Revealing pulsar radio emissions in electron-positron plasmas by massively parallel Particle-in-cell code simulations

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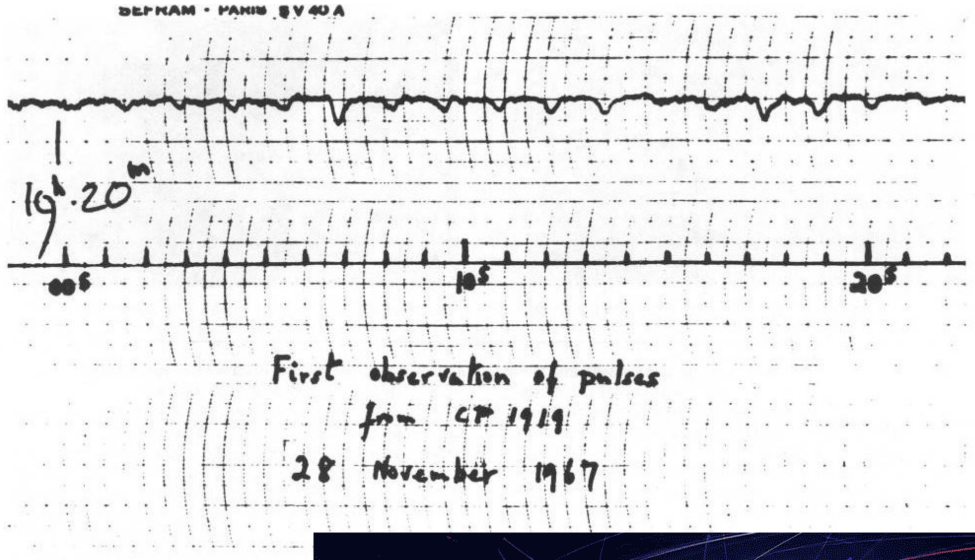
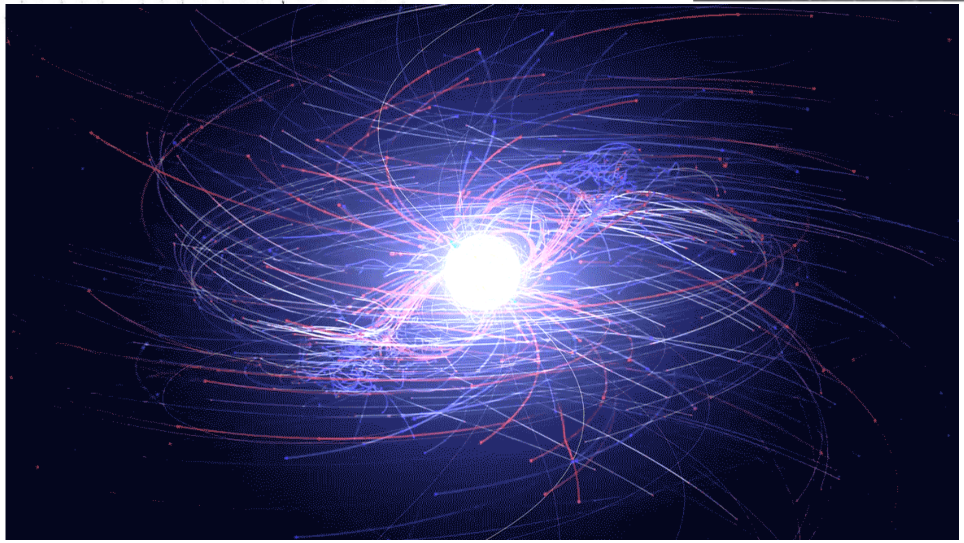
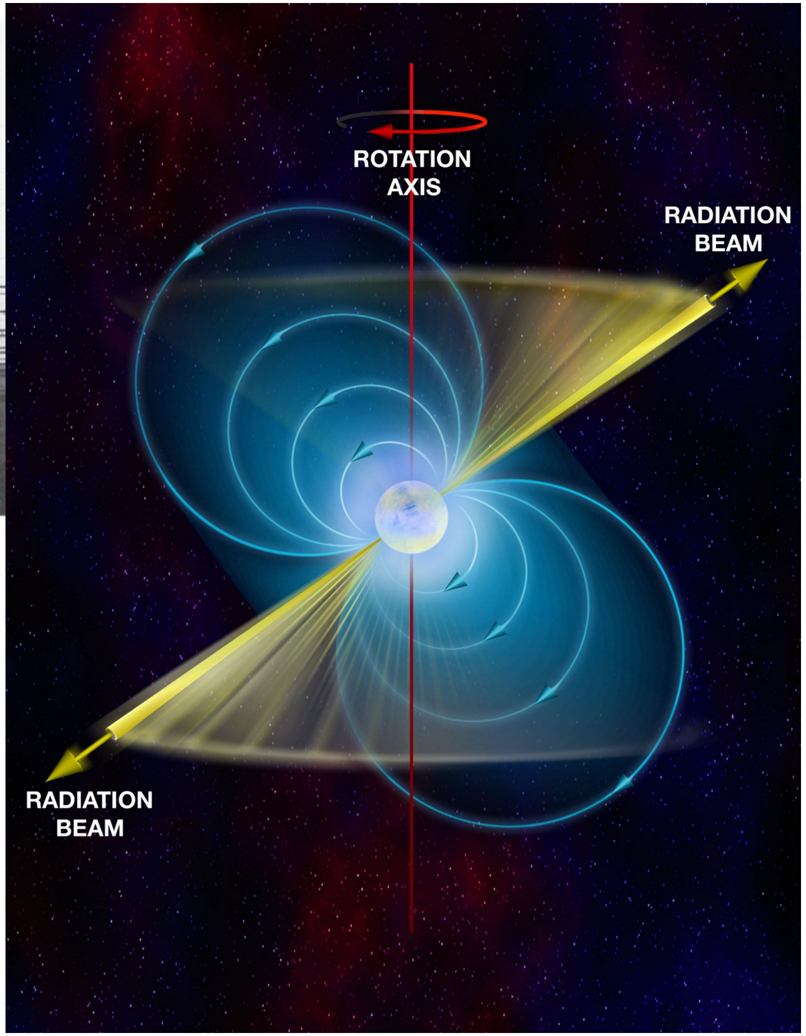
Pulsar radio emission mechanisms are uncertain

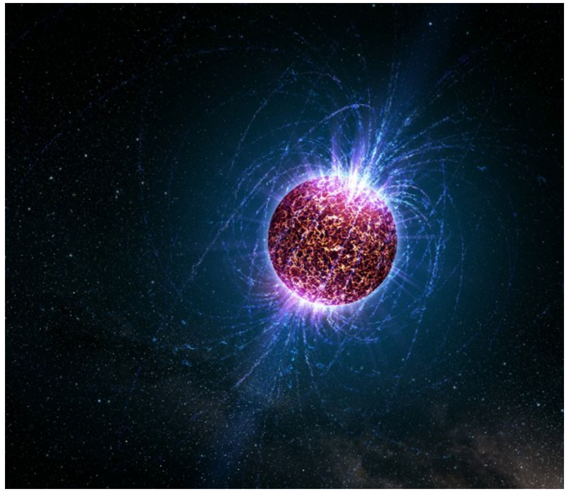






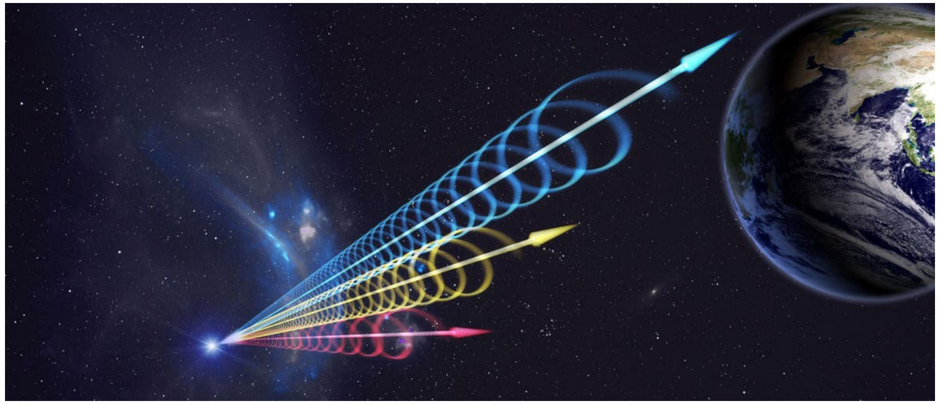
Neutron stars provide insights into a broad range of various astrophysical phenomena

