Radiation in relativistic plasmas

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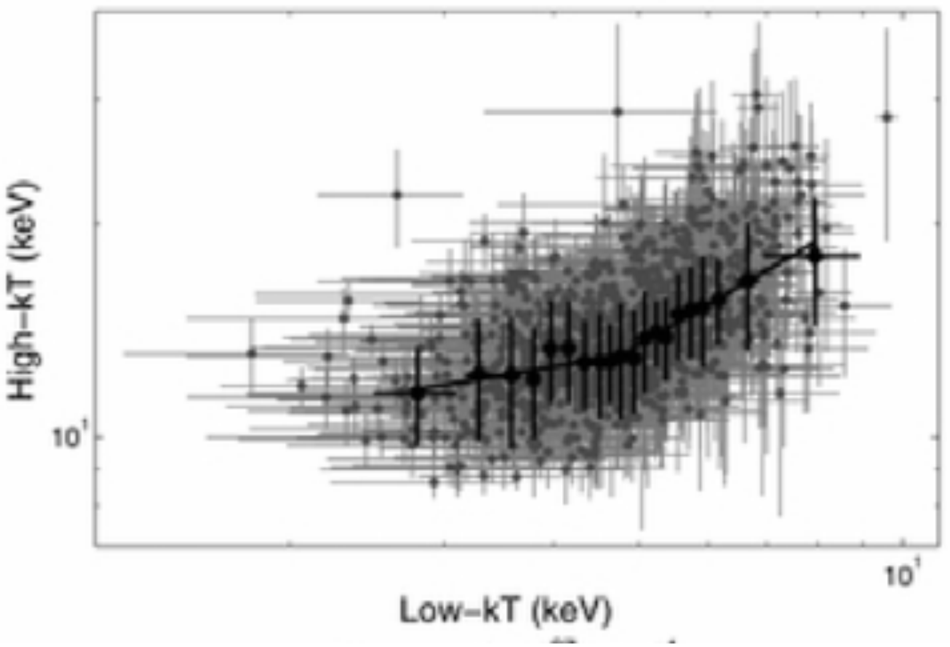
Magnetar bursts - ver low T (few keV)



Younes +, 2014

SGR J1550−5418, with RXTE bursts ~5 keV

1E1841-045, with NuSTAR bursts ~3.3 - 5 keV

1E1048.1-5937, with NuSTAR 6-8 keV

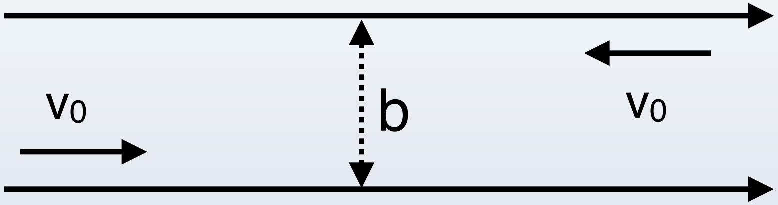
1E 1048.1-5937 with RXTE, ~3keV

Trapped pair plasma fireball: equilibrium pair density at few keV is minuscule

Radiation processes frozen out - cannot cool

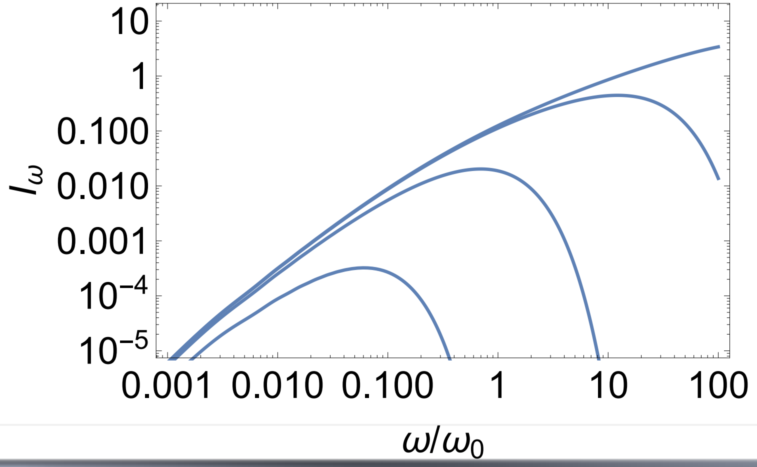
Something is wrong

Free-free emission in T << B (classical)



$$v = v_0\sqrt{1 \pm \frac{e^2}{m_e v_0^2\sqrt{b^2+(2z)^2}}}$$

- 1D motion - lowest Landau level
- nearly classical, in a sense $a_H = \sqrt{\frac{\hbar}{eB}} \to 0$
- Acceleration/emission usually $\mathbf{a}_\perp$, but now only $\mathbf{a}_{||}$
- Free-free emission:
  - $\omega \to 0,\ j_\omega \propto \left|\mathbf{v}_{in} - \mathbf{v}_{out}\right|^2$
  - Constant for B=0
  - = 0 for 1D
- emissivity in single collision
  - $j_\omega = \frac{1}{\pi^2 c^3} {a_\omega}^2 \sin^2\theta d\omega d\Omega$
  - low freq. $\propto \omega^2$

