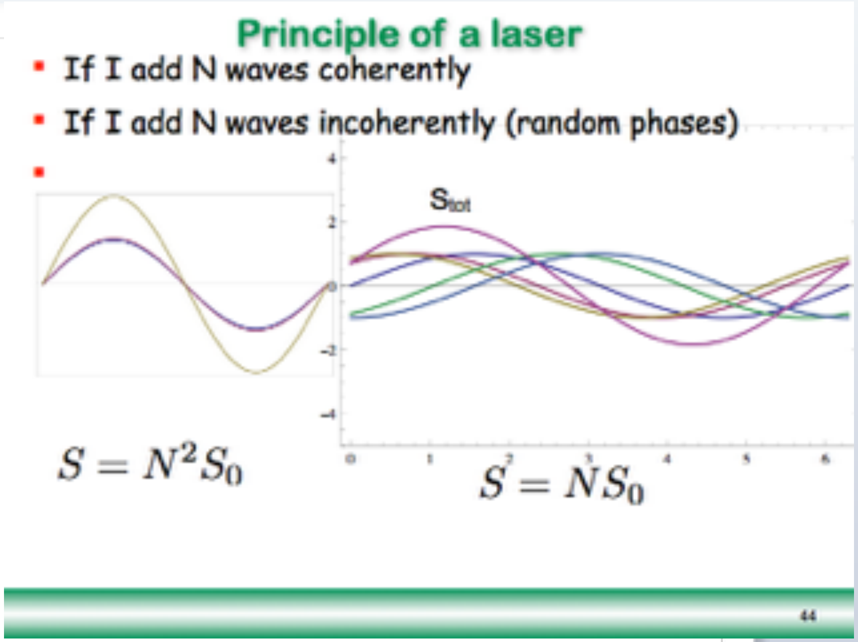
FRB emission mechanisms

Maxim Lyutikov (Purdue, McGill)

Preliminaries - coherent emission

Coherent emission - preliminaries

- Intensity: amplitude^2

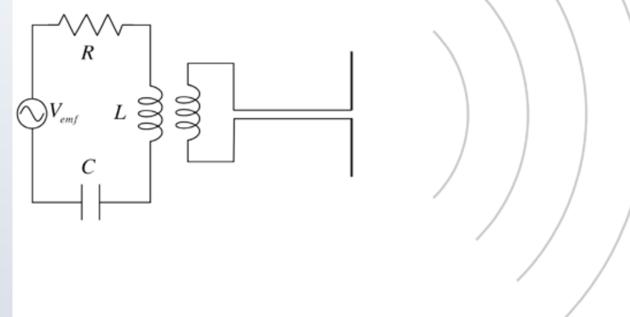


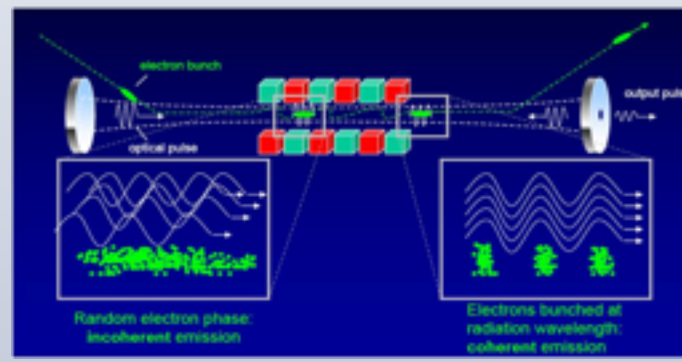
- Coherent emission:
  - Antenna mechanism (externally enforced, each particle emits independently of others - simple emission, but who is the music conductor?)
  - Plasma maser (intrinsically achieved, particles "decide" to emit together - difficult physics, no need for the conductor)

Antenna

- Antenna (curvature emission by bunches): **each particle emits on its own**. Particles do not "talk" to each other, they obey the "ultimate ruler", so that their waves add-up coherently. (E.g. deaf musicians watching a conductor.) Works well in the lab: experimentalist (like an orchestra conductor) makes special conditions, eg. the E-field driver
- Let's never again talk about **coherent curvature emission by bunches**.Yes, there are **wigglers (FELs; Goldreich-Keeley inst.).** But: generally, plasma process in astrophysics are in kinetic regime (random phase), while in laboratory in reactive regime (finely tuned, all in phase)
- Mild velocity dispersion suppresses bunching (Benford, Asseo)

Electrons in the antenna emit independently, made to do so by the driver





Narrow (in velocity) plasma beam creates non-linear density perturbations - bunches - that emit coherent curvature. In fact, beams are mostly broad, creating random-phased turbulence (if at all), not spacial coherent structures, see later

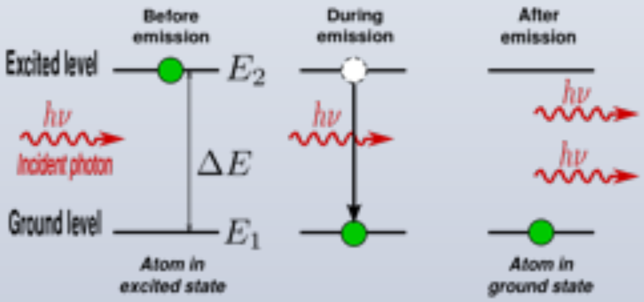
Plasma maser

- plasma has normal modes
- a particle can **resonantly** emit and absorb normal mode (need v>v_{ph} - Cherenkov!)
- emission and absorption rates is proportional to the number of waves present $n_{\mathbf{k}}$ - induced process
- a new **wave is emitted in phase** with the shaker-wave
- more particles can emit than absorb - **population inversion**
- Can be **continuous** unstable distribution
- No overall ruler/conductor
- Many (too many… ?) plasma masers

$$\omega(k)$$

$$\omega(k) - k_{\|} v_{\|} = \pm \omega_B / \gamma$$

$$\propto (1 + n_{\mathbf{k}})$$



$$E_2 - E_1 = \Delta E = h\nu$$

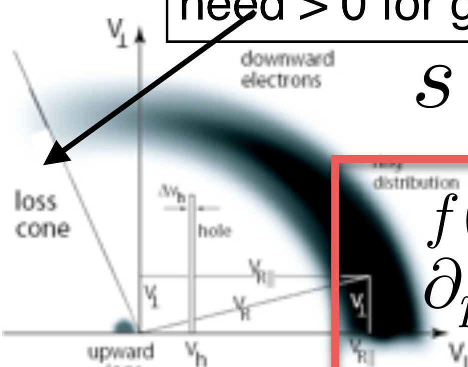
Plasma astrophysics primer: Plasma Maser.

