# Cosmological Fast Radio Bursts

## from Binary White Dwarf Mergers

Kunihito Ioka (KEK)

Kashiyama, KI & Mészáros 13

KEK HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

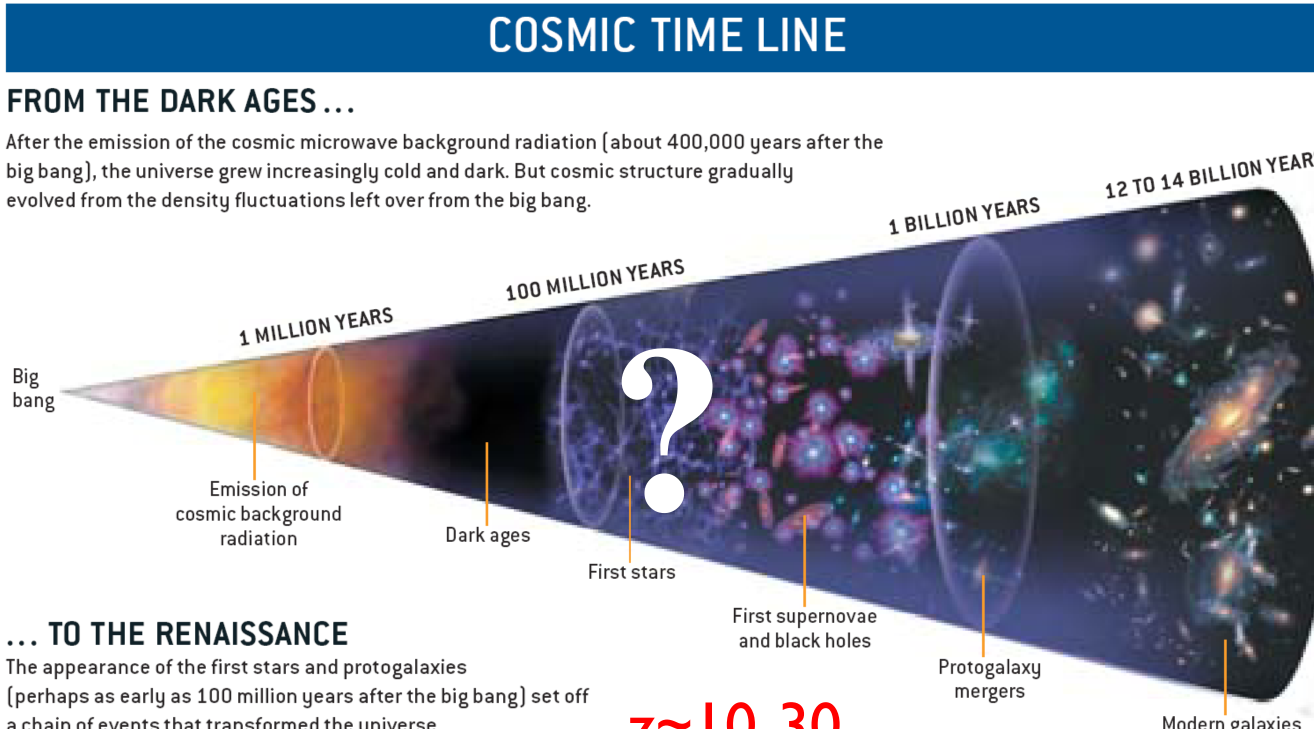
The Graduate University for Advanced Studies Sokendai

*~10 yr ago*

# GRB Cosmology

Massive star origin ⇒ High redshift GRBs

- Like QSO
- Like SN
- Star formation
- Reionization
- Metal, Dust
- Dark energy
- …




z~10-30

Larson & Bromm 02

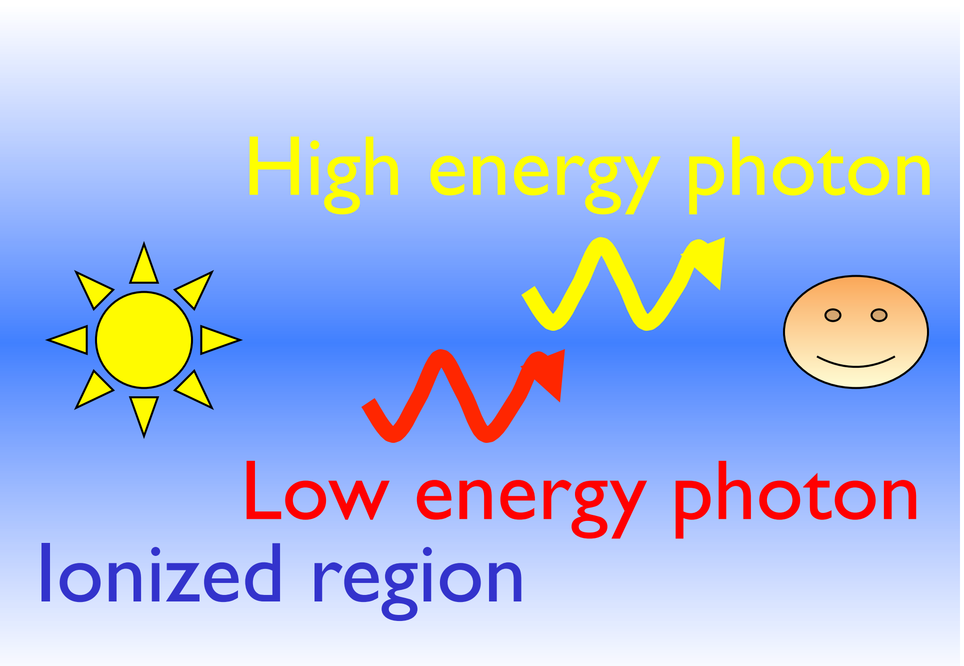
GRB

z~8

QSO, galaxy

GRBs are useful for probing high-z

# Radio Dispersion



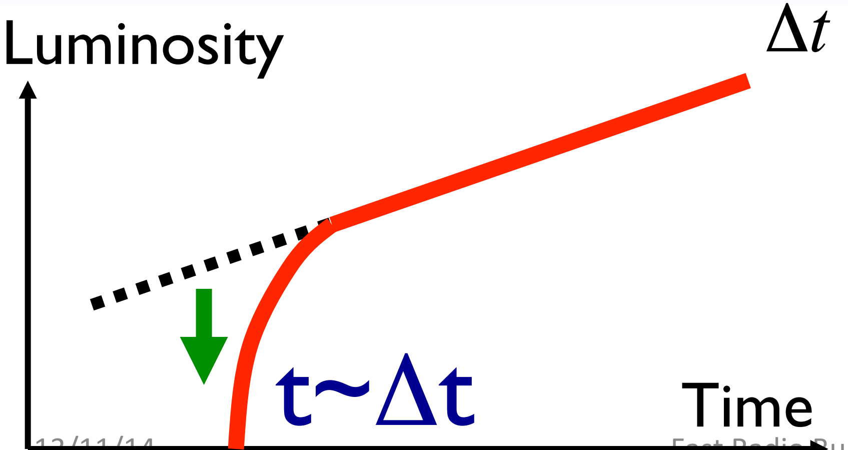

In a plasma, a light signal is delayed

$$\omega^2 = k^2c^2 + \omega_p^2$$

plasma frequency

$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}} = 5.63 \times 10^4 n^{1/2}\ \mathrm{s}^{-1}$$

$$\Delta t = 4.15\ \mathrm{s} \left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{-2} \left(\frac{\mathrm{DM}}{10^3\ \mathrm{pc\ cm}^{-3}}\right)$$



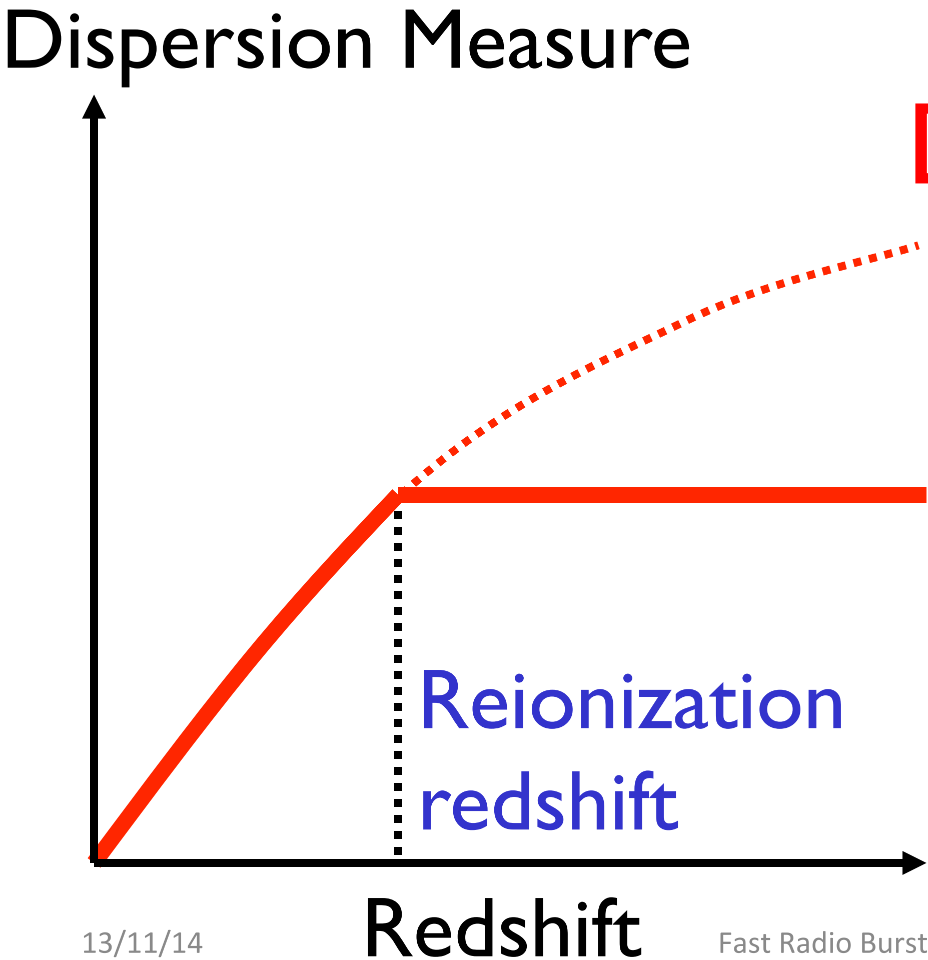

Distortion in light curve

⇒ DM

⇒ Reionization History

# Dispersion Measure

is the column density of free electrons along light path

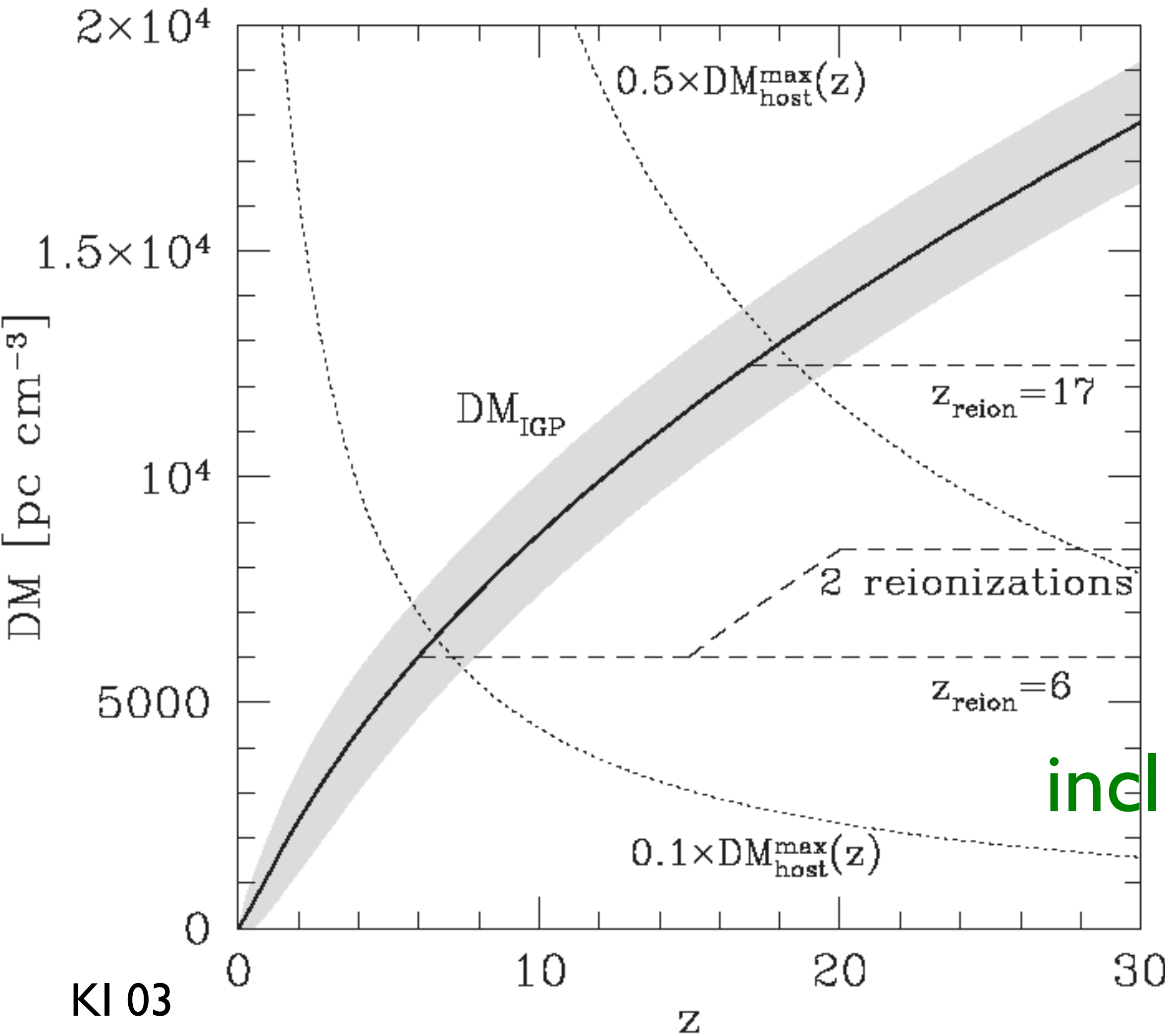



Dispersion Measure
↓
Reionization
History

Recombined electrons
provide no DM

KI 03, Inoue 04

# Intergalactic DM




KI 03

$$\Delta t = \int_0^z dz \frac{dt}{dz} \frac{1}{2} \frac{(1+z)\nu_p^2}{[(1+z)\nu]^2}$$

