Relativistic jets, from analytical to simulations

Christophe SAUTY (LUPM/LUTH)

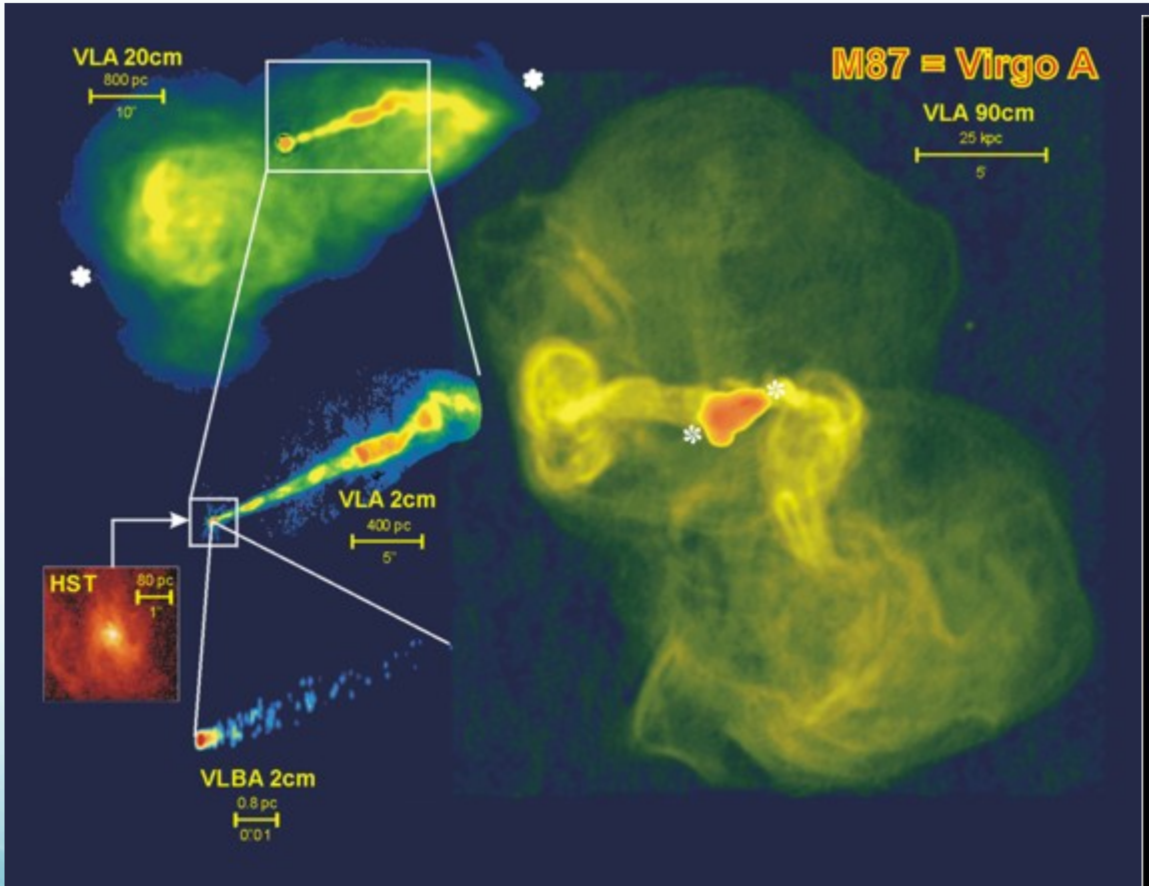
Coll. for this work
Véronique CAYATTE (LUTH,Obs. Paris)
Loïc CHANTRY (LUTH)
Nektarios VLAHAKIS (U. Athens)

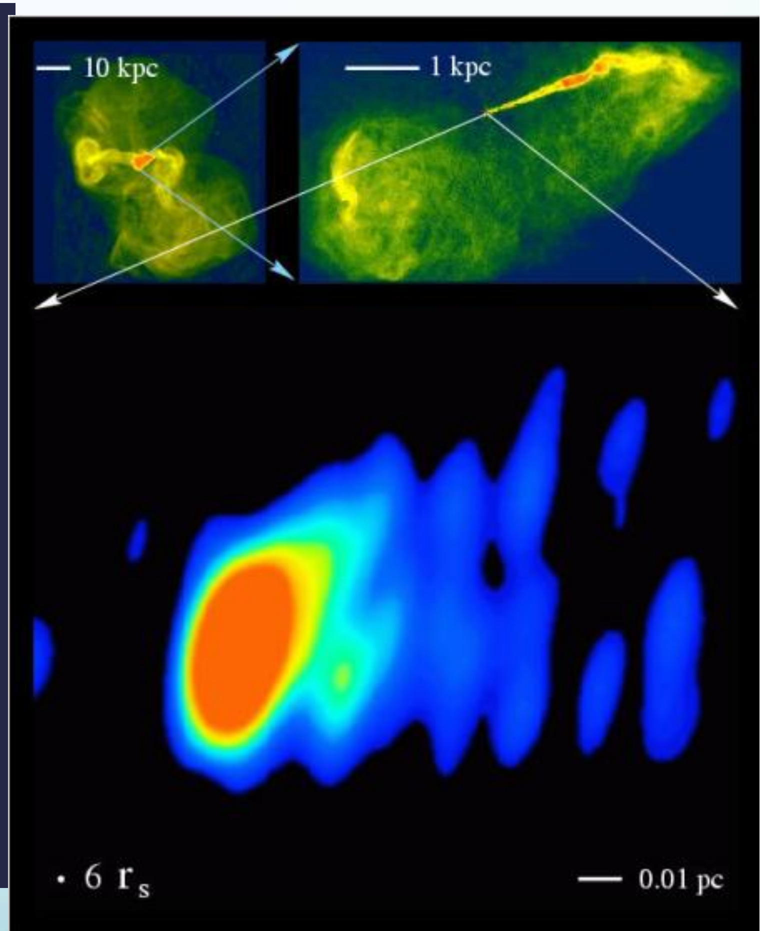
Kanaris TSINGANOS (U. Athens)
Raquel de ALBUQUERQUE (U. Porto / Obs Paris)
Filipe GAMEIRO (U. Porto
João LIMA (U. Porto)
Titos MATSAKOS
Alexandre Marcowith (LUPM)
Vincent Guillet (LUPM, IAS)

Relativistic Jets

ACTIVE GALACTIC NUCLEI Radio Loud, Narrow Line Radio Galaxies

M87 the case

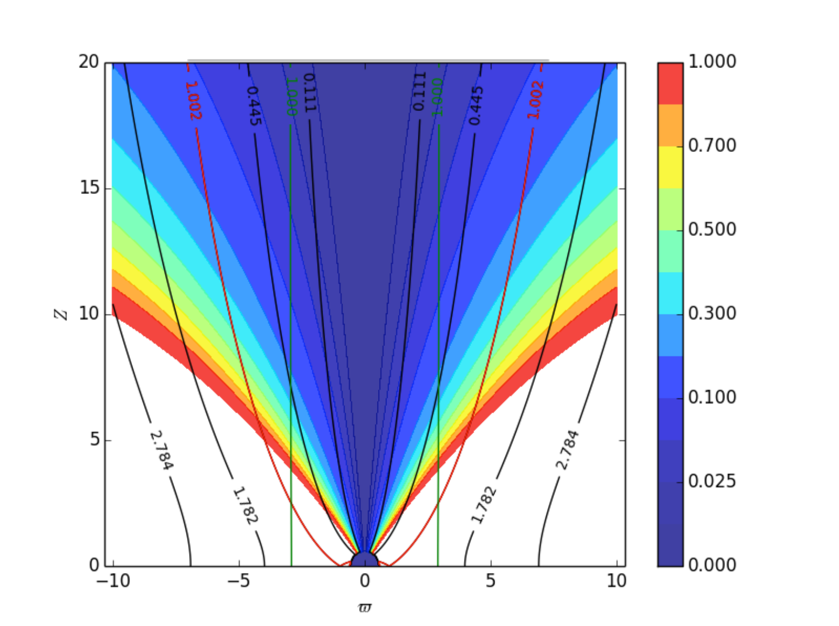




The Model *(Chantry et al. 2018)*

Self-similar MHD model with Kerr metric

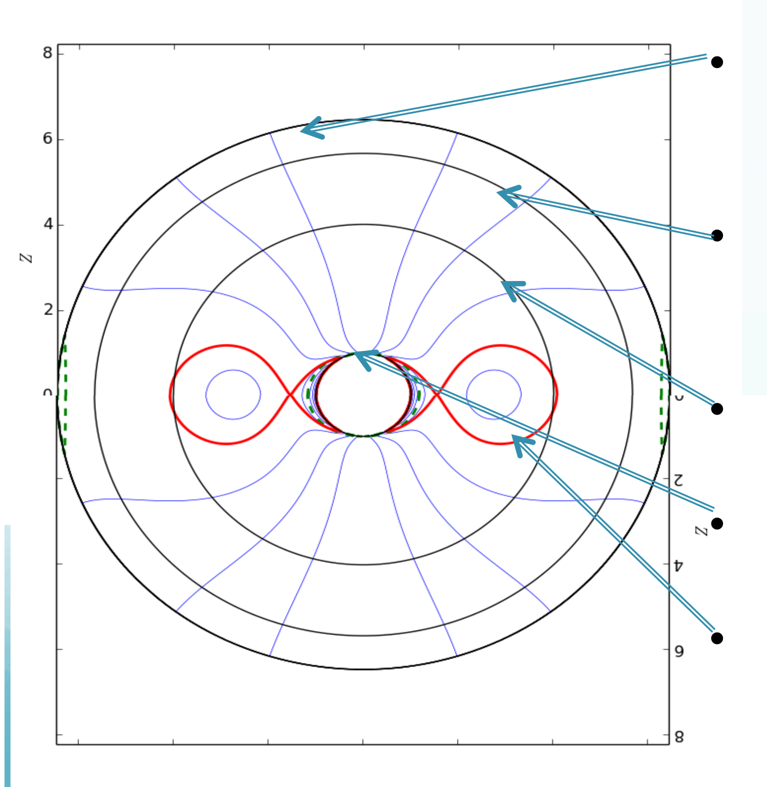
- Extension of the classical model, and in Schwarzschild and Kerr metrics
- 3+1 formalism in Kerr metric.
- Not exact solution but expansion in colatitude of the metric and the GRMHD equations, equivalent to an expansion in magnetic flux.
- Non polytropic solutions with non thermal heating.
- No force-free approximation in the spine jet, conversely to several models
- No fixed geometry.
- Taking account the effects of the light cylinder contrary to our previous extensions.



