Sub-photospheric shocks in relativistic explosions

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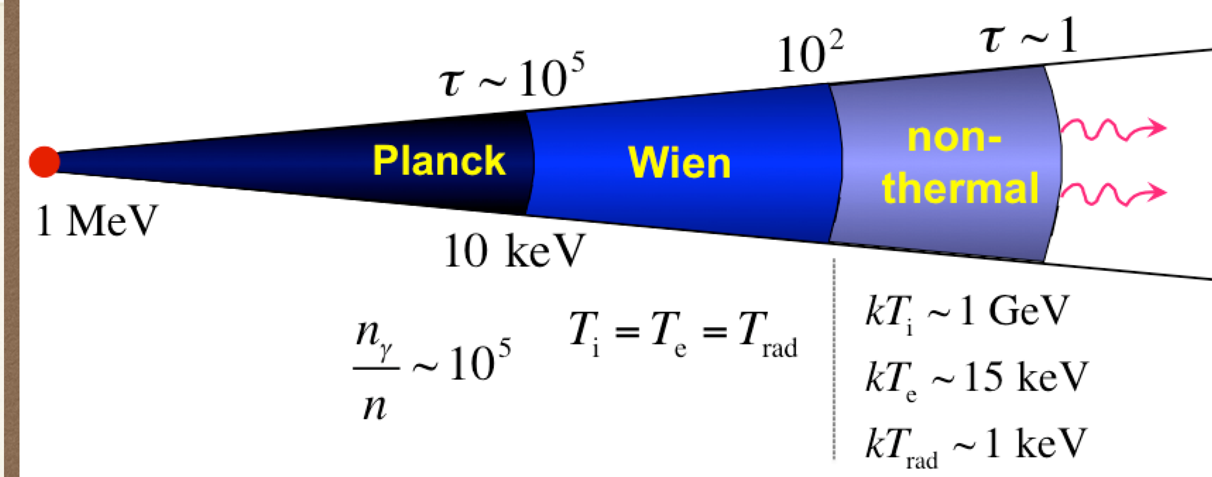
riders sit on an orange circular platform (known as the discovery vessel) with 24 outward-facing seats

sub-photospheric shocks in GRBs

- affect observed emission released at photosphere
- potential neutrino source



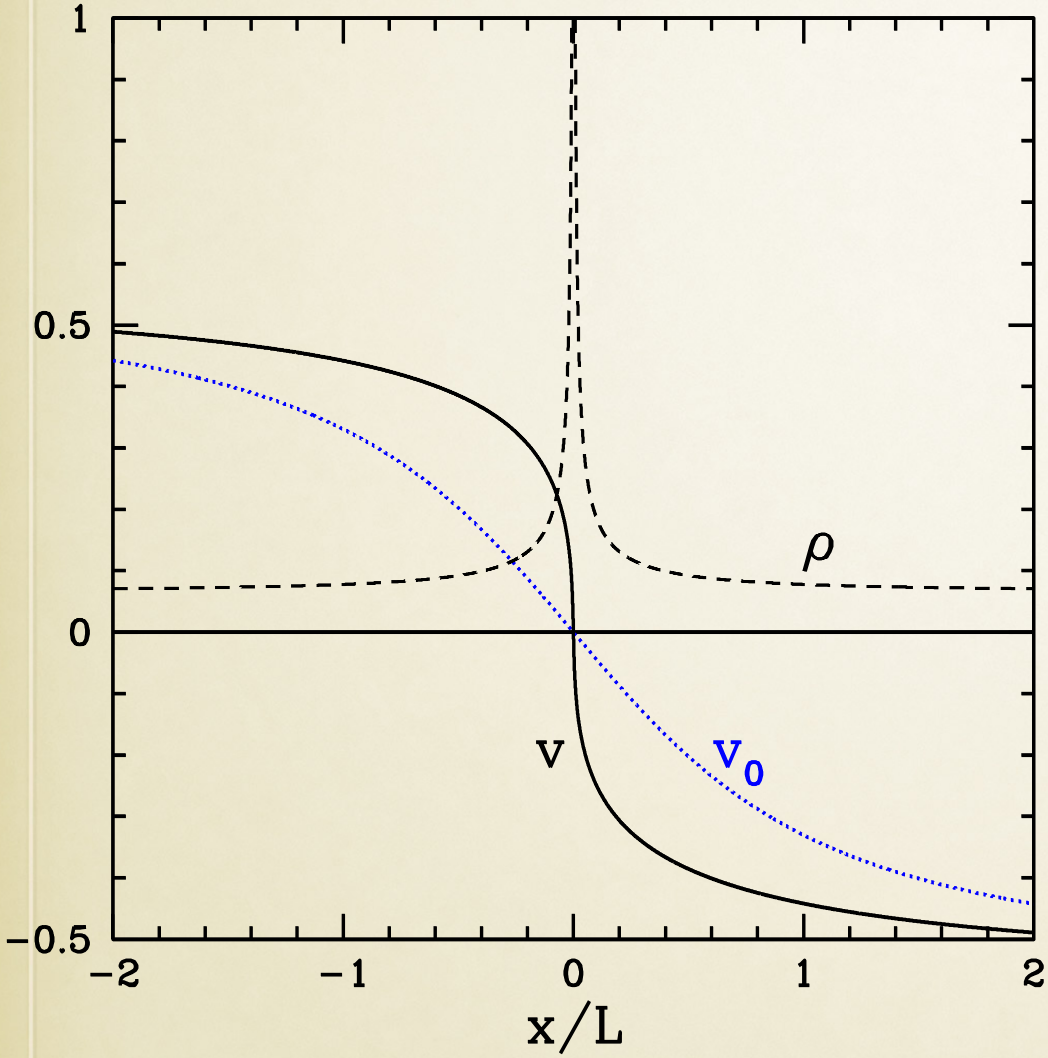
Do sub-photospheric shocks generate energetic particles?

