Neutrino Emission from GRB Sources

— Prospect of Detection

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IV PHD SUMMER SCHOOL ON NEUTRINOS HERE, THERE & EVERYWHERE

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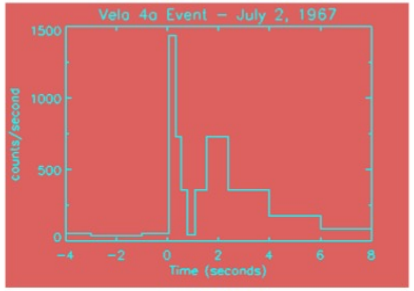
Gamma-ray burst (GRB)

Discovery : 1967-1973



THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

The Vela ("Watch") Satellites (1959-1985)
Monitor compliance with the 1963 Partial Test Ban Treaty by the Soviet Union

Stage 1: 1967(1973) – 1990
(dark era)

By mid 90's, 118 different theoretical models

Stage 2: 1991-1996
(CGRO(BATSE) era)

Stage 3: 1997-2003
(BeppoSAX-HETE era)

Stage 4: 2004-2008
(Swift era)

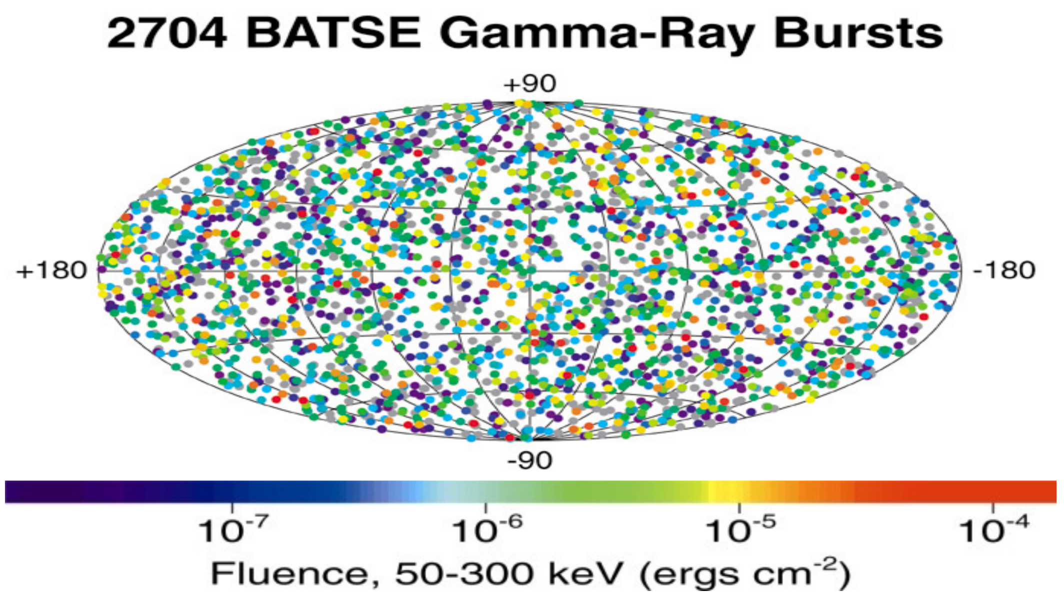
Stage 5: 2008 -
(Fermi/Swift era)

Flashes in Gamma-ray band, about 1-3 GRBs detected per day

Observational Facts of GRBs (Stage 2)

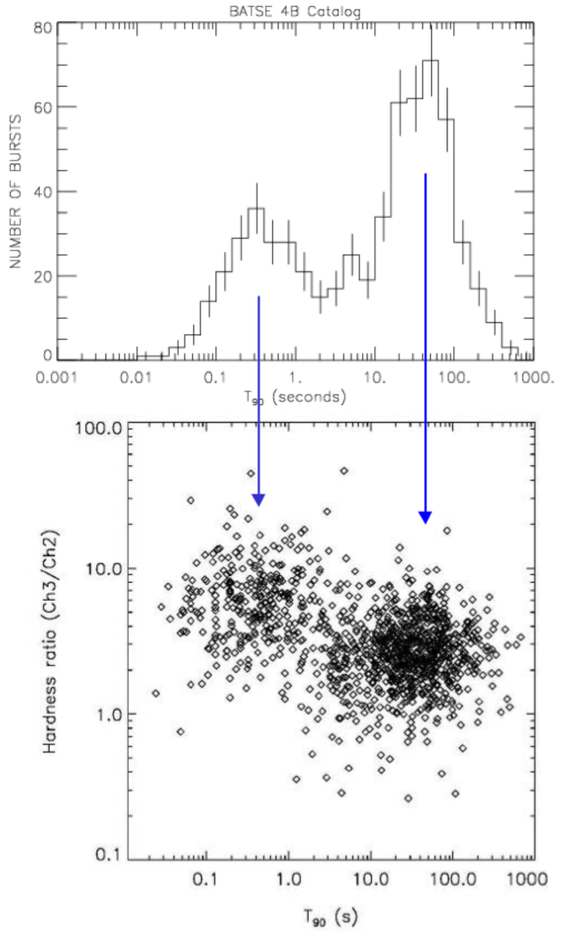
Early samples : 1991-1996

Isotropically distributed



Credit: NASA/Marshall Space Flight Center/Space Sciences Laboratory

Long GRBs vs. short GRBs

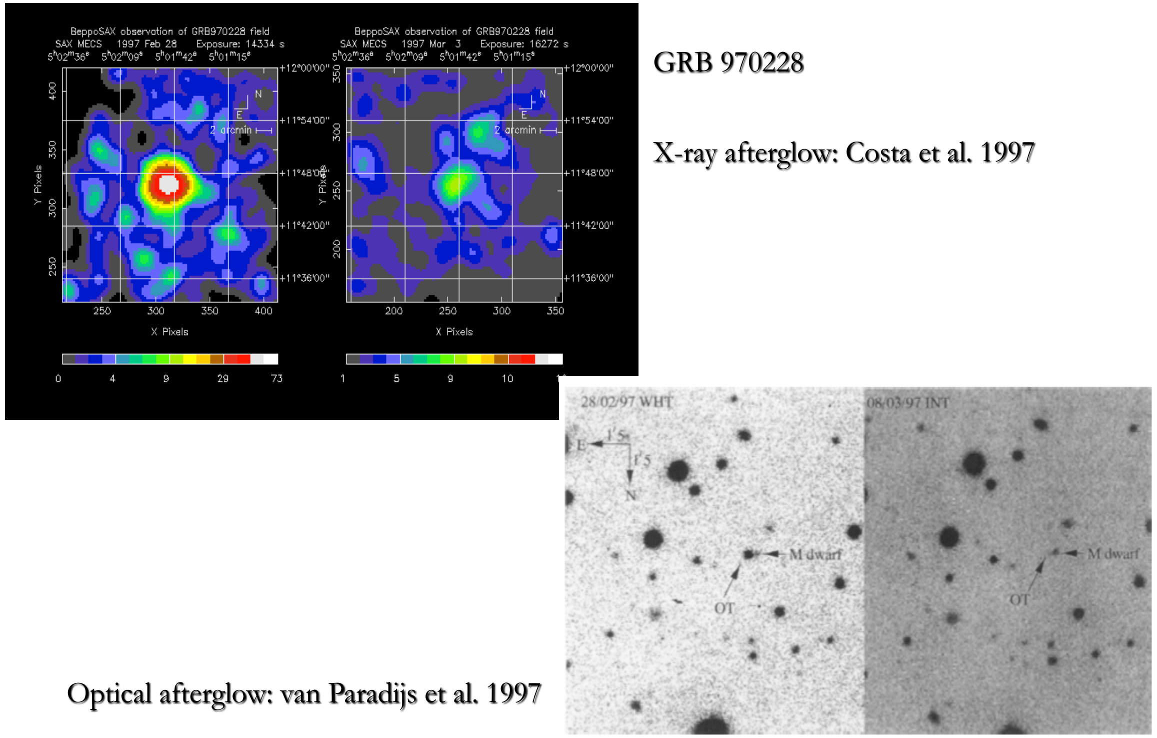


(Kouveliotou et al., 1993)

- ☐ **have an extragalactic origin**
- ☐ **have different types**

Observational Facts of GRBs (Stage 3)

Detection of GRB afterglow



GRB 970228

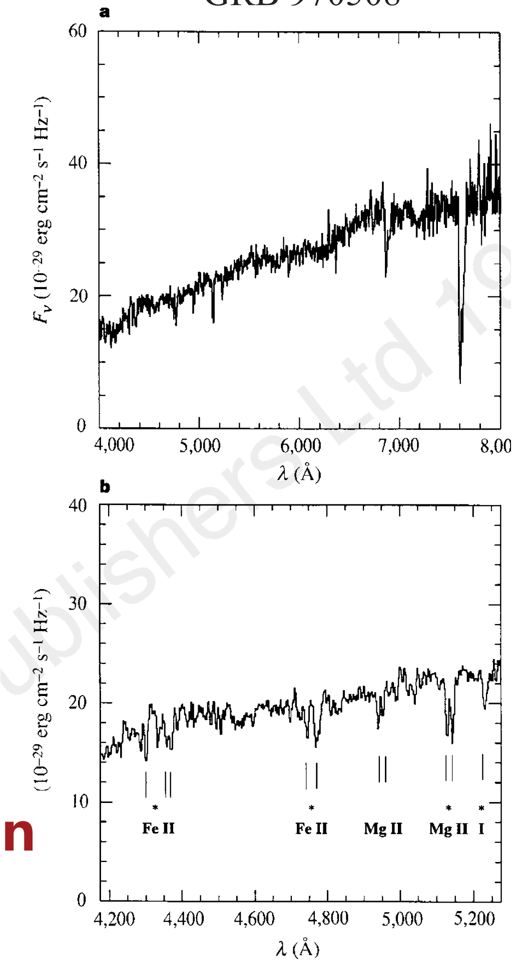
X-ray afterglow: Costa et al. 1997

Optical afterglow: van Paradijs et al. 1997

NATURE | VOL 386 | 17 APRIL 1997

Determination of redshift

GRB 970508



Luminosity estimation

Galactic halo:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{42}\,\mathrm{erg/s}\left(\frac{d}{30\,\mathrm{kpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