Magnetars

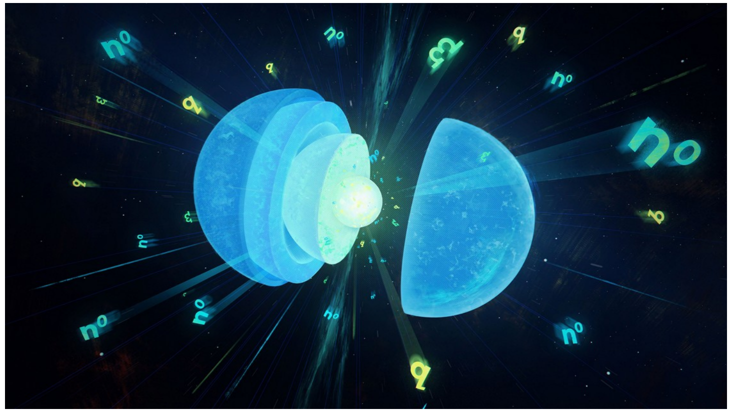


Gravitational waves

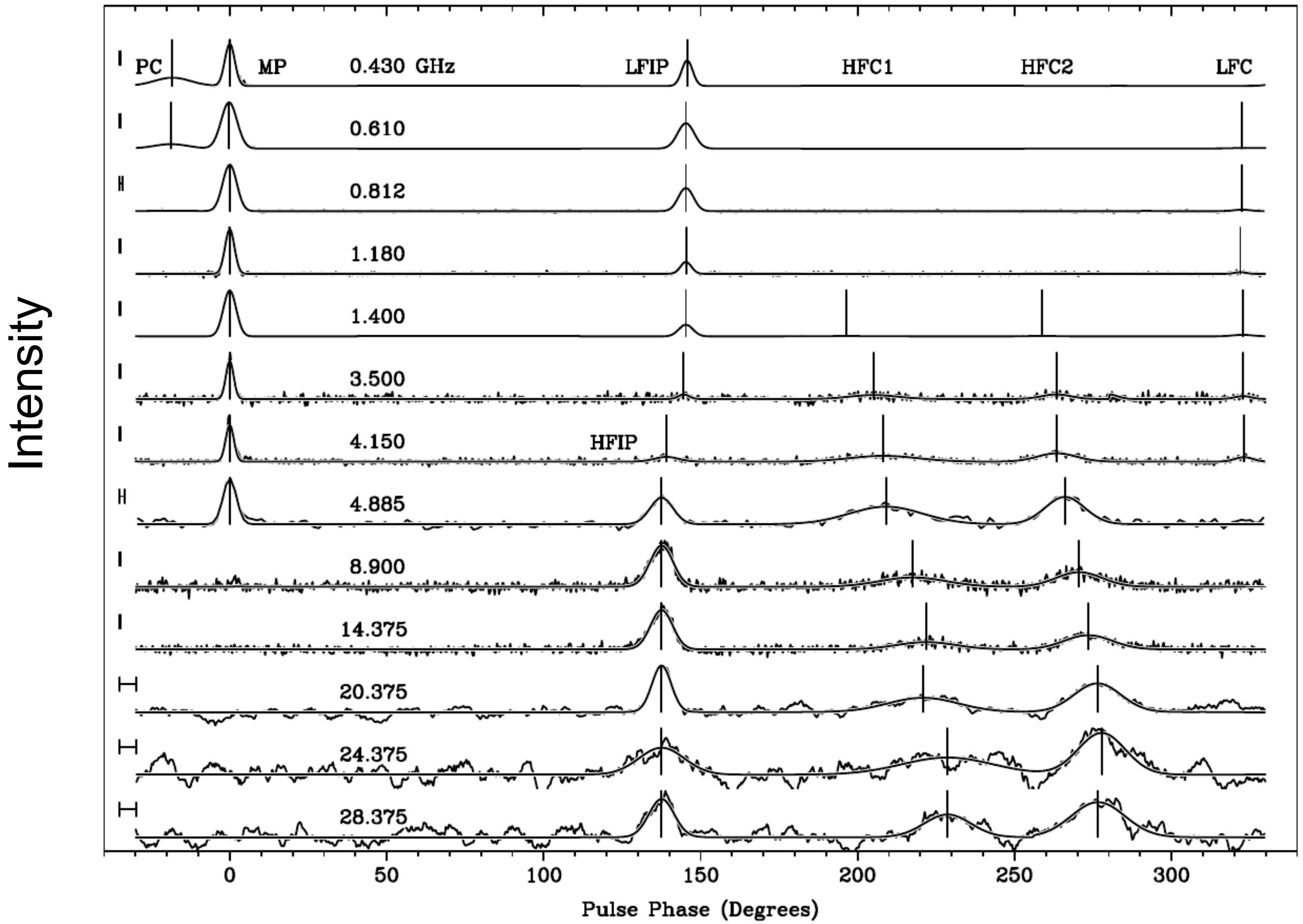
Fast radio bursts



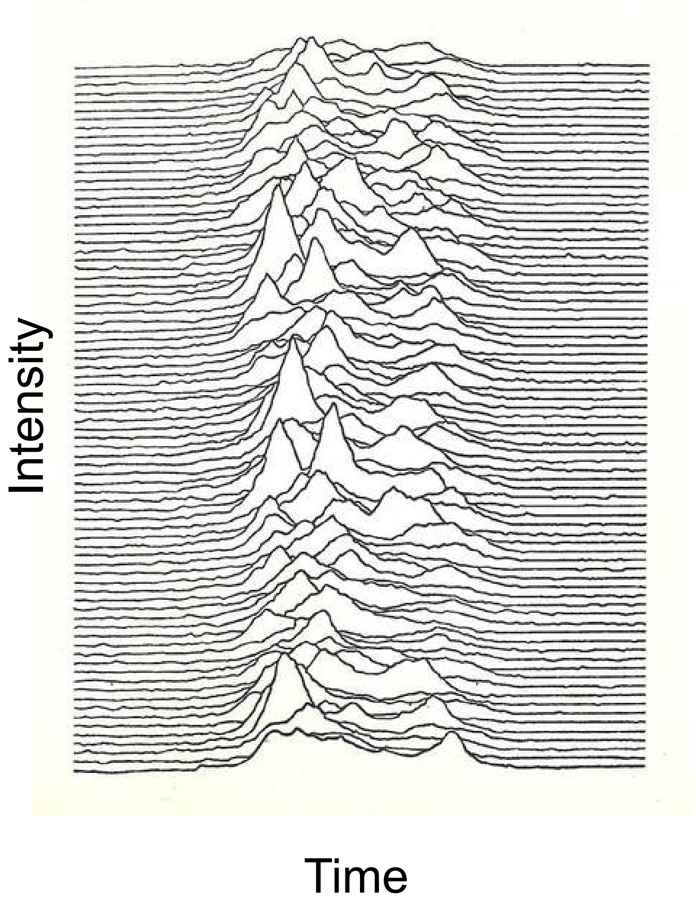
Extreme physical environments



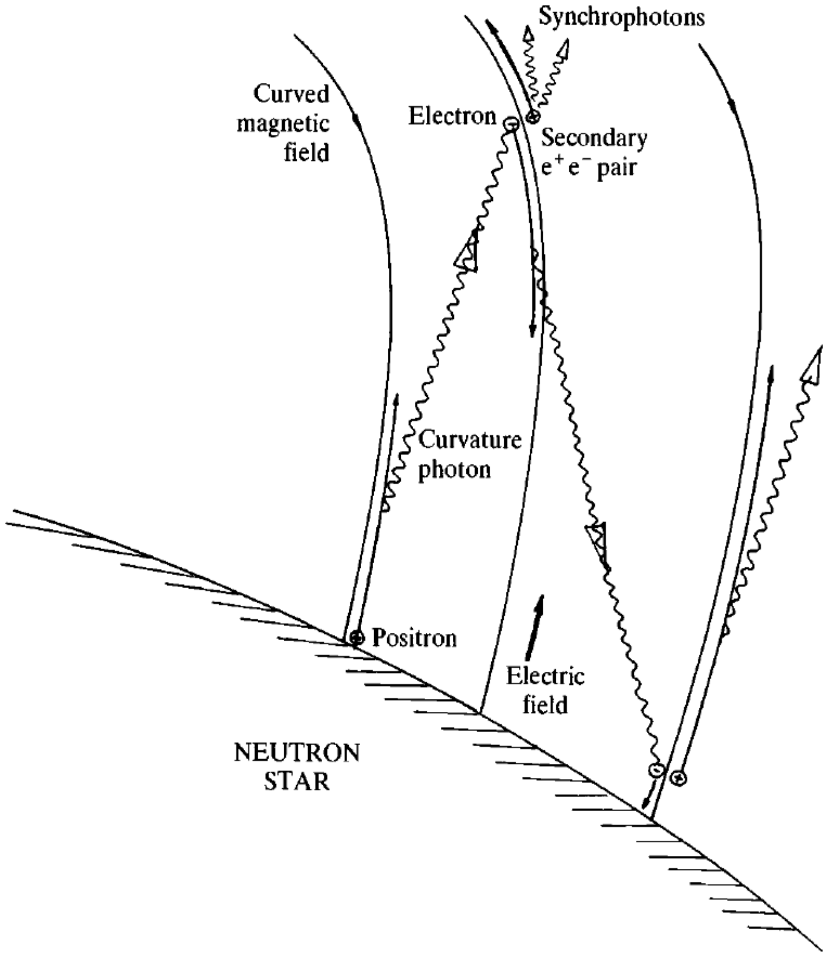
Radio pulses provide wide range of features on various timescales



