Fast Radio Bursts: An Astrophysical Mystery

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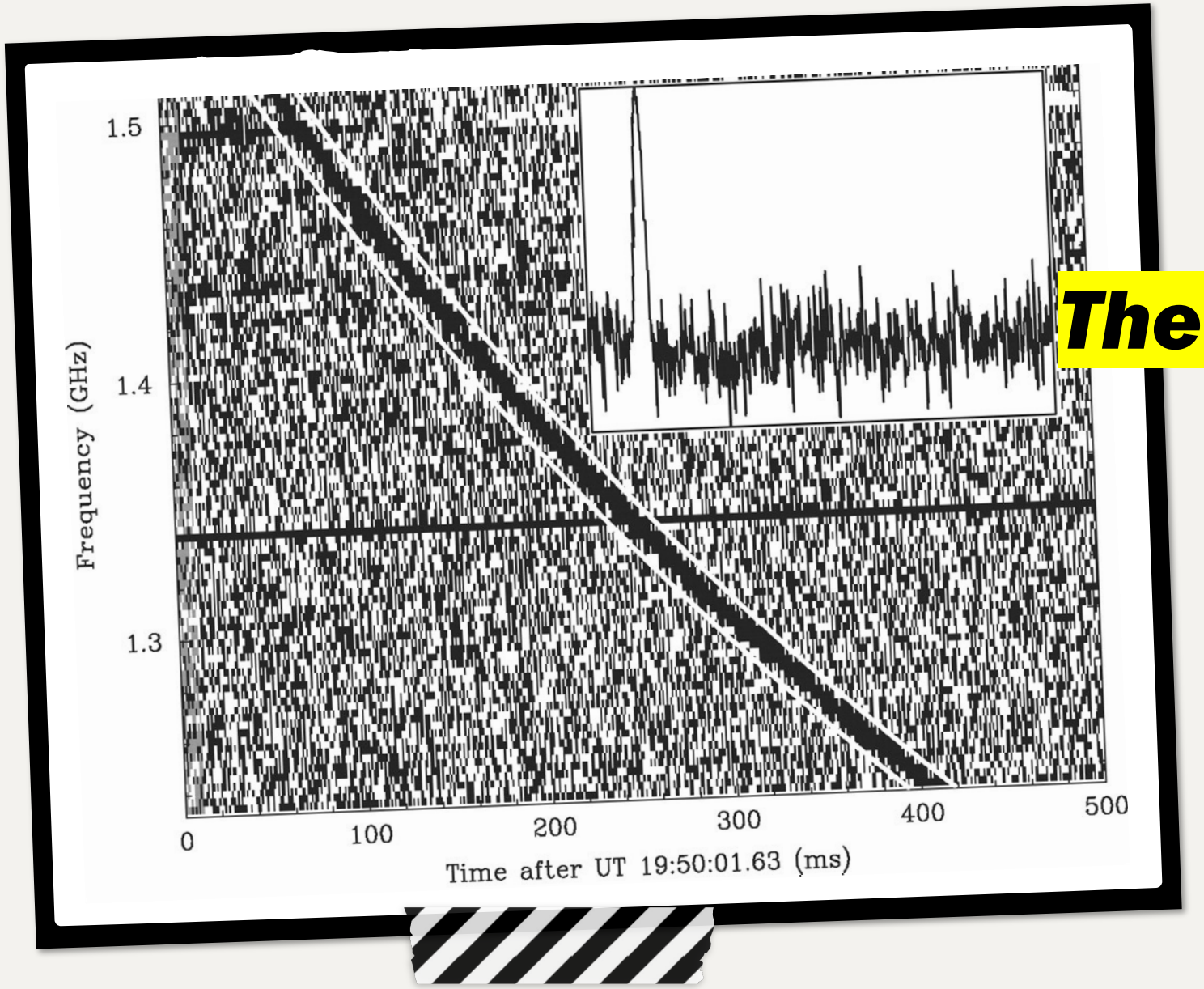
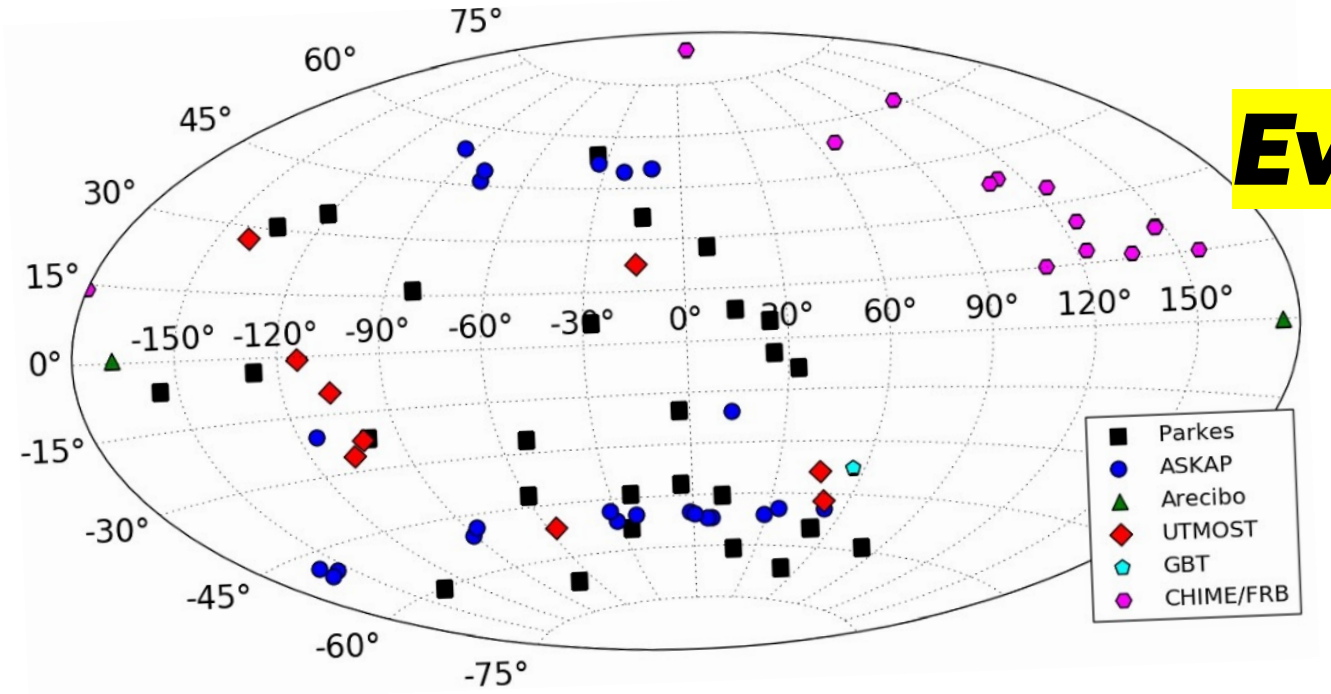
What are FRB's?

- FRB's are millisecond-duration bursts in the radio sky that originate from cosmological distances.
- Since first observations, hundreds of FRB's have been observed and localized solidifying FRB's as a real astrophysical phenomena.
- They are associated with highly energetic events.
- Some sources have been observed to repeat.



The Lorimer burst

- On August 24th 2001, the Parkes 64-m telescope detected the first Fast Radio Burst.
- The inferred energy of the burst was much higher than that previously observed from pulsars.
- No repeated burst was discovered.



Event-rate Density

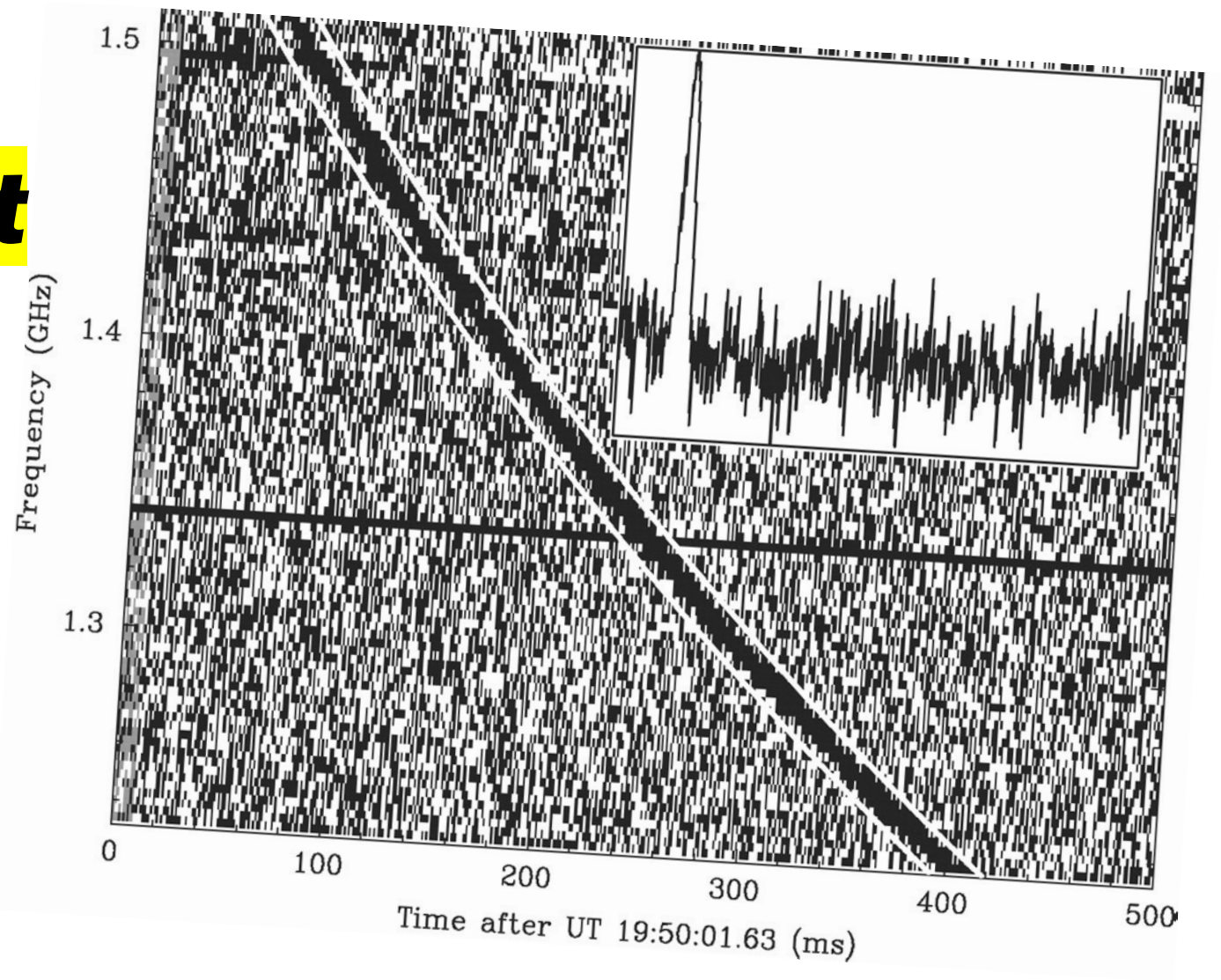
- By 2011 four more FRB signals were discovered affirming the existence of FRB's.
- The event-rate density of FRBs reaches ~3.5 × 10^4 Gpc^{-3} yr^{-1} above 10^{42} erg s^{-1}.
- This exceeds the event-rate densities of most catastrophic transient events in the Universe.

Repeaters

- More than 20 FRBs have been reported to repeat (as I am editing this another repeater has been observed!).
- Do all FRB sources repeat? If all FRBs are repeaters, then at least some apparent one-off FRBs must have a very low repetition rate.
- Is there a minority population of FRBs that do originate from catastrophic events?

