Relativistic magnetic reconnection in astrophysics: recent progress and new directions

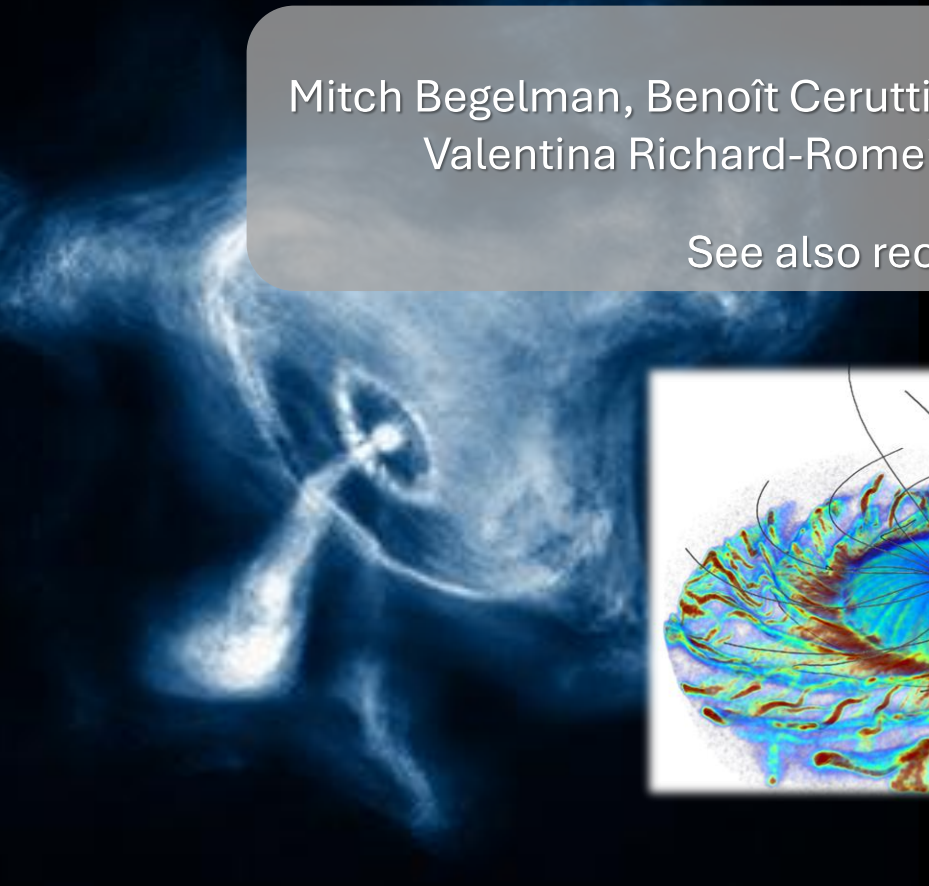
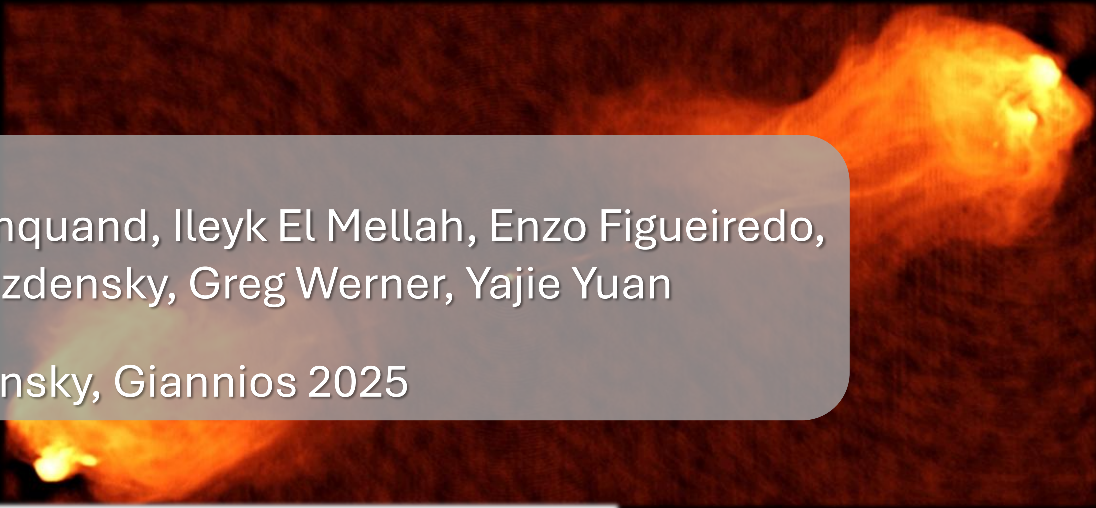
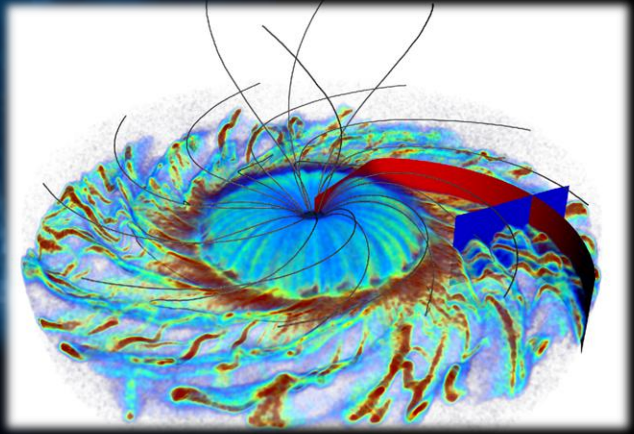
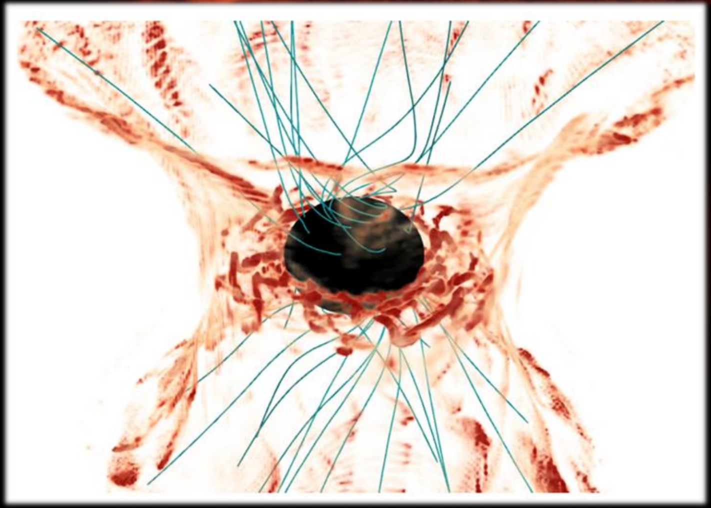
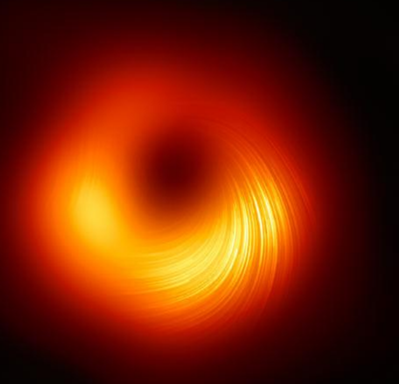
John Mehlhaff[1,2]

[1]*Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis; MO, 63130, USA*
[2]*Univ. Grenoble Alpes, CNRS, IPAG; Grenoble, France*

Kinetic physics of astrophysical plasmas; June 18-20; Sorbonne Université

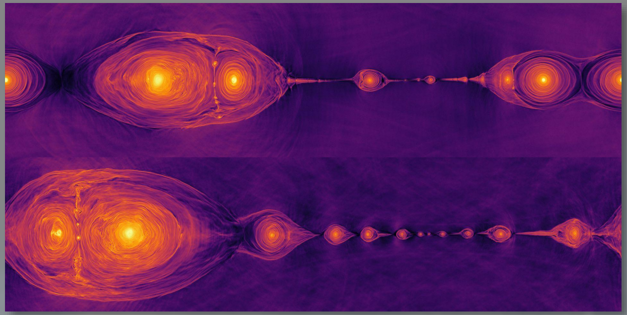
With thanks to...
Mitch Begelman, Benoît Cerutti, Alex Chen, Benjamin Crinquand, Ileyk El Mellah, Enzo Figueiredo, Valentina Richard-Romei, Adrien Soudais, Dmitri Uzdensky, Greg Werner, Yajie Yuan

See also recent review by Sironi, Uzdensky, Giannios 2025

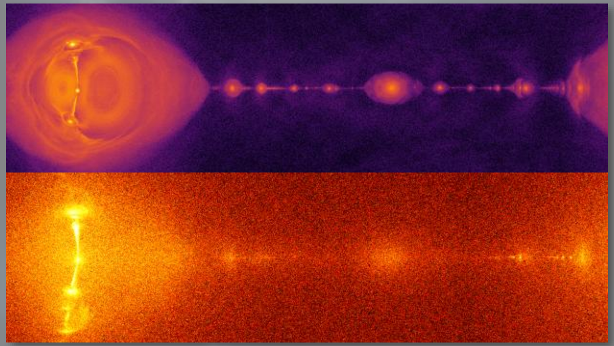






Outline

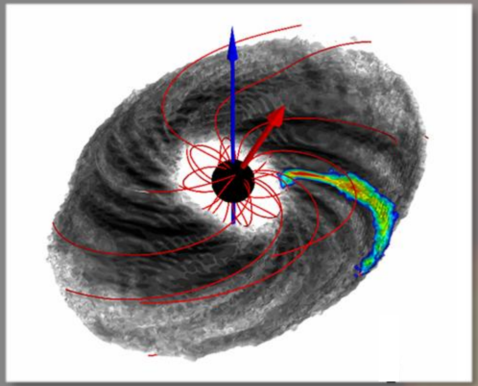
Highlights from two decades of local simulations



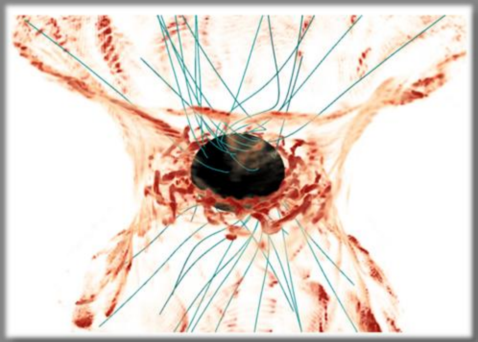
The radiative frontier



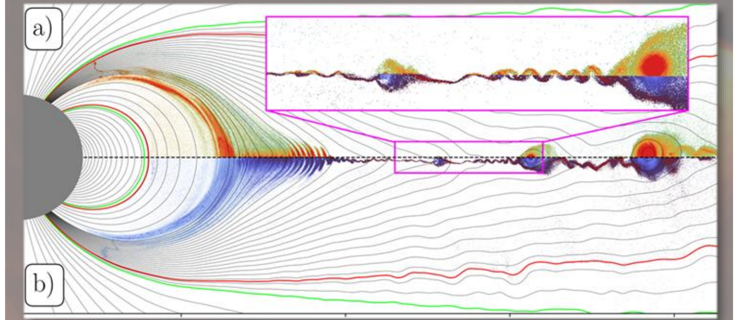
Highlights from one decade of global simulations



The gravitational frontier

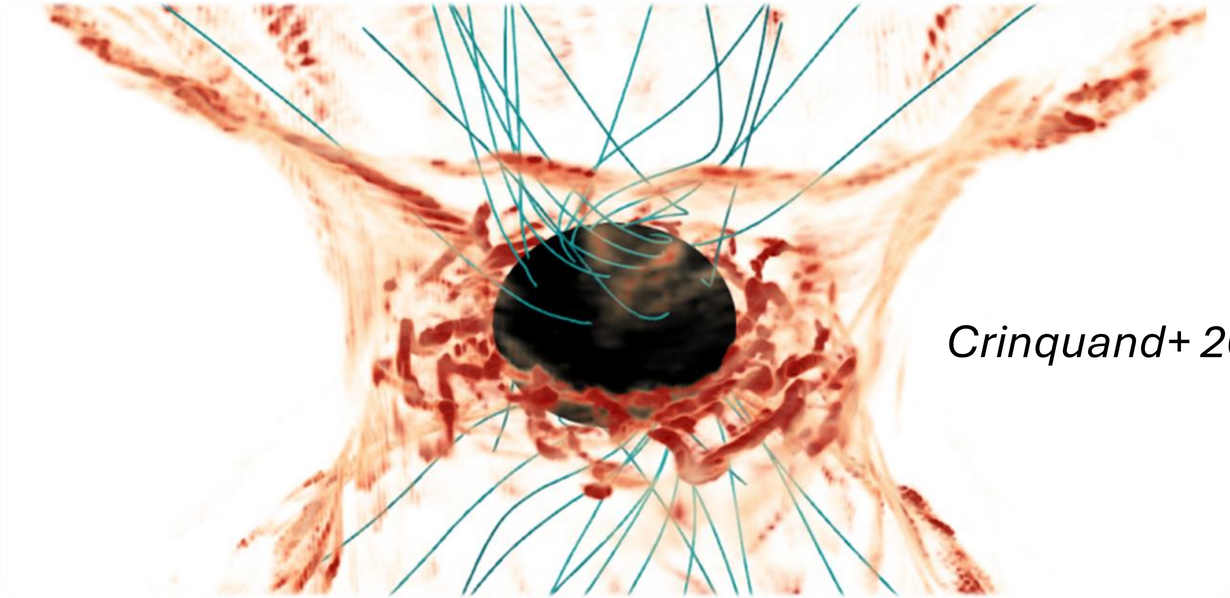


A bright future



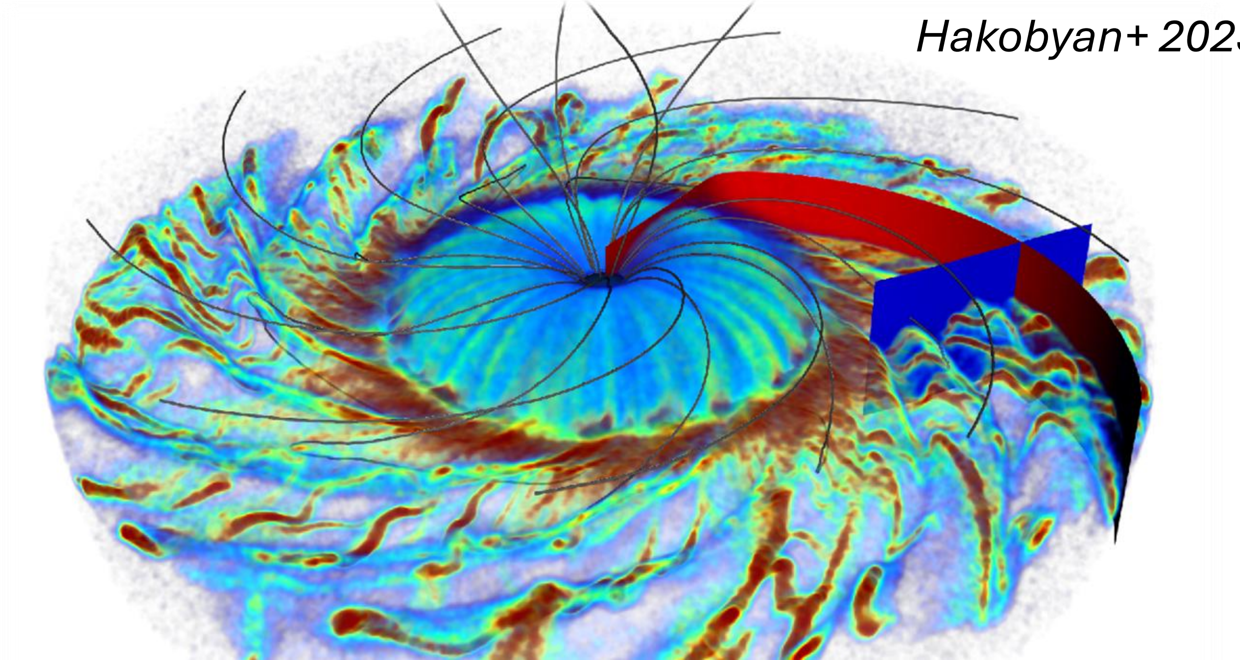
Conditions under which magnetic reconnection "shines"

- The emitting plasma is likely to be highly magnetized

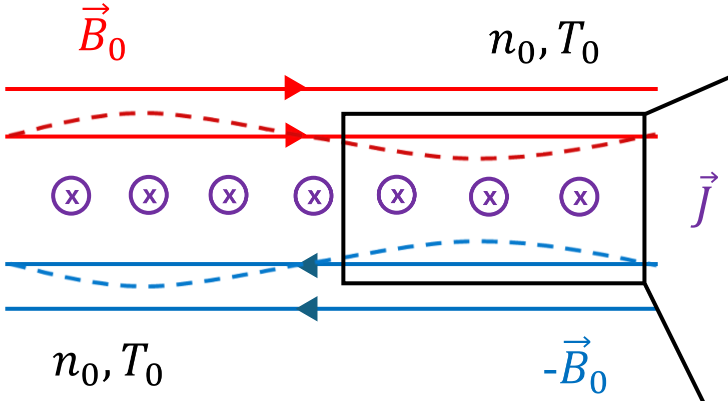


Crinquand+ 2022

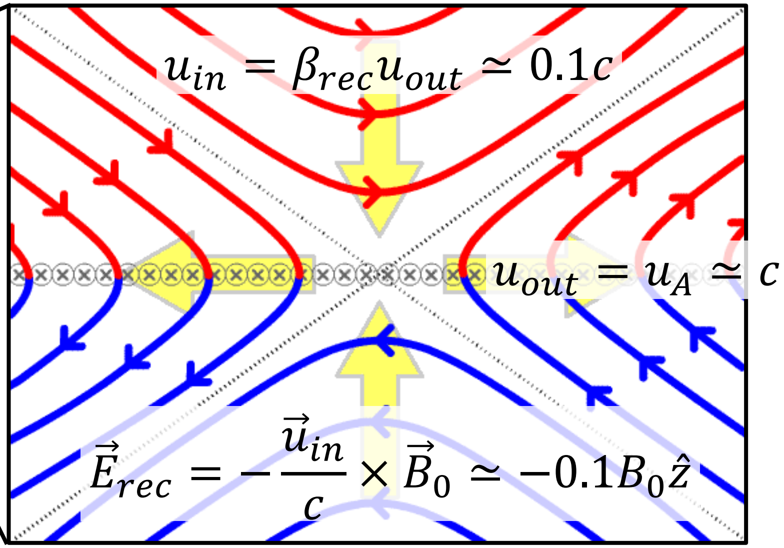
Hakobyan+ 2023



Relativistic reconnection is a magnetic particle accelerator

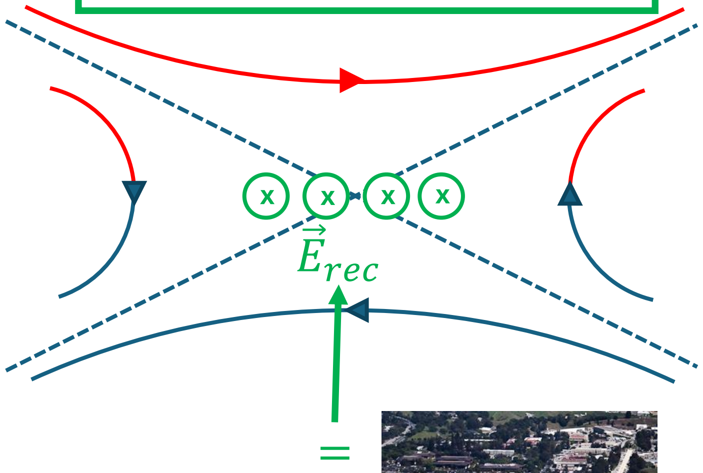


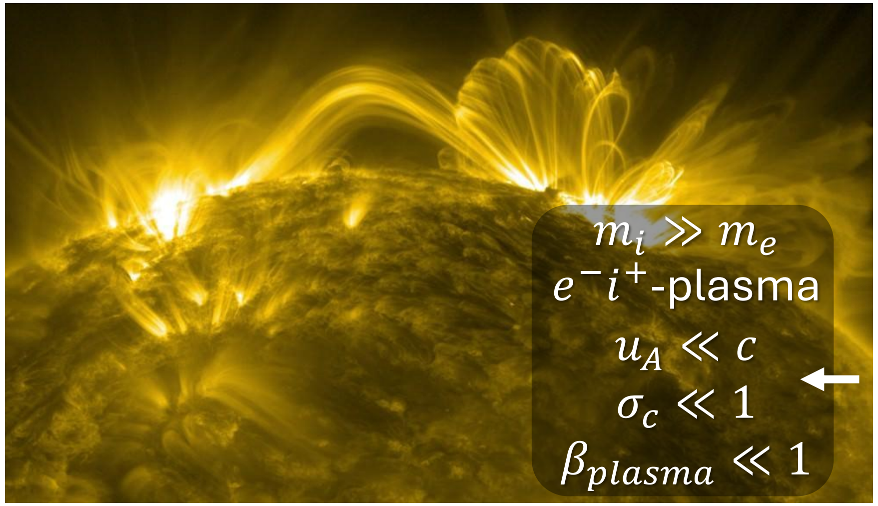
$$\begin{pmatrix} \beta_{plasma} = 8\pi n T_0 / B_0^2 \ll 1 \\ \sigma_c = B_0^2 / 4\pi n_0 m_e c^2 \gg 1 \end{pmatrix}$$



$$\vec{\nabla} \times \vec{E} = -\partial_t \vec{B} = 0$$
$$\Rightarrow \partial_x E_z = \partial_y E_z = 0$$

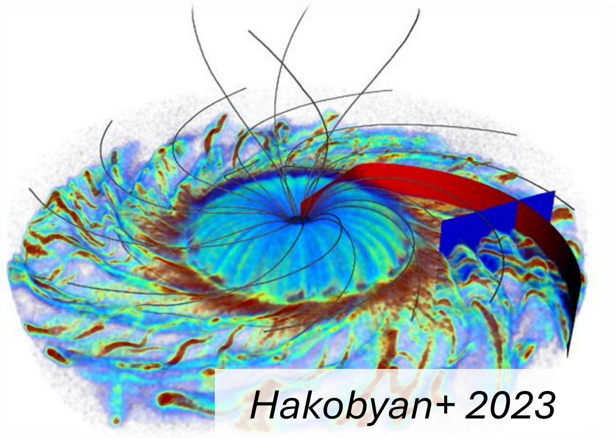
$\vec{E}_{rec} = -0.1 B_0 \hat{z}$ is uniform!





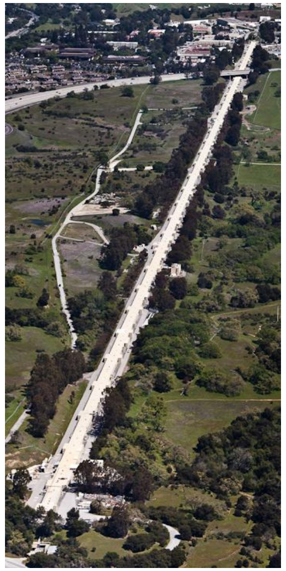
$m_i \gg m_e$
$e^- i^+$-plasma
$u_A \ll c$
$\sigma_c \ll 1$
$\beta_{plasma} \ll 1$

$m_i = m_e$*
$e^- e^+ i^+ \gamma$-plasma
$u_A \simeq c$
$\sigma_c \gg 1$
$\beta_{plasma} \ll 1$



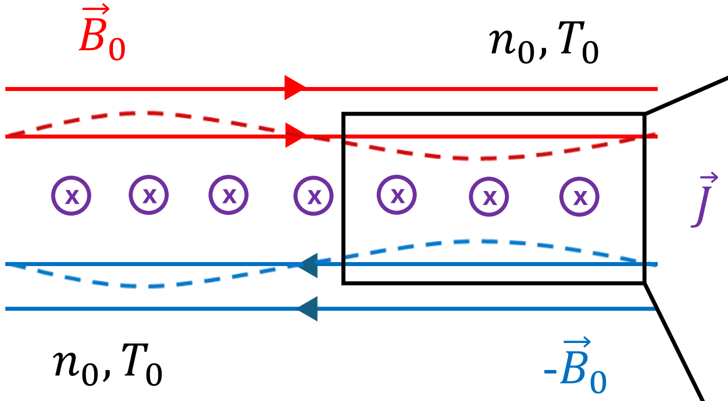
Hakobyan+ 2023

*sometimes

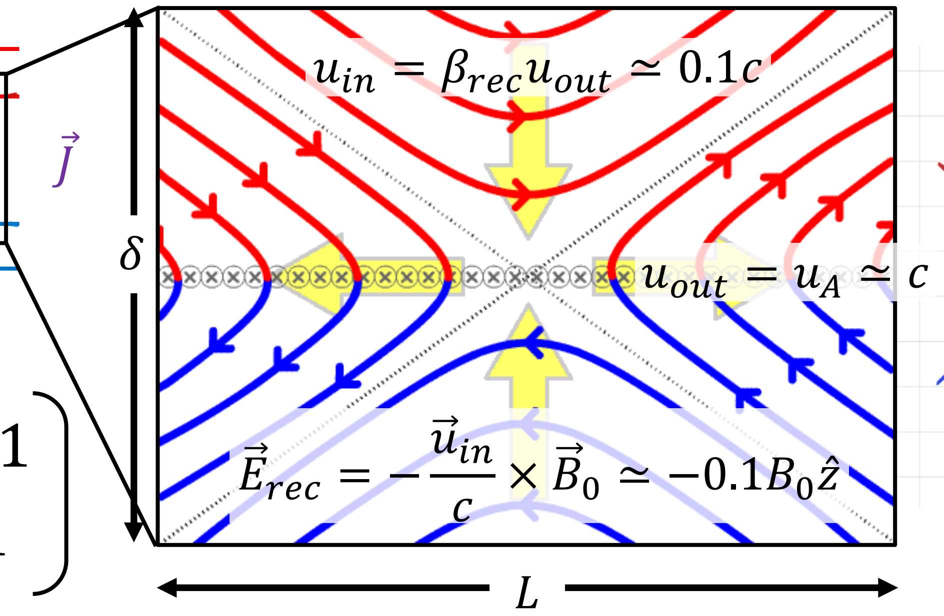


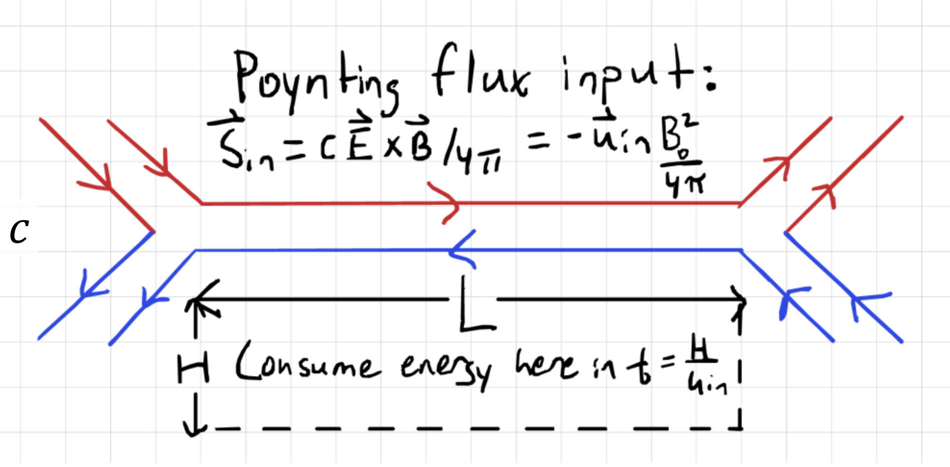
SLAC (Wikipedia)

Relativistic reconnection efficiently liberates magnetic energy



$$\beta_{plasma} = 8\pi n T_0 / B_0^2 \ll 1$$
$$\sigma_c = B_0^2 / 4\pi n_0 m_e c^2 \gg 1$$





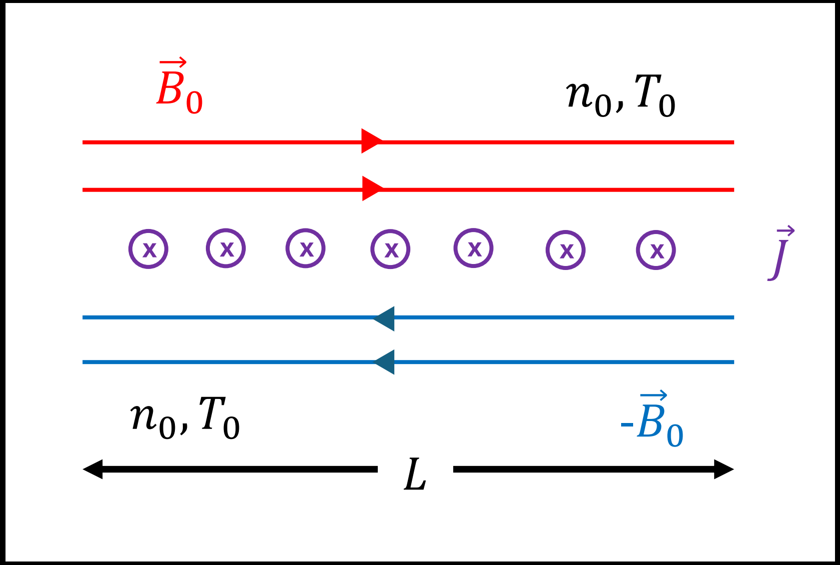
But why is reconnection so fast? (Why is $\beta_{rec} \simeq 0.1$?)