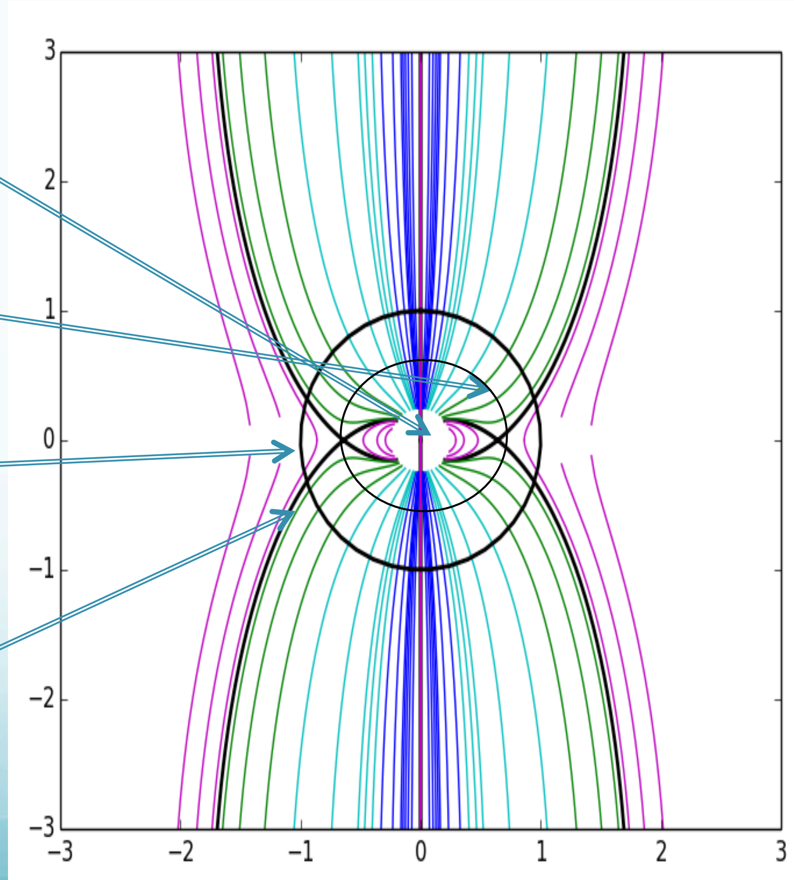
Relative error on the electric force for a recollimating oscillating solution in Kerr metric, K1,

The Model Inflow / Outflow

Technique:
Integrate from the Alfvén surface upstream to cross the slow magnetosonic surface and match the conditions at the stagantion point. Then, integrate downstream to reach the maximum velocity at infinity (outflow) or at the event horizon (inflow).



- Stagnation surface (exobase)
- Slow Magnetosonic surface
- Alfvén surface
- Event horizon
- last closed fieldline



Magnetic collimation criterion

$$\epsilon = -\frac{\nu^2 h_\star^4}{\mu \gamma_z^2 h_z^2} \frac{\partial}{\partial \alpha} \ln \left(\frac{P - P_0}{\rho_0 \xi} \right) \Bigg|_{\alpha=0}$$

$$\omega_{BH} = \frac{a_H c}{r_s \left(1 + \sqrt{1 - a_H^2} \right)},$$

$$\epsilon = \frac{2\lambda^2}{h_z^2} \left(\frac{\Lambda^2 N_B}{D} + \frac{\overline{\omega}_z}{\lambda} \right) + \lambda^2 \left(\frac{\Lambda N_V}{h_* G_0 D} \right)^2 - \frac{\nu^2 (2e_1 - 2m_1 + \delta - \kappa) R_0}{h_z^2 (R_0^2 + l^2)} - \frac{\nu^2 l^2 R_0 {G_0}^2}{h_z^2 (R_0^2 + l^2)^3}$$

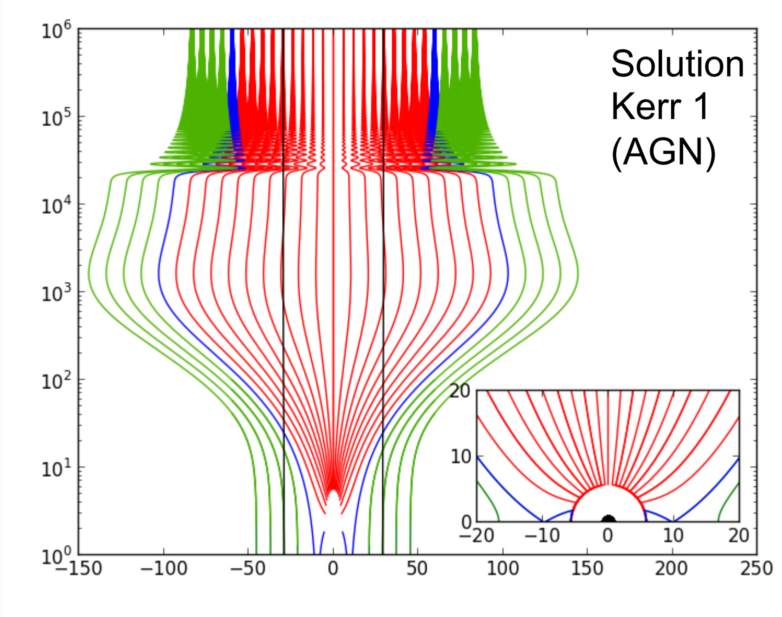
Generalisation of the magnetic criterion for magnetic collimation to relativistic jets in Kerr metric.

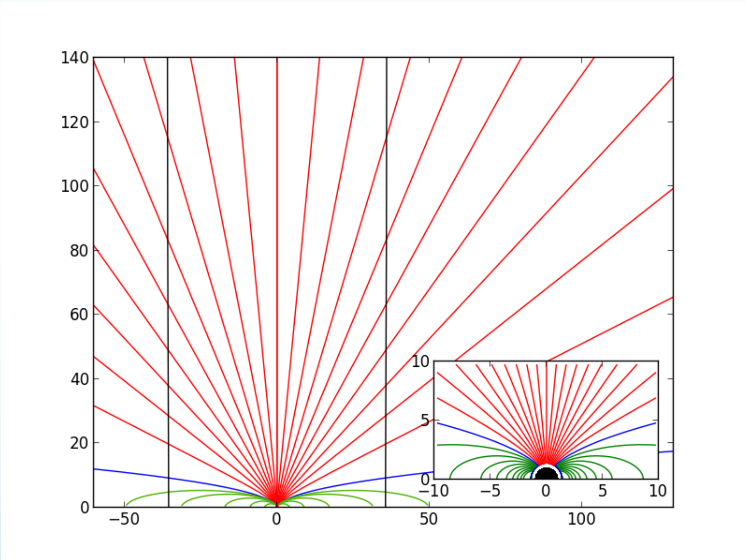
Outflows Jet / Winds

Caption, RED: field/streamlines connected to thρ black hole, GREEN: lines connected to the disk, BLUE: limiting solution, BLACK: light cylinder

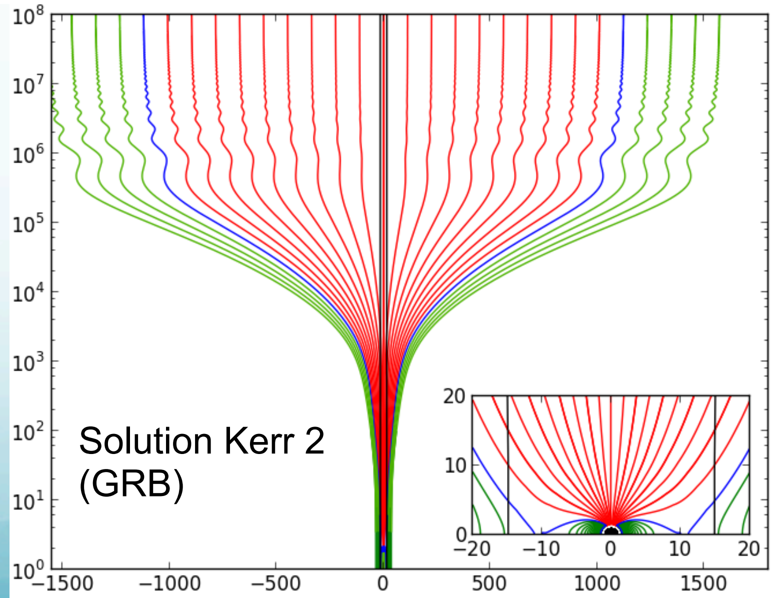
New generalization in Kerr metric:

➔ Taking into account the effects of the light cylinder allows for conical solutions with small opening angle ~1/γ, also interesting for GRBs.



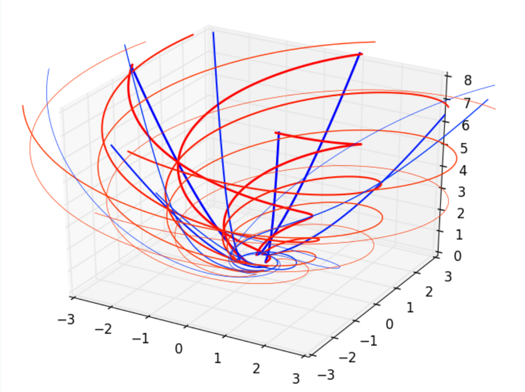


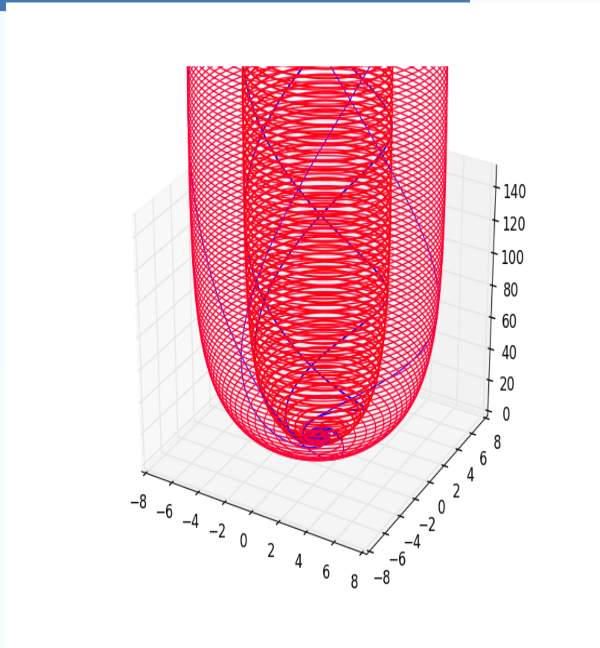
Conical solution K4



Outflows Jet/Winds: 3D plots

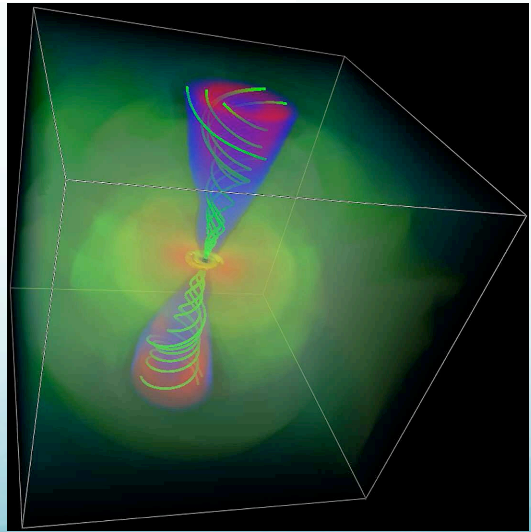
3D Magnetic (red lines) and flow (blue lines) geometry of Solution Kerr 1 (AGN cylindrical solution)

