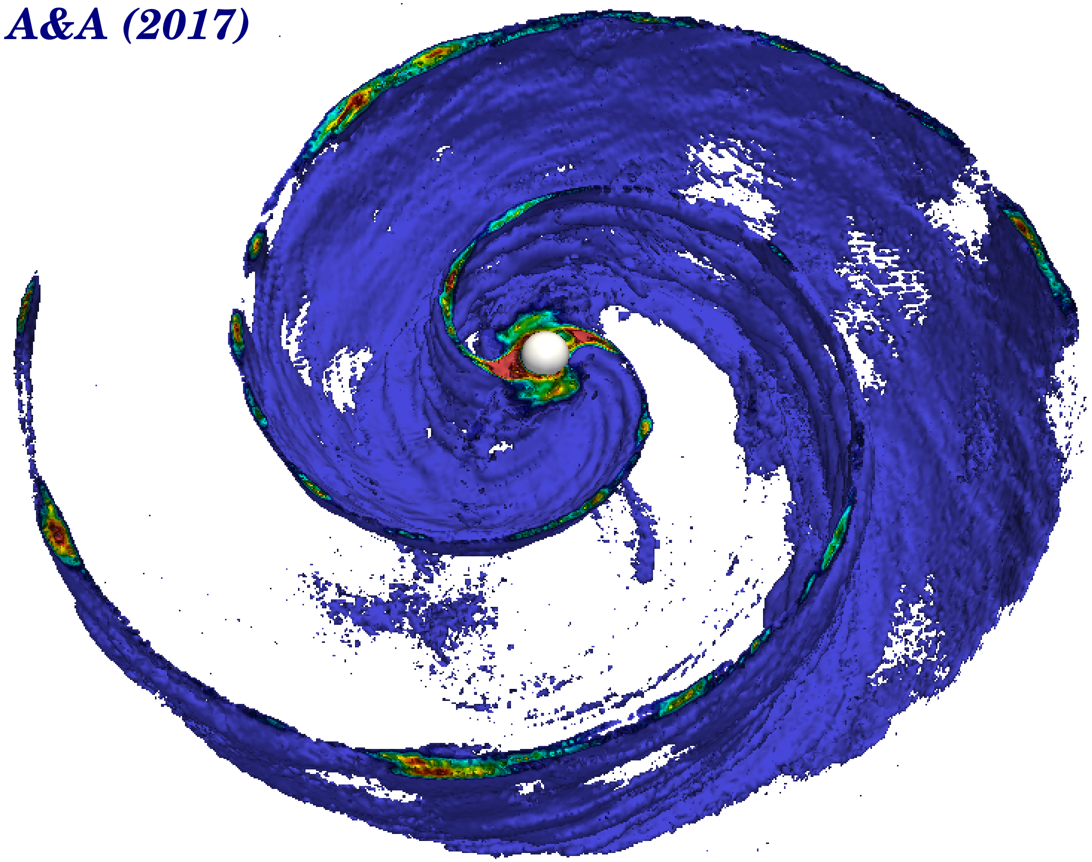
Magnetic dissipation in pulsar winds

Benoît Cerutti, *CNRS & Univ. Grenoble Alpes, France.*
In collaboration with **Sasha Philippov**, *UC Berkeley, USA.*

Cerutti & Philippov, A&A (2017)

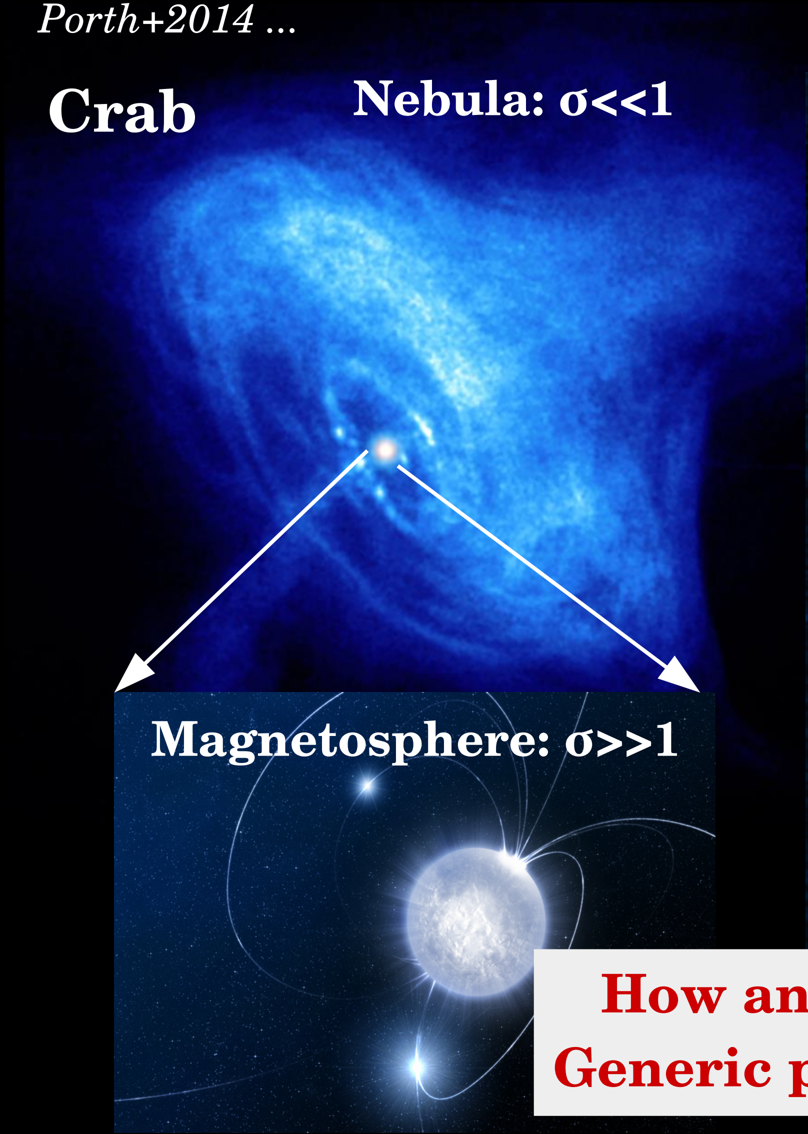


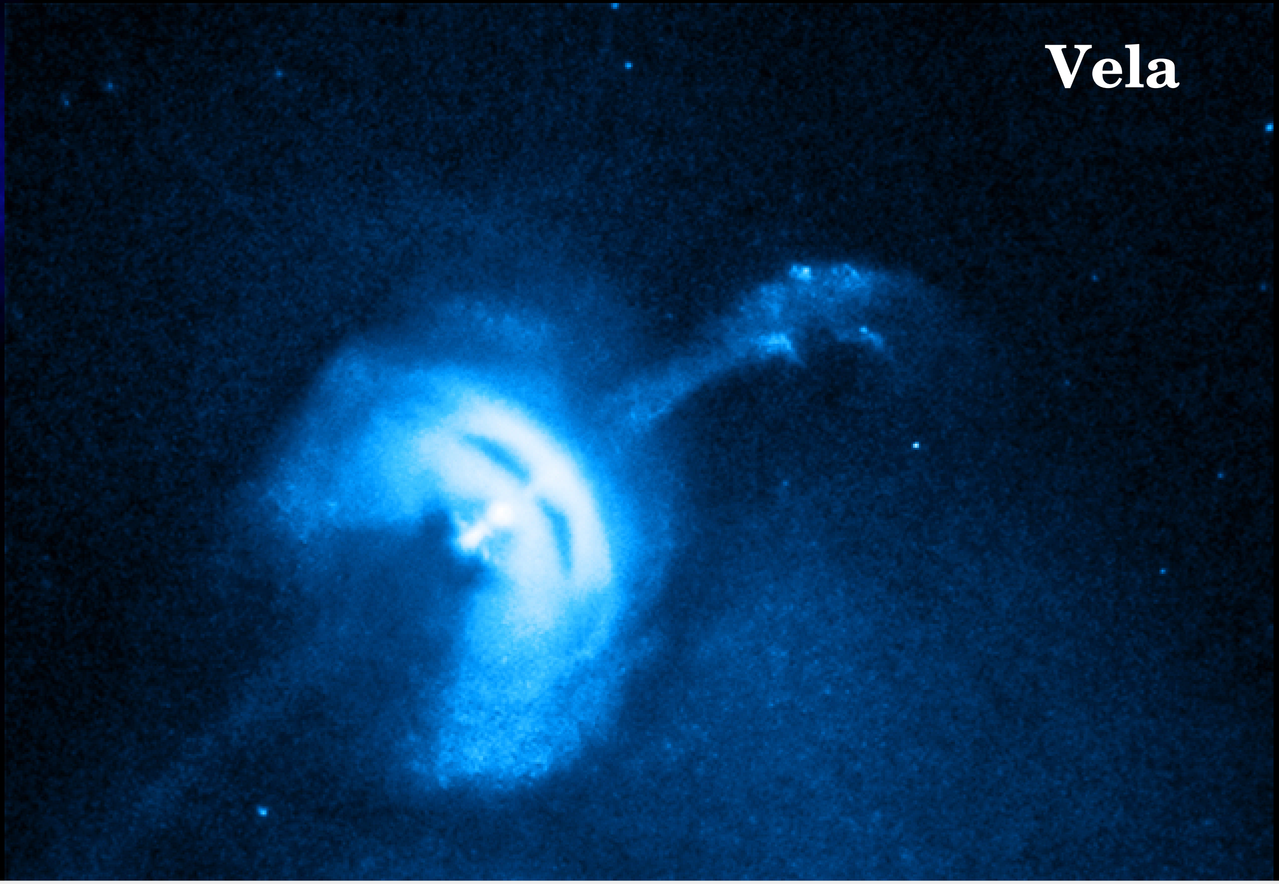
Third Purdue Workshop on Relativistic Plasma Astrophysics, West-Lafayette (IN), May 7-9 2018

The “sigma” problem

e.g., Rees & Gunn 1974
Kennel & Coroniti 1984a,b
Begelman & Li 1992
Coroniti 1990
Komissarov & Lyubarsky 2004
Lyutikov 2010
Porth+2014 ...

