Image credit: Science Communication Lab, DESY.

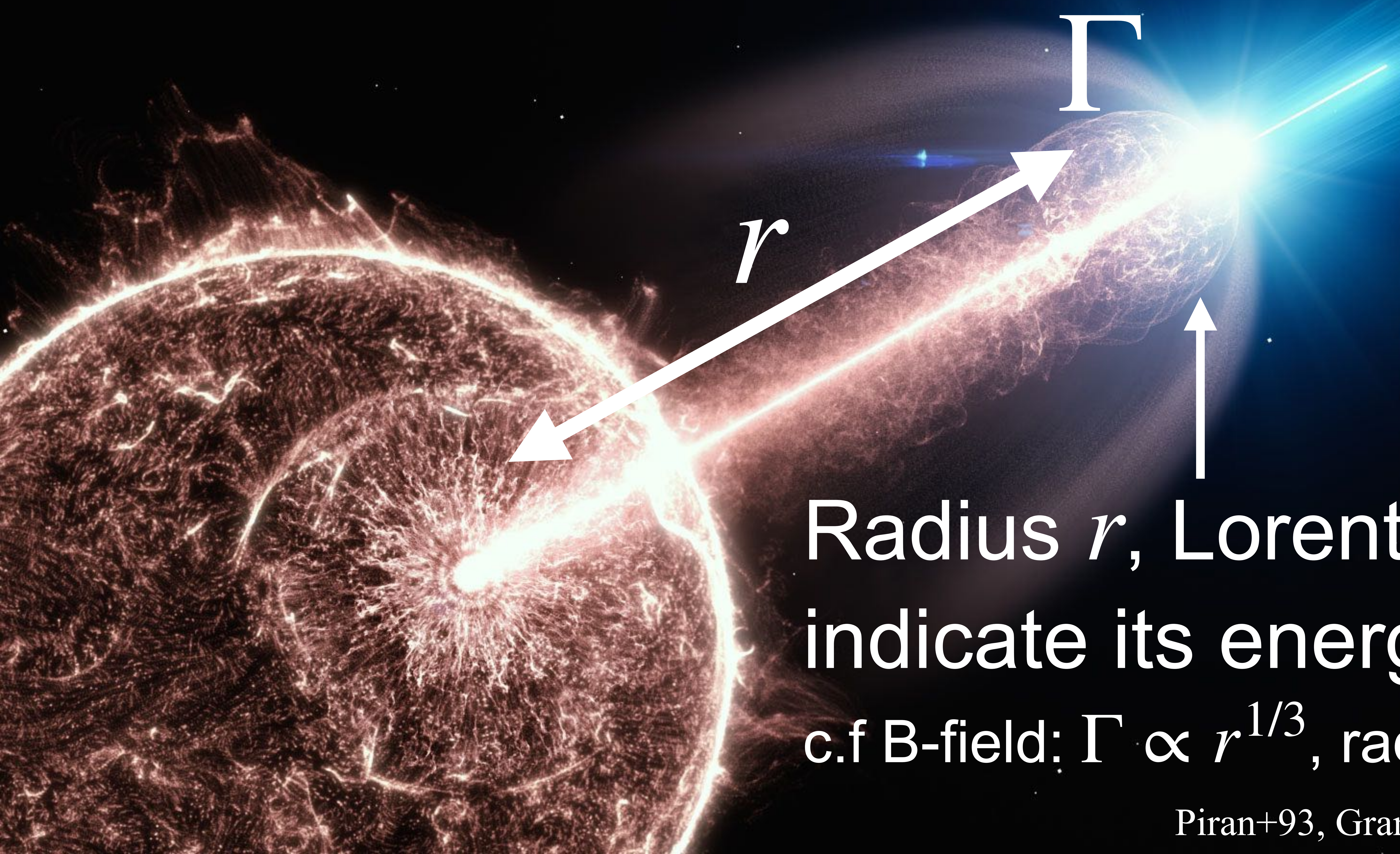
Predicting Multiwavelength Emission Associated with X-Ray Flares of Gamma-Ray Bursts

TeVPA 2026

Riki Matsui

with Shigeo Kimura, Kohta Murase, Bing Theodore Zahng

Gamma-ray burst (GRB)



Radius r, Lorentz factor Γ indicate its energy fraction.

c.f B-field: $\Gamma \propto r^{1/3}$, radiation: $\Gamma \propto r$

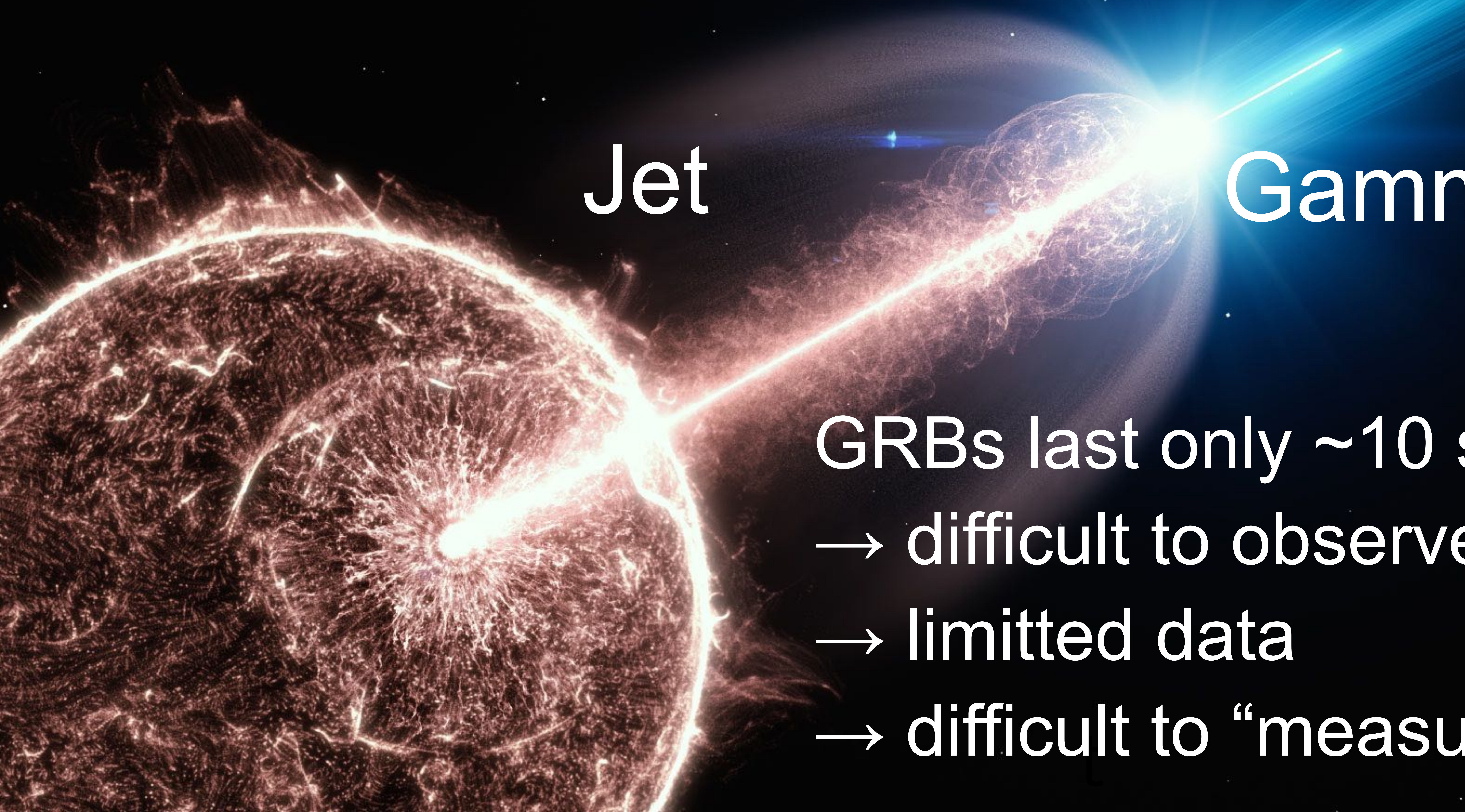
Piran+93, Granot+10, Kusafuka+23,

Gamma-ray burst (GRB)

$$L_\gamma = 4\pi r^2 \Gamma^2 U'_\gamma$$

requires three reliable obserbables.

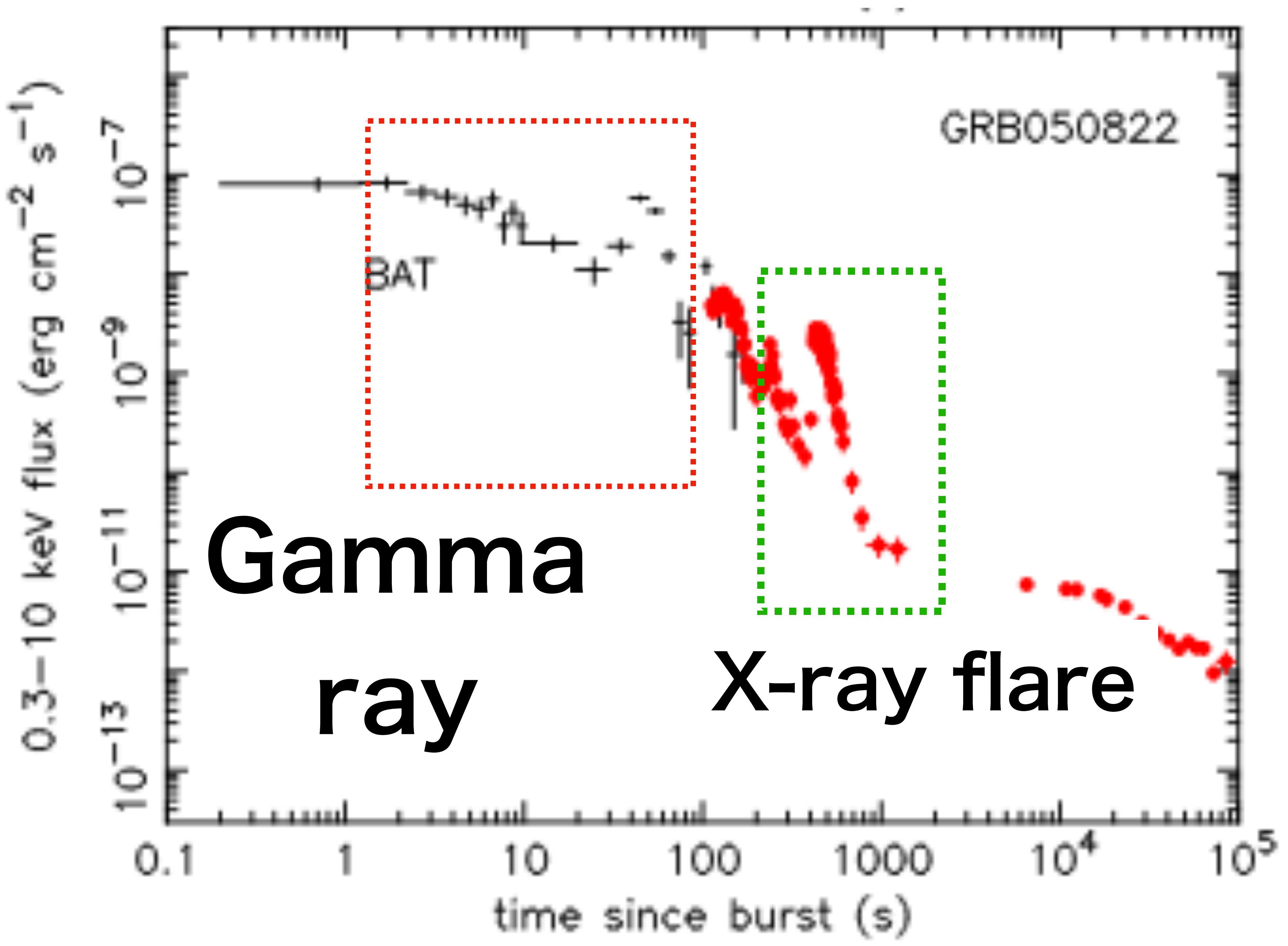
Gamma-ray burst (GRB)



GRBs last only ~10 s.
→ difficult to observe
→ limitted data
→ difficult to “measure”

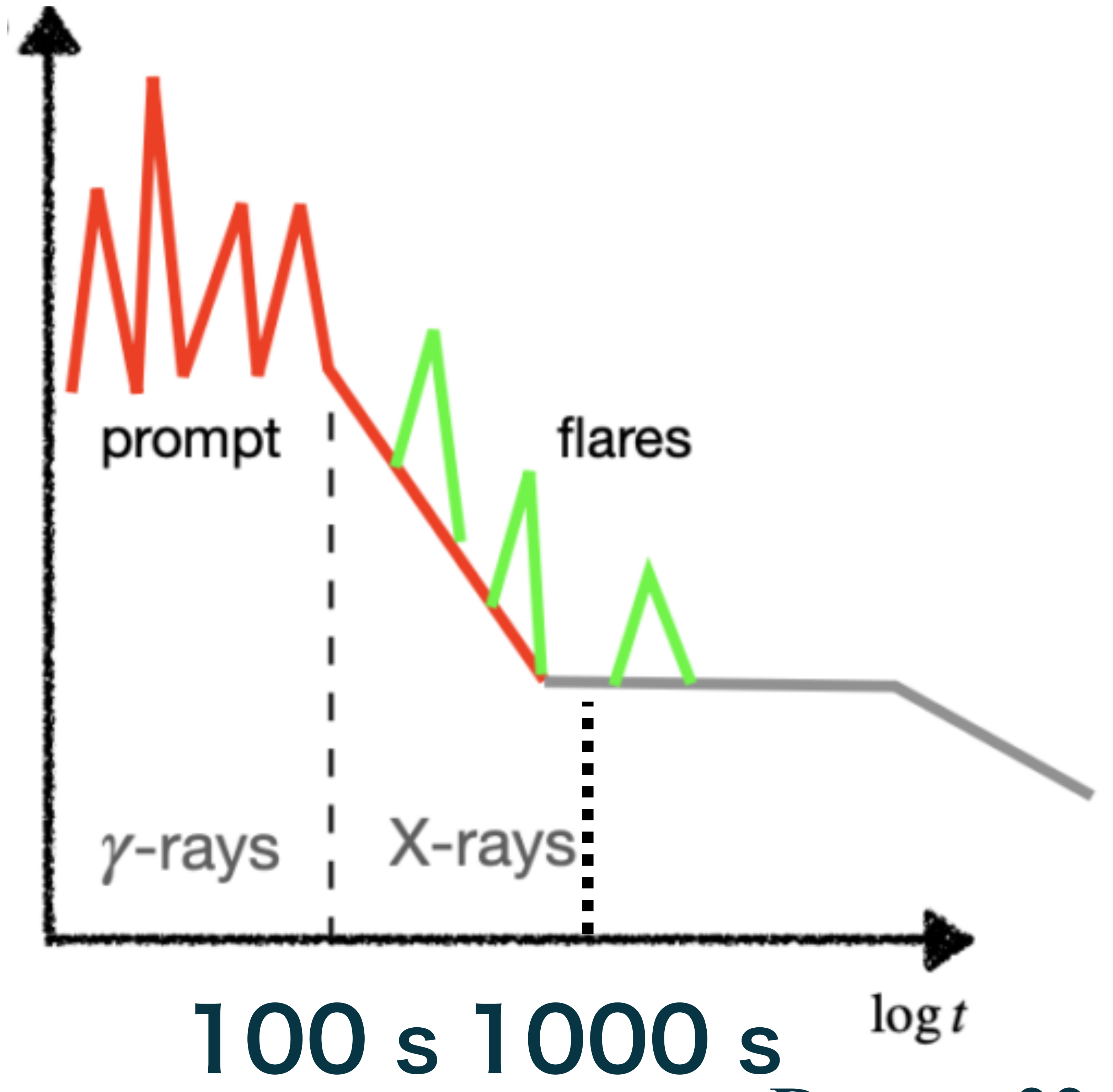
Our idea : Let’s see in 100-1000 s

X-ray flare : 100-1000 s emission after the main burst.



Time

O’Brien+06



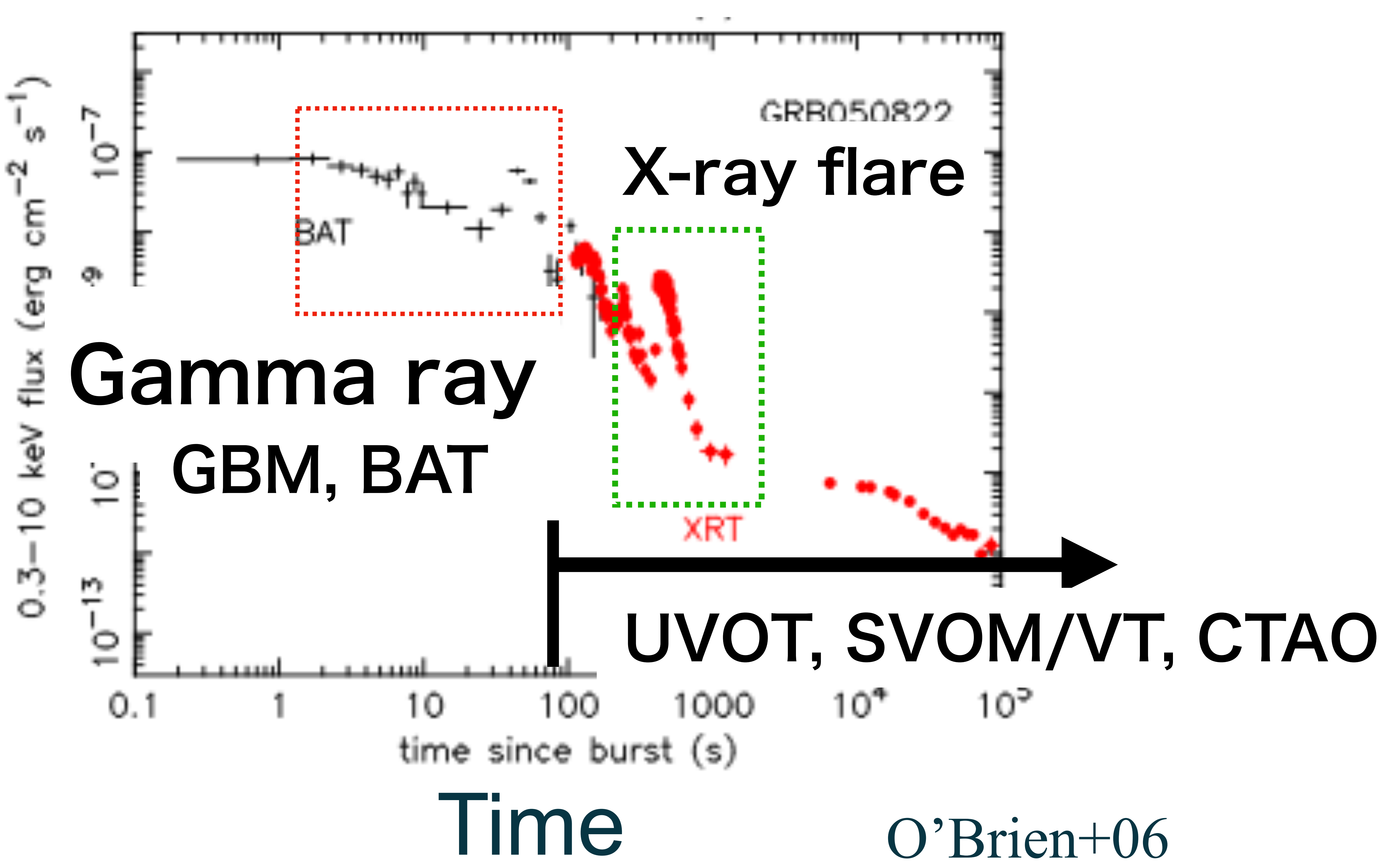
Duque+22

Jets are ejected for 100-1000 s.

