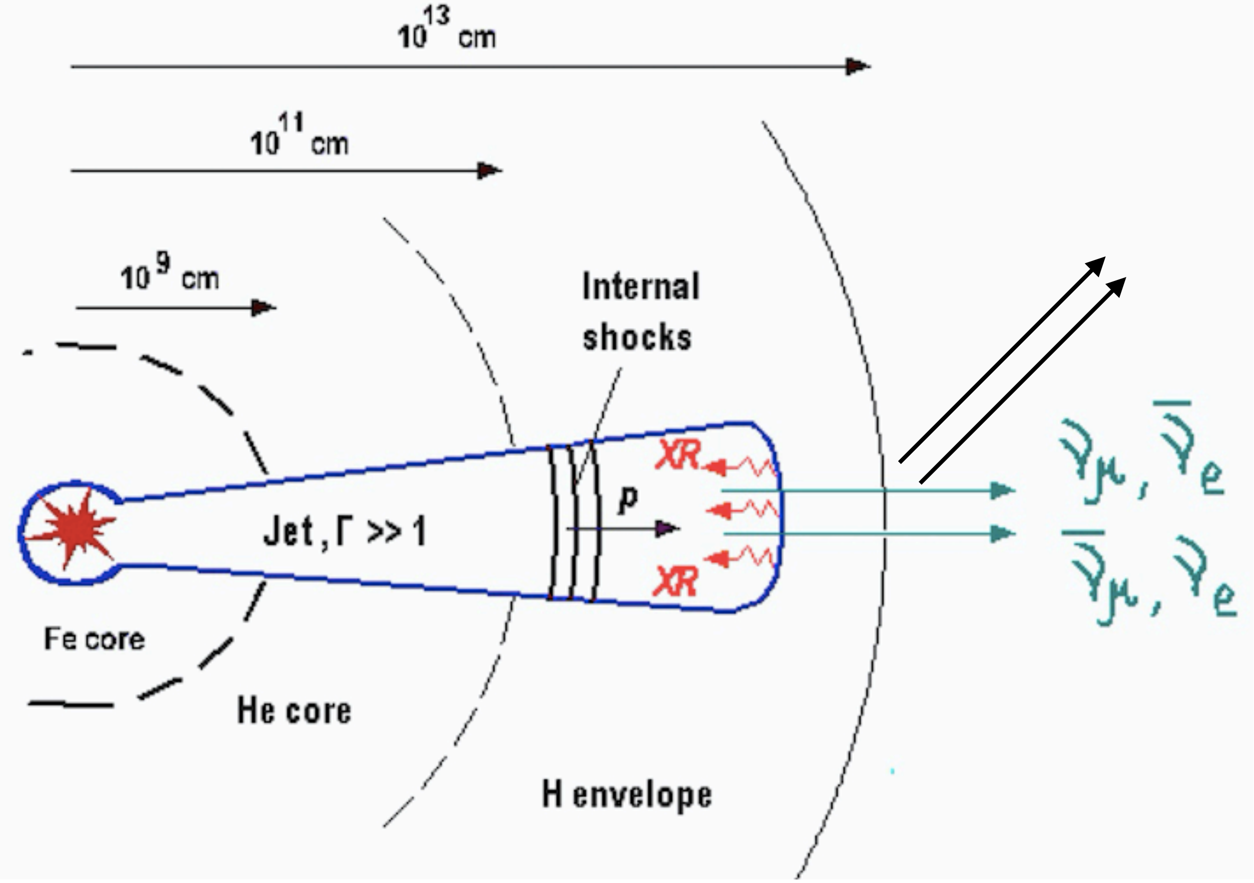
These may be:

- (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 jets ...



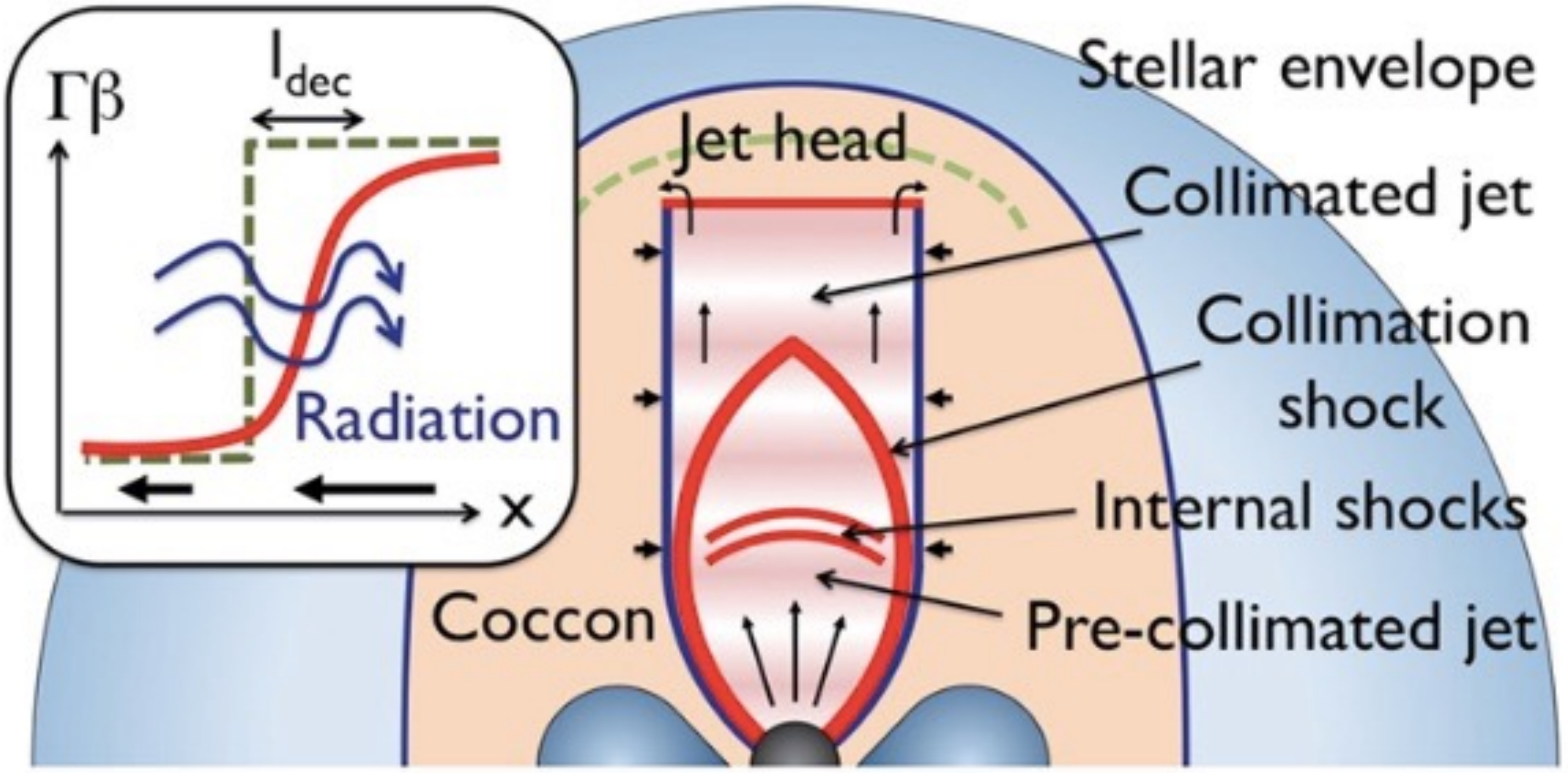
and later (for some)

Emergent jets

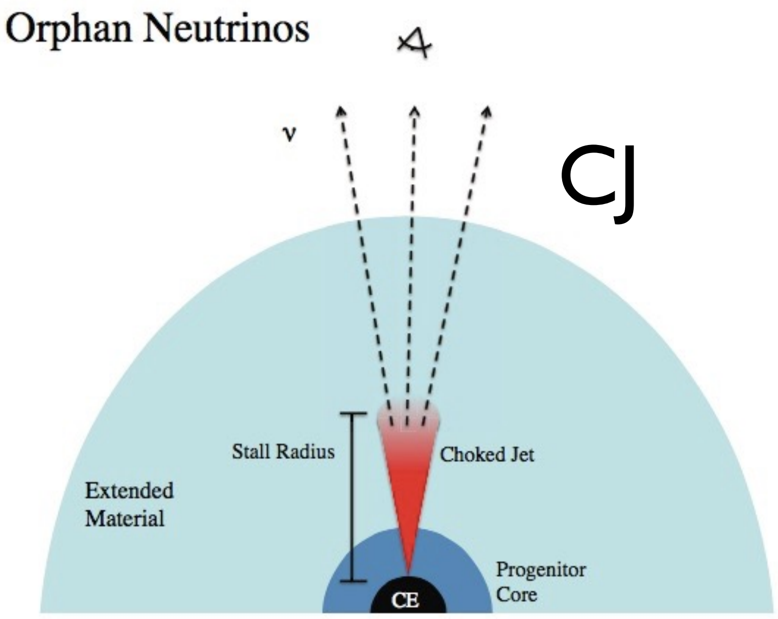
(Mészáros &Waxman, 2001, …..)

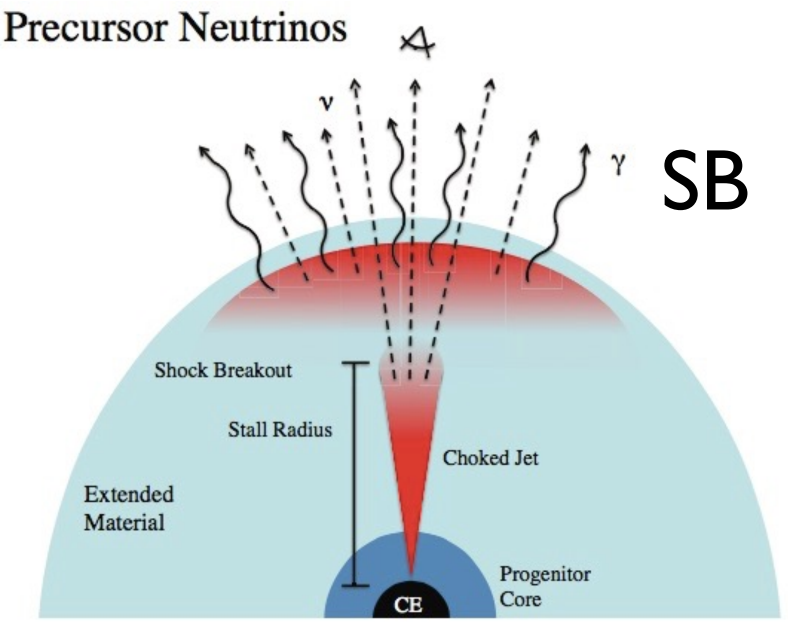
Star-penetrating jets

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

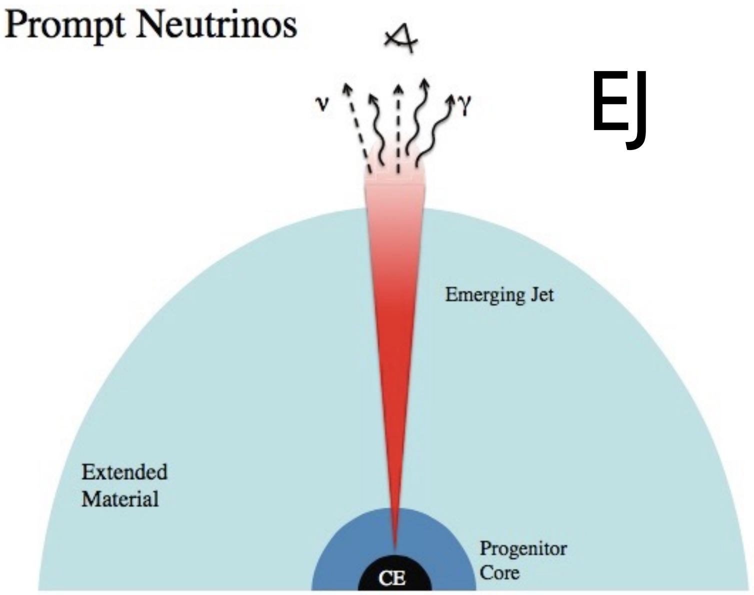


Choked / Shock Break-out / Emergent Jets as Hidden Neutrino Sources





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



Other previous work on choked GRBs:

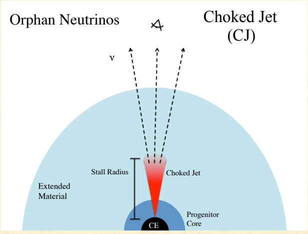
Mészáros &Waxman 2001, PRL 87, 171102

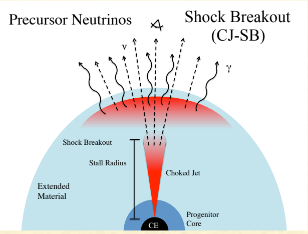
Waxman, Campana & PM 2006, ApJ 667, 351

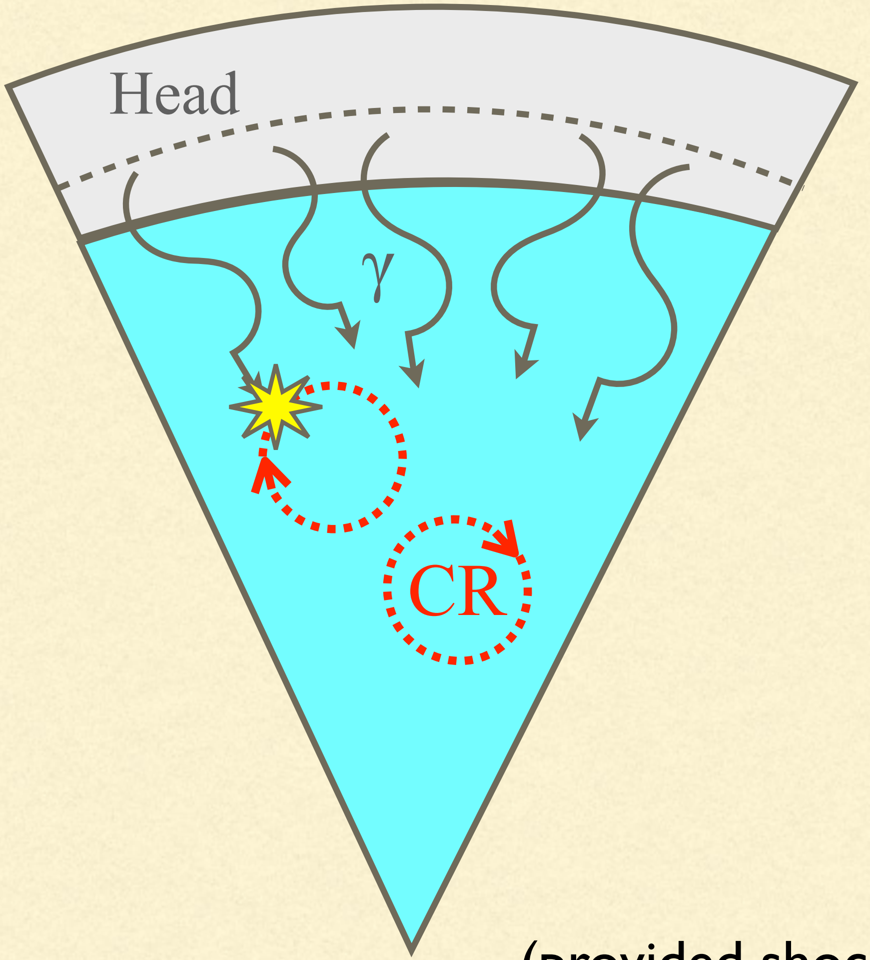
Murase & Ioka, 2013, PRL 111, 121102

Nakar, 2015, ApJ 807, 172, etc.

