The Mystery of Fast Radio Bursts and its possible resolution♪

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Outline†

- FRBs: summary of relevant observations
- Radiation mechanism and polarization
- FRB cosmology

♪Wenbin Lu

Niels Bohr Institute, July 5, 2018

Transient sources in the universe

Stellar explosions

Supernovae – and origin of elements – have been observed for ~10^3 yrs.

Gamma Ray Bursts (highest current redshift z=9.4) – 1st observed in 1967.

Star falling into a massive black hole – Tidal Disruption Events (1992)

Gravitational waves – black hole and neutron star mergers (2015 & 17)

Origin of heavier nuclei (A > 40)

Fast Radio Bursts (FRBs) – the 1st one found in 2007

Delete this slide for a general colloquium

Propagation of radio waves through ISM/IGM

- **Dispersion Measure:**

$$(kc)^2 = \omega^2 - \omega_p^2 \qquad \omega_p \sim 6 \times 10^4 n_e^{0.5} rad/s$$

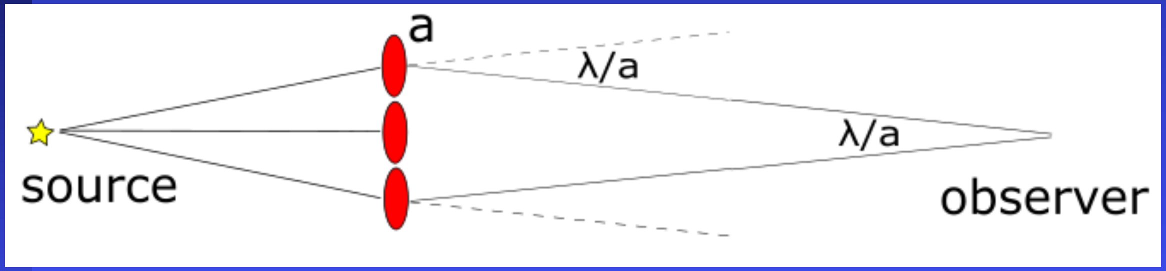
$$d\omega/dk = c[1 - (\omega_p/\omega)^2]^{0.5}$$

$$\delta t = (4.4\,\mathrm{ms})\ \nu_{\mathrm{GHz}}^{-2}\ \mathrm{DM}$$

$$\mathrm{DM} = \int n_e \mathrm{d}l$$

Unit: pc cm^{-3}

- **Pulse broadening due to scattering**



$$W = (\lambda/a)^2 D/c,\ a \propto \lambda^{-6/5} \quad \Rightarrow \quad W \propto \nu^{-4.4}$$

Fast Radio Bursts (FRBs): History

Discovered in 2007 – Parkes 64m radio telescope at 1.4 GHz

(3^o from SMC)

Duration (δt) = 5ms

Flux = 30 ± 10 Jy

(3×10^{-22} erg $s^{-1}cm^{-2}$ Hz^{-1})

DM = 375 cm^{-3} pc

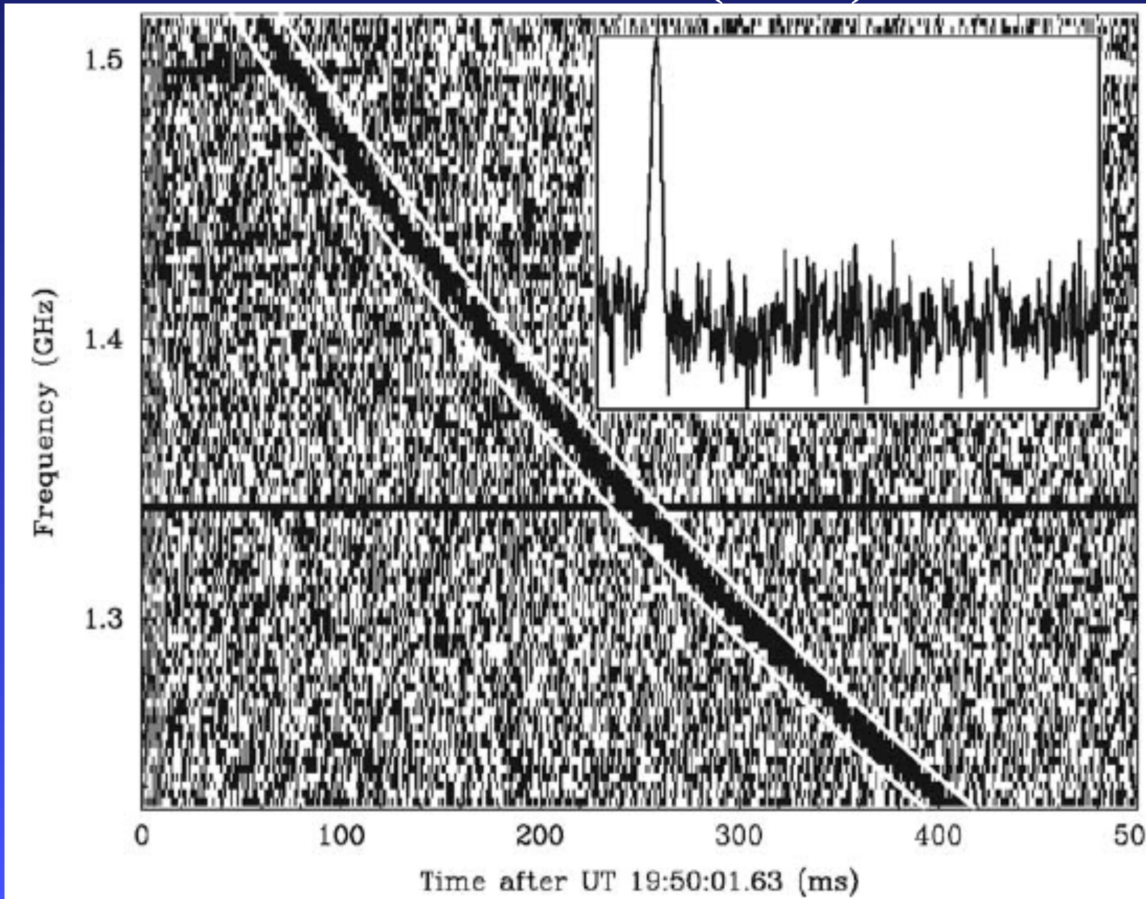
(DM from the Galaxy 25 cm^{-3}pc — high galactic latitude)

Estimated distance ~ 500 Mpc

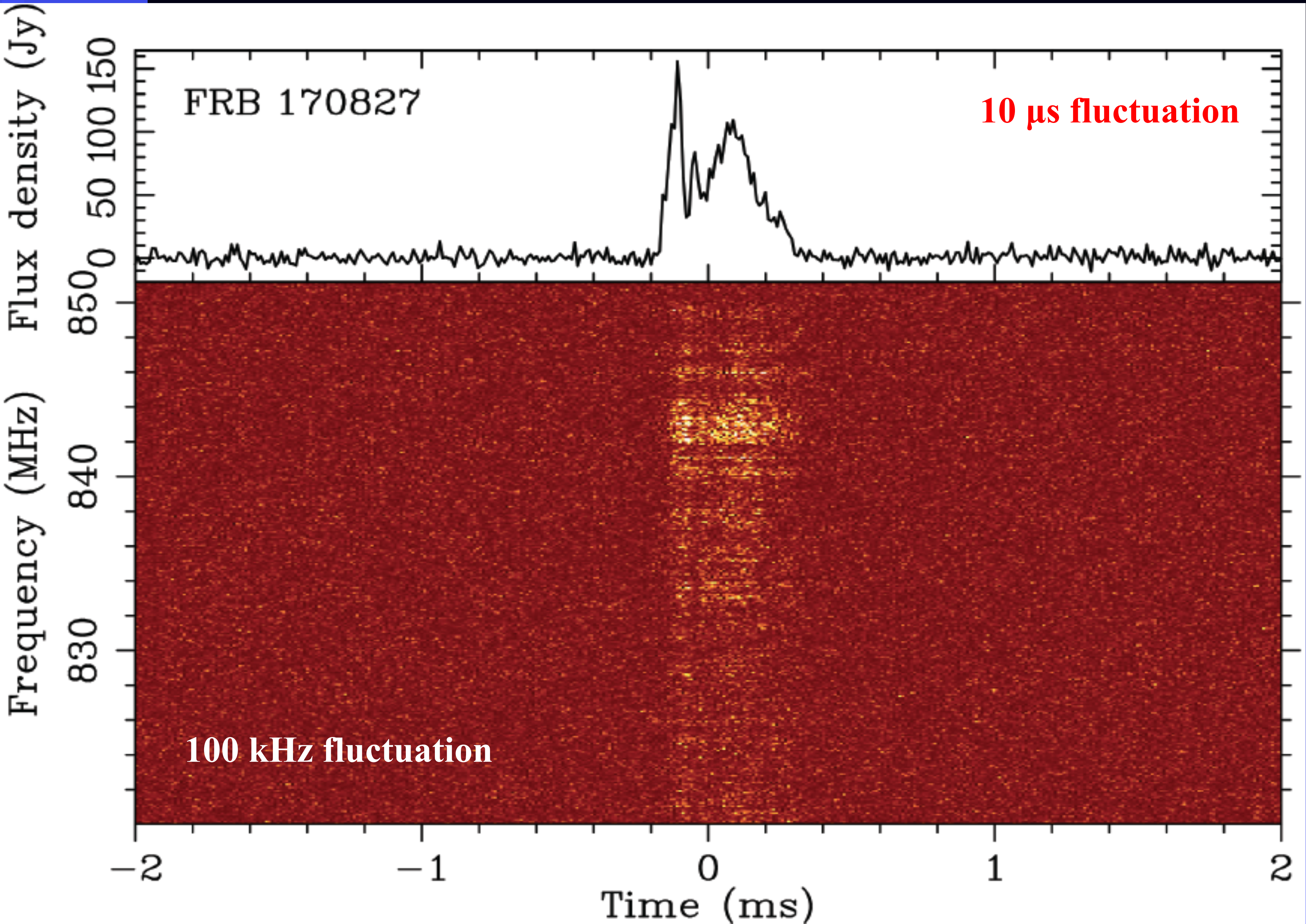
$\delta t(\lambda) \propto \lambda^{4.4}$

