Fast Radio Burst Breakouts from Magnetar Burst Fireballs

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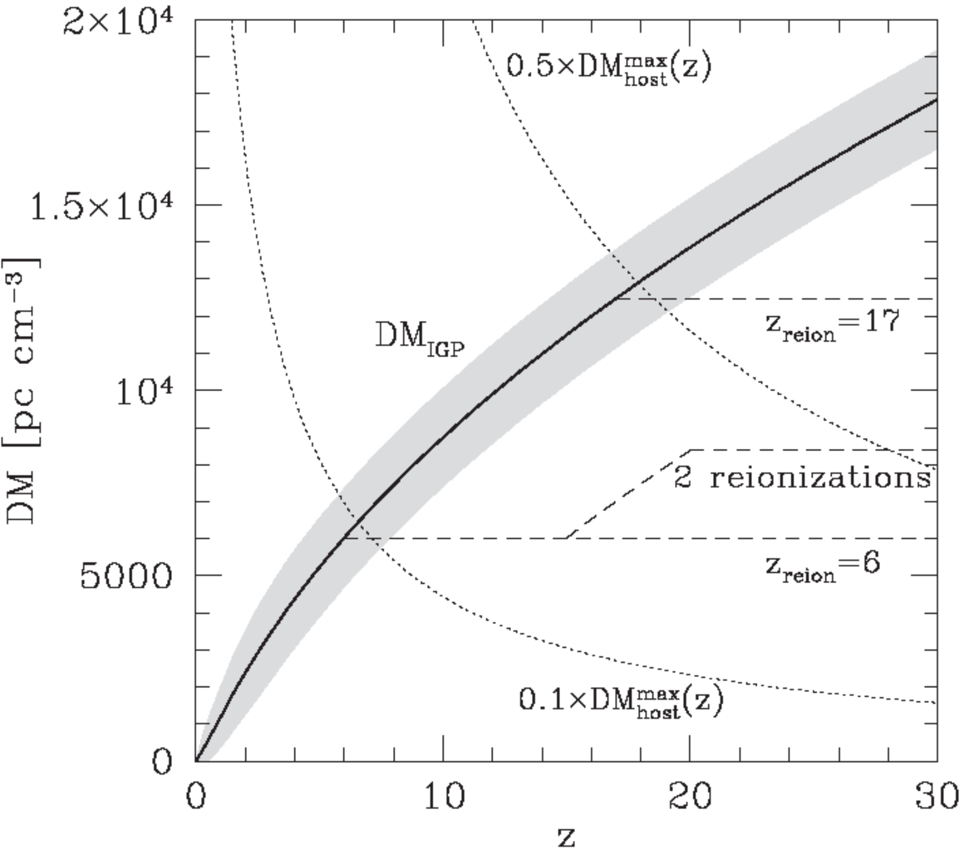
YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP
Center for Gravitational Physics
Yukawa Institute for Theoretical Physics

