Signatures of Collapsars as Sources for High-energy Neutrinos and *r*-process Nuclei

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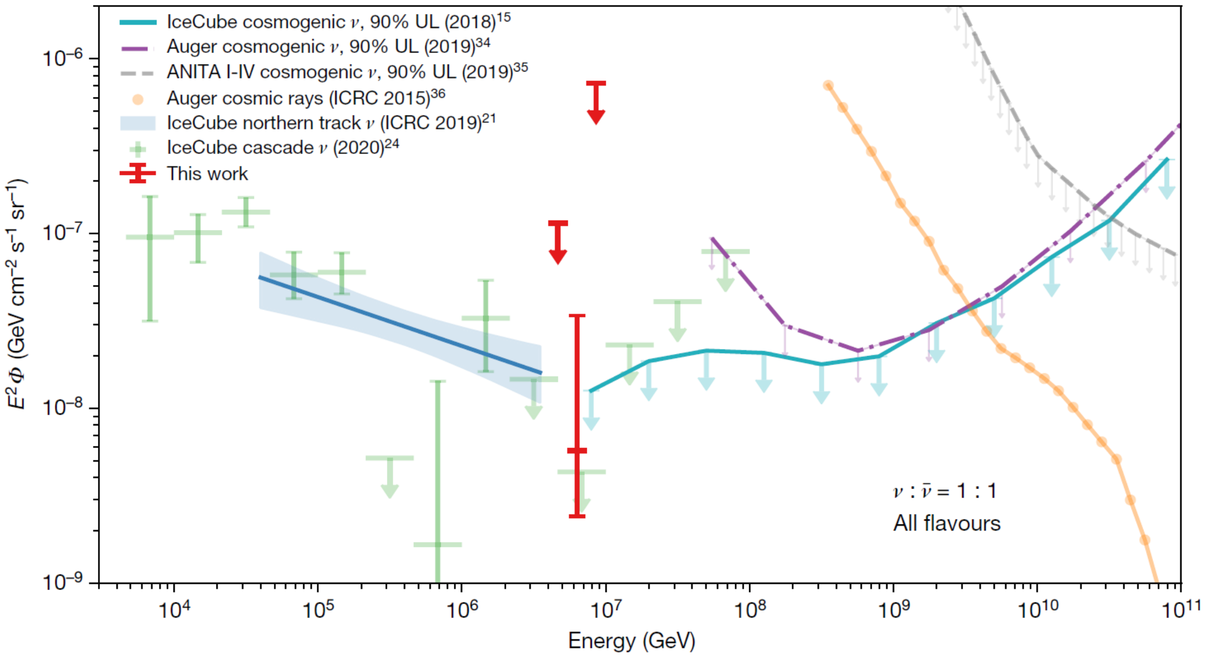
G. Guo, Y.-Z. Qian, and M.-R. Wu, arXiv: 2212.08266, to appear in PRD Letter

HE neutrino events at ICeCube



One Blazar (TXS 0506+056), three TDEs, and one near galaxy (NGC 1068) have been found to be correlated with some HE neutrino events, …

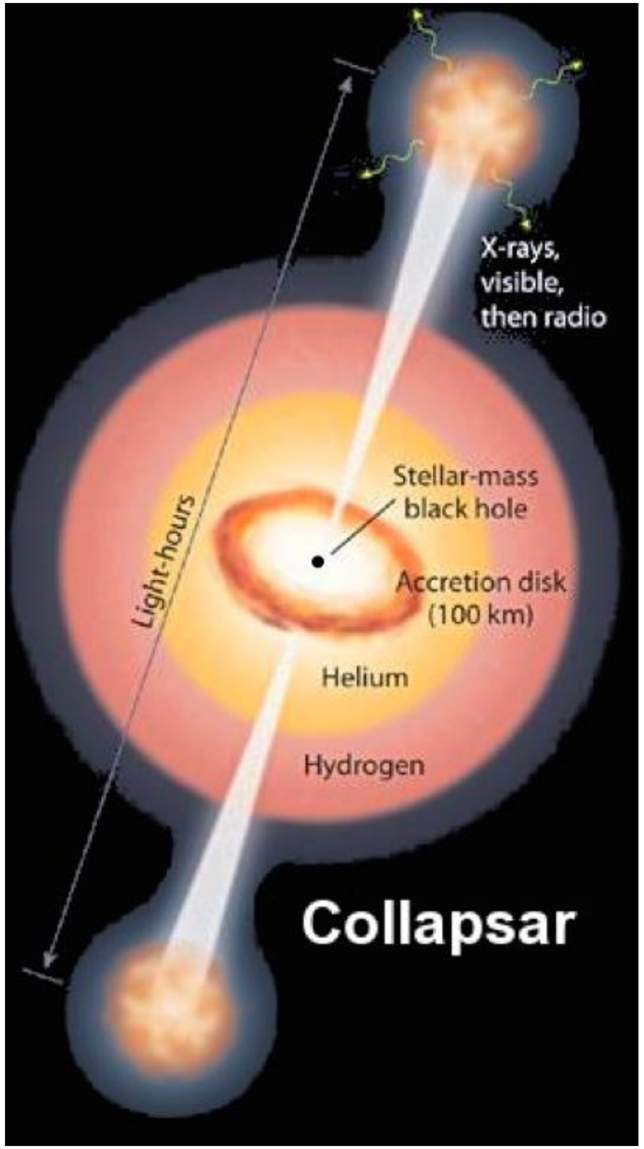
Origin of IceCube events is largely unknown

From gamma-neutrino connection, hidden sources for HE neutrinos may be more likely

(see e.g., Murase+16,20; Fang+22)

This talk discusses one kind of hidden source：

relativistic jets inside **collapsars**



Produced by collapse of massive stars into a BH surrounded by an accretion disk;

