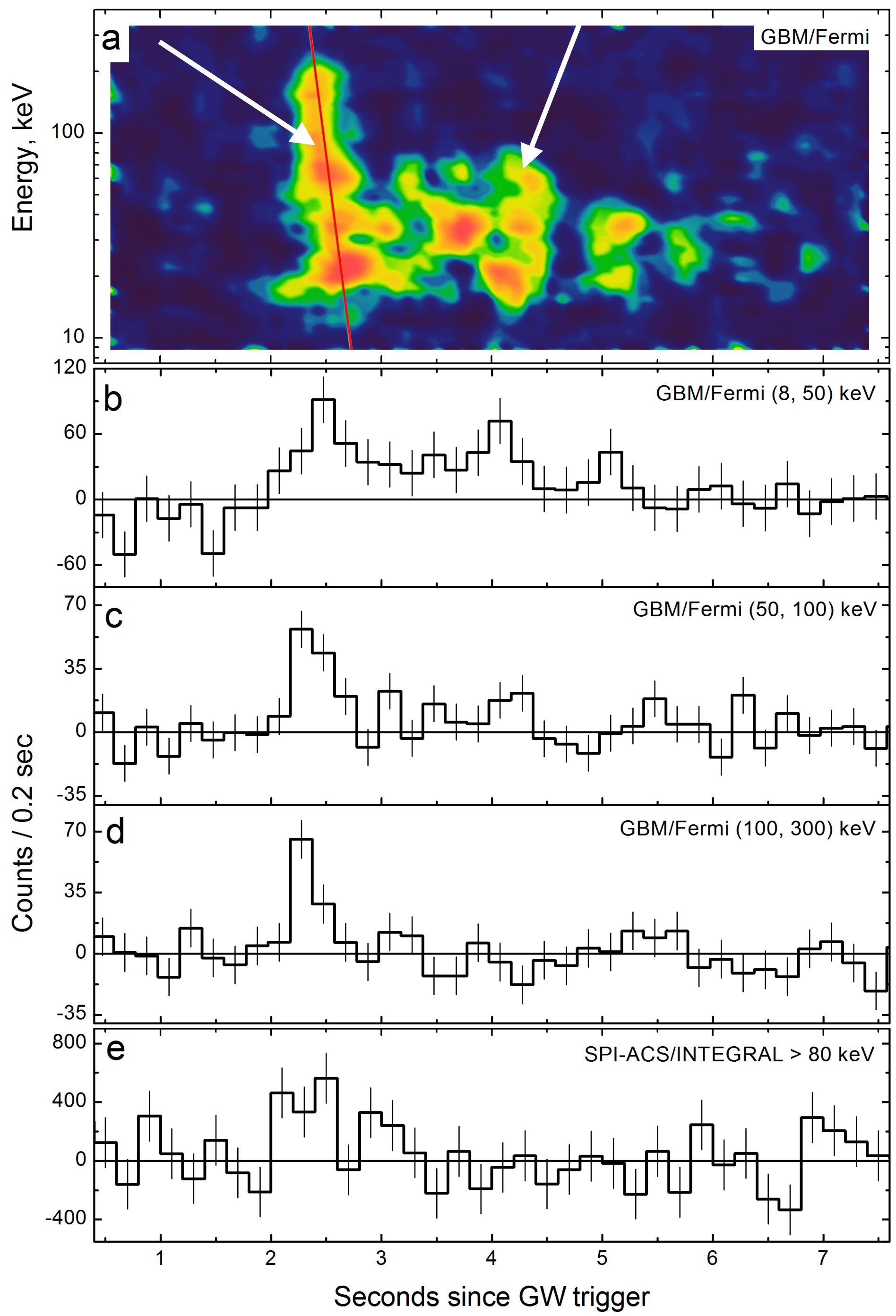
Jets and shocks in GRB/GW170817

Maxim Lyutikov (Purdue U.)

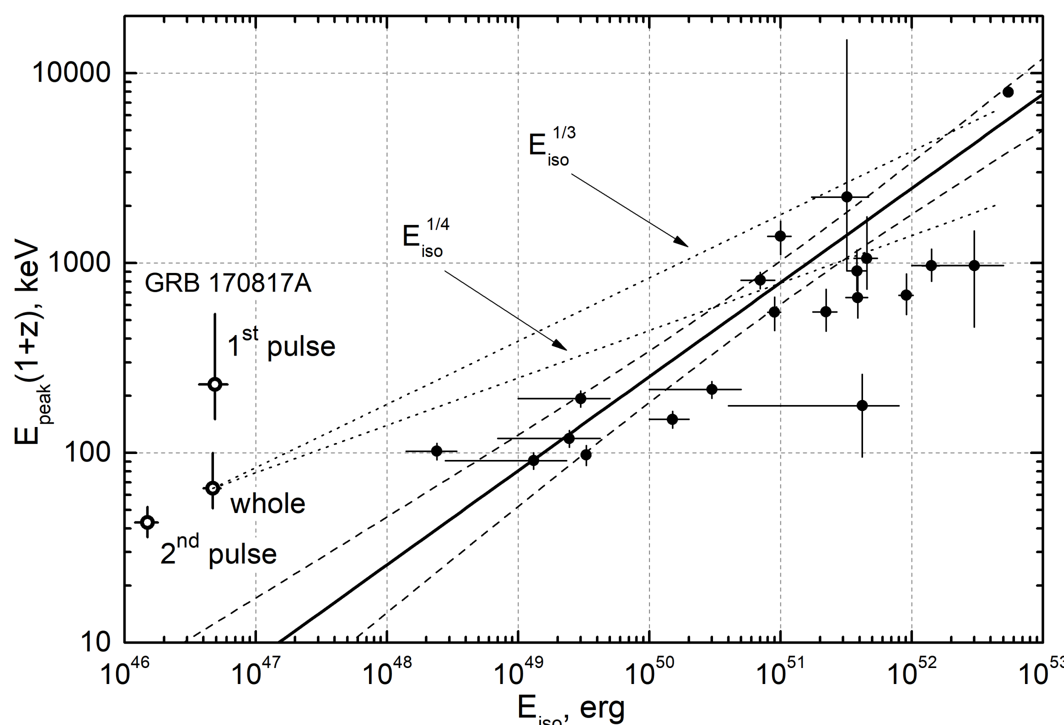
- MHD effects
- Radiation transfer

GRB170817 was unusual

Hard prompt ~ 10 keV soft tail



Way too hard/dim



Pozanenko +, 2018

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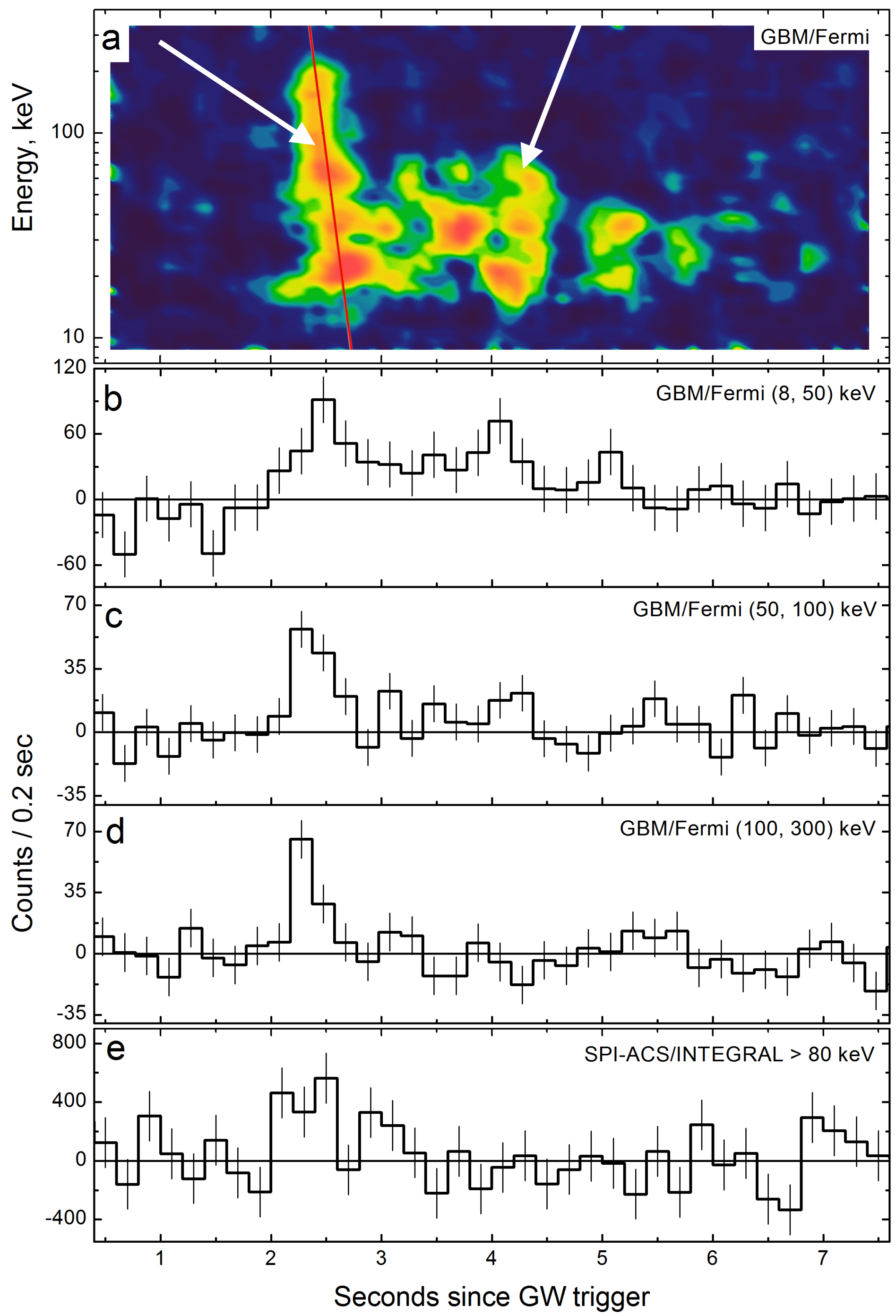