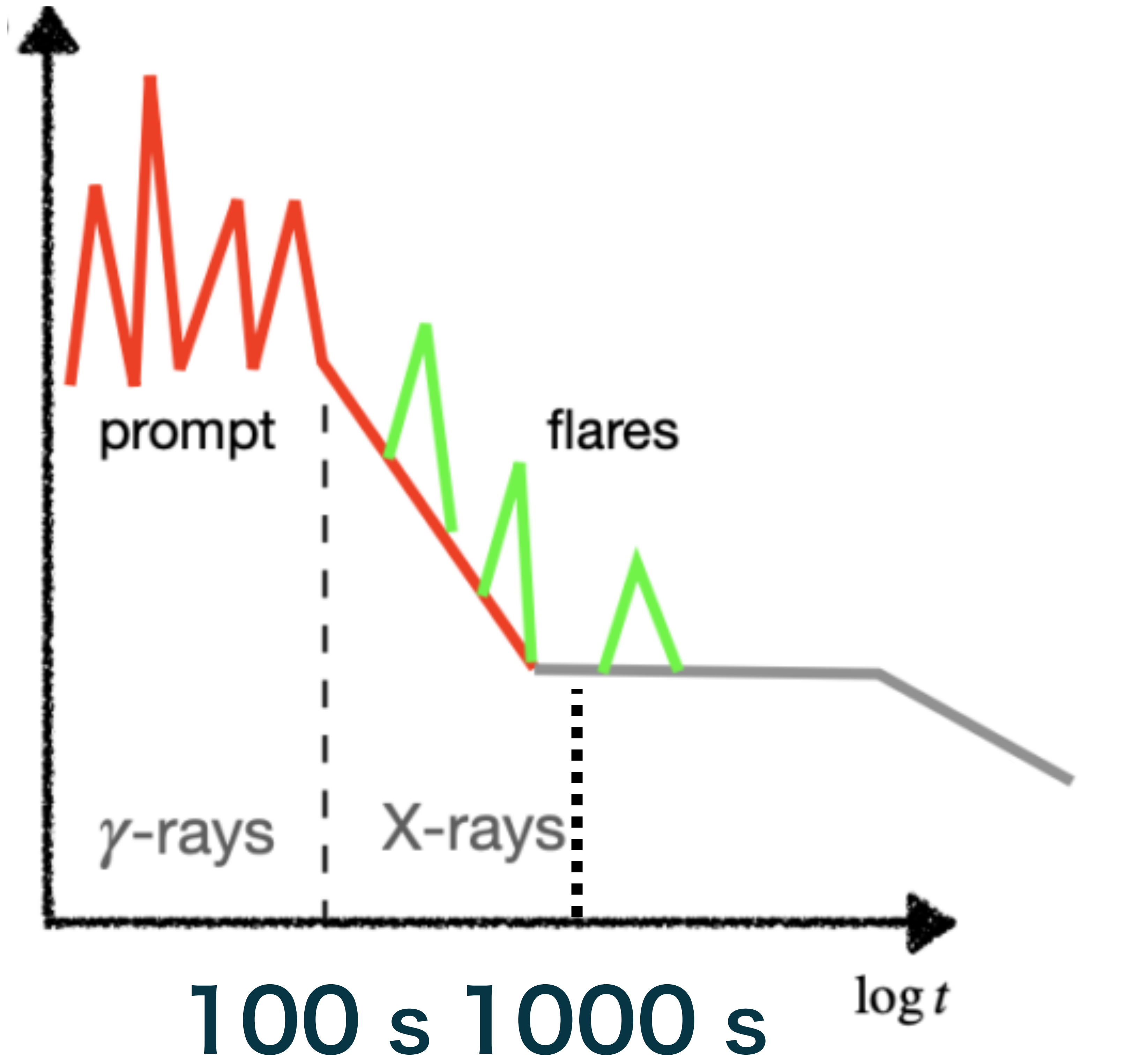
See also Ioka+05, Perna+06, Zhang+06

Our idea : Let's see in 100-1000 s

X-ray flare : 100-1000 s emission after the main burst.



O'Brien+06

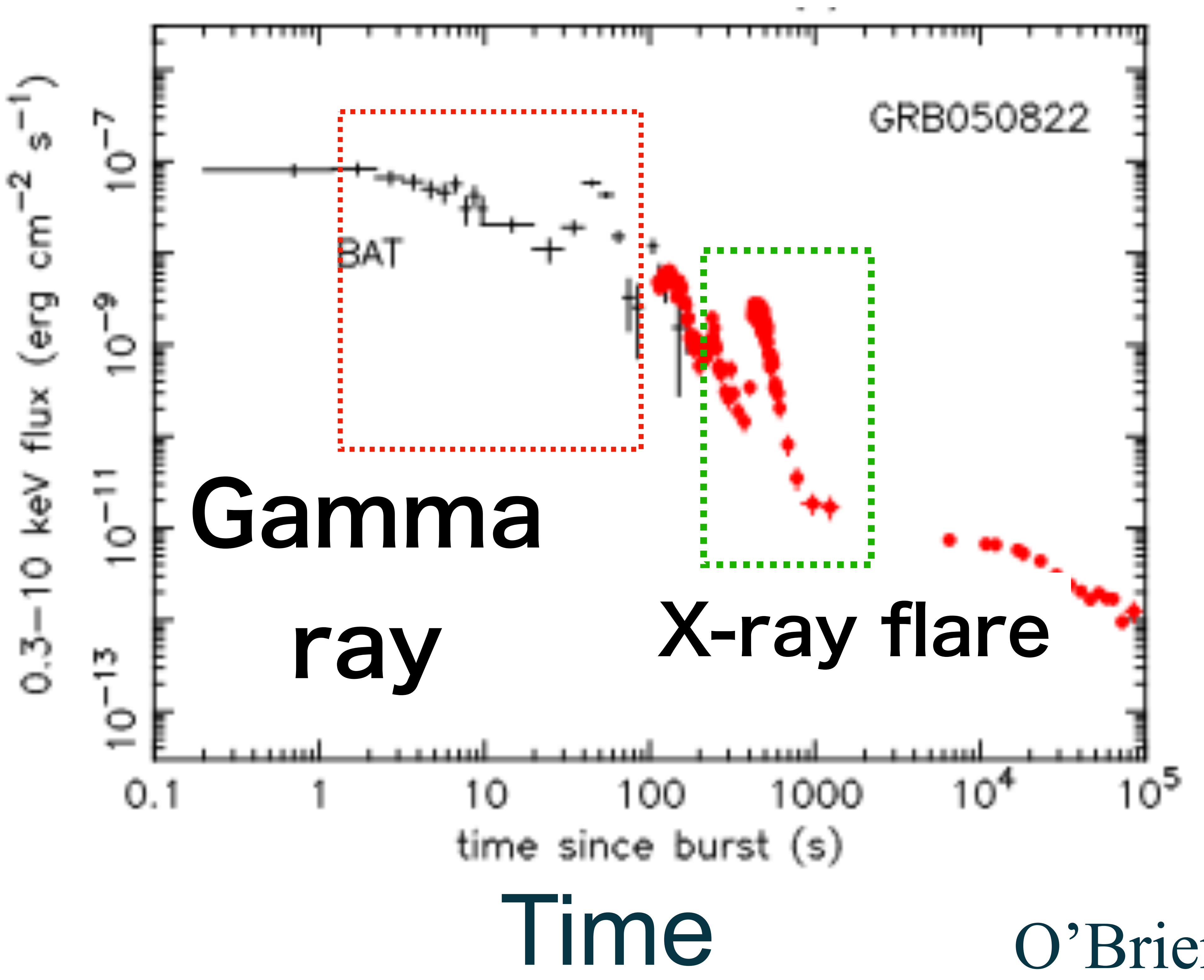


Duque+22

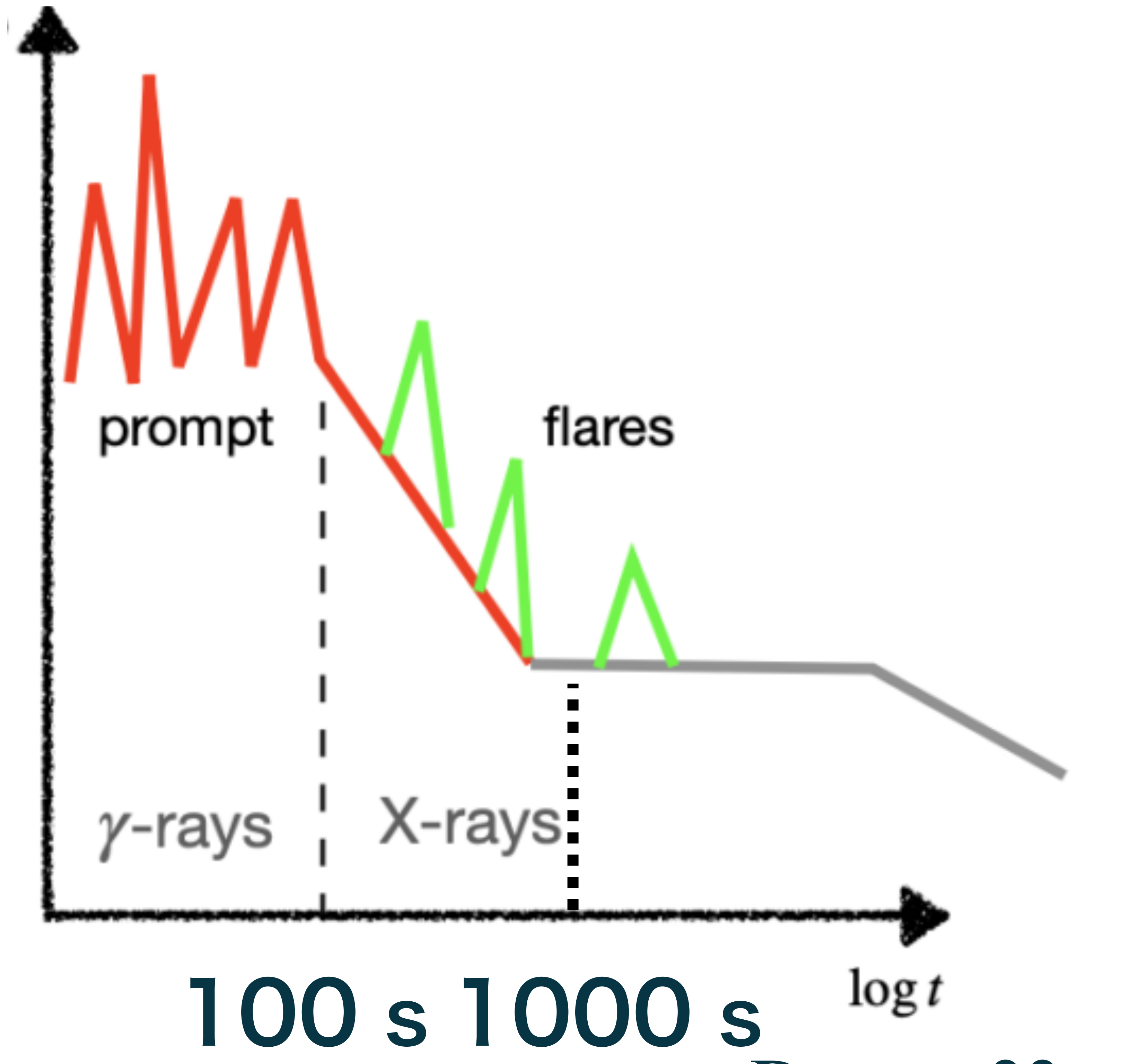
They are **less luminous,**
but **recent detectors are sensitive enough.**

Our idea : Let's see in 100-1000 s

X-ray flare : 100-1000 s emission after the main burst.



O'Brien+06

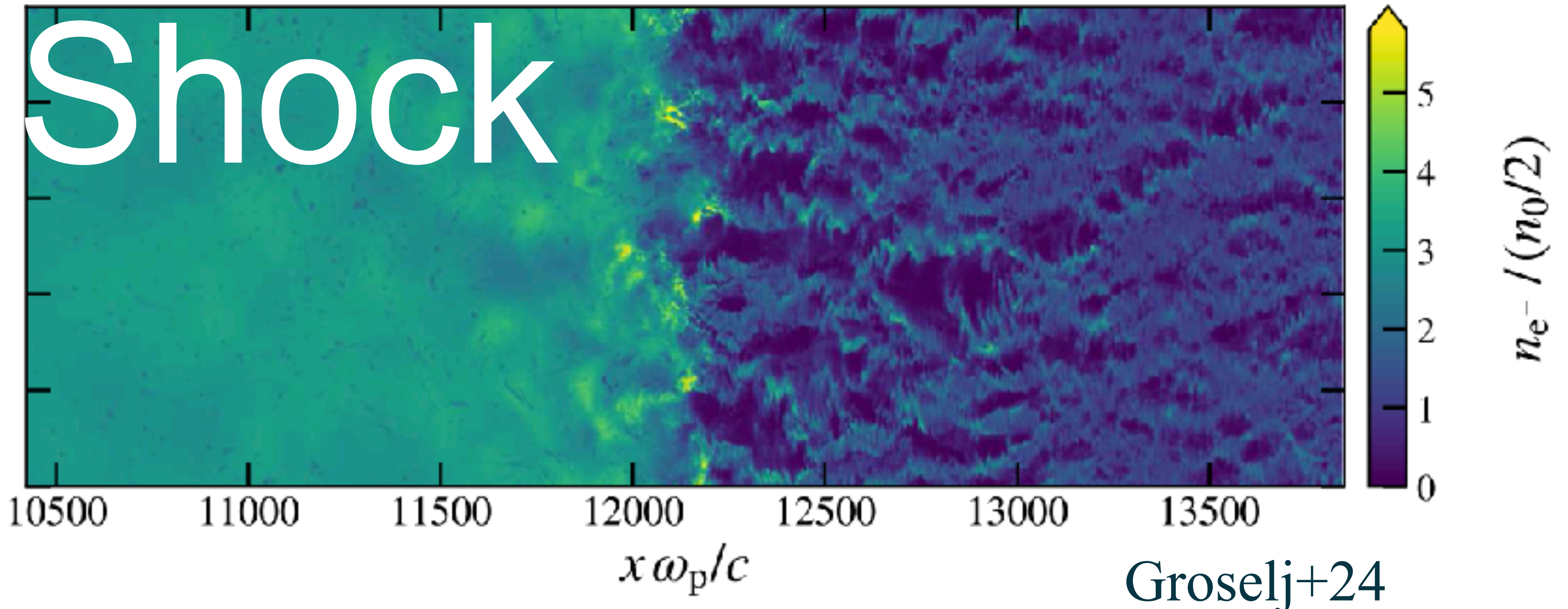


Duque+22

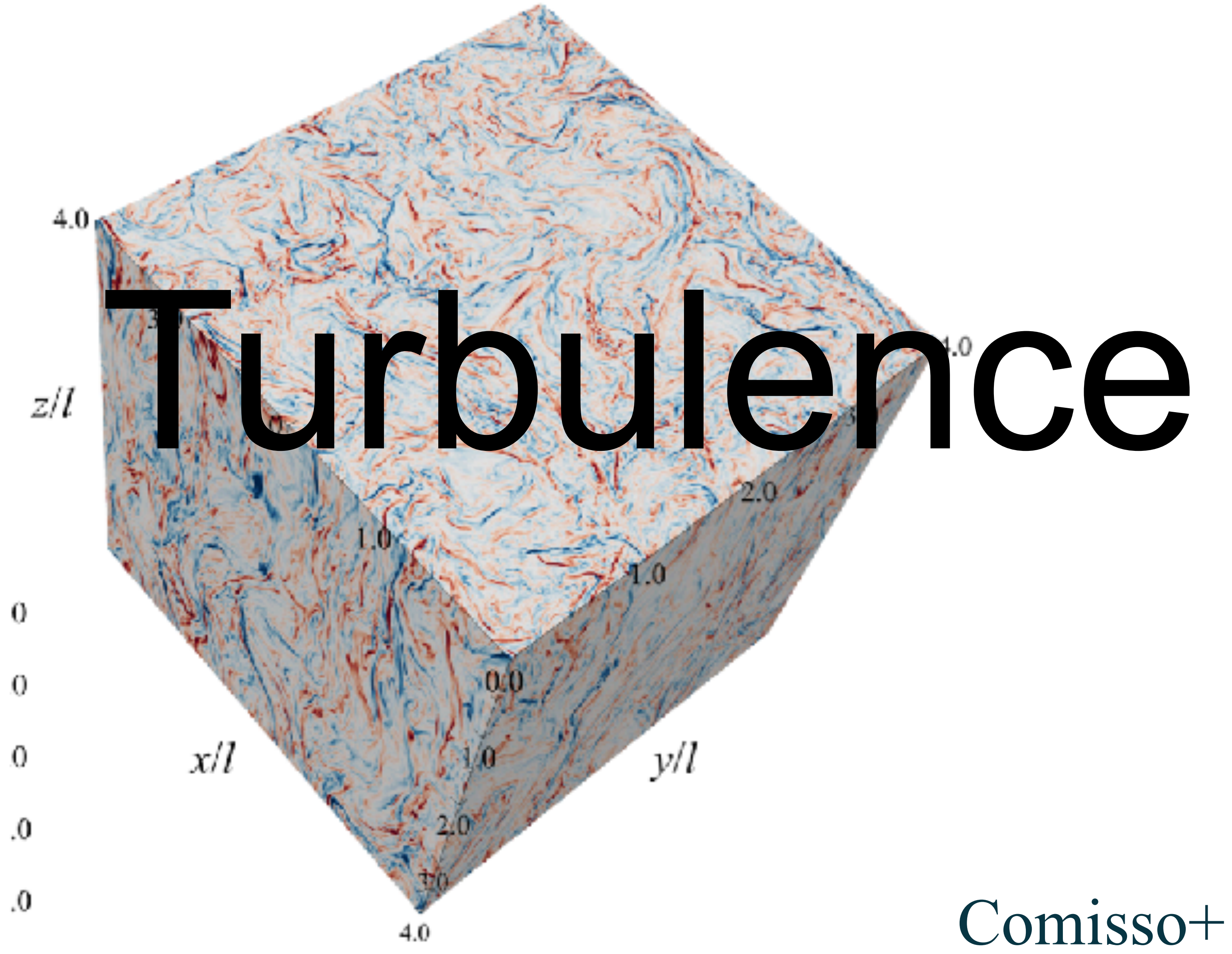
Our target:
What can we say from the multi-messenger observations?

