Jet launching at small radii:

Results from 2D axisymmetric simulations

Christiaan Brinkerink

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Advisor: Heino Falcke
Department of Astronomy, IMAPP,
Radboud University Nijmegen

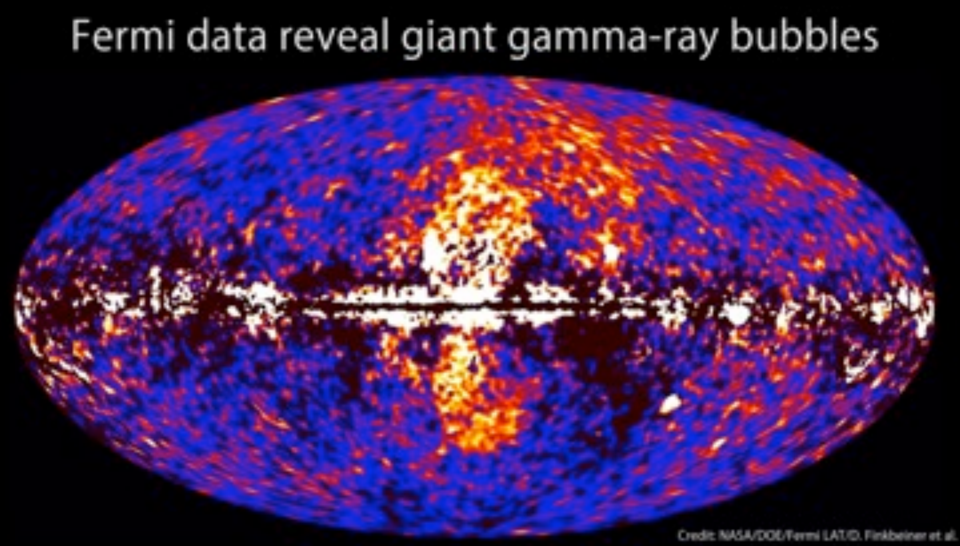
What did I do?

- Ran GRMHD simulation of accretion flow
- Compared results to model predictions
- Compared results to other simulations
- Trace gas flow into jet (ongoing research)

Overview of this talk

- Context of this work
  - Sagittarius A*
  - Falcke-Biermann jet model
  - Relations to be investigated
- Execution of this work
  - Setup of simulation
  - Results: accretion & outflow statistics
  - Results: flow variables evolution in jet
  - Comparison to analytical jet model
  - Comparison to other simulations
- Conclusions

Sagittarius A*



Radio (6cm): inner arcmin

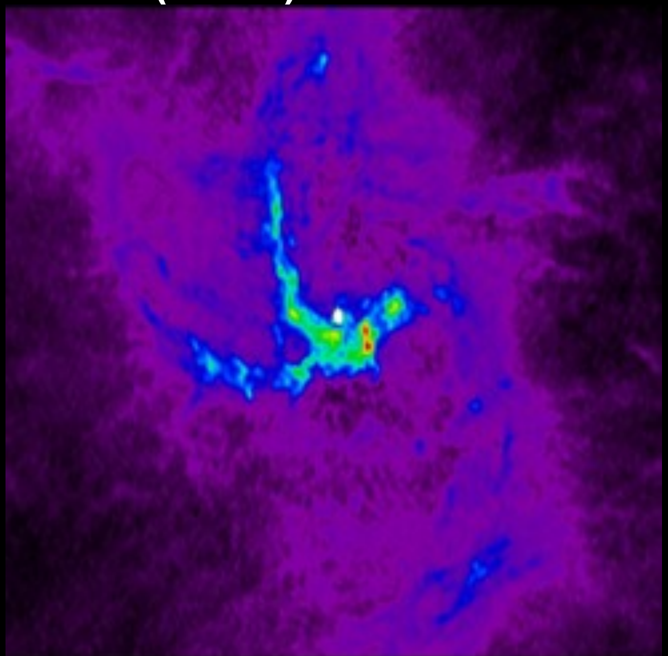


Image credit: F. Yusef-Zadeh et al

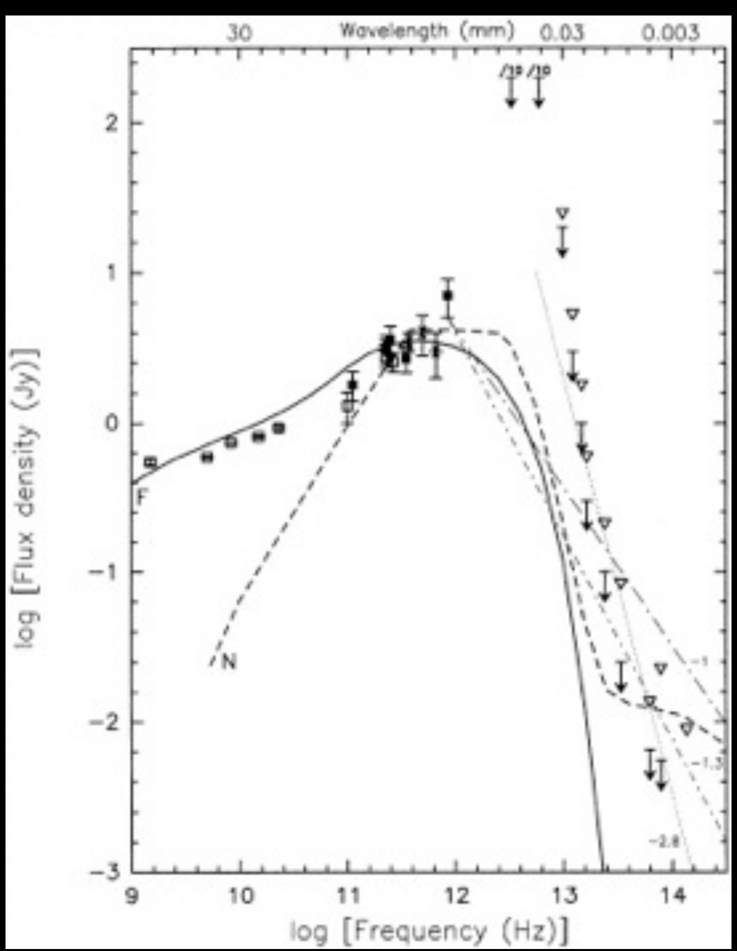
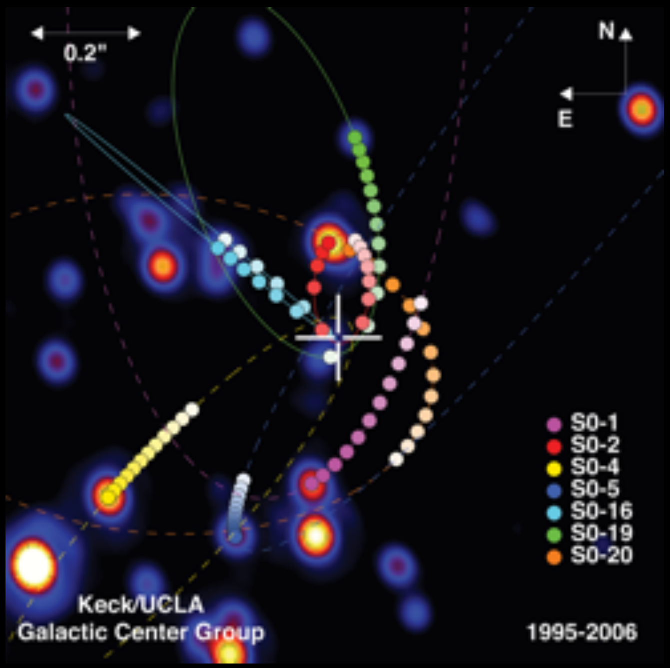


Image credit: Serabyn et al, 1997



Observations of Sgr A*

Gas density at galactic center could support an accretion rate of up to $10^{-5} M_{\odot}$/yr... [Yuan, 2006]

...but we only see emission consistent with $10^{-8} M_{\odot}$/yr. Points to a radiatively inefficient accretion flow! [Falcke et al,1993],[Quataert & Gruzinov, 2000]

Observations of Sgr A*

What do we expect to be going on?

- Low luminosity: radiatively inefficient accretion flow
- Hot, low-density gas in thick accretion disk
- Low-frequency emission: synchrotron in (weak) jet - high electron temperatures needed...

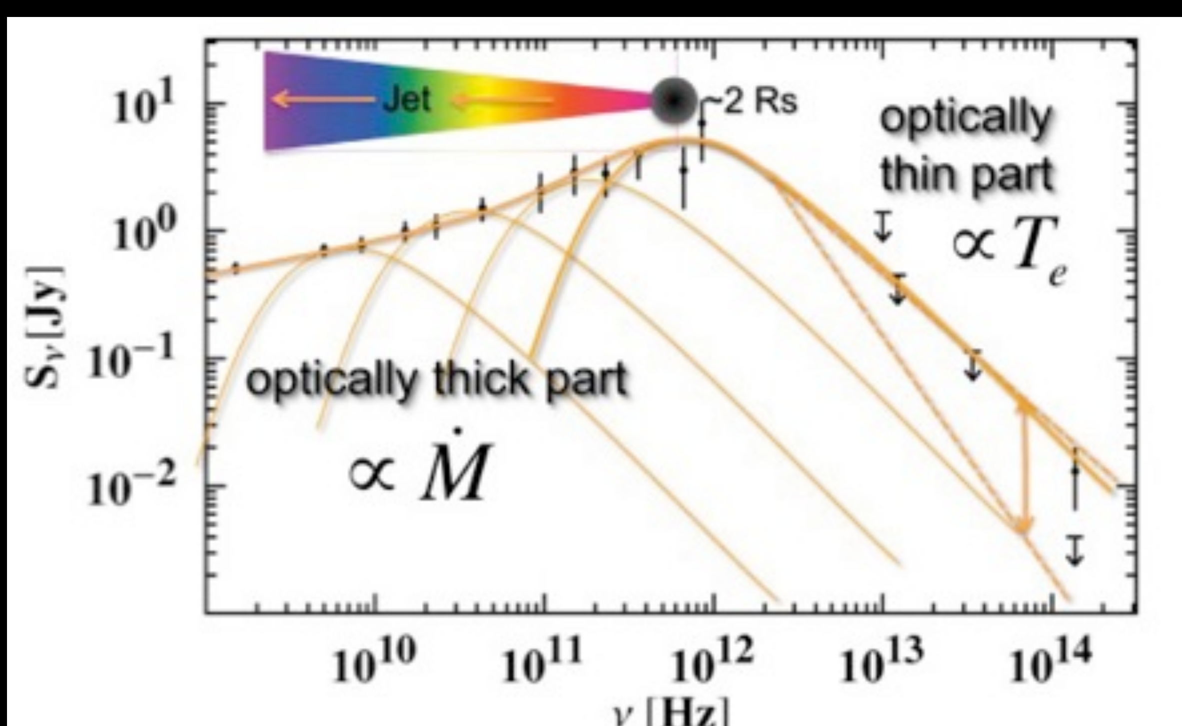
The Falcke-Biermann jet model

Evolution of jet: Blandford-Königl jet

Conically expanding and accelerating flow

No significant lateral acceleration

Gives flat spectrum!