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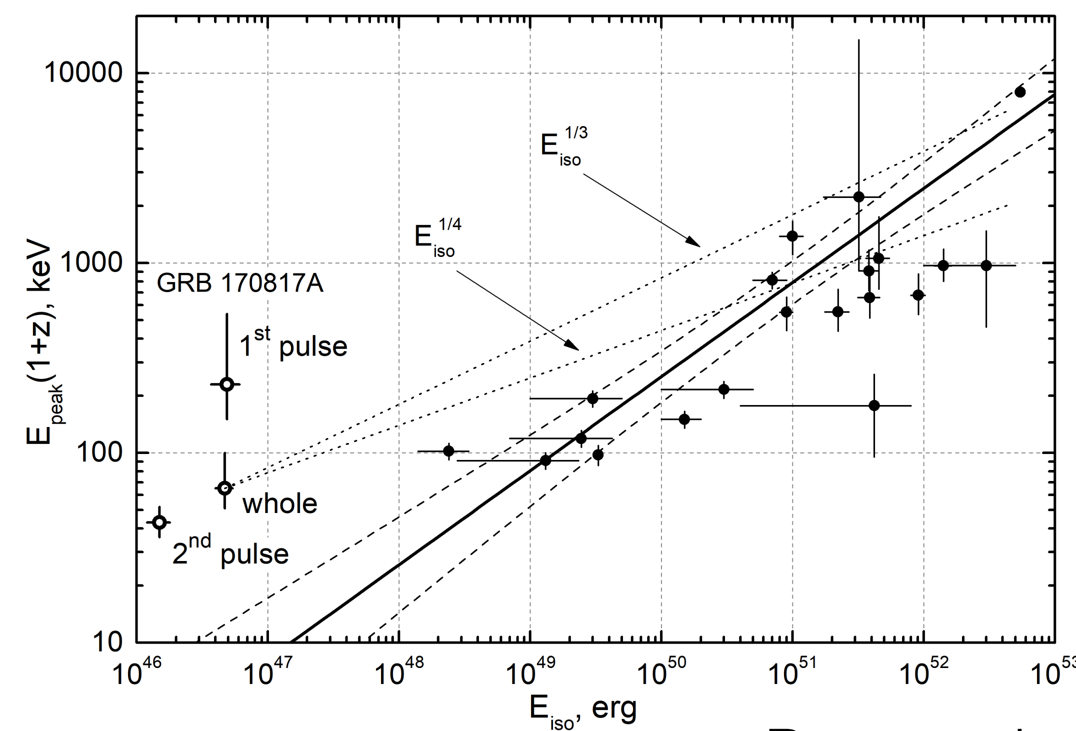
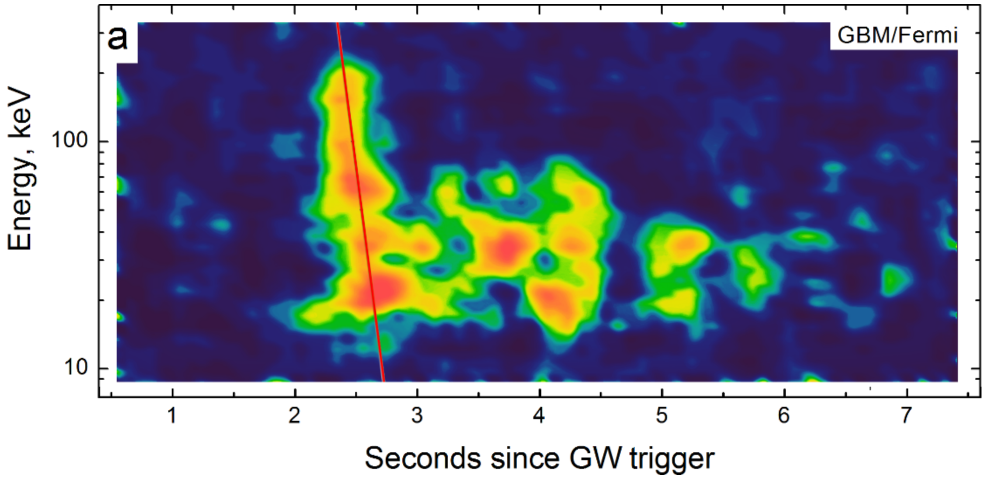
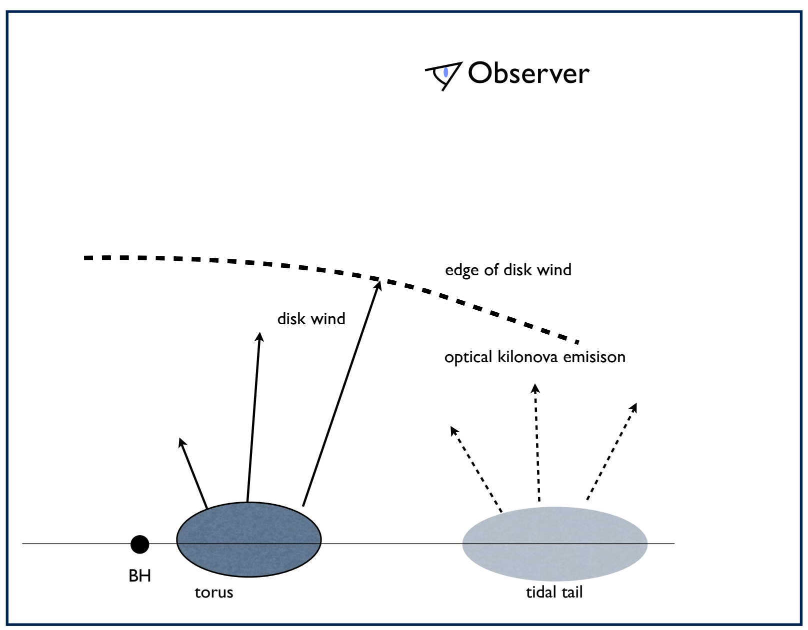


Pozanenko +, 2018

Close-by sGRB seen off-axis

Cocoon - prompt, Jet- to be 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

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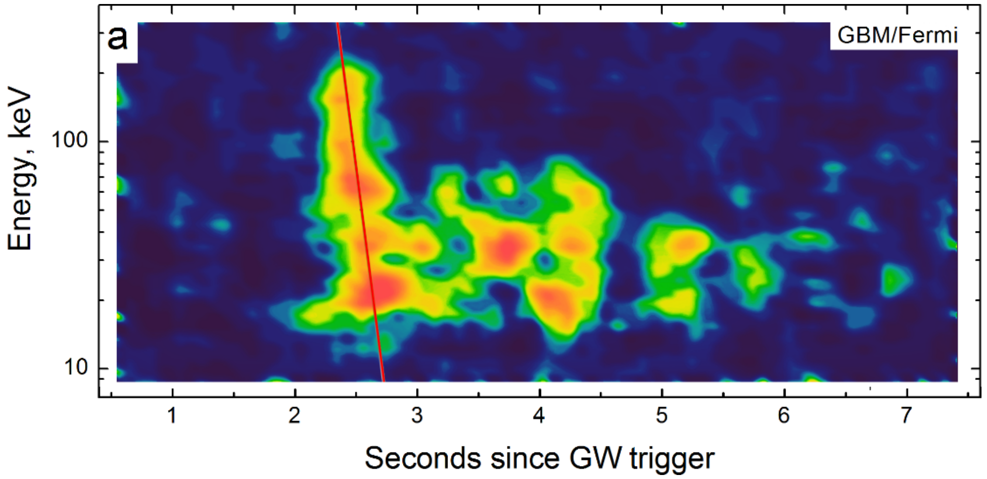