$$= \frac{e^2}{2\pi m_e c} \frac{1}{\nu^2} \times$$

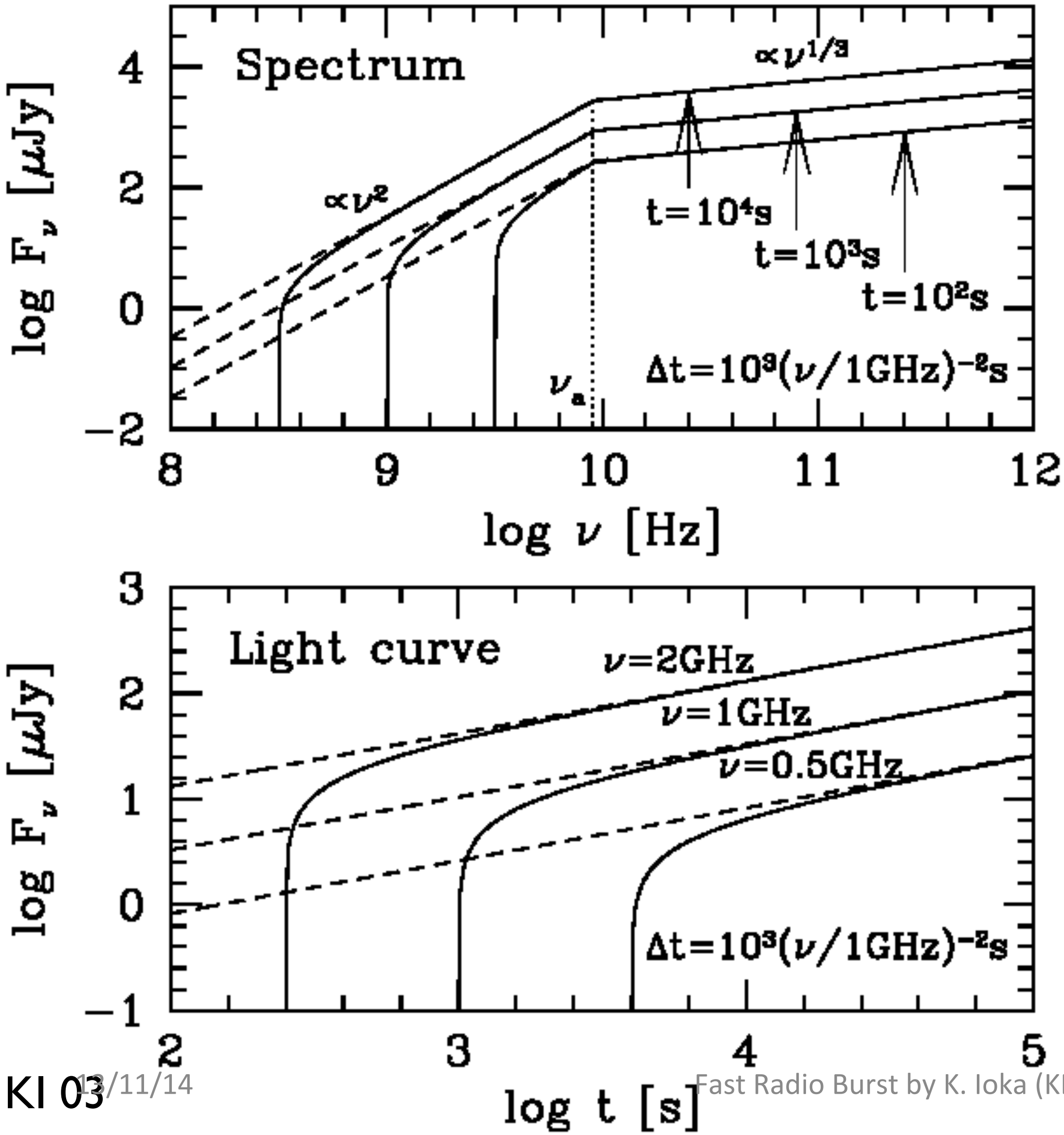
$$\frac{cn_0}{H_0} \int_0^z \frac{(1+z)dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

$DM_{IGP}$

including missing baryon

$DM_{Galaxy} \sim 30\text{-}10^3$ pc cm$^{-3}$

# DM from Afterglow

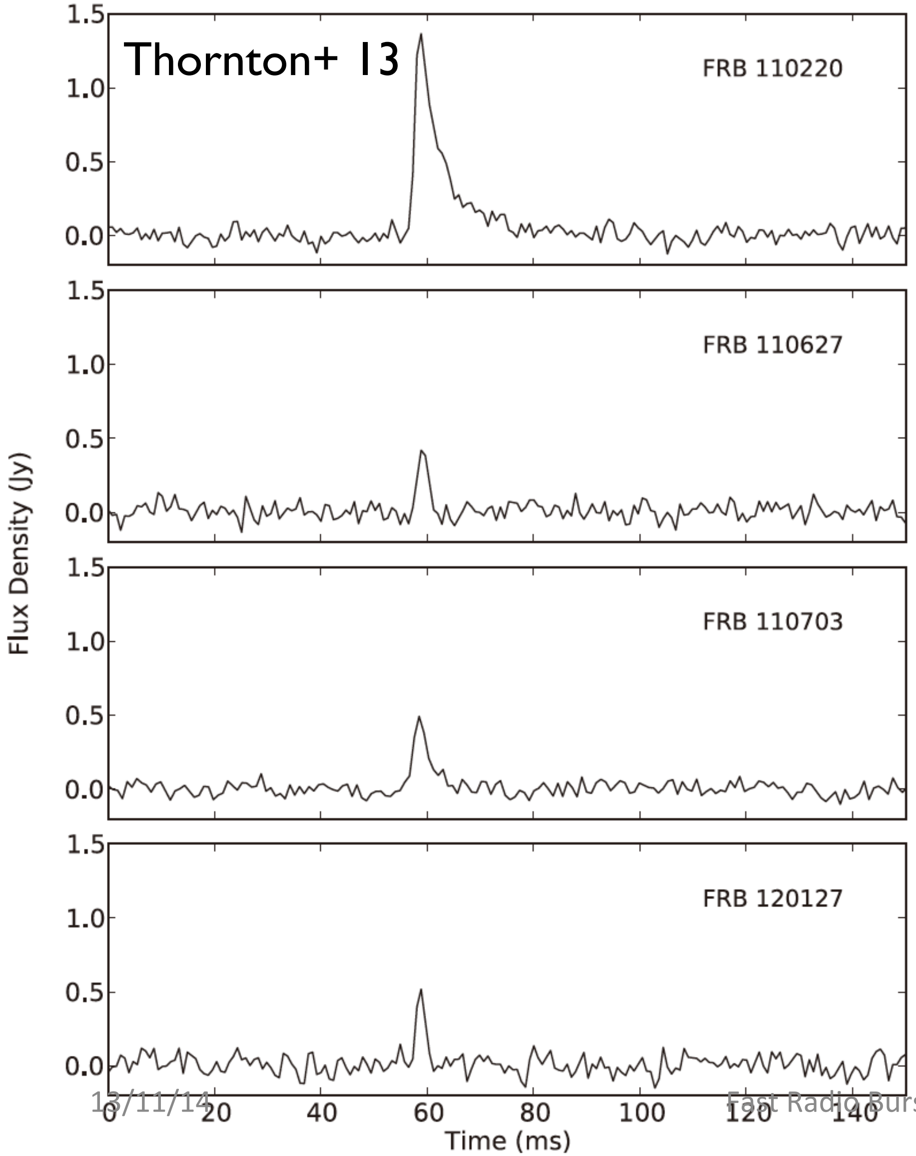



Distortion at t~Δt ⇒ DM

$\Delta t \propto \nu^{-2}$

Unfortunately radio afterglows are not so bright

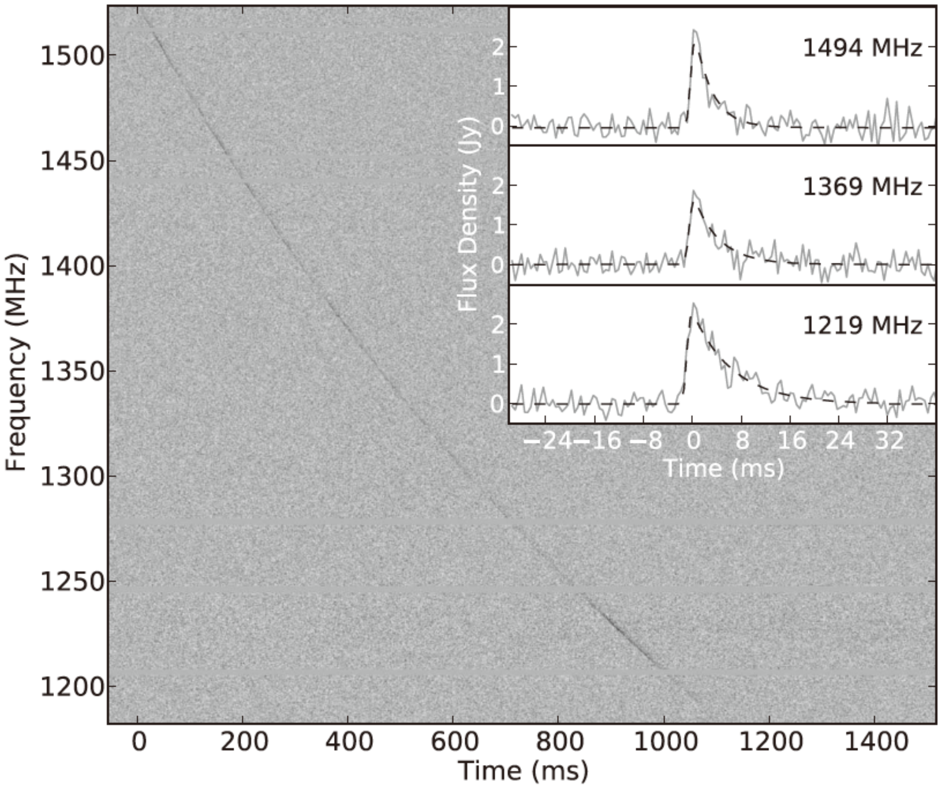
# Fast Radio Bursts



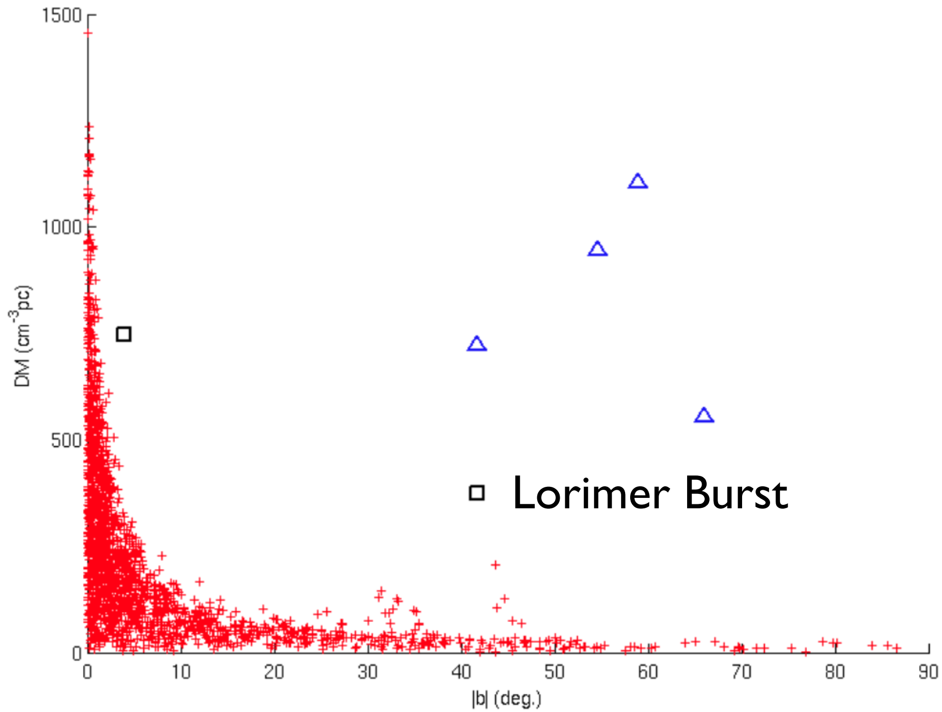


**F=0.6-8.0 Jy ms !!!**
**Most luminous radio transients if cosmological**

# Dispersion Measure




Thornton+ 13




Galactic latitude

$\delta t \propto DM \cdot \nu^{-2}$

**DM=500-1000 cm$^{-3}$ pc**

# Summary of FRB Obs.

- DM=500-1000 $cm^{-3}$ pc ($z=0.5-1$, $d_L \sim 2-6$Gpc)
- $S_\nu \sim$Jy $\Rightarrow$ $E_{iso} \sim 10^{38-40}$ erg
- $\delta t=5.6$ms,<4.3,1.4,1.1ms
  $\Rightarrow$ $c\delta t(1+z)^{-1} < 1500(1+z)^{-1}$ km
- Rate~$(1\pm0.5)\times10^4$/sky/day~$10^{-3}$/yr/galaxy
  $\Leftrightarrow$ Supernova rate $10^{-2}$/yr/galaxy
- No repeated bursts so far
- No counterparts so far

