@NS WS 2019 Kyoto
on 18 Feb. 2019

中性子星フレアに伴う定常電波放射の消失

Radio Suppression at the Onset of Short Magnetar Bursts

Shotaro Yamasaki (U. Tokyo)

with Shota Kisaka (Tohoku U.), Toshio Terasawa (NAOJ, ICRR) & Teruaki Enoto (Kyoto U.)

“Relativistic Fireball Reprise: Radio Suppression at the Onset of Short Magnetar Bursts”

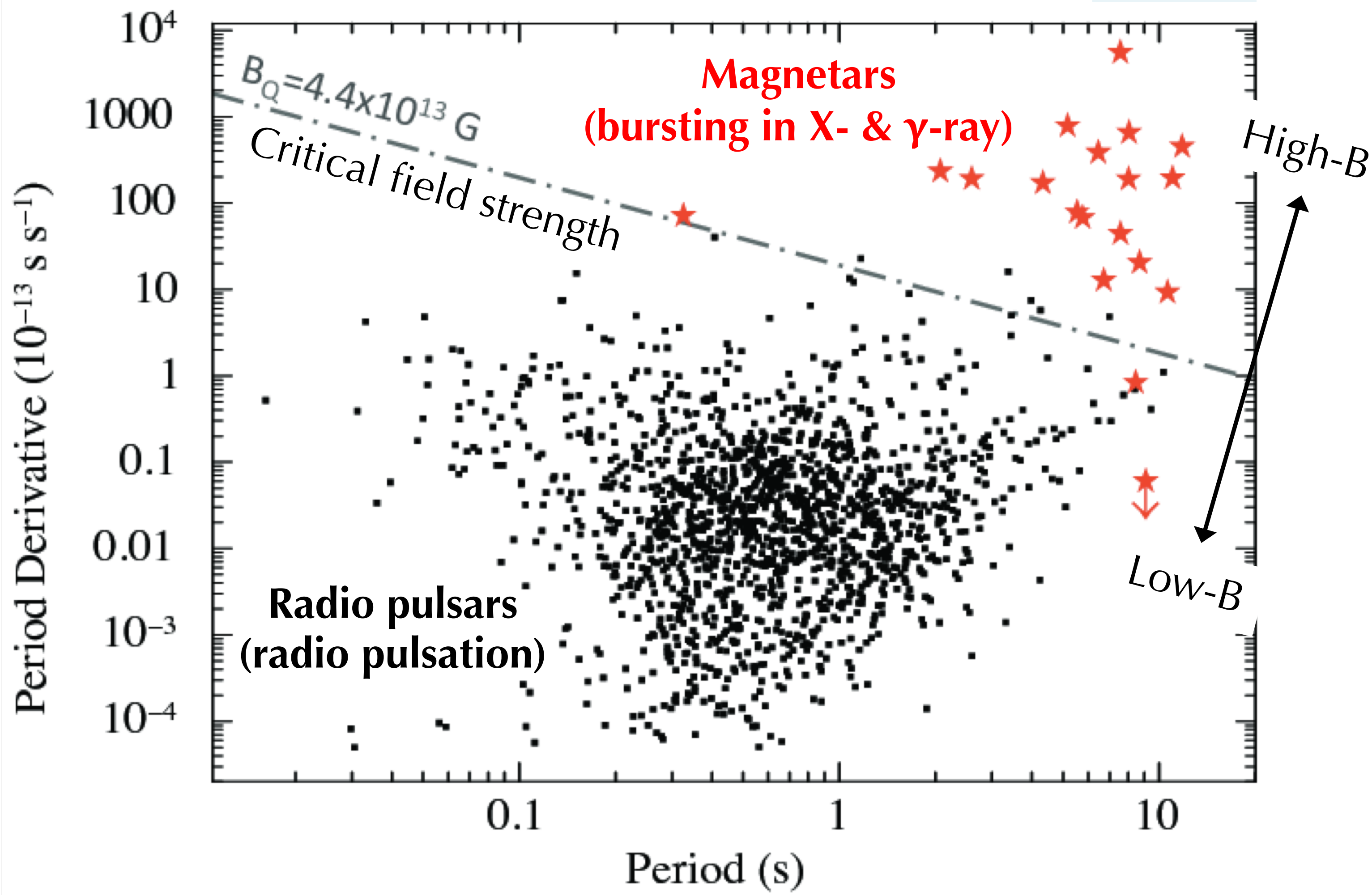
(SY, S. Kisaka, T. Terasawa, T. Enoto 2018, MNRAS, 483, 4175)

Outline

1. **Introduction**
2. Motivation
3. Model
4. Discussion
5. Conclusions

Magnetar = Magnetic Neutron Star

Rea '13

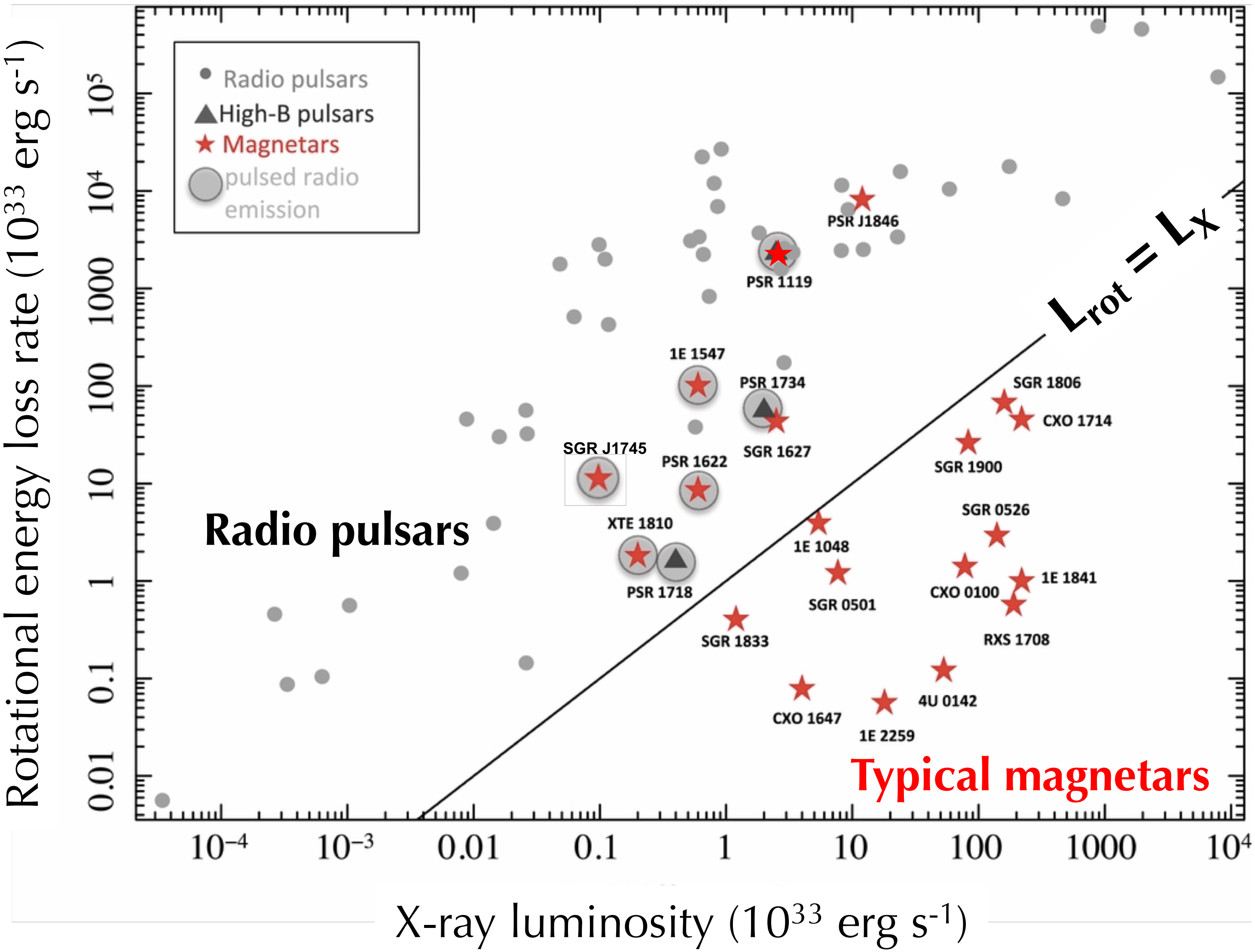


$B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ Gauss

(assuming rotational energy loss = dipole radiation)

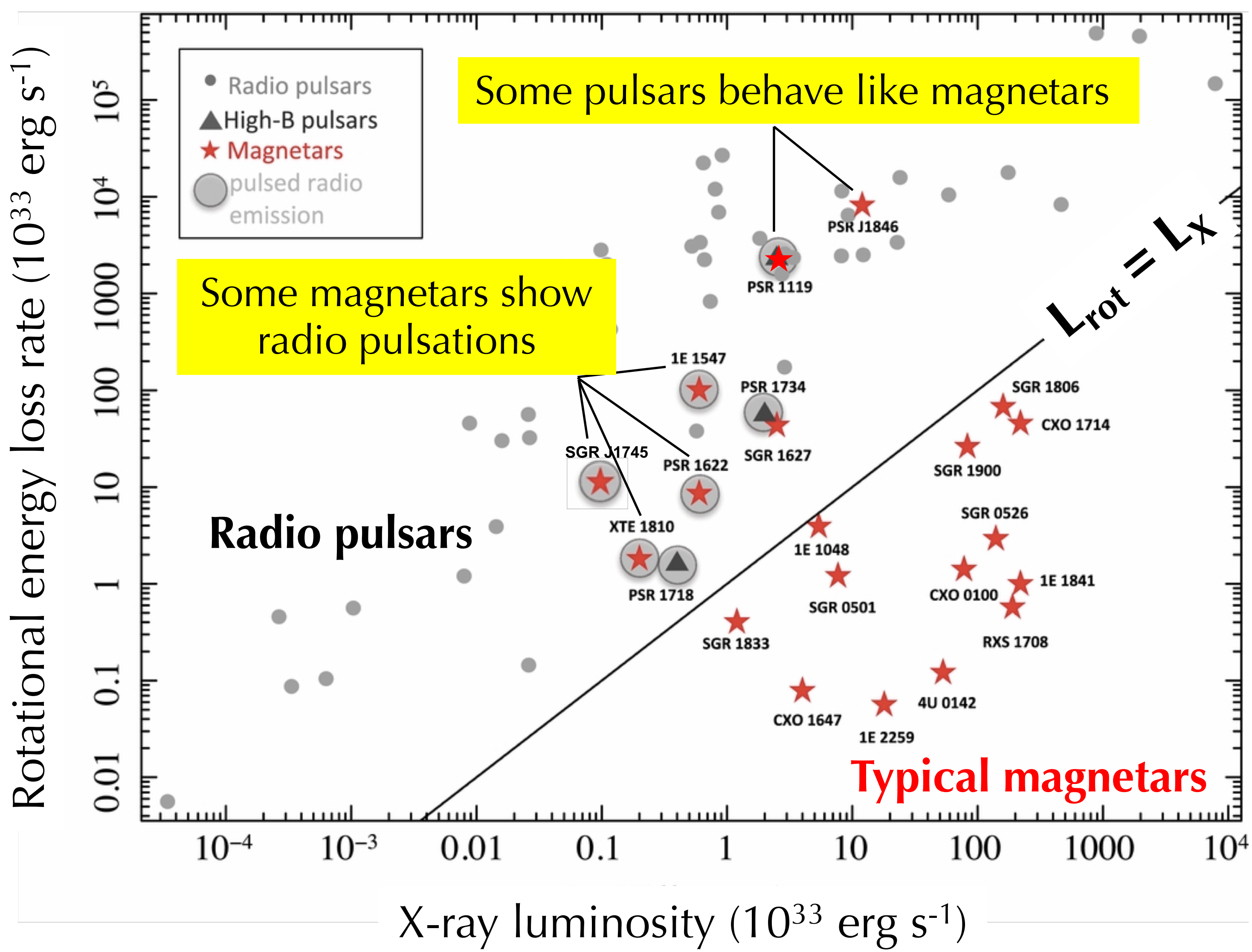
Radio pulsars = quiescent magnetars?