Framework

Jet energy to radiations



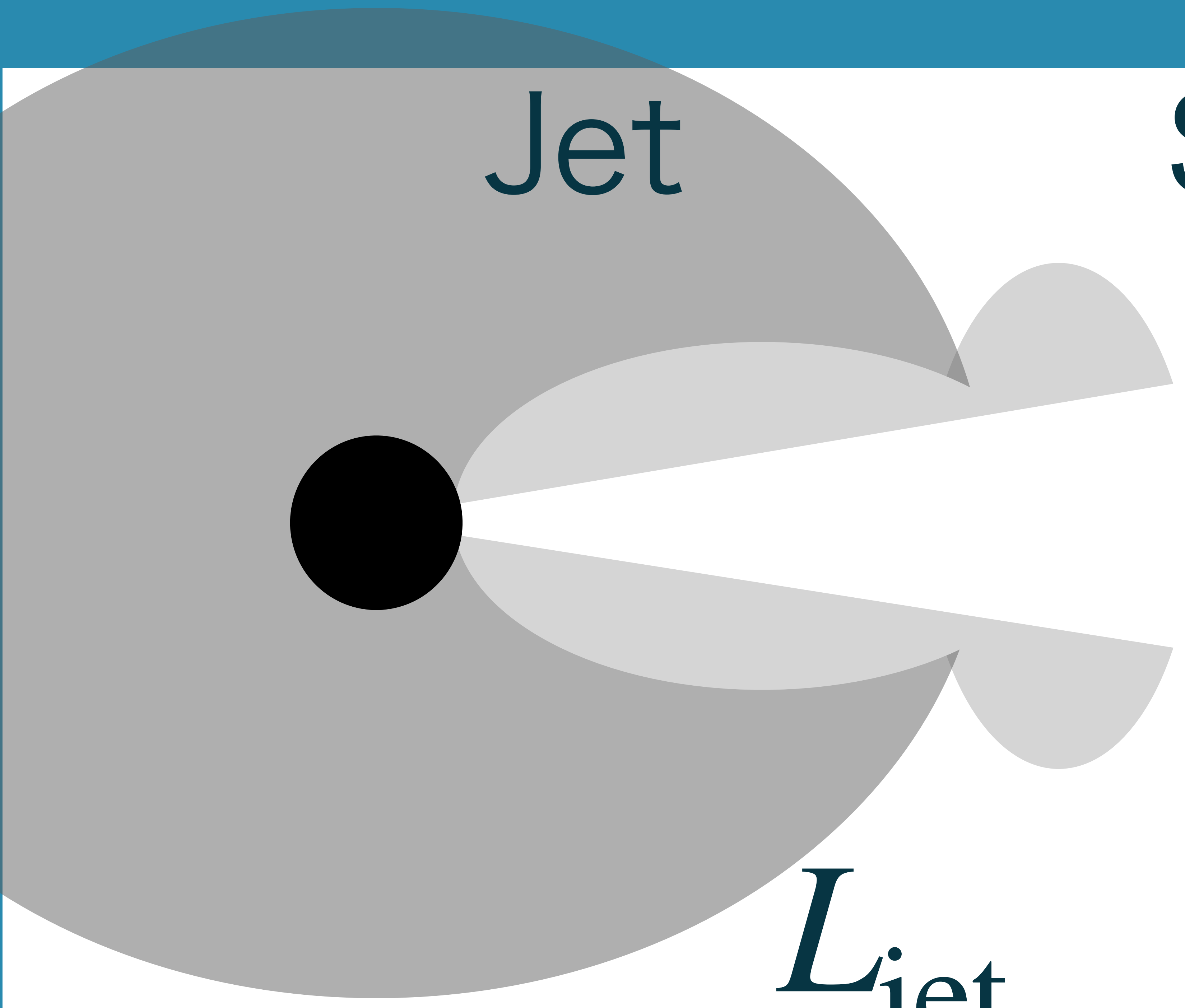
Groselj+24



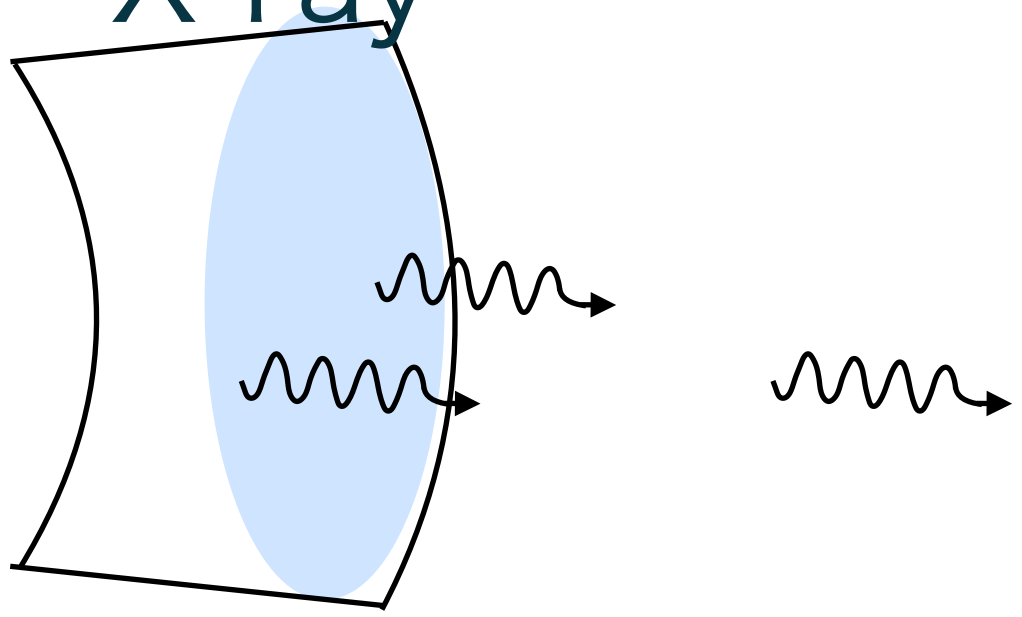
Comisso+19

Framework

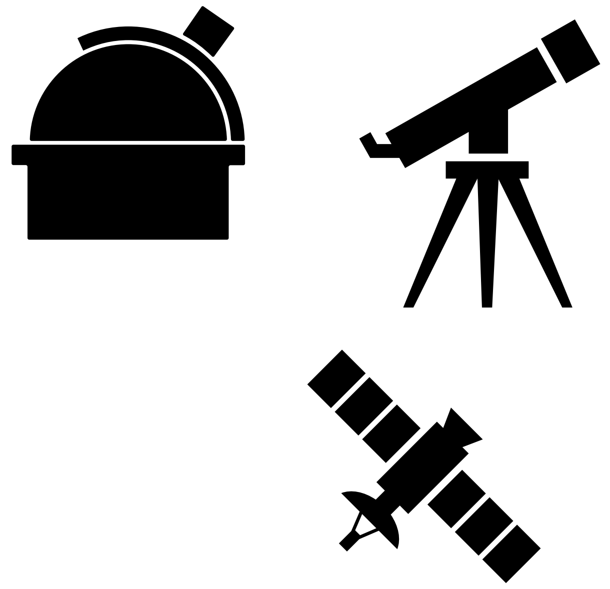
Jet



Shock/Turbulence



Observer



$$U'_{\mathrm{diss}} = \frac{L_{\mathrm{jet}}}{4\pi r^2 \Gamma^2 c}$$

$$U'_{\mathrm{B}} = \epsilon_B U'_{\mathrm{diss}}$$

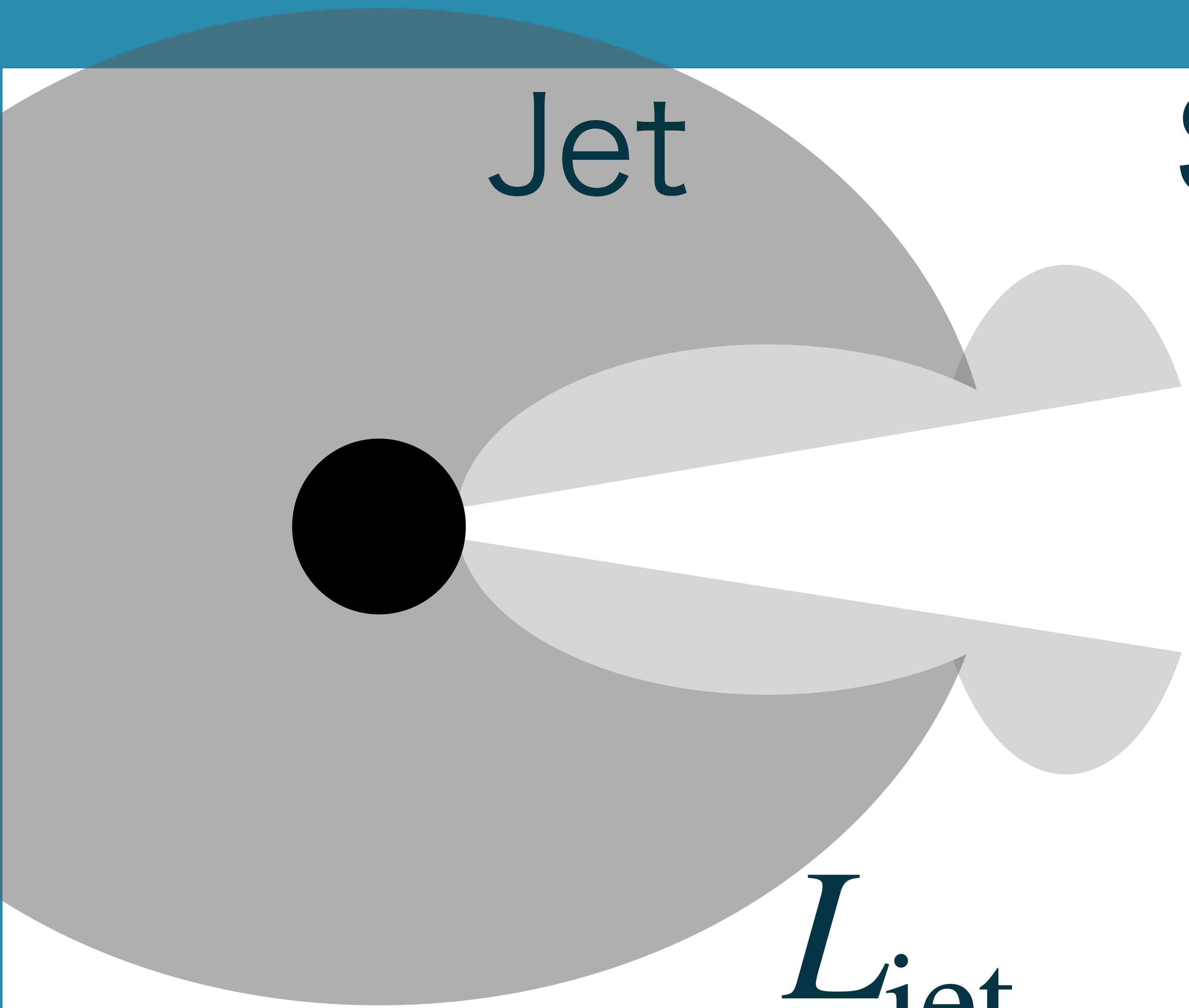
$$U'_{\mathrm{e}} = \epsilon_e U'_{\mathrm{diss}}$$

$$\longrightarrow L_\gamma$$

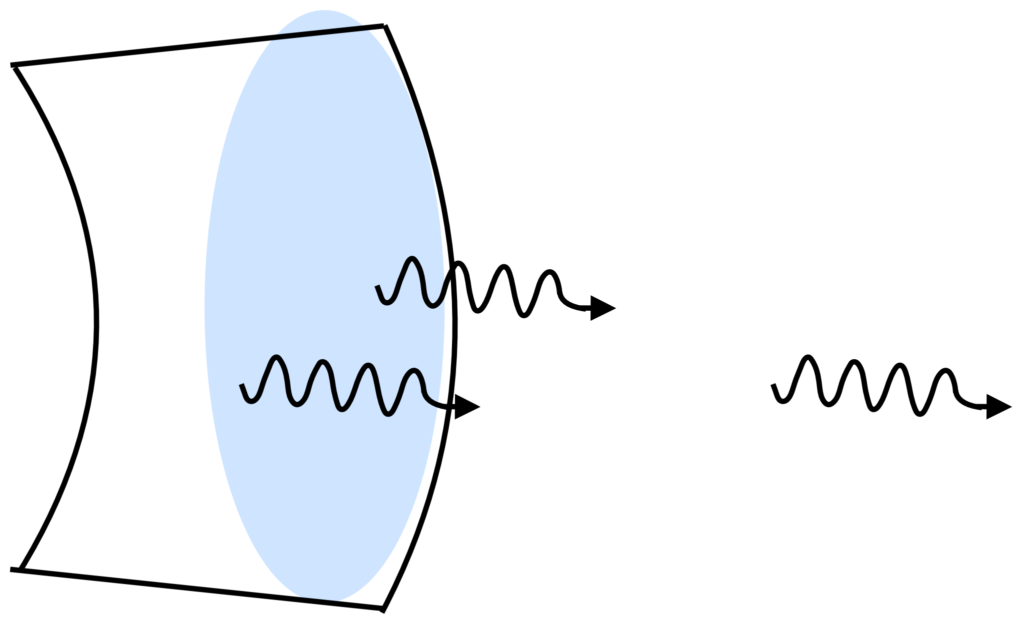
Synchrotron emission e.t.c.

