High Energy Neutrino and Gamma-Ray Transients from Relativistic Supernova Shock Breakouts

Kazumi Kashiyama (Penn state)

Collaborators : Kohta Murase, Shunsaku Horiuchi,
Shan Gao, and Peter Meszaros

Contents

1. intro

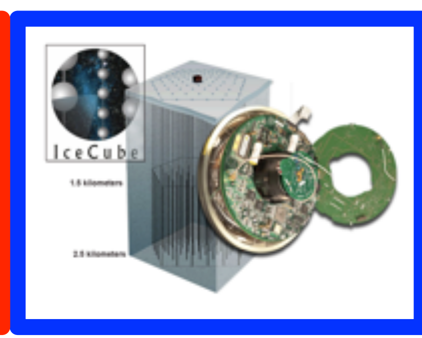
Hadron Colliders in the Universe

✓ Hadron accelerators (at least up to $10^{19.5}$ eV)

✓ Target photons or hadrons

$$N\gamma \quad \text{or} \quad Np \rightarrow \begin{cases} \rightarrow \pi^+ \\ \quad \pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu \\ \quad\quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \rightarrow \pi^0 \rightarrow \gamma\gamma \end{cases}$$

✓ Man-made detectors (Probe *who? where? how? when?*)



with GW UV/Opt/IR radio

Wealthy Population in the Universe

"Diffusive shock acceleration" or "1st order Fermi acceleration"

Blandford & Ostriker 1978, Bell 1978 and etc

✓ Particle are accelerated by …

crossing the shock from up. to down.

↓

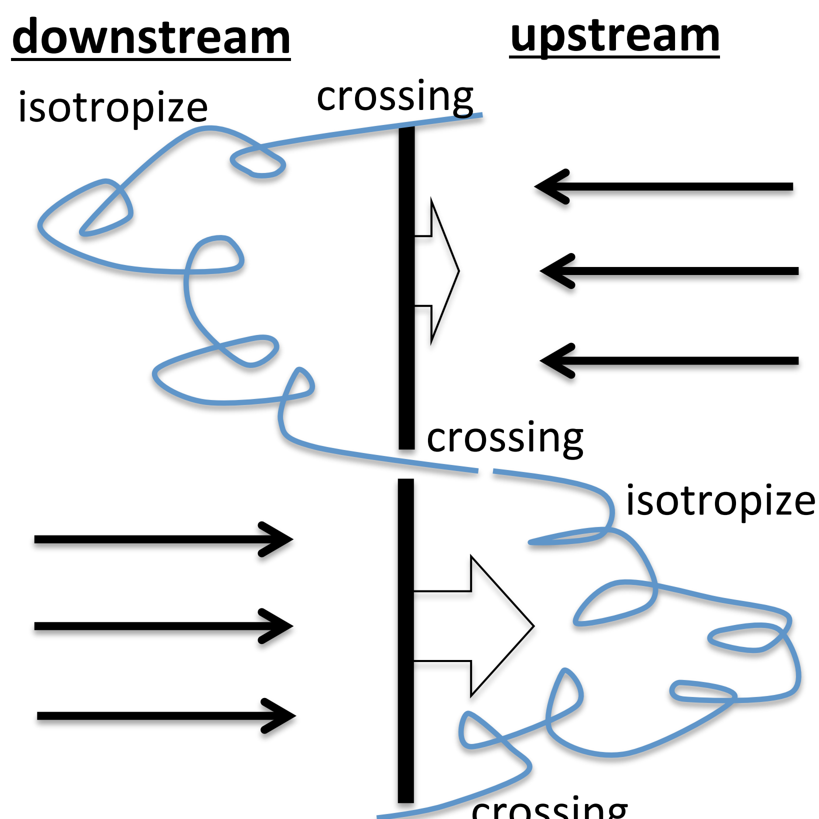
being isotropized in down.

↓

crossing the shock from down. to up.

↓

being isotropized in up.



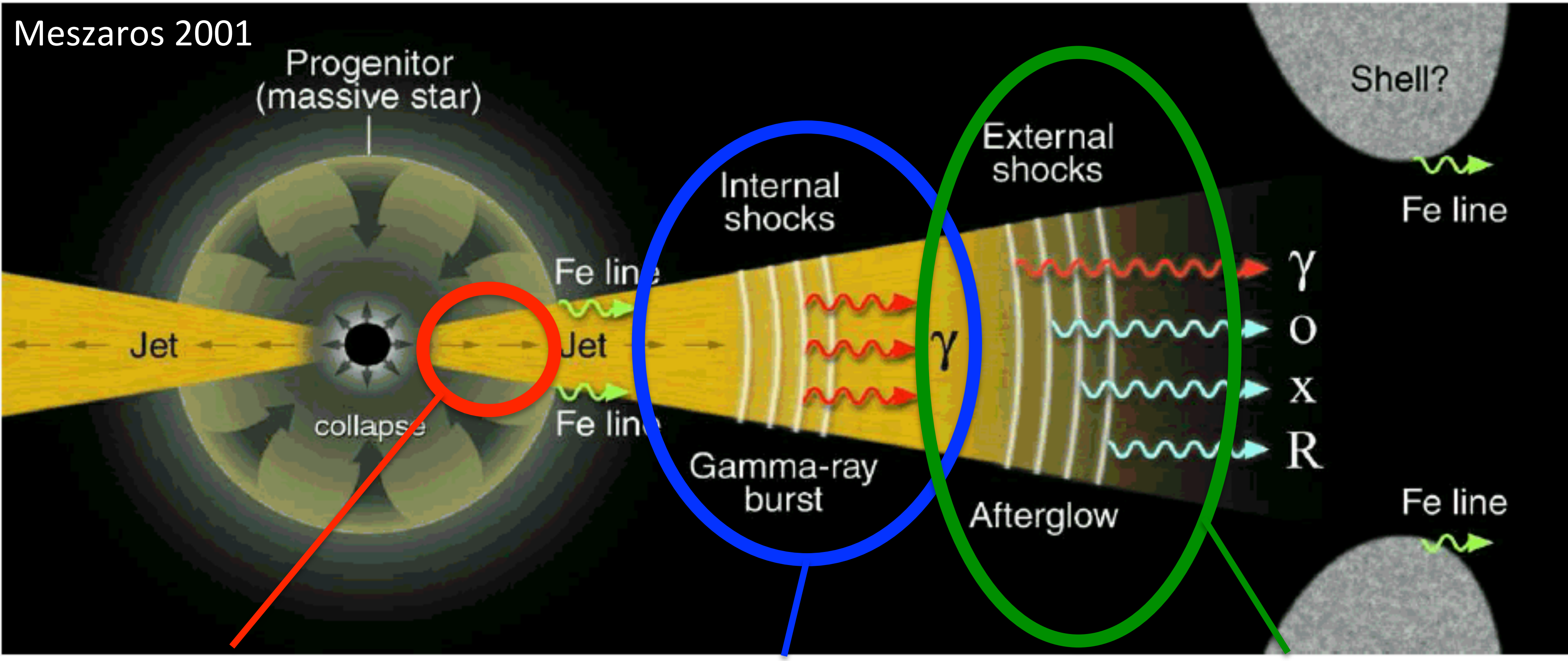
✓ energy gain + escape probability per cycle