CJ NEUTRINOS FROM pγ INTERACTIONS







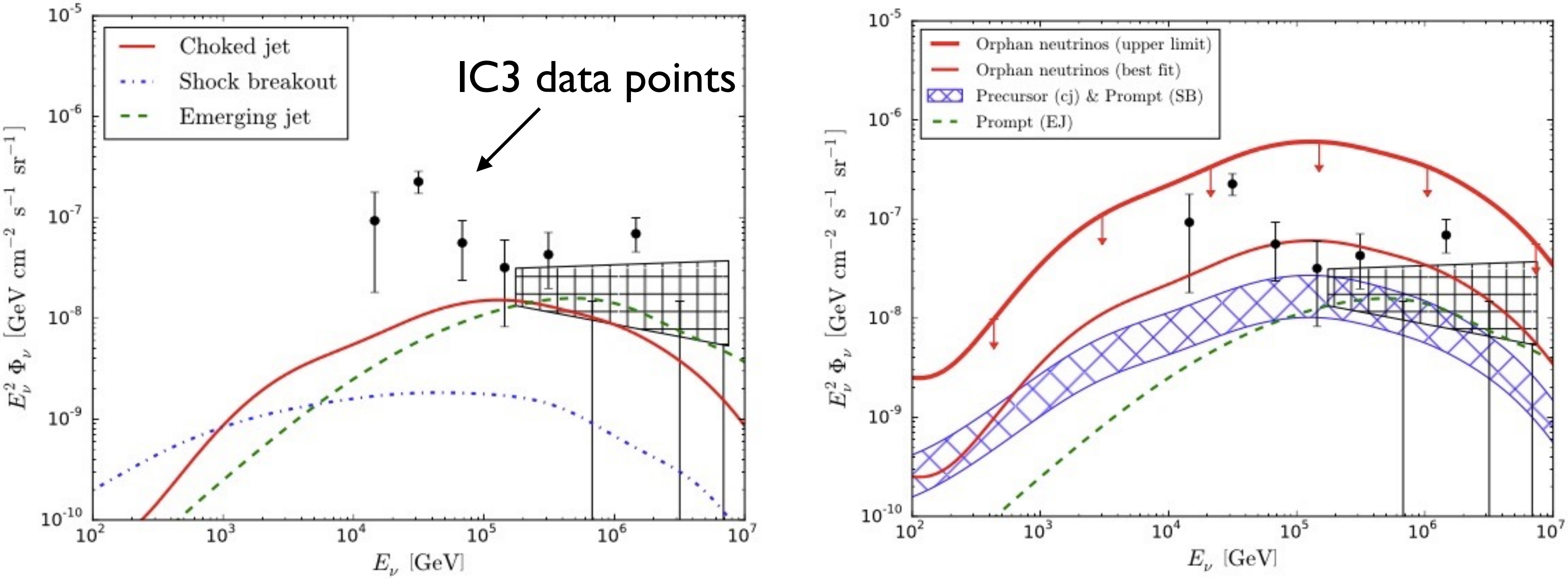
- The plasma surrounding the jet is optically thick
- The dominant photon field for pγ interactions is from photons generated in the jet head

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

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

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

Choked jet, shock breakout & emergent jet ν-spectra


IC3 data points

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

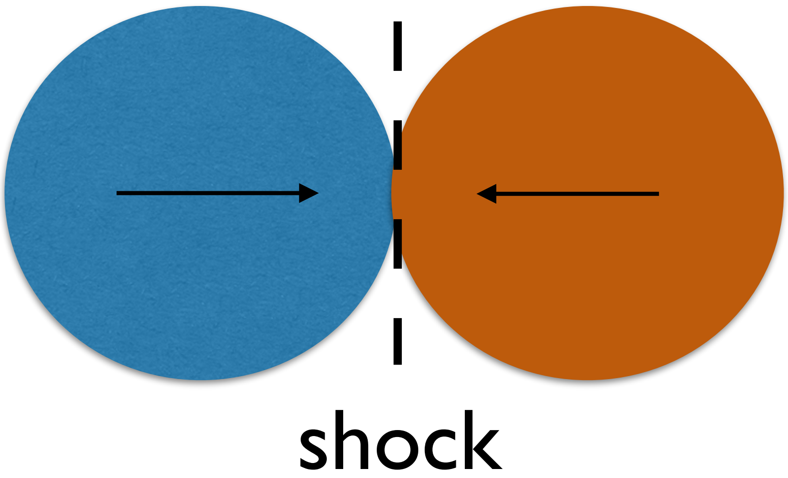
Senno, Murase, Mészáros, PRD, 93, 083003

Another possibility:

Could it be due to Galaxy & Cluster Mergers?

These will not be “γ-hidden” at low z,
but they start occurring at ***high z*** $\gtrsim 10$,
where $\tau_{\gamma\gamma} >> 1$

Galaxy merger shocks



$M_{*}\sim10^{11}\ M_{\odot}$, $M_{gas}\sim10^{10}\ M_{\odot}$

$v_s \sim 3\text{-}5\times10^{7}$ km/s

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

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

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

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

$$L_{gms} \sim 4.0\times10^{43}\ \overline{E}_{gms,58.5} v_{s,7.6} R_{gal,22.5}{}^{-1} \text{ erg s}^{-1}$$

Cosmic ray energy input into Universe:

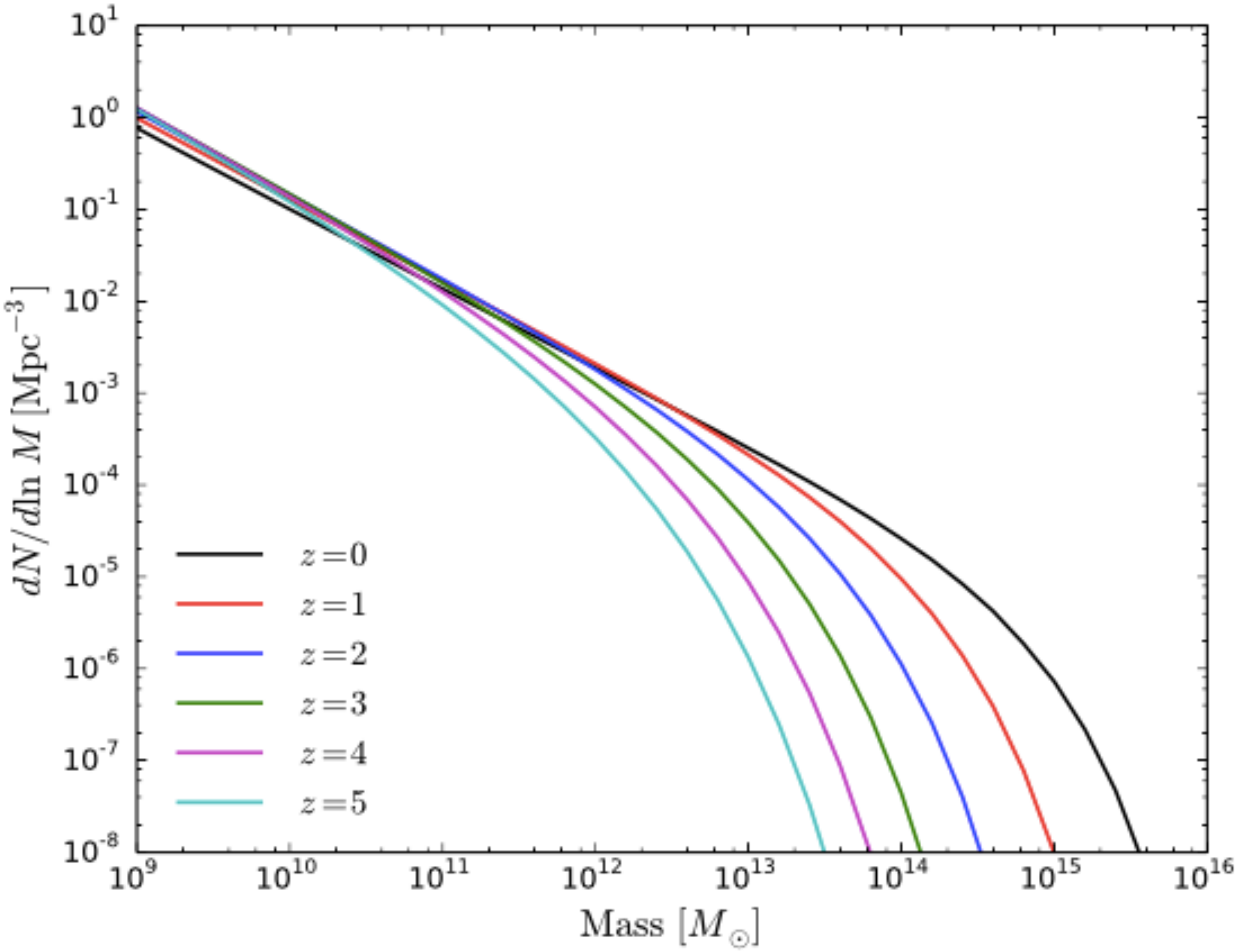
$$Q_{cr,gms} \sim 3.2\times10^{44} \text{ erg Mpc}^{-3}\text{ yr}^{-1} \times \xi_{cr,-1} \overline{E}_{gms,58.5} \mathcal{R}_{gms,-4}$$

But : galaxy mergers are only an* intermediate *step in a continuum process:

- DM halos collapsing out of Hubble flow→virialize
- Baryons (gas) collapse inside the virialized halos →galaxies: stars + ISM
- Smaller DM halos merge → baryonic galaxies merge →shocks in galactic ISM
- Larger DM halos→Clusters: multiple galaxies + IGM
- Cluster-Cluster IGM shock + galaxy-galaxy ISM shocks

CC Yuan, P. Mészáros, K. Murase, D. Jeong, 2018, ApJ 857:50

LSS formation (cont.)



- DM halo mass function dN/d lnM , e.g. from N-body simulations and ← Seth- Tormen'97 fit
- This halo mass function i.e. number of halos per unit comoving volume within log. mass interval d lnM can be analytically approximated using Press & Schechter '74

$$\frac{dN}{d\ln M} = \frac{\bar{\rho}}{M} f(\nu) \frac{d\ln\sigma_M^{-1}}{d\ln M}$$

Diffusion time & neutrino production in ***galaxy mergers:***

Diffusion coefficient in magnetic field - large and small angle scattering :

where $D=D_c\,[\,(\varepsilon/\varepsilon_c)^{1/2}+(\varepsilon/\varepsilon_c)^2\,]$; with $D_c=c\, r_L(\varepsilon_{c,g})/4$, $r_L(\varepsilon_{c,g})=l_c/5$

and r_L =Larmor radius, B~30 μG, l_c= B-field coherence length~30 pc,

so

$$t_{\rm diff} \simeq 3.2\times10^5\ {\rm yr}\ \left(\frac{h(z)}{3\ {\rm kpc}}\right)^2 \left[(\varepsilon/\varepsilon_c)^{1/2}+(\varepsilon/\varepsilon_c)^2\right]^{-1}$$

where $\varepsilon_c \simeq 1.7\times10^9\ {\rm GeV}\ \left(\frac{h(z)}{3\ {\rm kpc}}\right)\left(\frac{B_g}{30\ \mu G}\right)$

and taking $B_g^2R_g^3 \propto GM_g^2/R_g$, i.e. $B_g\propto\rho_gR_g\propto g(z)R_g(z)$.

get, for galaxy mergers:

$$\boxed{f_{pp}^g = \kappa_{pp}cg(z)n_{g,0}\sigma_{pp}{\rm min}[t_{\rm dyn},t_{\rm diff}] \simeq 0.24\ g(z)\left(\frac{n_{g,0}}{1\ {\rm cm}^{-3}}\right)\left(\frac{\sigma_{pp}}{50\ {\rm mb}}\right)\left(\frac{{\rm min}[t_{\rm dyn},t_{\rm diff}]}{10\ {\rm Myr}}\right)}$$

i.e. → calorimetric for z≳ 1 gal. mergers

Diffusion & neutrino prod. in
galaxy halo and the host gal. cluster

$$t_{\rm diff} = R_{\rm cl}(z)^2/(6D_{\rm cl}) \qquad B_{\rm cl,0} \approx 1 \ \mu G \qquad l_{c,\rm cl} \approx 30 \ \rm kpc.$$

$$\varepsilon_{p,\rm cl} \approx 5.6 \times 10^9 \ \rm GeV$$

cluster of mass $10^{15} M_\odot$, $R_{\rm cl,0} = (3M/(4\pi\rho_{cl,0}))^{1/3} \approx 2.1 \ \rm Mpc.$

$$R_{\rm cl} \propto (1+z)^{-(3-\gamma)/\gamma} \qquad B_{\rm cl} \propto \rho_{\rm cl} R_{\rm cl} \propto g(z) R_{\rm cl}(z).$$

and with CR injection time $t_{\rm inj}$ ~ $t_{\rm age}$(cluster), have

$$f_{pp}^{\rm cl} = \kappa_{pp} c g(z) n_{\rm cl,0} \sigma_{pp} \min[t_{\rm inj}, t_{\rm diff,cl}] \simeq 0.24 \quad g(z) \left(\frac{n_{\rm cl,0}}{10^{-3}\ \rm cm^{-3}}\right) \left(\frac{\sigma_{pp}}{50\ \rm mb}\right) \left(\frac{\min[t_{\rm age}, t_{\rm diff}]}{10\ \rm Gyr}\right)$$

and, for lower z have also *Cluster-Cluster mergers*

→ get formally similar $f_{pp}^{\mathrm{cl\text{-}cl}}$, with comparable numbers

- Take Cl-Cl mergers ocurring for $M_{\mathrm{cl}} \gtrsim 10^{13}\, M_\odot$ (=“HM”)

