SYNCHROTRON MASER FROM WEAKLY MAGNETISED NEUTRON STARS AS THE EMISSION MECHANISM OF FAST RADIO BURSTS

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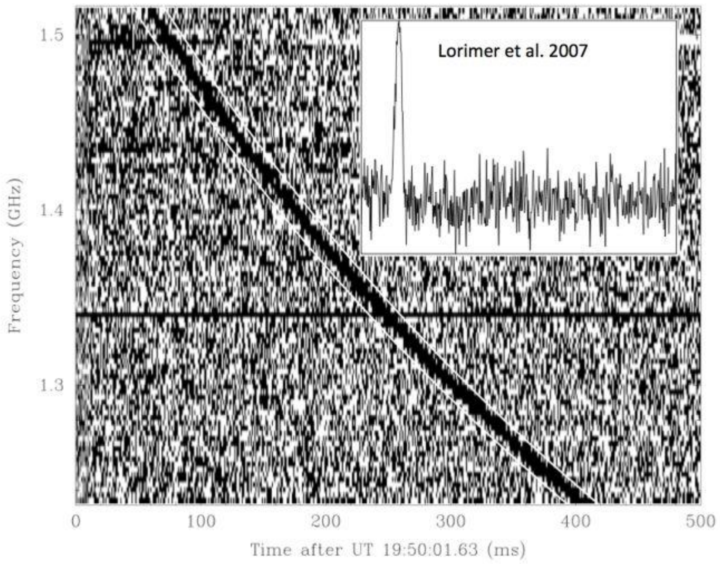
FAST RADIO BURSTS

Typical fluxes of ~1 Jy and durations of ~1 ms

First reported by Lorimer et al. in 2007

Over 70 published to date (frbcat.org)

Majority originally detected at 1.4 GHz by the Parkes telescope in Australia (now mostly CHIME)



FRB 010724 signal (Lorimer et al. 2007)

Parkes telescope (skatelescope.org)

DISPERSION MEASURE

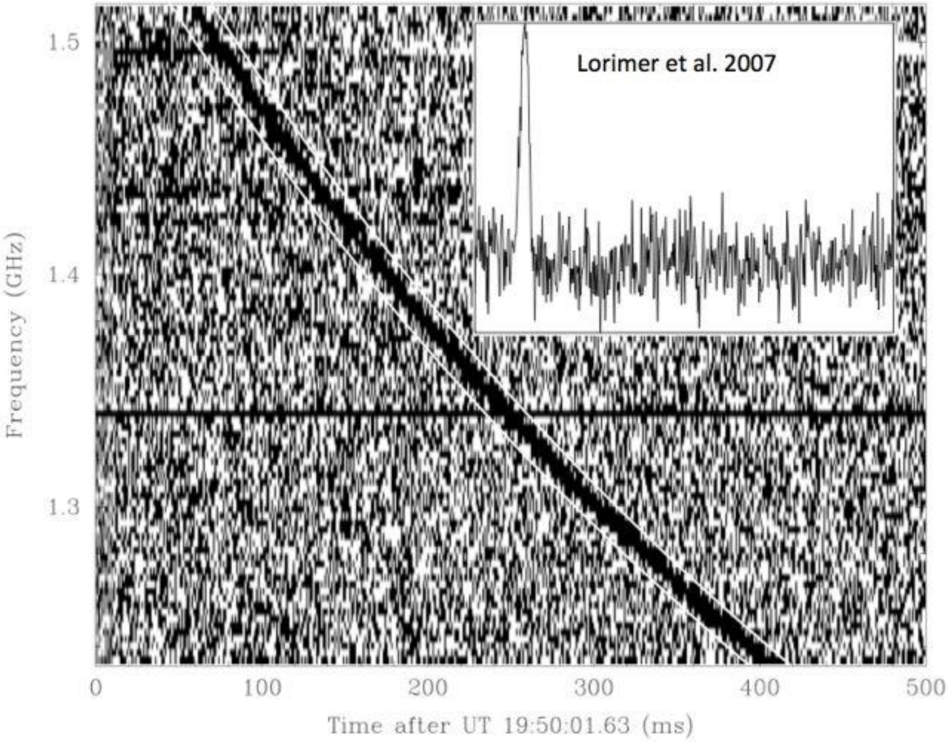
FRBs can have extremely high dispersion measures (DM) of up to 2600 pc cm^{-3}

$$DM = \int_0^D n dl$$

Suggested extragalactic origin

Time delay of signal passing through cold plasma:

$$t_d = \frac{e^2}{2\pi m_e c}\frac{DM}{\nu^2}$$



FRB 010724 signal (Lorimer et al. 2007)

