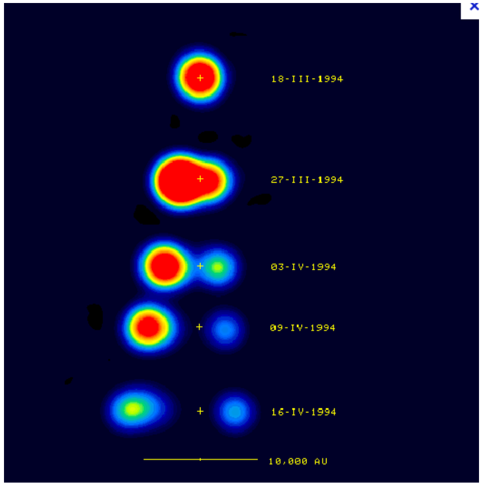
Modeling of accretion and ejection flows in High Energy Astrophysics

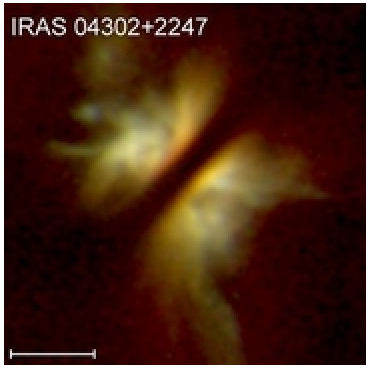
René W. Goosmann

Annual meeting of the PNHE
Paris, March 30th 2016

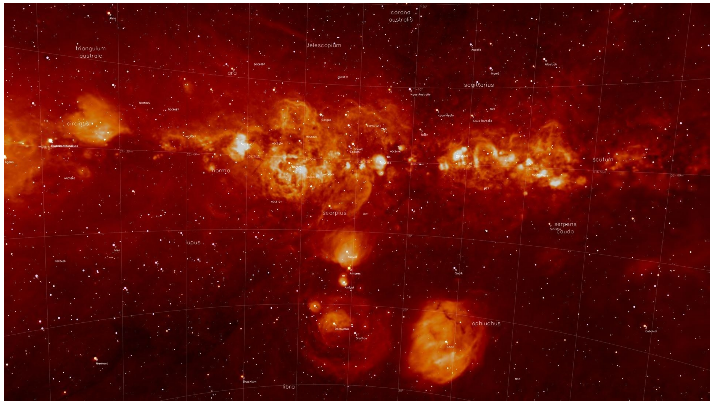
Active Galactic Nuclei



Microquasars

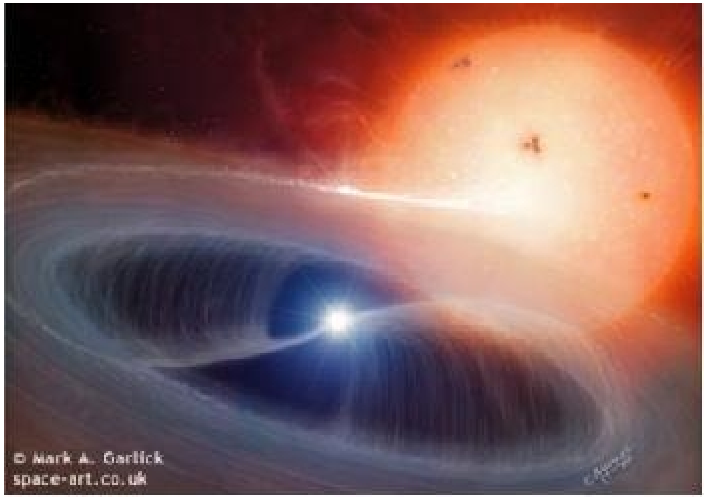


Young Stellar Objects



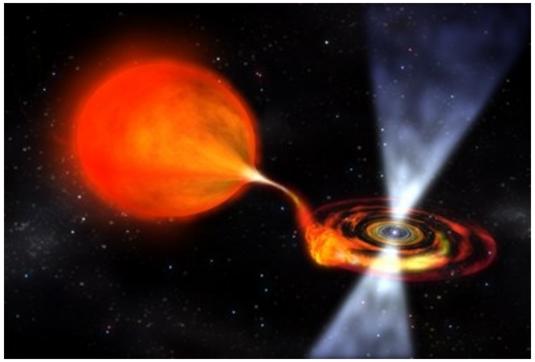
Galactic Centre

Cataclysmic Variable

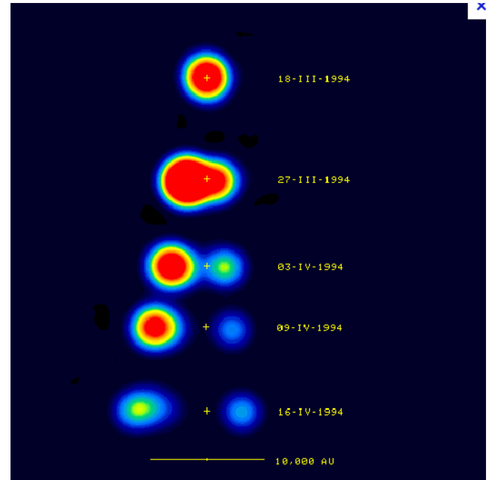


Gamma Ray Burst

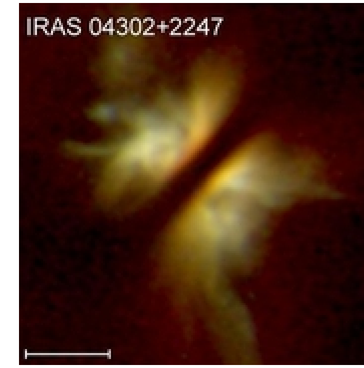
Accreting Millisecond pulsar



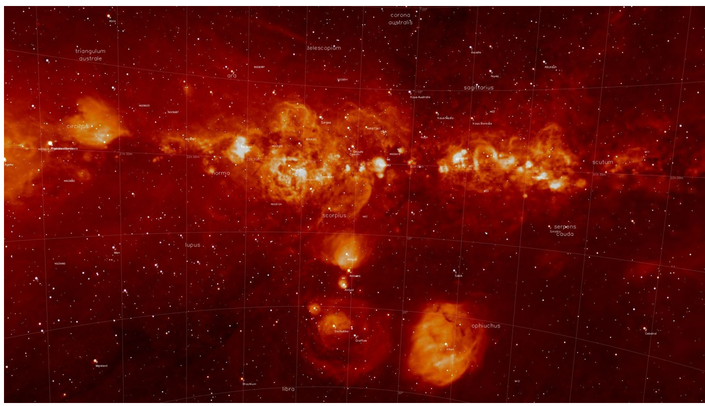
Active Galactic Nuclei



Microquasars



Young Stellar Objects



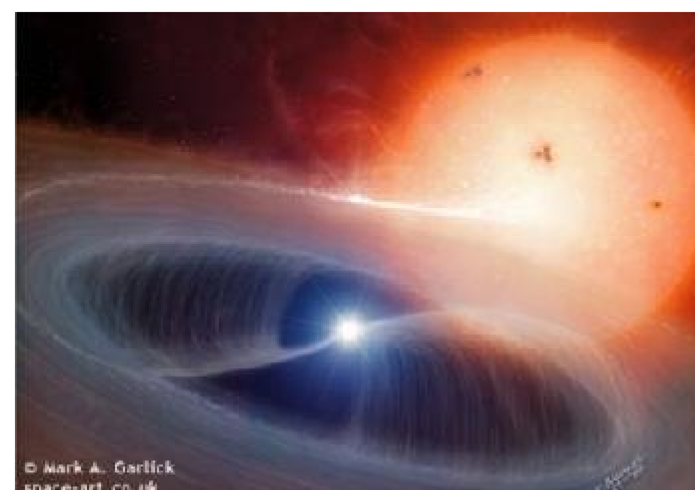
Galactic Centre

PNHE

Programme national hautes énergies

cnrs cnes cea

Cataclysmic Variable



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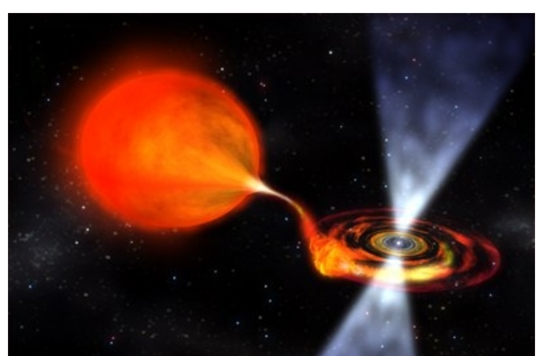


Theoretical grounds of accretion physics I.