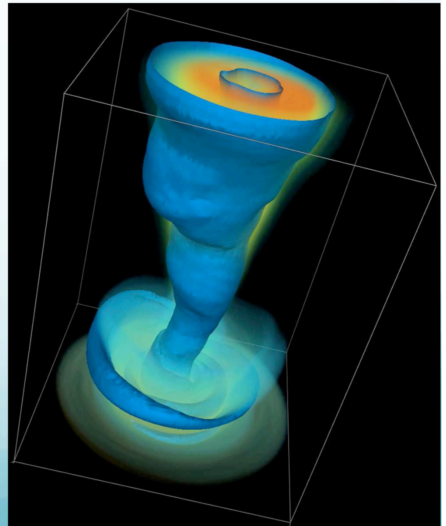




3D Magnetic (red lines) and flow (blue lines) geometry of a conical solution

McKinney, Blandford, 2009





Magnetic collimation criterion

Generalisation of the magnetic criterion for magnetic collimation [11] & [8] to relativistic jets in Kerr metric.

$$\epsilon = -\frac{\nu^2 h_\star^4}{\mu \gamma_z^2 h_z^2} \frac{\partial}{\partial \alpha} \ln \left(\frac{P - P_0}{\rho_0 \xi} \right) \Bigg|_{\alpha=0}$$

$$\omega_{BH} = \frac{a_H c}{r_s \left(1 + \sqrt{1 - a_H^2}\right)},$$

$$\epsilon = \frac{2\lambda^2}{h_z^2} \left(\frac{\Lambda^2 N_B}{D} + \frac{\overline{\omega}_z}{\lambda} \right) + \lambda^2 \left(\frac{\Lambda N_V}{h_* G_0 D} \right)^2 - \frac{\nu^2 (2e_1 - 2m_1 + \delta - \kappa) R_0}{h_z^2 (R_0^2 + l^2)} - \frac{\nu^2 l^2 R_0 {G_0}^2}{h_z^2 (R_0^2 + l^2)^3}$$

Cylindrical Outflows, Jet Efficiency

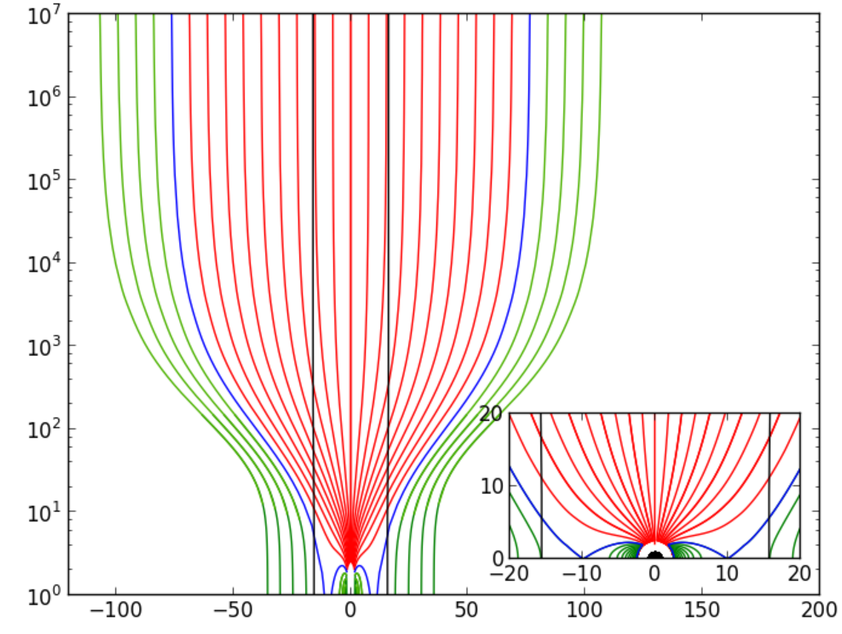
Outflows, they carry a significant power in the jet (50%) with high Lorentz factors.

- Mass accretion rate estimated from the magnetic flux, Zamaninasab et al.[13],

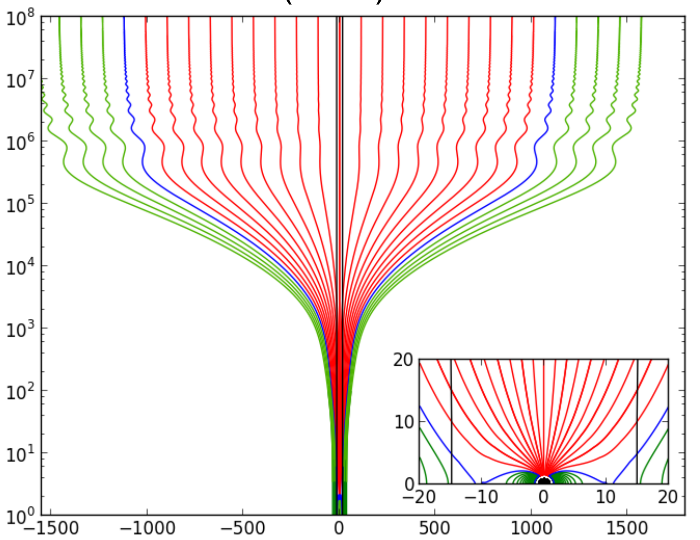
$$\Phi_{\rm BH} \simeq 50\sqrt{\dot{M}c\left(\frac{r_s}{2}\right)^2}.$$

- Estimate Power in the Jet, $$\eta_{Jet} = \frac{P_{Jet}}{\dot{M}_{acc}c^2}$$

Solution Kerr 3 (M87) $\eta_{Jet} = 0.40$



Solution Kerr 2 (GRB) $\eta_{Jet} = 0.52$



Compare to McKinney, Tchekovskoy...

McKinney 2005 η≈0.01-0.1

Tchekovskoy 2011, McKinney 2012, η>1 for fast rotating BH

Inflows

Globus & Levinson

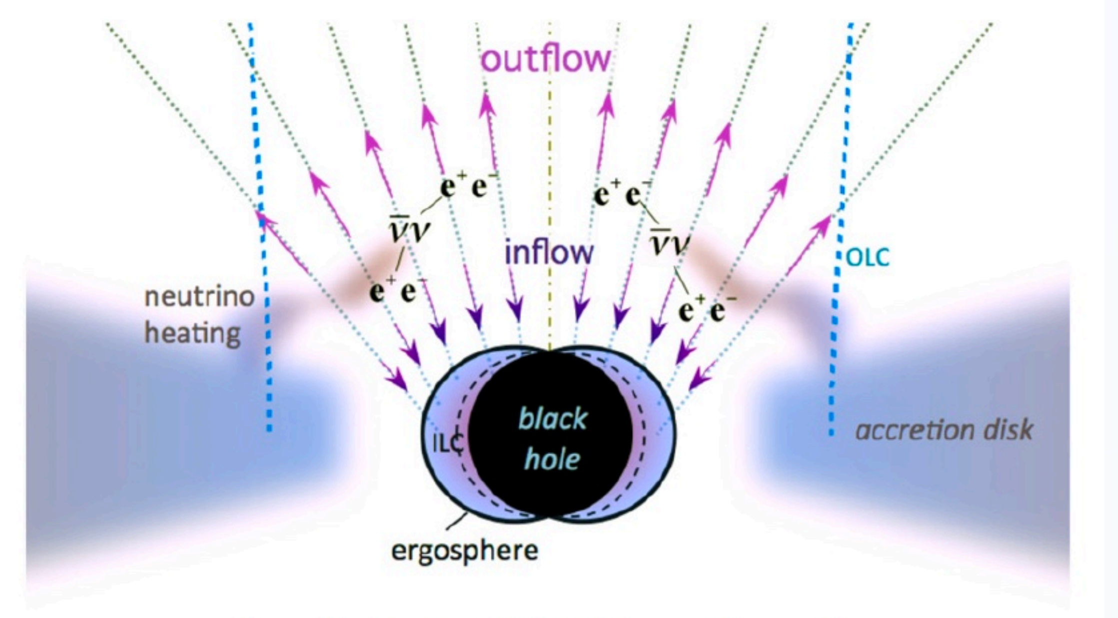


Figure 1. Illustration of the double-transonic flow model.

2013 :Surface injection

2014: Volume injection

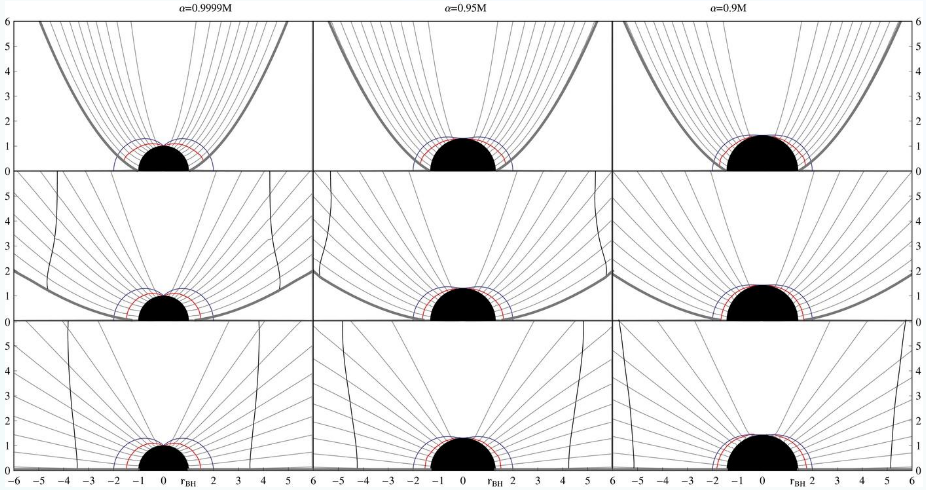
Fixed geometry -> Integrating the Bernoulli Equation and crossing the critical points