Rea '13 (updated)



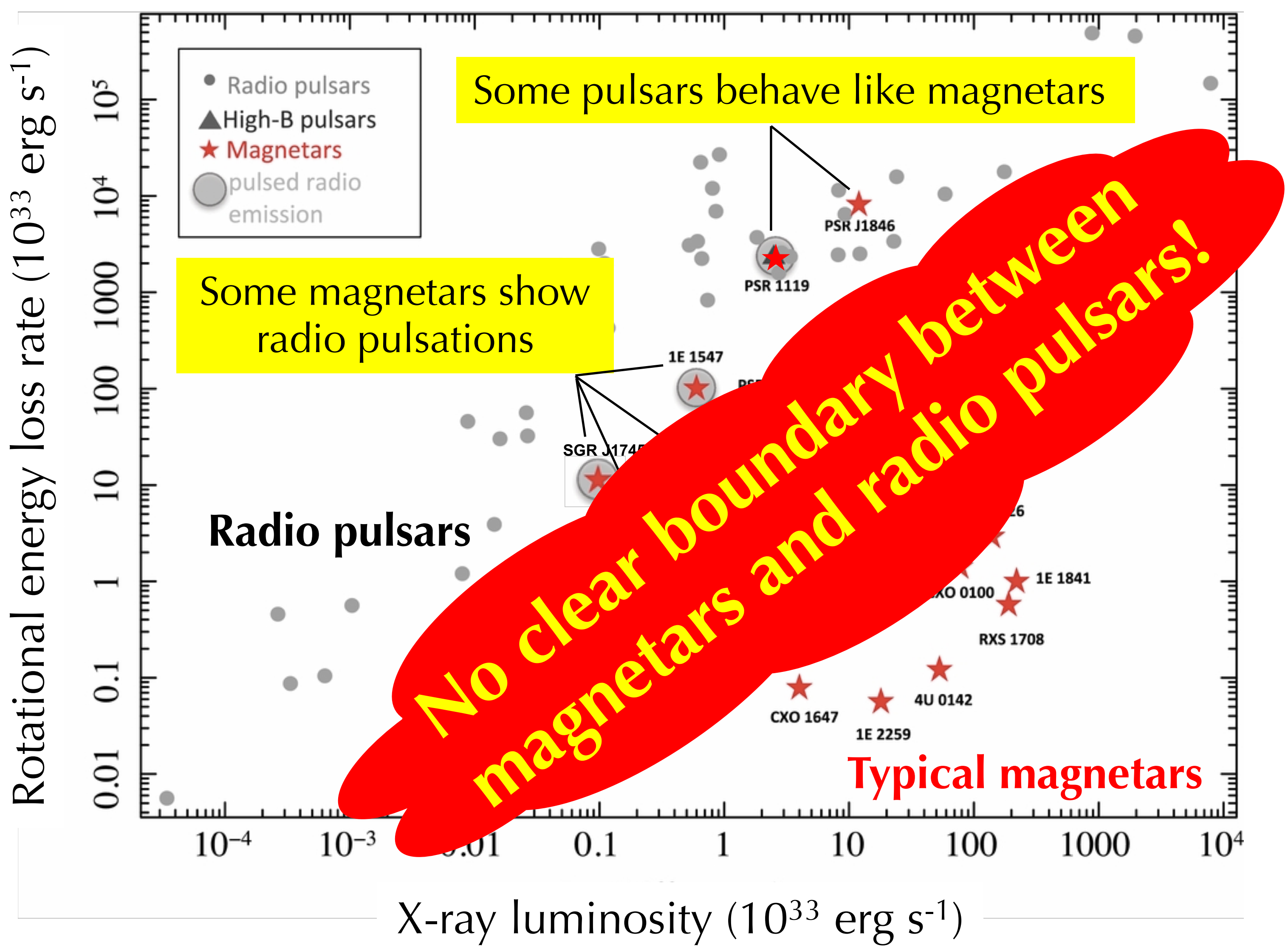
Radio pulsars = quiescent magnetars?

Rea '13 (updated)



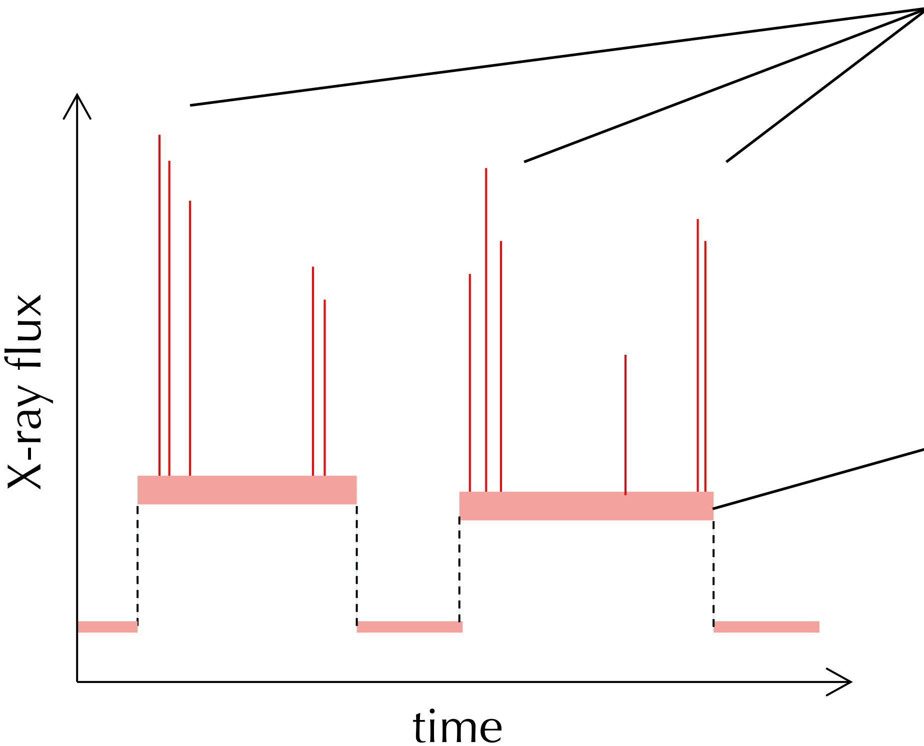
Radio pulsars = quiescent magnetars?

Rea '13 (updated)



Short bursts: the most common magnetar flares

Observationally, magnetars are found by their bursting activities in X- & γ-ray



Short bursts

- ✓ the most common events
- ✓ τ = a few msec to a few sec
- ✓ $L_{peak} = 10^{36}$-10^{43} erg s^{-1}
- ✓ <~10 keV thermal spectra

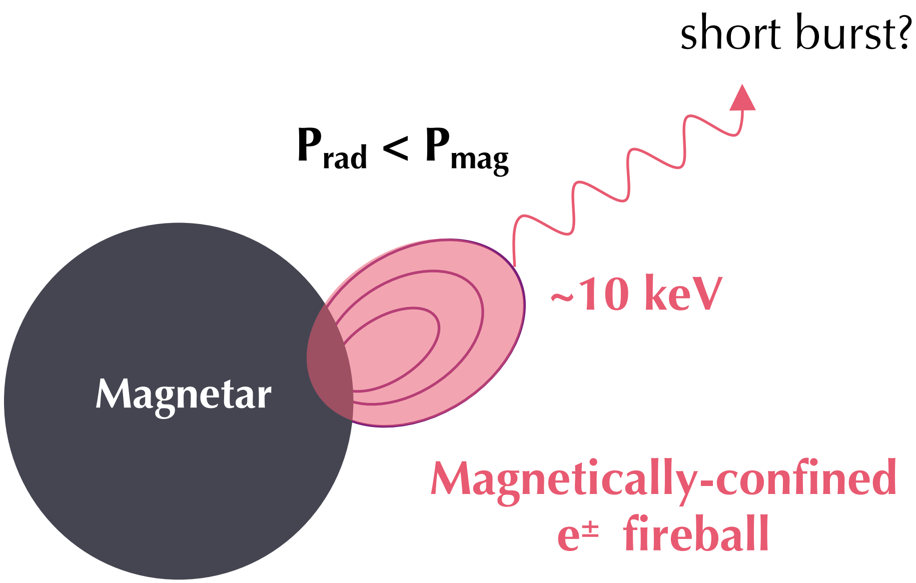
Outbursts

- ✓ large and sudden X-ray flux increases (x10–1000)
- ✓ τ = several months
- ✓ L_{peak} <~ 10^{36} erg s^{-1}
- ✓ often accompany short bursts

A conventional model for short bursts

- ✓ A sudden magnetic energy release into magnetosphere creates a fireball
- ✓ Fireball = a tightly coupled plasma of photons & $e^{\pm}$ pairs
- ✓ Fireball is magnetically confined to the stellar surface and evaporates, radiating (non-)thermal X-ray emission

e.g., Thompson & Duncan '95; Lyutikov '03

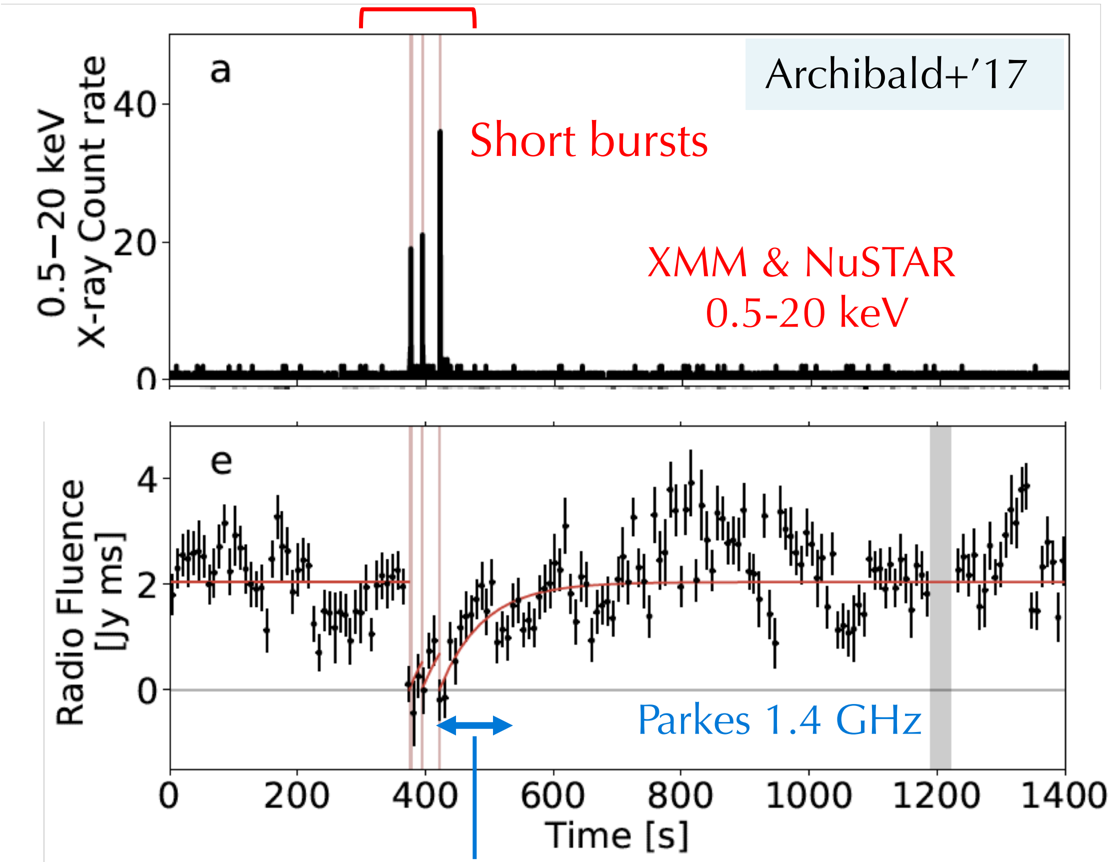


$P_{rad} = aT^4 \sim 10^{25}\,(T/m_ec^2)^4$ erg cm^{-3}

$P_{mag} = B^2/(8\pi) \sim 4 \times 10^{26}\,(B/10^{14}\text{ G})^2$ erg cm^{-3}

Radio suppression at the onset of short bursts

- Durations ~ a few seconds
- E_{rad} ~ 10^{37} erg with 2 keV blackbody

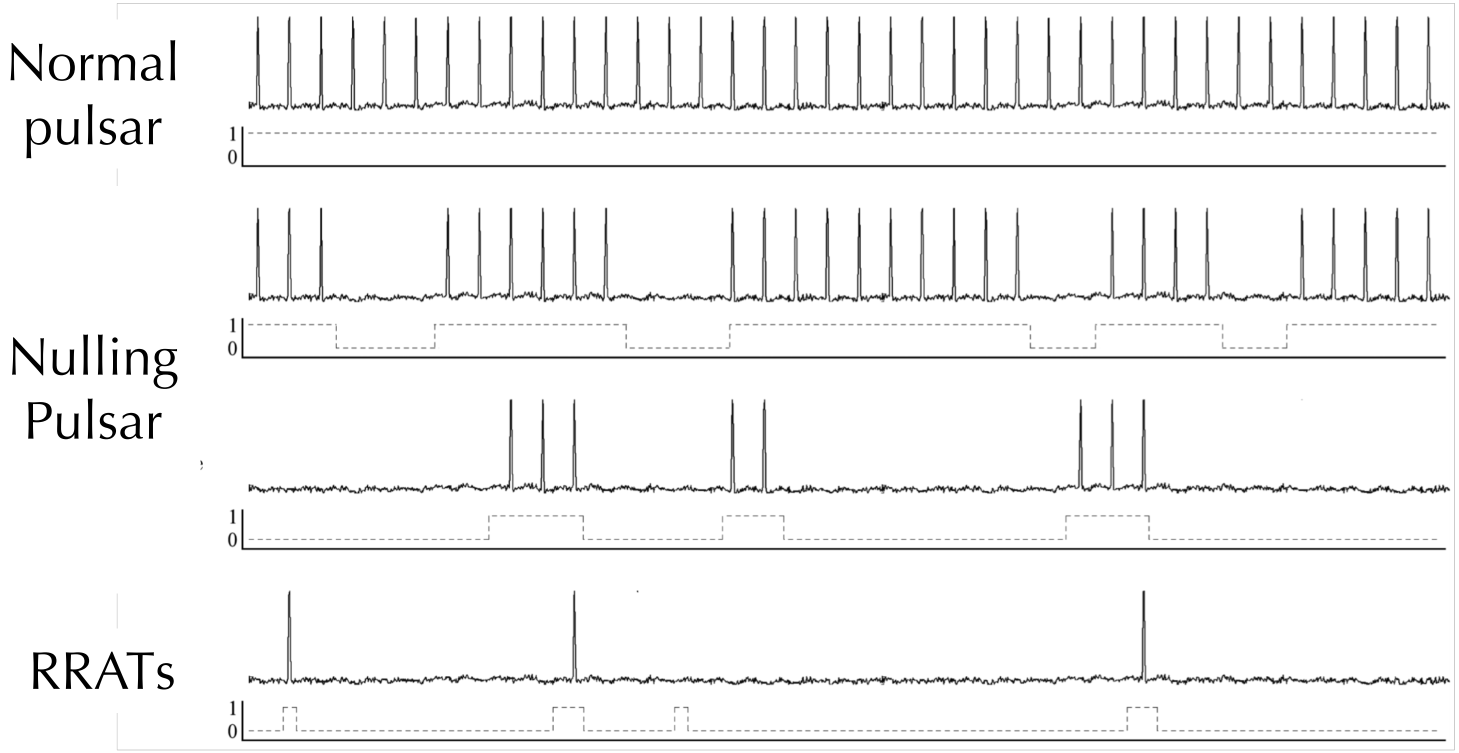


Radio recovery timescale τ_{rec} ~ 100 sec

- ✓ Radio pulsar J1119-6127 behaves like magnetars
- ✓ Pulsed radio emissions disappear for **τ_{rec} ~100 sec** coinciding with three short bursts
- ✓ This is unusually long compared to the radio pulse period (**P~0.4 sec**)
- ✓ **What causes these radio disappearances?**

