Simulating wind-fed microquasars

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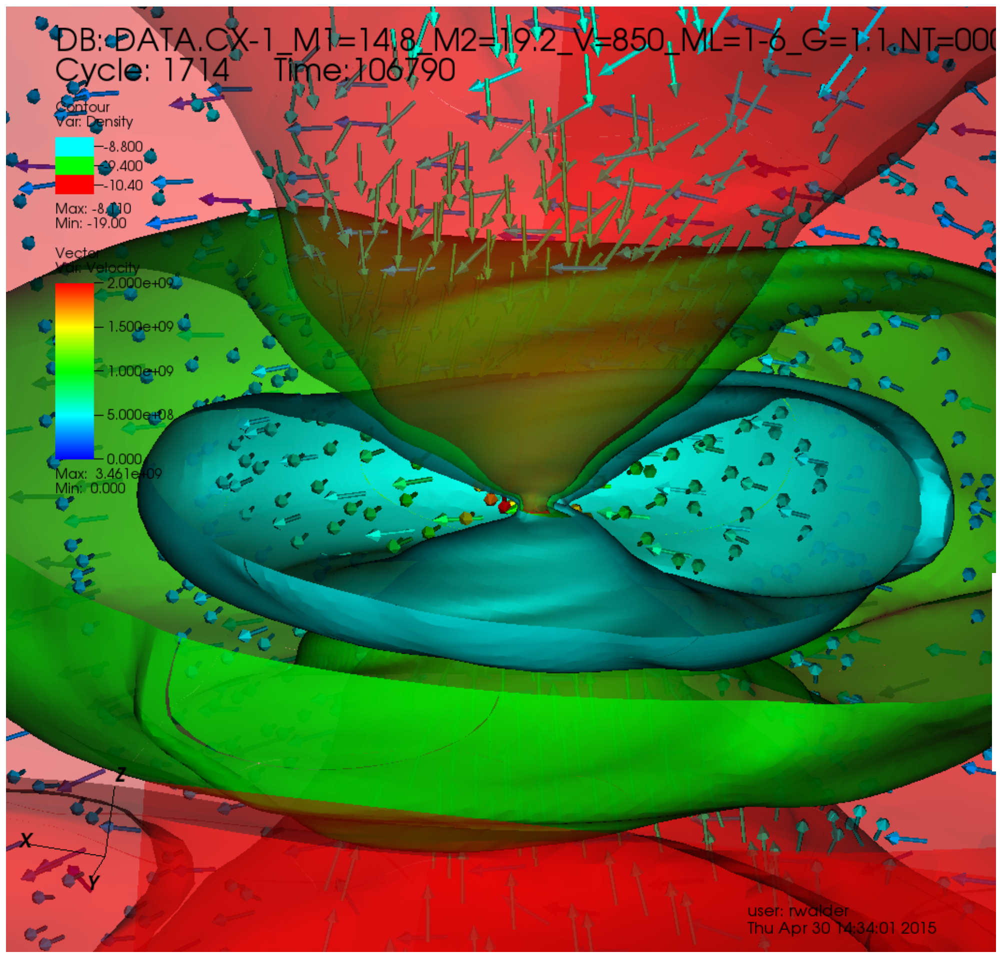
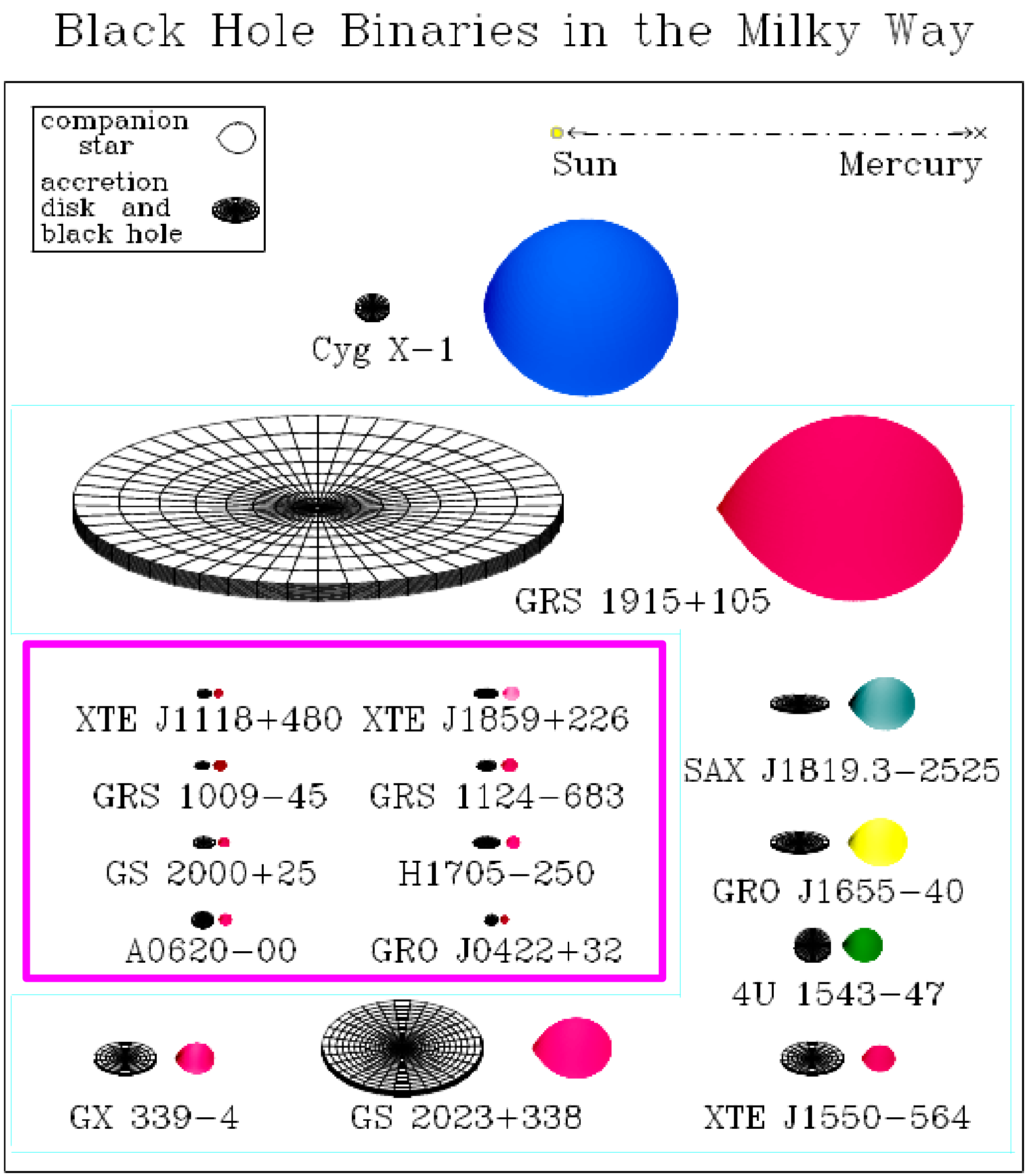
CRAL, ENS-Lyon





Cyg X-3 ?

R.A. Remillard & J.E. McClintock (courtasy J. Orosz)

Annual Review of Astronomy & Astrophysics, 44, 49-92, 2006.

'Classical' LMXRB:

MS low mass star with RLOF

'non-classical' LMXRB:

Evolved low mass star with RLOF
+ low speed wind ?
V ~ 20-100 km/s,
low mass-loss rates
Massloss ~ (10^{-8} – 10^{-10}) $M_\odot$/y

HMXRB:

Always fast wind !
V ~ 1000-3000 km/s
High mass-loss rates
Massloss ~ (10^{-5} – 10^{-8}) $M_\odot$/y

Influence of Roche geometry?

Do what degree fit these paradigm for wind fed systems ?

Wind-accreting high mass systems (e.g. Cyg X-1) do not really fit the classical scheme.

- **No switch-off state (persistent X-ray emission).**
- **Non-thermal emission contributes always significantly.**
- **Soft state of Cyg X–1 not consistent with a thermal interpretation (Zhang etal. 1997).**
- **Soft state spectrum is dominated by a steep PL component ($\Gamma\sim2.5$). (Zhang etal. 1997)**
- **In Cyg X-1 dark jets bow-shocks (Tudose et al. 2006; Russell et al.2007)?**
- **Jets in states with relative large thermal emission only (Fender et al. 2006)?**
- **With the exception of Cyg X–1, QPOs generally appear whenever the SPL contributes more than 20% of the flux at 2–20 keV (Sobczak et al. 2000).**

- **Cyg X–1 is not a useful prototype for the high/soft state (Remillard&McClintock 2006).**

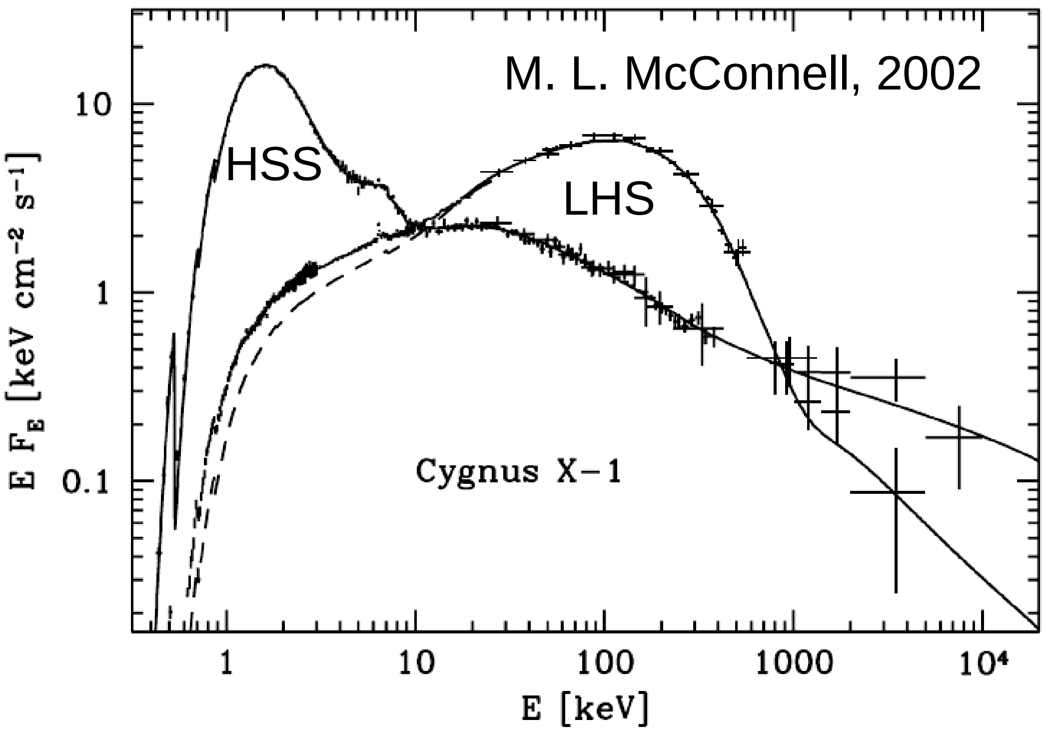
High emission, even in MeV and GeV

→ does this point to particle accelerators,

→ production sites for neutrinos?