# Expected Rate

Hassall+ 13
Lorimer+ 13
Trott+ 13

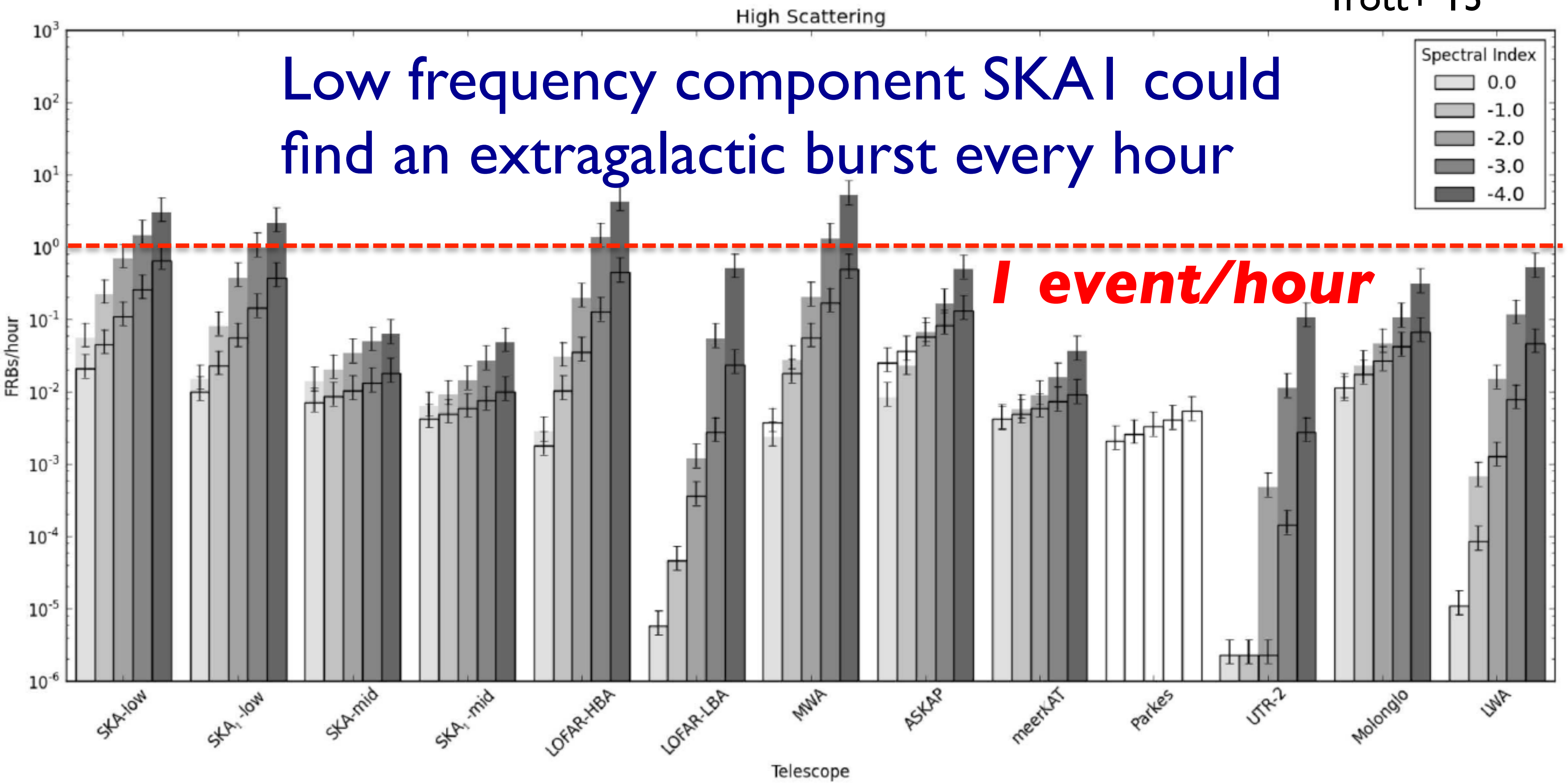


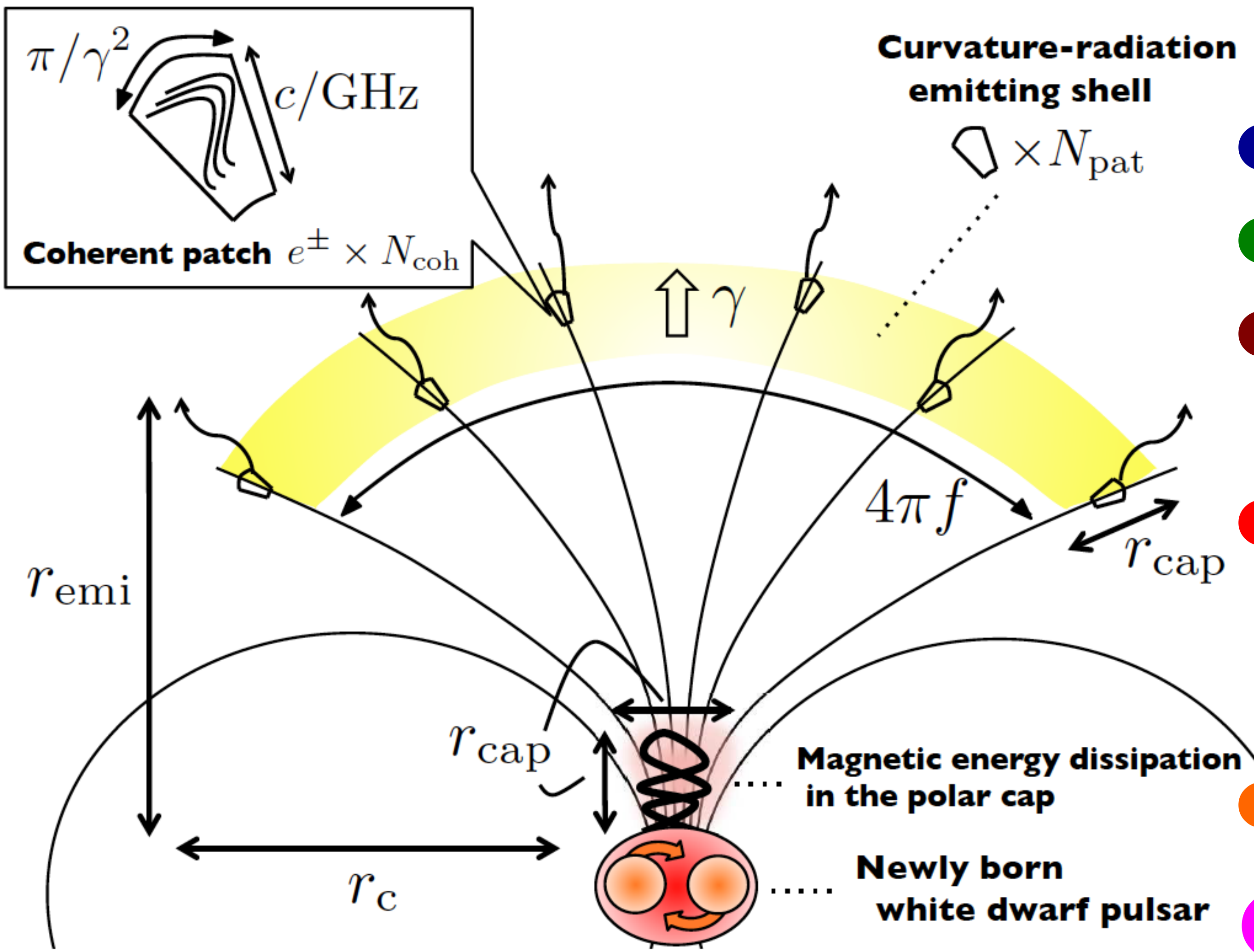

**Figure 2.** Expected number of FRBs per hour for various observatories in the high-scattering simulations. The solid bars show the number of FRBs detectable in imaging surveys, assuming different spectral indices of: 0.0 (white), -1.0, -2.0, -3.0 and -4.0 (darkest grey). The number of FRBs detectable in beamformed surveys are indicated by the corresponding transparent bars. The DM range used was $0 - 6000\ \mathrm{pc\ cm^{-3}}$.

# Possible Origins

- RRAT (Rotating Radio Transient; intermittent pulsar)
- Giant pulse from a msec/young pulsar
- Evaporation of BH — Rees 77; Blandford 77; Kavic+ 08; Keane+ 12
- SN into a nearby star — Colgate+ 71,75; Egorov & Postnov 09
- Magnetar giant flare — Popov & Postnov 07; Thornton+ 13
- Collapse of hypermassive NS — Falcke & Rezzolla 13; Zhang 13
- Binary NS mergers — Hansen & Lyutikov 01; Totani 13
- Superconducting cosmic strings — Cai+ 12
- Nearby flaring stars — Loeb+ 12

# Binary White Dwarf Mergers?

Kashiyama, KI & Meszaros 13




- Massive WD
- SN Ia
- Short GRB via →NS
- WD pulsar CR e$^{\pm}$ excess

Kashiyama+ 11

- GW sources
- ***FRB?***

# Minimum Requirements

- Energetics
- Timescale
- Event rate

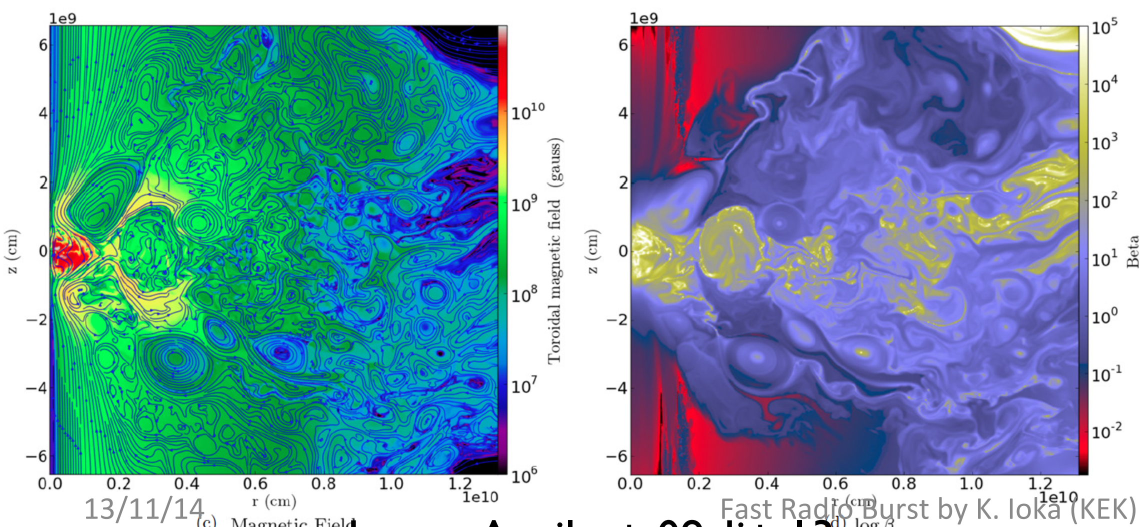
# Energetics

**Magnetic Energy**

$B_{obs,max} \sim 10^9$G

$$E_B \approx \frac{B^2}{8\pi} \times \frac{4\pi r^3}{3} \sim 2\times 10^{43}\,\mathrm{erg}\; B_9^2 r_{8.7}^3$$

