Physics of Stellar Remnants Activity

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Stellar remnants are not dead (even in isolation!)

The power of compact objects:

$$\Phi \sim c^2$$

X-ray binaries

AGN

ULXs

Pulsars

Magnetars

Mergers

GRBs

SN

Energy release in compact objects:

gravity -> differential rotation -> magnetic fields -> jets
-> accelerated particles, radiation (radio to gamma)

$B^2/8\pi$ can exceed ρc^2 in the emission region

Observed phenomena are powered by conversion of macroscopic (kinetic, magnetic) energy to heat, accelerated particles, radiation

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Mechanisms:

$\left\{ \begin{array}{l} \textbf{I.}\ \text{Magnetic reconnection} \\ \textbf{II.}\ \text{Shocks} \\ \textbf{III.}\ \text{Electric discharge} \\ \textbf{IV.}\ \text{Turbulence/wave damping} \end{array} \right.$

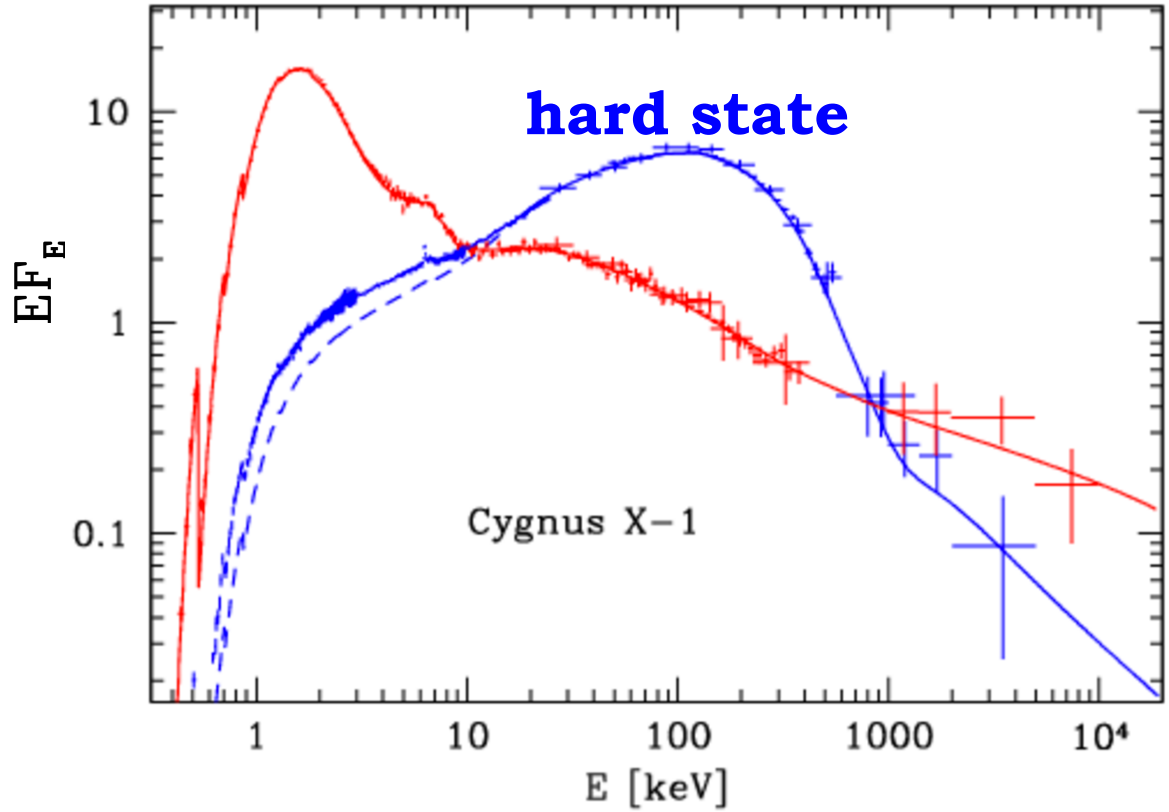
I. Magnetic reconnection

– Magnetic flares near accreting black holes

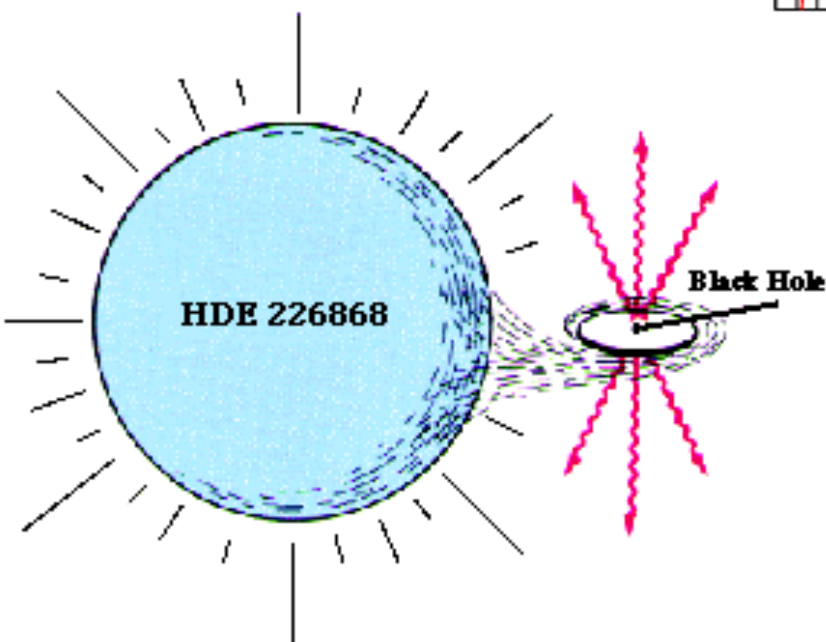
– Flares in magnetars (fireballs)

– Reconnection in pulsar winds and BH jets (Crab Nebula, blazars, GRBs…)