- **Plasma maser**: non-equilibrium distribution f(p) (in momentum space, not physical space) results in coherent emission of plasma *normal modes*. **Population inversion:** there is more particles willing to emit a wave than willing to absorb it

$$\Gamma \propto \left(\frac{s\omega_B}{\gamma\beta_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel \frac{\partial}{\partial p_\parallel} \right) f(p_\parallel, p_\perp)$$

need > 0 for growth

$$s > 0$$



$$f(p_\perp) \propto \delta(p_\perp)/p_\perp$$

$$\partial_{p_\perp} f < 0$$

$$s = \Delta n < 0$$

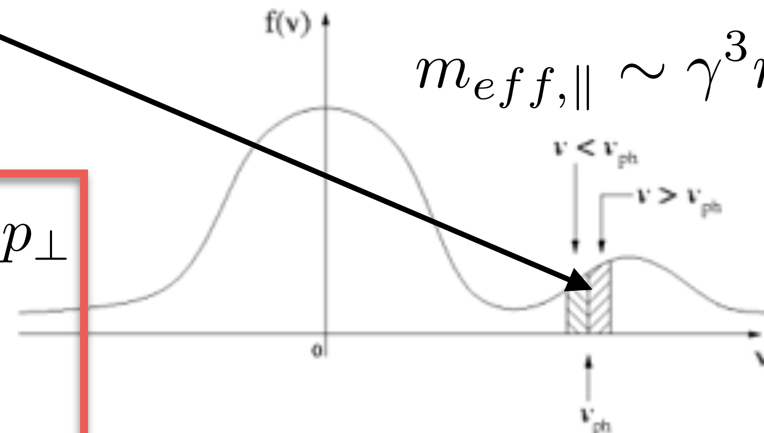
$$\epsilon = (n + 1/2)\hbar\omega_B$$

$$m_{eff,\perp} \sim \gamma m_e$$

$$s = \Delta n > 0$$

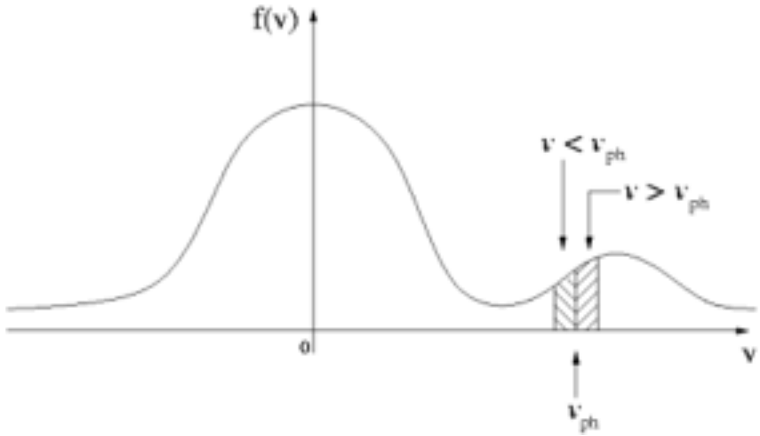
Landau levels

$$m_{eff,\parallel} \sim \gamma^3 m_e$$

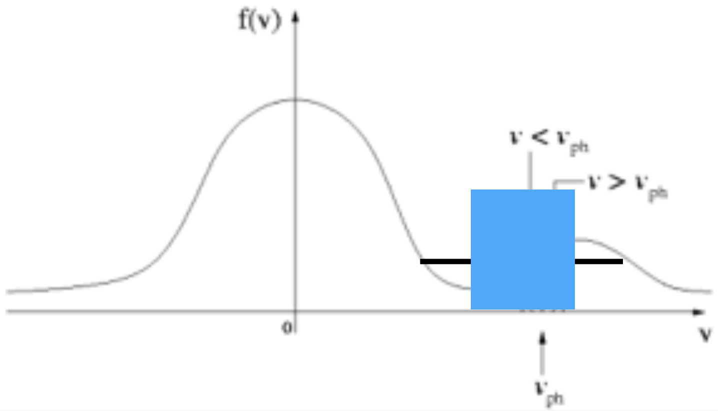


Random phase (kinetic) instabilities

- Unstable distribution



- Particles emit waves. Instability driven by +derivative -> =0



Plasma turbulence, with random phases,
no coherent structures in real space, no “bunches”

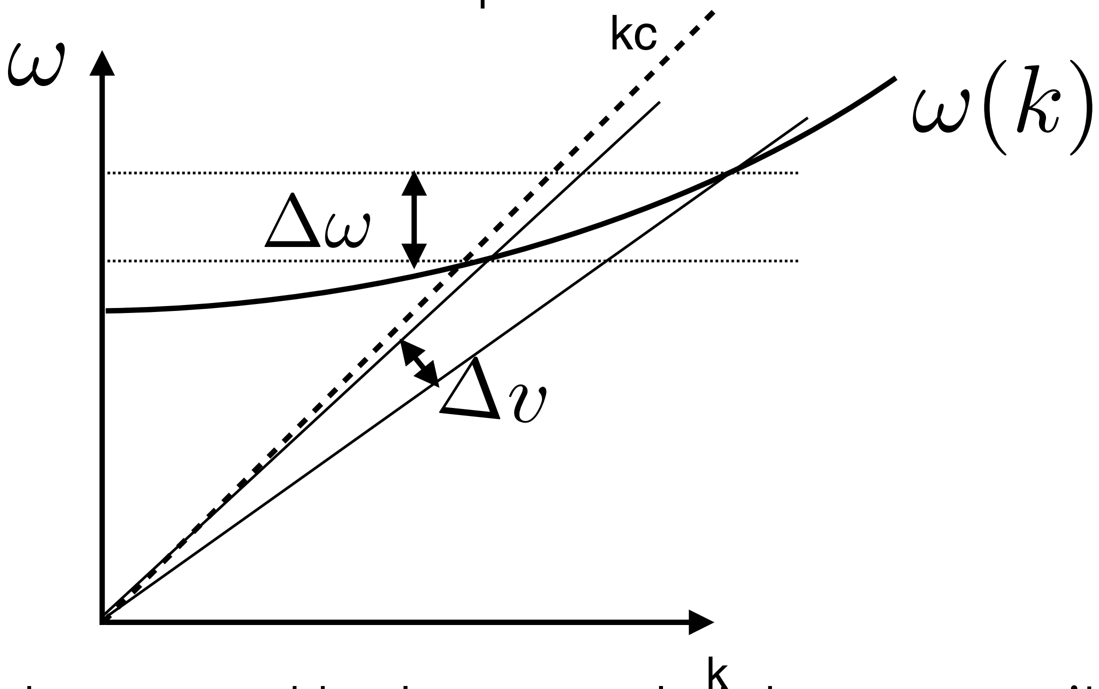
A music theory of radio emission:

- Build a guitar:
  - Guess (justify, calculate) the distribution functions f(p)
  - Find dispersion relation for normal modes $\omega(k)$
- Find a musician to play:
  - Find resonant condition - are there any resonant particles to excite the normal modes?

    $$\omega(k) - k_{\|} v_{\|} = s\omega_B/\gamma \rightarrow v_{res}$$
- Can he play well?
  - Find growth rate $\Gamma \propto \left(\frac{s\omega_B}{\gamma\beta_\perp} \frac{\partial}{\partial p_\perp} + k_{\|} \frac{\partial}{\partial p_{\|}} \right) f(p_{\|}, p_\perp)$
- Can he play loud?
  - Find saturation level (quasilinear?)
- But there no conductor to keep the rhythm - self-organization