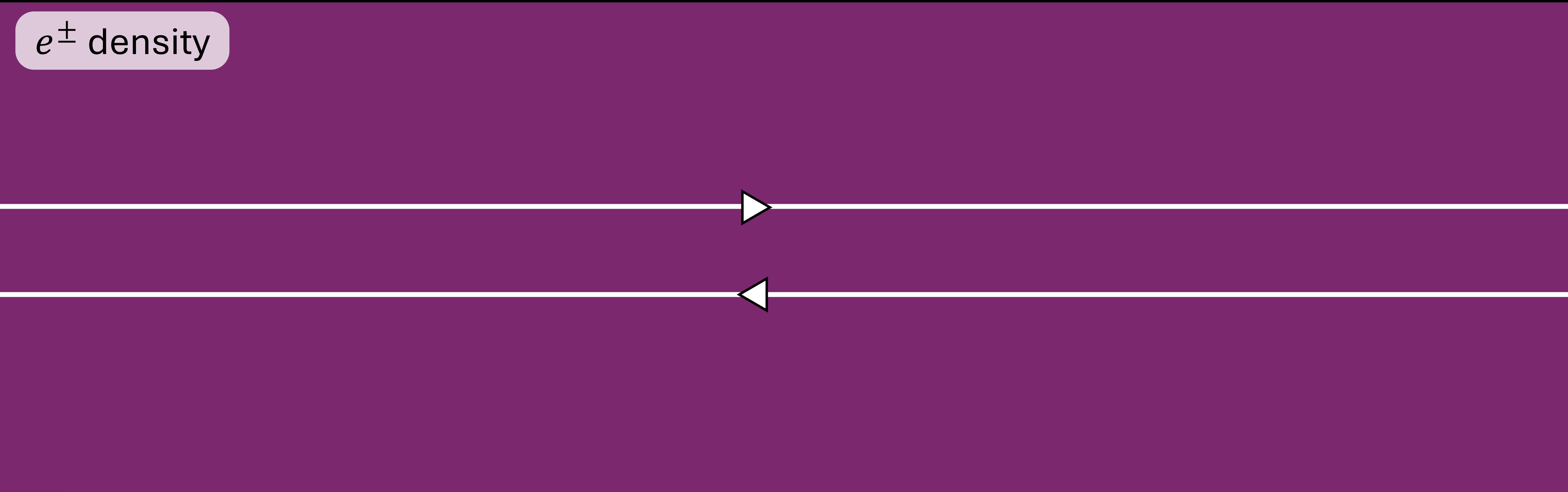
How can we claim that: $\beta_{rec} = u_{in}/u_{out} = \delta/L \simeq 0.1$?

The global dynamics can set L to be arbitrarily large, right?

PIC simulations reveal a dynamic "plasmoid-dominated" current layer

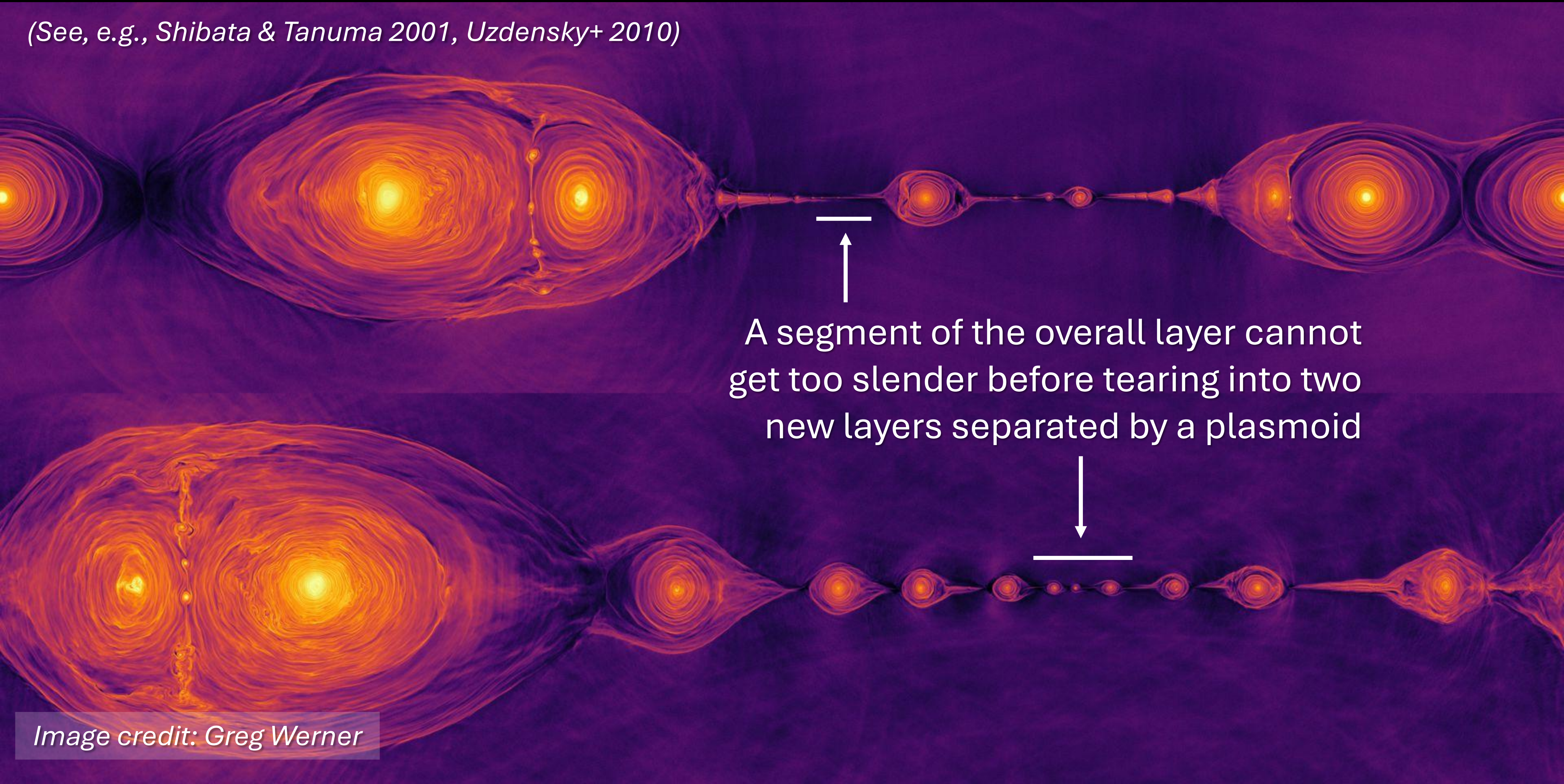
Harris sheet initial condition (used/adapted for all local simulation studies in this talk)





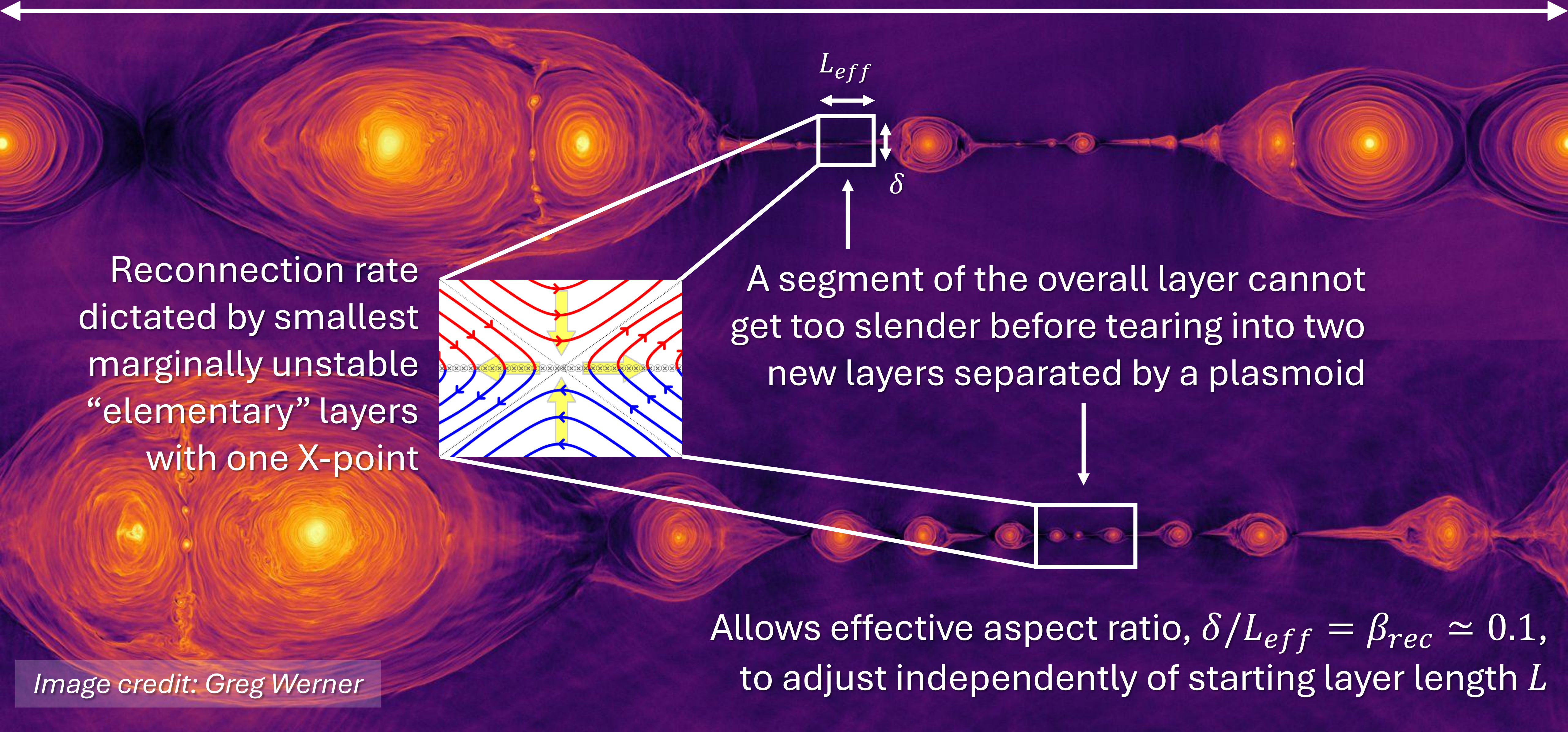
Layer-tearing keeps X-points open, promoting fast reconnection

(See, e.g., Shibata & Tanuma 2001, Uzdensky+ 2010)



Layer-tearing keeps X-points open, promoting fast reconnection

(See, e.g., Shibata & Tanuma 2001, Uzdensky+ 2010)



Reconnection rate dictated by smallest marginally unstable “elementary” layers with one X-point

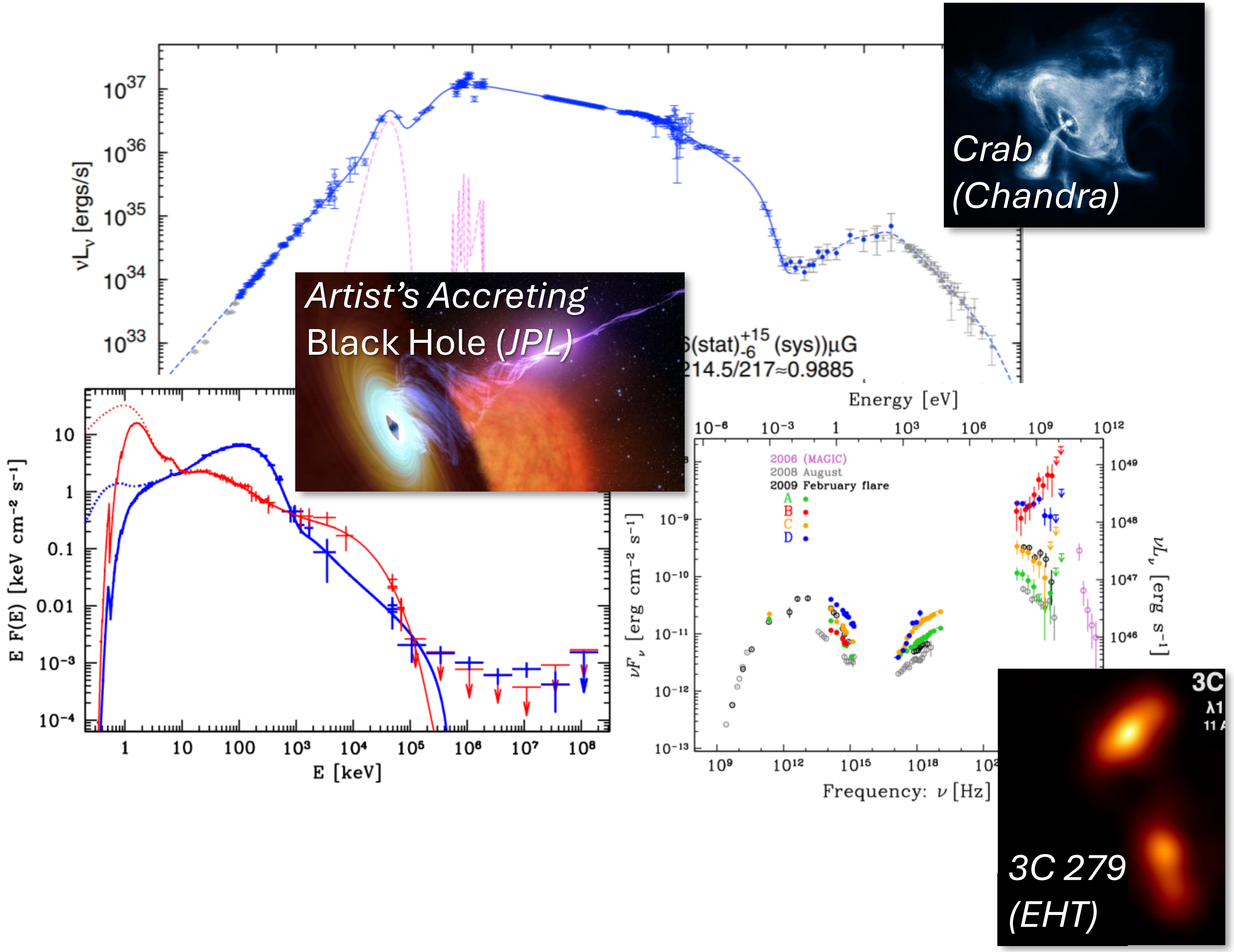
A segment of the overall layer cannot get too slender before tearing into two new layers separated by a plasmoid

Allows effective aspect ratio, $\delta / L_{eff} = \beta_{rec} \simeq 0.1$, to adjust independently of starting layer length L

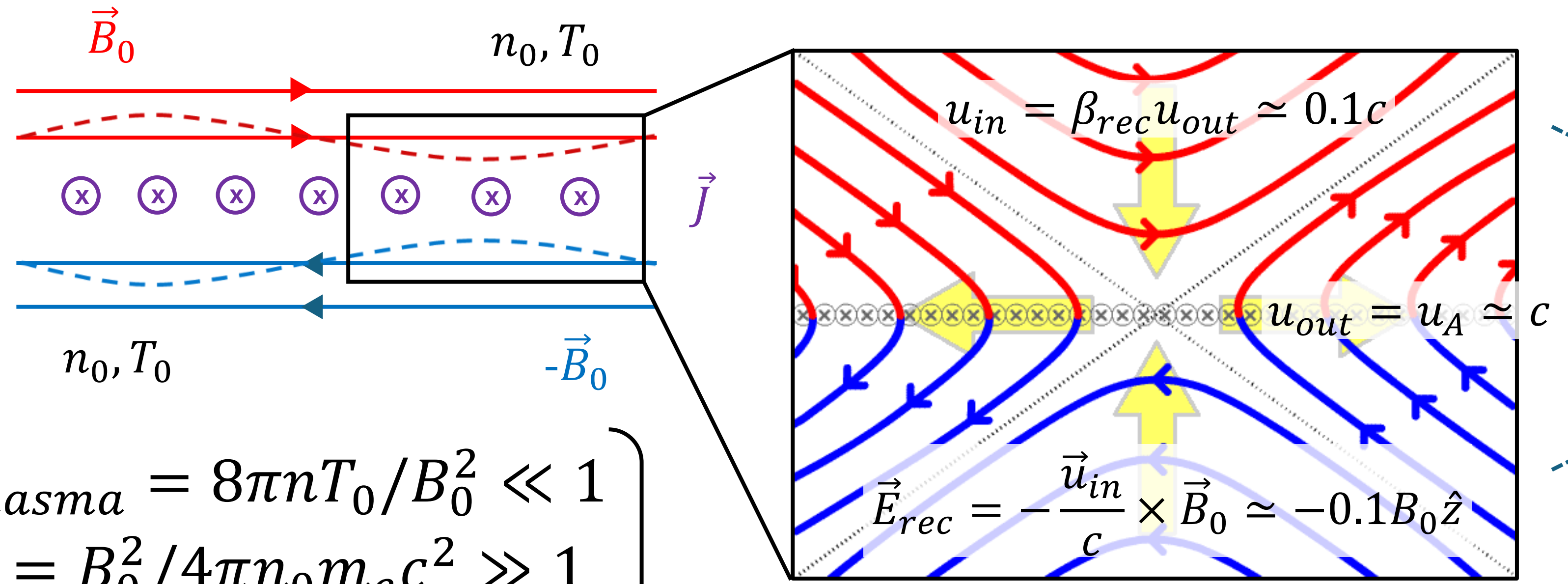
Image credit: Greg Werner

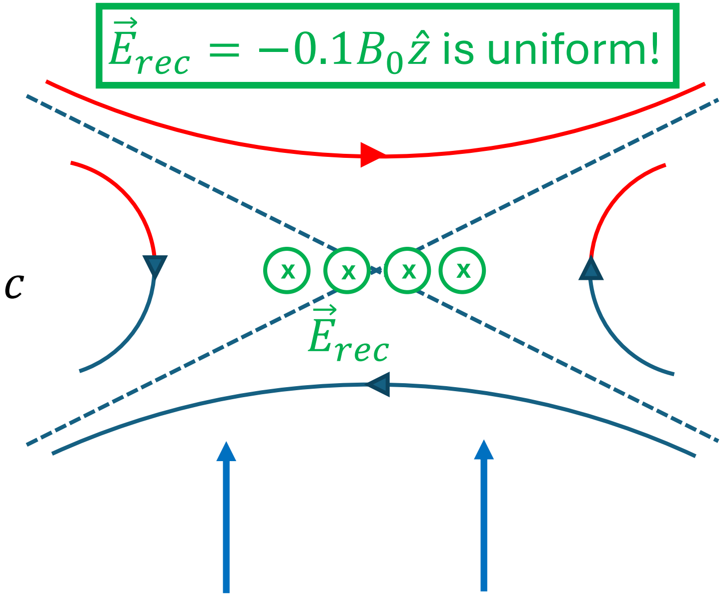
Conditions under which magnetic reconnection "shines"

- The emitting plasma is likely to be highly magnetized
- The observed spectrum of radiation is highly nonthermal



Relativistic reconnection is a ***nonthermal*** particle accelerator





$$\begin{cases} \beta_{plasma} = 8\pi n T_0 / B_0^2 \ll 1 \\ \sigma_c = B_0^2 / 4\pi n_0 m_e c^2 \gg 1 \end{cases}$$

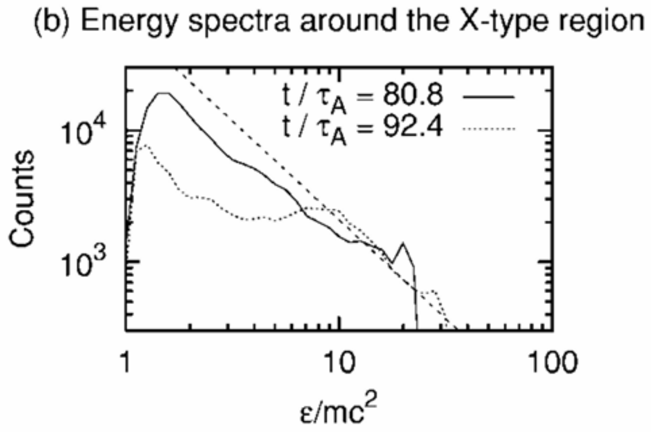
Why nonthermal? (See Zenitani & Hoshino 2001, Uzdensky 2022)

- Balance particle acceleration in X-point region with escape:

$$0 = \partial_t f = -\partial_\gamma (\dot{\gamma}_{acc} f) - f/\tau_{esc}$$

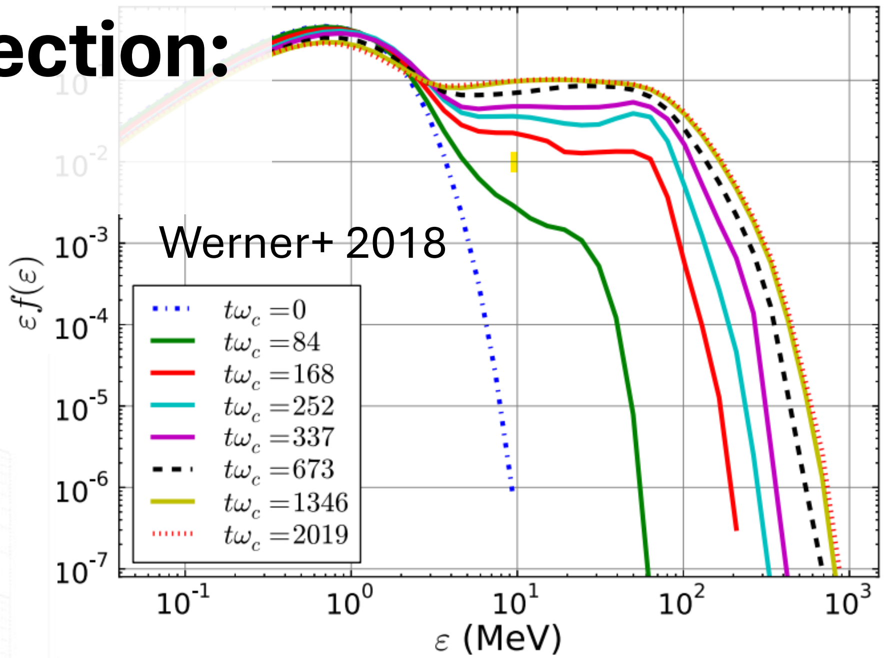
- Acceleration rate is $\dot{\gamma}_{acc} = ecE_{rec}/m_e c^2 \sim 0.1 e B_0 / m_e c$
- Escape time is $\tau_{esc} \sim \Omega_{gyro}^{-1} = \gamma m_e c / 0.1 e B_0$

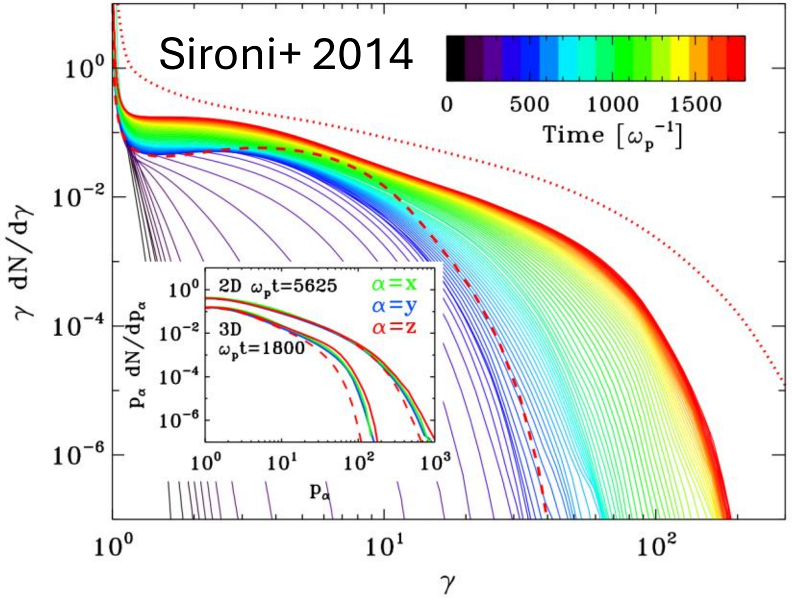
$$\Rightarrow \partial_\gamma \ln f = -\gamma^{-1} \Rightarrow f(\gamma) \propto \gamma^{-1}$$

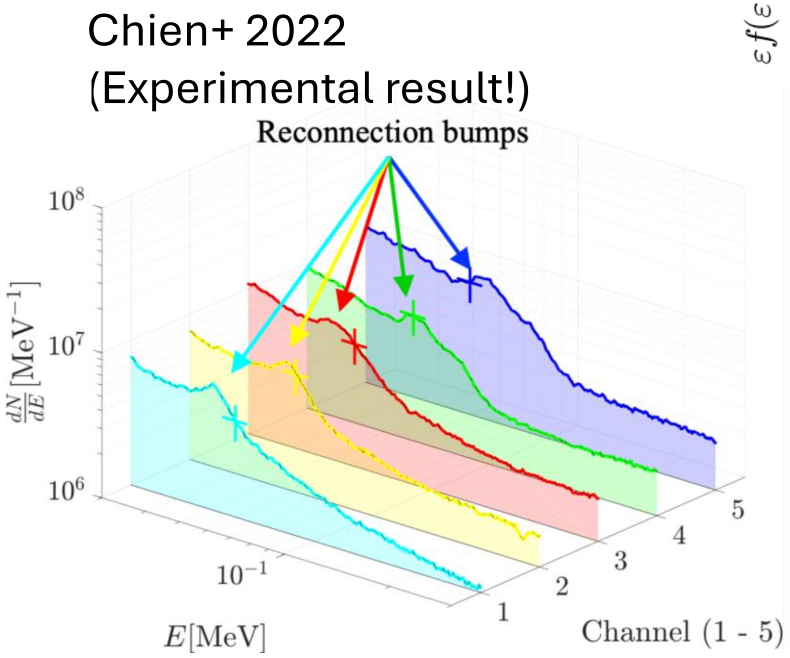


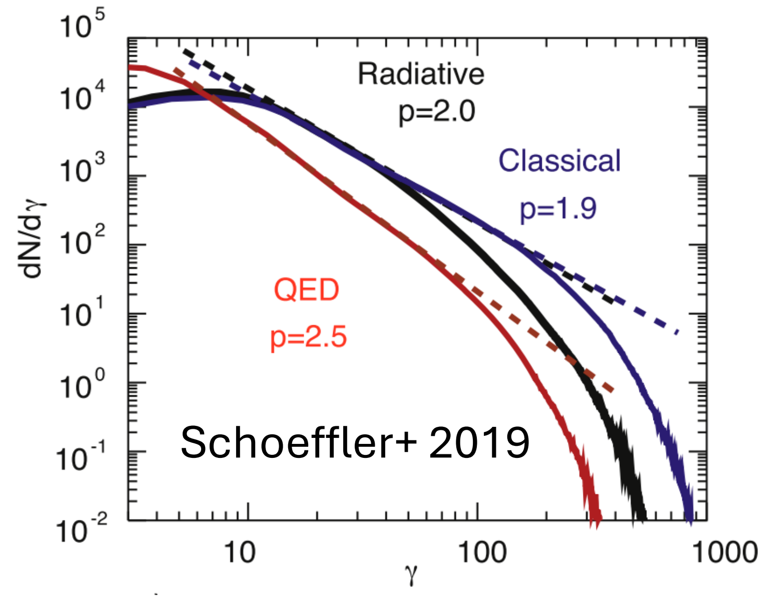
Zenitani & Hoshino 2001

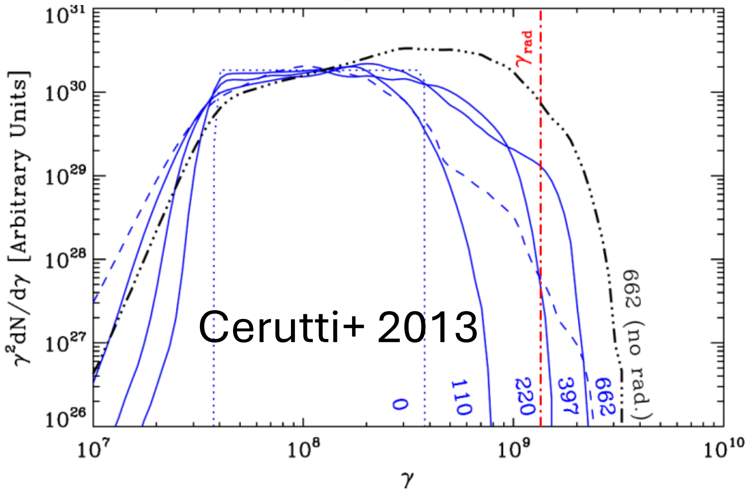
Nonthermal particle acceleration in reconnection: a robust feature of two decades of research