→ power low index

- non-rela strong shock $s = 2.0$
- ultra-rela shock $s = 2.2$

$$dN/dE \propto E^{-s}$$

e.g. Tomography of GRB Jets



Jet in the progenitor

$r \lesssim 10^{12}$ cm

GeV-TeV ν

Bahcall & Meszaros 2000
Meszaros & Waxman 2001
and more

Internal shock × prompt

$r \sim 10^{12-16}$ cm

PeV ν and GeV-TeV γ

Waxman & Bahcall 1997
and more

External shock × afterglow

$r \sim 10^{16-17}$ cm

EeV ν and GeV-TeV γ

Waxman & Bahcall 2000
and more

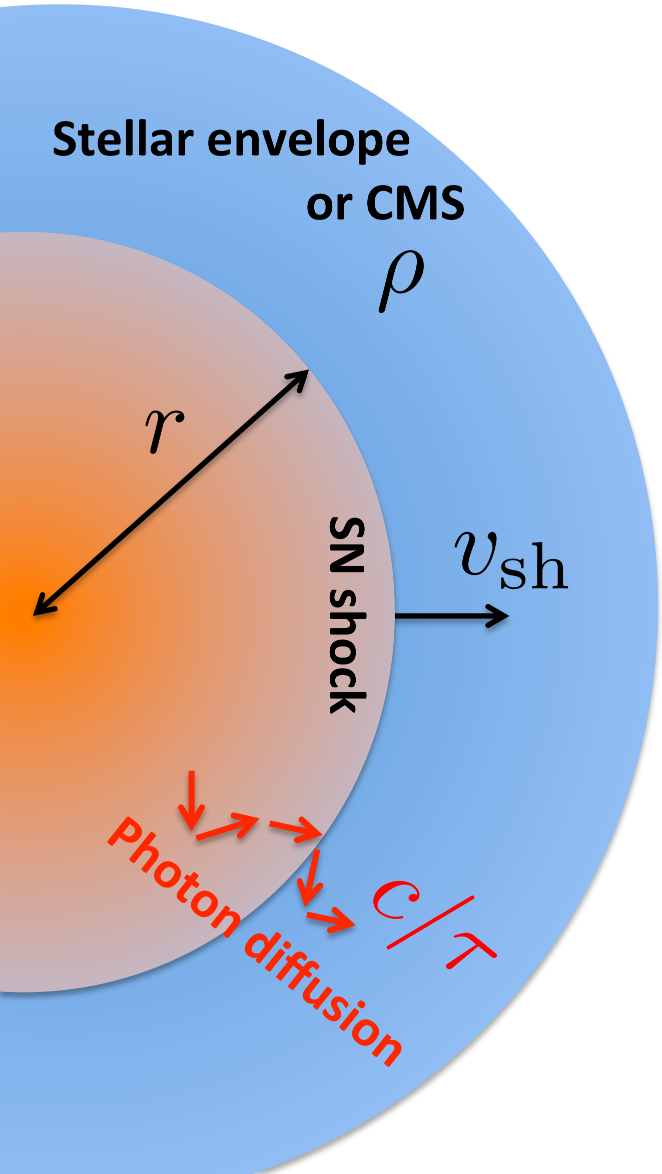
Today's Topic

Relativistic Supernovae Shock Breakouts and the Neutrino and Gamma-Ray Counterparts

What is shock breakout?
Why relativistic supernovae?
What kinds of emissions can we expect?
Are they detectable?
What can we know from them?

2. relativistic SN shock breakouts

SN Shock Breakouts



- ✓ The shock downstream is radiation-dominated.

$$P_{\rm rad} > P_{\rm gas}$$

- ✓ The shock is initially inside optically-thick media.

$$\tau \approx \rho \kappa_{\rm T} r \gg 1$$

⇩

Radiation-mediated shock

"The photons stops incoming particles."

Shock breakout @ $r = r_{\rm sb}$
where $c/\tau \approx v_{\rm sh}$

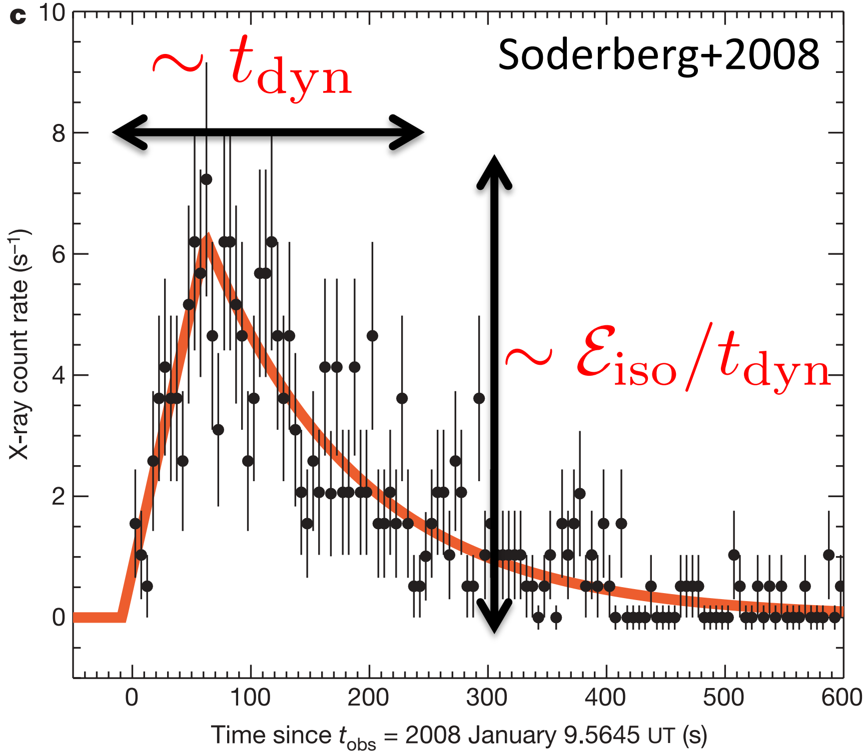
⇩

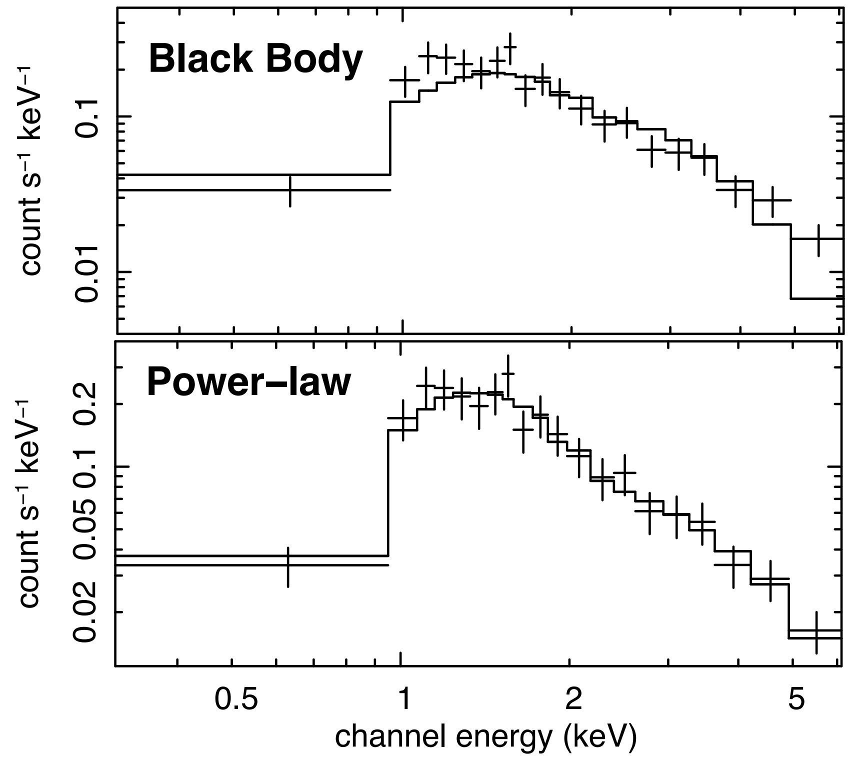
The downstream photons begin to escape.

→
- ✓ Shock breakout emission
- ✓ No longer radiation-mediated

Shock Breakout Emission

e.g. SN2008D





$$t_{\rm dyn} \sim r_{\rm sb}/c\beta_{\rm sh}$$

$$\mathcal{E}_{\rm iso} \sim 2\pi\rho {r_{\rm sb}}^3 {\beta_{\rm sh}}^2 c^2$$

$$\rho \sim 1/\kappa_{\rm T} r_{\rm sb}\beta_{\rm sh}$$

Light curve ⟶ $r_{\rm sb}, \beta_{\rm sh}$

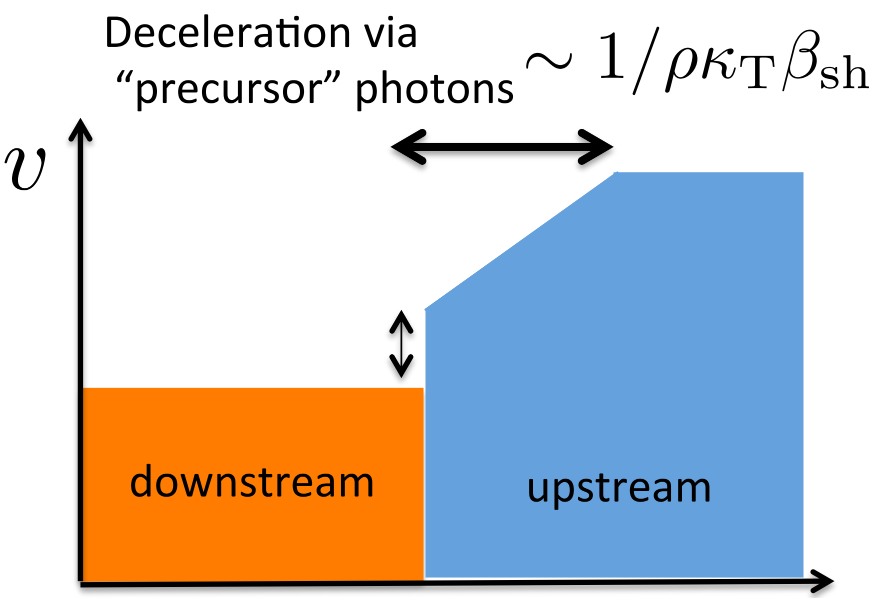
Spectrum: quasi-thermal

The temperature and the power low tail depends on the details of breakout.