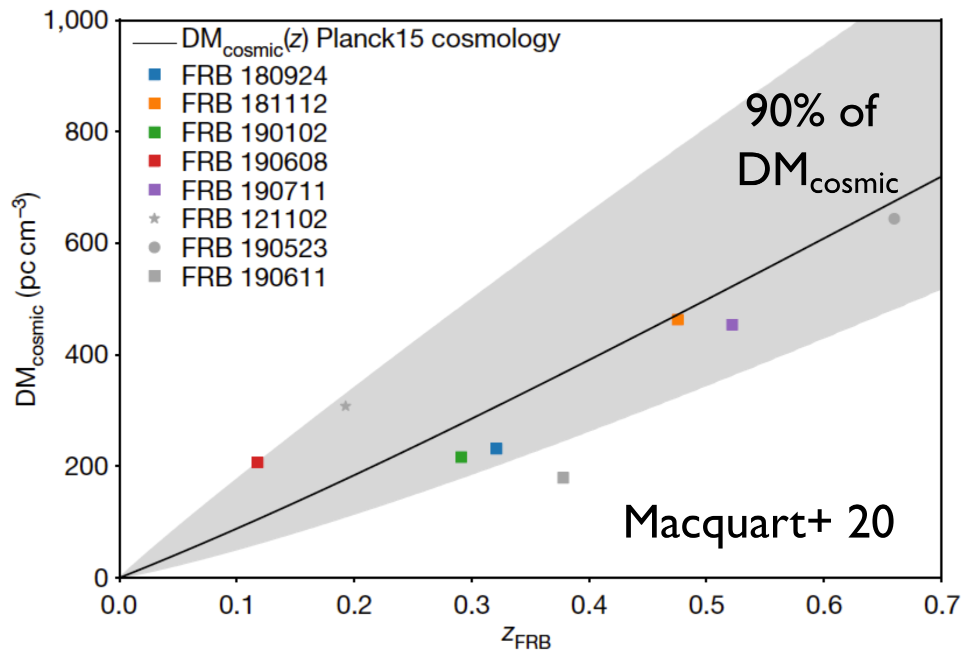
FRB Cosmology

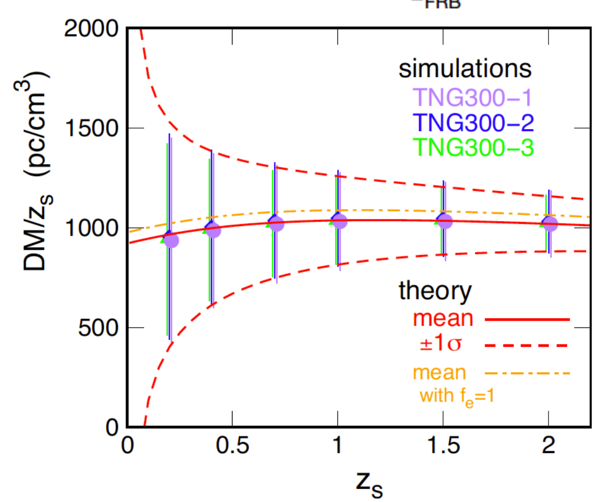
Kumar's, Hashimoto's, Takahashi's talks



$$\mathrm{DM}_{\mathrm{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}$$

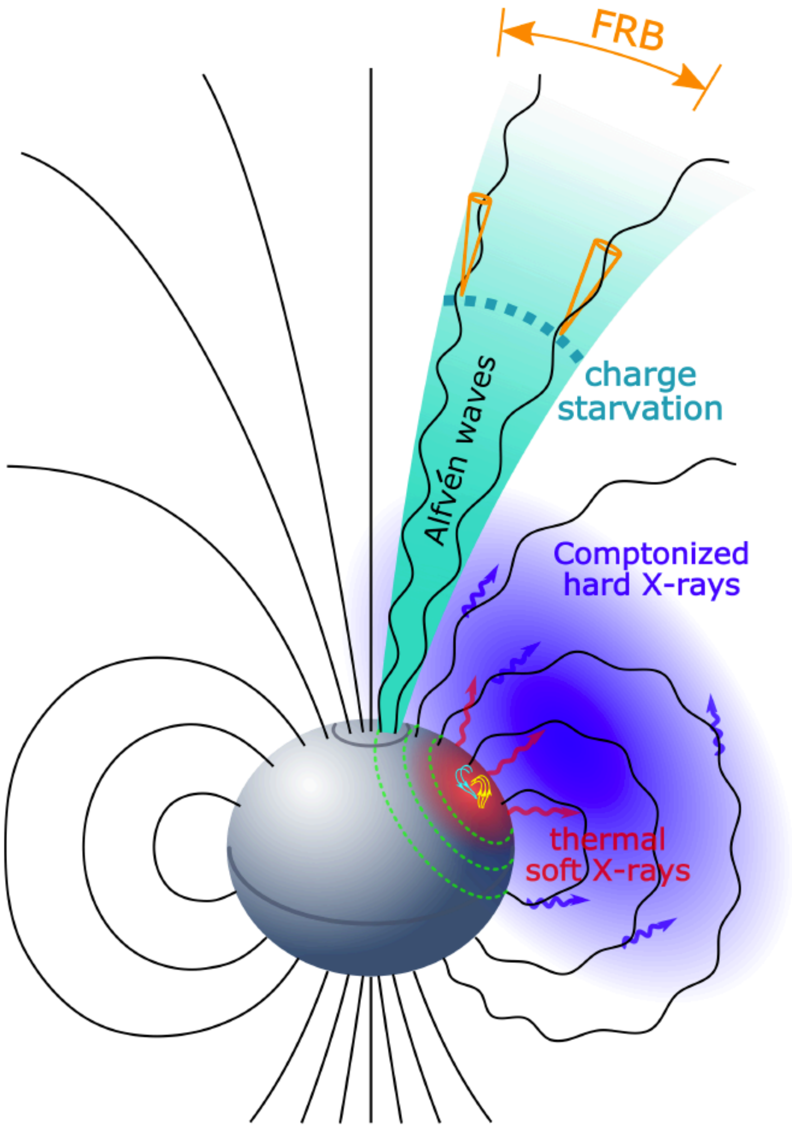
KI 03, Inoue 04





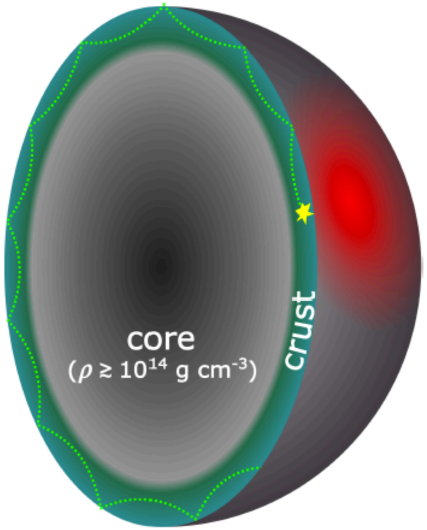
Takahashi, KI+ 20

Magnetosphere Model



FRB from near-by magentar magnetosphere

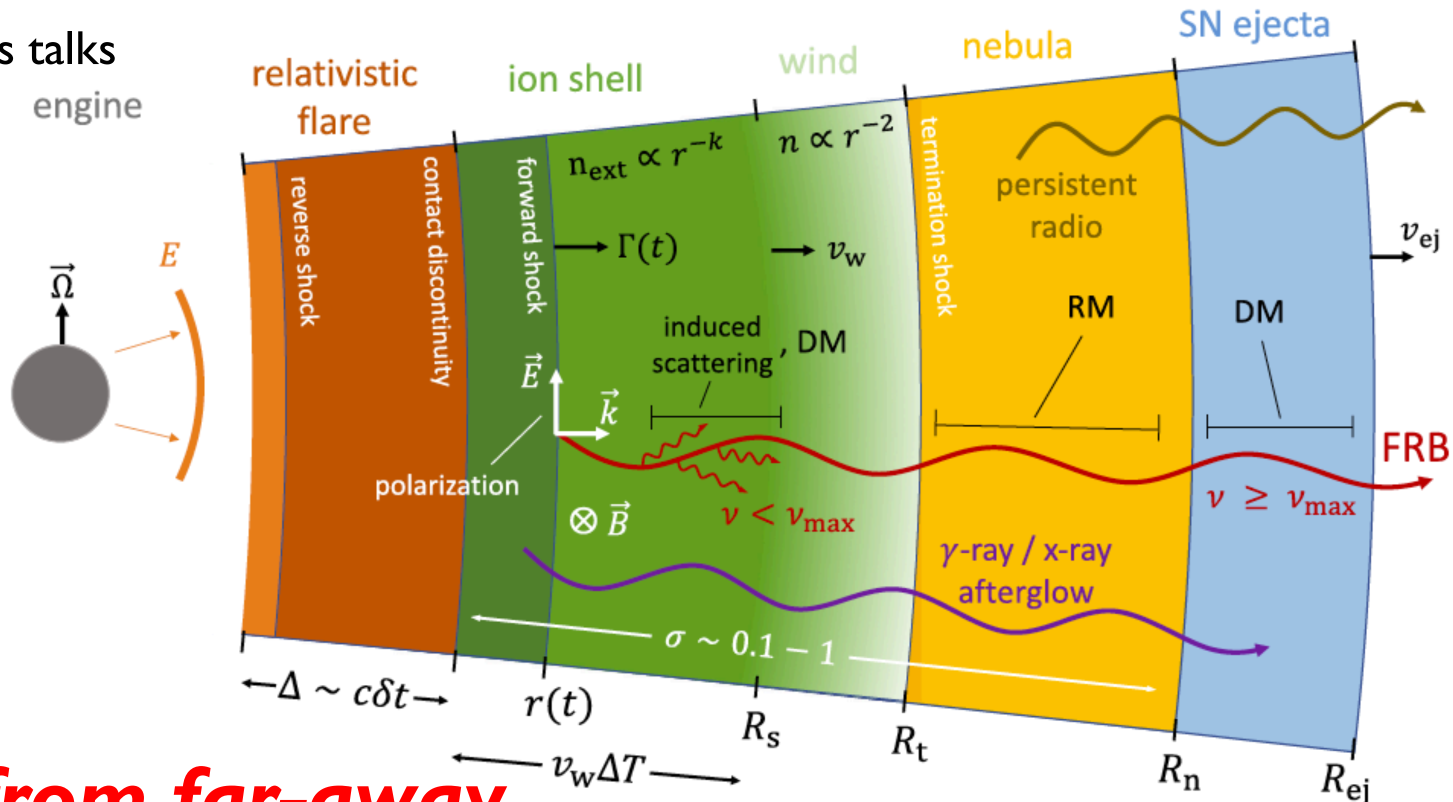
Lu et al. 2020; Lyutikov & Popov 2020; Katz 2020;
Kashiyama et al. 2013; Cordes & Wasserman 2016;
Lyutikov et al. 2016; Kumar et al. 2017; Zhang 2017;
Yang & Zhang 2018; Lyubarsky 2020;
Kumar & Bošnjak 2020; Ioka & Zhang 2020



