Jet – Environment Interactions

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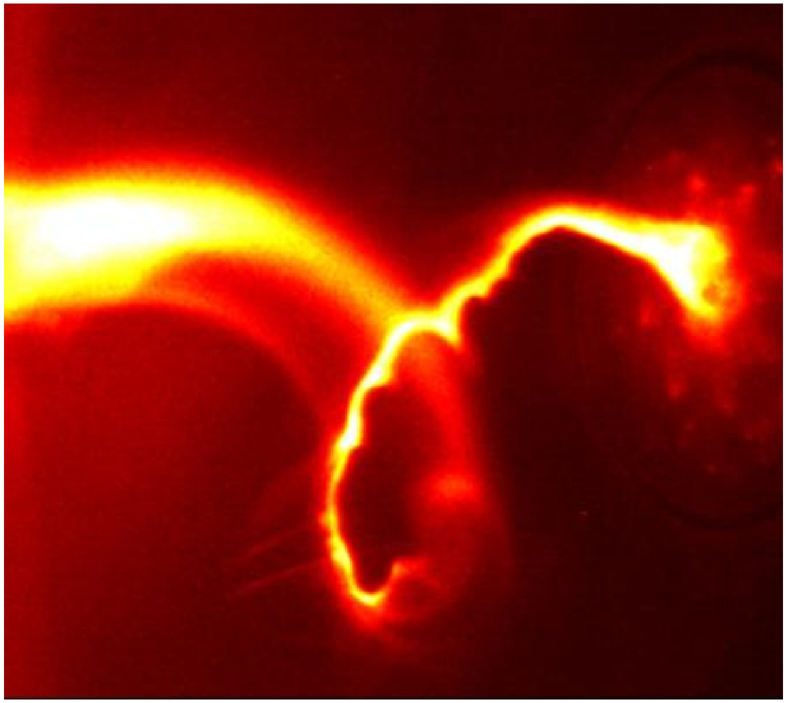
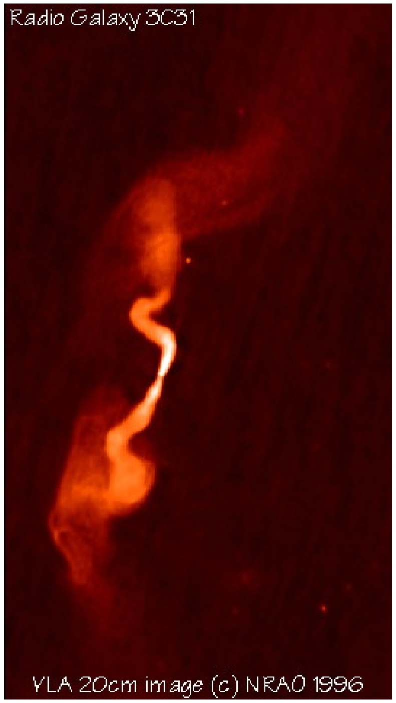
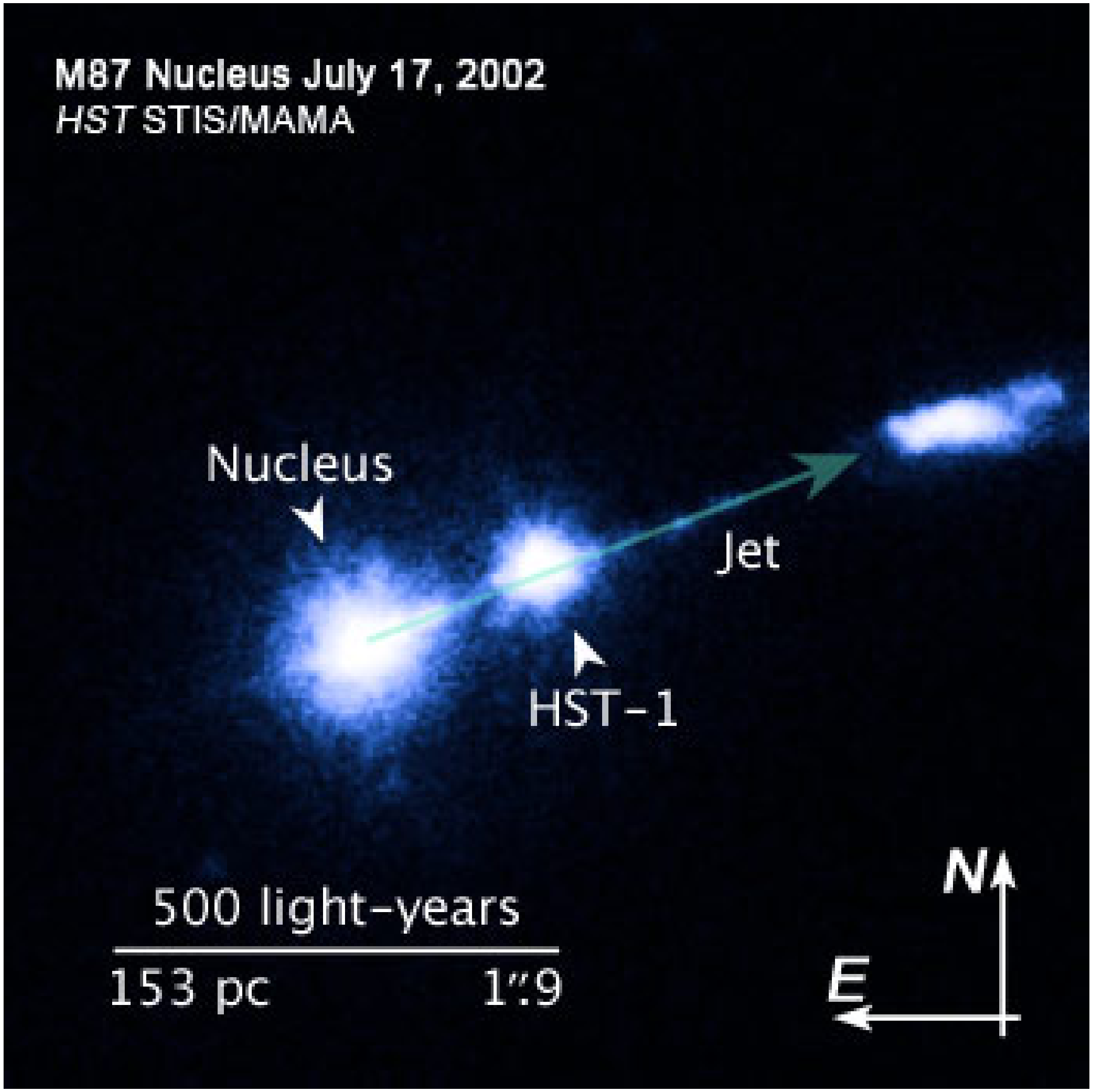
Outline

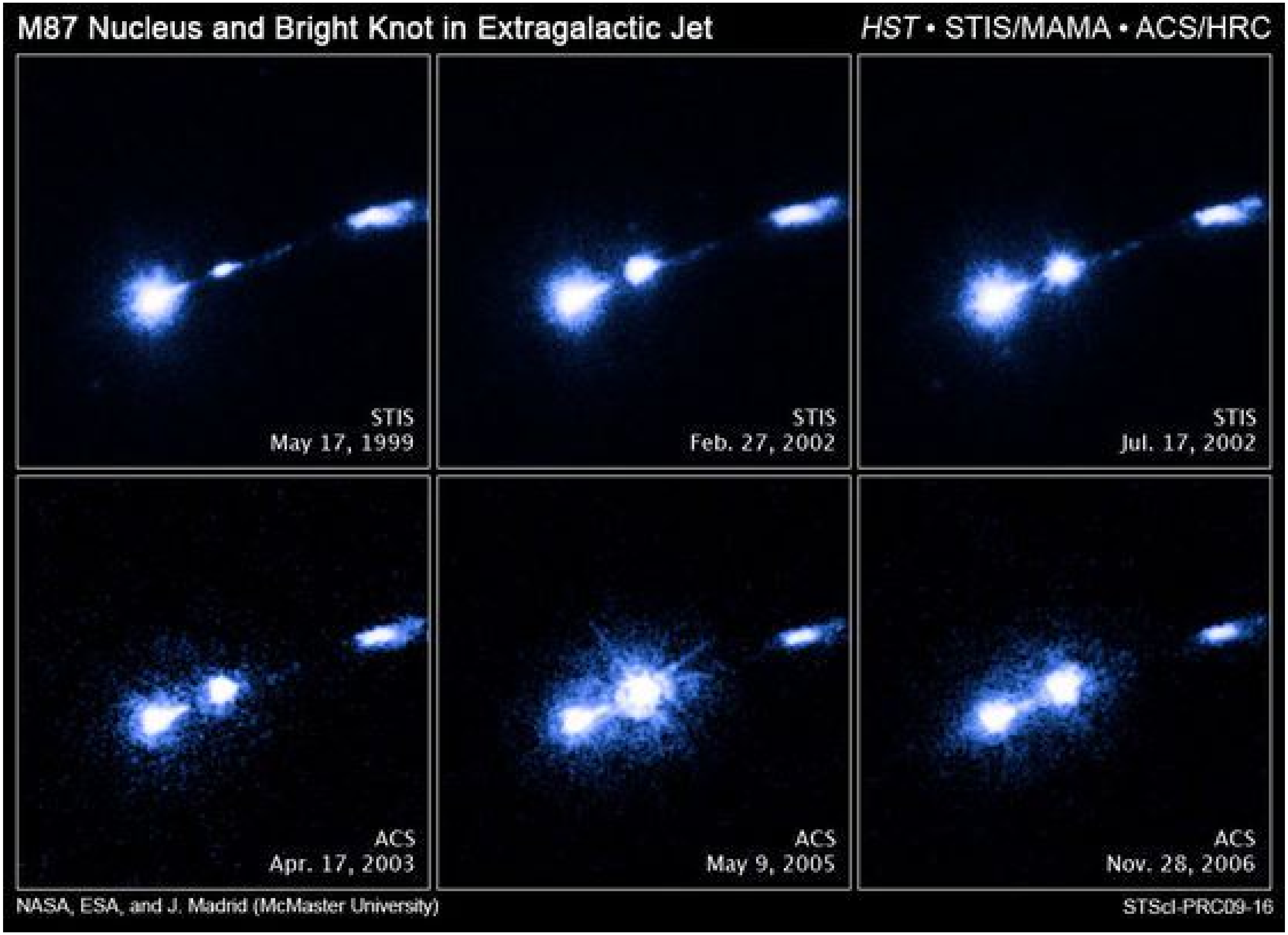
- “body” interactions
- “surface” interactions – the Riemann problem
- models/simulations – application to AGN jets