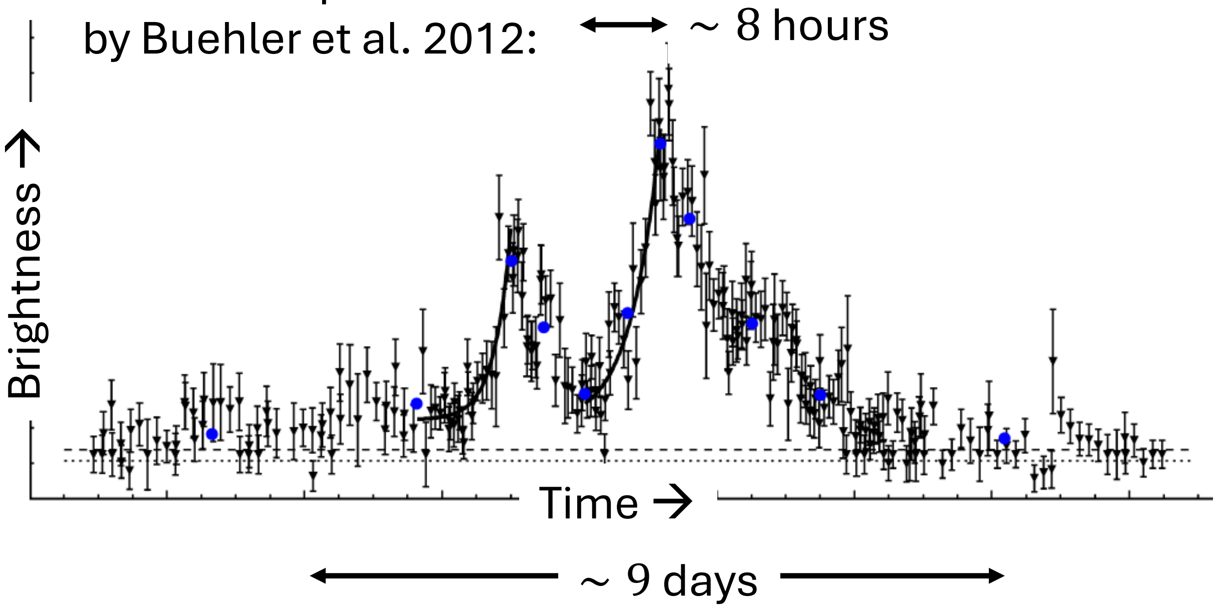


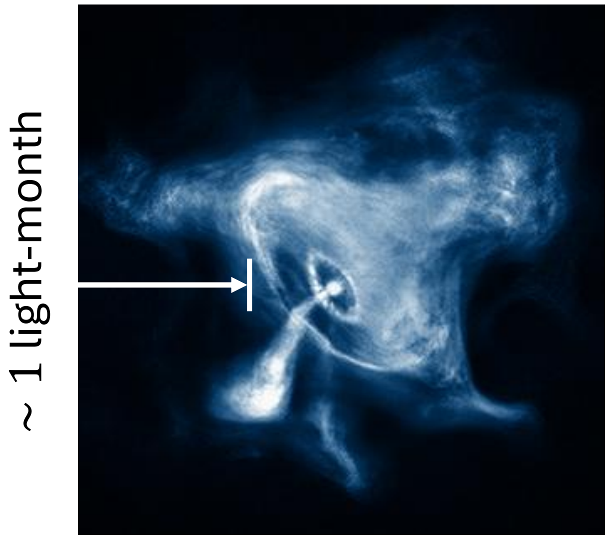
- In 2D and 3D
- In pair plasmas and electron/ion plasmas
- With(out) radiative cooling
- With(out) QED effects

Conditions under which magnetic reconnection "shines"

- The emitting plasma is likely to be highly magnetized
- The observed spectrum of radiation is highly nonthermal
- The variability is extremely fast ($ct_{var} < L$)

Crab flares presented by Buehler et al. 2012:

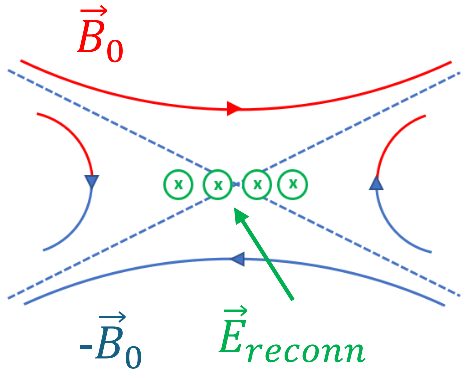


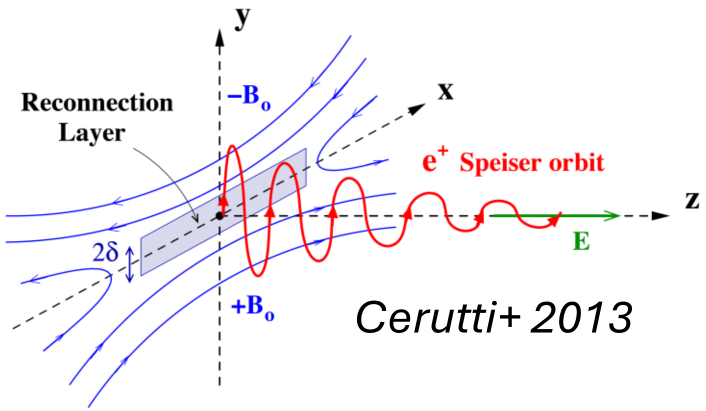


Kinetic beaming in reconnection generates rapid variability

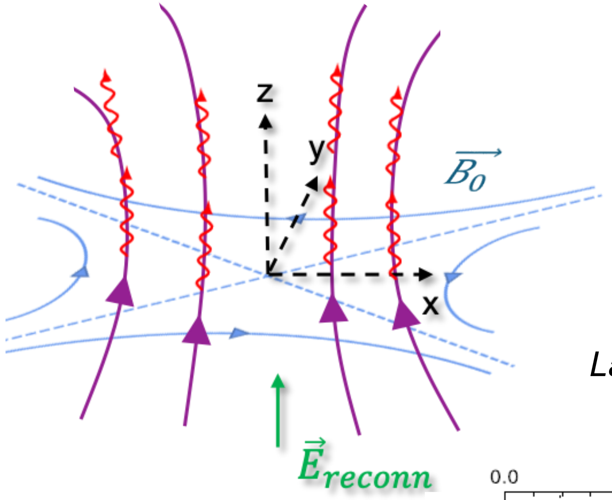
Particle Tracks
Photons

Relativistic particles emit parallel to their velocities!

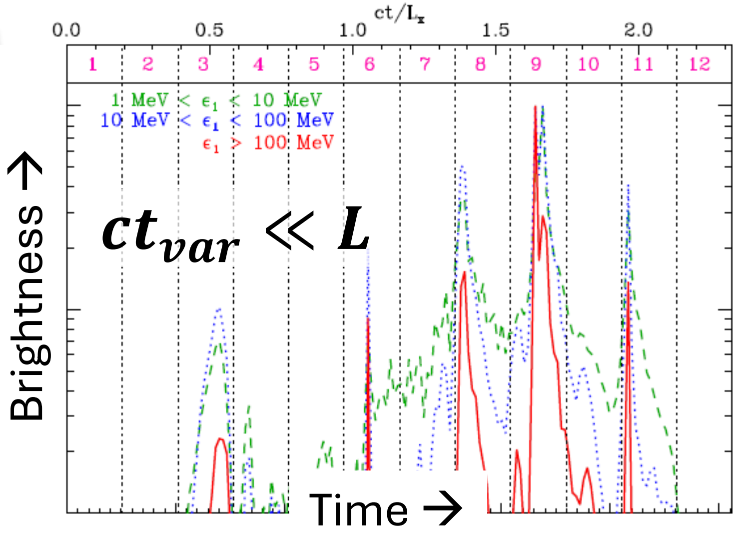




Cerutti+ 2013



Dominique Lavoie/Shutterstock



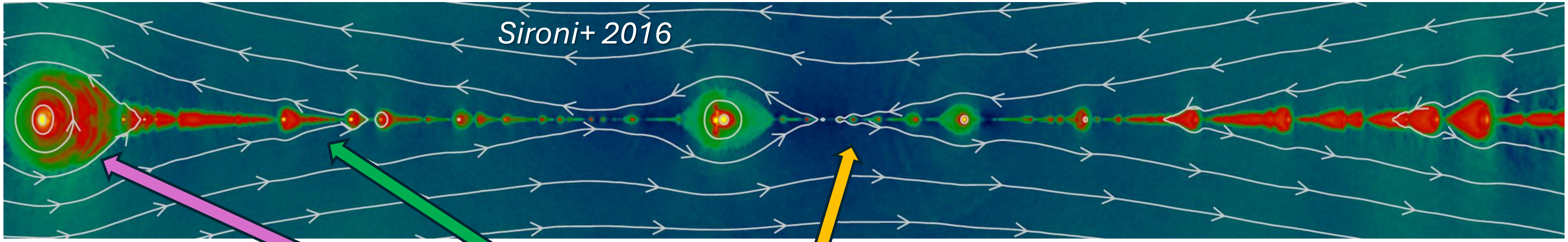
Synthetic synchrotron lightcurve; *Cerutti+ 2013*

<u>Kinetic Beaming</u>:

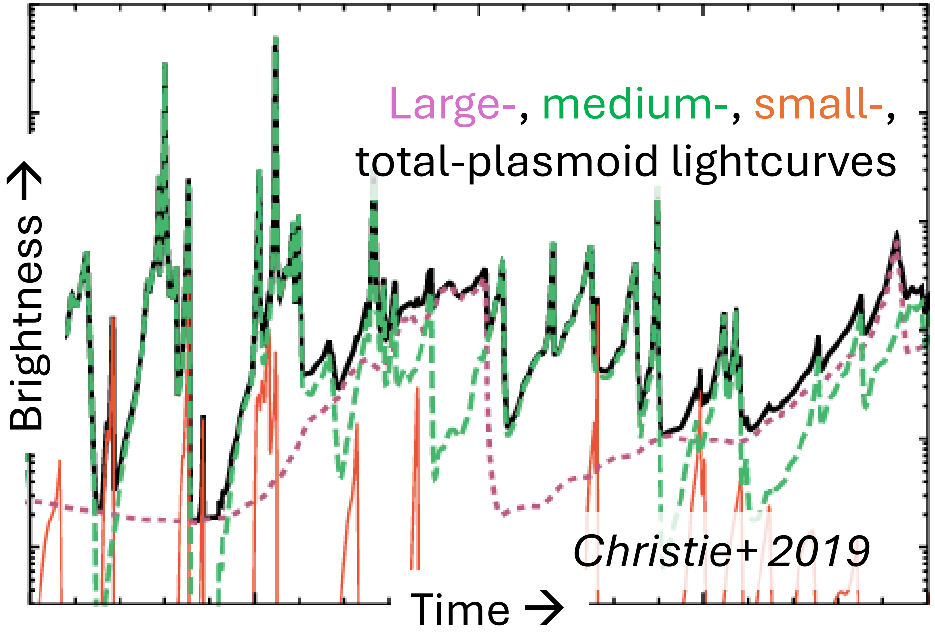
Acceleration preferentially focuses high-energy particle beams (Cerutti+ 2012; **Mehlhaff+ 2020**)

Sweeping beams cause rapid lightcurve variability (lighthouse effect)

Plasmoid motion in reconnection generates rapid variability



Large, medium, and small plasmoids yield
long, medium, and short respective variability timescales

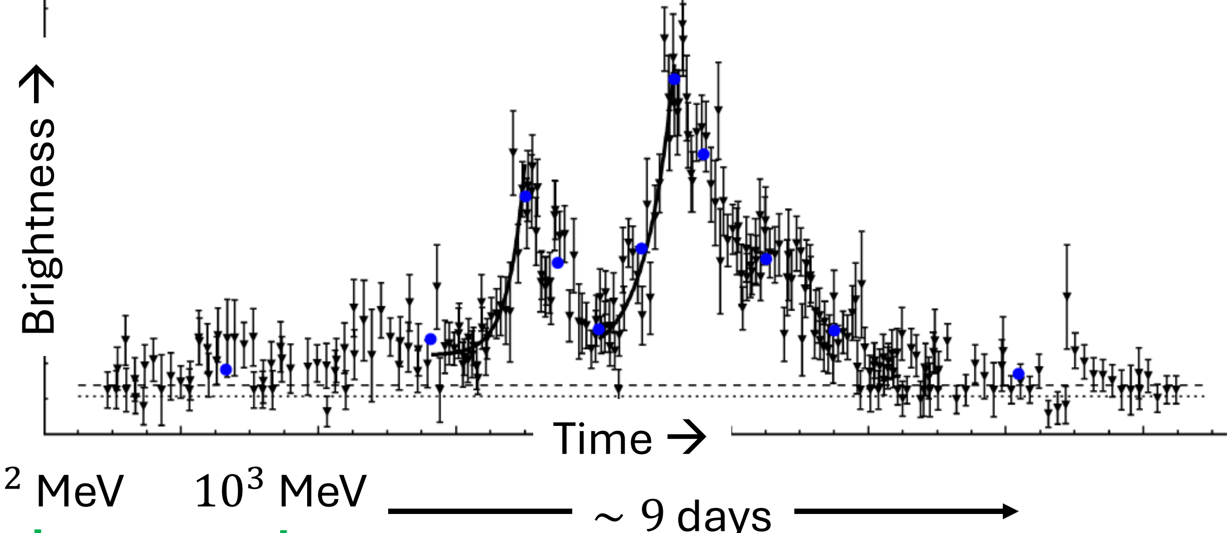


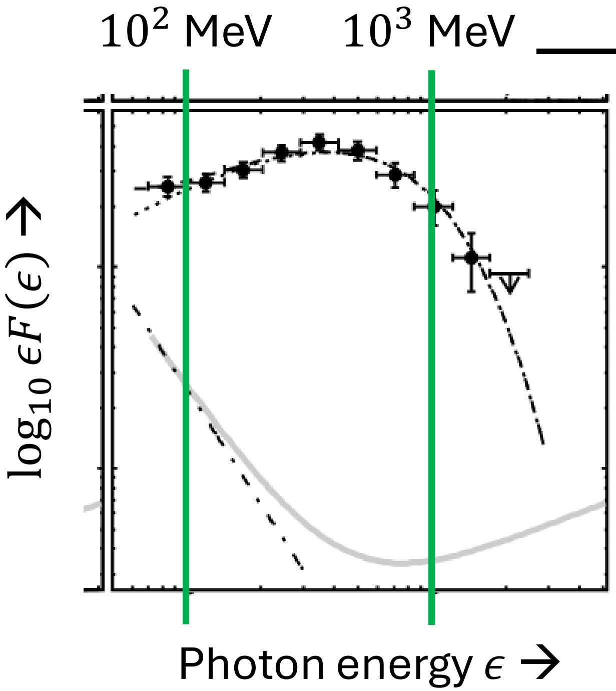
Overall spectrum of observed timescales probably has contributions from both the plasmoid chain (hierarchical/fluid-level) and kinetic beaming

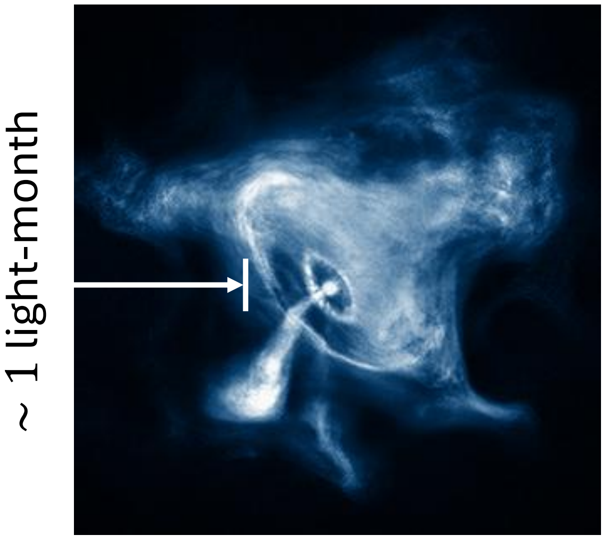
Conditions under which magnetic reconnection “shines”

- The emitting plasma is likely to be highly magnetized
- The observed spectrum of radiation is highly nonthermal
- The variability is extremely fast ($ct_{var} < L$)
- Synchrotron radiation above 160 MeV is observed

Crab flares presented by Buehler et al. 2012:







Radiative cooling limits particle/photon energies

<u>Example: **Synchrotron radiation**</u>

- A relativistic electron radiates synchrotron power:

Component of magnetic field perpendicular to particle velocity

$$P_{syn} = \frac{2}{3} r_e^2 c \gamma^2 B_\perp^2$$

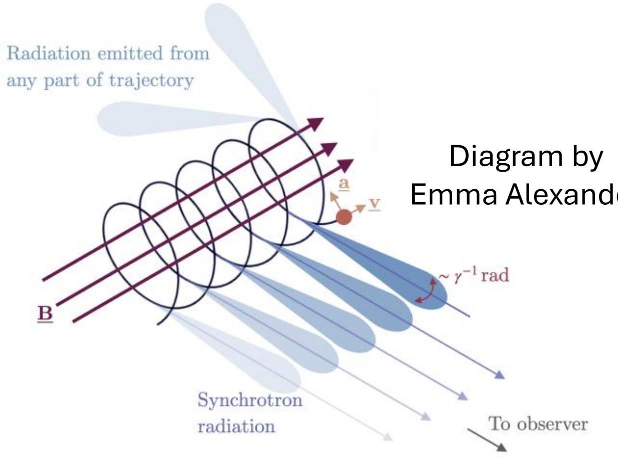


Diagram by Emma Alexander

- The radiation reaction force, $f_{rad} = P_{syn}/c$, balances the force, $f_{acc} = eE$, from an electric field E when

$$\gamma = \gamma_{syn} = \sqrt{\frac{3eE}{2r_e^2 B_\perp^2}}$$

- This limits synchrotron radiation to photon energies below

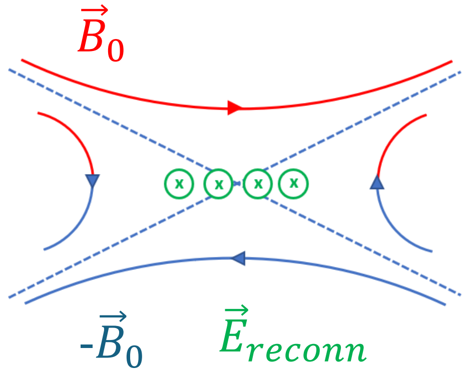
$$\epsilon < \frac{3}{2} \frac{\hbar e B_\perp}{m_e c} \gamma_{syn}^2 = \frac{9}{4} \left(\frac{\hbar c}{e^2}\right) \left(\frac{E}{B_\perp}\right) m_e c^2 \leq \epsilon_{syn} = \frac{9}{4} \left(\frac{1}{\alpha_{FS}}\right) m_e c^2 = 160\ \text{MeV}$$

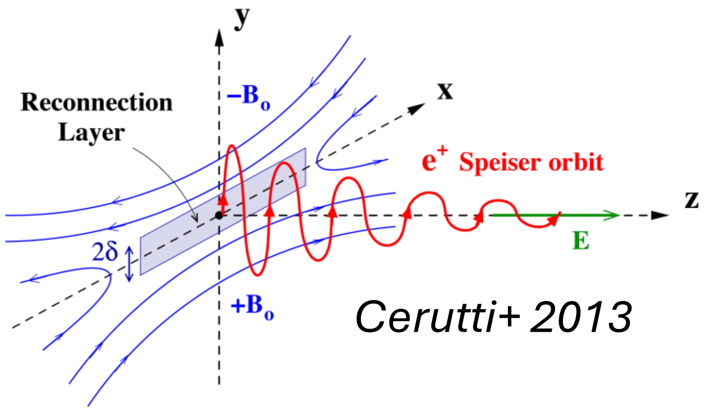
Exceeding ϵ_{syn} requires going beyond ideal MHD

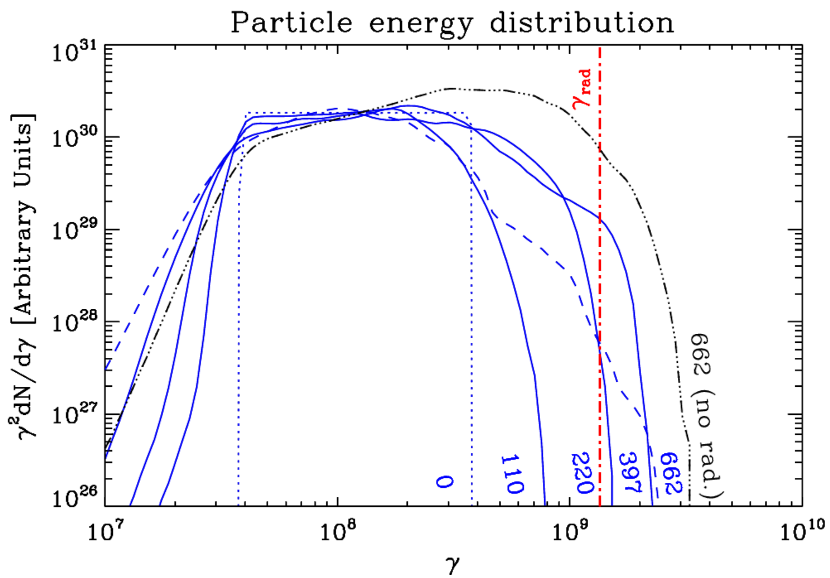
!! Fine structure constant $\alpha_{FS} = e^2/\hbar c$

In ideal MHD, $|\vec{E}| = \left|-\frac{\vec{u}}{c} \times \vec{B}\right| \lesssim B_\perp$

In reconnection, particles can exceed the synchrotron burnoff limit



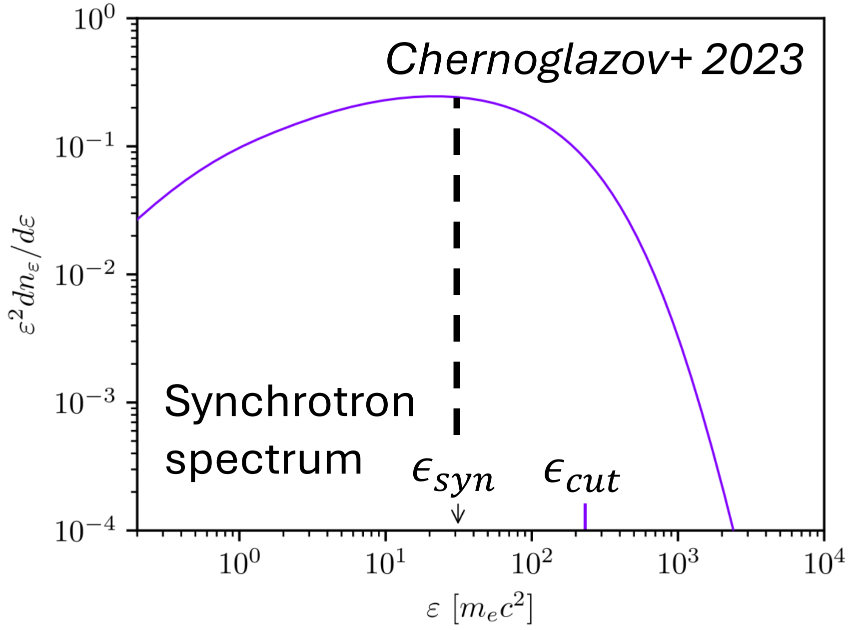




X-points are precisely regions where $E > B_\perp \simeq 0$

Particles near X-points focused toward midplane (recall kinetic beaming effect)

Allows particles to surpass nominal γ_{syn} and radiation above $\epsilon_{syn} = 160$ MeV



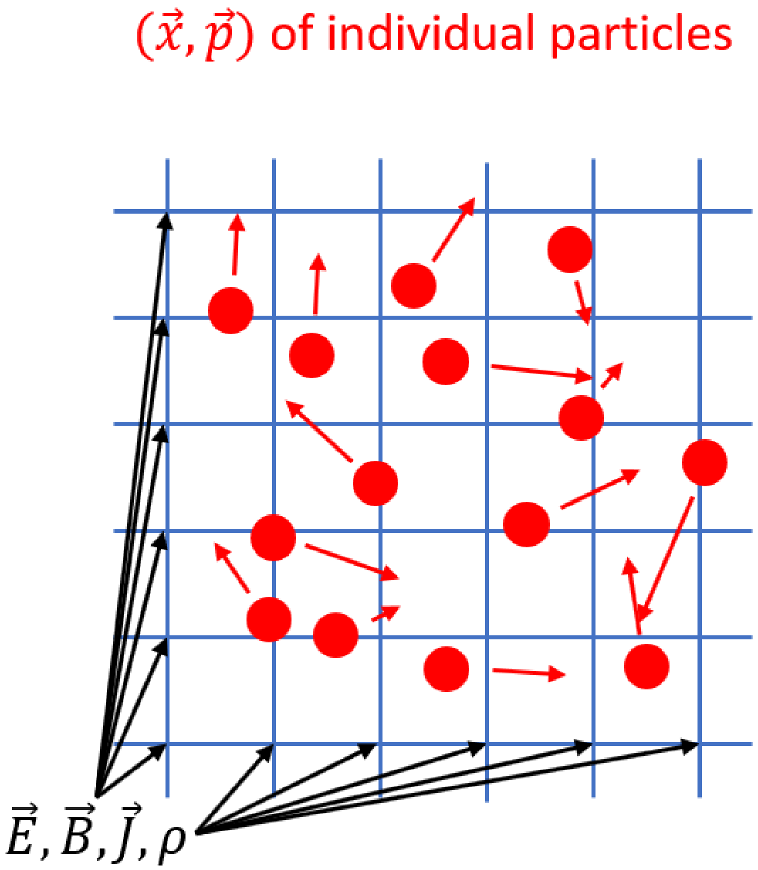
Conditions under which magnetic reconnection "shines"

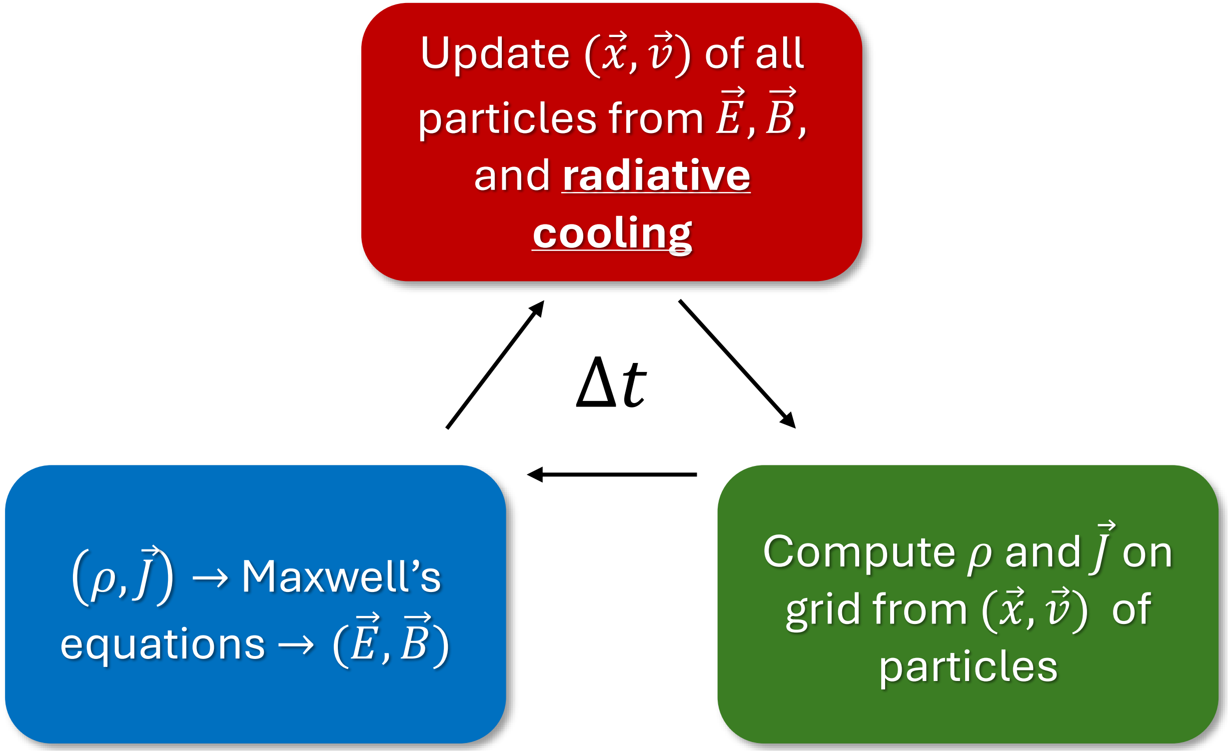
That is, when the plasma:

- The emitting plasma is likely to be highly magnetized → Is too magnetized
- The observed spectrum of radiation is highly nonthermal → Is too nonthermal
- The variability is extremely fast ($ct_{var} < L$) → Is too variable
- Synchrotron radiation above 160 MeV is observed → Emits too energetic photons

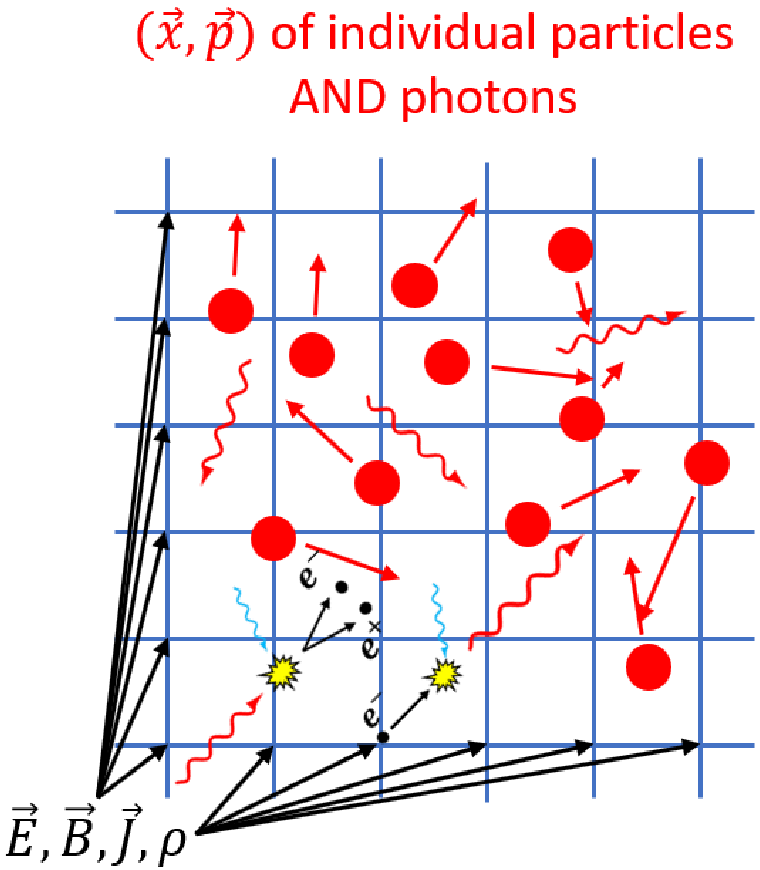
One example of a new frontier of radiative reconnection research