Multi-scale hydro-simulation of high-mass systems Cyg X-1

A case study for more to come!



$R_{Roche,\ equiv.} = 0.415/a = 1.1 \quad R_{opt}$

Parameter-study :

- **different wind-speeds,**
- **Polytropic EOS, g=1.01 … 5/3**

Question to answer :

- **Circum-binary structure**
- **BHL-accretion rates correct**
- **Does accretion disk form**
- **Character of the disk**
- **(Non-) collisional plasma**
- **Optical depths**
- **Identify weak ingredient of model**

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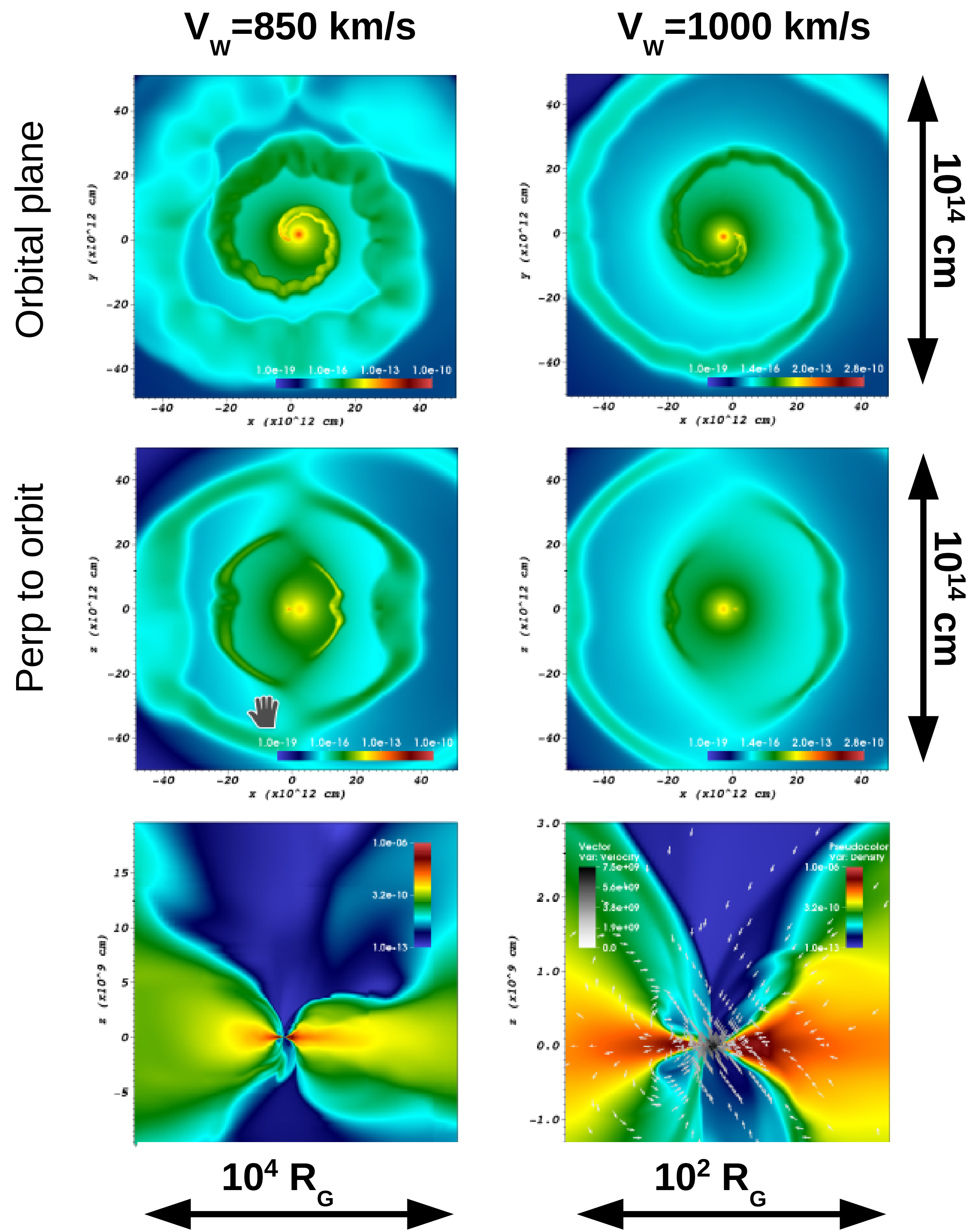
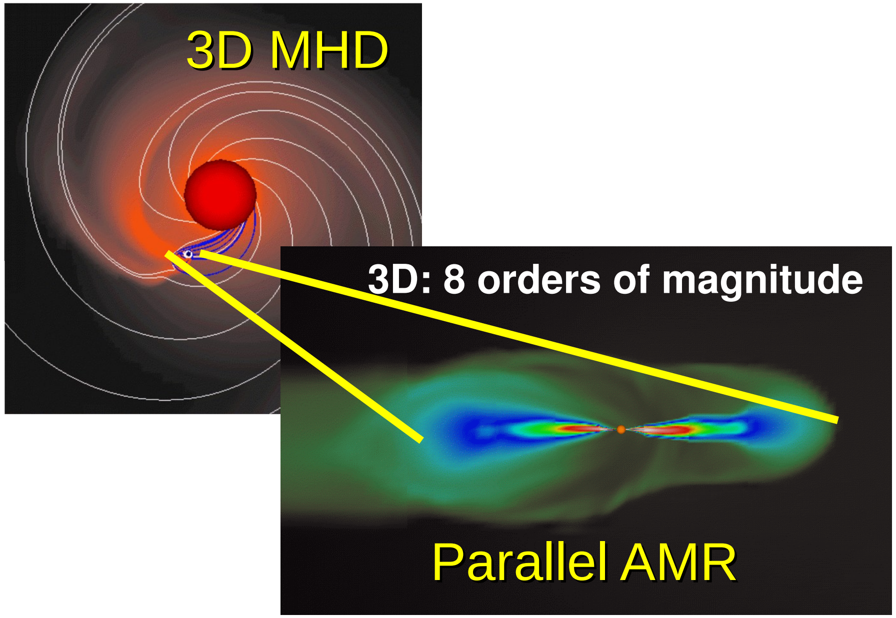
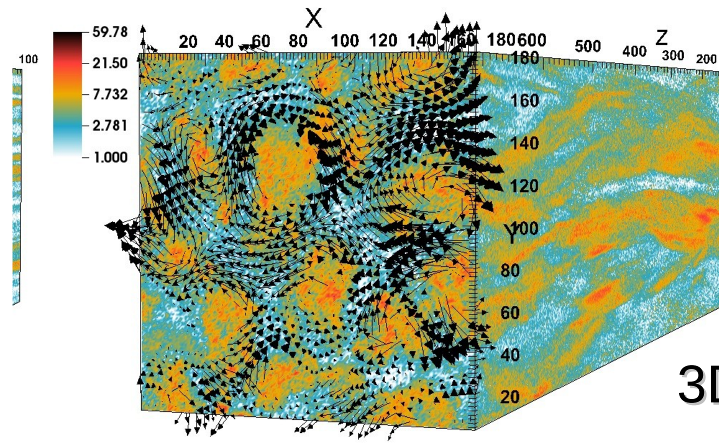