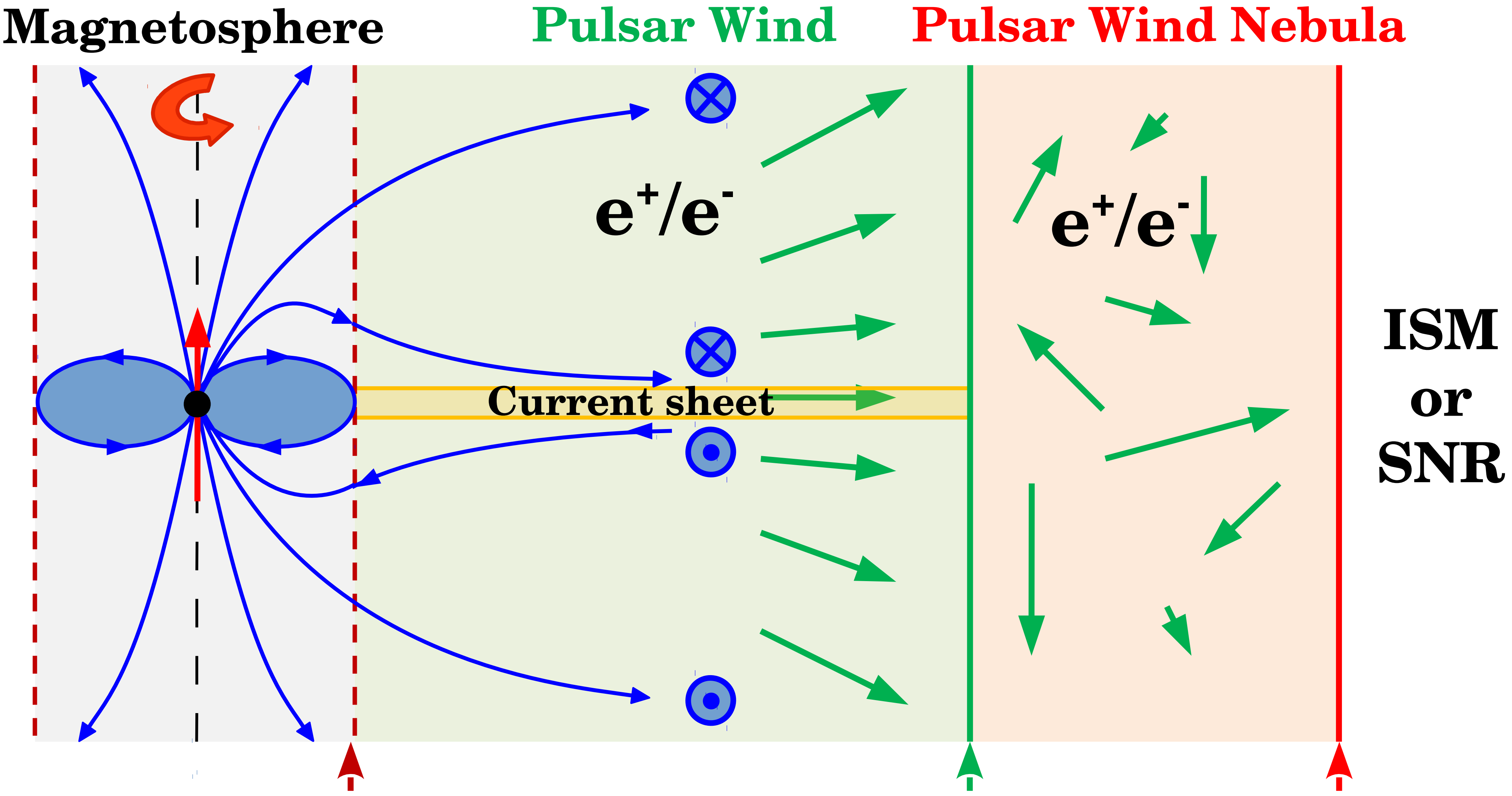
$$\sigma = \frac{B^2}{8\pi\Gamma n m c^2}$$





How and where is the magnetic energy dissipated ?
Generic problem in magnetized astrophysical outflows

The classical picture of pulsar wind nebulae



Magnetosphere

Pulsar Wind

Pulsar Wind Nebula

e^+/e^-

Current sheet

e^+/e^-

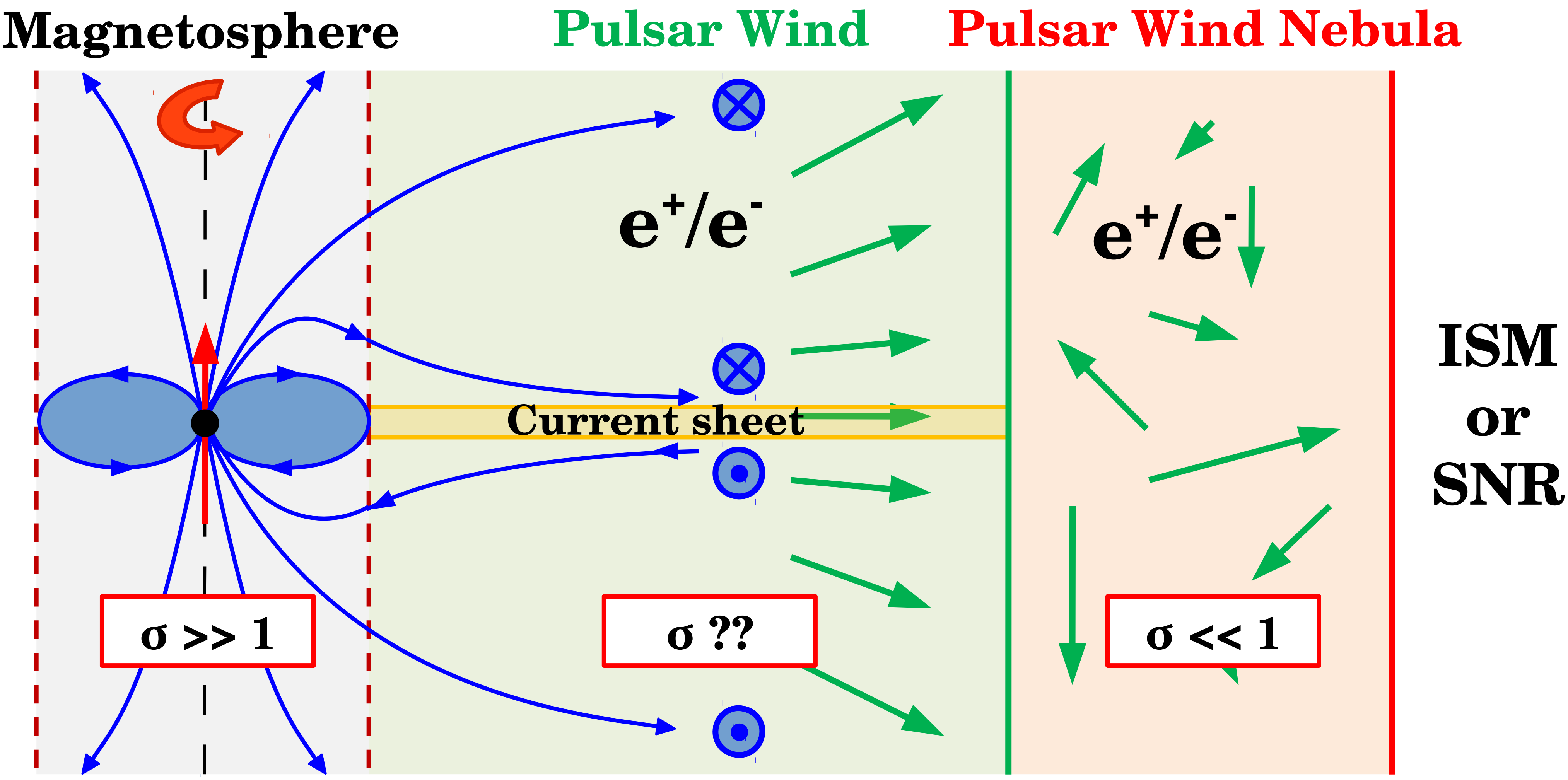
ISM
or
SNR

Light cylinder
radius: Pc/2π
~10^8 cm in Crab

Termination
shock radius
~0.1 pc in Crab
i.e., 10^9 R_{LC} !!

Contact
discontinuity
~1 pc in Crab

The σ-problem

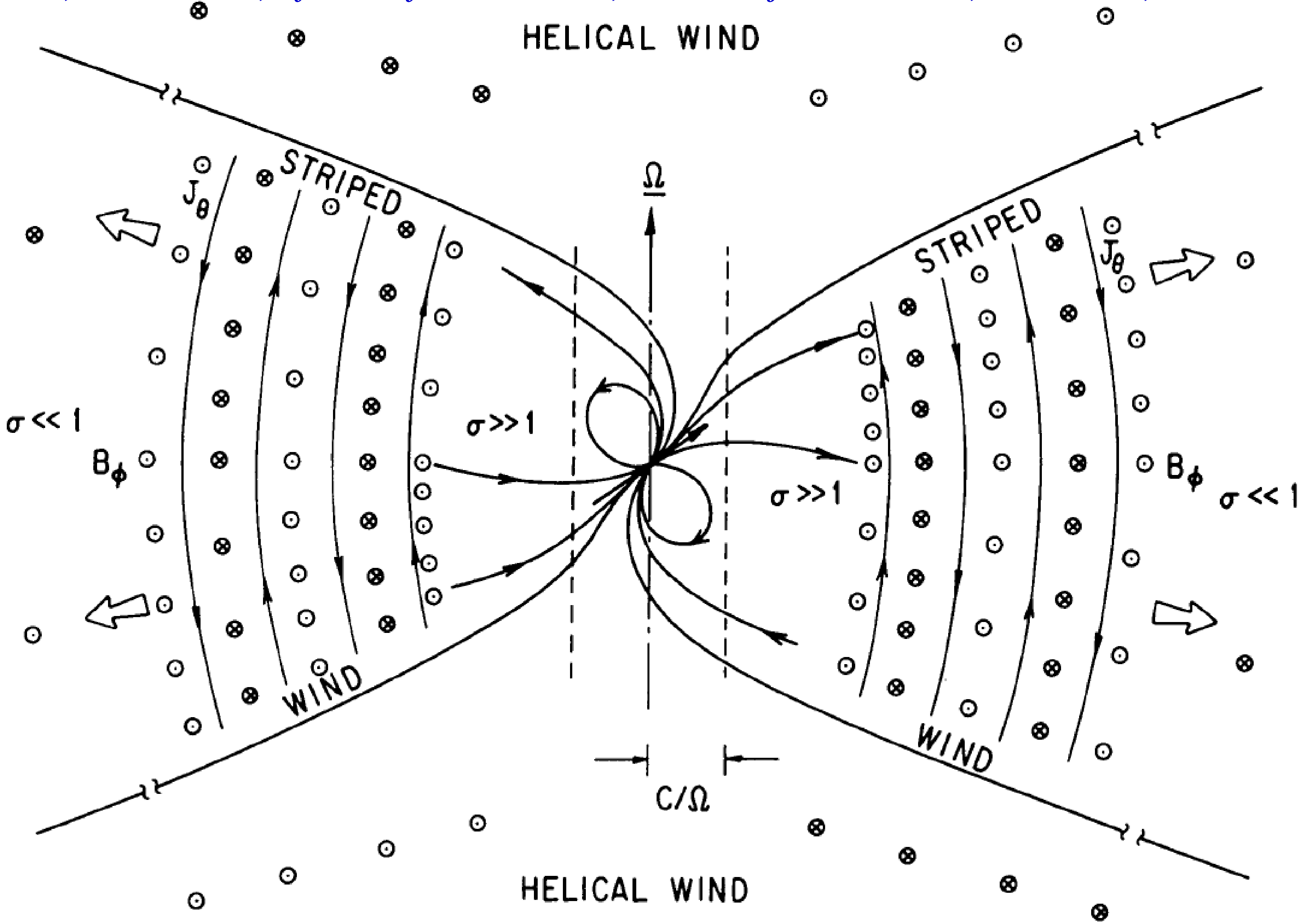


Transition σ >> 1 to σ << 1 unknown: "sigma" problem

=> Dissipation somewhere in between needed!

The equatorial current sheet : The ideal culprit !

Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003, Zrake 2016, Zrake & Arons 2016

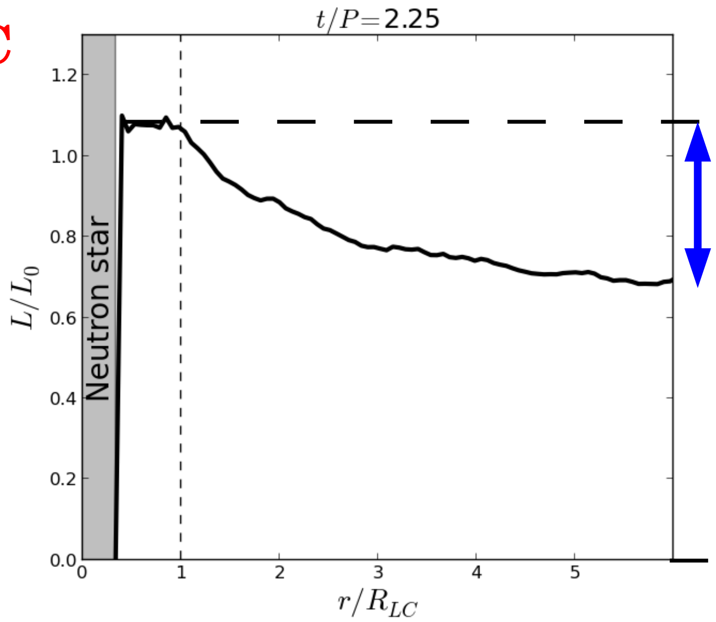


How far and how fast does magnetic reconnection proceed in the wind?