1. Pulsar nulling & mode changes

Wang+'07; Burke-Spolaor & Bailes+'10

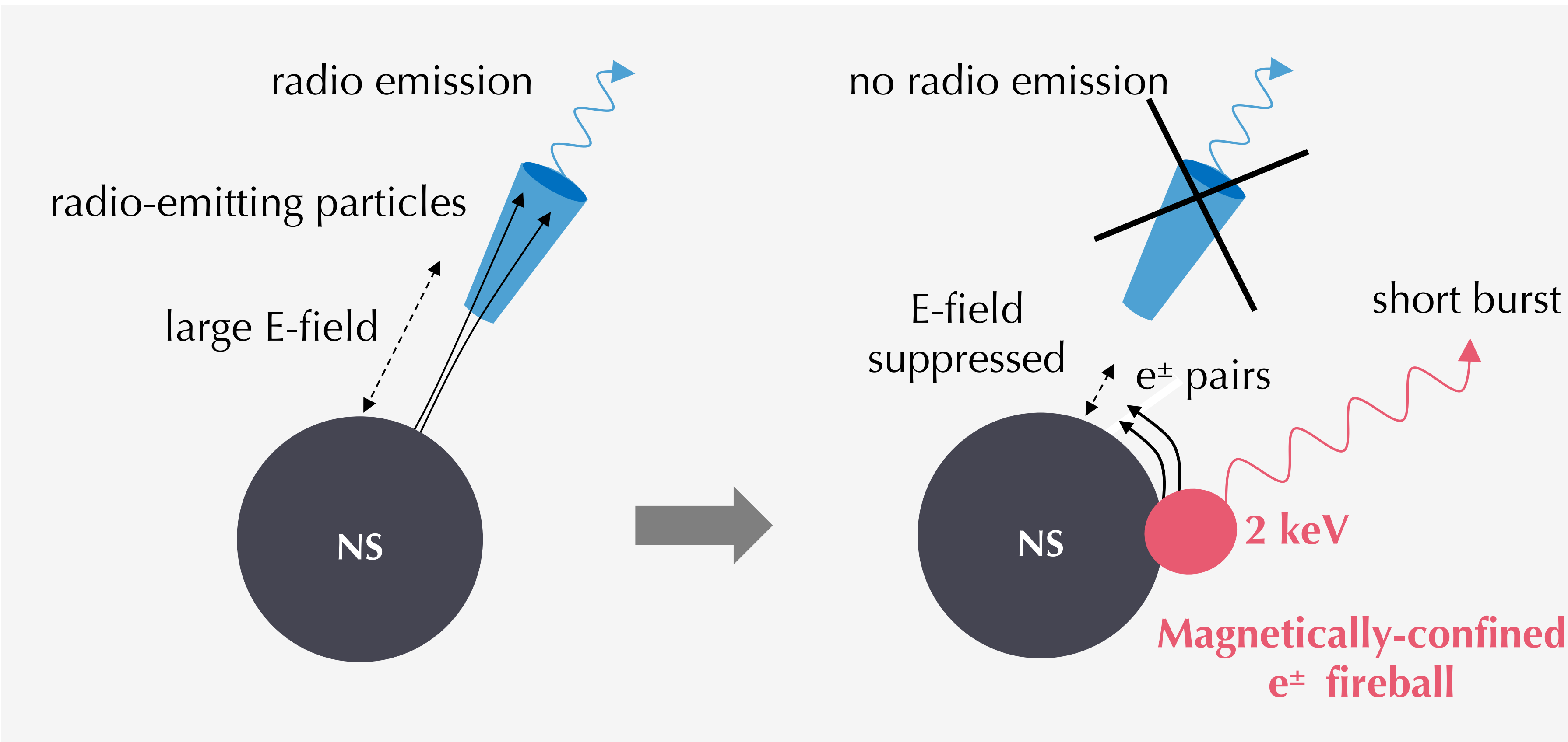


- ✓ Common phenomena for normal pulsars (possibly related to global magnetospheric changes, but not well understood)
- ✓ Since the duration varies from one or two rotations to even days, one cannot exclude the possibility of ~100 sec radio suppression

2. E-gap suppression due to additional plasmas

Archibald+'17

If e± plasma leak from the trapped fireball into the gap region which accelerates radio-emitting particles, the acceleration may be suppressed



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Motivations

- ✓ A clear boundary between magnetars & radio pulsars is now disappearing
- ✓ The number of bursting NSs with radio pulsation (e.g., PSR J1119-6127) could be potentially large
- ✓ Then, considering both radio pulsations & short bursts is important to better understand the burst mechanism
- ✓ Radio suppression at the onset of short bursts is difficult to explain by magnetospheric origin because of its long duration
- ✓ Rather, radio suppression is likely caused by **a sort of absorption by an expanding plasma flow**

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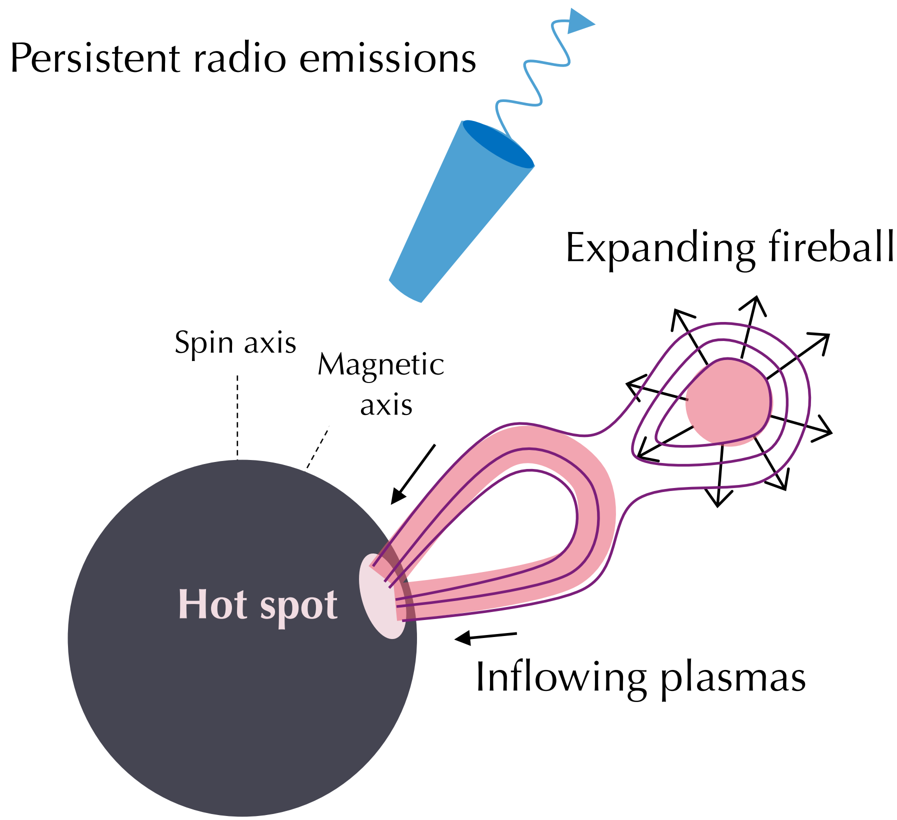
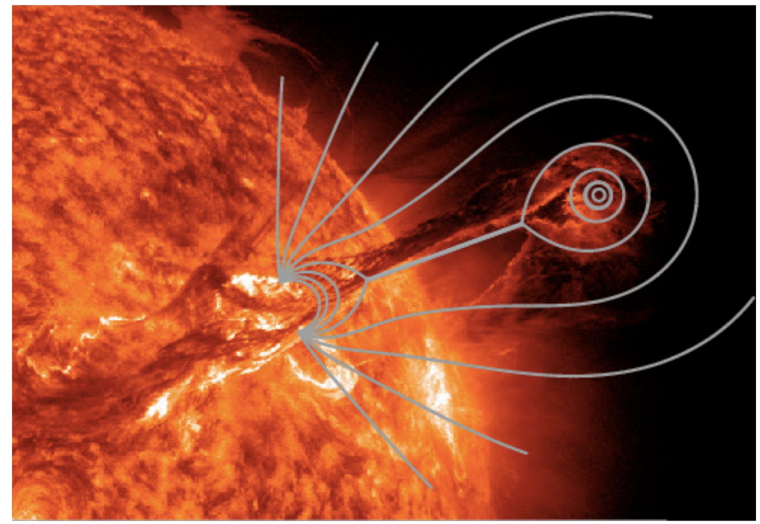
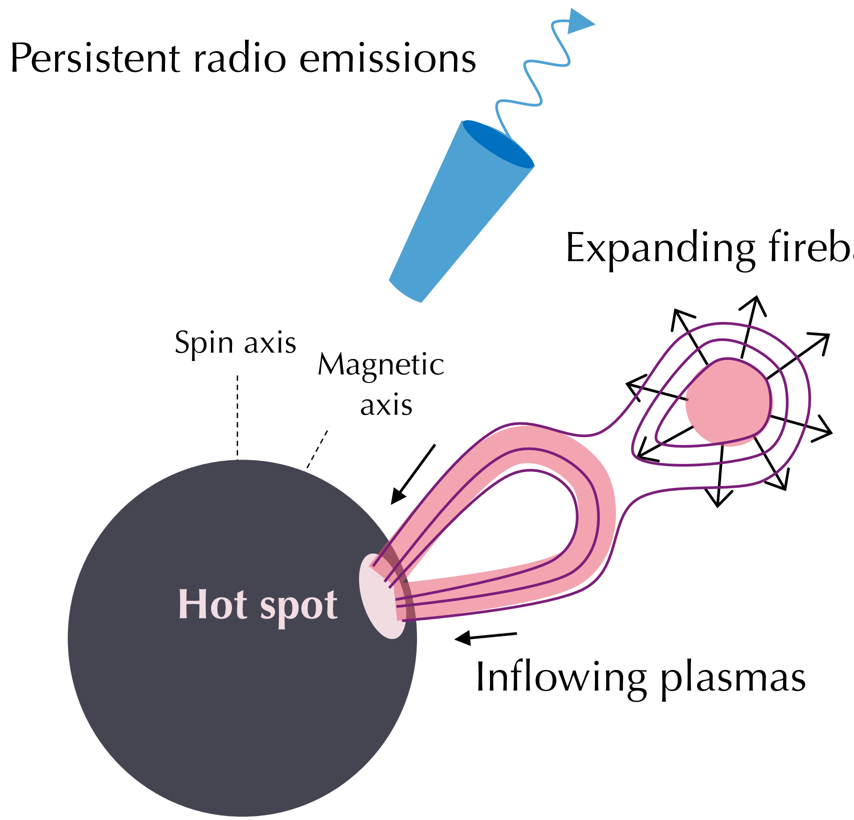
A model for short bursts & radio suppression



