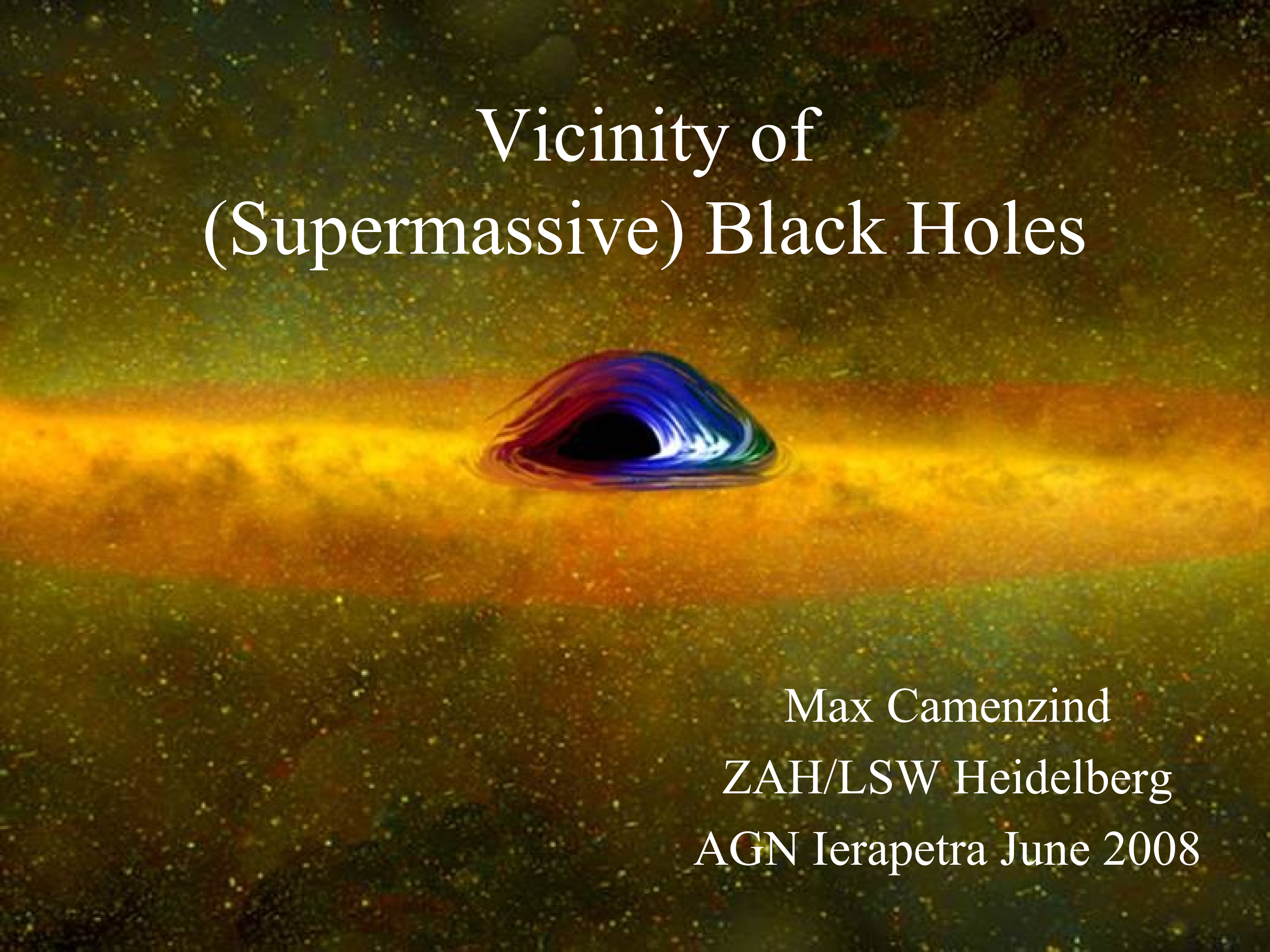
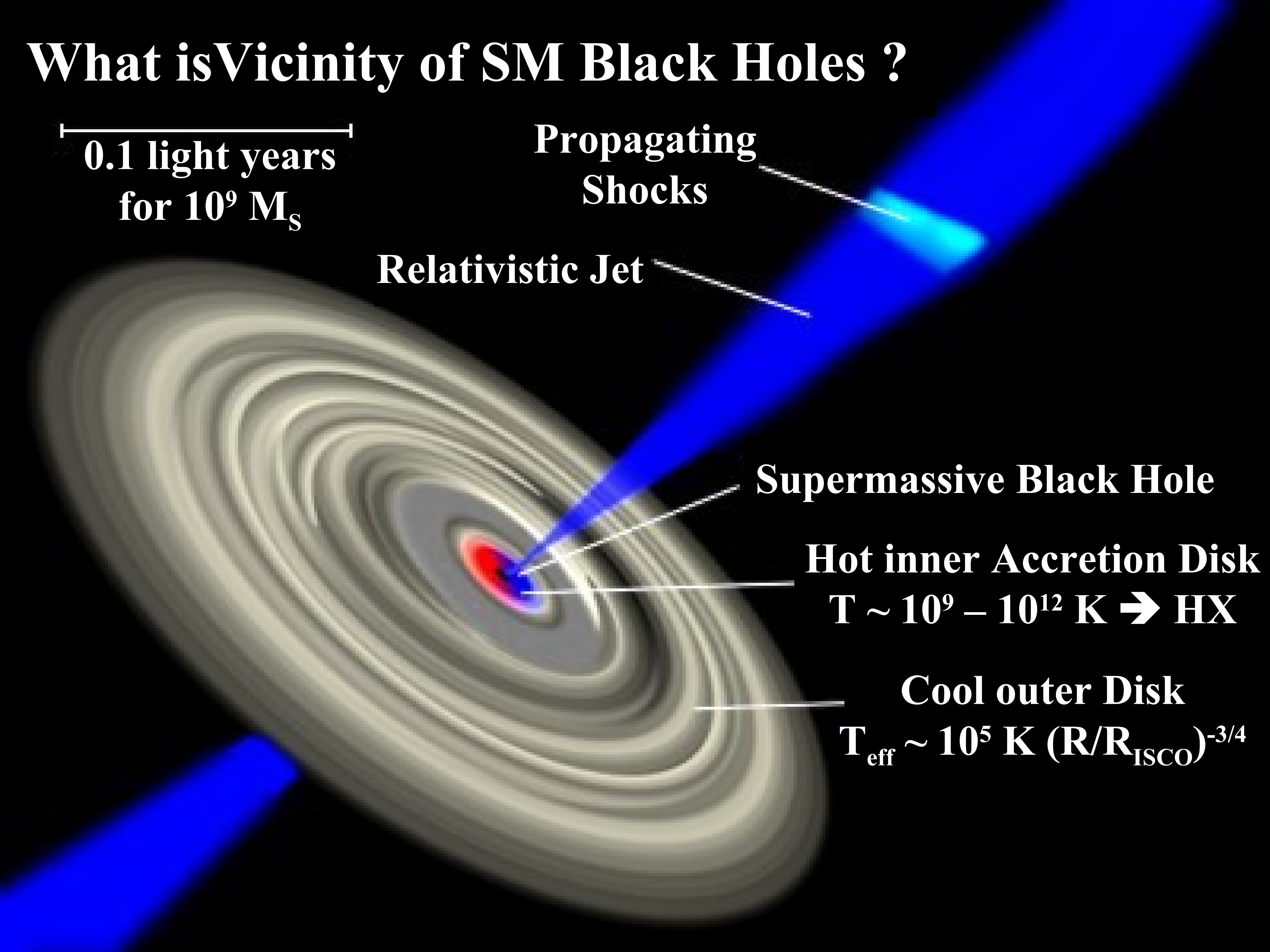
Vicinity of (Supermassive) Black Holes



Max Camenzind
ZAH/LSW Heidelberg
AGN Ierapetra June 2008

What isVicinity of SM Black Holes ?



0.1 light years for 10^9 M_S

Propagating Shocks

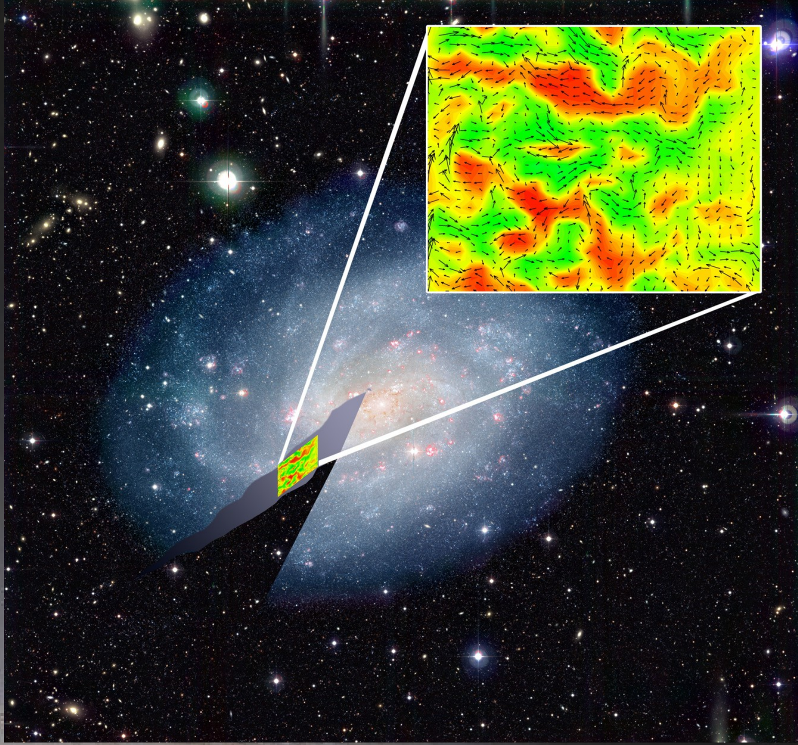
Relativistic Jet

Supermassive Black Hole

Hot inner Accretion Disk
$T \sim 10^9 - 10^{12}$ K ➔ HX

Cool outer Disk
$T_{eff} \sim 10^5$ K $(R/R_{ISCO})^{-3/4}$

„Accretion Disk Resolved“



~ 1000 R_S
limited by self-gravity

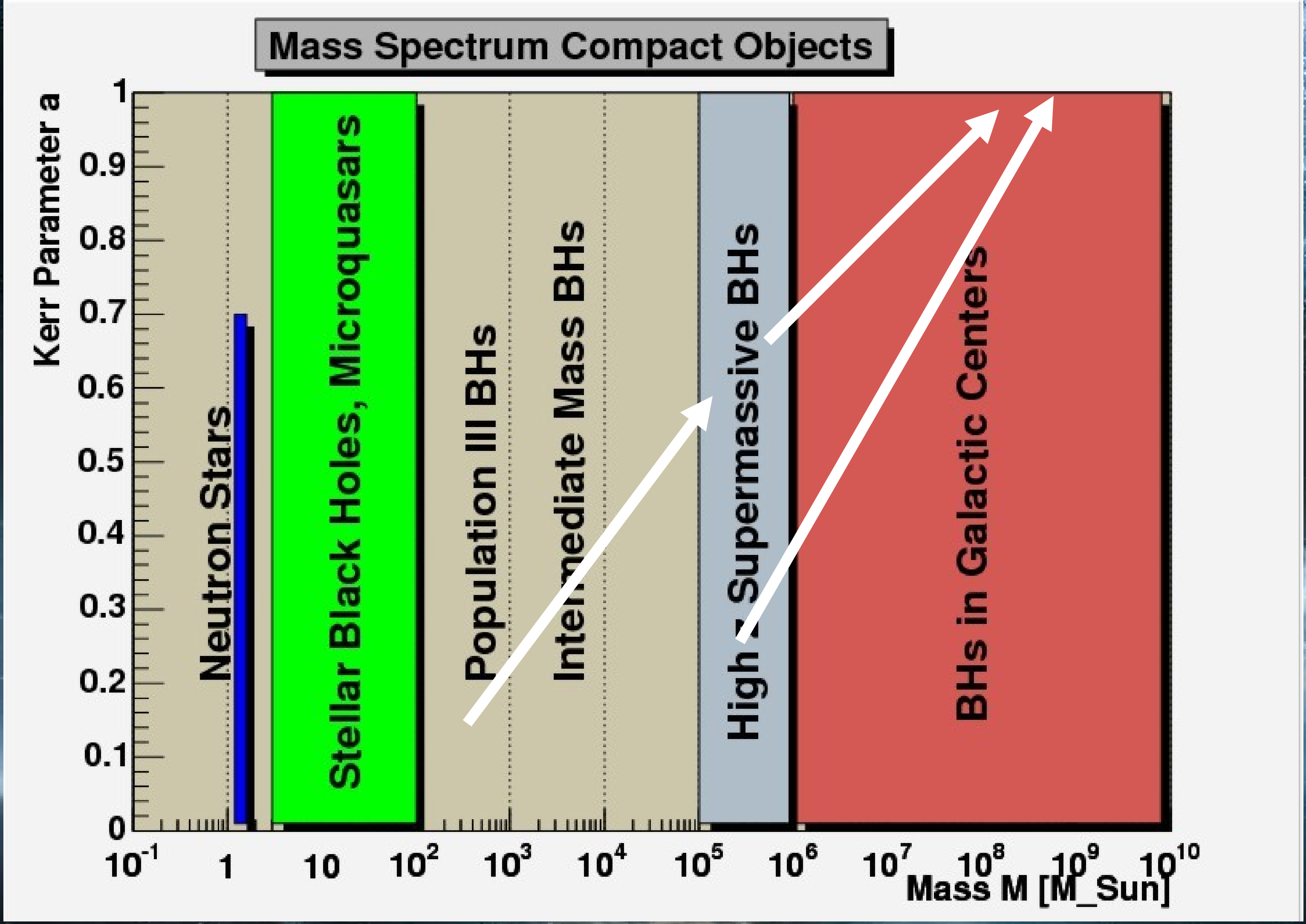
Temperature like
a low-mass star
(fully convective
➔ Dynamos for B-fields)

Internal state is like
a galactic disk:
➔fully turbulent,
probably driven by MRI

Topics – Vicinity of (SM)BHs

- **Black Hole gravity**: plasma frame-dragging, BZ mechanism and photon propagation.
- From **stellar to supermassive** Black Holes – accretion states, turbulence and jet production
- New **Unification scheme** for **AGN** ?
- The role of environment of **nearby SMBHs** – nuclear star cluster (GC, M 31, NGC 1068)
- … but probably not in ellipticals (M 87, …)
- Physics of the **ergosphere and plasma loading**

„Black Holes have 2 Hairs"



Camenzind 2006

Black Holes have 2 Energy Reservoirs

- Potential energy ➔ tapped by accretion ε(a, dotm)
- Rotational energy ➔ tapped by magnetic fields, similar to rotating neutron stars (BZ)

$$L_{Rot} = E_{Rot}/t_{brake}$$
$$\sim 10^{45}\ \mathrm{erg/s}\ (M_H/10^9\ M_S)\ (t_H/t_{brake})$$

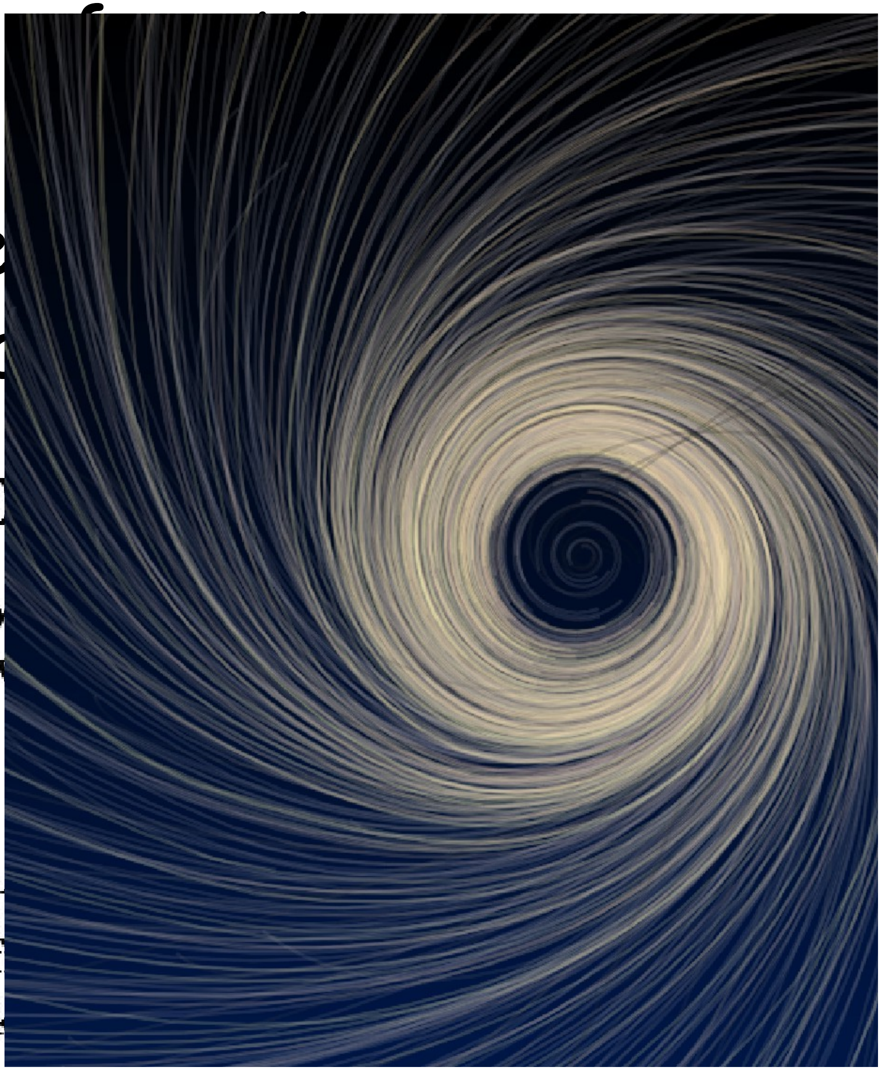
$$L_{Rot} = E_{Rot}/t_{brake}$$
$$\sim 10^{37}\ \mathrm{erg/s}\ (M_H/10\ M_S)\ (t_H/t_{brake})$$

$$t_{brake} = f\,(a, B, \ldots) \quad [\mathrm{BZ}\ 1977, \ldots]$$

Strong Gravity near Black Holes

- (i) Plasma is dragged along near BHs by frame-dragging, independent of its initial angular momentum ➔ when a = 0, plasma cannot rotate near the horion ➔ leads to incorrect boundary conditions in pseudo-Newtonian simulations.
- (ii) Photons are similarly affected ➔ characteristic line profiles (e.g. Fe Kα line).
- (iii) characteristic lightcurves emitted by hot spots near horizon.

Each form
will be driven
within the e
➔ Boundary Layer nec



Gravitational E

- Boundary layer: Angular frequency observers (fixed stars) is given by (

$$\Omega = \frac{U^\phi}{U^t}$$

where U^μ is the 4–velocity of mat poloidal motion of matter, angular f gular momentum are related over a k

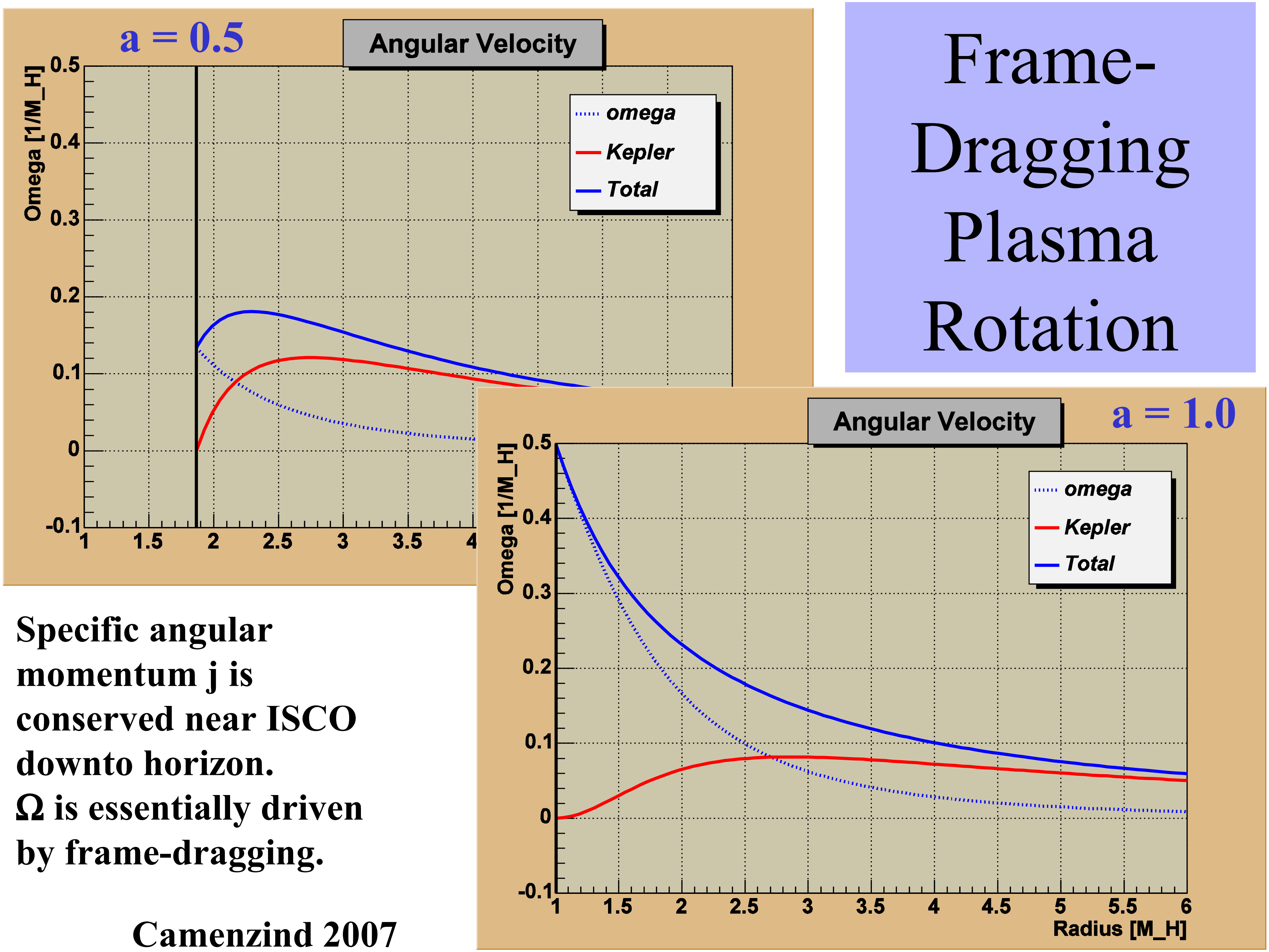
$\Omega_H = \omega(r_+)$

$$\Omega = \omega + \frac{\alpha^2}{R^2}\frac{\lambda}{1-\omega\lambda}\,. \qquad (2)$$

$R \equiv \sqrt{h_{\phi\phi}}$ is the cylindrical radius.