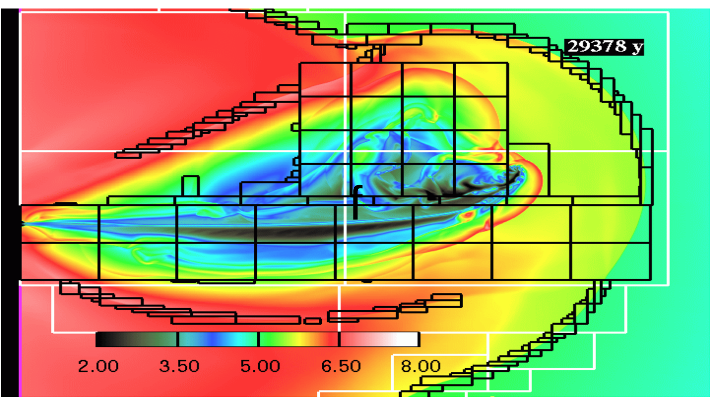
The project A-MAZE

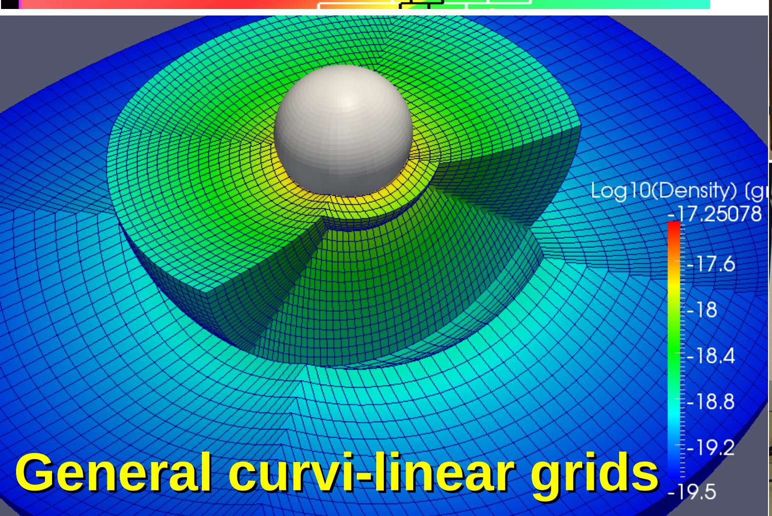


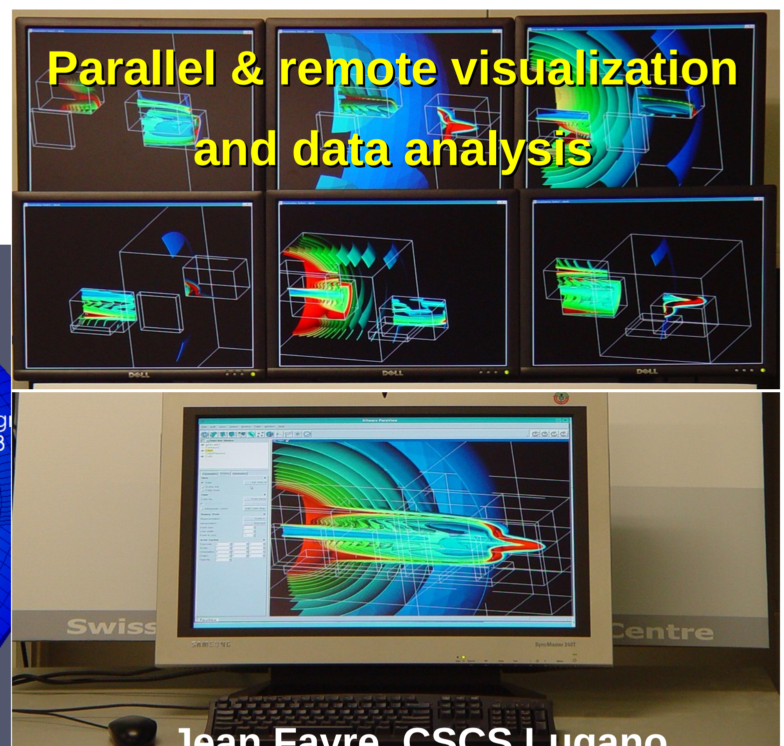
Modular tool-kit based on Fortran 2000+ / C++



3D PIC code

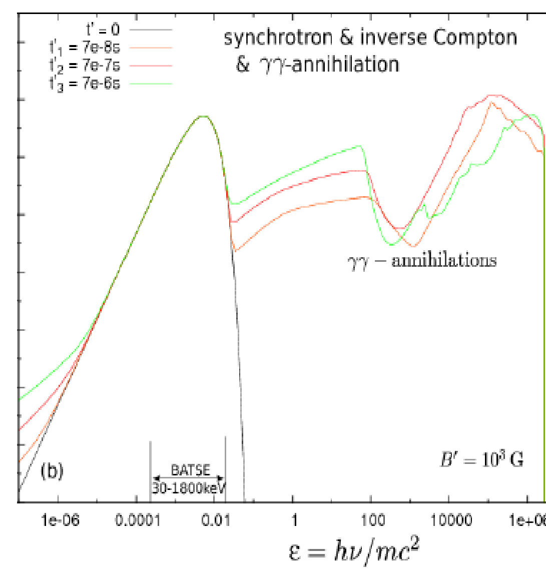






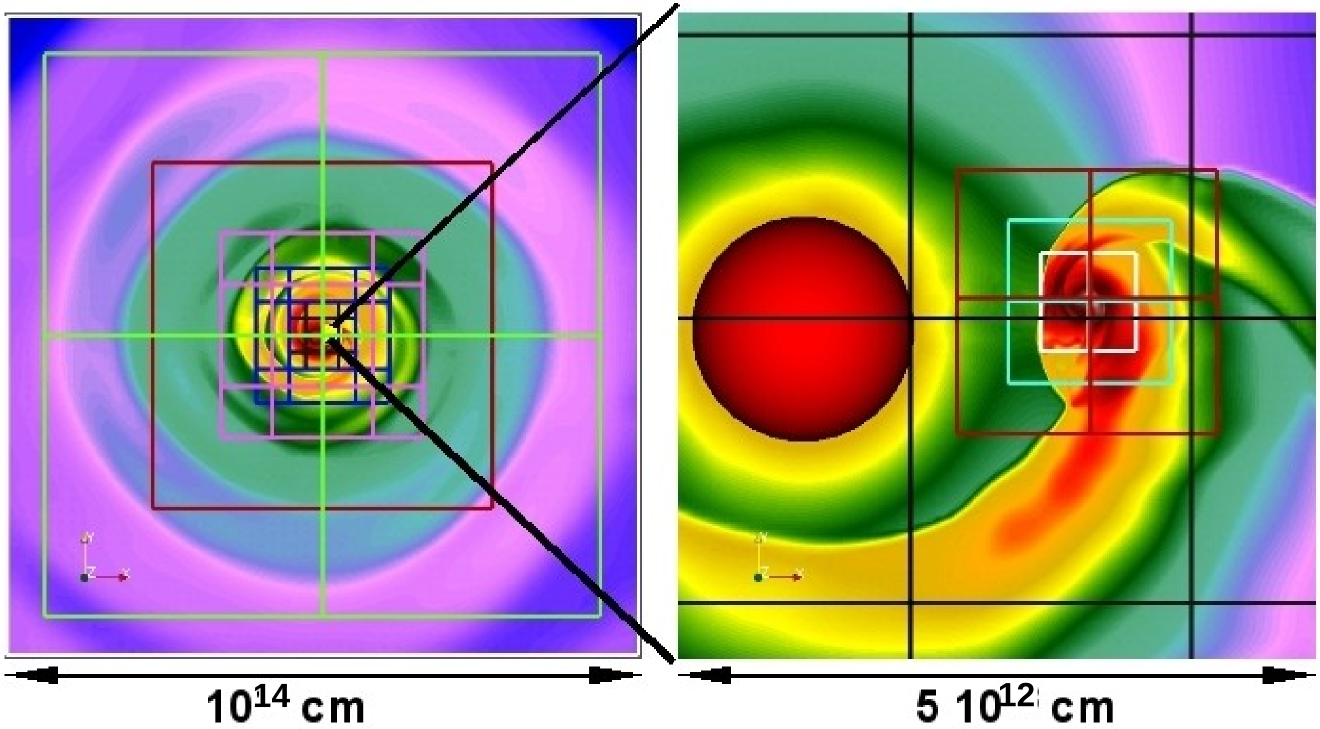
3D adaptive

radiation transfer code



Simulations are carried out in an Eulerian frame of reference

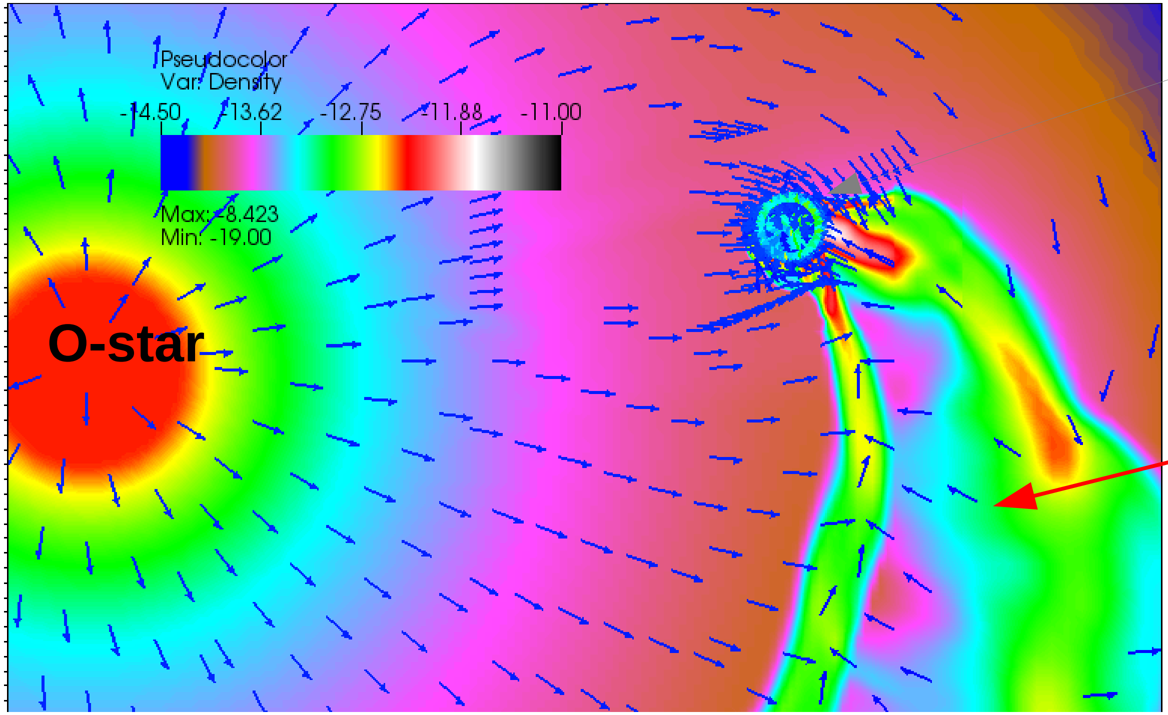
stars move within the computational domain 15-20 levels of refinement



