ガンマ線バーストの長期放射に伴う高エネルギーニュートリノ放射

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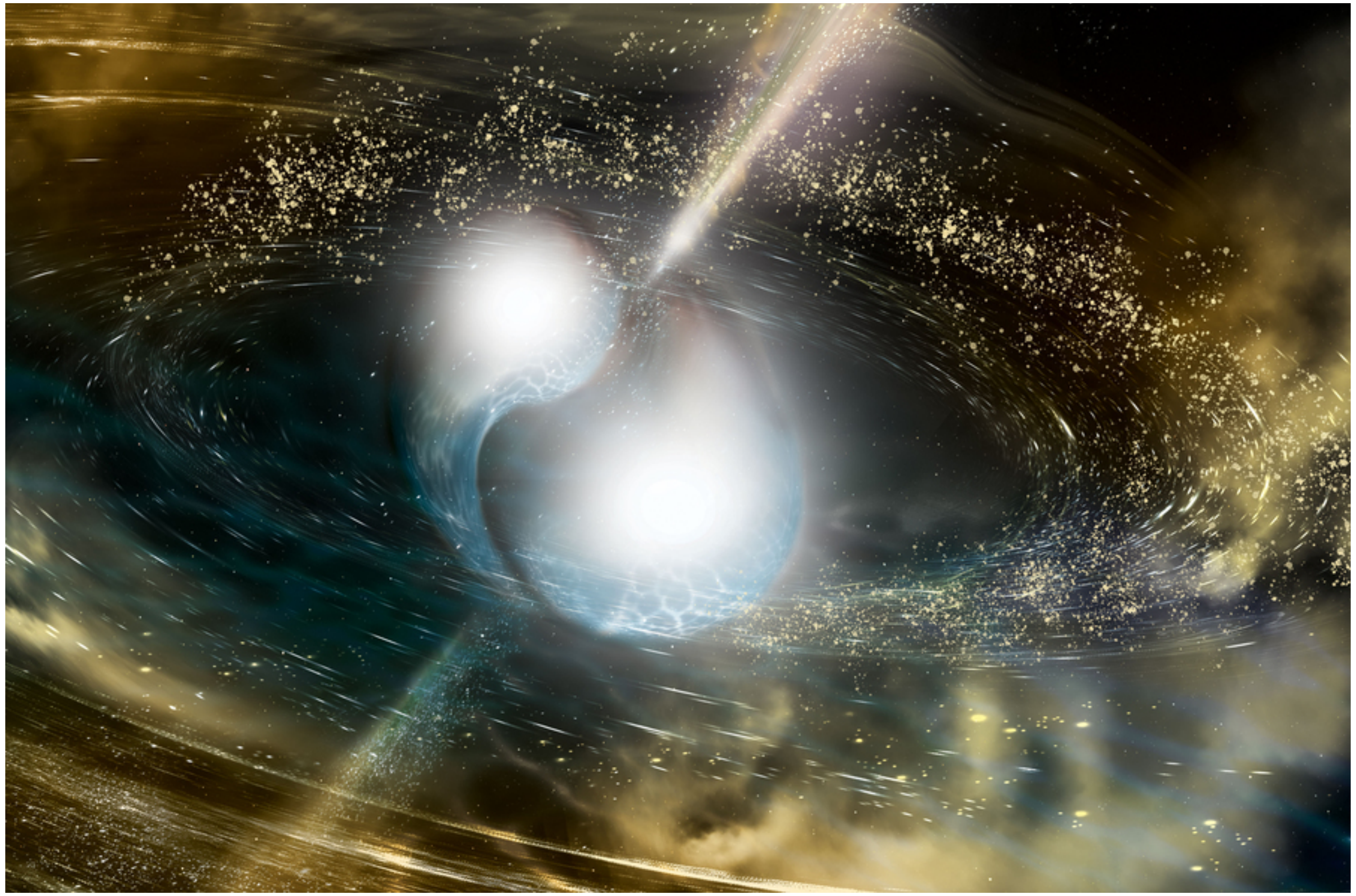
日本天文学会2023年秋季年会

Gamma-Ray Burst (GRB)

The most luminous transient (in EM wave).

Mechanism ? Central object ? (Progenitor ?)



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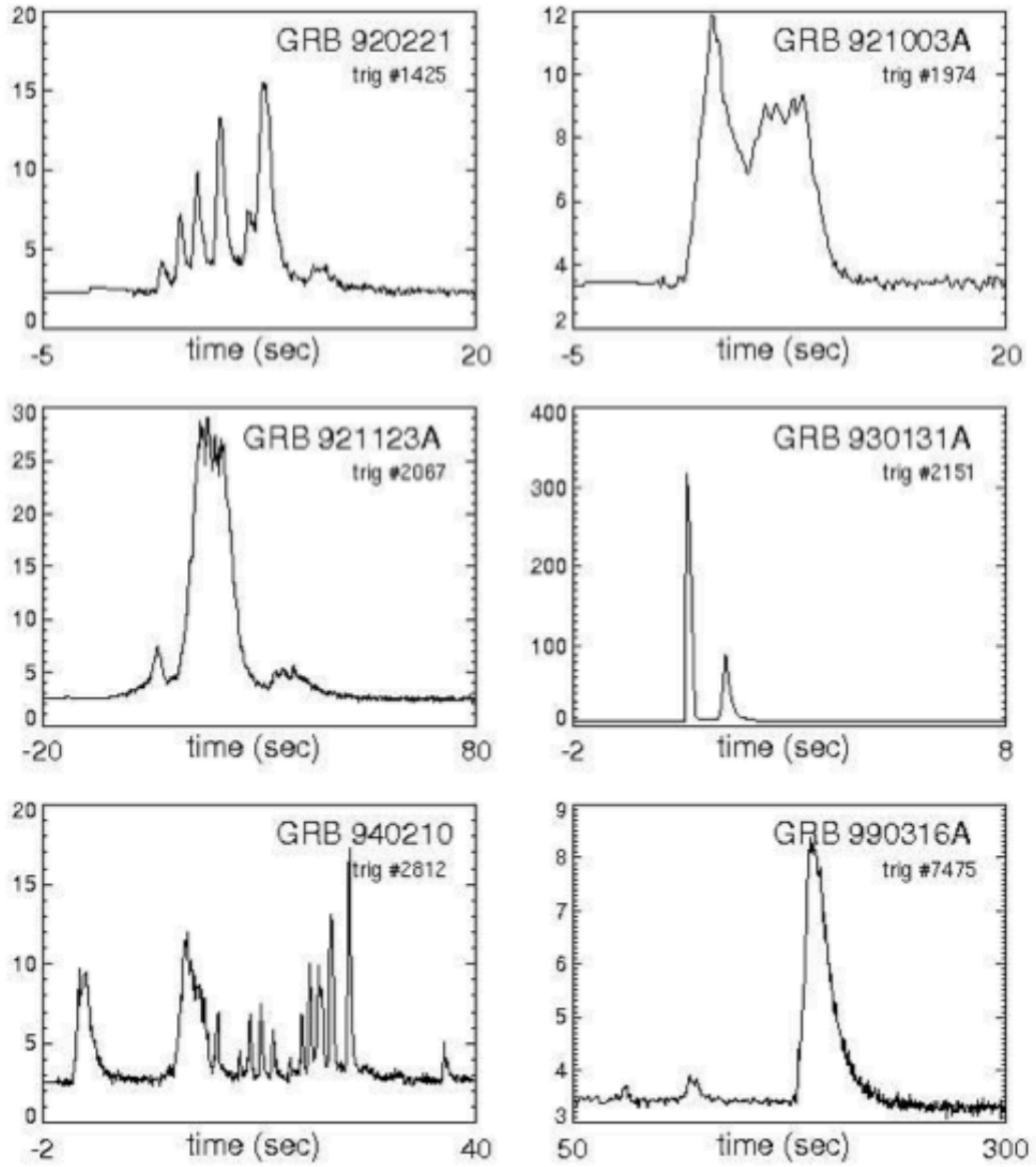
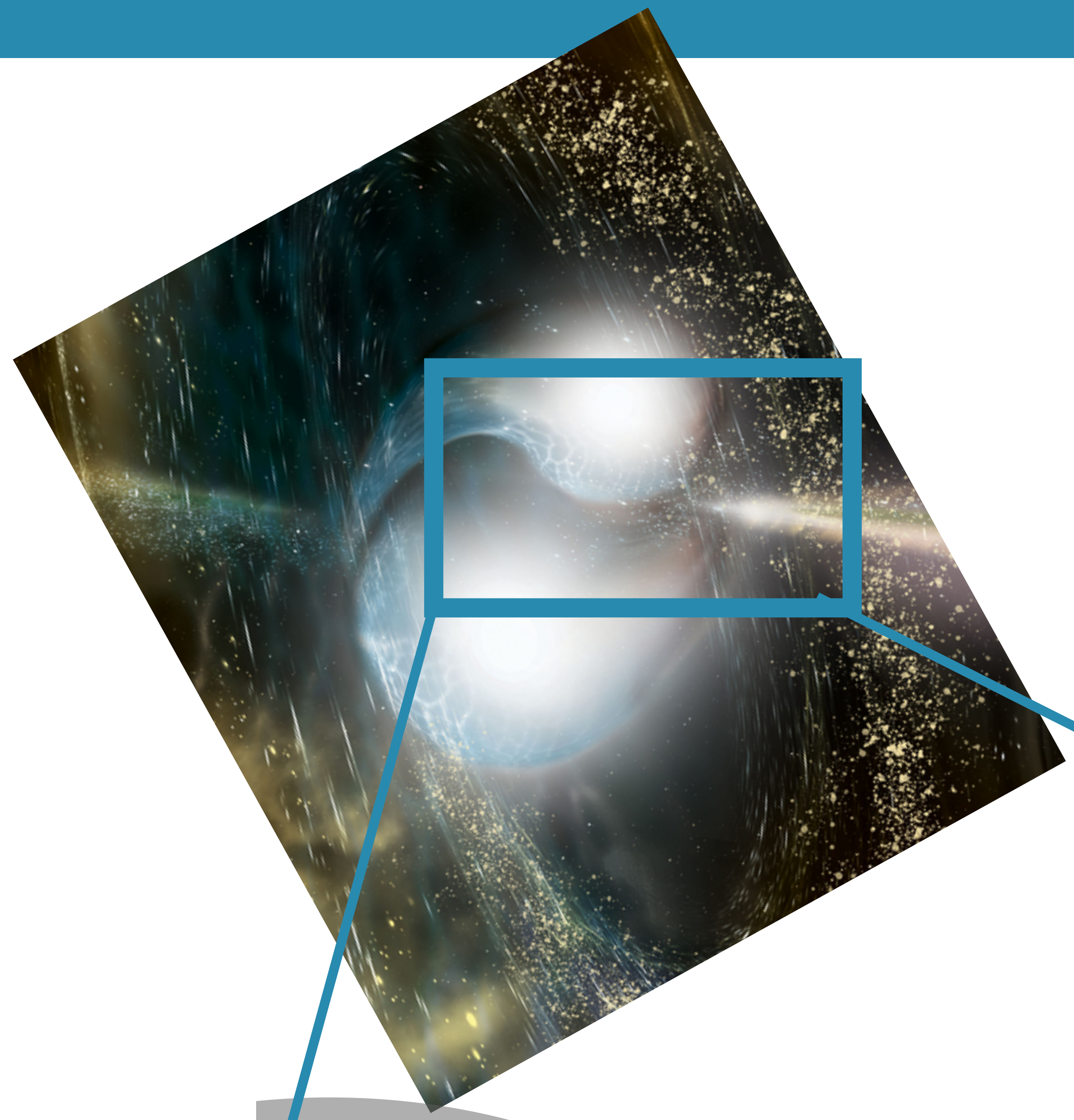


