Theory of Pulsars and Pulsar Wind Nebulae

Bronisław Rudak
CAMK PAN

KRAK, 20-21 May 2019

Theory of Pulsars and Pulsar Winds Nebulae

Bronisław Rudak
CAMK PAN

KRAK, 20-21 May 2019

„Pulsars: The Universe's Gift to Physics"
D. Finley (2012)

- EOS of ultradense matter

- QED in strong magnetic fields

- theories of gravitation in strong-field limits

- supernova outburst mechanisms

- interstellar medium

- low-frequency gravitational waves

- relativistic MHD flows and shocks

- origin of primary positrons in Cosmic Rays

- Lorentz Invariance Violation

Pulsar detections: from radio to gamma rays

~ 2600 in radio

1+2(?) in mIR, 5 in nIR,

~10 in optical,

10 in nUV, 4 in fUV

> 100 in X-rays (mostly Chandra and XMM Newton)

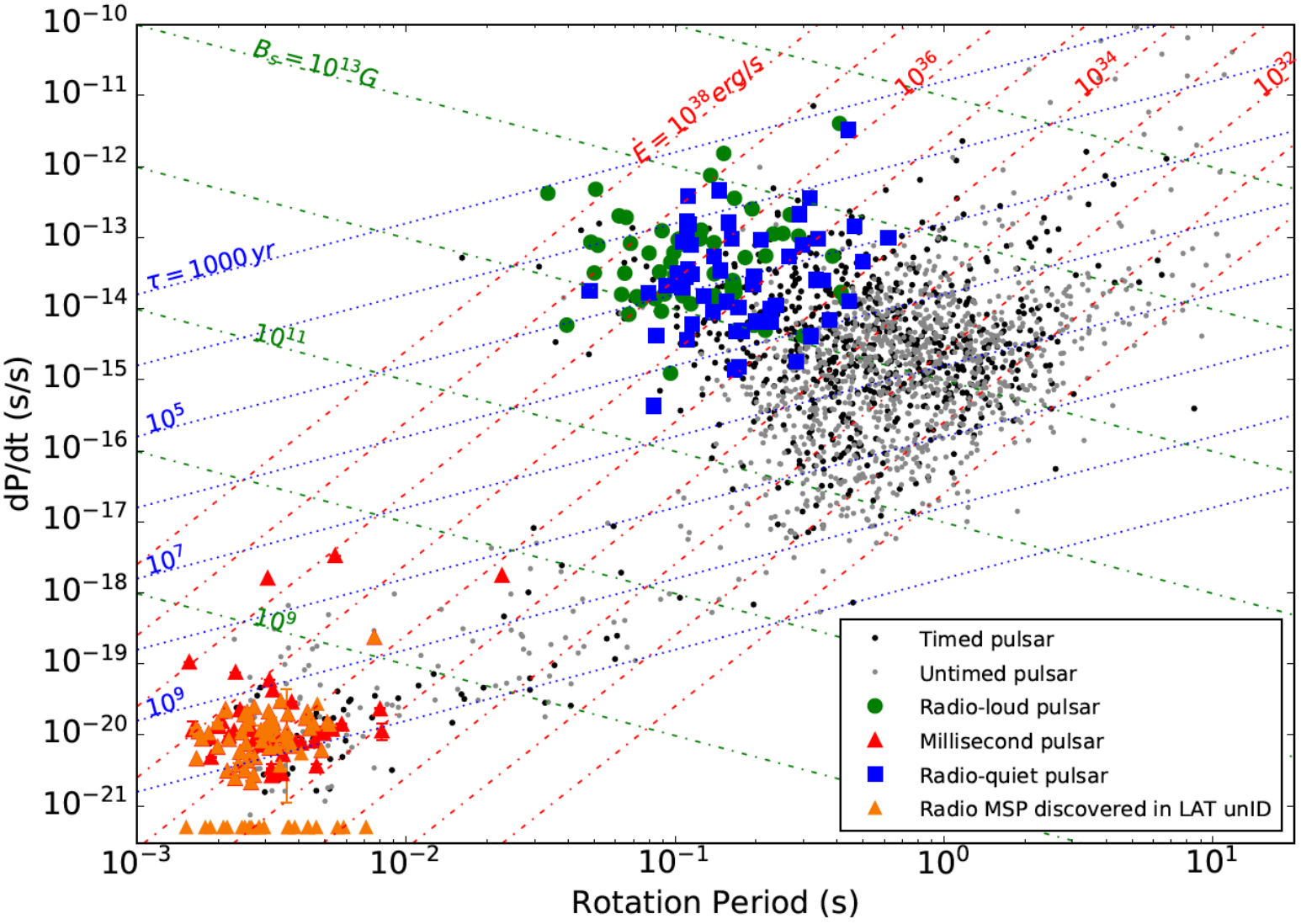
234 in gamma-rays (*Fermi* LAT, AGILE)

Detections by Cherenkov arrays:

Crab pulsar: 25 GeV – 1.5 TeV (MAGIC,VERITAS)