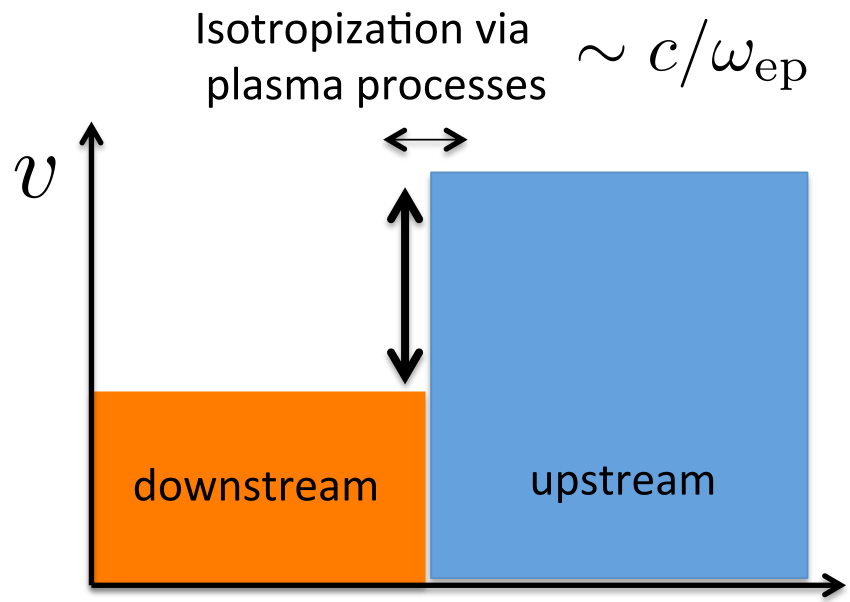
($e^{\pm}$ Is relevant for $\beta_{\rm sh} \gtrsim 0.1$.)

A Phase Transition at Shock Breakouts

Radiation-mediated shock → **Collisionless shock**



- ✓ Before shock breakouts
- ✓ Shock-acceleration is inefficient.



- ✓ After shock breakouts
- ✓ Shock-acceleration can be efficient.

Just beyond r_{sb} , particle acceleration in the collisionless shock starts to operate in the presence of breakout photons.

LL-GRB/SN = Relativistic Shock Breakout?

GRB060318/SN2006aj & GRB100614/SN2010bh

- ✓ smaller luminosities

$$L_{\rm iso,\gamma} \sim 10^{46} \ {\rm erg/s}$$

- ✓ longer duration

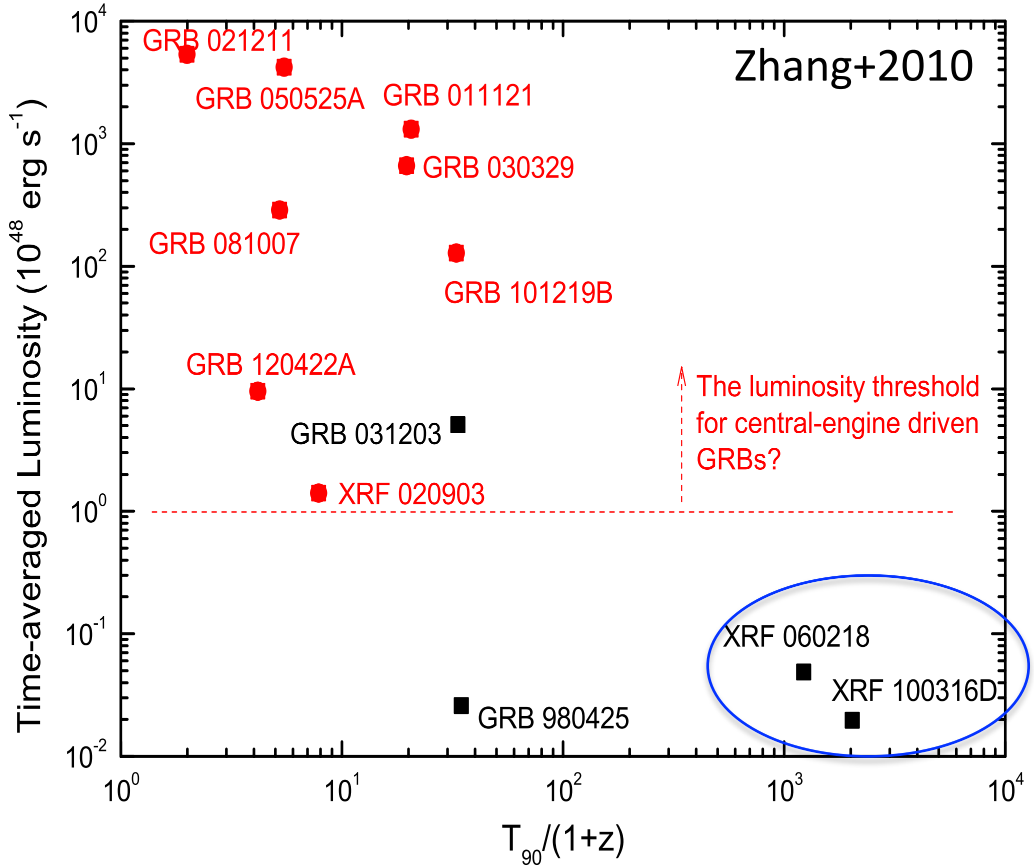
$$t_\gamma \sim 1000 \ {\rm sec}$$

- ✓ quasi-thermal spectrum with softer peak energies

$$\varepsilon_{\rm peak} \sim \text{1-10 keV}$$

Consistent with s.b.o

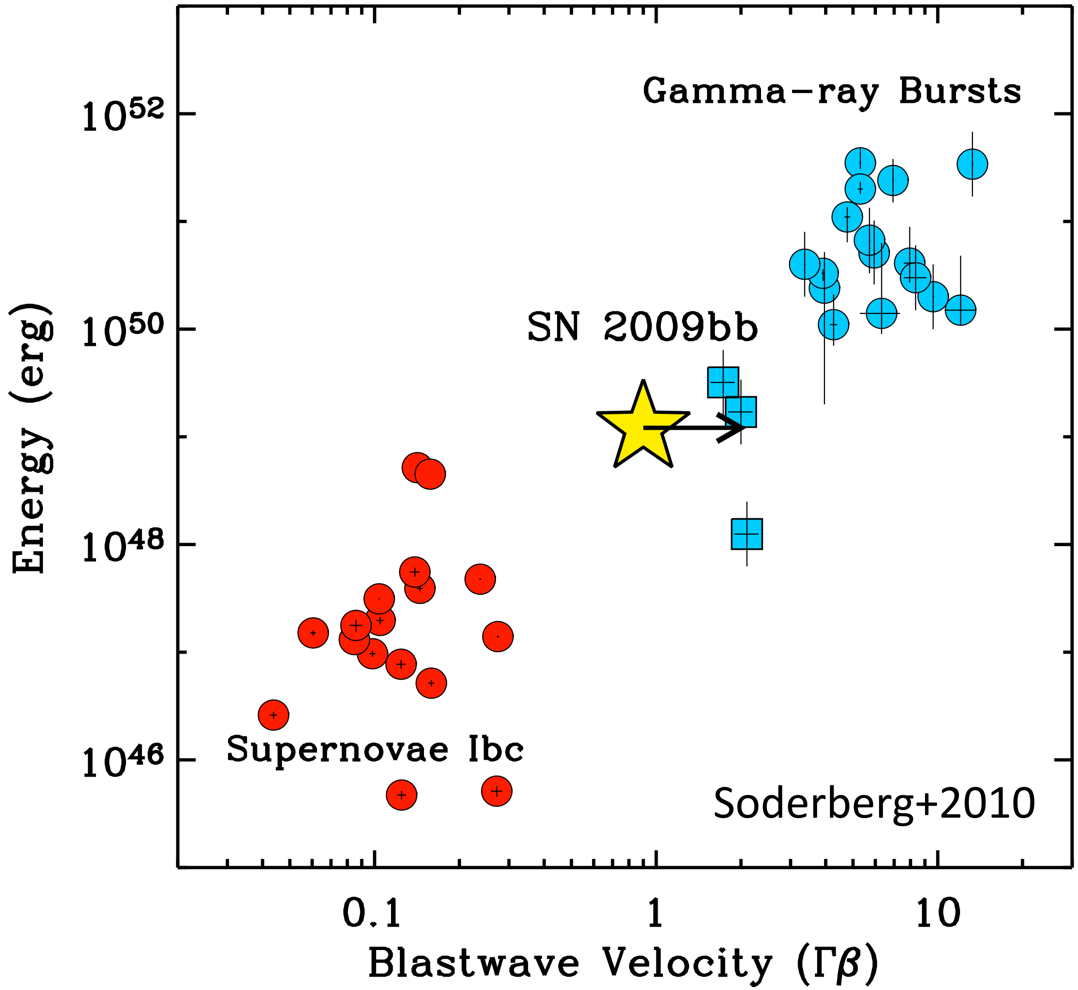
vs magnetar jet model (e.g., Toma+2007)



