Dissipation/plasma in compact objects

Andrei Beloborodov
Columbia University

”Compactness” in astrophysics

Gravitational: $$\ell_g = \frac{R_S}{R} \sim \frac{\Phi}{c^2}$$

Radiative: cooling time vs. light crossing time

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

$$\boxed{\ell \equiv \frac{U}{m_e c^2}\,\sigma_{\rm T}\, s} \sim \frac{m_p}{m_e}\,\frac{L}{L_{\rm Edd}}\,\frac{R_S}{R} \gg 1$$

(accreting neutron stars, black holes,
gamma-ray bursts)

Dissipative plasma processes:

reconnection, shocks, turbulence damping, discharge

In compact objects these processes occur in dense radiation

$\Rightarrow$

1) dominant radiative losses

2) "bulk Comptonization" of photons

(turns out more important than thermal Comptonization)

3) extension of radiation spectrum above $m_e c^2$

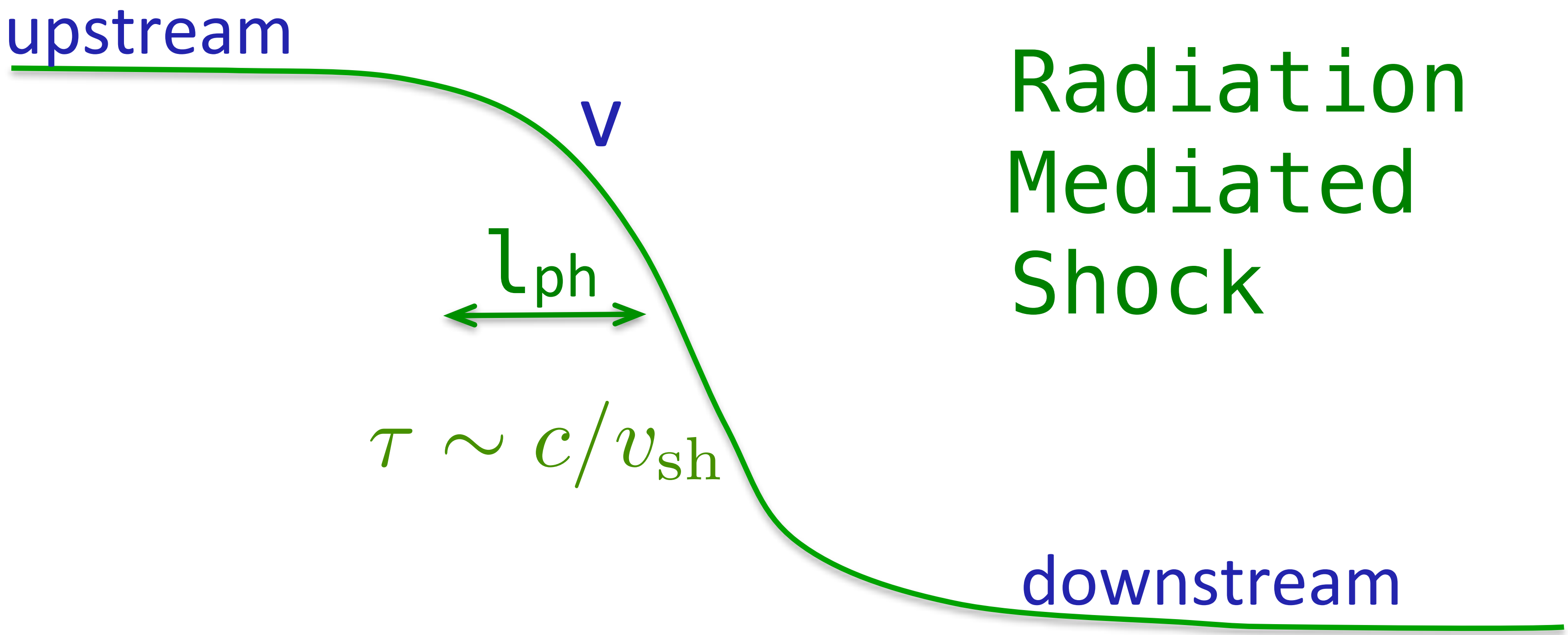
4) copious e+- pair creation

5) non-linear self-regulated state $(n_{\pm}/n_{\rm ion},\ n_{\rm ph}/n_{\rm ion})$

