Spectral Shapes of Pair Annihilation Line Emission in Magnetar Giant Flares

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with: Shigeo S. Kimura

Take-home message in 0 min

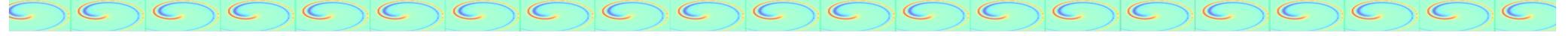Pair-annihilation line from giant flares is an important target for future MeV observations.
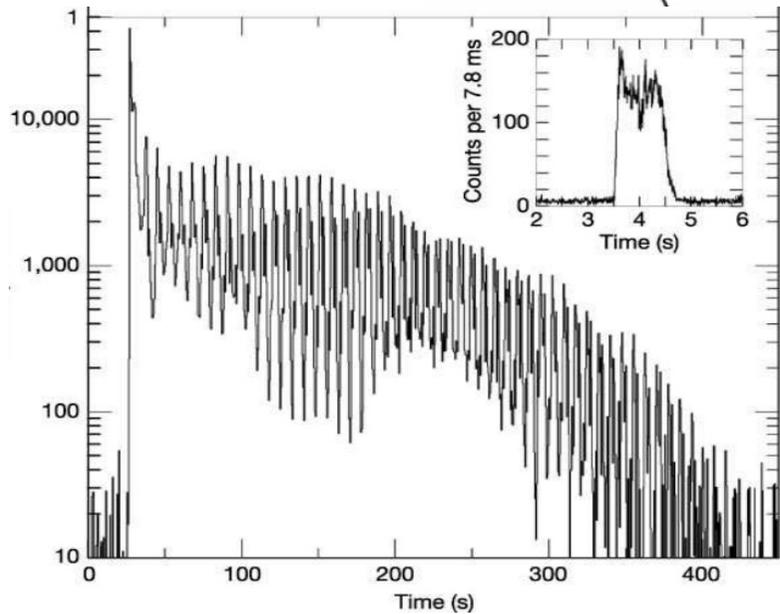

$O(100)$ photons!!

More baryons
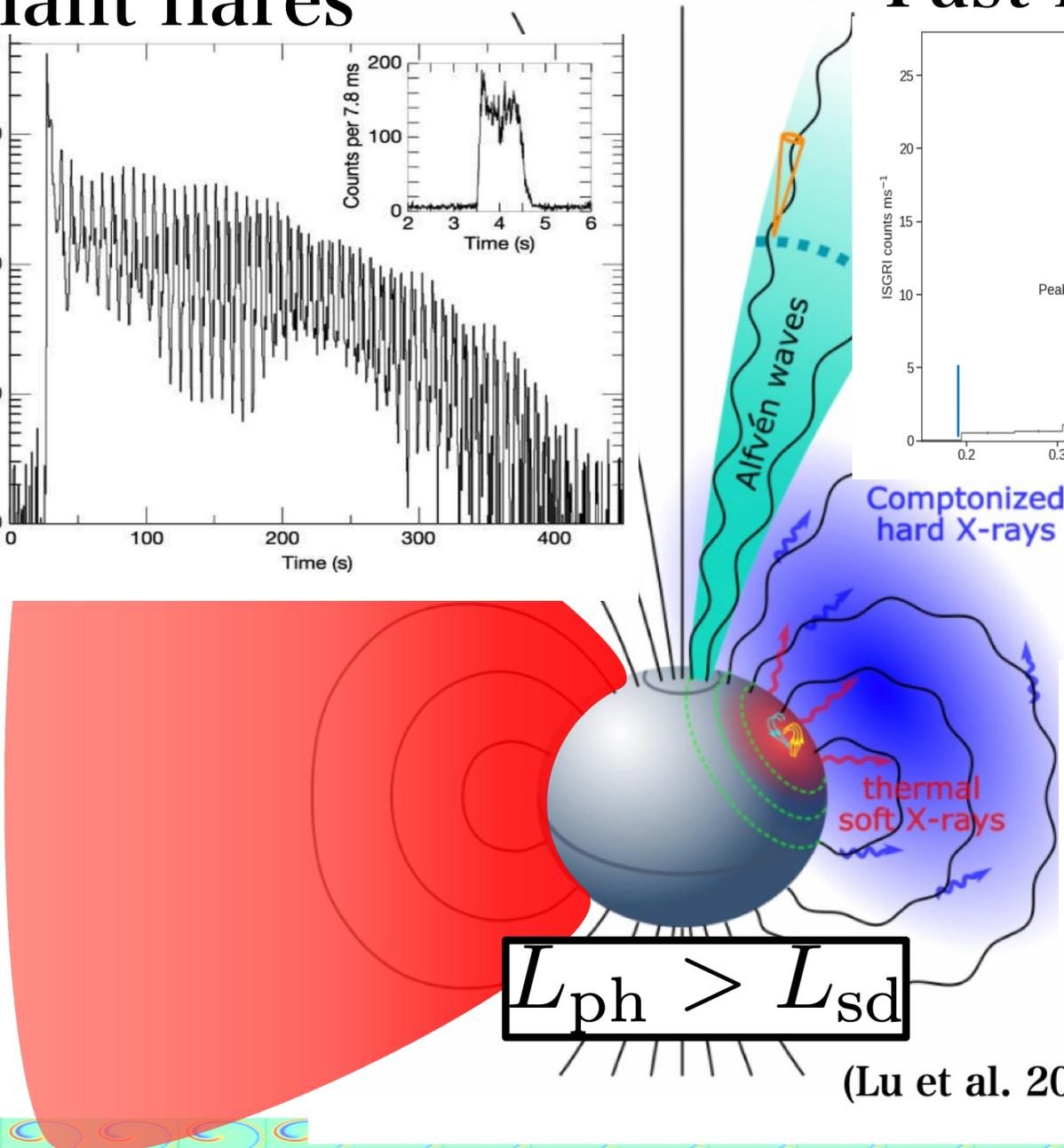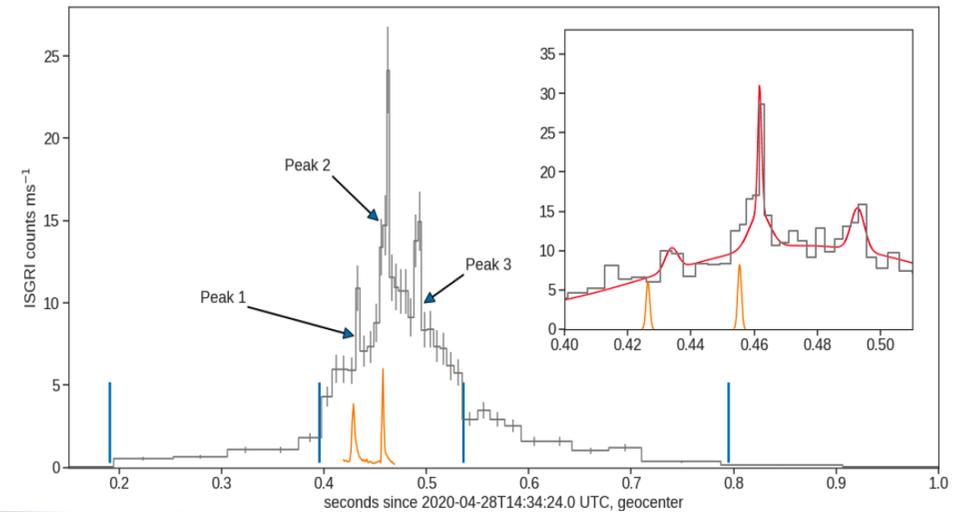-> Less MeV γ
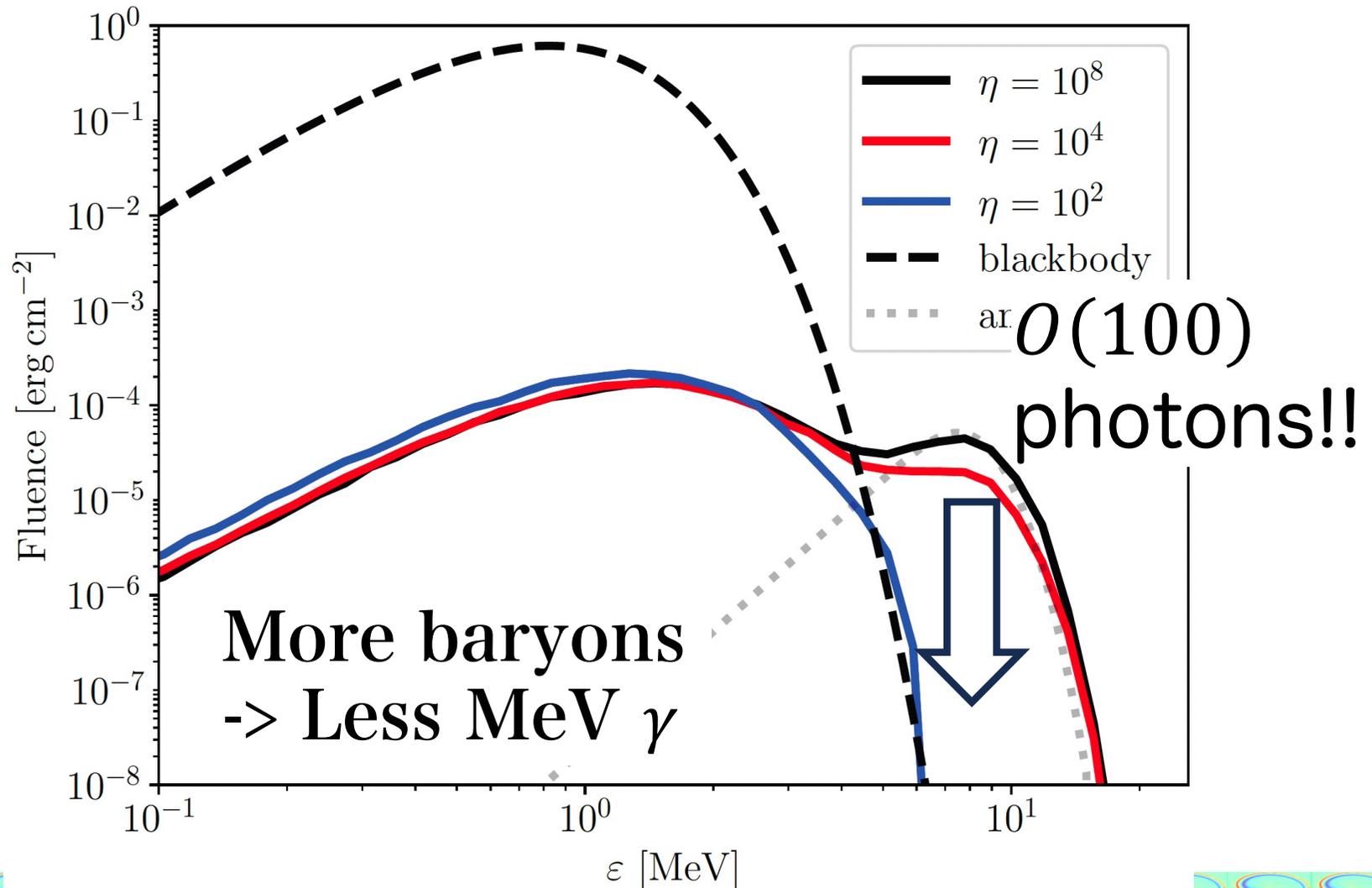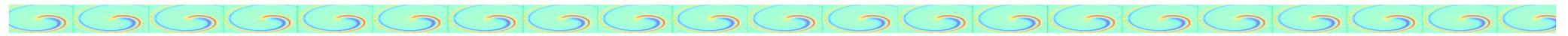
Introduction

Magnetar diverse bursting activities

Giant flares

Fast radio bursts

X-ray short bursts

Alfvén waves

Comptonized hard X-rays

thermal soft X-rays

$$L_{\mathrm{ph}} > L_{\mathrm{sd}}$$

(Lu et al. 2020)

time [s]
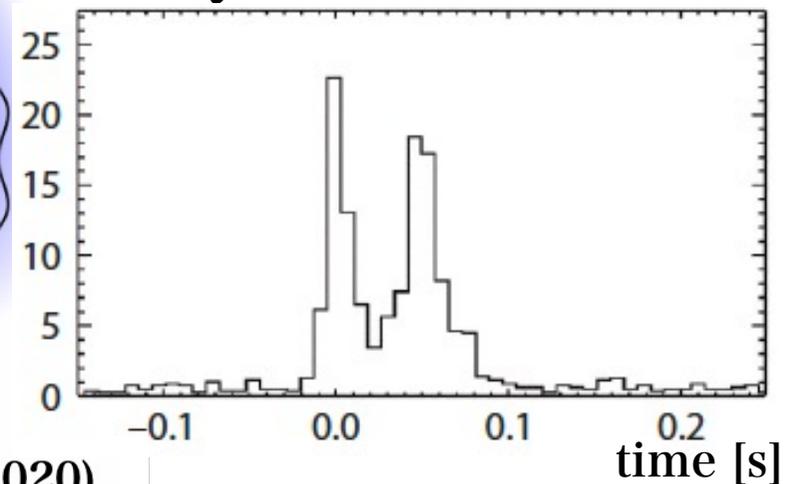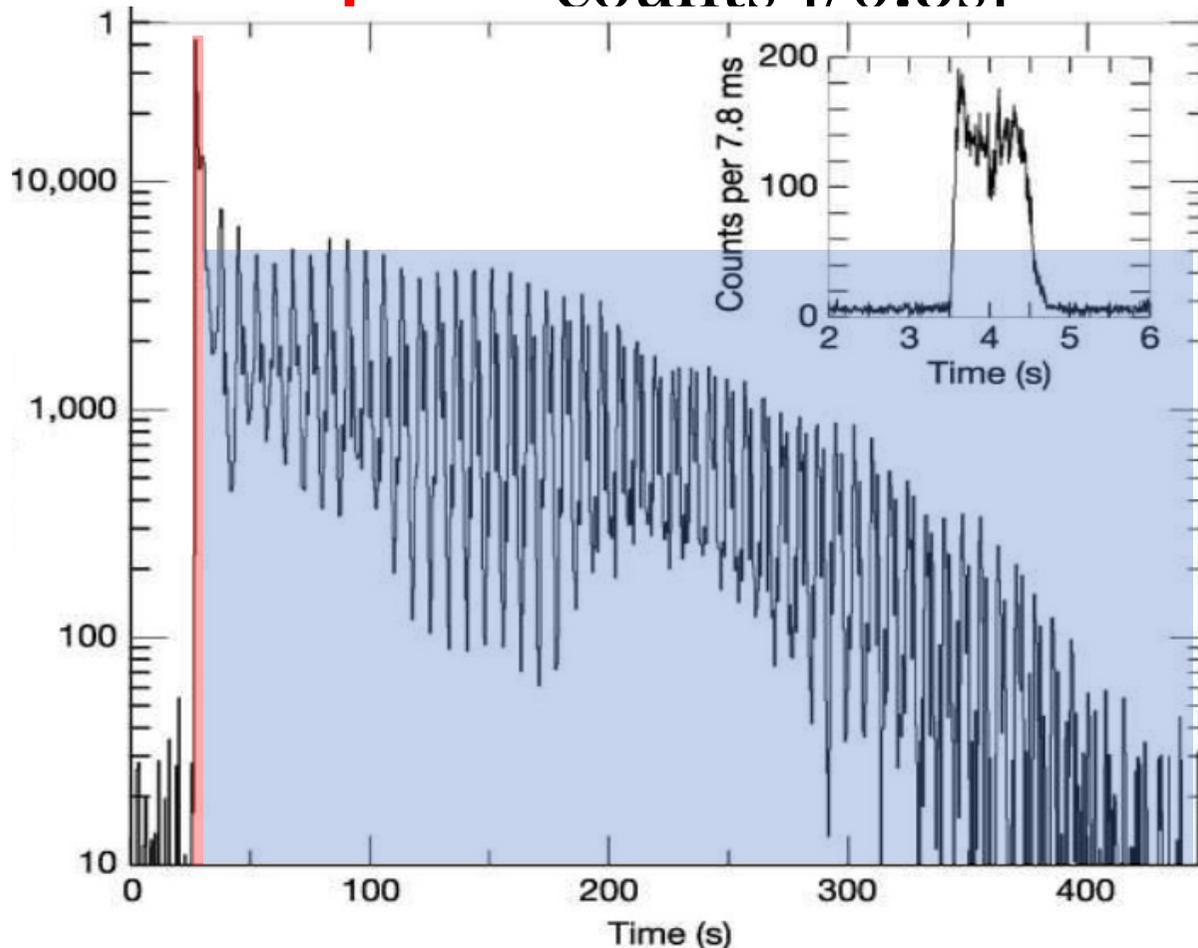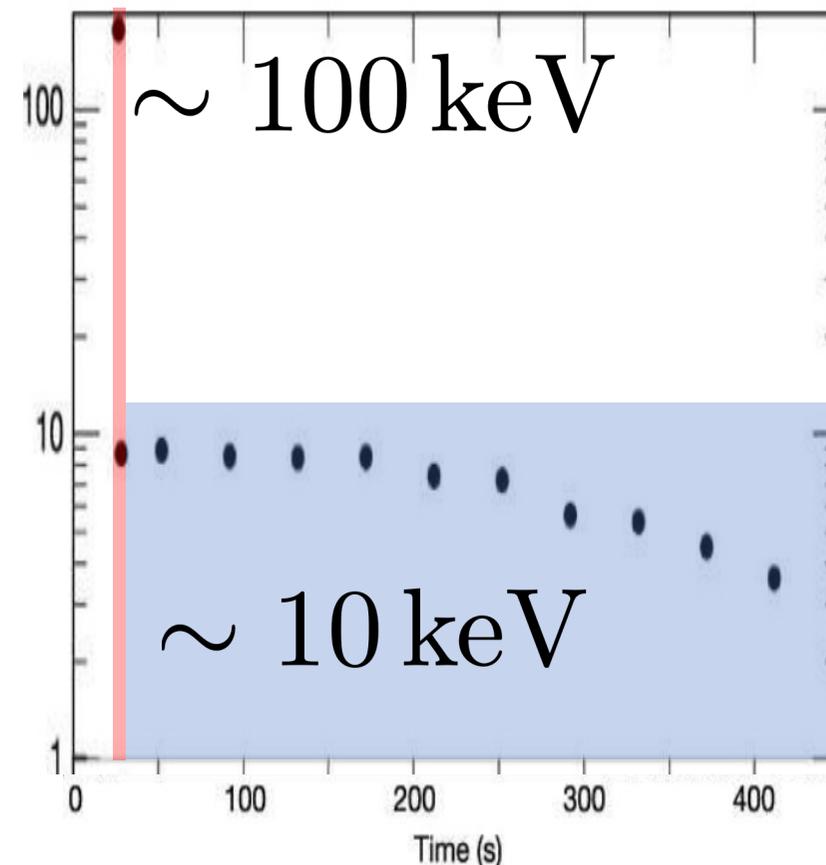
Giant flares

