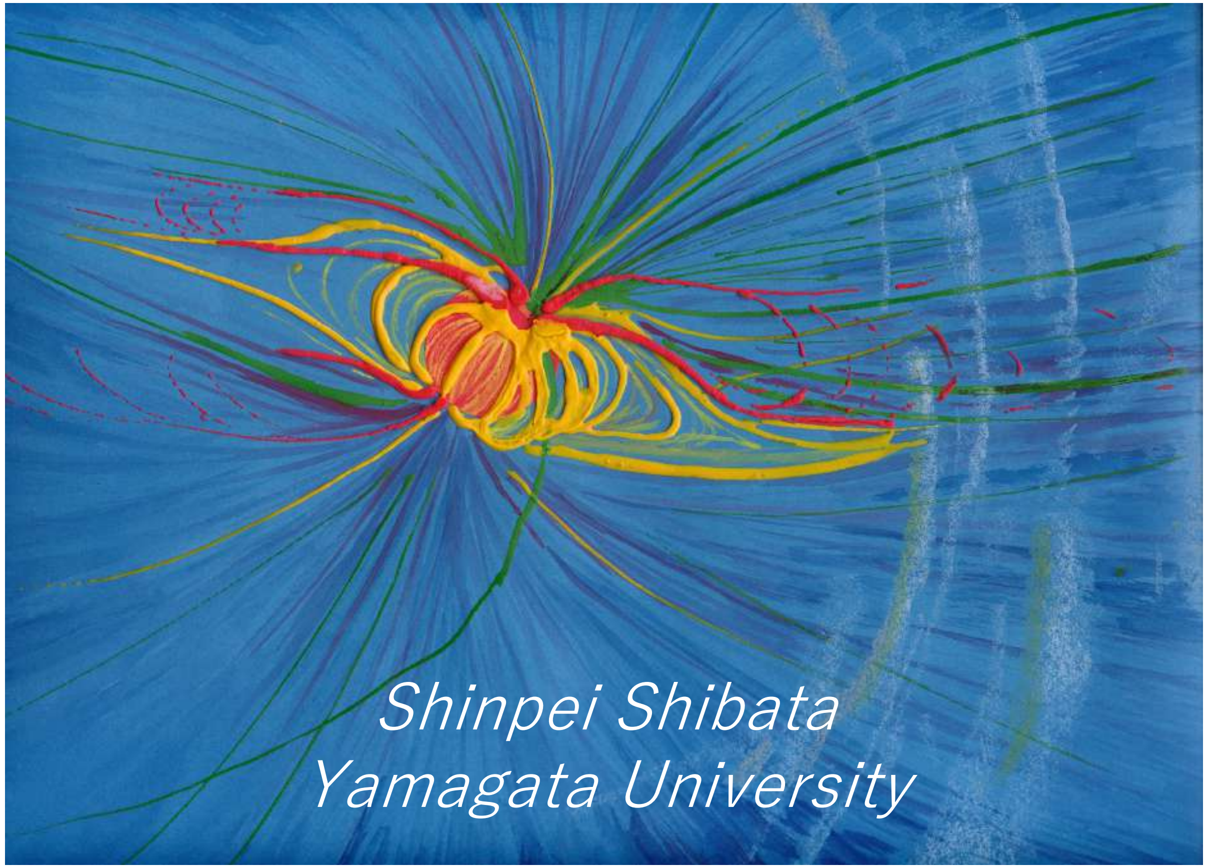
～中性子星の観測と理論～研究活性化ワークショップ 2023
2023年9月8日(金) 京都大学 理学研究科セミナーハウス

Current Understandings of the Pulsar Magnetosphere, and a comment on Crab Nebula Polarization



Shinpei Shibata
Yamagata University

Current Understandings of the Pulsar Magnetosphere

contents

1. Basic ideas and solid results.
2. A lot of challenge has been made; mess; magnetic reconnection?? no outer gap??
3. Untangle: go back to the original idea, “centrifugal acceleration”;

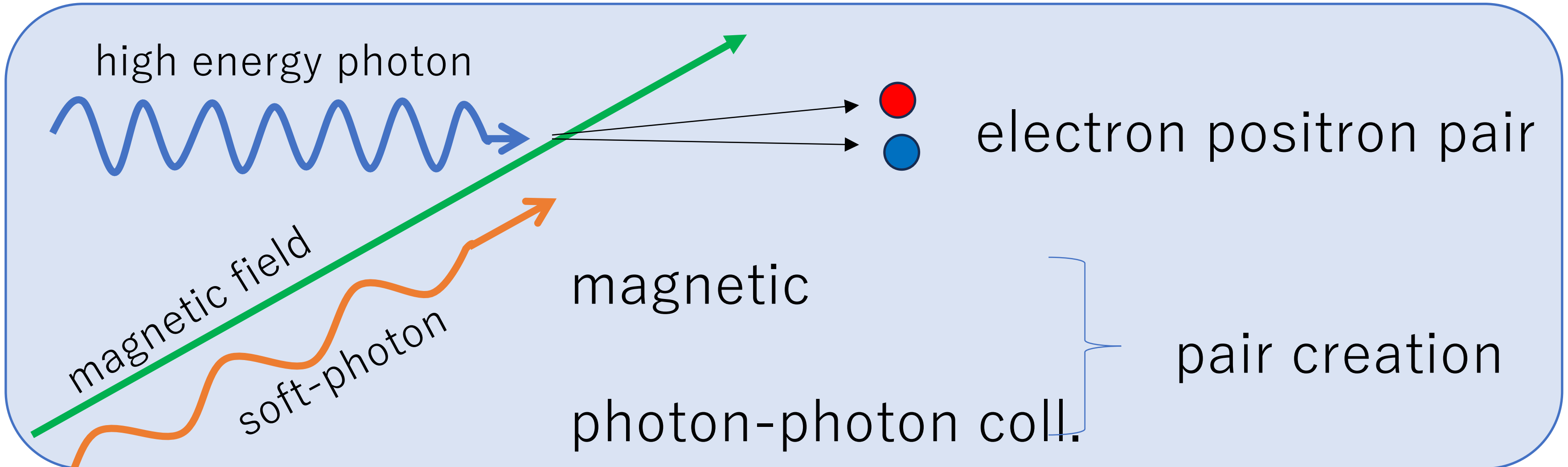
Basic ideas and solid results

The problem of the pulsar magnetosphere is well-defined.

What happens if a rotating magnet is put in space?

complication

due to pair plasmas.



Basic ideas and solid results

A rotating magnet produces EMF.

available voltage

$$V_0 \approx \frac{\mu\Omega^2}{c^2} \qquad \gamma_{max} = \frac{eV_0}{mc^2}$$

If a current circuit is established, the system works.