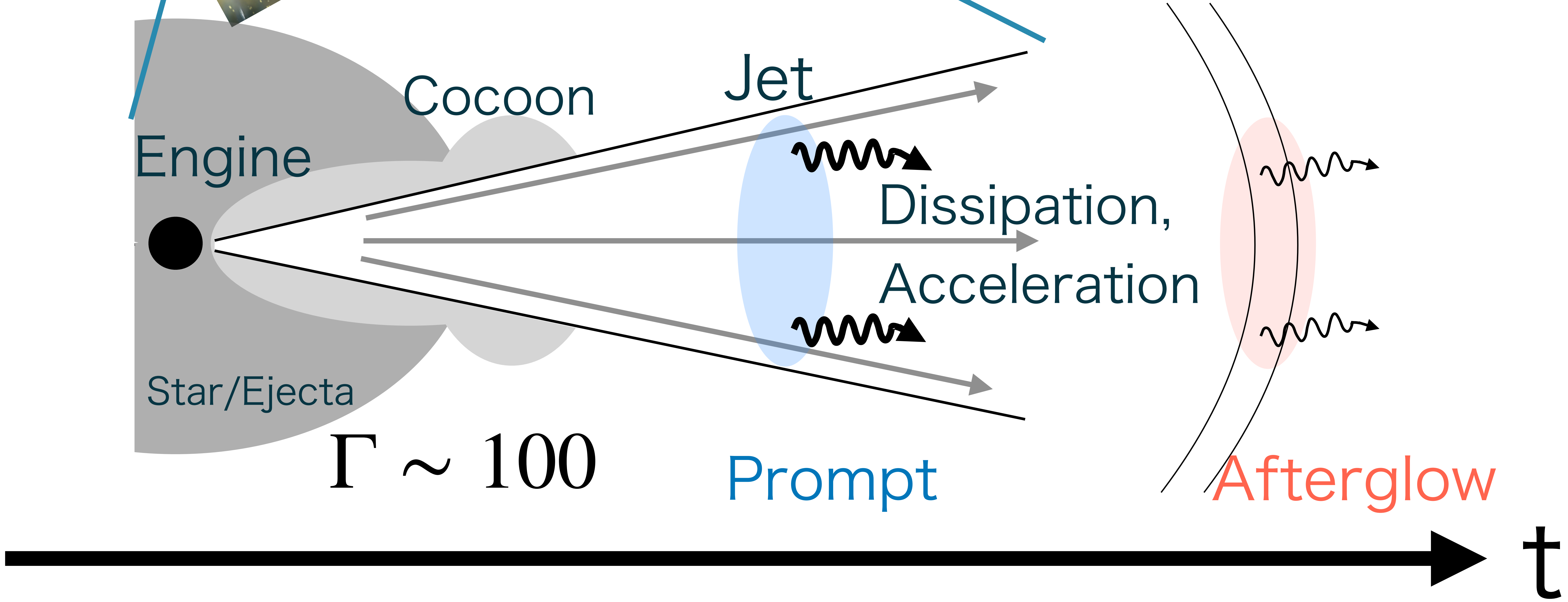
Pe'er +15

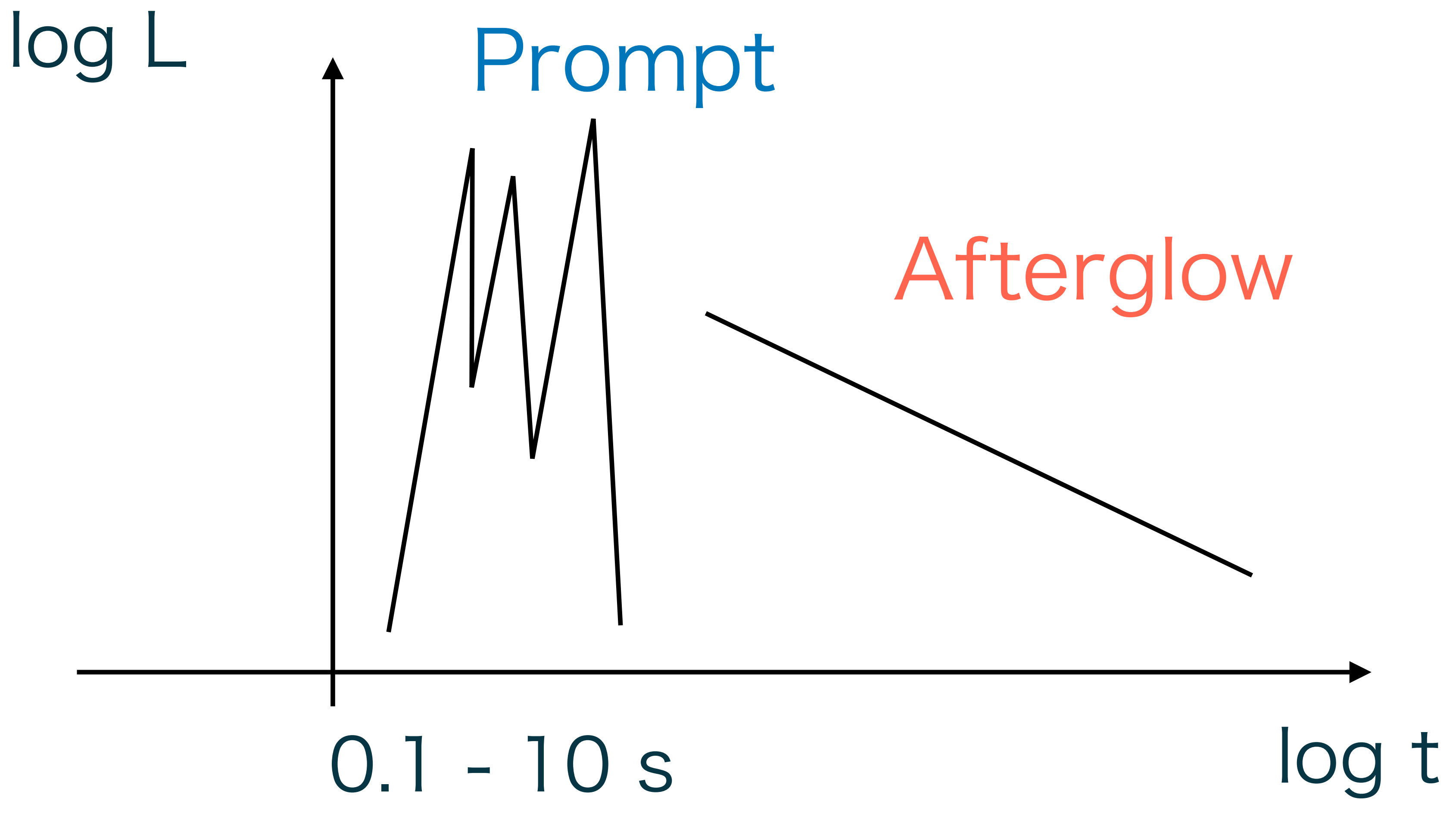
Relativistic Jets with $v \sim c, \Gamma \sim 100$



Canonical Theory of GRB

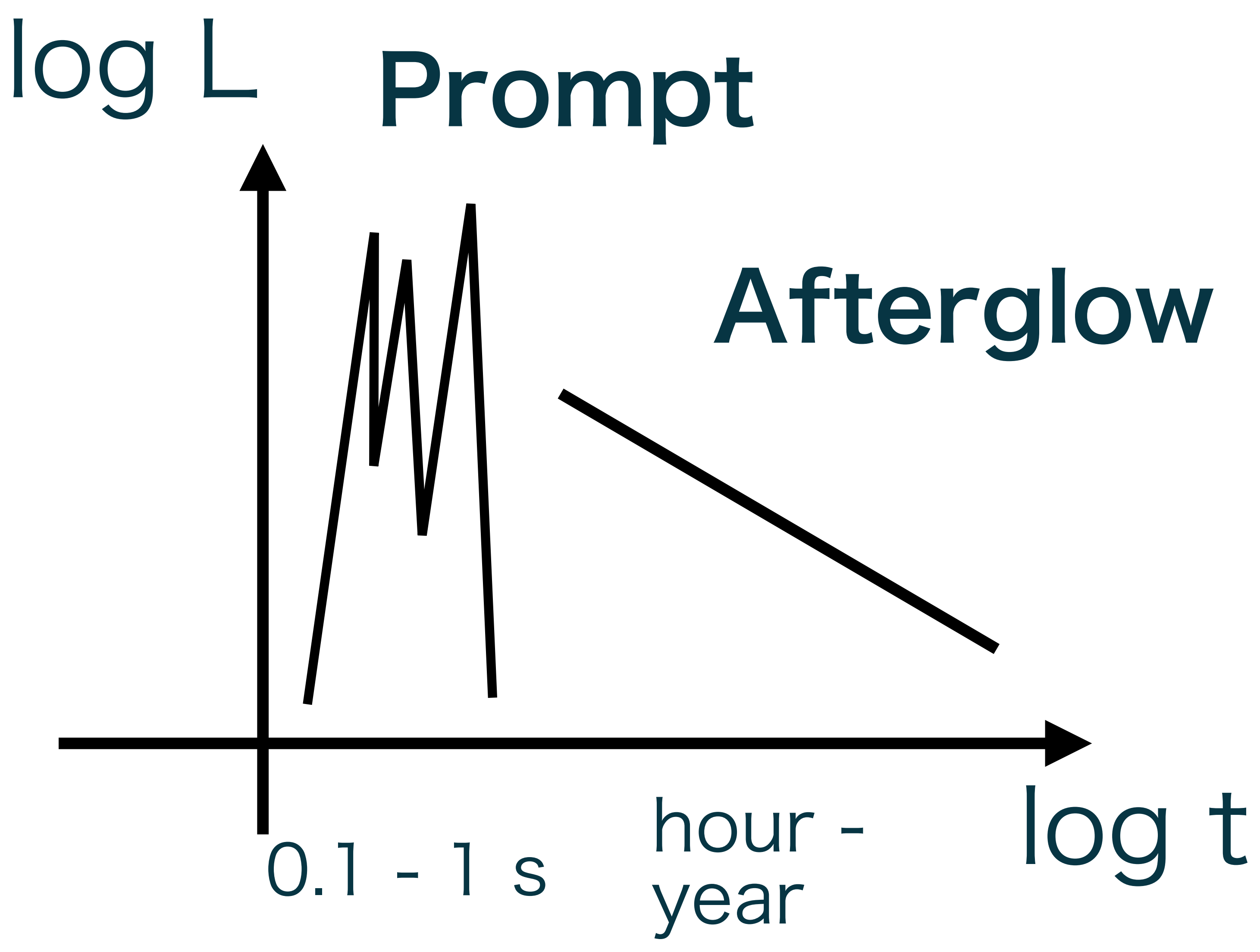
- Prompt emission : Jet internal dissipation
- Afterglow : Jet-ISM dissipation