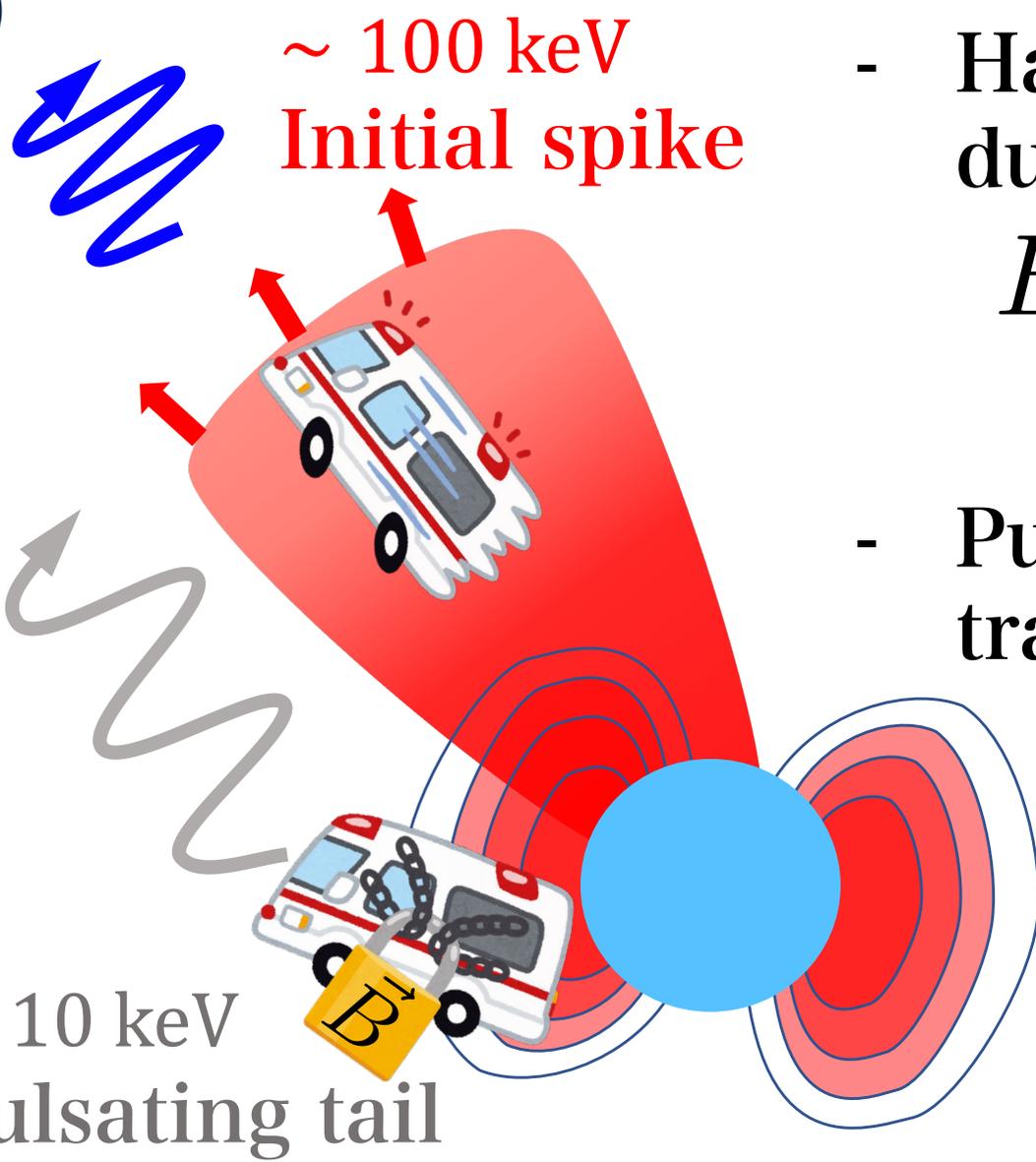**Initial spike**   counts [/0.5s]   energy [keV]

Kaspi&Beloborodov17

- Luminous X-ray bursts: $L_{\text{peak}} \sim 10^{44} - 10^{47} \text{ erg s}^{-1}$
- Hard spike + Pulsating tail
- 3 Galactic events so far

Giant Flare: Spike & Tail

~ 100 keV
Initial spike

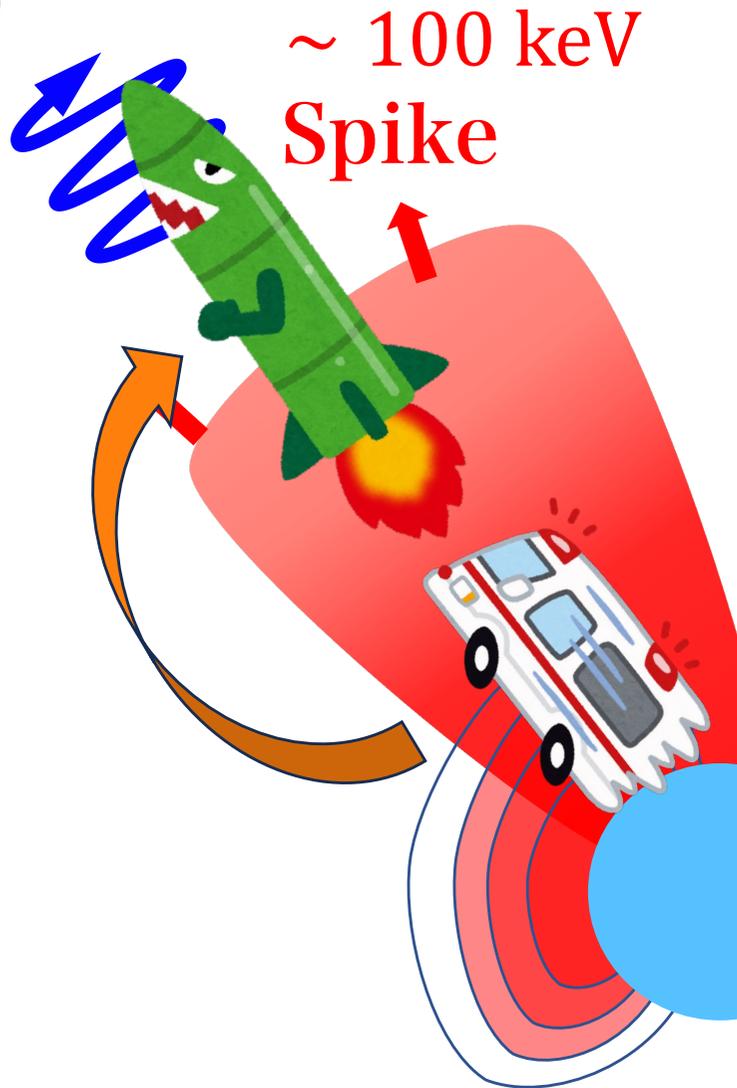- Hard X-ray emission due to Doppler shift