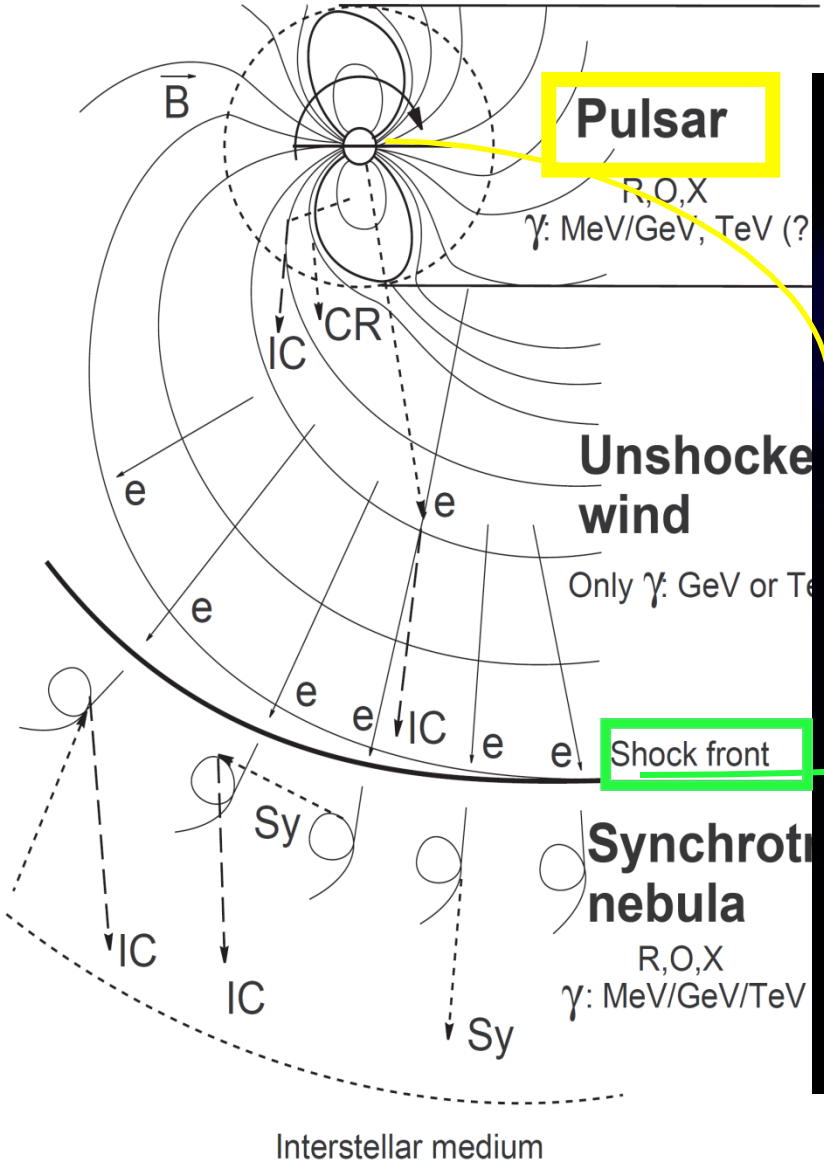
Vela pulsar: 20 – 120 GeV (H.E.S.S. II, mono), 3 TeV & 7 TeV (H.E.S.S. I, stereo)