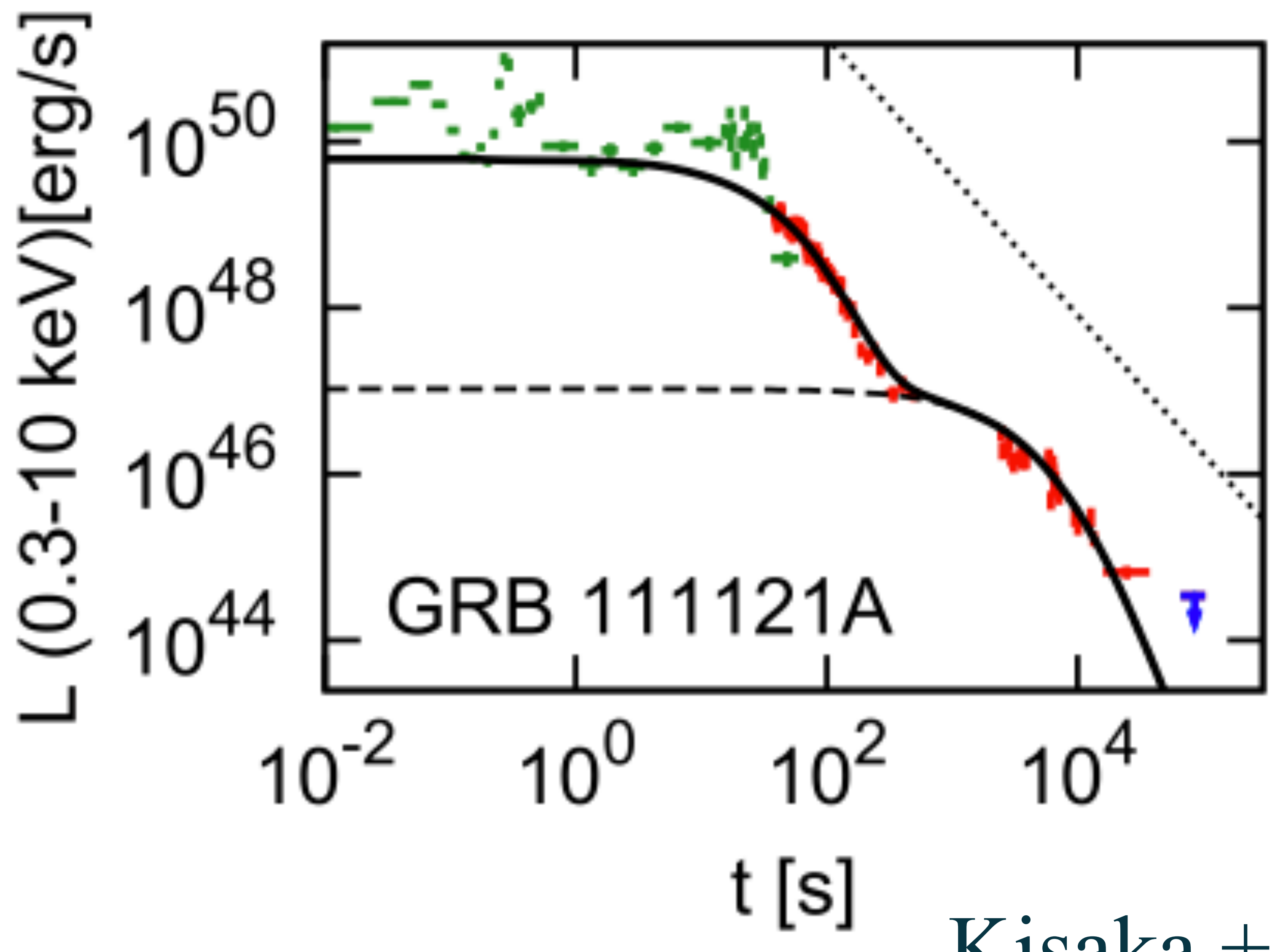


Late-time Emission of Gamma-Ray Burst

Theory of GRB



Short GRB

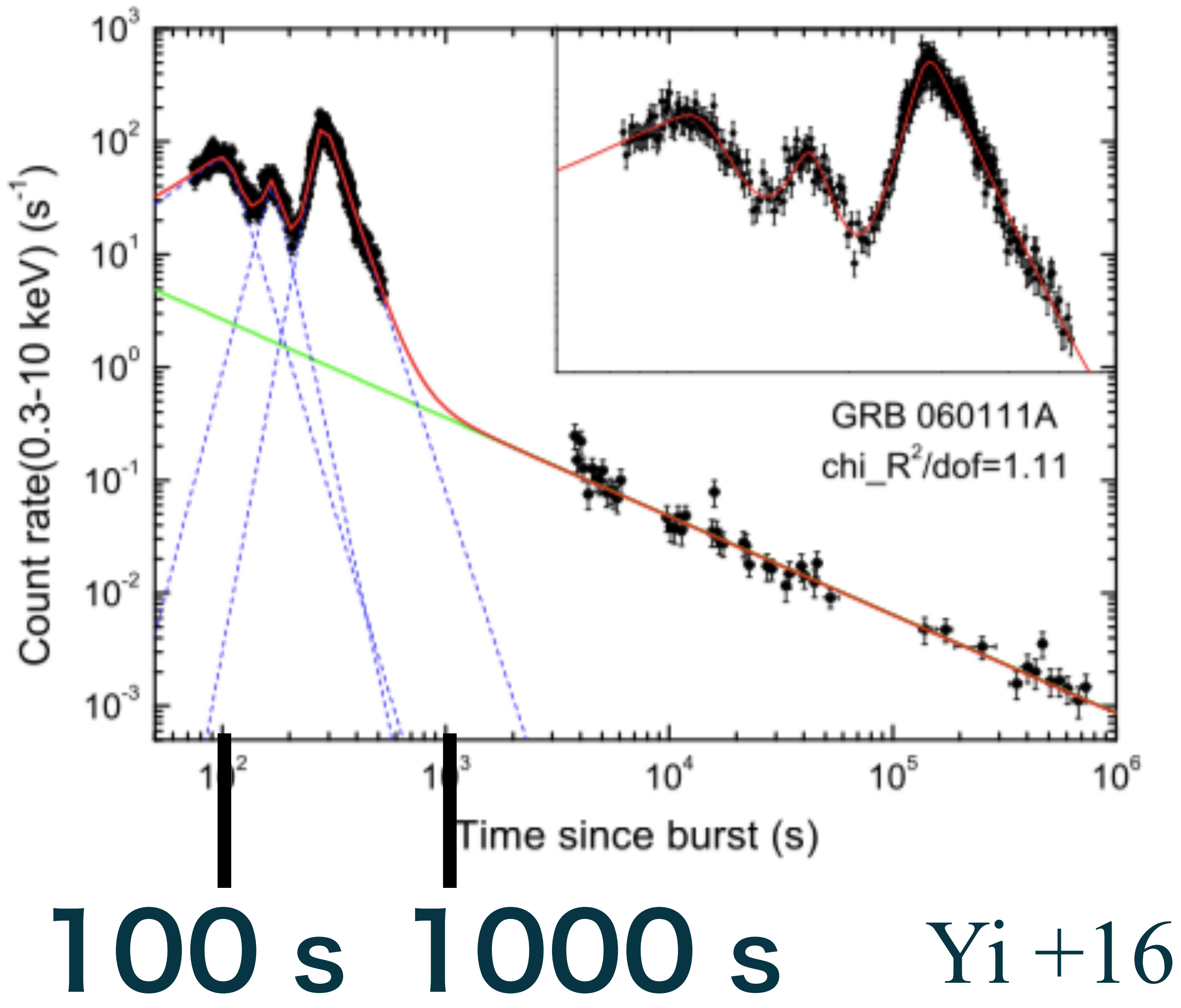


Kisaka +17

"Extended Emission"

(~ 2/3 of SGRBs)

Long GRB

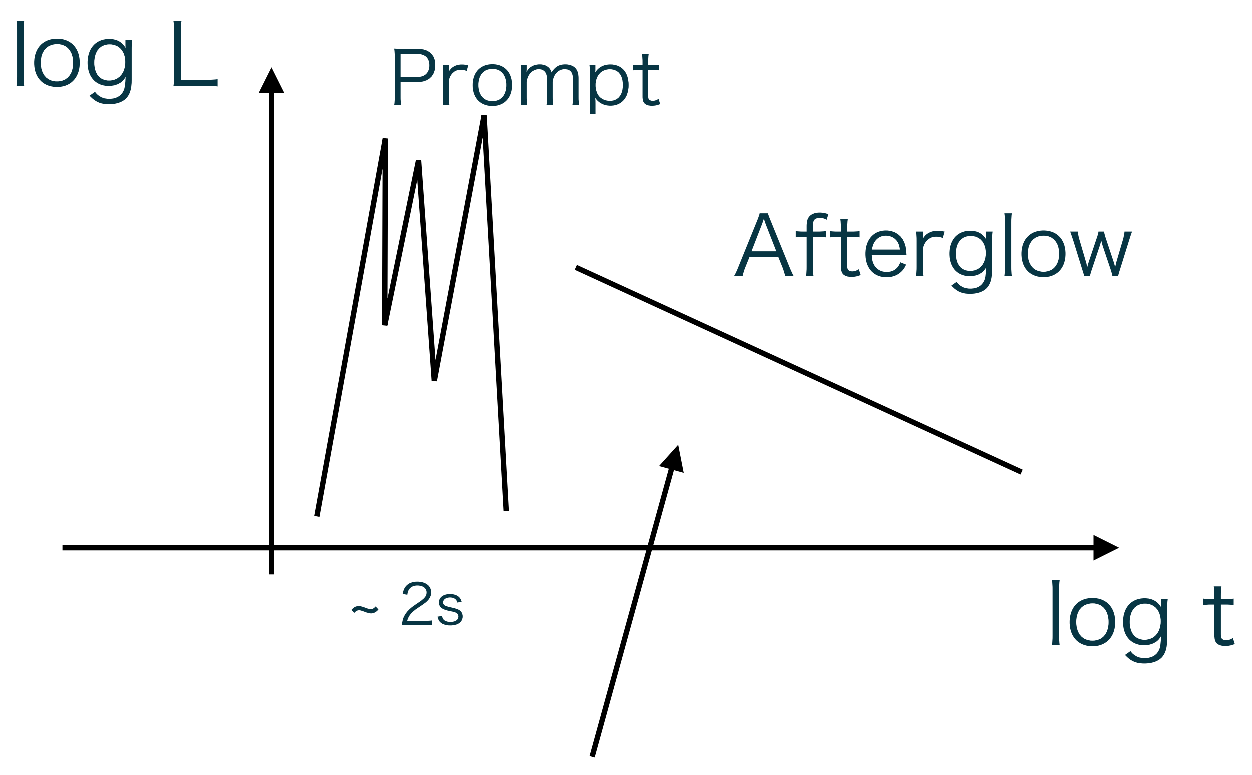


Yi +16

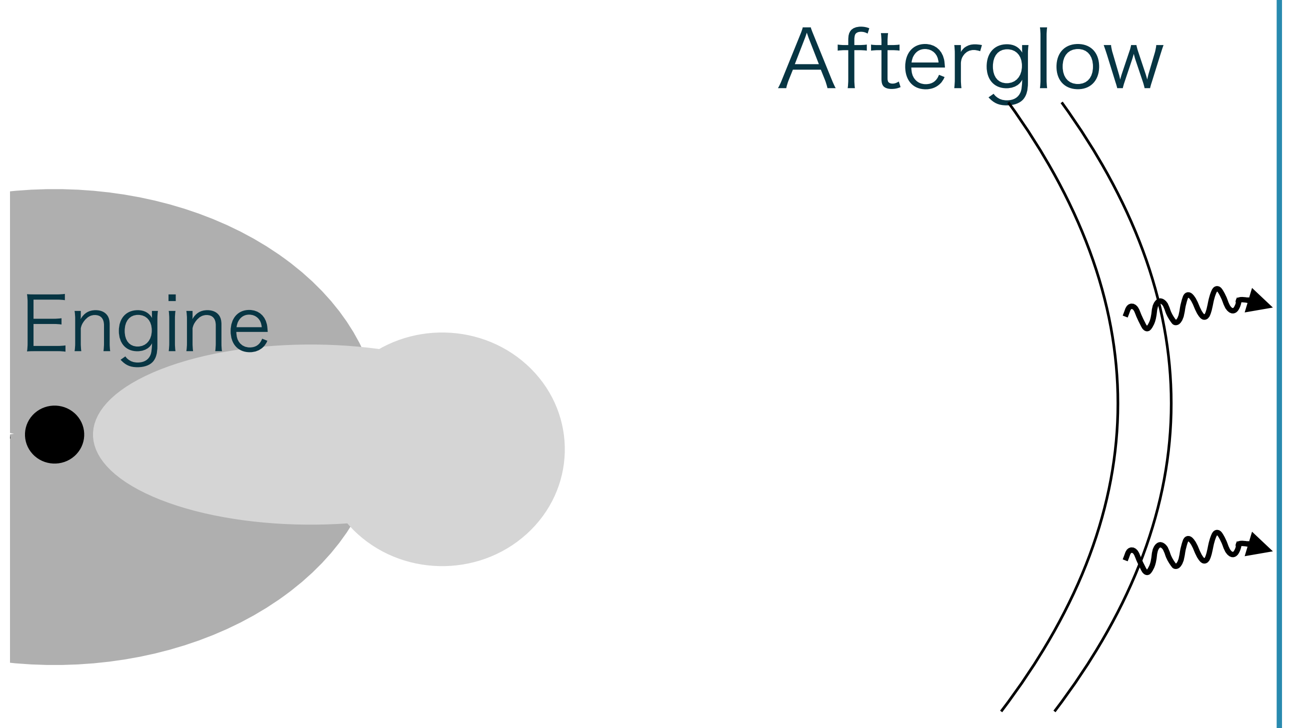
"X-ray Flare"

(~ 1/3 of LGRBs)