Cosmological:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{51}\,\mathrm{erg/s}\left(\frac{d}{1\,\mathrm{Gpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

For comparison:

$$L_\otimes \sim 10^{33}\,\mathrm{erg/s},\quad L_{gal} \sim 10^{44}\,\mathrm{erg/s},\quad L_{\mathrm{AGN,M}} \sim 10^{48}\,\mathrm{erg/s}$$

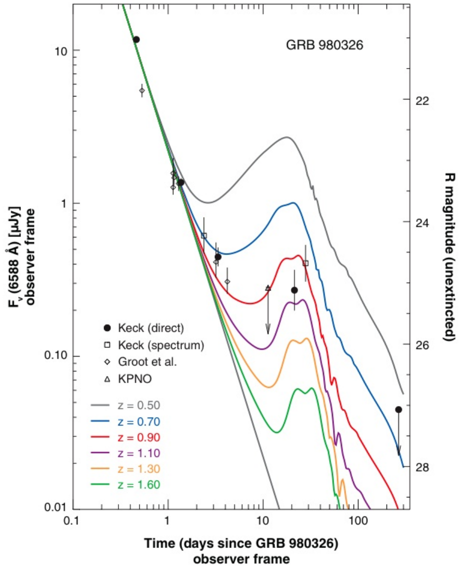
(Metzger et al. 1997)

- ☐ **GRBs have multi-wavelength radiation**
- ☐ **GRBs originate from distant universe**

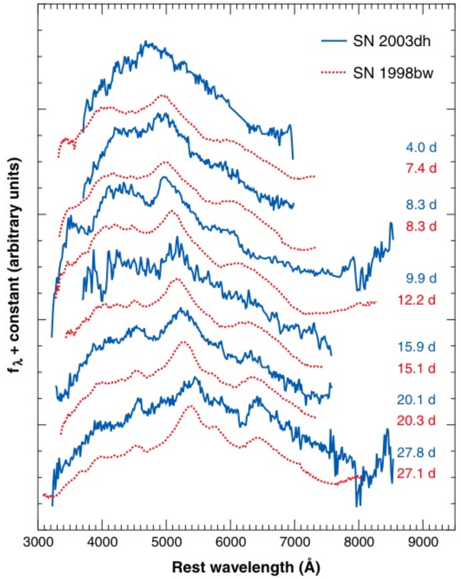
Observational Facts of GRBs

The origin of long GRBs

GRB/SN associations



Bloom et al. (1999)



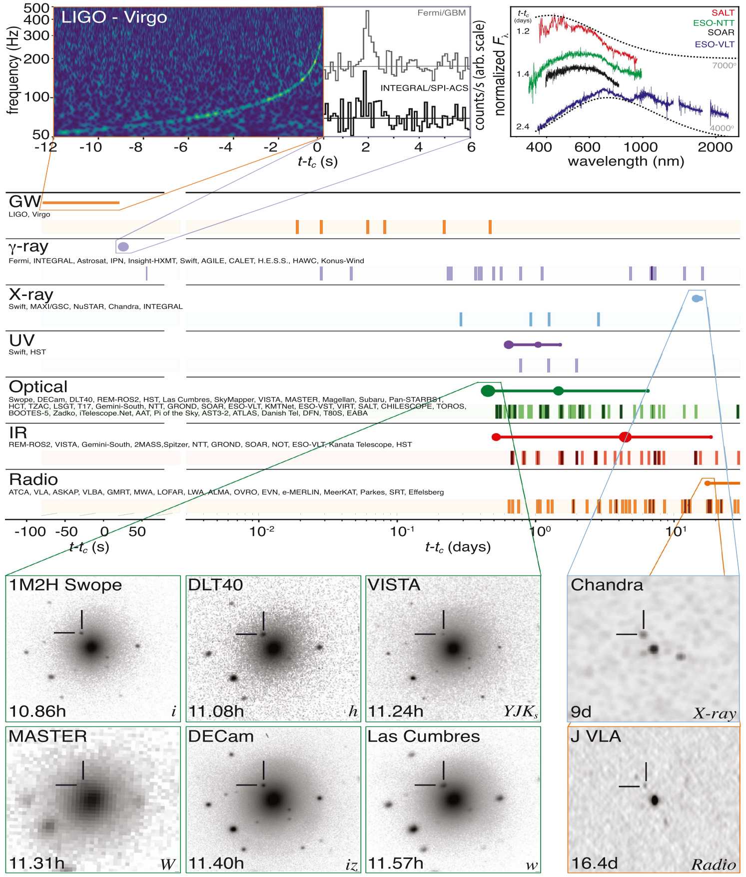
Hjorth et al. (2003)

A few (5) solid cases. Others are consistent.
Host galaxy with active star formation.

Collapse of massive stars

The origin of short GRBs

GW 170817/GRB/KN

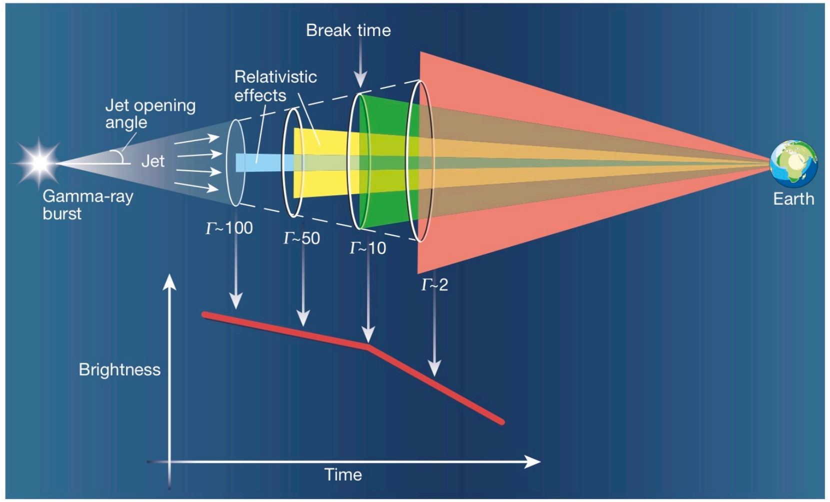


(Abbott et al. 2017)

Binary-neutron-star mergers

Observational Facts of GRBs : Relativistic Jet

Woosley (2001)



*** The huge luminosity of GRBs raises the "Compactness Problem".**
*** The only solution is that the GRB ejecta is moving with a speed very close to speed of light!**

Compactness Problem

For isotropic emission, total radiated energy

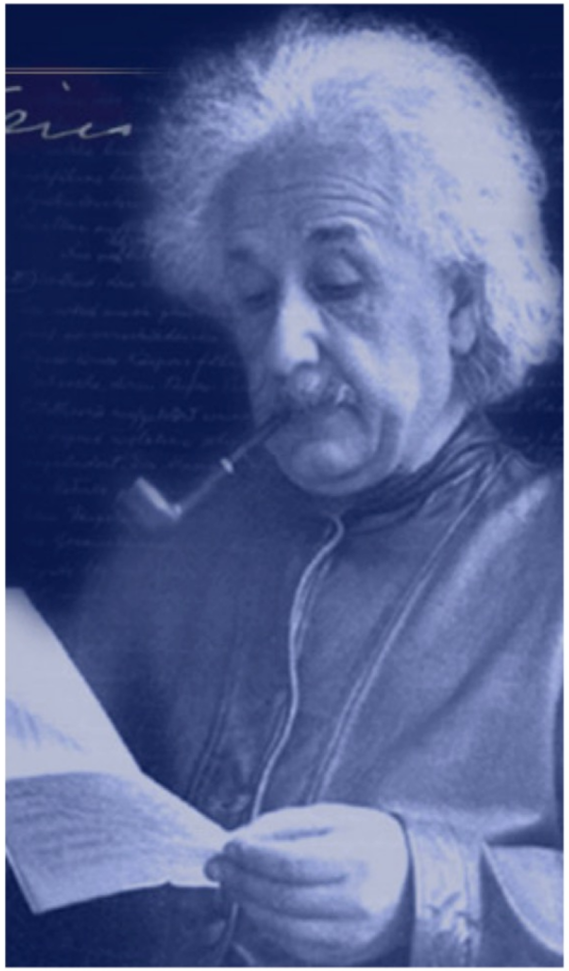
$$E_0 = F(4\pi D^2)$$
$$\approx 10^{51}(F/(10^{-6}\mathrm{ergs/cm^2}))(D/(3\mathrm{Gpc}))^2.$$

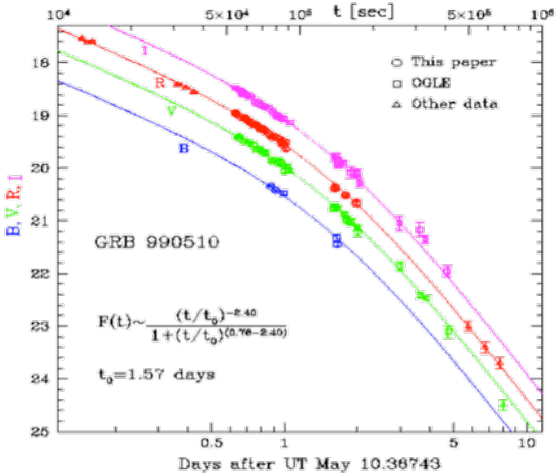
The source size $R_i = c\delta T \simeq 3\times 10^7\ \mathrm{cm}\,\delta T_{-3}$.
The optical depth for $\gamma\gamma \longrightarrow e^+e^-$, $\tau_{\gamma\gamma}$, is very large:

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{R_i^2 m_e c^2}$$
$$\sim 10^{17} f_p \left(\frac{F}{10^{-6}\mathrm{ergs/cm^2}}\right)\left(\frac{D}{3\ \mathrm{Gpc}}\right)^2\left(\frac{\delta T}{1\ \mathrm{ms}}\right)^{-2},$$

where f_p denotes the fraction of photon pairs satisfying $\sqrt{E_1 E_2} > m_e c^2$.