Period – Period time derivative

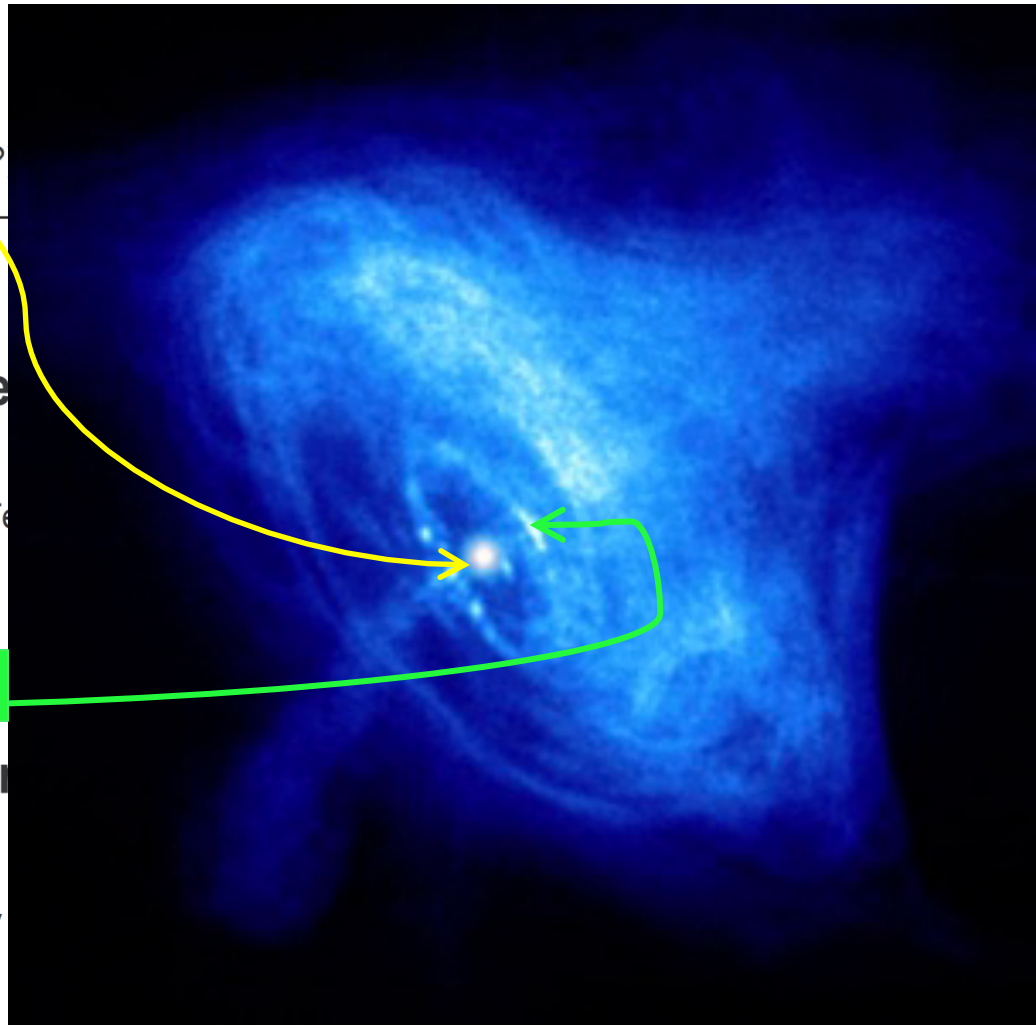


D.Smith+ 2017

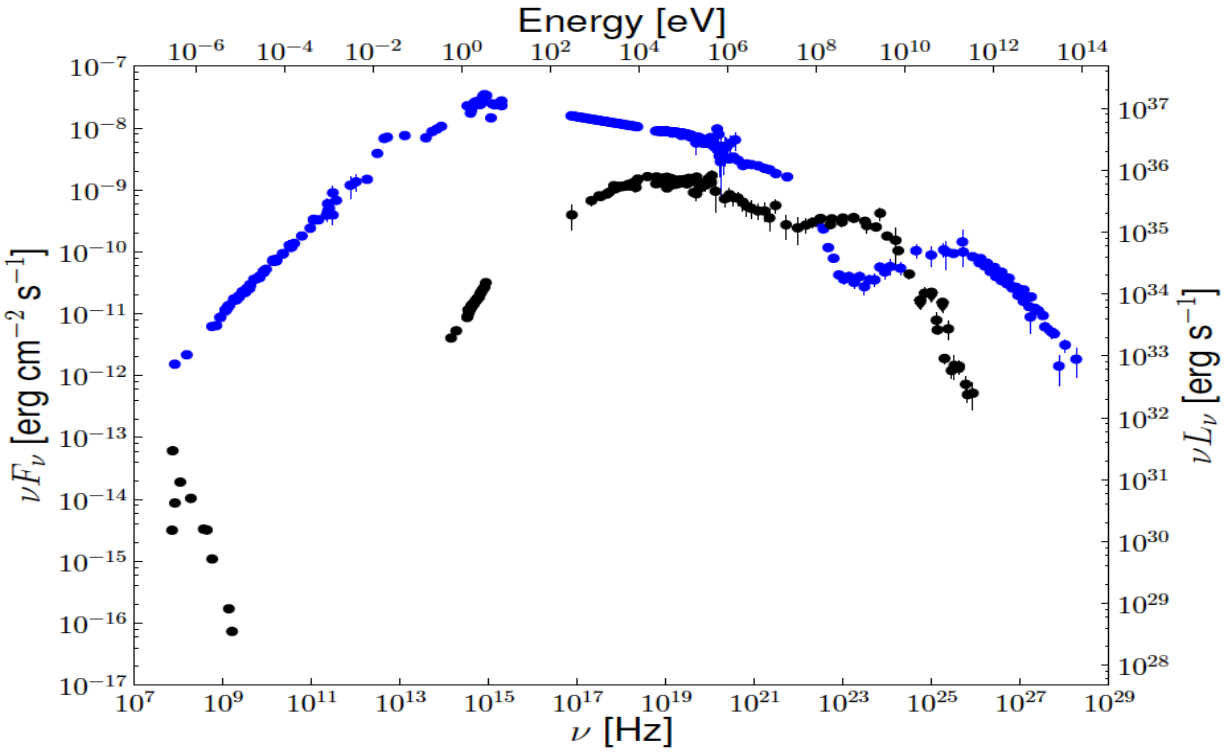
Radiation from a **Pulsar-wind-nebula** complex