Prolonged central enigine activity

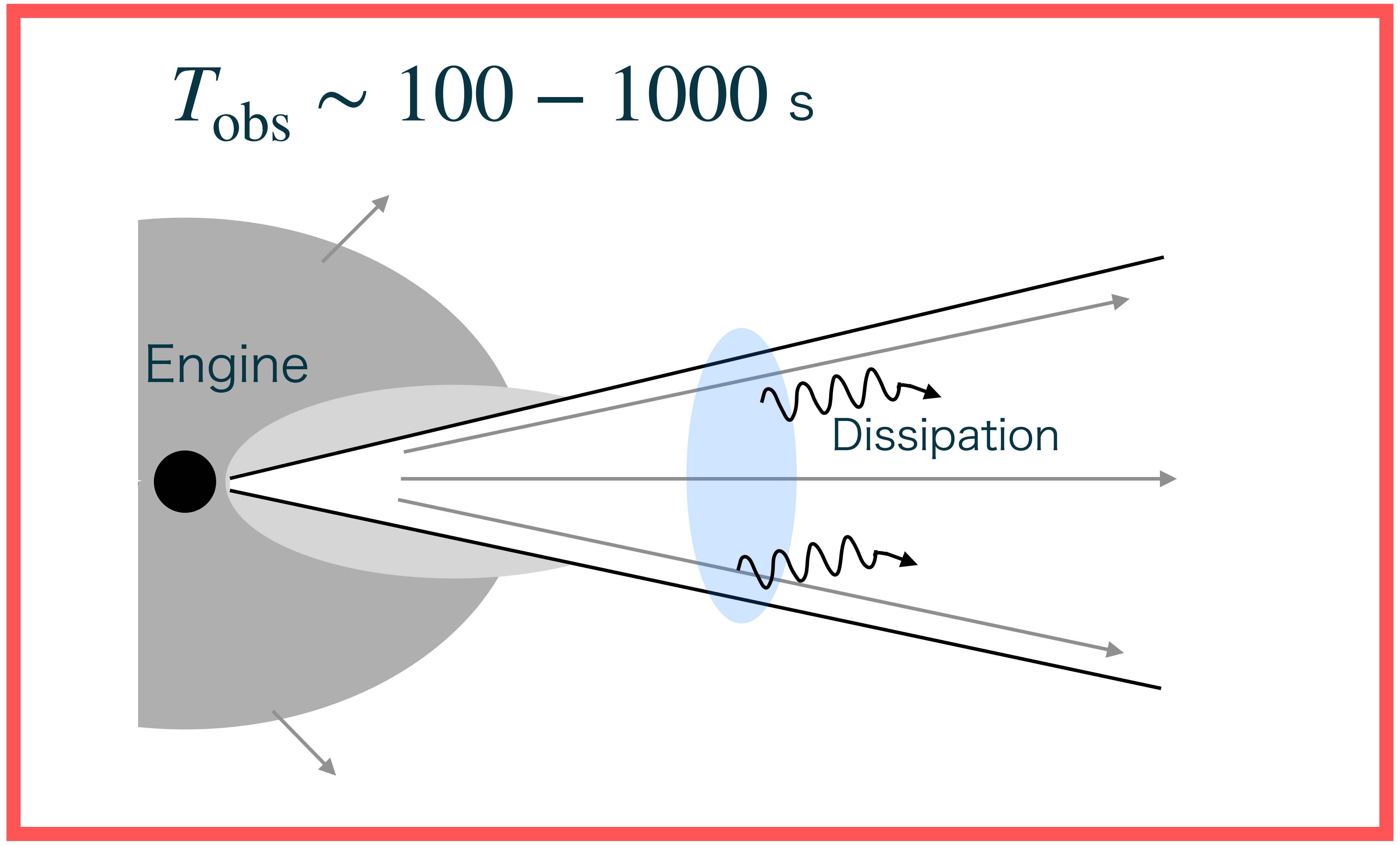


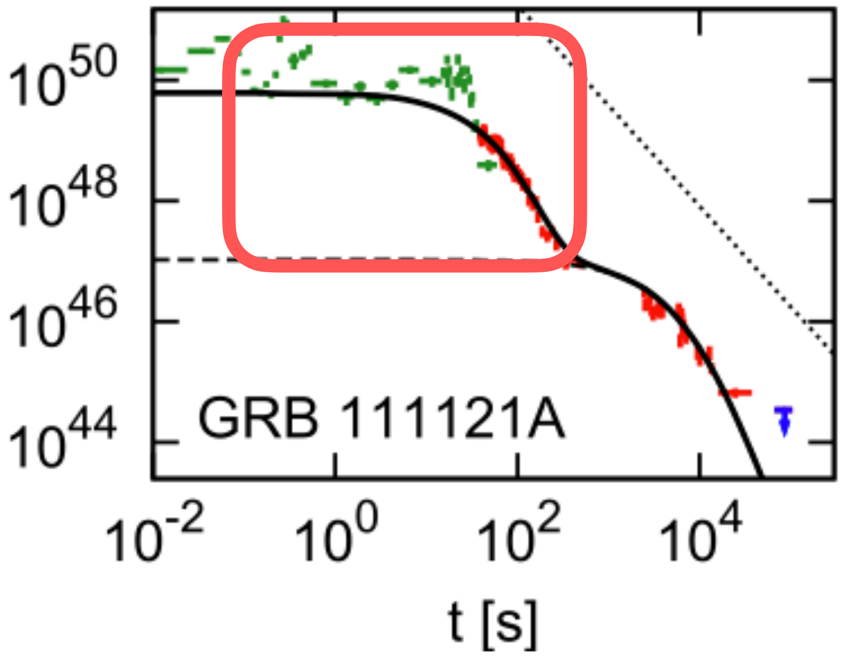
$T_{\rm obs} \sim 100 - 1000$ s



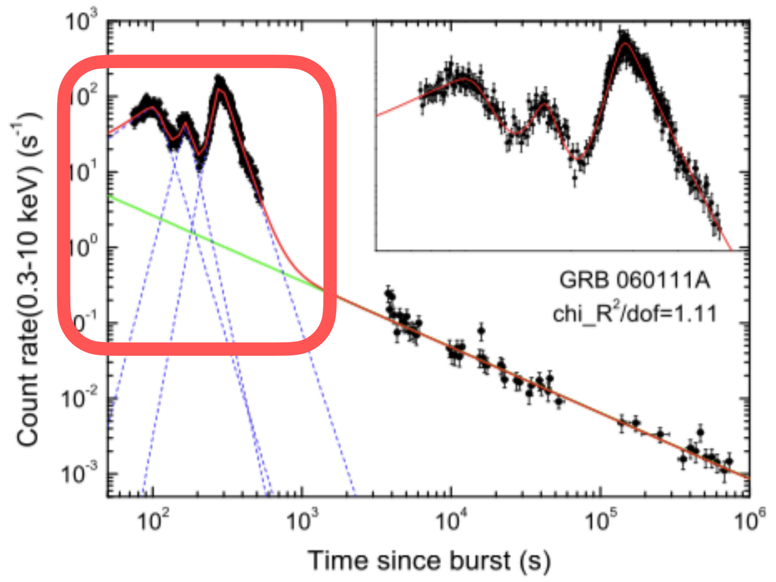
Standard Scenario for late-time emission :
Prolonged engine activity & Jet dissipation

(e.g. Ioka et al. 2005, Perna et al. 2006)





(Kisaka +17)



(Yi +16)

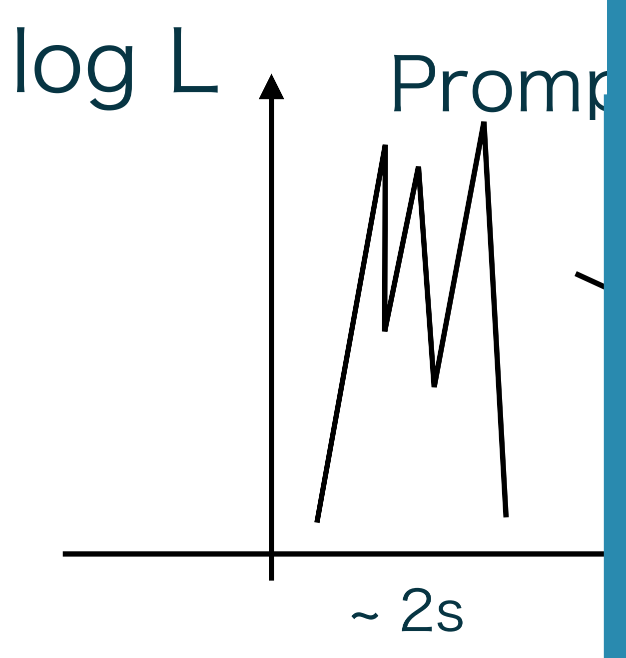
Problem :

Properties of the late-time jet are unknown.

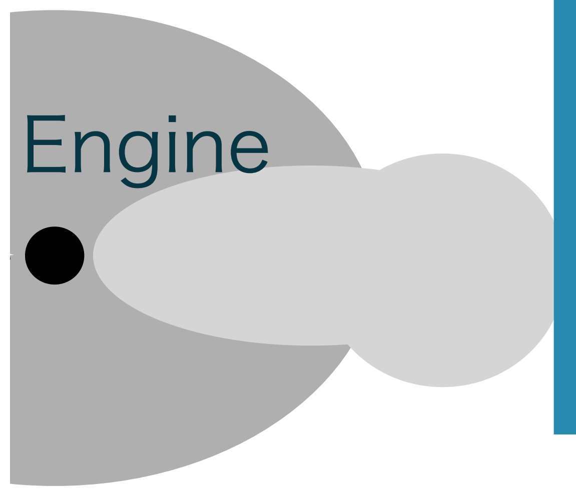
Prolonged central enigine activity

Theory

d Scenario for late-time emission :
ed engine activity & Jet dissipation



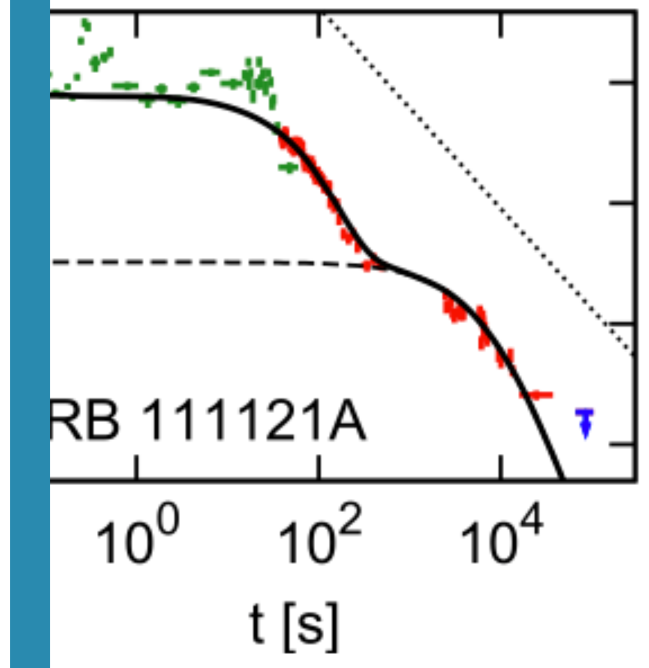
$T_{obs} \sim 10$



Question

Can we characterize it by other observations？

A. Yes. (Neutrino)



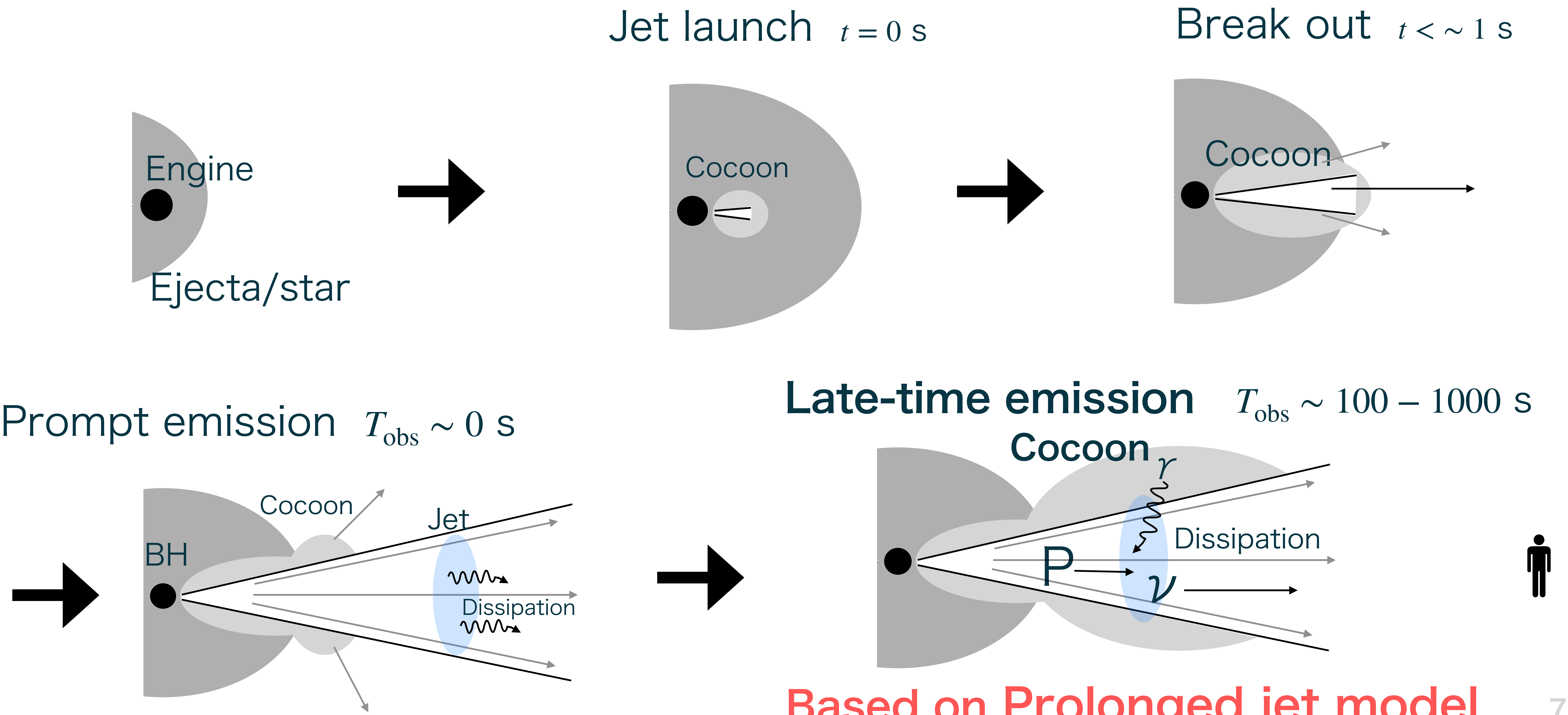
(Kisaka +17)

Problem :

Properties of the late-time jet are unknown.