The thin disk paradigm

Shakura & Sunyaev (1973), Novikov & Thorne (1973)

– low Eddington ratio

– (nearly) Keplerian thin disk

– thermal, multi-color spectrum

– angular momentum transport:

$$t_{\phi\rho} = \alpha \, P.$$

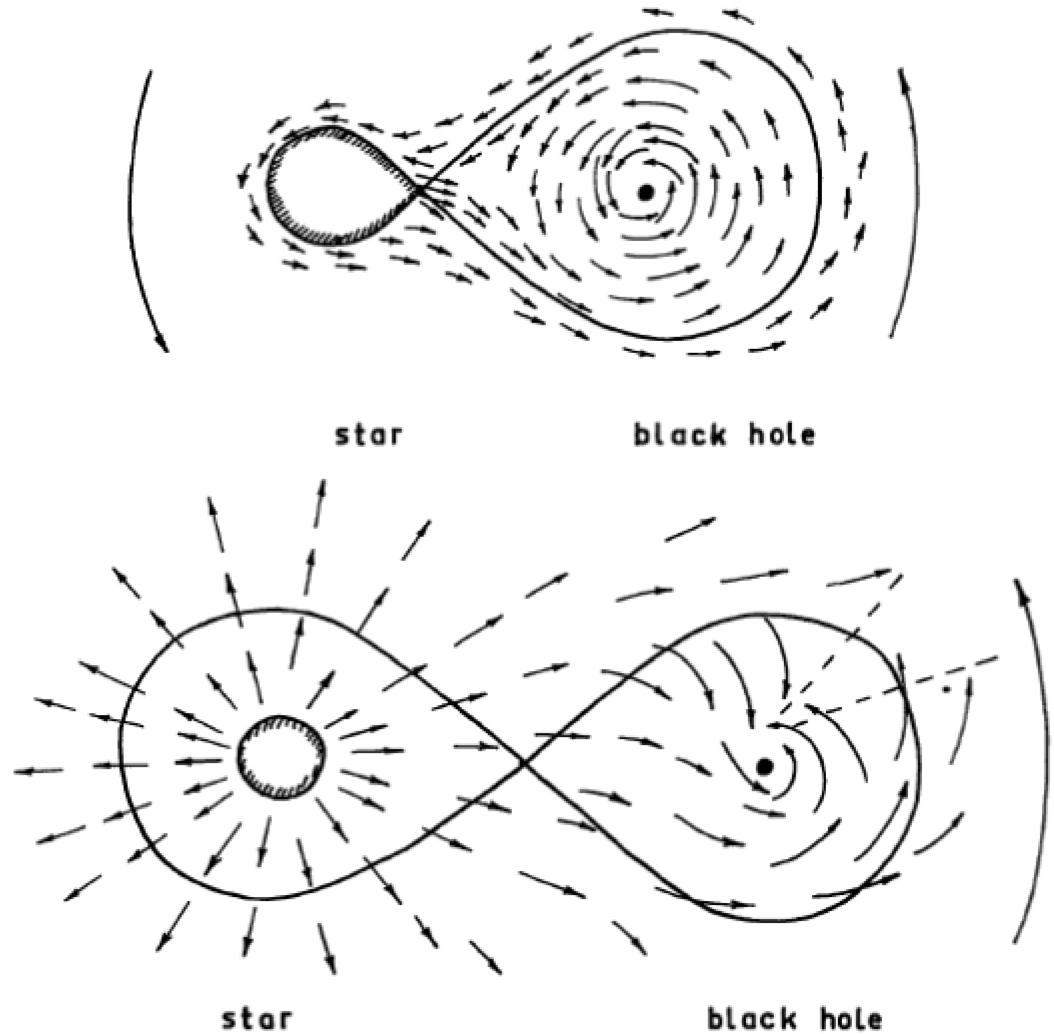


Fig. 1. Two regimes of matter capture by a collapsar: a) a normal companion fills up its Roche lobe, and the outflow goes, in the main, through the inner lagrangian point; b) the companion's size is much less than Roche lobe the outflow is connected with a stellar wind. The matter loses part of its kinetic energy in the shock wave and thereafter, gravitational capture of accreting matter becomes possible

Theoretical grounds of accretion physics II.

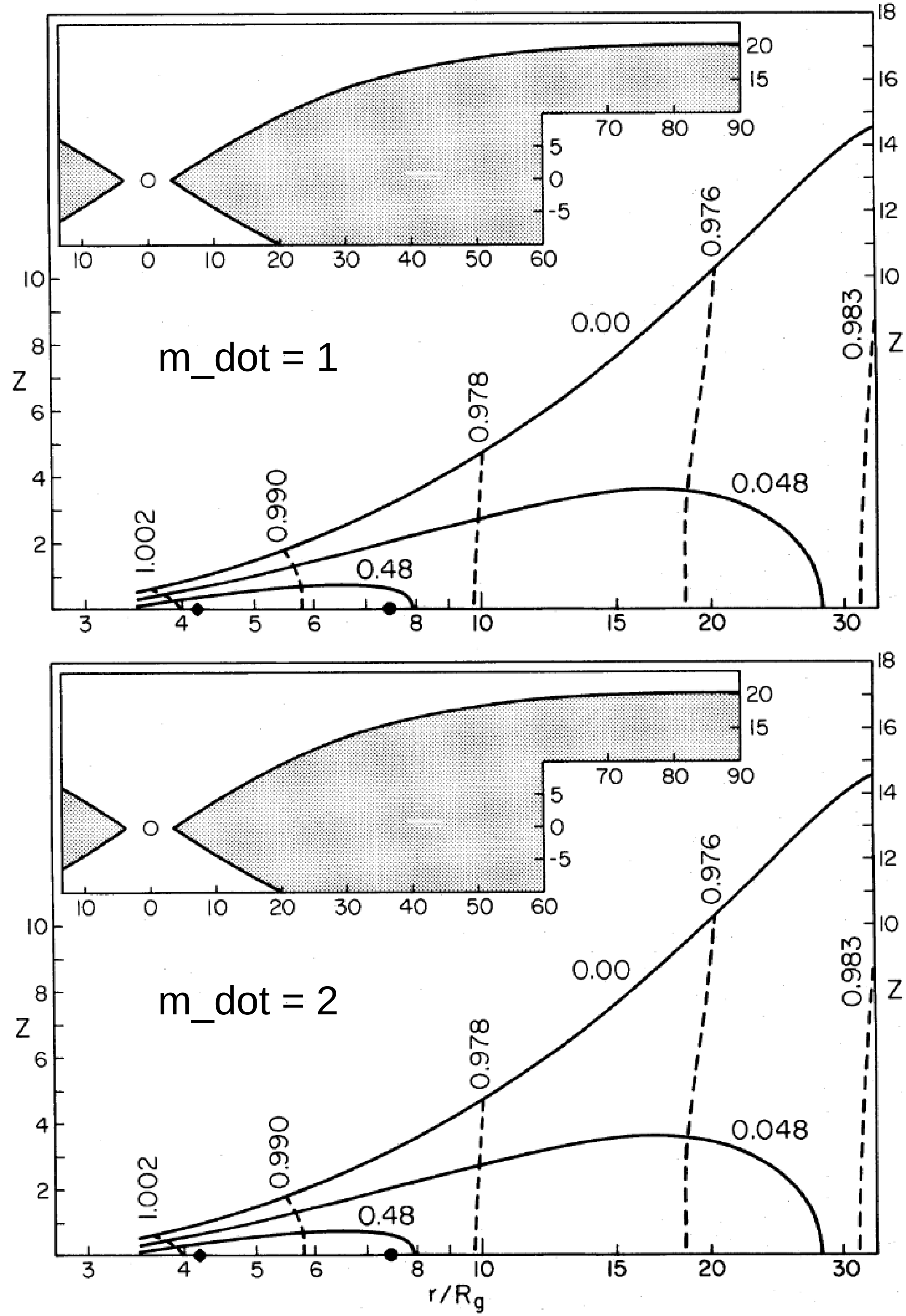
The Polish doughnut

Paczynski, Abramowicz (1982)