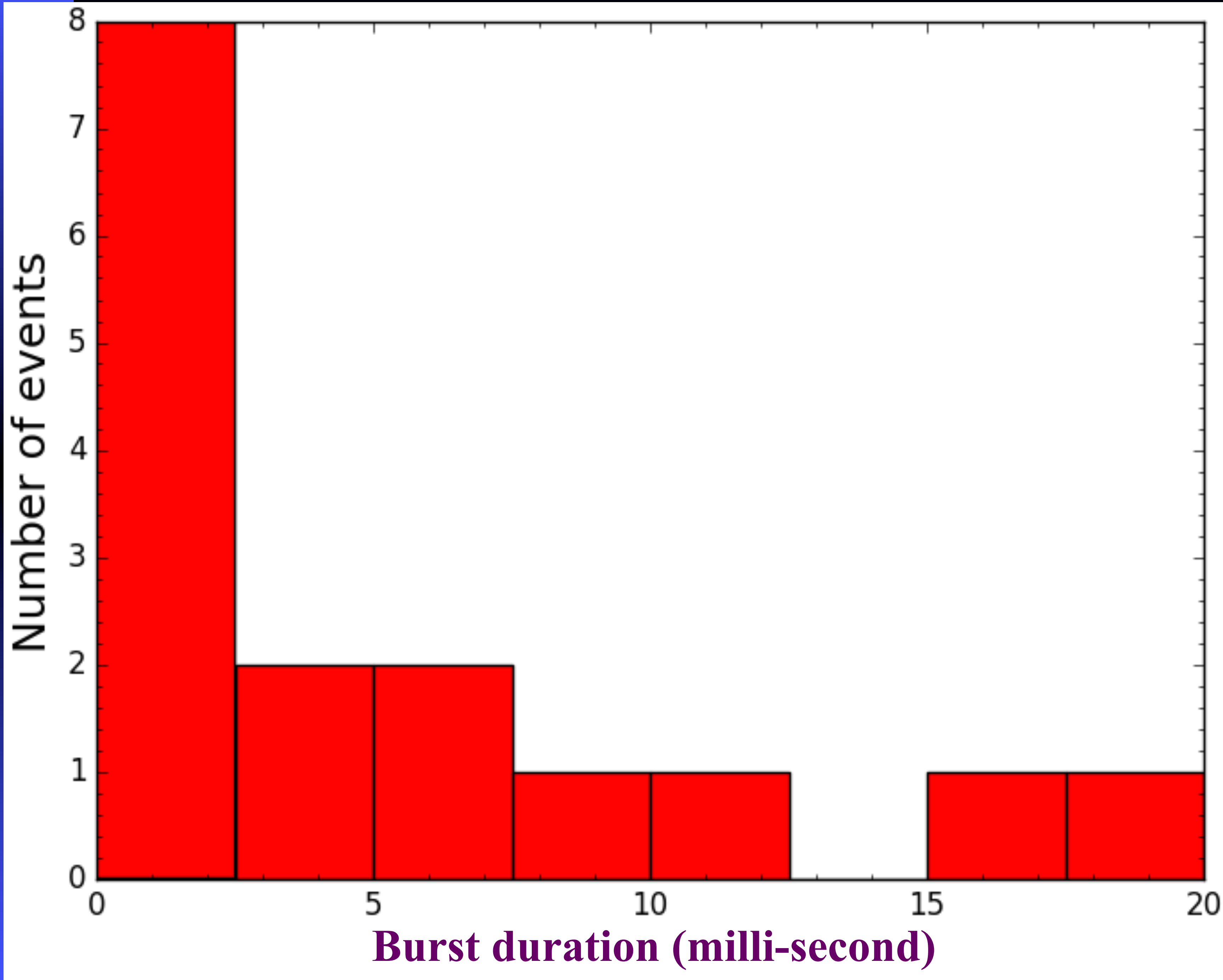
(Consistent with pulse broadening due to ISM/ IGM turbulence)

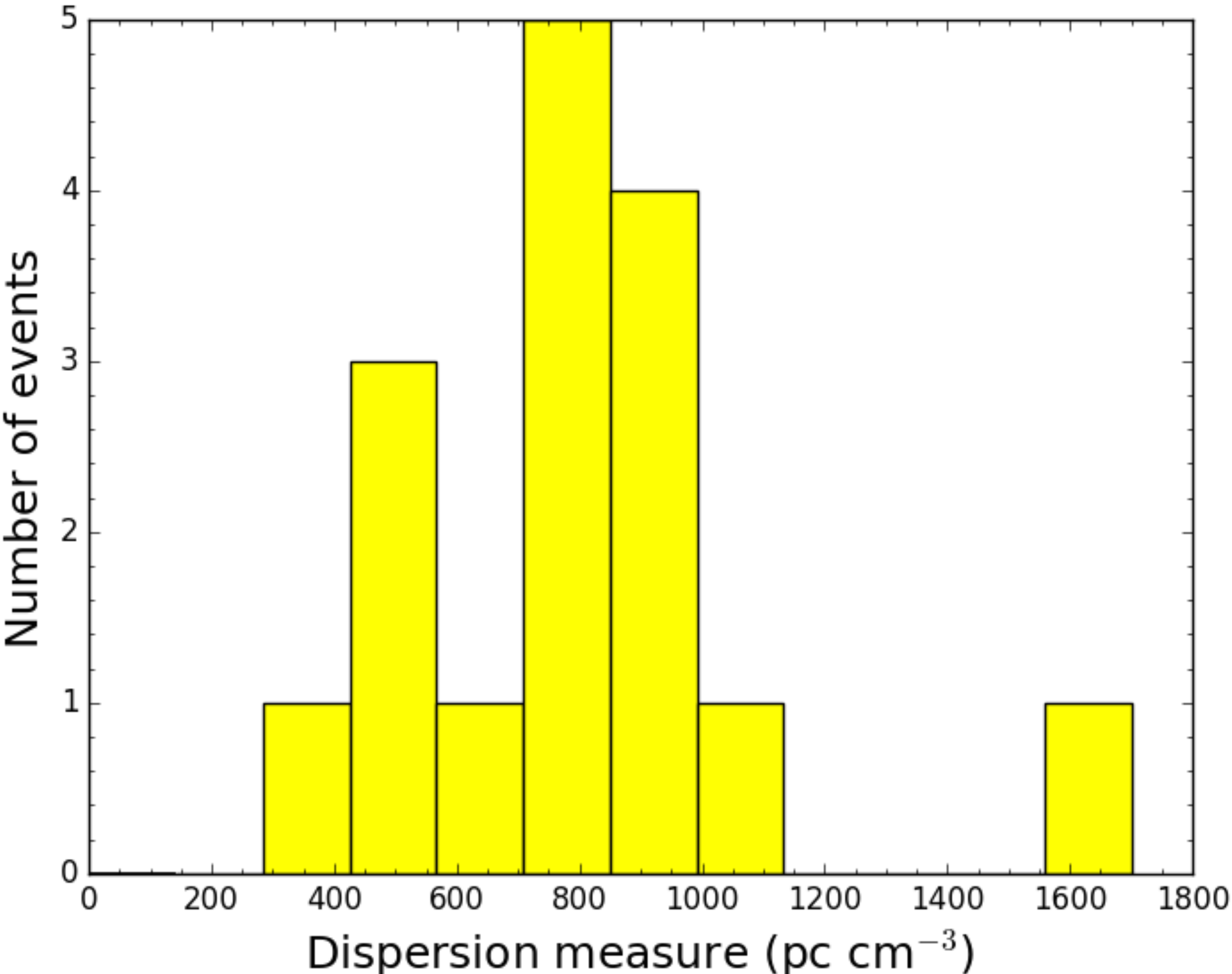
Lorimer et al. (2007)



