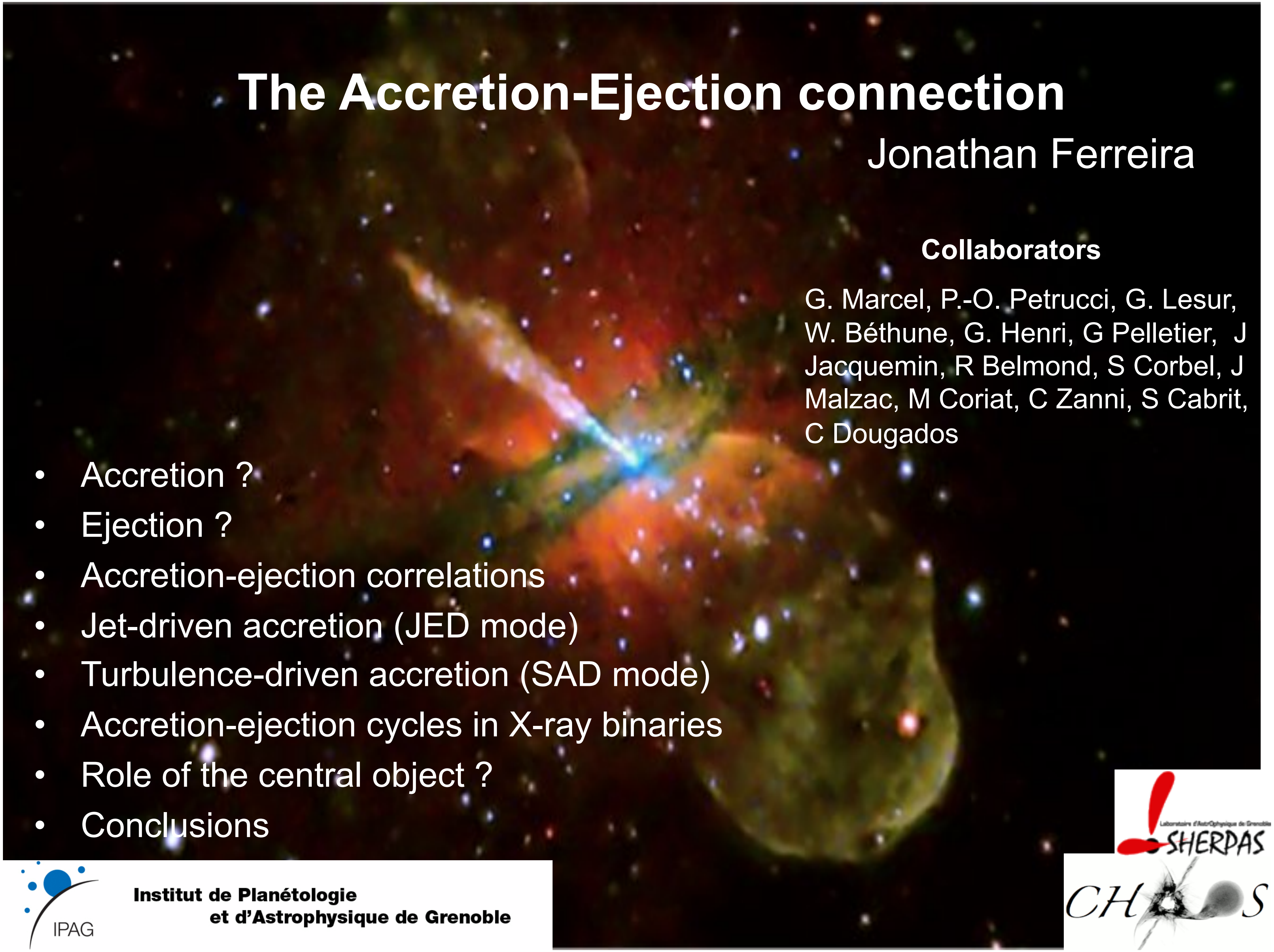

The Accretion-Ejection connection

Jonathan Ferreira

Collaborators

G. Marcel, P.-O. Petrucci, G. Lesur, W. Béthune, G. Henri, G Pelletier, J Jacquemin, R Belmond, S Corbel, J Malzac, M Coriat, C Zanni, S Cabrit, C Dougados

- Accretion ?
- Ejection ?
- Accretion-ejection correlations
- Jet-driven accretion (JED mode)
- Turbulence-driven accretion (SAD mode)
- Accretion-ejection cycles in X-ray binaries
- Role of the central object ?
- Conclusions

IPAG
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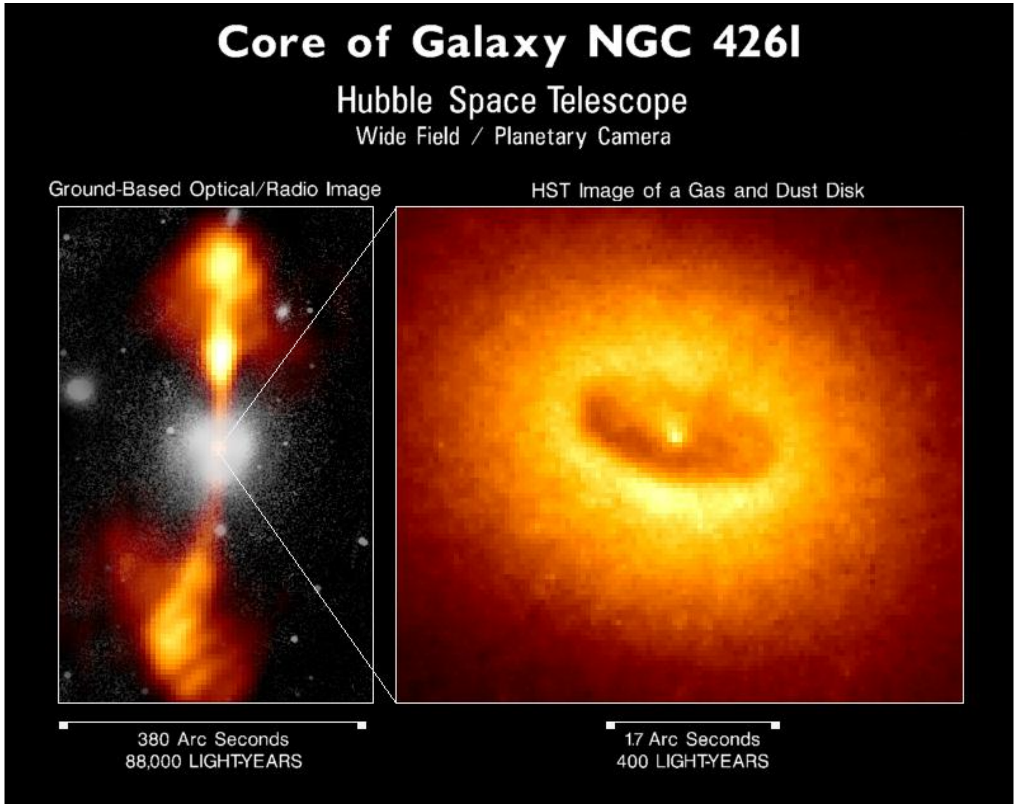
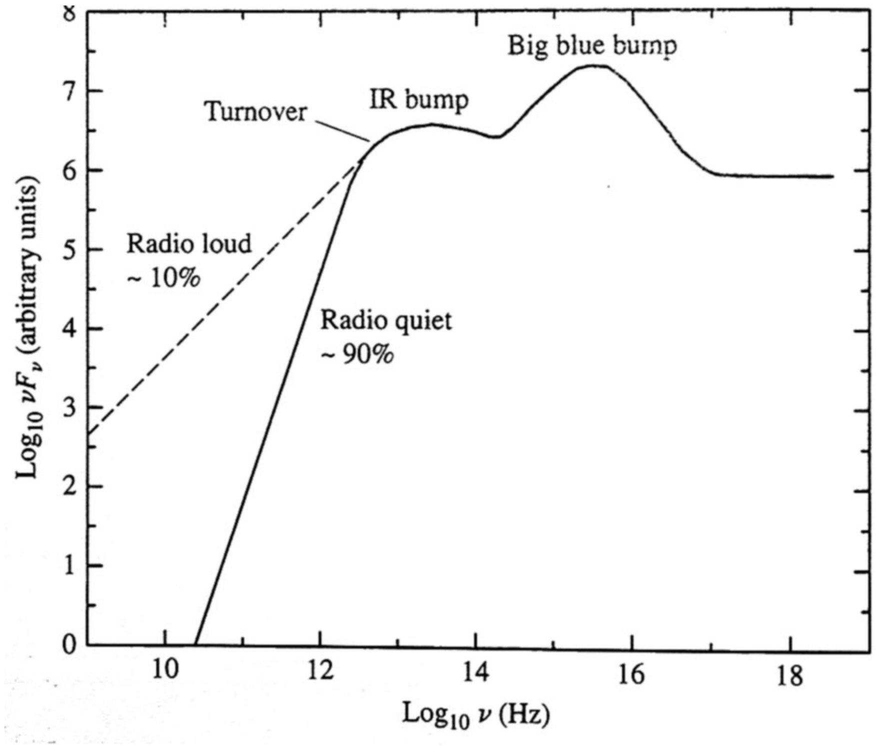
Laboratoire d'AstrOphysique de Grenoble
SHERPAS
CHAOS

AGN (Active Galactic Nuclei) & Quasars



Huge radiated power

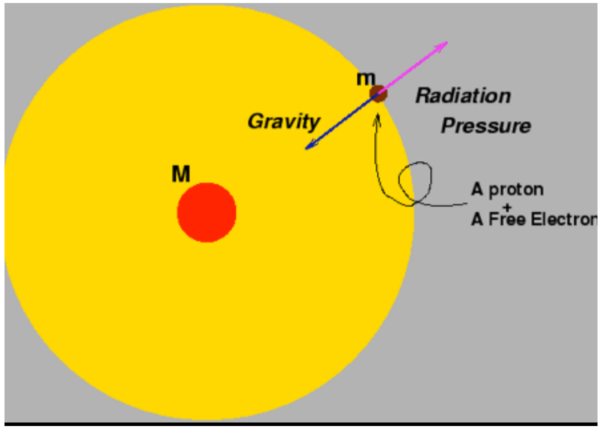
L = 10^{39}-10^{46} erg/s = 10^{6}-10^{13} L_{sun}



⇒ **Big Blue Blump**: spectrum cannot just be the sum of stars (« starburst » scenario)

⇒ Huge luminosity implies huge radiative pressure: how can this material remain there?

The Eddington luminosity limit



Spherical symmetry:

Fgrav = Frad

⇒ L_{Edd} = 1,3 10^{38} (M/M_{sun}) erg/s

~ 3 10^4 (M/M_{sun}) L_{sun}

Ex: quasar 3C 273 has L= 3 10^{13} Lsun requires a **minimum** mass of 10^9 M_{sun} !!

Variability requires luminosity emitted from region of size ~ few 100 au = few 10^9-10^{10} km

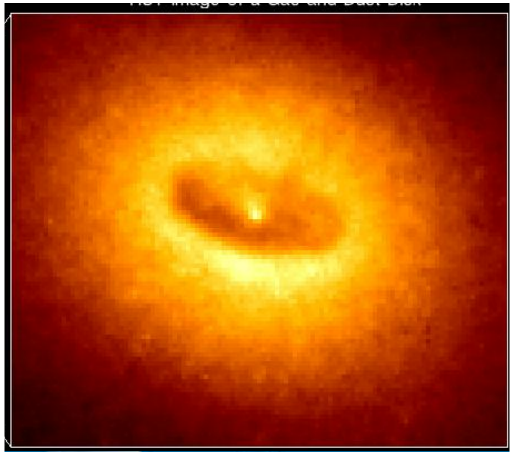
$$\Delta t = r_g/c$$

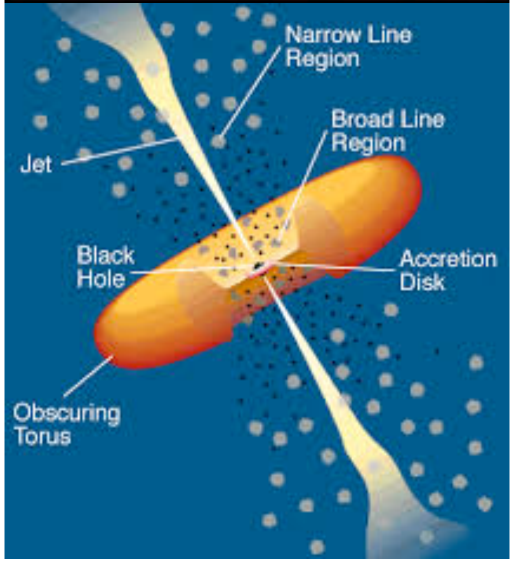
$$r_g = \frac{GM}{c^2} = 15km\left(\frac{M}{10M_\odot}\right)$$

⇒ Need of a central **supermassive black hole** **M=10^6-10^{10} M_{sun}** for AGN & quasars

⇒ Where does this energy come from ?

The accretion disk paradigm: Lynden-Bell (1969)





Assume a rotating Keplerian disk around BH with $r_g = \frac{GM}{c^2}$

$$E = \frac{u^2}{2} - \frac{GM}{r} = -\frac{GM}{2r}$$

$$\Delta E = E(r_{in}) - E(r_{out}) = \frac{GM}{2r_{in}}\left(1 - \frac{r_{in}}{r_{out}}\right) \simeq \frac{GM}{2r_{in}}$$

Assuming a **mass flux** through the disk $\dot{M}_a$ leads to a released **accretion luminosity**

$$L = \dot{M}_a \Delta E = \frac{GM\dot{M}_a}{2r_{in}} = \dot{M}_a c^2 \left(\frac{r_g}{r_{in}}\right)$$

$$L = \eta \dot{M}_a c^2$$

with η ~ 5 to 40% efficiency, depending on BH spin

Typical luminosities require BH fed with up to 10^{-2} - 1 M_{sun}/yr

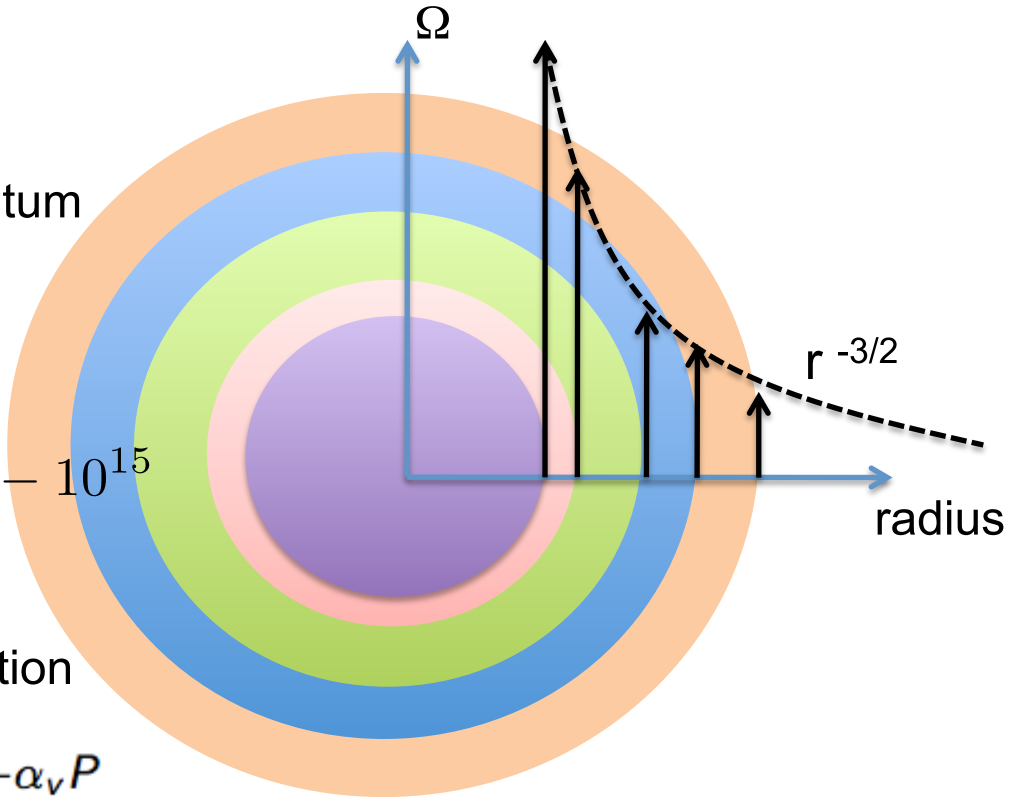
=> **Need to find a way to brake down the rotating disk**

The Standard Accretion Disk (SAD): Shakura & Sunyaev 1973

Quasi-keplerian disk material
⇒ Differential rotation
⇒ viscous transport of angular momentum

BUT
Collisional viscosity far too small

$$\mathcal{R}_e = \frac{r u_r}{\nu_v} = \frac{u_r}{r} \times \frac{r^2}{\nu_v} = \frac{\tau_{coll}}{\tau_{acc}} \sim 10^8 - 10^{15}$$



=> turbulent torque: the ‘alpha’ prescription

$$T_{r\phi} = T_{\phi r} = \left\langle \frac{\delta B_\phi \delta B_r}{\mu_o} - \rho \delta u_\phi \delta u_r \right\rangle \equiv -\alpha_v P$$
$$\equiv \rho \nu_v r \frac{\partial \Omega}{\partial r}$$

with **$\nu_v = \alpha C_s.H$** and $\alpha <$ 1 free parameter

where $H << r$, local disk thickness
C_s = sound speed

$$u_r / C_s \sim \alpha H / r$$

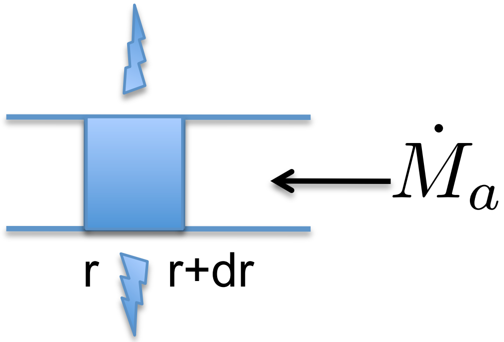
⇒ Highly subsonic accretion

⇒ for large $\dot{M}_a$ disk is optically thick

The Standard Accretion Disk (SAD): Shakura & Sunyaev 1973

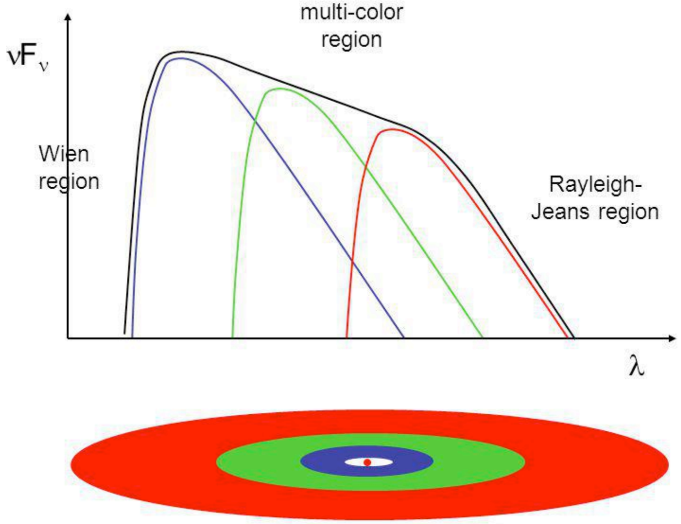
Emitted broadband spectrum: sum of local blackbody of temperature T

$$
\begin{aligned}
dL &= d(\dot{M}_a E) = -\dot{M}_a d\frac{GM}{2r} = \frac{GM\dot{M}_a}{2r^2}dr \\
&= 2 \times \sigma T^4 2\pi r dr
\end{aligned}
$$