The combined all-flavor **neutrino production rate** is then

$$\varepsilon_\nu Q^{(\mathrm{g})}_{\varepsilon_\nu} = \frac{1}{2}(1-e^{-f^{g}_{pp}})\varepsilon_p Q^{(\mathrm{LM})}_{\varepsilon_p}$$

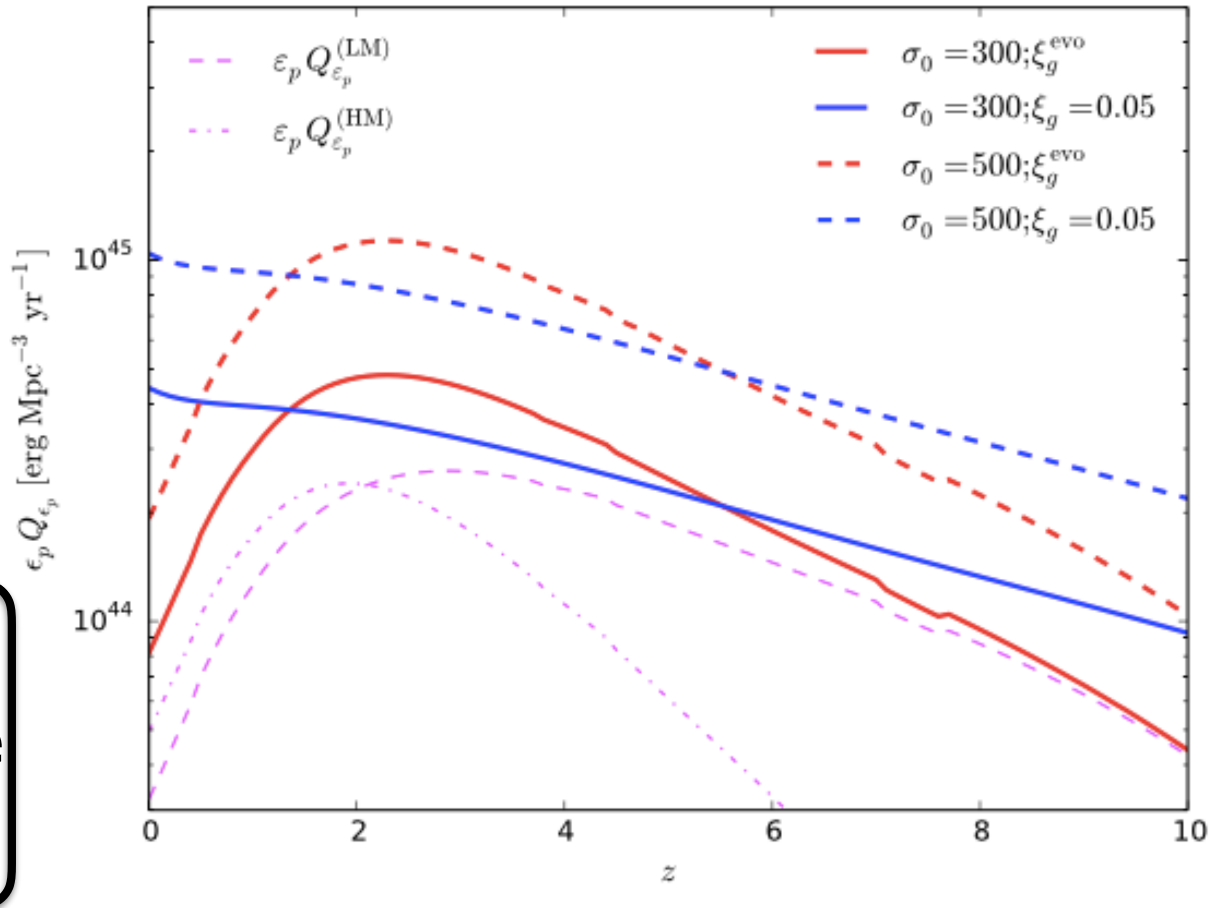
$$\varepsilon_\nu Q^{(\mathrm{cl})}_{\varepsilon_\nu} = \frac{1}{2}[(1-e^{-f^{\mathrm{cl}}_{pp}})\varepsilon_p Q^{(\mathrm{HM})}_{\varepsilon_p} + \eta(1-e^{-f^{\mathrm{cl}}_{pp}})e^{-f^{\mathrm{g}}_{pp}}\varepsilon_p Q^{(\mathrm{LM})}_{\varepsilon_p}]$$

The 1st term (gal-gal mergers) and 2nd term (cl-cl mergers) **dominate**; 3d term (w. $\eta \lesssim 0.1$-0.2, gal-gal CRs escaping to cl.), is **sub-dominant**, essentially because f_{pp}^{g} (~**calorimetric**) > f_{pp}^{cl}

Thus,

Local CR input rate as fcn (z) →

& the resulting ν, γ are seen after they propagate through cosmic space↓



$$\varepsilon_\nu^2 \Phi_{\varepsilon_\nu} = \frac{c}{4\pi} \int \frac{\varepsilon_\nu Q^{(\mathrm{g})}_{\varepsilon_\nu} + \varepsilon_\nu Q^{(\mathrm{cl})}_{\varepsilon_\nu}}{(1+z)} \left| \frac{dt}{dz} \right| dz$$

$$\varepsilon_\gamma^2 \Phi_{\varepsilon_\gamma} = \frac{c}{4\pi} \int \frac{2}{3} \left[\frac{\varepsilon_\nu Q^{(\mathrm{g})}_{\varepsilon_\nu} + \varepsilon_\nu Q^{(\mathrm{cl})}_{\varepsilon_\nu}}{(1+z)} \left| \frac{dt}{dz} \right| \right] \times \exp[-\tau_{\gamma\gamma}(\varepsilon_\gamma, z)] dz$$

and for γ-rays, additional

The locally produced γ-rays are ***degraded*** via **γγ** interactions with infrared ***EBL*** photons

→γ cascades to ***lower energies***
→ universal final spectrum

$$\varepsilon_\gamma \frac{dN}{d\varepsilon_\gamma} \propto G(\varepsilon_\gamma) = \begin{cases} \left(\frac{\varepsilon_\gamma}{\varepsilon_\gamma^{\rm br}}\right)^{-1/2} & \varepsilon_\gamma \le \varepsilon_\gamma^{\rm br} \\ \left(\frac{\varepsilon_\gamma}{\varepsilon_\gamma^{\rm cut}}\right)^{-1} & \varepsilon_\gamma^{\rm br} < \varepsilon_\gamma < \varepsilon_\gamma^{\rm cut} \end{cases}$$

where $\varepsilon_\gamma^{\rm cut}$ is defined by $\tau_\gamma(\varepsilon_\gamma^{\rm cut}, z) = 1$ and $\varepsilon_\gamma^{\rm br} = 0.0085\ {\rm GeV}(1+z)^2 \left(\frac{\varepsilon_\gamma^{\rm cut}}{100{\rm GeV}}\right)^2$.

Calculated ν and γ bkgs.

✔

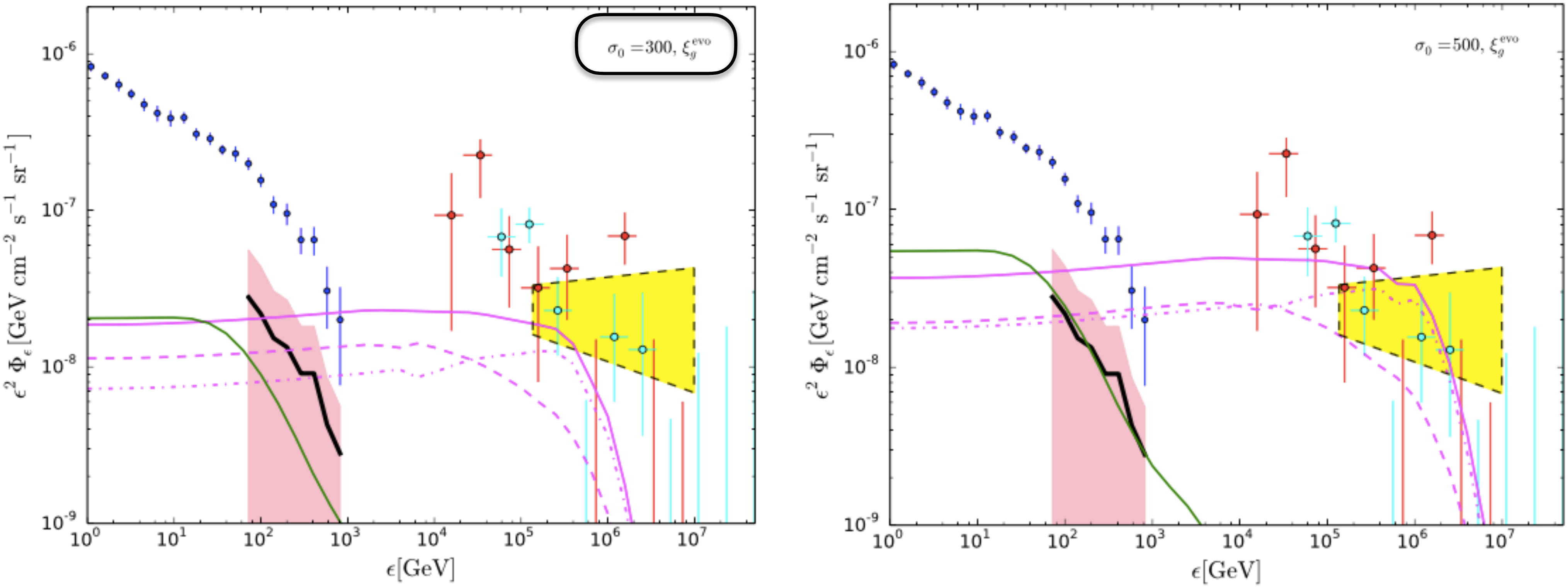


Figure 4. Left panel: Neutrino (all flavor) and γ-ray fluxes from halo mergers with redshift-evolving gas fraction $\xi_g^{\rm evo}$, $R_{g,0} =$ 10 kpc, $H_{g,0} = 500$ pc. The shock velocity is obtained using $r_0^{\rm sc}(z)$ and $\sigma_0 = 300$. The magenta line is the neutrino spectrum while the green line is the corresponding γ-ray spectrum. Galaxy and cluster contributions to the neutrino flux are illustrated as the dashed and dash-dotted lines, respectively. Right panel: same as left panel except $\sigma_0 = 500$ is utilized for v_s.

Both ν and ϒ fits are OK ✔

ChengChao Yuan, P. Mészáros, K. Murase, D. Jeong, 2018, ApJ 857:50

Dependence on CR spectrum

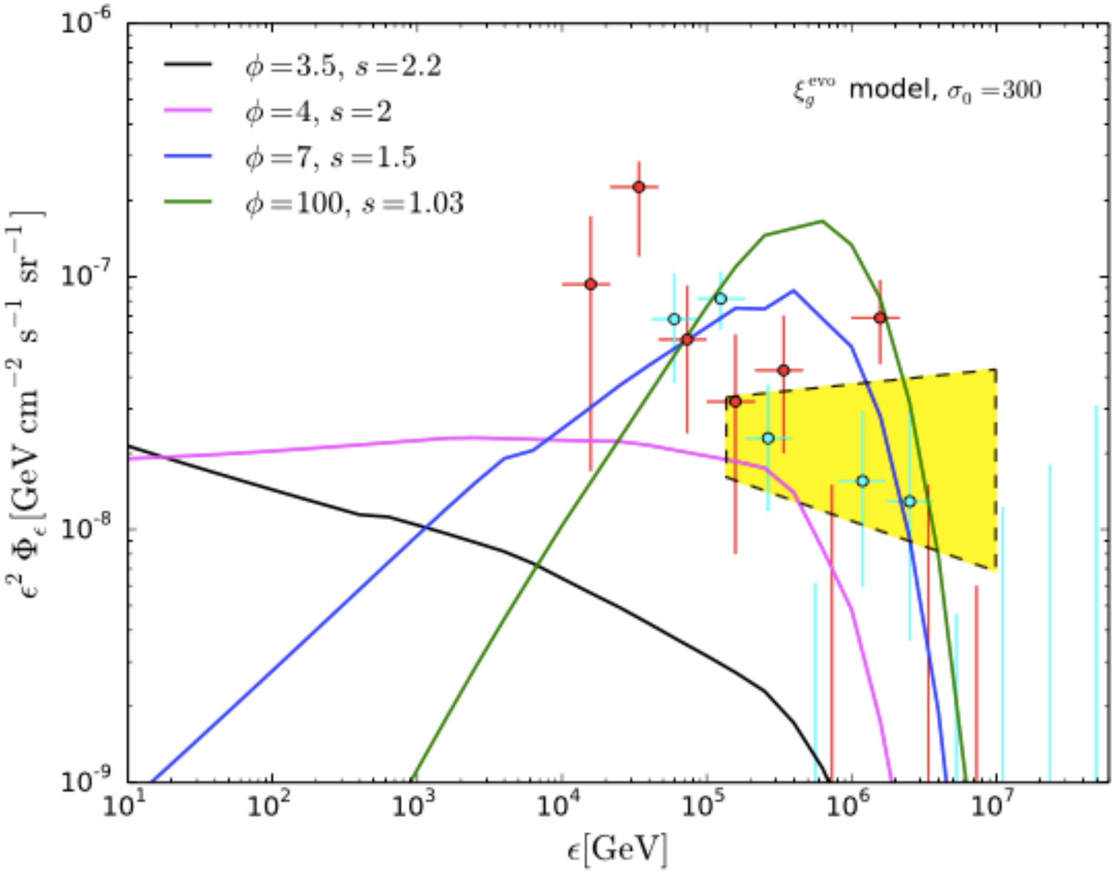


Figure 6. The neutrino fluxes for different compression ratios and CR power-law indices. The black, magenta, blue and greens lines correspond to the power-law indices $s = 2.2,\ 2.0,\ 1.5$ and 1.03.

- Adiabatic shock: expect index s=2
- But radiative shocks, expect s=(r+2)/(r-1), r=compression ratio,
  →harder CR spectra
  →harder ν-spectra
- γ-ray sp. unchanged (γγ-cascade leads to universal spectrum) ✔
- could accomodate slopes s~2 or s~1.5 ✔

Overall Conclusions for INB-IGB

- There are at least ***three*** possible (non-exclusive) contributors to the ***IceCube INB*** & the ***Fermi IGB***
- One are ***LLGRBs*** (they act as "hidden sources")
- Another is ***HNe/SNe*** (they are "hidden" if their strongest contribution is at ***high z***)
- A third is ***galaxy & cluster mergers*** across redshifts
- **However**: there is one blazar TXS 0506+056 with a modest confidence ν-γ flare coincidence! May need to revisit the ***lack*** of global blazar EM-nu correlations (?)