- ➔ **Basic domain discretization: $\Delta x = 10^{12}$ cm** **$\Delta t \sim 30$ s**
- ➔ **Orbital scale (~0.1 AU): $\Delta x = 3.125 \cdot 10^{10}$ cm** **$\Delta t \sim 1$s**
- ➔ **BHL scale (10^{10} – 10^{11} cm) : $\Delta x = 10^{8} – 10^{9}$ cm** **$\Delta t \sim 1/100$ s**
- ➔ **Accretor scale, (RG = M/c^2=21.7 km): $\Delta x = 2.5\ 10^{6}$ cm** **$\Delta t = 0.05$ ms**

Explicit 2[nd] order scheme, integrated till some 10'000 orbits on BH scale

Flow within the wake



Compact object and inner (secondary) dissipation region

Accretion wake and outer (primary) dissipation region

About all material which flows through the BHL-accretion cylinder finally will be accreted

→ **BHL-theory predicts about the correct value for mass accretion!**

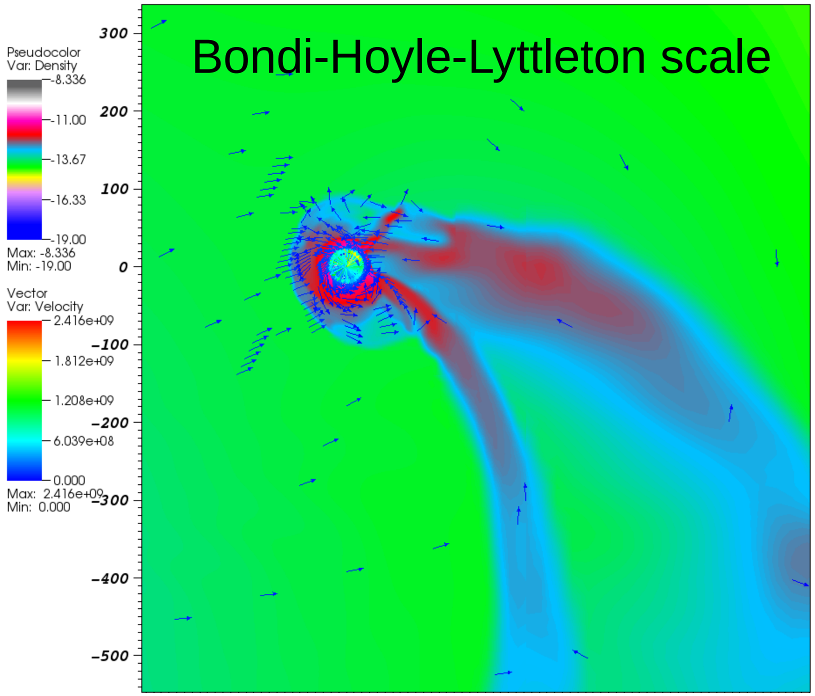
But: wind material moves ballistically. By this, most of the material passes through the accretion wake on its way down into the BH.

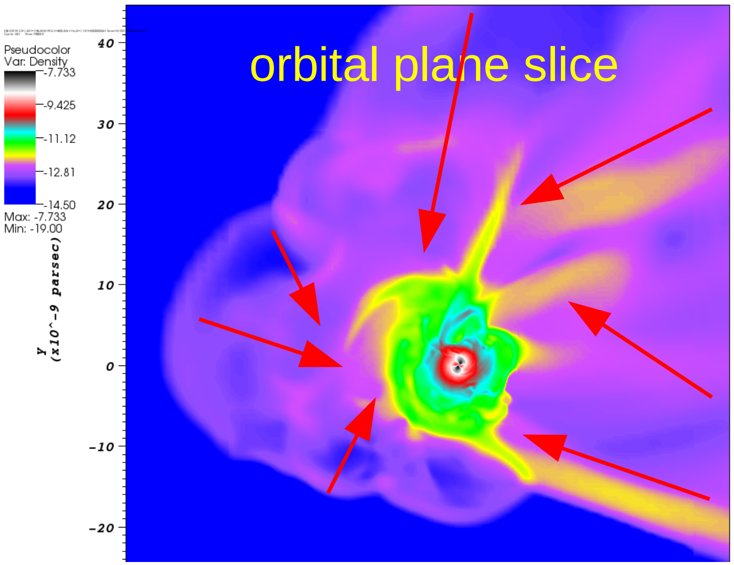
→ Dissipation of energy and angular momentum on the bounding shocks !

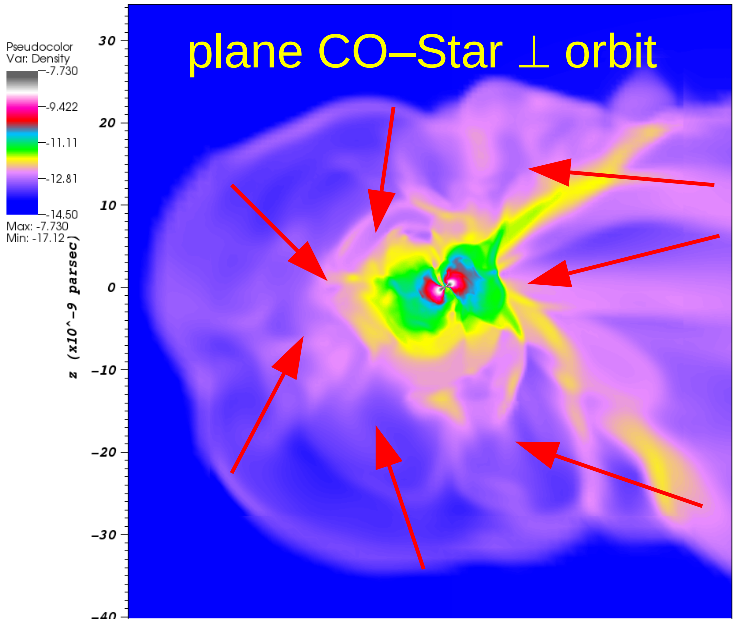
BHL-theory does **NOT** predict the correct amount of accreted angular momentum!

The wake regime

Courtyard scale ~ $R_{BHL}/5$ ~ 2000 R_G







Supersonic turbulence develops in the courtyard

Flat density with order of magnitude fluctuations.