The Lorimer burst

- Burst duration
- Frequency dependent time delay
- Energetics



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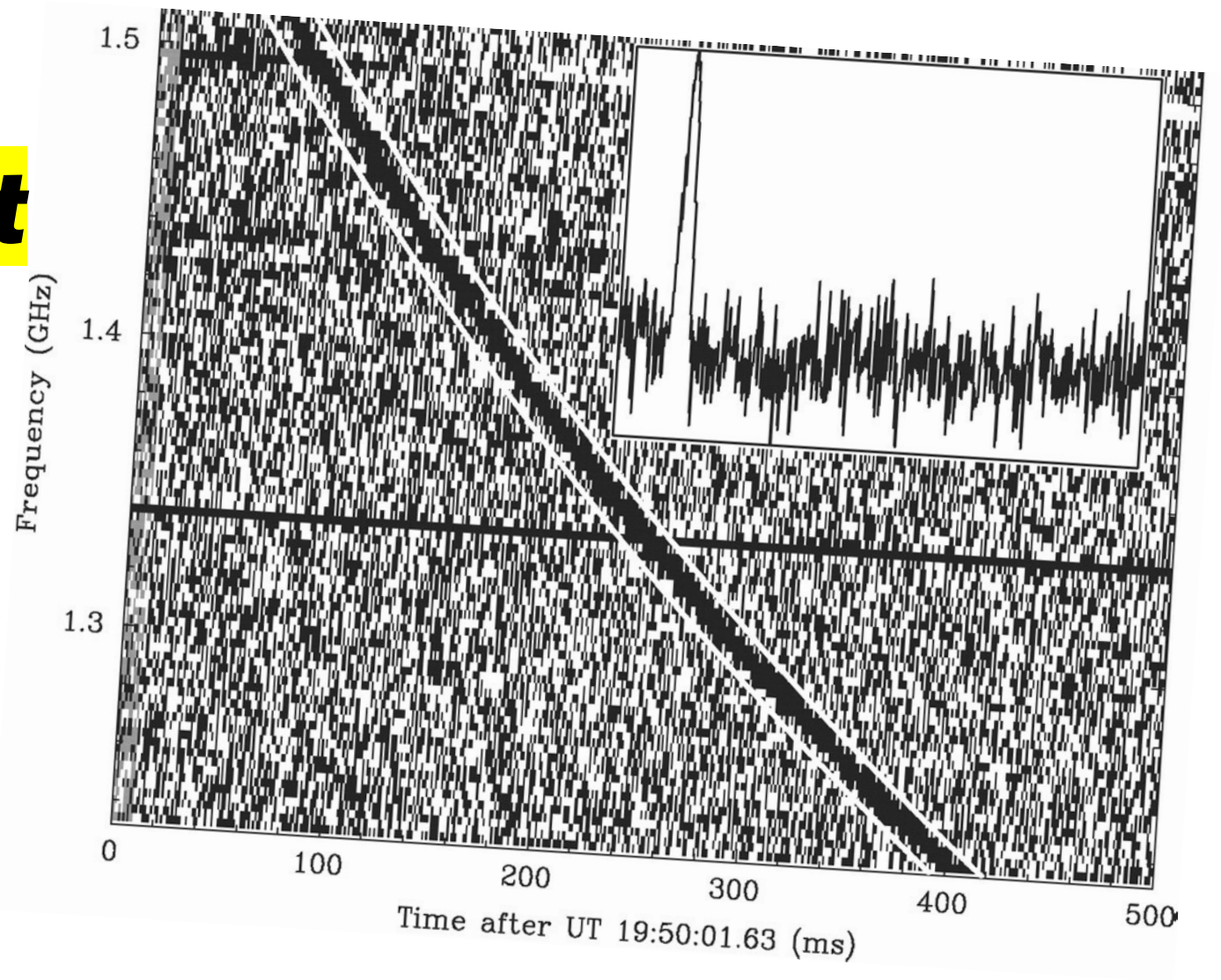
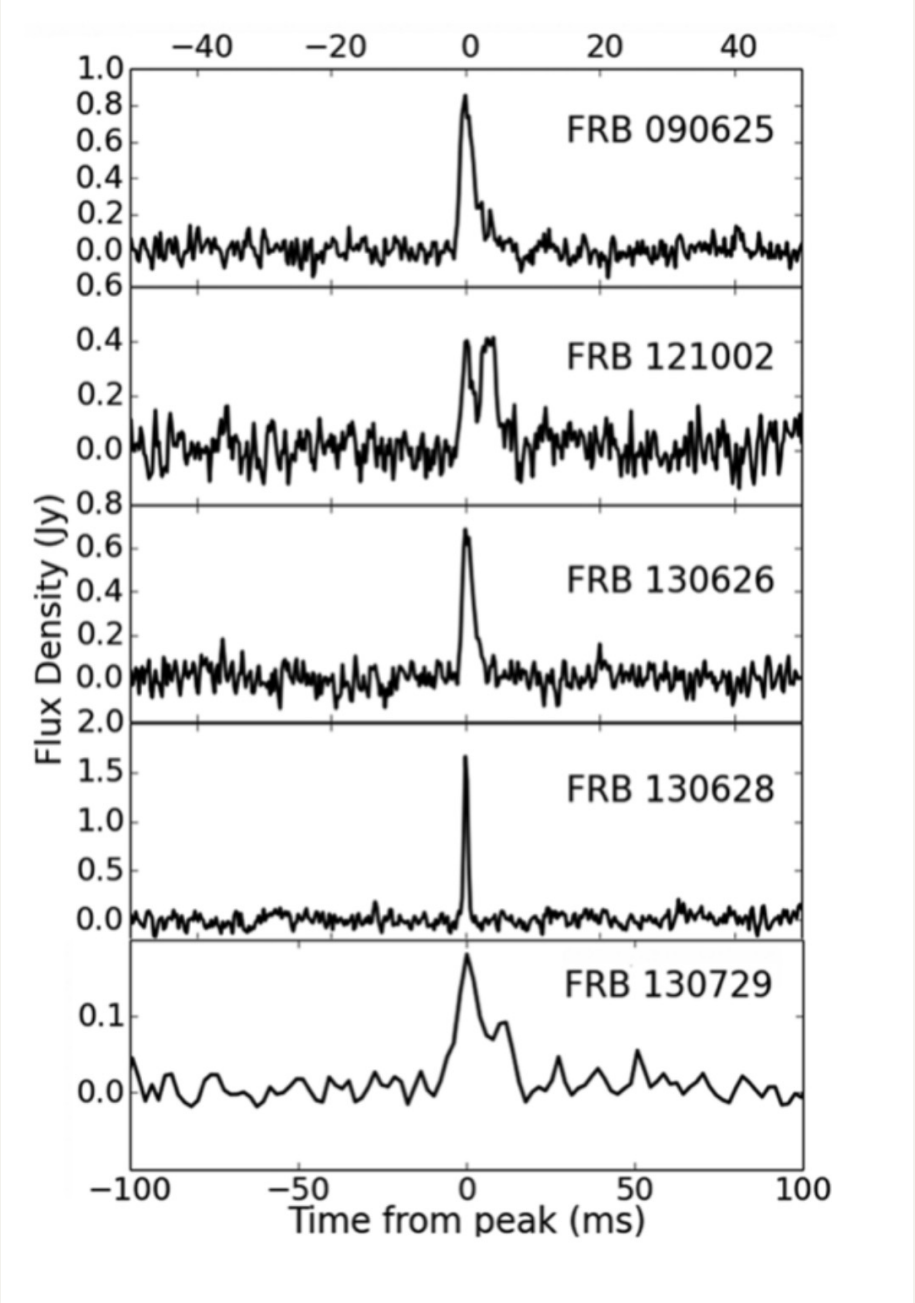


Pulse Duration

- The typical observed FRB duration (also known as width w) is some milliseconds.
- This defines a characteristic length scale of the engine that powers FRBs, that is, l >= cw = w (3×10^7) cm.
- This points towards compact objects as the most likely engines for FRB's: a neutron star or a stellar-mass black hole



Champion et al., 2016

The Lorimer burst

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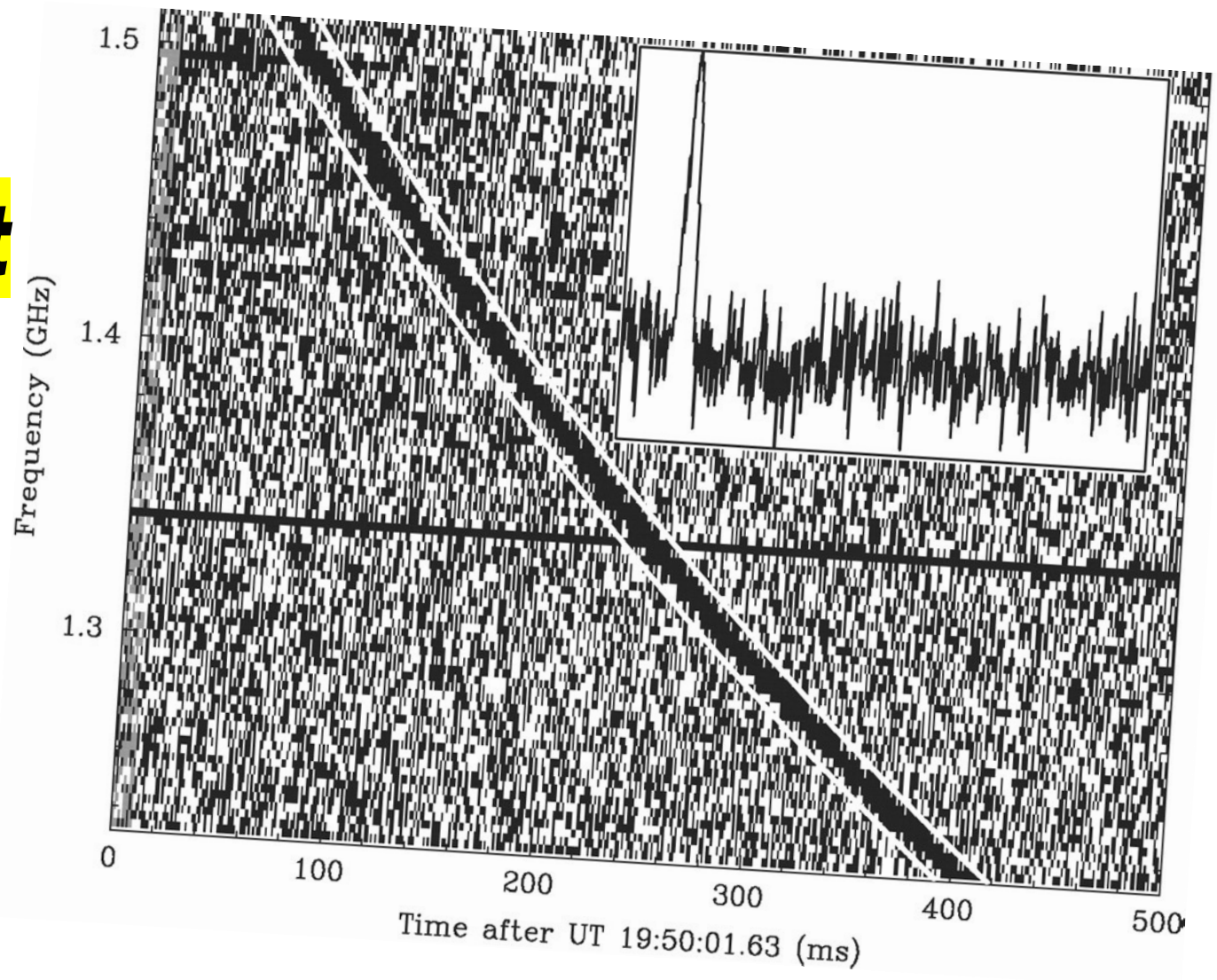
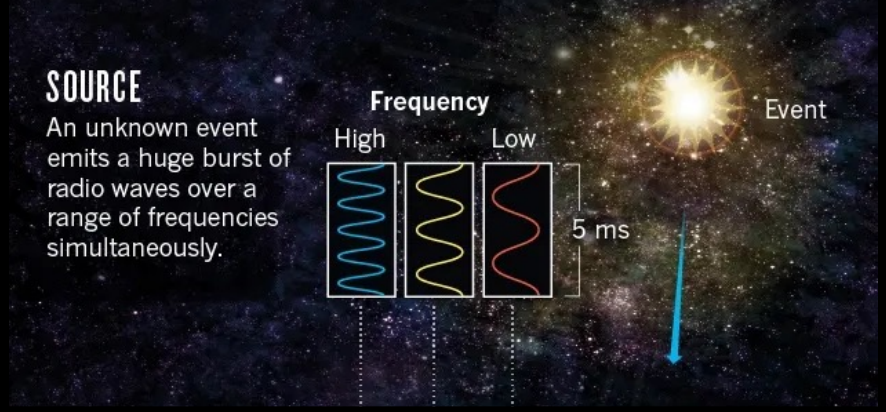
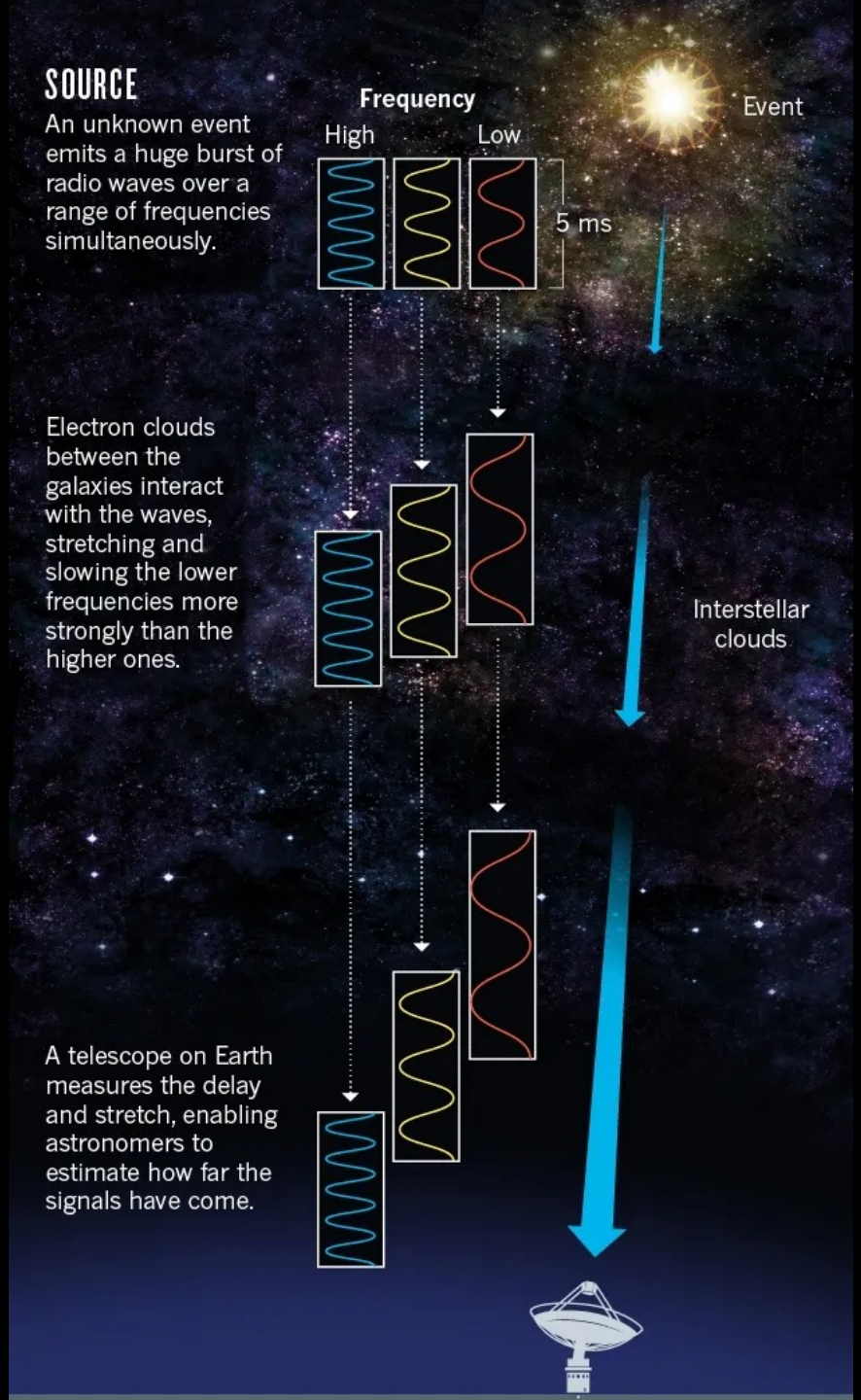