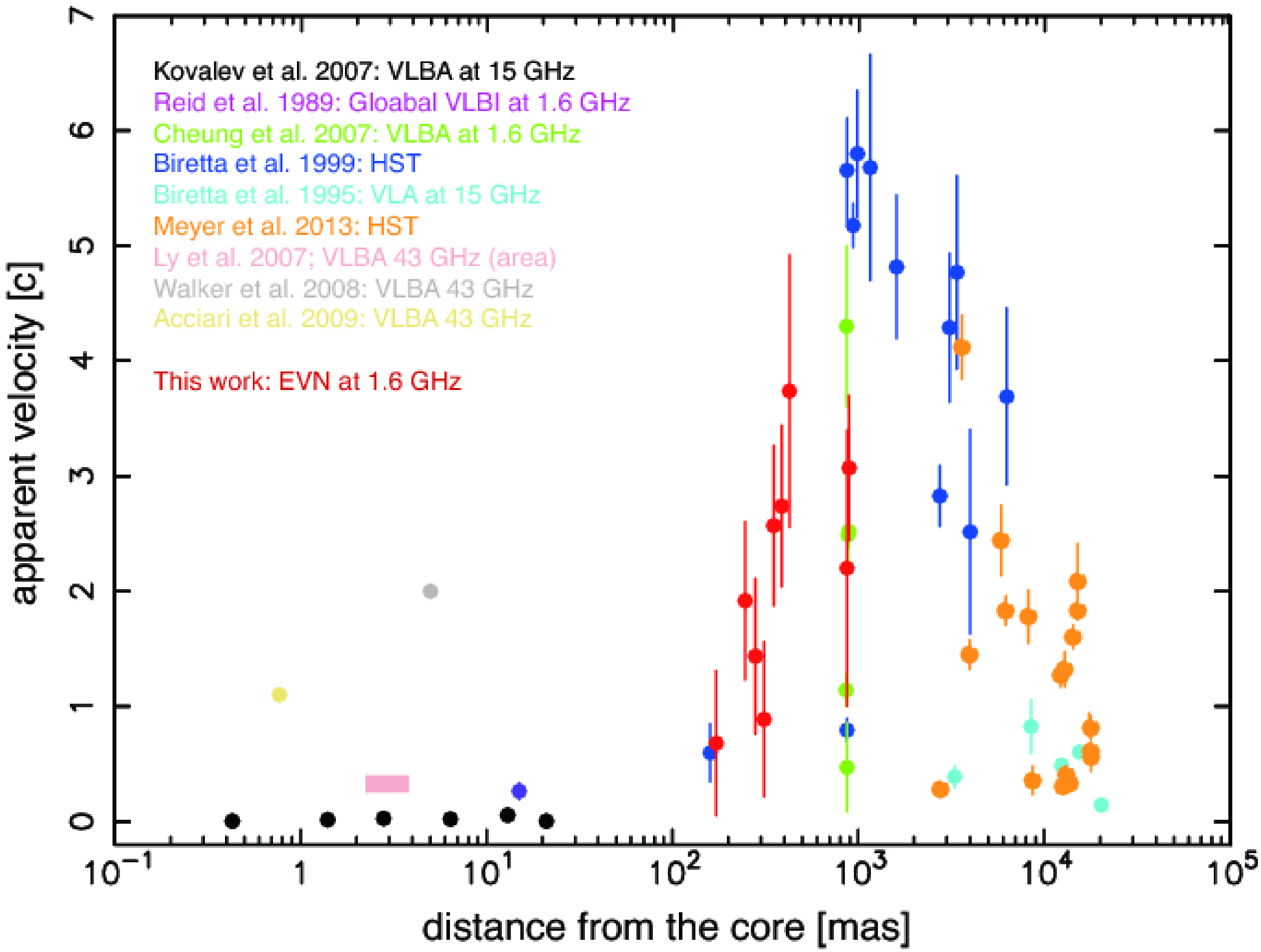
Jet examples



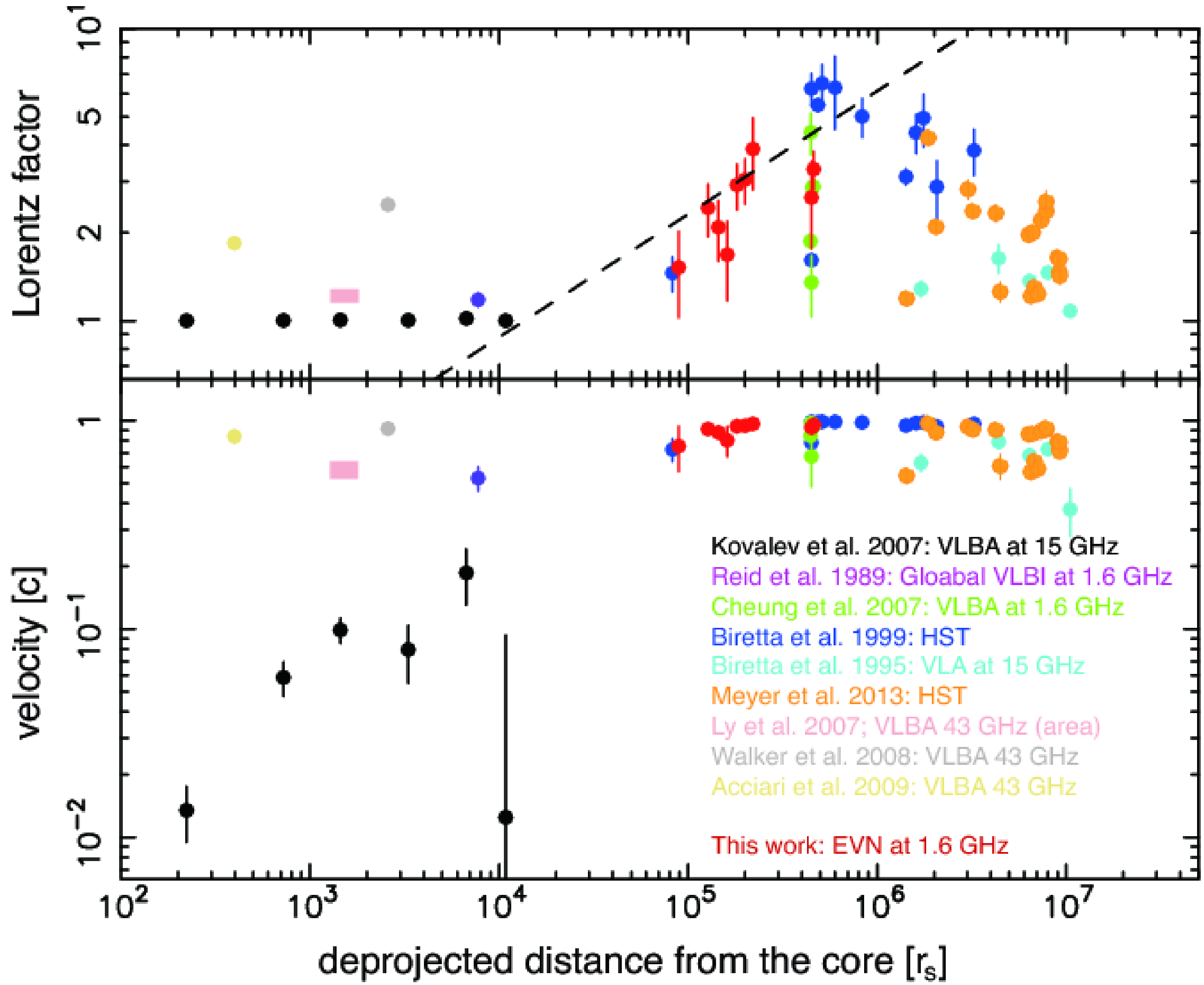



M87 Nucleus July 17, 2002
HST STIS/MAMA
Nucleus
Jet
HST-1
500 light-years
153 pc
1″.9
N
E