$$E_{\mathrm{obs}} = \Gamma \times E'$$

- Pulsating tail from trapped fireball

$\vec{B}$

~ 10 keV
Pulsating tail

Thompson & Duncan 1995, 1996

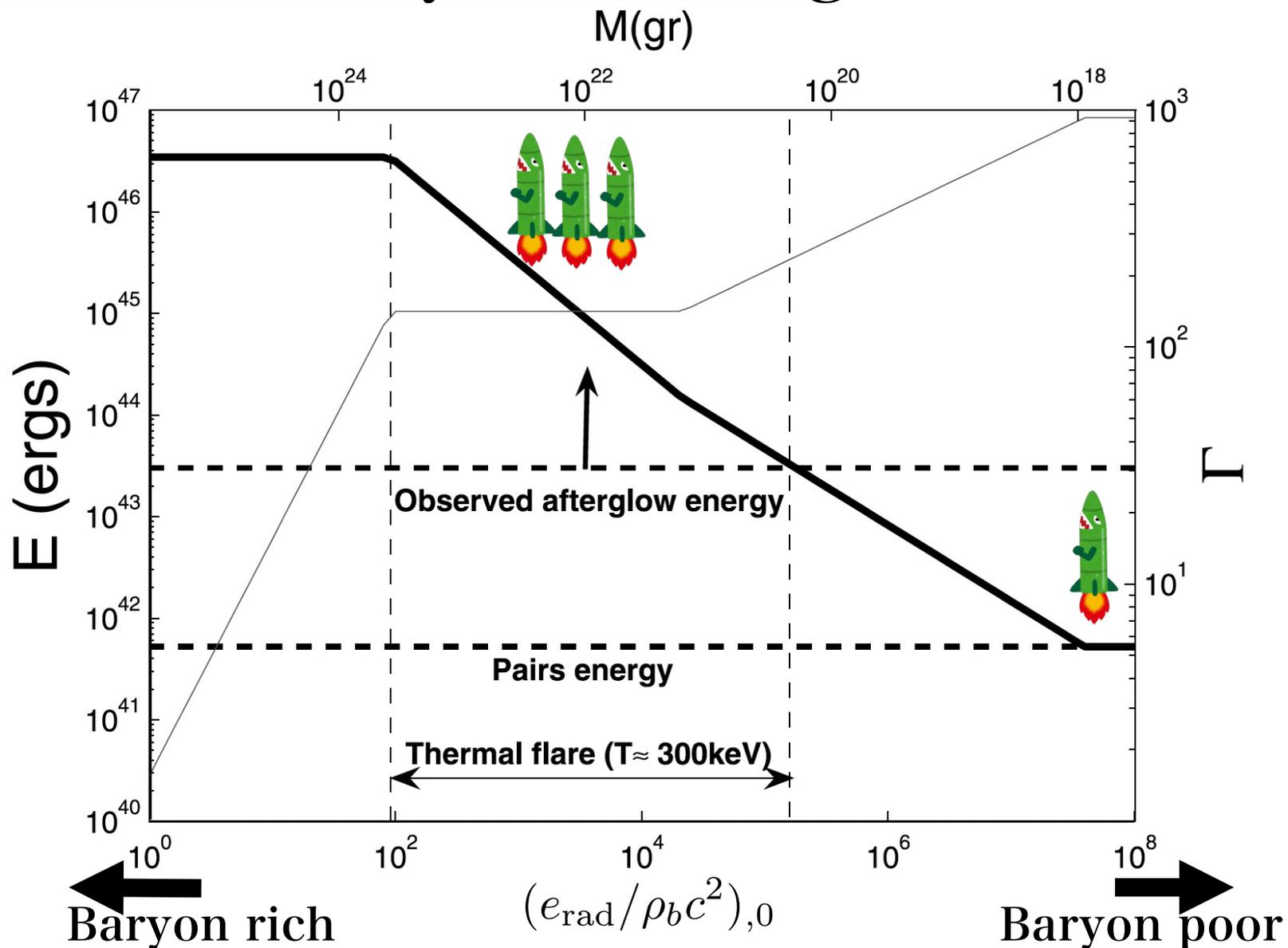# Plasma outflow from initial spike

~ 100 keV
Spike

Radiative acceleration
of the plasma outflow

➡ Afterglow!!
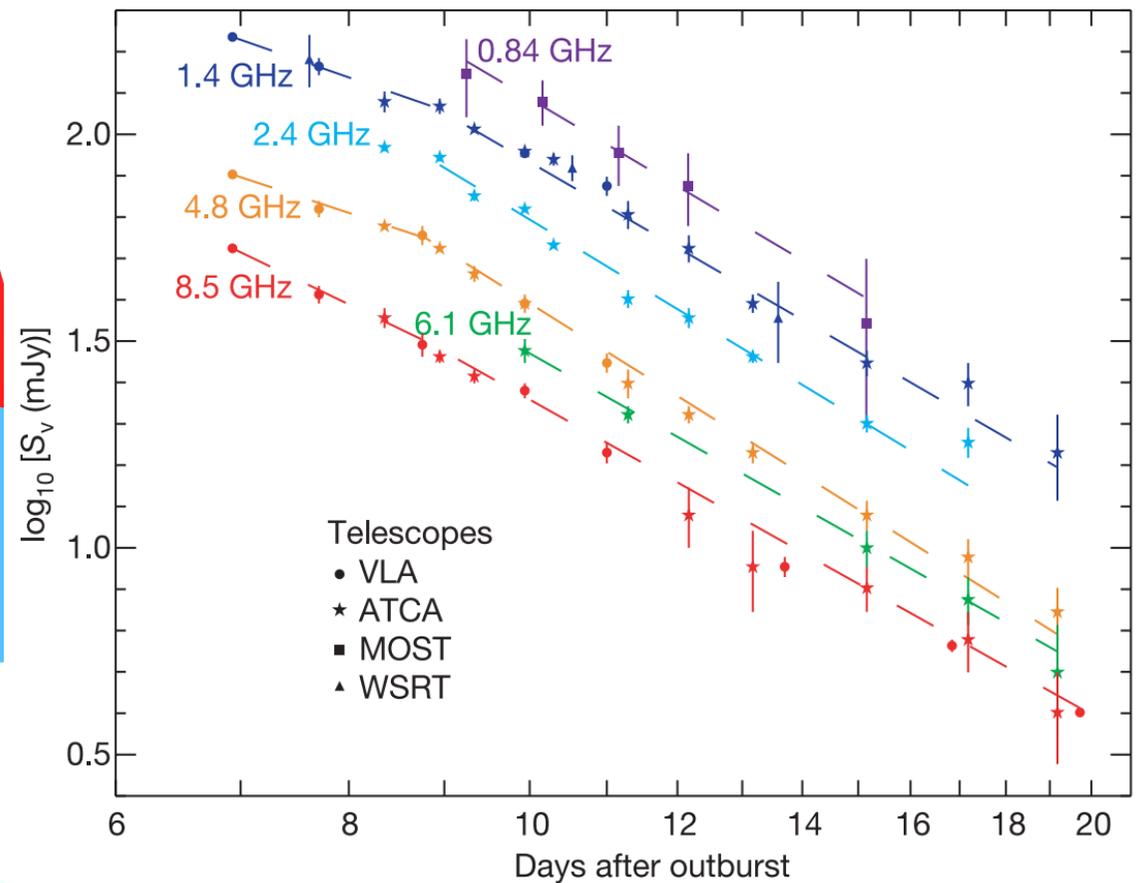
Thompson & Duncan 1995, 1996
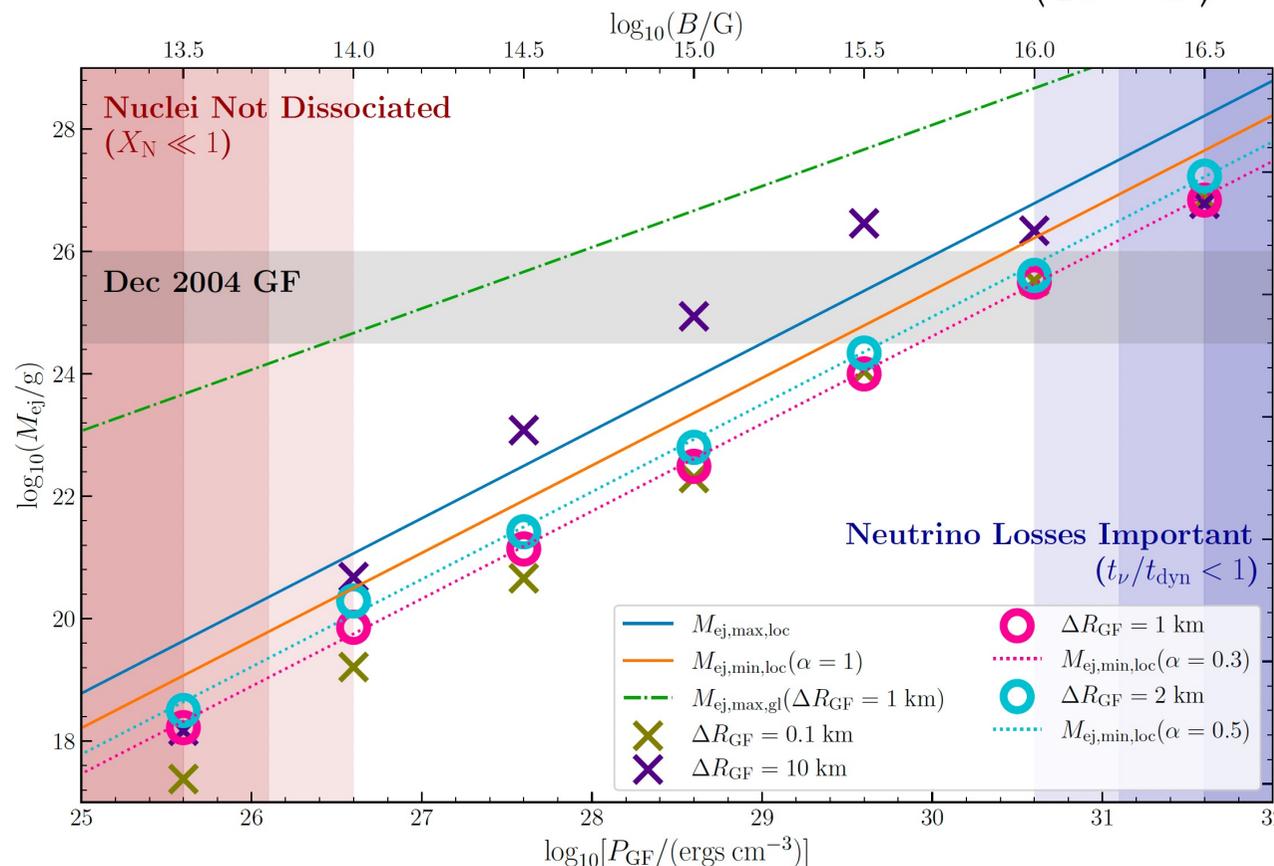Gaensler+2005, Cameron+2005

Giant flares: Baryon loading

Nakar+2005
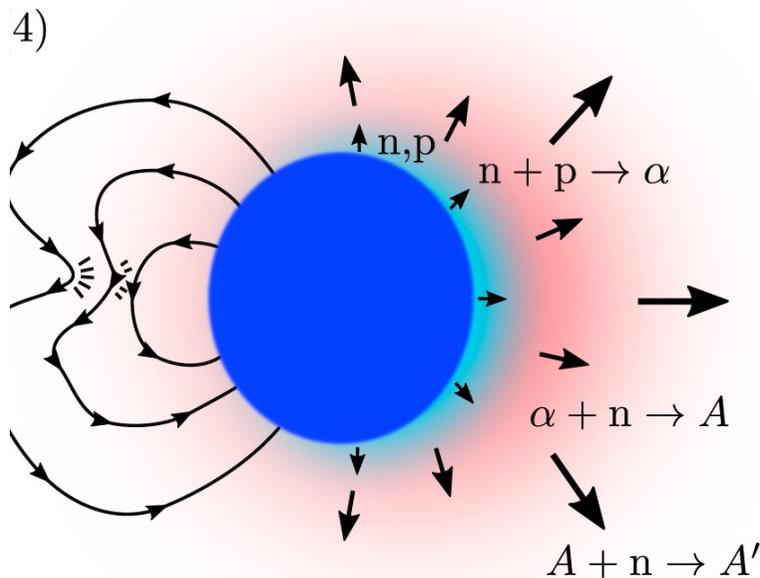
Radio afterglow of giant flares
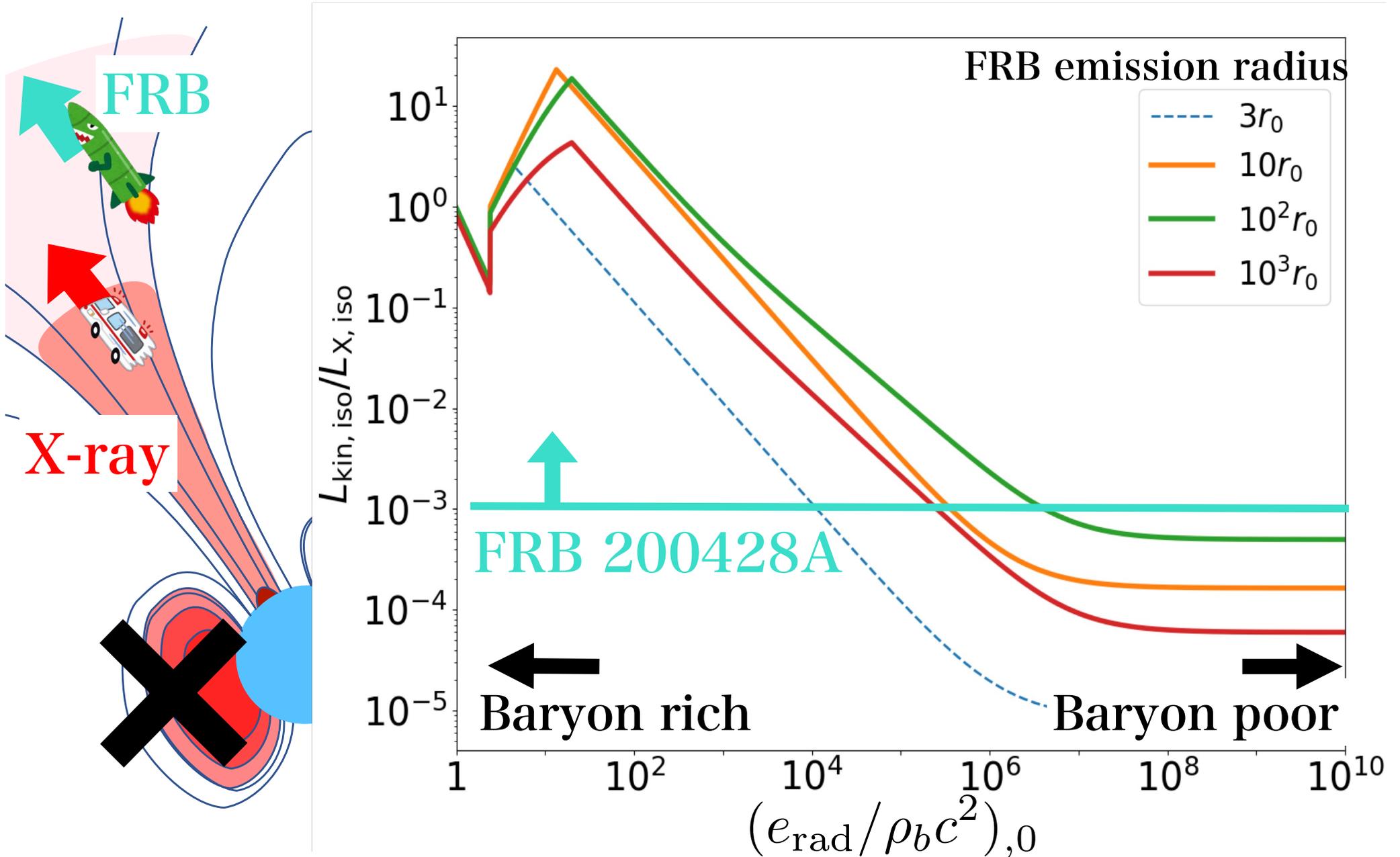Kinetic energy of outflow $> 3 \times 10^{43}$ erg

Giant flares: Baryon-ejection

$$P_{\rm GF} \approx \frac{B^2}{8\pi} \simeq 4 \times 10^{28} \ {\rm ergs \ cm^{-3}} \left(\frac{B}{10^{15} \ {\rm G}}\right)^2$$

Hydrodynamic simulation also suggest baryon loading in the giant flare. (possible r-process elements)

Cehula+2023,

Connection to FRBs

FRB

X-ray

FRB emission radius

- - - $3r_0$
—— $10r_0$
—— $10^2 r_0$
—— $10^3 r_0$

$L_{\mathrm{kin,iso}}/L_{\mathrm{X,iso}}$

FRB 200428A

Baryon rich

Baryon poor

$(e_{\mathrm{rad}}/\rho_b c^2)_{,0}$

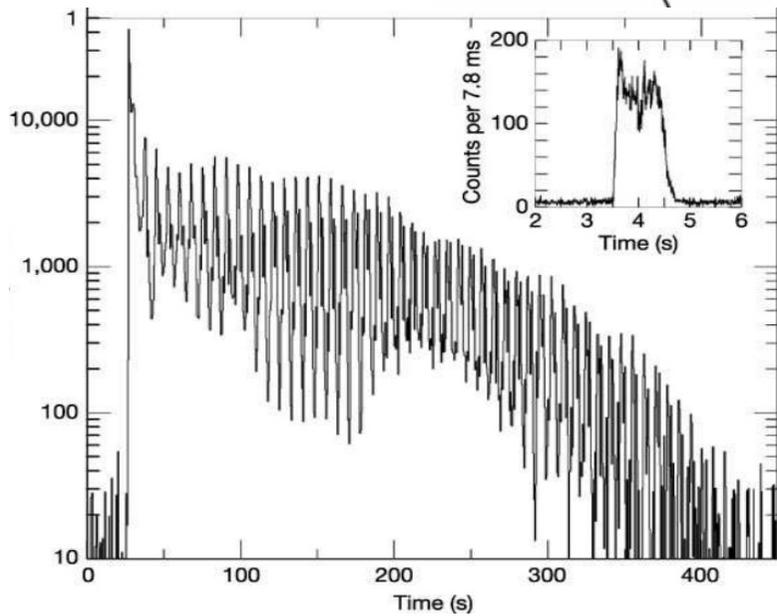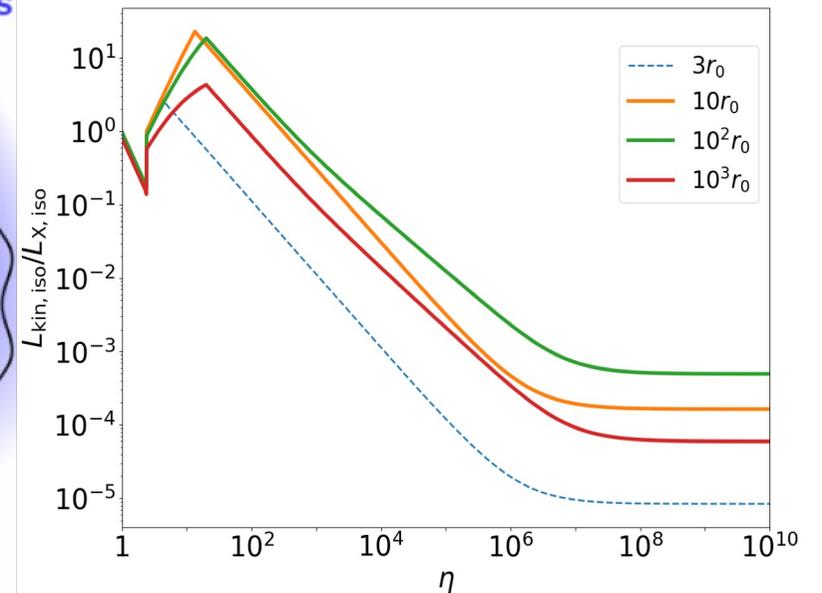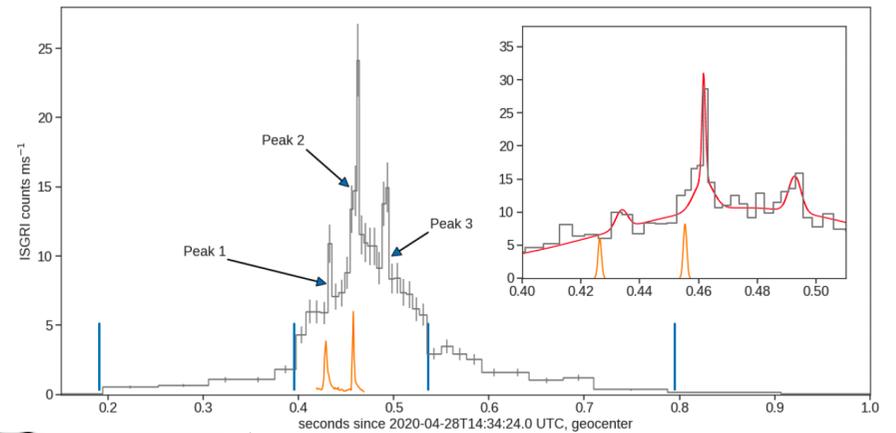**Baryon-rich fireball is preferred in energetics.**

