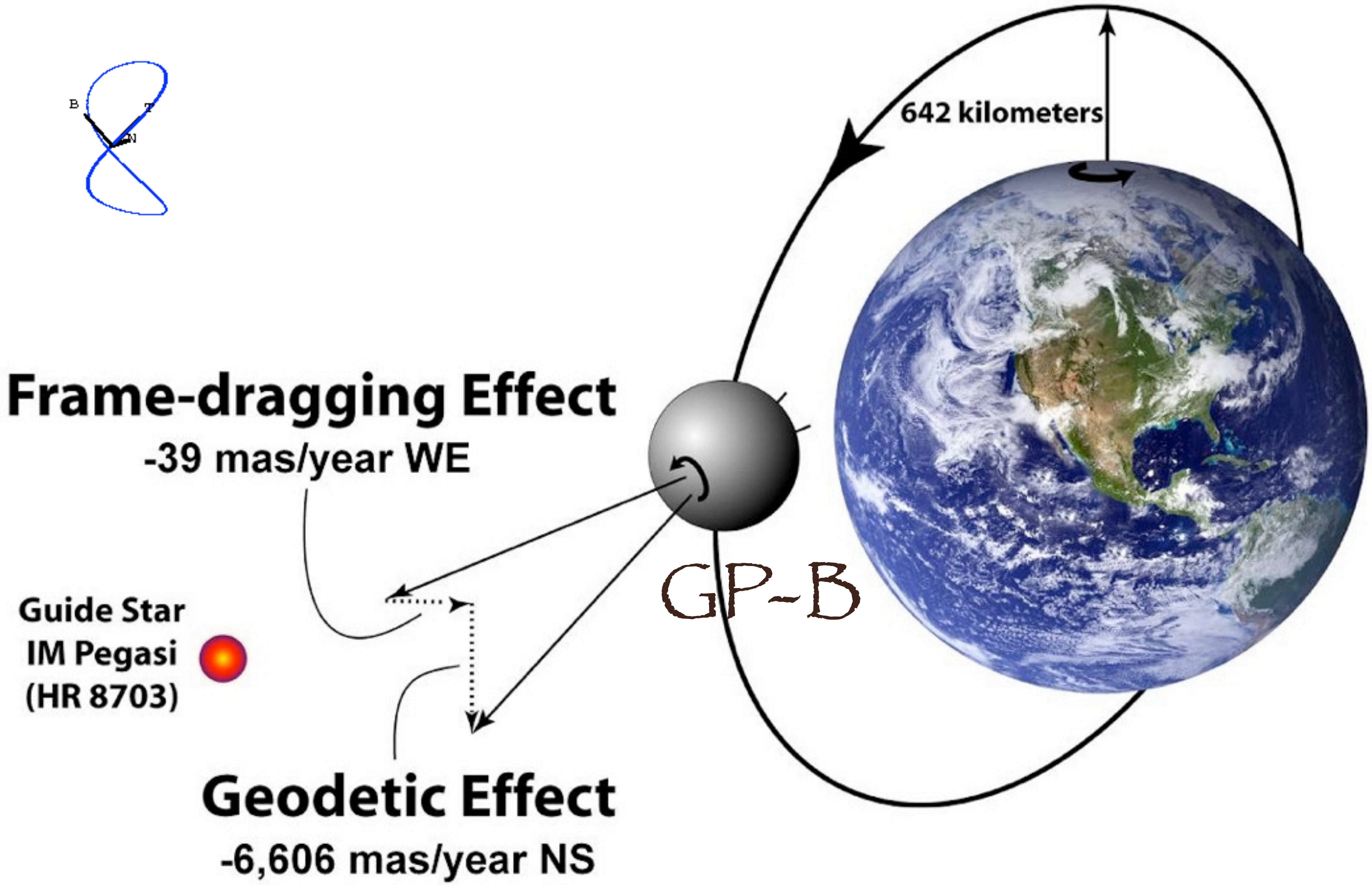
Black holes spin

Jean-Pierre Lasota

IAP

8 February 2013

«Dragging of inertial frames»



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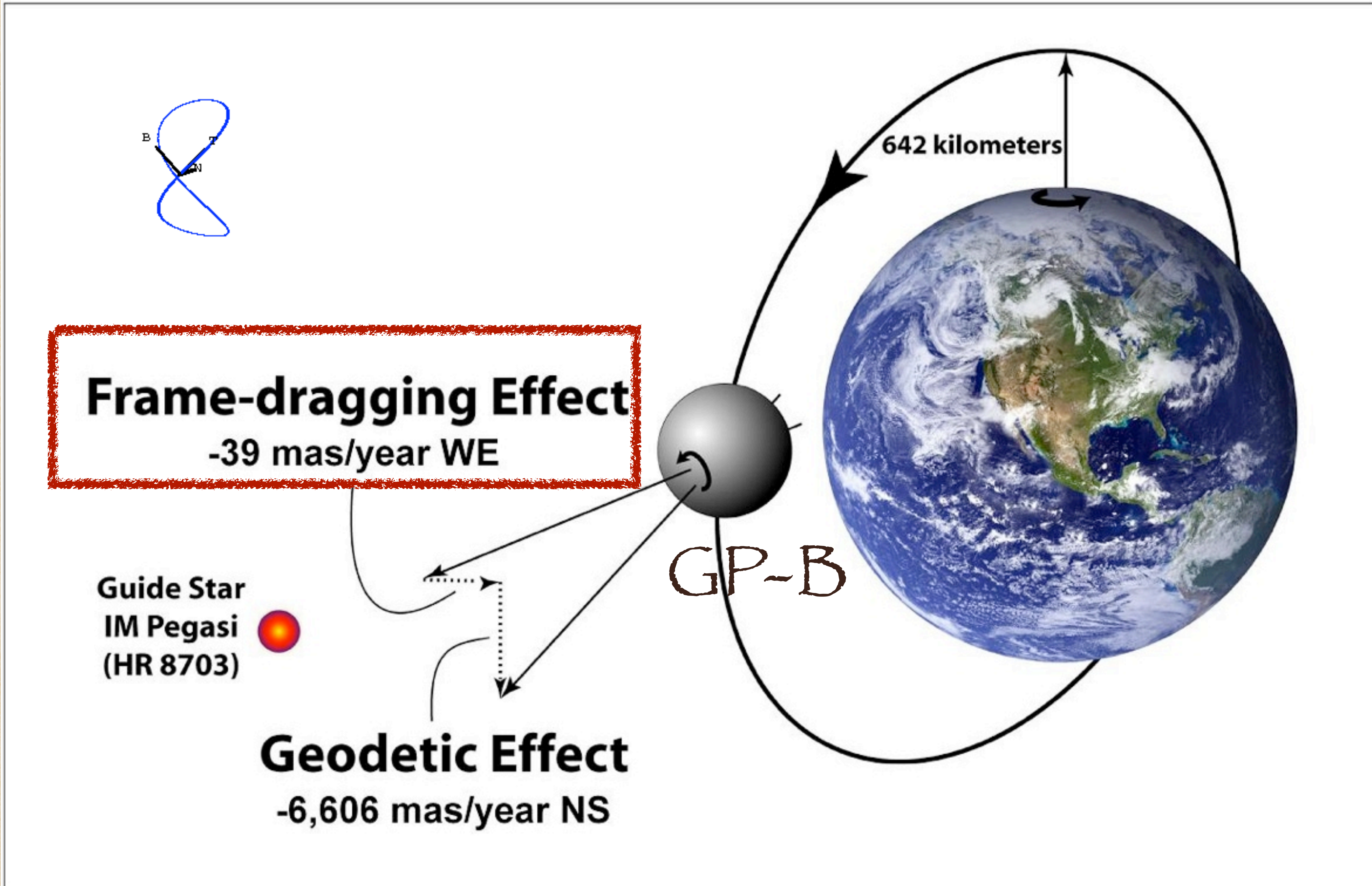
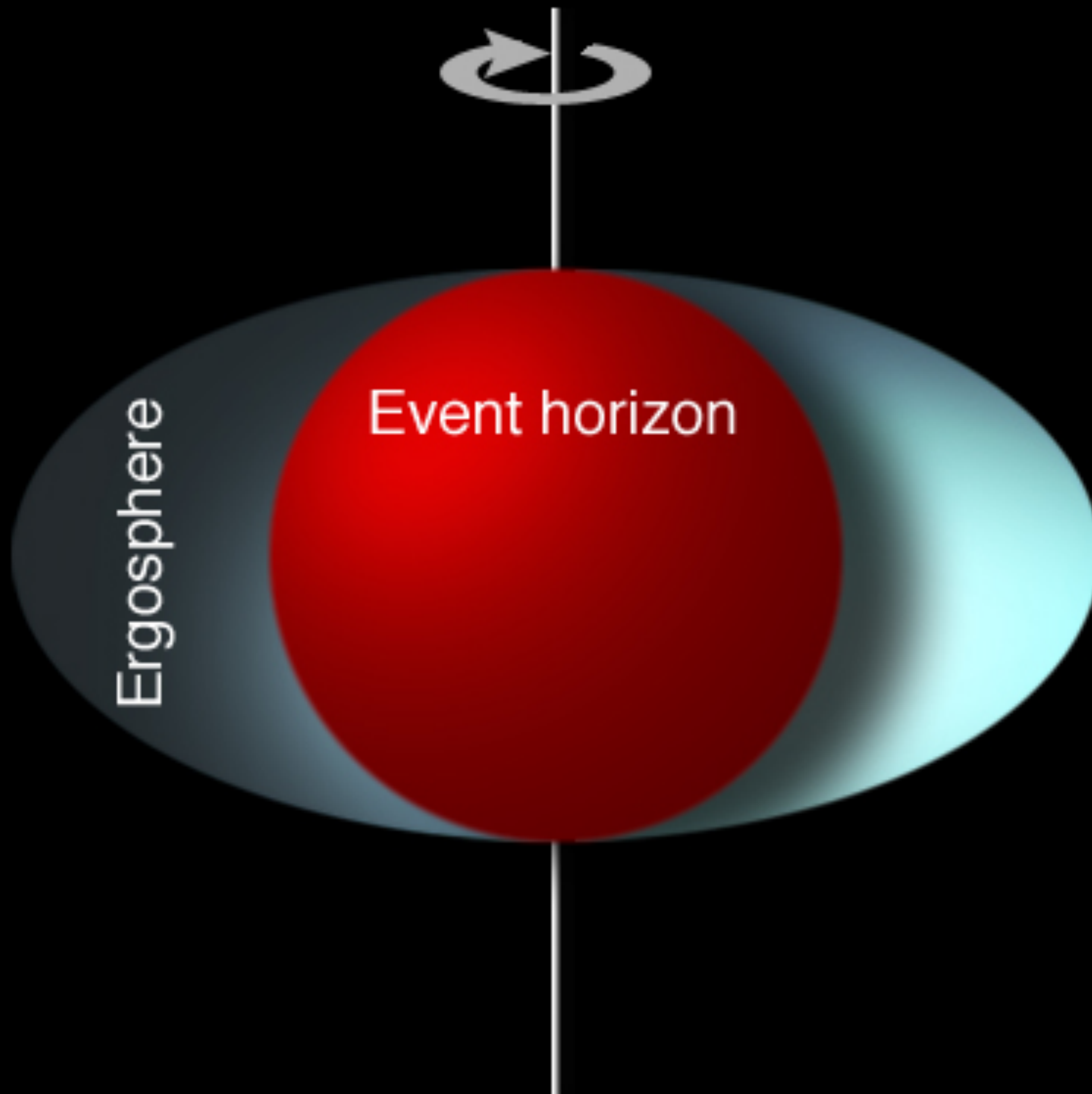


Rotation of space: in the ergosphere stationary (with respect to infinity) observers would have to move with v > c