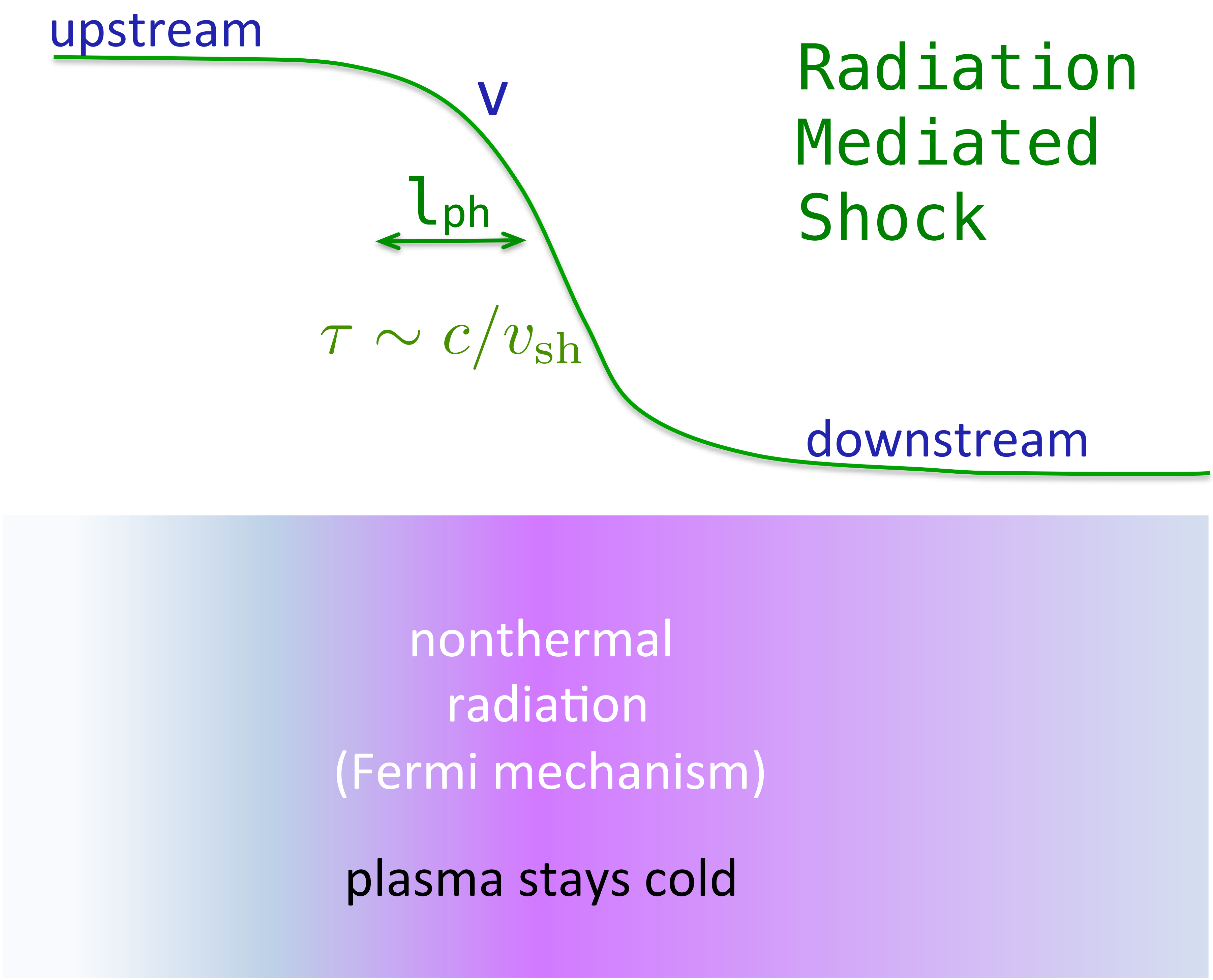
I. Shocks

Plasma shocks in dense radiation become mediated by photons

$\Rightarrow$ fundamental change in the shock dissipation mechanism



Radiation Mediated Shock



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

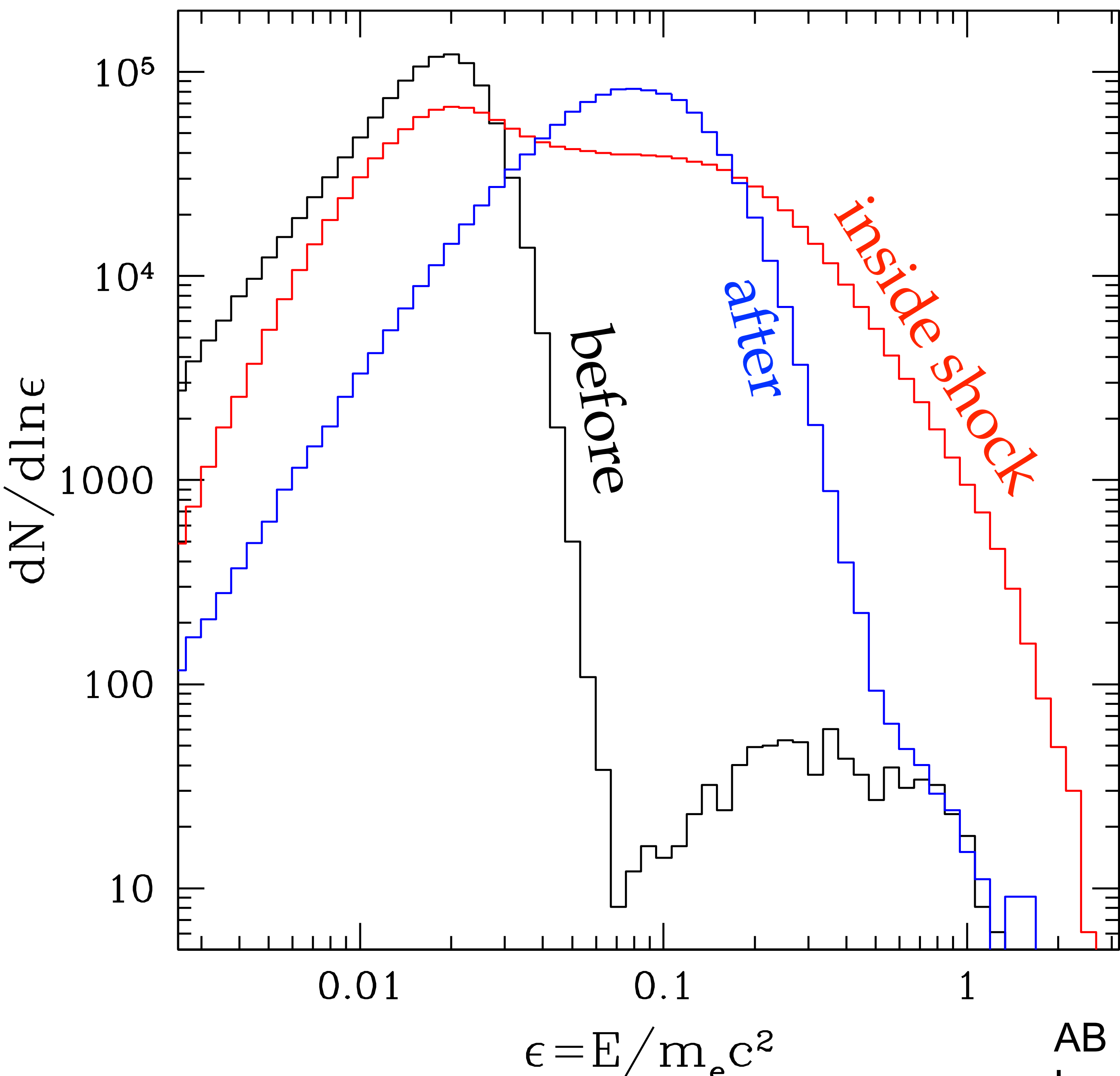
Radiative MHD from first principles: “Photon In Cell”

Fluid motion: Lagrangian grid

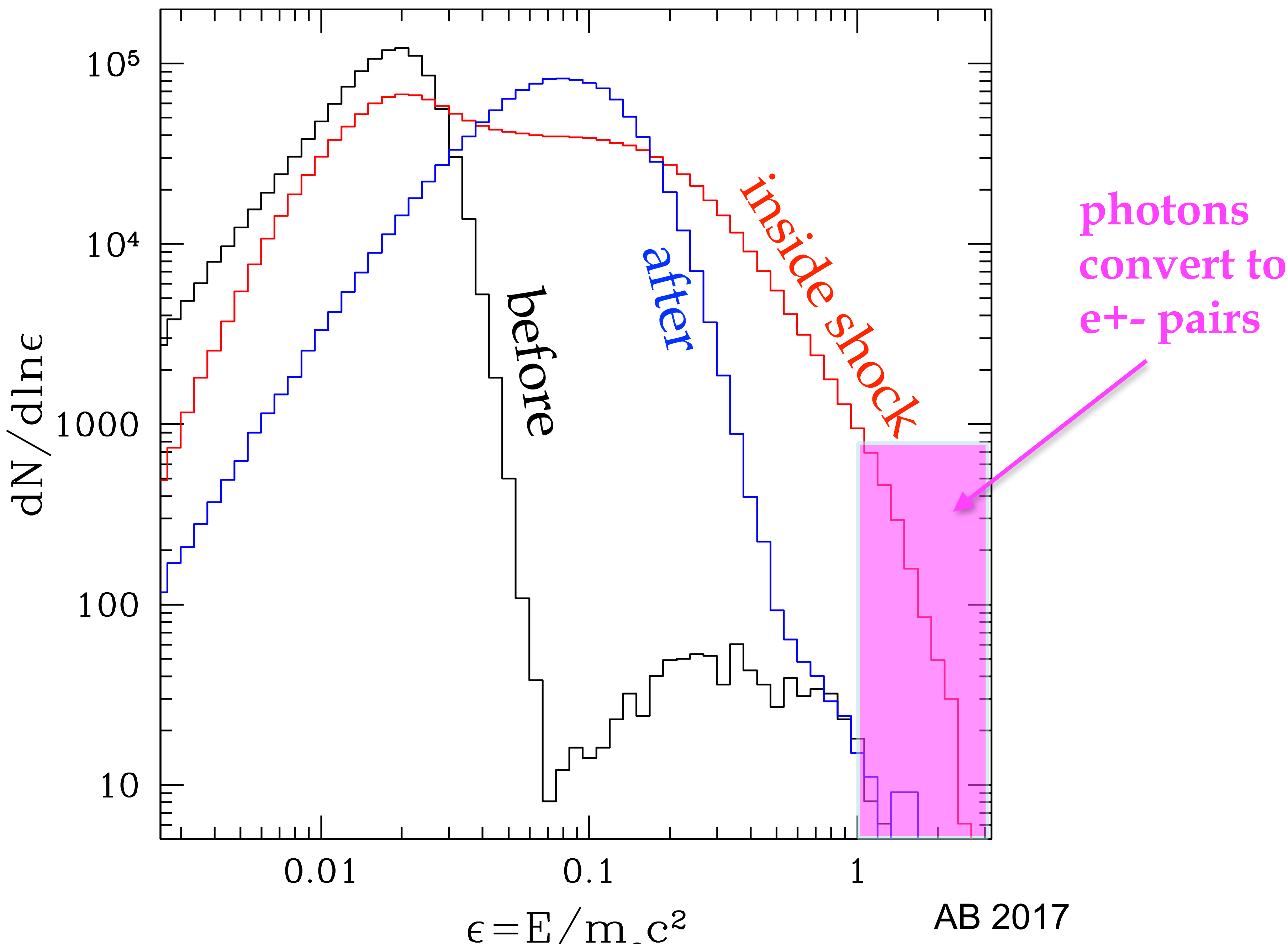
Radiative transfer: individual photons (Monte-Carlo)