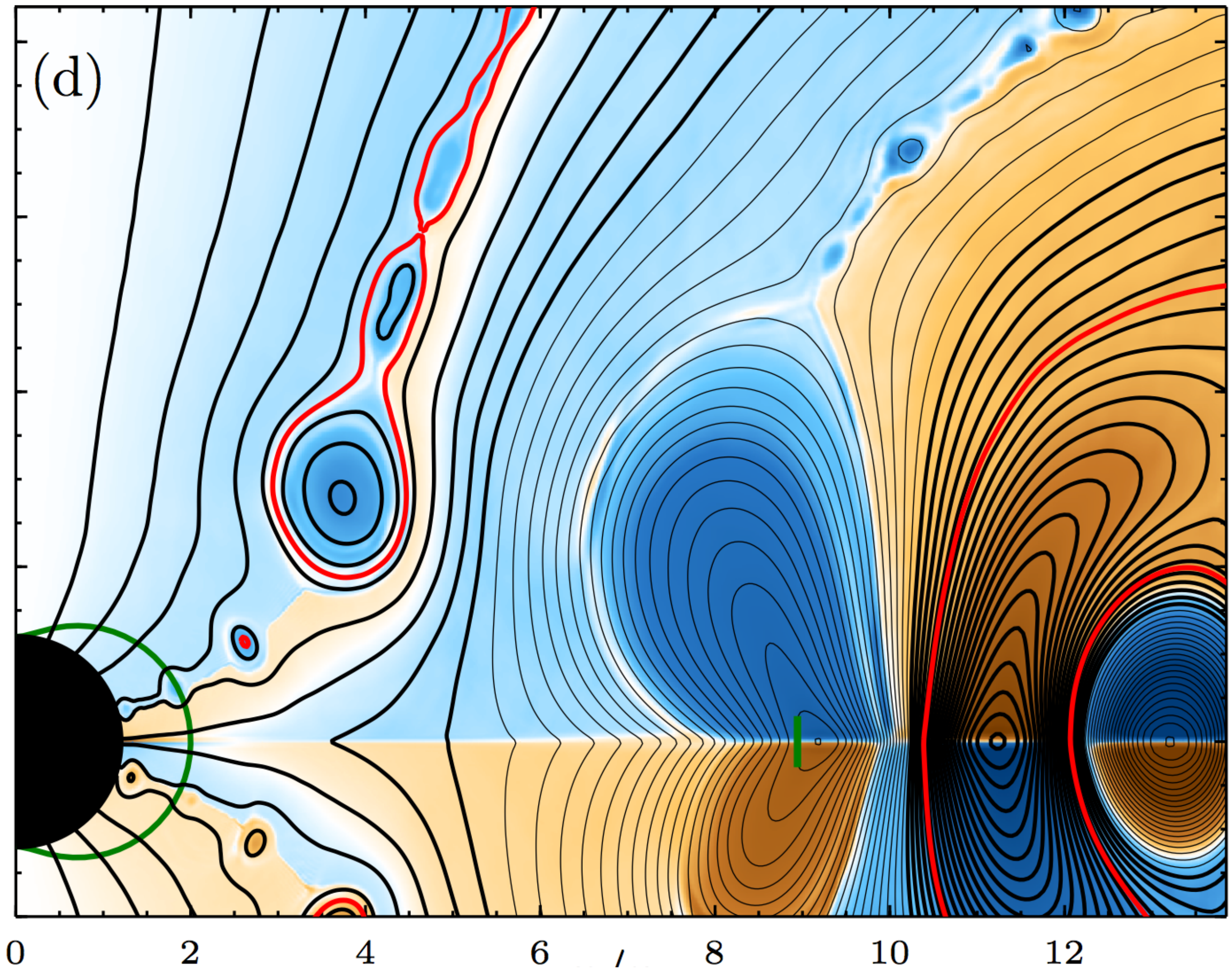
Hard X-rays from accreting black holes



McConnell et al. 2002

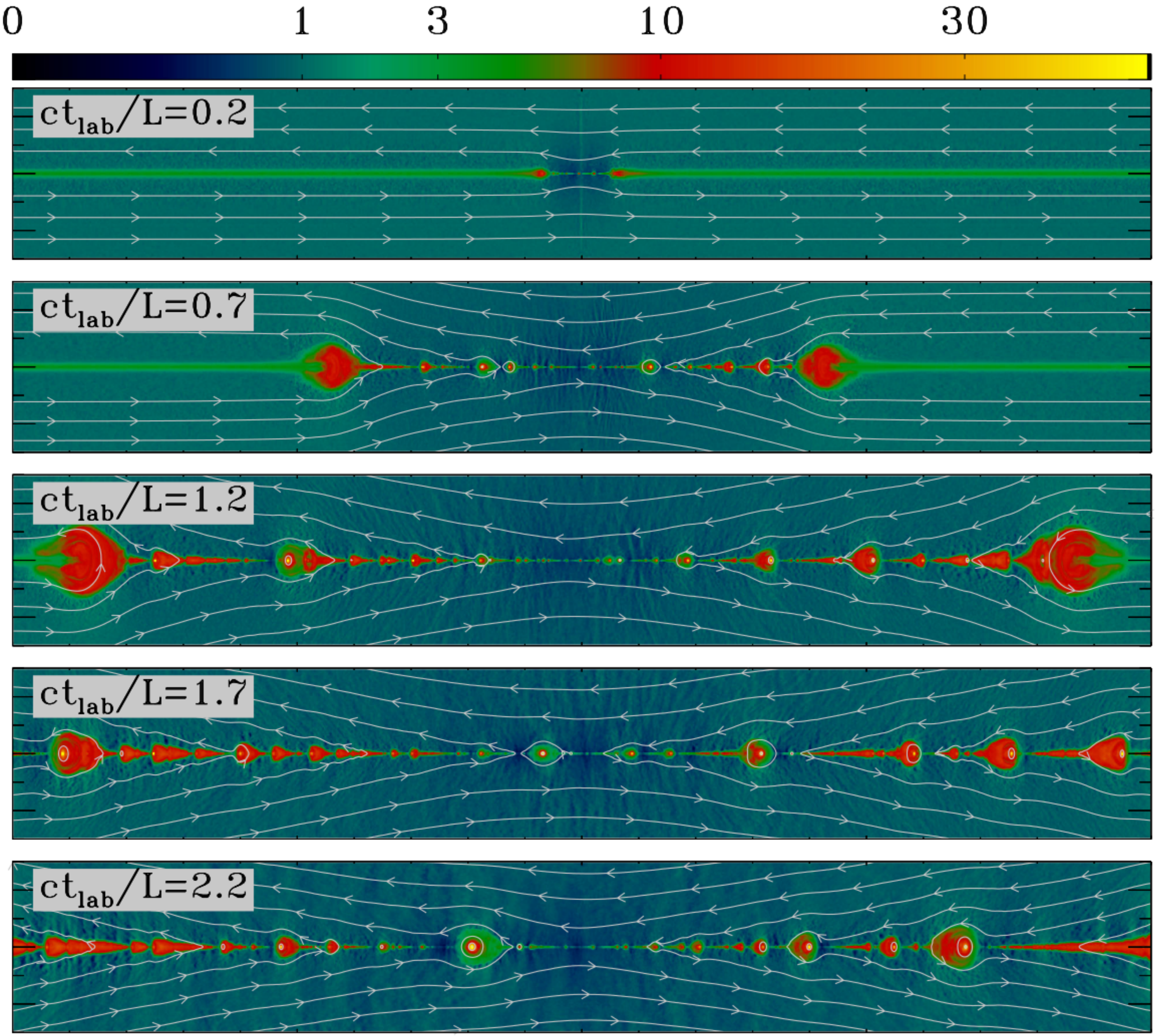


Reconnection near black holes



Parfrey, Giannious, AB 2015

ab initio (PIC) simulations



Self-similar chain of plasmoids

$v_{rec} \approx 0.1c$

Uzdensky et al. 10

Melzani et al. 14

Sironi, Spitkovsky 14

Guo et al.16

Sironi et al.16

Werner et al.16

Parameters of the reconnection problem

Magnetization:
(MHD)

$$\boxed{\sigma = \frac{B^2}{4\pi\rho c^2} = \frac{2U_B}{\rho c^2}}$$

energy per unit rest mass

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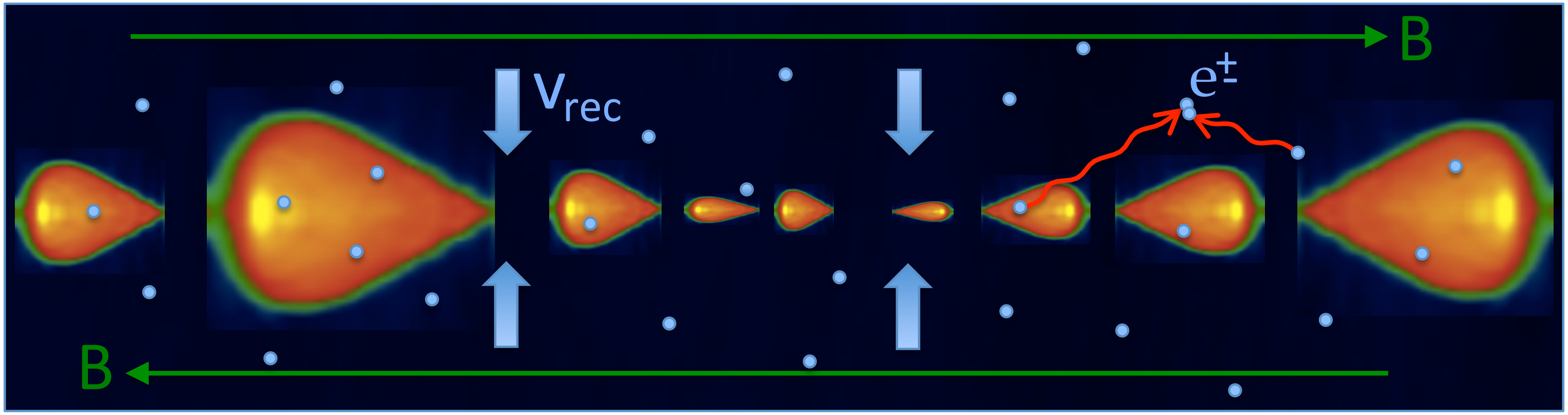
2. Compactness: cooling time vs. light crossing time
(radiative)

$$\frac{t_{\rm cool}}{s/c} \sim \frac{1}{\gamma_e \ell}$$

$$\boxed{\ell \equiv \frac{U}{m_e c^2}\,\sigma_{\rm T}\, s} \sim \frac{m_p}{m_e}\,\frac{L}{L_{\rm Edd}}\,\frac{R_S}{R} \sim 10^3$$