$u \cdot u < 0$

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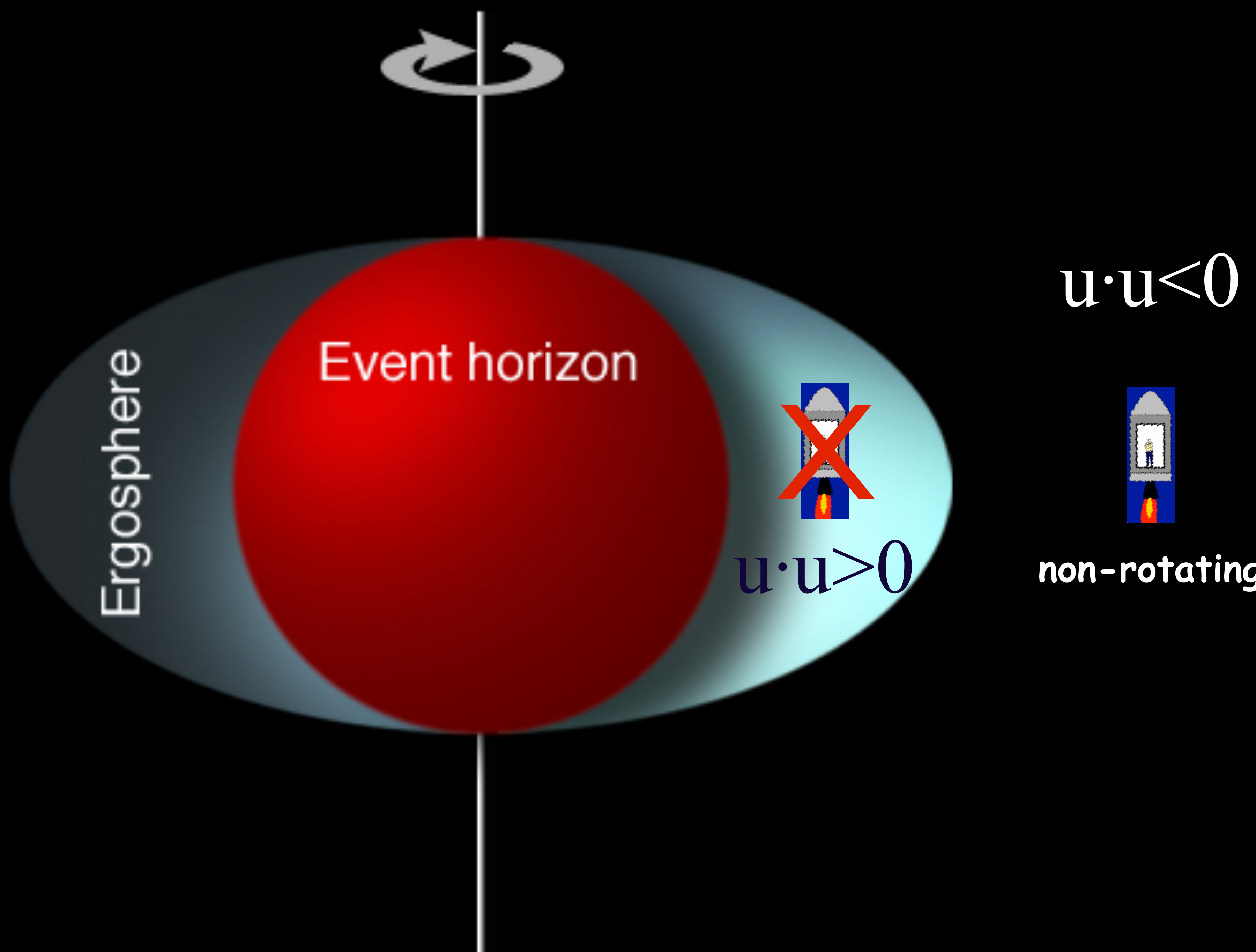
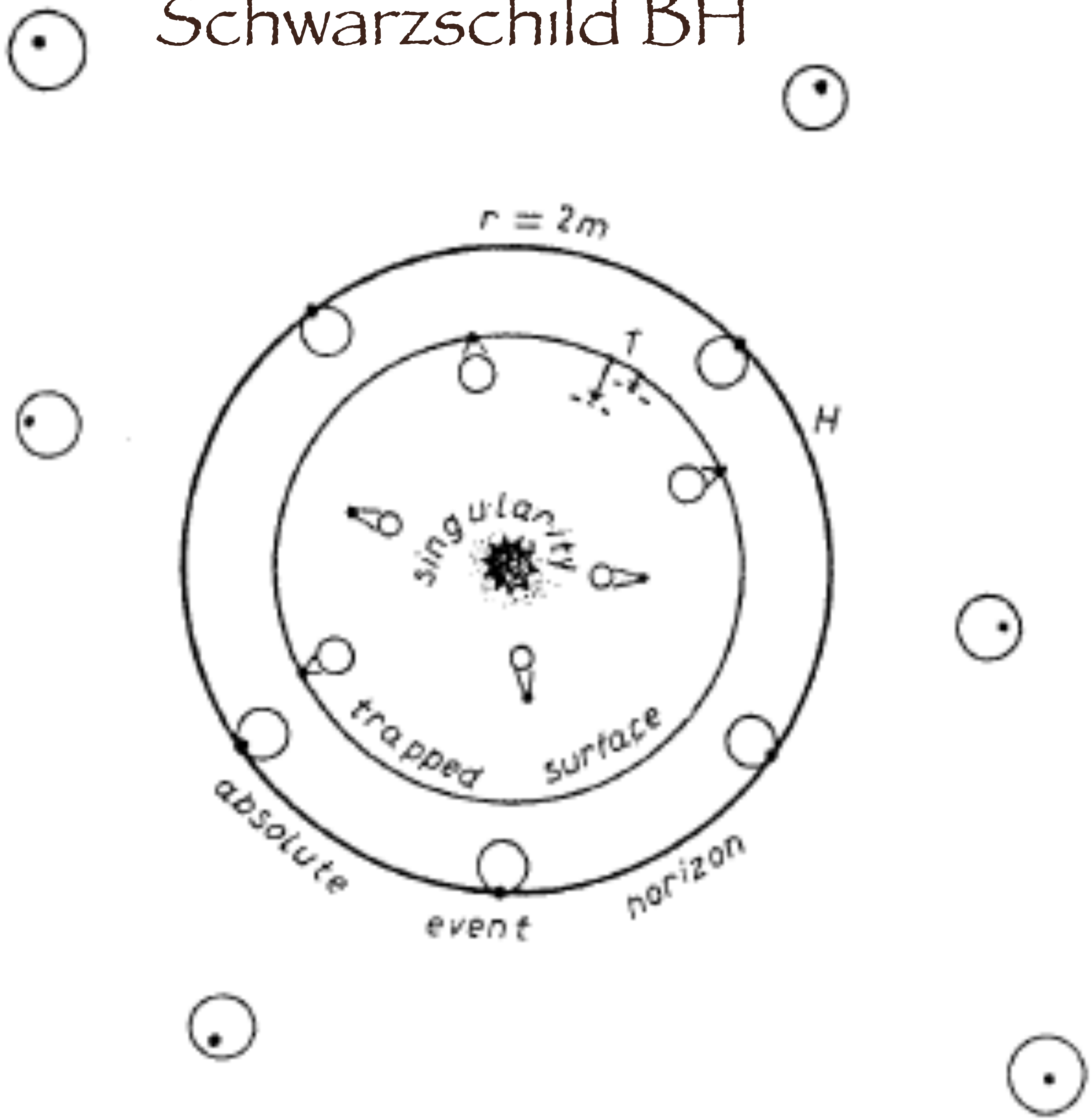
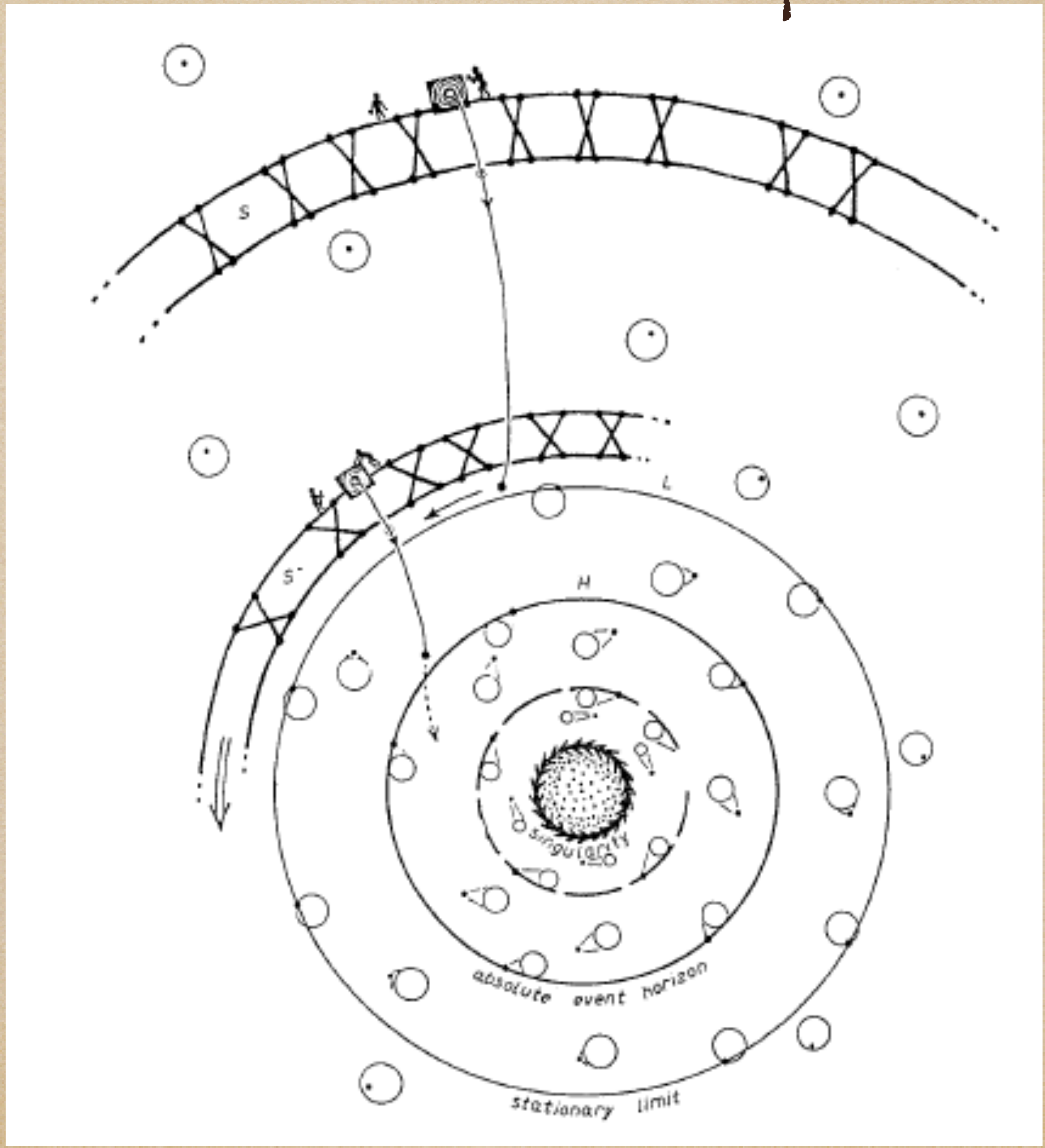