$$I_0 \approx \frac{\mu\Omega^2}{c}$$ GJ current

$$F_{gj} = \frac{I_0}{e} \qquad \mathcal{M} = \frac{F}{F_{gj}}$$

multiplicity

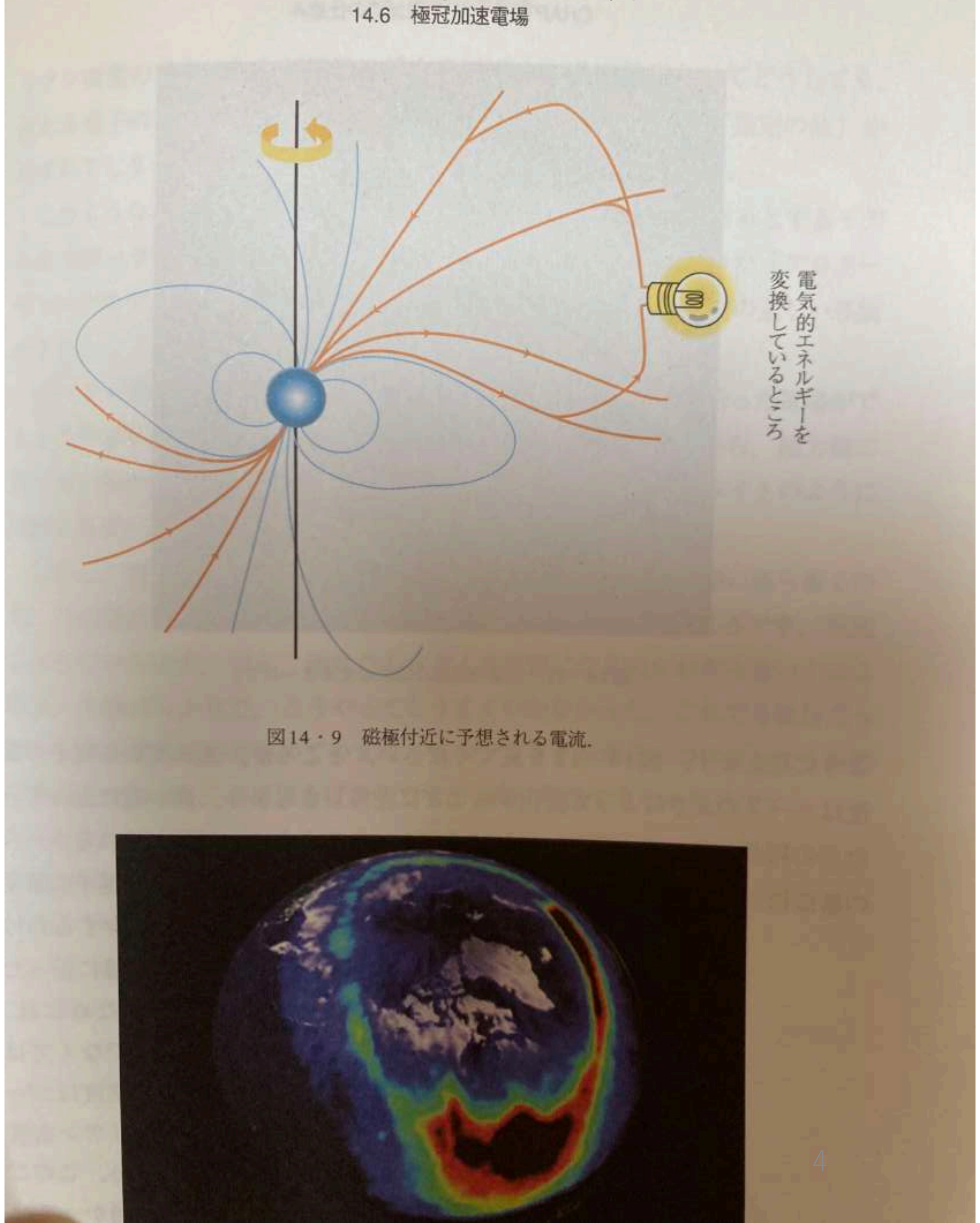
the expected power

$$L_0 \approx \frac{\mu^2\Omega^4}{c^3} \qquad L_{vac} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\chi$$

$$L_{ff} = (1+\sin^2\chi)\frac{\mu^2\Omega^4}{c^3}$$

(Spitkovsky A., 2006, ApJ 648, L51)

宇宙の灯台　パルサー より



Basic ideas and solid results

The two solid solutions

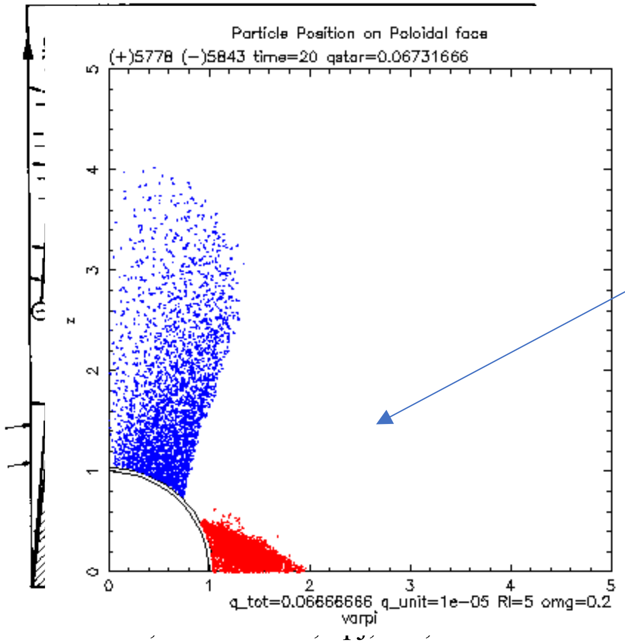
both have no acceleration

Electrostatic solution: "electrosphere"

if no pair creation

Jackson, E.A., 1976, ApJ, 206, 831-841

Krause-Polstorf, J., Michel, F.C., 1985, A&A, 144, 72-80



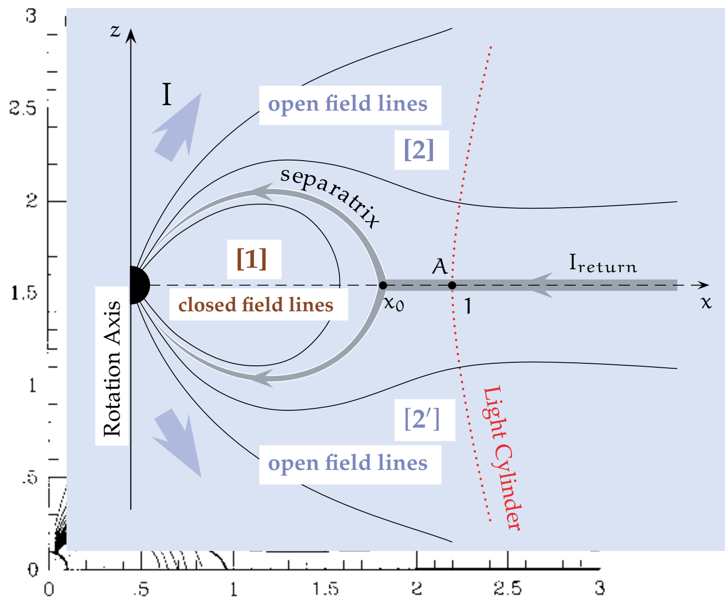
Gaps
unstable to pair-creation because of very strong E// (electric field parallel to the magnetic field)

force-free solution

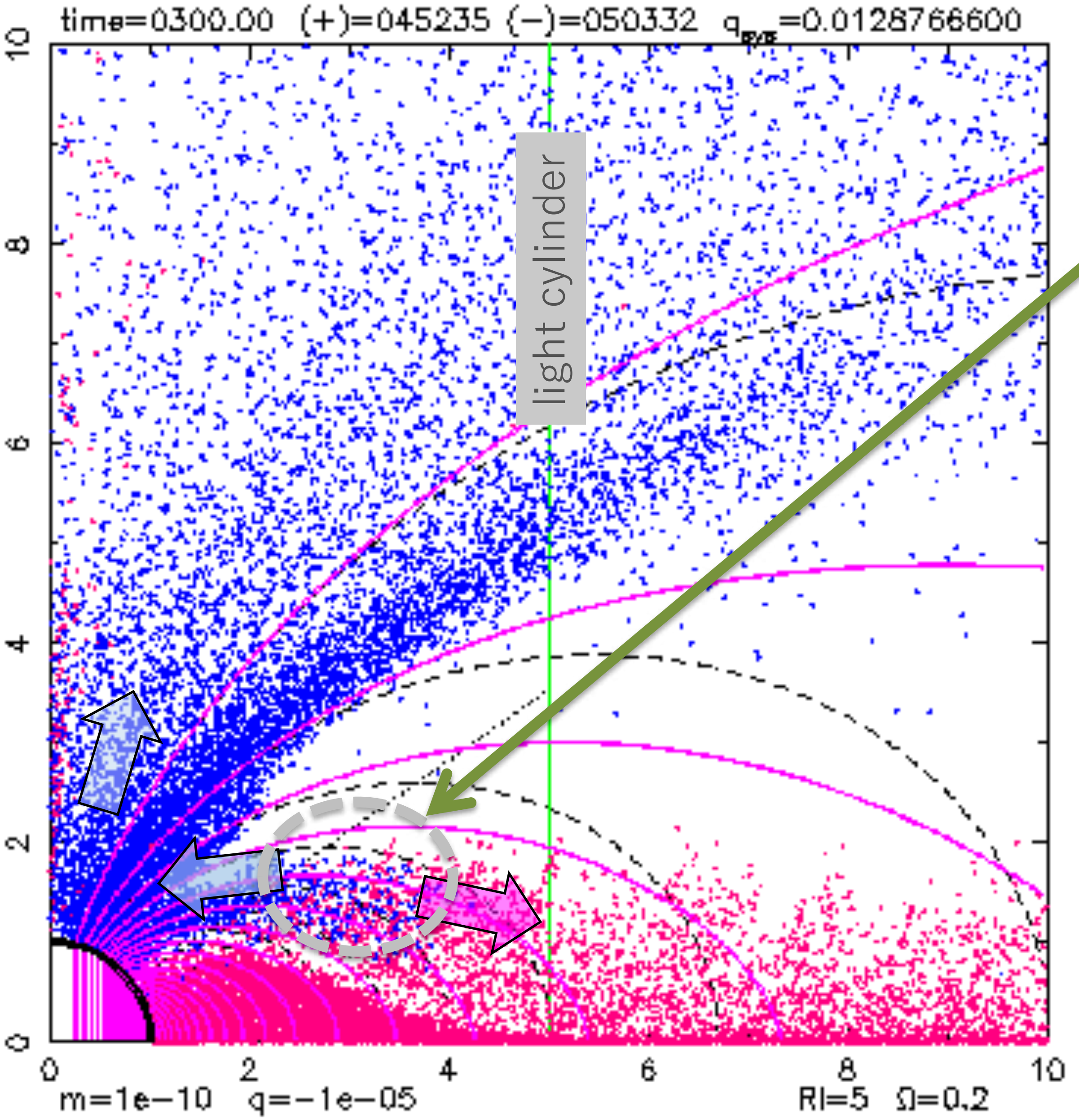
sufficient plasma source

Contopoulos, I., Kazanas, D., & Fendt, C. 1999, apj, 511, 351

Timokhin, A~N. 2006, mnras, 368, 1055



resistive / acceleration region is hidden in a infinitely thin layer, which is outside of the solution.



outer gap

Pairs are continuously produced.