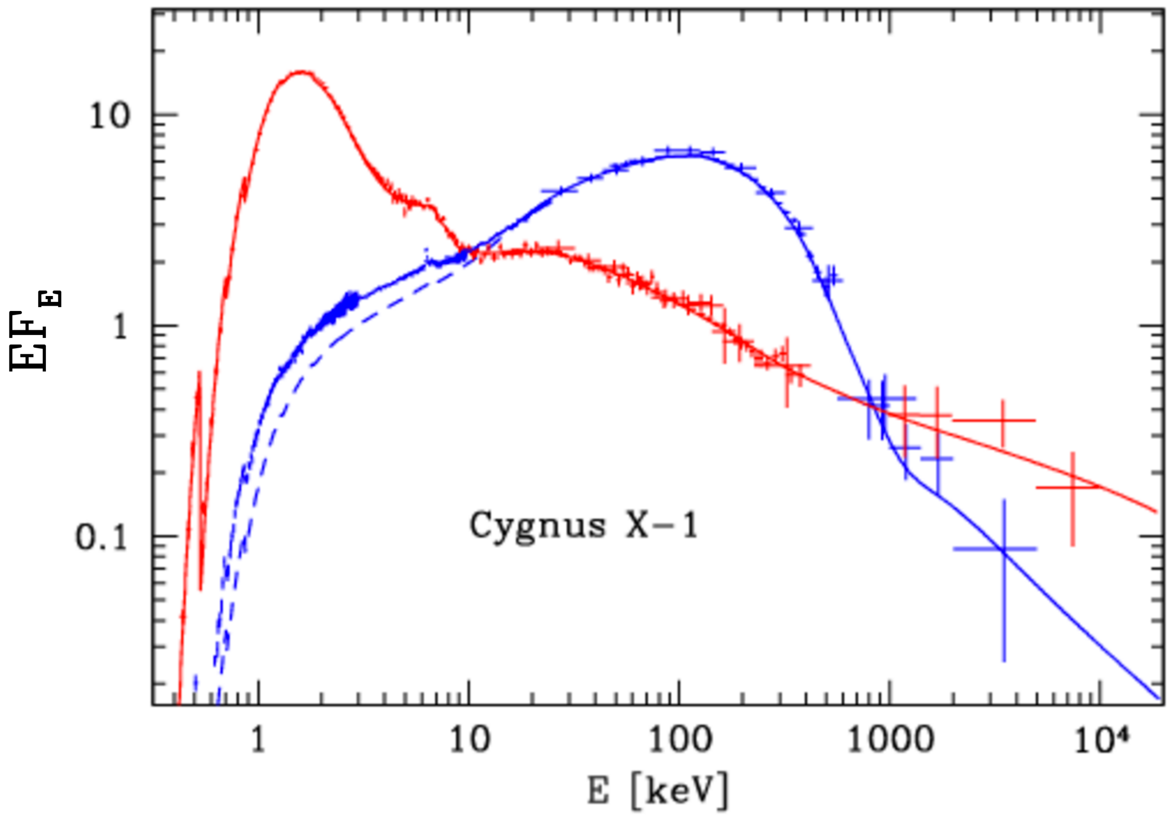
Radiative reconnection
(cooling time << light crossing time)

AB 2017

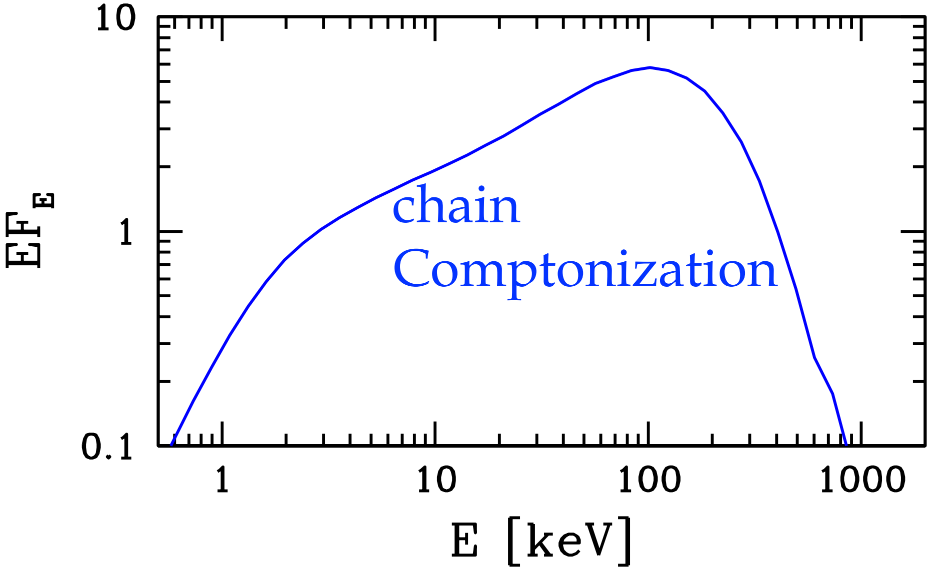


1. Plasmoids are cool + fast => "chain Comptonization"

2. Energetic photons (>1 MeV) convert to e+- pairs
   => reconnection layer self-feeds with plasma



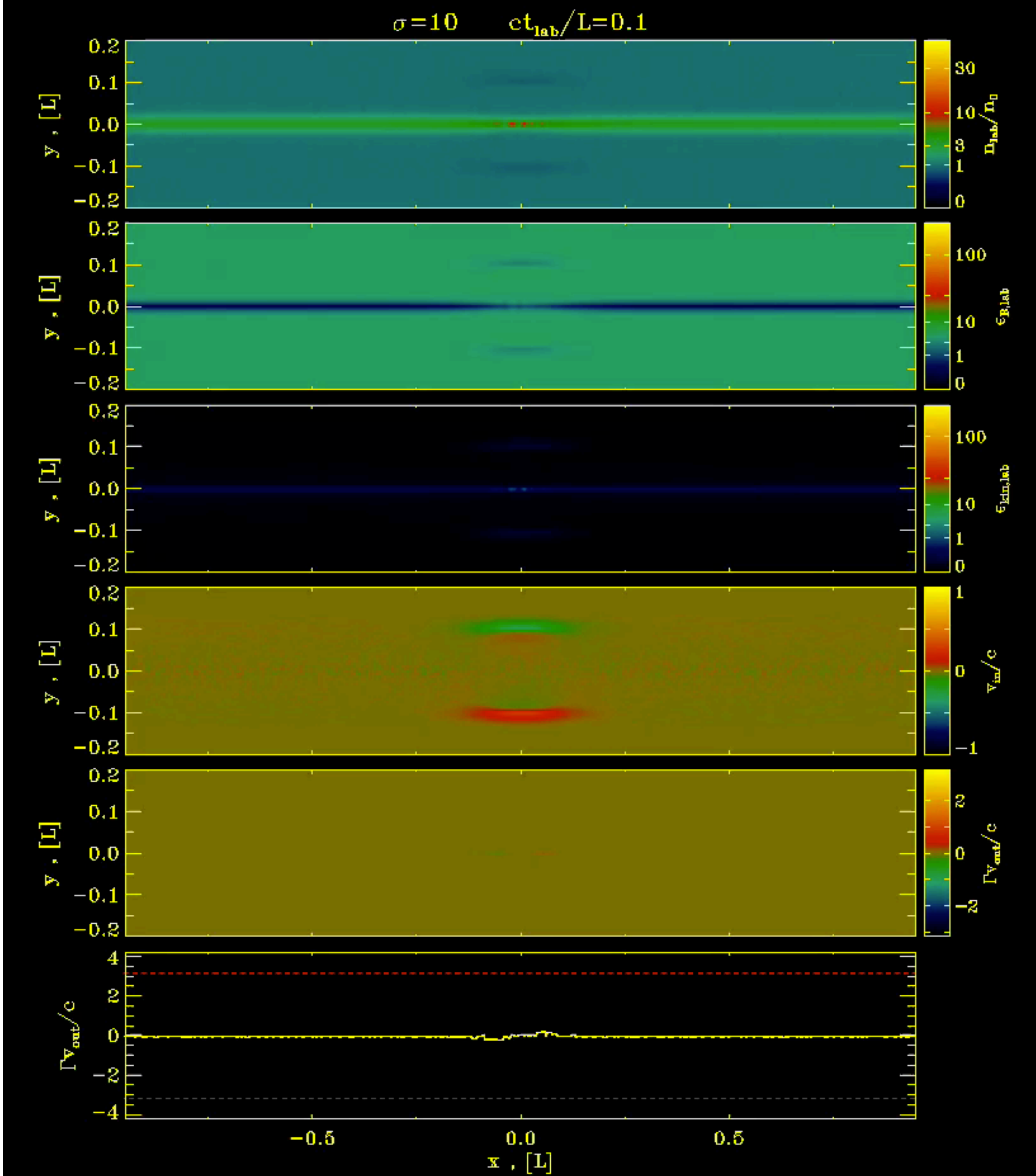
McConnell et al. 2002



AB 2017

In progress:
radiative
PIC simulations
(Sironi, AB)

plasmoid chain
controlled by
magnetic stresses
(and drag)