Schwarzschild BH



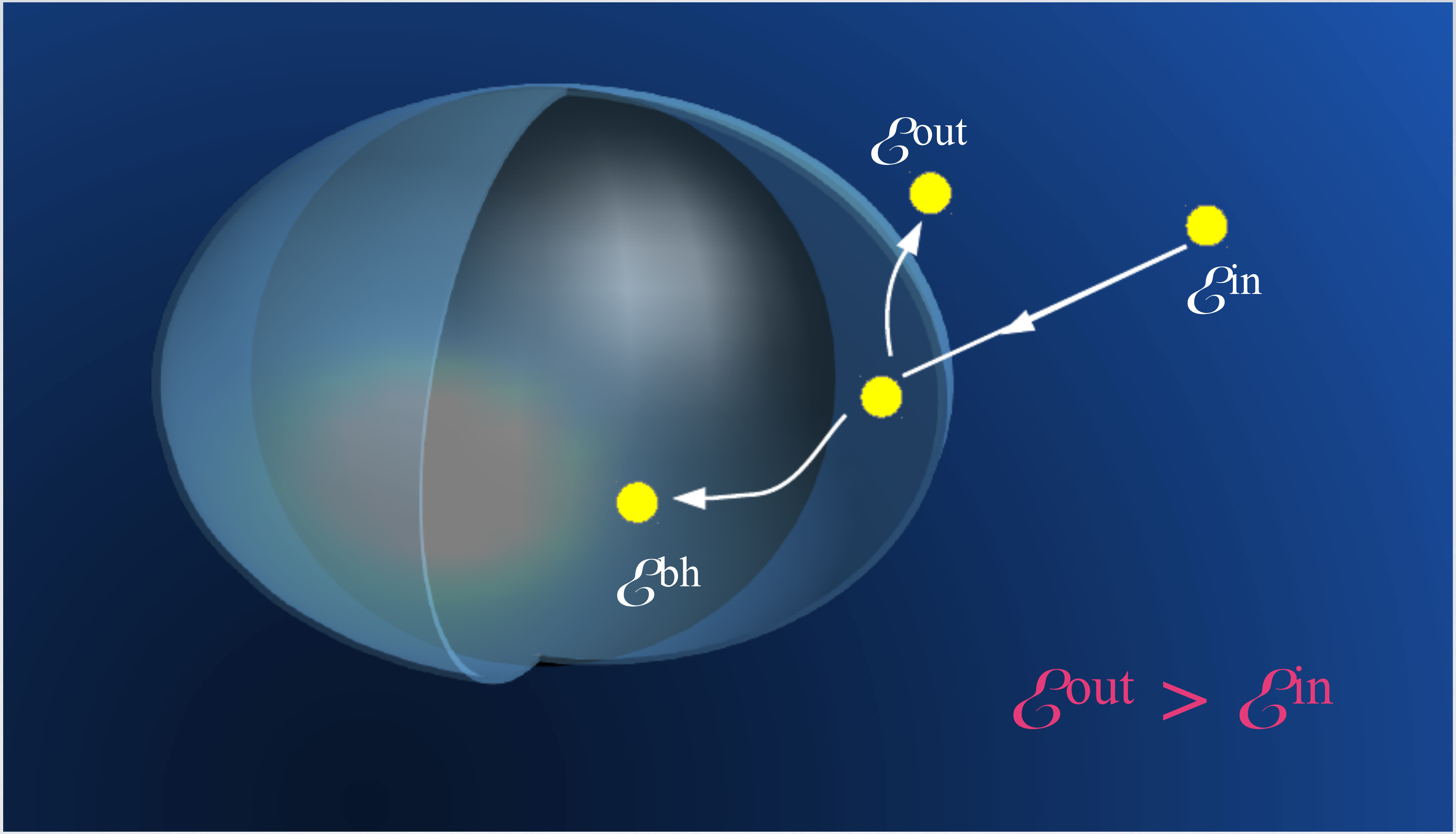
Penrose 1969

Kerr BH and Penrose process

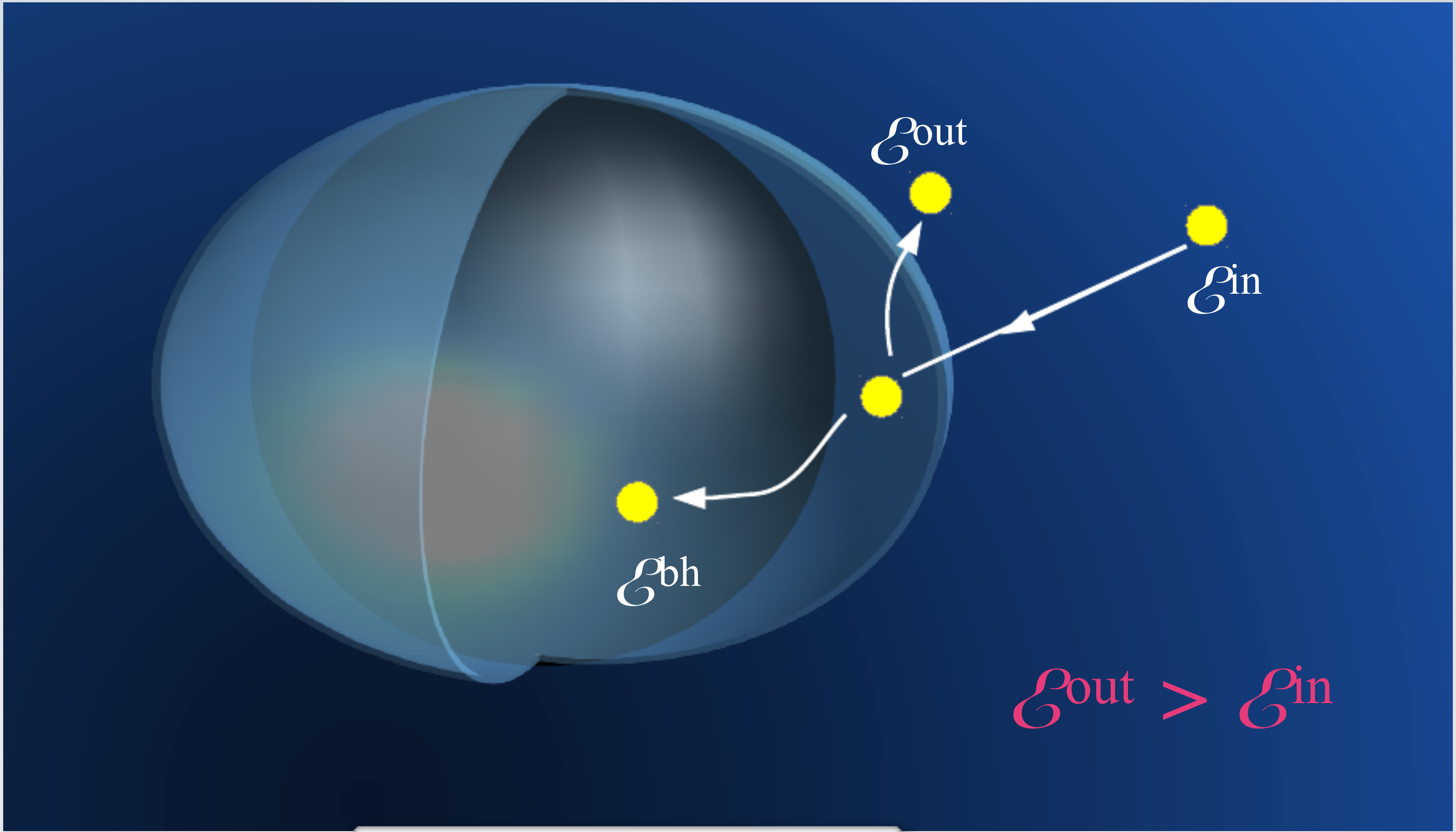


Penrose 1969

The Penrose process



The Penrose process



Therefore $\mathcal{E}^{bh} < 0$

Timelike (at ∞) Killing vector $\boldsymbol{\eta}$, Spacelike Killing vector $\boldsymbol{\xi}$

Energy: $\mathcal{E}_\infty = -\mathbf{p}\cdot\boldsymbol{\eta}$ Angular momentum: $\mathcal{J}_\infty = \mathbf{p}\cdot\boldsymbol{\xi}$

$$\mathbf{p}^{\mathrm{in}} = \mathbf{p}^{\mathrm{bh}} + \mathbf{p}^{\mathrm{out}}$$

$$\mathcal{E}_\infty^{\mathrm{out}} = \mathcal{E}_\infty^{\mathrm{in}} - \mathcal{E}_\infty^{\mathrm{bh}}$$

When $\mathcal{E}_\infty^{\mathrm{bh}} < 0$: $\mathcal{E}_\infty^{\mathrm{out}} > \mathcal{E}_\infty^{\mathrm{in}}$, but (bh) never leaves the ergosphere

where $\boldsymbol{\eta}\cdot\boldsymbol{\eta} > 0$: $\mathcal{E}_\infty^{\mathrm{bh}} < 0$ is a component of momentum

****

ZAMOs: $u^i_{\mathrm{ZAMO}} = q\left(\eta^i + \omega\,\xi^i\right)$ $u^i_{\mathrm{ZAMO}}\,\xi_i = 0$

$\left(q > 0 \text{ from } u^i_{\mathrm{ZAMO}}\,u_i^{\mathrm{ZAMO}} = -1\right)$

Locally measured energy $\mathcal{E}^{\mathrm{bh}} \equiv -(\boldsymbol{\eta} + \omega\,\boldsymbol{\xi})\cdot\mathbf{p}^{\mathrm{bh}} \geq 0$

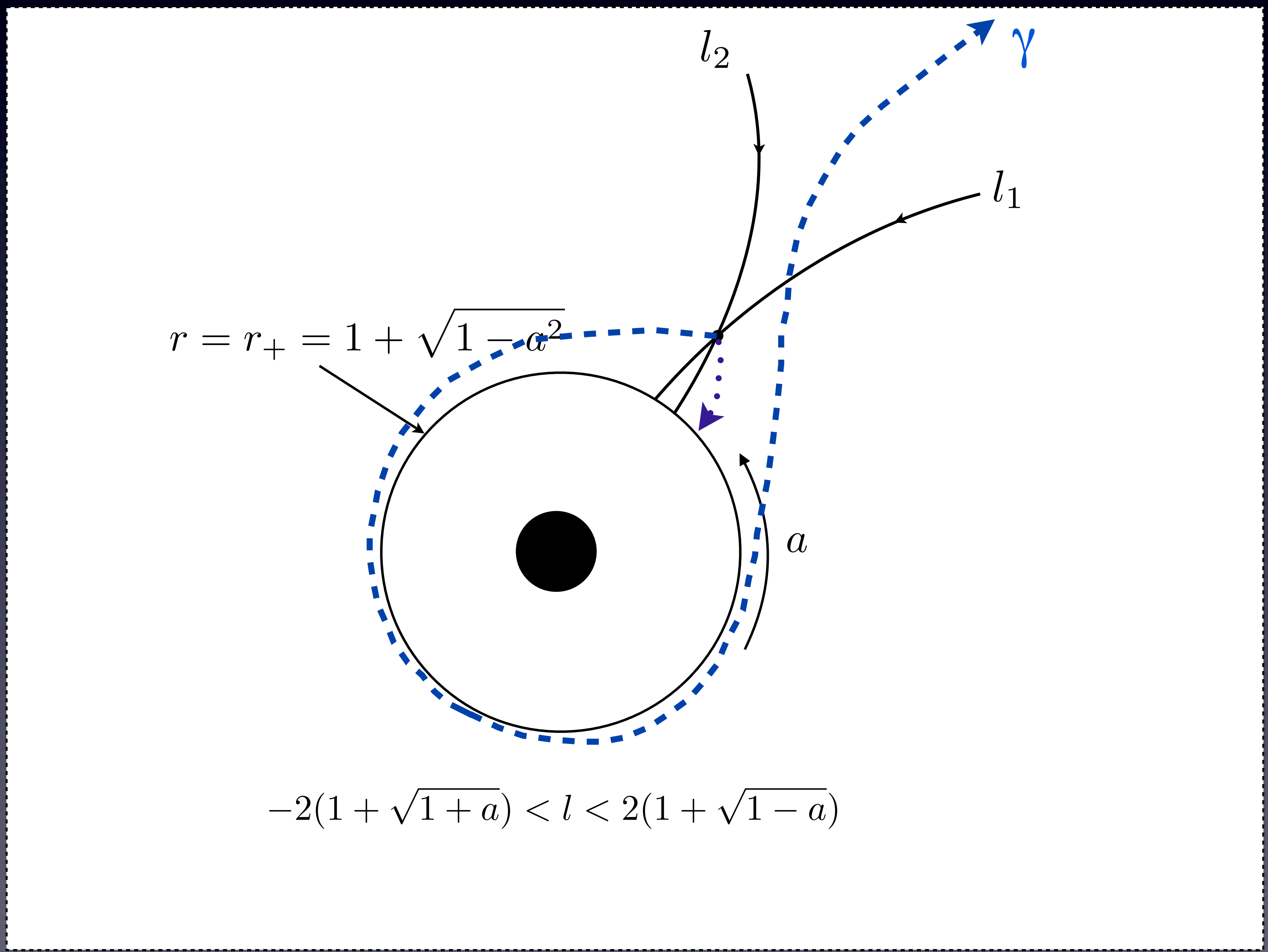
hence $\mathcal{E}_\infty^{\mathrm{bh}} \geq \omega\,\mathcal{J}_\infty^{\mathrm{bh}}$

When $\mathcal{E}_\infty^{\mathrm{bh}} < 0$ (since $\omega > 0$) $\mathcal{J}_\infty^{\mathrm{bh}} < 0$

Spinning black-holes as Planck scale particle accelerators ?