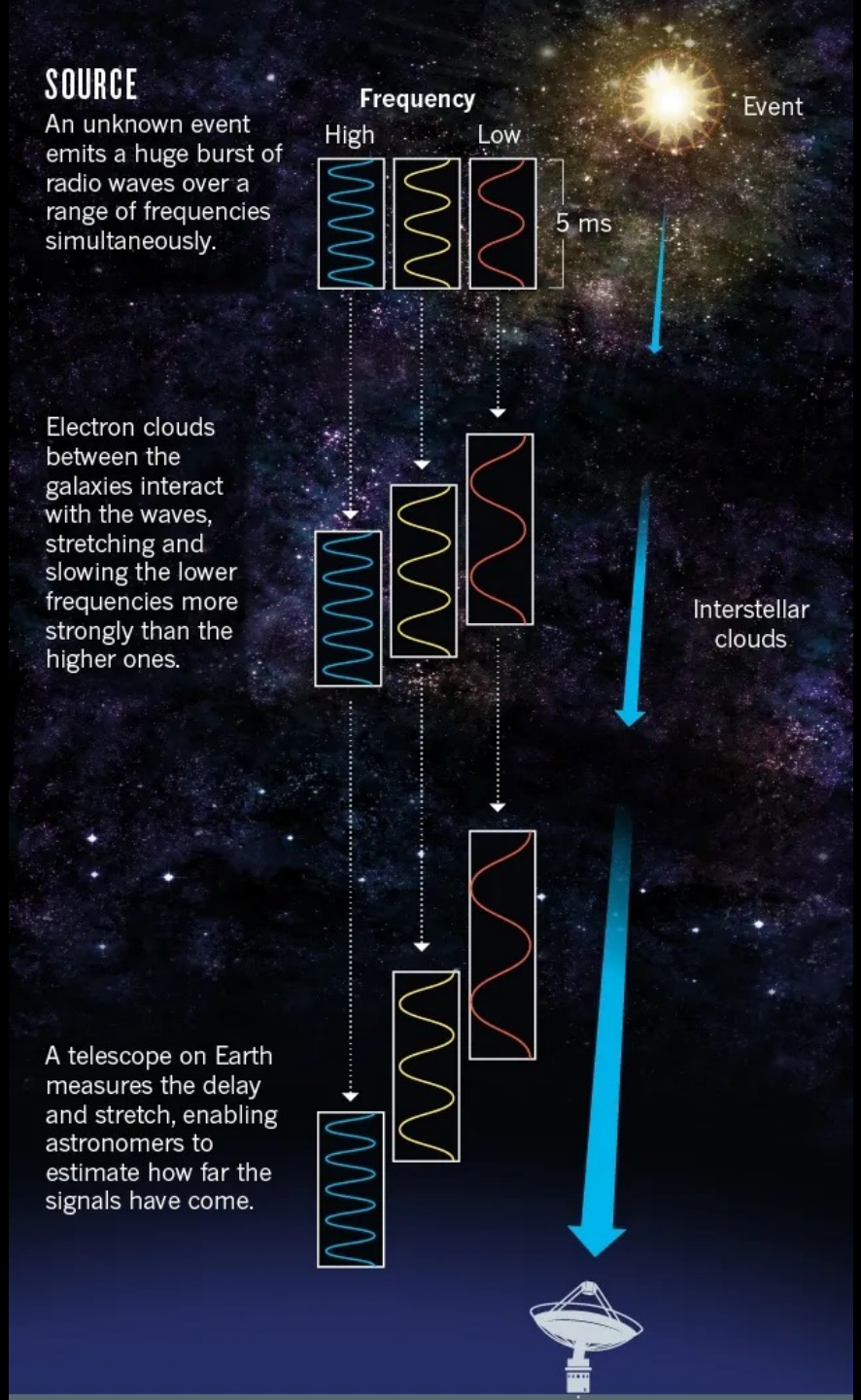

SOURCE
An unknown event emits a huge burst of radio waves over a range of frequencies simultaneously.
Frequency
High
Low
5 ms
Event

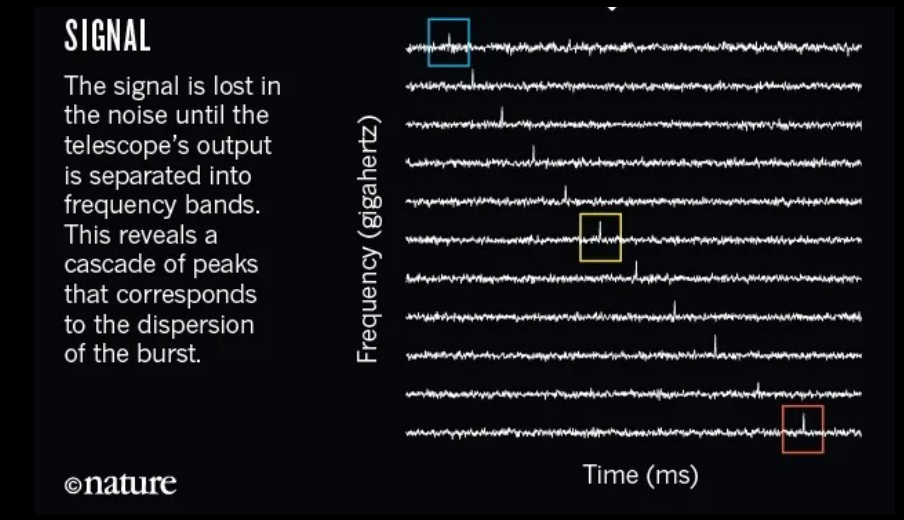
Time delay

Time delay


SOURCE
An unknown event emits a huge burst of radio waves over a range of frequencies simultaneously.
Frequency
High
Low
5 ms
Event
Electron clouds between the galaxies interact with the waves, stretching and slowing the lower frequencies more strongly than the higher ones.
Interstellar clouds
A telescope on Earth measures the delay and stretch, enabling astronomers to estimate how far the signals have come.

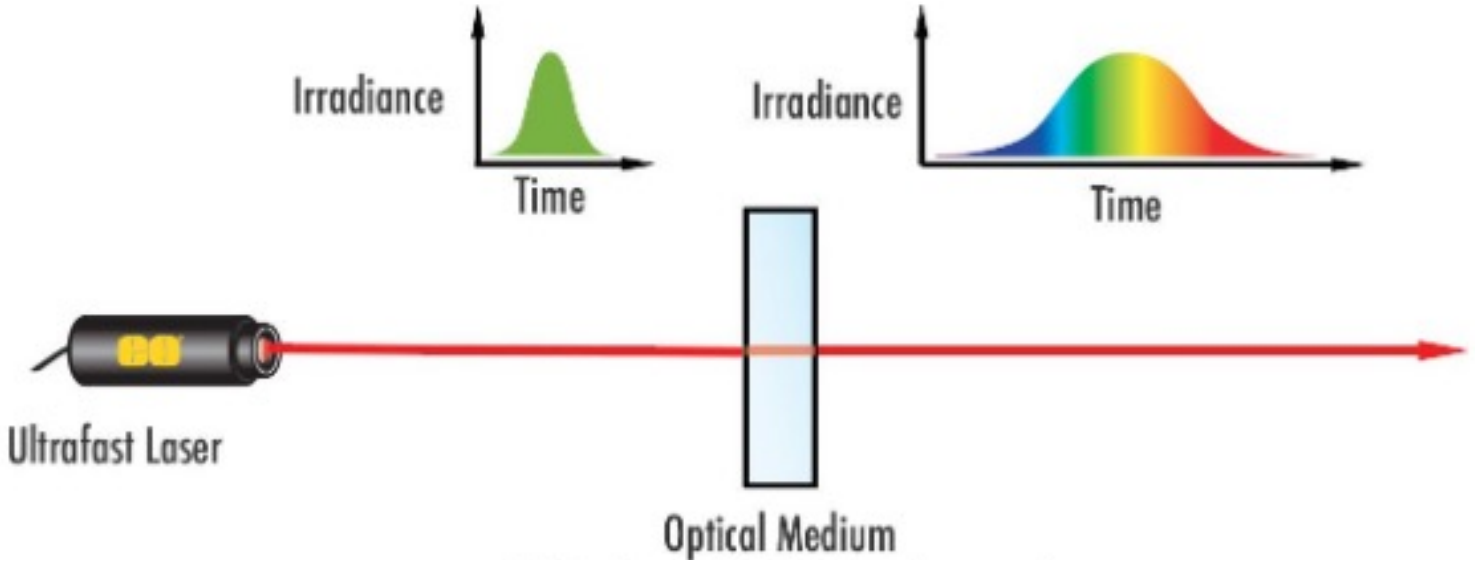
Time delay





Keane, E. F. et al., 2016

Time delay



$$v_g = c\mu \qquad \mu = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2} \qquad \nu_p = \sqrt{\frac{e^2 n_e}{\pi m_e}}$$