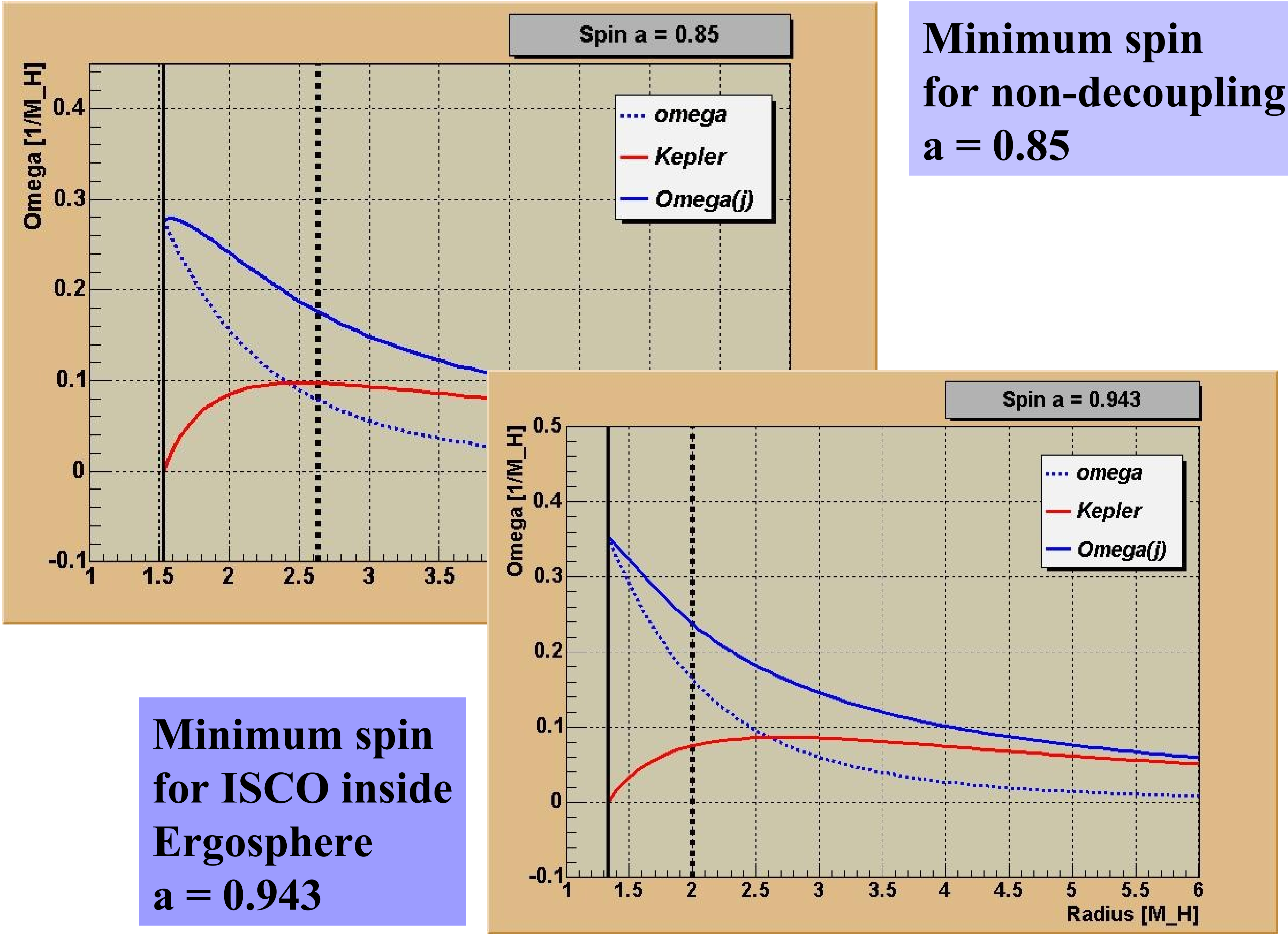
In Schwarzschild:
➔No rotation
near Horizon !

Frame-Dragging Plasma Rotation



Specific angular momentum j is conserved near ISCO downto horizon.
Ω is essentially driven by frame-dragging.

Camenzind 2007



Minimum spin for non-decoupling
a = 0.85

Minimum spin for ISCO inside Ergosphere
a = 0.943

➔ Twisting of Magnetic Fields

- Except for induction terms, evolution of toroidal magnetic field ~ Newtonian MHD

✂➔ Source: Differential plasma rotation

✂➔ Schwarzschild: anti-shear ! ➔ decoupling from hor

✂➔ Extreme Kerr: biggest effect !

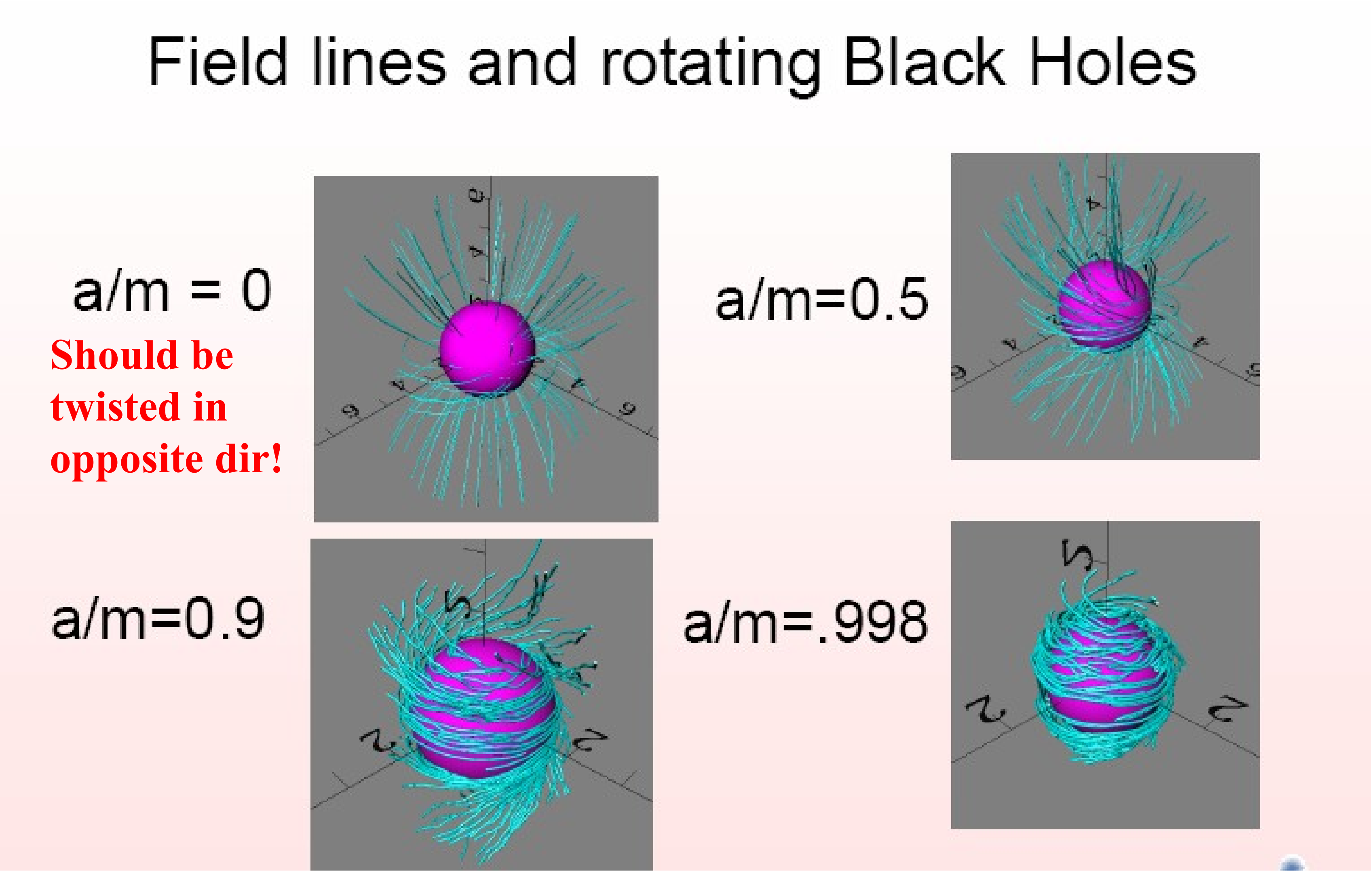
$$\frac{\partial T}{\partial t} + \alpha(\boldsymbol{v}_p \cdot \nabla)T - \alpha\tilde{\varpi}^2\,\nabla\cdot\left(\frac{T}{\tilde{\varpi}^2}\boldsymbol{v}_p\right) - \alpha\tilde{\varpi}^2\,\nabla\cdot\left(\frac{\eta}{\gamma\tilde{\varpi}^2}\nabla T\right)$$

$T \sim RB_\phi$

$$= \alpha\tilde{\varpi}^2\,\boldsymbol{B}_p \cdot \nabla\Omega + \alpha\tilde{\varpi}\,\boldsymbol{e}_\phi \cdot \nabla \times \left(\frac{\eta}{\gamma}\frac{\partial \boldsymbol{E}_p}{\partial t}\right).$$

Operates outside horizon

BHs – Magnetic fields are twisted !



Field lines and rotating Black Holes

a/m = 0

Should be twisted in opposite dir!

a/m=0.5

a/m=0.9

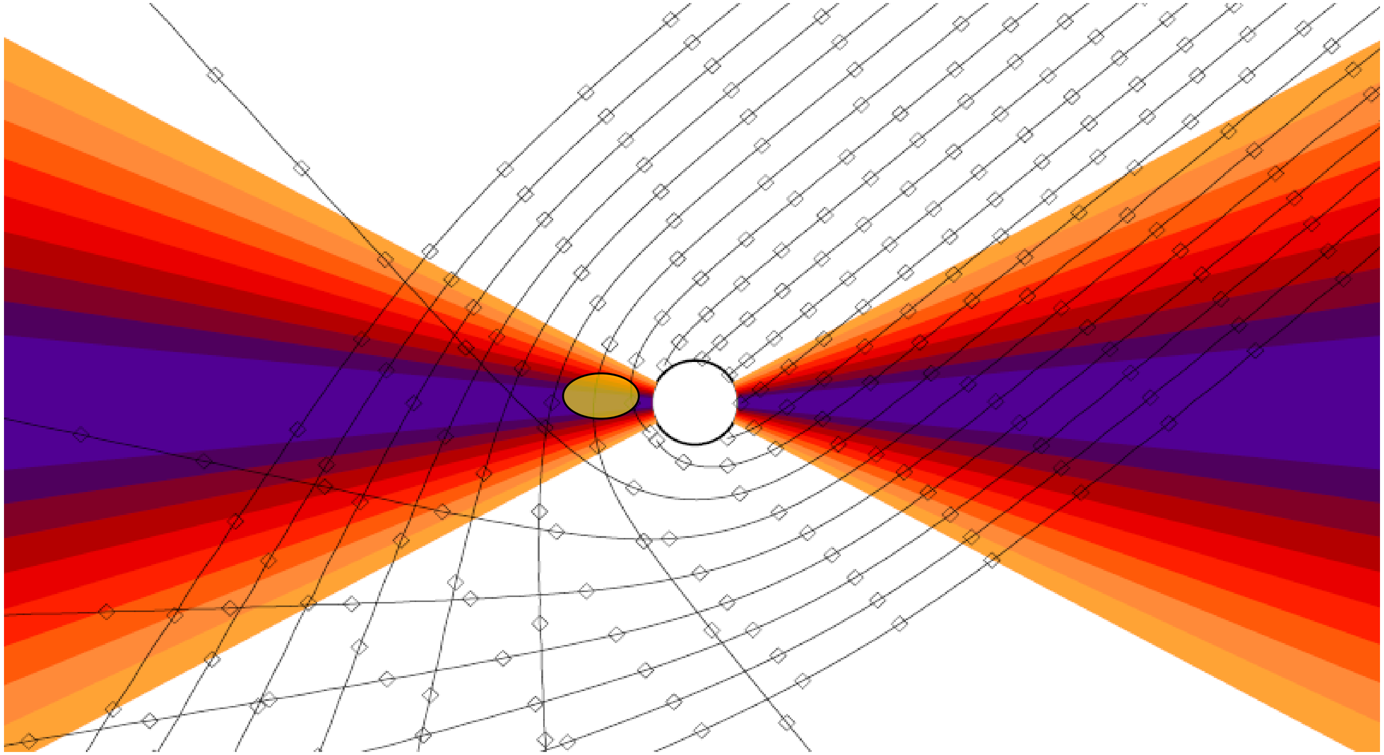
a/m=.998

Hawley 2005

Understanding BZ Mechanism

- The unavoidable rotation of plasma inside ergosphere **forces magnetic fields to rotate** as well.
- The **magnetic twist** propagates away from the BH, resulting in an **outgoing Poynting flux**.
- As a feedback action, magnetic forces push plasma into **orbits with negative mechanical energy** at infinity before they plunge into the BH.
- **Total flux of energy is conserved**: it changes from almost purely mechanical near horizon to Poynting flux further away, which is then ultimately transformed into mechanical energy at infinity.

Tracing Spots around BHs - Direct and Indirect Images



A. Müller, B. Zink, A. Kaminski, F. Neuschäfer [LSW 2003 – 2008]

Hot Spot around eKerr: Orbit = 7 R_g, 60° Inclination [Neuschäfer LSW]

Strong Gravity Effects – Existence of (inf)Horizon ?

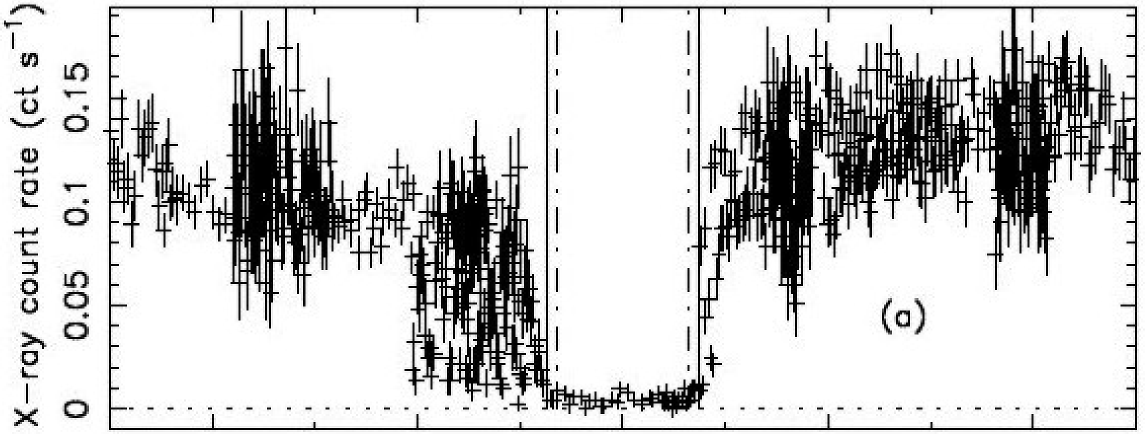
- … or, is the Black Hole really black ?
- According to modern concepts, the internal state of the BH is probably not a classical vacuum – a vacuum is never empty (Universe)!

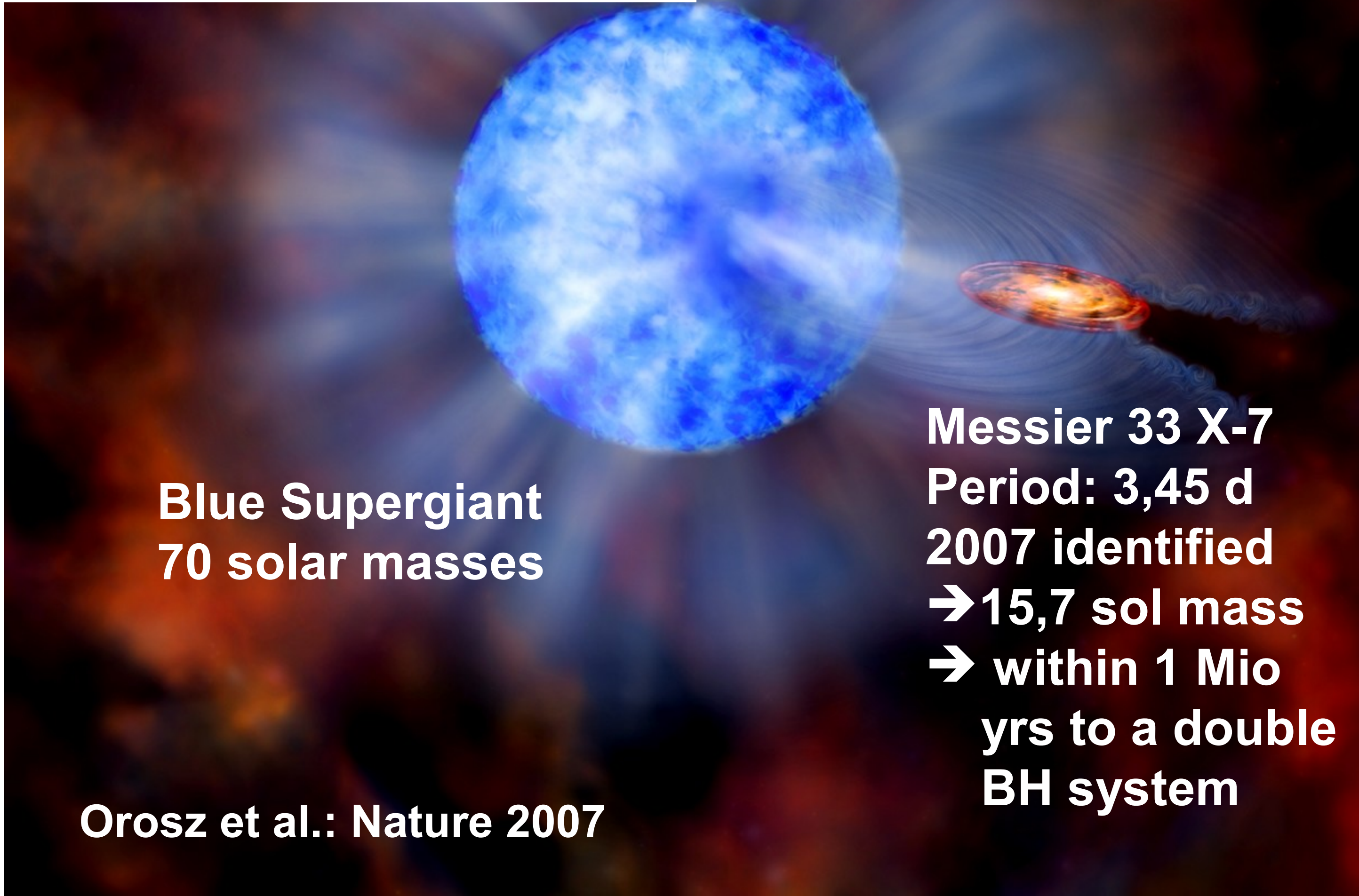
✂➔ Mass of BH is in vacuum energy with EoS **P = - ρ ➔ to non-singular solutions.**

✂➔ Essential question: how is accreting matter transformed to vacuum energy? **P = ρ at hor**

✂➔ Would this produce violent reactions?