FRB 121102: THE FIRST REPEATING FRB

Discovered by Spitler et al. in 2016

One of only two repeating bursts published to date (FRB 180814)

No periodicity

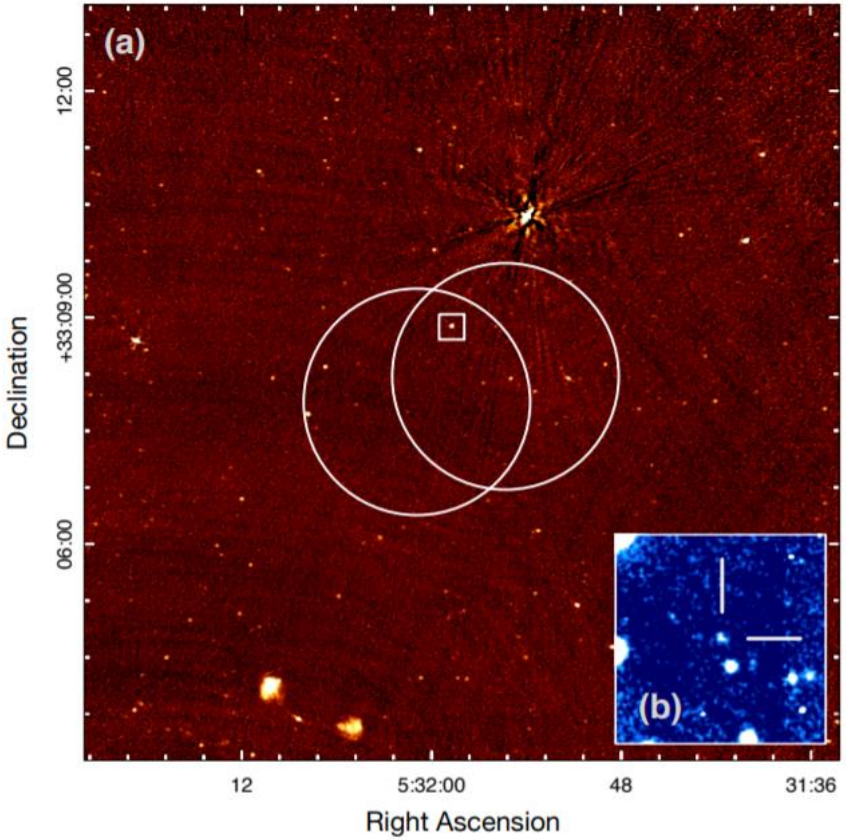
Localised to a host galaxy at

$z = 0.192$ (D = 972 Mpc)

Confirms extragalactic origin of FRBs

FRB 180924 - $z = 0.3214$ (Bannister et al 2019)

FRB 190523 - $z = 0.66$ (Ravi et al 2019)



(a) Radio and (b) optical images of FRB 121102 field (Chatterjee et al. 2017)

COHERENT EMISSION

High intensity and short duration → extremely high brightness temperatures T_b of up to 10^{37} K (Katz 2016)

Radiation intensity

$$T_b = \frac{I_v c^2}{2 k_B \nu^2}$$

Above 10^{12} K electrons rapidly cool due to Compton losses

FRBs require a coherent emission mechanism!

SYNCHROTRON MASER

Negative synchrotron self absorption coefficient α_υ → stimulated, coherent emission

Electron energy

Electron distribution function

$$\alpha_\upsilon = -\frac{c^2}{4\pi\upsilon^2}\int E^2 \frac{d}{dE}\left[\frac{n(E)}{E^2}\right] \mathrm{P}(\upsilon, E)\, dE$$

(Ginzburg 1989)