– high(er) Eddington ratio

– non-Keplerian rotation and no angular momentum transport

– due to General Relativity effects, the disk may lie partially inside the ISCO



The very beginning of numerical accretion modeling

NUMERICAL STUDY OF FLUID FLOW IN A KERR SPACE*

JAMES R. WILSON
Lawrence Radiation Laboratory, University of California, Livermore
Received 1971 July 12; revised 1971 November 12

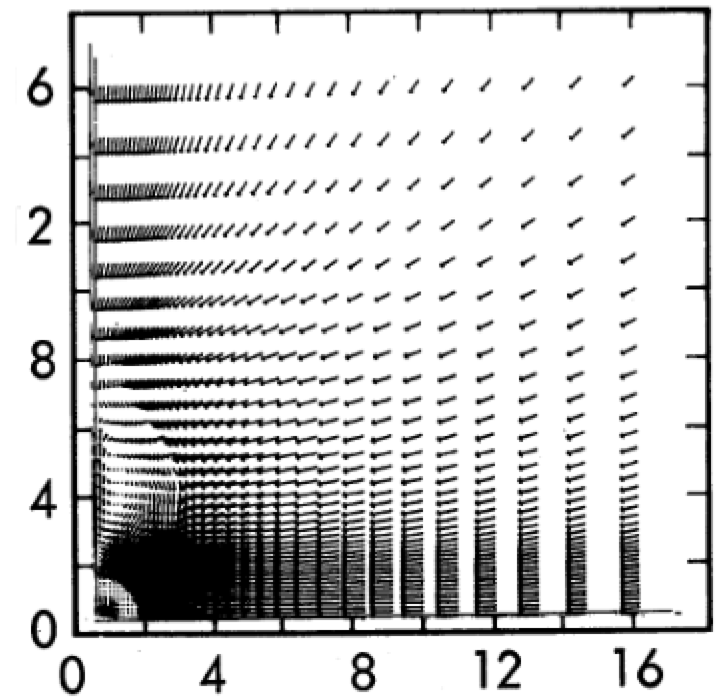
ABSTRACT

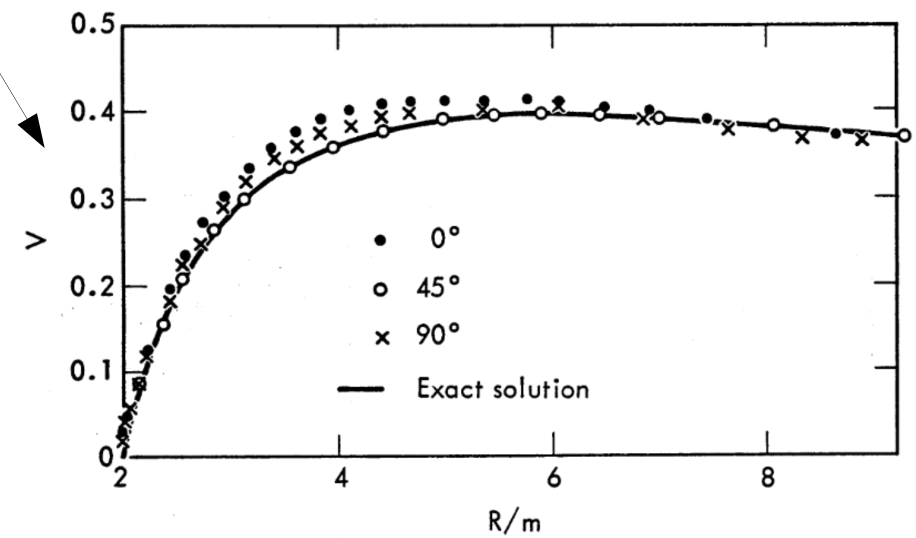
The equation of motion of a perfect gas is solved on a computer for several cases of matter falling into a Kerr black hole. In most cases, the gas falls into the hole with no appreciable heating. When the material falling in is corotating with the metric, shock waves are formed if the specific angular momentum of the hole, Jc/GM^2, is close to 1 and if the specific angular momentum of the infalling material, $U_\phi c/GM$, is greater than 2.

General relativistic fluid dynamics in Kerr metric - numerically solved <u>already 45 years</u> ago!

Equations of motion solved in Eulerian form using a first-order backward spacing technique (and certainly some magic...).

Only inflow – how to get rid of the angular momentum?





Accuracy of velocity field versus exact solution.

(Re-)discovery of the magneto-rotational instability (MRI)

Seminal work by Balbus & Hawley (1991,1998)

MRI first discovered by Velikhov and Chandrasekhar during the 1960s

MRI should play a dominant role for angular momentum transport in all ionized astrophysical disks.

MRI produces friction in agreement with the phenomenological α-prescription by Shakura & Sunyaev (1973), <u>but often does not yet reach the required level of viscosity</u>.

→ <u>Question:</u> what if (photo-)ionization is properly included in the modeling and how would this change the level of MRI?

Parameterizing Magnetized Accretion-Ejection Structures

Axis-symmetric approach for **cold** disk solutions (Ferreira 1997):

