Prediction of HE ν signals associated with GWs: effects of cocoon photons

Riki Matsui (Tohoku University)

TeVPA 2022 @ Queen's University

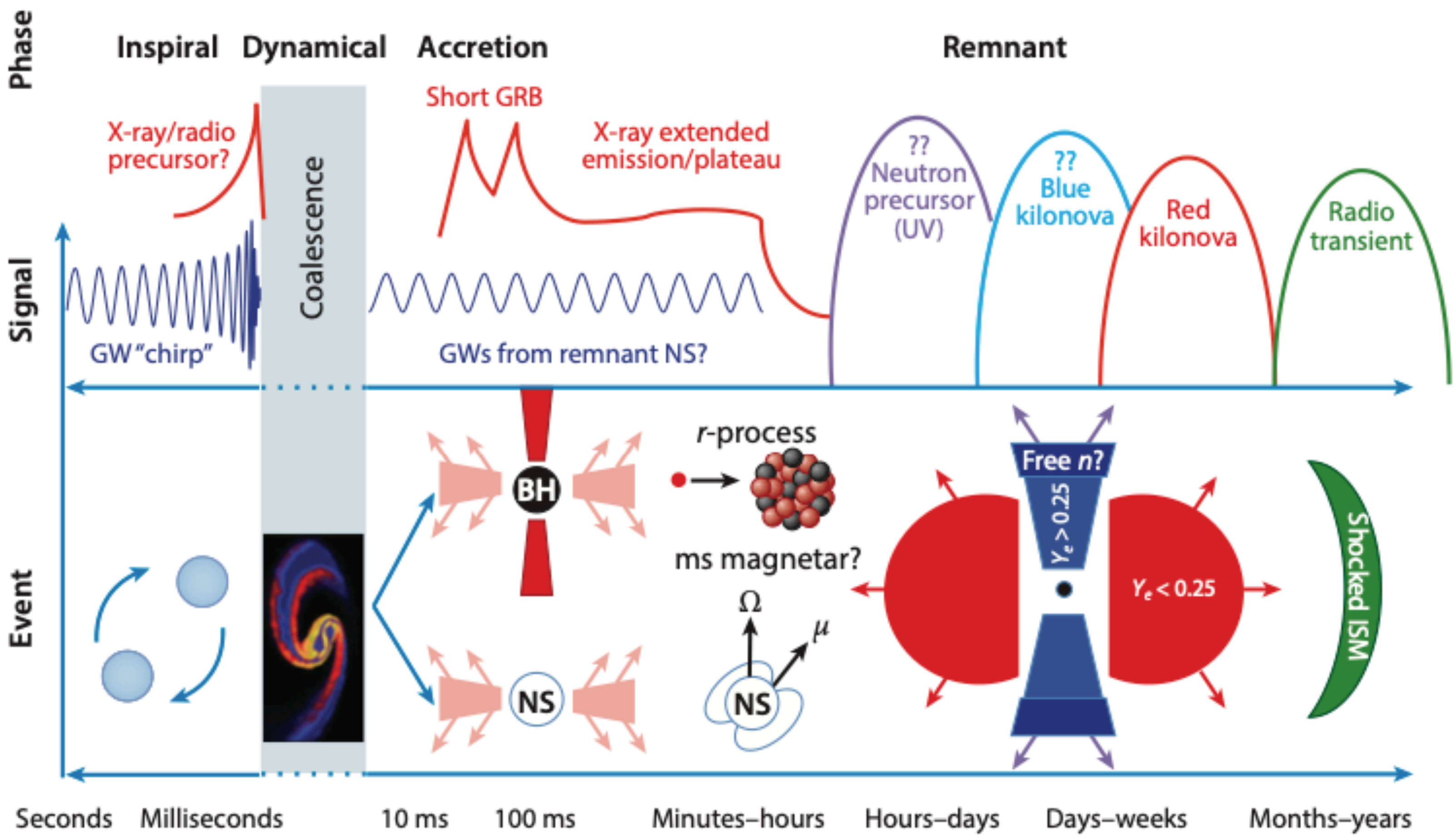
Co-authors
Shigeo S Kimura, Kenji Toma (Tohoku University)

Outline

- **Introduction**
  - BNS merger
  - Late-time emission of sGRB
  - IceCube observation
- **Method**
  - Model : Cocoon photons
  - Estimation of ν emission
- **Results & Discussion**

Introduction

BNS merger /sGRB /kilonova



Fernandez & Metzger 2016

GW170817 (e.g. Abbott et al. 2017a, Kasliwal et al. 2017)

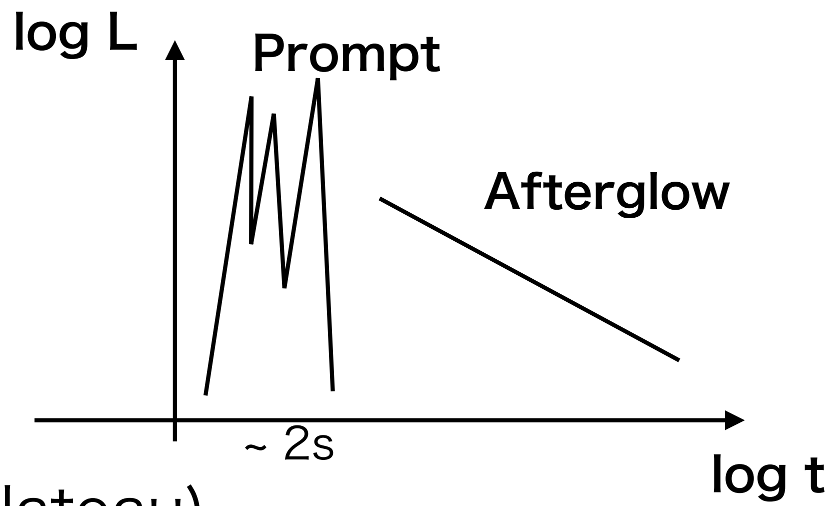
→ BNS mergers cause GW emission, sGRBs and kilonovae.

Late-time emission of sGRB

- Canonical sGRB :

  Short activity of central engine

  → prompt emission + afterglow



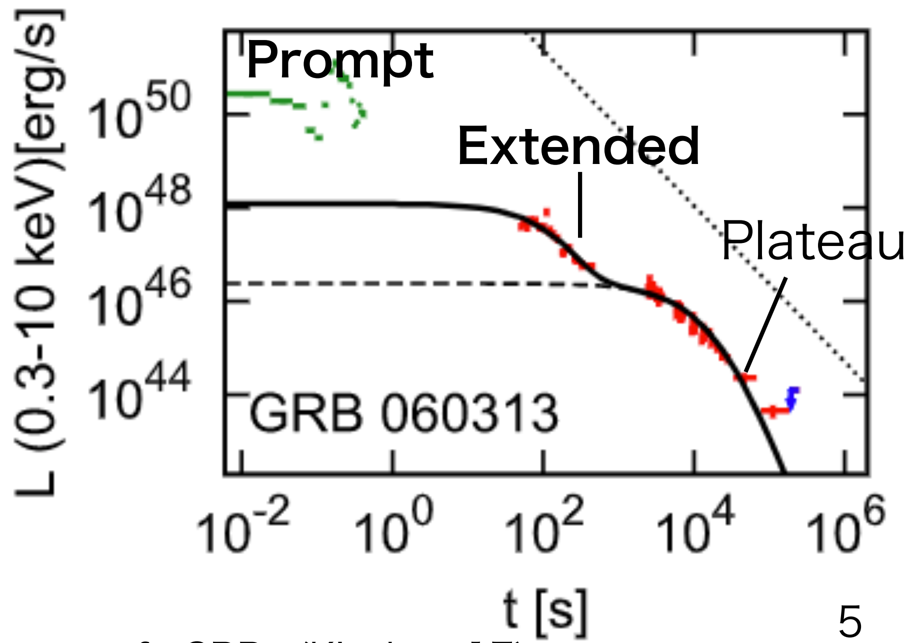
- X-ray long-term excess (Extended, Plateau)

  → **Prolonged engine activity &**

  energy injection into jet

  → **Mechanism ?**

  Dissipation process ?



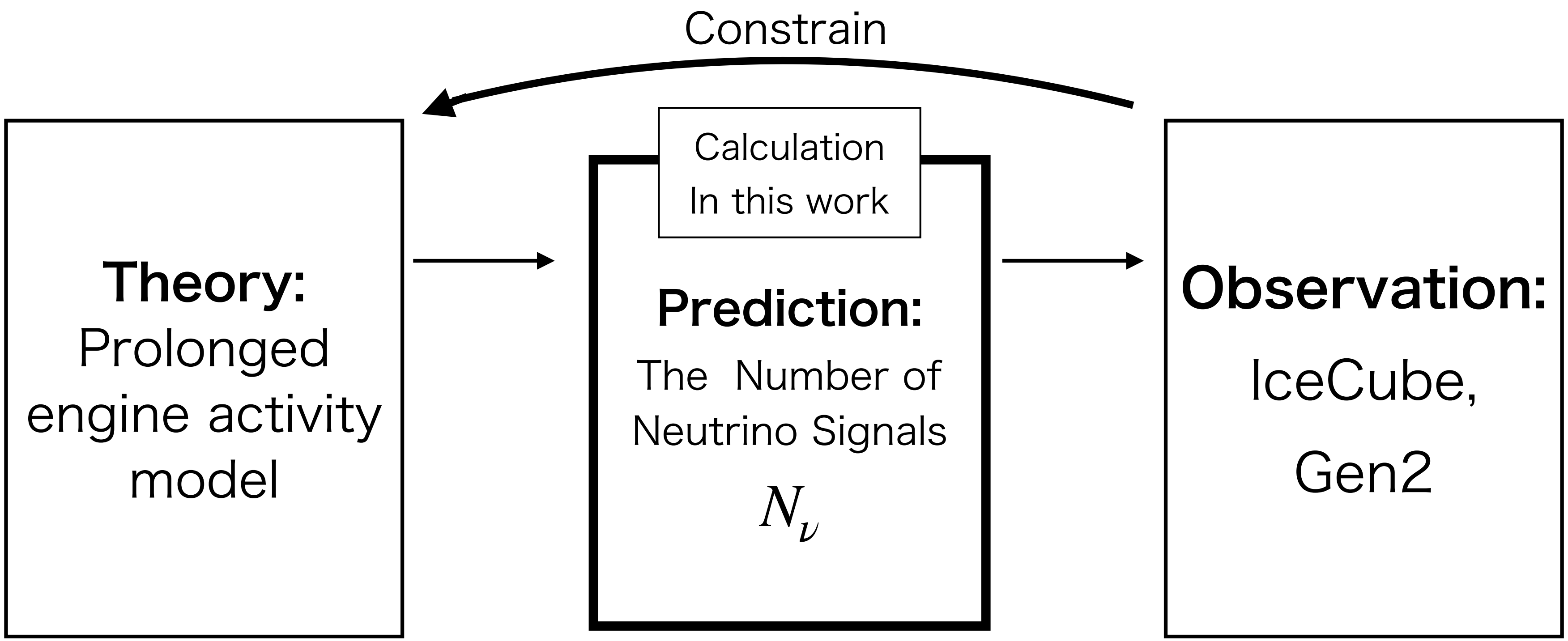
X-ray lightcurve of sGRBs (Kisaka +17)