Farah et al. (2018) – Molonglo telescope – UTMOST project




Number of events
8
7
6
5
4
3
2
1
0
0
5
10
15
20
Burst duration (milli-second)



Number of events
0
1
2
3
4
5
0
200
400
600
800
1000
1200
1400
1600
1800
Dispersion measure (pc cm^{-3})

One object (121102) had multiple outbursts (~10^2 in 4 yrs)

(Spitler et al. 2016; Chatterjee et al. 2016; not a catastrophic event; VLBI – 3 milli-arcsec)

DM = 558.1 ±3.3 pc cm^{-3}
(same for all bursts)

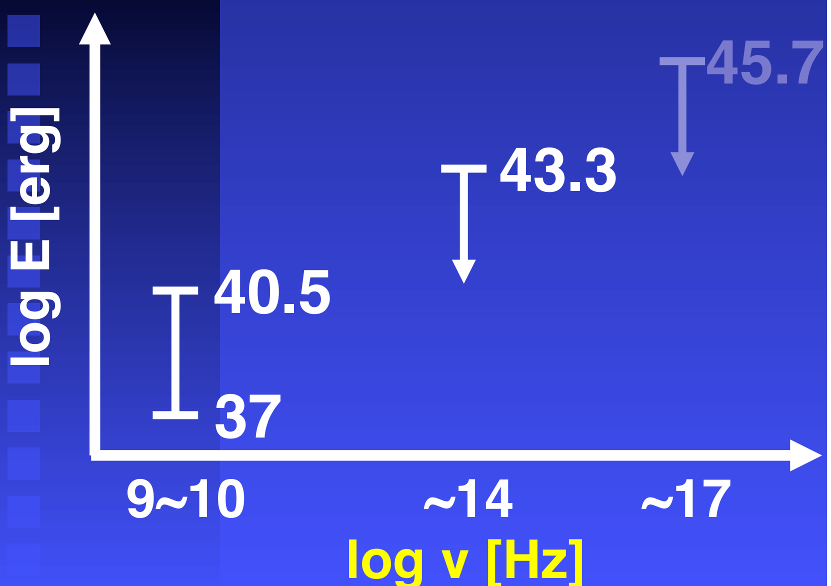
Z=0.19 (3.2x10^9 light years)
No optical/X-ray counter-part

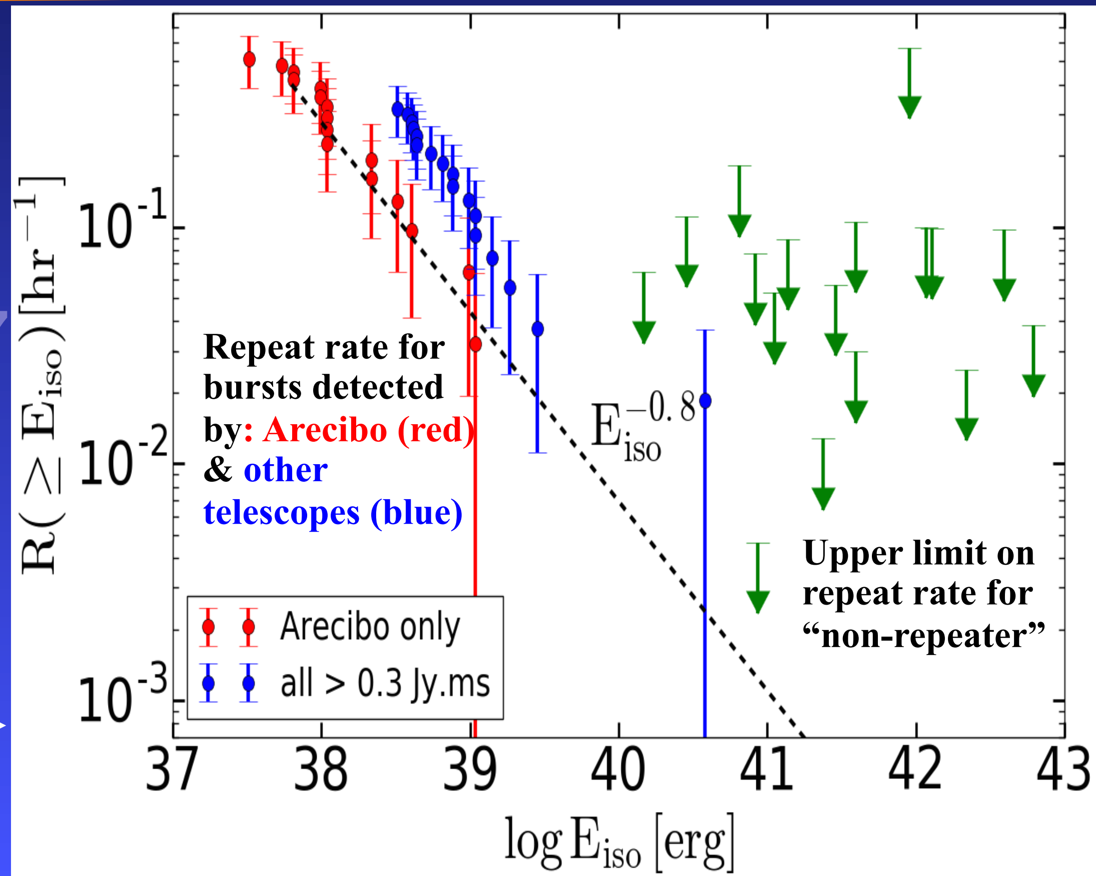
$L_{iso} = 10^{40} - 3\text{x}10^{43}$ erg s^{-1}

Duration, $\delta t \sim (1, 10)$ ms (no broadening)

$$f_\nu \propto \nu^\alpha \quad -10 < \alpha < 14$$

No optical/X-ray counter-part





Properties of FRBs (summary)

- **Duration:** $\delta t \sim 1$ ms **Observed between 0.8 and 8 GHZ**
- $10^2 <$ DM $\lesssim 10^3$ pc cm^{-3} (>10^2 means outside our galaxy); $0.2 < z < 3$
- **isotropic distribution**
- **About 40 bursts have been detected; the all sky rate is estimated to be ~10^4/day. Some polarized some not.**
- **Isotropic energy energy release:**

$$E_{iso} \simeq 1.2 \times 10^{39} \frac{F}{Jy.ms} f_r^{-1} D_{Gpc}^2 \Delta\nu_9 \; erg$$

Models for FRBs

Mergers (WDs, NSs)

Collapsing NSs

Galactic flaring stars

Magnetar flares

Giant pulses

Asteroids colliding with NSs

Extra-terrestrial intellegent life communication

……

Question

If FRBs are from catastrophic events then where did most of the 10^{51} erg energy go?

Progenitors?

