Whence to FRB

Maxim Lyutikov (Purdue University)

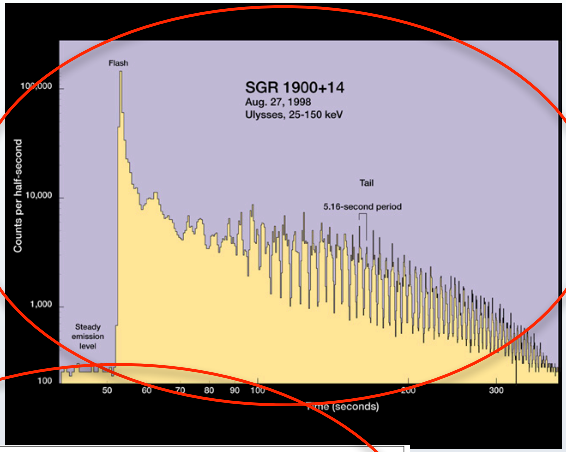
Outline

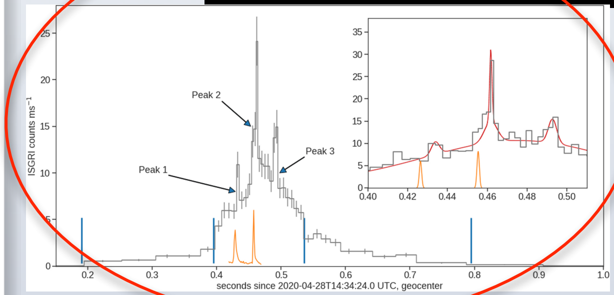
- **Where from:** magnetospheres of magnetars
  - long list of confirmed predictions
- **Global dynamics:**
  - "star-quake" versus "Solar flare"
  - **"rare big" vs "many small" flares**
  - more prediction: very particular, unusual polarization properties
- **How:** Free Electron Laser
  - parametric instability: not "antenna", not "plasma laser"
  - ~ threshold to work

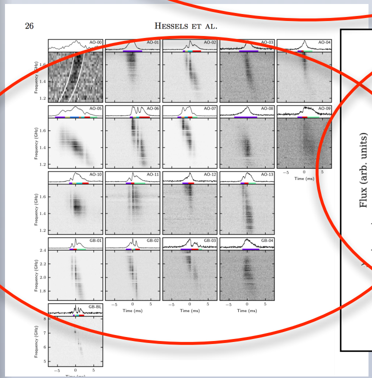
1. Where from? - Magnetospheres

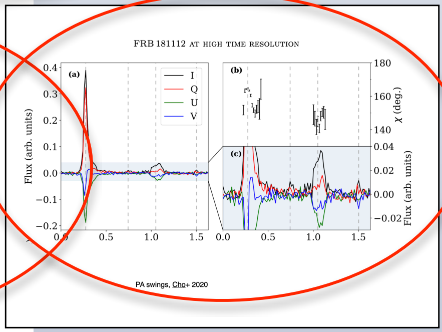
FRBs are magnetospheric

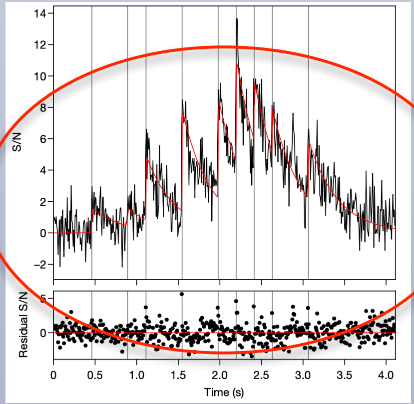
- All!(?) observations are consistent with magnetospheric origin of FRBs
    - Temporal coincidence X-ray-radio/ magnetar association
    - Radio leads X-ray
    - frequency drifts (both the rate and the range are consistent with magnetospheric origin)
    - PA swings
    - periodicity
    - micro-nano structure
- Most predicted and confirmed (to various degrees)

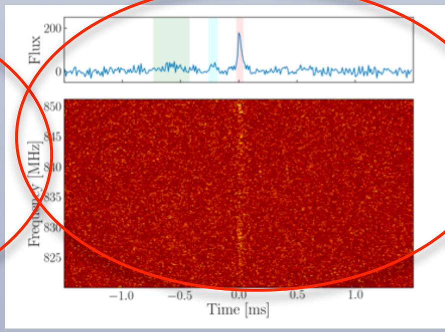












Magnetar/FRB predictions

RADIO EMISSION FROM MAGNETARS

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ABSTRACT

We discuss properties of the expected radio emission from soft gamma-ray repeaters (SGRs) during their bursting activity in the framework of the model of Thompson, Lyutikov, & Kulkarni, in which the high-energy emission is powered by the dissipation of superstrong magnetic fields in the magnetospheres through reconnection-type events. Drawing on analogies with solar flares, we predict that coherent radio emission resembling solar type III radio bursts may be emitted in SGRs during X-ray bursts. The radio emission should have correlated pulse profiles with X-rays, a narrowband-type radio spectrum with $\Delta\nu \leq \nu$, with the typical frequency $\nu \geq 10$ GHz, and, possibly, a drifting central frequency. We encourage sensitive radio observations of SGRs during the bursting activity.

That's a lot of confirmed predictions for a small paper

Lyutikov + 2016

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 (lower limit):

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

- NS magnetospheres: clean, relativistic, known to produce coherent radio
- X-ray energetics: about a football field of energy near the surface to produce regular X-ray burst of 10^{41} ergs
- Radio — X-ray time-alignment of few msec: radio is also generated relatively close to the NS's surface, at ≤ 10^8 cm (not far out)
- FRB duration:
  - **lateral** extent of the emission region (not radial)
  - peaks as short as nano-second substructure $R_{NS}/\gamma^2 \sim {\rm nano-seconds}$
- Periodicity

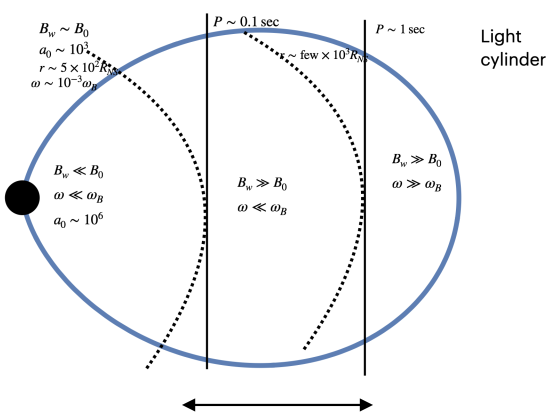
Production and escape condition

- Large B-field **is needed** to kill "normal'' loses
- Laser intensity parameter "a₀" $a_0 \equiv \frac{eE'}{2\pi m_e c\nu'} = \frac{e\sqrt{\nu k_B T_b}}{m_e c^{5/2}\delta} > 3\times 10^5$

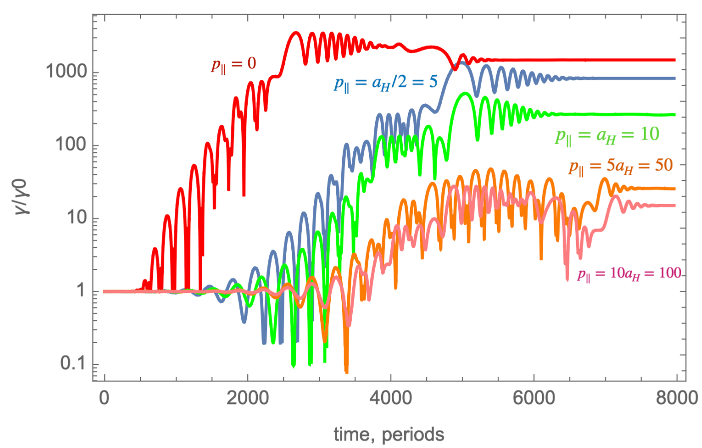
- (most powerful lasers can get to $a_0 \sim 100$)
- If no B-field: $\gamma \sim a_0$ huge radiative "normal" loses
- In B-field: if $\omega_B \geq \omega$ slow drift with E_w/B_0

Large B-fields are required to avoid catastrophic "normal" loses at origin

- **Escape** from magnetosphere: Problems appear only if P> 0.1 sec
- $a_0 \sim 10^6$ near the star, $a_0 \sim 10^3$ where $B_w \sim B_0$ - half problem solved
- Polarization (O-mode), mild $p_{\parallel} \sim$ few further decrease absorption



region of possible problems



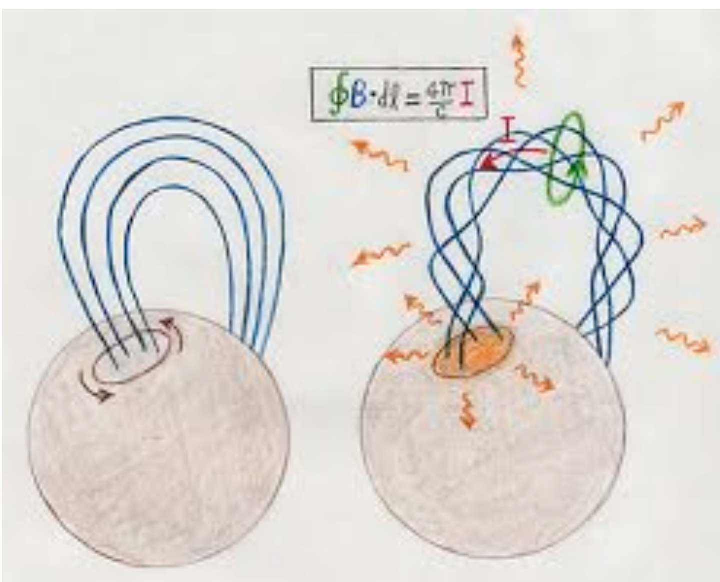
$\gamma \sim 10^3 \rightarrow \gamma \sim 10$

2. Global dynamics: star-quake vs Solar flare

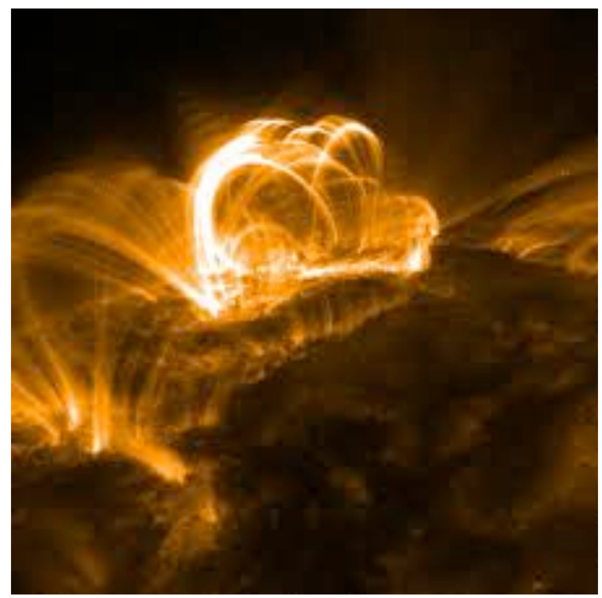
How magnetars work: Star-quakes vs Solar flares

- Thom
  shear
  - m
    c
  - su
  - dissipation in the magnetosphere
  - Needs crust to crack

- Need powerful source:
  - Rotational?: NO (Repeater stays the same for too long - no spindown)
  - **Magnetic**

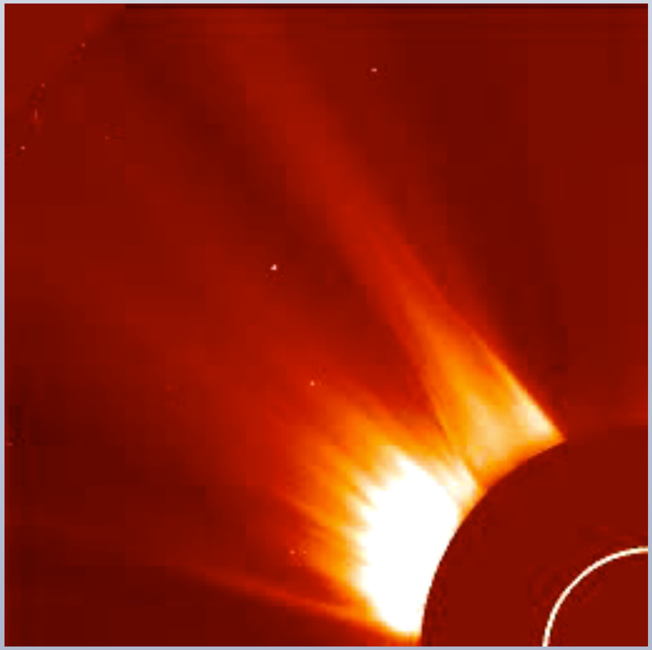


- ven time
- elds twists
- dissipation in the magnetosphere
- Crust can respond plastically (or can be infinitely rigid)



“Solar physics of magnetars” (and FRBs)

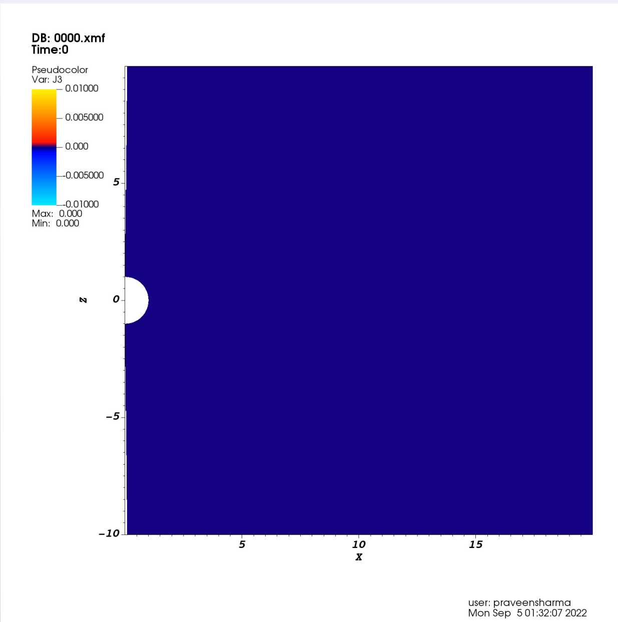
- “Solar Physics of Magnetars” (Lyutikov 2002, 2006)
- Burst and flares are magnetospheric events (not starquakes)
- All data are consistent with magnetospheric origin of FRBs in magnetars (Popov & Postnov 2007, Lyutikov & Popov 2020)