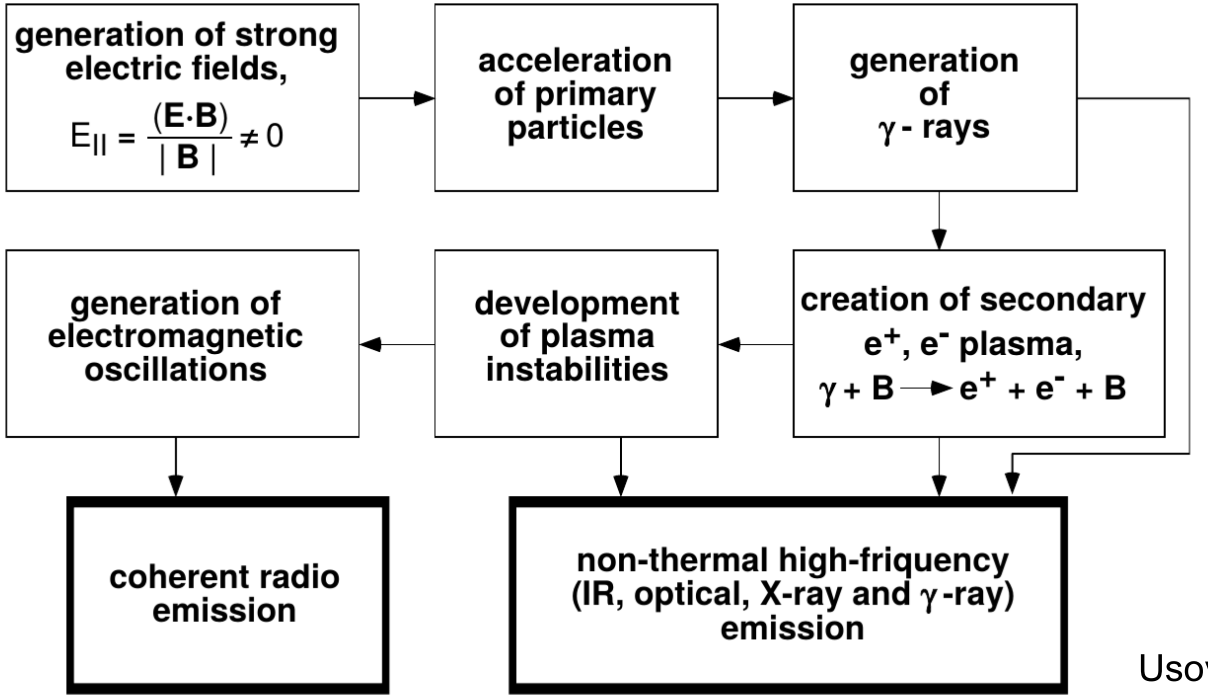
Crab pulsar, Hankins et al. (2015)



Sparking mechanism is a source of electron–positron plasma in gap regions



Beskin et al. (1993)

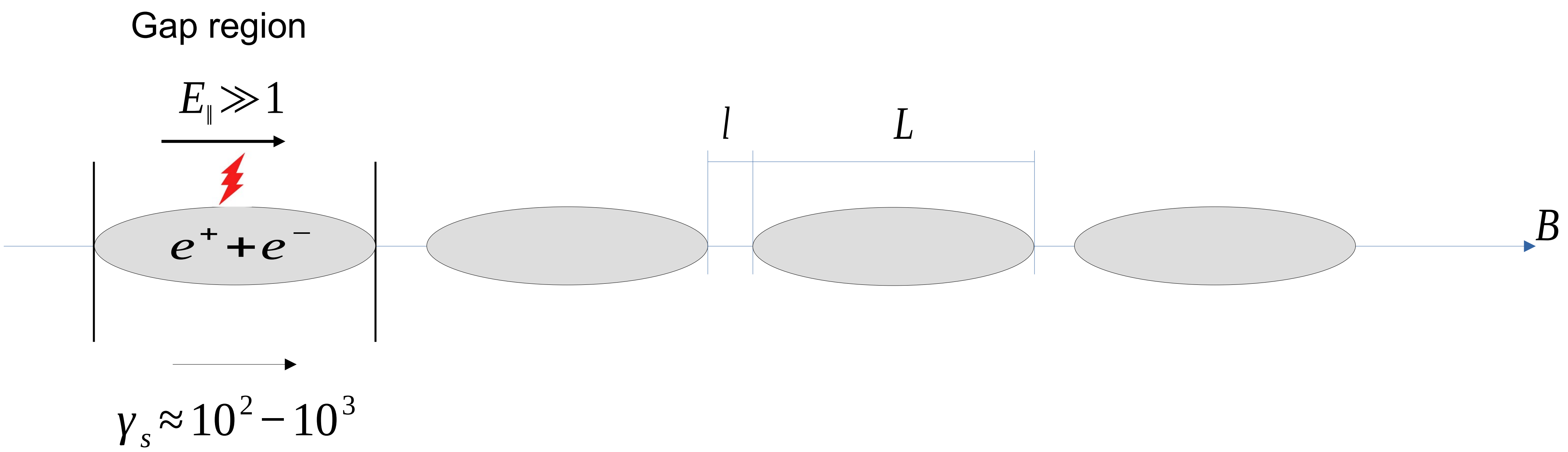


Usov (2002)

Polar cap region: $\gamma + \vec{B} \rightarrow e^{+} + e^{-} + \vec{B}$

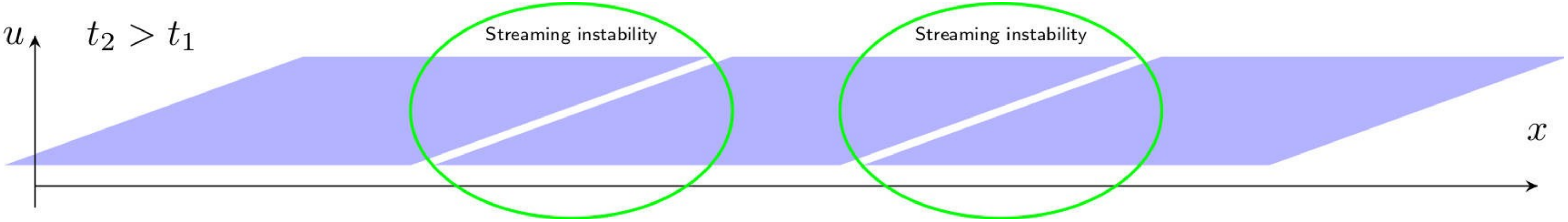
Magnetospheric reconnection: $\gamma + \gamma \rightarrow e^{+} + e^{-}$

Train of particle clouds (bunches) outflows from the gap region



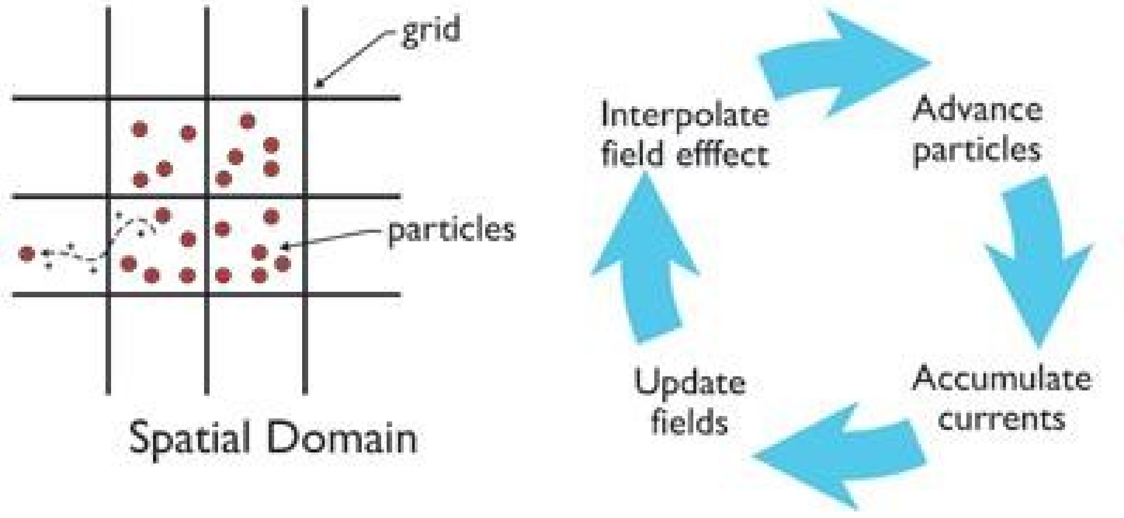
Sturrock (1971)