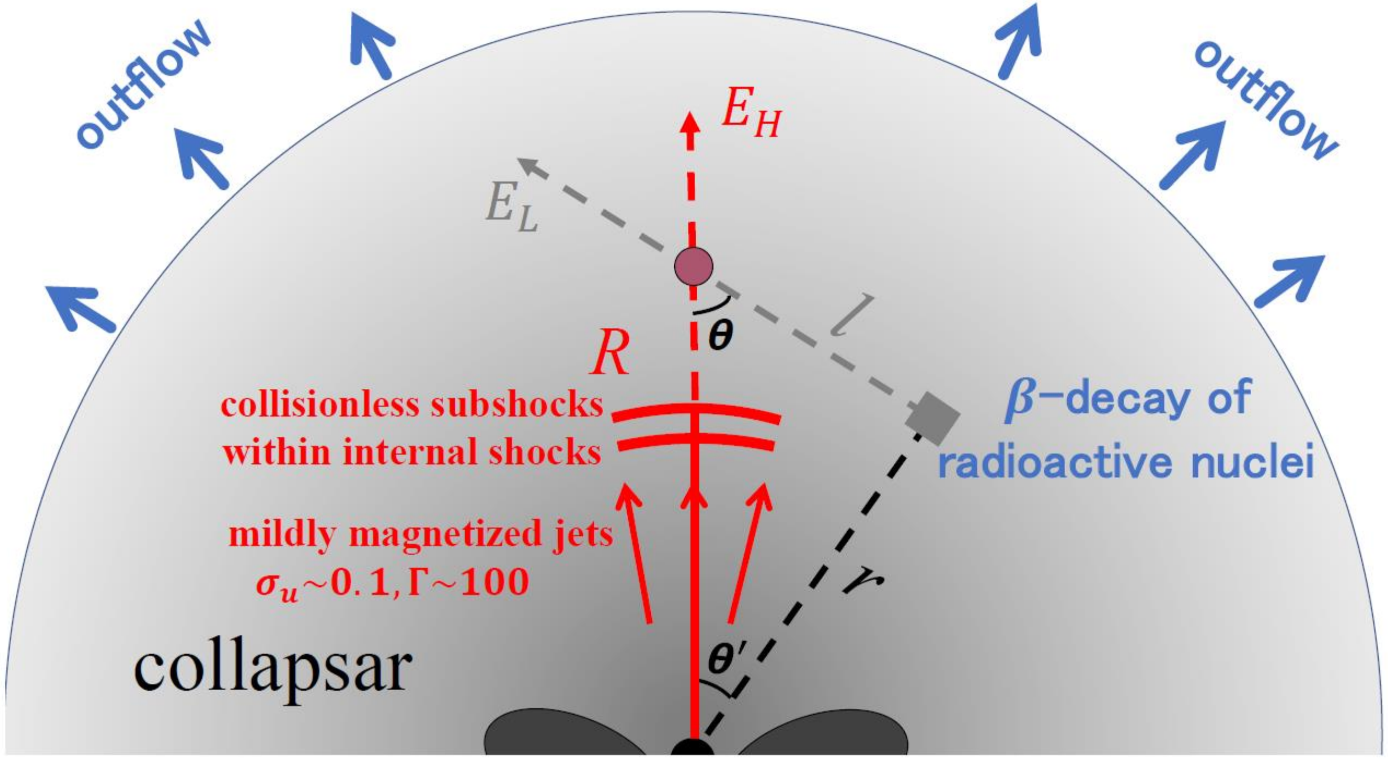
Relativistic jets: power long GRBs; HE neutrinos
Non-relativistic outflow: *r*-process nuclei

Multi-messengers:

EM in different energy bands;
Low-Energy & High-Energy neutrinos
GWs

Aim of this talk:

1) To revisit HE neutrino production inside the progenitor star of collapsars
2) To investigate a novel connection between HE & LE neutrinos from collapsars



HE neutrino production at jet-induced shocks in GRBs/CCSNe

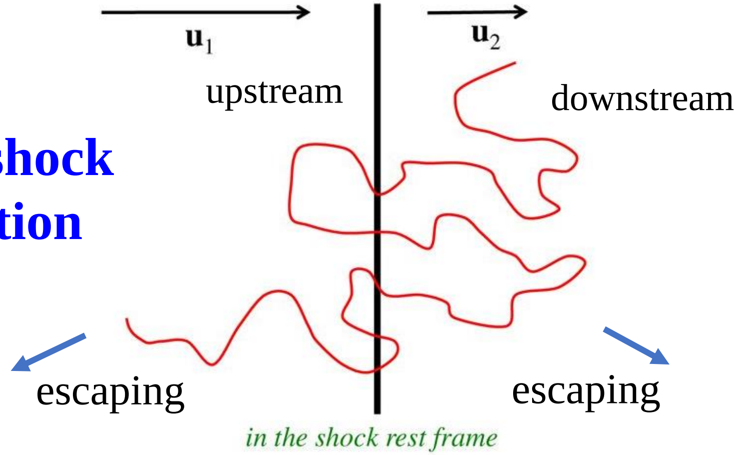
Basic picture for HE neutrino production by shocks:

- proton acceleration by shocks

$$F(E_p) \propto E_p^{-\gamma} \mathrm{Exp}\left[-\frac{E_p}{E_{p,\max}}\right], \qquad \gamma{\sim}2-2.2$$

$E_{p,\max}$ is determined by the balance between acceleration and cooling timescales

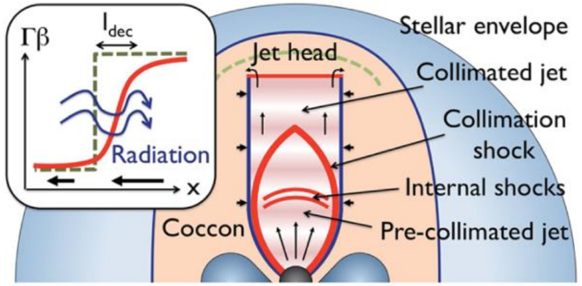
diffusive shock acceleration



- pp or $p\gamma$ process produce $\pi^{\pm}$ and $K^{\pm}$ in shocked jets

- HE neutrinos from decay of $\pi^{\pm}$ and $K^{\pm}$ (cooling of mesons suppresses the produced neutrino flux)

Various sites for HE neutrino production:



Murase+13

prompt neutrino(Waxman+97…), neutrino afterglow(Waxman+99…), neutrinos from shock breakout, neutrino produced by jets propagating inside stellar envelope (more common for jets to be choked)

Meszaros+01,Razzaque03,Ando+05, Murase+13,Xiao+14,Tamborra+16,Senno+15,He+18,Denton+18…

HE neutrino production deep inside progenitor star

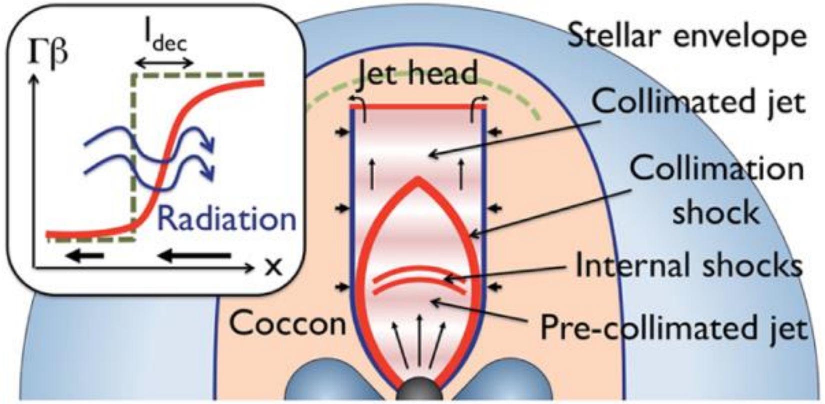
Downside factors:

- ➢ Neutrino fluxes are highly suppressed at small radius due to strong synchrotron cooling of charged meson (more severe for slow jets, i.e., with small Lorentz factor Γ)

$$pp、p\gamma \rightarrow \pi^{\pm}、K^{\pm} \rightarrow \nu \qquad t_{\rm syn}^{-1} \propto B^2 \propto \epsilon_B L/(\Gamma^2 r^2)$$

- ➢ Shocks produced deep inside stars are easily radiation-mediated & do not support particle acceleration

radiation energy density$\propto \epsilon_e L/(\Gamma^2 r^2)$



Murase+13

To form a collisionless internal shock by pre-collimated jets

$$L_{52} r_{\rm is,10}^{-1} \Gamma_2^{-3} \lesssim 5.7 \times 10^{-3} \min[\Gamma_{\rm rel,0.5}^2, 0.32 C_1^{-1} \Gamma_{\rm rel,0.5}^3]$$

Murase+13

low power & fast jets, large shock radius are favored

mildly magnetized jets may provide a way out

- If the jets are sufficiently magnetized, a strong collisionless internal subshock can still develop in radiation dominated region.

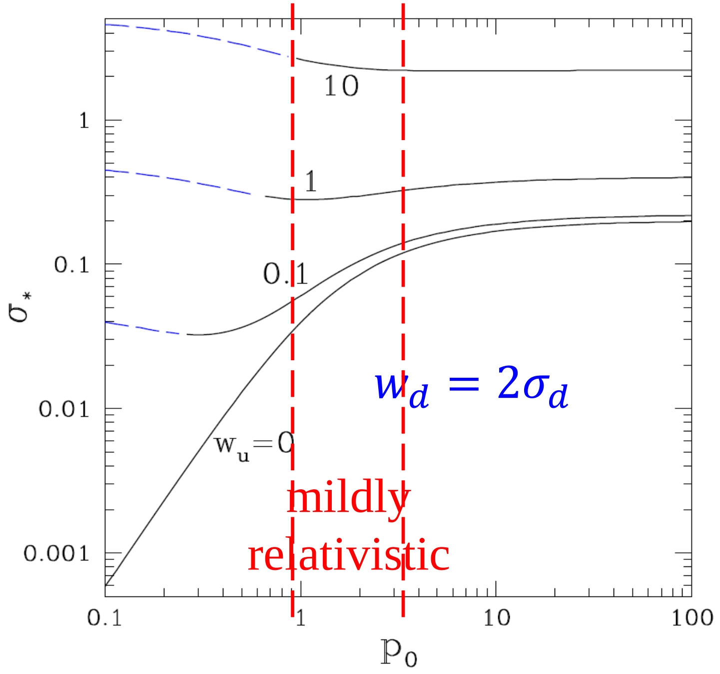
$$w_d \sim \sigma_d$$

$$w = \frac{P_{\rm rad} + U_{\rm rad}}{\tilde{\rho} c^2} = \frac{4P_{\rm rad}}{\tilde{\rho} c^2} \qquad \sigma = \frac{P_B + U_B}{\tilde{\rho} c^2} = \frac{\mathcal{B}^2}{4\pi \tilde{\rho} c^2}$$

$$\begin{tikzcd}(p_0, p_u, w_u, \sigma_u) \arrow[d, "\text{jump conditions}"'] \\ (p_d, w_u, \sigma_u)\end{tikzcd}$$

$$\boldsymbol{\sigma_u \gtrsim \sigma_* \sim 0.01 - 0.1}$$

Beloborodov17, Lundman+19

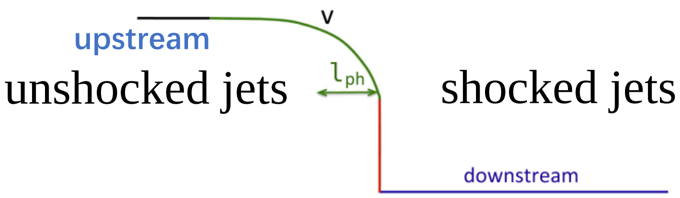


$w_d = 2\sigma_d$

mildly relativistic

radiation mediated shock (RMS)

width ~ photon mean free path λ_γ



unshocked jets

shocked jets

subshock

width ~ proton Larmor radius ≪ λ_γ

[subshock may be more realistic as HE charged particle would decelerate or heat the particles moving from upstream to downstream]

* Magnetization helps to avoid strong mixing of jets with stellar matter and to reach a fast jet

Gottlieb+20, 21

HE neutrino production at internal shocks inside progenitor star revisited

Consider fast, luminous, mildly-magnetized (instead of slow and non-magnetized) jets before collimation:

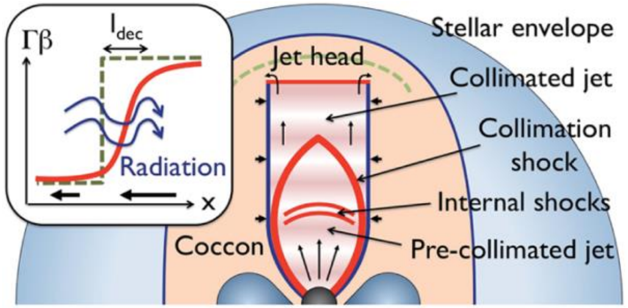
In our benchmark study, we take $R_{\rm is} = 3\times 10^9$ cm,
$\underline{L_{\rm iso} = 10^{53}\ \mathrm{erg/s}}$, $\underline{\Gamma_r = 2\Gamma \approx 90L_{\rm iso,49}^{0.18} \approx 472}$,
$\underline{\sigma_d = \xi\sigma_u \approx 2\epsilon_{B,d} = 0.25}$, $\xi = 5$, $\epsilon_{e,d} = 0.5$,
and $\epsilon_{e,u} = 0.3$.