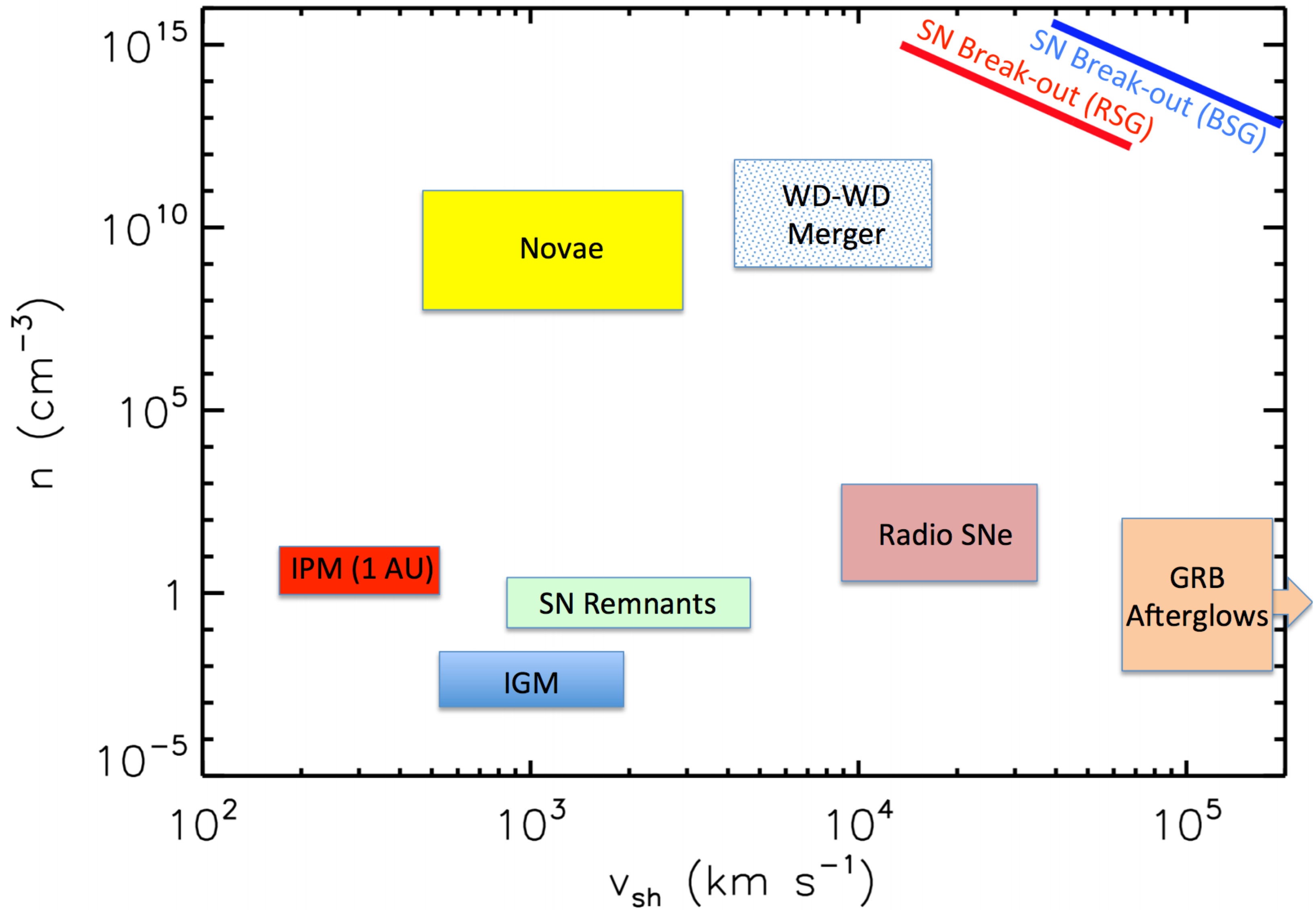
The radiative reconnection layer takes care of itself:

- feeds itself with plasma (e+-)
- feeds itself with photons (synchrotron)

a self-organized nonlinear machine with 2 parameters (ℓ, σ), produces hard X-rays via bulk Comptonization

II. Shocks

Ejecta-powered radiation + cosmic rays



Types of shocks

- collisional (atmospheric explosions)
- collisionless (solar system, SN remnants,
  AGN jets, GRB afterglow)
- radiation-mediated (novae, SN breakout,
  GRB jets,
  GW counterparts)

non-relativistic & relativistic

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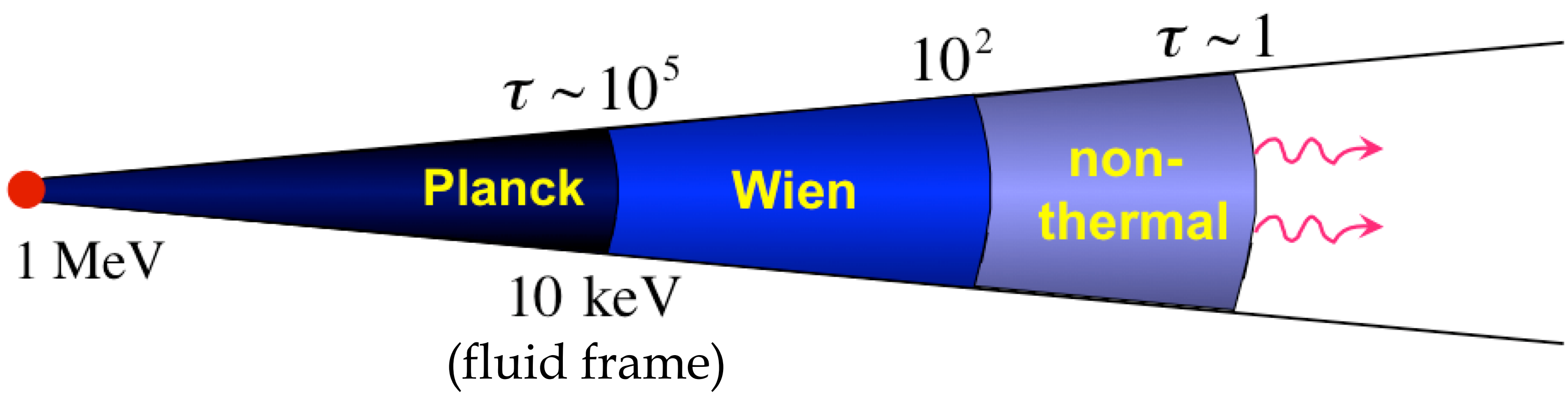
Zeldovich, Raizer 1966; Weaver 1976
Blandford, Payne 1981; Budnik et al. 2010
Levinson 2012

non-relativistic & relativistic

Gamma-Ray Bursts



sub-photospheric shocks are mediated by radiation;
extremely powerful machines, up to 10^{54} erg/s
(isotropic equivalent)

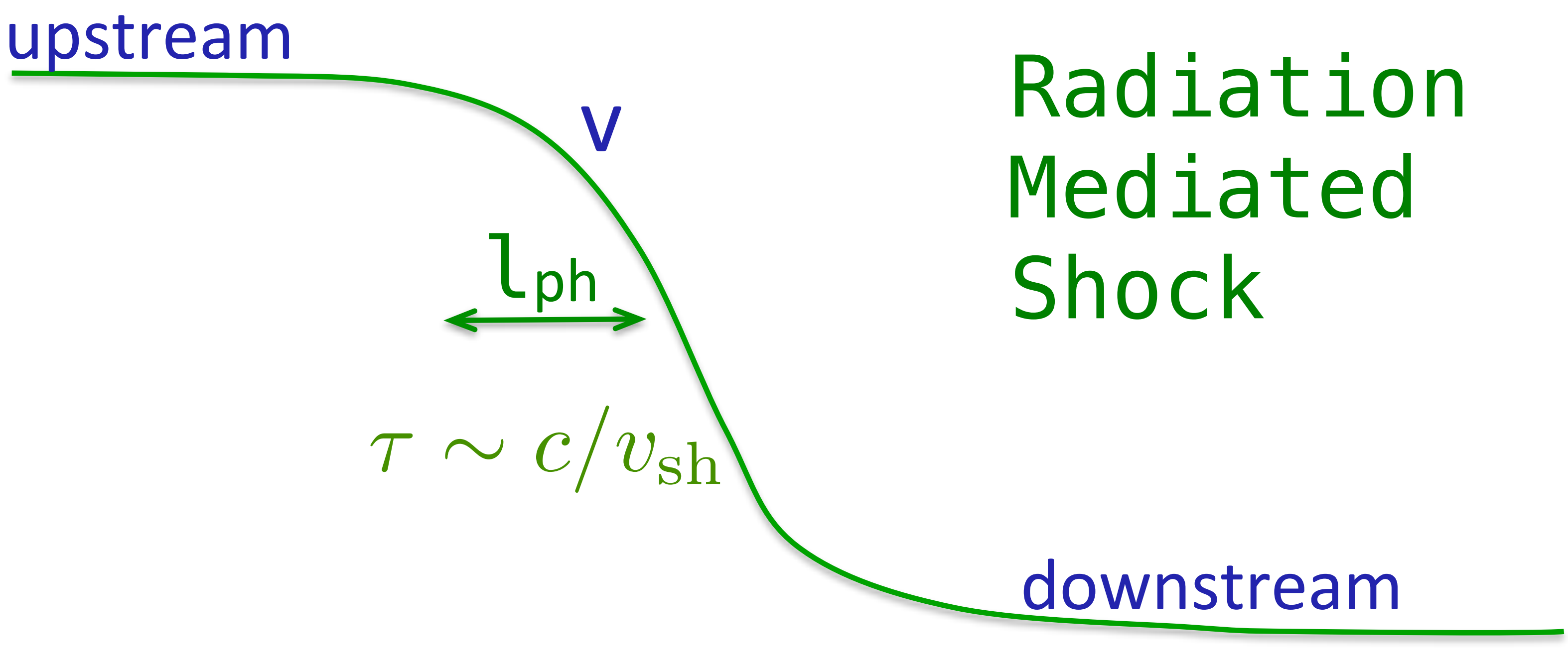
GRB photon number $\dfrac{n_{\rm ph}}{n_{\rm ion}} = 10^6 - 10^5$