then photon production (synchrotron)
particle production (e+- pairs)
neutrino emission

History: radiation mediated shocks

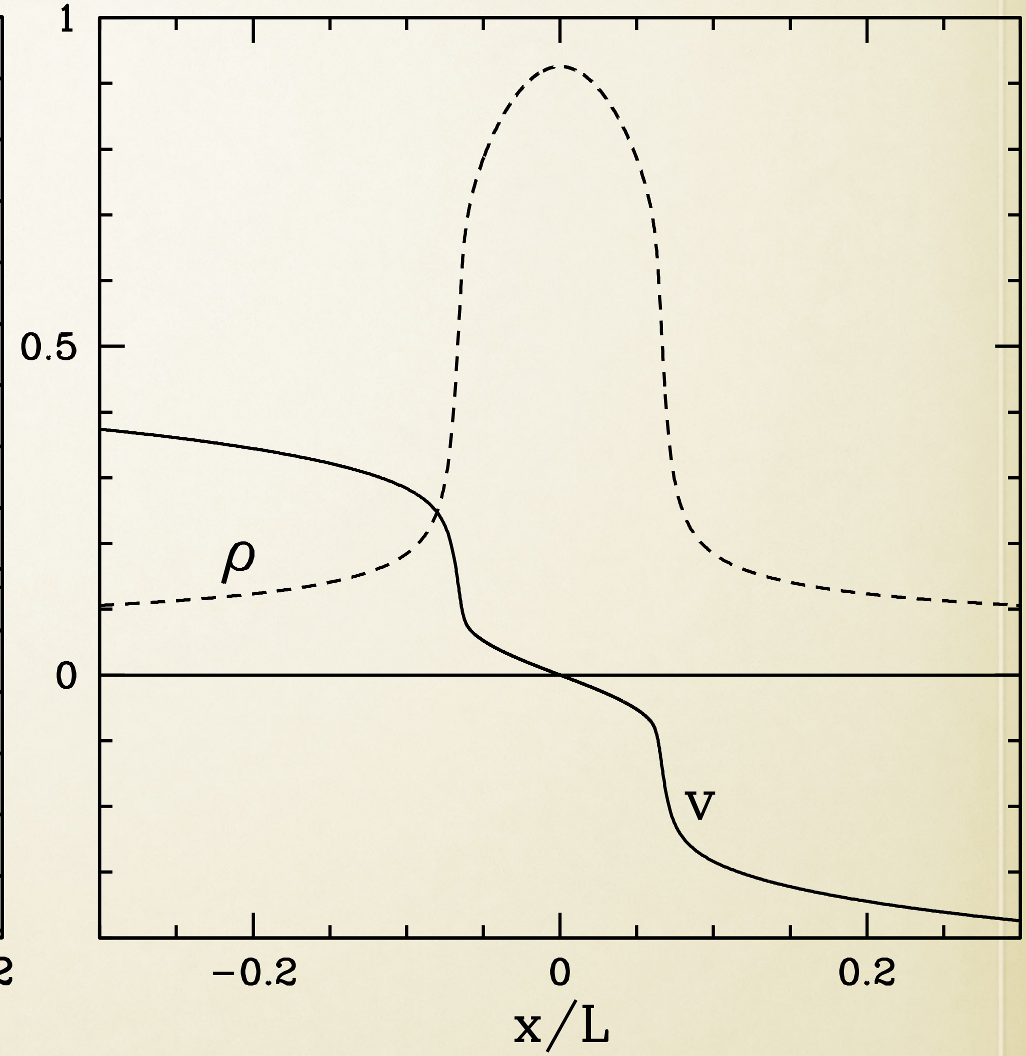
Zeldovich, Raizer 1966
Weaver 1976
Blandford, Payne 1981
Budnik et al. 2010
Levinson 2012

ballistic flow: caustic



(rest frame of the caustic)