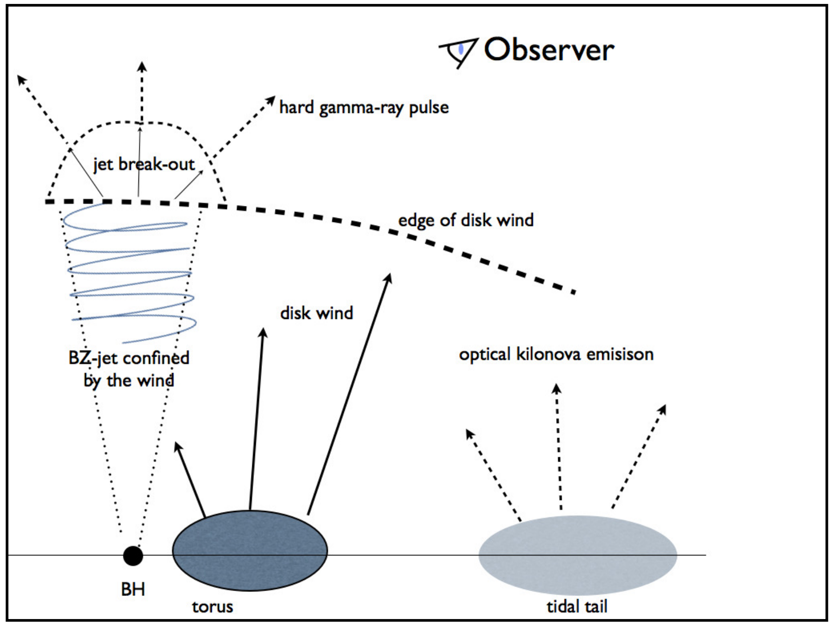

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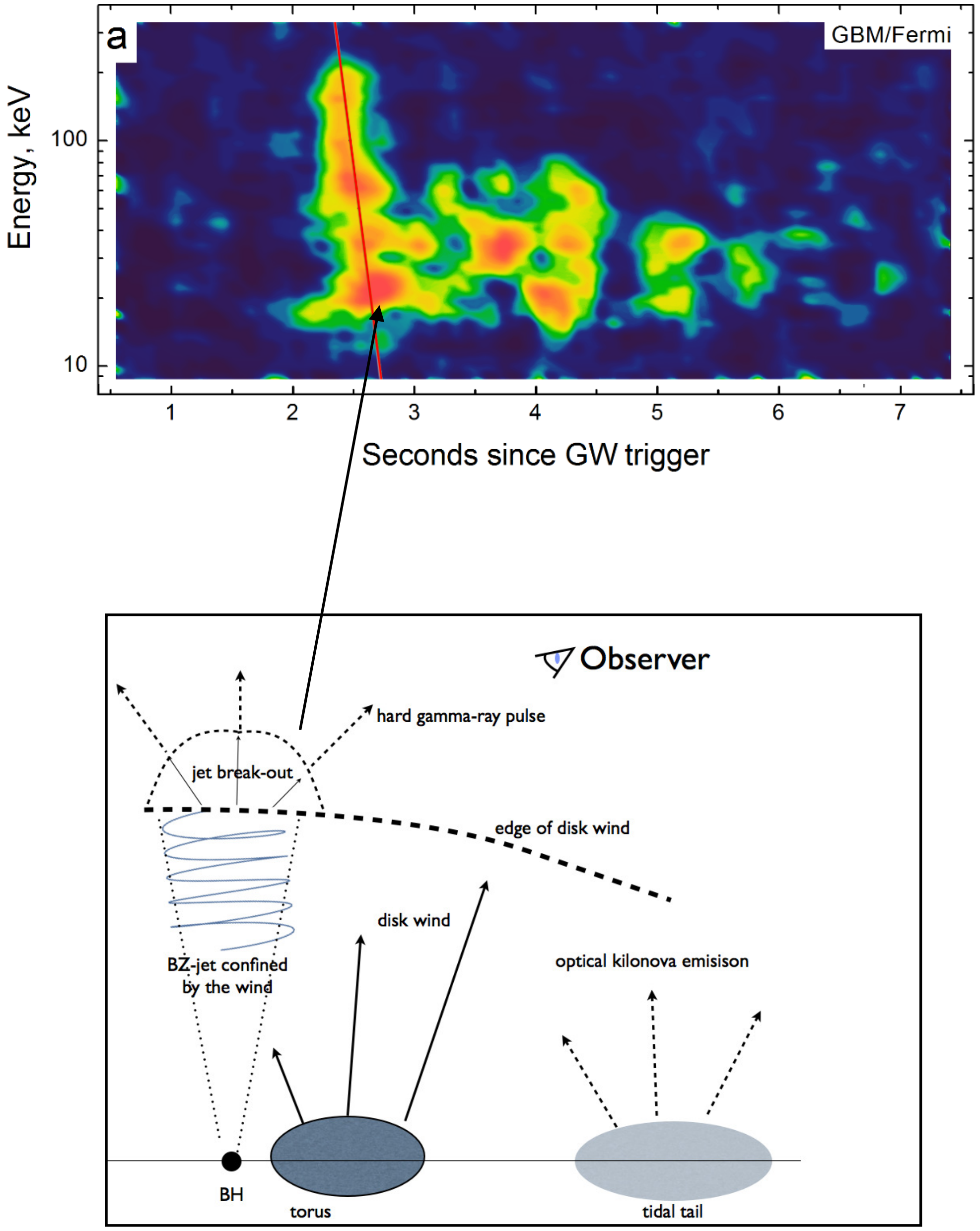

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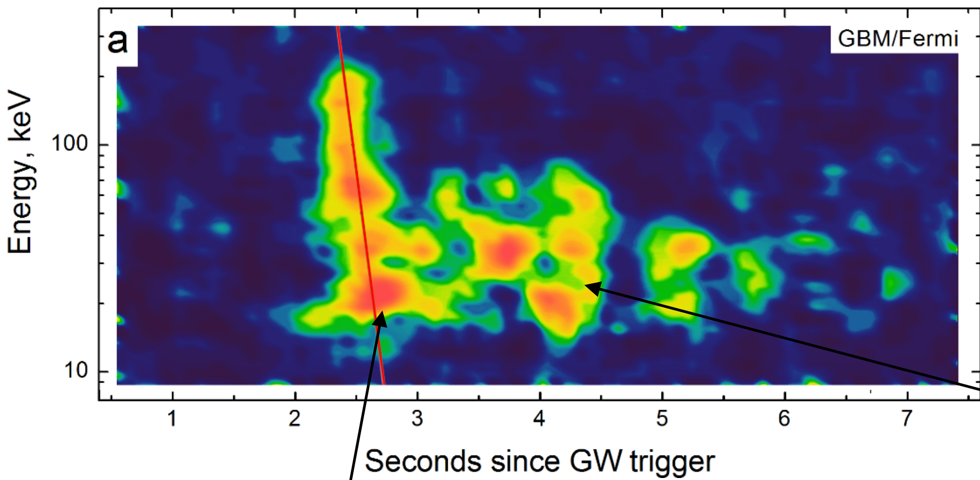
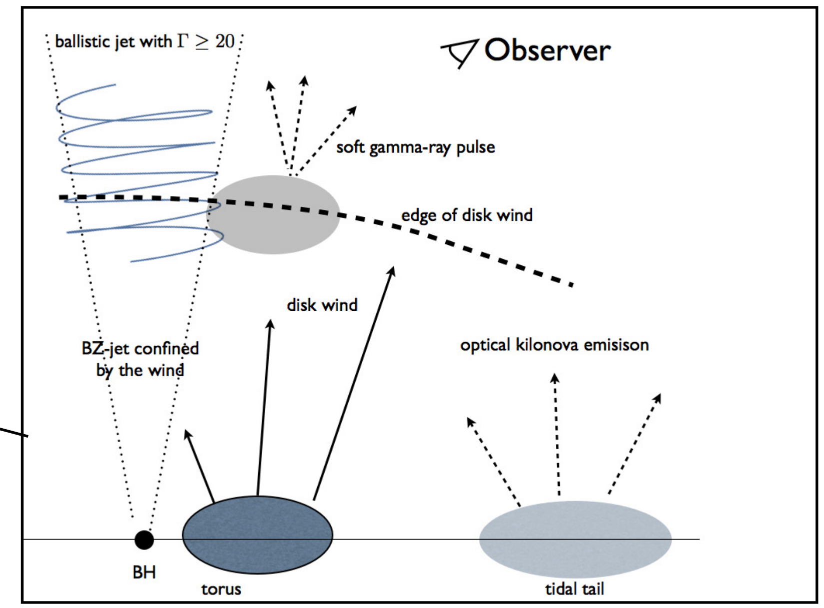
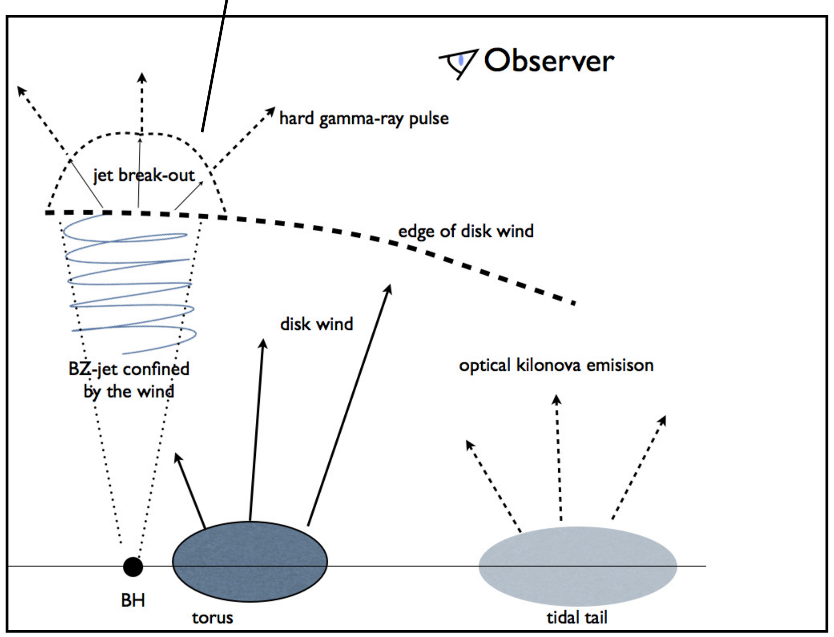




- Second peak from shock-heated wind
- Fast spine not yet seen



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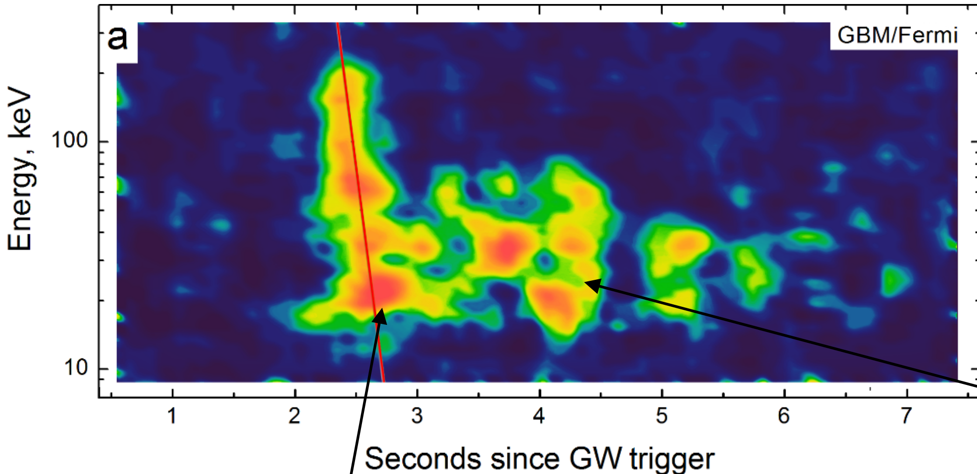