WD-WD merger ⇒ Differential rotation ⇒ B




Loren-Aguilar+ 09, Ji+ 13

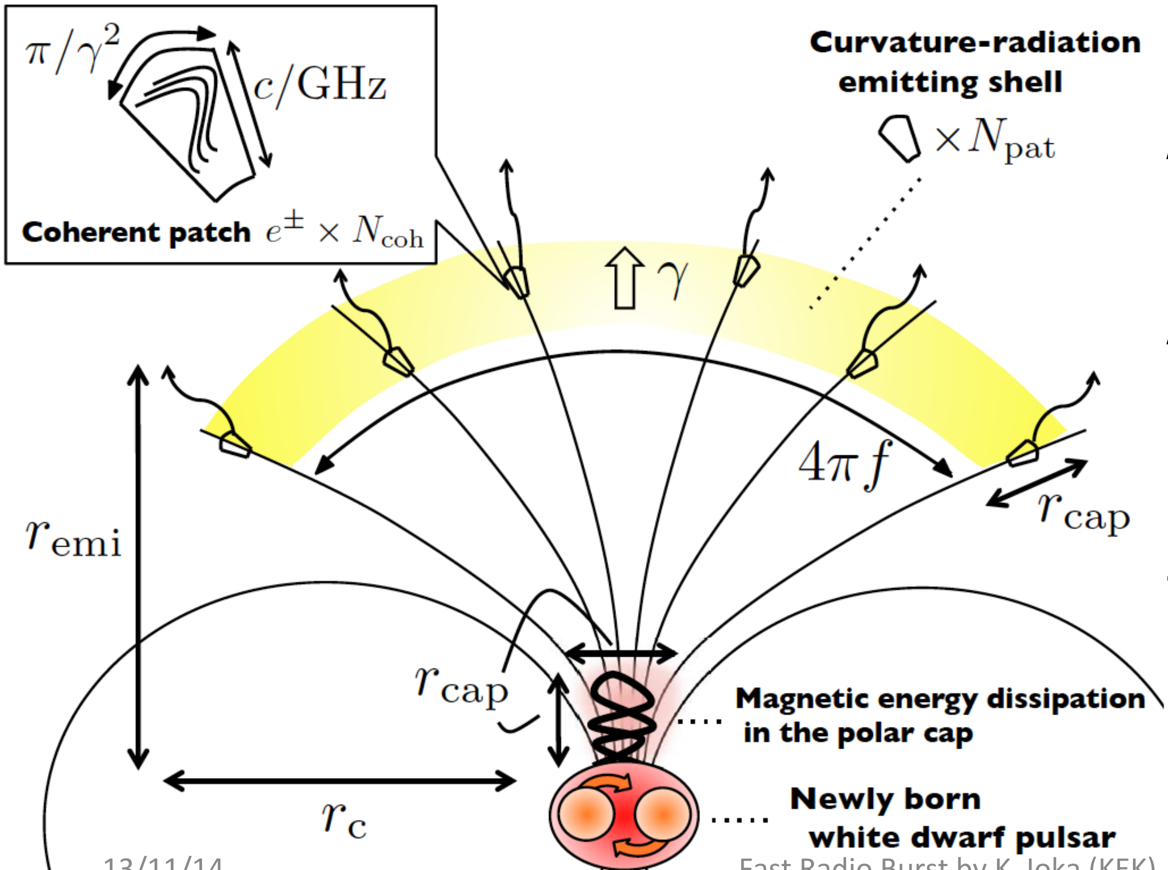
$$E_{max} \approx \frac{GM^2}{r} \approx 10^{50}\,\mathrm{erg}$$

$$\Omega \approx \frac{v}{r} \sim 1\ \mathrm{s}^{-1} r_{8.7}^{-3/2}$$

# Timescale

WD radius

$$c\delta t(1+z)^{-1} \leq 1.5\times 10^{8}(1+z)^{-1}\ \mathrm{cm} \quad < 10^{8.7}\mathrm{cm}$$




$$r_{\rm cap} \approx r\left(\frac{r\Omega}{c}\right)^{1/2}$$

$$\sim 6.7\times 10^{7}\ \mathrm{cm}\ r_{8.7}^{3/2}\Omega_{0}^{1/2}$$

$$\frac{r_{\rm cap}}{c} \sim 2.3\ \mathrm{ms}\ r_{8.7}^{3/2}\Omega_{0}^{1/2}$$

# Event Rate

**WD-WD merger rate**

$$R_{WD^2} \sim 10^{-2} - 10^{-3}\ \mathrm{yr}^{-1}\ \mathrm{galaxy}^{-1}$$

~4000 WDs in SDSS

Radial velocity ⇒ Binary fraction & distribution $n(a) \propto a^{\alpha}$

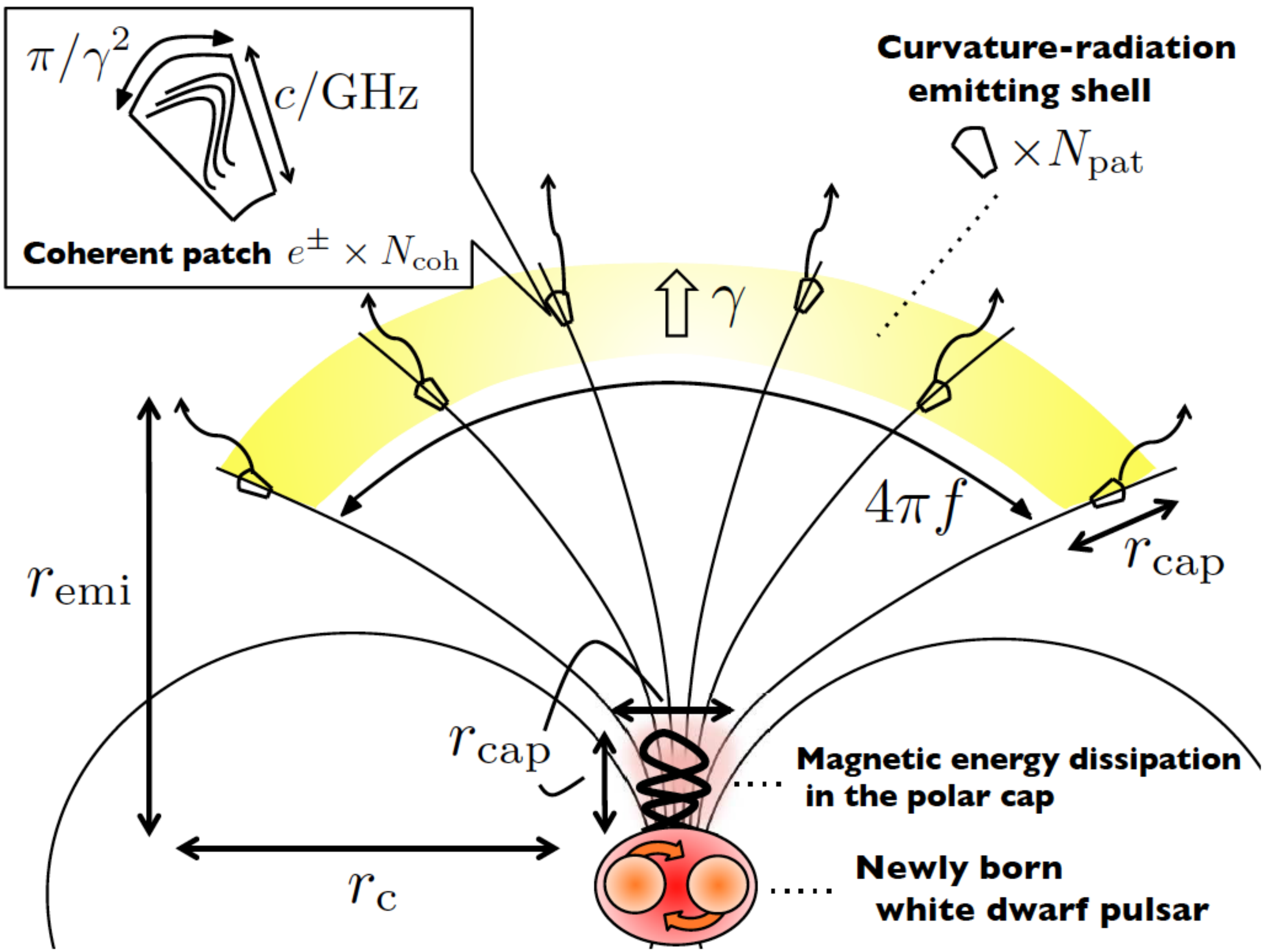
**Table 1**
Local WD Merger Rates and 95% Confidence Limits

Badenes & Maoz 12

| $\alpha$ | $f_{\rm bin}$ | Total Rate ($10^{-13}$ mergers $\mathrm{yr}^{-1}$ $M_\odot^{-1}$) | Super-Chandrasekhar Rate ($10^{-13}$ mergers $\mathrm{yr}^{-1}$ $M_\odot^{-1}$) |
|---|---|---|---|
| Entire range | 0.014–0.32 | 1.4 (0.16, 7.2) | 0.1 (0.016, 0.4) |
| 1.0 | 0.11–0.24 | 0.3 (0.065, 0.5) | 0.03 (0.017, 0.045) |
| 0.0 | 0.046–0.22 | 1.0 (0.46, 2.2) | 0.08 (0.03, 0.16) |
| −1.0 | 0.021–0.11 | 3.0 (1.0, 6.0) | 0.16 (0.05, 0.3) |

# Binary White Dwarf Mergers?

Kashiyama, KI & Meszaros 13



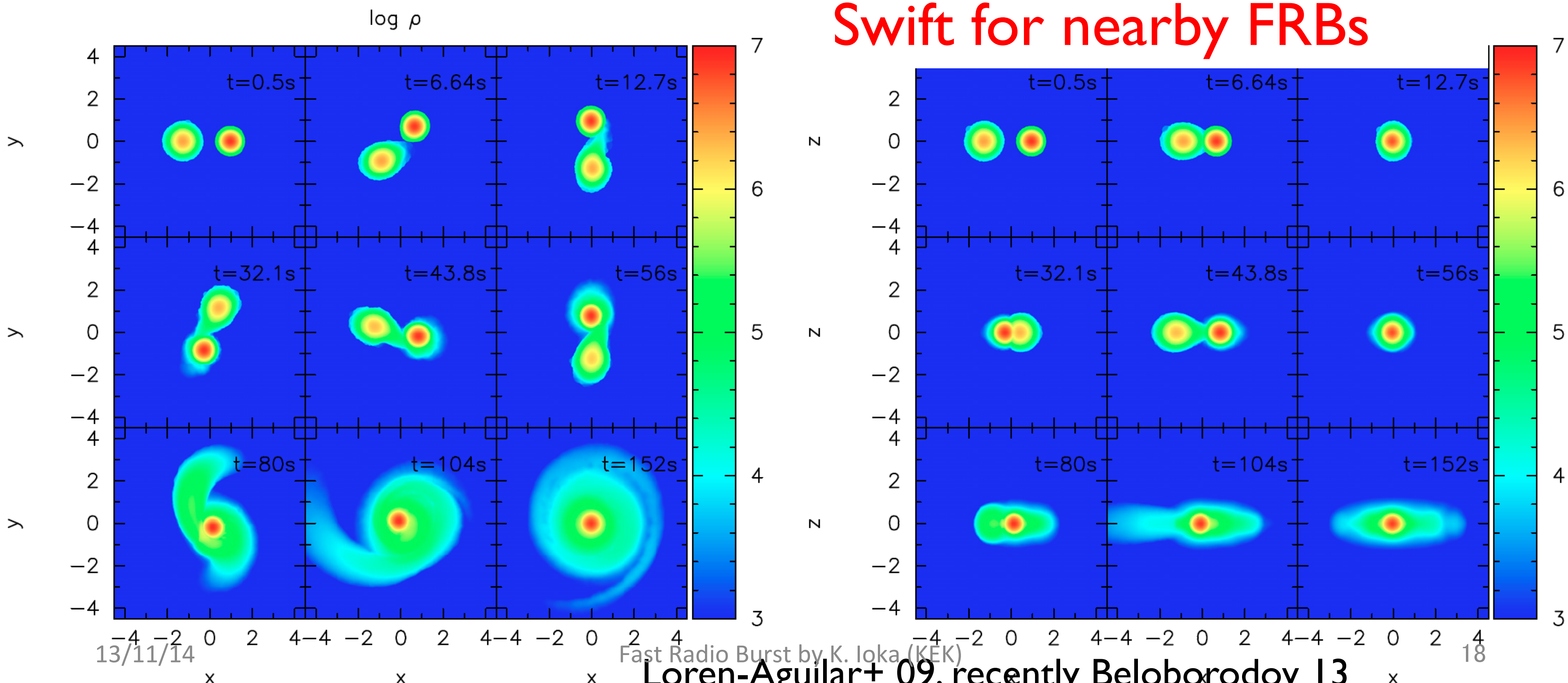

- Energetics $E_B \sim 10^{40}$erg
- Timescale $r_{cap}/c \sim$ms
- Event rate ~SN Ia
- SN Ia as a counterpart?