Both events are nearby (z=0.033 and 0.059)

→ **a high local event rate:** $R_{\rm LL}(z=0) \lesssim 500 \ {\rm Gpc^{-3} yr^{-1}}$

Relativistic Component of SN Explosion



Non-GRB broad-line SN Ibc ⟶ less energetic but more frequent!

$$R_{\mathrm{Ibc}}(z=0) \sim 2 \times 10^4\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

3. the neutrino and gamma-ray counterparts

Set-Up 1

Shock Breakout Photons × Proton Accelerated in the Collisionless Shock
⟶ High Energy Neutrino and Gamma-Ray Emissions

✓ Shock breakout radius & shock velocity

$$r_{\rm sb} = 6 \cdot 10^{13}\ {\rm cm}\ \ \&\ \ \beta_{\rm sh} = 1$$

⇩

$$t_\gamma \sim 2 \cdot 10^3\ r_{{\rm sb},13.8}{\beta_{\rm sh}}^{-1}\ {\rm sec}$$

$$\mathcal{E}_{\rm iso} \sim 5 \cdot 10^{49}\ {r_{{\rm sb},13.8}}^2 \beta_{\rm sh}\ {\rm erg}$$

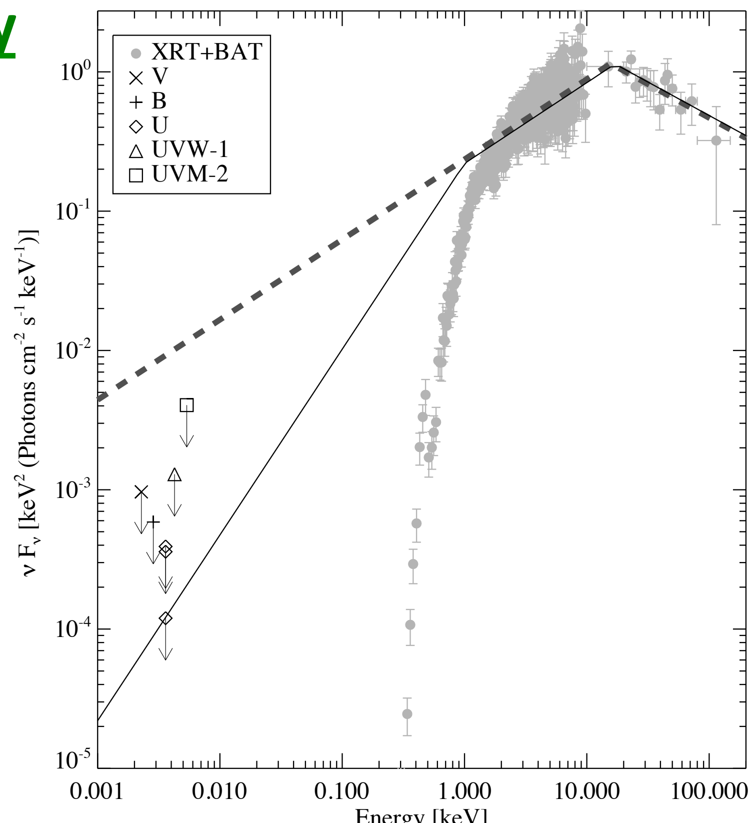
$$L_{{\rm iso},\gamma} \sim 3 \cdot 10^{46}\ \epsilon_\gamma r_{{\rm sb},13.8}\beta_{\rm sh}^2\ {\rm erg/sec}$$

⇩

Roughly reproduce LL-GRBs

✓ Breakout photon spectrum

Substituting the observed one of GRB100316



Fan+2010

Set-Up 2

Shock Breakout Photons × Proton Accelerated in the Collisionless Shock

⟶ High Energy Neutrino and Gamma-Ray Emissions

✓ Magnetic fields in the collisionless shock

$$B^2/8\pi = \xi_{\rm B} U_\gamma \quad \text{with} \quad U_\gamma \equiv L_{{\rm iso},\gamma}/4\pi {r_{\rm sb}}^2 c$$

$$\longrightarrow \quad B \sim 10^5 \ (\xi_{\rm B}/0.1)^{1/2} {r_{{\rm sb},13.8}}^{-1/2} \beta_{\rm sh} \ {\rm G}$$

✓ Acceleration of protons

Assuming 1st order Fermi acceleration $\longrightarrow$ $dN/dE_{\rm p} \propto E_{\rm p}^{-2}$

The energy budget

$$\epsilon_{\rm CR} \equiv \mathcal{E}_{\rm CR}/\mathcal{E}_{\rm iso} \ \text{with} \ \mathcal{E}_{\rm CR} \equiv \int^{E_{\rm p,max}} E_{\rm p}(dN/dE_{\rm p})dE_{\rm p}$$

$E_{\rm p,max}$ is given by $t_{\rm acc}$ vs $t_{\rm cool}$

Set-Up 3

Shock Breakout Photons × Proton Accelerated in the Collisionless Shock

→ High Energy Neutrino and Gamma-Ray Emissions

✓ **Hadronic interactions**

$$N\gamma \quad \text{or} \quad Np \rightarrow \begin{cases} \rightarrow \pi^+ \\ \quad \pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu \\ \quad\quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \rightarrow \pi^0 \rightarrow \gamma\gamma \end{cases}$$

