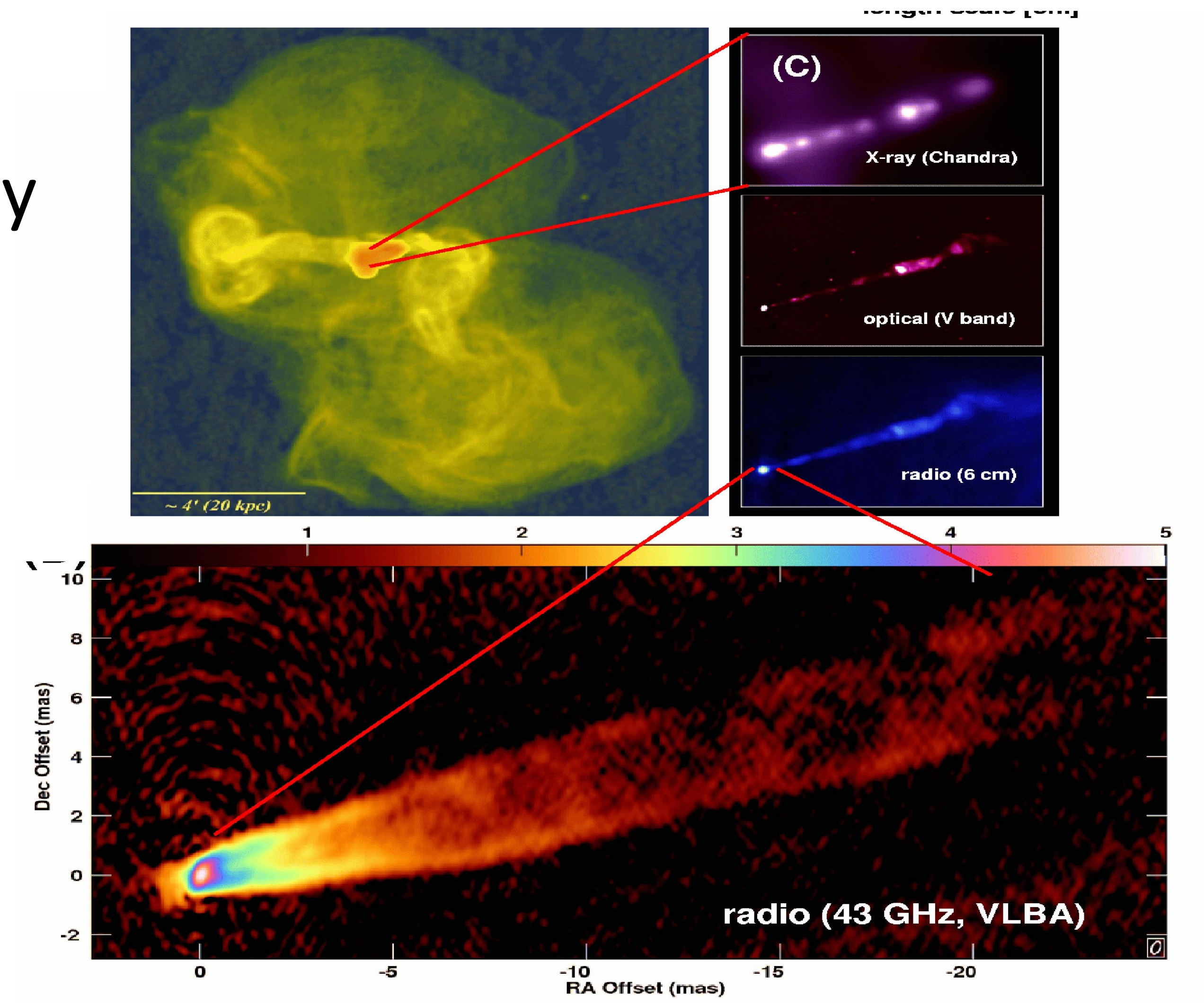
From jets to disks: Accretion-Ejection theory

Jonathan Ferreira



Collaborators

N. Zimniak , T. Jannaud, J. Jacquemin-Ide, G. Marcel, P.-O. Petrucci, S. Barnier, G. Lesur, G. Henri, S. Chakravorty, R. Belmont, J. Malzac, S. Corbel, J. Rodriguez

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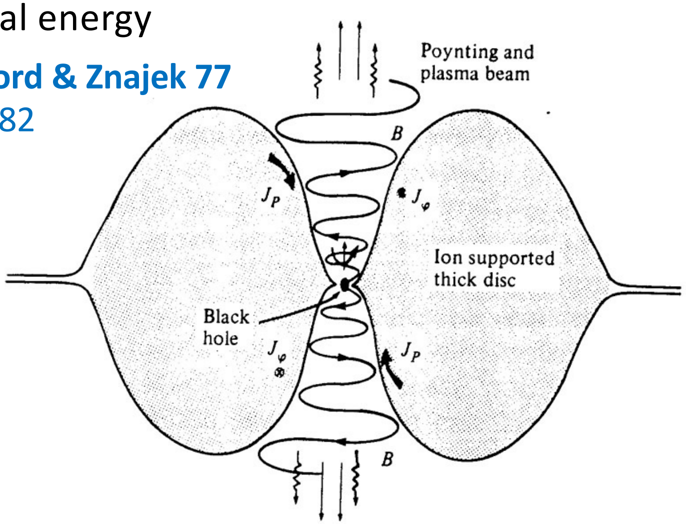
Self-collimated jets: need of a large scale B_z field

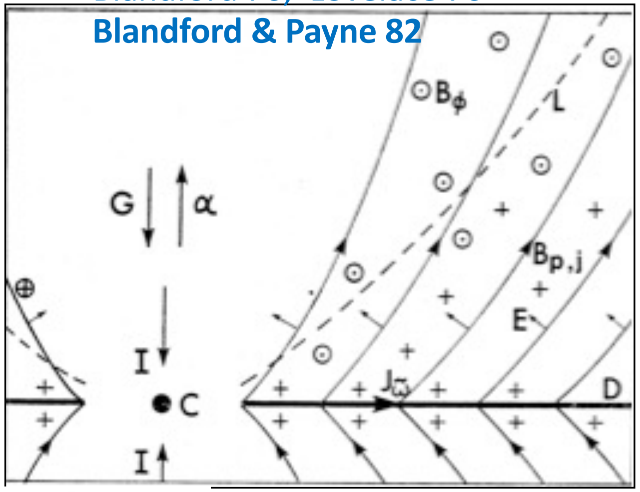
Important only near BH: extracting BH rotational energy

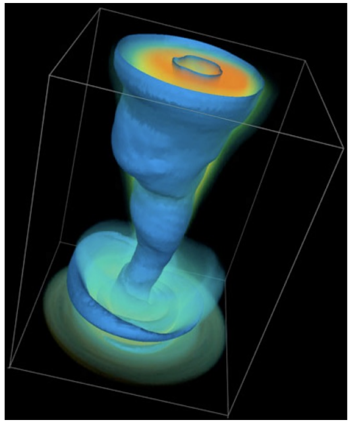
Blandford & Znajek 77
Rees+ 82



BZ
or
BP ?

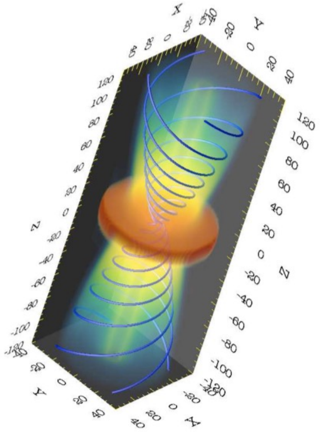
Distributed in the disk: extracting accretion energy
Blandford 76, Lovelace 76
Blandford & Payne 82





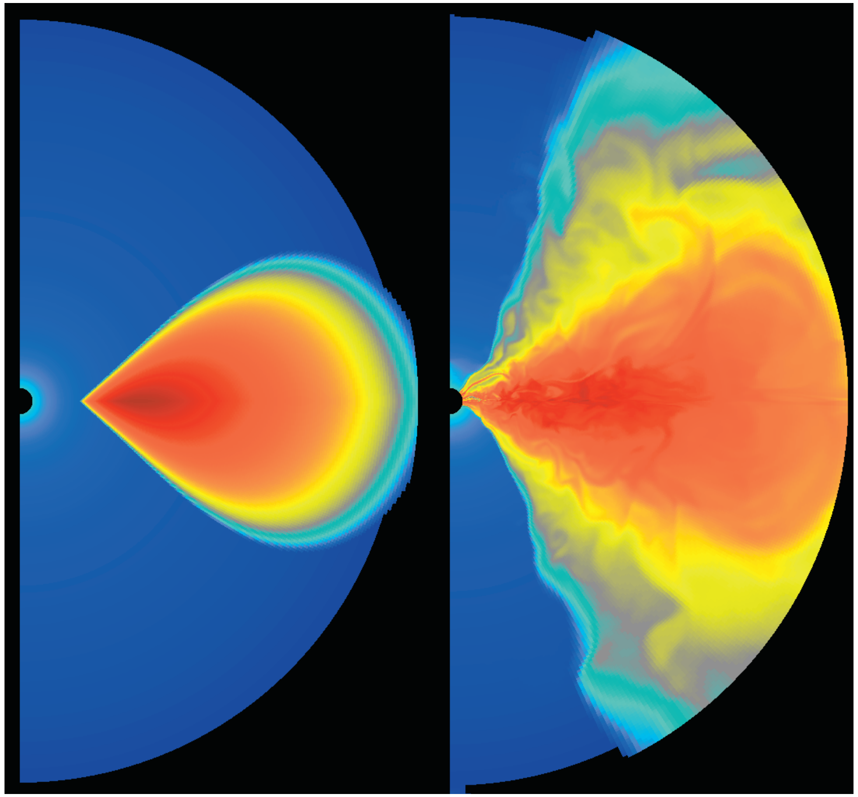
Global 3D « turbulent » disks GRMHD simulations