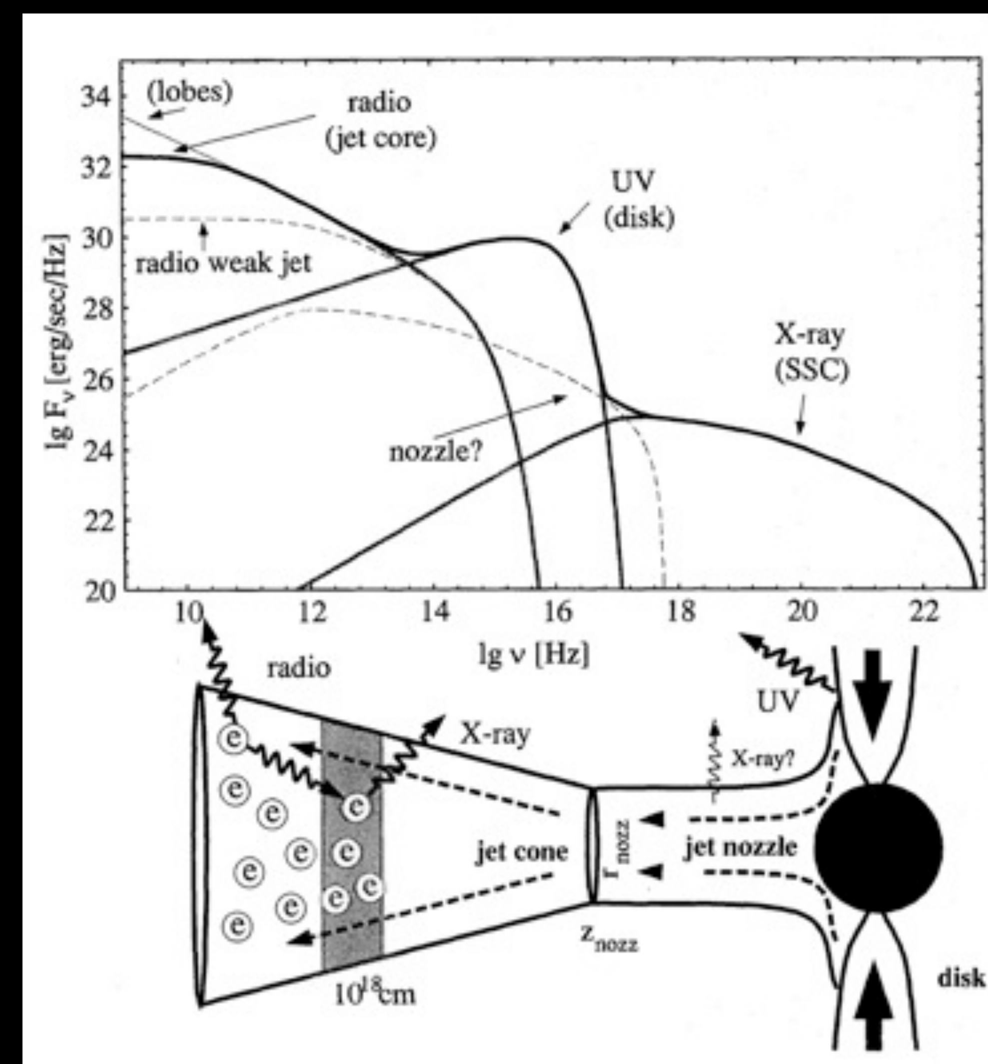


Image credit: Falcke & Biermann, 1995

The Falcke-Biermann jet model

Assumes equipartition of thermal and magnetic energy at jet nozzle

With only a small fraction of the mass forming the jet, limits internal energy of jet!

$$\gamma_{\mathrm{j}} \leq \frac{Q_{\mathrm{j}}}{\dot{M}_{\mathrm{j}} c^2} \leq 2\gamma_{\mathrm{j}}$$

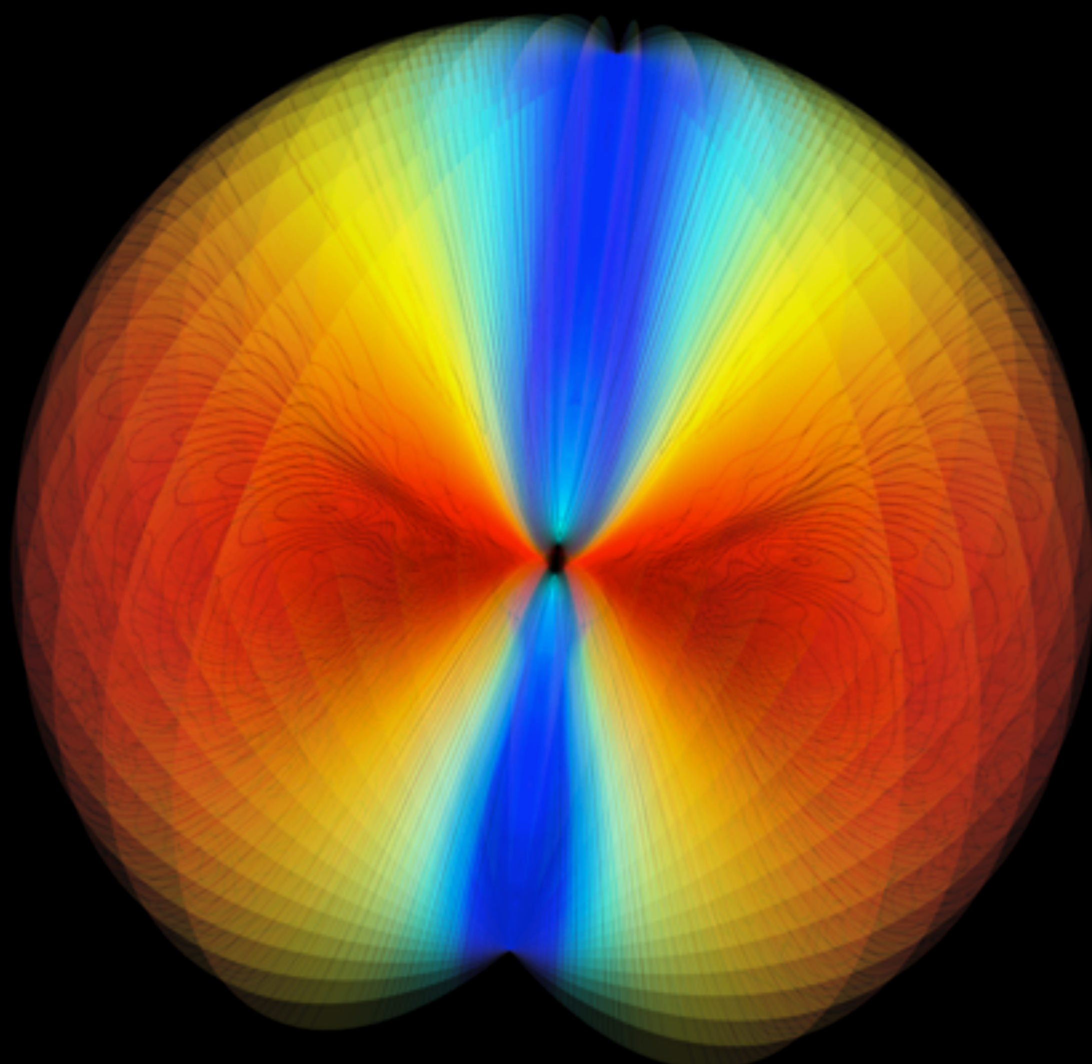
What are we looking for?

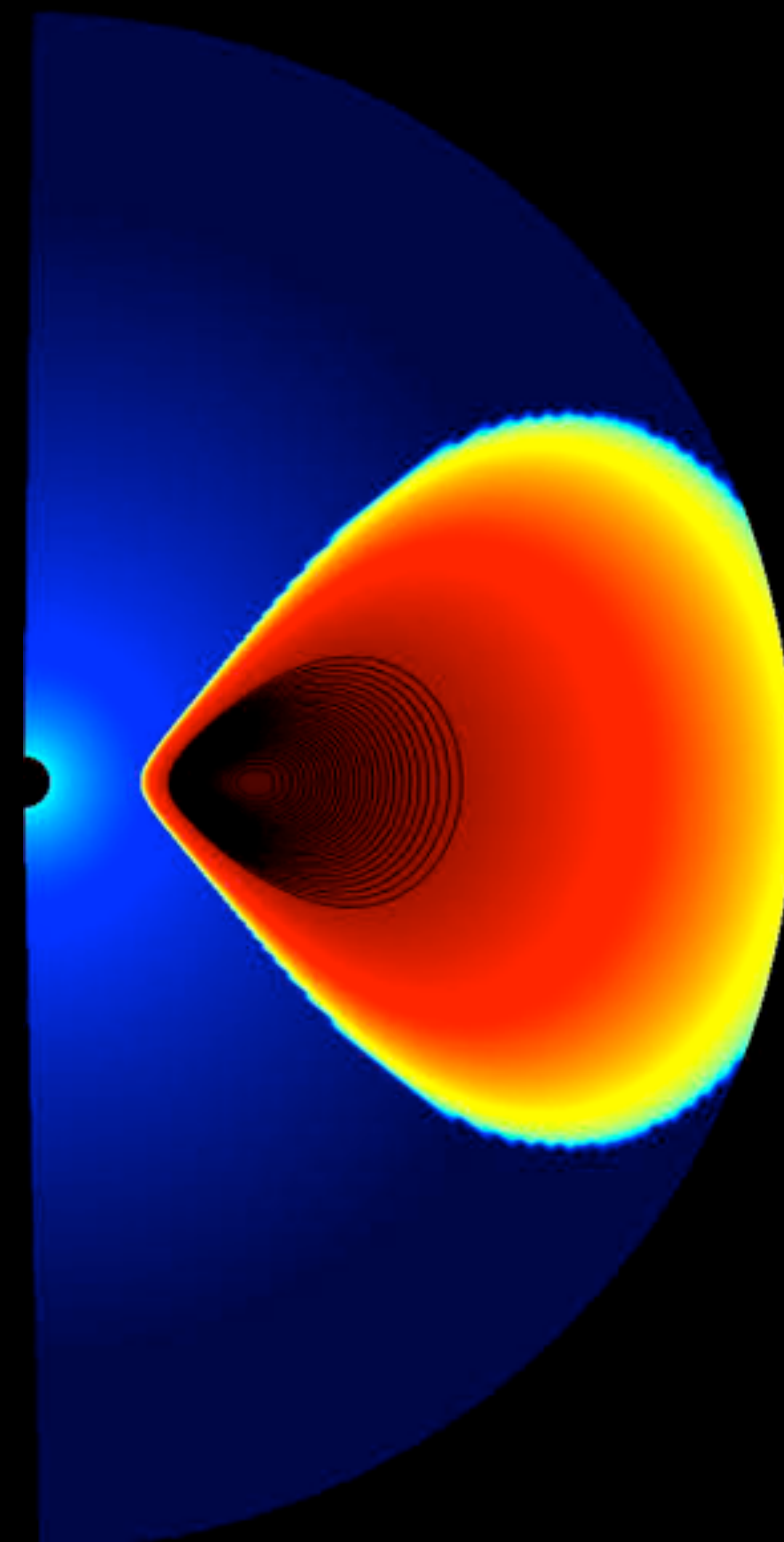
- How does the jet evolve close to the BH?
- How does matter get accelerated?
- What kind of spectrum would we see?