1.) Streaming instability is produced by bunches overlapping in phase space



Usov & Ursov (1987), Usov (1987), Weatherall (1992), Usov (2002)

Particle-in-cell simulation allows study plasma at kinetic scales



ACRONYM: Kilian et al. (2012)

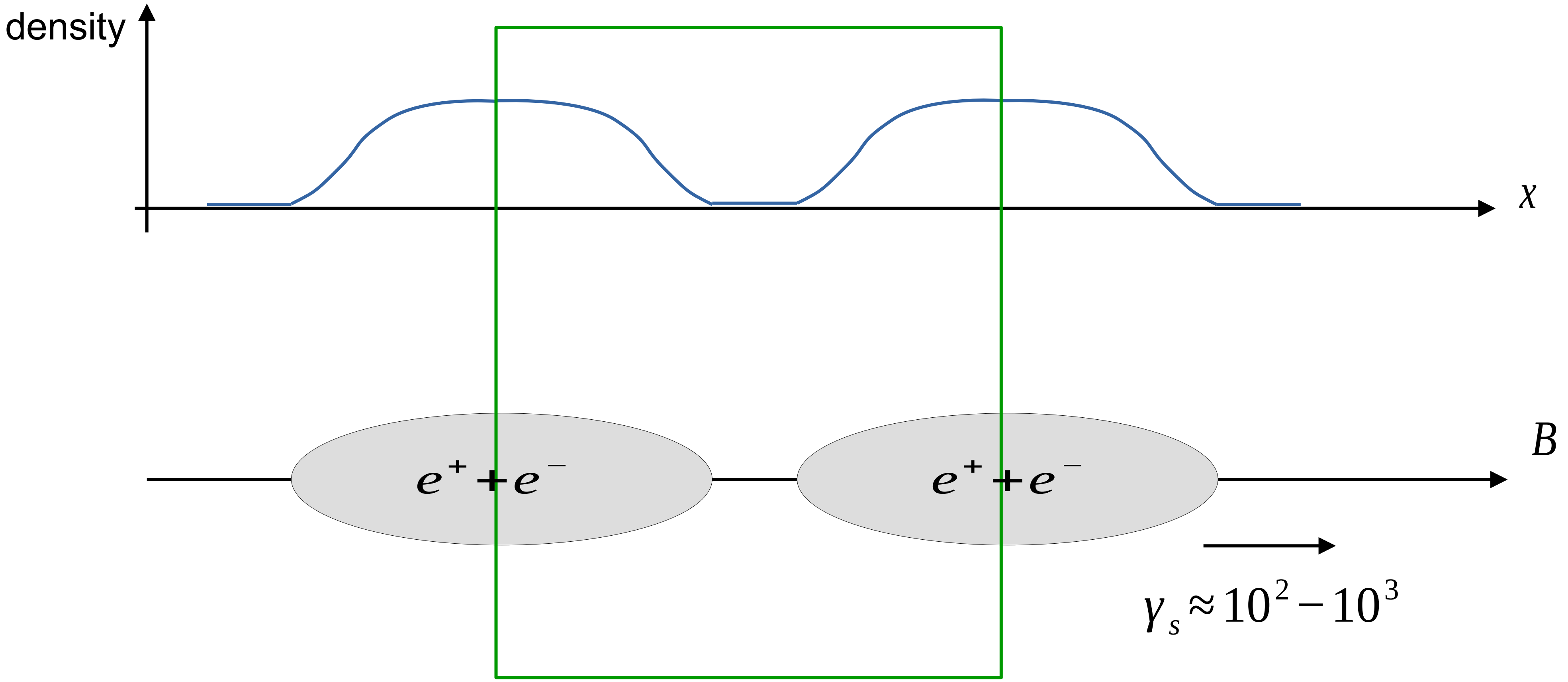
PIC codes:

- Electric and magnetic fields on grids
- Velocity distribution sampled into (macro)particles

Numerical solving:

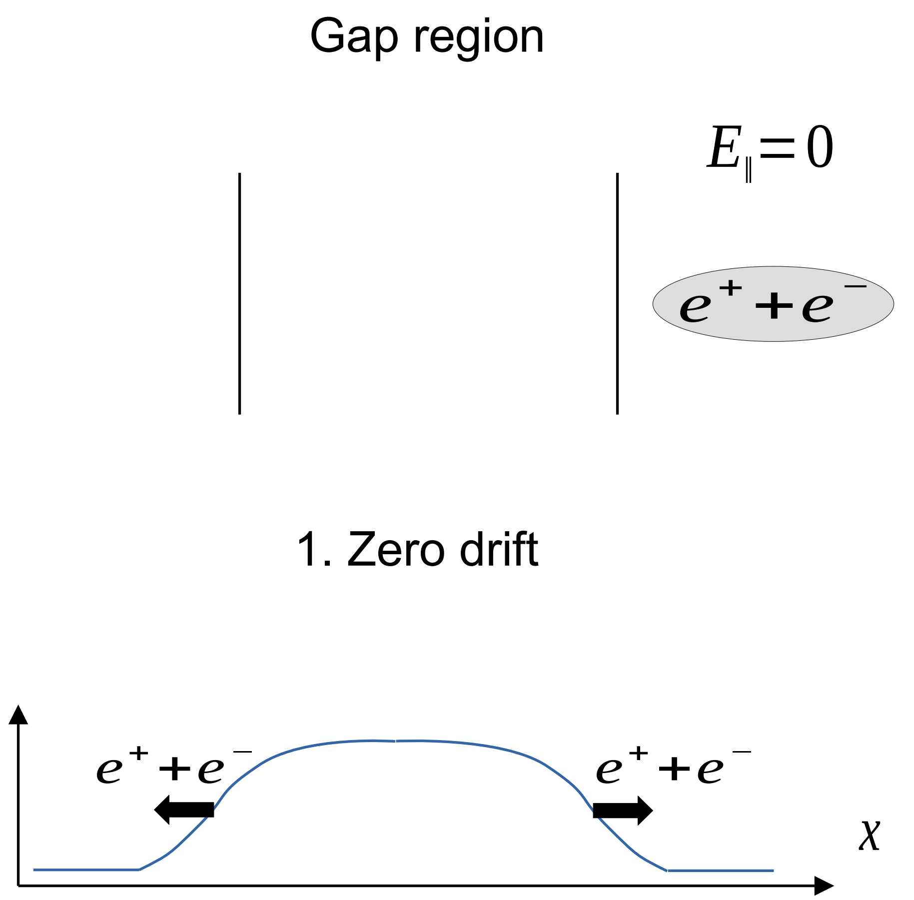
- Vlasov-Boltzmann equation
- Maxwell equation