Framework

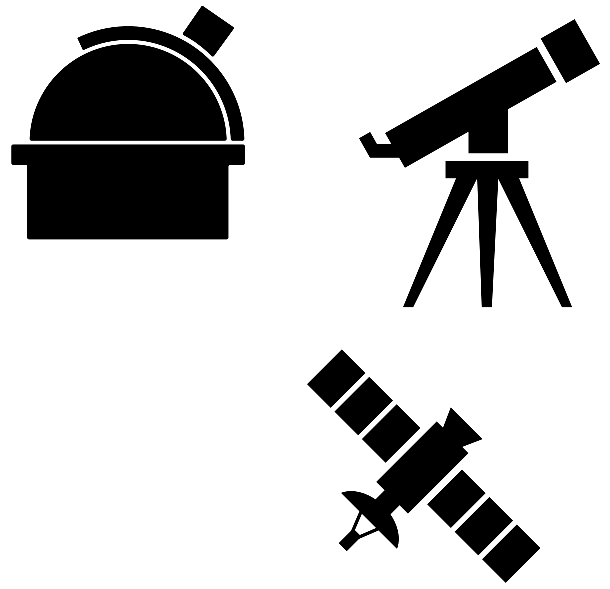
Jet



Shock/Turbulence



Observer



$$U'_{\rm diss} = \frac{L_{\rm jet}}{4\pi r^2 \Gamma^2 c}$$

$$U'_{\rm B} = \epsilon_B U'_{\rm diss}$$

$$U'_{\rm e} = \epsilon_e U'_{\rm diss}$$

$$L_\gamma$$

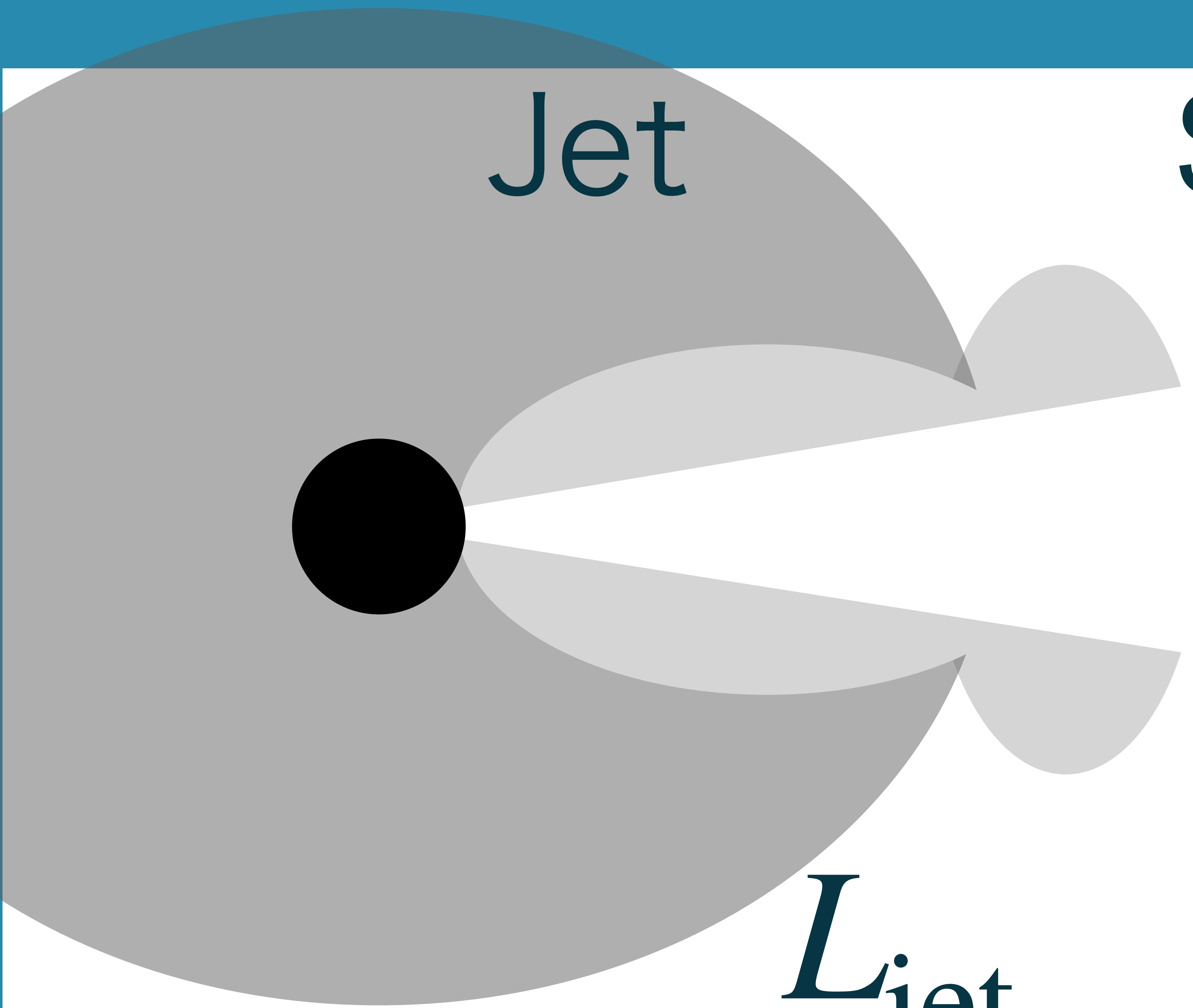
$$\nu F_\nu$$

$$\frac{d\dot{U}'_e}{d\gamma'_e} \propto \gamma_e'^{-p+1}$$

$\gamma_{\rm e,min} = 200,\ f_e \sim 1$

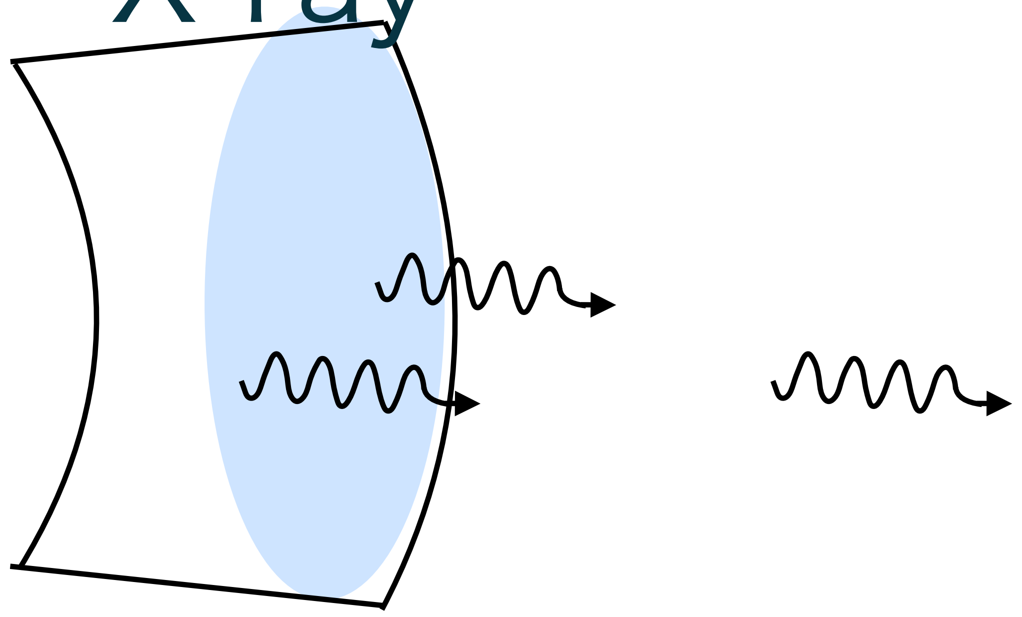
Framework

Jet



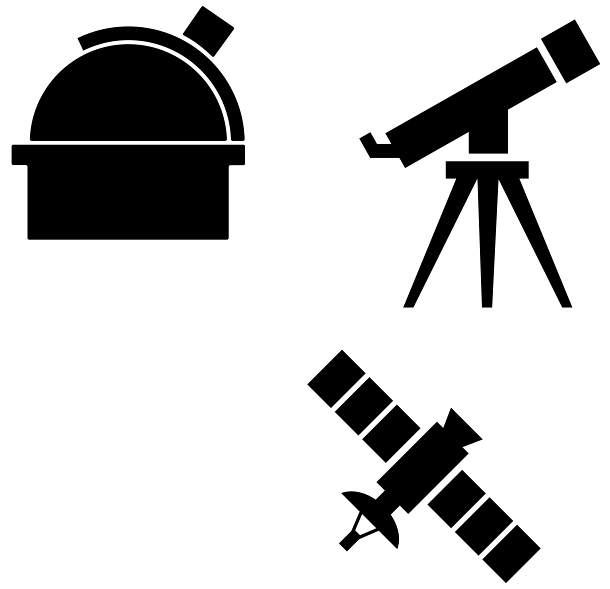
Shock/Turbulence

X-ray



Gamma ray

Observer



$$U'_{\rm diss} = \frac{L_{\rm jet}}{4\pi r^2 \Gamma^2 c}$$

$$U'_{\rm B} = \epsilon_B U'_{\rm diss}$$

$$U'_{\rm e} = \epsilon_e U'_{\rm diss}$$

$$\frac{d\dot{U}'_e}{d\gamma'_e} \propto \gamma_e'^{-p+1}$$

Synchrotron

Compton

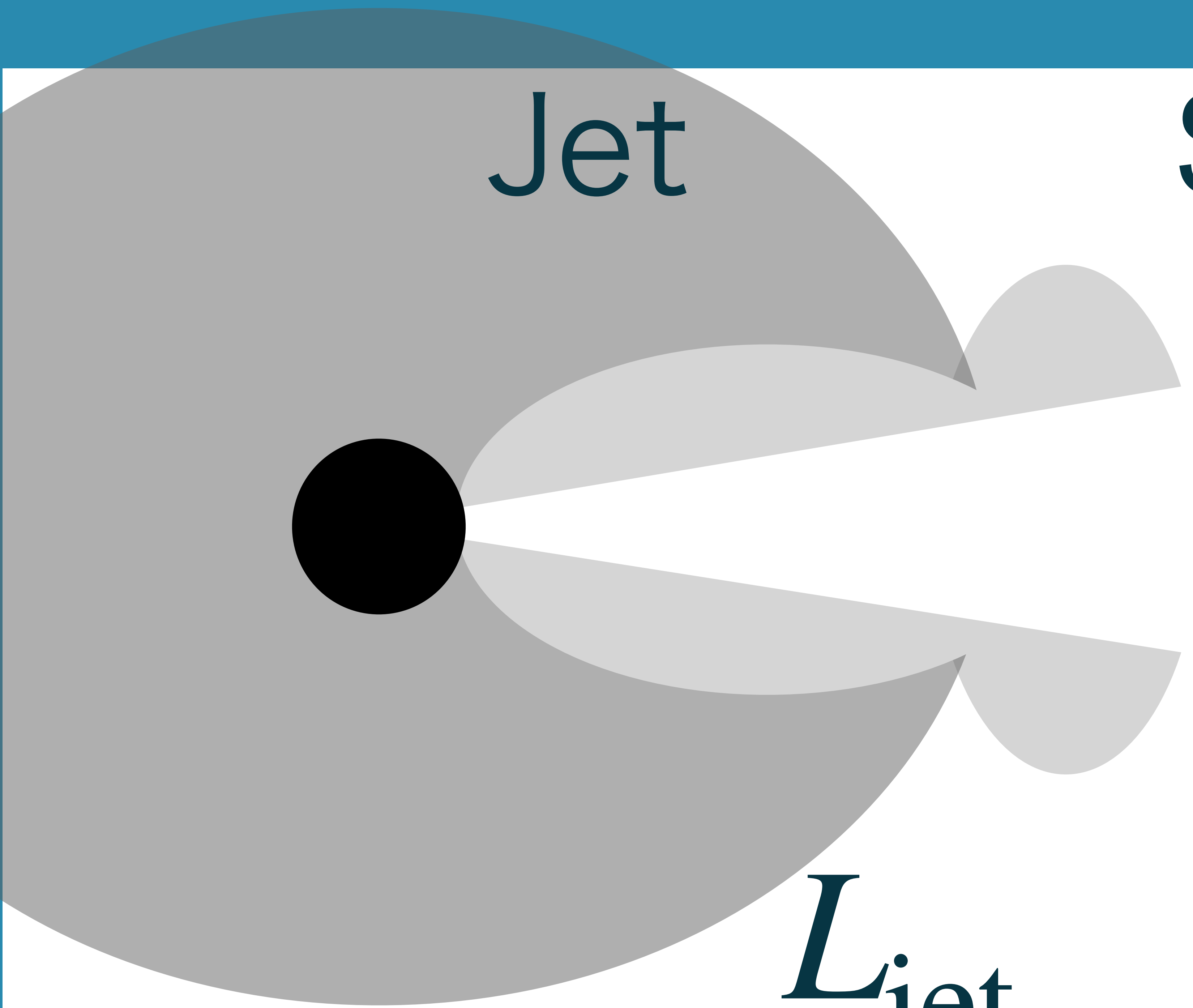
$2\gamma \rightarrow e^{\pm}$

$$L_\gamma$$

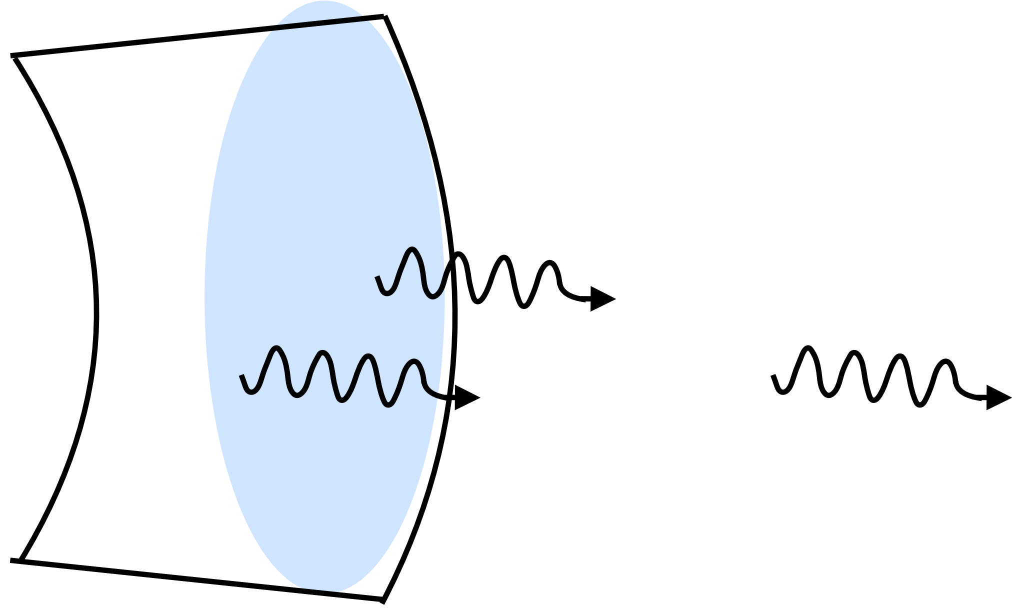
$$\nu F_\nu$$

Framework

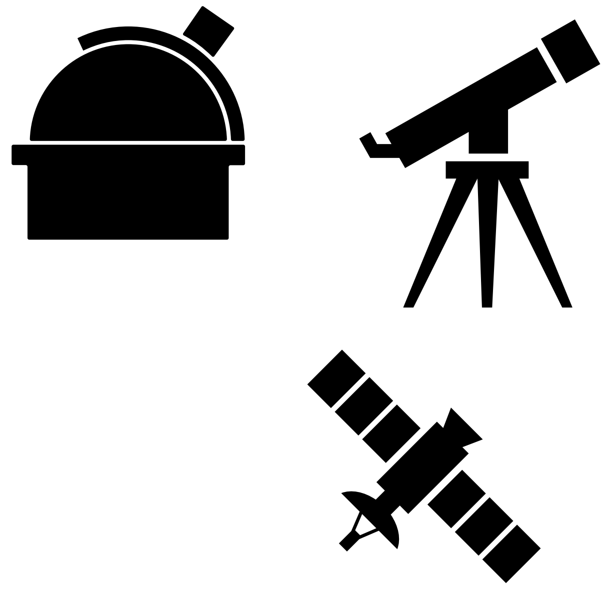
Jet



Shock/Turbulence



Observer



$$U'_{\mathrm{diss}} = \frac{L_{\mathrm{jet}}}{4\pi \underline{r}^2 \underline{\Gamma}^2 c}$$

Variable

$$U'_{\mathrm{B}} = \epsilon_B U'_{\mathrm{diss}}$$

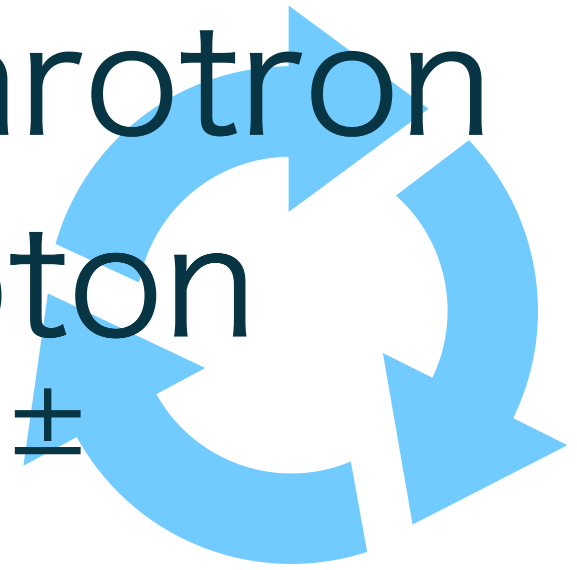
$$U'_{\mathrm{e}} = \epsilon_e U'_{\mathrm{diss}}$$

$$\frac{d\dot{U}'_e}{d\gamma'_e} \propto \gamma_e'^{-p+1}$$

Synchrotron

Compton

$2\gamma \to e^{\pm}$



L_γ

νF_ν

AMES (Astoronomical Multimessenger Emission Simulator)

- Coded by Bing T. Zhang, Kohta Murase, RM, etc
- Solving kinematic equations (One-zone) :

$$\frac{\partial N_{\varepsilon,i}}{\partial t} = -\frac{N_{\varepsilon,i}}{t_{\rm decay}} + \frac{\partial}{\partial \varepsilon_i}\left(\frac{\varepsilon_i N_{\varepsilon,i}}{t_{\rm cool}}\right) + \int d\varepsilon_j \left(\frac{dP_{ij}}{dt d\varepsilon_i}\right) N_{\varepsilon,j} + \dot{N}_{\varepsilon,\rm inj}$$

Loss Cool Production Injection

- Including

$i = \gamma, e^{\pm}, \mu^{\pm}, p, n, N, \pi^{\pm}, \pi^0$

$\gamma\gamma$, synchrotron($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$), inverse Compton($e^{\pm}$, $\mu^{\pm}$), pp, $p\gamma$, Bethe-Heitler, Brems, Coulomb, photodisintegration, difusion, escape, adiabatic cool, EBL.

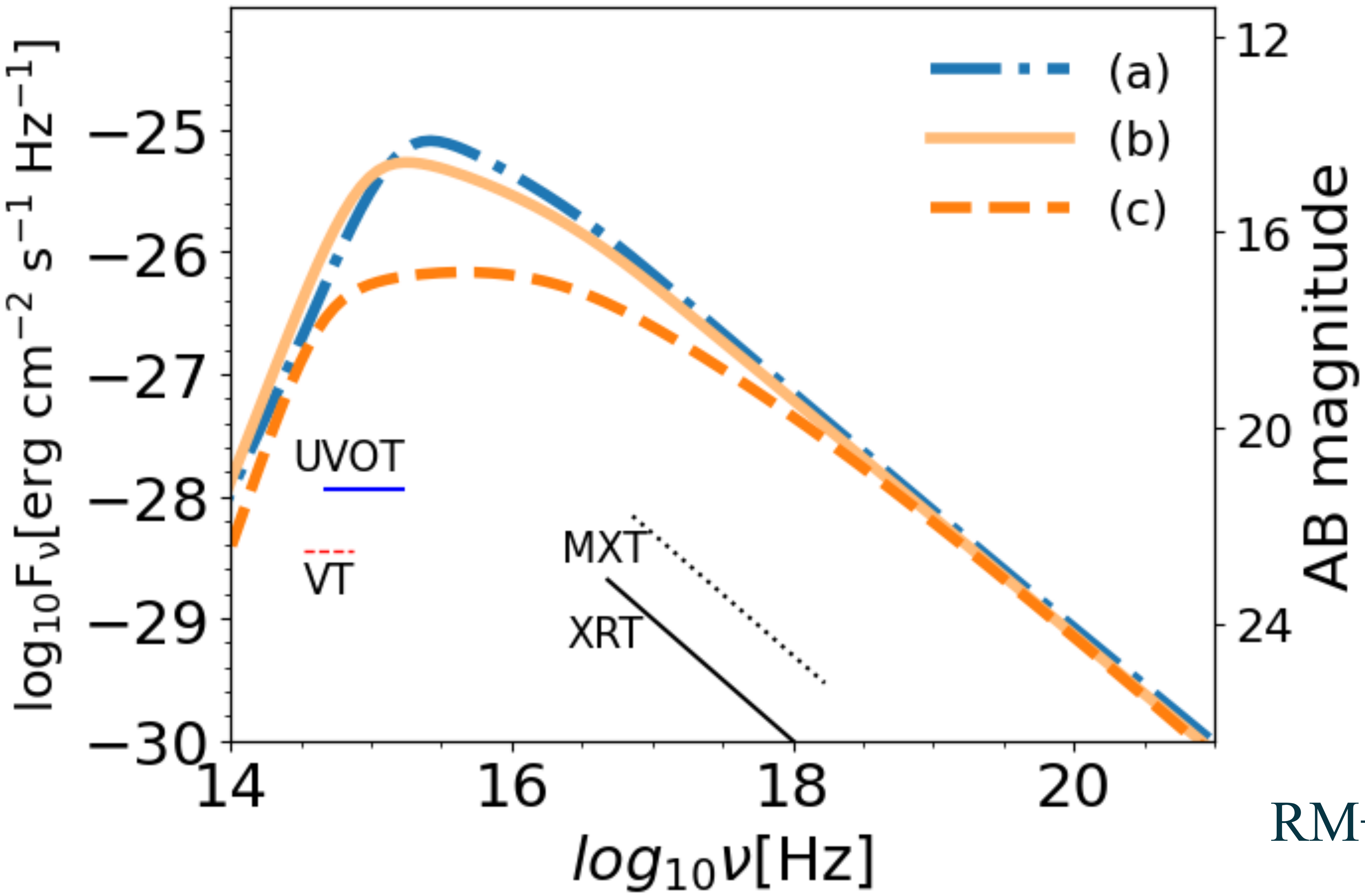
- To be included or updated

Inverse Compton($\pi^{\pm}$) , pair annhilation, Comptonization

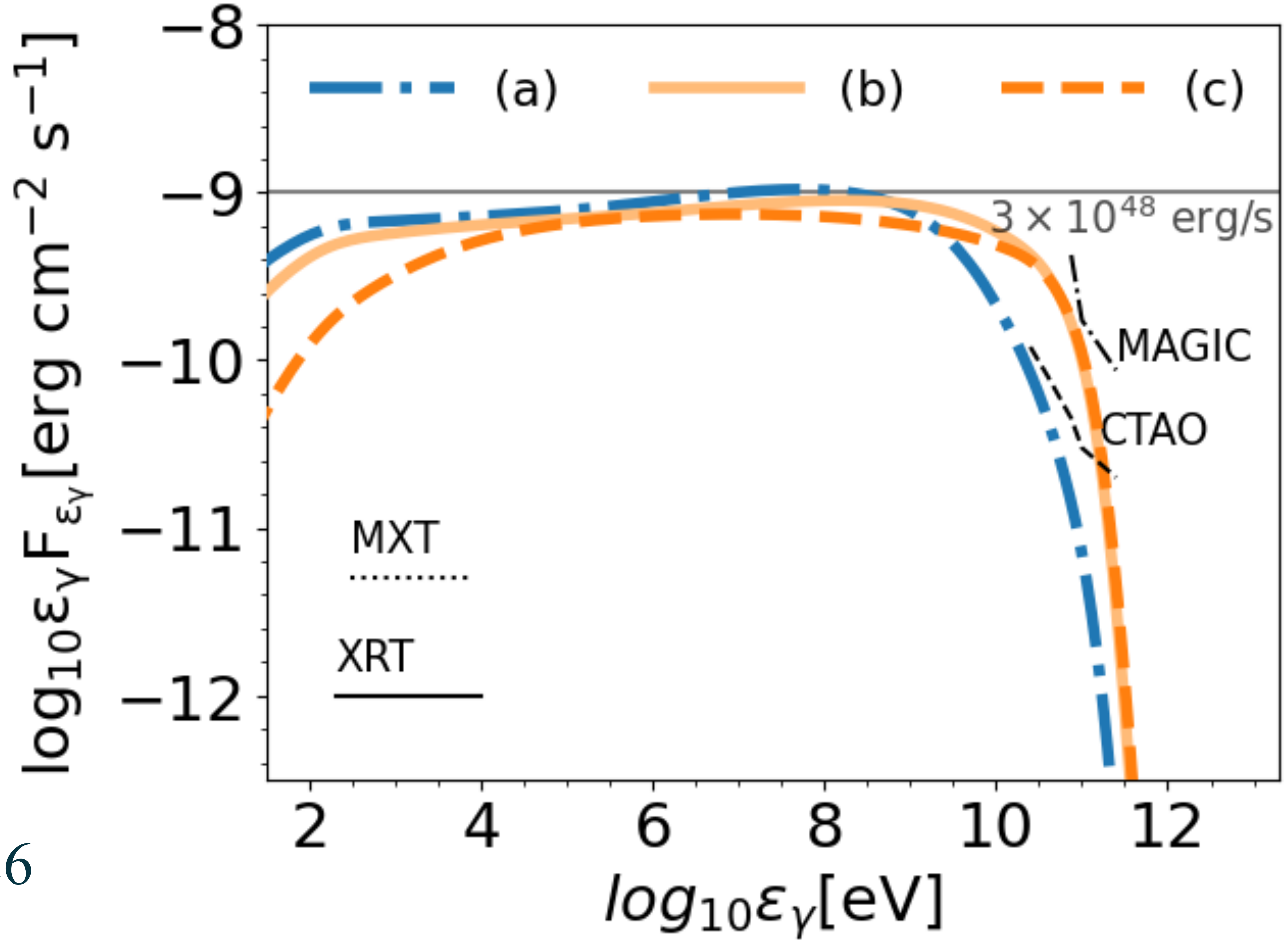
Multi-wavelength Detectability

	$r_{\rm diss}$ (cm)	Γ
(a)	10^{14}	80
(b)	10^{14}	200
(c)	10^{14}	500

$L_{\rm j,iso}$ (erg/s)	ϵ_e	ϵ_B	$p'_{e,\rm min}$ ($m_e c$)	$\gamma'_{p,\rm diss}$	p	d_L (Gpc)	z
10^{51}	10^{-1}	10^{-2}	200	10	2	6.6	1.0