$$\nabla \cdot \rho \boldsymbol{u} = 0 \tag{1}$$

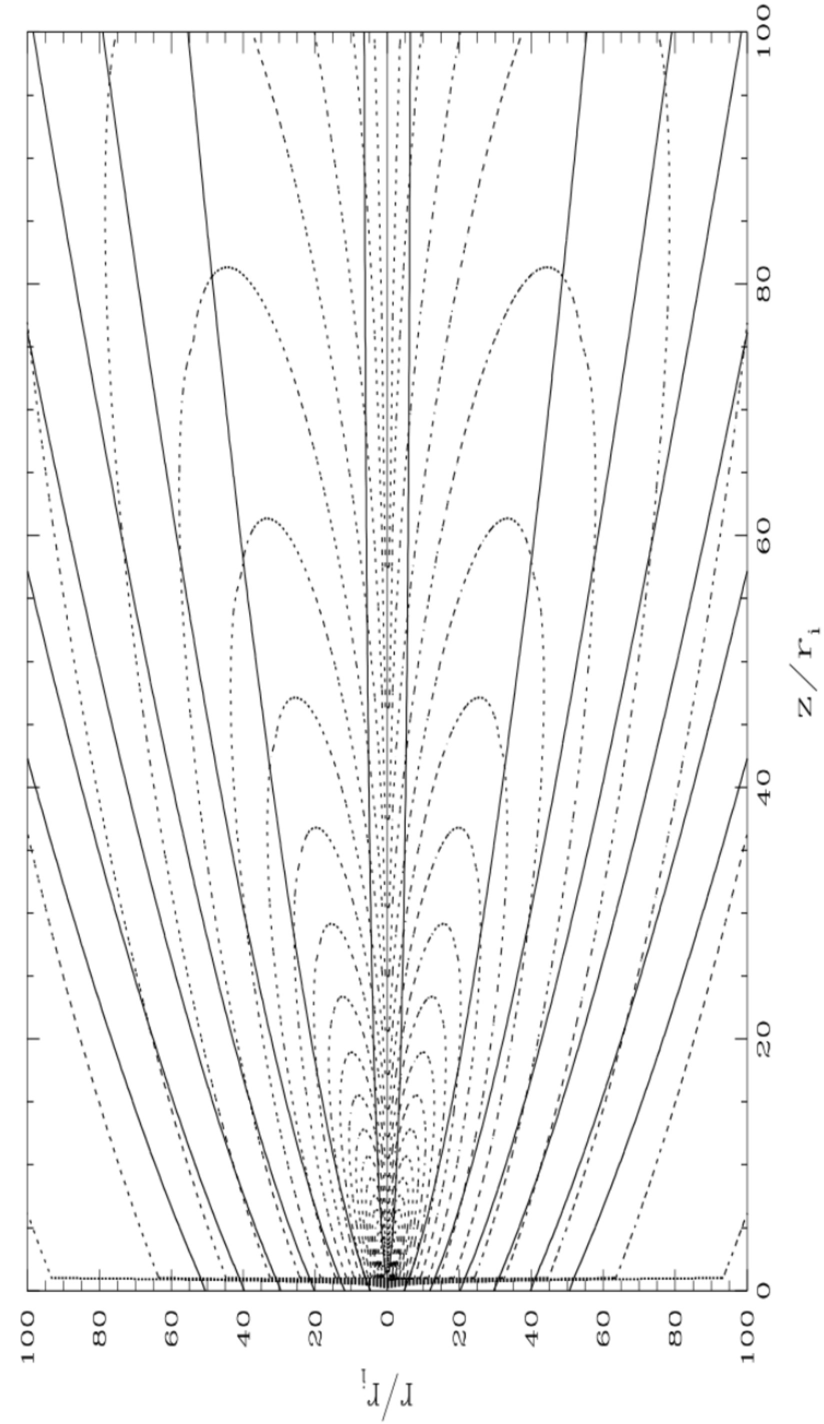
$$\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\rho \nabla \Phi_G \; - \; \nabla P \; + \; \boldsymbol{J} \times \boldsymbol{B} \; + \; \nabla \cdot \boldsymbol{T} \tag{2}$$

$$\boldsymbol{J} = \frac{1}{\mu_o} \nabla \times \boldsymbol{B} \tag{3}$$

$$\eta_m J_\phi = \boldsymbol{u}_p \times \boldsymbol{B}_p \tag{4}$$

$$\nabla \cdot (\frac{\nu_m'}{r^2} \nabla r B_\phi) = \nabla \cdot \frac{1}{r} (B_\phi \boldsymbol{u}_p - \boldsymbol{B}_p \Omega r) \tag{5}$$

where $\Phi_G = -GM/(r^2 + z^2)^{1/2}$ is the gravitational potential of the central object (disc self-gravity is neglected) and $\boldsymbol{T}$ is a viscous stress tensor (Shakura & Sunyaev 1973). Both disc



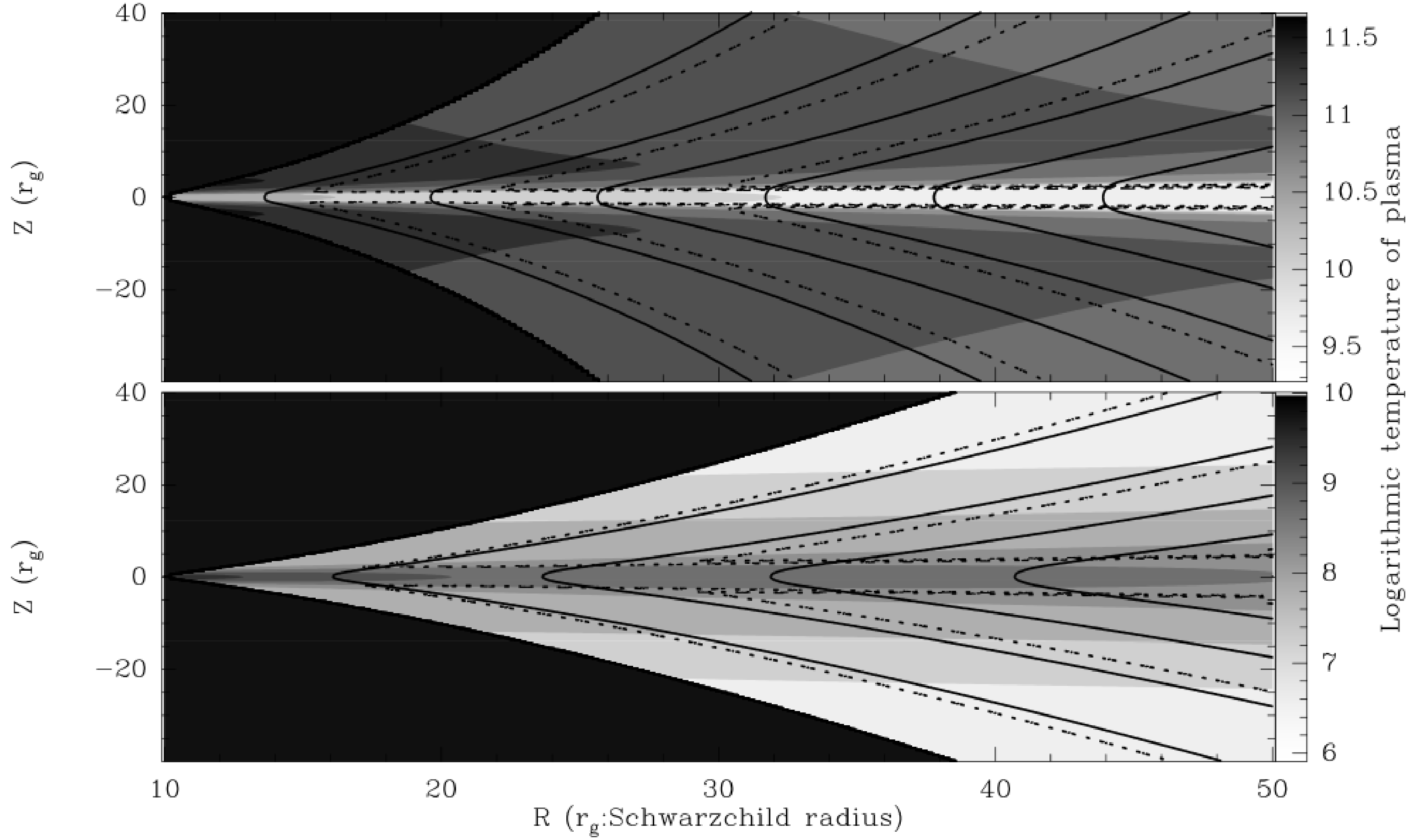
Underlying assumption that a weak, bipolar, large-scale magnetic field runs through the disk.