Our approach

Based on prolonged engine activity model,

- **Prediction of** another observable phenomena by **neutrino**
- **Constraining** on physical quantity of **sGRBs**
- Especially **dissipation radius & composition** of jet

→ Test the model

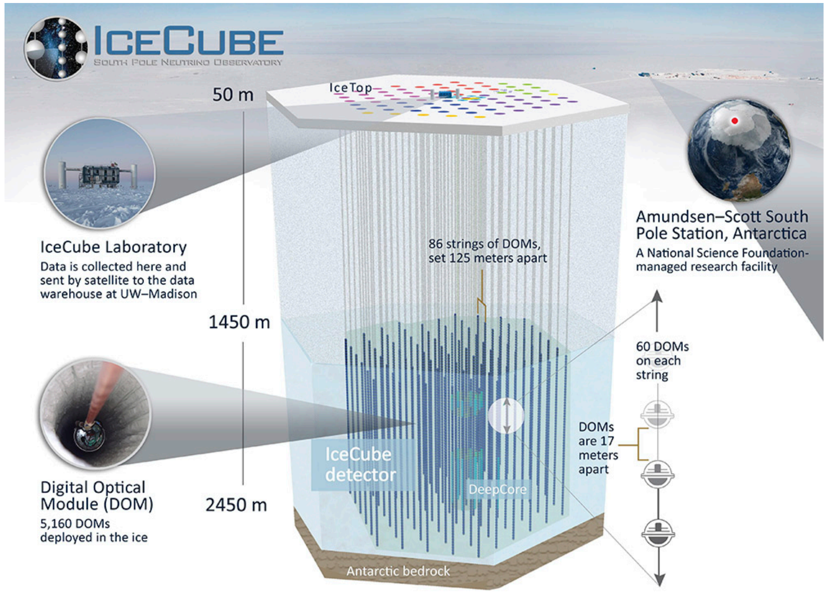


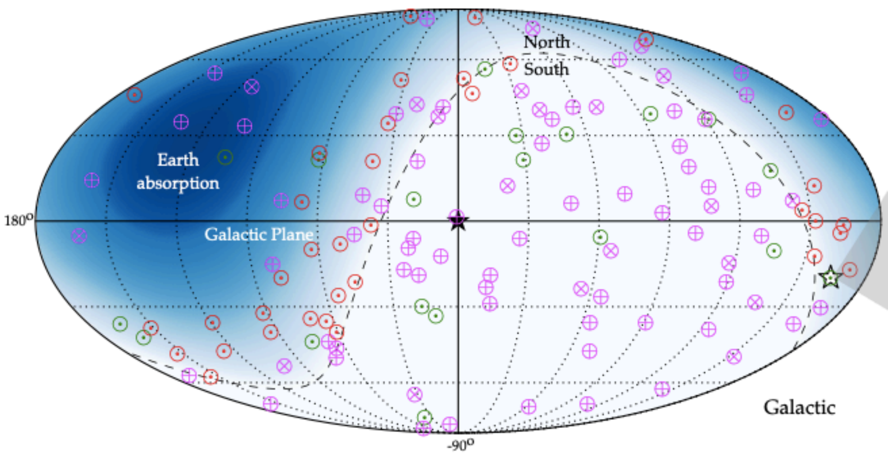
IceCube

- IceCube：Neutrino Observatory @ the South Pole

  detecting astrophysical ν **with ~ 10^{15}eV**

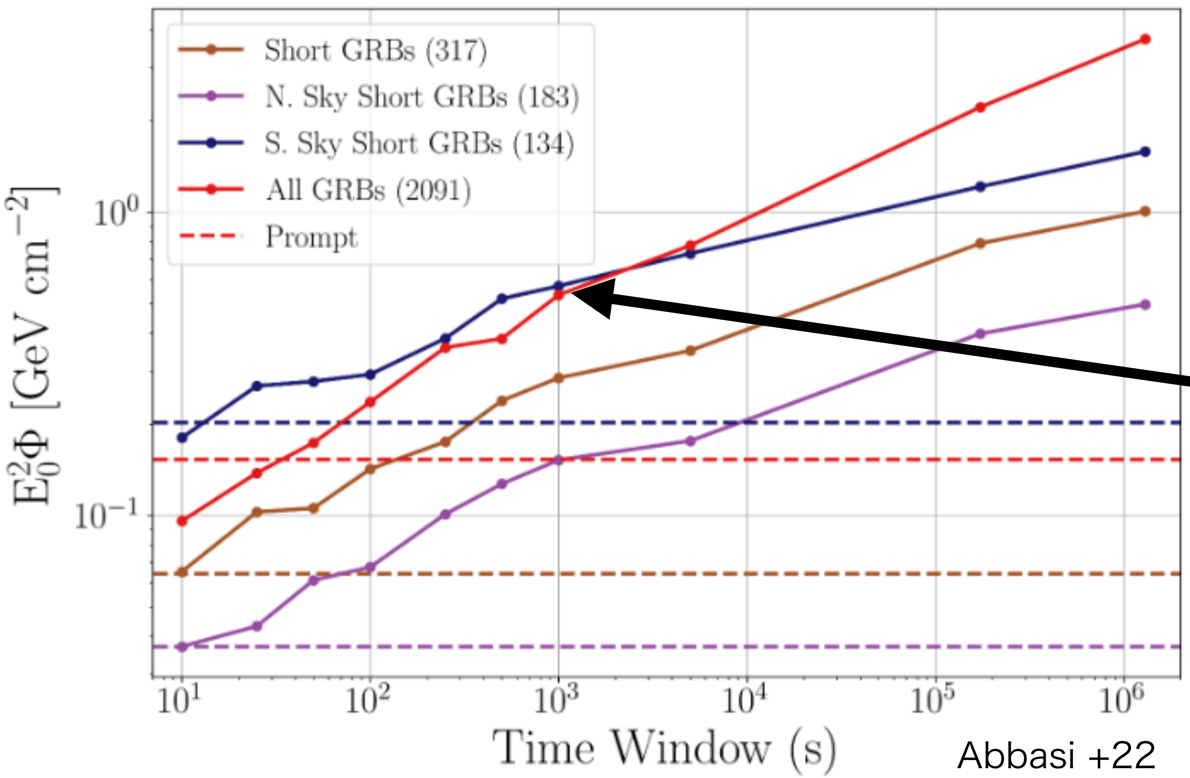
- IceCube-Gen2 **:** Future plan, ~ 5 times sensitivity
- IceCube has already detected many events.
- Sources ?





IceCube-Gen2 Collaboration+ 2020

Constraint on GRBs



Abbasi +22

Extended & Plateau :

$t_{\rm dur} \sim 10^{2.5} - 10^4$ s

upper limits :

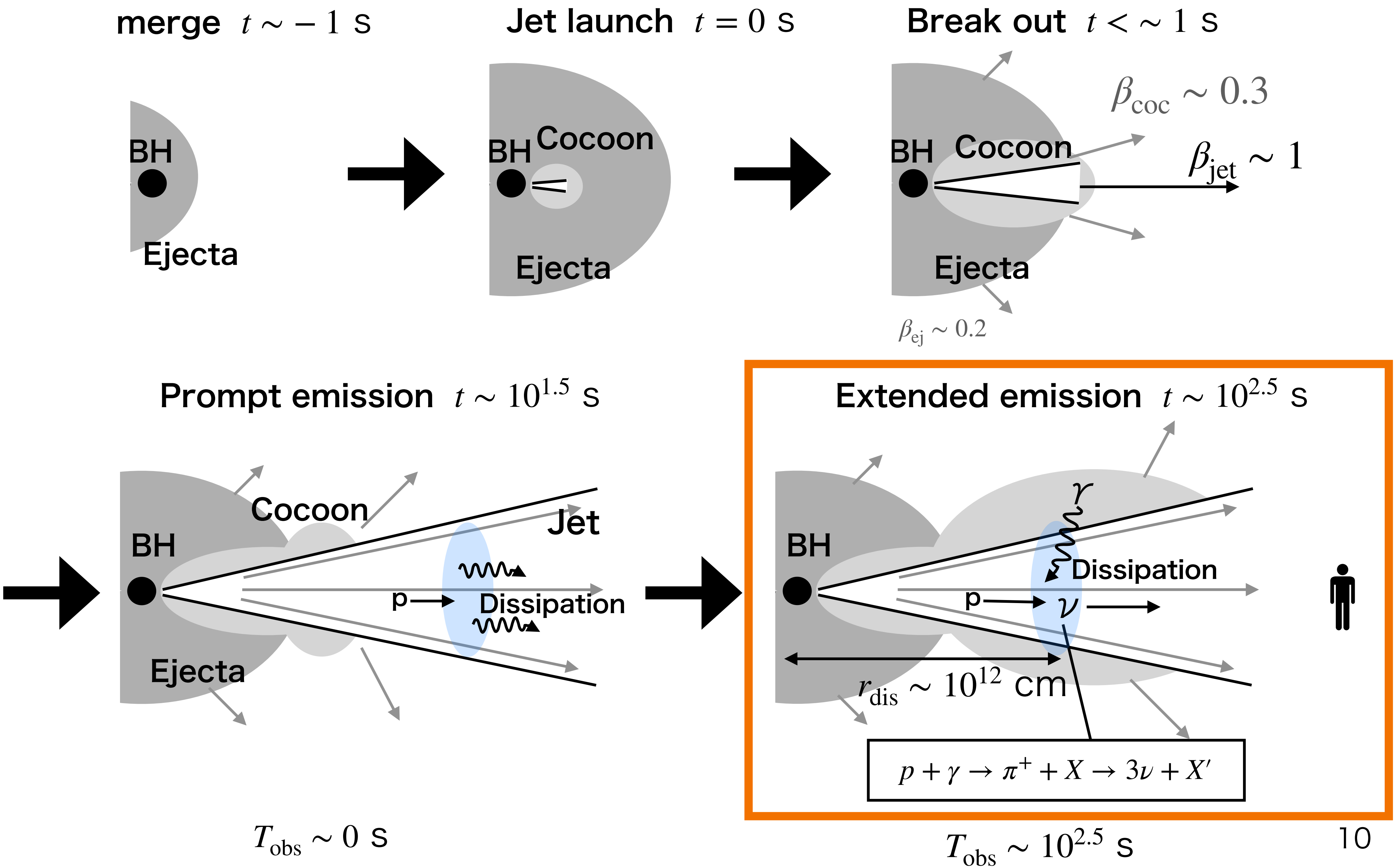
$L_\nu \sim 10^{49}$ **erg/s**

No association of GRBs and ν (e.g. IceCube+15, 17, Abbasi 2022).
but they are cosmological GRBs

