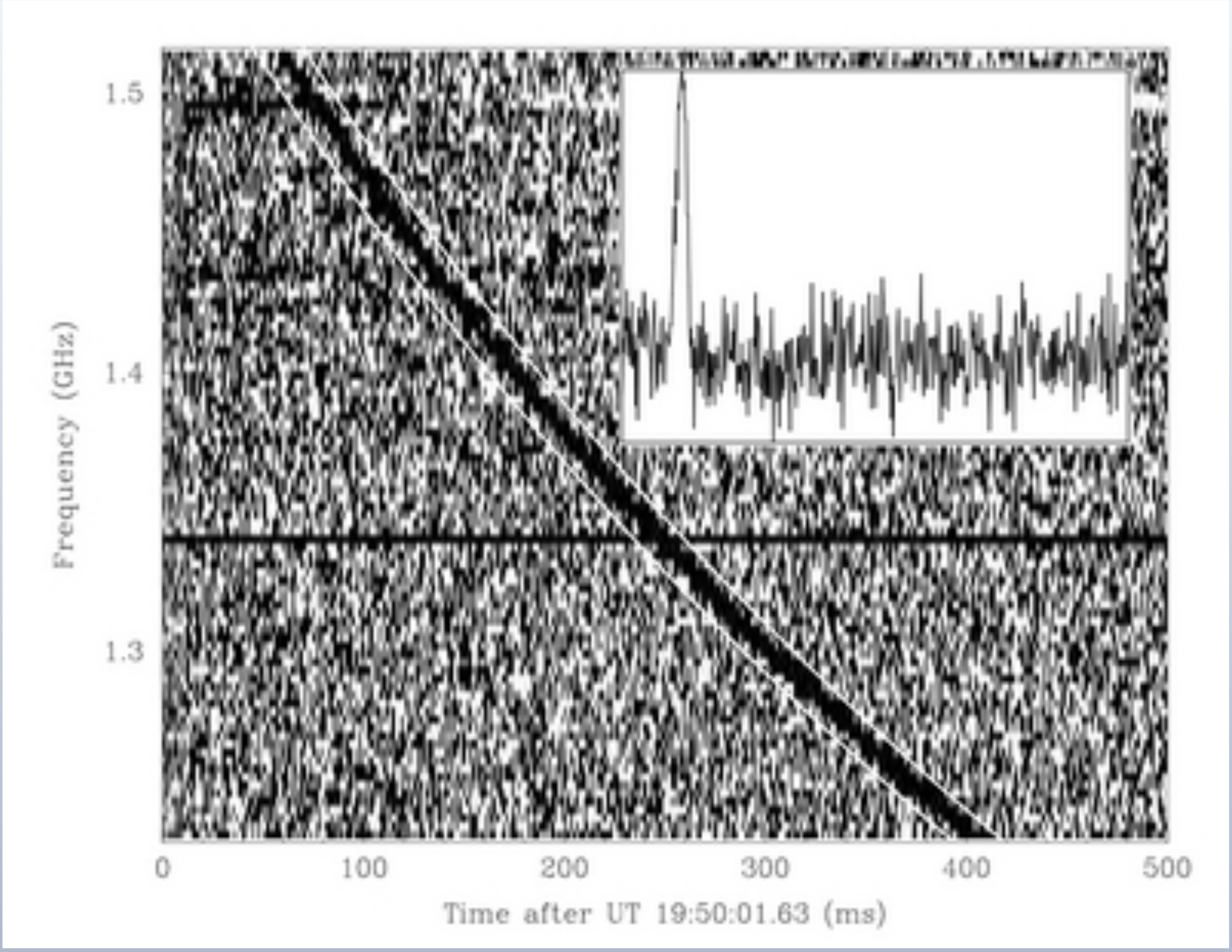
Физические параметры Быстрых Радио Всплесков

Максим Лютиков (Purdue University)

The Lorimer burst (2007)



Observational constraints on FRB emission mechanisms

- few msec. in duration, peak L ~ 10^{40} erg/s, ν > 700 MHz
- > 10^4 per day (not prompt GRBs)
- repetitive - 2 repeaters (not catastrophic like NS-NS mergers)
- isotropic (extra-Galactic); D ~ 1 Gpc - (cosmological)
- coherent emission, $T_b \approx 10^{34}\,\mathrm{K}$
- DM ~ 1000, constant to ~ % over few years
- Polarization is messy
- no clear evidence for two different populations
- one localized to star-forming, another to regular massive galaxy

FRBs - new/tougher constraints (compared to pulsars) from coherent emission on the parameters at the source

- Crab's radio: $T_b \sim 10^{40}$K, 10^{-6} of spindown, highest GP: 10^{-2}
- No energetic constraints
- Repeater: some 5-10 orders of magnitude larger energy density at the source - macroscopic physical constraints on plasma parameters at the source.
- Can they be satisfied?

(Lyutikov 2019, Lyutikov & Melrose, in prep.)

Plasma density and B-field

- Let $c\tau \sim$ source size.
- Radiation energy density

$$u_r = \frac{\nu F_\nu d^2}{c^3 \tau^2}$$

- The brightness T_b:

$$k_B T_b = \frac{c^2}{2\nu^2} I_\nu = \frac{1}{2\pi} \lambda^3 u_r$$

- brightness temperature is ~ energy density of radiation within a volume of wavelength cubed

(Lyutikov 2019)

- Radiation energy density < of emitting particles' energy density

$$u_r < \gamma n m_e c^2$$

$$\gamma n \lambda^3 \geq \frac{k_B T_b}{m_e c^2}$$

- Equipartition B-field

$$B_{eq} = \sqrt{8\pi} \sqrt{\frac{T_b}{\lambda^3}} = 10^8 \nu_{GHz}^{3/2} T_{b,35}^{1/2}\, \mathrm{G}$$

(can be larger)

- NS magnetospheres

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(can be larger)

- NS magnetospheres

“Normal” (non-coherent) loses may dominate

- Laser intensity parameter “a”

$$a \equiv \frac{eE'}{2\pi m_e c \nu'} = \frac{e\sqrt{\nu k_B T_b}}{m_e c^{5/2}\delta} > 3 \times 10^5$$