Simulation setup

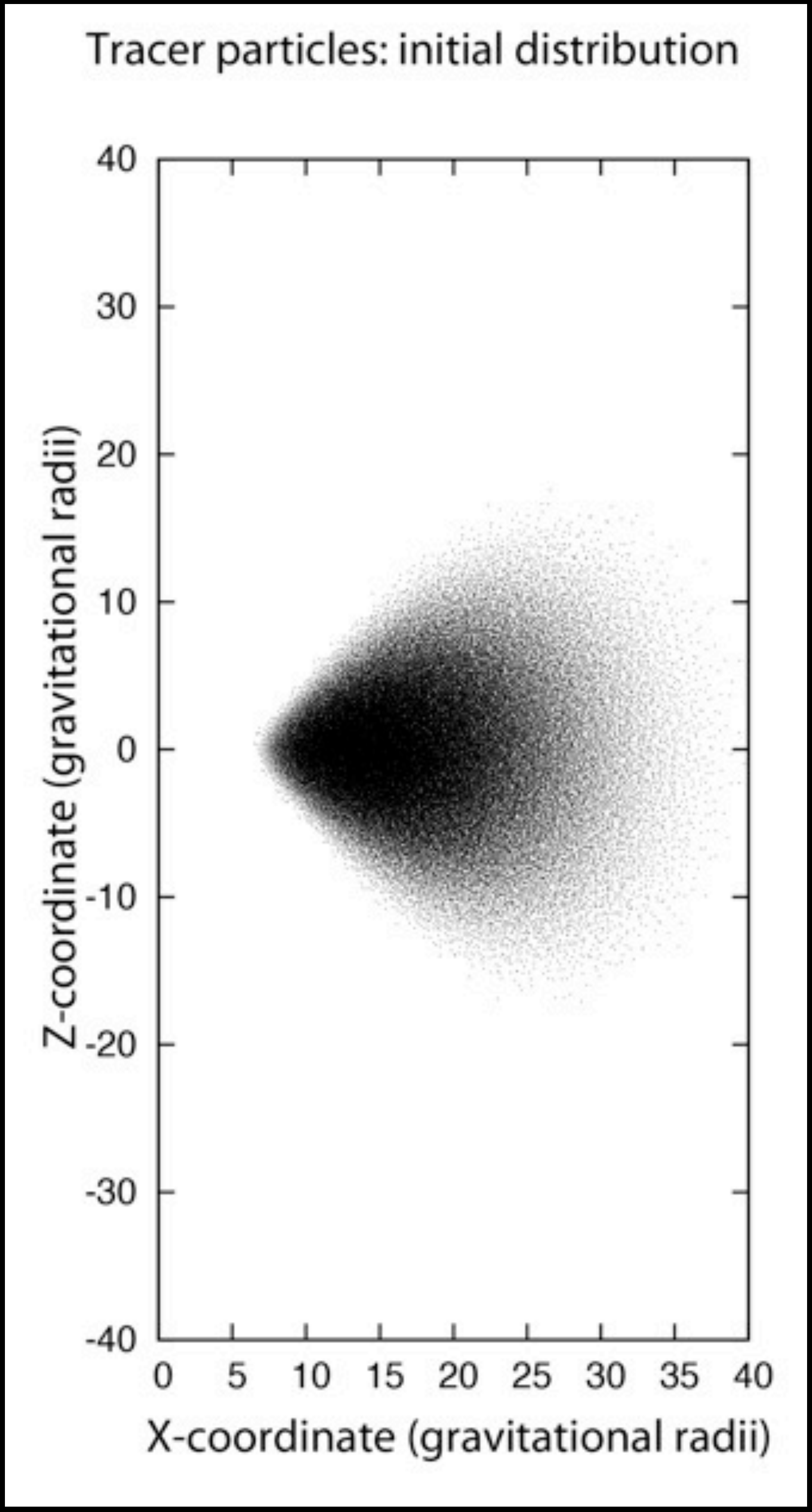
- Code used: HARM2d [Gammie et al., 2003]
- 2D axisymmetric
- Domain: 256 x 256 cells
- General-relativistic magnetohydrodynamics
- No radiative transfer, no cooling, zero viscosity