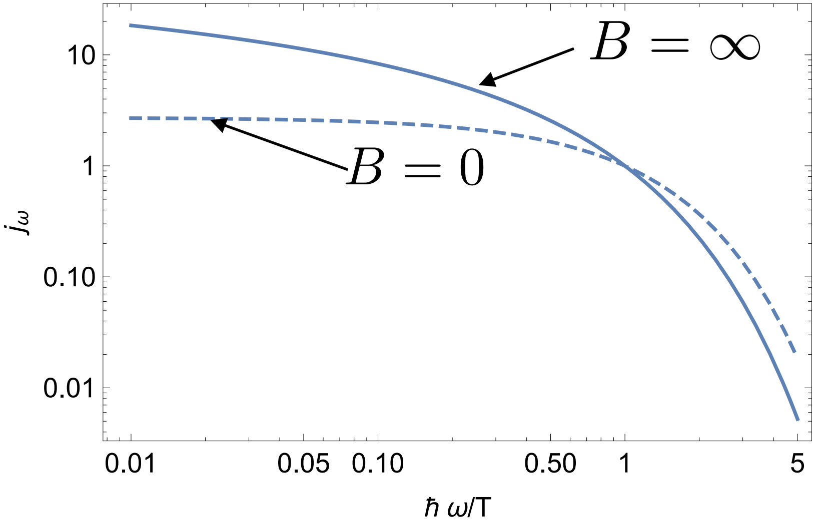


Free-free in infinite B: only e^--e^+

- Averaged over thermal

$$\boxed{j_\omega = \frac{n_\pm^2}{32\sqrt{\pi}} \frac{e^6}{c^3 m_e^{3/2}} \frac{\sin^2\theta}{\sqrt{T}} \Gamma_0\left(\frac{\hbar\omega}{T}\right)}$$

Less power at high freq. $\propto e^{-\hbar\omega/T} \dfrac{T}{\hbar\omega}$



Fit magnetized free-free with B=0 formula

$T_{real} = 12\ T_{fit}$

- Small absorption at > T
- Compton redistribution

Relaxation in 1D pair plasma

e^-e^- & e^+e^+

Keep the same lvl
No way to tell them apart

No relaxation due to binary collisions

Triple collisions

$$\nu_3 \approx v_T n_\pm \pi \left(\frac{e^2}{T}\right)^2 \left[\left(\frac{e^2}{T}\right)^3 n_\pm\right]$$

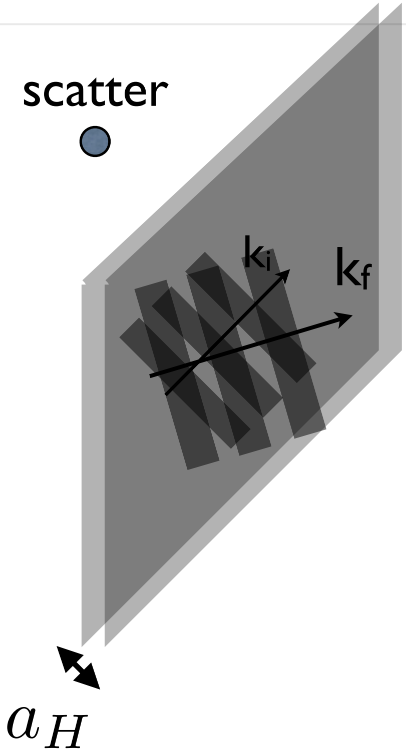
some 10 orders of magnitude smaller
(also, no Coulomb logarithm!)

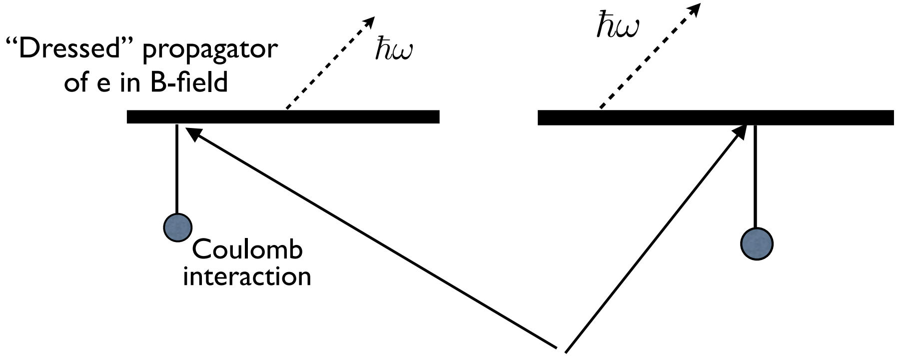
cross-section

relative # of 3 particles within strong interaction sphere

Quantum at zero Landau

- Landau gauge
- sheets of 2D waves
- change in momentum within the 2D sheet
- Feinmann diagrams





Coulomb vertex for 0th Landau
can be calculated exactly!

$$f = \frac{2\pi \exp\left(\frac{1}{4} a_H^2 \left(\left(\kappa_{x,1} + \kappa_{x,2} + \Delta_\kappa\right)^2 - 2\left(\kappa_{x,1}^2 + \kappa_{x,2}^2\right)\right)\right)}{\Delta_\kappa} \rightarrow \frac{2\pi}{\Delta_\kappa}$$

