FRB Conference at YITP, Kyoto
Feb 15, 2021

Multi-Wavelength Constraints on the Outflow Properties of Extremely Bright Millisecond Radio Bursts from Galactic Magnetar SGR 1935+2154

SY, K. Kashiyama, K. Murase 2021 (under review, arXiv: 2008.03634)

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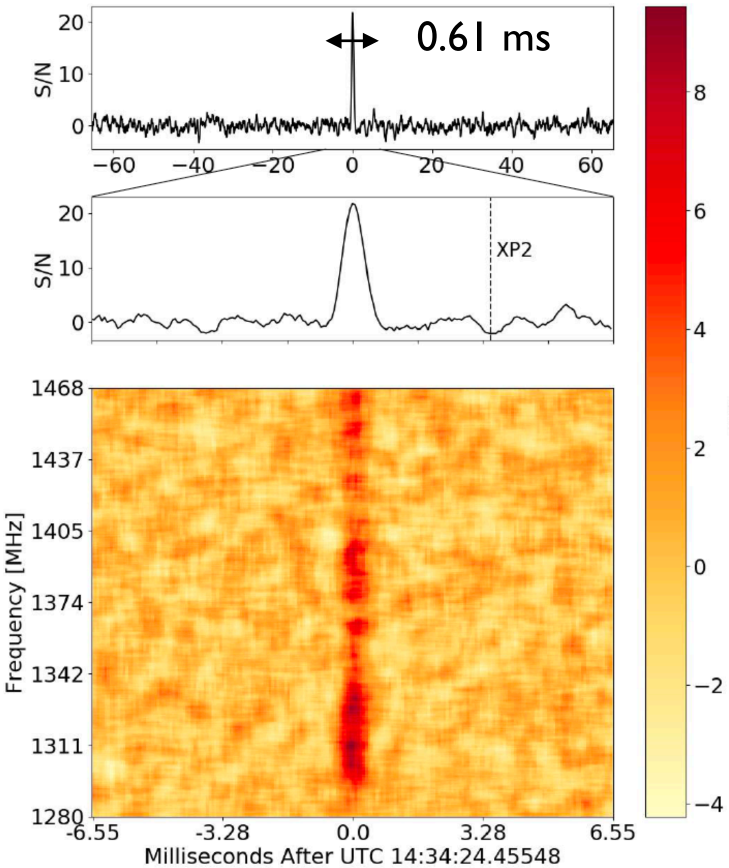
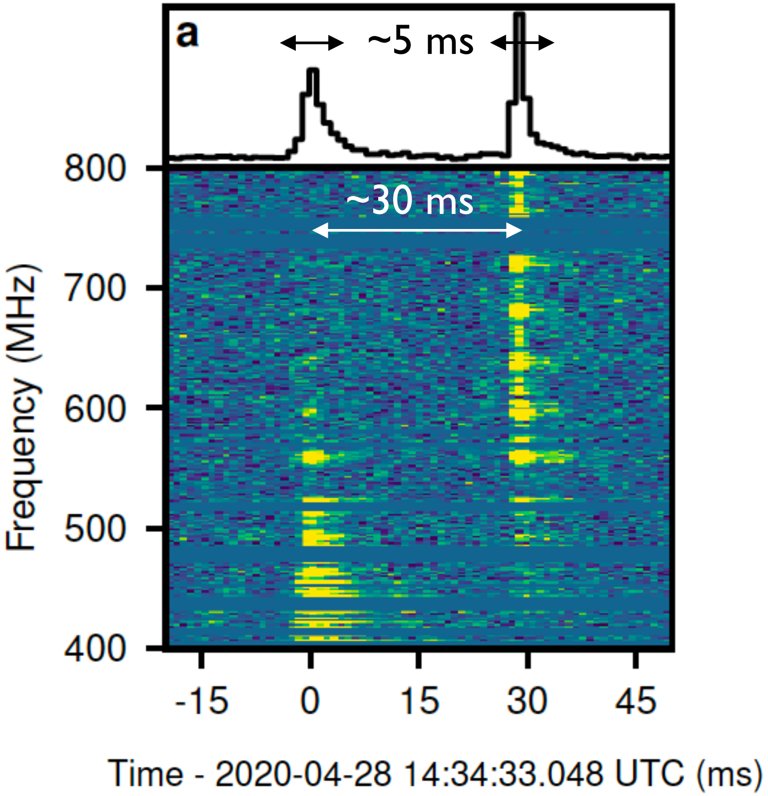
Observational Summary of April 28 Event

Coherent Radio Bursts

STARE2 @1.4 GHz (Bochanek+20)



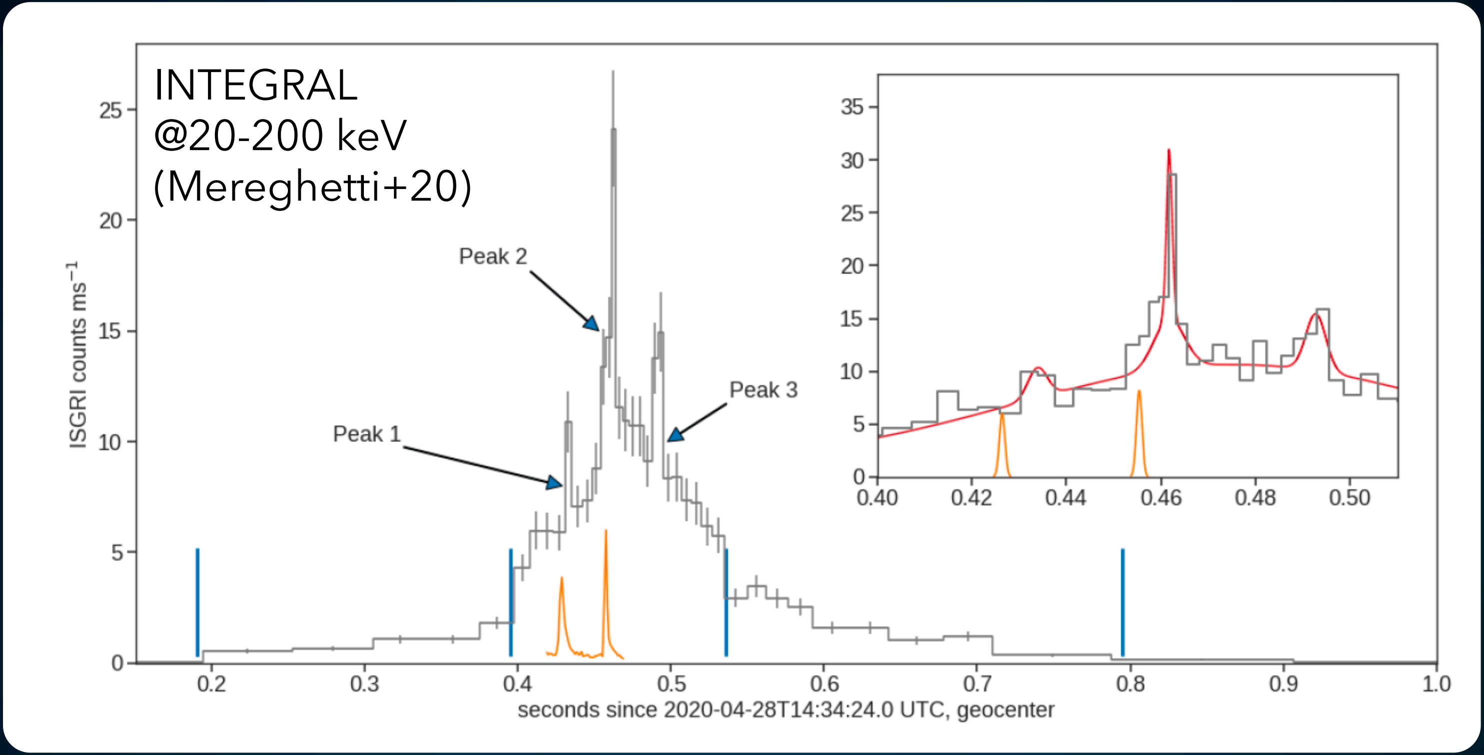
CHIME @600 MHz (CHIME/FRB+20)