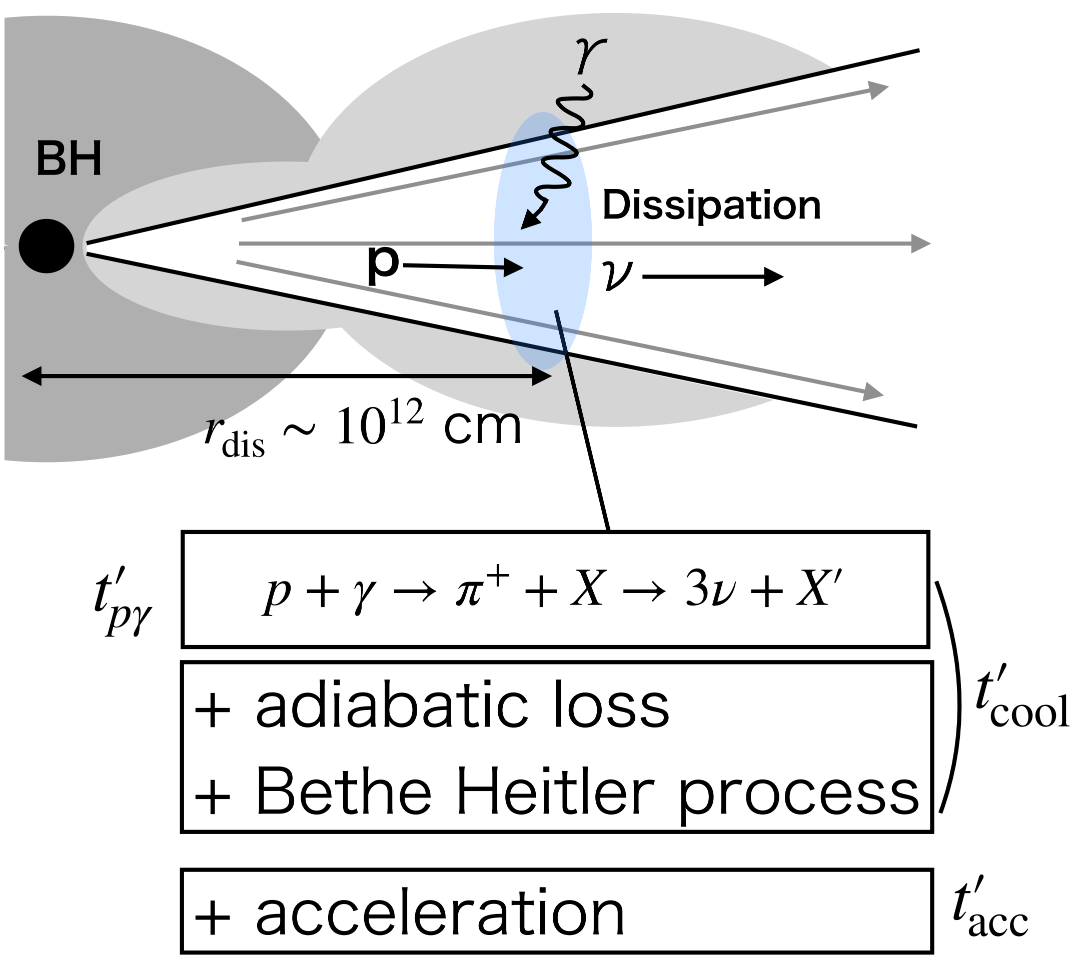
→ **Local sGRBs** are not strongly constrained.
They would associate with GWs. ($d_L < 300$ Mpc, O5)

Method

The model : Cocoon photons



Calculations



Neutrino

$$\varepsilon_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{d\varepsilon_{\nu_\mu}} \approx \frac{1}{8} f_{p\gamma} \varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}\Bigg|_{\varepsilon_p = \varepsilon_{\nu_\mu}/0.05}$$

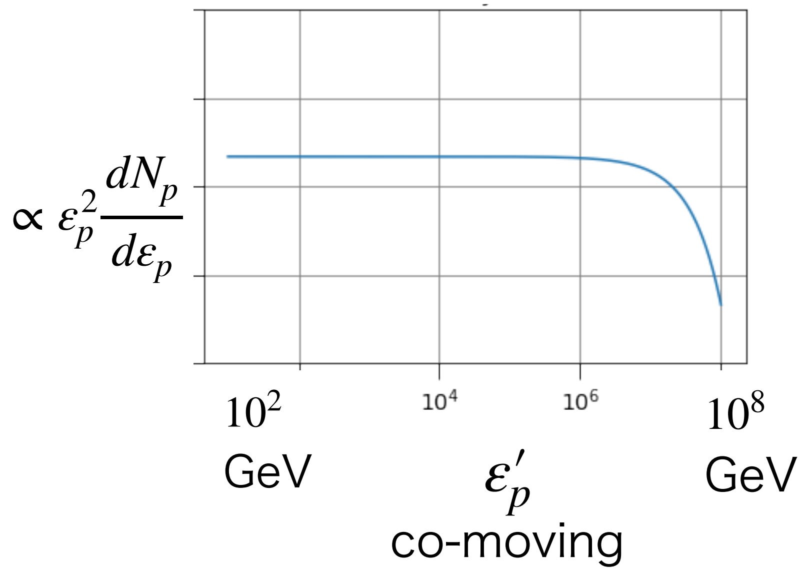
where $f_{p\gamma} = t'_{\rm cool}/t'_{p\gamma}$

$$t'^{-1}_{p\gamma} = \frac{c}{2\gamma'^2_p} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/2\gamma_p}^{\infty} d\varepsilon'_\gamma \varepsilon'^{-2}_\gamma \frac{dn'_\gamma}{d\varepsilon'_\gamma}$$

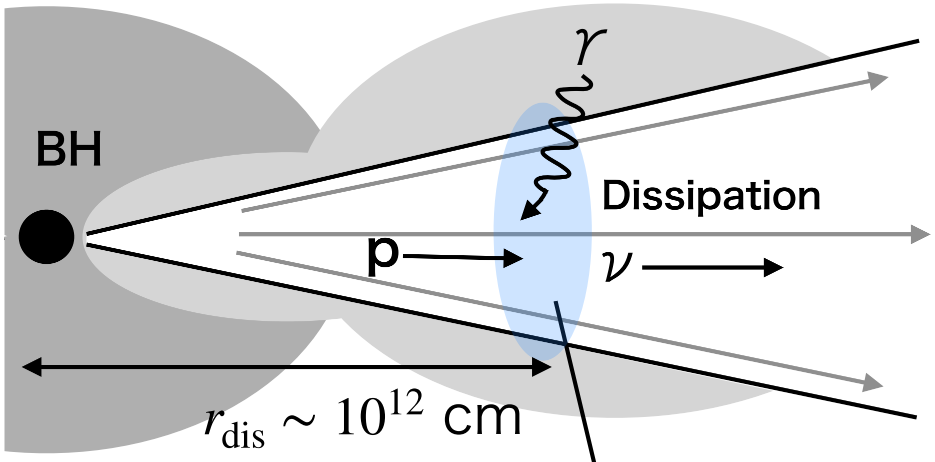
Proton (Cosmic-ray)

$$\frac{dN_p}{d\varepsilon_p} = N_{\varepsilon_p,\rm nor} \left(\frac{\varepsilon_p}{\varepsilon_{p,\rm cut}}\right)^{-2} \exp\left(-\frac{\varepsilon_p}{\varepsilon_{p,\rm cut}}\right)$$

$(t'^{-1}_{\rm acc} = t'^{-1}_{\rm cool} \rightarrow \varepsilon_{p,\rm cut})$



Calculations



$t'_{p\gamma}$: $p + \gamma \rightarrow \pi^{+} + X \rightarrow 3\nu + X'$

+ adiabatic loss
+ Bethe Heitler process

$t'_{\rm cool}$

+ acceleration

$t'_{\rm acc}$

Photon

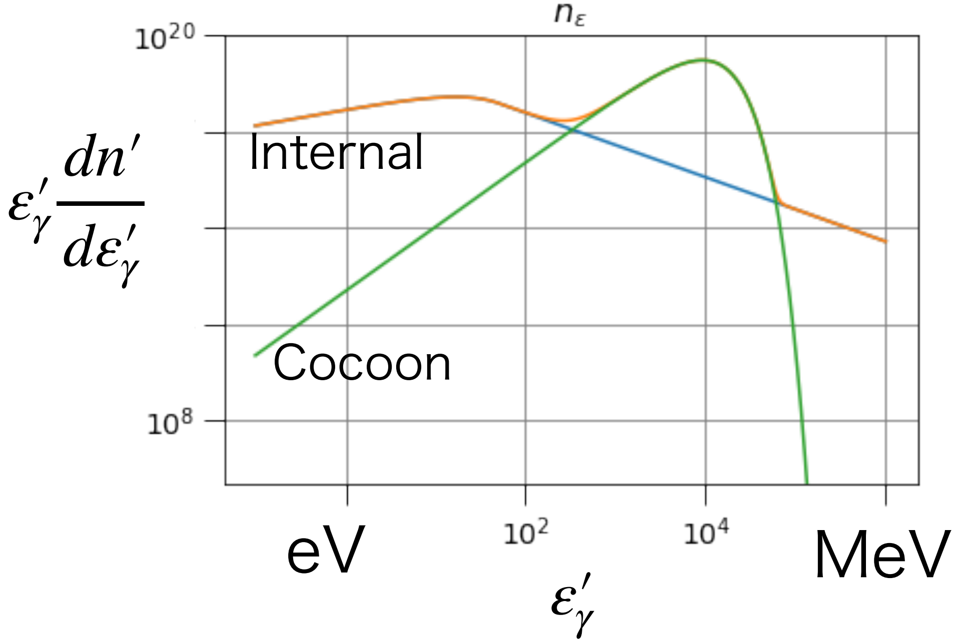
- Internal

$$\frac{dn'^{\rm in}}{d\varepsilon'_\gamma} \propto \varepsilon'^{-0.5}_\gamma \quad (\varepsilon'_\gamma \geq \varepsilon'_{\gamma,\rm pk})$$

$$\propto \varepsilon'^{-2}_\gamma \quad (\varepsilon'_\gamma < \varepsilon'_{\gamma,\rm pk})$$

- Cocoon

$$\varepsilon'_\gamma \frac{dn'^{\rm ex}}{d\varepsilon'_\gamma} = \Gamma_j \frac{8\pi(\varepsilon'_\gamma/\Gamma_j)^3}{h^3c^3} \frac{1}{\exp(\varepsilon'_\gamma/\Gamma_j k_B T_{coc}) - 1}$$



(in co-moving flame of jet)