Zhang's, Lu's,
Kumar's talks

Metzger's,
Sridhar's,
Sironi's,
Iwamoto's talks

Ejecta Model

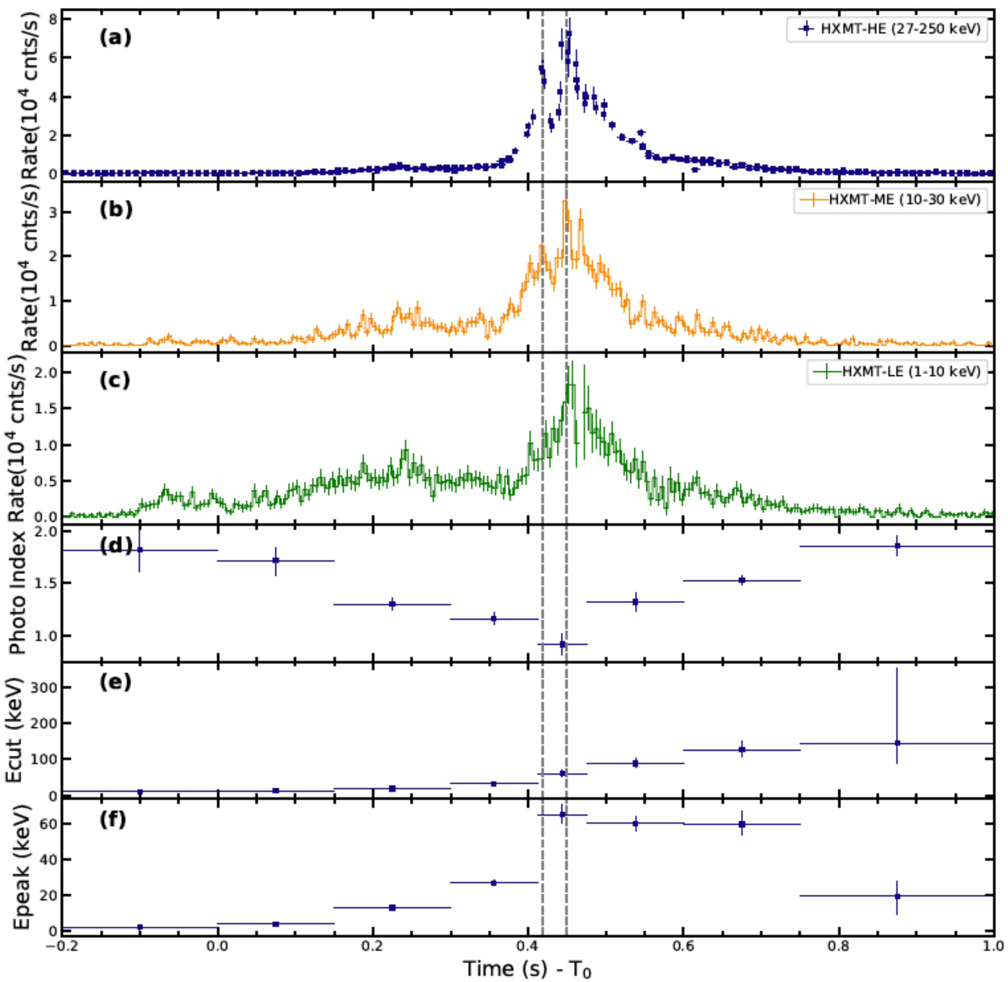


FRB from far-away circum-stellar matter interacting with relativistic ejecta

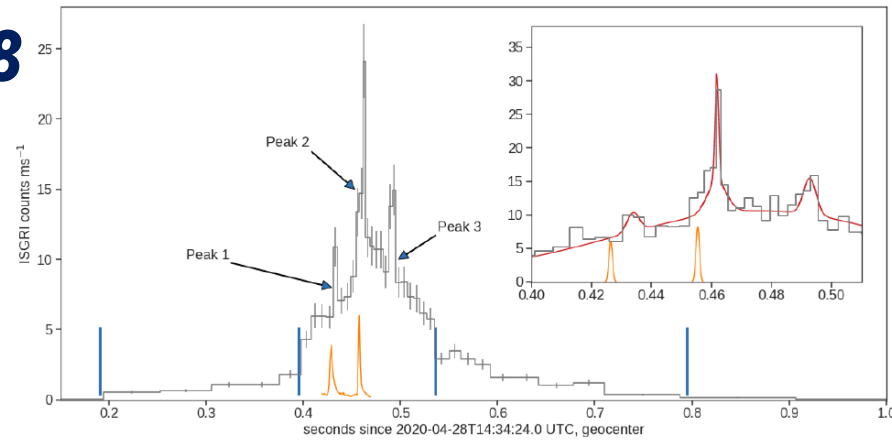
Margalit et al. 2020; Yu et al. 2020; Yuan et al. 2020
Lyubarsky 2014; Murase et al. 2016; Waxman 2017; Beloborodov 2017; Metzger et al. 2017

