Astrophysical pair plasmas

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1. Sites of pair creation
2. Shocks (explosions)
3. Magnetic reconnection
4. Electric discharge

Pair plasma is created in compact objects:

Persistent sources:

- accreting black holes
- pulsars, magnetars

Explosions:

- magnetar flares
- cosmological gamma-ray bursts (GRBs)

Energy transformation in compact objects

gravity -> kinetic energy -> magnetic fields, heat -> radiation

main ways of particle acceleration

reconnection, shocks, electric gaps

Explosions

Dissipation power up to 10^{54} erg/s in a region as small as 10 km.

Thermalized energy density $U \sim aT^4$

temperatures $kT > m_e c^2 = 0.511$ MeV

magnetic fields up to $B \sim 10^{16}$ G

Ultra-dense, neutron-dominated, object (a star or an accretion disk) surrounded by pair-dominated magnetized plasma with kT ~ MeV. Powerful outflows/jets.

In the expanding ejecta: further dissipation of magnetic energy and bulk motions.
It is capable of producing high-energy particles and photons.

Main mechanism of pair creation: photon-photon collisions $\gamma + \gamma \rightarrow e^+ + e^-$

threshold	$E_1 E_2 > (m_e c^2)^2$
cross section near threshold	$\sigma_{\gamma\gamma} \sim 0.1\sigma_\mathrm{T}$
optical depth	$\tau_{\gamma\gamma} = \sigma_{\gamma\gamma} n_\gamma\, s$
compactness parameter	$\boxed{\ell \equiv \frac{U_\mathrm{rad}\sigma_\mathrm{T} s}{m_e c^2}}$

Radiative cooling

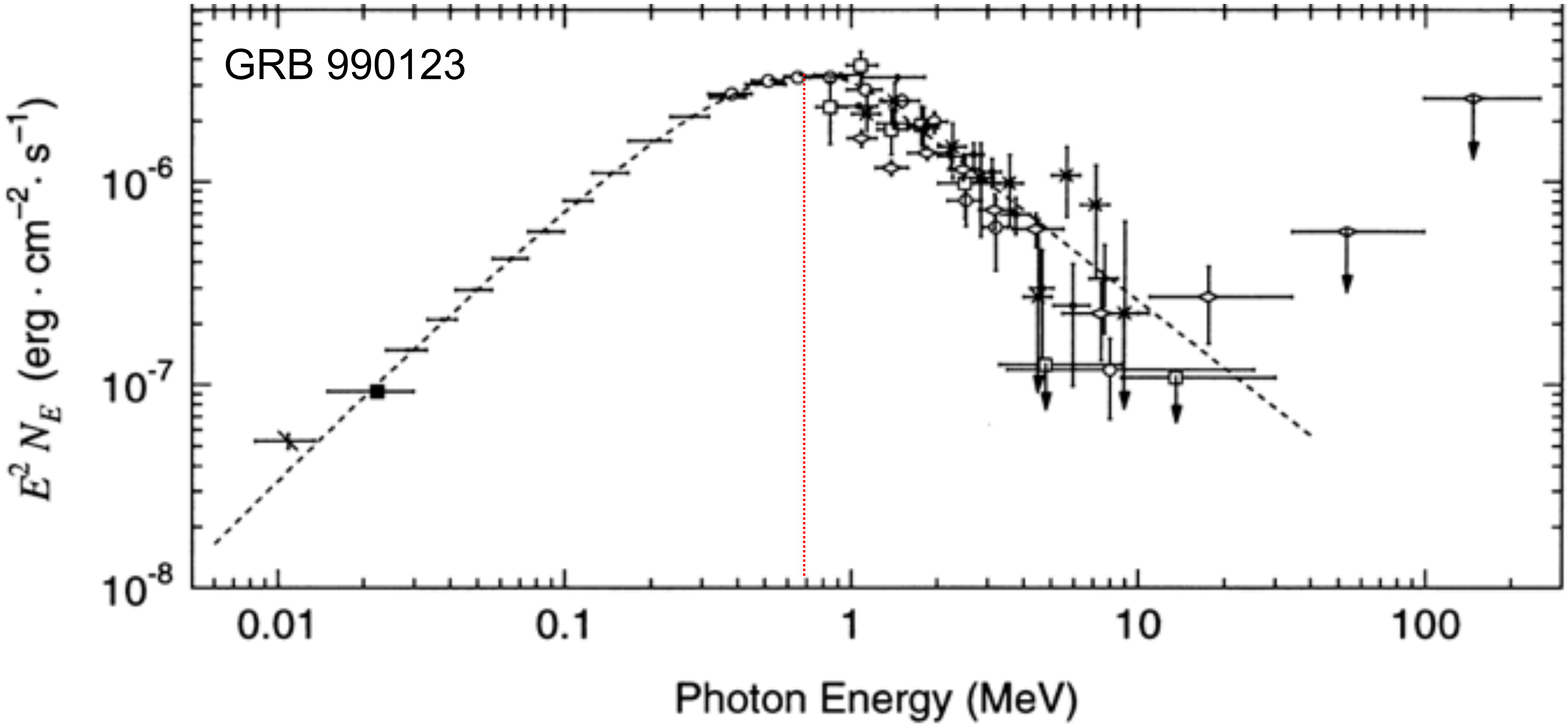
Compton cooling time < light-crossing time

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

Dissipation processes affected by pair creation

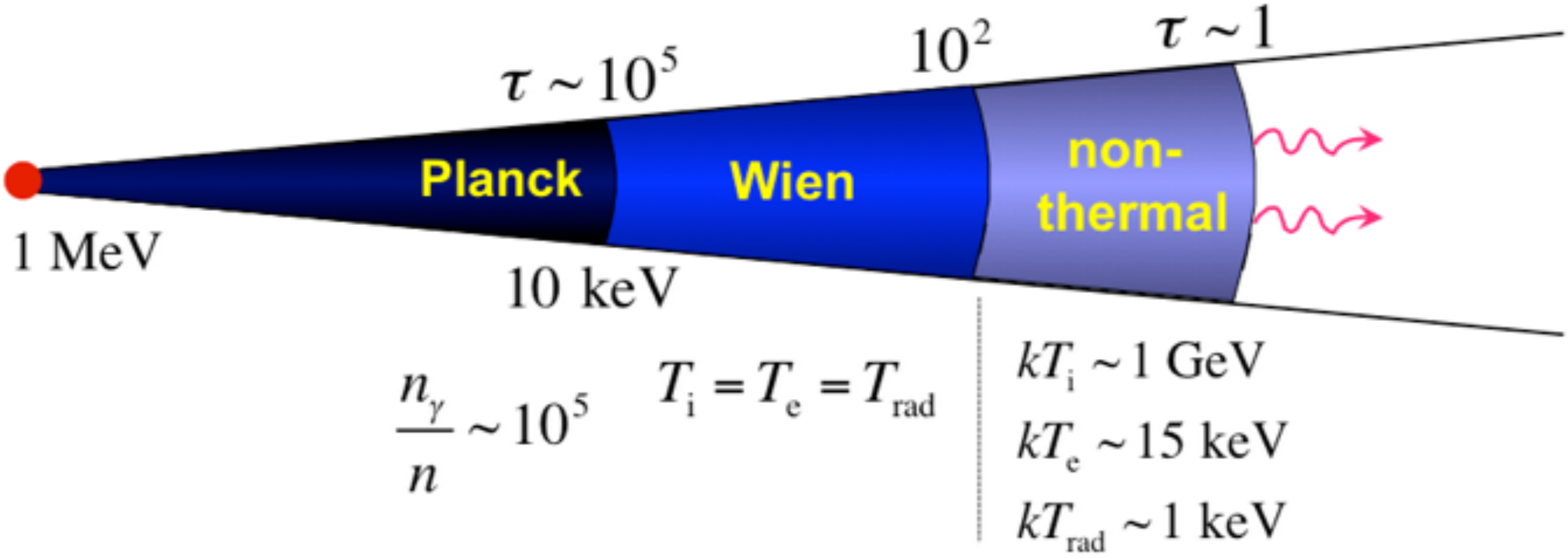
I. Shock waves in GRBs

GRB spectrum



Briggs et al. (1999)

GRB: opaque heated fireball (cf. big bang)



internal shocks — one of a few possible dissipation processes in the outflow (also magnetic dissipation, n-p friction)

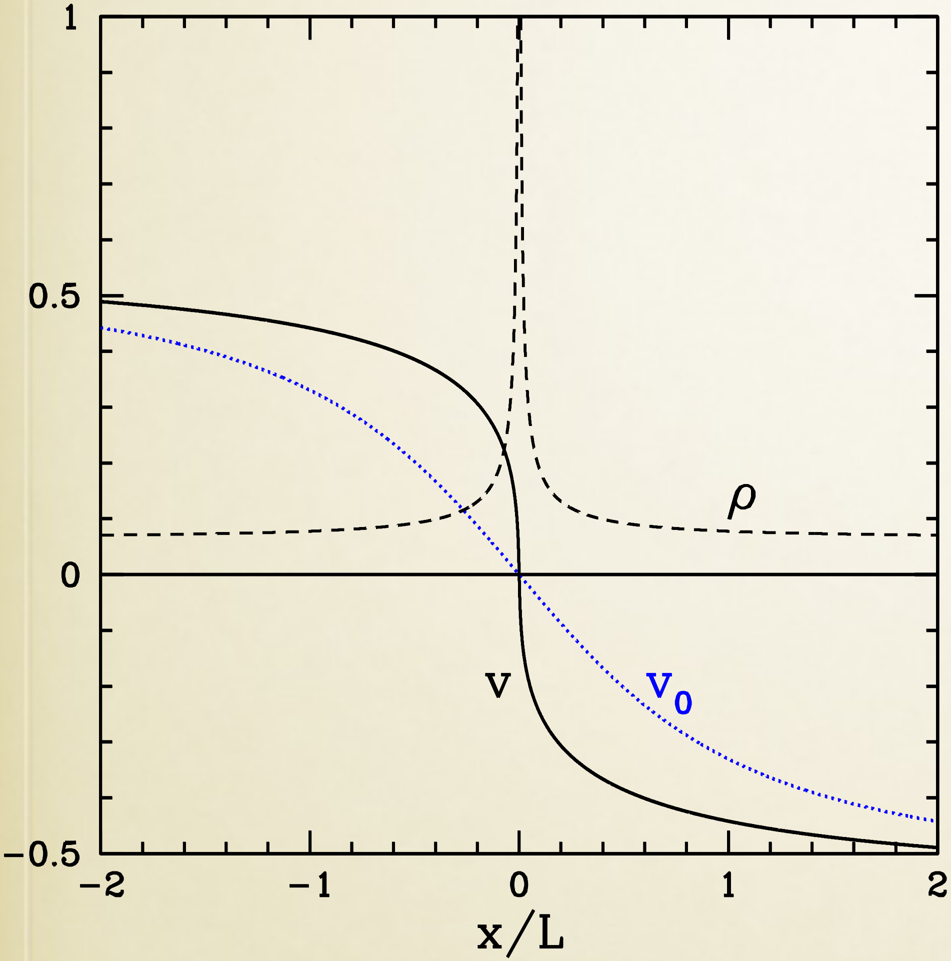
$n_\gamma/n_b \sim 10^5$

radiation mediated shocks

Zeldovich, Raizer 1966
Weaver 1976
Blandford, Payne 1981
Budnik et al. 2010
Levinson 2012
AB 2017

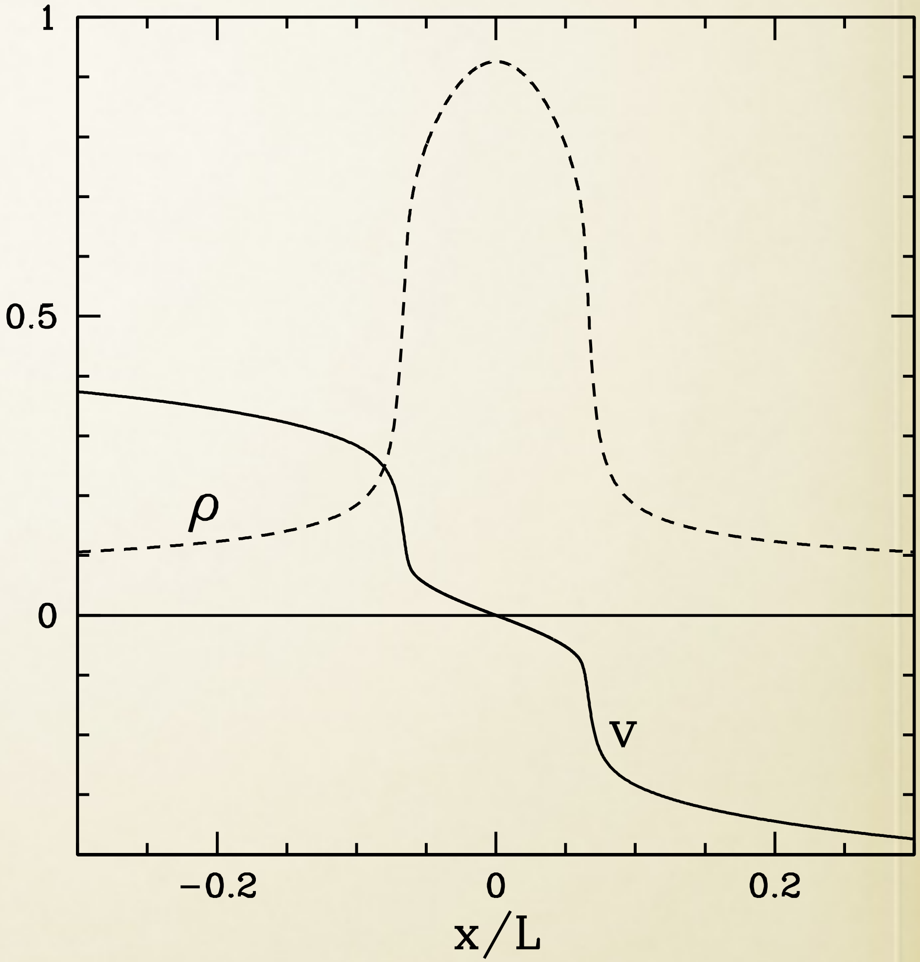
Do shocks generate energetic particles?
Do shocks create e+- pairs?