- (most powerful lasers can get to a ~ 1)
- In no B-field: $p_{\rm fluct}/(m_e c) \sim a$ -> huge radiative (IC and synch) loses (e.g., loss time can be shorter than pulse duration)
- In B-field: if $\omega_B \geq \omega'$, the drift with $v_d/c \sim E'/B$

$$B \geq \frac{m_e c^2}{e\lambda\delta} \approx 100\nu_{GHz}\delta^{-1}\,{\rm G}$$

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Large B-fields are required to avoid catastrophic “normal” loses

Limits on B-field

- Radiation energy density < particle energy density < B-field:

$$B \geq \sqrt{\frac{8\pi k_B T_b}{\lambda^3}} \approx 10^8 \mathrm{G}$$

- Weak "normal" losses:

$$B \geq \frac{m_e c^2}{e\lambda} \approx 100 \mathrm{G}$$

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These are high fields: NS magnetospheres

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(super-Giant Pulses)

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These are high fields: NS magnetospheres

Rotationally-powered (super-Giant Pulses)

Magnetically-powered (super-Solar flares)

Radio emission from NSs

- There are three types of coherent emission from NS: type-I, type-II, type-III
  - Type I: log-normal dist., Crab precursor, polar caps, rotationally-driven
  - Type II: GPs, power-law, Crab MP&IP, border between open/closed field lines, rotationally-driven
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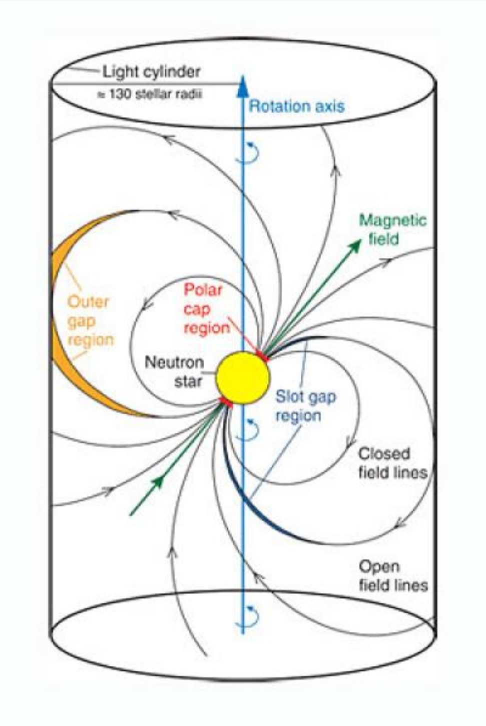

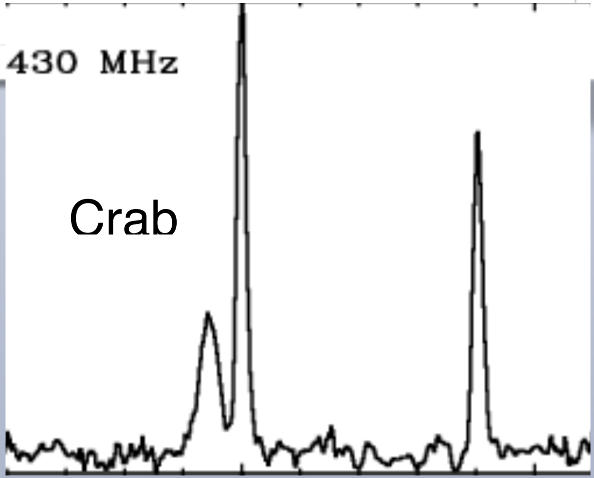

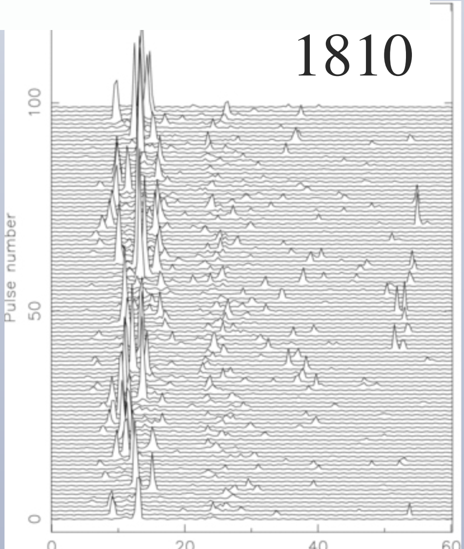

Serylak+ 2009

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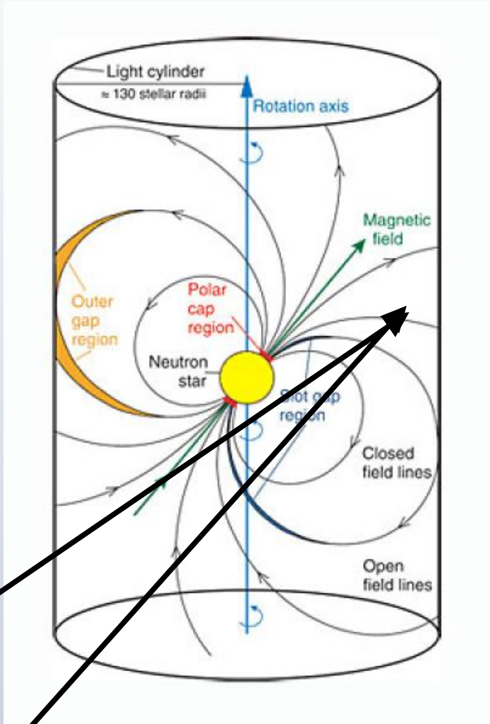

