The Mystery of Fast Radio Bursts

Pawan Kumar

Outline[†]

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

Kyoto, September 25, 2019

Fast Radio Bursts (FRBs)

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

(3^o from SMC)

Duration (δt) = 5ms **Flux = 30 ± 10 Jy** **($3x10^{-22}$ erg $s^{-1}cm^{-2}$ Hz^{-1})**

$V_{EM}(\nu)$ in plasma increases with ν

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

$$\mathrm{DM} = \int n_e \mathrm{d}l$$ **Unit: pc cm^{-3}**

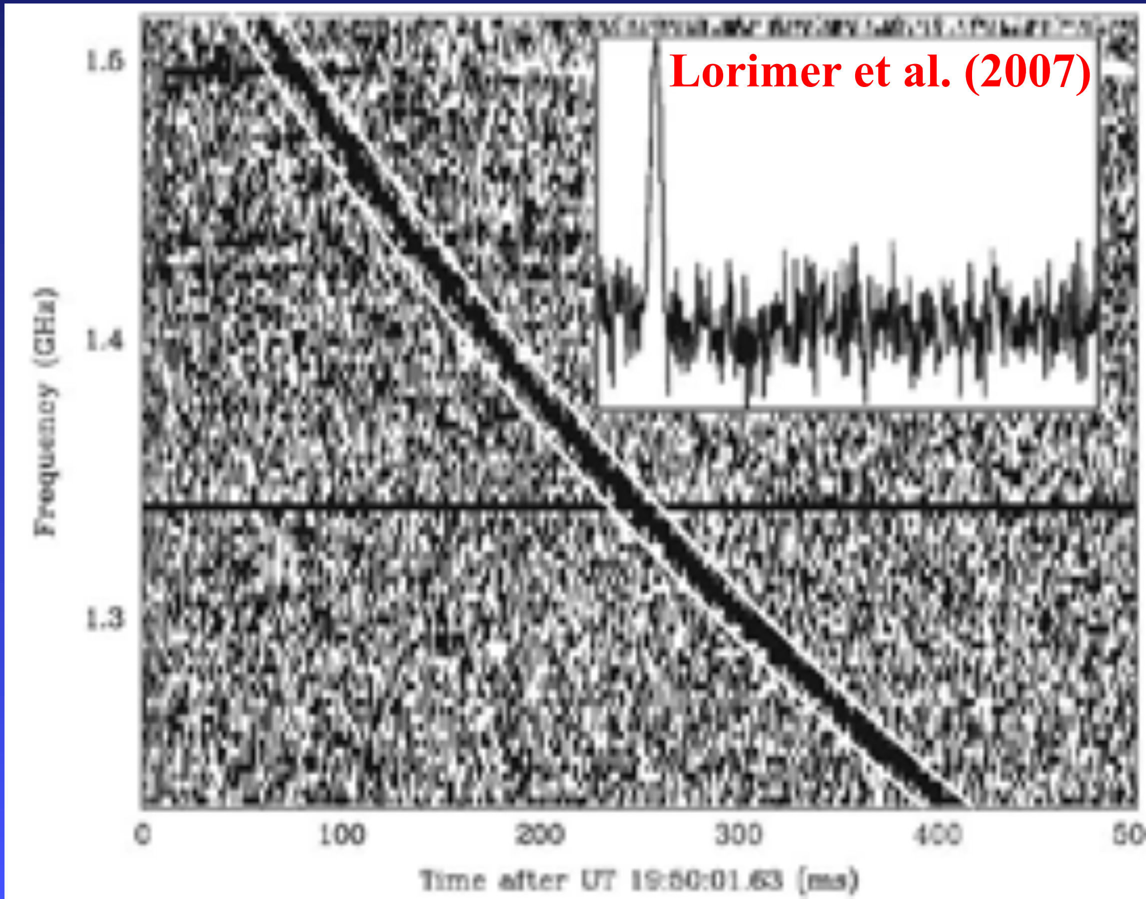
DM = 375 cm^{-3} pc

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

Estimated distance ~ 500 Mpc
(if DM = 350 from IGM)

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

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



~10 years of confusion and then a breakthrough

- **16 more bursts detected (2010) in Parkes archival data by *Bailes & Burke-Spolaor***

  These bursts were detected in all 13 beams of the telescope, i.e. most likely terrestrial in origin.

  They named these Peryton – *after the mythical winged stag*

  Many people suspected that the Lorimer burst was not cosmological but a Peryton.

- *Emily Petroff et al. (2015) established the origin of Perytons (microwave oven!). And concluded that the Lorimer burst was not a Peryton.*

Arecibo detects a burst in 2012; repeat activity found in 2015 (Spitler et al. 2016), which established that these events were not catastrophic. Accurate localization …

FRB 121102: the "old repeater" (>10^2 in 4 yrs)

(Spitler et al. 2016; Chatterjee et al. 2016; not a catastrophic event; VLBI – 7 milli-arcsec)

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

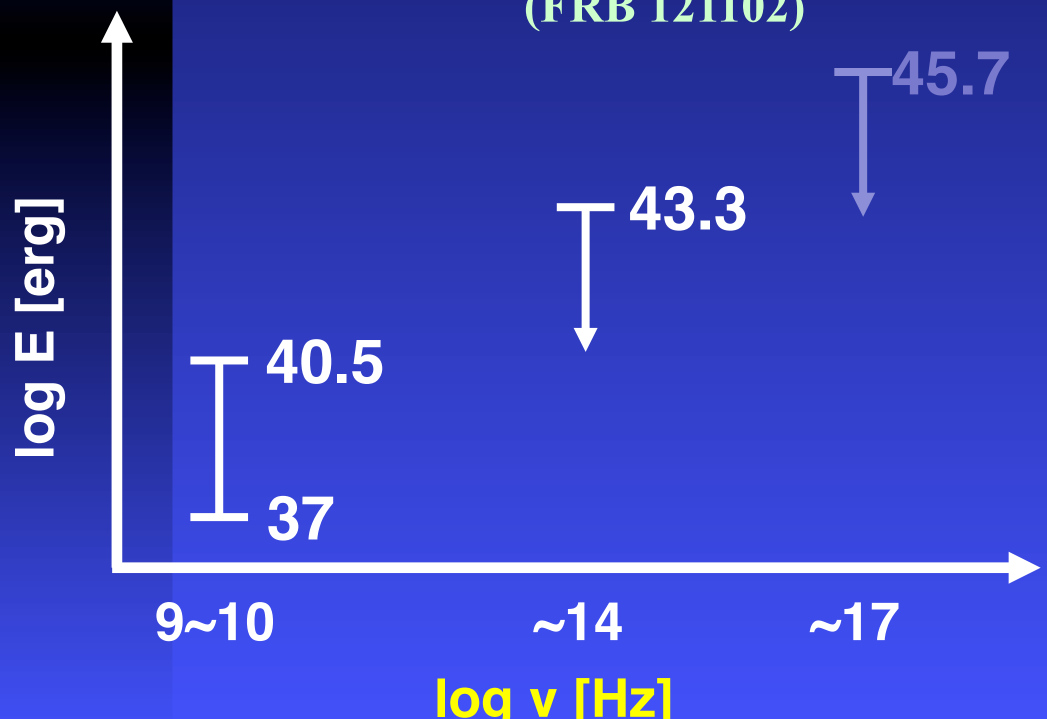
Z=0.19 (3.2x10^9 light years)
No optical/X-ray counter-part

$L_{iso} = 10^{41} - 3\times10^{43}$ erg s^{-1}

Duration, δt ~ (1, 10) ms (no broadening)

No optical/X-ray counter-part

(FRB 121102)



Petroff et al. (2015, 2017) report finding no counterpart to FRB 140514 & 150215 (t < 1d) in radio-optical-X-ray follow up observations thereby ruling out SNa or GRB association.

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

Properties of FRBs (summary)

- **Duration:** $1\ \text{ms} \lesssim t_{frb} \lesssim 20\ \text{ms} \Longrightarrow$ NS or BH (0.4 – 8 GHz)

  Flux variation time < 10 μs $\Longrightarrow$ source size $< 10^5\,\Gamma$ cm (compact source)

- $10^2 < \text{DM} \lesssim 10^3\ \text{pc cm}^{-3}$ $[0.2 < z < 3]$ – $10^{40}\ \text{erg s}^{-1} < L_{iso} < 10^{44}\ \text{erg s}^{-1}$

- >300 FRBs observed; 11 repeaters; 121102 is 100% linearly polarized.

  Birth Rate

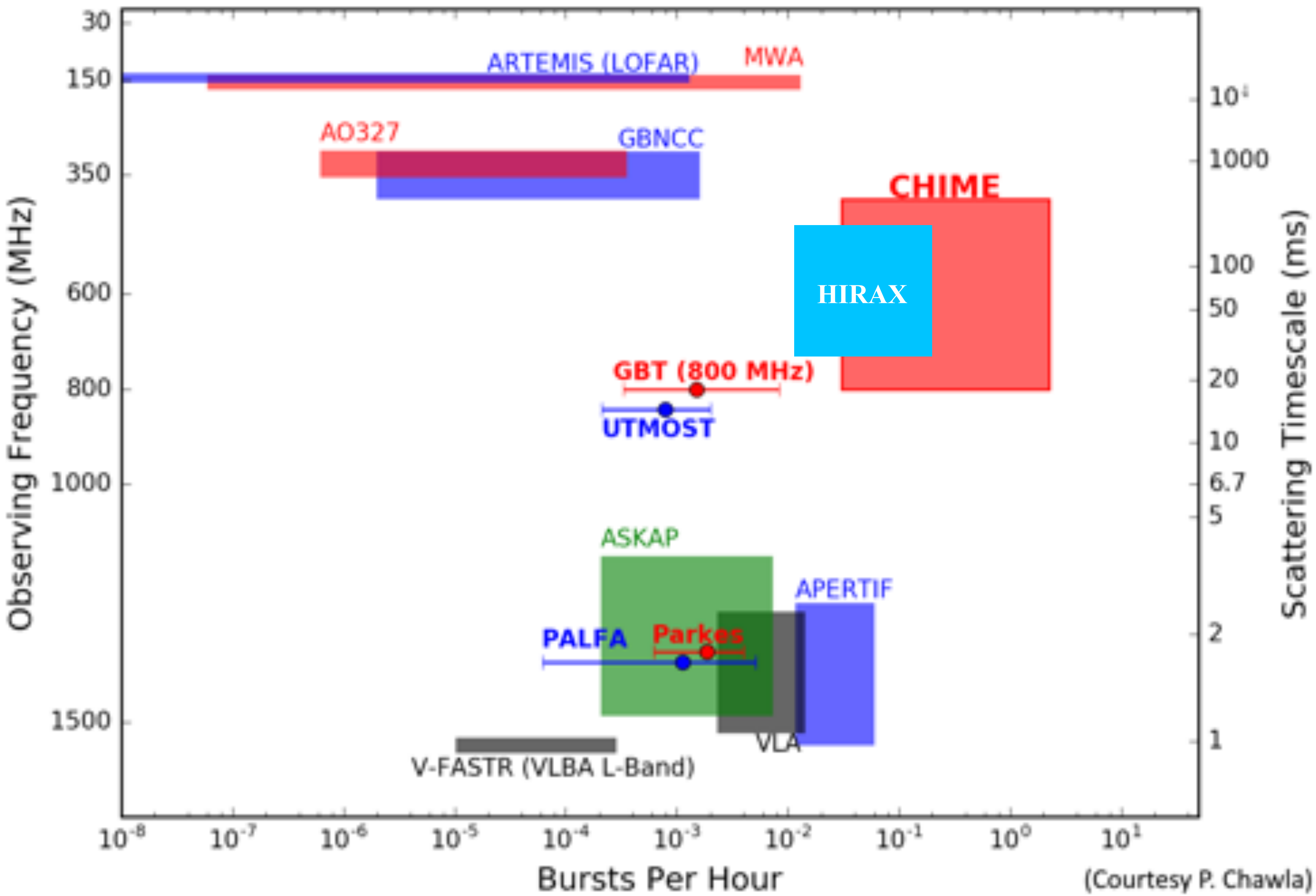
  non-repeating: rate ~ $10^4\ \text{d}^{-1}$ (>1 Jy ms) (~10% cc-SNe; 10^2 x bNS); beam?