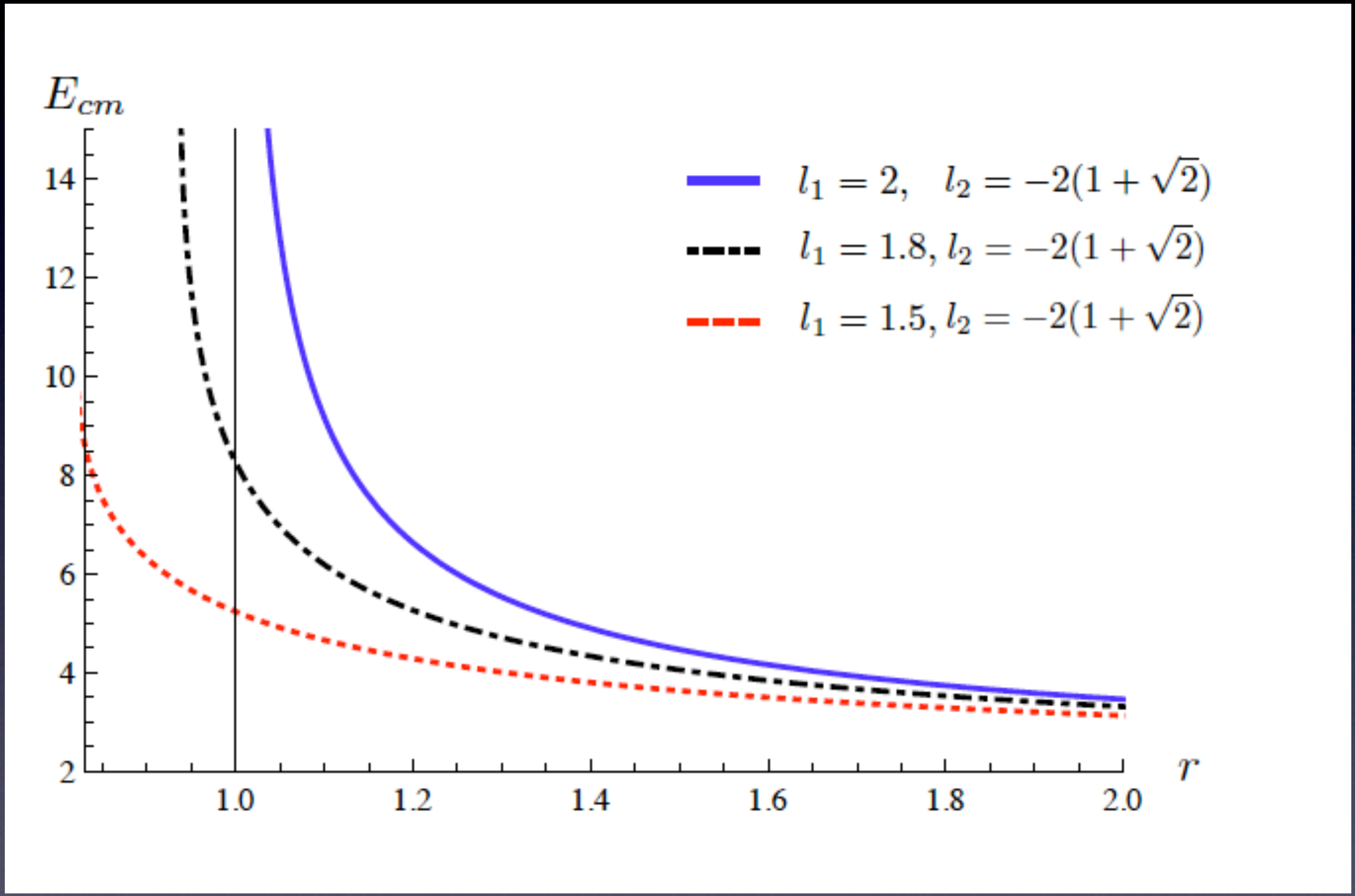
(desintegration does not work, Wald 1974)

Collisional Penrose process



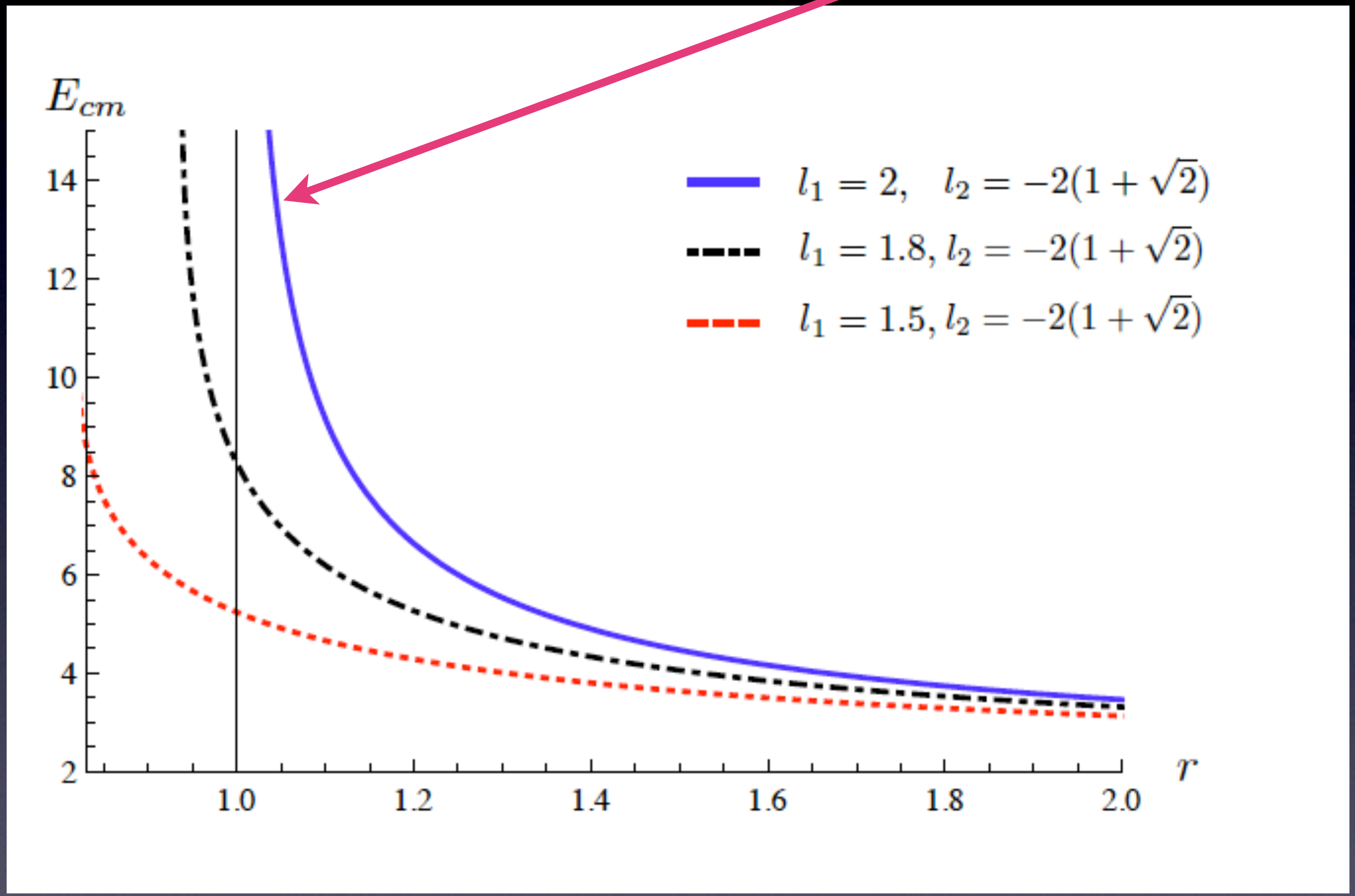
Bañados, Silk & West 2009

Center of mass energy blows up for l_1=2



$a_\star = 1$

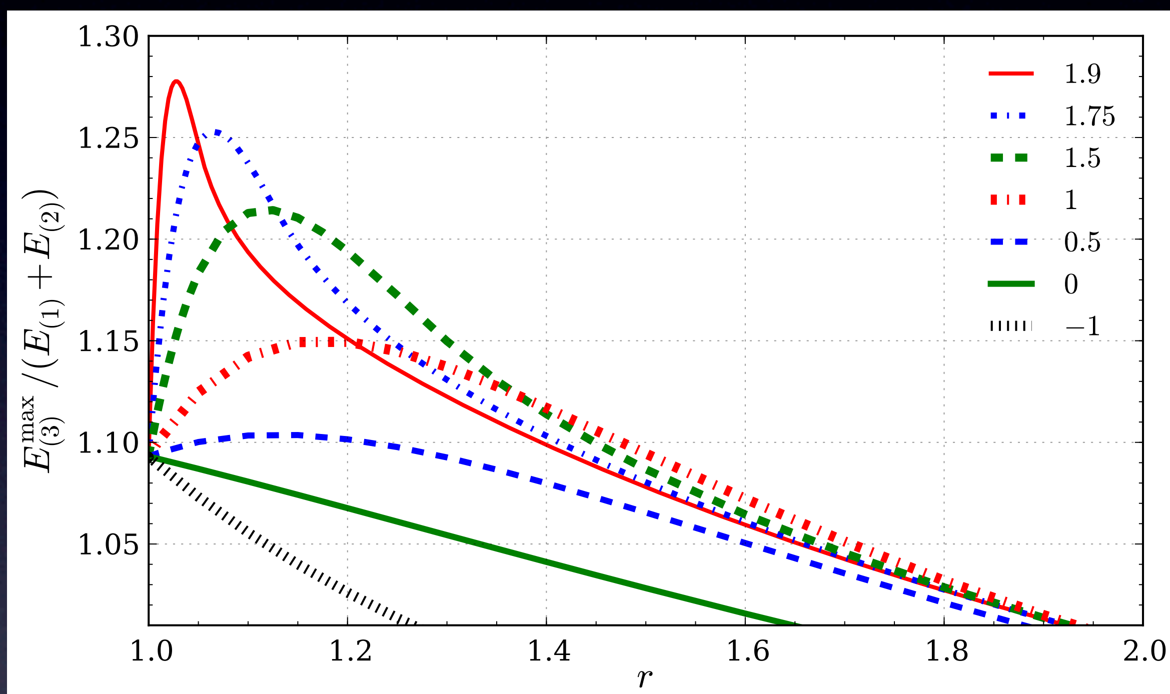
Center of mass energy blows up for l_1=2