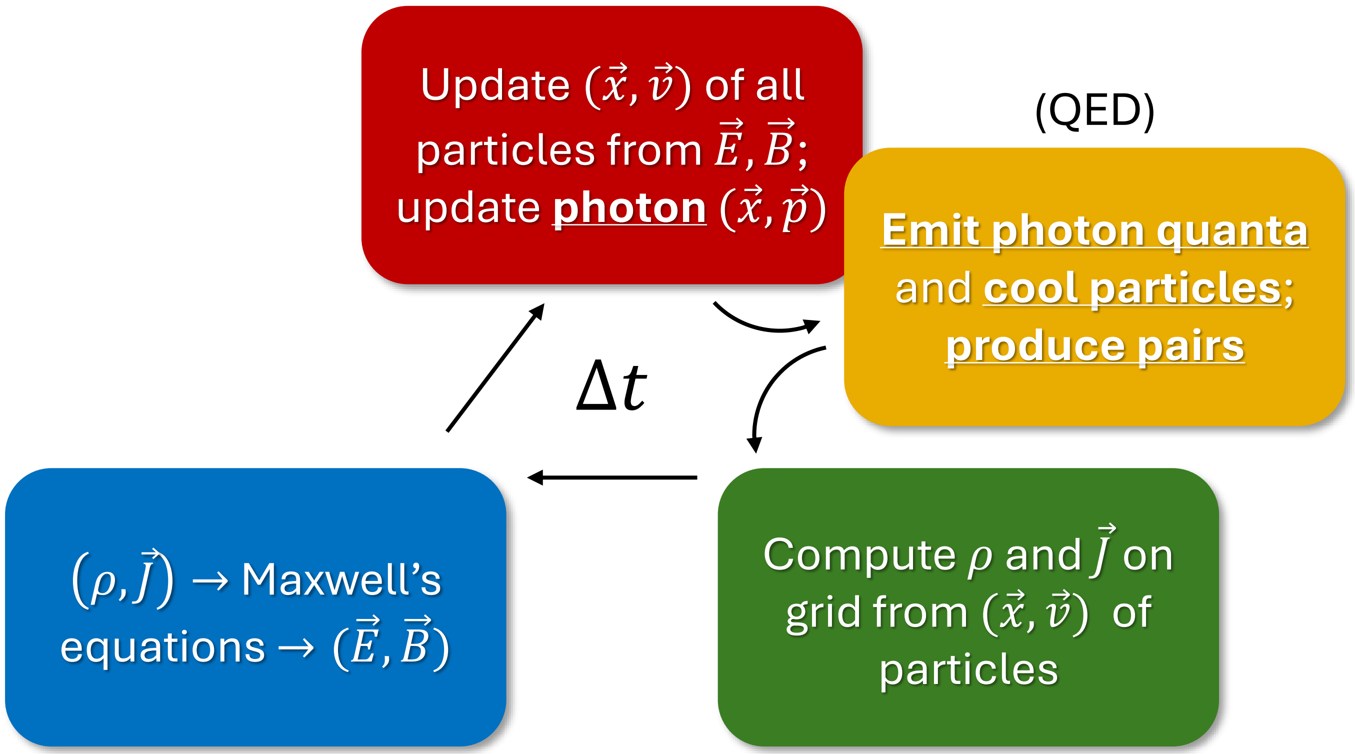
Radiative effects require an upgraded PIC framework



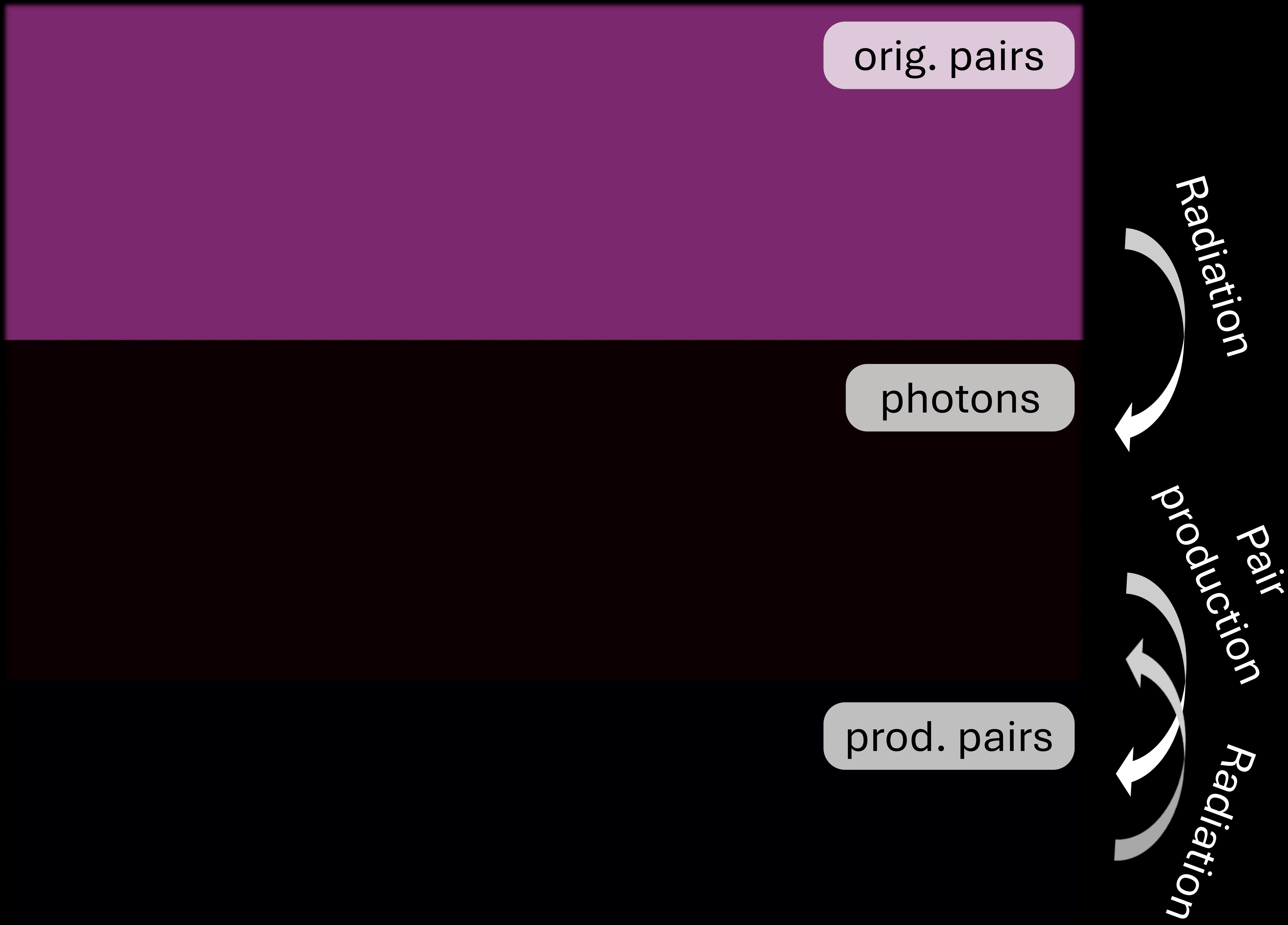


Radiative effects require an upgraded PIC framework



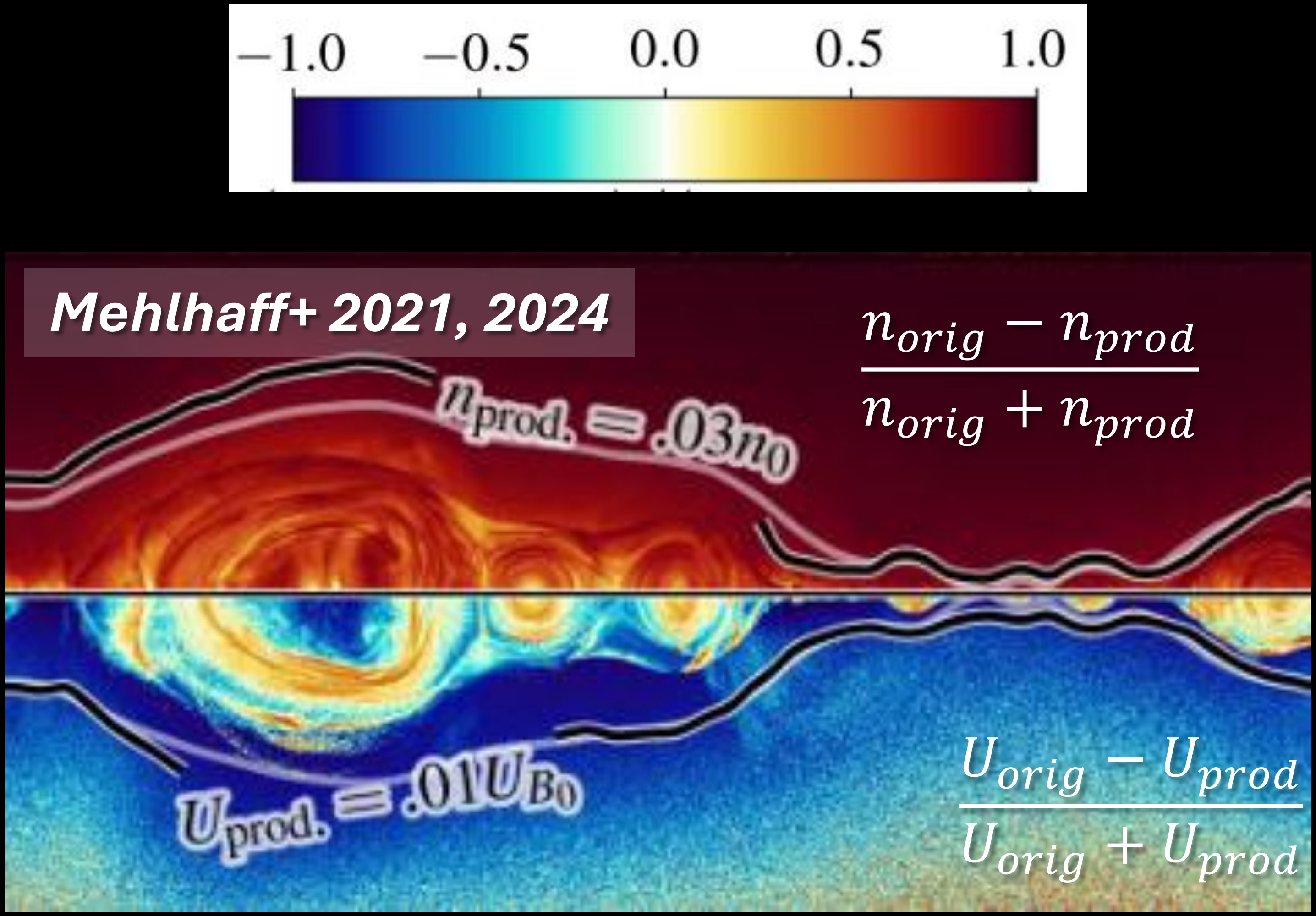


Radiative electron-positron-photon reconnection is a new astrophysical frontier



Mehlhaff+ 2024

Nonlocal energy transport can regulate radiative reconnection

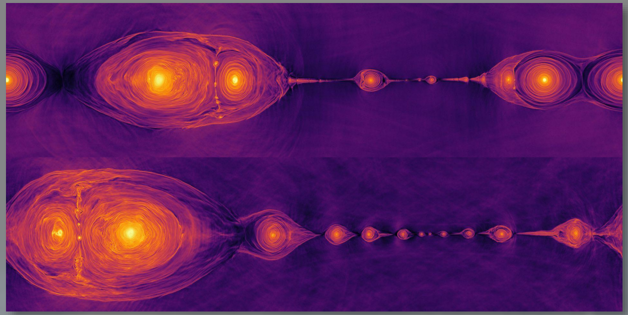


- Photons transport some of dissipated energy back upstream
- Pairs born upstream can dominate inflow plasma energy density and pressure
- Reconnection decides its own upstream plasma state!

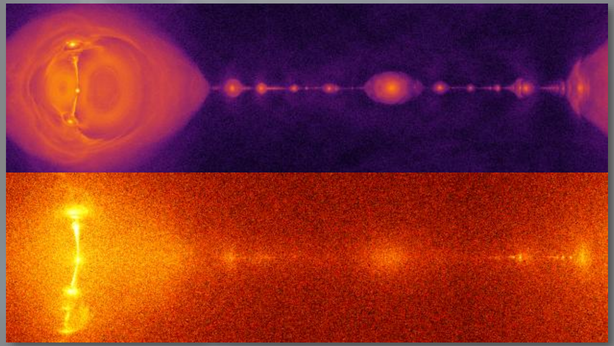
See also Hakobyan+ 2019; Schoeffler+ 2019, 2023

Outline

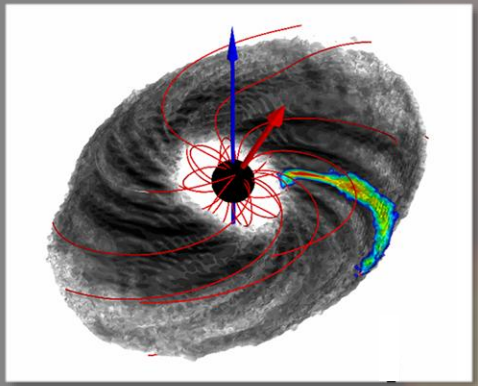
Highlights from two decades of local simulations



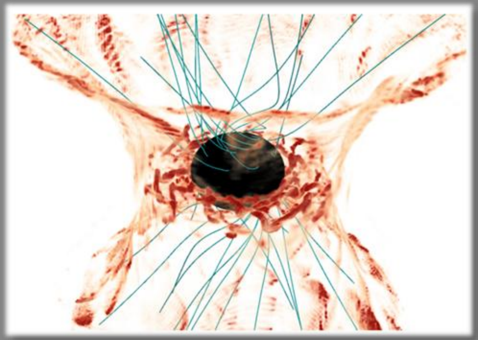
The radiative frontier



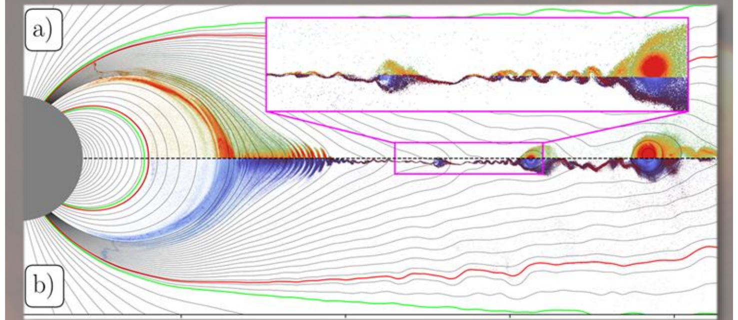
Highlights from one decade of global simulations



The gravitational frontier



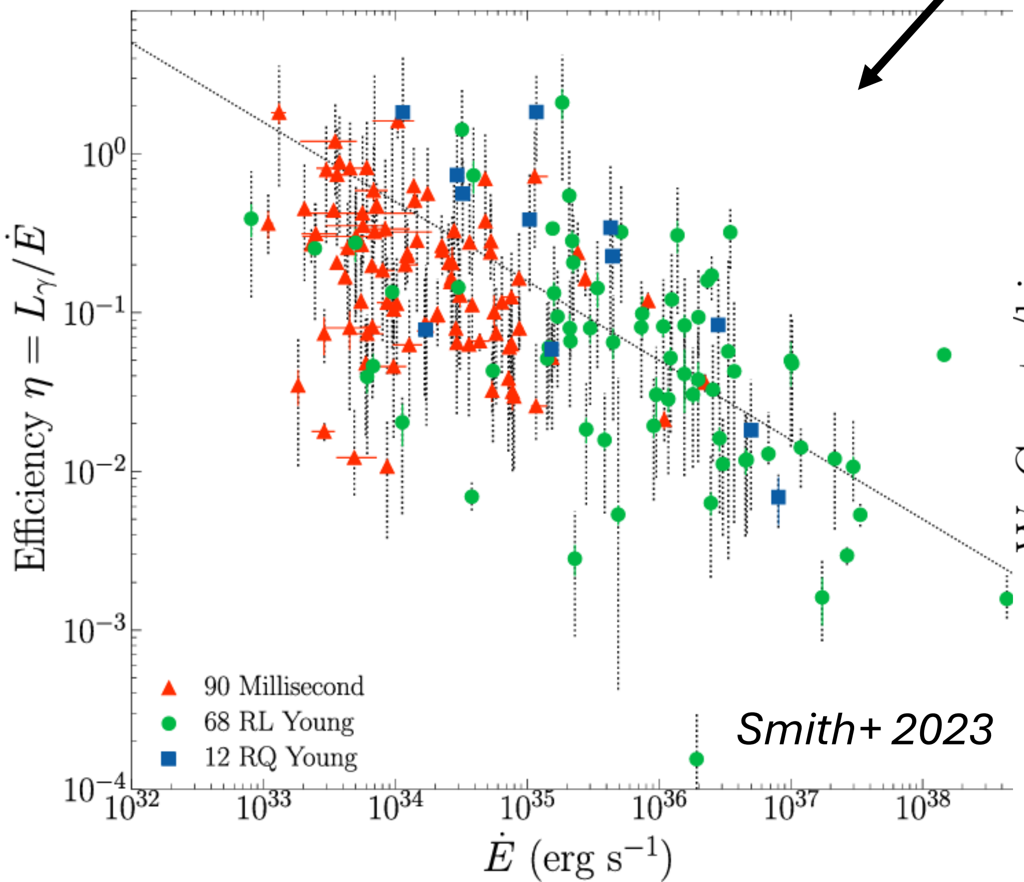
A bright future

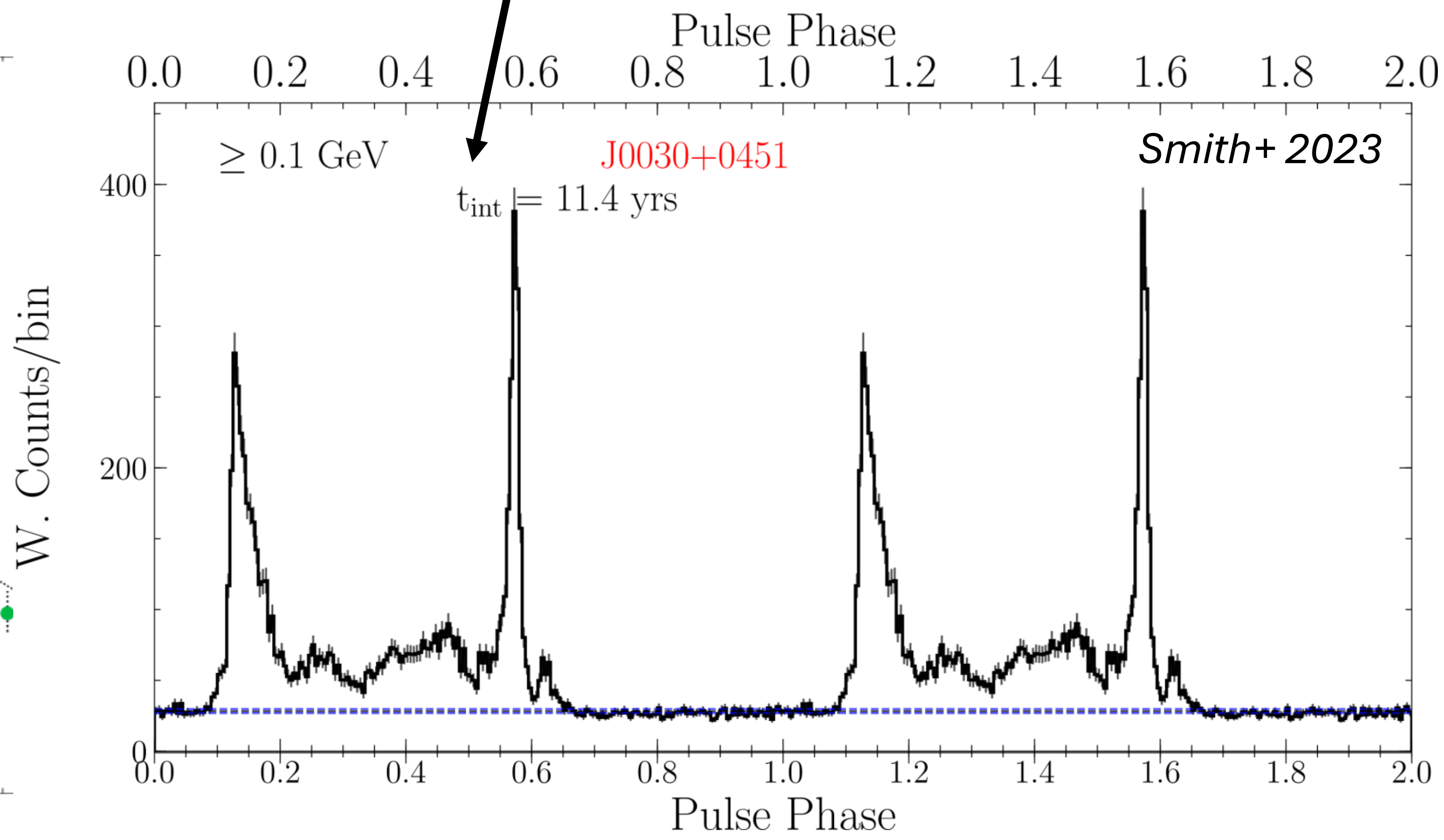


Fermi has ushered in a new era of gamma-ray pulsar science

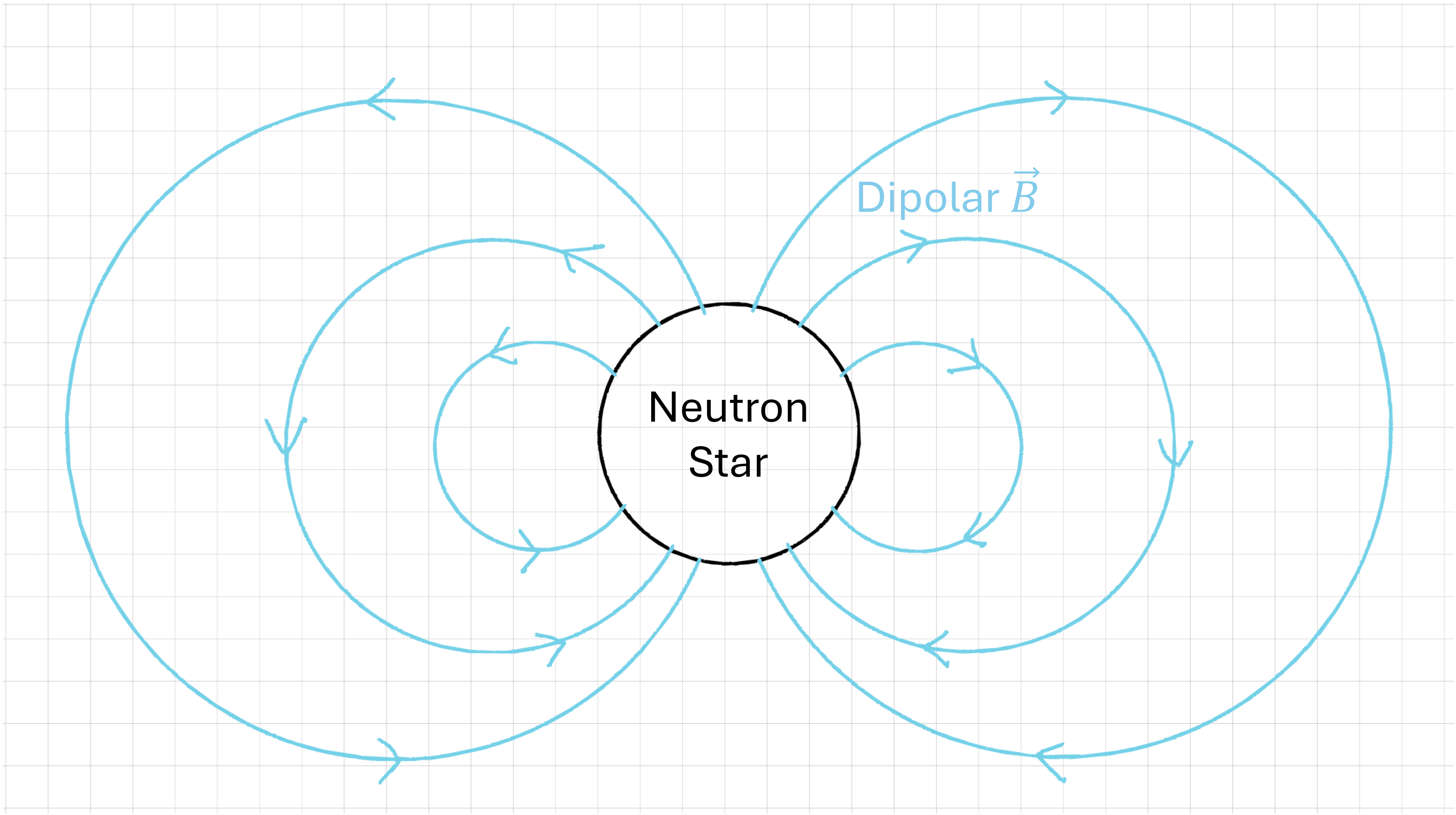
- Now ~300 known gamma-ray pulsars (only 11 pre-Fermi)

- How to explain the gamma-ray efficiency and pulse profiles?