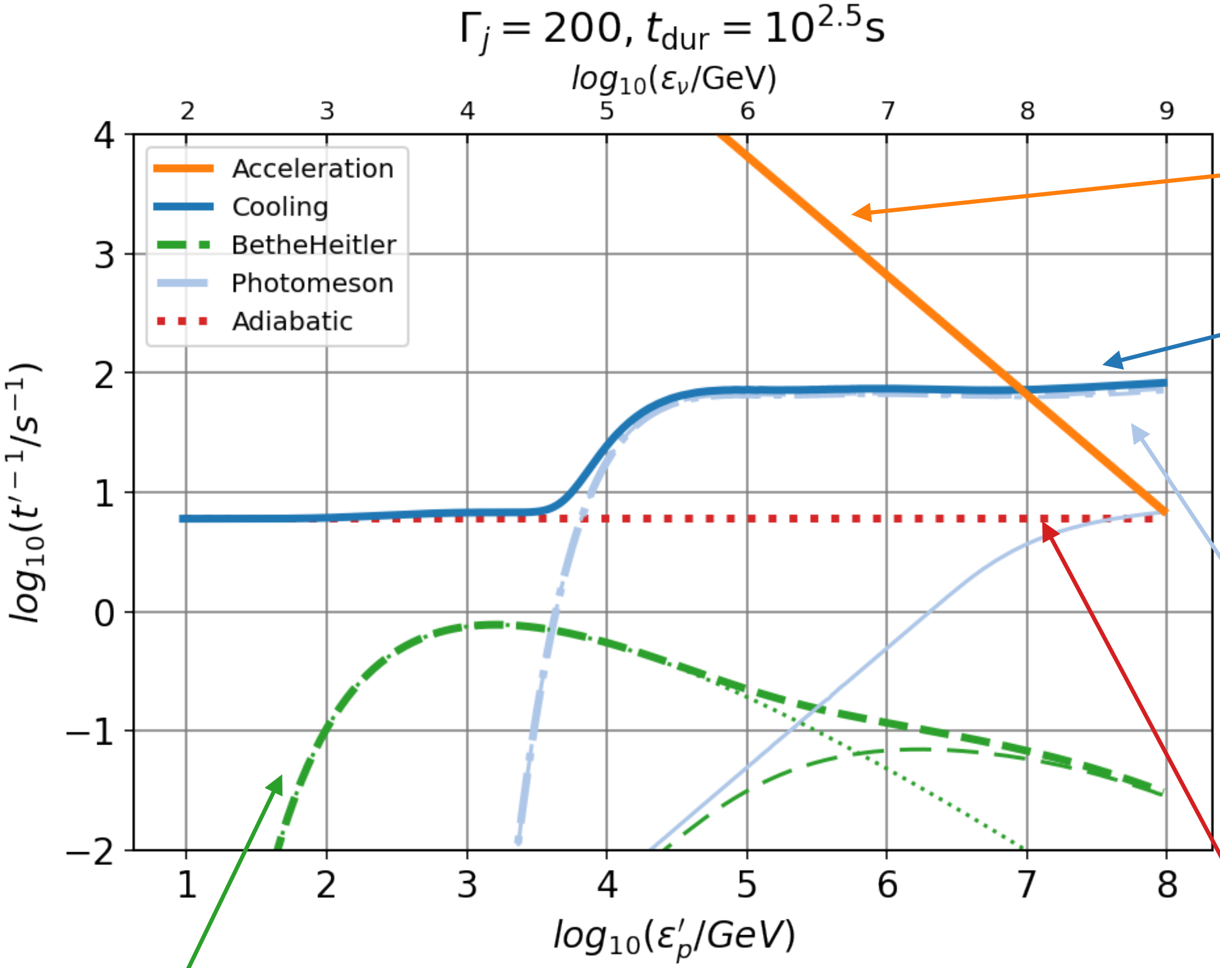
Results & Discussion

Timescale and ν production rate

Cooling and acceleration of proton

Fast

Slow



acceleration $t'^{-1}_{\rm acc}$

Total cooling $t'^{-1}_{\rm cool}$

Ratio is $f_{p\gamma}$

Neutrino production $t'^{-1}_{p\gamma}$

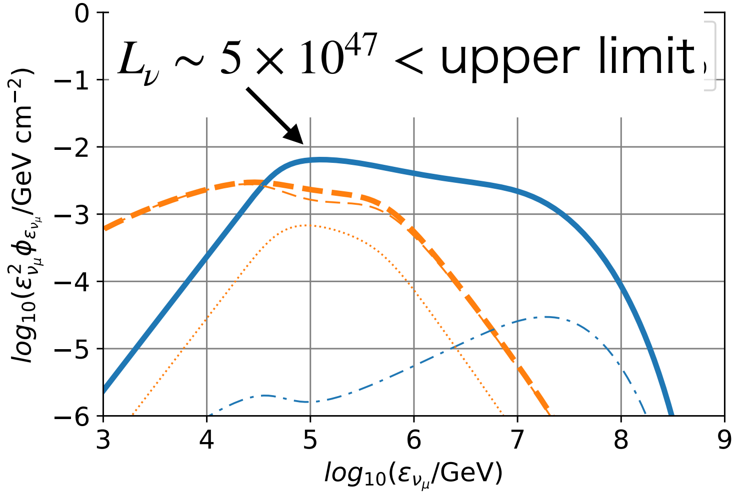
Adiabatic loss $t'^{-1}_{\rm ad}$

Bethe Heitler process $t'^{-1}_{\rm BH}$

$p + \gamma \rightarrow p + e^+ + e^-$, not effective in this case

Detectability & Γ dependence

$d_L = 300\text{Mpc}$ $t_{\rm dur} = 10^{2.5}$s $r_{\rm dis} = 10^{12}$ cm, $\xi_p = 10$

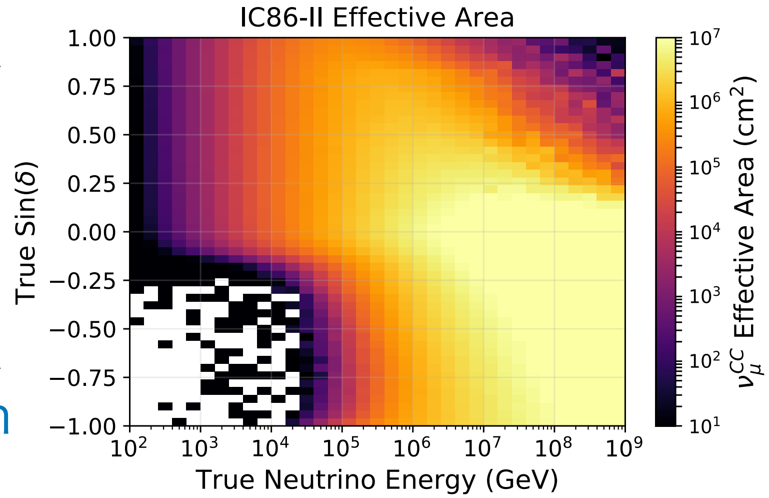


resultant spectrum

×

North

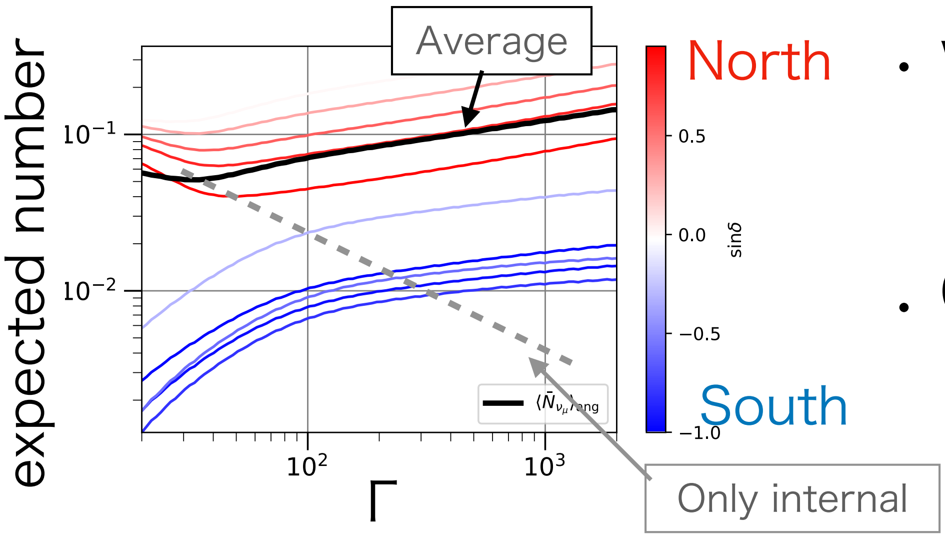
South



Effective area of IceCube

Integration

→ expected number of signals (in every Γ, $sin\delta$)

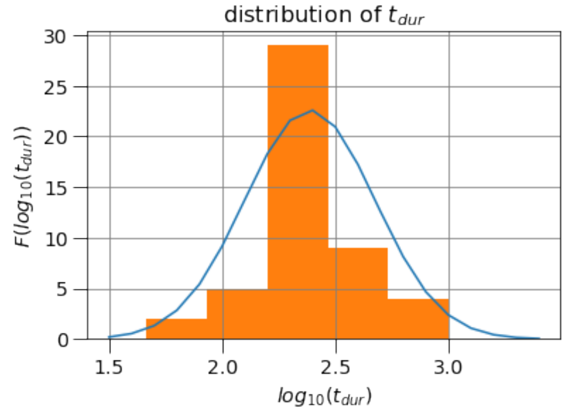


- Week dependence on Γ
  (cf. only internal photons → $\propto \Gamma^{-2}$)

- **0.1 ν from 1 sGRB** at $d_L = 300\text{Mpc}$
  (by IceCube)

Operation time

- $log t_{\rm dur}$: normal distribution
- d_L, δ: homogeneous



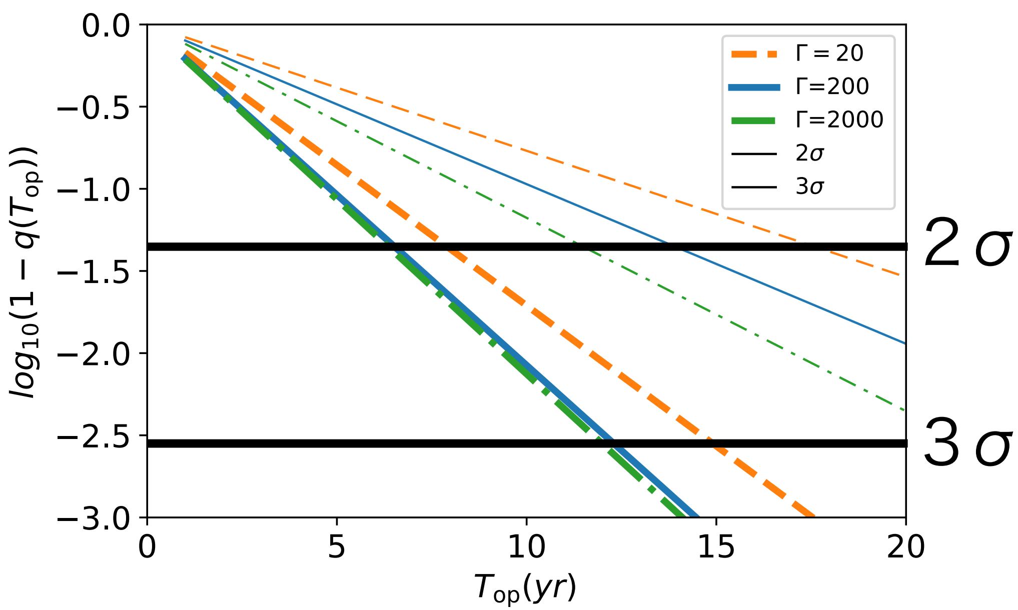
distribution of $log t_{\rm dur}$

based on Kisaka+17

$r_{\rm dis} = 10^{12}$ cm, $\xi_p = 10$

Low probability

High probability



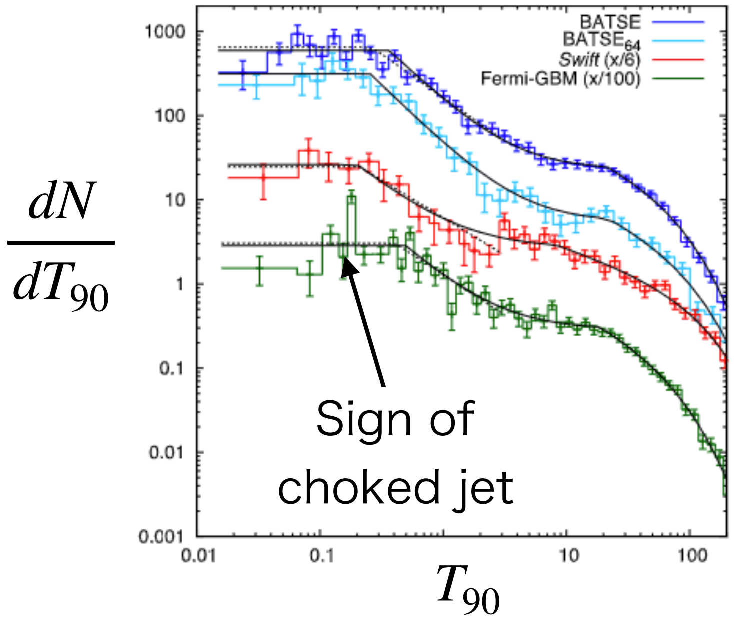
→ highly probable to find ν signals in 13 years (IceCube : 2σ, Gen2 : 3σ)