Rate:

non-repeating: rate ~ $10^4\ d^{-1}$ (~10% core-collapse SNa rate)

Repeating: progenitor birth rate $\lesssim 10^{-3}$ core-collapse SNe

Timescale: suggests NS or BH

NS or BHs ($t_{ff} \sim 10^{-4}$ s)

Relativistic jets $\delta t \sim r/\Gamma^2 c \simeq (3\,\mathrm{ms})\, r_{12}\Gamma_2^{-2}$

Energetics: (for the repeater FRB 121102)

$E(6\mathrm{yr}) \sim 2 \times 10^{43}\ \mathrm{erg}$ NS B-field strength $B \gtrsim 10^{12}$ G

(for object size ~ c δt ~ 10^7 cm)

(NS dipole spin-down cannot power FRBs)

Radiation Mechanism

Brightness temperature

$S \propto N$

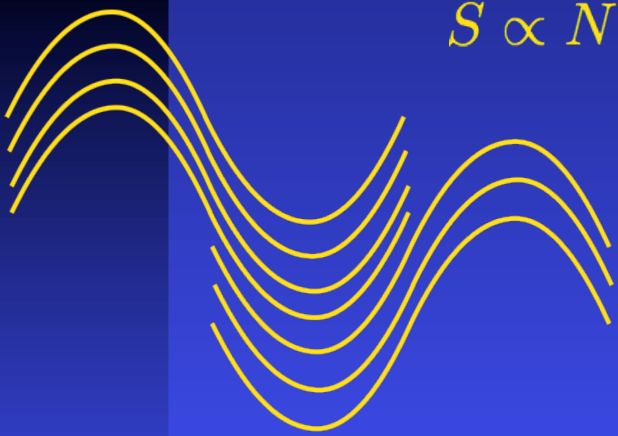
Black body Flux: $F_\nu = \frac{2k_B T_B \nu^2}{c^2}\left[\frac{R_s}{d_A}\right]^2$ for $h\nu \ll k_B T_B$

$$T_B = \frac{F_\nu d_A^2 c^2}{2(c\delta t)^2 \nu^2 k_B} > 10^{35}\mathrm{k}\ d_{A28}^2$$

coherent emission:

$\vec{\mathbf{E}}(\mathbf{x}, \mathbf{t})$

$S \propto N^2$



Maser:

Synchrotron, curvature, etc.
negative absorption

Collective plasma emission:

Cherenkov, cyclotron-Cherenkov etc.
Beam instability, wave amplification

Antenna mechanism:

Coherent curvature radiation by charge bunches of size < λ

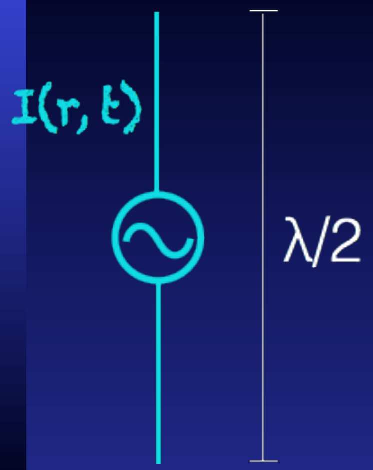
FRBs are more luminous – by a factor $>10^6$ – than radio sources in our galaxy

	L_{iso} [erg/s]	T_B [K]	δt	dN/dE
FRBs	10^{43}	$> 10^{35}$	< ms	$E^{-1.7}$
Crab giant pulses	10^{37}	10^{41}	ns	$E^{-2.3\sim-3.5}$
Crab normal pulses	10^{34}	10^{32}	μs	log-normal

Crab has spindown luminosity $L_{\rm sd} \simeq 4\times 10^{38}\,{\rm erg\,s^{-1}}$

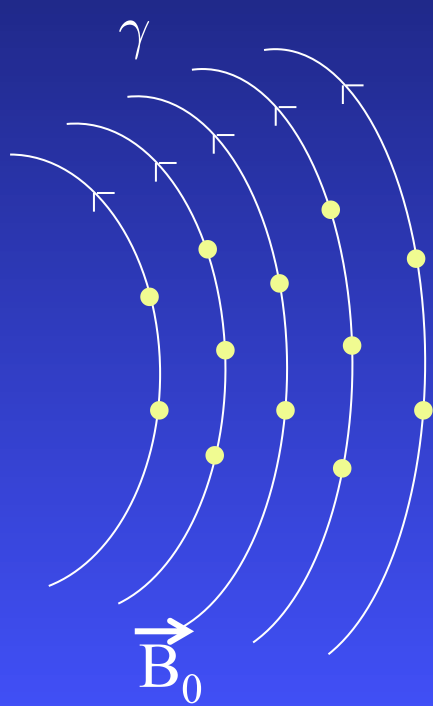
and by a factor ~10^2 compared to long-GRBs at ~GHz!

Coherent curvature radiation



Antenna mechanism

Consider a charge bunch of longitudinal size λ moving along curved magnetic field



Frequency of radiation:

$$\nu = \frac{c\gamma^3}{2\pi\rho} \longrightarrow \gamma = 30\,\nu_9^{1/3}\rho_5^{1/3}$$

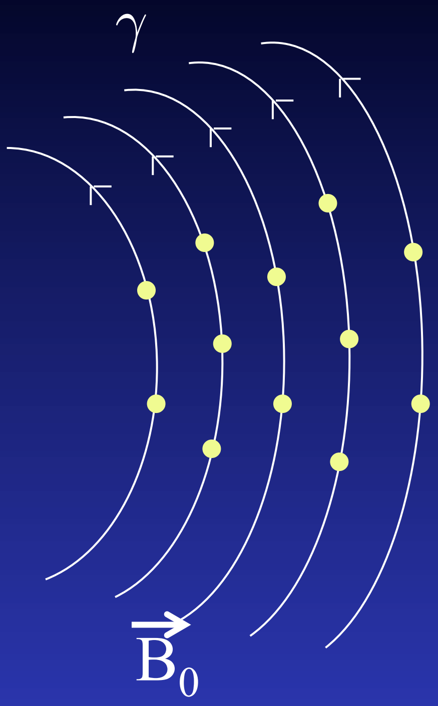
ρ **: radius of curvature of field lines**

γ **: Lorentz factor of particles**

$$L \approx \frac{8\pi^2 c^5 q^2 n_e^2 \gamma^6}{3\nu^4} \longrightarrow n_e \sim 10^{17}\,\mathrm{cm}^{-3} L_{43}^{1/2}$$

Coherent curvature radiation

(Antenna mechanism)



$$L \approx \frac{8\pi^2 c^5 q^2 n_e^2 \gamma^6}{3\nu^4} \longrightarrow n_e \sim 10^{17}\,\mathrm{cm}^{-3} L_{43}^{1/2}$$

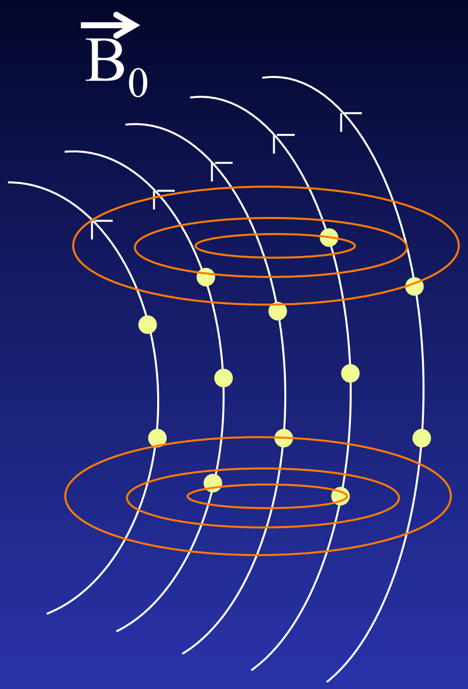
Magnetic field produced by the current associated with particles streaming along the field lines

$$B_{ind} \sim 10^{12}\mathrm{G}\,\frac{L_{43}^{1/2}\nu_9^{1/3}}{\rho_5^{2/3}}$$

This "induced" field is perpendicular to the original field

Lower limit on B_0

The "induced" field will tilt the original magnetic field by different angles at different locations (because the "induced" field lines are closed loops in planes perpendicular to $\vec{B}_0$)



This will cause the particle velocities to be no longer parallel

and that will destroy coherent radiation, unless

$$B_0 > 10^{14}\ \mathrm{G}$$

This suggests that we are dealing with a magnetar

Particle acceleration

The radiative cooling time of electrons is very short:

$$t_c = \frac{m_e c^2 \gamma \left(n_e \ell^2 \lambda\right)}{L_{lab}} \approx 10^{-15}\mathrm{s}$$

This time is much smaller than the wave period (1 ns for 1 GHz radiation)