goal: self-consistent solution: radiation + shock structure

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



AB 2017
Lundman, AB, Vurm 2018



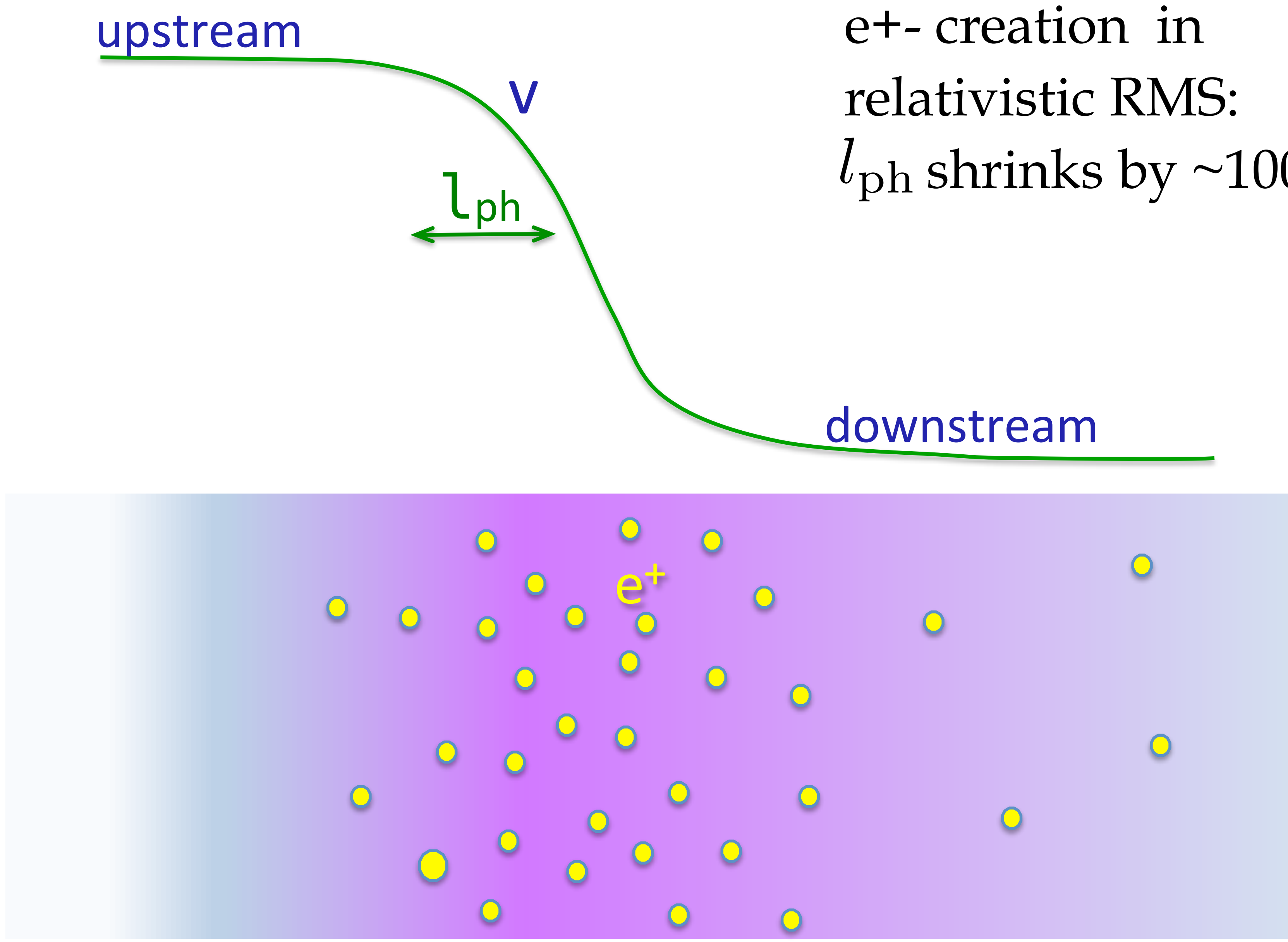
AB 2017
Lundman, AB, Vurm 2018

Bulk Comptonization in non-relativistic shocks

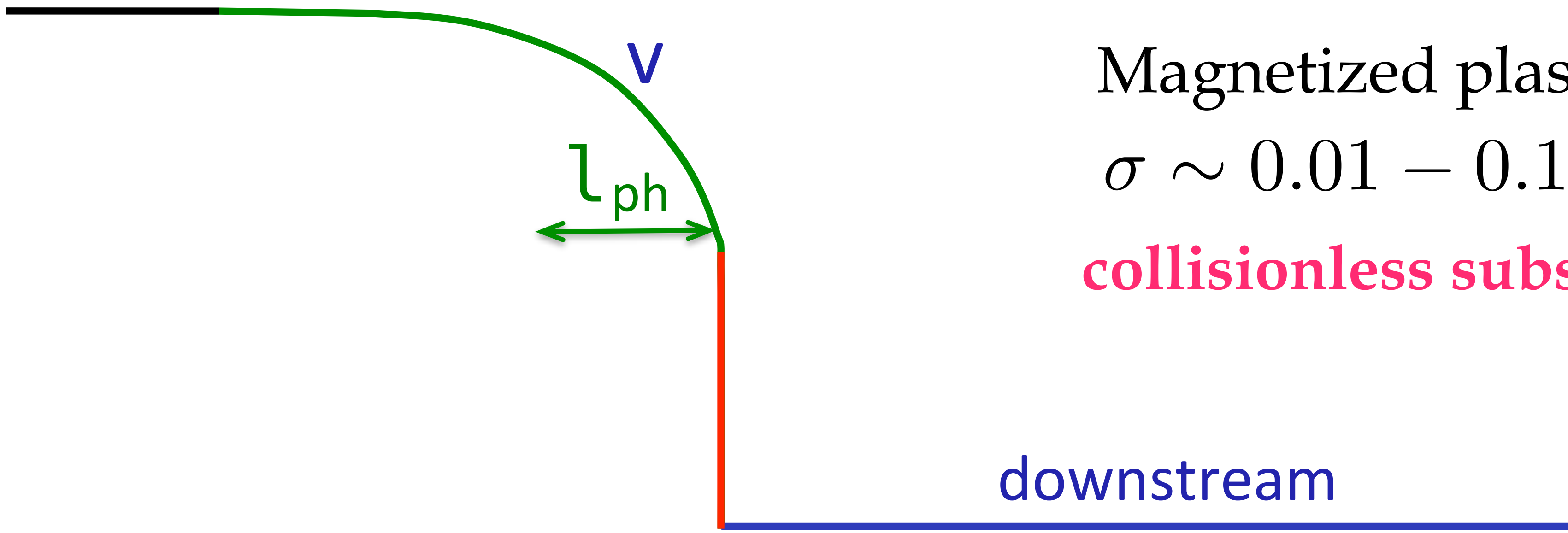
$$\left.\begin{array}{ll} \text{inverse Compton:} & \dfrac{\Delta\epsilon}{\epsilon} \sim \dfrac{v^2}{c^2} \\ \\ \text{recoil:} & \dfrac{\Delta\epsilon}{\epsilon} \sim -\epsilon \end{array}\right\} \Rightarrow \quad \epsilon_{\mathrm{max}} \sim \frac{v^2}{c^2}$$