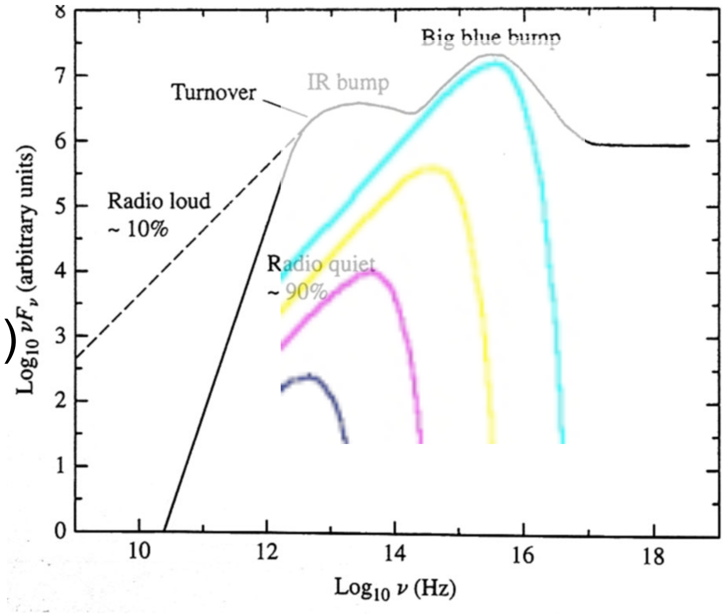


$$
T = \left(\frac{GM\dot{M}_a}{8\pi\sigma r^3}\right)^{1/4}
$$

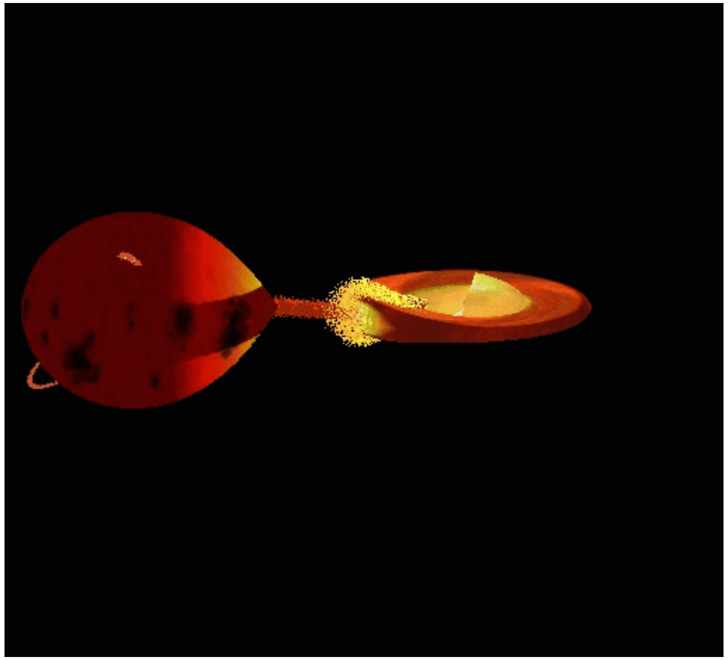
Successfully explains
⇒ UV bump for AGN (supermassive BH)

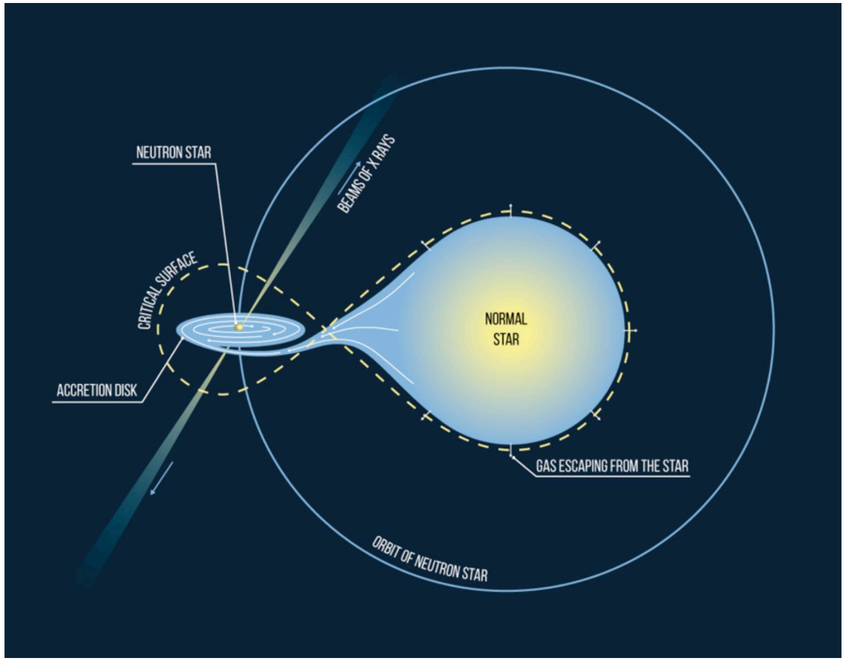


But also
- X-rays for binaries (BH and neutron stars)
- UV for CV
- IR for YSO



Binary systems with mass transfer





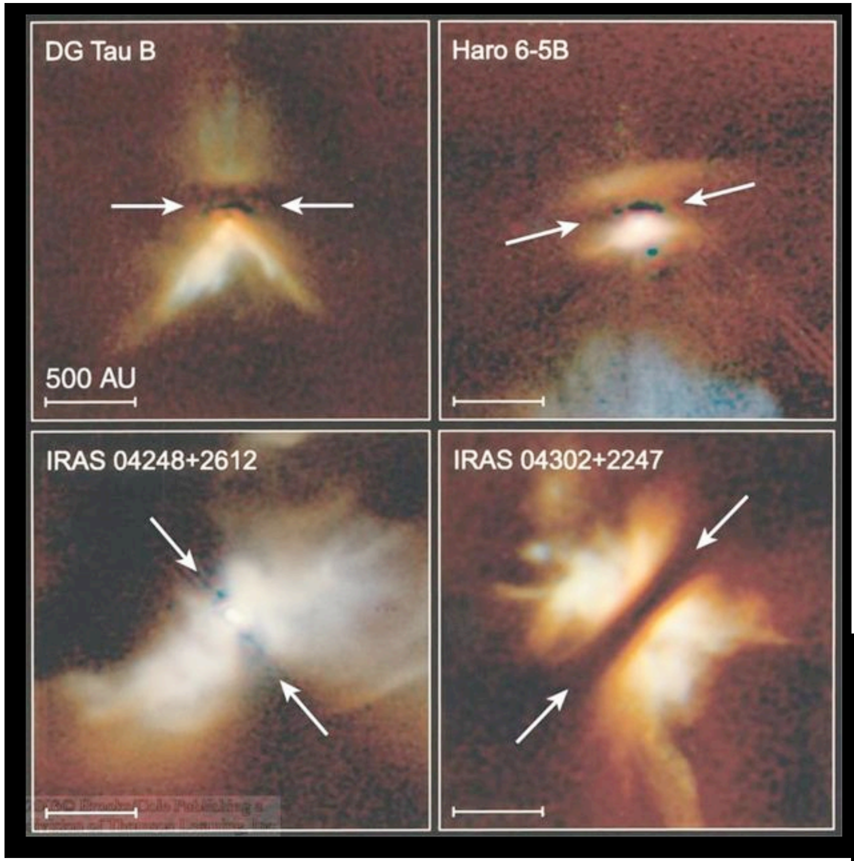
Compact object + normal star => **accretion disk around compact object**

- Compact object = White Dwarf => Cataclysmic Variable, **seen in UV**
- Compact object = BH or neutron star => X-ray Binary… **seen in X-rays**

Mass transfer via

- Roche-lobe overflow, for low-mass ($M < 2\ M_{sun}$) star companion
- wind-fed, for high-mass (O/B $M > 8\ M_{sun}$) companion

Young Stellar Objects (YSO) also



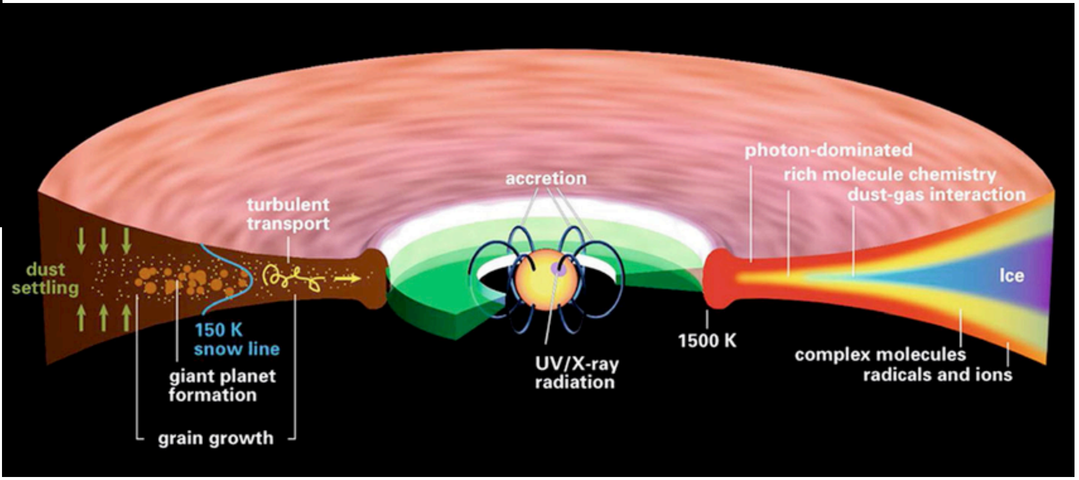
Gravitational collapse of a rotating cloud

⇒ Disk formation around a protostar, seen as

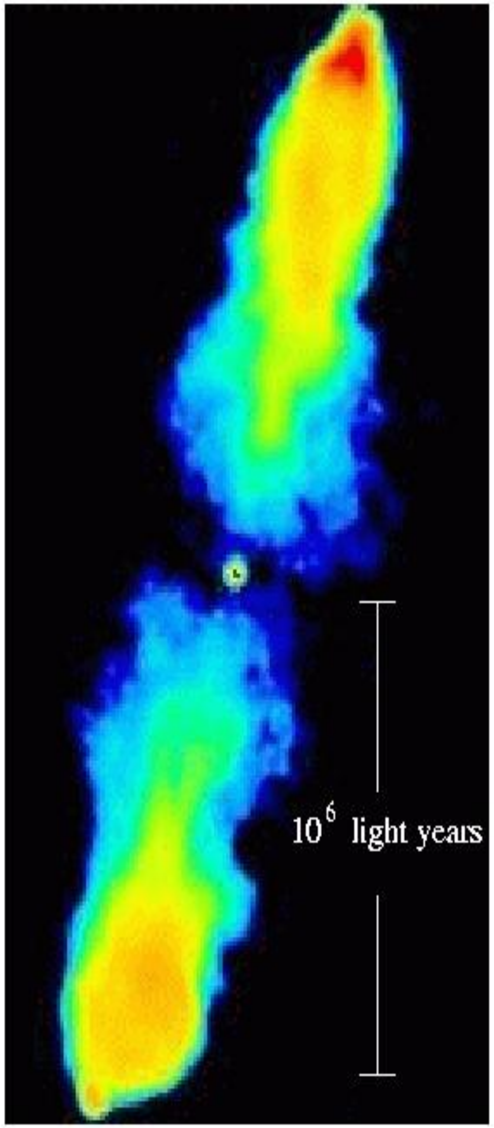
(i) absorbing (dust) layer in optical

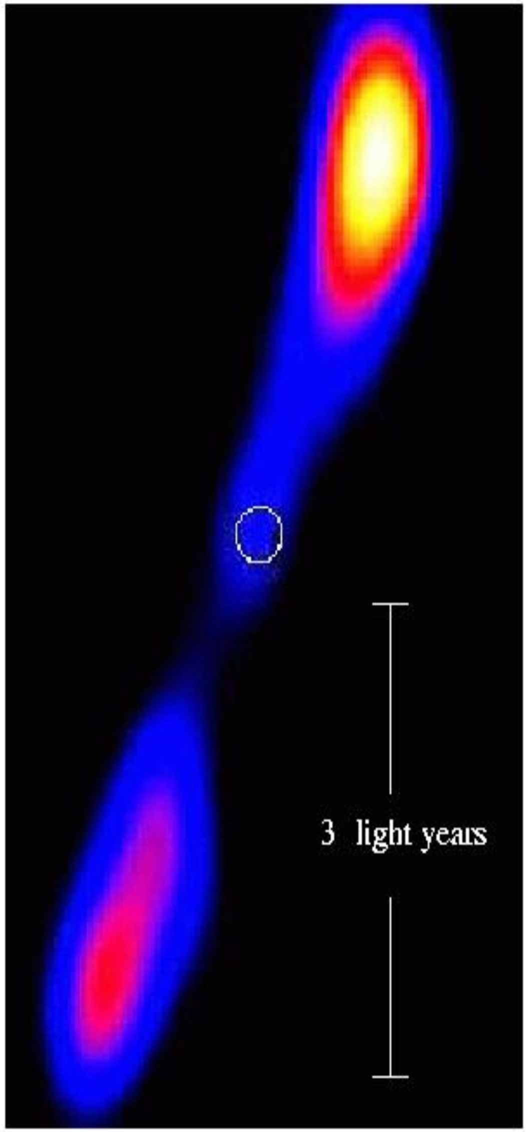
(ii) an infrared excess

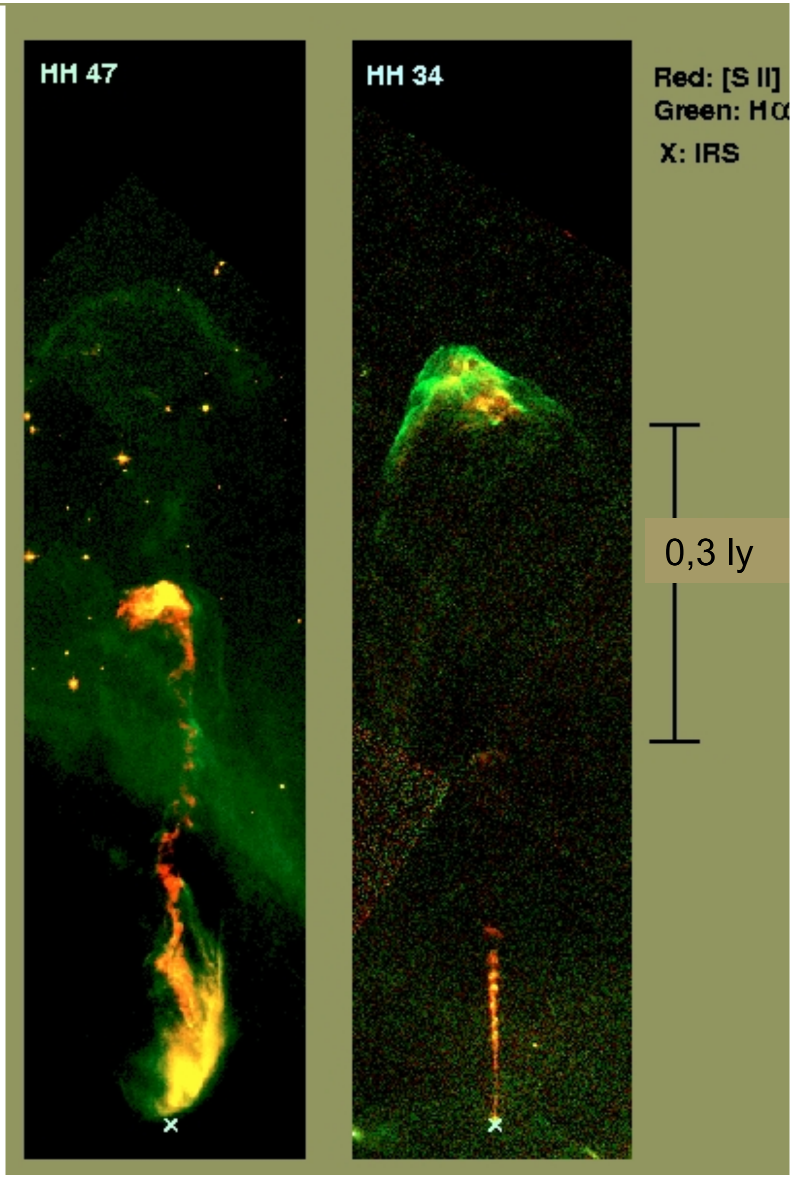
=> Circumstellar disk= nursery of planets



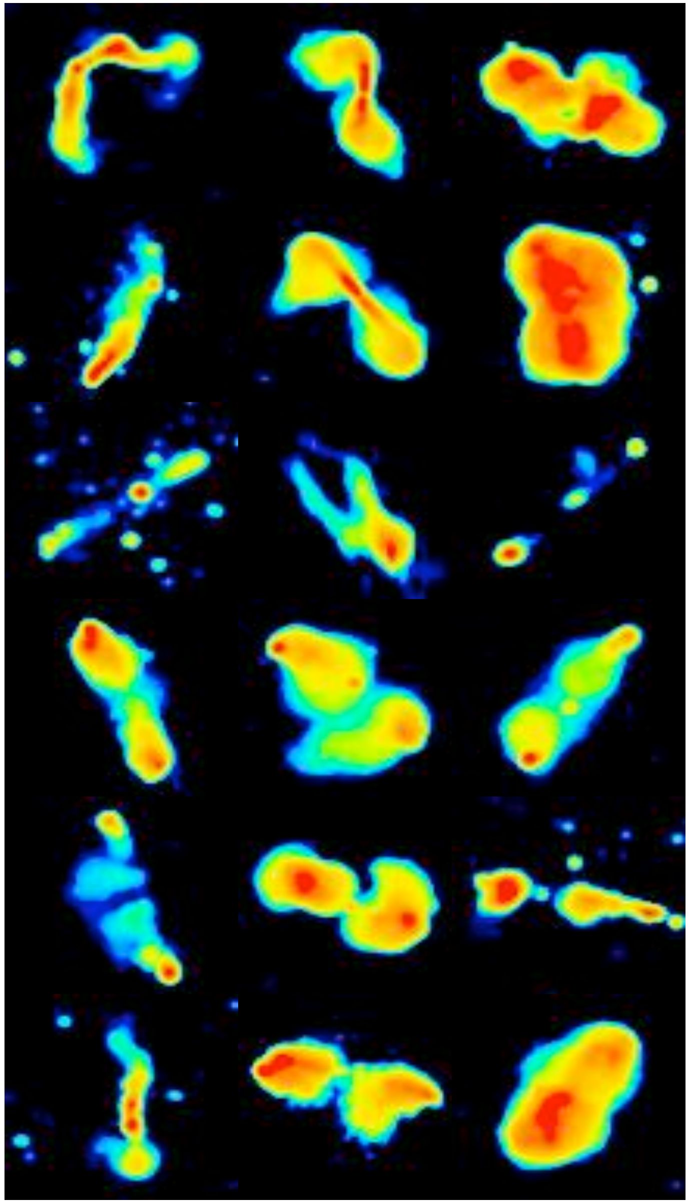
Jets in all classes of accreting objects