  Kulkarni et al. 2015: "This high rate allows us to eliminate all forms of catastrophic stellar death as a progenitor"

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

- Energetics:

  The total energy release by the repeater – FRB 121102 – in 6 yrs $\sim 2\text{x}10^{43}$ erg $\Longrightarrow$ magnetic field strength $\gtrsim 10^{13}$ G (for NS)



ARTEMIS (LOFAR)
MWA
AO327
GBNCC
CHIME
HIRAX
GBT (800 MHz)
UTMOST
ASKAP
APERTIF
PALFA
Parkes
VLA
V-FASTR (VLBA L-Band)
Observing Frequency (MHz)
30
150
350
600
800
1000
1500
Scattering Timescale (ms)
1000
100
50
20
10
6.7
5
2
1
Bursts Per Hour
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
(Courtesy P. Chawla)

Models for FRBs

Galactic flaring stars

Giant pulses from NS

Magnetar flares

Collapsing NSs

Mergers (WDs, NSs)

AGN flare interaction with NS

Asteroids colliding with NSs

Extra-terrestrial intellegent life communication

. . . . . . (50 more models)

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

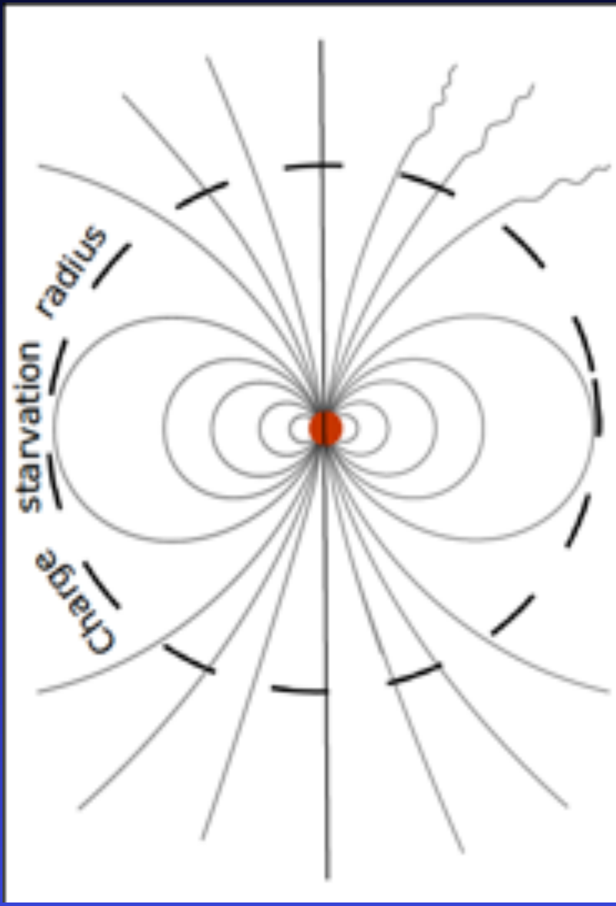
Overview of the FRB model I will describe

- NS with strong magnetic field (> 10^{14} G)

- Surface activity launches high luminosity Alfven waves

  (youngish neutron star)

- Alfven waves become charge starved at a few R_{NS} and produce coherent curvature radiation (GHz pulse from FRBs).



Radiation Mechanism

Brightness temperature

$L \propto N$

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

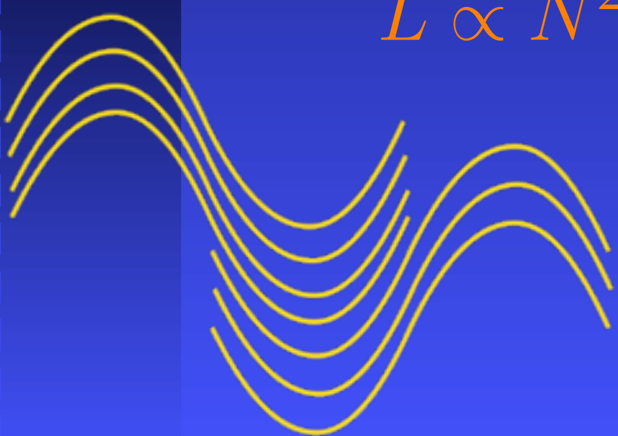
$$T_B = \frac{F_\nu d_A^2 c^2}{2(c\delta t)^2 \nu^2 k_B} > 10^{35}\mathrm{k}\ d_{A28}^2$$

Number of photons in each quantum state: $\frac{k_B T_B}{h \nu} \approx 10^{36}$

coherent emission:

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

$L \propto N^2$



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

General constraints

Electric field associated with FRB radiation

$L = c\,E^2\,R^2 \quad \Longrightarrow \quad E = 2\text{x}10^3\ \text{esu}\quad L_{43}^{1/2}/R_{13}$

$\sim 10^6$ volts/cm (at a distance of ~ 1 AU)

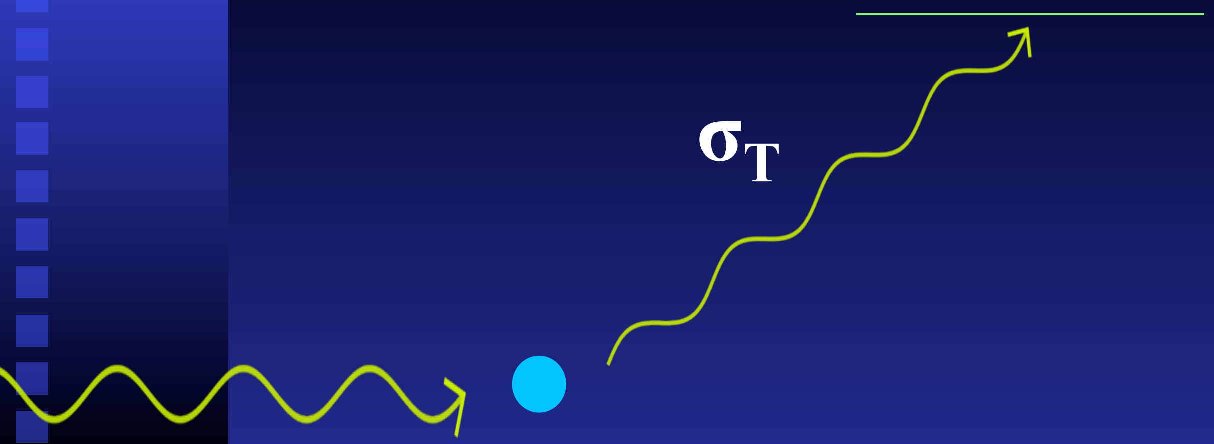
EM wave Non-linearity parameter: $a = \dfrac{q\,E}{m_e c\,\omega} \approx 3$

Electrons exposed to FRB radiation are accelerated to Lorentz factor $2a^2 > 10$ for $R < 10^{13}$ cm.

This raises questions about confinement of the plasma in the source region.

But the problem gets worse…

Large radiation force due to induced Compton Scattering



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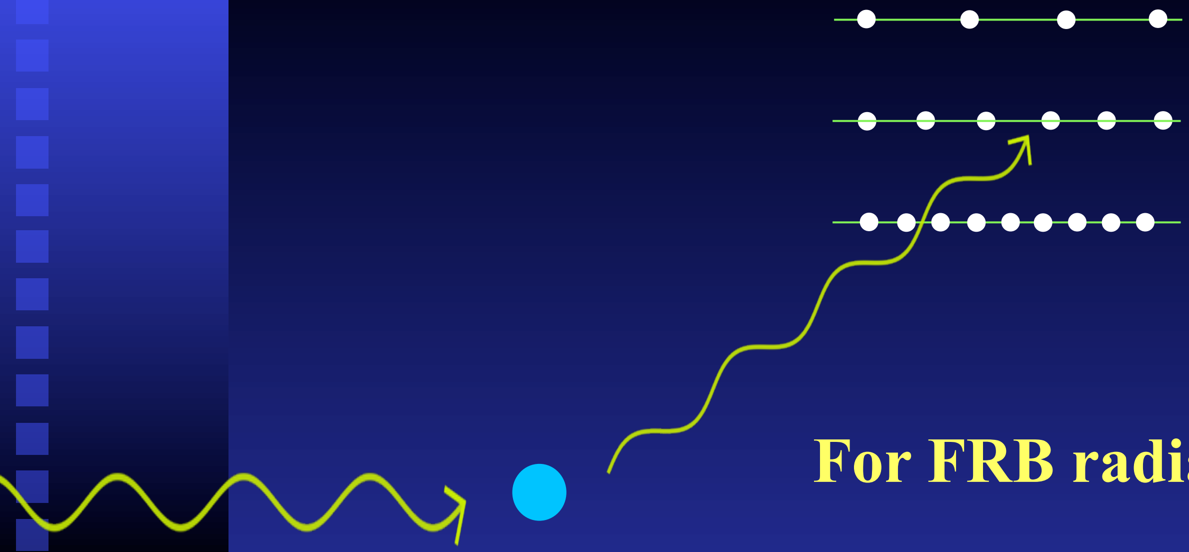


Scattering probability is enhanced by the "occupation number" of the final state (n_γ)

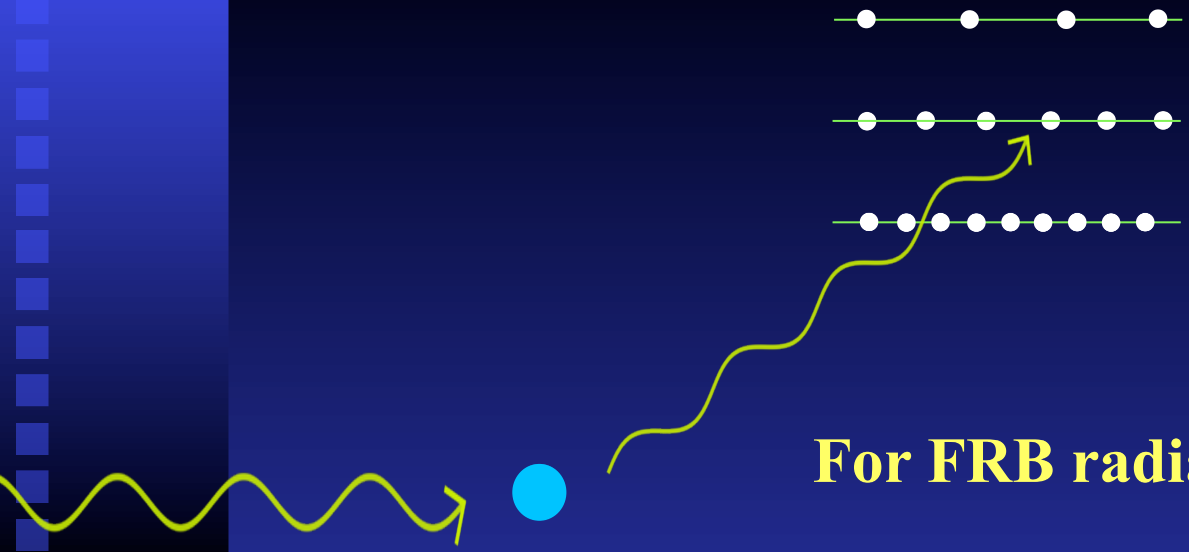
For FRB radiation, $n_\gamma = \dfrac{k_B T_B}{h \nu} \approx 10^{36}$

Because of cancellations, the effective cross-section is not enhanced by the factor n_γ; the effective enhancement factor is $\sim 10^9$ at $R = 10^{13}$ cm (declines with distance as R^{-3}).