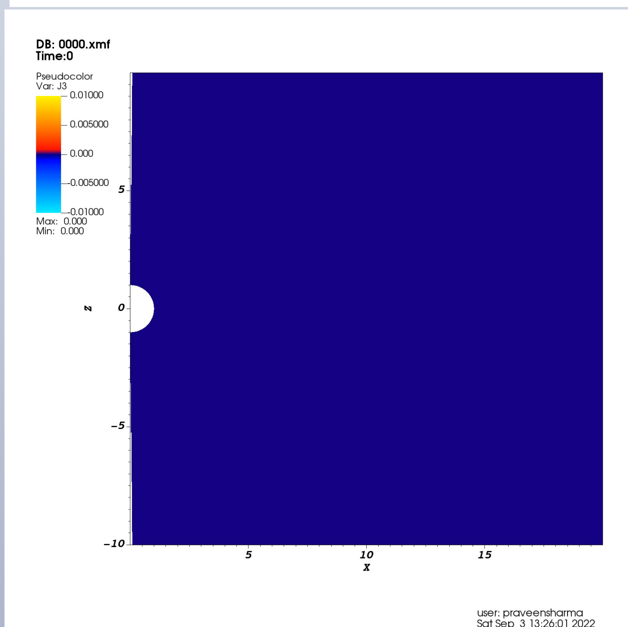


- Slow evolution (~AXP)
- Explosive stage (SGR)
- Type-I-II-III-IV-V radio emission
- Ejections of a CME
- All seen in magnetars

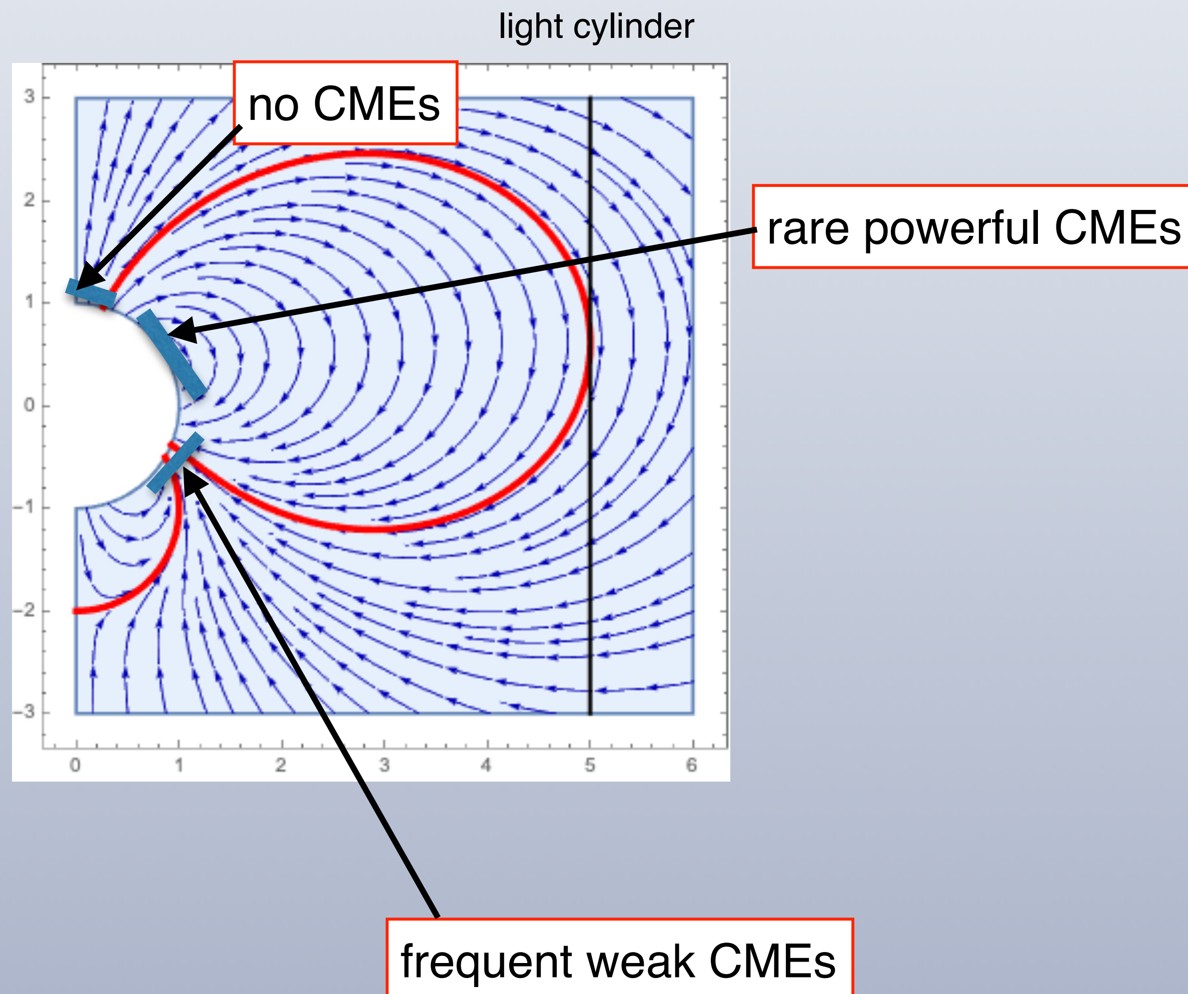
Rare and big versus numerous and small

Magnetar's Coronal Mass Ejection (CMEs) by shearing footpoints





Dipole + quadrupole: same magnetic structure, different shearing location



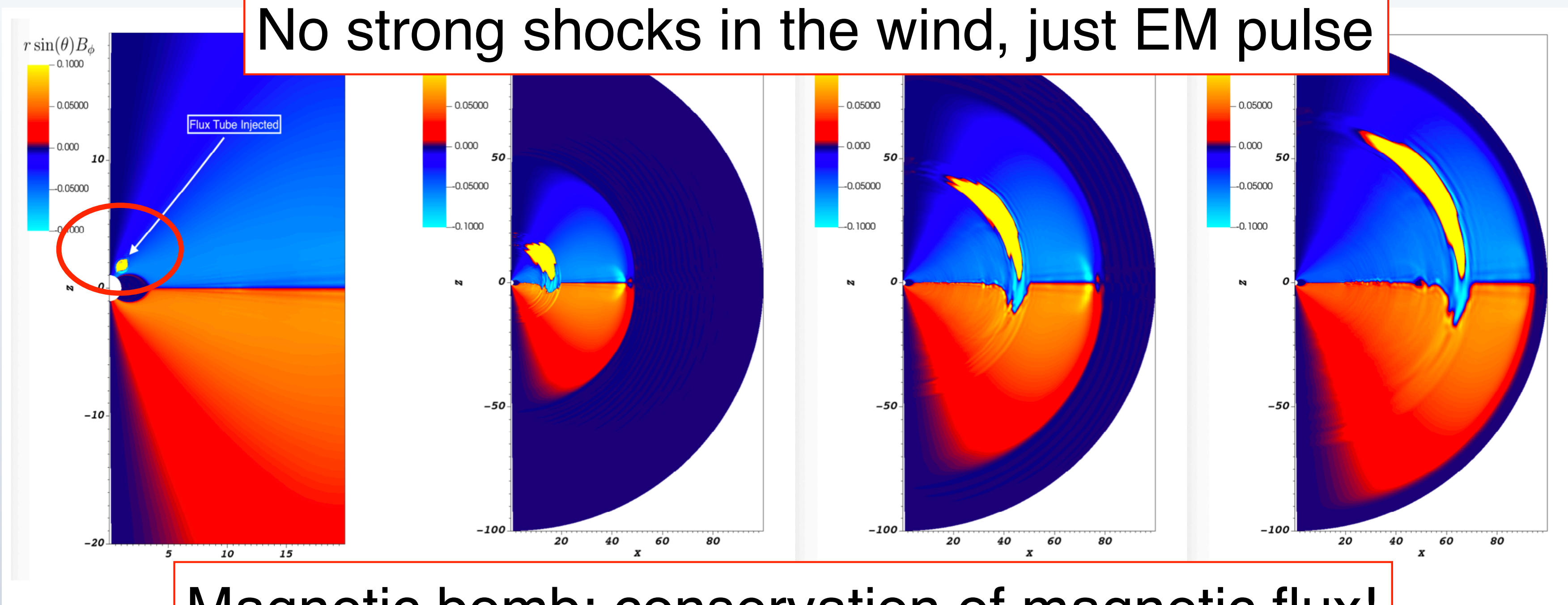
“Plenty of Room at the Bottom”

- Solar flares paradigm. What matters are:
  - size of active region
  - value of B-field (naturally, $E \sim B^2 R^3$)
  - Hall shearing rate ~ B (small rate relaxes)
- location of shear
  - do field lines extend far out? - if yes, then small flares (twist concentrates near smallest B-field)
  - Period - long P harder to break out (when the top of the arc reaches the light cylinder the twist relaxes)

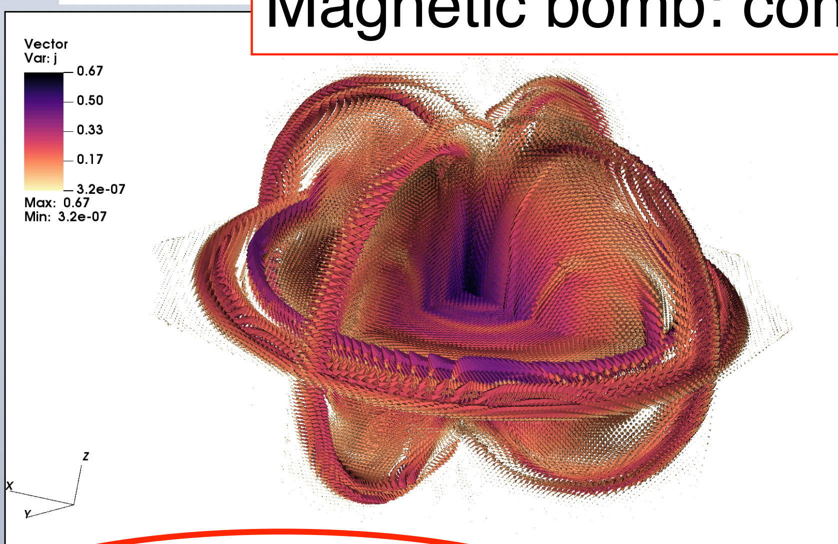
CMEs in the wind

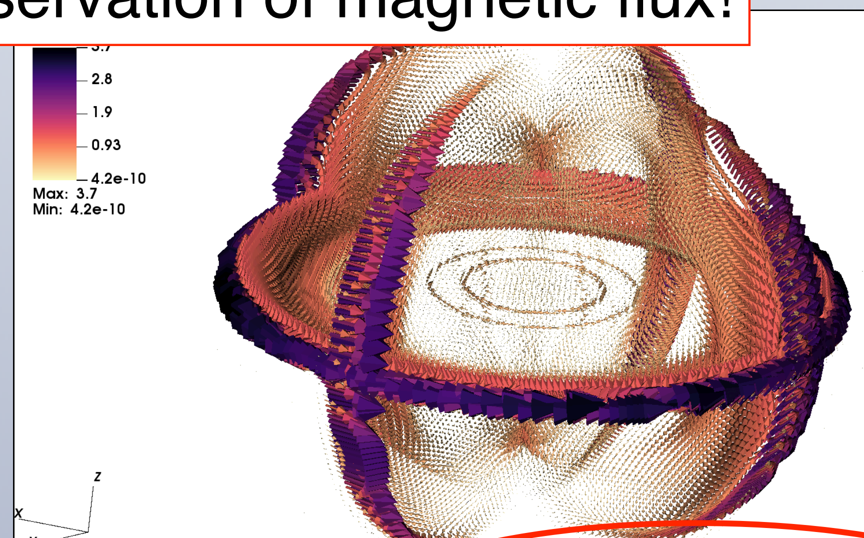
Lyutikov 2022
Barkov+ 2022

No strong shocks in the wind, just EM pulse



Magnetic bomb: conservation of magnetic flux!





puff-up, slowly expands
(filled-in structure)

$$E_0 \frac{R_0}{R_{LC}} \gg B_{LC}^2 R_{LC}^3$$

detonates
(magnetic shell)