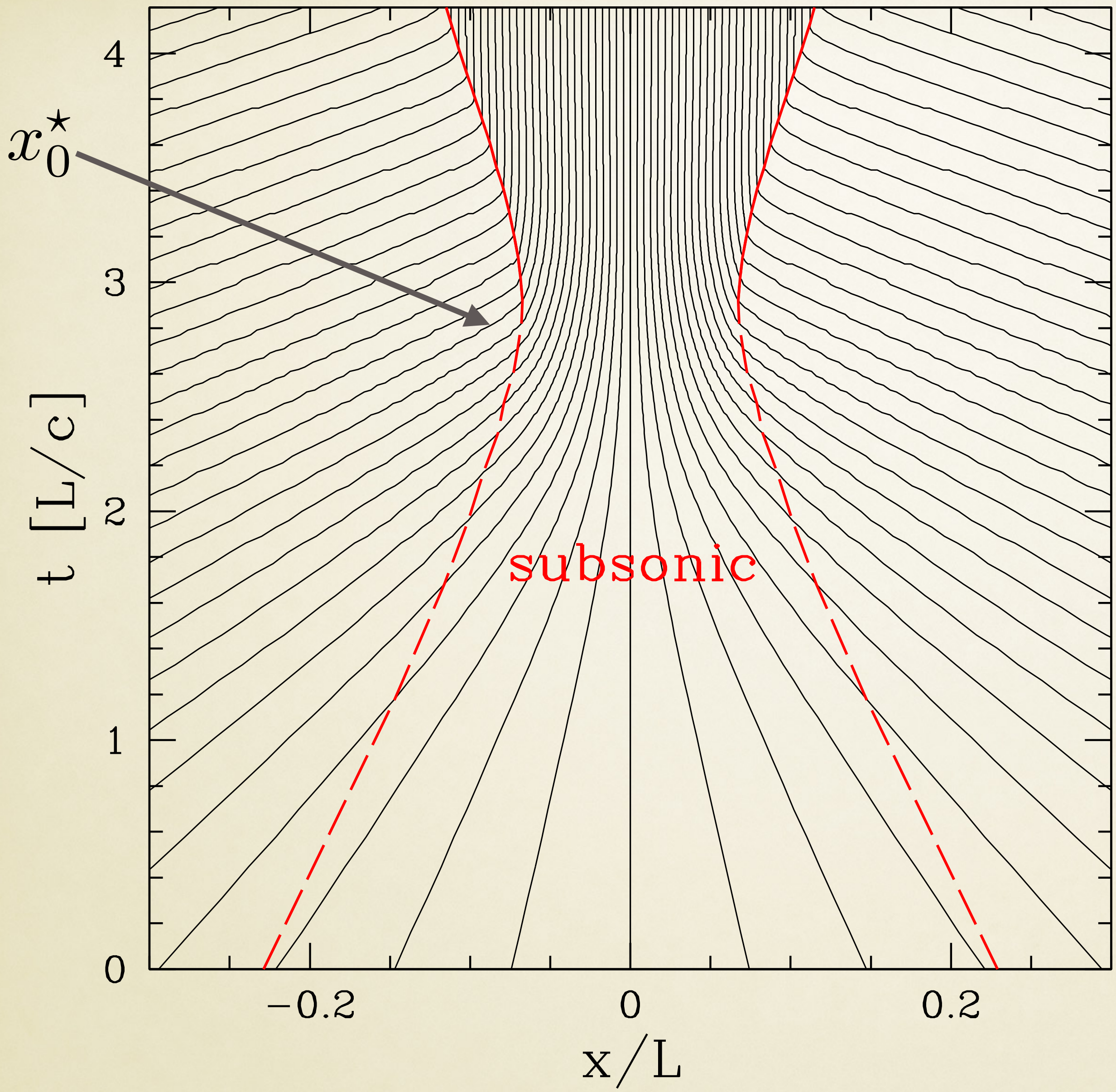
shock formation



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

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

transverse



$$p_0 = -p_{\rm max} \sin \frac{x_0}{L}$$

$$(p = \gamma\beta)$$

$$P_\star \sim p_{\rm max}^2 \rho_0 c^2$$

at shock formation

Radiation trapping condition: $\tau_\star \gg \dfrac{c}{v_0^\star}$ or $\dfrac{c_0}{c} \gg \tau_L^{-2/3}$