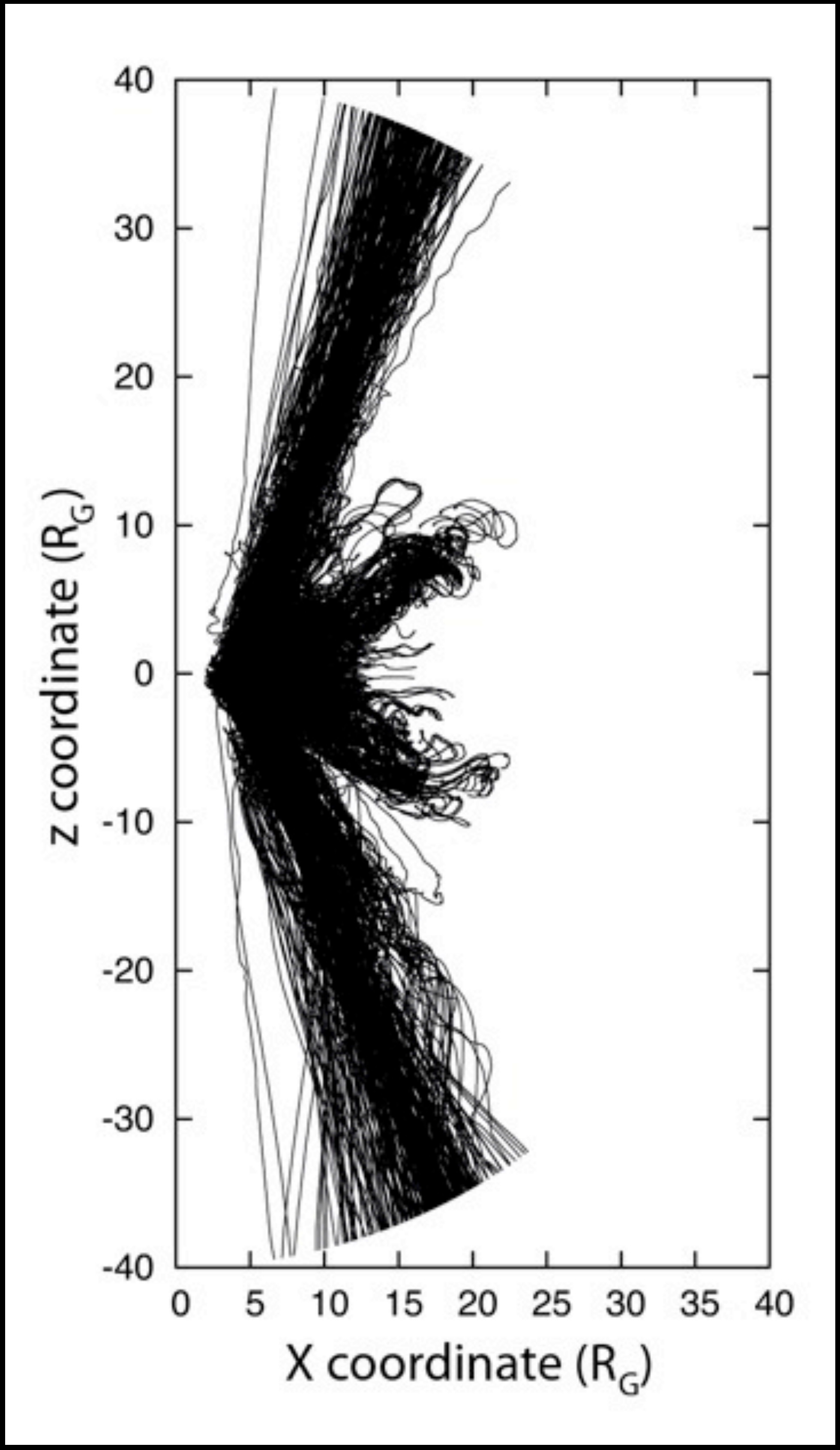
Simulation setup



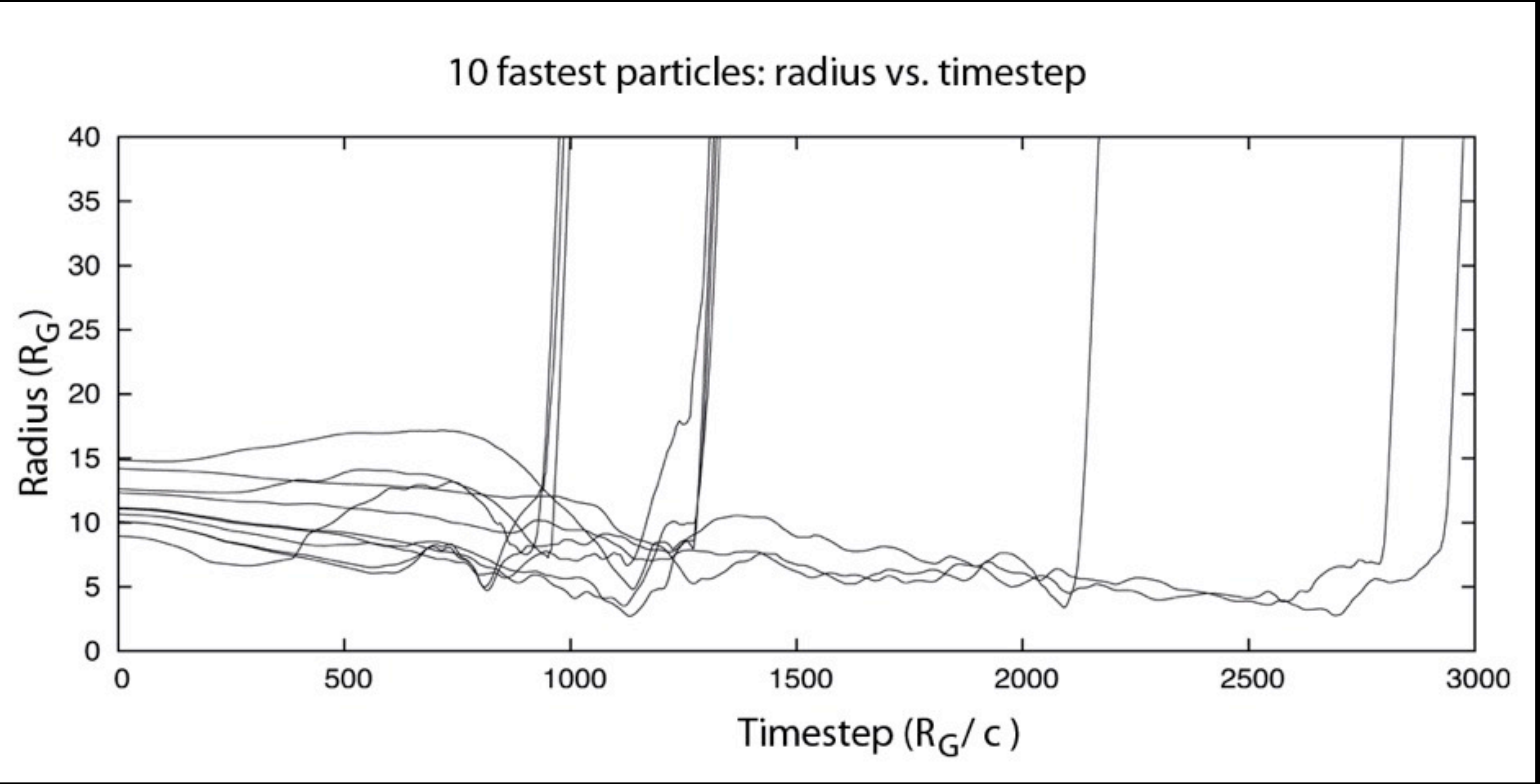


Accretion & outflow stats



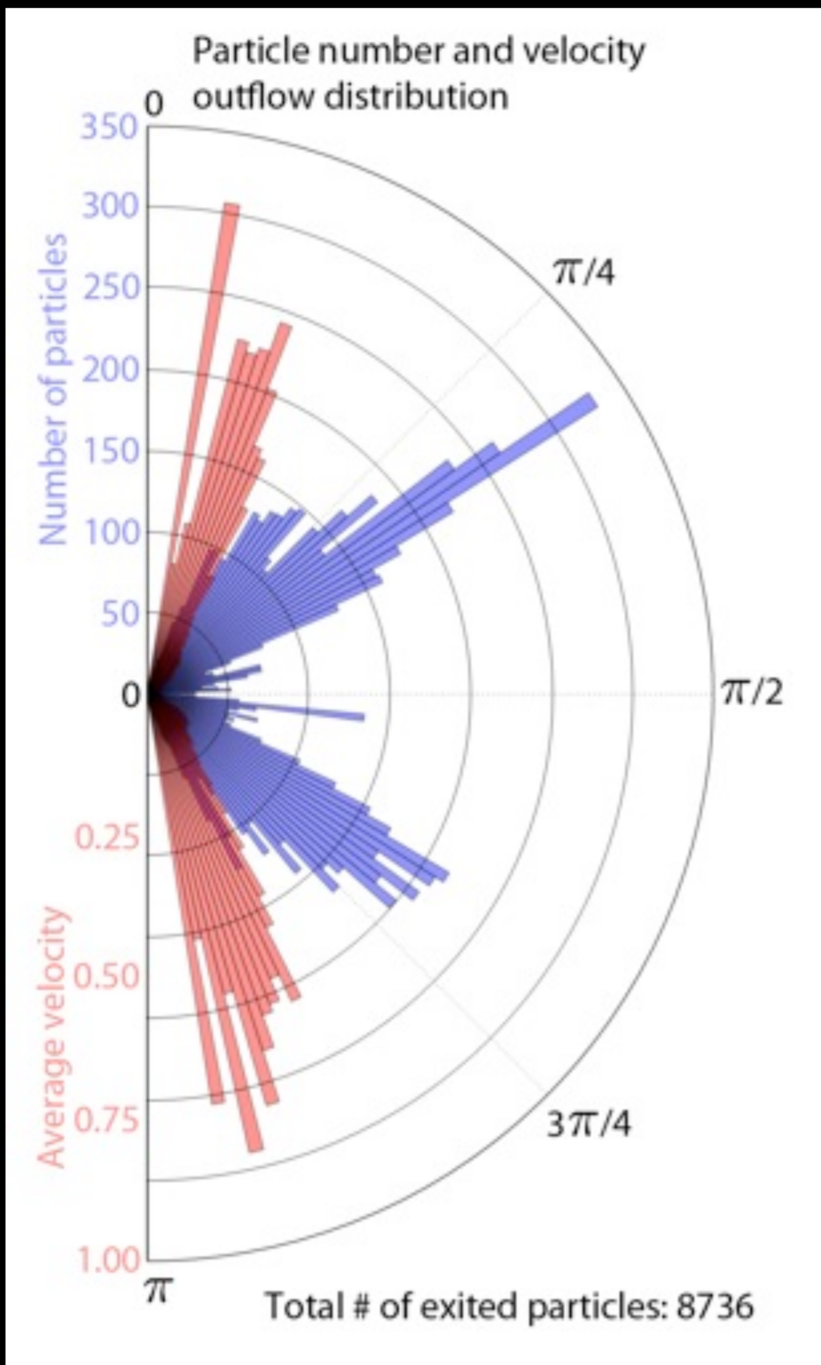


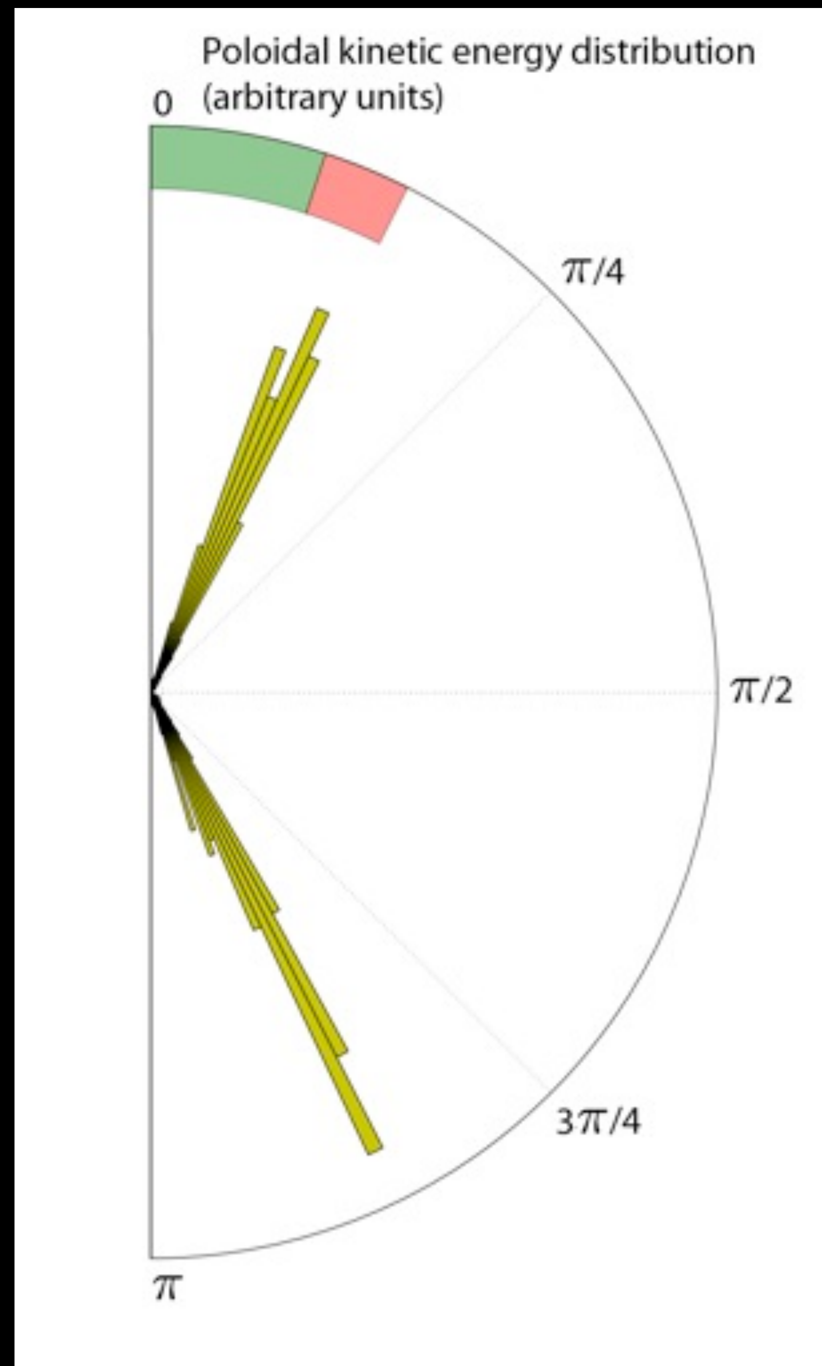
Accretion & outflow stats

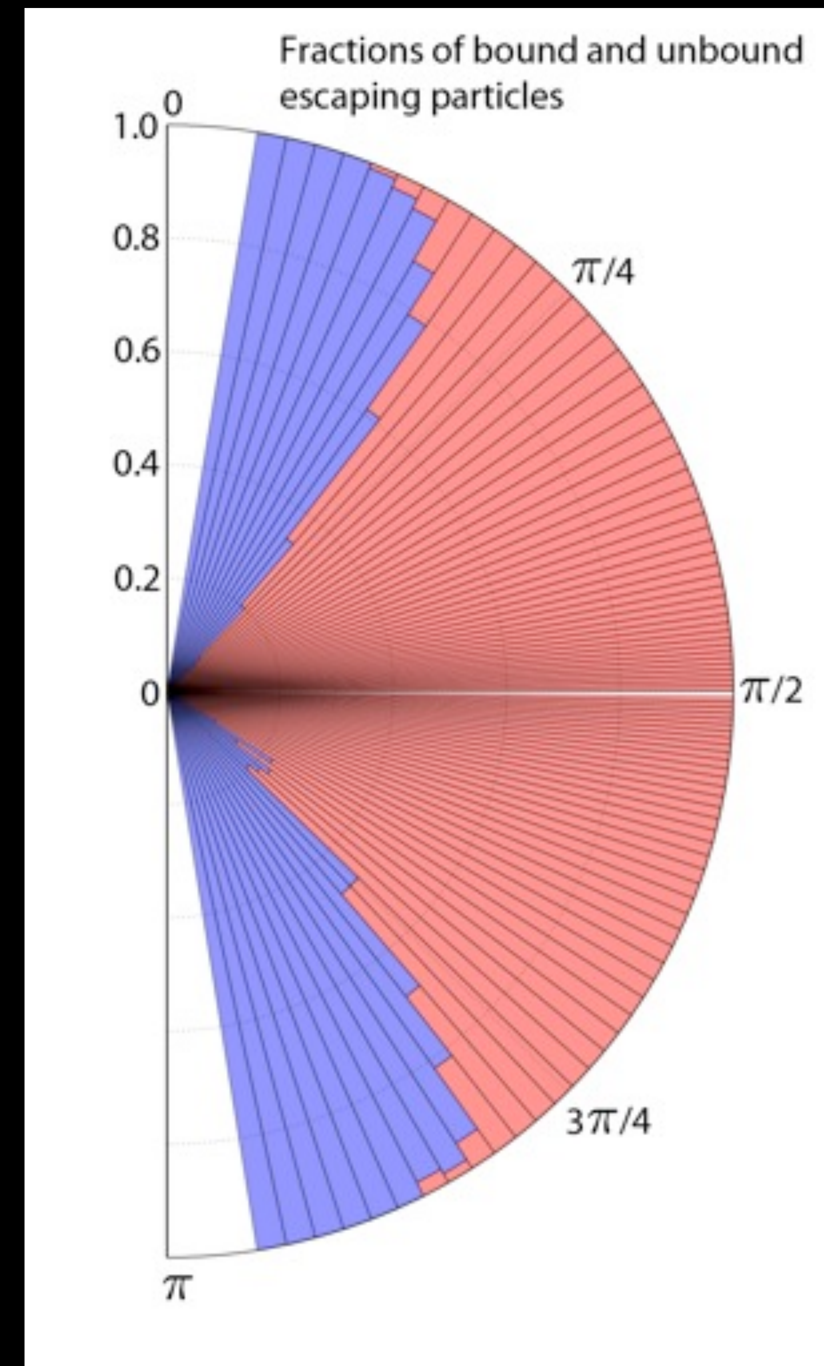


Sudden acceleration: characteristic for shocks

Accretion & outflow stats







Accretion & outflow stats