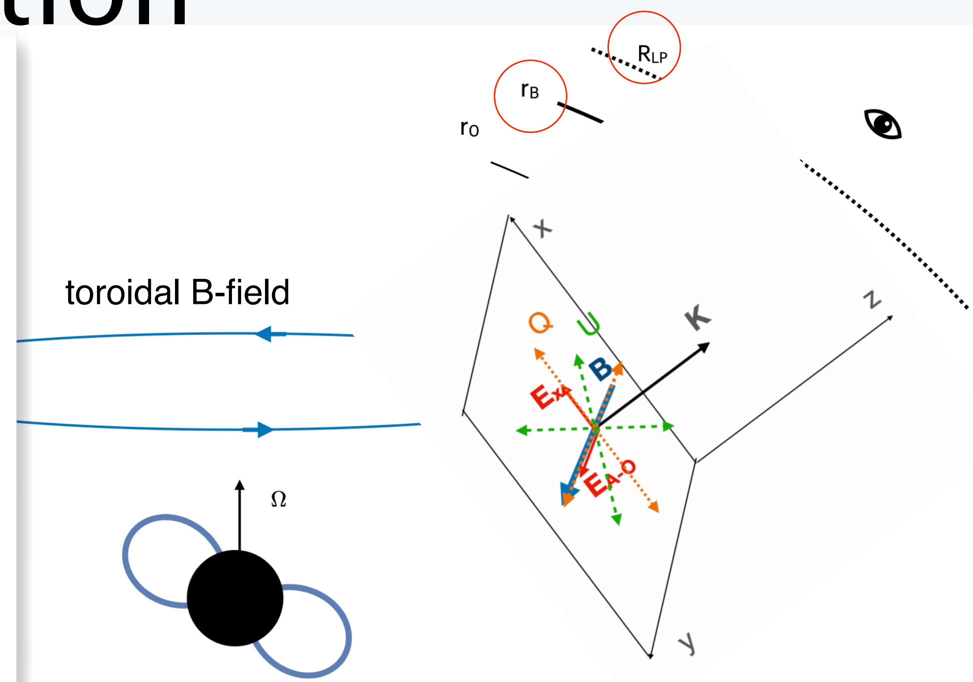
Prediction - Polarization Evolution

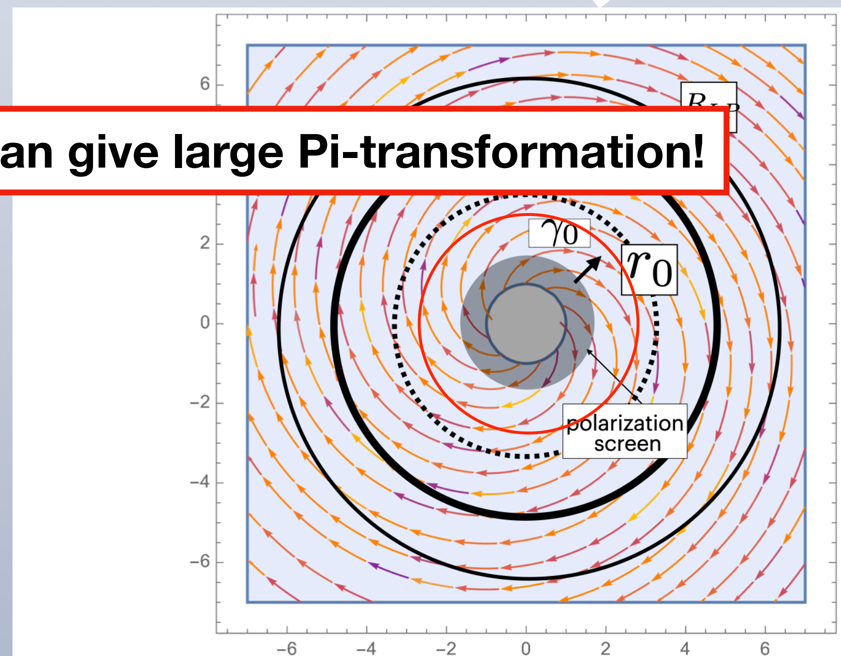
Polarization

Lyutikov 2022

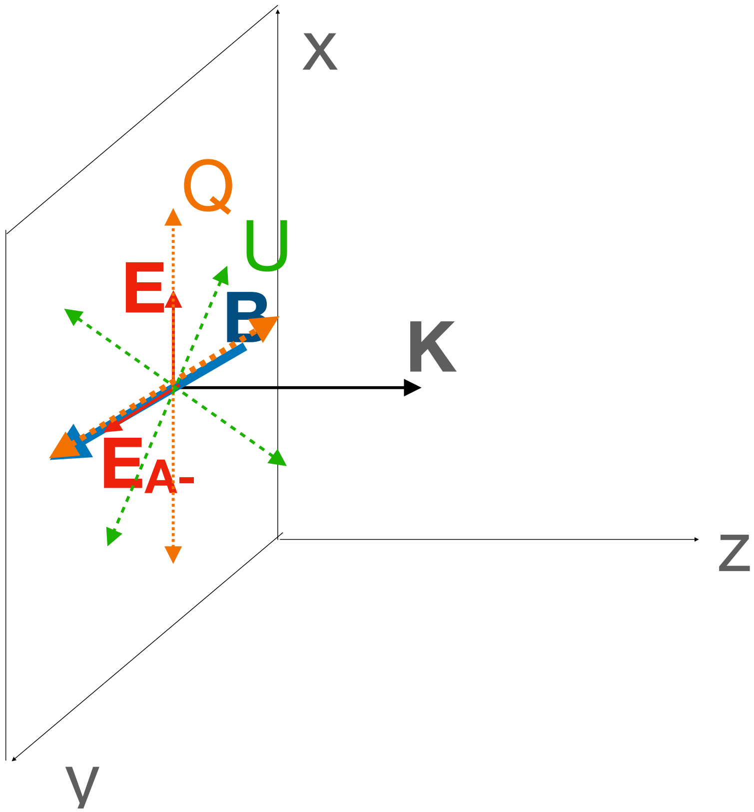
- Petroff + 2019 "some FRBs appear to be completely unpolarized, some show only circular polarization, some show only linear polarization, and some show both"
  - RM ~ 10^5, with large fluctuations and changing sign
  - changing sign of V
  - on short times
- Large $\Delta\chi$: Cotton-Mutton $\Delta n_{O-X}, \theta \neq 0$ (not Faraday), a B^2 effect
- sr[illegible] LC
- Polarization: non-standard $RM \propto \lambda^{\alpha}, \alpha \neq 2$
- at small rotation angles $\alpha = 2$
- Large Circular, large RM, with changing sign!

Pair plasma screen of DM= 10^{-6} pc cm^{-3} can give large Pi-transformation!



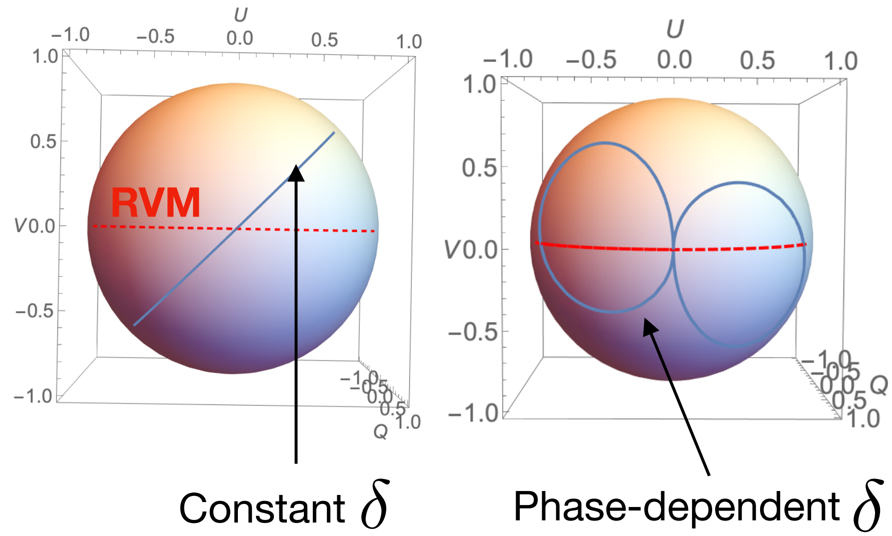


RVM+ Π-conversion



$$\partial_z \hat{P} = \mathbf{\Omega} \times \hat{P}$$

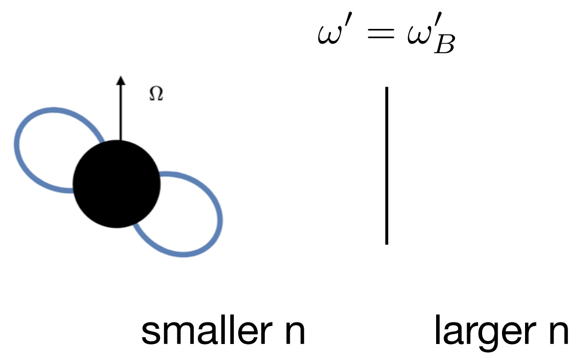
$$\mathbf{\Omega} = \{\partial_z \delta, 0, 0\} \to \{2\frac{\omega_p^2}{\omega c}, 0, 0\}$$



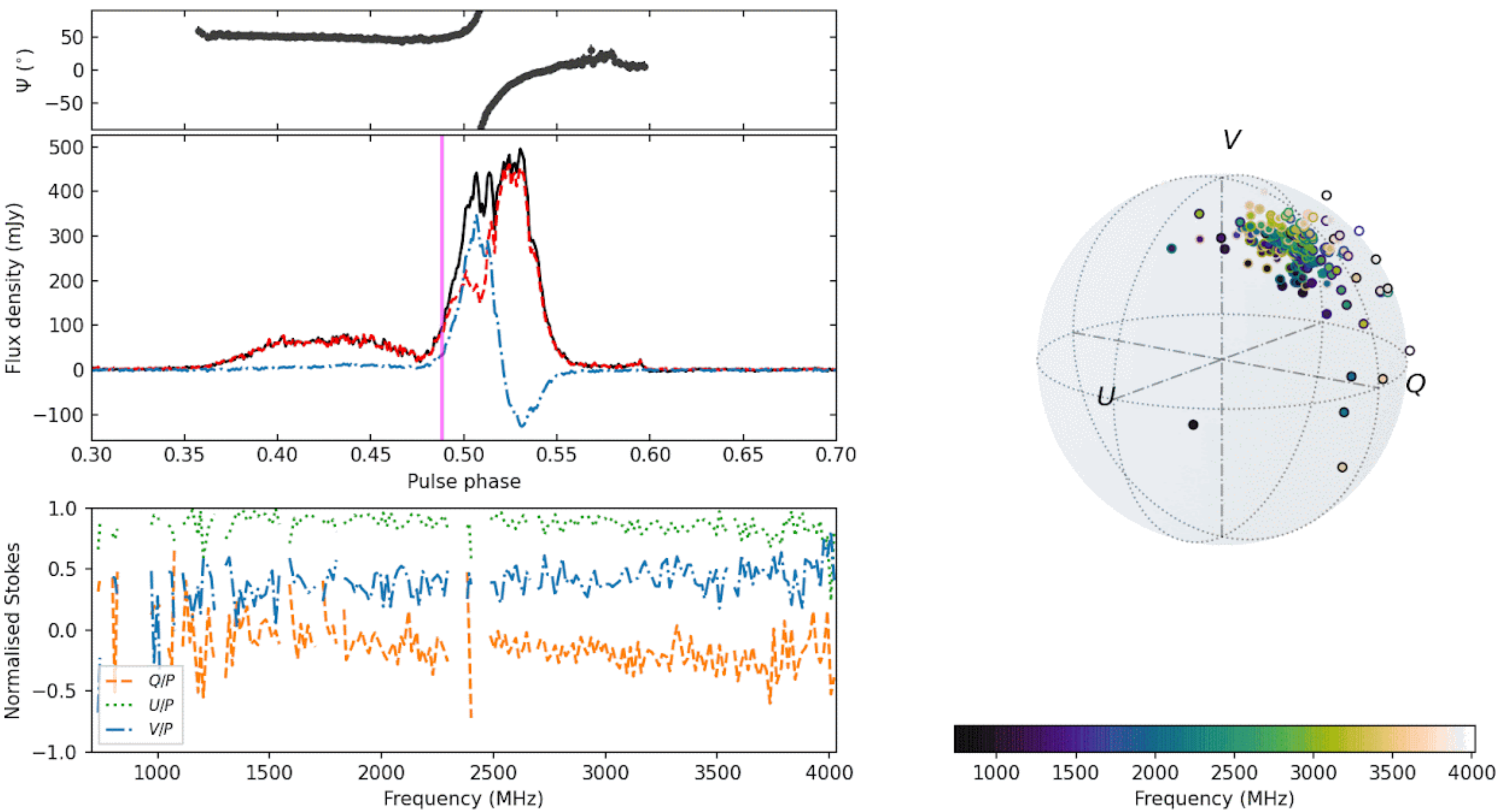
Faraday conversion near cyclotron resonance in the wind

$(\Delta n) \sim 2\frac{\omega_B^2 \omega_p^2}{\omega^2(\omega^2 - \omega_B^2)}$ Large/huge contribution near the resonance

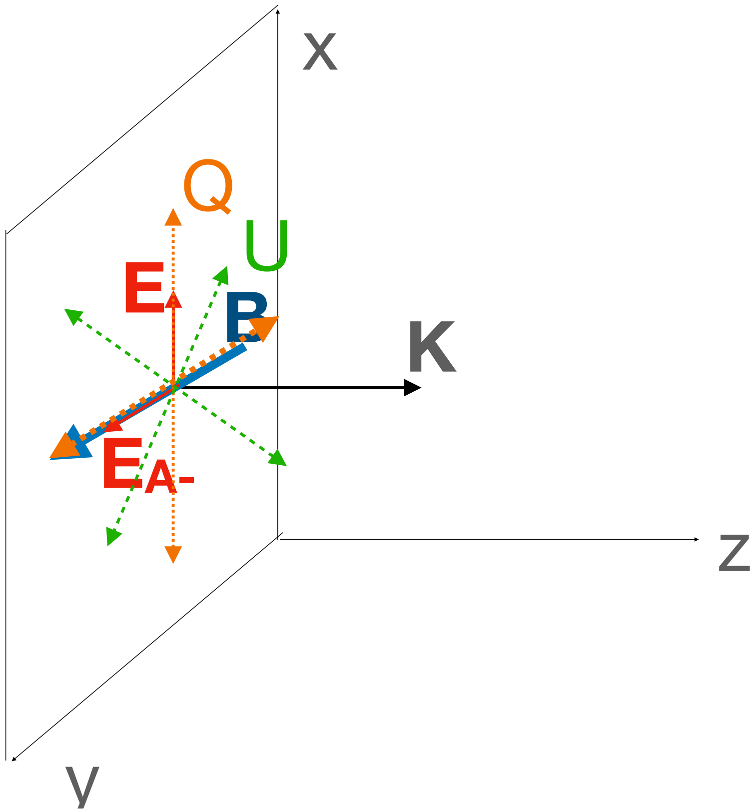
$\delta|_{\rm res} \approx \frac{R_{LC}\omega}{2c\mu} \ln(r_B/R_{LC})$ $\leftarrow \propto 1/\lambda$ larger frequencies resonate at smaller r, where density is higher by r^{-2}



XTE J1810-197 (Lower, Melrose and Lyutikov, in prep.)



Faraday conversion in pair plasma



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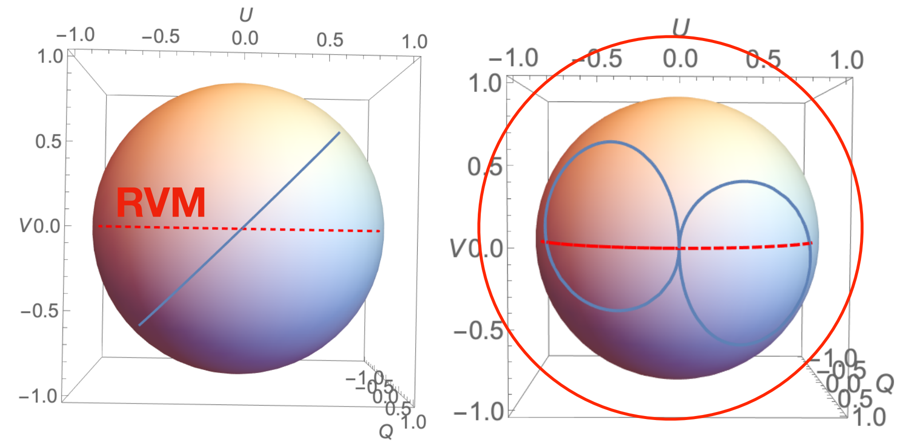

Constant δ Phase-dependent δ

Faraday conversion near cyclotron resonance in the wind

$$(\Delta n) \sim 2\frac{\omega_B^2\omega_p^2}{\omega^2(\omega^2-\omega_B^2)}$$ Large contribution near the resonance

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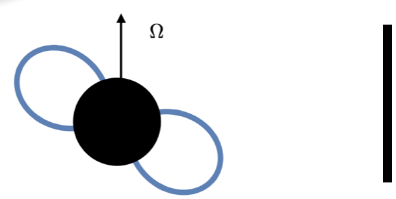
$\omega' = \omega'_B$