$\epsilon_B \approx 0.5\,\sigma$

	$B_{d(u),8}$	$n_{p,d(u),19}$	$T_{\gamma,d(u),\rm keV}$
downstream	$8.2(\epsilon_{B,d}L_{\rm iso,52})^{1/2}/(R_{\rm is,10}\Gamma_2)$	$1.8L_{\rm iso,52}(1-\epsilon_{e,d}-\epsilon_{B,d})R_{\rm is,10}^{-2}\Gamma_2^{-2}$	$3.7(\epsilon_{e,d}L_{\rm iso,52})^{1/4}R_{\rm is,10}^{-1/2}\Gamma_2^{-1/2}$
upstream	$B_{d,8}/\xi$	$n_{p,d,19}/\xi$	$T_{\gamma,d,\rm keV}(\epsilon_{e,u}/\epsilon_{e,d})^{1/4}(\Gamma/\Gamma_r)^{1/2}$

Previous studies, by default, consider HE neutrino production in shocked jets (downstream of shock)

We, instead, consider HE neutrino production in unshocked jets (upstream of shock)



Murase+13

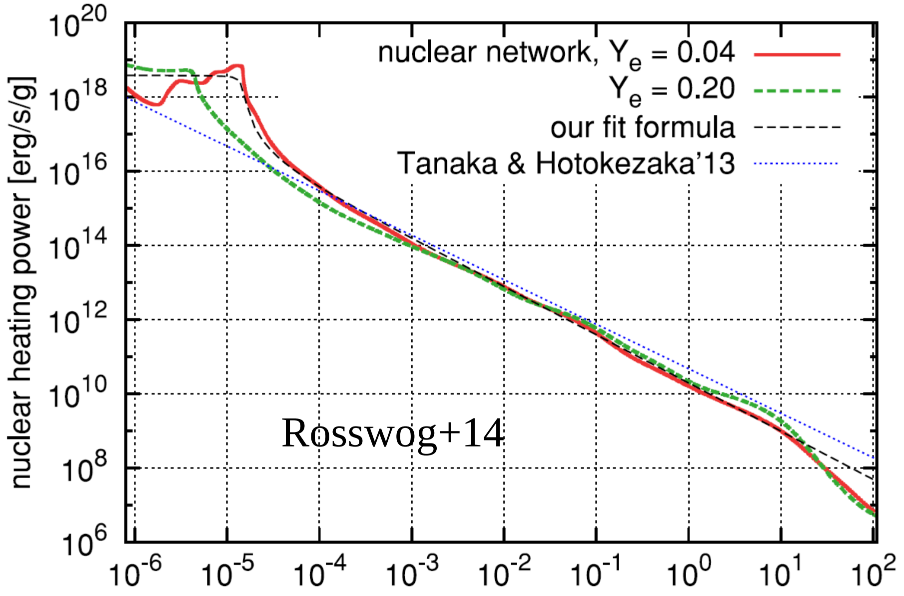
$$pp、p\gamma \to \pi^{\pm}、K^{\pm} \to \nu$$

$$F(E_p) \propto E_p^{-2}\mathrm{Exp}\left[-\frac{E_p}{E_{p,\rm max}}\right]$$

Pythia8 for pp yields; SOPHIA for $p\gamma$ yields

antineutrinos from β-decay of synthesized elements

Collapsars as sources for *r*-process (*rapid neutron capture*) nuclei
Siegel+19



$$\dot{\epsilon}_{\bar{\nu}_e,0} = 5 \times 10^{18}\ \mathrm{erg/g/s}$$

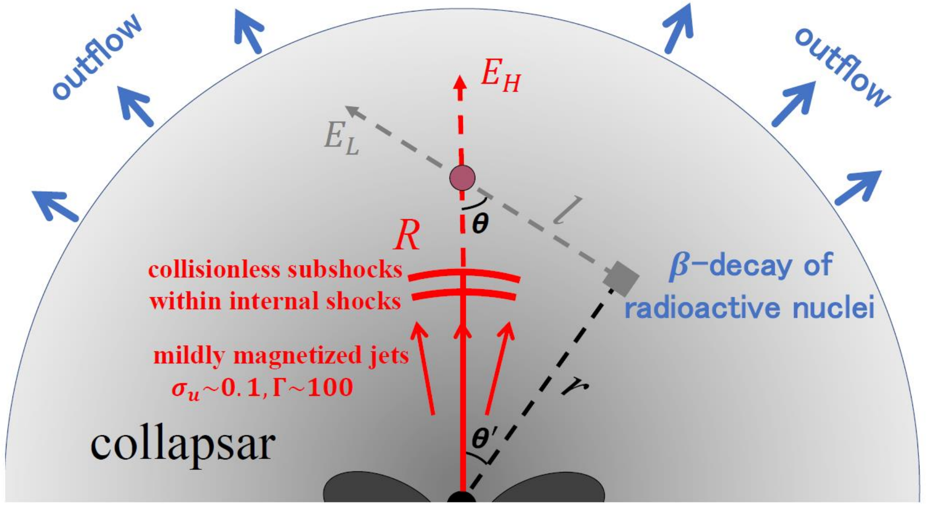
$$\eta(t) \approx \left[\frac{1}{2} - \frac{1}{\pi}\arctan\left(\frac{t - T_r}{0.11\ \mathrm{s}}\right)\right]^{1.3} \qquad T_r = 0.4\ \mathrm{s} \qquad Y_e = 0.2$$

Rosswog+14, Wu+19

$$j_{\bar{\nu}_e}(E,r) = \frac{\dot{\epsilon}_{\bar{\nu}_e,0}\,\eta(r/v_{\mathrm{ej}})}{\langle E_L \rangle}\underline{\left[\frac{15(2\langle E_L\rangle - E)^2 E^2}{16\langle E_L\rangle^5}\right]}$$

$< E_L > = 4$ MeV

normalized spectrum of antineutrino;
purely from the phase space



$$I_{\bar{\nu}_e}(E,R,\theta) = \int \frac{\rho(r)\, j_{\bar{\nu}_e}(E,r)}{4\pi} dl$$

$$= \frac{R\dot{M}}{16\pi^2 v_{\mathrm{ej}}} \int \frac{j_{\bar{\nu}_e}(E,r)\sin\theta}{r^2 \sin^2(\theta+\theta')} d\theta'$$

$\bar{\nu}_e$ flux
(/MeV/cm^2/s/sr)

$$\rho(r) = \dot{M}/(4\pi r^2 v_{\mathrm{ej}})$$

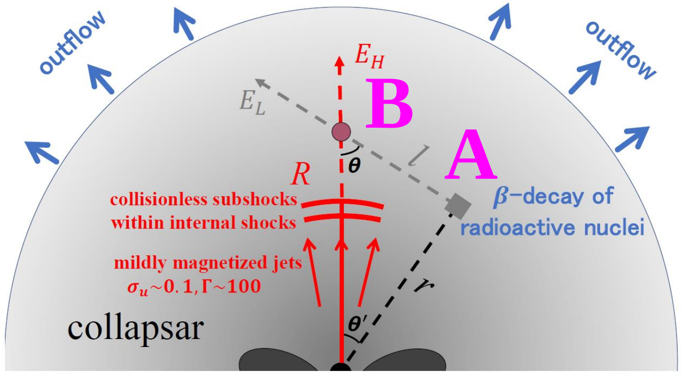
← assuming spherically symmetric outflow

ejecta mass density	ejecta mass loss rate	ejecta velocity
	$0.01 - 0.1\ M_\odot$/s	0.05c

oscillations of LE antineutrinos

Depending on the densities at points A (emit. LE $\bar{\nu}_e$) & B (pair ann.), if densities vary slowly.