About 7% of all tracer particles ends up in the jet: only a small fraction of total accreting matter!

To explain low-frequency emission, high electron temperatures are needed in the jet region.

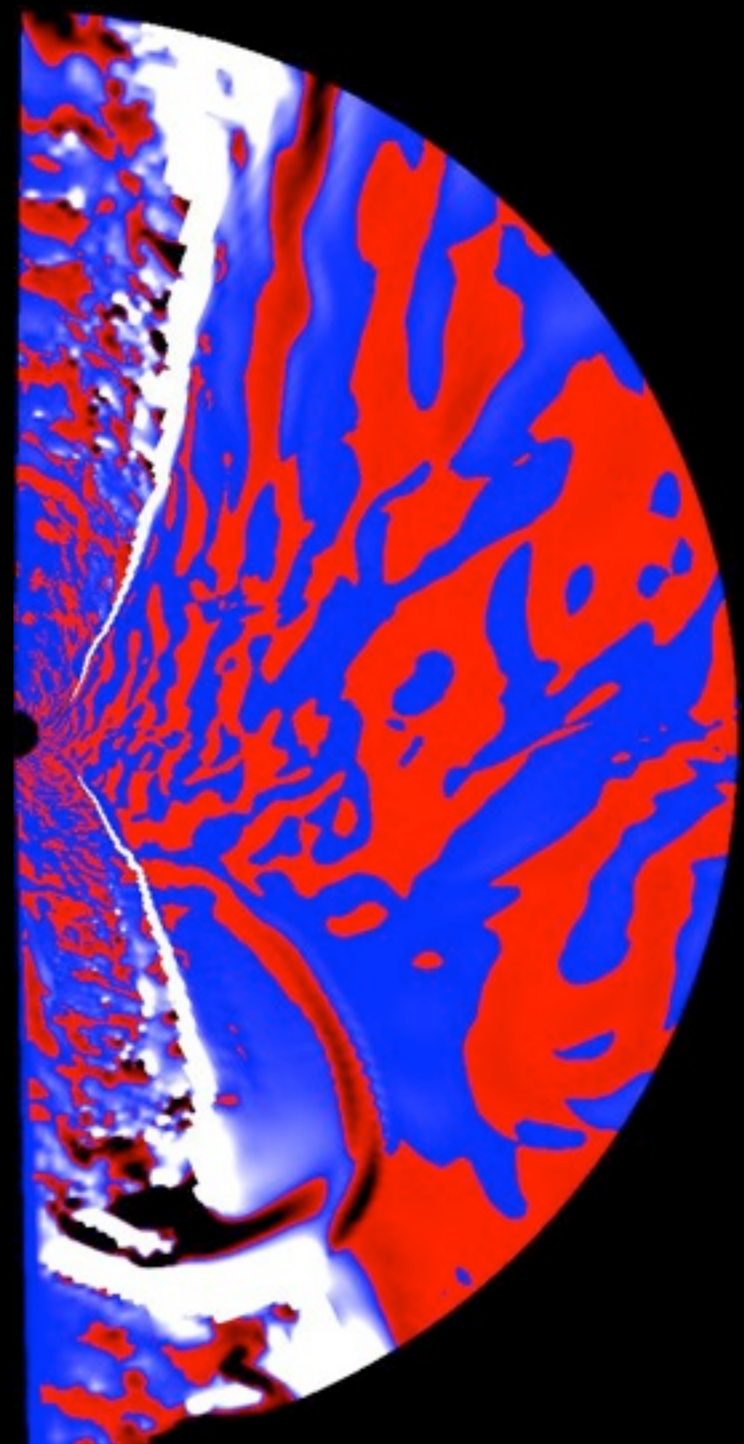
Acceleration mechanisms in the jet?

Accretion & outflow stats

$\nabla \cdot (\rho\vec{v})/\rho$ for t = 2750

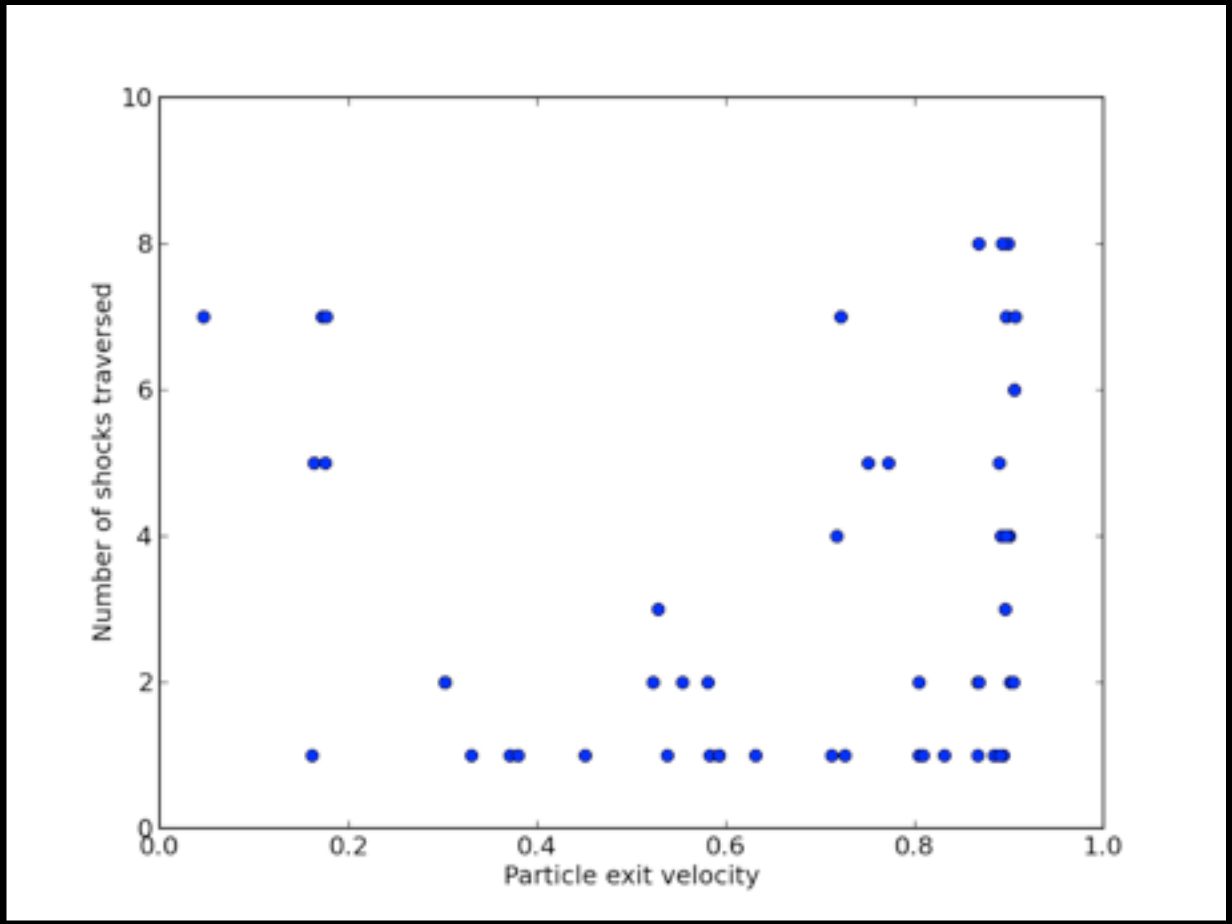
Blue to white: negative divergence (compression)