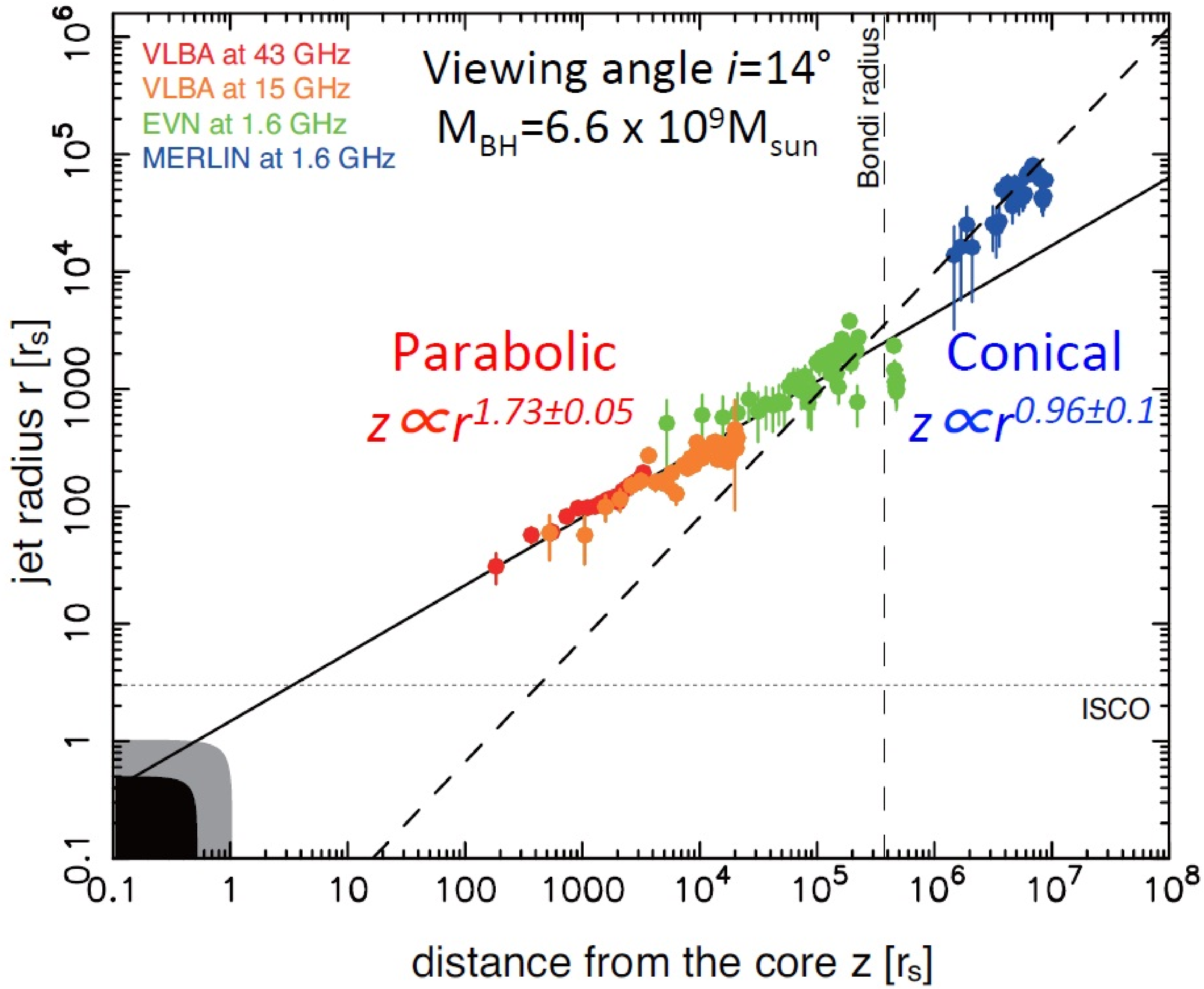

M87 Nucleus and Bright Knot in Extragalactic Jet
HST • STIS/MAMA • ACS/HRC
STIS
May 17, 1999
STIS
Feb. 27, 2002
STIS
Jul. 17, 2002
ACS
Apr. 17, 2003
ACS
May 9, 2005
ACS
Nov. 28, 2006
NASA, ESA, and J. Madrid (McMaster University)
STScI-PRC09-16


Kovalev et al. 2007: VLBA at 15 GHz
Reid et al. 1989: Gloabal VLBI at 1.6 GHz
Cheung et al. 2007: VLBA at 1.6 GHz
Biretta et al. 1999: HST
Biretta et al. 1995: VLA at 15 GHz
Meyer et al. 2013: HST
Ly et al. 2007; VLBA 43 GHz (area)
Walker et al. 2008: VLBA 43 GHz
Acciari et al. 2009: VLBA 43 GHz
This work: EVN at 1.6 GHz
apparent velocity [c]
distance from the core [mas]
0
1
2
3
4
5
6
7
10^-1
1
10^1
10^2
10^3
10^4
10^5

Asada+2013


Lorentz factor
velocity [c]
deprojected distance from the core [r_s]
Kovalev et al. 2007: VLBA at 15 GHz
Reid et al. 1989: Gloabal VLBI at 1.6 GHz
Cheung et al. 2007: VLBA at 1.6 GHz
Biretta et al. 1999: HST
Biretta et al. 1995: VLA at 15 GHz
Meyer et al. 2013: HST
Ly et al. 2007; VLBA 43 GHz (area)
Walker et al. 2008: VLBA 43 GHz
Acciari et al. 2009: VLBA 43 GHz
This work: EVN at 1.6 GHz

(Asada & Nakamura 2011)



“body” interactions

- External pressure keeps the jet collimated (at jet surface) $\rightarrow$ causal connection $\vartheta \sim 1/\Gamma$ $\rightarrow$ efficient magnetic bulk acceleration

- for M87 jet before z_{Bondi} : $z \propto r^{1.7}$, $\Gamma \propto 1/\vartheta \sim z/r \propto z^{0.4}$ as in theoretical works NV+Königl 2003, 2004, Komissarov+NV+2007, 2009, Tchekhovskoy+2009, Lyubarsky 2009

- σ controversy:

☞ collimated flows are efficiently accelerated reaching $\Gamma \sim \mu$ (= ejected energy per mass)

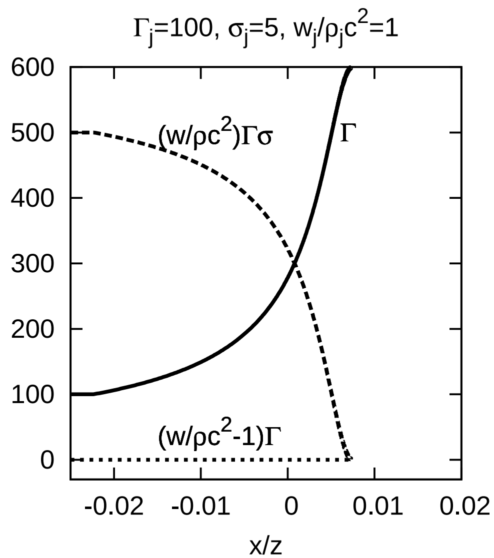
☞ unconfined high σ flows remain Poynting-dominated (Michel scaling $\Gamma \sim \mu^{1/3}$)

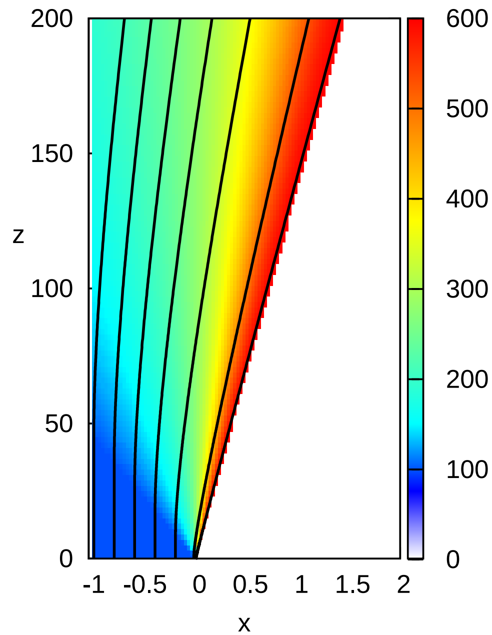
“surface” interactions

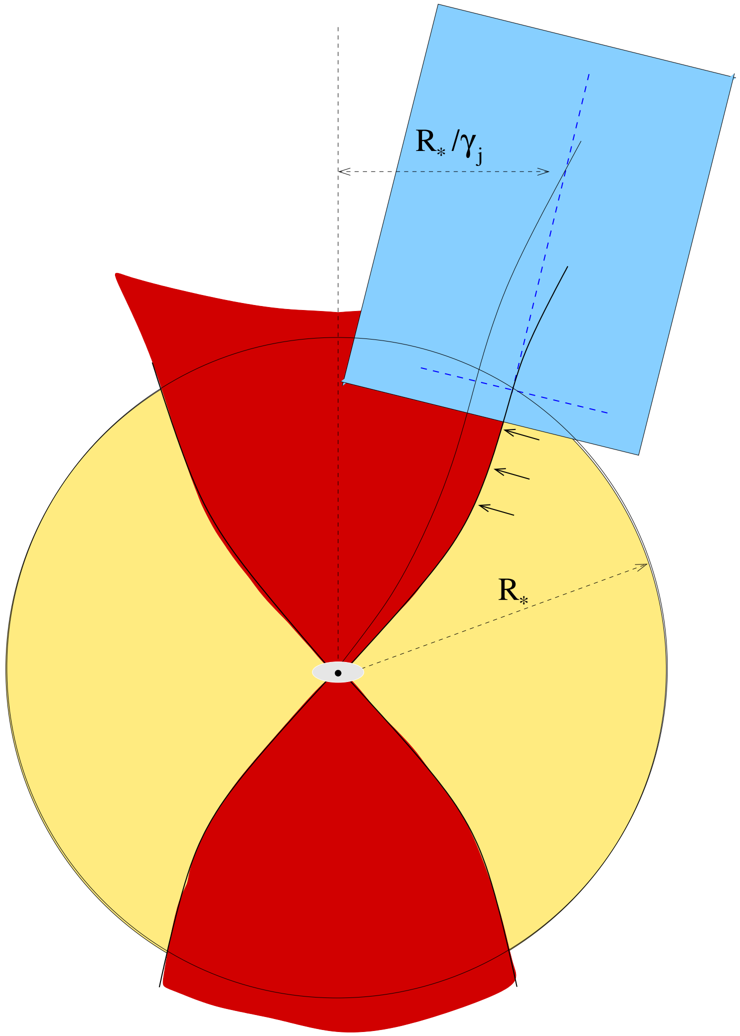
abrupt changes of the environment affect the dynamics (not only at the surface!)