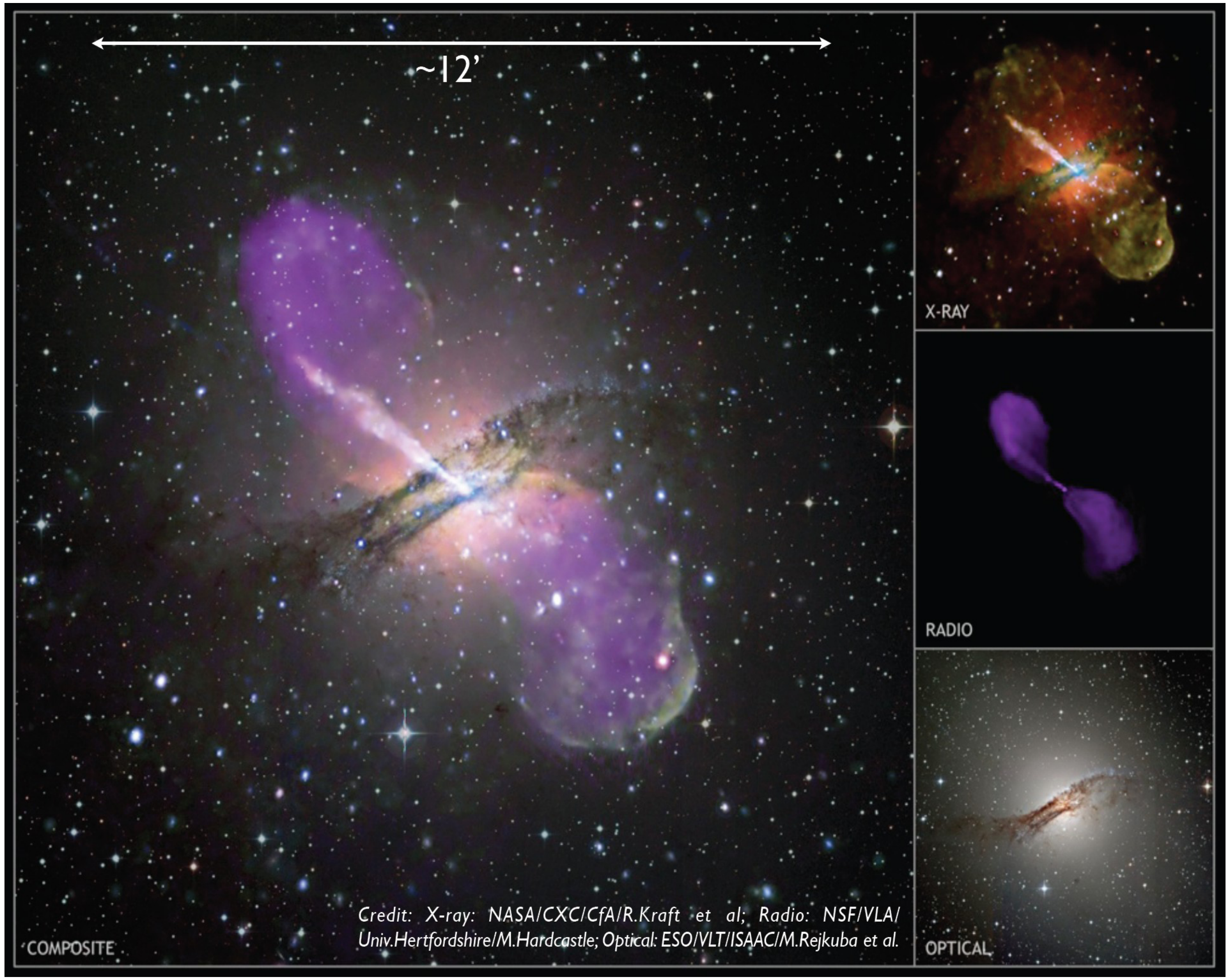

Quasar/radio galaxy


Microquasar 1E1740.7-2942


Young stars

Radio galaxies & Quasar gallery





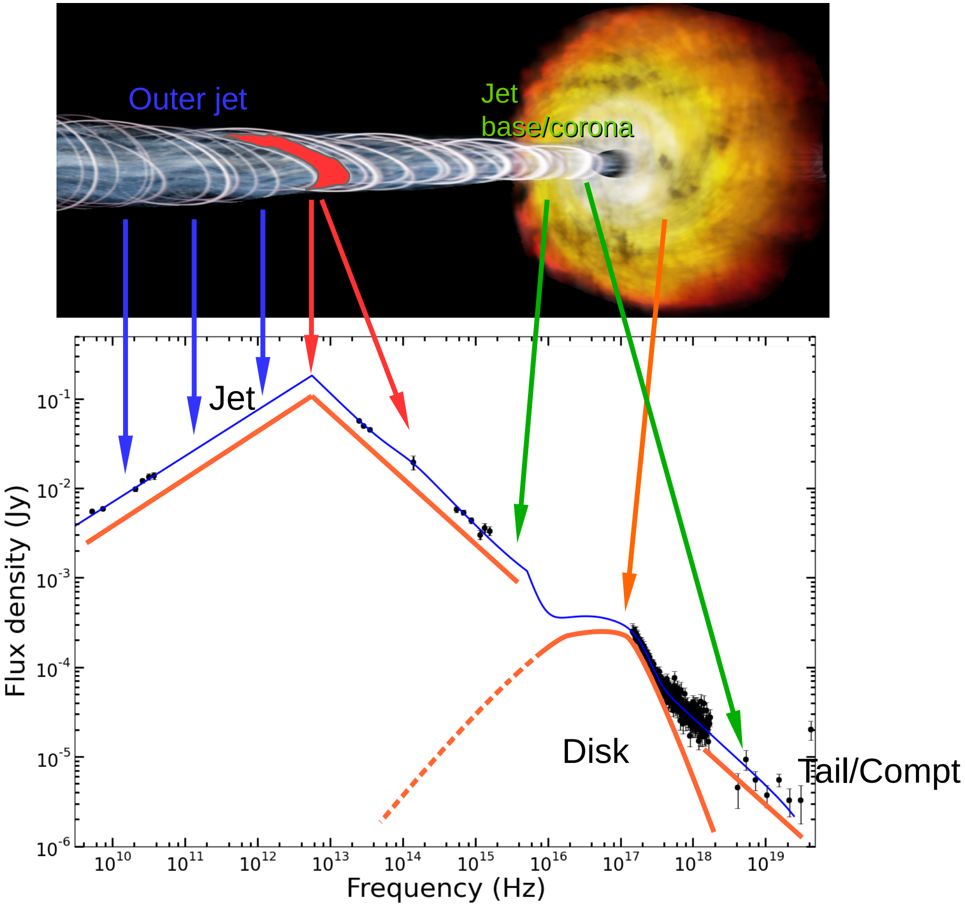
Credit: X-ray: NASA/CXC/CfA/R.Kraft et al; Radio: NSF/VLA/ Univ.Hertfordshire/M.Hardcastle; Optical: ESO/VLT/ISAAC/M.Rejkuba et al.

Radio galaxy Centaurus A

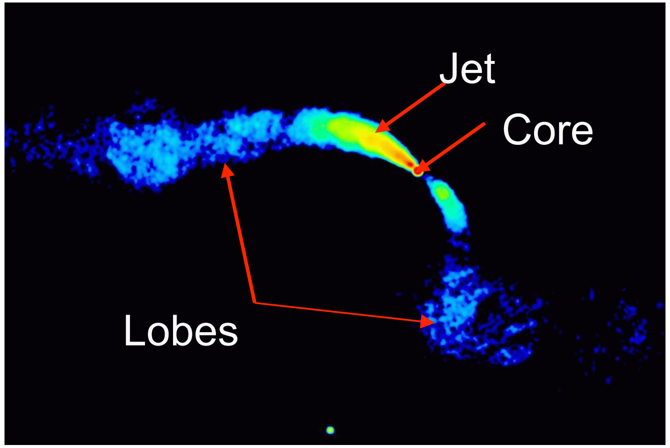
Leahy, JP

Jets from AGN & binary systems

Seen in Radio: synchrotron emission
from non-thermal electron population
⇒ Magnetic fields present
⇒ Spectra + images : collimated flows

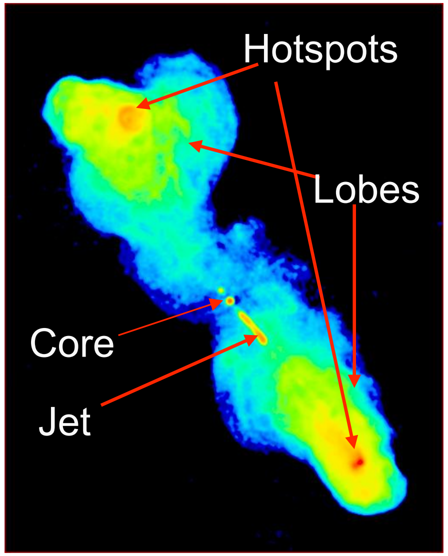


FR I (low power)



Flows slow to <0.3c on ~10 kpc scales

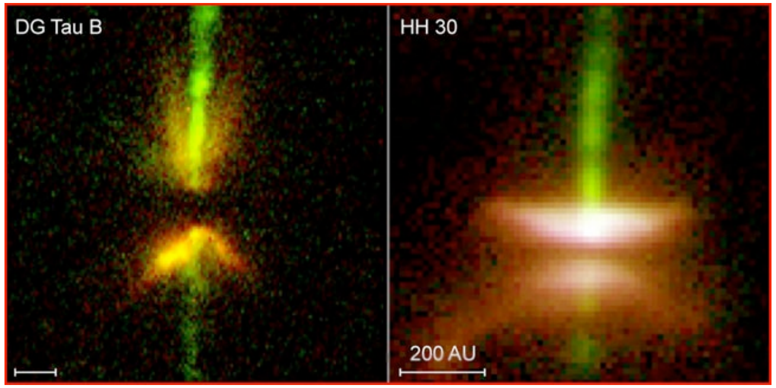
FR II (high power)

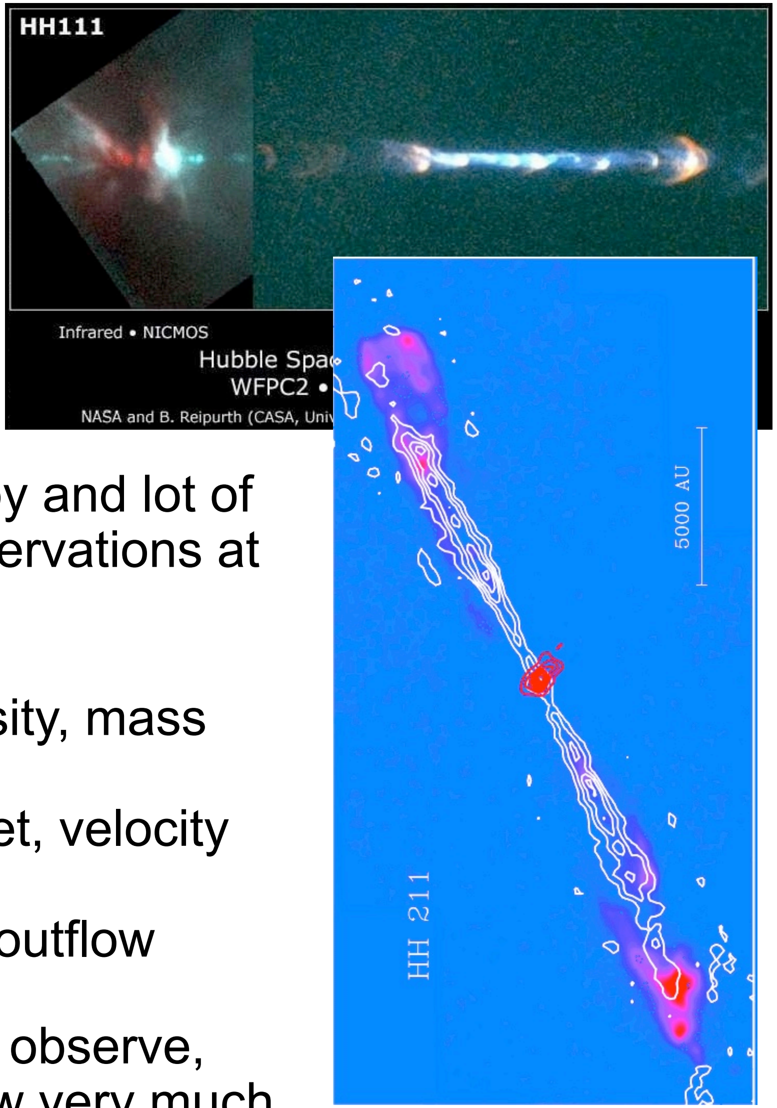


Flows likely still ≥0.7c on Mpc scales.

Brightest in the lobes

Jets from Young Stellar Objects





Same collimation issue

Large number of known YSOs, nearby and lot of information can be obtained from observations at different wavelengths

Optical & IR → Temperature, density, mass

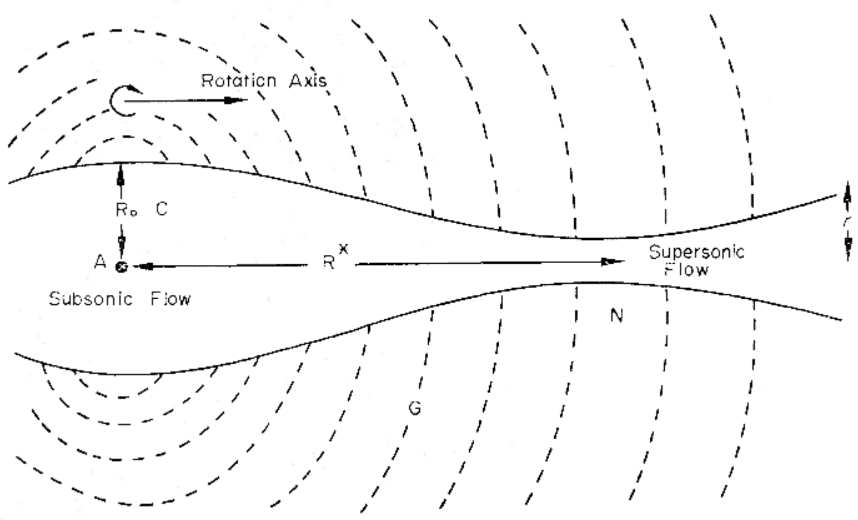
Radio → ionized gas, base of the jet, velocity

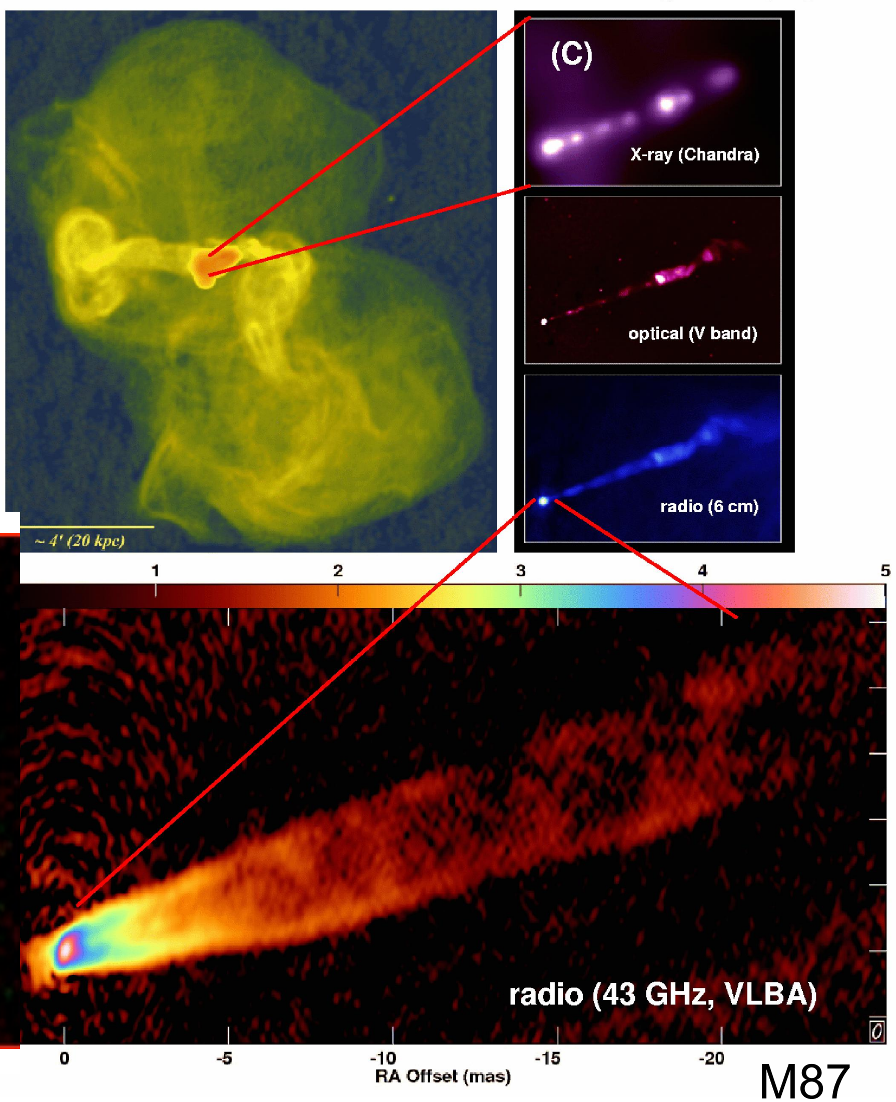
mm/submm → Disk, molecular outflow

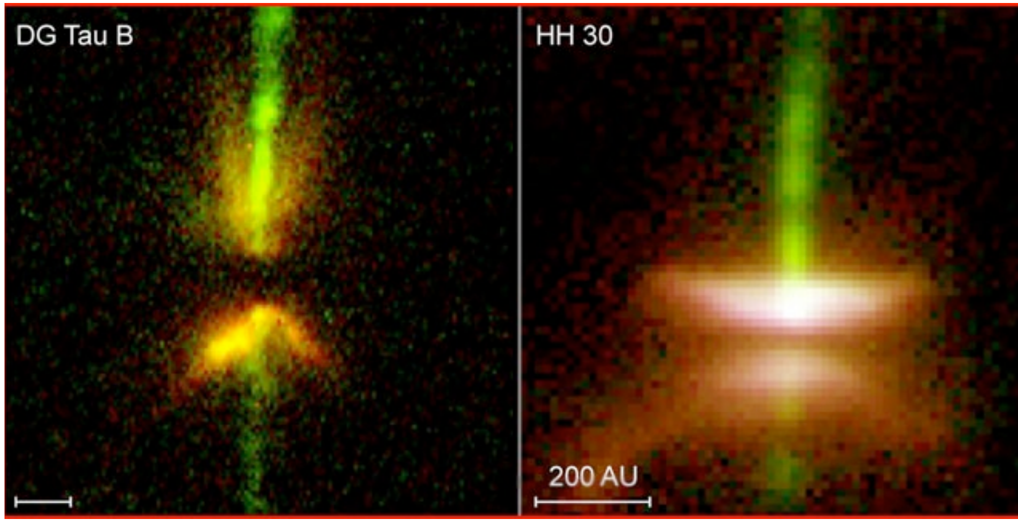
But **magnetic field**, very difficult to observe, specially in the jet, and we do not know very much about it

First tentative: a de Laval nozzle ?

Blandford & Rees 74
Canto 80





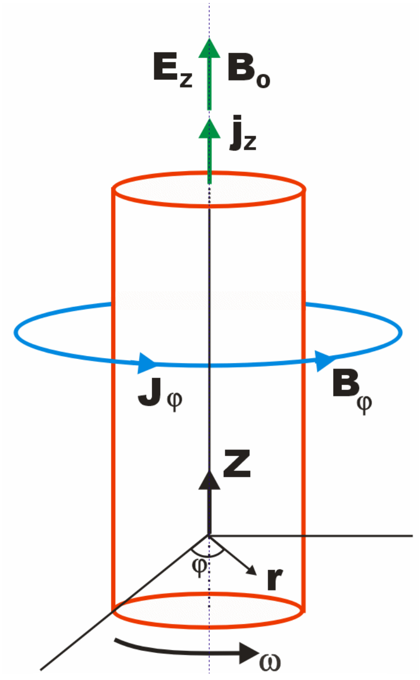


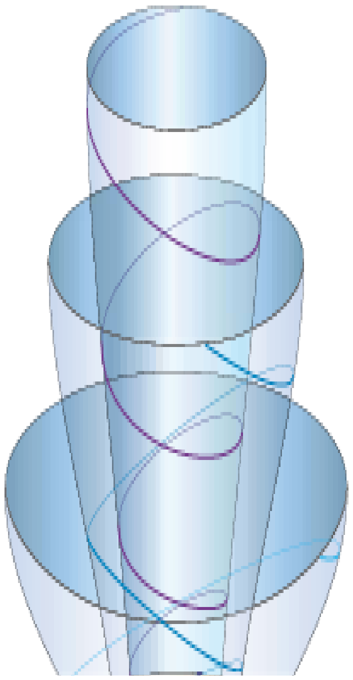
Young stars

M87

Magnetized jets

Blandford 76, Lovelace 76
Blandford & Payne 82





Jet = electron-proton **plasma** carrying a large scale helicoidal (Bz and Bphi) magnetic field

=> **Magneto-hydrodynamics (MHD)**

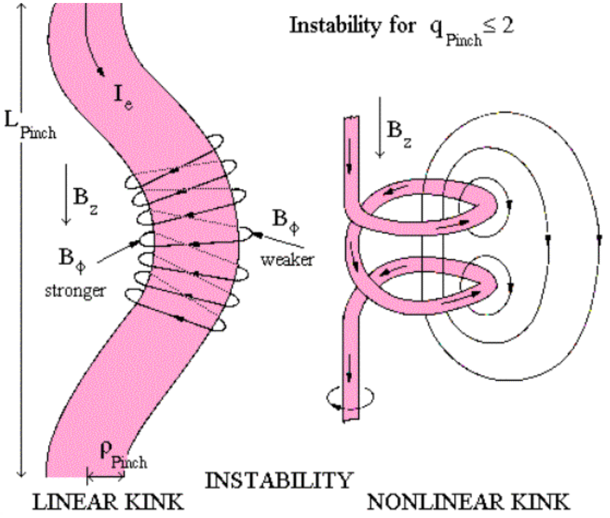
Axisymmetry => magnetic surfaces nested around each other, anchored onto a rotating object
- central mass (BH, star)
- or surrounding accretion disk

Collimation = usual **hoop-stress** (Bphi) as in **Z-pinch**
Controled by generalized Grad-Shafranov equation

Power = conversion of initial MHD Poynting flux into plasma kinetic energy (Bernoulli invariant)

Theory of steady-state jets is known… (it depends on 5 MHD invariants whose radial distribution must be given) …. *but not solved yet :-/*

and MHD instabilities !?