$E_{\text{radio, iso}} \sim 10^{35}$ erg @10 kpc

(in btw. Crab giant radio pulses and cosmological FRBs)

Hard X-ray Burst: Temporal Properties



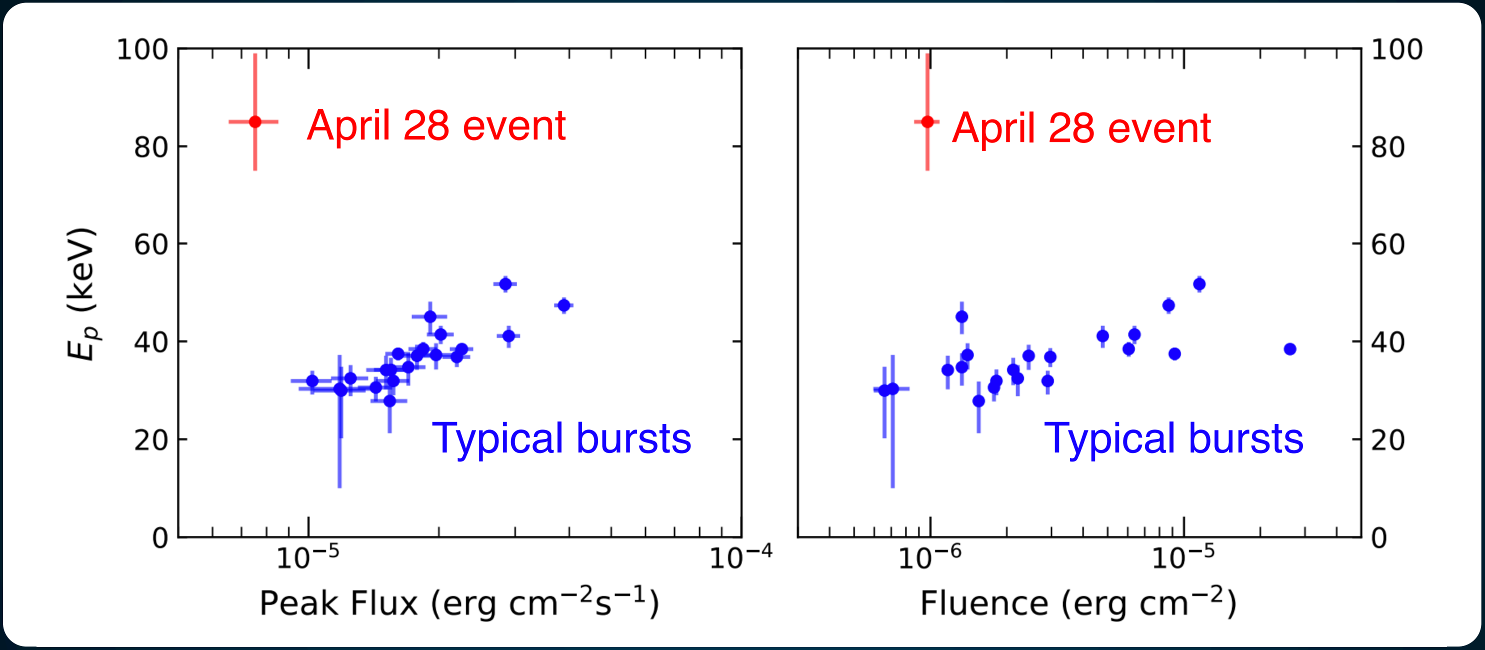
- **There are four co-detections of the hard X-ray burst associated with the coherent radio burst**

  (Li+20; Ridnaia+20; Mereghetti+20; Tavani+20)

- **Hard X-ray spikes (~10 ms) within entire duration of 0.3–0.5 s**

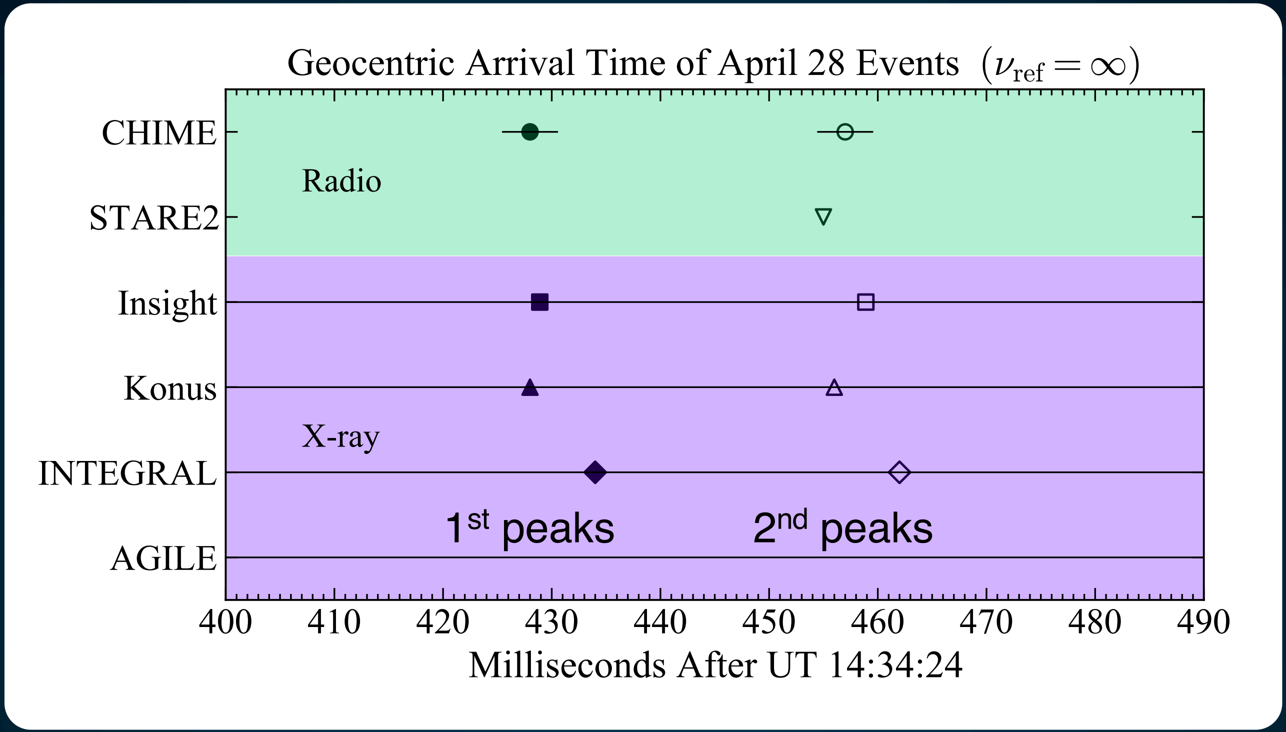
Hard X-ray burst: Spectral Properties

From Konus-Wind paper (Ridnaia+20)



- **E_{peak}~50–100 keV is the hardest among typical magnetar bursts with $E_{X,\,iso}$~10^{40} erg** (Younes+20; Ridnaia+20; Li+20; Mereghetti+20)
- **Typical magnetar bursts from SGR 1935+2154 do NOT always accompany coherent radio bursts** (Lin+20)

Arrival Time Difference



- **Arrival time difference btw. radio and X-ray bursts $\Delta t_{x,radio}$ <~10 ms**
- **Assuming a single outflow, the intrinsic emission regions cannot be separated by more than ~ $\Gamma^2 c \Delta t_{x,radio}$**

Interpreting X-ray observations

A Classic Model for Magnetar Flares

(see Kaspi & Beloborodov 17; Enoto+20 **for recent reviews)**

- **Flare fluence distributes continuously over 8 orders of magnitude** (e.g. Cheng+96; Gogus+01; Nakagawa+07)
- **X- and gamma-ray emission from recurrent bursts (short bursts & pulsating tails of giant flares) → evaporating "trapped" fireball**