Example:

Rarefaction GRB acceleration (Sapountzis+NV 2013,2014)



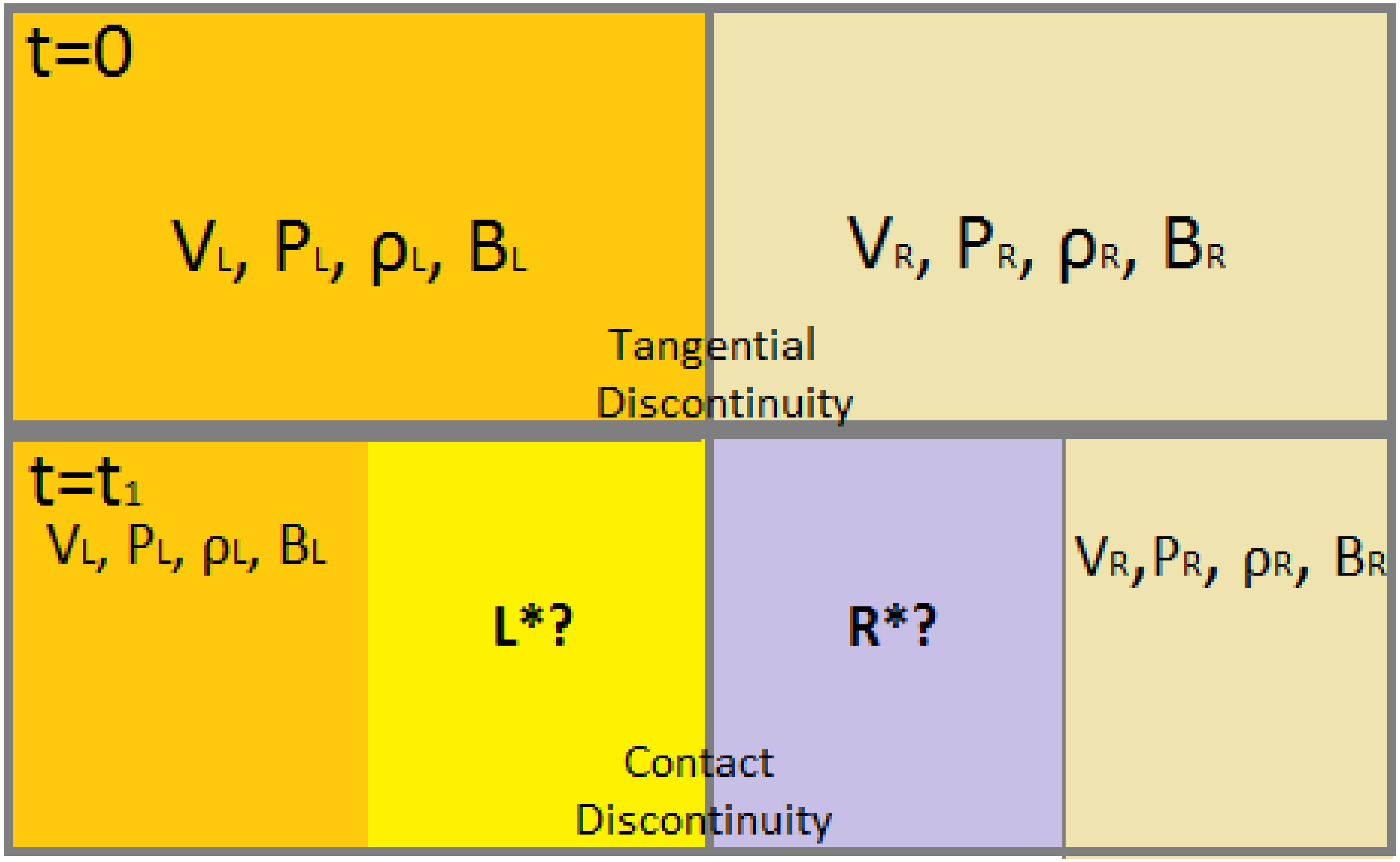




In AGN jets?

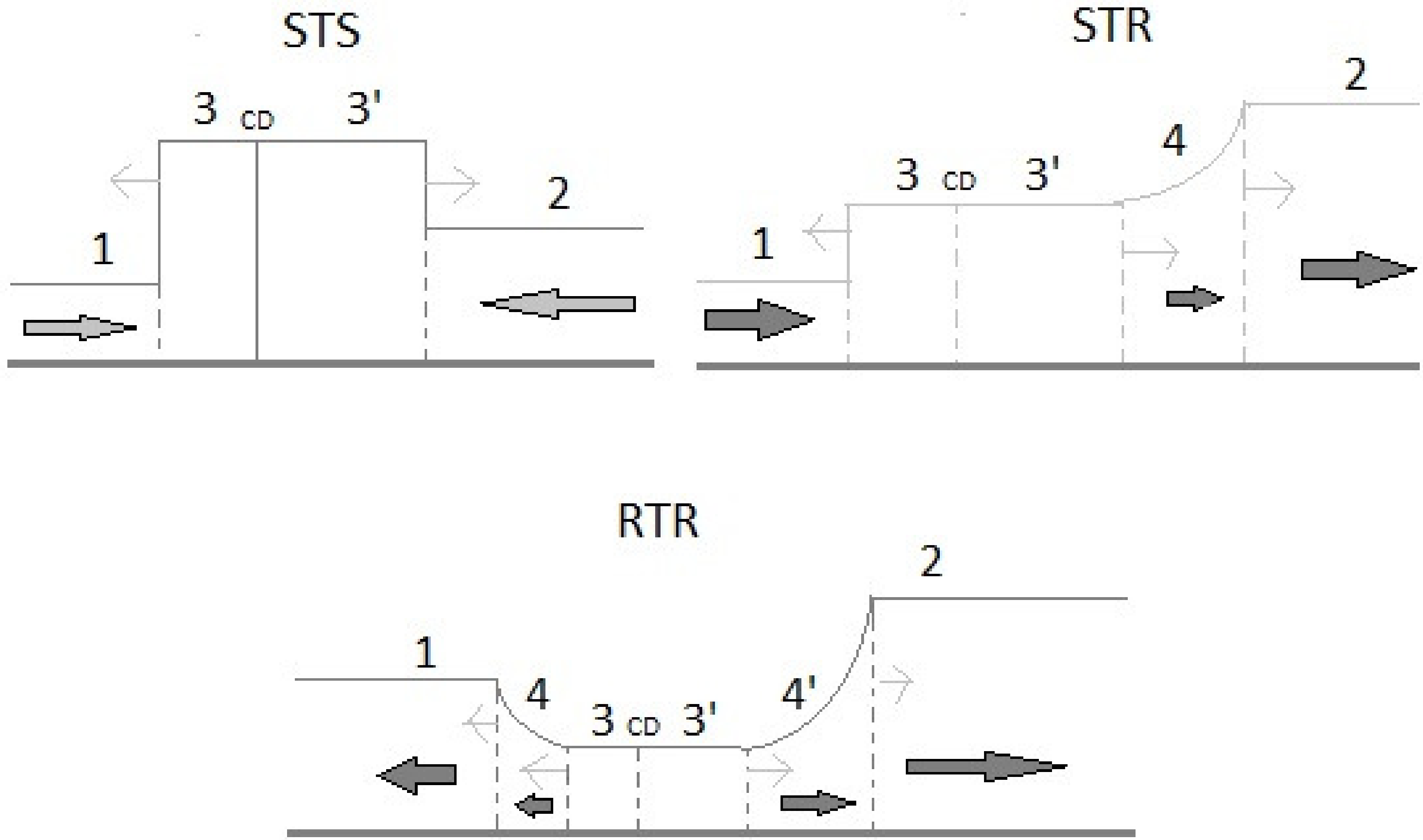
The Riemann problem

Initially two uniform states are in contact.
Two travelling waves are formed.



Simple waves: self-similar solutions that depend only on $\xi = x/t$.

Possible cases:



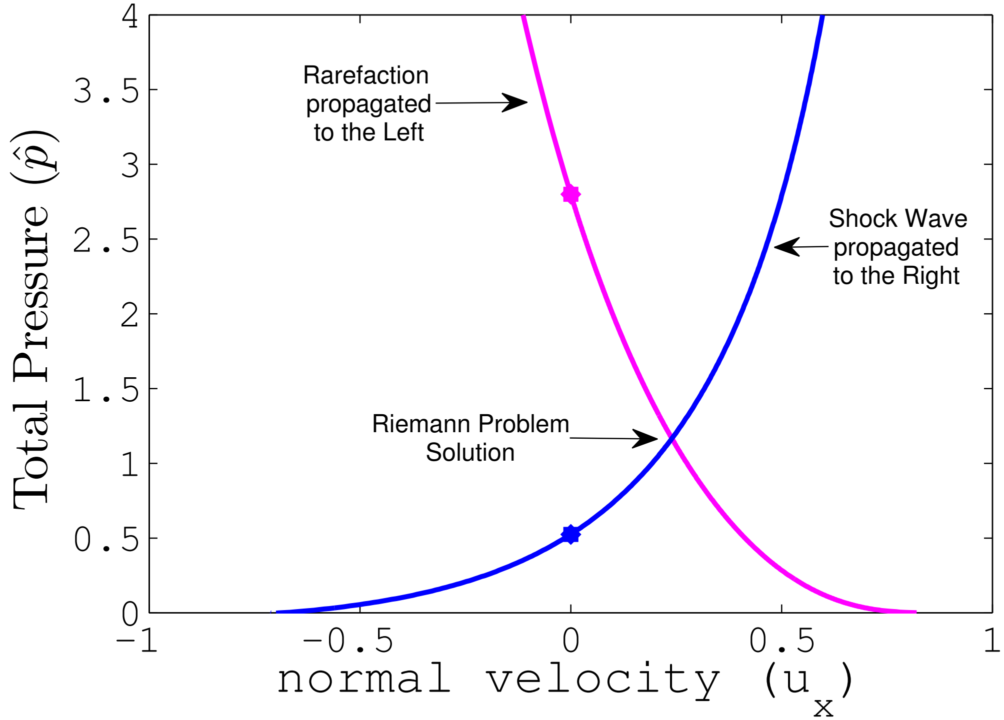
We (Katsoulakos & NV in preparation) include relativity, B_y (transverse) and u_z.