Frequency

Power emitted by electron with energy E

Requires a population inversion → electron distribution grows faster than E^2

Impossible in vacuum

SYNCHROTRON MASER: RAZIN EFFECT

Modification of emission from a relativistic plasma compared to the vacuum case

Synchrotron beaming angle is changed: $\theta_b \sim (1 - N_r^2 \beta^2)^{1/2}$

Refractive index = 1 in vacuum case

Important at frequencies $\nu_p < \nu < \nu_R^*$

Plasma frequency

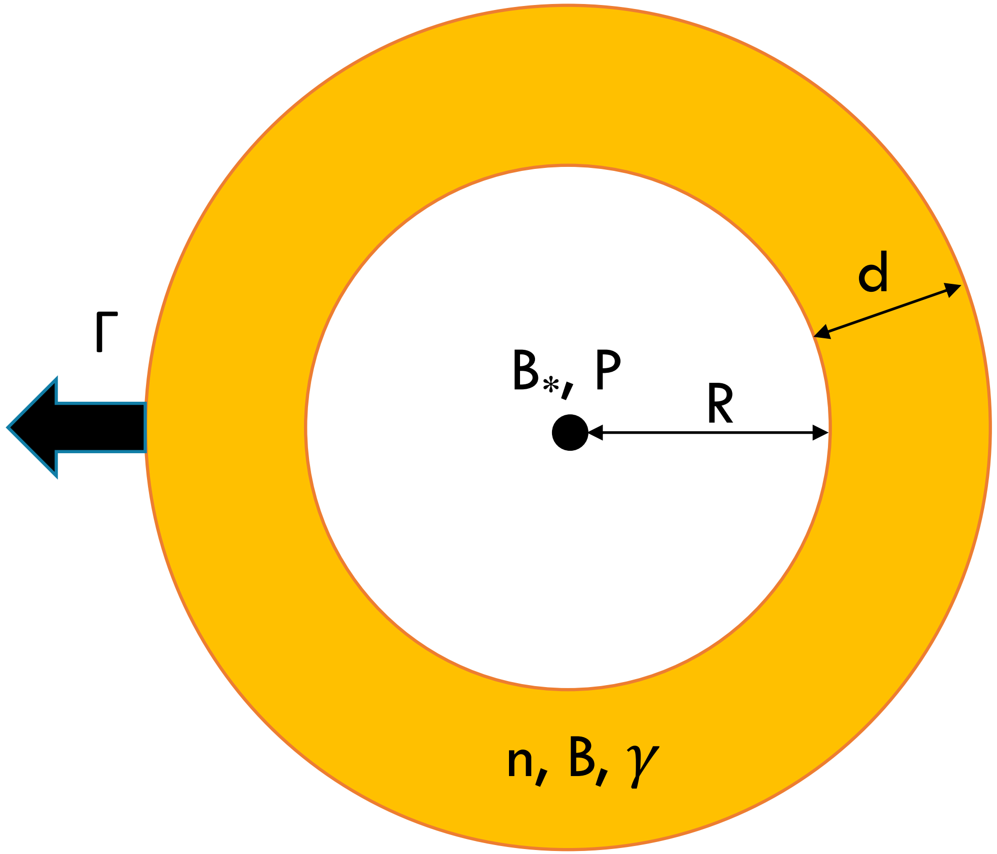
Razin frequency

$$\nu_R^* \sim \upsilon_p min\{\gamma, \sqrt{\nu_p/\nu_B}\}$$

Gyration frequency

(Sagiv & Waxman 2002)

MODEL



B_* - Neutron star (NS) surface magnetic field

P - NS period

R - Distance from NS to shell

d - Width of shell

n - Electron number density in shell

B - Magnetic field in shell

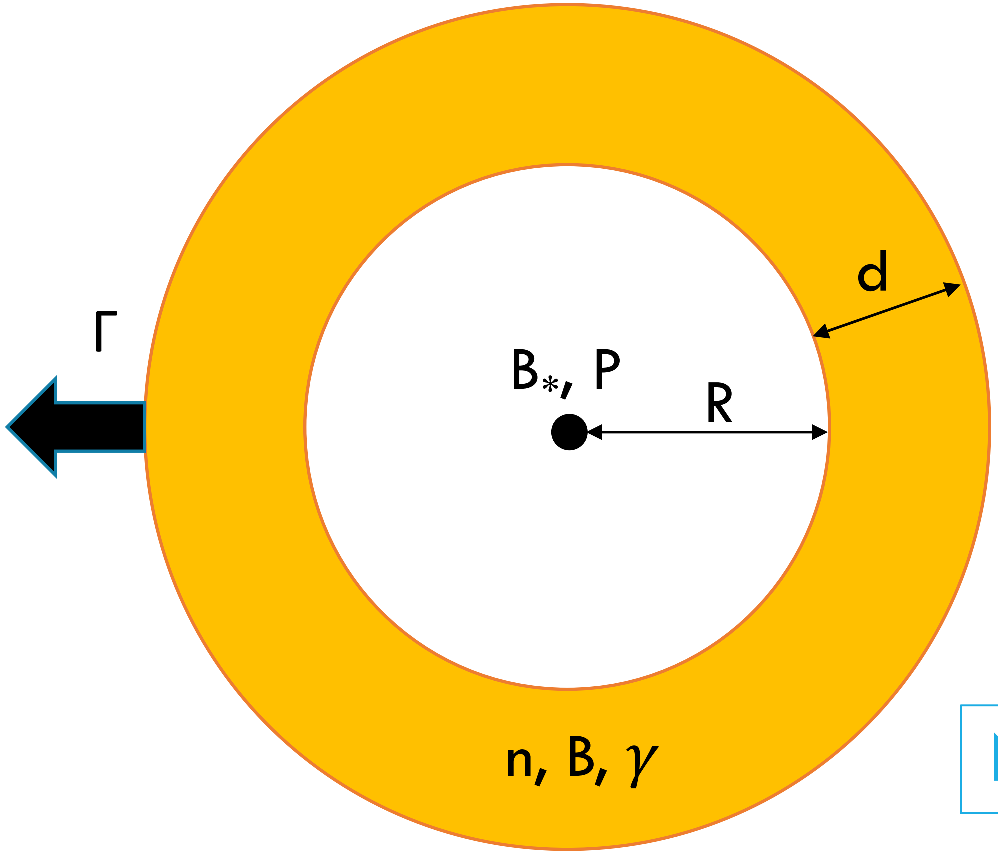
Γ - Bulk Lorentz factor of electrons in shell