→ **$\mathbf{r}_{\rm dis}$ and number of proton in jet**

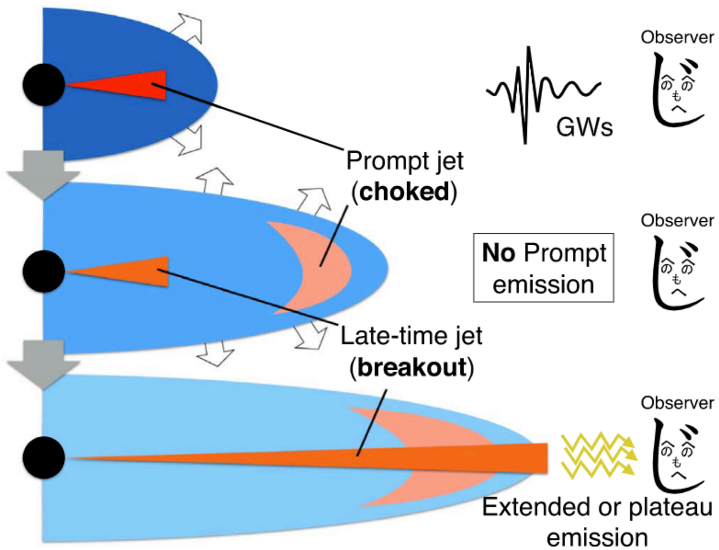
will be constrained by observation in the future.

Choked-jet events

Some prompt jets are choked by ejecta (Moharana & Piran 17), but prolonged jets may break out. (Matsumoto & Kimura 18)



Moharana & Piran 2017



Matsumoto & Kimura 2018

- Detection is the direct evidence of prolonged engine activity.
- But difficult to find by EM → **GW/ν association is important.**
- choked/successful ~ 0.5 (Sarin +22) → **possible in ~20 years**

Summary

- We calculated neutrino emission from sGRB considering the prolonged jet model and cocoon photons.
- Neutrinos are efficiently emitted with Extended Emission ($t \sim 10^{2.5}$ s)
- 0.1 neutrino will be found from 1 sGRBs at $d_L \sim 300$ Mpc $\sim$ detection horizon of LIGO/VIRGO/KAGRA O5.
- **It is highly probable to detect neutrinos from sGRB in 13 years.** (IceCube : 2σ, Gen2 : 3σ)
- **Dissipation radius and composition of prolonged jet will be constrained** by comparing the observation in the future with the prediction in this work.
- **GW/neutrino association is important** to detect choked-jet events and prove the model of prolonged engine activity.

Back Up

Temperature of cocoon

$T_{\rm coc}$: Cocoon temperature (Kimura+19)

$$T_{\rm coc} = (3\mathscr{E}_{\rm coc}/4\pi R_{\rm coc}^3 a_{\rm rad})^{1/4}$$

$v_{\rm coc}$, $E_{\rm kin,coc}$, $E_{\rm int,coc}$
(at break out time)
from Hamidani +20

$$R_{\rm coc} = 3 \times 10^{12}\,(t_{\rm dur}/10^{2.5}{\rm s})\ {\rm cm}$$ (Constant velocity)

$$\mathscr{E}_{\rm coc} = 8.8 \times 10^{44}\,(t_{\rm dur}/10^{2.5}{\rm s})^{-1}\,{\rm erg} + 9.3 \times 10^{44}\,(t_{\rm dur}/10^{2.5}{\rm s})^{-0.3}\,{\rm erg}$$

Part of initial internal energy

Injected by radioactive decay

Also we considered

- Synchrotron cooling of π $(f_{sup,\pi})$
- Synchrotron cooling of μ $(f_{sup,\mu})$
- flavors of ν & ν oscillation $(N_\nu$, $\nu_e\ \nu_\mu\ \bar{\nu}_\mu)$
- Secondary energy distribution of π & μ decay

$$\begin{aligned} p + \gamma &\to \pi^+ + n \\ &\to \mu^+ + \nu_\mu + n \\ &\to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu + n \end{aligned}$$

$$\varepsilon_{\bar{\nu}_e}^2 \frac{dN_{\bar{\nu}_e}}{d\varepsilon_{\bar{\nu}_e}} \approx \frac{1}{8} f_{p\gamma} f_{sup,\pi} f_{sup,\mu} \varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}\Bigg|_{\varepsilon_p=\varepsilon_{\nu_e}/0.05}$$

$$f_{p\gamma} = t'_{\rm cool}/t'_{p\gamma}$$

$$t_{p\gamma}^{'-1} = \frac{c}{2\gamma_p^{'2}} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/2\gamma_p}^{\infty} d\varepsilon'_\gamma \varepsilon_\gamma^{'-2} \frac{dn'_\gamma}{d\varepsilon'_\gamma}$$

Cosmic-ray distribution

$$\varepsilon_{\bar{\nu}_e}^2 \frac{dN_{\bar{\nu}_e}}{d\varepsilon_{\bar{\nu}_e}} \approx \frac{1}{8} f_{p\gamma} f_{sup,\pi} f_{sup,\mu} \varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}\bigg|_{\varepsilon_p=\varepsilon_{\nu_e}/0.05}, \quad f_{p\gamma} = t'_{\rm cool}/t'_{p\gamma}$$: ν production rate

$$t'^{-1}_{p\gamma} = \frac{c}{2\gamma_p'^2} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/2\gamma_p}^{\infty} d\varepsilon'_\gamma \varepsilon'^{-2}_\gamma \frac{dn'_\gamma}{d\varepsilon'_\gamma} \sim n'_\gamma \sigma c$$: production timescale

Cosmic ray ($\varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}$): $\frac{dN_p}{d\varepsilon_p} = N_{\varepsilon_p,{\rm nor}} \left(\frac{\varepsilon_p}{\varepsilon_{p,{\rm cut}}}\right)^{-p_{\rm inj}} \exp\left(-\frac{\varepsilon_p}{\varepsilon_{p,{\rm cut}}}\right)$

Cutoff energy is determined by
the balance between the cooling $t'^{-1}_{\rm acc} = t'^{-1}_{\rm cool}$

$$t'_{\rm acc} = \varepsilon'_p/ceB', \; B' = \sqrt{2L_{\gamma,{\rm iso}}\xi_B/c\Gamma_j^2 r_{\rm dis}^2}$$

π & μ cooling

$$\varepsilon_{\bar{\nu}_e}^2 \frac{dN_{\bar{\nu}_e}}{d\varepsilon_{\bar{\nu}_e}} \approx \frac{1}{8} f_{p\gamma} f_{sup,\pi} f_{sup,\mu} \varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}\bigg|_{\varepsilon_p=\varepsilon_{\nu_e}/0.05}, \quad f_{p\gamma} = t'_{\rm cool}/t'_{p\gamma}$$: ν production

rate

$$t_{p\gamma}^{'-1} = \frac{c}{2\gamma_p^{'2}} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/2\gamma_p}^{\infty} d\varepsilon'_\gamma \varepsilon_\gamma^{'-2} \frac{dn'_\gamma}{d\varepsilon'_\gamma} \sim n'_\gamma \sigma c$$: production timescale

Synchrotron cooling of π & μ ($f_{sup,\pi}$, $f_{sup,\mu}$)

$$f_{sup,i} = 1 - \exp(-t'_{\rm i,cool}/t'_{\rm i,dec})$$

$$t'_{\rm i,dec} \propto \varepsilon'_{\rm i}$$

$$t'_{\rm i,cool} = t_{\rm i,syn}^{'-1} + t_{\rm add}^{'-1}$$

$$t_{\rm i,syn}^{'-1} = 6\pi m_{\rm i}^4 c^3 / m_{\rm e}^2 \sigma_T B^2 \varepsilon'_{\rm i}$$

Neutrino oscillation

Photomeson : $p + \gamma \rightarrow \pi^{+} + n \rightarrow \mu^{+} + \nu_{\mu} + n \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu} + n$

$$\phi_{\nu_e+\bar{\nu}_e} = \frac{10}{18}\phi^0_{\nu_e+\bar{\nu}_e} + \frac{4}{18}(\phi^0_{\nu_\mu+\bar{\nu}_\mu} + \phi^0_{\nu_\tau+\bar{\nu}_\tau})$$

$$\phi_{\nu_\mu+\bar{\nu}_\mu} = \frac{4}{18}\phi^0_{\nu_e+\bar{\nu}_e} + \frac{7}{18}(\phi^0_{\nu_\mu+\bar{\nu}_\mu} + \phi^0_{\nu_\tau+\bar{\nu}_\tau})$$

where $\phi^0_i = \frac{dN_i}{d\varepsilon_i}/4\pi d_L^2$ is the neutrino fluences measured at the source and d_L is luminosity distance.