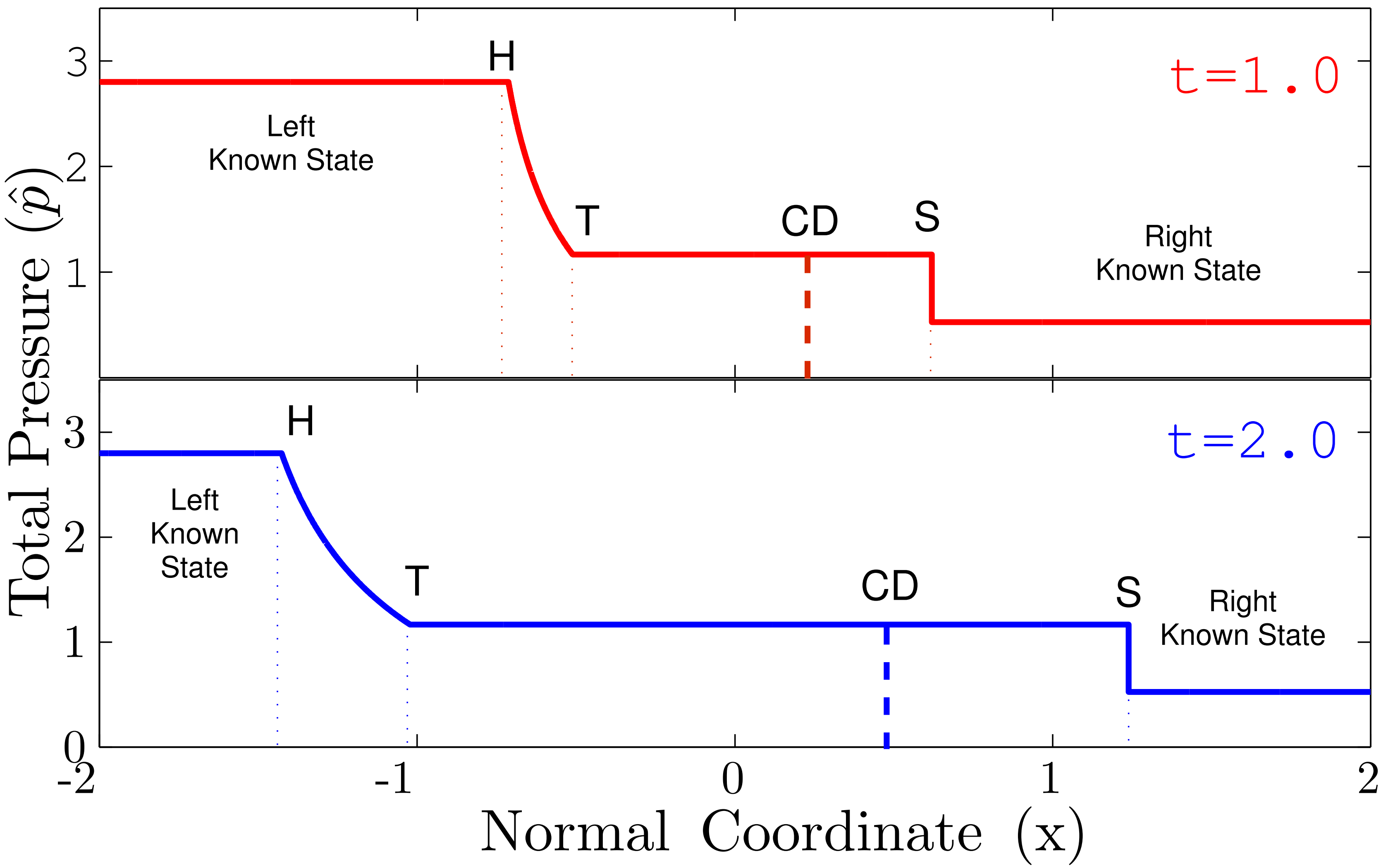
For the rarefaction, we solve the MHD equations for proper speed $u^\mu = (\Gamma, \Gamma u_x, 0, \Gamma u_z)$, comoving magnetic field $b^\mu = (0, 0, b, 0)$, pressure and density (all functions of x/t).

For the shock we solve the jump conditions for various u_s.

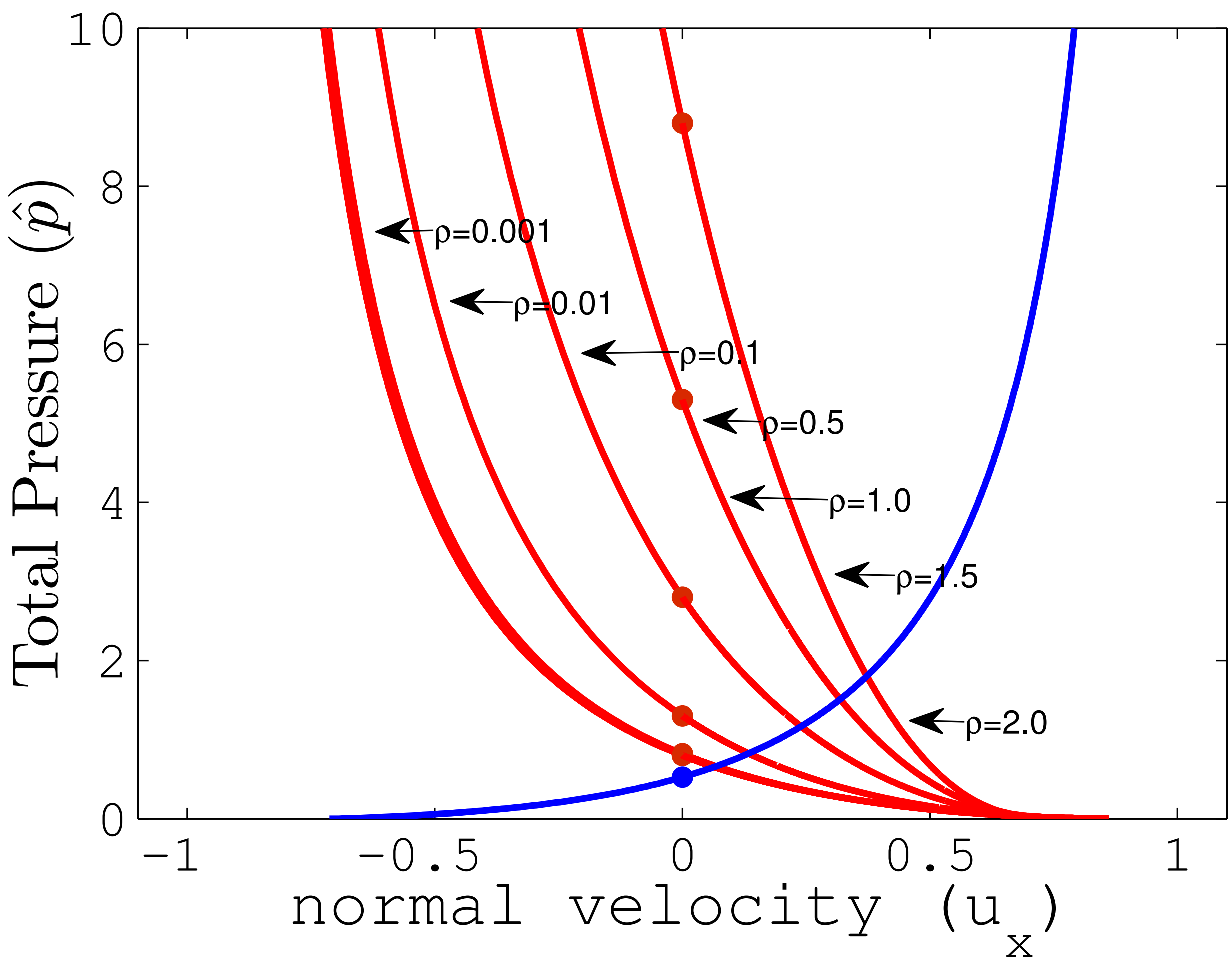
The solution is found requiring same total pressure and x-velocity at CD.

Example:
Left state $P = 0.80$, $u_x = 0.0$, $\rho = 1.0$, $u_z = 0.6$, $b = 2.0$.
Right state $P = 0.40$, $u_x = 0.0$, $\rho = 0.5$, $u_z = 0.6$, $b = 0.5$.




t=1.0
H
Left
Known State
T
CD
S
Right
Known State
t=2.0
H
Left
Known
State
T
CD
S
Right
Known State
Total Pressure ($\hat{p}$)
Normal Coordinate (x)
3
2
1
0
-2
-1
0
1
2

The acceleration efficiency



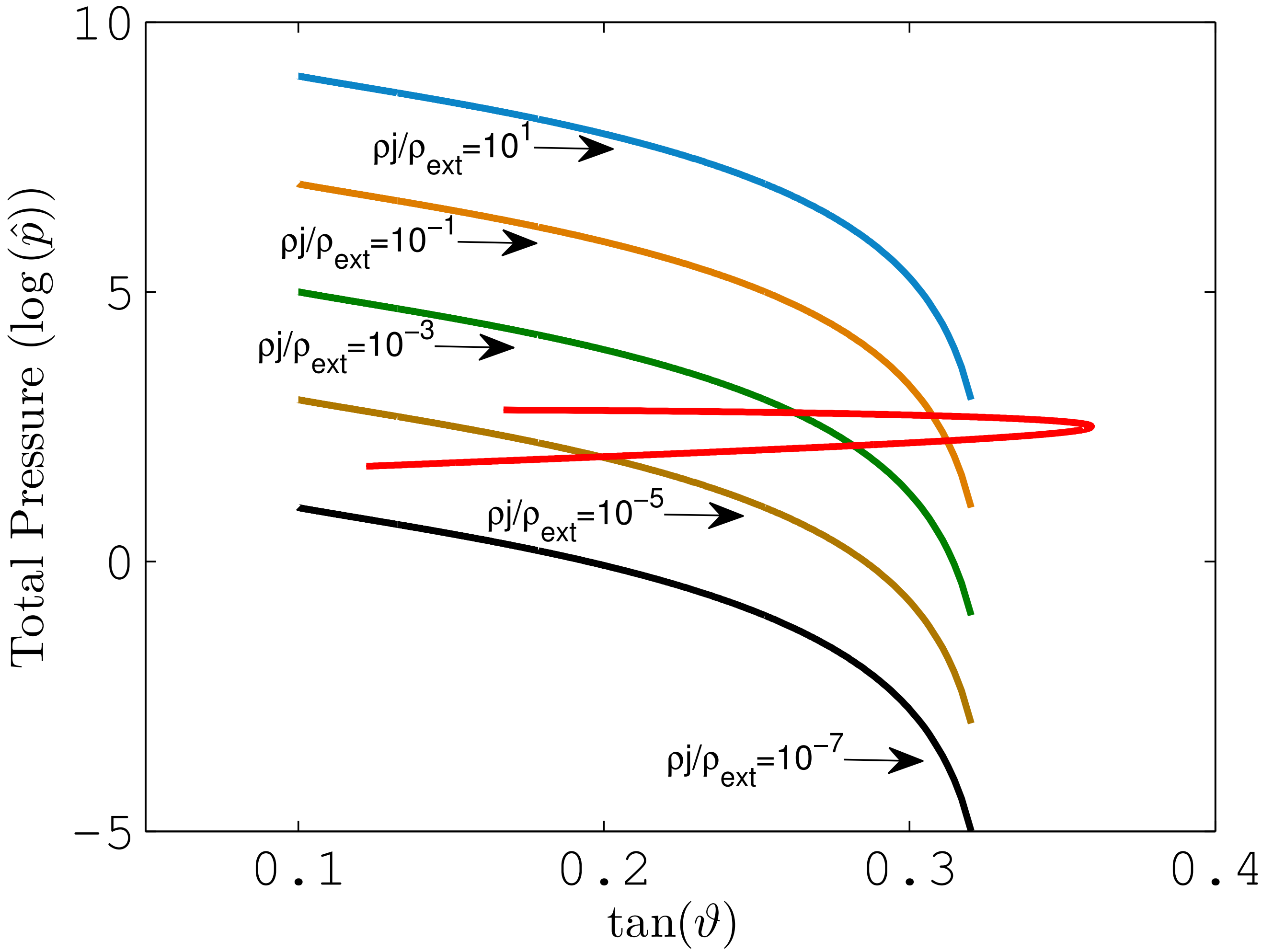
depends on the density ratio ($\rho = \rho_{Left}$)