Very similar to classical

scattering amplitude

Cooling wave in pair plasma

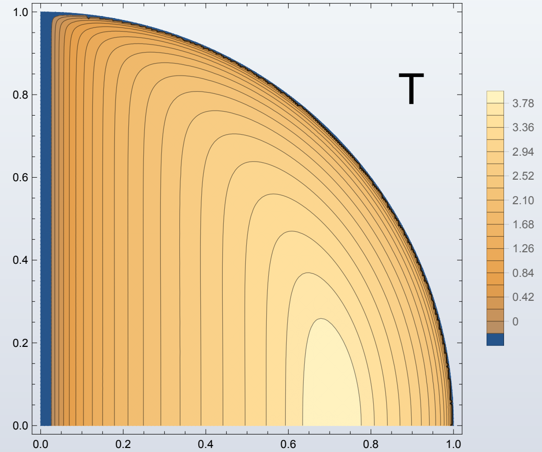
- Trapped fireball (a la spheromak/Hills vortex but with pressure)
- Cools by radiation - how?
- Half space filled with pair plasma, open the lid - how T evolves.

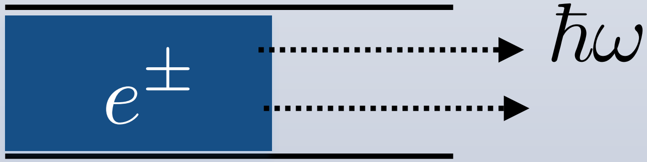
$$\dot{w} + F'_z = 0$$

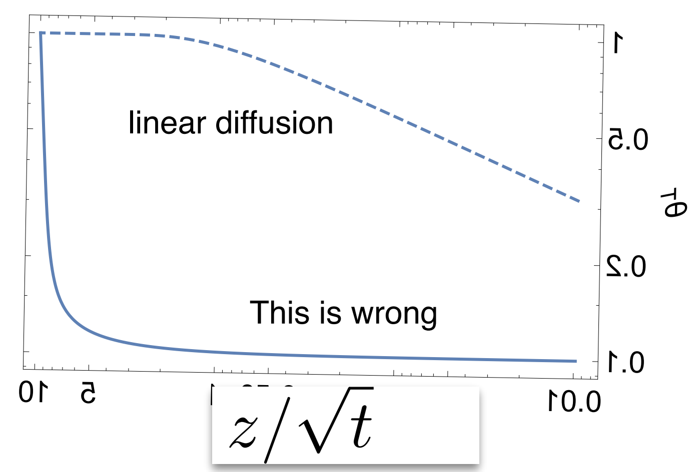
$$w = pairs + radiation$$

$$F = -\frac{4}{3}\frac{acT^3}{n\sigma_T}T'_z$$

- LTE (may not be good enough - photon production rate may not be able to catch up)
- Diffusion?

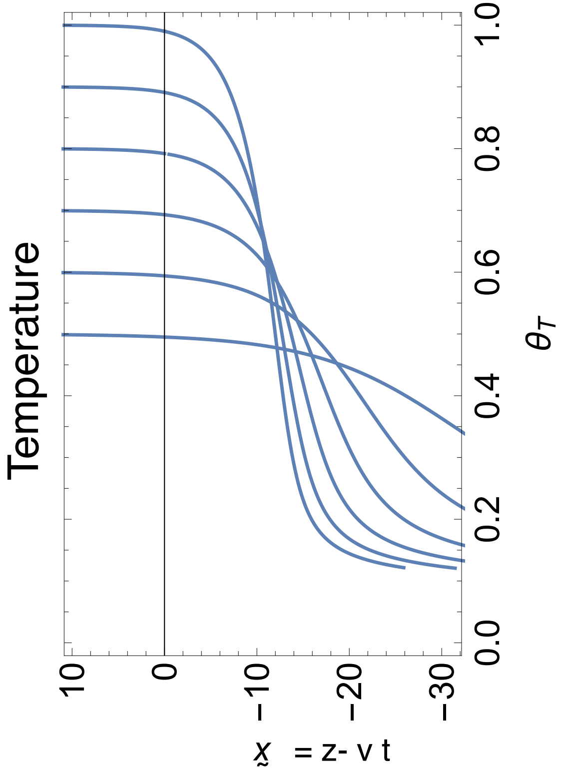






Colling wave

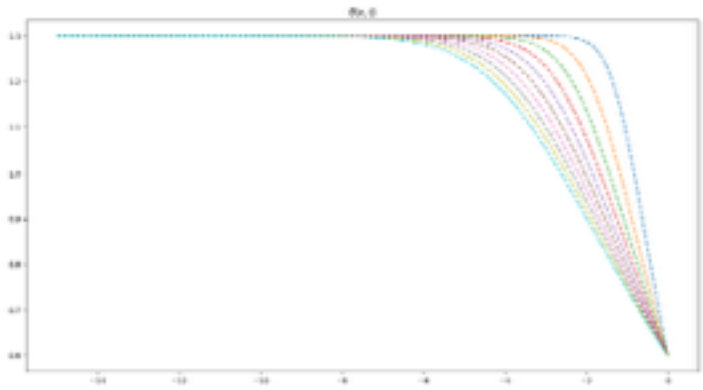
- Read Zeldovich & Raizer - cooling waves
- Nuclear explosions first few 100 meters
- Nonlinear diffusion: cooling wave regime T(z-v t)