Time delay

$$t(\nu) = \int_0^D \frac{dl}{v_g(\nu)} \simeq \int_0^D \frac{dl}{c}\left(1 + \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right)$$

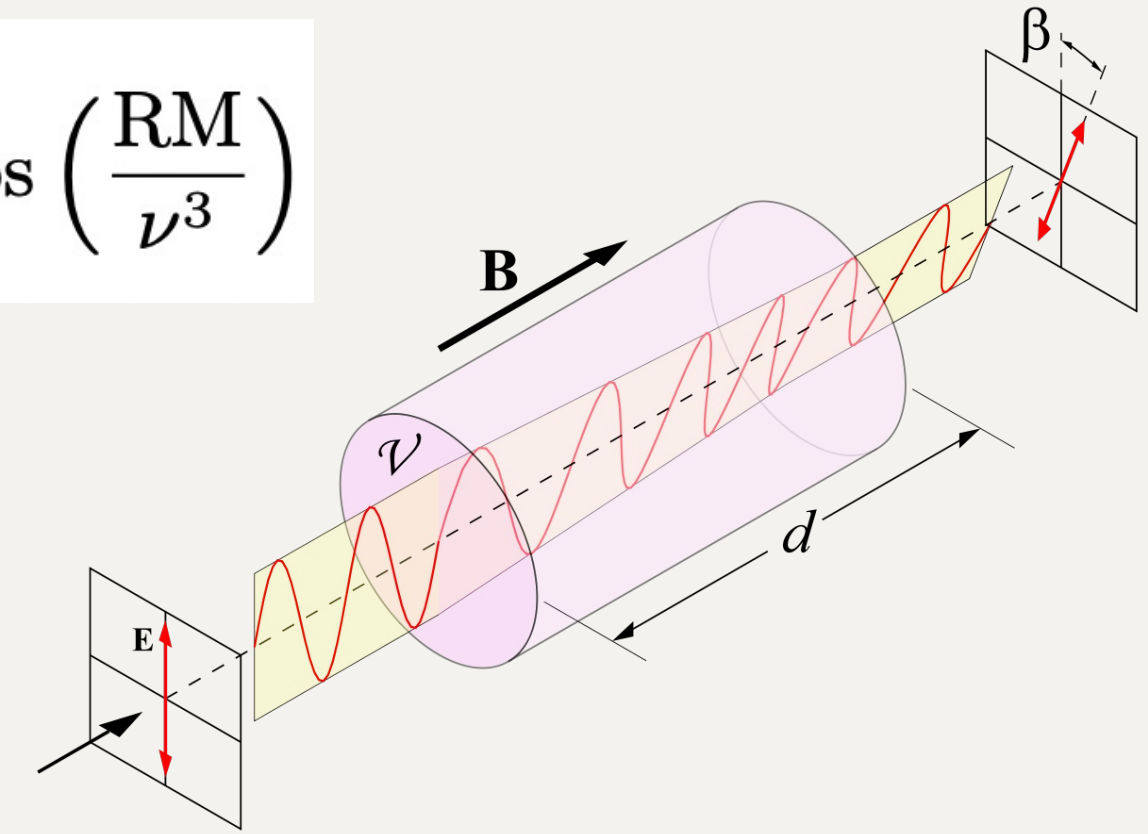
$$\mathrm{DM} = \int_0^D n_e dl$$

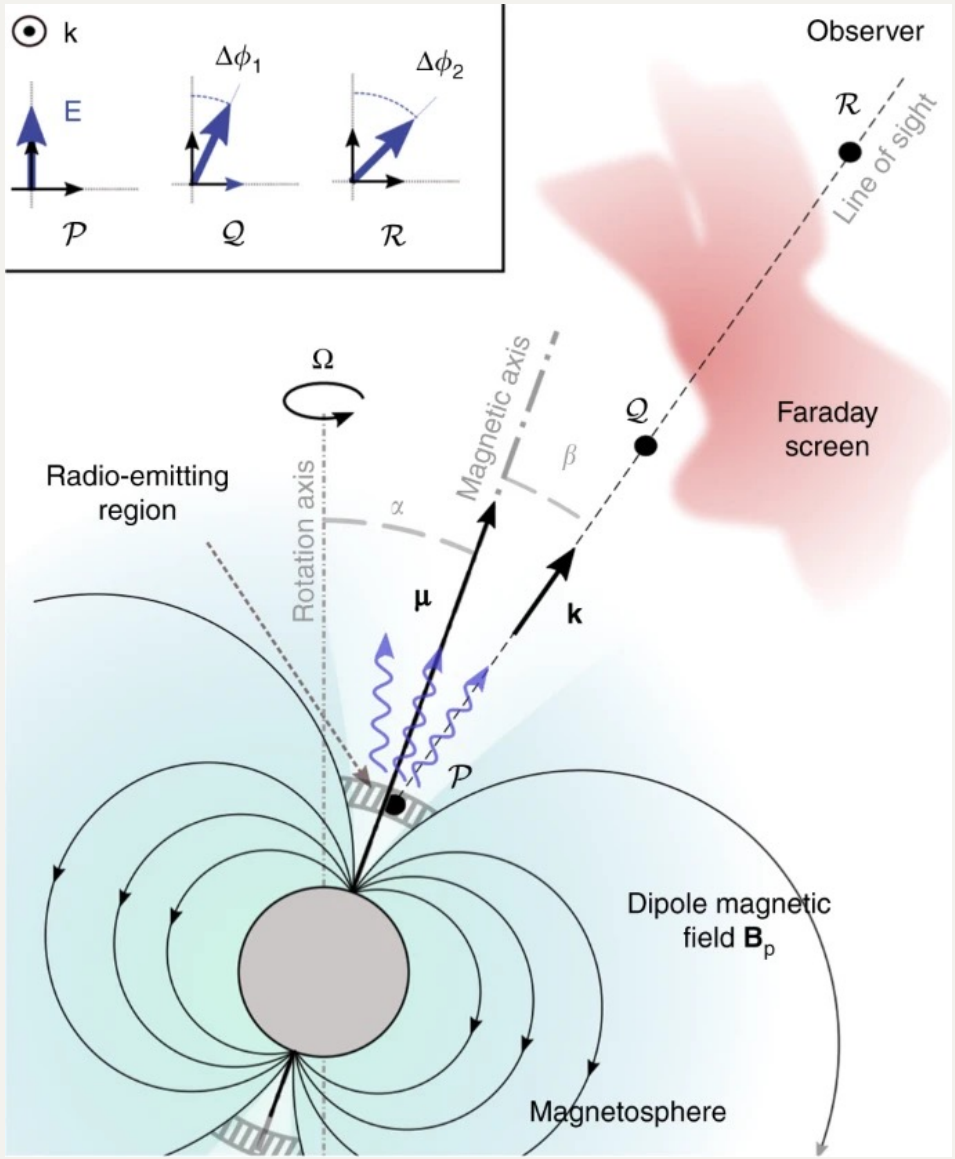
$$t(\nu) = 4.15\ \mathrm{ms}\left(\frac{\mathrm{DM}}{\nu^2}\right)$$

Even More Time Delay

$$t(\nu) = 4.15 \text{ ms} \left(\frac{\text{DM}}{\nu^2}\right) \pm 28.6 \text{ ps} \left(\frac{\text{RM}}{\nu^3}\right)$$

$$\text{RM} = 0.810 \int_0^D n_e \boldsymbol{B} \cdot d\boldsymbol{l}$$

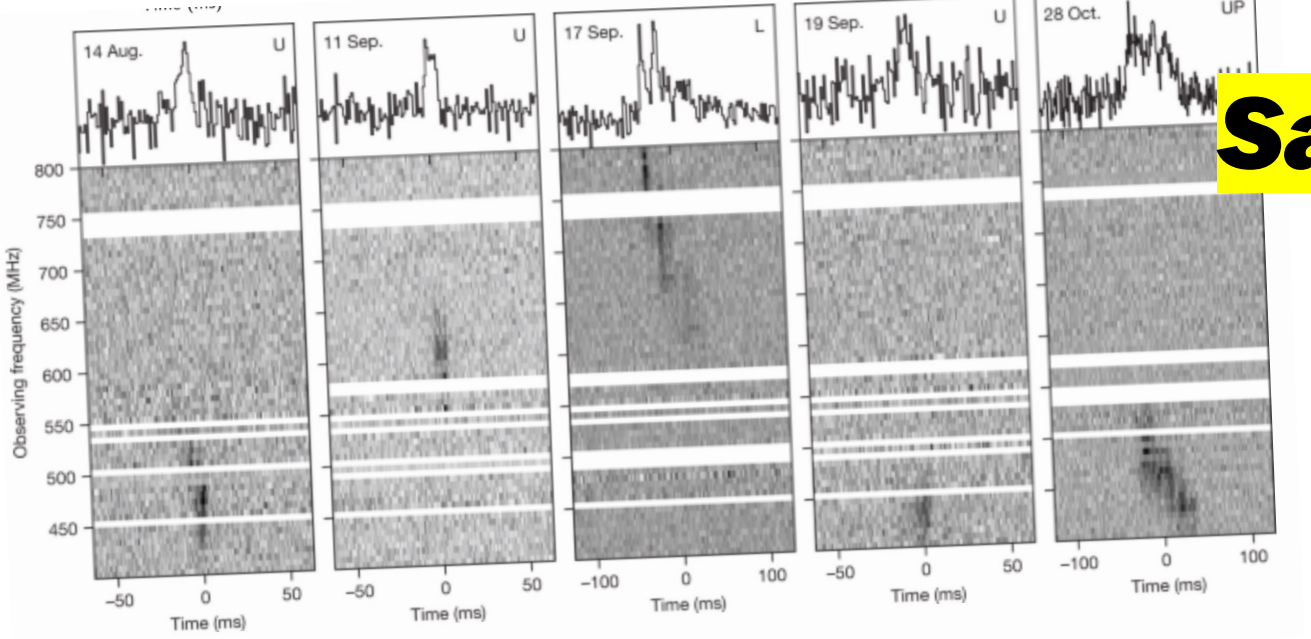




Gueroult et al., 2019

Rotation Measure

- Evidence of large rotation measure in excess of the Galactic value was reported for FRB 110523, which suggested a dense magnetized plasma associated with the FRB.
- Extreme RM variations were observed for FRB's. This points towards a dynamical evolving magnetized environment around repeating FRB sources

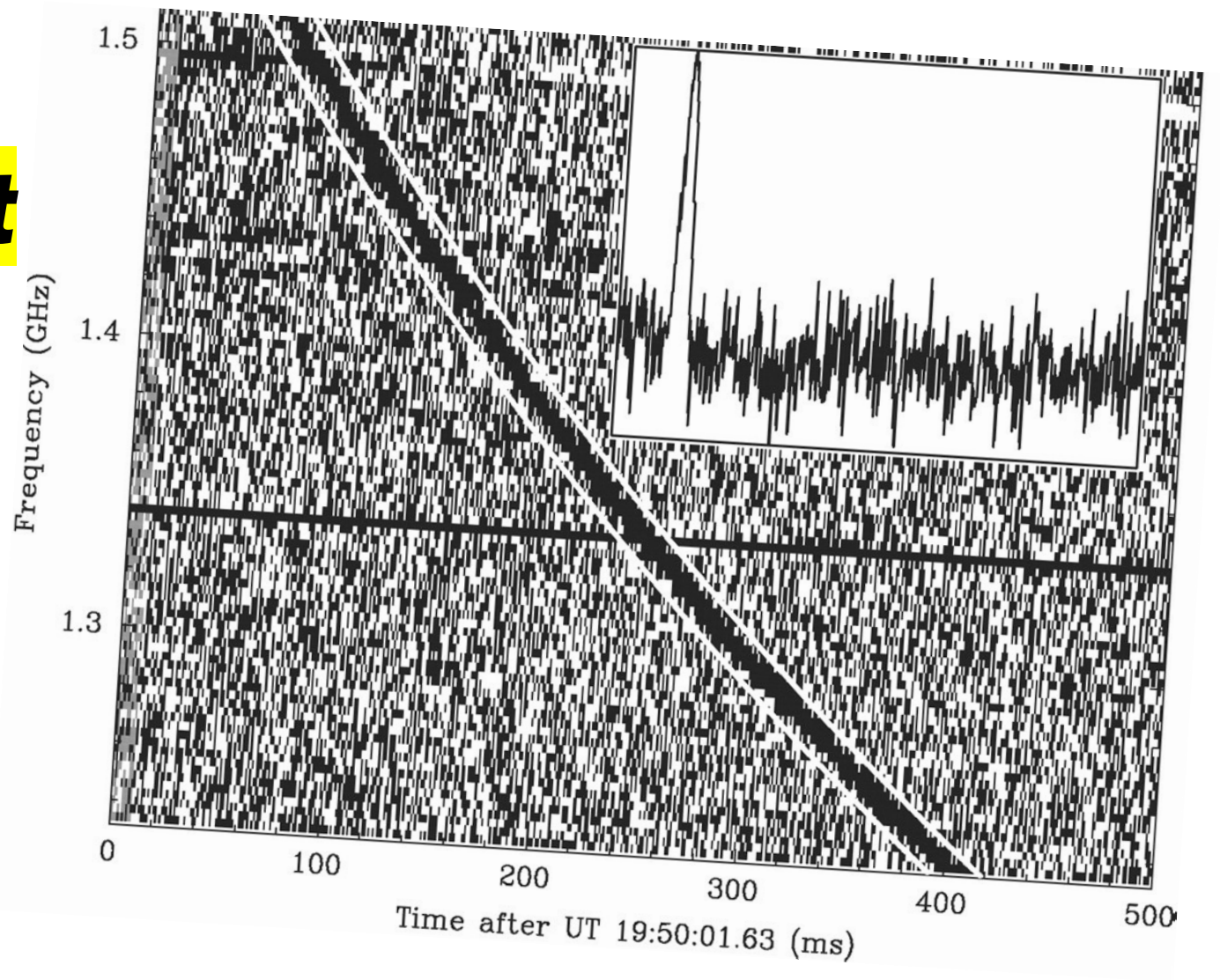


Sad Trombone

- Down-drifting of pulses with frequency.
- Such a behavior is often seen in repeating FRB bursts.
- Likely related to the intrinsic radiation physics of FRB’s.