McKinney & Gammie 04
Hawley & Krolik 06, Beckwith+ 08
McKinney & Blandford 09, 12
Punsly+ 09, Tchekhovskoy+ 10,11,12
Tchekhovskoy & Bromberg 16
Avara+16, Marshall+18
Lancova+19, Mishra+21
Narayan+22, Huang+23

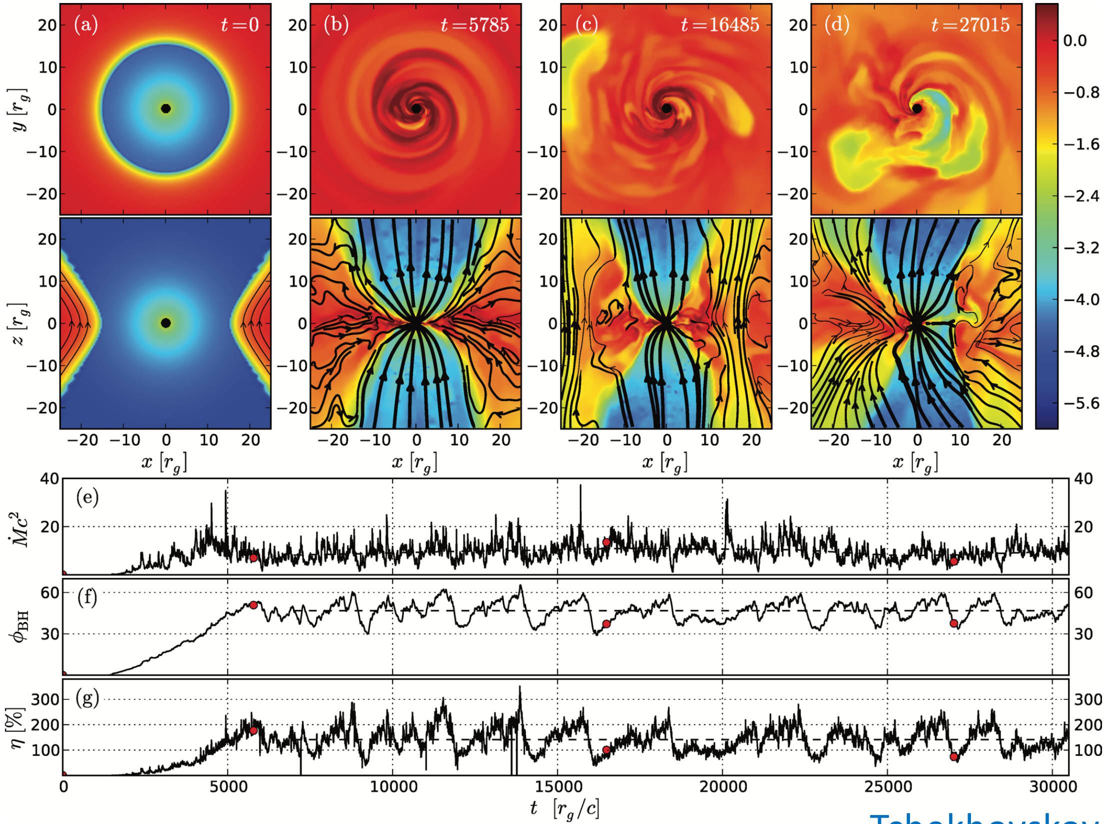


Global 2D « alpha » disks up to observable scales + 3D turbulent disks

Casse & Keppens 02, 04
Zanni+ 07, Tzeferacos+ 09, 13
Murphy+ 10
Sheikhnezami+ 12, Stepanovs & Fendt 16
Zhu & Stone 18, 20
Jacquemin-Ide+ 21



McKinney & Gammie 04

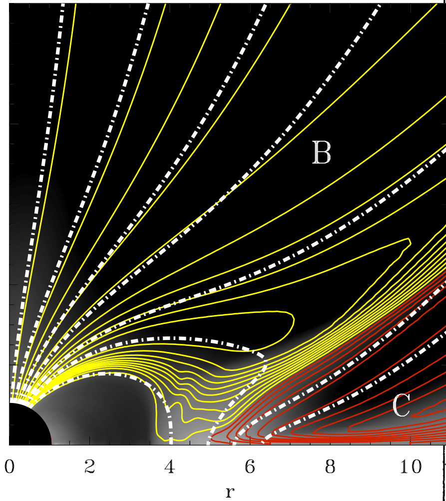


Tchekhovskoy+ 11
Narayan+ 22

For ~20 yrs only focus on inner BZ process, never on outer disk outflow (called « wind »):

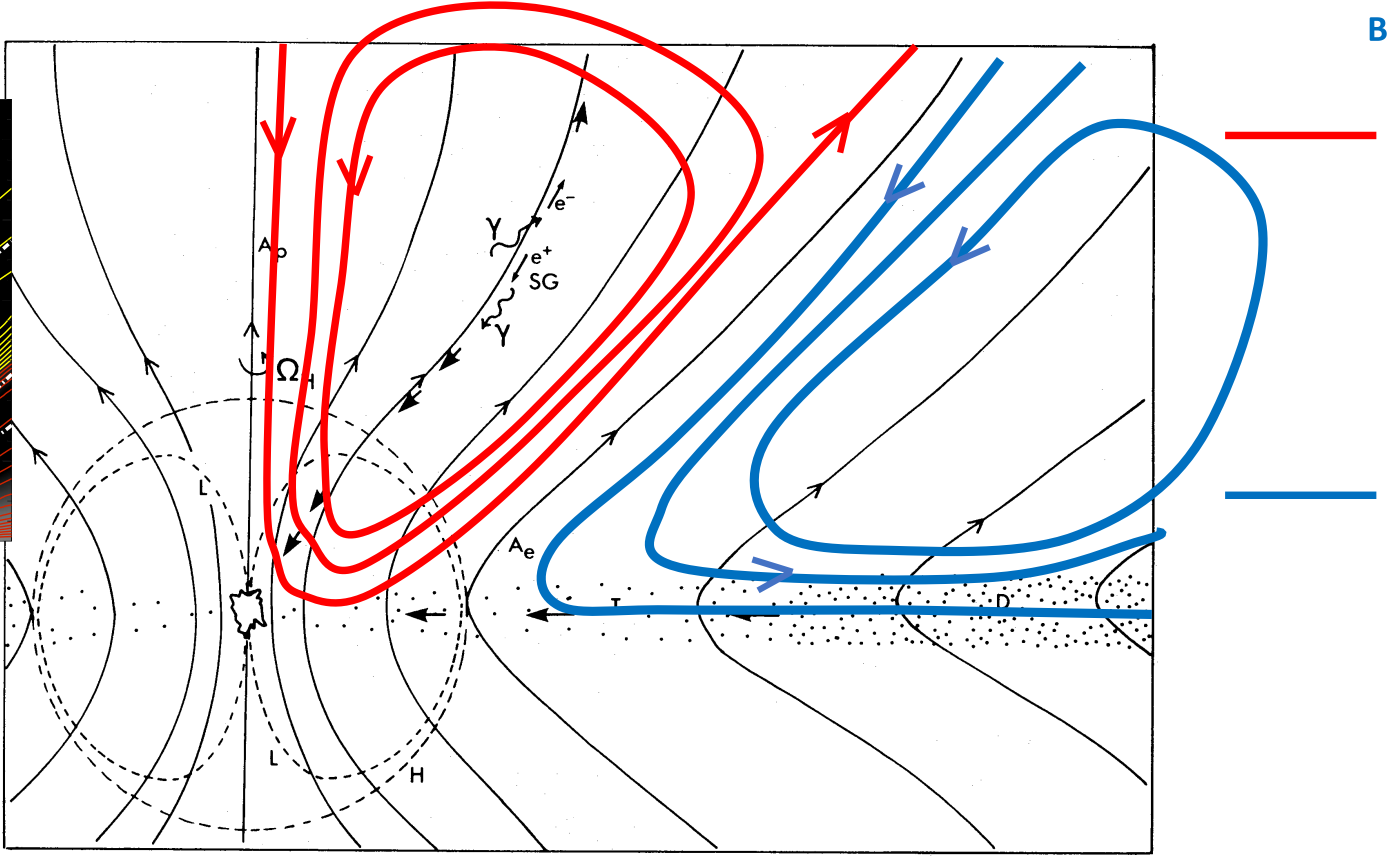
1- **MAD « Magnetically Arrested Disk » state** (Narayan+03), depends on available **initial magnetic flux**
2- huge impact of disk thermodynamics H/R
3- **outflows are systematic** with Bz (but inner spine has density floor + ceiling on Lorentz factor)
4- best current simulation duration only ~ 10^6 r_g/c (~50 sec in XrBs, ~10 yrs in AGN)

Jets as self-collimated outflows: need of a B_z field



Zanni & Ferreira 2013

Blandford & Znajek 77



Electric current due to BH emf

$I = r B_\phi$

Electric current due to DISK emf

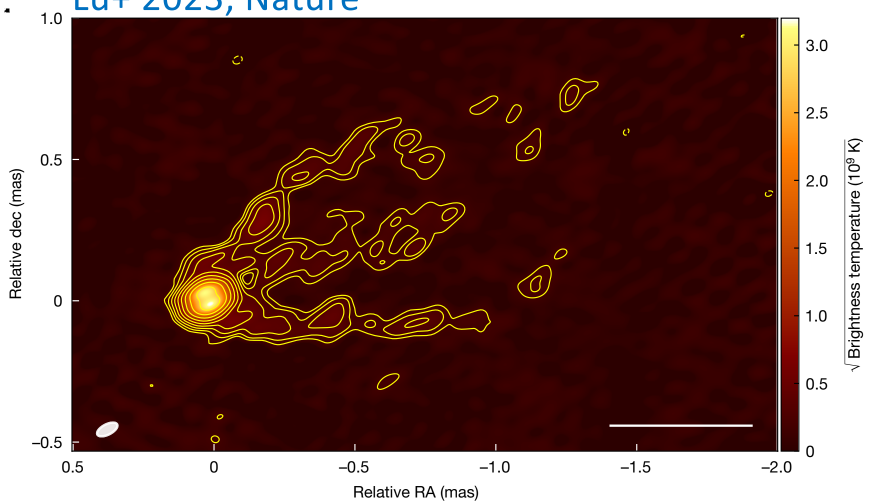
Two independent E.M.F. **=> two independent outflows are to be expected, SPINE (BZ) + DISK wind (BP)**

Besides, jets are seen for non-BH systems (neutrons stars, young forming stars) !