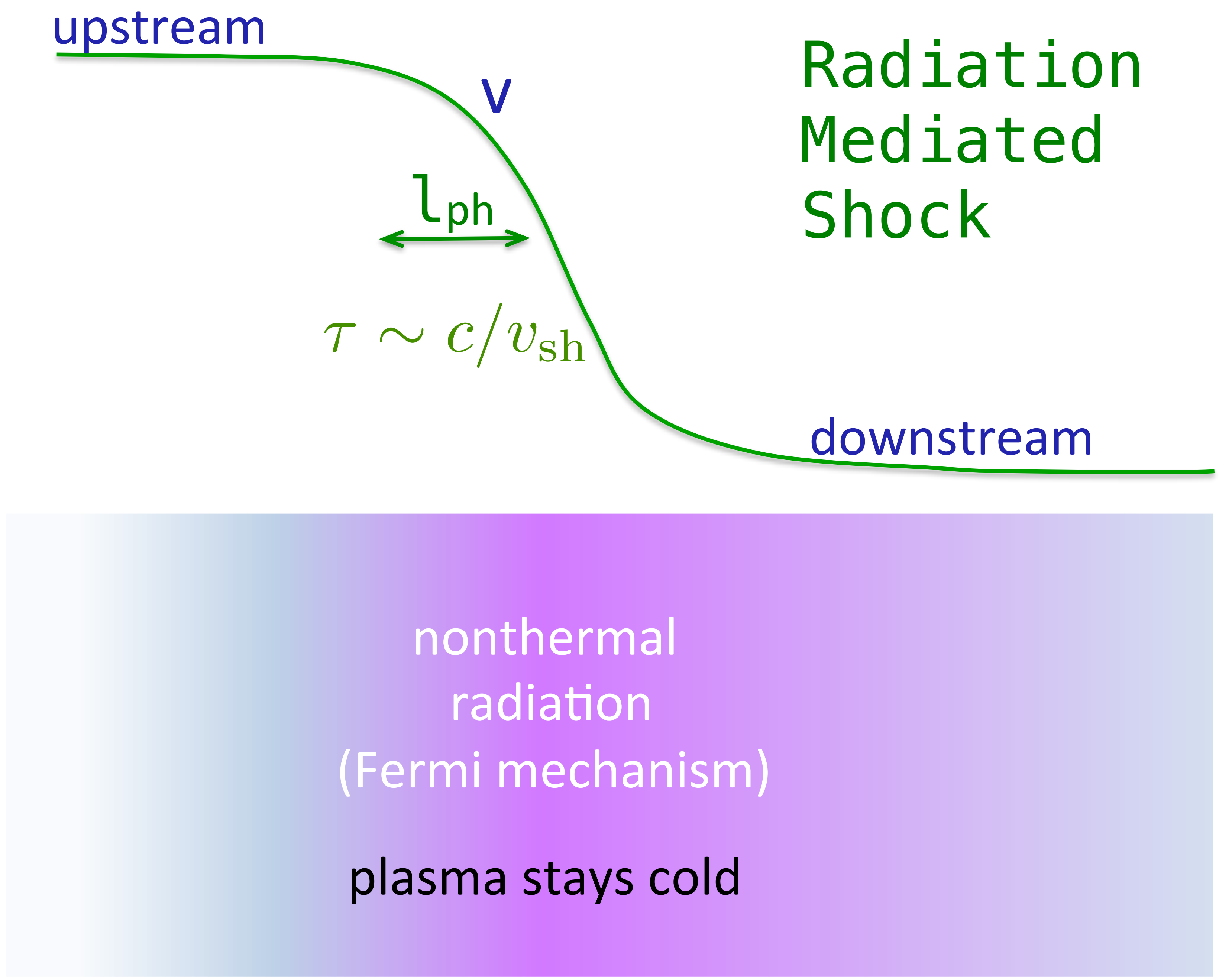
$\Updownarrow$

GRB spectra peak at $E_{\rm peak} = 0.1 - 1$ MeV

photon supply from the hot central engine is short by ~ 10

$\Longrightarrow$ photons are produced by dissipation in the jet
(which also makes the GRB spectrum nonthermal)


upstream
v
Radiation
Mediated
Shock
l_{ph}
$\tau \sim c/v_{\rm sh}$
downstream


upstream
v
l_{ph}
$\tau \sim c/v_{sh}$
downstream
Radiation
Mediated
Shock
nonthermal
radiation
(Fermi mechanism)
plasma stays cold

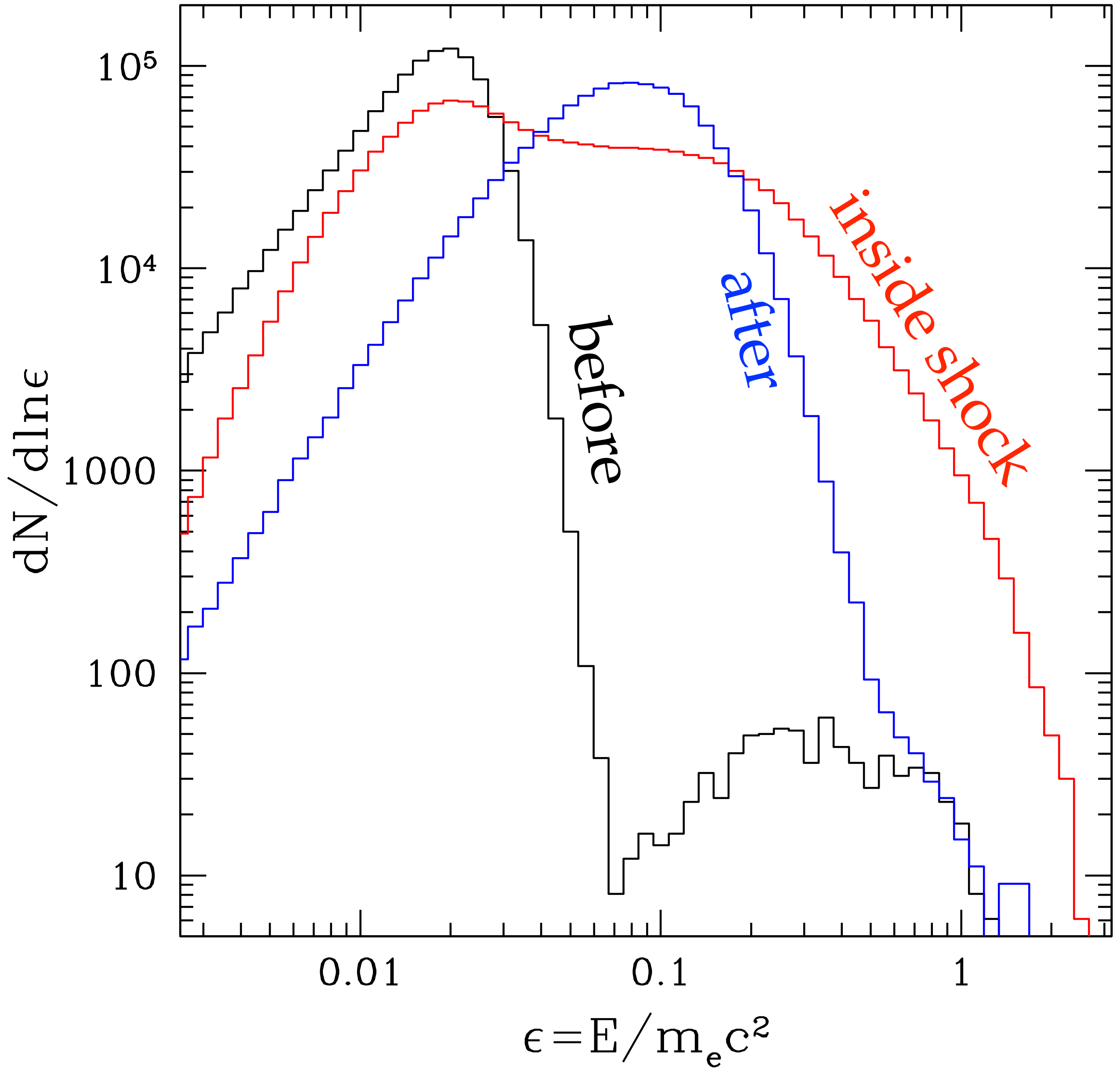
Radiative MHD from first principles: “Photon In Cell”

Fluid motion: Lagrangian grid

Radiative transfer: individual photons (Monte-Carlo)