Pair annihilation occurs inside jets with density below ~1 g/ cm^3 (ρ_B is low)



Wind density is $\rho \sim \dot{M}/(4\pi r^2 v_{\rm ej}) \sim 10^3\ {\rm g/cm^3}$ at $r \sim 10^9$ cm

The density of stellar matter at 10^9 cm can reach 10^6 g/ cm^3
(stellar matter may be blown away by the earlier jets or winds)

The emission site of $\bar{\nu}_e$ can span a wide range with different local densities (ρ_A has a wide range), we consider extremes cases

(1) pure vacuum oscillation ($\rho_A = 0$)

(2) MSW effect ($\rho_A \gg 10^4$ g/ cm^3):

$\bar{\nu}_e$ is identical to $\bar{\nu}_{1m}$ for normal (NH) and $\bar{\nu}_{3m}$ for inverted (IH) neutrino mass hierarchies

$$(P_{\bar{\nu}_e}, P_{\bar{\nu}_\mu}, P_{\bar{\nu}_\tau}) \approx (0.55, 0.18, 0.27)$$

pure vacuum osc.

$$(0.675, 0.095, 0.23)$$

MSW under NH

$$(0.022, 0.545, 0.433)$$

MSW under IH

neutrino pair annihilation

- Relativistic jets & the nonrelativistic winds/ejecta are launched almost simultaneously after the formation of accretion disk & have similar duration (Just+22, Fujibayashi+22)

- Steady LE antineutrino background

- We construct a 1D MC simulation code to simulate neutrino pair annihilation taking into account decays of charged meson and leptons (though the secondary processes are not too relevant)

$$\nu_\alpha + \bar{\nu}_\alpha \rightarrow f + \bar{f}$$

enhanced cross section
due to Z-resonance

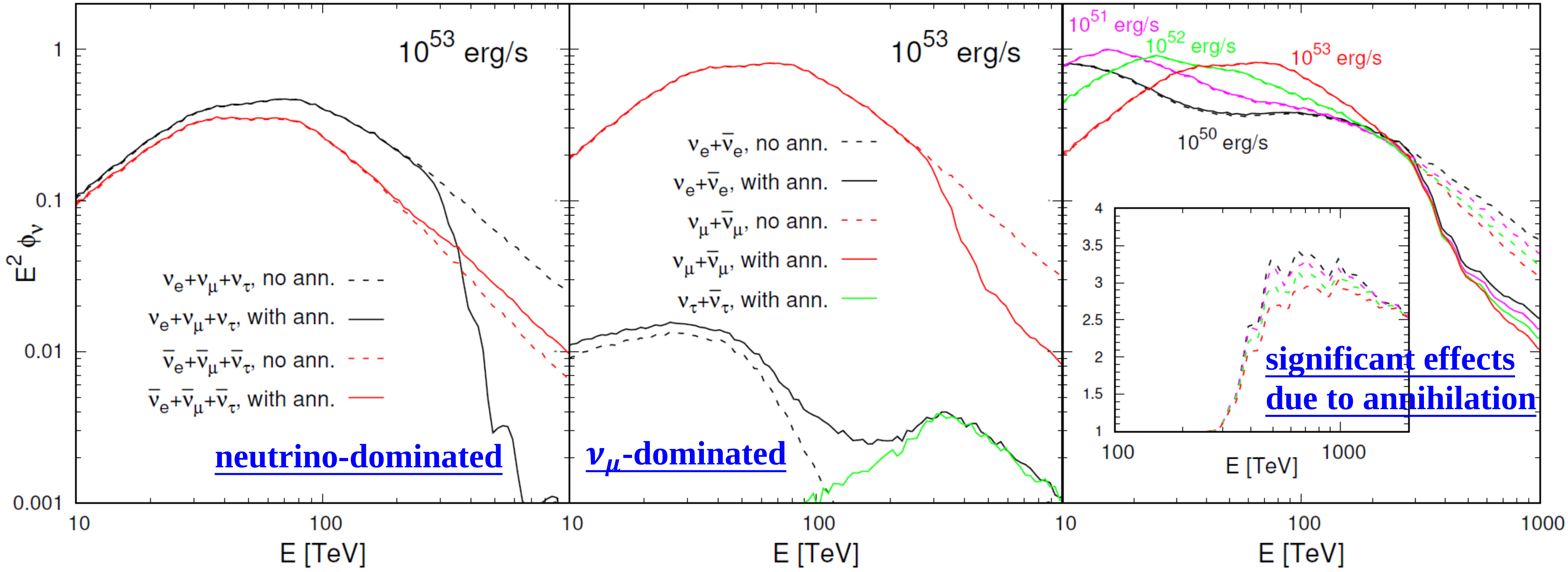
quarks (hadronize), charged leptons, neutrinos

$\pi^\pm, K^\pm$ $\mu^\pm, \tau^\pm$

secondary or
regenerated neutrinos

- Particle yields from $\nu_\alpha \bar{\nu}_\alpha$ are obtained from Pythia8, and only the dominant decay channels are considered