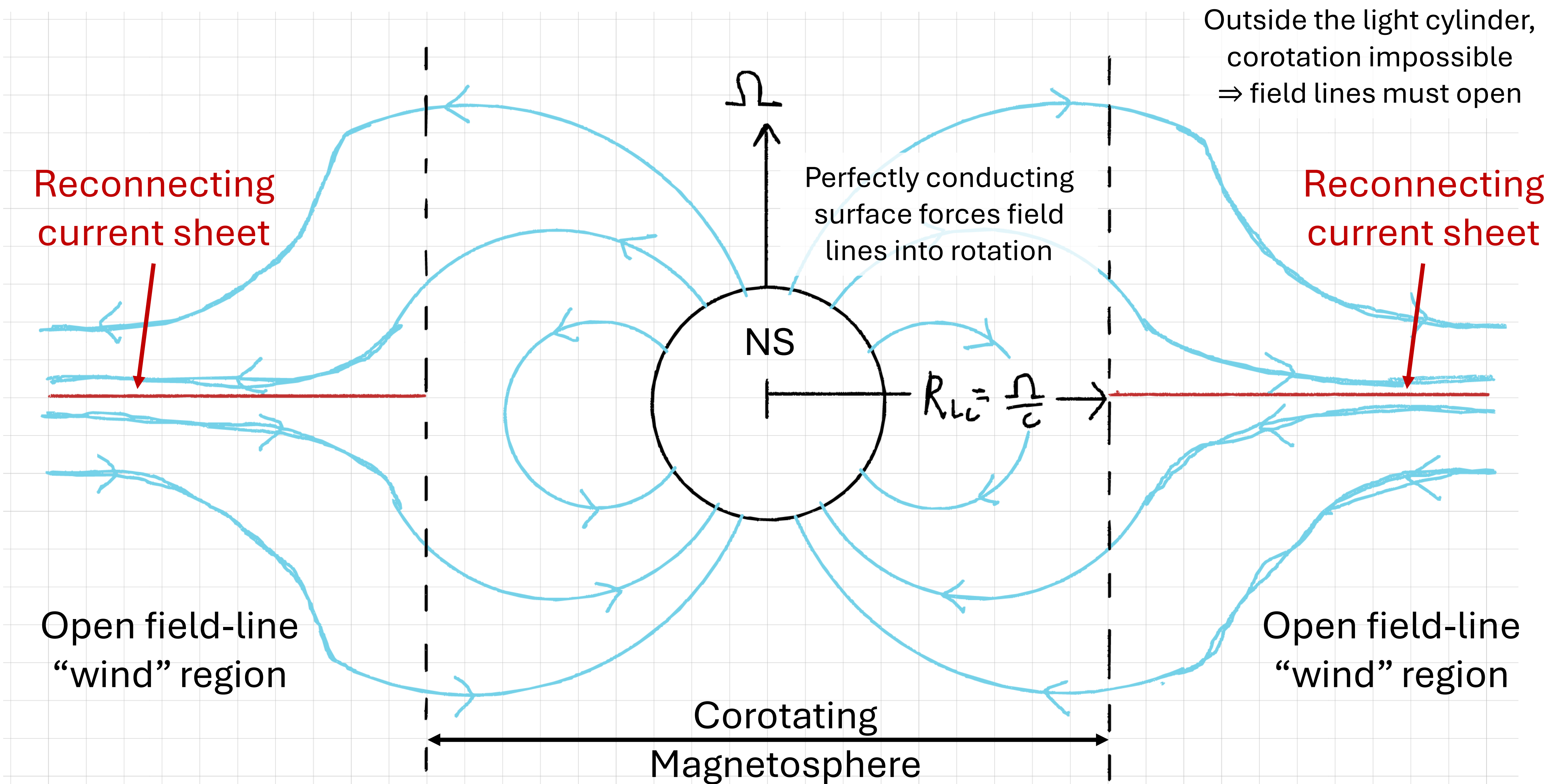




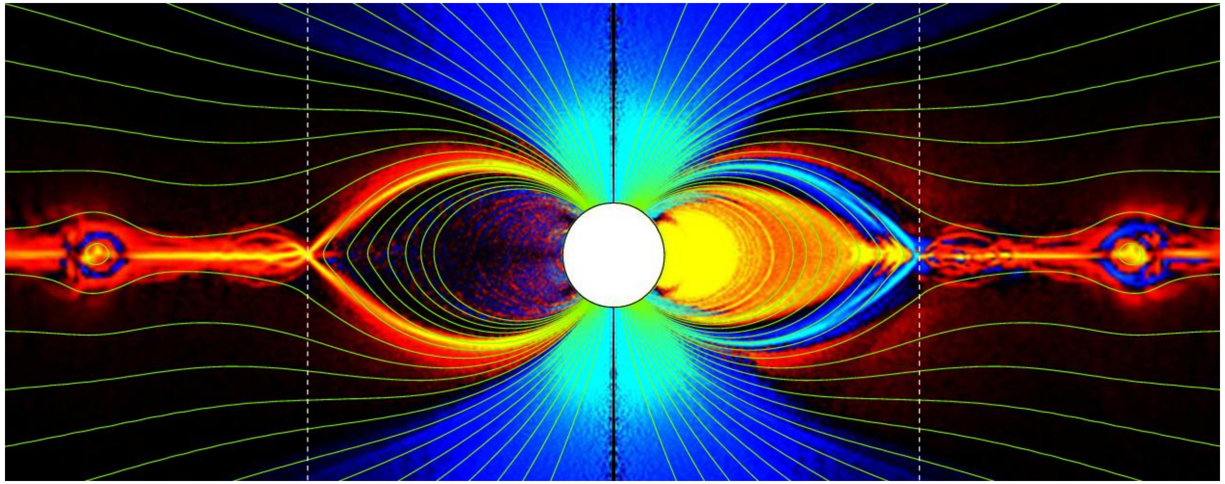
Pulsar: a rotating conductor embedded with a magnetic dipole



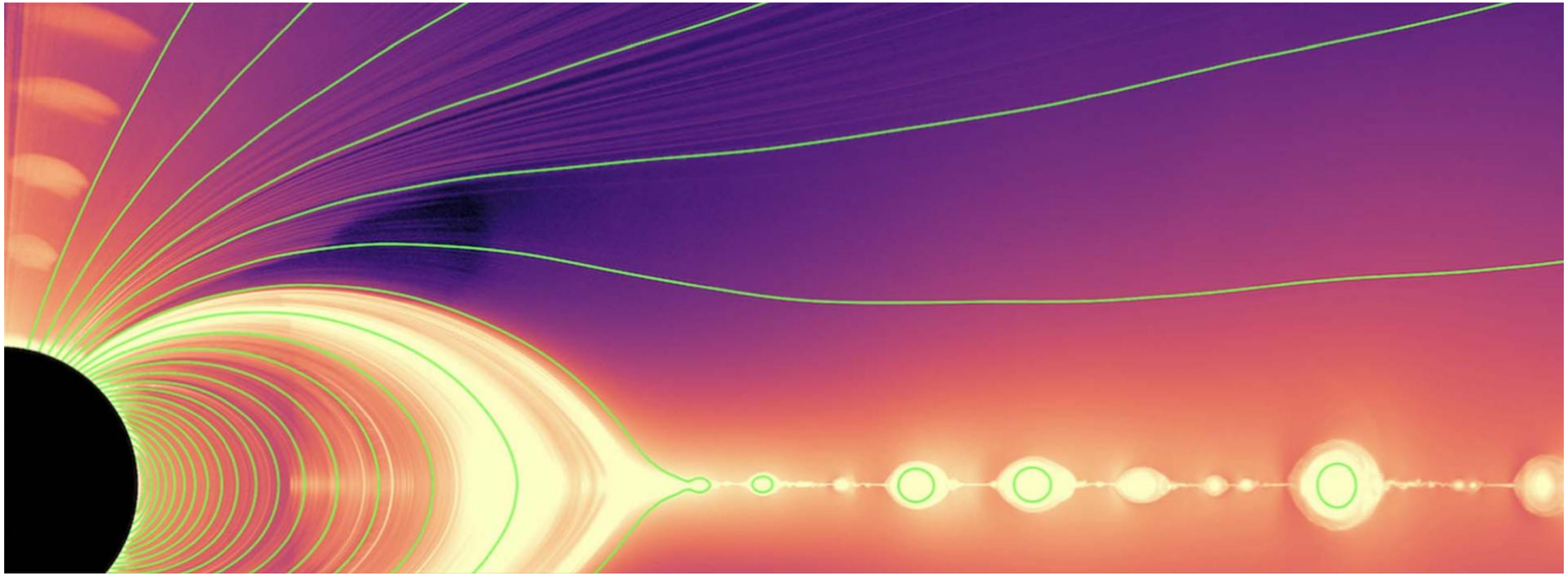
Pulsar: a *rotating* conductor embedded with a magnetic dipole



One decade of pulsar simulations: aligned rotators

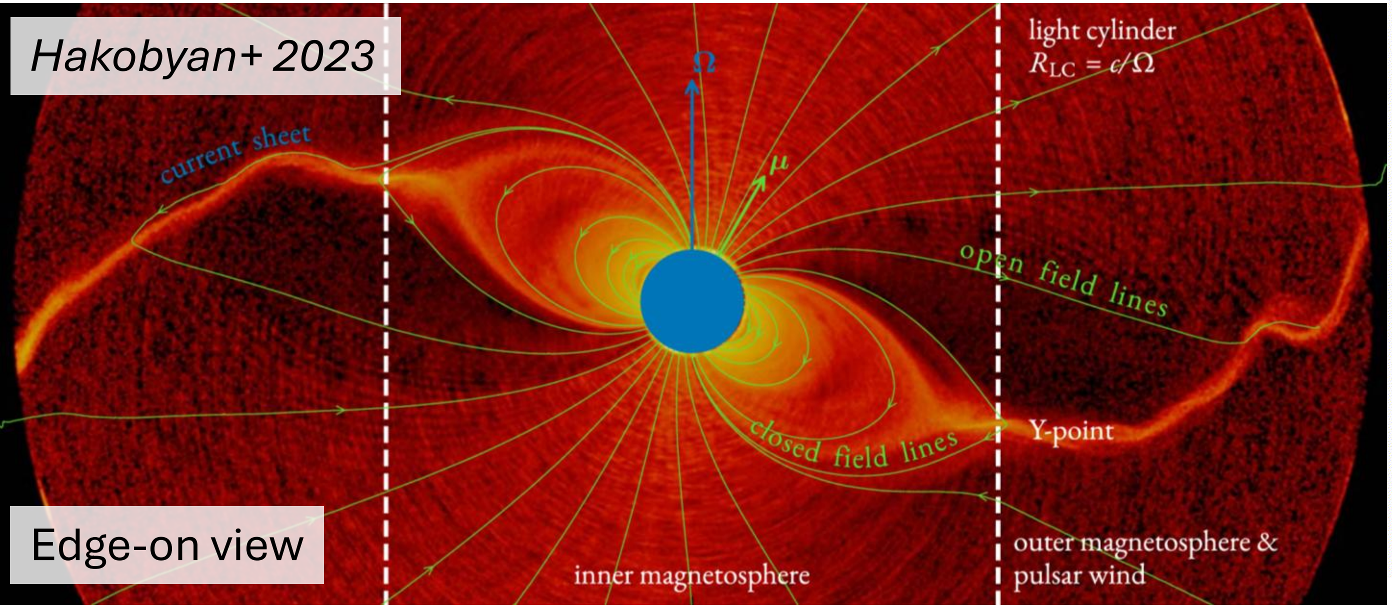


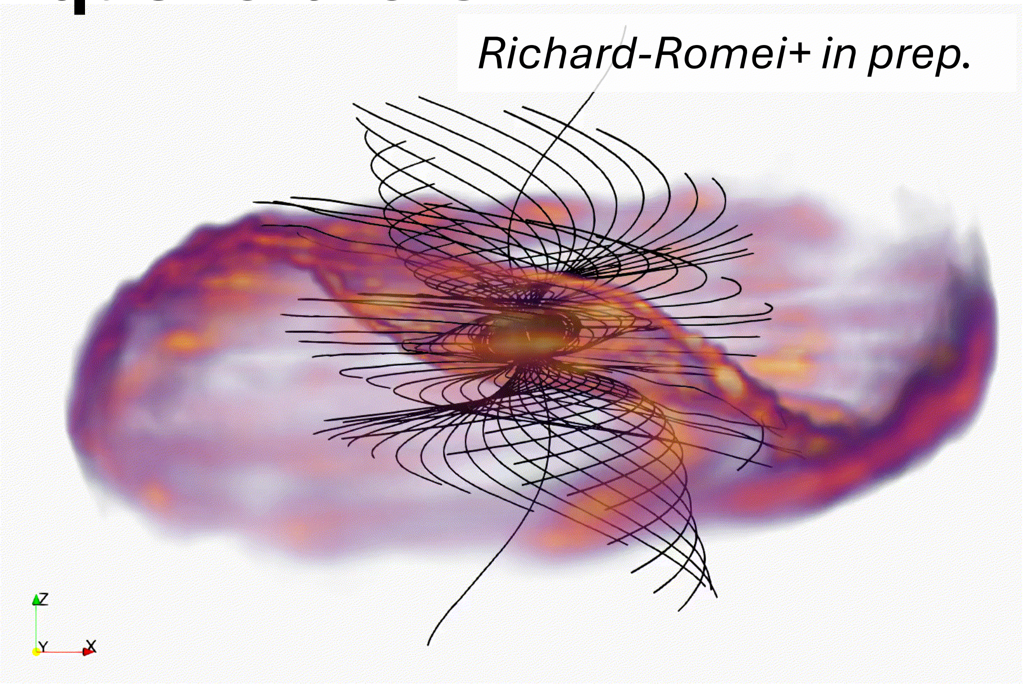
Chen & Beloborodov 2014

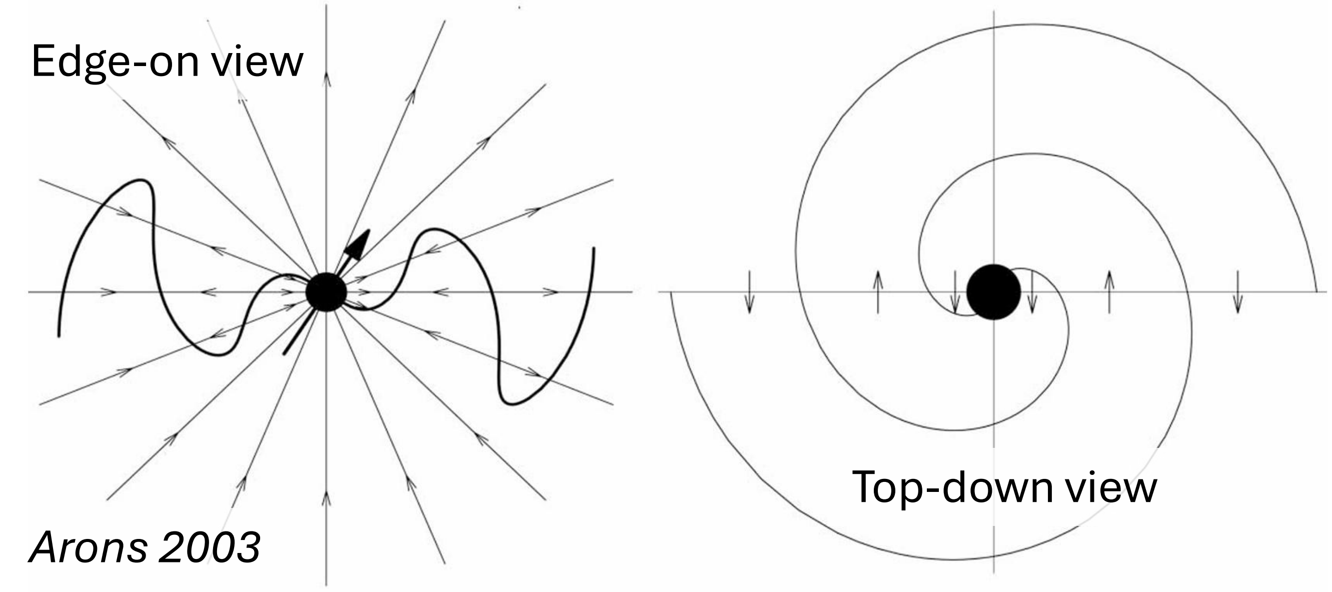


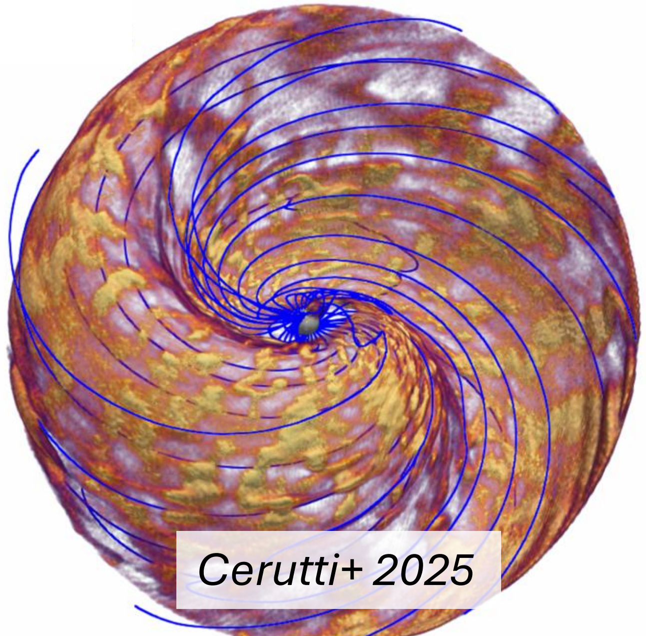
Bransgrove+ 2023

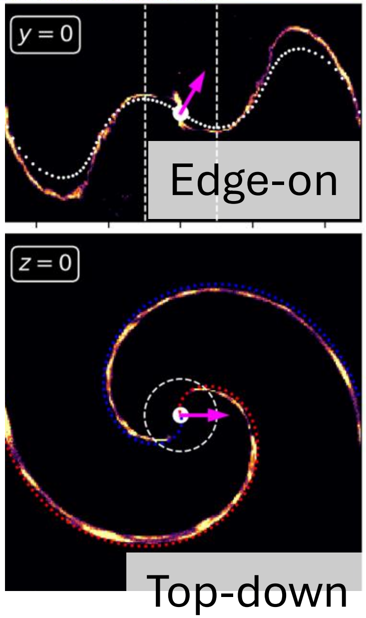
One decade of pulsar simulations: oblique rotators











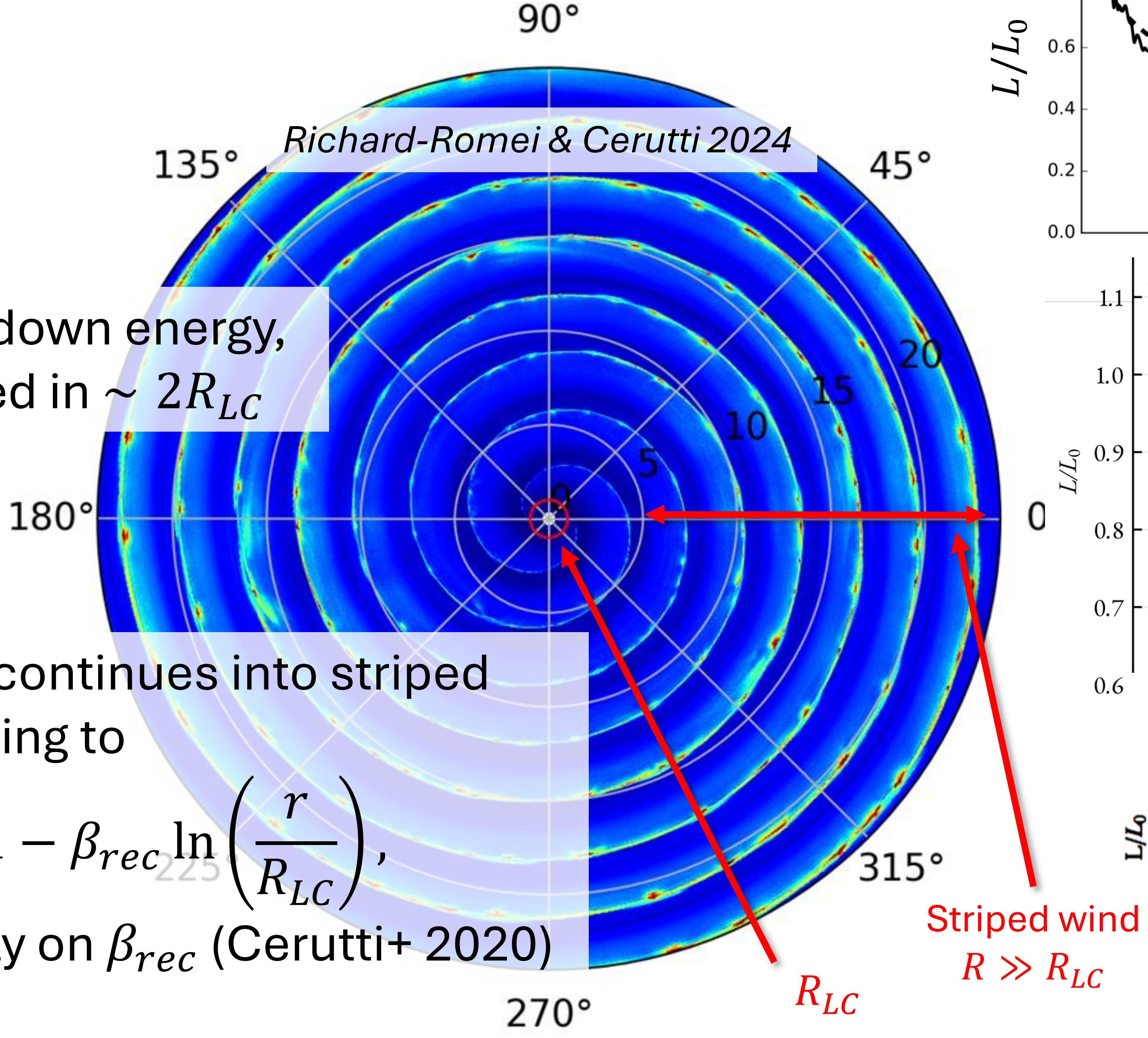
Reconnection controls the energetics

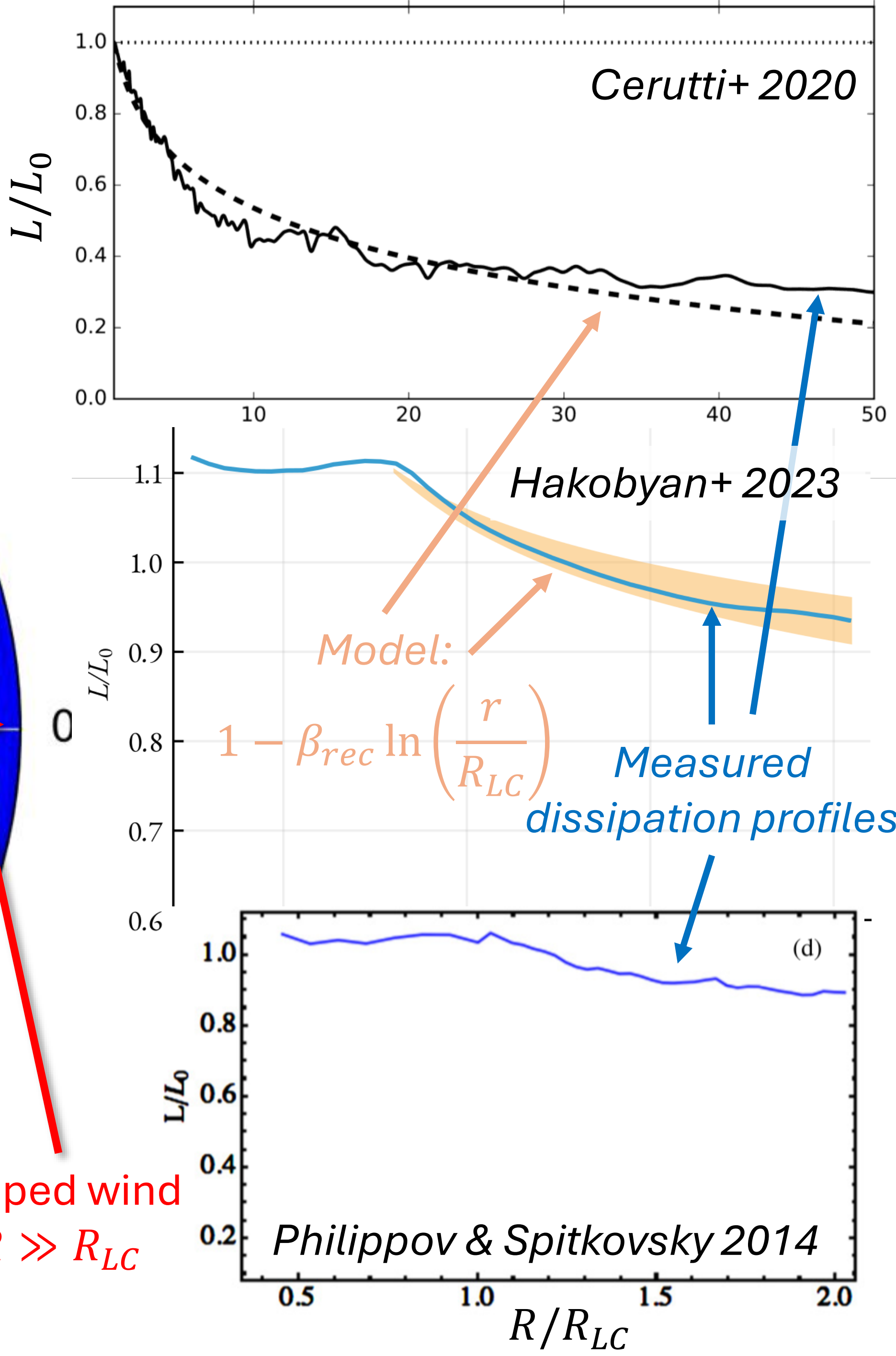
- $\sim 10\%$ spindown energy, L_0, dissipated in $\sim 2R_{LC}$

- Dissipation continues into striped wind according to

$$\frac{L}{L_0} = 1 - \beta_{rec} \ln\left(\frac{r}{R_{LC}}\right),$$

depends only on β_{rec} (Cerutti+ 2020)



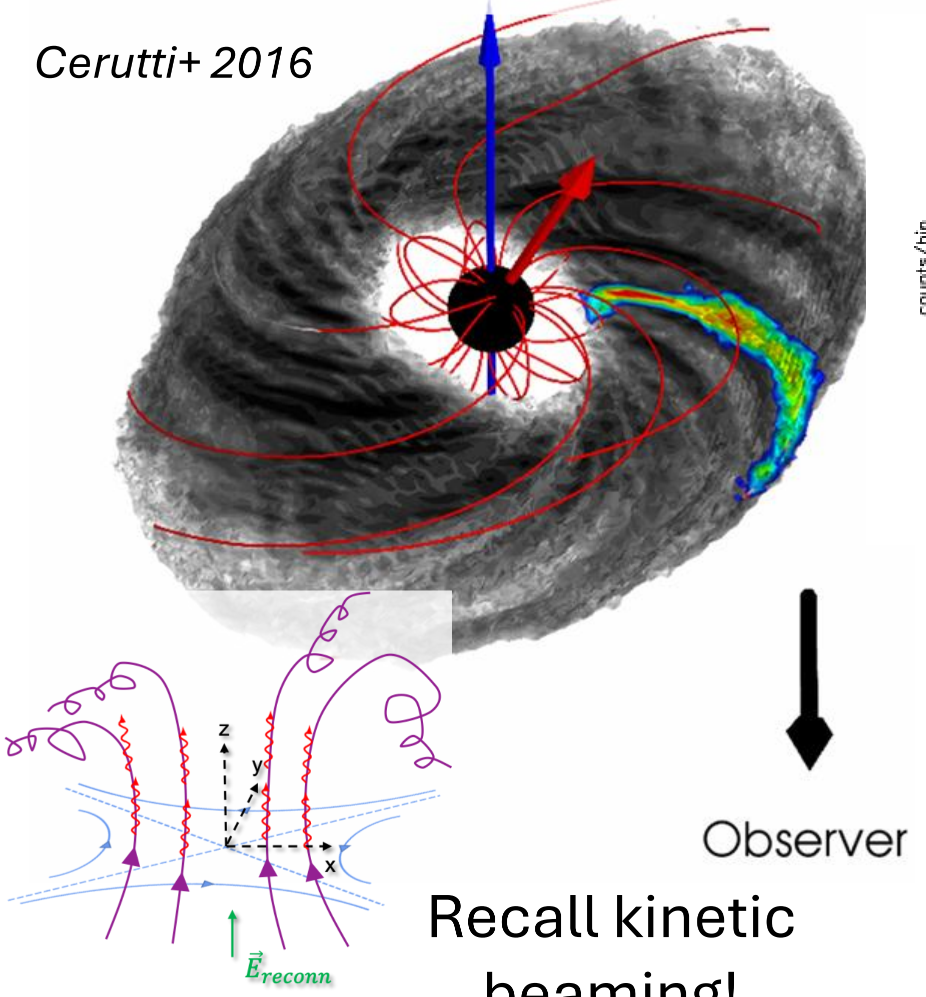


Reconnection powers the observed radiation, especially gamma-rays

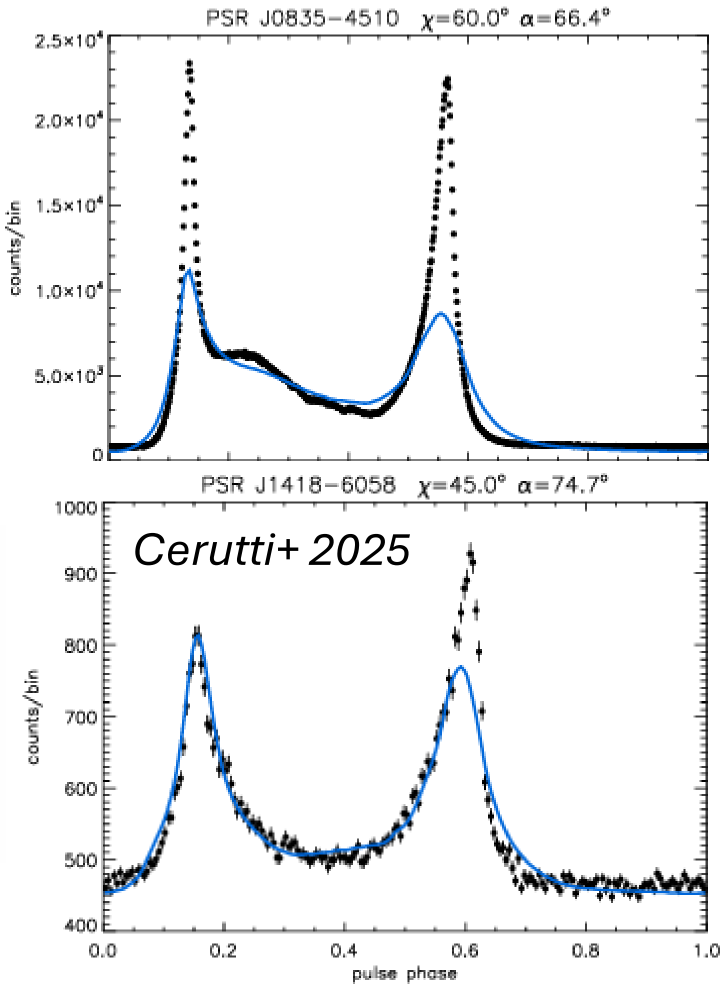
One gamma-ray synchrotron pulse each time line-of-sight crosses beam of energetic particles in the current sheet

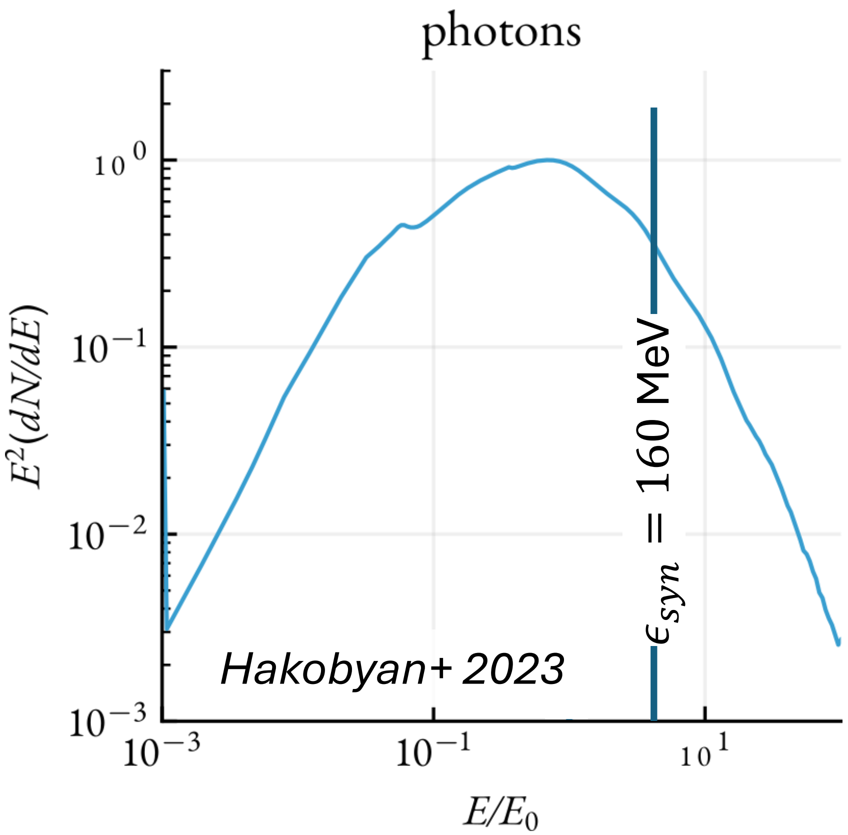
Gamma-rays can exceed 160-MeV ideal-MHD limit!

