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

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What causes HENUs at < few PeV?

or rather:

What causes HECRs, at < 100 PeV?
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

IceCube Lab

IceTop
80 Stations, each with 2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors

2010: 79 strings in operation
2011: Project completion, 86 strings

IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors

AMANDA

DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors

Eiffel Tower
324 m

1 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 ($\nu_e:\nu_\mu:\nu_\tau$) 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.

\[ p + p/\gamma \rightarrow N + \pi^\pm + \pi^0 + \ldots \]
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\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu, \\
\mu^+ & \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
K^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu, \\
\mu^- & \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\
\pi^0 & \rightarrow \gamma + \gamma \\
n & \rightarrow p + e^- + \bar{\nu}_e
\end{align*}
\]

- Both $\nu_e$ and $\nu_\mu$ are produced by charged pion decay,
- $\gamma$-ray photons are produced by neutral pion decay
- Secondary leptonic pairs also up-scatter ambient photons to GeV–TeV energies
Both $\nu_e$ and $\nu_\mu$ are produced by charged pion decay,

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- Secondary leptonic pairs also up-scatter ambient photons to GeV–TeV energies
\[ p + p/\gamma \rightarrow N + \pi^\pm + \pi^0 + \ldots \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]

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

\[ \pi^0 \rightarrow \gamma + \gamma \]

- Both \( \nu_e \) and \( \nu_\mu \) are produced by charged pion decay,
- \( \gamma \)-ray photons are produced by neutral pion decay
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**expect a corresponding \( \gamma \)-ray background!**
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) : $\sim 14\%$ of EGB
VHE $\gamma$–rays are expected to accompany neutrinos. They are related via:

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

**(injection spectrum similar)**

**BUT:**

- A fraction $\sim 1 - e^{-\tau_{\gamma\gamma}}$ of $\gamma$–rays are attenuated by extra-galactic background light (EBL)

- The resulting spectrum is **universal** for large distances

  ($\gamma\gamma \rightarrow e^+ e^-$ cascades)

High energy γ-ray propagation in intergalactic space

- γ_h + γ_s → e^+ + e^-
- Threshold: E_{γ_h} > (m_e c^2)/E_{γ_s}
- Target photons E_{γ_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 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 ❌

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

(Murase, Waxman’16, PRD 94:103006).

(BUT: see TXS 0506+056)
Galaxy clusters

- 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 $E_{\gamma}F_{\gamma} \sim E_{\nu}F_{\nu}$, $\approx$ to full Fermi IGB

- Clusters mainly at $z \lesssim 1$, intervening $T_{YY} \leq 1$, 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)
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 (HNe) are a class of Type Ibc core collapse supernovae (ccSNe) that release up to 10x more energy in their ejecta ($\sim 10^{52}$ ergs).

They have fast trans-relativistic ejecta, possibly from a stalled jet.

SNe are presumed CR accelerators up to $\sim$ PeV energies. HNe should be capable of producing 100 PeV protons.
HN/SN Energetics & pp rate

\( R_{\text{hn}} \sim 4 \times 10^{-6} \xi_{\text{hn},-1.4} \ Mpc^{-3} \ \text{yr}^{-1} \)

\[
\left( \epsilon_p Q_{\epsilon_p} \right)_{\text{hn}} \approx 6.4 \times 10^{44} \xi_{\text{hn},-1.4} C_{18}^{-1} E_{\text{cr},\text{hn},51.4} \ \text{erg} \ Mpc^{-3} \ \text{yr}^{-1},
\]

\[
\left( \epsilon_p Q_{\epsilon_p} \right)_{\text{sn}} = \frac{1 - \xi_{\text{hn}}}{\xi_{\text{hn}}} \frac{C_{\text{hn}}}{C_{\text{sn}}} \frac{E_{\text{cr,sn}}}{E_{\text{cr,hn}}} \left( \epsilon_p Q_{\epsilon_p} \right)_{\text{hn}}
\]