Density and velocity fluctuations

→ shock position gets oblique

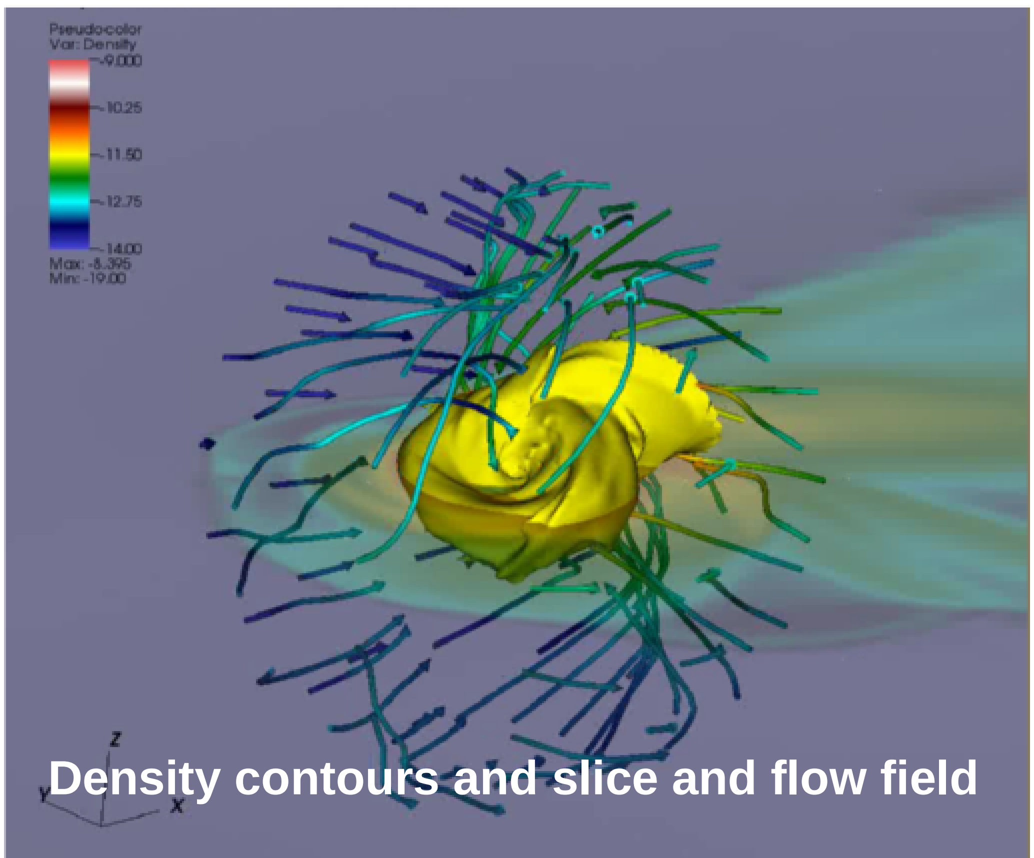
Oblique shock position

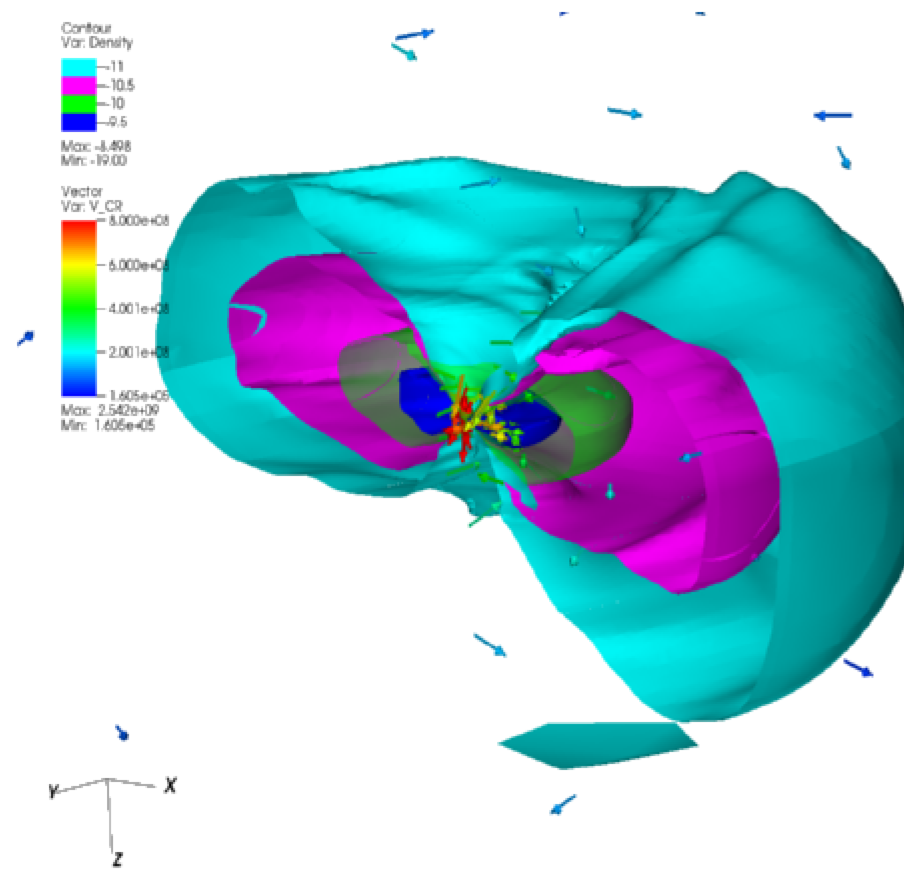
→ energy input varies locally and temporarily

turbulence is forced

Disk formation : (V_W = 750 km/s, γ= 1.1)

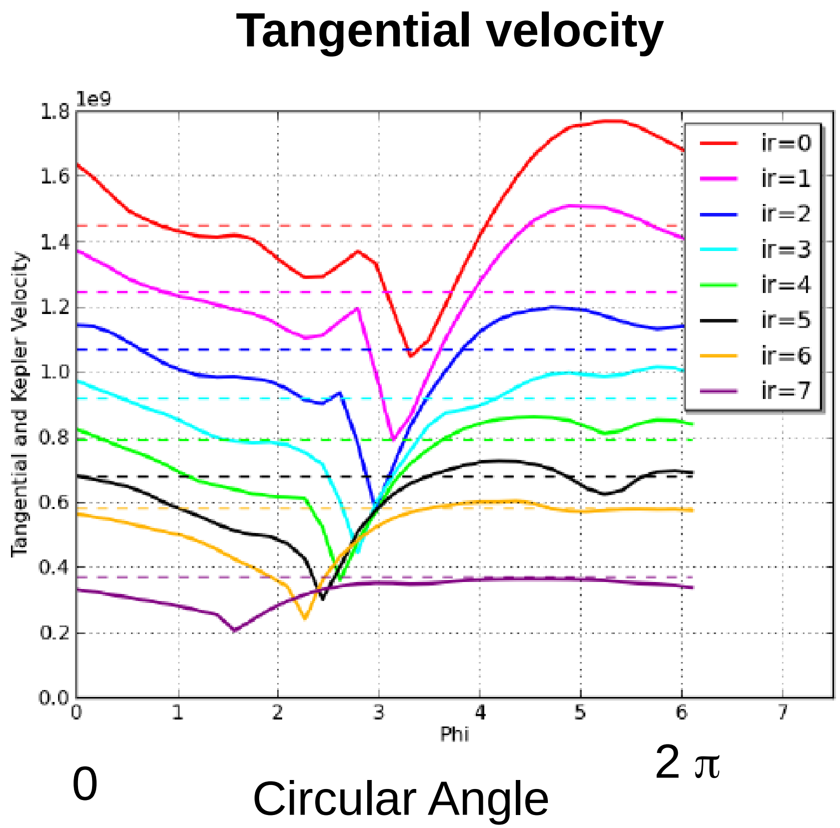
- Spinning structure: at about half of the shock scale
- Flattened structure: at about 1/1000 of the shock scale
- The disk forms over 3 orders of magnitude to be fully present on a scale of about 250 the gravitational radius.
- The disk is not Keplerian, carries shocks, is vertically connected.

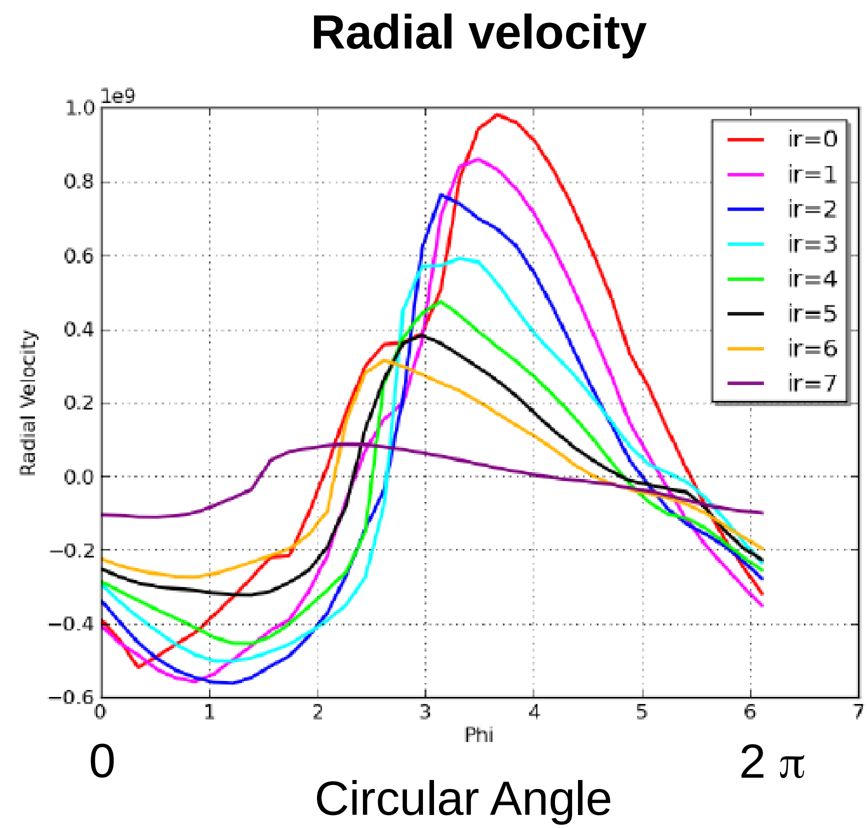




50'000 R_G — 500 R_G

No classical disk ! (V_W = 750 km/s, γ= 1.1)