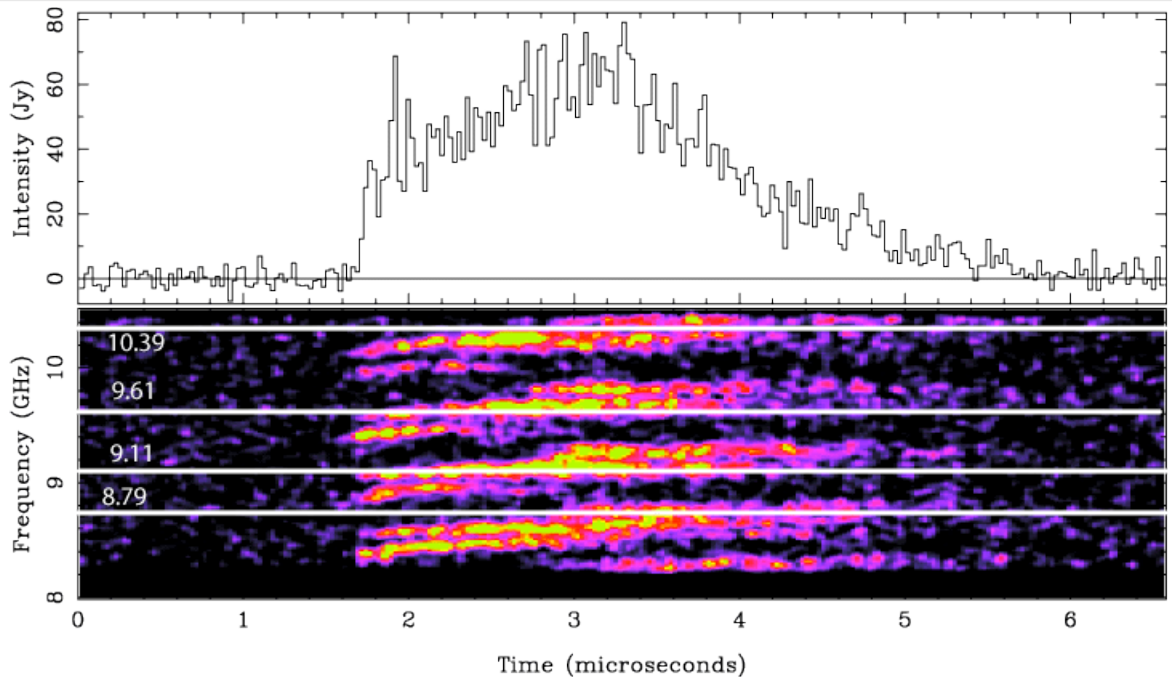
Narrow spectral features expected

- Resonances: narrow spectral features



- Can be erased by large-scale inhomogeneities in density/ B-field
- How to escape?
- How to distinguish from propagation? - nu–scaling (?)

Narrow features in pulsar spectra

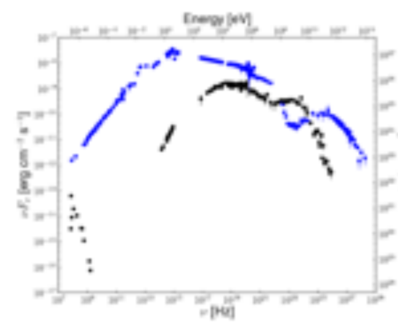


Hankins + 2003

Back to FRBs

Radio typically has very little energy

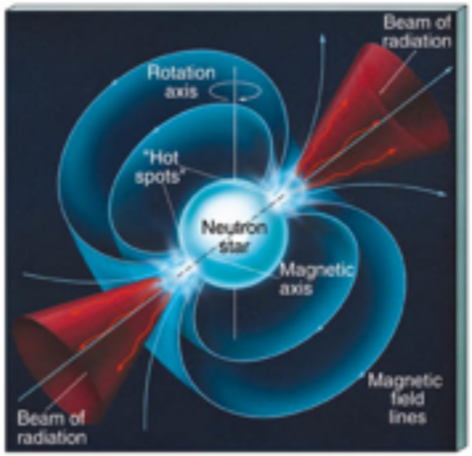
- Energy collected by all radio telescopes over half a century ~ energy of a falling snowflake.
- Walking at 1 m/sec, stop on reaction time of 100ms, convert into radio - 100 Jy FRB seen at the Moon. **Cannot compare with available mechanical energy.**
- **But:** Repeater: ~ 10^{40} erg/sec in radio - huge!
- Crab pulsar in radio - 10^{-6} of L_{sd} , 10^{32} erg/s
  - can reach 1% during Giant Pulse
  - this is a high frequency EM part of the EM power, not mechanical
- System can be in force balance (so, no pressure jumps, no shocks), yet unstable to produce radio emission, eg. due to kinetic anisotropy - can converted into radio large fraction of free energy, no "waste" on baryons, bulk motion etc



Road fork # I - msec duration. Relativistic bulk motion or intrinsic?

- Time scale $t_{ob} \sim \mathrm{msec} = \frac{\Delta r}{c} \frac{1}{2\Gamma_{bulk}^2}$, luminosity $L \propto \delta^4$
- Is $\Gamma_{bulk} \sim 1$ or $\Gamma_{bulk} \sim 10^4$?

$$\Gamma_{bulk} \sim 1$$



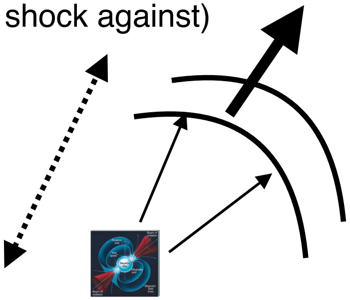
- Crab on steroids
- Solar-like radio with magnetar flares

$$\Gamma_{bulk} \sim 10^4$$

(Due to large-scale motion; Large Gamma invoked shocks - need enough material to shock against)

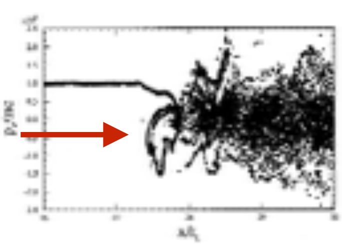
~ 10^{15}-10^{17} cm

Lots of power – needs large volume to shock



Cyclotron maser at a shock (Lyubarsky, Beloborodov)

Ring distribution



Gallant +,1992

(Lyutikov, 2016-17)

$\Gamma_{bulk} \sim 1$— NS magnetospheres

- Instantaneous luminosity for the Repeater:

$$L_{\rm iso} = 4\pi D^2(\nu F_\nu) \sim 10^{41} {\rm erg s}^{-1}$$

- duration (assume intrinsic)-> size
- Equipartition B-field:

$$B_{eq} = \sqrt{8\pi}\frac{\sqrt{\nu F_\nu} D}{c^{3/2}\tau} = 3\times 10^8 \tau_{-3}^{-1} \text{ G}$$

(Large gamma within magnetosphere: similar B-field to collimate a beam)

- **NS magnetospheres!** (Clean, relativistic)
  - Stellar-mass BHs (?) - accretion-supplied B-field is dirty.
  - WD magnetosphere(?)