RM+26



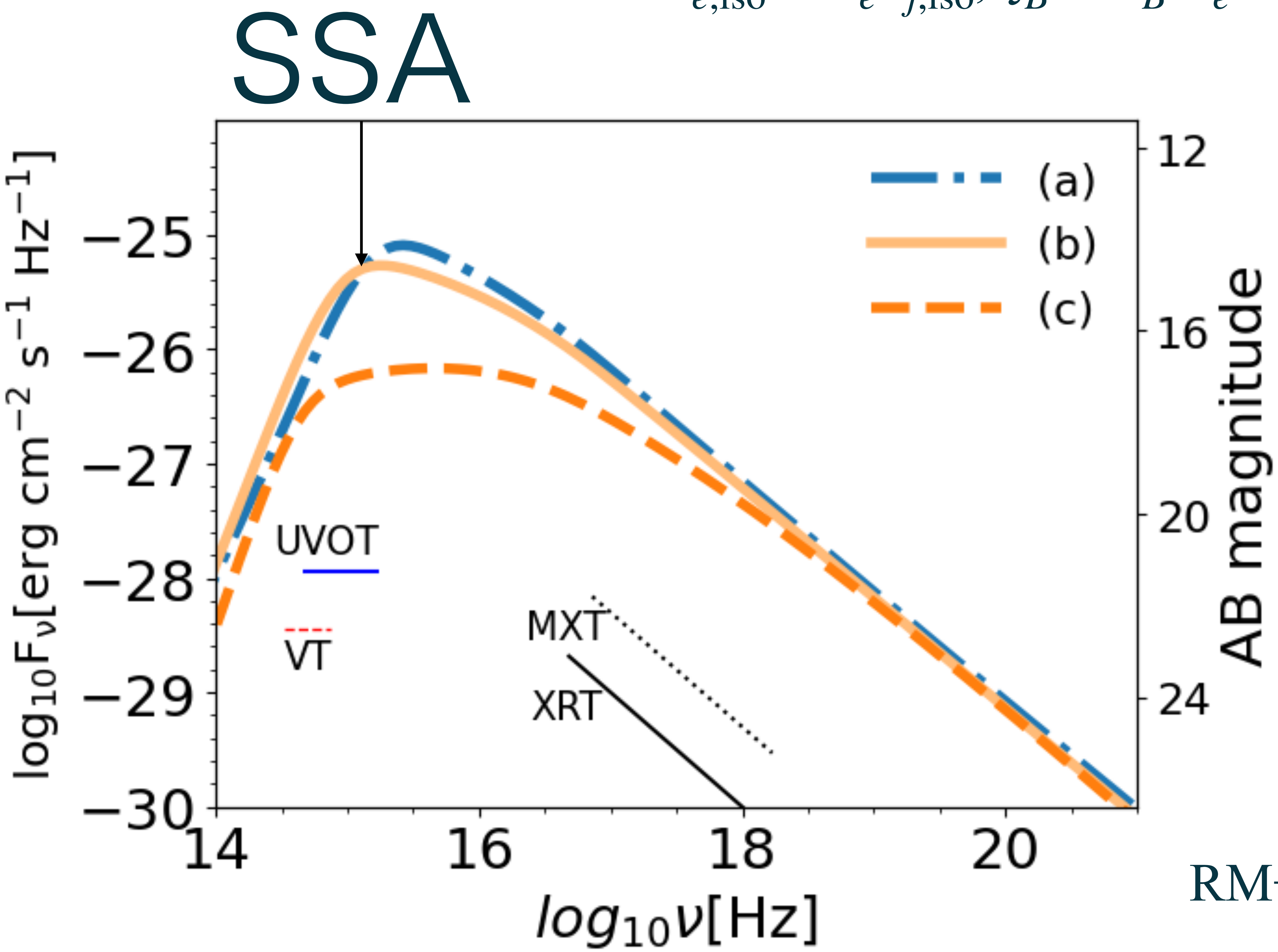
Possible detection in UV, X-ray, and subTeV γ.

Multi-wavelength Detectability

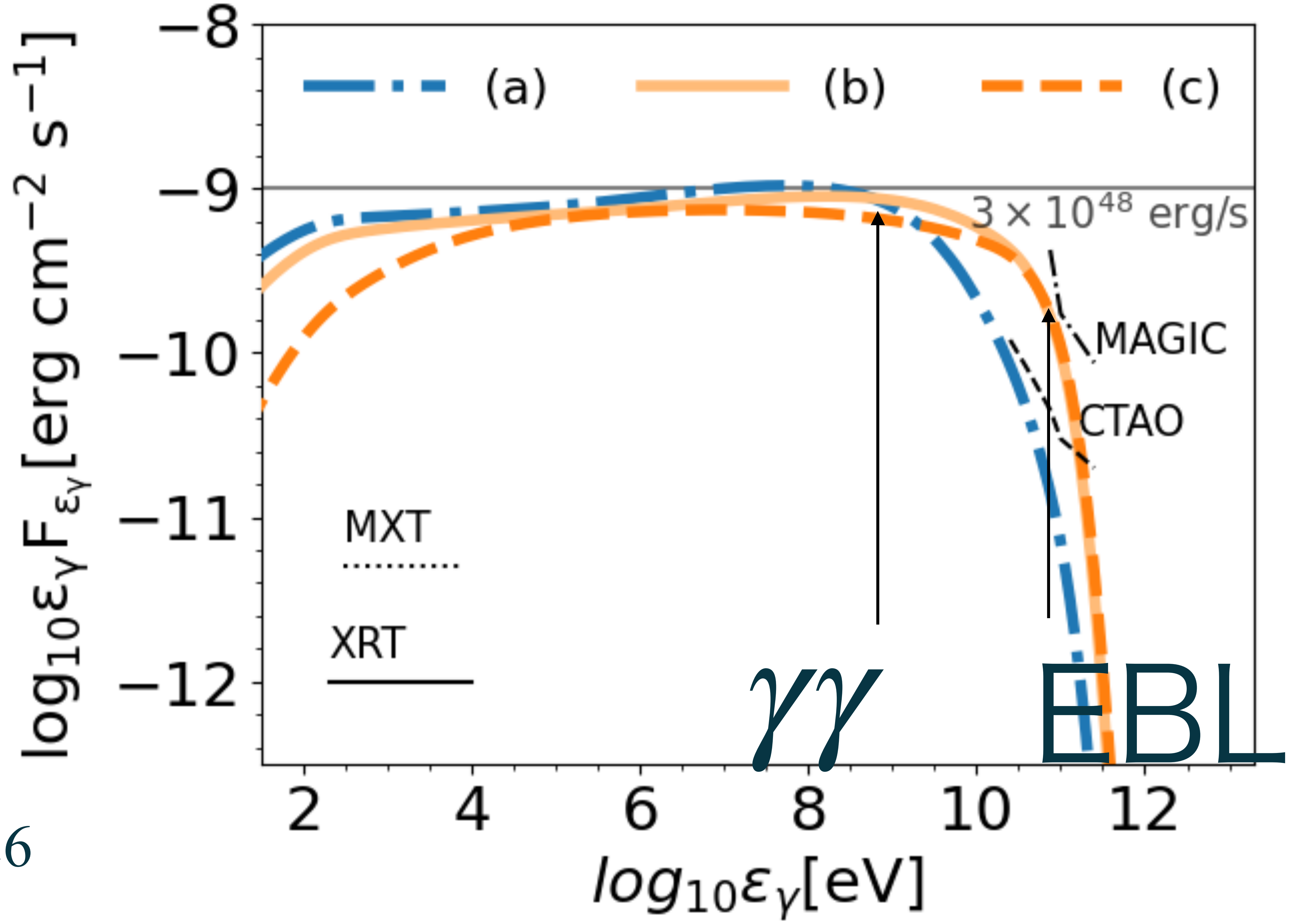
	$r_{\rm diss}$ (cm)	Γ
(a)	10^{14}	80
(b)	10^{14}	200
(c)	10^{14}	500

$L_{\rm j,iso}$ (erg/s)	ϵ_e	ϵ_B	$p'_{\rm e,min}$ ($m_e c$)	$\gamma'_{\rm p,diss}$	p	d_L (Gpc)	z
10^{51}	10^{-1}	10^{-2}	200	10	2	5.0	0.8

$L_{e,\rm iso} = \epsilon_e L_{j,\rm iso},\ \xi_B = \epsilon_B/\epsilon_e$



RM+26



Possible detection in UV, X-ray, and subTeV γ.

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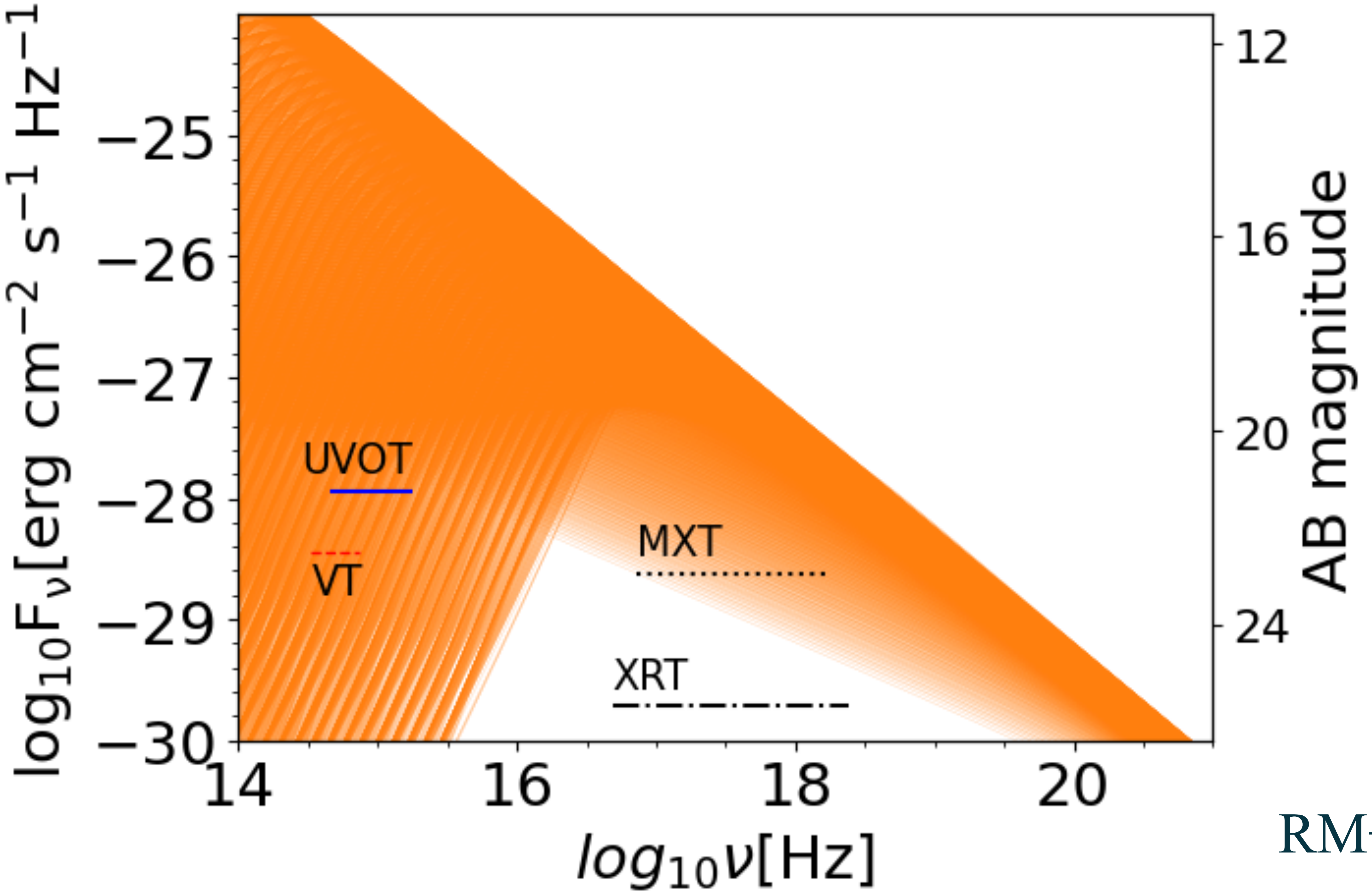
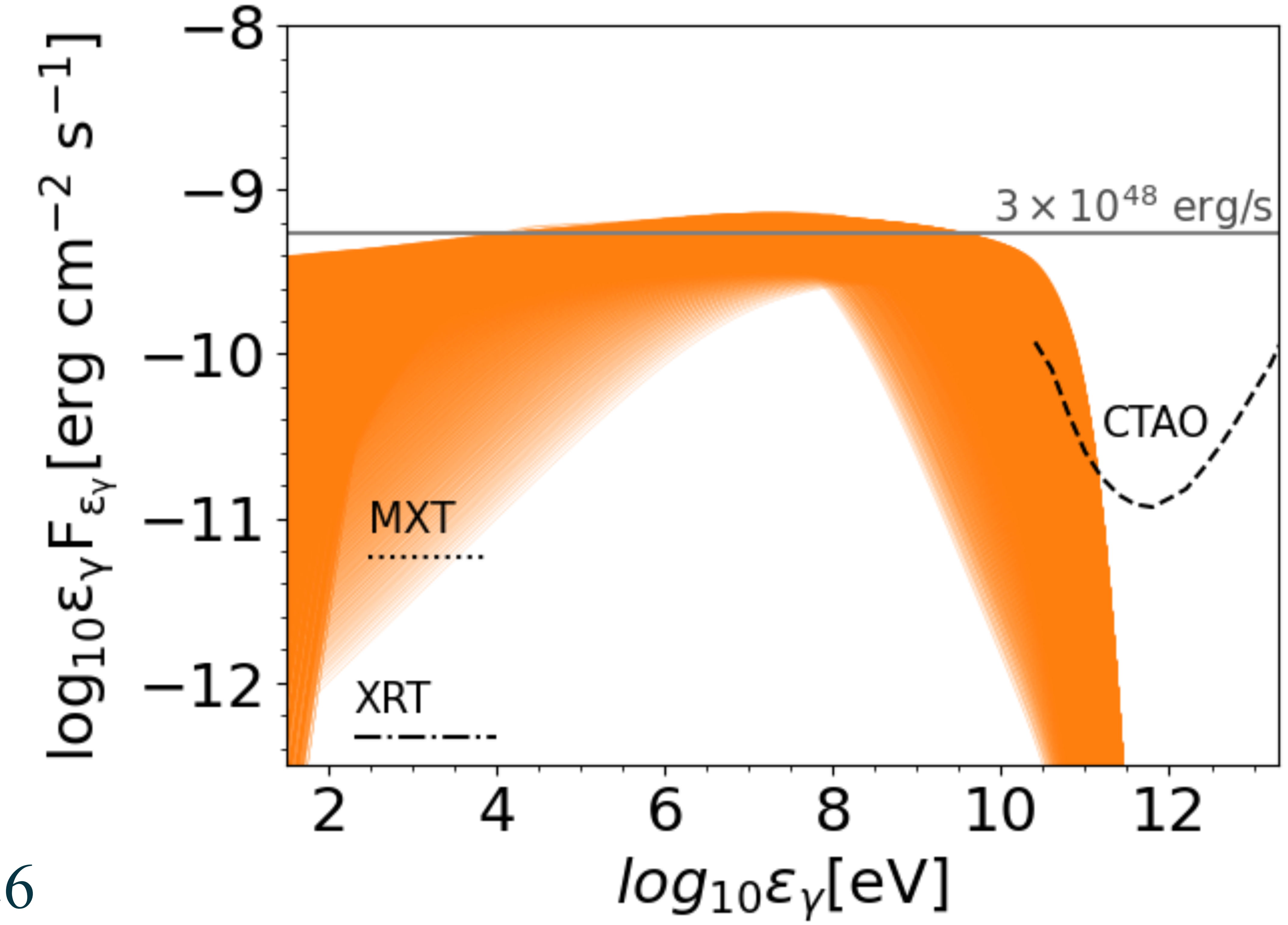
$L_{\rm j,iso}$ (erg/s)	ϵ_e	ϵ_B	$p'_{\rm e,min}$ $(m_e c)$	$\gamma'_{\rm p,diss}$	p	d_L (Gpc)	z
10^{51}	10^{-1}	10^{-2}	200	10	2	6.6	1.0

~10000 calculations

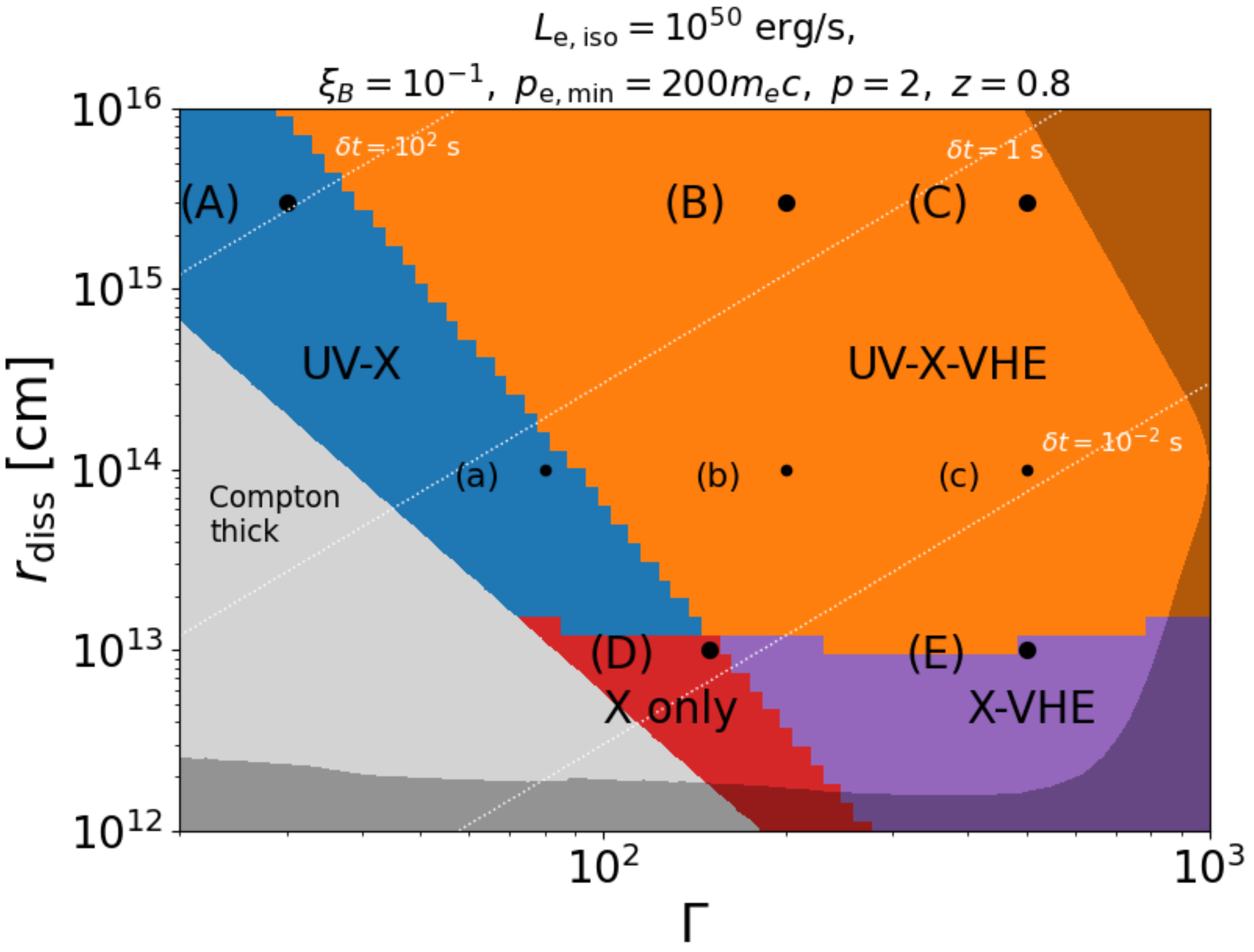




RM+26

Possible detection in UV, X-ray, and subTeV γ.