# Counterparts

- Supernova Ia (Double degenerate model)
- X-ray debris disk

$L_X < 10^{47}$ erg/s for ~100sec

Swift for nearby FRBs

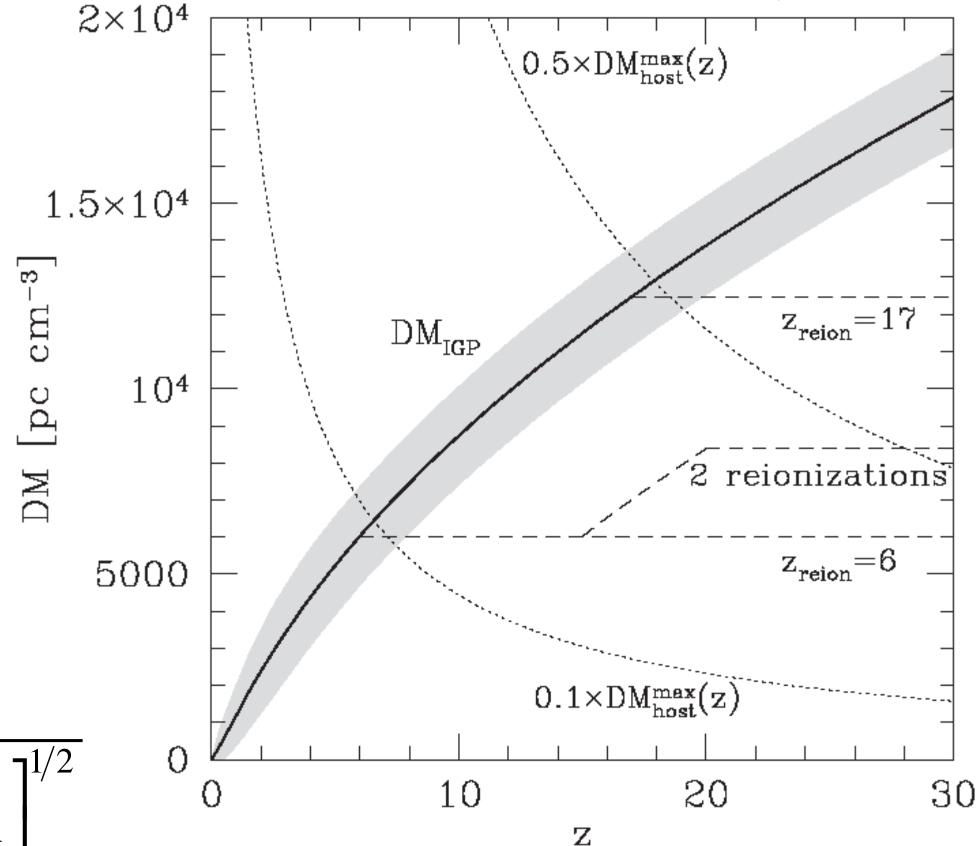



Loren-Aguilar+ 09, recently Beloborodov 13

# FRB Cosmology

KI 03
McQuinn 13

- Reionization
- Missing baryon
- Dark energy, cosmological parameters




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

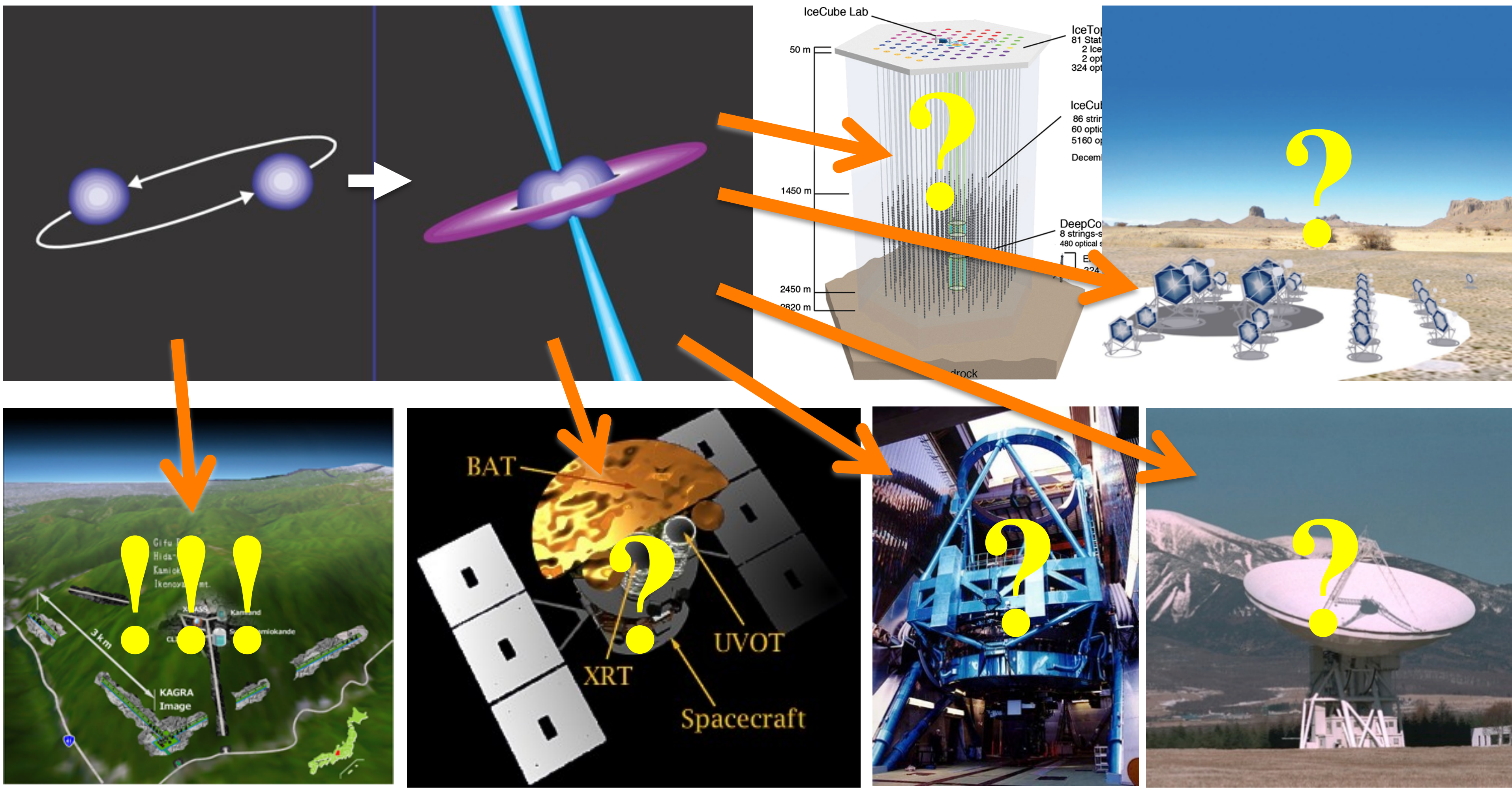
$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