Parameterizing Magnetized Accretion-Ejection Structures

Passing on to **warm/hot** solutions including a valid equation of state *P = nkT* (Casse & Ferreira 2000, Ferreira 2004) and an irradiating, coronal source

with coronal irradiation

without coronal irradiation

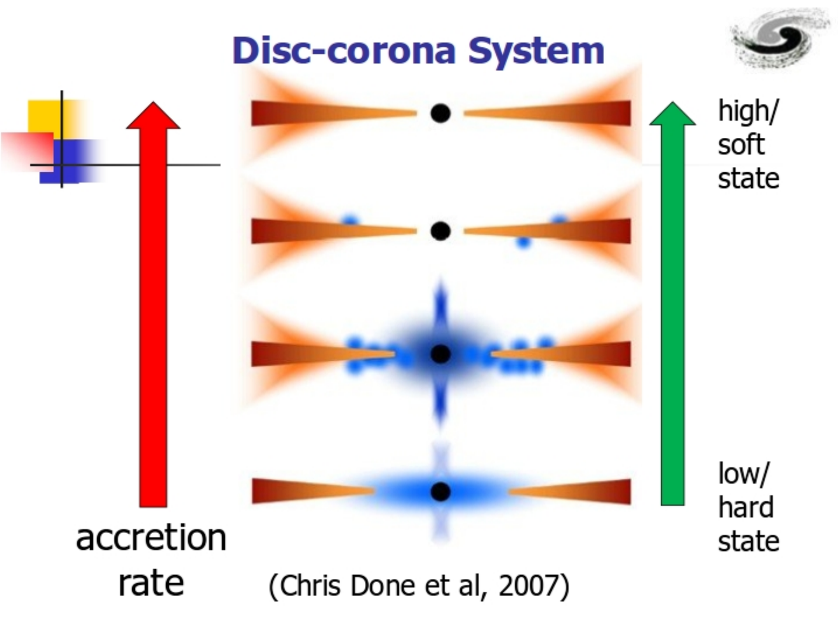


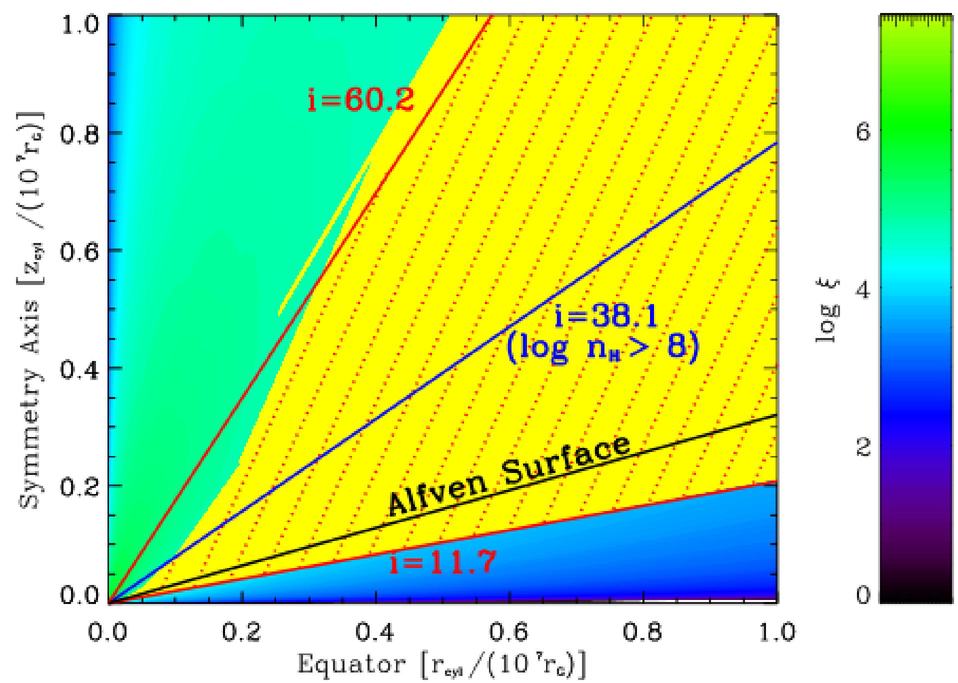
Strongly magnetized accretion flow around a neutron star: coronal irradiation produces significantly higher ejection efficiencies.

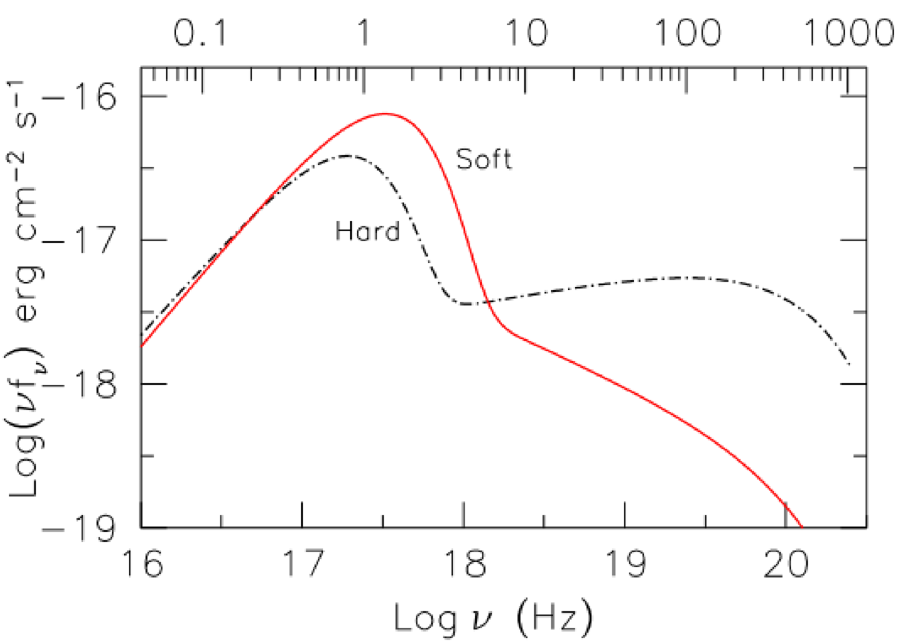
→ <u>Question:</u> can the formation and heating of the corona be included self-consistently?

Comparison to observation of Black Hole X-ray Binaries

Both, observed soft and hard spectral states are being considered







Comparison between model and X-ray observations of winds (Chakrovarty et al. 2016):

– hot solutions (with irradiation) and massive, slow outflows are required

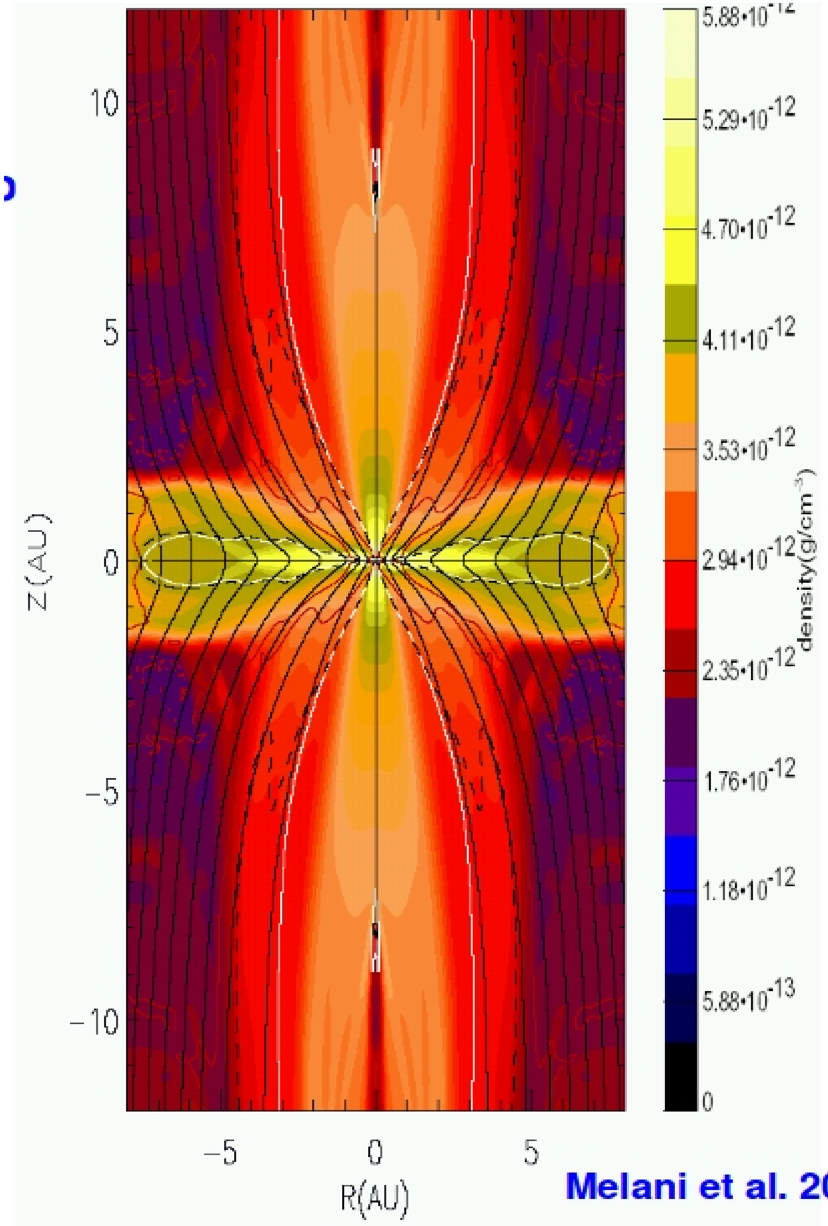
– constraints on the wind density (!)