Prolonged Engine and Cocoon Scenario

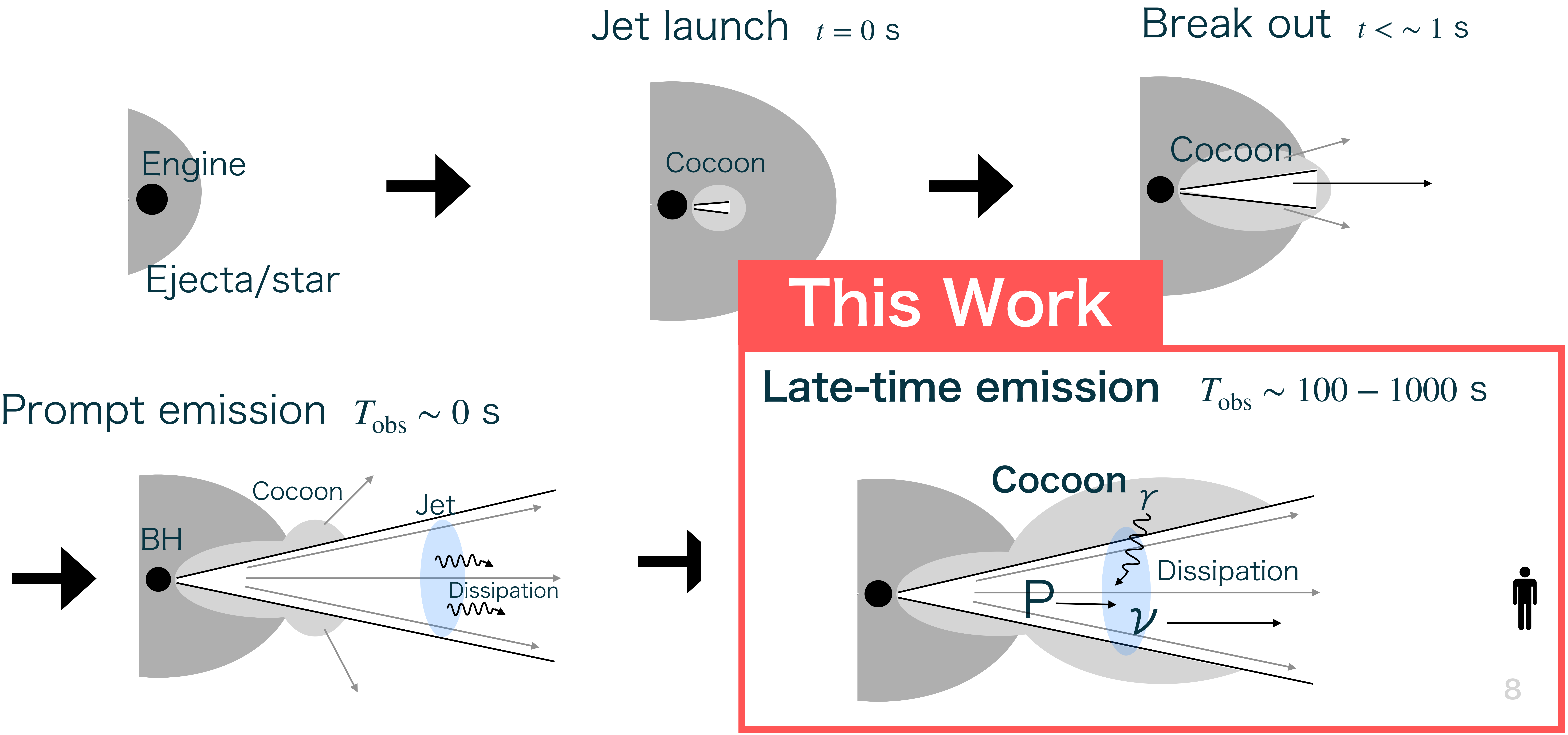
See also, Kimura+19 (γ), Hamid+21, 23 (simu), Mei+22 (γ, obs)



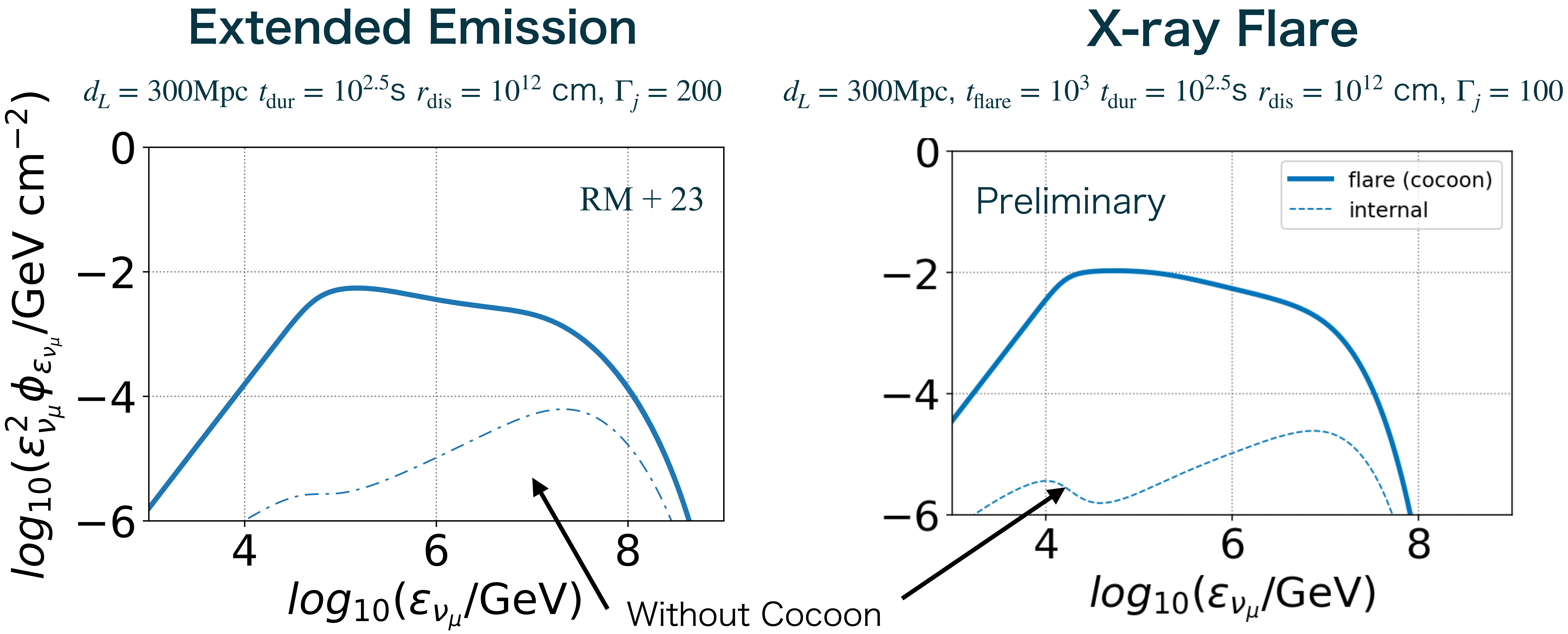
Based on Prolonged jet model

Prolonged Engine and Cocoon Scenario

See also, Kimura+19 (γ), Hamid+21, 23 (simu), Mei+22 (γ, obs)



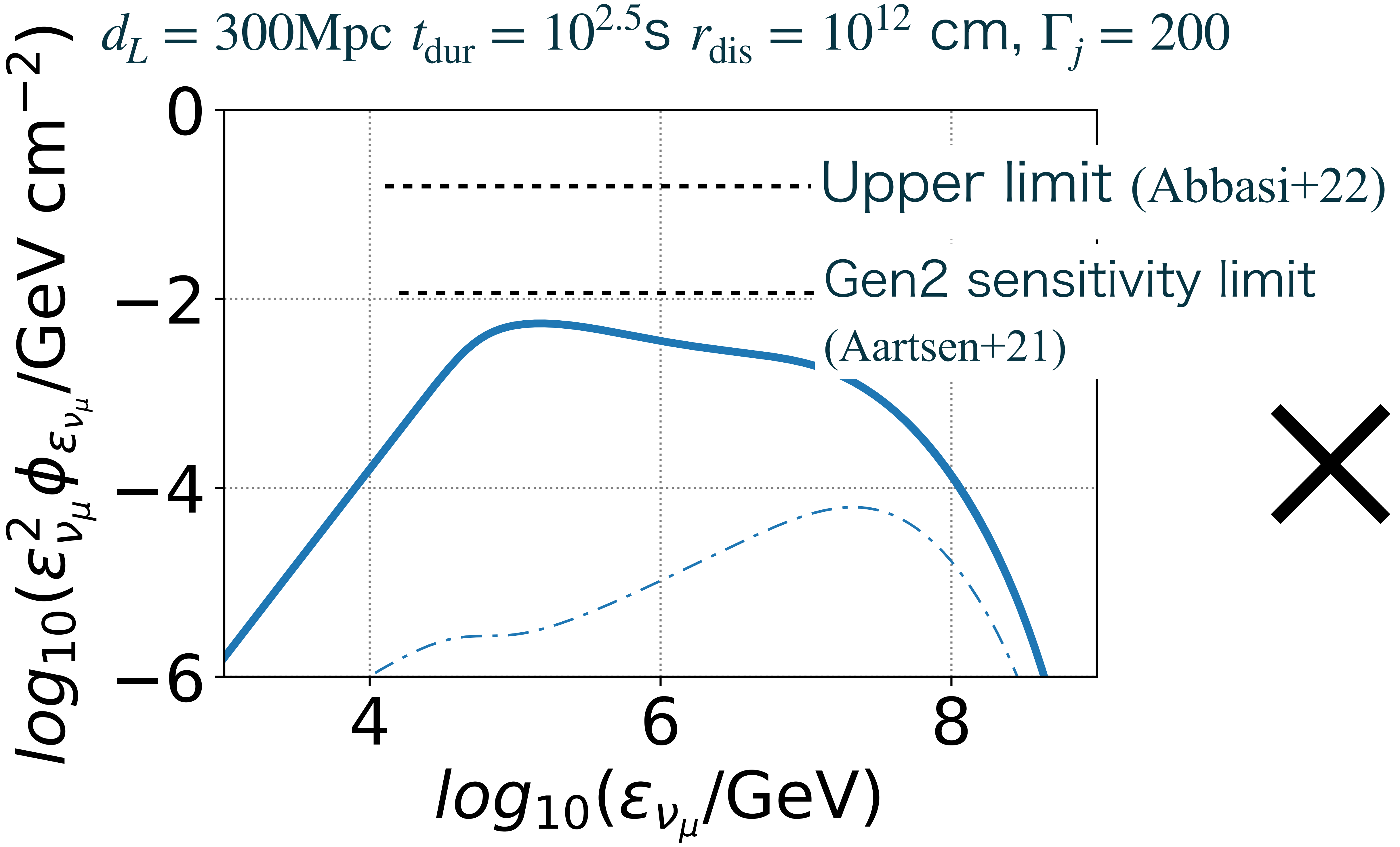
Results 1 : Neutrino Spectra



Cocoon increase the ν flux by 1000 times at ~PeV.