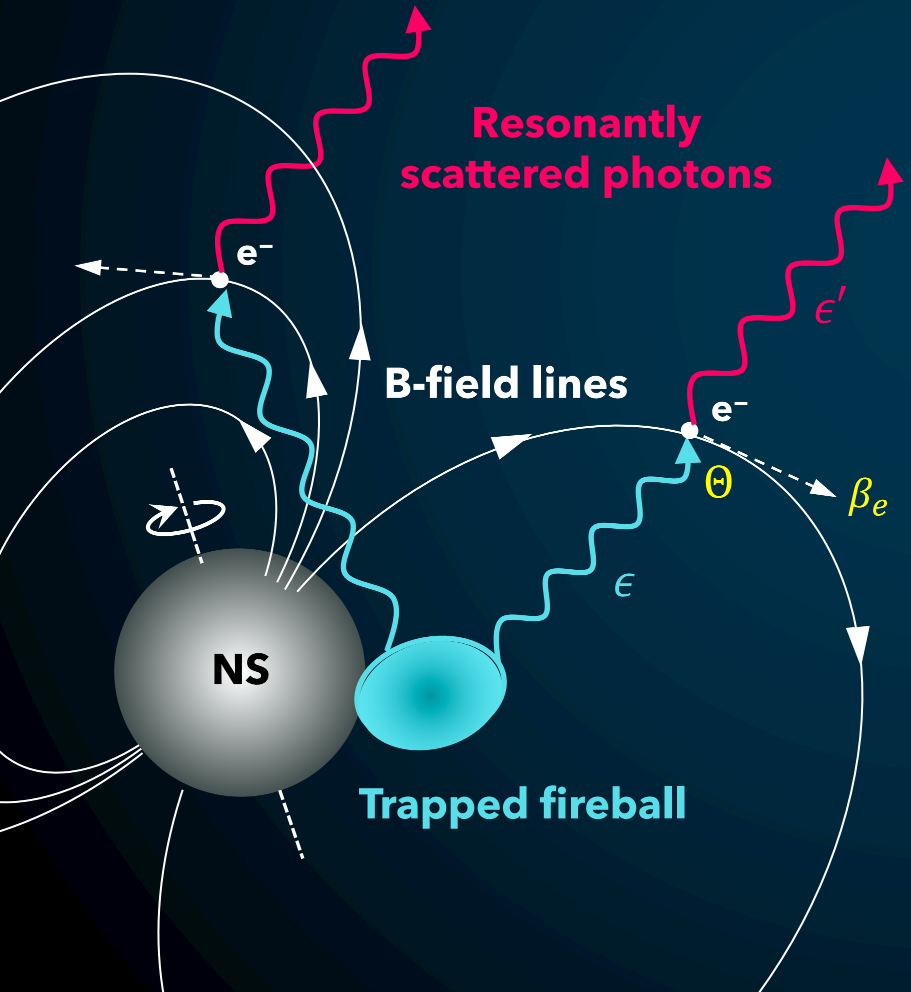
Trapped fireball =

A optically-thick photon-pair plasma ($e^{\pm}$) confined by strong magnetic pressure

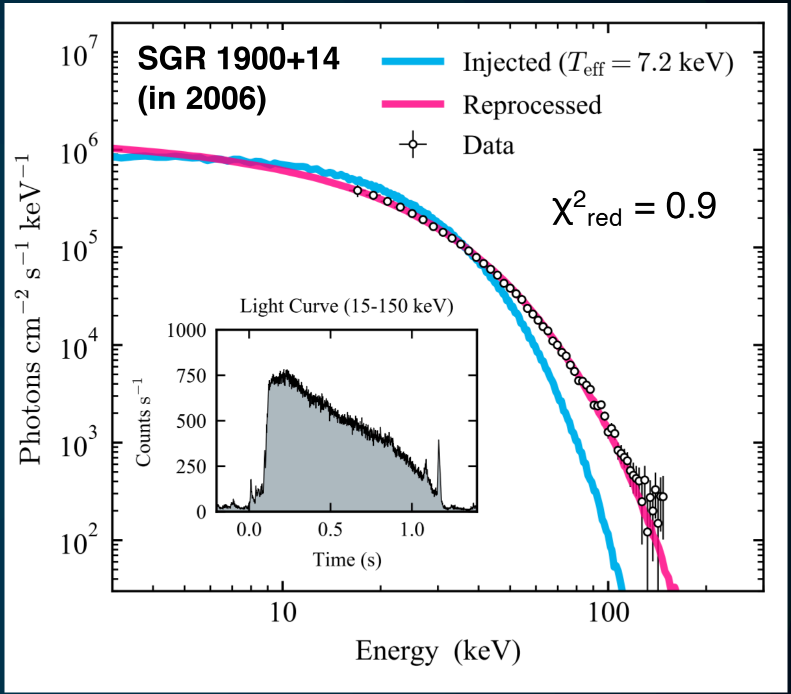
(Thompson & Duncan 95)

Spectral Modification of Trapped FB Emission

- **“Trapped fireball” emission should be reprocessed by magnetospheric e$^\pm$** (Lyubarsky 02)