Pairs are immediately separated by the field-aligned electric field.

A lot of challenges were made

something between the two (ES and FF)

Electrostatic solution:
“electrosphere”

force-free solution

with pair creation
coupled with particle
acceleration and
photon emission

very complicated
rely on numerical works

MHD approaches difficult

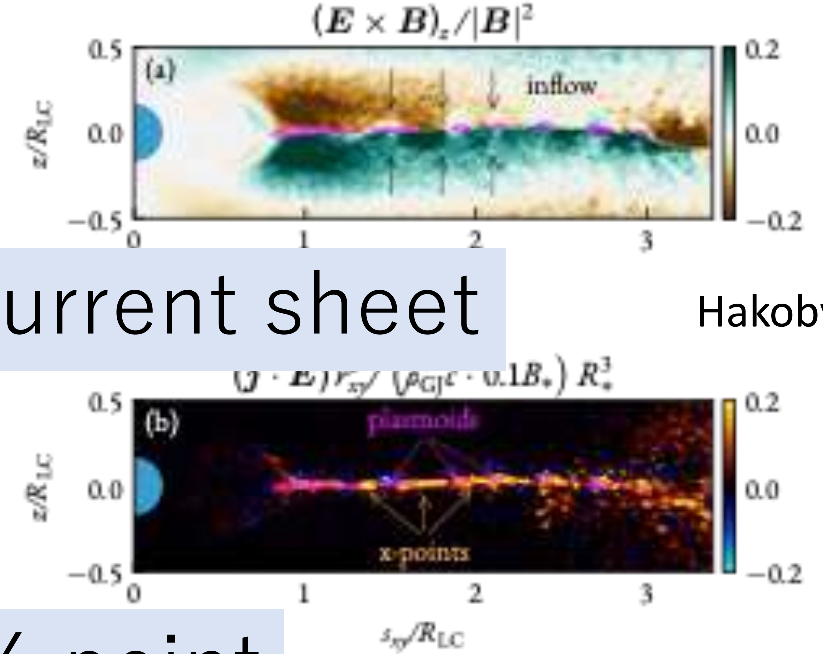
PIC applicable

A lot of challenges were made

Summary of Previous PIC approaches

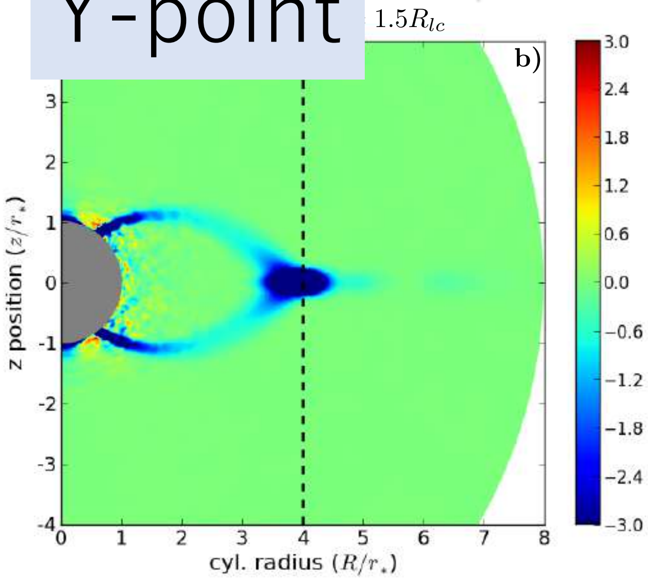
- With the current computer performance, pair plasmas are injected by hand (difficult to treat whole process).
- Once the closed current circuit is established by pair injection, a pulsar becomes active.
- how one makes a setting for the pair injection.
  ➔For any setting, whatever, a simulator gives a solution even if the setting is not realistic.
- ➔Results of PIC simulations fully depend on the assumptions ➔mess. No convincing result.

Analyse what setting makes what ➔S. Kisaka's talk current sheet



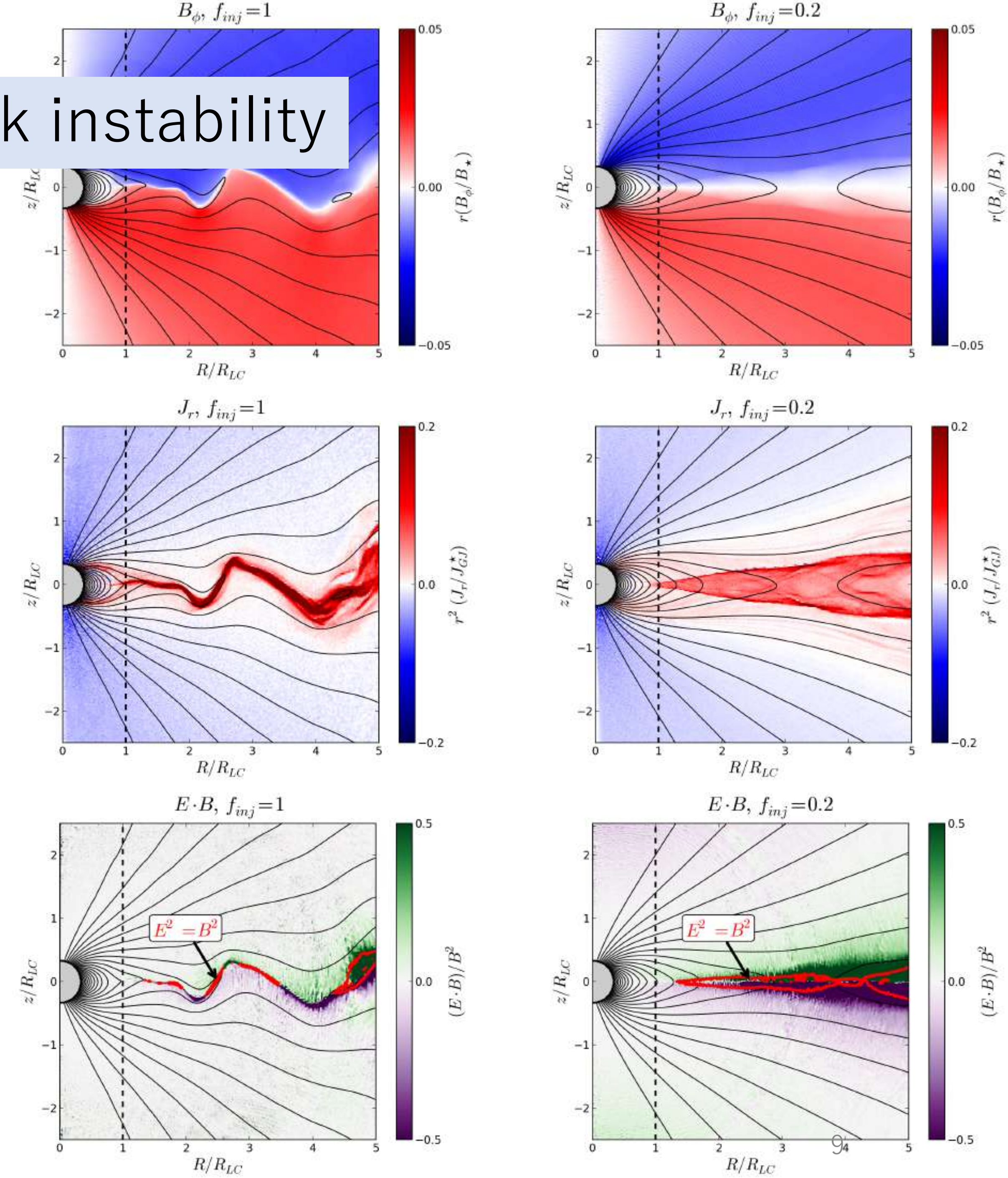
Hakobyan et al.,2022

Y-point



Belyaev, M.~A. 2015, mnras, 449, 2759

kink instability



Cerutti, B., Philippov, A., Parfrey, K., ¥& Spitkovsky, A.¥ 2015, ¥mnras, 448, 606

A lot of challenges were made

Summary of Previous PIC approaches

- With the current computer performance, pair plasmas are injected by hand (difficult to treat whole process).
- Once the closed current circuit is established by pair injection, a pulsar becomes active.
- how one makes a setting for the pair injection.
  ➔For any setting, whatever, a simulator gives a solution even if the setting is not realistic.
- ➔Results of PIC simulations fully depend on the assumptions ➔mess. No convincing result.

Analyse what setting makes what ➔S. Kisaka's talk

A lot of challenges were made

A case of surface injection

Natural supply of charged particles by E//

➔ electrosphere (not active)

high density pairs (high multiplicity) are injected near the surface typically with some initial speed.