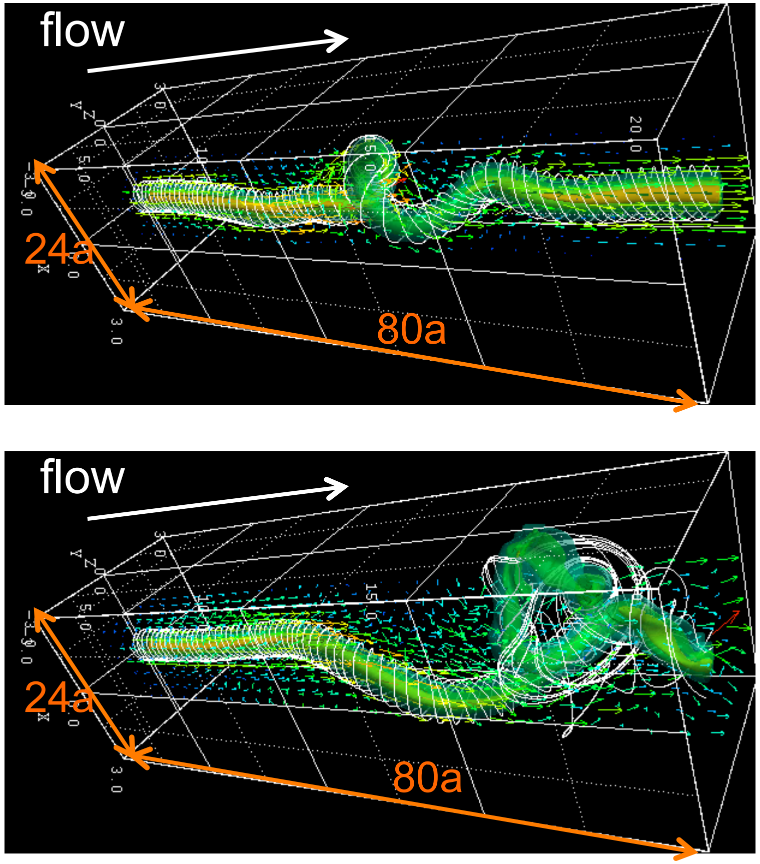
Since 60’s, Z-pinch are known to be highly unstable to current-driven instabilities:

- sausage
- kink modes

May potentially destroy the jet, as in numerical simulations…

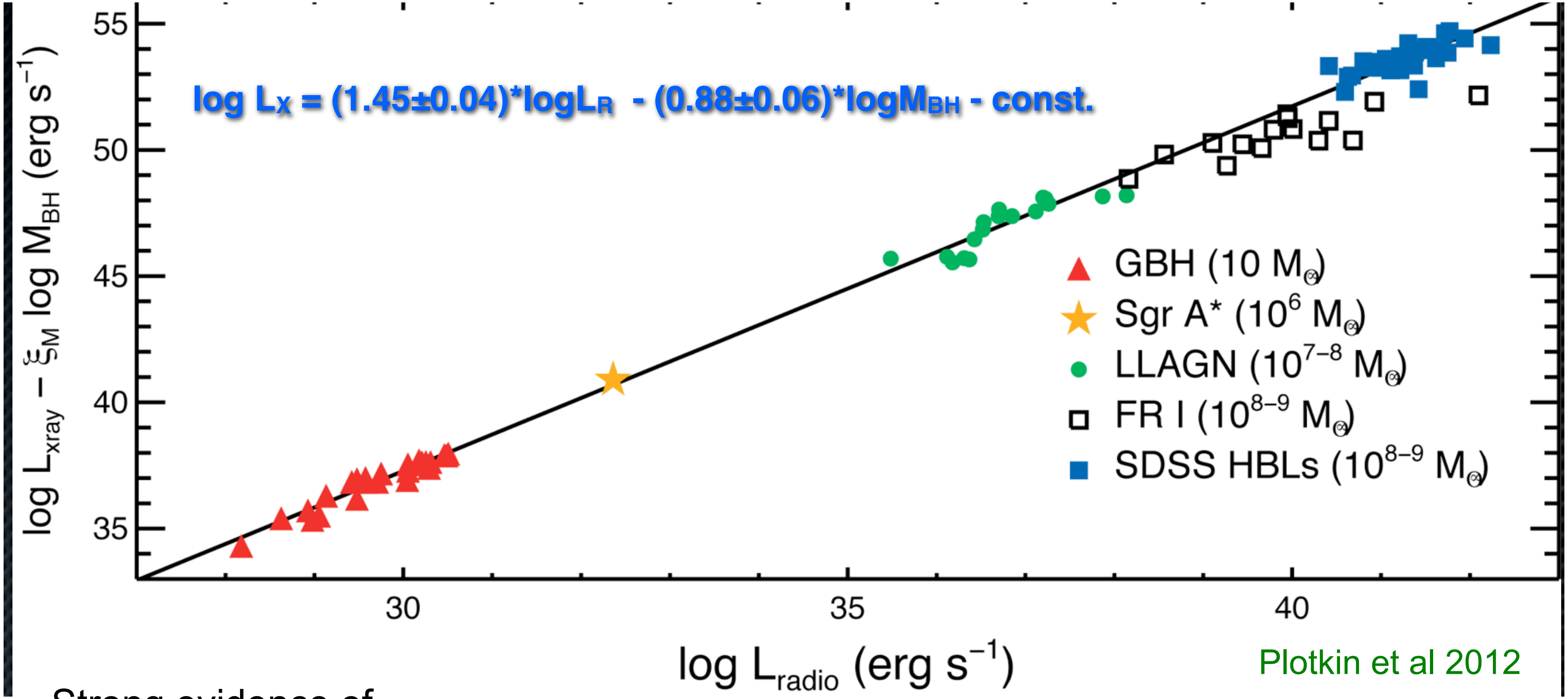
Why are real jets so stable ?

HINT: transport barrier due to differential rotation of magnetic surfaces => disk ?



Mizuno et al 2013

Fundamental plane of BH activity



Plotkin et al 2012

Strong evidence of

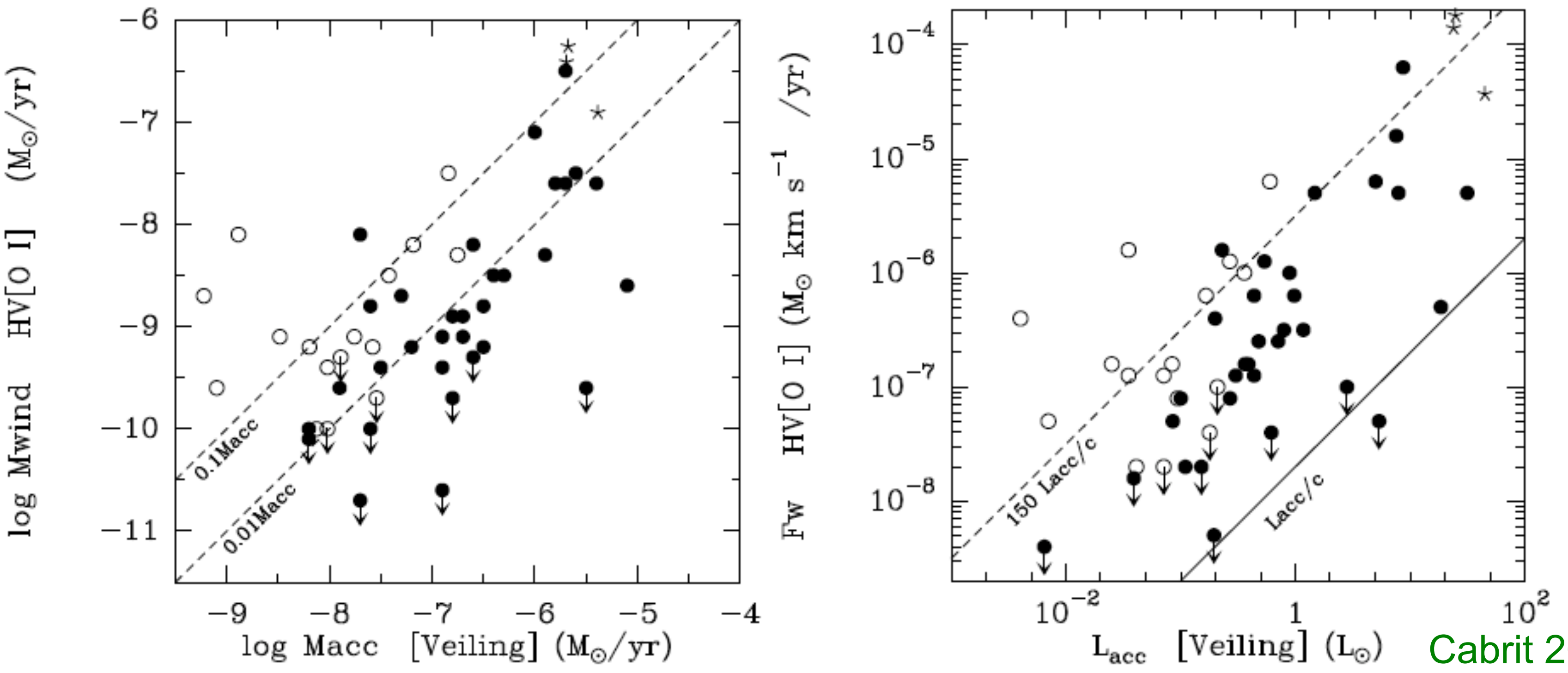
(1) A correlation between

- Accretion (using X rays as a proxy)
- Ejection= steady jets, emitting self-absorbed synchrotron emission (radio)

(2) Physics scaling with BH mass

=> X-ray Binaries could be seen as micro- or even nano-quasars

Accretion-Ejection correlation in YSO



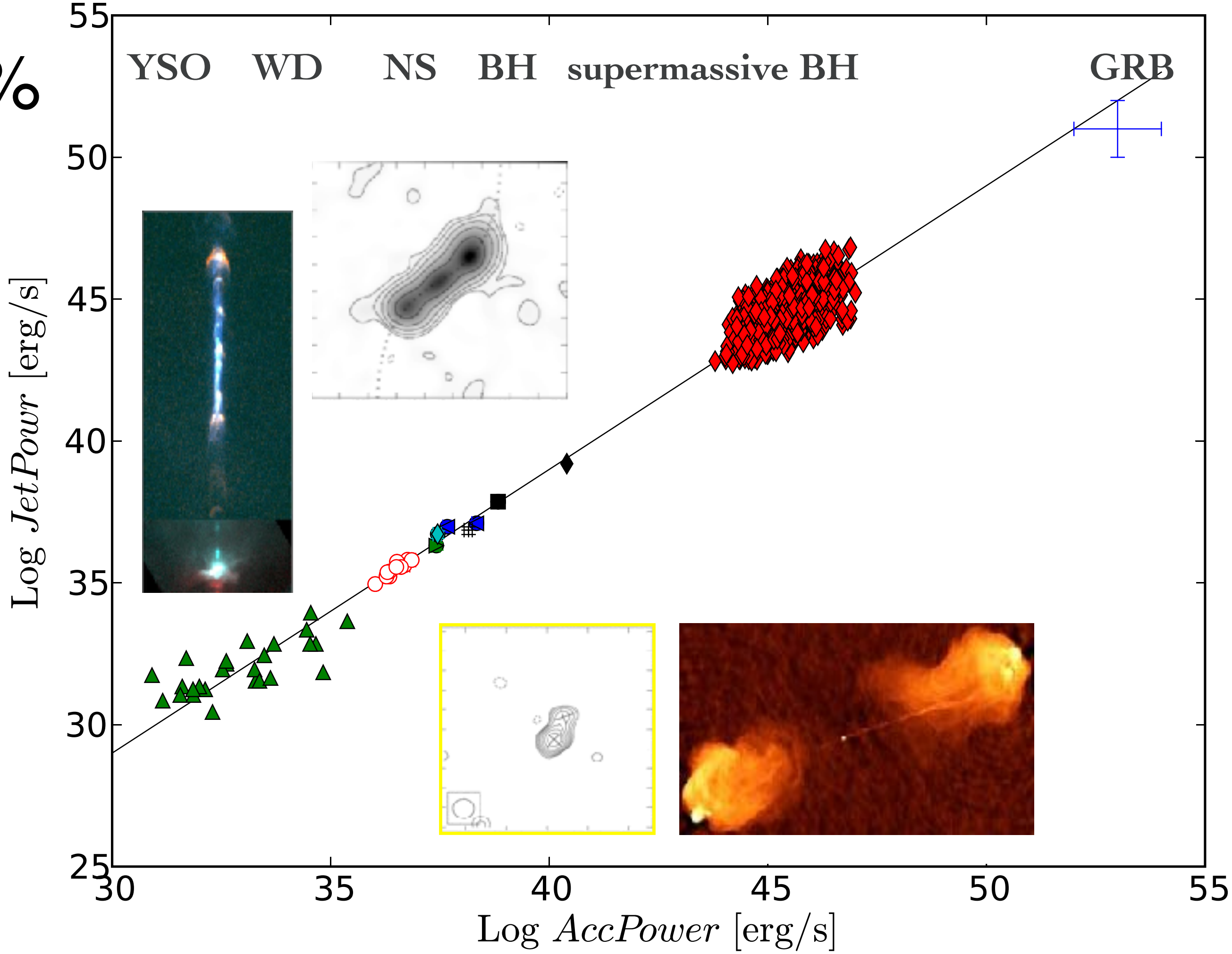
Cabrit 2007

(i) Mass loss in wind correlated with disk accretion rate

(ii) $F_w = M_{wind}.V_{wind}$ jet momentum thrust >> radiation thrust: YSO jets cannot be radiatively driven

A universal correlation..?

10%

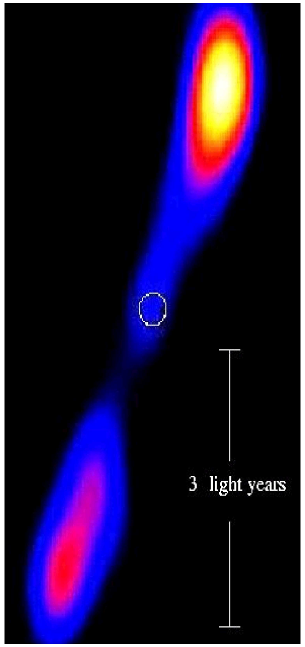


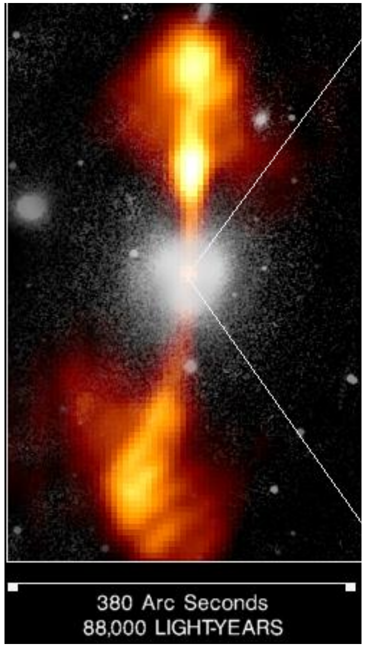
Sterling et al 01
Crocker et al 07
Tudose et al 08

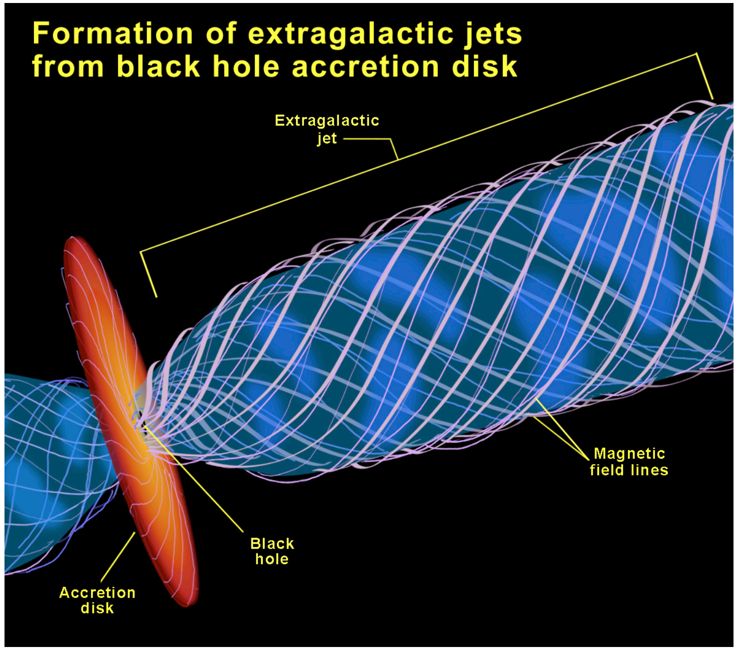
Regardless of the nature of the central object !