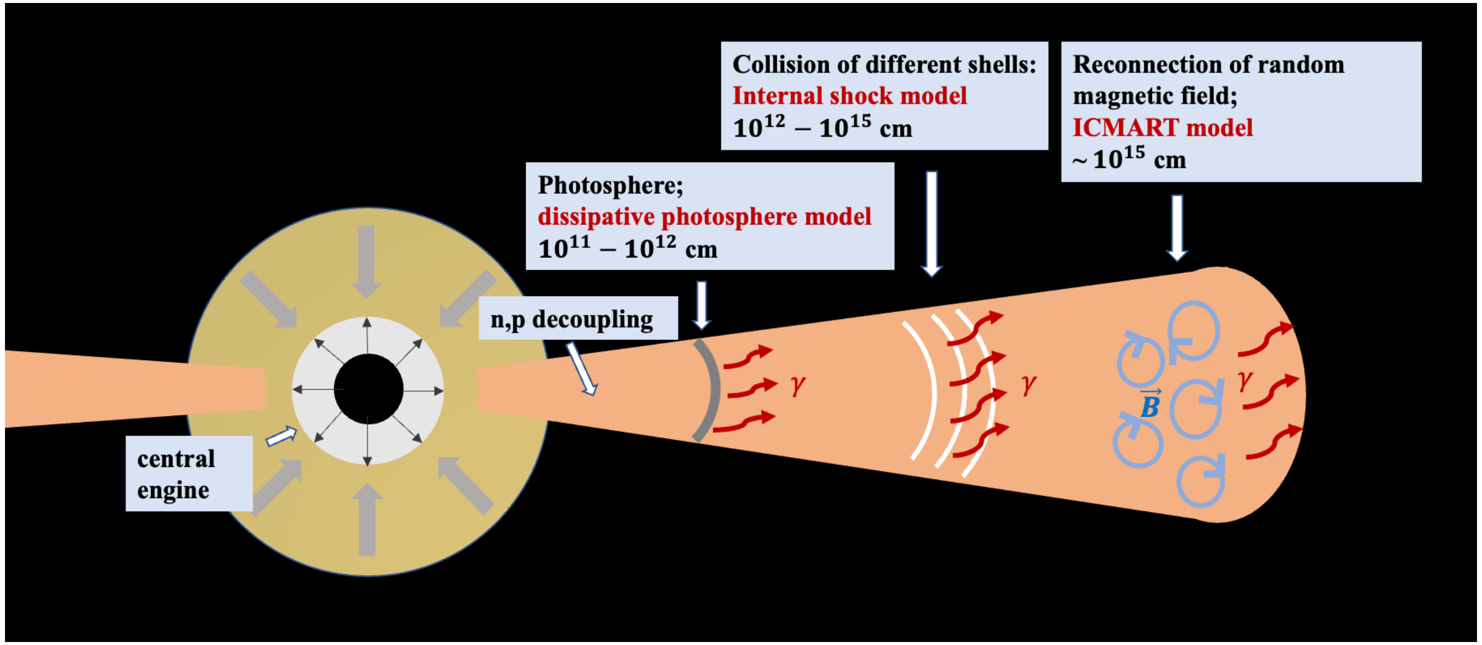
$$\frac{\tau_{\gamma\gamma}(\mathrm{R})}{\tau_{\gamma\gamma}(\mathrm{NR})} = \frac{f_R R_R^{-2}}{f_{NR} R_{NR}^{-2}} = \Gamma^{2\beta-2} \qquad \beta \sim -2.2$$





Stanek et al. 99

GRB prompt emission model



- **Dissipative photosphere model**
  (Rees & Meszaros 2005)
  $R_{ph} \sim 3.7 \times 10^{11} \mathrm{cm}\ L_{w,52} \Gamma_{2.5}^{-3}$
- **Standard internal shock model**
  (Rees & Meszaros 1994)
  $R_{IS} = 2\Gamma^2 c\delta t_{min} \sim 10^{12} - 10^{13} \mathrm{cm}$
- **ICMART model**
  Internal-Collision-Induced MAgnetic Reconnection and Turbulence
  (Zhang & Yan 2010)
  $R_{ICMART} \sim 10^{15} \mathrm{cm}$

Almost everything related to GRBs has been comfirmed, **except for the prompt emission model.**

Could the detection of neutrinos be helpful?

Neutrino emission: pγ interaction

Δ-resonance $E_p E_\gamma \sim 0.16\ \mathrm{GeV}^2 \left(\frac{\Gamma}{1+z}\right)^2$

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu, & \text{fraction } 1/3, \\ p\pi^0 \rightarrow p\gamma\gamma, & \text{fraction } 2/3. \end{cases}$$

π^+ typically carries ~1/5 of proton energy
Each lepton shares 1/4 of the π^+ energy

$$E_\nu \cong 0.05 E_p$$

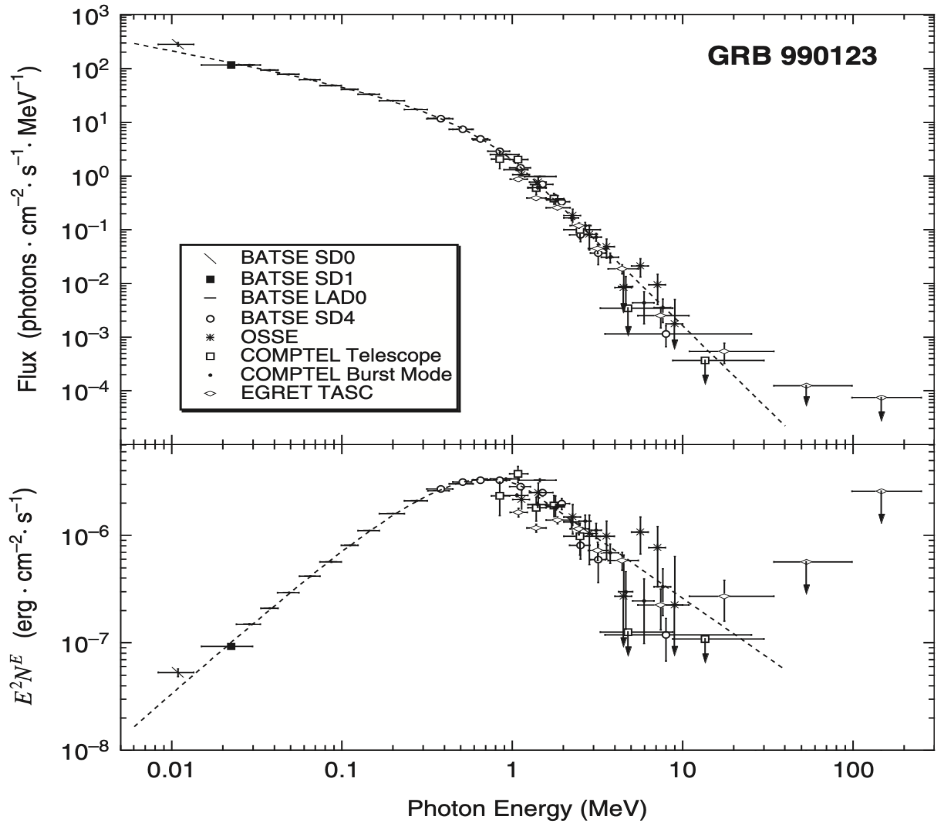
$E_\gamma \sim 1\mathrm{MeV};\ \Gamma \sim 100$ ➡ $E_\nu \sim 10^4 - 10^5 \mathrm{GeV}$ **IceCube range**

Neutrino Emission

Spectrum of GRBs: Band function

$$n_\gamma(E_\gamma) = \frac{dN_\gamma(E_\gamma)}{E_\gamma} = n_{\gamma,b}\begin{cases}\epsilon_{\gamma,b}^{\alpha} E_\gamma^{-\alpha}, & E_\gamma < \epsilon_{\gamma,b} \\ \epsilon_{\gamma,b}^{\beta} E_\gamma^{-\beta}, & E_\gamma \geqslant \epsilon_{\gamma,b},\end{cases}$$

(Band et al., 1993, Briggs et al. 1999)