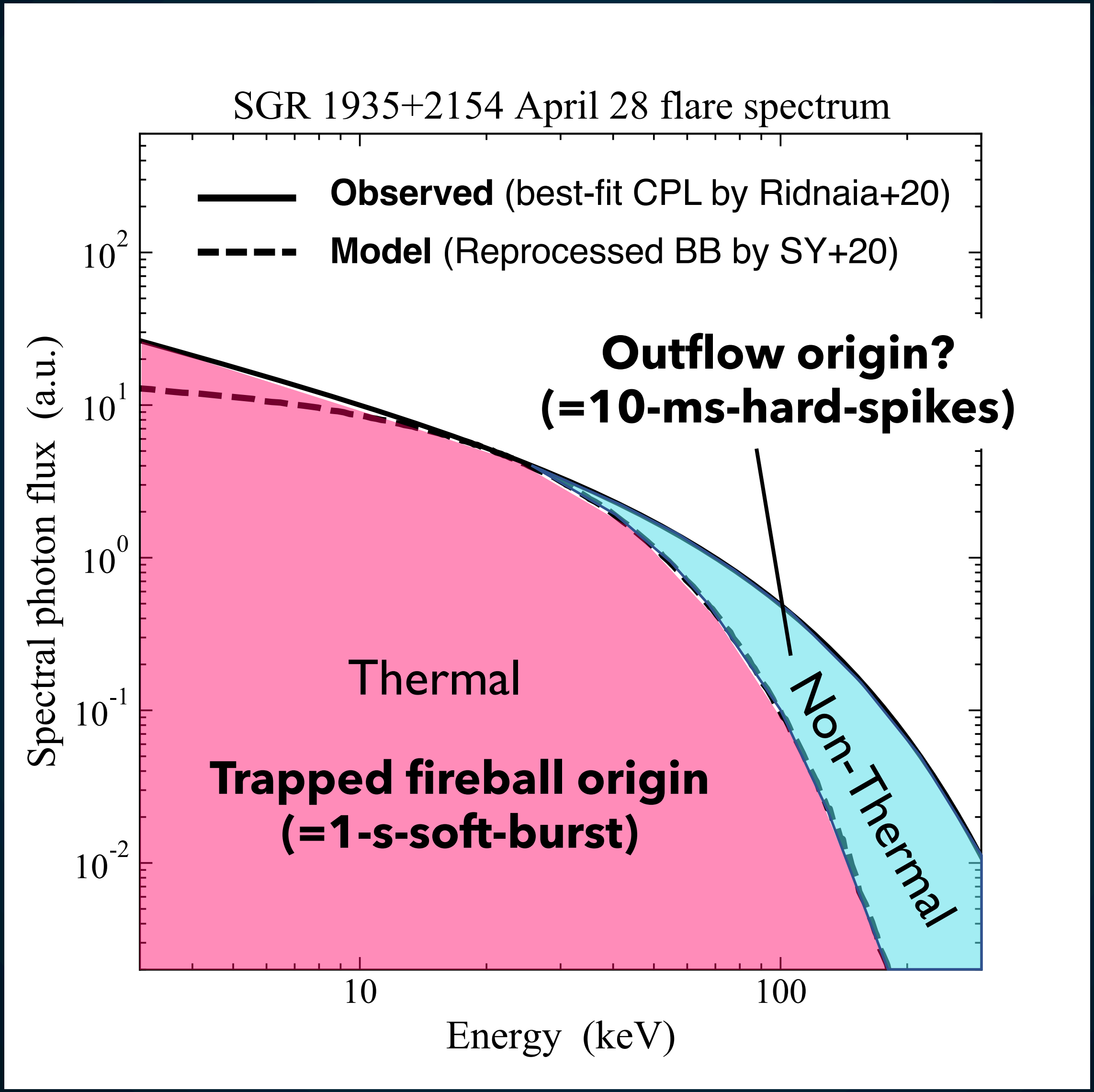


SY, Lyubarsky, Granot, Gogus 20

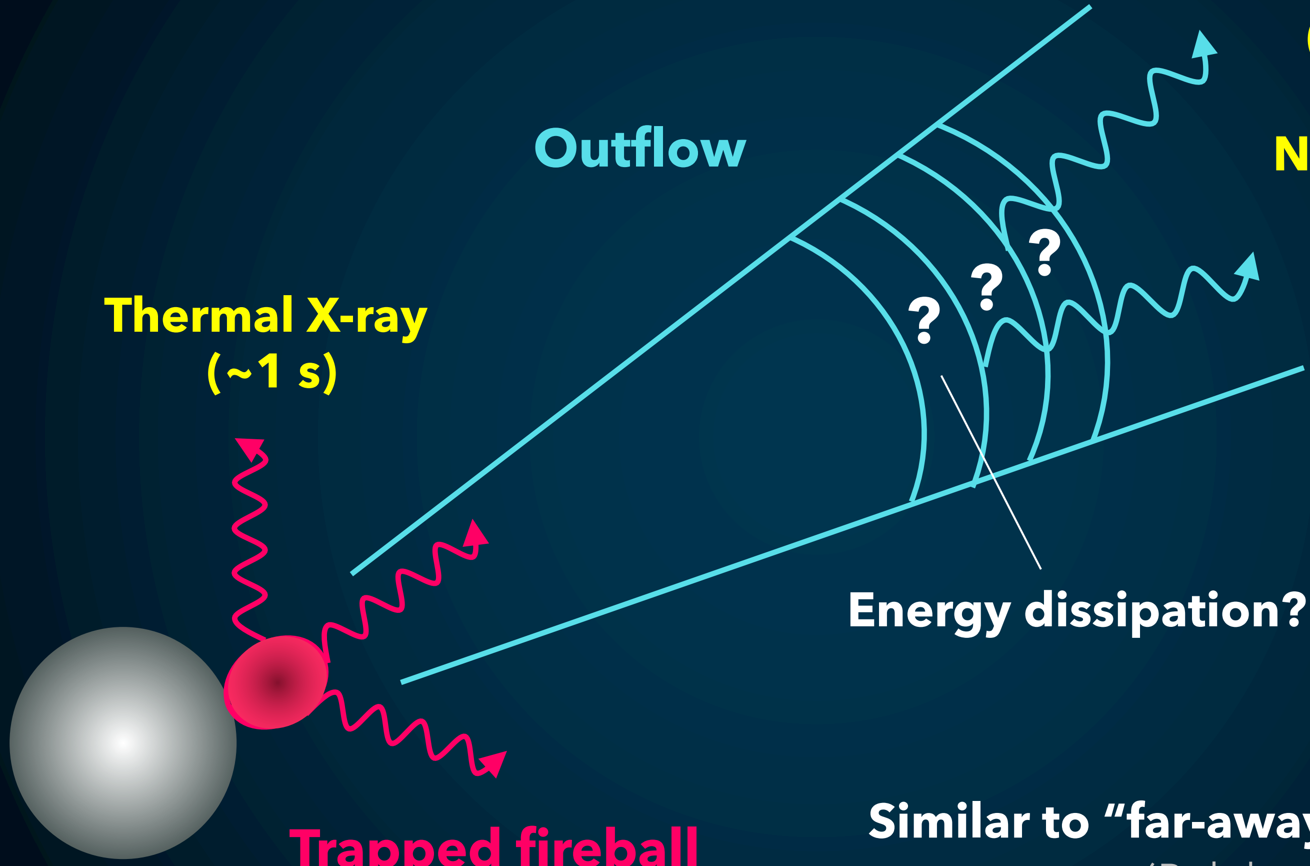


- **A toy model for resonant scattering successfully explains typical magnetar flare spectra** (SY+20)

Hard X-ray Burst Spectrum: Possible Interpretation



Global Picture



Coherent radio (~GHz, ~10 ms)
+
Non-thermal X-ray (~10 ms)

Outflow

Thermal X-ray (~1 s)

Energy dissipation?

Trapped fireball

Magnetar
SGR 1935+2154

Similar to "far-away" models in some ways (Beloborodov 17 & 19; Metzger+19; Margalit+20; Yuan+20)

Trapped Fireball Properties

Assumptions

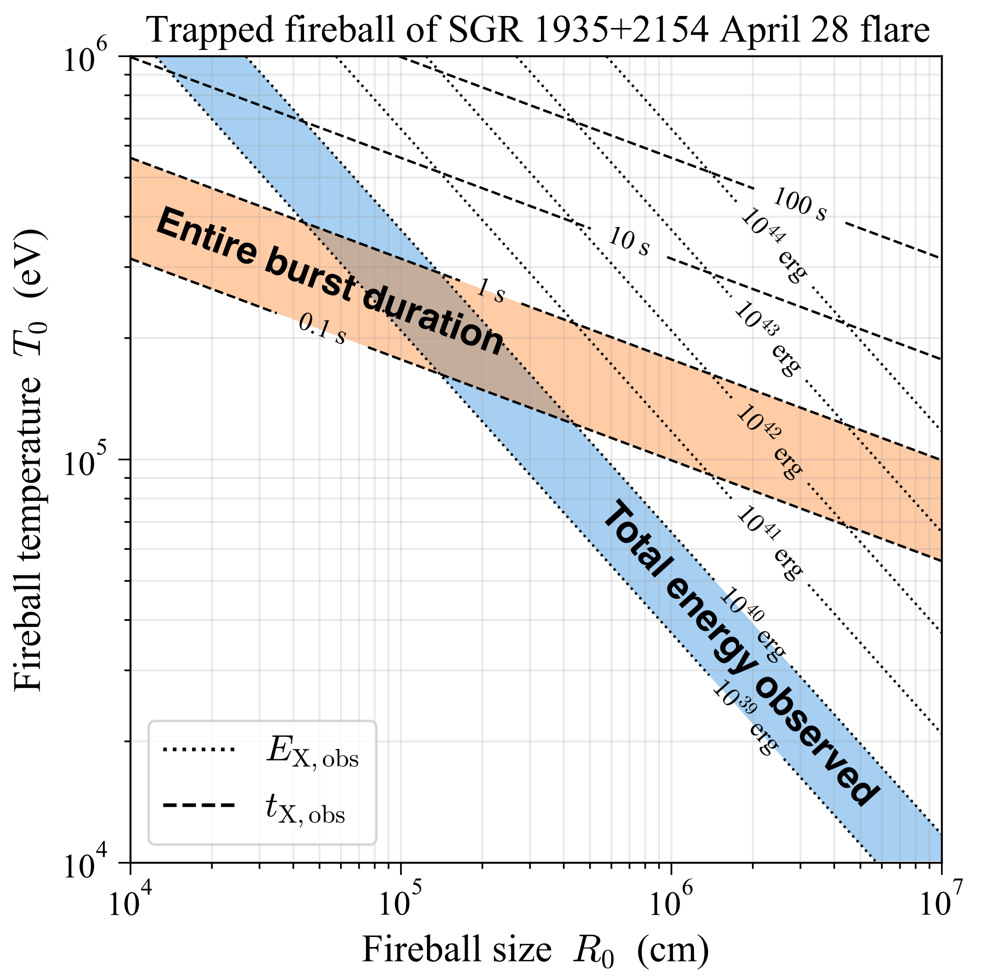
- **TD95 model**
- **Photon diffusion at surface layer of trapped FB with T_{obs} ~ 10 keV**