$$\epsilon = \frac{h\nu}{m_e c^2}$$

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



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

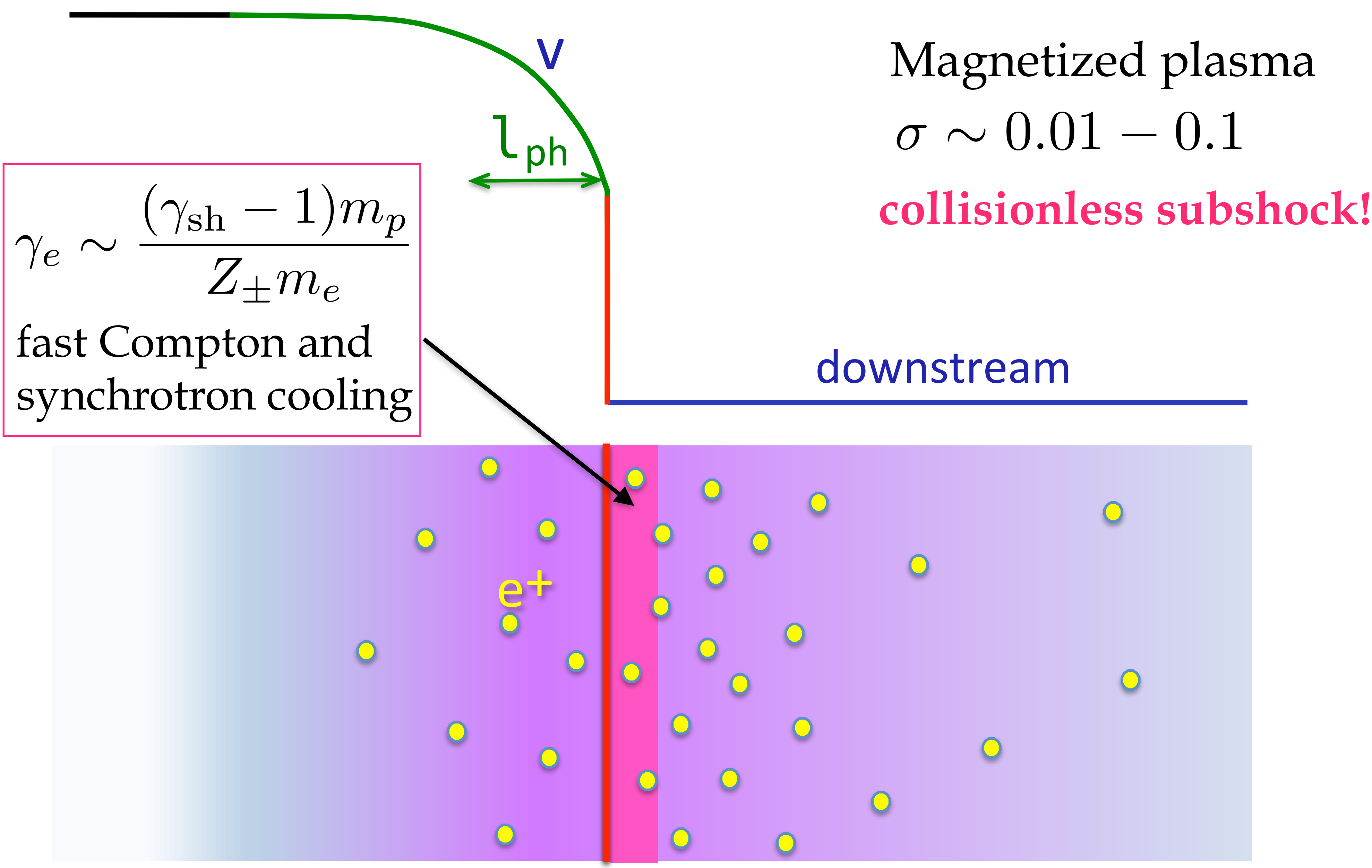


Magnetized plasma

$\sigma \sim 0.01 - 0.1$

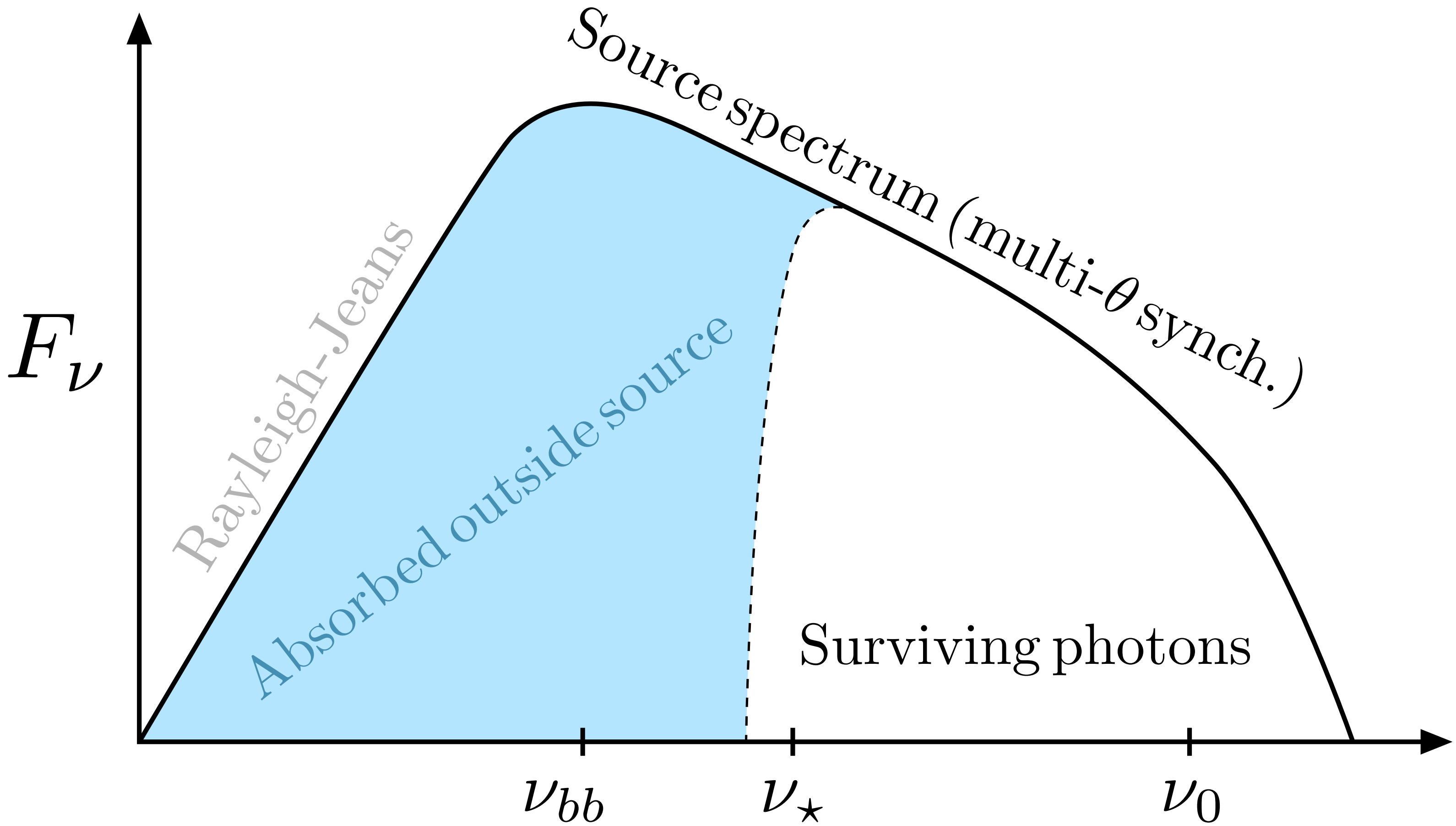
collisionless subshock!

AB 2017



Magnetized plasma
$\sigma \sim 0.01 - 0.1$
collisionless subshock!
v
l_{ph}
$\gamma_e \sim \frac{(\gamma_{\rm sh} - 1) m_p}{Z_{\pm} m_e}$
fast Compton and synchrotron cooling
downstream
e^+

AB 2017



Lundman & AB 2018

Synchrotron photon number:

– peaks at low photon energies

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

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

$$\Rightarrow \boxed{\frac{n_{\rm ph}}{n_{\rm ion}} \approx \alpha\,\frac{m_p v_{\rm sh}^2}{m_e c^2}\,\sigma\,\gamma_e^4}$$

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

(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:

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

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:

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

2 dimensionless parameters:
$v_{\rm sh}/c$ and medium magnetization σ

current work: shock spectrum emerging from photosphere

(Lundman & AB)