High Mass Objects
Messier 33 X-7
Wind-Disk Accretion





Blue Supergiant
70 solar masses

Messier 33 X-7
Period: 3,45 d
2007 identified
➔15,7 sol mass
➔ within 1 Mio yrs to a double BH system

Orosz et al.: Nature 2007

Object	Bin. Period	Donor Star	Mass of BH	Spin a
GRS1915+105	33.5 d	K/M III	14 +/- 4	0.9 – 1.0
V404 Cyg	6.470 d	K0 IV	12 +/- 2	-
Cyg X-1	5.600 d	O9.7ab	8 +/- 2	0.4 – 0.6
LMC X-1	4.229 d	O7 III	> 4	-
M33 X-7	3.45 d	O7 III	15.6 +/- 1.4	0.77+/-0.05
LMC X-3	1.704 d	B3 V	7.6 +/- 1.2	0.2 – 0.4
GRO J1655-40	2.620 d	F3 IV	6.3 +/- 0.3	0.6 – 0.8
XTEJ1819-254	2.816 d	B9 III	7.1 +/- 0.3	-
GX 339-4	1.754 d	Stripped giant	> 7	0.93+/-0.04 (Suz)
XTEJ1550-564	1.542 d	G8 IV	9.6 +/- 1.2	-
4U 1543-47	1.125 d	A2 V	9.4 +/- 1.0	0.75-0.85
H 1705-250	0.520 d	K3 V	6 +/- 2	-
GS 1124-168	0.433 d	K3 V	7.0 +/- 0.6	-
XTE 1859+226	0.382 d	-	-	-
GS 2000+25	0.345 d	K3 V	7.5 +/- 0.3	-
A 0620-00	0.325 d	K4 V	11 +/- 2	-
XTEJ1650-500	0.321 d	K4 V	-	-
GRS 1009-45	0.283 d	K7 V	5.2 +/- 0.6	-
GROJ0422+32	0.212 d	M2 V	4 +/- 1	-
XTEJ1118+480	0.171 d	K5 V	6.8 +/- 0.4	-

Remillard & McClintock 2006; Camenzind 2007

	Object	Core Radius	Donor Nucleus	Mass of BH	Expected Spin
→	**Galactic Center**	**1 pc**	**NStarCluster**	**4 Mio**	**0.99 – 1.0 (Asch)**
	Andromeda (Sb)	**10 pc**	**NStarCluster**	**40 Mio**	**a < 0.6 ?**
→	**Circinus (Sb)**	**-**	**NStarCluster**	**10 Mio**	**a < 0,5 ?**
	NGC 1068 (SBb)	**10 pc**	**NStarCluster**	**10 Mio**	**Low spin**
→	**MCG-6-30-15**		**NStarCluster**	**4 Mio**	**-**
	Ark 564 (Sb)		**NStarCluster**	**3 Mio**	**-**
	NGC 4151 (Sb)		**NStarCluster**	**10 Mio**	**-**
	NGC 5548 (Sb)		**NStarCluster**	**80 Mio**	**-**
→	**3C 120 (Sa)**		**Bulge-dominated**	**40 Mio**	**High Spin**
	M 87 (E1)	**680 pc**	**E-Bulge-Core/Disk**	**3000 Mio**	**a ~ 0.9 ?**
	M 84 (E0)	**1000 pc**	**E-Bulge**	**1000 Mio**	**-**
	Sombrero (S0)	**10 pc**	**NStarCluster**	**1000 Mio**	**-**
	Cyg A (E+S)		**E-Bulge/Disk**	**3200 Mio (T)**	**-**
	BL Lac		**E-Bulge**	**200 Mio**	**-**
	Hercules A	**800 pc**	**E-Bulge**	**1000 Mio**	**a ~ 0.98 ?**
	Typical Quasar	**1000 pc**	**E-Bulge**	**1000 Mio**	**-**
	3C 273	**1000 pc**	**E-Bulge**	**3000 Mio**	**a ~ 0.98 ?**

Camenzind 2008

Vicinity of SMBH in Sy-Galaxies
Nucleus and Dust-Torus

Dust is heated by UV-flux from disk

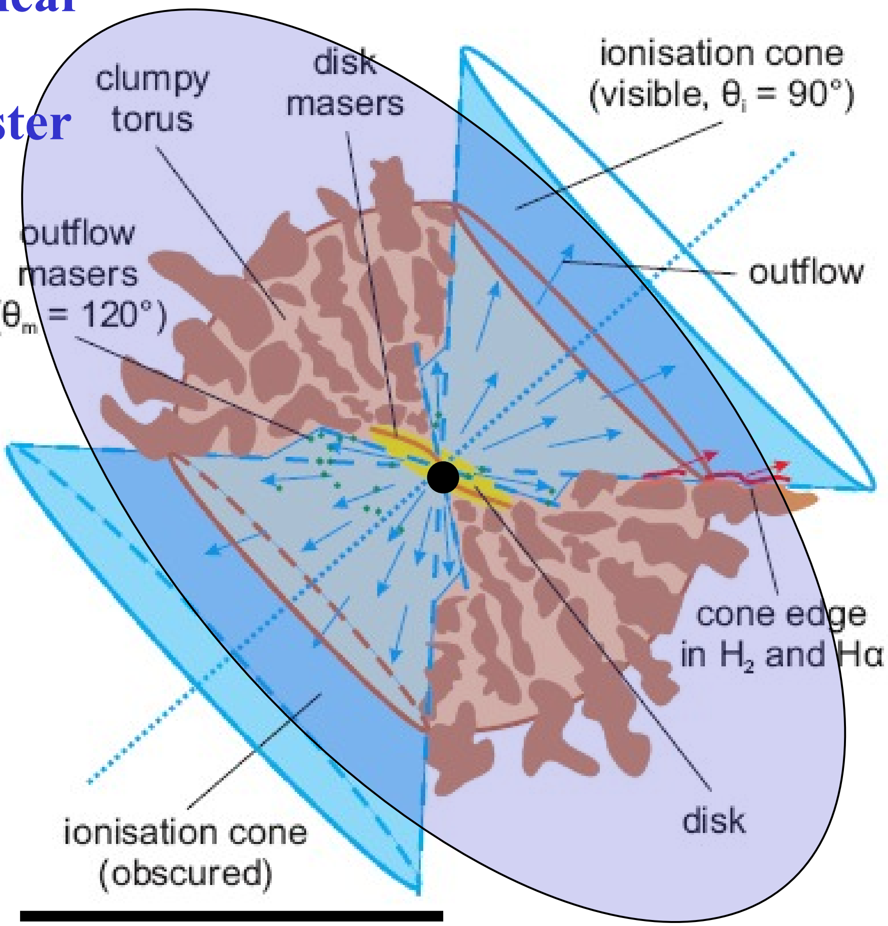
$$T_{\mathrm{N}}(r) = 194 \left(\frac{L_{\mathrm{acc}}}{r^2} \frac{\mathrm{pc}^2}{10^{10}\,\mathrm{L}_\odot} \right)^{1/4} \mathrm{K}.$$

With exact opacity:

$$T_{\mathrm{B}}(r) = 624 \left(\frac{L_{\mathrm{acc}}}{r^2} \frac{\mathrm{pc}^2}{10^{10}\,\mathrm{L}_\odot} \right)^{1/5.6} \mathrm{K}.$$

K. Tristram et al. 2007
M. Schartmann et al. 2008

Nuclear Star Cluster



~ 10 pc

Nuclear Star Cluster in NGC 1068

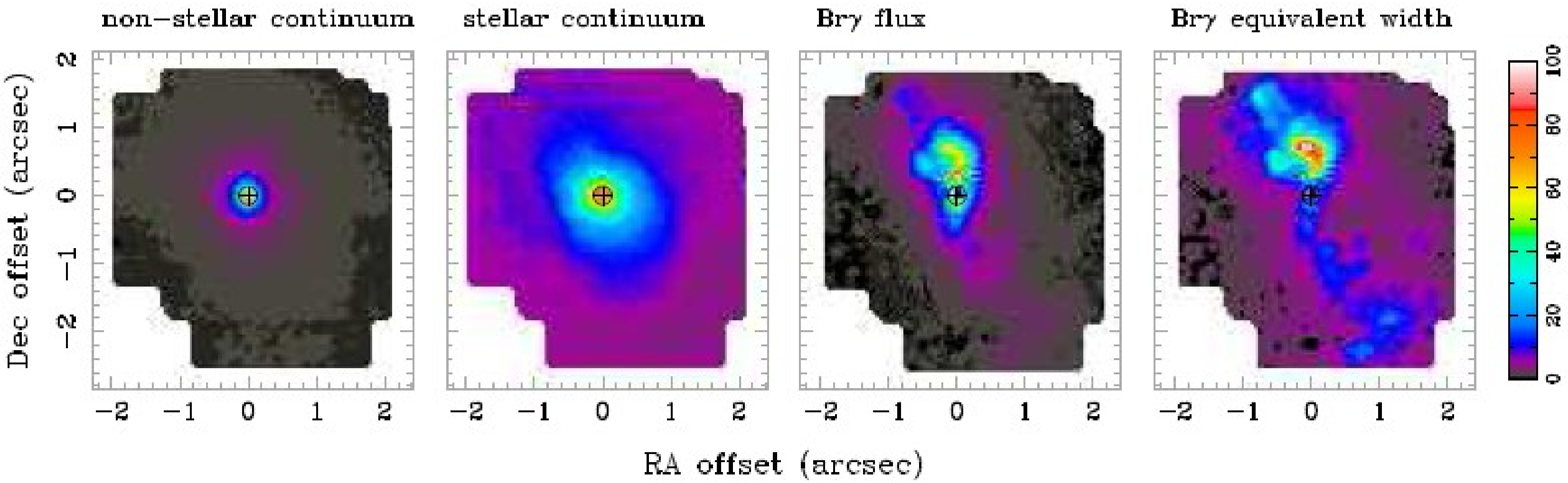
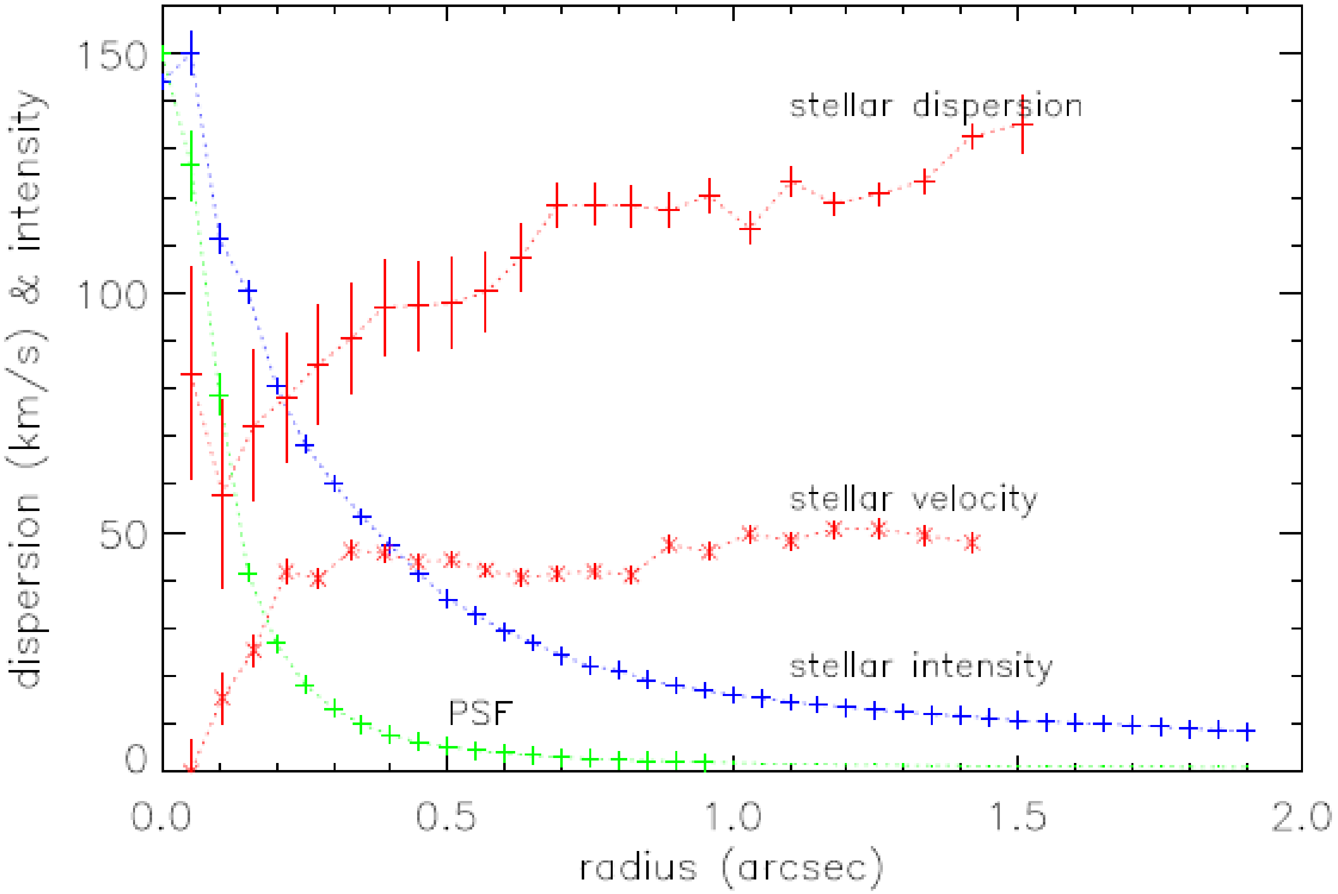


Fig. 23.— Maps of the central few arcsec of NGC 1068 ($1'' = 70\,\mathrm{pc}$): H-band non-stellar continuum (far left) and stellar continuum (centre left); also Brγ line flux (center right) and Brγ equivalent width (far right). In each case, the centre (as defined by the non-stellar continuum) is marked by a crossed circle. The colour scale is shown on the right, as percentage of the peak in each map (and also as $W_{\mathrm{Br}\gamma}$ in Å).

Davies et al. 2007 / d = 14.4 pc / 1´´ = 70 pc

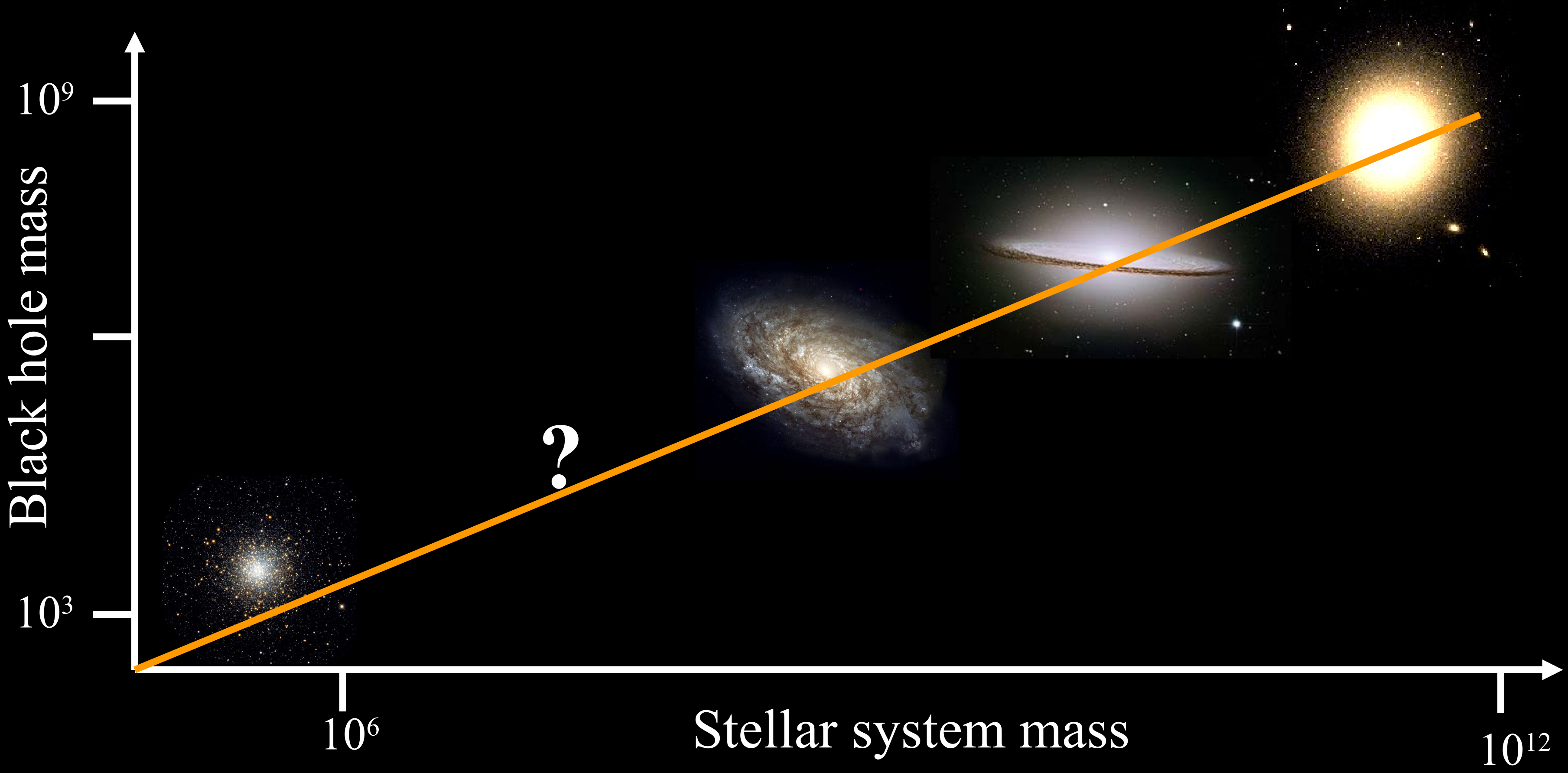
NGC 1068 – Rotating Nucleus



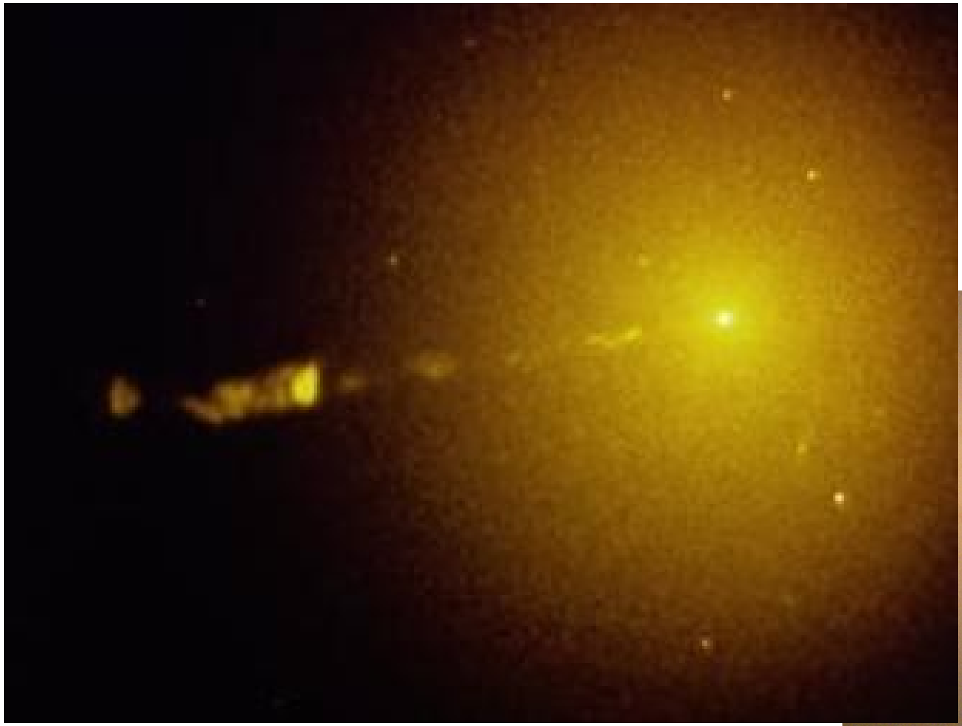
Davies et al. 2007 / 1´´ = 70 pc

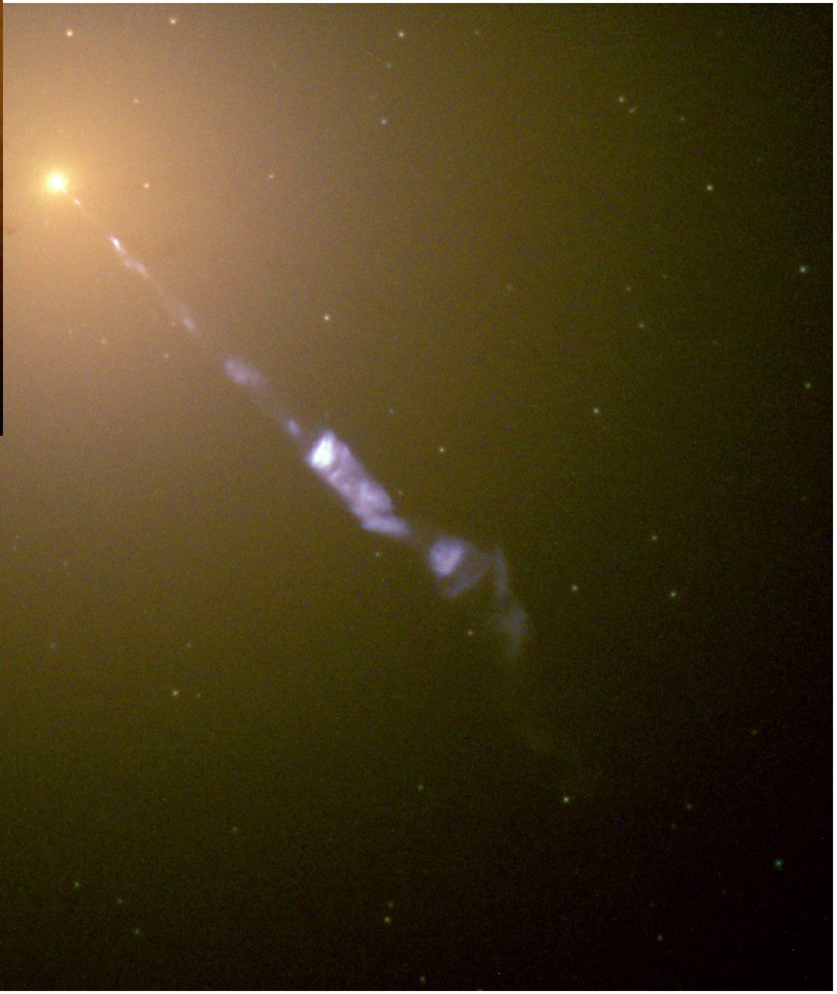
Black Holes in Galactic Nuclei

- stellar bulge gives BH mass – link between galaxy and BH (Magorrian relation: better between σ of stars and M_{BH})
- QSOs peak at z~2-3, L/L_{Edd} ~1 onto ~10^8 M_0 (local NLS1)