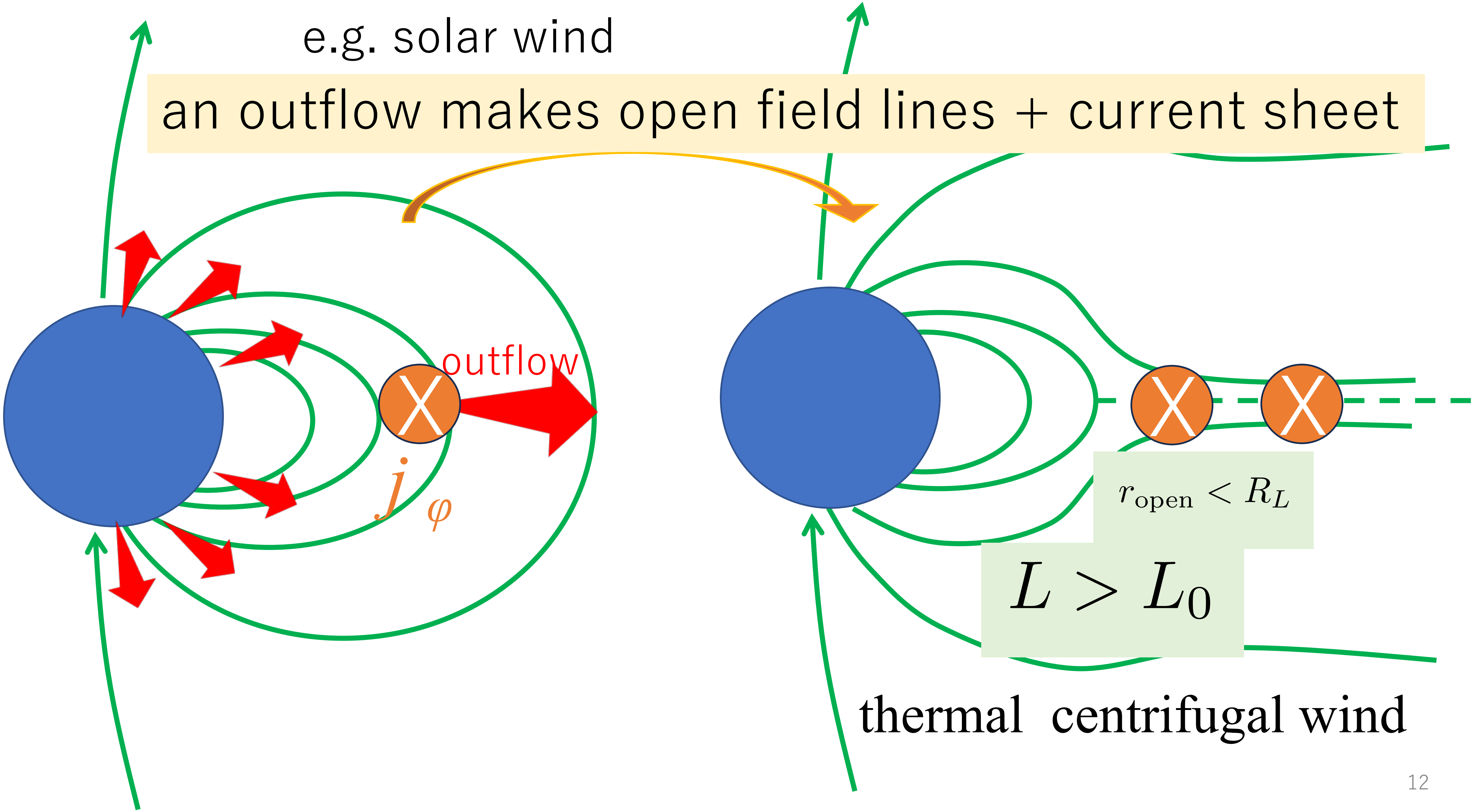
maybe to obtain an open field structure, something like the force-free solution.

A lot of challenges were made

A case of surface injection

e.g. solar wind

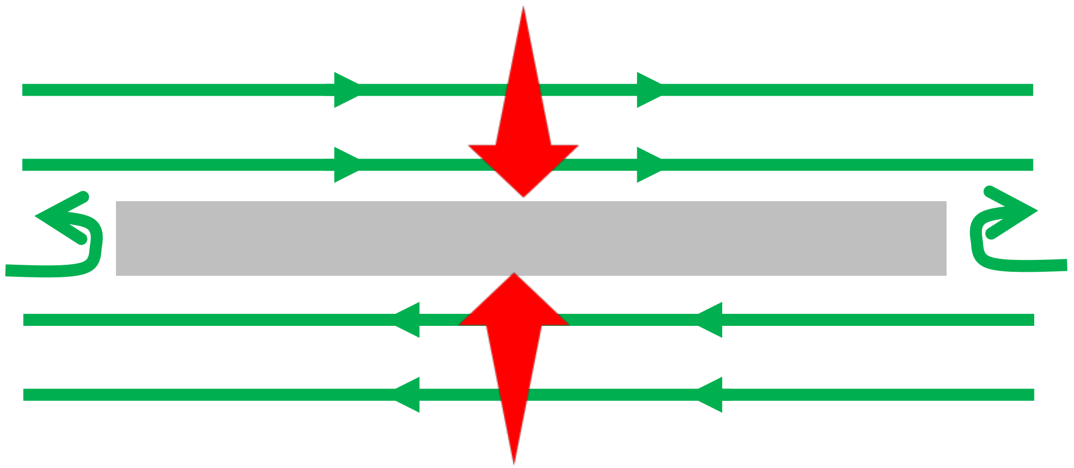
an outflow makes open field lines + current sheet



thermal centrifugal wind

misleading by too much injection from the surface

- magnetic field is opened.
- reconnection is the origin of acceleration.
- instabilities in the neutral sheet