– hard state irradiation is inefficient to launch winds

Passing from 2D to 3D simulations
(e.g. Casse & Kepens 2002, 2004)

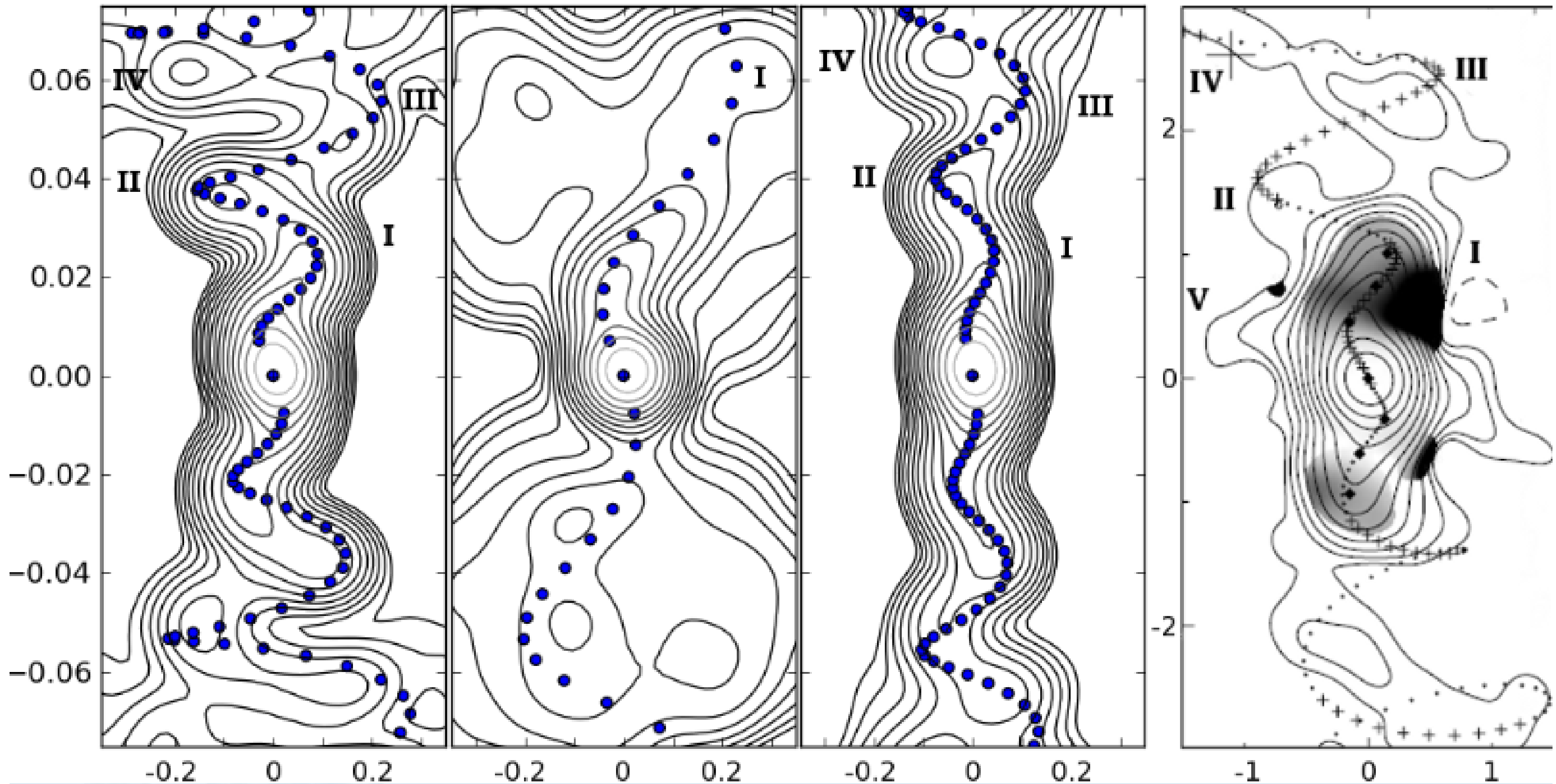
First 3D simulation providing a time-dependent jet ejection from the accretion disk.

A longterm evolution towards a steady state can be "observed". Follow-up work by Meliani et al. 2006 et Zanni et al 2008.



Melani et al. 2006

Reproducing the precessing outflow of SS 433
(Monceau-Baroux et al. 2014)



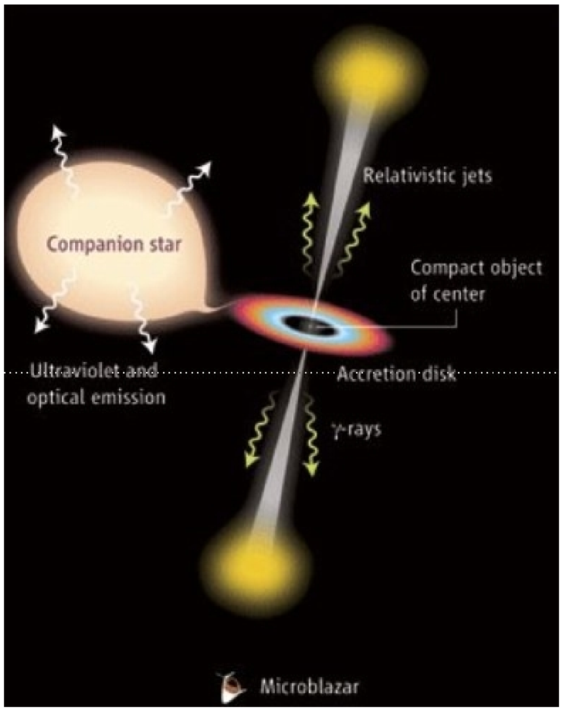
Similar appearance of SS 433 in the VLA data and rel. HD model... some discrepancies remain, but still!