Spectrum of GRB neutrino

$$n_\nu \propto n_p \tau_{p\gamma} \propto E_p^{-p} E_p^{(\alpha\ or\ \beta)-1}$$

$$n_\nu(E_\nu) = \frac{dN(E_\nu)}{dE_\nu} \propto \begin{cases}\epsilon_{\nu_1}^{\alpha_\nu} E_\nu^{-\alpha_\nu}, & E_\nu \le \epsilon_{\nu,1} \\ \epsilon_{\nu_1}^{\beta_\nu} E_\nu^{-\beta_\nu}, & \epsilon_{\nu,1} \le E_\nu \le \epsilon_{\nu,2} \\ \epsilon_{\nu_1}^{\beta_\nu} \epsilon_{\nu_2}^{\gamma_\nu - \beta_\nu} E_\nu^{-\gamma_\nu}, & E_\nu \ge \epsilon_{\nu,2}\end{cases}$$

$\alpha_\gamma/\beta_\gamma$: gamma-ray spectra index (Band function)
p: proton spectra index
$\epsilon_{\nu,1}$: depends on the break in GRB spectrum
$\epsilon_{\nu,2}$: determined by π^+ synchrotron cooling

$$\alpha_\nu = p + 1 - \beta_\gamma;\ \ \beta_\nu = p + 1 - \alpha_\gamma;\ \ \gamma_\nu = \beta_\nu + 2$$

Neutrino Emission

$$\int_{\epsilon_{\nu,1}}^{\epsilon_{\nu,2}} n_\nu E_\nu dE_\nu = \boxed{\frac{1}{8}} \int_{E_{p,1}}^{E_{p,2}} f_\pi E_p \frac{dN_p}{dE_p} dE_p,$$

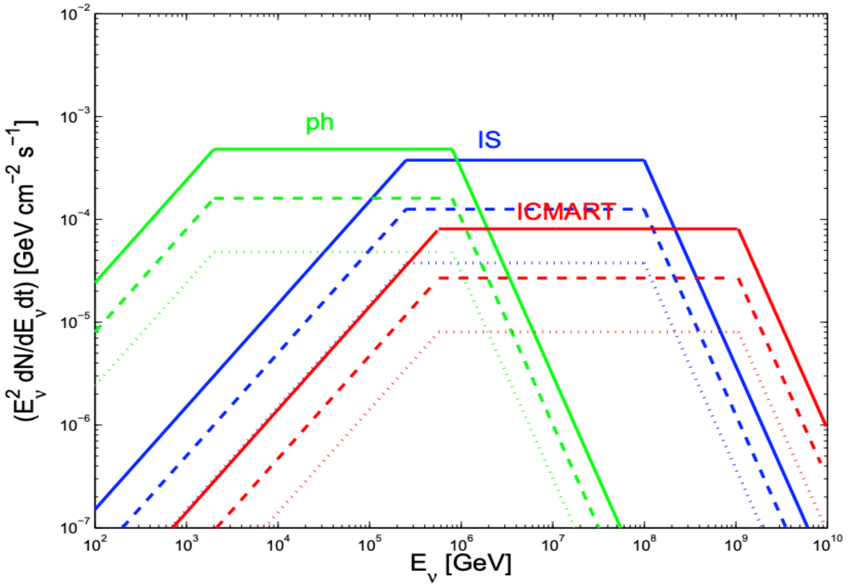
$$\frac{1}{8} = \frac{1}{2} \times \frac{1}{4}$$

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu, & \text{fraction } 1/3, \\ p\pi^0 \rightarrow p\gamma\gamma, & \text{fraction } 2/3. \end{cases}$$

→ $1/2$

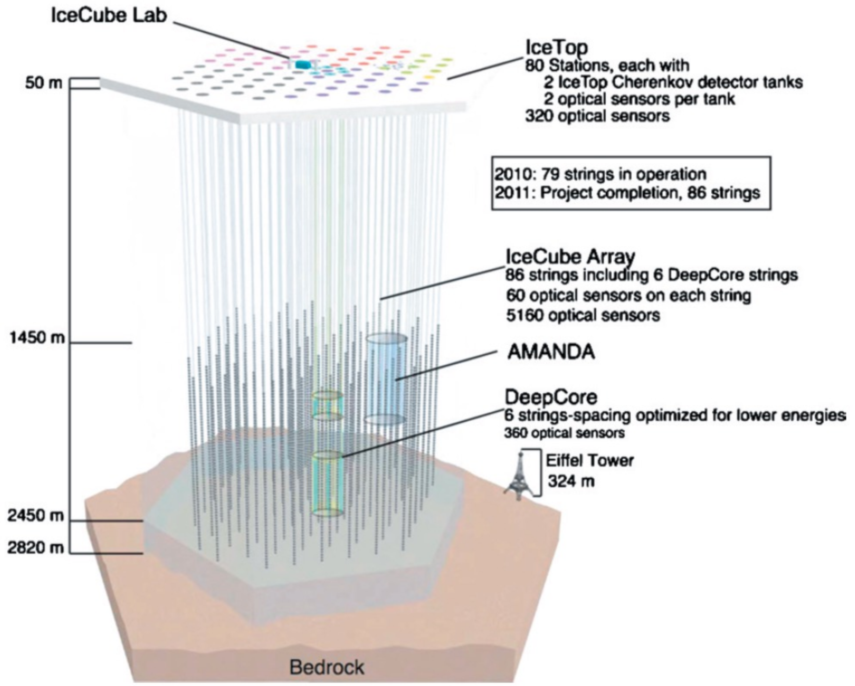
$$\frac{dN_p}{dE_p} = \frac{\boxed{(\epsilon_p/\epsilon_e)} E_{\rm GRB}}{\ln(E_{p,\max}/E_{p,\min})} E_p^{-p}$$

$$\phi_\nu(E_\nu) = \frac{E_\nu^2 n_\nu(E_\nu)}{4\pi D^2}$$

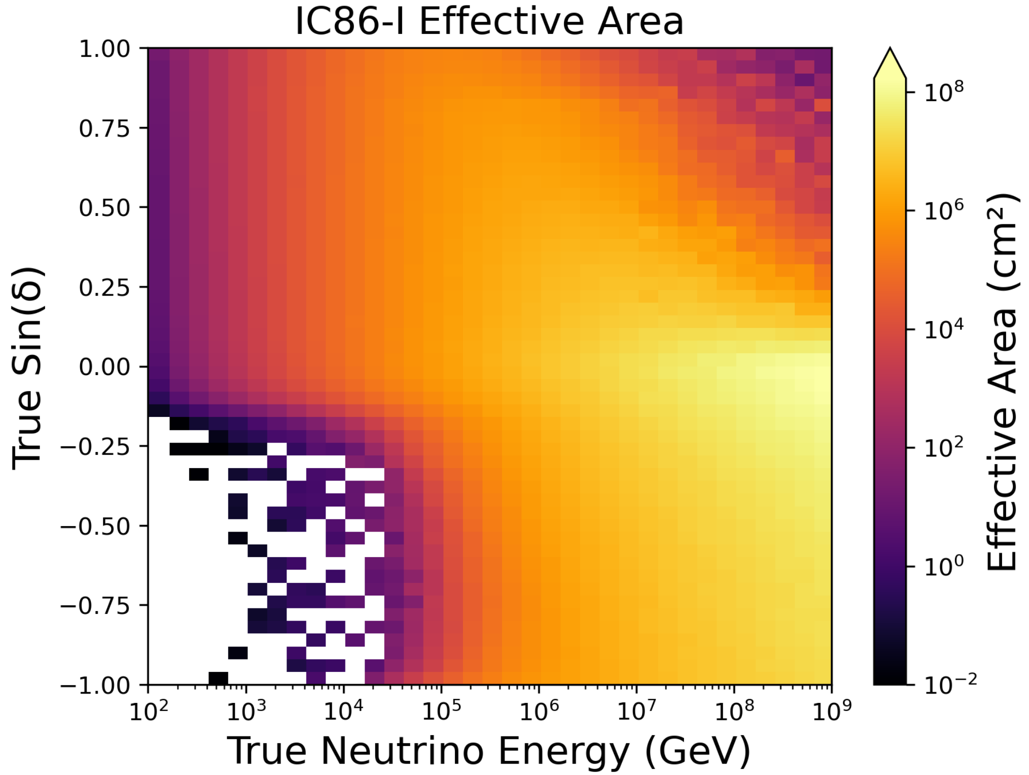


(Zhang & Kumar 2013)

IceCube Neutrino Detection



Credit: IceCube Science Team - Francis Halzen



- **Targeting on high-energy astrophysical neutrinos,** $10^2\mathrm{GeV} - 10^9\mathrm{GeV}$
- **Effective area depends source position ,** $A_{\mathrm{eff,max}} \sim 10^8\mathrm{cm}^2$

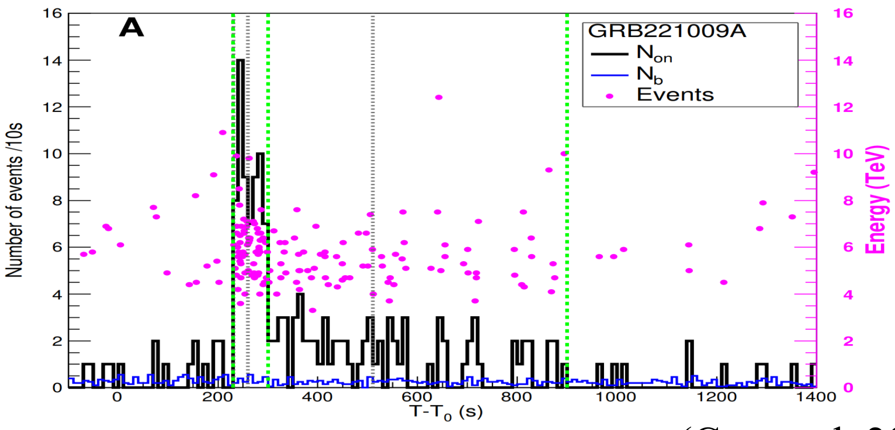
$$N_\nu = \int dt \int d\Omega \int_0^\infty dE A_{\mathrm{eff}}(E_\nu, \Omega)\phi_\nu(E_\nu, \Omega, t)$$