***Fast radio bursts as cosmological tools***

***New frontier?***

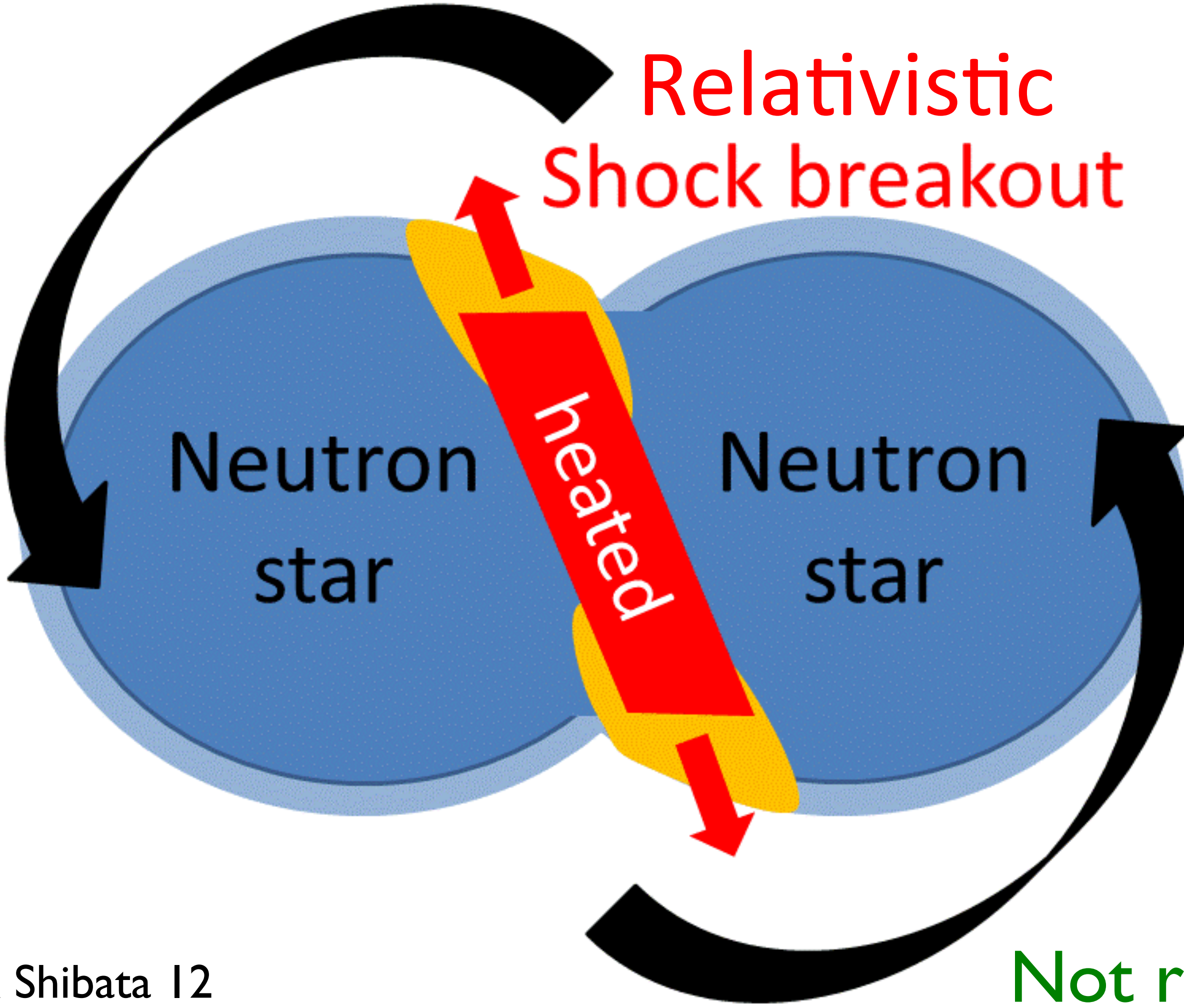
# Counterparts to GW

Gravitational Wave Sources Neutrino Gamma-ray




Gravitational wave X-ray IR-Opt Radio

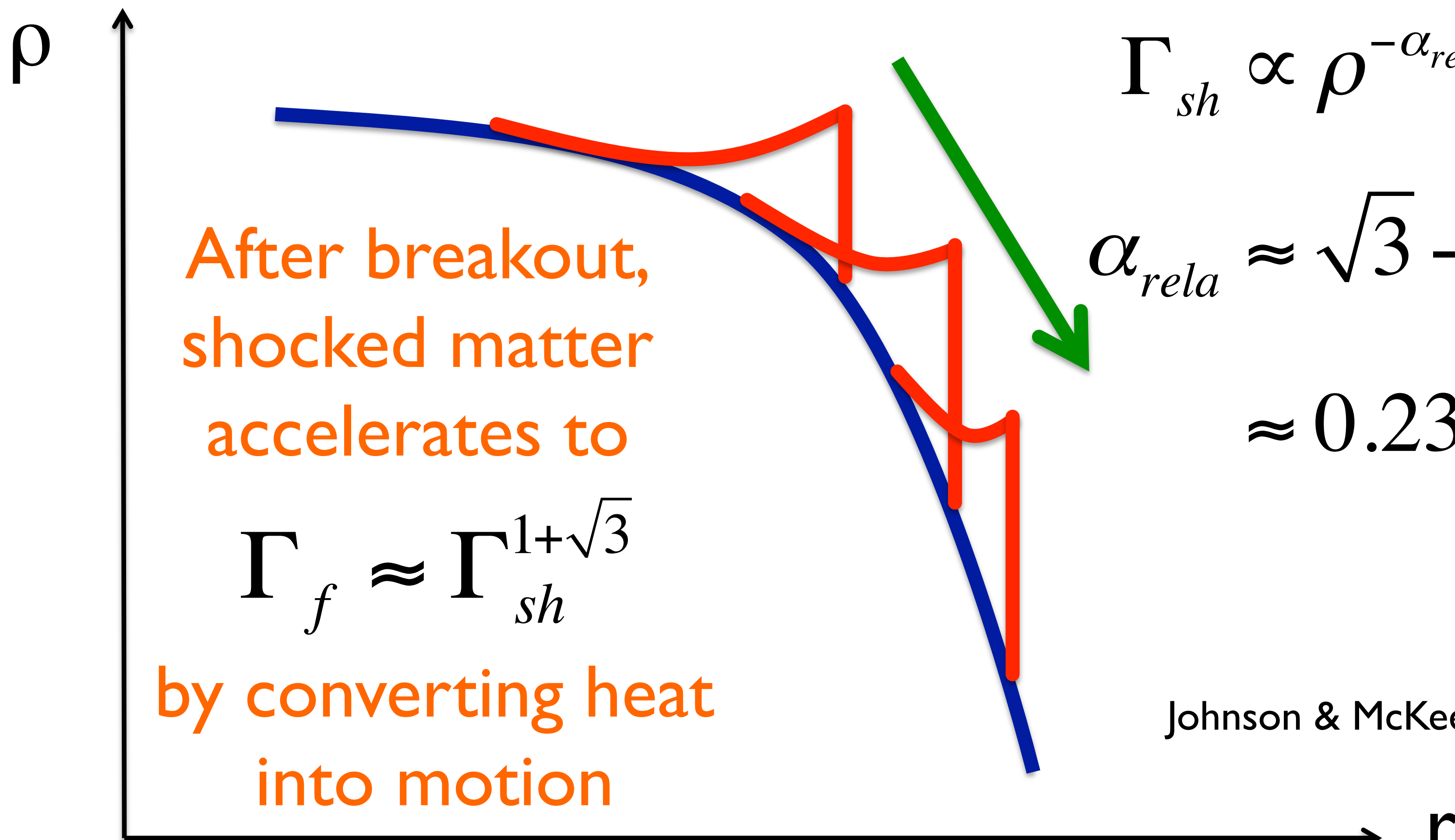
# Relativistic Shock Breakout




Kyutoku, KI & Shibata 12

Not resolved yet
by numerical simulation

# Relativistic Shock Acceleration




After breakout, shocked matter accelerates to

$$\Gamma_f \approx \Gamma_{sh}^{1+\sqrt{3}}$$

by converting heat into motion

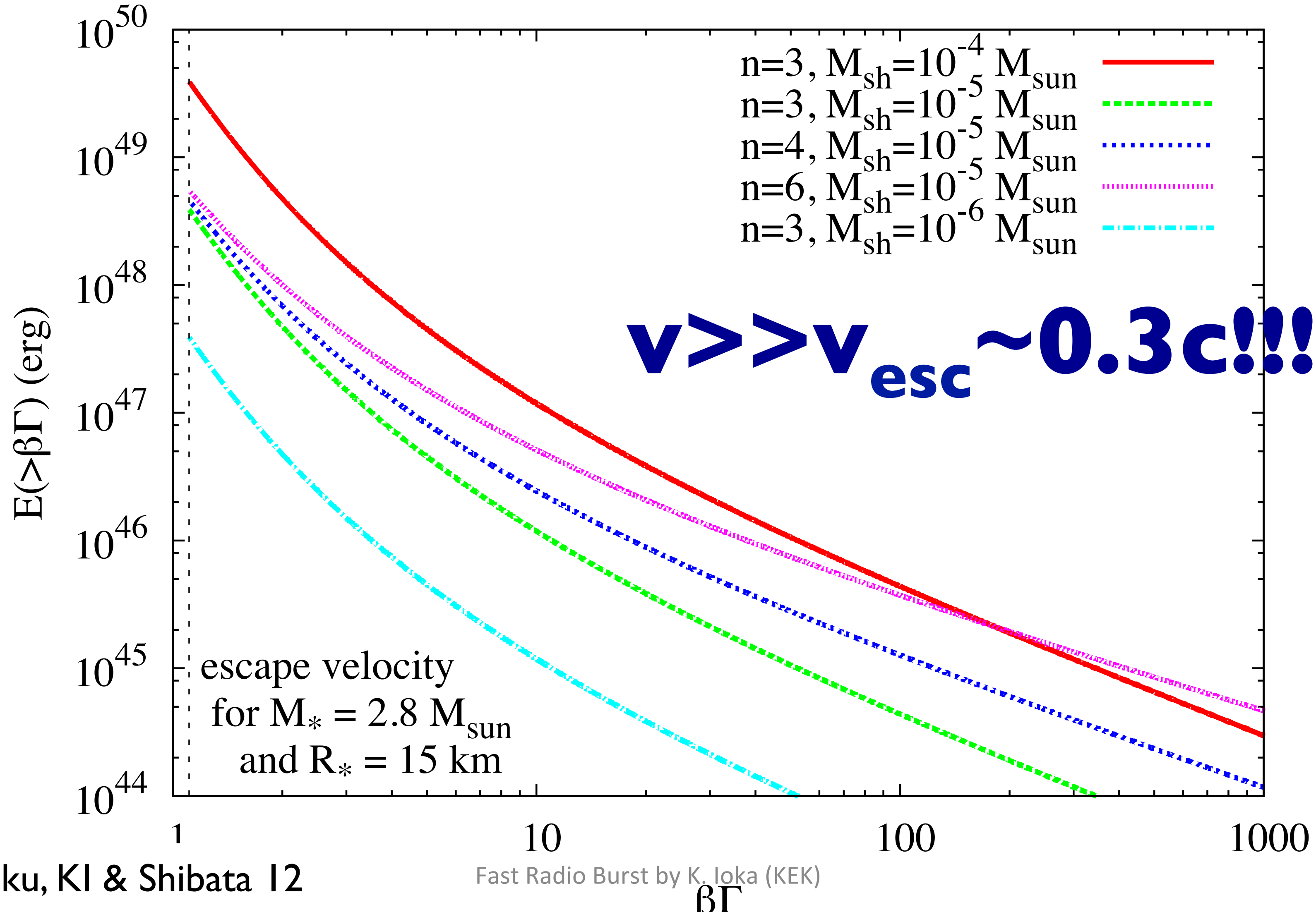
$$\Gamma_{sh} \propto \rho^{-\alpha_{rela}}$$

$$\alpha_{rela} \approx \sqrt{3} - \frac{3}{2}$$

$$\approx 0.232$$

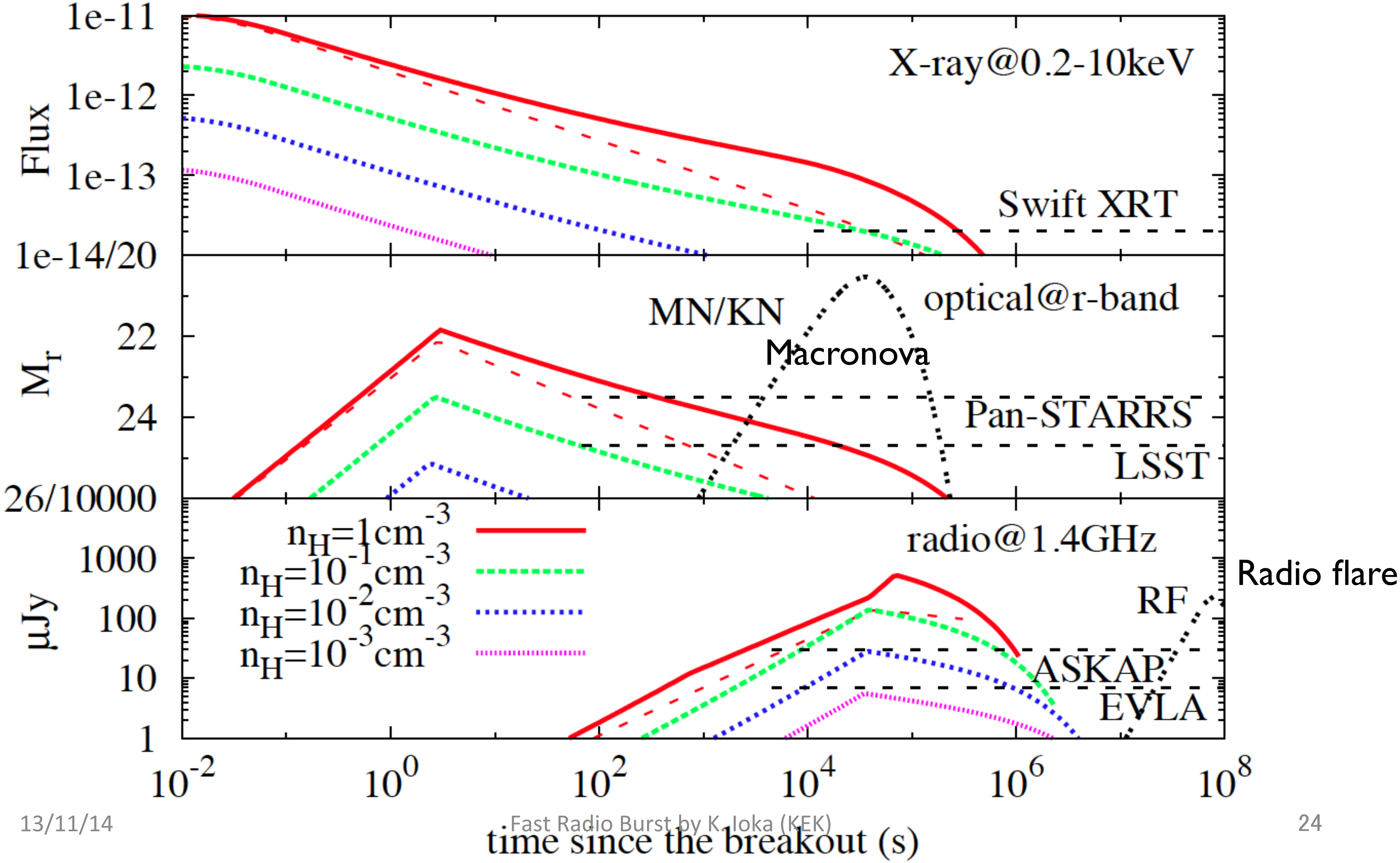
Johnson & McKee 71

# Relativistic Outflow




Kyutoku, KI & Shibata 12

# Early & High-Energy Emission



# Summary

- Fast Radio Burst

Thornton+ 13

- Dispersion Measure ⇒ Cosmological?

KI 03

- Binary White Dwarf Merger
  - Energetics ✔, Timescale ✔, Event Rate ✔
  - SN Ia, X-ray debris disk

Kashiyama, KI & Mészáros 13

- FRB Cosmology

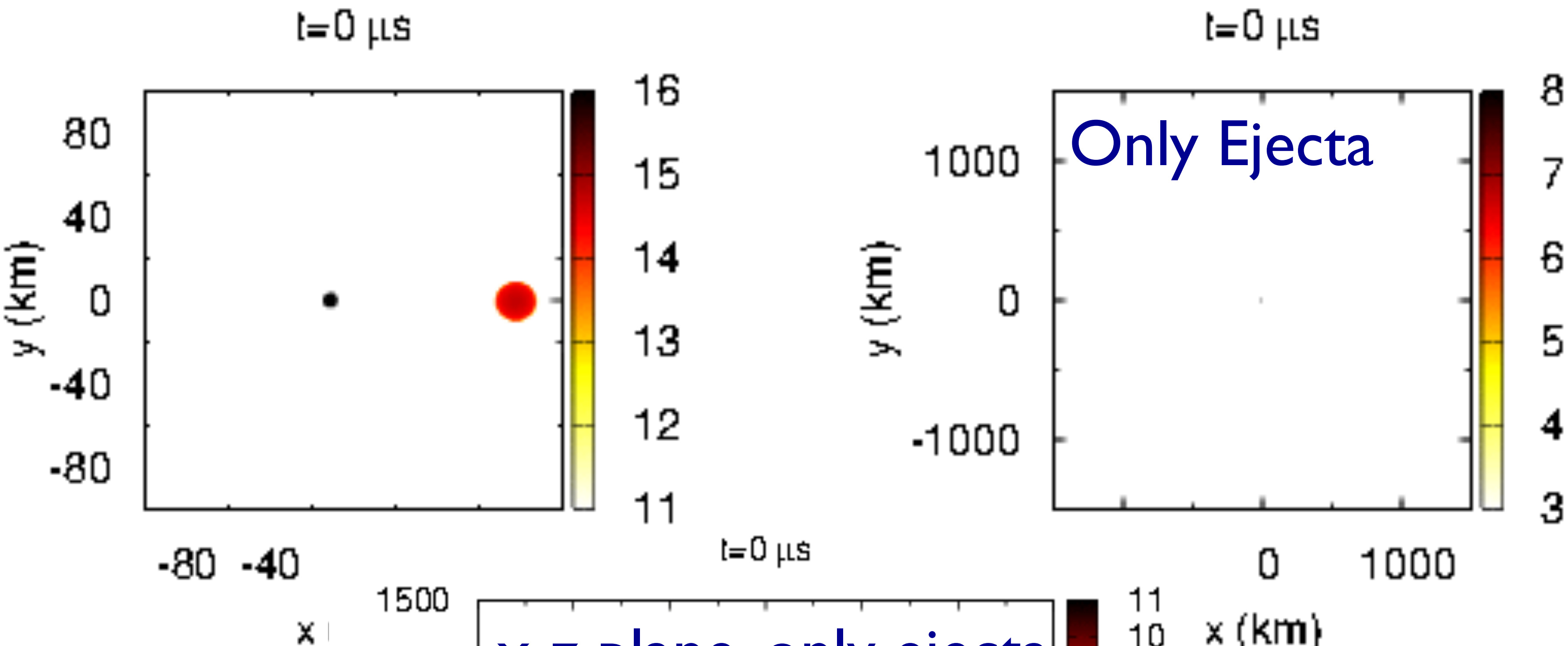
- Ultrarelativistic EM Counterpart to $NS^2$