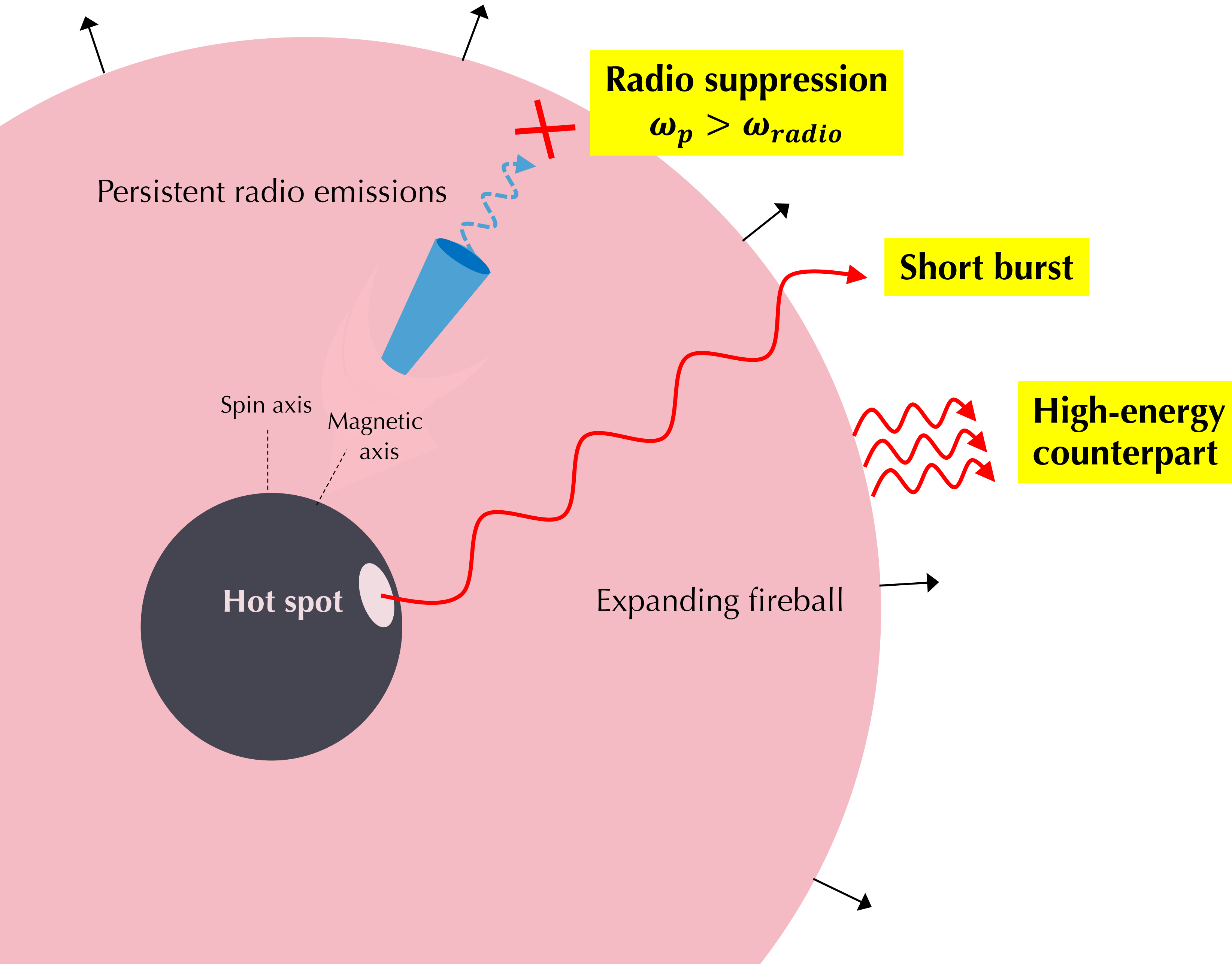


Similar mechanism is proposed for cornal mass ejection of solar flares (Meng+'14)

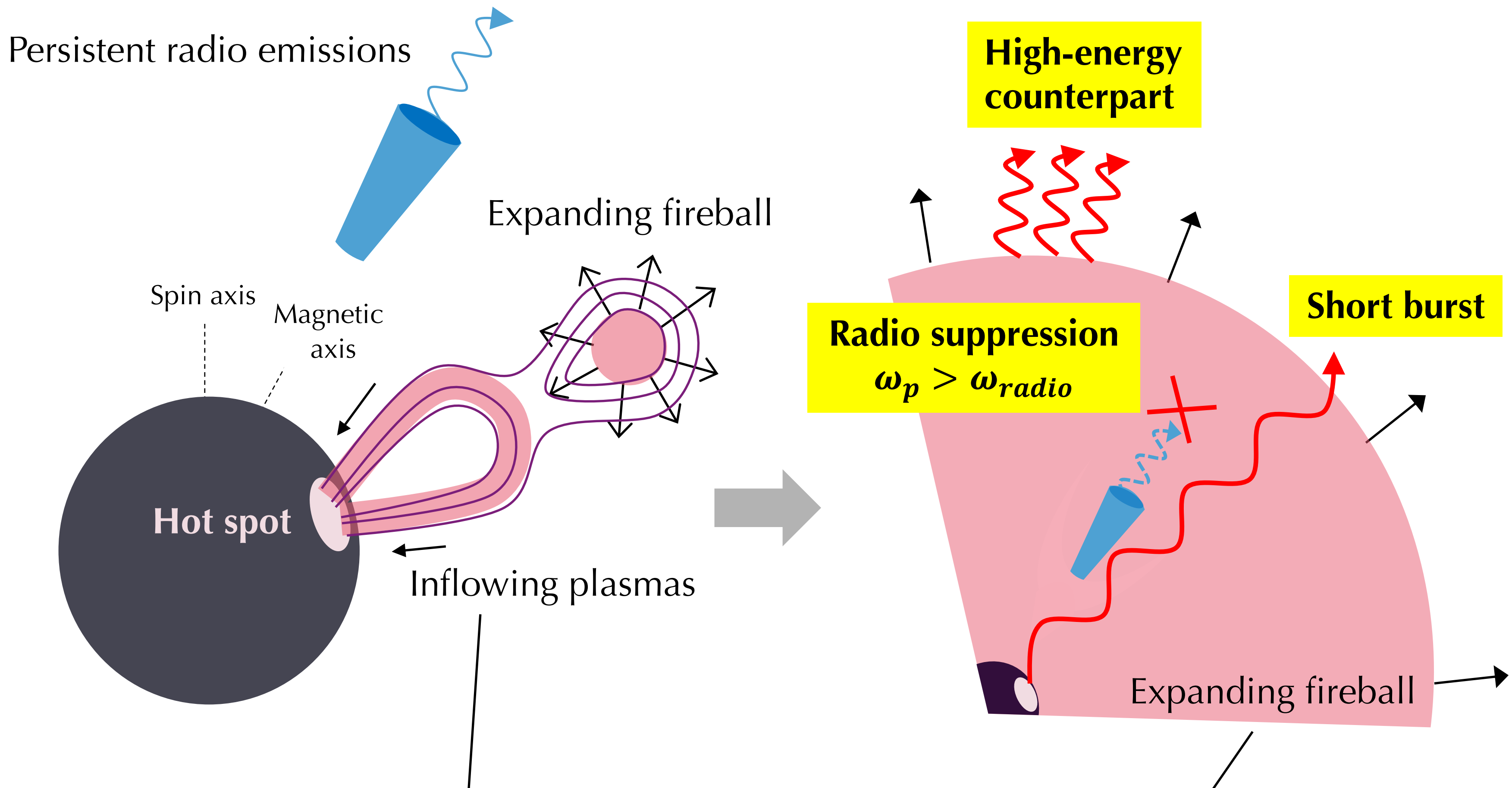
A model for short bursts & radio suppression



A model for short bursts & radio suppression



A model for short bursts & radio suppression



✓ **Short burst = inflowing component**

✓ **Radio suppression + high-energy counterpart = expanding component**

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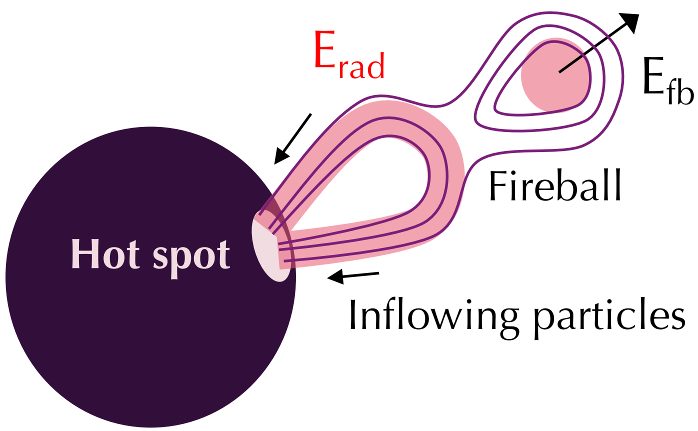
Short bursts from hot spot(s)

- ✓ A fraction of initial fireball energy (E_{fb}) is used to bombard the NS surface, creating a hot spot

$$\boxed{E_{\rm fb} = aT_i^4 r_i^3 \sim 10^{40}\, r_{i,5}^3 \left(\frac{T_i}{m_e}\right)^4 \text{ erg}}$$



r_i (size) & T_i (temperature)

- ✓ E_{rad} ($<E_{fb}$) is radiated away as a thermal emission with temperature T_{spot}

- ✓ Assuming observational values $E_{rad} = 10^{38}$ erg, $T_{spot} = 10$ keV and $r_{spot} = 1$ km, the duration of short bursts is

$$\boxed{\Delta t_{\rm rad} \approx \frac{E_{\rm rad}}{\sigma_{SB} T_{\rm spot}^4 4\pi r_{\rm spot}^2} \sim 80 \quad E_{\rm rad,38}\, r_{\rm spot,5}^{-2} \left(\frac{T_{\rm spot}}{10\ {\rm keV}}\right)^{-4} \quad {\rm ms}}$$

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Absorption by plasma cutoff frequency

✓ Plasma frequency: $$\boxed{\omega_p \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}}}$$

✓ Dispersion relation: $$\omega^2 = \omega_p^2 + c^2 k^2$$

✓ Wave function for $\omega < \omega_p$:

$$Ae^{i(kx-\omega t)} = A\exp\underbrace{\left(-\sqrt{|\omega^2-\omega_p^2|}\,\frac{x}{c}\right)}_{\text{damped}} e^{-i\omega t}$$

→ radiation with $\omega < \omega_p$ cannot propagate through the medium due to absorption of waves

✓ Radio recovery timescale is given by $\omega_p\,(\tau_{rec}) = \omega_{radio}$

→ need to know n_e evolution of fireball

Fireball evolution

Paczynski '86; Goodman '86; Grimusrud & Wassermann '98

✓ Energy & momentum conservation:

$$\frac{1}{r^2}\frac{d}{dr}\left\{r^2(U+P)\,\Gamma^2\beta\right\} = G^0$$

$$\frac{1}{r^2}\frac{d}{dr}\left\{r^2(U+P)\,\Gamma^2\beta^2\right\} + \frac{dP}{dr} = G^1$$

A relativistic outflow with

$$\boxed{\Gamma \approx \Gamma_i(r/r_i), \quad T \approx T_i(r_i/r)}$$

✓ Dynamical pair equation (Boltzmann's equation):

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 n_e \Gamma\beta\right) = -\langle\sigma_{\rm ann} v\rangle \left(n_e^2 - n_{e,\rm eq}^2\right),$$

✓ Equilibrium pair number density (initial condition)

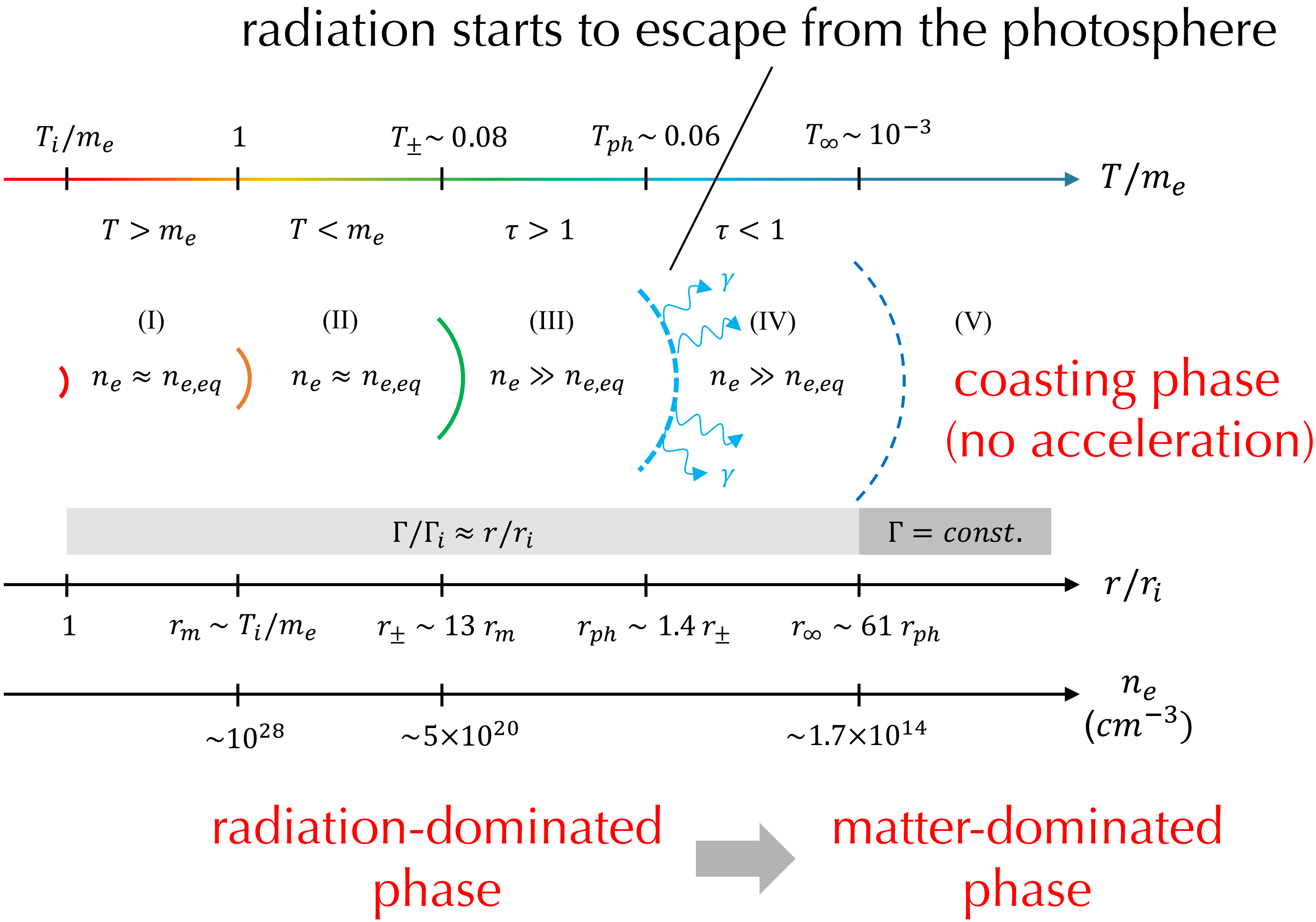
$$n_{e,\rm eq}(T) \approx \frac{2}{(2\pi)^{3/2}}\lambda_C^{-3}\,(T/m_e)^{3/2}\,e^{-m_e/T}$$

$$\sim 10^{28}\,\,(T/m_e)^{3/2}\,e^{-m_e/T}\quad {\rm cm}^{-3}$$

m_e : the rest-mass energy of an electron ($m_e c^2$~511 keV)

Fireball evolution (contd.)