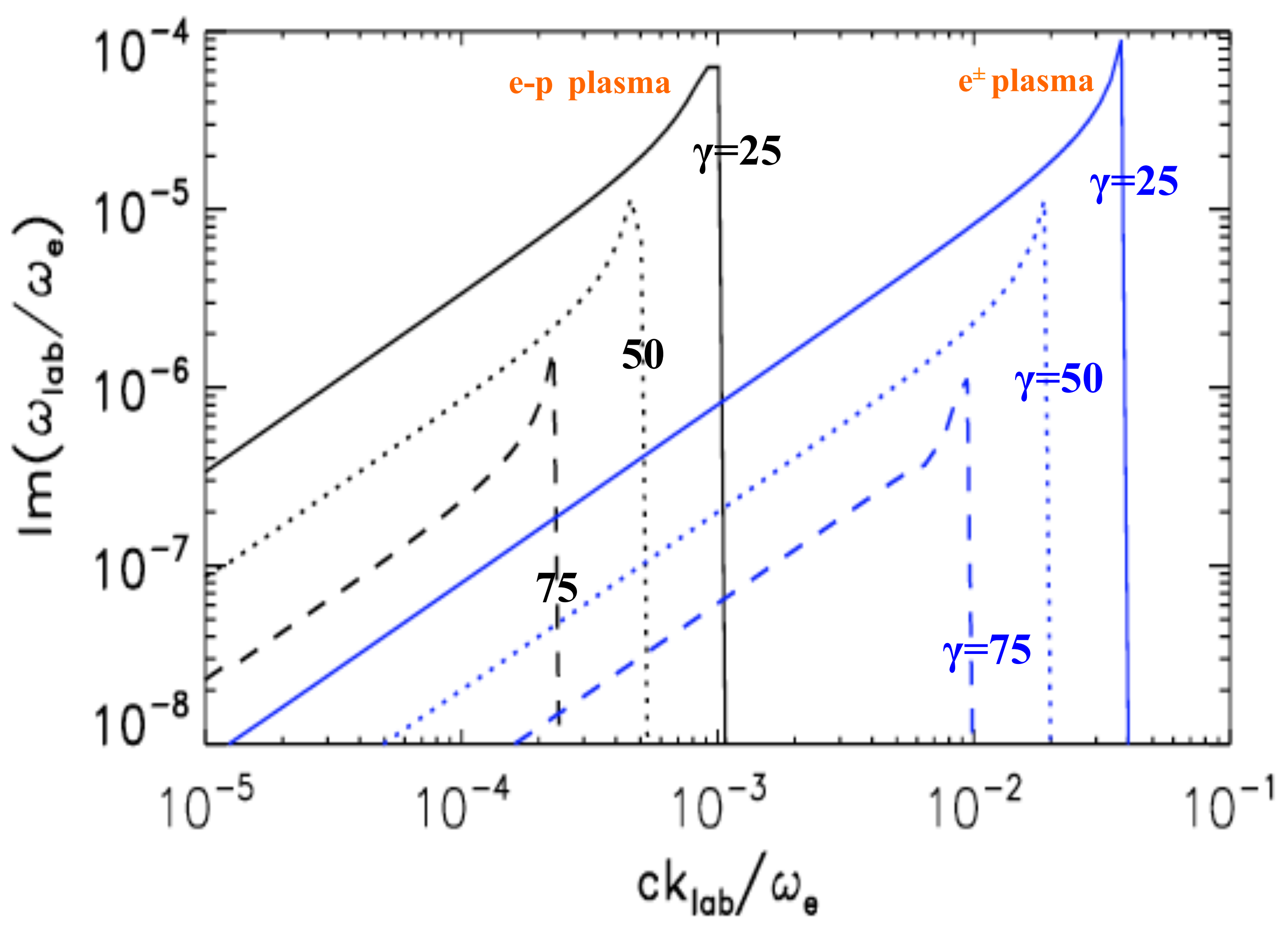
To prevent this rapid loss of energy, we need an electric field that is parallel to $\vec{B}_0$ to keep the particles moving with Lorentz factor γ.

The required electric field: $E_{\|} \sim 10^{11}\mathrm{esu}\; L_{43}^{1/2} \rho_5^{-1}$

$$\oint B \cdot dl = \frac{4\pi}{c} I$$

Coherent radiation requires particle clumps of size ~λ

Electrons & positrons moving in opposite directions due to the electric field suffer from 2-stream instability, which can generate particle clumps.



The length scale for the fastest growing modes is of order 50 cm and the growth time is ~ a few μs.

Energetics

- The total energy release is modest:

$$E = L\,\delta t/(4\gamma^2) \sim 10^{36}\,\mathrm{erg}$$

- Whereas the total energy in the magnetic field is ~ 10^{45} erg

- So there is no problem powering a large number of bursts!

The total number of electrons/positrons needed for producing a FRB radiation is ~ 10^{30}.

So about one kilogram of matter is producing the radiation we see at a redshift ~ 1.

Predictions of the model

We should see FRB like bursts at much higher frequencies (mm and possibly higher) – if the model I have described is correct.

The reason for this is that the peak frequency for curvature radiation depends strongly on γ:

$$\nu = \frac{c\gamma^3}{2\pi\rho} \quad \textbf{and} \quad \gamma \propto E_{\parallel}^{1/2}$$

$L \sim E_{\parallel}^2 \rho^2 c \propto \nu^{-2/3}$. **The event rate** $\propto \nu^{-2/3}$

Polarization Properties of the FRB Repeater

- **Polarization has been measured for about 25 outbursts of the repeater (FRB 121102), in 4-8 GHz, during a seven month period (Michilli et al. 2018; Gajjar et al. 2018):**

  All these outbursts were 100% linearly polarized

  The polarization angle varied by ±20^{o} from one burst to another over the 7 month period.

  The rotation measure was ~10^{5} rad m^{-2} and varied by 10%

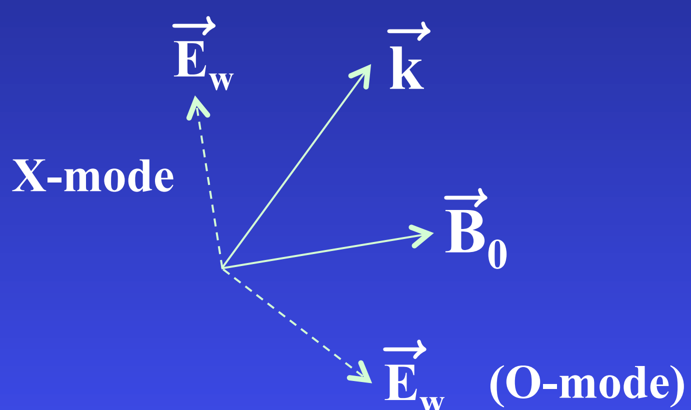
- **Polarization has also been reported for several non-repeaters at 1.4 GHz and found to be between 0 and 80% linearly polarized – the less than 100% polarization could be due to Faraday depolarization in finite channel width (0.4 MHz).**

What is responsible for 100% polarization and nearly fixed direction for the electric field over a period of 7 months?