ballistic flow: caustic



(rest frame of the caustic)

shock formation



$$P_{\rm rad} \propto \tilde{\rho}^{4/3}$$

transverse

$$P_B = \frac{\mathcal{B}^2}{8\pi} \propto \tilde{\rho}^2$$

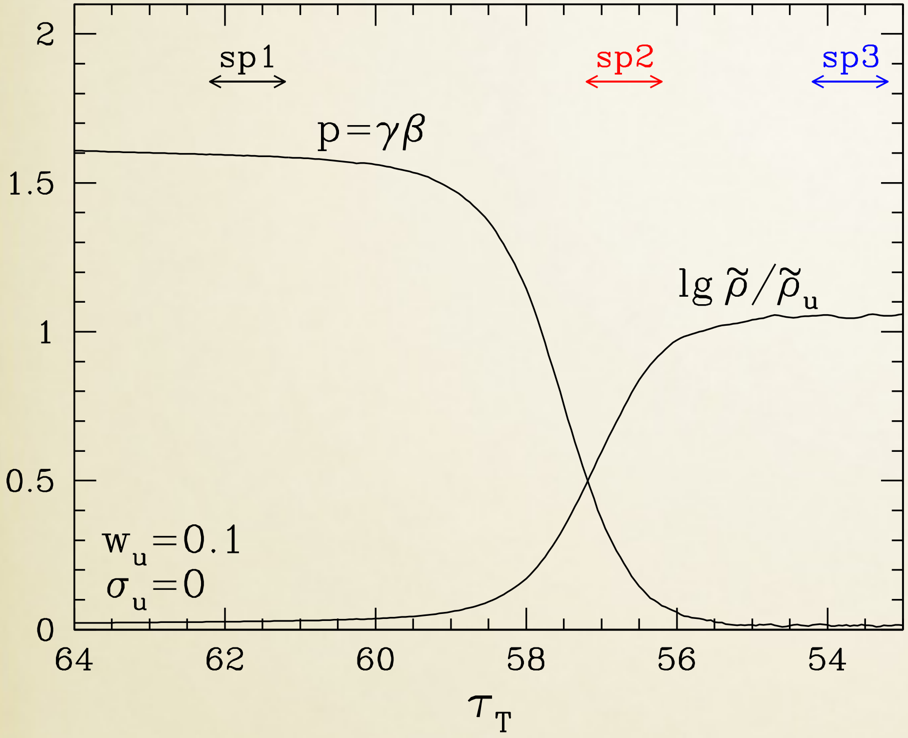
Radiation MHD from first principles: “Photon In Cell”

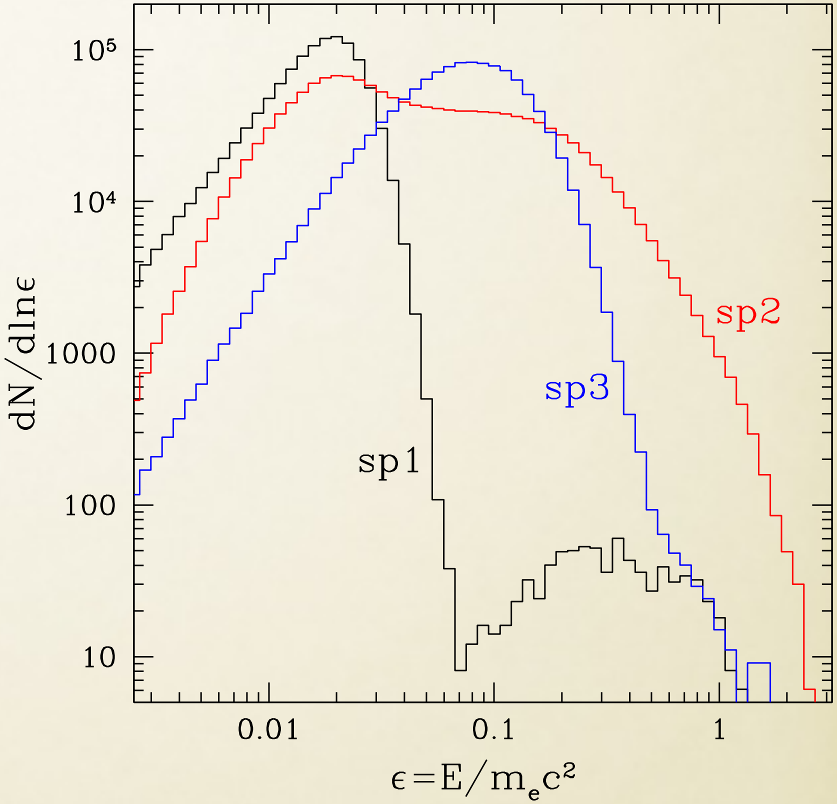
Fluid motion: Lagrangian grid

Radiation: individual photons
Monte-Carlo scattering

1D problem: $\sim 10^4$ shells
$\sim 10^8$ photons

Radiation mediated shock (B=0)



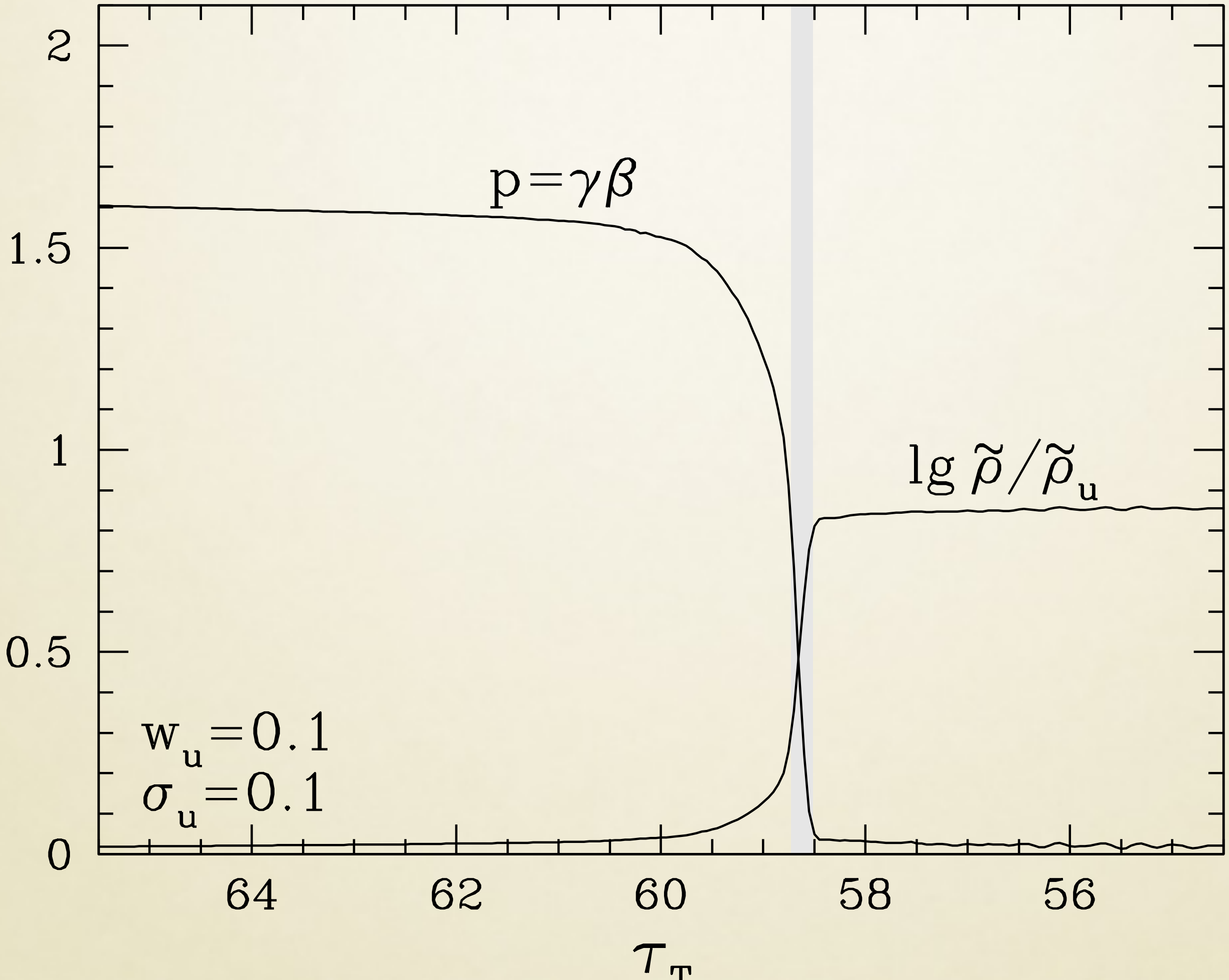


Bulk Comptonization, Klein-Nishina, and pair creation

$$n_\pm \sim 10^{-3} n_\gamma \qquad Z_\pm \sim 10^2 \left(\frac{n_\gamma/n_b}{10^5}\right)$$