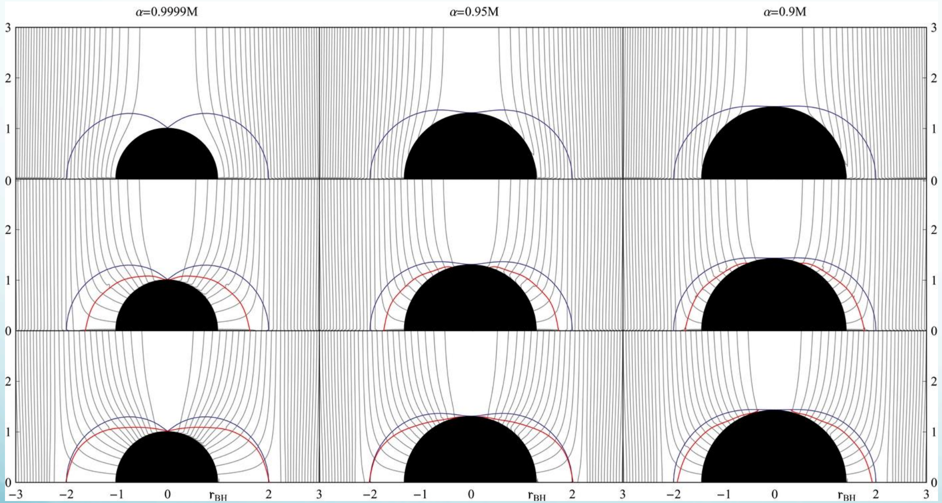
Any rotation

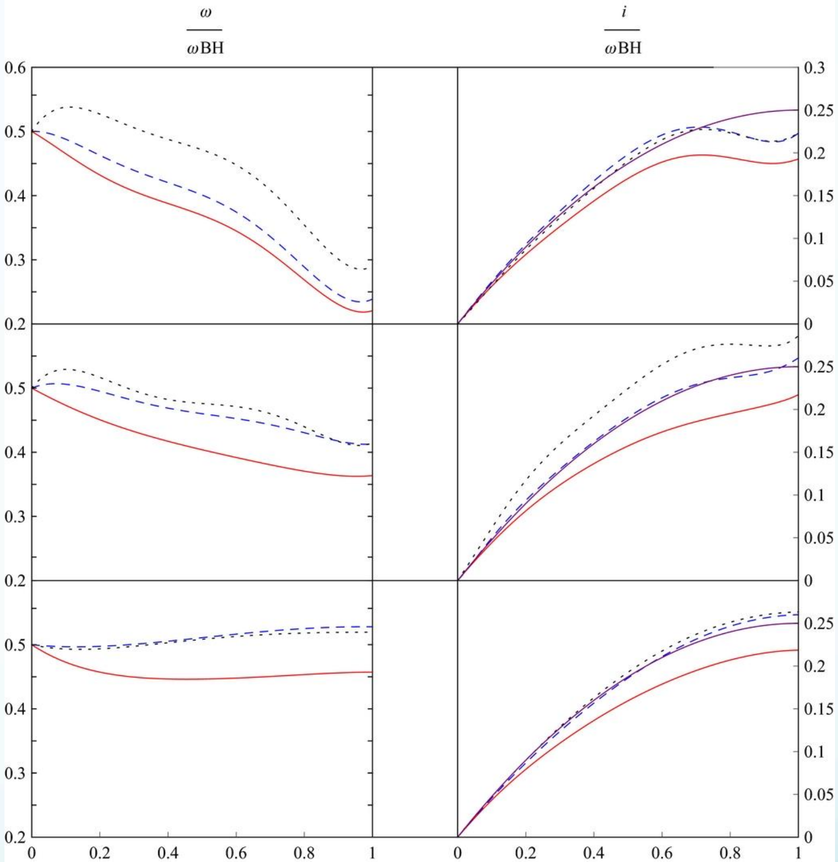
Blandford-Znajek :
- pure force free, low rotation
- First order change in the geometry

Inflows

Nathanail & Contopoulos Free Geometry, Force Free

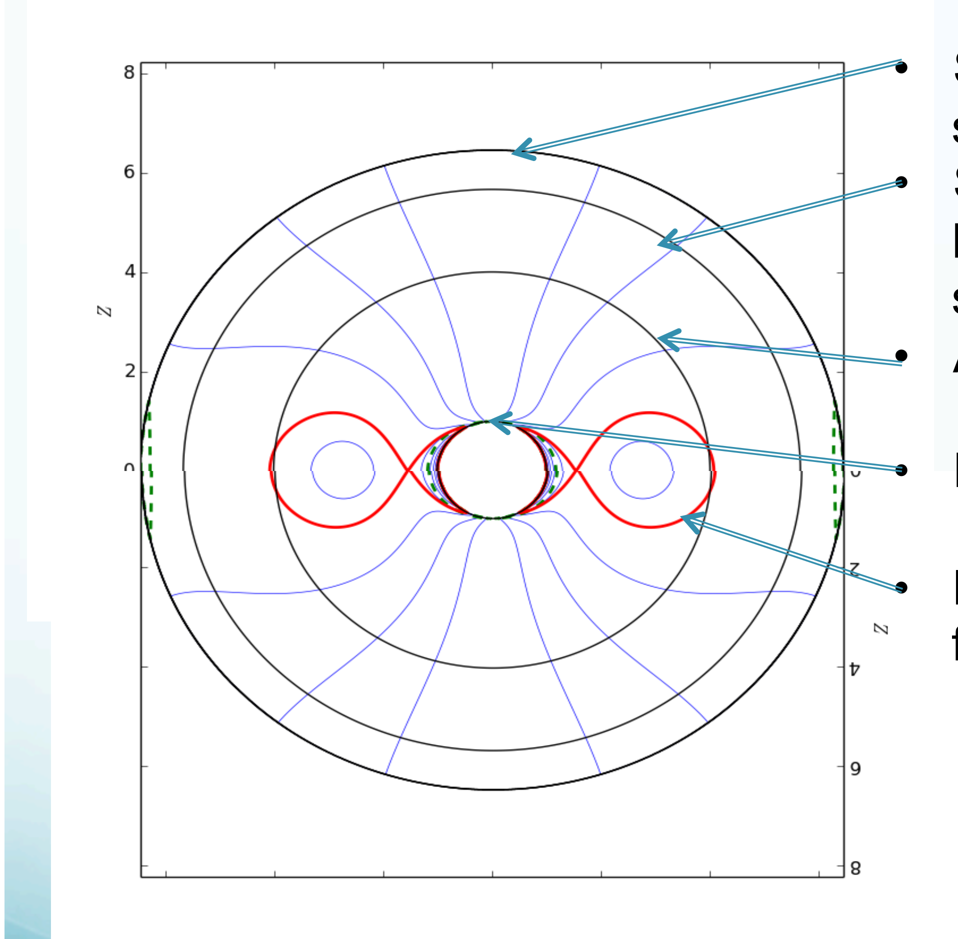






Inflows

Surface injection
Extraction of angular momentum, partial extraction of energy



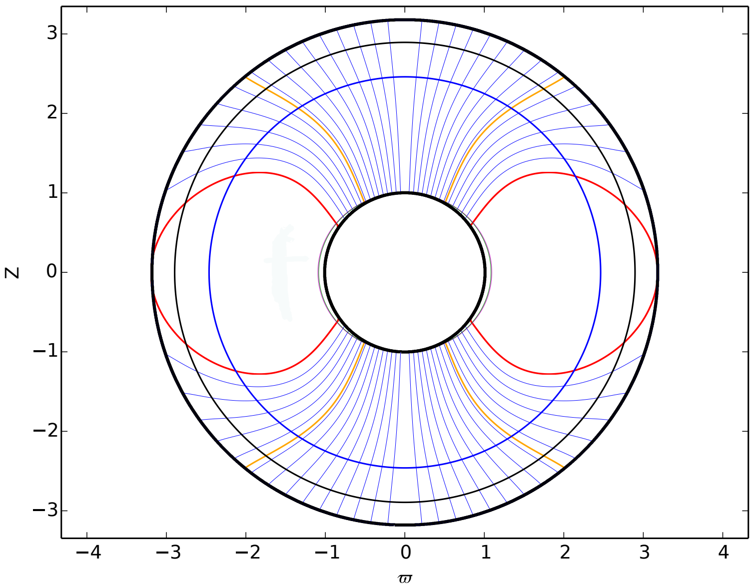
- Stagnation surface (exobase)
- Slow Magnetosinic surface
- Alfvén surface
- Event horizon
- last closed fieldline

Same technique starting integrating from the Alfvén surface but with negative velocity. The flow goes from the exobase to the B.H.

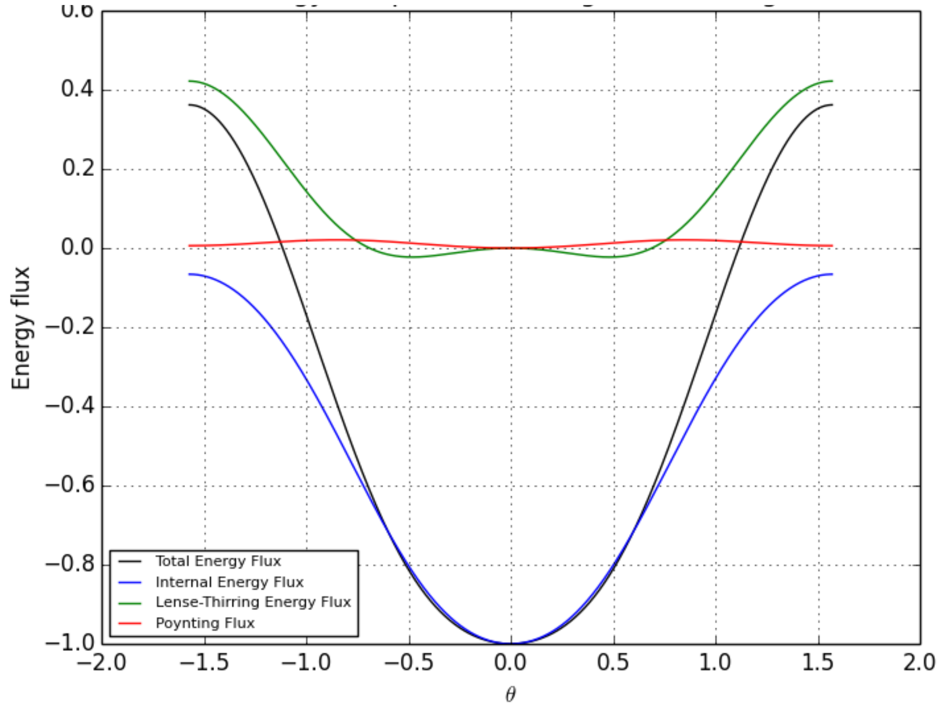
III. Inflows

- Extract angular momentum via Magnetized Penrose process
- At large latitude only, extraction of energy via Penrose mechanism.

The solution in fig. has a free geometry



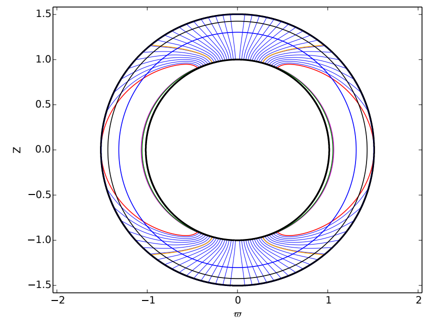
Normalized Energy fluxes with colatitude on the Event Horizon



Magnetic geometry of the extracting solution

Inflows

Extraction of angular momentum, partial extraction of energy



The solution :

- Can extract angular momentum via the Blandford Znajek process at mid latitudes (red line Fig. III.3).