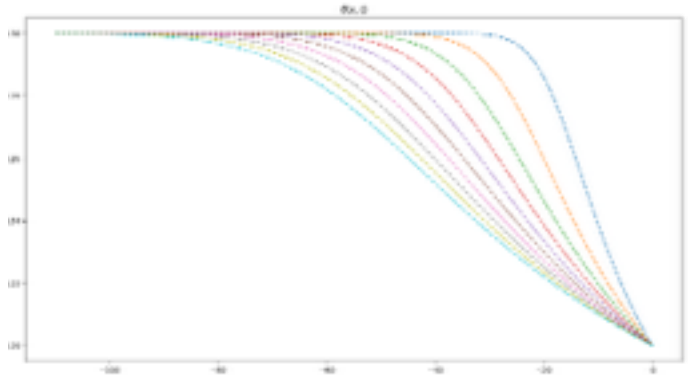
Qualitatively: non-linear diffusion

$$\frac{T''_{zz}}{T'_z} \propto \pm$$

Full integration (with Jedidiah Riebing)



~ diffusive

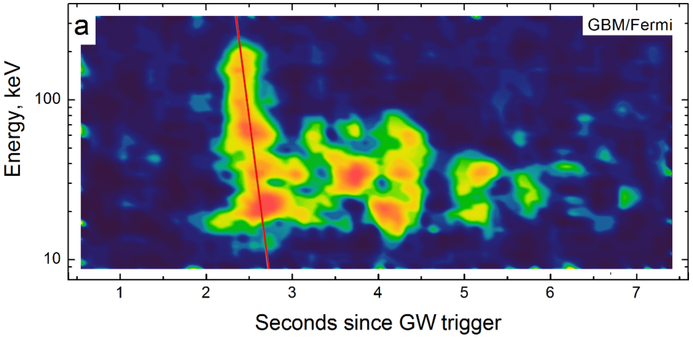


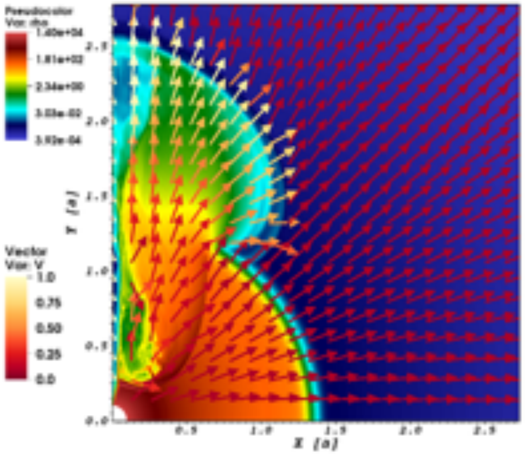
~ cooling wave

No clear separation of diffusive/cooling wave regime

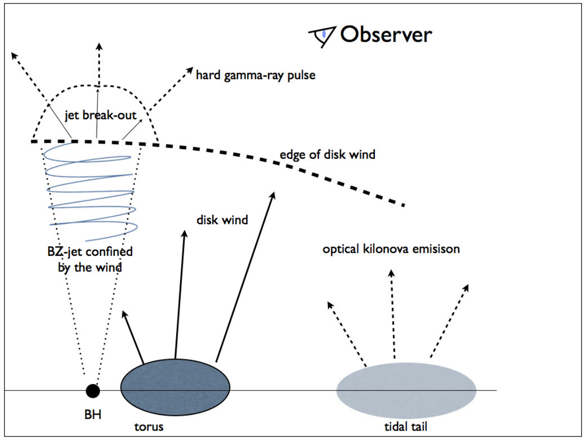
Radiation and pairs in shocks

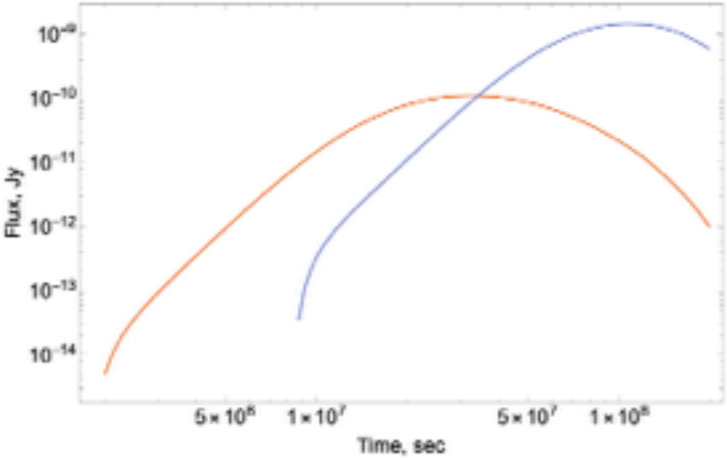
Cocoon - prompt, Jet- to be seen





- Second peak from fast spine (not yet seen)