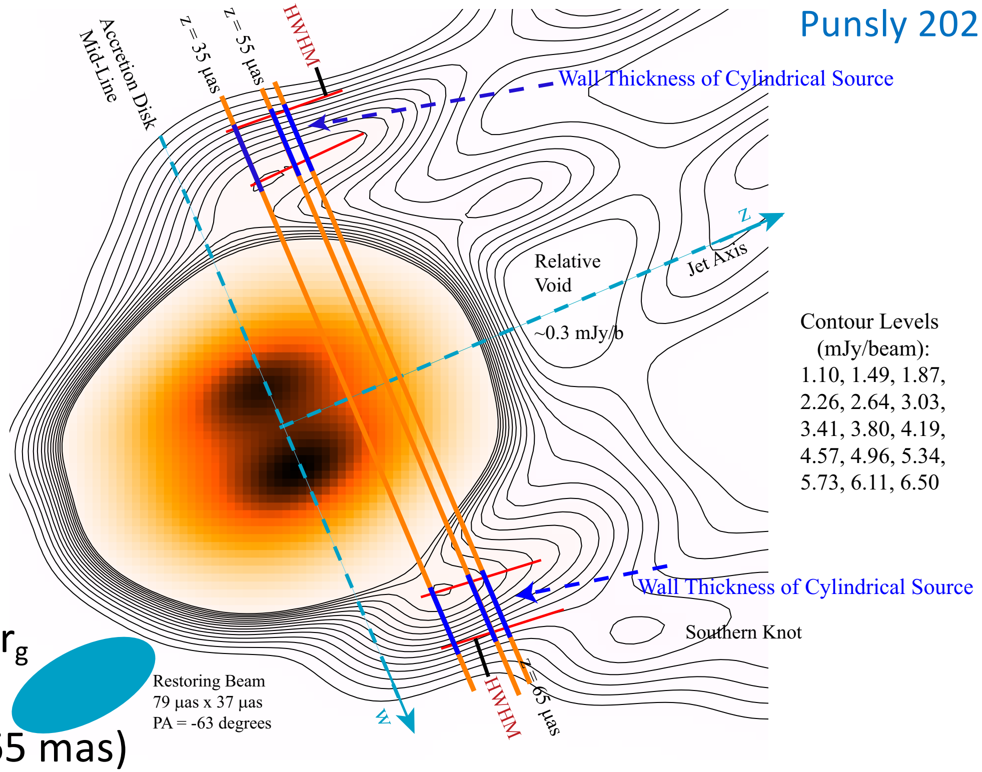
Unfortunately, not much attention paid so far to the disk wind in GRMHD simulations…

What do jets tell us about accretion disks?

Lu+ 2023, Nature



Punsly 2023



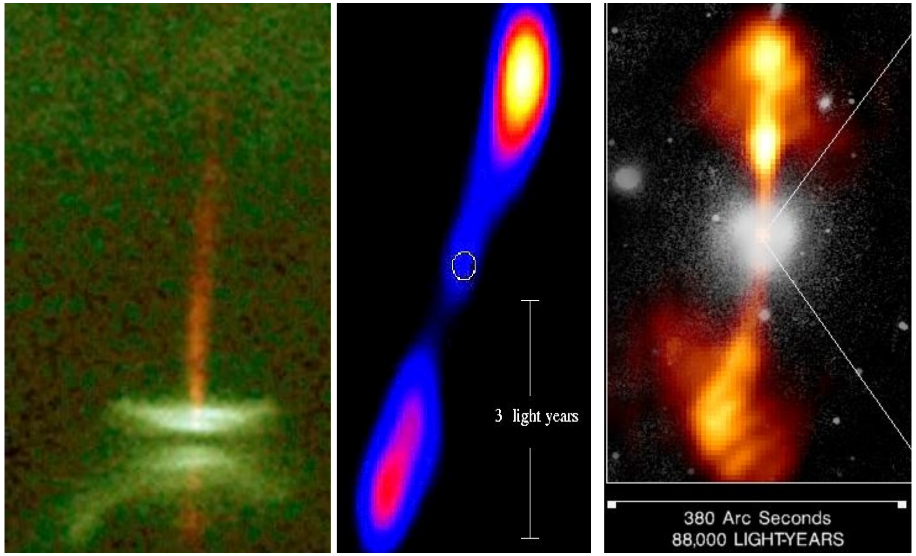
Quasi-cylindrical structure radius R~38 r_g from Z ~ 9 r_g to 26 r_g
of width W~ 9 r_g
and connecting to the limb-brightened jet @ Z > 170 r_g (0,65 mas)

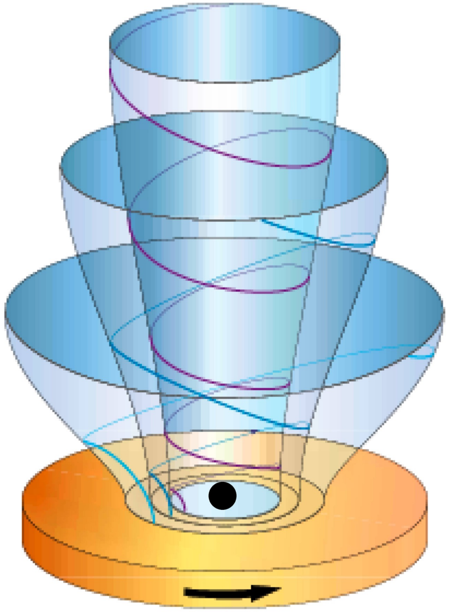
=> Jet radius + width much wider than BZ jets from GRMHD simulations

+ axial spine already associated to the BZ jet/spine

=> Calls for another DISK-JET connection

A universal accretion-ejection structure





Major assumption: **a large scale Bz field threading the keplerian disk MUST BE a common thing**

disk magnetization $\mu = \frac{B_z^2}{\mu_o P}$ leads to super-FM outflow (wind or jet): $\dot{M}_a \propto r^{\xi}$

(P= P_{tot}= P_{gas} + P_{rad})

Ferreira & Pelletier 95

The disk ejection efficiency $0< \xi<1$ must be computed as function of the disk parameters:
magnetization μ, disk aspect ratio ε =H/R + MHD turbulence

A universal accretion-ejection structure

A request to the numericians

Plasma beta $\beta = \frac{P_{gas}}{P_{mag}}$ is instructive BUT does not allow to compare with theory because $P_{mag} =< B^2 > + < \delta B^2 >$

Vertical laminar field B_z is the relevant control parameter (β is an outcome)

- Rotation + accretion => laminar components B_r and B_ϕ
- MHD turbulence => turbulent field $<\delta B>$

=> e.g. use of **disk magnetization at midplane** $\mu = \frac{V_{Az}^2}{C_s^2}$ $C_s = \sqrt{\frac{P_{gas} + P_{rad}}{\rho}}$

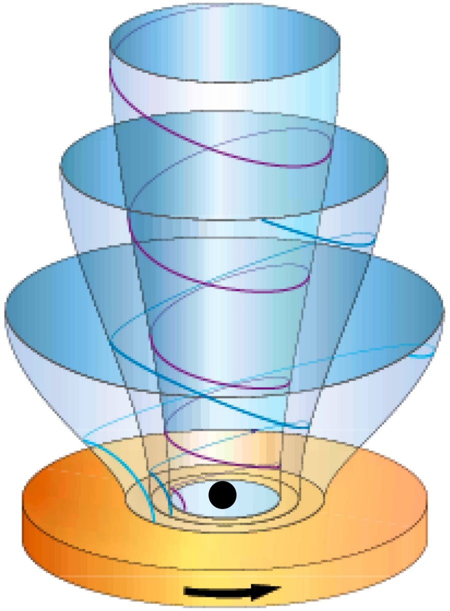
tier 95

The disk ejection efficiency $0< \xi<1$ must be computed as function of the disk parameters: magnetization μ, disk aspect ratio ε =H/R + MHD turbulence

2D Accretion-ejection theory

Ferreira & Pelletier 93, 95
Ferreira 97
Casse & Ferreira 2000a,b
Ferreira & Casse 04, 13
Jacquemin-Ide+ 19