Multi-wavelength Detectability



RM+26

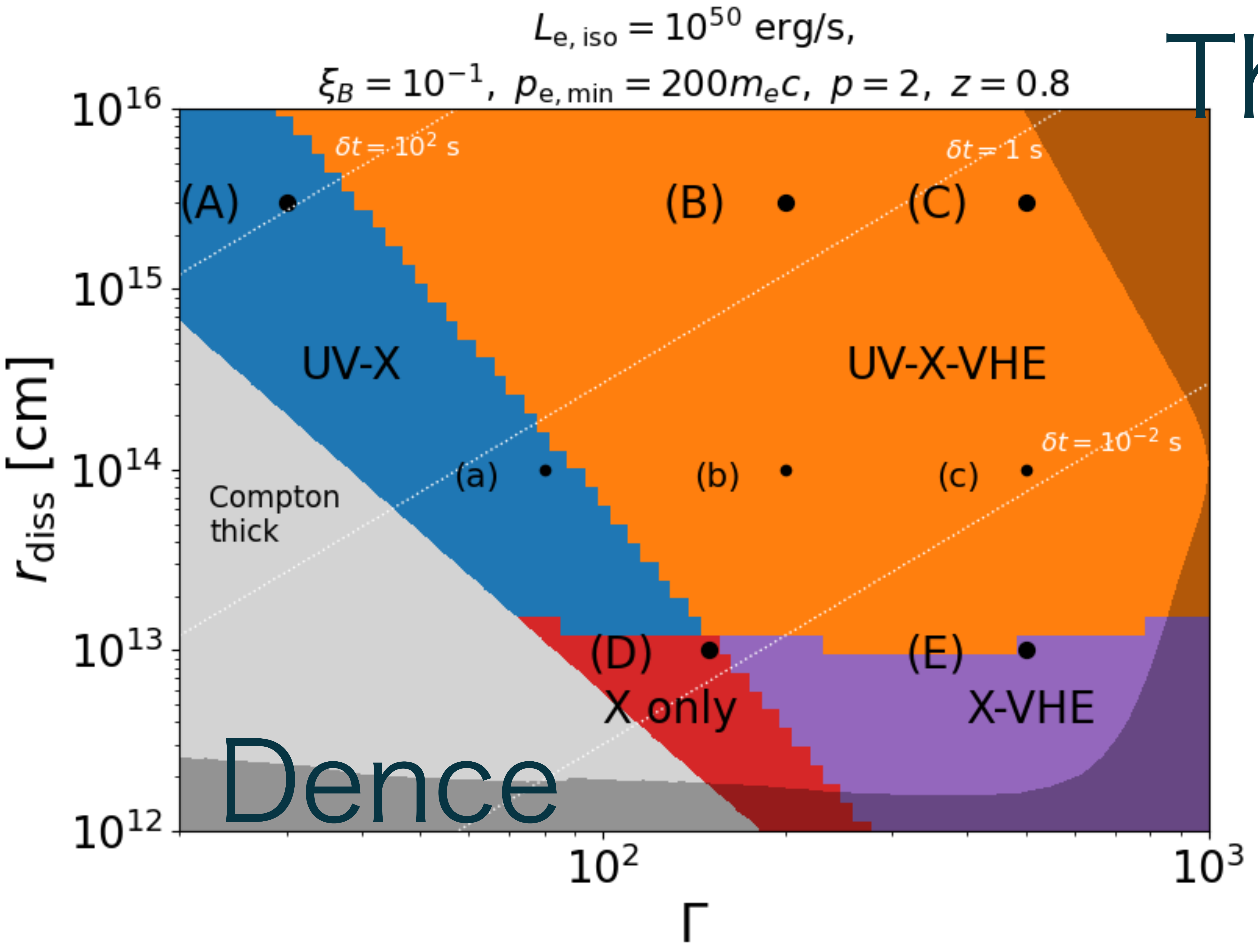
$\mathrm{X} \to L_{\mathrm{jet}}$

$\mathrm{UV} \to r$

$\sim 10\ \mathrm{GeV}\ \gamma \to \Gamma$

We can "measure" r and Γ for the future.

Multi-wavelength Detectability



Thin

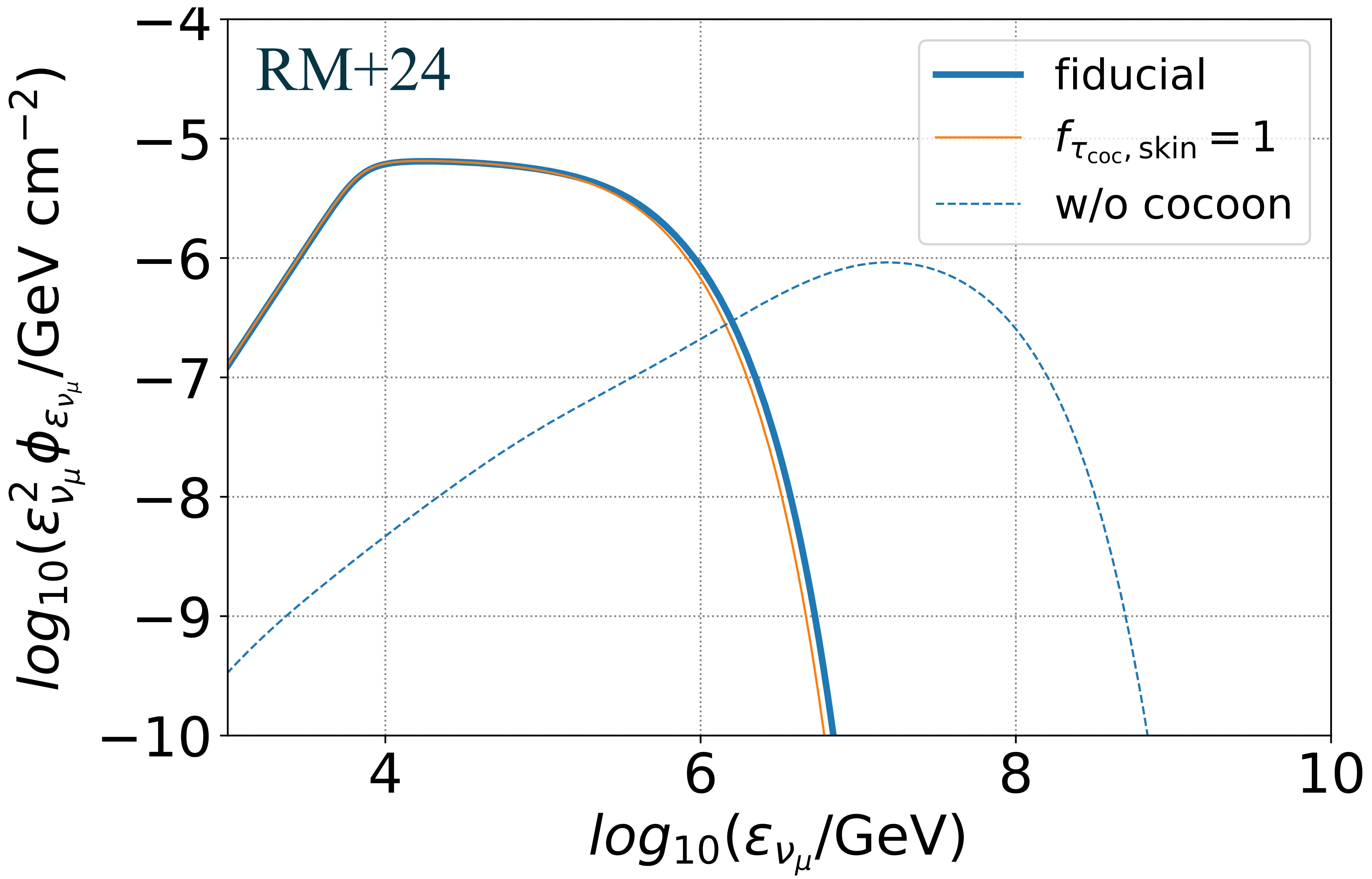
$$U'_{\rm diss} = \frac{L_{\rm jet}}{4\pi r^2 \Gamma^2 c}$$

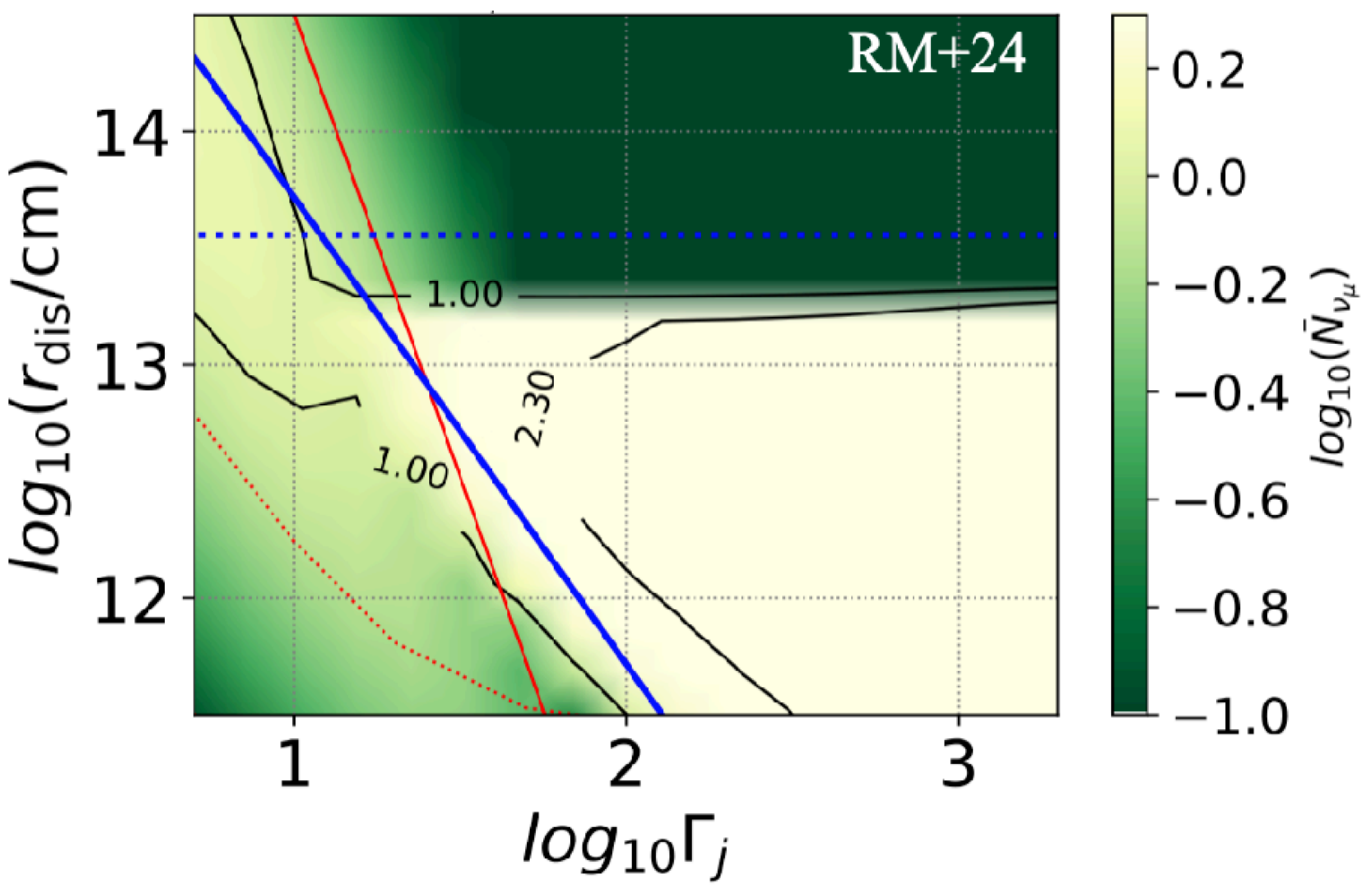
UV criterion ←SSA

VHE criterion ← $\gamma\gamma$

We can “measure” r and Γ for the future.

Neutrino Detectability





IceCube-Gen2 may detect neutrinos.

Also we can "measure" r and Γ for the future.

We need combination

X, γ-ray
(EP, SVOM etc.)

UV-optical
(SVOM, HiZ-GUMDAM etc.)

Neutrinos
(IceCube etc.)

TeV γ
(CTAO etc.)

Gamma-ray burst (GRB)

Where? r

How fast ? Γ

A first step to see through the center.

Summary

- It is difficult to detect multi-wavelength emission from (main burst of) GRBs
due to the short duration $\sim$ 10 s.

- X-ray flares at 100-1000 s after the GRBs are good opportunities to observe in multi-wavelength.

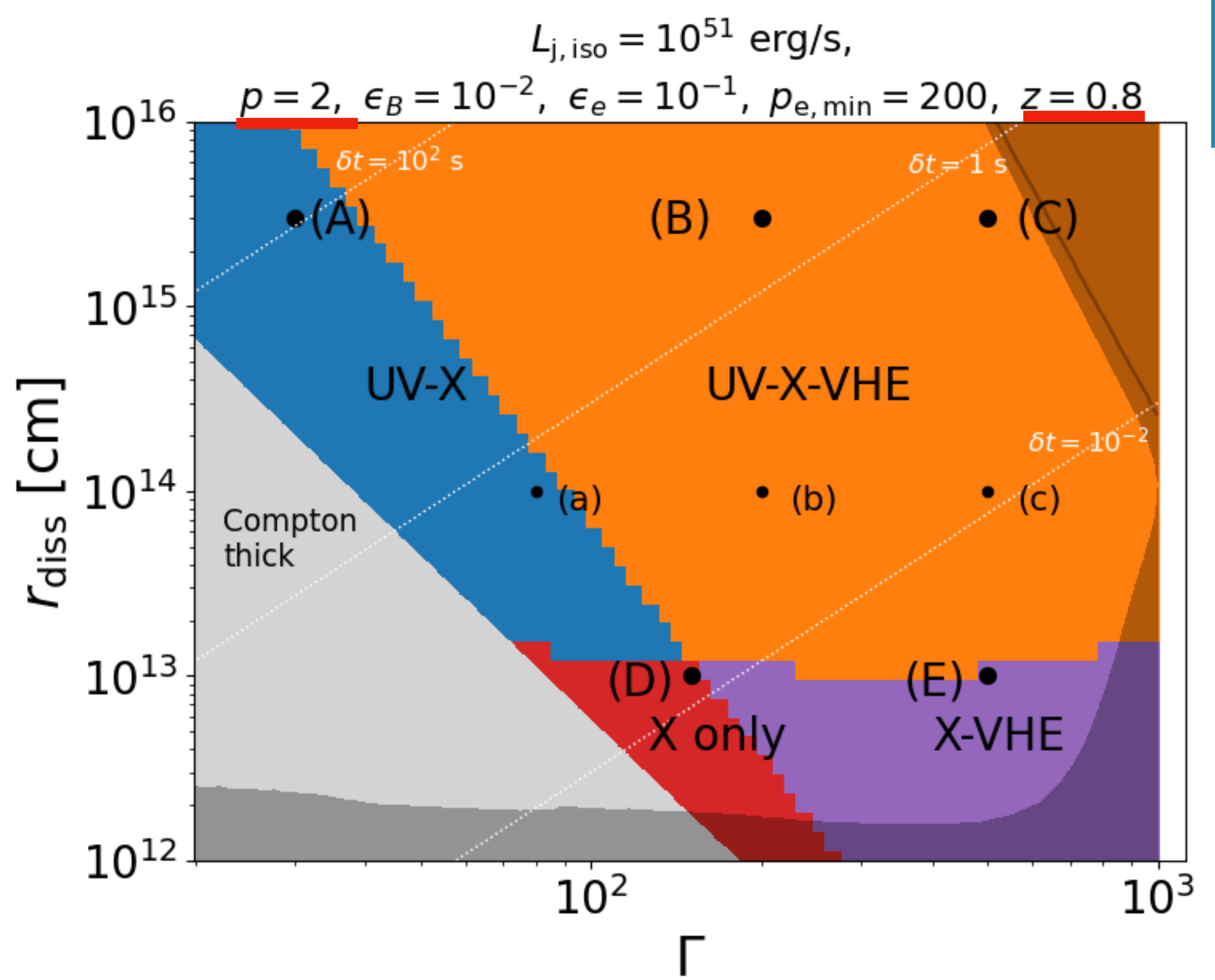
- **I found that** Future UV, subTeV, and Neutrino observations will reveal the jet physics.