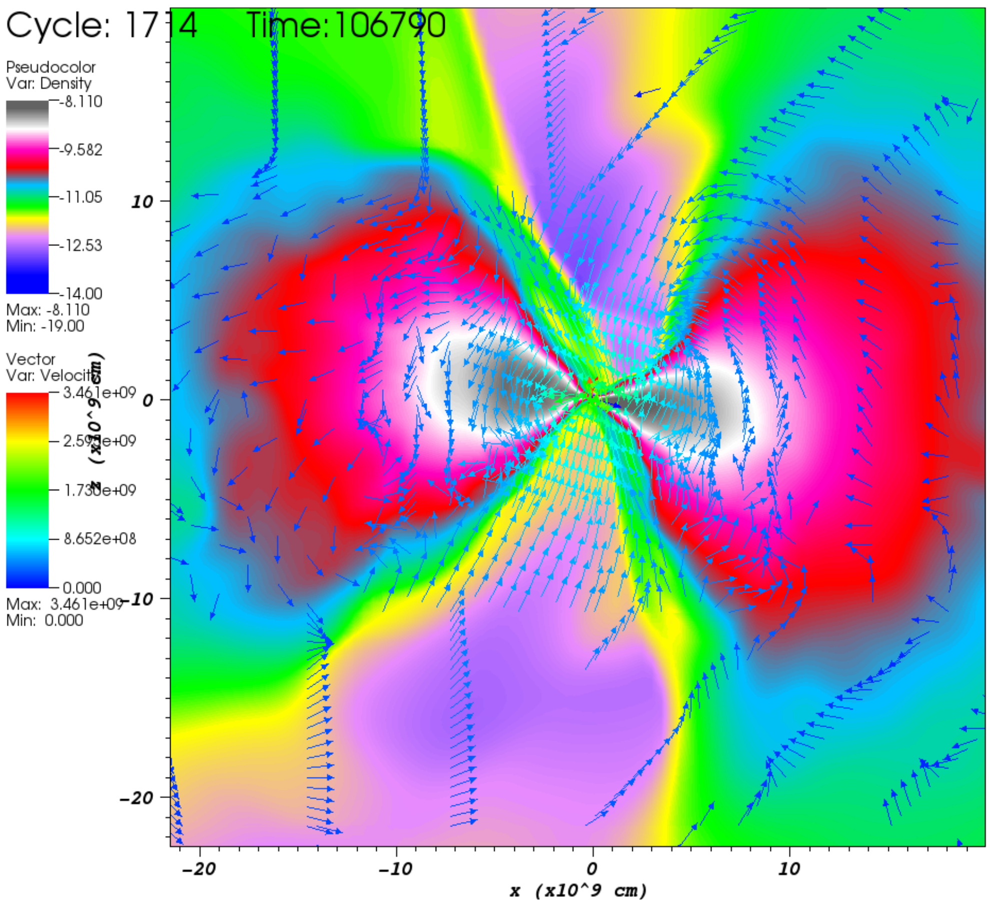


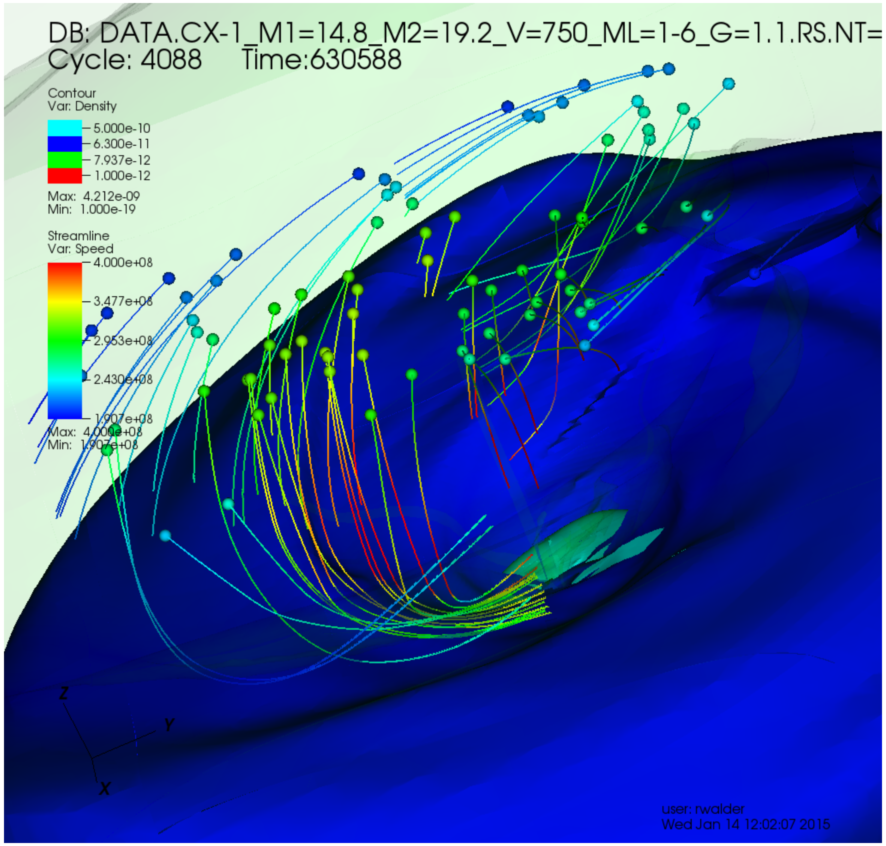
On circles around BH:

- **Tangential velocity : ~ 50 % variation around Kepler velocity !**
- **Radial velocity : Change of sign**

Walder et al. ASTRONUM, 2013

Vertically connected disk !





V_W = 850 km/s, γ = 1.1

V_W = 750 km/s, γ = 1.1

The disk is in steady interchange with the surrounding flow:

Angular momentum is fed in and taken out

No need for MRI or other turbulence forcing!

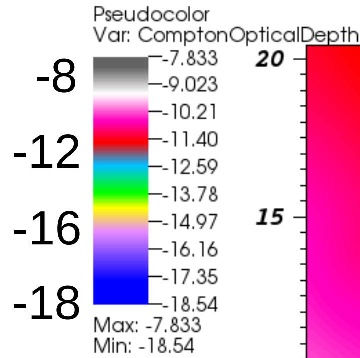
Photon optical depth

Thermalization of photons, and radiation pressure

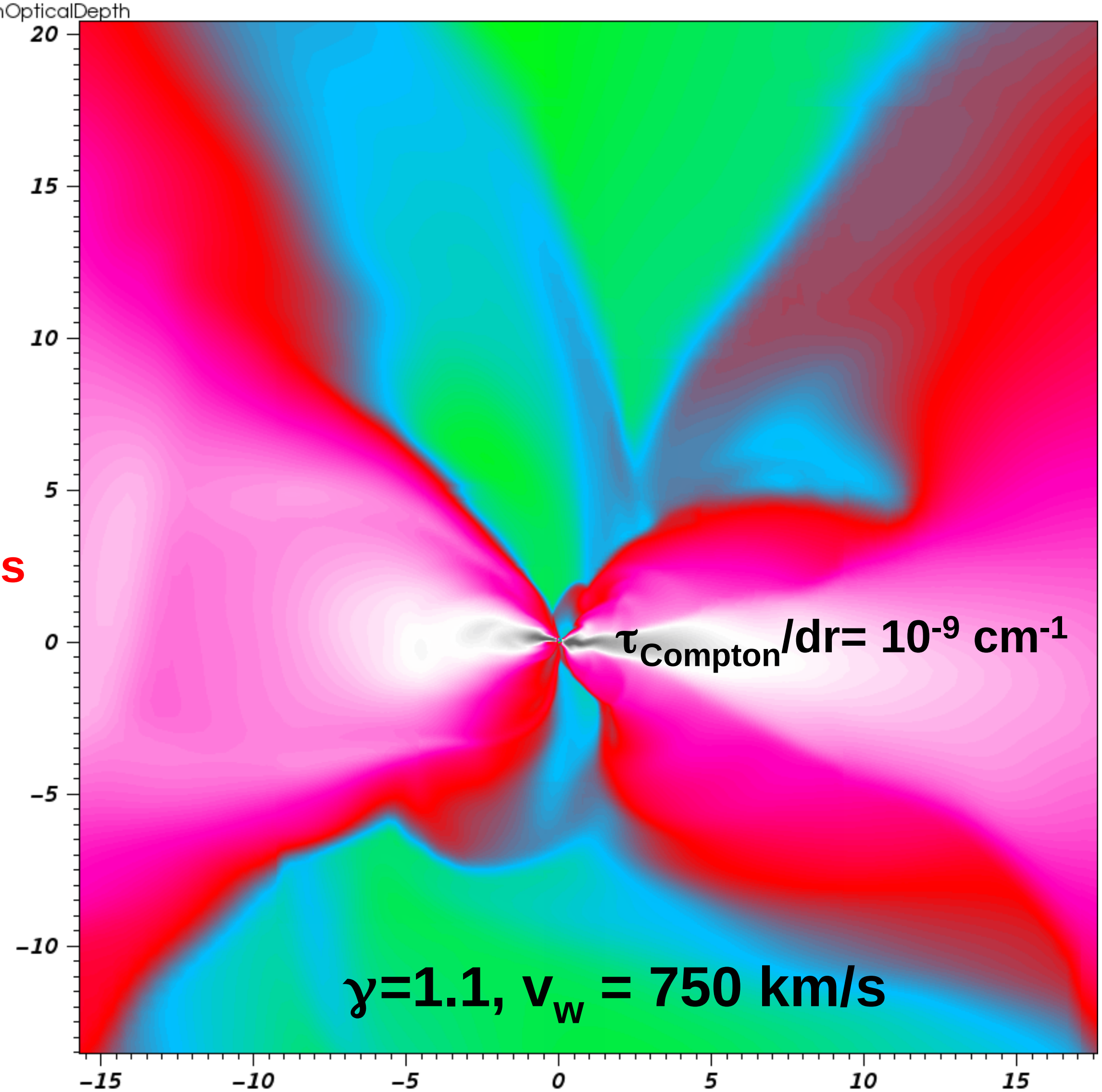
$\upsilon = \sigma_T$

N_e on the basis of $\dot{N}_e$

$M_W = 10^{-6}\ M_\odot$ /y



υ: optical depth/length [cm^{-1}]



-1.5^10 cm log(R) 1.5^10 cm

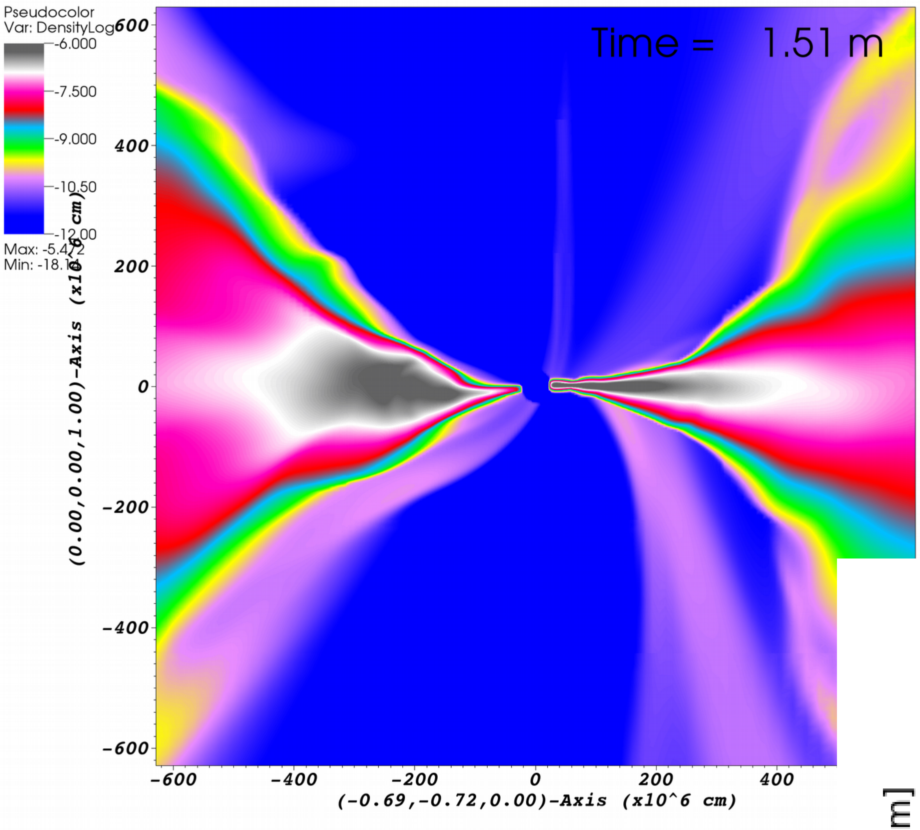
More or less independent of χ and v_W:

Optical depth is such that X-ray photons – produced by free-free emission – escape after some collisions.