=> Look for an **interdependent accretion-ejection process**

Accretion-ejection in Astrophysics



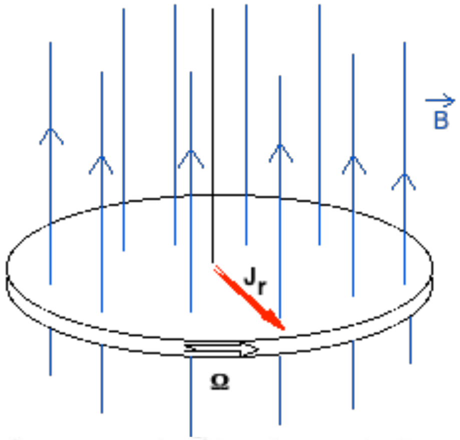




Main assumption: a large scale magnetic field threads the disk

Disk as a unipolar inductor: 2 jets

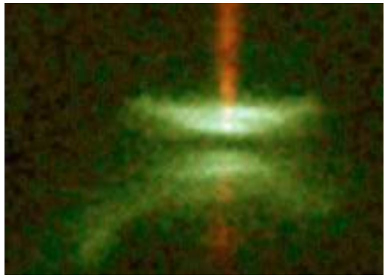
Barlow wheel (1822): unipolar induction effect

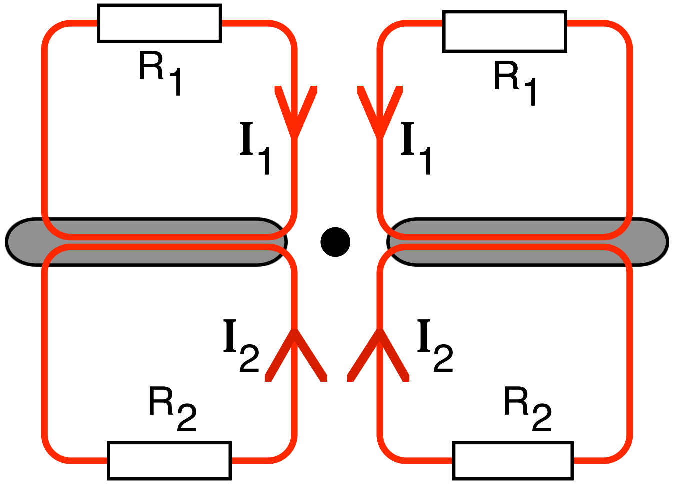


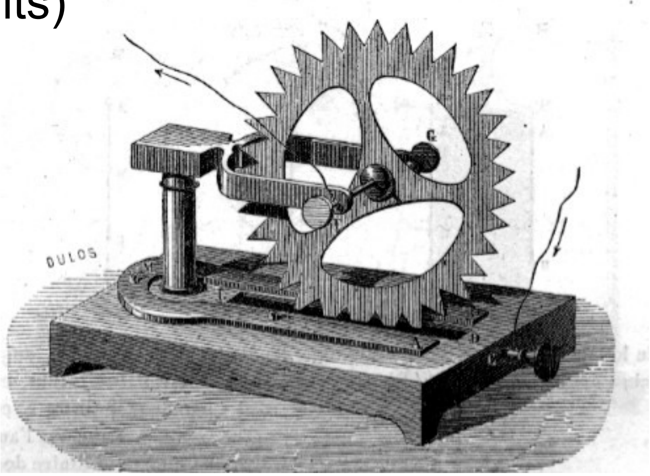
1) Gravitation + Magnetic Field => e.m.f

$$e = \int \Omega r \, B_z \, dr$$

2) e.m.f => electric current (2 independent circuits)

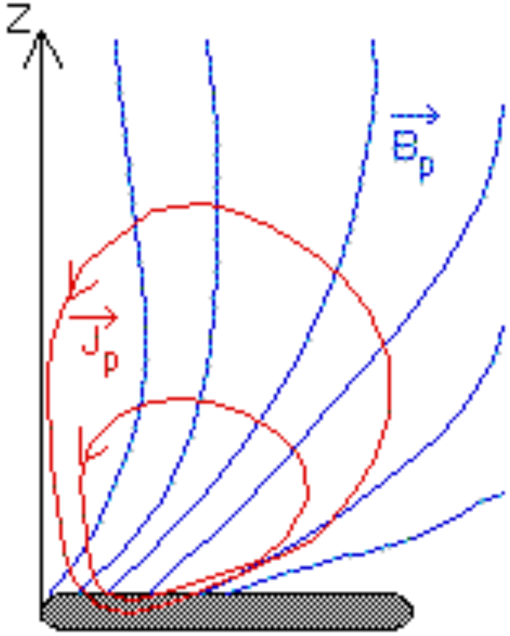






3) Conversion of mechanical energy into MHD Poynting flux
4) Existence of a torque braking down the disk => **accretion**
5) If $R_1 \neq R_2$, asymmetric jets are produced (mass flux, velocity)

The role of the poloidal electric current (Bphi)



Ideal MHD: Jet acceleration and confinement

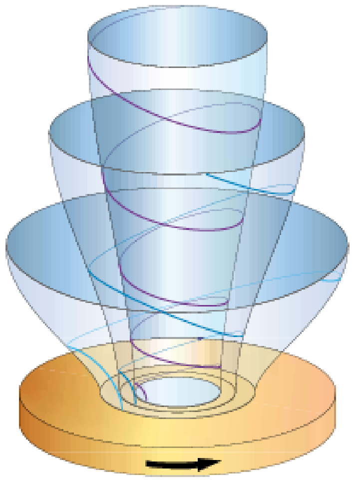
Collimation due to magnetic hoop-stress (toroidal field) Heyvaerts & Norman 89, 03, Ferreira 97, Okamoto 01

$$F_\phi = \frac{B_p}{2\pi r}\nabla_\parallel I$$

$$F_\parallel = -\frac{B_\phi}{2\pi r}\nabla_\parallel I$$

$$F_\perp = B_p J_\phi - \frac{B_\phi}{2\pi r}\nabla_\perp I$$

- Depends on ***asymptotic*** current distribution I(r)
- Not all field lines can be collimated: outer pressure required



$$\dot{M}_a \propto r^\xi$$

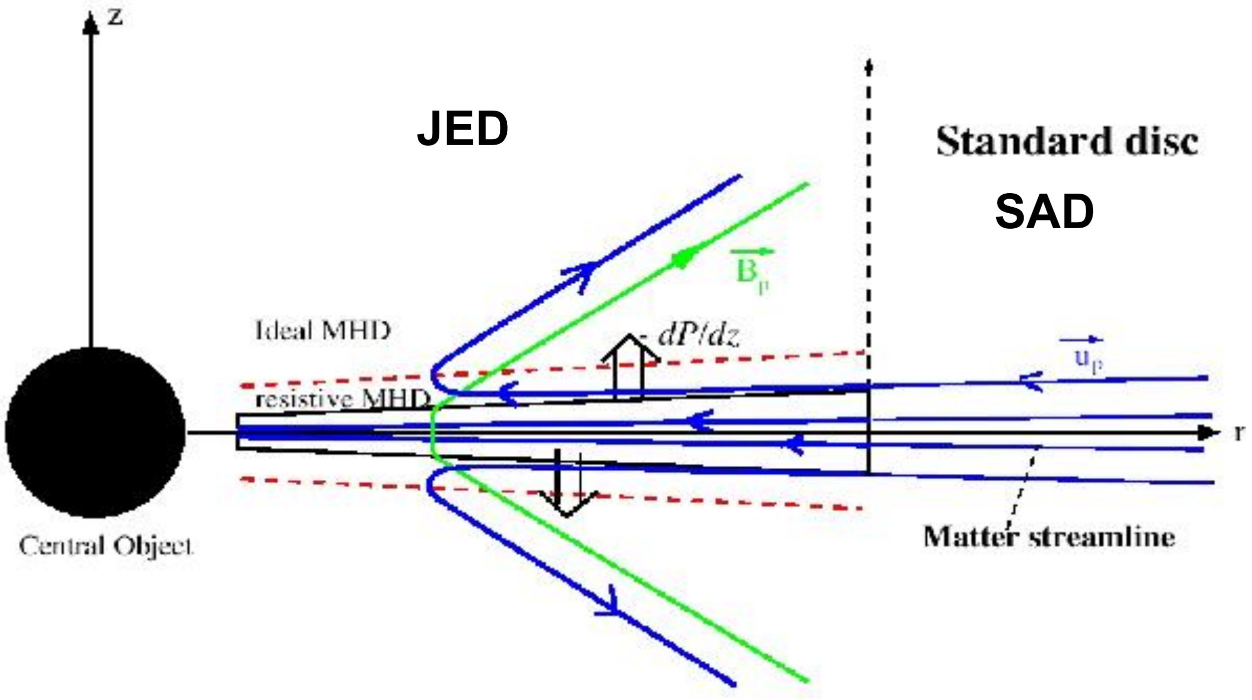
Resistive MHD: Disc torque and mass loss

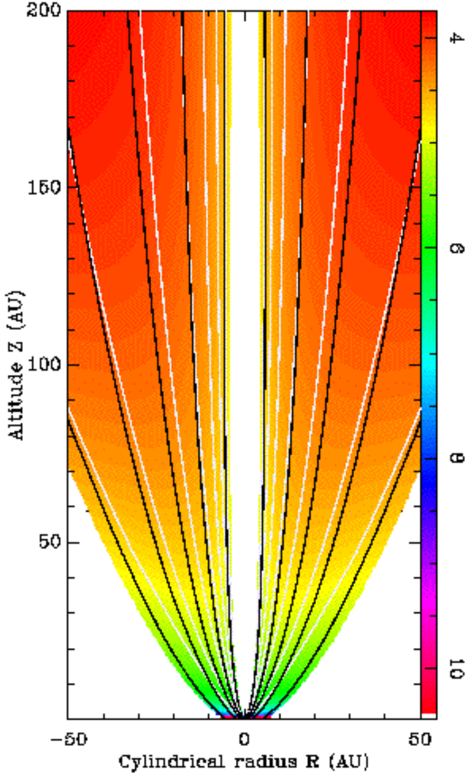
The disc ejection efficiency ξ must be computed as function of the disc parameters

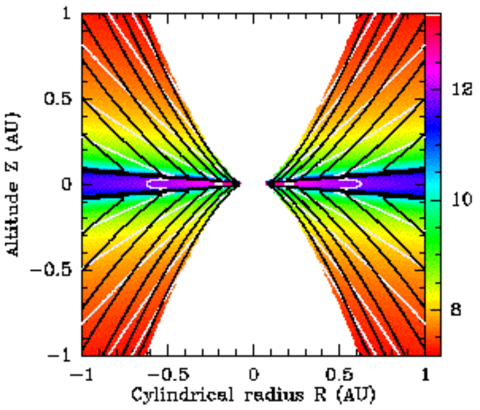
=> NEW MHD flow model where parameter space is constrained by smoothly crossing critical points

Jet Emitting Disks (JEDs)

Ferreira & Pelletier 93,95
Ferreira 97
Casse & Ferreira 00a,b
Ferreira & Casse 04





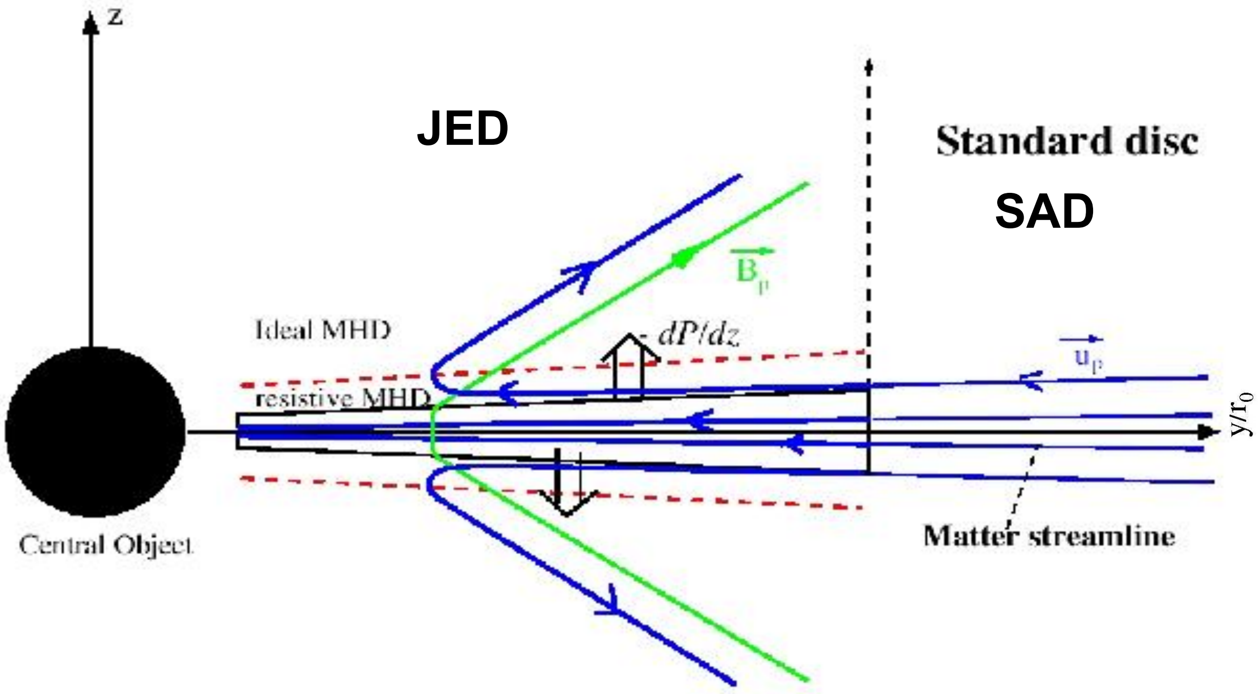


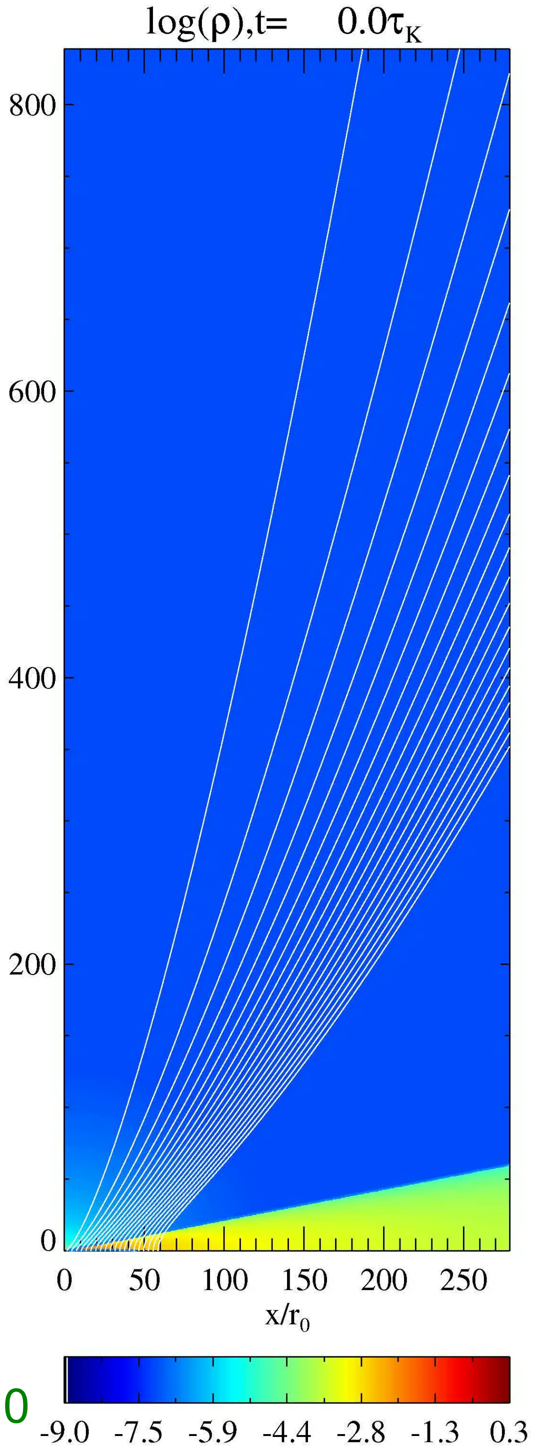
JED: magnetic field close to equipartition

- all disk angular momentum carried away by jets
- sizeable fraction of released accretion energy also
- accretion is supersonic => spectrum affected
- still only model linking accretion to ejection

BUT requires nevertheless a turbulence (mass diffusion) within the disk

Jet Emitting Disks (JEDs)





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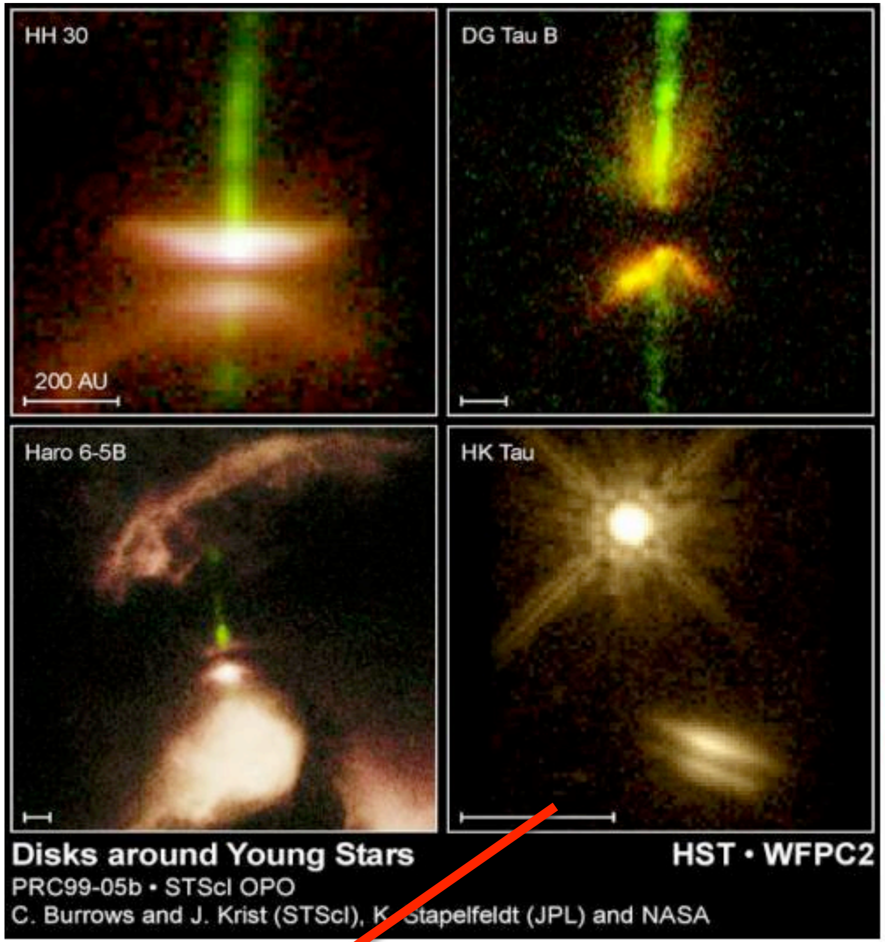
Murphy et al 10

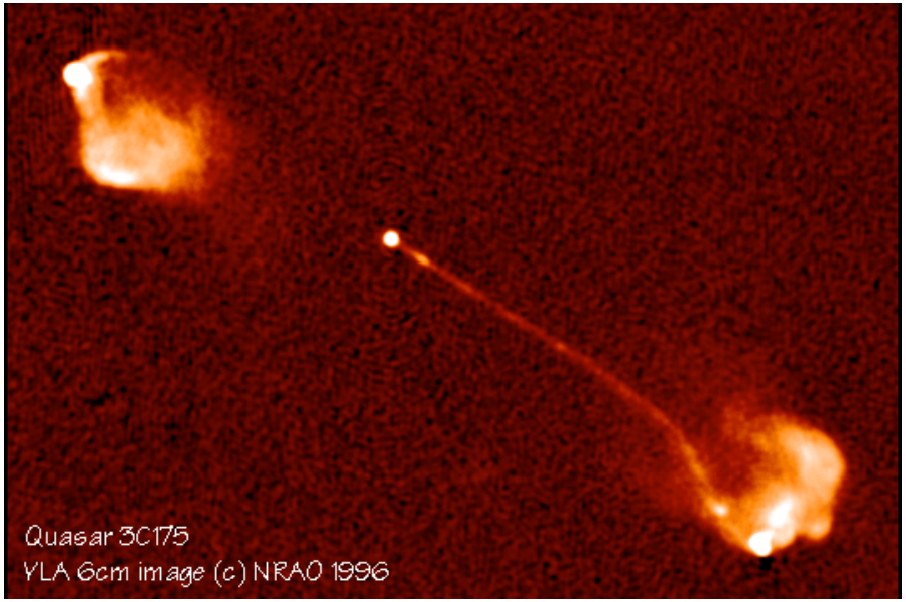
But JEDs are not the whole story



Disks around Young Stars

PRC99-05b • STScI OPO

C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA



Quasar 3C175

VLA 6cm image (c) NRAO 1996

Only ~ 10% of AGN have jets

Not all YSO accretion disks have jets

=> Another mechanism of disk angular momentum removal must be at work

Back to the old idea of radial transport via turbulence (SAD)

Turbulence: ok, but which instability?