(IceCube Collaboration 2021) https://icecube.wisc.edu/datareleases/2021/01/all-sky-point-source-icecube-data-years-2008-2018/

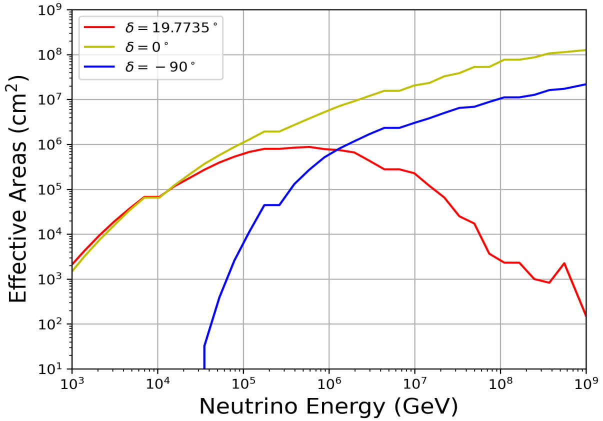
Current Status of GRB neutrino detection: GRB 221009A

"The brightest GRB of all time (BOAT)"

$E_{\gamma,iso} \sim 10^{55}$ erg; $L_{\gamma,iso} \sim 10^{54}$ erg/s; z = 0.151



(Cao et al. 2023)



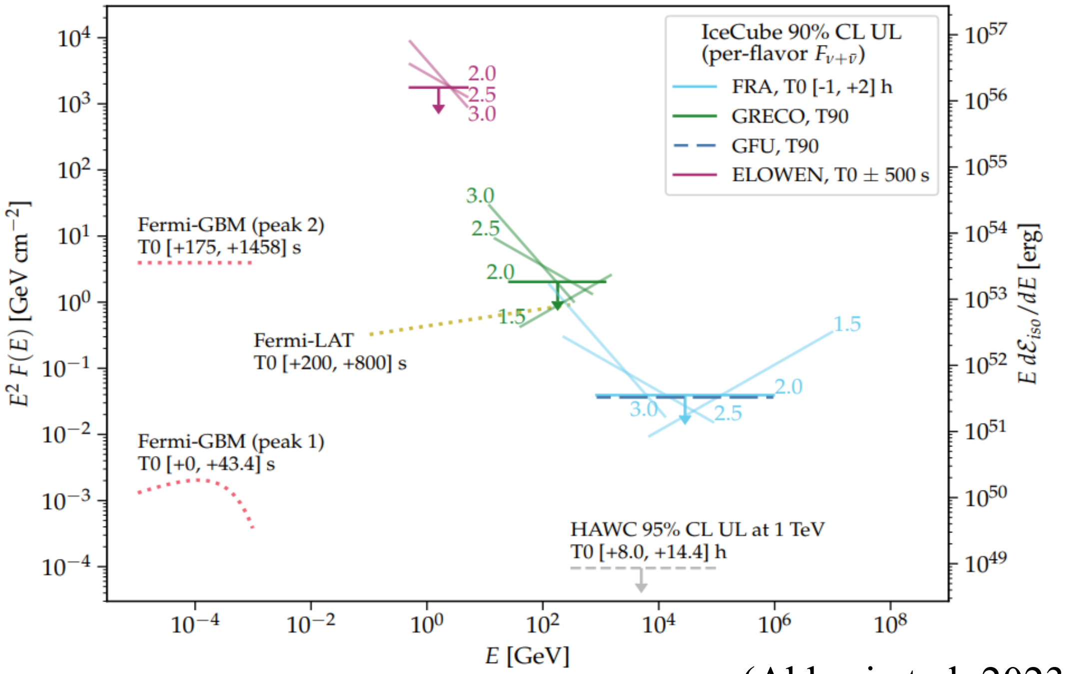
RA = 288.2645°

Dec = +19.7735°

Non-detection of associated neutrino IceCube provides the upper limit

$E_\nu^2 \phi_\nu < 4.1 \times 10^{-2}$ GeV cm^{-2}

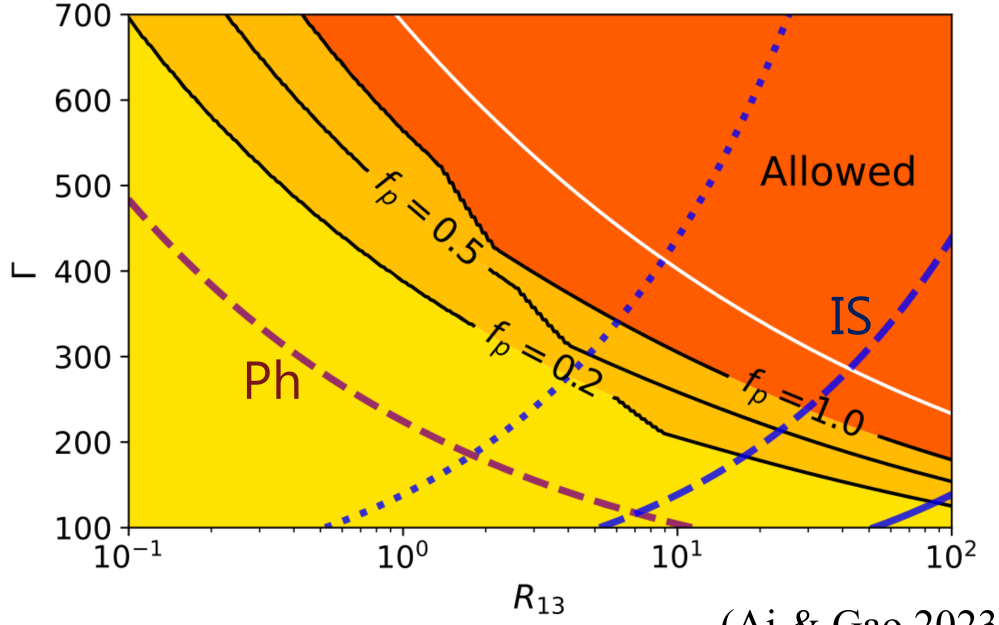
(based on E^{-2} neutrino spectrum)



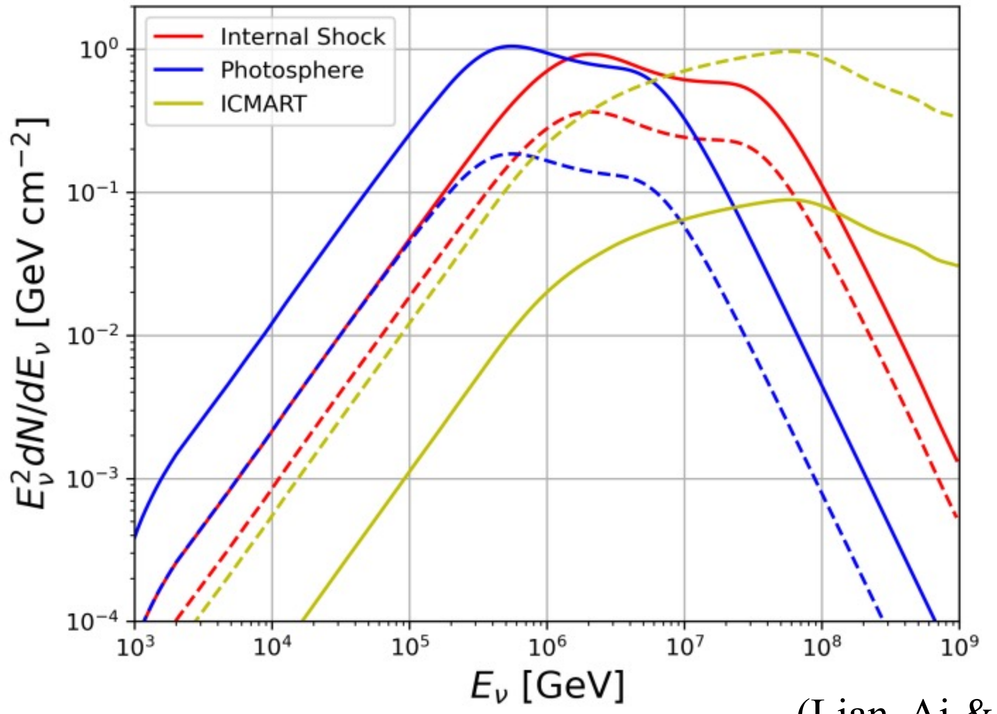
(Abbasi et al. 2023)

Current Status of GRB neutrino detection: GRB 221009A

Model selection



(Ai & Gao 2023)