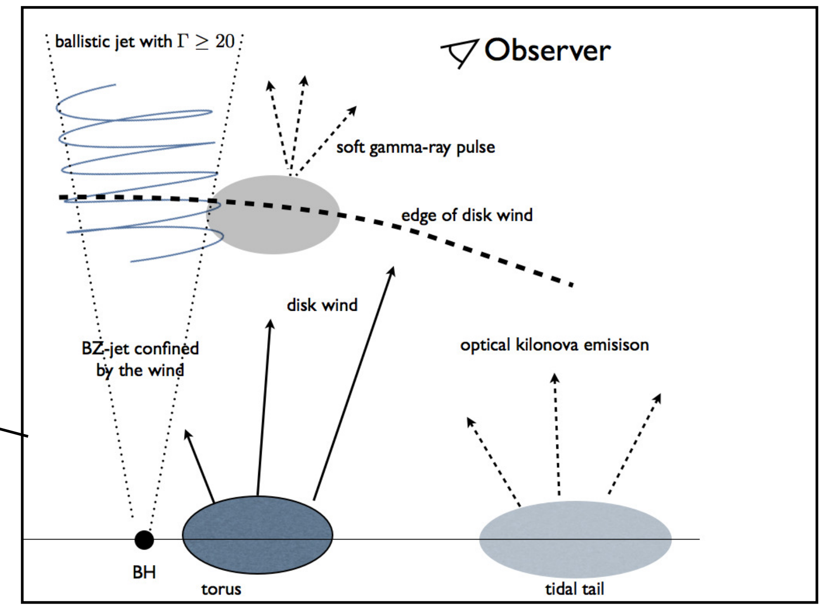

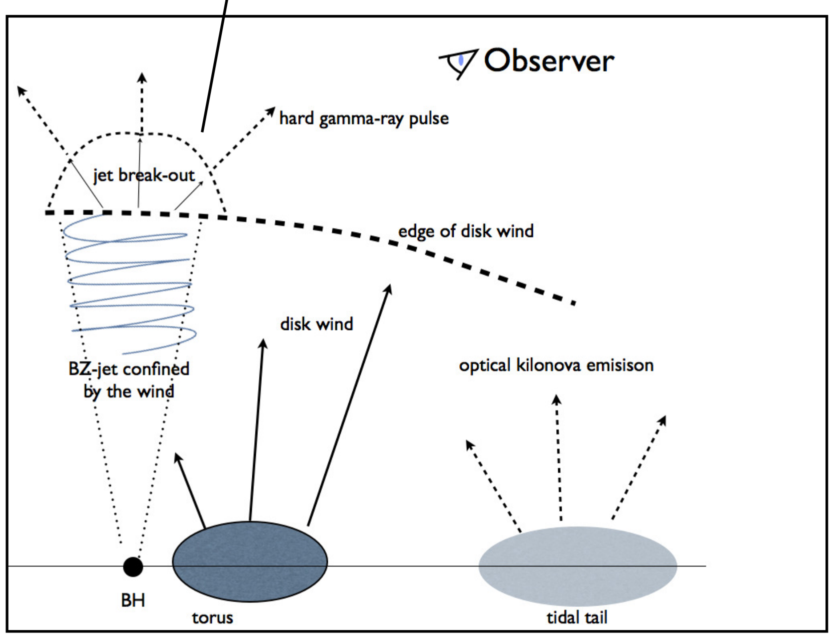

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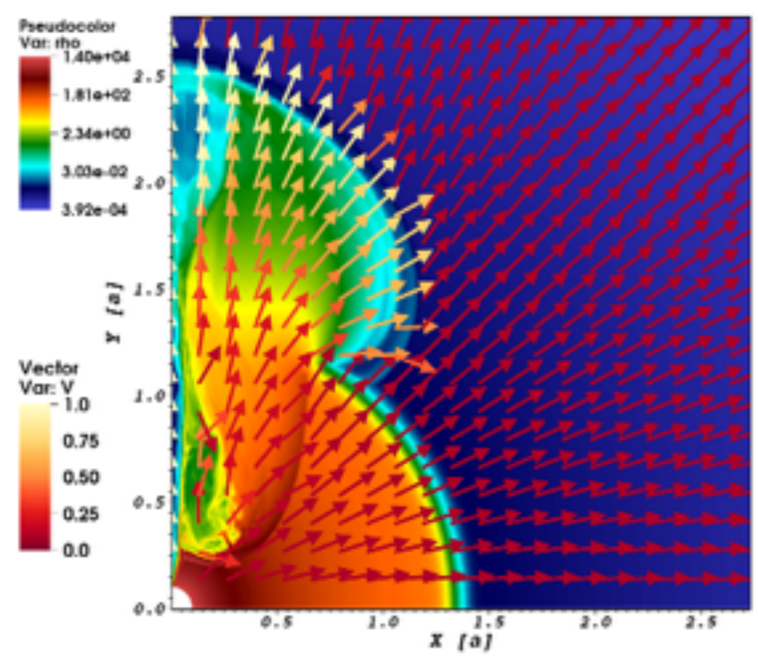
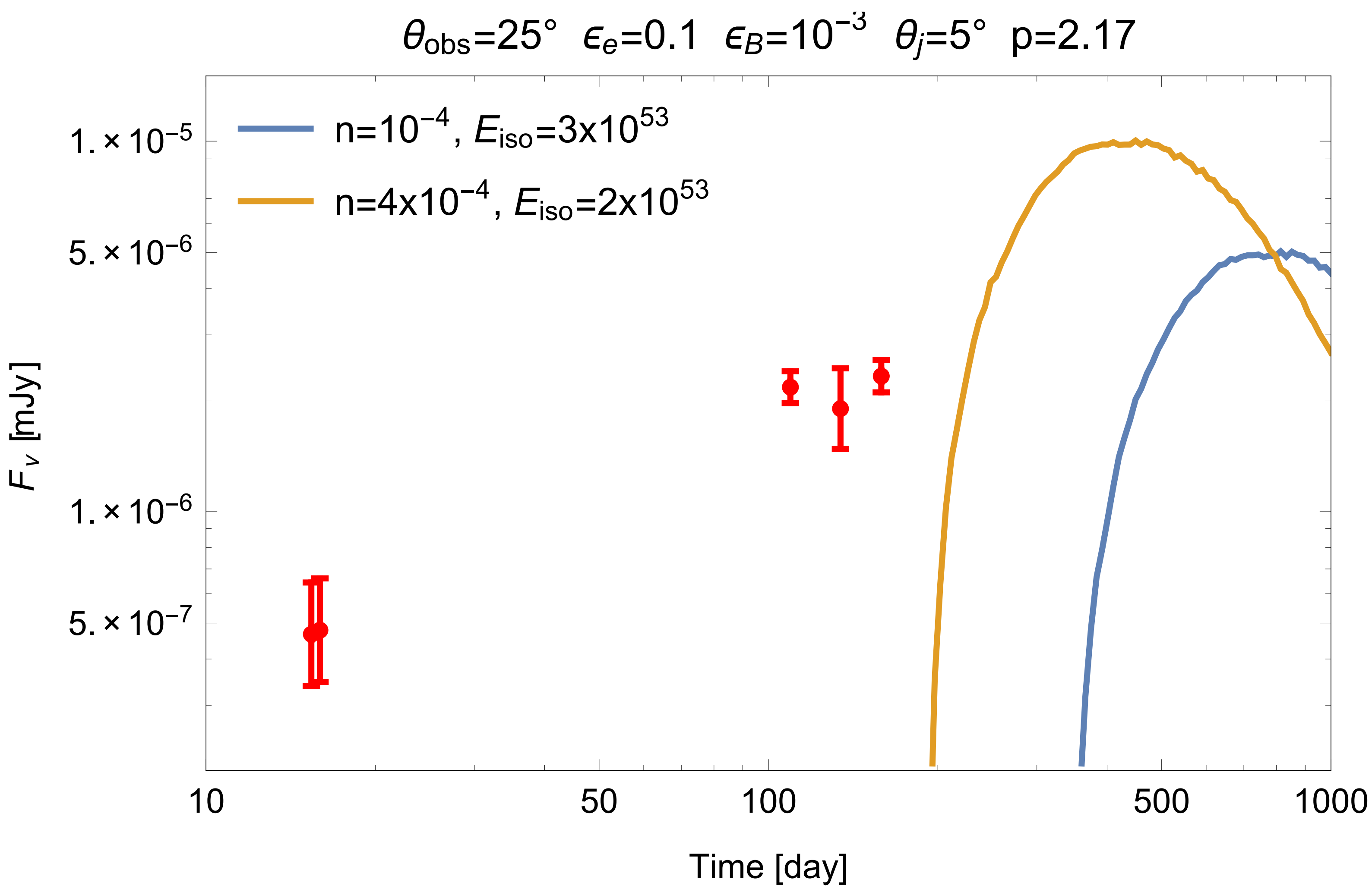


Barkov et al, in prep

We predict: a second bump in afterglow



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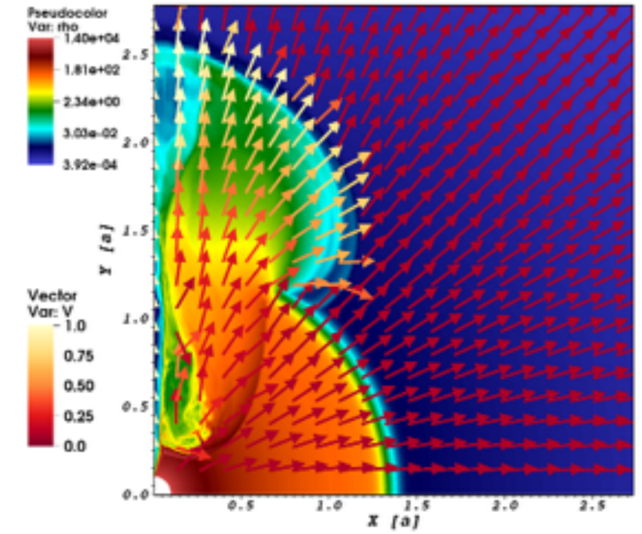
Mildly relativistic shock propagating through $\rho \sim 10^4\,\mathrm{g\,cm^3}$ $(\sim 10^{-2} M_\odot \text{ over } 10^9 cm)$