Even a low density medium that is highly transparent to Thomson scattering can be opaque to FRB coherent radiation.

Particles at a distance from the source $< 10^{14}$ cm are accelerated to LF $\gg 1$ due to induced-Compton scatterings (if the medium is transparent).

Large radiation force due to induced Compton Scattering



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Plasma in the source region needs to be confined so that the enormous radiation pressure does not shut down the radiation process.

$R \lesssim 10^7$ cm

magnetic field is very strong and suppresses x-mode photon scatterings by a factor $(\omega_B/\omega)^2$.

$\omega_B = 10^{18} B_{12}$ Hz is cyclotron frequency and, and ω is FRB photon frequency

$R \gtrsim 10^{13}$ cm

Photon beam size is small and scattering is not a problem.

$t_{FRB} \sim R/(2c\Gamma^2) \sim 1$ ms $\rightarrow$ $\Gamma > 10^3$

$E_{jet} > 10^{47}$ erg for $\Gamma > 10^3$

& $E_{jet} \propto R^2 \propto L_{FRB}$

Constraints on FRB source and radiation mechanism

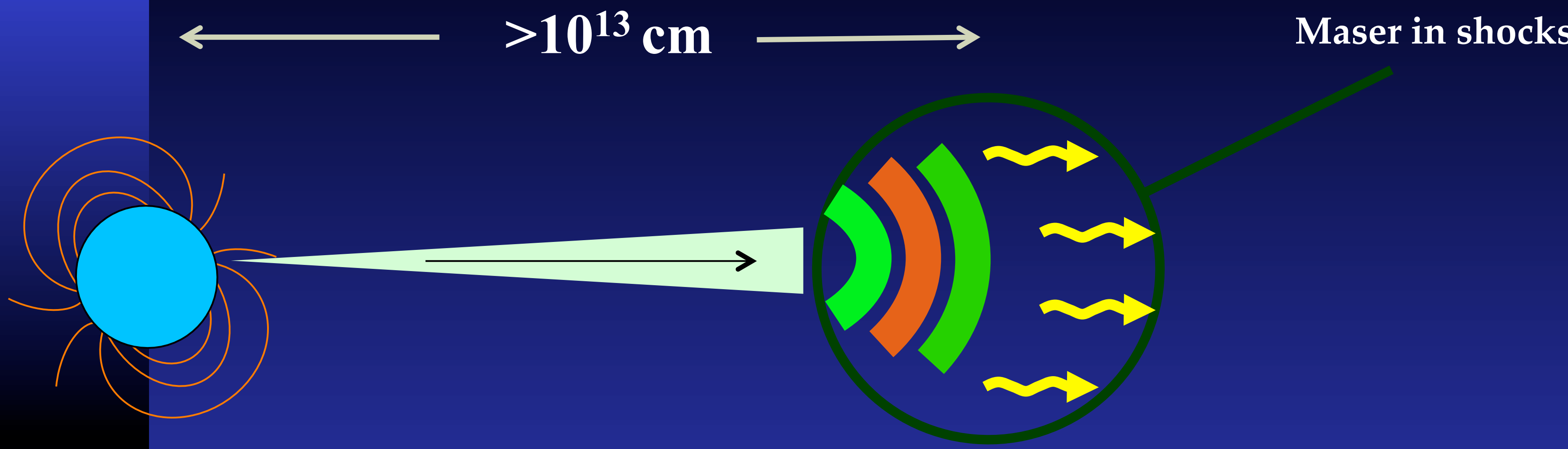
1. Compact source of size $\sim 10^5\ \Gamma$ cm; Γ is the LF of the source

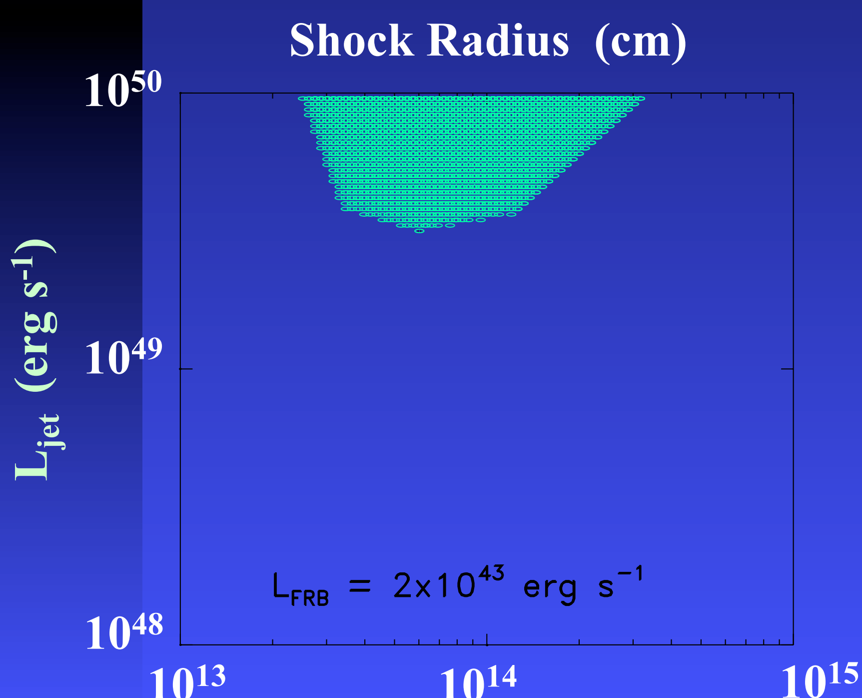
2. Energy for FRBs is produced within ~10 R_{NS} (not enough energy at larger radius)

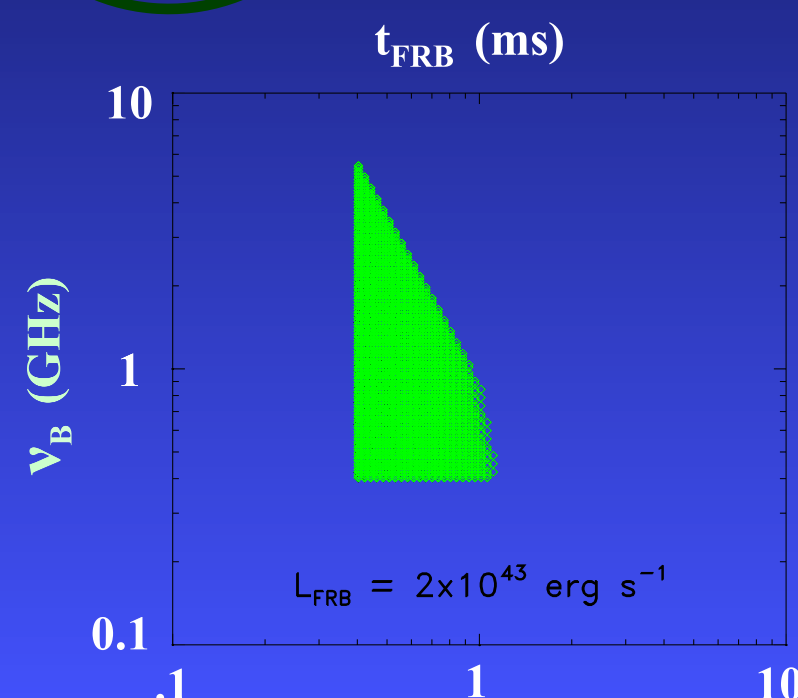
3. Plasma should be able to withstand the radiation pressure due to induced-Compton:

$\Longrightarrow$ source distance from NS $< 10^7$ or $>10^{13}$ cm.

Let us consider radiation production at distance $>10^{13}$ cm





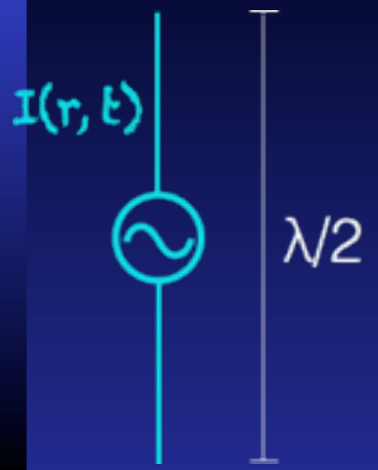


FRB radiation source within a few 10s of neutron star radius

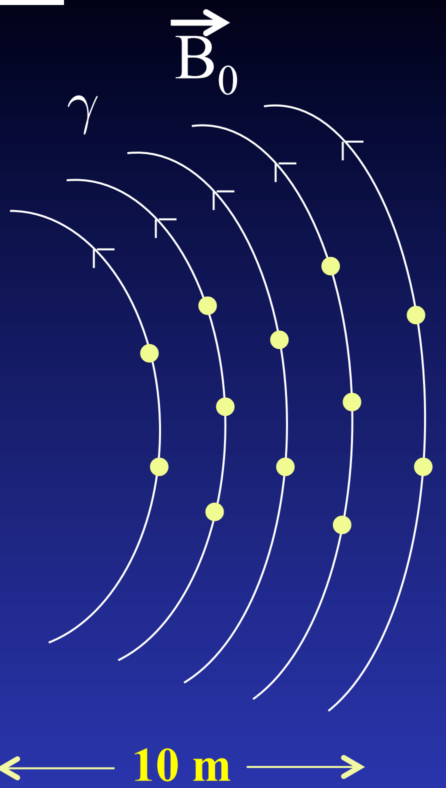
One model that satisfies these constraints is the coherent curvature radiation model that operates not too far from the NS surface.

Coherent curvature radiation

(Antenna mechanism)



Particle *clumps* of ~ cm size (in longitudinal direction) moving along curved magnetic field



R_B : curvature radius of field lines

γ : Lorentz factor of particles

Frequency of radiation:

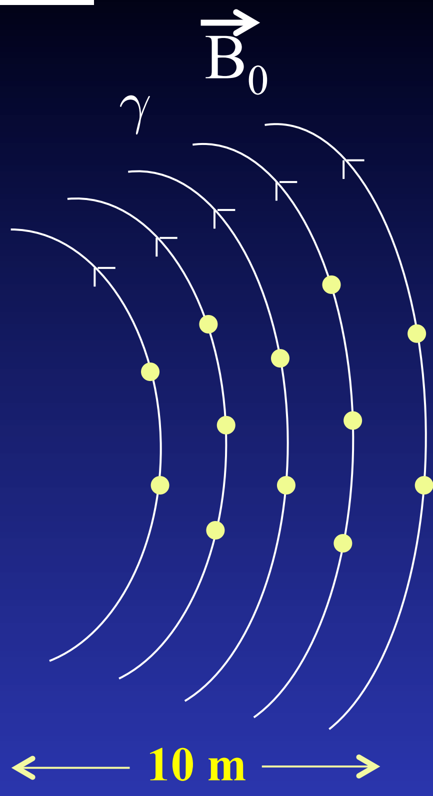
$$\nu = \frac{c\gamma^3}{2\pi R_B} \longrightarrow \gamma = 270\, \nu_9^{1/3} R_{B,8}^{1/3}$$

FRB luminosity:

$$L \approx \frac{8\pi^2 c^5 q^2 n_e^2 \gamma^6}{3\nu^4} \longrightarrow n_e \sim 10^{14}\,\mathrm{cm}^{-3} L_{43}^{1/2} R_{B,8}^{-1}$$

Coherent curvature radiation

(Antenna mechanism)