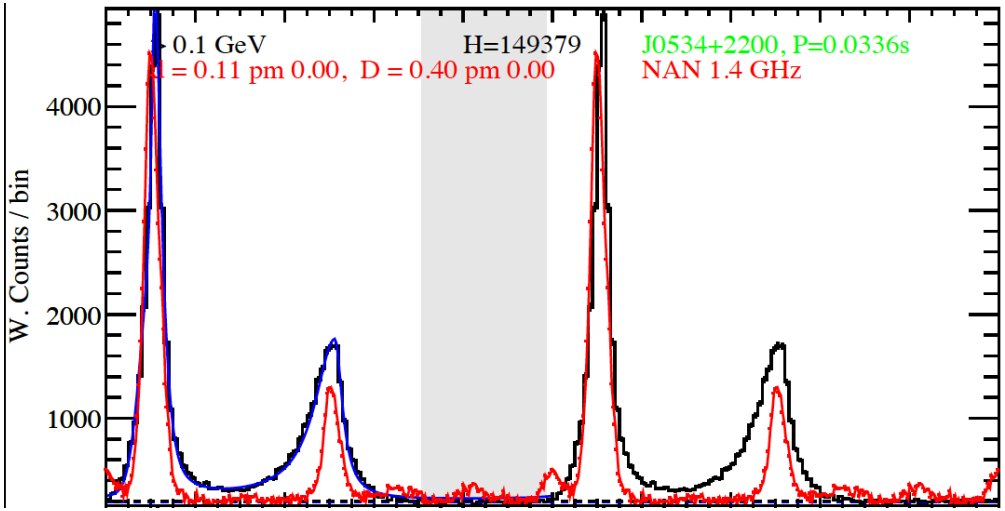


Crab Nebula in X-rays

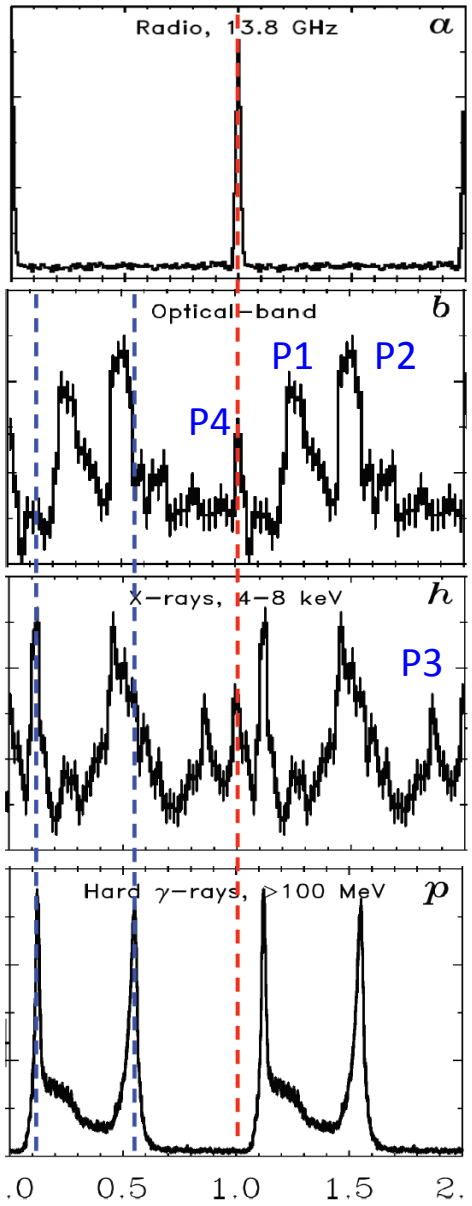


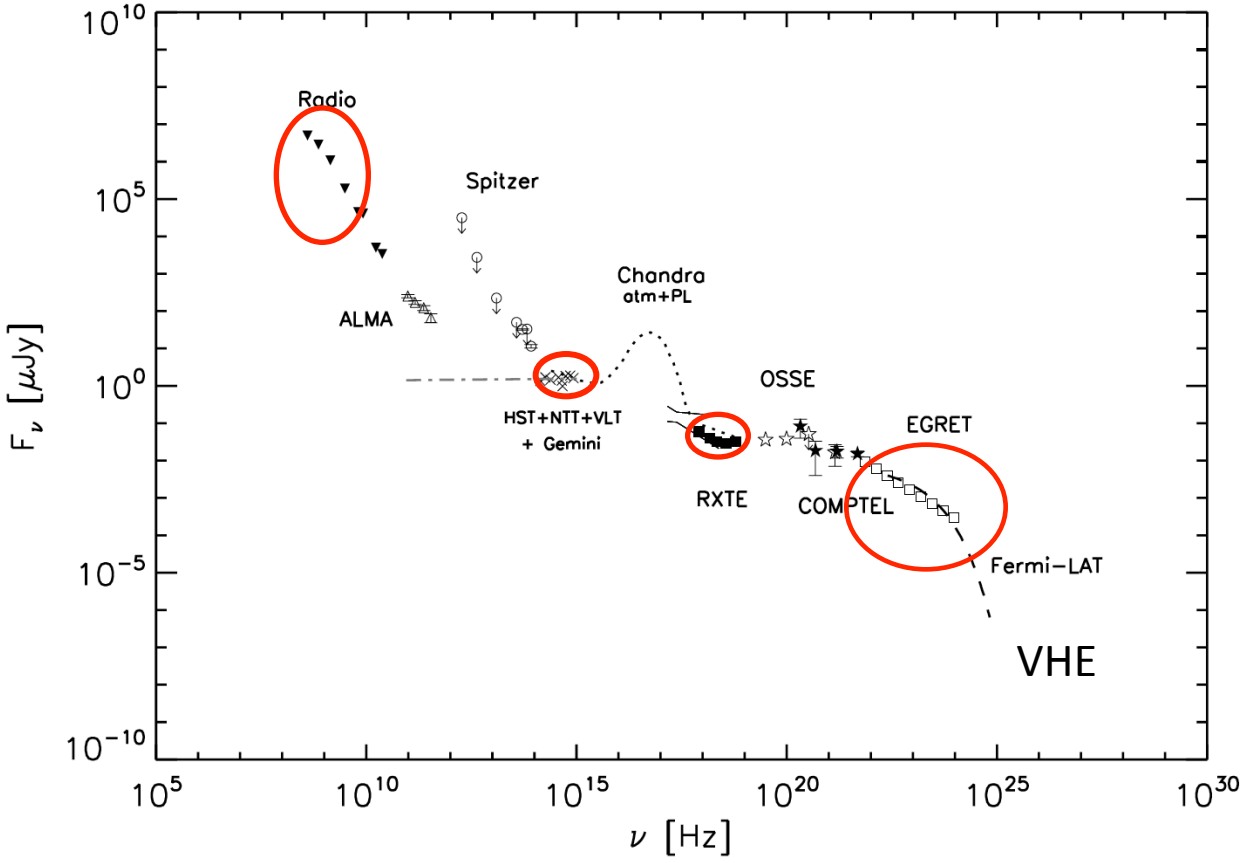
SED and pulse profiles of the Crab pulsar, SED of the Crab Pulsar Nebula,





The Vela pulsar





A brief history of pulsar models

1. The vacuum magnetic dipole model

   basic features still in use

2. The co-rotating magnetosphere models in low-density, charge-separation limit

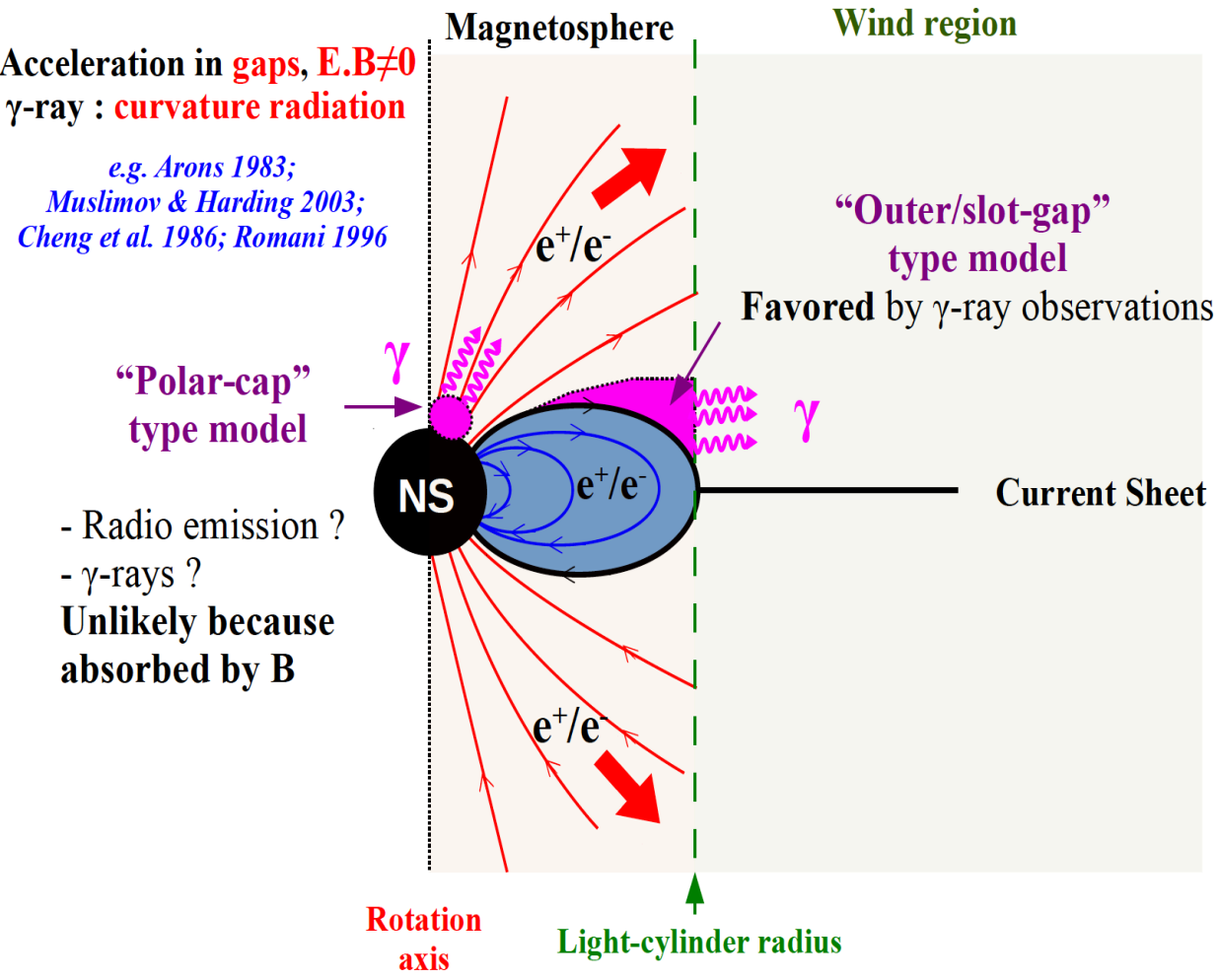
   in retreat (according to some sources)