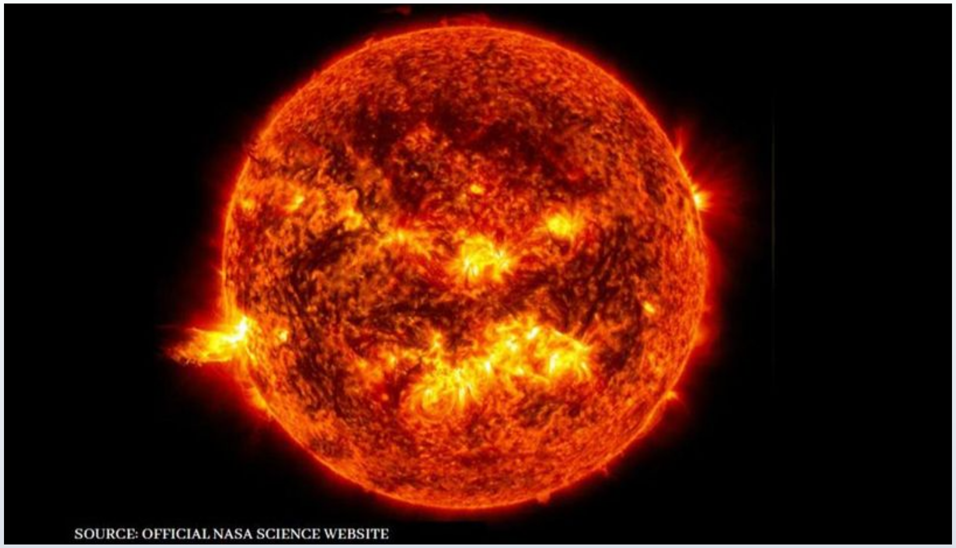


larger n smaller n

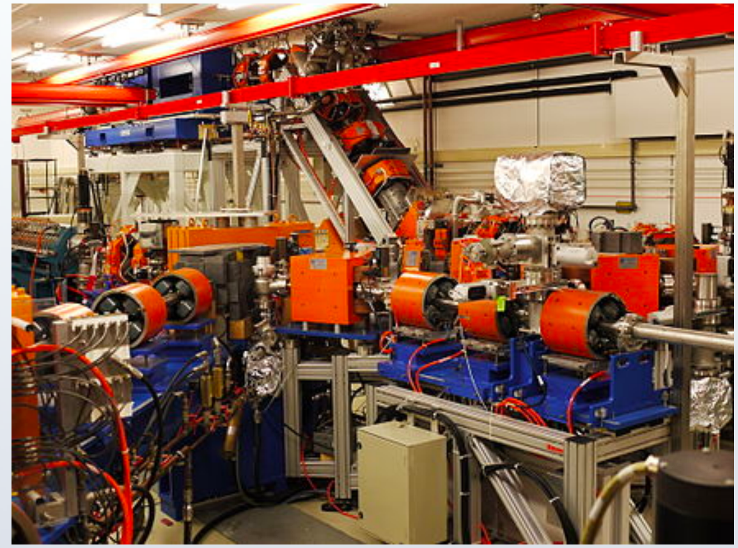
4. How - Free electron laser

Lots of problems in radio, for observers and theorists

- Coherent emission is the enemy of theoretical astrophysics
  - pulsars: 50+ yrs problem
  - Usually take emissivity, multiply by N
  - Coherent: multiply by 0-N-N^2, N ~ 10^{15}
- Observational
  - Addition of phases of interferometric observations (“getting fringes”)
  - Interference (microwaves, cell phones)
  - small field of view (hard to do surveys)
- Theoretical: hard to interpret
  - Radio typically has minuscule power: All the energy collected by all radio telescopes over a history of radio astronomy ~ 1 falling snow flake
  - Coherence is addition of phases: distribution over 2 pi - dimensionless, no order-of-magnitude guess



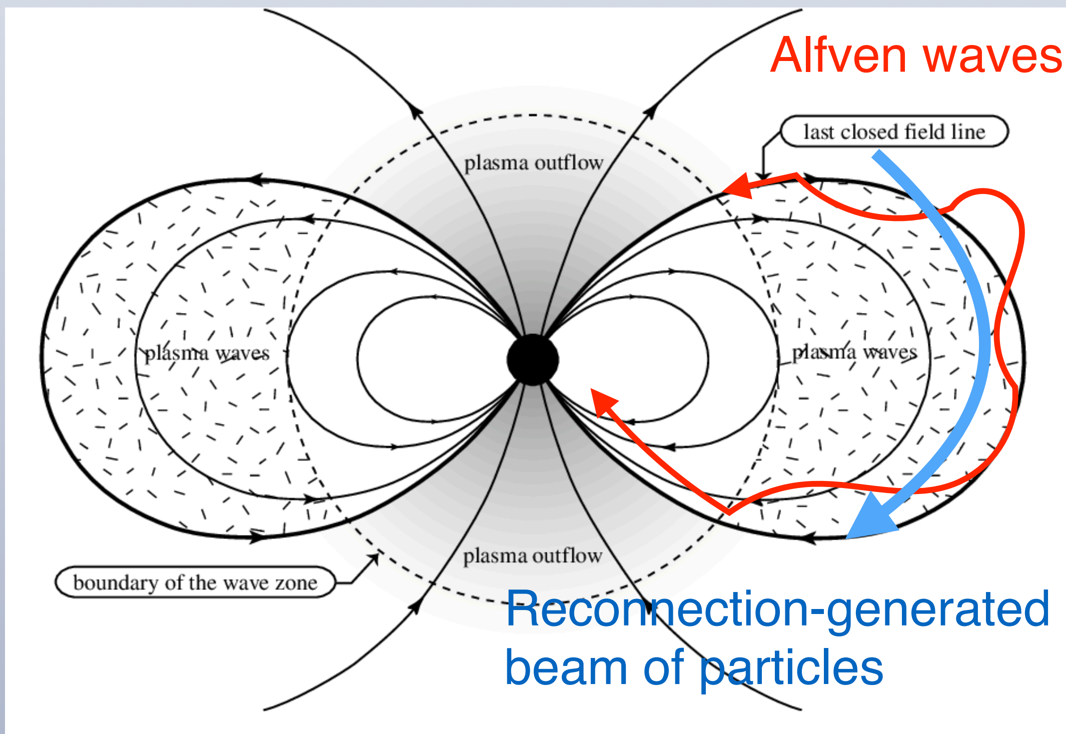
Reconnection on the Sun



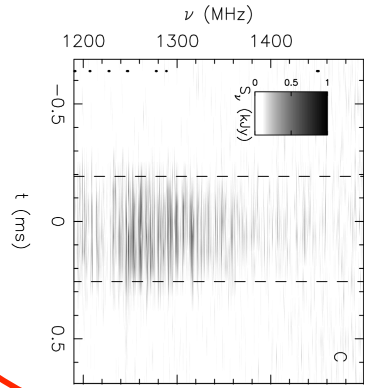
Free Electron Laser

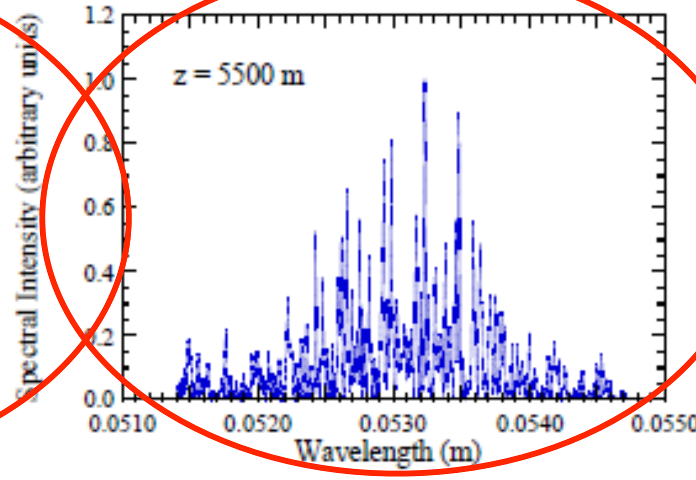
100 meters long, coherence at Angstrem: precision at 10^{-14}

For NSs: 10^{-6} is OK, no need to work perfectly

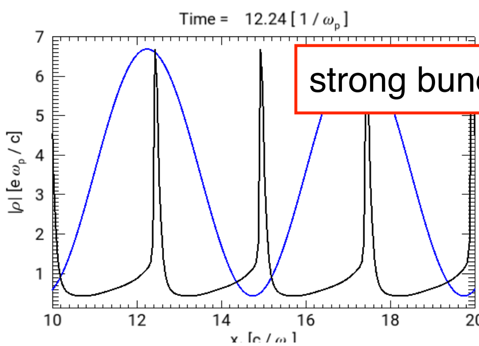


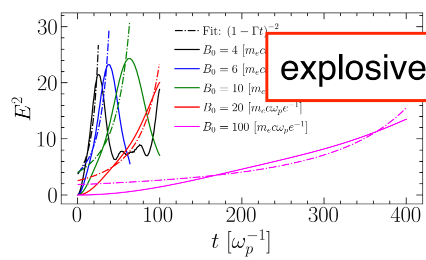
- Guide-field dominated regime
- Alfven waves in the magnetosphere (wiggler)
- **Reconnection-driven** beam of charged particles
- bunches induced in the beam by wiggler emit collectively

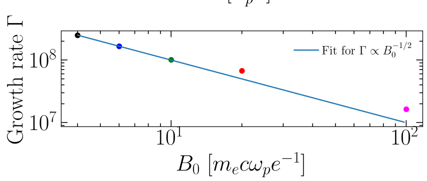




Narrow band pulse with sub-structure (natural in saturated SASE regime)







- As long as $\Delta p/p \leq 1$
- Frequency $\omega \sim \gamma^2 (k_w c)$: **independent of B-field**: works in MSPs, magnetars, far out in Crab
- gamma ~ 10^2 - 10^3 - cannot be less demanding
- Saturation: nearly threshold

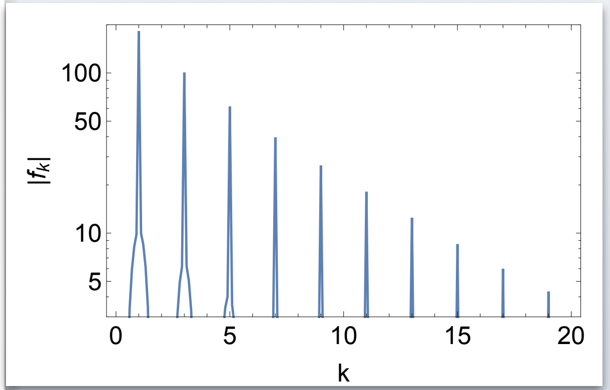
$$\eta_{b-r} \equiv \frac{B_{EM}^2/(4\pi)}{n\gamma m_e c^2} = 4\gamma^3 a_H^4 \frac{\omega_p^2}{\omega^2}$$

$$a_H = \frac{B_w}{B_0}$$

The model explains a subtlety: spectrum & polarization

- FRBs: narrow emission bands come with linear polarization, while broadband with more varies polarization properties
- Harmonic linear wiggler -> Multiple stripes (non-linear magnetic Thomson scattering - recall 8-figure for particles: beat)

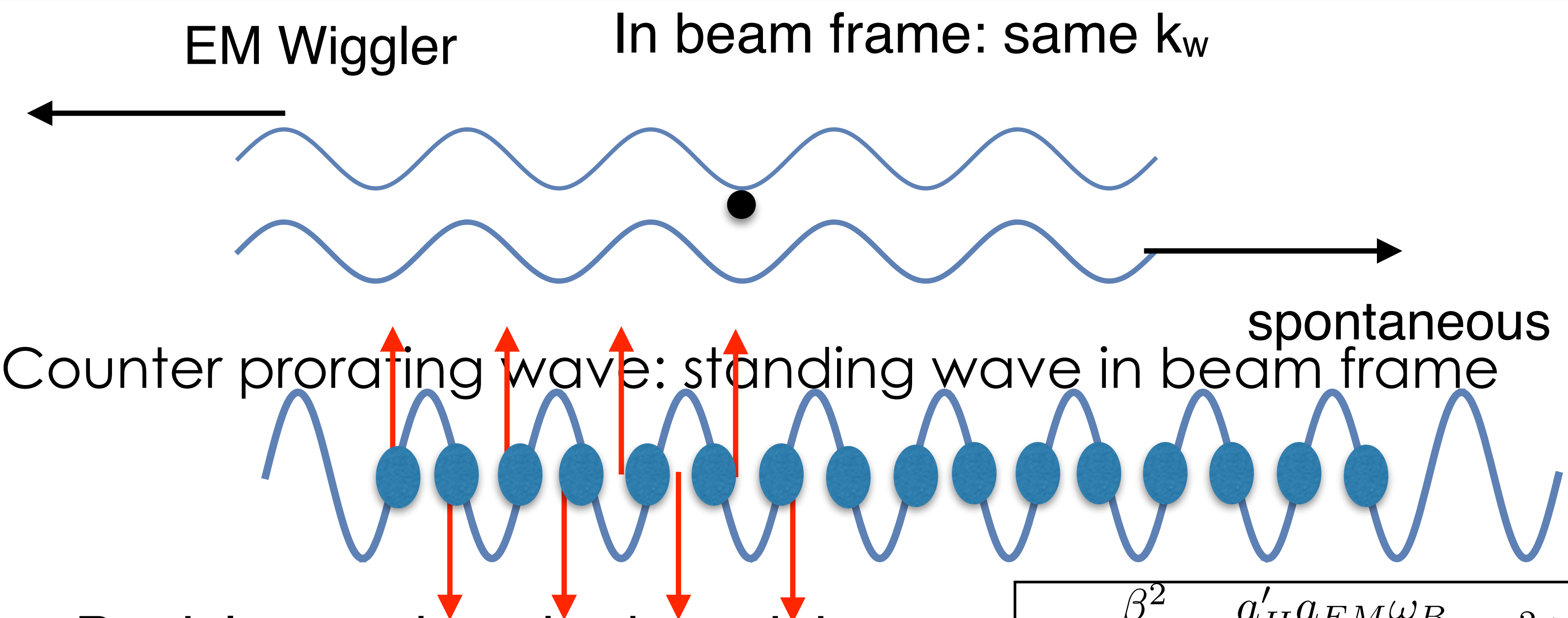
Model reproduces subtle correlation of polarization and spectral properties



Spectrum expected for linear polarization

Extra slides

Parametric excitation of EM



- Counter prorating wave: standing wave in beam frame

Particles are bunched at minima of the ponderomotive potential

$$\mathcal{H} = \frac{\beta_z^2}{2} + \frac{a'_H a_{EM} \omega_B}{k'_w} \sin^2(k'_w z)$$

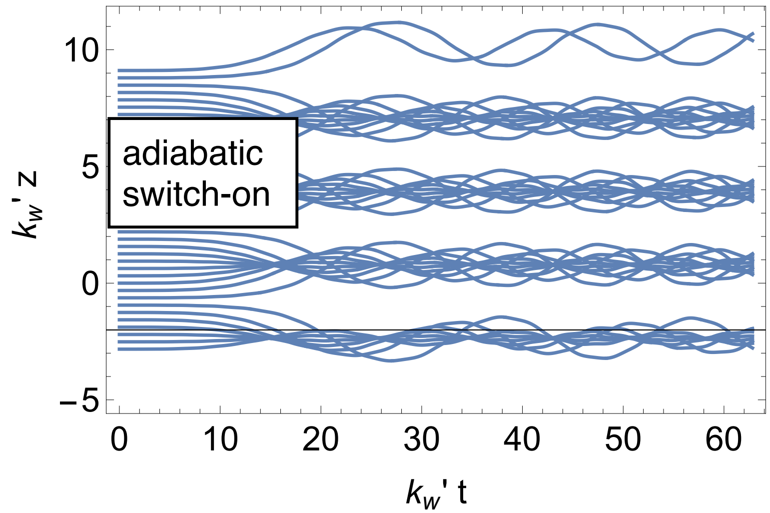
wiggler shakes them
phases from different bunches also add constructively