γ - Electron Lorentz factor

CONSTRAINTS

1) Shell size
2) Dispersion measure
3) Burst energy/efficiency
4) Frequency

CONSTRAINTS: SHELL SIZE



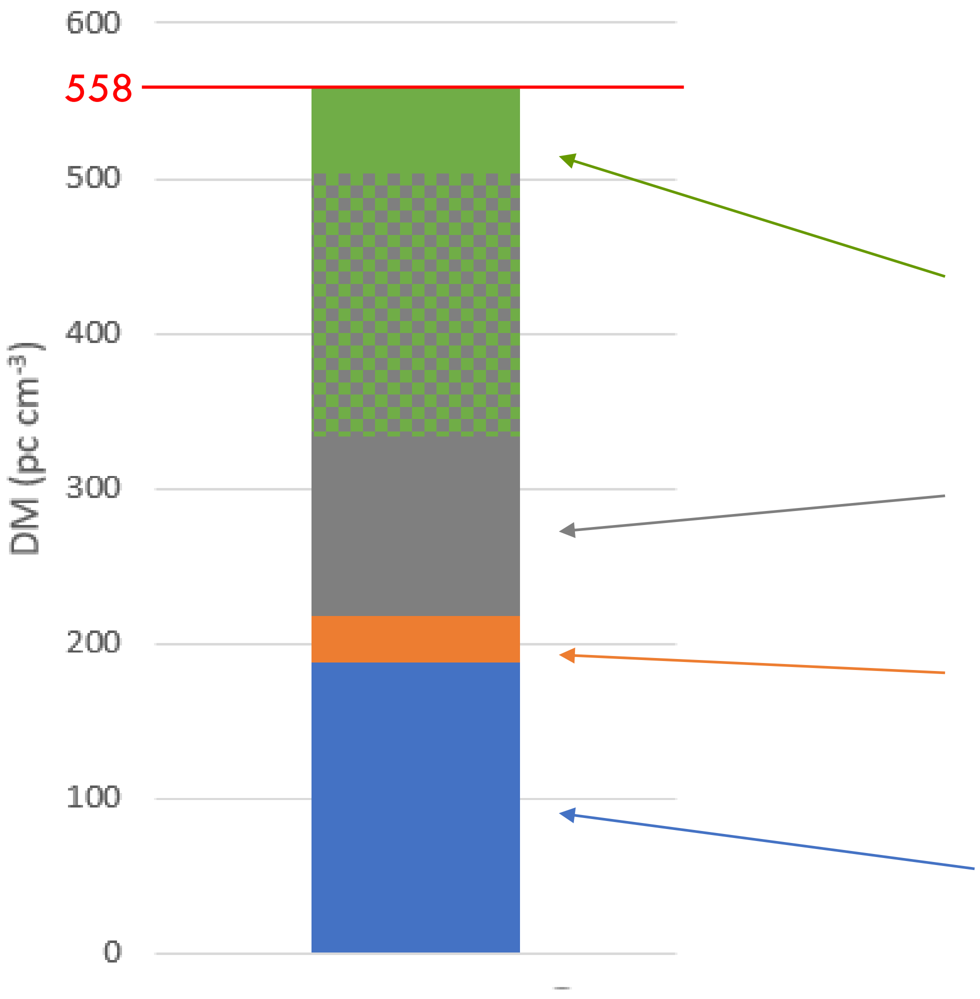
For a relativistic blast wave, the shocked plasma has width:

$$d \sim \frac{R}{\Gamma}$$

Note: $\gamma \approx \Gamma$

(Blandford & McKee 1976)