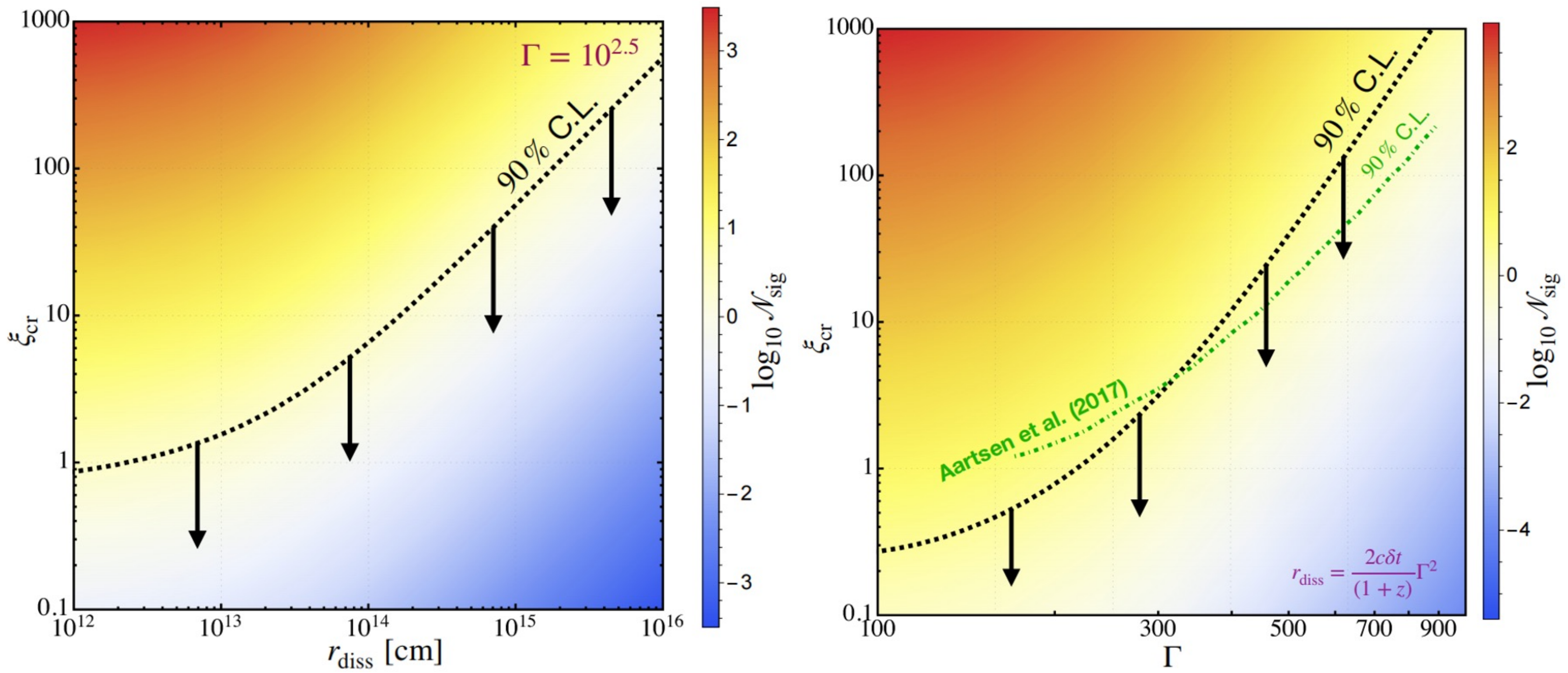


(Lian, Ai & Gao 2025)

- **Dissipative photosphere model → Disfavored**
- **Standard internal shock model → high radiation radius, high jet Γ required**
- **ICMART model → Survive**

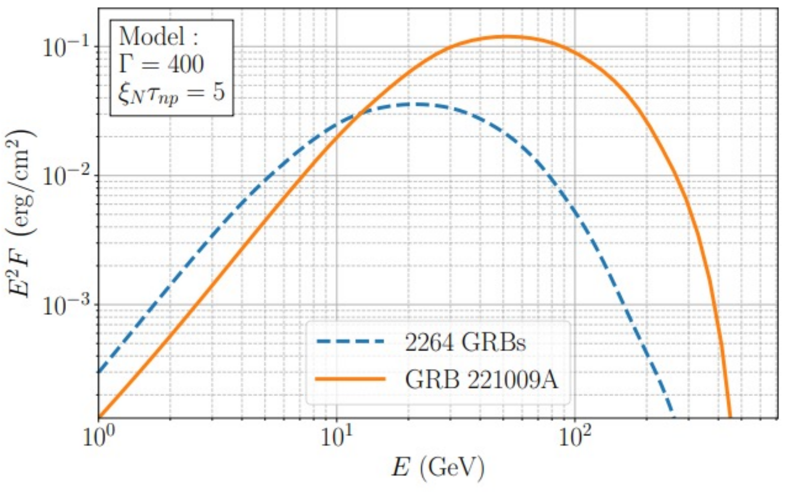
Current Status of GRB neutrino detection: GRB 221009A

Constraints on model parameters



(Murase et al. 2022)

Stacking GRBs



(Abbasi et al. 2024)

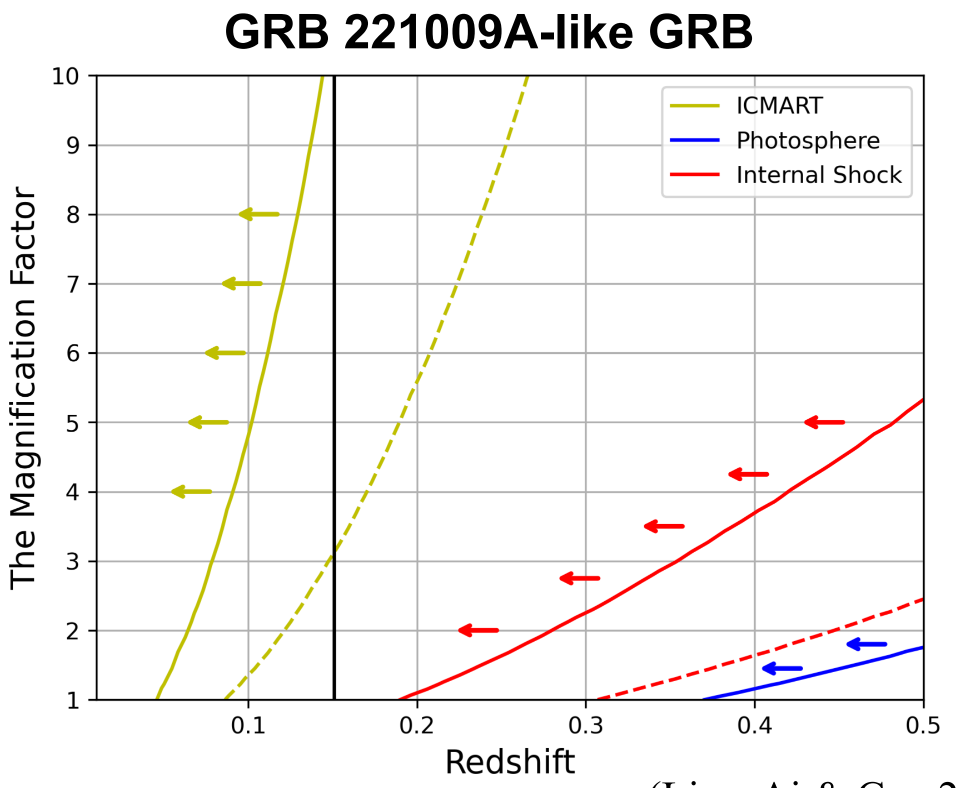
When $\Gamma = 300, R = 10^{15}$cm, $\xi_{cr} = \epsilon_p/\epsilon_e < \sim 10$
When $\Gamma = 300, R = 10^{14}$cm, $\xi_{cr} = \epsilon_p/\epsilon_e < \sim 3$

cannot provide tighter constraints than the'BOAT'.

Prospect of Neutrino Detection: Single GRB Event

How sensitive should a detector be?

- **Assume a future neutrino detector $\mathcal{M}$ times more sensitive than IceCube ($\mathcal{M} = A_{\mathrm{eff}}/A_{\mathrm{eff,IC86-II}}$)**



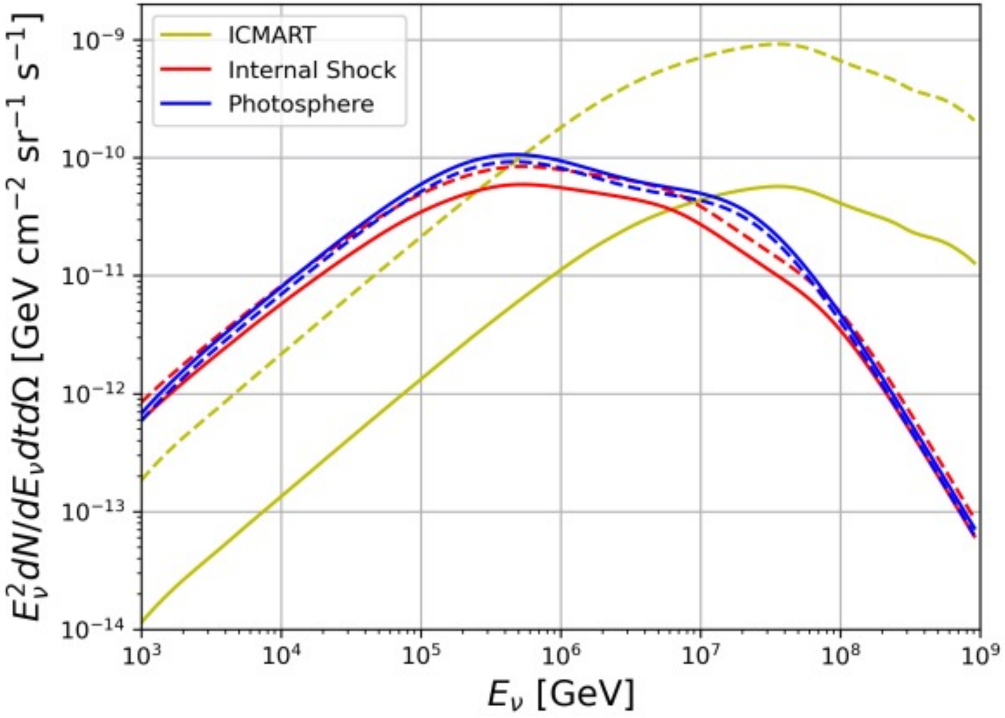
(Lian, Ai & Gao 2025)