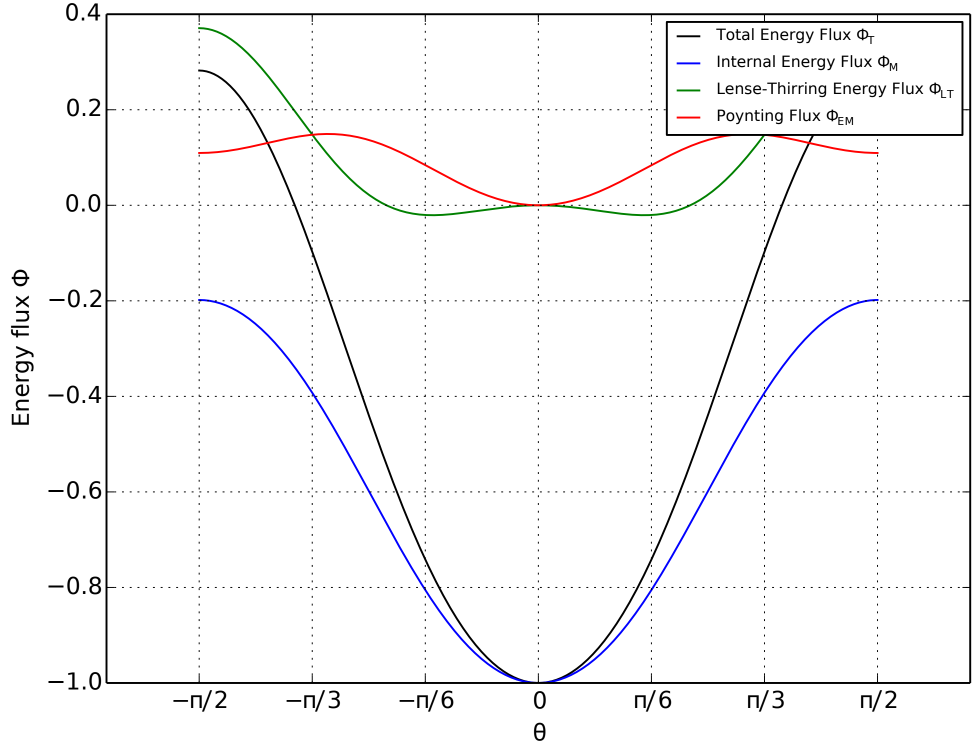
$$0 \leq \Omega \leq \omega_H$$

- At large latitude, extraction of energy via Penrose mechanism.

$$\omega_H \Delta J_H \leq \Delta E_H \leq 0$$

- Geometry of the inflow not prescribed unlike other models

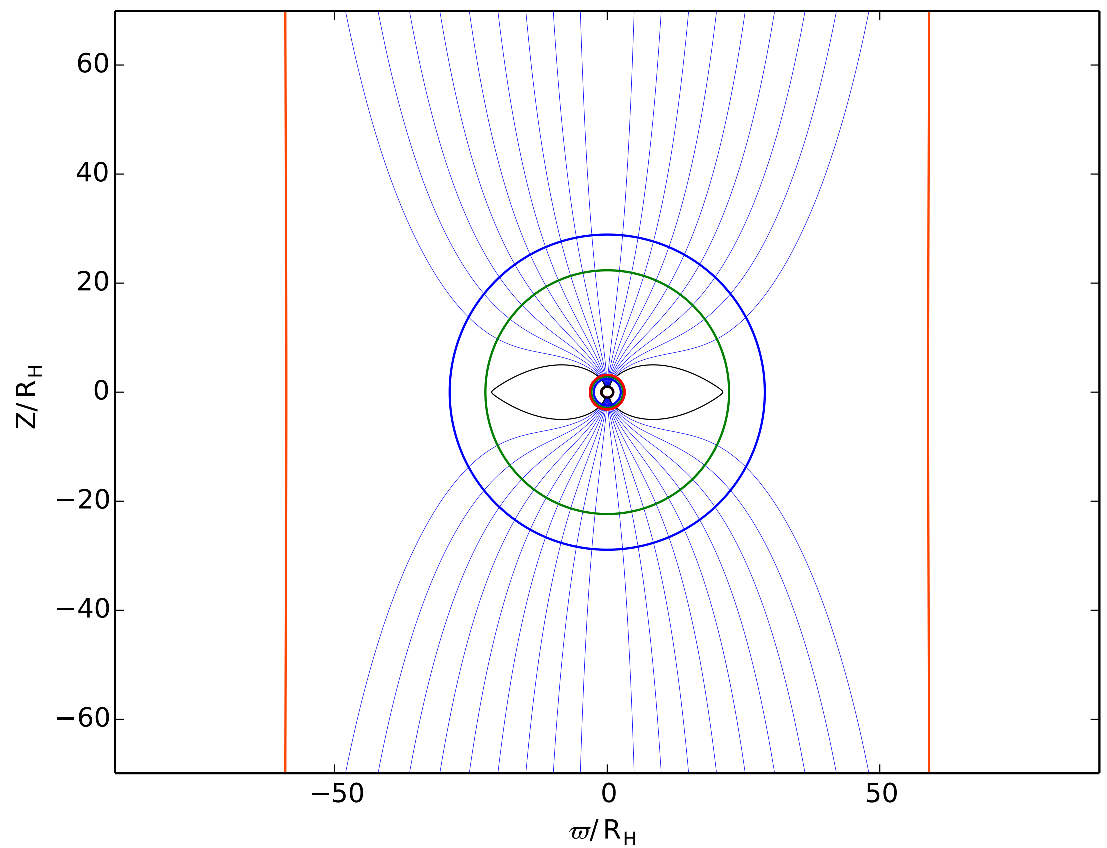
Normalized Energy fluxes with colatitude on the Event Horizon

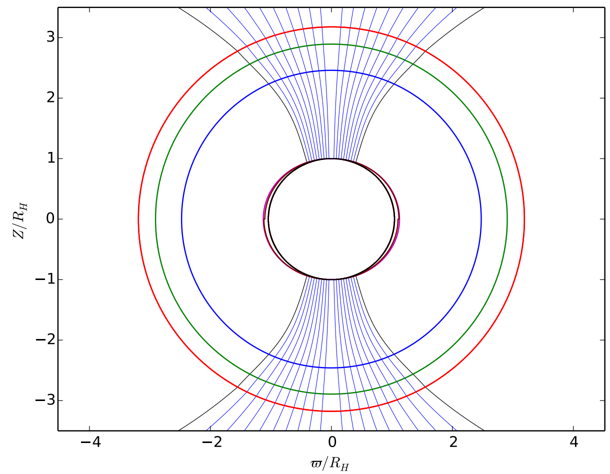


III. In-Out flow structure

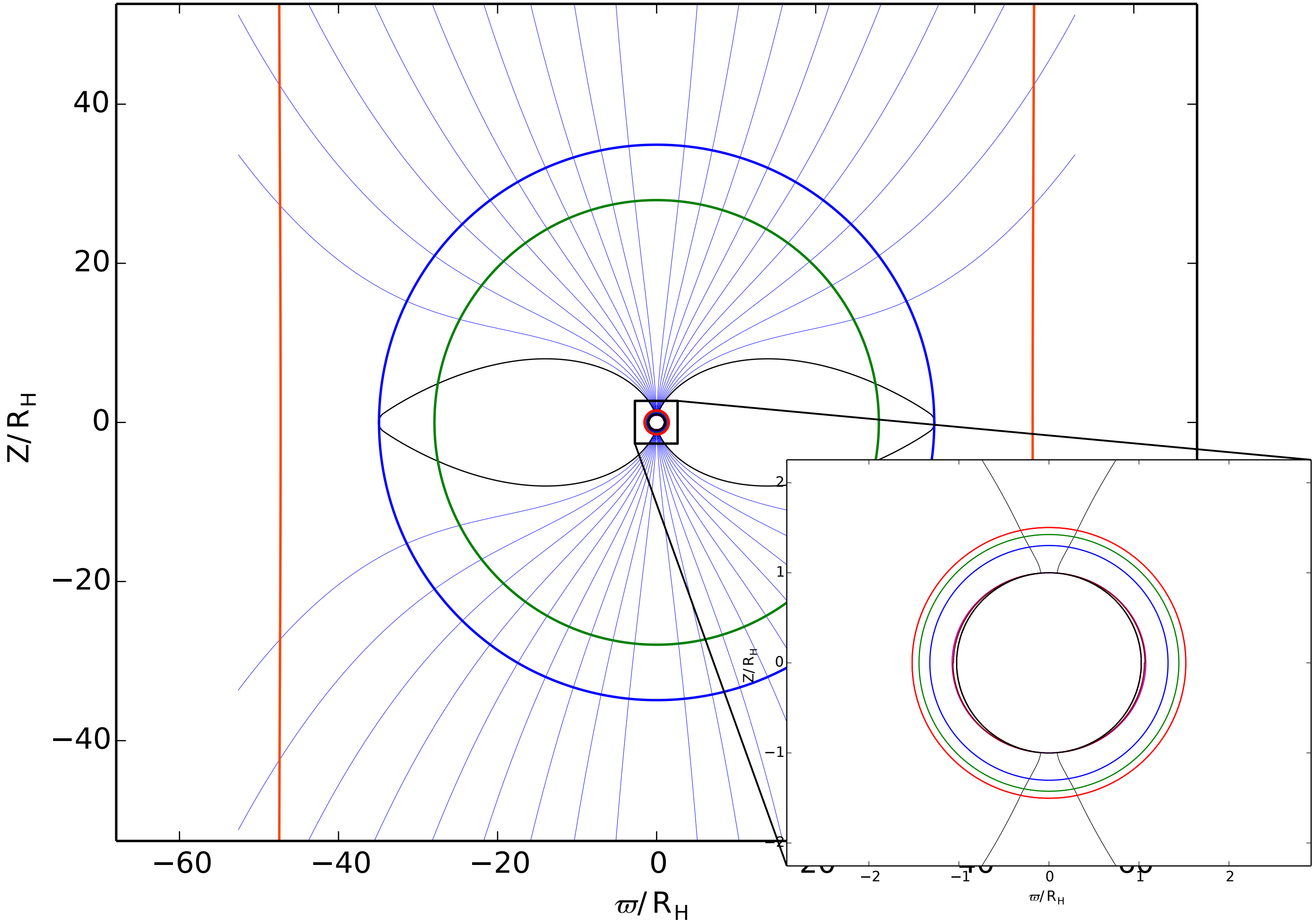
- rough estimate : 98% of pairs
- mostly neutrino origin