Also: the non-linearity parameter “a”

- EM non-linearity parameter

$$a = \frac{eE}{m_e c\omega} \approx 10^5 \gg 1$$

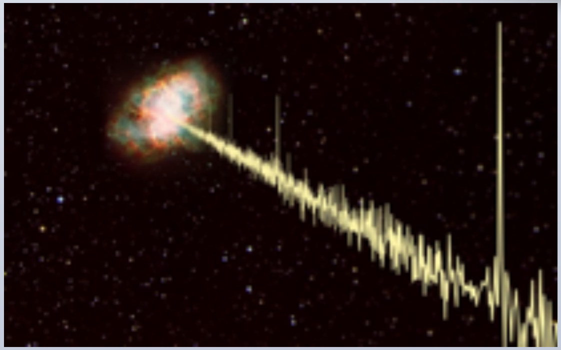
- If no B: $\gamma \sim a$ huge radiative losses (eg. induced Compton)
- Actually, ExB drift, so

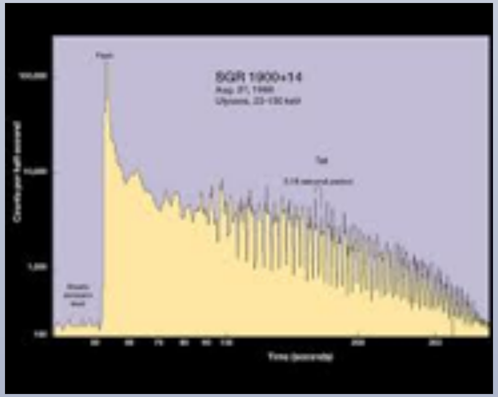
$$a = \frac{eE}{m_e c\omega_B} \leq 1$$

(so, emission from magnetosphere is not self-contradictory)

Road fork # II - giant pulses vs magnetar flares

- We are not yet in a position to construct **microscopic** models of radio emission
- we are left only to discuss the **macroscopic** limitations





- Model I: Giant pulses, Crab on steroids, rotationally powered – theoretical limitations

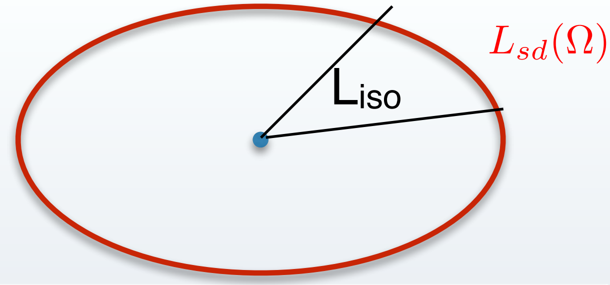
- Model II (hypothetical): magnetar flares, magnetically powered – observational limitations

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)

It was a good model, but not from ~ 1 Gpc



- Radio power L_{iso} cannot be larger than the spin-down (must be magnetospheric, hard to store much more energy in the magnetosphere)

$$\nu F_\nu = \eta \frac{L_{sd}}{4\pi D^2}$$

The most powerful Crab's GP have eta = 10^{-2}

- Need high B - short P (at least few msec)

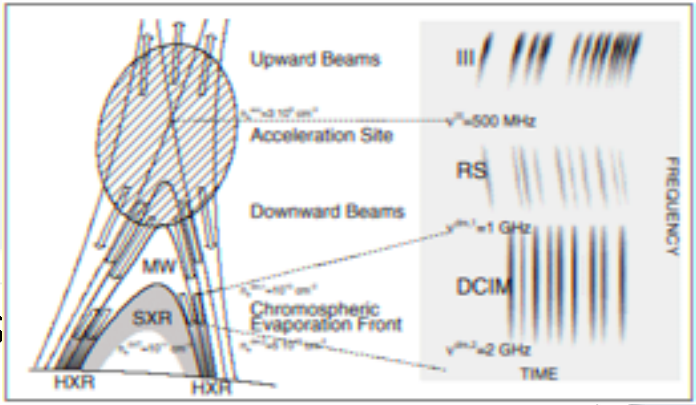
$$\tau_{SD} = \eta \frac{\pi I_{NS}}{2D^2 \nu F_\nu P_{min}^2} \approx 600\, \eta\, \mathrm{yrs}$$

For Crab: 6 yrs if all in GPs
FRB 160102 could be even worth

- Constant DM: t >100 yrs
- eta ~ 1 + 1 msec spin at birth + 100 yrs< age < 600 yrs - NO.

Repeating FRB at 1 Gpc + constant large DM excludes rotationally powered emission

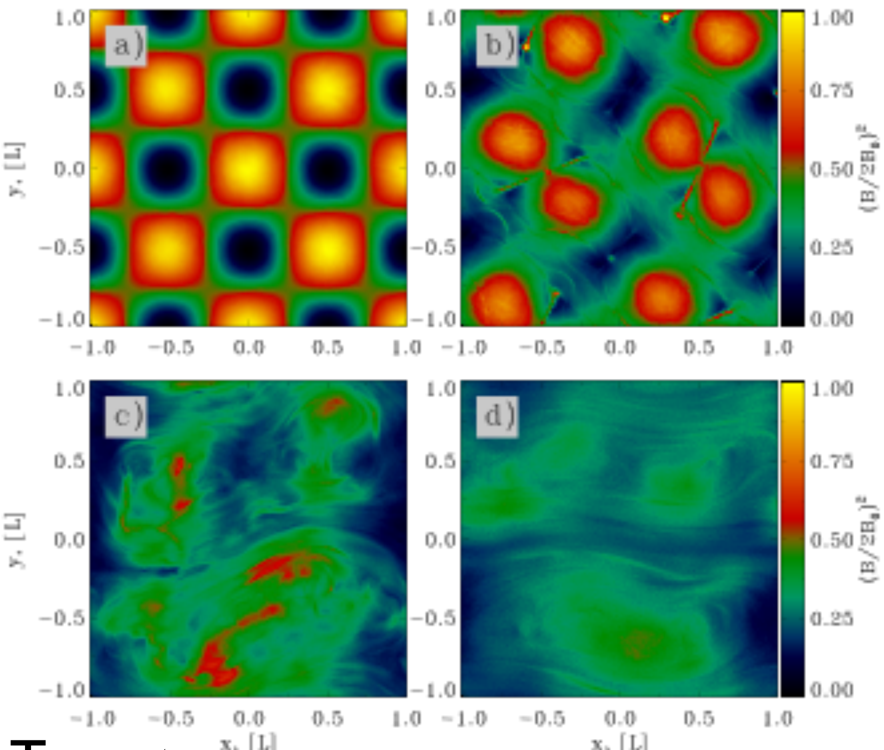
Macroscopic Model II: magnetar flares (type-iii)