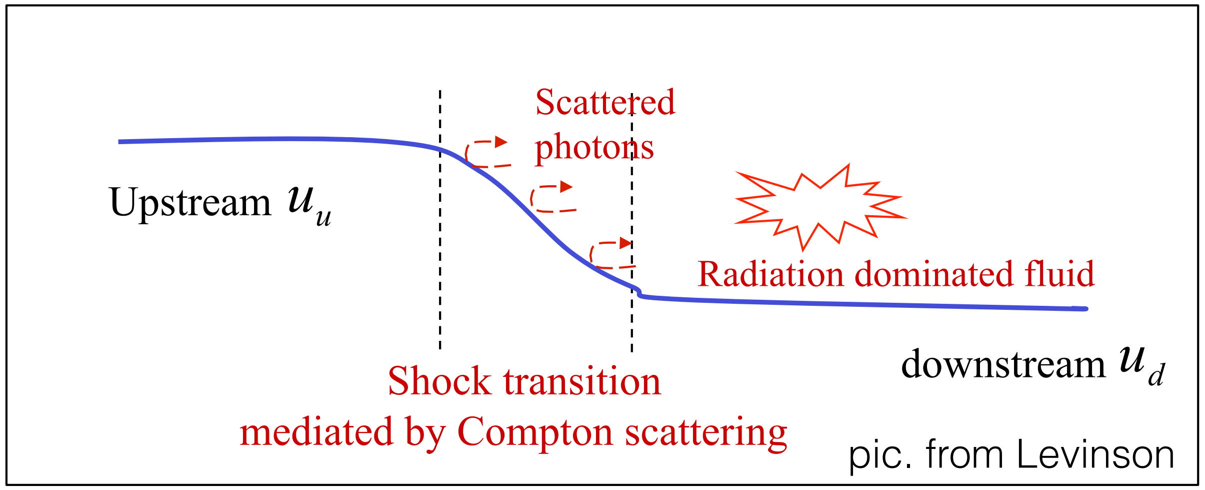


Radiation-mediated shocks

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 $\rho v^2 \sim \sigma_{SB} T^4/c$



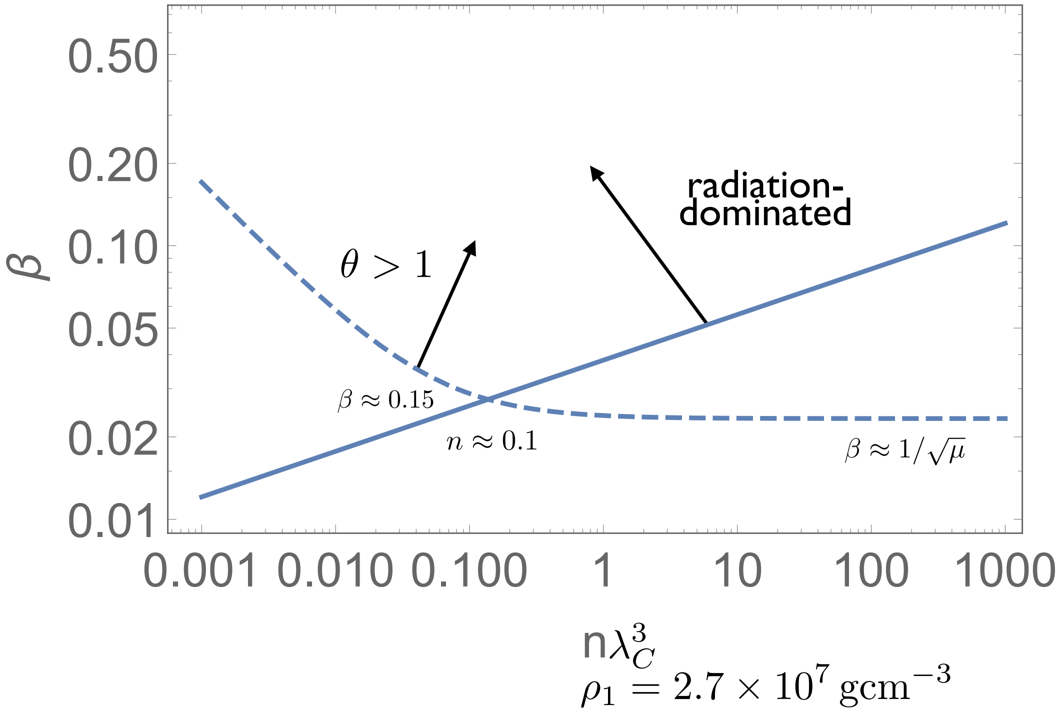
pic. from Levinson

- 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:

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

Pair production (and nuclear reactions) in the wind



Resolving radiation and pair-mediated shock transitions

$$\beta_1 \rho_1 = \beta \rho$$ matter flux

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

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

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

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overall jump condition

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energy flux

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

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

Energy redistribution by radiation. Diffusive - approximation!

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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

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

$$\rho_1 \beta_1^2 = \frac{\rho}{m_p} T + \rho \beta^2$$

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$$p = nT$$

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

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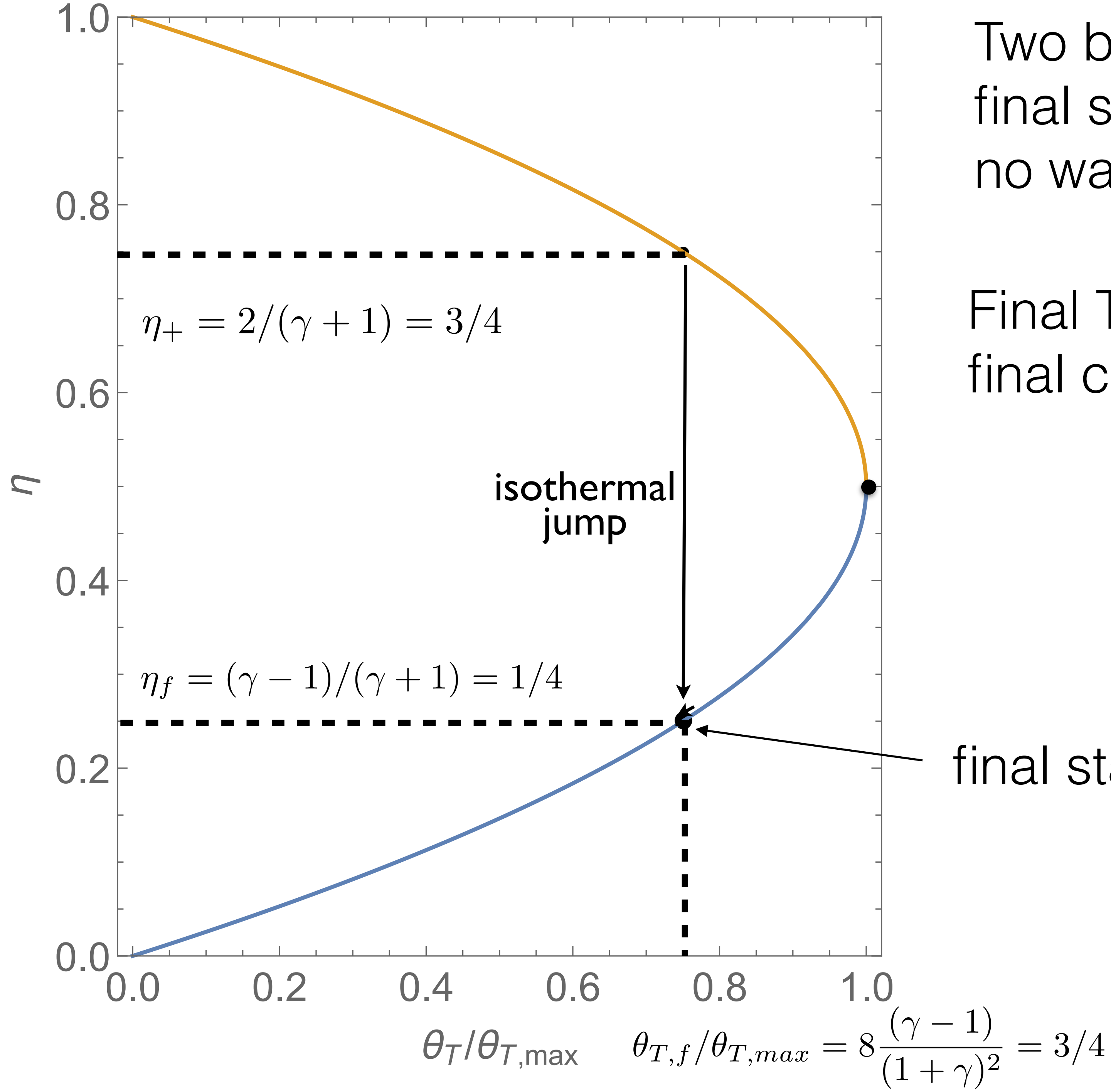
Zeldovich & Raiser