\( \epsilon_{p,\text{max}} \approx \left( \frac{3}{20} \right) Z e B_s R_{\text{dec}} \beta_{ej} \approx 10^{17} Z_{\text{g},2.3} \epsilon_{k,hn,52} M_{\text{ej,0.5}}^{-2/3} \ eV \)

\[
D(\epsilon_p) = D_\star \left[ (\epsilon_p/\epsilon_{p,*})^\alpha + (\epsilon_p/\epsilon_{p,*})^2 \right] \quad r_L(\epsilon_{p,*}) = \ell_c/5
\]

\[
t_{d,g} = H_g^2 / 6D_g \approx 1.5 \times 10^{12} H_{g,21}^2 \epsilon_{g,20} B_{g,-3.7} \epsilon_{p,17.2}^{-1/3} \ \text{s} \quad t_{w,g} = H_g / V_w \approx 6.2 \times 10^{12} H_{g,21} V_{w,3.2}^{-1} \ \text{s}
\]

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

(Propagation in ISM and IGM)

(optical depth for nu-production)
HN/SN diffuse nu-bkg

\[ f_{pp,\text{sbg}} = \xi_{\text{sbg}} (1 - e^{-\tau_{pp,g,\text{sbg}}}) \]

\[ f_{pp,\text{sfg}} = \xi_{\text{sfg}} (1 - e^{-\tau_{pp,g,\text{sfg}}}) \quad ; \quad \xi_{\text{sfg}} = 1 - \xi_{\text{sbg}} \]

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

\[
\left( \varepsilon_p Q_{\varepsilon_p} \right)_{\text{phys}} (z) = \left[ \left( \varepsilon_p Q_{\varepsilon_p} \right)_{\text{hn}} + \left( \varepsilon_p Q_{\varepsilon_p} \right)_{\text{sn}} \right] (1 + z)^3 S(z) \\
S(z) = \left[ (1 + z)^{a \eta} + \left( \frac{1 + z}{B} \right)^{b \eta} + \left( \frac{1 + z}{C} \right)^{c \eta} \right]^{1/\eta},
\]

\[
\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int_0^z \sum_i f_{i,pp} \frac{\left( \varepsilon_p Q_{\varepsilon_p} \right)_{\text{phys}}}{6 (1 + z')^4} \left| \frac{dt}{dz'} \right| dz'.
\]
HNe & SNe in SBG, SFG


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

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

- the \( t_{\text{diff}} \) at low energies is limited by \( t_{\text{esc}}, t_{\text{wind}}, t_{\text{Hubble}} \)
  \( \rightarrow \) 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 & $z \lesssim 4$ Starburst SNe/HNe

- They can address mainly the PeV neutrinos, whereas the more recent TeV nu-flux is higher
- One need **subtract** from Fermi EGB the $\sim 86\%$ 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


- 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 $\gamma\gamma$ absorption!
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.
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)?
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).
Classical collapsar GRB model

- If \( \frac{L_p}{L_\gamma} \sim 10 \), expect that \( \frac{L_\nu}{L_\gamma} \sim 1 \),
- and IC3 observ.: such high \( L_\nu \) seems disproven

This is for standard internal shock model where \( \gamma \) and CR produced in same IS shocks

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

Low optical depth \( \rightarrow \) no hiding \( \rightarrow \) Not classical GRBs!
An alternative: LLGRBs?

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

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

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 $\sim$ comparable in all 3 cases.

- All 3 cases: expect low $L_{\gamma}$, 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

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
Murase & Ioka, 2013, PRL 111, 121102
The plasma surrounding the jet is optically thick

The dominant photon field for $p\gamma$ interactions is from photons generated in the jet head

$$kT_j \approx 5.3 \text{ keV} \Gamma_{\text{rel},1.2}$$

$$U_{\gamma,j} \approx \Gamma_{\text{rel}}^2 U_{\gamma,h}$$

(provided shocks NOT radiation dominated, i.e. LLGRBs)
Choked jet, shock breakout & emergent jet $\nu$-spectra

May do the job - LLGRBs produce practically no IGB $\Rightarrow$ 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 \( \tau_{\gamma\gamma} \gg 1 \).
Galaxy merger shocks

\[ M_* \sim 10^{11} \, M_\odot, \quad M_{\text{gas}} \sim 10^{10} \, M_\odot \]
\[ v_s \sim 3-5 \times 10^7 \, \text{km/s} \]