The Lorimer burst

- Burst duration
- Frequency dependent time delay
- Energetics

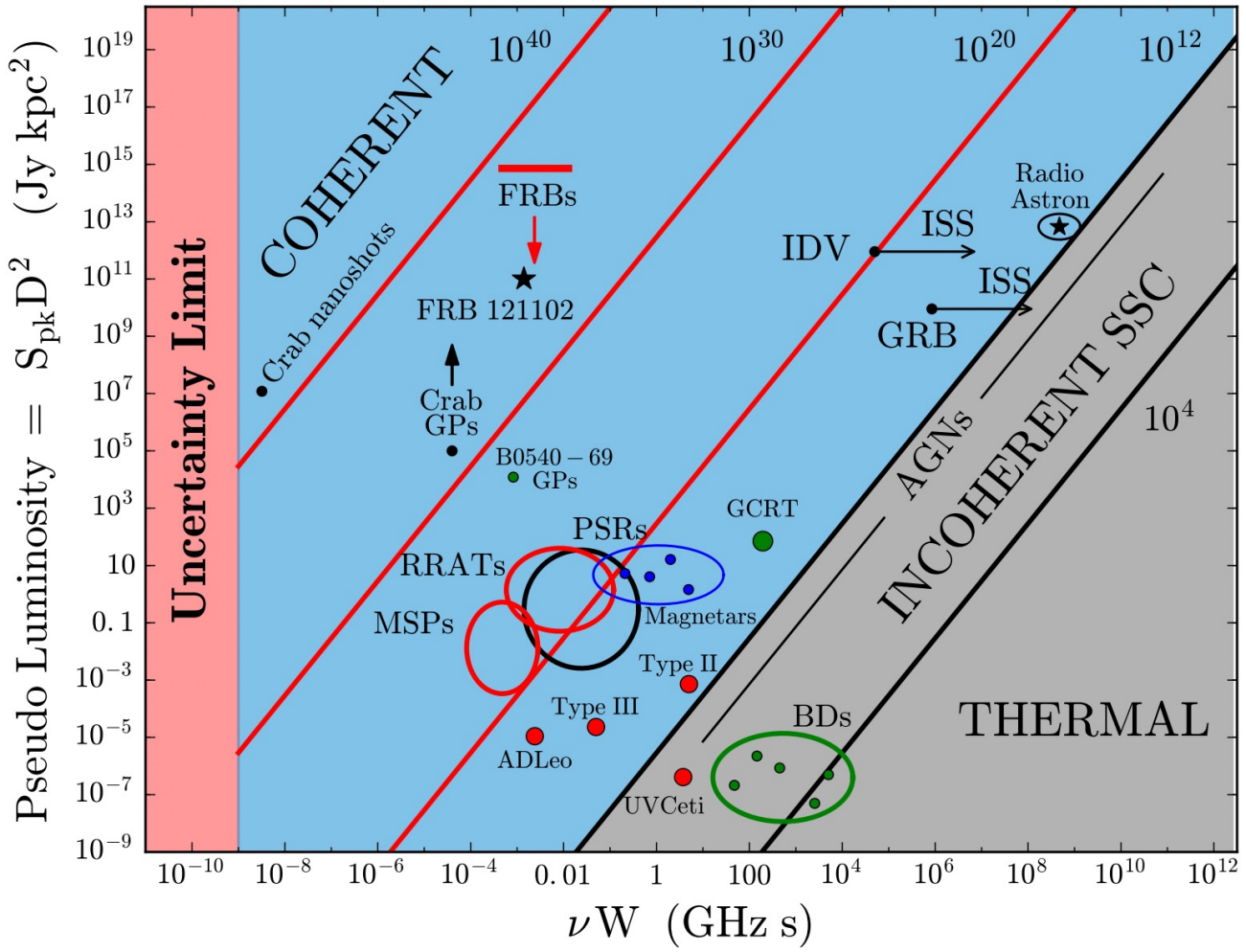


Energetics & Brightness Temperature

$$F_\nu = I_\nu \Omega \sim \frac{a^2}{D^2} I_\nu,$$

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

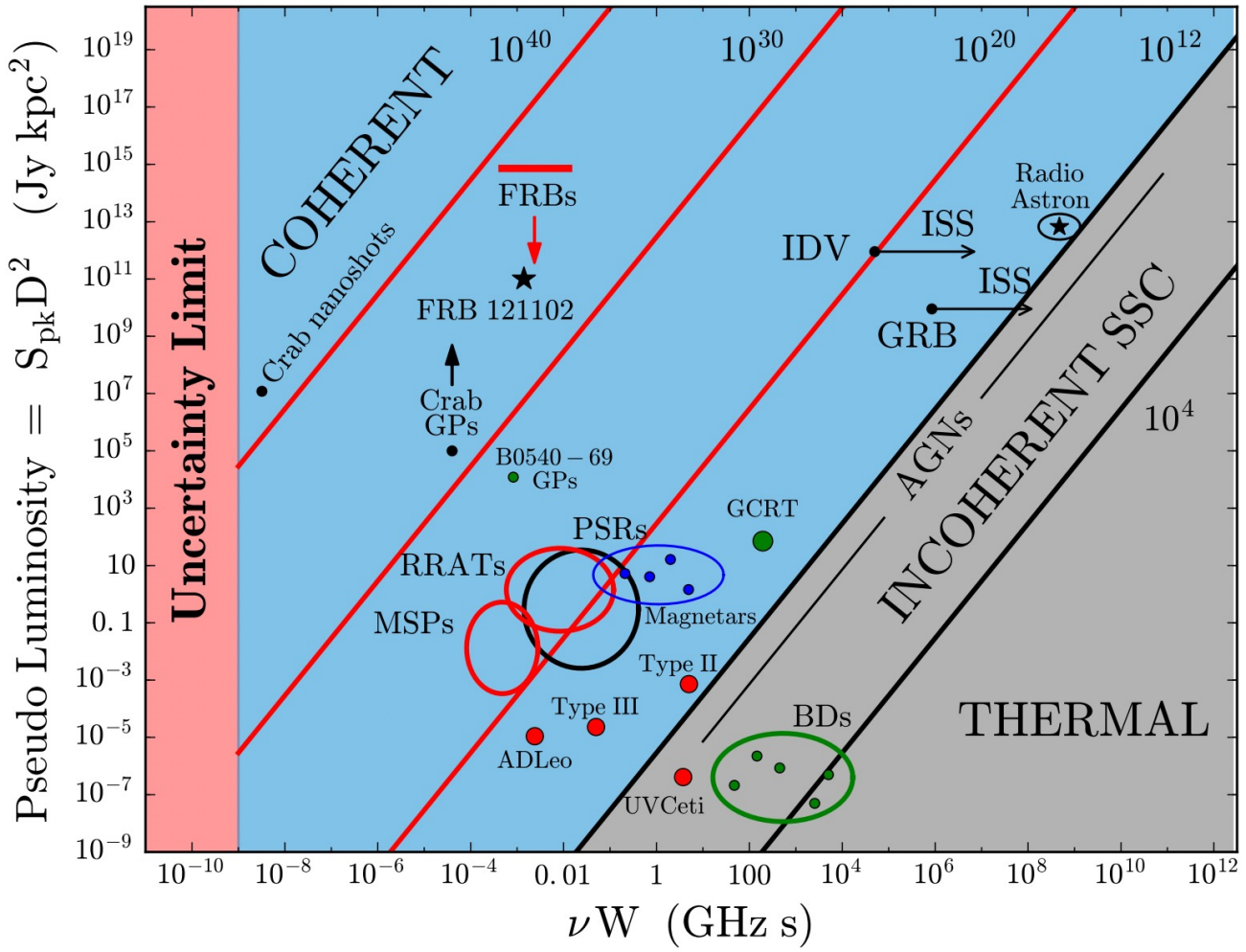
$$T_b \sim \frac{F_\nu D^2}{k_B \tau^2 \nu^2} = 7 \cdot 10^{35} \frac{F_{\nu,\mathrm{Jy}} D^2_{\mathrm{Gpc}}}{\tau^2_{\mathrm{ms}} \nu^2_{\mathrm{GHz}}} \,\mathrm{K}.$$



Cordes, 2019

Brightness Temperature

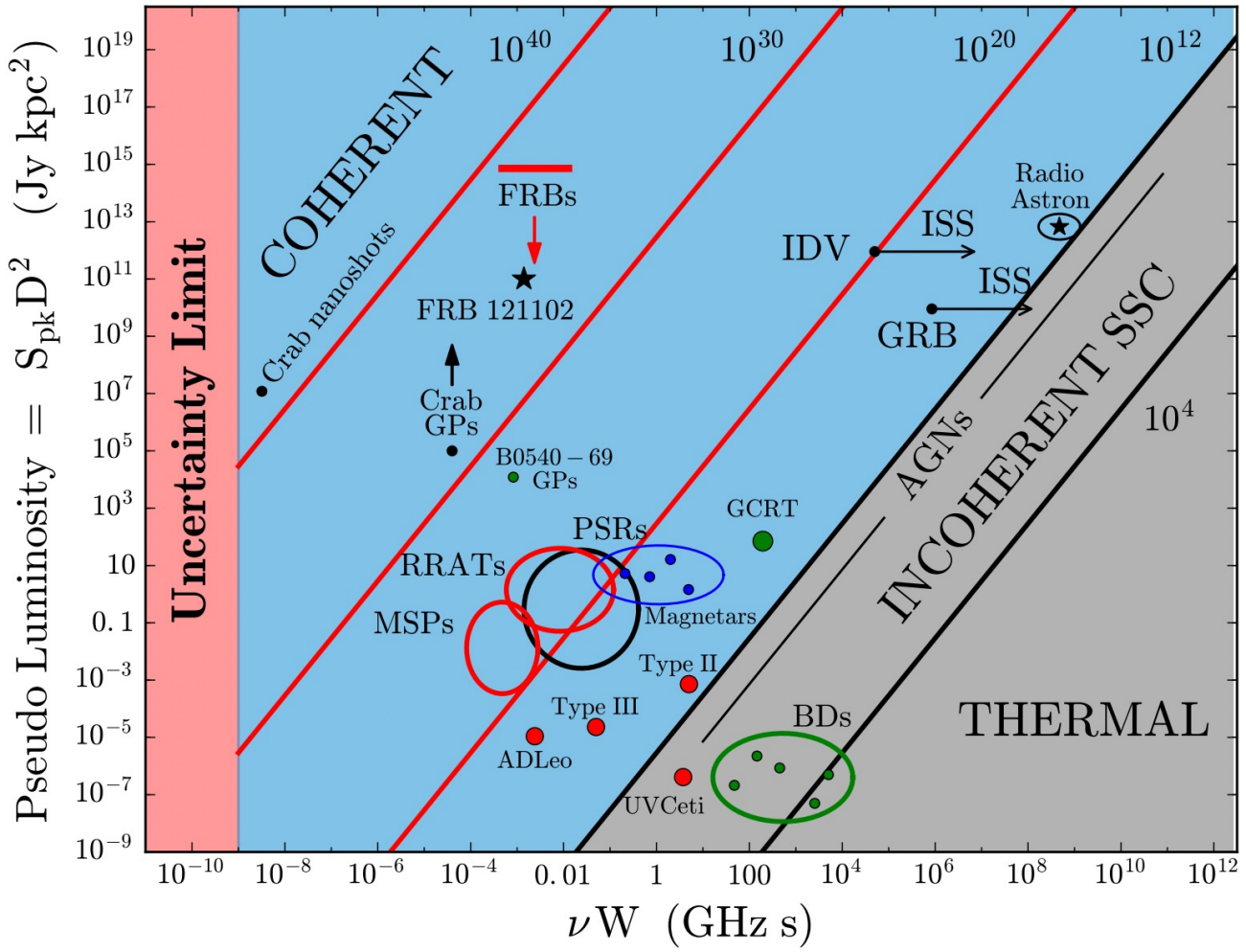
The physical meaning of T_b is the imaginary temperature of the emitter if the photons and the electrons that emit the photons were in thermal equilibrium.