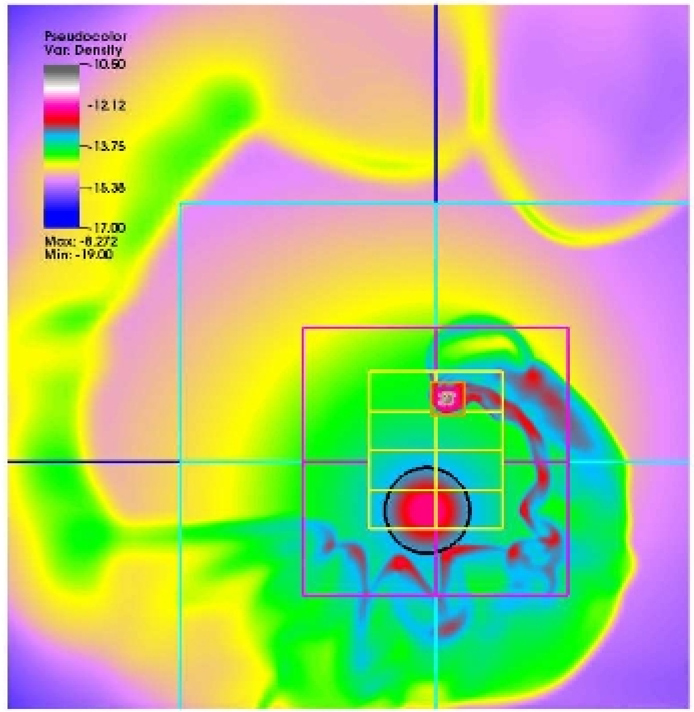
Framework

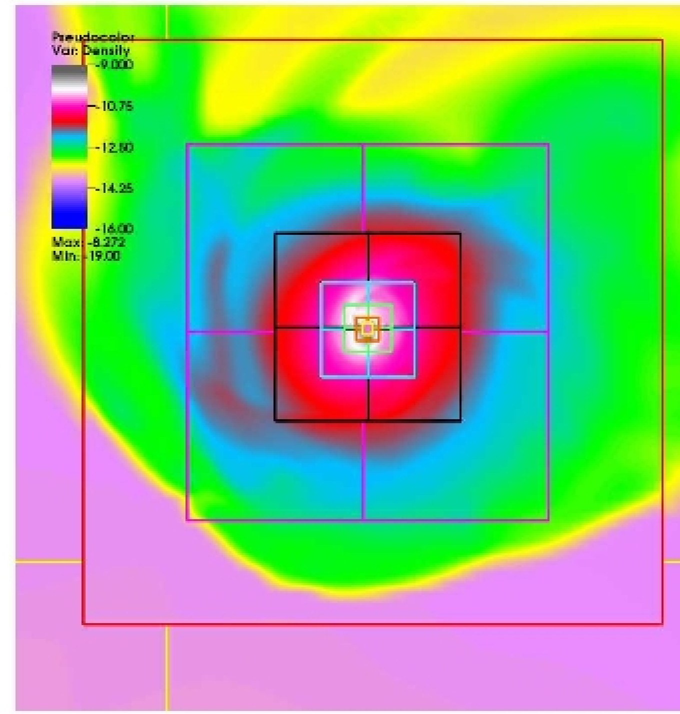
1. Relativistic version of hydrodynamical equations
2. Synge gas equation of state
3. Code used for the simulations: MPI-AMRVAC (https://gitorious.org/amrvac/)
4. Adaptive Mesh Refinement and Message Passing Interface

The challenge of very different spatial scales

Density structure on scale of two-orders of magnitude difference.







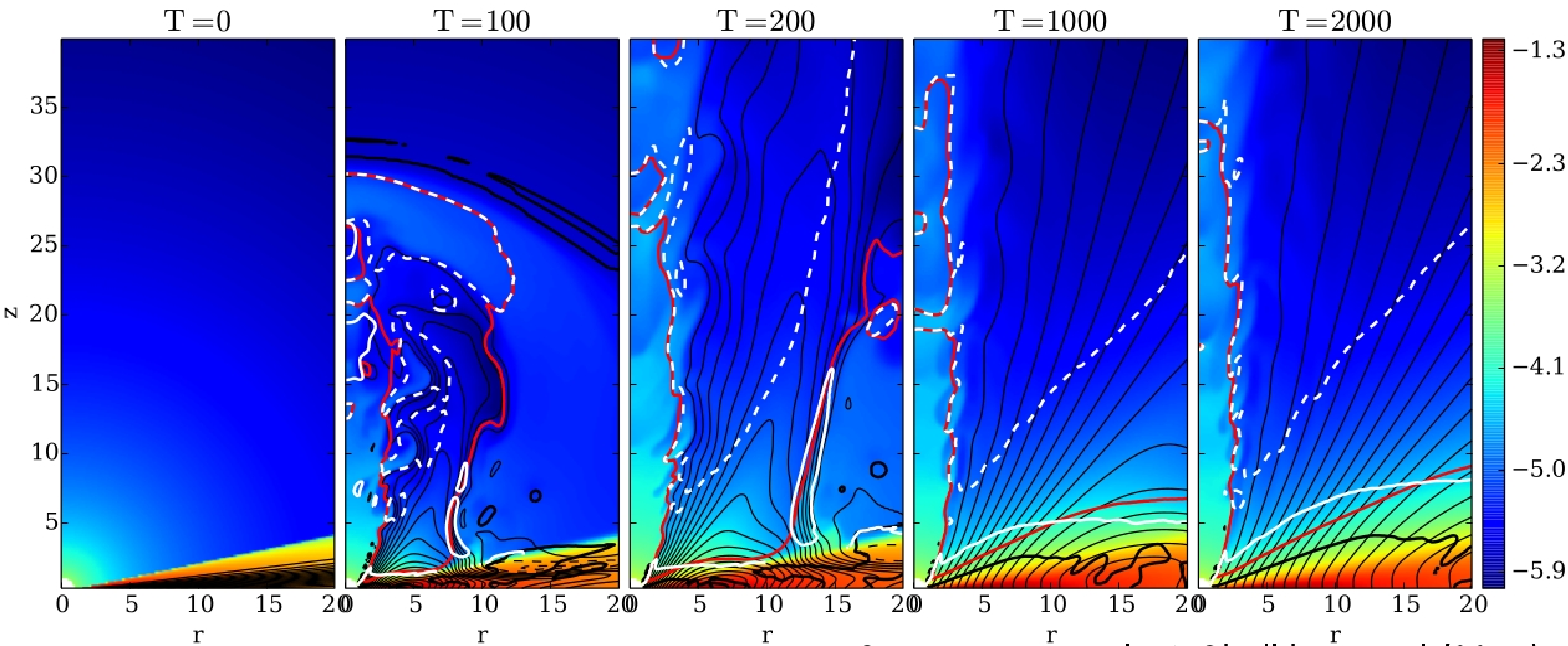
Walder et al. 2014

Modeling accretion (wind or Roche lobe overflow) onto a stellar mass black hole from a companion star: accounting for macro- and micro-physics.

Testing different accretion regimes (m_dot): an accretion disk does not form for all scenarios.

Disk-jet connection with internal dynamo

State-of-the-art modeling by solving the time-dependent resistive MHD equations and <u>including the dynamo effect.</u> The flow produces and maintains its own B-field, no large scale B-field is necessary.



Stepanovs, Fendt, & Sheikhnezami (2014)