Secondary distribution

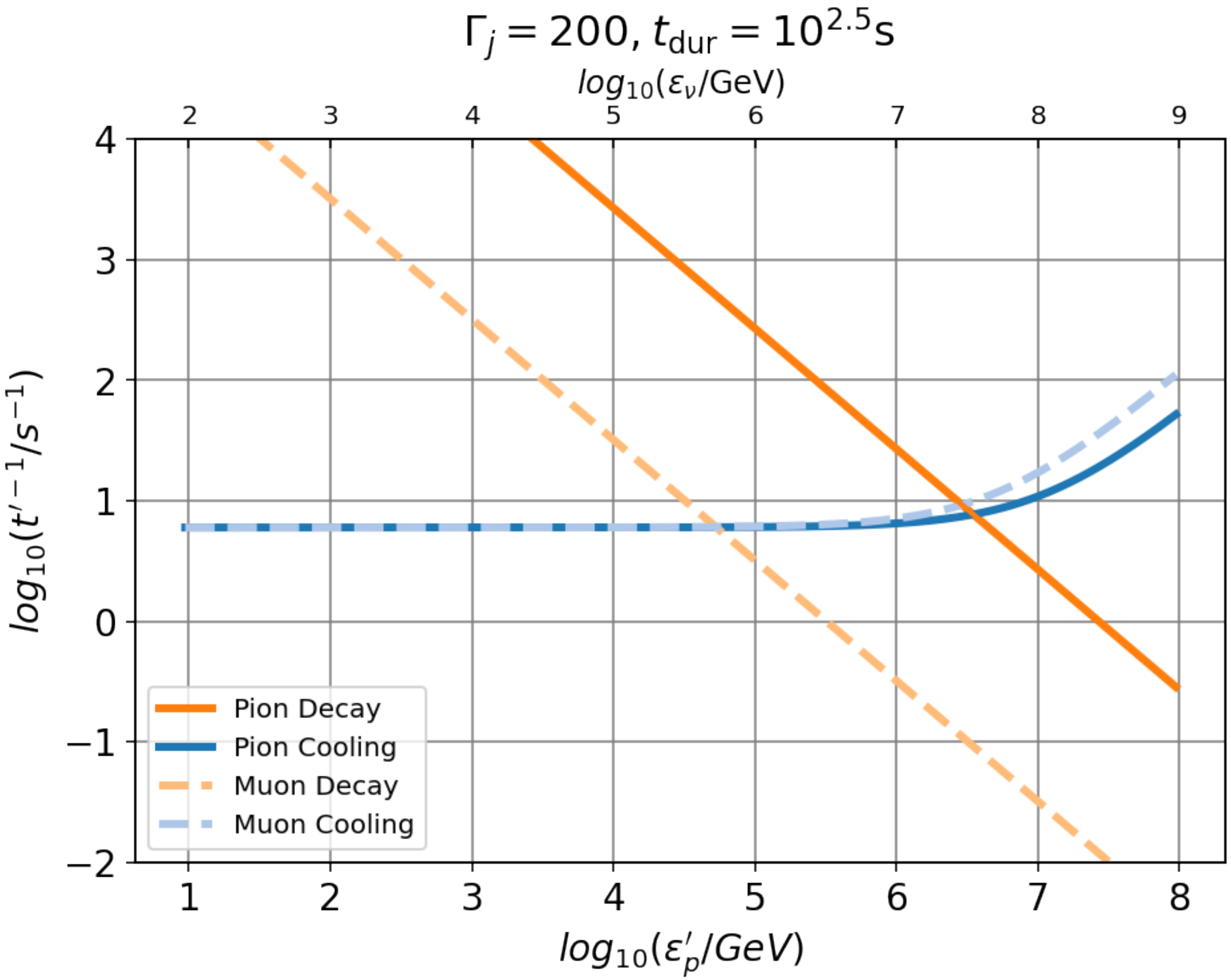
muon-neutrino

$$\frac{dN_{\nu_\mu}}{d\varepsilon_{\nu_\mu}} \approx \int d\varepsilon_\pi g(\varepsilon_\pi, \varepsilon_{\nu_\mu}) f_{sup,\pi} (f_{p\gamma} \frac{dN_p}{d\varepsilon_p}) \Bigg|_{\varepsilon_p = 5\varepsilon_\pi}, \; g(\varepsilon_\pi, \varepsilon_{\nu_\mu}) = \frac{\theta(1/4\varepsilon_{pi} - \varepsilon_{\nu_\mu})}{1/4\varepsilon_\pi}$$

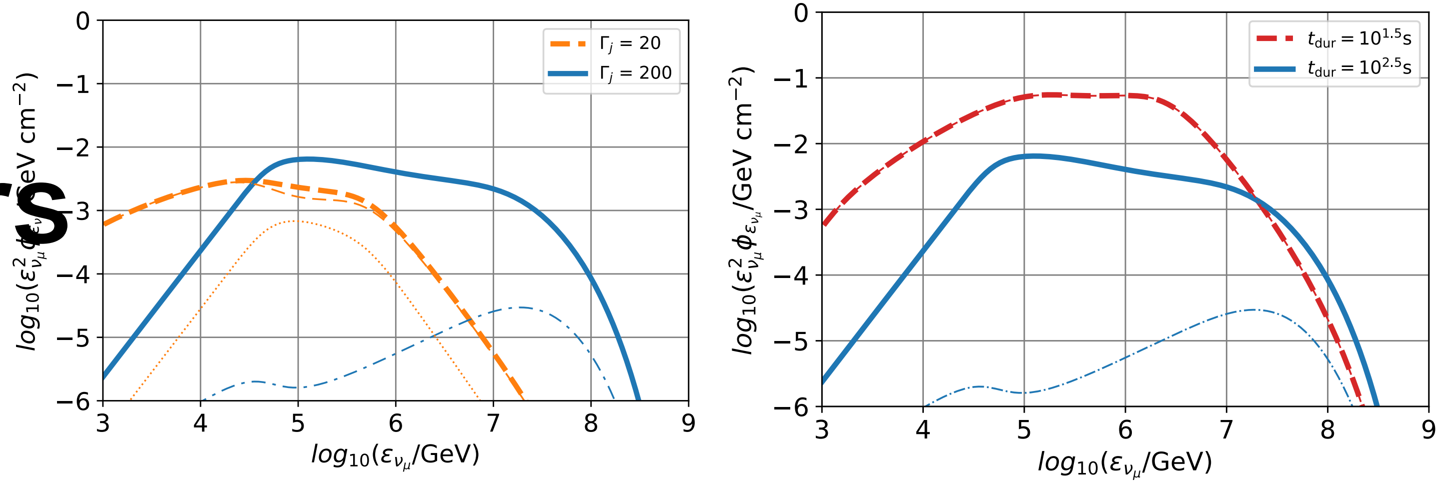
Anti muon-neutrino, electron-neutrino

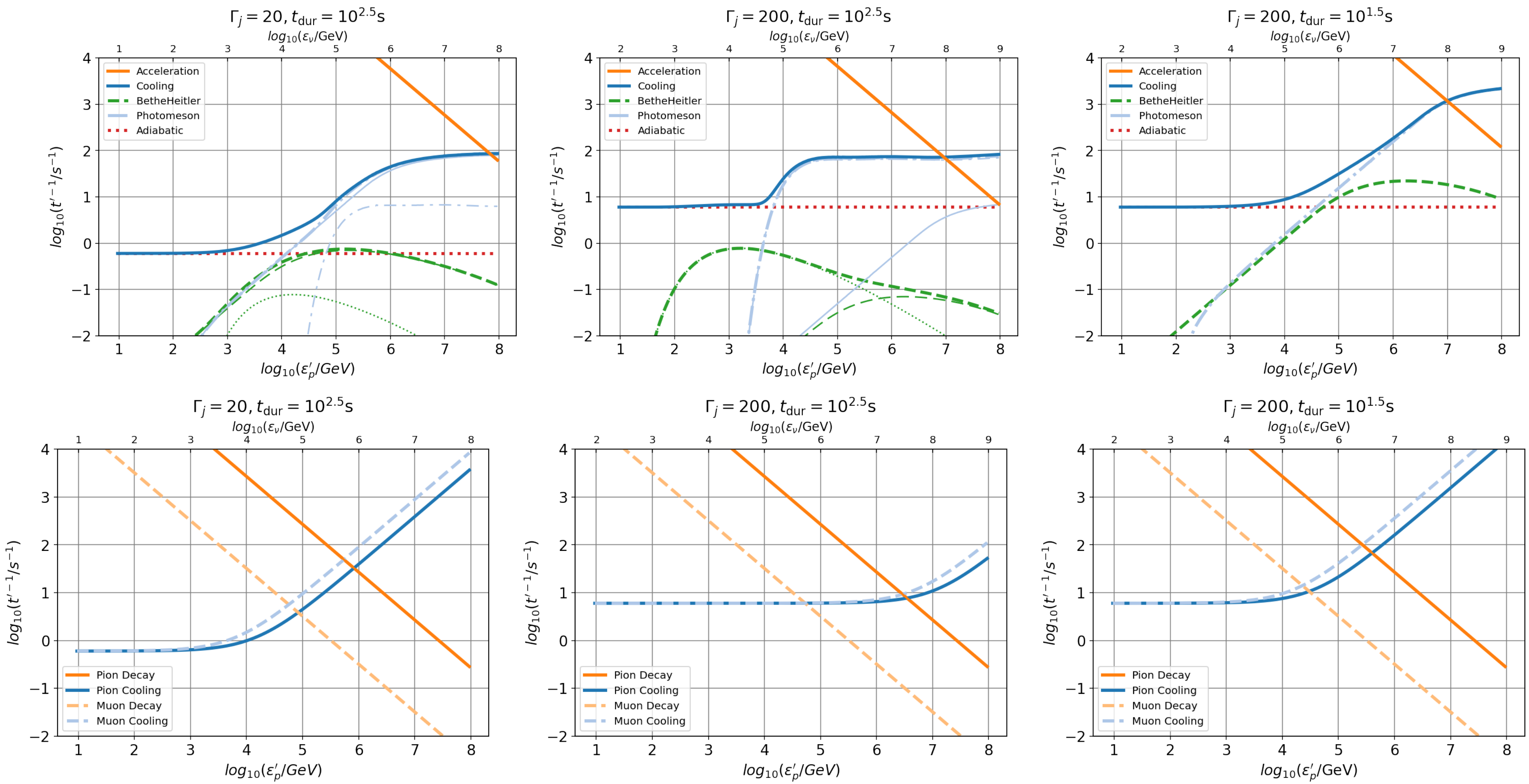
$$\frac{dN_{\bar{\nu}_\mu}}{d\varepsilon_{\bar{\nu}_\mu}} \approx \frac{dN_{\nu_e}}{d\varepsilon_{\nu_e}} \approx \int d\varepsilon_\mu g(\varepsilon_\mu, \varepsilon_{\nu_e}) f_{sup,\mu} (f_{sup,\pi} f_{p\gamma} \frac{dN_p}{d\varepsilon_p}) \Bigg|_{\varepsilon_p = 5\varepsilon_\pi = \frac{20}{3}\varepsilon_\mu}, \; g(\varepsilon_\mu, \varepsilon_{\nu_e}) = \frac{\theta(1/3\varepsilon_\mu - \varepsilon_{\nu_e})}{1/3\varepsilon_\mu}$$