Cosmic ray energy input into Universe:

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

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

DM halo mass function \( \frac{dN}{d \ln M} \), 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 \( d \ln M \) 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 coefficient in magnetic field - large and small angle scattering:

\[ D = D_c \left[ \left( \frac{\varepsilon}{\varepsilon_c} \right)^{1/2} + \left( \frac{\varepsilon}{\varepsilon_c} \right)^2 \right] \quad \text{with} \quad D_c = c \frac{r_L(\varepsilon_{c,g})}{4}, \quad r_L(\varepsilon_{c,g}) = \frac{l_c}{5} \]

and \( r_L \) = Larmor radius, \( B \sim 30 \, \mu G \), \( l_c = \text{B-field coherence length} \sim 30 \, \text{pc} \), so

\[ t_{\text{diff}} \simeq 3.2 \times 10^5 \, \text{yr} \left( \frac{h(z)}{3 \, \text{kpc}} \right)^2 \left[ \left( \frac{\varepsilon}{\varepsilon_c} \right)^{1/2} + \left( \frac{\varepsilon}{\varepsilon_c} \right)^2 \right]^{-1} \]

where \( \varepsilon_c \simeq 1.7 \times 10^9 \, \text{GeV} \left( \frac{h(z)}{3 \, \text{kpc}} \right) \left( \frac{B_g}{30 \, \mu G} \right) \)

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

get, for galaxy mergers:

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

i.e. → calorimetric for \( z \gtrsim 1 \) gal. mergers
Diffusion & neutrino prod. in galaxy halo and the host gal. cluster

\[ t_{\text{diff}} = \frac{R_{\text{cl}}(z)^2}{6D_{\text{cl}}} \quad B_{\text{cl},0} \approx 1 \mu G \quad l_{c,\text{cl}} \approx 30 \text{ kpc.} \]

\[ \varepsilon_{p,\text{cl}} \approx 5.6 \times 10^9 \text{ GeV} \]

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

\[ R_{\text{cl}} \propto (1 + z)^{-(3-\gamma)/\gamma} \quad B_{\text{cl}} \propto \rho_{\text{cl}} R_{\text{cl}} \propto g(z)R_{\text{cl}}(z). \]

and with CR injection time \( t_{\text{inj}} \sim t_{\text{age}}(\text{cluster}) \), have

\[ f_{pp}^{\text{cl}} = \kappa_{pp}g(z)n_{\text{cl},0}\sigma_{pp}\min[t_{\text{inj}}, t_{\text{diff},\text{cl}}] \approx 0.24 \quad g(z) \left( \frac{n_{\text{cl},0}}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{\sigma_{pp}}{50 \text{ mb}} \right) \left( \frac{\min[t_{\text{age}}, t_{\text{diff}}]}{10 \text{ Gyr}} \right) \]
and, for lower z have also \textbf{Cluster-Cluster mergers}

- Take Cl-Cl mergers occurring for $M_{\text{cl}} \gtrsim 10^{13} \, M_\odot \ (= \text{"HM"})$

The combined all-flavor \textbf{neutrino production rate} is then

\[
\epsilon_\nu Q_{\epsilon_\nu}^{(g)} = \frac{1}{2} (1 - e^{-f_{pp}^g}) \epsilon_p Q_{\epsilon_p}^{(LM)}
\]

\[
\epsilon_\nu Q_{\epsilon_\nu}^{(cl)} = \frac{1}{2} [ (1 - e^{-f_{pp}^{cl}}) \epsilon_p Q_{\epsilon_p}^{(HM)} + \eta (1 - e^{-f_{pp}^{cl}}) e^{-f_{pp}^g} \epsilon_p Q_{\epsilon_p}^{(LM)} ]
\]

The 1st term (gal-gal mergers) and 2nd term (cl-cl mergers) dominate; 3rd term (w. $\eta \approx 0.1-0.2$, gal-gal CRs escaping to cl.), is sub-dominant, essentially because $f_{pp}^g \ (> f_{pp}^{cl}$)
Thus, **Local CR input rate as fcn (z)** → & the resulting $\nu, \gamma$ are seen after they propagate through cosmic space↓