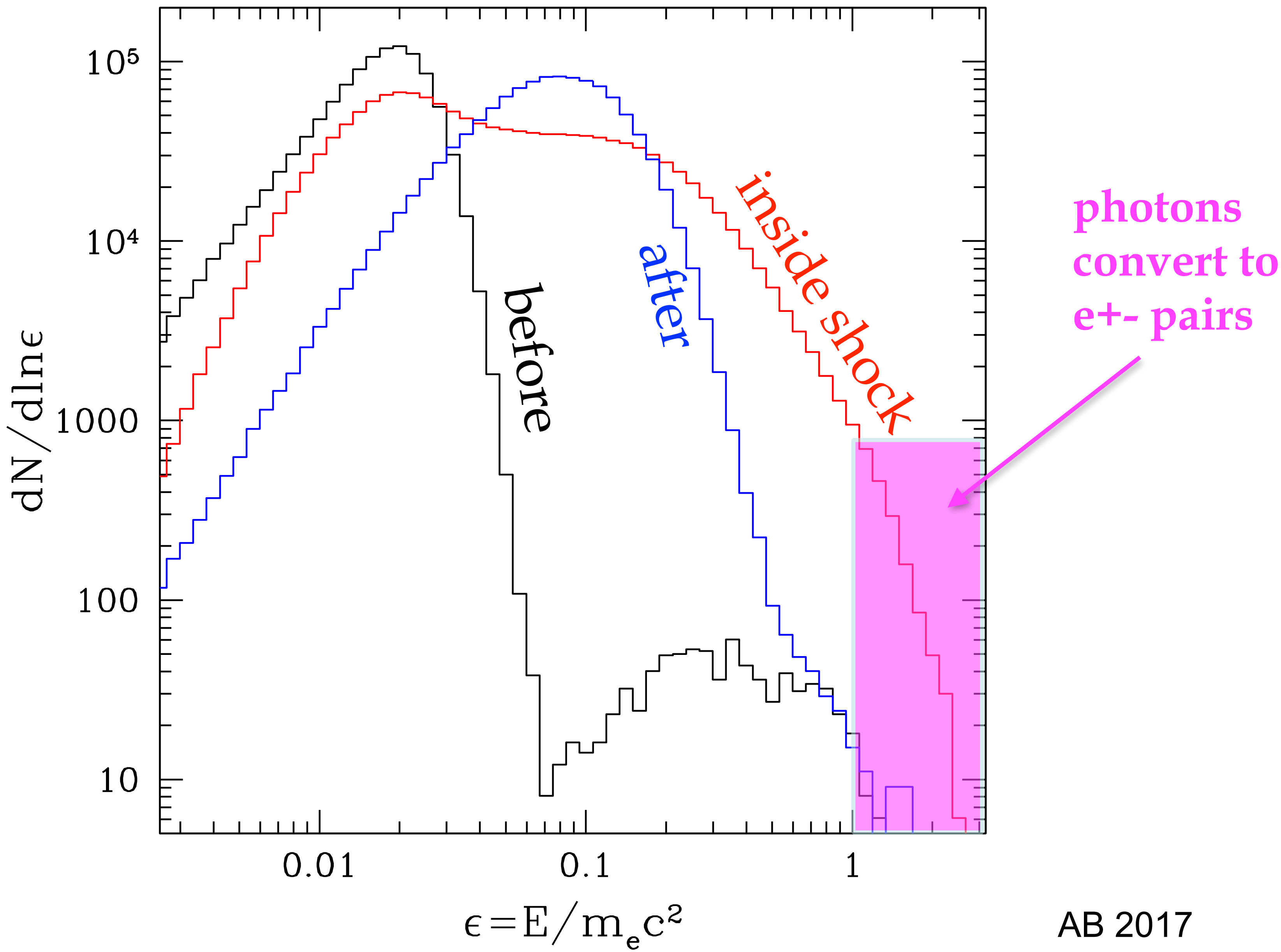
goal: self-consistent solution: radiation + shock structure

AB 2017
Lundman, AB, Vurm 2018
Ito et al. 2018



dN/dlnϵ
10^5
10^4
1000
100
10
0.01
0.1
1
ϵ=E/m$_e$c^2
before
after
inside shock

AB 2017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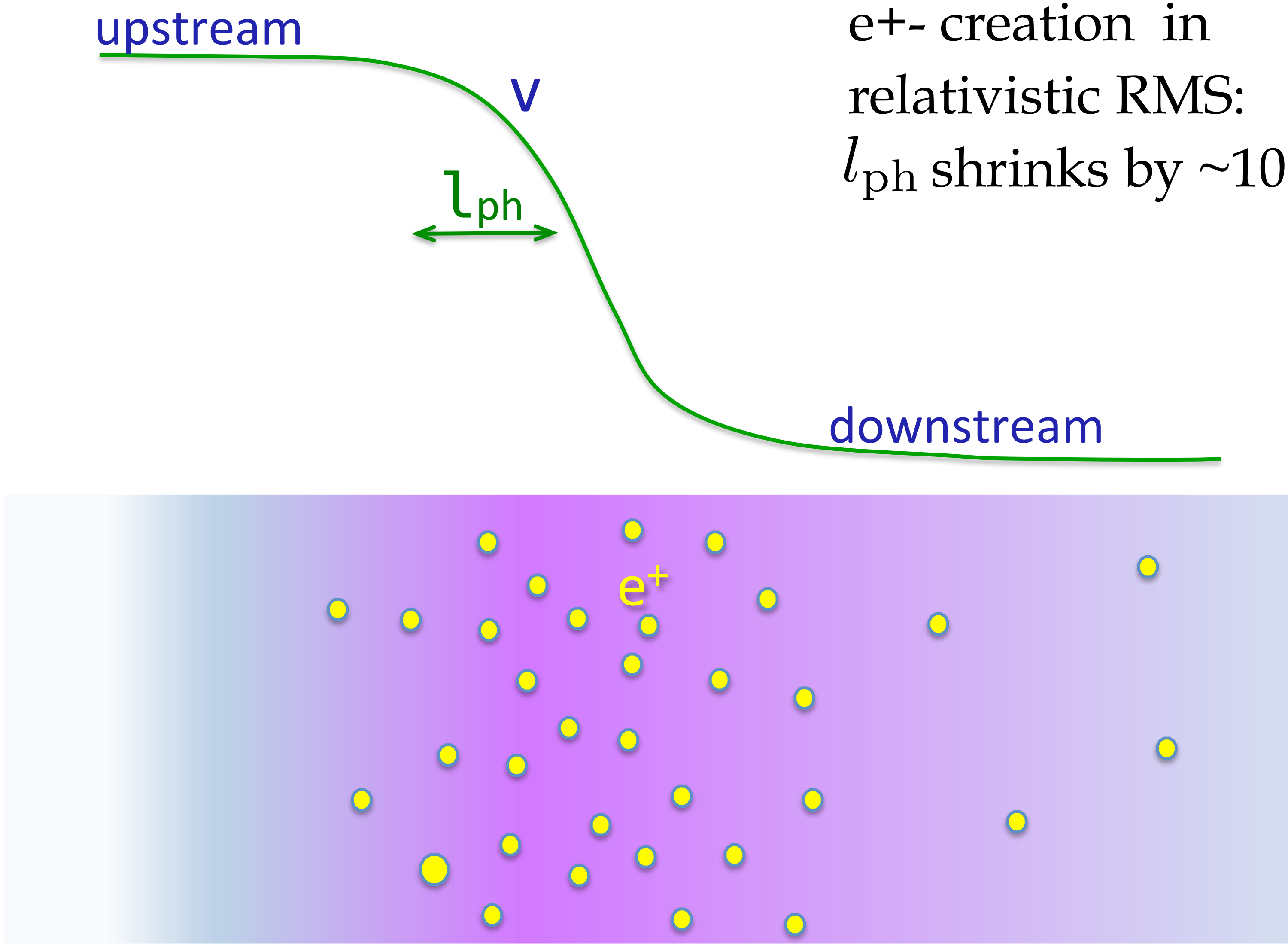
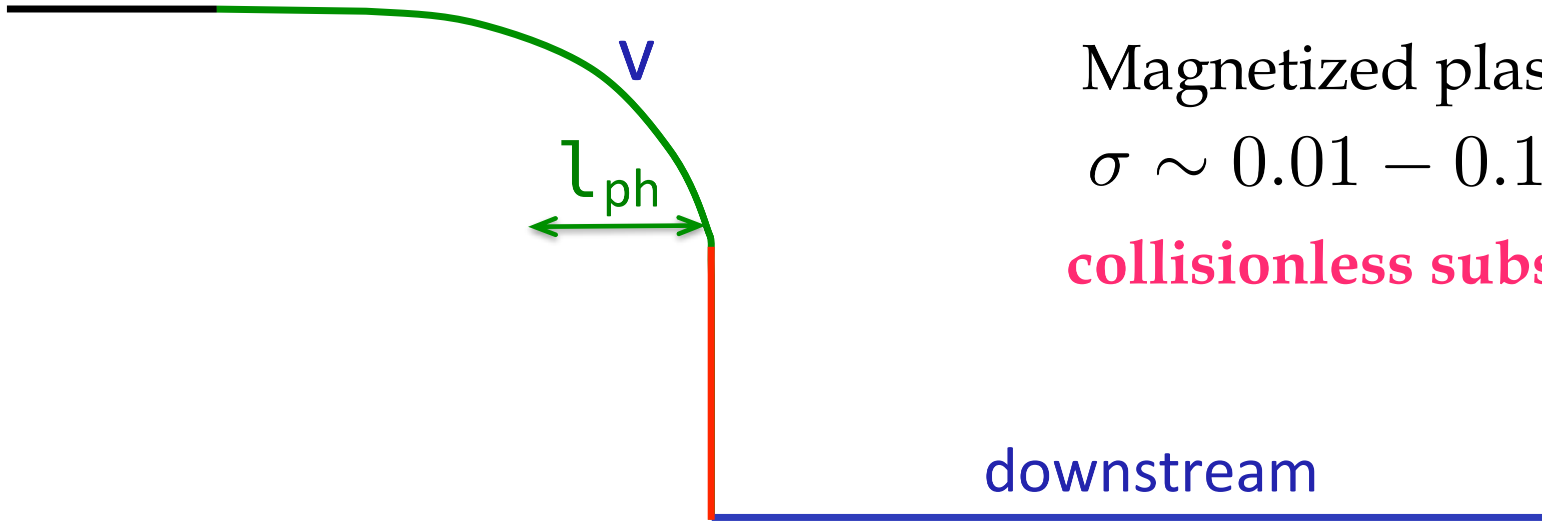
before
after
inside shock
photons
convert to
e+- pairs
AB 2017

e+- creation in relativistic RMS:
$l_{\rm ph}$ shrinks by ~100



$$Z_\pm = n_\pm / n_{\rm ion} \sim 100 - 300 \quad \text{if} \quad \gamma_{\rm sh}\beta_{\rm sh} > 1$$