3. Towards Global Electrodynamics, microscopic conductivity (PIC simulations)

   a long way to go

A brief history of pulsar models

Proposed sites for particle acceleration



Ad 2:
The co-rotating magnetosphere in low-density, charge-separation limit

Cartoon by B. Cerutti

Global electrodynamics with the plasma - I

Starting point: force-free electrodynamics (FFE) models

The electromagnetic force per unit volume

$$\boldsymbol{f}\_em = \sigma \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B} + \delta \boldsymbol{P}\_em/\delta t \ .$$

Assumptions in FFE:

- the inertial mass density of the plasma ignored ($<<$ $B^2/8\pi c^2$)
- the momentum density of EM ignored

The force-free condition becomes

$$\boldsymbol{f}\_em = \sigma \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}/c = 0$$

but it cannot hold everywhere .

Goal: self-consistent electrodynamics, with global current closure

Two approaches to model dissipative magnetospheres and winds

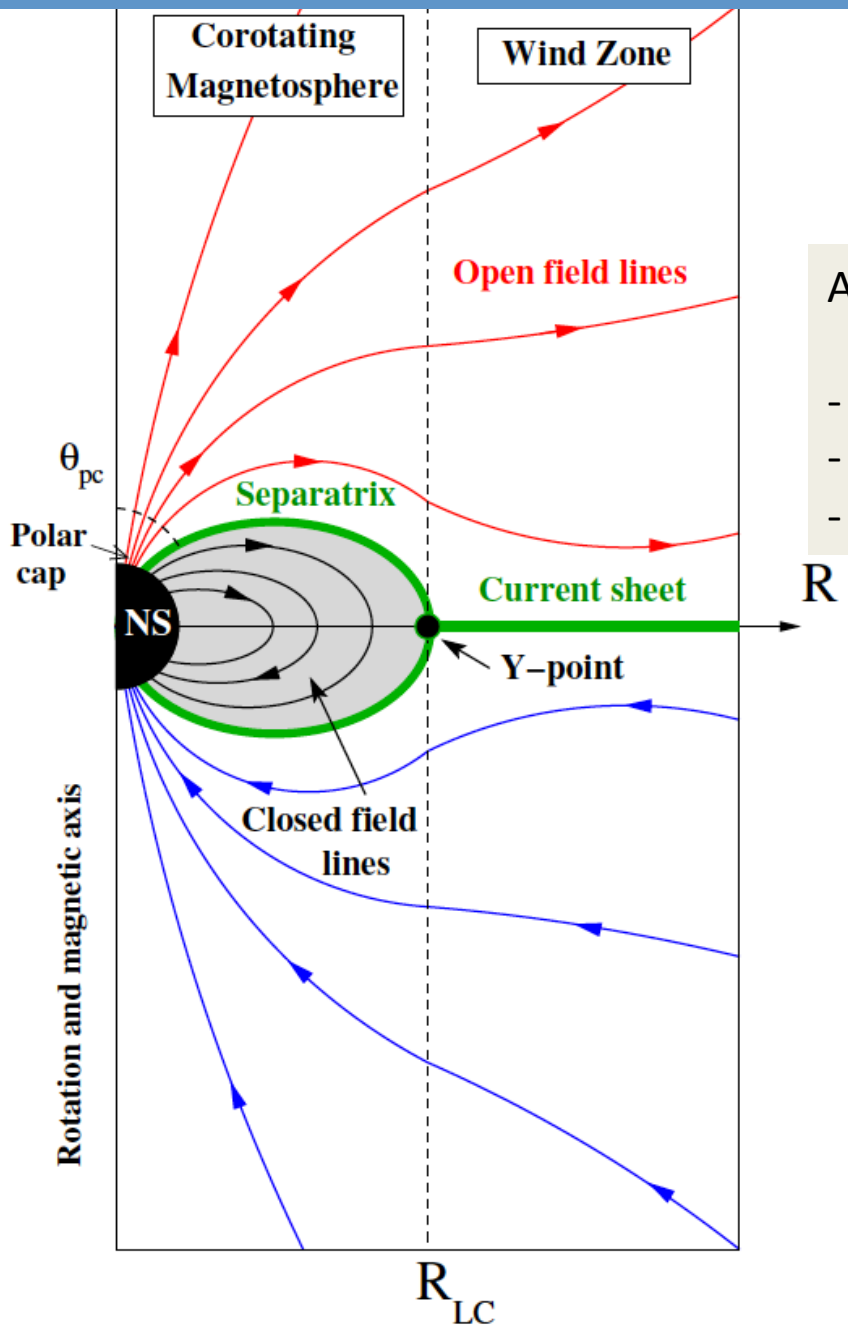
1) MHD with macroscopic conductivity (phenomenological, free parameter),

2) Particle-In-Cell (PIC) simulations:
include particle inertia, pair creation and acceleration.

Weakness: low-resolution calculations possible so far.

A hybrid approach might be helpful (?)

Global electrodynamics with the plasma - II



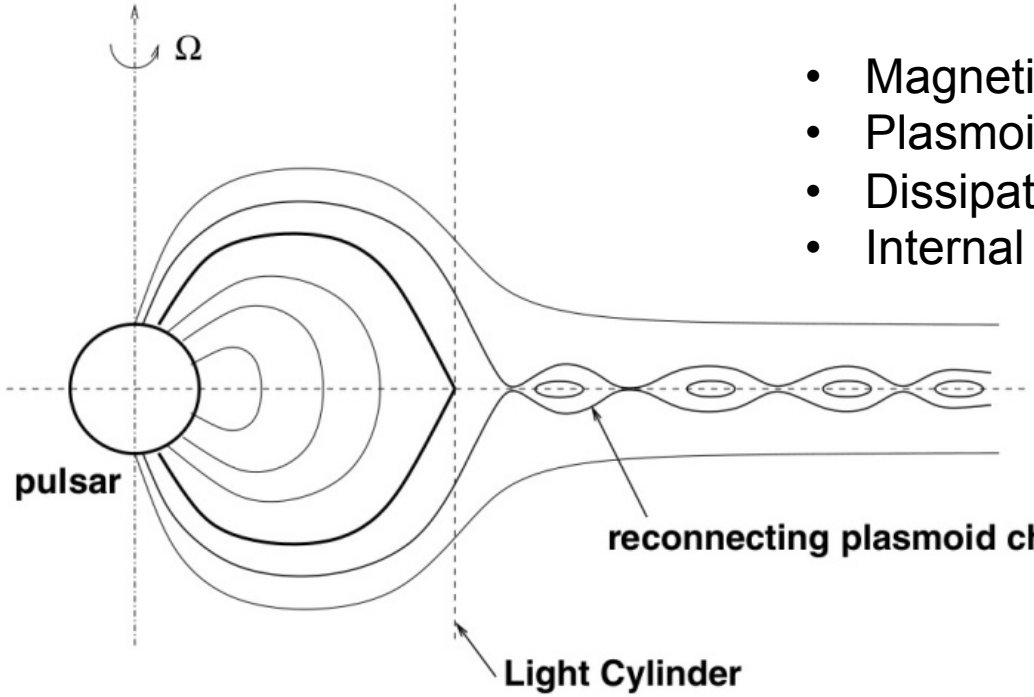
Lyubarskii 1990, … ,
Cerutti & Beloborodov 2016