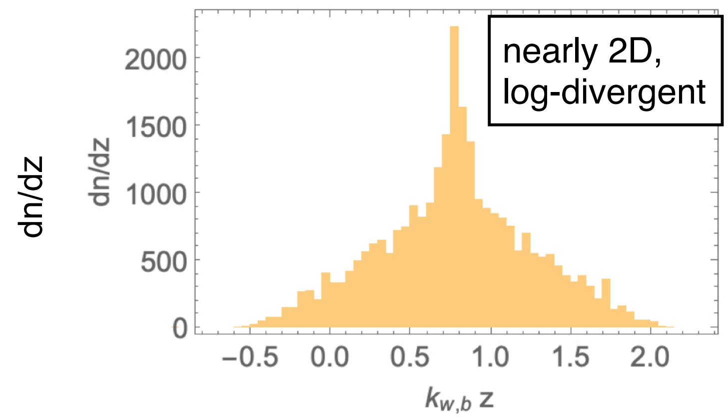
each bunch emits coherently + addition from different bunches

Parametric excitation of EM (SASE FEL)

- Standing wave in beam frame!

bunches are formed: 2 per period





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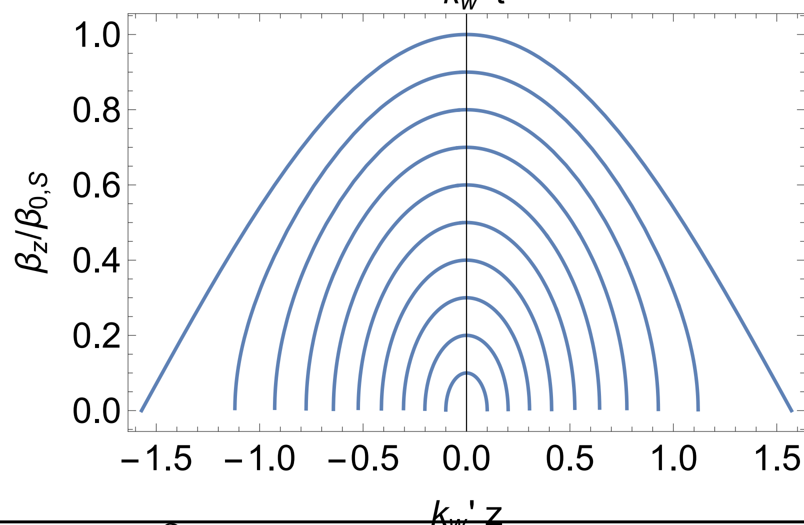
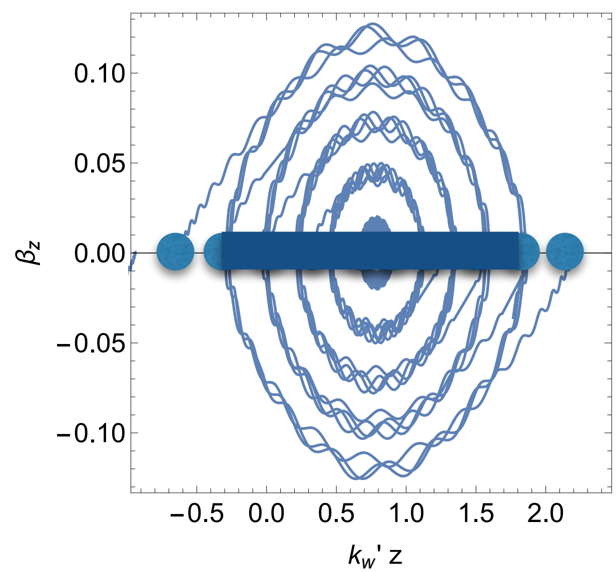


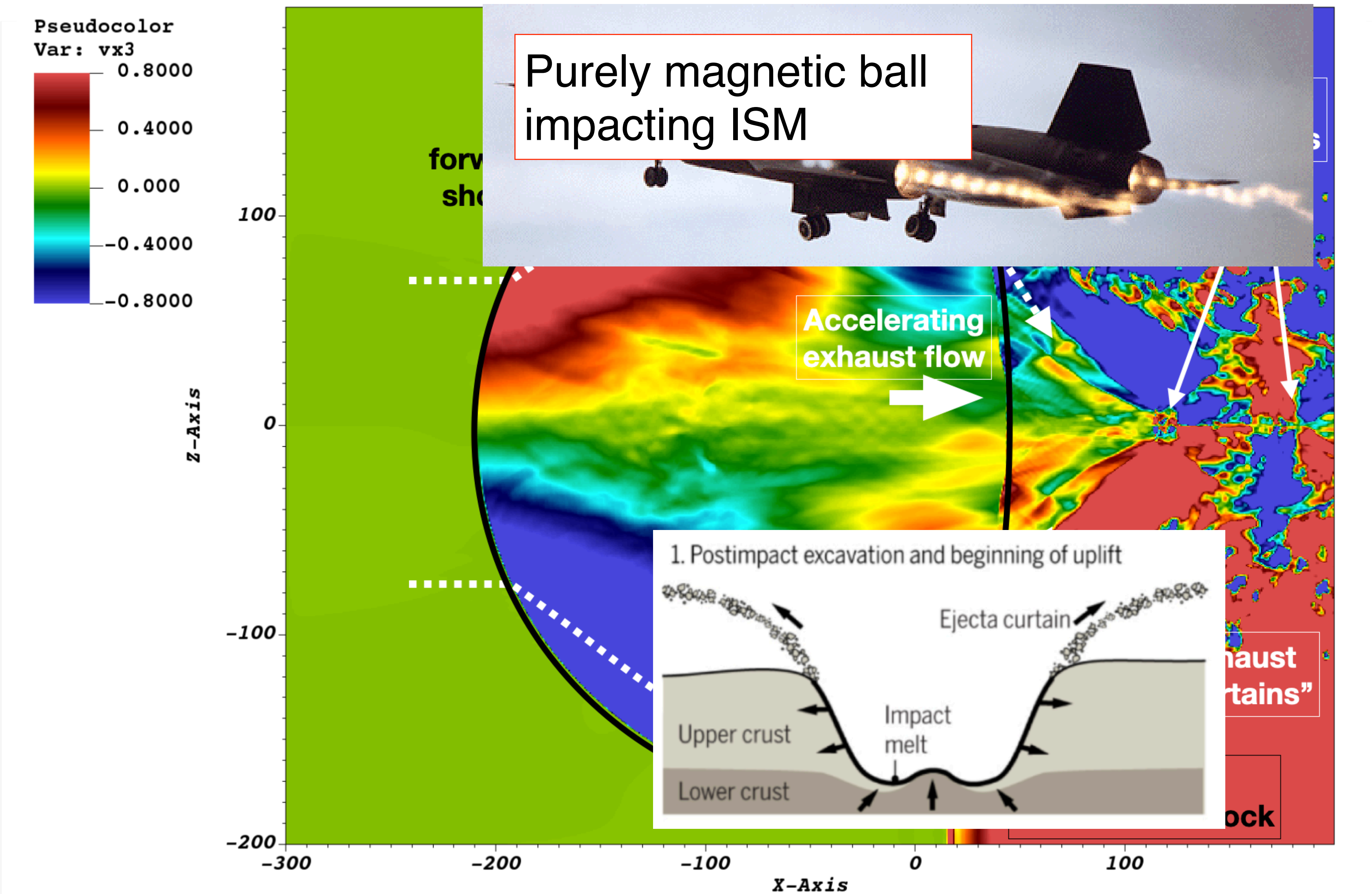


Bunching

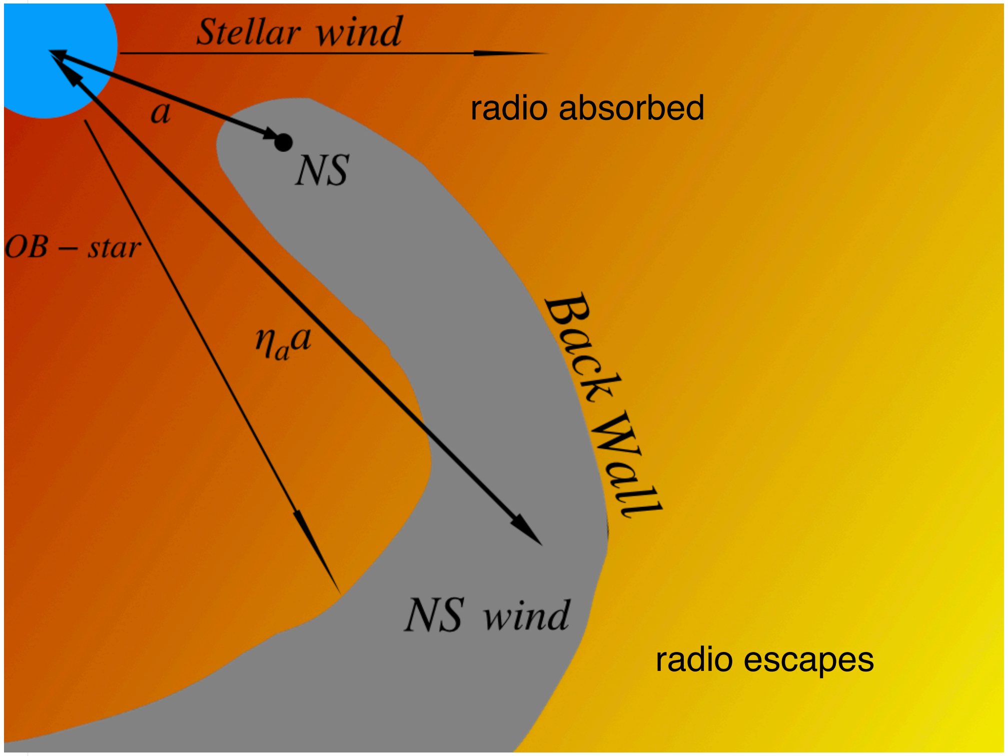
$$\mathcal{H} = \frac{\beta_z^2}{2} + \frac{a'_H a_{EM} \omega_B}{k'_w} \sin^2(k'_w z)$$

Fast jitter + slow parametric modulation

4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)



Periodicity: absorption of FRB pulse in the companion wind



FRB Periodicity: Mild Pulsars in Tight O/B-star Binaries

Show affiliations

Lyutikov, Maxim; Barkov, Maxim V.; Giannios, Dimitrios

Periodicities observed in two fast radio burst (FRB) sources (16 days in FRB 180916.J0158+65 and 160 days in FRB 121102) are consistent with that of tight, stellar-mass binary systems. In the case of FRB 180916.J0158+65 the primary is an early OB-type star with the mass-loss rate $\dot{M} \sim 10^{-8}$--$10^{-7} M_{\odot}$ yr^{-1}, and the secondary is a neutron star. The observed periodicity is not intrinsic to the FRB's source, but is due to the orbital phase-dependent modulation of the absorption conditions in the massive star's wind. The observed relatively narrow FRB activity window implies that the primary's wind dynamically dominates that of the pulsar, $\eta = L_{sd}/(\dot{M} V_w c) \leqslant 1$, where L_{sd} is the pulsar spin-down, $\dot{M}$ is the primary's wind mass-loss rate, and V_w is its velocity. The condition $\eta \lesssim 1$ requires a mildly powerful pulsar with $L_{sd} \lesssim 10^{37}$ erg s^{-1}. The observations are consistent with magnetically powered radio emission originating in the magnetospheres of young, strongly magnetized neutron stars, the classical magnetars.

Publication: The Astrophysical Journal Letters, Volume 893, Issue 2, id.L39, 6 pp. (2020)

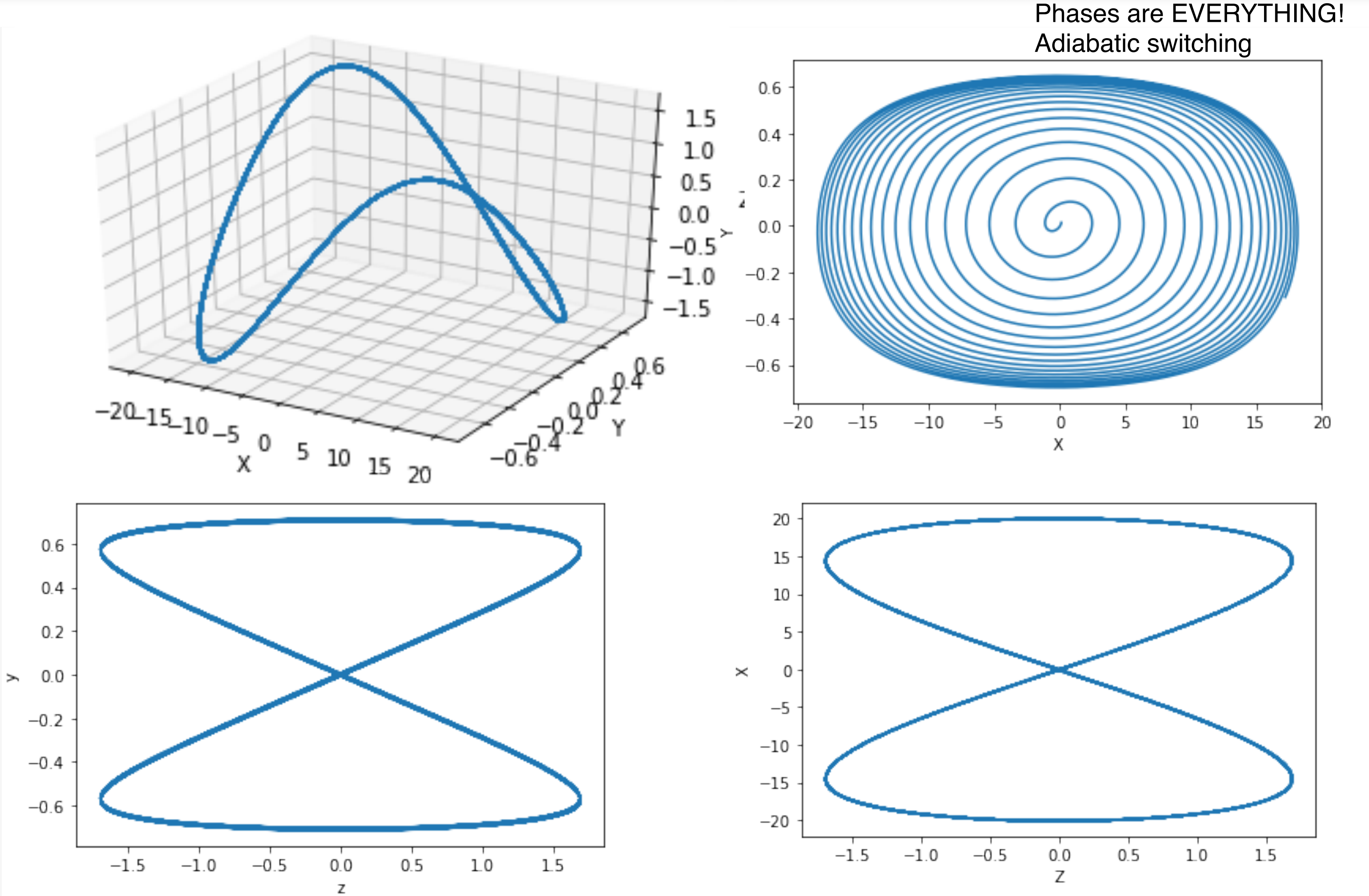
Pub Date: April 2020

classical: not millisecond magnetars

Conclusion I.