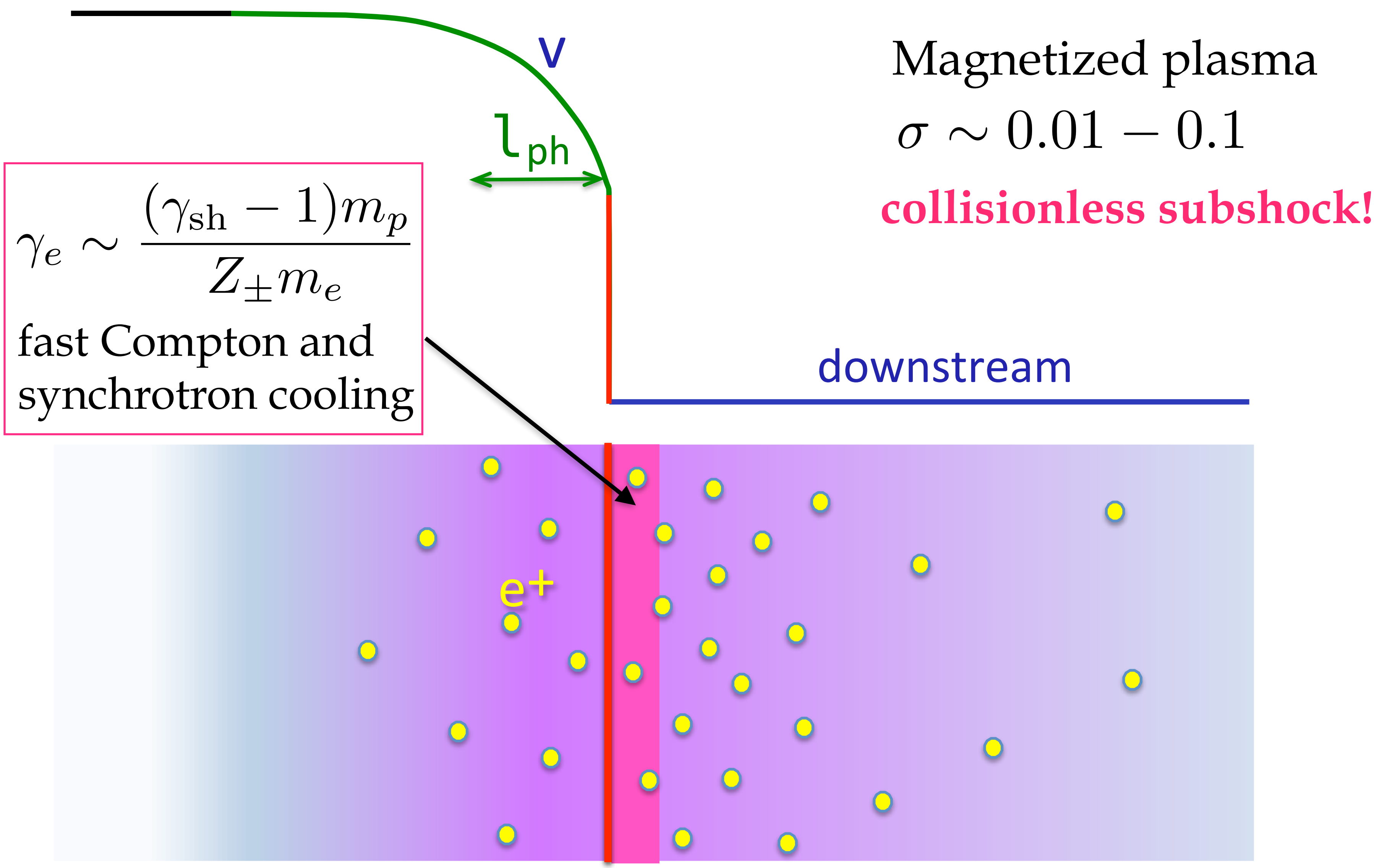


Magnetized plasma

$\sigma \sim 0.01 - 0.1$

collisionless subshock!

AB 2017;   Lundman & AB 2018



AB 2017; Lundman & AB 2018

Synchrotron photon number:

– peaks at low photon energies

– controlled by **induced down-scattering limit**:

$$\frac{kT_b}{m_e c^2}\,\tau_{\rm T}^2 \sim 1 \qquad\qquad (\tau_{\rm T} \sim c/v_{\rm sh})$$

Zeldovich, Levich 1968

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$$\gamma_e \sim 30 \qquad \left[\sqrt{\gamma_e} - 2 - \ln\frac{\gamma_e}{4} \approx 1\right]$$

(regulated by e+- creation)

Shock self-organization

- Dresses itself in pair plasma: $n_{\pm}/n_{\rm ion} \sim 100$

  => "carries" the explosion photosphere
  (delayed shock breakout)

- Feeds itself with photons that mediate the shock:

$$n_{\rm ph}/n_{\rm ion} \sim 10^5 - 10^6$$

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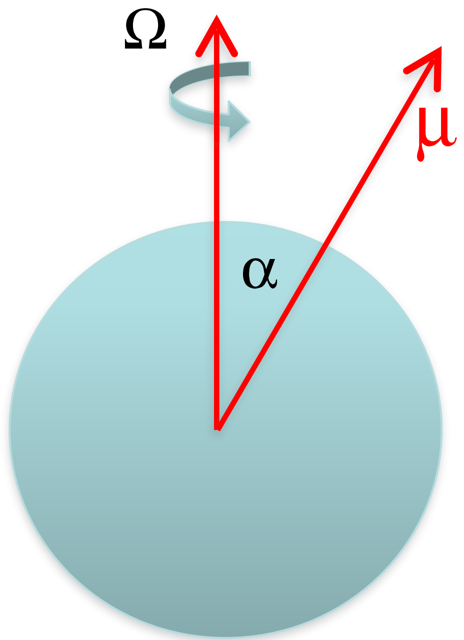
– self-sufficient machine with 2 dimensionless parameters:
$v_{\rm sh}/c$ and medium magnetization σ

– similar to radiative magnetic reconnection (ℓ, σ):
Comptonization => e+- => synchrotron => induced scattering

III. Electric discharge

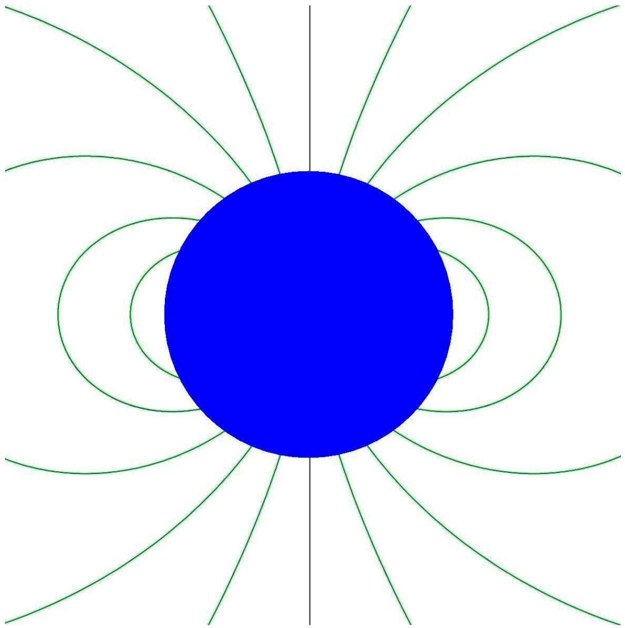
– works in magnetically dominated, low optical depth systems

Pulsar problem:



where is the gap?