and photon less important

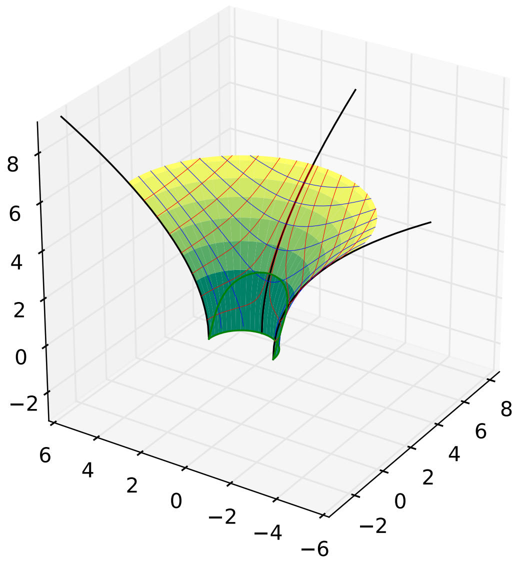


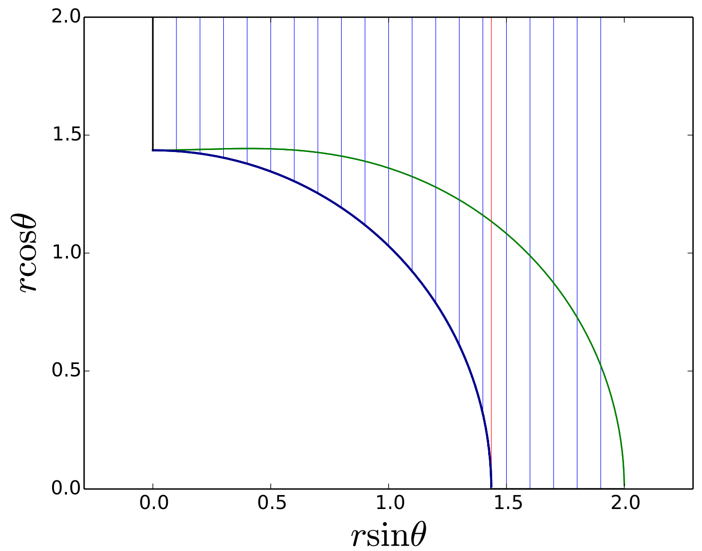


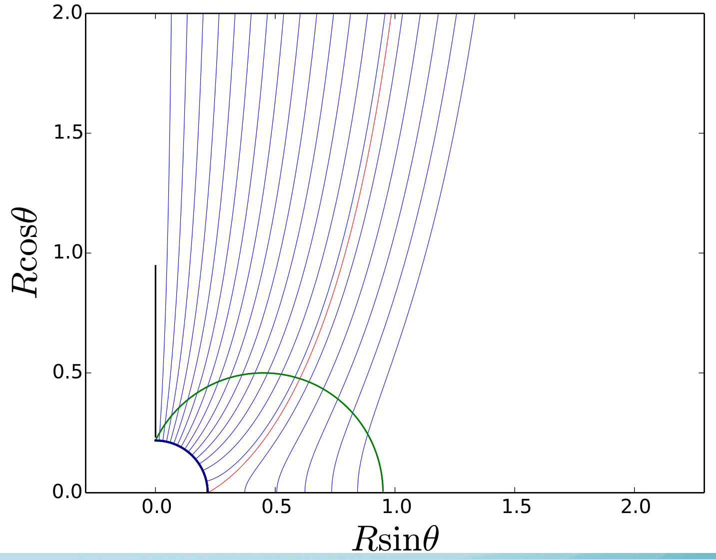
III. In-Out flow structure



Conformal representation





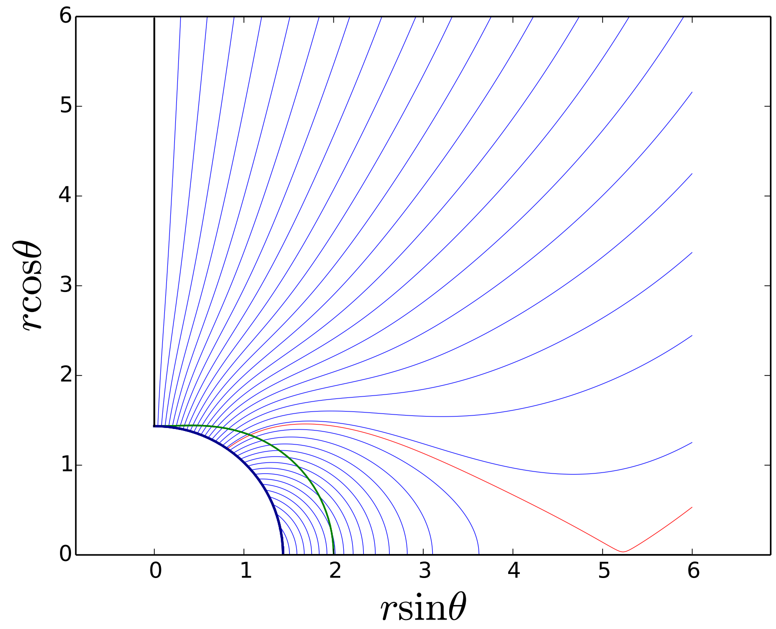


Chantry et al. 2020

B perpendicular to Horizon

Cao & Spruit 2002
Lyutikov 2009
Magneto-centrifugal driving easier in GR

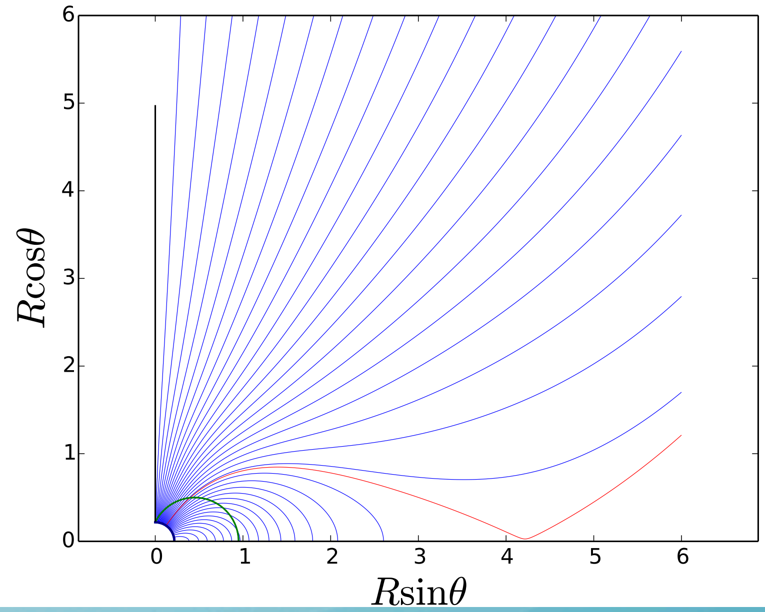
Conformal representation



Chantry et al. 2020

B perpendicular to Horizon

Cao & Spruit 2002
Lyutikov 2009
Magneto-centrifugal driving easier in GR



Simulations of Relativistic 2 component jets, FRI/FRII

Hervet et al, 2017

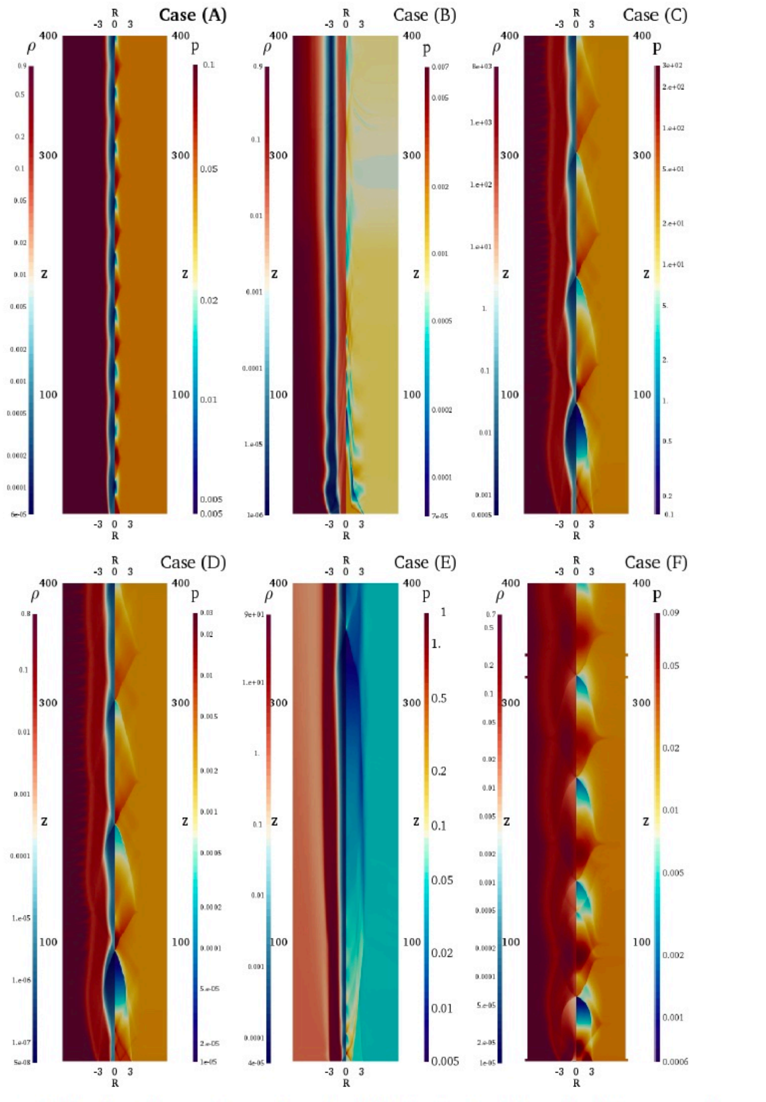
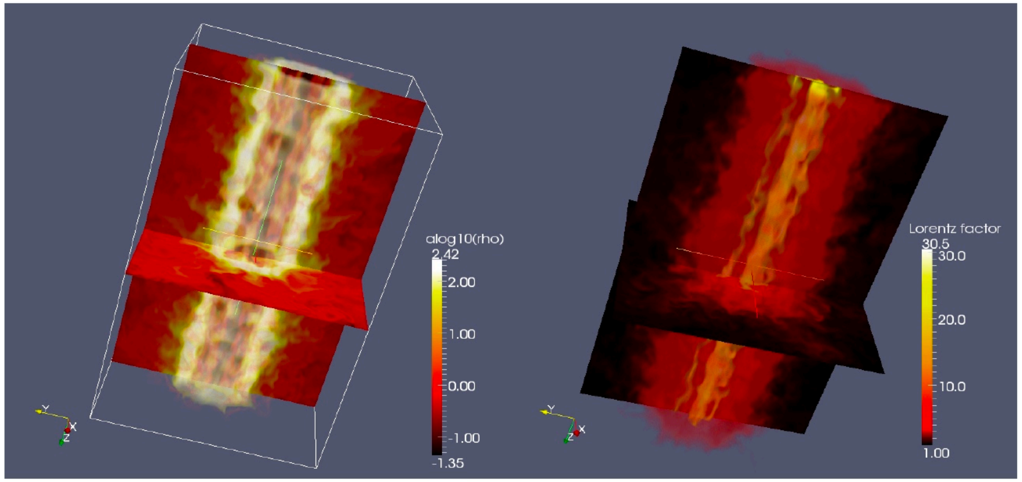