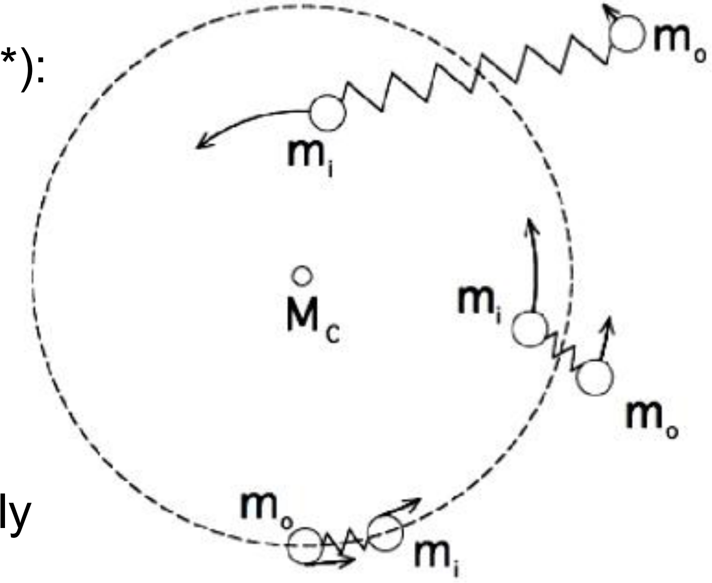
Shakura & Sunyaev 1973: the alpha prescription

BUT Keplerian disks are Rayleigh stable: 20 years of theoretical efforts within the context of hydro disks…

…Until **Balbus & Hawley 1991**: magnetic fields where introduced in disks

⇒ Existence of an ideal MHD instability (*):
Magneto-Rotational Instability (MRI)

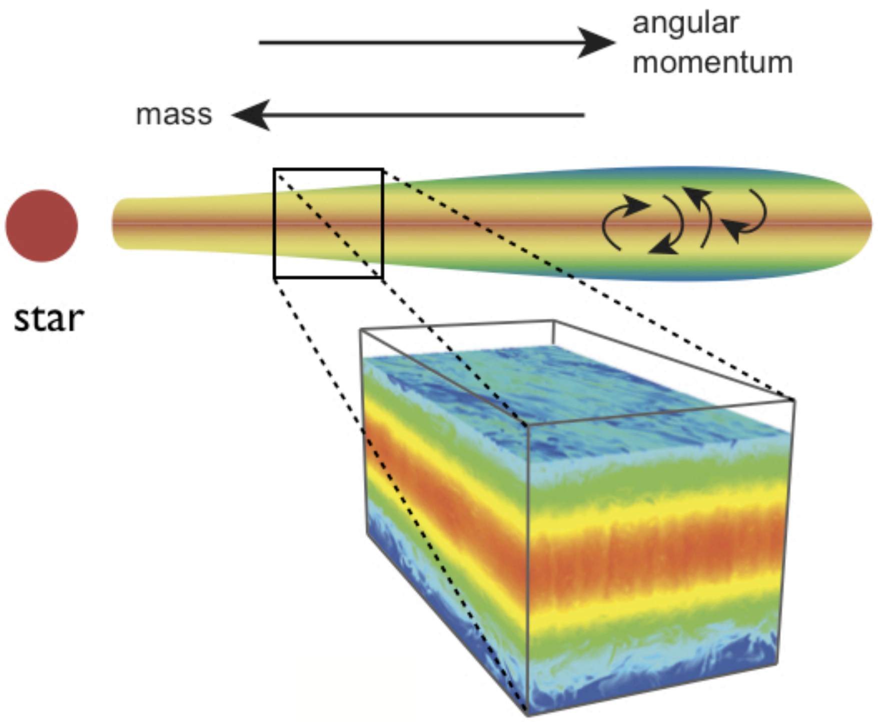
- Requires a sub-equipartition field
- Non-linear stage is a self-sustained TURBULENCE



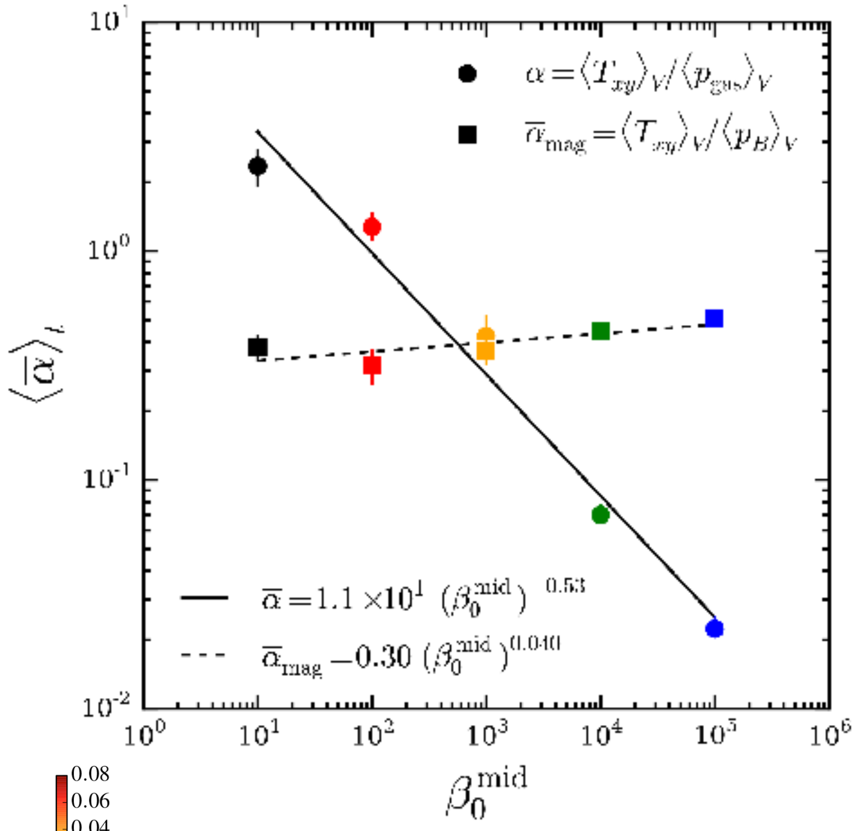
(*): requires a fully ionized plasma, partially quenched in non-ideal contexts (outer CV and YSO disks)

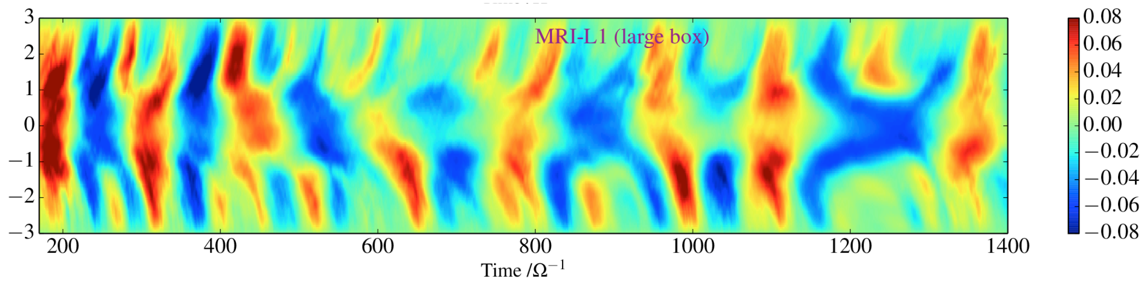
Shearing box (local) simulations

Shakura-Sunyaev viscosity $\alpha_v = 10\sqrt{\frac{B^2/2\mu_o}{P}}$



disk turbulence in local simulation





Hawley et al 1995
Pessah etal 07
Lesur & Longaretti 07
Latter et al
Salvesen et al 16

Shearing box (local) simulations

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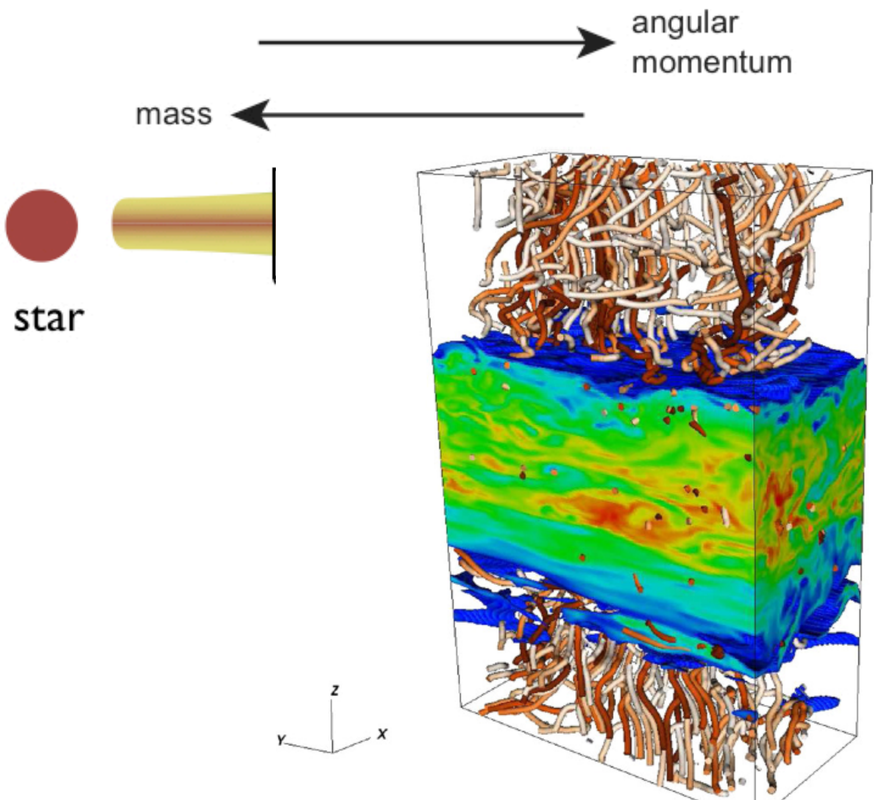
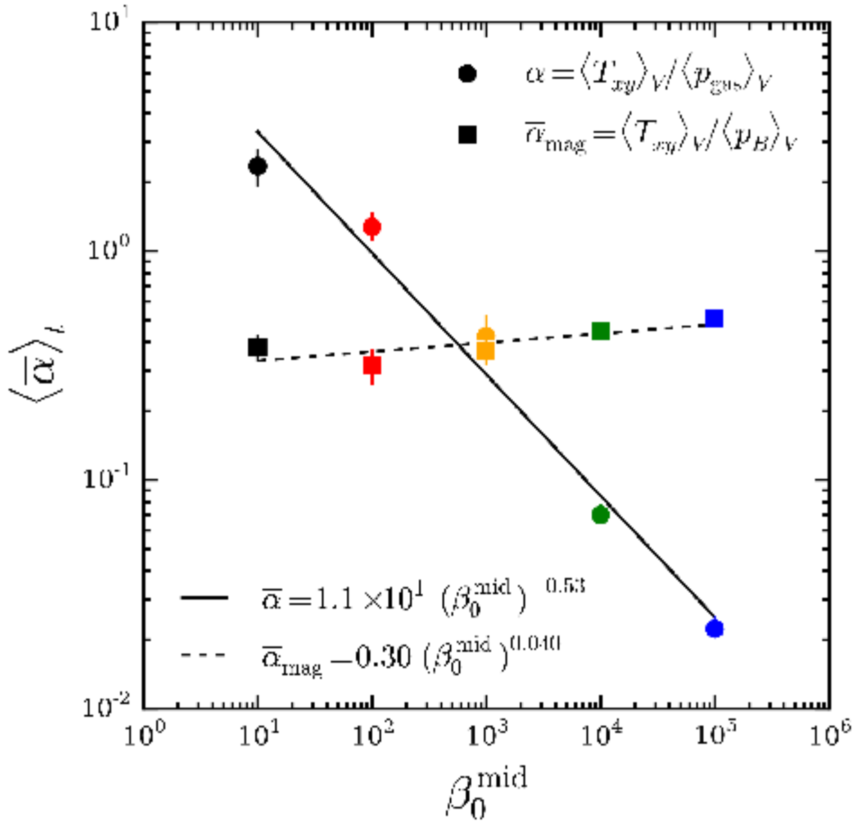


Fromang et al 2013, Bai & Stone 2013



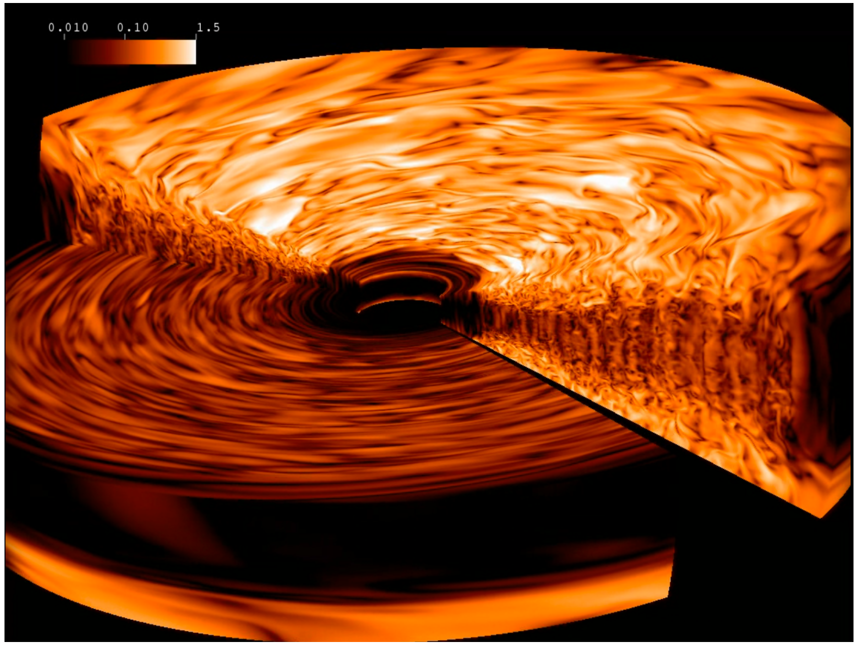
Hawley et al 1995
Pessah etal 07
Lesur & Longaretti 07
Latter et al
Salvesen et al 16

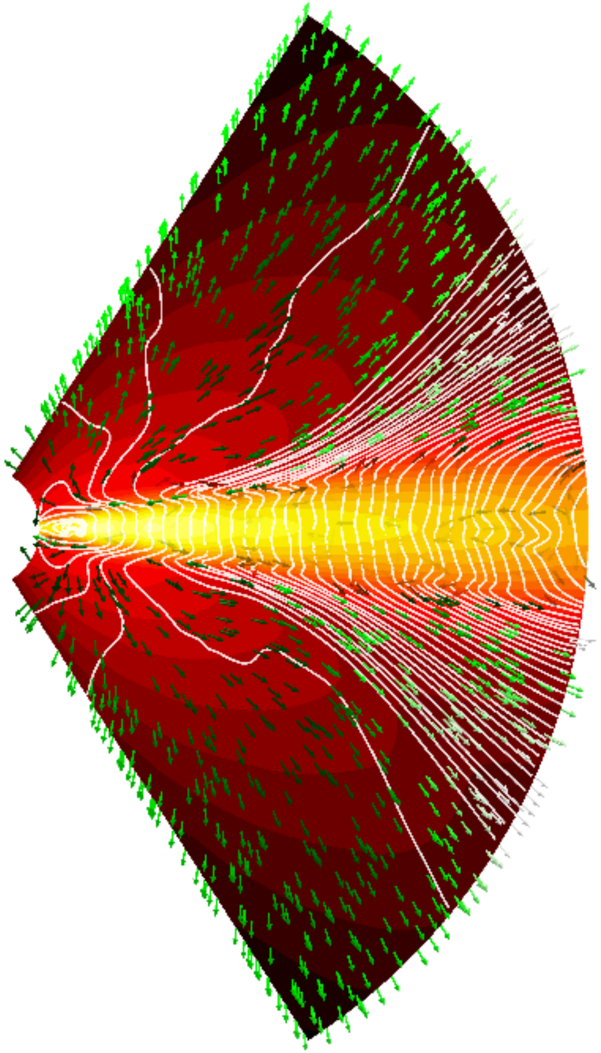
⇒ Discovery that large scale Bz enhances transport via a laminar torque = mass loss : winds and/or jets !!

Need to go for global 3D simulations

« MRI-driven » winds: global simulations

Flock et al 11





Suzuki & Inutsuka 14
Gressel et al 15
Zhu & Stone 17
Béthune et al 17

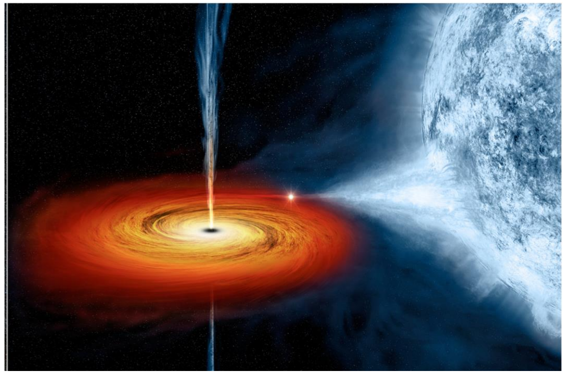
Without large scale Bz: accretion with no wind

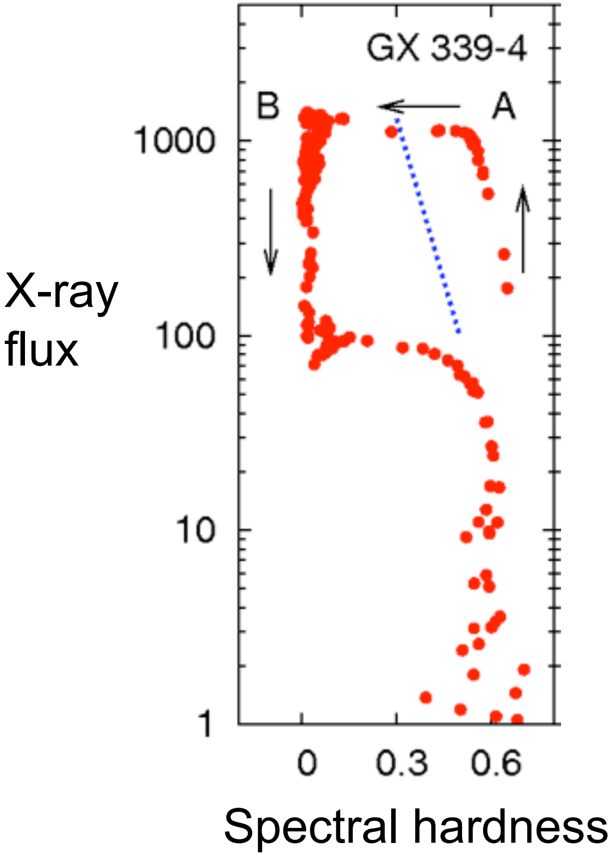
With large scale Bz: enhanced accretion speed and winds… or self-confined jets ??

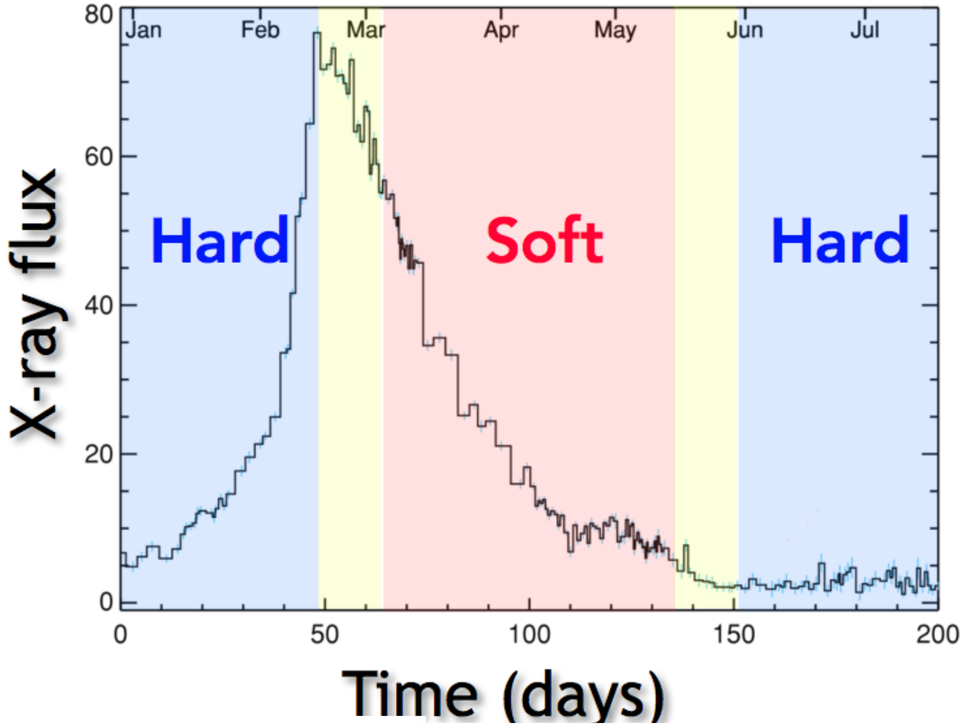
Numerical challenge: following 3D turbulence and addressing large spatial scales for flow collimation

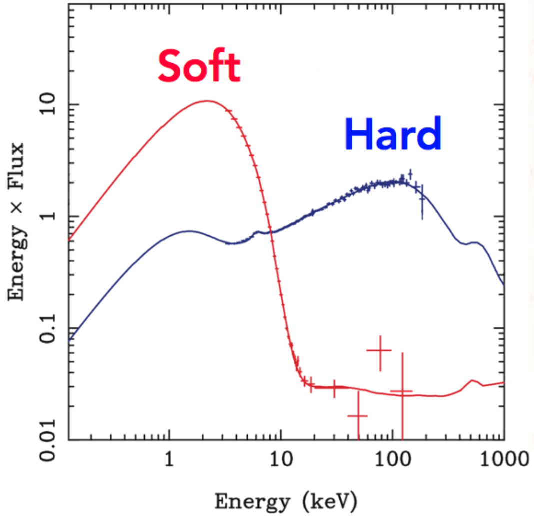
Hint of flux accumulation: increasing magnetization?