AB 2017

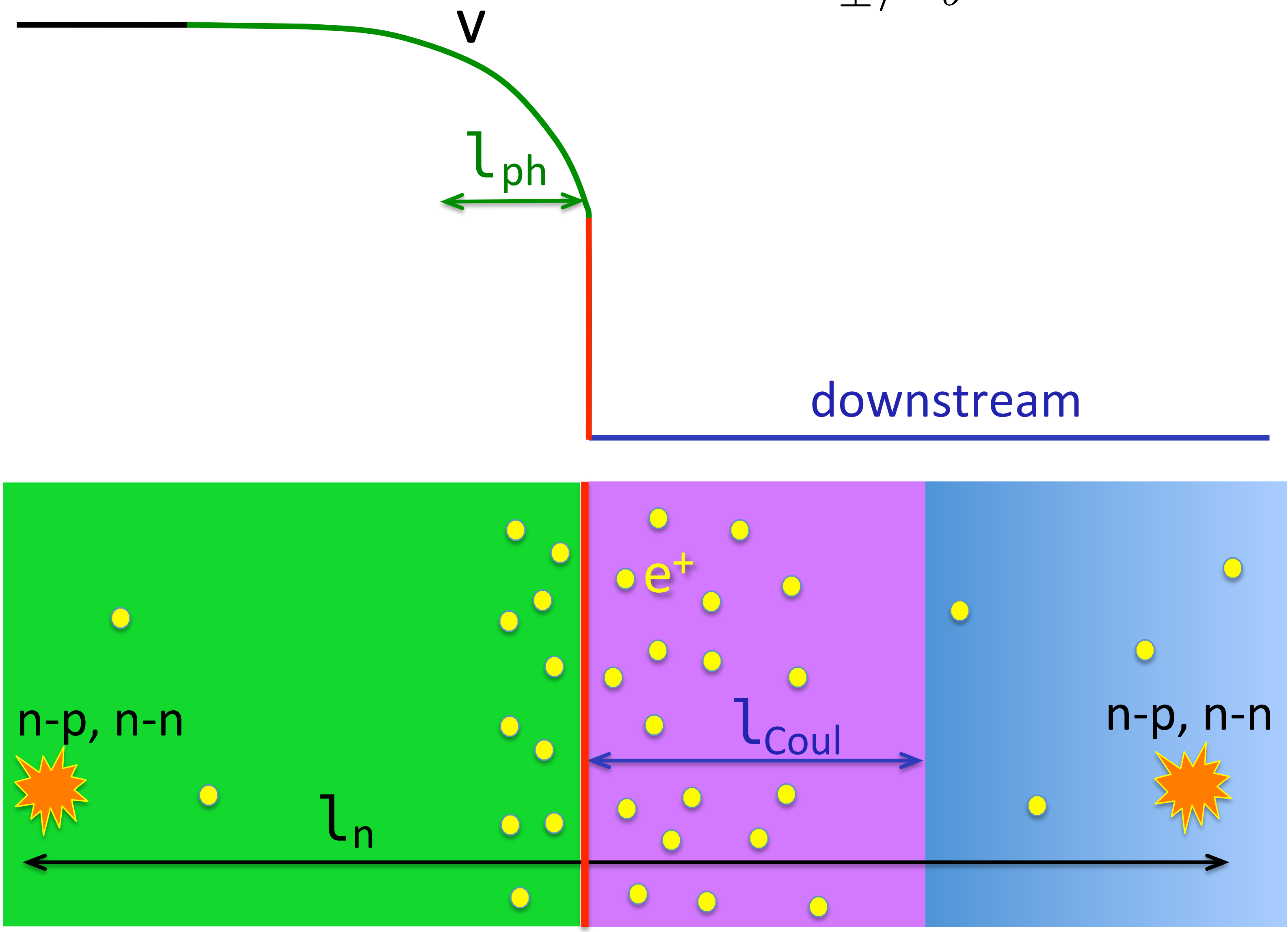
Shock in a magnetized flow



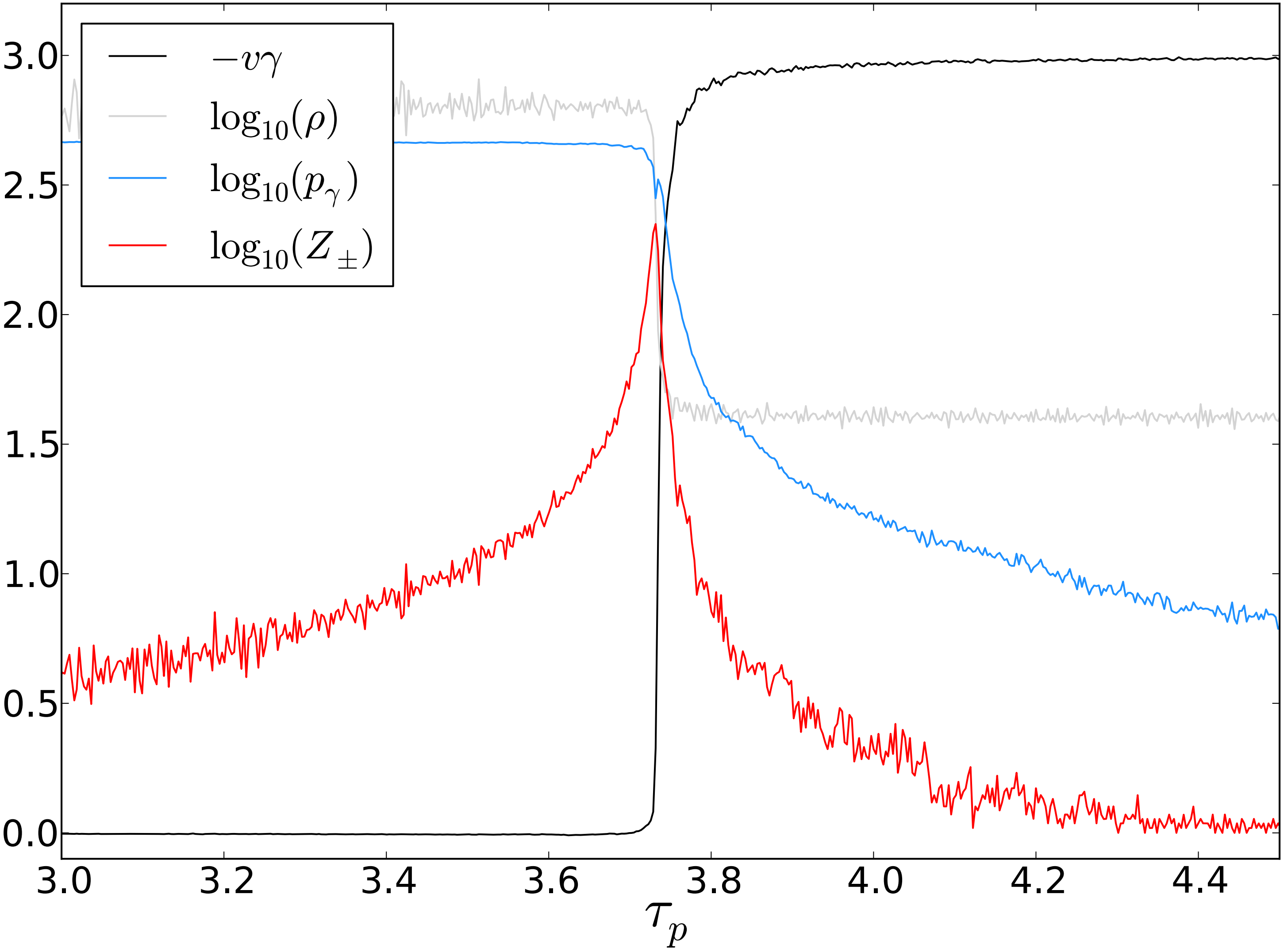
Sub-photospheric shock:

e+- dressed

$n_\pm / n_b \sim 10^2$



Radiation-mediated shock



cold plasma; pair creation without high-energy particles!

Lundman & AB, in preparation

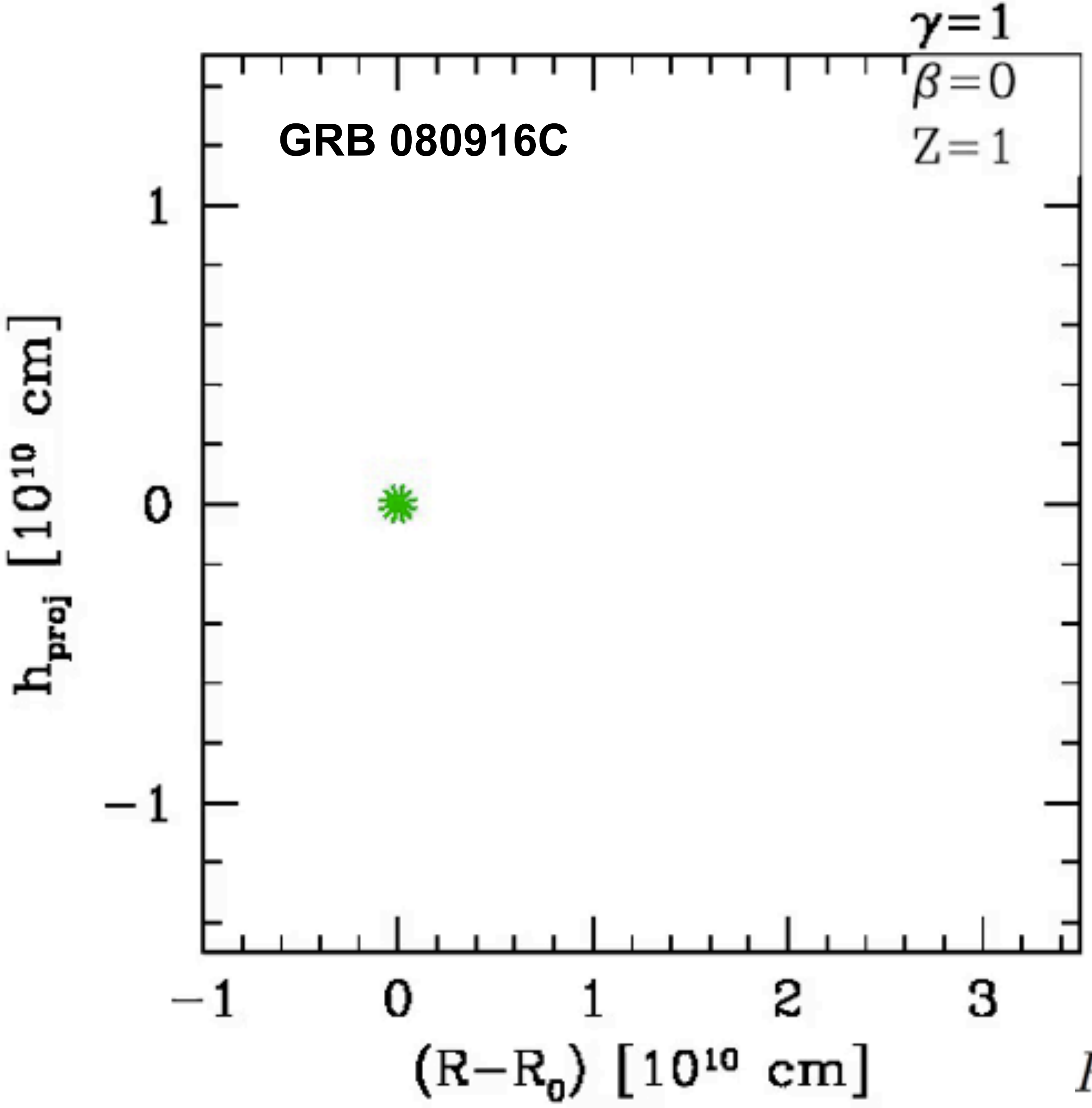
Consequences of pair creation:

- shock thickness shrinks
- pairs increase optical depth and give “grip” to radiation
- energy per electron is reduced

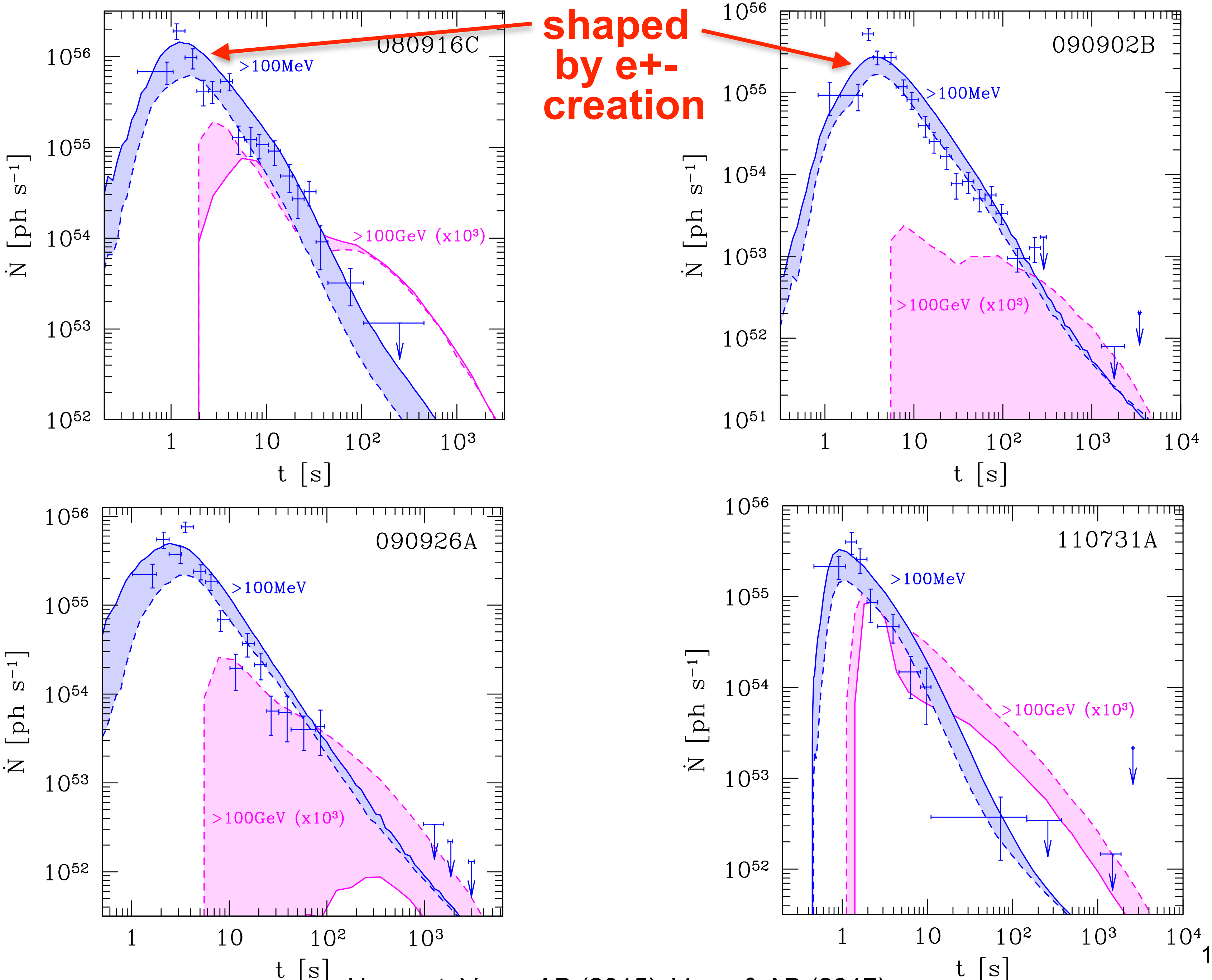
Shocks “carry” the photosphere with them.
Velocity profile between upstream and downstream is shaped by radiation pressure + collisionless jump

Pairs in the shock are producers of inverse Compton and synchrotron radiation.