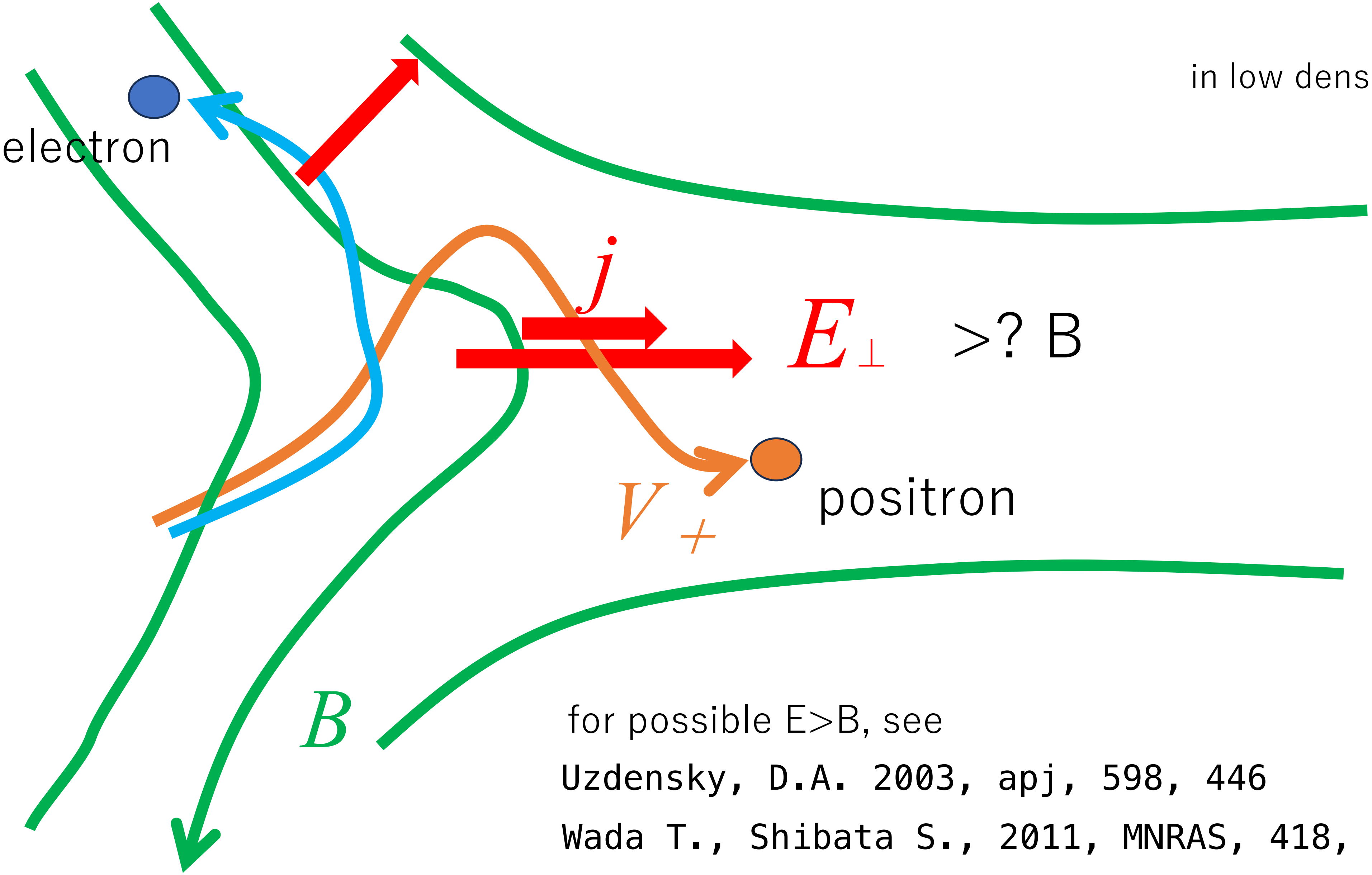


$\boldsymbol{E}_{\perp}$ acceleration

and
centrifugal acceleration

direct $E_{\perp}$ acceleration

in low density cases



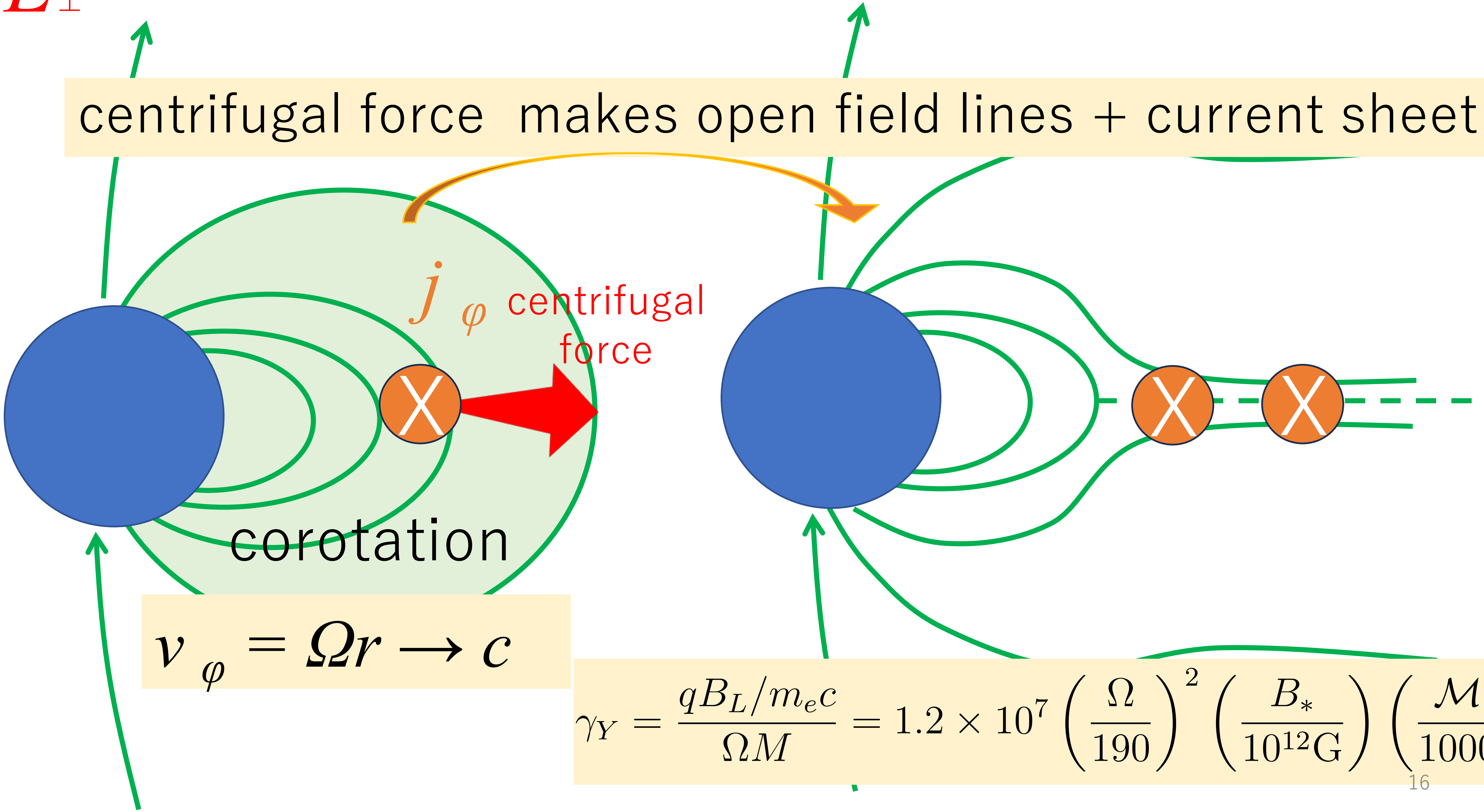
for possible E>B, see

Uzdensky, D.A. 2003, apj, 598, 446

Wada T., Shibata S., 2011, MNRAS, 418, 612.

$E_{\perp}$ acceleration in rich plasma is “centrifugal acceleration”.

centrifugal force makes open field lines + current sheet



$$v_{\varphi} = \Omega r \rightarrow c$$

$$\gamma_Y = \frac{qB_L/m_e c}{\Omega M} = 1.2 \times 10^7 \left(\frac{\Omega}{190}\right)^2 \left(\frac{B_*}{10^{12}\mathrm{G}}\right) \left(\frac{\mathcal{M}}{1000}\right)$$

Untangle back to the original idea.

1. $E_\perp$ causes the corotation motion.

2. the corotation speed tends to the light speed

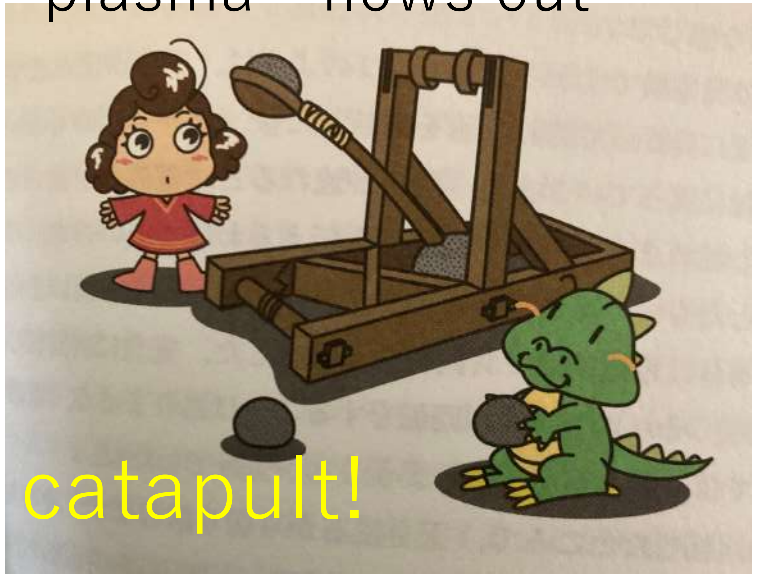
$$v_\varphi = \Omega r \to c$$

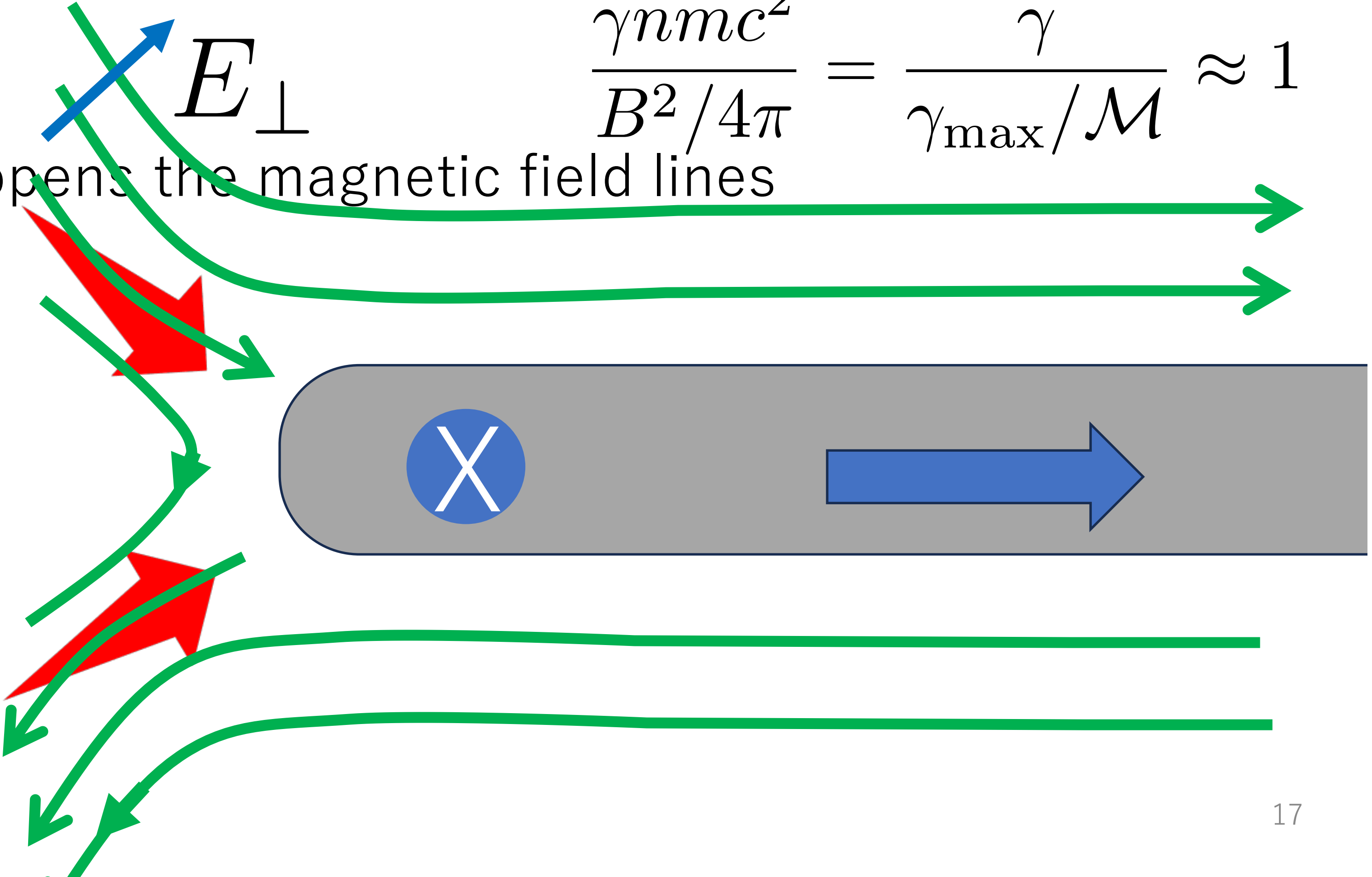
3. inertia increases.