Cerutti+ 2016

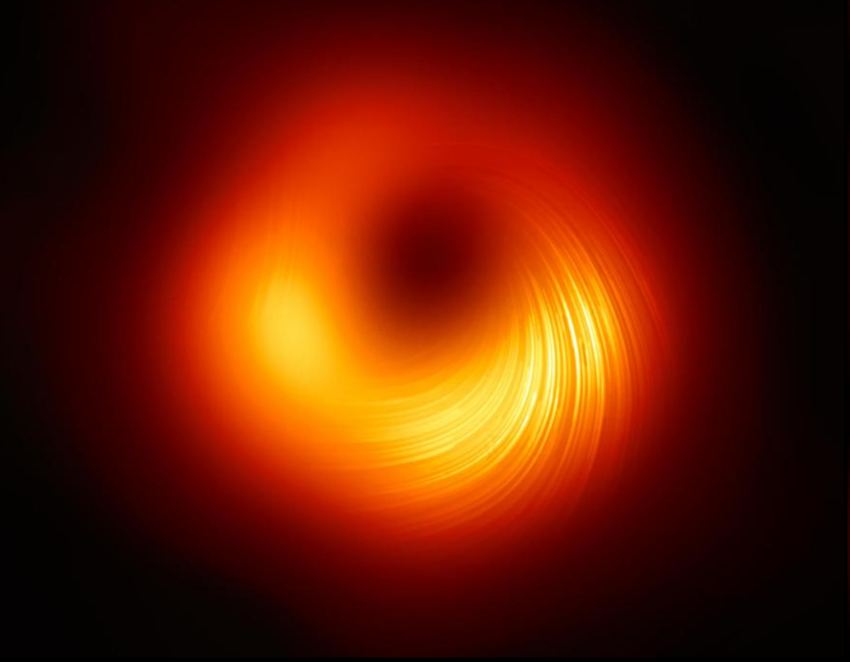


Recall kinetic beaming!

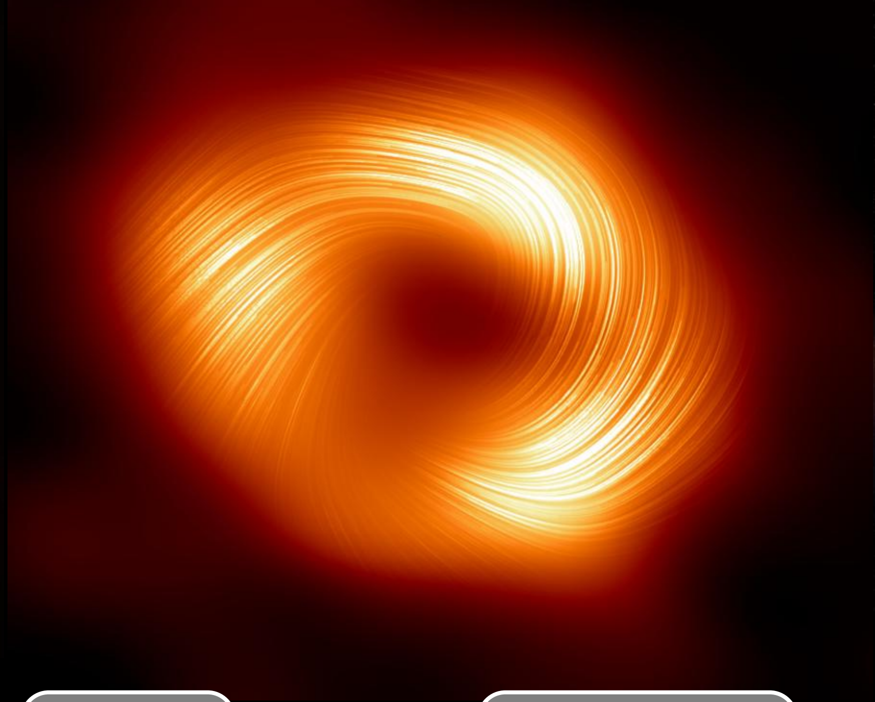




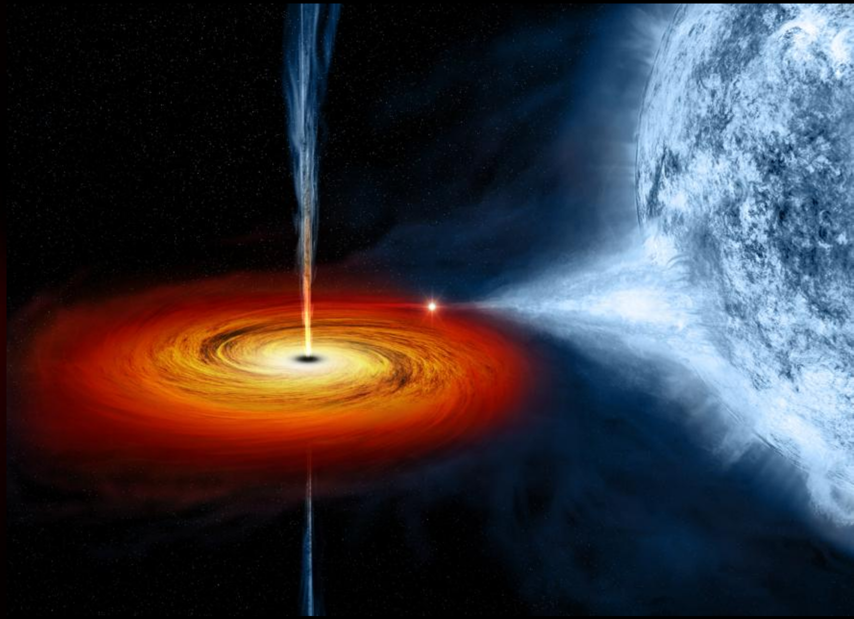
M87*
(EHT)



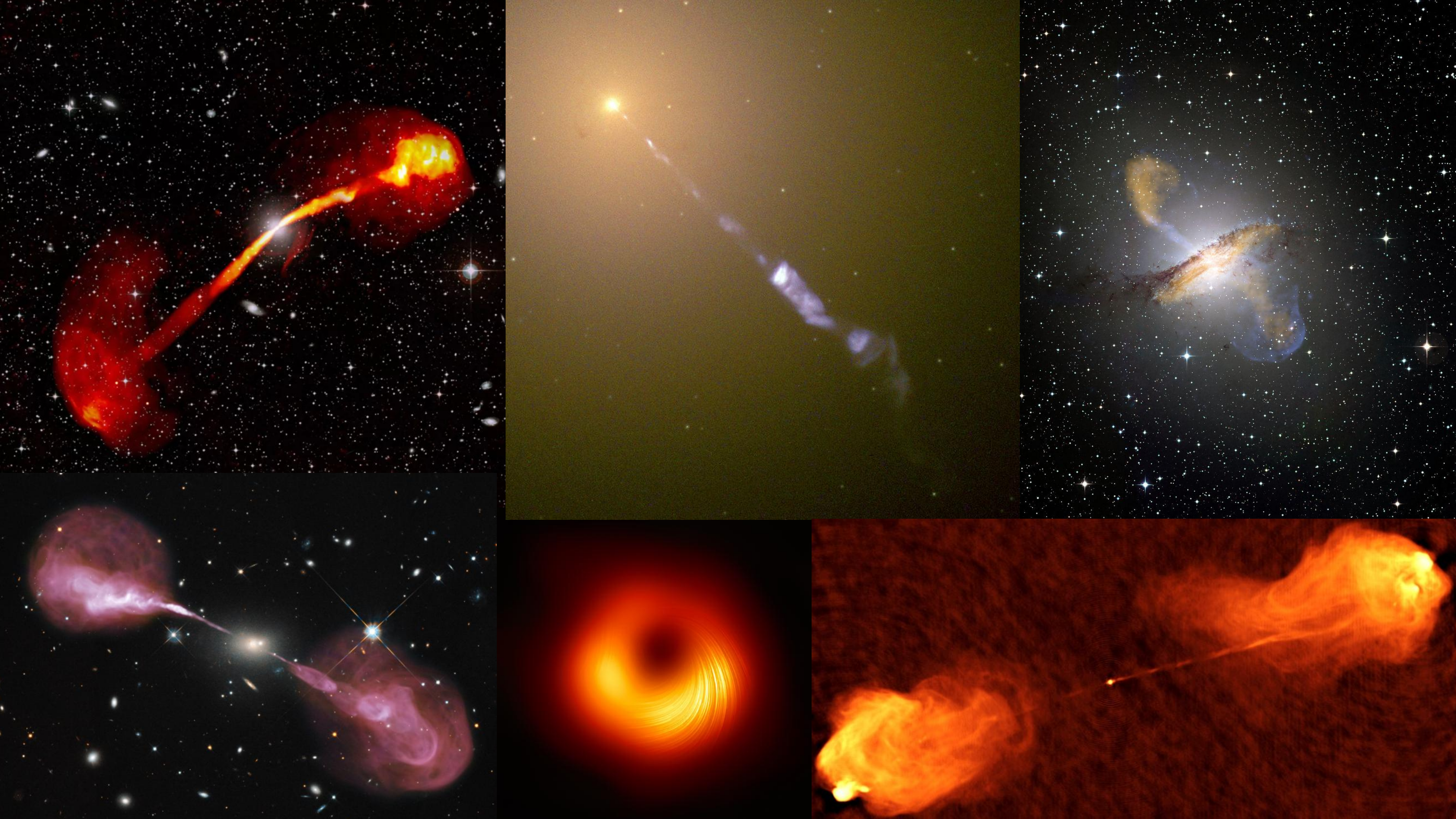
Sgr A*
(EHT)

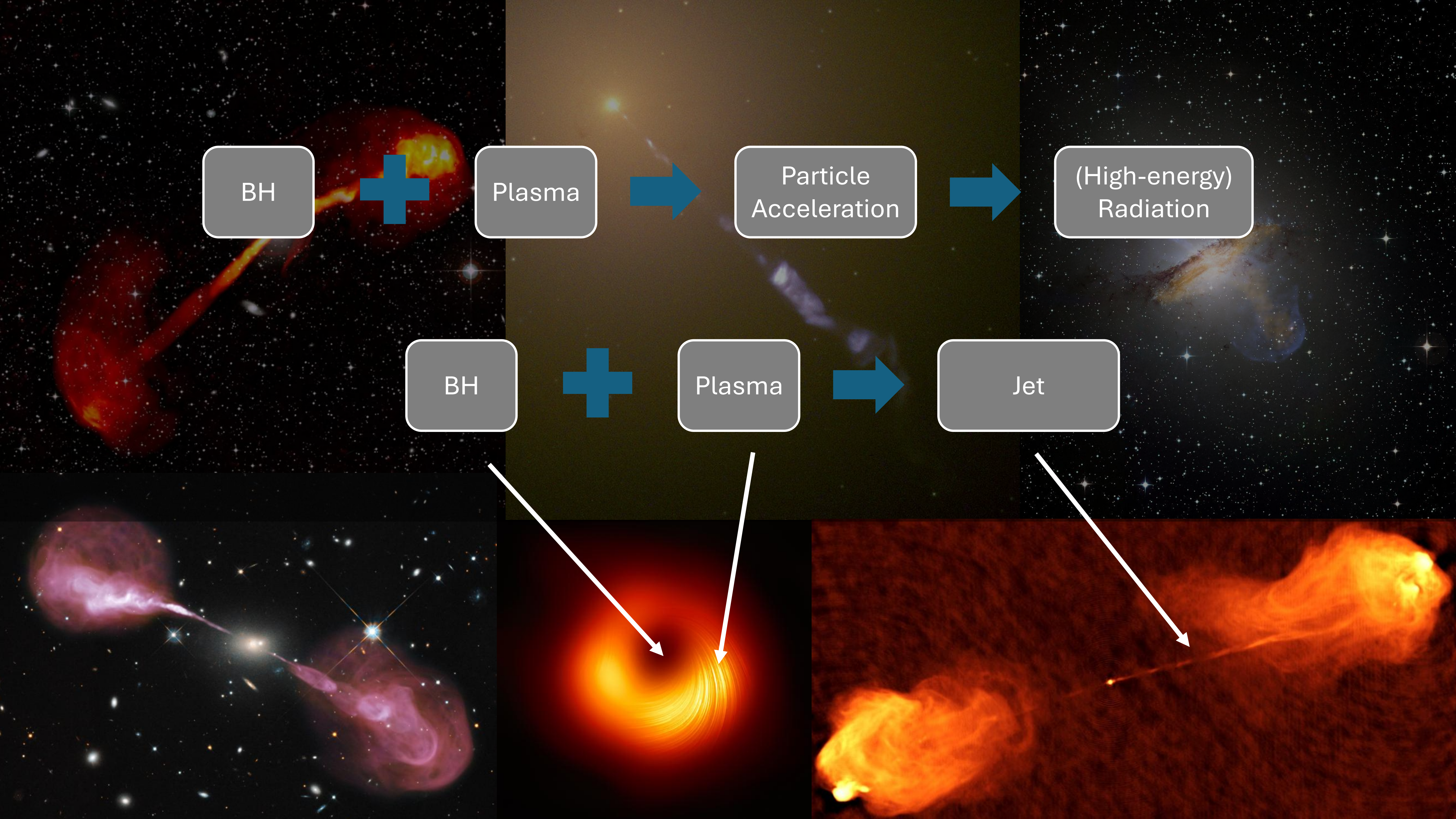


Cyg X-1
(artist’s impression; NASA)



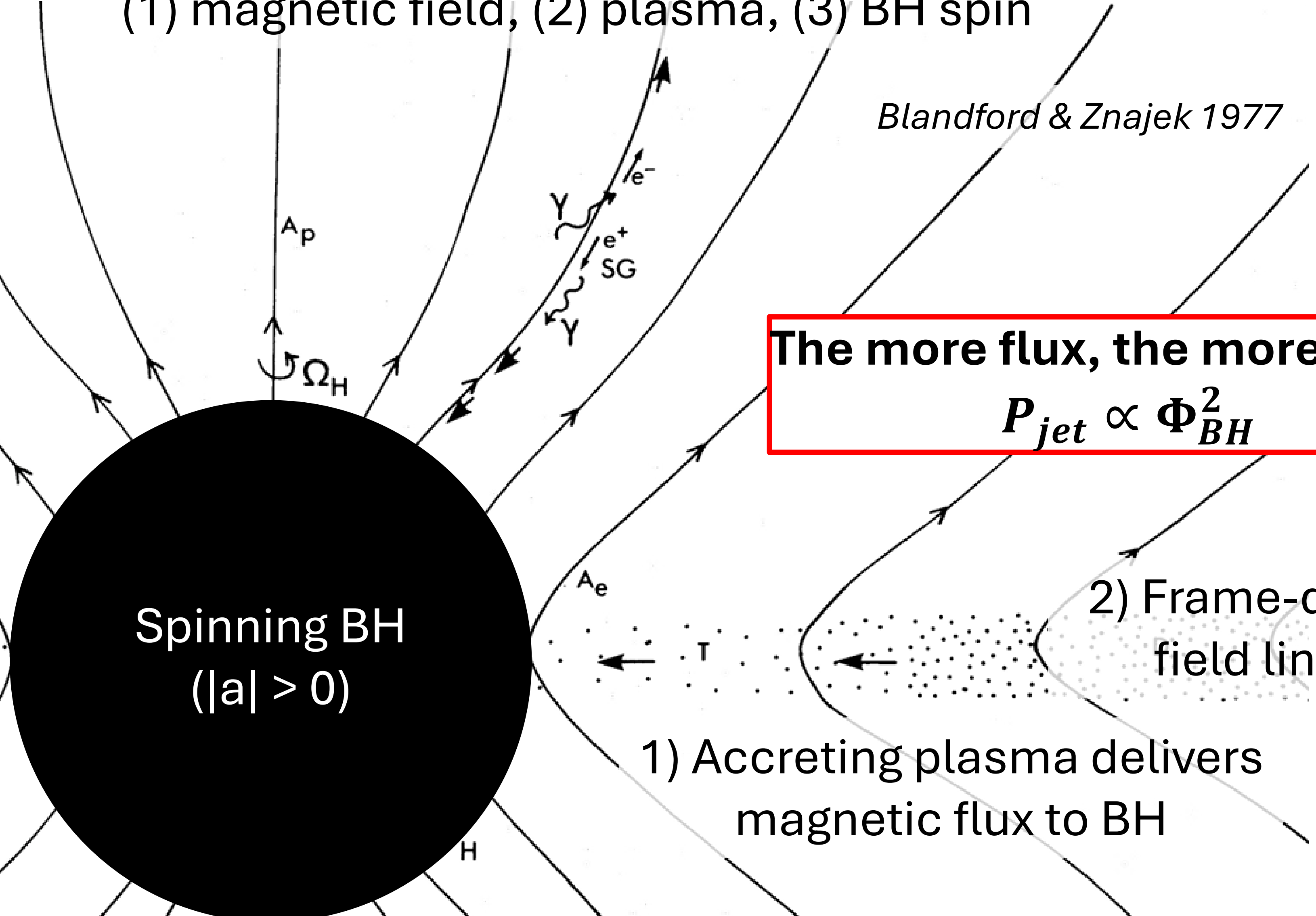
BH + Plasma → Particle Acceleration → (High-energy) Radiation




BH
Plasma
Particle Acceleration
(High-energy) Radiation
BH
Plasma
Jet

Primer: Blandford-Znajek jet-launch mechanism

Three ingredients:
(1) magnetic field, (2) plasma, (3) BH spin



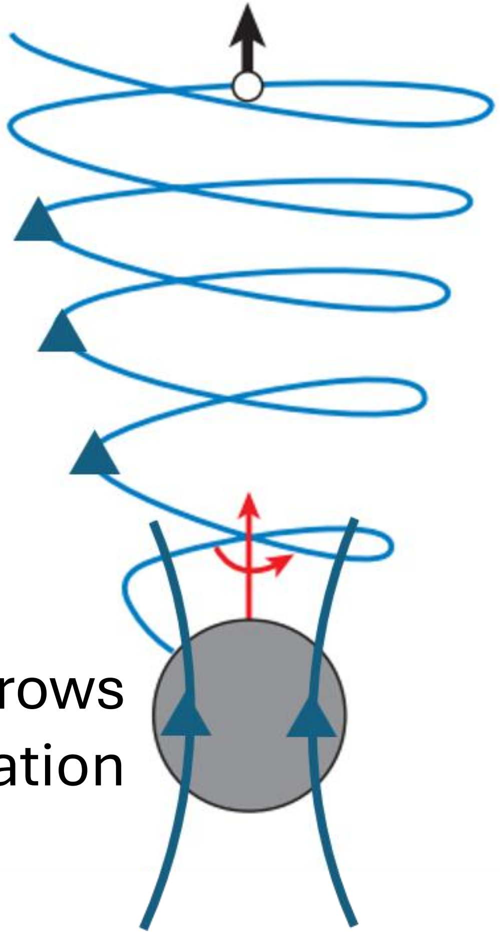
Blandford & Znajek 1977

The more flux, the more power
$$P_{jet} \propto \Phi_{BH}^2$$

1) Accreting plasma delivers magnetic flux to BH

2) Frame-dragging throws field lines into rotation

3) Magnetic helix forms, expands outwards as a relativistic force-free jet



Davis & Tchekhovskoy 2020

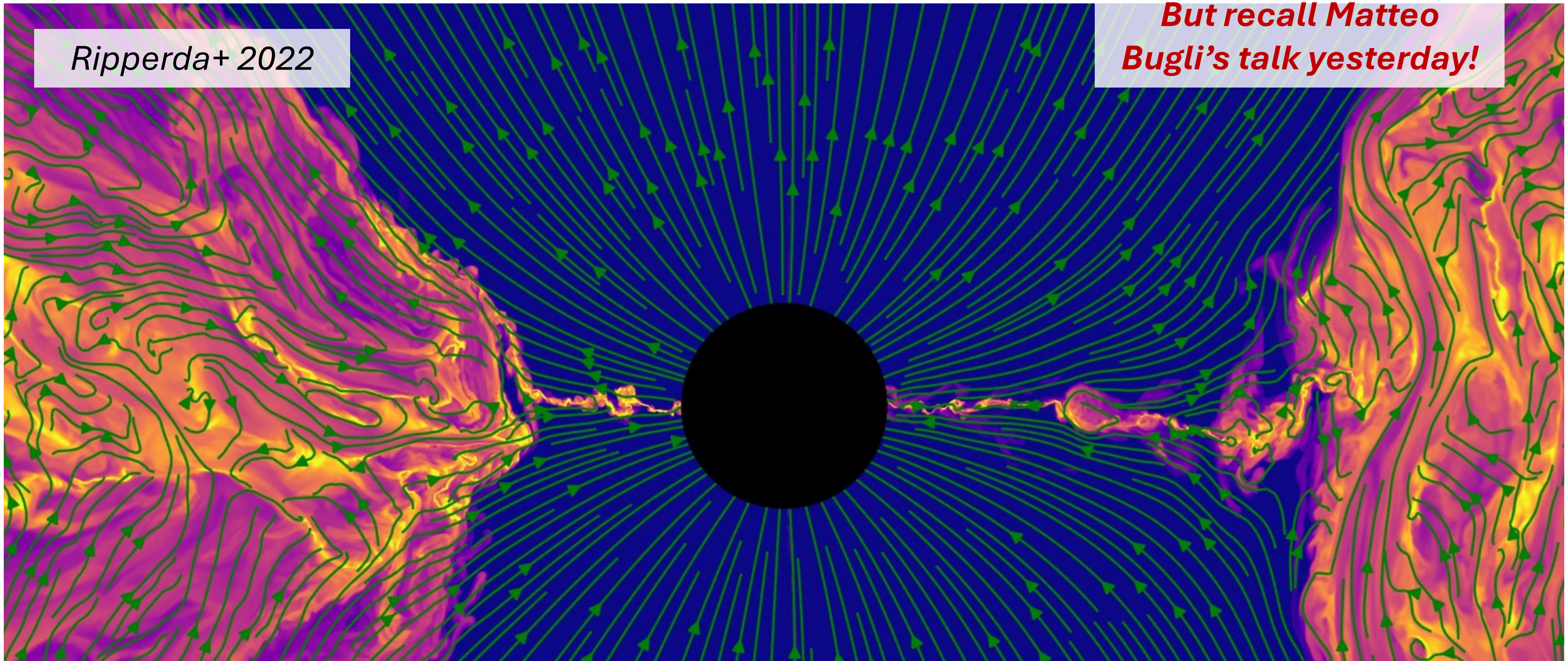
Reconnection throttles magnetic flux on BH, regulates jet power

Flux cannot accumulate indefinitely onto BH.

Magnetic reconnection triggers periodic flux eruptions, regulating jet power. ($P_{jet} \propto \Phi_{BH}^2$)

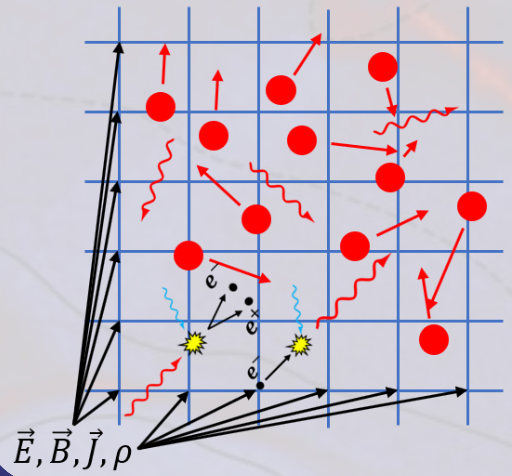
In MHD, $\beta_{rec,MHD} = 0.01$ is too low by a factor of 10.

Need kinetic simulations to accurately determine jet power!



GRPIC: a new* method built on a familiar architecture

($c = 1$ on this slide)



Based on the 3+1 formalism:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$
$$= (\beta_i \beta^i - \alpha^2) dt^2 + 2\beta_i dx^i dt + h_{ij} dx^i dx^j$$

α = "Lapse function"; β^i = "Shift vector"

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\vec{u}}{\Gamma}$$
$$\frac{d\vec{u}}{dt} = \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

⇓

$$\frac{dx^i}{dt} = \alpha \frac{h^{ij} u_j}{\Gamma} - \beta^i$$
$$\frac{du_i}{dt} = -\Gamma \partial_i \alpha + u_j \partial_i \beta^j - \frac{\alpha}{2\Gamma} u_j u_k \partial_i h^{jk} + \frac{q}{m} \alpha \left(h_{ij} D^j + e_{ijk} \frac{h^{jl} u_l}{\Gamma} B^k \right)$$

Preserves structure of classic explicit PIC algorithm

Update (x^i, u_i) of all particles and photons from $\vec{D}, \vec{B}$

QED step: Emit photons and produce pairs

Compute ρ and J_i on grid from $(x^i, v^i = dx^i/dt)$ of particles

Calculate $\vec{E}, \vec{H}$; $(\rho, J_i) \rightarrow$ Maxwell's equations $\rightarrow (\vec{D}, \vec{B})$

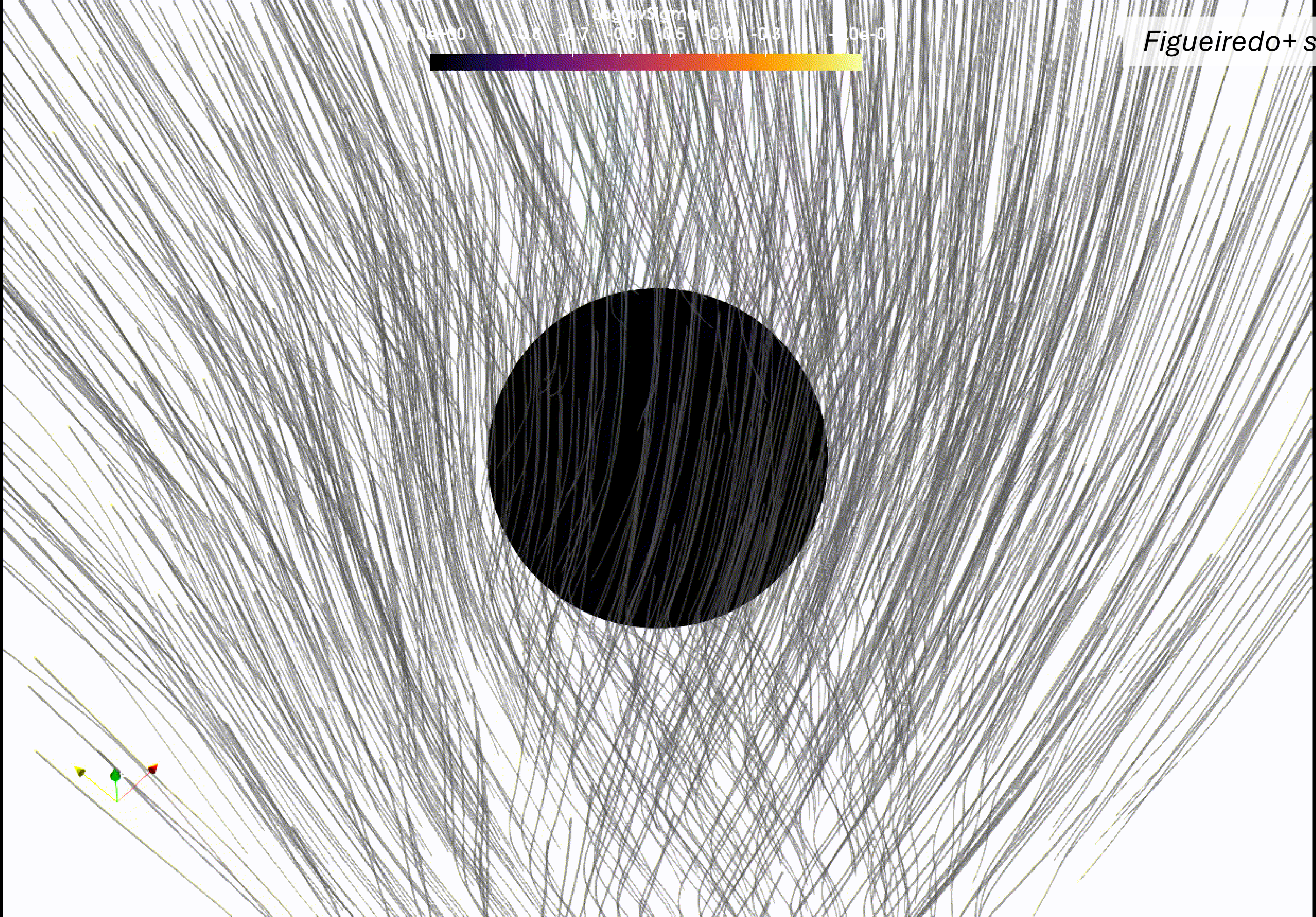
Δt

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho$$
$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\partial_t \vec{B} = -\vec{\nabla} \times \vec{E}$$
$$\partial_t \vec{E} = \vec{\nabla} \times \vec{B} - 4\pi \vec{J}$$