FRB from Magnetar Bursts

SGR 1935+2154 & FRB 200428



Lin's, Enoto's, Kulkarni's, Lee's talks

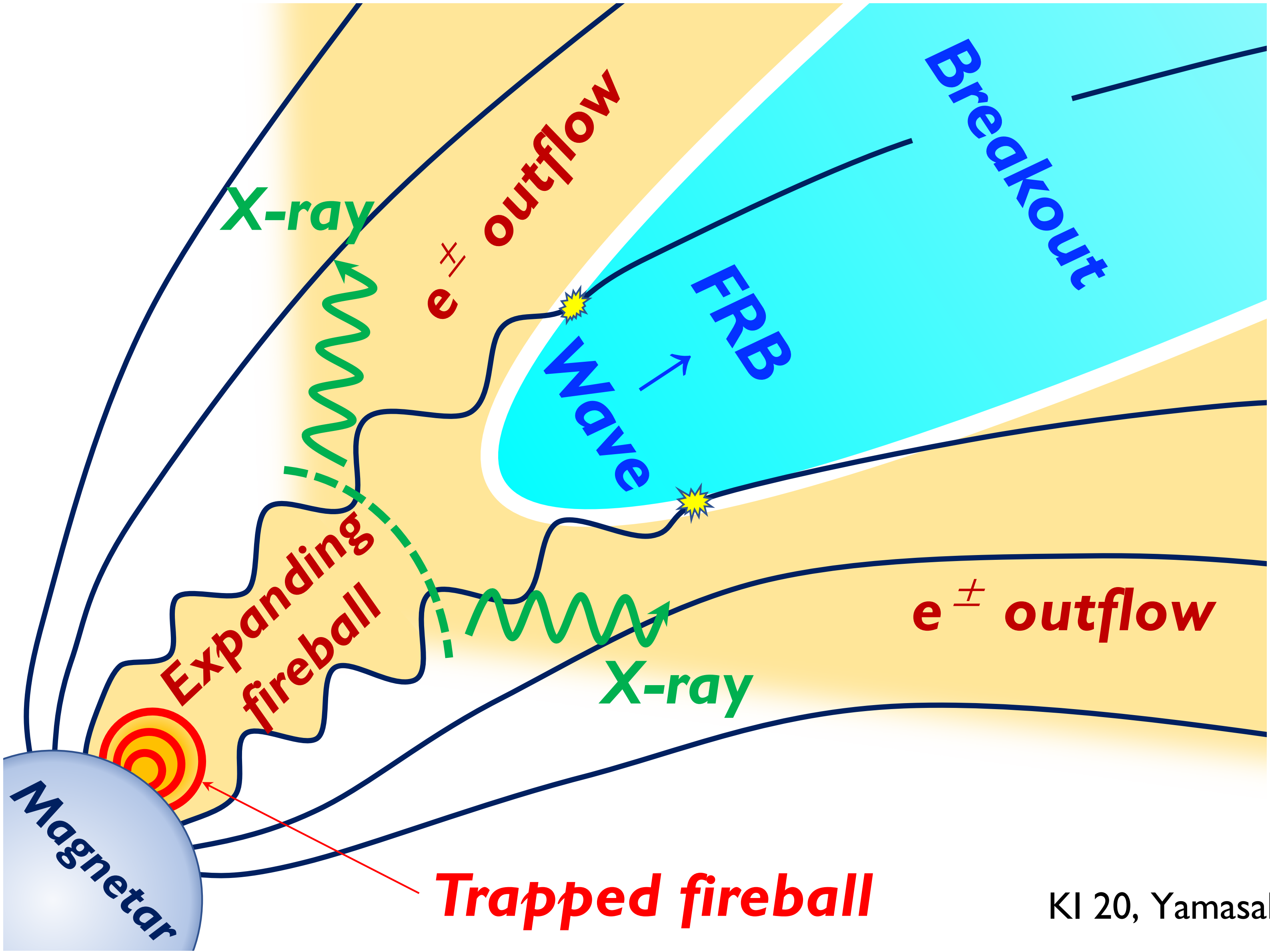


Li+ 20, Mereghetti+ 20, Bochenek+ 20, CHIME/FRB+ 20, Ridnaia+ 20, Tavani+ 20

1. $e^{\pm}$ fireball opaque for FRB

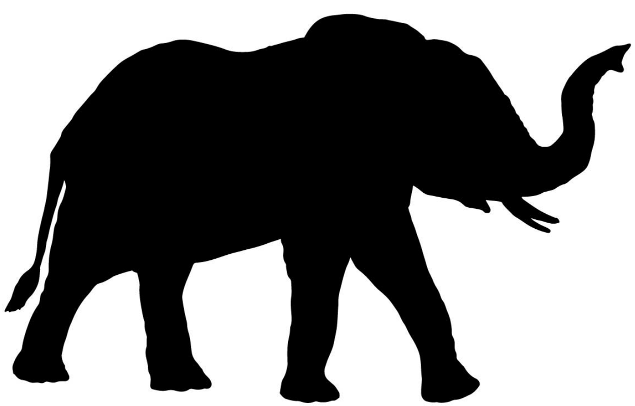
2. But FRB could break out of $e^{\pm}$

$e^{\pm}$ Fireball before FRB



KI 20, Yamasaki's talk

Energetics



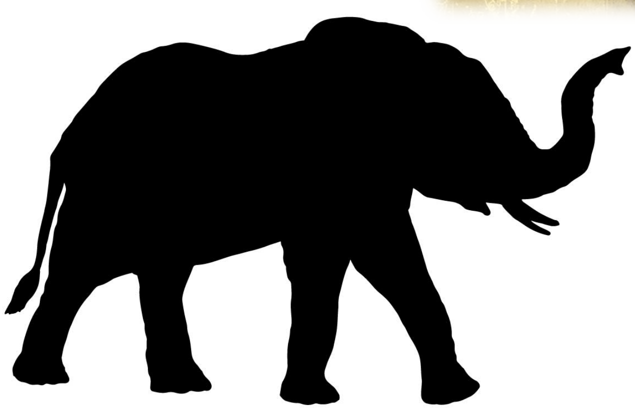
FRB ~ 10^{38} erg/s

Lu's talk

$e^{\pm}$ ~ $10^{36}\, r_7^{-1}$ erg/s

Energetics

X-ray burst
~ 10^{41} erg/s

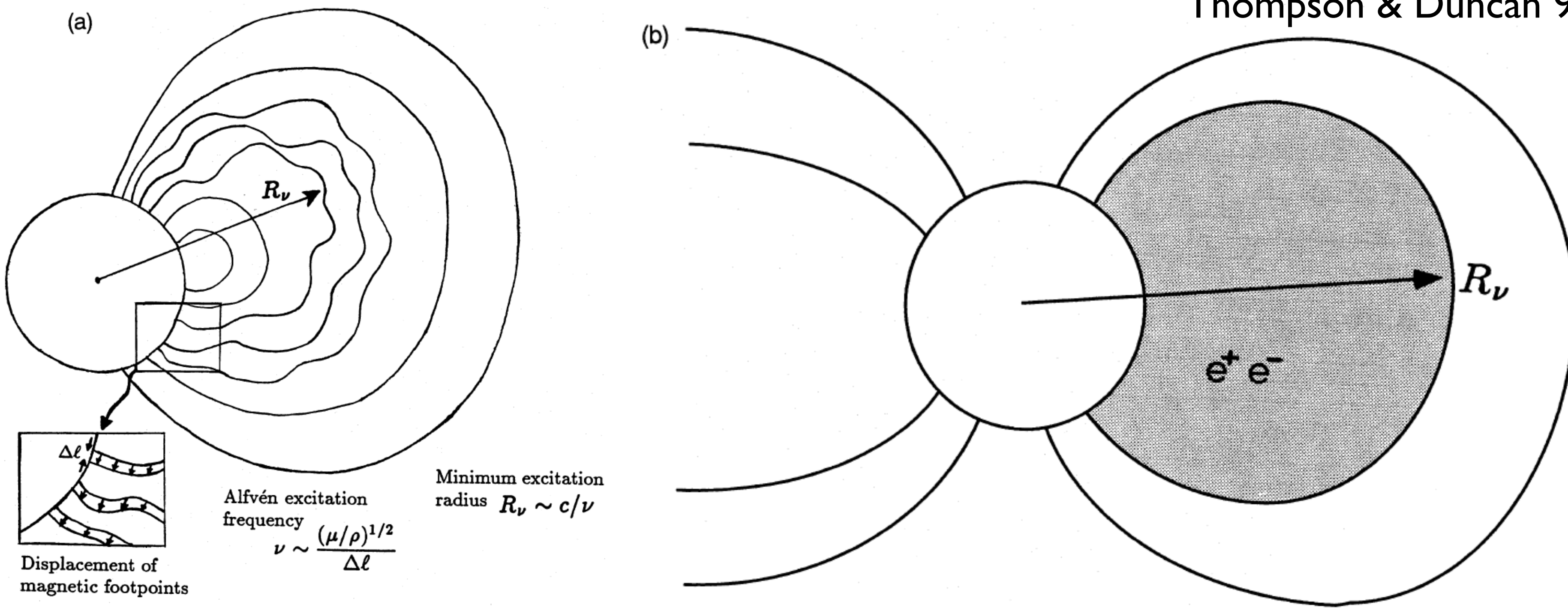


FRB ~ 10^{38} erg/s

$e^{\pm}$ ~ $10^{36}\, r_7^{-1}$ erg/s

Trapped Fireball

Thompson & Duncan 95



$$\ell_X \sim \left(\frac{L_X}{2\pi c a T^4}\right)^{1/2} \sim 1\times 10^4\,\mathrm{cm}\,L_{X,41}^{1/2} T_{1.9}^{-2},$$