Pair creation by GRB radiation in the external medium

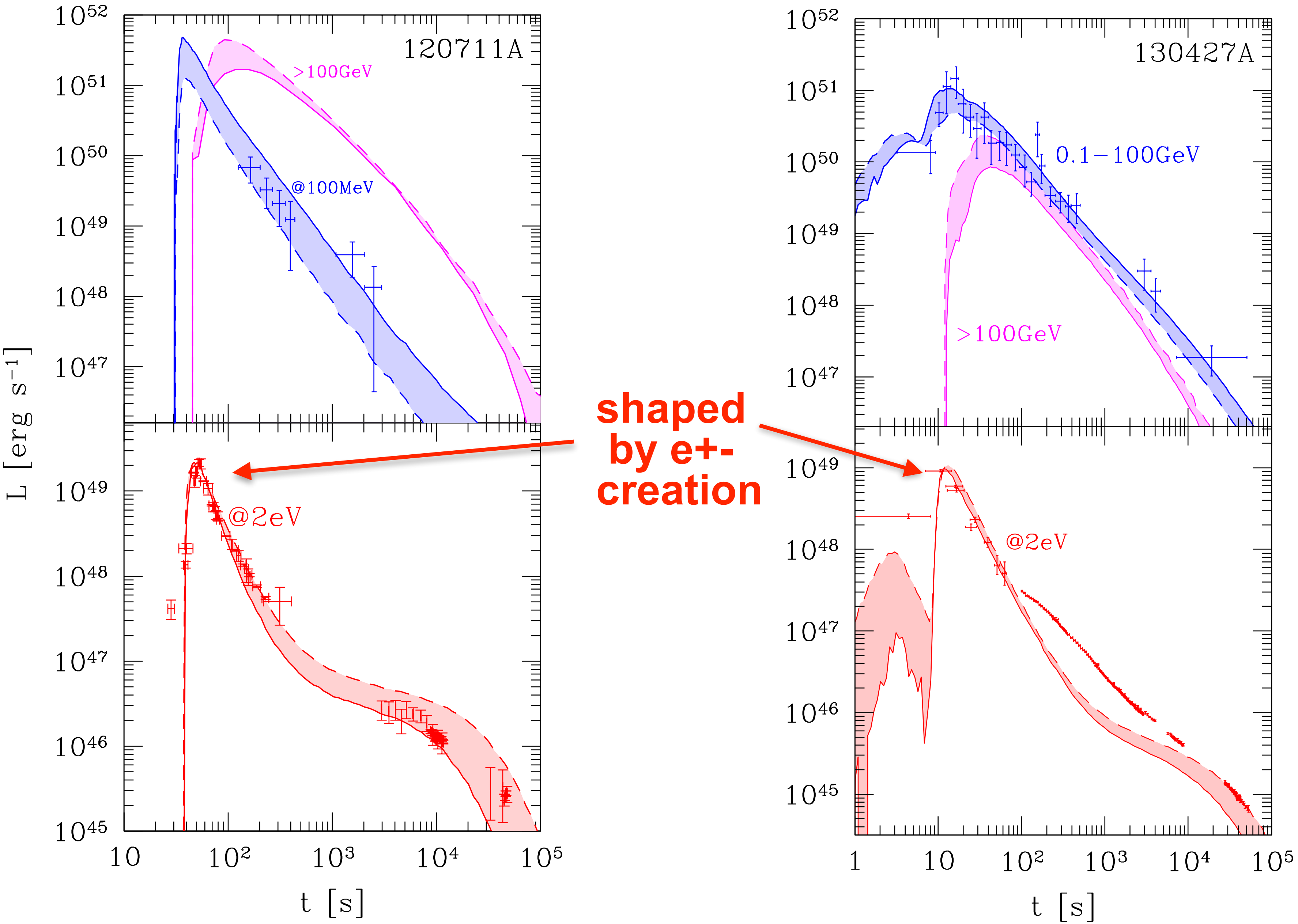


$R_0 = 1.5 \times 10^{16}\,\mathrm{cm}$



shaped by e+- creation

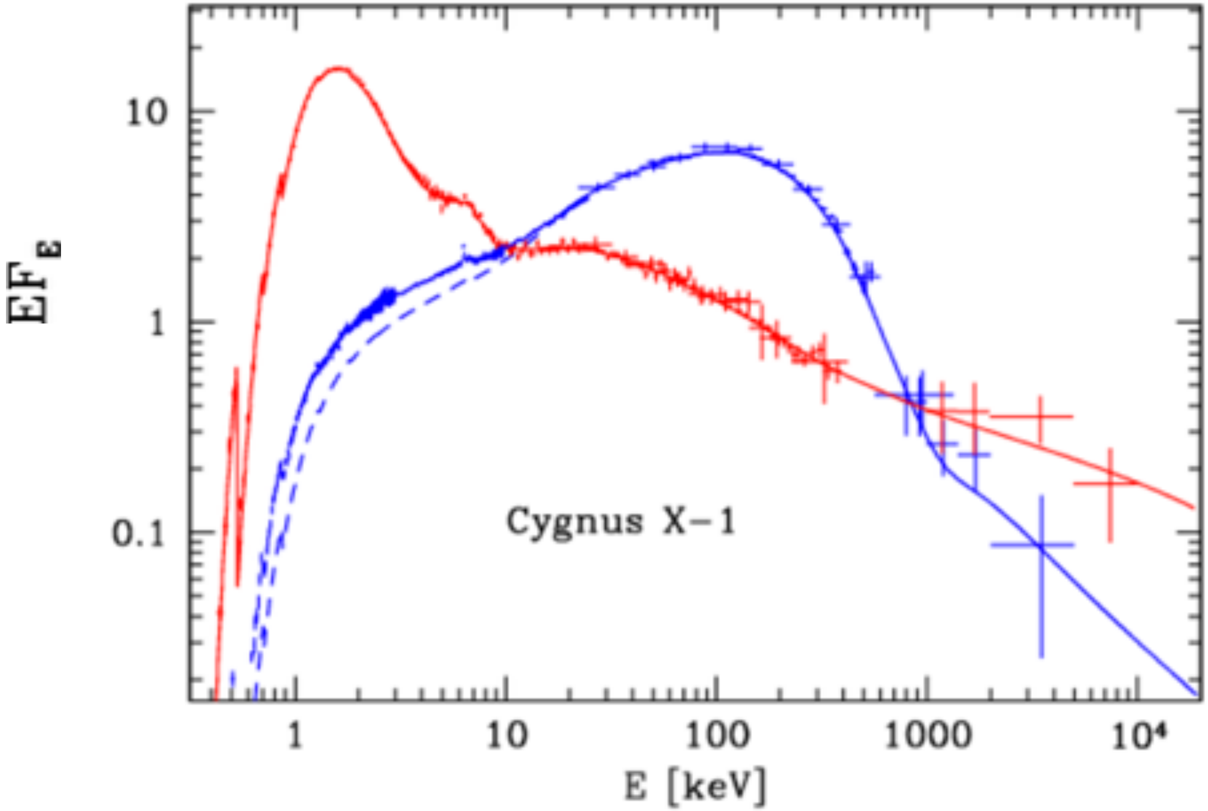
Hascoet, Vurm, AB (2015); Vurm & AB (2017)



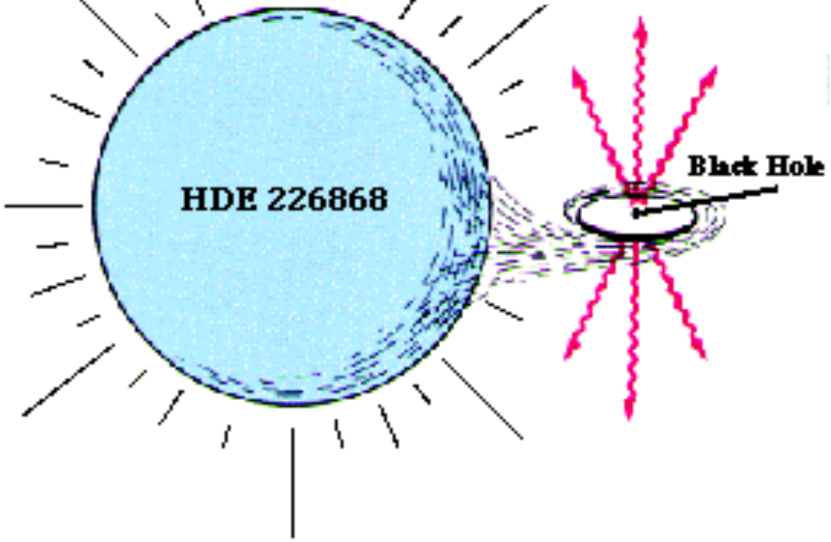
shaped by e+- creation

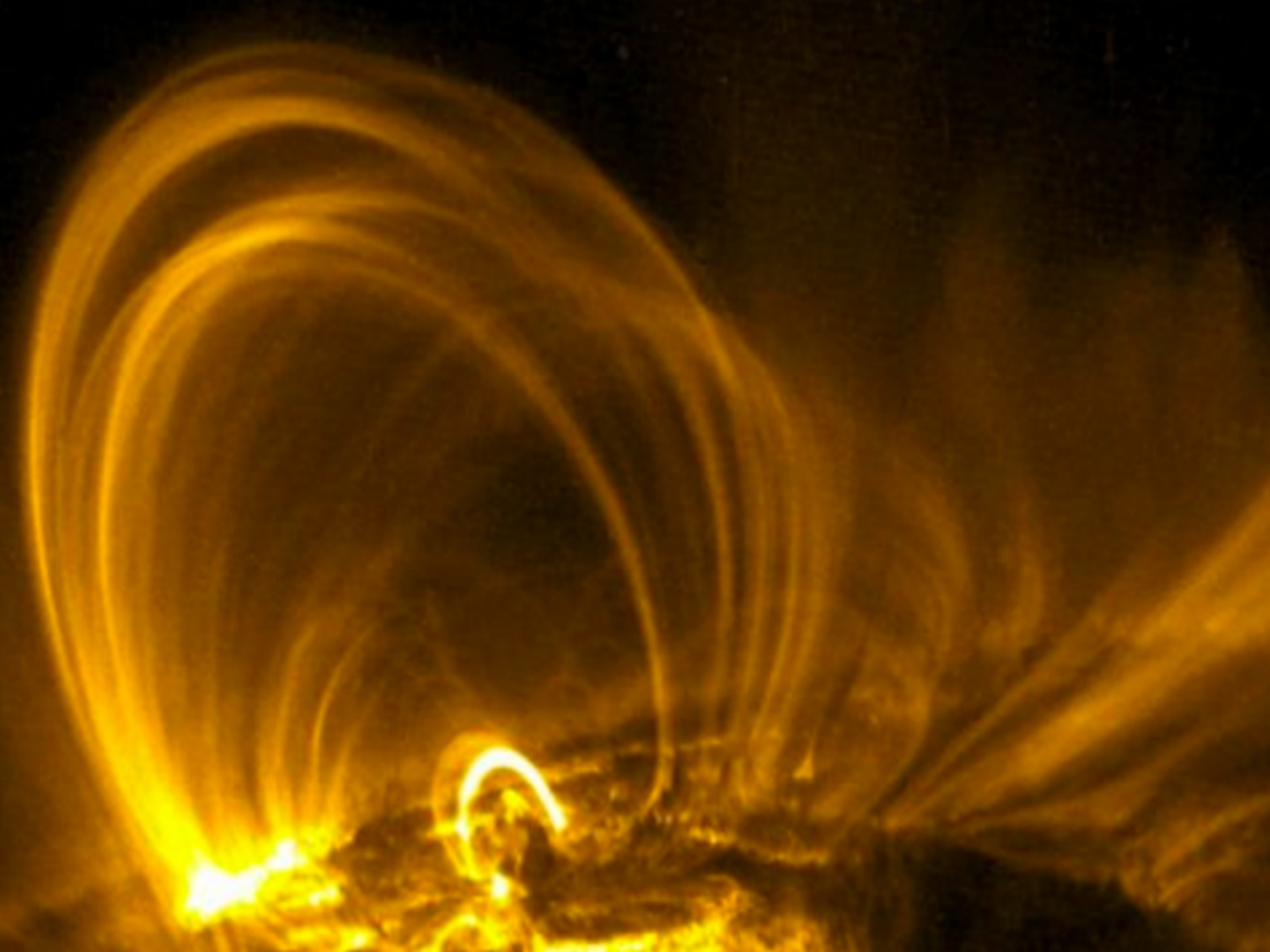
Dissipation processes affected by pair creation

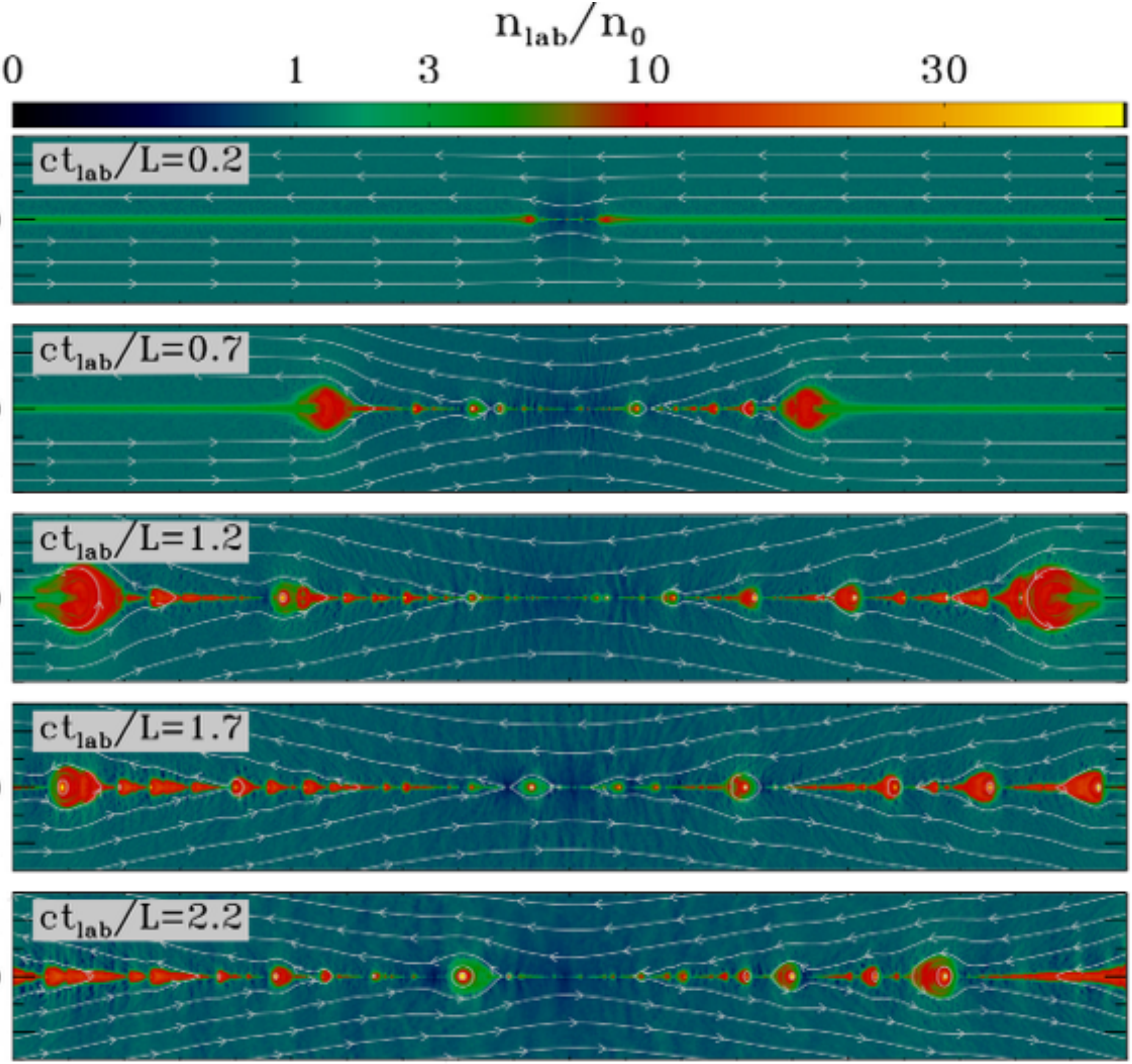
II. Magnetic flares near accreting black holes