resulting HE neutrino spectrum and flavor composition



neutrino-dominated

ν_μ-dominated

significant effects due to annihilation

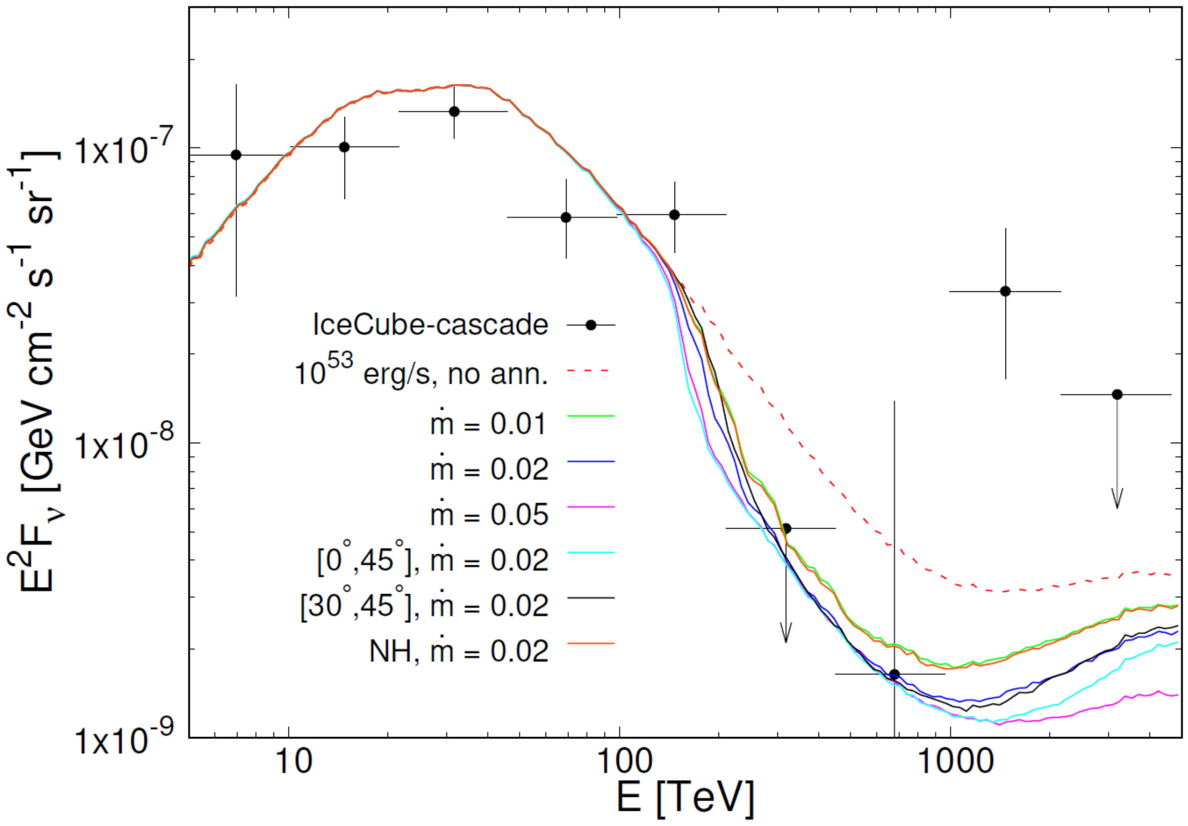
unnormalized flux assuming $\phi_p(E_p) = E_p^{-2}\mathrm{Exp}\left[-\frac{E_p}{E_{p,\max}}\right]$

Diffuse HE neutrino flux

$$\frac{c}{4\pi H_0}\frac{f_z f_\star \dot{n}_{\rm GRB} f_{\rm cr} E_{\rm iso}}{\ln(E_{p,{\rm max}}/E_{p,{\rm min}})}\frac{1}{\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

$$\sim 7\times 10^{-9}\left(\frac{f_z f_\star \dot{n}_{\rm GRB}}{\rm Gpc^{-3}\ yr^{-1}}\right) f_{\rm cr} E_{\rm iso,53}$$

$\times E^2\phi_\nu$



$f_*\sim 10$: the ratio of collapsar rate with mildly-magnetized jets to that of bright GRBs

major contributor: LLGRBs & potentially, choked GRBs,
all hosting relativistic jets with similar properties (luminosity, opening angle, Lorentz factor, etc.) Nakar+15, Senno+16

Stacked precursor search at IceCube limits contributions from bright GRBs to be within ~10% (2205.11410)

Predictions from our HE neutrino model

- ✓ Precursor neutrino burst from nearby LLGRBs (benchmark values for jets taken, ~10 cascades expected at **IceCube-Gen2** from a **nearby LLGRB at 100 Mpc**, duration of a few tens seconds)

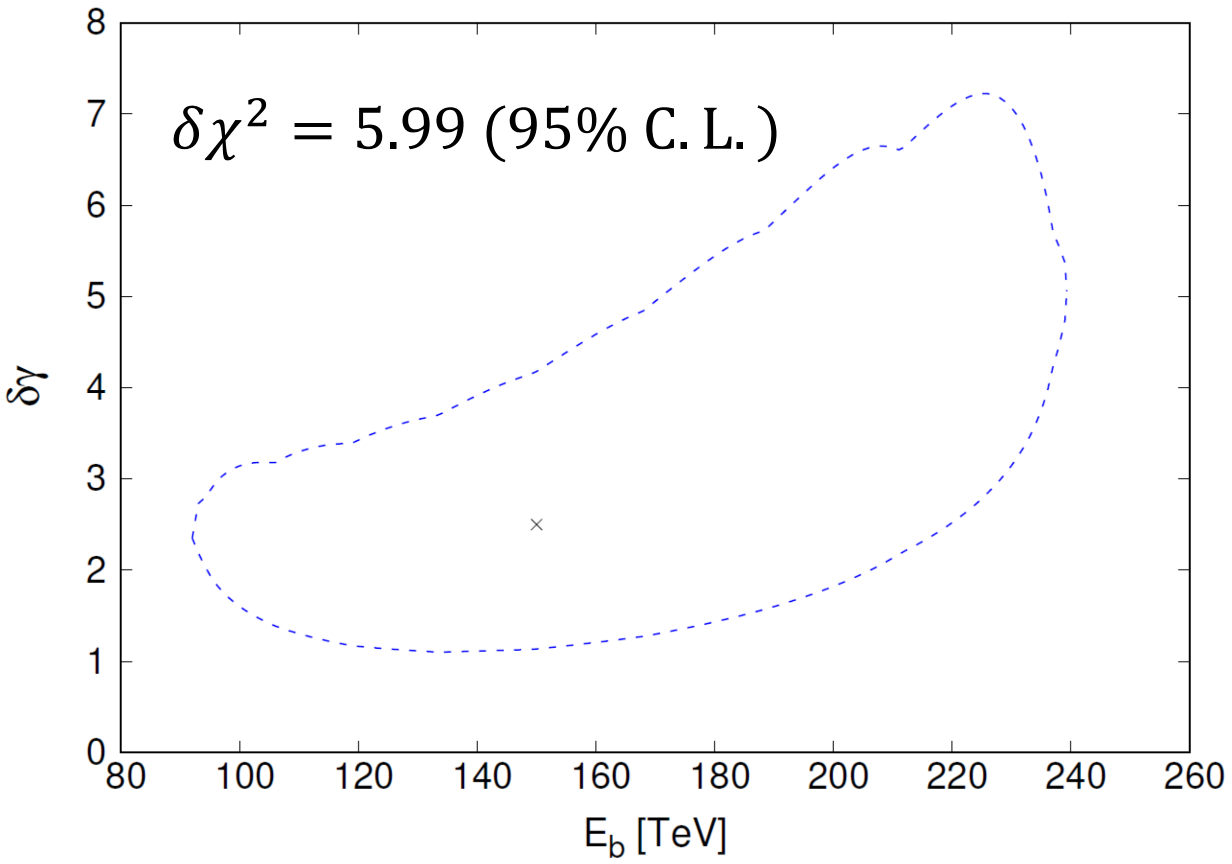
  testing models of LLGRBs (low- or high-luminosity jets)