$e^{\pm}$ Creation

Equilibrium number density of $e^{\pm}$

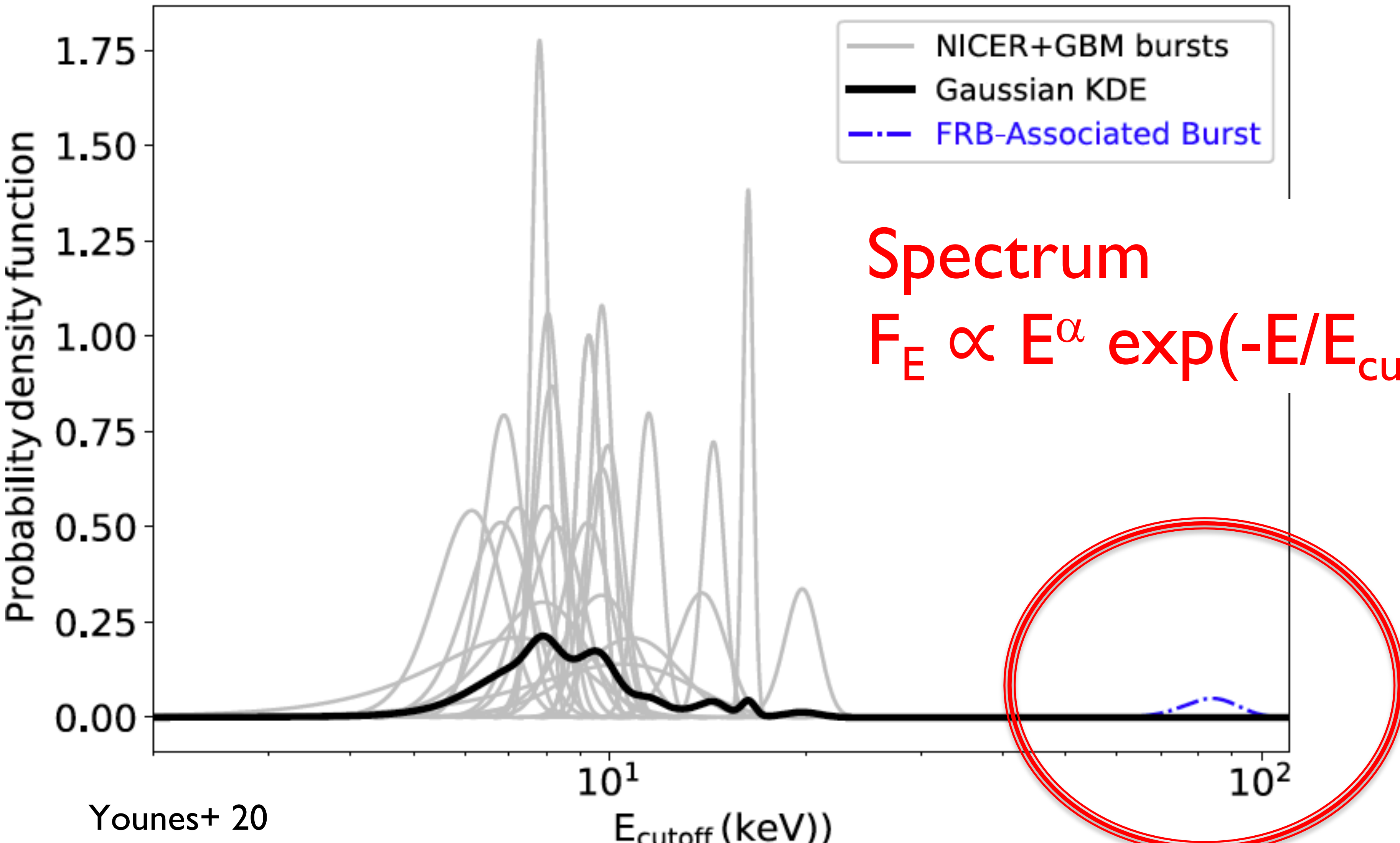
$$n_{\pm} = \frac{eBm_e}{(2\pi^3)^{1/2}\hbar^2}\left(\frac{T}{m_e c^2}\right)^{1/2} \exp\left(-\frac{m_e c^2}{T}\right),$$

Optical depth

$$\tau_{\perp} = \frac{4\pi^2}{5}\sigma_T \left(\frac{T}{m_e c^2}\frac{B_Q}{B}\right)^2 n_{\pm}\ell_X,$$