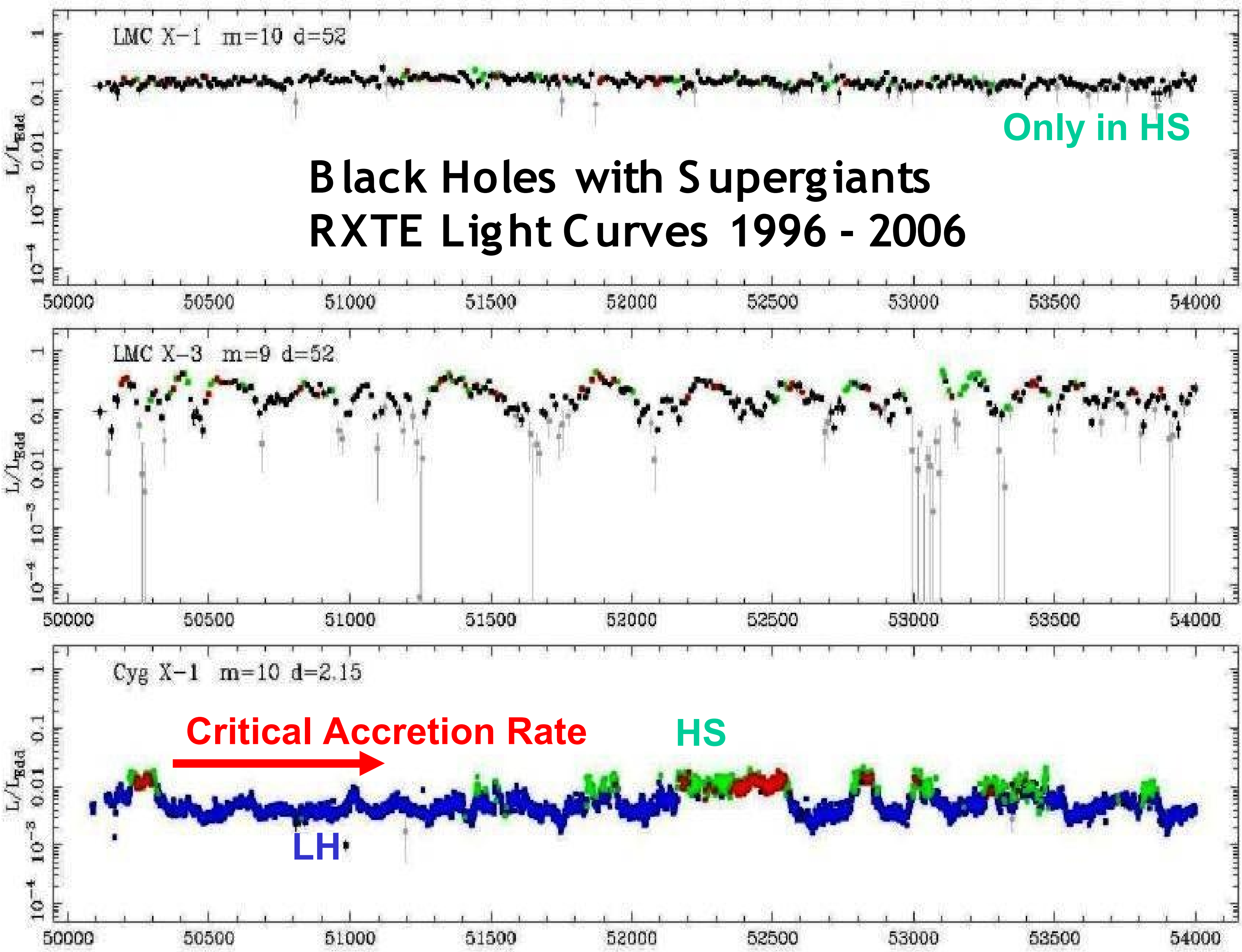
Vicinity of SMBH in M87

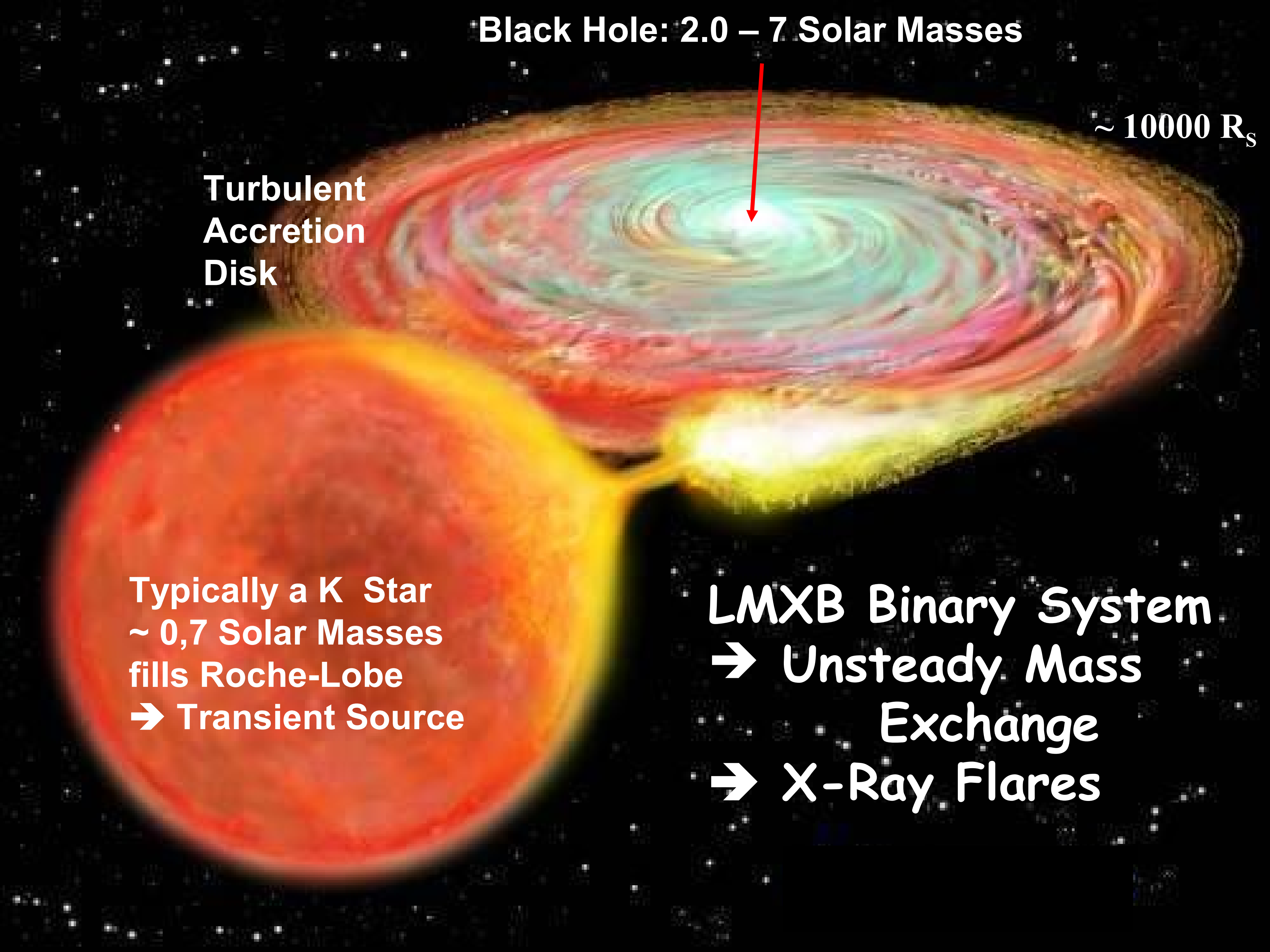




BH embedded into stellar core of 650 pc.
➔ No molecular Torus !!!! - only disk - in contrast to many bright 3C sources

Black Holes with Supergiants
RXTE Light Curves 1996 - 2006





Black Hole: 2.0 – 7 Solar Masses

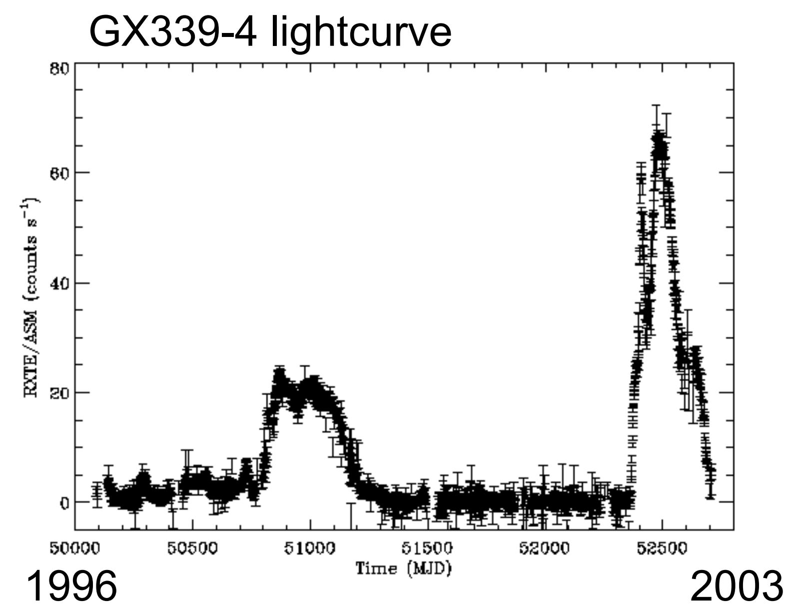
$\sim 10000\ R_S$

Turbulent
Accretion
Disk

Typically a K Star
~ 0,7 Solar Masses
fills Roche-Lobe
➔ Transient Source

LMXB Binary System
➔ Unsteady Mass
Exchange
➔ X-Ray Flares

LMXBs →Transients are variable: VARIABILITY on all Time Scales



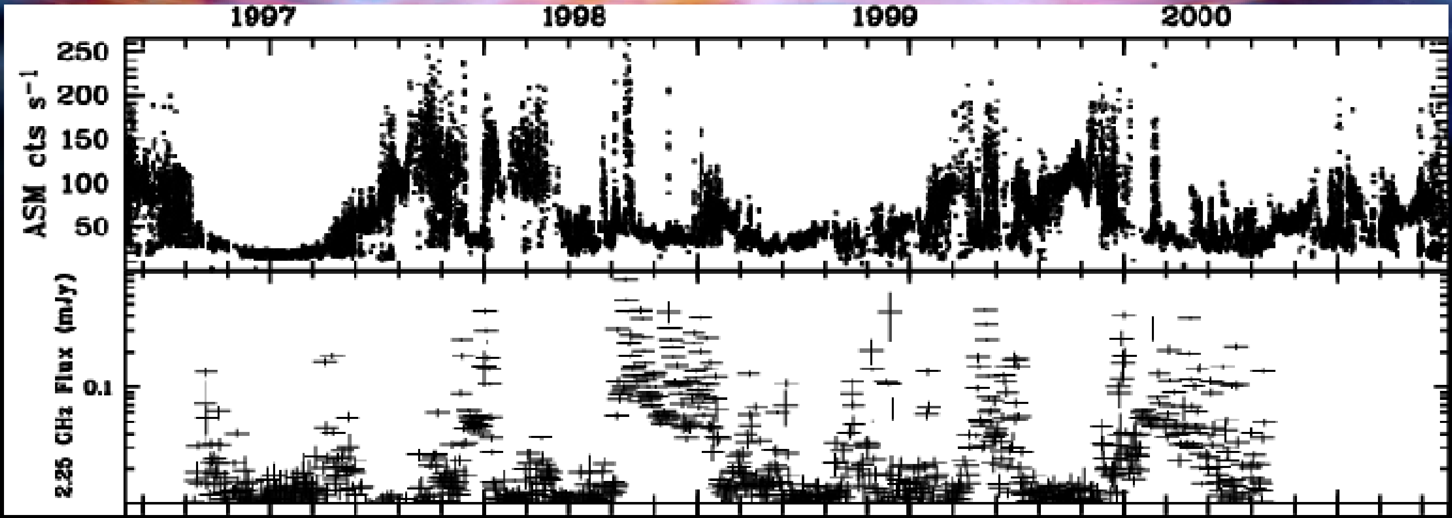
- Variations = changes in the state of the source
- lightcurves:
  GX 339-4 / GRS 1915+105

↳ Variations on very different time scales !

↳ “easy” observations for human time scale

→ 10 Mio years in Quasars

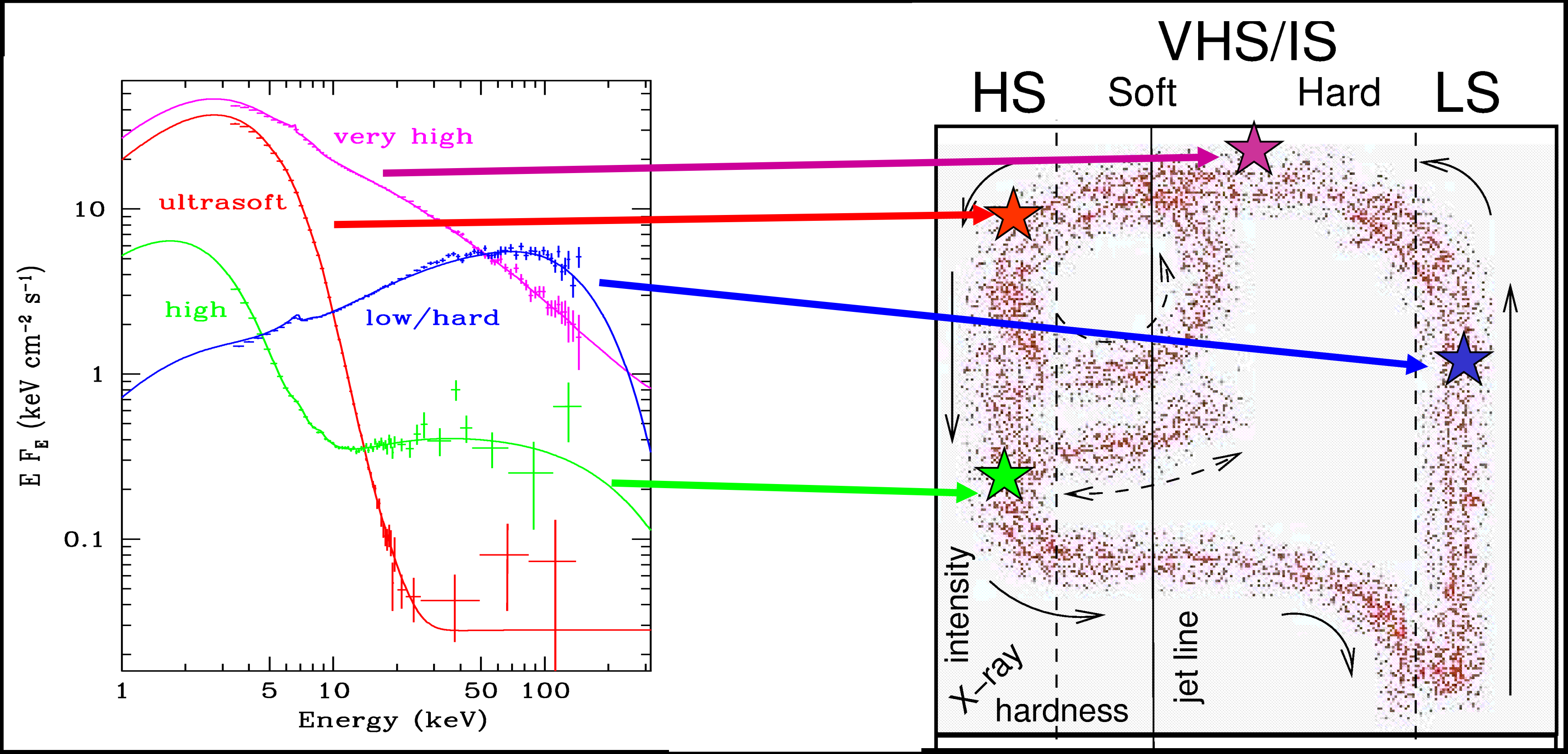
GRS 1915+105



Rau et al (2003)

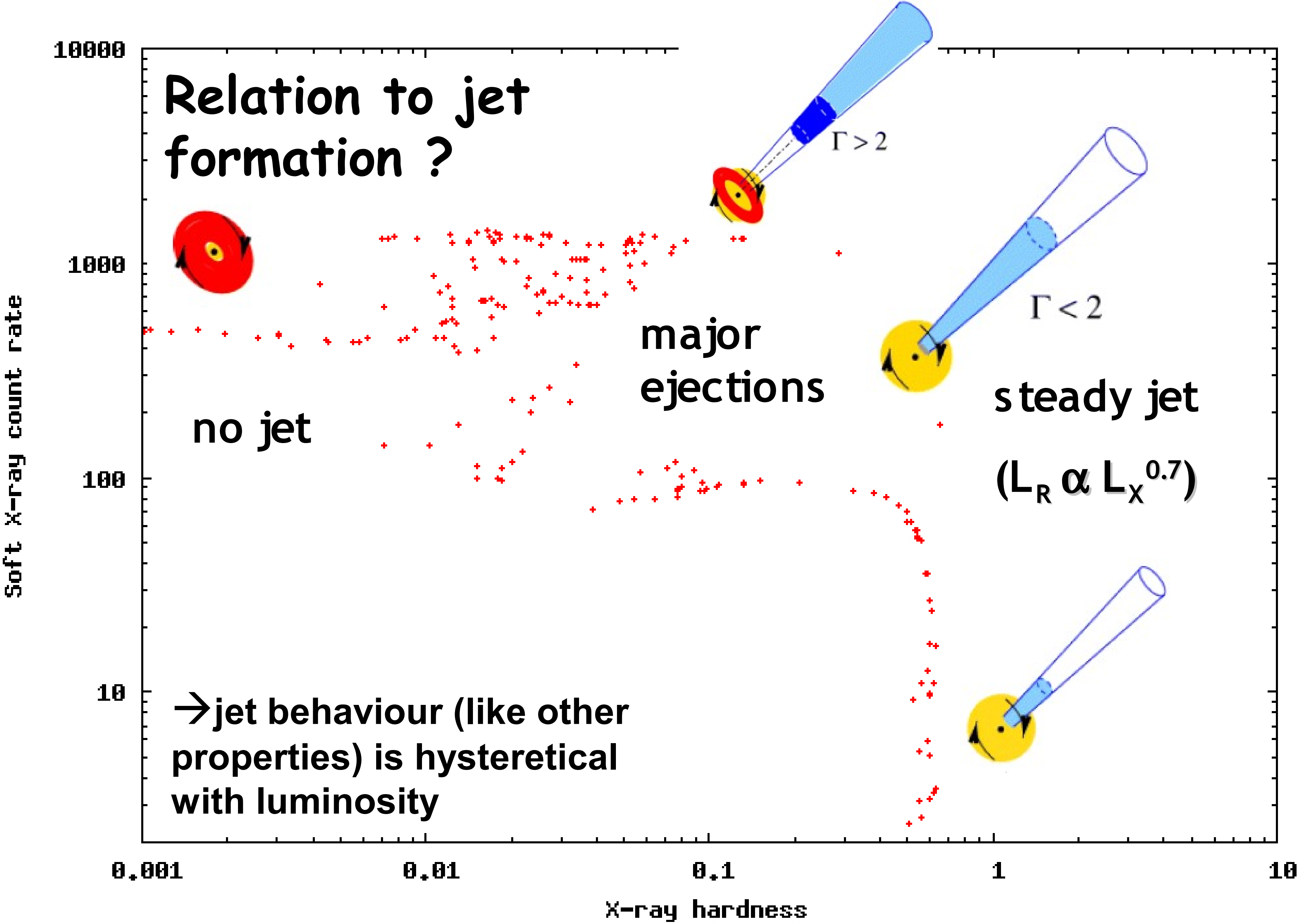
Accretion States - Spectra

- Bewildering variety for disky spectra in single objects!
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail.
- All XBH in RXTE archive consistent with SAME spectral evolution $10^{-3} < L/L_{\mathrm{Edd}} < 1$.



Fender Belloni & Gallo 2004

Relation to jet formation ?



no jet

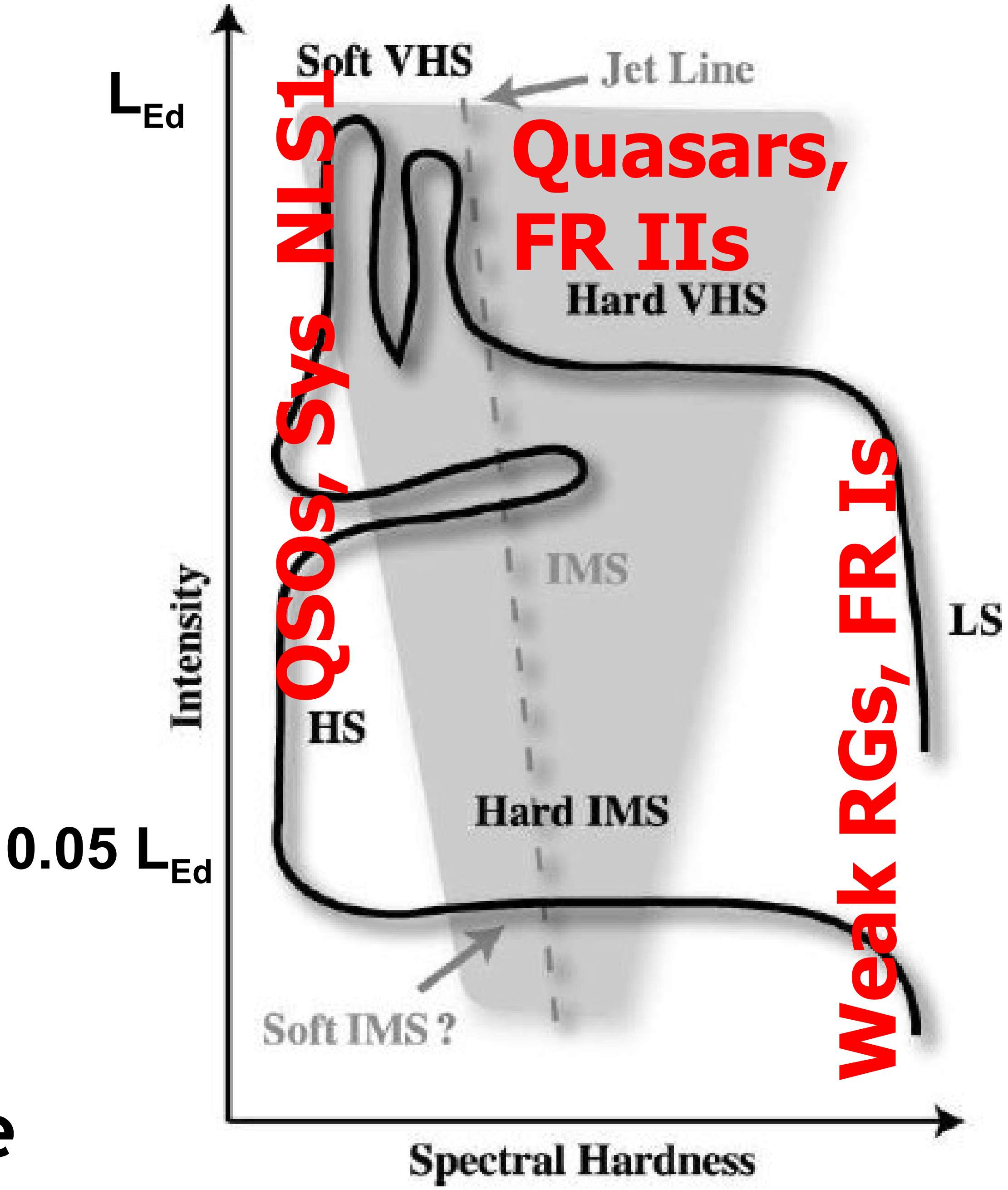
major ejections

steady jet

($L_R \alpha L_X^{0.7}$)

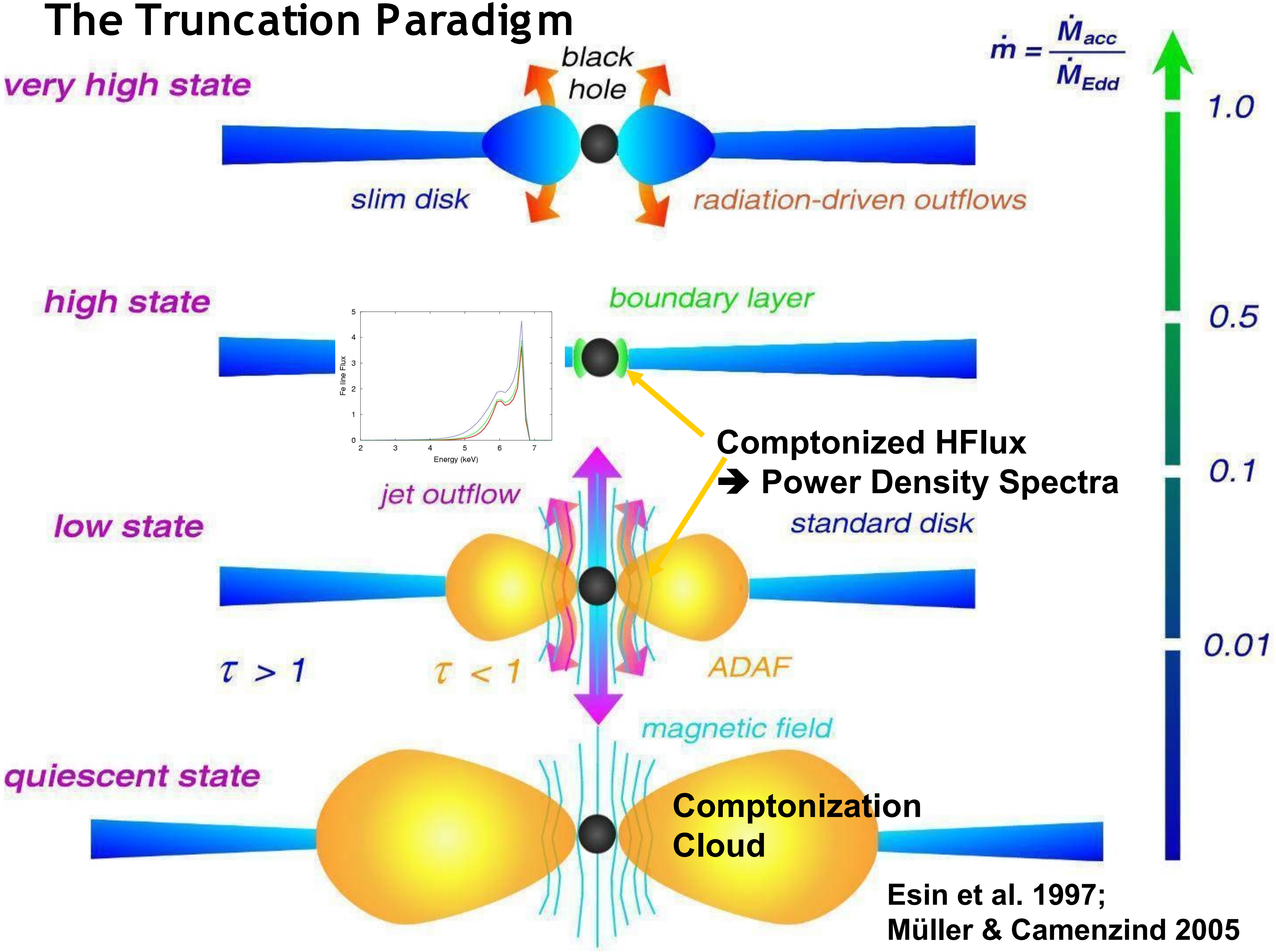
→jet behaviour (like other properties) is hysteretical with luminosity

New Twist: Accretion States of AGN - Hysteresis in Intensity and Hardness over evolution time



Koerding et al. 2006; ….