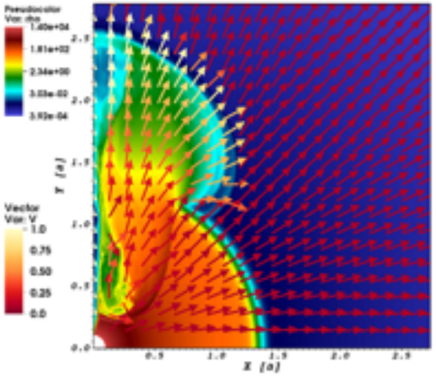




- NS-NS merger: hot disk
- Time to accumulate B-flux on BH ~ 1 sec
- Jet plows through ~ 0.01 M_{Sun}
- Breakout after ~ 1 sec
- Nearly spherical break-out: prompt

Barkov, Giannios, Luo, Kathirgamaraju, Lyutikov, in prep.

Mildly relativistic shock propagating through $\rho \sim 10^4\,\mathrm{g\,cm}^3$ $(\sim 10^{-2} M_\odot\ \mathrm{over}\ 10^9 cm)$

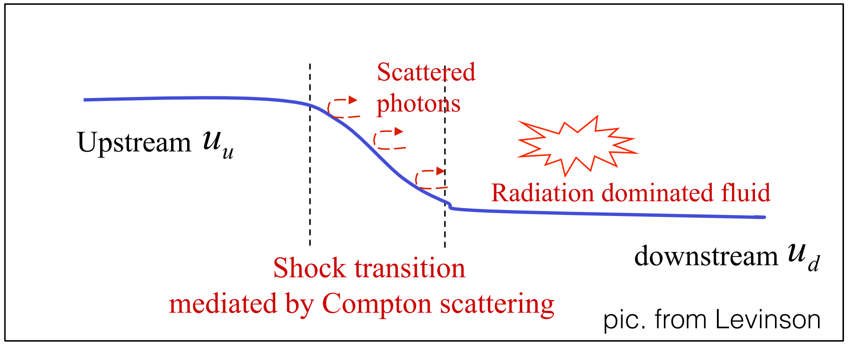


Radiation-mediated shocks

For $\beta \geq \mu^{-1/2}(n\lambda_C^3)^{1/6} \approx 10^{-2}$ post-shock radiation pressure > kinetic pressure

$\mu = m_p/m_e$

Momentum flux ~ radiation flux $\rho v^2 \sim \sigma_{SB} T^4/c$


Scattered photons

Upstream u_u

Radiation dominated fluid

Shock transition mediated by Compton scattering

downstream u_d

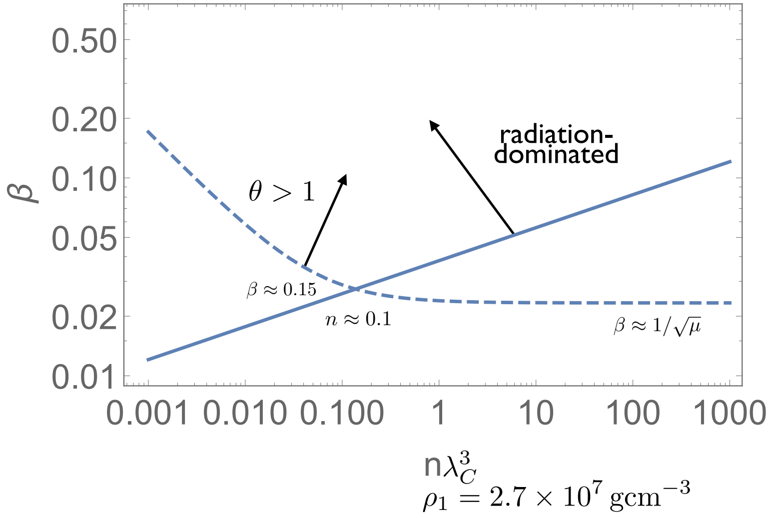
pic. from Levinson

- Hot post-shock fluid emits photons - photon pressure decelerates the flow
- Mildly relativistic flows can be strongly affected by radiation
- High optical depth - LTE (?)

Highly radiation-dominated:

$$\frac{T}{m_e c^2} \sim \mu^{1/4}(n\lambda_C^3)^{1/4}\sqrt{\beta} \sim 1\ \mathrm{for}\ \beta \geq 0.3$$

Pair production (and nuclear reactions) in the wind



Resolving radiation and pair-mediated shock transitions

overall jump condition

$$\beta_1\rho_1 = \beta\rho$$

matter flux

$$\rho_1\beta_1^2 = p_{tot} + \rho_{tot}\beta^2$$

momentum flux

$$\rho_1\beta_1^3/2 = (w_{tot} + \rho_{tot}\beta^2/2)\beta + F_r$$

energy flux

$$F_r = -\frac{c}{3n_{tot}\sigma_T}\nabla u_{rad}$$

$$u_{rad} = \frac{4}{c}\sigma_{SB}T^4$$

Energy redistribution
by radiation.
Diffusive - approximation!