- ✓ **ν_μ-dominated** flavor composition at source (strong cooling for charged mesons inside stars; can be clearly observed at IceCube-Gen2, see Song+2021)

  distinguishable from the pion-decay scenario with (1: 2: 0) at source

- ✓ If neutrino pair annihilation is considered, a sudden drop above 100-200 TeV in the diffuse spectrum would be expected

observing a sudden drop in the diffuse neutrino flux at IceCube-Gen2



A broken power-law flux for the diffuse flux

$$E^2 F_\nu = A \times \begin{cases} (E/100\ \mathrm{TeV})^{-\gamma}, & E < E_b, \\ (E_b/100\ \mathrm{TeV})^{-\gamma} (E/E_b)^{-\gamma-\delta\gamma}, & E > E_b. \end{cases}$$

We generate the so-called Asimov dataset assuming $A_0 = 2 \times 10^{-8}$ GeV cm^{-2} s^{-2} sr^{-1}, $E_{b0} = 150$ TeV, $\gamma_0 = 0.5$, and $\delta\gamma_0 = 2.5$. using 10 years of IceCube-Gen2 data

Consider atm. neutrino background only;

$$\chi^2(E_b, \delta\gamma) = \min_{\{A,\gamma,\alpha\}} \left[-2 \sum_{i,j} (n_{ij} \ln \mu_{ij} - \mu_{ij}) \right]$$

Summary

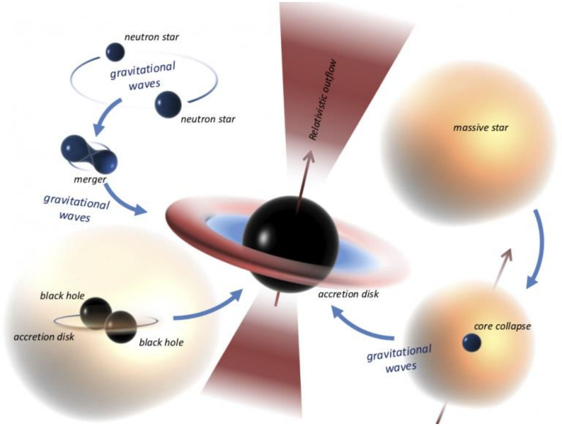
HE production by internal shocks inside progenitor stars:

Mildly-magnetized jets produce collisionless subshocks
HE production in upstream of shocks instead of downstream

Annihilation with LE antineutrinos from β-decay of newly synthesized leave clear imprints on the spectrum and flavor composition of HE neutrino flux

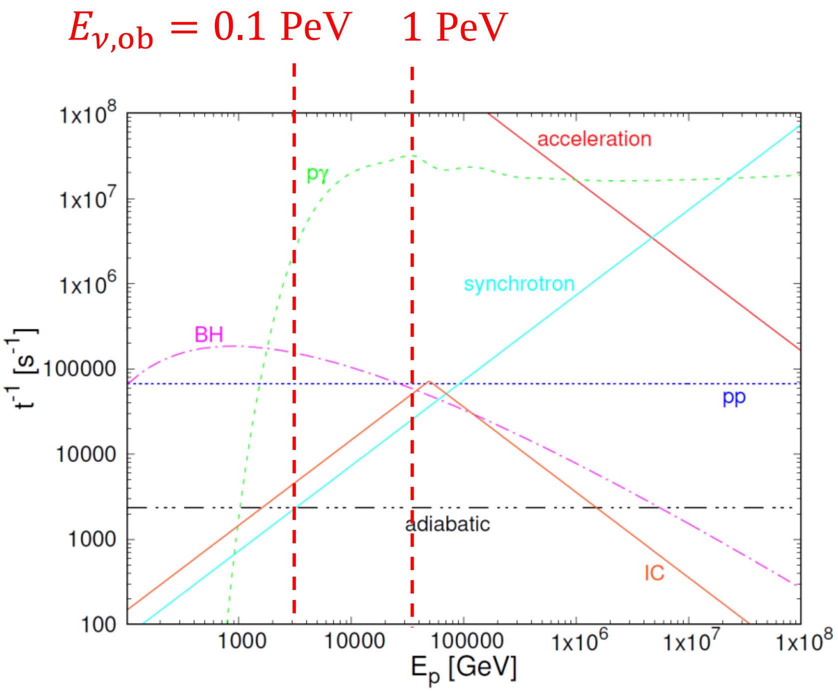
Similar studies can be applied for BNSMs (or SGRBs)