⇒

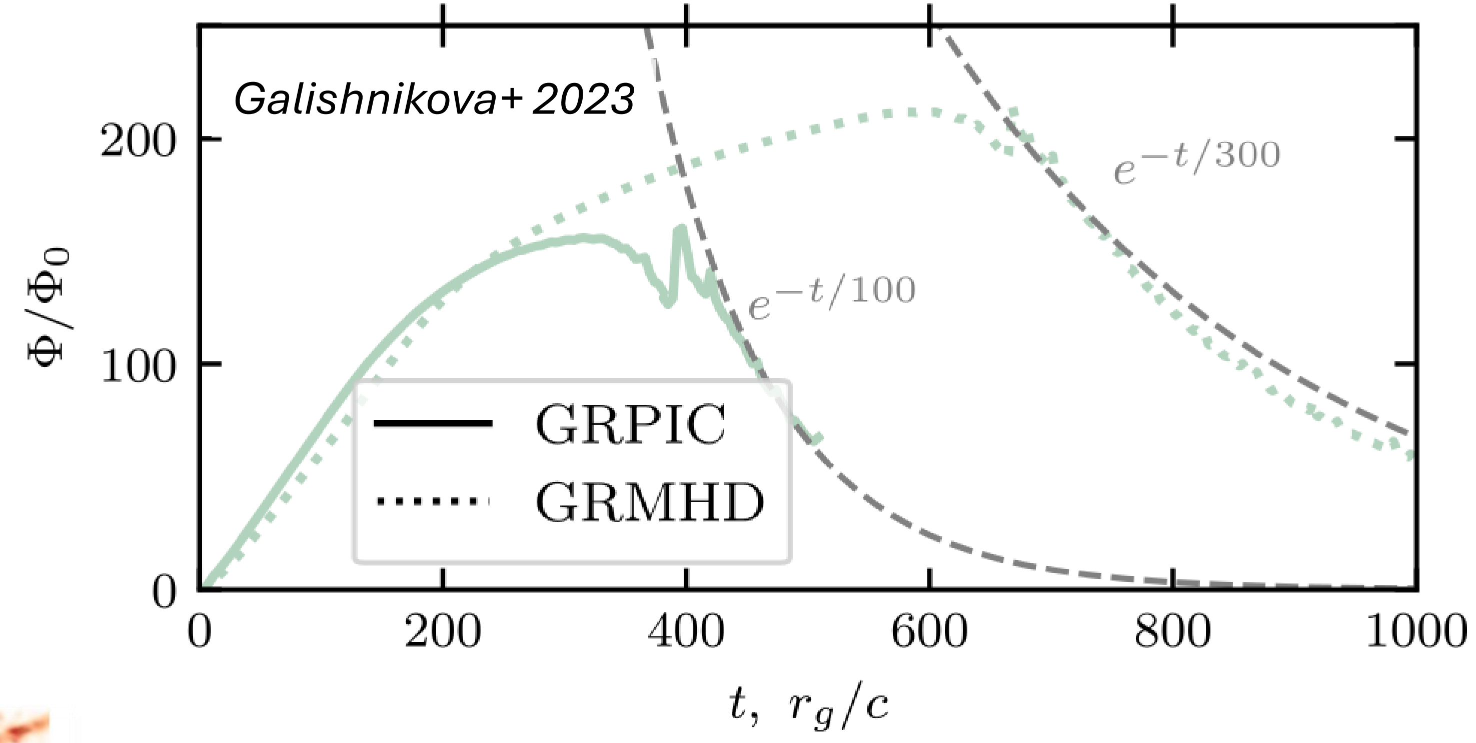
$$\vec{\nabla} \cdot \vec{D} = 4\pi\rho$$
$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\partial_t \vec{B} = -\vec{\nabla} \times \vec{E}$$
$$\partial_t \vec{D} = \vec{\nabla} \times \vec{H} - 4\pi \vec{J}$$
$$\vec{E} = \alpha \vec{D} + \vec{\beta} \times \vec{B}$$
$$\vec{H} = \alpha \vec{B} - \vec{\beta} \times \vec{D}$$

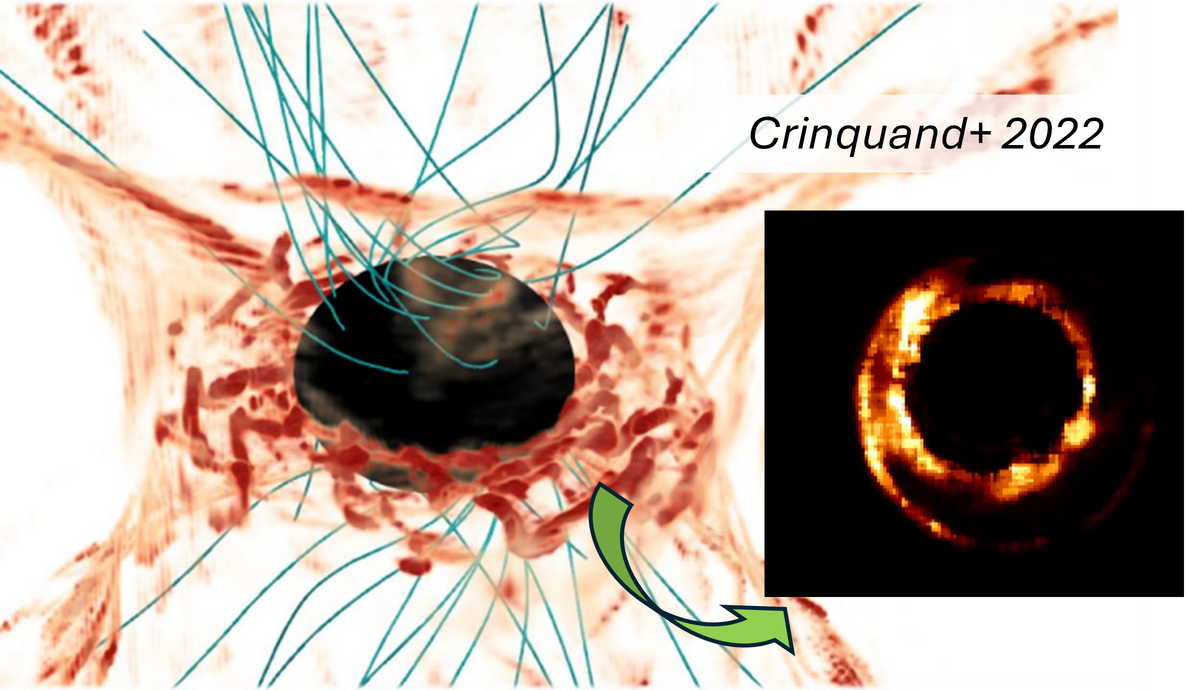
*Parfrey+ 2019, Chen+ 2025



Figueiredo+ submitted

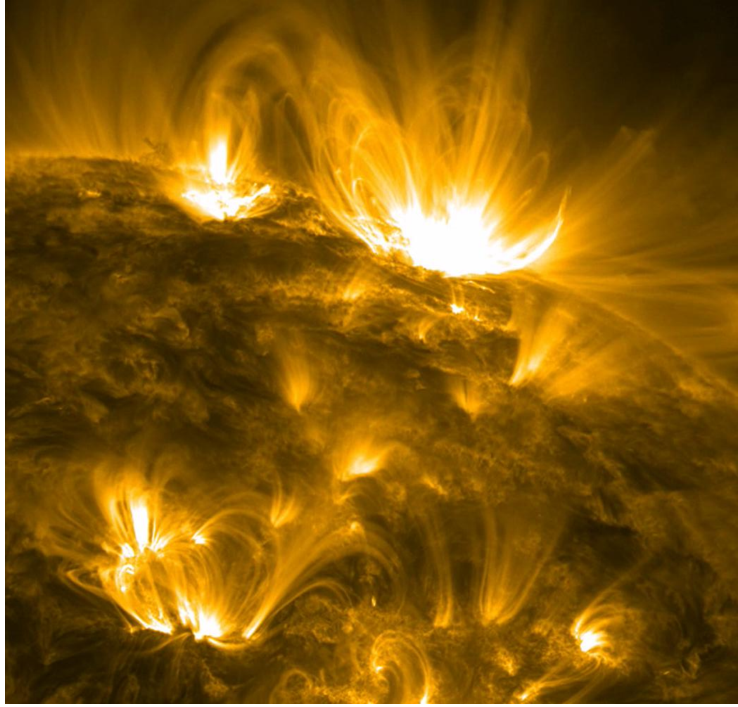
BH acquires less flux when modeled using PIC → weaker jet



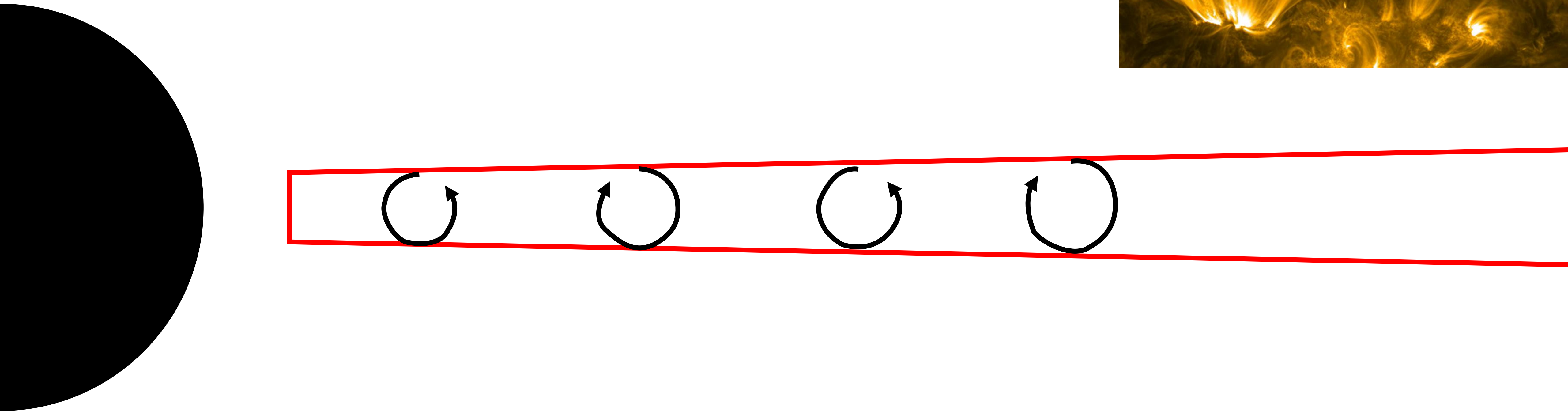


Simulations with pair production: vigorous reconnection helps supply magnetospheric plasma and powers bright synchrotron emission

Accretion disk coronae as high-energy analogs to the solar corona

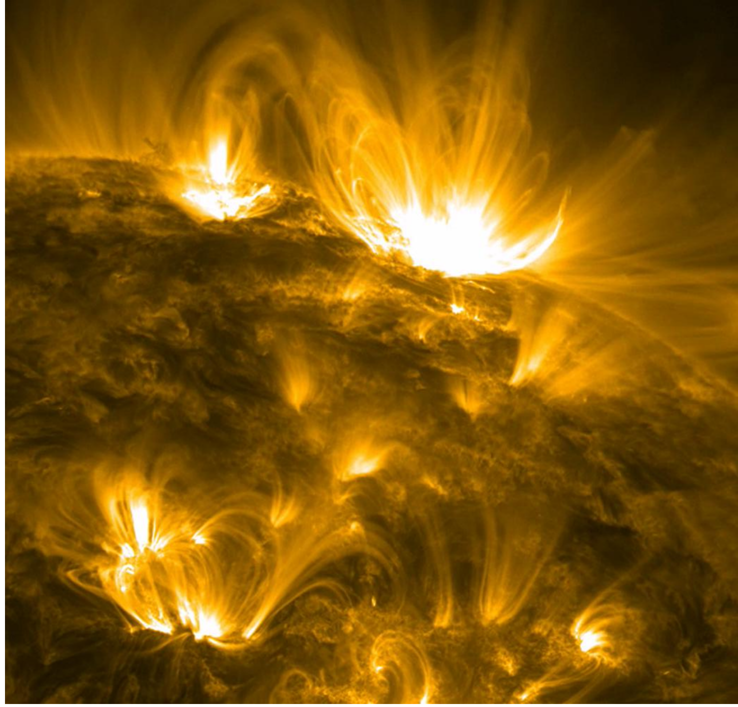


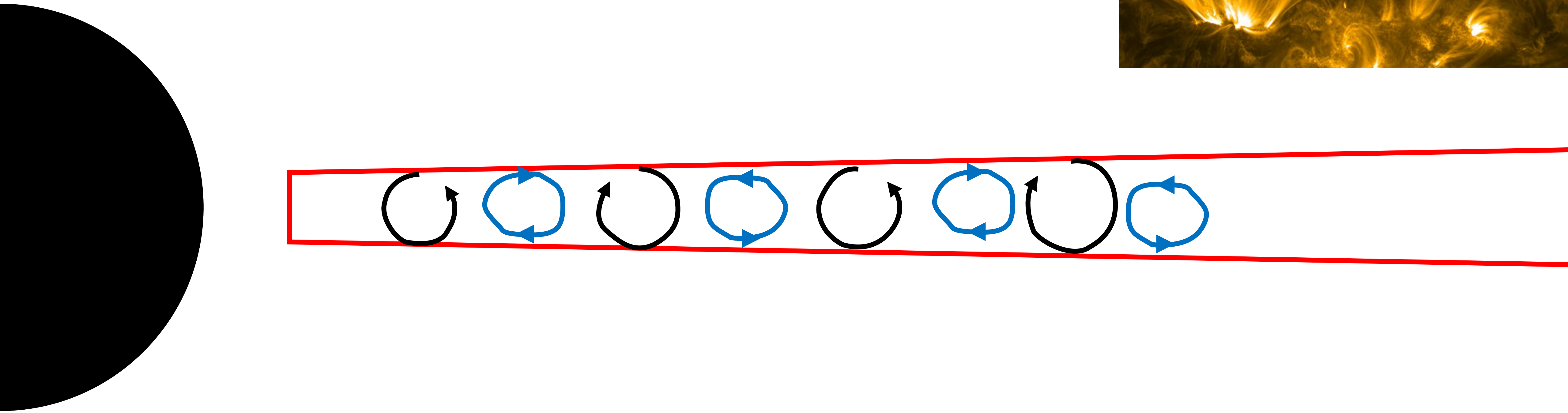
(See, e.g., Shakura & Sunyaev 1973, Liang & Price 1977, Galeev et al. 1979)



Accretion disk coronae as high-energy analogs to the solar corona

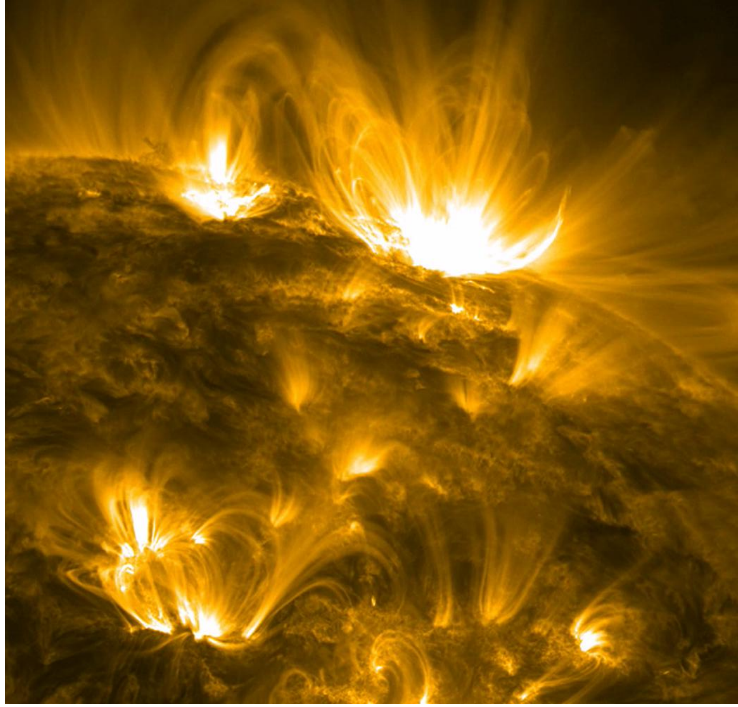
See, e.g., Shakura & Sunyaev 1973, Liang & Price 1977, Galeev et al. 1979

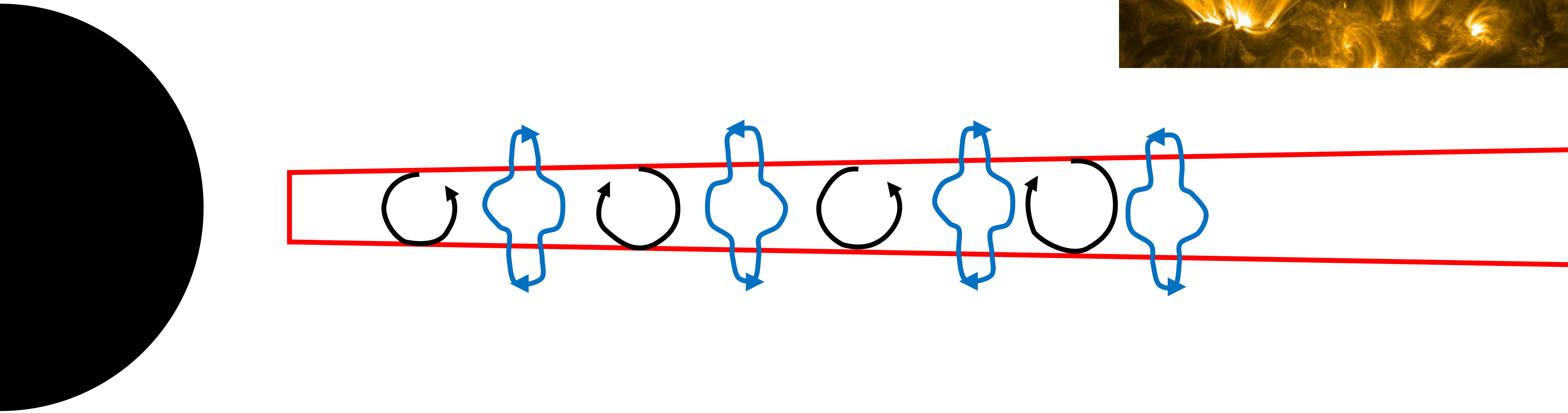




Accretion disk coronae as high-energy analogs to the solar corona

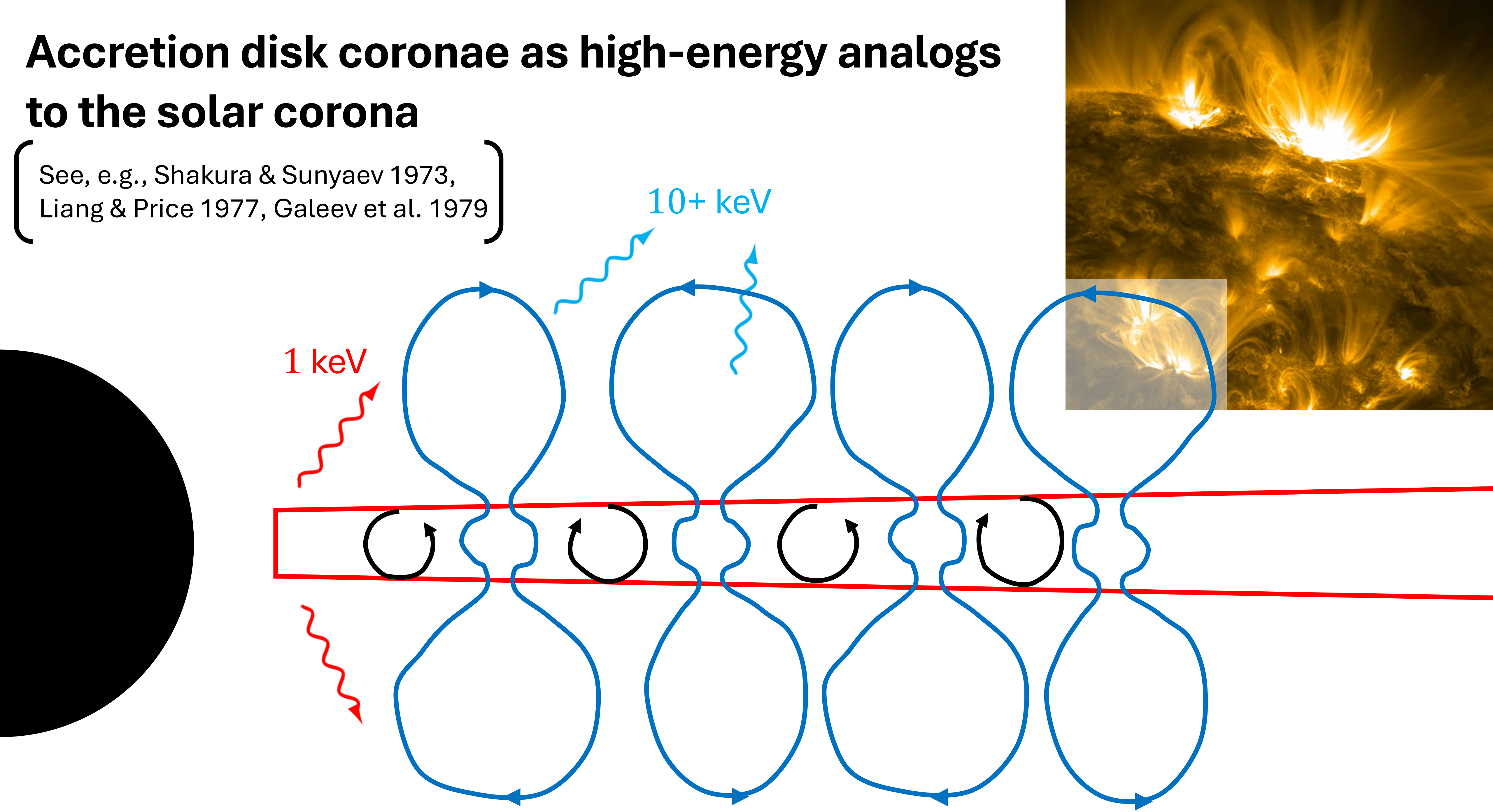
See, e.g., Shakura & Sunyaev 1973, Liang & Price 1977, Galeev et al. 1979



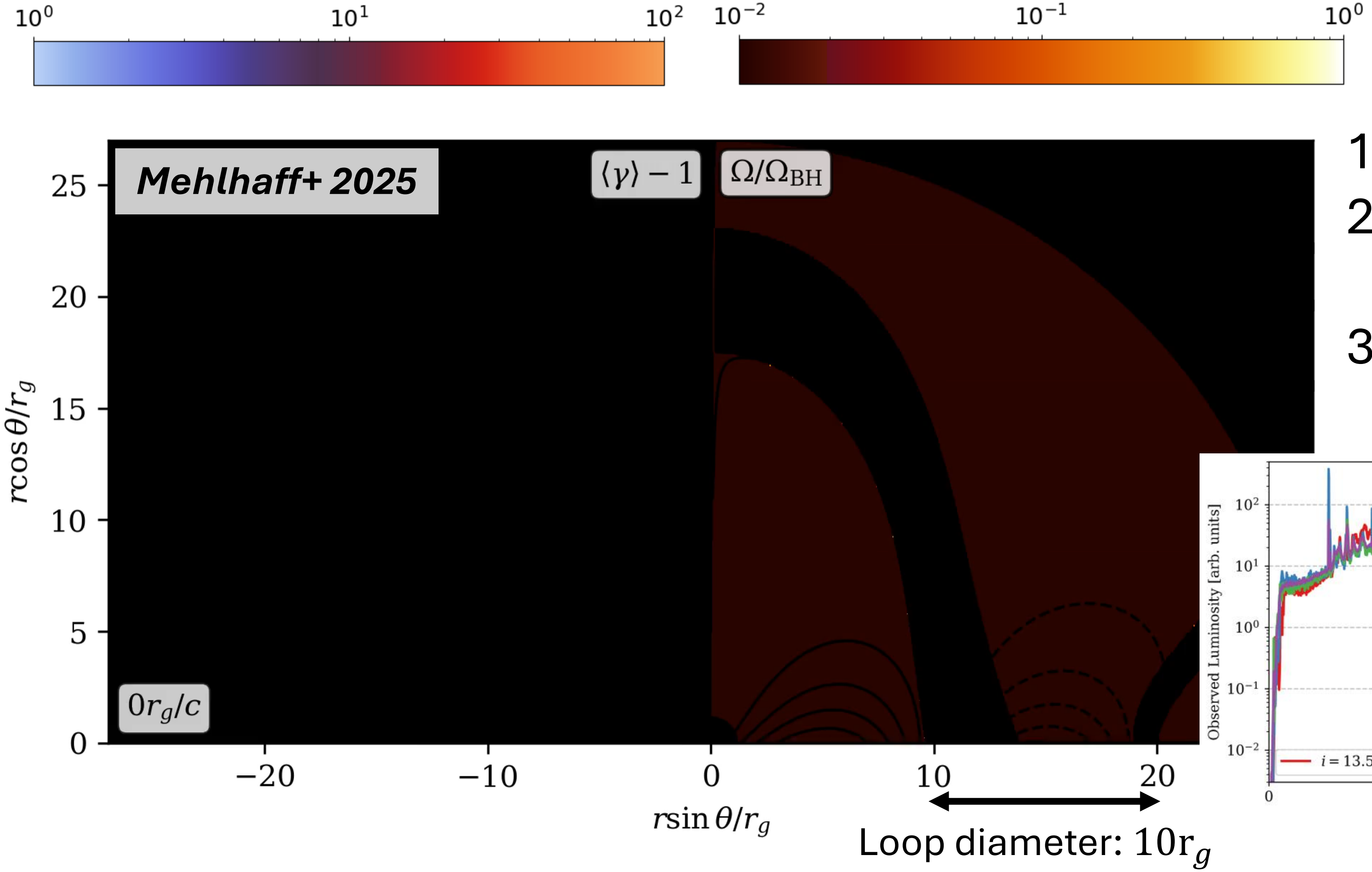


Accretion disk coronae as high-energy analogs to the solar corona

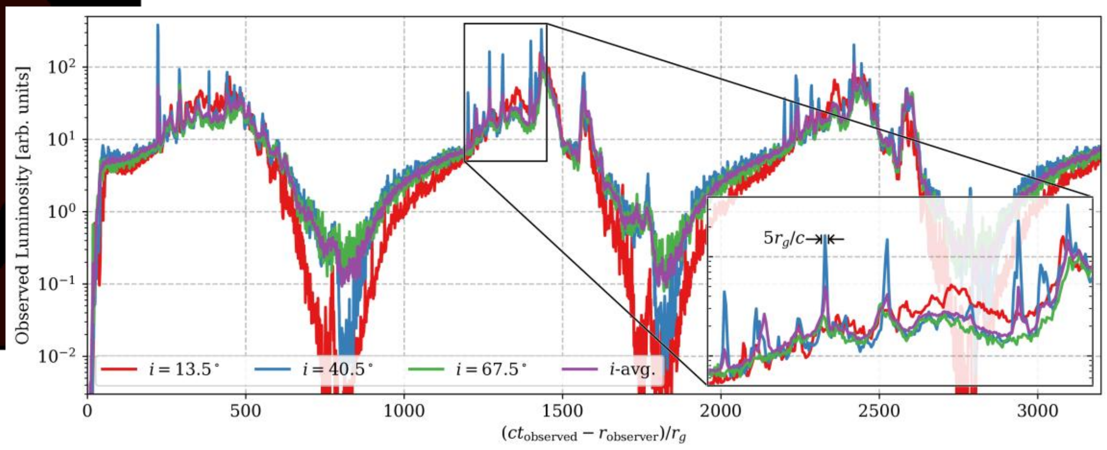
See, e.g., Shakura & Sunyaev 1973, Liang & Price 1977, Galeev et al. 1979



Reconnection couples jet power to coronal X-ray emission



1. Most dissipation on jet wall
2. Magnetic reconnection feeds on/whittles down jet
3. Jet waning/extinction correlated with X-ray flaring

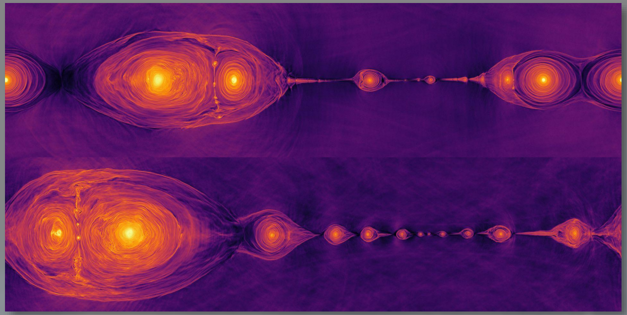


Can calculate:

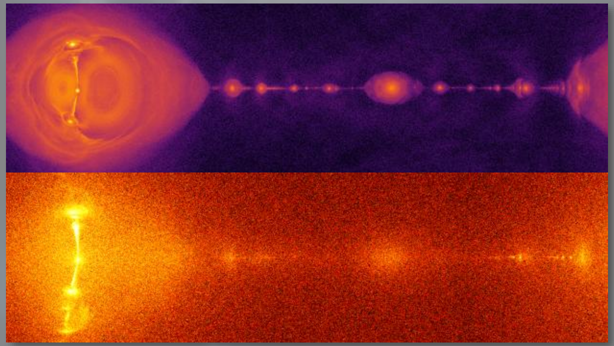
- How much energy magnetic reconnection dissipates and where
- Jet power
- Observable signatures

Outline

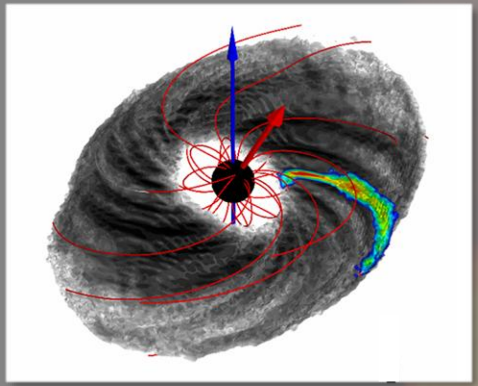
Highlights from two decades of local simulations