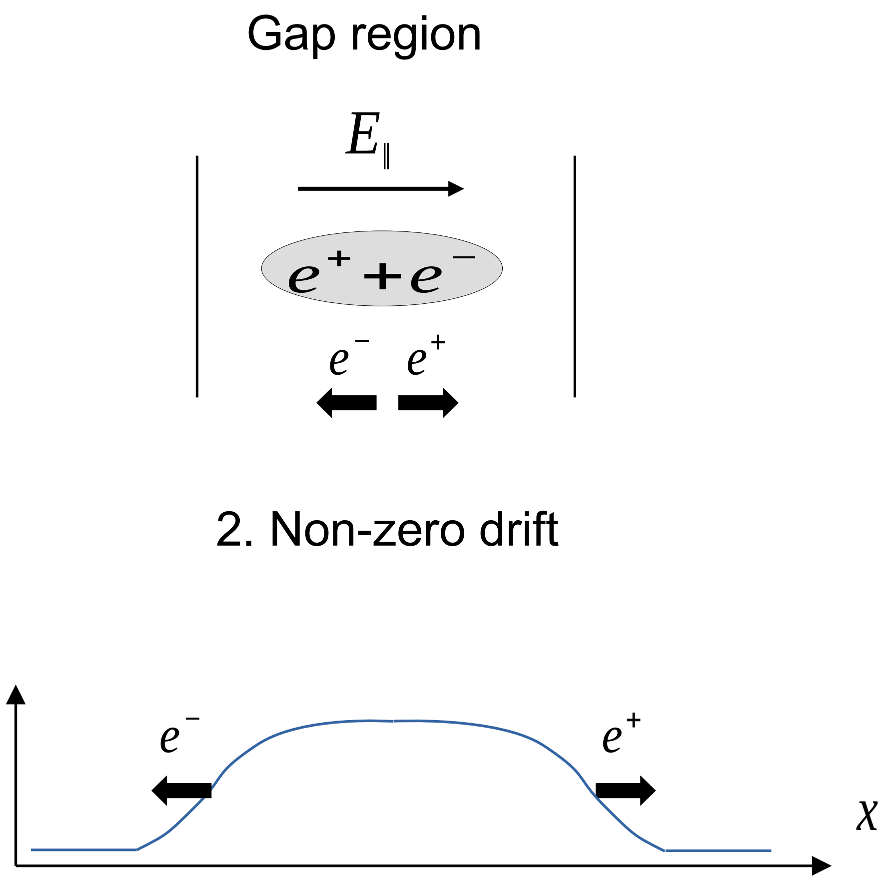
Bunch-bunch interaction results



Simulation domain
Co-moving frame with bunches

If pairs are created in the gap electric field, they gain initial drift between them



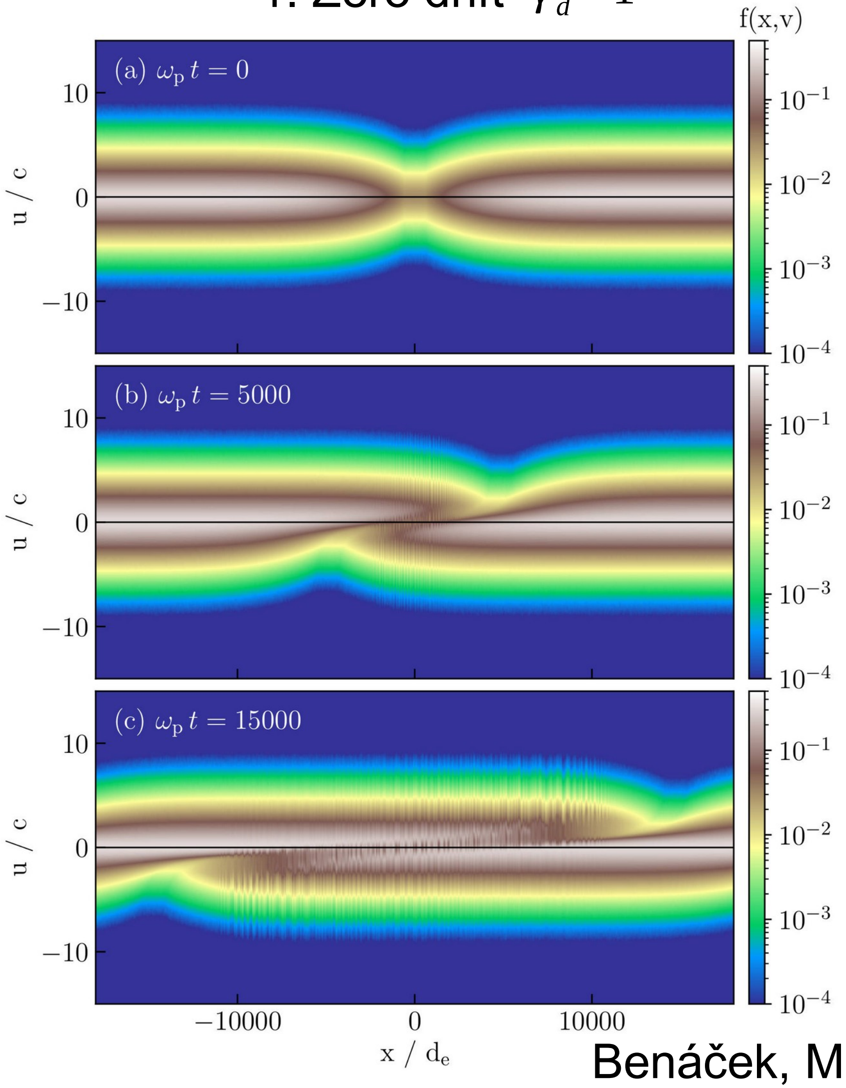


Benáček, Muñoz & Büchner (2021)

The bunch expansion completely changes when drift velocity added

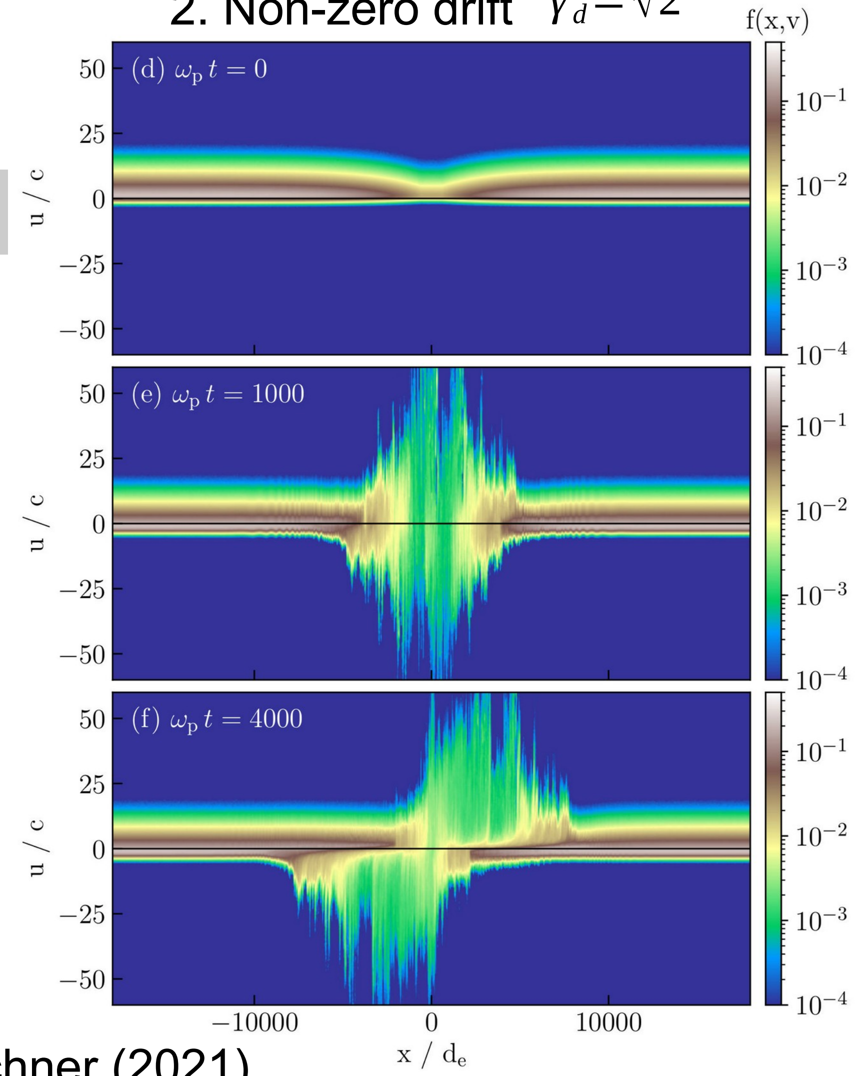
$$u = \frac{p}{m_e}$$

1. Zero drift $\gamma_d = 1$



$$\rho = \frac{mc^2}{k_B T} = 1$$

2. Non-zero drift $\gamma_d = \sqrt{2}$



Benáček, Muñoz & Büchner (2021)