Aligned rotator with a force-free magnetosphere:

- dense (n > n_GJ) plasma outflow,
- split monopole magnetic field at r >> R_LC
- current sheet forms.

Strong non-thermal emission can be produced in the CS and in the separatrix sheets inside the light cylinder.

Properties of Current Sheets

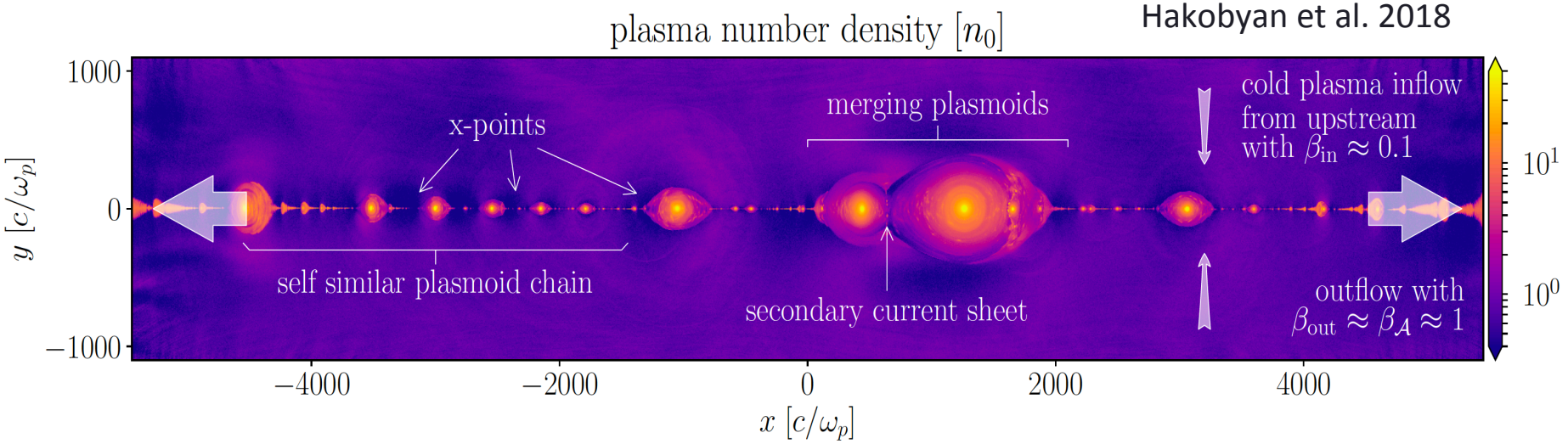


- Magnetic reconnection?
- Plasmoids?
- Dissipation?
- Internal thermal pressure / thickness?

Uzdensky & Spitkovsky (2014)