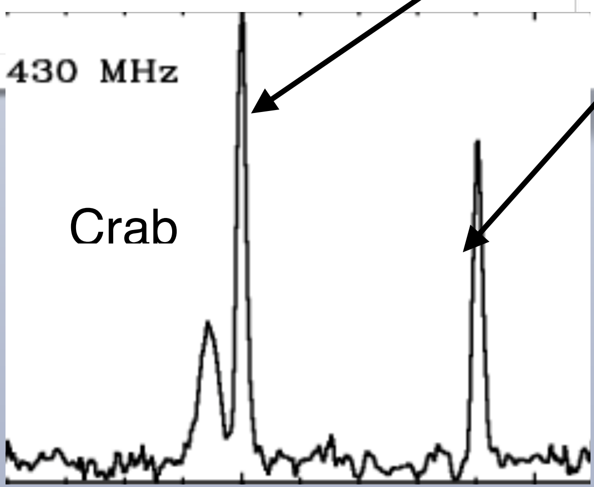

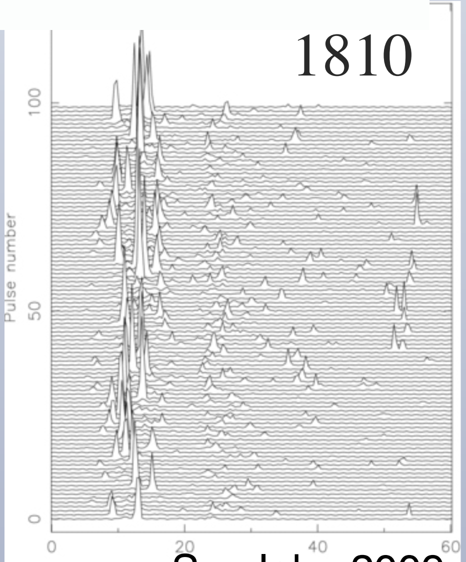

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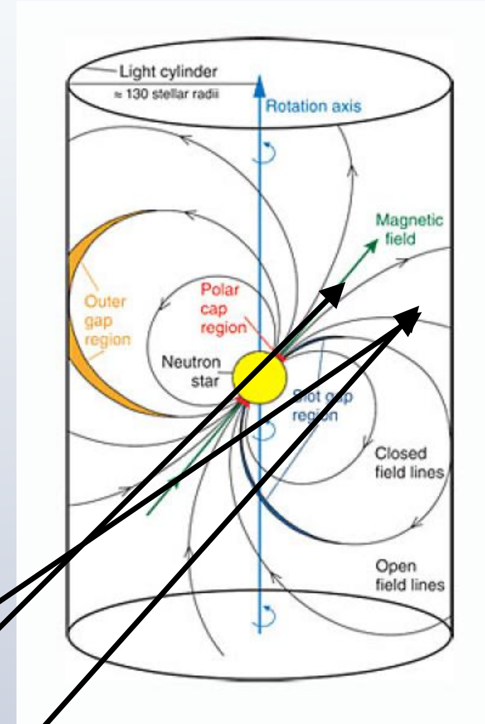

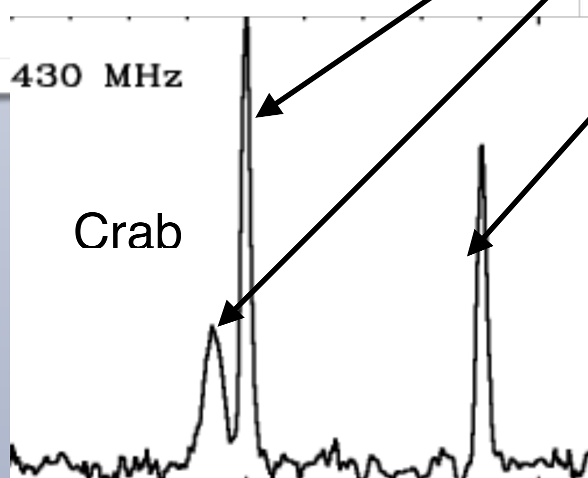

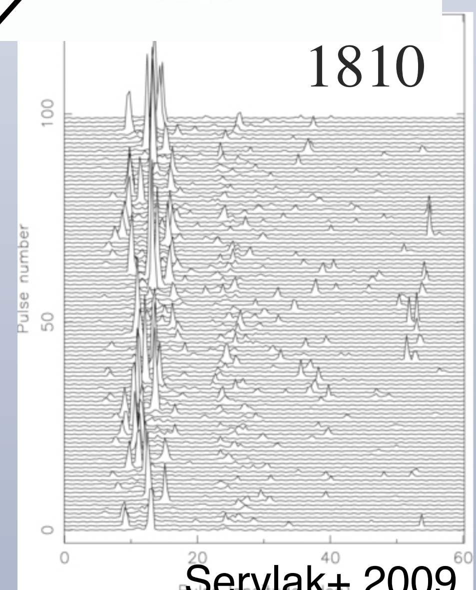

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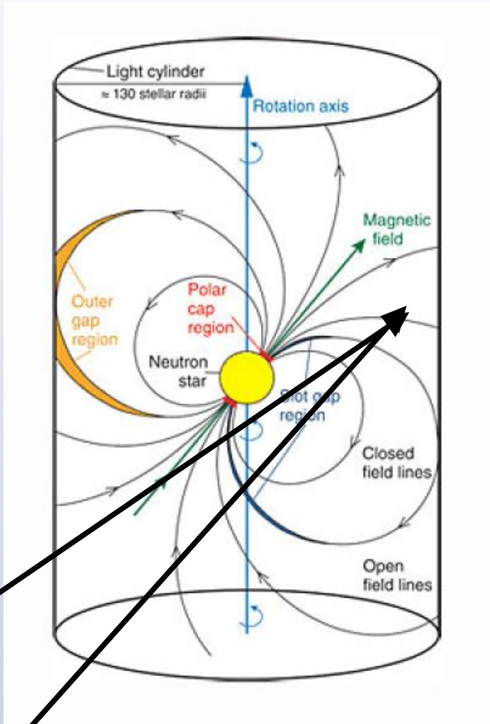