Essentially NO Comptonization of free-free photons normal to disk:

→ 'good' for simulation results.

→ 'bad news' for synthetic spectra and exact cooling/heating: complex radiative transfer .

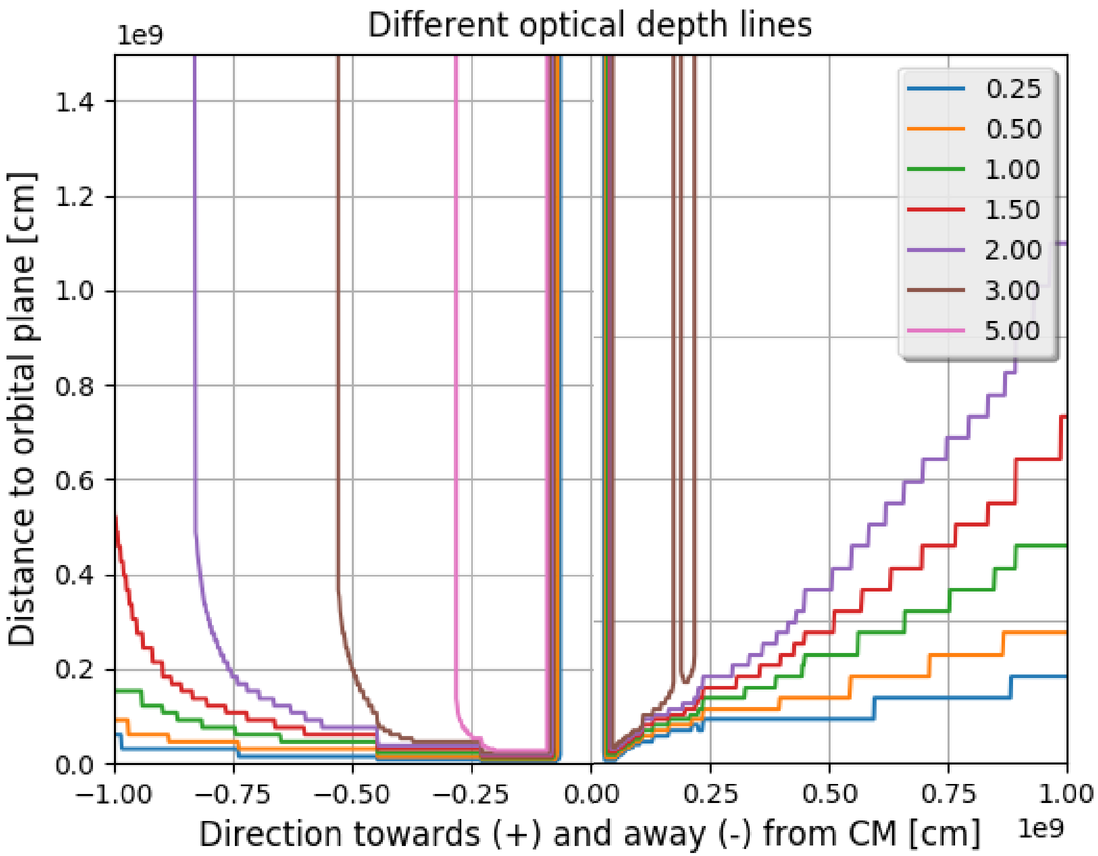


Disk at 25 RG

(where X-rays are originating)

Disk is only marginally optically thick

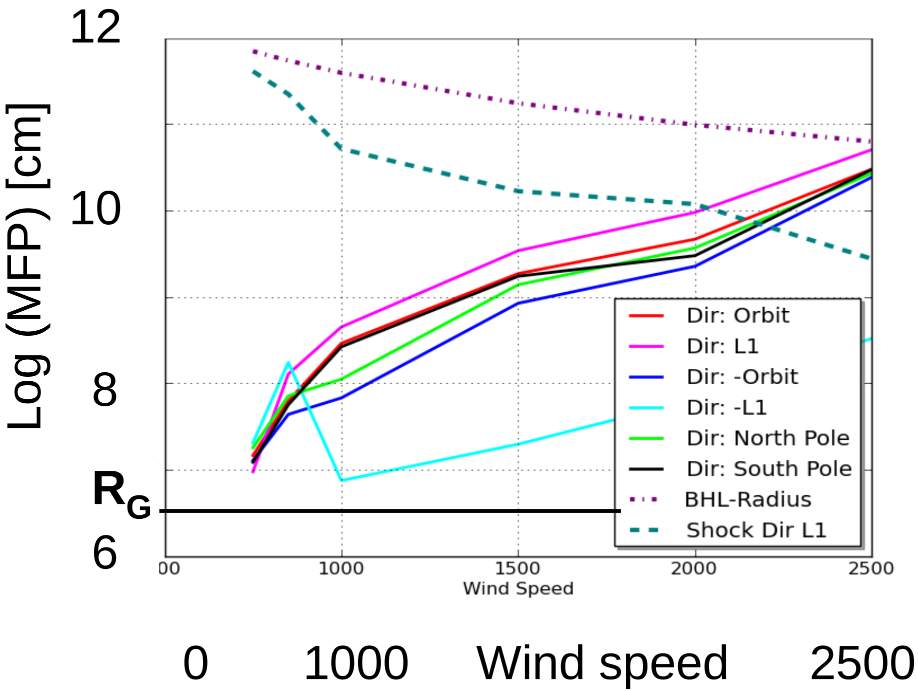
Comptonization may be incomplete



Plasma is (mostly) non-collisional

Mean free path

(Spitzer-formula – Fokker-Planck grazing collisions)

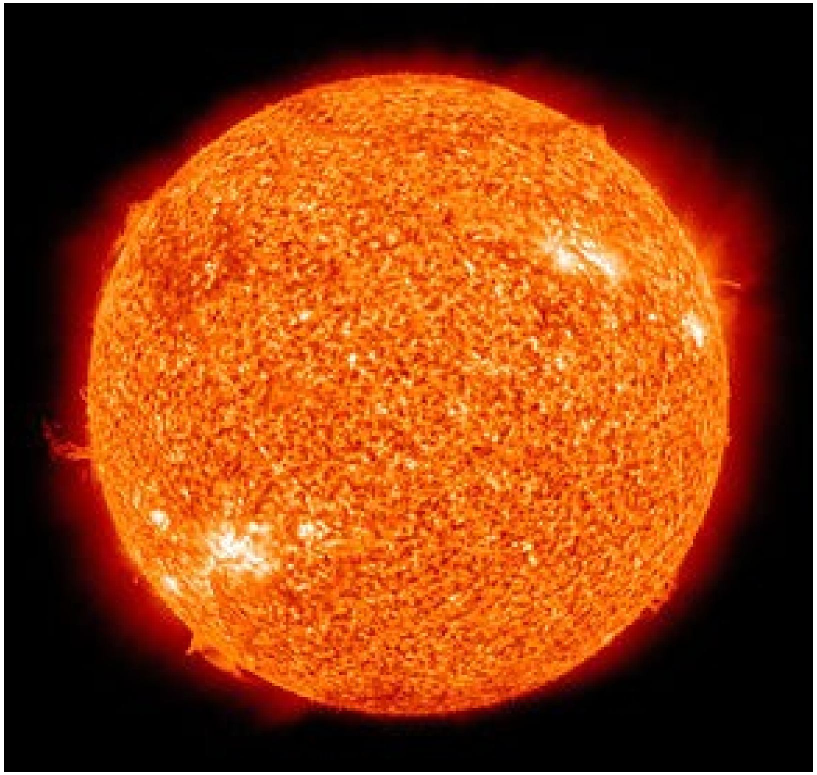


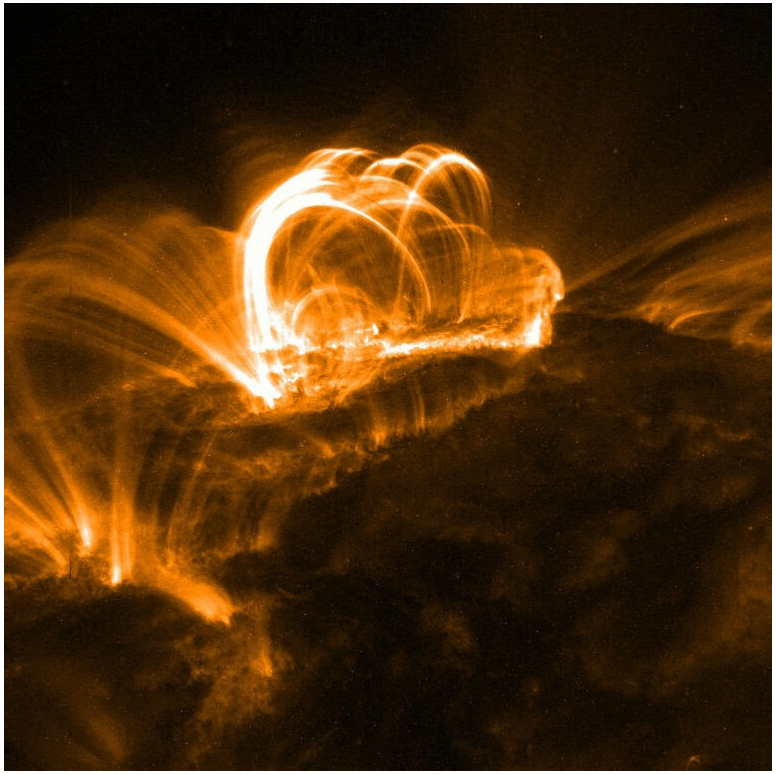
post-shock values, γ=1.1

Notes:

- Plasma-instabilities and waves lead to (much) faster thermalization.
- Kinetics on scales responsible of shock mediation and **magnetic reconnection** are much smaller, of order cm [electrons] – m [ions].

micro-quasars: reconnection takes likely place





Situation in Sun:

electrons are accelerated in flares (or shocks of CMEs) up to MeV

In Microquasars:

with much higher magnetic fields ?