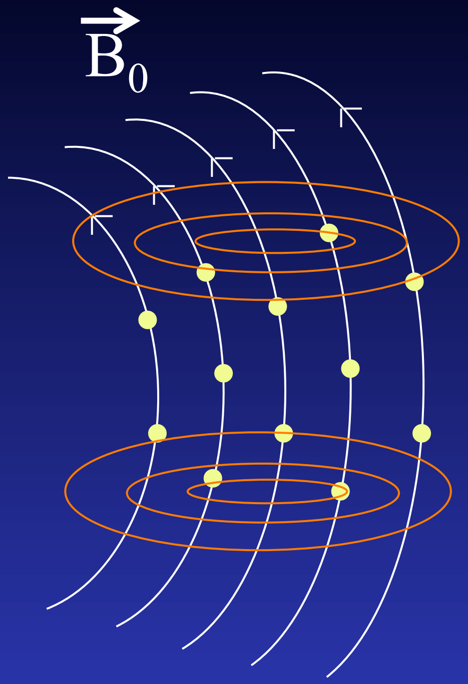
Magnetic field produced by the current associated with particles streaming along the field lines

$$B_{ind} \sim 10^{11}\,\mathrm{G}\,\frac{L_{43}^{1/2}\,\nu_9^{1/3}}{R_{B,8}^{2/3}}$$

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

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

This suggests that we are dealing with a magnetar

Particle acceleration

- **The radiative cooling time of electrons is very short:**

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

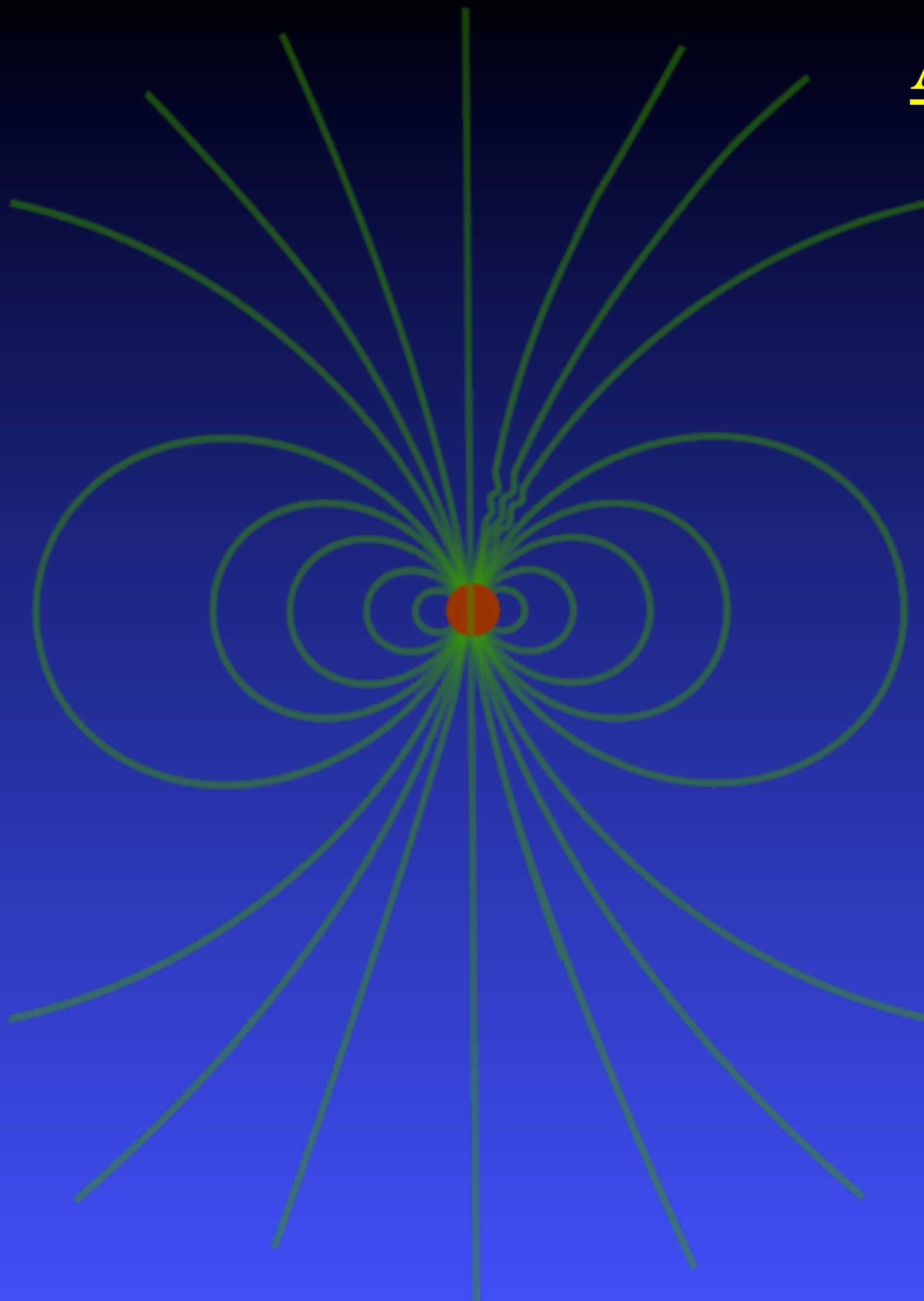
This time is much smaller than the wave period (1 ns for 1 GHz radiation)

- **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: $E_{||} \sim 10^{10}\mathrm{esu}\ L_{43}^{1/2} R_{B,8}^{-1}$

Alfven waves

What produces this Electric field? And supplies energy for the radiation?



$$\frac{\delta B}{B} \approx 10^{-4}$$

$$\frac{\delta B}{B} \propto R^{3/2}$$

Alfven waves

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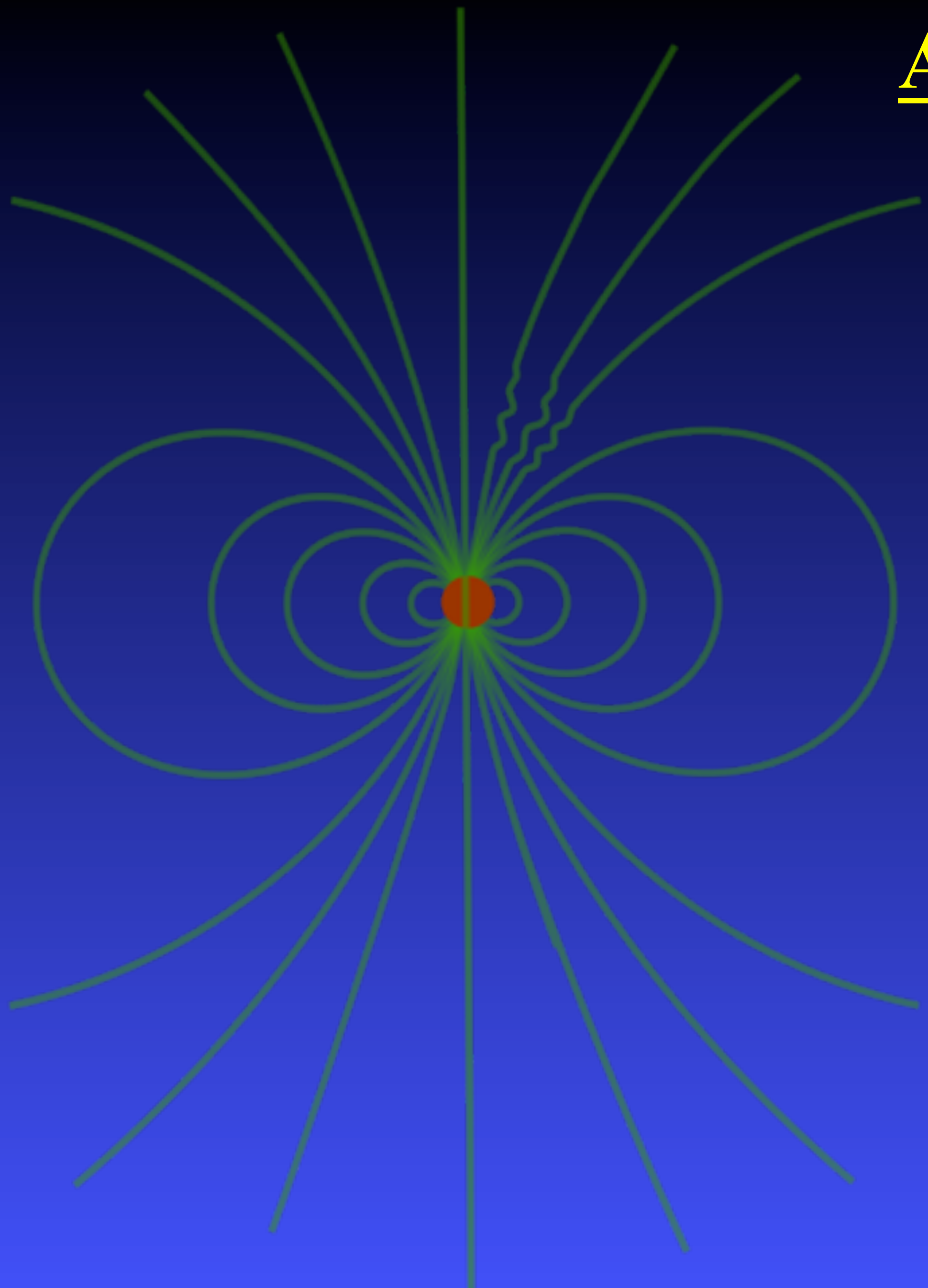
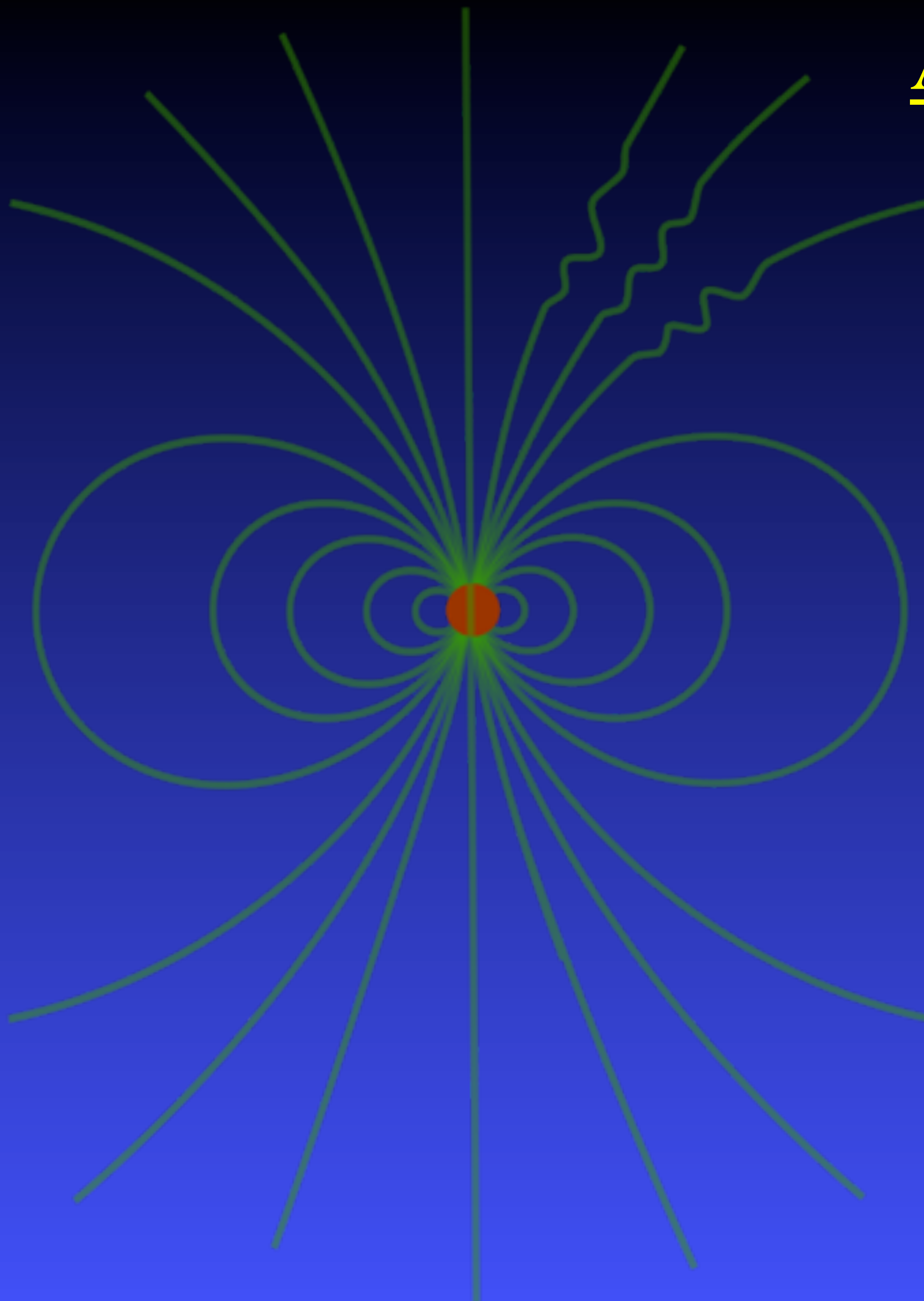