- Mass $\boldsymbol{\nabla}\cdot\rho\boldsymbol{u}=0$
- Momentum $\rho\boldsymbol{u}\cdot\boldsymbol{\nabla}\boldsymbol{u}=-\boldsymbol{\nabla}P-\rho\boldsymbol{\nabla}\Phi_G+\boldsymbol{J}\times\boldsymbol{B}+\boldsymbol{\nabla}\cdot\mathsf{T}$
- Energy $\rho T\frac{dS}{dt}=\rho T\boldsymbol{u_p}\cdot\boldsymbol{\nabla}S=Q$
- Perfect gas $P=\frac{k_B}{\mu m_p}T$
- Diffusion Bp $\eta_m J_\phi\boldsymbol{e_\phi}\ =\ \boldsymbol{u_p}\times\boldsymbol{B_p}$
- Induction Bϕ $\boldsymbol{\nabla}\cdot(\frac{\nu'_m}{r^2}\boldsymbol{\nabla}rB_\phi)\ =\ \boldsymbol{\nabla}\cdot\frac{1}{r}(B_\phi\boldsymbol{u_p}-\boldsymbol{B_p}\Omega r)$



\+ 3 anomalous transport coefficients: **viscosity** ν_v, **magnetic diffusivities** ν_m and ν_m'
=> Prescriptions for amplitude + vertical profiles

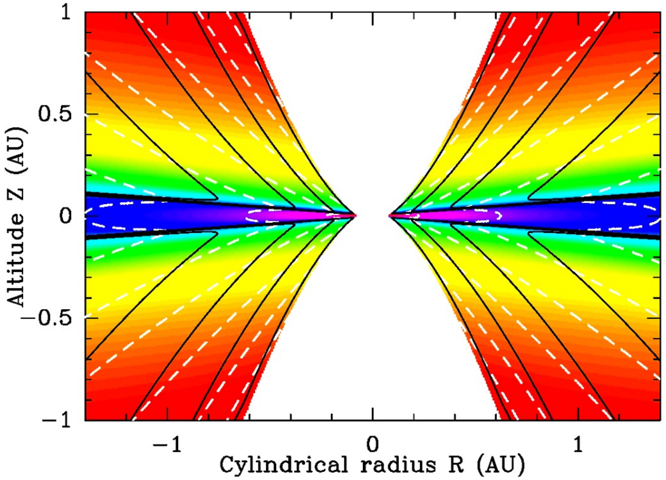
Exact MHD solutions (resistive-ideal MHD, super-SM/A/FM outflow) computed using **self-similarity**

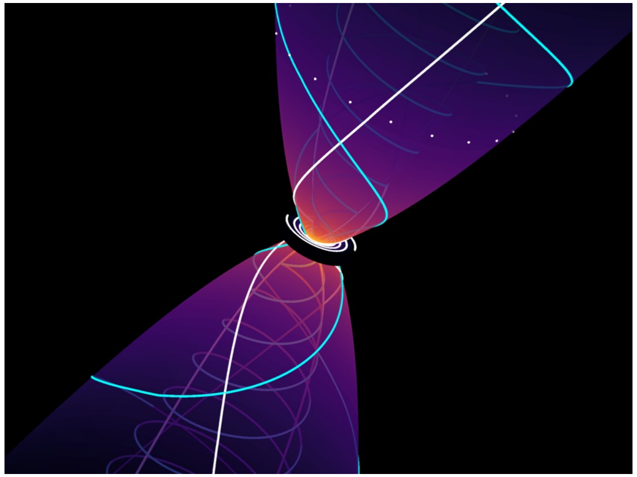
Main properties of Jet Emitting Disks (JED)

Ferreira & Pelletier 93, 95
Ferreira 97
Casse & Ferreira 2000a,b
Ferreira & Casse 04, 13
Jacquemin-Ide+ 19

$$\dot{M}_a \propto r^{\xi} \qquad B_z \propto r^{\frac{\xi}{2}-\frac{5}{4}}$$

$$\mu = \frac{B_z^2}{\mu_o P}$$

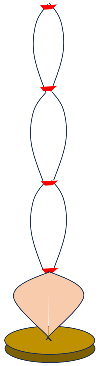




Courtesy N. Zimniak

1- **Near equipartition** (0.1< μ <1) **large scale** Bz

2- High level of turbulence $\alpha_m \geq 1$ where $\nu_m = \alpha_m V_{Az} H$
consistent with MRI turbulence



3- **Mass loss** typically

ξ~ 0.01 if cold wind (isothermal or adiabatic)

ξ~ 0.3-0.5 if warm (magneto-thermal): Casse & Ferreira 2000b

=> Bulk Lorentz factors 2-5 possible (Petrucci+10)

=> Jets undergo series of recollimation shocks (Jannaud+ 23)

4- Jet torque is dominant (**~ factor R/H**, Ferreira 97)

=> Most disk angular momentum carried away by jets and **supersonic accretion**

5- For given Mdot, JED density much smaller

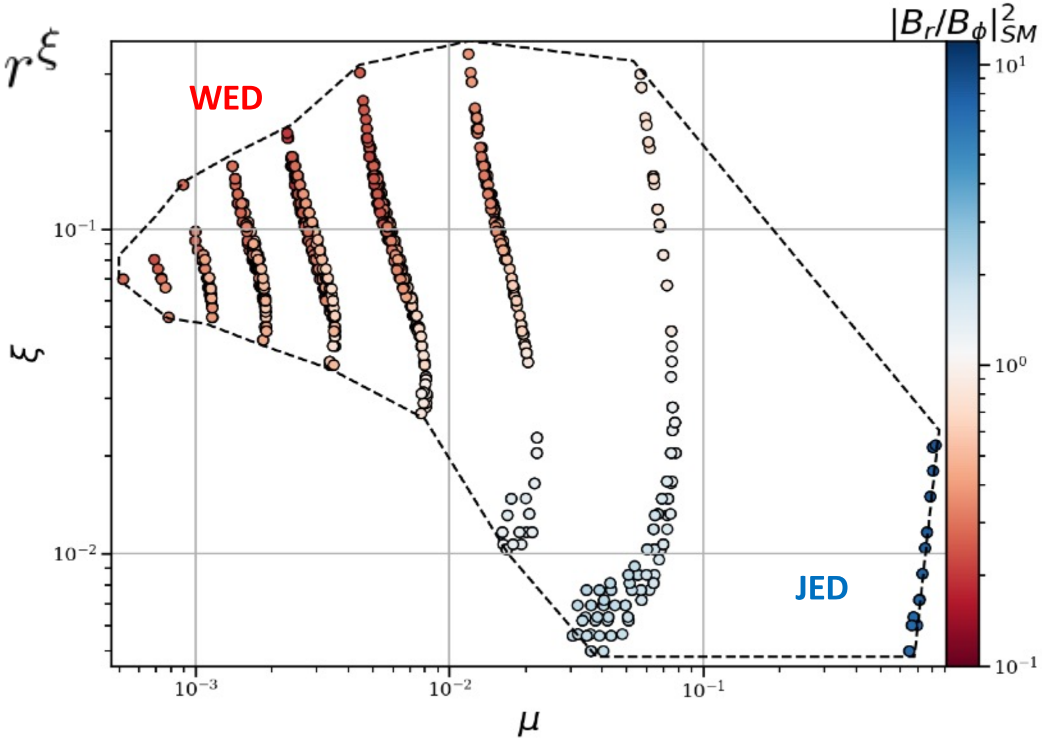
=> **JEDs are less luminous** than usual Standard Accretion Disk (SAD) Shakura Sunyaev α-disks

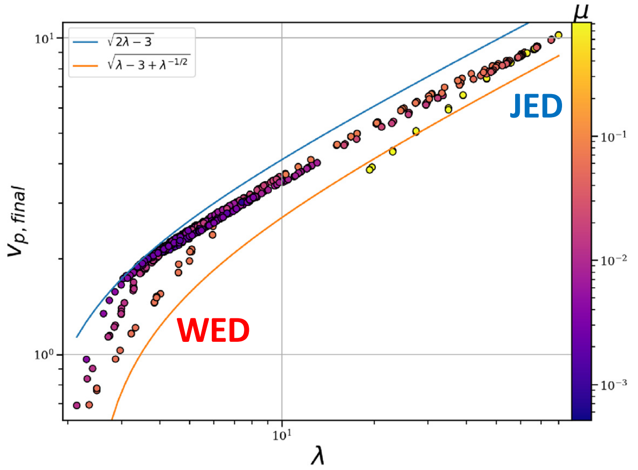
$$P_{acc} = P_{rad} + P_{adv} + 2P_{jet}$$

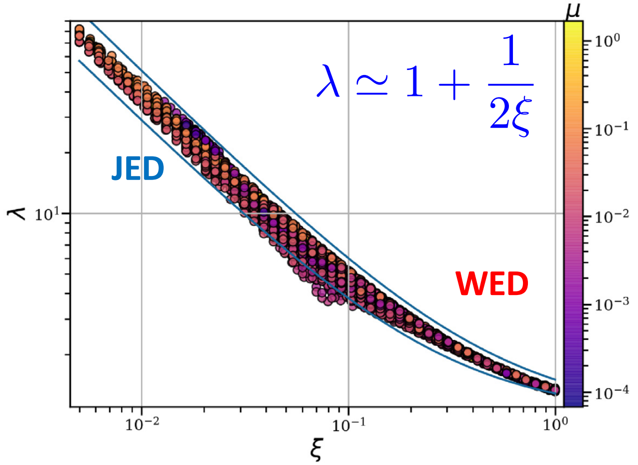
From jets to winds only by playing with μ ?

Jacquemin-Ide+ 19

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







Weakly magnetized disks (WEDs) have

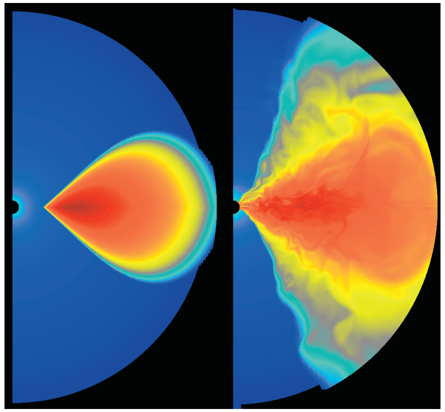
- subsonic accretion
- more massive ejection $\xi>0.1$, small $\lambda < 5$
- dominant B_ϕ : « magnetic tower » -like
- low-speed outflows: « winds » ?