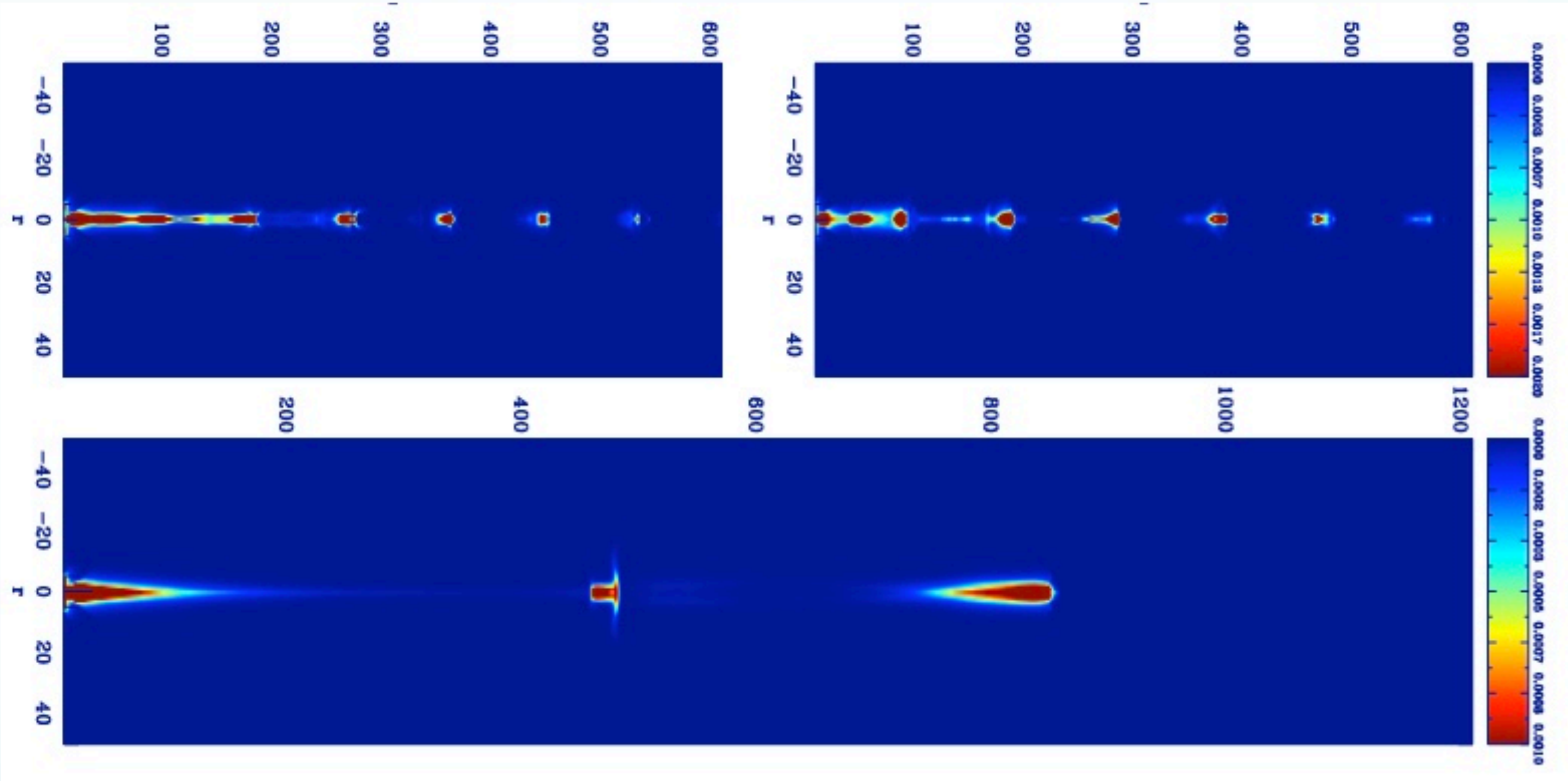
Fig. 4. 2D view of all the simulated cases of the jets along the poloidal direction. In each figure, the density contour is drawn at theleft side and the pressure contour at the right side. We should notice that the jet figures are stretched in the radial direction and squeezed in the longitudinal direction.

Meliani et al, 2009



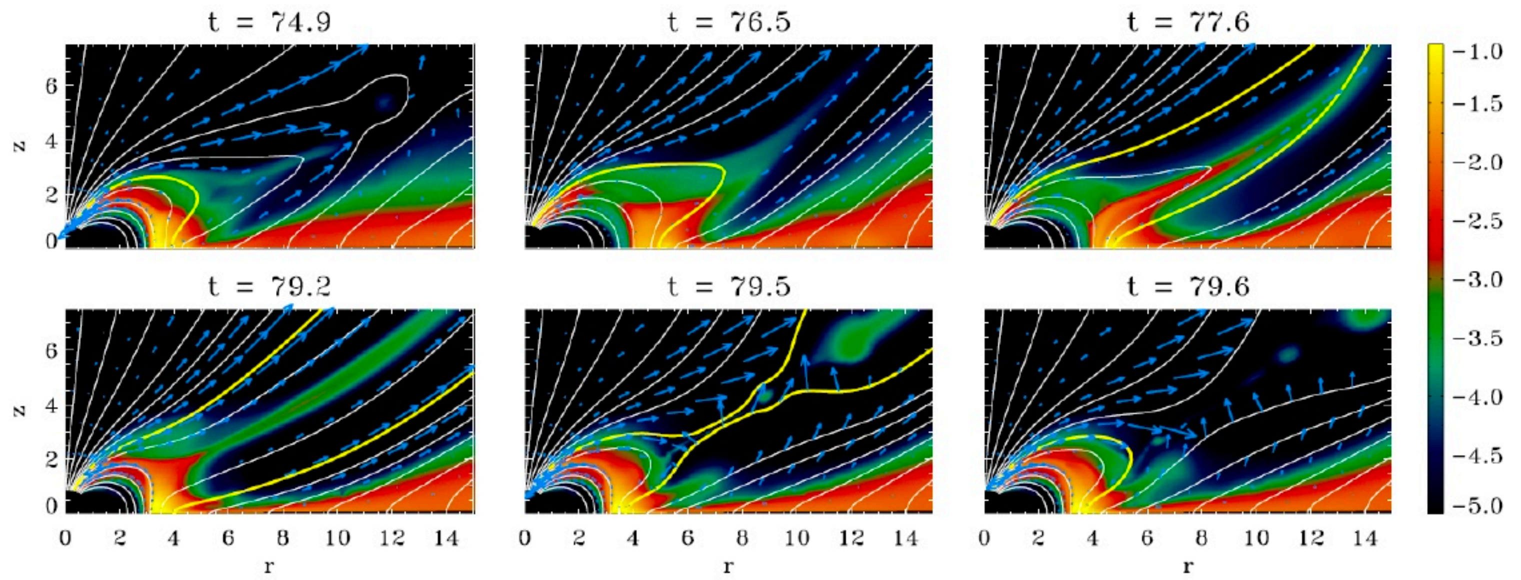
Simulations of YSO jets

Propagation at long distances of adiabatic stellar jet and disk wind, formation of shocks



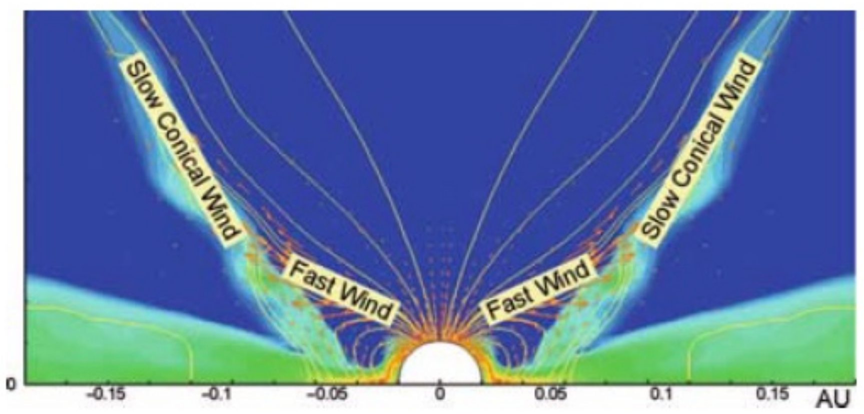
Matsakos et al. 2009 Plot of $\rho^2\sqrt{T} \approx$ emissivity unit=1 AU
top: 2 models for HH30 spacing 10 AU, mass flux fluctuations 1 yr
bottom: model for HH34 spacing 100 AU, mass flux fluctuations 10 yr