CONSTRAINTS: DISPERSION MEASURE



FRB 121102 DM: 558 pc cm^{-3}

Host Galaxy + Source: 55-225 pc cm^{-3}

Intergalactic Medium (IGM): 115-285 pc cm^{-3}

Milky Way Halo: 30 pc cm^{-3}

Milky Way: 188 pc cm^{-3}

CONSTRAINTS: DISPERSION MEASURE

Take representative limits of $DM_{source} = 100, 200\ pc\ cm^{-3}$

Number density

$$DM_{cold} = nd \qquad\qquad DM_{rel} \approx \frac{nd}{2\gamma}$$

Width of shell

Electron Lorentz factor

CONSTRAINTS: BURST ENERGY/EFFICIENCY

Total number of energetic electrons:

$$N_e = \frac{E}{\eta \langle E_e \rangle}$$

Burst energy $(10^{38} - 10^{40}\ \mathrm{erg})$

Efficiency

Average electron energy

When the maser reaches saturation growth will cease.

$\eta \sim 10^{-1} - 10^{-3}$

(Sironi & Spitkovsky 2007, Gallant et al 1992…)

CONSTRAINTS: FREQUENCY

$$\frac{\upsilon_{obs}}{\Gamma} \sim \nu_R^* = \upsilon_p min\{\gamma, \sqrt{\nu_p/\nu_B}\}$$