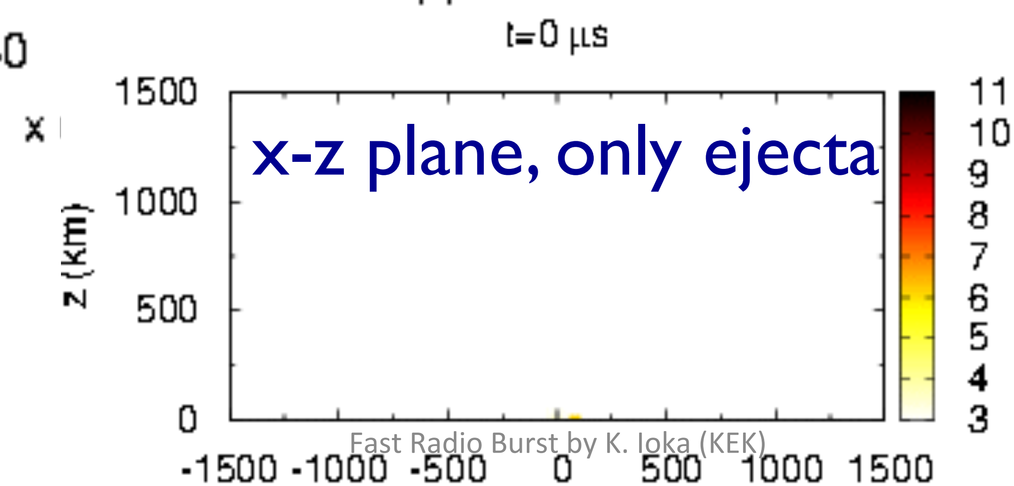
Kyutoku, KI & Shibata 13

# Thank You

# BH-NS Merger

©Kyutoku

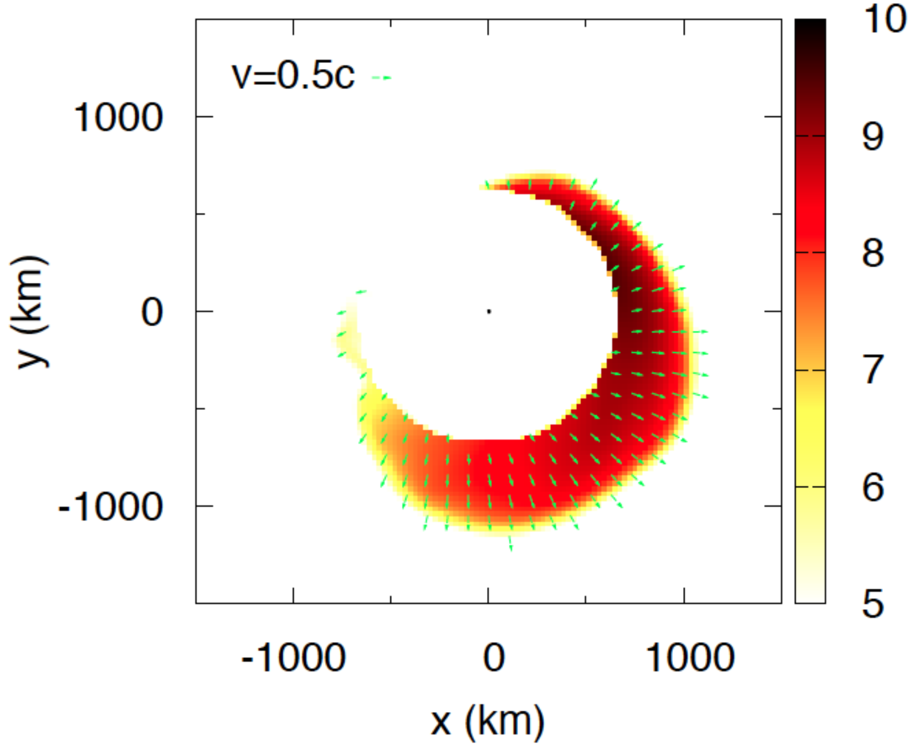


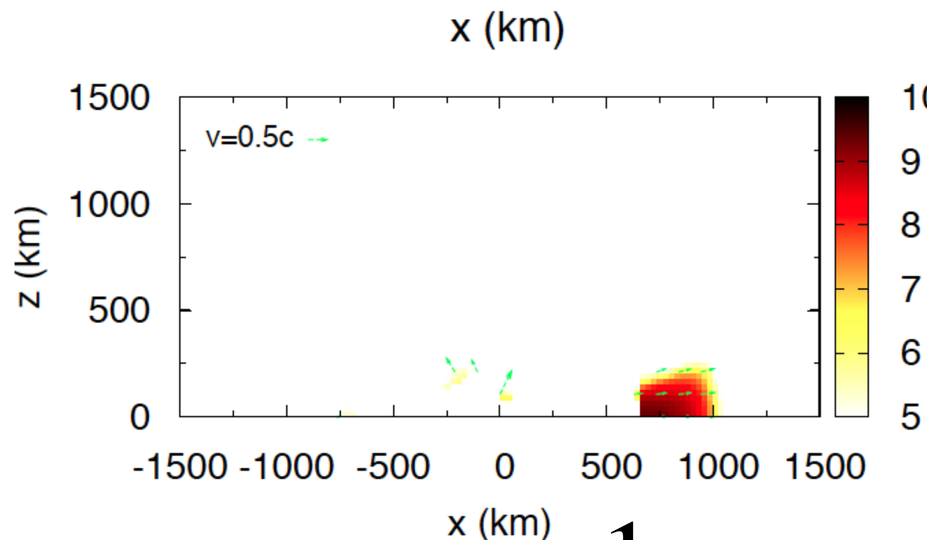




Full GR
Q=5
$\chi$=0.75
H4 EOS

Kyutoku, KI & Shibata 13

# Anisotropic Mass Ejection




$$\theta_{ej} \approx \frac{1}{5}$$

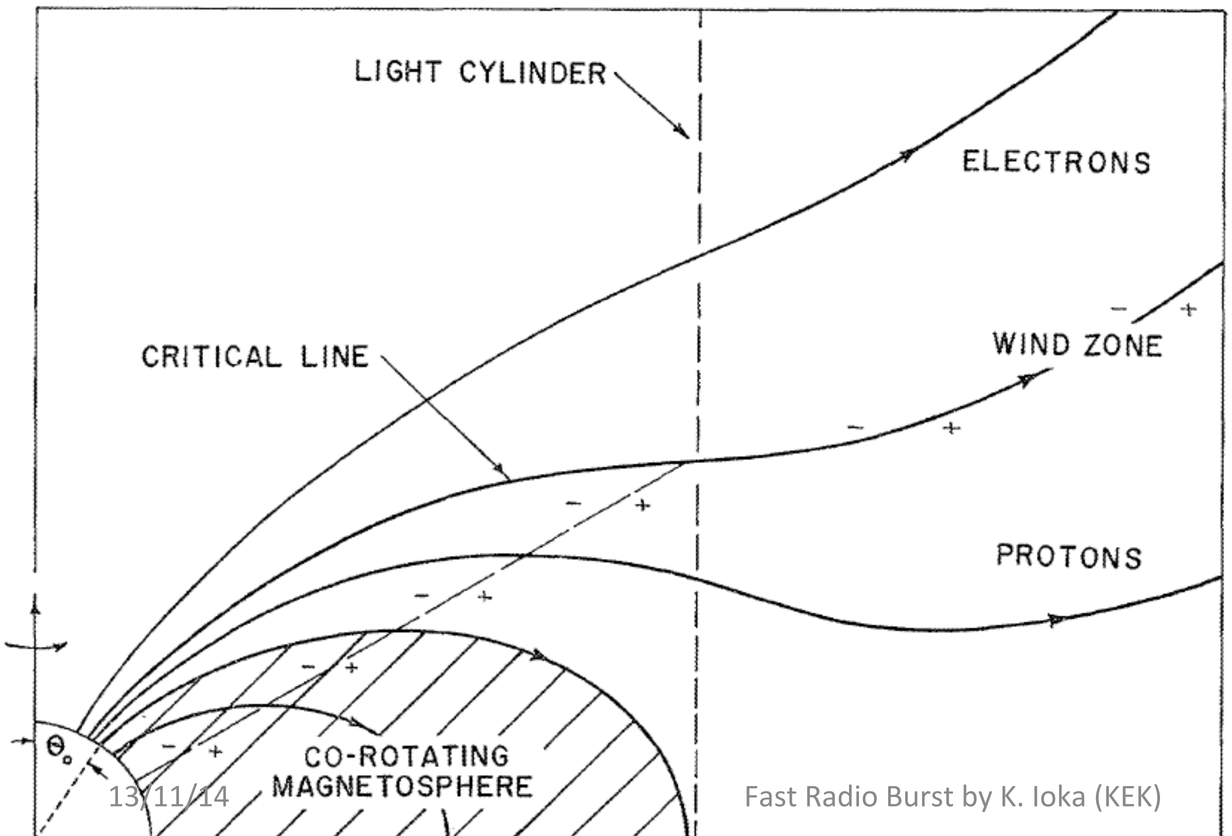
$$\varphi_{ej} \approx \pi$$

***Viewing angle diversity***
***Polarization***
***Proper motion***

Kyutoku, KI & Shibata 13

# Spin Down Luminosity

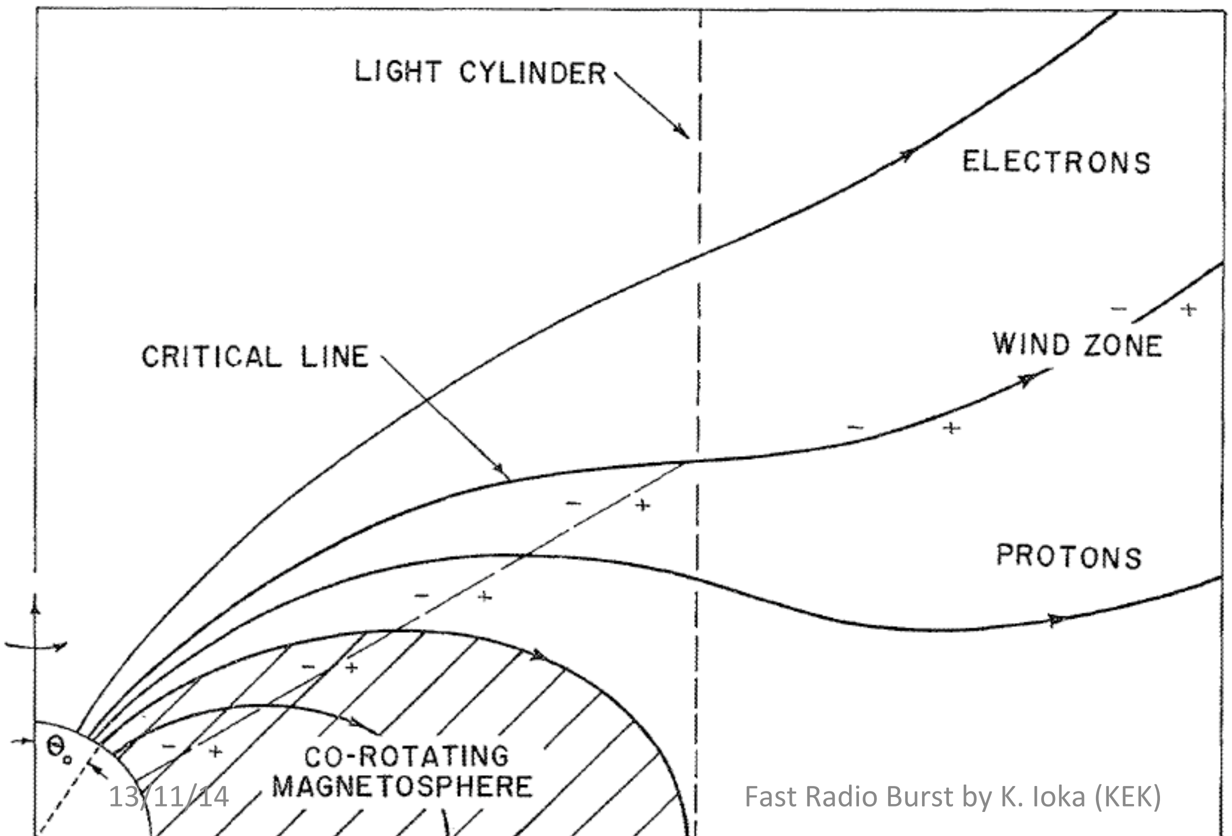
$$L_{spin} \approx \frac{B^2 r^6 \Omega^4}{c^3} \sim 1.7 \times 10^{38} \mathrm{erg\ s^{-1}} B_9^2 r_{8.7}^6 \Omega_0^4 \ll 10^{43}\ \mathrm{erg/s}$$