Aside from the INB / IGB issue,

Can we expect any νs from short GRBs (SGRBs)?

Highly relevant,
in view of GW/GRB170817,
a confirmed multimessenger source !

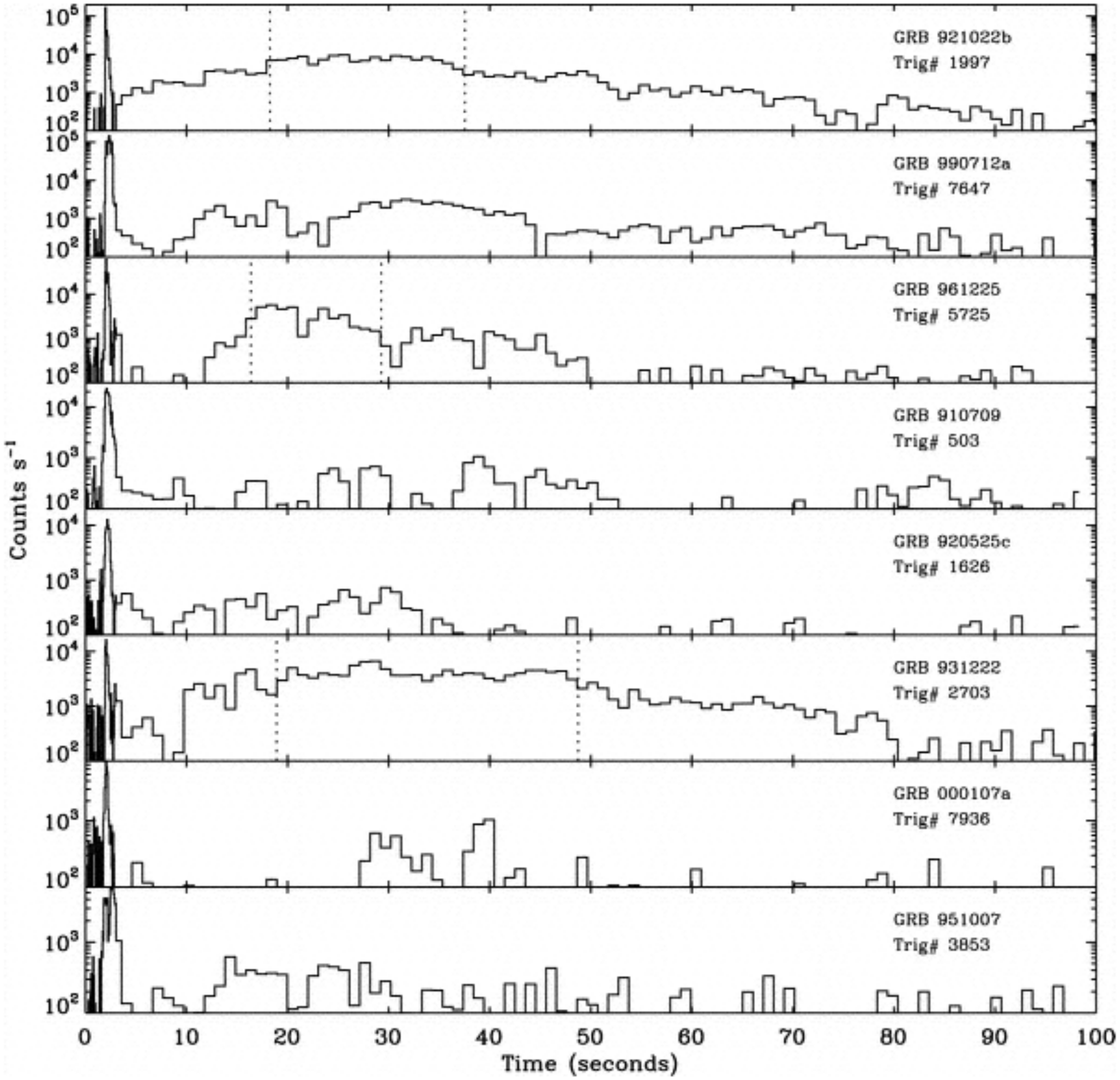
Observed VHE neutrinos apparently **do not** come from ***Classical GRBs***

- IceCube finds that <1% of the EM-observed "classical" long, bright GRBs can be contributing to this observed neutrino flux (time/direction)
- This tests for neutrinos in close time/direction coincidence with ***prompt*** (main) jet MeV gammas
- But these are mostly **long GRBs** from ccSNe; and **short GRB**s (BNS) are much **fainter;** not surprisingly,

➡ **These neutrinos DO NOT come from SGRB PROMPT emissions either !**

However:

SGRB are ***not*** always “**short**”!



Norris+06, ApJ 643:266

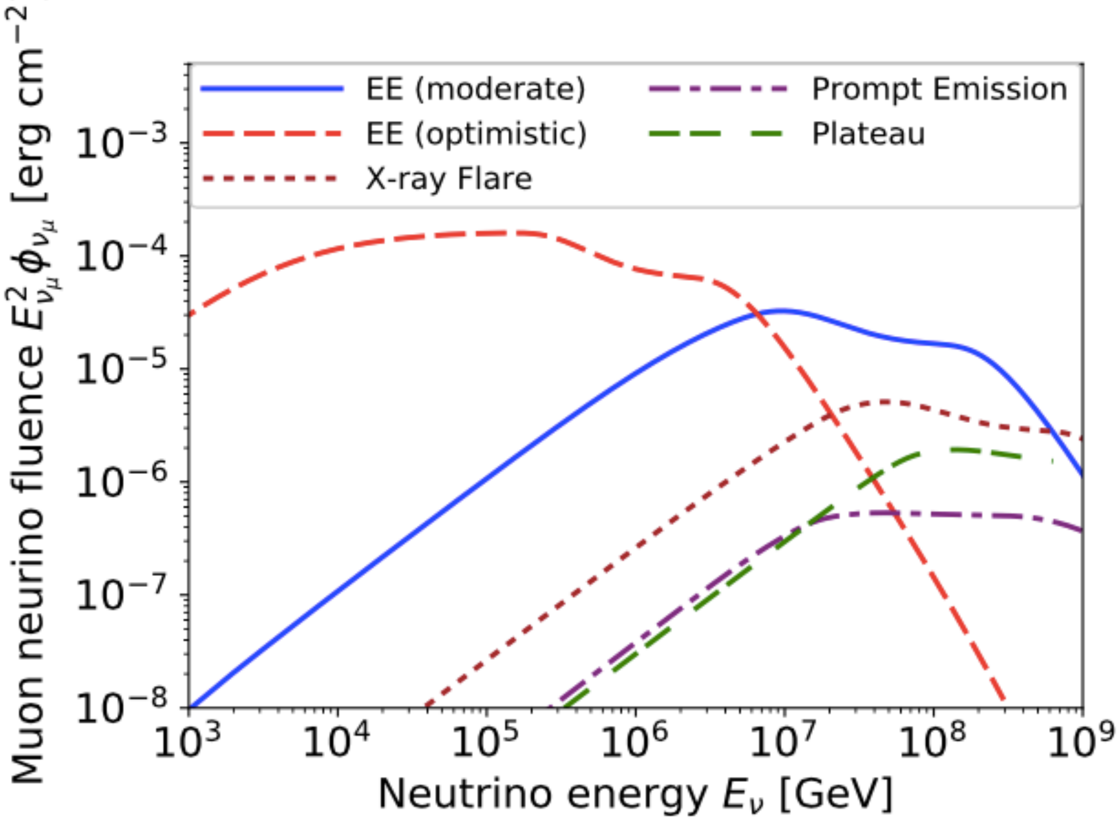
in 30-50% of cases:

- ***Extended*** emission (EE) in 30-50% cases
- EE spectrum is ***softer*** than that of the “prompt”
- Prompt: E~1-3 MeV
- Ext’d: E~ 30-60 KeV
- $\Delta t_{EE} \sim\leq 10^2$ s

calculate now BNS Merger
Neutrino light curves

including also ***delayed*** components

e.g. SGRB extended emission (EE), etc



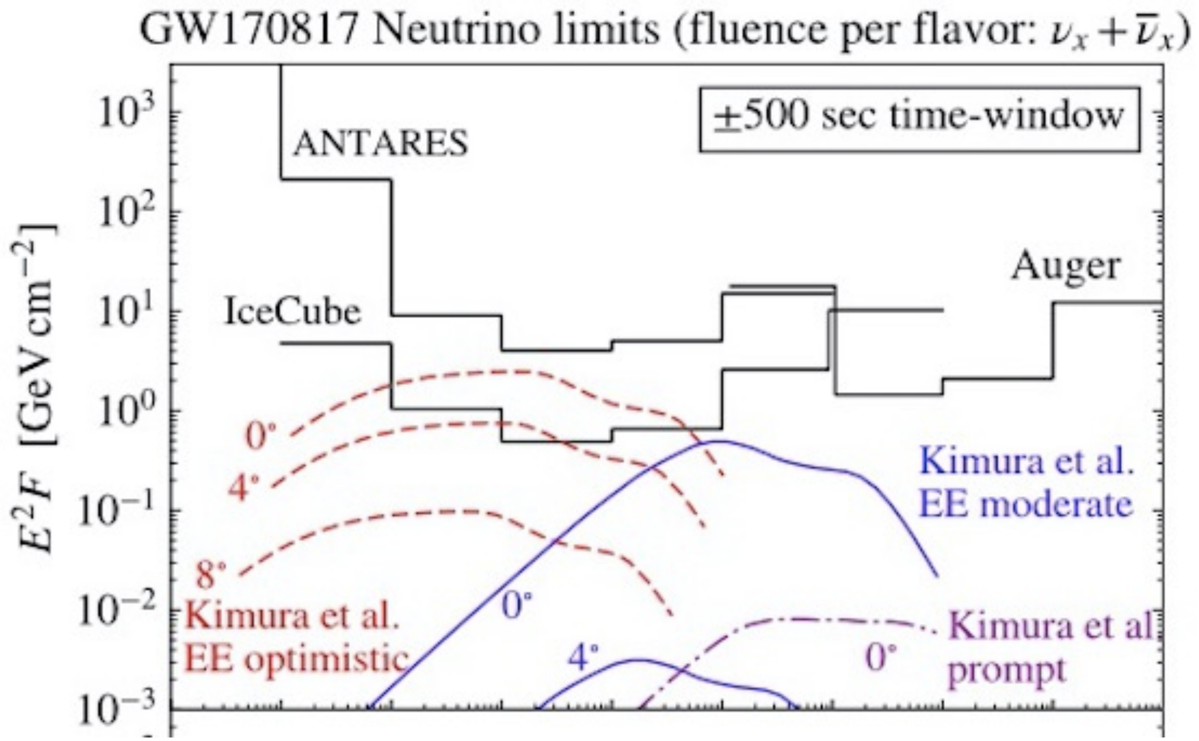
Neutrino fluence from *on-axis* SGRB for EE-mod, EE-opt, prompt, flare & plateau component @ d_L=200 Mpc (e.g. aLIGO)

Kimura, Murase, Mészáros & Kiuchi, 2017, ApJL, 848:L4

ν-dominance of BNS EE:

- Caused by ***lower*** Γ, ***higher baryon*** load
- ⇒ ***higher photon*** density and ***shorter*** $\boldsymbol{t_{p\gamma}}$
- →***higher B***-field, stronger ***pion cooling***
- →***lower*** pion cooling break, TeV-PeV spectra
- ***Still***, fluence ***low*** for IC3, unless ***very*** nearby

IceCube, Antares, Auger ν-limits on GW170817:



- GW indicates off-axis jet, $\theta_{obs} \in [0°, 36°]$,
- Kimura et al. models for Doppler factor at various θ_{obs}-θ_j offset
- No detection (OK, ✔)

Antares, IceCube, Auger, LIGO-Virgo coll, 2017, ApJ 850:L35

Det. Prob.(≥k events)

Det.Prob(≥1 event) vs. d$_L$

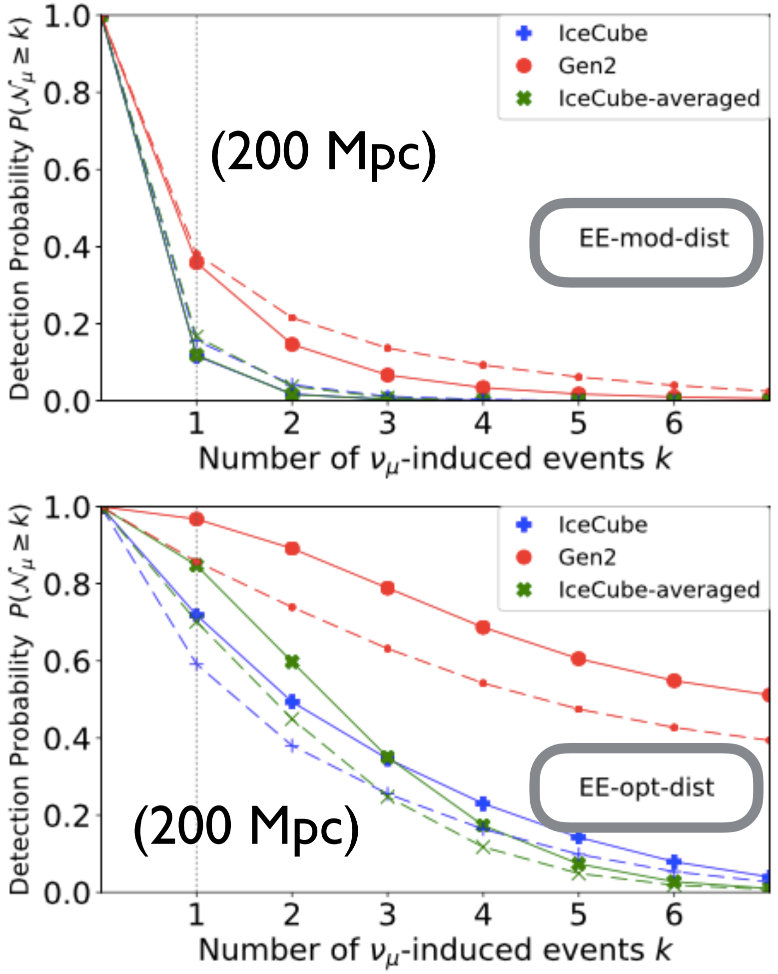


Figure 2. The detection probability $P(\mathcal{N}_\mu \geq k)$ for d_L = 200 Mpc. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The solid and dashed lines are for the cases with $\sigma_\Gamma = 2$ and $\sigma_\Gamma = 4$, respectively. The vertical thin-dotted line shows $\mathcal{N}_\mu = 1$.