3 parameters: r_i , T_i , Γ_i



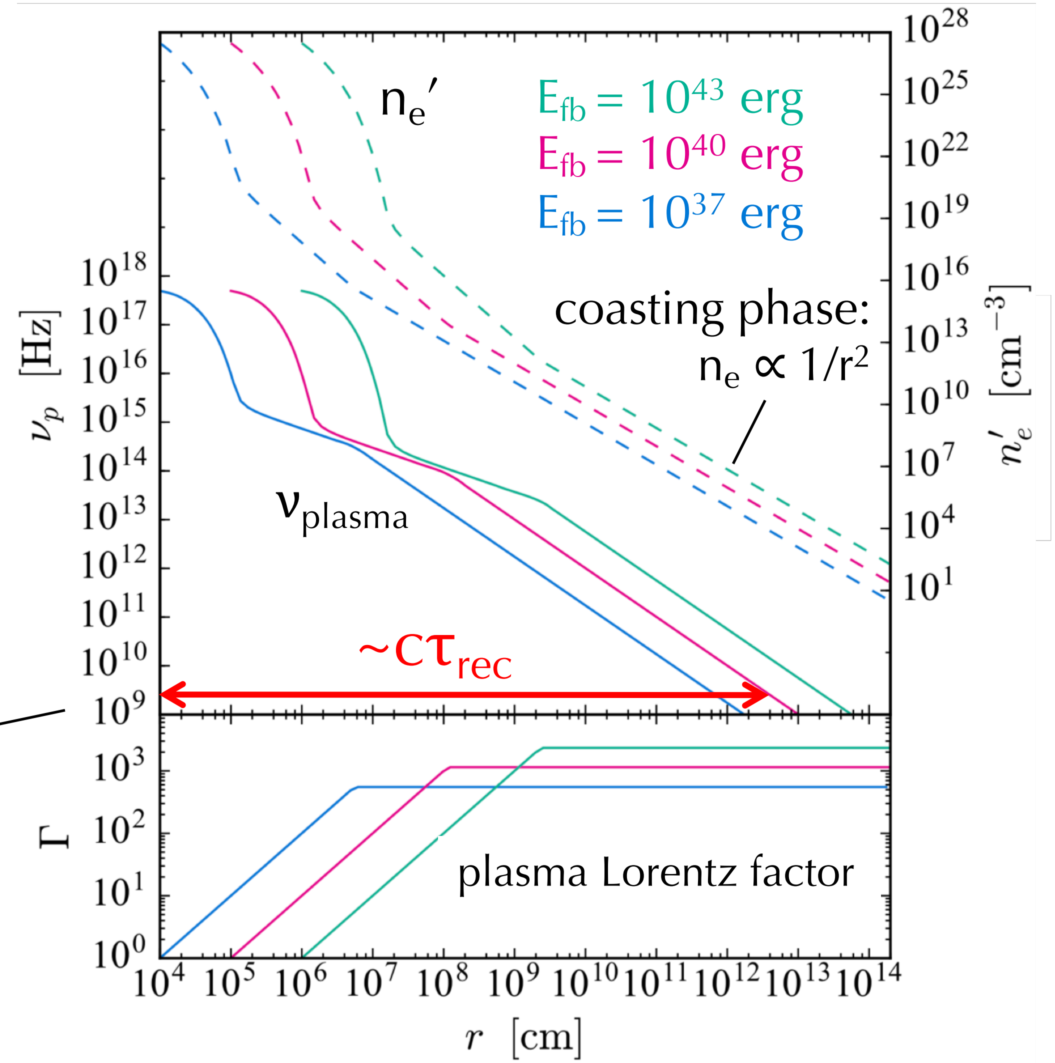
Radio suppression (recovery) timescale

- ✓ Fireball evolution is uniquely determined once you choose initial fireball energy ($E_{fb} \sim aT_i^4 r_i^3$)
- ✓ Radio recovery timescale:

$$\tau_{\rm rec} \approx 470 \text{ sec} \times \left(\frac{r_i}{10^5 \text{ cm}}\right)^{-7/8} \left(\frac{E_{\rm fb}}{10^{40} \text{ erg}}\right)^{1/2} \nu_9^{-1}$$

observing frequecy ~GHz

- ✓ **Radio recovery timescale (τ_{rec}) tells you total fireball energy (E_{fb})!**



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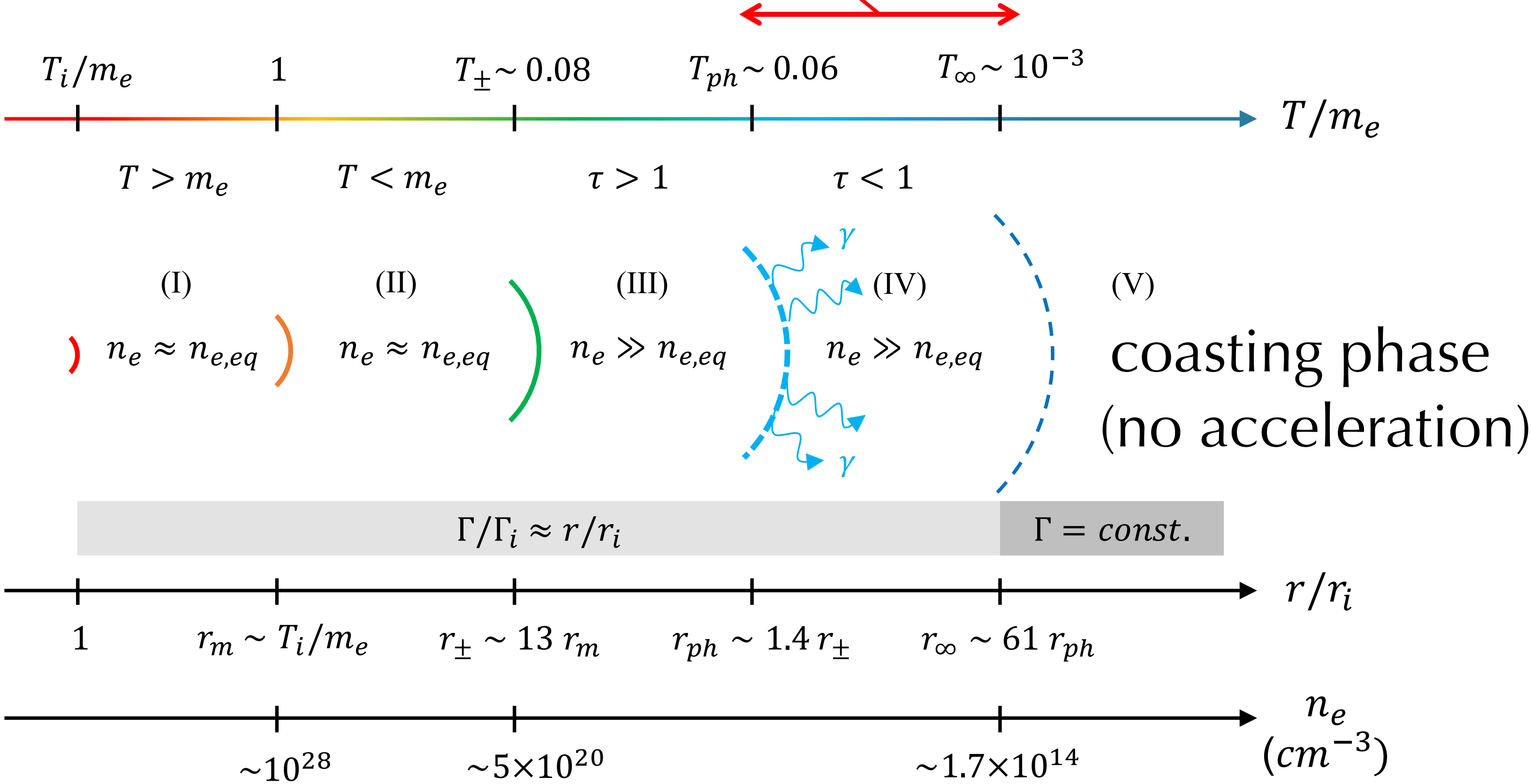
Fireball evolution

Photospheric emission is expected

$\Gamma_\infty \sim 10^3$
$r_\infty \sim 10^3 r_i = 10^8\, r_{i,5}$ cm
$T_\infty \sim 10^{-3}\, m_e \sim 0.5$ keV

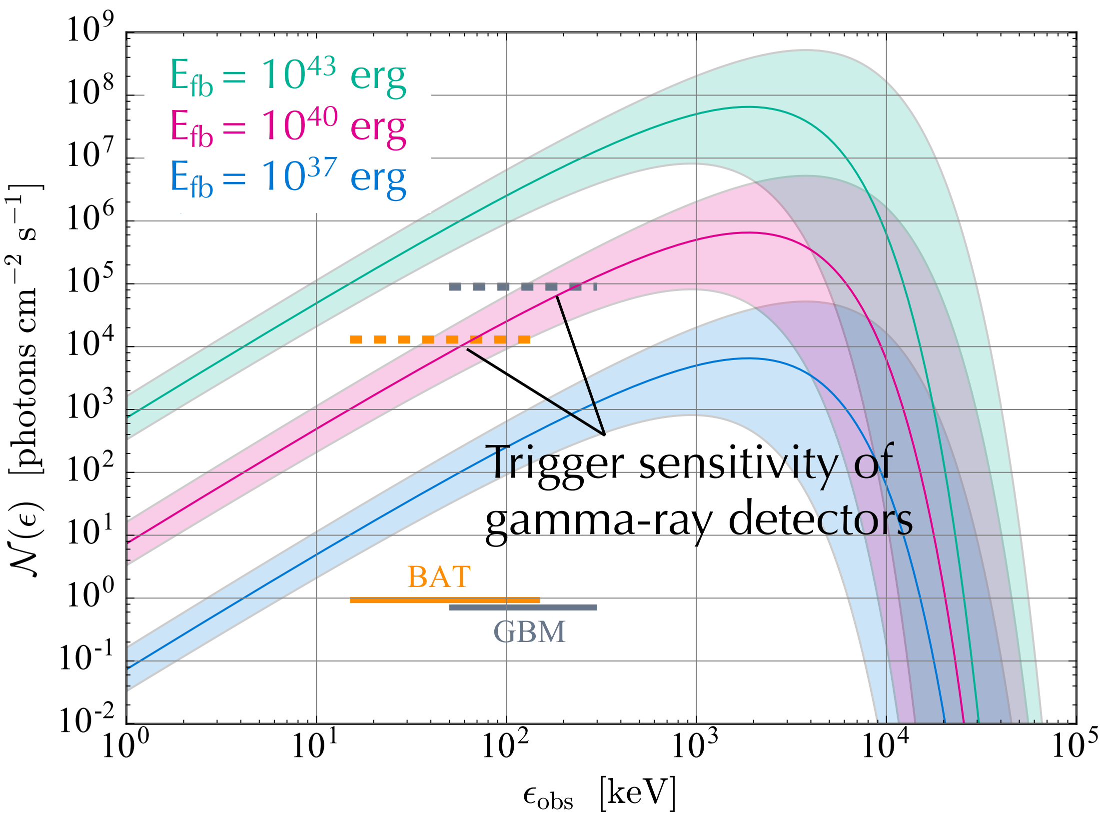


radiation-dominated ➡ matter-dominated

High-energy counterparts detectability

✓ Blackbody spectrum with temperature T_{obs}:

$$\boxed{\mathcal{N}(\epsilon_{\rm obs}) = \frac{4\pi\epsilon_{\rm obs}^3}{h^3c^2}\int_{-1}^{1}\frac{\mu d\mu}{\exp\left(\epsilon_{\rm obs}/T_{\rm obs}\right)-1}}$$



✓ Observed temperature:

$$T_{\rm obs} = \frac{T}{\Gamma(1-\beta\mu)} \equiv \mathcal{D}T$$

(D~Γ: Doppler factor)

$$\boxed{T_{\rm peak} = \Gamma T = \Gamma_i T_i \sim m_e}$$

Peaks at ~ MeV

✓ Observed duration:

$$\delta t_{\rm obs} = \mathcal{D}^{-1}\delta t',$$

$$\delta t' \sim r_\infty/c \lesssim 10^{-2}\ {\rm s}$$

$$\boxed{\delta t_{\rm obs} \sim \delta t'/2\Gamma_\infty \lesssim 10^{-5}\ {\rm s}}$$