McConnell et al. 2002







Self-similar chain of plasmoids: $r_{\rm L} < w < 0.1s$

Uzdensky et al. 10

Melzani et al. 14

Sironi, Spitkovsky 14

Guo et al.16

Sironi et al.16

Werner et al.16

Radiative magnetic reconnection:

1. Magnetization: $$\boxed{\sigma = \frac{B^2}{4\pi\rho c^2} = \frac{2U_B}{\rho c^2}} = 1 - 10^3$$

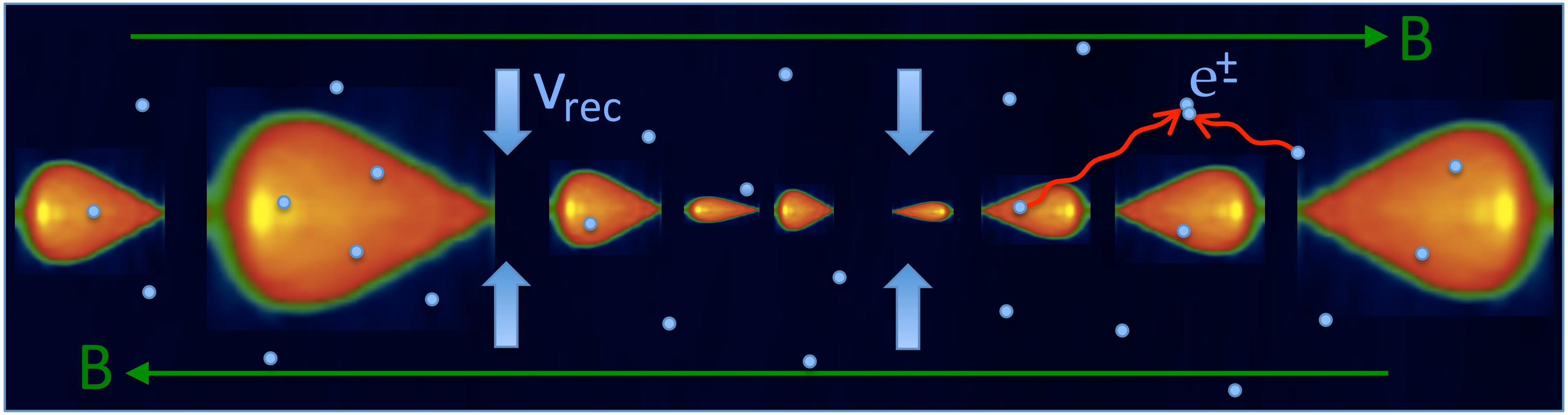
2. Compactness: cooling time vs. light crossing time

$$\frac{t_{\rm IC}}{s/c} = \frac{3}{4\gamma_{\rm e}\,\ell_{\rm rad}} \qquad \ell_{\rm rad} = \frac{U_{\rm rad}\sigma_{\rm T}s}{m_e c^2}$$

$$U_{\rm rad}c \sim U_B v_{\rm rec} \qquad \ell_{\rm rad} \sim \frac{v_{\rm rec}}{c}\,\ell_B$$

$$\boxed{\ell_B = \frac{U_B\sigma_{\rm T}s}{m_e c^2}} \sim 10^3$$

Reconnection in the radiative regime (high compactness parameter)



$\ell \gg 1 \quad \Rightarrow$

1. Plasmoids are cooled
2. Energetic photons (>1 MeV) convert to e+- pairs

Pair creation and optical depth

e+- creation: $\dot{n}_{\pm} \sim \frac{Y f_{\rm HE} U_B}{t_{\rm res} m_e c^2}$ $\dot{n}_{\rm ann} = \frac{3}{8} \sigma_{\rm T} c\, n_+ n_-$

annihilation balance:

$$\tau_{\rm T} \sim \frac{16}{3} \beta_{\rm rec} \times \begin{cases} u, & u < 1 \\ u^{1/2}, & u > 1 \end{cases} \qquad u = (3/16) Y f_{\rm HE}\, \ell_B$$

$$\Rightarrow \quad \boxed{\tau_{\rm T} \sim 1}$$

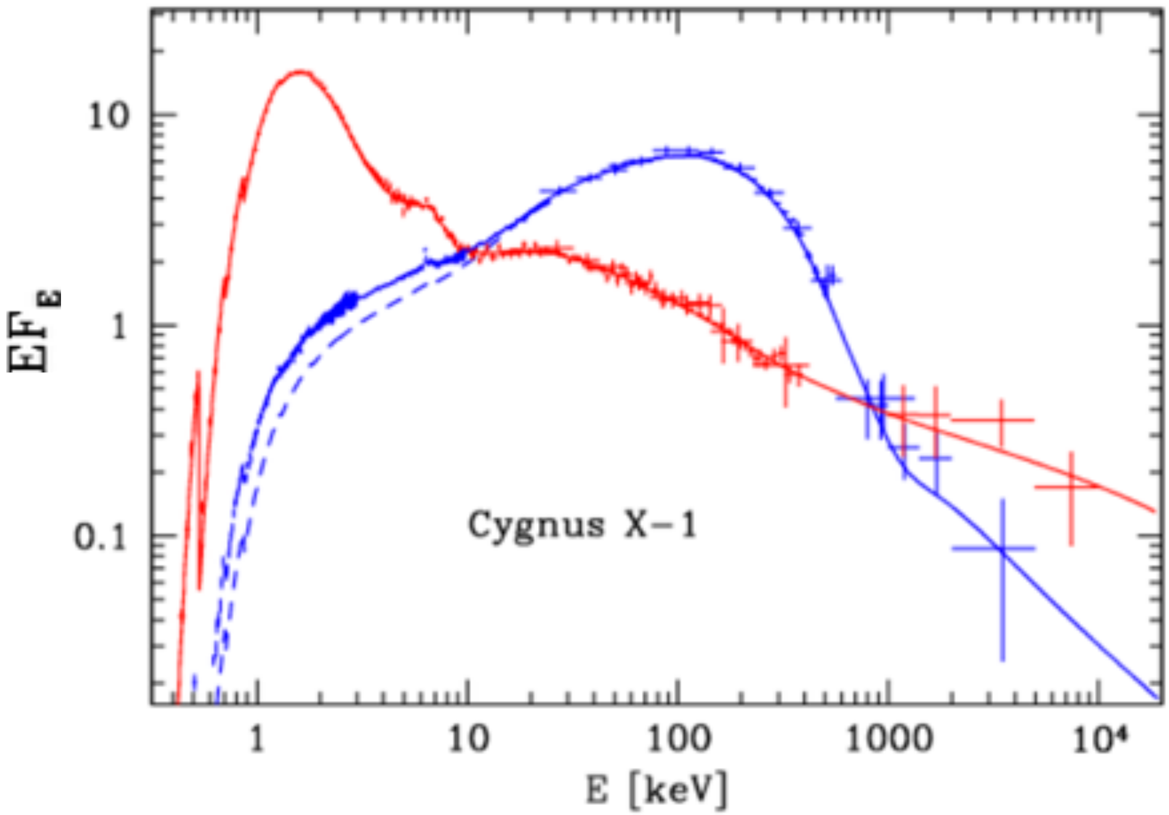
Bulk motion of pair-loaded plasmoids

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

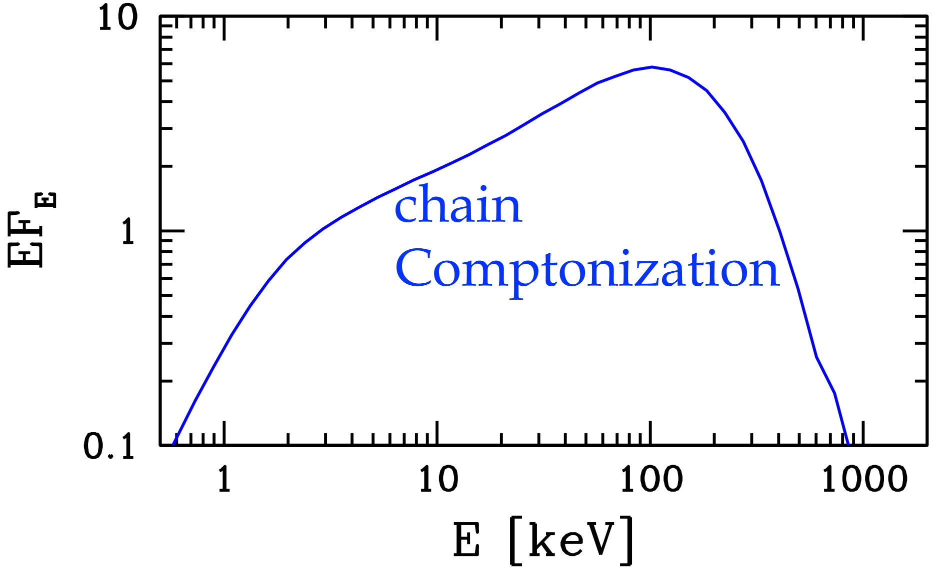
Radiation exerts drag: $f_{\rm drag} \approx \beta\gamma^2 U_{\rm rad}\sigma_{\rm T} n_{\pm}$

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

$$\tau_\star \equiv \xi\,\frac{U_B}{U_{\rm rad}} \approx \frac{\xi}{\beta_{\rm rec}}$$