Results 2 : Expected Number of Detection

Neutrino Spectra



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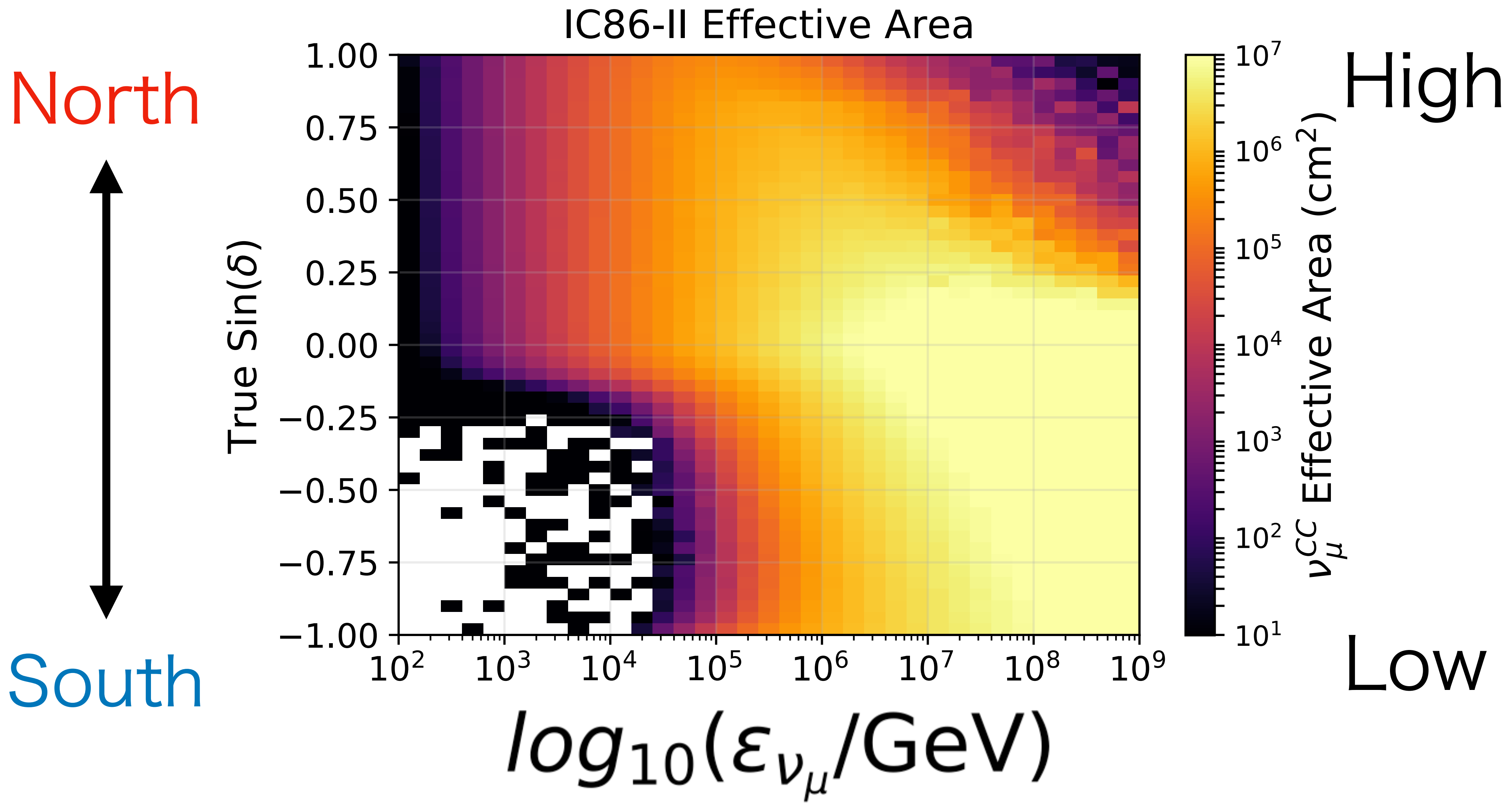
IceCube Effective Area



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

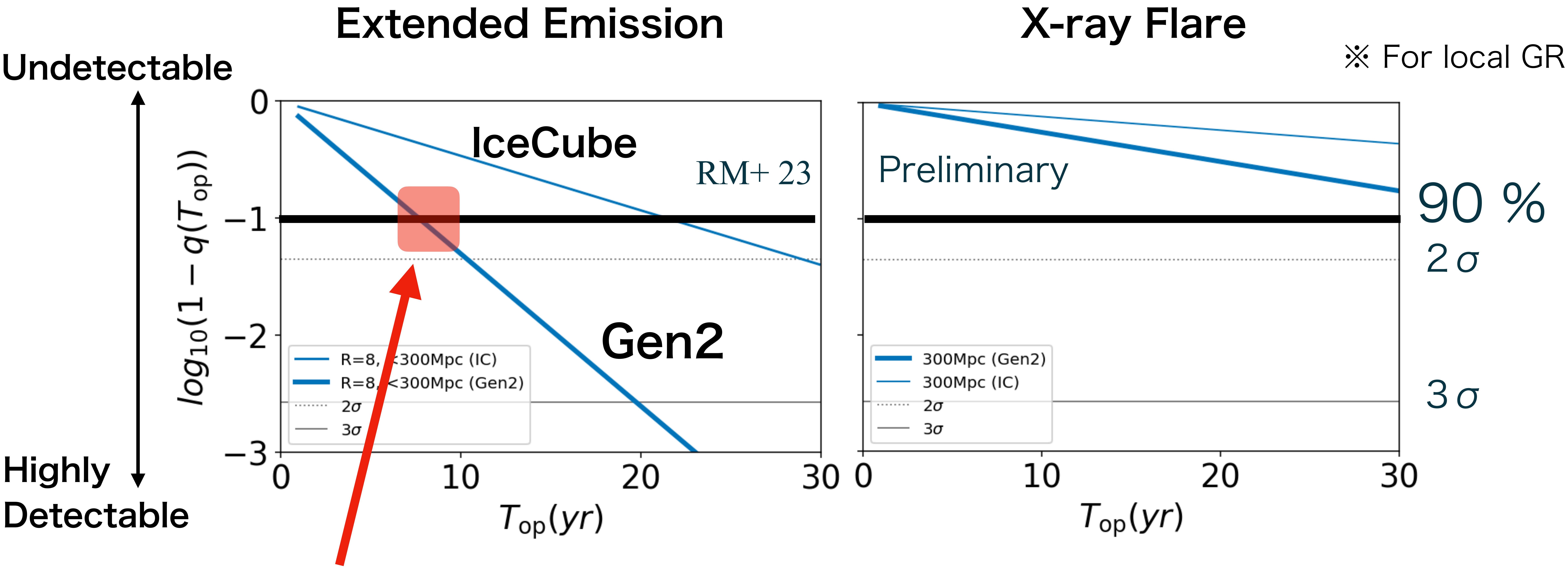
→

Number of the Detection

1 ν /10 GRBs by IceCube ※ Fixed d_L = 300 Mpc, $t_{\mathrm{dur}} \sim 300$ s e.t.c.

Results 3 : Operation time

※ For local GRBs



Neutrinos are 90% detectable in 10 years (Gen2, E.E of local sGRB).

※ X-ray flares take more than 30 years.

Cosmological GRB

Typical distance : $z \sim 0.5$ (SGRB) / $z \sim 2$ (LGRB)

Rough estimation

Flux $\propto d_L^{-2}$, Event rate $\propto d_L^3 \rightarrow$ Neutrino signal $\propto d_L$

Exactly,

- Flux : Comparable with the atomospheric BG ?
- Event rate $\propto d_L^3\, f(z)/\,(1+z)^4$

Model Parameters

Table 1. fiducial parameters

Parameters	Γ_j	$t_{\rm dur}$ (s)	$L_{\rm X}$ (erg/s)	$r_{\rm dis}$ (cm)	$\varepsilon_{\gamma,\rm pk}$ (keV)
Extended	200	$10^{2.5}$	10^{48}	10^{12}	10
Plateau	100	10^{4}	10^{46}	10^{13}	1

either case	$p_{\rm inj}$	ξ_p	ξ_B	d_L (Mpc)	Energy band (keV)
	2.0	10	0.33	300	0.3 – 10 (XRT)