(IceCube-averaged includes down-going events)

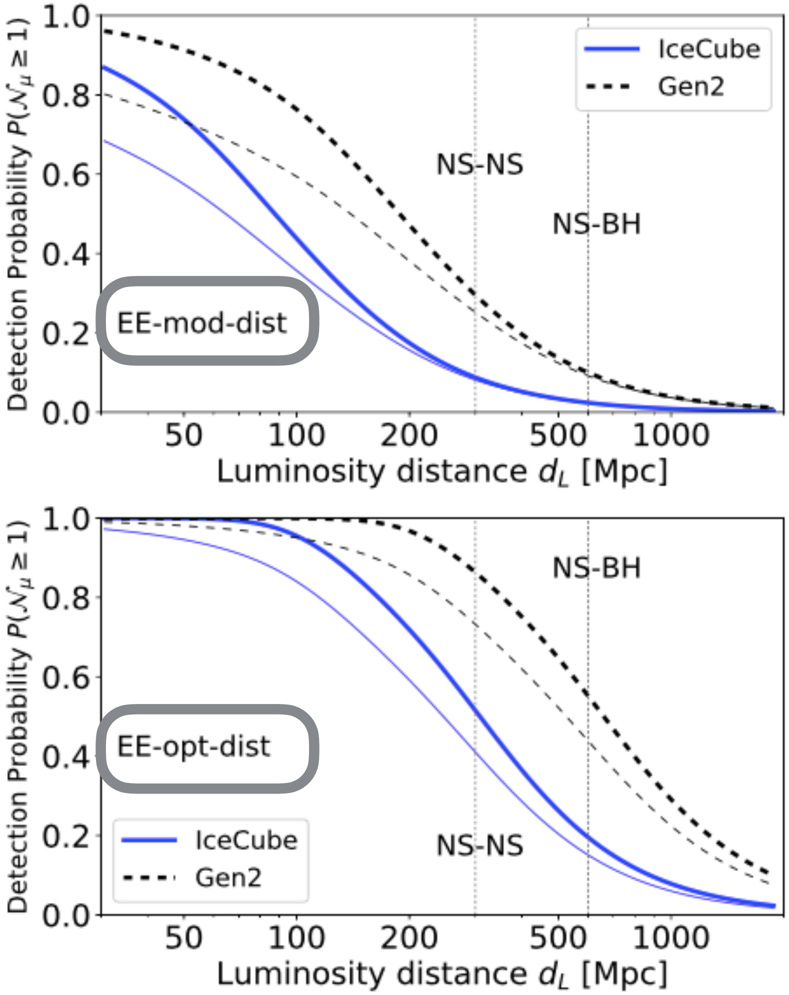


Figure 3. The detection probability $P(\mathcal{N}_\mu \geq 1)$ as a function of luminosity distance d_L. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The thick and thin lines are for the cases with $\sigma_\Gamma = 2$ and $\sigma_\Gamma = 4$, respectively. The vertical thin-dotted lines show $d_L = 300$ Mpc and $d_L = 600$ Mpc.

i.e., IC3: maybe - Gen-2: likely

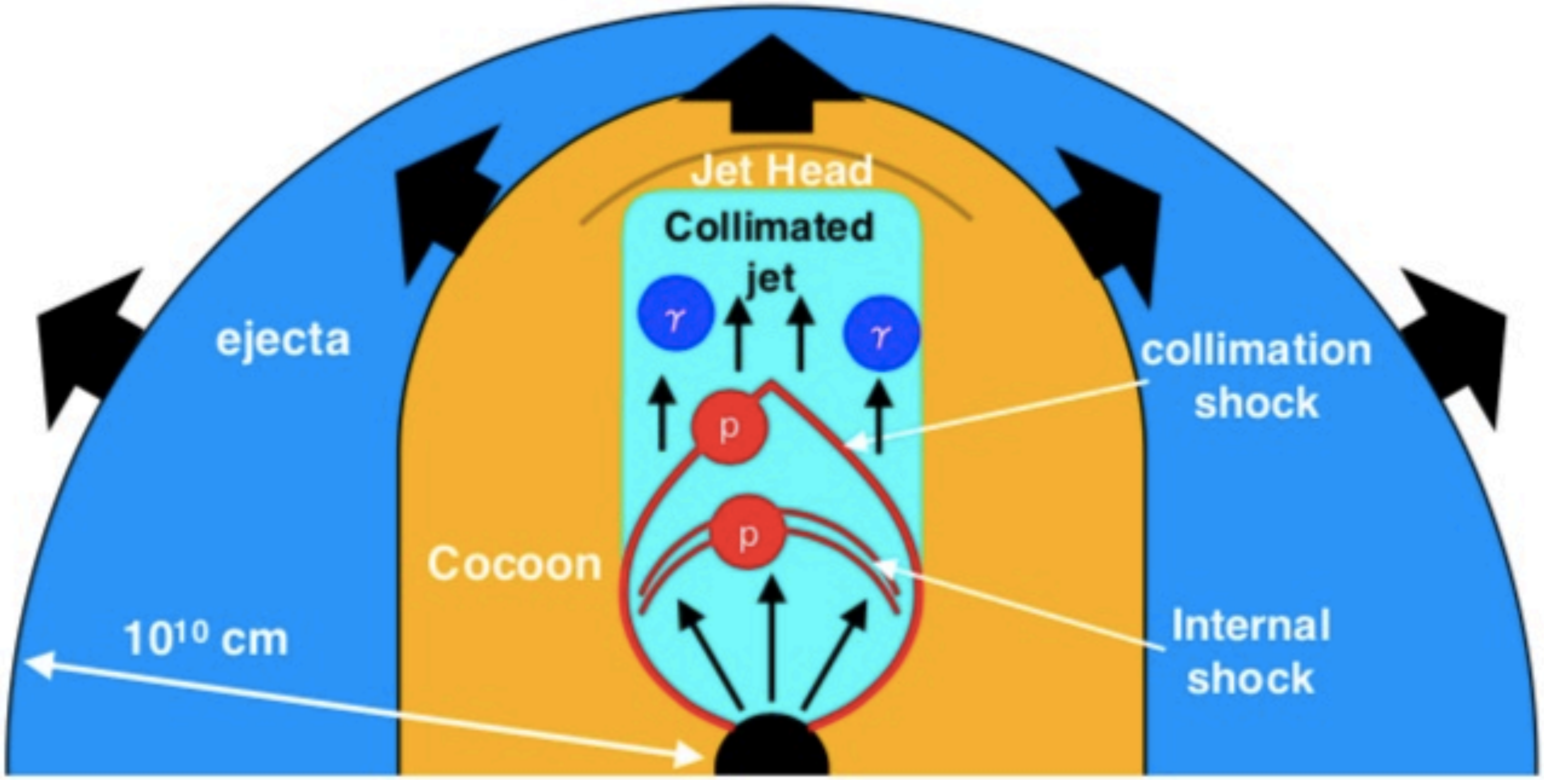
Kimura, Murase, Mészáros & Kiuchi,
2017, ApJL, 848:L4

Another possible HENU mechanism for SGRB :

Jet choked in the merger dynamical ejecta

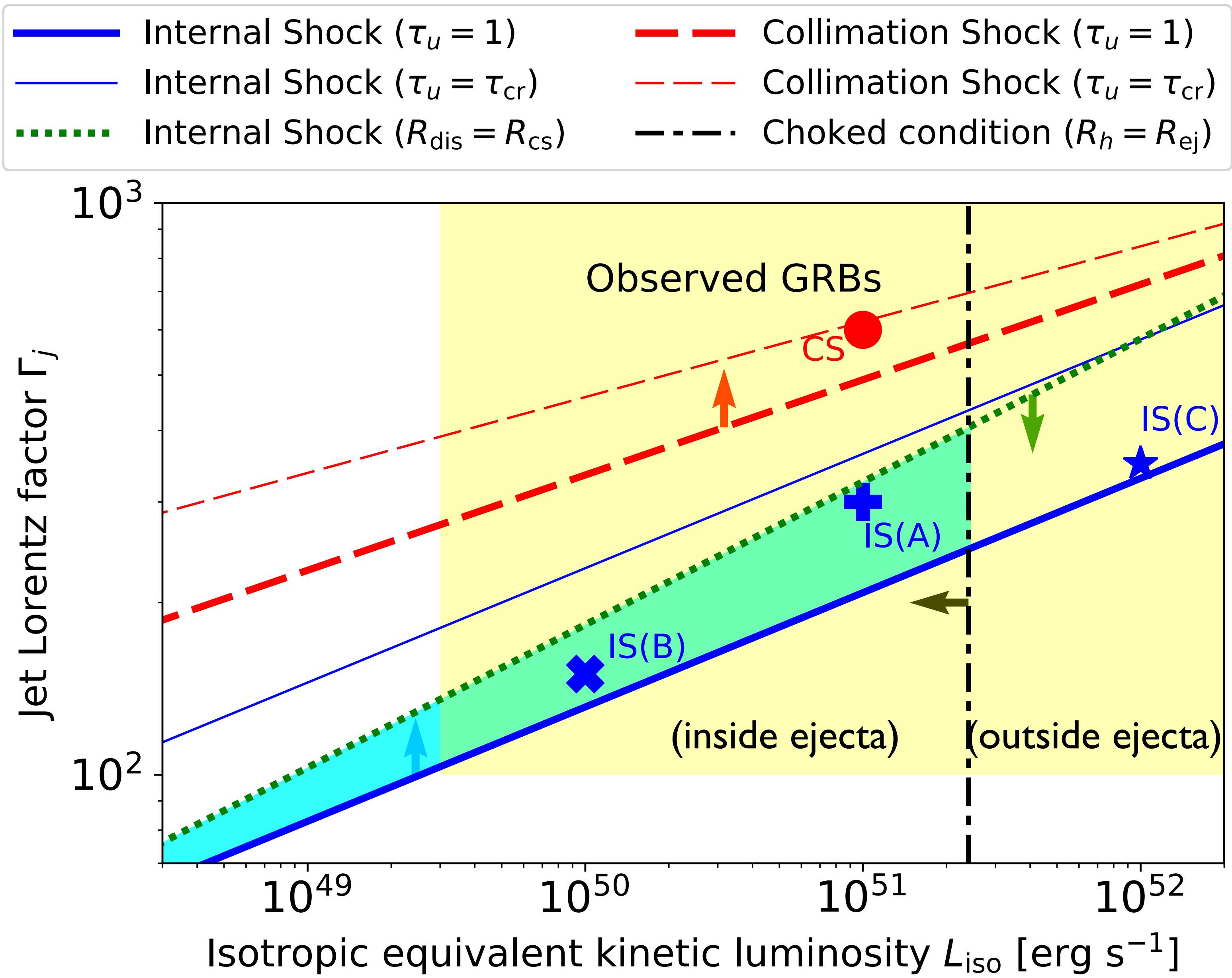
Trans-Ejecta HE Neutrinos

Internal and collimation shocks in BNS jet-cocoons within the dynamical ejecta

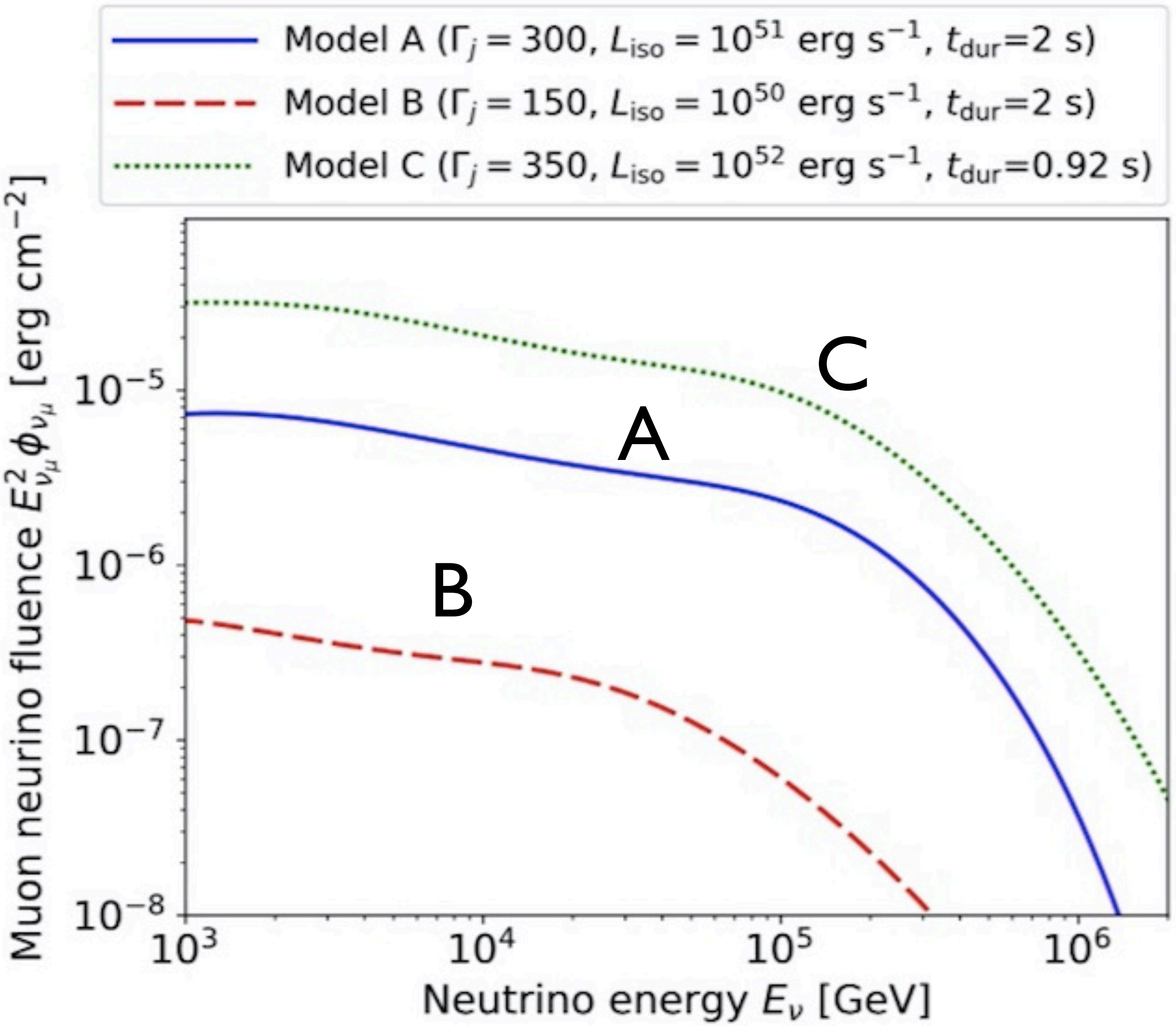


Kimura, Murase, Bartos, Mészáros+18

Allowed parameters for Fermi acceleration by internal & collimation shocks inside ejecta