Observational facts

- **X-ray energy budget $E_{X,obs}$ ~ 10^{40} erg**
- **X-ray burst duration $t_{X,obs}$ <~ 1 s**

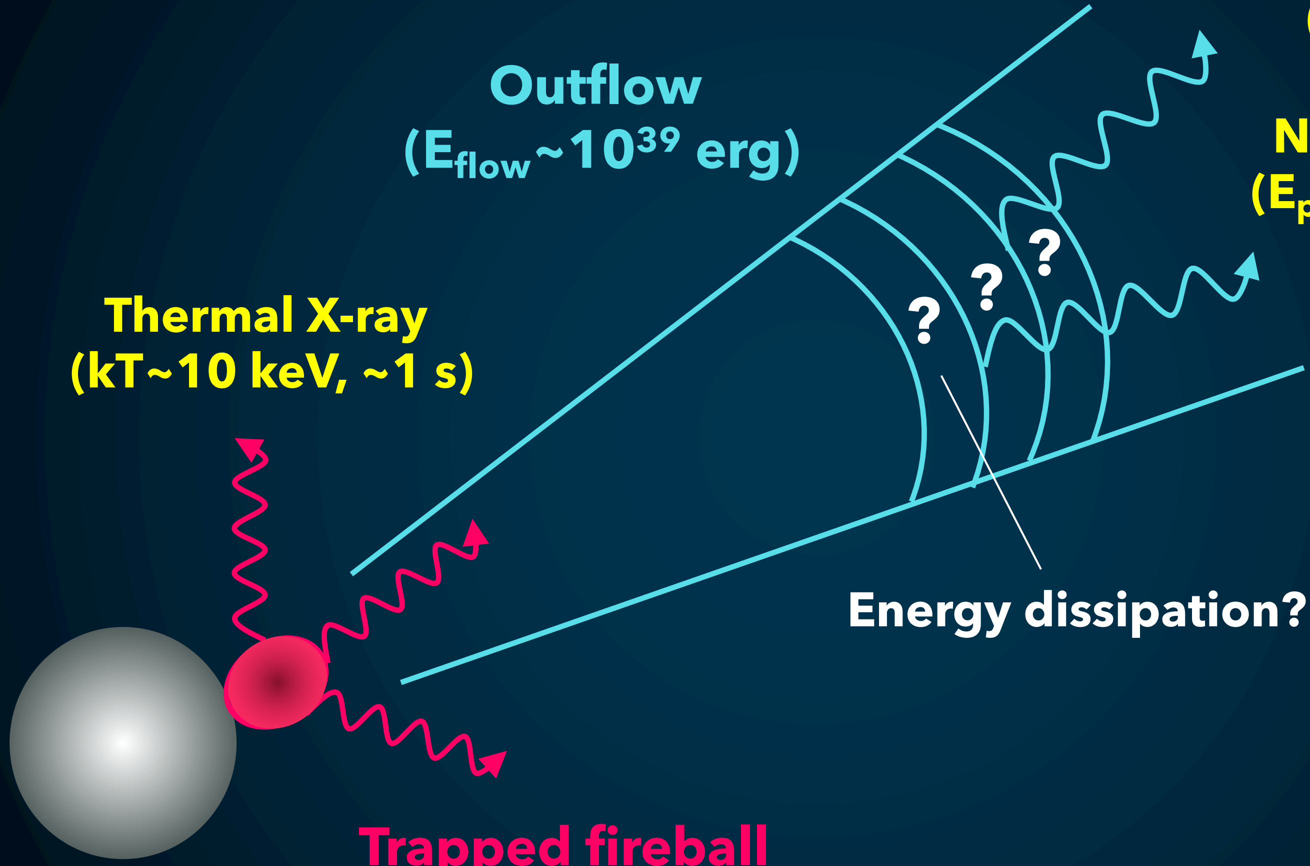
Inferred FB properties

- **Mean FB temperature T_0 ~ 200-300 keV**
- **FB size R_0 ~10^5 cm**



Constraints on the Outflow Properties

Global Picture



Coherent radio
(~GHz, ~10 ms)
+
Non-thermal X-ray
(E_p~80 keV, ~10 ms)

Outflow
(E_{flow}~10^{39} erg)

Thermal X-ray
(kT~10 keV, ~1 s)

?
?
?

Energy dissipation?

Trapped fireball
(E_{FB}~10^{40} erg, R_0~1km, kT_0~200-300 keV)

Magnetar
SGR 1935+2154

Outflow Models

- **Relativistic outflow models in the context of GRBs:**
  - **Leptonic outflow** (Grimusrud & Wassermann 98; Li & Sari 02)
    - $e^{\pm}$ + photons
    - Non-equilibrium effects on pair number density
  - **Baryonic outflow** (Grimusrud & Wassermann 98; Nakar+05)
    - $e^{\pm}$ + protons + photons
    - Free parameter η (degree of baryon load)
  - **Magnetic outflow** (Drenkhahn 02; Drenkhahn & Spruit 02)
    - $e^{\pm}$ + magnetic energy
    - Free parameter σ_0 (initial magnetization)
    - Magnetic reconnection above light-cylinder radius ($\sim 10^{10}$ cm)
- **Initial outflow properties are set based on trapped FB parameters (T_0 = 200 keV, $r_0 = 10^5$ cm, $E_{flow} = 10^{39}$ erg)**
- **Assume energy dissipation occurs within the outflow**

Limits on Radio Emission Radius

1. Plasma cutoff frequency (upper limit on $r_{\rm radio}$)

Plasma cutoff condition (written as a function of plasma frequency) limits the radio wave propagation:

$$\boxed{\omega_{\rm p,obs}(r_{\rm radio}) \lesssim \omega_{\rm obs},}$$

Assuming that coherent radio emission is generated via synchrotron maser

(Iwamoto+17 &19; Metzger+19; Plotnikov & Sironi 2019)

$$\omega_{p,\rm obs} \approx \Gamma\,\omega_p\,\max[1, \sigma^{1/2}]$$

where

$$\omega_{\rm p} \equiv \sqrt{\frac{4\pi n'_e e^2}{m_e}}$$

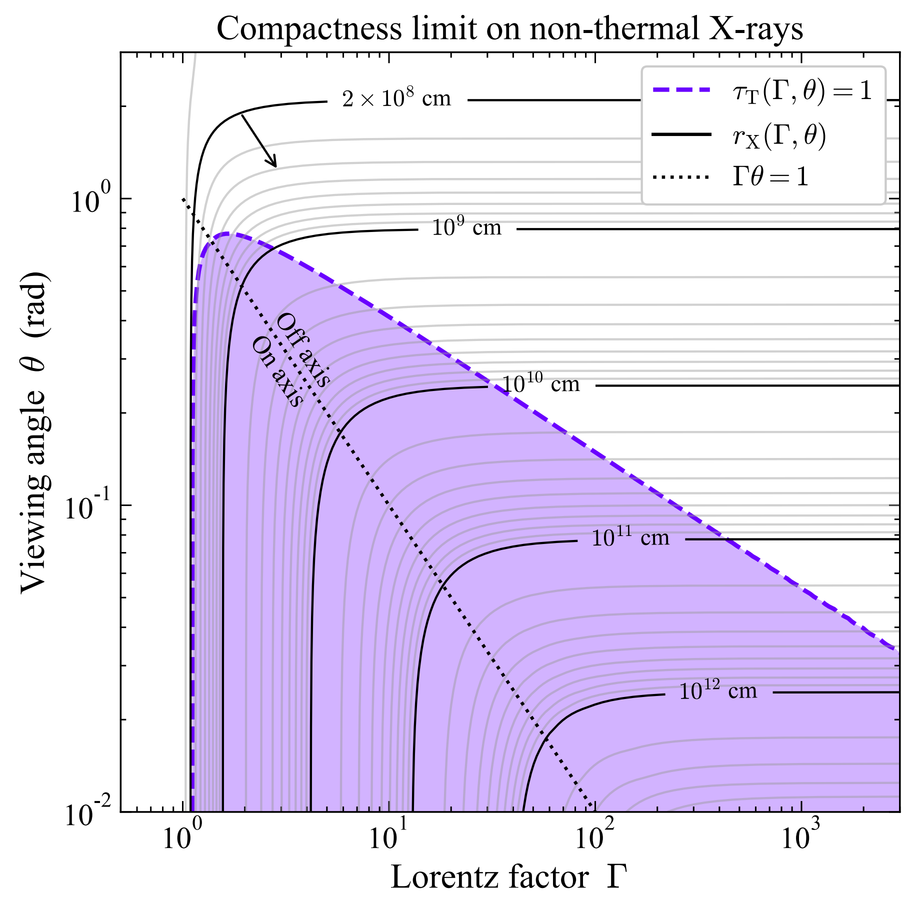
2. Time delay between hard X-ray and coherent radio bursts (upper limit on $r_{\rm radio}$)