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

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

The locally produced $\gamma$-rays are *degraded* via $\gamma\gamma$ interactions with infrared *EBL* photons

$\rightarrow \gamma$ cascades to **lower energies**

$\rightarrow$ universal final spectrum

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

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

Figure 4. Left panel: Neutrino (all flavor) and $\gamma$-ray fluxes from halo mergers with redshift-evolving gas fraction $\xi_g^{\text{evo}}$, $R_{g,0} = 10$ kpc, $H_{g,0} = 500$ pc. The shock velocity is obtained using $r_0^{\text{sc}}(z)$ and $\sigma_0 = 300$. The magenta line is the neutrino spectrum while the green line is the corresponding $\gamma$-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 $\nu$ and $\gamma$ fits are OK ✔

Dependence on CR spectrum

- Adiabatic shock: expect index \( s=2 \)
- But radiative shocks, expect \( s=(r+2)/(r-1) \), \( r=\)compression ratio, → harder CR spectra → harder \( \nu \)-spectra
- \( \gamma \)-ray sp. unchanged (\( \gamma\gamma \)-cascade leads to universal spectrum) ✔
- could accommodate slopes \( s \sim 2 \) or \( s \sim 1.5 \) ✔

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 \( 1.03 \).
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 $\nu$-$\gamma$ flare coincidence! May need to revisit the lack of global blazar EM-nu correlations (?)
Aside from the INB / IGB issue,

Can we expect any Vs 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 GRBs (BNS) are much fainter; not surprisingly,

These neutrinos DO NOT come from SGRB PROMPT emissions either!
However:

SGRB are *not* always “short”!

*Extended* emission (EE) in 30-50% cases

- EE spectrum is *softer* than that of the “prompt”
  - Prompt: $E \sim 1-3$ MeV
  - Ext’d: $E \sim 30-60$ 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)

ν-dominance of BNS EE:

- Caused by lower $\Gamma$, higher baryon load
- $\Rightarrow$ higher photon density and shorter $t_{p\gamma}$
- $\Rightarrow$ higher B-field, stronger pion cooling
- $\Rightarrow$ 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, \( \theta_{\text{obs}} \in [0^\circ, 36^\circ] \),
- Kimura et al. models for Doppler factor at various \( \theta_{\text{obs}} - \theta_j \) offset
- No detection (OK, ✔)

Figure 2. The detection probability $P(N_\mu \geq k)$ 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 $\sigma_T = 2$ and $\sigma_T = 4$, respectively. The vertical thin-dotted line shows $N_\mu = 1$.
(IceCube-averaged includes down-going events)

Figure 3. The detection probability $P(N_\mu \geq 1)$ 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 $\sigma_T = 2$ and $\sigma_T = 4$, respectively. The vertical thin-dotted lines show $d_L = 300$ Mpc and $d_L = 600$ Mpc.

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

- Internal Shock ($\tau_u = 1$)
- Internal Shock ($\tau_u = \tau_{cr}$)
- Internal Shock ($R_{dis} = R_{cs}$)
- Collimation Shock ($\tau_u = 1$)
- Collimation Shock ($\tau_u = \tau_{cr}$)
- Choked condition ($R_h = R_{ej}$)

Jet Lorentz factor $\Gamma_j$

Isotropic equivalent kinetic luminosity $L_{iso}$ [erg s$^{-1}$]
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**

<table>
<thead>
<tr>
<th>Number of detected neutrinos from single event at</th>
<th>40 Mpc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>model</strong></td>
<td><strong>IceCube (up+hor)</strong></td>
</tr>
<tr>
<td>A</td>
<td>6.6</td>
</tr>
<tr>
<td>B</td>
<td>0.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of detected neutrinos from single event at</th>
<th>300 Mpc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>model</strong></td>
<td><strong>IceCube (up+hor)</strong></td>
</tr>
<tr>
<td>A</td>
<td>0.12</td>
</tr>
<tr>
<td>B</td>
<td>6.2×10⁻³</td>
</tr>
</tbody>
</table>

**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
Photon

Cosmic Ray

Gravitational Wave

21st Century: Multi-Messenger Era

(slide: K. Ioka)
Thanks!
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