The Truncation Paradigm



Comptonized HFlux

➔ Power Density Spectra

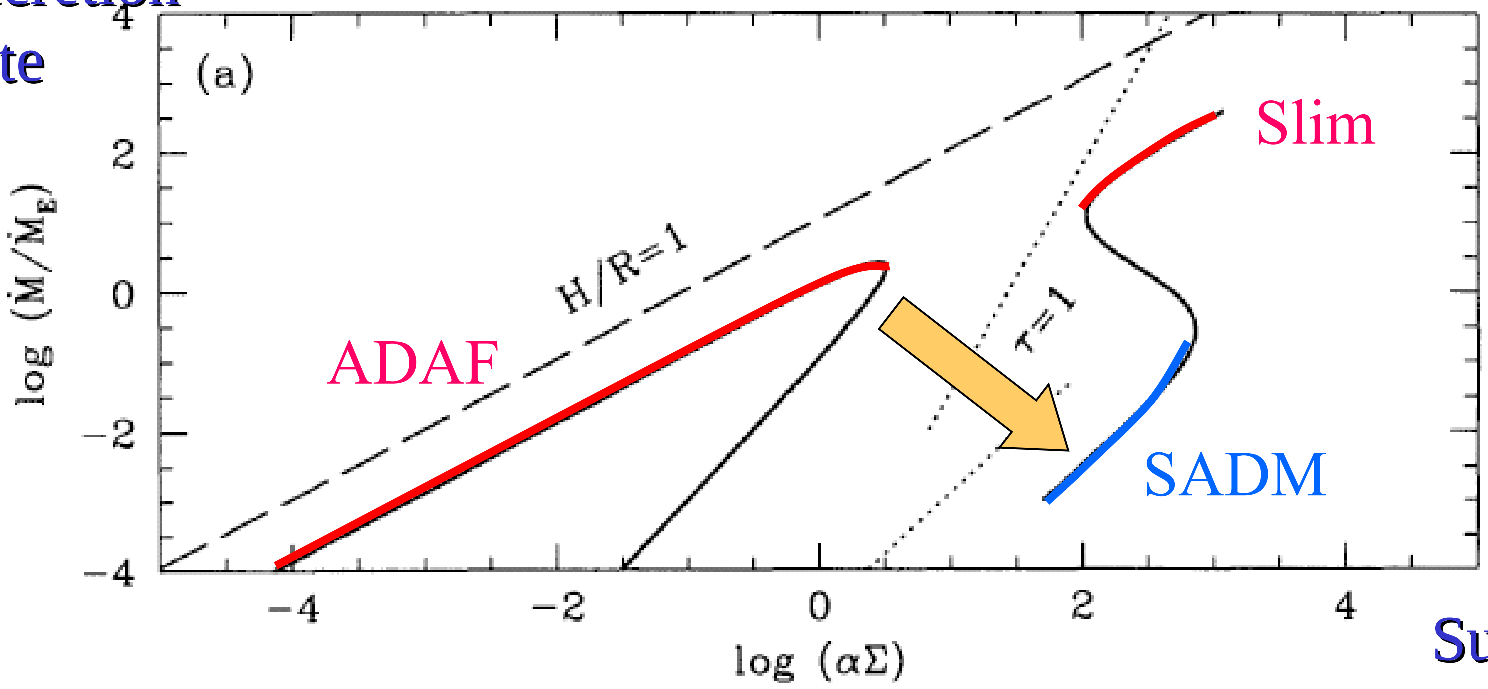
Comptonization Cloud

Esin et al. 1997;
Müller & Camenzind 2005

During the Transition from Low/hard State to High/soft state, Mdot Decreases

Abramowicz et al. 1995

Accretion Rate

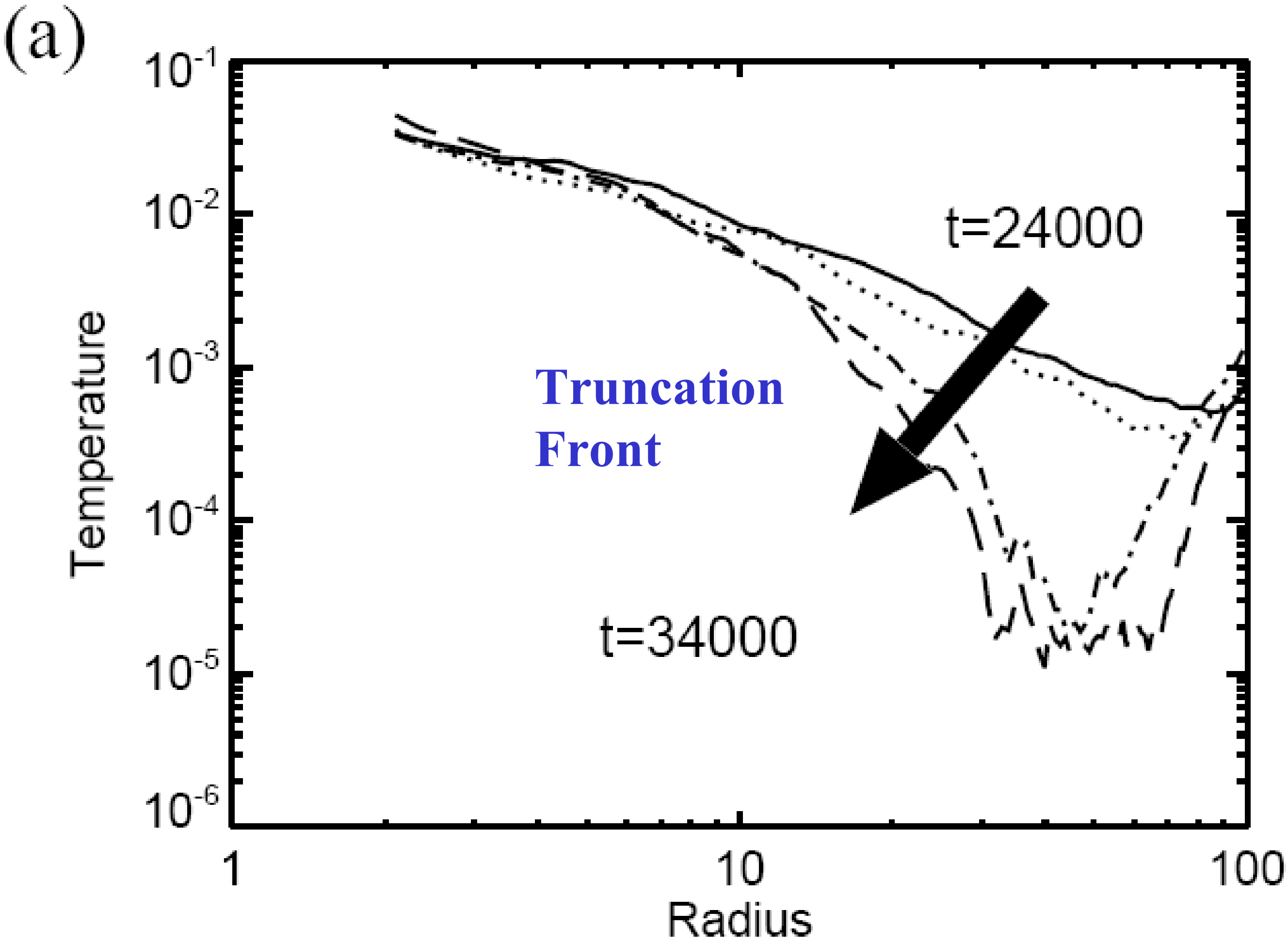


Surface Density

Optically thin ← → Optically thick

State Transitions around BHs in Numerical Simulations

- When mass acretion increases, cooling starts in outer part
- Transition front moves inwards.

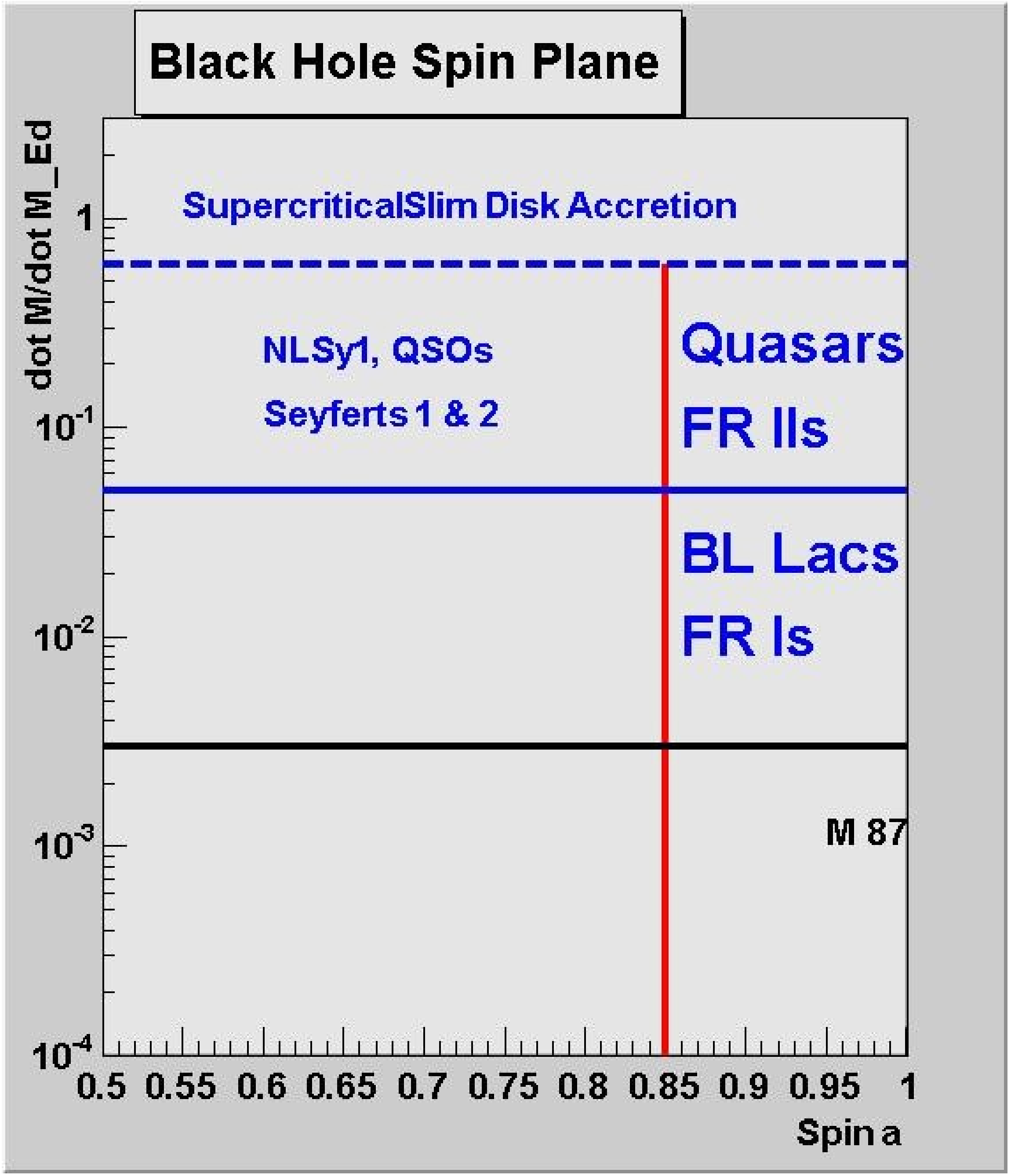


Machida 2006

Ad Truncation Paradigm

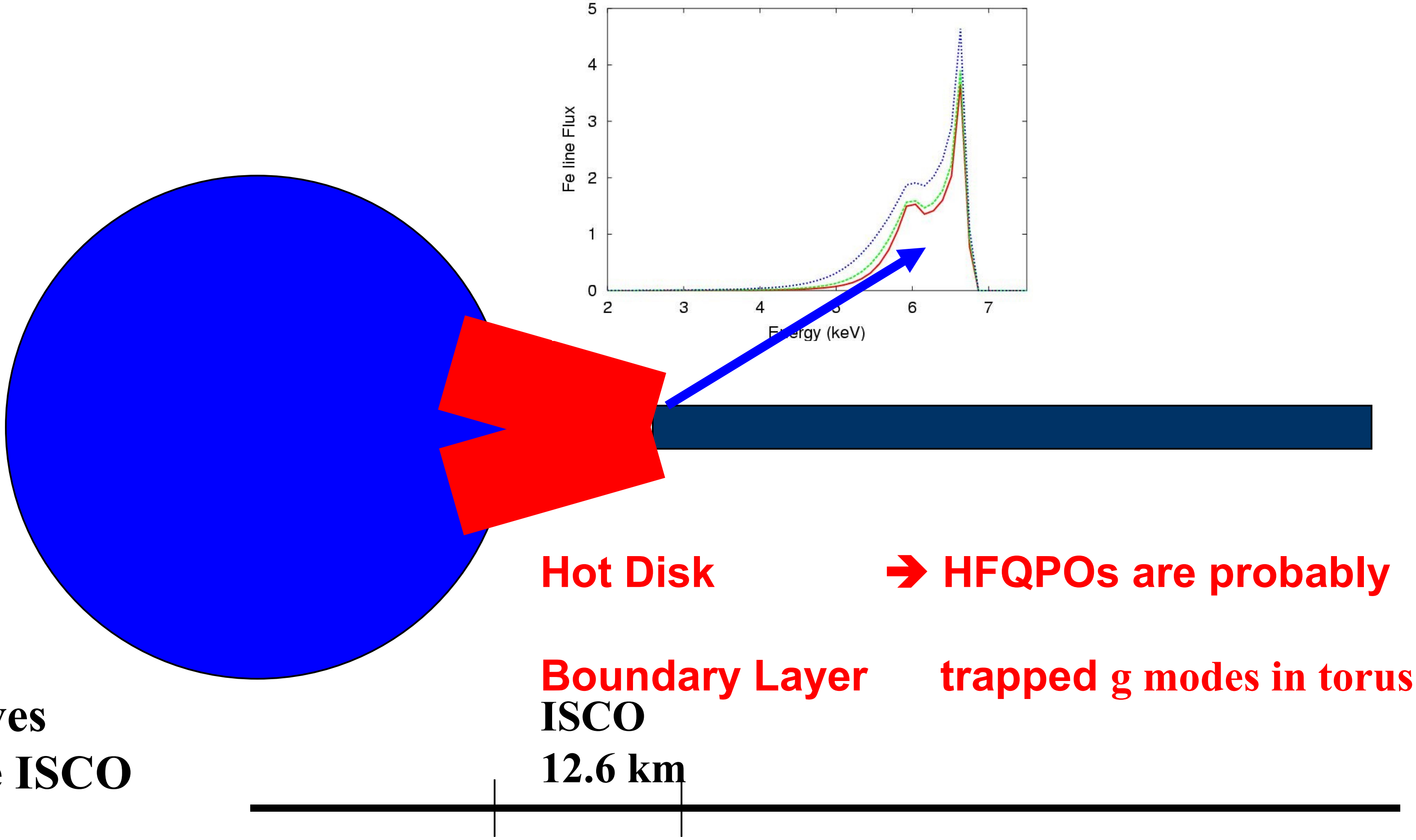
- … is basis for all MRI simulations, which neglect radiation on disk instabilities.
- … if truncation paradigm were not satisfied, forget about all results obtained from those simulations.
- … gets support from X-ray timing: Cyg X-1 etc, and the fact that jets disappear in VHS.
- … 2D & 3D simulations for the transition from optically thick to optically thin and vice versa disks still missing (hysteresis!).

What is the Role of the Black Hole Spin ?



Camenzind 2008

Truncated Disks also in NSs !



Hot Disk

Boundary Layer

➔ HFQPOs are probably

trapped g modes in torus

ISCO
12.6 km

NS lives inside ISCO
➔
From Suzaku observations

11 km

15 km

LMXB “Atoll Sources”

Low luminosity (atoll sources) have luminosities –

few x 10^{36} erg/s

~ 0.01 – 0.05 L_{Edd}

Two spectral states: soft (look like a Z-source) and hard (look like an X-ray binary with a black hole e.g. Cyg X-1)

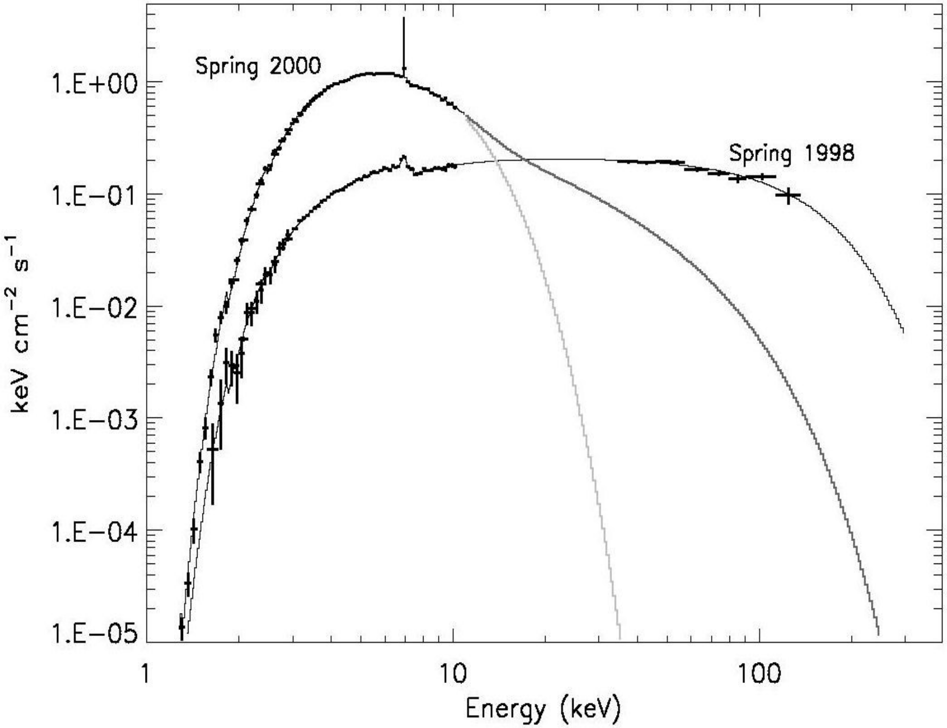
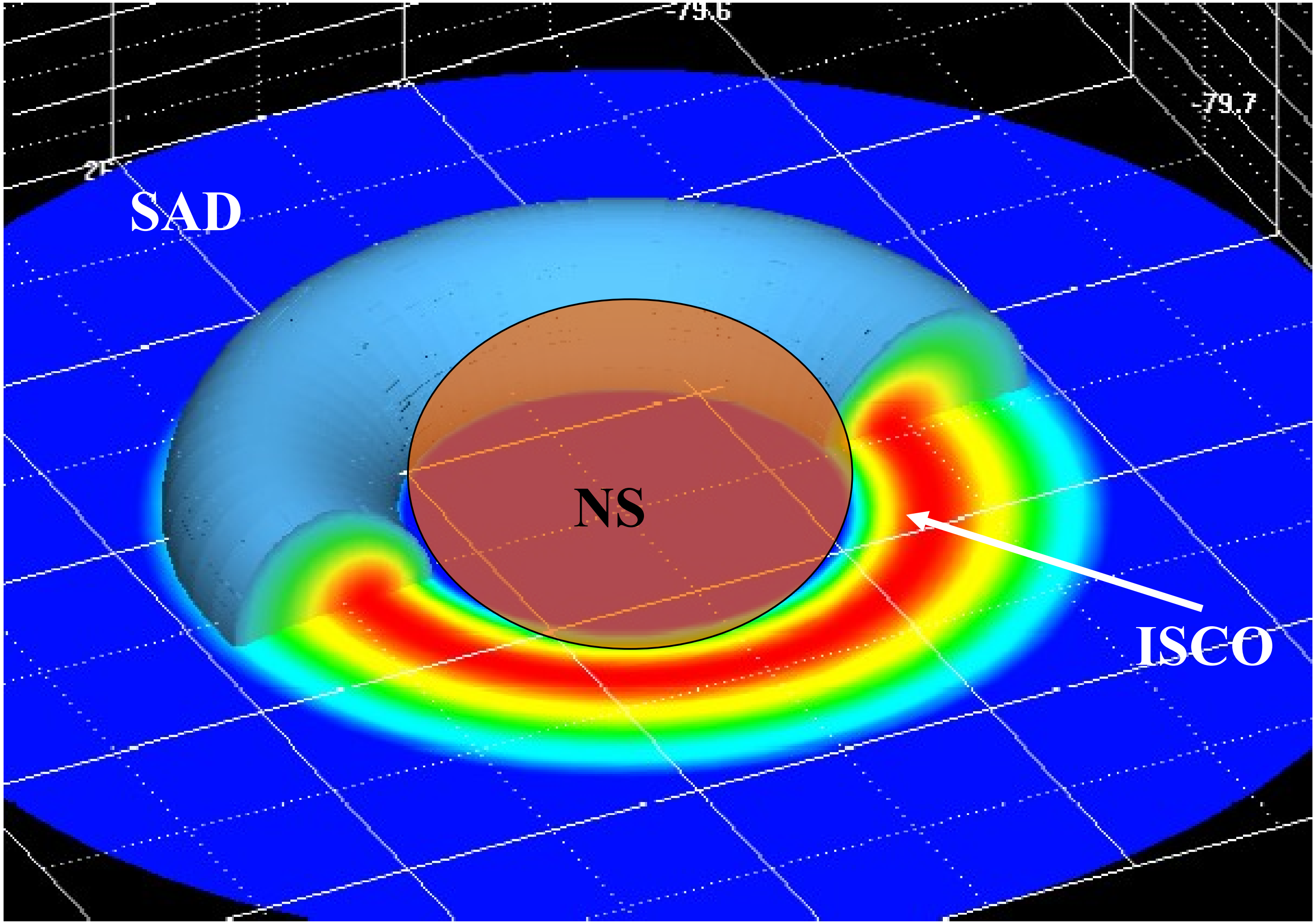