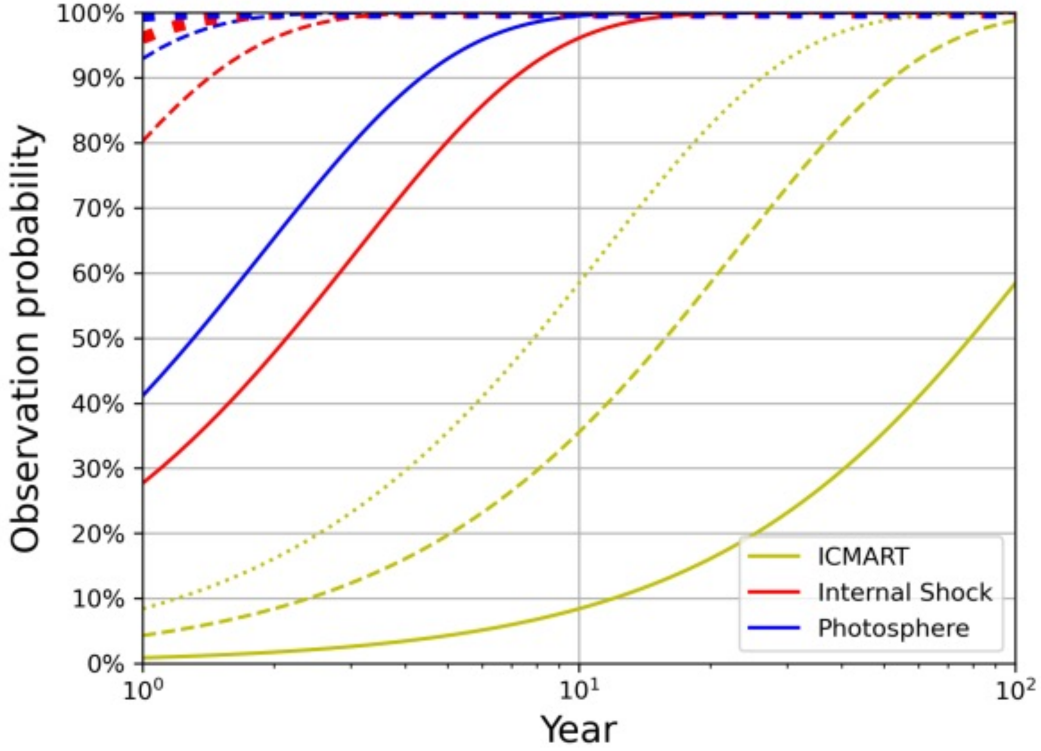
- ❑ **Photosphere model:**
  IceCube sensitivity → Detection limit $z \sim 0.37$
- ❑ **Standard internal shock model:**
  $\mathcal{M} = 5$ → Detection limit $z \sim 0.5$
- ❑ **ICMART model:**
- **Same distance and same sky position as GRB 221009A:**
  $\mathcal{M} = 10$ required
- **Same distance and best sky position:**
  $\mathcal{M} = 3$ required

Prospect of Neutrino Detection: Stacking GRBs

(Lian, Ai & Gao 2025)

2019 – 2023， 5-year sample, 1503 GRBs



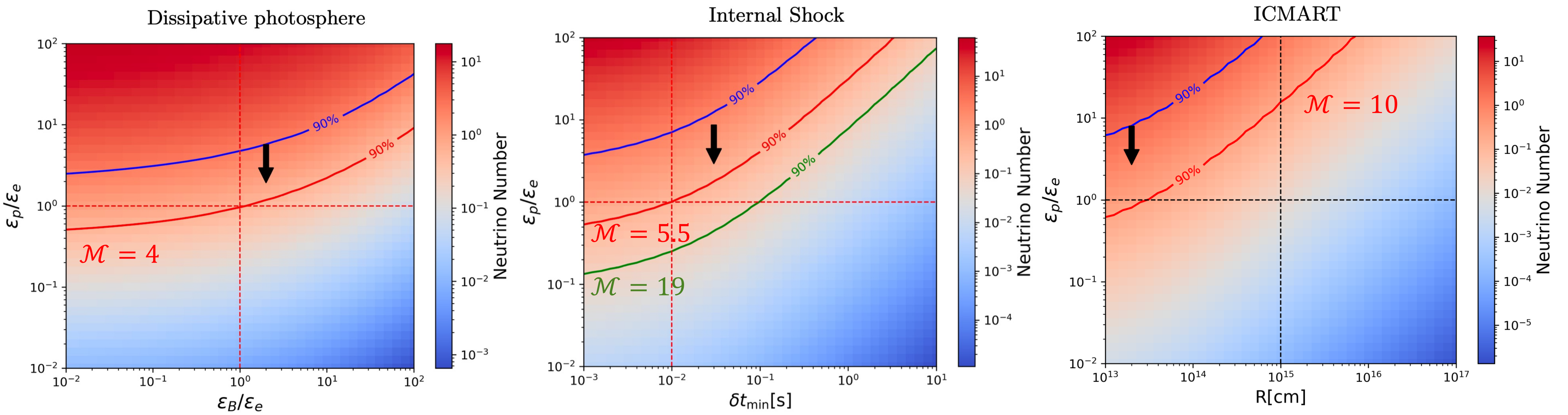


Enlarge the effective area by a factor of $\mathcal{M} = 5 - 10$

- **If GRBs originate from the photosphere model or the standard internal shock model, then after 5 years of data accumulation, the chance of detecting GRB-associated neutrinos is close to 100%.**
- **If GRBs originate from ICMART model, then after 5 to 10 years of data accumulation , the chance of detecting GRB-associated neutrinos could reach 35% - 60%**

Prospect of Neutrino Detection: Stacking GRBs

What if **GRB-associated neutrinos** are still **not detected** with advanced detector ⋯?

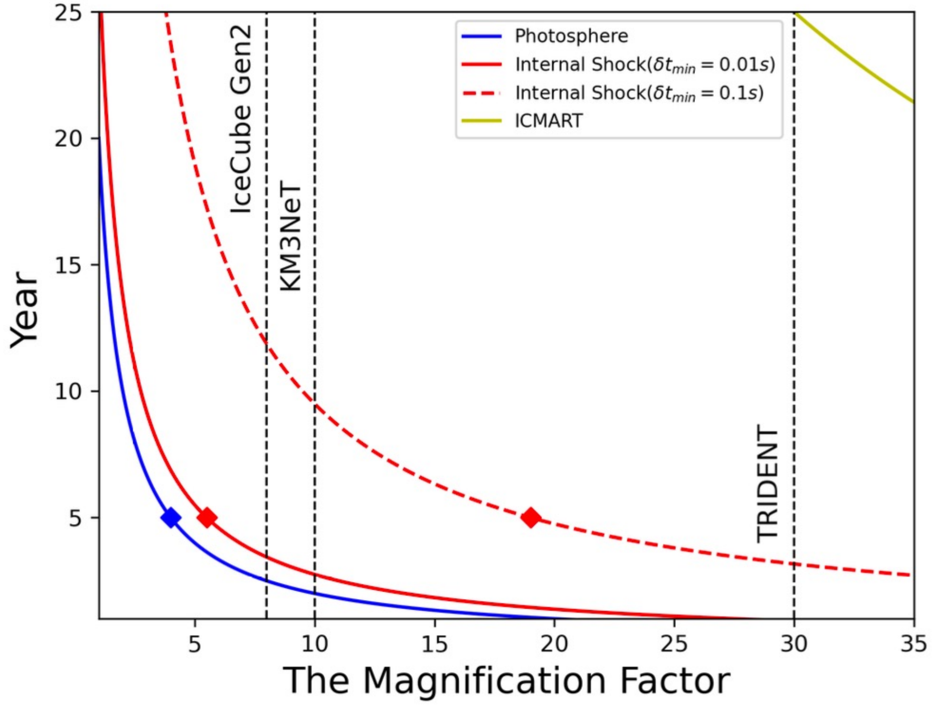


(Lian, Ai & Gao 2025)

- **More stringent constraints on model parameters**
- **Rule out the model** if the required parameter space is unreasonable.