BUT

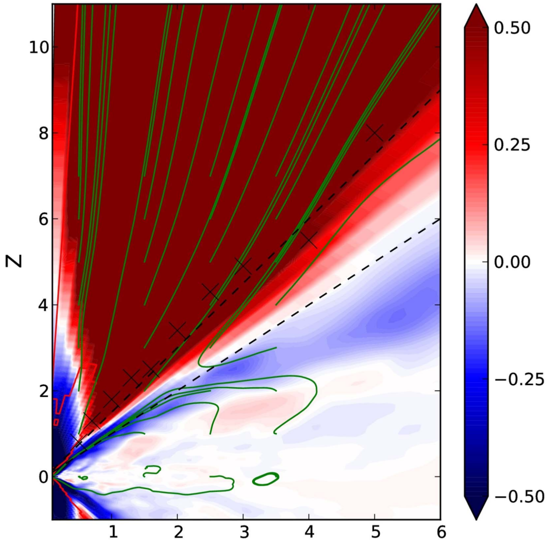
solutions rely on 3 anomalous transport coefficients (**viscosity** and **magnetic diffusivities)**

What do 3D global simulations tell us ?

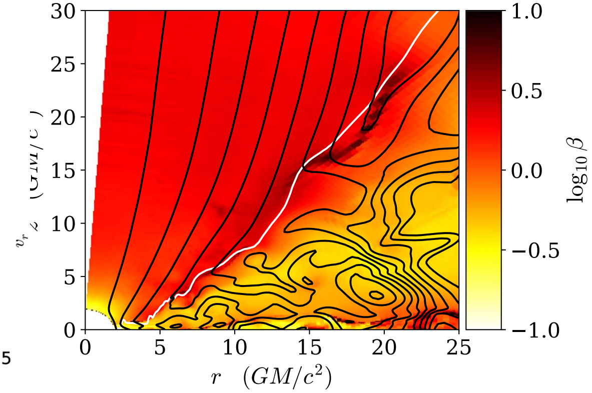
Igumenshchev+03
McKinney & Gammie 04
Hawley & Krolik 06, Beckwith+ 08
McKinney & Blandford 09, 12
Punsly+ 09, Tchekhovskoy+ 10,11,12
Tchekhovskoy & Bromberg 16
Avara+16, Marshall+18
Lancova+19, Zhu & Stone 18
Mishra+21, Jacquemin-Ide+ 21
Narayan+22, Huang+23



McKinney & Gammie 04



Zhu & Stone 18



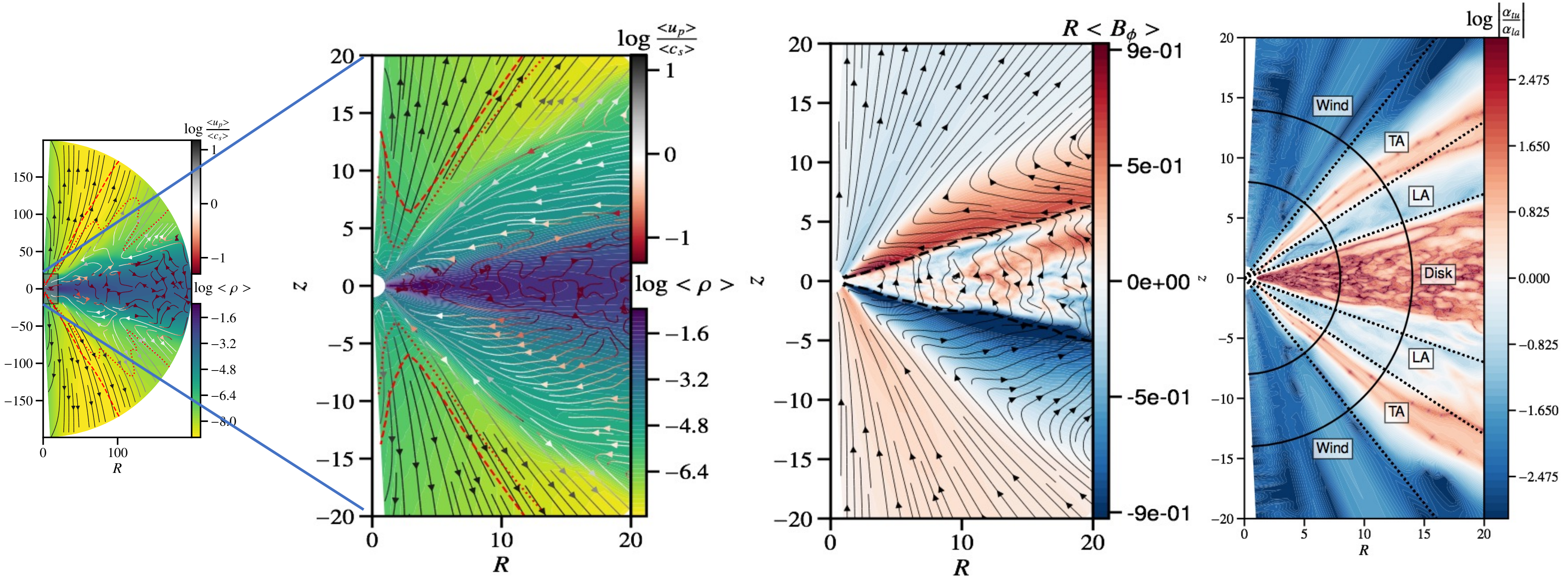
Lancova+ 19

- Innermost disk region: highly (aka « **MAD** ») or weakly (aka « **SANE** ») magnetized [initial conditions]
- Disks have been **thick (H/R >0.5) for ~ 15 yrs**
- Only recently slim or thin with H/R < 0.1 (Avara+16, Sadowski 16, Scepi+23)

=> **Puffy disks are systematic at low magnetization** (Zhu & Stone 18, Lancova+19, Jacquemin-Ide+21, Huang+23)
=> Thin (vertically compressed) disks at near-equipartition fields
=> All simulations **have disk winds** (but rarely studied)

3D Global MHD simulations of a **WED**

Jacquemin-Ide, Lesur, Ferreira 2021

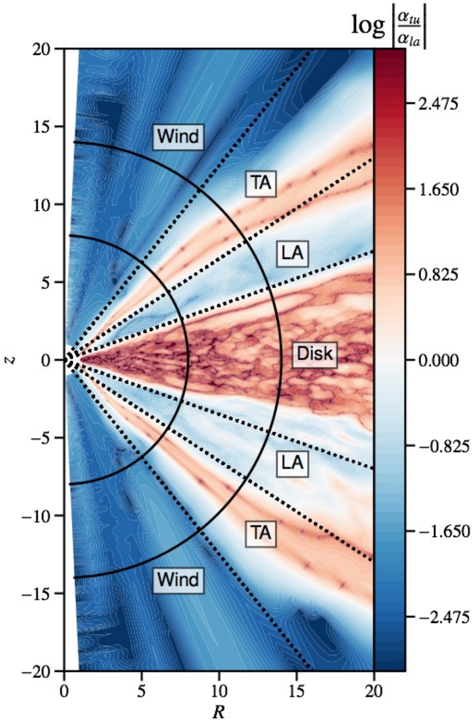


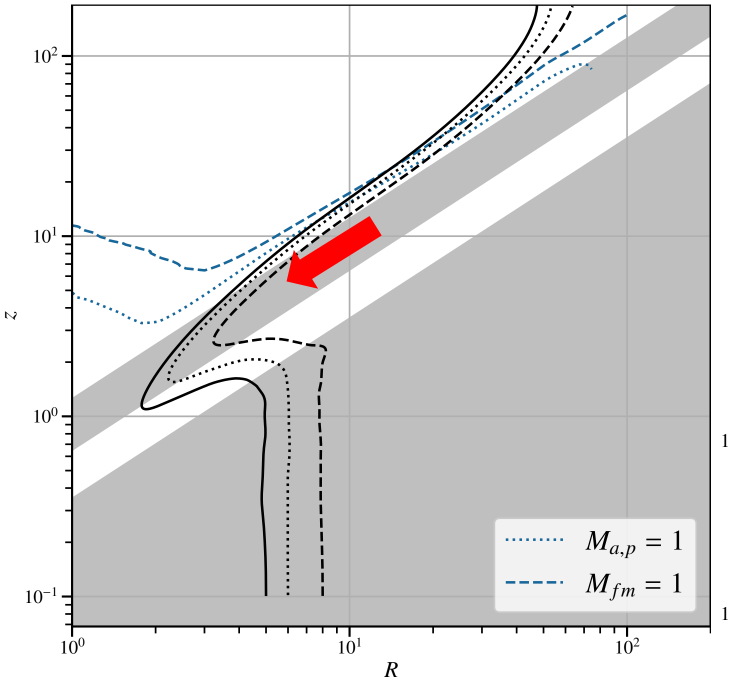
Quasi steady-state accretion-ejection configuration at $\mu \sim 10^{-4}$ **(WED)** with