+ Bethe-Heitler process, + kaon contribution + meson cooling…

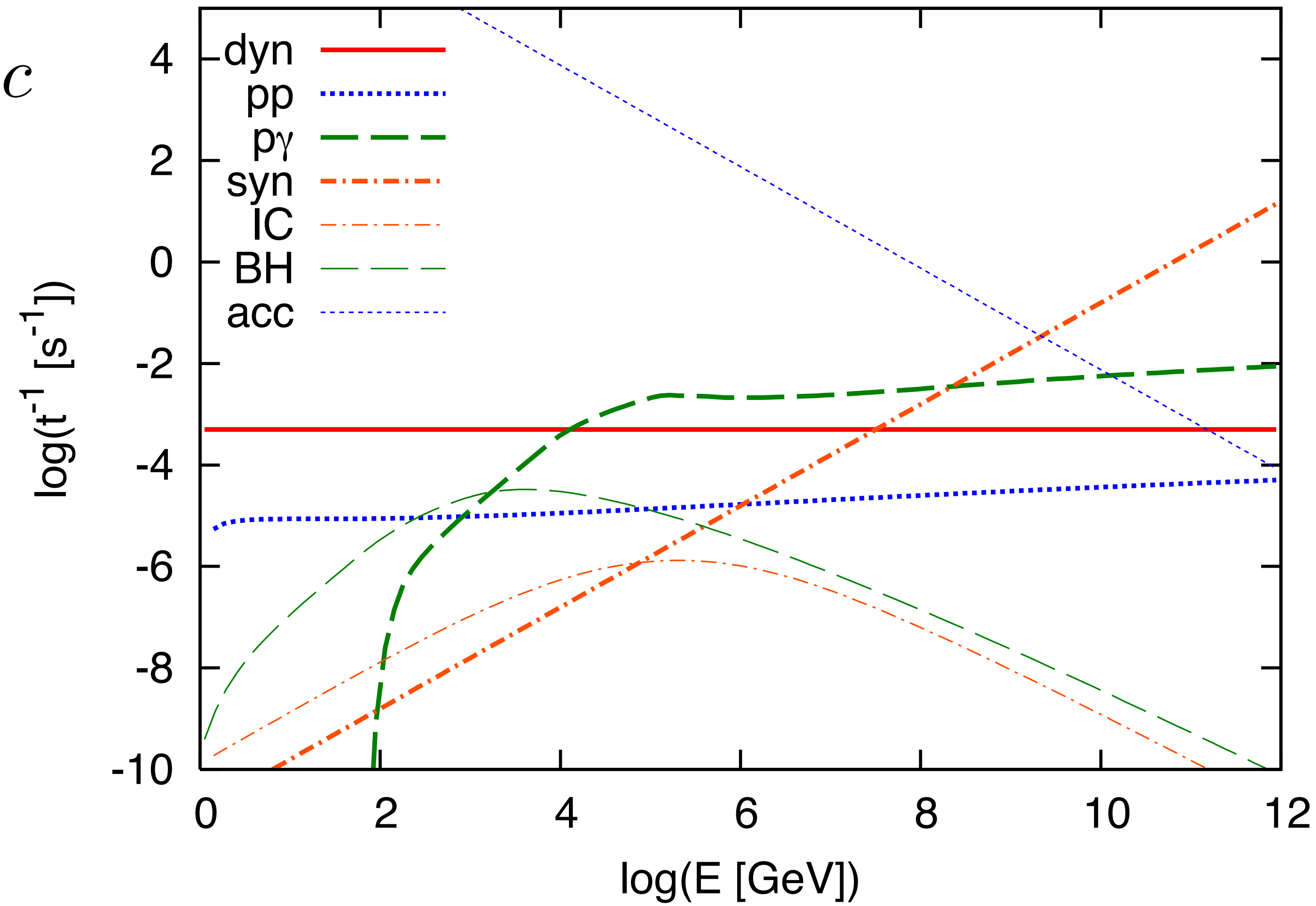
Calculation code given by Murase 2008

Acceleration vs Cooling

$$t_{\rm acc} = \eta E_{\rm p}/eBc$$

the Bohm diffusion limit

$$\eta \sim 2\pi$$

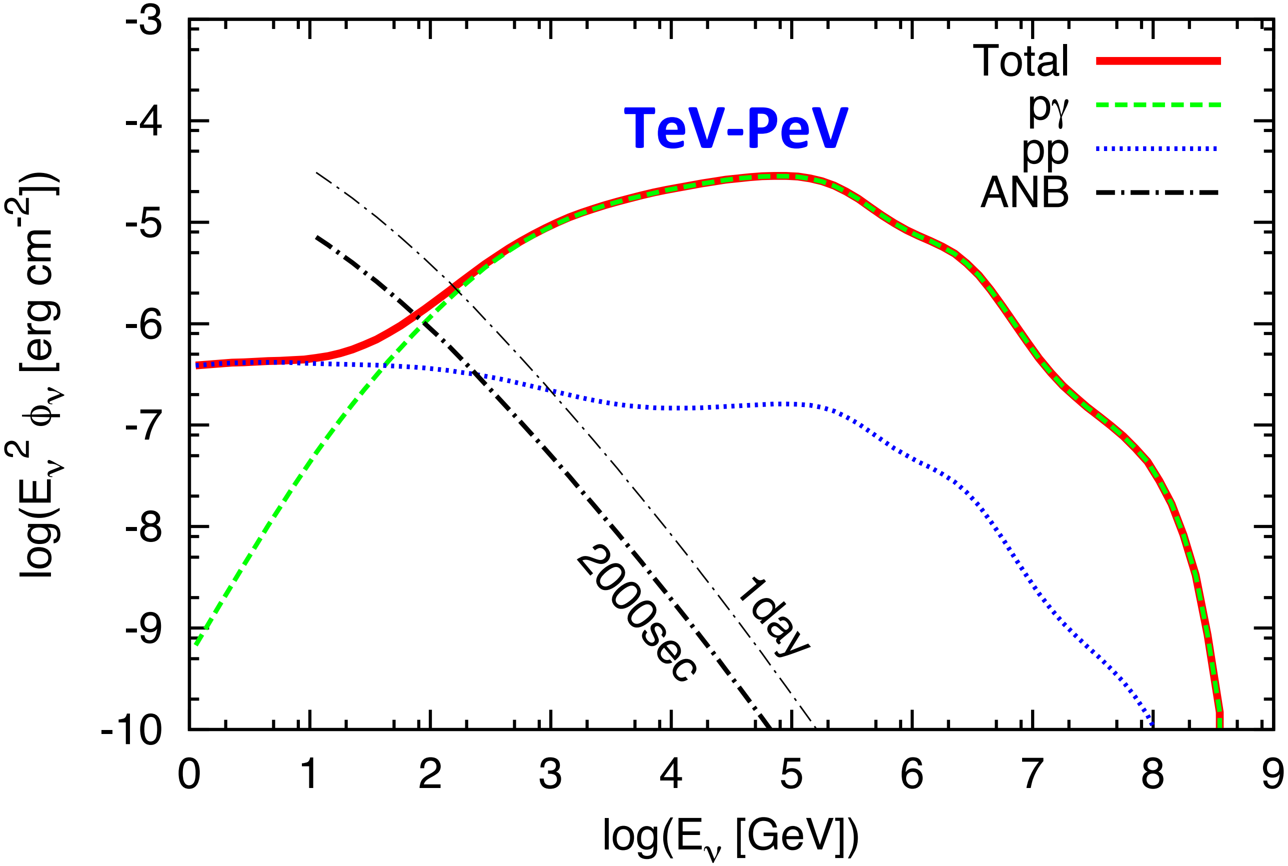


$$E_{\rm p} \lesssim 6.3 \left(\frac{\xi_{\rm B}}{0.1}\right)^{-1/4} \left(\frac{\eta}{2\pi}\right)^{-1/2} {r_{\rm sb,13.8}}^{1/4} {\beta_{\rm sh}}^{-1/2}\ {\rm EeV}.$$

Protons can be accelerated up to $\lesssim 10^{19}{\rm eV}$

The Neutrino Counterpart

Relativistic SN s.b.o @ 10Mpc



The anticipated number of muon events using IceCube/KM3net.

$$N_\mu \sim 0.2\ (\epsilon_{\rm CR}/0.2)(D_{\rm L}/10{\rm Mpc})^{-2} {r_{\rm sb,13.8}}^2 \beta_{\rm sh}$$