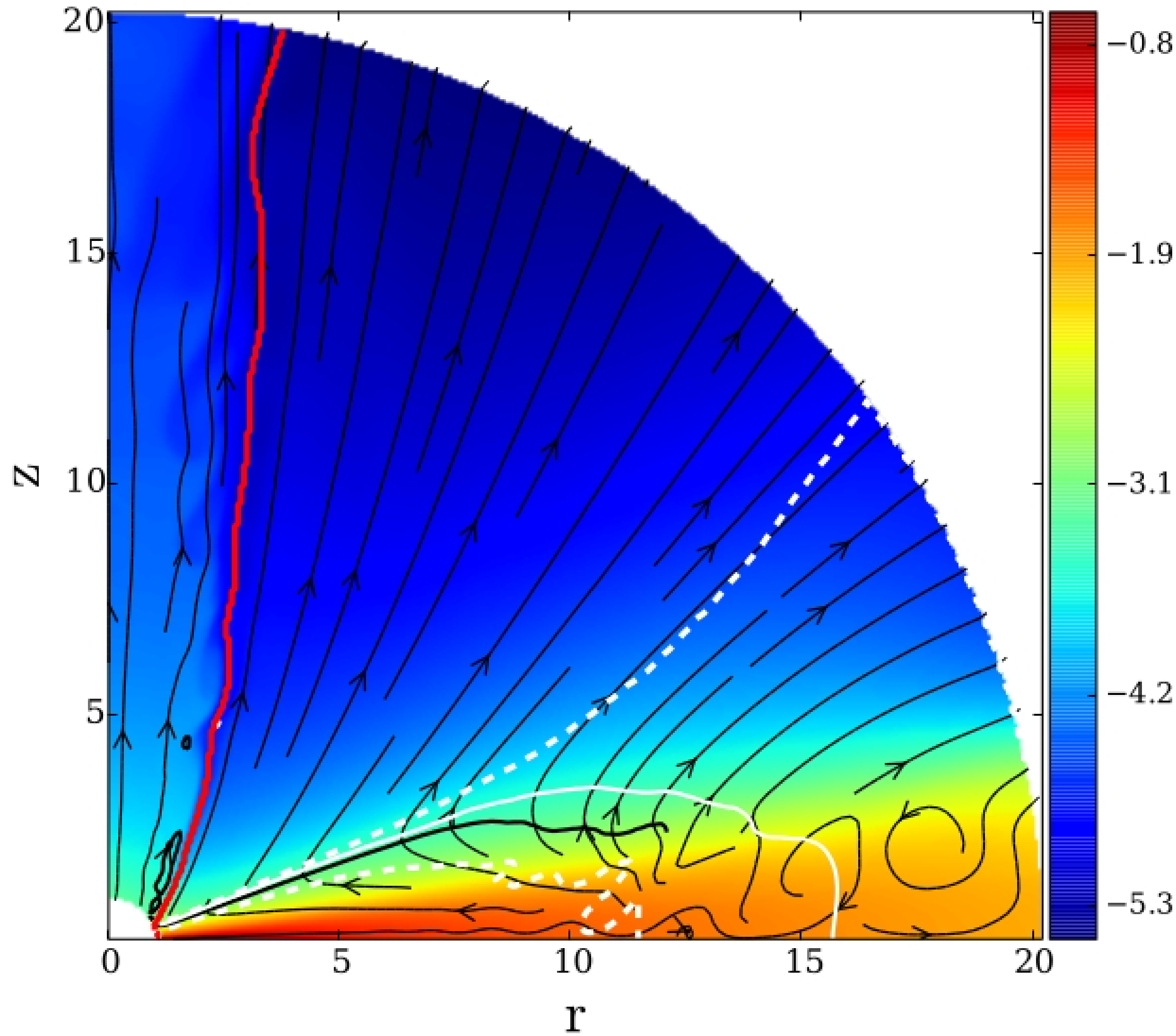
Density (color),
Poloidal mag. field (thin black lines)
Disk surface (thick black line)
Sound and Alfven speed (red/white)

The model reproduces discrete ejection of magnetized blobs!

Disk-jet connection with internal dynamo

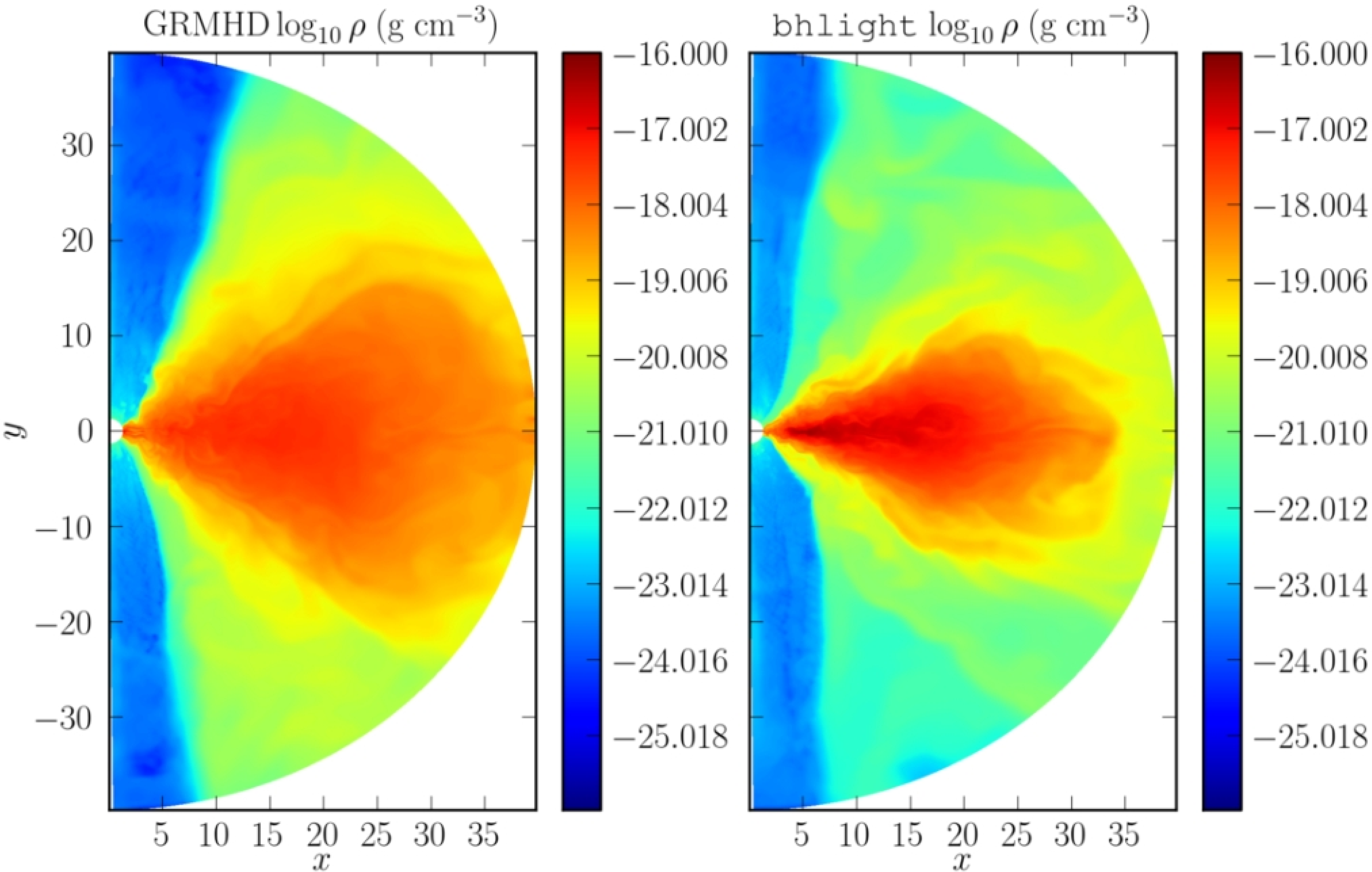
State-of-the-art modeling by solving the time-dependent resistive MHD equations and <u>including the dynamo effect.</u>The flow produces and maintains its own B-field, no large scale B-field is necessary.

The model produces jets and winds launched close to the inner edge of the accretion disk.



Density (color)
Stream lines (black)

Cutting edge with “bhlight” : Monte-Carlo GR-Radiation-MHD
(Ryan, Dolence & Gammie 2015)



Facts and challenges:

Hydrodynamic and magneto-hydrodynamic activities are well developed in our community. Different modeling approaches are being applied (including adaptive mesh techniques and others).

→Question for discussion: can we find non-explored synergy effects between the different French HD/MHD groups?

Our international colleagues start to combine (GR)(M)HD modeling with (Monte-Carlo) radiative transfer simulations to

- take into account eventual effects of radiation pressure and photo-ionization of the medium,
- to provide accurate model predictions for time-dependent spectroscopy and imaging.

→Question for discussion: Is it useful and how can we compete with or even extend these activities?

Facts and challenges:

Other domains at the heart of the PNHE that I did not talk about are explored by MHD modeling (such as pulsar winds or cataclysmic variables, etc...)

→<u>Question for discussion:</u> is it useful to provide an MHD modeling tool robust enough to be used by independent users in a “public” domain (similar to what is being done for, e.g., radiative transfer models)?