$$\boxed{r_{\rm radio\,(X)} \lesssim \Gamma^2 c \Delta t_{\rm X,radio}}$$

where

$$\Delta t_{\rm X,radio} \lesssim 10\ {\rm ms}$$

Limits on Hard X-ray Emission Radius



Based on Matsumoto, Nakar & Piran 19

1. **Compactness limit (lower limit on r_X)**

   Hard spectrum with E_{peak}~80 keV suggests source must be optically-thin to Thomson scattering on $e^{\pm}$ pairs

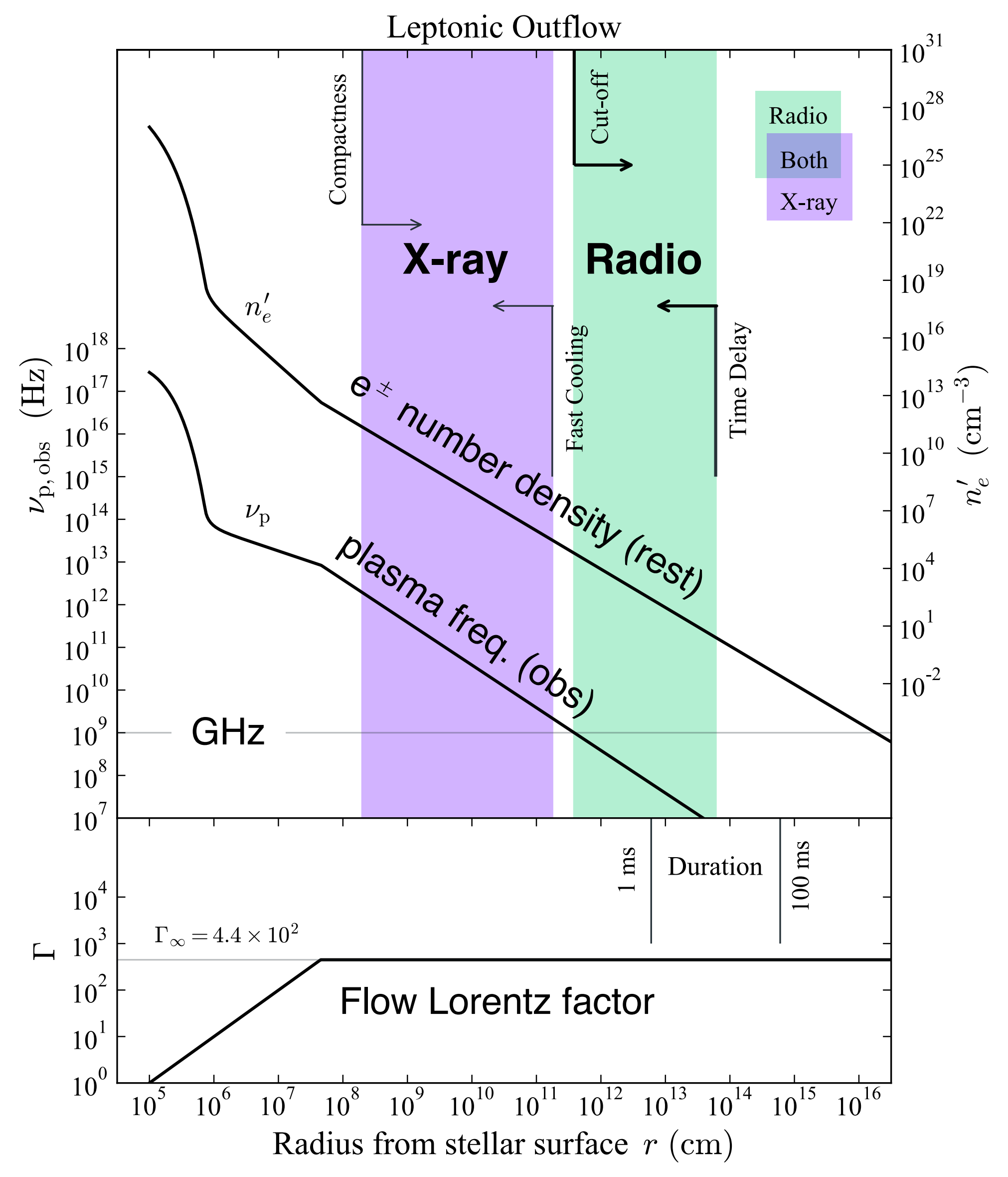
   → r_X ~> 10^8 cm (generic)

2. **Fast-cooling condition (upper limit on r_X)**

   Very bright emission with L_X ~> 10^{41} erg/s

   → $t_{cool} < t_{dyn}$

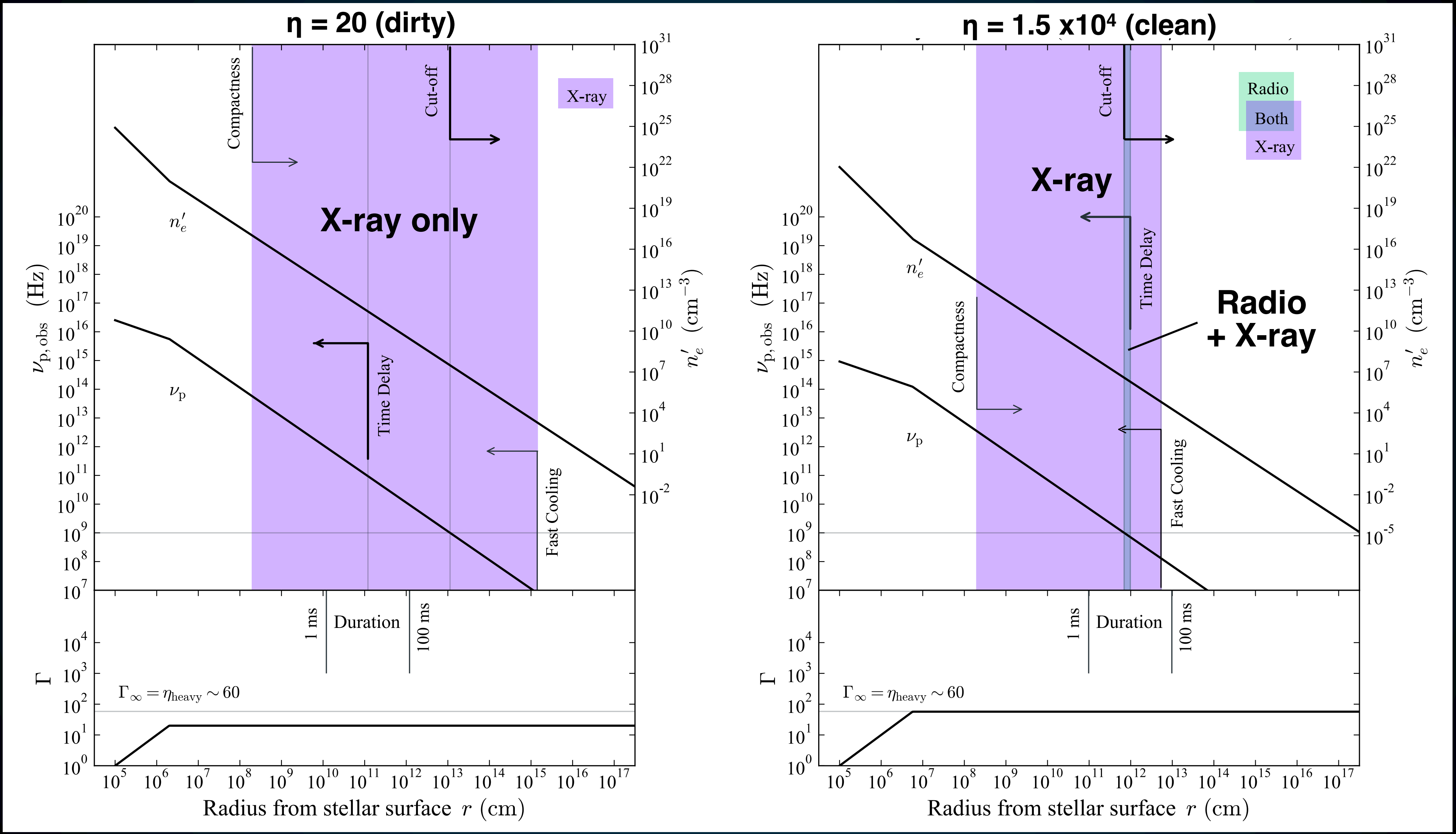
Pure Leptonic Outflow ($E_{radiation}/E_{matter}$ >>1)