$$\frac{\delta B}{B} \approx 2\times10^{-4}$$

$$\frac{\delta B}{B} \propto R^{3/2}$$

Alfven waves

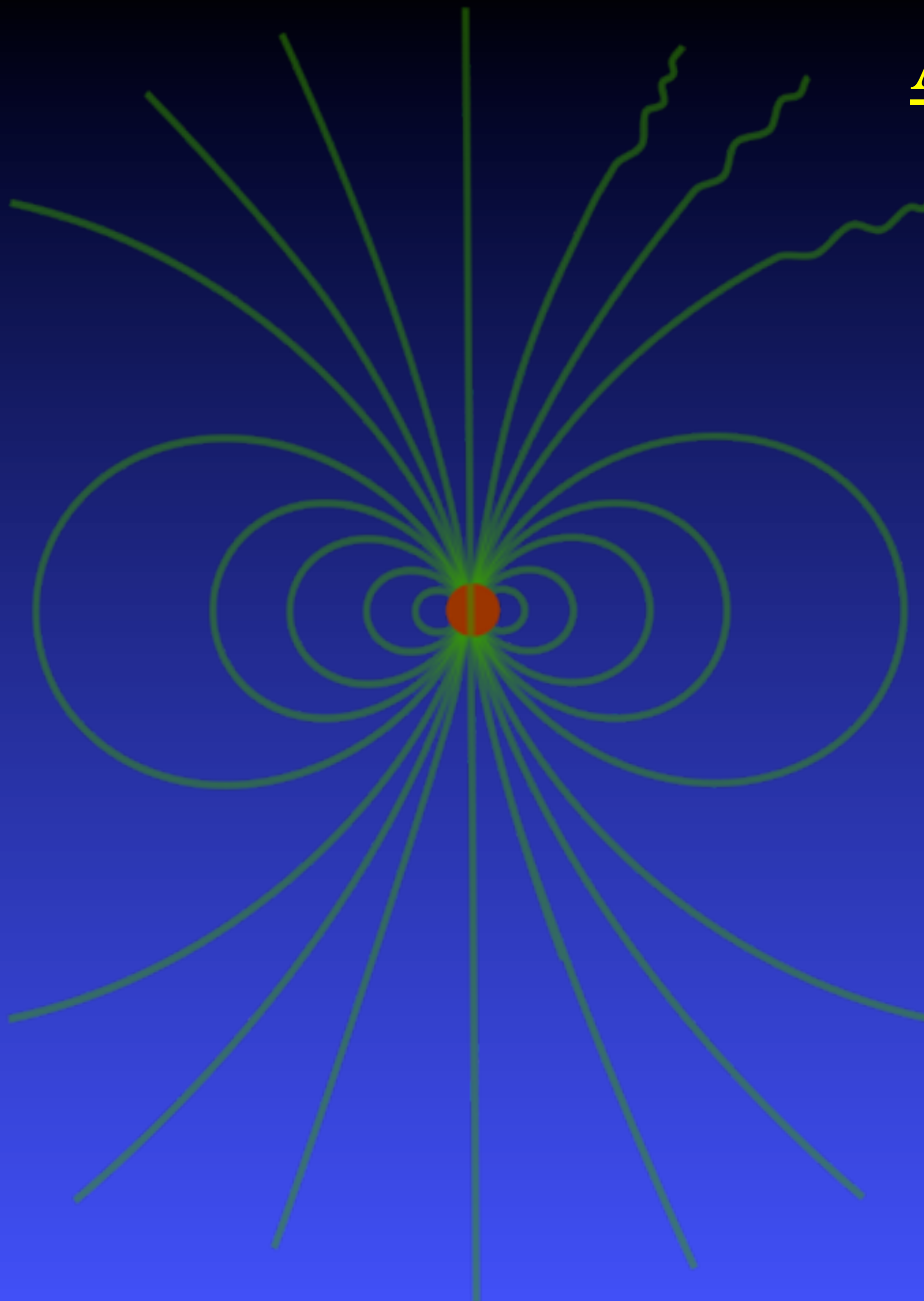
What produces this Electric field? And supplies energy for the radiation?



$$\frac{\delta B}{B} \approx 4x10^{-4}$$

$$\frac{\delta B}{B} \propto R^{3/2}$$

What produces this Electric field? And supplies energy for the radiation?



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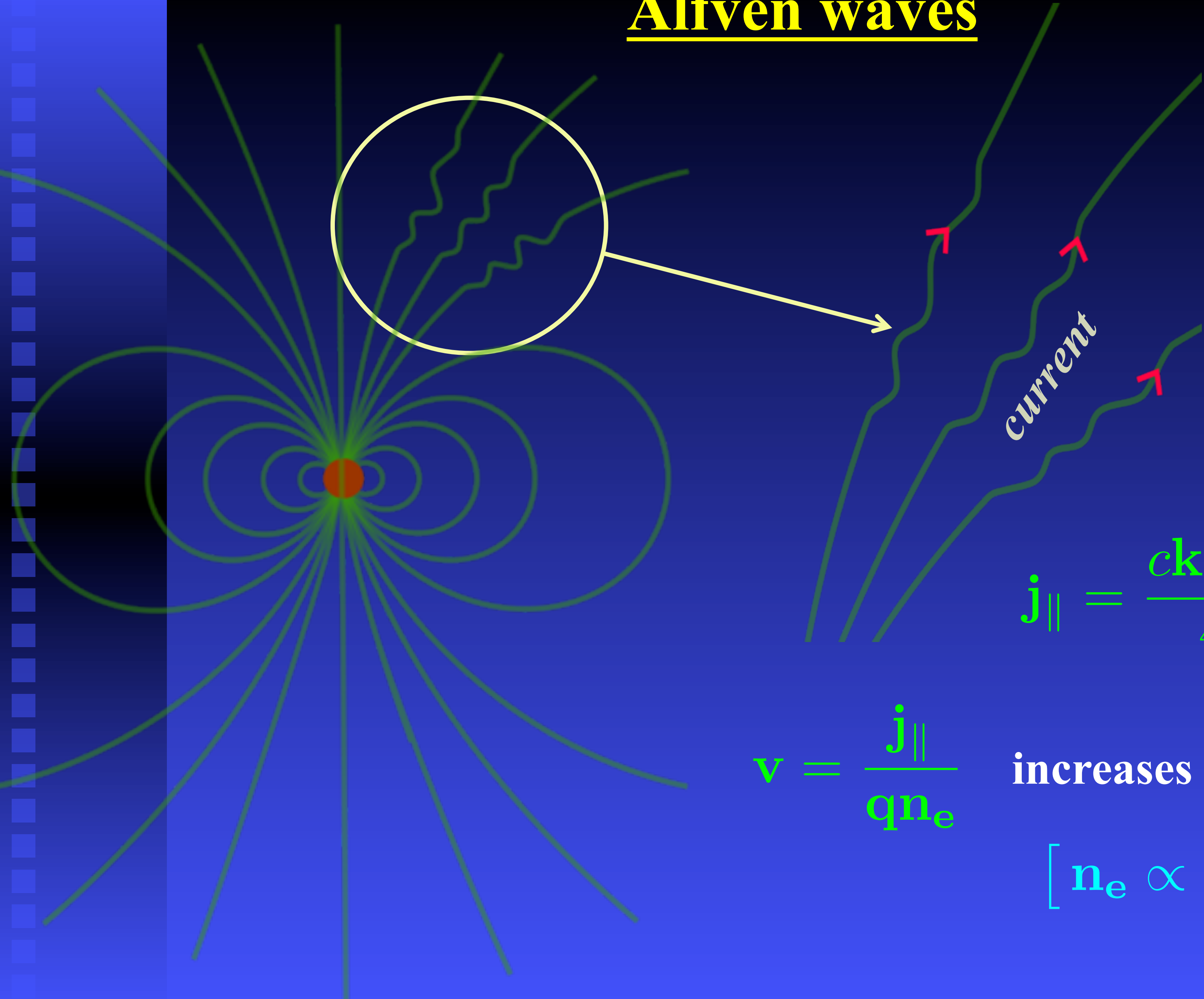
Alfven waves

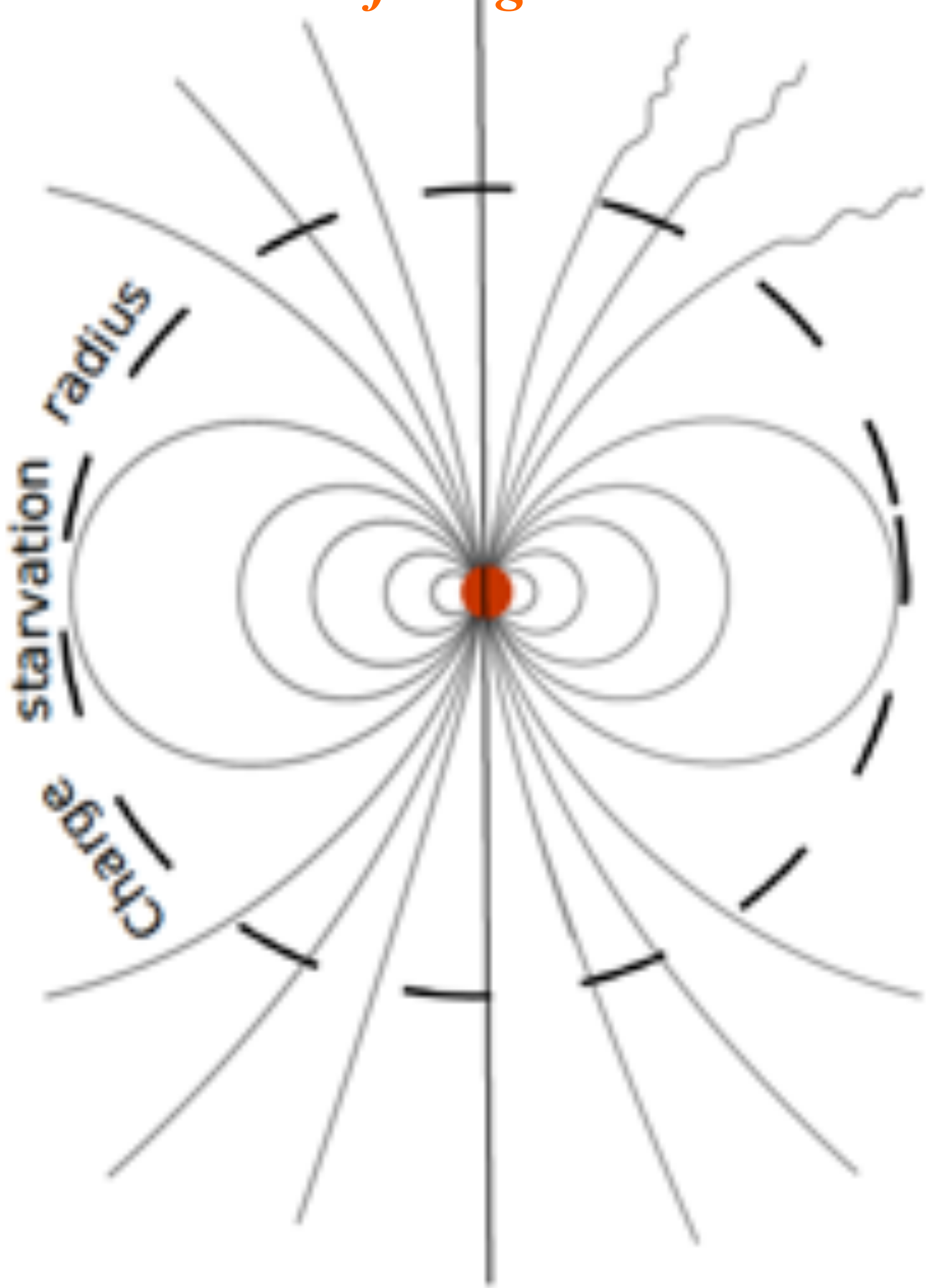


$$\mathbf{j}_{\parallel} = \frac{c\mathbf{k}_{\perp}\delta B}{4\pi}$$

$$\mathbf{v} = \frac{\mathbf{j}_{\parallel}}{\mathbf{q n_e}}$$ **increases with R**