Pressure, enthalpy, density: sums of baryons, pairs and radiation

Even though the radiation pressure is small, it can fly far-far

Higher order diff. equation - very different structure of solutions

Very simple case

- Radiation energy density is negligible, but efficient redistribution

$$\boxed{\begin{aligned} \beta_1\rho_1 &= \beta\rho \\ \rho_1\beta_1^2 &= \frac{\rho}{m_p}T + \rho\beta^2 \end{aligned}}$$

$$\eta = \frac{\rho_1}{\rho} = \frac{v}{v_1}$$

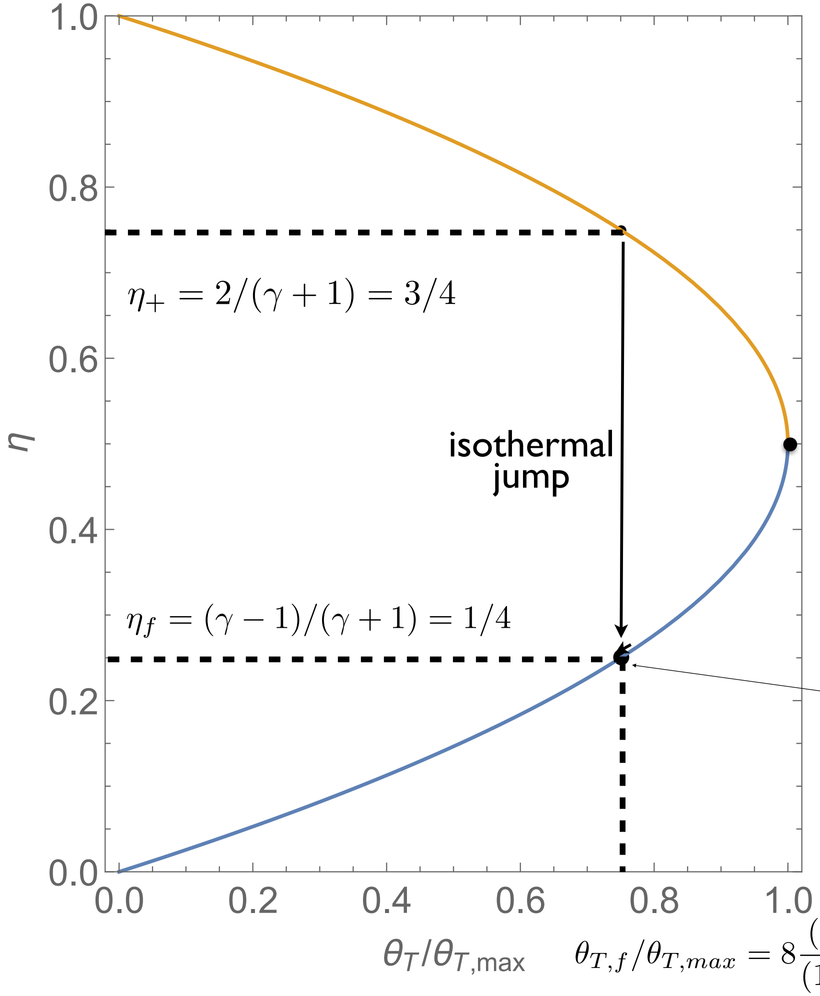
$$p = nT$$

$$\rho_1\beta_1^3/2 = (\frac{\gamma}{\gamma-1}\frac{\rho}{m_p}T + \rho\beta^2/2)\beta + F_r$$