Baryon loading in magnetar bursts
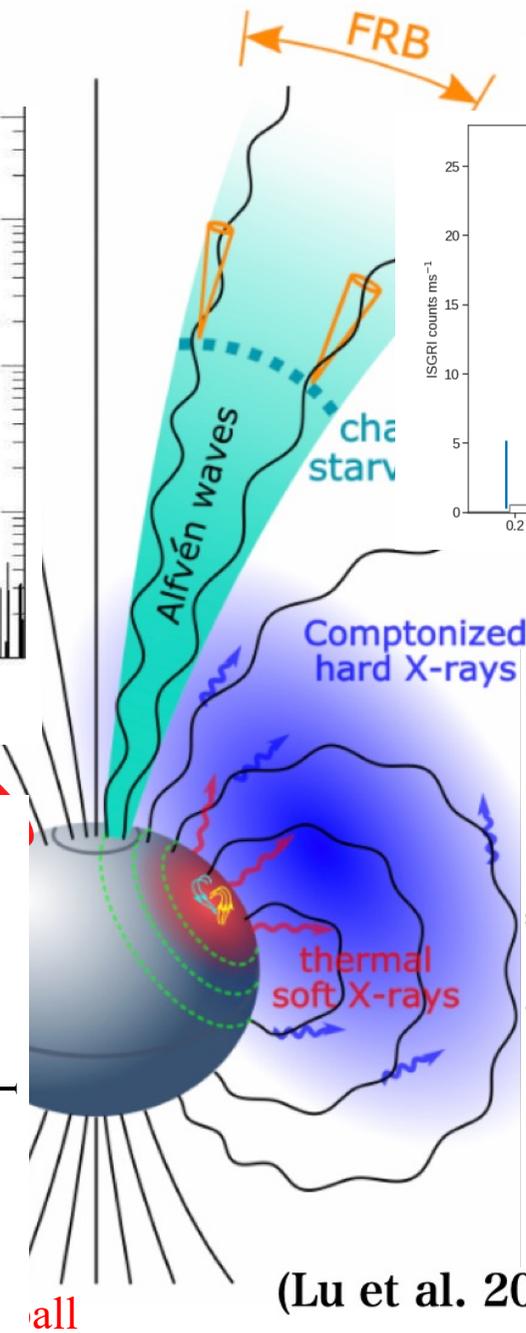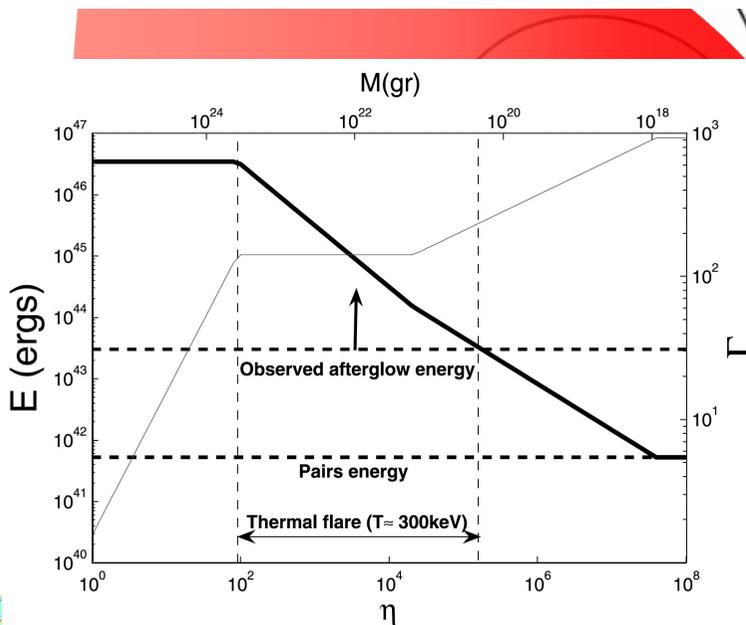
Giant Flares

Fast Radio Bursts?

(Lu et al. 2020)

Baryon loading in magnetar bursts
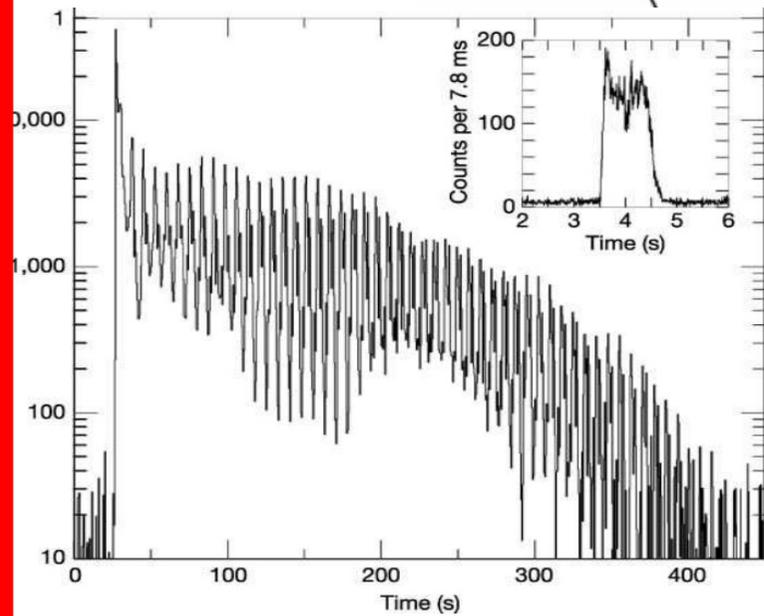
Giant Flares

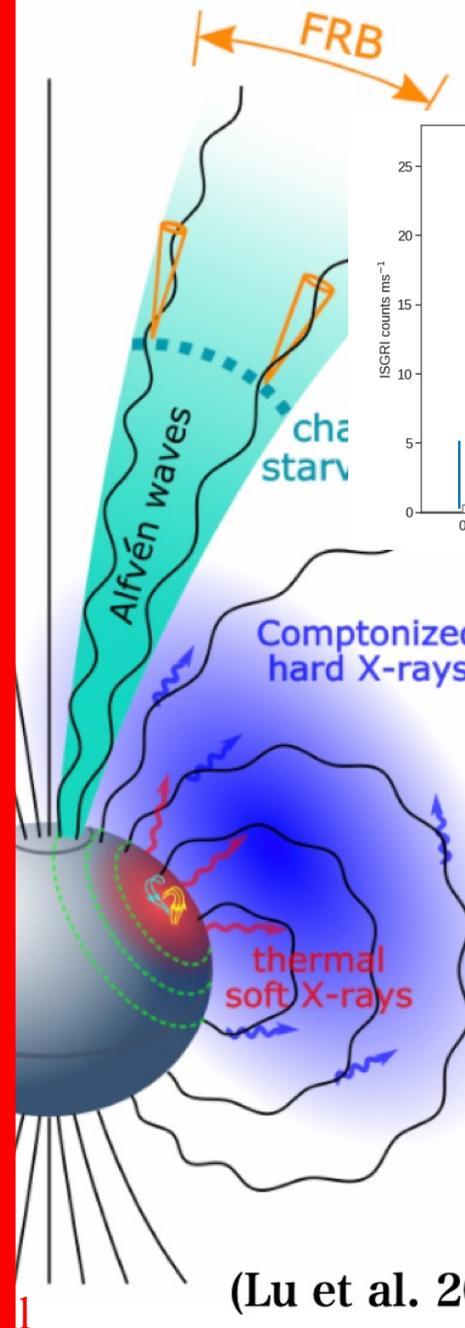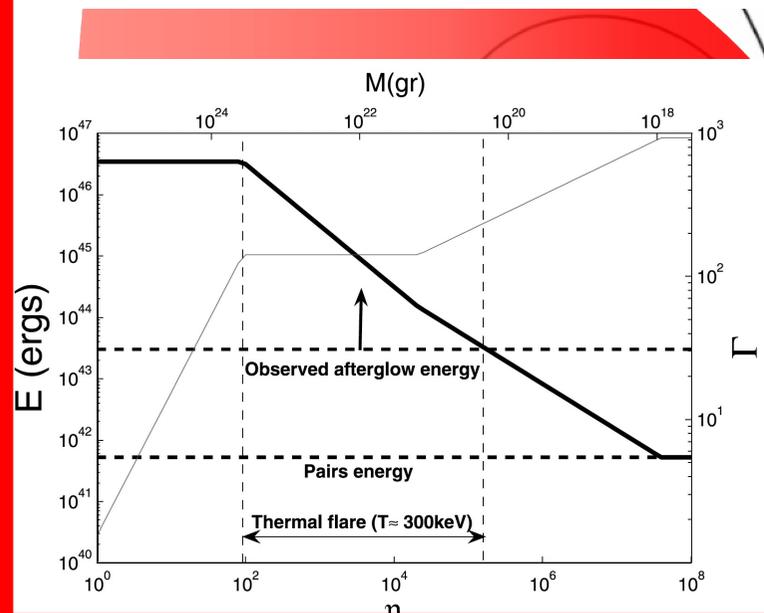

Fast Radio Bursts?

(Lu et al. 2020)
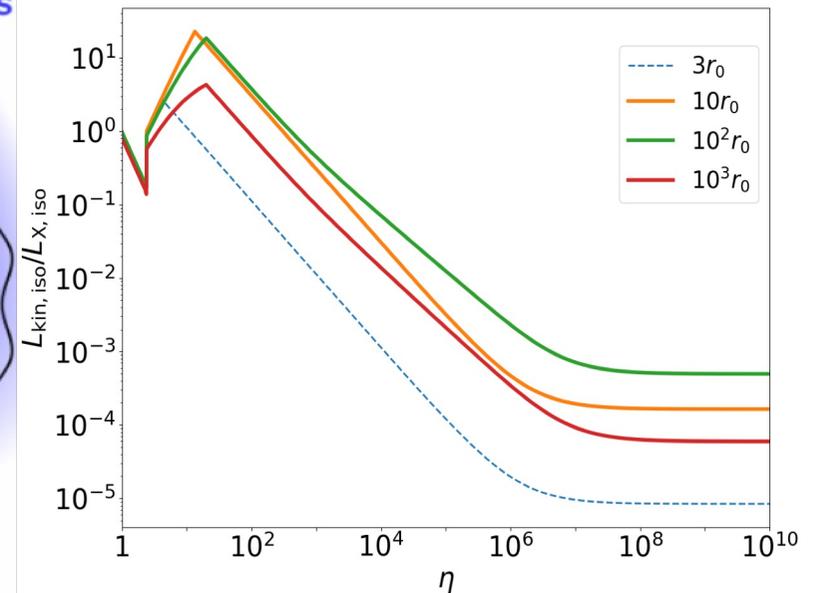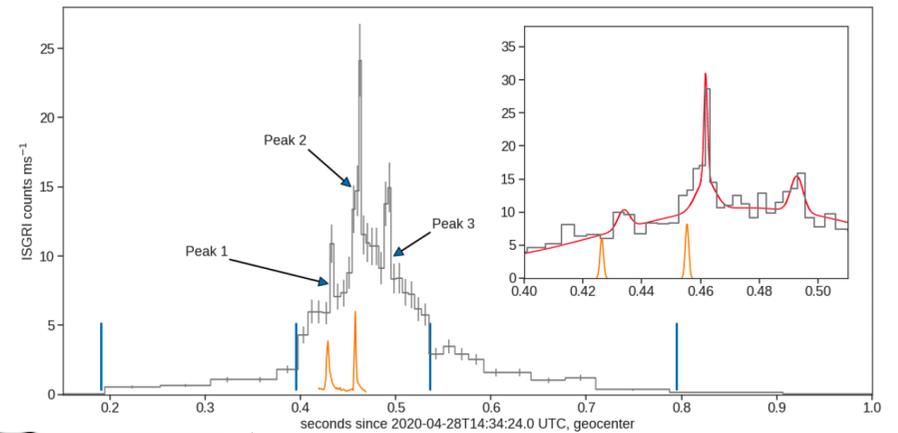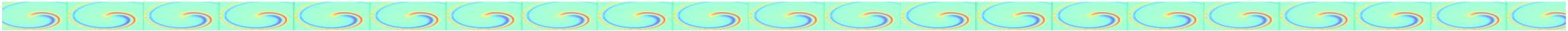
MeV line emission

**Measuring baryonic component
using MeV gamma-ray from giant flares**
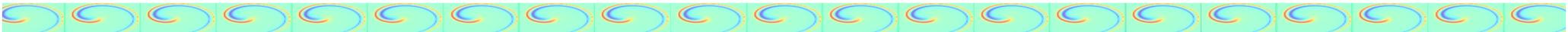
MeV line: Pair annihilation
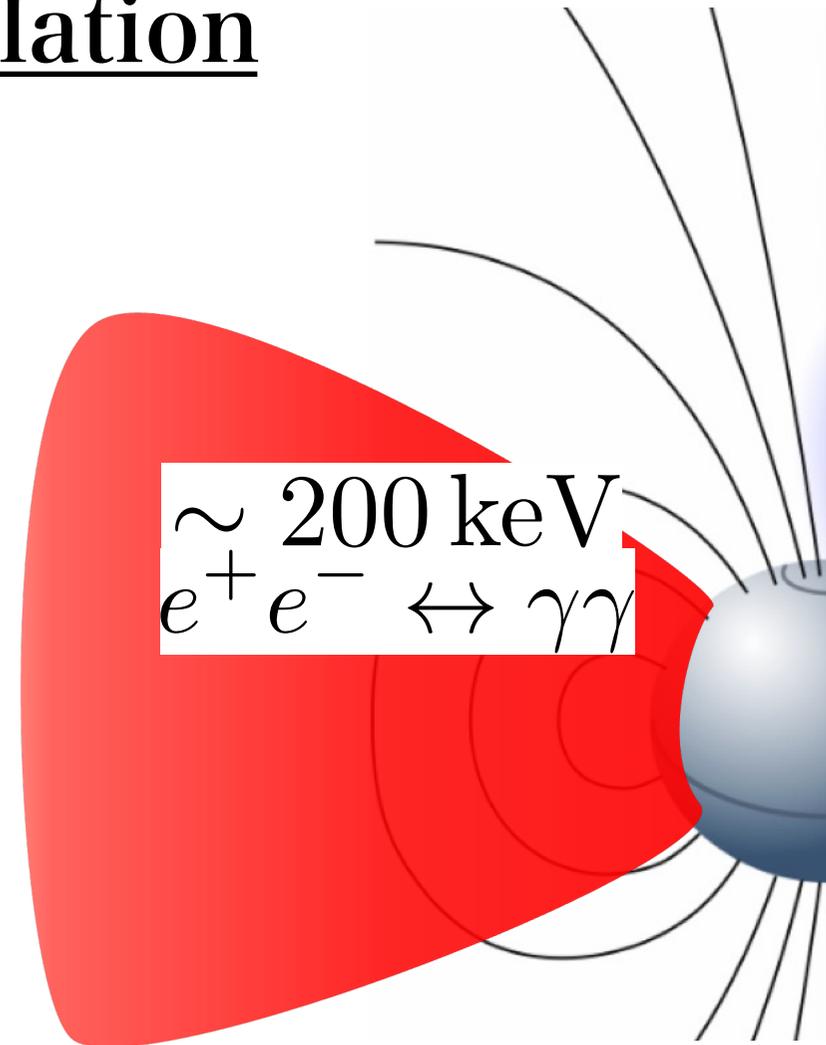
$$\sim 200\,\mathrm{keV}$$
$$e^+ e^- \leftrightarrow \gamma\gamma$$

c.f. for GRB case
Pe'er & Waxman 2004,
Pe'er+2006, Ioka+2007
Murase & Ioka 2007,
Salafia's talk