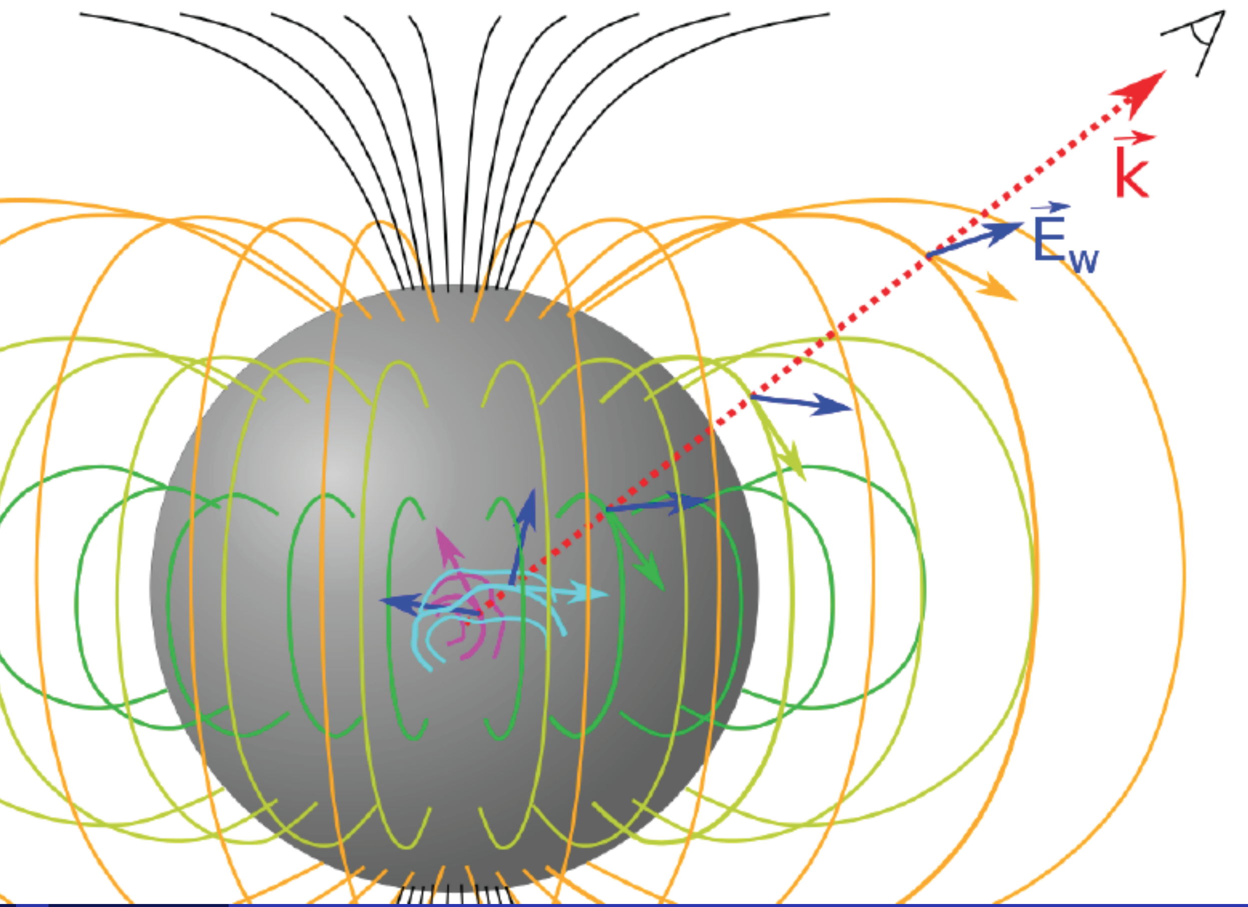
The answer is strong magnetic field such that the cyclotron frequency is >> GHz, and plasma frequency of order 10^2 GHz.

The mode that escapes to infinity is the X-mode:

$\vec{E}_w$ perpendicular to $\vec{k}$ and $\vec{B}_0$



As the wave travels outward it keeps the electric field || $\vec{k}$ x $\vec{B}_0$



The electric field direction is || $\vec{k} \times \vec{B}_0$ at the freeze-out radius.

If the freeze out radius is >> R_s then $\vec{k} \parallel \vec{r}$ and

Since,

$$\vec{B}_0 = \frac{3\hat{r}(\hat{r}\cdot\vec{m}) - \vec{m}}{r^3}$$

$\vec{m}$: magnetic moment of the NS

Then $\vec{E} \parallel \vec{k} \times \vec{B}_0 \parallel \vec{k} \times \vec{m}$

$\therefore$ **The direction of $\vec{E}$ changes from one burst to another if the magnetic & rotation (Ω) axes are miss-aligned.**

±20° swing in E_w for 121102 suggests the angle between $\vec{m}$ & $\vec{\Omega}$ ~20°

General constraints on Maser & Plasma mechanisms

These mechanisms are favored for radio pulsars, and so are obvious possibilities to consider for FRBs.

Magnetic field energy converted to Particle beam kinetic energy

$$L_{beam} < R^2 B^2 c/4\pi = 10^{49} \text{ erg s}^{-1} B_{14}^2/R_6^4$$

$$L_{beam} > L_{frb} \sim 10^{43} \text{ erg s}^{-1}$$

$\therefore$ The outflow launch radius: $R \lesssim 10^7 \text{ cm } L_{frb,43}^{-1/4} B_{14}^{1/2}$

- **Synchrotron maser *in plasma*, and plasma waves produce radiation at a frequency ~ $\nu_p \gamma^a$**

$0 < a < 1$ γ: e^- LF
ν_p: plasma frequency
Γ: source Lorentz factor

Observed frequency: $\nu = \Gamma \nu_p \gamma^a$

($\nu \sim 1$ GHz)

- **Kinetic luminosity of the beam converted to GHz radiation:**

$$L_{beam} = 4\pi R^2 n_e m \gamma c^3 \Gamma^2$$

We can eliminate n_e in terms of ν_p ($\nu_p \propto n_e^{1/2}$)

$$L_{beam} \approx (4\text{x}10^{39}\,\text{erg s}^{-1})\, R_{12}^2 \nu_9^2 \gamma^{2-2a}$$

$$\boxed{L_{beam} > L_{frb} \sim 10^{43}\text{ erg s}^{-1} \Longrightarrow R > 10^{14}\gamma^{a-1}\text{cm} >> R_{LC}}$$

$R_{LC} = 5\text{x}10^9 P$ cm

- **Stimulated-IC loss limits brightness temperature:**

$T_B < 10^{10}\, \tau_T^{-1}\, \gamma^5 << 10^{35}$ K (or the radiative efficiency $< 10^{-8}$)

Curvature Maser

frequency: $\nu_c = \gamma^3 c/(2\pi\rho) \simeq (\gamma/60)^3 \rho_6^{-1}\,\mathrm{GHz}$

strong B-field inside NS magnetosphere

$$B_{\rm EM} \simeq (2\times10^{10}\,\mathrm{G})\,L_{\rm iso,43}^{1/2} r_6^{-1}$$

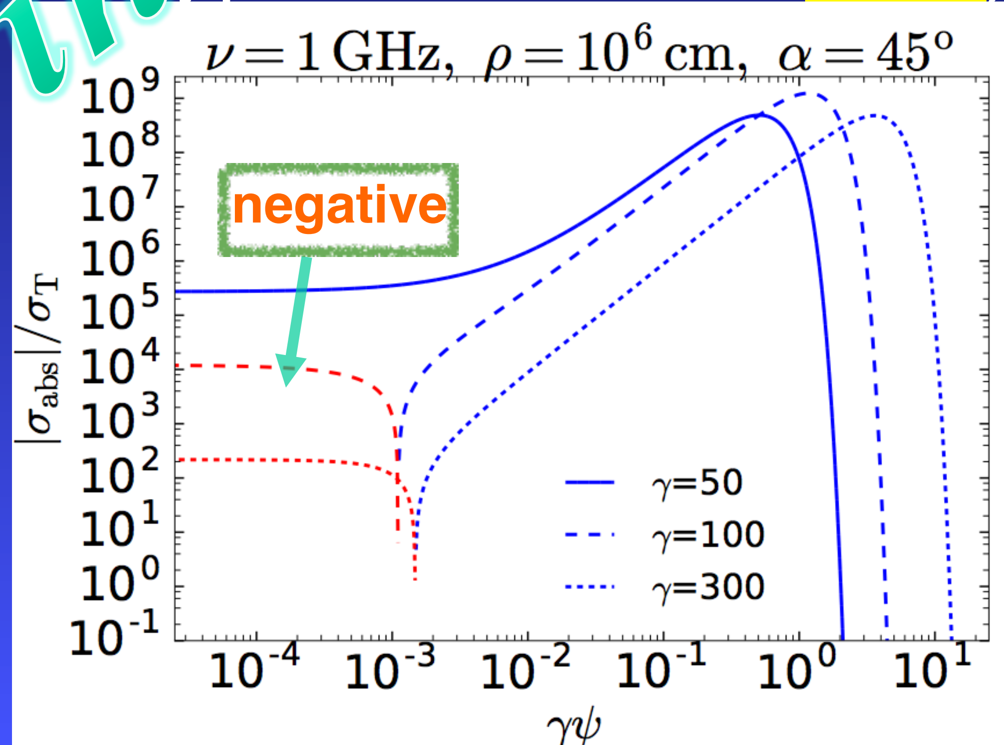
$$B = B_* r_6^{-3} \gg B_{\rm EM}$$

$$r \lesssim (3\times10^7\,\mathrm{cm})\,B_{*,14}^{1/2} L_{\rm iso,43}^{1/4}$$

$$B \gtrsim (2\times10^9\,\mathrm{G})\,B_{*,14}^{-1/2} L_{\rm iso,43}^{3/4}$$

This also applies to collective plasma emission

(only possible when there is torsion)



ψ is the angle between electron & photon momenta.