Close in or at the termination shock ?

2D PIC

Poynting flux



$r>>R_{LC}$??

~30% drop over few R_{LC}

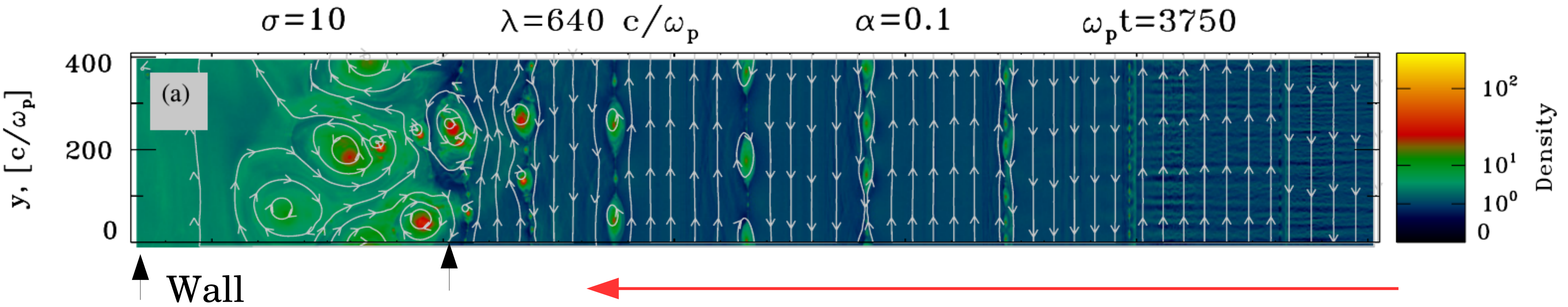
Philippov & Spitkovsky 2014
Chen & Beloborodov 2014
Cerutti+2015
Belyaev 2015
Brambilla+2017

Scenario 1 : Complete dissipation far before the shock

Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003

Scenario 2 *:* Shock-driven reconnection at the termination shock

Lyubarsky 2003 ; Pétri & Lyubarsky 2007 ; Sironi & Spitkovsky 2011



Wall

Shock

Striped wind

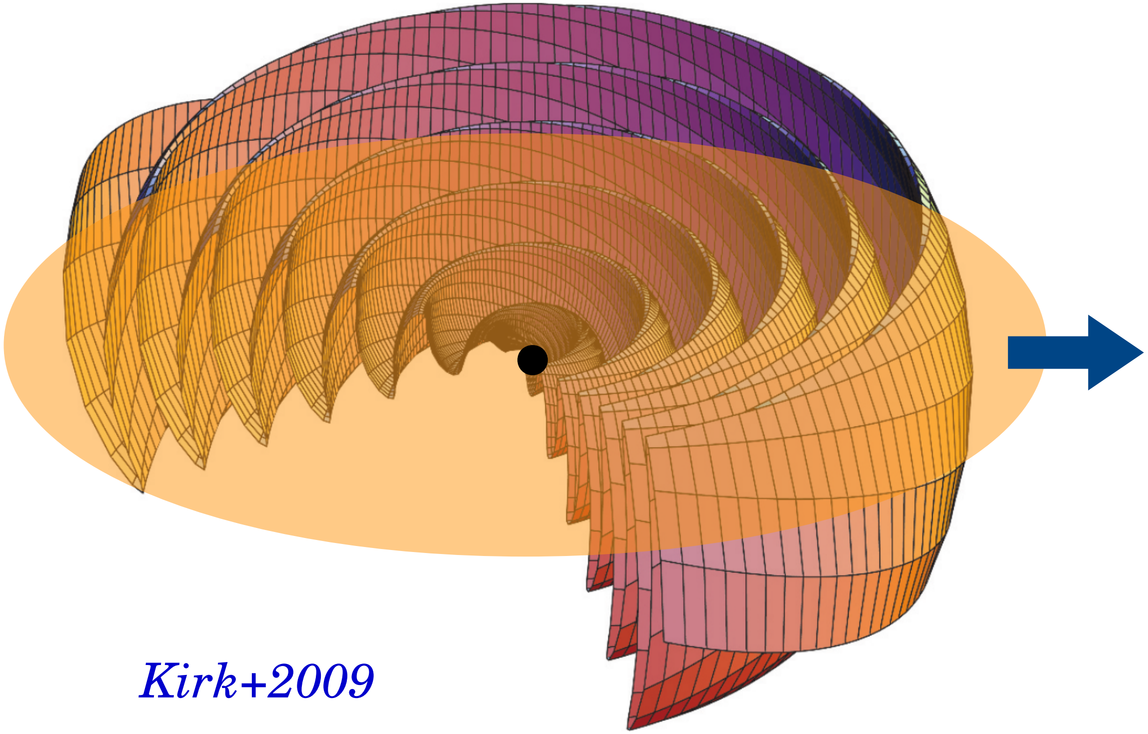
The numerical challenge

PIC simulations are needed to capture dissipation.

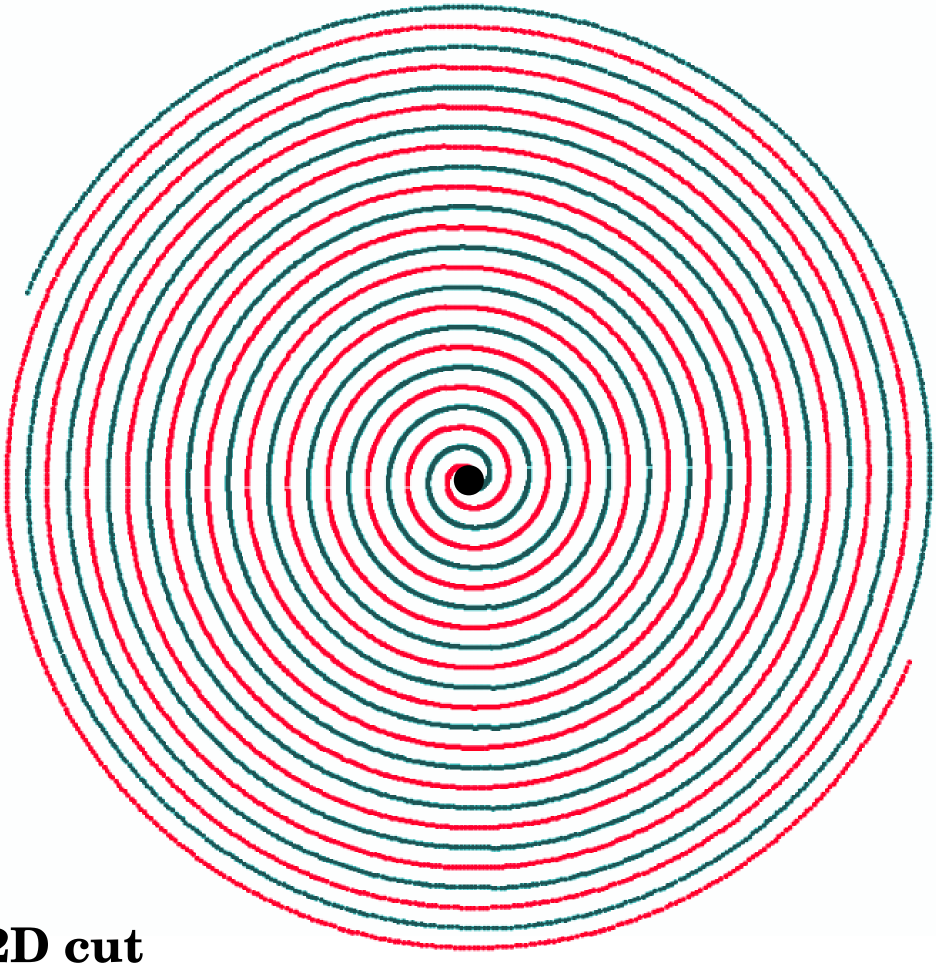
We need to probe large radii, very large box $r>>R_{LC}$!!

3D simulations too expansive!

=> 2D simulations of the oblique rotator!?



Kirk+2009



Equatorial 2D cut

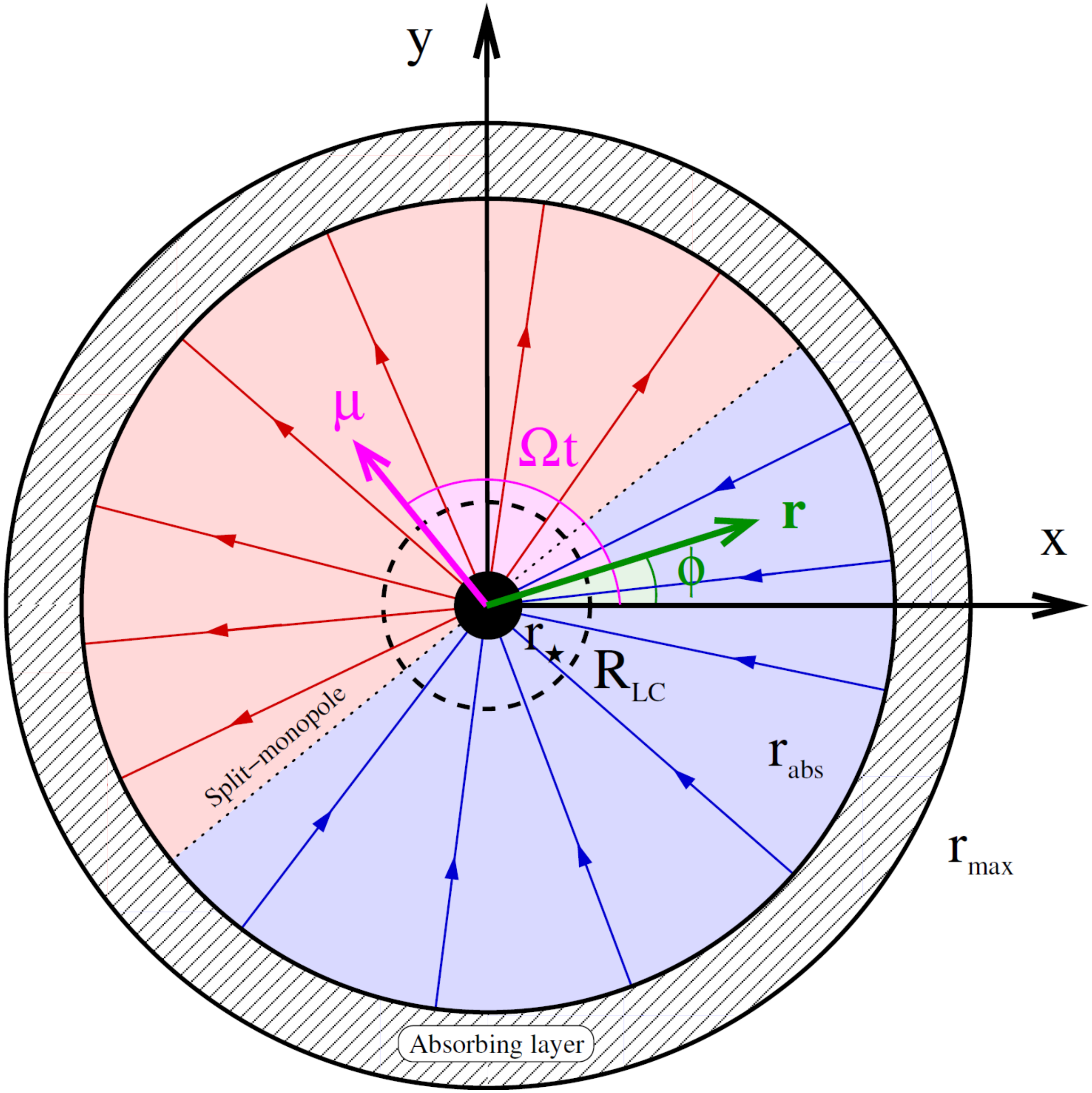
The numerical setup

Split monopole

[Michel 1973 ; Bogovalov 1999]