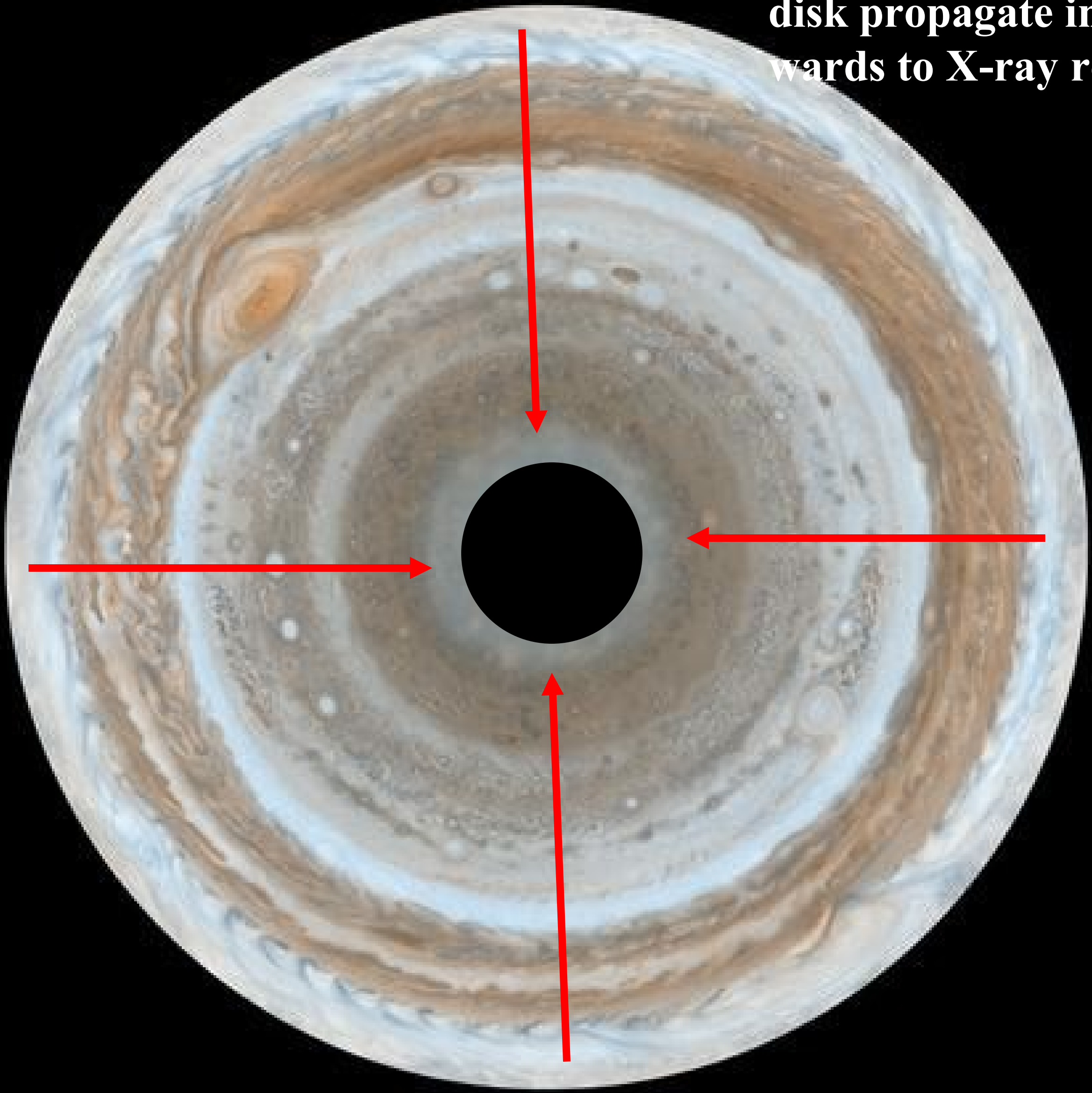
Figure from Natalucci et al (2004) (BeppoSAX)

Accreting Neutron Stars
Atoll Sources: $L < 0.05\ L_{Ed}$



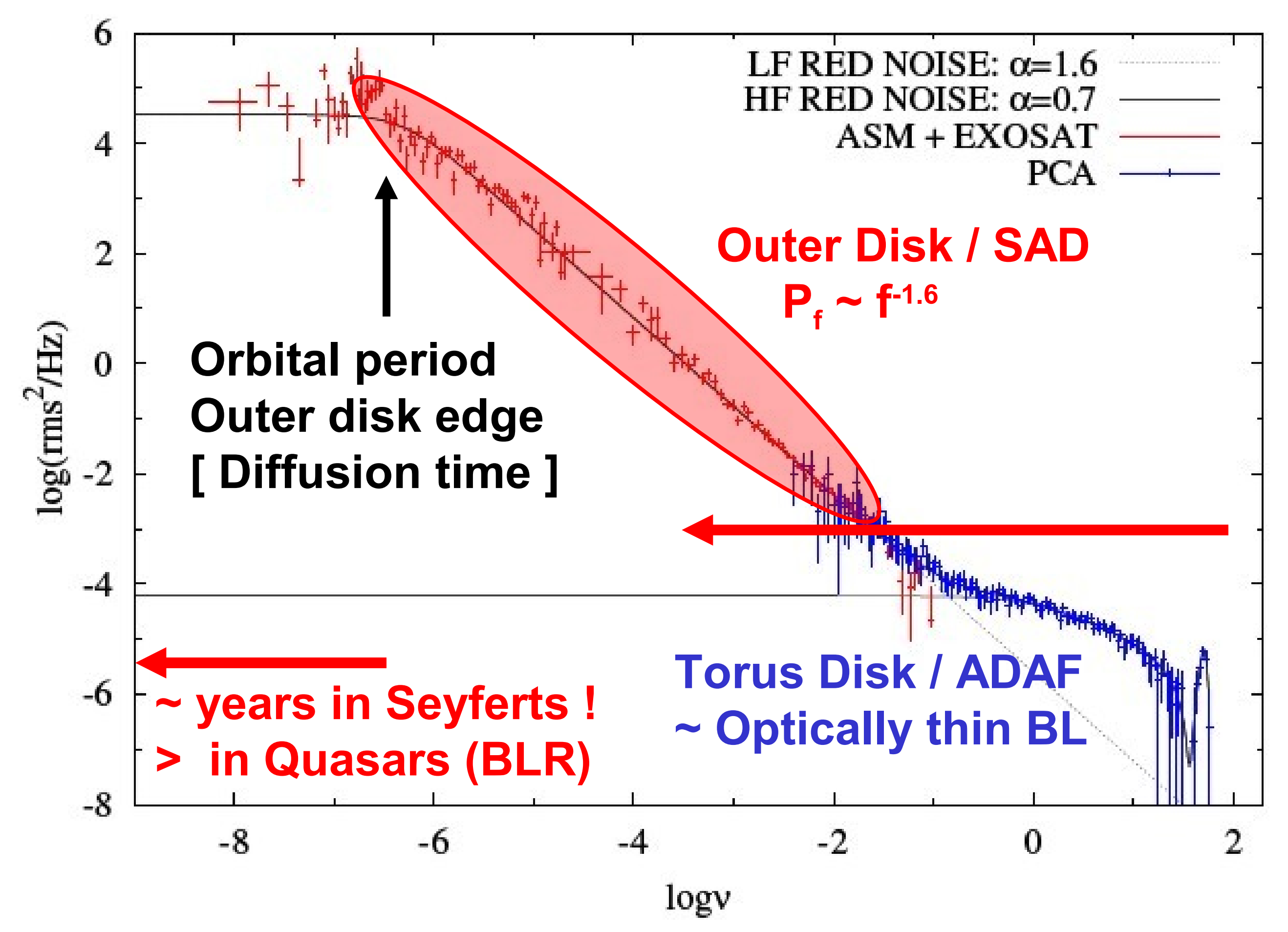
Turbulent Accretion Disks around CObjects

→ Reactive-Diffusion Stochastic System



Low frequency pert generated in outer disk propagate inwards to X-ray region

PDS of HX: 2 Components– Cyg X-2



Orbital period
Outer disk edge
[Diffusion time]

Outer Disk / SAD
$P_f \sim f^{-1.6}$

Torus Disk / ADAF
~ Optically thin BL

~ years in Seyferts !
> in Quasars (BLR)

Marat Gilfanov 2008; Lev Titarchuk et al. 2007

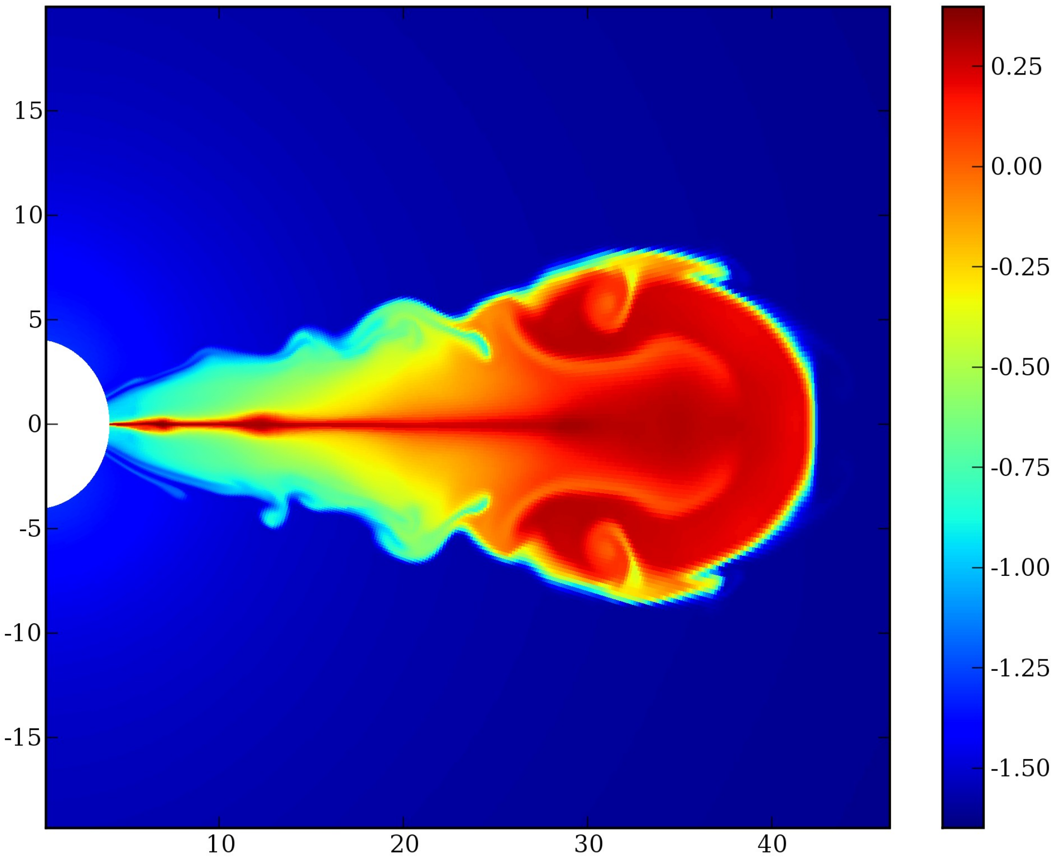
Is Disk Turbulence due to MRI ?

- Initial torus configuration
- Pseudo-Newtonian 10 M_S
- SRelativistic + conservative PLUTO code
- Torus ~ 30 r_g

✂➔ 1500 lcts

- ~ 26 ISCO rotations
- 1 lct = r_g/c

∀ ν_{lct} = 20,000 Hz



Roman Gold LSW 2008

Magnetorotational Turbulence

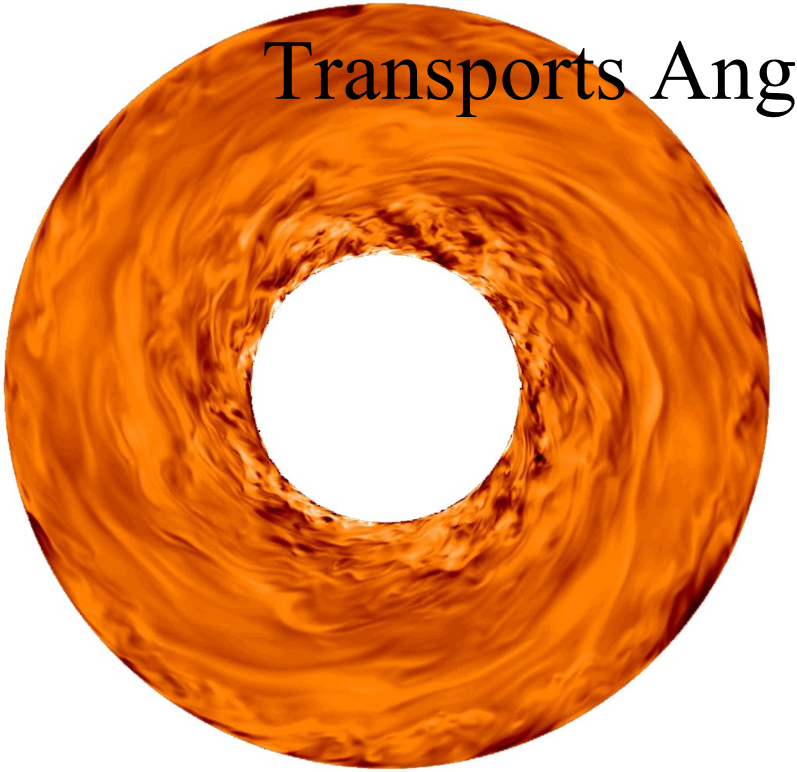
- MRI is carried by slow **magnetosonic waves (or inertial-Alfven waves)**, which replace the **acoustic-inertial waves** in the pure hydro case for disks

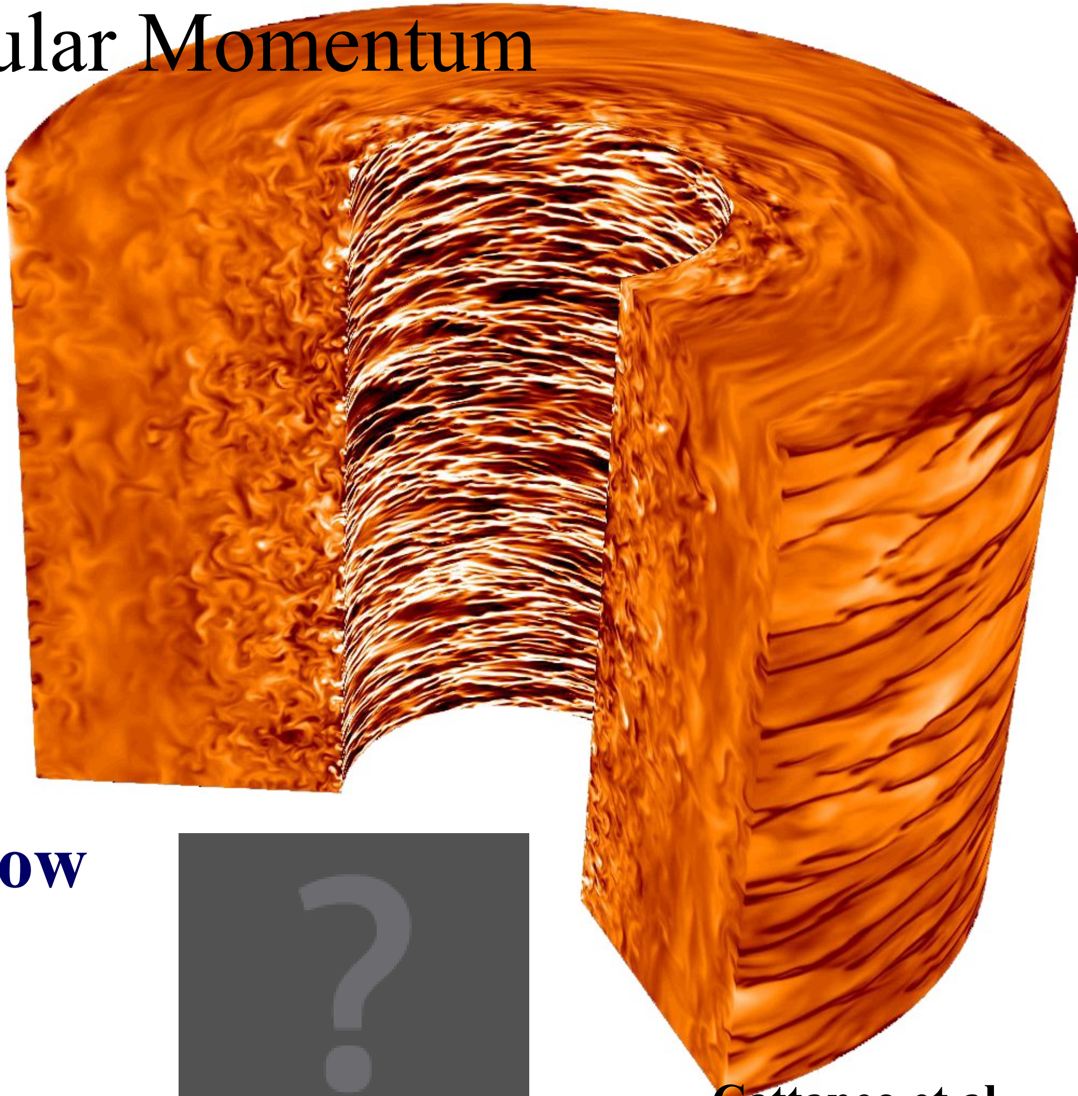
$$\boldsymbol{\omega}^2 = [\boldsymbol{\kappa}^2 + 2(\mathbf{k}.\mathbf{V}_A)^2]/2 + [\boldsymbol{\kappa}^4 + 2(\mathbf{k}.\mathbf{V}_A)^4 + ..]^{1/2}/2$$

$\boldsymbol{\kappa}$: epicyclic frequency ~ **$\boldsymbol{\Omega}$, which vanishes at ISCO!**

- **At each ring with $\Omega' < 0$, a resonance is generated with wave-length** $\boldsymbol{\lambda \sim 2\pi V_A/\Omega \sim 2\pi H / \beta^{1/2}}$

Magneto-Rotational Turbulence in Taylor-Couette Flows Transports Angular Momentum