$$B_Q = m_e^2 c^3/\hbar e = 4.4 \times 10^{13}\,\mathrm{G}.$$

High Temperature

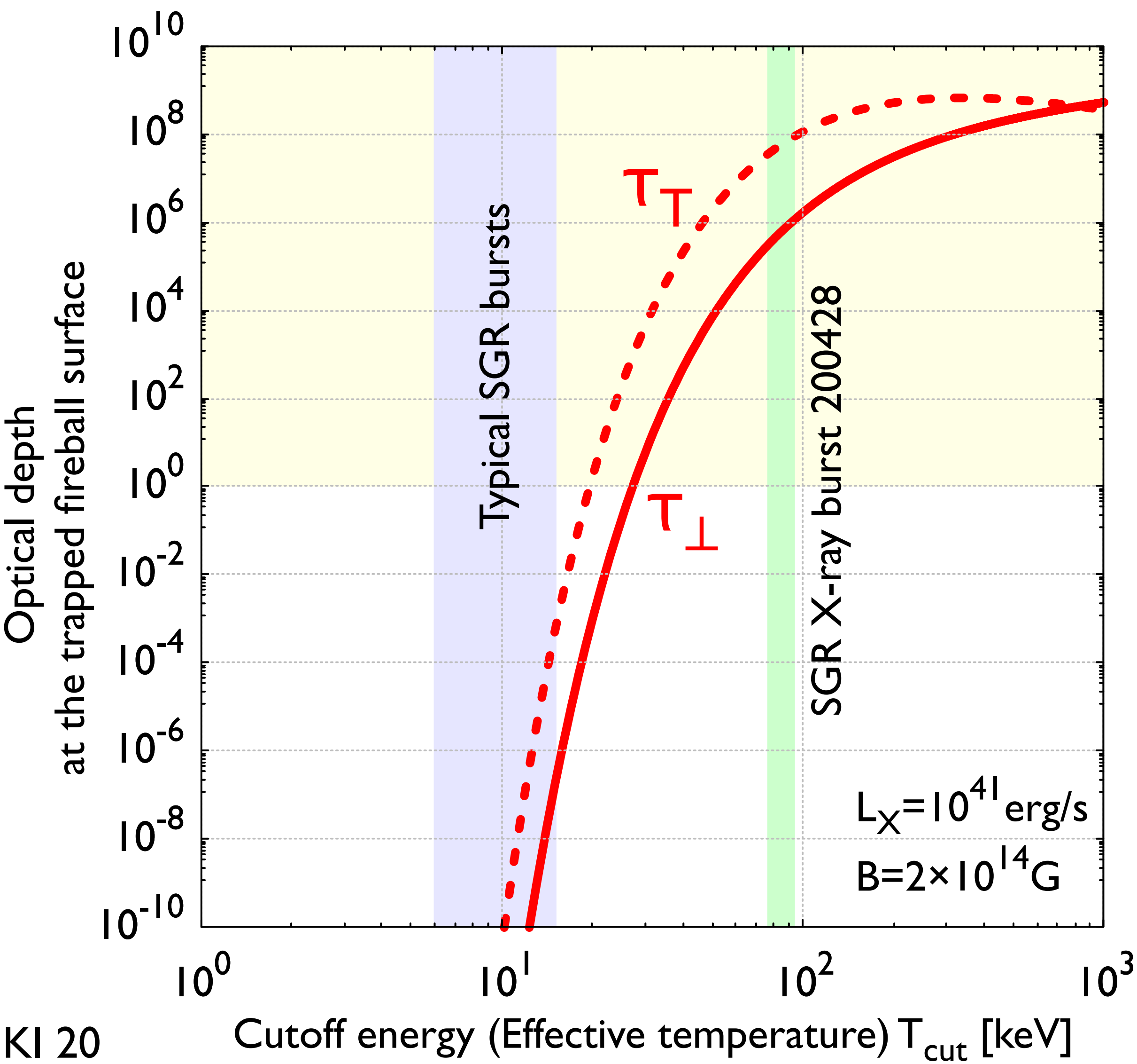


Spectrum

$F_E \propto E^{\alpha} \exp(-E/E_{cut})$

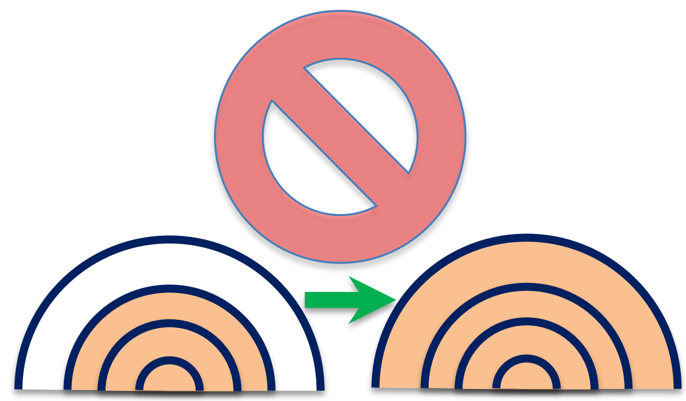
Younes+ 20

Optical Depth



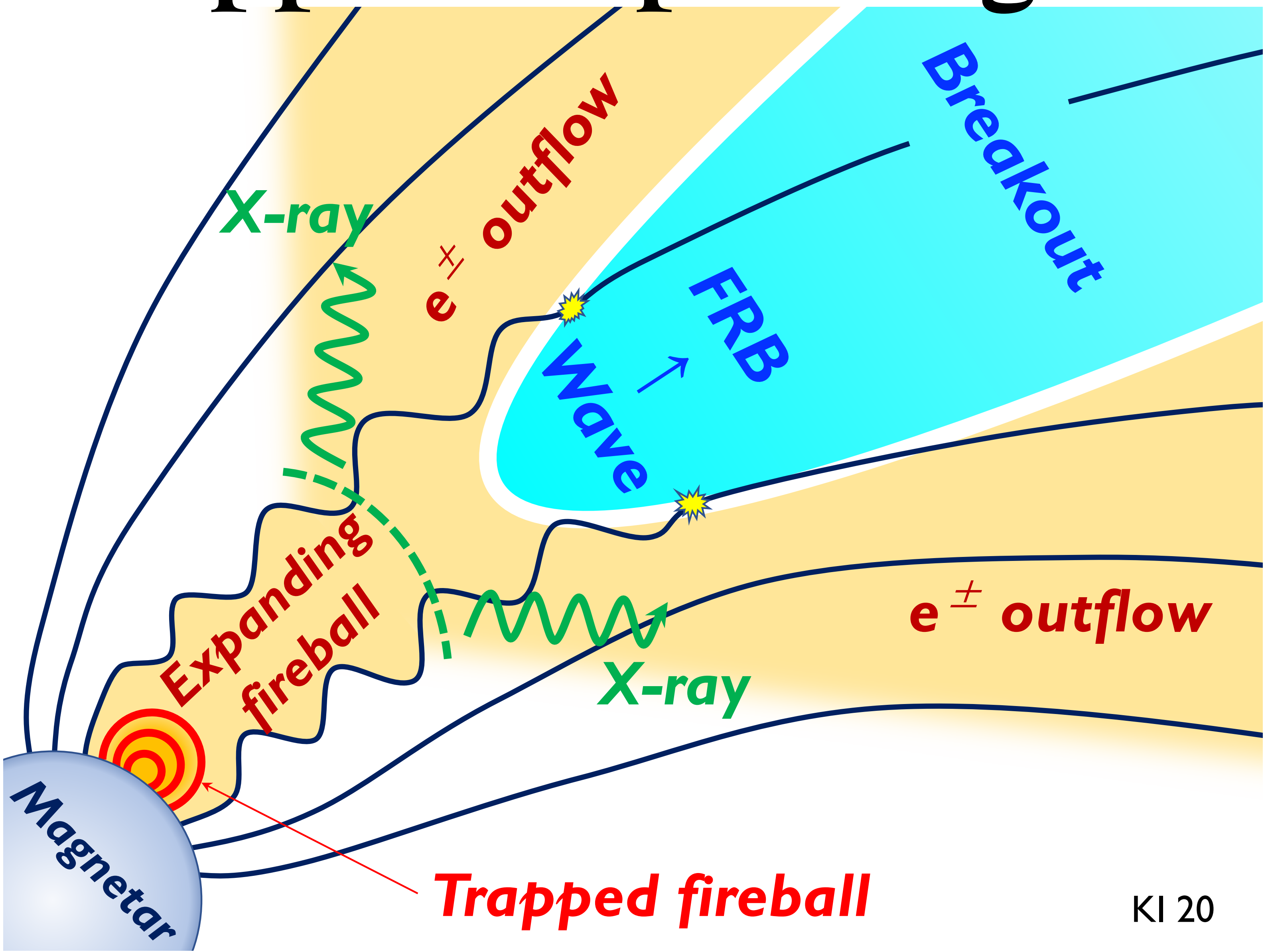
τ**>>1** at the surface of the trapped fireball

X-rays create $e^{\pm}$
→ Surrounding field should be open
→ Expanding fireball



T~80keV T<80keV

Trapped-Expanding FB



KI 20

$e^{\pm}\gamma$ Diffusion across B

Fireball acceleration

Meszaros & Rees 00

$$\Gamma \sim (r/R)^{3/2}, \quad T' \sim T_{\rm cut}(r/R)^{-3/2}.$$

Diffusion condition across B

$$t'_{\rm diff} \equiv \frac{\ell_\perp}{c}\tau_\perp < \frac{r}{c\Gamma} \equiv t'_{\rm dyn},$$

is satisfied at

$\sim 10^6$ cm

$$r = r_d \sim 1.9R, \quad \Gamma = \Gamma_d \sim 2.6,$$

→ *X-rays are released with $T \sim T_0$*

$e^{\pm}$ Outflow

Annihilation freezes out at t_{ann}~t_{dyn}

$$n'_{\pm}(r_d) \sim \frac{\Gamma_d}{\sigma_T r_d} \sim \frac{\Gamma_d^{1/3}}{\sigma_T R} \sim 2\times 10^{18}\,\mathrm{cm}^{-3}\,\Gamma_{d,0.4}^{1/3},$$

$e^{\pm}$ Outflow

$$n'_{\pm}(r) \sim \frac{\Gamma_d^{1/3}}{\sigma_T R}\frac{\Gamma_d}{\Gamma_{\pm}}\left(\frac{r}{r_d}\right)^{-3} \sim 3\times 10^{16}\,\mathrm{cm}^{-3}\,\Gamma_{d,0.4}^{10/3}\Gamma_{\pm}^{-1} r_7^{-3},$$