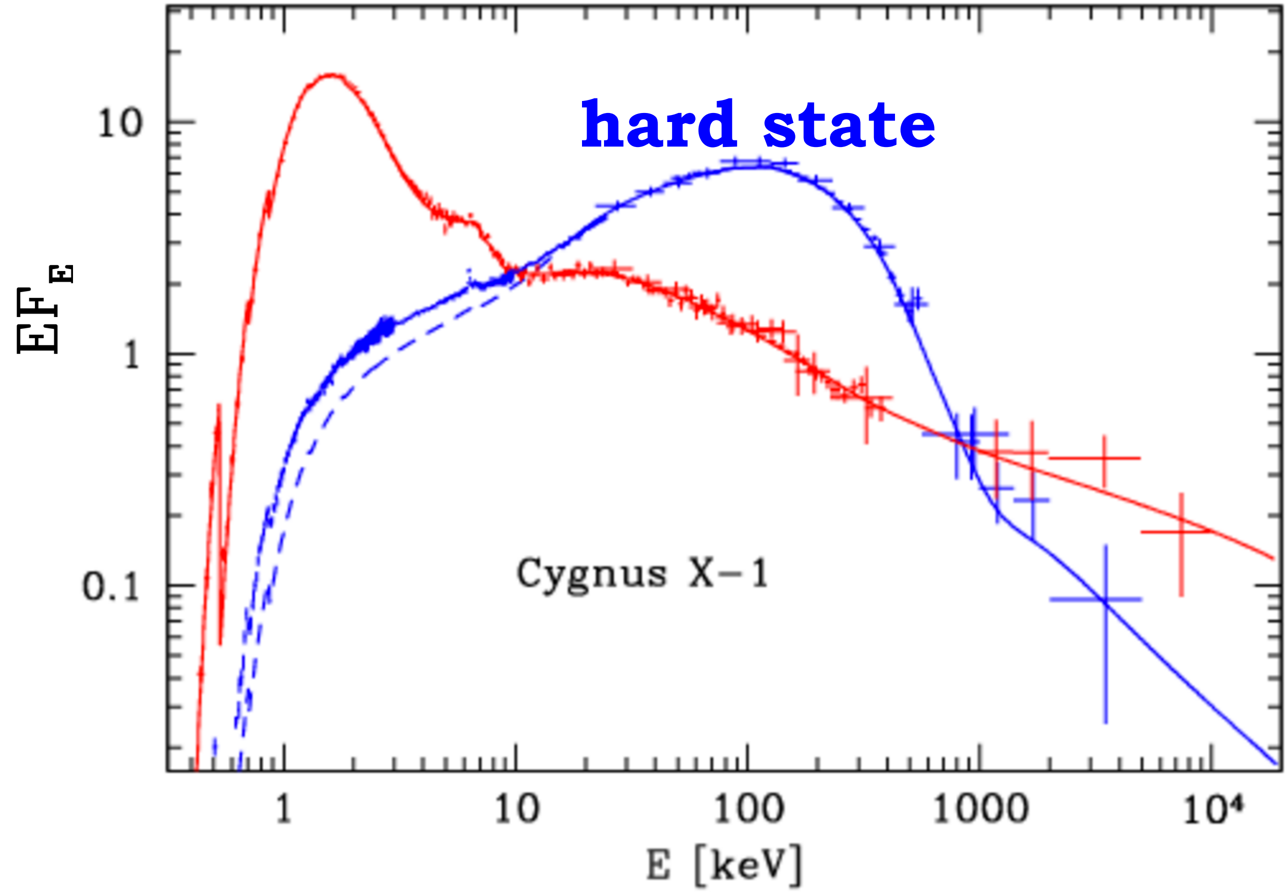
II. Magnetic reconnection

– Magnetic flares near accreting black holes

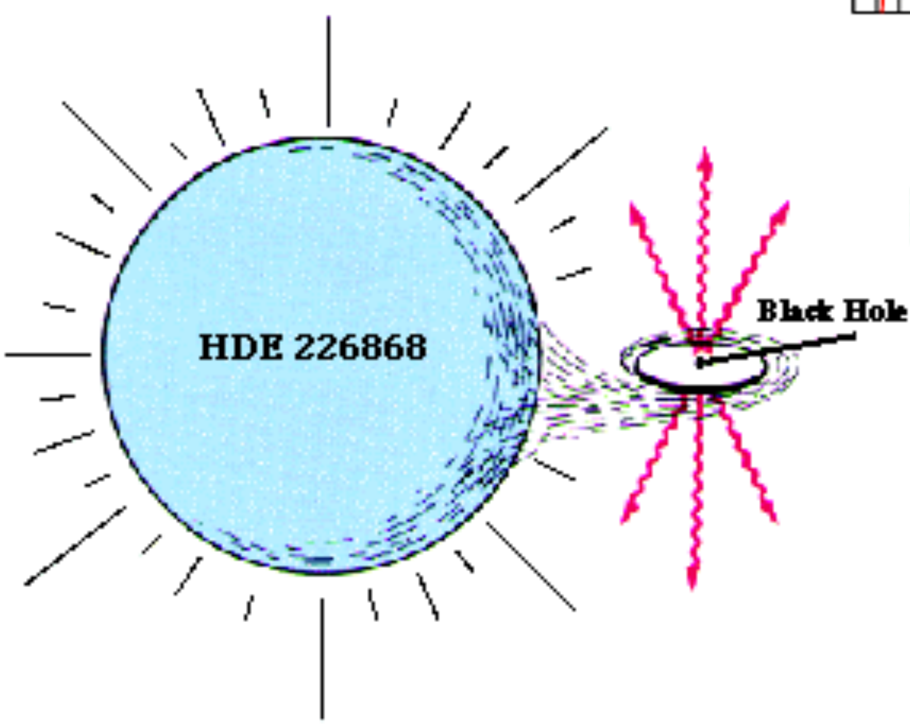
– Flares in magnetars (fireballs)

– Reconnection in pulsar winds and BH corona/jets
(X-ray binaries, AGN, GRBs)