Outbursting cycles in XrB: GX339-4





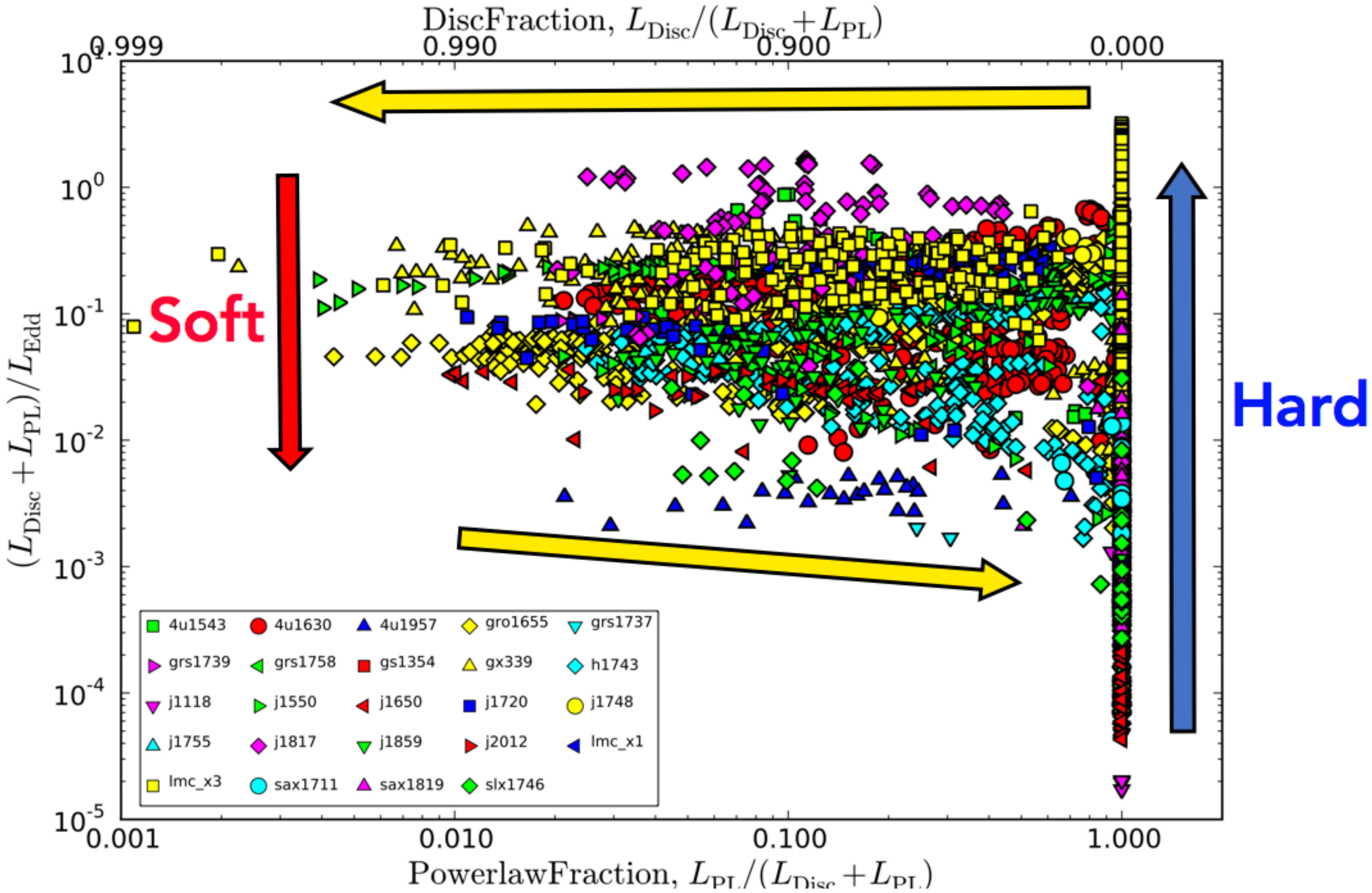




Evolution on days, cycle on almost a year

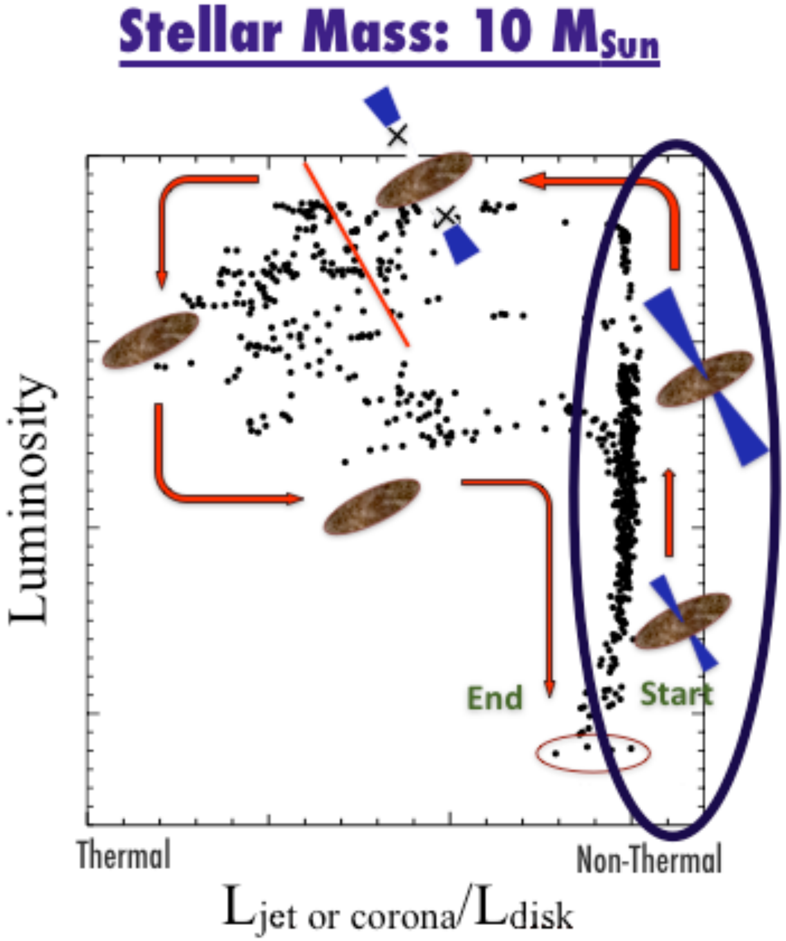
Inner dynamical time on ms

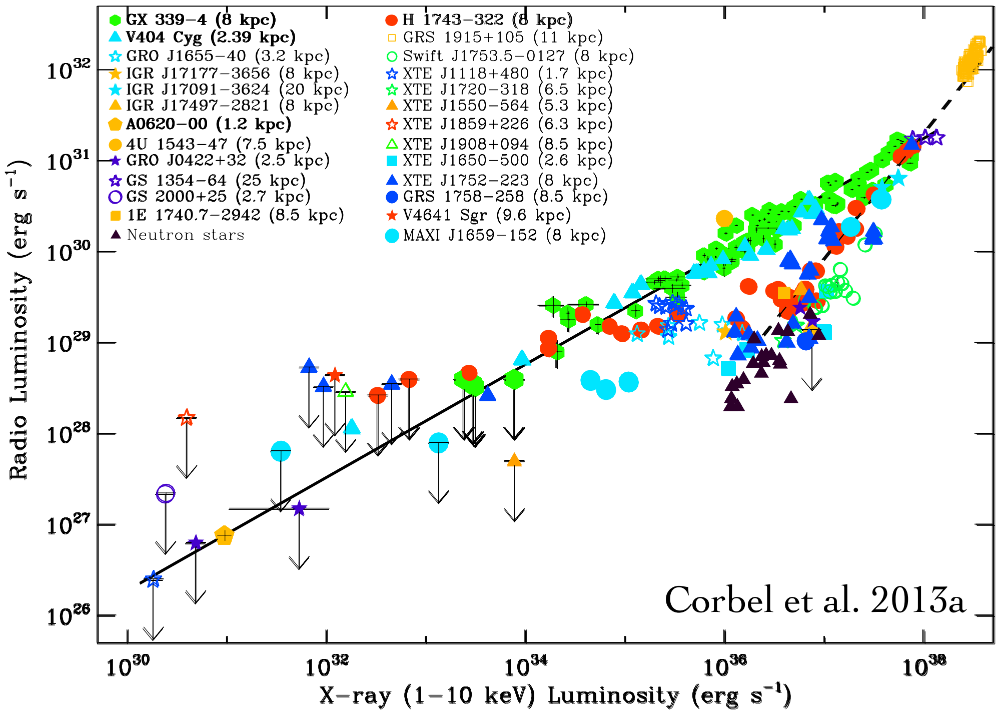
A quite generic behavior



Dunn et al 09

Accretion-ejection correlation

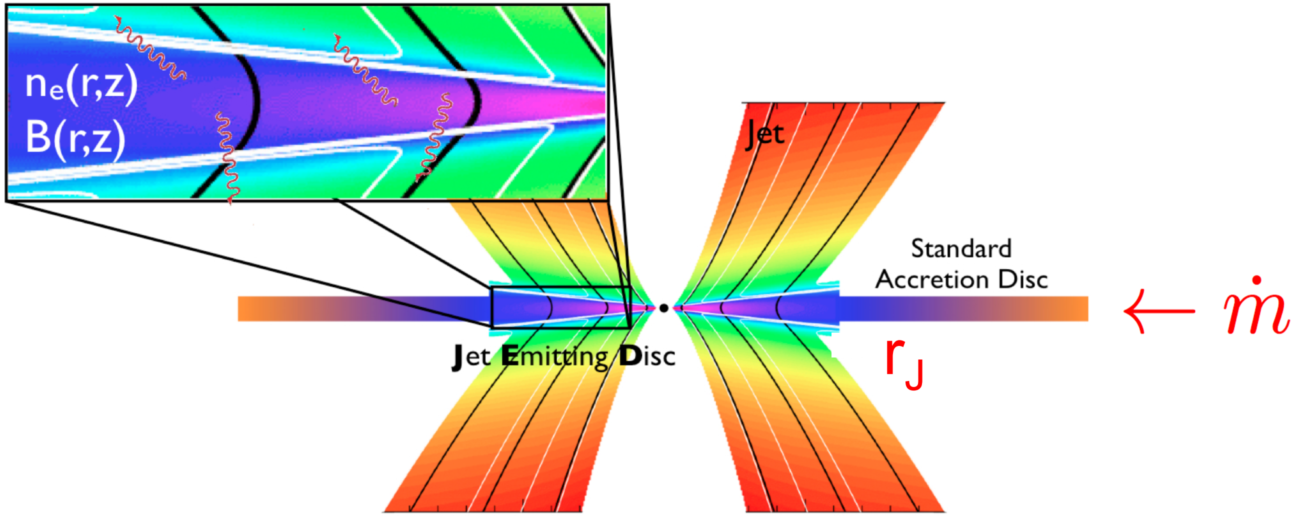




Corbel et al. 2013a

- Jets always associated with HARD states, no-jet always in SOFT states
- Each « state » lasts for several days, object evolves on time scales >> local dynamical time scale

The JED-SAD paradigm



Assume that disk magnetization varies radially such that

- MRI-driven accretion from outer regions down to r_J (SAD)
- Jet-driven accretion from r_J down to BH (JED)

=> Use disk accretion rate $\dot{m}$ and transition radius r_J as free parameters

=> Compute self-consistent energy equation + spectrum taking into account:

- JED and SAD dynamical properties
- optically thin emission (Synchrotron, Bremsstrahlung)
- local and external comptonization of soft photons
- collisional Coulomb coupling between ions and electrons
- advection of energy

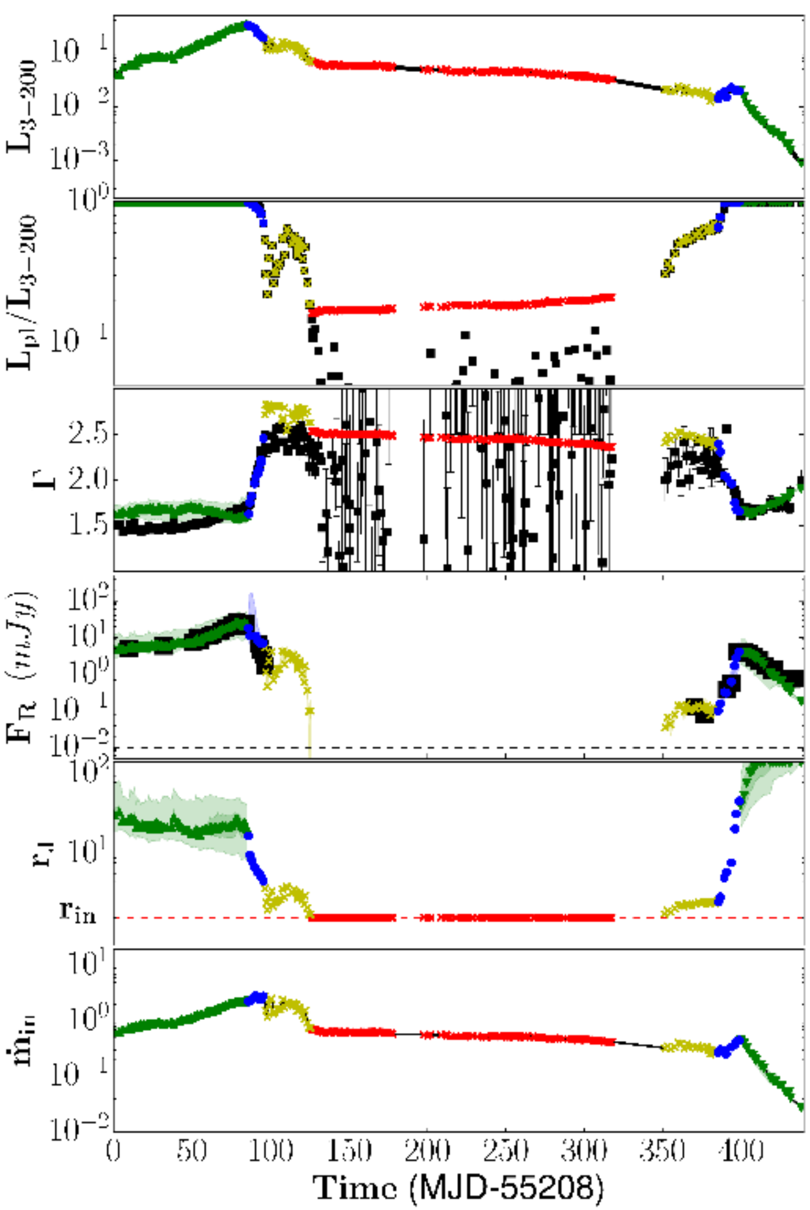
The 2010-2011 outburst of GX339-4

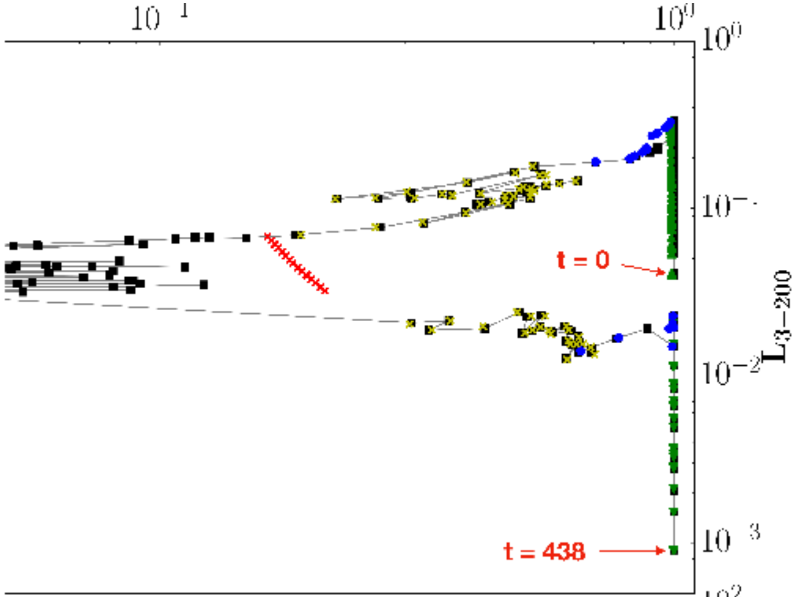
X-ray flux

Hardness

Spectral index

Radio flux





- Whole cycle well reproduced
- Only 2 parameters for much more constraints (spectral shape, flux in X & radio)

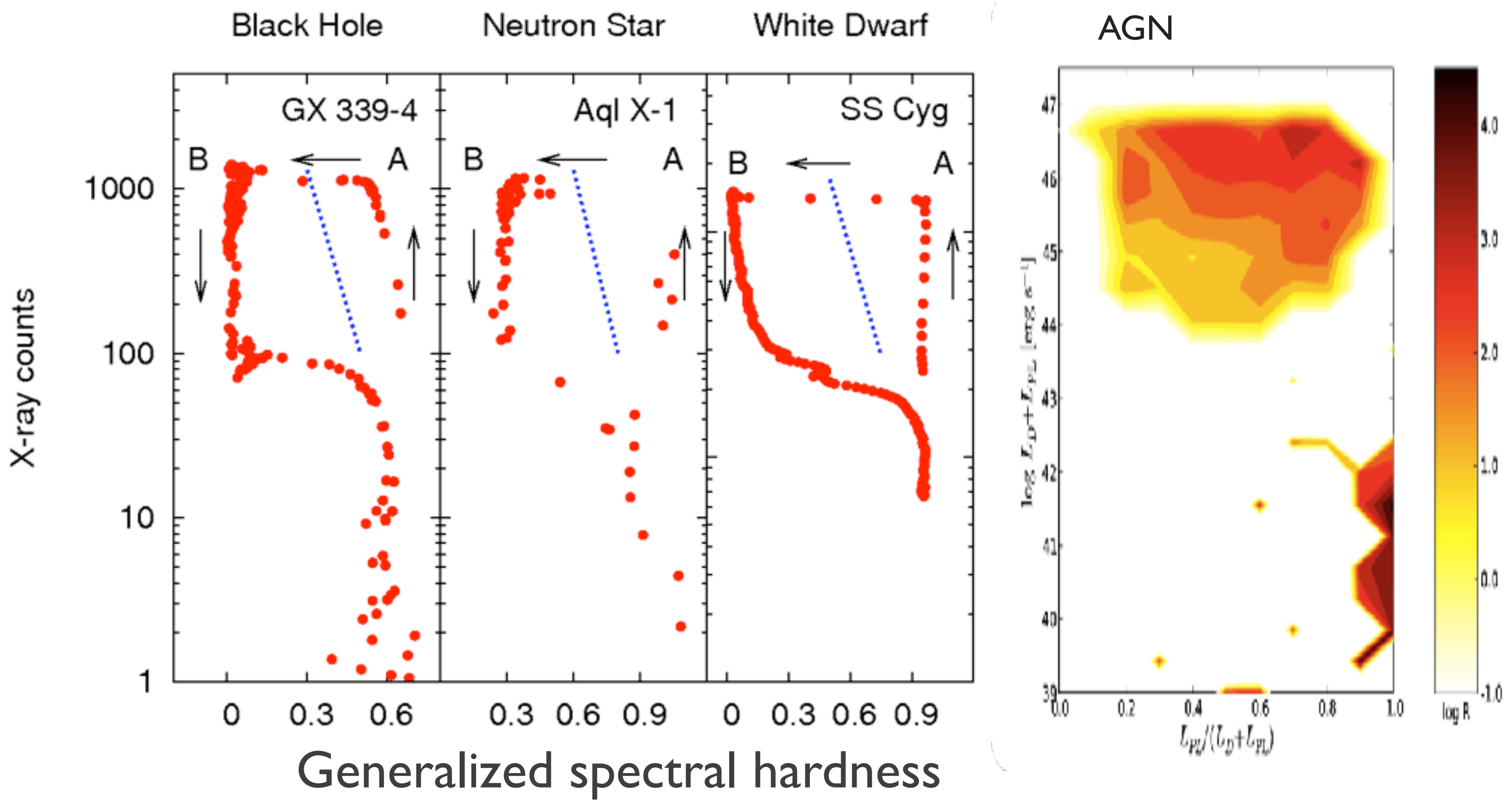
Is the JED-SAD geometry generic?