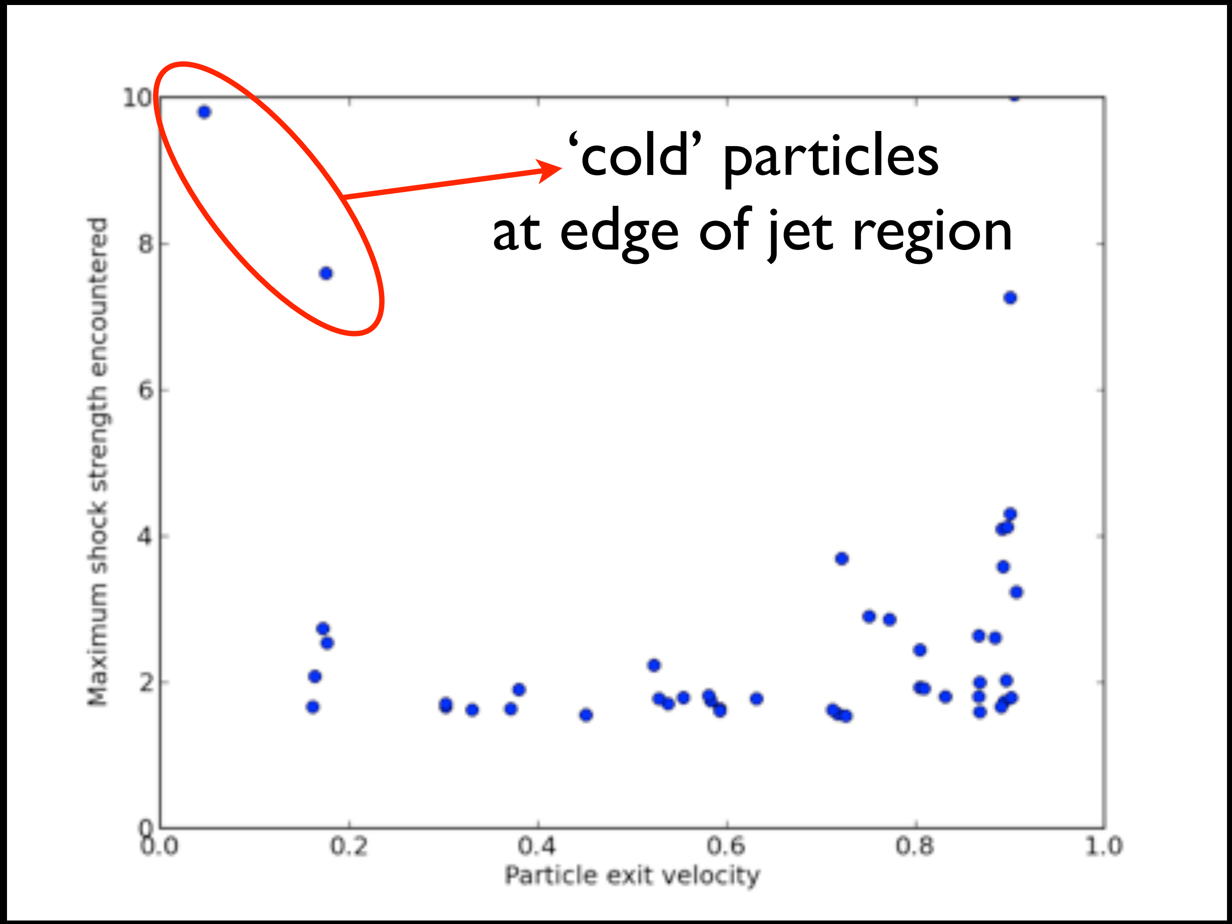
Red to black: positive divergence (expansion)



Accretion & outflow stats

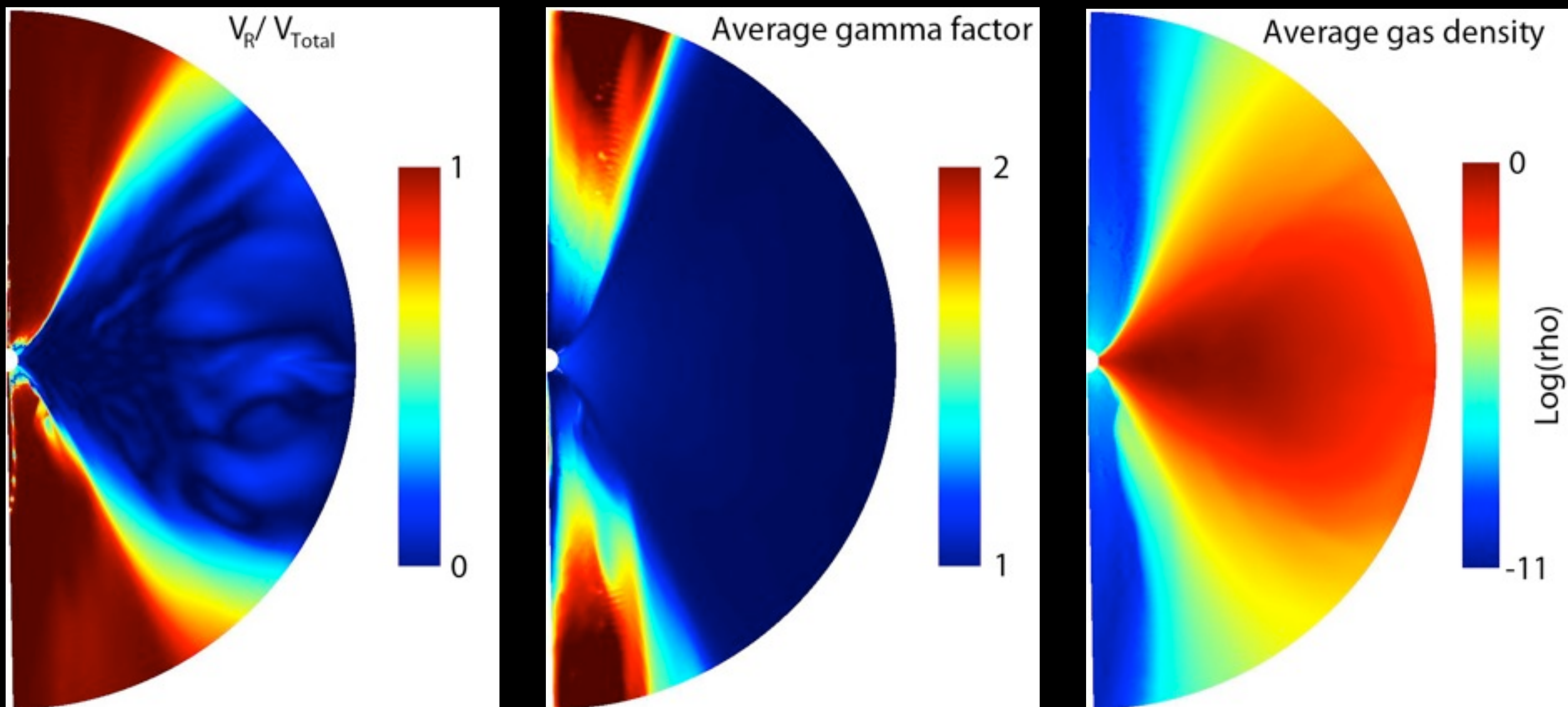
Follow particles that end up in the jet: see what shocks they travel through





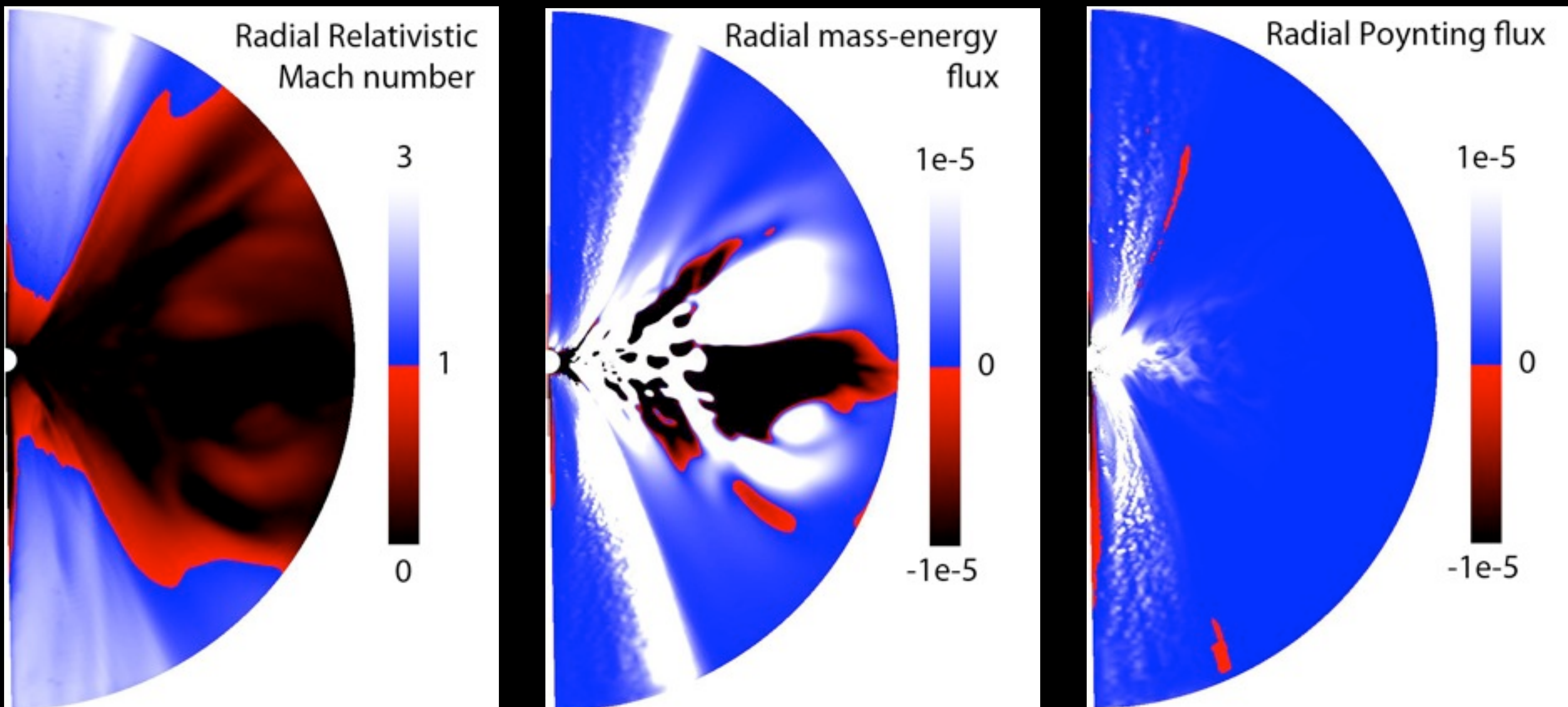
Shock strength defined as: $(u/\rho)_{\rm new}/(u/\rho)_{\rm old}$

Flow variables evolution



Jet flow is highly radial, highest gamma factors reached in jet spine. Mixing region is slower.