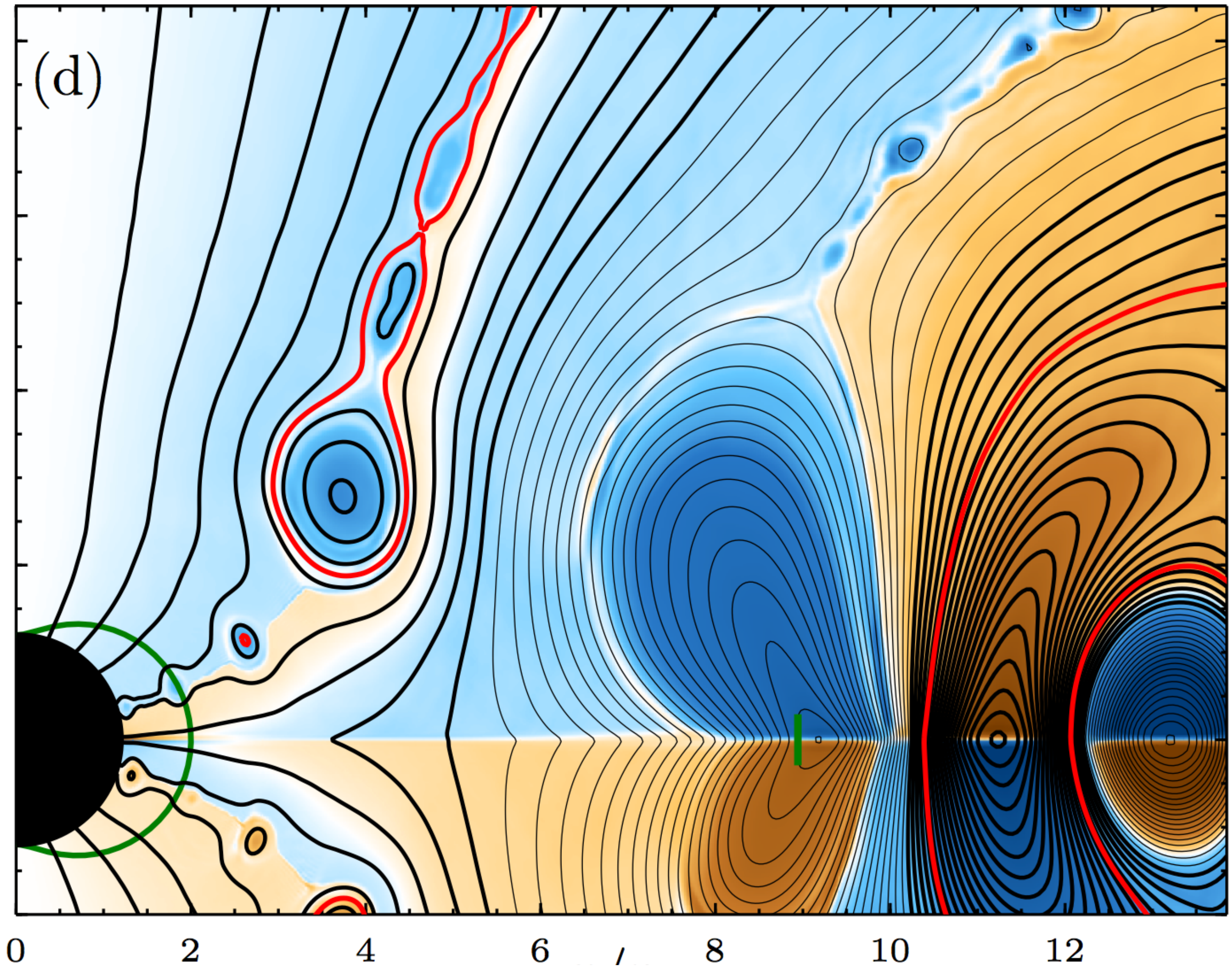
Hard X-rays from accreting black holes



McConnell et al. 2002

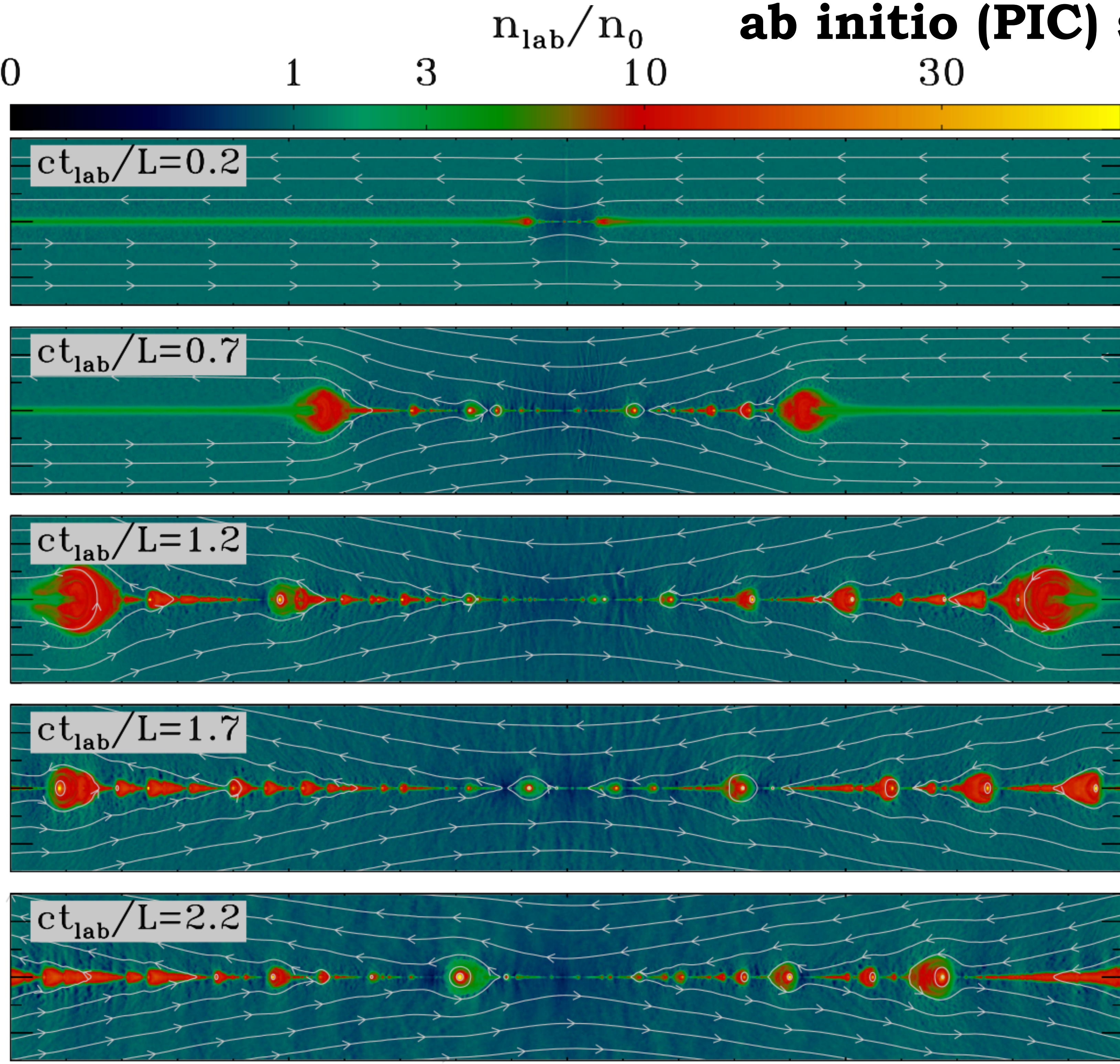


Reconnection near black holes



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 relativistic reconnection

1. Magnetization:
(MHD)

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

$\gg 1$
in accretion disk
corona/jet

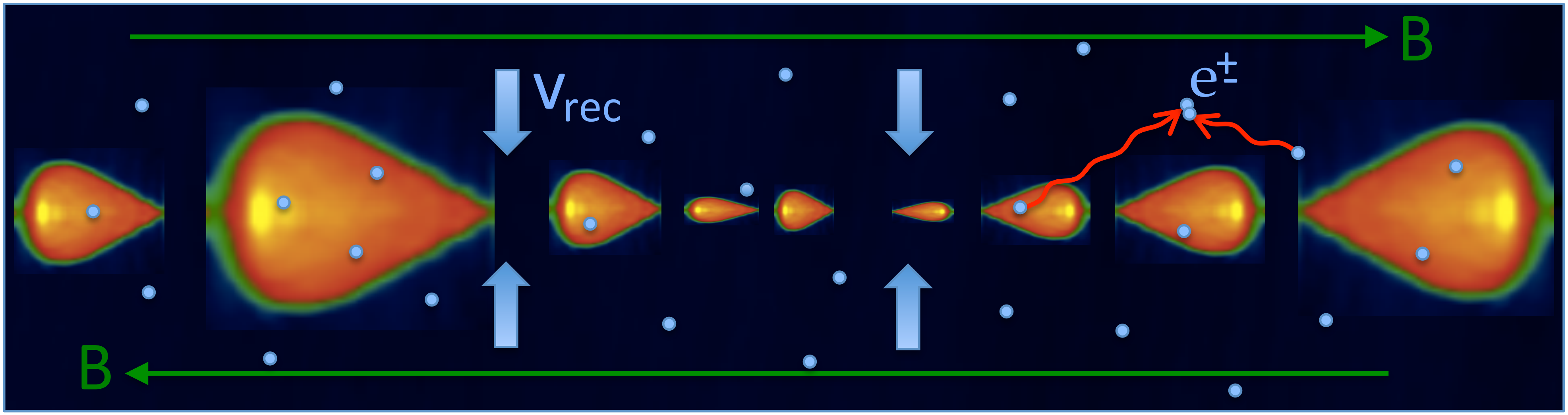
2. Compactness: cooling time vs. light crossing time
(radiative)

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

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

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

$$\Rightarrow \quad \tau_T \sim 1$$

High-energy particles from X-points

X-point acceleration: $$t_X \sim \frac{\bar{\gamma}_e m_e c}{eB} \sim 10^{-9} \left(\frac{M}{10 M_\odot} \right)^{-1/2} \frac{r_g}{c}$$

Synchrotron cooling: $$t_{\rm syn}^{\rm min} \sim \frac{m_e c}{\sigma_{\rm T} U_B \bar{\gamma}_e} \sim 10^{-5} \frac{r_g}{c} \quad (\gamma_e \sim \sigma)$$

Compton cooling of growing plasmoids

Inverse Compton: $t'_{\rm IC} \lesssim \frac{10}{\ell_B} \frac{r_g}{c}$

$t'_{\rm age} \sim 10(w/c)$ Sironi et al. 2016

=> Strong cooling of plasmoids of size $w \gg r_g/\ell_B$

Plasmoid bulk motion

Magnetic stresses push plasmoids: $$f_{\rm push} = \xi \, \frac{U_B}{w}$$

$$\frac{f_{\rm drag}}{f_{\rm push}} = \beta\gamma^2 \, \frac{\tau_{\rm pl}}{\tau_\star} \qquad \tau_\star \equiv \xi \, \frac{U_B}{U_{\rm rad}} \approx \frac{\xi}{\beta_{\rm rec}} \sim 1$$