Razin frequency

For $\nu_R^* = \upsilon_p\sqrt{\nu_p/\nu_B}$ we also have the constraint

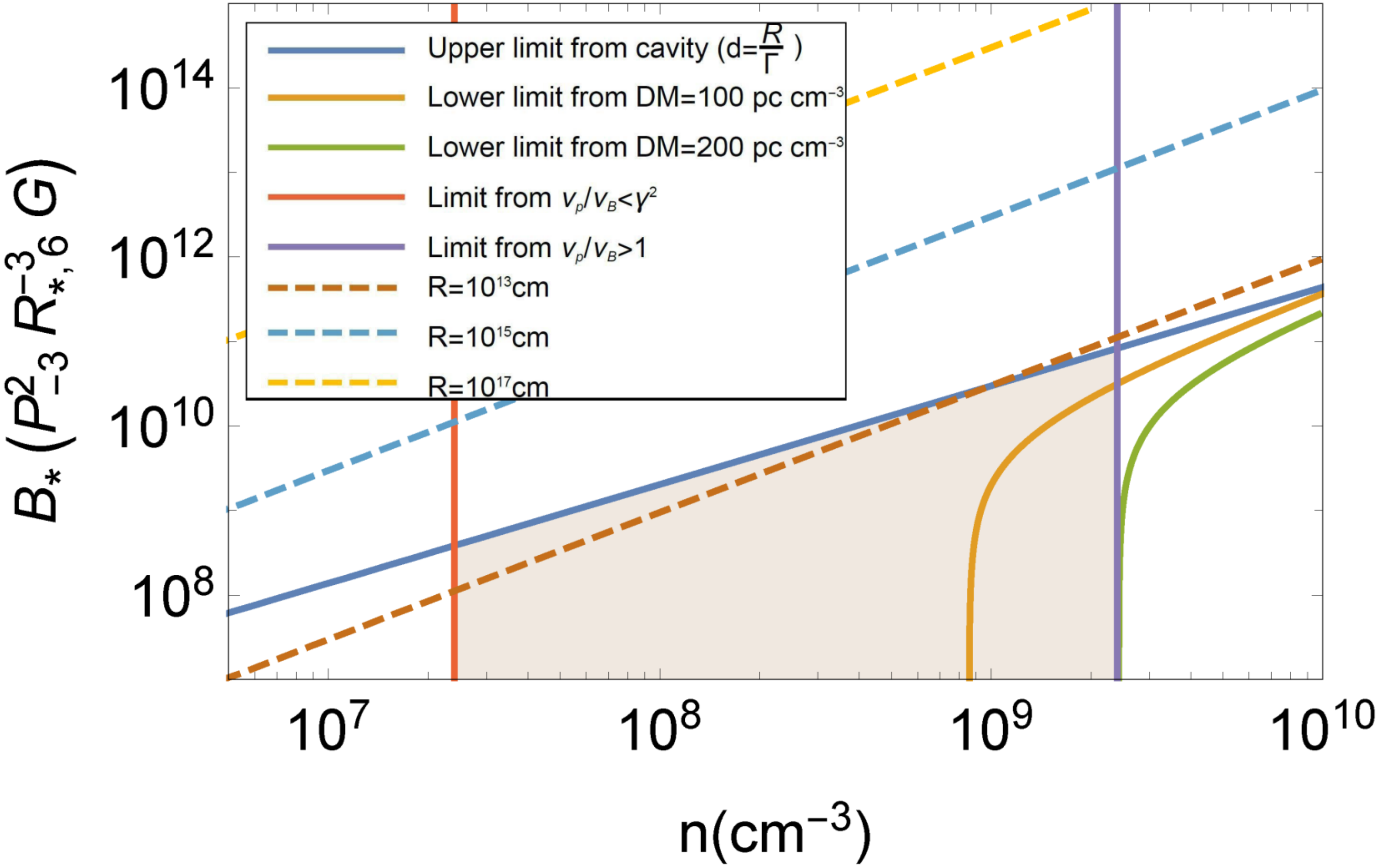
$$1 < \frac{\nu_p}{\nu_B} < \gamma^2$$

The allowed parameter space for $\frac{\nu_p}{\nu_B} > \gamma^2$ is negligible

Note: $\gamma \approx \Gamma$

Fast Radio Bursts are observed at GHz frequencies

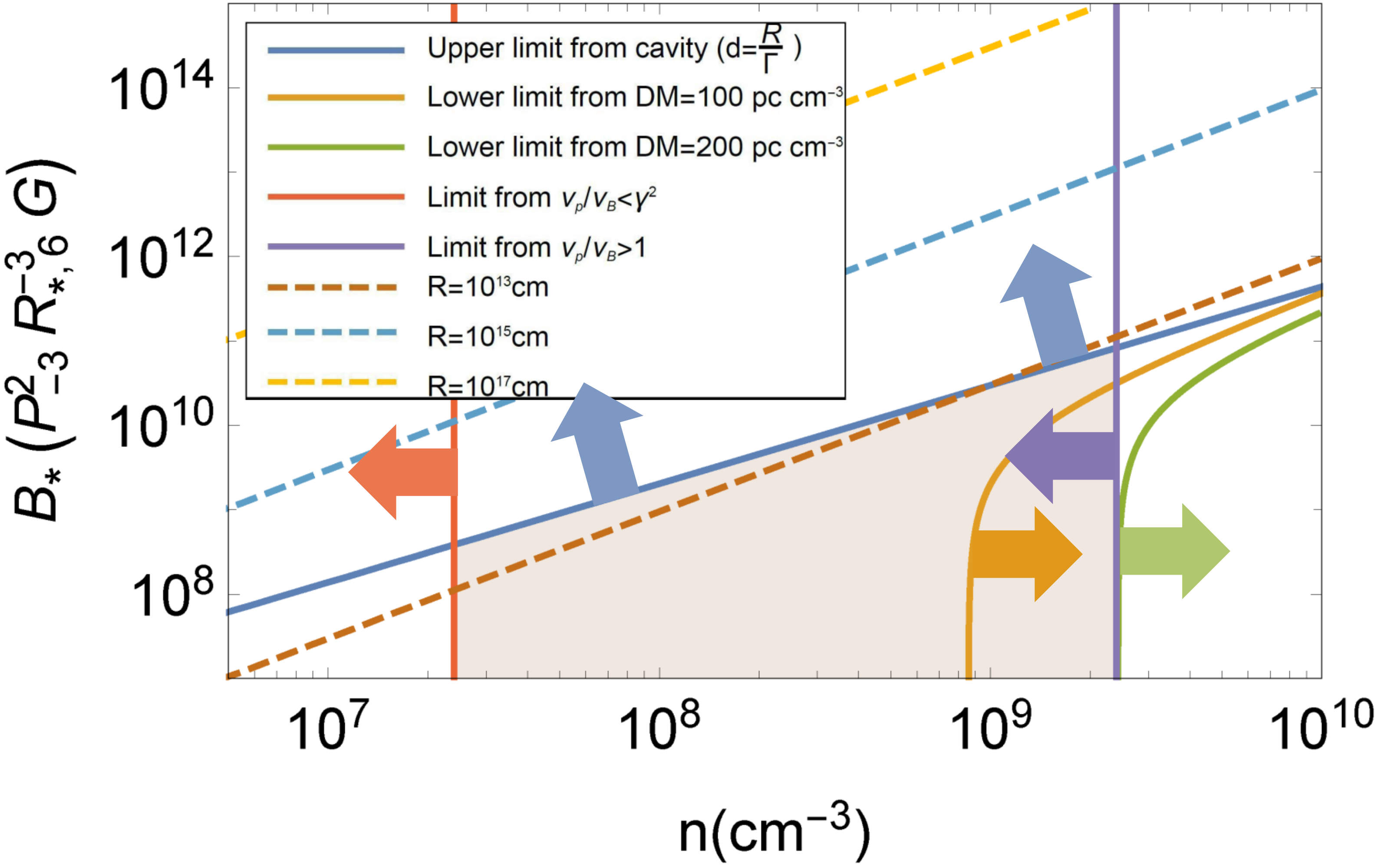
RESULTS: WEAKLY MAGNETISED PLASMA



$$\gamma = \Gamma = 10$$
$$\eta = 10^{-3}$$
$$E = 10^{40}\text{ erg}$$

(Long & Pe’er 2018)