Sound speed in a hot magnetized plasma

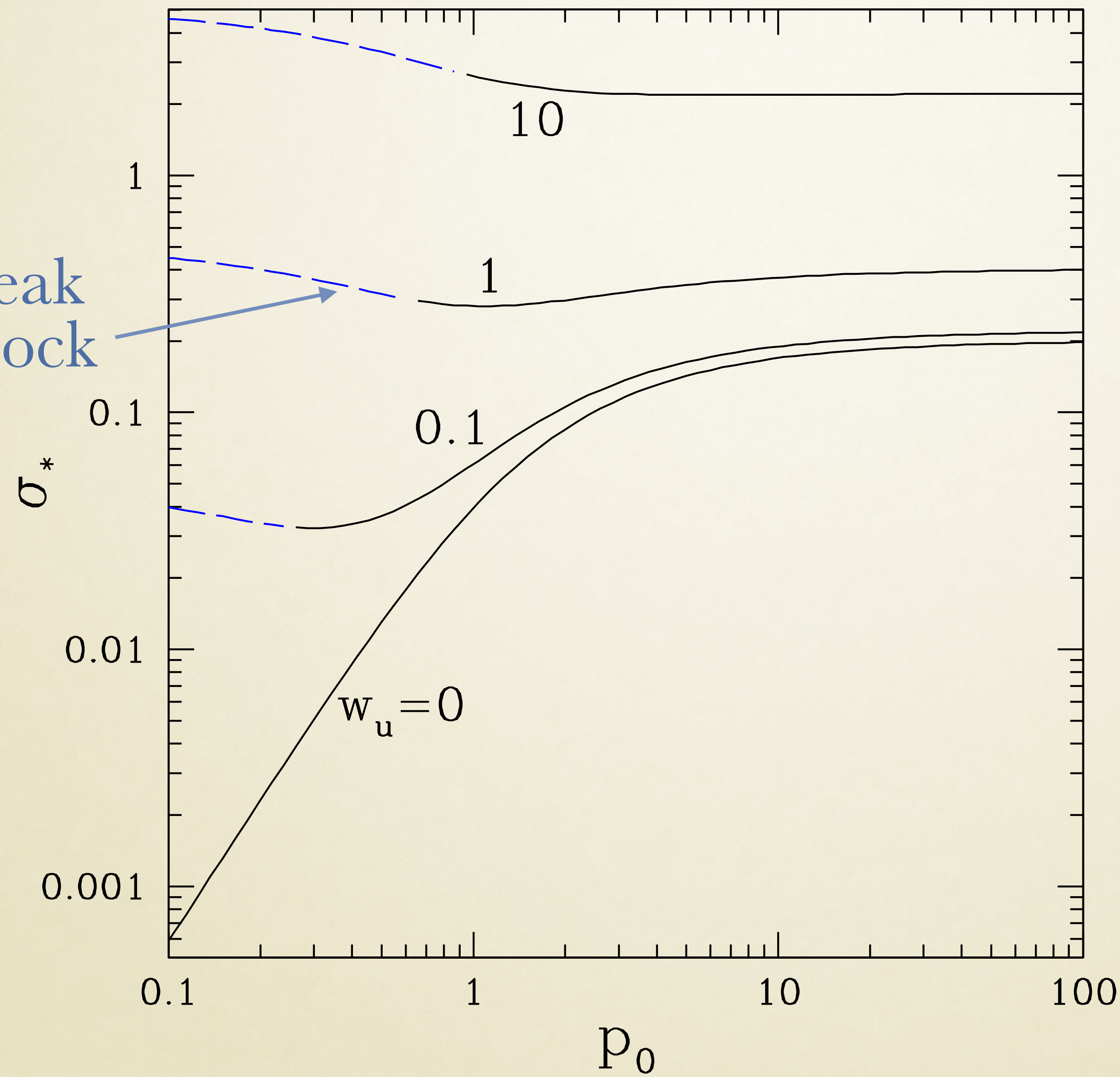
$$P \propto \tilde{\rho}^{\alpha} \qquad w \equiv \frac{U+P}{\tilde{\rho}c^2} \qquad \sigma \equiv \frac{\mathcal{B}^2}{4\pi\tilde{\rho}c^2}$$

$$\boxed{\frac{c_s^2}{c^2} = \frac{(\alpha-1)w+\sigma}{1+w+\sigma}}$$

Parameters of the shock problem:

$$w \qquad \sigma \qquad p_0 \ \text{(momentum jump)}$$

“Critical” magnetization (from jump conditions)



weak shock

(momentum jump)