4096×4096 cells
rφ-plane spherical
- logarithmic in r
- uniform in φ

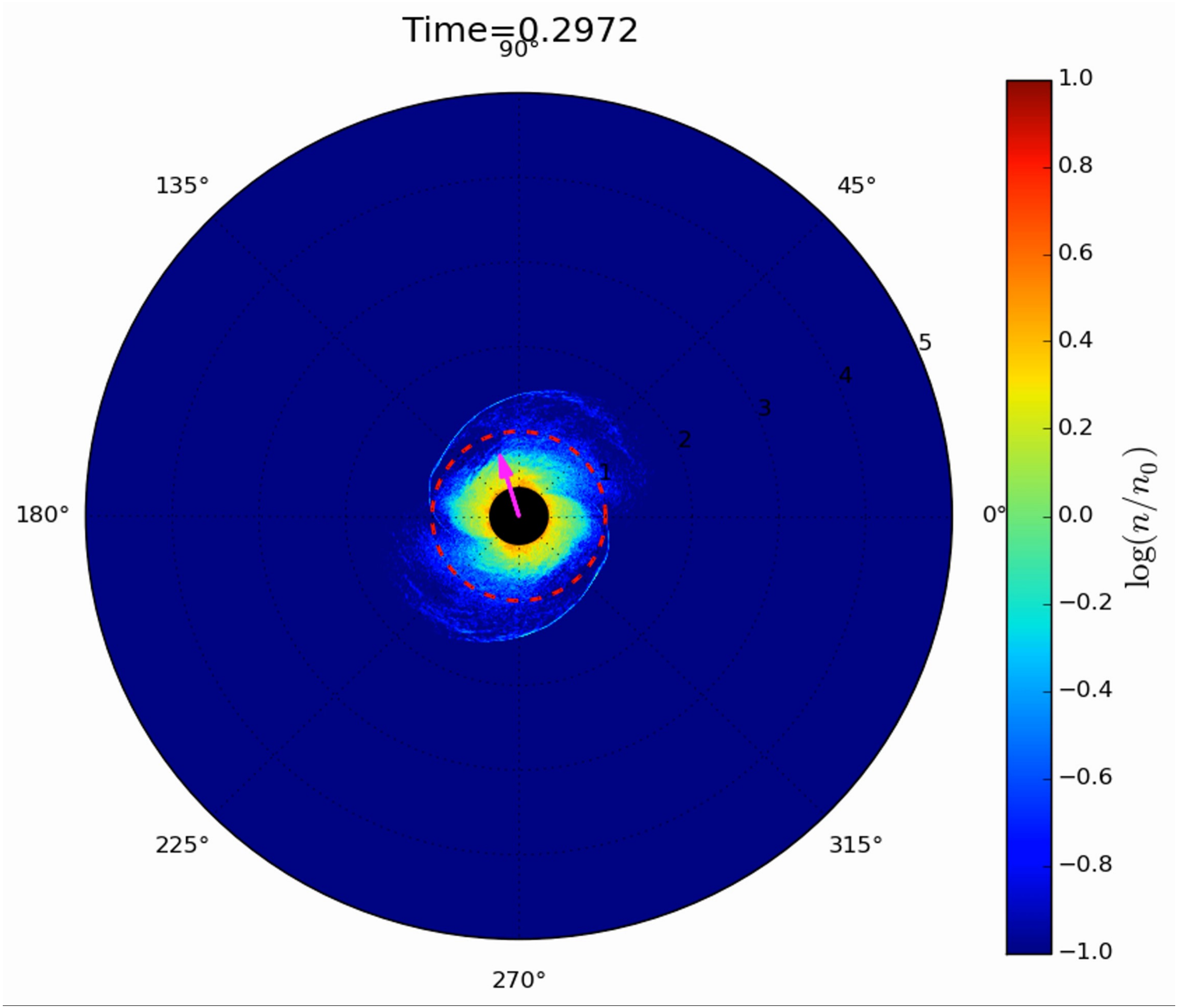
r_{max} = 150 R_{LC}
R_{LC}/R_* = 3, 6, 9
σ_* = 250 ,1000, 2500
κ_* = 5, 10, 20

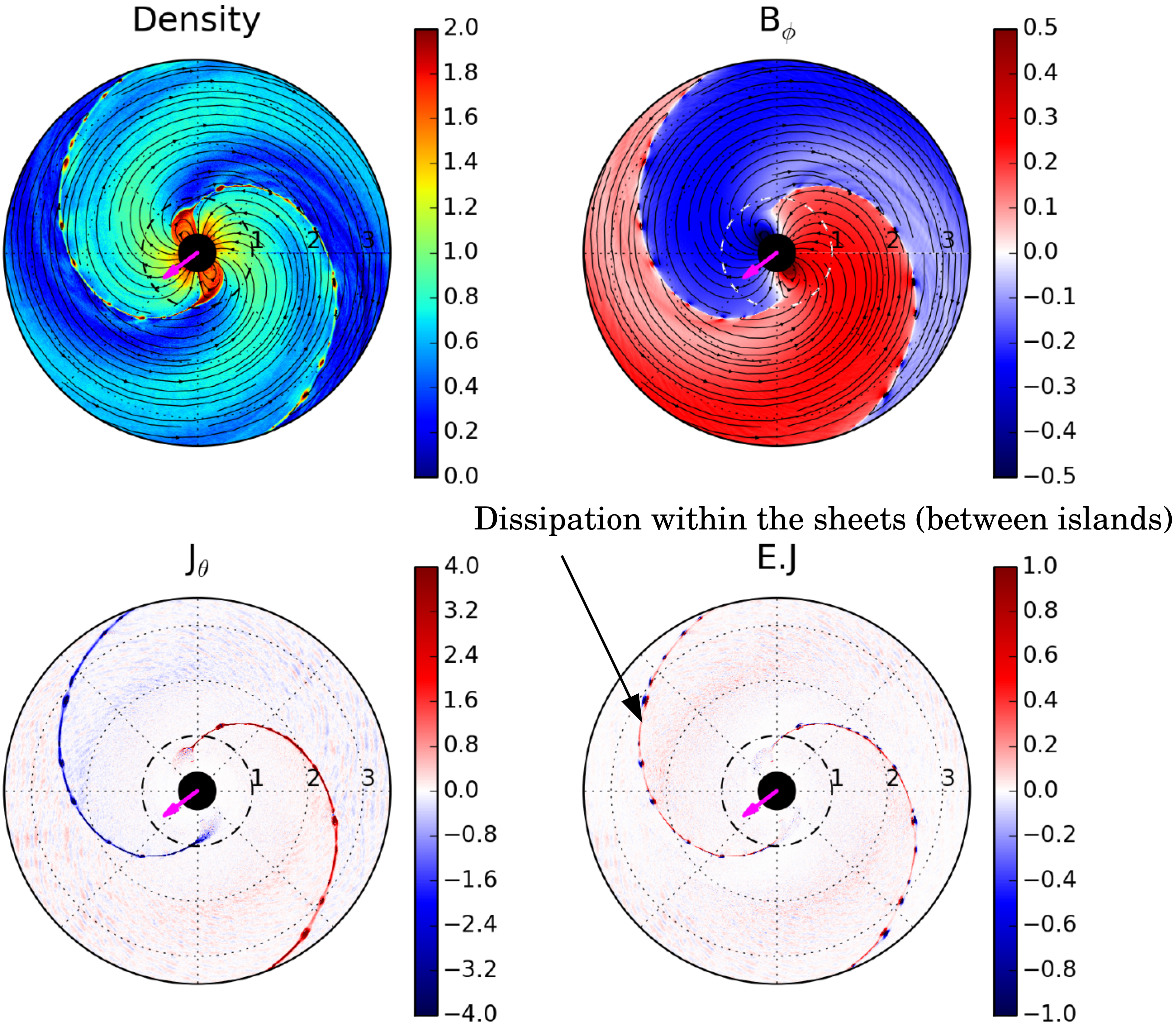


Neutral $e^{+/-}$ plasma injected from the surface at the E×B drift velocity :

$$
\begin{aligned}
V_r &= \frac{c}{1+R_{LC}^2/r^2}, \\
V_\theta &= 0, \\
V_\phi &= \frac{r\Omega}{1+r^2/R_{LC}^2}.
\end{aligned}
$$

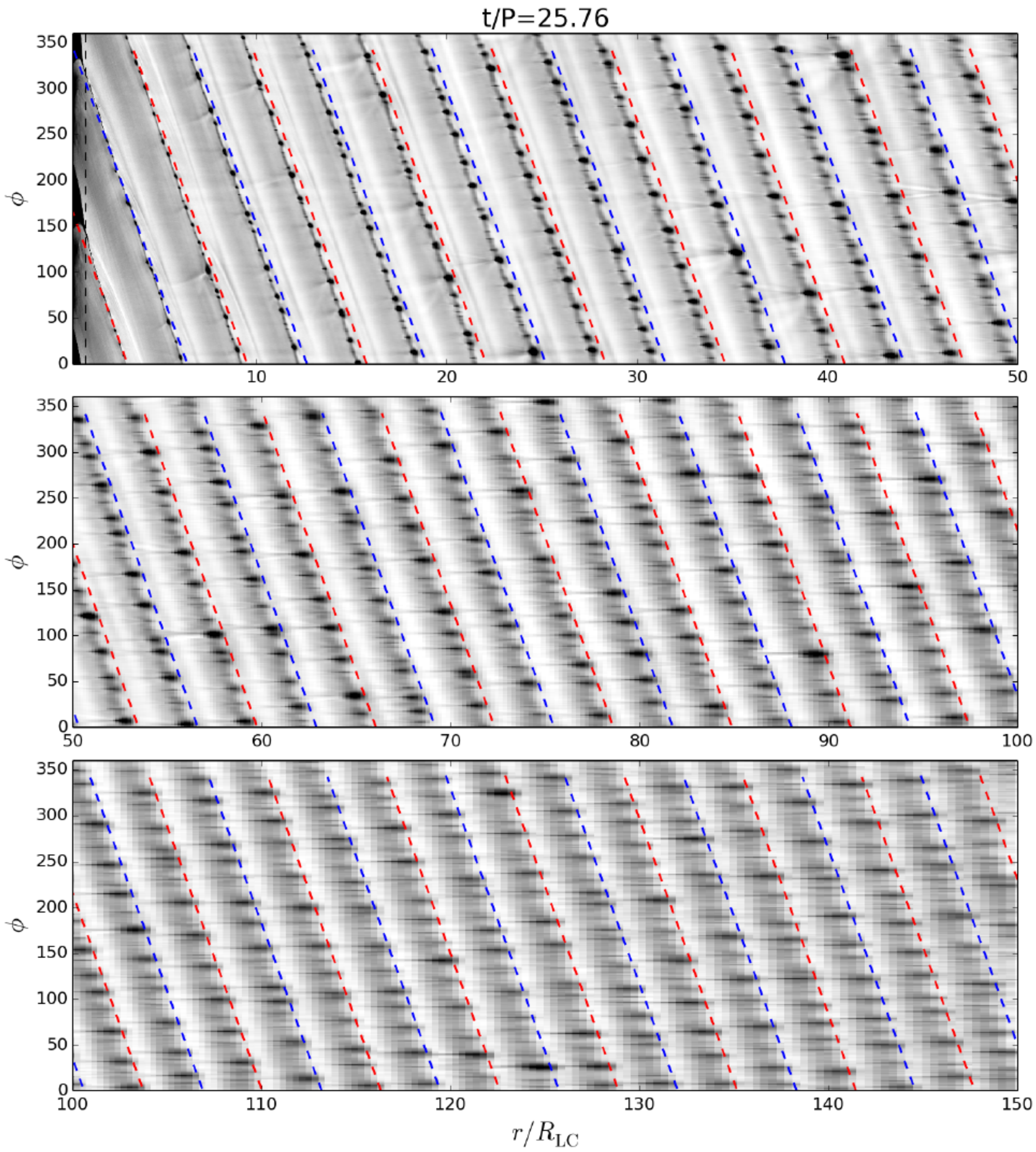
NB: A "cylindrical" (Rφ-plane) pulsar wind does not work ($E_z \neq B_\varphi$)