efficient in GRBs, but in AGN?

The steady-state Riemann problem

We solve the steady-state rarefaction using x/z (or the polar angle) as the similarity variable.

The shock is static, at some angle wrt z. For various values of that angle we solve the jump conditions and require same total pressure and parallel flows at CD.

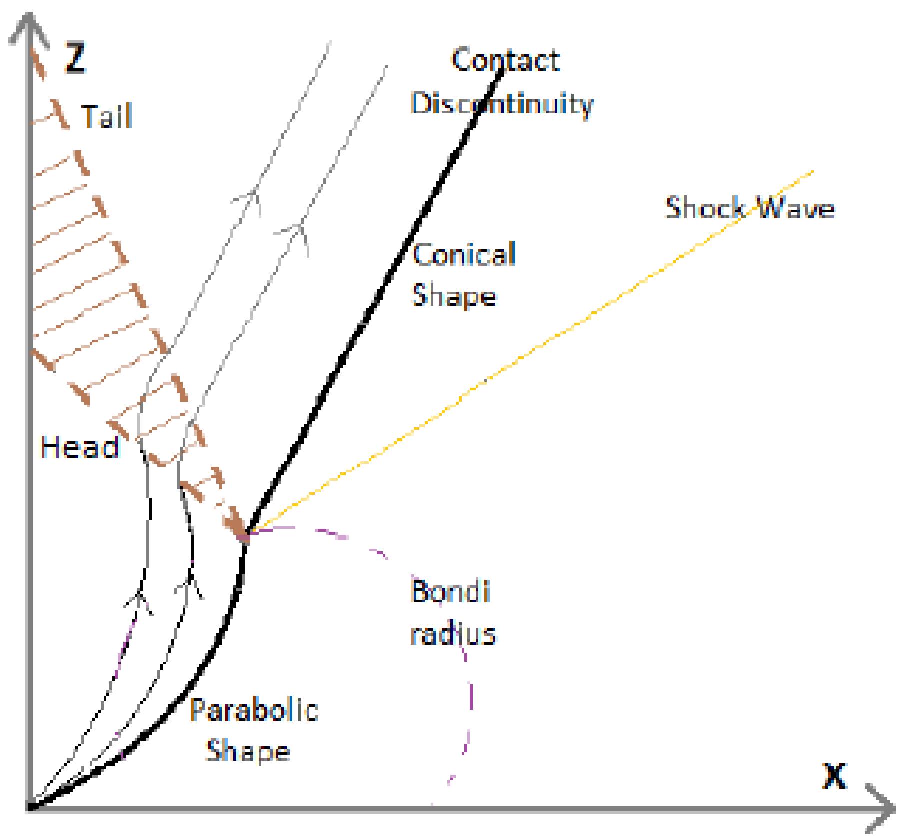


red = shock, other colors = rarefaction for various density contrasts

0, 1, or 2 solutions (nature chooses the weak shock)

Application to AGN jets

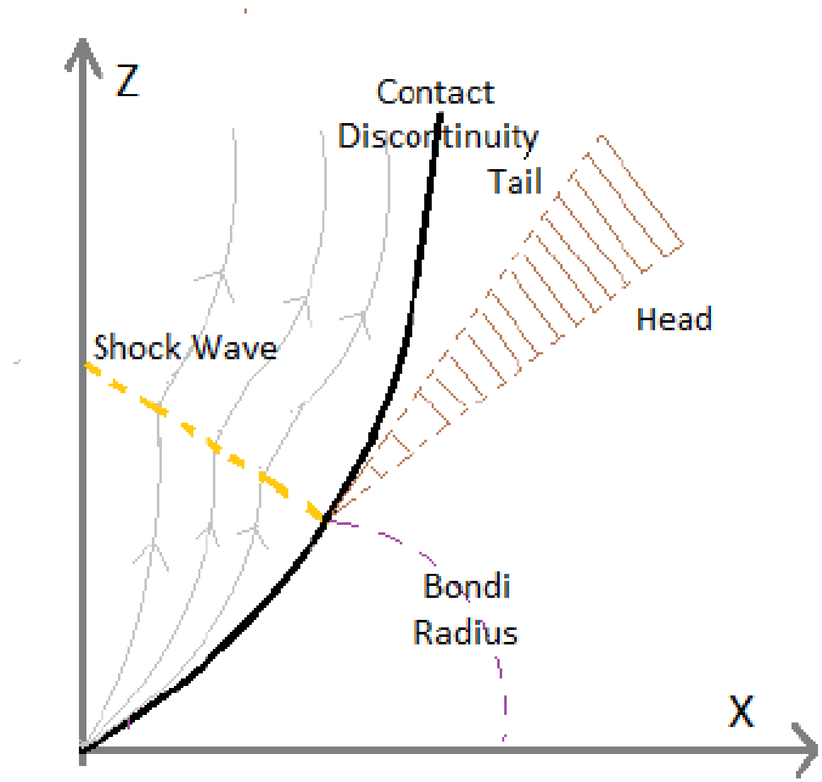
(1) Rarefaction wave inside jet



overpressured HST-1 (Stawarz+2006)