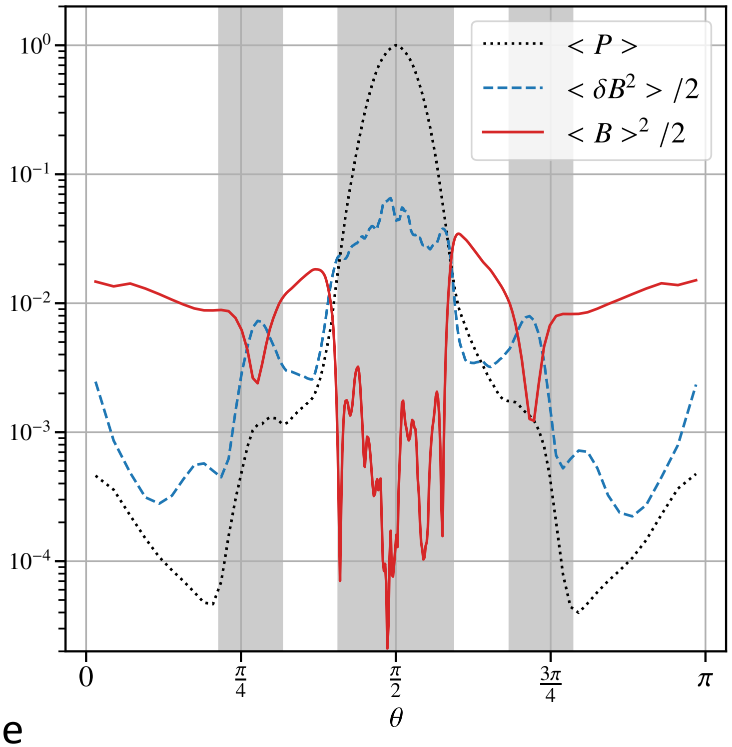
- Turbulent disc H=0.1R
- Laminar « levitating » atmosphere (LA)
- Turbulent atmosphere (TA) accreting **@ supersonic speed** (but mass-weighted subsonic)
- super-FM wind starting at Z ~ 10H = R

3D Global MHD simulations of a **WED**

Jacquemin-Ide, Lesur, Ferreira 2021



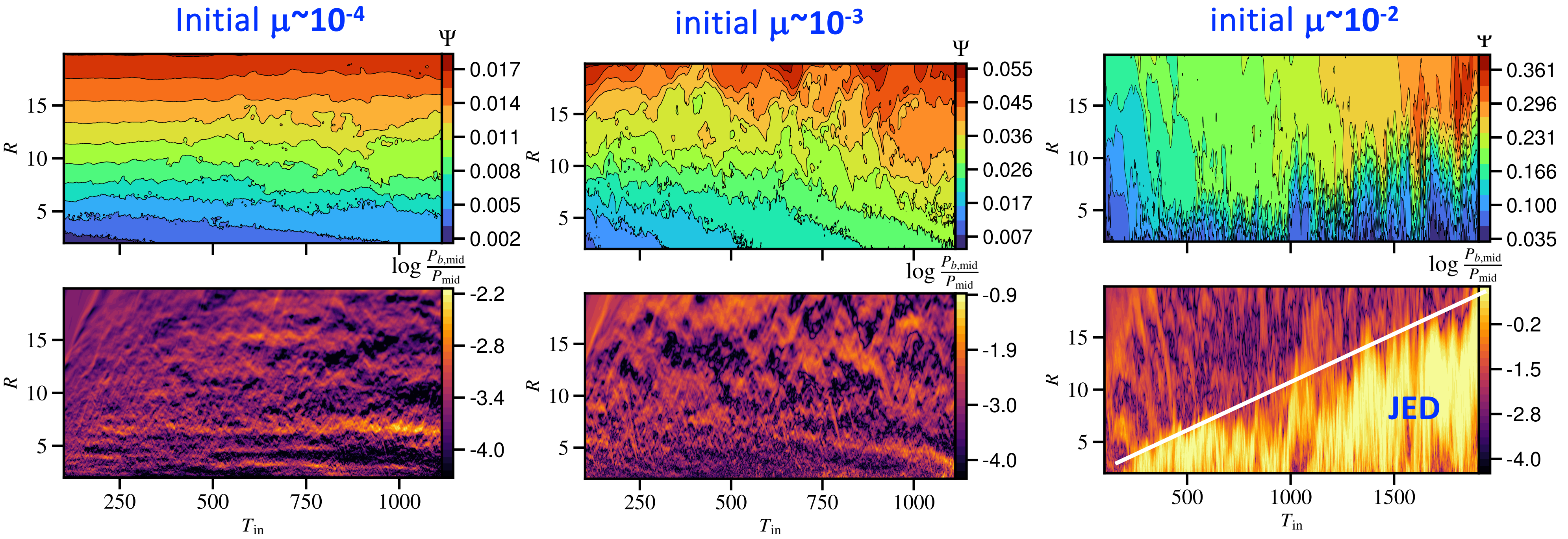




- Disk: MRI-driven turbulence is active, quasi-static vertical balance
- Atmosphere: MRI quenched, vertical balance due to **turbulent magnetic pressure** (Begelman & Pringle 07), material is lifted up and falls inwards winding up field lines
- MRI is re-ignited @ near equipartition (Kim & Ostriker 00, Pessah & Psialtis 05), turbulent supersonic accreting layer (jet + disk torques)=> **Bz field is being advected** (Contopoulos 96, Rothstein & Lovelace 08)

3D Global MHD simulations: from **WED** to **JED**

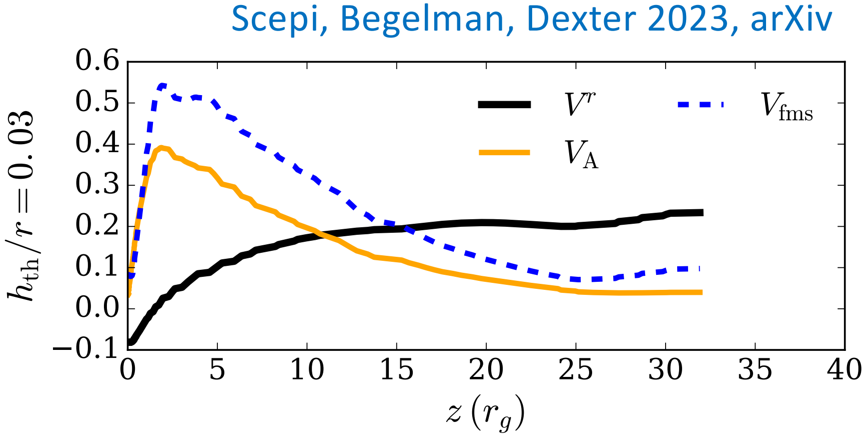
Jacquemin-Ide, Lesur, Ferreira 2021



Initial μ~10^{-4} initial μ~10^{-3} initial μ~10^{-2}

- Magnetic field advection done at **mass-weighted** accretion speed
- Self-organization around **theshold** in μ ~[10^{-3}-10^{-2}] (proposed in Ferreira+06, Petrucci+10, Marcel+18b)
- Inner saturated state = JED-like configuration **with μ~1 (OK with main JED properties)**
- Inside-out increase of the JED region: much alike in GRMHD simulations with **MADs**

How do **MADs** compare to **JEDs** ?


Scepi, Begelman, Dexter 2023, arXiv

Many disk and wind diagnostics NOT provided so far, but

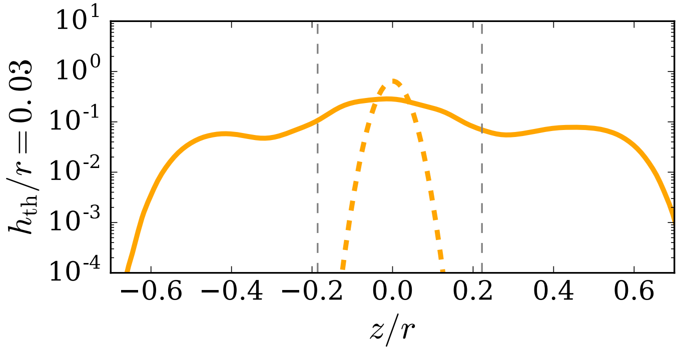
- MRI-driven turbulence is active with $\mu \sim 0.03\text{-}0.5$
- Keplerian deviation follows JED theory (a MAD is **not** Arrested)
- Transsonic accretion due to dominant jet torque (MAD drives super-FM jets)

$\Rightarrow$ numerical MADs fulfill most theoretical JED conditions

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

BUT **major discrepancy on mass loss**: numerical ejection efficiency **$\xi \sim 0.5\text{-}1$**

1. JED model needs to incorporate **turbulent magnetic pressure** (Zimniak et al, in prep)
2. MAD simulations have **turbulent heating at disk surface, known to enhance mass loss** (Casse & Ferreira 2000b)



Both effects can be easily accounted for in analytical model *educated by 3D simulations*

Concluding remarks (1/3)

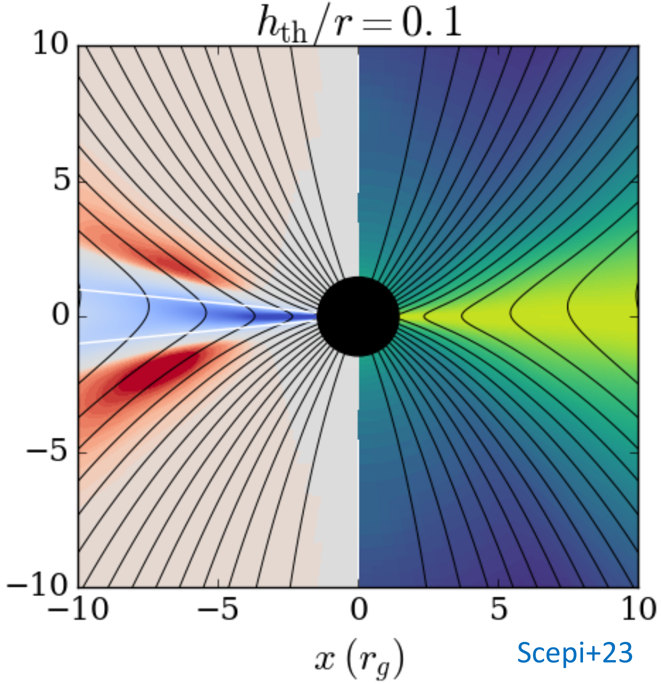
(1) JEDs as the mathematical description of numerical MADs ?