Time=0.2972
90°
135°
45°
180°
0°
225°
315°
270°
1
2
3
4
5
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
$\log(n/n_0)$



Dissipation within the sheets (between islands)

The whole box



Most dynamical region

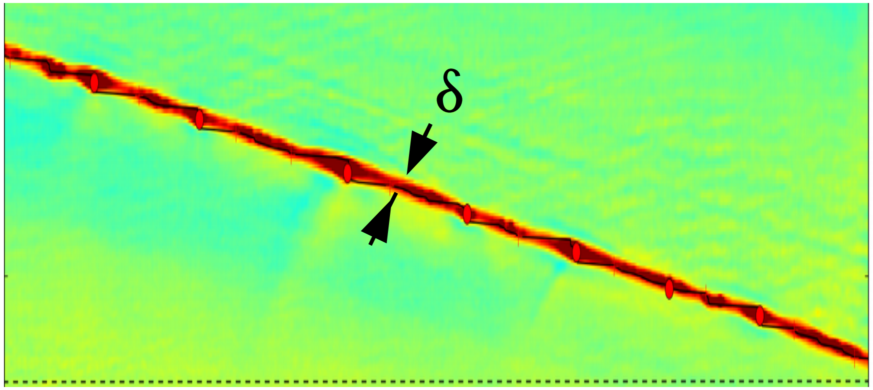
Formation of plasmoids and **mergers**

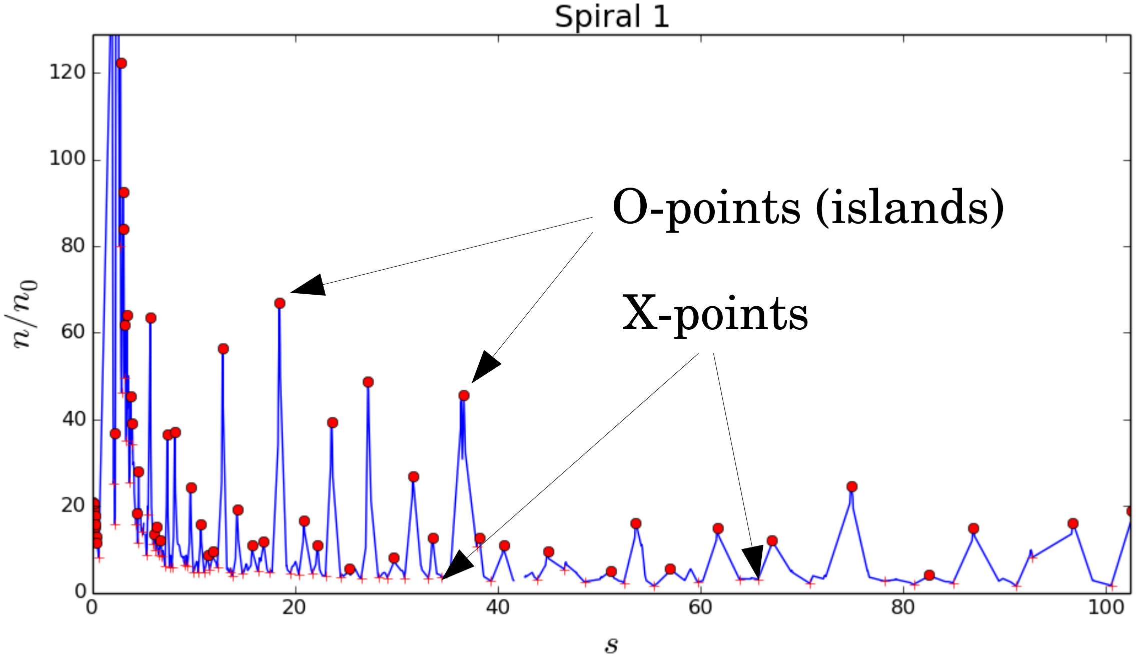
Structure frozen by the expansion of the wind

 # islands ~ constant

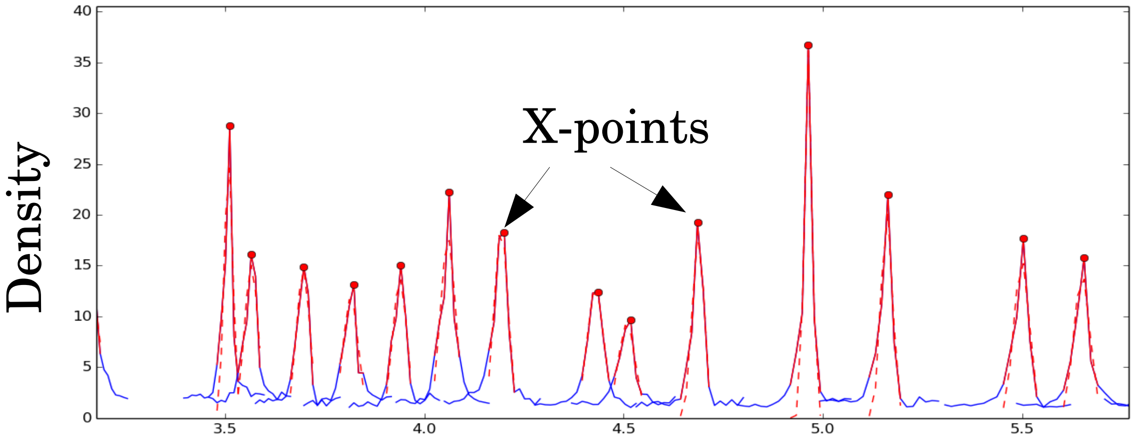
Layer thickness analysis

1. Look for plasma **density minima** along the sheet to **identify X-points**



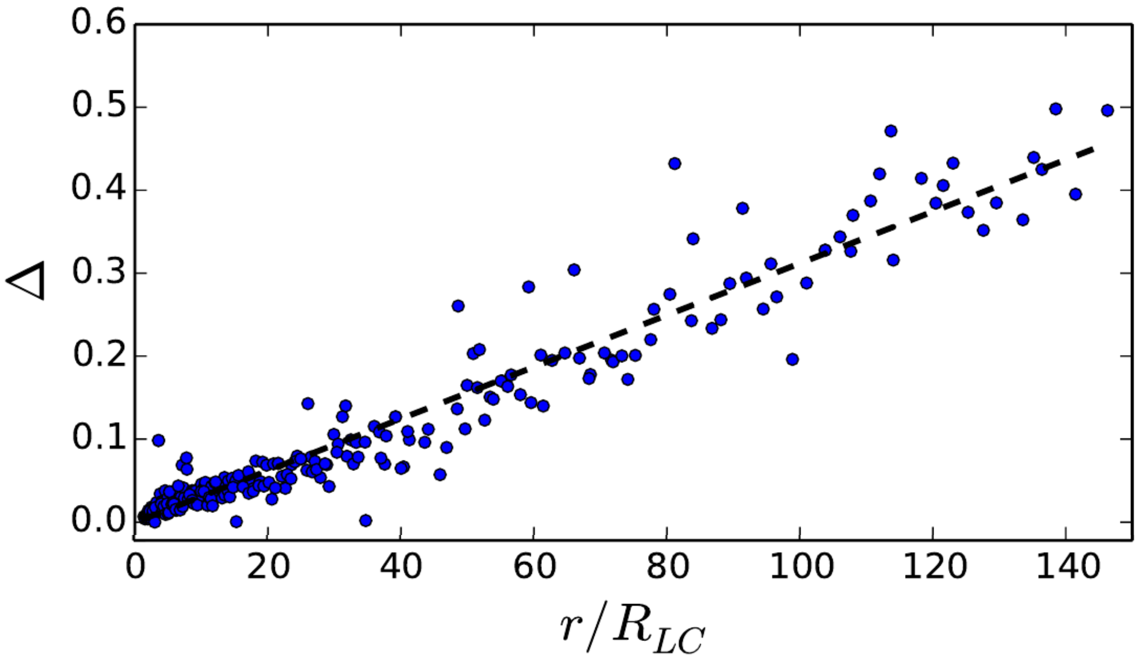


2. Fit the **transverse density profile** with a gaussian



3. Measure the local sheet width with the Full Width at Half Maximum, **$\delta(r)$=FWHM**

Expansion of the sheet thickness



Linear expansion of the sheet :

$$\Delta = \delta / \pi R_{\mathrm{LC}}$$

$$\Delta\left(r\right) \approx \Delta_{\mathrm{LC}}\left(\frac{r}{R_{\mathrm{LC}}}\right)$$

$$\Delta\left(r\right) \approx \frac{1}{\pi \Gamma_{\mathrm{LC}} \kappa_{\mathrm{LC}}}\left(\frac{r}{R_{\mathrm{LC}}}\right) = \frac{1}{\pi \Gamma_{\mathrm{LC}} \kappa}$$

Complete dissipation Δ=1 => $r_{diss}/R_{LC}=\pi\Gamma_{LC}\kappa_{LC}\sim10^3\text{-}10^6 \ll R_{shock}/R_{LC}$

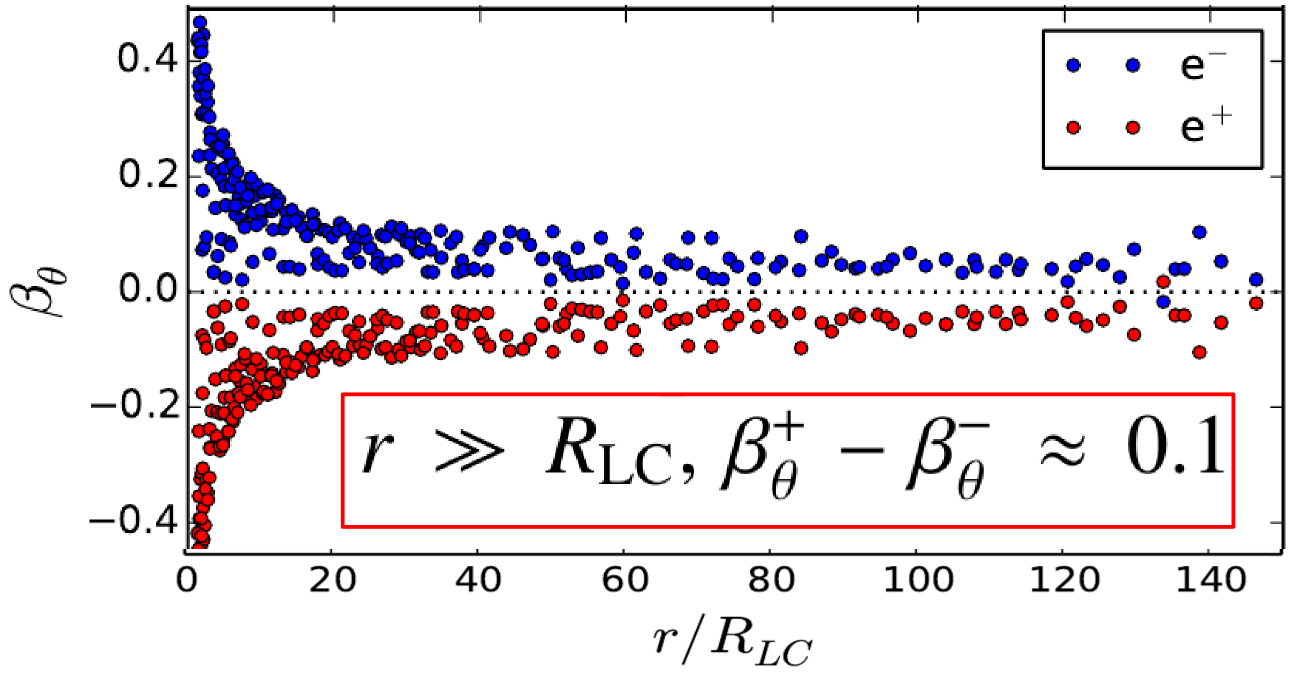
See also Lyubarsky & Kirk 2001

Expansion of the sheet thickness

Results consistent with *Coroniti (1990)* and *Michel (1994)*

Ampère's law accros the sheet yields ($r>>R_{LC}$) :

$$2\underbrace{B_\phi}_{\sim 1/r} = \frac{4\pi}{c} J_\theta \delta = 4\pi \underbrace{n}_{\sim 1/r^2} e \underbrace{\left(\beta_\theta^+ - \beta_\theta^-\right)\delta}_{\sim r},$$