MeV line: Pair annihilation

$\Gamma \sim 10$

$\sim 20\,\mathrm{keV}$
$e^+ e^- \to \gamma\gamma$

$\sim 200\,\mathrm{keV}$
$e^+ e^- \leftrightarrow \gamma\gamma$

c.f. for GRB case
Pe'er & Waxman 2004,
Pe'er+2006, Ioka+2007
Murase & Ioka 2007,
Salafia's talk

MeV line: Pair annihilation

$\Gamma \sim 10$

$\sim 20\,\mathrm{keV}$
$e^+ e^- \to \gamma\gamma$

$\sim 200\,\mathrm{keV}$
$e^+ e^- \leftrightarrow \gamma\gamma$

MeV photon

$E_{\mathrm{obs}} = \Gamma \times m_e c^2$

$\sim 10\,\mathrm{MeV}$
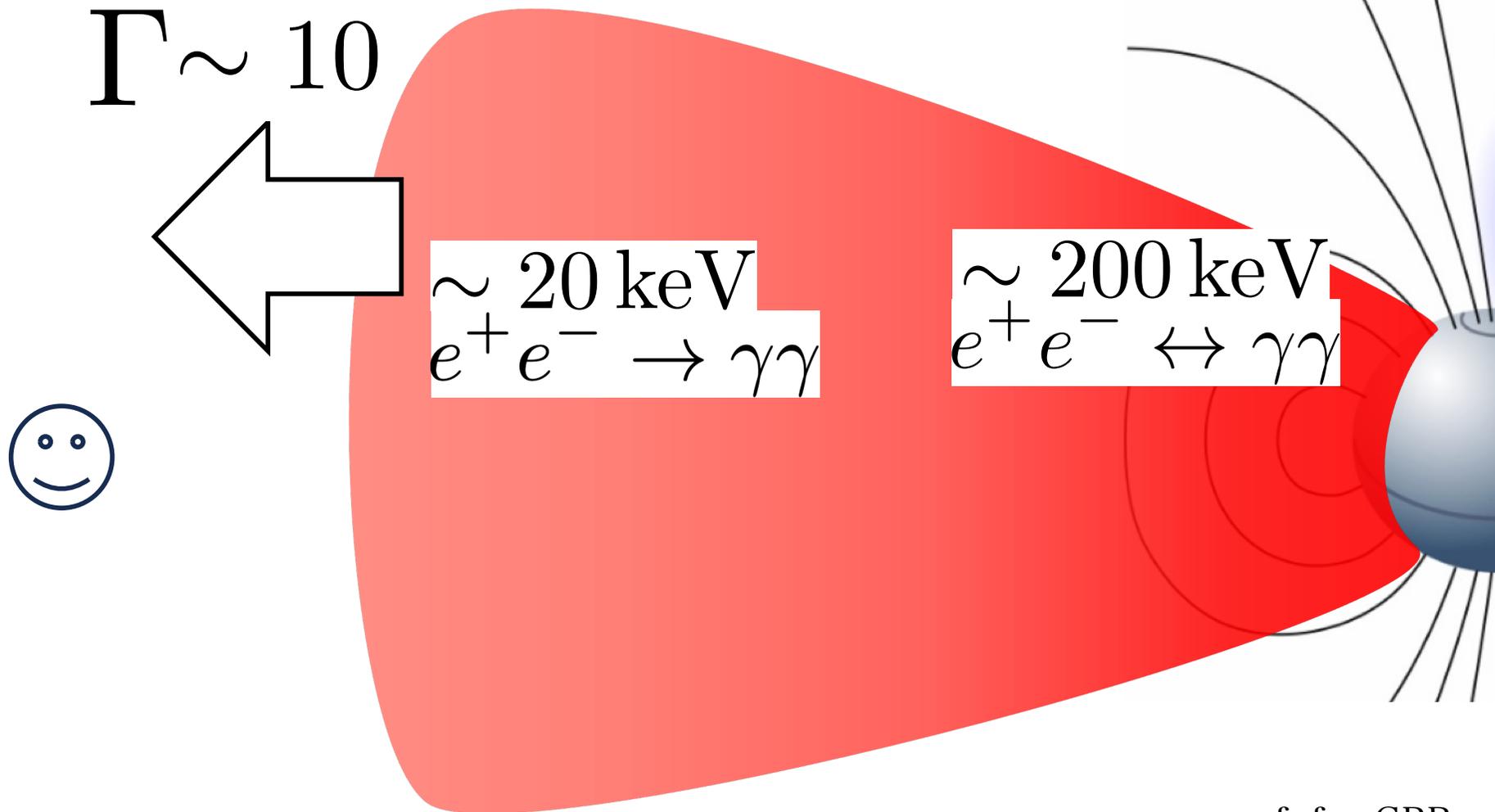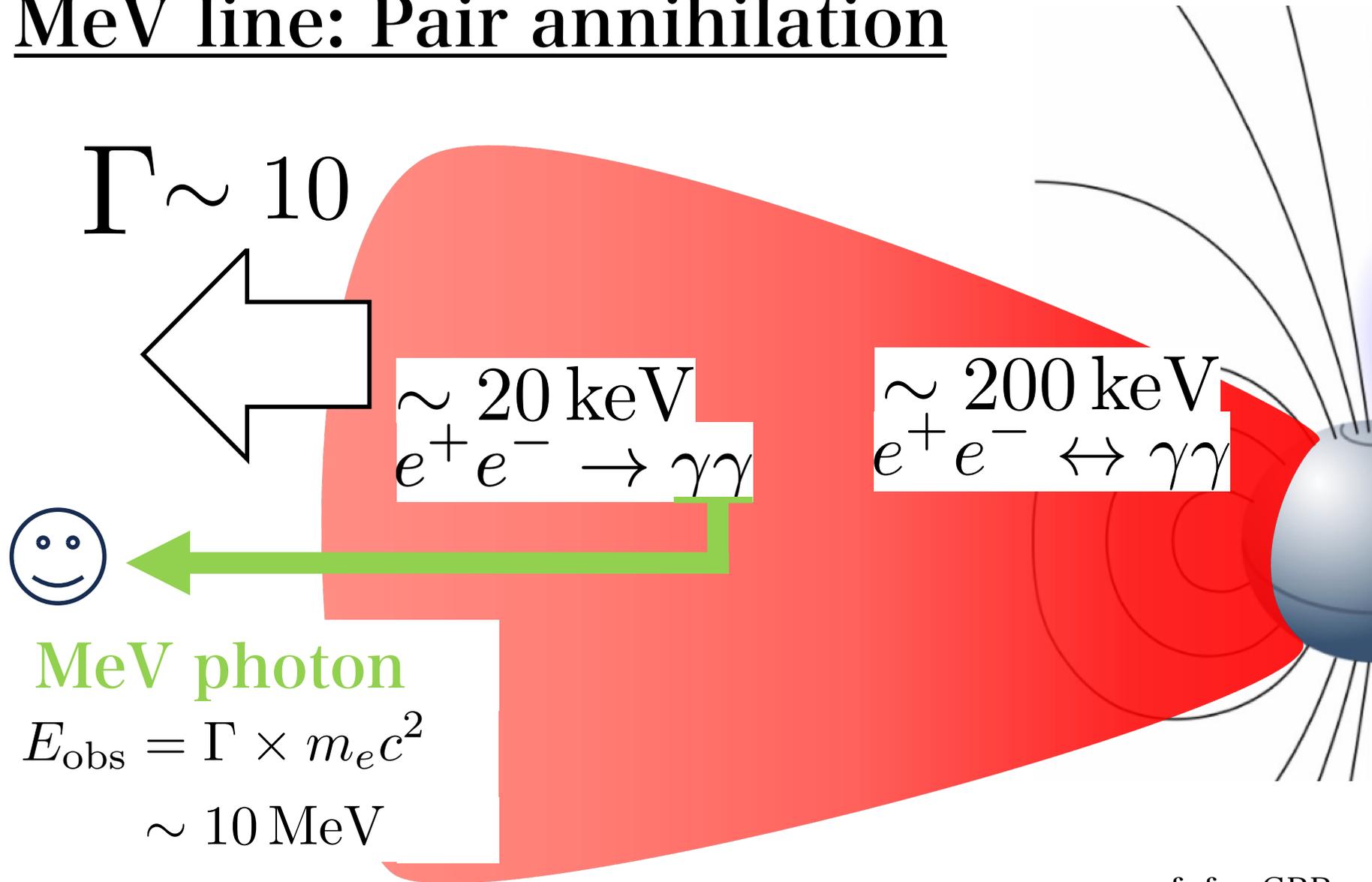
In Galactic magnetar giant flare, annihilation line is expected.

c.f. for GRB case
Pe'er & Waxman 2004,
Pe'er+2006, Ioka+2007
Murase & Ioka 2007,
Salafia's talk
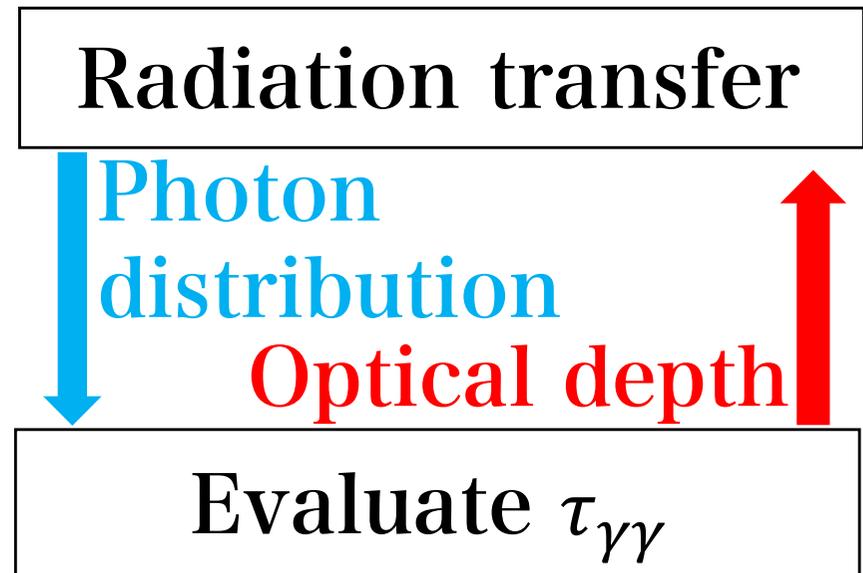
1D radiation transfer simulation

- Background plasma profile

$$\Gamma = \Gamma_0 \bar{r}, \quad T = T_0 \bar{r}^{-1}, \quad \rho = \rho_0 \bar{r}^{-3},$$

$$n_+ = -\frac{\rho}{2m_p} + \left[\frac{\rho^2}{4m_p^2} + 4\left(\frac{m_e T}{2\pi\hbar^2}\right)^3 e^{-2m_e c^2/T} \right]^{1/2}$$

- Radiation is solved by Monte Carlo method.

- Pair annihilation is incorporated iteratively.

Radiation transfer

↓ Photon distribution

Optical depth ↑

Evaluate $\tau_{\gamma\gamma}$

$$\frac{d\tau_{\gamma\gamma}}{dl} = \Gamma(1 - \beta\mu_L) \int d^3 p' f_\gamma(p') \sigma_{\gamma\gamma}(1 - \mu'_{\gamma\gamma})$$