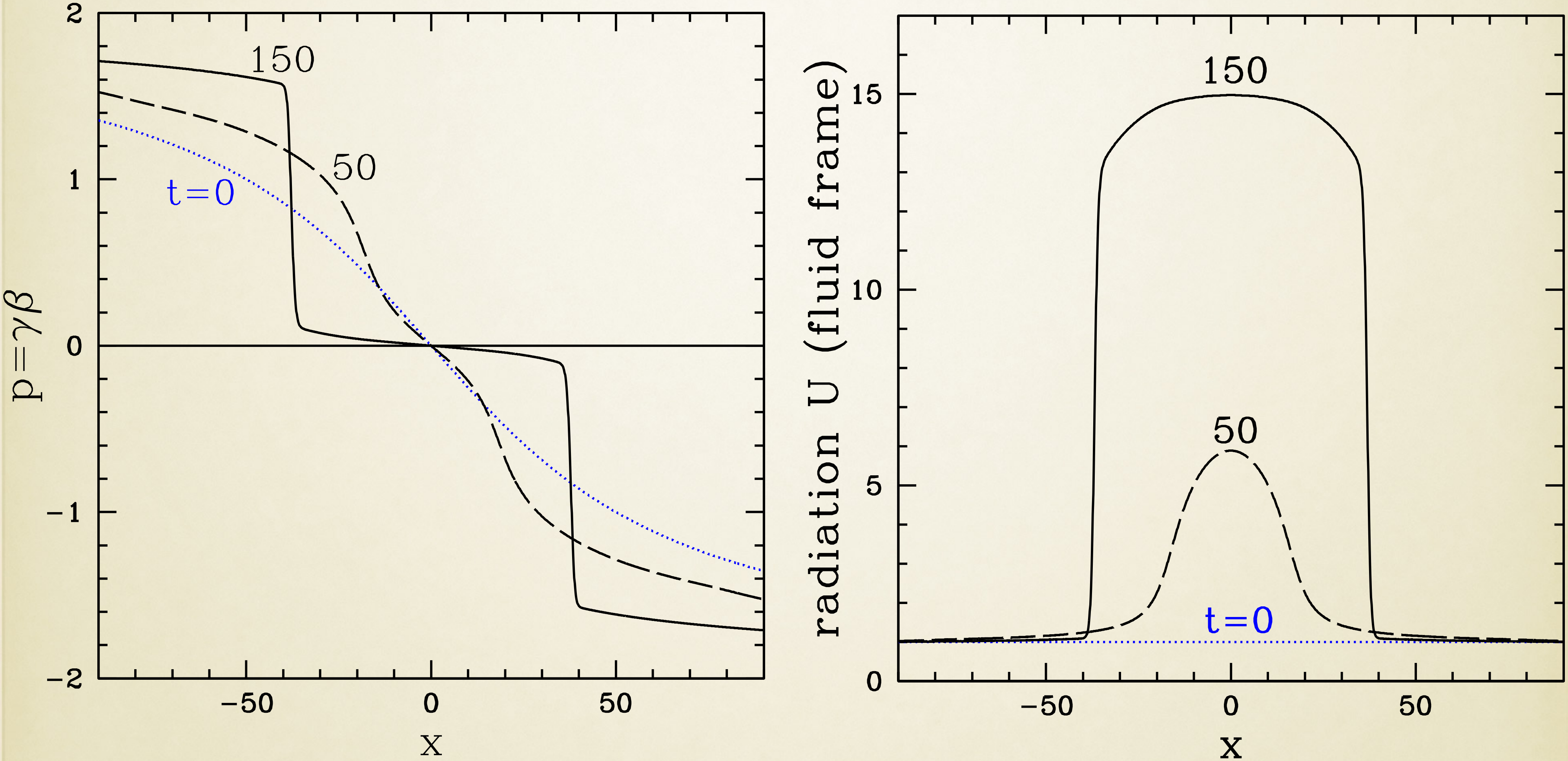
$\sigma_u > \sigma_\star \Rightarrow$

$$\frac{\mathcal{B}^2}{8\pi} > 4P_{\rm rad}$$

(downstream)

Shock structure

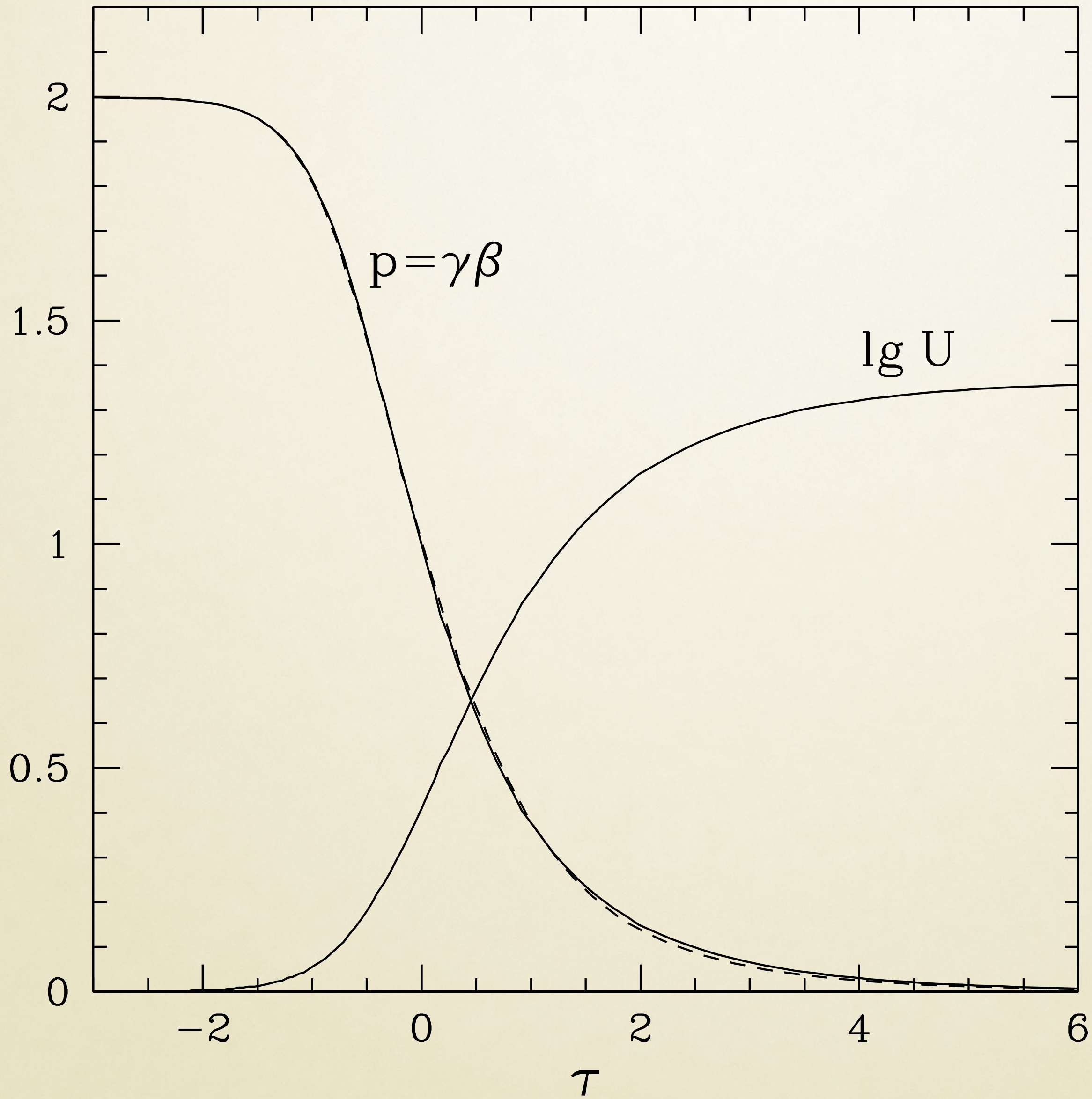
Shock formation in "photon gas" $(w \gg \sigma \gg 1)$