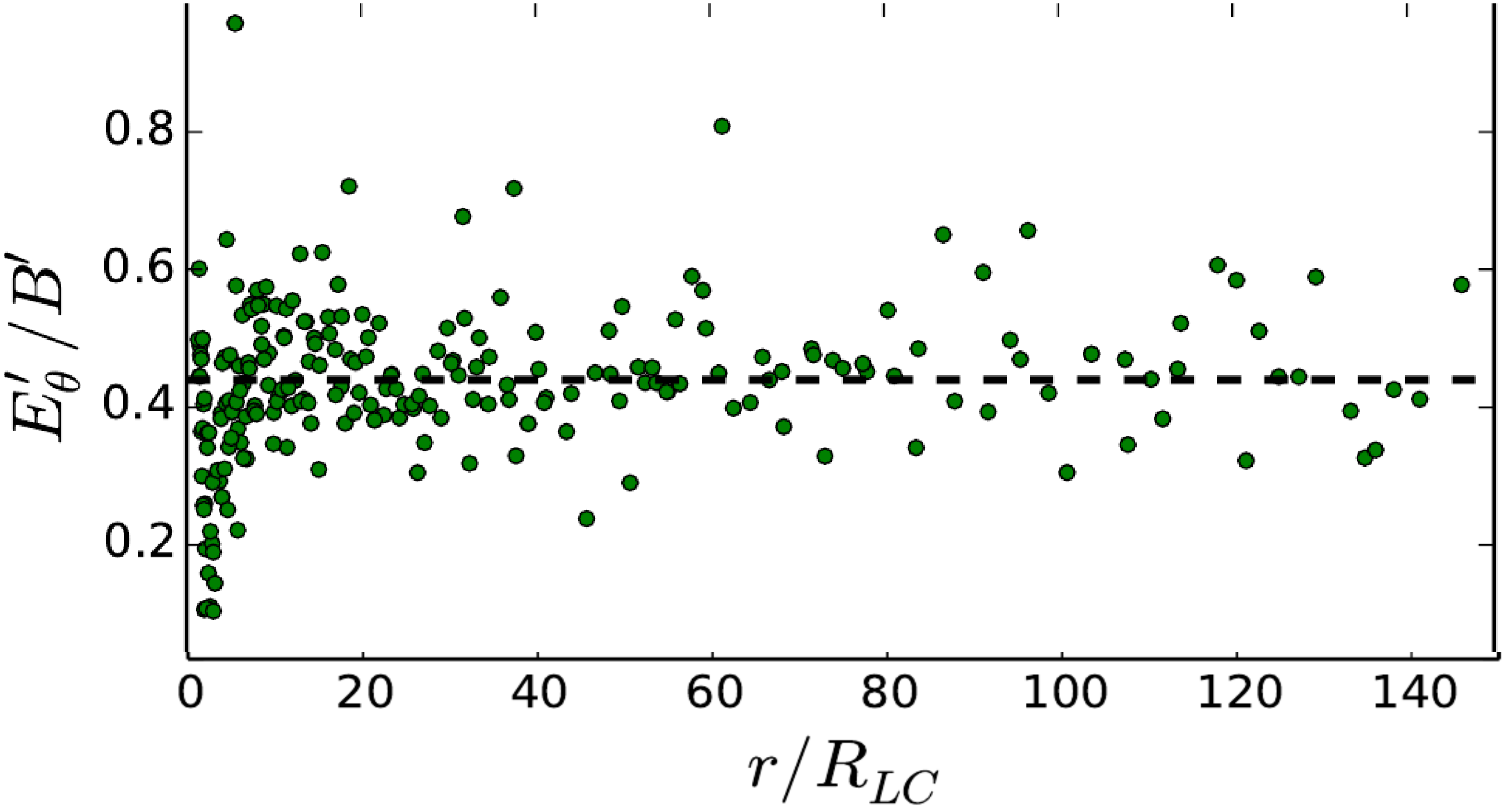
$$r \gg R_{\mathrm{LC}},\ \beta_\theta^+ - \beta_\theta^- \approx 0.1$$

Important consequence : **Current starvation does not happen** if there are enough charges to begin with, in agreement with *Arons 2012*, but in contradiction with *Usov 1975.*

Reconnection rate

Appropriately described into the co-moving frame

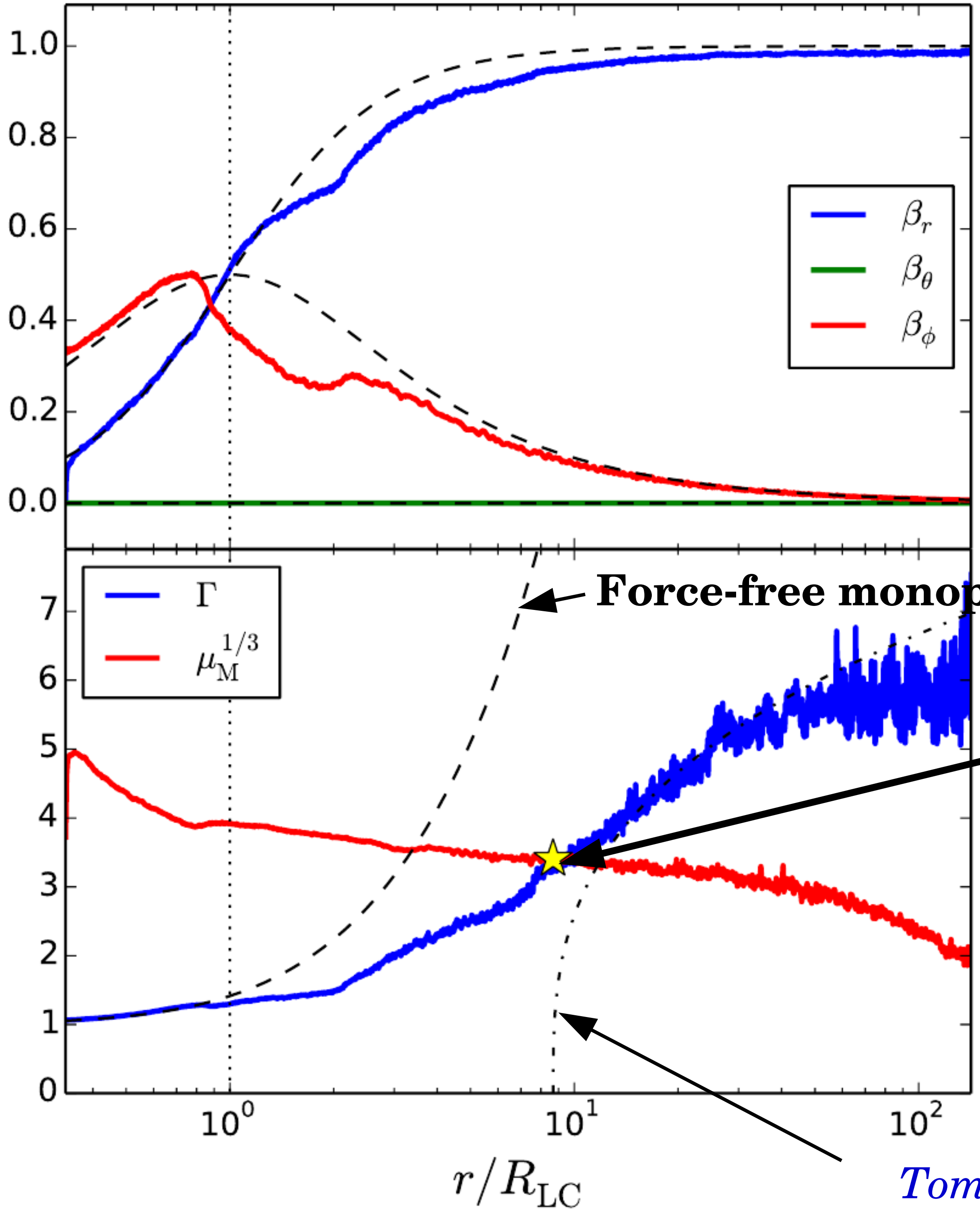
[Lyubarskii 1996 ; Uzdensky & Spitkovsky 2014]



Hard to measure (the wind accelerates) but approximatively constant ~ **0.45**
High rate compared with local simulations of reconnection (~0.1-0.2).

Reconnection driven by large scale plasma motion ?

Wind kinematics



------- **Force-free monopole**

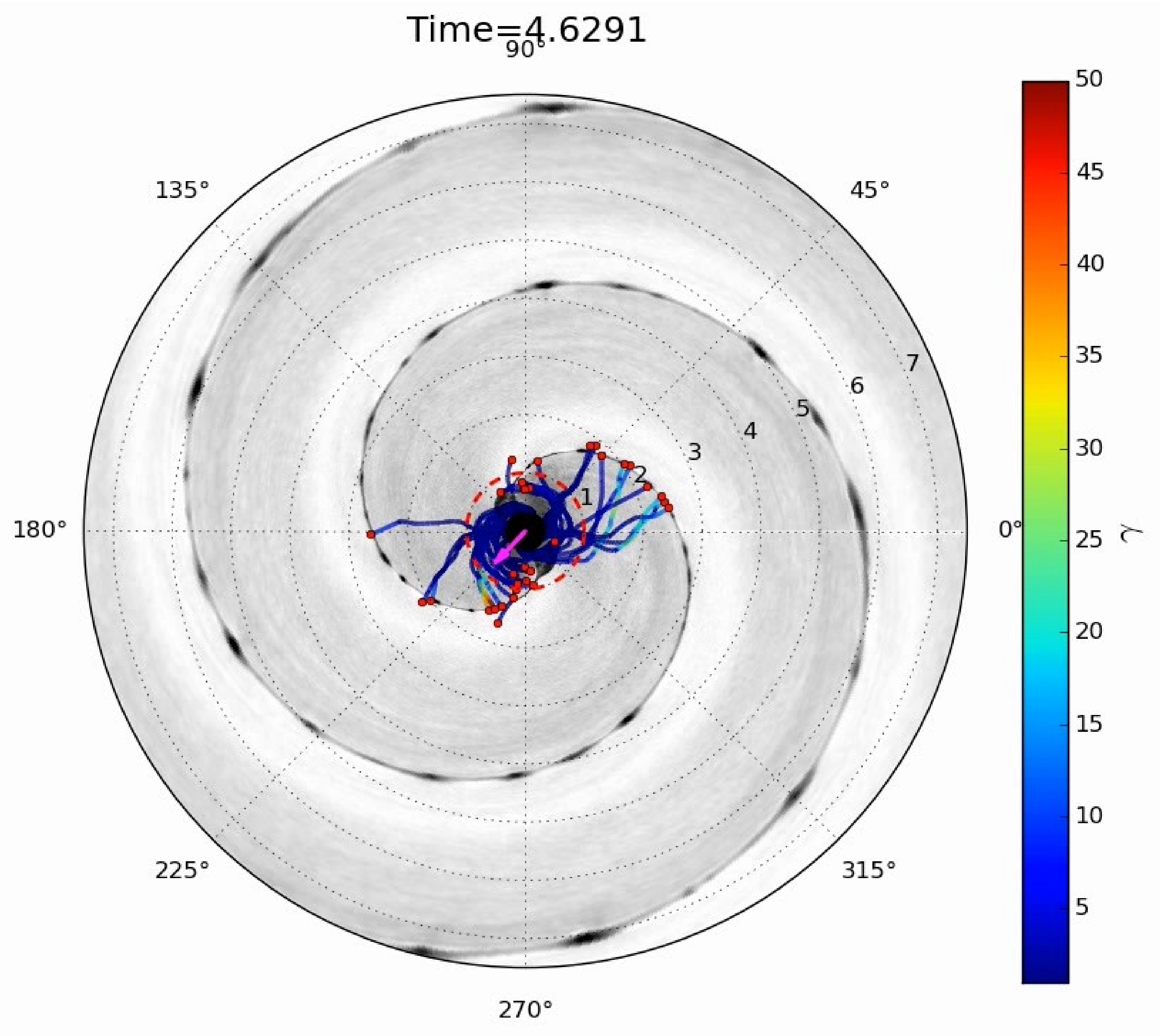
Force-free monopole

Fast magnetosonic point :