$$\left[\, \mathbf{n_e} \propto \mathbf{R}^{-3} \,\right]$$

Electric field generation



At a distance, R_c , from the NS:

$$v = \frac{j_{\|}}{q n_e} \approx c$$

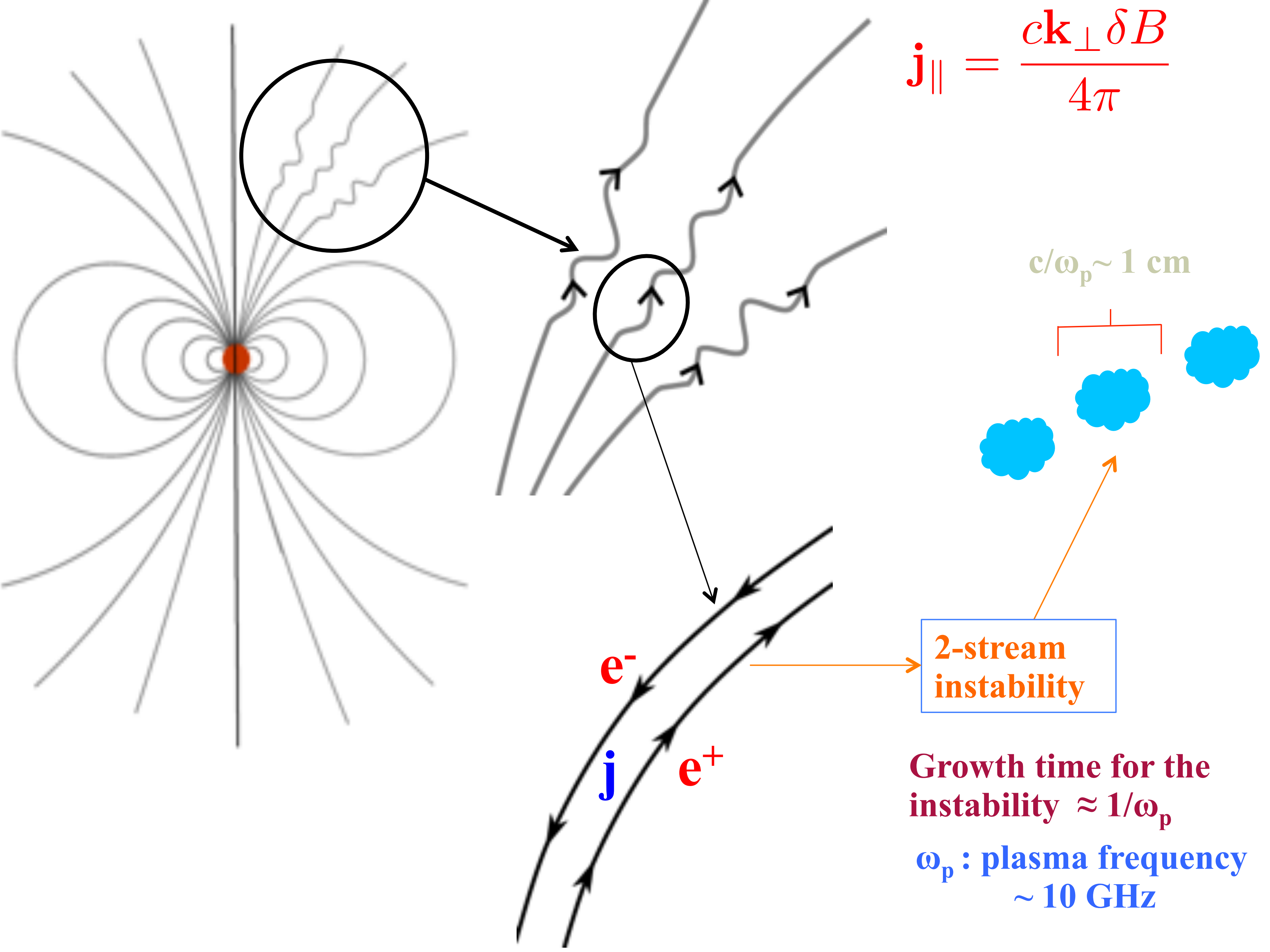
And for $R > R_c$ particle density is insufficient to carry the current required by the Alfven wave packet.

Strong electric field develops at $R > R_c$

[The displacement current ($\partial E/\partial t$) compensates for the insufficient plasma current]

Formation of particle clumps

Inside charge starvation radius

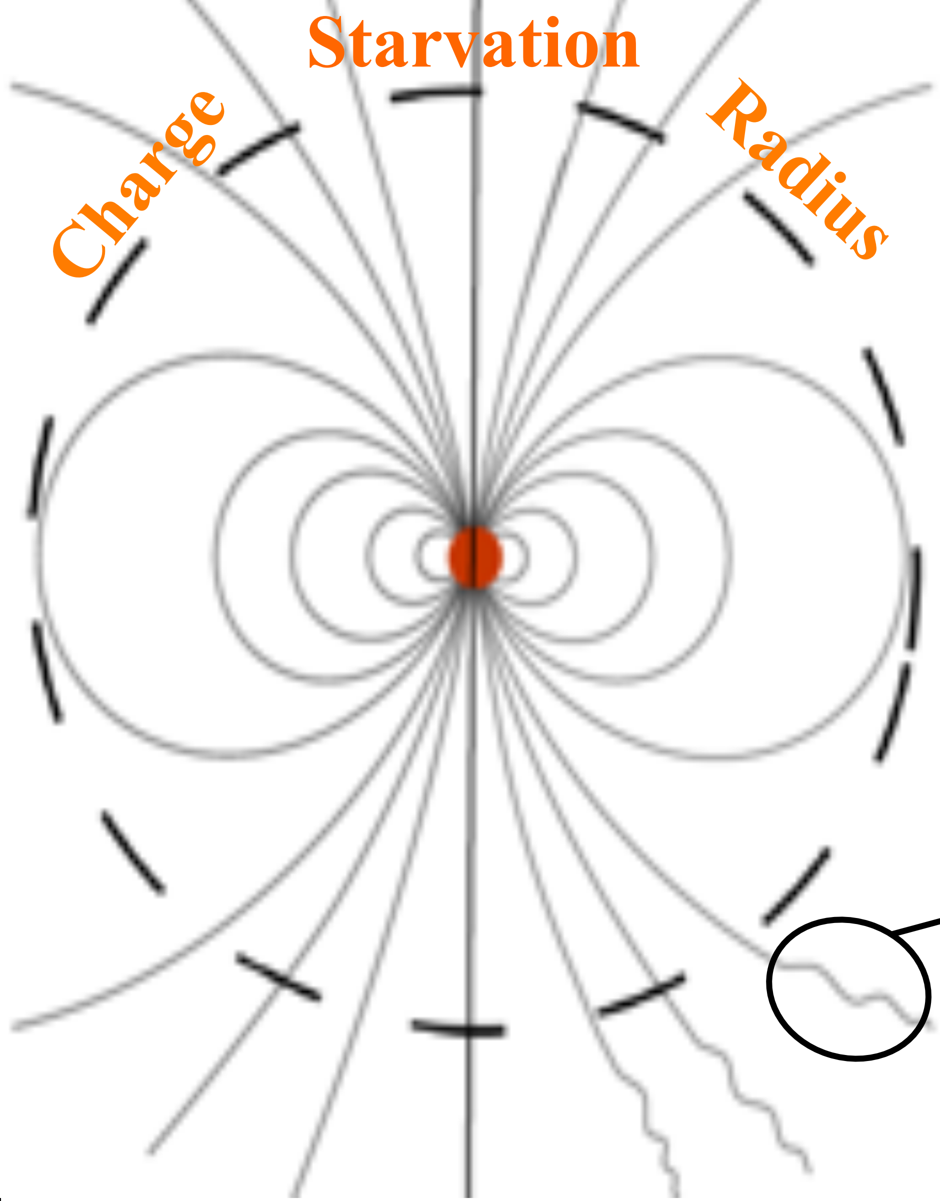


$\mathbf{j}_\parallel = \frac{c\mathbf{k}_\perp \delta B}{4\pi}$
$c/\omega_p \sim 1$ cm
e^-
$\mathbf{j}$
e^+
2-stream instability
Growth time for the instability $\approx 1/\omega_p$
ω_p : plasma frequency ~ 10 GHz