Extreme Fine Tuning

Synchrotron Maser (vacuum)

Consider a jet with Lorentz factor Γ

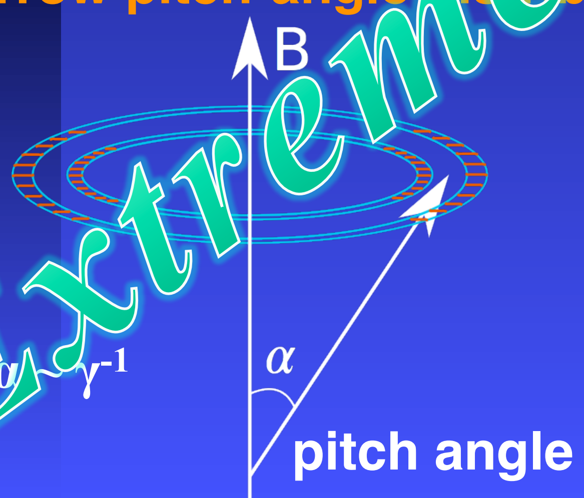
Frequency: $\nu = \dfrac{qB'\Gamma\gamma^2 \sin\alpha}{2\pi m_e c}$

Luminosity: $L_{iso} \leq 4\pi r^2 n'_e (B'^2 \gamma^2 \sin^2\alpha / 6\pi)\Gamma^2 c$

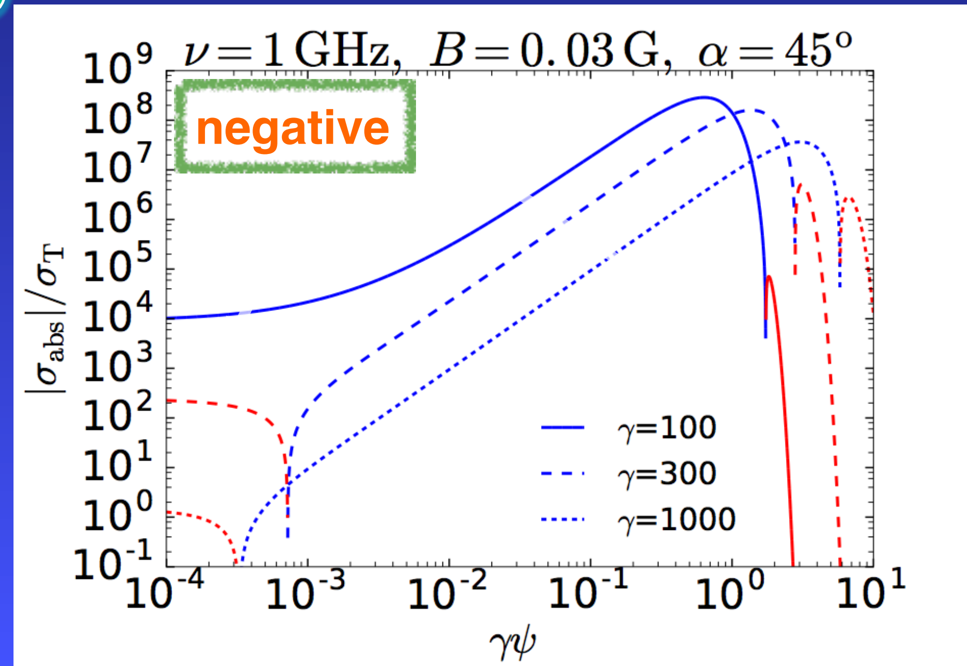
Emission radius: $r \gtrsim (10^{14}\ \mathrm{cm})\ \epsilon_{\mathrm{B}}^{1/2} L_{\mathrm{iso},43}^{1/2} \nu_9^{-1}$

- population inversion $\dfrac{\partial (N/\gamma^2)}{\partial \gamma} >$
- nearly uniform B-field
- narrow pitch-angle distribution

Extreme Fine Tuning



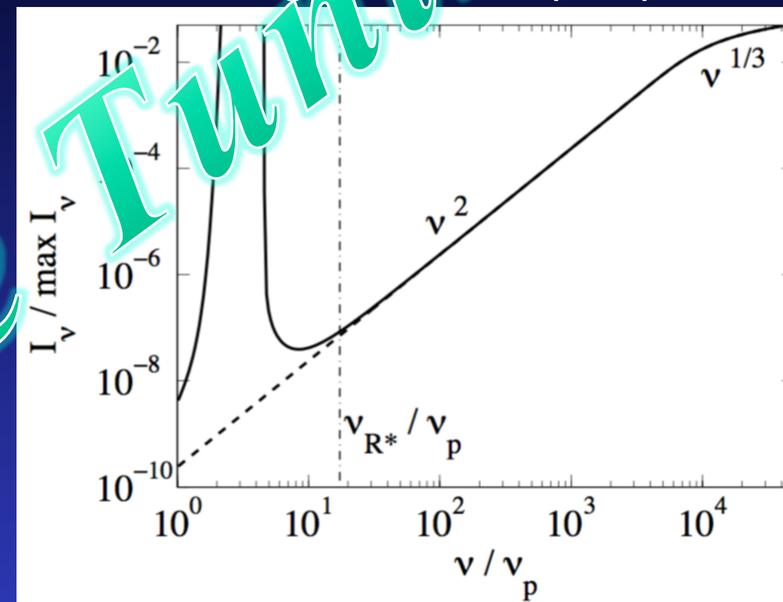
ψ is the angle between LoS & electron momentum vector



Synchrotron Maser (plasma)

- **population inversion** – $dn_e/d\gamma' \propto \gamma'^{>2}$ **(in shock)**
- $\nu \sim \Gamma \nu_p (\epsilon_e/\epsilon_B)^{1/4}$
- $\varepsilon_B \lesssim 10^{-9}\,\Gamma_3^4$ **(for ν ~ 4 GHz)**

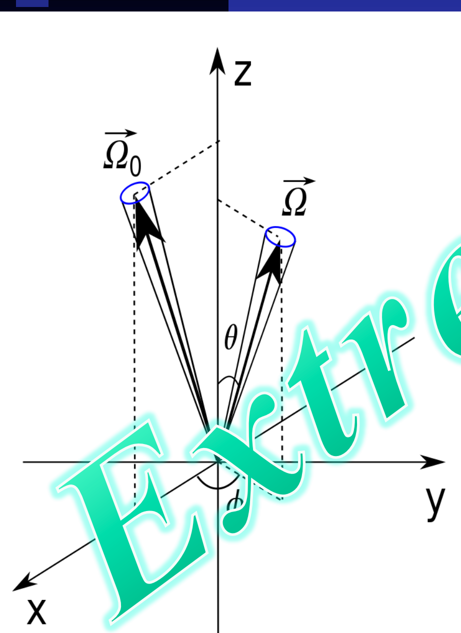
Sagiv & Waxman (2002)



Luminosity: $L_{\rm iso} < 4\pi r^2 \Gamma^2 n' \gamma' m_e c^3$

Emission radius: $r \approx 3\mathrm{x}10^{10}\mathrm{cm}\,\frac{L_{iso,43}^{\frac{1}{2}}}{\gamma_3'}\left[\frac{\epsilon_e}{\epsilon_B}\right]^{\frac{1}{4}}$

$\approx 3\mathrm{x}10^{12}\mathrm{cm}$



Duration: $\delta t \sim \frac{r}{2c\Gamma^2} \sim 0.1\mathrm{ms}\,\Gamma_3^{-2}$

number of particles: $N \sim \frac{4\pi r^3 n'}{\Gamma} \sim 5\mathrm{x}10^{43}\gamma'^{-\frac{1}{2}} \sim 10^{10} N_{\rm tot}$!!

induced Compton scattering limit: $T_{\rm B} \lesssim 10^{26}\gamma'^2\,\mathrm{K}$

Waxman (2017) has $\gamma' \approx 10^3 \implies T_B \le 10^{32} K$ **($T_{FRB} \sim 10^{35}$ K)**

Extreme Fine Tuning

Collective Plasma Emission

Plane-wave perturbation $\propto \exp(-i\omega t + i\boldsymbol{k}\cdot\boldsymbol{r})$

Wave dispersion relation:

$$\boldsymbol{k} \times [\boldsymbol{k} \times \boldsymbol{E}(\omega, \boldsymbol{k})] + \omega^2 \boldsymbol{E}(\omega, \boldsymbol{k}) = -4\pi i \omega \overset{\leftrightarrow}{\sigma}(f, \omega, \boldsymbol{k}) \boldsymbol{E}(\omega, \boldsymbol{k})$$

$$\Longleftrightarrow \quad \overset{\leftrightarrow}{\mathcal{D}} \boldsymbol{E} = 0 \quad \Longleftrightarrow \quad \det[\overset{\leftrightarrow}{\mathcal{D}}(f, \omega, \boldsymbol{k})] = 0$$