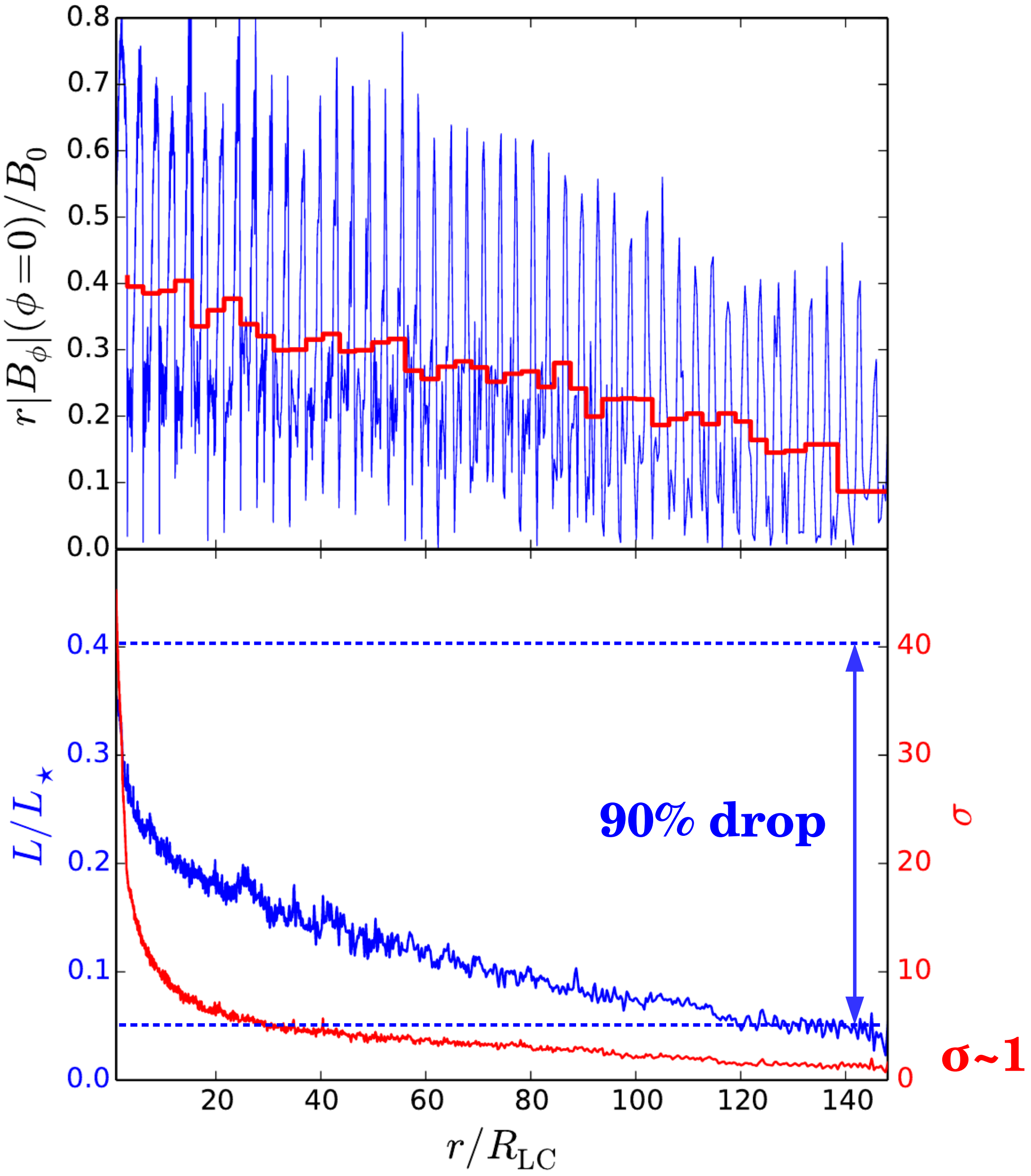
$$v_{wind} = c\sqrt{\frac{\sigma}{1+\sigma}}$$

Tomimatsu 1994

Particle acceleration



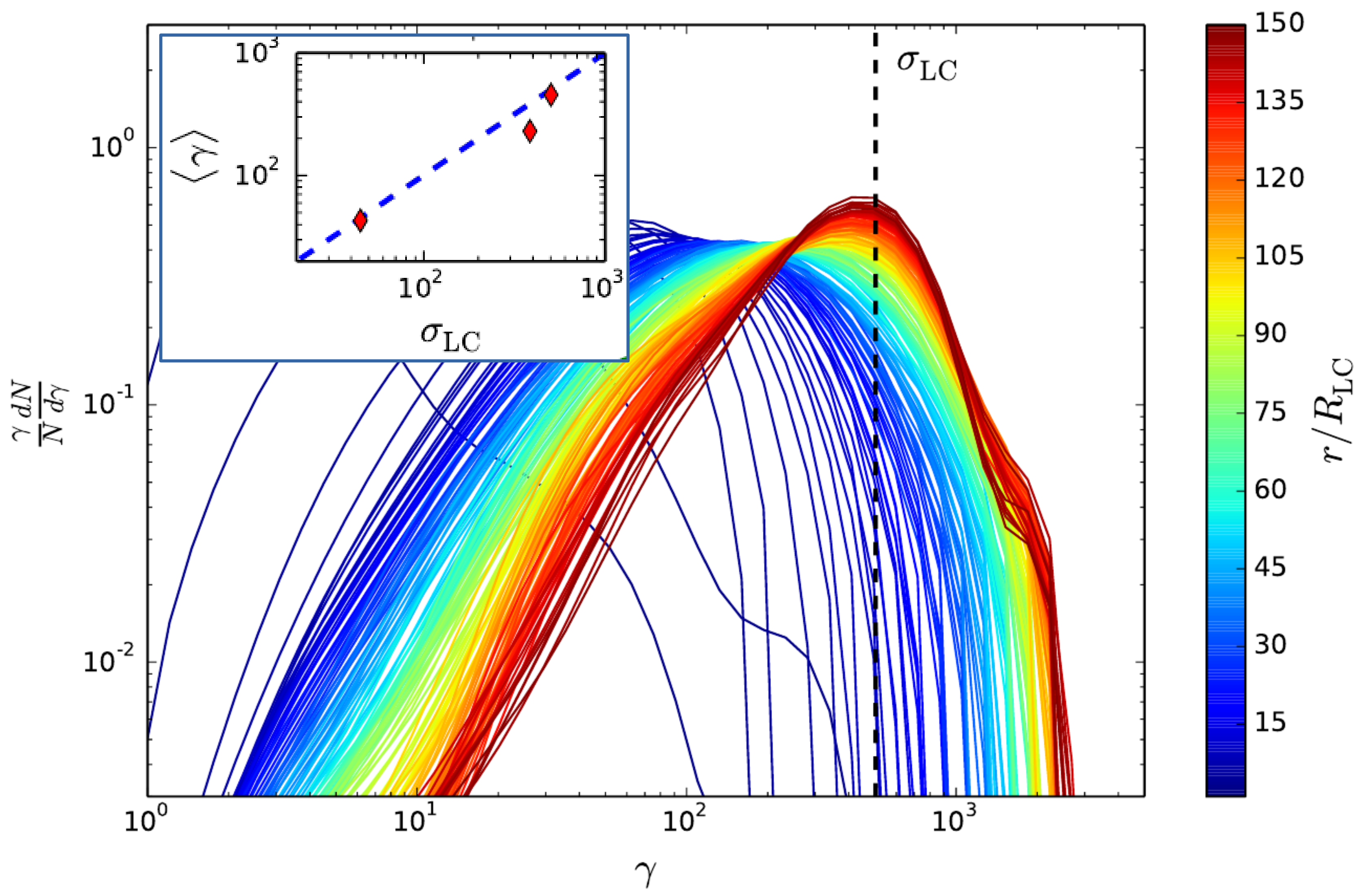
Magnetic dissipation in the wind



90% drop

σ~1

Particle spectral evolution in the wind



"Narrow" particle energy distribution set by :

$$\boxed{\sigma_{LC} \sim \Phi_{pc}/\Gamma_{LC}\kappa_{LC}}$$

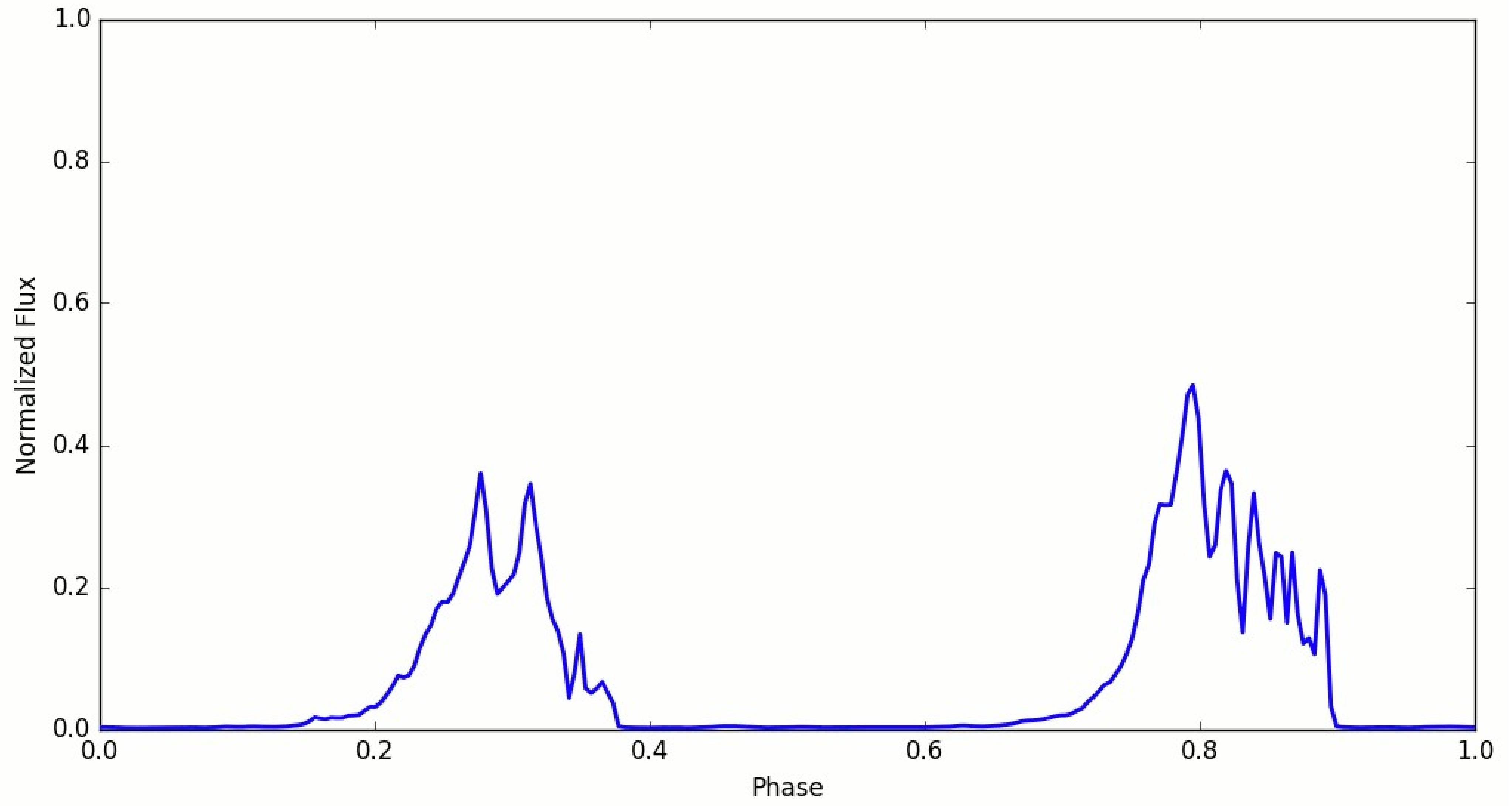
Macroscopic

Microscopic

Radiative signatures

Synchrotron pulse profile : One peak per line-of-sight crossing of the sheet.