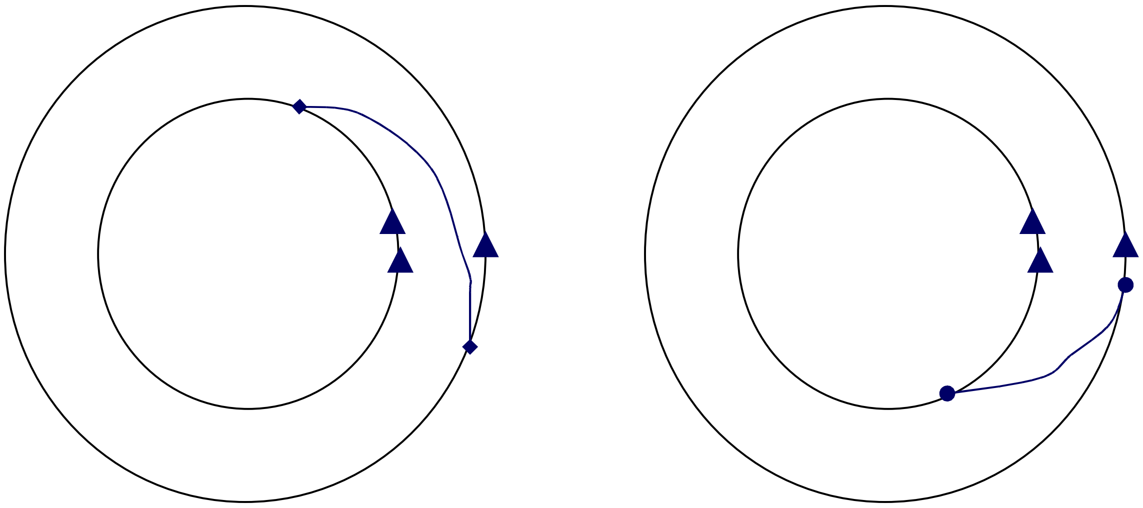




⇒ **Streaks of high and low speed or angular momentum**

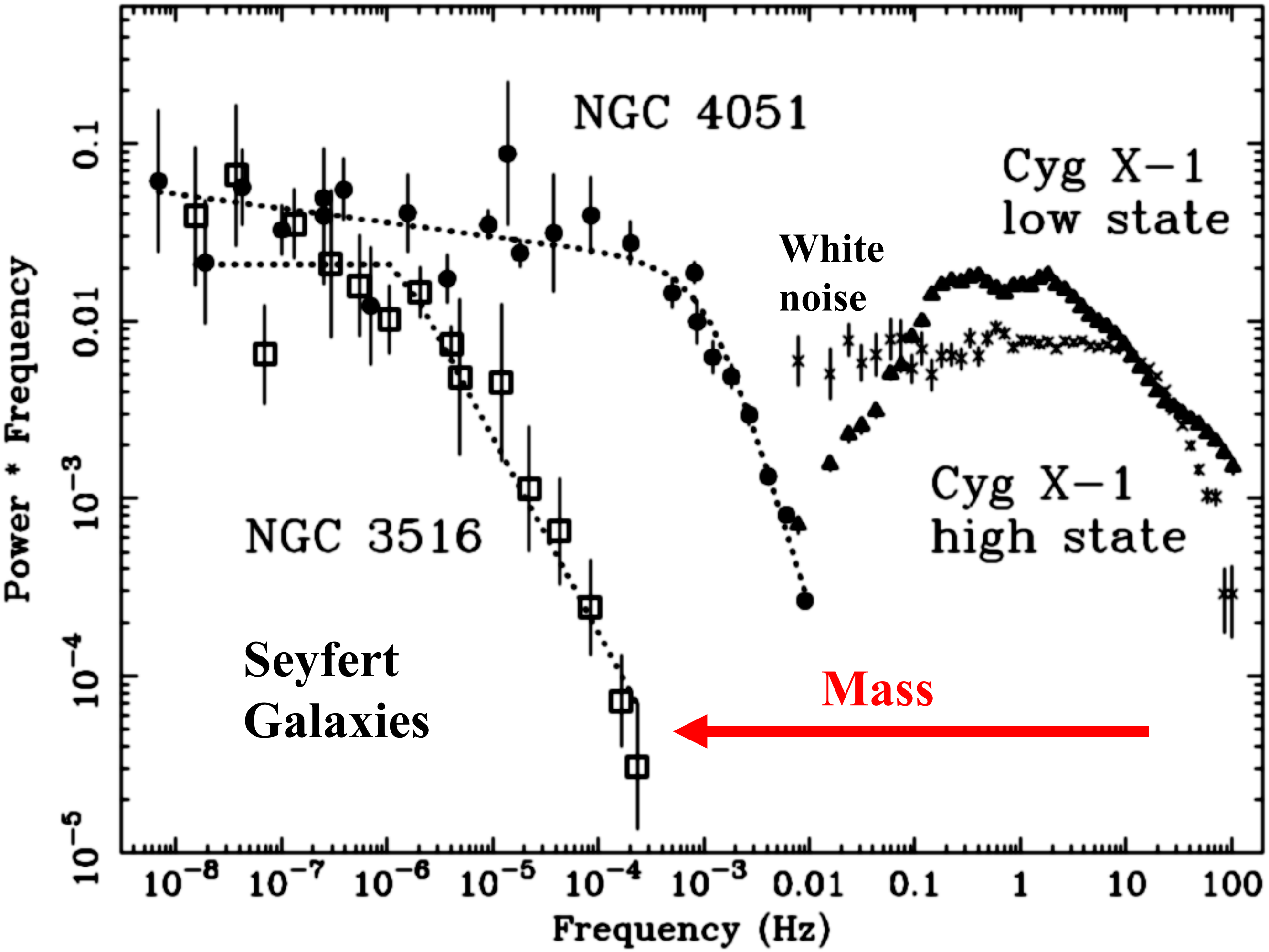
Cattaneo et al.

- **Maxwell stress flux domination due to the correlation of B_r and B_ϕ**



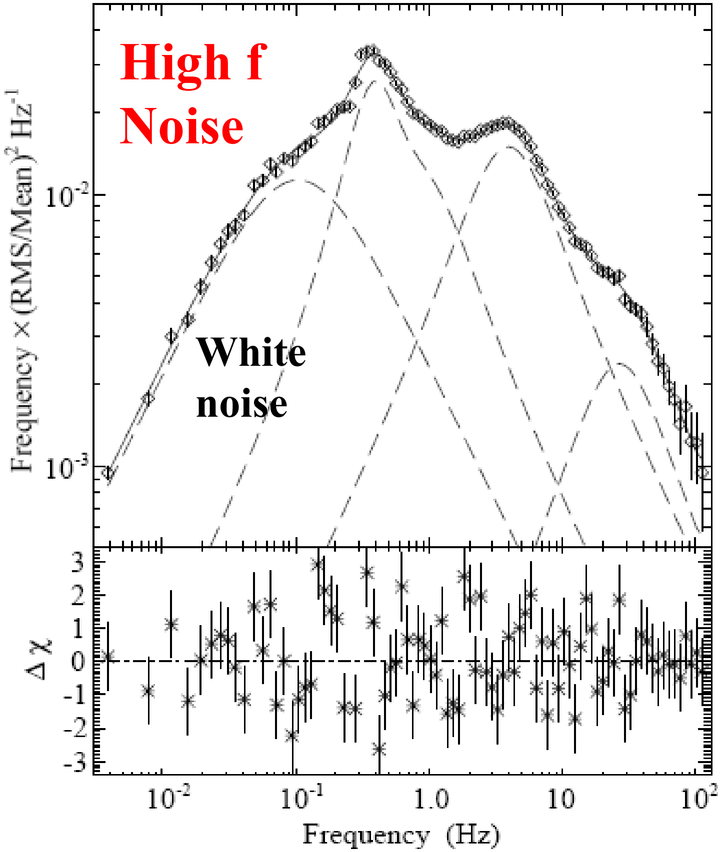
- **Angular momentum is carried outwards (inwards) by magnetic fluctuations that correspond to winding (unwinding) spirals -i.e. getting longer (shorter)**
- **In a random circular sheared motion there are more winding than unwinding spirals (can wind forever; can only unwind for a finite time)**
- **If angular velocity increases inwards (due to shear) Maxwell stress will carry angular momentum outwards (kinematic effect)**

Turbulence **is** Visible in HXs from Stellar BHs to SMBHs



Ian McHardy

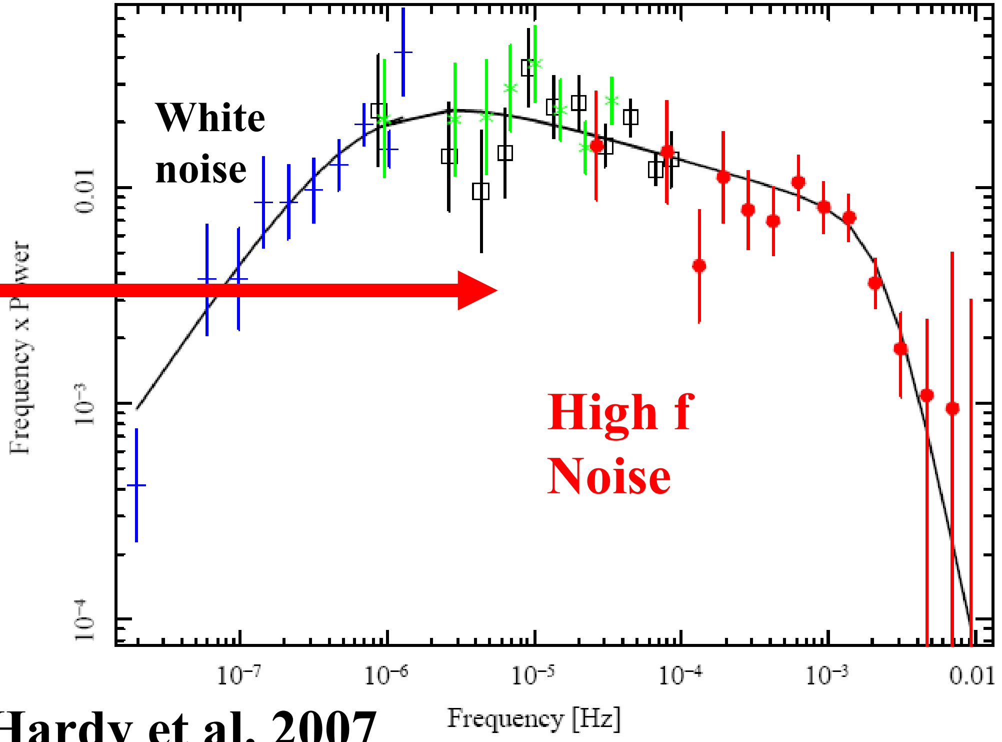
GX 339-4 / 7 sol mass



Noise = sum over Lorentz profiles, given by resonance freq and width

➔ each ring generates a resonance

Ark 564 / 2.6 Mio M_S

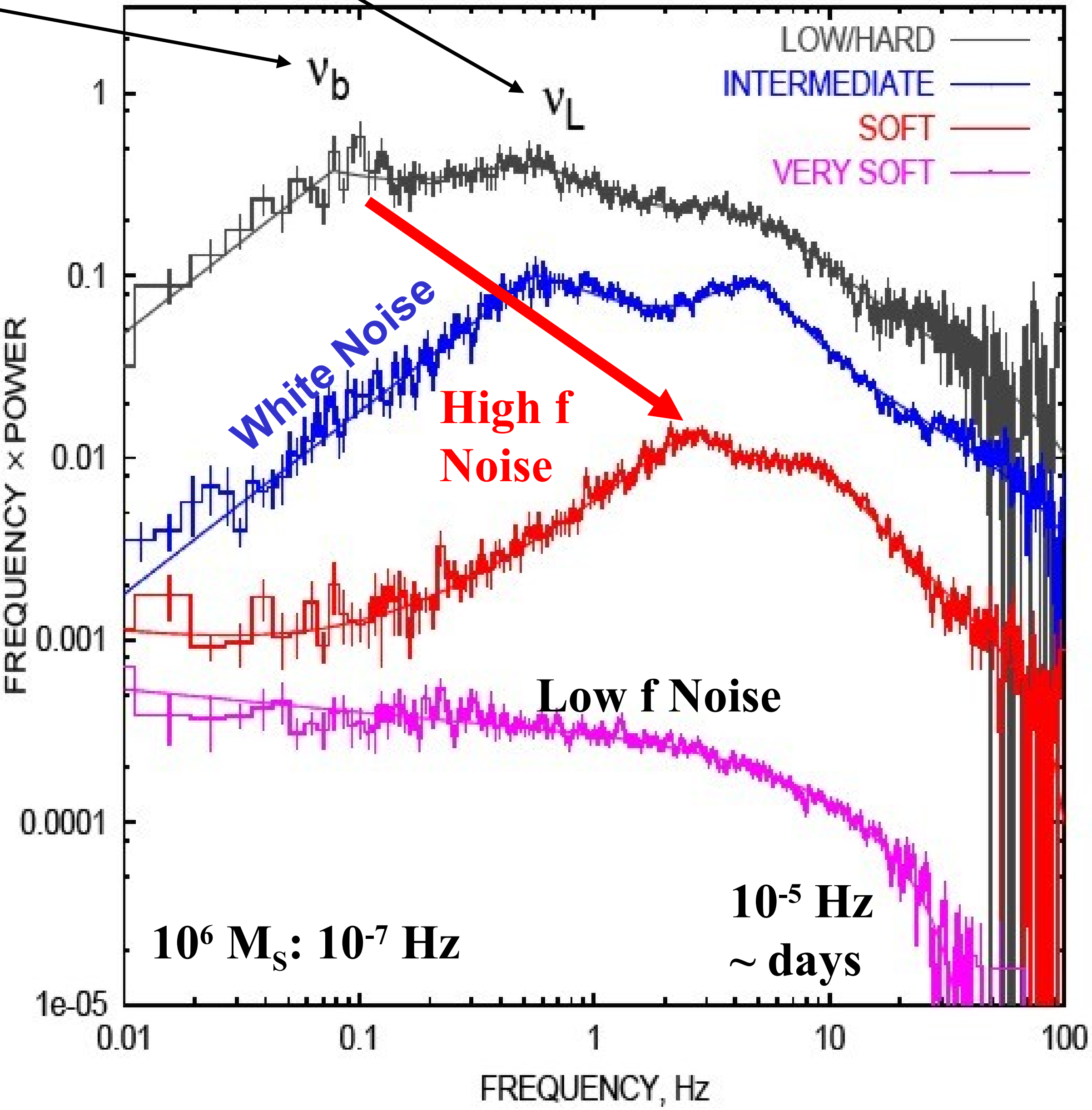


McHardy et al. 2007

Disk Emission turbulent in Cyg X-1 → Truncation

Break Frequency

LF QPO



White Noise

High f Noise

Low f Noise

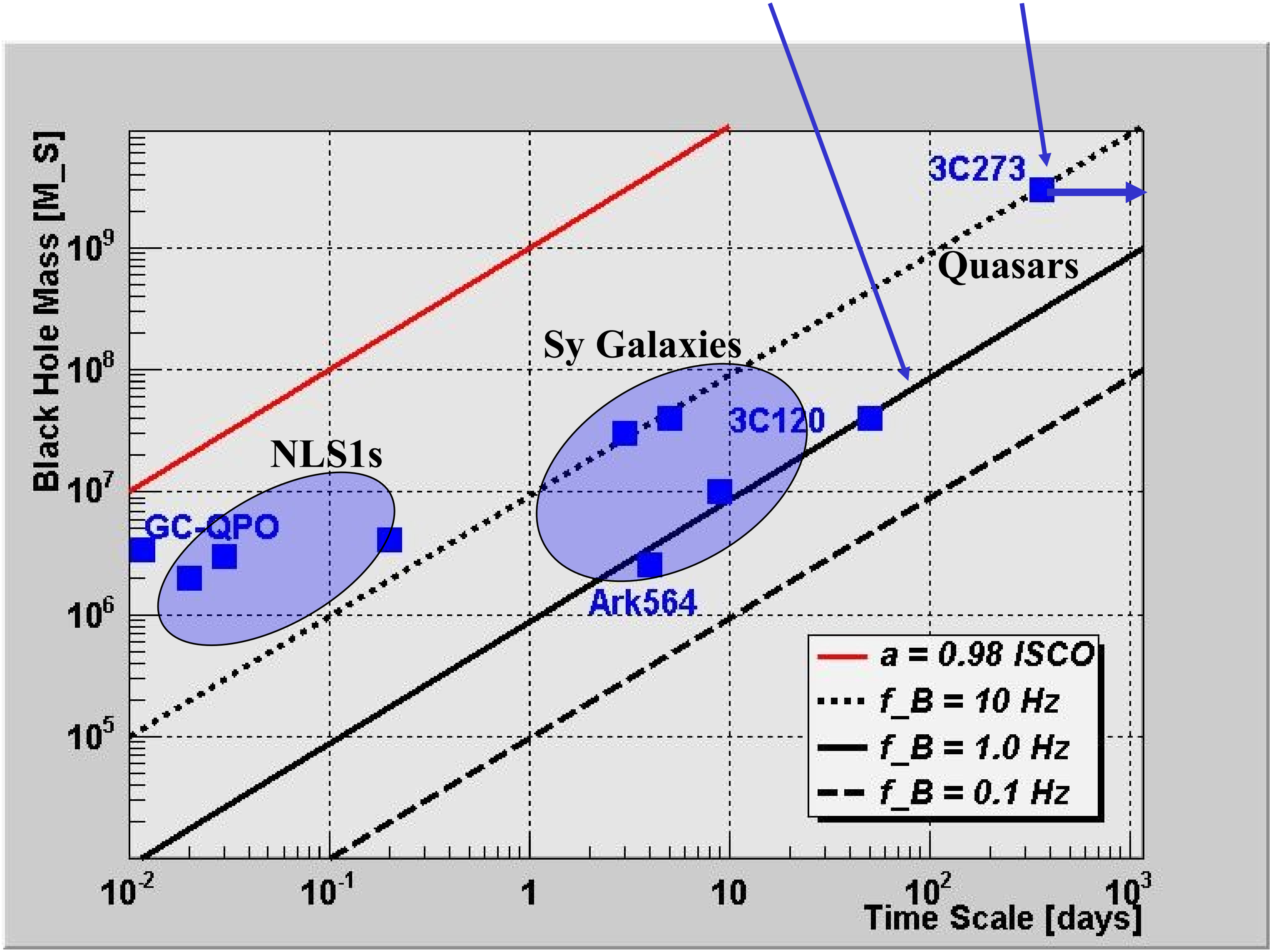
10^6 M_S: 10^{-7} Hz

10^{-5} Hz ~ days

Keplerian at ISCO

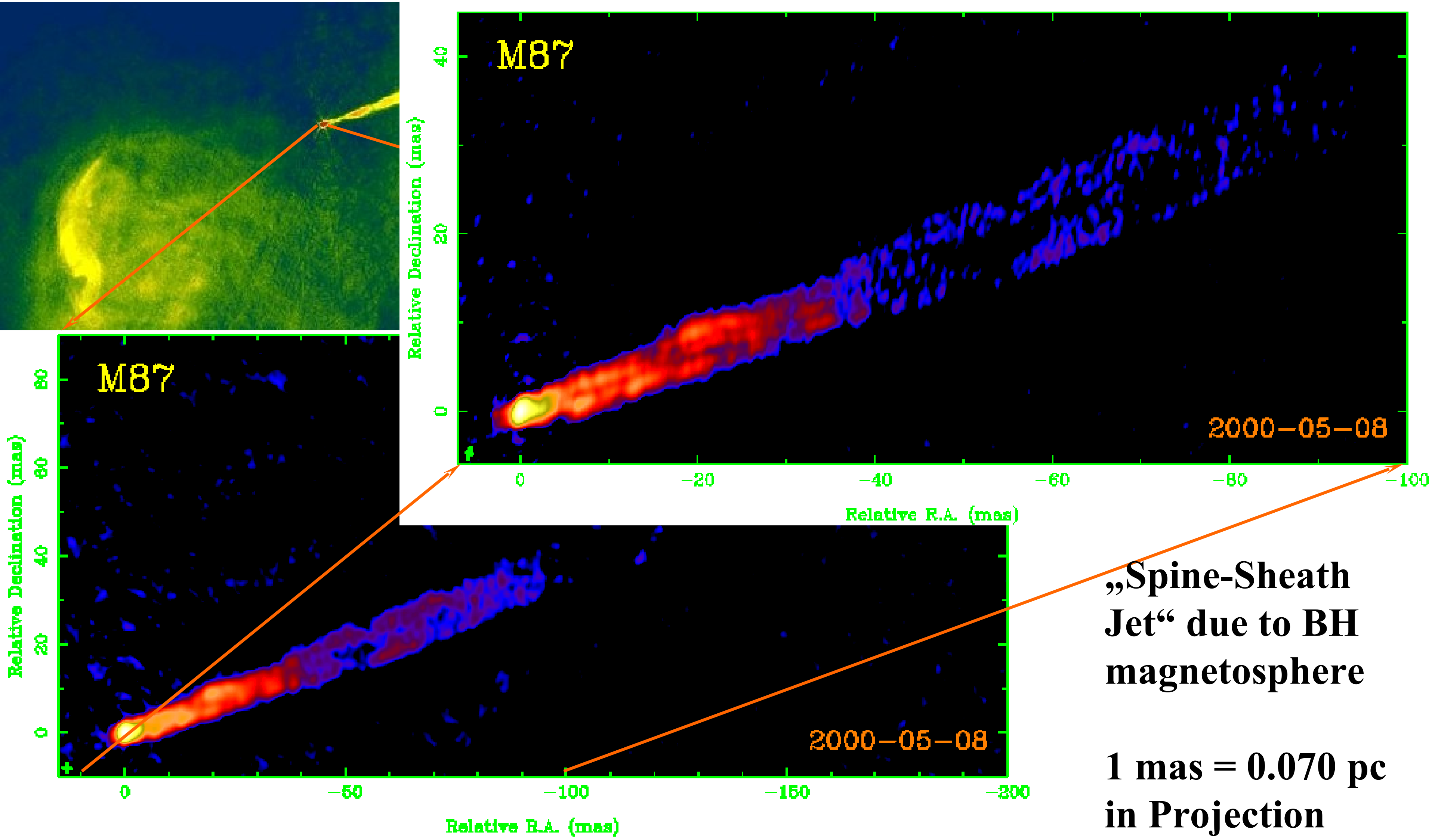
Lev Titarchuk et al. 2007

Time-Scales ~ Mass: f_B / LF QPOs



Camenzind 2007/2008

Jets are formed near BH / M87 @ 15 GHz



„Spine-Sheath Jet“ due to BH magnetosphere

1 mas = 0.070 pc in Projection

Kovalev et al. 2007

Physics of the Ergosphere

- Magnetic fields are dragged inwards by disk accretion - probably generated by dynamos in the **cool convective disk** at R ~ 1000R_S (quadrupole?)