Flow variables evolution



Sonic point is close to BH. Jet sheath dominates mass-energy flux. Poynting flux quickly drops.

Comparison to FB model

Jet power vs. accretion power

In the jet sheath: $0.1\rho < u < \rho$

$$\gamma_j \approx 1.5$$

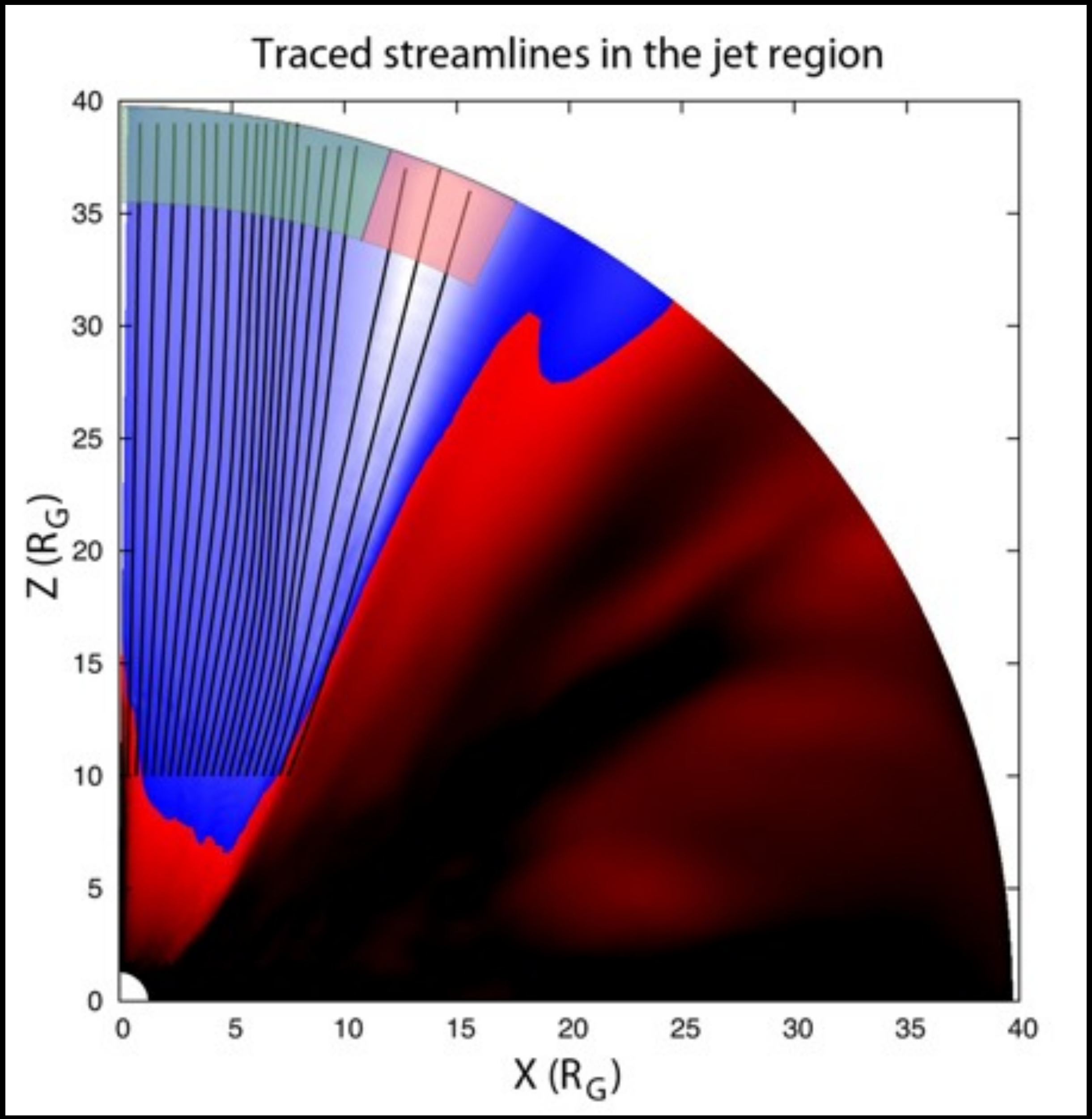
$$\frac{Q_\mathrm{j}}{\dot{M}_\mathrm{j} c^2} = \gamma_\mathrm{j}(1 + \Gamma u/\rho) = 2.5 < 2\gamma_\mathrm{j}$$

so: $\gamma_\mathrm{j} q_\mathrm{m}(1 + \Gamma u/\rho) = \dfrac{Q_\mathrm{j}}{Q_\mathrm{accr}} \approx 0.175$

Jet power is ~18% of accretion power!

Comparison to FB model

Evolution of jet flow

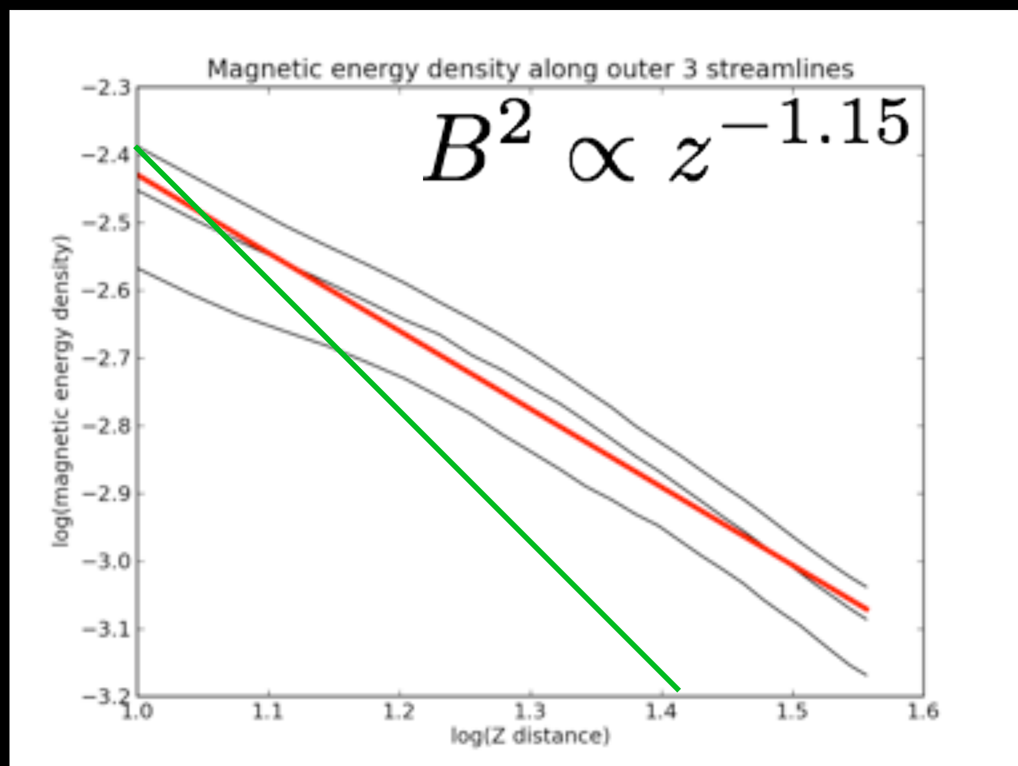


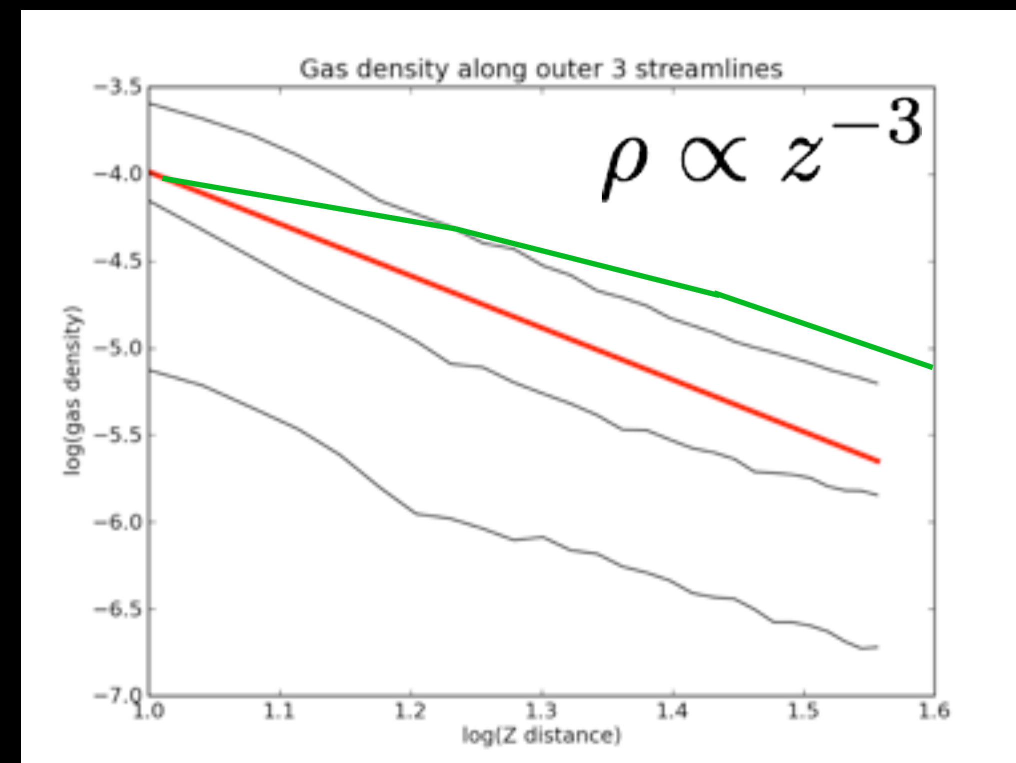
Look at:

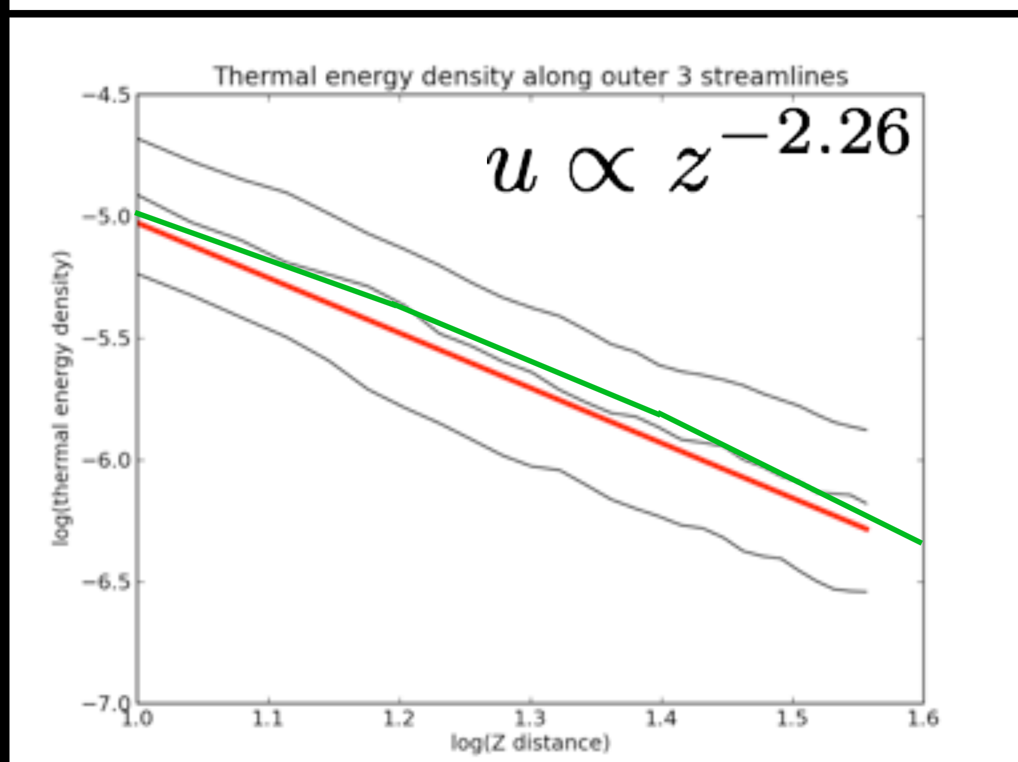
- Magnetic energy density
- Internal energy density
- Matter density

Comparison to FB model

Evaluate variables along streamlines in jet sheath







Magnetic field drops slowly! For conical flow: advected field $B^2 \propto z^{-2}$. But here field is stationary, and confined by disk.

Comparison to FB model

Agreements:

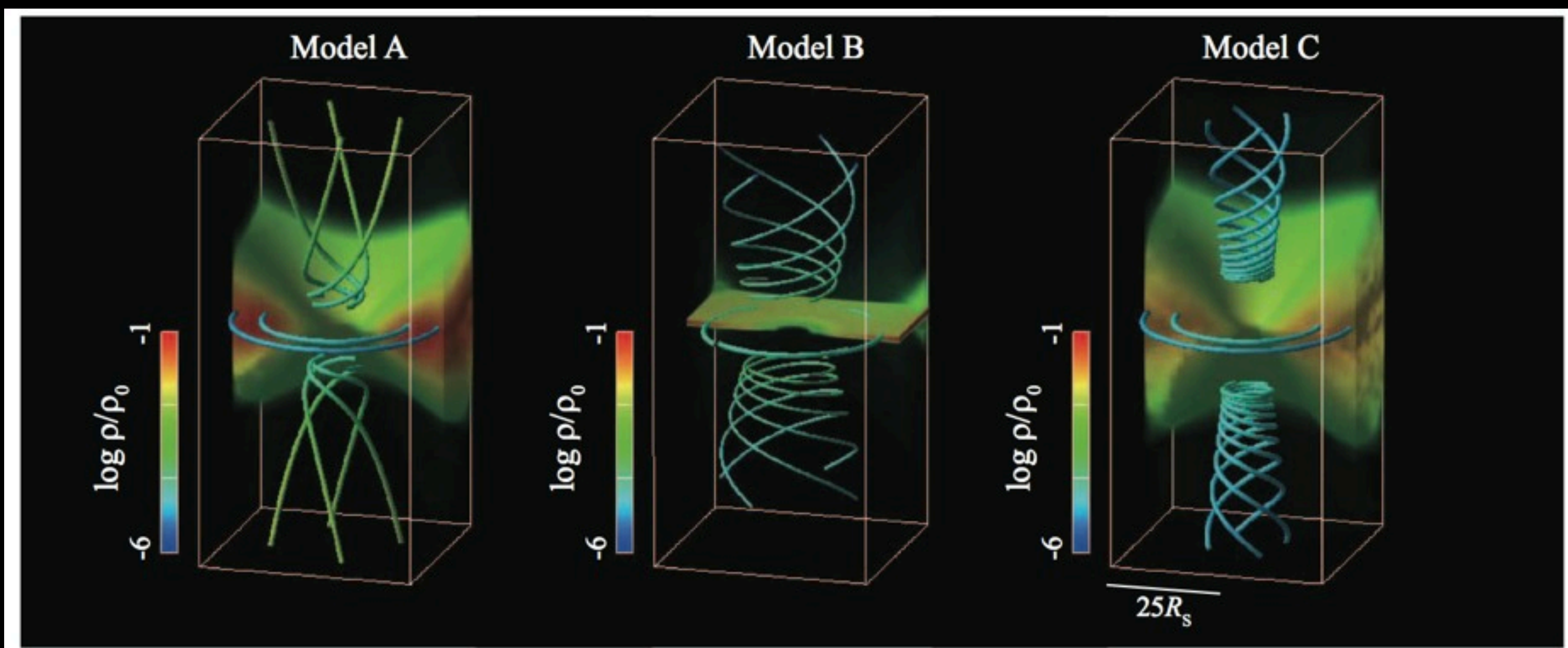
- Location of sonic point
- Internal energy density evolution and initial value

Differences:

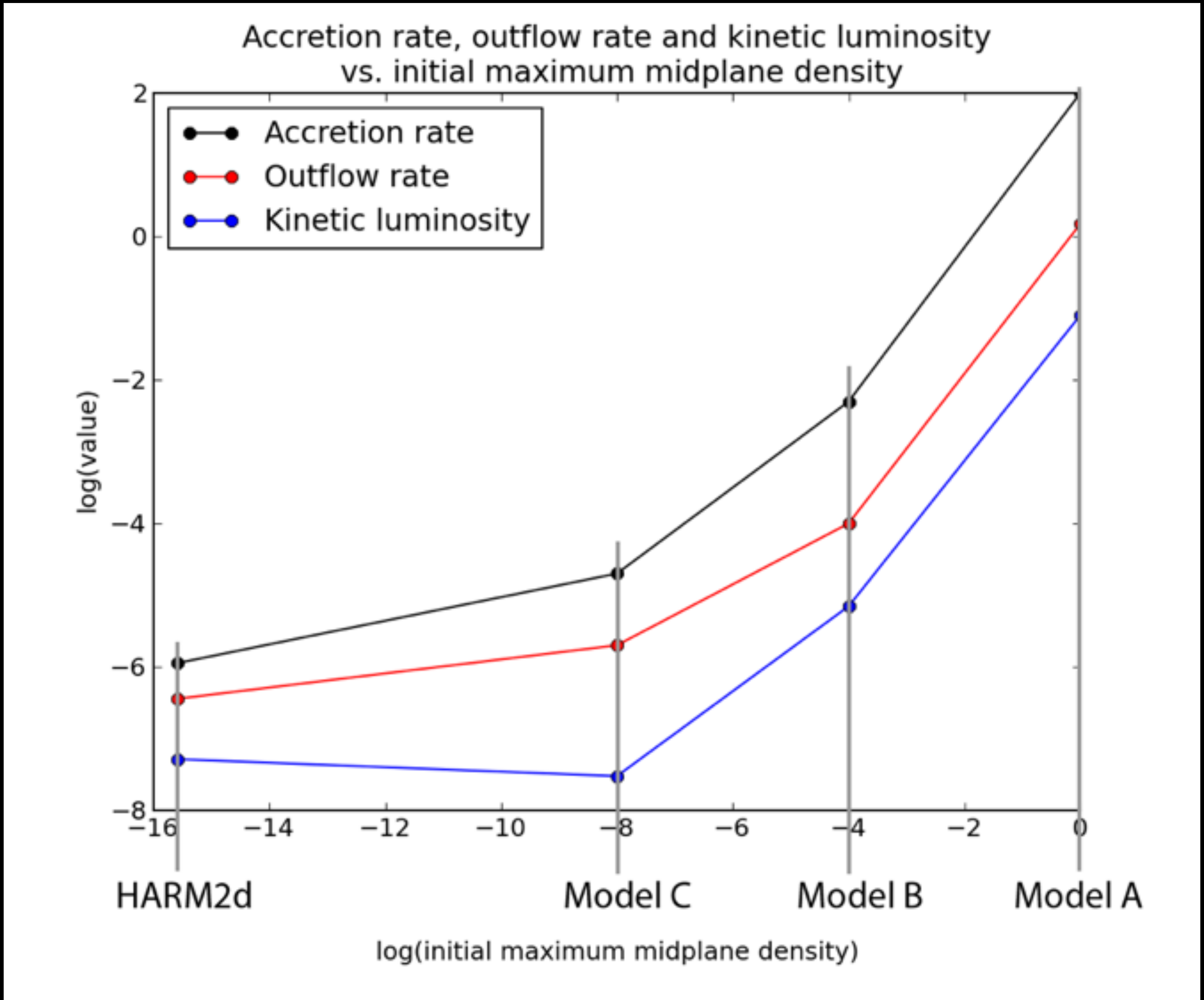
- Magnetic field strength and evolution
- Density evolution
- Gas acceleration profile

Comparison to other sims

Ohsuga & Mineshige: 2D axisymmetric flow, including radiative transfer: solve flow for 3 different midplane densities



Comparison to other sims



Conclusions

- Good agreement with FB model found regarding total jet power vs. accretion power, partial agreement regarding jet flow evolution
- Good agreement with Ohsuga-Mineshige simulation found regarding accretion rate and jet power
- Likely acceleration sites for high-energy electrons found at jet boundary and in jet