After ~20 yrs, simulations and theory are finally converging

=> JED theory needs to include educated turbulence profiles

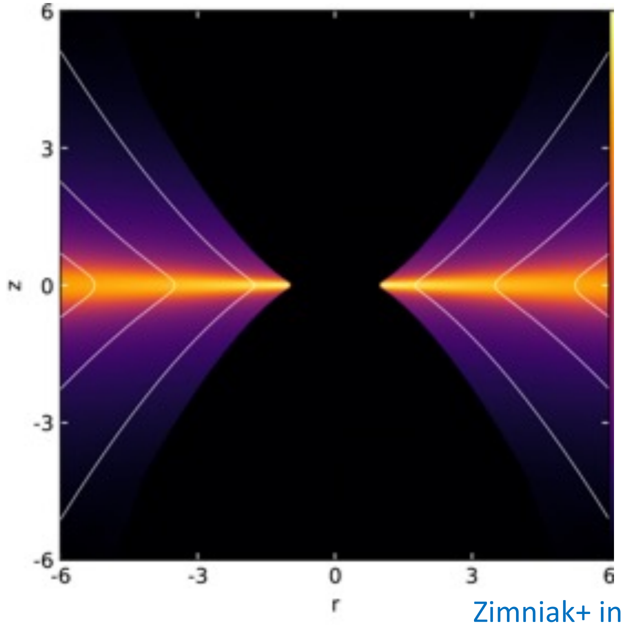
=> MAD simulations need to provide specific disk + wind diagnostics

MAD



Scepi+23

JED



Zimniak+ in prep

Concluding remarks (2/3)

(2) Critical role played by the disk midplane magnetization

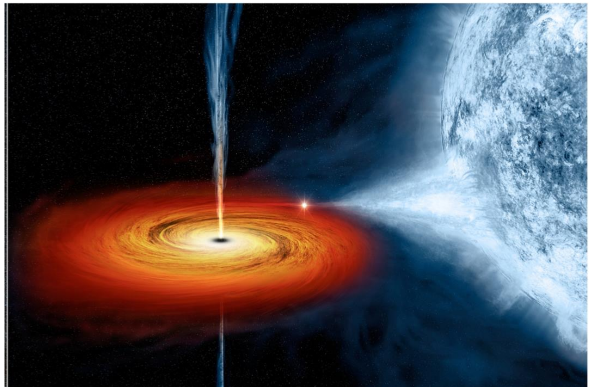
$$\mu = \frac{V_{Az}^2}{C_s^2}$$

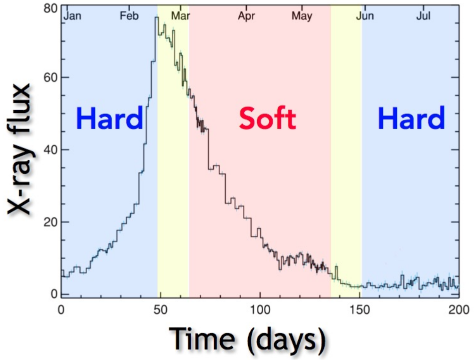
Radial self-organization of the disk beyond a threshold on μ (Ferreira+ 06, Jacquemin-Ide+21)

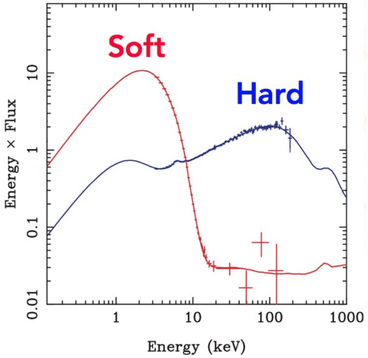
=> Provides mechanism for ubiquitous **outer disk winds** and **inner fast jets**

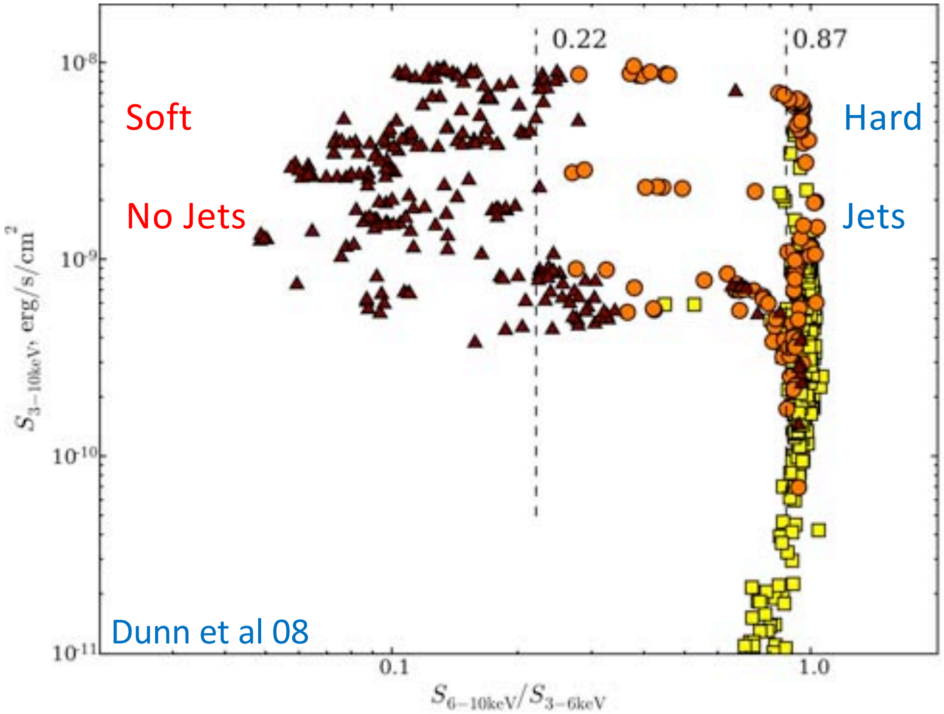
=> May explain **XrB hysterisis cycles** (Ferreira+06, Petrucci+08, Marcel+ 18,19 etc..)