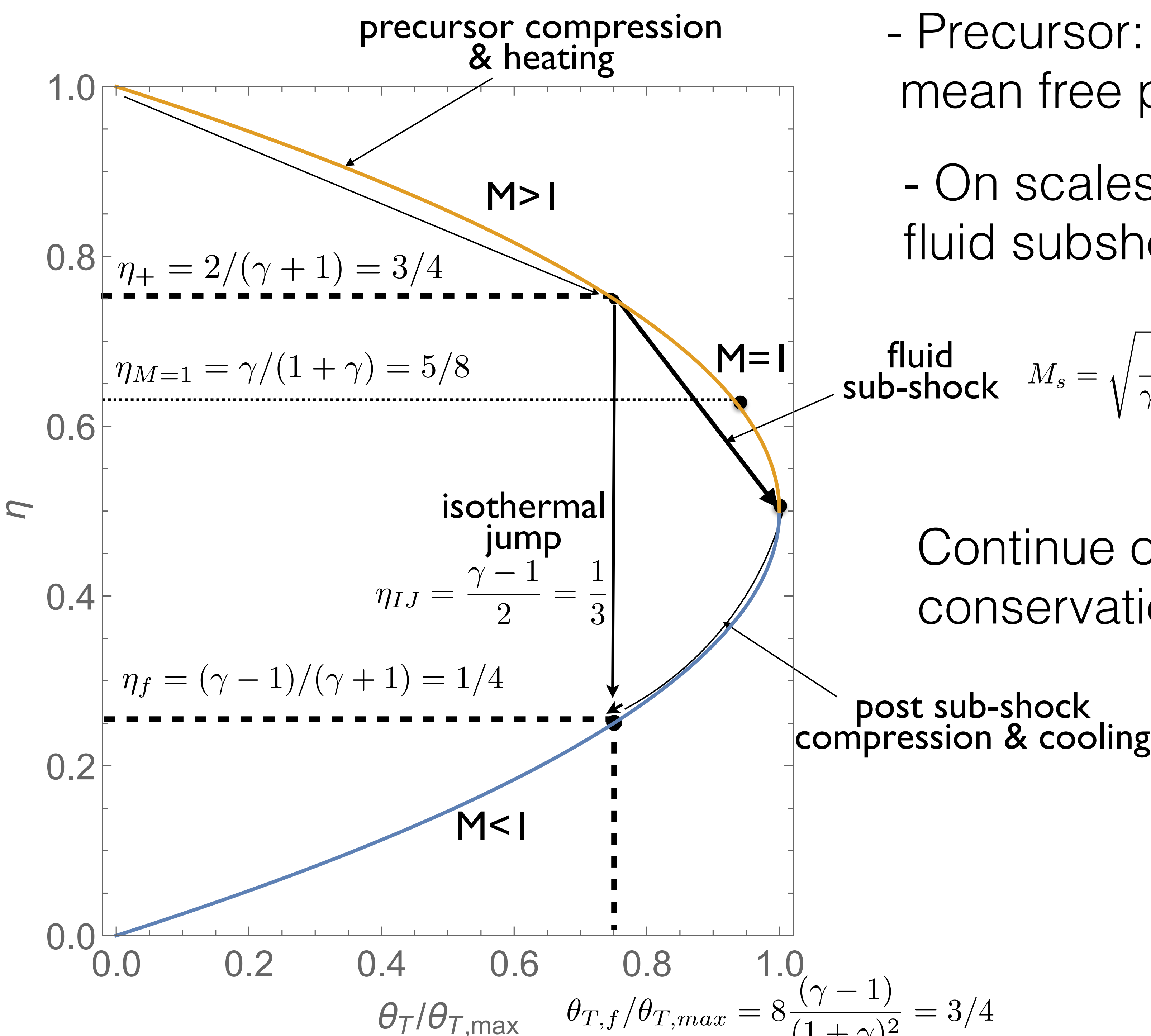


Two branches - initially on upper, final state on lower, no way to pass throughout

Final T reached before final compression

final state

Fluid subshock



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

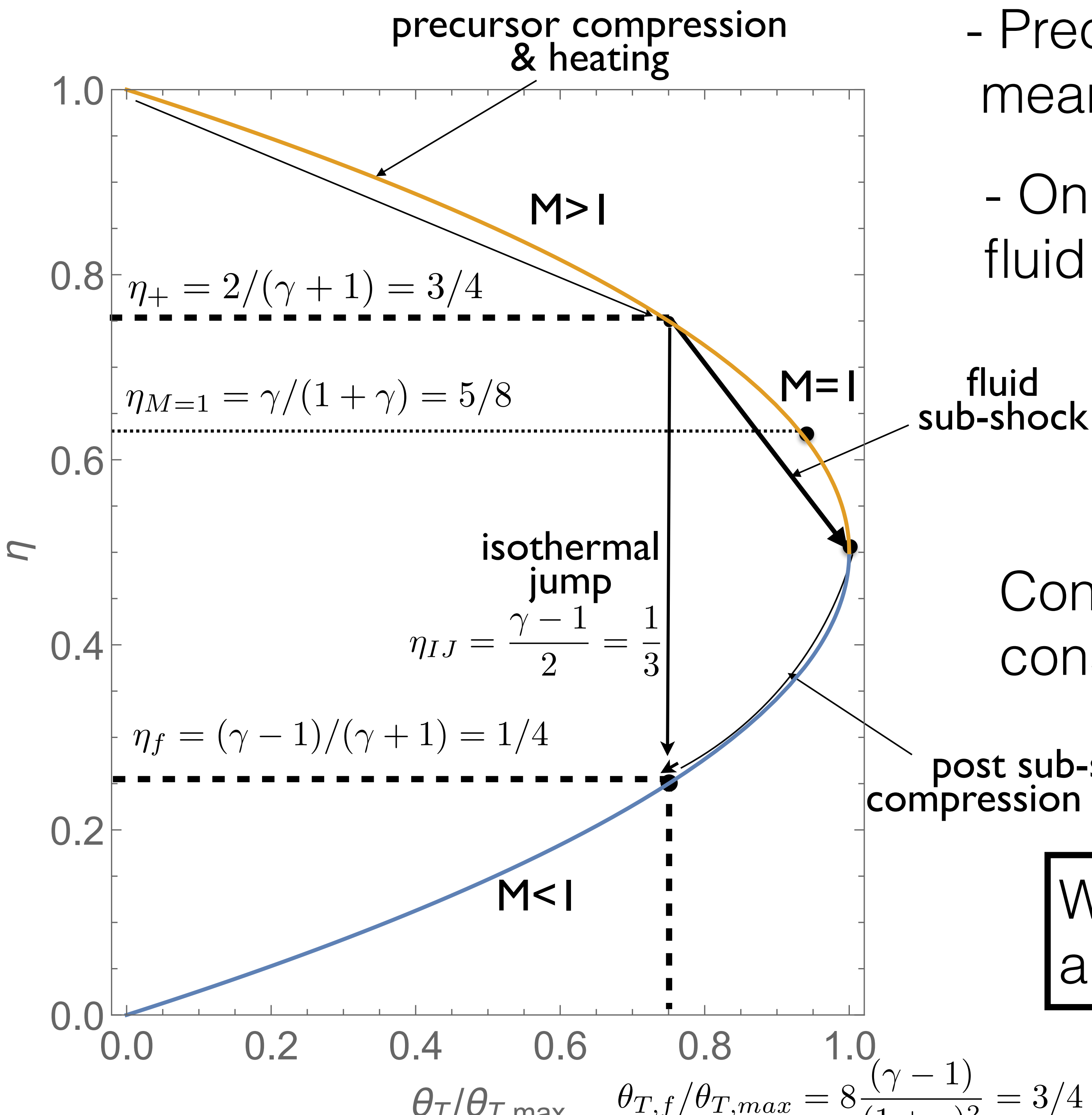
$$\theta_{T,f}/\theta_{T,max} = 8\frac{(\gamma-1)}{(1+\gamma)^2} = 3/4$$

- 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

Fluid subshock



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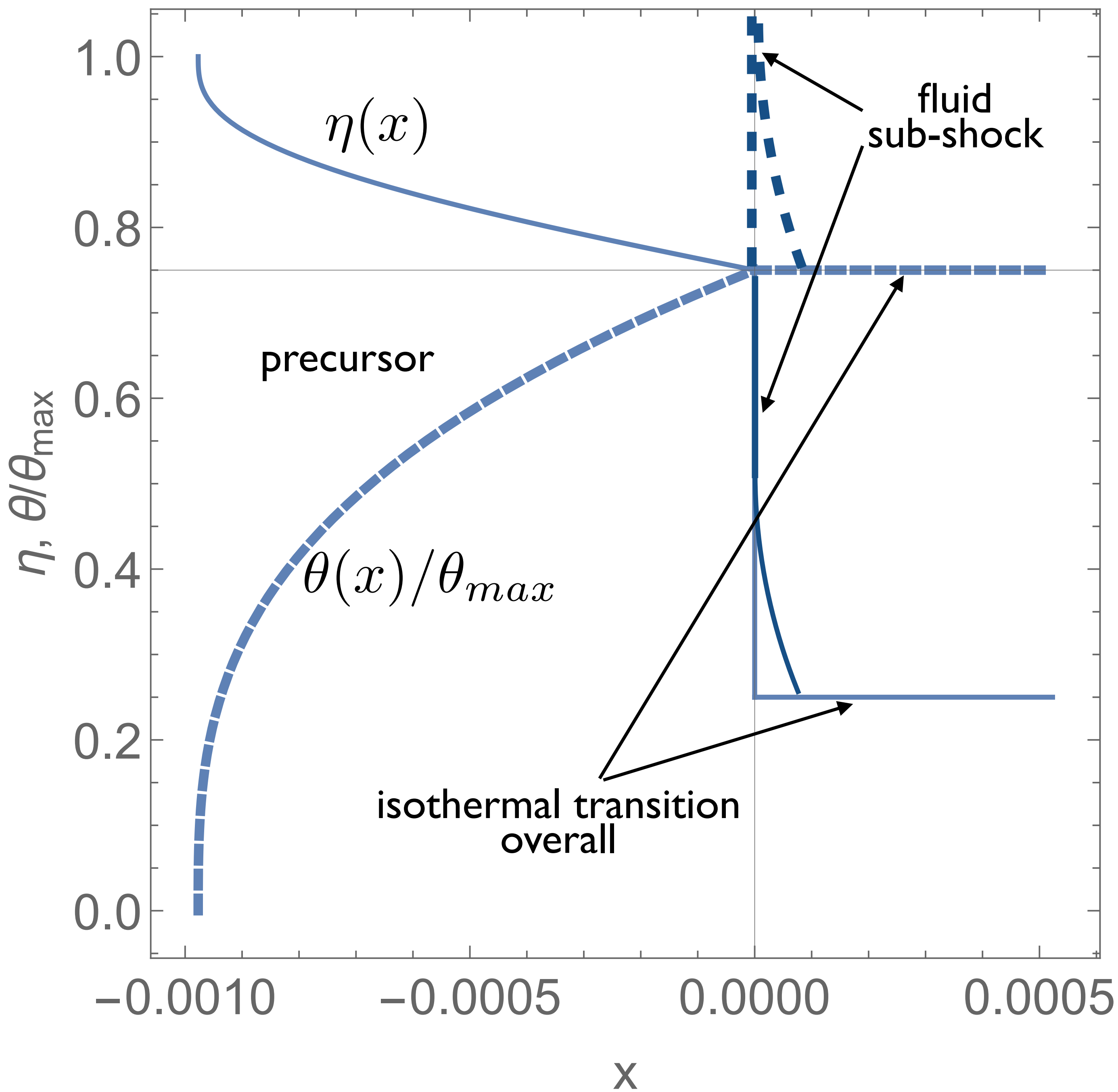
Continue on momentum conservation curve

We did not say anything about how energy is redistributed!