Time scale of pion, muon

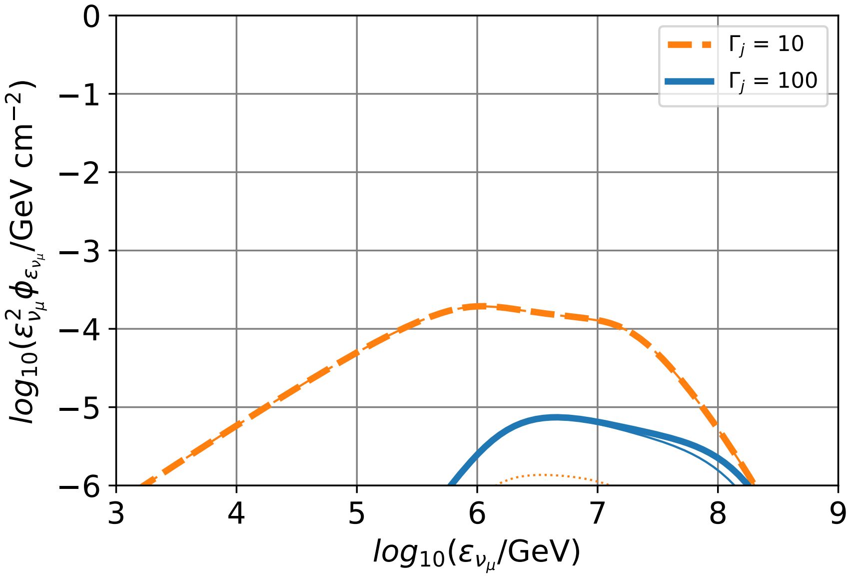


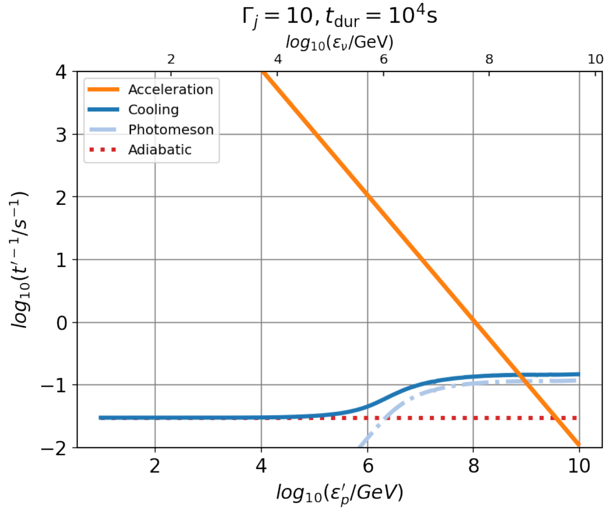
Other Parameters

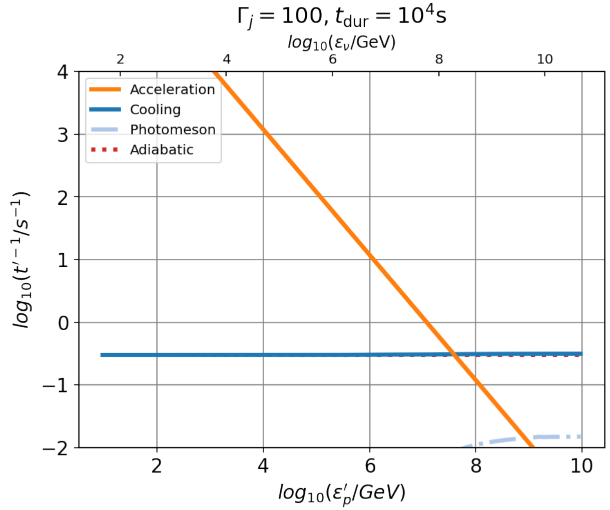


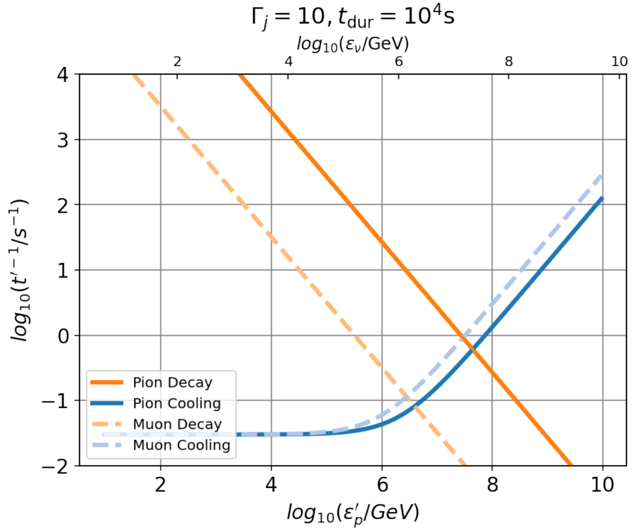


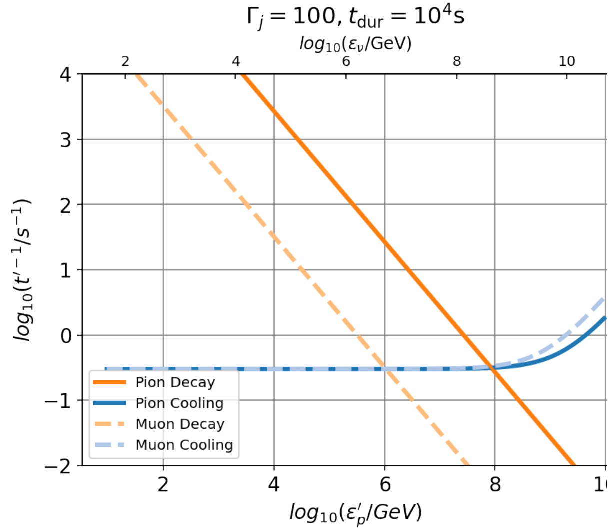
Plateau Emission



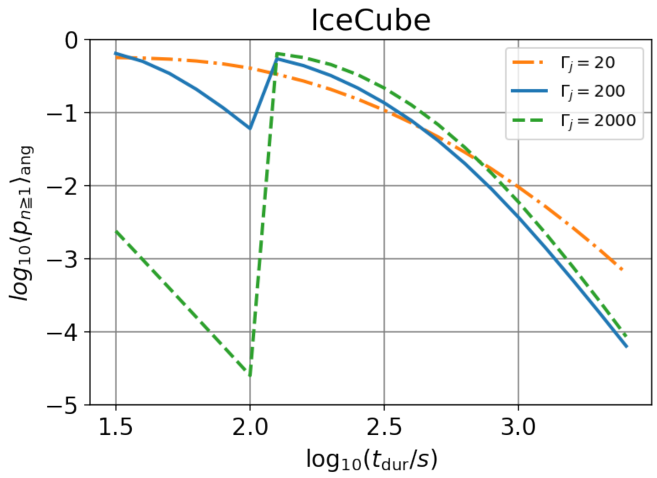


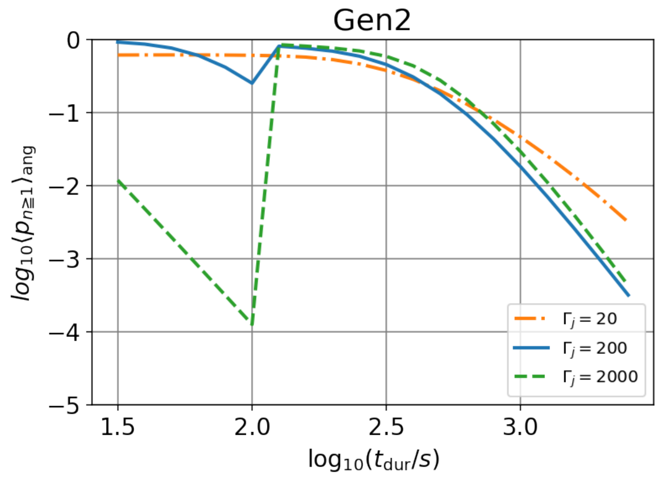


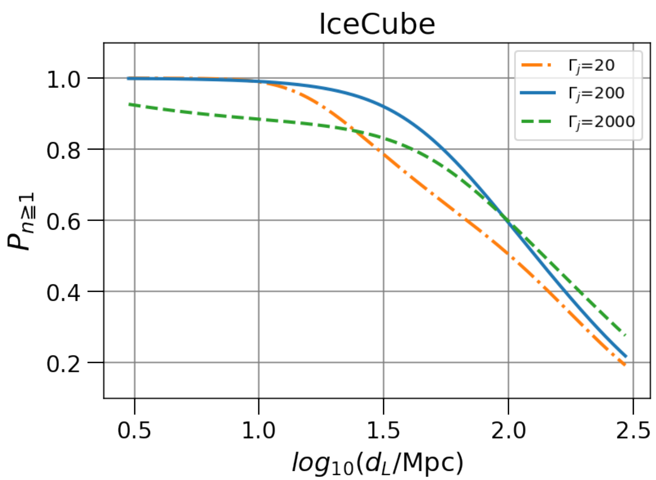


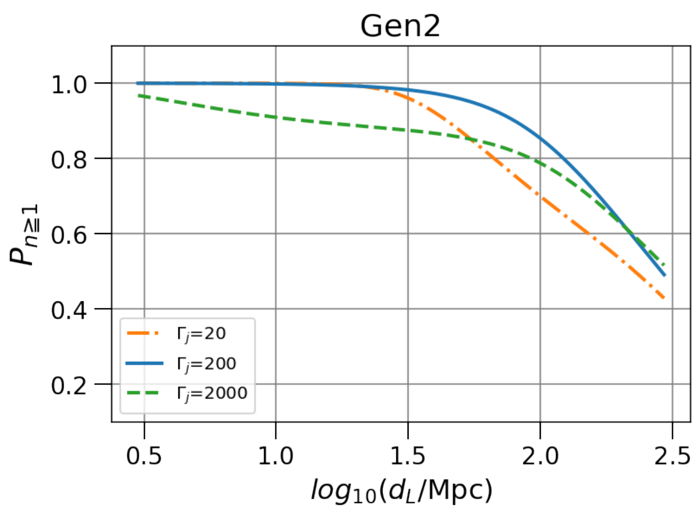


Comparison of IC with Gen2









Estimation of Operation time

$$q(T) = 1 - \exp(-TR_{\rm SGRB}4\pi \int^{300{\rm Mpc}} d(d_L)d_L^2 P_{n\geq 1}\ ) \ \sim R_{\rm SGRB}\ (T\frac{4}{3}\pi d_L^3)\ P_{n\geq 1}$$

$$P_{n\geq 1} = \int d(\ln (t_{\rm dur}/{\rm s}))F(t_{\rm dur})\,\langle p_{n\geq 1}\rangle_{\rm ang}$$ (average for duration)

$$\langle p_{n\geq 1}\rangle_{\rm ang} = \frac{1}{4\pi}\int d\Omega\ p_{n\geq 1}(\delta)$$ (average for angle)

$$p_{n\geq 1}(\delta) = 1 - \exp(-\bar{N}_{\nu_\mu})$$ (Poisson distribution)