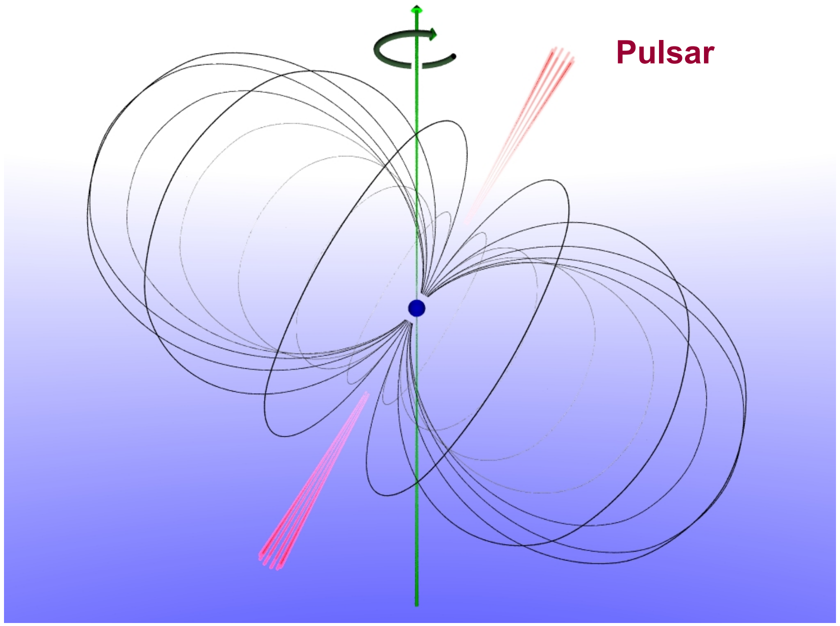


McConnell et al. 2002

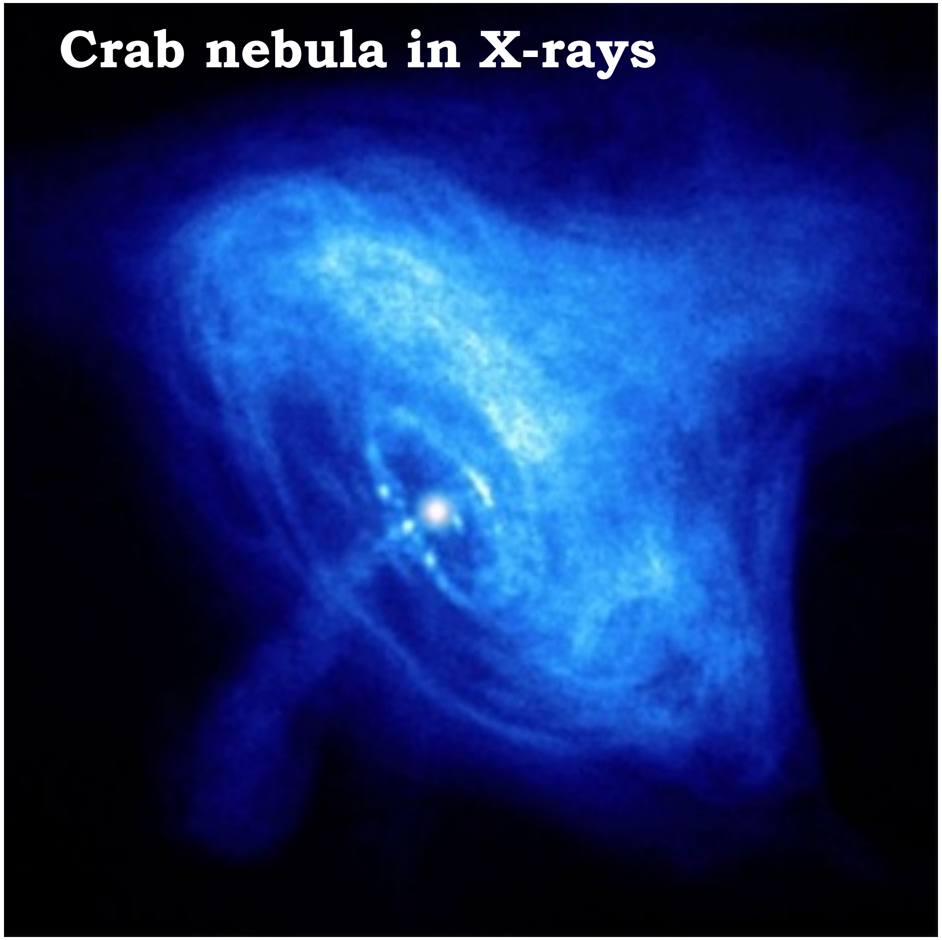


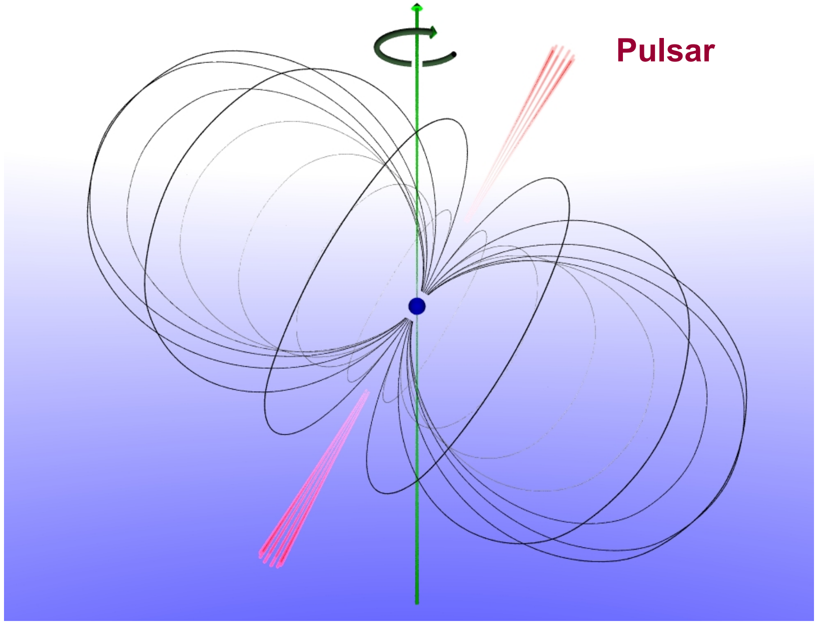
AB 2017

III. Rotation-powered pulsars



- beamed coherent radio emission
- X/γ-ray emission
- e+-loaded wind





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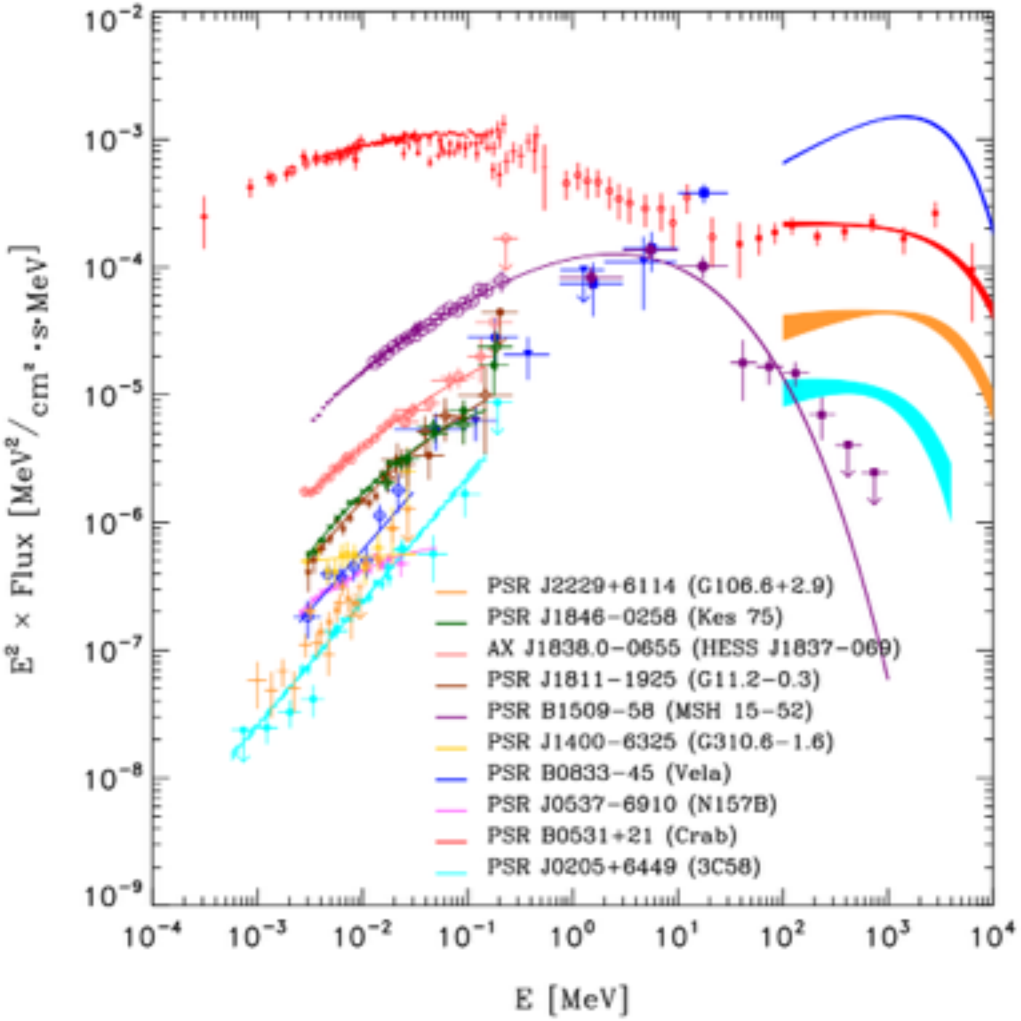


Kuiper, Hermsen 2015

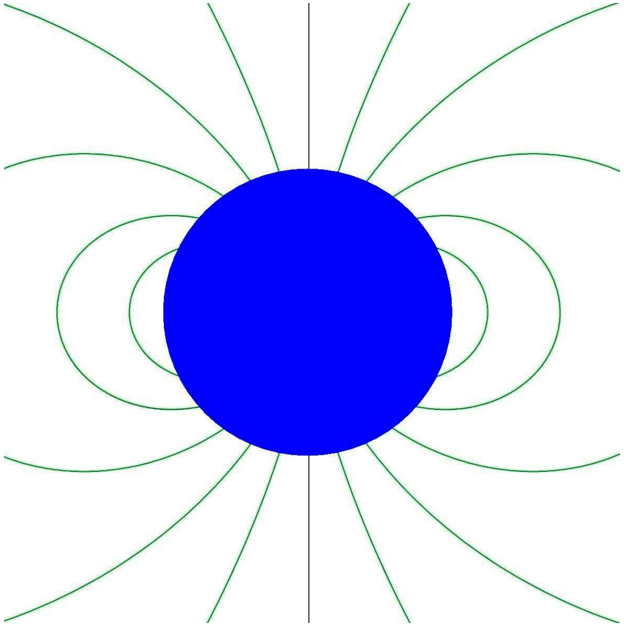
Pulsar magnetosphere: pair dominated

- Where is plasma created?
- How much plasma is ejected in a wind?
- Where are gamma-rays emitted?
- How are coherent radio waves emitted?

New approach to the old puzzle: global PIC simulations

Chen, AB 2014; Philippov et al. 2014, 2015; Cerutti et al. 2015, 2016; Belyaev 2015

First-principle numerical experiment



$$d\mathbf{p}/dt = e\,\mathbf{E} + e\,\mathbf{v} \times \mathbf{B}/c$$

$$\partial\mathbf{B}/\partial t = -c\nabla \times \mathbf{E}$$

$$\partial\mathbf{E}/\partial t = c\nabla \times \mathbf{B} - 4\pi\,\mathbf{J}$$

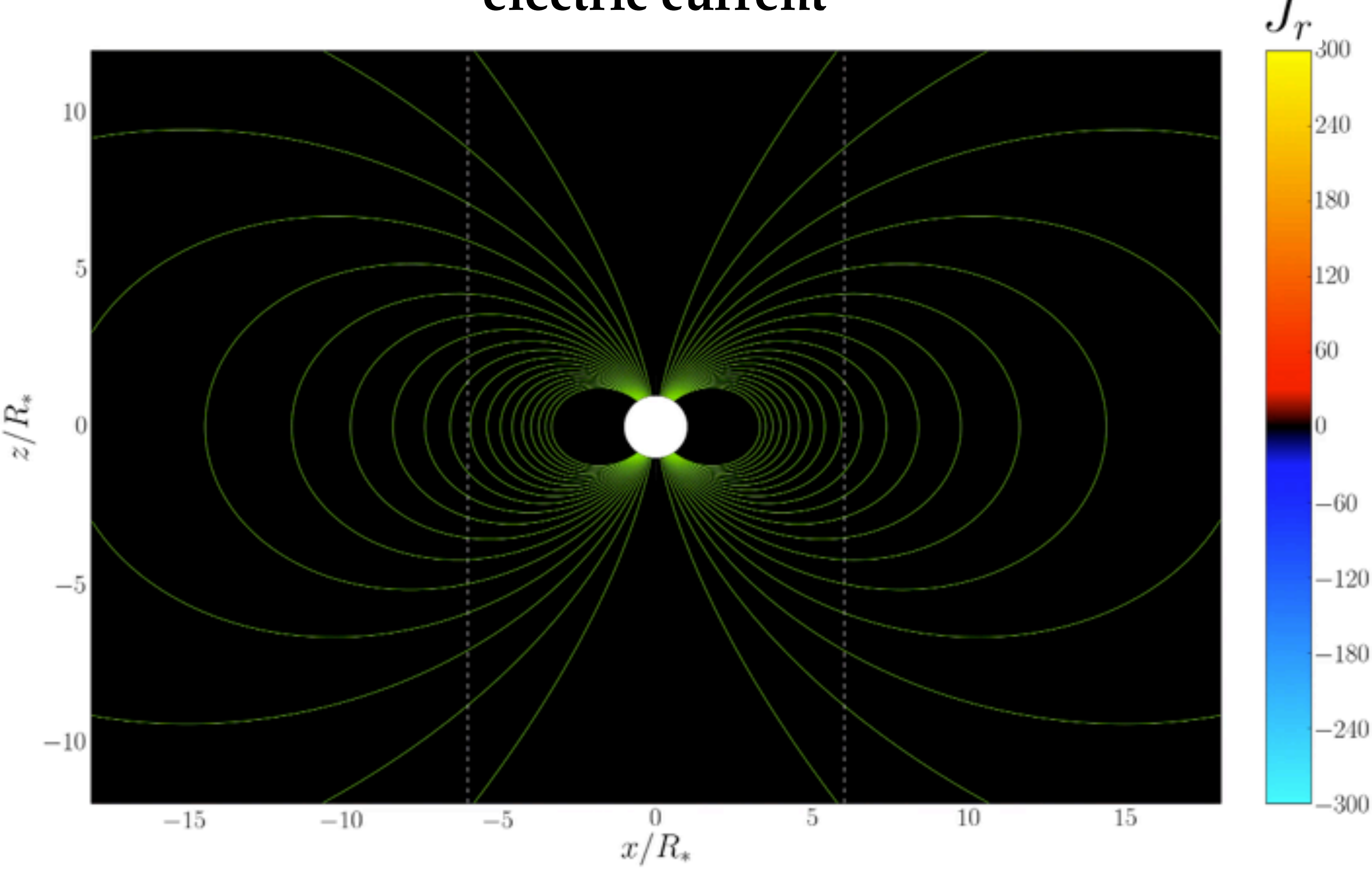
- Start with a non-rotating star and spin it up. E will be induced
- Particles lifted from the star will move in the self-consistent electromagnetic field
- E and B: fixed inside the star, calculated from Maxwell equations outside the star
- Accelerated particles emit photons
- High-energy photons convert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