$$\frac{\gamma n m c^2}{B^2/4\pi} = \frac{\gamma}{\gamma_{\max}/\mathcal{M}} \approx 1$$

4. centrifugal drift current opens the magnetic field lines

5 "massive corotating plasma" flows out





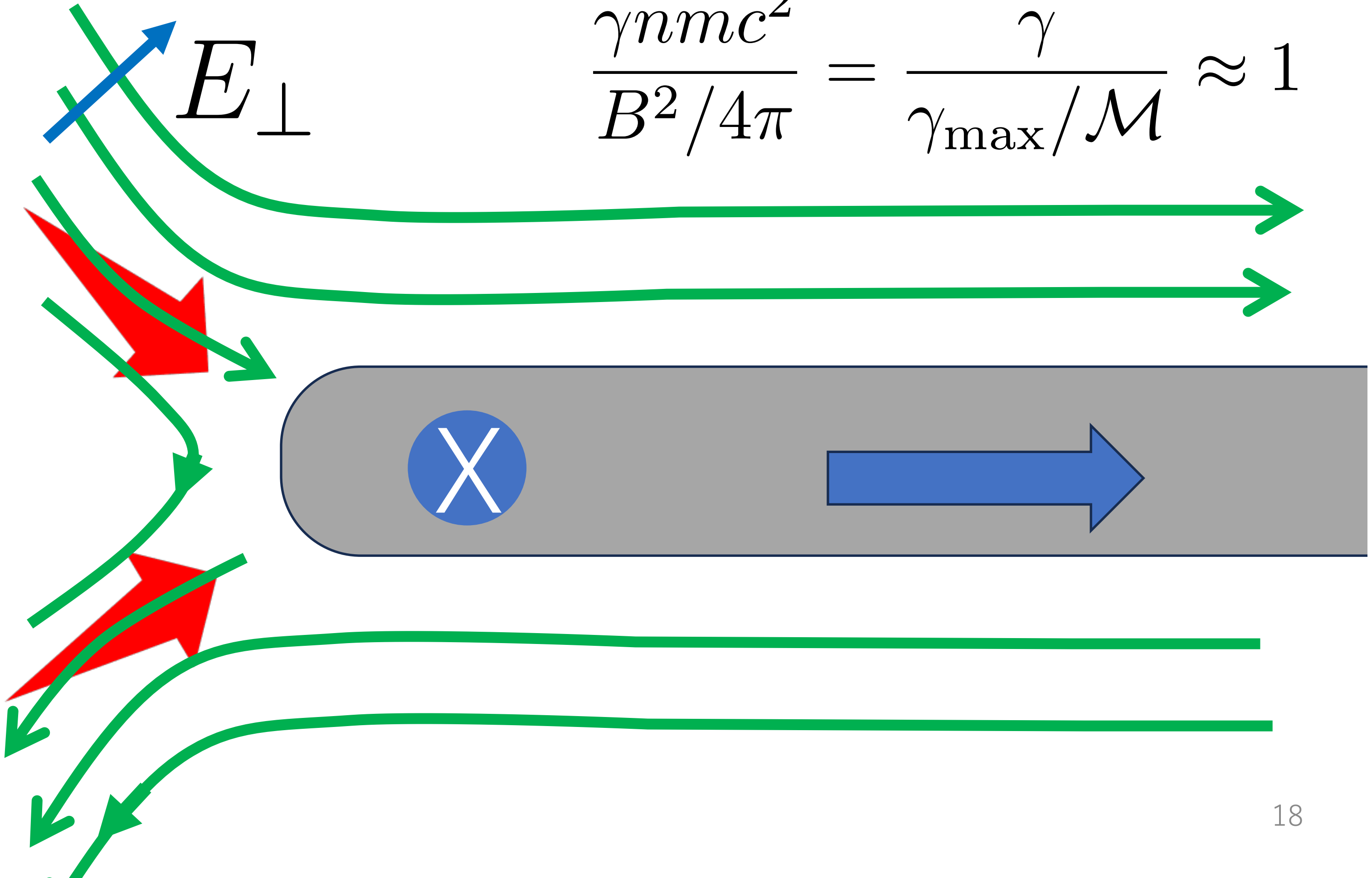
Untangle back to the original idea.

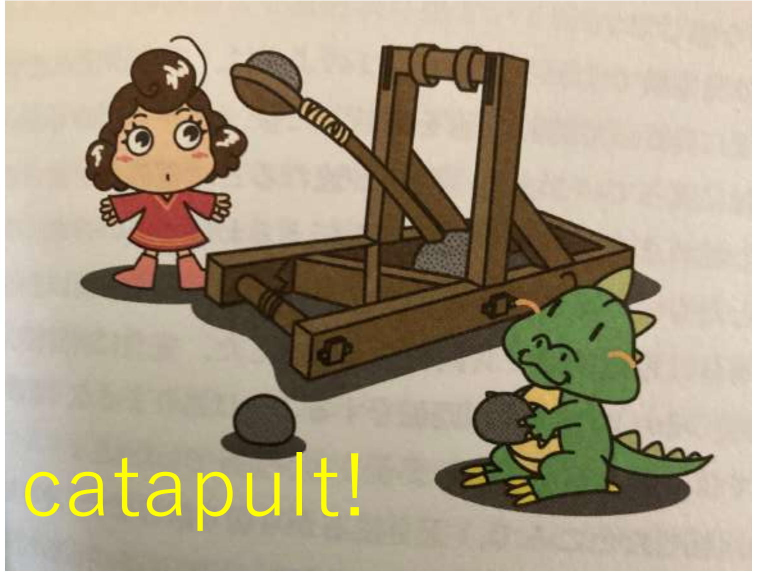
Acceleration efficiency

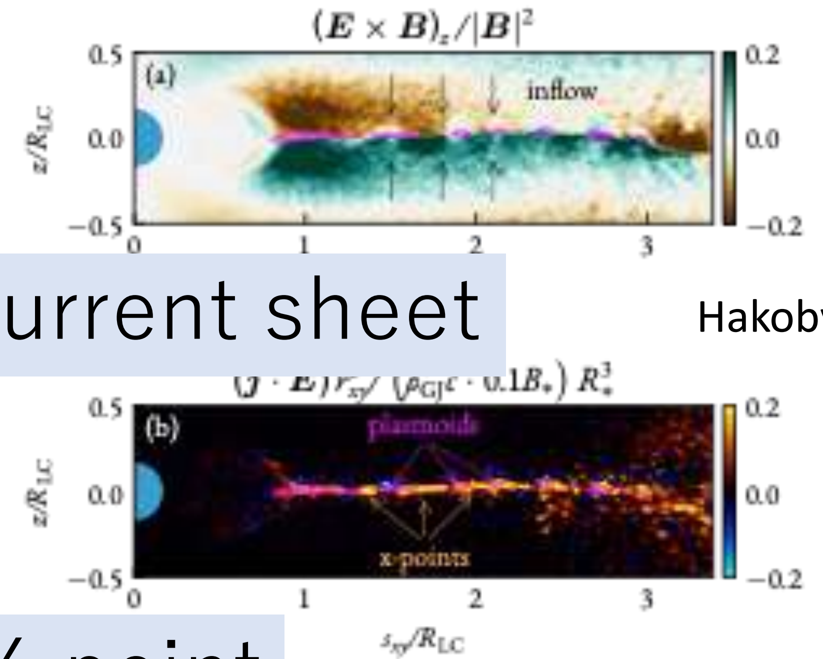
$$\frac{L_{acc}}{L_0} \approx \frac{\ell}{R_L}$$

$$v_\varphi = \Omega r \rightarrow c$$

$$\frac{\gamma n m c^2}{B^2/4\pi} = \frac{\gamma}{\gamma_{\max}/\mathcal{M}} \approx 1$$