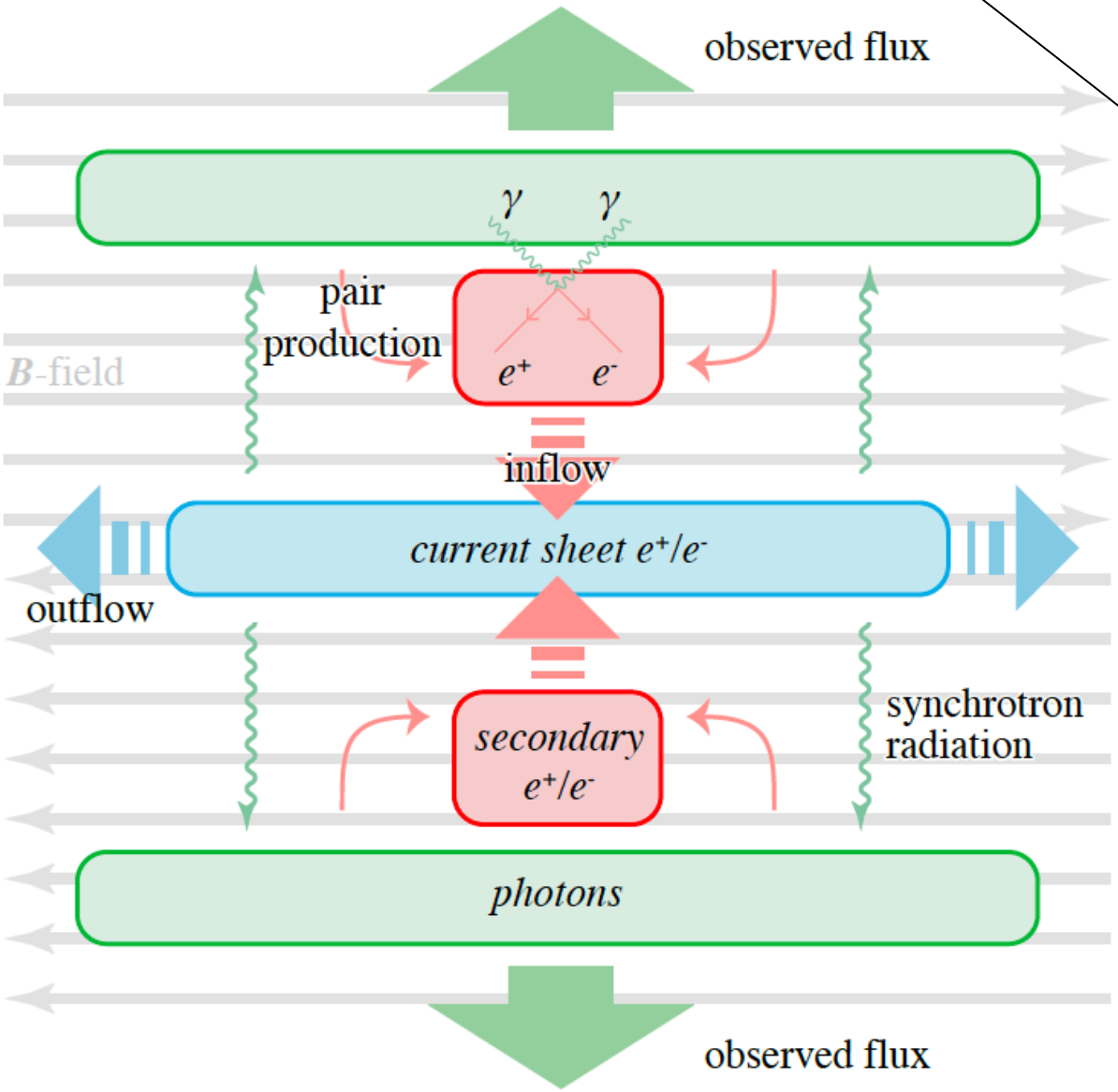
Magnetic reconnection - PIC in 2D

Hakobyan et al. 2018



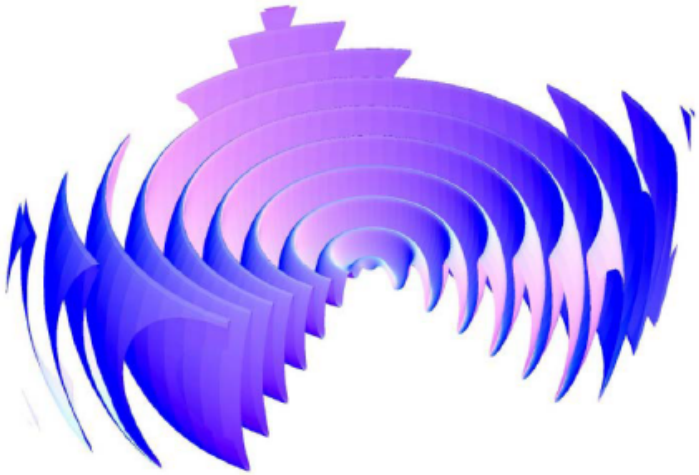
Reconnecting current sheet with acceleration and $e^{\pm}$ – pair creation