RESULTS: WEAKLY MAGNETISED PLASMA



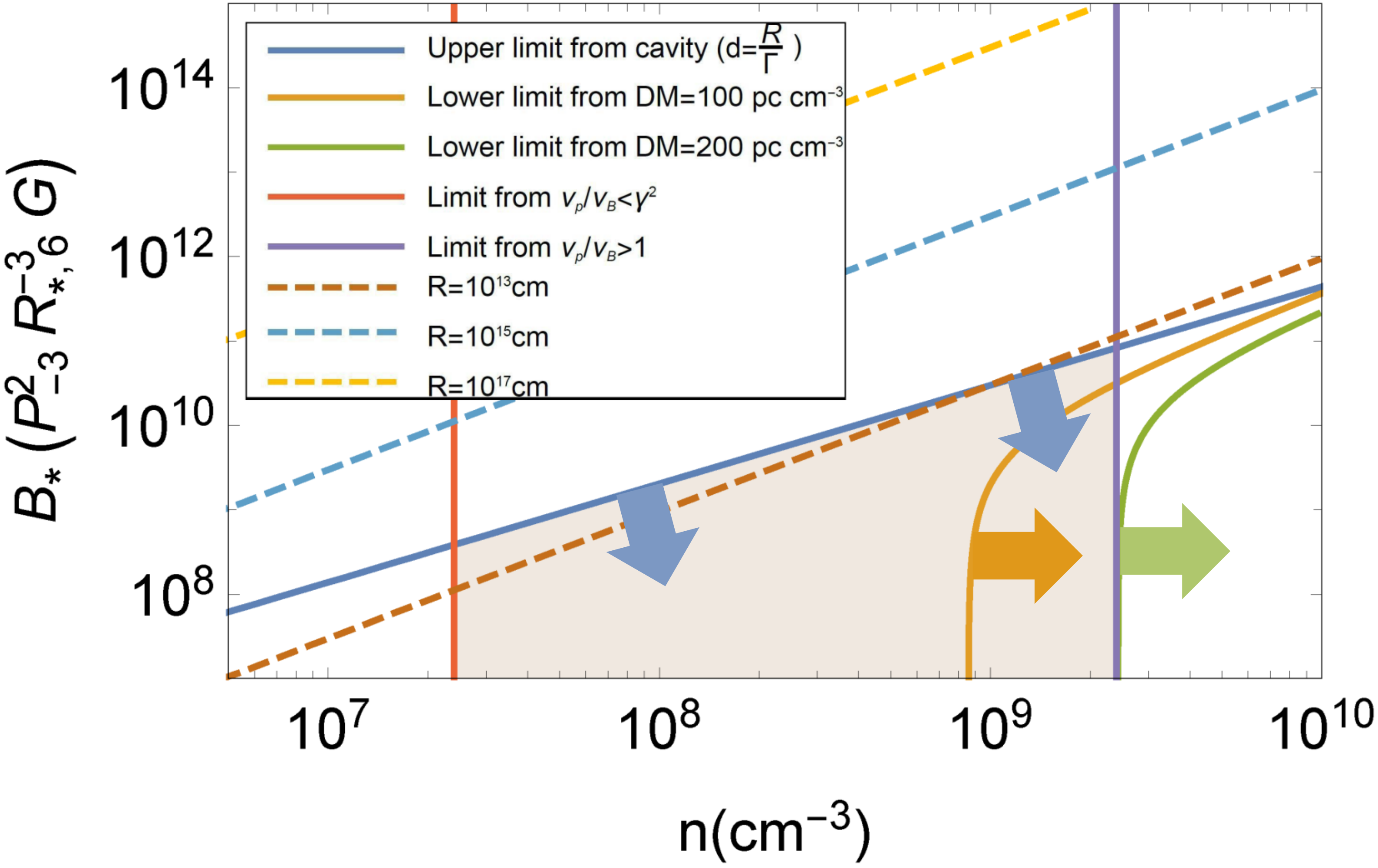
Increasing γ

$$n_{max} \propto \gamma^{-1}$$

$$B_{*,max} \propto \gamma^{1/3}$$

(Long & Pe’er 2018)