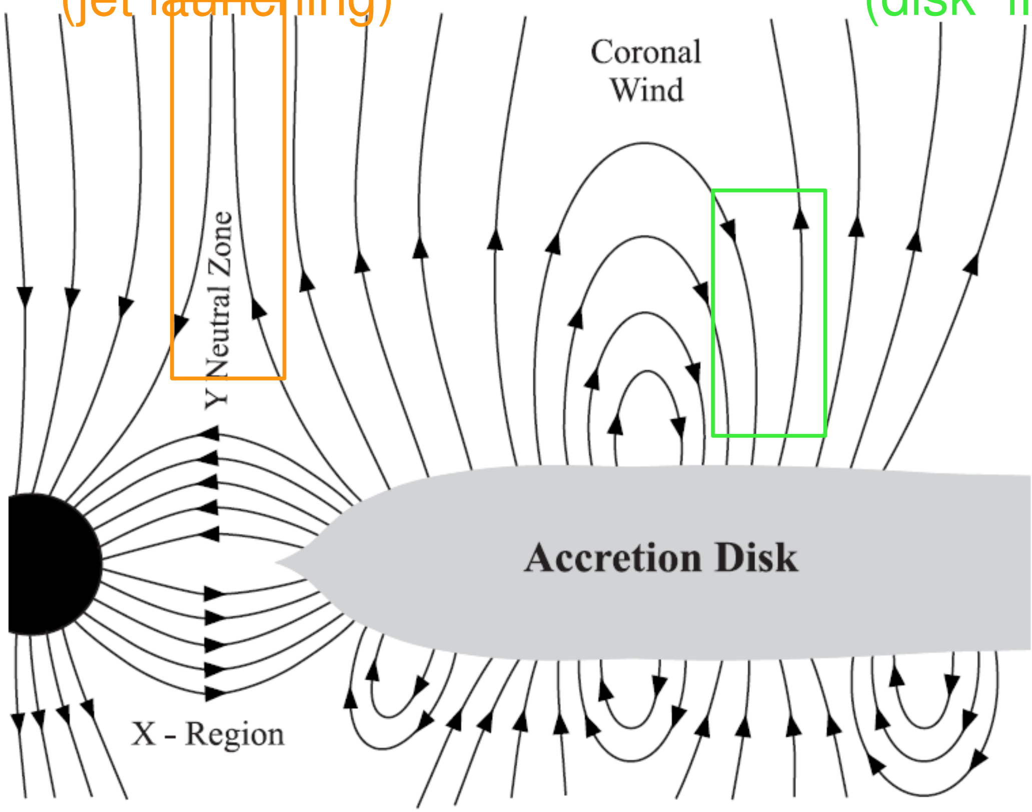
Micro-quasars: reconnection locations

'large scale' reconnection?

(jet launching)

'small scale' reconnection?

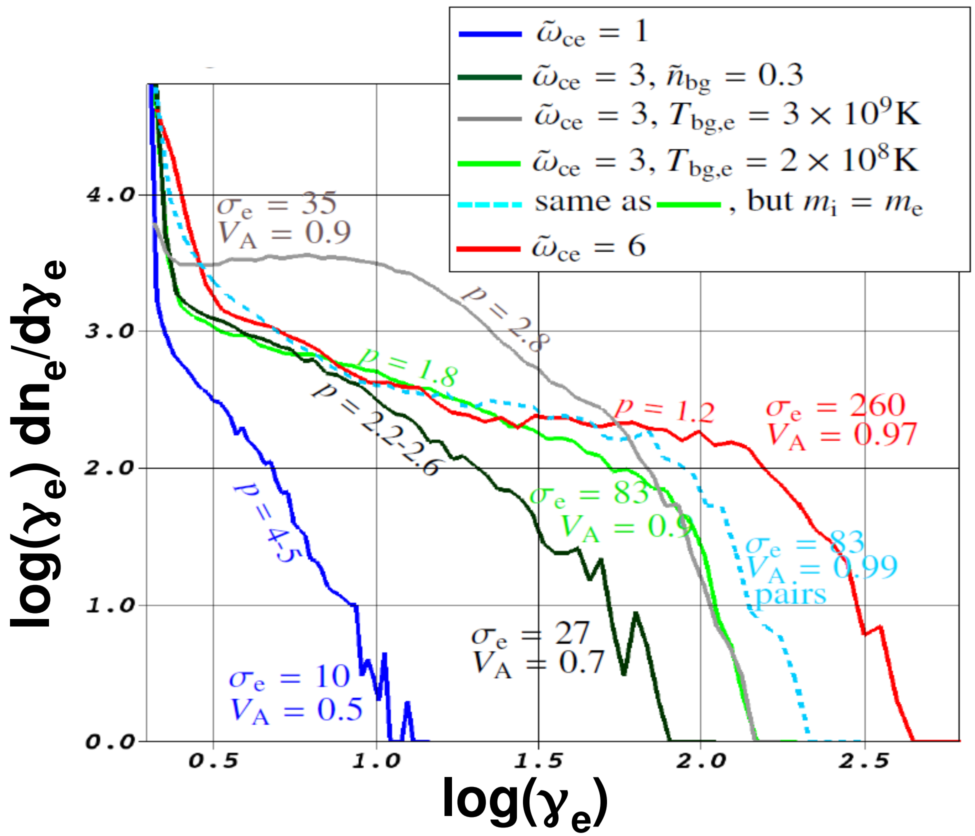
(disk flaring)

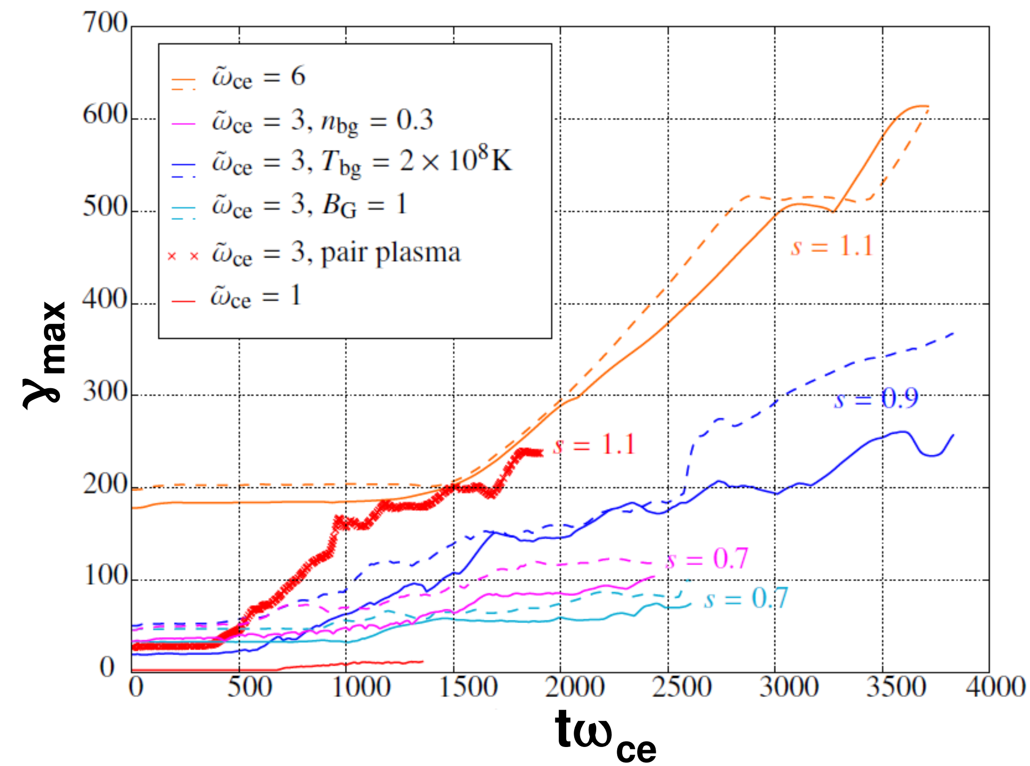


'turbulent' reconnection?

de Gouveia dal Pino et al, (2005)

electron distribution and maximum Lorentz factor γ_{max}





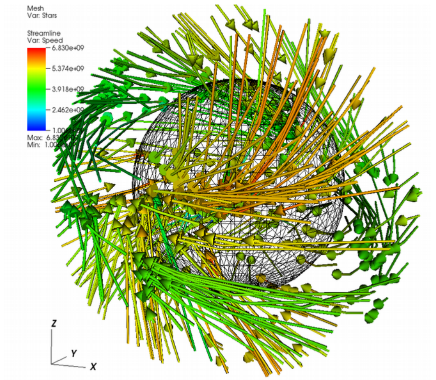
harder distributions for

- larger magnetization
- smaller background density n_{bg}
- smaller temperature

$\gamma_{max} \propto t^s$, with larger s for

- larger magnetization
- zero background field B_G

Summary & Conclusions



Full-scale simulations of microquasars show:

- **Understand the large scale structure of inter- and circum-binary matter (spirals) → provides opacities responsible to attenuate radiation.**
- **Mass accretion corresponds roughly to BHL accretion rates.**
- **Understand the formation of an accretion disk in the supersonically turbulent accretion wake and the non-Keplerian character of this disk.**
- **Provide an idea to what degree X-ray emission is thermal.**

Perspectives

Go relativistic

- **investigate BH neighborhood (BH-Corona, Jet launching)**
- **Jet propagation in accretion flow and stellar wind**