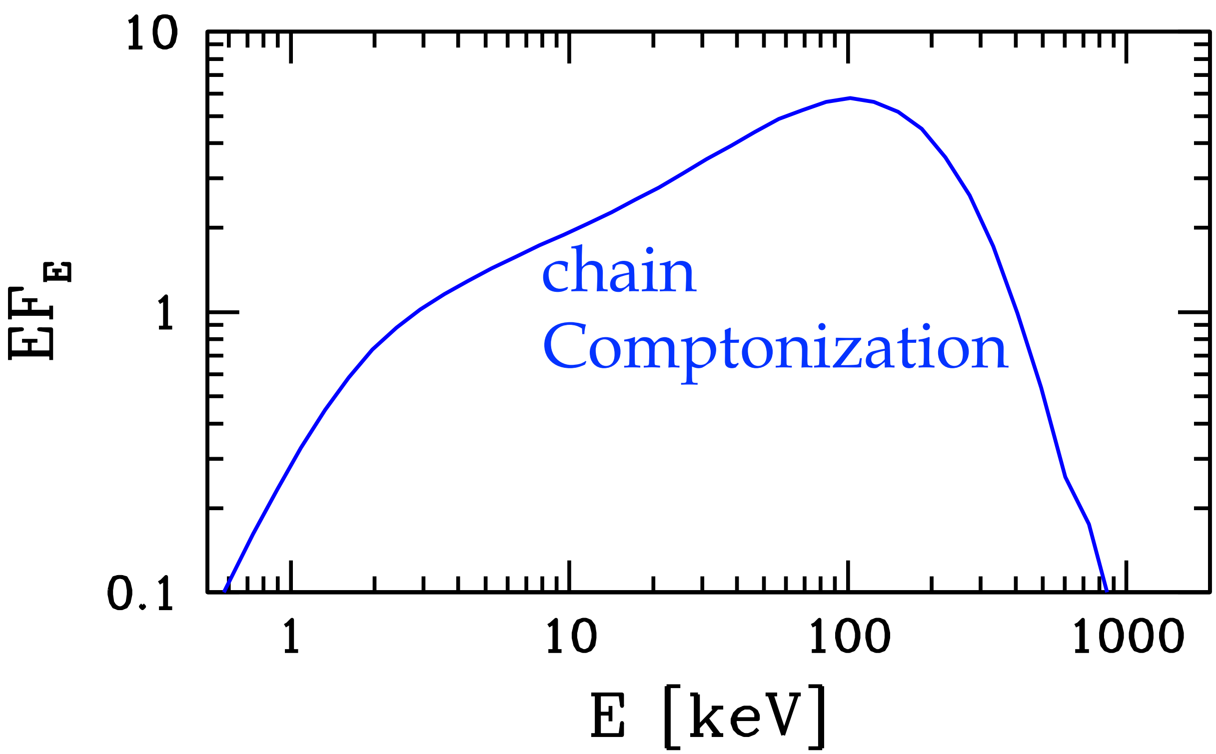
$$\tau_{\rm pl} = n_\pm \sigma_{\rm T} w$$

Drag-limited motion: $\gamma \approx (\tau_\star/\tau_{\rm pl})^{1/2}$ $\quad (\gamma \leq \sigma^{1/2})$

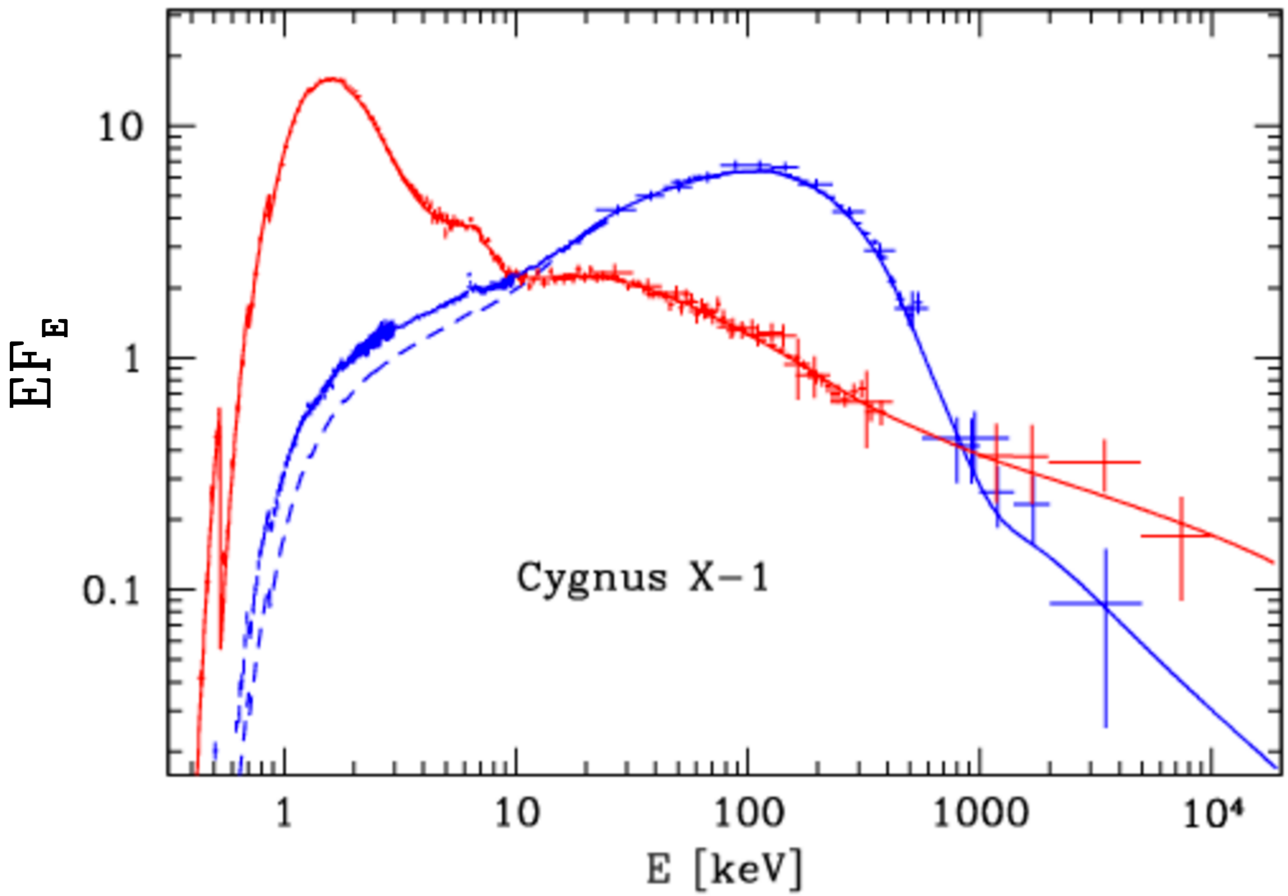
Power deposited in the plasmoid chain:

$$\frac{dL}{d\ln a} \propto \begin{cases} a^{q/2}, & a < 1 \\ a^{q-1}, & a > 1 \end{cases} \qquad a \equiv \beta^2\gamma^2$$