$$\boxed{T = \eta(1-\eta)m_p v^2}$$

$$\boxed{T = \eta(1 - \eta) m_p v^2}$$

Read Zeldovich & Raizer: isothermal jump



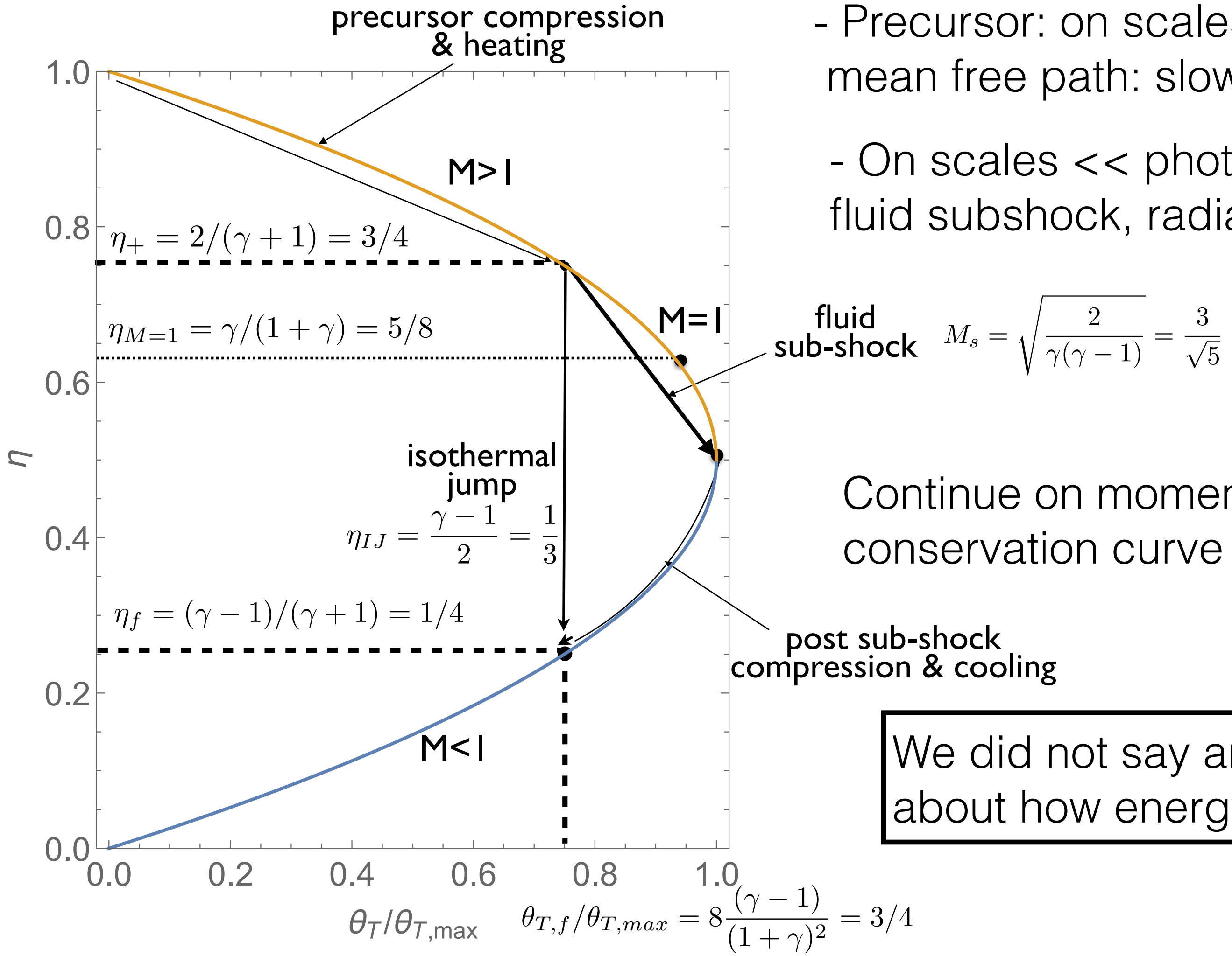
$$\theta_{T,f}/\theta_{T,max} = 8\frac{(\gamma-1)}{(1+\gamma)^2} = 3/4$$

Two branches - initially on upper,
final state on lower,
no way to pass throughout

Final T reached before
final compression

final state

Fluid subshock



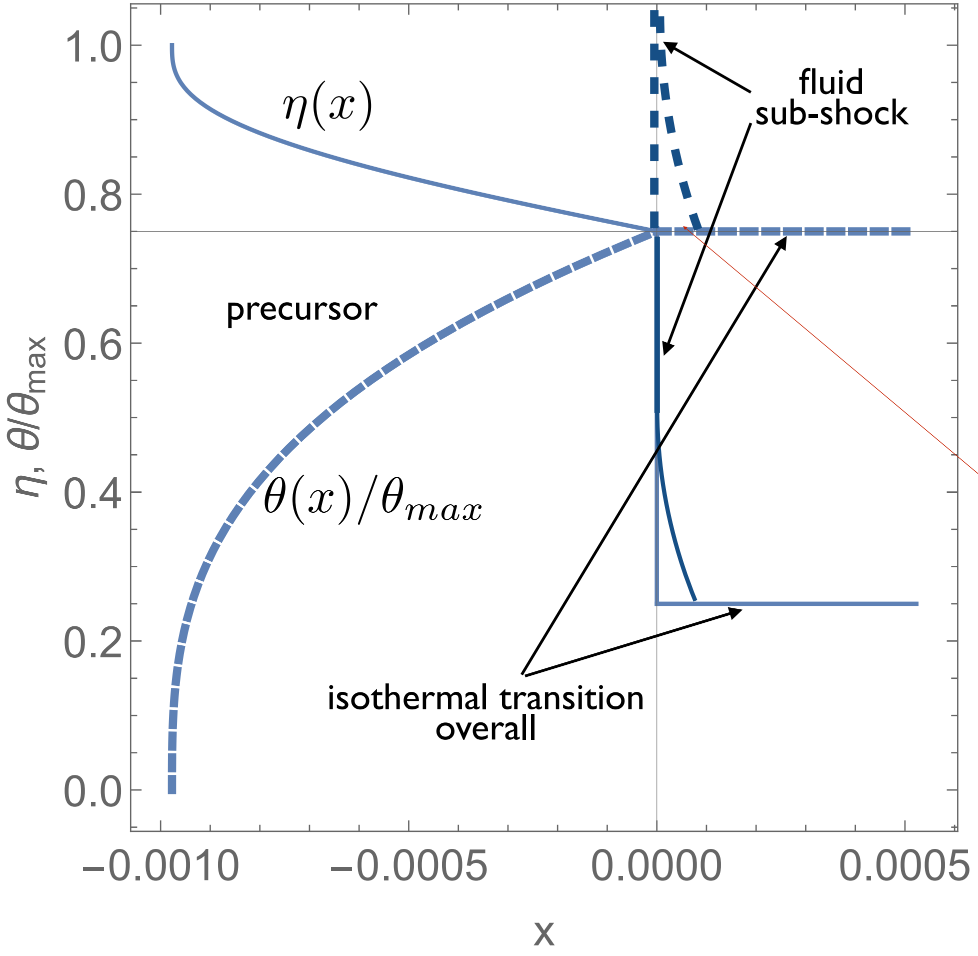
- Precursor: on scales >> photon mean free path: slow down and heat-up

- On scales << photon mean free path: fluid subshock, radiation continuous

Continue on momentum conservation curve

We did not say anything about how energy is redistributed!