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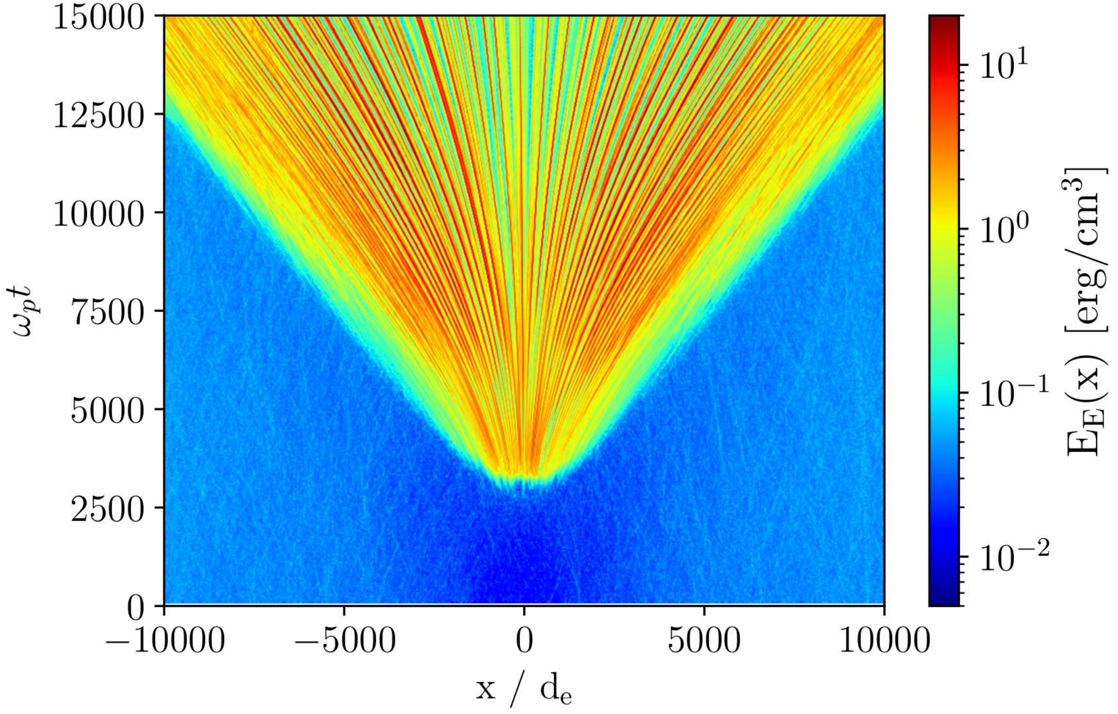

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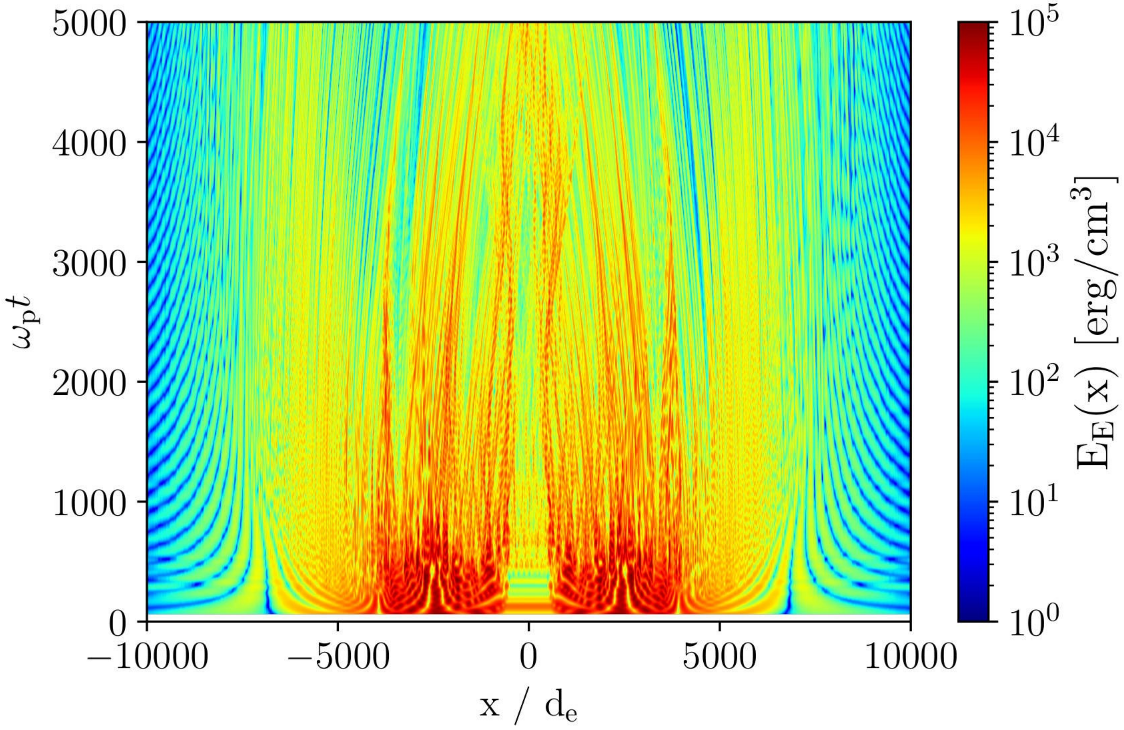
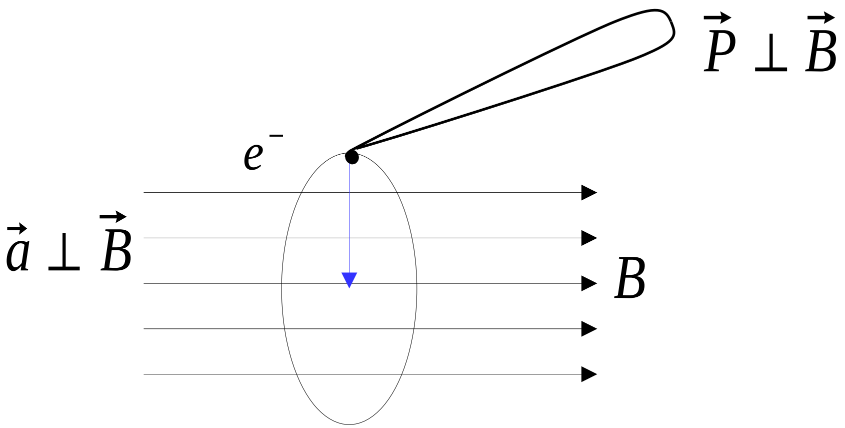


Benáček, Muñoz & Büchner (2021)

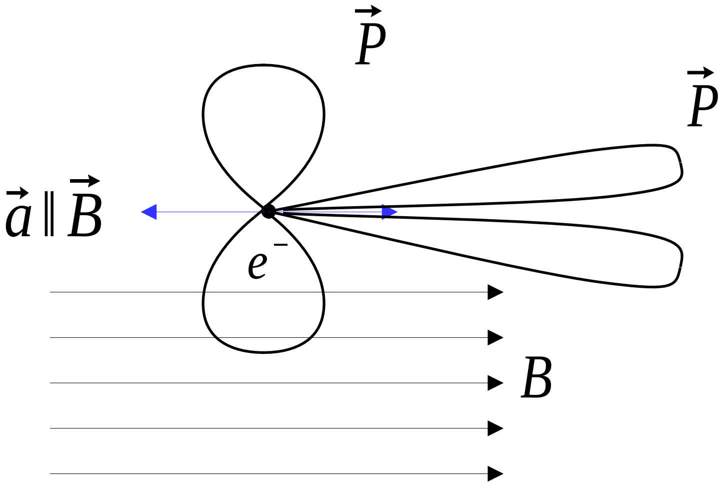
Linear acceleration emission vs. Synchrotron emission

Synchrotron emission



$$\theta \approx \frac{1}{\gamma_{particle}} \qquad P_{total} \sim \gamma^2_{particle}$$

Linear acceleration emission



$$\theta \approx \frac{1}{\gamma_{frame}} \qquad P_{total} \sim \gamma^2_{frame}$$

Tracking of plasma particles

$$\frac{dE}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} \frac{\boldsymbol{n} \times [(\boldsymbol{n}-\boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^2} e^{i(\omega t - \mathbf{k}\cdot\mathbf{x}(t))} dt\right|^2,$$

Using plasma electric current

$$\frac{dE}{d\omega d\Omega} = \frac{\omega^2}{16\pi^3 \varepsilon_0 c^3} |J(\omega, \mathbf{k})|^2 \sin^2\theta,$$

Bunches with nonzero drifts produce significantly stronger radiation

Benáček, Muñoz, Büchner & Jessner (accepted in A&A)