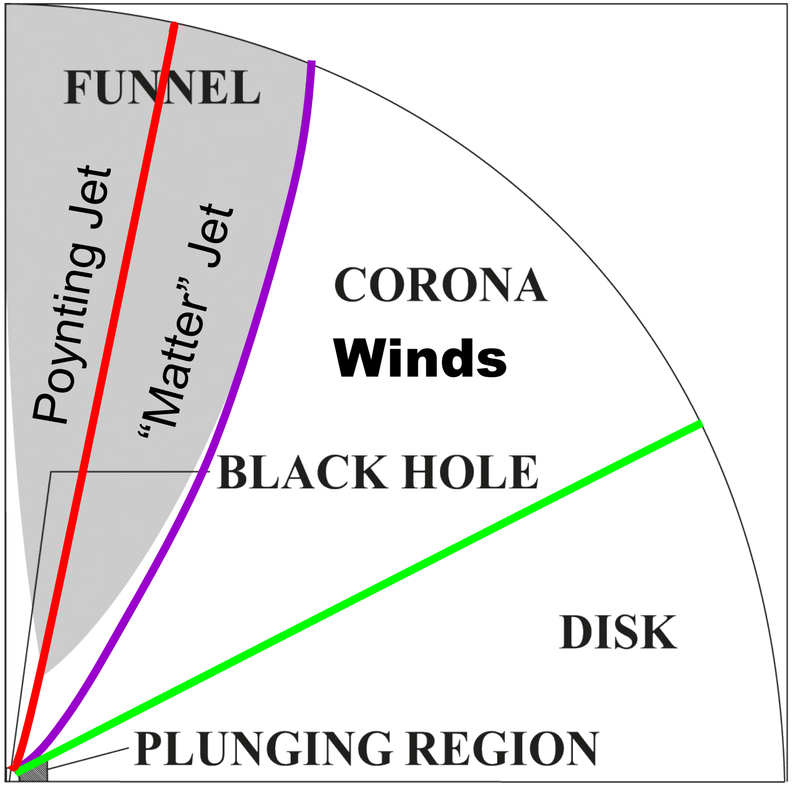
  ➔ „zero-net flux jets“, all magnetic fields closed
- Plasma loaded to the magnetosphere drag the fields in polar directions ➔ can be collimated by currents to jets on scales ~ 1000 R_g.
- Field lines are closed ! ➔ **Jets = Reverse field pinch** ➔ instabilities along jet boundary (M 87).
- Poloidal fields cover the horizon ➔ **Poynting flux generation inside ergosphere**.
- Poynting fluxes are transformed to kinetic energy along converging flux tubes.

Launching Jets around BHs

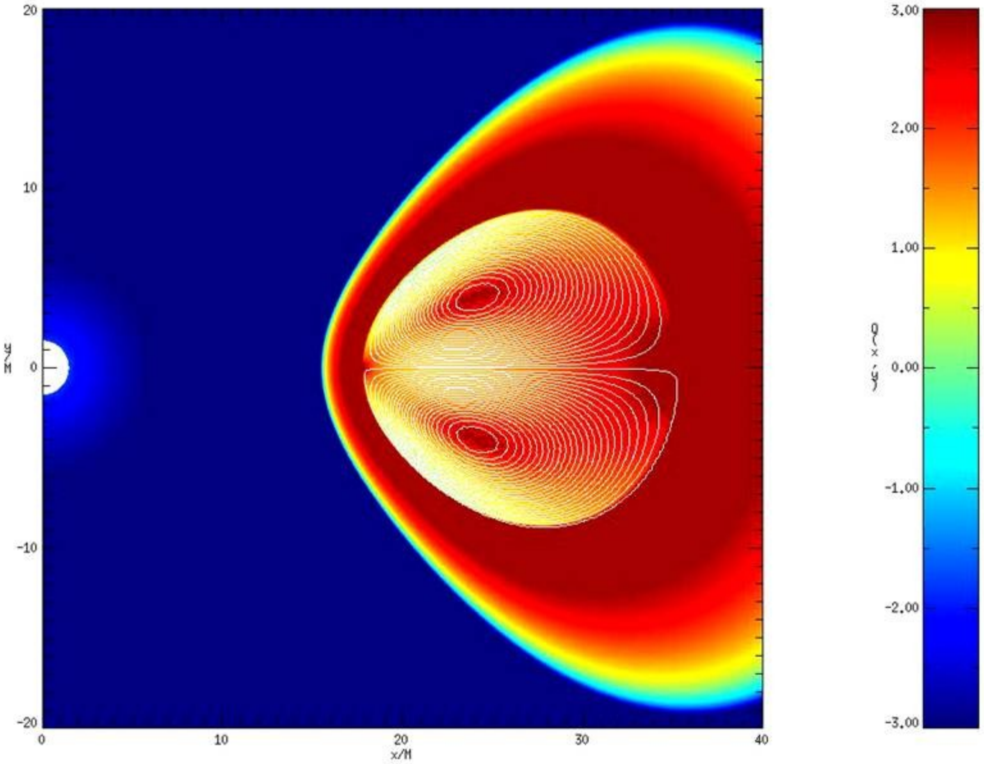
Poloidal fields are advected inwards and cover the BH with magnetosphere

Ergosphere: EM dominated

JETS: Poynting flux converted into kinetic energy, probably have a spine-sheath structure



Zero-Net Flux Magnetic Structure: Quadrupole Geometry leads to Reconnection, makes Jets Weaker and Episodic Outbursts



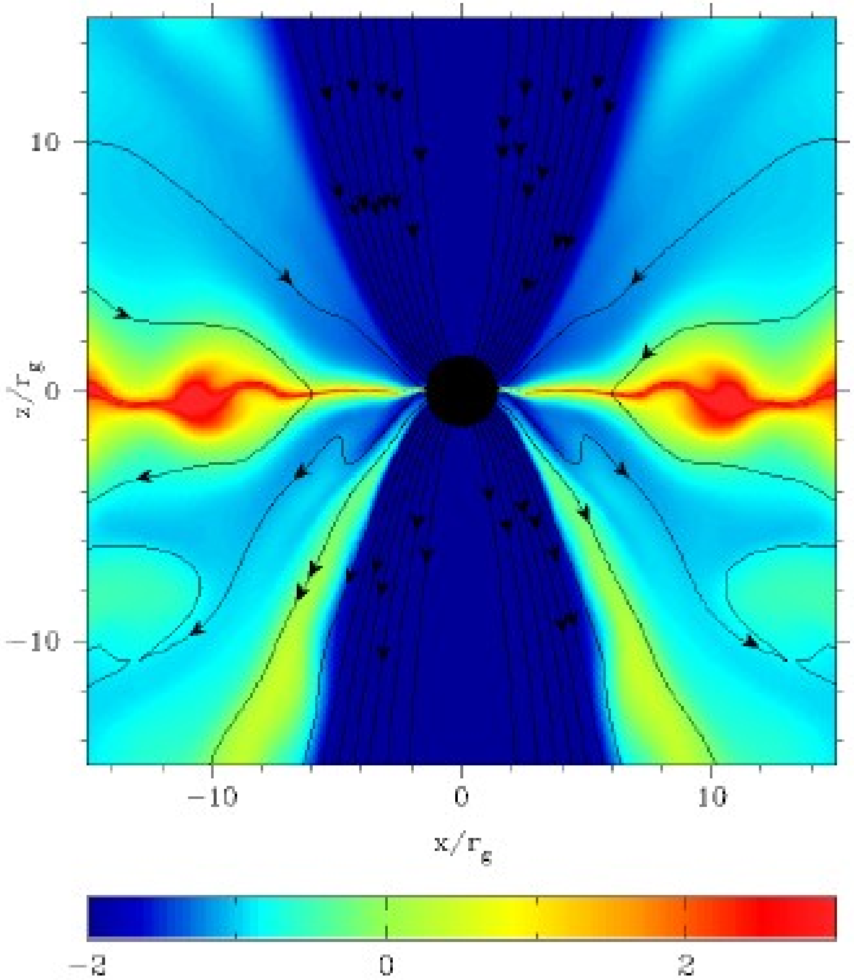
Beckwith, Hawley & Krolik 2008

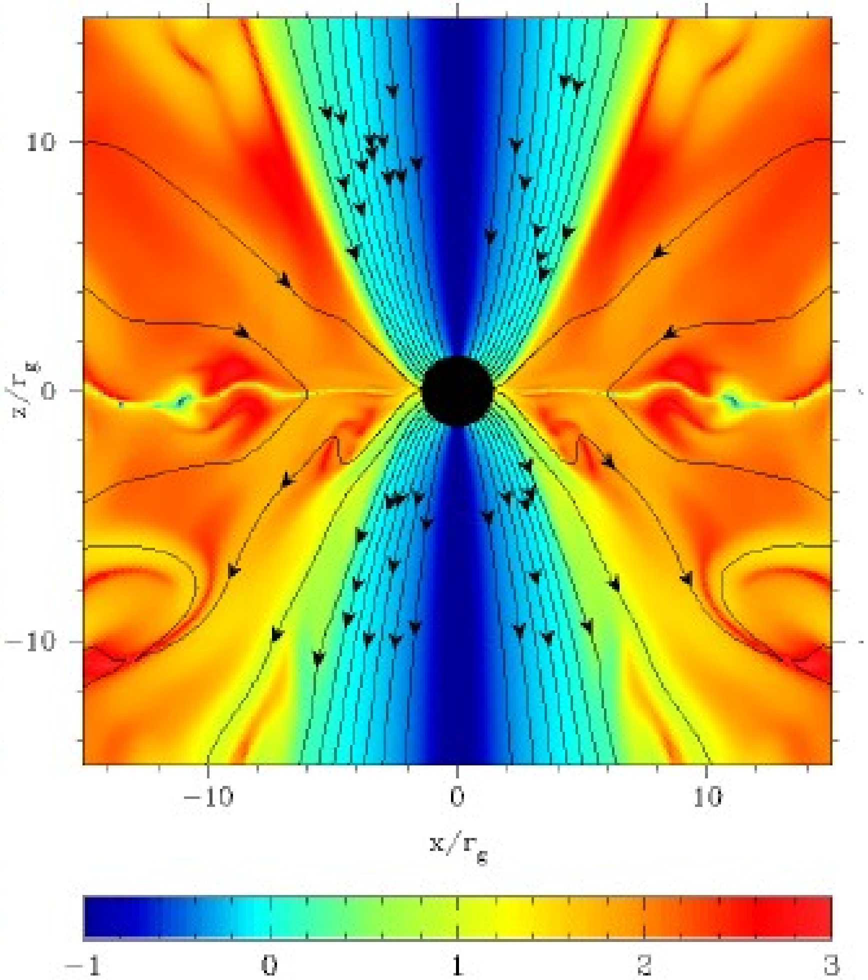
Small dipole loops lead to similar results; toroidal field makes no jet at all.

Poloidal fields should retain a large-scale structure for at least ~1500 M to drive a strong jet.

Flow Structure from Core Collapse

Komissarov & Barkov 2008



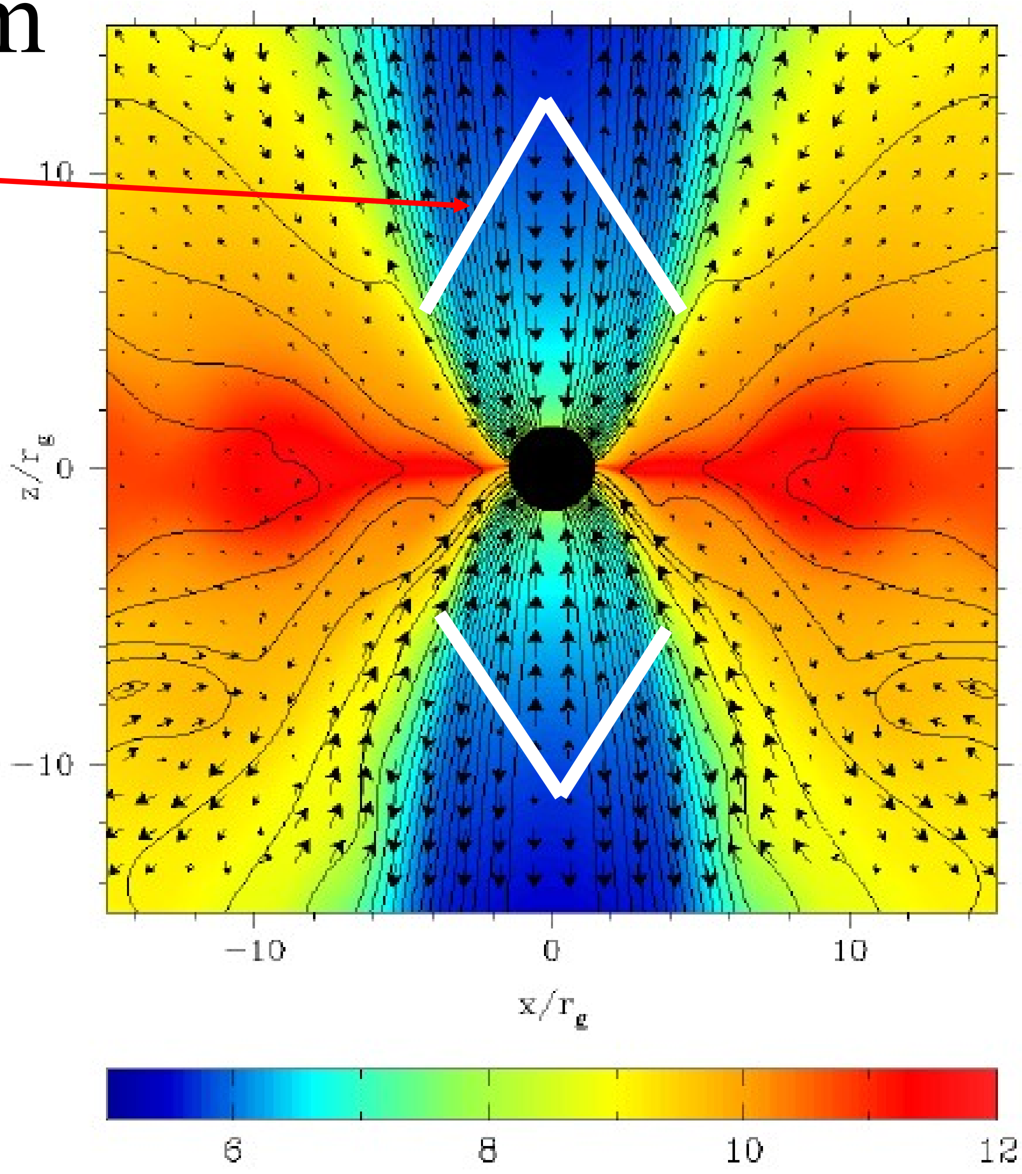


log(Plasma beta)

log(Tor/pol field) strength

Injection Problem

Stagnation surface



- ➔ Funnel fields exceed disk fields by two orders of magnitude
- ➔ i for magnetisation !

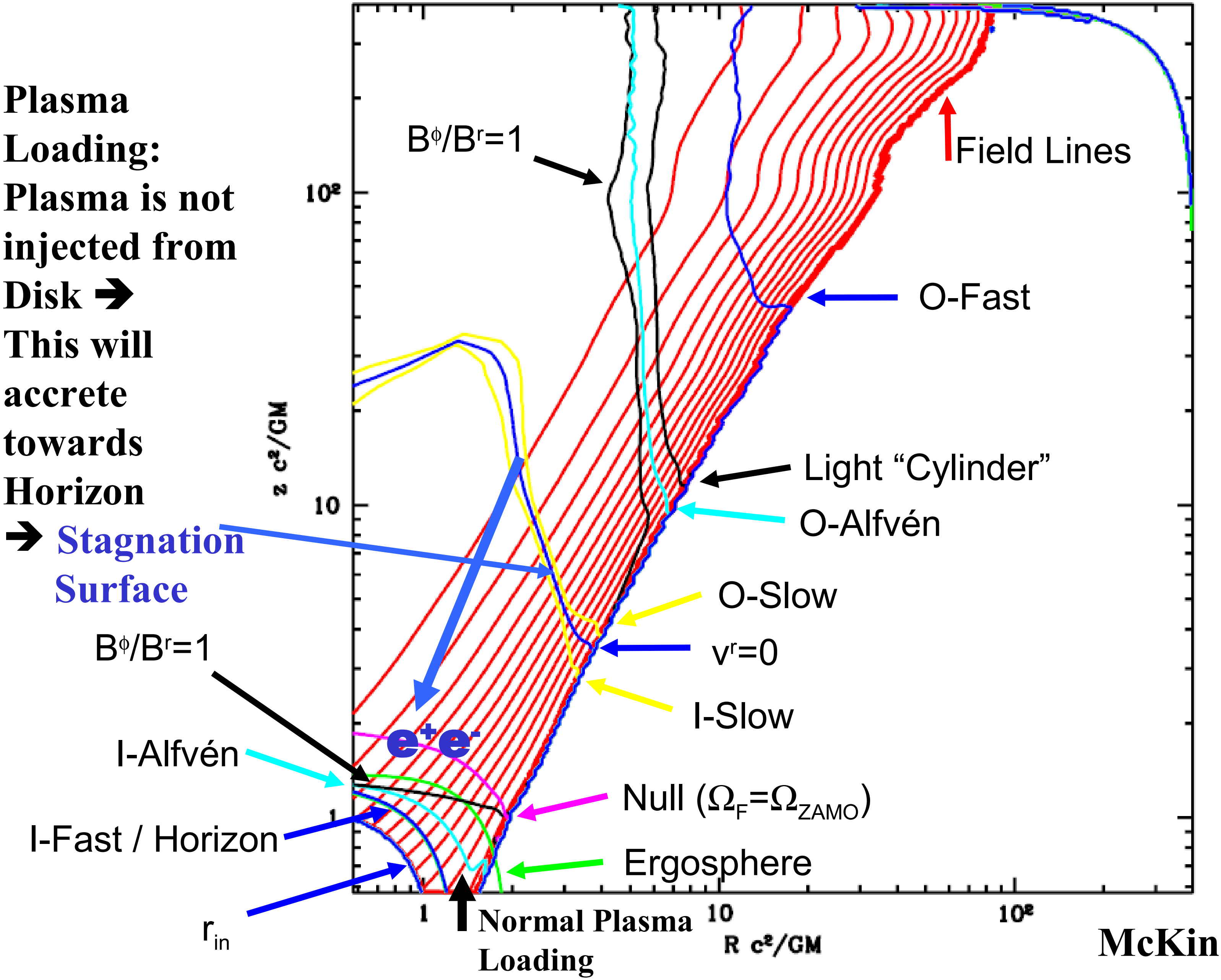
- ➔Toroidal field is weak in funnel, reaches maximum at funnel edge.

- ➔Rotational energy is extracted by Poynting flux

Komissarov & Barkov 2008

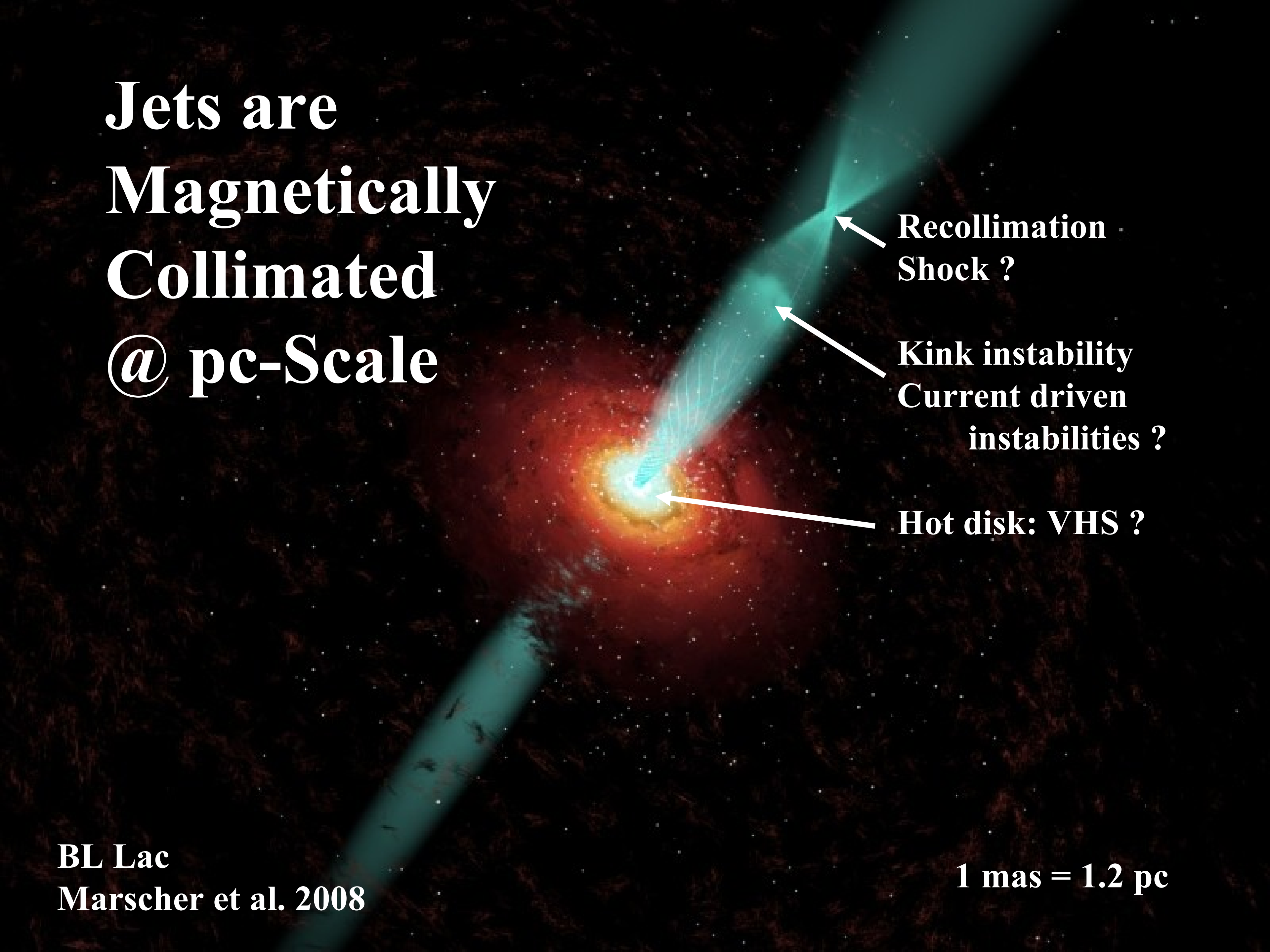
MHD Characteristic Surfaces - Collimation

Plasma Loading: Plasma is not injected from Disk ➔ This will accrete towards Horizon ➔ Stagnation Surface



McKinney 2006

Jets are Magnetically Collimated @ pc-Scale



Recollimation Shock ?

Kink instability
Current driven
instabilities ?

Hot disk: VHS ?

BL Lac
Marscher et al. 2008

1 mas = 1.2 pc

Conclusions

- Disk physics essential from self-gravity radius down to horizon ➔ **feeding B fields**.
- You must measure **spin a** for SMBHs.
- Analogies between μQuasars and Quasars.
- Future: extended disk simulations including radiation and relativistic effects
  ➔ RadGRMHD is the ultimate challenge!
- Ergospheric physics is complex: structure of magnetosphere covering ergosphere, loading of plasma, spine-sheath structure, …

Textbook: Compact Objects in Astrophysics – Springer 2007