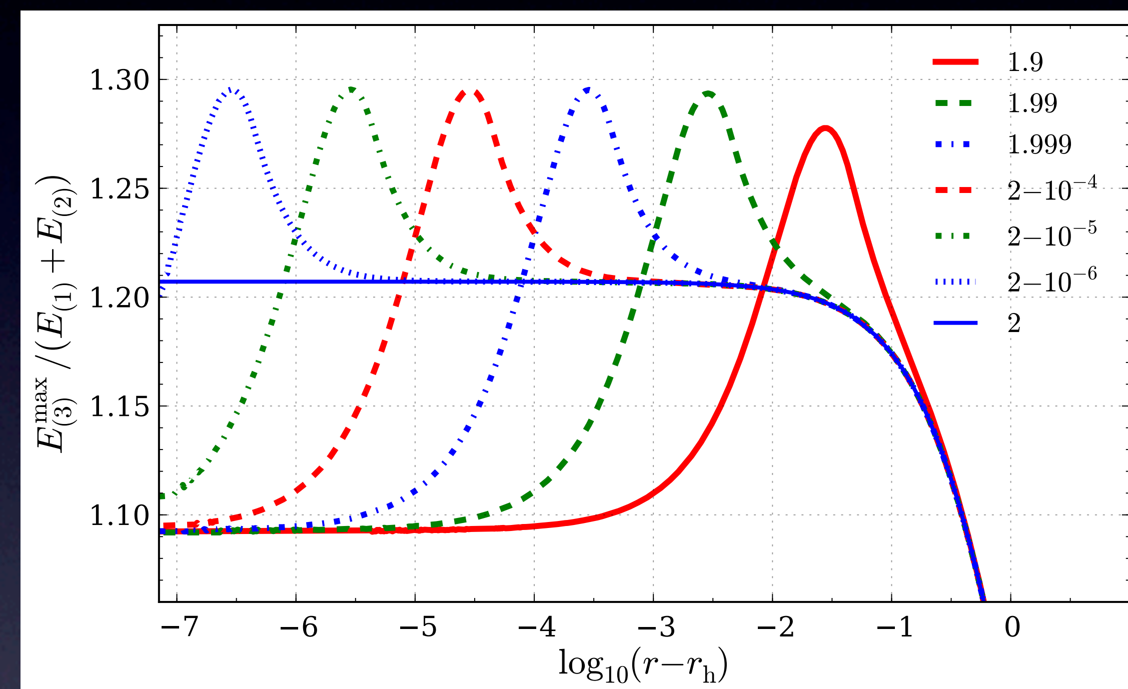


$a_\star=1$

Maximum energy of particles that actually escape to infinity

For a$_\star$=1 the maximum gain = 1.295



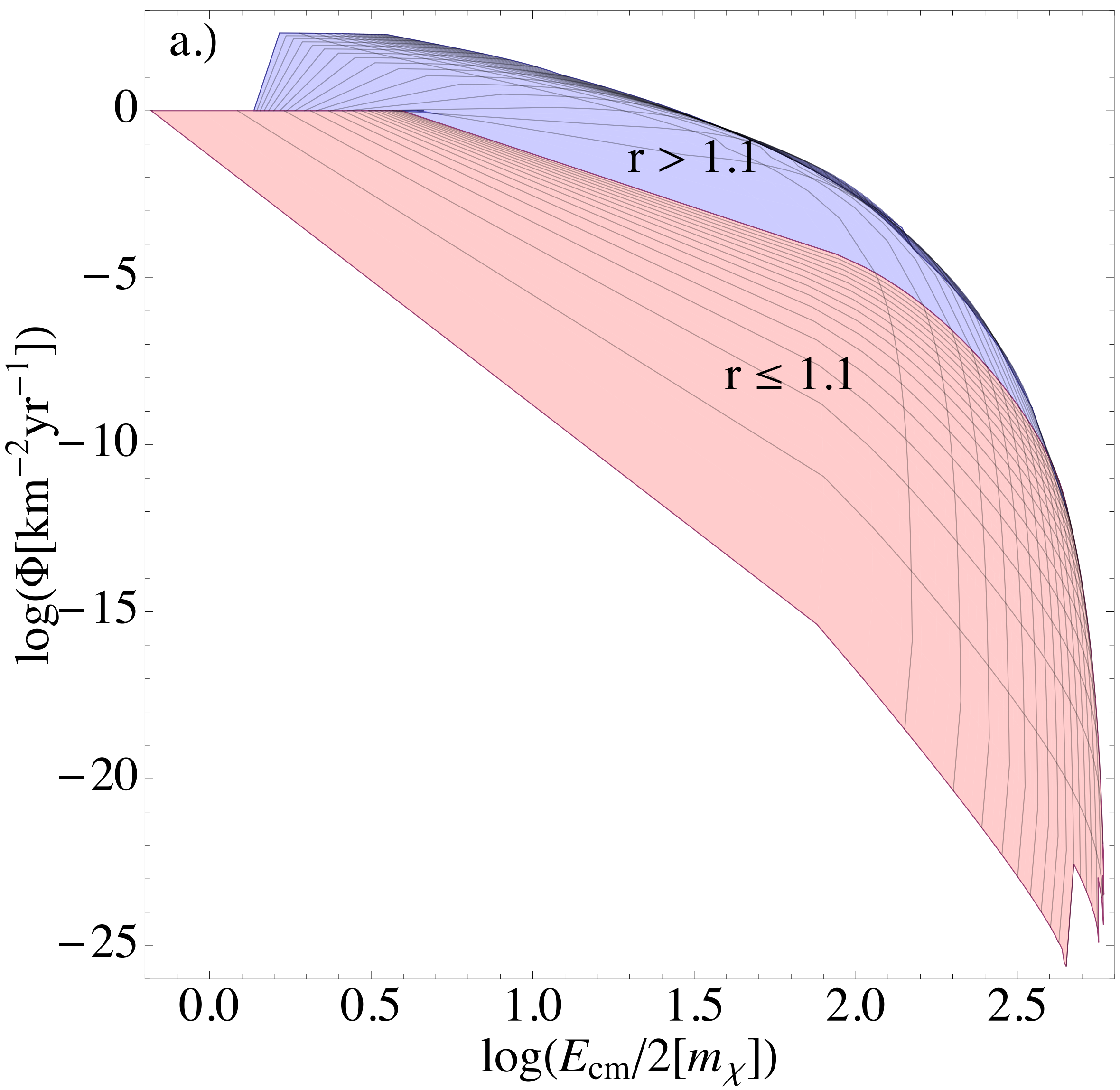


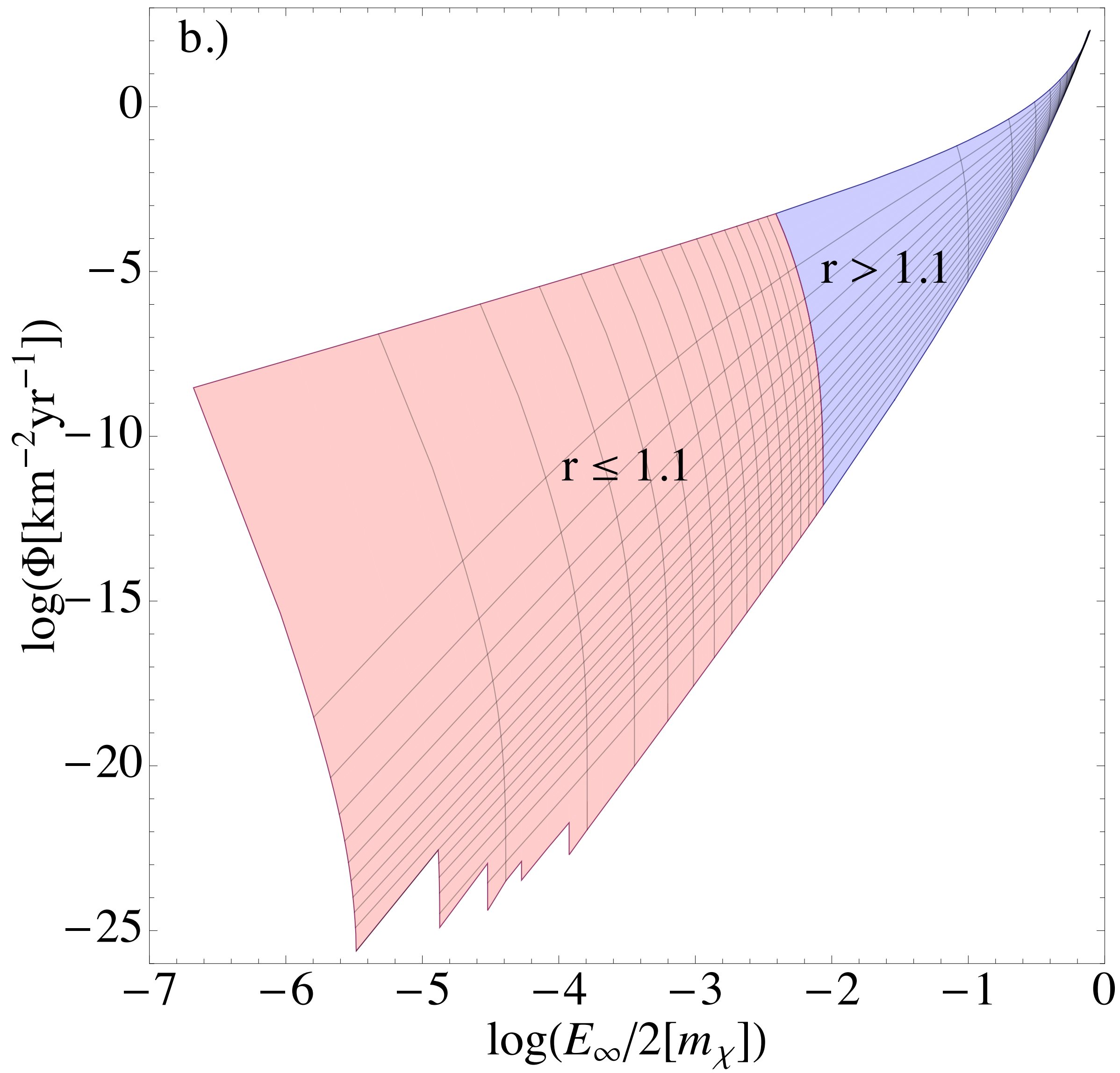
$$E_{(3)} = -\mathbf{p}_i\eta^i$$

The highest CoM energies are close to the horizon...where the CoM has large negative radial momentum.

Bejger, Piran, Abramowicz, Håkanson 2012; Piran & Shaham 1977

2-photon annihilation fluxes

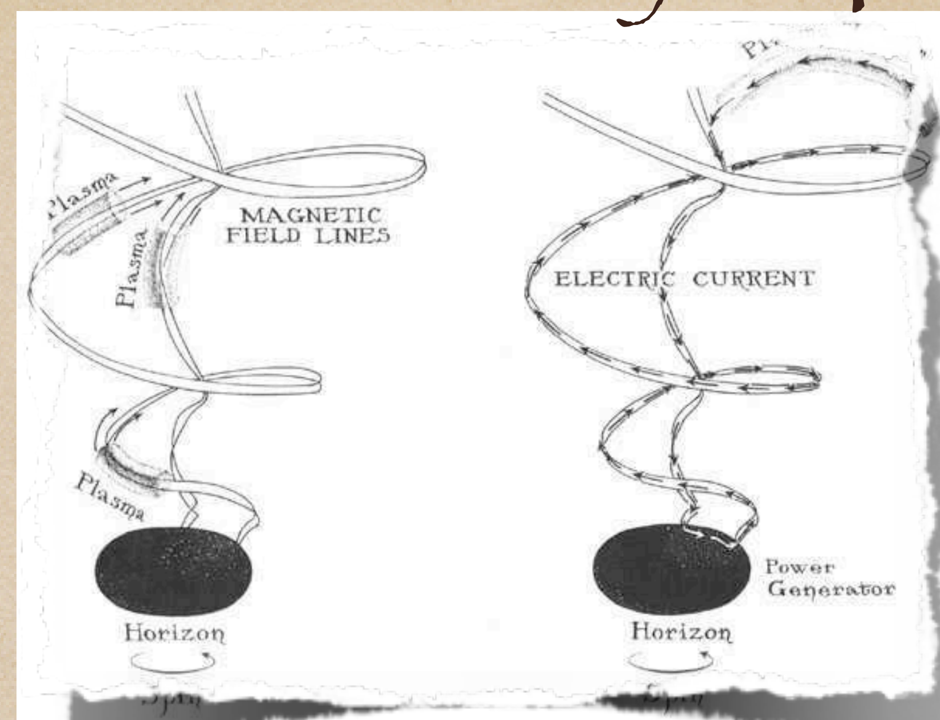


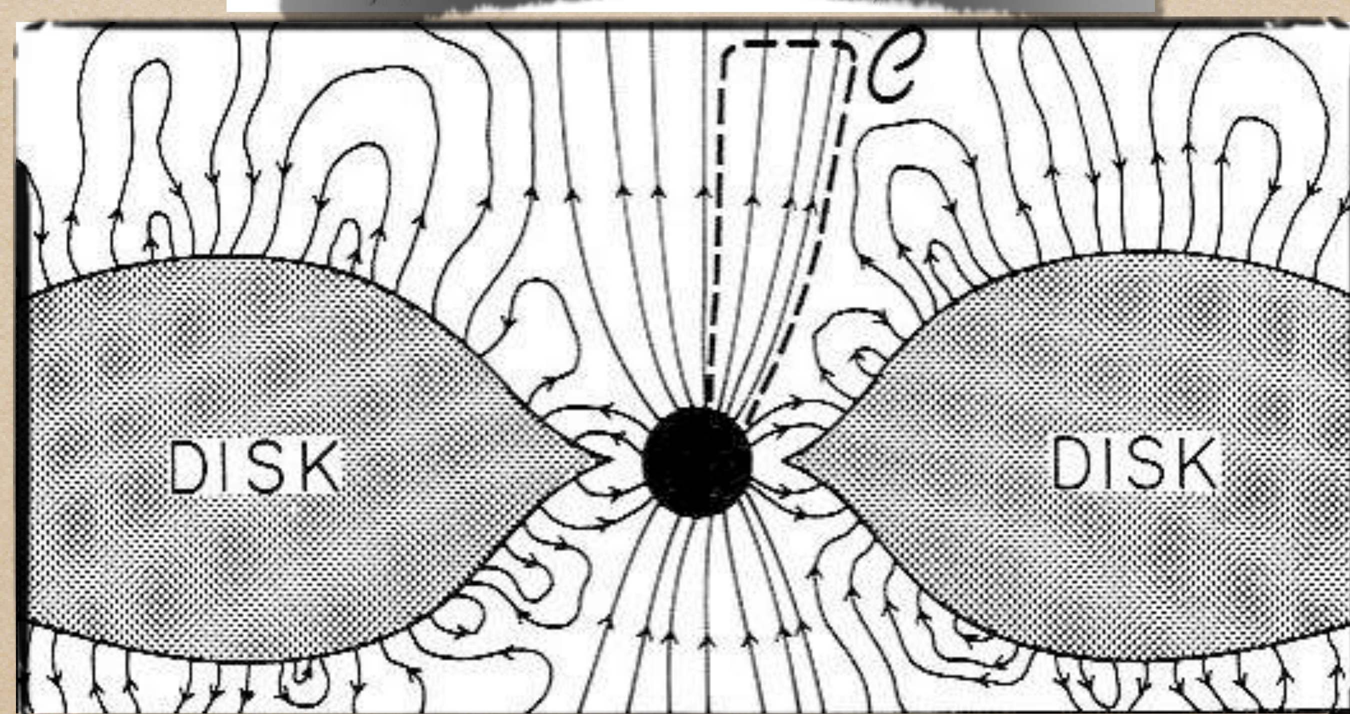


Photons created near the horizon that reach distant observers have relatively low energies and the most energetic photons are created far from the horizon.

McWilliams 2013

Blandford-Znajek process





Is it an (electromagnetic) Penrose process?