Geometry from Asada+2013

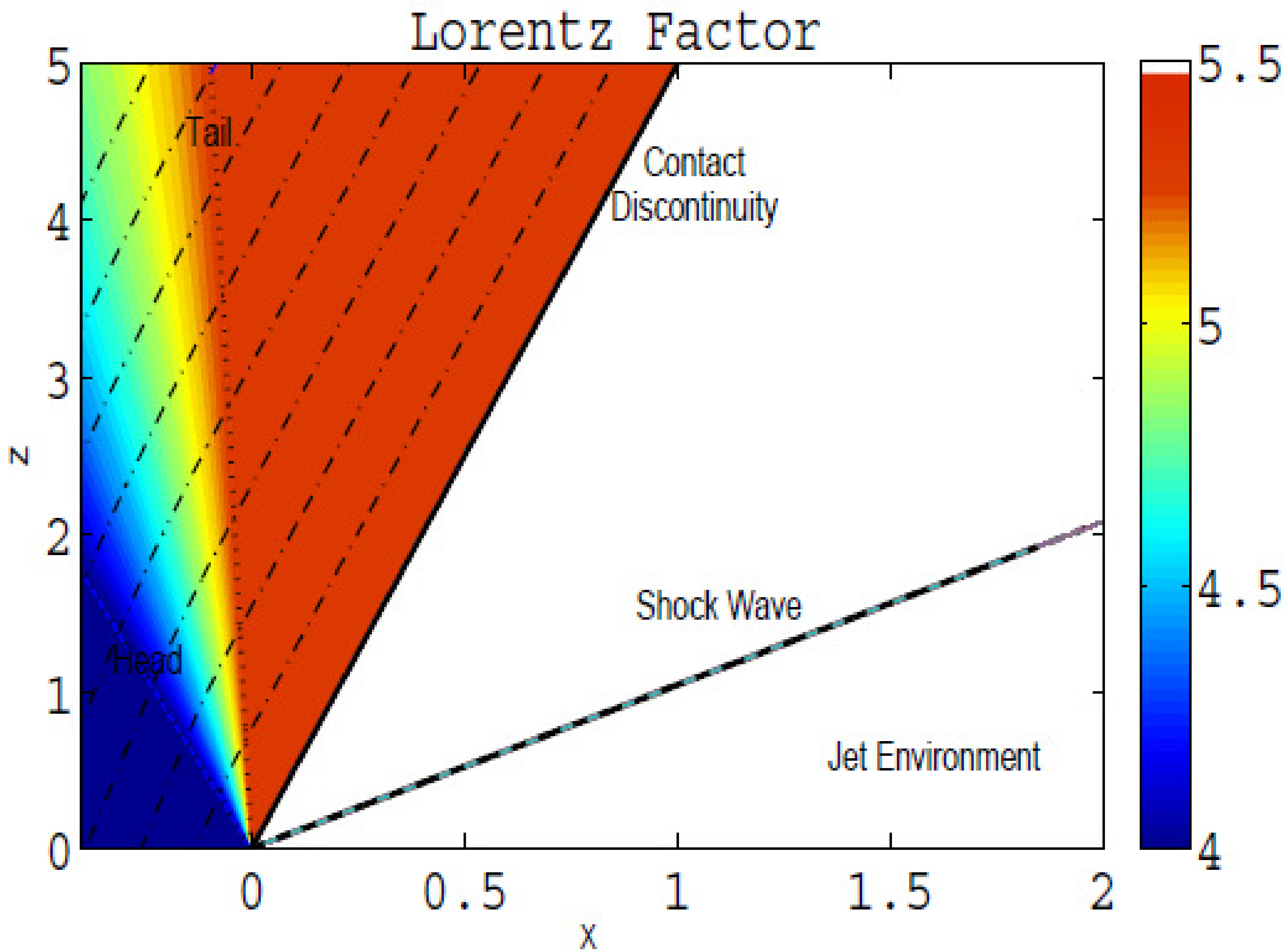
(2) Shock wave inside jet



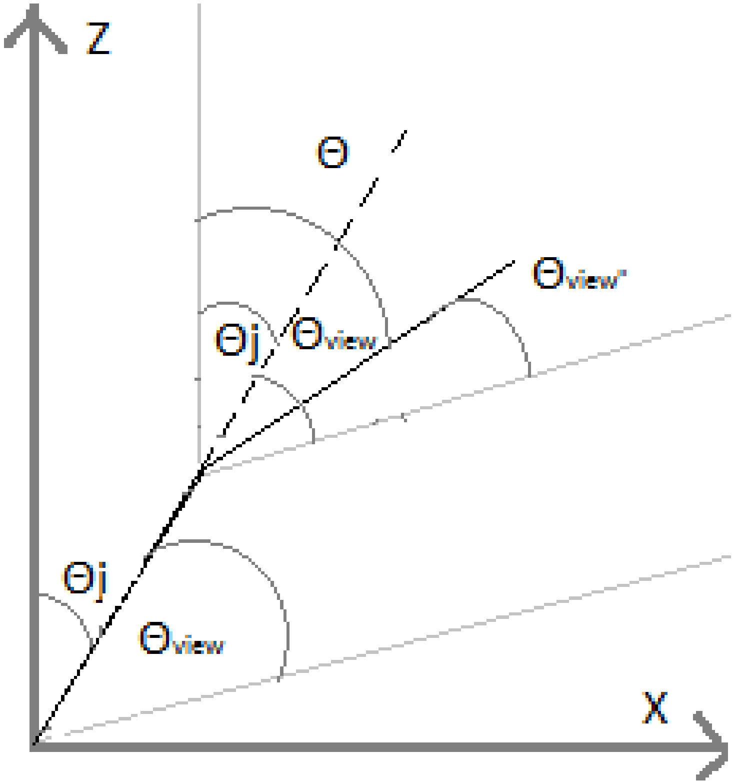
Re-confinement Shock

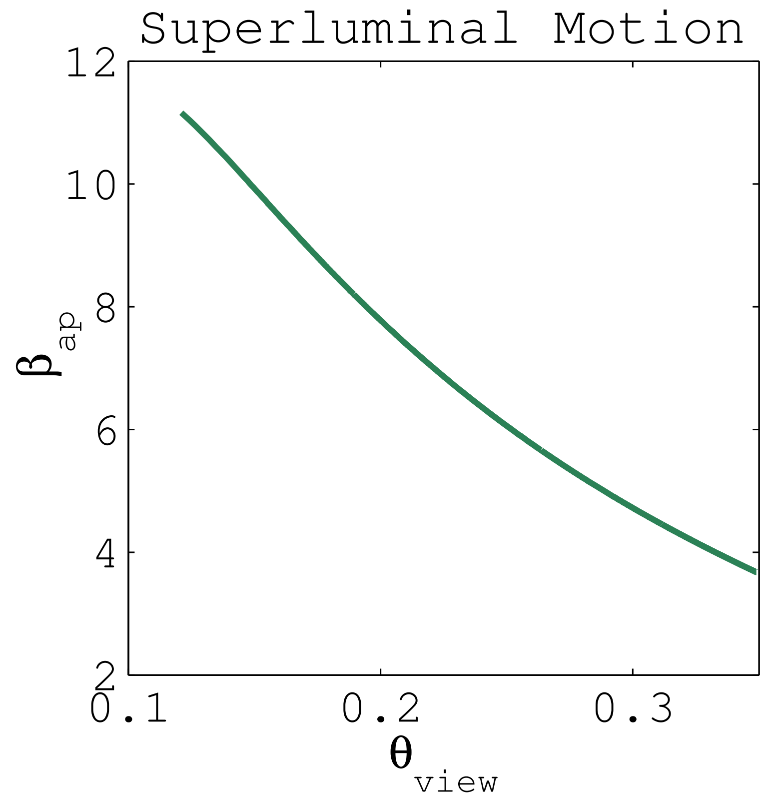
Particle acceleration and radiation?

Case (1)



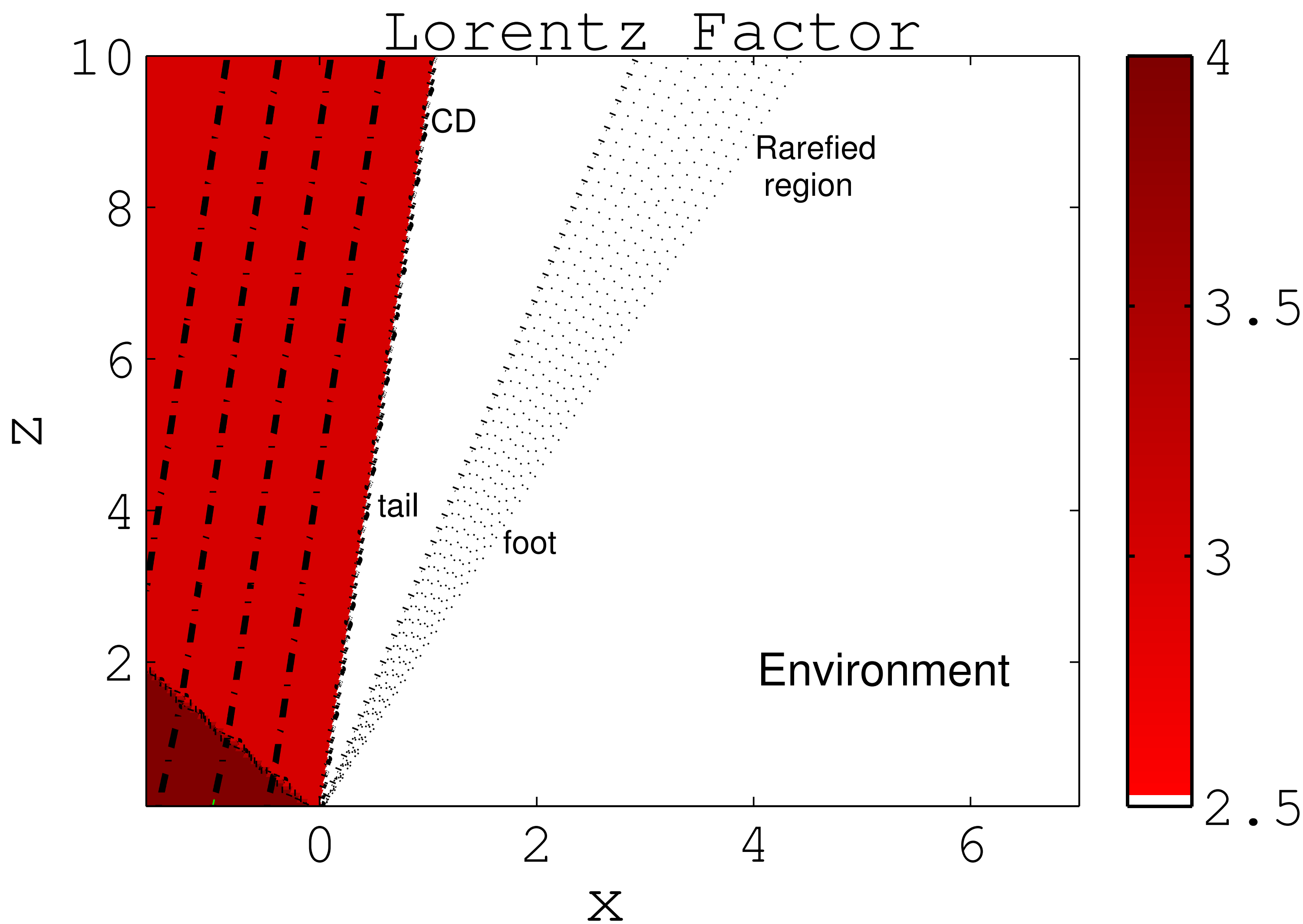
Lorentz Factor
5
4
3
2
1
0
z
0
0.5
1
1.5
2
x
Tail
Head
Contact
Discontinuity
Shock Wave
Jet Environment
5.5
5
4.5
4





The acceleration and bending although weak (due to the small ρ_j/ρ_{ext}) could significantly change the apparent motion.