Note: Timescales
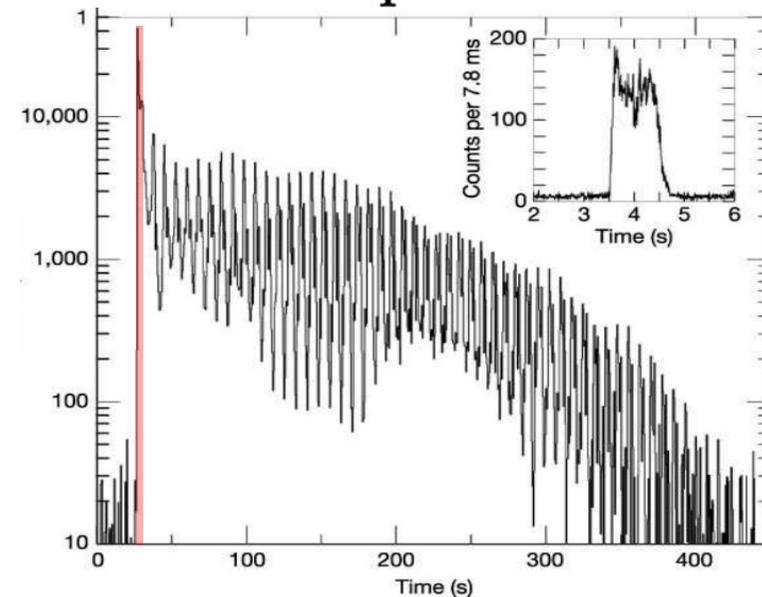

$r_{\text{em}} \sim 10^7 \text{m}$

$$\Delta t \sim \frac{r_{em}}{c\Gamma_{em}^2} \sim 10^{-6}\text{s}$$

Λ
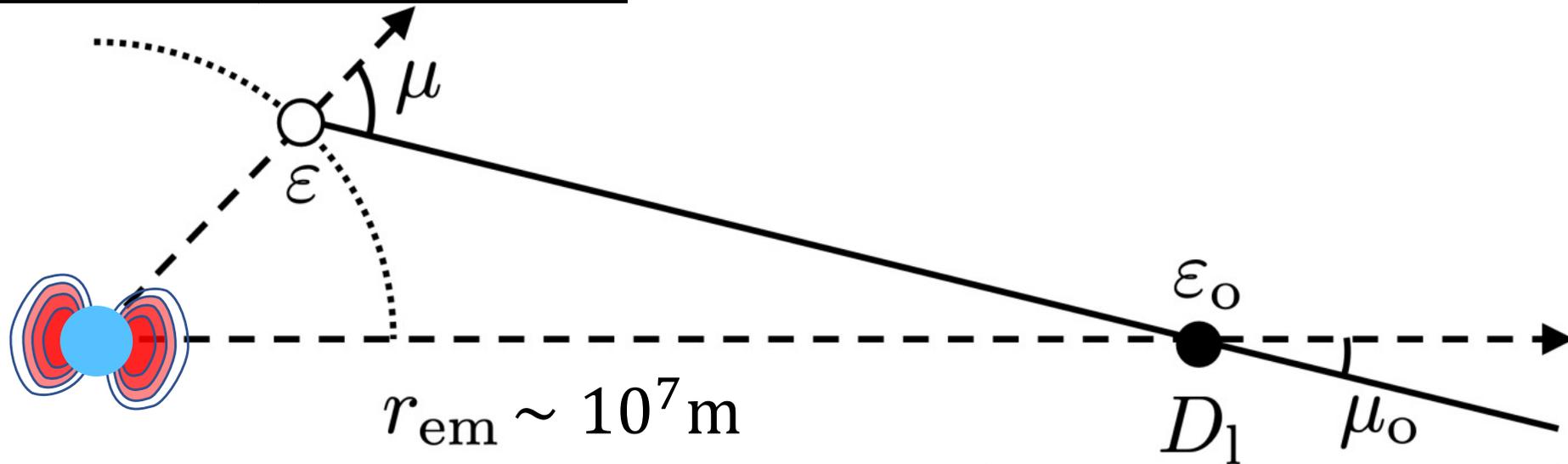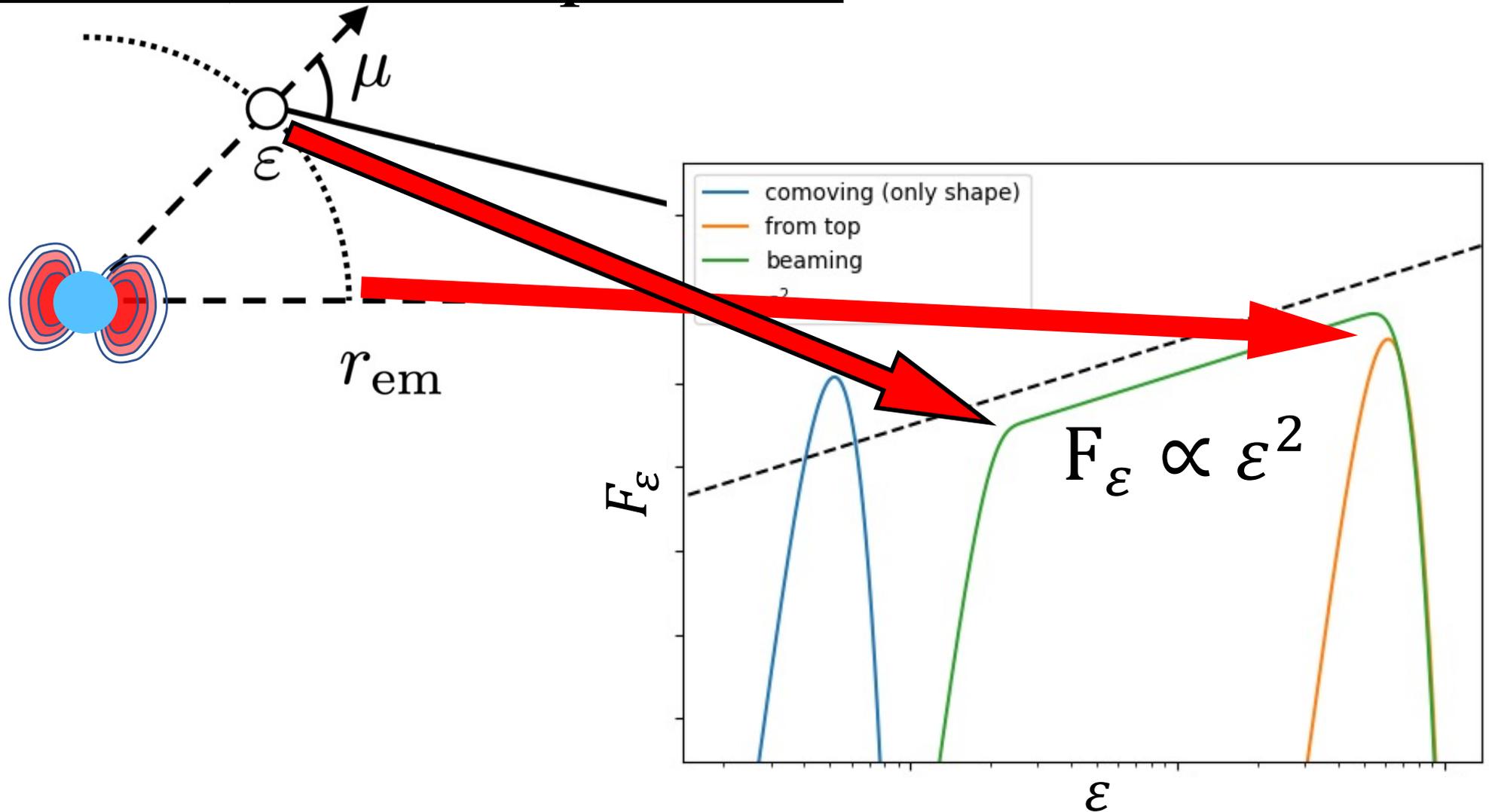
Initial spike ~ 1s

High-latitude emissions are observed simultaneously
➔ No evolution in giant flares.
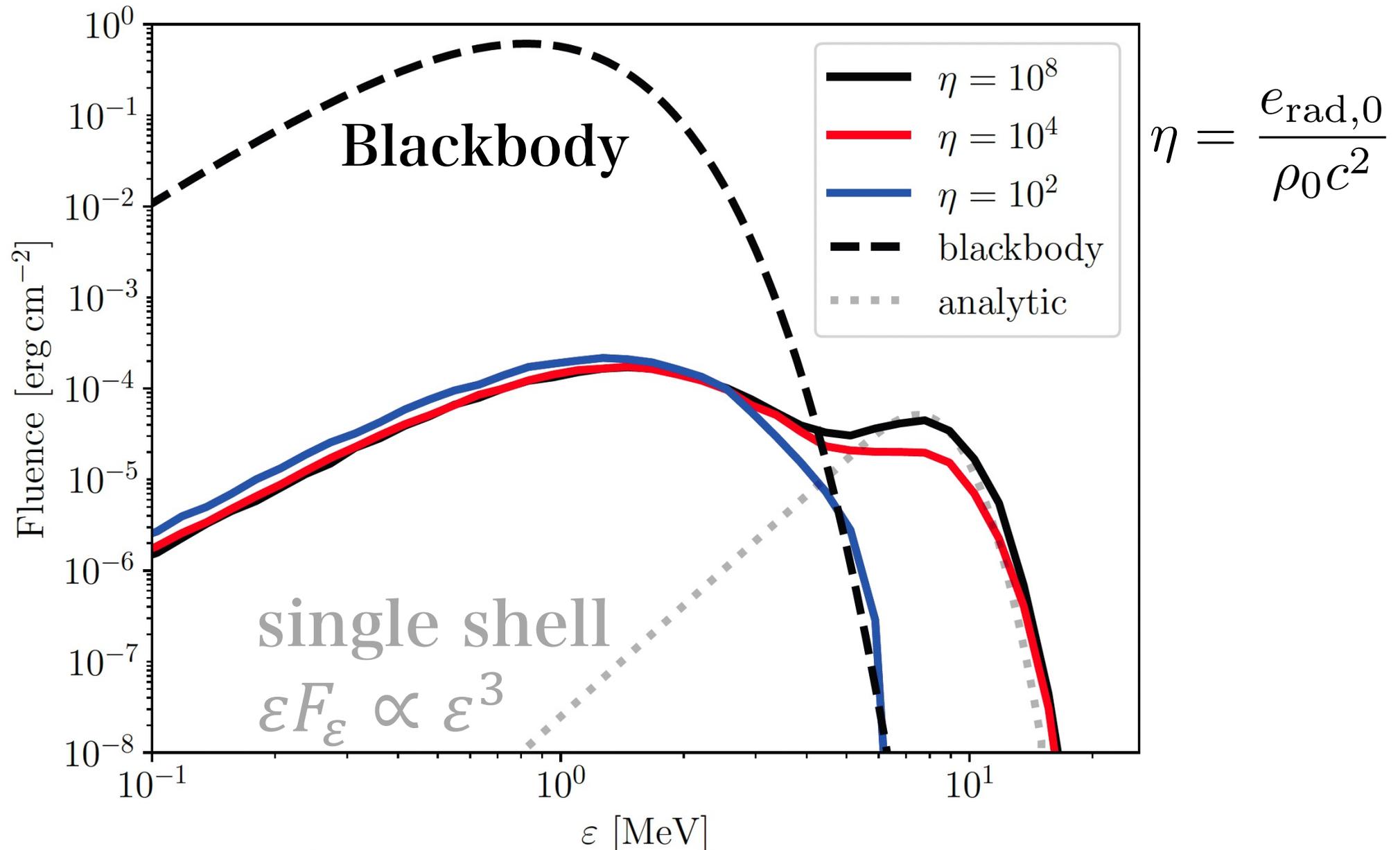
Timescales and spectrum

High-latitude emissions are observed simultaneously
➔ No evolution in giant flares.
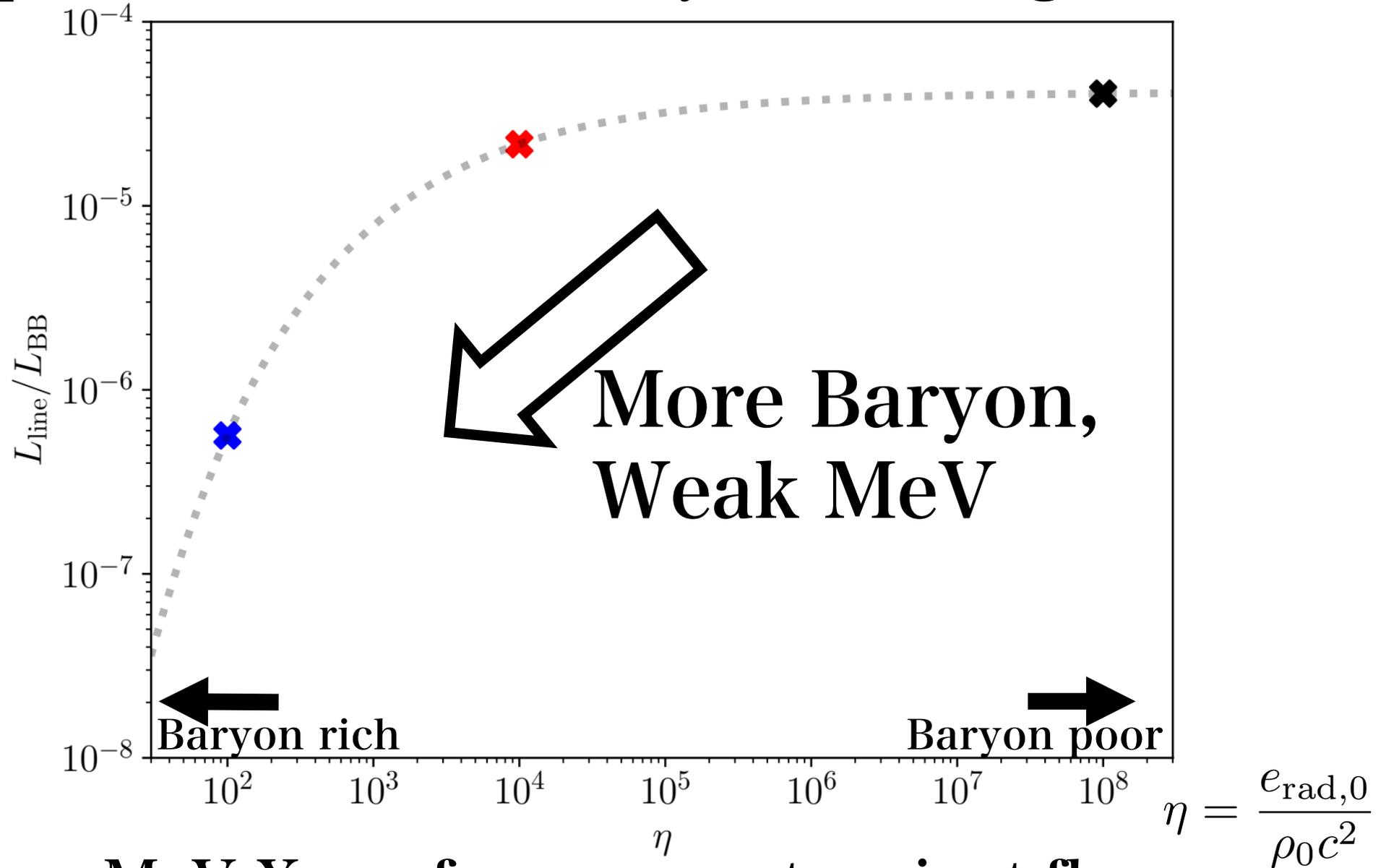➔ Power-low spectrum $F_\varepsilon \propto \varepsilon^2$

Result: MeV line spectrum

$$\eta = \frac{e_{\mathrm{rad},0}}{\rho_0 c^2}$$

Legend:
- $\eta = 10^8$ (black)
- $\eta = 10^4$ (red)
- $\eta = 10^2$ (blue)
- blackbody (dashed)
- analytic (dotted)

Blackbody

single shell $\varepsilon F_\varepsilon \propto \varepsilon^3$

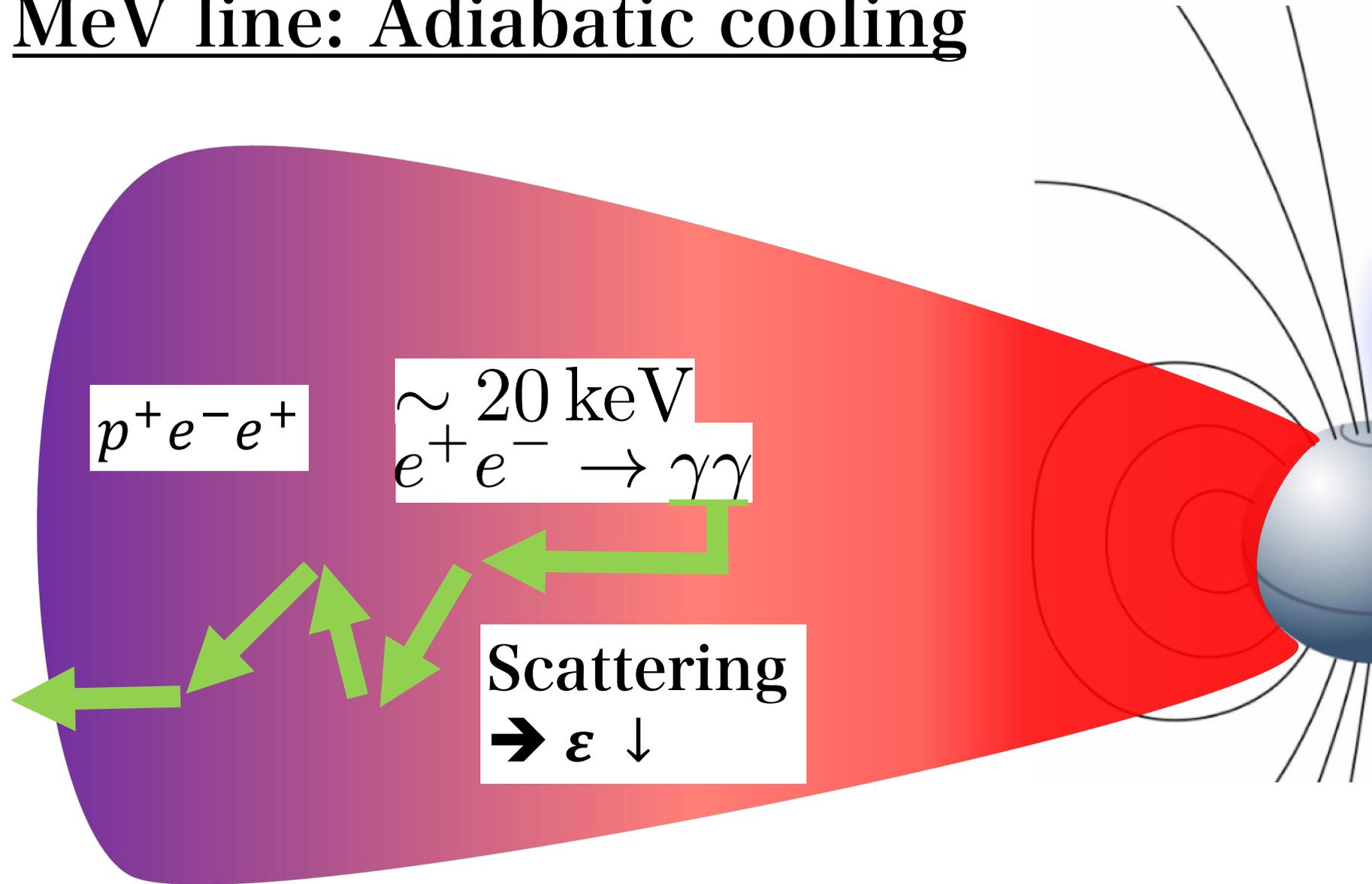Axes: Fluence [erg cm^{-2}] vs ε [MeV]