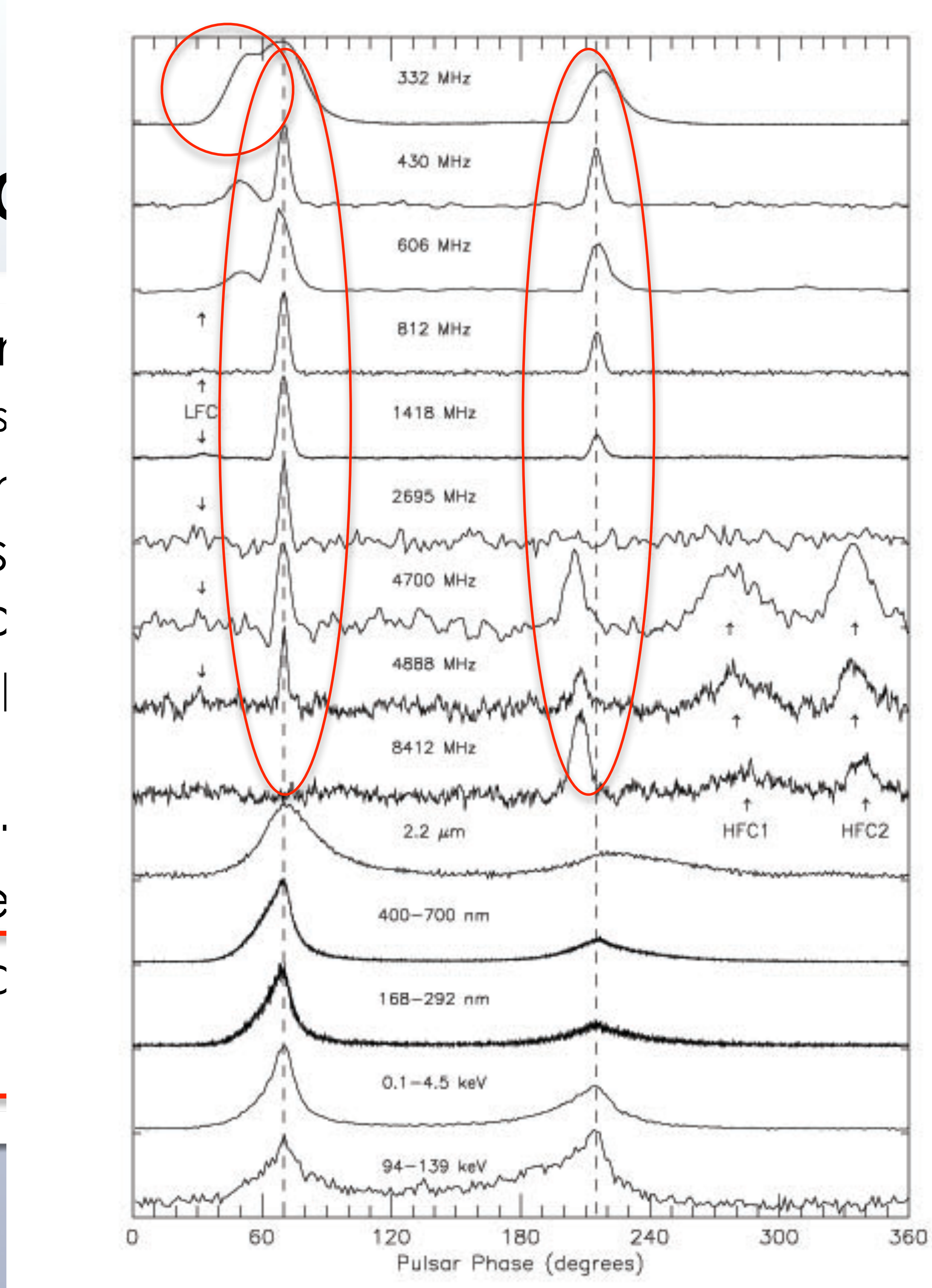
- All!(?) observations are consistent with magnetospheric origin of FRBs
  - Temporal coincidence X-ray-radio
  - Radio leads X-ray
  - freq. drifts
  - PA swings
- Most predicted and confirmed (to various degrees)

Particles' trajectories, harmonic linearly P. EM wiggler with guide field, figure-8 -> beat (Boris-type simulations by Yegor Lyutikov)



Pulsar coh
mec

- 50+yrs problem - please r
  - "we assume bunches are s
- "Coherent curvature em electrostatic energy cos prohibitively high (Lyutikc
- Non a single emission pul precursor)
- Crab's MP/IM: **reconnec** Cylinder: FRBs cannot be
- **Crab/Magnetars/FRBs:** rc rotationally driven)



SLIDE FROM ASPEN 2017

Repeater: FRBs not Rotationally powered

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

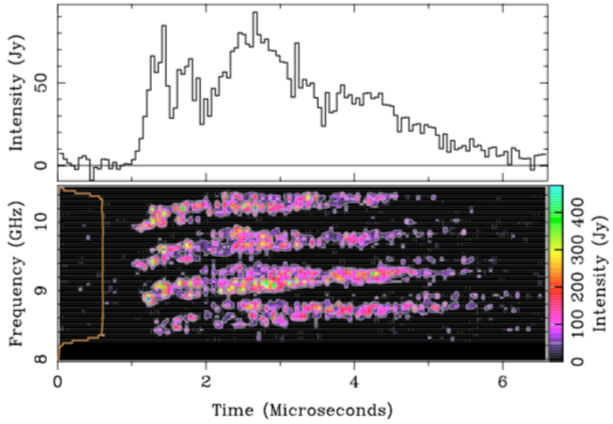
$$\nu F_\nu < \frac{L_{sd}}{4\pi d^2}$$ - need powerful source

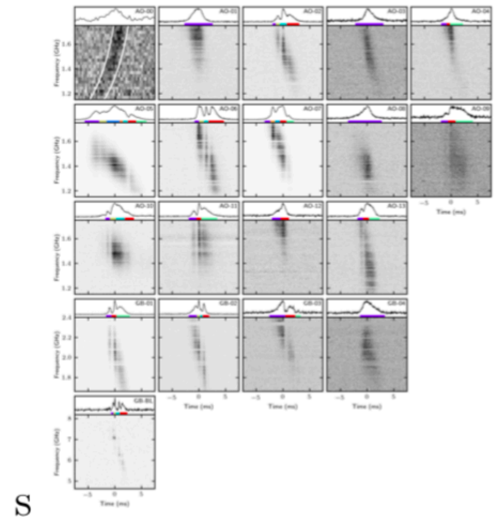
- Could have worked from 100Mpc (Lyutikov+ 2016)

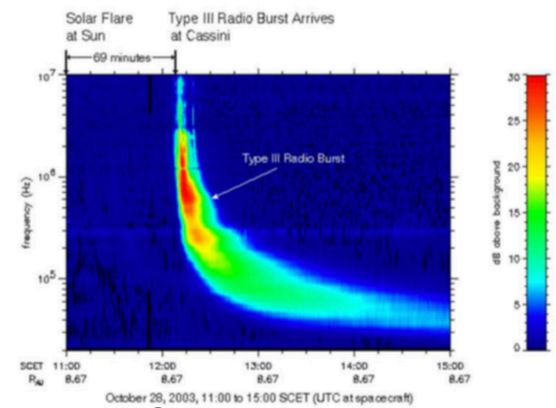
Requirement of large L_{sd} and no DM changes excludes young rotationally-powered pulsars as FRB sources (Lyutikov 2017)

- Magnetically-driven - OK by energy (eg. initial stage of a "reconnection flare"), some observational limits from SGR 1806-20 flare
  - SGR flare was 10^{47} erg/s -> radio efficiency of Repeater 10^{-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})

Narrow bands: Crab, FRBs, the Sun







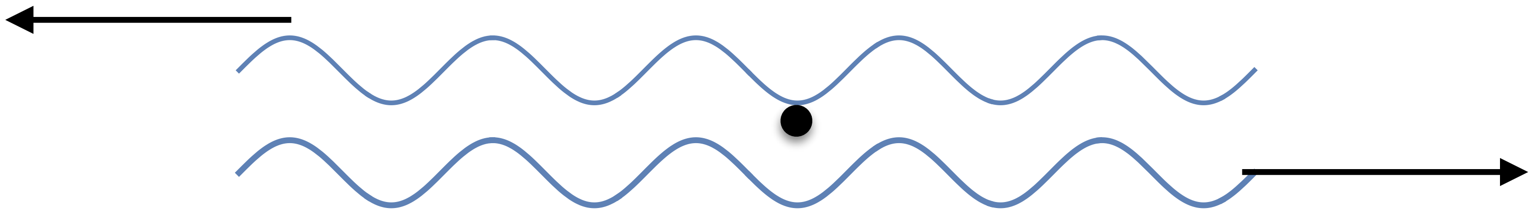
Type-III Solar radio bursts

- Some kind of a stiff confining structures – magnetic field (radius-to-frequency mapping in pulsars)

Parametric excitation of EM

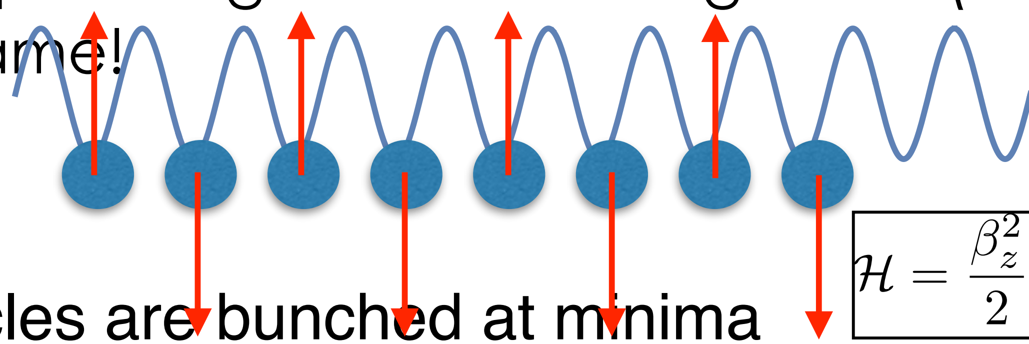
EM Wiggler

In beam frame: same k_w



spontaneous EM

- Counter prorating wave: standing wave (charge bunches) in beam frame!
-



$$\mathcal{H} = \frac{\beta_z^2}{2} + \frac{a'_H a_{EM} \omega_B}{k'_w} \sin^2(k'_w z)$$

Particles are bunched at minima of the ponderomotive potential

wiggler shakes them

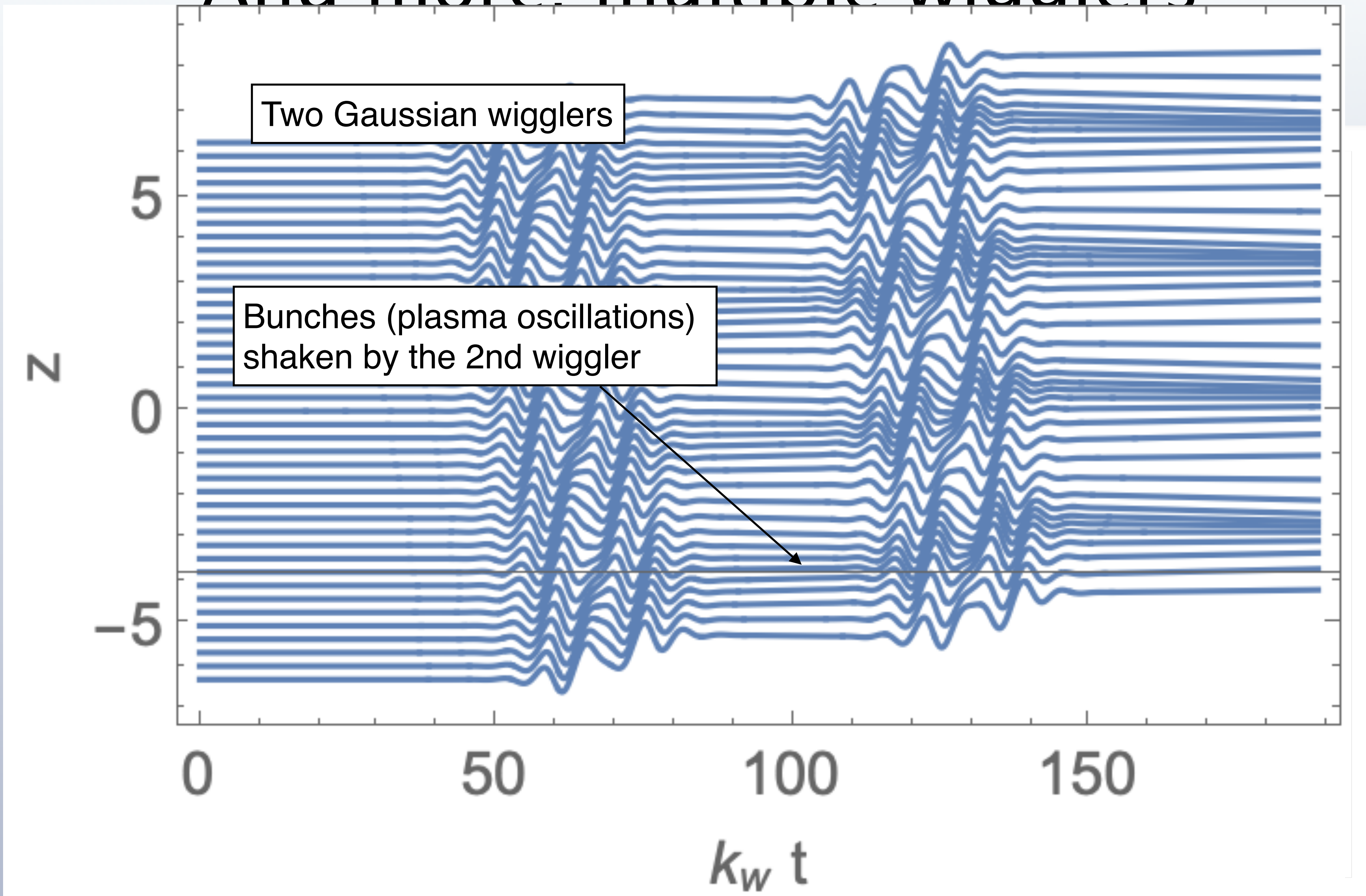
phases from different bunches also add constructively