And **changing look AGN…**





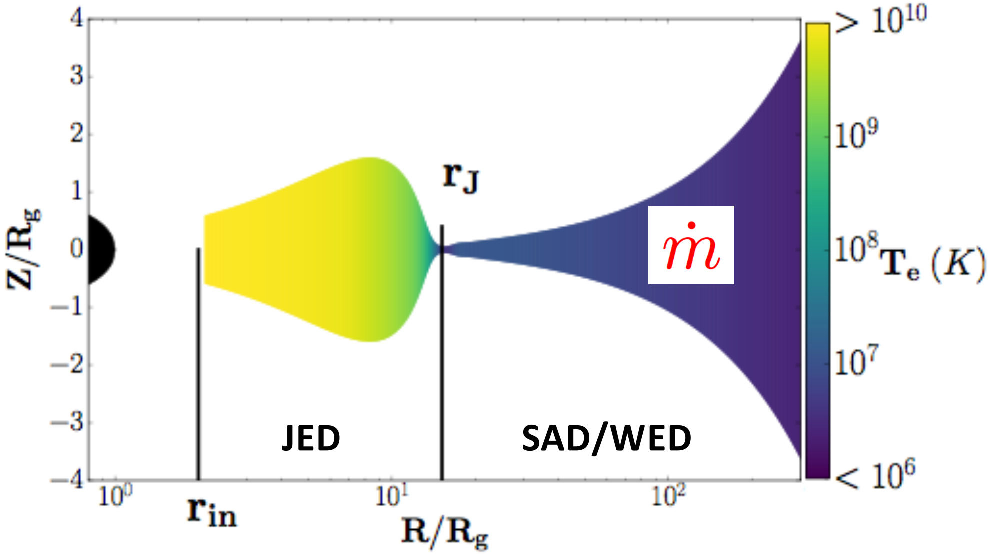


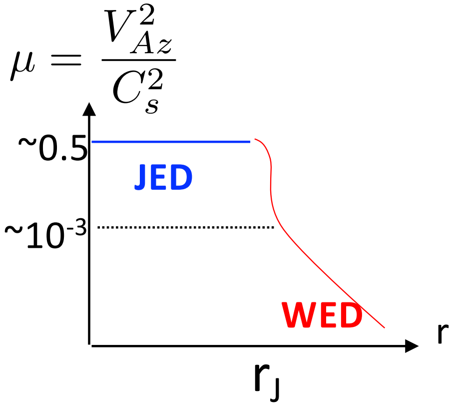


Dunn et al 08

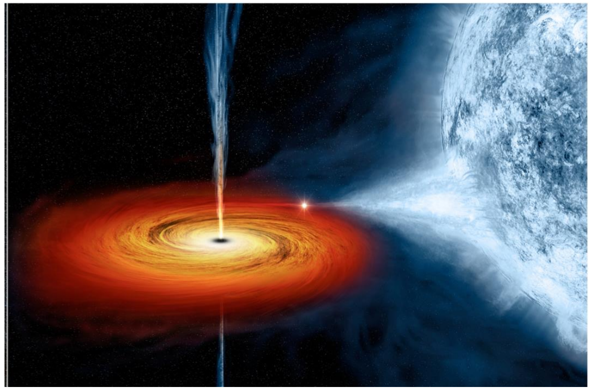
A hybrid JED-SAD disk configuration

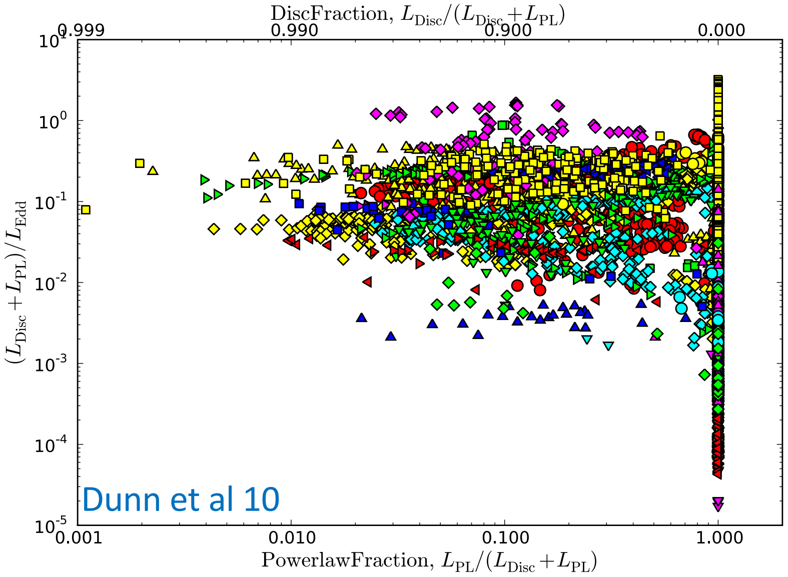
Ferreira+ 06, 22
Petrucci+ 08,10,21,23
Marcel+ 18ab,19,20,22
Barnier+ 22





$$\mu = \frac{V_{Az}^2}{C_s^2}$$

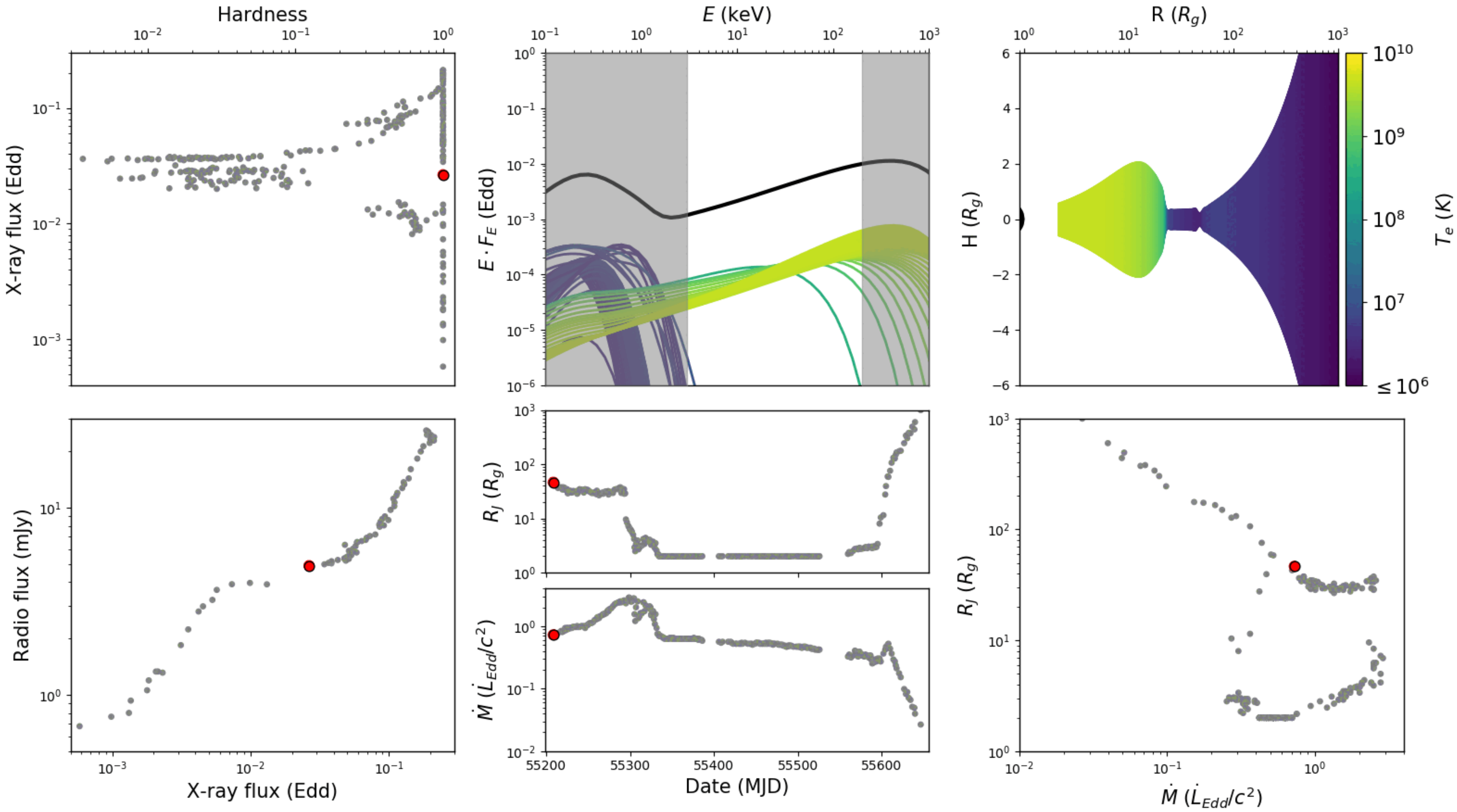


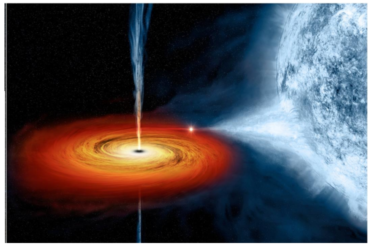


Dunn et al 10

=> **TWO independent quantities** provided by outer reservoir
- mass Σ(t)
- magnetic field B_z(t)

=> Translates into two time variable independent model parameters:
- disk transition radius **r_J(t)**
- inner accretion rate **Mdot(t)**





Ferreira+06,22
Petrucci+08,10

Marcel+ 18a,b
19, 20, 21, 22
Barnier+22

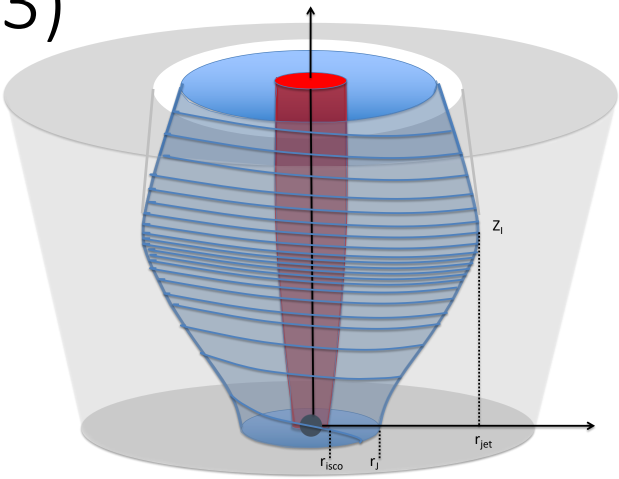
Ursini+20
Petrucci+21,23
Marino+21
Barnier+23

Courtesy Grégoire Marcel

Concluding remarks (3/3)

(3) JED interfaces ?

Both sides may affect large scale jet acceleration+collimation properties and jet radiation



Ferreira+ 22

- Outer Wind emitting region

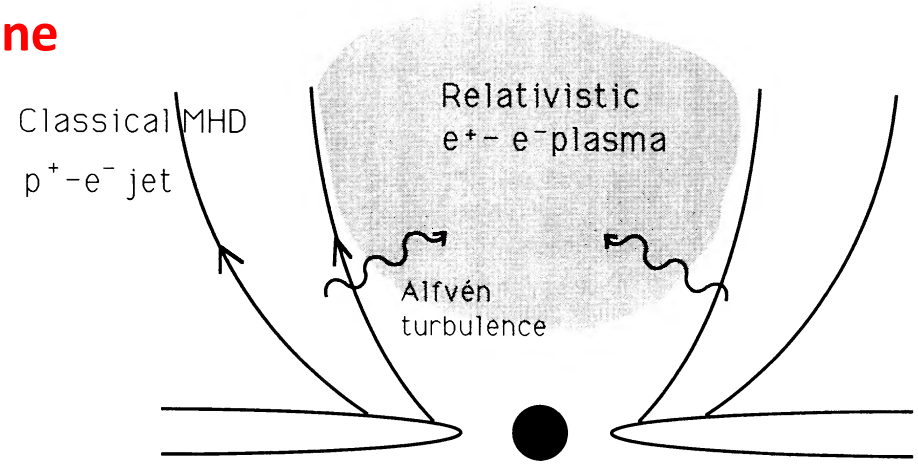
Timing properties are sensitive to radial zones and their transitions (Ferreira+ 22, Jannaud+ 23, Malzac & Marcel to be subm)

- Inner (leptonic or hadronic ?) Blandford-Znajek spine

GRMHD simulations are pure MHD (with density floor bias)

=> **Radiation effects** may play a **dominant role on e$^+$-e$^-$ pairs**, best suited to be efficiciently accelerated along the axis « two-flow model »

Sol et al 89, Henri & Pelletier 91,
Saugé & Henri 04, Vuillaume+18



Henri & Pelletier 91

Take away messages

MADs reveal their JED nature

Analytics + Numerics must now learn to work hand in hand.

Large scale B_z field pleads guilty for :

1- the disparition of the Standard Accretion Disk

2- leading microquasars to wild accretion-ejection events

Invisible agent suspected to work behind the scene also on other systems.