Future high-energy neutrino detectors

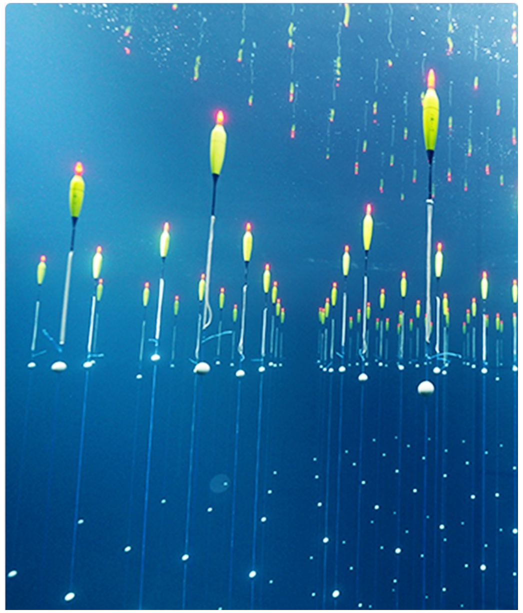
Stacking GRBs



(Lian, Ai & Gao 2025)

TRIDENT

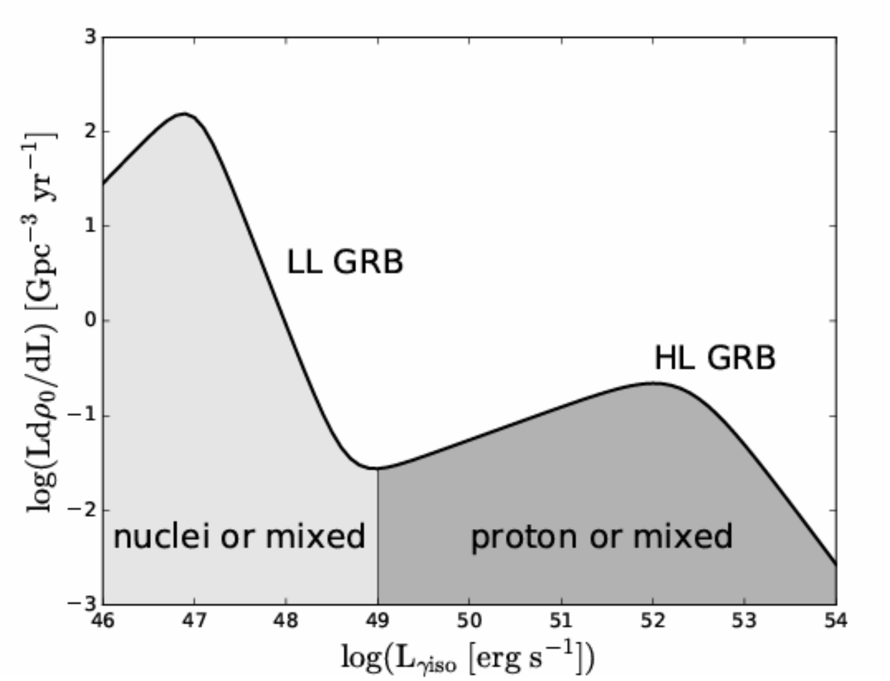
The tRopIcal DEep-sea Neutrino Telescope



TRIDENT Collaboration arXiv: 2207.04519

Prospect of Neutrino Detection: Low-Luminosity GRBs

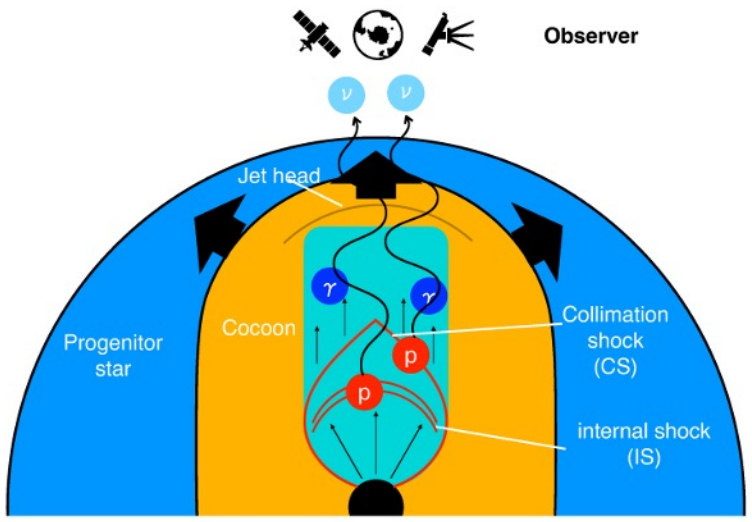
- **Low isotropic luminosity** : $10^{46}\sim10^{49}$ erg/s
- **High event rate: (100-200)** $\mathrm{Gpc^{-3}\ yr^{-1}}$
  200 times higher than high-luminosity GRBs



(Zhang et al. 2018)

Theotical model

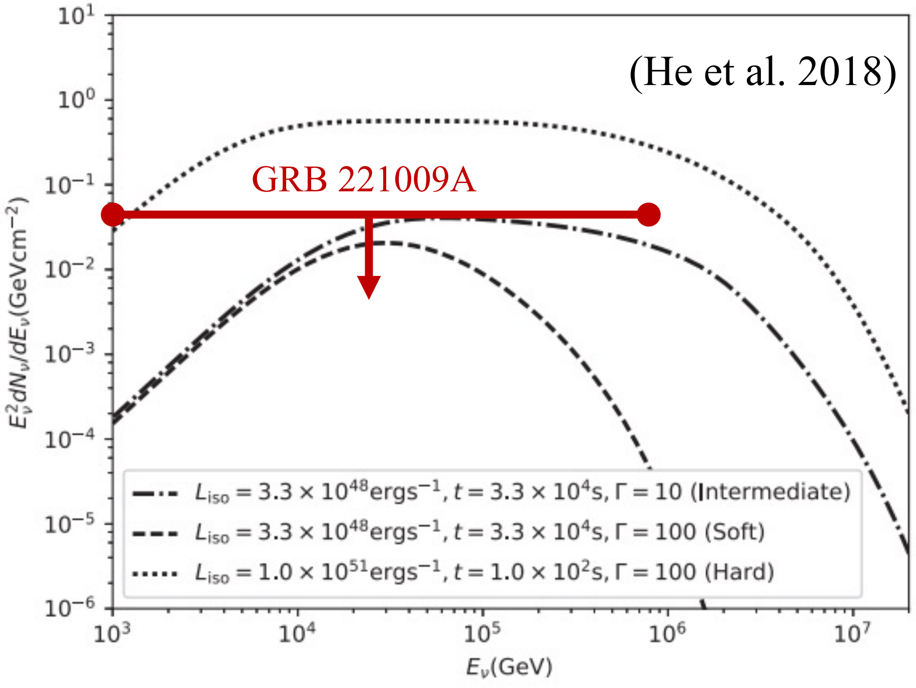
- **Model I: weak jet** $(\Gamma \leq 30)$
  high baryon loading $(\epsilon_p/\epsilon_e\sim20)$
  high neutrino flux
- **Model II: chocked jet**
  keV – MeV photons (shock breakout)
  trapped photons + accelerated protons produce high-energy neutrinos
  (Meszaros & Waxman 2001)



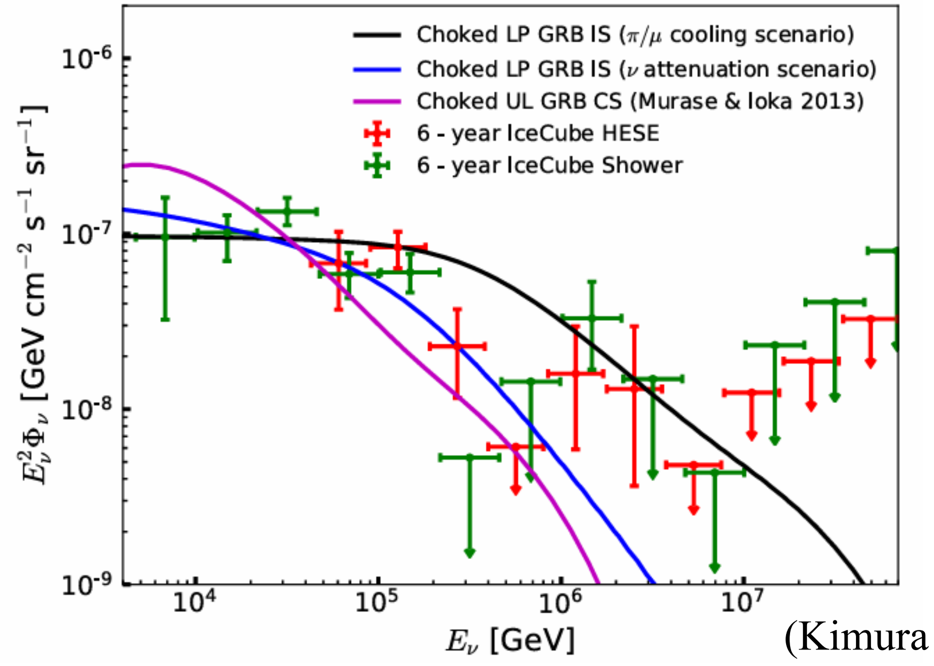
(Kimura 2022)

Prospect of Neutrino Detection: Low-Luminosity GRBs (LLGRBs)

Single chocked jet event， $1\ \mathrm{Gpc} \sim z = 0.2$



Diffuse neutrino background



(Kimura 2022)

- **Single LLGRB (chocked jet model) produce neutrinos with flux comparable with GRB 221009A (BOAT)**
- **Low γ-ray flux**

- **LLGRBs are considered one of the primary candidate sources of the IceCube diffuse neutrino background.**

Summary and Discussion

- Multi-messenger detection with **neutrinos** is significant for **differentiating GRB prompt emission models.**
- The **neutrino flux** associated with GRBs is **lower than anticipated**.
- Increasing the effective area of neutrino detectors can achieve the GRB-neutrino joint detection in the near future.
- **Low-luminosity GRBs** have **higher neutrino flux** and **higher event rate**. More sensitive neutrino detectors, in coordination with high-energy satellites (**X-ray telescopes**) may enable joint detections.