γ number density

Proton number

$\theta_j = 5^\circ$

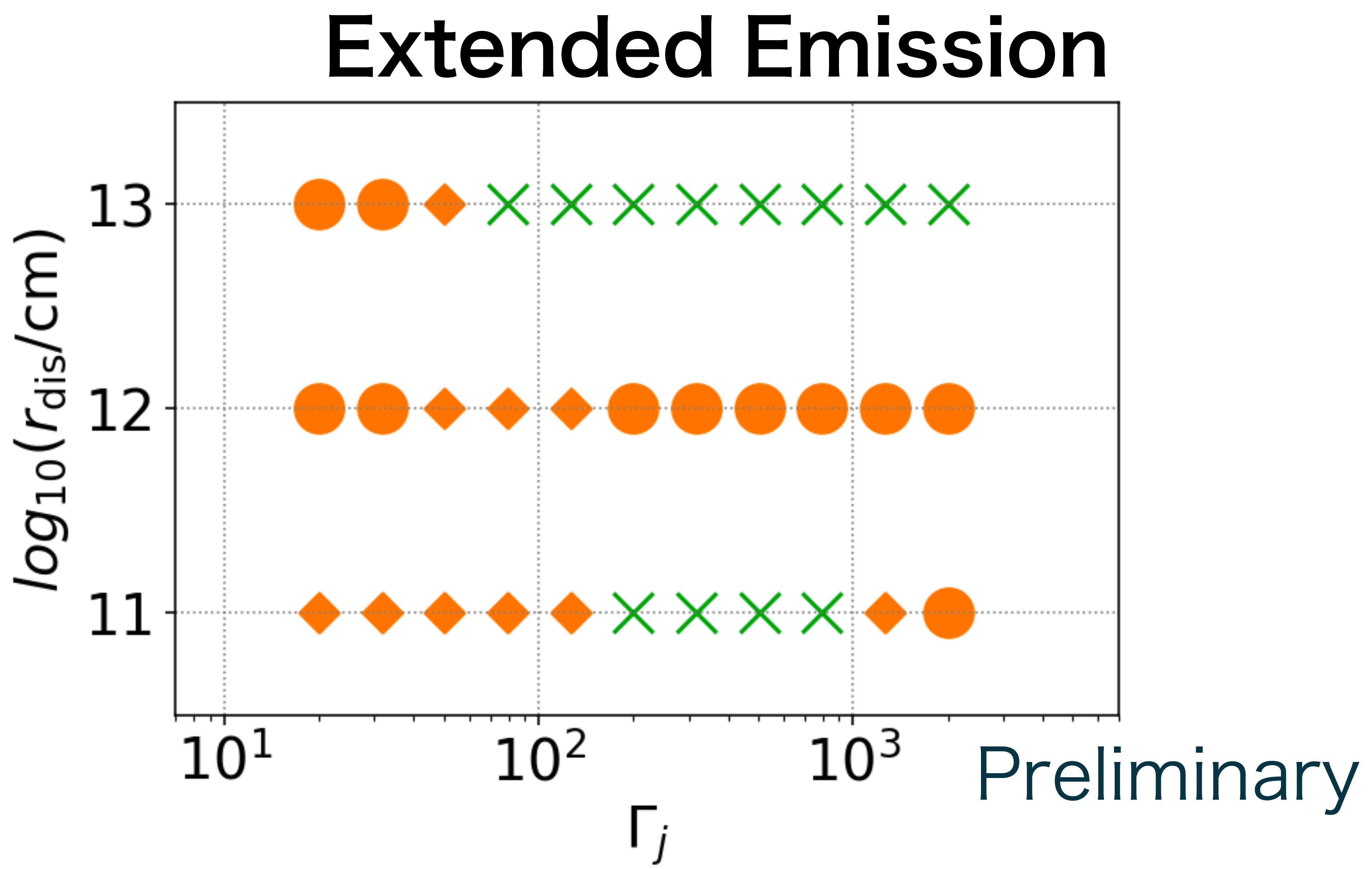
$\xi_p = U_{\rm p}/U_\gamma,$

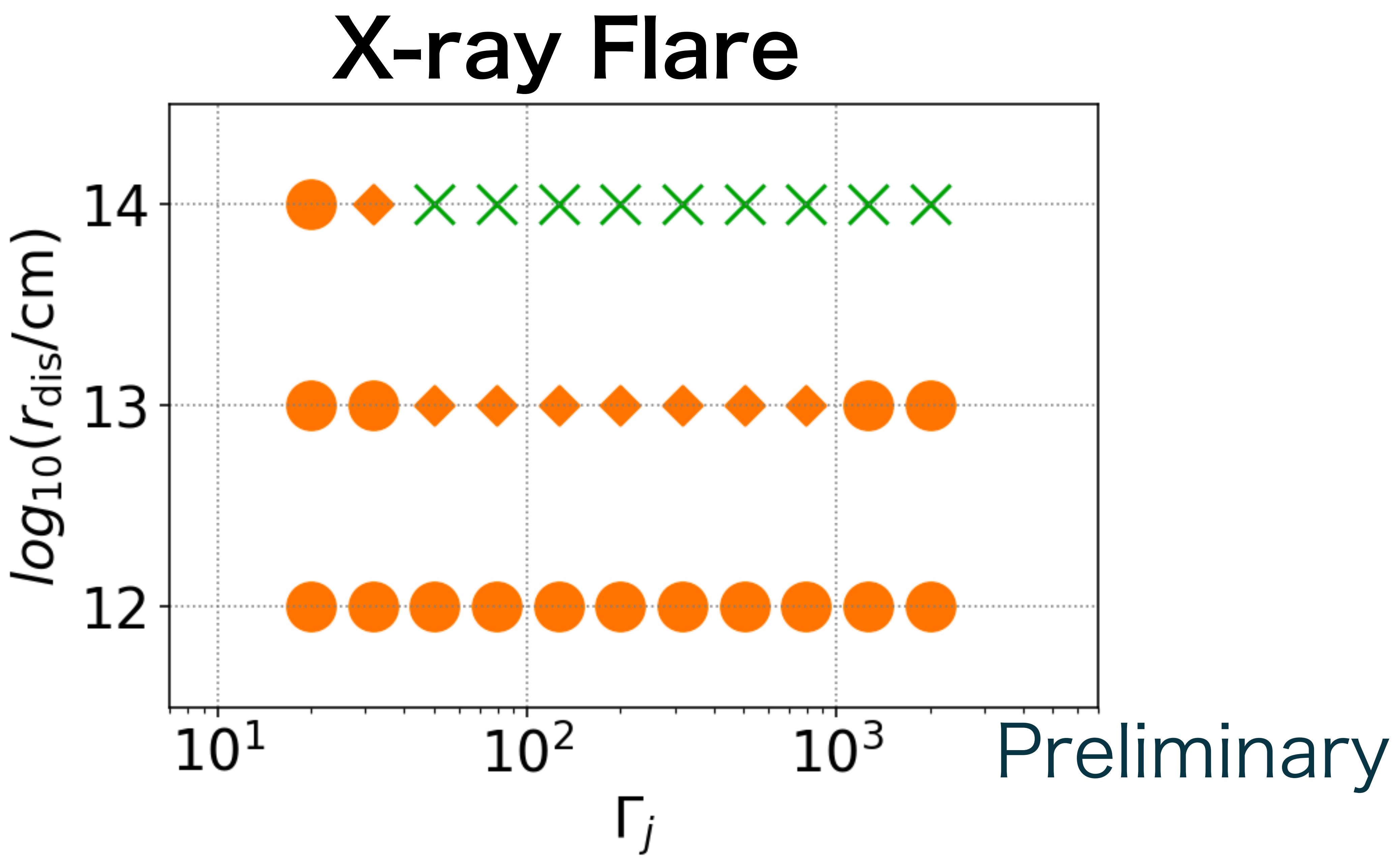
$\xi_B = U_B/U_\gamma$

$\epsilon_p = U_{\rm p}/U_{\rm k} \sim 0.3,$

$\epsilon_B = U_B/U_k \sim 0.01$

Discussion : Constraints on physics of sGRB





>> 1 event/10 yr

or

<< 1event/10yr

Propaty of late-time Jet

- How jets launched ?
- How jets dissipated ?
- How many CRs ?

Mechanisim of the prolonged central engine activity ?

Summary

- **We calculated the neutrino emission associated with the late-time emission of Gamma-Ray Bursts,** considering the **prolonged engine activity model** and **cocoon** photons.

- **1 neutrino will be detected with 10 local GRB**s $(d_L \sim 300 \text{ Mpc})$

- **Neutrinos should be detected** from GRBs **in 10 years.** (Gen2 : 90%)

- The **dissipation radius** and **the Lorentz factor of late-time jet** will be constrained by the high energy observation in the future.

Take-home message

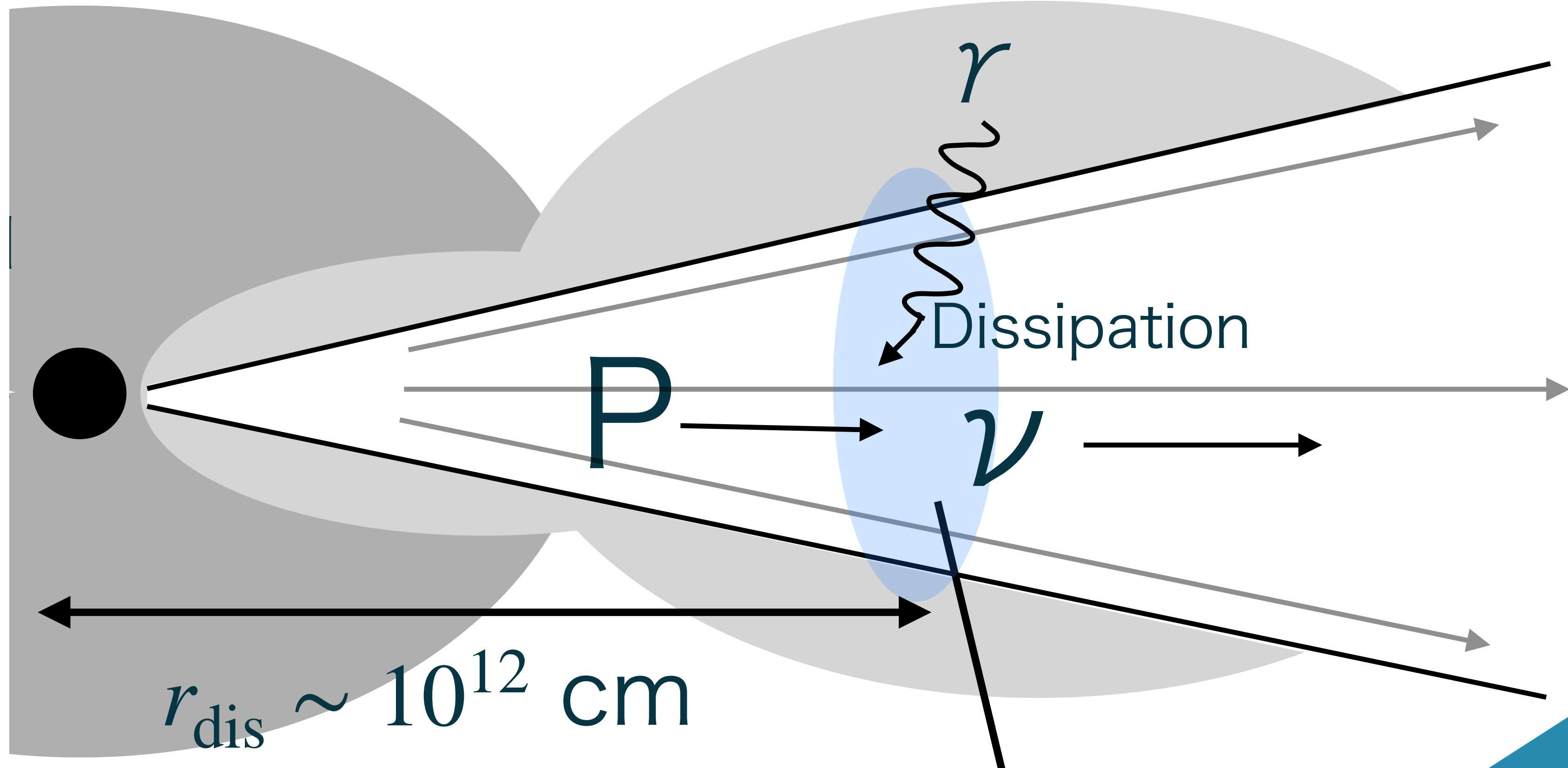
ガンマ線バーストの100 -1000 s 後に
100 TeV - 1 PeV のニュートリノが
X線と相関して見つかるかも

(特に重力波も相関する、

SGRBのExtended emission に注目)

Back Up

Method 1 : Neutrino emission



$t'_{p\gamma}$ $p + \gamma \to \pi^+ + X \to \mathbf{3}\nu + X'$

+ **Adiabatic** cooling
+ Bethe Heitler process
+ Synchrotron cooling

$t'_{\rm cool}$

+ diffusive **acceleration** $t'_{\rm acc}$

Neutrino Spectrum (One-Zone approx.)

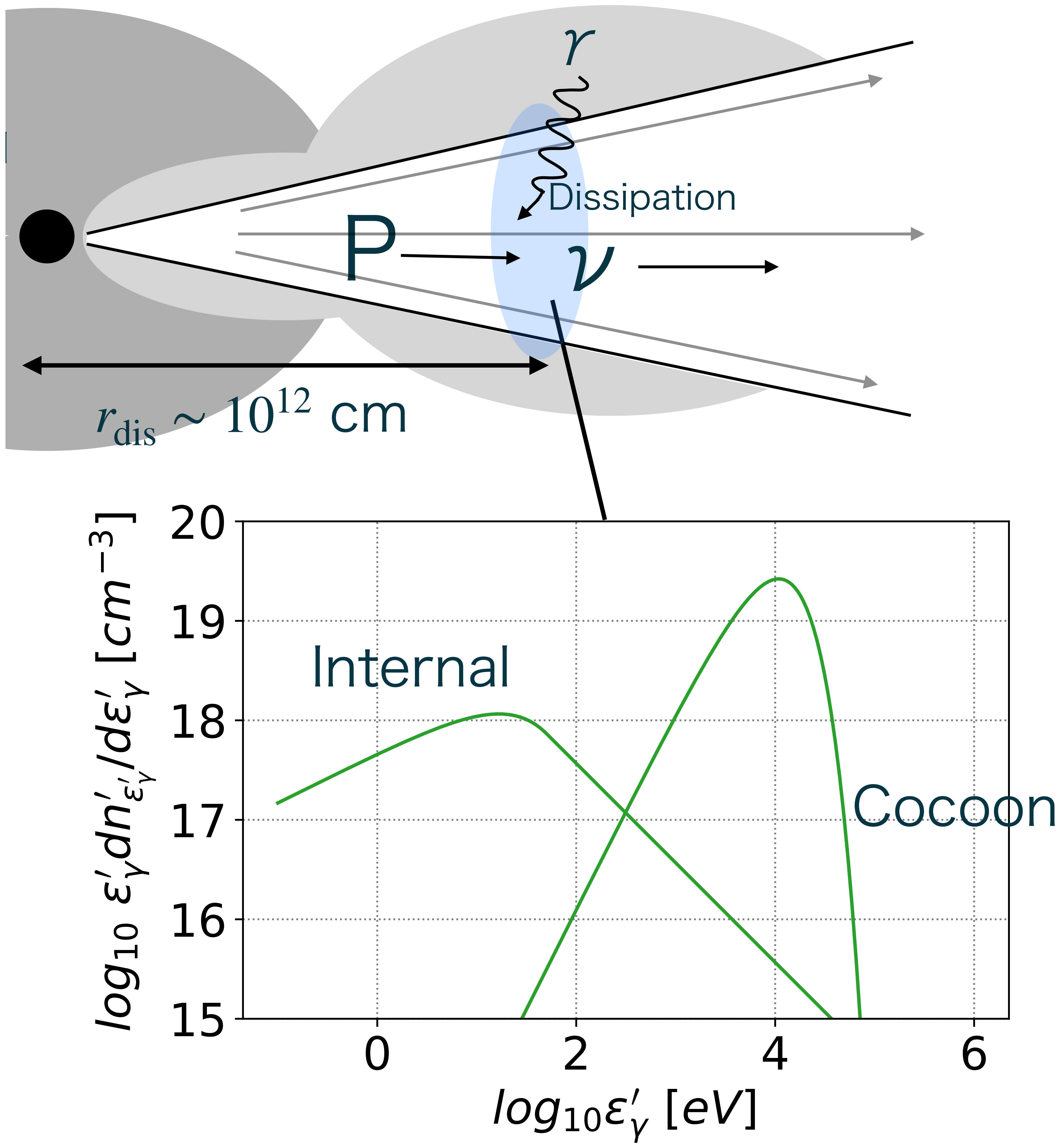
$$\varepsilon_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{d\varepsilon_{\nu_\mu}} \approx \frac{1}{8} f_{p\gamma}\, \varepsilon_p^2 \frac{dN_p}{d\varepsilon_p}\bigg|_{\varepsilon_p=\varepsilon_{\nu_\mu}/0.05},$$

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

$$t'^{-1}_{p\gamma} = \left(\frac{c}{2\gamma_p'^2} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/2\gamma_p}^{\infty} d\varepsilon'_\gamma \varepsilon'^{-2}_\gamma \frac{dn'_\gamma}{d\varepsilon'_\gamma} \right) \sim n_\gamma \sigma c$$

Spectra of Photon and Proton are required.