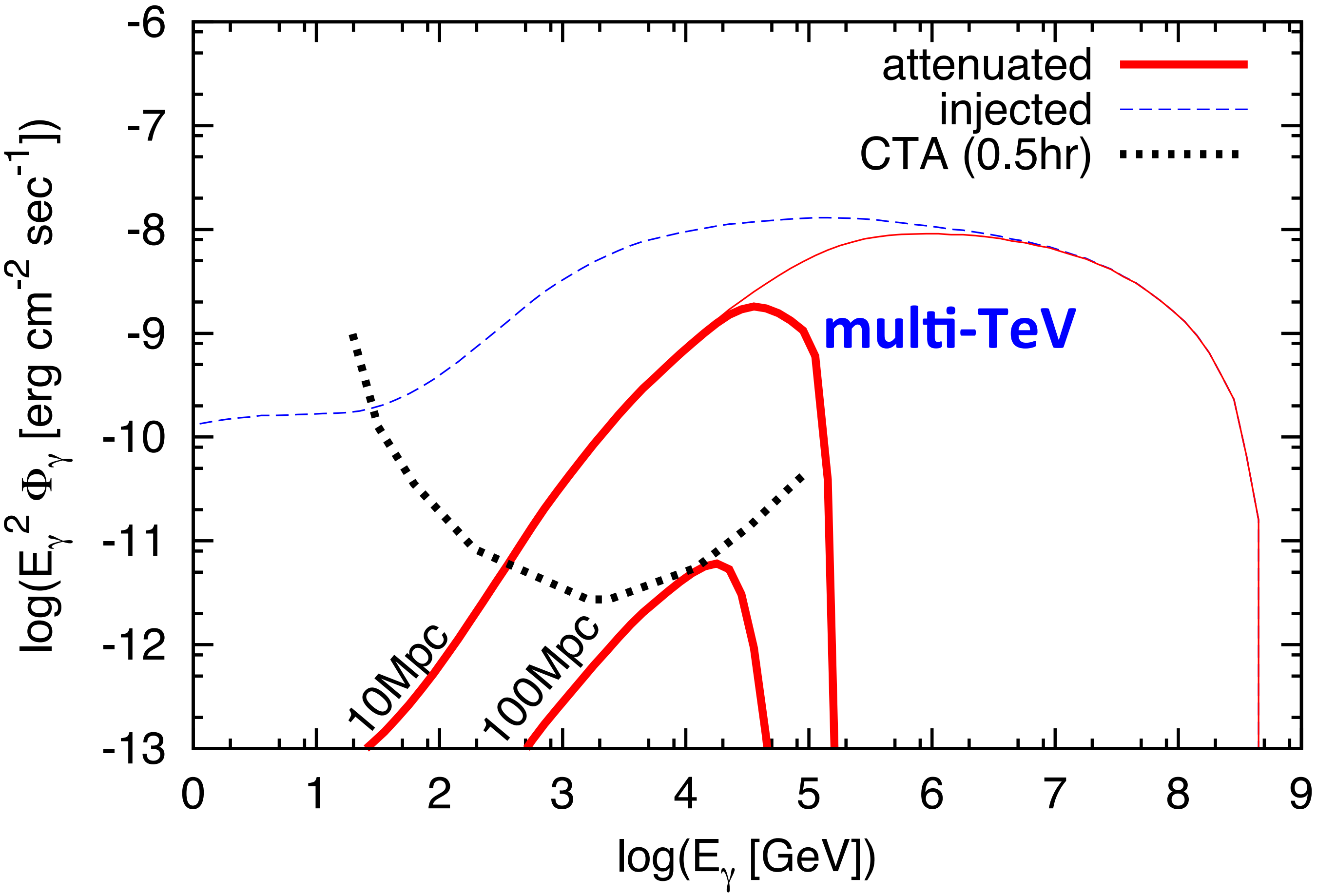
The neutrinos may be detectable from 10 Mpc away.

The Gamma-Ray Counterpart

Including the effect of

$$\gamma\gamma \to e^{\pm}$$

within the source and during propagation



The gamma rays can be detected even from 100 Mpc away by CTA!

Observation Strategies : TeV-PeV neutrino

- **The anticipated all-sky event rate**

$$R_{\rm LL}(z=0) \lesssim 500\ {\rm Gpc}^{-3}{\rm yr}^{-1}$$

$\Longrightarrow$ $\lesssim 0.002\ {\rm yr}^{-1}$ for $\leq 10\ {\rm Mpc}$

- **A statistical technique could be possible**

A decadal SN search up to $z \gtrsim 0.3$ with a sky coverage $\gtrsim 10\%$

$\Longrightarrow$ $O(10^5)$ relativistic SNe

$\Longrightarrow$ $\gtrsim O(1)$ astrophysical muon events by stacking

possible in the LSST era ?

Observation Strategies : multi-TeV gamma

- **The anticipated all-sky event rate**

$$R_{\rm LL}(z=0) \lesssim 500~{\rm Gpc^{-3}yr^{-1}}$$

$\Longrightarrow$ $\lesssim 2~{\rm yr^{-1}}$ for $\leq 100~{\rm Mpc}$

The FOV of CTA $\sim 5~{\rm deg}$ would not be wide enough for a blind search...

- **A rapid follow-up observation is necessary.**

A wide-field X-ray telescope with a sky coverage $\gtrsim 10\%$

$\Longrightarrow$ $\lesssim 0.2~{\rm yr^{-1}}$ LL GRBs

A Swift-type instrument is needed.

4. summary and discussion

Summary

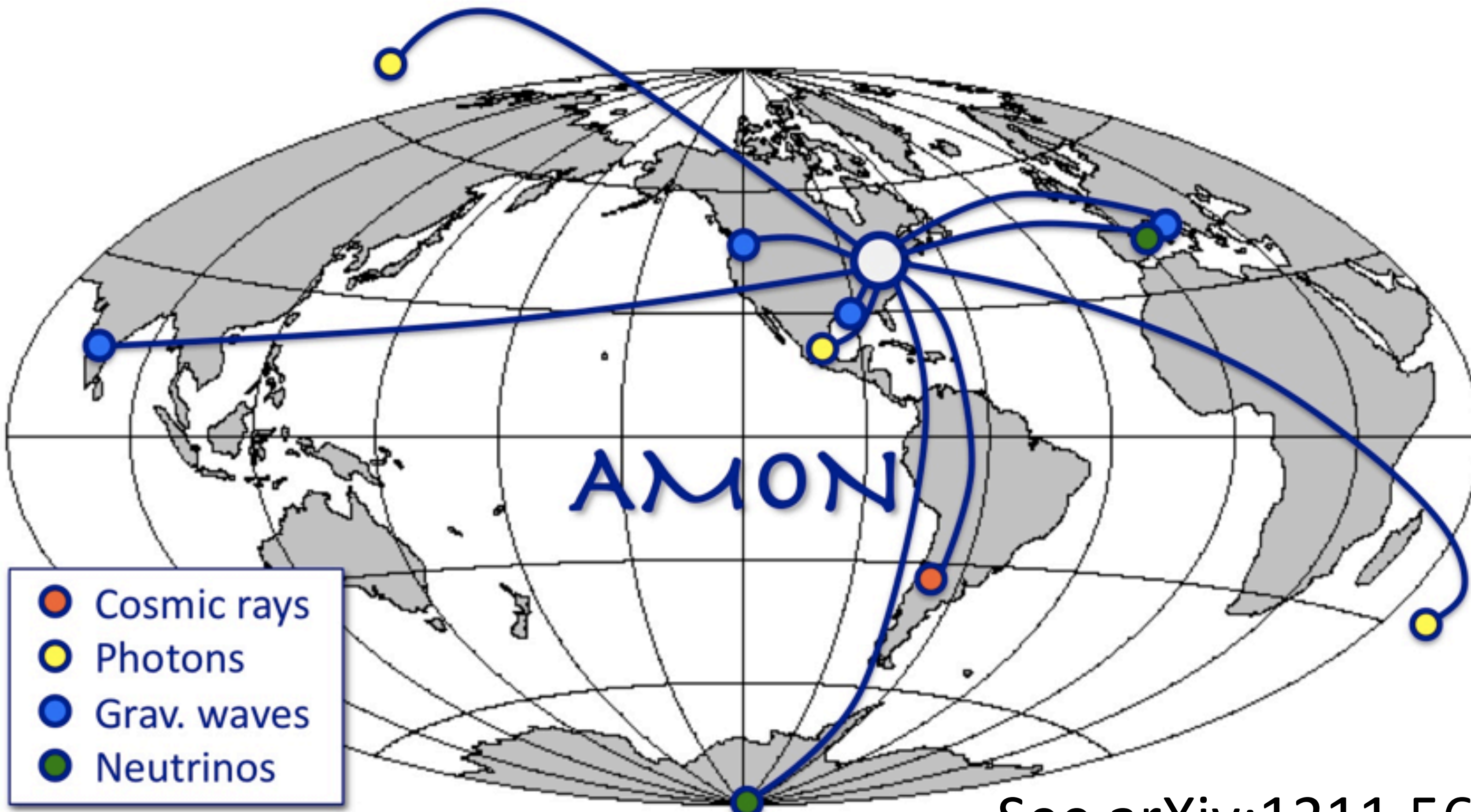
- **Relativistic SN shock breakouts**
  - LL GRBs?
  - The breakout X-ray photons
    → probing the progenitor and its environment
  - Transition form Radiation-mediated to collisionless
    → Particle acceleration in the presence of the b.o X-rays
- **The neutrino counterpart**
  - TeV-PeV ones could be detectable by IceCube from 10 Mpc.
  - A stacking approach could be also possible in the LSST era.
- **The gamma-ray counterpart**
  - Multi-TeV ones could be detectable by CTA even from 100 Mpc.
  - A rapid follow up triggered by a Swift-type instrument is needed.