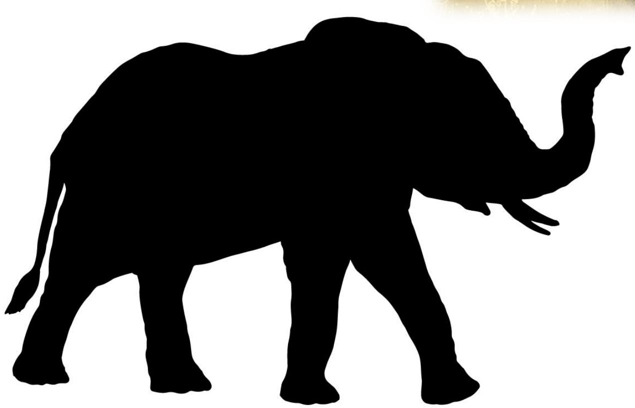
$L_{\pm}$ ~ 10^{36} r_7^{-1} erg/s

L_X~10^{41} erg/s
L_{FRB}~10^{38} erg/s

Thomson thin, but opaque for FRB

Energetics

X-ray burst
~ 10^{41} erg/s



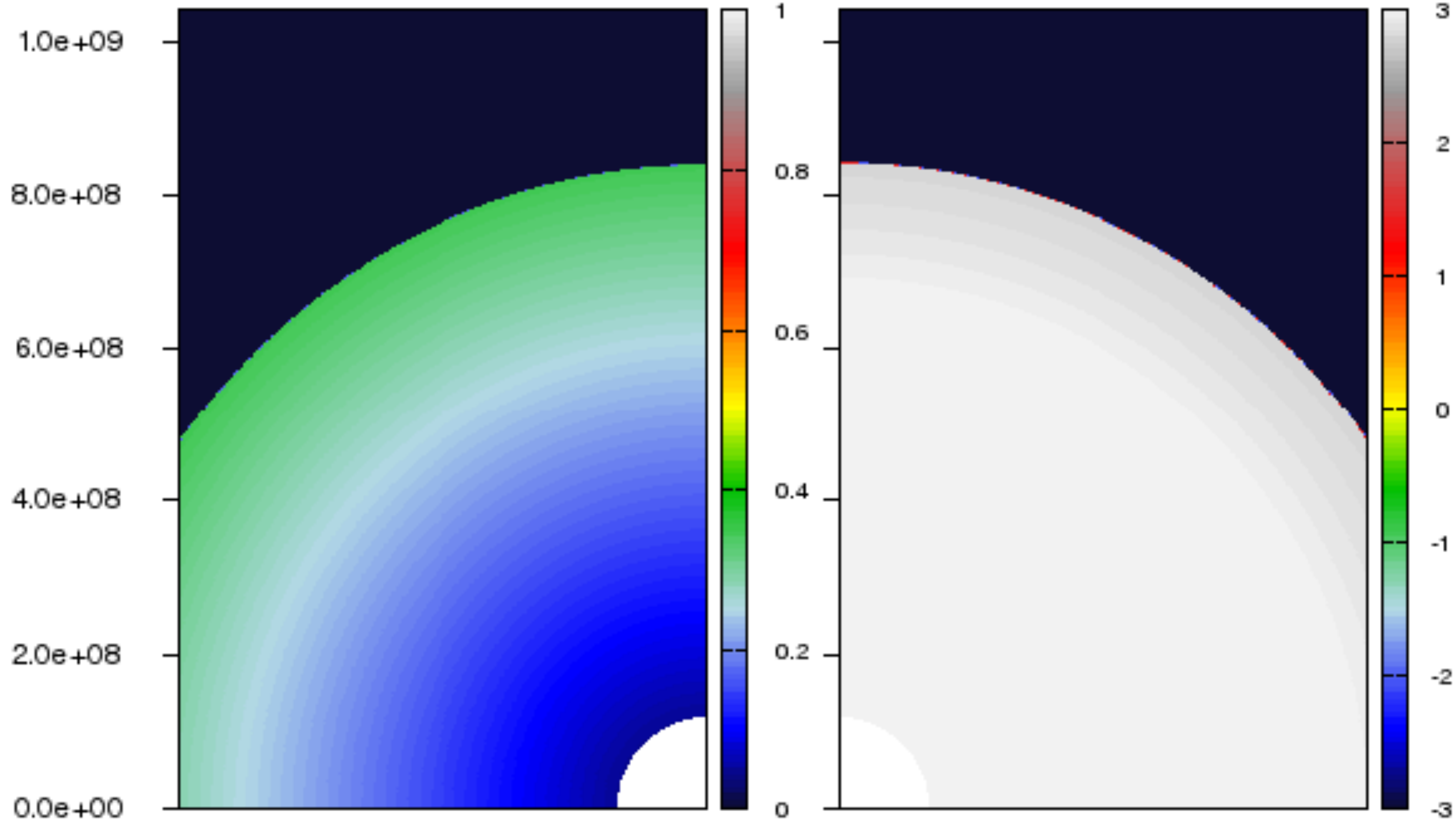
FRB ~ 10^{38} erg/s

$e^{\pm}$ ~ 10^{36} r_7^{-1} erg/s

Idea from GRB Breakout

Hamidani+ 20, 21

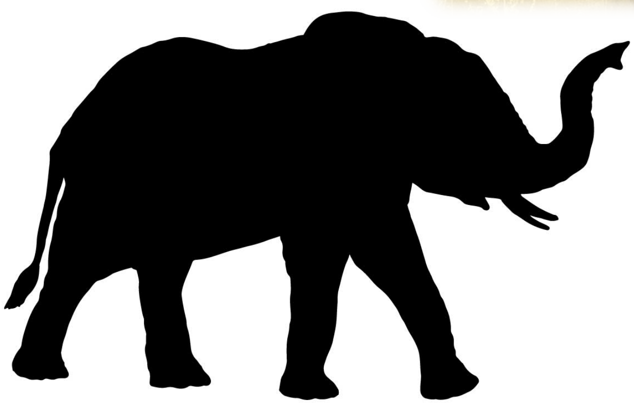
$\beta = \sqrt{\beta_r^2 + \beta_\theta^2}$ $log_{10}(\rho)$