Spectral nu-flux @ 300 Mpc



Note: Due to strong pion cooling, the initial flavor ratio at source is (0,1,0). After oscillations, using the tri-bimaximal matrix for propagation, the flavor ratio at Earth is (4,7,7), so nue/numu ~1/2. Also, the IceCube eff. area for cascades is lower than for tracks at this energy, so here we neglected nue fluence

Detection probability

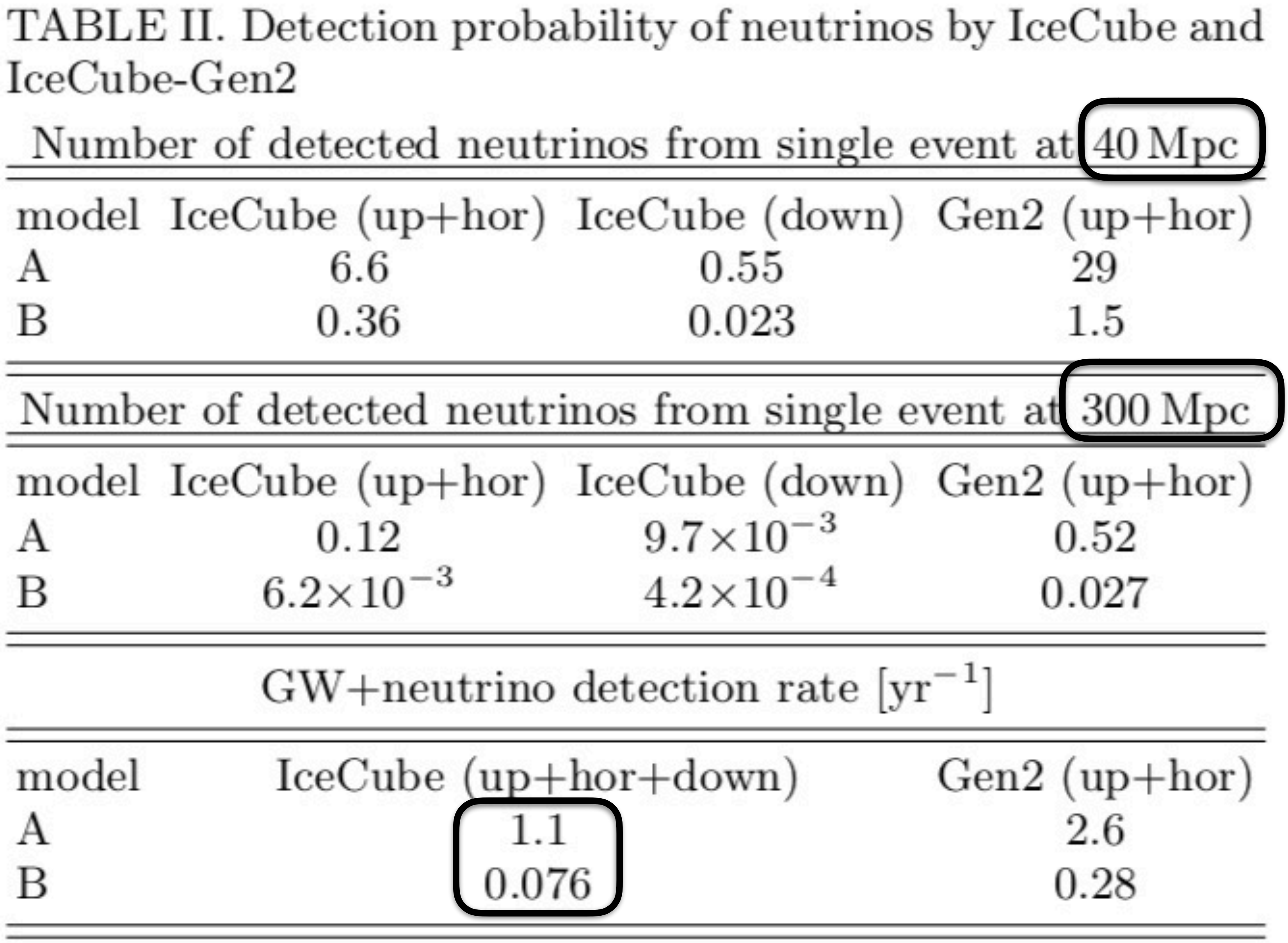


TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

Number of detected neutrinos from single event at 40 Mpc

model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A	6.6	0.55	29
B	0.36	0.023	1.5

Number of detected neutrinos from single event at 300 Mpc

model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]

model	IceCube (up+hor+down)	Gen2 (up+hor)
A	1.1	2.6
B	0.076	0.28

possible ↗ (?)

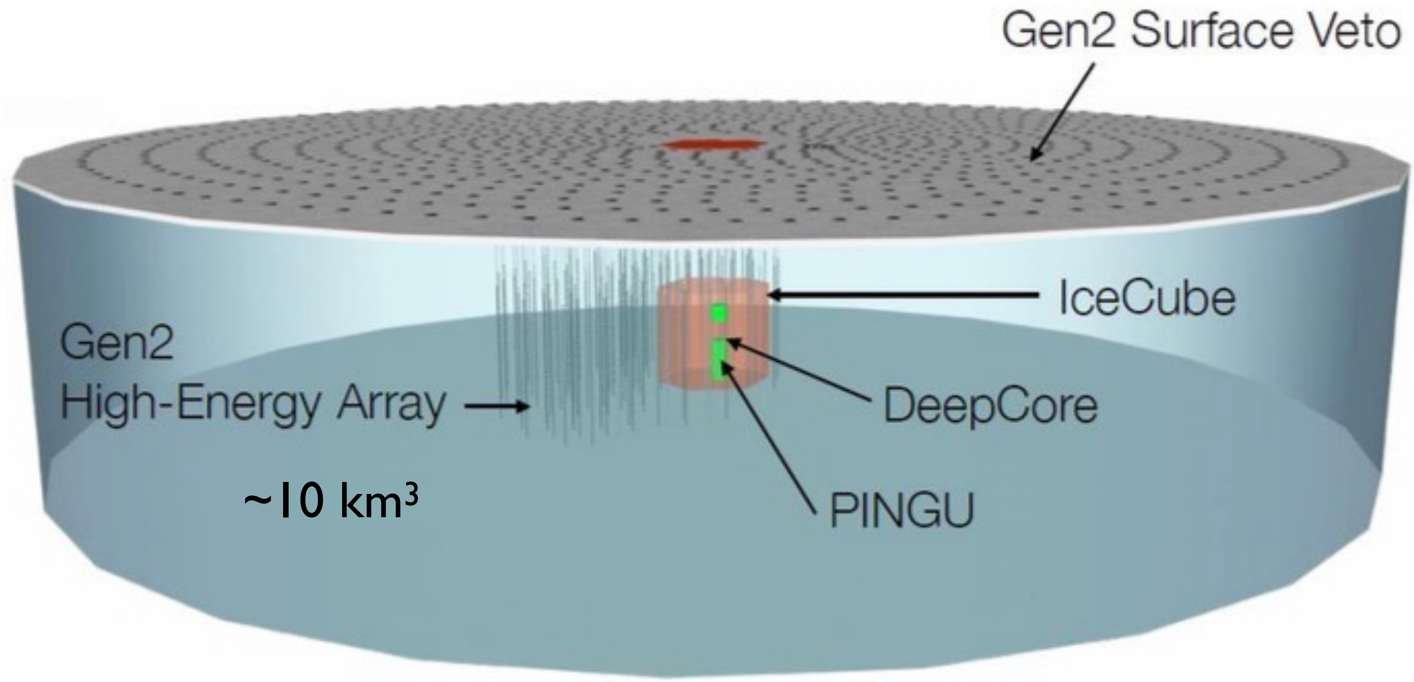
Kimura, Murase, Bartos, Mészáros+18

21th Century: Multi-Messenger Era

(slide: K. Ioka)

Thanks!

IceCube Gen-2



(Spiering 2017)

Figure 12: Schematic view of IceCube Gen-2, comprising the existing IceCube array with its densely equipped inner region DeepCore, the high-energy array of Gen2, the super-densely equipped PINGU sub-detector, and an extended surface array. Not shown is the radio array ARA with its size exceeding that of the basic surface array.

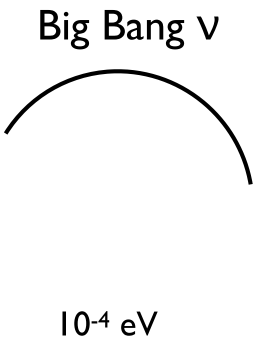
IC3-Gen2: may hope for nearby off-axis GW/sGRB ν-detection

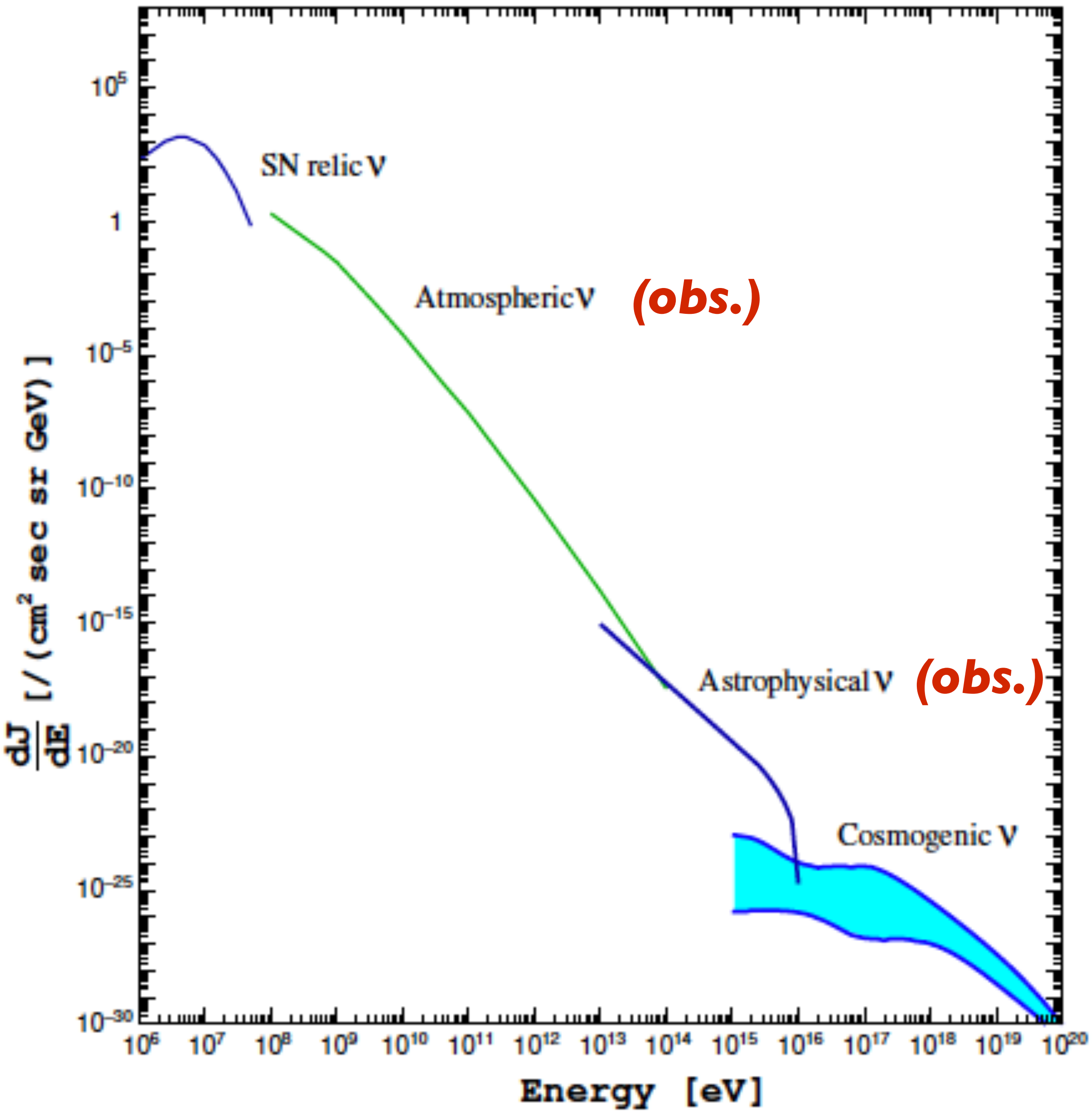
Conclusions for mergers

- $\gtrsim$ 50% of the IceCube neutrino bkg. could be produced by LSS (cluster, galaxy) mergers, with ~ the right ν-spectrum.
- Can do this without violating the 14% of non-blazar diffuse γ-ray spectrum observed by Fermi
- Reduced γ-background is because most contributions come from high-z, where τ_{pp} and $\tau_{\gamma\gamma}$ both larger
- Could also acommodate steeper slopes of s~1.5 resulting from, e.g., cooling shocks
- But any greater merger contribution to the ν-bkg. would violate the Fermi allowed non-blazar γ-bkg. (might the rest be blazars?)
- A possible feature (hump) at ~30 TeV remains unexplained - for this may require an extra component.