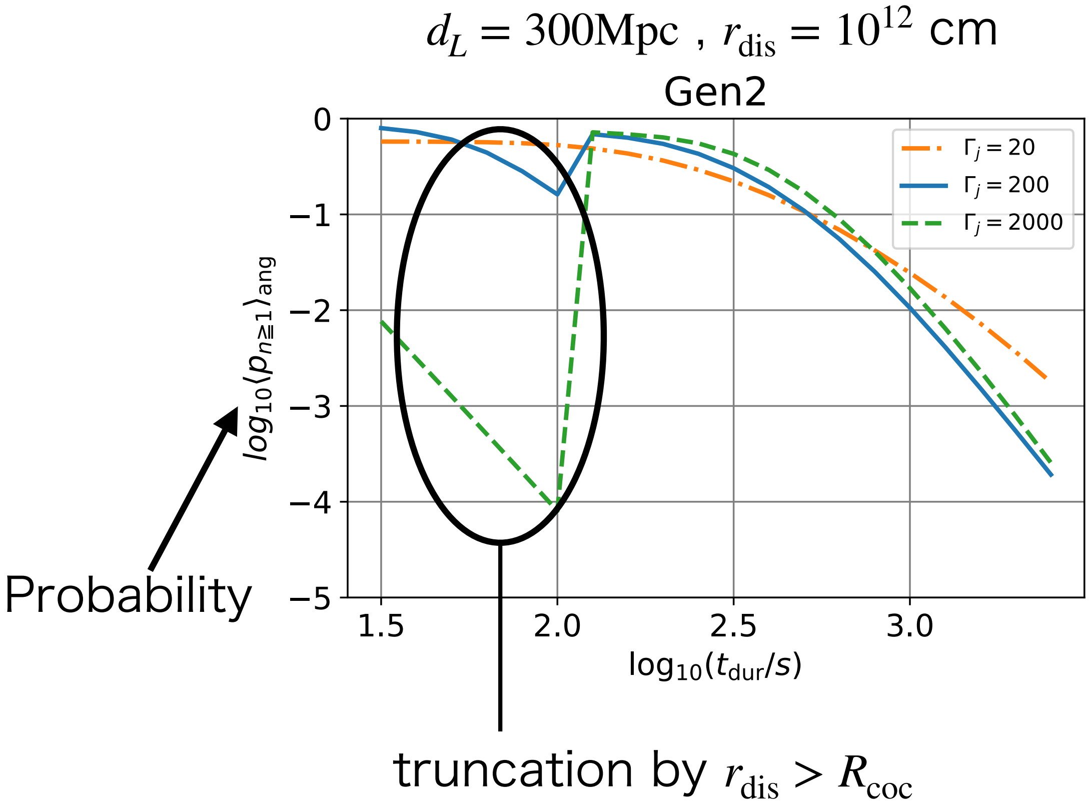
$$\bar{N}_{\nu_\mu} = \int d\varepsilon_{\nu_\mu}\phi_{\nu_\mu+\bar{\nu}_\mu}(\varepsilon_{\nu_\mu})A_{\rm eff}(\delta, \varepsilon_{\nu_\mu})$$ (expected number)

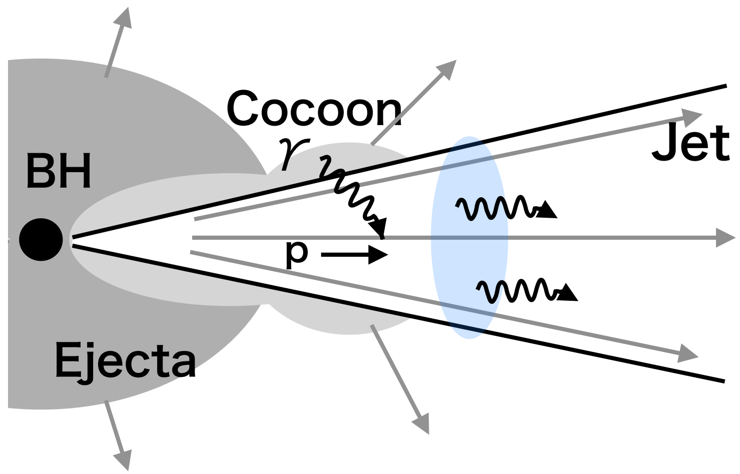
Duration dependence

Not enough duration → $r_{\rm dis} < R_{\rm coc} = c\beta_{\rm coc} t_{\rm dur}$

→ Cocoon can't cover the dissipative region.

→ **Detectability highly depends on** $t_{\rm dur}$





Schematic image
in the case of $r_{\rm dis} > R_{\rm coc}$

GRB211211A : long GRB with kilonova

Repoted by Rastinejad +22

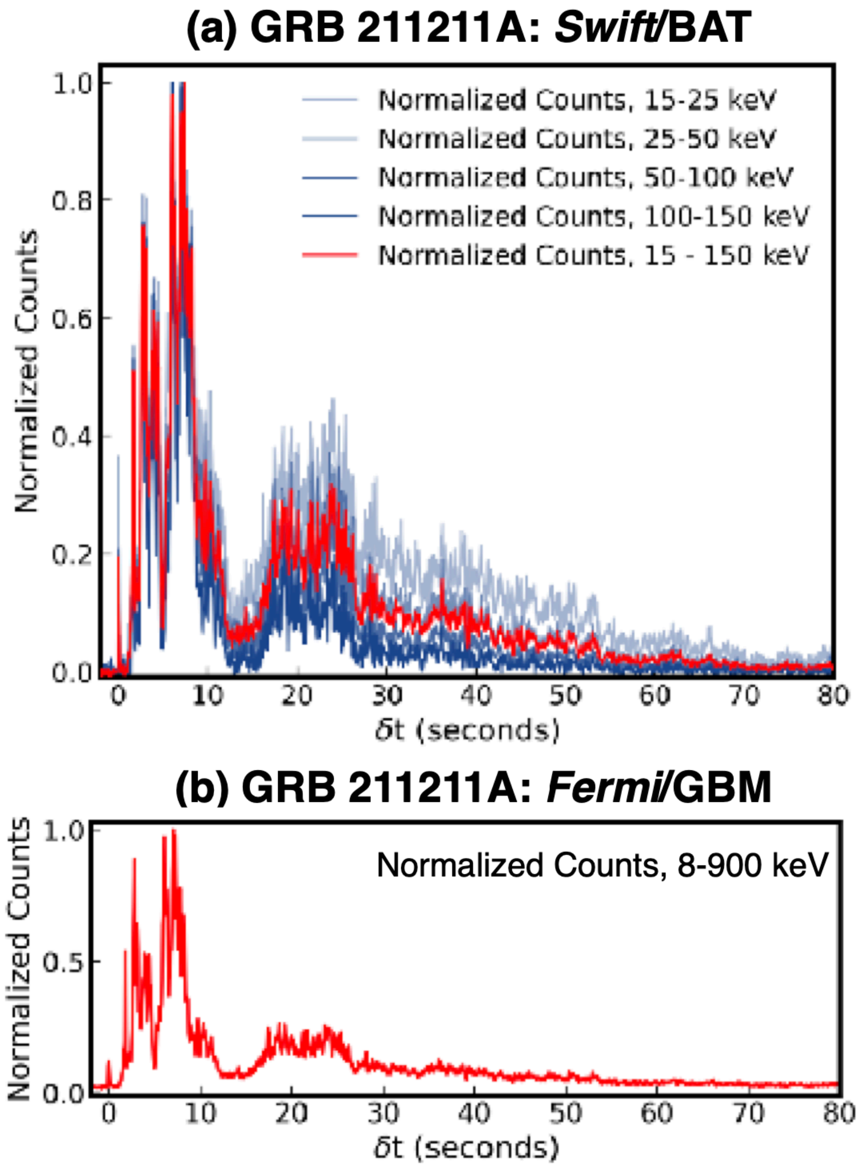
$d_L = 350$ Mpc

LIGO/Virgo were not in operation.

$t_{\rm dur} \sim 50$ s

$\rightarrow$ Non-detection of ν is consistent with the case of $r_{\rm dis} > R_{\rm coc}$

※ It is possible to be associated with GeV gamma-ray by Fermi/LAT at t~10^4 s (Mei et al. 2022).

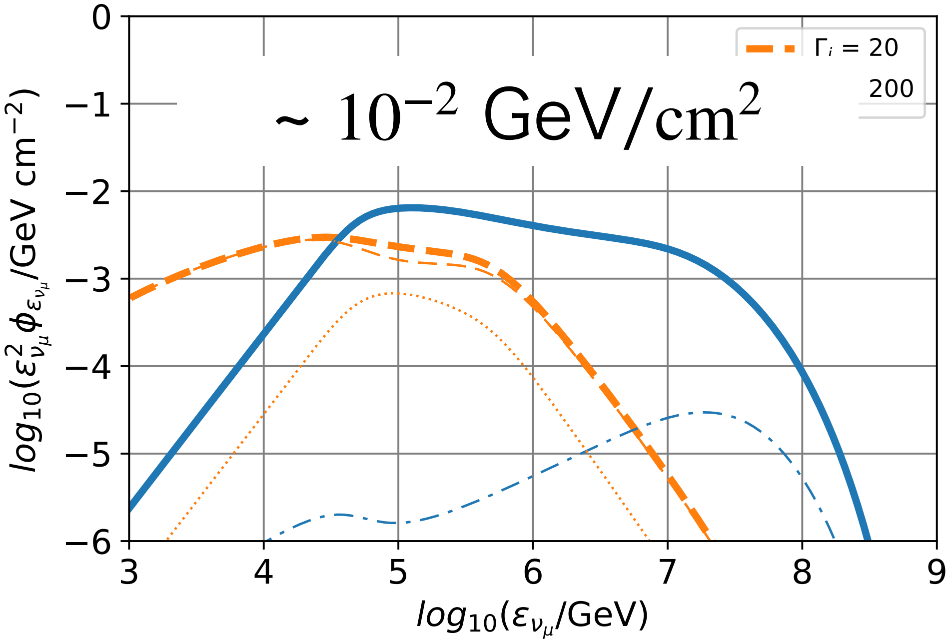


Rastinejad +22

Comparison with IceCube analysis

Analyzed GRBs are cosmological (z ~ 1-2)
→ **If the result is apply z~ 1-2,**
fluence become 100 times smaller.
→ It is consistent.

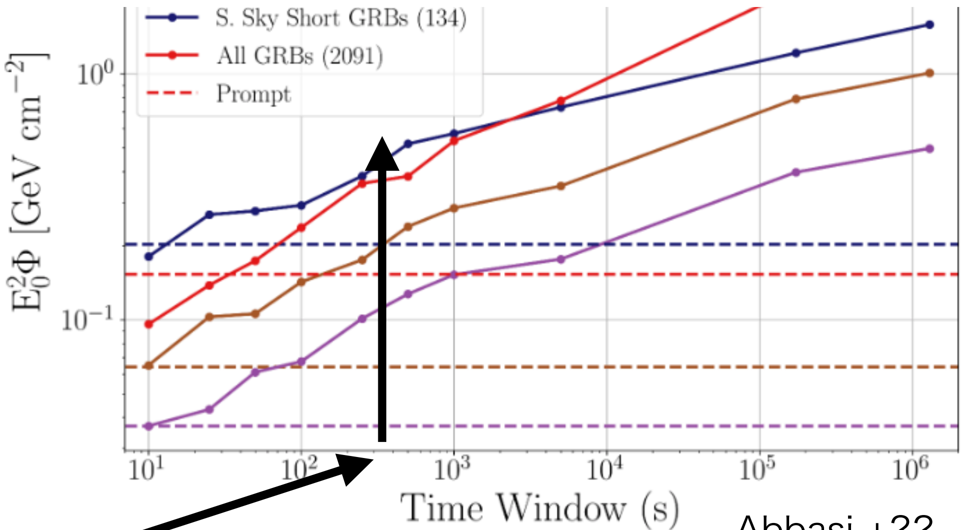
Resultant spectrum



$d_L = 300$ Mpc, $t_{\rm dur} = 10^{2.5}$ s

Upper limits

$\sim 5 \times 10^{-3}$ GeV/cm^2/events



Abbasi +22

z ~ 0.5, 2 Gpc

EM observation of choked-jet

Prompt jet is choked.
→ No prompt emission
→ gamma-ray is not strong.
→ It’s difficult to find.

Prolonged jet break out
→ Extended, Plateau emission
→ It’s blight in soft X-ray.

- XRT and others : FOV is small.
- MAXI (FOV: 7.3×10^{-2} str) cannot follow up
- Swift/BAT (FOV: 1.4 str): energy range is hard X-ray.
  → Future wide-field X-ray monitor is necessary.