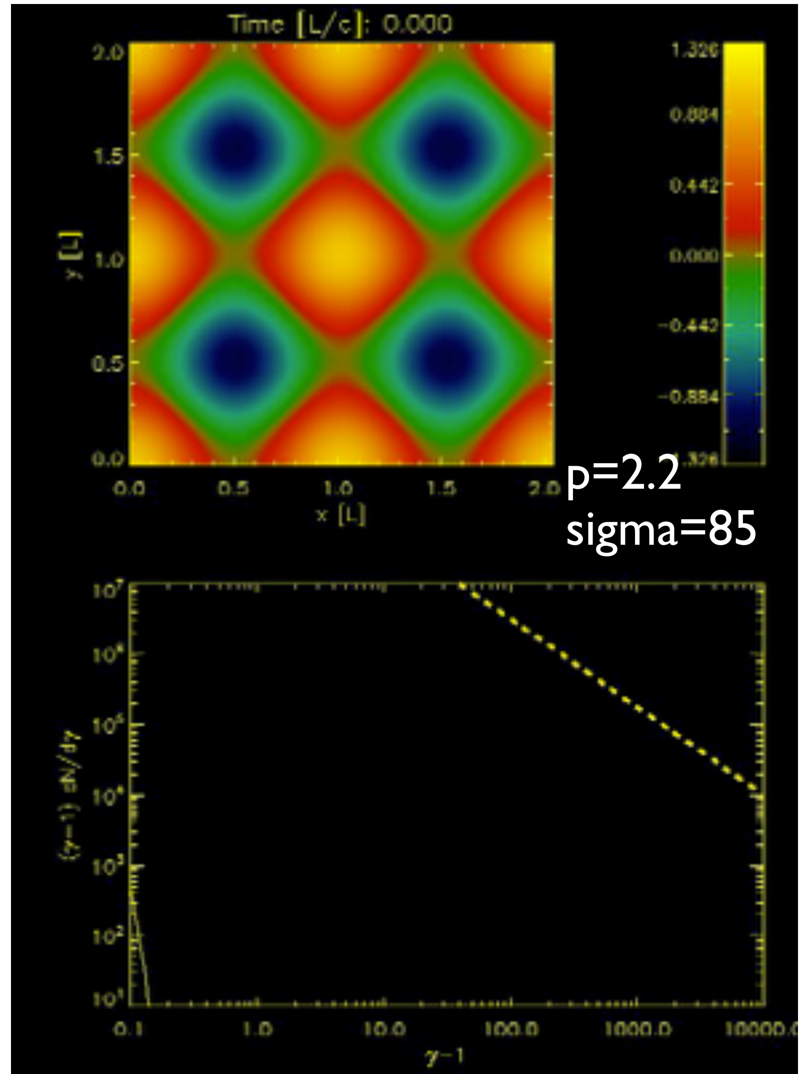


- Solar type-III radio emission in magnetars (Lyutikov 2006)
- **Initial** stage of a "reconnection flare" - jets of particles, hence coherent emission - like Crab flares (Lyutikov et al. 2016)
- Best case - observe radio burst associated with magnetar burst and flares.
- Constraining limits from SGR 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})

Collapse of an ABC system of magnetic islands

Lyutikov+ 2017



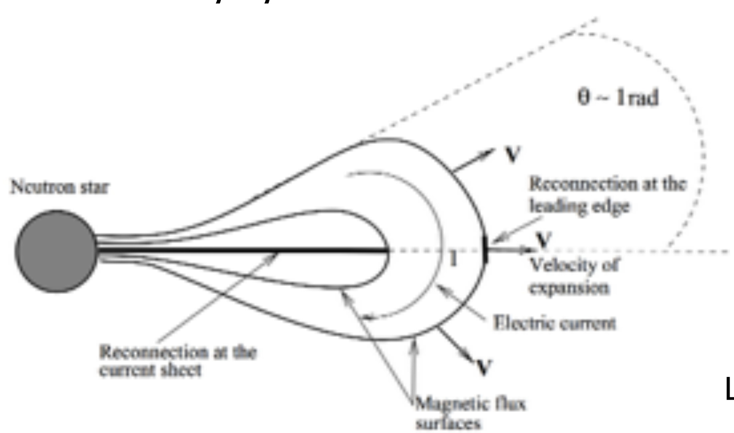


p=2.2
sigma=85

Two stages:
- Fast acceleration, not much B-field dissipated (X-point collapse)
- Slower acceleration, dissipation (island merger)

Best hope: other wavebands

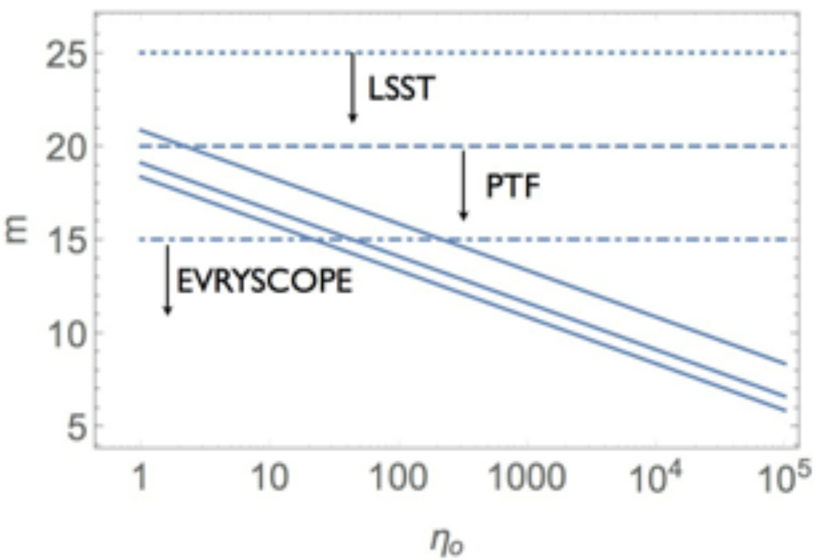
- Radio: > 10^{40} erg/s   for flat (νF_{ν})
- **Optical > 10^{45} erg/s**
- X-rays> 10^{50} erg/s, GRB-like rates - not correct
- All sky X-rays monitors can see magnetar-type flare to ~ 40 Mpc, but targeted observation (eg. of the Repeating FRB) can detect weaker
- Afterglows: jetted magnetar post- burst outflows (Keane 2016, Lyutikov 2006)?)