B reconnection
⇒ FRB
like solar flares,
magnetar flares

# Acceleration

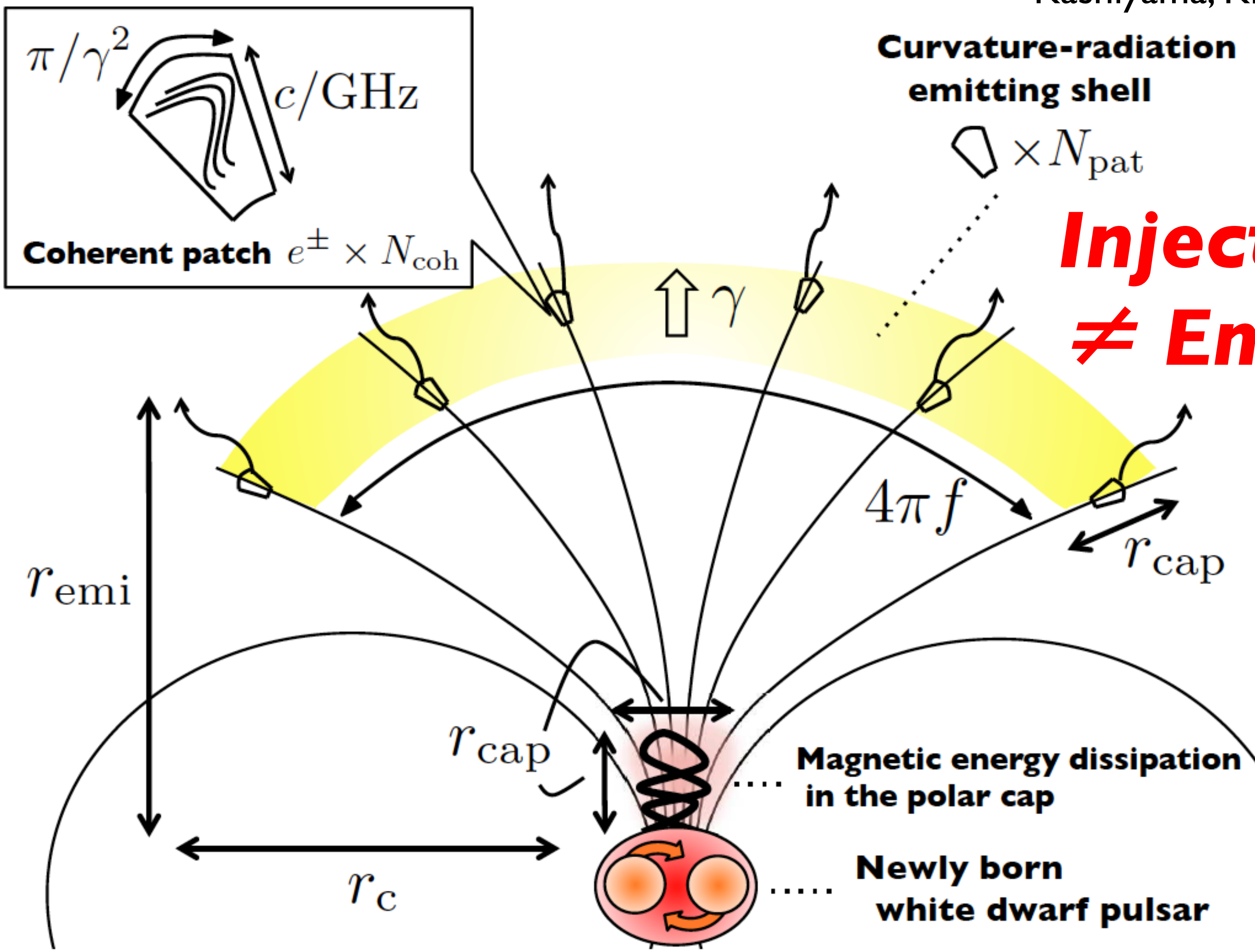
$$\Phi_{\max} \approx \frac{B\Omega^2 r^3}{2c^2} \sim 2.5\times 10^{16}\ \text{Volt}\ B_9 \Omega_0^2 r_{8.7}^3$$




⇒ $e^{\pm}$ production
⇒ Coherent radio emission

# Beaming

Kashiyama, KI & Meszaros 13




**Injection ≠ Emission**

# Brightness Temperature

$$F_\nu = \frac{\pi r_\perp^2}{d^2} \frac{2\nu^2}{c^2} kT$$

$$T \sim 3 \times 10^{41}\,\mathrm{K}\, L_{43} r_{emi,10}^{-2}$$

⇒ Coherent emission

$P \sim |E|^2 \sim |E_1 + E_2 + E_3 + \ldots + E_N|^2$

$\sim N|E_1|^2$ (incoherent)

$\sim N^2|E_1|^2$ (coherent)

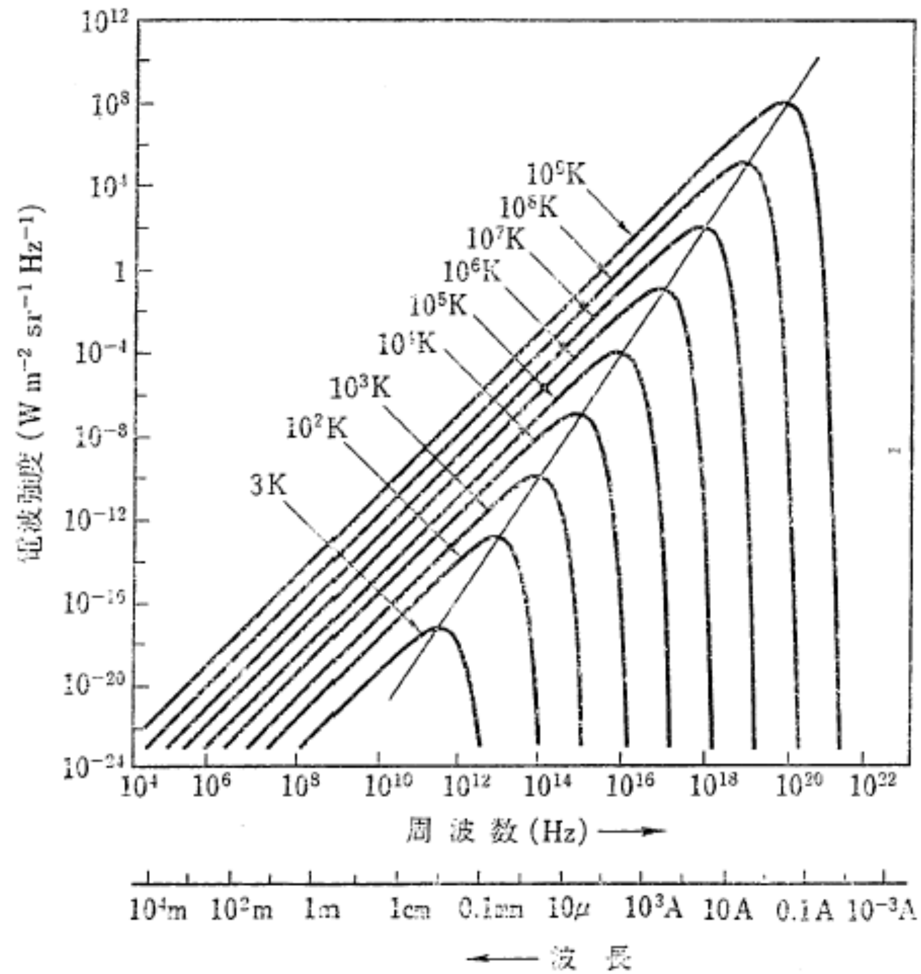
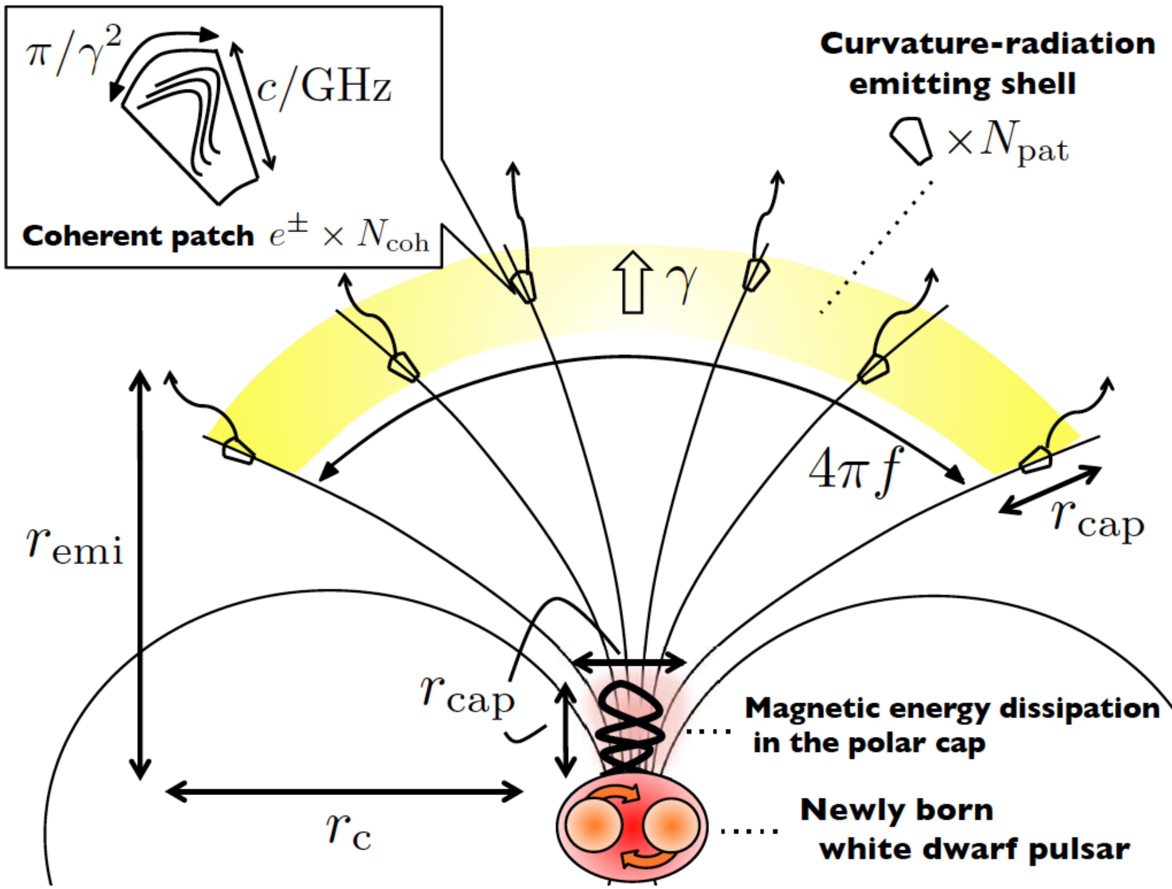



図 2·6 熱放射（プランク放射）の強度スペクトル

# Curvature Radiation




$$\nu_c \approx \gamma^3 \frac{3c}{4\pi r_c}$$

$$\sim 0.72\ \mathrm{GHz}\ \gamma_3^3 r_{c,10}^{-1}$$

$$\gamma \geq 1100 \nu_9^{1/3} r_{c,10}^{1/3}$$

# Luminosity

$$L_{\rm tot} \approx \left(P_c N_{\rm coh}^2\right) \times N_{\rm pat}$$

$$P_c \sim \frac{2\gamma^4 e^2 c}{3 r_c^2} \sim 5\times 10^{-17}\ {\rm erg\ s^{-1}}\ \gamma_3^4 r_{c,10}^{-2}$$

$$N_{\rm coh} \approx n_e \times V_{\rm coh} \approx n_e \times \frac{4}{\gamma^2} r_{\rm emi}^2 \frac{c}{\nu_c} \sim n_e \times 2\times 10^{16}\ {\rm cm^3}\ \gamma_3^{-5} r_{c,10} r_{\rm emi,10}^2$$

$$N_{\rm pat} \approx \frac{V_{\rm emi}}{V_{\rm coh}} \approx \frac{1}{V_{\rm coh}} 4\pi f r_{\rm emi}^2 \delta r_{\rm emi} \sim \frac{1}{V_{\rm coh}} \times 9\times 10^{28}\ {\rm cm^3} f r_{\rm emi,10}^2 \delta r_{\rm emi,7.8}$$

$$L_{\rm tot} \sim 4\times 10^{42}\ {\rm erg\ s^{-1}}\ f n_{e,7}^2 \gamma_3^{-1} r_{c,10}^{-1} r_{\rm emi,10}^4 \delta r_{\rm emi,7.8}$$

# Electron Density

$$n_e \sim 2\times10^7\,\mathrm{cm}\,L_{43}^{1/2}\gamma_3^{1/2}r_{c,10}^{1/2}r_{emi,10}^{-2}\delta r_{emi,7.8}^{-1/2}$$

**Necessary multiplicity**

$$\kappa_{\mathrm{GJ}} = \frac{n_e}{n_{\mathrm{GJ}}} = \frac{n_e}{B_{\mathrm{emi}}\Omega/2\pi ce} \sim 8\times10^3 n_{e,7}B_{\mathrm{emi},5}^{-1}\Omega_0^{-1}$$

**Plasma frequency limit**

$$\nu_c \geq \nu_p \approx \frac{\gamma}{2\pi}\left(\frac{4\pi n_e' e^2}{m_e}\right)^{1/2},\; n_e' = \frac{n_e}{\gamma}$$

$$n_e \leq 0.6\times10^7\,\mathrm{cm}^{-3}\,\gamma_3^5 r_{c,10}^{-2}$$

# Induced Compton

Melrose 71
Wilson & Rees 78
Lyubarsky 08

$$\frac{\partial n(\nu,\boldsymbol{\Omega})}{\partial t} + c(\boldsymbol{\Omega}\cdot\nabla)n(\nu,\boldsymbol{\Omega}) = \frac{3\sigma_{\mathrm{T}}}{8\pi}N\frac{h}{m_e c}n(\nu,\boldsymbol{\Omega})$$
$$\times\int(\boldsymbol{e}\cdot\boldsymbol{e}_1)^2(1-\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}_1)\frac{\partial\nu^2 n(\nu,\boldsymbol{\Omega}_1)}{\partial\nu}d\boldsymbol{\Omega}_1,$$

Compton scattering is enhanced by photons

To evade the induced Compton

$$\gamma \geq 2000\ r_{c,10}^{3/14} r_{\mathrm{emi},10}^{3/14} n_{e,7}^{3/14}$$