$O(100)$ of MeV photons
by e-ASTROGAM, GRAMS, AMEGO-X

Dependence on the baryon loading

More Baryon,
Weak MeV

Baryon rich

Baryon poor
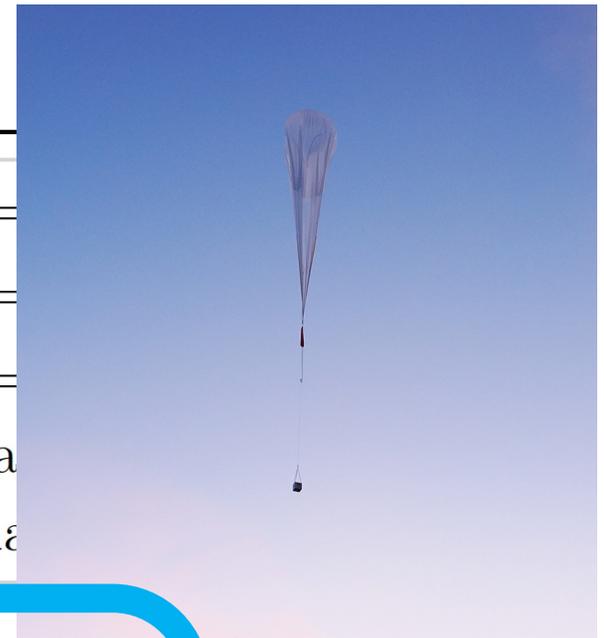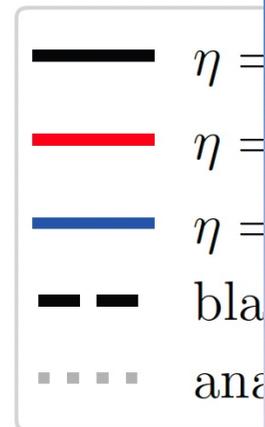
$$\eta = \frac{e_{\mathrm{rad},0}}{\rho_0 c^2}$$

MeV X-ray from magnetar giant flares
→ Measurement on baryons

MeV line: Adiabatic cooling

$p^+ e^- e^+$

$\sim 20\,\mathrm{keV}$
$e^+ e^- \to \gamma\gamma$

Scattering
➔ $\varepsilon \downarrow$
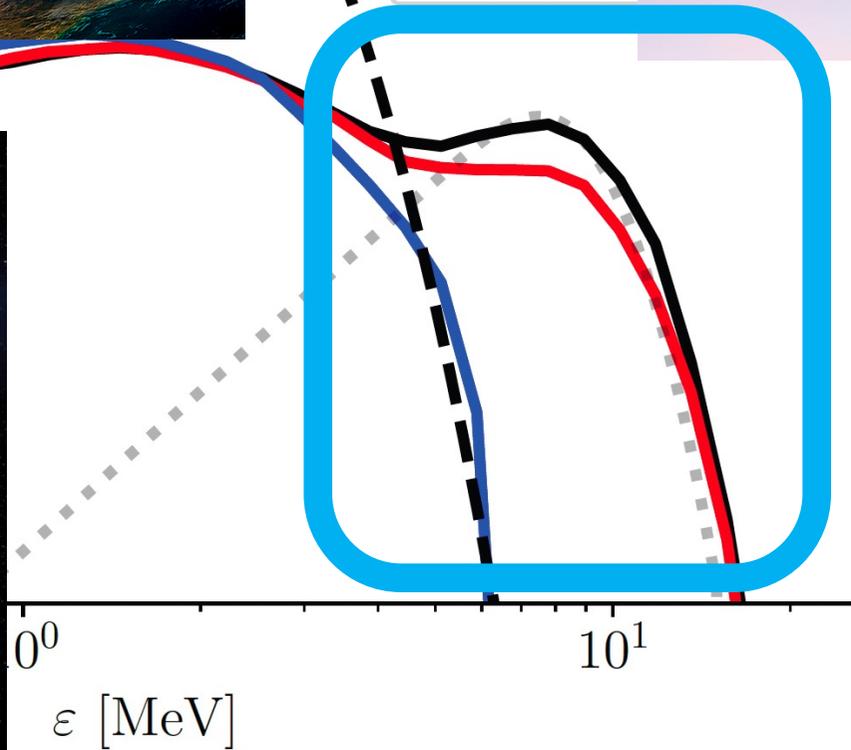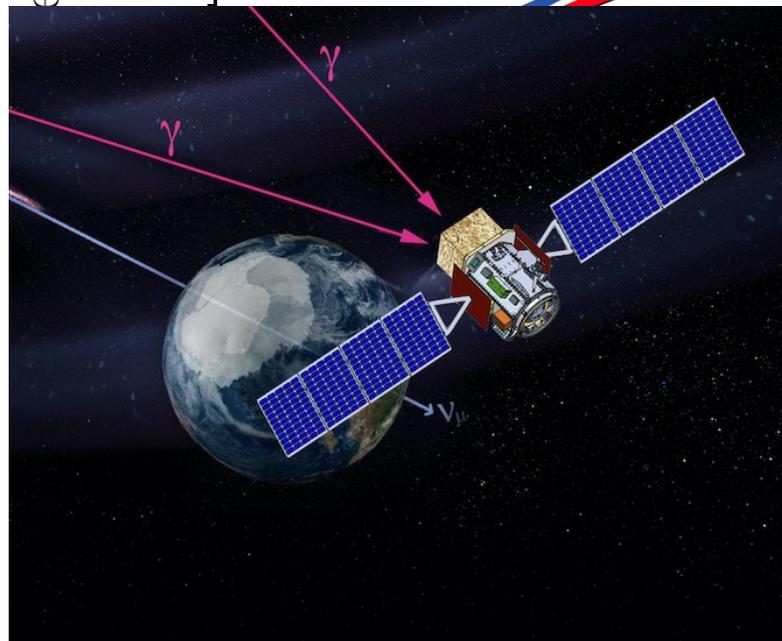
Due to the adiabatic cooling,
MeV photons are cooled in baryon-rich fireball.
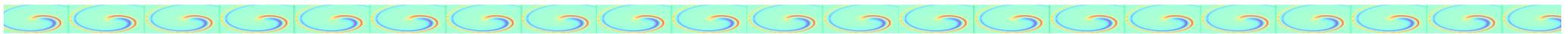
Future observations
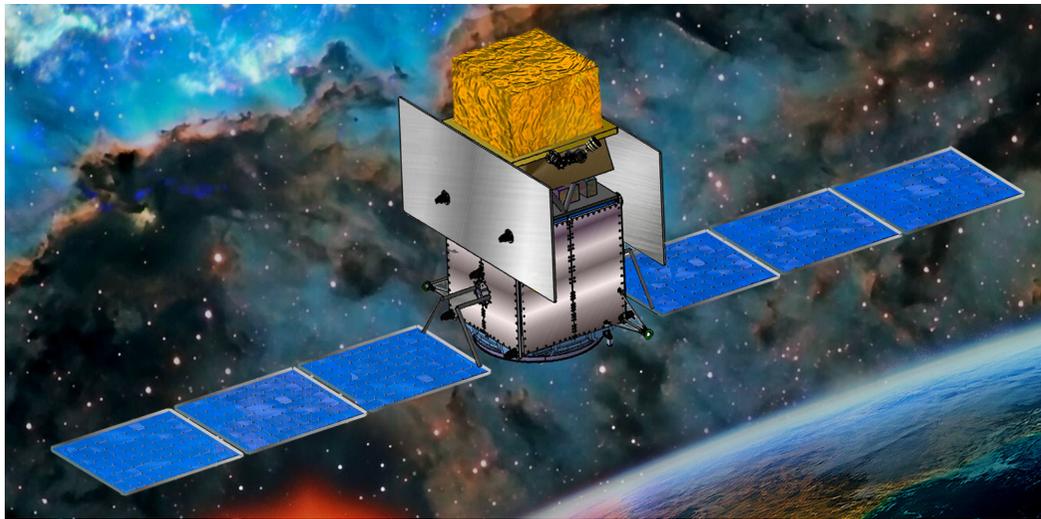
e-ASTROGAM, GRAMS, AMEGO-X, fermi/LAT

Summary

- MeV line from giant flare is observable in future observations (e-ASTROGAM, GRAMS, AMEGO-X).

- O(100) photons are expected at ~10 MeV.

- MeV line is an independent method to measure the baryons loading.
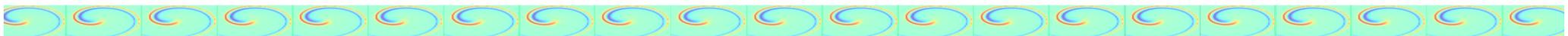
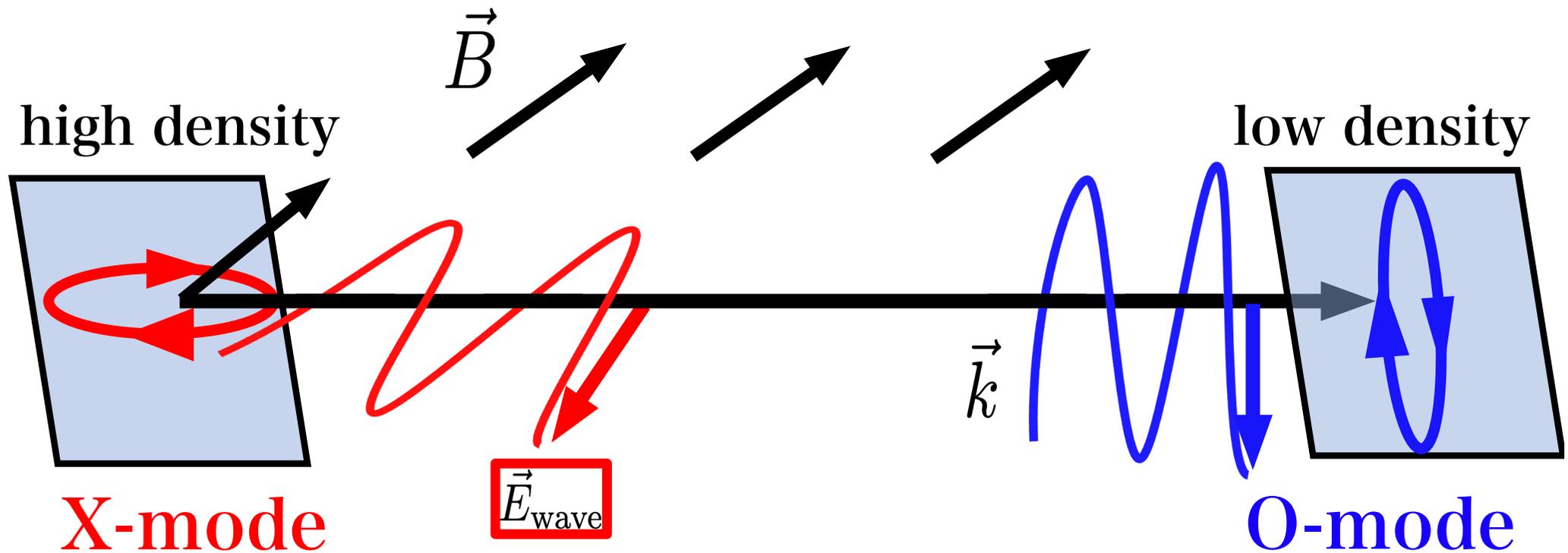Thanks for taking the time

On a related note···

Polarization

Wada 2025

Measuring baryonic component using X-ray polarization

p^+e^- plasma + Vacuum polarization

Normal modes: Left/Right
Ellipticity depends on plasma density

high density

$\vec{B}$

low density

X-mode

$\vec{E}_{\text{wave}}$
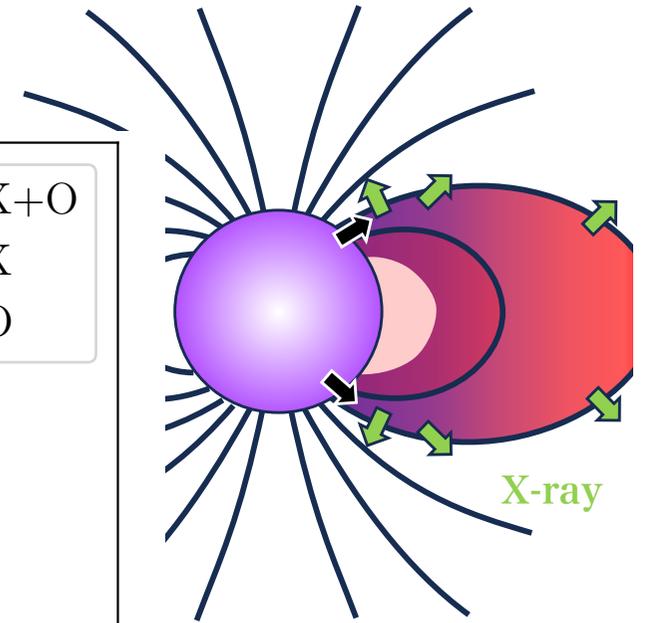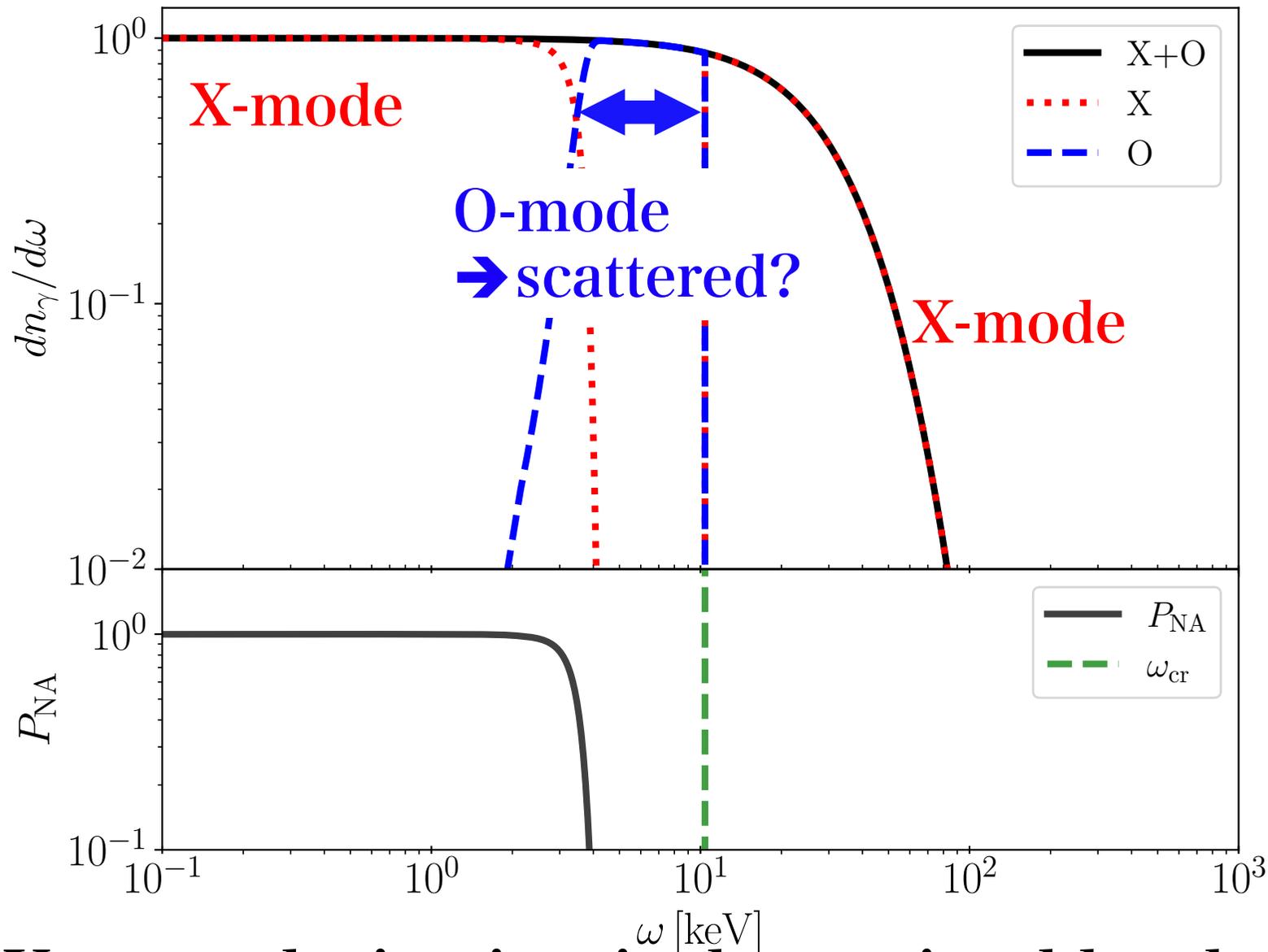
$\vec{k}$