Gravitational-Wave Counterpart

- ？？？
- LL GRBs may be *choked*.
  - Possible GW counterparts as successful long GRBs
- Generally, GW emitters as violent phenomena would accompany relativistic ejecta, which inevitably breaks at some radii.
- In any case, HE neutrino or gamma rays would not be a good channel to be blindly searched…

AMON

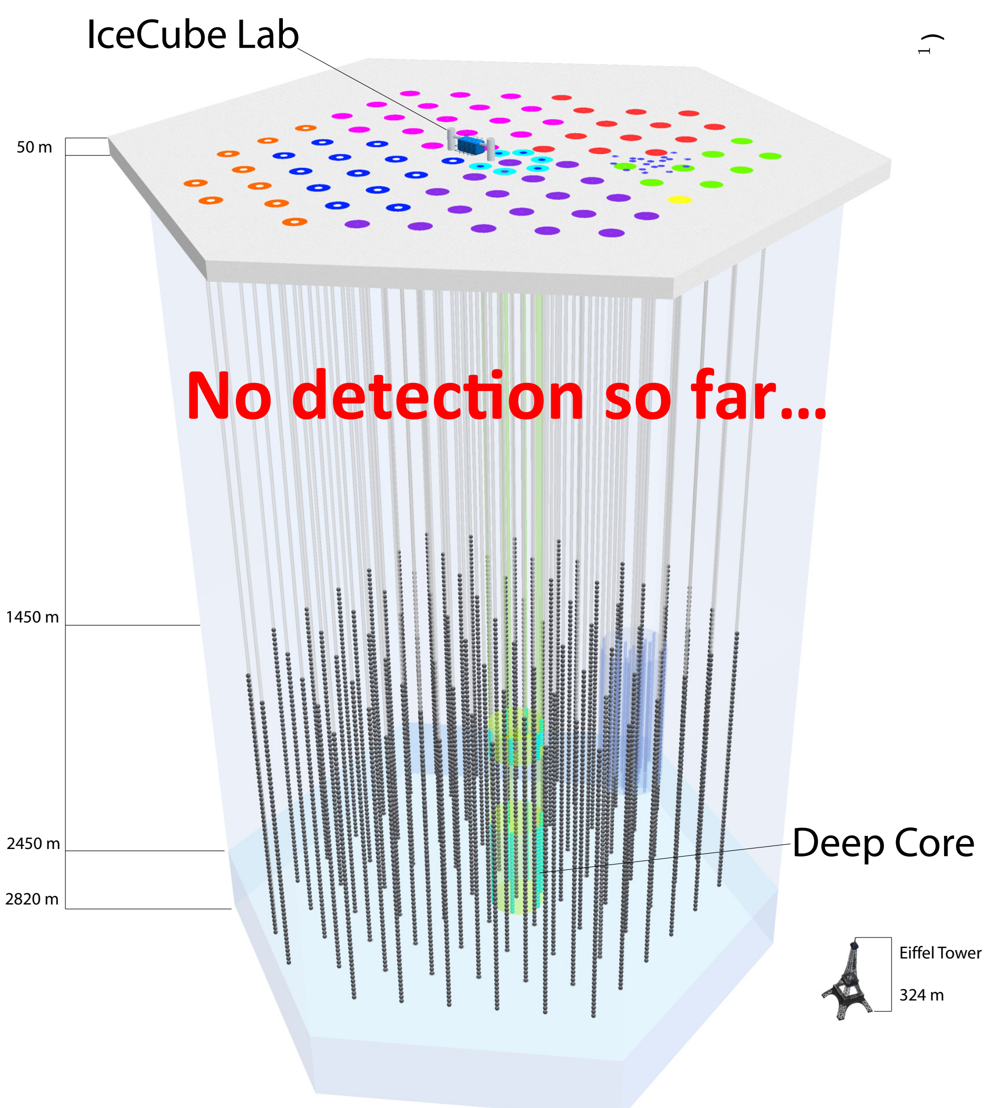
Astrophysical Multimessenger Observatory Network



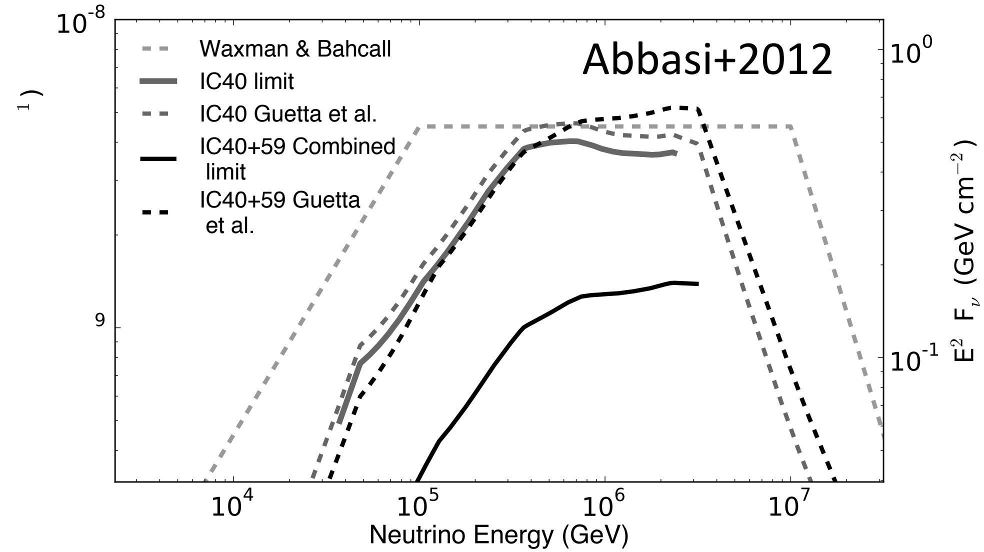
See arXiv:1211.5602

Backups

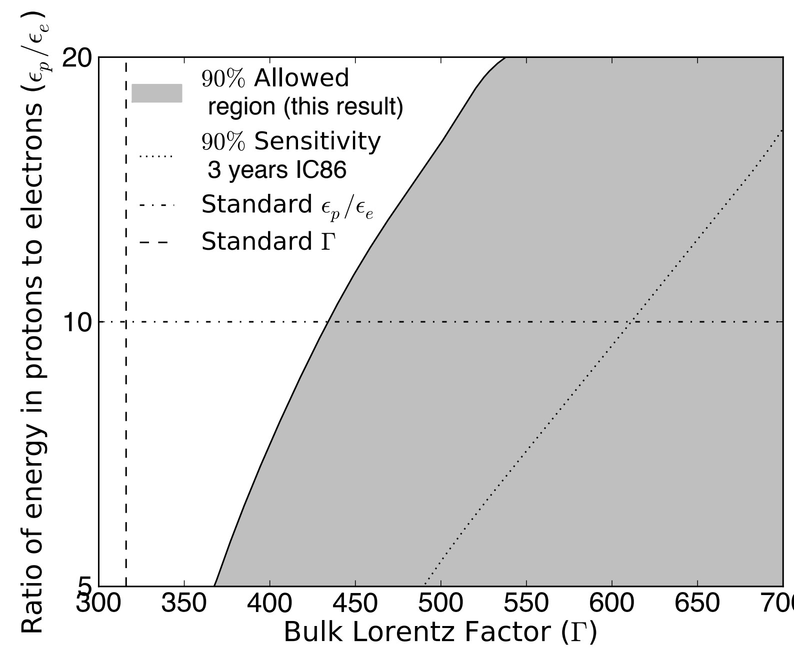
IceCube Constraints on GRB Prompt Neutrino