Lyutikov 2006

Counter-part strategy: optical

Lyutikov & Lorimer 2016



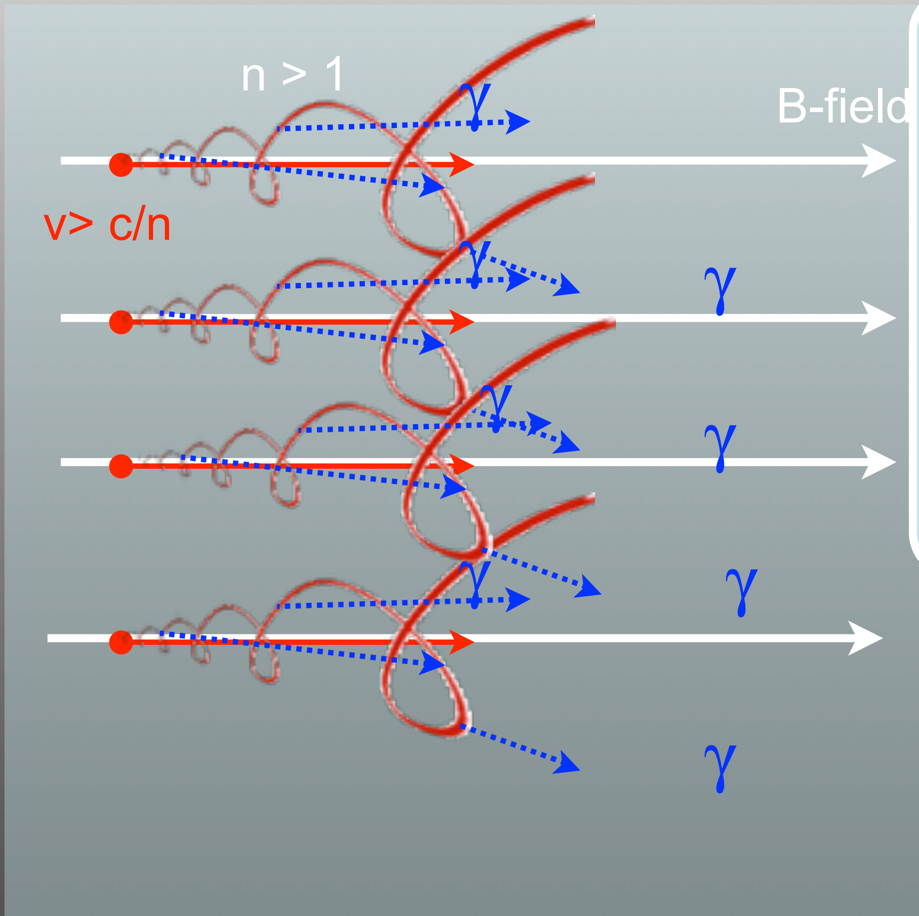
- Optical energetics >> radio (If !)
- Peak flux ~ 9m (but only for few msec - fast read-outs!)
- m~ 15 image in 60 sec PTF, ASAS-SN, EVRYSCOPE (LSST!) - PTF might have seen, as star-like points in single exposure.
- Optical would look at FRB every ~ 10 hours (10 sq. degrees field of view)
- fast readout is good
- **Radio and optical - stare at the same patch**
- For The Repeater, the optical power is in the 10^{45} erg/sec
- Multi-frequency radio (triggered LOFAR obs.)

Conclusion

- Amazingly, radio power (+ constant DM and non-changing properties of The Repeater) puts energetic limits on the **type** of emission (rotationally vs magnetically powered; does not yet constrain particular instability that drives radio emission). Neither looks too promising for now.
- Perhaps there is some slack left in either:
  - Highly non-stationary processes in pulsar outer magnetospheres
  - Explosive reconnection events in magnetar magnetospheres - can they generate unstable distributions and radio bursts?

My favorite pulsar radio emission mechanism

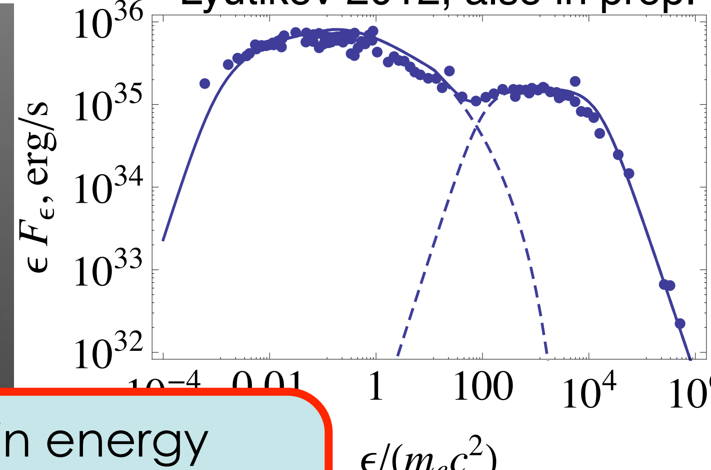
What excites gyration: anomalous cyclotron resonance



- A particle can emit a cyclotron photon with no initial gyration

$$\omega - k_{\|} v_{\|} = -\omega_B / \gamma$$

- Particle goes **up** in Landau levels **and** emits a photon - radio
- Spontaneous **down** cyclotron boosted in UV-X-rays
- IC - VHE gamma rays

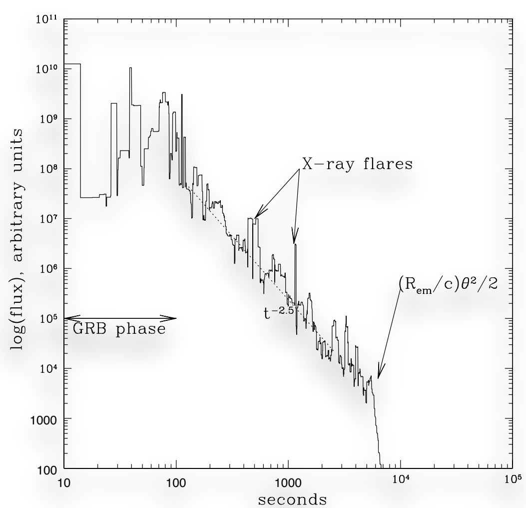


From ~100 MHz to ~ 2 TeV - 20 orders in energy

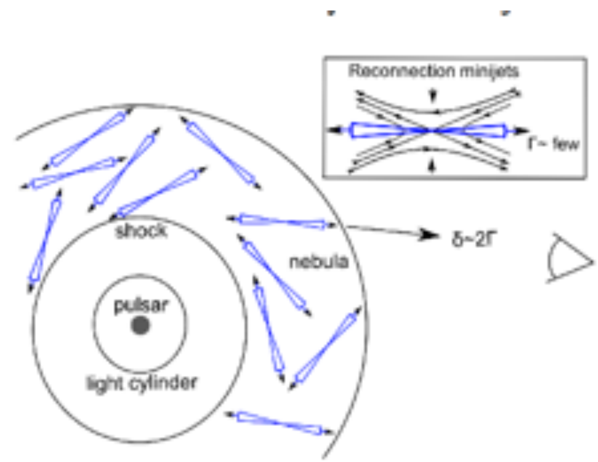
Relativistic reconnection, kinetic beaming - Sterl's talk

- There is a paradigm shift in high energy astrophysics - acceleration in reconnection events (no shocks) - Crab nebula flares.
- Reconnection mini-jets
- Kinetic beaming, but, like in pulsars – what is the coherence mechanism?