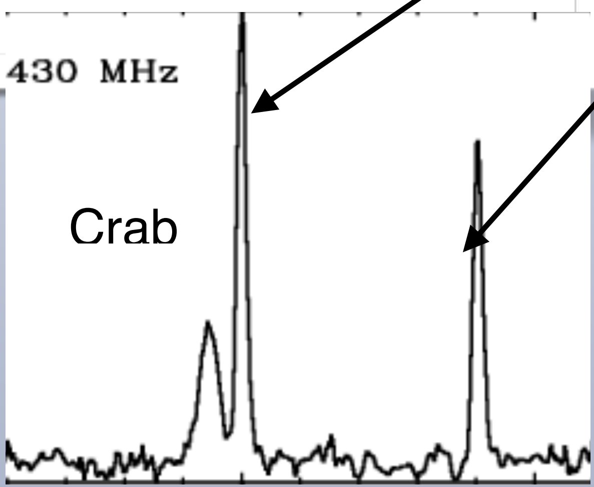

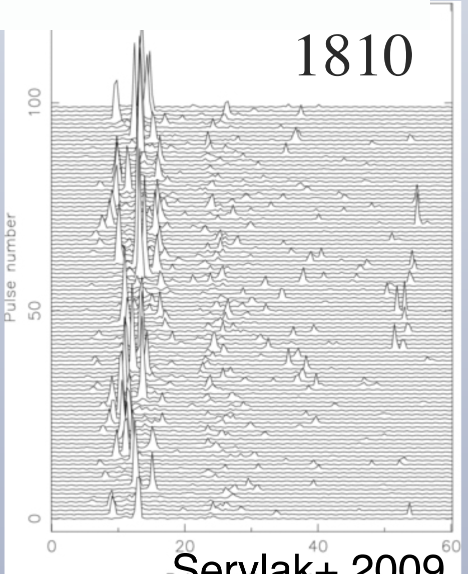

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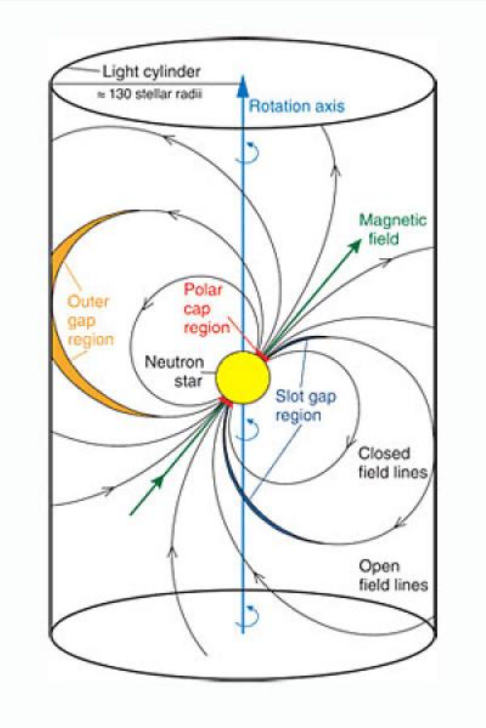

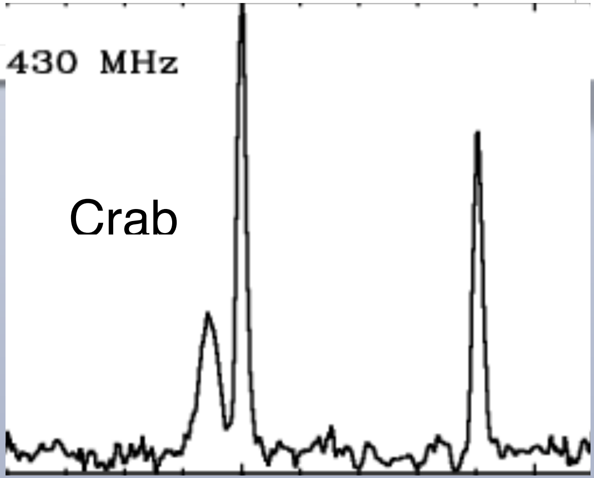

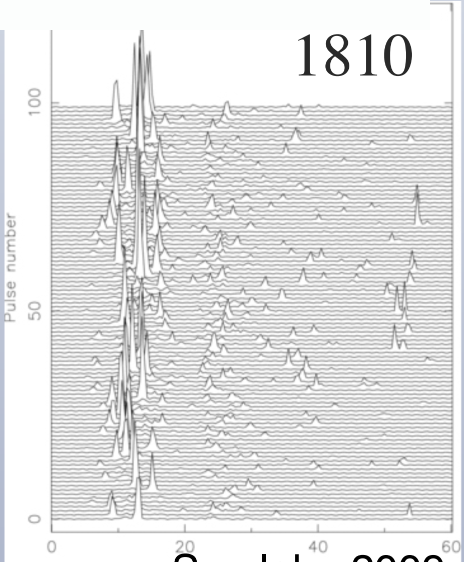

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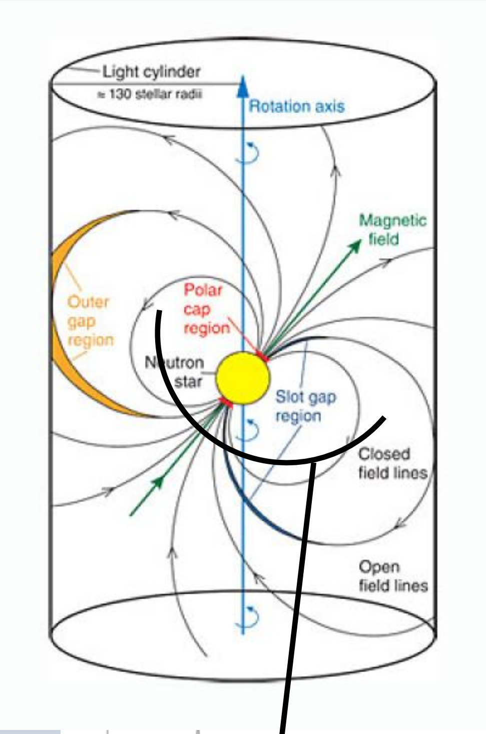

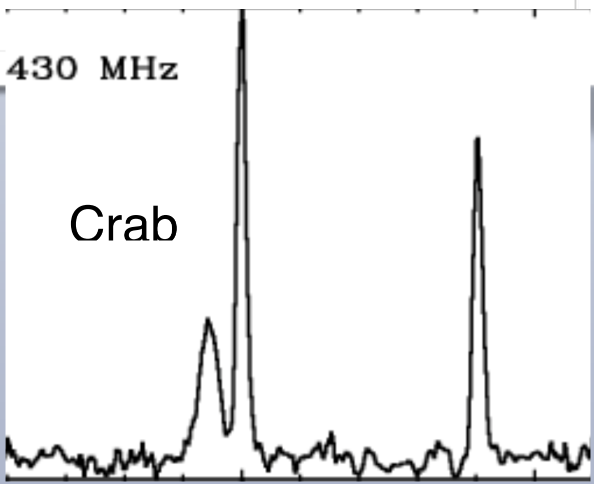

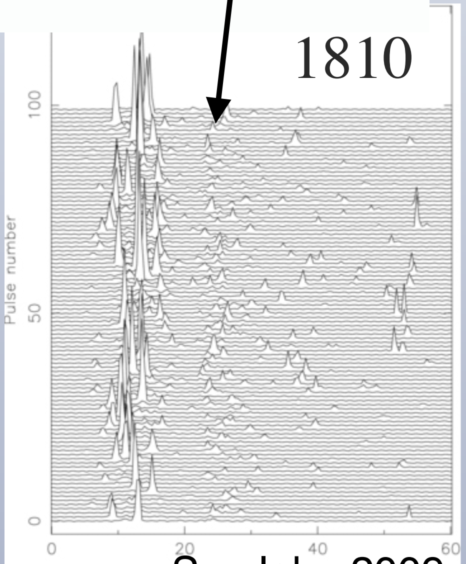

Serylak+ 2009

Rotationally vs magnetically powered

- Rotationally (super-giant pulses), scale with GJ:

$$n'_{pulsar} = \kappa \frac{\Omega B}{2\pi e c \Gamma}$$

- Crab GP and nano-shots:

$$\kappa \gamma \Gamma^3 > 3 \times 10^{13} \nu_{GHz}^3 \left(\frac{r}{R_{LC}} \right)^3 T_{b,35}$$

$$\kappa \sim 10^3 - 10^6$$

$$\gamma \sim \Gamma \sim 10^3 - 10^4$$

- Pulsars: no correlation between coherent radio and other freq. - not expected for FRBs

- Magnetically: scale density with magnetar twist:

$$n'_{magnetar} = \Delta\phi \frac{B}{2\pi e r \Gamma}$$

$$\gamma \Gamma^3 \geq 10^7 \nu_{GHz}^3 \left(\frac{P}{10^{-3}\mathrm{sec}} \right)^4$$

$$\frac{T_{b,35}}{\Delta\phi} \left(\frac{B}{B_Q} \right)^{-1} \left(\frac{r}{R_{LC}} \right)^4$$

- ~ OK
- Solar flares: both radio, optical and high energy - is expected for ``magnetar flare'' model

Macroscopic Model I: Rotationally powered super-Giant Pulses

Lyutikov + 2016

- very young SNRs, 10-100 years
  - free-free absorption in new SN shell $\tau_{ff} \sim 1 \,@\, 300\,\mathrm{MHz}$ (no LOFAR)
  - DM through the shell $$DM \approx 100s \left(\frac{t}{yrs}\right)^{-2}$$
- Crab's GPs reach ~ 1% efficiency of L_{sd}
- If $\nu F_\nu \propto L_{sd}$ need ~ 10^4 higher peak power from **100 Mpc**
  - Few msec period, with Crab-like B-field - reasonable to expect
  - Spin-down times ~ 10-100 yrs
  - Rates within 100 Mpc are OK.
- Injection rate $f_{inj} \propto \dot{E}^{-1}$ (observed $f \propto \dot{E}^{-3/2}$ - consistent with observed distribution of fast pulsar)
  - Very flat distribution of distances to a given brightness (type of Malmquist bias)

Repeater: FRBs not Rotationally powered

- observed radio flux a fraction <1 of the spin-down

$$\nu F_\nu < \frac{L_{sd}}{4\pi d^2}$$ - need powerful source

- (L_{sd} is the EM power, need to put energy in particles to emit)
- Could have worked from 100Mpc (Lyutikov+ 2016)
- Can get from millisecond pulsar, but spin-down time is then short, no evolution seen in the 1st Repeater (and no DM changes - expected ~ $1/t^2$ through ejecta).
- lack of periodicities in the Repeater

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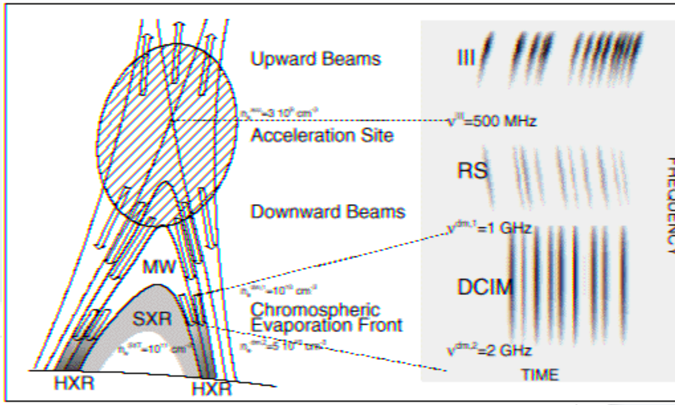
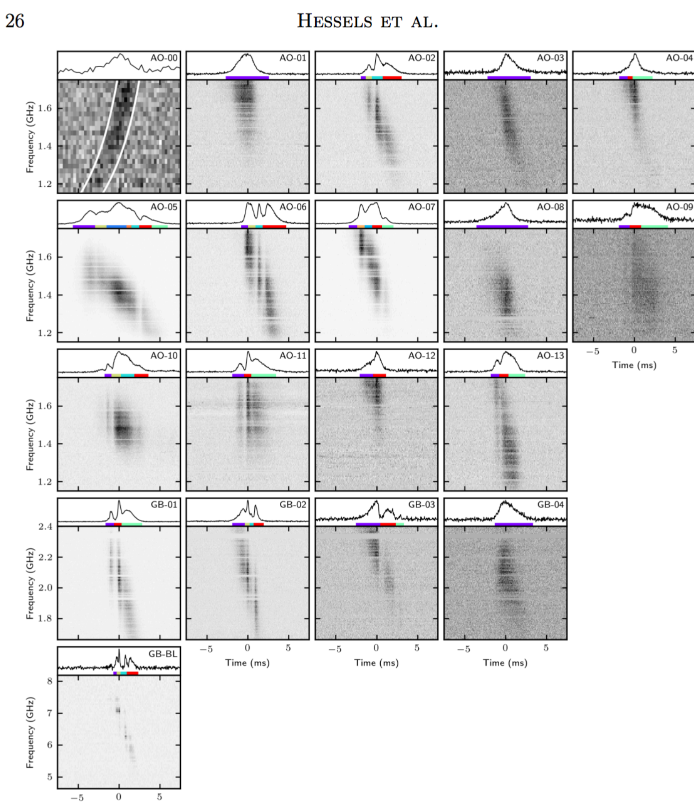
Requirement of large L_{sd} and no DM changes excludes young rotationally-powered pulsars as FRB sources (Lyutikov 2017)