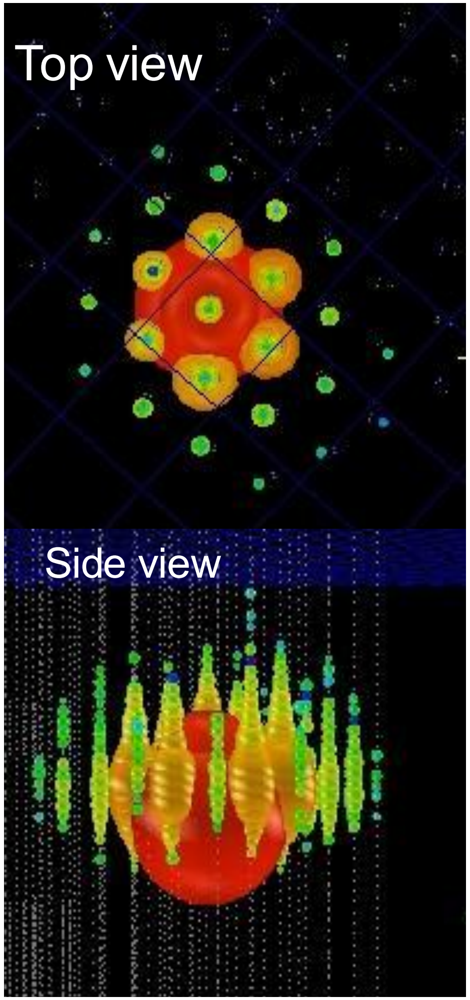
No detection so far…



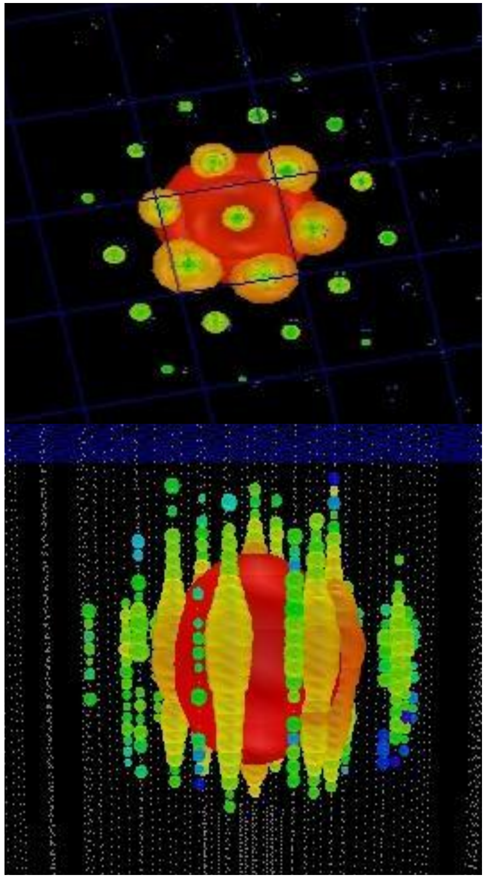
A model dependent constraint



The Two Electron-Cascade Events



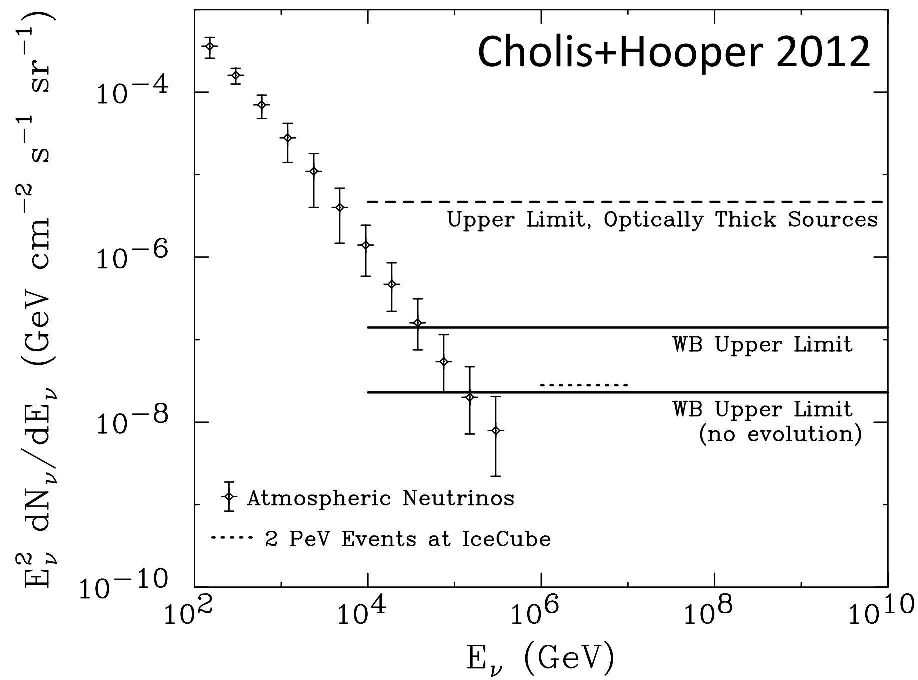
Aug 2011
1.14 PeV



Jan 2012
1.3 PeV

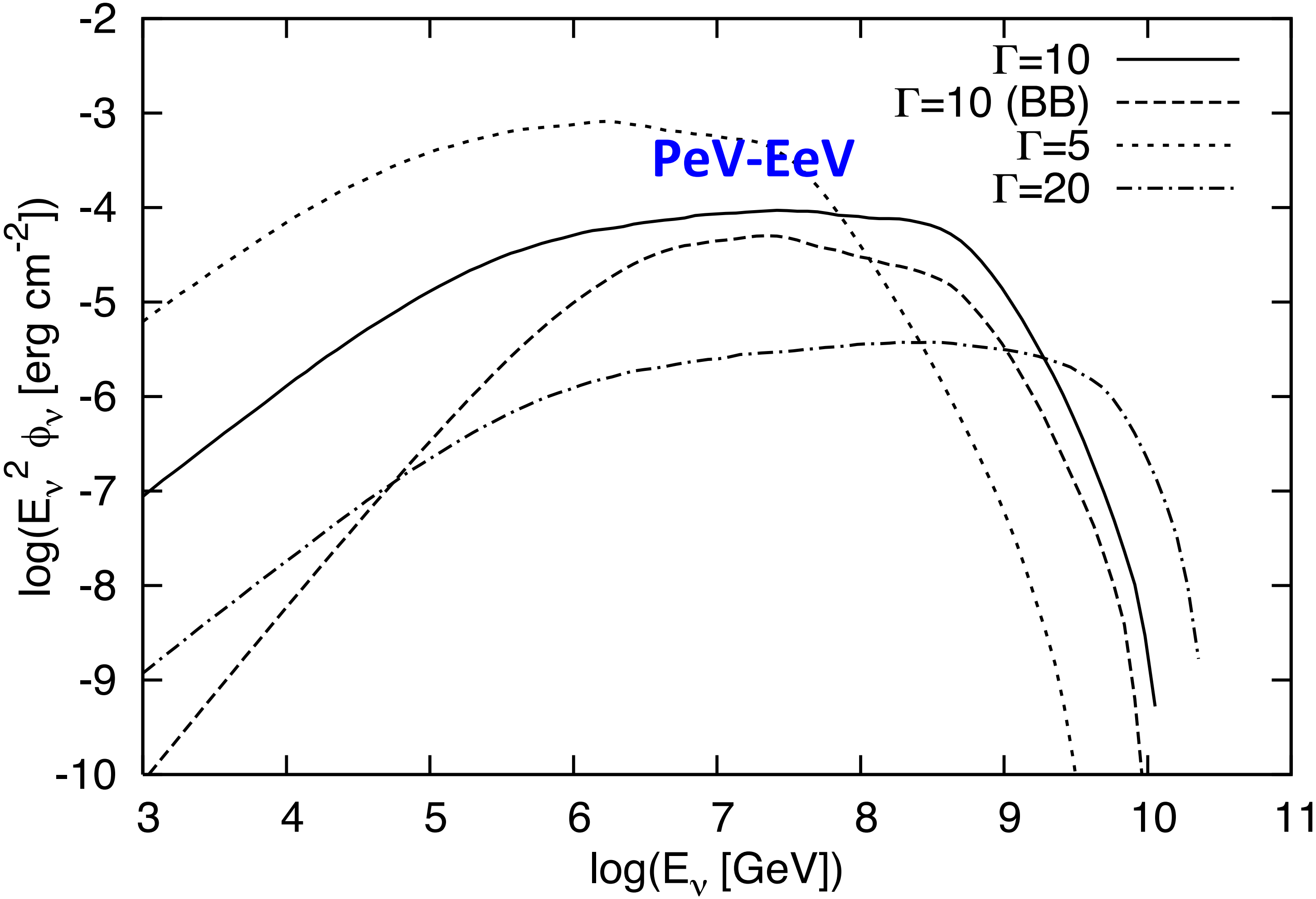
Ishihara 2012

2 event/670days
b.g. exp. 0.057 events



Astrophysical or not?
Muon-track events have been confirmed?

vs jet scenario



✓ **PeV-EeV neutrino, not TeV-PeV**

✓ **Multi-TeV gamma-ray counterpart cannot be expected.**