each bunch emits coherently + addition from different bunches

Plasma effects in the beam: Raman and Compton regimes

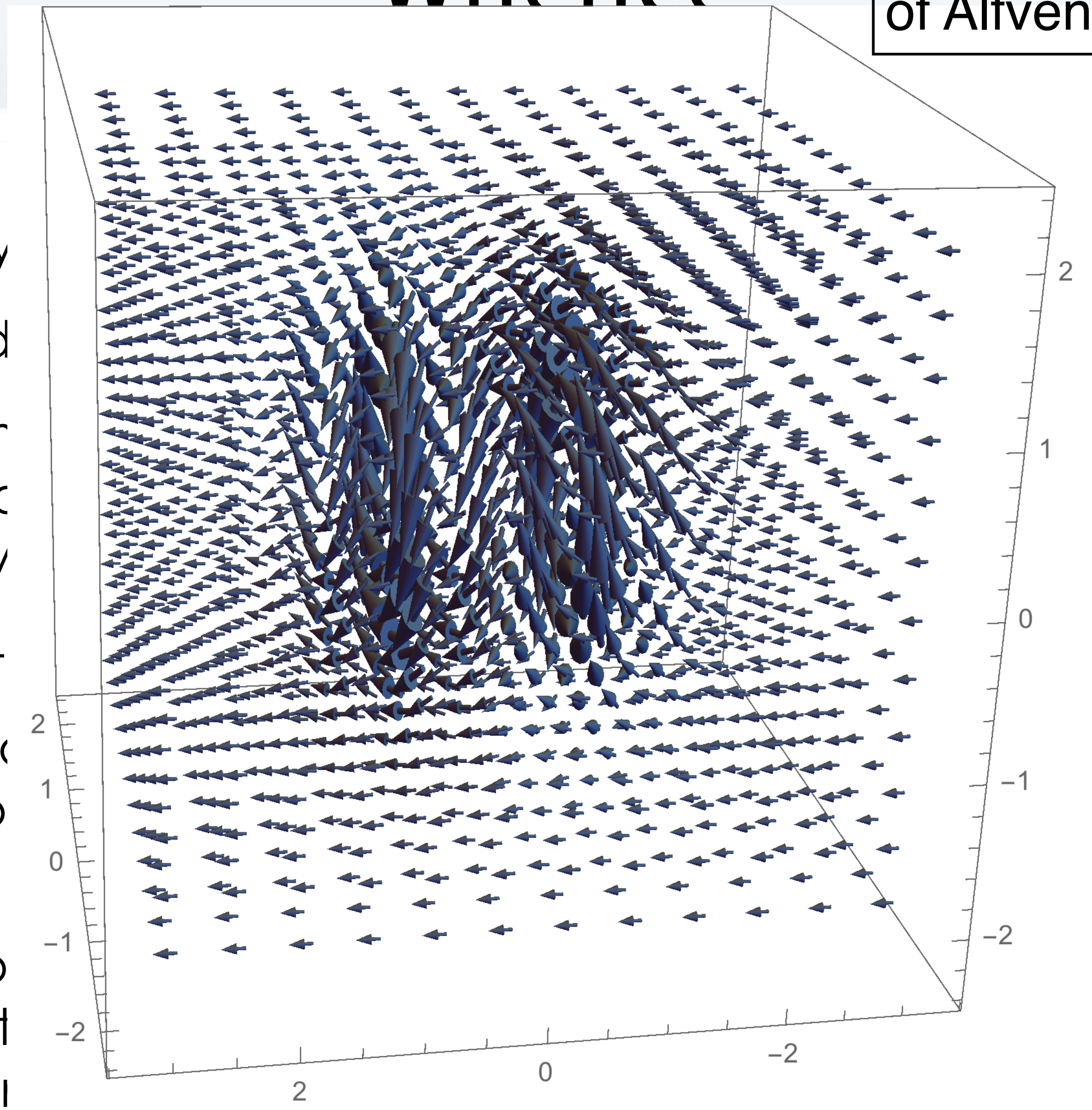
- Ponderomotive force creates bunches - will electrostatic repulsion destroy them? - No!
  - This is highly important: bunches of **repulsing** charges oscillate but are **not** destroyed!
- “Parallel” driving can be with any omega
- resonance at k_w c = $omega_p$
- This enhances the amplitude, but **keeps the phase**

And more: multiple wigglers



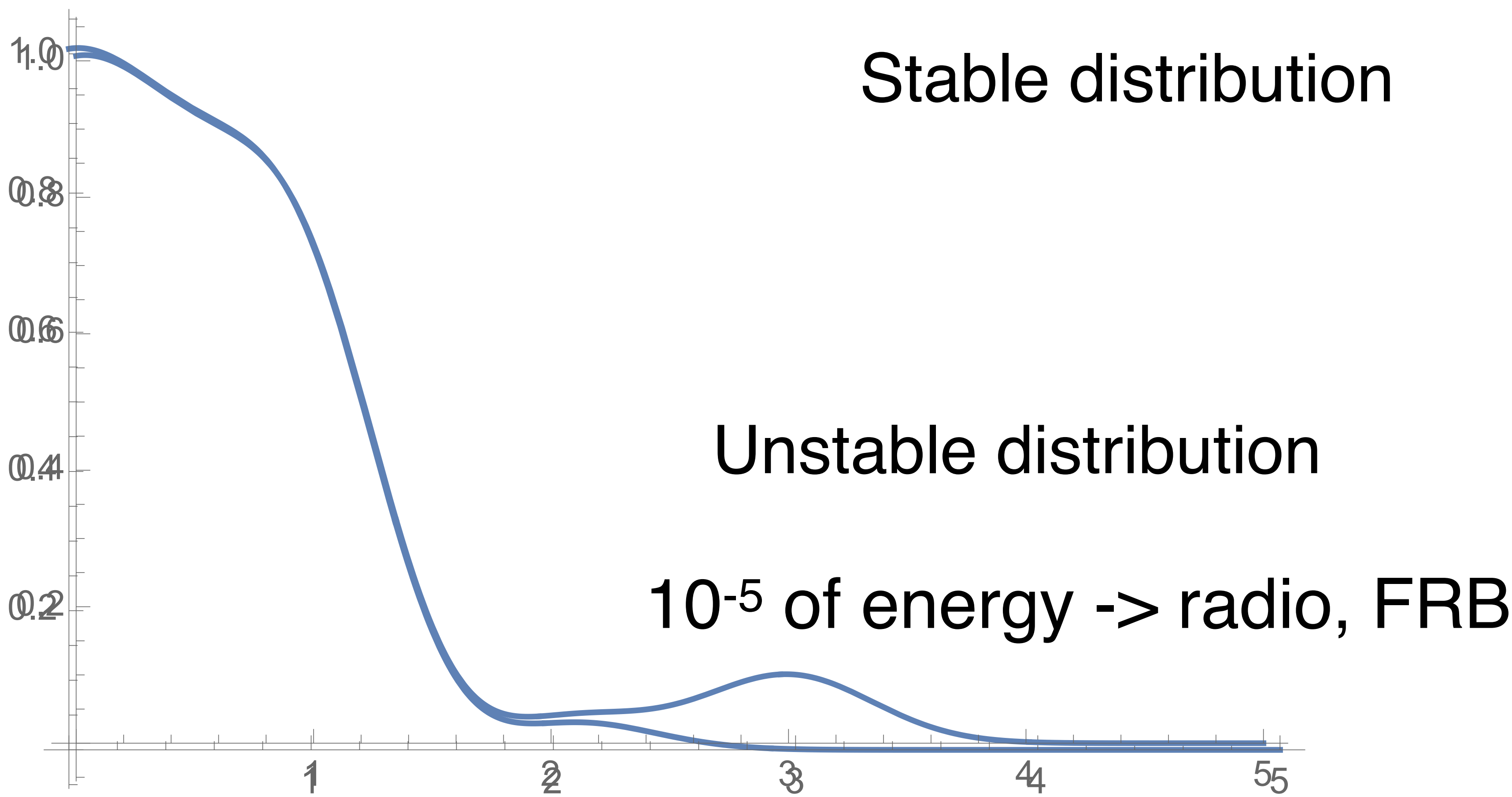
Whence?

E.g. cigar-shaped pulse of Alfven waves



- Origin of … /or firehose instability…
  - "Light d…
- radio em… magneto… …phere is still relatively…
  - giant γ-…
  - Initial st… …er-efficient (Lyutiko…
- Duration … -ray flare accomp… …dius; hence FRB, emit… …riod - millisecon… …an be as short as light crossing time over 100 meters, a microsecond.

Plasma is no astro. To predict 10^{-5} efficiency one needs precision 10^{-5}



History & Challengers

- History:
  - The first model of pulsar radio emission (Goldreich & Keeley 1971) - a variant of FEL (radiative reaction leads to bunching)
  - Blandford 1973: inflection points are needed for coherent synchrotron (but FEL is not synchrotron - phases mix-up, Landau-Pomeranchuk)
- Needed:
  - PIC simulations in highly radiative damped regime
  - Why GPs only in Crab (and few other MSPs)?
- The problem is difficult, 50+ yrs… please no
  - "We assume bunches are created"
  - "We assume pulsar mechanism operates"
  - something about energetics

Coherent emission mechanism(s)…

- I am critical, there is really not much discussion between different "denominations" of theorists
- "Coherent curvature emission by bunches", 50yr old model (Goldrech&Keely 71)
  - There is a reason why best theorists in 70-80-90, basically, discarded it
  - "Similar charges repulse" - one cannot just assume bunches are created
  - "Simple" model: "assume" bunches, give it to student, done. Does not work.
- Synchrotron maser in the wind
  - Gallant & Arons '92: months long variations in Crab wisps (FRB: still need to get <10msec: 8 orders in timing)
  - Lyubarsky 2014: EM luminosity 10^{52} erg/sec: but FRBs are not GRB
  - Beloborodov: adopt GRB model (shells of ejected mater, collide, shock). Need to be ejected during the same 10msec. Highly magnetized: shocks are inefficient, shells magnetically isolated. Baryon (where from? need 10^3 times more energy).
  - Synch.maser may still work at the base, few LC away
  - Prediction of wind model: X-ray ahead of radio
- Clouds in the wind: Will be blown out by persistent; need post-shock Gamma ~100.

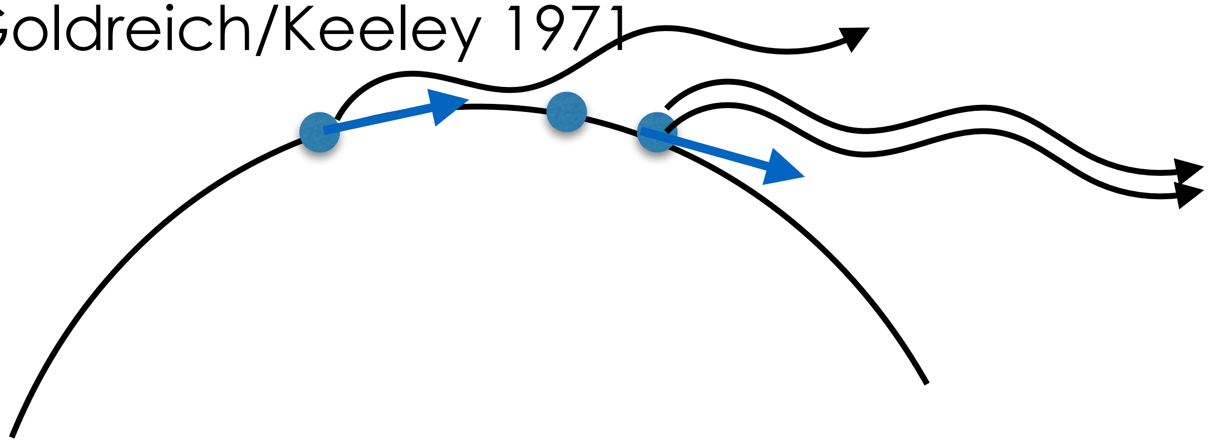
Theoretical efforts are…

$$P \propto Q^2 \propto N^2 e^2$$

- "Coherent curvature emission by bunches" (circa 2020)

been long discussed as the mechanism for radio pulsars and recently for FRBs. Assuming that bunches are already generated in pulsar magnetospheres, we calculate the spectrum

- How one can "assume" that electrostatically repulsing bunches are created? - Possible, but not easy - 50 yrs…
- Compare: The first model of pulsar coherent emission: Goldreich/Keeley 1971

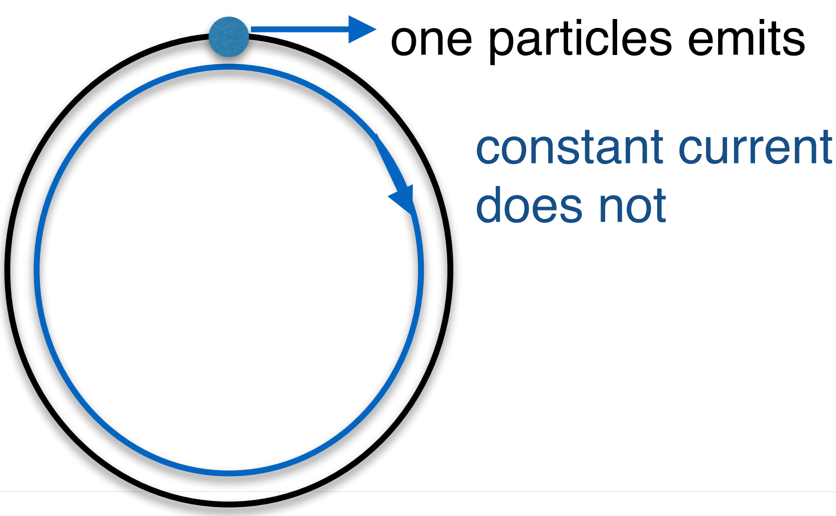


It's a radiation reaction effect - very weak,
easily destroyed by v-dispersion (Melrose, Asseo, Benford +)