How do we explain the required temporal variations ?

Marcel et al

Accretion states of compact objets

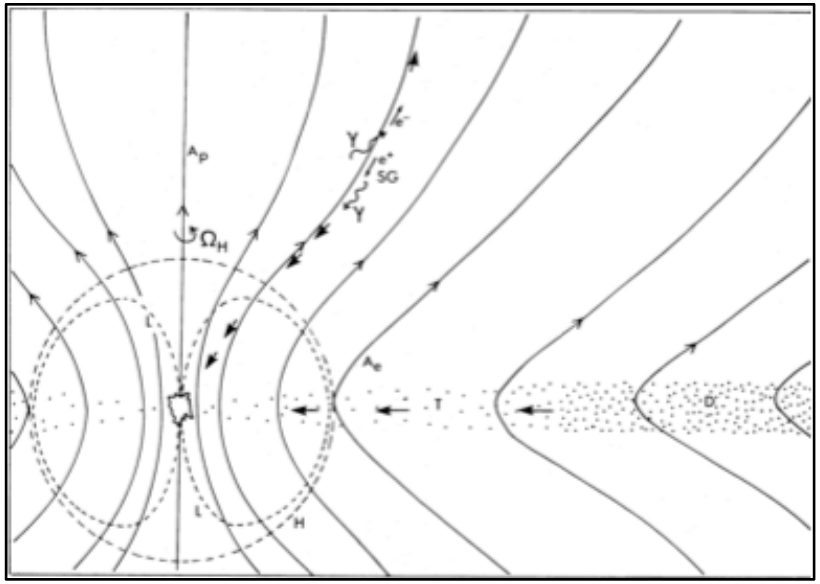
Körding et al, 2006, 2008



Does NOT seem to require a black hole, only the surrounding accretion disk.

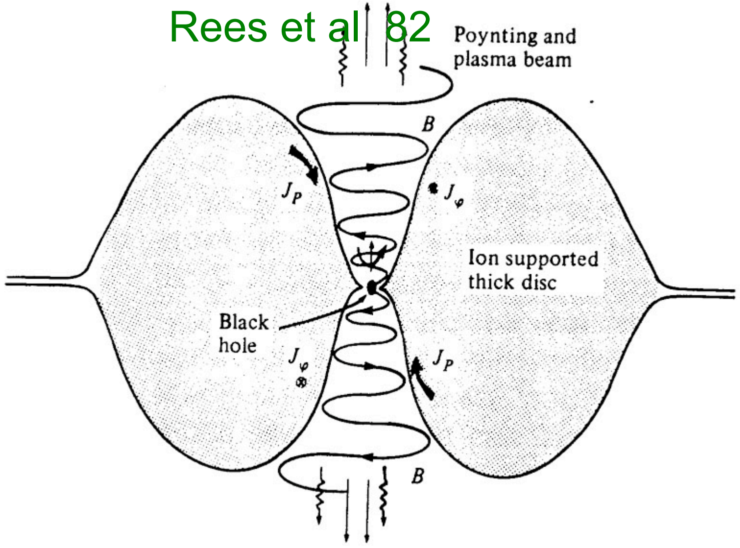
But what would be its influence ?

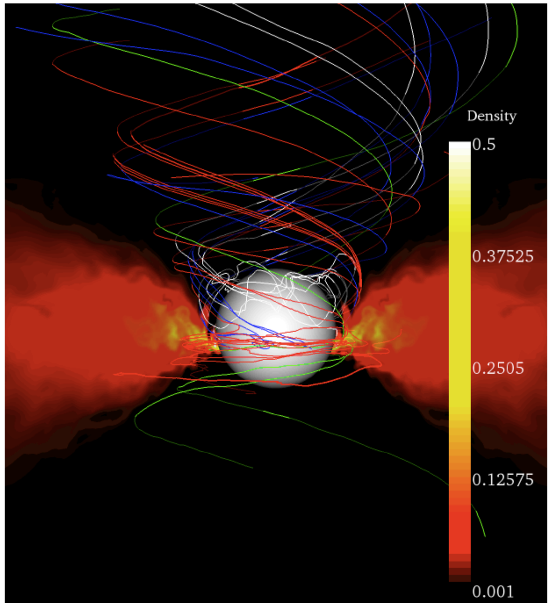
Large scale Bz field and rotating black holes: the Blandford-Znajek (1977) process



Blandford & Znajek 77

Rees et al 82





Punsly, Igumenshchev & Hirose 09
Tchekhovskoy et al 10,11
McKinney et al 12

- Extract BH rotational energy
- Drive relativistic jet (spine)
- Jet power depends on magnetic flux brought in by outer accretion disk

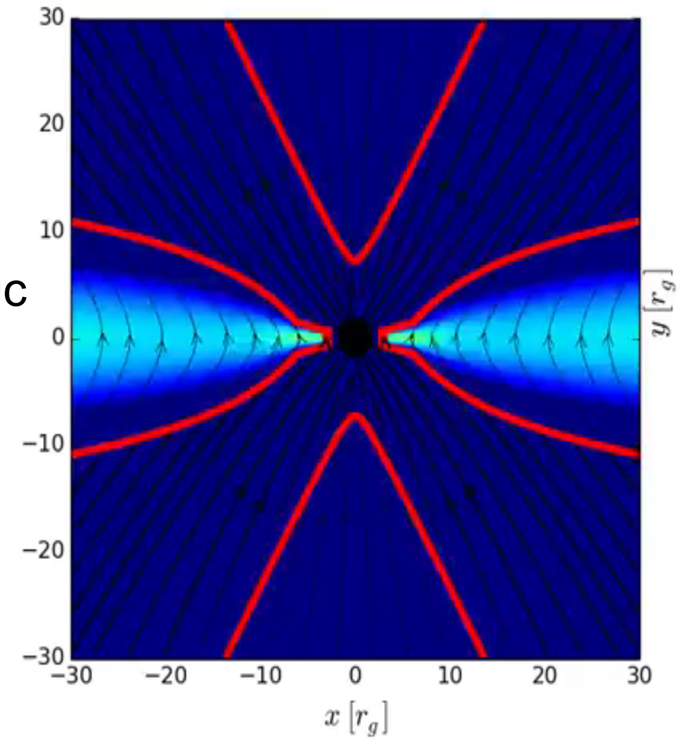
=> Numerical challenge: density floor and huge spatial scales in 3D GRMHD

Black lines: magnetic field

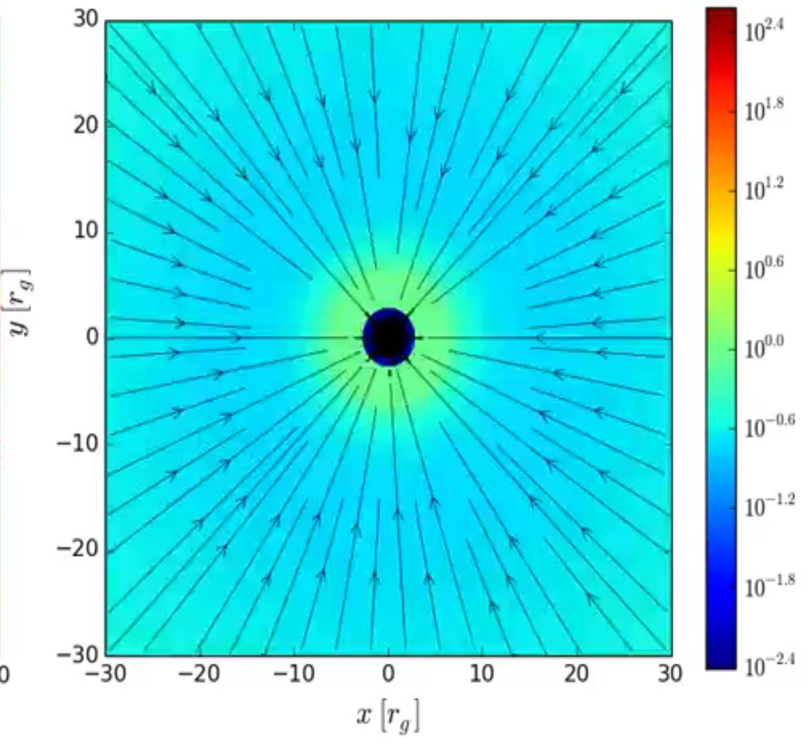
Red line: magnetic energy density in equipartition with rest mass energy density

Color: density

Meridional view



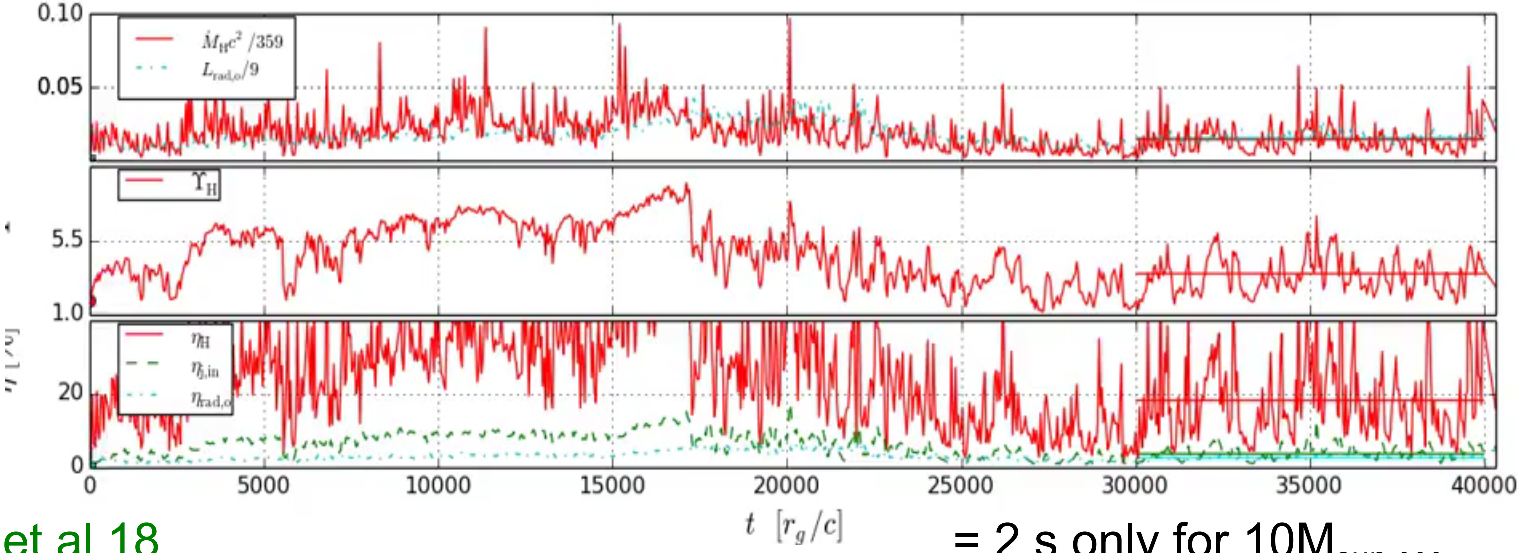
Pole-on view



Accretion rate

Magnetic flux

Efficiency

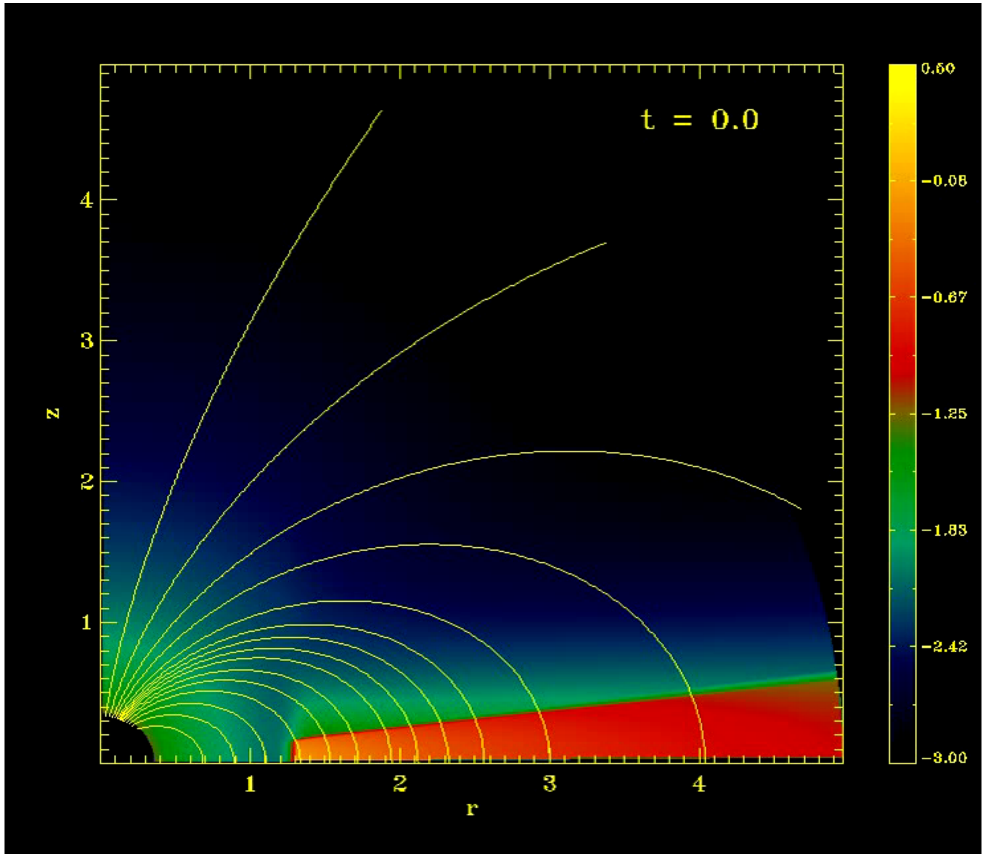


Morales Teixeira et al 18

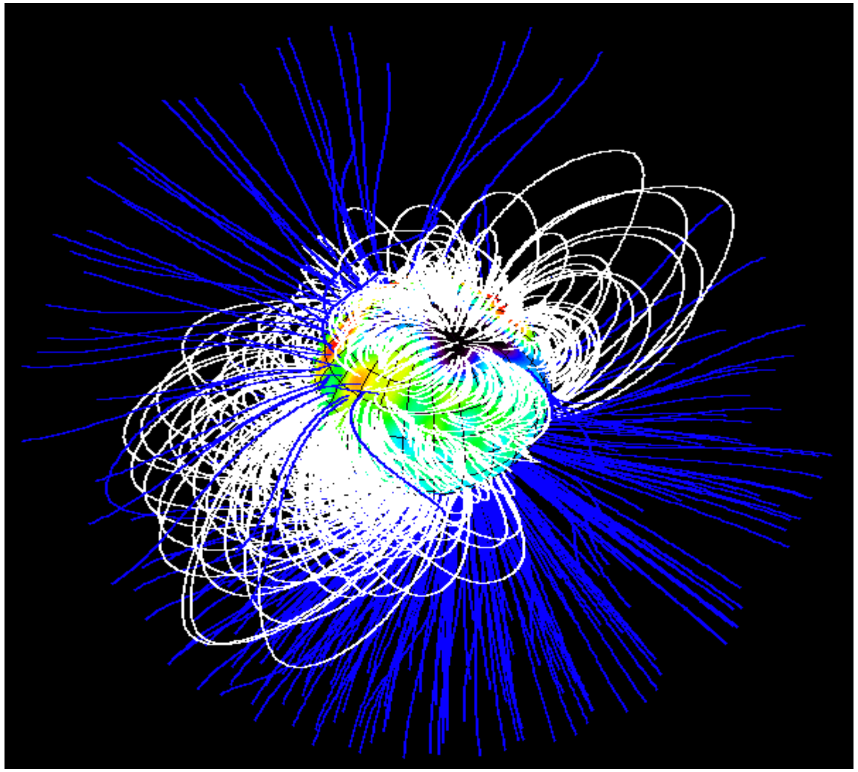
= 2 s only for $10M_{sun}$ …

Magnetic star-disk interaction: YSO, neutron star, white dwarf

2D MHD simulations Zanni & Ferreira 09,13



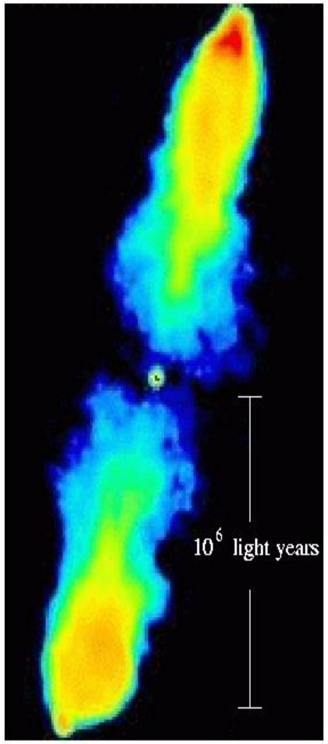
3D YSO magnetic field maps: Donati et al



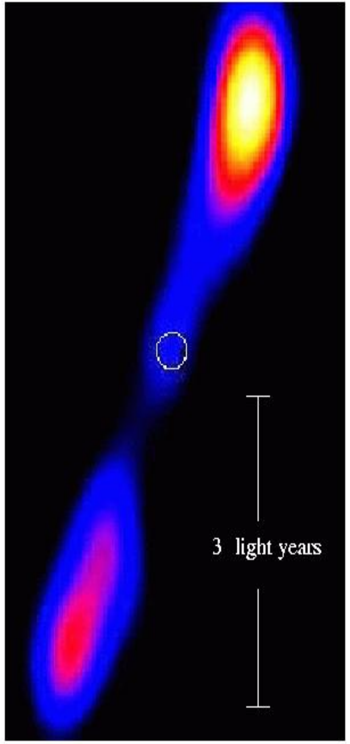
Unsteady ejecta @ interface:
- May provide efficient spin down of rotating object
- May affect large scale jet dynamics (collimation, jet emission via shocks)
- Numerical challenge: need to go 3D

Conclusions

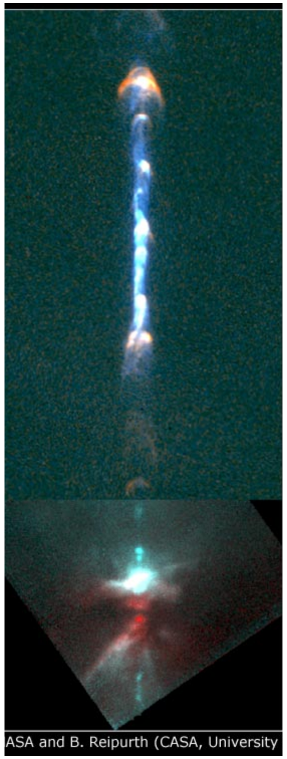
AGN



X-ray Binary



YSO


ASA and B. Reipurth (CASA, University

Accretion-Ejection is a universal process (possibly also GRB, TDE), mostly independant of central object

Complex interplay between disk turbulence and large scale jets

Requires a feedback between
- Throrough analytical models
- 3D HP MHD computations (high res, long time scales, large spatial scales)

Process relies on the existence of a large scale magnetic field
- of unknown origin
- barely detectable

But this invisible agent is ultimately shaping the accretion-ejection process and its long term variability