Method: **“Particle in cell” (PIC) + pair creation:**

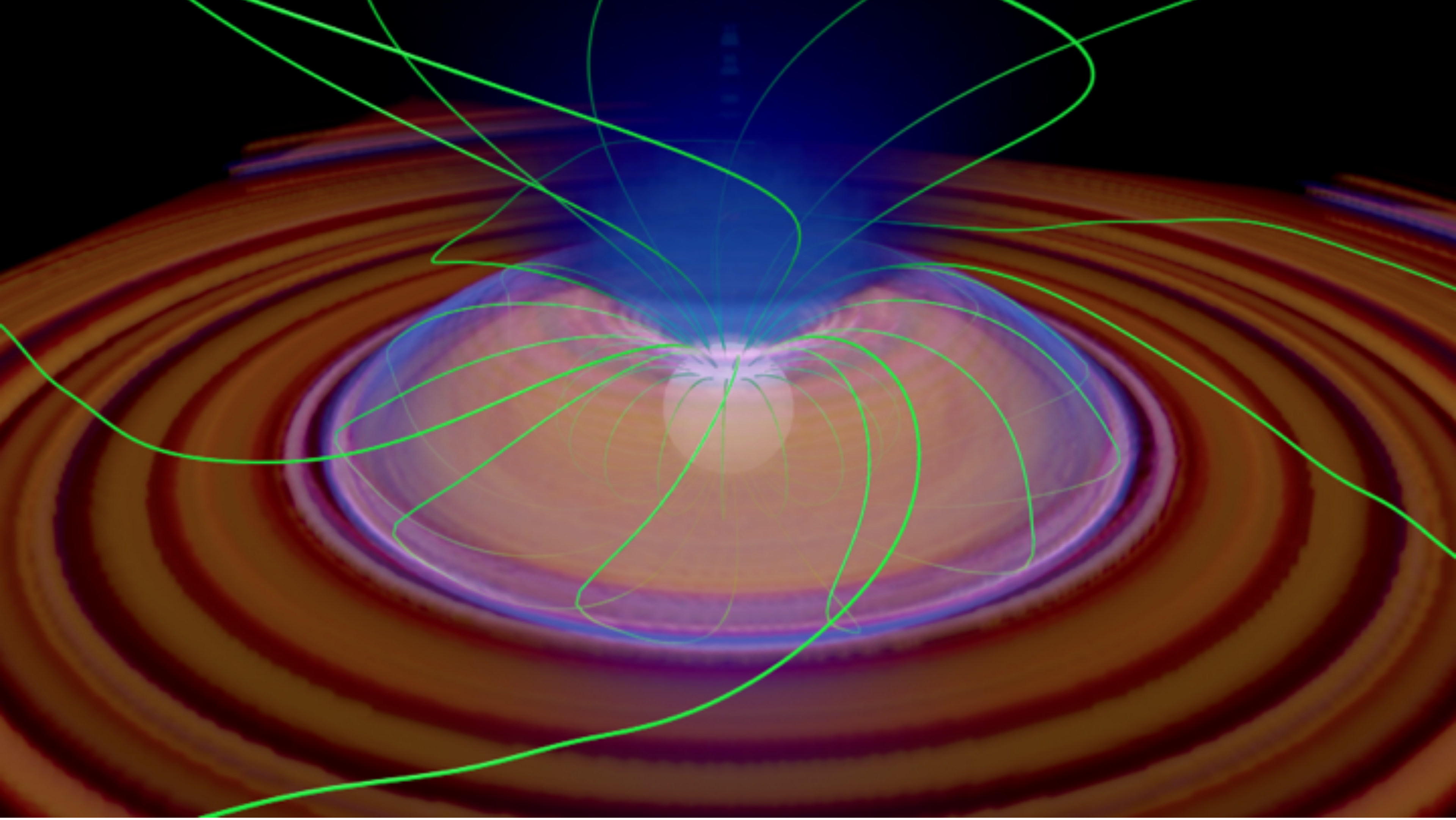
- fields calculated on a grid
- particles followed individually
- photon emission, tracing, and pair creation: Monte-Carlo

Time = 0.08

electric current

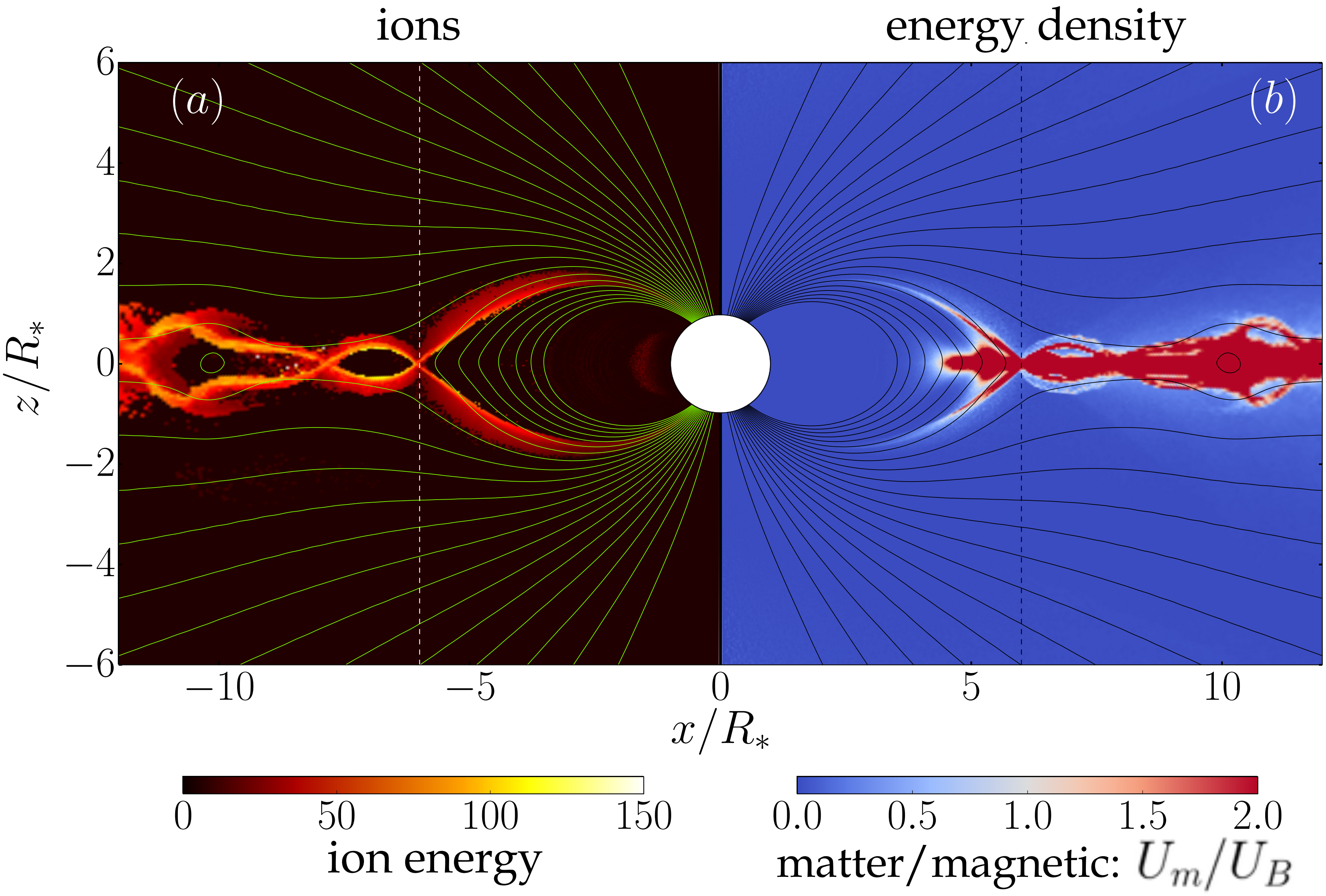


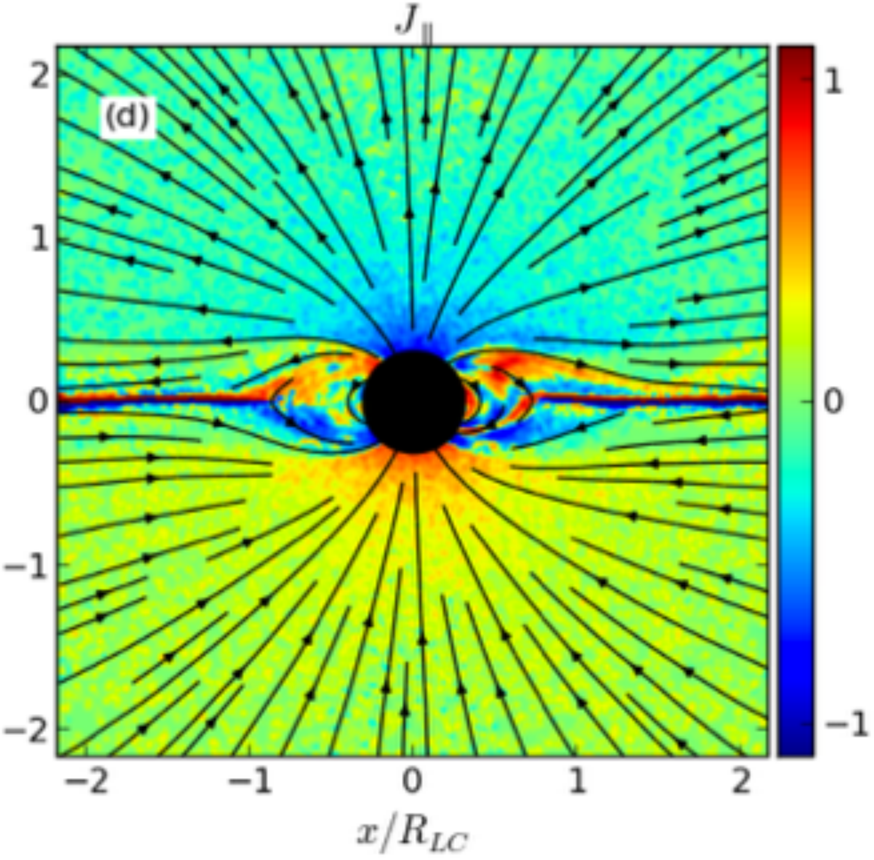
Chen & AB 2014

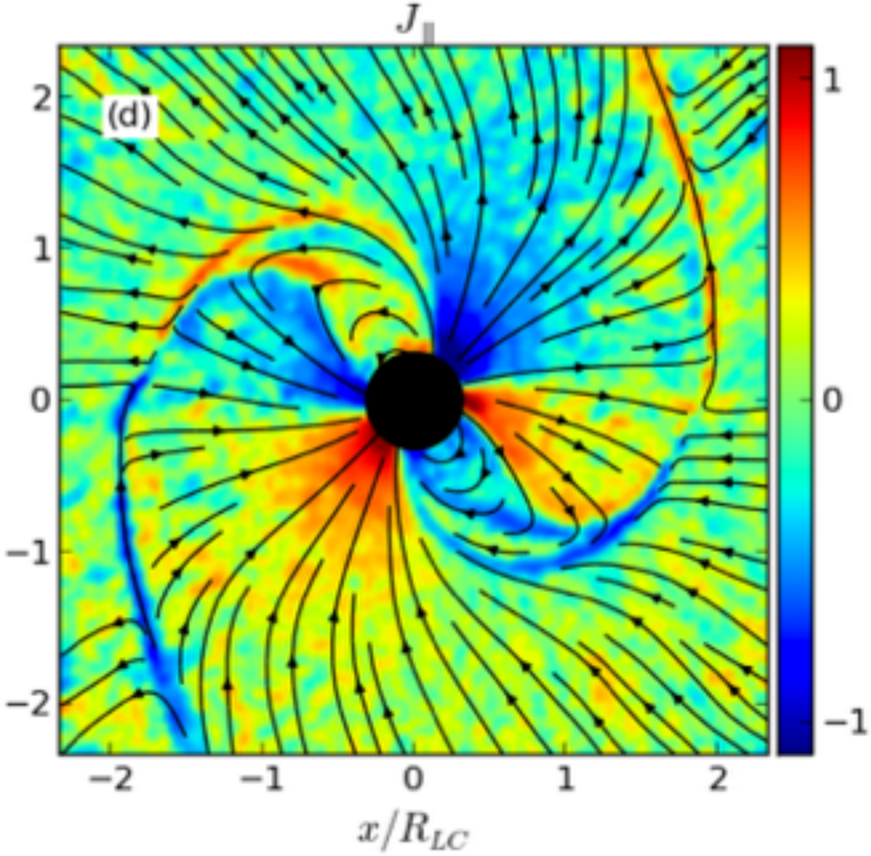


aligned rotator

charge density: - blue + orange


ions
energy density
(a)
(b)
6
4
2
0
−2
−4
−6
z/R_*
−10
−5
0
5
10
x/R_*
0
50
100
150
ion energy
0.0
0.5
1.0
1.5
2.0
matter/magnetic: U_m/U_B





Pilippov et al. 2015

Pair creation rate

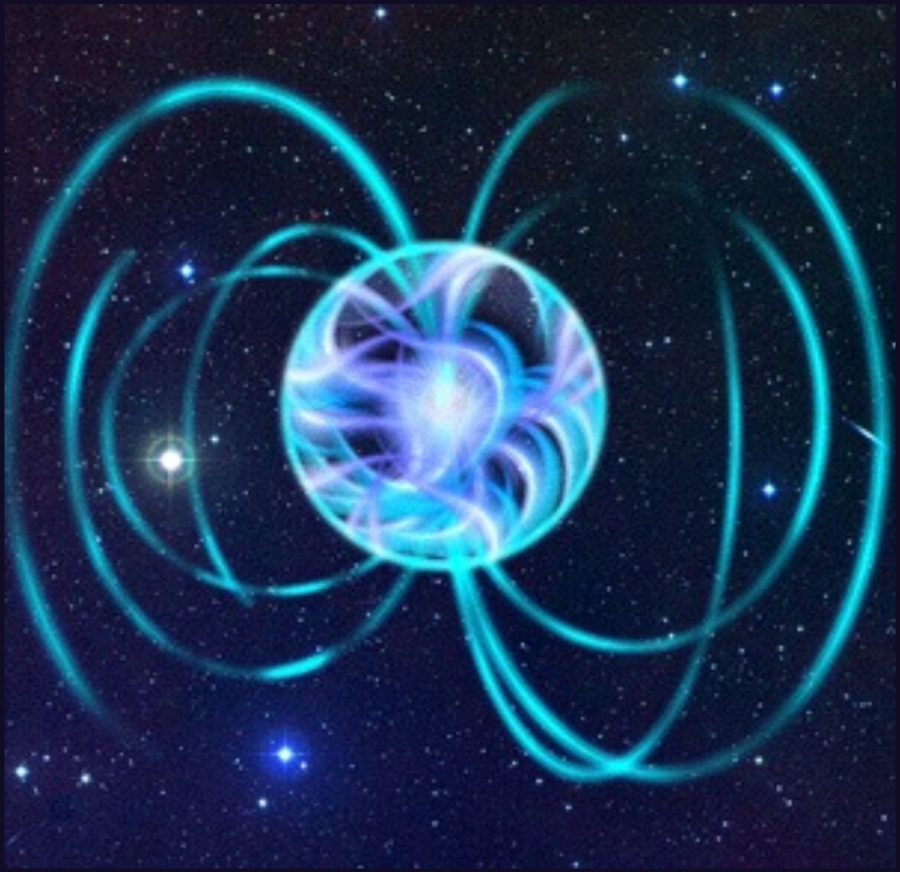
$$\dot{N}_{\pm} = 2\mathcal{M}\,\frac{I}{e} \qquad\qquad I \approx \frac{\mu\Omega^2}{c}$$

$$\dot{N}_{\pm} t = \mathcal{M} N_0 \qquad N_0 \sim \frac{c^2\mathcal{K}}{e\mu} \sim 2\times 10^{44}\,\mu_{31}^{-1}$$