Case (2)

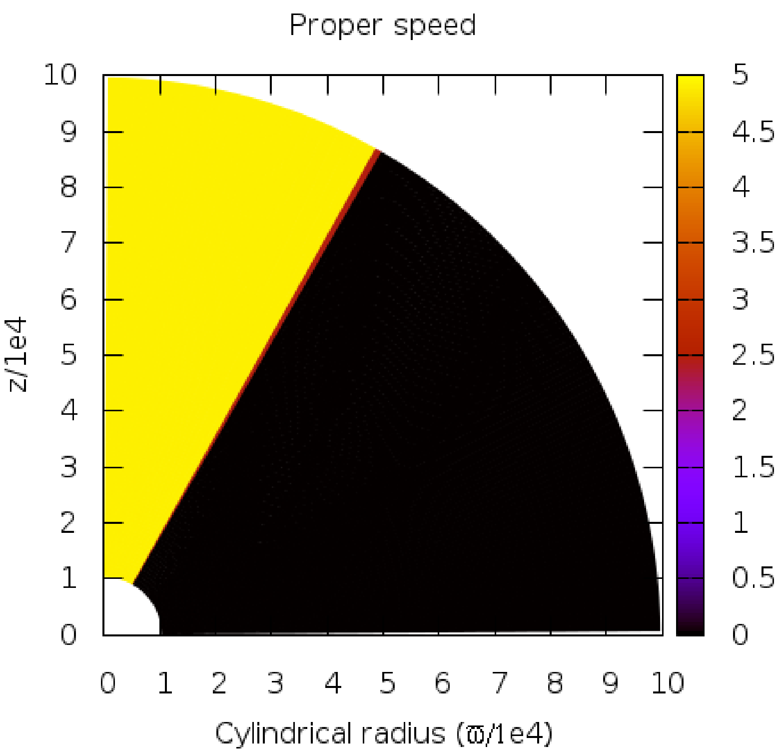


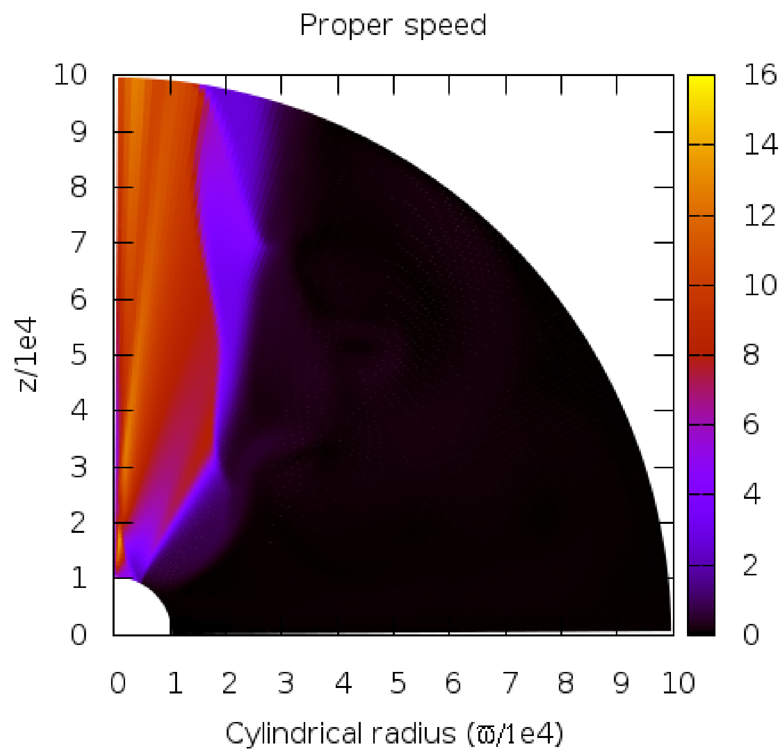
Lorentz Factor
10
8
6
4
2
z
0
2
4
6
x
CD
Rarefied region
tail
foot
Environment
4
3.5
3
2.5

Simulations

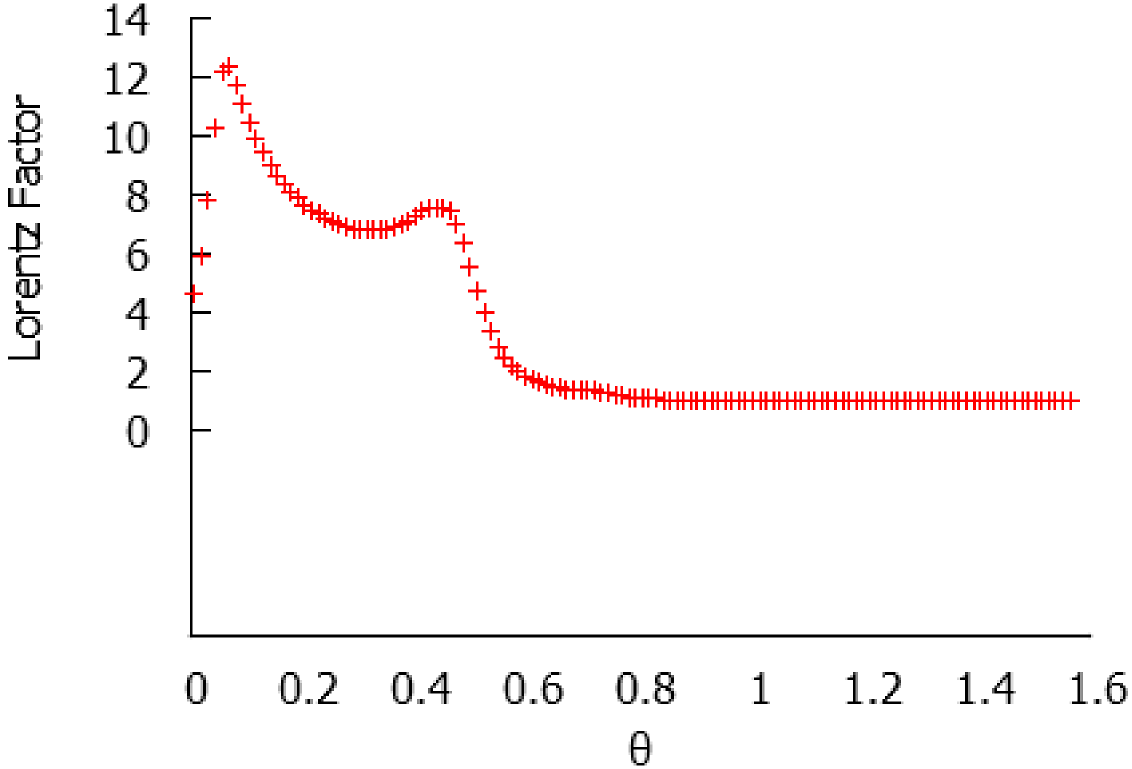
(Millas & NV in preparation)

- ⋆ simulate both, jet+environment (static atmosphere or Bondi accretion)
- ⋆ use realistic values for M87 jet around HST-1 (external temperature from Bondi radius, density ratio from pressure equilibrium at base $\rightarrow$ sound crossing time $\gg$ light crossing time)
- ⋆ bell-shaped B_ϕ, ignore B_p since we are at $r \gg$ light cylinder radius
- ⋆ include gravity
- ⋆ use PLUTO code `http://plutocode.ph.unito.it/`

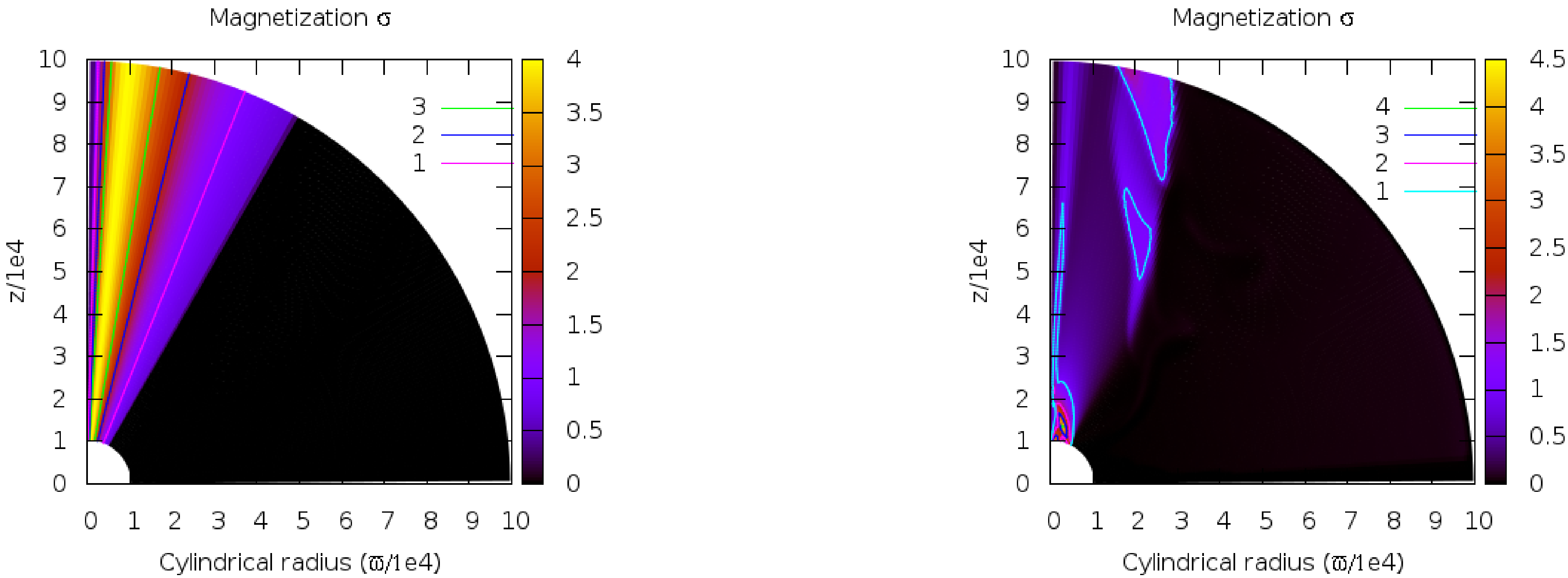




$u = \frac{\Gamma V}{c}$ for $t = 0$ (left) and $t = 10$ external sound crossing times (right)



Lorentz factor at distance $R = 3 \times 10^5$. The first peak corresponds to the magnetic acceleration/collimation mechanism and the second to the rarefaction acceleration.



σ for $t = 0$ (left) and $t = 10$ external sound crossing times (right)

A quasi-steady jet is found (with well defined characteristics near the axis and at $R < R_{Bondi}$ where the environment is shocked)

Shocks AND rarefaction is seen in the volume of the jet

Summary

⋆ Environment could significantly affect jet dynamics (jet-shape, re-confinement shocks, rarefaction waves, shocks).

⋆ Riemann Problem offers 0th order description

⋆ A rarefaction wave accelerates the flow (how much depends on magnetization). Not so efficient for AGN; nevertheless it may affect the apparent motion.

⋆ The jet-environment interaction is complicated but important to understand in more detail.