Outside charge starvation radius

Strong electric field, particle acceleration

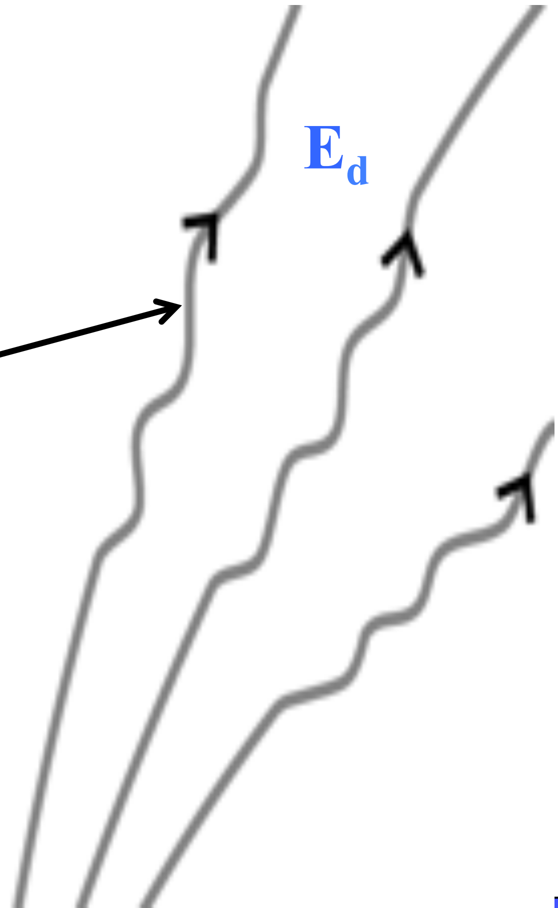
and curvature radiation

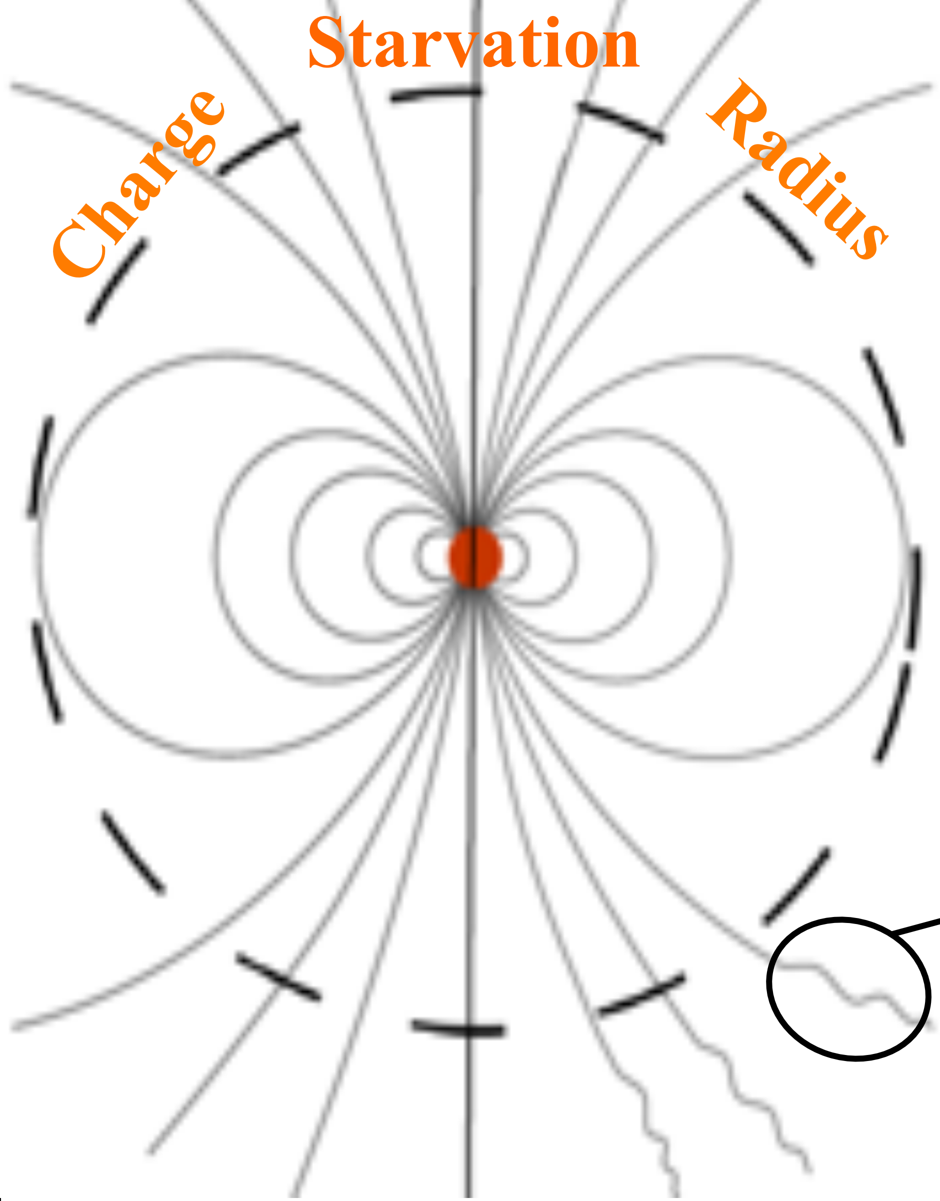


Displacement current:

$$\frac{\partial \vec{E}_d}{\partial t} = c\vec{\nabla} \times (\delta \vec{B}) - 4\pi \vec{j}$$

$$\frac{\partial \mathbf{E_d}}{\partial t} = ic\mathbf{k}_{\perp}\delta B$$





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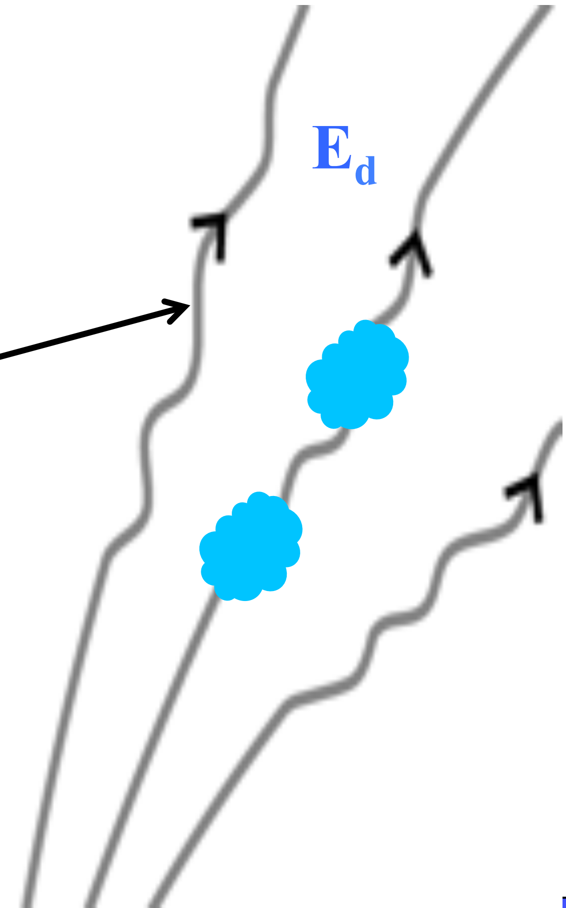

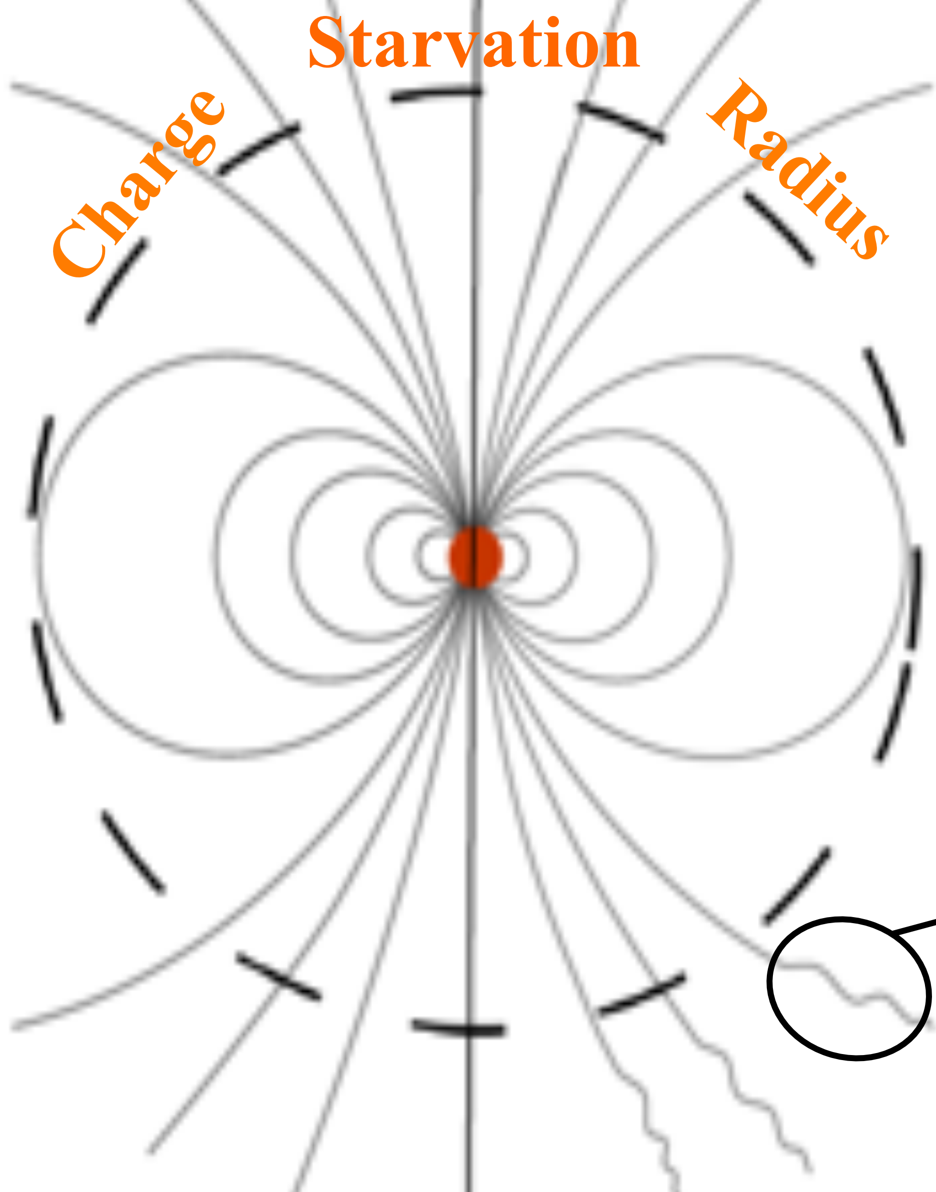

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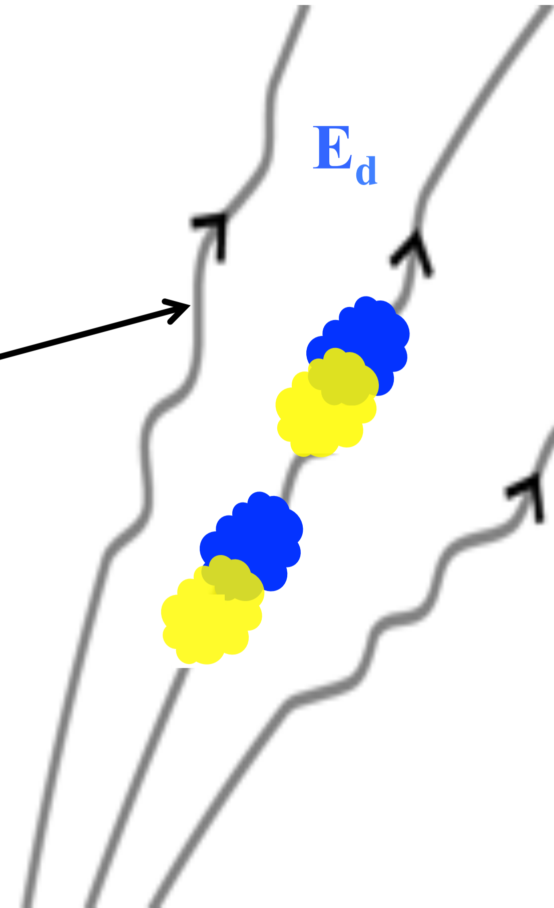
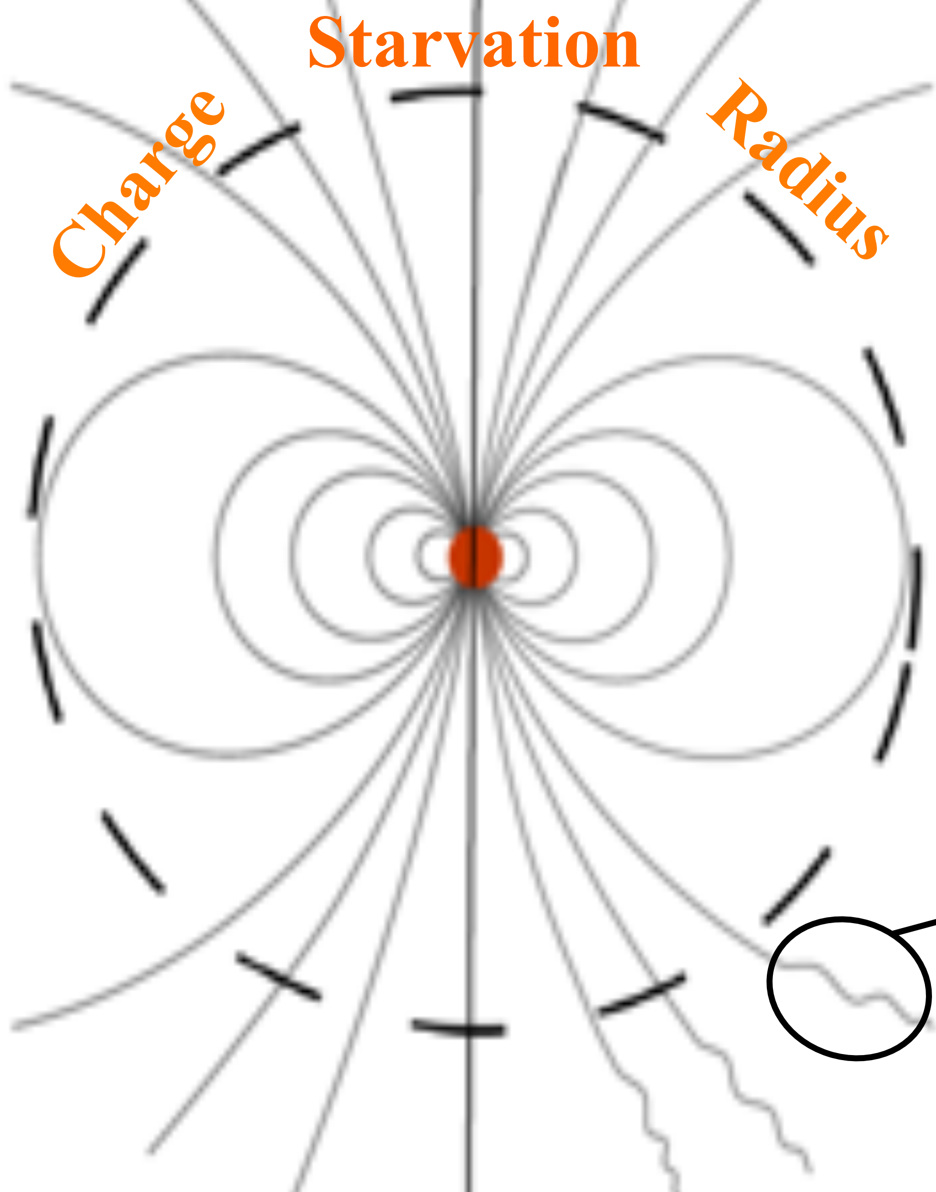


This electric field keeps the charge particles accelerated as they lose energy to coherent curvature radiation.