O-mode

e.g., Gnedin+1978,
Pavlov&Shibanov1979,
Soffel+1983,
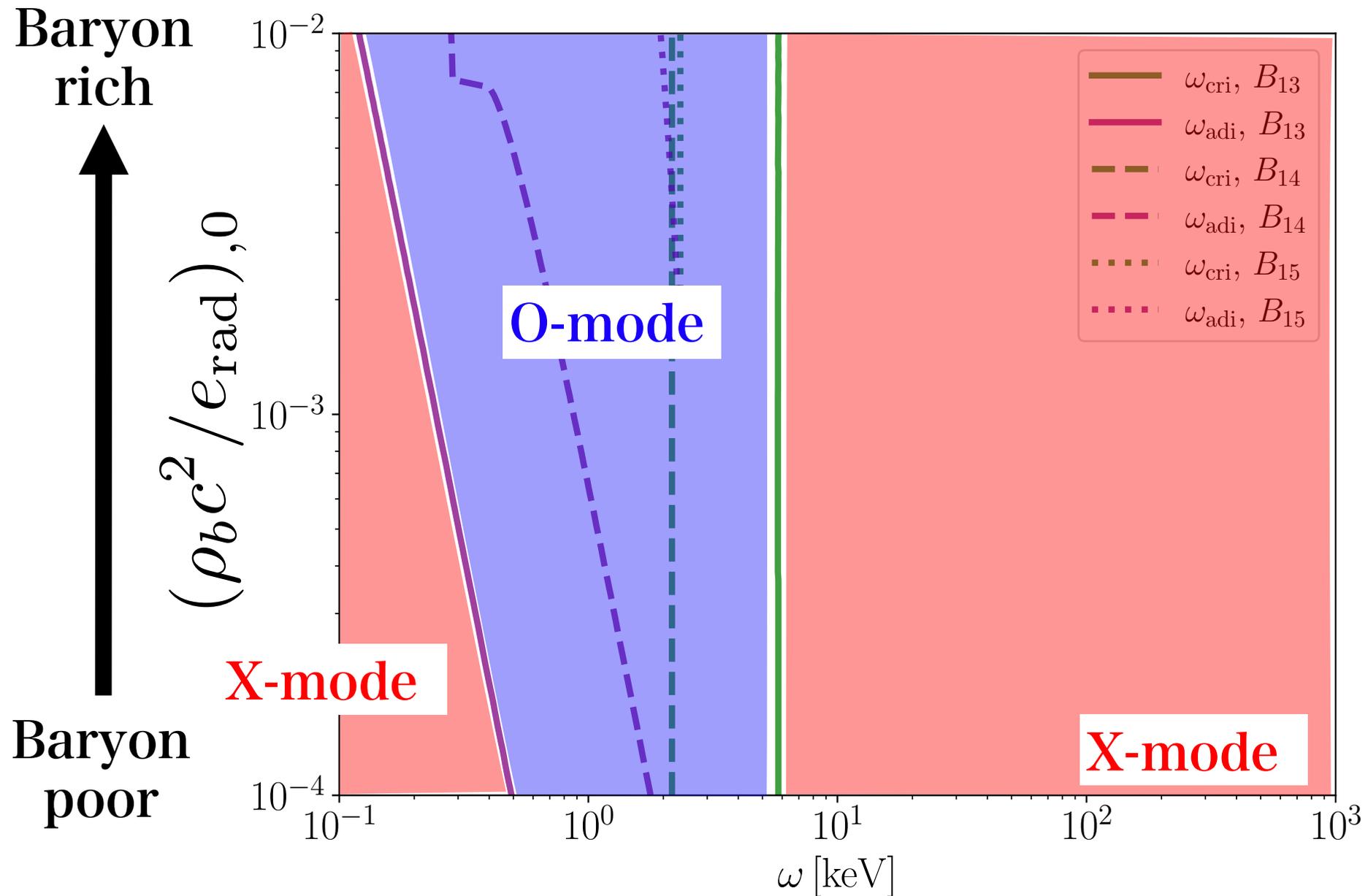Lai&Ho2002

Ellipticity $\quad K_\pm = \beta \pm \sqrt{\beta^2 + R}$

$$\beta = \frac{u^{1/2}(1 - u_b)\sin^2\theta_{kB}}{2\cos\theta_{kB}}\left[1 - \frac{(M+Q)(1 - u^{-1})}{v}\right] \quad v = \frac{\omega_p^2}{\omega^2} \quad \omega_p^2 = \frac{4\pi e^2 n_e}{m_e}$$
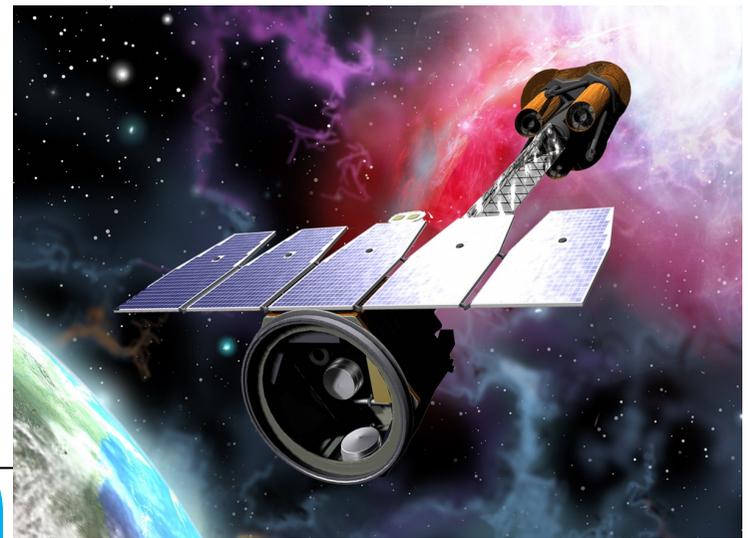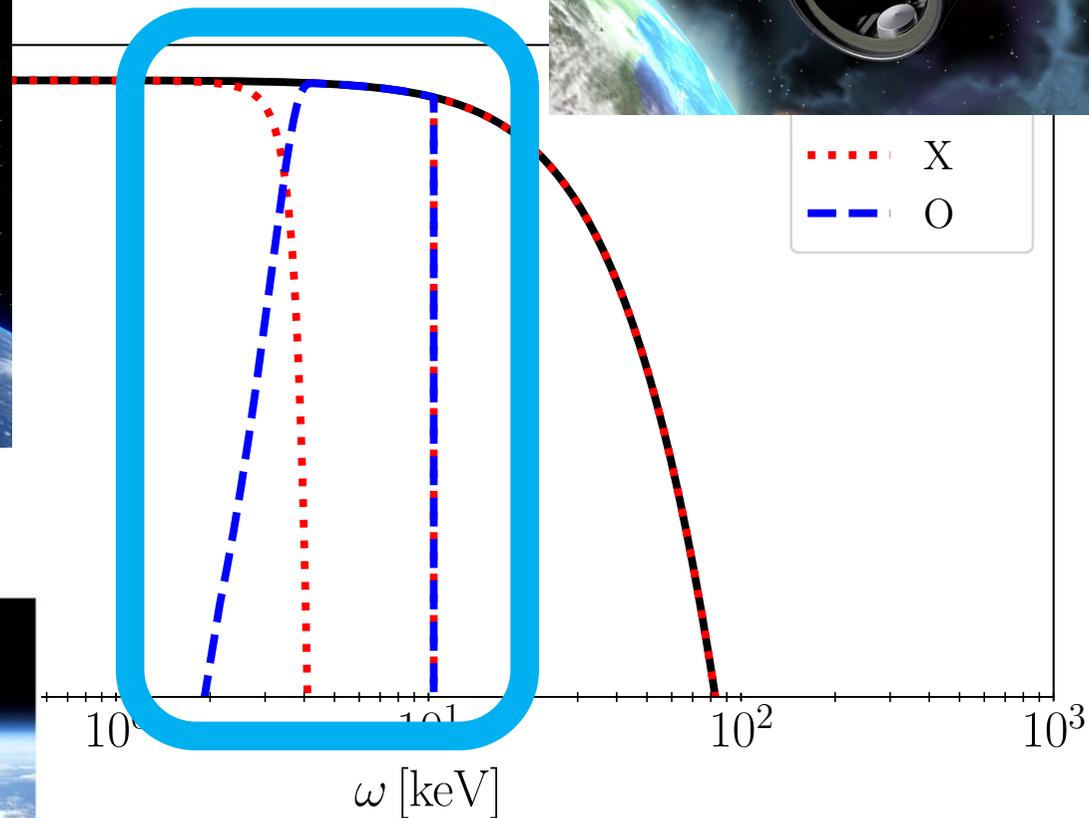
Polarization of trapped fireball

X-ray polarization is determined by the baryon
➔ Baryon measurement

Polarization-baryon map

Baryon
rich

Baryon
poor

$(\rho_b c^2 / e_{\rm rad})_{,0}$

ω [keV]

O-mode

X-mode

X-mode

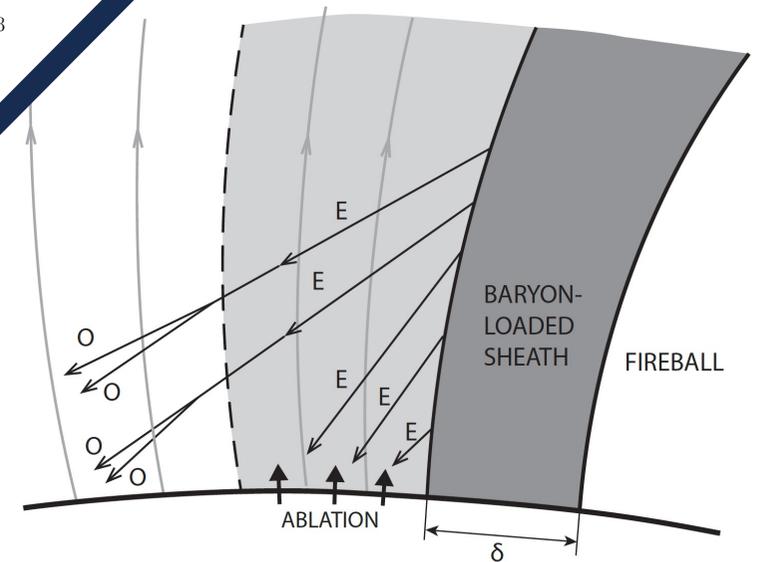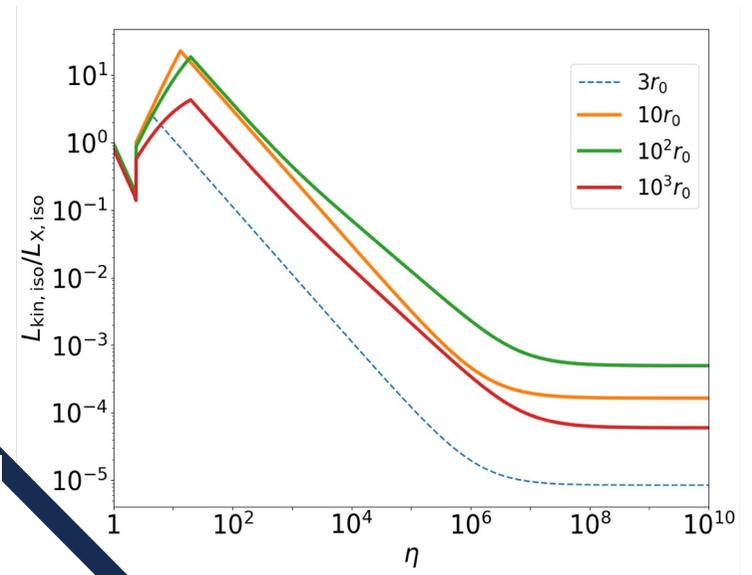|	
——	$\omega_{\rm cri}$, B_{13}
——	$\omega_{\rm adi}$, B_{13}
- - -	$\omega_{\rm cri}$, B_{14}
- - -	$\omega_{\rm adi}$, B_{14}
⋯⋯	$\omega_{\rm cri}$, B_{15}
⋯⋯	$\omega_{\rm adi}$, B_{15}

X-ray polarization -> Baryon loading on fireball
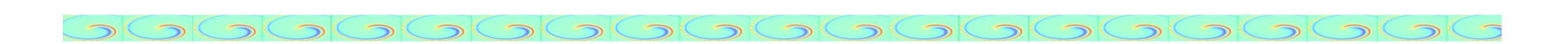
Future observation

ω [keV]

Legend:
- ⋯⋯ X
- — — O

POLAR, POLAR-2,
IXPE, eXTP

Future observation
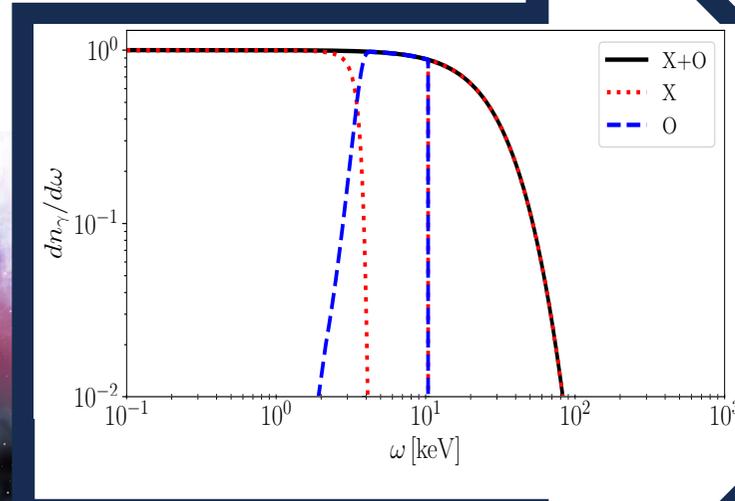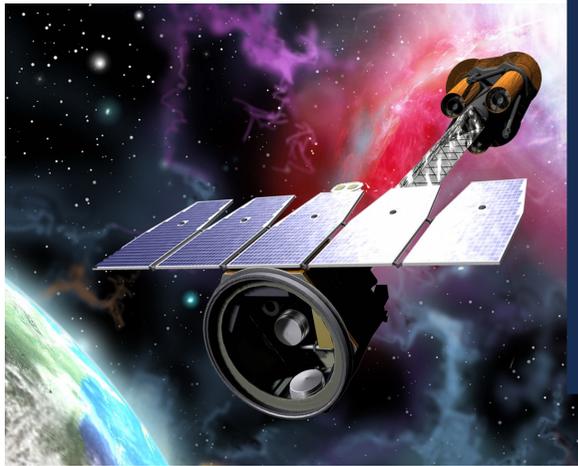
Summary

- New insight on magnetar bursts will be introduced by MeV emission (e-ASTROGAM, GRAMS, AMEGO-X) and X-ray polarization (IXPE, POLAR, POLAR-2, eXTP).

- Polarization of short bursts
  -> Fireball model/ FRB emission

- MeV component of giant flares
  -> Consistency with radio afterglow