$$\Gamma_{eff} \sim 2\Gamma\gamma_j$$



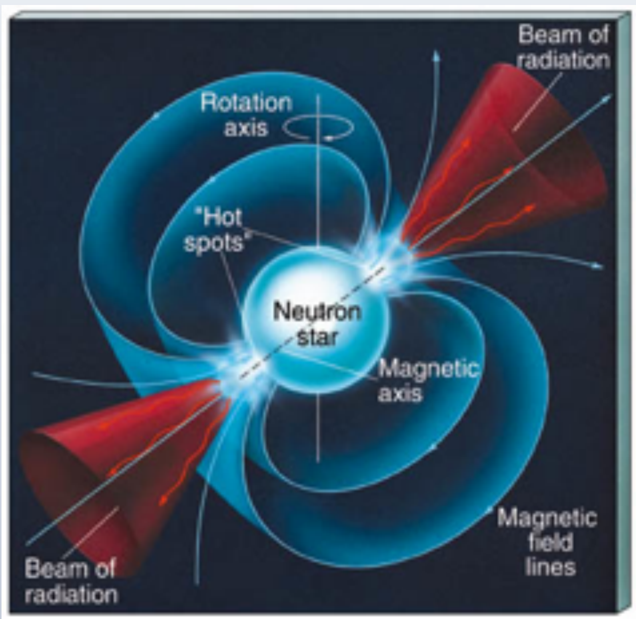
Lyutikov 2006



Clausen-Brown & Lyutikov 2012

Is $\Gamma_{bulk} \sim 1$ or $\Gamma_{bulk} \sim 10^4$?

$\Gamma_{bulk} \sim 1$



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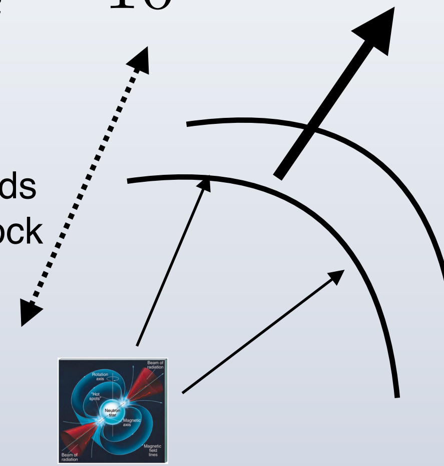
- Solar-like radio with magnetar flares

$\Gamma_{bulk} \sim 10^4$

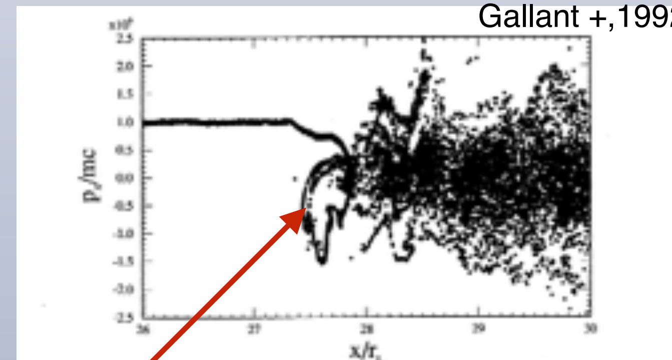
~ 10^{15}-10^{17} cm

Lots of power – needs large volume to shock



Cyclotron maser at a shock (Lyubarsky, Beloborodov)

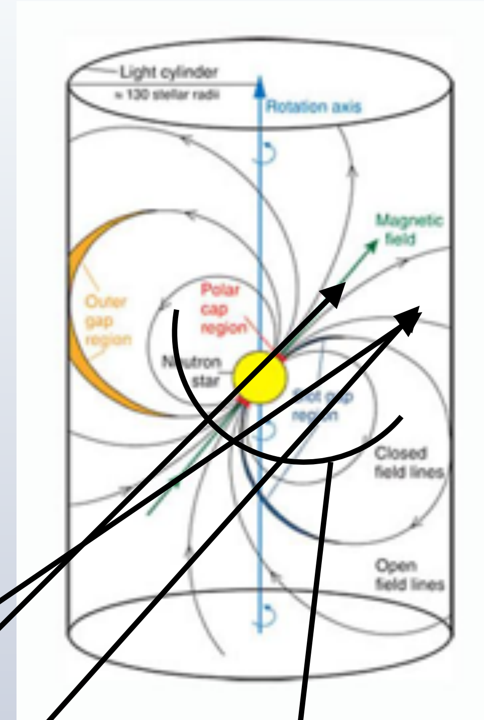
Gallant +,1992

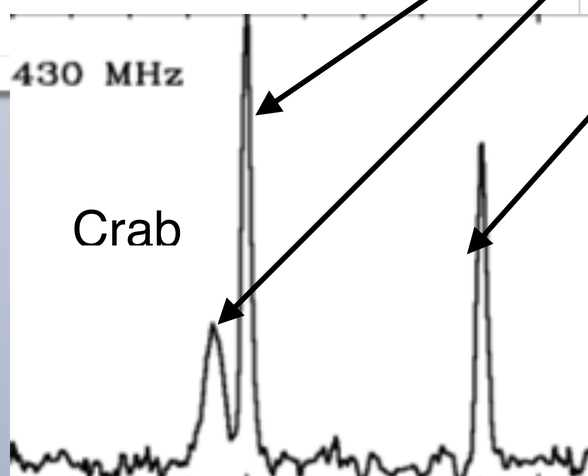


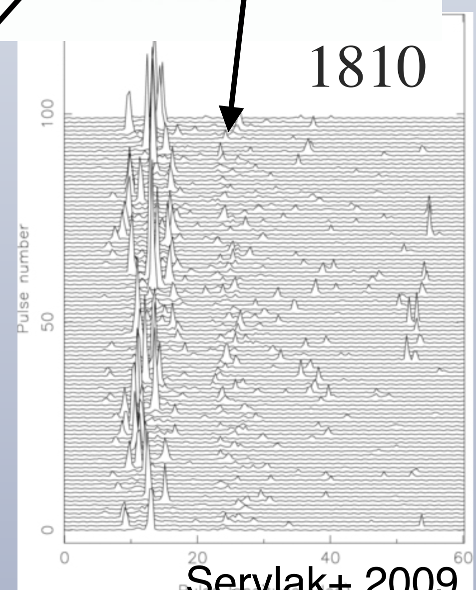
Ring distribution

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
  - Type III: magnetars, on close field lines, crustal shear-driven (reconnection, ~ Solar)