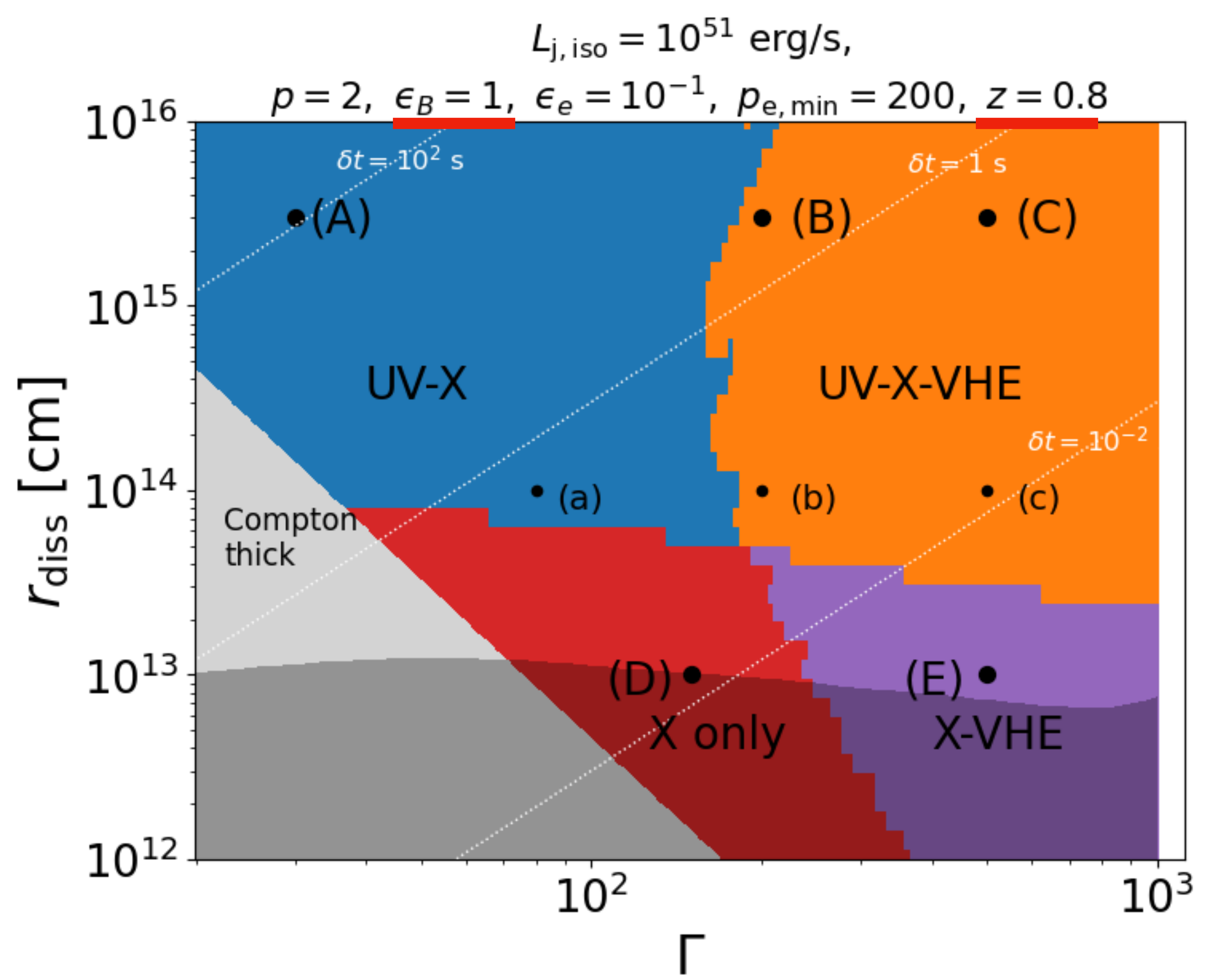
Back up

Multi-wavelength Detectability

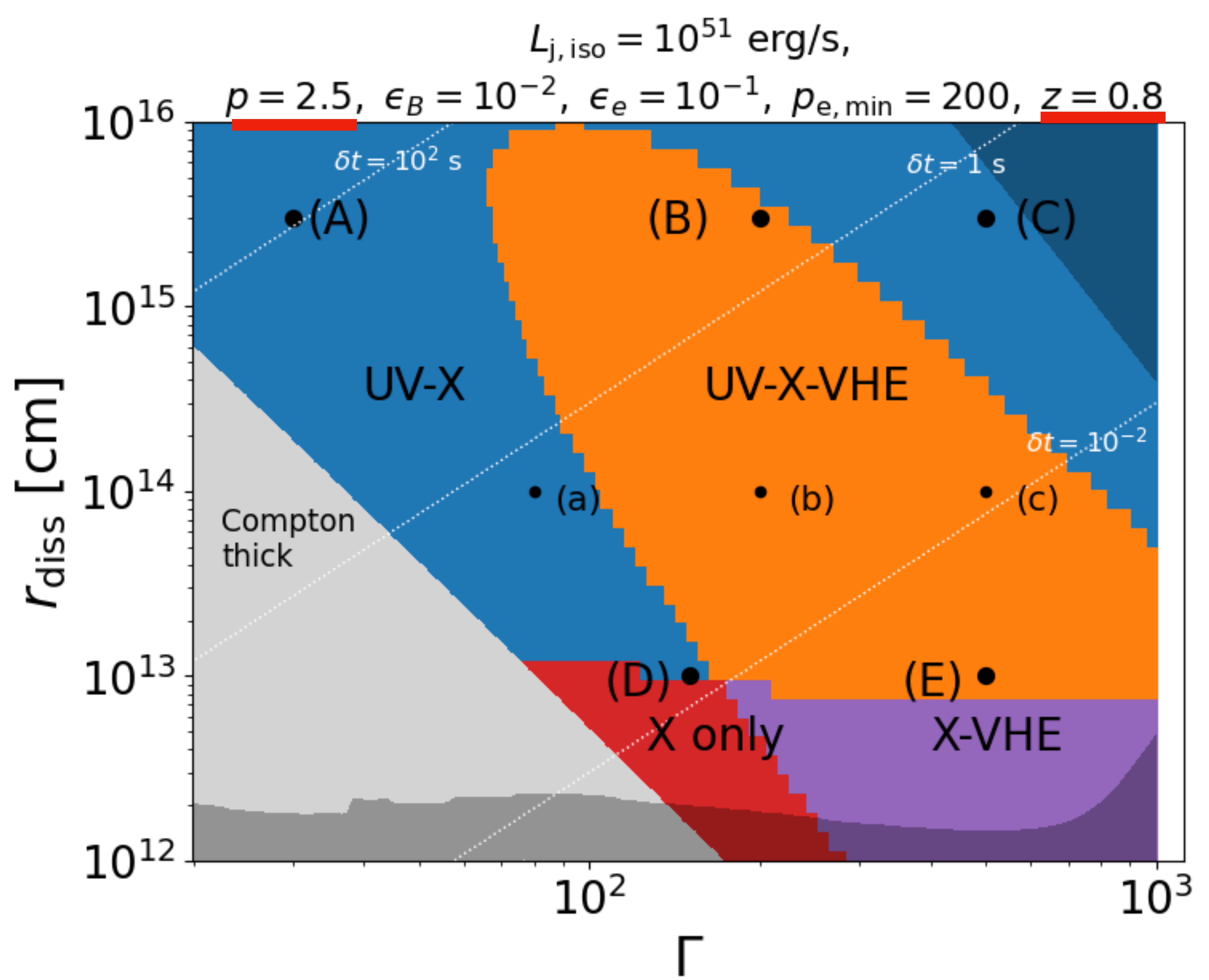
Swift/UVOT
Observations are conducted.
30% of GRBs have flares.
Association? Sewnson+2013

CTAO
→ ~ 1 deg localization
→ Swift/BAT detection
→ 80 GRBs/yr
→ 10 GRBs($z \lesssim 0.8$)/yr
→ 3 flares($z \lesssim 0.8$)/yr
→ 0.3 CTAO flare/yr


$L_{\rm j,iso} = 10^{51}$ erg/s,
$p = 2,\ \epsilon_B = 10^{-2},\ \epsilon_e = 10^{-1},\ p_{\rm e,min} = 200,\ z = 0.8$
$\delta t = 10^2$ s
$\delta t = 1$ s
$\delta t = 10^{-2}$
(A)
(B)
(C)
UV-X
UV-X-VHE
(a)
(b)
(c)
Compton thick
(D)
(E)
X only
X-VHE
$r_{\rm diss}$ [cm]
Γ
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^2
10^3

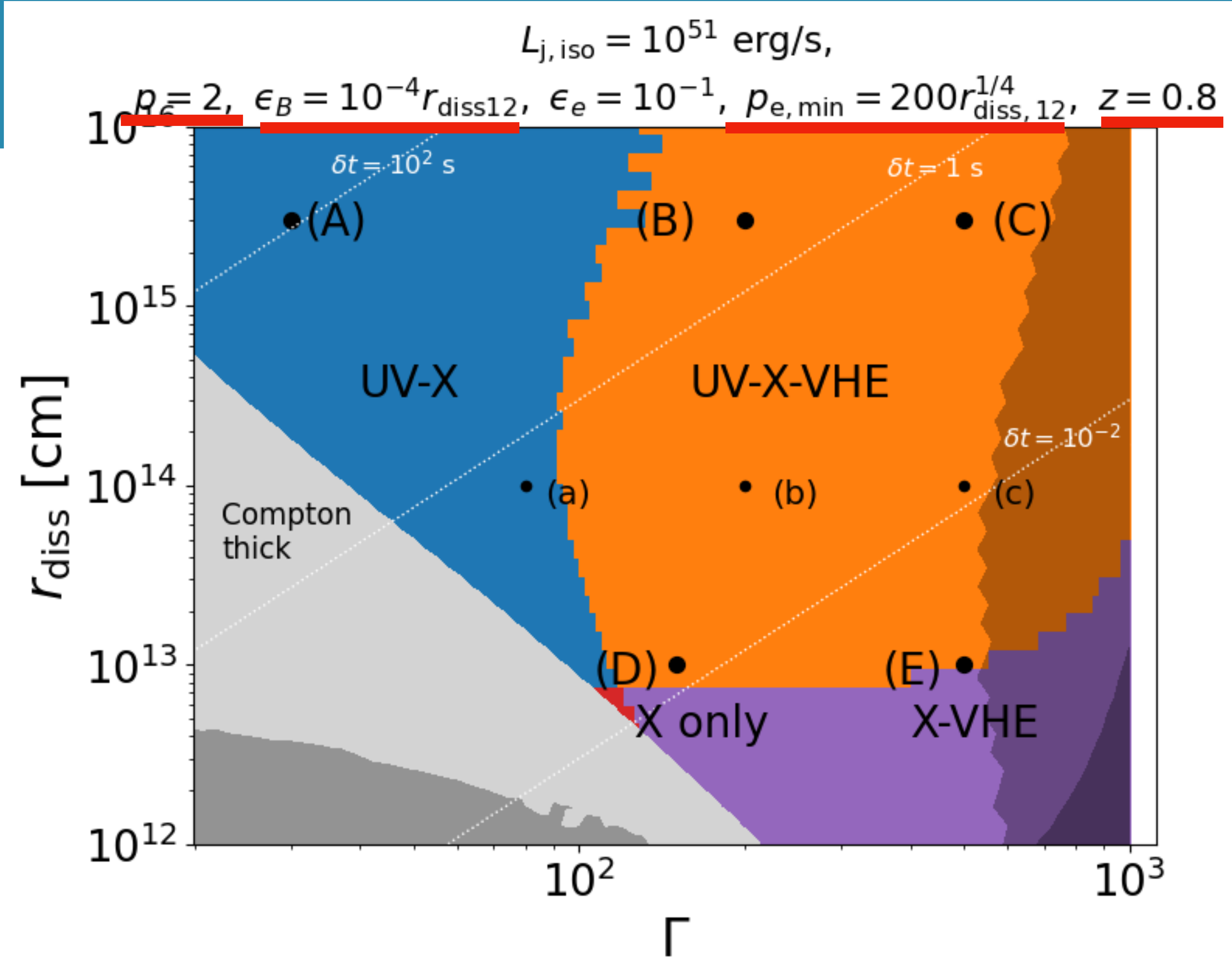


$L_{\rm j,iso} = 10^{51}$ erg/s,
$p = 2$, $\epsilon_B = 1$, $\epsilon_e = 10^{-1}$, $p_{\rm e,min} = 200$, $z = 0.8$
$\delta t = 10^2$ s
$\delta t = 1$ s
$\delta t = 10^{-2}$
(A)
(B)
(C)
(a)
(b)
(c)
(D)
(E)
UV-X
UV-X-VHE
Compton thick
X only
X-VHE
$r_{\rm diss}$ [cm]
Γ
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{2}
10^{3}


$L_{\rm j,iso} = 10^{51}$ erg/s,
$p = 2.5$, $\epsilon_B = 10^{-2}$, $\epsilon_e = 10^{-1}$, $p_{\rm e,min} = 200$, $z = 0.8$
$\delta t = 10^2$ s
$\delta t = 1$ s
$\delta t = 10^{-2}$
(A)
(B)
(C)
(a)
(b)
(c)
(D)
(E)
UV-X
UV-X-VHE
Compton thick
X only
X-VHE
$r_{\rm diss}$ [cm]
Γ
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^2
10^3

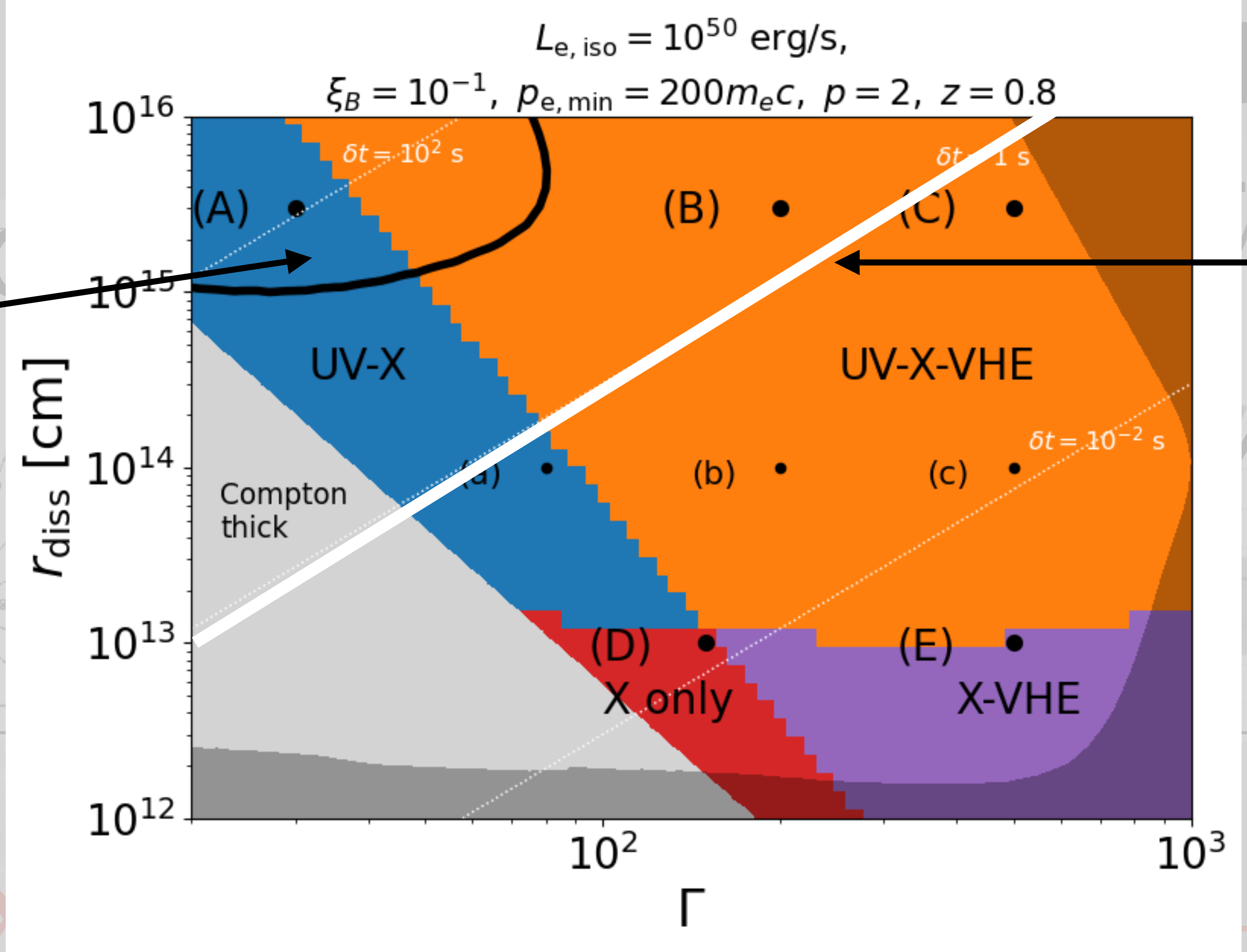
$E_b = 1$ keV

で固定

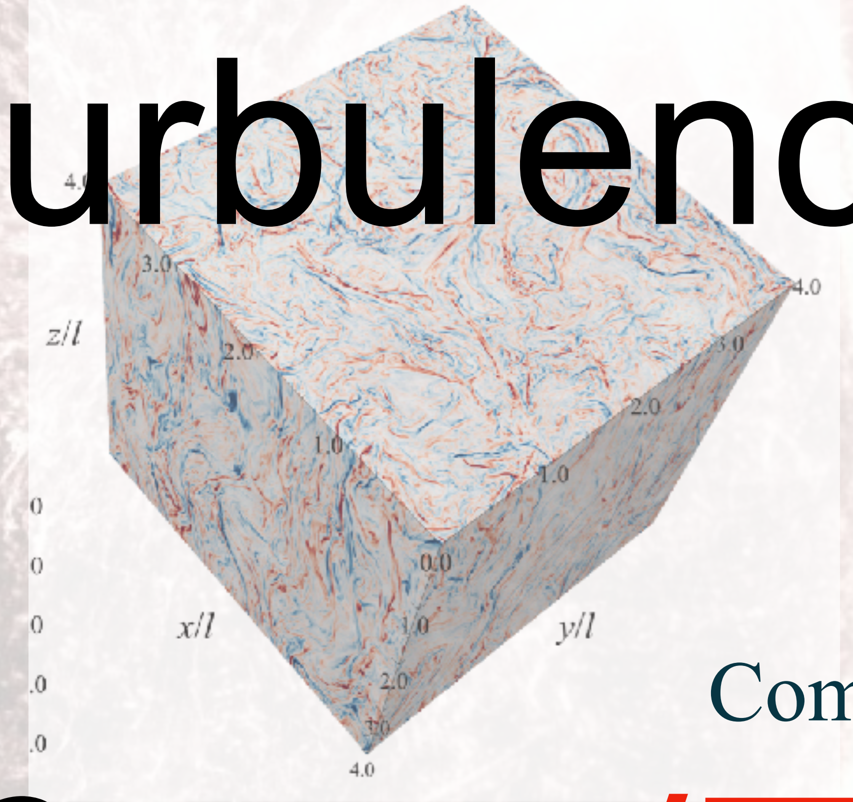


$L_{\mathrm{j,iso}} = 10^{51}$ erg/s,
$p = 2$, $\epsilon_B = 10^{-4} r_{\mathrm{diss12}}$, $\epsilon_e = 10^{-1}$, $p_{\mathrm{e,min}} = 200 r_{\mathrm{diss,12}}^{1/4}$, $z = 0.8$
$\delta t = 10^2$ s
$\delta t = 1$ s
$\delta t = 10^{-2}$
(A)
(B)
(C)
UV-X
UV-X-VHE
(a)
(b)
(c)
Compton thick
(D)
(E)
X only
X-VHE
r_{diss} [cm]
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^2
10^3
Γ