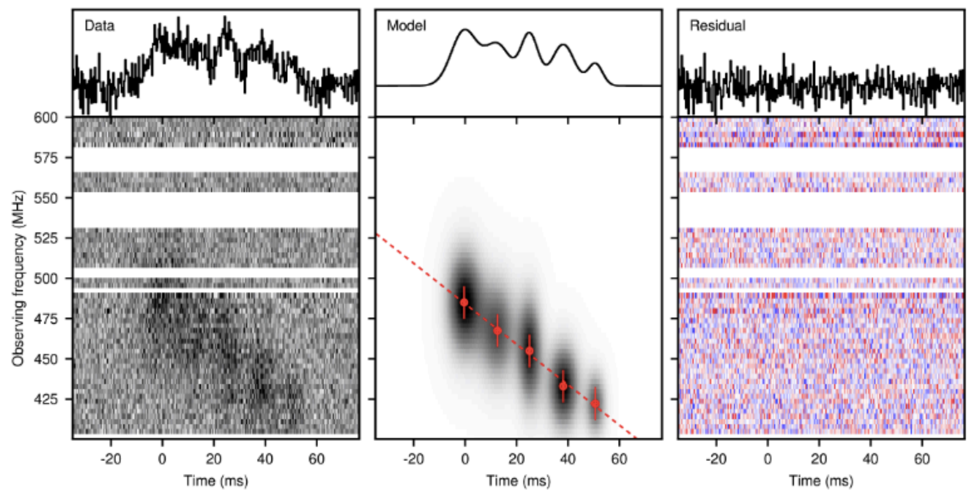
Macroscopic Model II: magnetar flares (type-iii)



- Solar type-III radio emission in magnetars (Lyutikov 2006)
- **Initial** stage of a “reconnection flare” - jets of particles, hence coherent emission - like Crab flares (Lyutikov et al. 2016)
- Best case - observe radio burst associated with magnetar burst and flares.
- Acceleration will “waste” energy on high energy emission: problems with energetics (like GBRs, but wrong rate)
- Constraining limits from SGR 1806-20 flare
  - SGR flare was 10^{47} erg/s -> radio efficiency of Repeater10^{-6} - OK?
  - But would give a GJy from 10 kpc - not seen in Parkes side-lobes (Tendulkar + 2016)
  - No radio from PSR J1119-6127 X-ray (radio efficiency < 10^{-8})

CHIME: same frequency drift in two repeaters





CHIME/FRB Collaboration

- Some kind of a stiff confining structures – most likely magnetic field (radius-to-frequency mapping in pulsars)
- Constructive interference through changing lens: up and down drifts

Two “predictions” of magnetars’ radio emission

(Shitov + 1999)

THE ASTROPHYSICAL JOURNAL, 580:L65–L68, 2002 November 20

RADIO EMISSION FROM MAGNETARS

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COHERENT EMISSION FROM MAGNETARS

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Two "predictions" of magnetars' radio emission

(Shitov + 1999)

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Department ... 3A 2T8, Canada;

The radio emission of SGRs during bursting activity will resemble the solar radio type III bursts. In solar type III bursts, the energy is consecutively converted from the magnetic energy into fast particles, then into electrostatic plasma waves, and finally into escaping electromagnetic waves. The frequency of the generated emission measure waves is the double of the plasma frequency $\omega \sim 2\omega_p$. Thus, one expects a *narrowband emission* $\Delta\omega/\omega \leq 1$. The growth rate of Langmuir instability,

$$\Gamma \sim (n_b/n)^{1/3}\omega_p \leq \omega_p \quad (4)$$

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(where n_b is the beam density), is indeed much higher than the dynamical time,

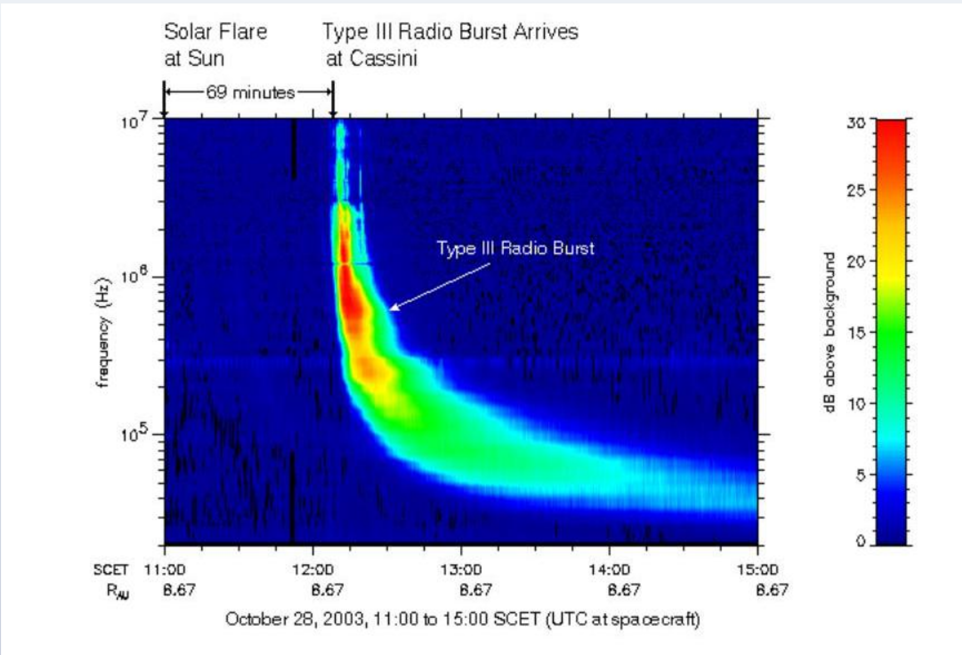
$$\Gamma/(c/R) \sim \sqrt{\omega_B/(c/R)} \gg 1. \quad (5)$$