$$\frac{1}{c}\frac{\partial I}{\partial t} = -\cos\theta \frac{\partial I}{\partial x} + n\sigma_{\mathrm{T}}(1-\beta\cos\theta)(S-I)$$

$$\tilde{I}_1 = \gamma^2\left[-\beta(I_0+I_2)+(1+\beta^2)I_1\right] = 0$$

shock in photon gas



quasi-thermal

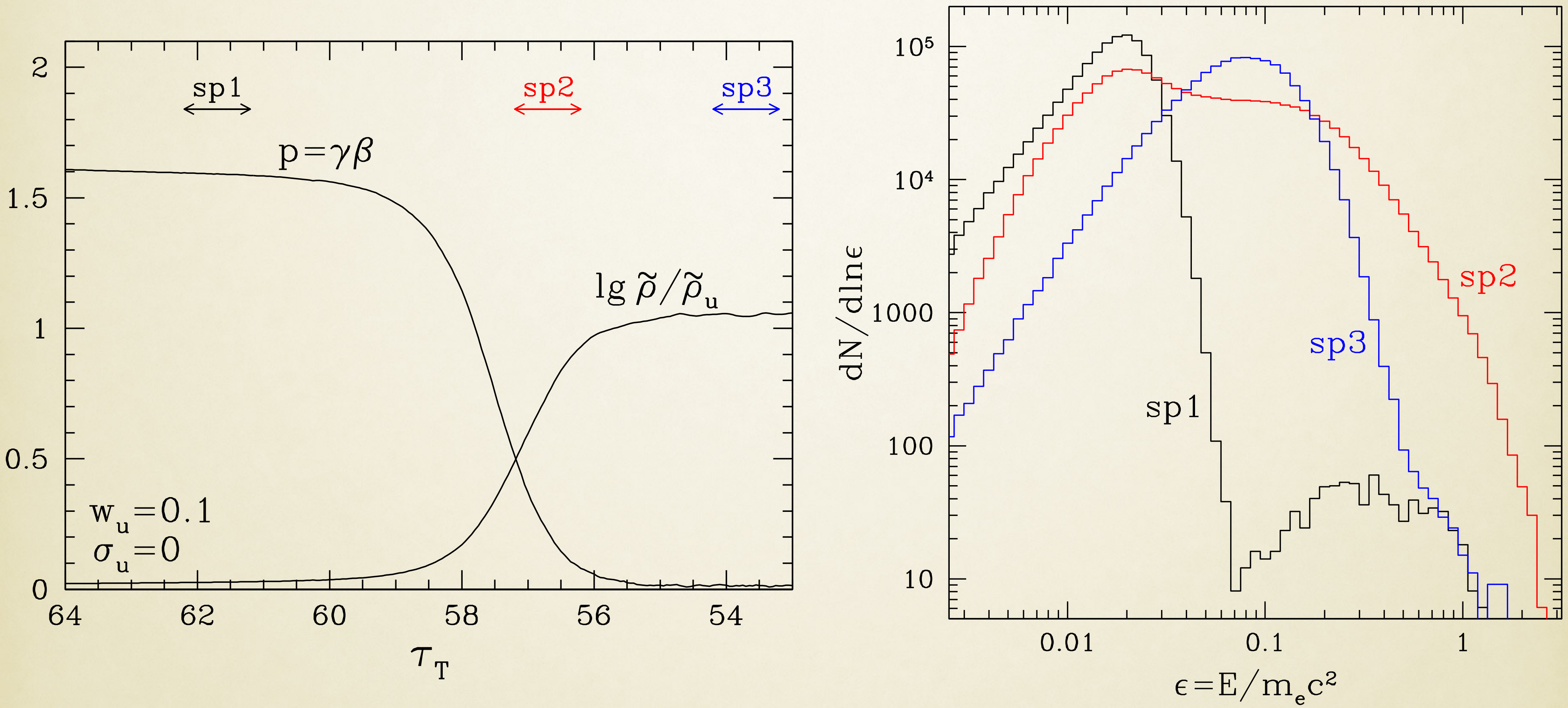
Radiation MHD: "Photon in cell"