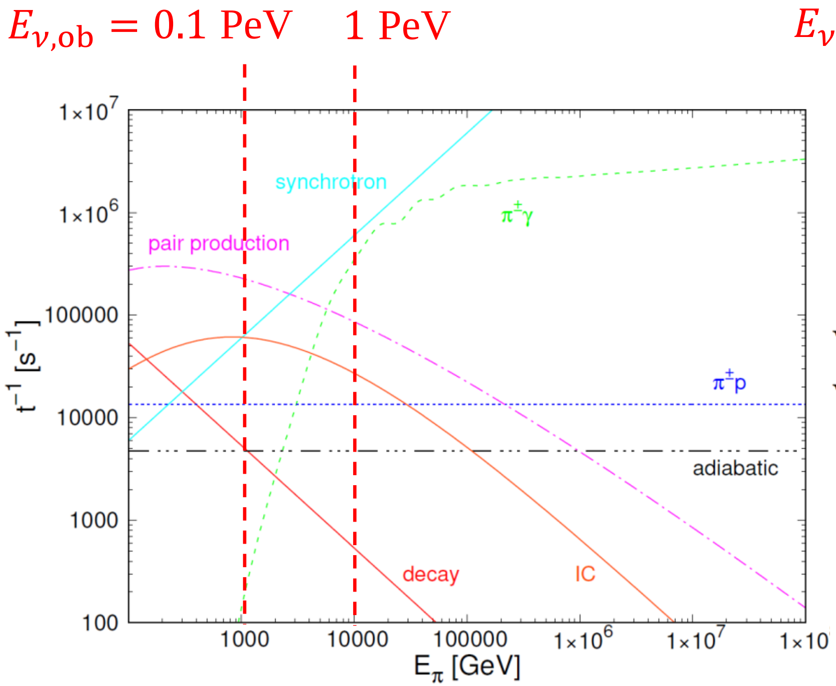
Thanks

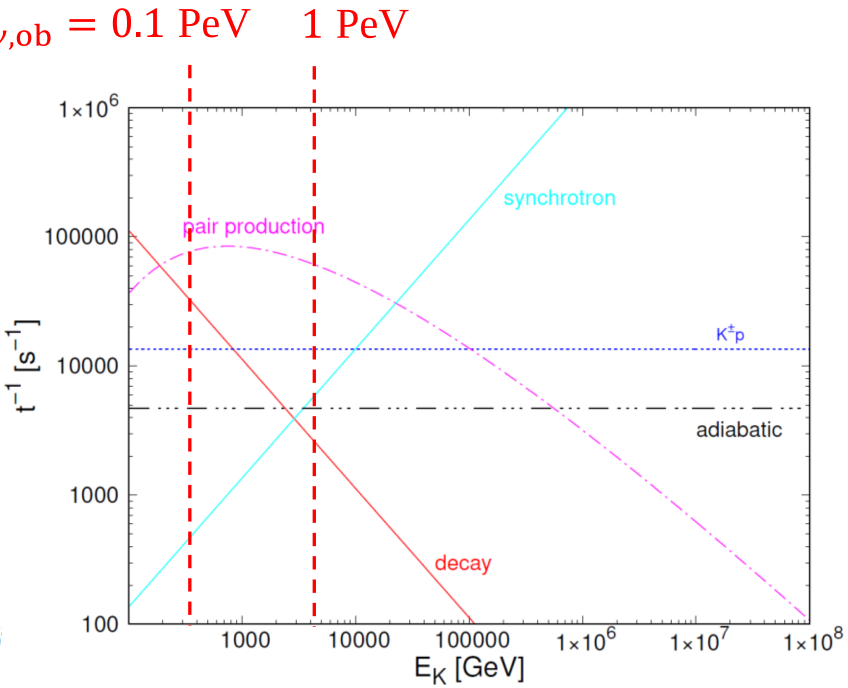


common central engines for LGRBs & SGRBs

relevant timescales for proton and $\pi^{\pm}/K^{\pm}$







proton can be accelerated to
high energies

pair production ($\pi^{\pm}/K^{\pm} + \gamma \rightarrow \pi^{\pm}/K^{\pm} + e^{-} + e^{+}$) dominates
Kaon dominates HE neutrino production

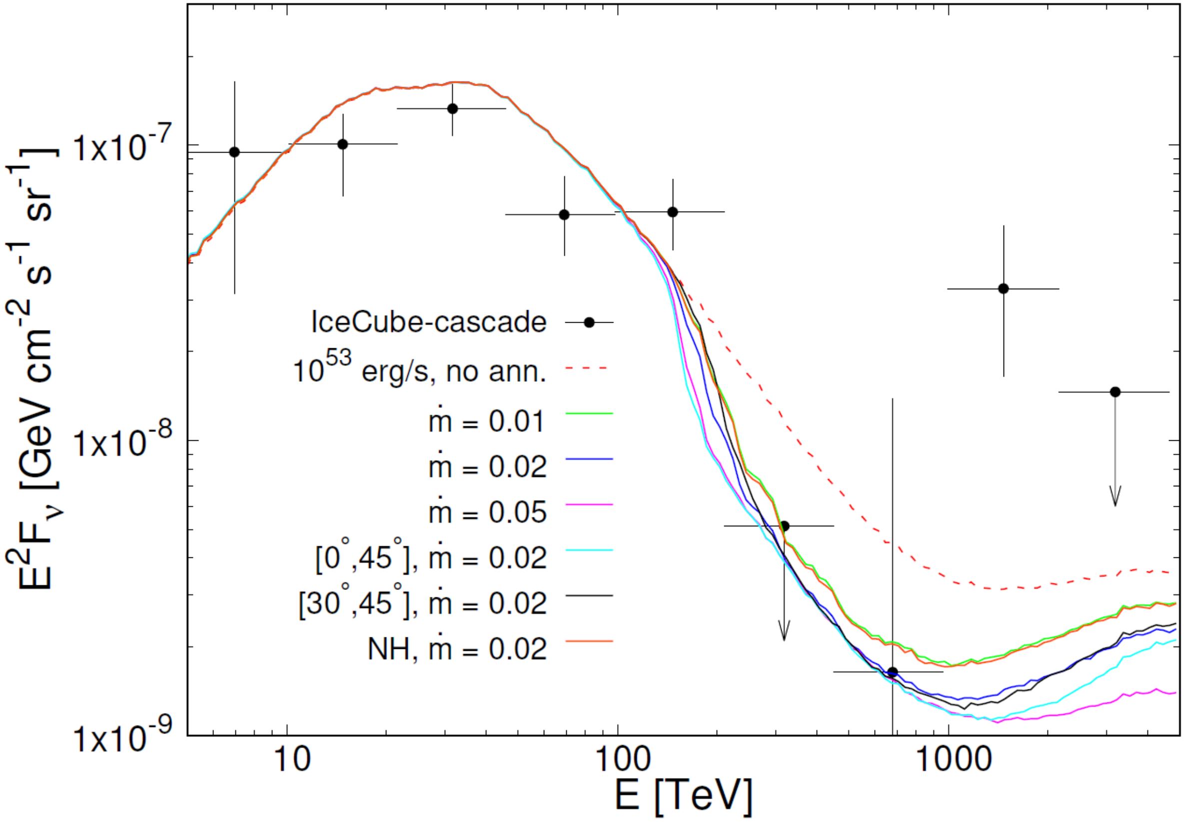
$$E_{\nu,\mathrm{ob}} \sim 0.05\,\Gamma_r\,E_p \sim 0.25\,\Gamma_r\,E_\pi \sim 0.5\,\Gamma_r\,E_K$$

Diffuse HE neutrino flux

$$\frac{c}{4\pi H_0}\frac{f_z f_\star \dot{n}_{\rm GRB} f_{\rm cr} E_{\rm iso}}{\ln(E_{p,\rm max}/E_{p,\rm min})}\frac{1}{\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

$$\sim 7\times 10^{-9}\left(\frac{f_z f_\star \dot{n}_{\rm GRB}}{\rm Gpc^{-3}\ yr^{-1}}\right) f_{\rm cr} E_{\rm iso,53}$$

$\times E^2\phi_\nu$



Benchmark study:
vacuum oscillation of LE antineutrinos
spherical wind

MSW + NH (reduced by ~2);
Asymmetric winds confined to:
$[0^\circ, 45^\circ]$ (enhanced by ~3) or
$[30^\circ, 45^\circ]$ (similar)

MacFadyen+99, Hayakawa+18

Under a range of assumptions, the annihilation effect is significant.