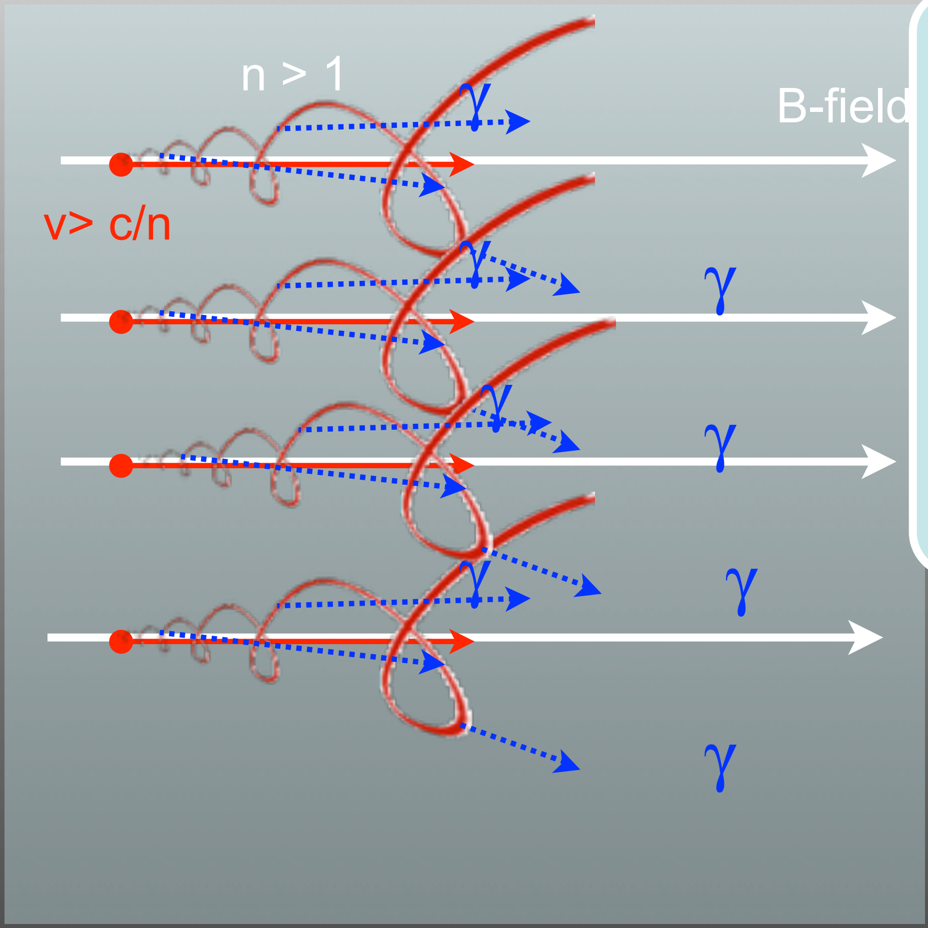
Serylak+ 2009

Glitches?

- There are no bright EM signals with glitches
- Magnetospheric changes are tiny, 10^{-6}
- Time scales - crustal shear ~ 100 msec (for ~ msec time scale the energy must be stored in the magnetosphere).

- **Juste pour rire/just for laughs, let's make a glitch FRB model**
  - Imagine you are walking at 1 m/sec. And then, "suddenly" a glitch: on human reaction time of 100 msec, you change your speed by 10^{-6} to (1 m - micrometer)/sec. And then you convert all that energy into radio waves at 1 GHz.
  - Boom! - Mega-Jy signal 3 km away!
- This is obviously ridiculous, but astrophysically, scaling "this with that", it makes sense, right?
- Not for radio (could be OK for high energy)
- (Mechanical to radio vs EM to radio)

What excites gyration: anomalous cyclotron resonance



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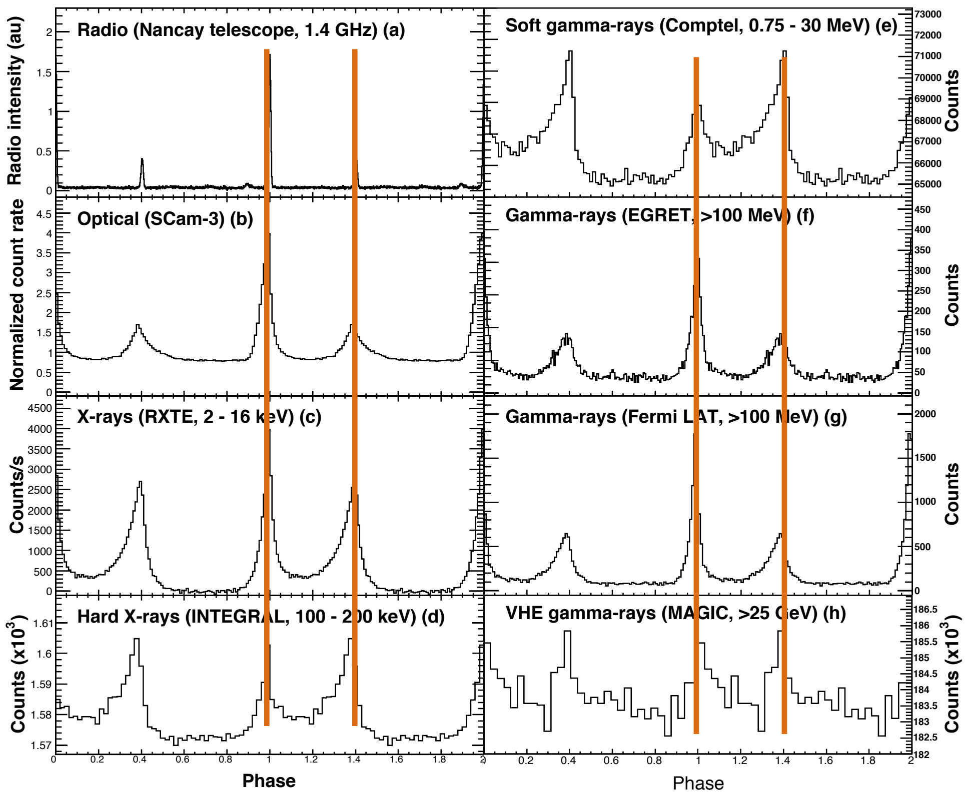
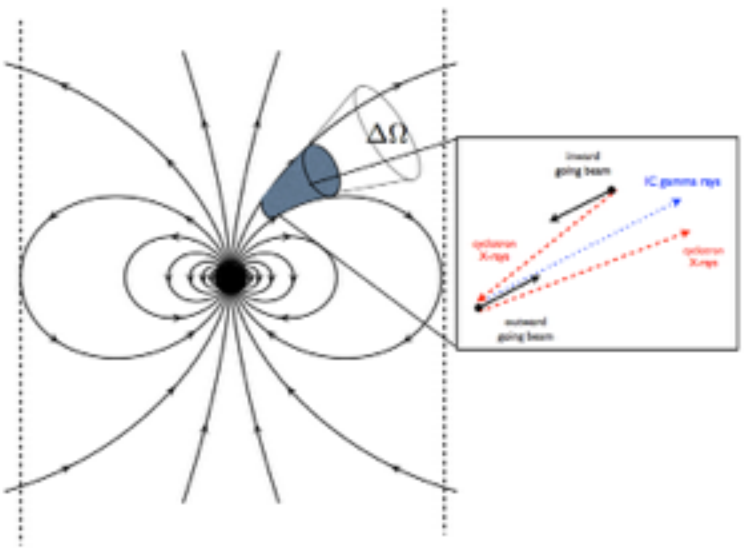
Observational constraints on FRB emission mechanisms

- > 10^4 per day (not prompt GRBs)
- repetitive (not catastrophic events like NS-NS mergers)
- isotropic (extra-Galactic); D ~ 1 Gpc - (cosmological)
- coherent emission, $T_b \approx 10^{34}\,\mathrm{K}$
- DM is constant to ~ % over few years
- Polarization is messy
- Very unfortunately, there is no clear evidence for two different populations

Crab





Aligned from radio to VHE gamma - common origin