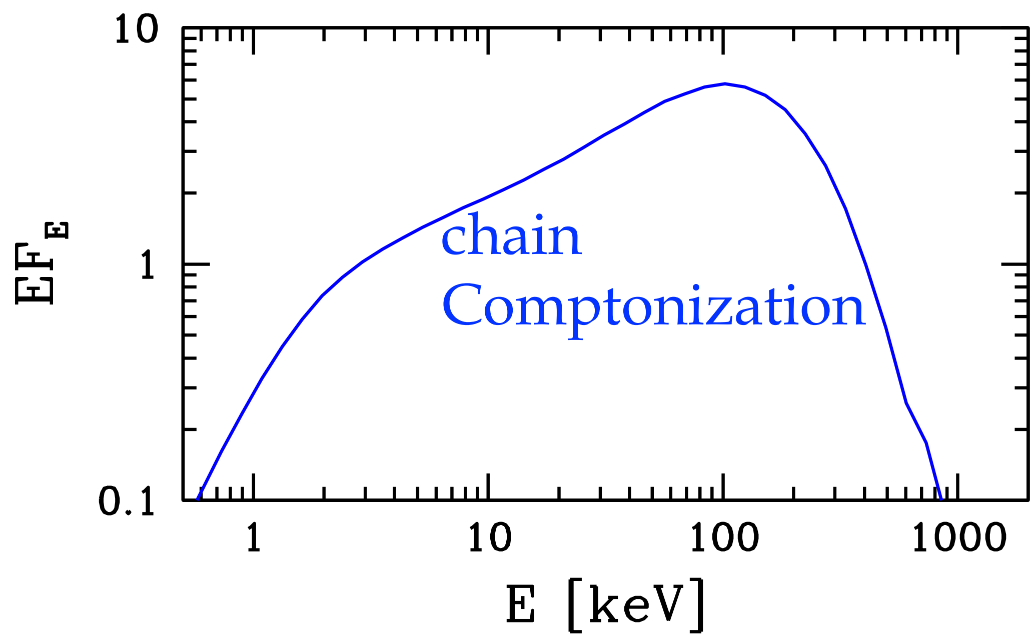
$$\frac{dN}{d\ln w} \propto w^{-q}$$



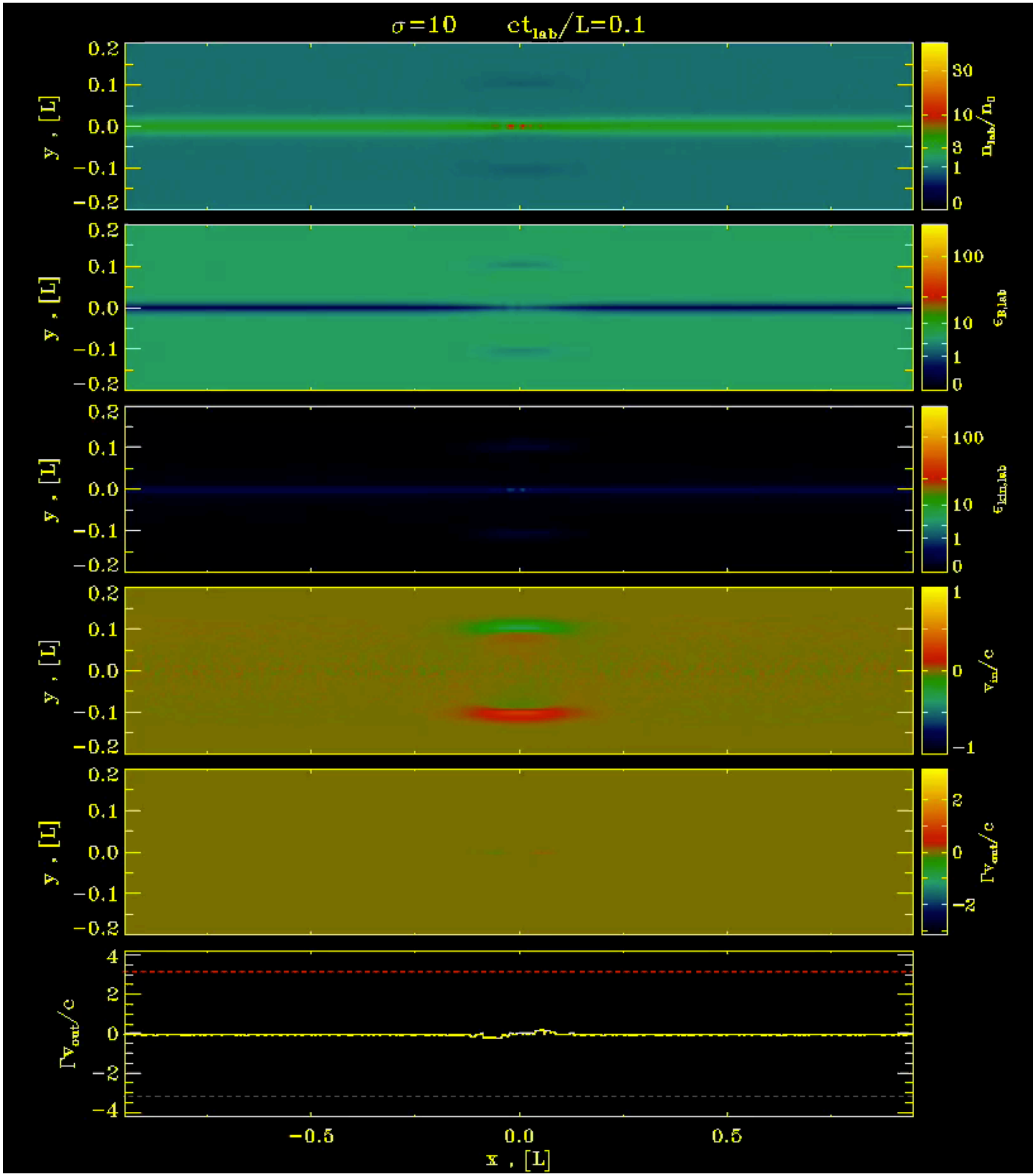
AB 2017



McConnell et al. 2002



Radiative
PIC simulations
(Sironi, AB in prep.)



III. Turbulence

(accretion disks, jets, mergers, magnetar flares)

Radiation damping of turbulence cascade

cascade power: $\dot{Q} \sim \frac{h\rho v_0^3}{\ell_0}$ spectrum: $v(\ell) = v_0 \left(\frac{\ell}{\ell_0}\right)^{1/3}$

$$\dot{U}_{\rm damp}(\ell) \sim \frac{h\rho v^2(\ell)}{t_{\rm damp}(\ell)} \qquad t_{\rm damp}(\ell) \sim \frac{\ell^2}{\nu}$$

$$\nu \sim \frac{U}{U + \rho c^2}\, l_\star c$$

Radiation damping of turbulence cascade

cascade power: $\dot{Q} \sim \frac{h\rho v_0^3}{\ell_0}$ spectrum: $v(\ell) = v_0 \left(\frac{\ell}{\ell_0}\right)^{1/3}$

$$\dot{U}_{\rm damp}(\ell) \sim \frac{h\rho v^2(\ell)}{t_{\rm damp}(\ell)} \qquad t_{\rm damp}(\ell) \sim \frac{\ell^2}{\nu}$$

$$\nu \sim \frac{U}{U + \rho c^2}\, l_\star c$$

$$\dot{U}_{\rm damp} = \dot{Q}$$

$$Re = \frac{\ell_0 v_0}{\nu} \qquad \ell_{\rm damp} \sim \ell_0\, Re^{-3/4} \qquad \ell_0 = \tau \ell_\star$$

$$\ell_{\rm damp} \gg \ell_\star \quad \Leftrightarrow \quad Re \ll \tau^{4/3}$$

– "viscous" regime
shear Comptonization

Collisionless dissipation regime: $Re > \tau^{4/3}$

$$t_{\rm damp}(\ell) > t_{\rm turb} = \frac{\ell}{v(\ell)}$$

if true at $\ell \geq \ell_\star$ then also true at all ℓ

$$t_{\rm damp}(\ell) \sim \frac{U + \rho c^2}{U} \frac{\ell_\star}{c} \times \begin{cases} (\ell/\ell_\star)^2 & \ell > \ell_\star \\ 1 & \ell < \ell_\star \end{cases}$$

Turbulent jets in GRBs

ξ = turbulence injection power divided by total jet power

switch from viscous regime to collisionless dissipation: $$\tau_{\rm switch} \sim \frac{1}{8\xi^2}$$

Zrake, AB, Lundman 2018

Turbulent jets in GRBs

ξ = turbulence injection power divided by total jet power

switch from viscous regime to collisionless dissipation: $\tau_{\rm switch} \sim \dfrac{1}{8\xi^2}$

Compton → $\theta_{\rm C}$

injected → ξ

energy balance: $(\theta - \theta_{\rm C})\,\tau \approx \dfrac{\xi}{3}\,\dfrac{\rho c^2}{U}$

Zrake, AB, Lundman 2018

Dissipation at high compactness: summary

- Luminosity is powered by dissipation of magnetic/kinetic energy in a compact region filled with dense radiation

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

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

- Best method of study: direct numerical experiment (PIC/Vlasov plasma + radiative transfer)