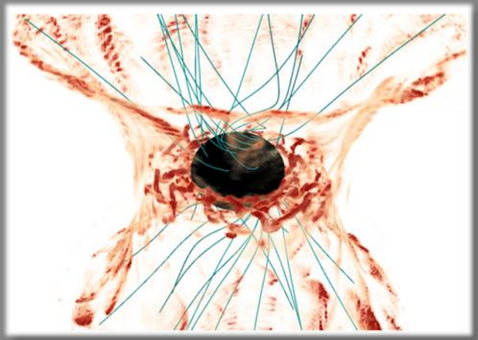
The radiative frontier



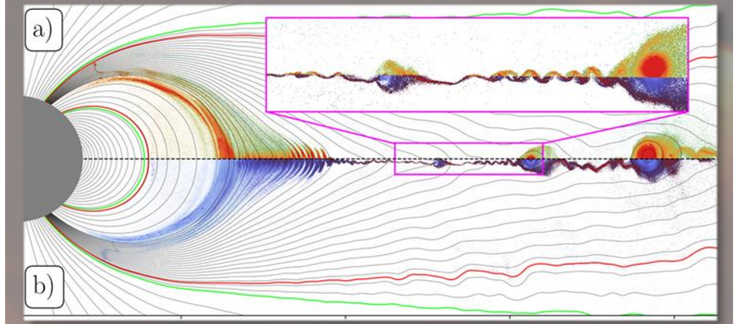
Highlights from one decade of global simulations



The gravitational frontier



A bright future

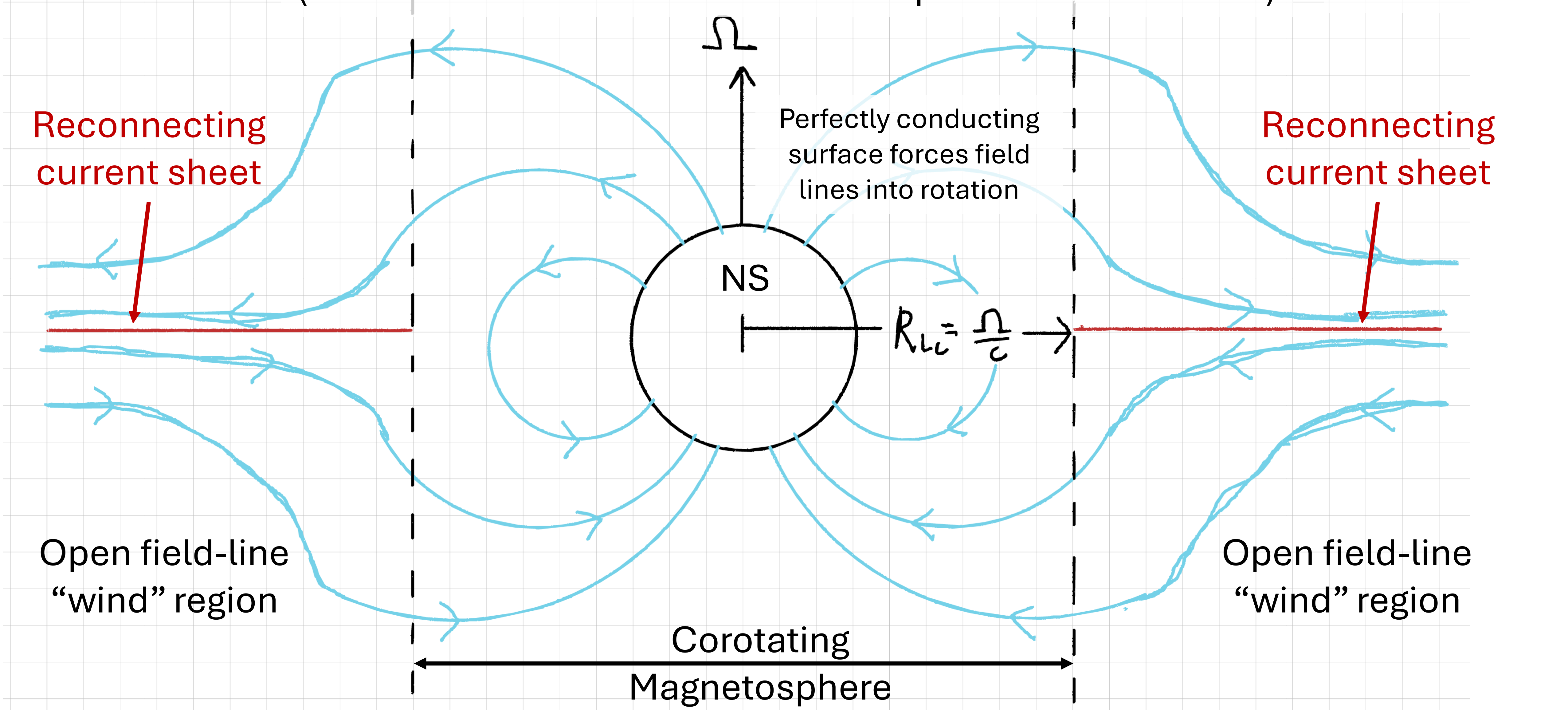


Prospects: hybrid methods to better focus numerical resources

Do we really need PIC to model all of this?

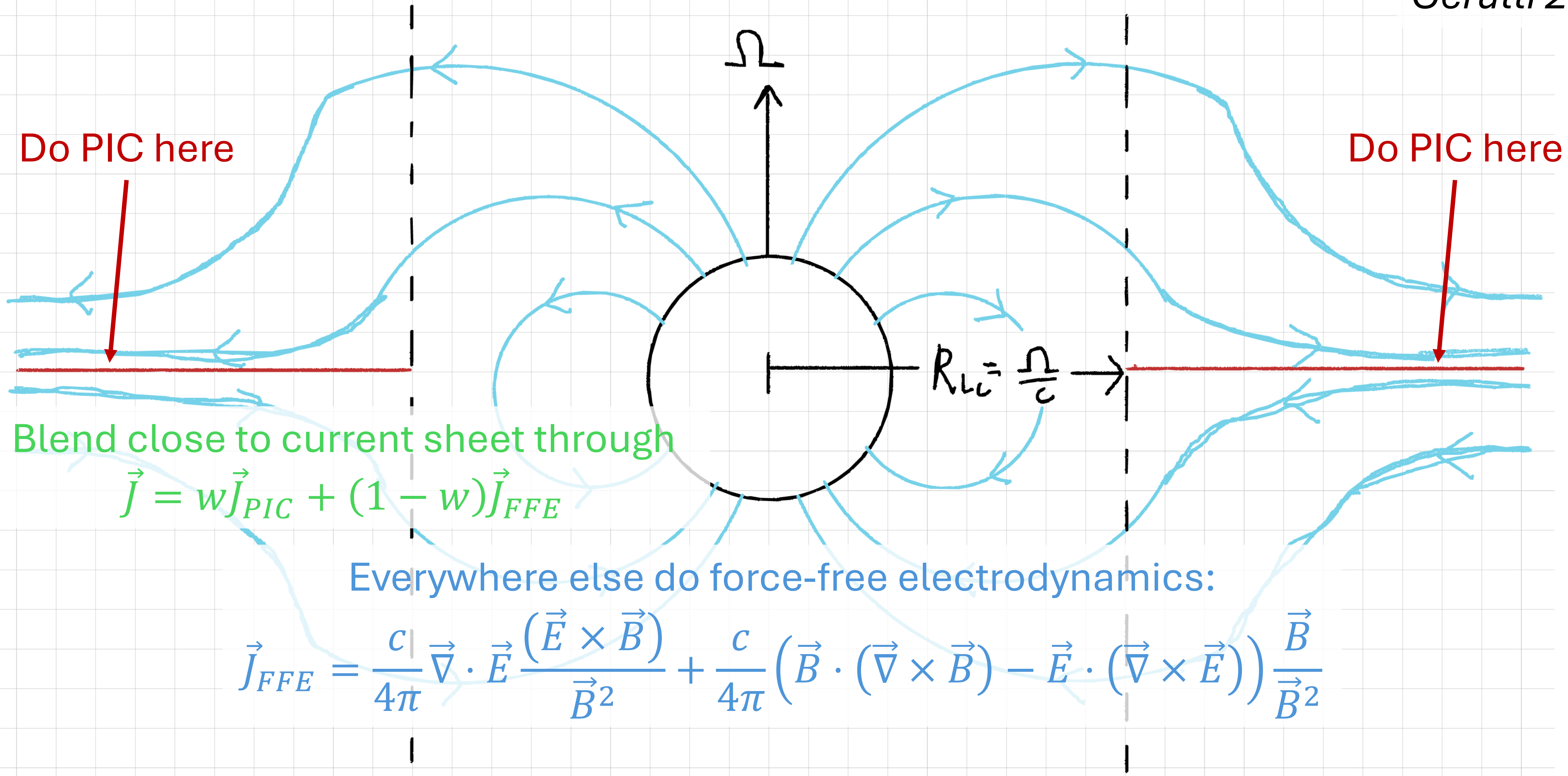
(The whole domain is force-free except the current sheets)

Soudais & Cerutti 2024



Force-free/PIC hybrid: a whole magnetosphere for the price of the current sheet

Soudais & Cerutti 2024



Blend close to current sheet through

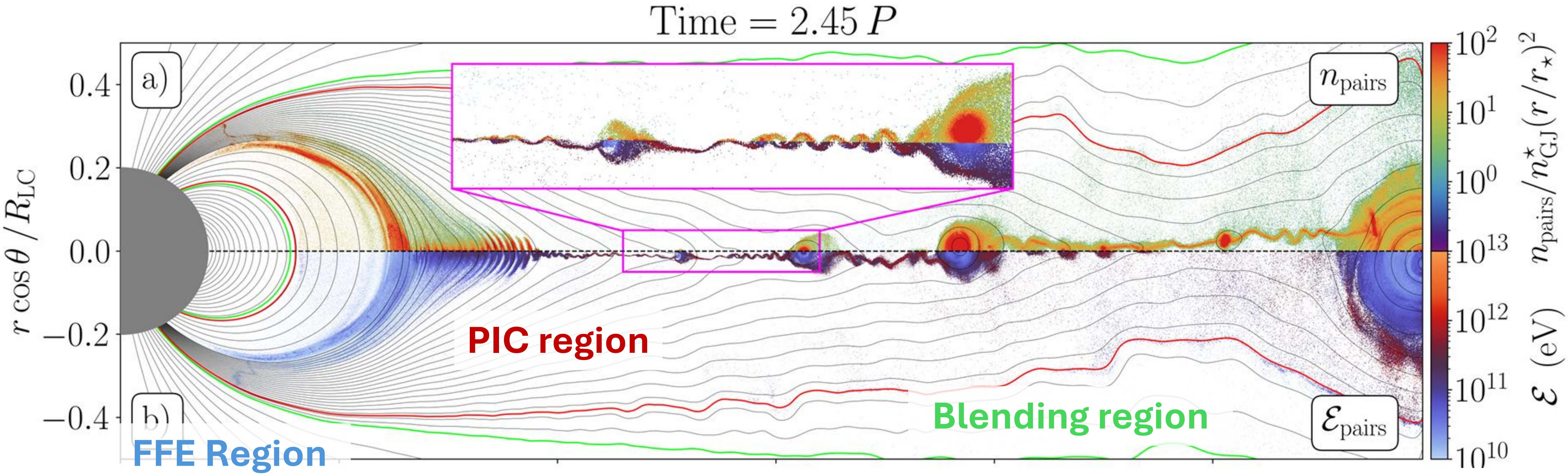
$$\vec{J} = w\vec{J}_{PIC} + (1-w)\vec{J}_{FFE}$$

Everywhere else do force-free electrodynamics:

$$\vec{J}_{FFE} = \frac{c}{4\pi}\vec{\nabla}\cdot\vec{E}\,\frac{(\vec{E}\times\vec{B})}{\vec{B}^2} + \frac{c}{4\pi}\left(\vec{B}\cdot(\vec{\nabla}\times\vec{B}) - \vec{E}\cdot(\vec{\nabla}\times\vec{E})\right)\frac{\vec{B}}{\vec{B}^2}$$

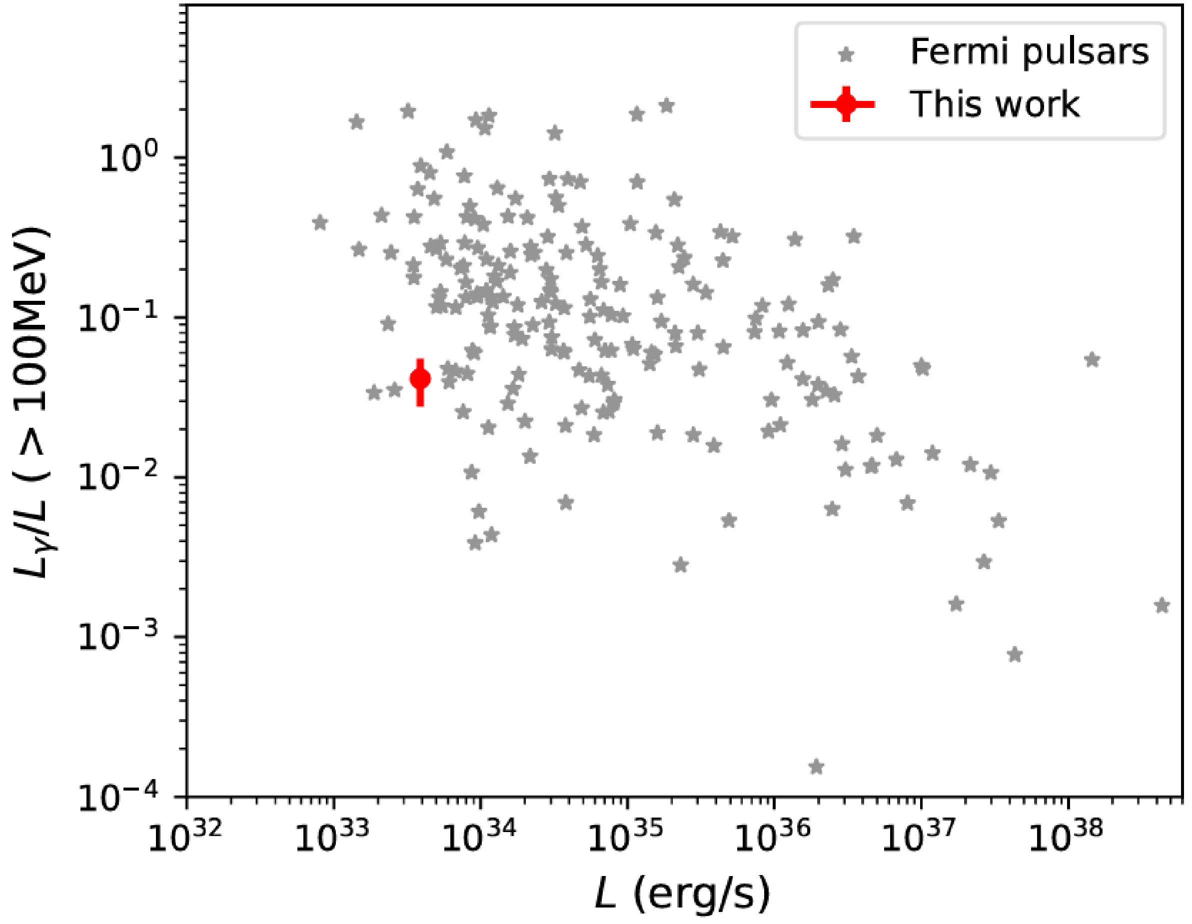
Force-free/PIC hybrid: a whole magnetosphere for the price of the current sheet

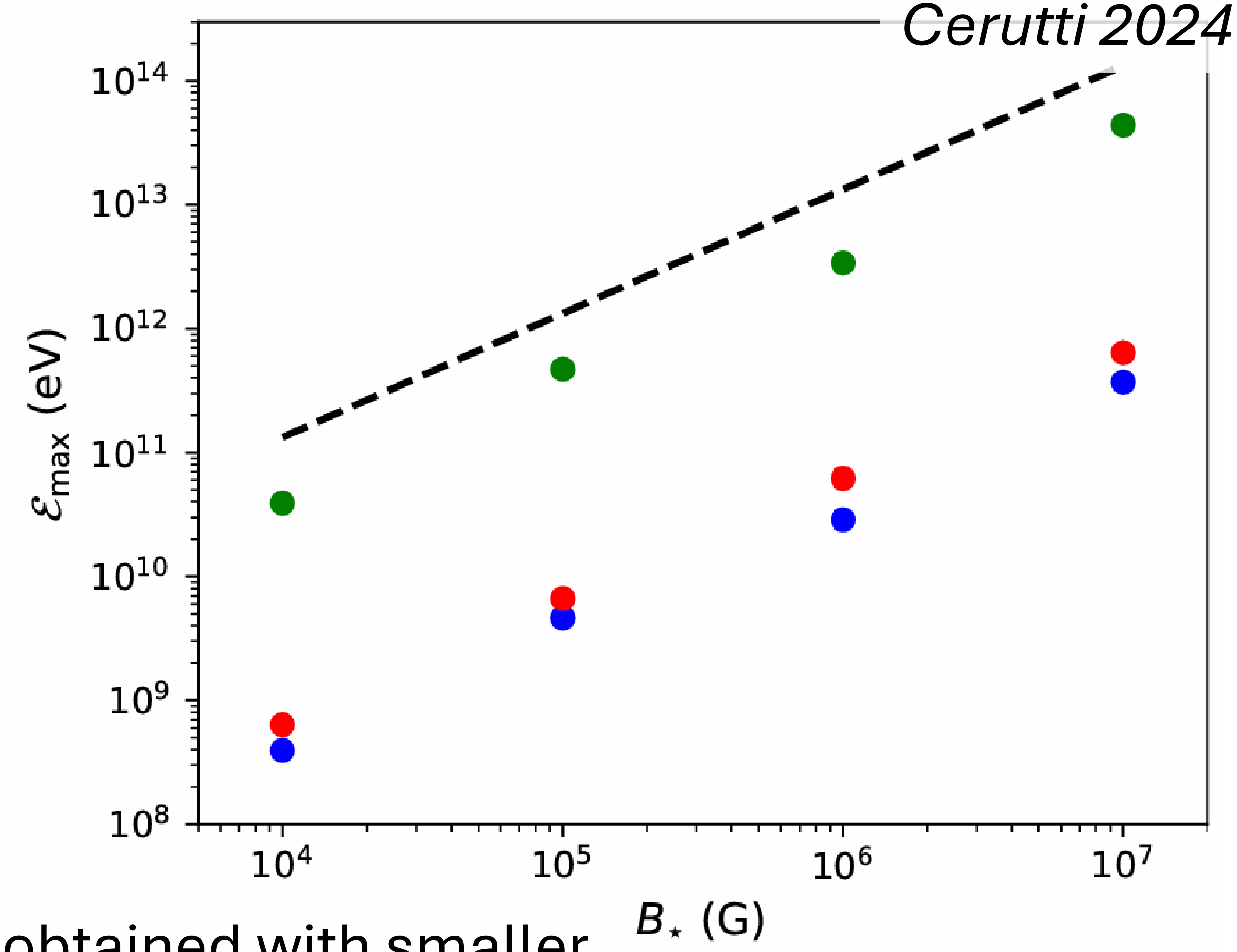
Soudais & Cerutti 2024



Force-free/PIC hybrid: a real *Fermi* pulsar

Soudais & Cerutti 2024

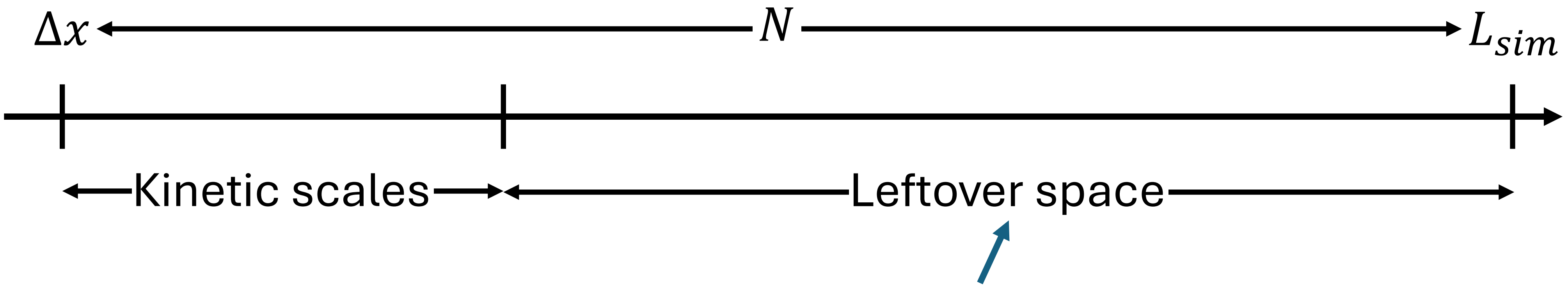




Plus a systematic verification that PIC results obtained with smaller simulations do indeed scale up as expected to ***real*** system sizes

But problem-dependent.
Lots of trial-and-error.

Prospects: the GPU revolution and multiscale PIC simulations



Need to fit all intermediate scales (e.g., BH/NS radius, photon mean-free-path, particle cooling length, etc.) in here

Crudely, on CPUs, state-of-the-art is $N = 10^4$ in 2D or $N = 10^3$ in 3D

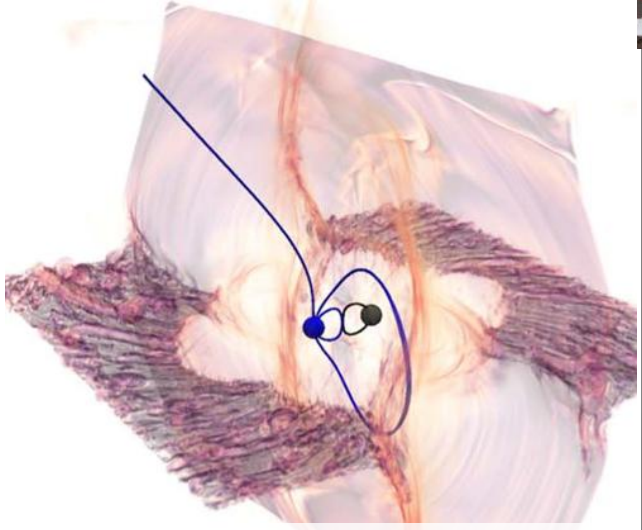
Often enough for 2 intermediate scales in 2D, or 1 in 3D: both with little remaining wiggle room for parameter scans

GPUs could open up today's maximum box size to tomorrow's parameter scans

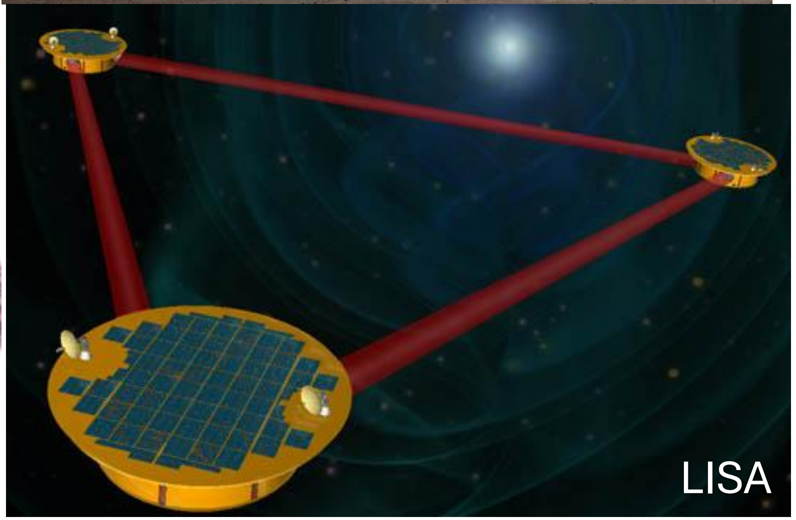
Tomorrow's maximum size may allow one extra intermediate scale in each dimension

Prospects: new discoveries are certain thanks to next-generation observatories coming online in the near-to-long term

- Pointed instruments provide enhance sensitivity in energy space (CTAO), time (ngEHT) and spatial resolution (ELT)
- Survey instruments (Vera Rubin, NewAthena) will capture transients; strong synergy with upcoming gravitational wave observatories (LISA)



Mahlmann & Beloborodov 2025

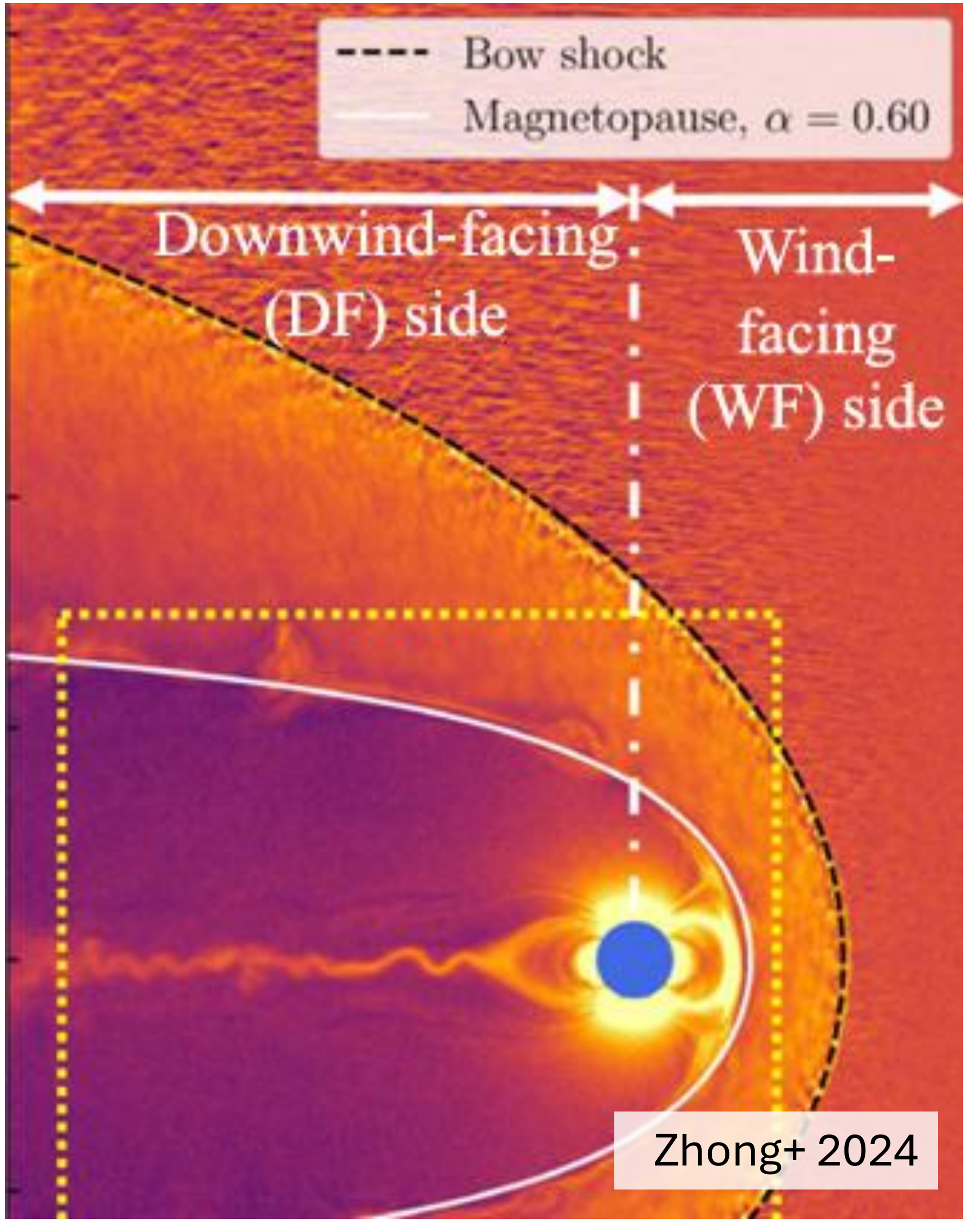


Prospects: strengthened ties to solar and space physics communities?

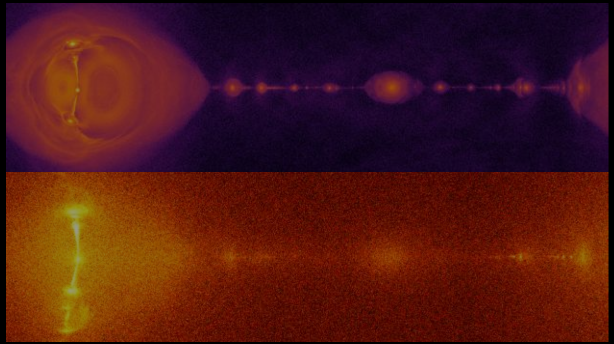
Historically, high-energy astrophysics has stolen from solar and space physics, but it's hard to know what we've missed.

What about the other way?

Could global kinetic models of high-energy sources build useful intuition for lower-energy objects (e.g., planetary bow shocks), even if, there, the simplifications $m_i = m_e$ and $u_A = c$ don't apply?



Conclusions



- Local simulations show that magnetic reconnection:
  - Dissipates energy efficiently
  - Powers nonthermal particle acceleration
  - Produces rapid variability
  - Radiates profusely at high energies
- Global simulations highlight how reconnection regulates key aspects of NS/BH magnetospheres:
  - Energy budget
  - Observable signatures
  - Inflow and outflow
- Strong observational synergy with guarantee of new discoveries to come

Thank you!