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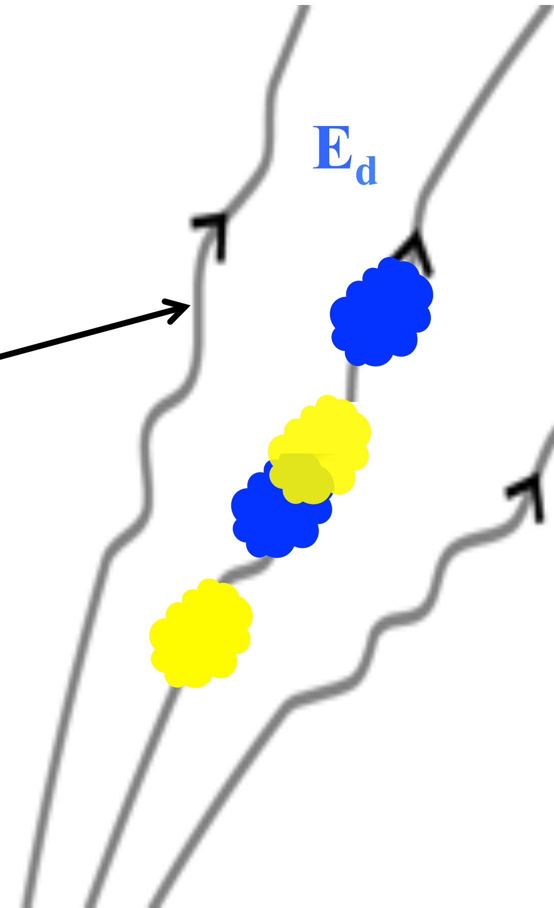


This electric field keeps the charge particles accelerated as they lose energy to coherent curvature radiation.

Energetics

- The total energy release in one burst is modest:

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

- Whereas the total energy in the magnetic field is $\sim 10^{45}$ 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 $\sim 10^{30}$.

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

Overview of the FRB model

- **NS with strong magnetic field (> 10^{14} G)**

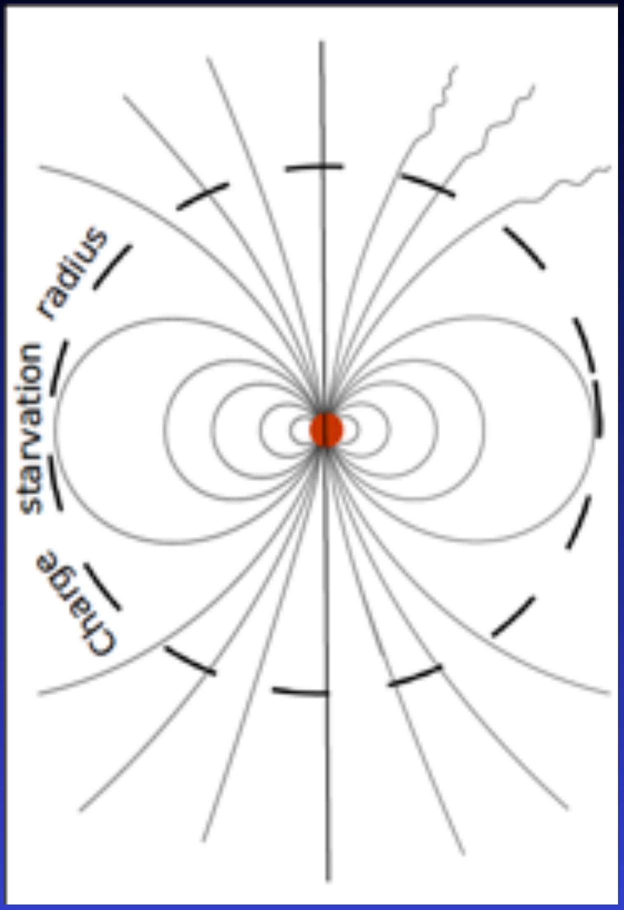
- **Surface activity launches high luminosity Alfven waves**

  (youngish neutron star)

- **Alfven waves become charge starved at a few R_{NS} and produce coherent curvature radiation (GHz pulse from FRBs).**

  Outbursts are in the polar region along open field lines:

  $$\theta_{pc} \sim (R_{ns}\, \Omega_{ns}/c)^{1/2} \sim 2\times10^{-2}\, P_{ns}^{-1/2}\ \mathrm{rad}$$



∴ **The probability of seeing outbursts from a young magnetar is ~ 10^{-4}.**

Predictions of the model

We should see FRB like bursts at 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:

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

$$L \sim E_{\|}^2 \rho^2 c \propto \nu^{-2/3}. \qquad \textbf{Event rate} \propto \nu^{-2/3}$$

Maximum FRB Luminosity **~ 10^{47} erg s^{-1}**

As the electric field approaches the *Schwinger limit* – 4×10^{13} esu – $e^{\pm}$ are pulled from vacuum, and the cascade shorts the electric field needed for accelerating particles for coherent radiation.

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.

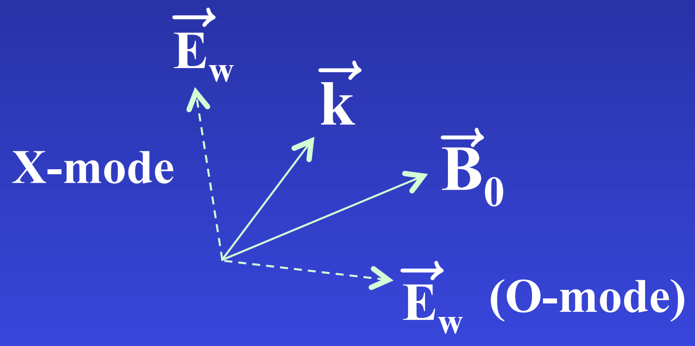
  The rotation measure was ~10^{5} rad m^{-2} and varied by 10%

- **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 > a few 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 || $\vec{k} \times \vec{B}_0$

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

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

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

So, photons are polarized perpendicular to the magnetic axis (projected in the sky plane).

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

Synchrotron Maser (plasma)

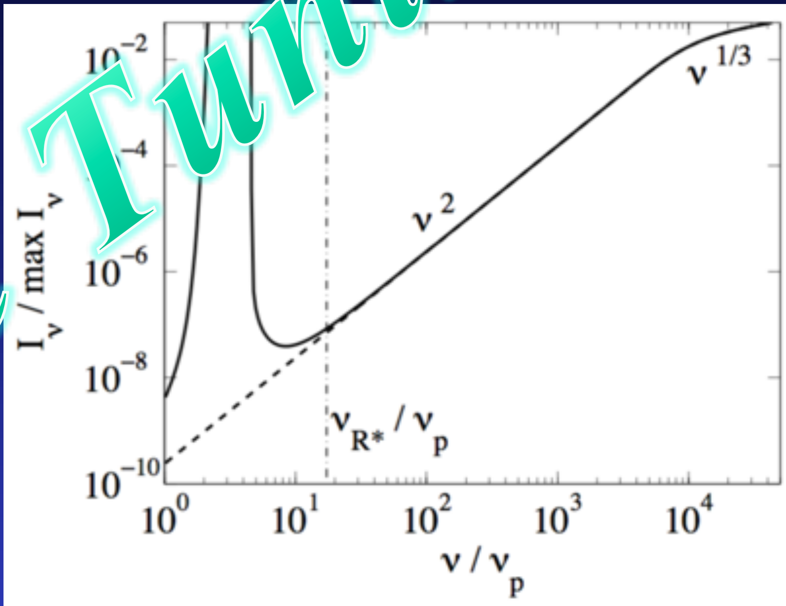
- **population inversion** $-\ dn_e/d\gamma' \propto \gamma'^{>2}$ **(in shock)**
- $\nu \sim \Gamma \nu_p (\epsilon_e/\epsilon_B)^{1/4}$
- $\epsilon_B \lesssim 10^{-9}\,\Gamma_3^4$ (for $\nu \sim 4$ GHz)

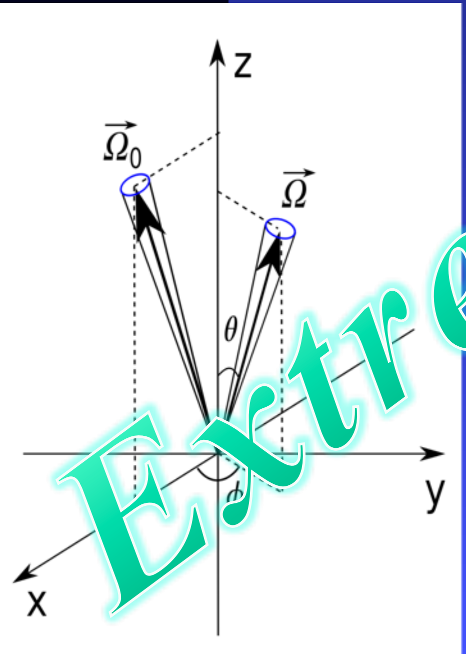
Luminosity: $L_{\rm iso} < 4\pi r^2 \Gamma^2 n' \gamma' m_e c^3$

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

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

Sagiv & Waxman (2002)





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

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

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

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

Extreme Fine Tuning

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: $\Gamma^2 \gamma' n' m_e c^3 > L_{\mathrm{iso}}/(4\pi r^2)$

$$\omega' = \omega/2\Gamma \simeq 3 \times 10^7\,\mathrm{s}^{-1}\,\nu_9 \Gamma_2^{-1} \qquad \omega'_{\mathrm{p}} \gtrsim 3 \times 10^{14}\,\mathrm{s}^{-1} \frac{L_{\mathrm{iso},43}^{1/2}}{r_7 \Gamma_2 \gamma'^{1/2}}$$

$$\omega'_{\mathrm{B}} = \omega_{\mathrm{B}} \simeq 2 \times 10^{17}\,\mathrm{s}^{-1}\, B_{10}$$

- 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:

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

curvature cooling

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

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

Extreme Fine Tuning

Summary

- **FRBs are from extra-galactic NSs with magnetic field > 10^{14} G.**
- **The physical constraints I have described are likely to guide our ultimate understanding of FRBs.**

  Alfven waves launched from NS surface become charge starved at some radius. $e^{\pm}$ are accelerated in this process and produce curvature radiation.

- **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.**