Extremely short duration; onboard detection may be challenging

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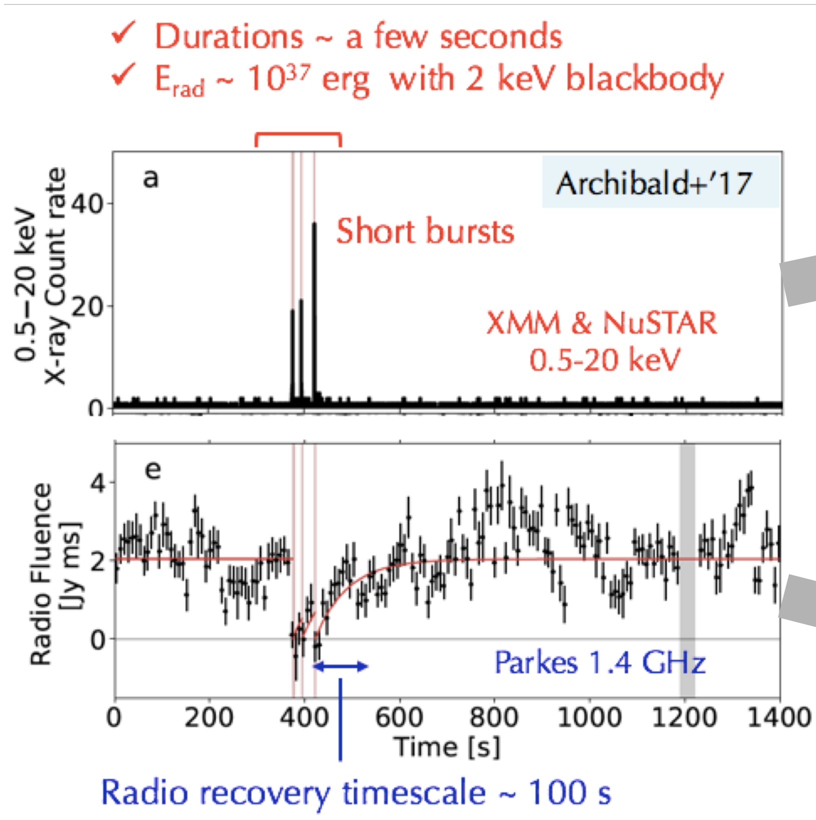
Application: radio pulsar J1119-6127



- ✓ **Short bursts** are explained by radiation from hot spots:
  - size = 1km
  - T_{spot} = 2 keV
  - $E_{rad} = 10^{37}$ erg
  - Δt_{rad} = a few sec

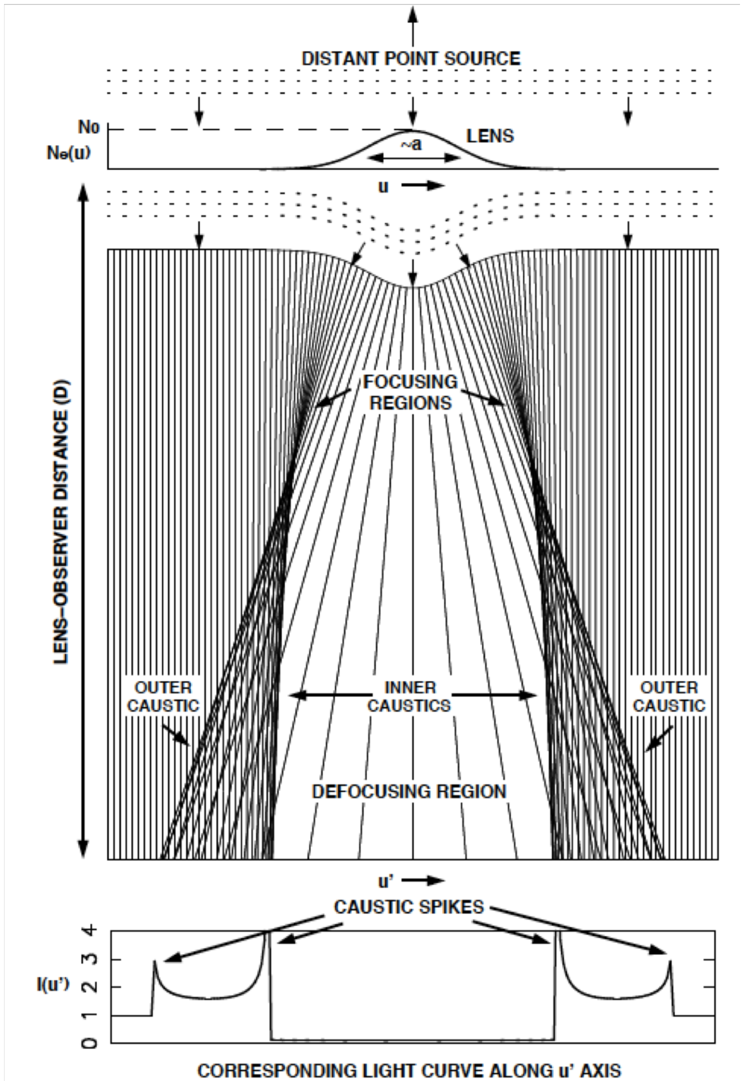
- ✓ **Radio suppression timescale** τ_{rec} ~100 sec is explained by **$E_{fb} = 10^{38}$ erg** ($T_i = 0.5\ m_e$ and r_i = 1km)

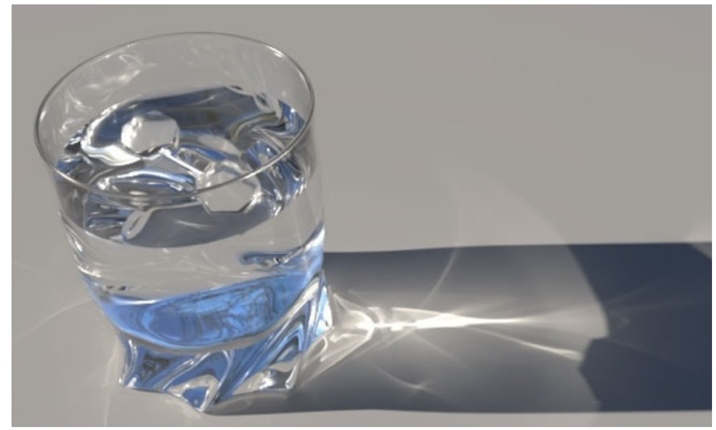
$$\tau_{\rm rec} \approx 470\ {\rm sec} \times \left(\frac{r_i}{10^5\ {\rm cm}}\right)^{-7/8} \left(\frac{E_{\rm fb}}{10^{40}\ {\rm erg}}\right)^{1/2} \nu_9^{-1}$$

- ✓ No report on the **high-energy counterpart**: consistent with our result

Plasma lensing

Clegg+ '97

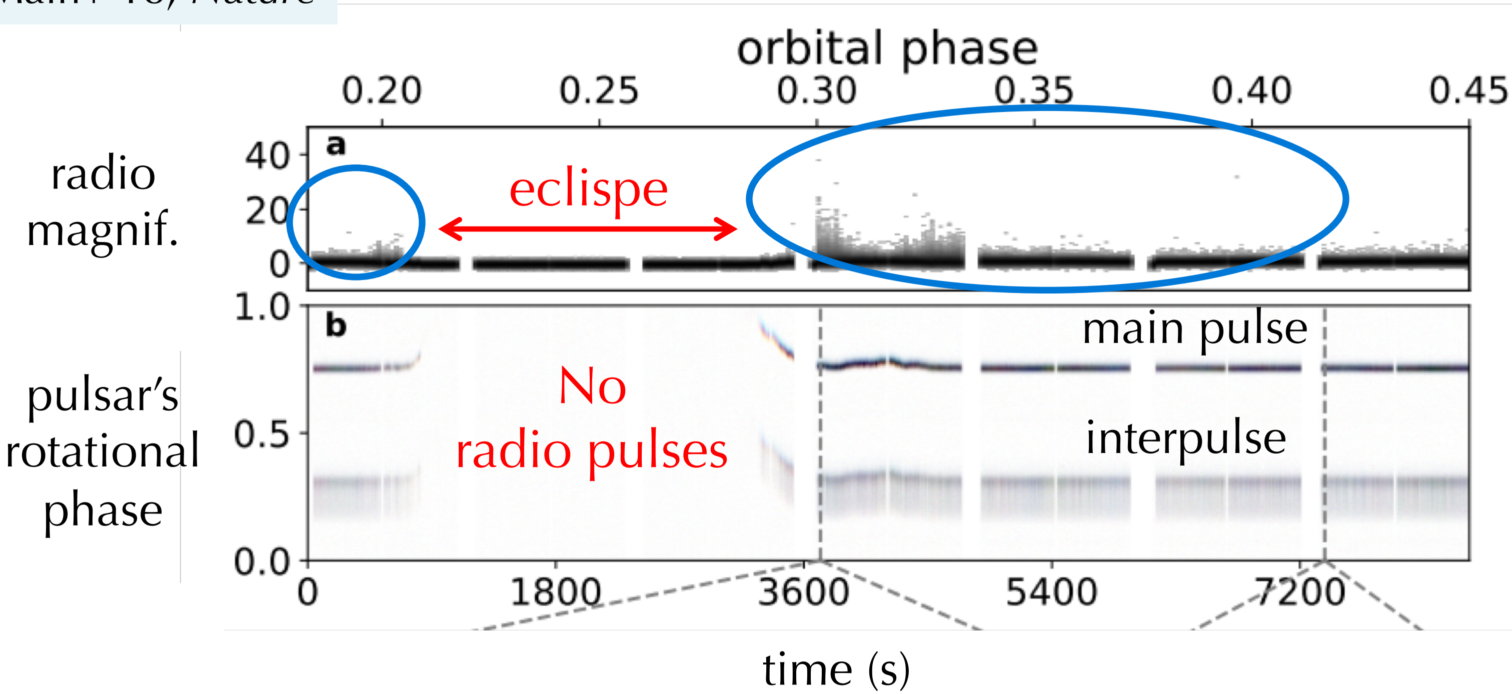




Caustics

Plasma lens confirmed: PSR B1957+20

Main+'18, *Nature*



- ✓ msec radio pulsar + companion in close orbit (9.2 hrs)
- ✓ Lensing (<~80x) near ingress and egress of the eclipse of the pulsar by its companion's outflow

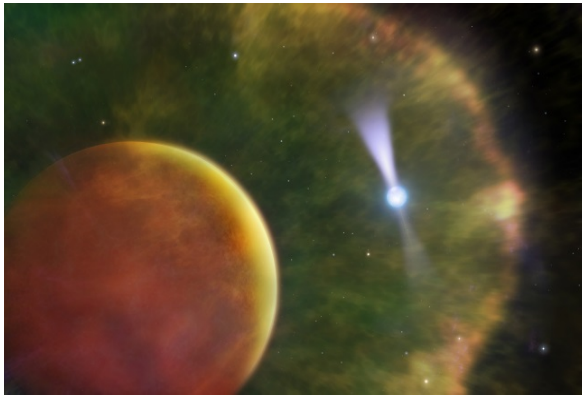
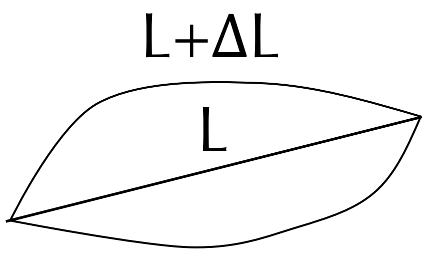


Image credit: Mark A. Garlick (U. Tronto)

Condition for lensing (qualitative)

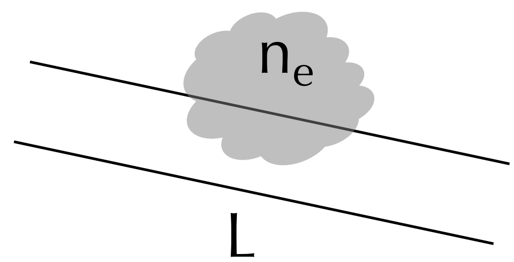
✓ The phase of an electromagnetic wave going through different paths has contributions from both geometric and dispersive time delays: $\Phi = \Phi_g + \Phi_{DM}$