For real k,

- If ω = real, wave propagation
- If $\mathrm{Im}(\omega) < 0$, wave damping
- If $\mathrm{Im}(\omega) > 0$, wave growth and there is an instability

aka plasma maser, because it is a maser-like process with exponential growth rate = $\mathrm{Im}(\omega)$

Collective Plasma Emission

B-field constraint: $r \lesssim (3 \times 10^7\,\mathrm{cm})\, B_{*,14}^{1/2} L_{\mathrm{iso},43}^{1/4}$ $\quad B \gtrsim (2 \times 10^9\,\mathrm{G})\, B_{*,14}^{-1/2} L_{\mathrm{iso},43}^{3/4}$

Particles are in the lowest Landau level and have: 1D distribution function

Consider a plasma moving towards the observer: $\Gamma^2 \gamma' n' m_e c^3 > L_{\mathrm{iso}}/(4\pi r^2)$

$$\omega' = \omega/2\Gamma \simeq 3 \times 10^7\,\mathrm{s}^{-1}\, \nu_9 \Gamma_2^{-1}$$

$$\omega'_{\mathrm{B}} = \omega_{\mathrm{B}} \simeq 2 \times 10^{17}\,\mathrm{s}^{-1}\, B_{10} \qquad \omega'_{\mathrm{p}} \gtrsim 3 \times 10^{14}\,\mathrm{s}^{-1} \frac{L_{\mathrm{iso},43}^{1/2}}{r_7 \Gamma_2 \gamma'^{1/2}}$$

- Another beam runs through this plasma → instabilities where Im(ω)>0
- Two-stream instability: impossible to grow at $\omega' \lll \omega'_{\mathrm{p}}$
- Cyclotron-Cherenkov (anomalous Doppler) instability:

$$\omega' - \beta'_{\mathrm{b}} k'_{\parallel} + \omega'_{\mathrm{B}}/\gamma'_{\mathrm{b}} = 0 \rightarrow \gamma_{\mathrm{b}} \simeq 2\Gamma\gamma'_{\mathrm{b}} \gg 2\Gamma\omega'_{\mathrm{B}}/\omega' \simeq 10^{12} B_{10} \nu_9^{-1} \Gamma_2^2$$

curvature cooling

- Cherenkov instability: $\omega' - \beta'_{\mathrm{b}} k'_{\parallel} = 0$

growth rate too low at $\omega' \lll \omega'_{\mathrm{p}}$

Extreme Fine Tuning

FRBs as probe of Dark Energy & Intergalactic Medium

Dark energy equation of state

$$\mathrm{DM} = \int d\ell\, n_e \rightarrow \text{distance}$$

Localize to within arc-sec

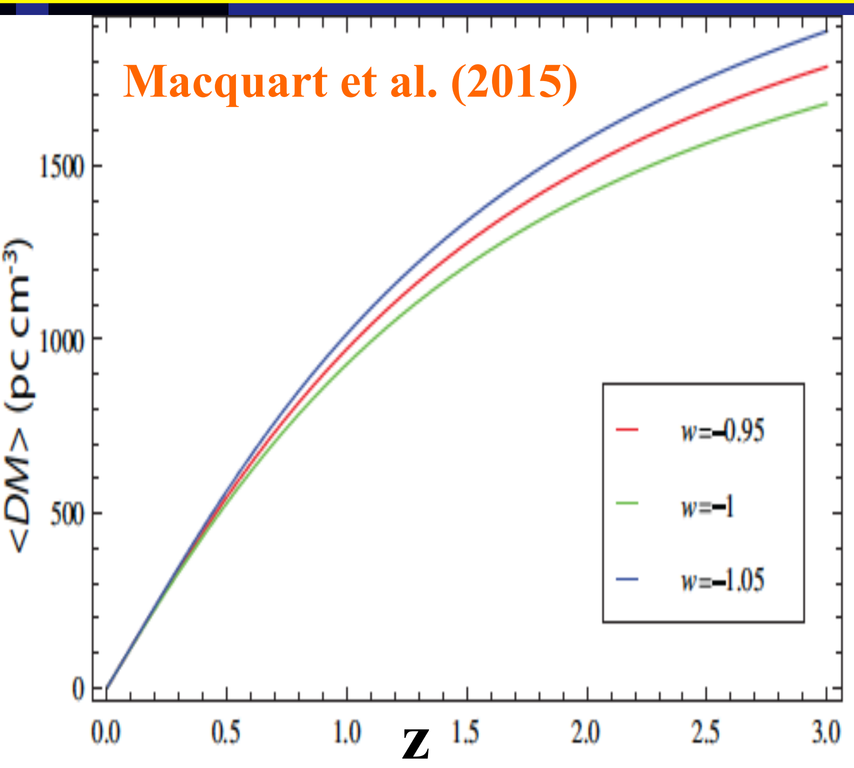
→ z of the host galaxy

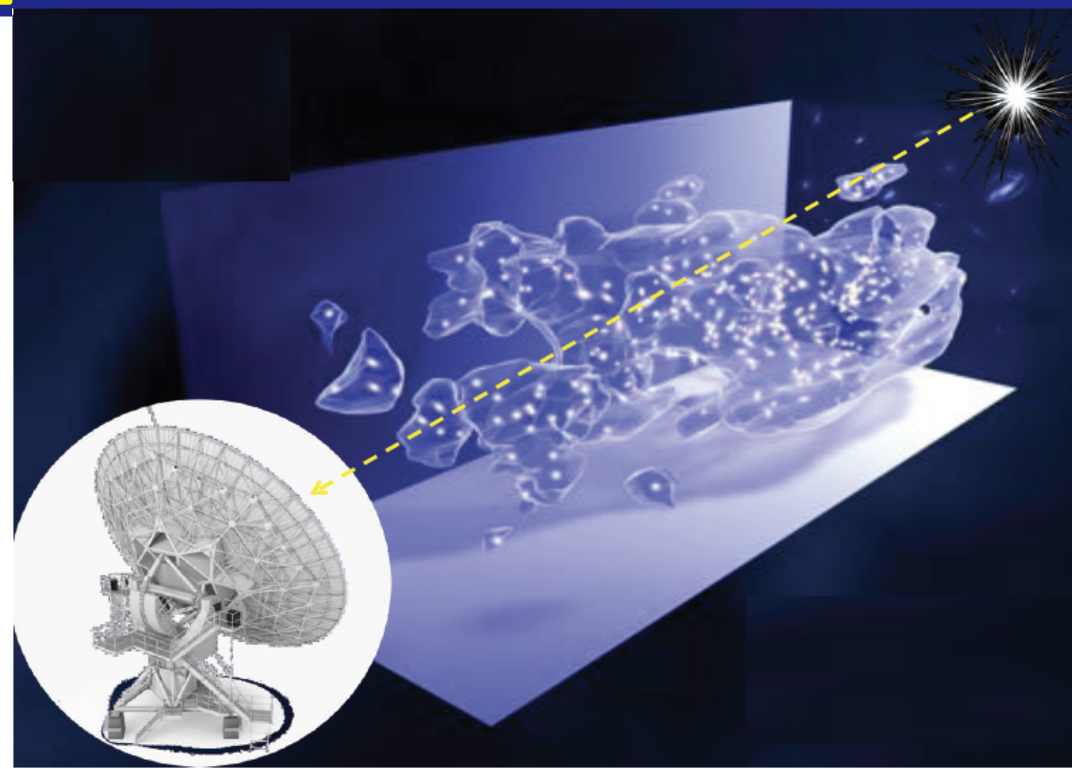
→

Baryons in intergalactic medium (DM)

Intergalactic medium magnetic field

Turbulence spectrum in IGM (duration)





Summary

- FRBs are from extra-galactic NSs with magnetic field > 10^{14} G.

- The radiation is likely coherent curvature radiation; $e^{\pm}$ are accelerated in magnetic reconnection. Multiple outbursts from the same object is a natural expectation of this model.

- The model predicts FRB like bursts (ms duration) at larger frequencies with L $\propto \nu^{-2/3}$, at a decreasing rate ($\nu^{-2/3}$).

- Polarization properties of the repeater (FRB 121102) are consistent with the coherent curvature model.