In broader context:

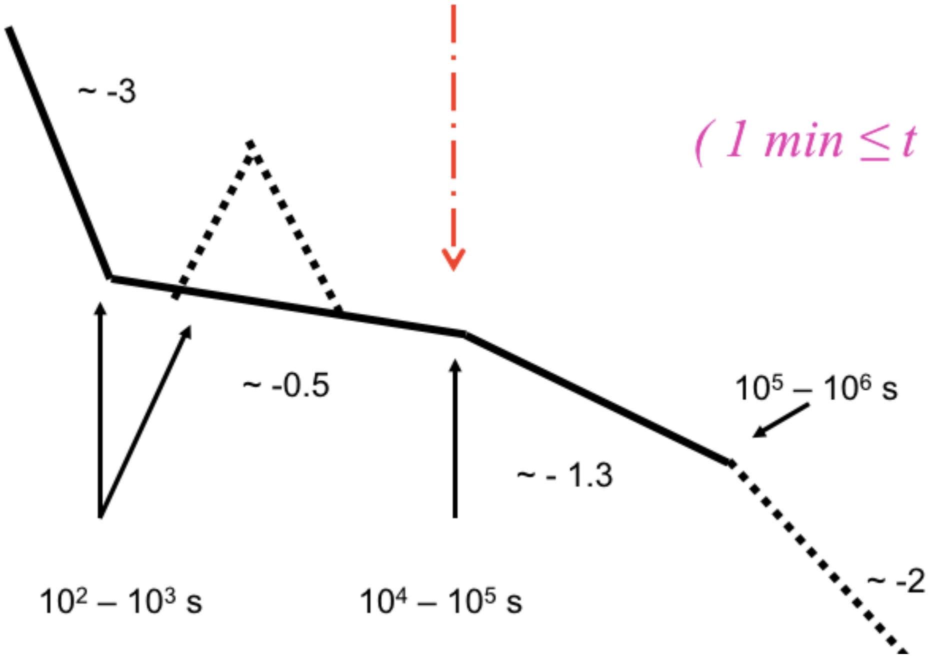
Other neutrino backgrounds:





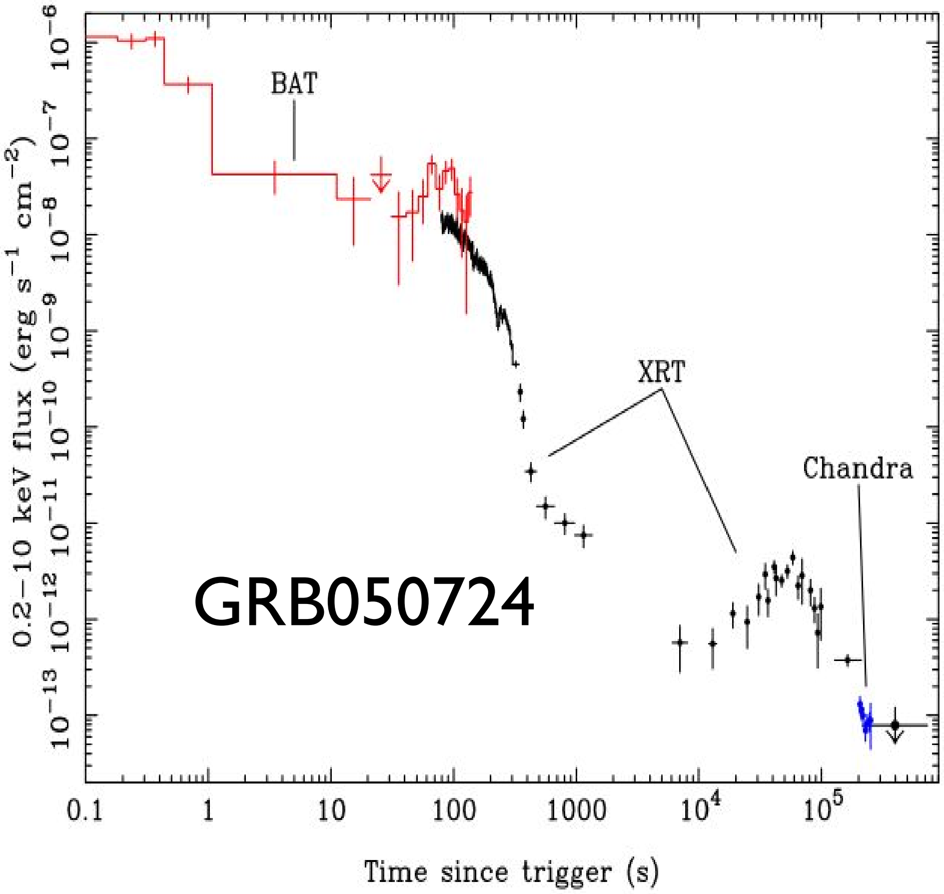
And even later, afterglow

show ***plateau*** (<10^5 s) & ***flares***



Plateau, flares

(1 min ≤ t ≤



First:

Pop. I/II SNe/HNe (only)

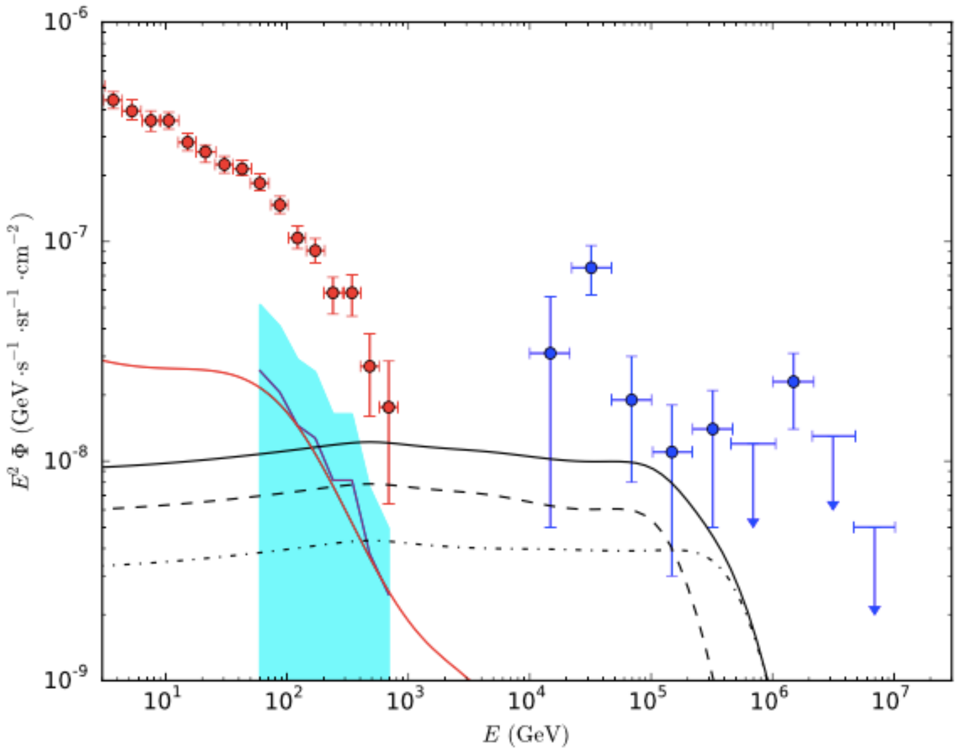
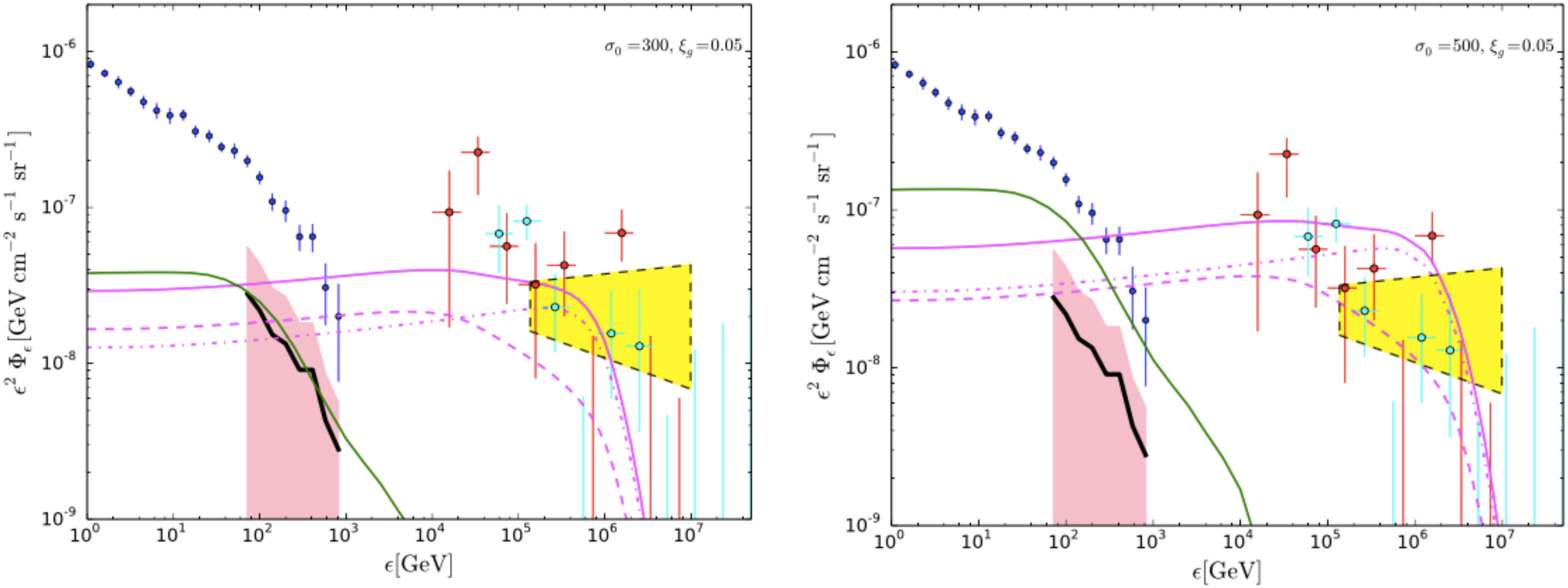


FIG. 1.— Combined fit of diffuse neutrino flux and gamma-ray flux for the case $\alpha = -1$ for the conventional case. The IceCube neutrino and the Fermi-LAT extragalactic gamma-ray background observations are shown by blue and red data points respectively (Ackermann et al. 2015; Aartsen et al. 2015). 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.

- Low redshift only, $z \leq 4$ SNe & HNe
- Nominal kin. en., CR effic., $B_{\rm ext}$, $n_{\rm ext}$
- In order to fit the non-blazar IGB (14% of total Fermi EGB), cannot produce more than 50% of the observed INB

Xiao+16, ApJ 826:133

No evolution, ξ_g=0.05 case



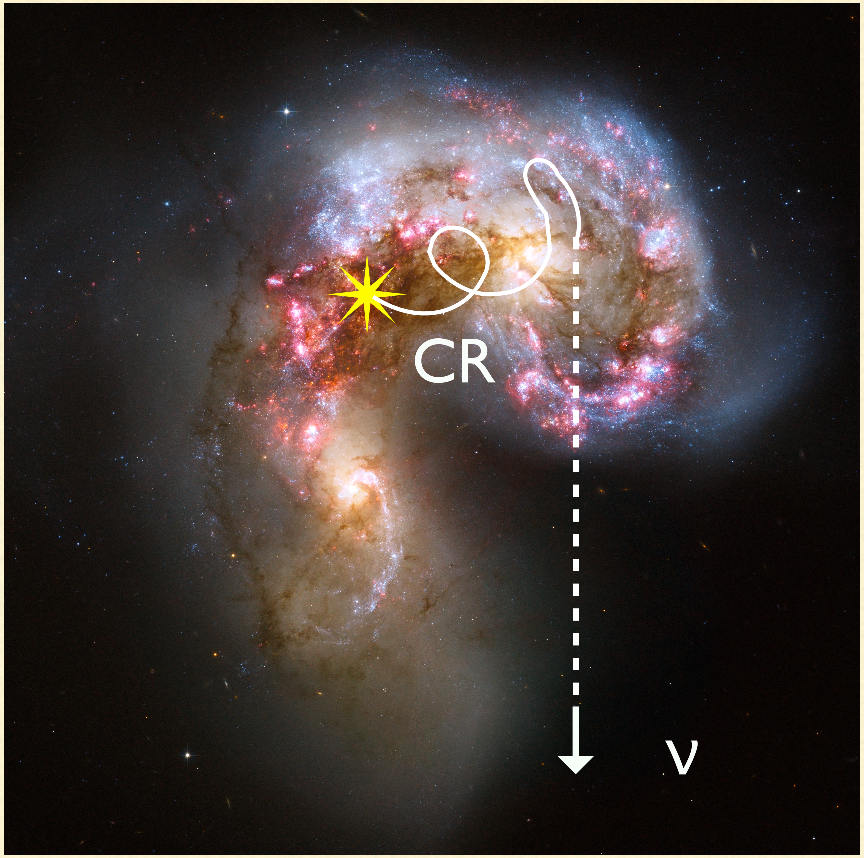
Overproduce γ-bkg !

Figure 5. Left panel: same as Fig. 4 (a), $\sigma_0 = 300$, except that $\xi_g = 0.05$ is used to estimate the redshift evolution of the halo gas fraction. Right panel: same as left figure except with $\sigma_0 = 500$.

ChengChao Yuan, P. Mészáros, K. Murase, D. Jeong, 2018, ApJ 857:50

CR

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:

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

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

- Compare with typical Milky Way Galaxy:

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

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

Galaxy mergers

- Mergers happen, they are a fact of life
- The gas components must undergo a strong shock
- Shock →particles Fermi accelerated →CRs
- Dense gas →ample targets for pp

Shock CR acceleration in gal. merg. shock

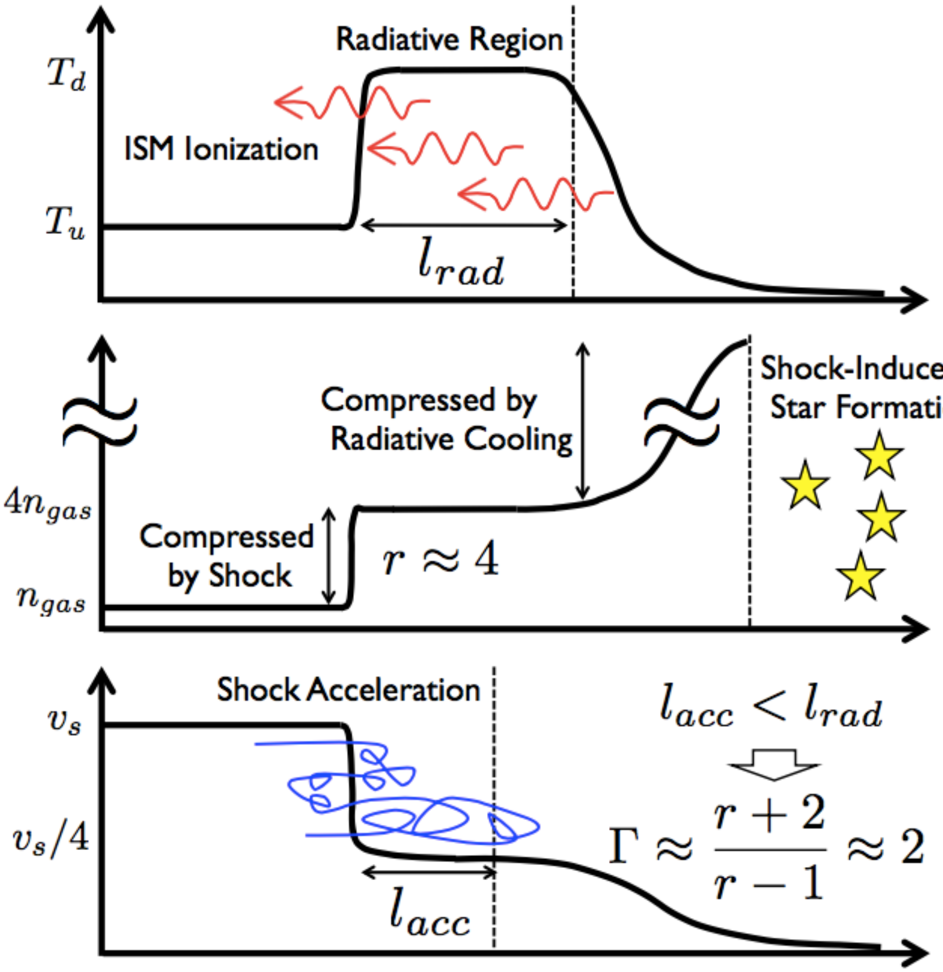


FIG. 1.— The schematic picture of GMS and the DSA in-situ; temperature (top), density (middle), and velocity in the shock rest frame (bottom).