Varying The Dead Zone



Zanni & Ferreira 2013

Romanova et al. 2009



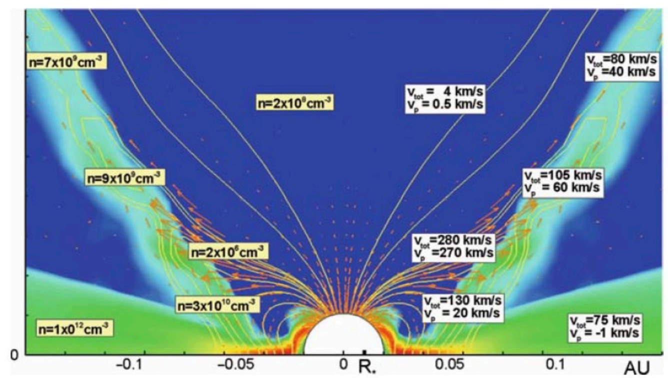
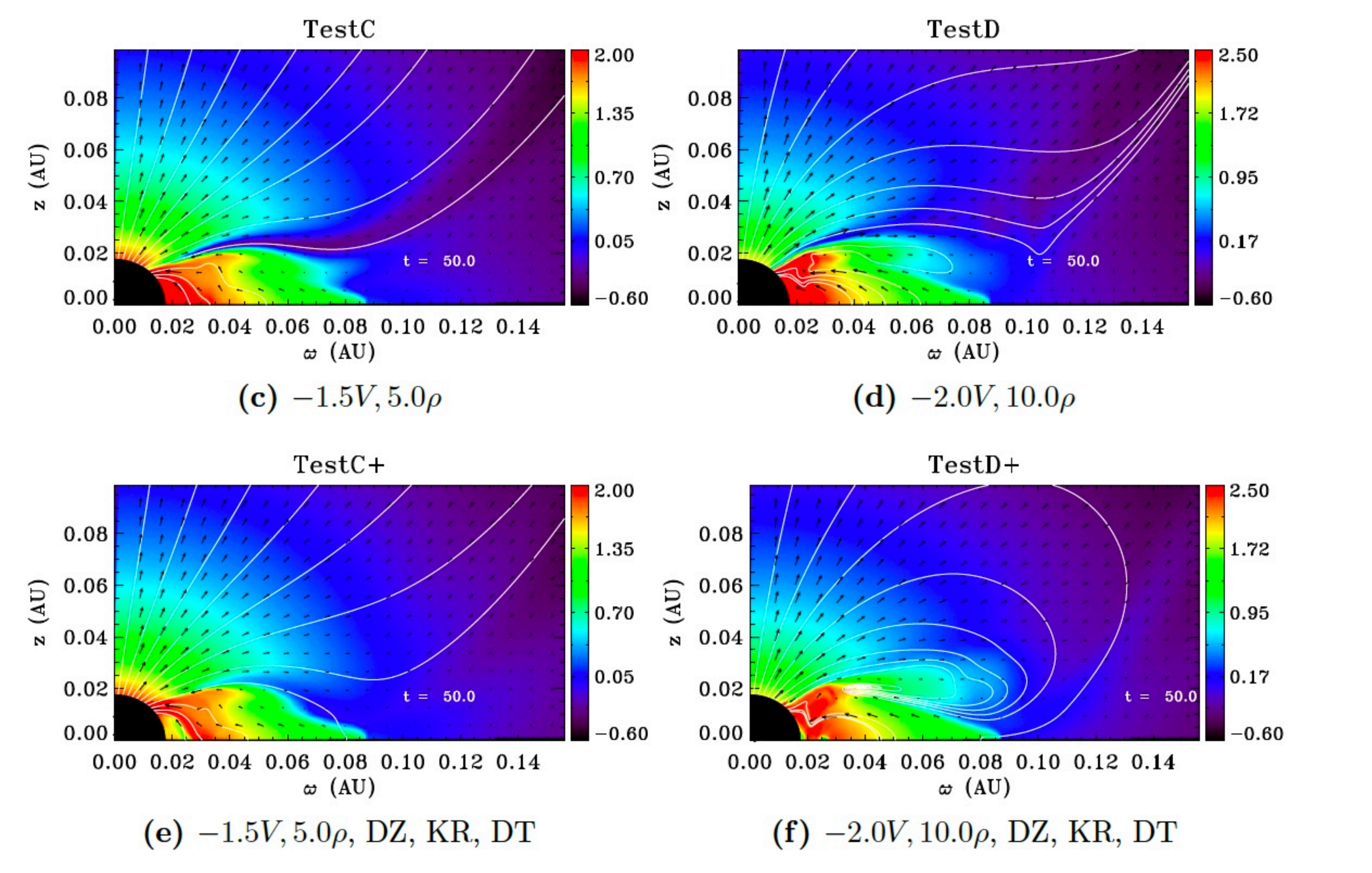
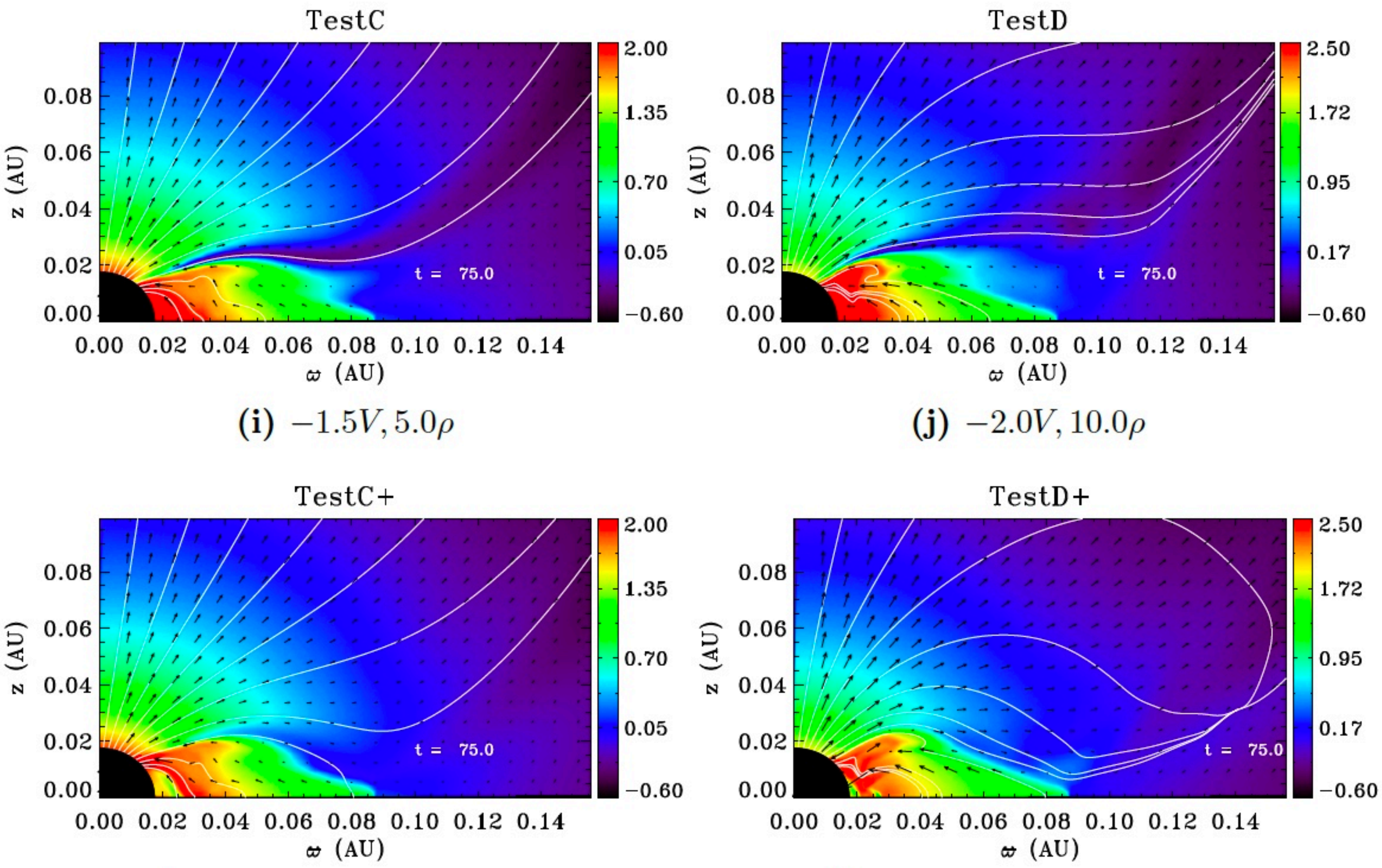


Fig. 2 Typical flow in conical winds (at t = 380 days). The background shows matter flux, lines are selected field lines, arrows are proportional to velocity. The numbers show poloidal v_p and total v_{tot} velocities and number density at sample places of the simulation region. *A color version of this plot can be found in the electronic version of this book and in Appendix A (Fig. A.13)*

With a Keplerian disk time 50



With a Keplerian disk time 75



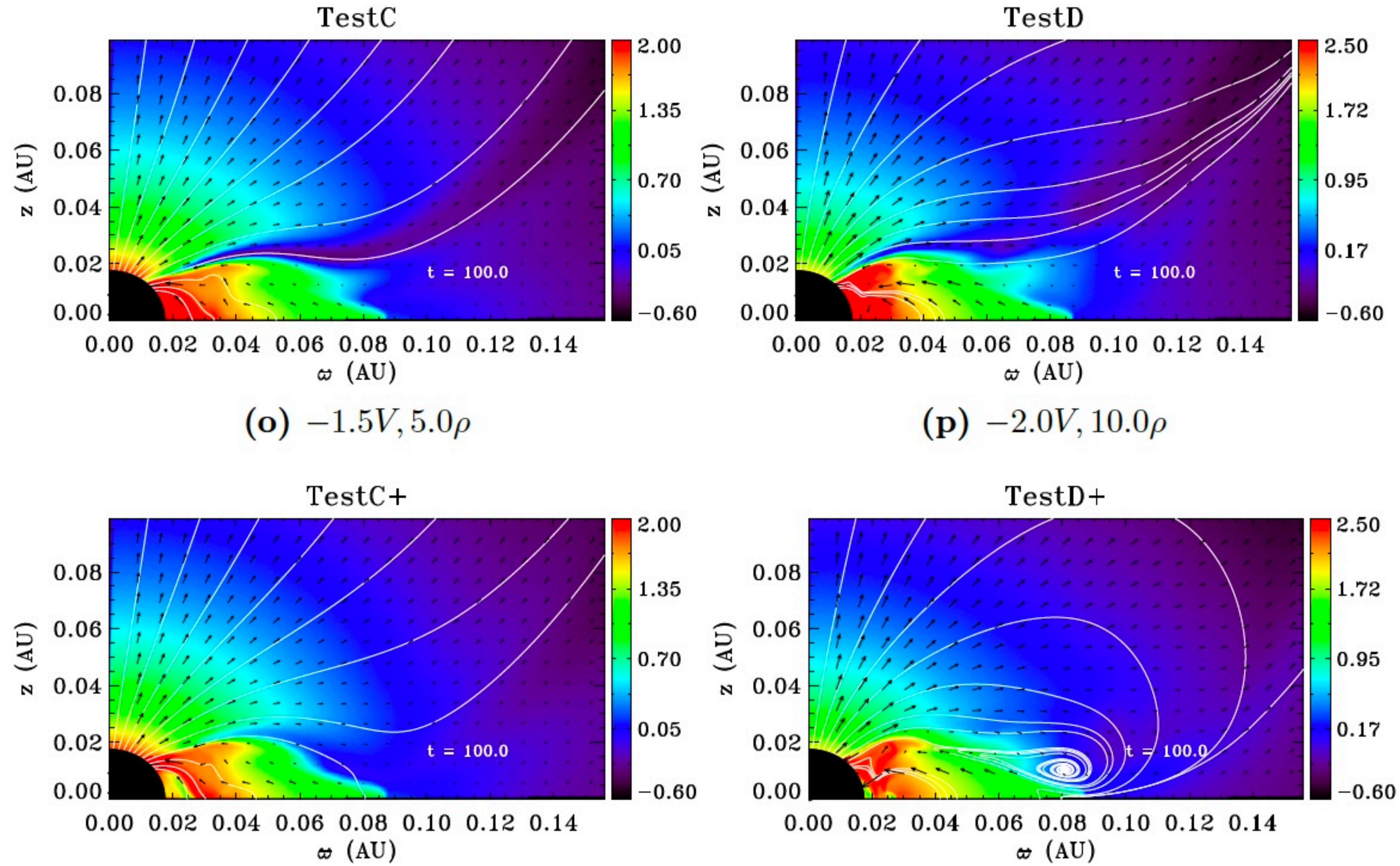
(i) $-1.5V, 5.0\rho$

(j) $-2.0V, 10.0\rho$

(k) $-1.5V, 5.0\rho$, DZ, KR, DT

(l) $-2.0V, 10.0\rho$, DZ, KR, DT

With a Keplerian disk time 100 density



(o) $-1.5V, 5.0\rho$

(p) $-2.0V, 10.0\rho$

(q) $-1.5V, 5.0\rho$, DZ, KR, DT

(r) $-2.0V, 10.0\rho$, DZ, KR, DT

Conclusions

- The model gives a large set off parameters to study Outflow and Inflow structures.
- The outflow extracts a significant fraction of the accretion energy and mass.
- The inflow can extract angular momentum and rotation energy from the central black hole.
- GR make magnetocentrifugal launching easier

- It can also extract energy of rotation of the black hole with some open line.
- ➔ Need to connect the Inflow to the Outflow on the stagnation surface with pair production.
- → Model with volumetric injection is ready

Conclusions

- Extension to the disk
- analytically
- numerically (simulations PLUTO, AMRVAC)

- Multicomponent jet simulations but by implementing the heating/cooling but not the dynamics

- ANR project on simulations
- ETN project on YSO (with relativistic simulations)
- ERC advanced in May, simulations