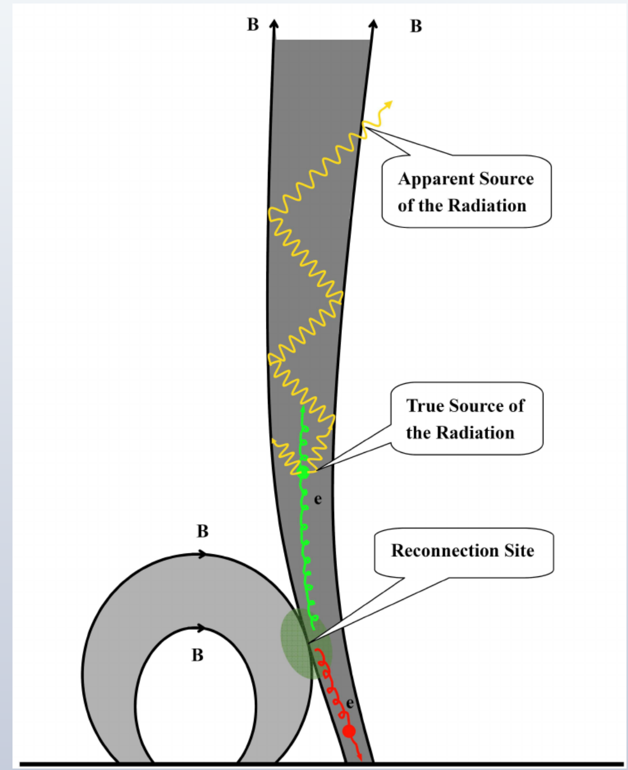
Thus, the plasma instability has enough time to develop.

A distinct feature of the type III burst is the drift of the central frequency that is due to the spatial propagation of the emitting beam in the inhomogeneous plasma. Since the velocities of the emitting electrons are likely to be weakly relativistic, the resulting emission may not be narrowband emission, since the electrons propagate in the inhomogeneous plasma. Still, one may expect the frequency drift of the peak of radio emission, characteristic of type III bursts. Since the plasma density in the SGR mag-

05, Israel;

Type-III Solar Radio bursts

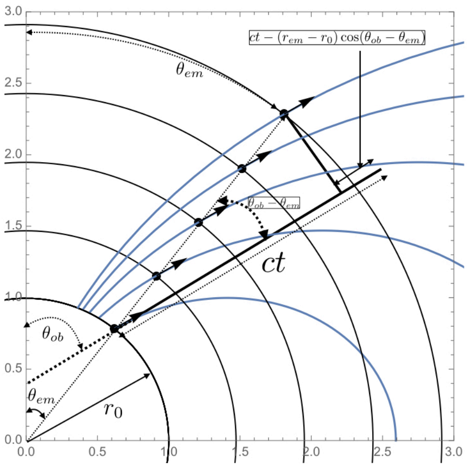


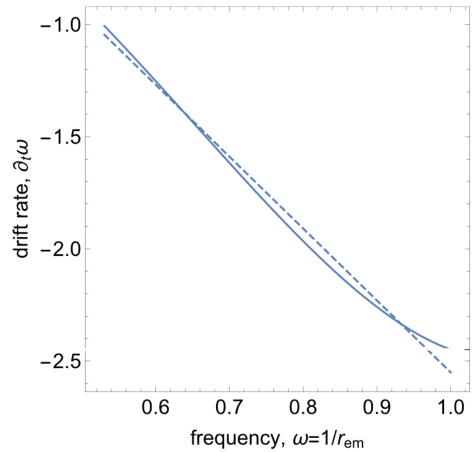


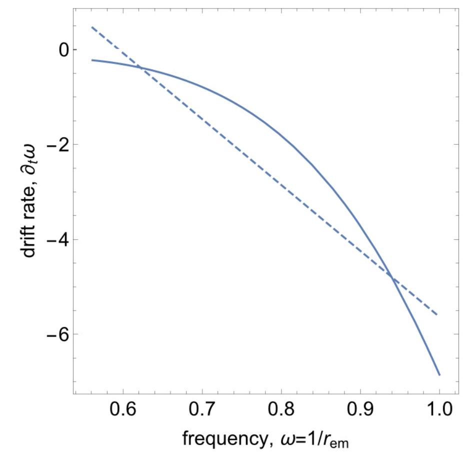
- plasma jets (electrons) from reconnection region propagating up in the corona
- Reconnection in magnetars - beamed up

Radius-to-frequency mapping

- $\omega(r)$, given frequency at given radius, emission along B

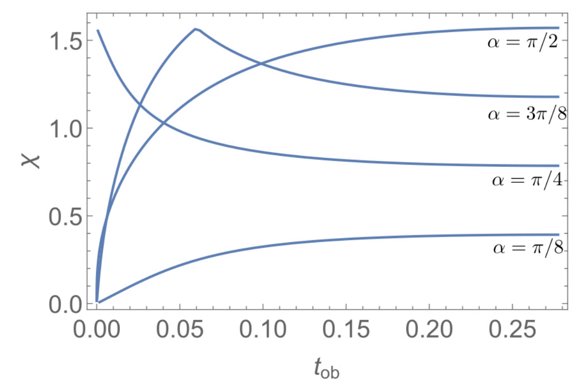






- Typical linear frequency drift, rates matched observed, sometimes complicated
- Faster rotation - larger drifts
- Prediction: PA swings

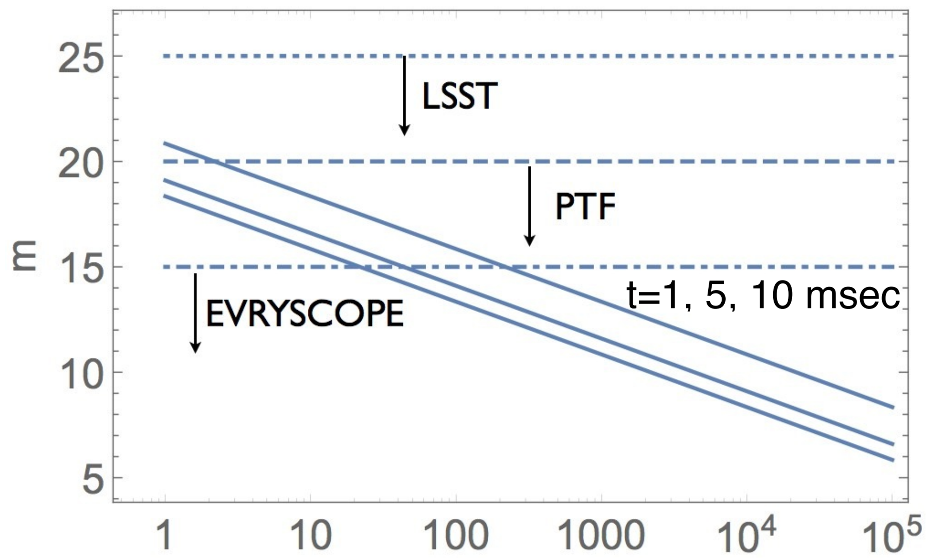
  (RVM - but smaller than in pulsars)



Counter-part strategy: optical

- Optical energetics >> radio, ~ 10^{45} erg/sec
- Peak flux ~ 9m (but only for few msec - fast read-outs!)
- m~ 15 image in 60 sec PTF, ASAS-SN, EVRYSCOPE (LSST!) - PTF might have seen, as star-like points in single exposure
- Radio and optical - stare at the same patch
- 2 optical?
- Multi-frequency radio
  - triggered LOFAR obs.
  - CHIME

- let's hope!