Brightness Temperature

If particles are accelerated by some field to deviate from thermal equilibrium, then the radiation becomes non-thermal.

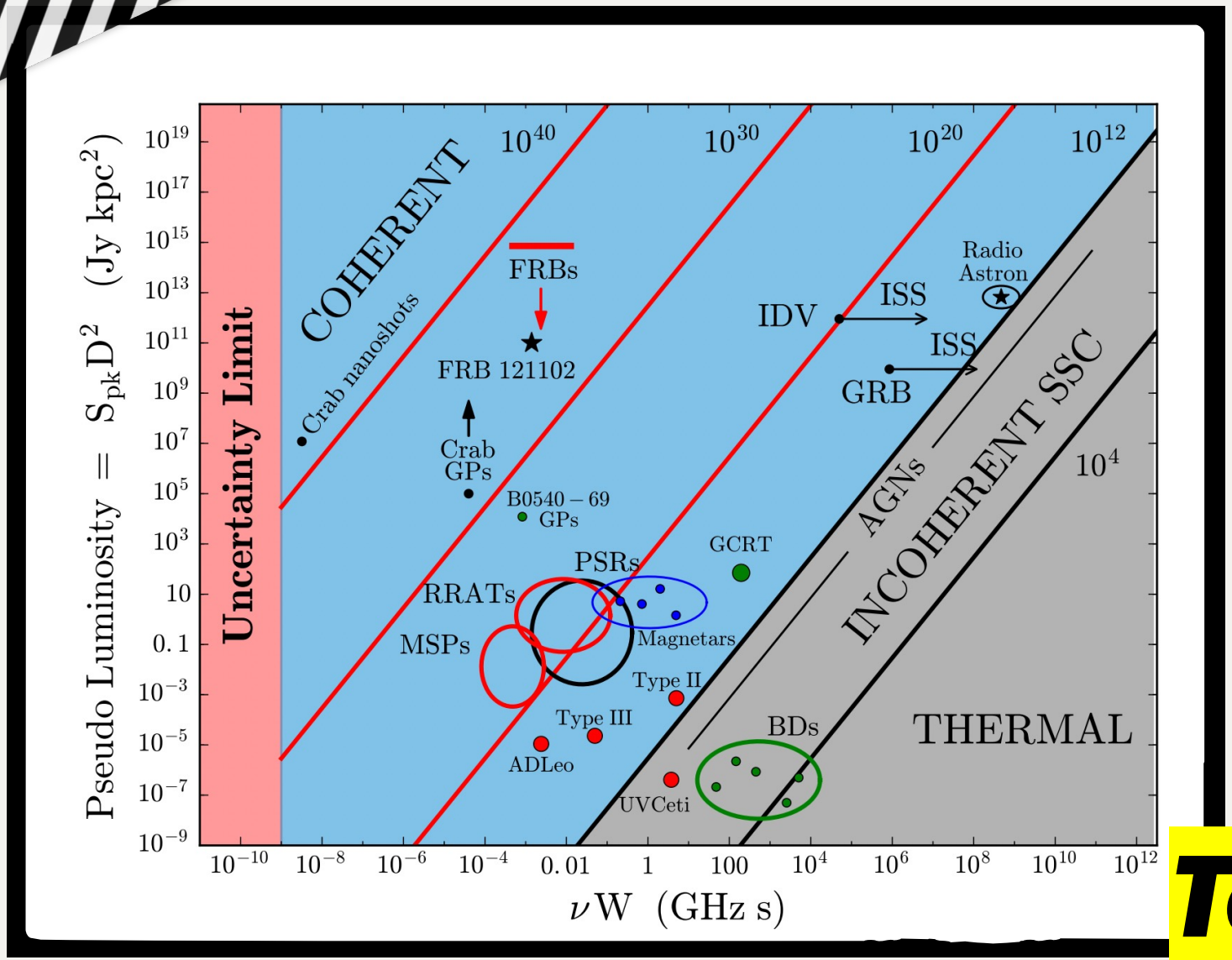
Cordes, 2019



Cordes, 2019

Brightness Temperature

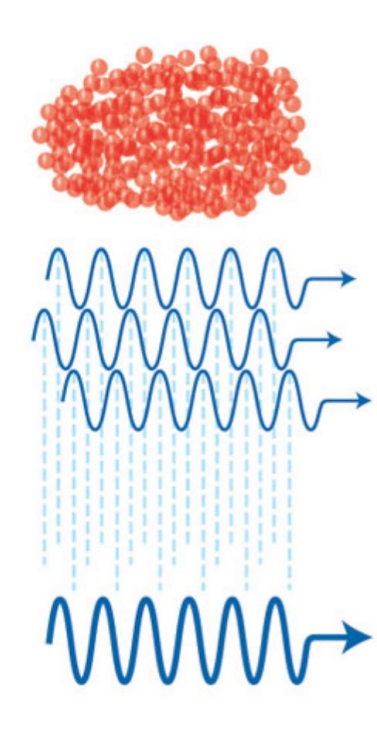
When the apparent source brightness temperature approaches the equivalent kinetic temperature of the emitting particles, self absorption becomes important.



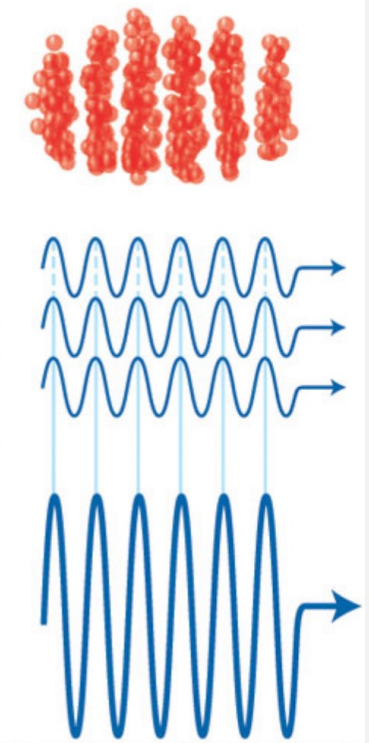
Cordes, 2019

High Brightness Temperature

Incoherent vs. Coherent Emission



Incoherent emission: particles randomly phased
$P \propto N$



Coherent emission: electrons bunched at radiation wavelength
$P \propto N^2$

FRB Models

- Global Properties:
  + Event-rate Density
  + Energy Budget
  + Host DM and RM

- Radiation Mechanism:
  + Coherent Radio Emission
  + Brightness Temperature
  + Duration

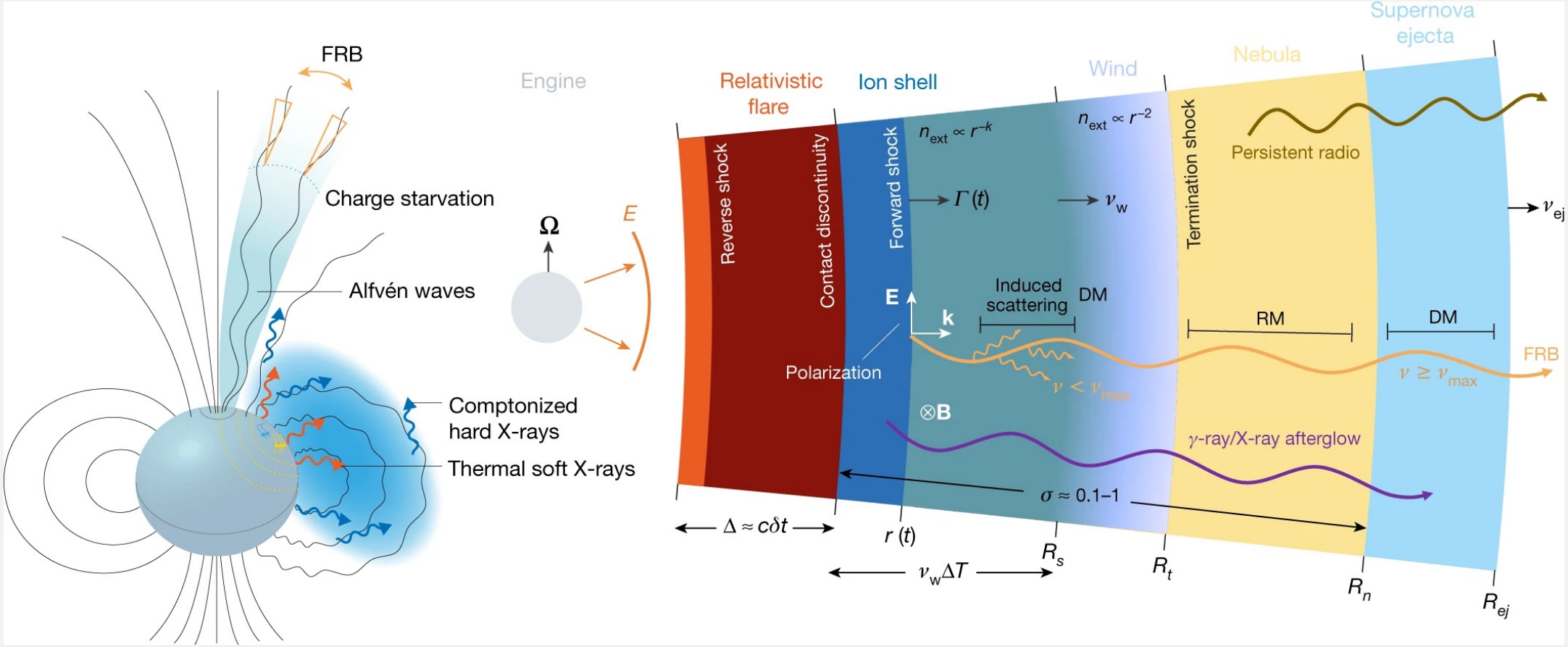
Magnetospheric

(Pulsar-like)