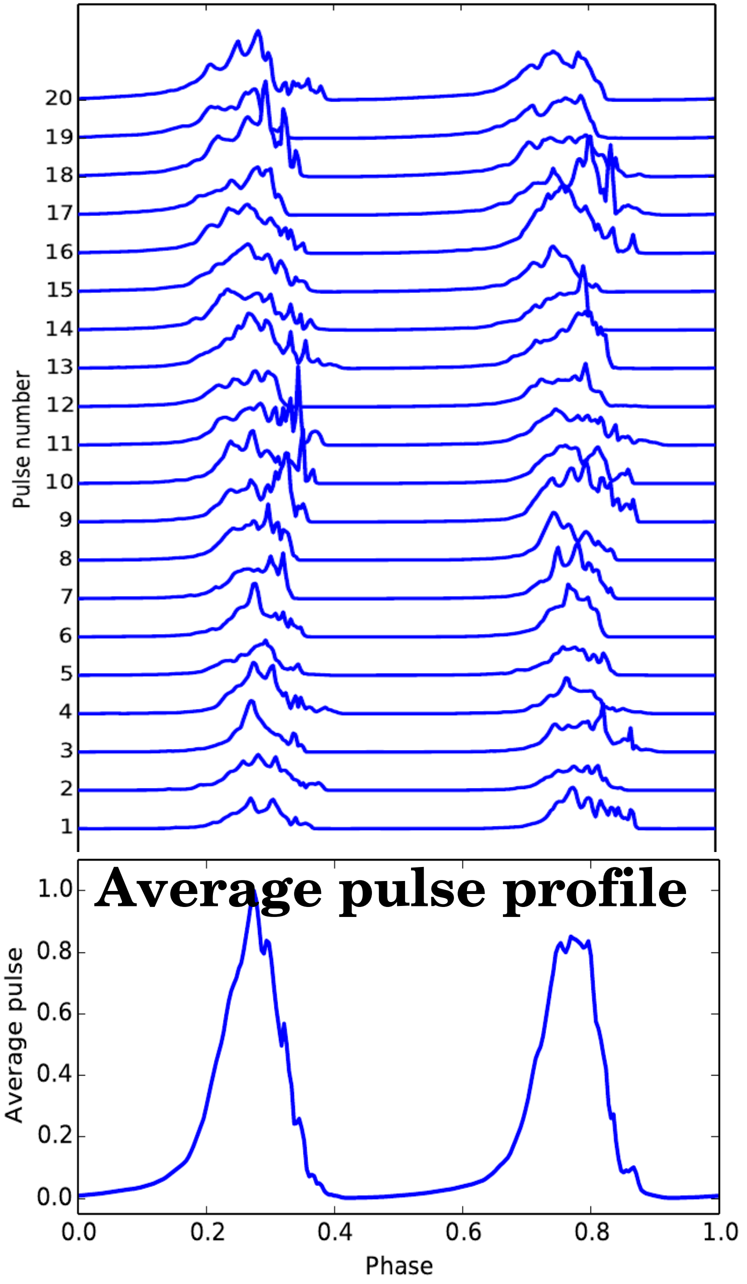
[Cerutti+16, Philippov & Spitkovsky 2017, Kalapotharakos+2017]



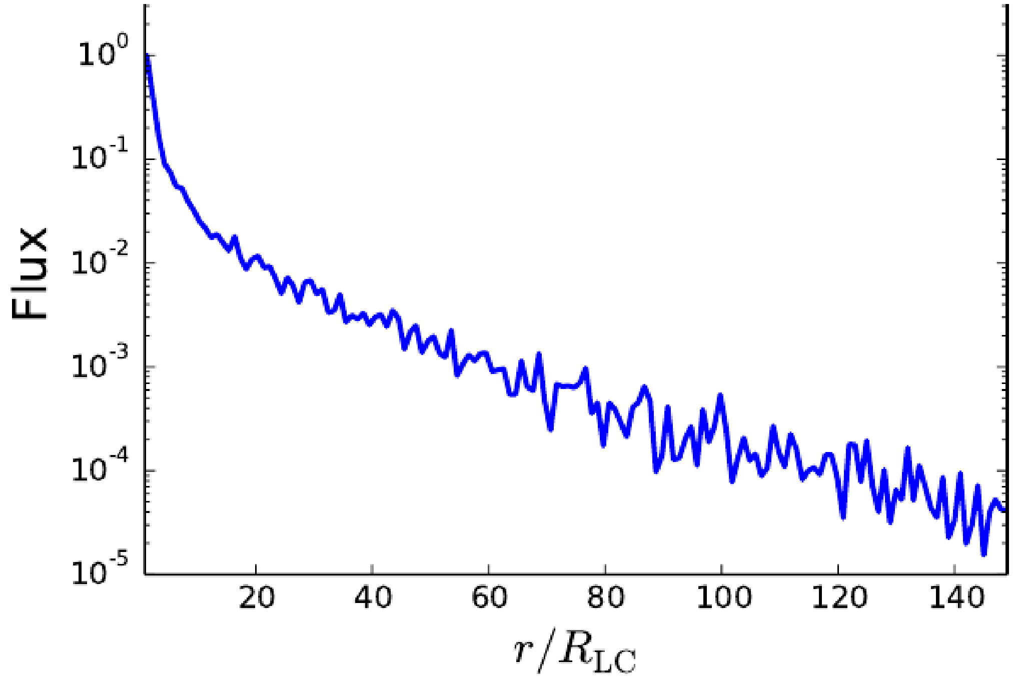
Significant pulse-to-pulse variability

Radiative signatures

Synchrotron pulse profiles


Average pulse profile

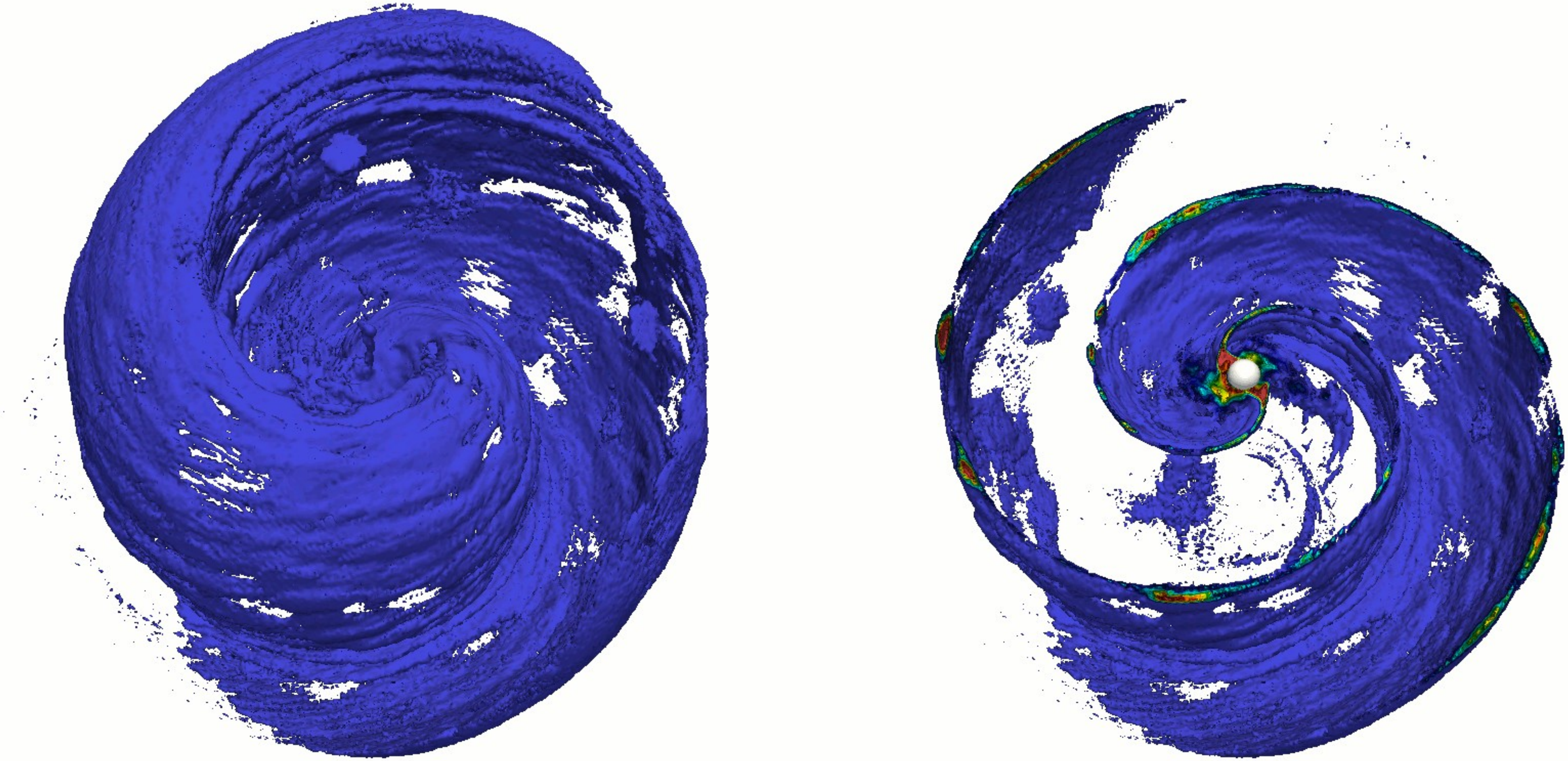
Significant **pulse-to-pulse** **variability** due to the passage of plasmoids along the line of sight.



Synchrotron emission mostly concentrated **near the light-cylinder.**

=> Gamma-rays probe the **most active regions** of the sheet (formation of islands & merging episodes)

Coming up : Large 3D simulations



Conclusions

- Relativistic reconnection **proceeds in the wind**

- **Complete dissipation** most likely far before the termination shock radius, **R_{diss}/R_{LC}~κ_{LC}~10^2-10^5 << R_{shock}**

- Particle distribution "thermalize" into a **narrow distribution** centered around Lorentz factor given by **σ_{LC}~Φ_{pc}/κ_{LC}**

- **=> Need better constraints for pair creation @ LC!**

- **Current starvation does not happen** as long as there are enough charges to begin with (at LC)

- **Pulsars in binary** systems (transitional ms & γ-ray binaries) good targets to probe magnetic dissipation within the wind as **R_{shock}~R_{diss}**