Resolving the isothermal jump



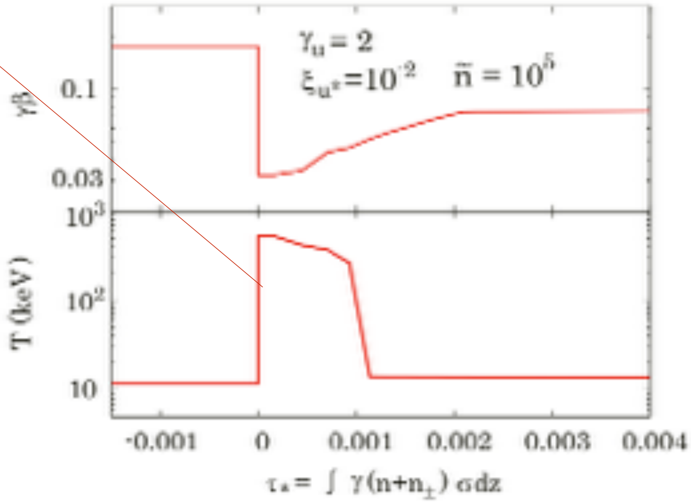
fluid sub-shock

precursor

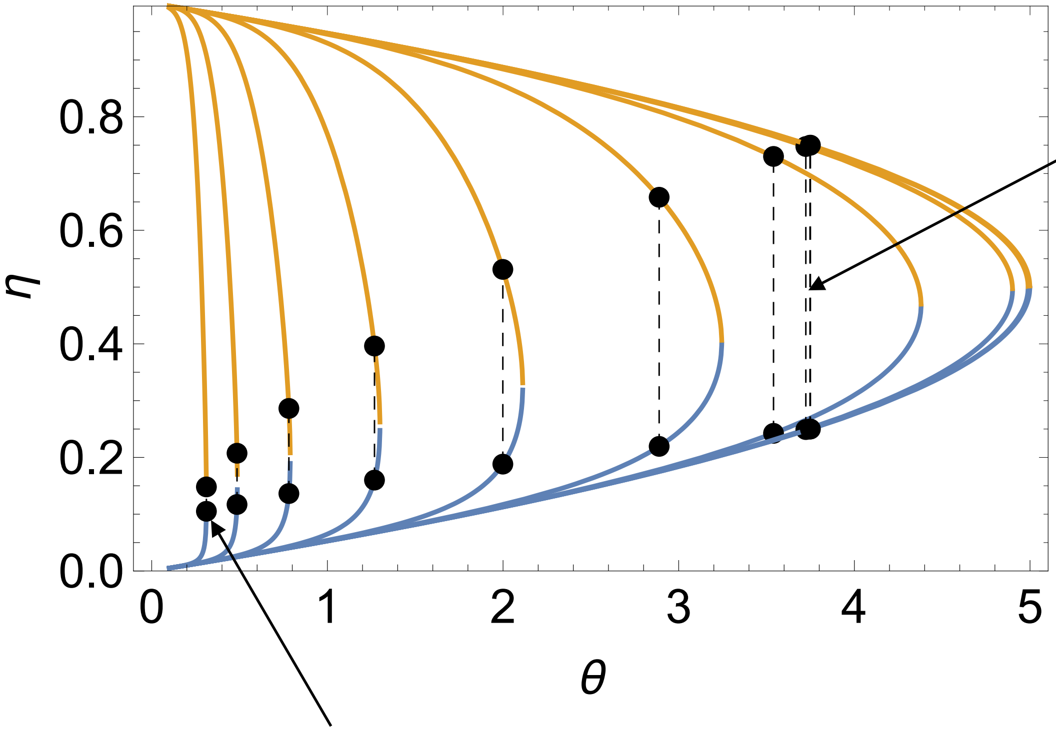
isothermal transition overall

$$M_s = \sqrt{\frac{2}{\gamma(\gamma-1)}} = \frac{3}{\sqrt{5}}$$

Itoh + 2018



Add pairs and radiation



limit of large density

Standing shocks in core collapse, high density limit: isothermal jump - post-shock T is 25% higher, but density 30% lower

- For highly radiatively dominated shocks (low density) isothermal jump disappears - no shock, continuos transition (can also be shown analytically)
- This turns out to be the regime in post NS-NS merger winds.

Conclusion

- Shocks in NS-NS mergers evolve in new, poorly explored regime of mildly relativistic velocities, relativistic temperatures, photon and pair loading, perhaps induced nuclear reactions