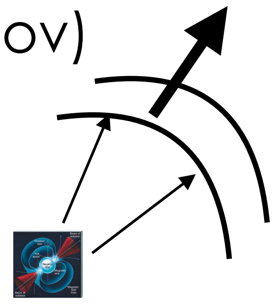
Lyutikov & Lorimer 2016 η_o

Conclusion

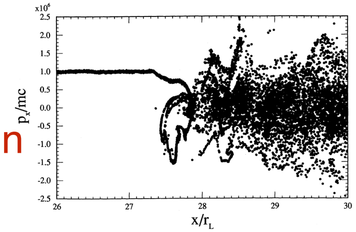
- FRBs' radio energetics is huge: macroscopic constraints at the source! (did not have for pulsars)
- NS magnetospheres are the best bet for now, a bit boring
  - overall duration
  - frequency drifts
  - Predicted PA swings
- Must be a special, powerful NS, not even average magnetar
- Radio power (+ constant DM and non-changing properties of The Repeater) seem to exclude super-GPs
- (Special) Magnetars:
  - energetics OK
  - frequency drift ~ Solar type-III
  - some, weak, observational arguments against
  - but must be "quiet", not GRB, not much at high energies

Alternatives

- Cyclotron maser at shocks (Lyubarsky, Beloborodov)
  - from 10^{14}-10^{15} cm: Gamma ~ 10^4 is needed
  - energy is "wasted" on bulk motion (we are tight already)
  - not clear if can work in 3D

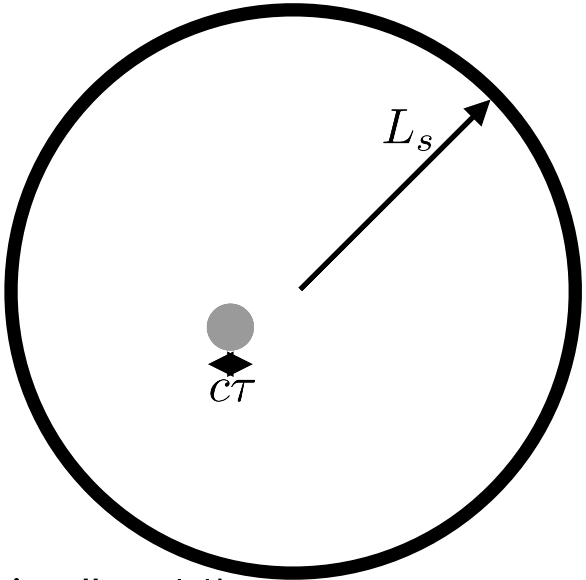


Ring distribution



Gallant +,1992

- Super-radiance
  - (In lab: excite to inverted population, like laser without mirrors)
  - coherently emitting blob L_s
  - Increased pumping within $c\mathcal{T}$
  - triggered rate of induced transitions
  - Energy within L_s, duration $c\mathcal{T}$ (if induced rate is fast enough)
  - Not clear if there is a good "lab technician" out there



Alternatives

- Cyclotron maser at shocks (Lyubarsky, Beloborodov)
  - from 10^{14}-10^{15} cm: Gamma ~ 10^4 is needed
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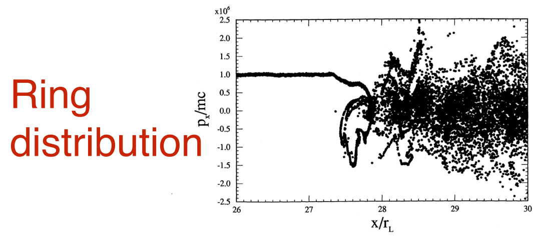

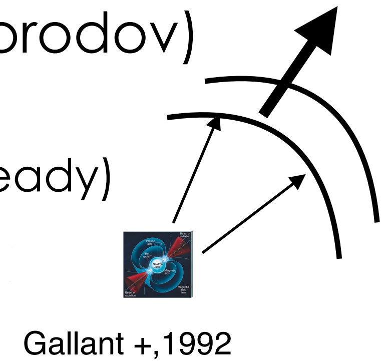

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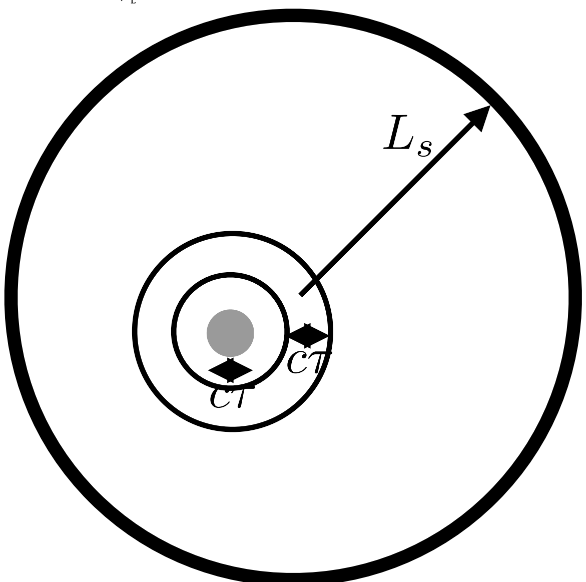

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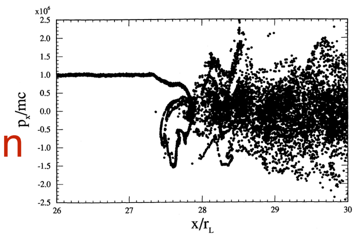

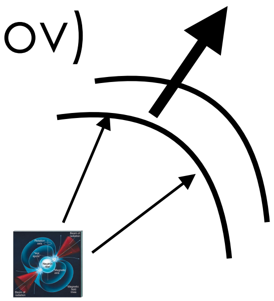

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