- **Evolution is uniquely determined by initial outflow conditions**
- **r_X ~10^8–10^{11} cm << r_{radio} ~10^{12}–10^{14} cm**
- **Predicted duration does not match the observations**

→ A pure leptonic outflow may be disfavored

Baryonic Outflow with η =$E_{\mathrm{radiation}}/E_{\mathrm{matter}}$



Flow acceleration is limited by the critical baryon load parameters

Baryonic Outflow with η =$E_{\mathrm{radiation}}/E_{\mathrm{matter}}$

- **Conditions for radio emission**

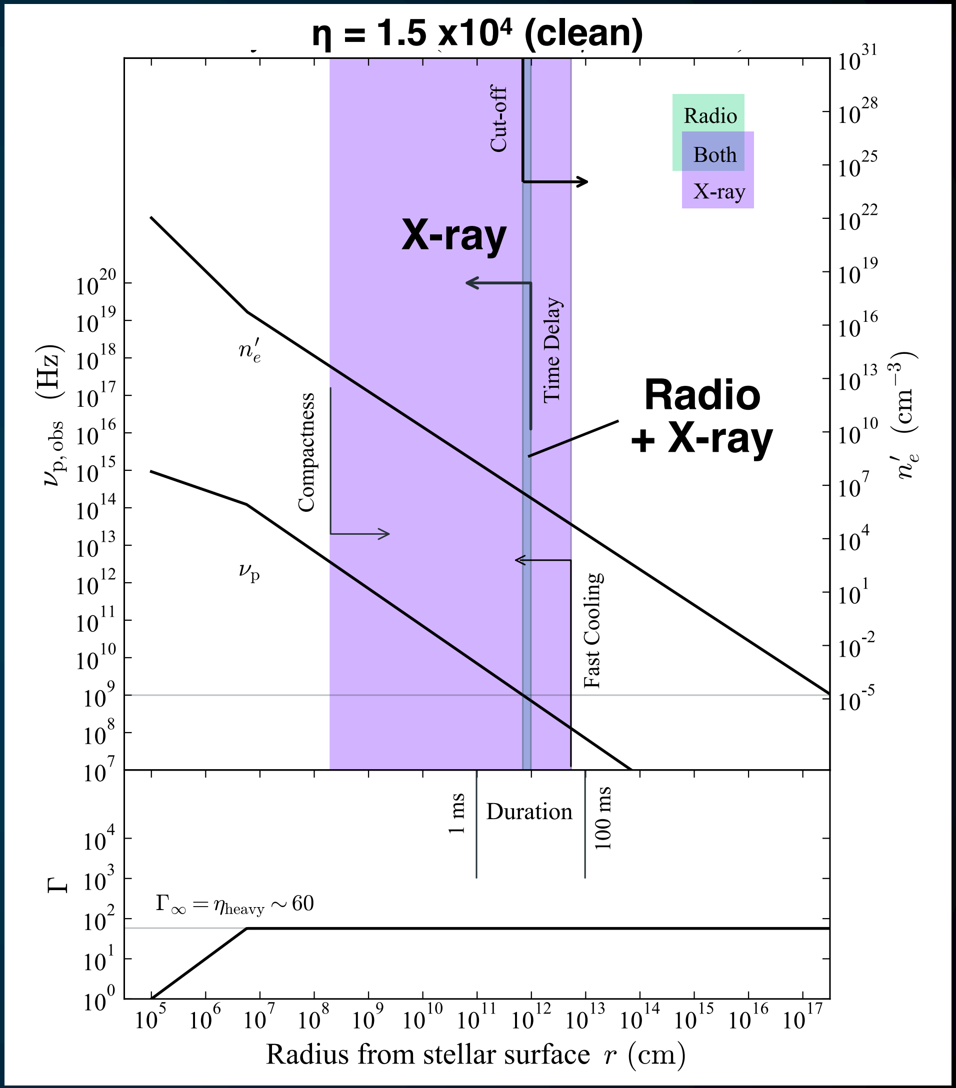
$$r_{\mathrm{radio}} \gtrsim r_{\mathrm{cutoff}} \propto r_0\, T_0^2\, \nu_{\mathrm{obs},9}^{-1}\, \eta^{-1/2}$$

$$r_{\mathrm{radio}} \lesssim \Gamma_\infty^2 c \Delta t_{\mathrm{X,radio}} \propto \Delta t_{\mathrm{X,radio}}$$