Method 2 : Photons in Dissipation Region



Photon Spectrum

- Internal photons (Kimura +17)

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

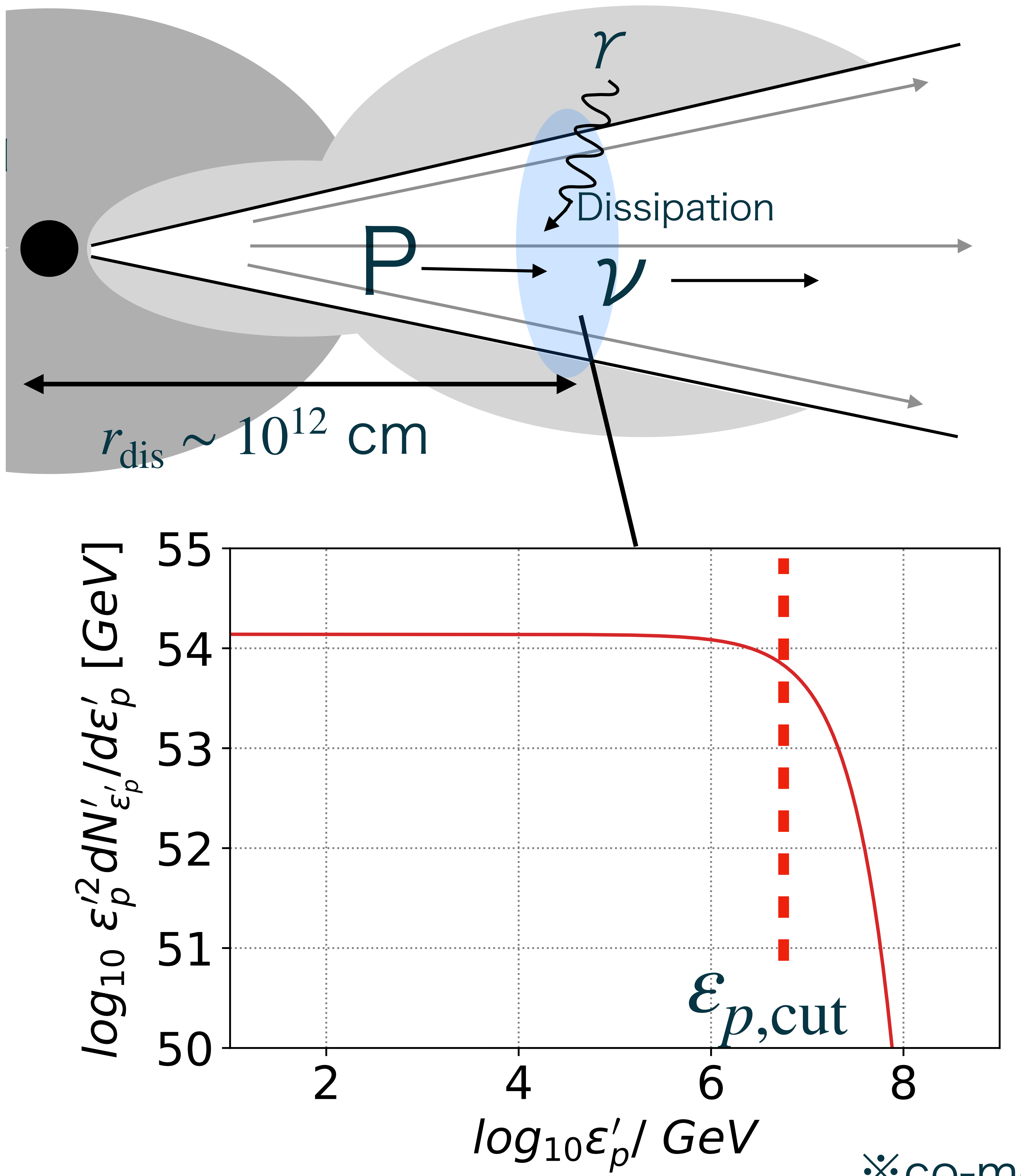
$$\propto \varepsilon'^{-2}_\gamma \qquad (\varepsilon'_\gamma < \varepsilon'_{\gamma,\rm pk})$$

- **Cocoon photons (←New)**

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

$k_B T_{\rm coc} \sim 20$ eV

Method 3 : Protons in Dissipation Region



※co-moving

Proton (Cosmic-Ray) Spectrum

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

(assuming Fermi accelelation)

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

Cocoon model for Extended emission

$T_{\rm coc}$: 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

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

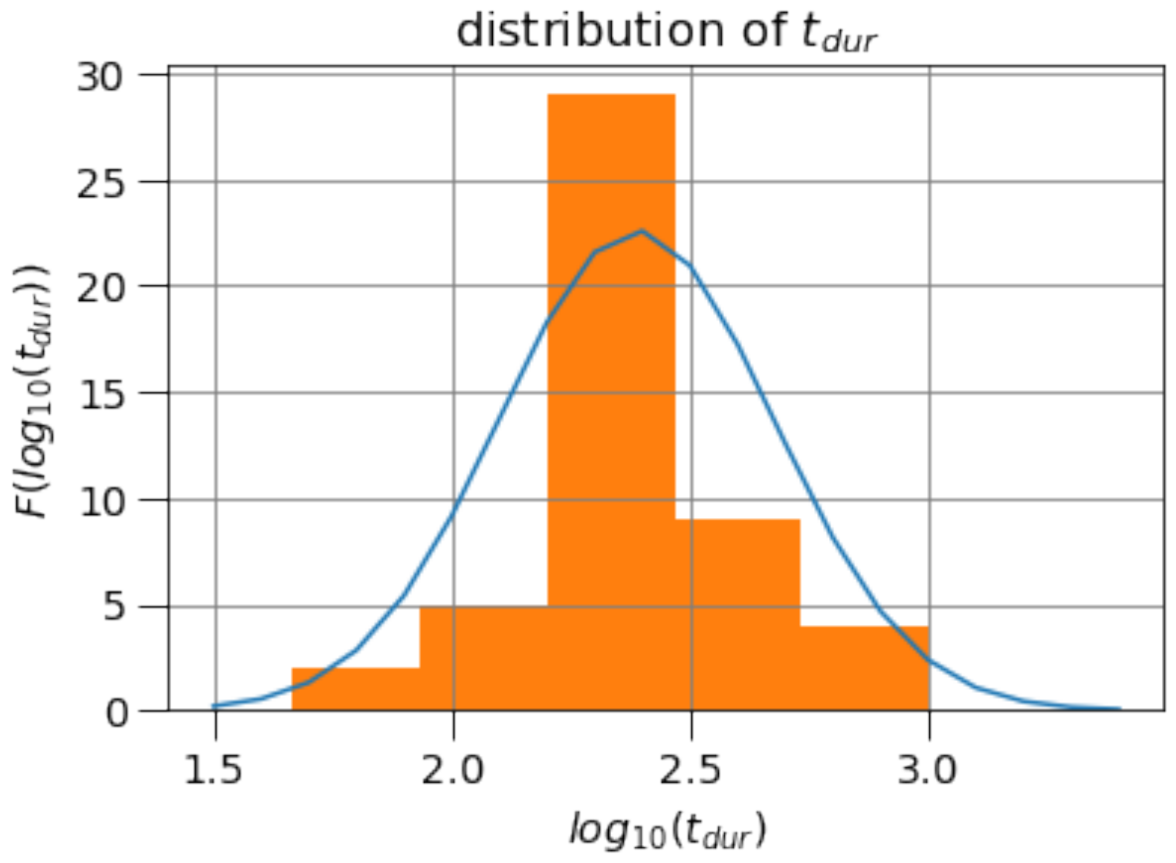
$$\mathscr{E}_{\rm coc} = 8.8 \times 10^{44}\,(t_{\rm dur}/10^{2.5}{\rm s})^{-1}\,{\rm erg} + 9.3 \times 10^{44}\,(t_{\rm dur}/10^{2.5}{\rm s})^{-0.3}\,{\rm erg}$$

Part of initial internal energy

Injected by radioactive decay

Emprical relation for Extended emission

- Duration, $\log t_{\rm dur}$: Gaussian by Observational data
- $L_X \propto t_{\rm dur}^{-2.5}$ (Emprical Low , Kisaka +17)
- Location : homogenous, $d_L < 300$Mpc
- Event rate : $R_{\rm sGRB} \sim 8\ {\rm Gpc^{-3} yr^{-1}}$



(Kisaka +17)

Cocoon model for X-ray flare

Internal energy density : $aT_{\rm coc}^4 = \frac{E_{i,{\rm coc,br}}}{4\pi r_{\rm diss}^3/3}\frac{r_*}{ct_{\rm flare}}$

Internal E. at break out : $E_{i,{\rm coc,br}} = L_j t_b \times (1-\beta_h)$ (Hamidani & Ioka 2022)

Jet (kinetic) luminosity : $L_j = L_{k,iso}\theta_j^2/4$

Jet isotropic-equivalent luminnosity : $L_{\rm k,iso} = 30\ L_{\rm prompt,iso}$

break out time : $t_b = 0.9\ (r_*^2\theta_j^4 M_*/L_j)^{1/3}$ (Hamidani & Ioka 2022)

Jet velocity before break out : $\beta_h = r_*/ct_b$

where Prompt emission Luminosity : $L_{\rm prompt,iso}$, Dissipation radis : $r_{\rm diss}$, Jet opening angle θ_j,

Steller mass, radius : M_*, r_* ,

Emprical relation and distribution for X-ray flare

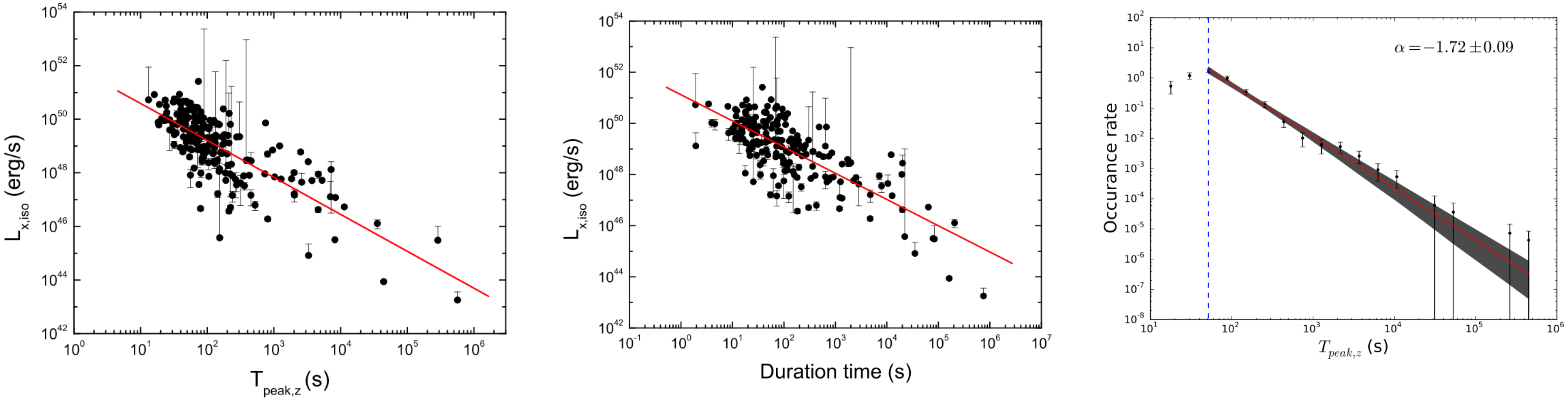
Prompt emission (radiation) luminonsity : $L_{\mathrm{prompt,iso}} \sim 30\ L_{\mathrm{x,flare}}$ (Liu & Mao 19)

X-ray flare luminosity : $L_{\mathrm{x,iso}} = 1.3 \times 10^{48} \times (t_{\mathrm{flare},3}\ (1+z))^{-1.02}\mathrm{erg/s}$ (Yi+16)

Duration of X-ray flare : $t_{\mathrm{dur}} = 450 \times (t_{\mathrm{flare},3}\ (1+z))^{1.12}\ \mathrm{s}$ (Yi+16)

Distribution of t_{flare} : $F(t_{\mathrm{flare}})\ dt_{\mathrm{flare}} \propto t_{\mathrm{flare}}^{-1.72}\ dt_{\mathrm{flare}}$ (Yi+16)

where X-ray flare peak time : t_{flare}, $t_{\mathrm{flare},3} = t_{\mathrm{flare}}/(1000\ \mathrm{s})$



Yi+16