Generalised Penrose process

Energy momentum vector $P^\alpha = -T^\alpha_{\ \mu}\eta^\mu$ $\quad\nabla_\mu P^\mu = 0$

From the Stokes theorem:

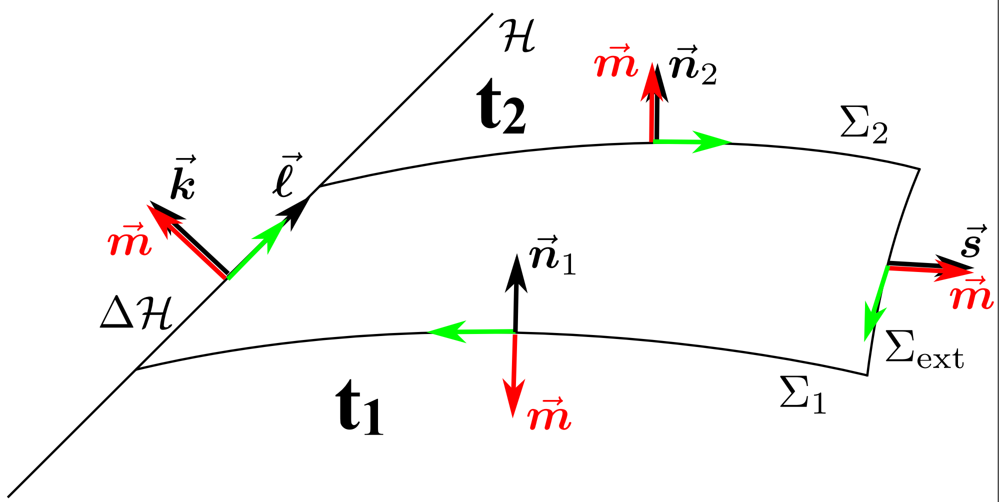
$$-\int_{\Sigma_1} P_\mu(-n_1^\mu)\,\mathrm{d}V - \int_{\Delta\mathcal{H}} P_\mu \ell^\mu\,\mathrm{d}V - \int_{\Sigma_2} P_\mu n_2^\mu\,\mathrm{d}V + \int_{\Sigma_{\rm ext}} P_\mu s^\mu\,\mathrm{d}V = 0$$

$$E_1 := -\int_{\Sigma_1} P_\mu n_1^\mu\,\mathrm{d}V = \int_{\Sigma_1} T_{\mu\nu}\eta^\mu n_1^\nu\,\sqrt{\gamma}\,\mathrm{d}x^1\,\mathrm{d}x^2\,\mathrm{d}x^3,$$

$$E_2 := -\int_{\Sigma_2} P_\mu n_2^\mu\,\mathrm{d}V = \int_{\Sigma_2} T_{\mu\nu}\eta^\mu n_2^\nu\,\sqrt{\gamma}\,\mathrm{d}x^1\,\mathrm{d}x^2\,\mathrm{d}x^3$$

$$E_H := -\int_{\Delta\mathcal{H}} P_\mu \ell^\mu\,\mathrm{d}V = \int_{\Delta\mathcal{H}} T_{\mu\nu}\eta^\mu \ell^\nu\,\sqrt{q}\,\mathrm{d}t\,\mathrm{d}y^1\,\mathrm{d}y^2$$

$$E_{\rm ext} := \int_{\Sigma_{\rm ext}} P_\mu s^\mu\,\mathrm{d}V = -\int_{\Sigma_{\rm ext}} T_{\mu\nu}\eta^\mu s^\nu\,\sqrt{-\gamma}\,\mathrm{d}t\,\mathrm{d}y^1\,\mathrm{d}y^2$$



$$\boxed{E_2 + E_{\rm ext} - E_1 = -E_H}$$

Energy gained by the world outside the black hole:

For $\Delta E > 0 \qquad \Delta E := E_2 + E_{\rm ext} - E_1$

$$\boxed{E_H < 0}$$

Null energy condition: $\qquad T_{\mu\nu}\ell^\mu \ell^\nu \geq 0|_{\mathcal{H}}$

$$T_{\mu\nu}\ell^\mu \ell^\nu = T_{\mu\nu}(\eta^\nu + \omega_H \xi^\nu)\ell^\mu = -P_\mu \ell^\mu + \omega_H M_\mu \ell^\mu$$

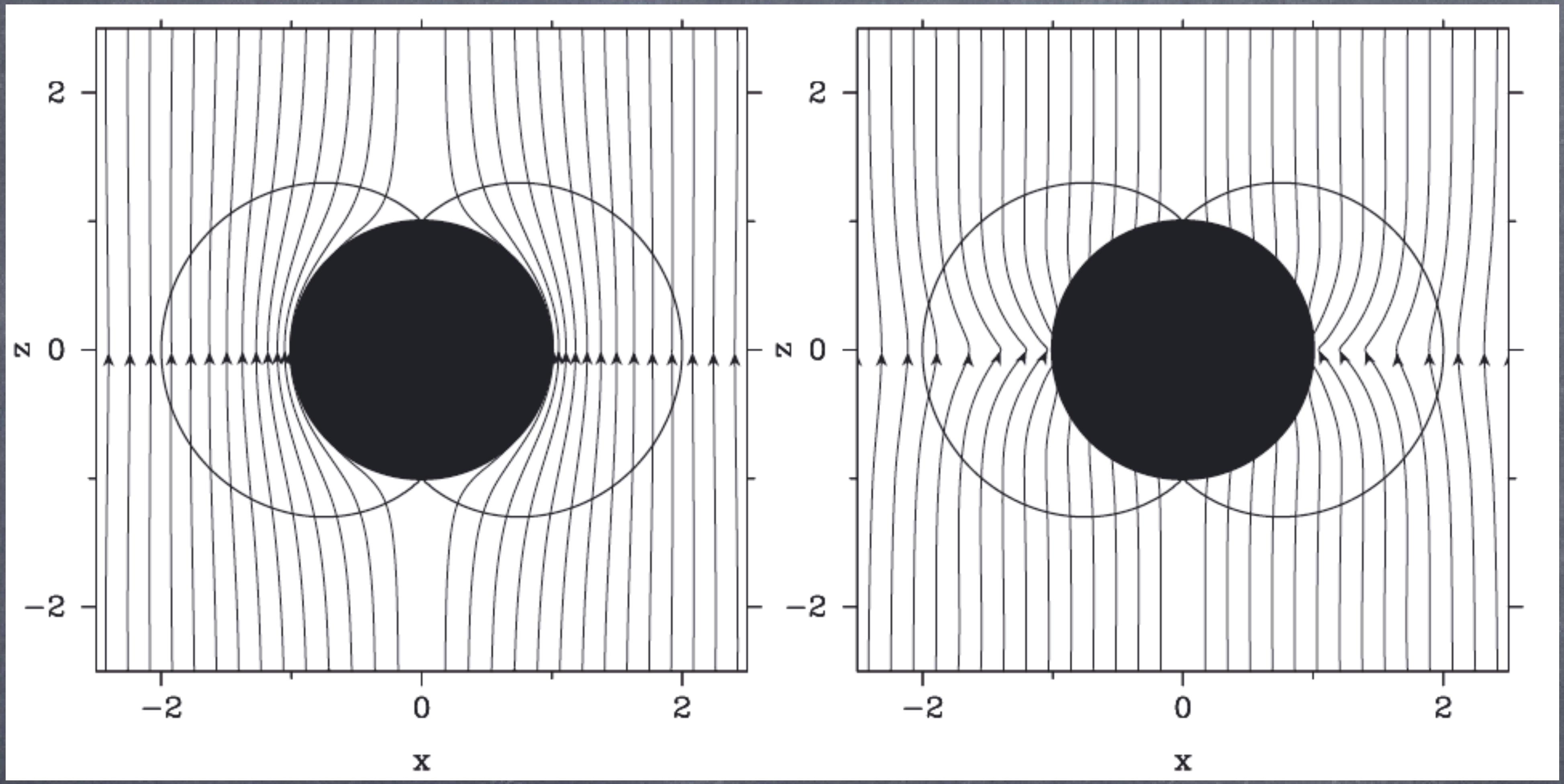
$$-\int_{\Delta\mathcal{H}} P_\mu \ell^\mu \, \mathrm{d}V + \omega_H \int_{\Delta\mathcal{H}} M_\mu \ell^\mu \, \mathrm{d}V \geq 0,$$

$E_H - \omega_H J_H \geq 0$ i.e. $\omega_H J_H \leq E_H \qquad \boxed{J_H < 0.}$

For a matter distribution or a non-gravitational field obeying the null energy condition, a necessary and sufficient condition for energy extraction from a rotating black hole is that it absorbs negative energy E_H and negative angular momentum J_H.