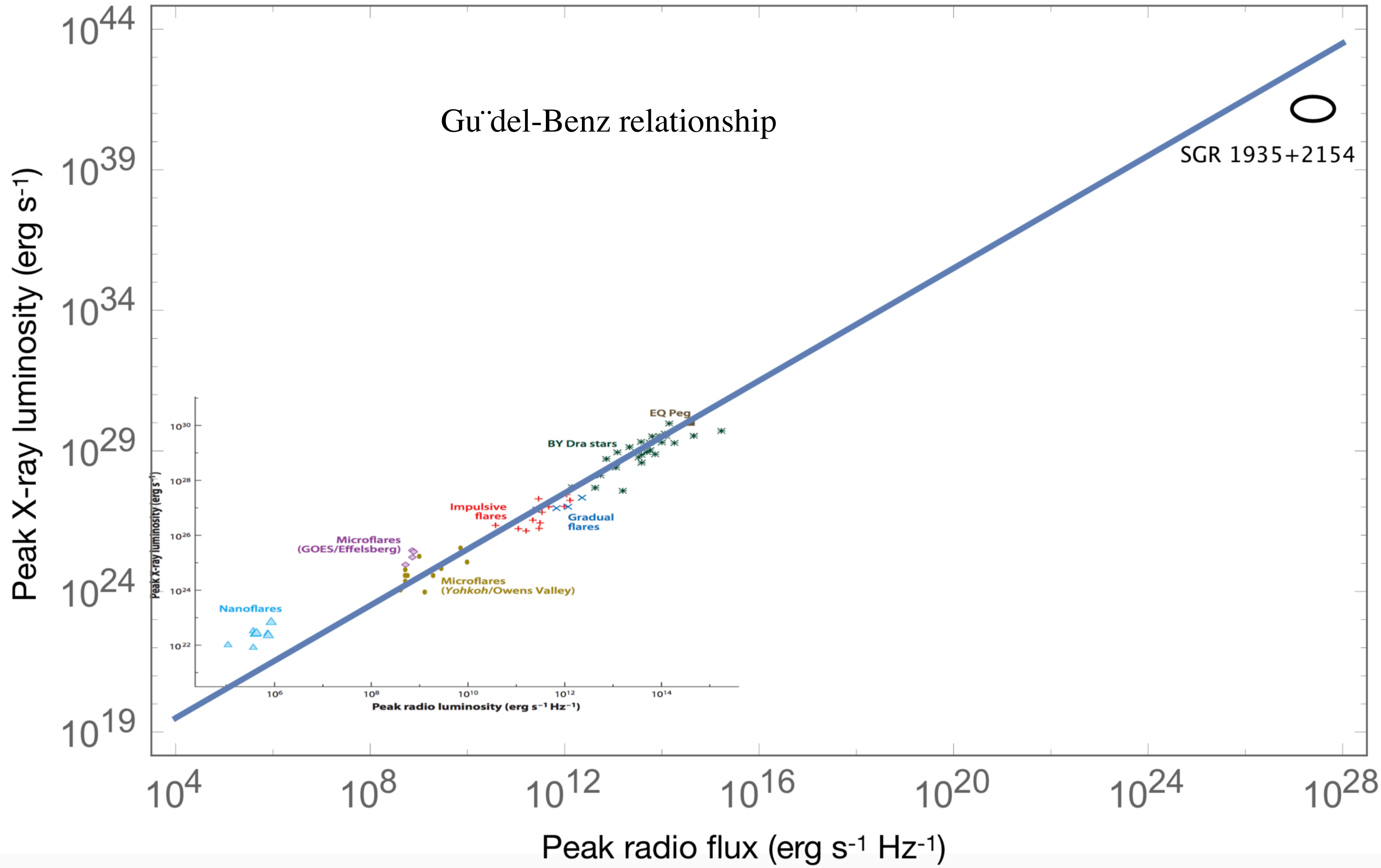
Challenges

- Coherent: at wavelength of 1cm need to add phases at ~ 0.1cm precision
- Cannot use dimensional arguments, between 0 and 2 pi.
- Radio energy is minuscule: any model with efficiency of < 10% may work (so, energetics is not an argument)
  - We are talking about saturation level of a coherent instability, how saturation mixes phases between 0 and 2pi – can hardly get it from "order-of-magnitude"estimates
- Need to take absorption into account

- Addition of emitted phases = particles emit and absorb
- Need to average Liénard–Wiechert potentials



Stellar flares: Radio-X-ray correlation

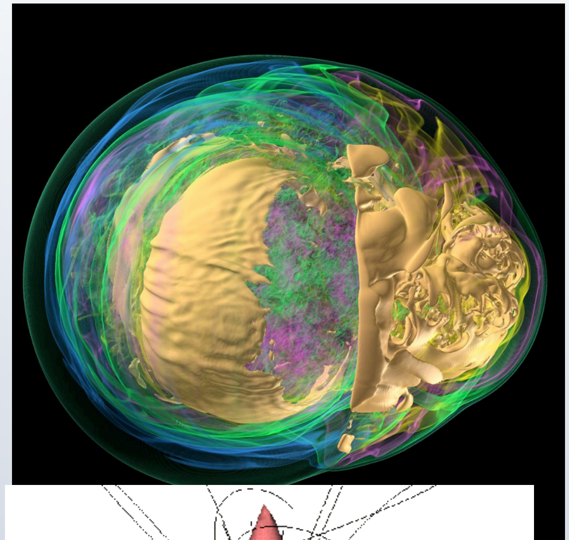


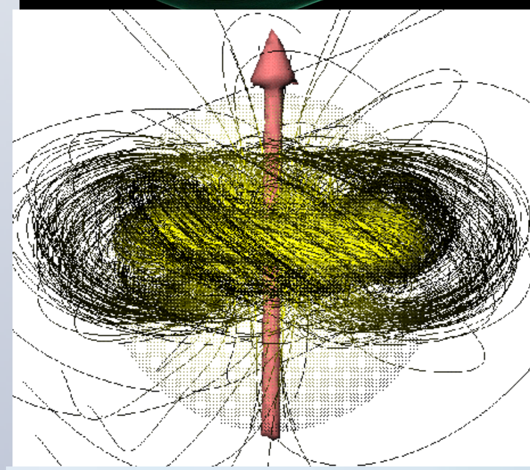
Footpoints are driven by eMHD

- Turbulence at ~ few sec after NS birth
- MHD relaxation at 10 sec
- Feezing at 100 sec
- steady MHD state is not steady ***eMHD:***

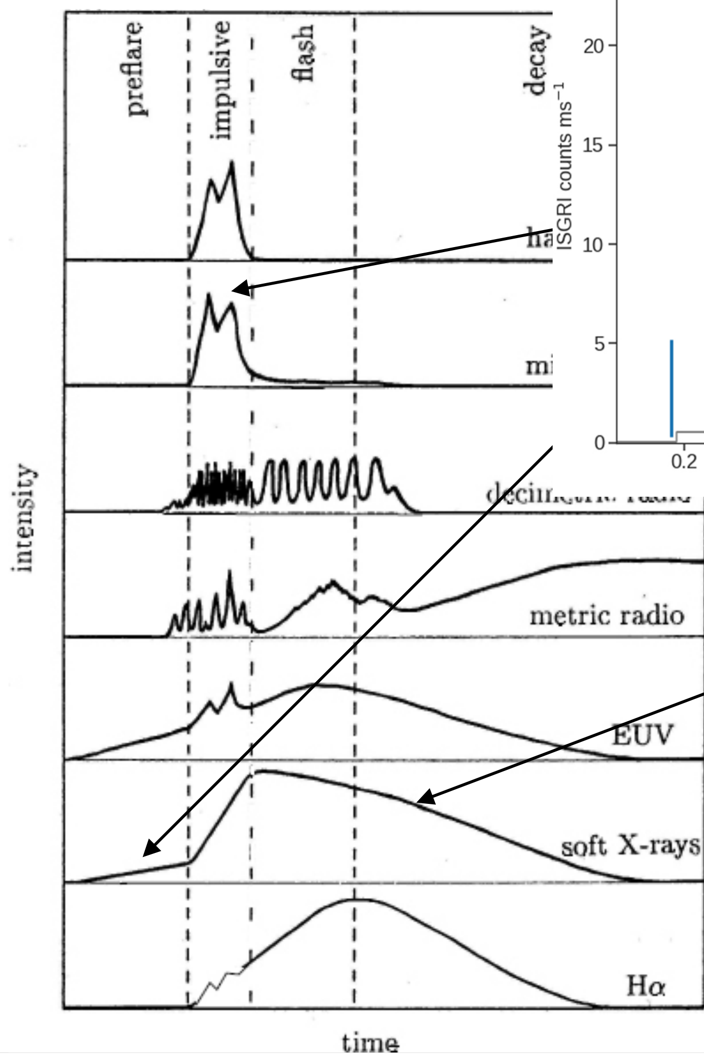
$$\frac{\partial \mathbf{B}}{\partial t} = -\frac{c}{4\pi e} \nabla \times \left(\frac{\nabla \times \mathbf{B}}{n} \times \mathbf{B} \right)$$

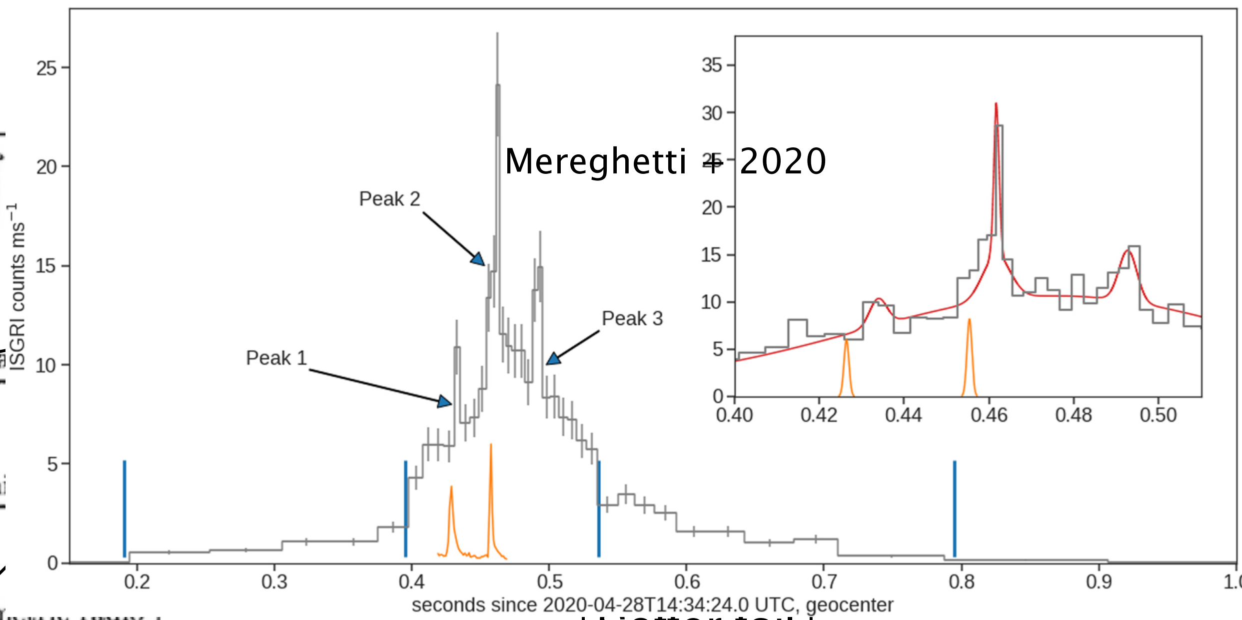
- Electrons start to flow as an inertialess fluid
- Evolve external B-field though plastic deformations of the crust.





Solar flares



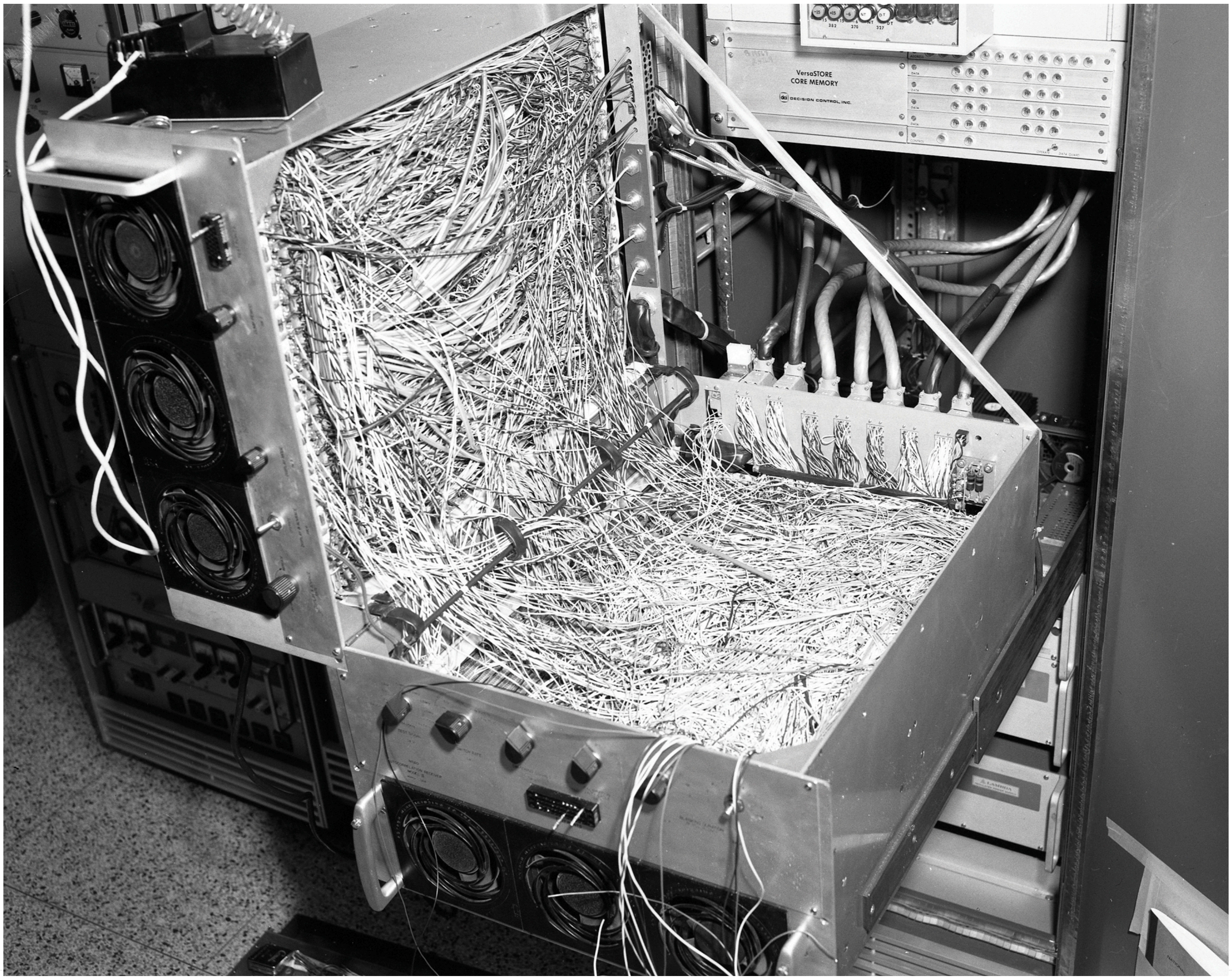


Mereghetti + 2020

Softer tail

All seen in magnetars/FRBs

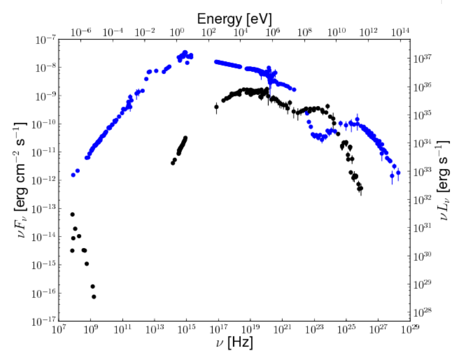
Green Bank Correlator from 60s



SLIDE FROM McGill 2017

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

- In astronomy we observe macroscopic effects.
- Theorists scale “this with that” (alpha-model of SS!)
- Coherent radio is different: no “scaling this with that”
    - phases are everything! - Cannot use dimensional arguments: between 0 and 2 pi.
    - at wavelength of 1cm need to add phases at ~ 1mm precision: If a **phase** is pi off - absorption instead of emission
    - Radio energy is minuscule: any model with efficiency of < 10% may work (cf. alpha model of disk turbulence, hydrodynamic, ~ 0.1-0.3)
    - no technician on site - occasionally it works, most of the time it does not.