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

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

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

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

$l_{acc} < l_{rad}$ → $M \gg 1$, $r \sim 4$
i.e. strong shock

$$\longrightarrow \varepsilon_{cr,max} \approx \eta ZeBR_{gal}v_s/c,$$

Kashiyama & Mészáros '14,
ApJL 790:L14

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

Conclusions : hidden sources

- At least ***two*** possible interpretations for the ***IceCube INB*** & the ***Fermi IGB***
- ***One*** is ***HNe/SNe*** (they are “hidden” if their strongest contribution is at ***high z***)
- ***Another*** are ***LLGRBs*** (act as “hidden sources”)
- ***And,*** can argue that they ***cannot be blazars*** (they would not be “hidden”; low optical depth)

Press-Schechter approximation

Number N of halos of mass M at redshift z is:

$$\frac{dN}{d\ln M} = \frac{\bar{\rho}}{M} f(\nu) \frac{d\ln \sigma_M^{-1}}{d\ln M}$$

where $\bar{\rho} = \Omega_{m,0}\rho_{c,0},$

$\rho_{c,0} = 3H_0^2/(8\pi G)$
= critical density

$$\sigma_M^2 = \int \frac{k^2 dk}{2\pi^2} P(k) |\hat{W}(kR)|^2$$

(variance of power spectrum)

$P(k) \sim k^n \sim (2\pi/\lambda)^n$ = matter power spectrum ($\lambda = \lambda[M]$)

$\hat{W}(kR) = 3j_1(kR)/kR$ top-hat filter function, $R = \left(\frac{3M}{4\pi\bar{\rho}}\right)^{1/3}$

$\delta = \delta\rho / \bar{\rho}$ $\delta_{c,0} \approx 1.686.$ $\nu = \delta_c/\sigma_M$

Growth of density contrast in LCDM:

$$D(z) = \frac{\delta(\boldsymbol{r}, z)}{\delta(\boldsymbol{r}, 0)} \propto \frac{5}{2}\Omega_{m,0}\sqrt{\Omega_{m,0}(1+z)^3 + 1 - \Omega_{m,0}} \times \int_z^\infty \frac{1+z'}{[\Omega_{m,0}(1+z')^3 + 1 - \Omega_{m,0}]^{3/2}} dz'.$$

where $\delta = \delta\rho / \bar{\rho}$ = density contrast

$$\nu = \delta_c / \sigma_M \qquad \delta_{c,0} \approx 1.686.$$ → collapse

and

$$\boxed{f_{S-T}(\nu) = A\sqrt{\frac{2a}{\pi}}\left[1 + (\nu^2 a)^{-p}\right] \nu \exp\left[-\frac{a\nu^2}{2}\right]}$$

Seth-Tormen fit to f(ν), (with A=0.322, a=0.707, p=0.3 fit to num. sim.)

Merger Rate & CR Luminosity

3 relevant timescales for CR luminosity production:

$$t_{\rm age} = \int_z^\infty \left| \frac{dt}{dz'} \right| dz'$$ where $|dt/dz| = 1/[(1+z)H(z)]$

$$t_{\rm dyn} = \lambda \frac{R_g(z)}{v_s(z)}$$ with $R_g(z)$=galaxy radius, $v_s(z)$=shock velocity, $\lambda \sim 1$ is a geometry parameter)

$$t_{\rm merger} = \left[\int d\zeta \frac{dN_m}{dz d\zeta} \left| \frac{dz}{dt} \right| \right]^{-1}$$, where $dN_m/dzd\zeta$ = dimensionless merger rate per unit halo mass ratio ζ

with these,

$$P(M,z) = \exp(-t_{\rm merger}/t_{\rm age})$$ = probability that halo of mass M merges within age of Universe (z)

Comoving CR energy input rate / ln ε_p

$$\varepsilon_p Q_{\varepsilon_p}(z) = \frac{E_{\rm merger}}{t_{\rm age}\mathcal{C}} = \epsilon_p \mathcal{C}^{-1} \int_{M_{\rm min}}^{M_{\rm max}} dM \left[\frac{1}{2}\xi_g(M,z) M v_s^2\right] \frac{dN}{dM} \frac{P(M,z)}{t_{\rm age}}$$

where ξ_g is the mass fraction in gas form, ϵ_p is the CR energy fraction (nominally taken as 0.1) and $\mathcal{C} = \ln(\varepsilon_p^{\rm max}/\varepsilon_p^{\rm min})$ is the normalization factor for a standard flat CR spectrum $N(\varepsilon_p) \propto \varepsilon_p^{-2}$. For $z \sim 1$, the typical maximum energy, $\varepsilon_p^{\rm max}$, is $\sim 10^{17}$ eV and $\mathcal{C} \simeq 18.4$ (Kashiyama & Mészáros 2014). However, $\varepsilon_p^{\rm max}$ varies with redshift, as we discuss in the next section. In

$$M_{\rm min} = 10^{10} M_\odot \qquad M_{\rm max} = 10^{15} M_\odot$$

$$\xi_g^{\rm evo} = M_{\rm gas}/M_h \qquad f_g = M_{\rm gas}/(M_{\rm gas} + M_*) \qquad M_* = \chi_*(M_h, z) M_h.$$

Gas mass fraction vs. z

$f_g = M_{\rm gas}/(M_{\rm gas} + M_*)$ $M_* = \chi_*(M_h, z)M_h.$ (χ_* = from obs.)

$\xi_g^{\rm evo} = M_{\rm gas}/M_h$ = gas mass fraction

$$\xi_g^{\rm evo} = \chi_* \frac{f_g}{1-f_g} = \chi_* \frac{K}{M_*^{1-\beta'}} {\rm sSFR}^{\beta'}$$

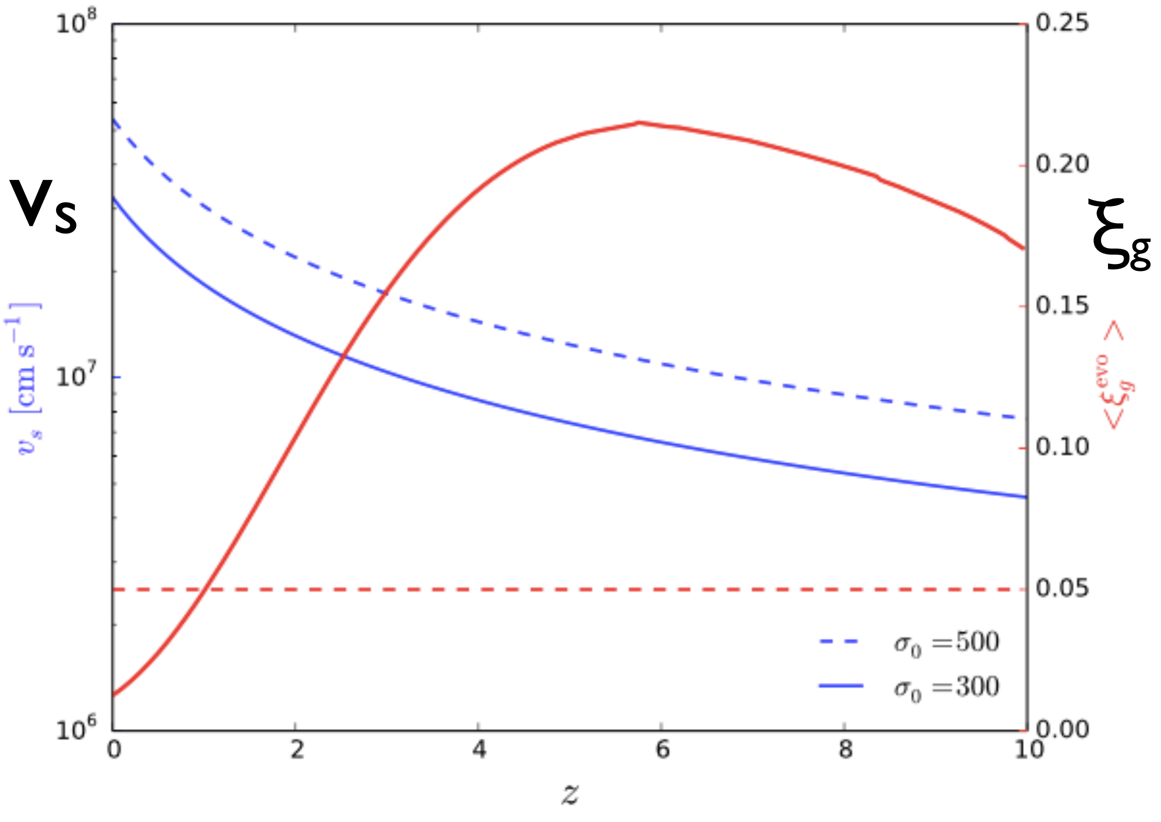
where $K = 10^{\alpha_{\rm SFR}}$ is a constant and the quantity sSFR is the specific star formation rate. For the gas fraction in normal galaxies, we use the parameters $(\alpha_{\rm SFR}, \beta') = (9.22 \pm 0.02, 0.81 \pm 0.03)$, together with the expression for sSFR given in the appendix of Sargent et al. (2014).

z-evolution of mean gas mass fraction given by ↓ →

$$\langle \xi_g^{\rm evo} \rangle = \frac{\int \xi_g^{\rm evo} \frac{dN}{dM} dM}{\int \frac{dN}{dM} dM},$$

(also plot shock velocity →)

$300 \lesssim \sigma_0 \lesssim 500$



Shock velocity evolution

- Peculiar velocity of the gas in a cluster ~O(virial velocity)
- Estimate shock velocity from pairwise velocity dispersion

- Locally (z=0): 2-point correlation fcn.: $\xi(r) = \left(\frac{r}{r_0}\right)^{\gamma}$

where $\gamma \approx 1.7$ and $r_0 \approx 5h^{-1}$ Mpc

- Combine 3-pt corr. fcn. with cosmic virial theorem → shock velocity

$$v_s = \sqrt{\bar{\sigma}^2(r)} \simeq \sigma_0 \left(\frac{r_0}{5h^{-1}\ \mathrm{Mpc}}\right)^{\gamma/2} \left(\frac{r}{1h^{-1}\ \mathrm{Mpc}}\right)^{-\gamma}\ \mathrm{km\ s^{-1}}$$

where $r = \left(\int \frac{dN}{dM} dM\right)^{-1/3}$

- Stable clustering hypothesis (Groth-Peebles): → $\xi(r, z) \propto (1+z)^{\gamma-3}$

- Thus, for varying z → $\boxed{r_0 \propto (1+z)^{-(3-\gamma)/\gamma} \quad \Rightarrow v_s(z)}$

(shock veloc. in previous plot)

Gas density and B evolution

$$\text{collapse if}: \quad \rho(z) \geq 1.686\mathcal{D}(z)^{-1}\rho_c(z) \quad ; \quad \text{where} \quad \rho_c(z) = 3H^2(z)/8\pi G$$

$$\text{virialized gas density} \quad : \quad \rho_g(z) = \Delta_c(z)\rho_c(z) \simeq 178\Omega_m^{0.45}$$

$$\text{where} \quad : \quad \Omega_m = \Omega_{m,0}(1+z)^3/[\Omega_{m,0}(1+z)^3 + 1 - \Omega_{m,0}].$$

$$\text{In general, virialized gas}: \quad \rho_{gas}(z) = g(z)n_{gas,0}m_p$$

$$\text{where} \quad : \quad g(z) = \frac{\Delta_c\rho_c(z)}{\Delta_{c,0}\rho_c(0)} = (1+z)^{1.35}[\Omega_{m,0}(1+z)^3 + 1 - \Omega_{m,0}]^{0.55}$$

$$\text{In shocks, usual equipartition argument} \quad : \quad B^2/8\pi \approx \frac{1}{2}\epsilon_B n_g m_p v_s^2 \propto \rho v_s^2$$

$$\boxed{B \approx \sqrt{4\pi\epsilon_B n_{g,0} m_p g(z) v_s^2} \approx 14\ \epsilon_{B,-2}^{1/2} n_{g,0}^{1/2} g(z)^{1/2} \times (\frac{v_s}{300km\ s^{-1}})\ \mu G}$$

CR acceleration & diffusion

- Adopt gas disk radius and scale height $R_g(z) \propto h_g(z) \propto (1+z)^{1.10}$ (HST obs.)

Colliding galaxies, define *effective scale height* : $h = (3\ h_g R_g^2/2)^{1/3}$

Hillas criterion, $t_{acc} < t_{esc}$:

$$\boxed{\varepsilon_p^{max} \sim \frac{3}{2} e B_s h (v_s/c) \simeq 1.3 \times 10^{16}\ \mathrm{eV}(\frac{B_s}{30\ \mu G})(\frac{h}{3\ kpc})(\frac{v_s}{300\ km\ s^{-1}})}$$

- Thereafter, CRs diffuse in merging galaxy system,
- Meson production efficiency: $\boxed{(1- e^{-f_{pp}}),\ \text{where } f_{pp} \sim \kappa_{pp}\, \sigma_{pp}\, g(z) n_{i,0}\, c t_i}$

where $\sigma_{pp} = \sigma_{pp}(\varepsilon_p) \sim 5\times10^{-26}$ cm^2, $\kappa^{pp} \sim 0.5$ inelasticity, t_i - residence time

$t_i = \min[t_{dyn}, t_{diff}]$, $t_{dyn} \sim h/v_s \sim 10^7$yr (h/3kpc)(300km s^{-1}/v_s) , $t_{diff} \sim h(z)^2/6 D_g$