Fluid motion: Lagrangian grid

Radiation: individual photons
Monte-Carlo scattering

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

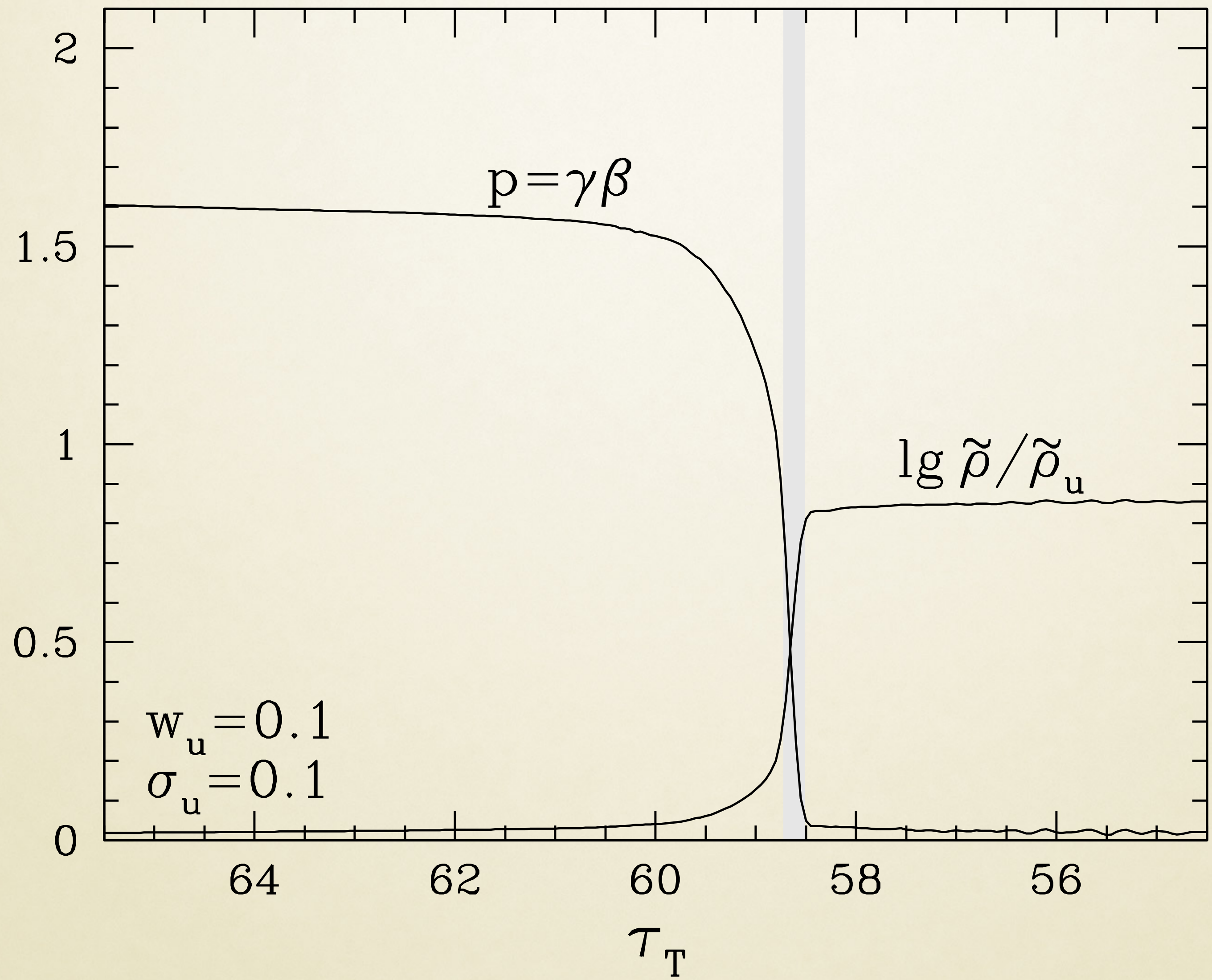
Radiation mediated shock (B=0)



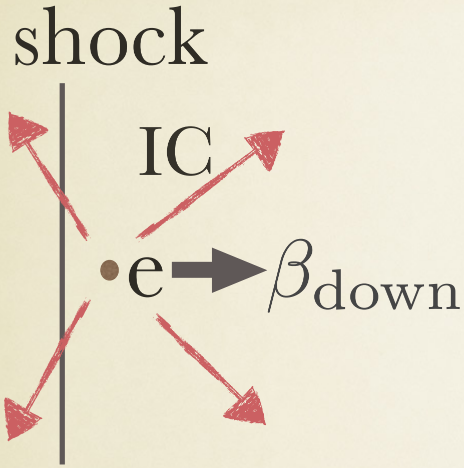
Bulk Comptonization, Klein-Nishina, and pair creation

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

Shock in moderately magnetized medium



Inverse Compton and e+- creation



$$\gamma_{\rm th,e} = f_e(\gamma_0 - 1)\frac{m_i}{Z_\pm m_e}; \quad \mathcal{M}_\pm \sim 0.2\gamma_{\rm th,e}$$

fraction created upstream $\dfrac{\mathcal{M}_{\rm up}}{\mathcal{M}_\pm} \sim \dfrac{1-\beta_{\rm down}}{2}$