Geometric phase change



$$\Phi_g = L\,\frac{\nu}{c}$$

Dispersive phase change

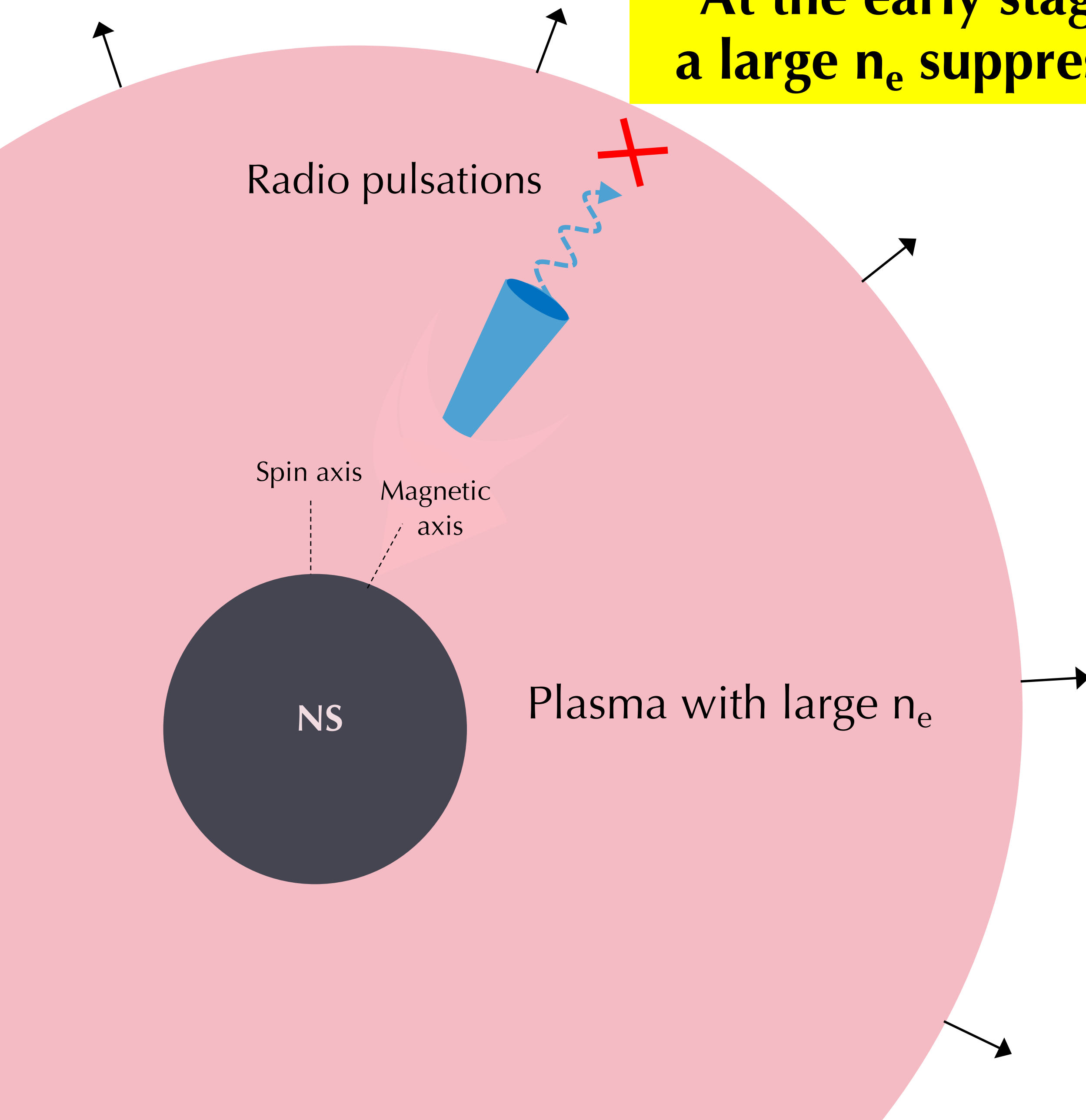


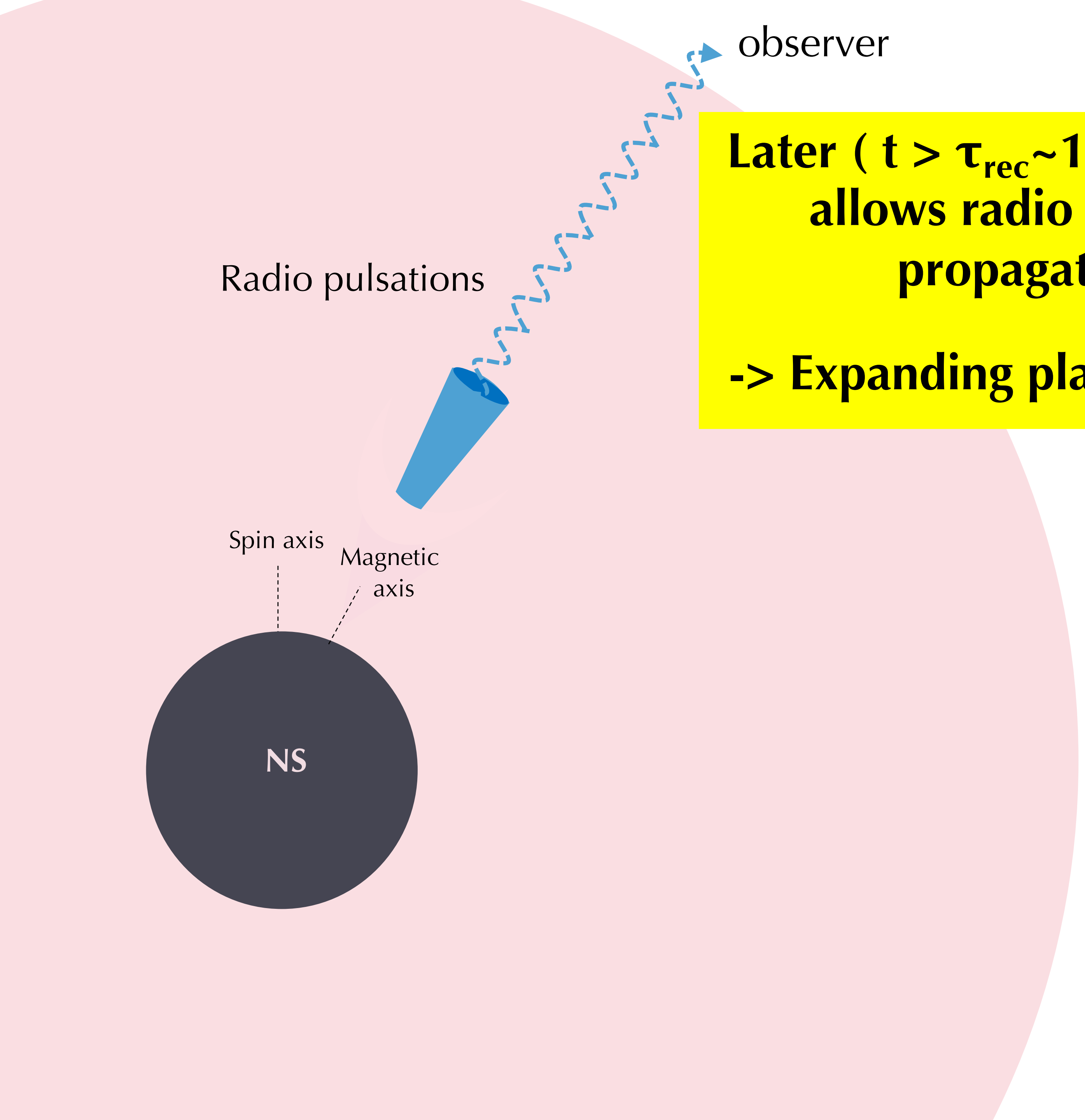
$$\Phi_{DM} = -\frac{k_{DM}}{\nu}\int_0^L n_e\,ds$$

strong frequency-dependence

✓ Lensing is expected when $\Delta\Phi_g$ and $\Delta\Phi_{DM}$ cancel out so that $\Delta\Phi = 0$ at some spatial scales

At the early stage (t < τ_{rec}~100s),
a large n_e suppresses radio emission

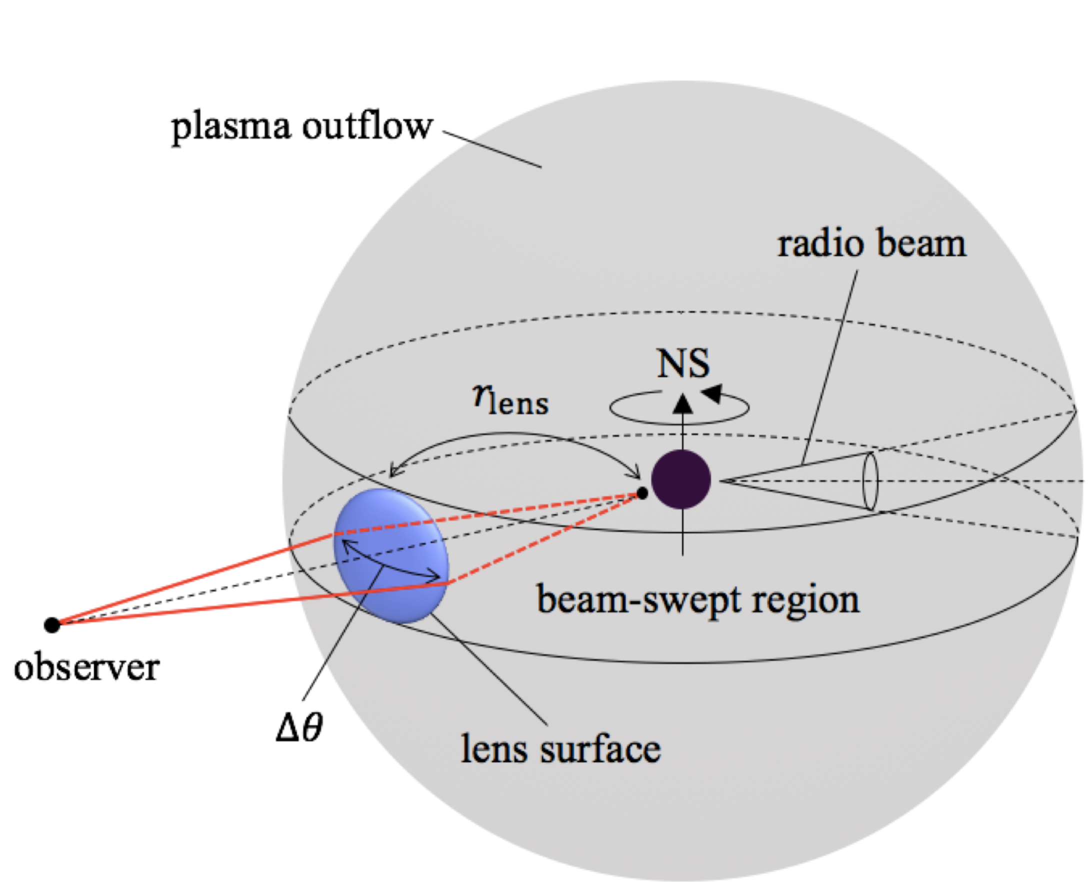




Later ($t > \tau_{rec}$~100s), a small n_e allows radio emission to propagate again

-> Expanding plasma as a lens!?

Setup & Assumption



- ✓ Angle btw. magnetic and spin axis is 90° for simplicity
- ✓ Beam-swept region is regarded to be persistently radiating radio emissions (since $P \ll \tau_{rec}$)
- ✓ $\Delta\theta$: radio beam size required for lensing

- ✓ A radio pulse leaves the source at $t = t_p$ ($> \tau_{rec}$) and reaches the lensing point at $t = t_{lens}$, corresponding to a travel distance of $r_{lens} = c\,(t_{lens} - t_p)$

Application

✓ $$\Delta\Phi_g = \frac{\nu\left(\overline{\mathrm{OL}_1} - \overline{\mathrm{OL}_0}\right)}{c} = \nu\left(t_{\mathrm{lens}} - t_p\right)\xi(\Delta\theta),$$

where $\xi(x) \equiv 1 - \cos(x/2)$

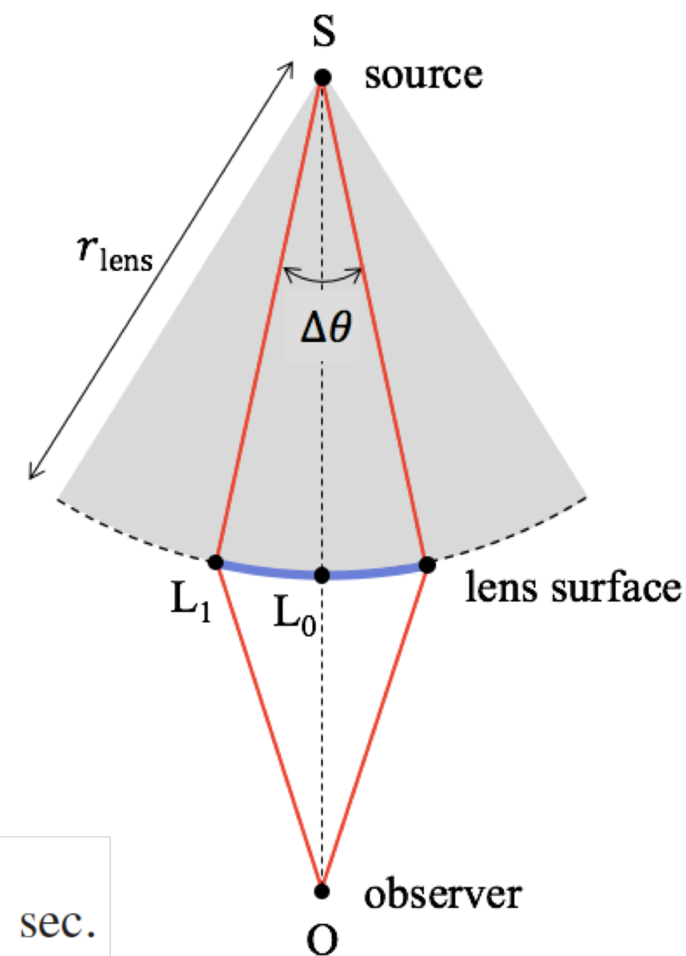
✓ $$\Delta\Phi_{\mathrm{DM}} = -\frac{k_{\mathrm{DM}}}{\nu}\Delta\mathrm{DM}$$

$$\left[\begin{array}{l} \Delta\mathrm{DM} = \displaystyle\int_{t_p}^{t_{\mathrm{lens}}} n_e(t')\, c\, dt' \\ n_e(t) = 2.3\times10^{9}\; r_{i,5}^{-3/4}\, E_{\mathrm{fb},40}^{1/2}\, t^{-2}\quad \mathrm{cm}^{-3}, \\ \text{(derived from dynamical equations)} \end{array}\right]$$

✓ solving $|\Delta\Phi_g| \approx |\Delta\Phi_{DM}|$, we obtain

$$t_{\mathrm{lens}} \sim 1.8\times10^{-4}\,\nu_9^{-1}\, r_{i,5}^{1/2}\left(\frac{t_p}{\tau_{\mathrm{rec}}}\right)^{-1}\xi(\Delta\theta)^{-1}\quad \mathrm{sec}.$$

Equatorial plane



Application (contd.)