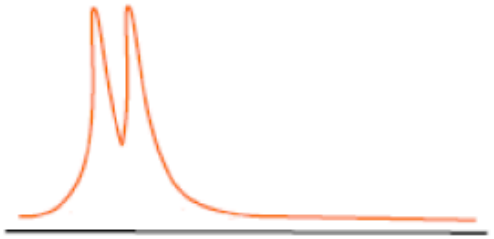
Hakobyan et al. 2018

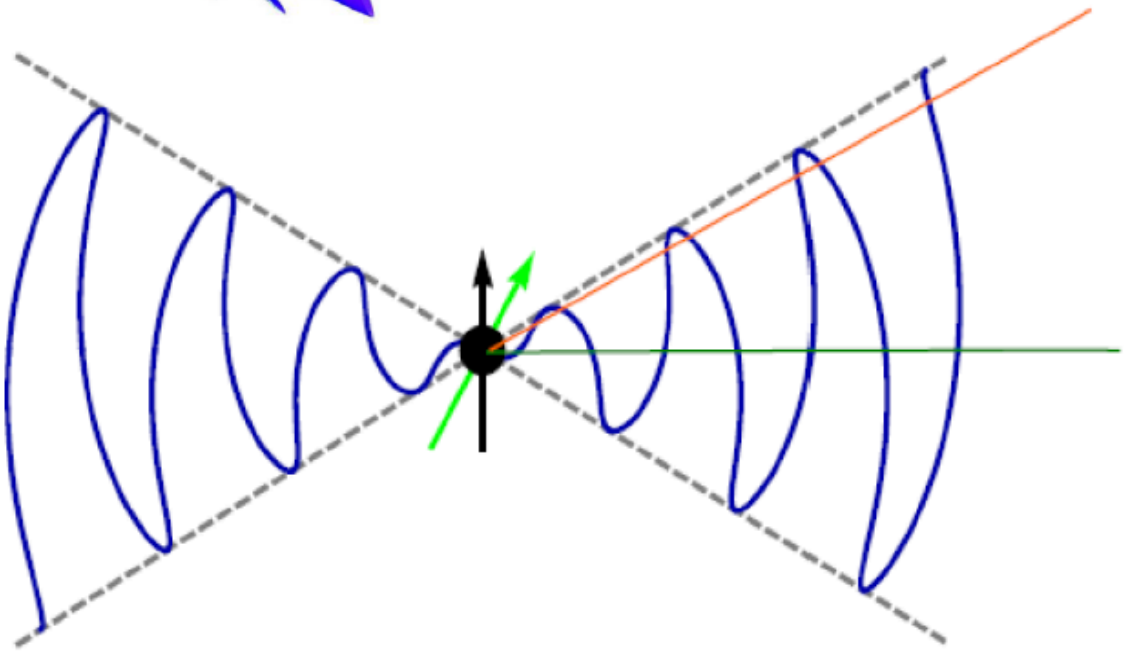


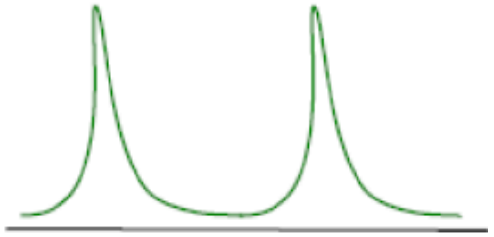
next talk by
K. Nalewajko

Oblique rotator –> Current Sheet becomes corrugated; striped wind forms

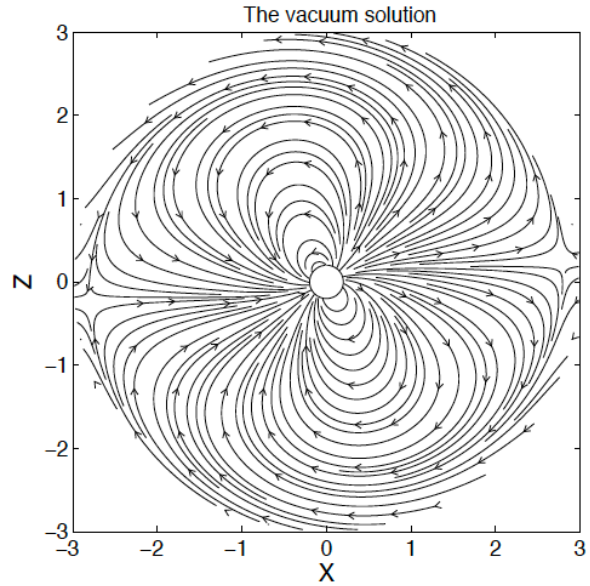


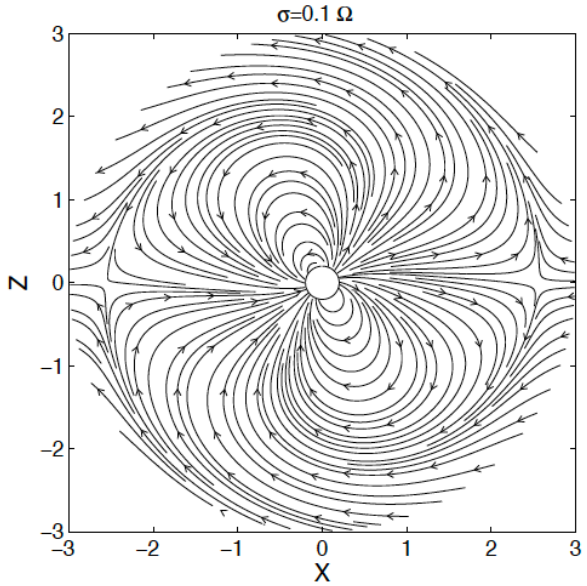


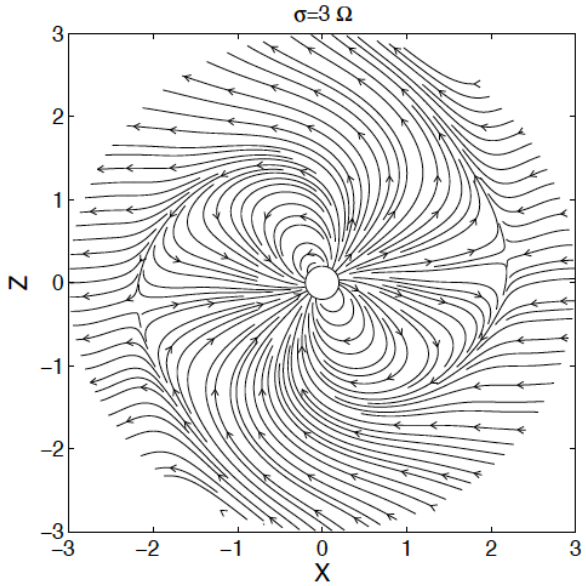


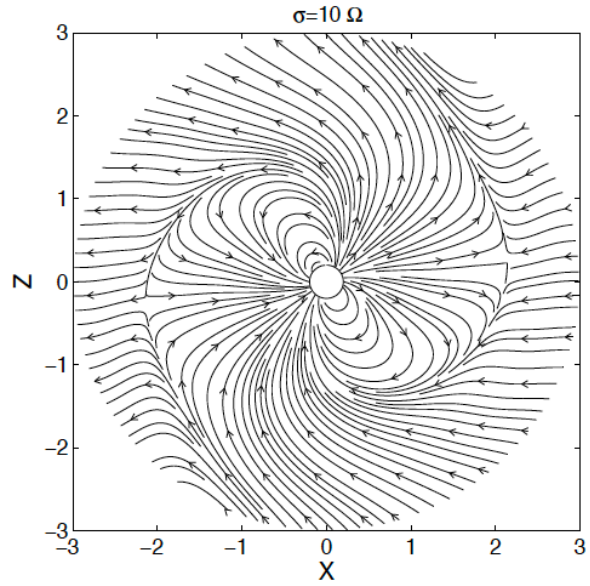


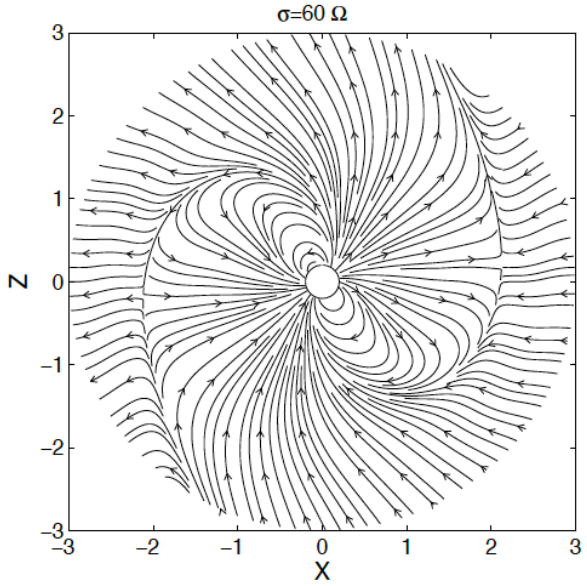
Magnetic field structure in the **Ω-μ** plane, inclination α = 60° Cao et al. 2019

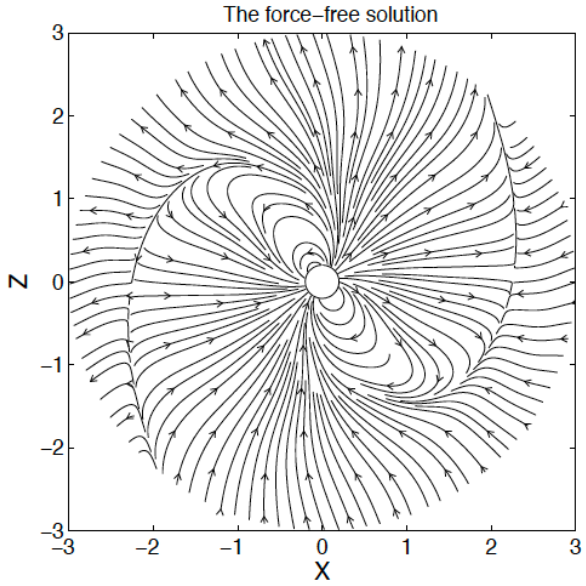












High-energy emission modeling with Particle-In-Cell simulations

Philippov+ 2017

Synchrotron emission by relativistic particles due to magnetic reconnection close to Y-point and in the current sheet.