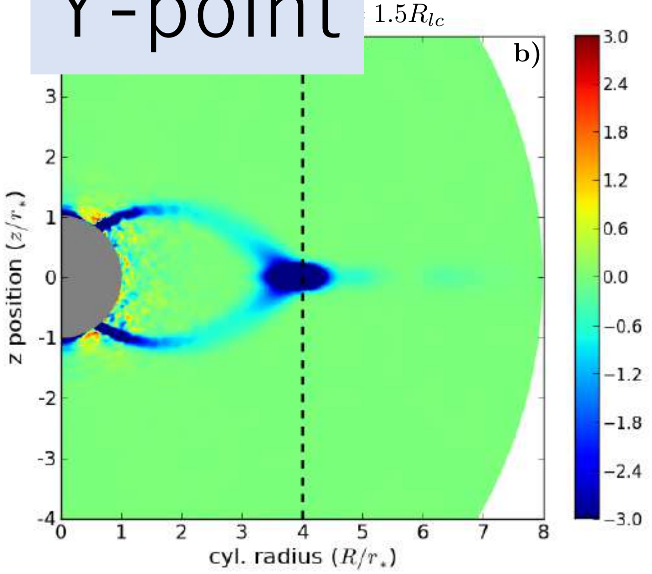




current sheet

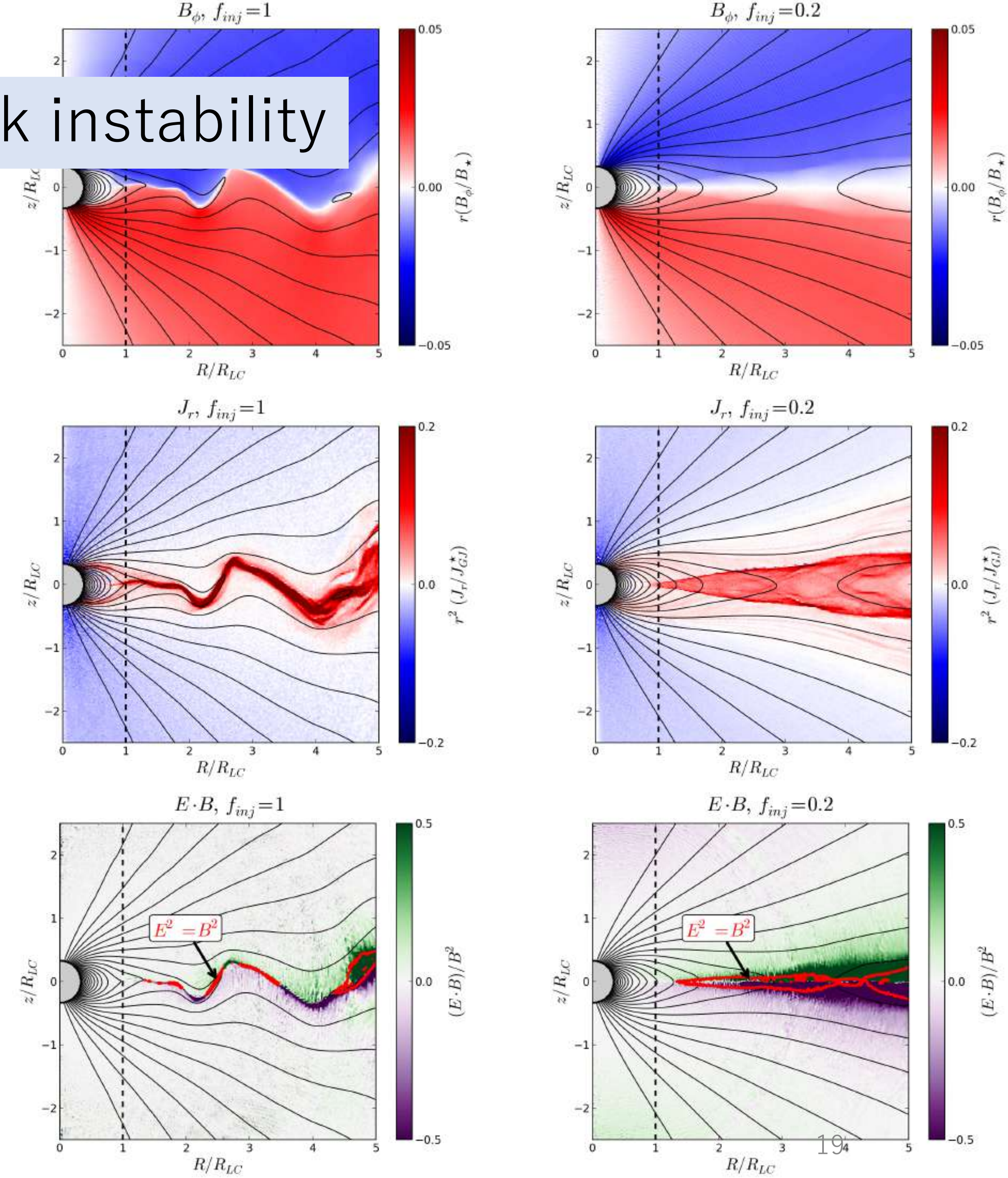
Hakobyan et al.,2022

Y-point



Belyaev, M.~A. 2015, mnras, 449, 2759

kink instability



Cerutti, B., Philippov, A., Parfrey, K., ¥& Spitkovsky, A.¥ 2015, ¥mnras, 448, 606

Summary for the future:
Let us see
. what setup for pair creation makes what,
. centrifugal acceleration in detail