- ✓ $\Delta\theta <\sim 10^{-3}$ is required for a lensing on $\gtrsim 10^3$ sec timescale after the burst
- ✓ Typical pulsar beam size is $\Delta\theta \sim \mathcal{O}(0.1)$
- ✓ A normal radio pulse with fine structures of $P\Delta\theta \lesssim$ msec in pulse width can give rise to plasma lensing!
- ✓ Rarer candidates are also allowed (e.g., Crab giant pulses and Fast Radio Bursts)

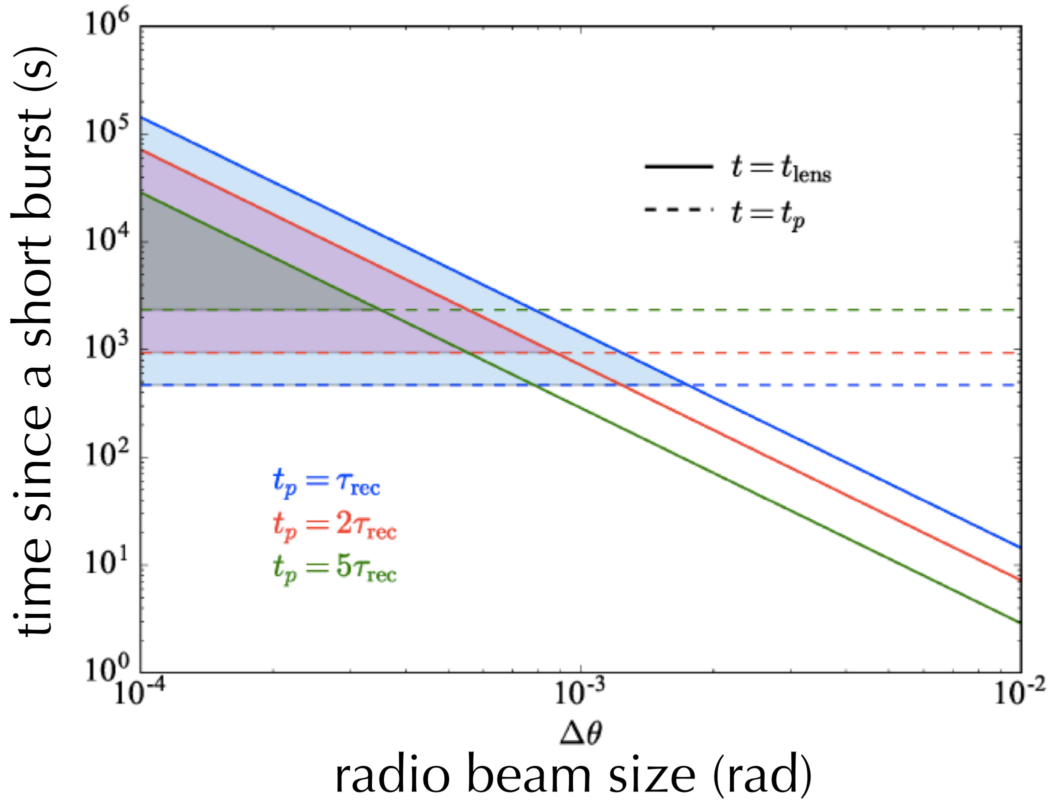


Figure 6. Constraints on the parameter space that might produce strong plasma lensing event: the elapsed time t since the burst onset and lensing pitch angle $\Delta\theta$ with assumptions of $t_p = \tau_{\rm rec}, 2\tau_{\rm rec}, 5\tau_{\rm rec}$ (colored). Solid lines and dashed lines represent the upper-limit ($t_{\rm lens}$) and lower-limit (t_p) on the timescale of plasma lensing, respectively.

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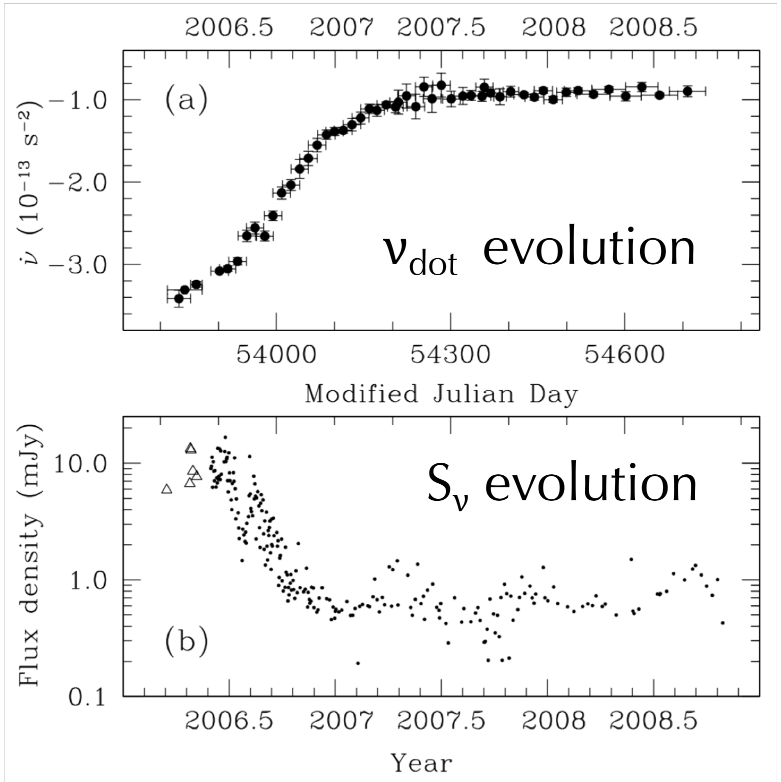
Conclusions

- ✓ SKA will find ~$\mathcal{O}(100)$ bursting NS (assuming ~1%) with radio pulsation, and considering both radio pulsation & burst is important
- ✓ Short bursts = thermal emission from a hot spot created by inflowing component of fireball plasma
- ✓ Radio suppression = due to plasma cutoff effect by expanding component of the fireball plasma
- ✓ Short duration (~>μsec) high-energy counterpart (@MeV) is expected from fireball photosphere
- ✓ Radio magnification by plasma lensing (100 sec after the burst) is also expected for fine
- ✓ We propose a possibility that radio suppression seen in bursting NS could be used as a tracer of underlying short bursts

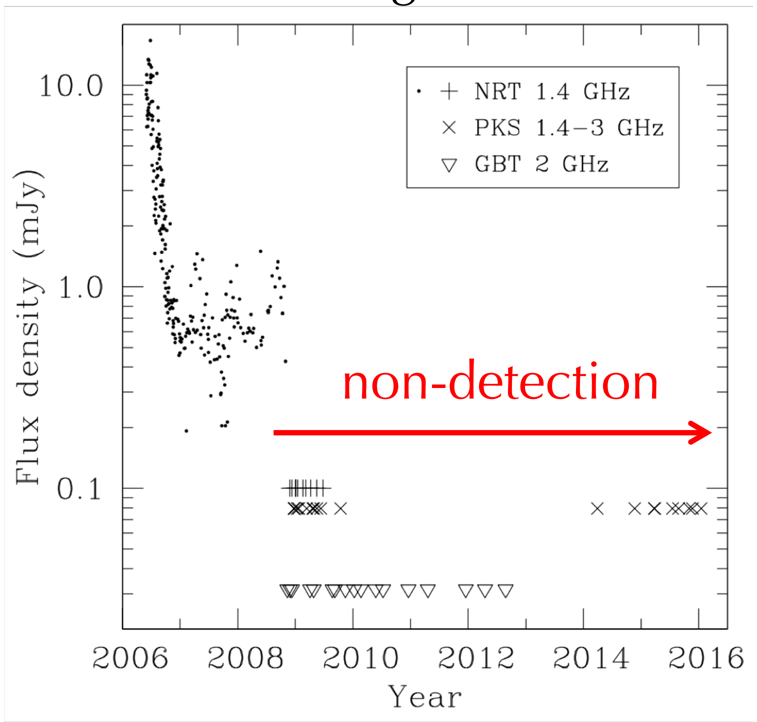
Recent topics

Magnetar XTE J1810-197 with radio pulsations

Camilo+'16



radio light curve



- ✓ The first magnetar for which the radio pulsation is confirmed
- ✓ Radio activity is rotation-powered (likely similar to radio pulsars)
- ✓ After ~10 yr dormancy in radio, very recently reactivated!

Magnetar XTE J1810-197 reactivated in radio

ATeL #12284, #12291

[Previous | Next | ADS]

Intense radio flare from the magnetar XTE J1810-197

ATel #12284; *Andrew Lyne (University of Manchester), Lina Levin (University of Manchester), Ben Stappers (University of Manchester), Mitch Mickaliger (University of Manchester), Gregory Desvignes (MPIfR, Bonn), Michael Kramer (MPIfR, Bonn)*
on *11 Dec 2018; 10:30 UT*
Credential Certification: Lina Levin (Lina.Preston@manchester.ac.uk)

Subjects: Radio, X-ray, Neutron Star, Pulsar, Magnetar

MAXI/GSC detection of the magnetar XTE J1810-197

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on *13 Dec 2018; 11:11 UT*
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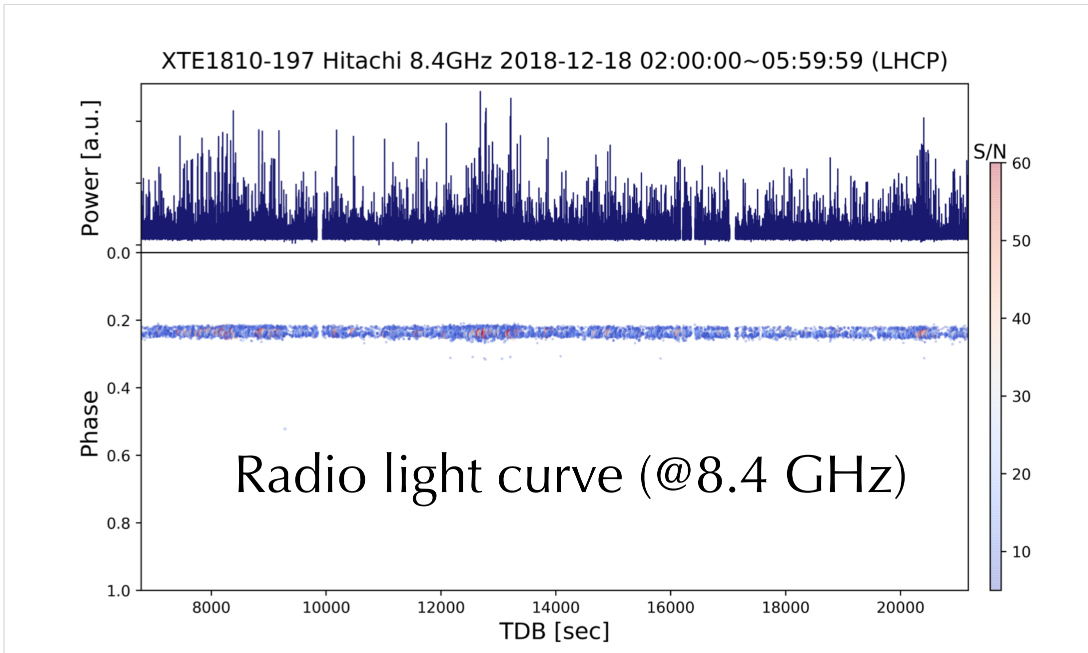
Credential Certification: Tatehiro Mihara (mihara@crab.riken.jp)

- ✓ Reactivated in radio & X-ray (outburst)
- ✓ No bursts detected yet
- ✓ Good target to test our model

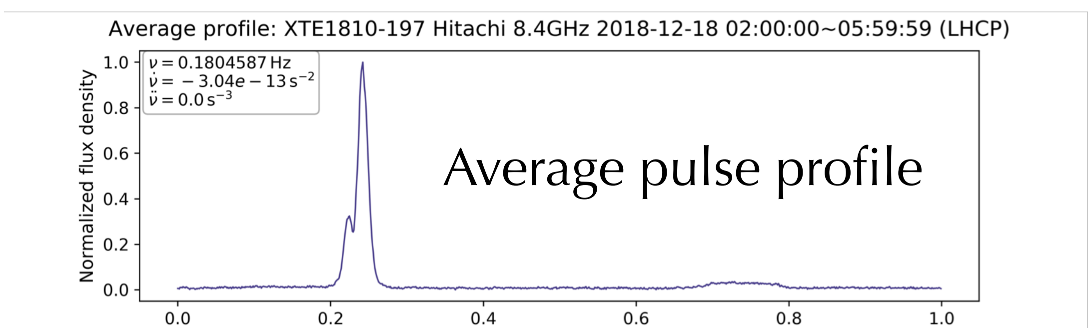
Ongoing radio monitoring of XTE J1810-197

Sujin Lee さん (U.Tokyo & NAOJ), 寺澤さん, 米倉さん, 本間さん +



- ✓ Hitachi 32 m
- ✓ 8.4 GHz
- ✓ 2018/12/18 (4 hrs)

Simultaneous monitoring in radio & X-ray band will provide us lots of information!



Phase

For details, see a poster by Sujin-san!