Lasota, Gourgoulhon et al. 2013

«Meissner effect» only in vacuum

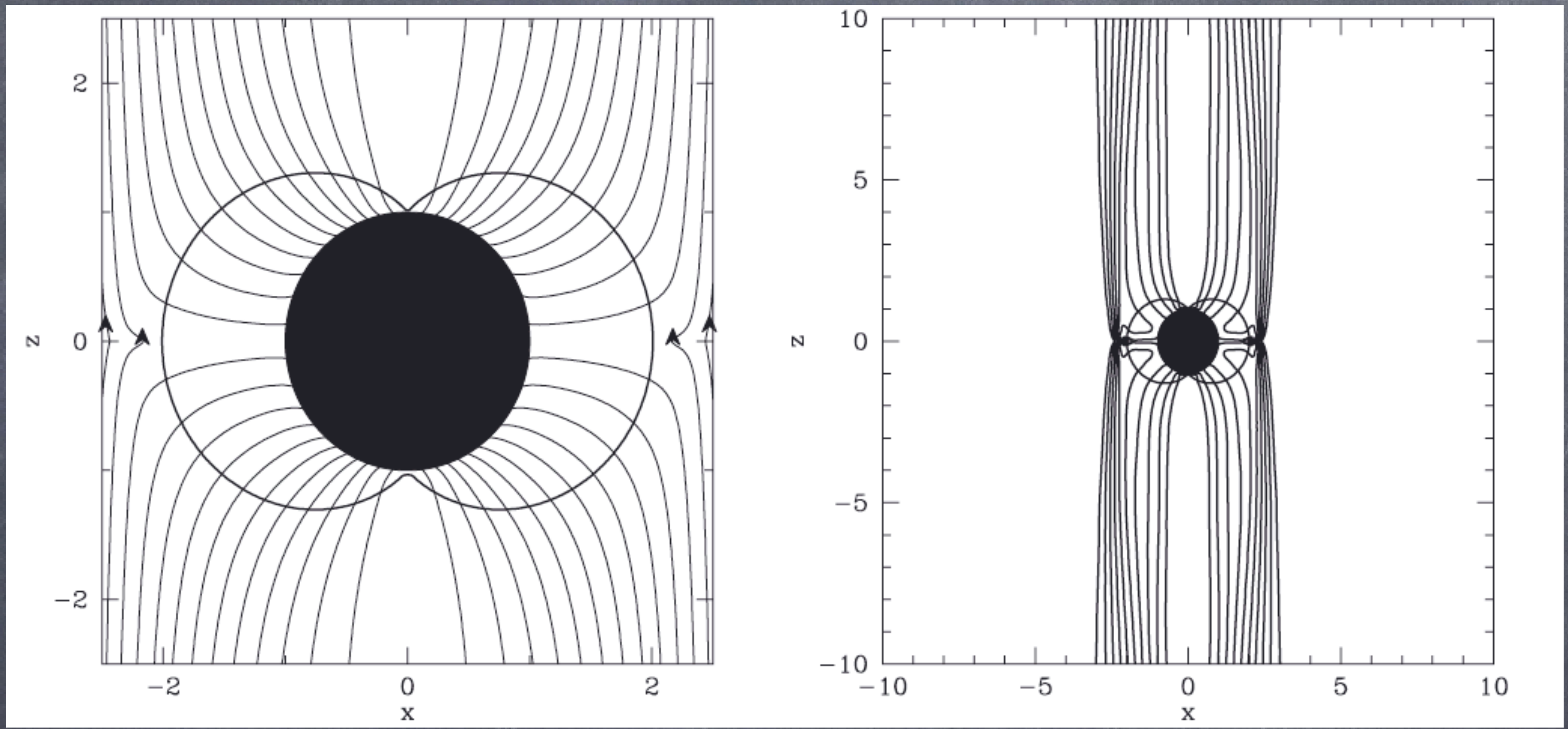


Vacuum Plasma

King, Lasota& Kundt 1975

Komissarov & Mc Kinney 2007

«Meissner effect» only in vacuum



King, Lasota& Kundt 1975
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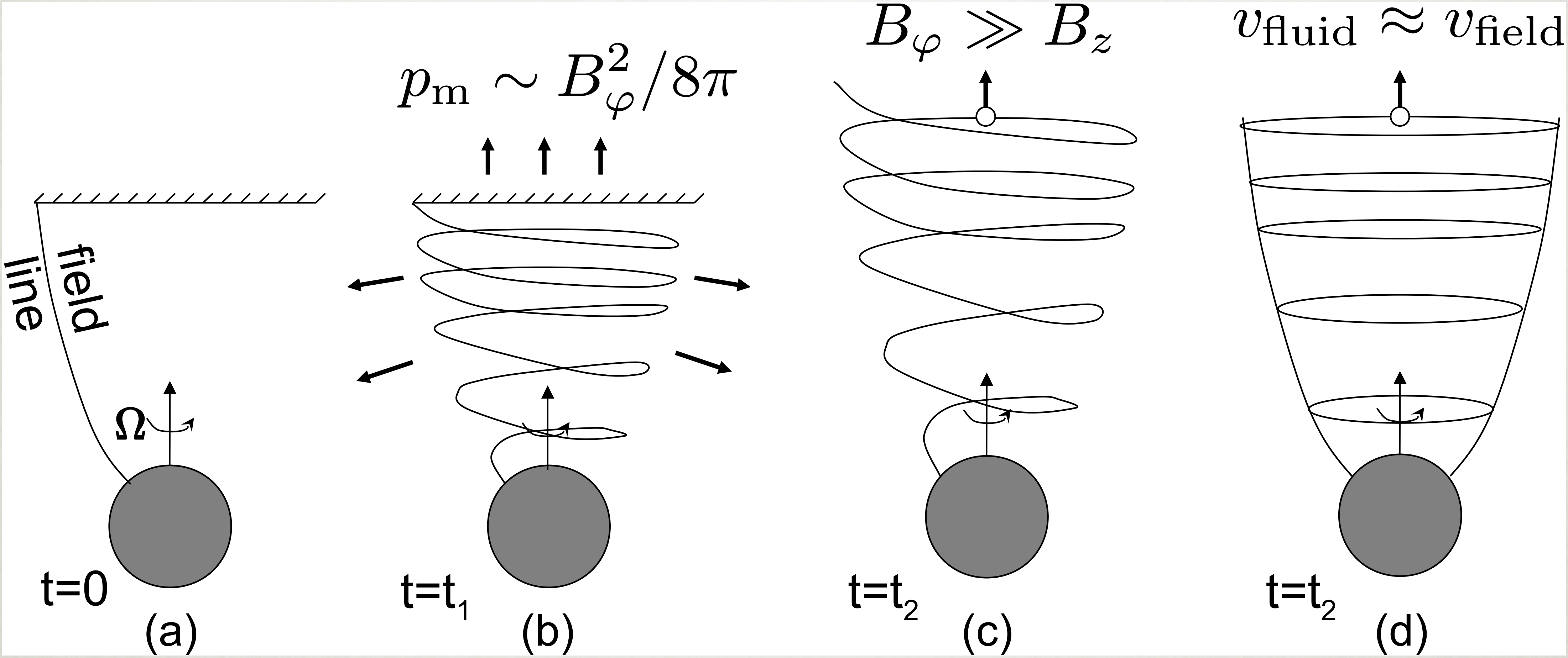
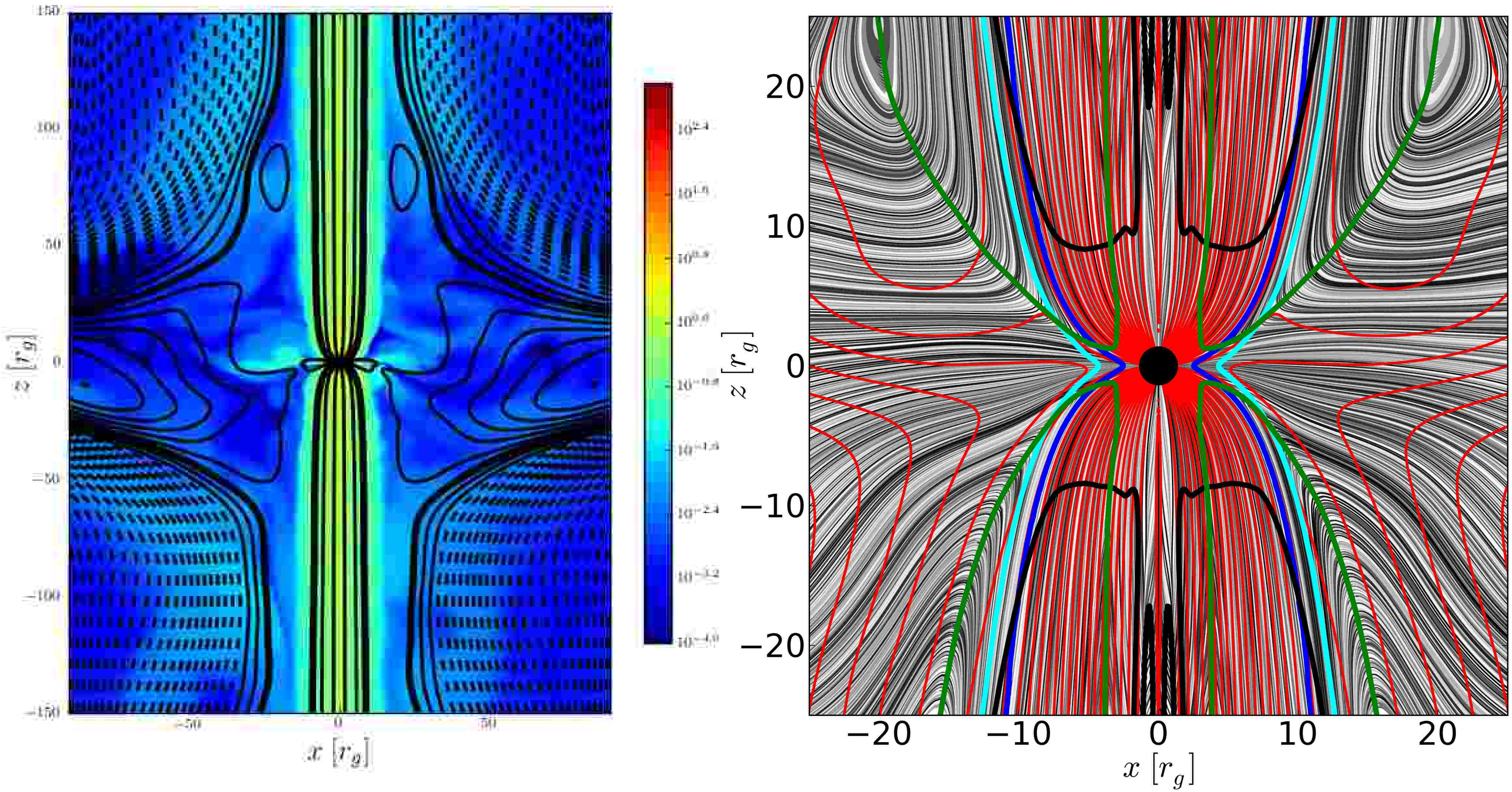
Jet formation for a poloidal magnetic field



Tchehkovskoy, McKinney & Narayan 2012

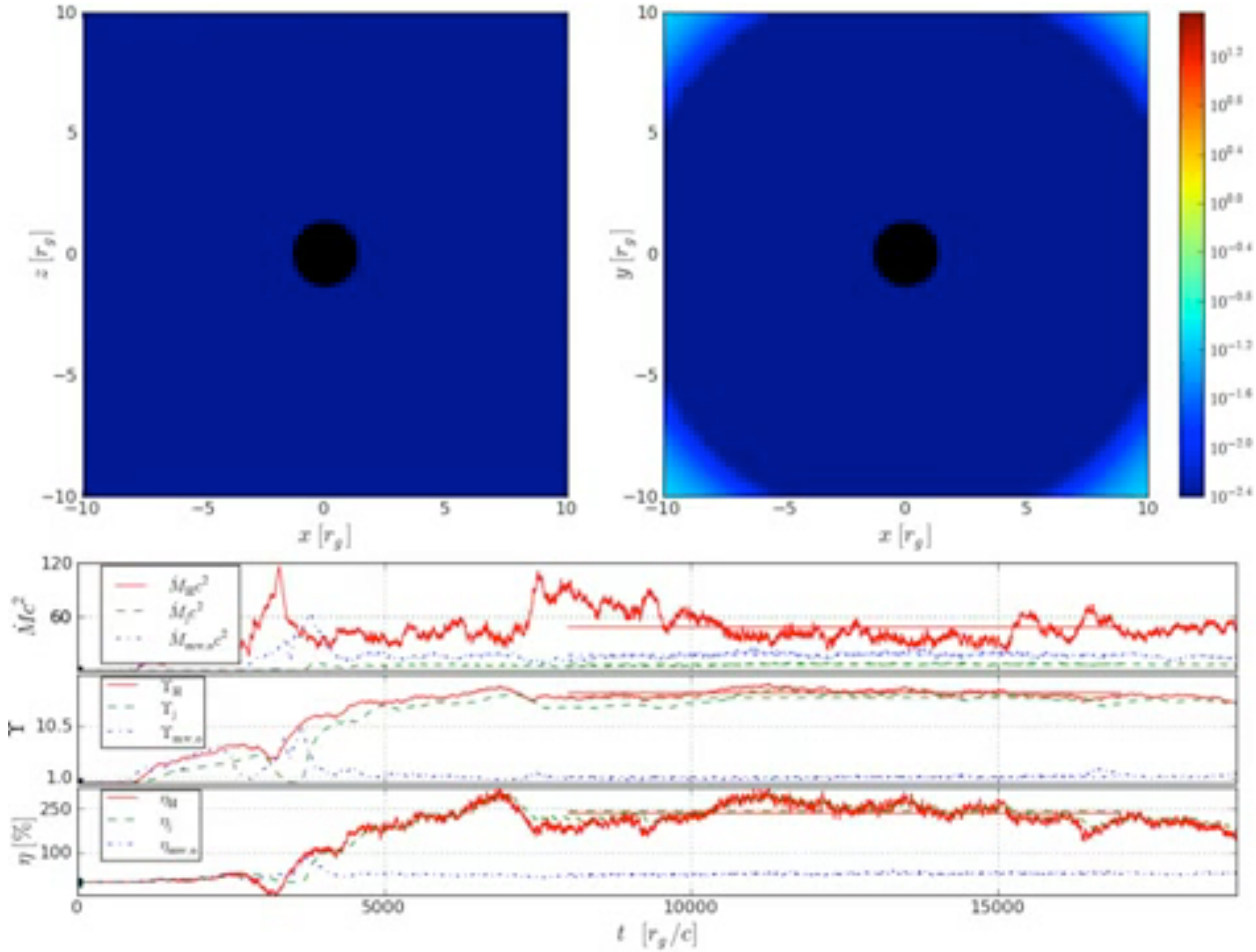


McKinney, Tchekhovskoy & Blandford 2012

Magnetically arrested accretion

$$P_{\rm BZ} = \frac{\kappa}{4\pi c}\,\Omega_{\rm H}^2\,\Phi_{\rm BH}^2\,f(\Omega_{\rm H})$$

$$\eta \equiv \frac{\dot{M} - \dot{E}_\infty}{\langle \dot{M} \rangle_t} \times 100\%$$



Tchekhovskoy, Narayan, McKinney, Blandford (2011,2012)

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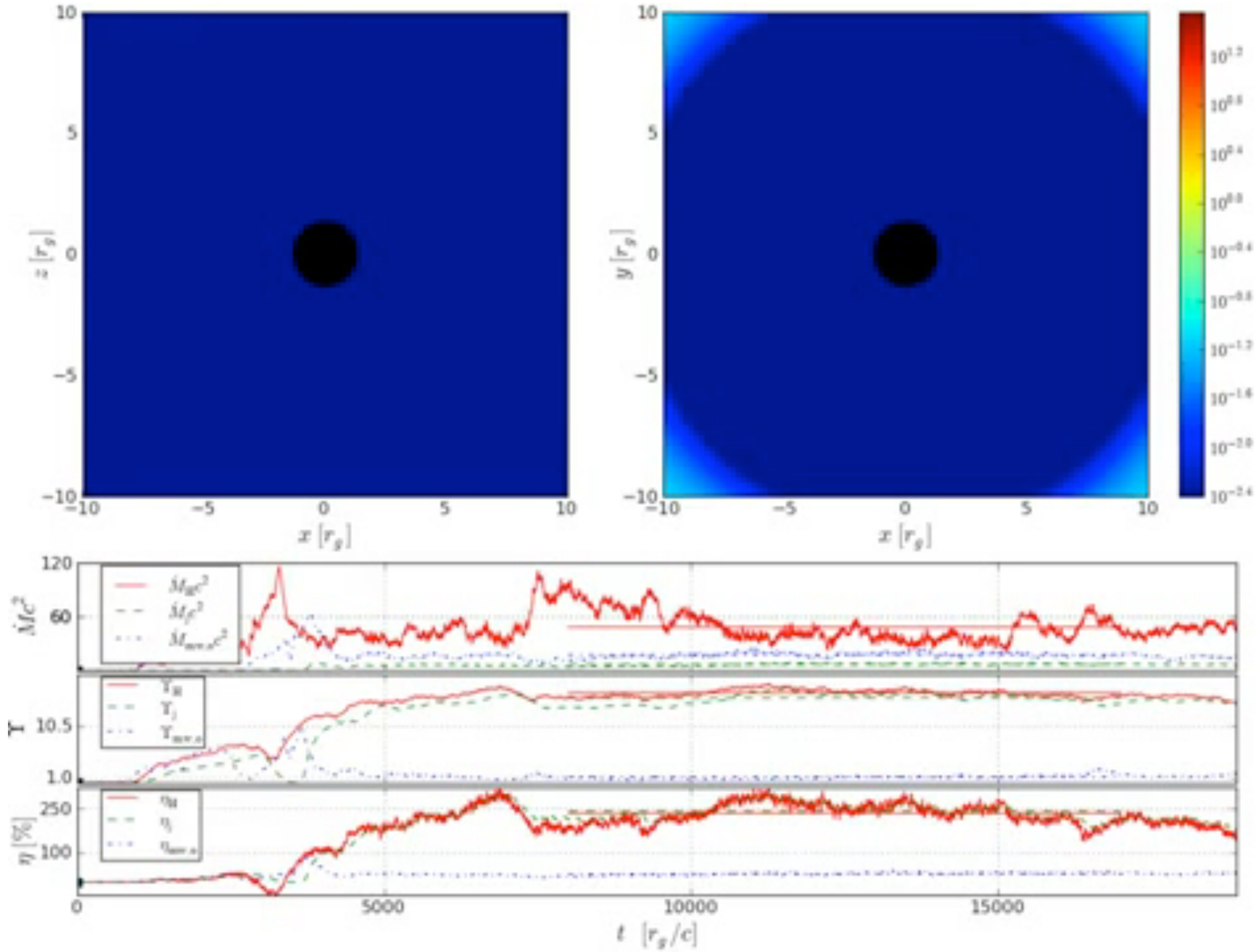

η to up 250% !