A short comment on the Crab Nebula

A short comment on the Crab Nebula

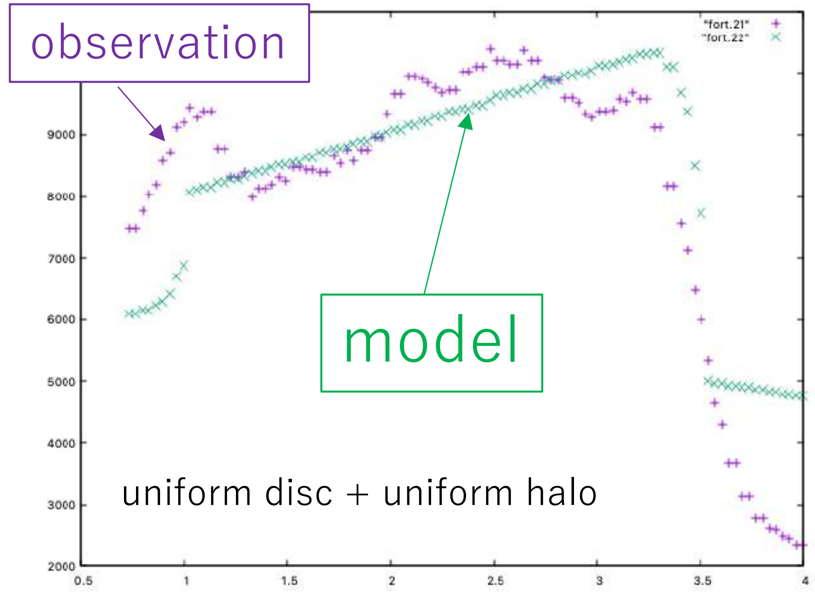
Preamble

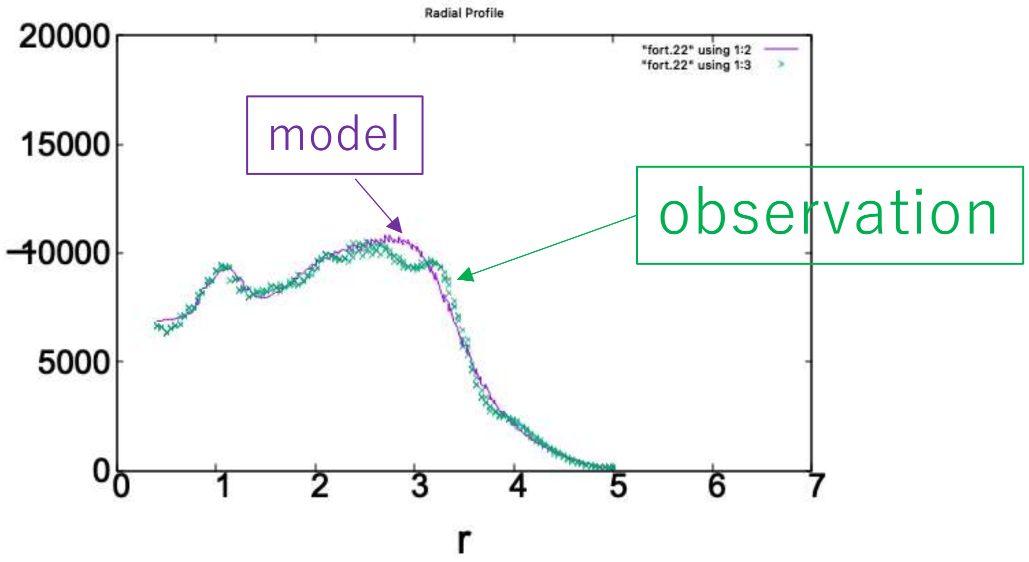
- IXPE gives a spatially resolved polarization measurement for the Crab Nebula. A good opportunity to improve nebula model.
- Nakamura and Shibata (2007) constructed a model to give a polarization map of the Crab Nebula. We concluded about 60 percent of the magnetic field energy is in the form of turbulent: $|¥delta B|^2 /B ¥sim 0.6$.
- It has already been suggest that the turbulent fields plays important roles on nebula dynamics and particle acceleration (see. eg. Porth et al., 2014; Tanaka et al., 2018).
- With the help of the data by IXPE, Chandra and IC gamma-rays telescopes, we are attempting an empirical model of the nebula.

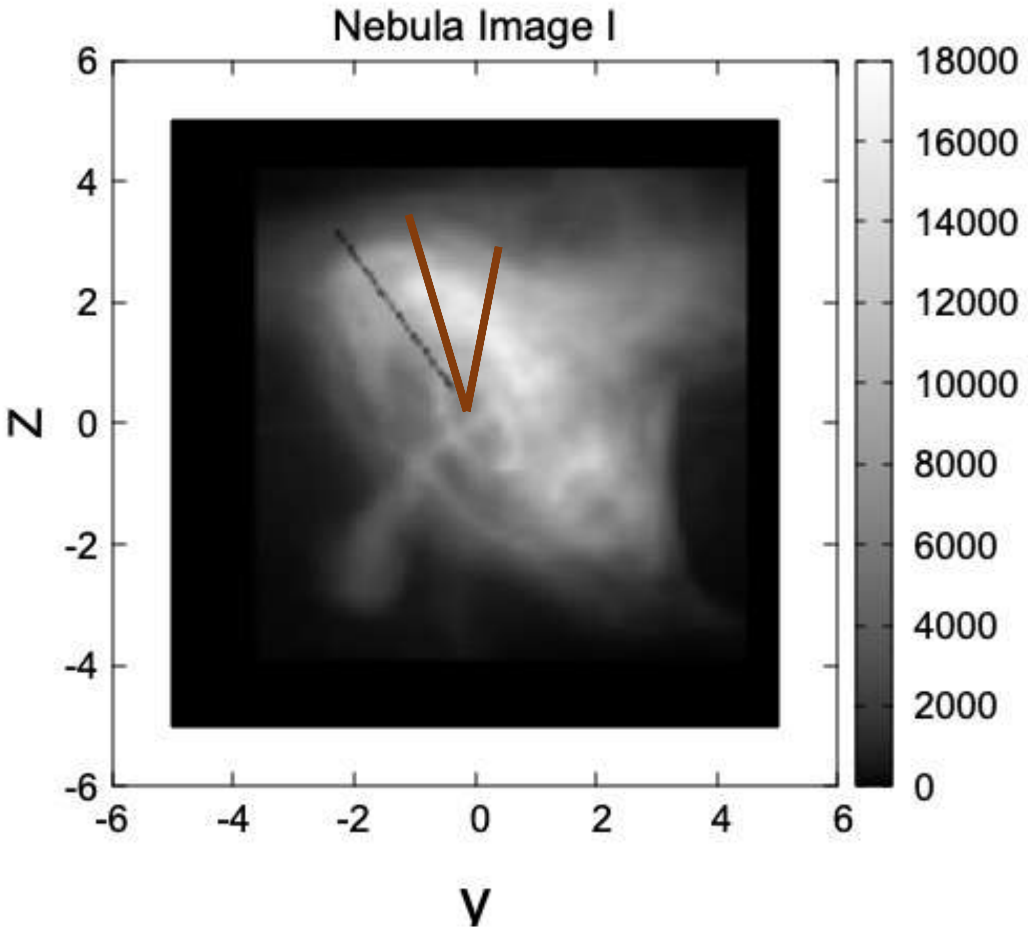
Let us make an empirical mode with minimized assumptions!

Axisymmetry. disc + inner ring + outer ring + jet + halo 4 component

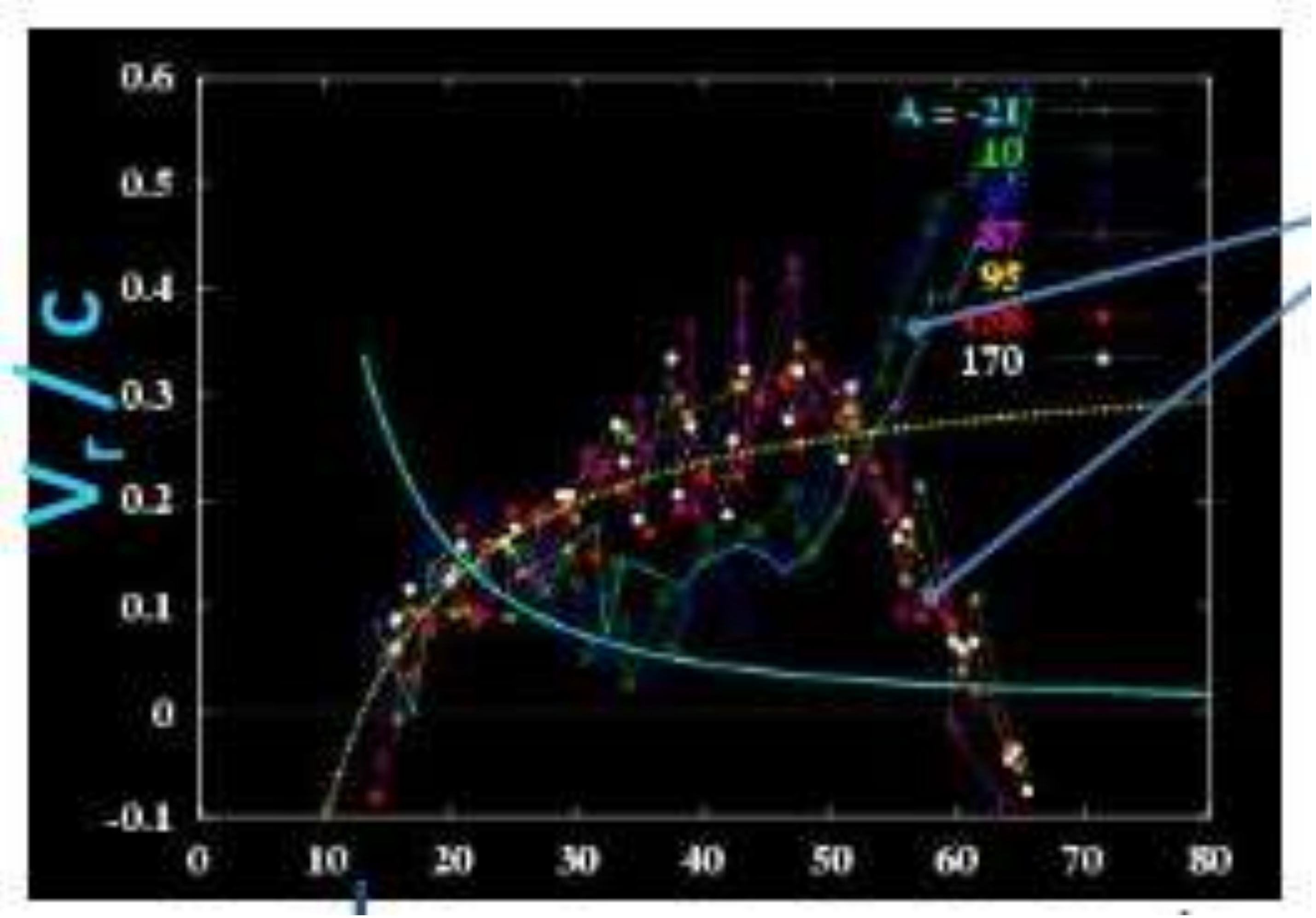
Chandra Image by Mori et al. ; Note pile-up corrected I and photon-index maps







Doppler boost free I(r) profile
➔ volume emissivity profile j(r)



The flow speed increases with the distance!

The Crab Nebula model in construction

I image → volume emissivity + velocity field

Q and U image → $\delta B^2/B^2$

axisymmetry

+continuity

+<B> ← IC

n(r), B^2(r) profile

+momentum eq.
+energy eq.

↓

radial profiles for
acceleration of the flow
dissipation of magnetic in the flow

Thank you