Pulsars: ab initio experiment



- Start with a non-rotating star and spin it up. **E** will be induced
- Particles lifted from the star will move in the self-consistent electromagnetic field
- **E** and **B**: fixed inside the star, calculated from Maxwell equations outside the star
- Accelerated particles emit photons
- High-energy photons convert to e+-

Chen, AB 2014, 2017
Philippov et al. 2014, 2015
Cerutti et al. 2015, 2016

First-principle (collisionless) plasma simulations

Vlasov equation (Boltzmann eq. coupled to Maxwell eqs.)

$$\frac{\partial f^s}{\partial t} + \mathbf{v} \cdot \frac{\partial f^s}{\partial \mathbf{x}} + \frac{q^s}{m^s}\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \cdot \frac{\partial f^s}{\partial (\gamma \mathbf{v})} = 0$$

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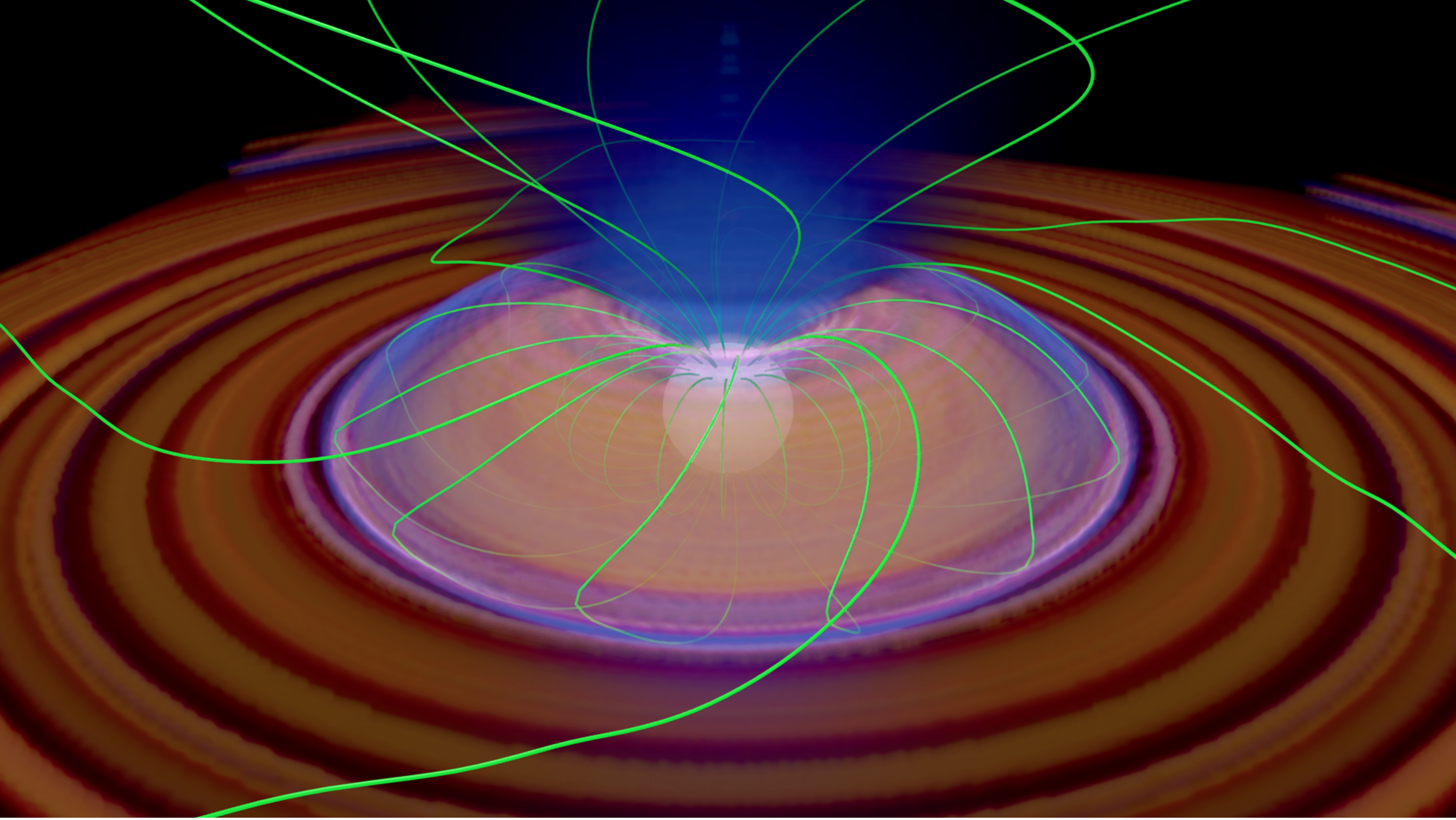
Particle-**I**n-**C**ell method:

$$\frac{d\mathbf{p}}{dt} = e \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right) + m\mathbf{g}$$

$$\partial_t \mathbf{B} = -c \nabla \times \mathbf{E}$$

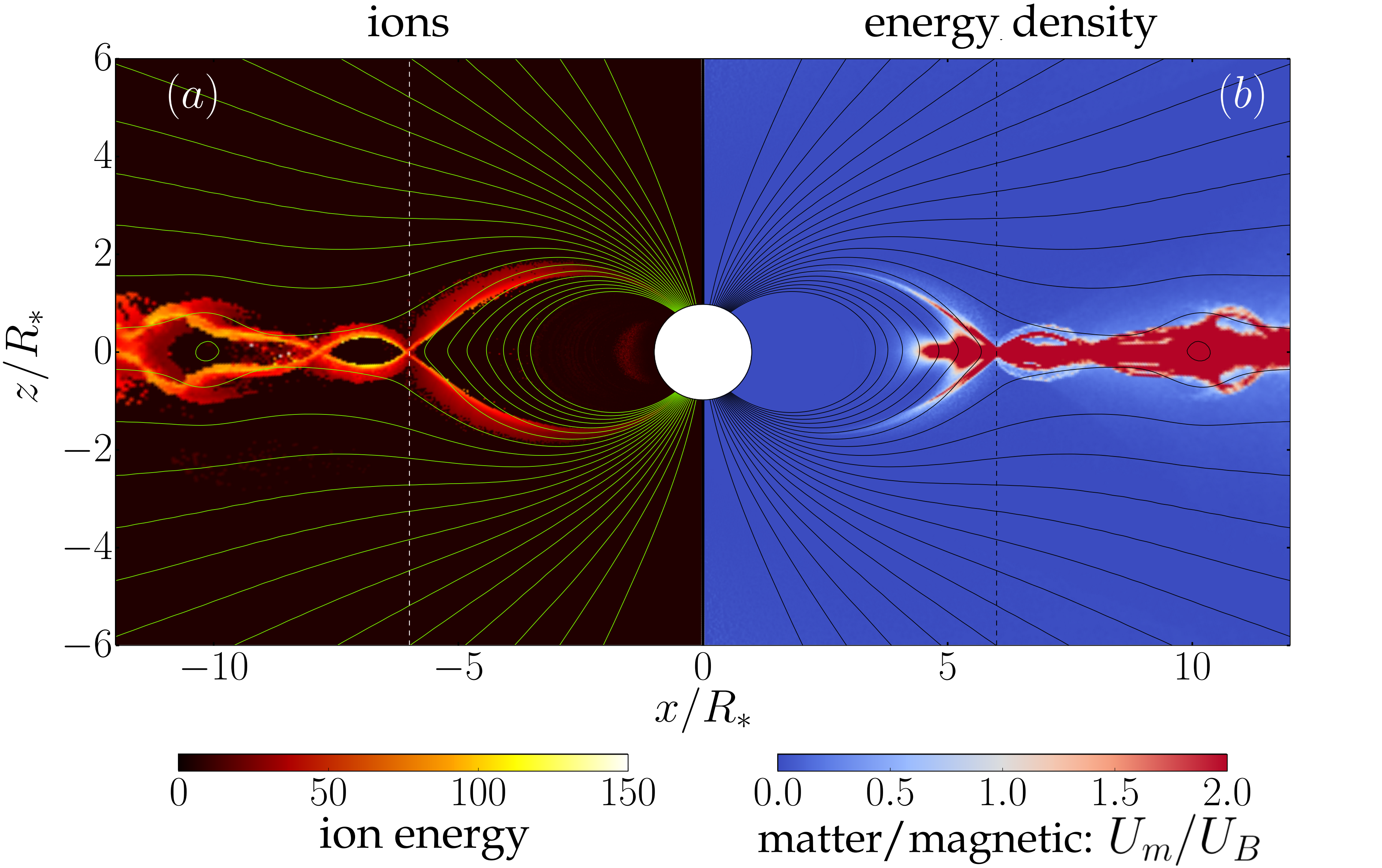
$$\partial_t \mathbf{E} = c \nabla \times \mathbf{B} - 4\pi \mathbf{J}$$



aligned rotator

charge density: - blue + orange

Chen, AB (2014, 2017)



Particle acceleration in the Y-shaped current sheet

Summary: luminous compact objects

- Luminosity is powered by dissipation of magnetic or kinetic energy in a compact region

- "Dissipation machine" (reconnection layer/shock/discharge) self-organizes into an essentially non-linear state, feeding itself with plasma, photons, and generating the observed spectrum

- — first-principle problem with few parameters, can be isolated from "mud wrestling" — MHD weather around compact objects

- Ubiquitous, from AGN to GRBs

- Best method of study: direct numerical experiment
  (Vlasov equation + radiative processes)