Resolving the isothermal jump



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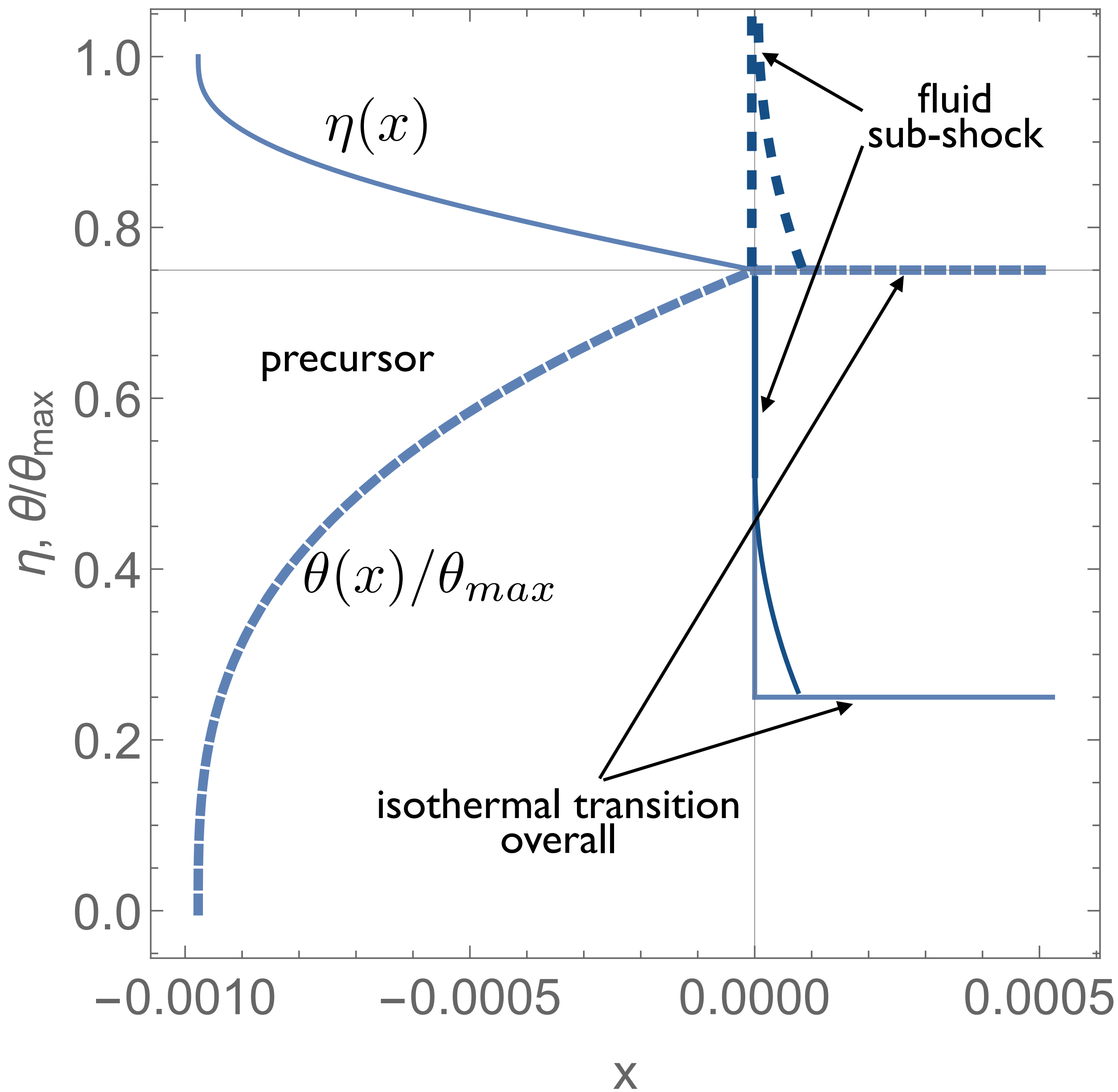

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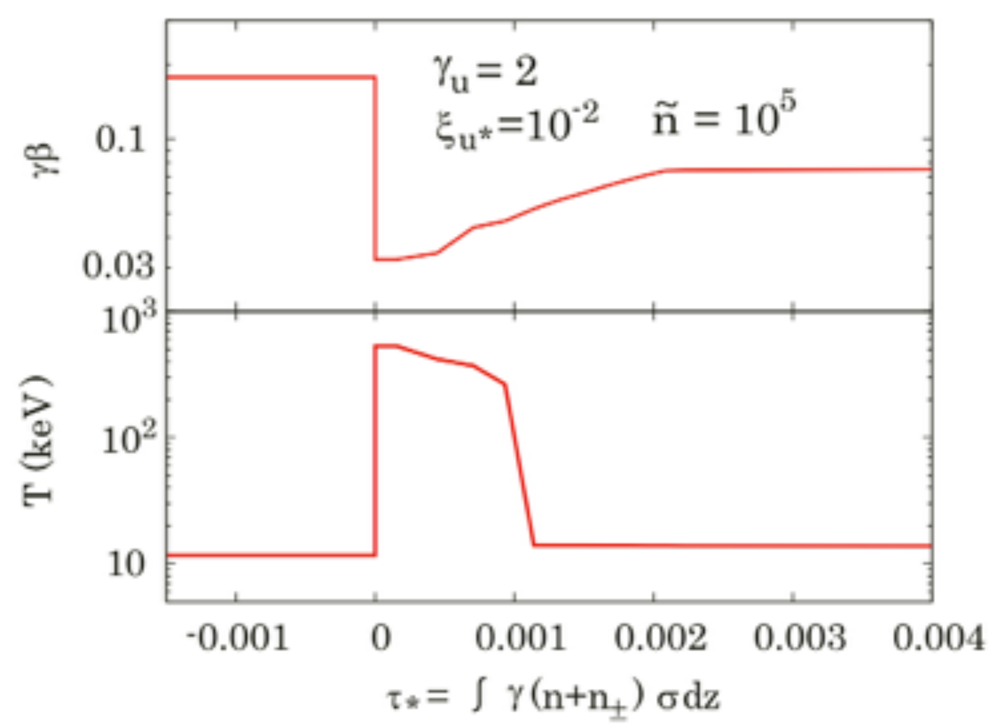
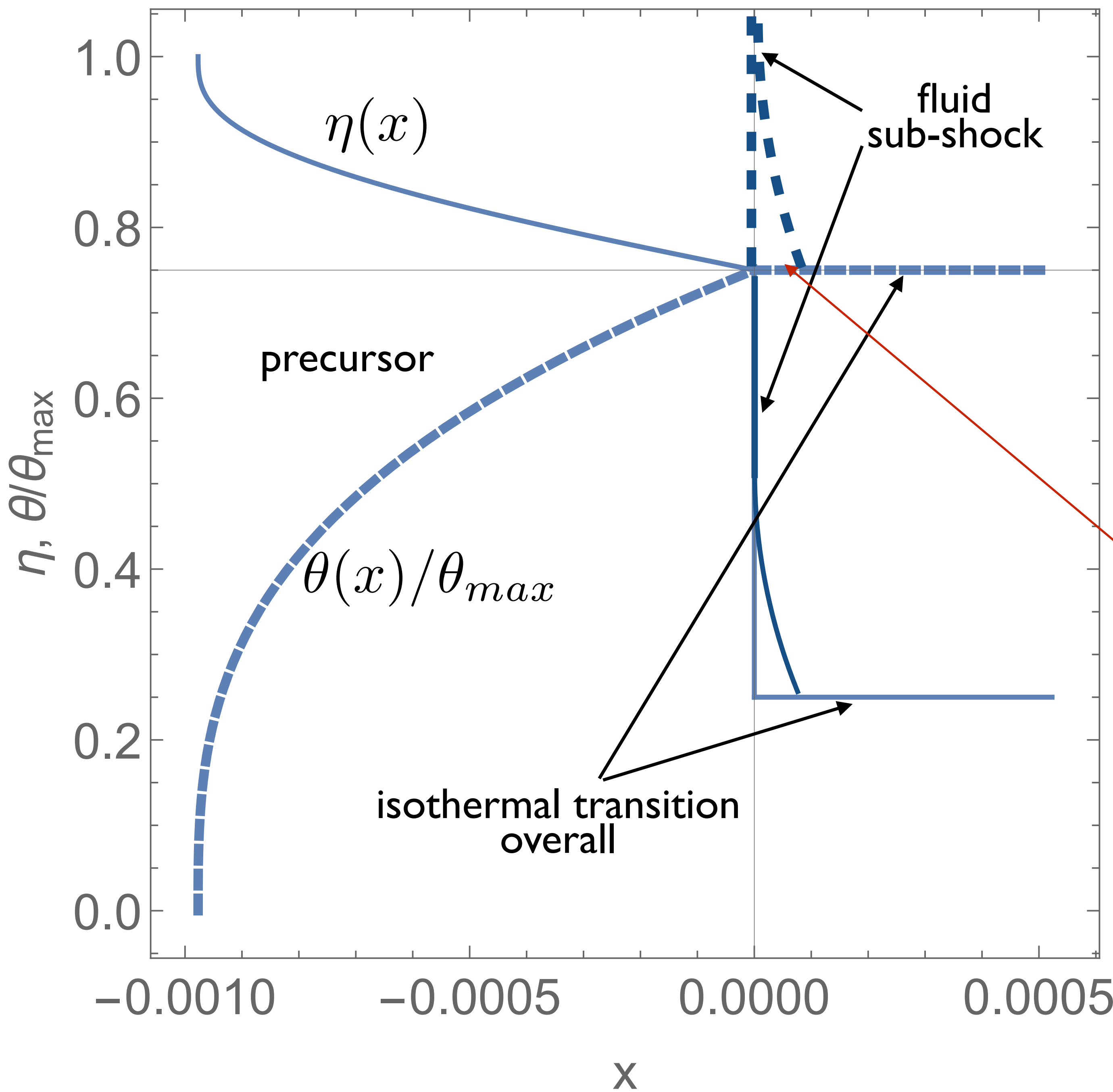
Itoh + 2018