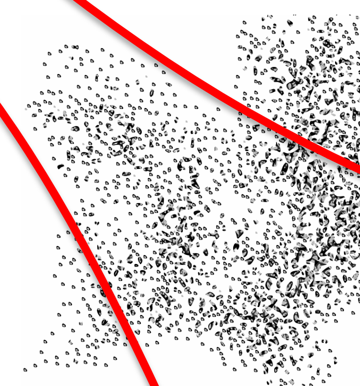


Velocity at t = 0.00 s Density at t = 0.00 s

Energetics

X-ray burst
~ 10^{41} erg/s





FRB ~ 10^{38} erg/s

$e^{\pm} \sim 10^{36}\, r_7^{-1}$ erg/s

Compton Drag is Strong

$e^{\pm}$ rest mass energy < Compton cooling energy

$$m_e c^2 < c\sigma_T u'_X t'_{dyn}$$

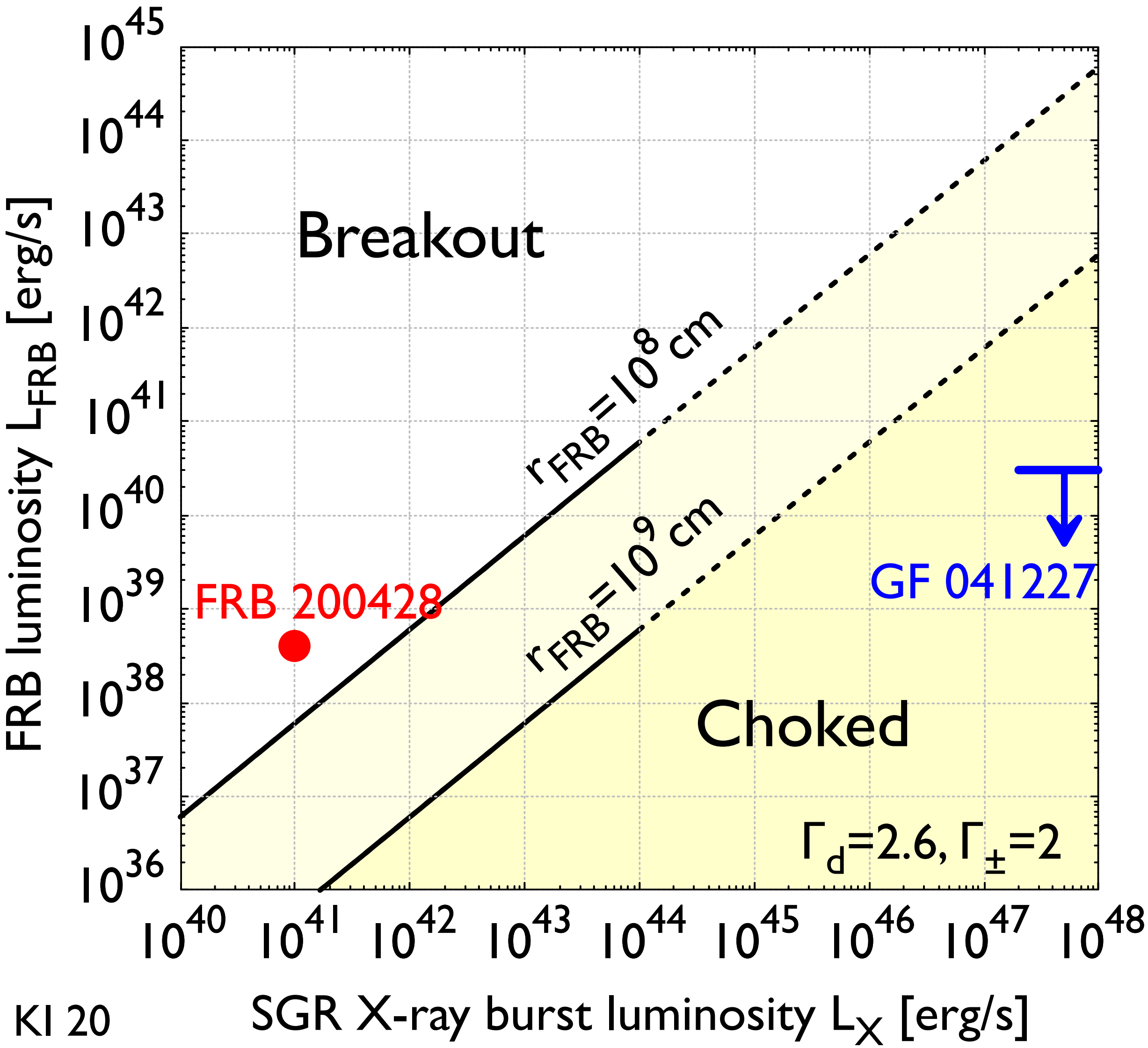
$$t'_{dyn} = r/c\Gamma_{\pm}$$

Breakout condition

$$u'_{\mathrm{FRB}} > n'_{\pm} c t'_{dyn} \sigma_T u'_X = \tau_T u'_X$$

$$1 < \frac{L_{\mathrm{FRB}}}{\tau_T L_X} \sim 2 \times 10^{-2} L_{\mathrm{FRB},38.6} L_{X,41}^{-1} \Gamma_{d,0.4}^{-10/3} \Gamma_{\pm}^{2} r_7^{2},$$

Breakout



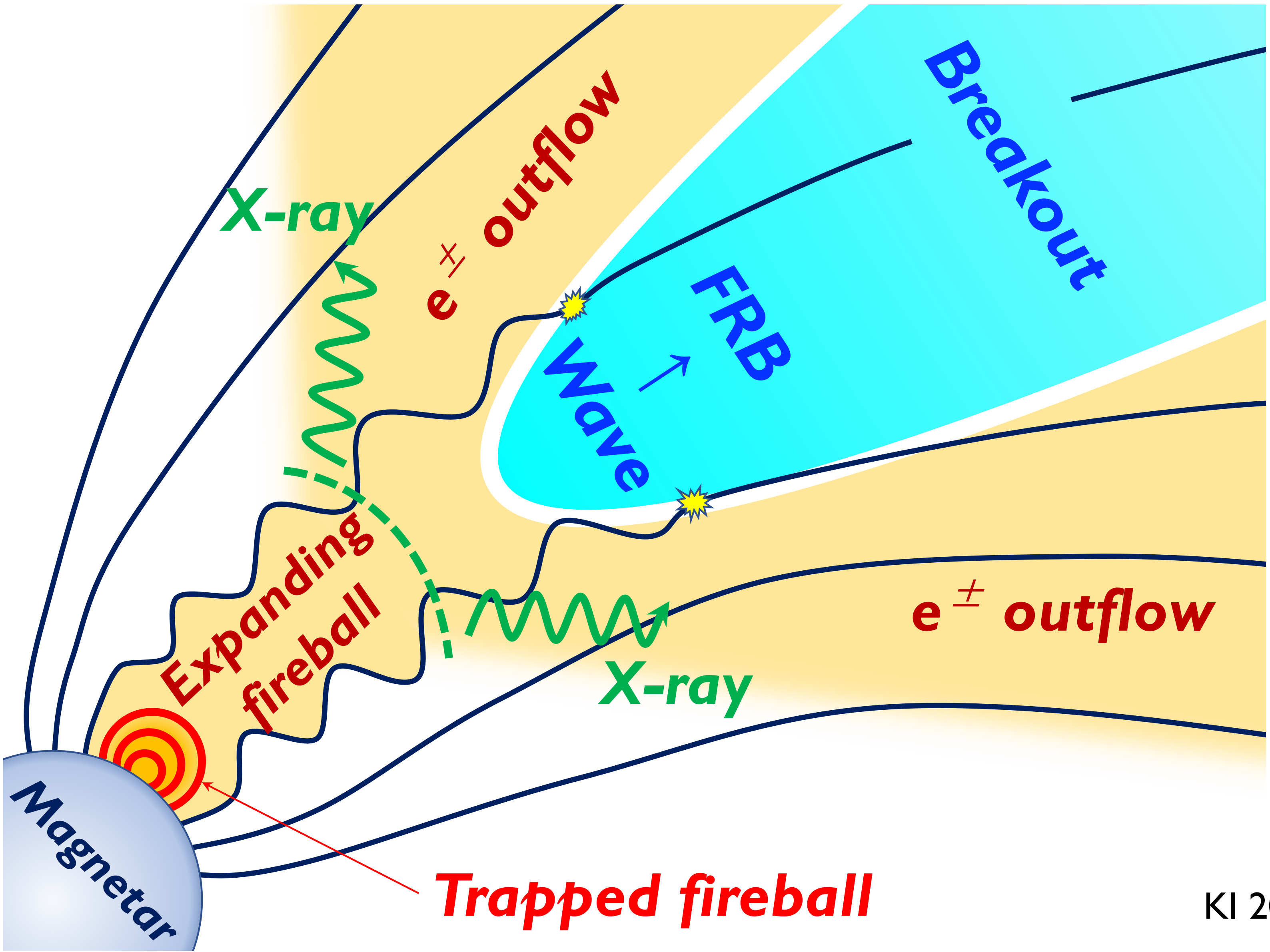
$e^{\pm}$ outflow is optically thick

FRB should break out the $e^{\pm}$ outflow

No X-ray burst with weak FRBs

No FRB with bright X-ray bursts

FRB Breakout from $e^{\pm}$



KI 20

Thank You