– falls short for Crab nebula by 1-2 orders

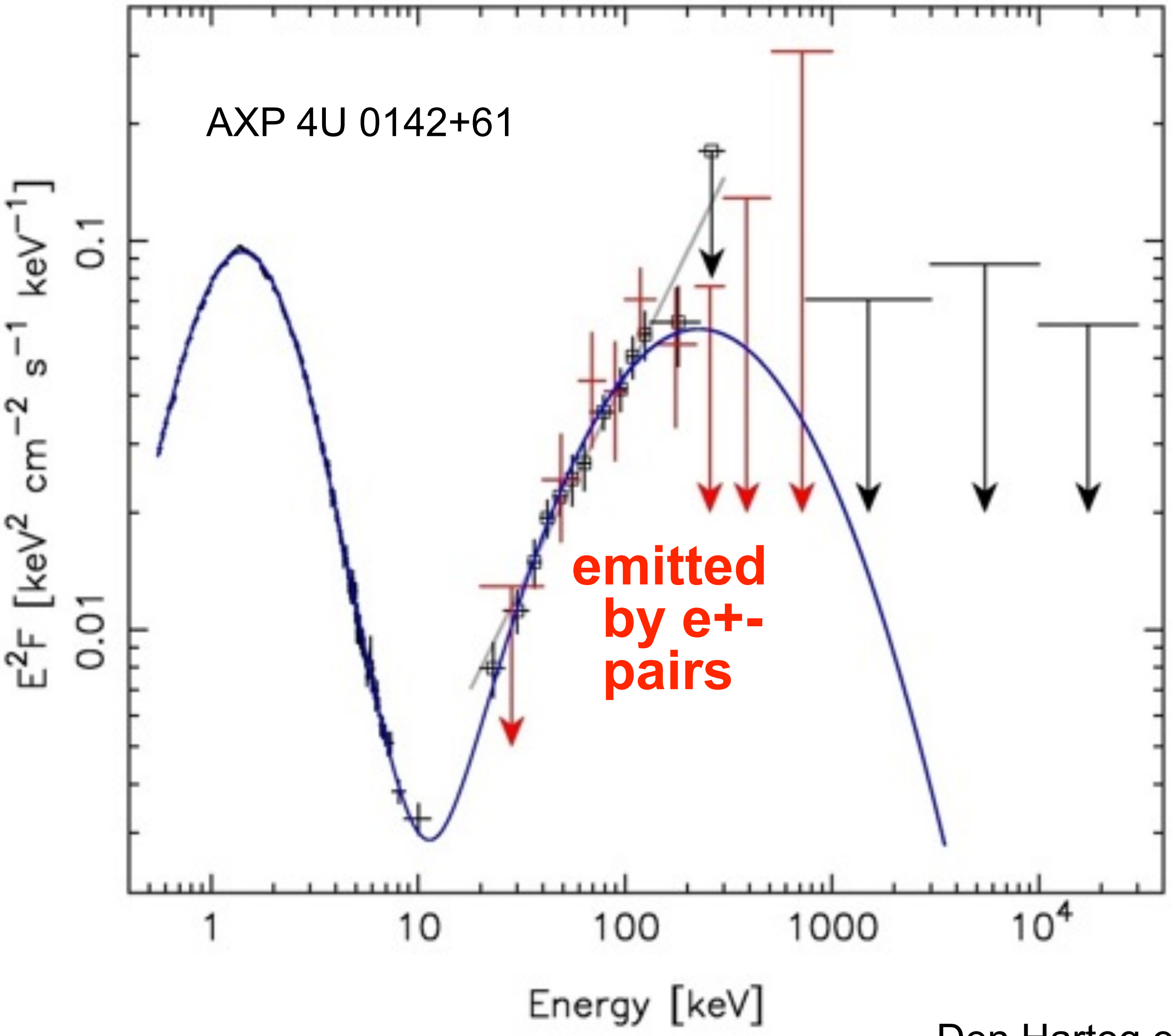
Alternative plasma source for pulsar wind nebula:
a compact shock at a young age (months to years):
PWN should contain pair-rich freeze-out

Magnetars

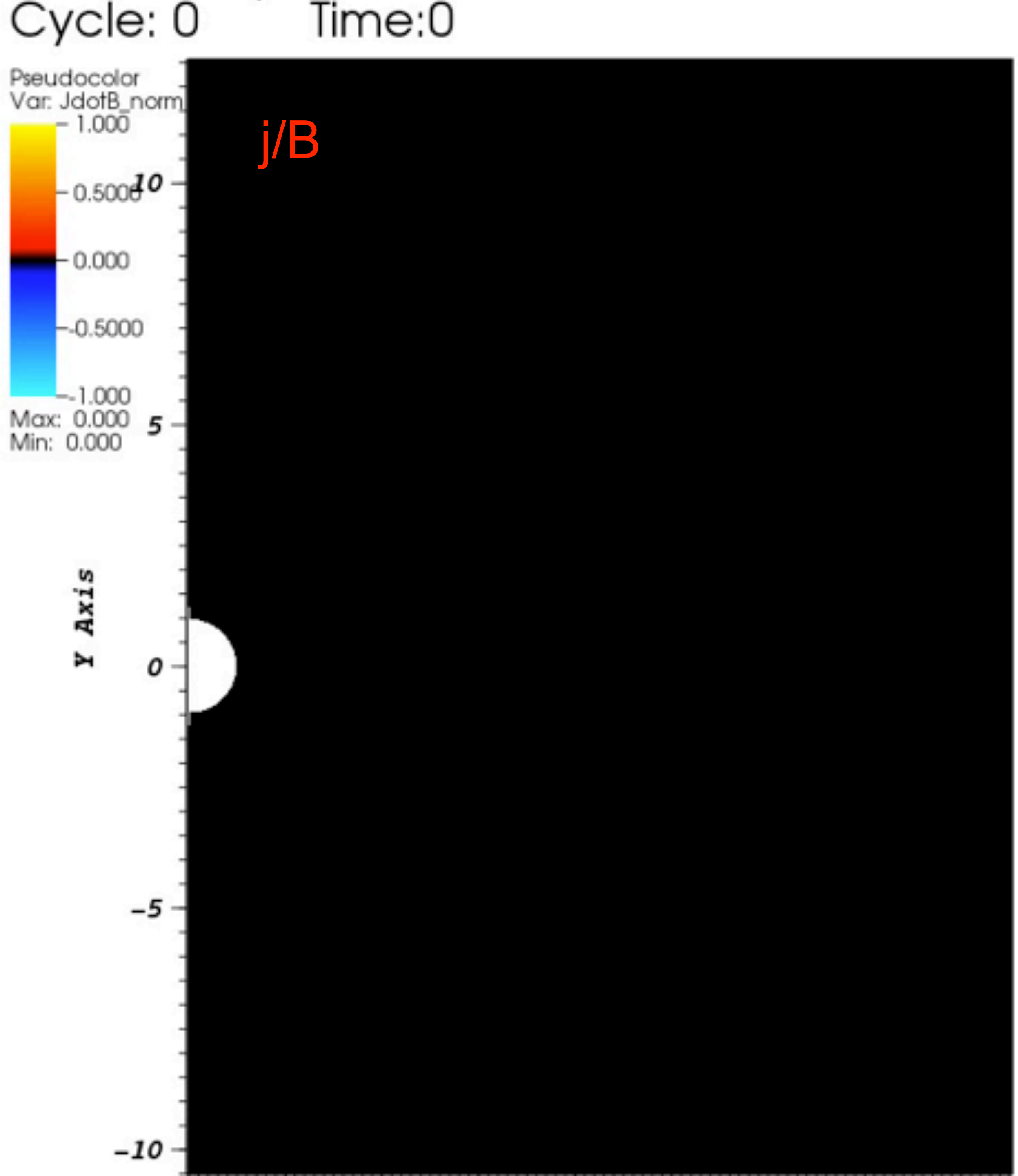


X-ray spectra: two peaks

(luminosity 10^{35}-10^{36} erg/s)



Den Hartog et al. (2008)



twisted closed magnetosphere: j-bundle formation and slow untwisting

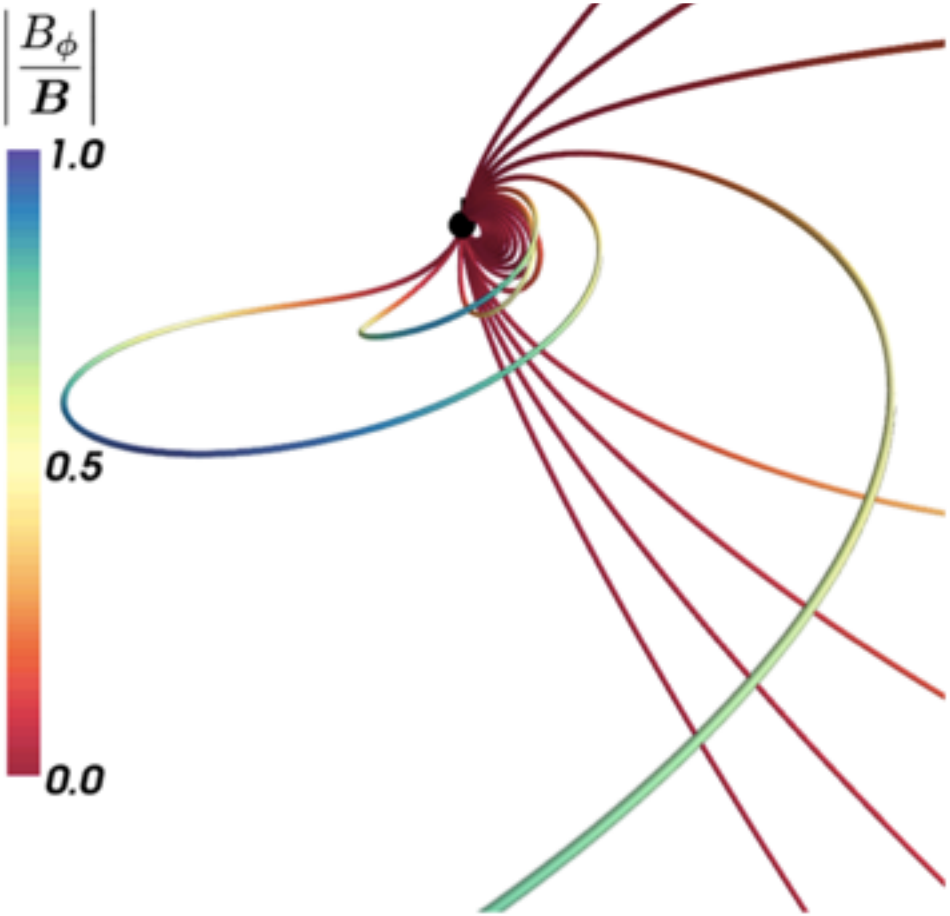
Chen & AB 2017:

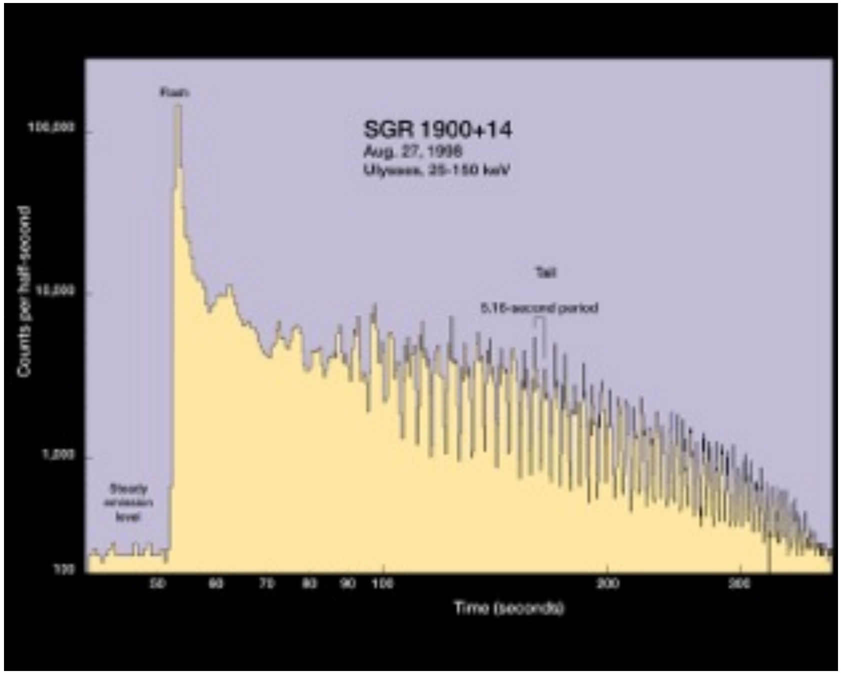
PIC simulations

e+- discharge controls magnetosphere evolution

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

Over-twisted magnetospheres: flares





Parfrey et al. 2013

Summary

- Energy release in compact sources is accompanied by copious pair creation
- Pair creation regulates the dissipation mechanism and dynamics
- Pairs dominate the plasma and shape its observed emission (synchrotron, inverse Compton)

More observational tests: annihilation line, polarization

Energy dissipation in compact objects:
shocks, reconnection, electric discharge

More theory: PIC simulations of e+- ion plasma