Resolving the isothermal jump



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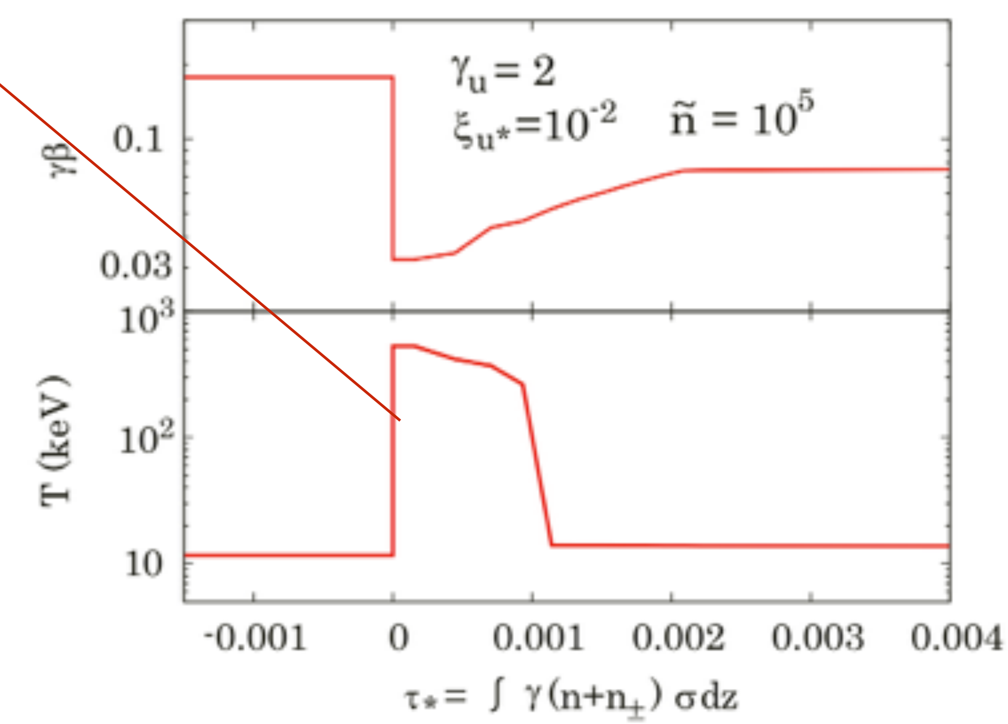
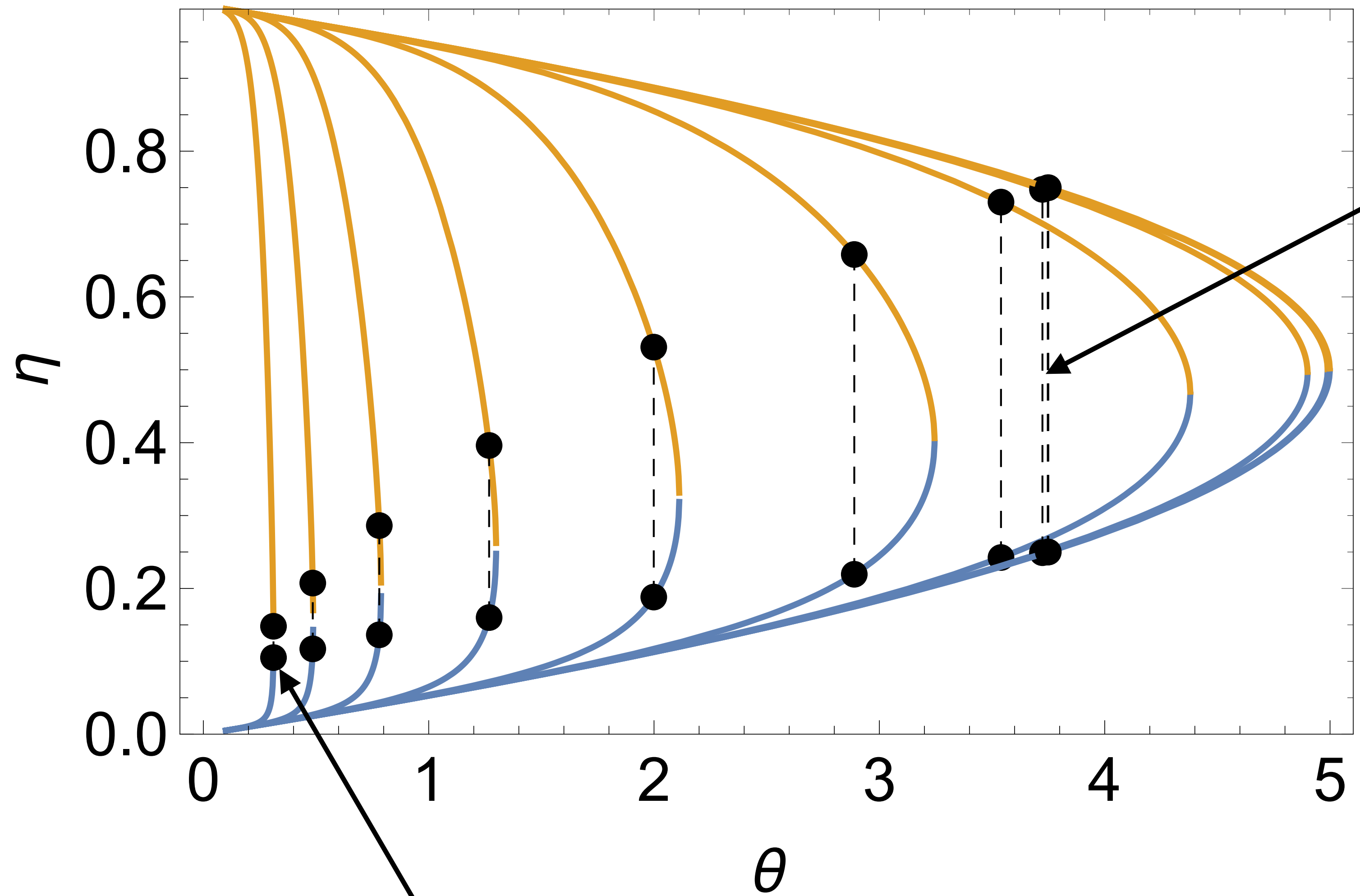
Itoh + 2018



Add pairs and radiation



limit of large density

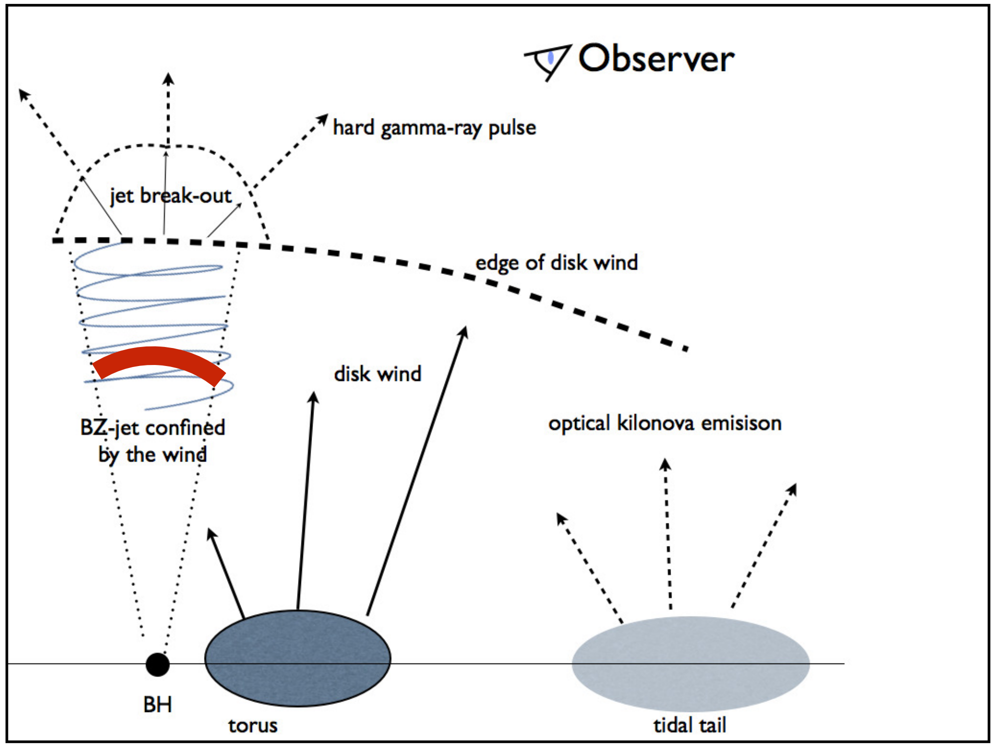
Standing shocks in core collapse, high density limit: isothermal jump - post-shock T is 25% higher, but density 30% lower

- 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.

From this workshop

Shock-induced nuclear reactions in the polar section of the wind (?)

- Mild $L_j \sim 10^{50}$ erg/sec, $\rho \sim 10^3 - 10^4 \mathrm{g\,cc}$
- T ~ $m_e c^2$
- can modify nuclear composition, blue bump?
- fairly low density, high tau
- Not LTE: low rate of photon production on tau=1 length (hot photons, but not enough by numbers)



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

Finite upstream Mach: bifurcation of solutions