$\Rightarrow$ **upstream e+- breeding**

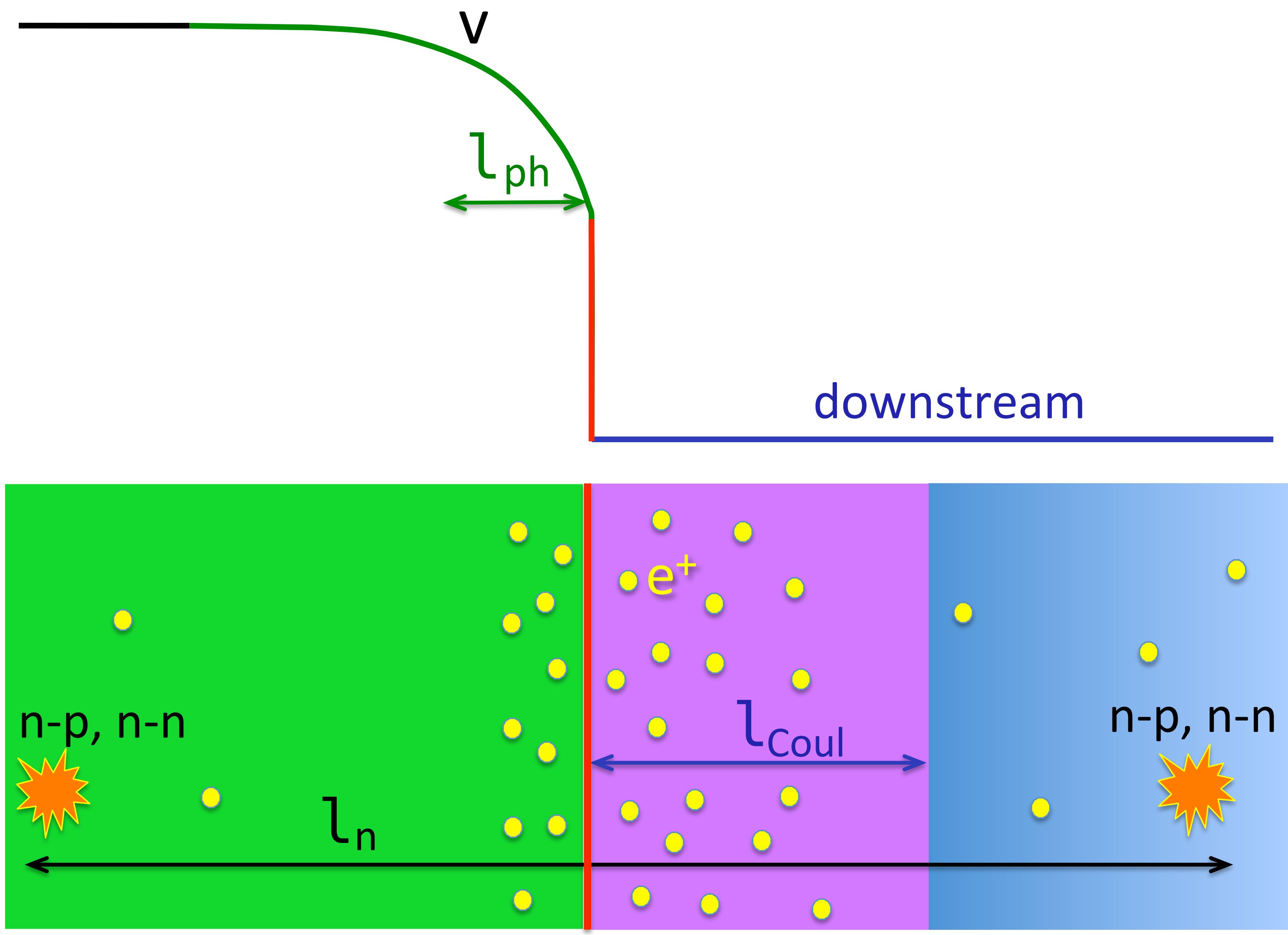
self-regulated state $\mathcal{M}_{\rm up} \sim 1$

regulation toward marginal conversion: $E_{\rm IC} \sim \gamma_{\rm cr}^2 E_{\rm target} \sim 3$ MeV

$$\Rightarrow \gamma_{\rm th,e} \sim \gamma_{\rm cr} \sim 20$$

$$\Rightarrow \boxed{Z_\pm \sim 100}$$

Sub-photospheric shock structure



Conclusions

AB 2016 (arXiv:1604.02794)

1. Sub-photospheric shocks are broad, with embedded subshocks. Not simple RMS! Shaped by nuclear collisions, photon scattering, photon-photon collisions, Coulomb collisions, and collective (plasma) processes (scales $\ell_n \gg \ell_{\rm ph}, \ell_{\gamma\gamma}, \ell_{\rm Coul} \ggg r_{\rm L}$)

2. Neutron collisions generate ultra-relativistic e+- pairs => shocks emit soft synchrotron photons + neutrinos $E_\nu \sim \Gamma m_\pi c^2$

3. Upstream magnetization leads to a strong collisionless subshock

4. Pair breeding regulates collisionless subshock $kT \sim 10\, m_e c^2$, $Z_\pm \sim 100$

5. Emergence at photosphere: the e+-dressed shock "carries" the photosphere with it up two decades in radius and keeps producing nonthermal photospheric emission