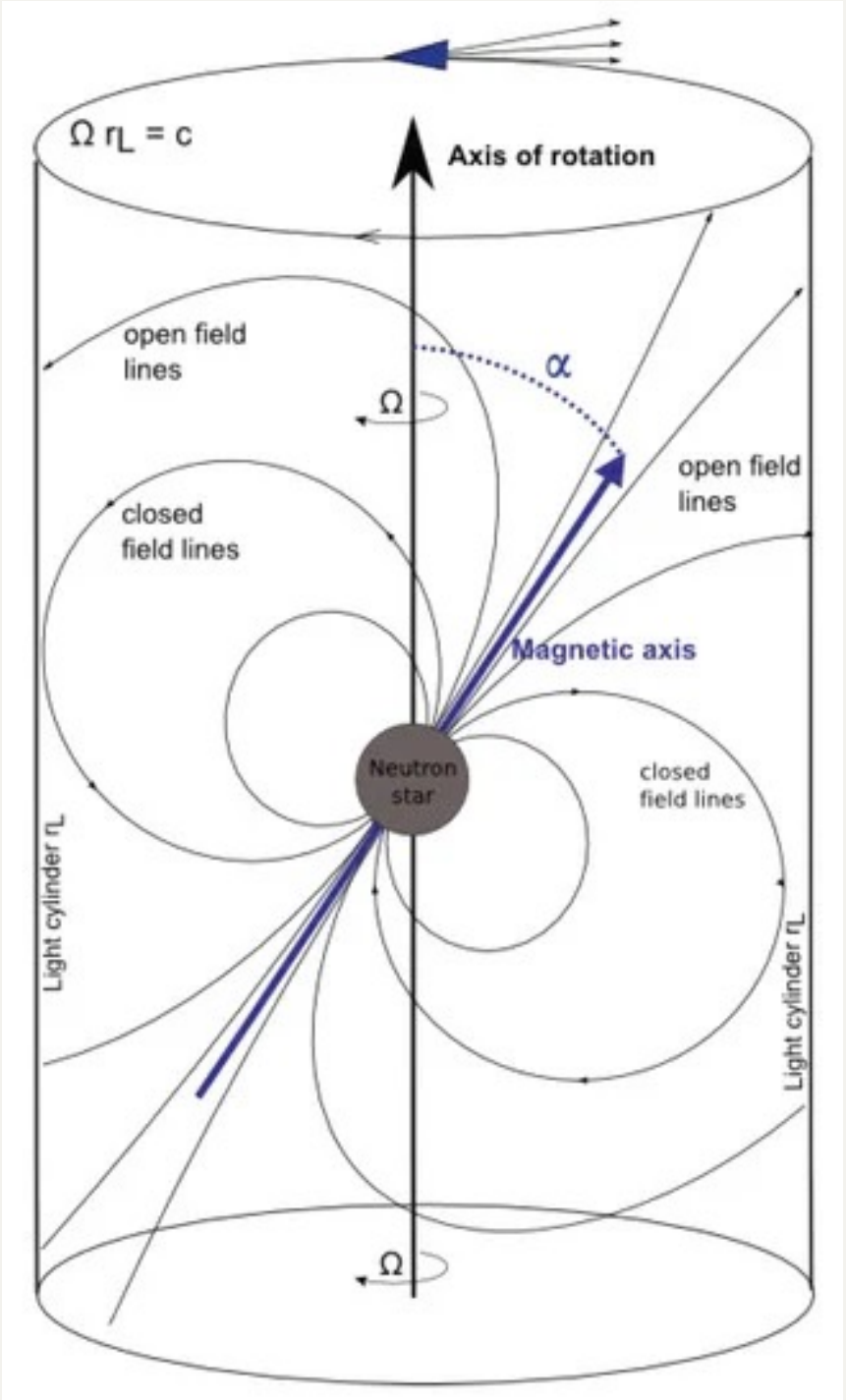
Relativistic Shocks

(GRB-like)

Models: Pulsar-like & GRB-like

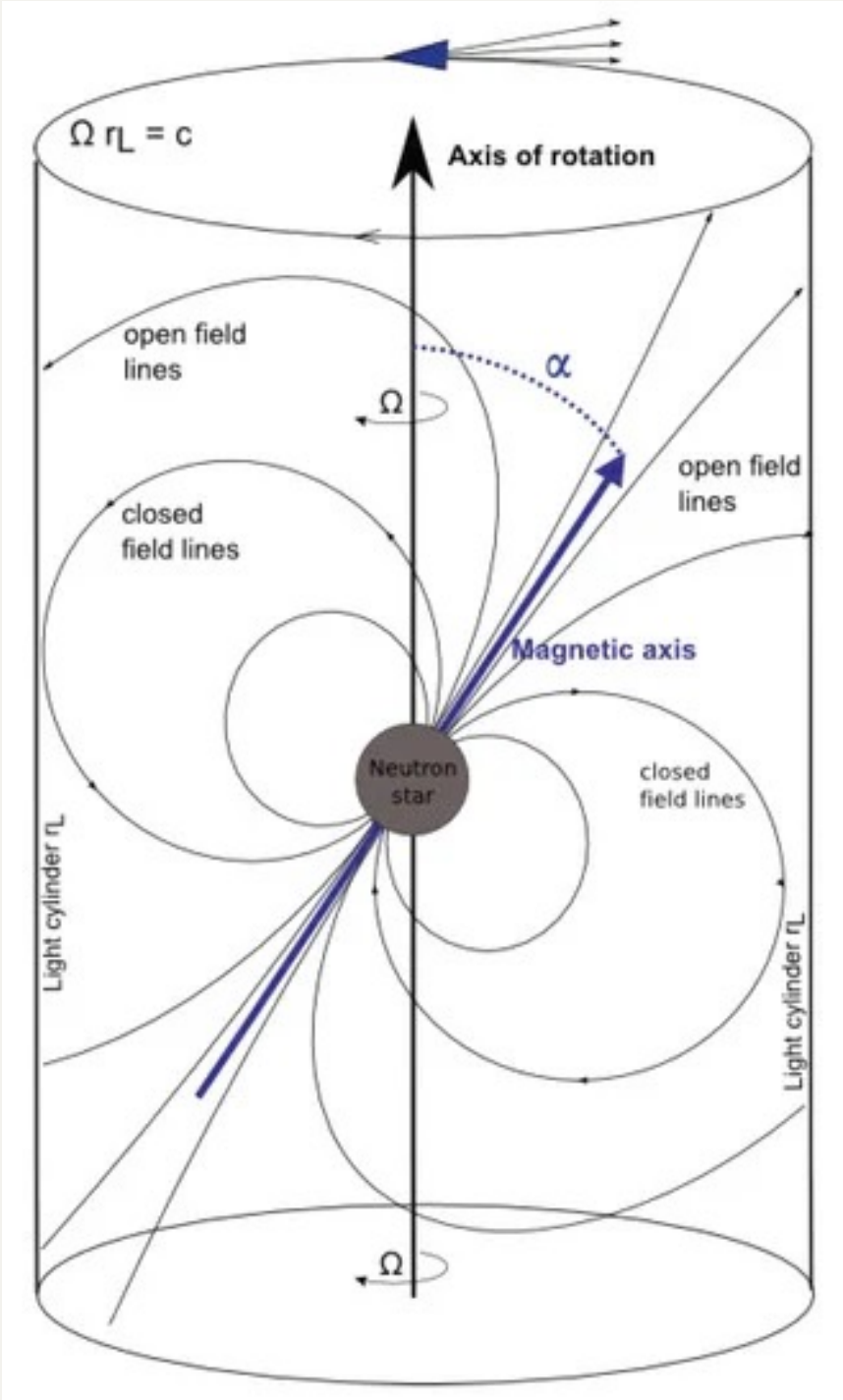


Pulsar Models: Coherent Curvature Radiation



Pulsar Models: Coherent Curvature Radiation

- Emission due to charged particles accelerated along open (curved) magnetic field lines.



Pulsar Models: Coherent Curvature Radiation

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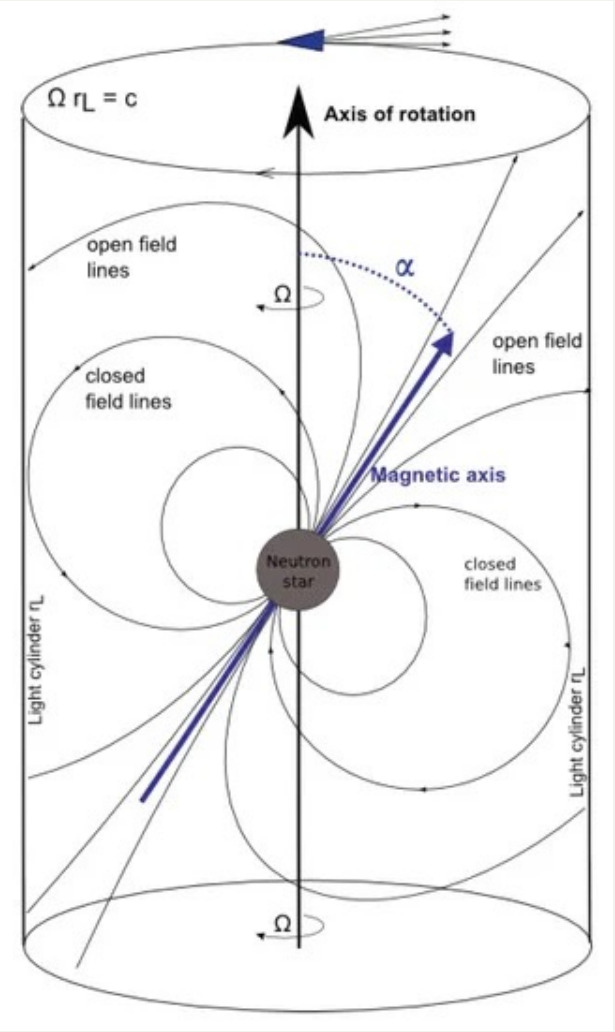
- We can invoke the two-stream instability to generate charged bunches.



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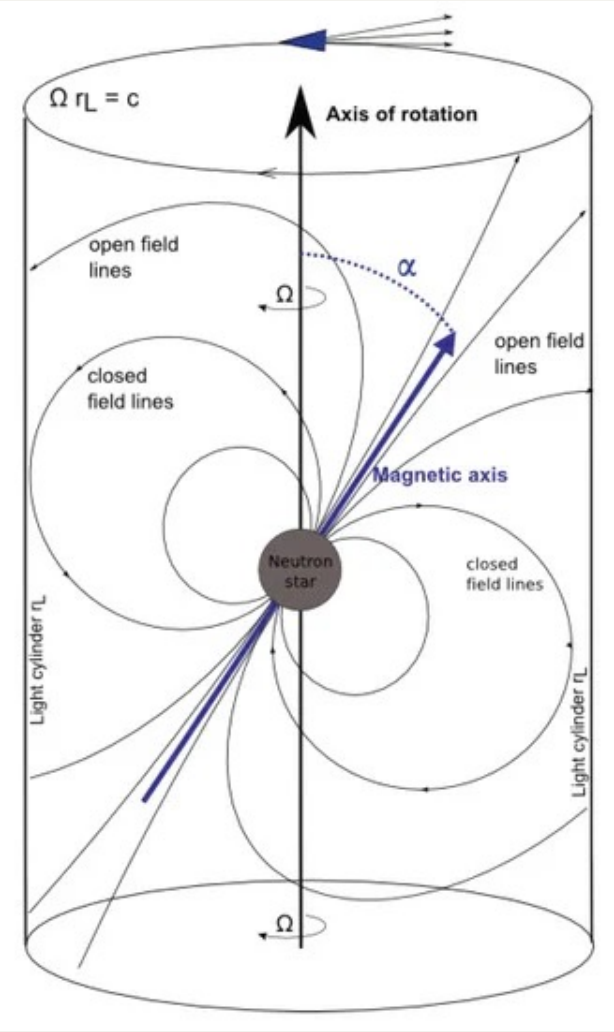
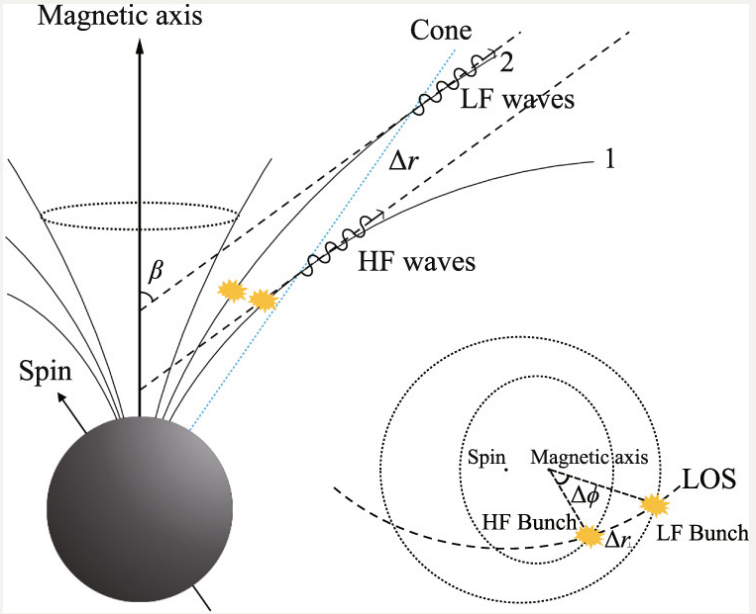
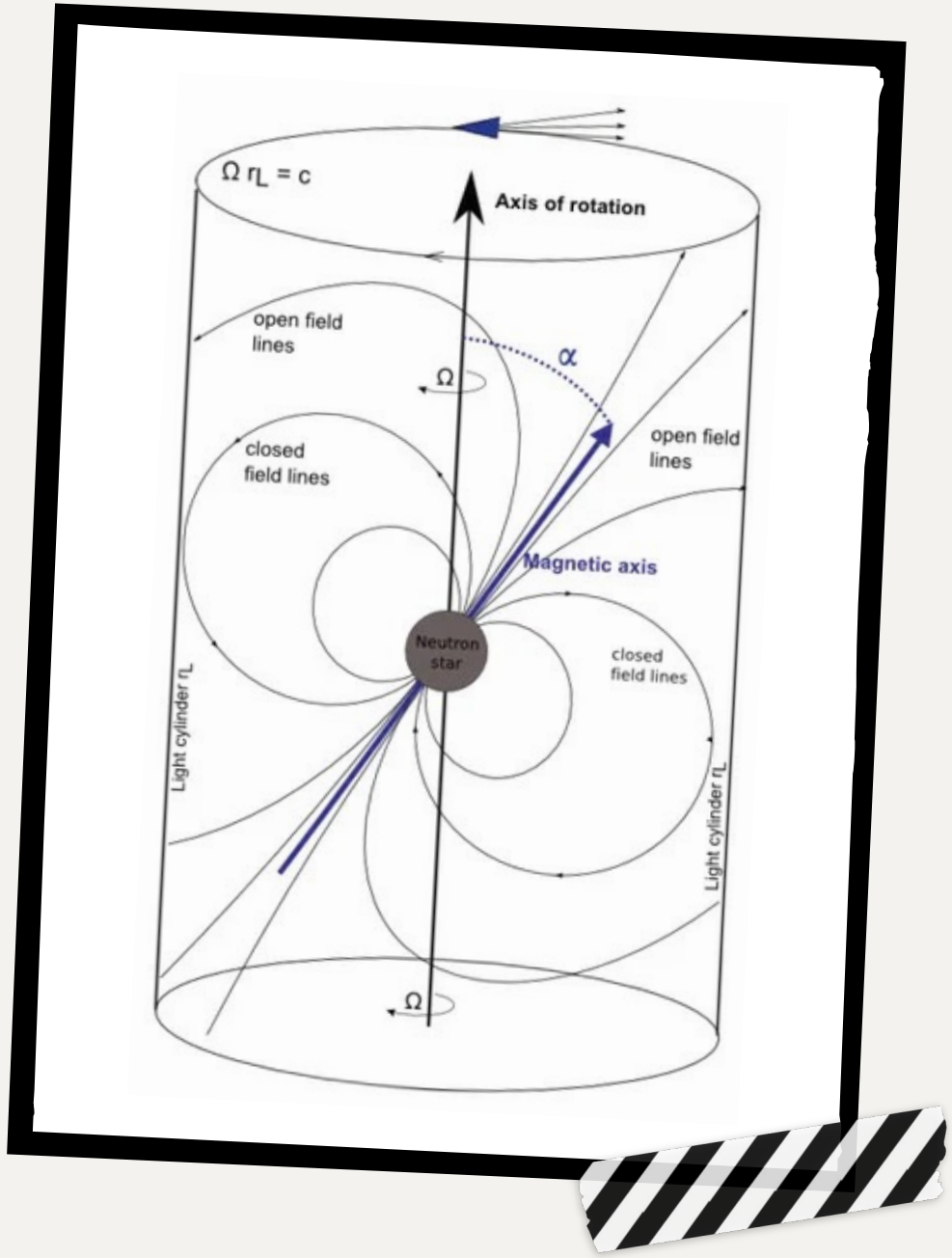