1. Overlapping plasma bunches

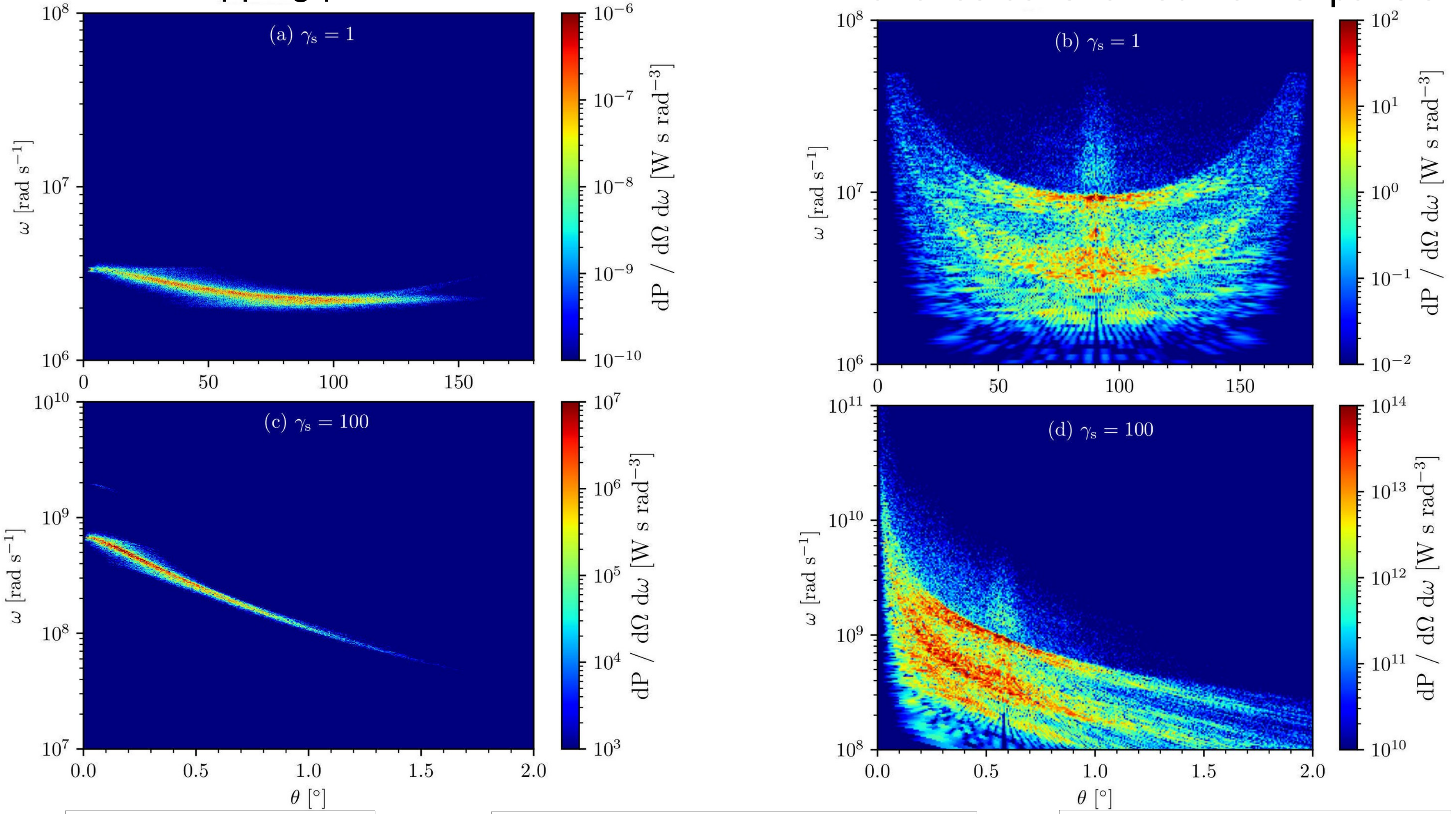
2. Bunches constrained from expansion

Plasma frame

$\gamma_{frame} = 1$

Pulsar frame

$\gamma_{frame} = 100$

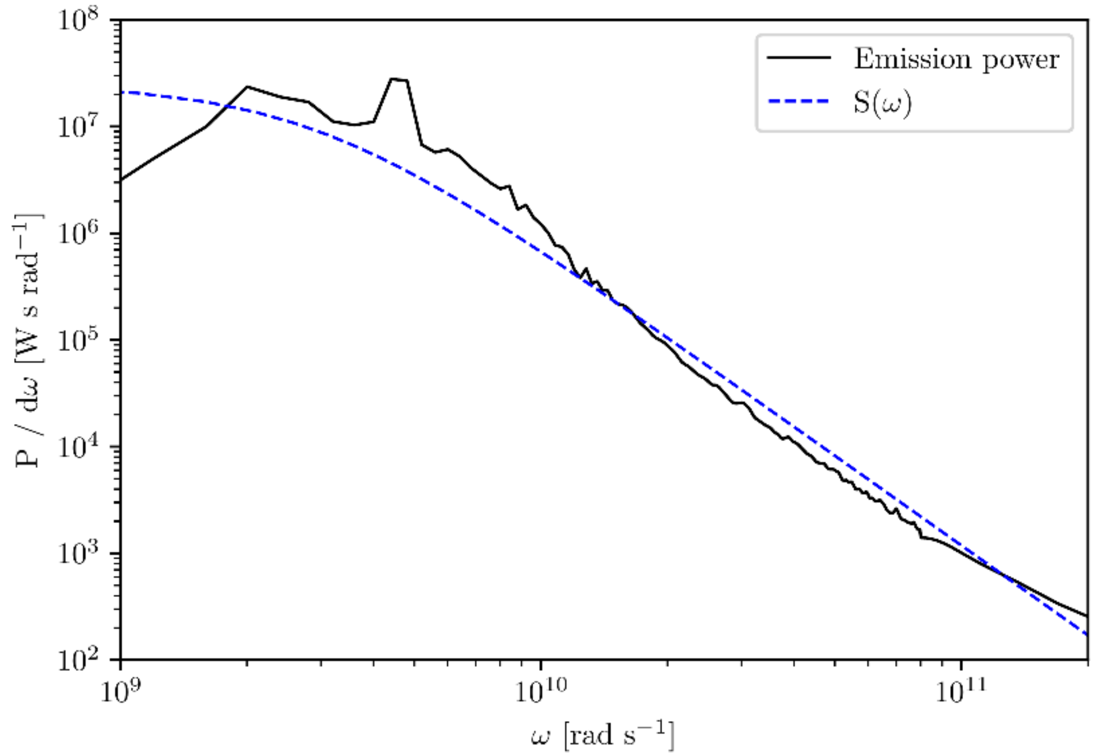


$P_{tot} \approx 3 \times 10^{8} W$

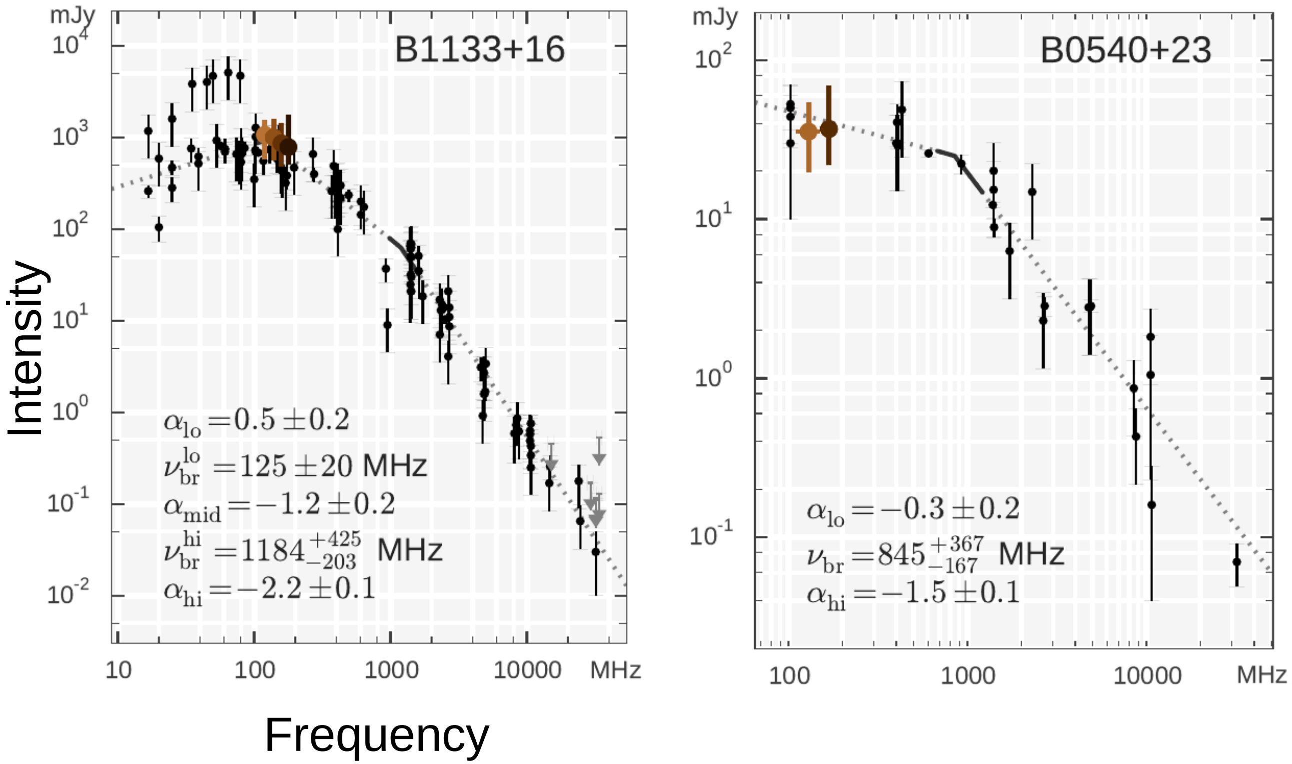
$P_{pulsar} \approx 10^{18} - 10^{22} W$