RESULTS: WEAKLY MAGNETISED PLASMA



Increasing η/

Decreasing E

(Long & Pe'er 2018)

RESULTS: WEAKLY MAGNETISED PLASMA

Allowed parameter space restricted to:

$$B_* < 10^{10} - 10^{11}\text{G}$$

$$n < \frac{10^{10}}{\gamma}$$

$B_{*,max} \propto \gamma^{1/3}$ does not depend strongly on γ

RATE COMPARISON

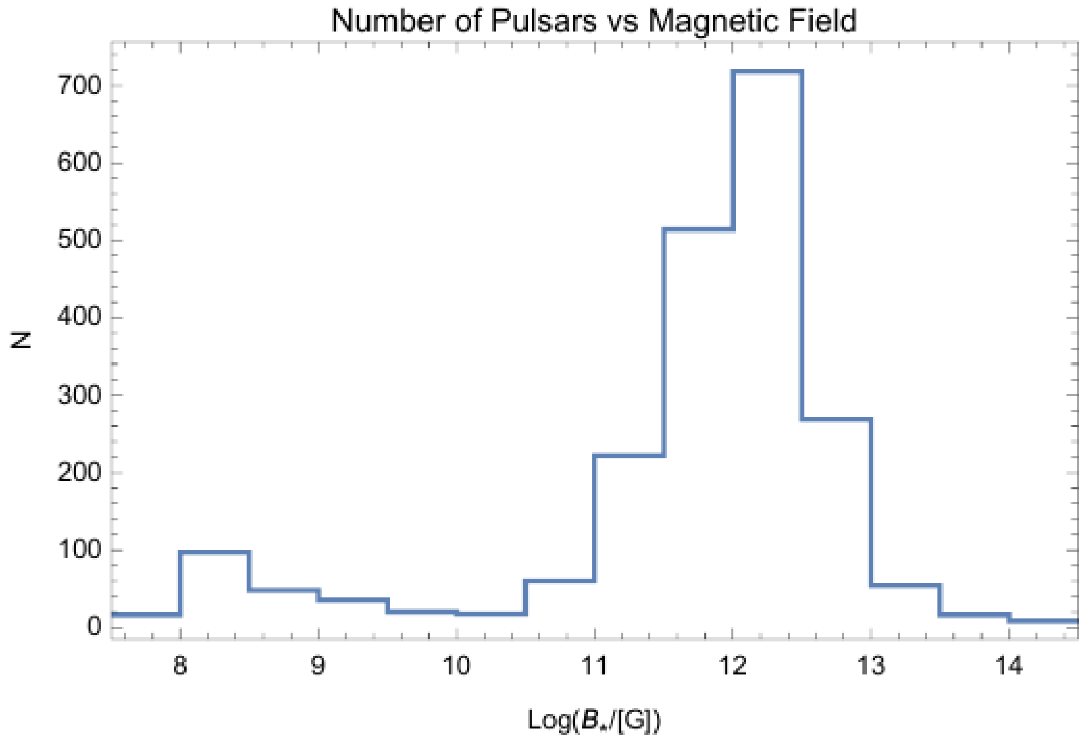
Only ~15% of pulsars have $B_* < 10^{11}$G

(Manchester et al. 2015)

The upper limit on B_* is therefore a very strong constraint.

$$\frac{FRB\ Rate}{NS\ Birth\ Rate} \sim 0.07$$

(Bazin et al. 2009, Champion et al. 2016)



PROPOSED MODEL

Shell where masing occurs originates from an accretion induced explosion

The majority of weakly magnetised pulsars are in binaries

A significant fraction of these objects must undergo this process

Low mass X-Ray binaries have wind density of $10^{13} - 10^{15}\ \mathrm{cm}^{-3}$ at $R{\sim}10^{10}\ \mathrm{cm}$

Could provide appropriate densities at $R{\sim}10^{13}\ \mathrm{cm}$ *(Díaz Trigo & Boirin 2016)*

SUMMARY

The synchrotron maser is a possible coherent FRB emission mechanism

The maser requires a central neutron star that is weakly magnetised : $B_* < 10^{10} - 10^{11}$G

We propose a model where a significant fraction of weakly magnetised neutron stars undergo accretion induced explosions, leading to an FRB.

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CONSTRAINTS: FREQUENCY

STRONGLY MAGNETISED PLASMA

$$\frac{v_{obs}}{\Gamma} \sim l \nu_B$$

Harmonic number of the fastest growing mode

$$B \approx 500 l^{-1}\ G$$