UV/X =0.2



$r/\Gamma^2 c$
$= \delta t = 1$ s



Turbulence

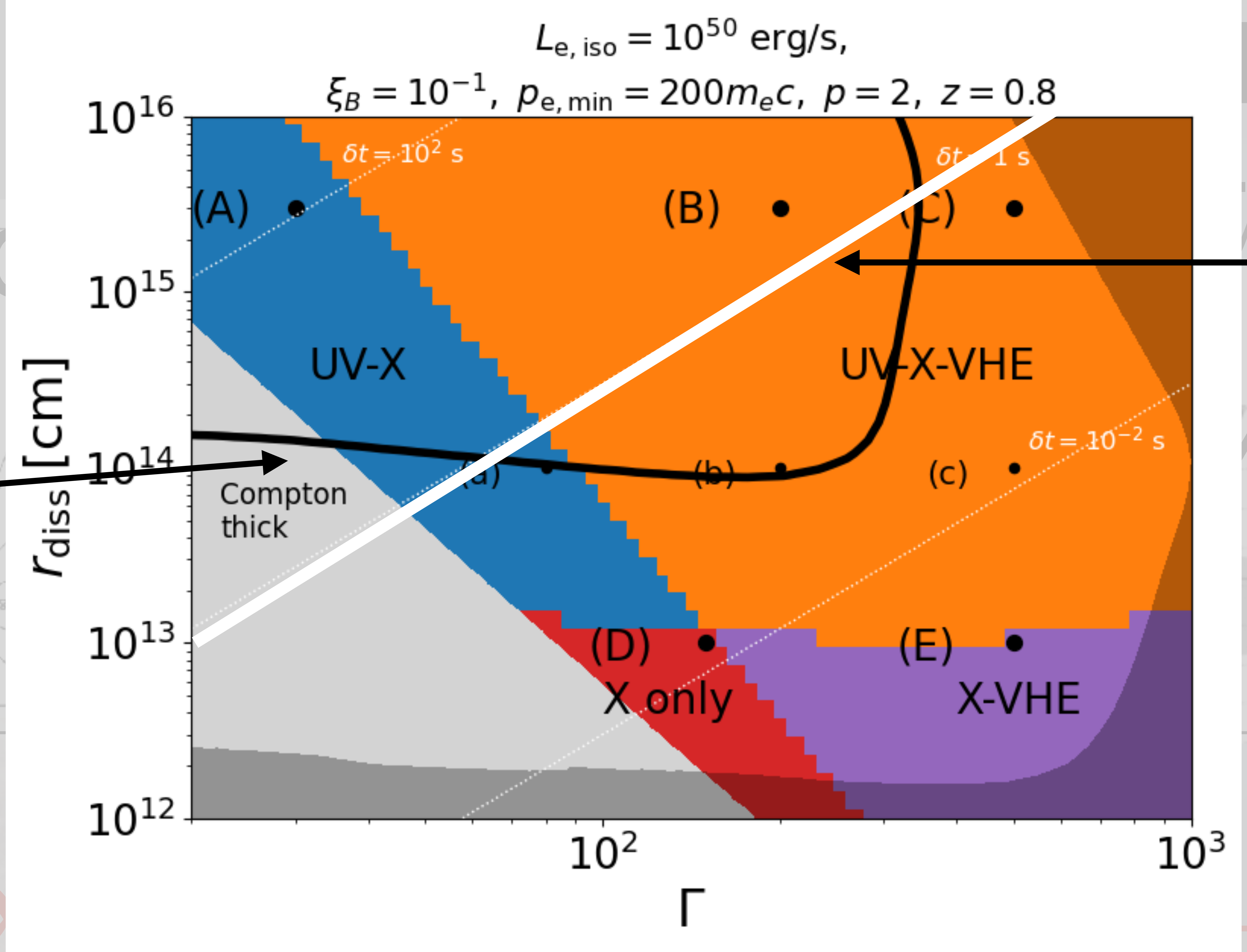
Dissipation

Comisso & Sironi 2019

$c\delta t < r/\Gamma^2$

Energy injection

UV/X =0.02



$= r/\Gamma^2 c$

$= \delta t = 1$ s

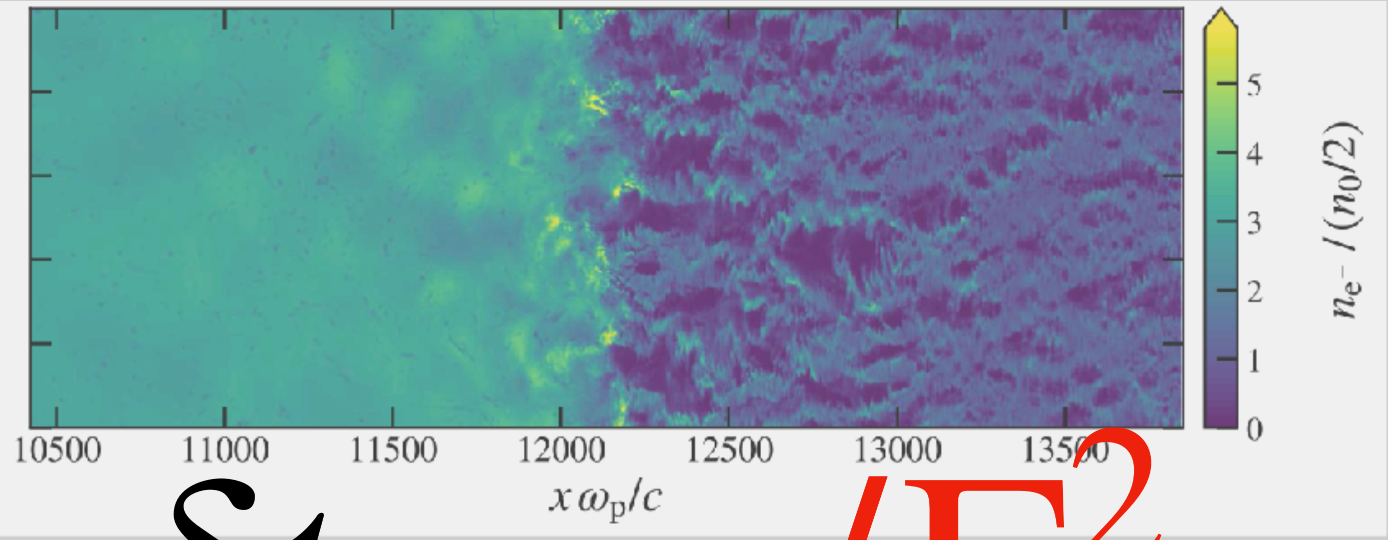
Liu +17

Acceleration

Granot +11

Dissipation

Shock

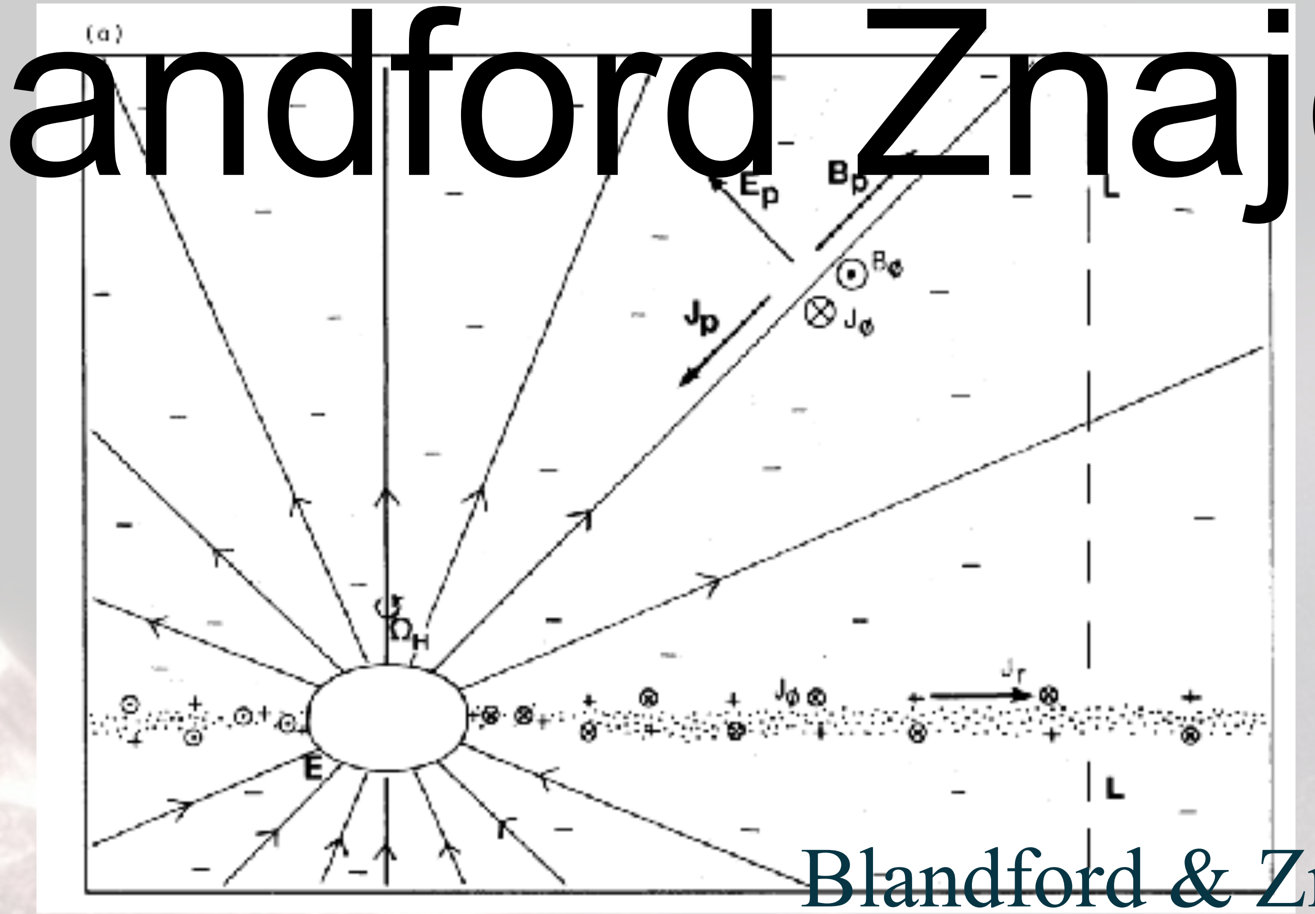


Groseji+24

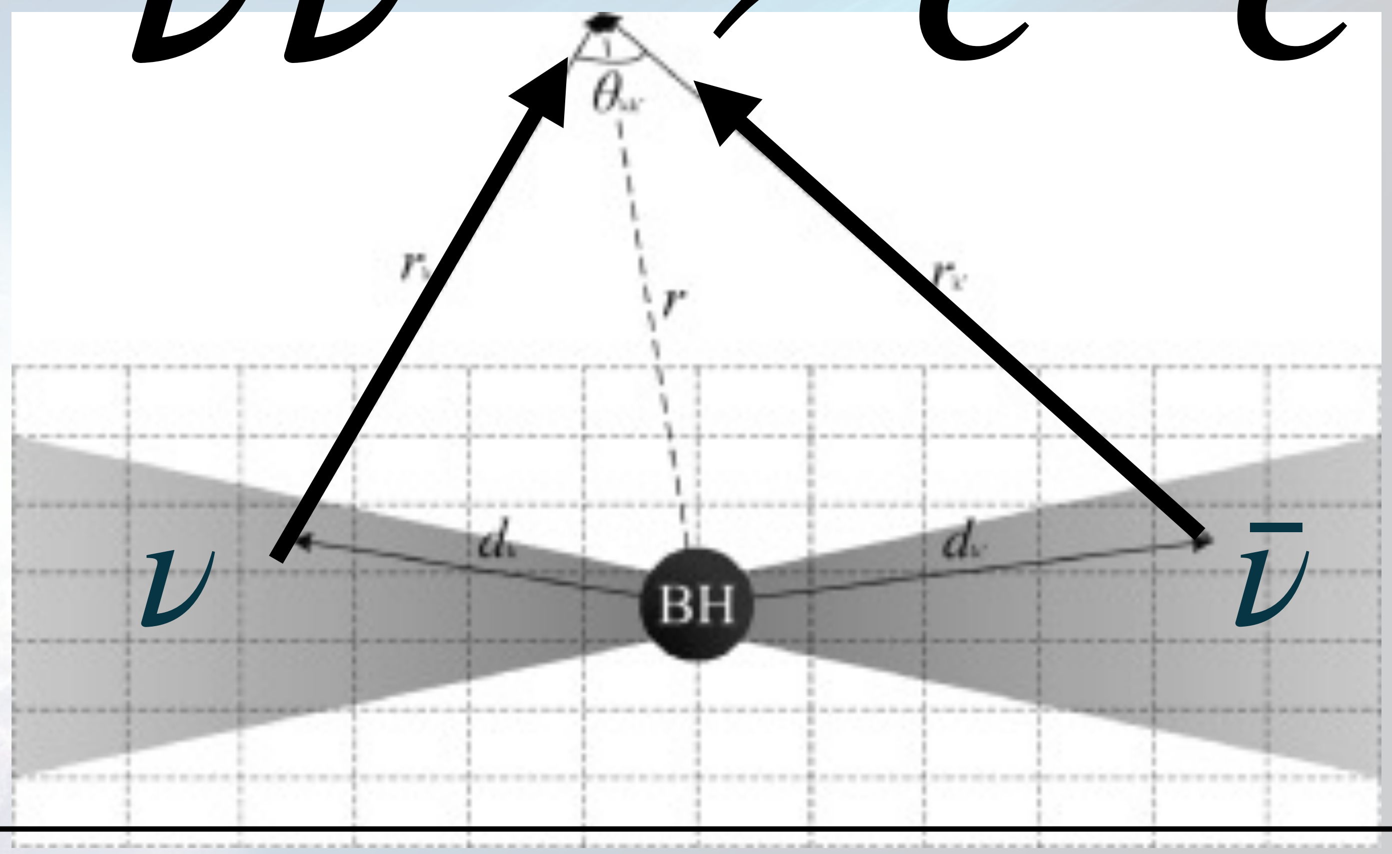
$c\delta t \sim r/\Gamma^2$

B field v.s. Radiation

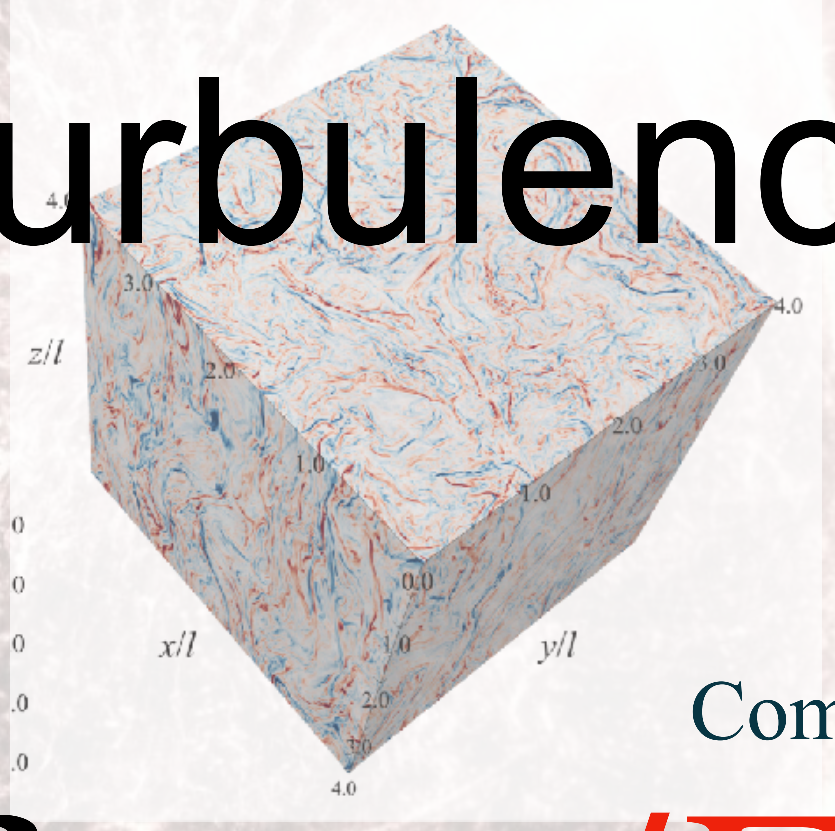
	B field	Radiation
Energy injection	Blandford Znajec	$\nu\bar{\nu} \rightarrow e^{-}e^{+}$
Acceleration	$\Gamma \propto r^{1/3}$ Granot +11	$\Gamma \propto r \rightarrow \Gamma = \mathrm{const.}$ (Matter dominant) Piran+93
Dissipation	Turbulence	Shock



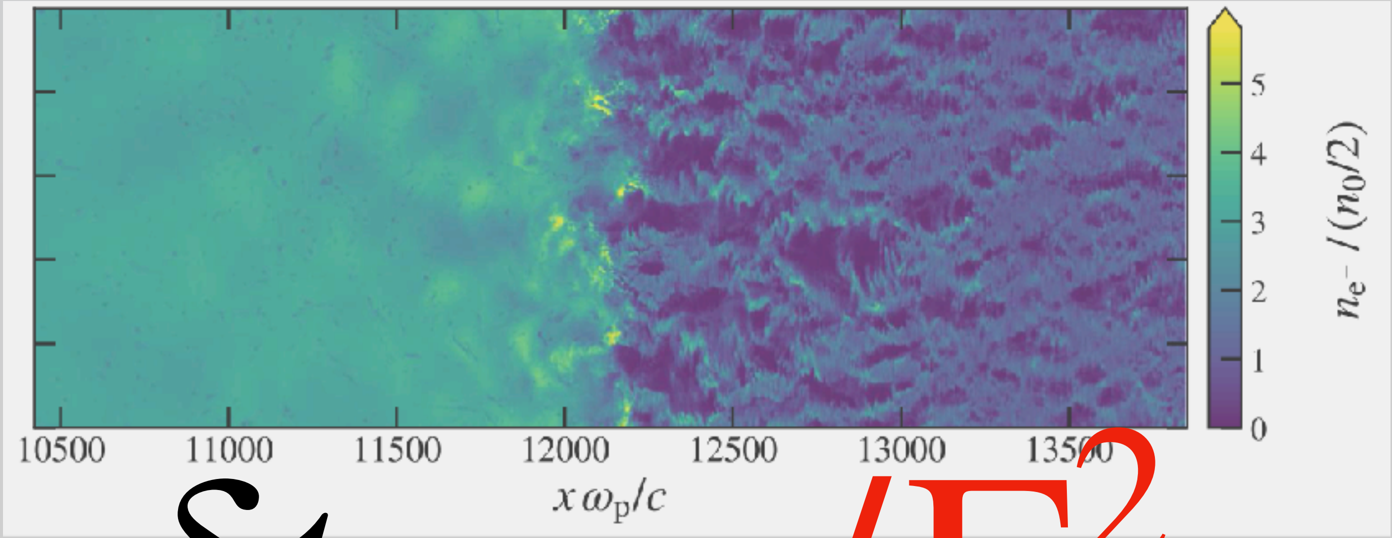
Blandford & Znajek +1976



Liu +17


Comisso & Sironi 2019

$$c\delta t < r/\Gamma^2$$


Groseji+24

$$c\delta t \sim r/\Gamma^2$$