$P_{tot} \approx 3 \times 10^{16} W$

The frequency profile of emission is similar to those observed



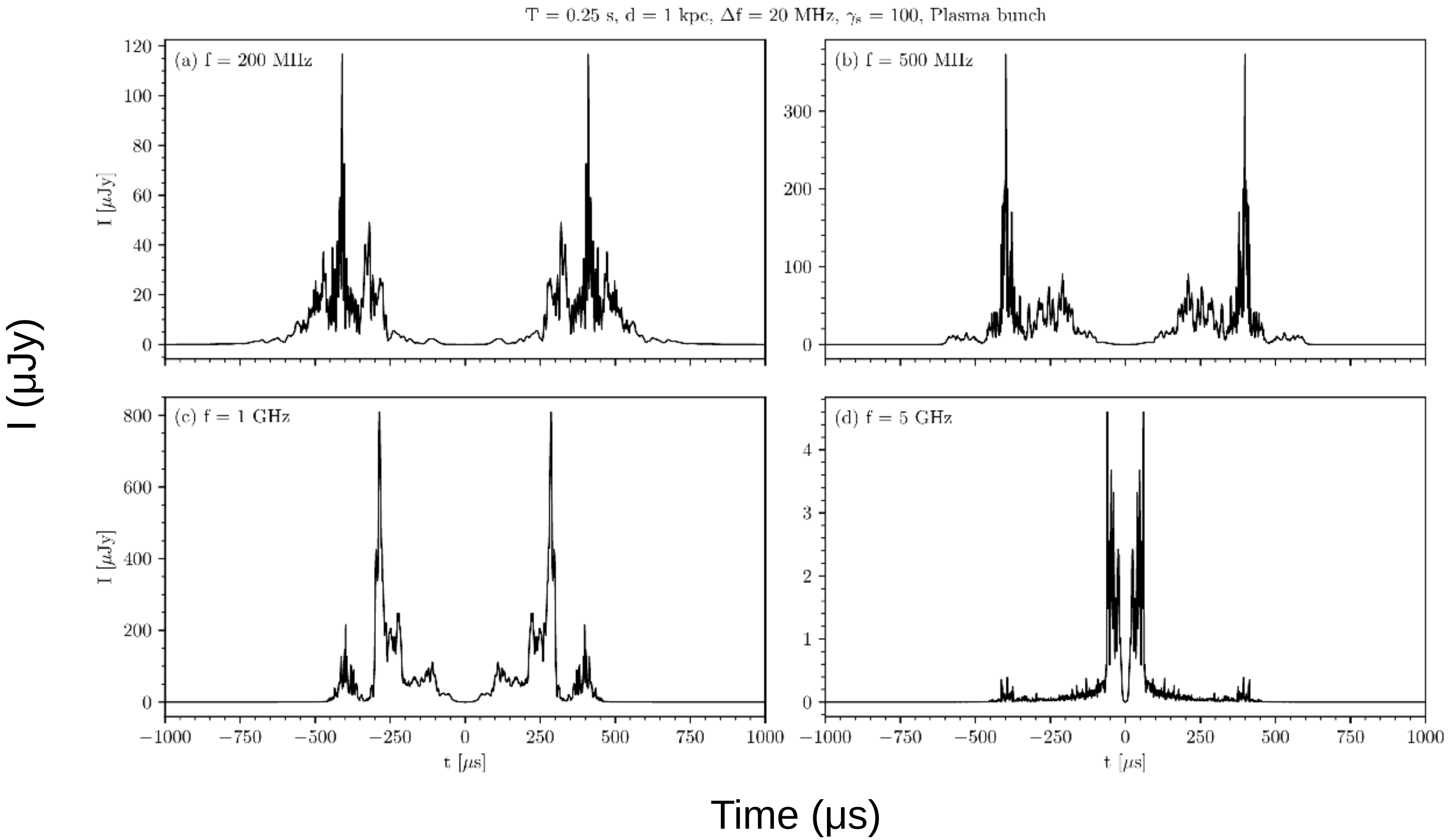
$$S(\omega)=\frac{S_0}{1-\omega^2\tau^2}$$



Benáček, Muñoz, Büchner & Jessner (accepted in A&A)

Bilous et al. (2016)

Pulse profiles at specific frequencies



P_{pulsar} = 0.25 s

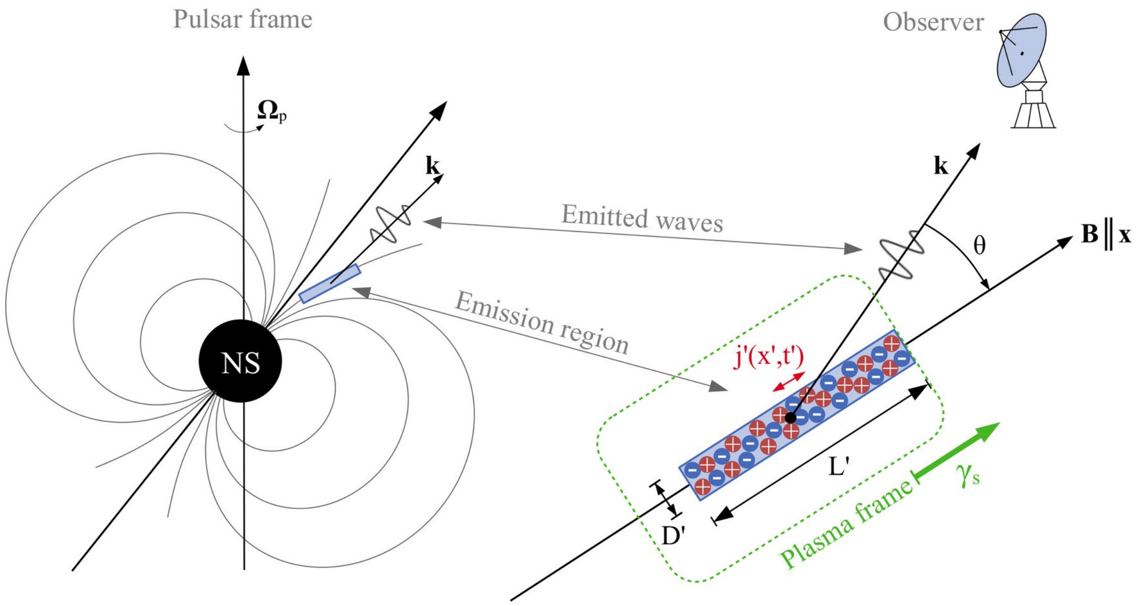
Distance = 1 kpc

Δf = 20 MHz

γ_{frame} = 100

Benáček, Muñoz, Büchner & Jessner (accepted in A&A)

Conclusions



- Coherent radio emission process of pulsars at kinetic microscales is still uncertain
- Bunch evolution strongly dependent on the initial drift between electrons and positrons
- Linear acceleration emission by bunches might explain the pulsar radiation

Papers on arXiv:

2111.05262

2106.13525

2101.03083

Jan Benáček:

0000-0002-4319-8083

Simulation setup for relativistic streaming instability

Relativistic numerical features

- Relativistic Boris push
- Cole–Kärkkäinen (CK) field solver
- “Weighting with Time dependancy” (WT) shape factor

Simulation setup

- 1D1V code, along mg. field axis
- 720,000 grid cells
- 10^4 PPC (e^- + e^+)
- Periodic boundary conditions

Plasma properties

- Maxwell–Jüttner velocity distribution
- Inverse temperature $\rho = mc^2/k_BT = 1$
- Drift between particle species = 1,

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