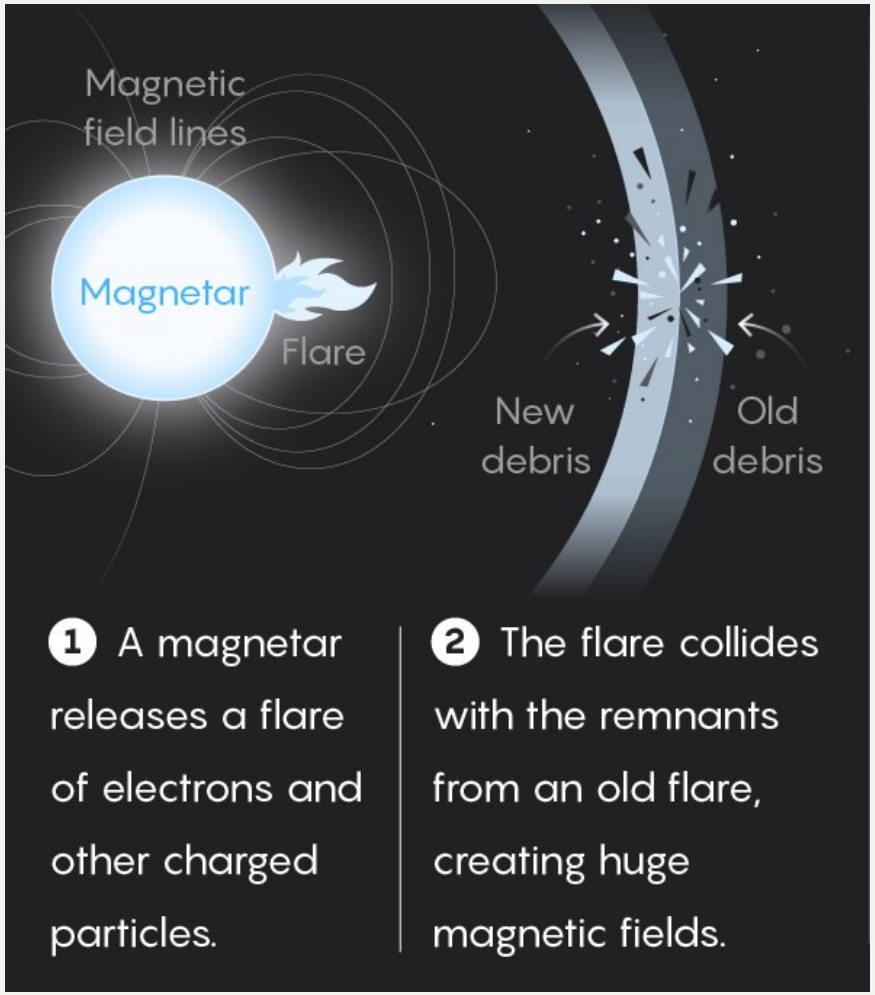


Drawbacks

- Fast cooling time
- Formation and dispersal of bunches
- Suppression due to plasma effects
- Curvature Emission has too broad of a spectrum



GRB Models: Relativistic Shock



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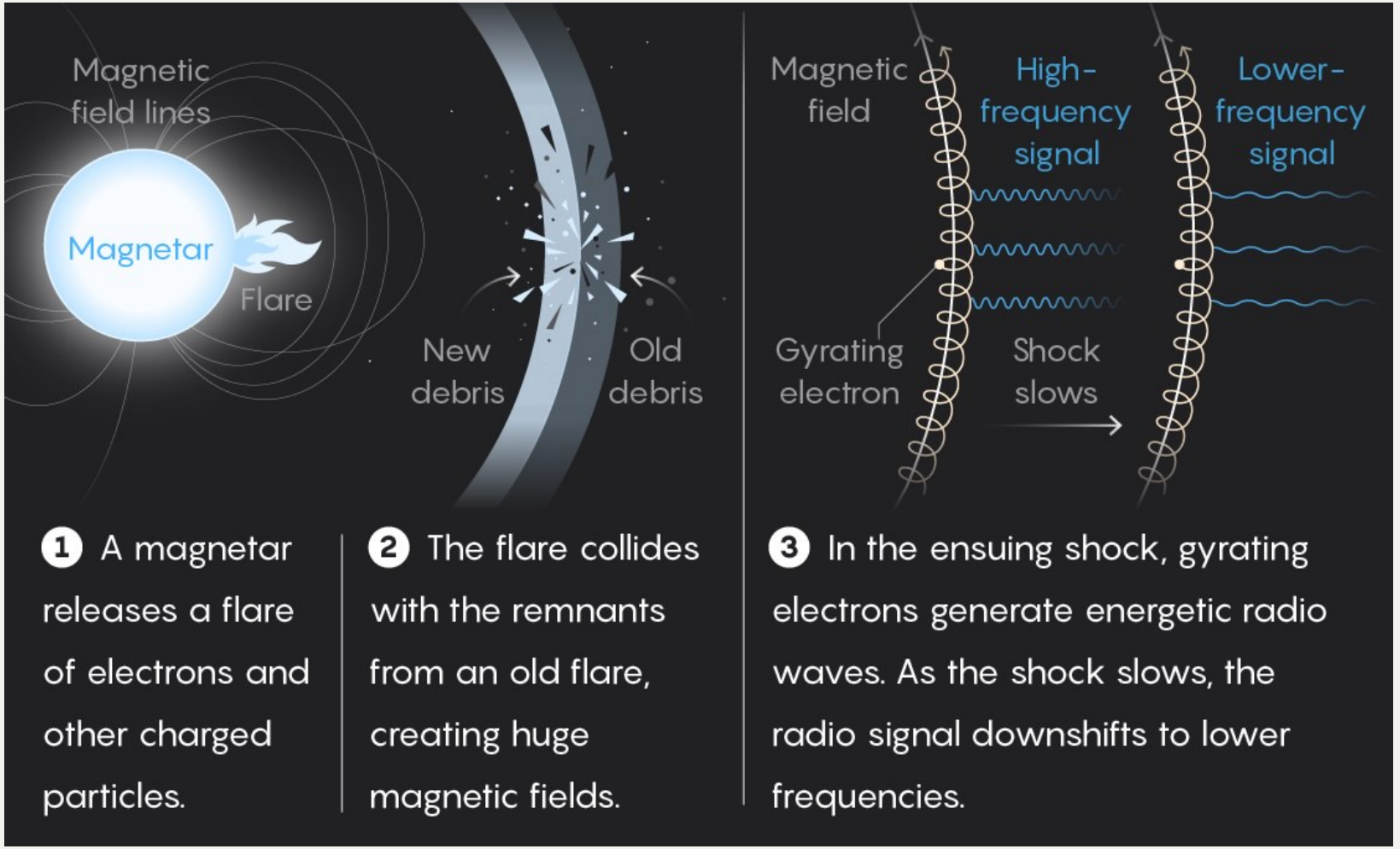
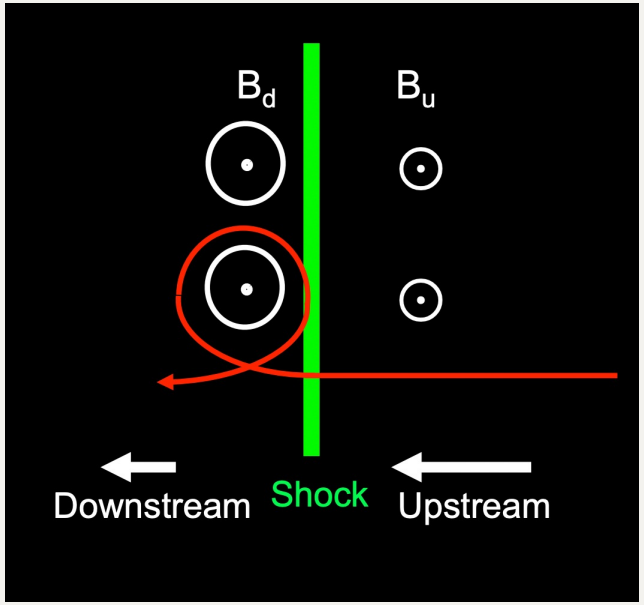


Drawbacks

- Model requires the existence of ordered magnetic fields in the upstream.
- Irregularities in the field configuration would greatly suppress the coherent emission.
- The upstream media must remain “cold”. Random motion of electrons in a hot plasma would smear up the degree of coherence, resulting in suppressed emission.
- Process has low radio efficiency so requires a high energy budget.



Counterparts?

- The radio burst was associated with a hard X-ray burst (HXRB) from a Galactic magnetar named Soft Gamma-ray Repeater (SGR) J1935+2154 during one of its active phases.
- Deep monitoring of the magnetar by FAST suggests that most of X-ray bursts emitted by the magnetar are not associated with FRBs.
- Magnetar FRB-HXRB associations are rare.

Open Questions

- Are there genuinely non-repeating FRBs? If so, what could be the plausible source(s)?
- Are there engines other than magnetars that could power repeating FRBs?
- How is FRB emission generated, from magnetospheres (pulsar-like mechanism) or relativistic shocks (GRB-like mechanisms)?
- What is the mechanism that produces coherent emission from FRBs?

Questions?