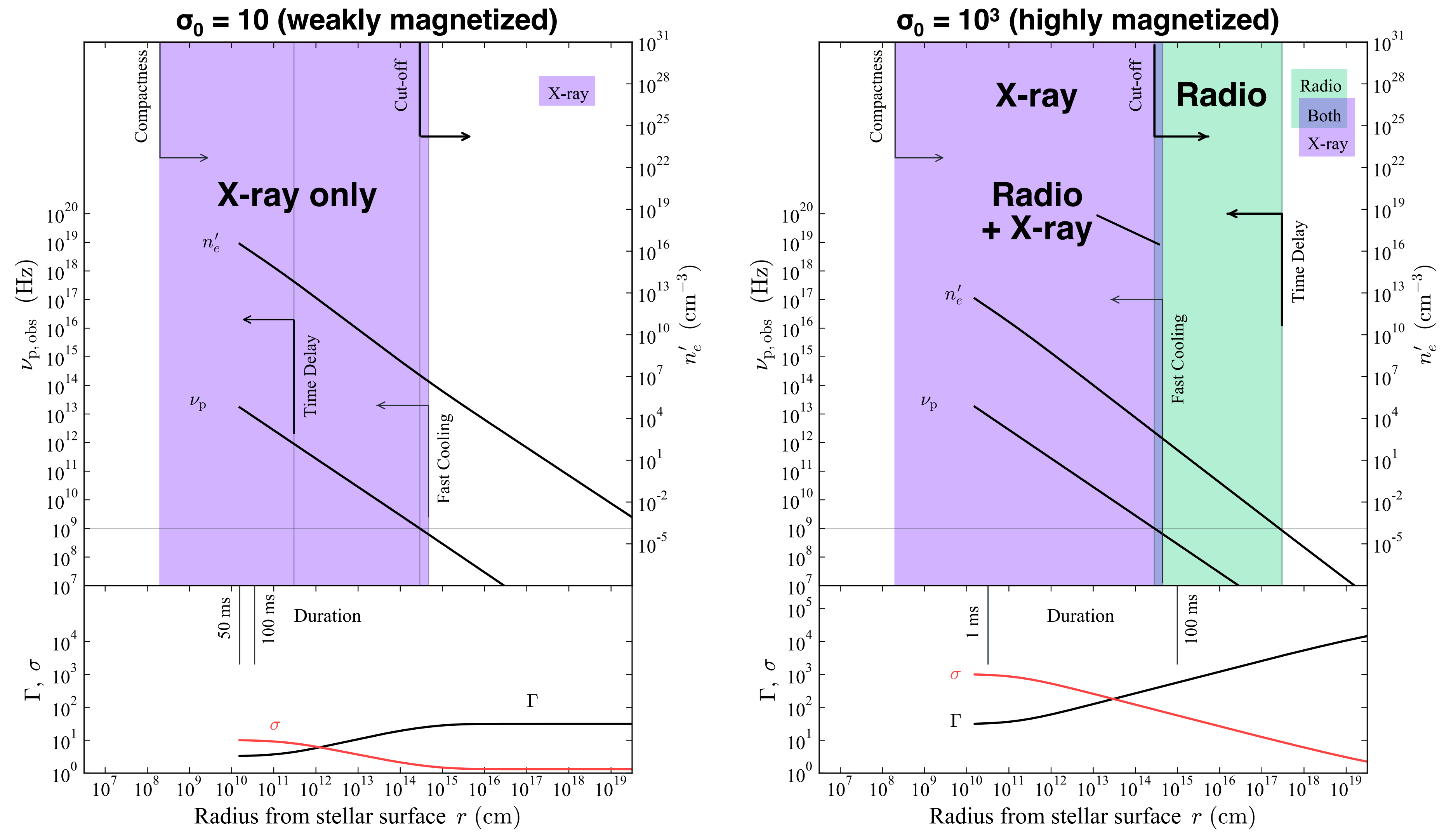
- **Upper limit on the baryon load:**

$$\eta \gtrsim 6.2 \times 10^3 \times r_{0,5}^{5/4} \left(\frac{kT_0}{200\ \mathrm{keV}}\right) \nu_{\mathrm{obs},9}^{-2} \left(\frac{\Delta t_{\mathrm{X,radio}}}{10\ \mathrm{ms}}\right)^{-2}$$

→ A mildly clean flow (η ~>10^4) might be favored



Magnetic Outflow with $\sigma_0 = (E_{\mathrm{Poynting}}/E_{\mathrm{matter}})_0$



$\sigma_0 = 10$ (weakly magnetized)

$\sigma_0 = 10^3$ (highly magnetized)

Flow slowly evolves as $\Gamma(r) \propto r^{1/3}$
from $\Gamma_0 \sim \sigma_0^{1/2}$ (at light cylinder radius) up to $\Gamma_\infty \sim \sigma_0^{3/2}$

Magnetic Outflow with $\sigma_0 = (E_{\rm Poynting}/E_{\rm matter})_0$

- **Conditions for radio emission**

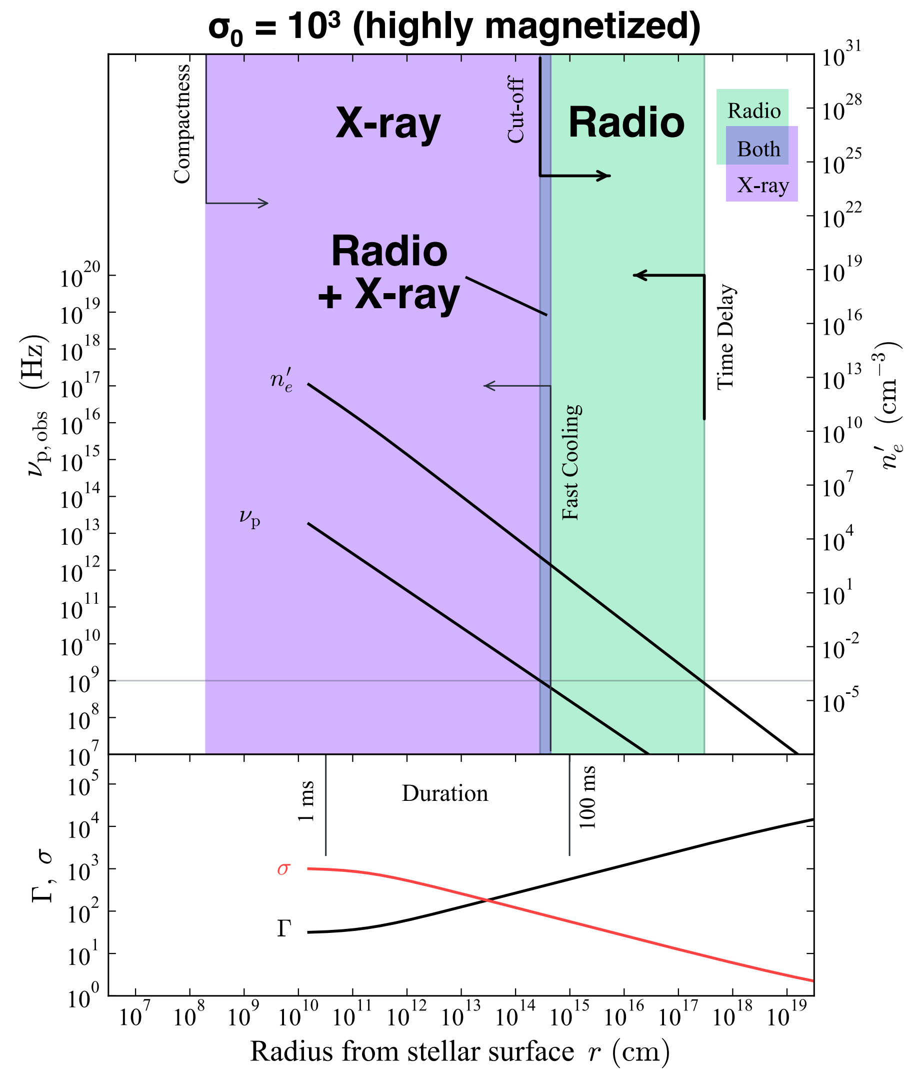
$$r_{\rm radio} \gtrsim r_{\rm cutoff} \propto r_0^{-1/2}\, E_{\rm flow}^{1/2}\, \nu_{\rm obs,9}^{-1}$$

$$r_{\rm radio} \lesssim \Gamma_\infty^2 c \Delta t_{\rm X,radio} \propto \Delta t_{\rm X,radio}\, \sigma_0^3$$

- **Lower limit on magnetization**

$$\sigma_0 \gtrsim 99 \times r_{0,5}^{-1/6}\, E_{\rm flow,39}^{1/6}\, \nu_{\rm obs,9}^{-1/3} \left(\frac{\Delta t_{\rm X,radio}}{10\ {\rm ms}}\right)^{-1/3}$$

→ **A highly Poynting-dominated flow (σ_0 >10^3) might be favored**



Summary

- **Soft X-ray = trapped FB, whereas hard X-ray & radio bursts = outflow?**
- **Trapped fireball**
  - Thermal X-ray emission can be interpreted by a classical trapped fireball model with $E_{FB}\sim10^{40}$ erg, $R_0\sim1$km, $kT_0\sim200$-300 keV
- **Outflow properties:**
  - Non-thermal X-ray spikes must be generated at $r_X \sim> 10^8$ cm
  - Outflow need to accelerate up to $\Gamma\sim>10^2$ within the magnetosphere and dissipation should occur at 10^{12} cm $<\sim r_{radio,X} <\sim 10^{14}$ cm
  - Requirements for radio emission set $\eta > 10^4$ and $\sigma_0 \sim> 10^2$
  - $m_b <\sim 10^{14}$ g for this event from SGR 1935+2154 (This work) is much smaller than $m_b <\sim 10^{20}$ –10^{23} g for SGR 1806–20 giant flare (Nakar+05; Granot+06)
- **Outflow generation with different η and σ_0 may be the reason for the rarity of April 28 event?**