Tchekhovskoy, Narayan, McKinney, Blandford (2011,2012)

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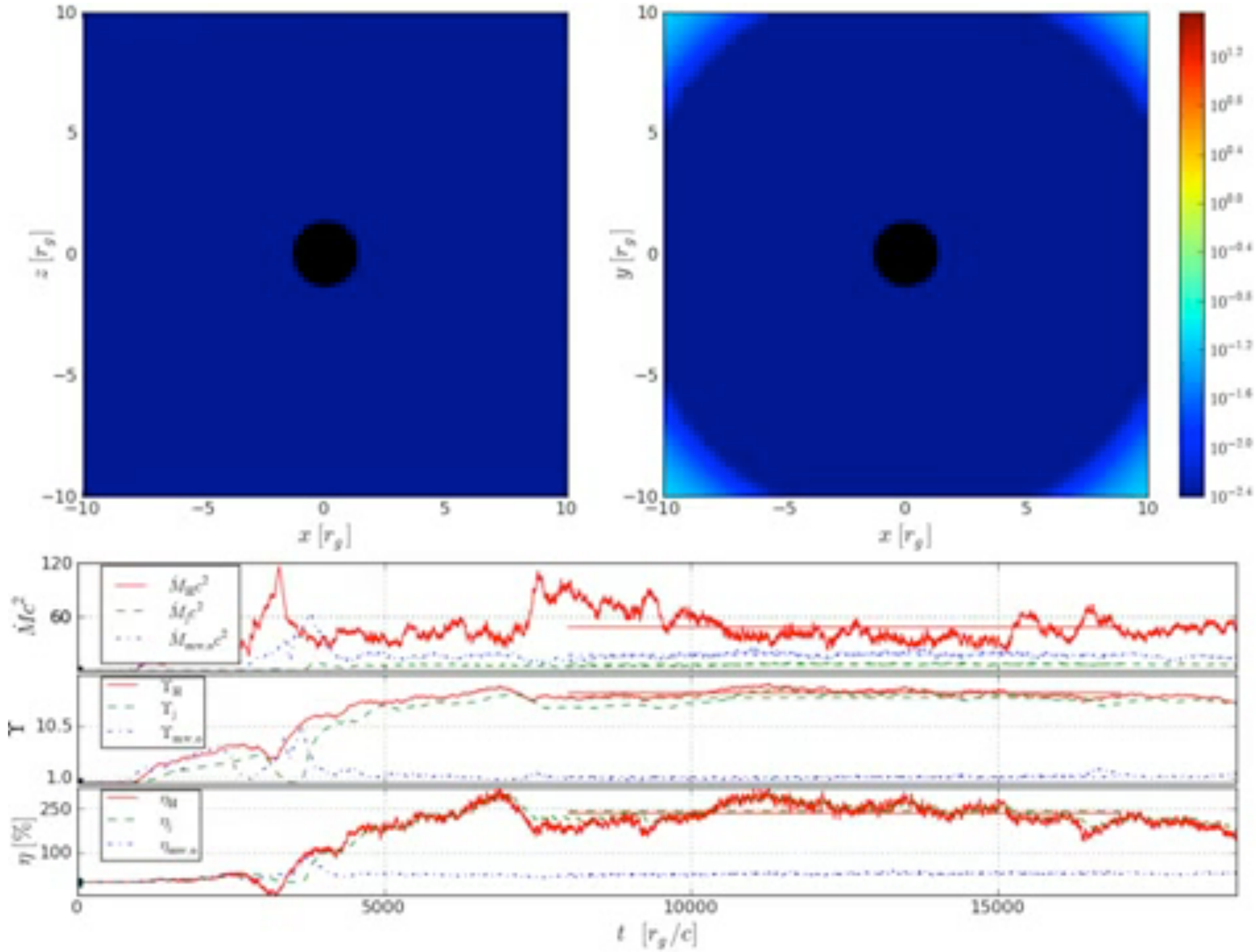

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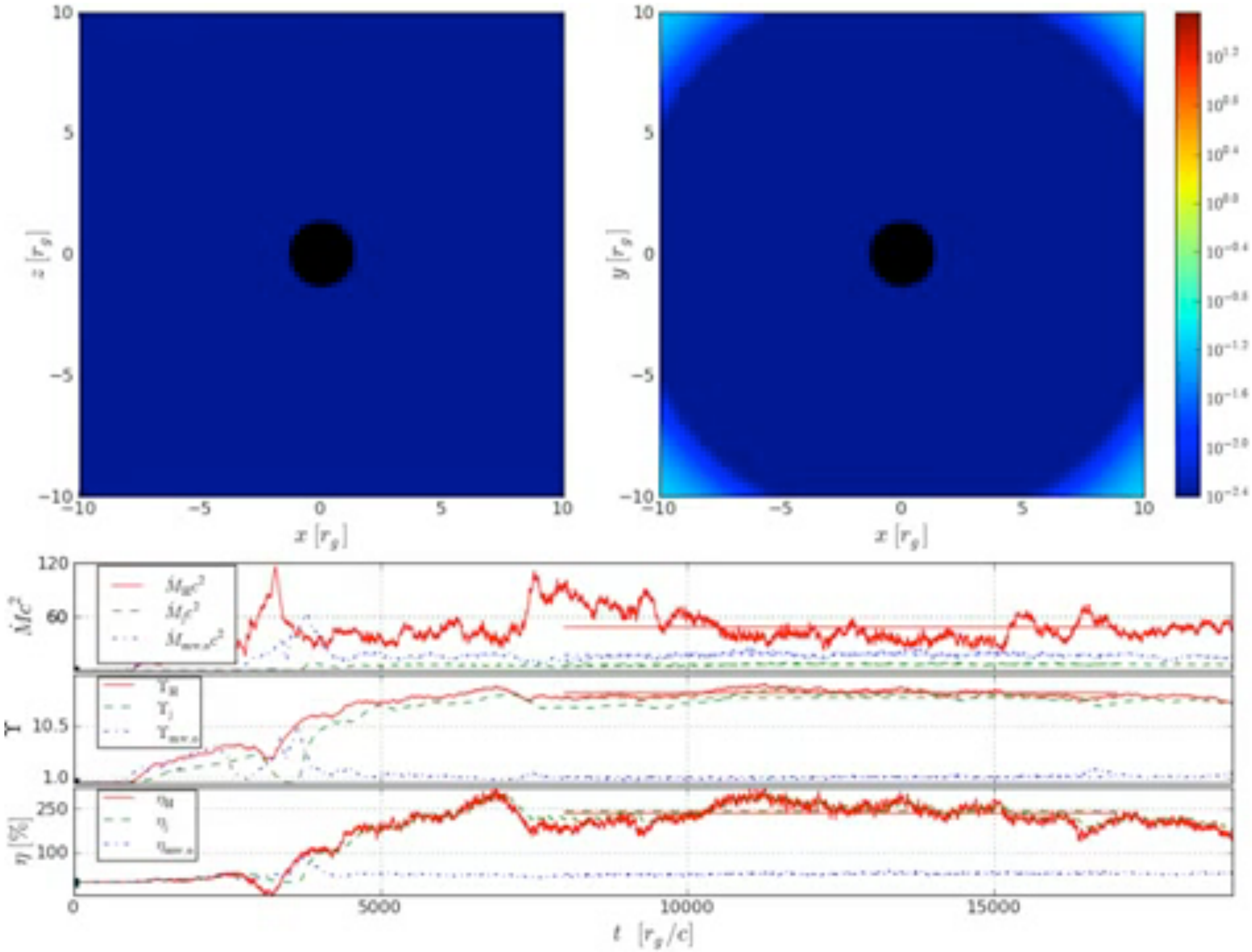

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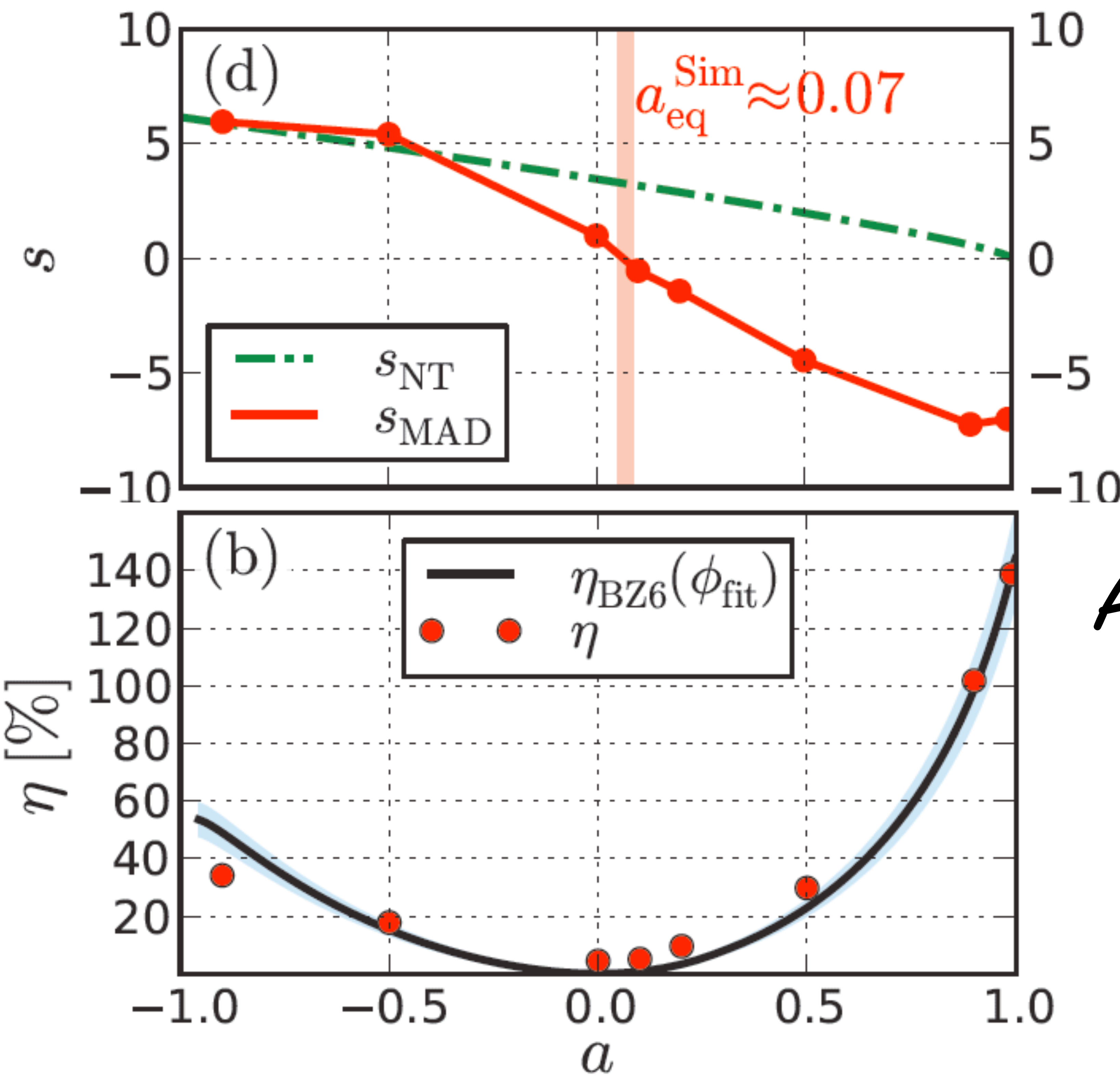
Blandford-Znajek is Penrose!

Tchekhovskoy, Narayan, McKinney, Blandford (2011,2012)



Spin-up parameter

$$s \equiv \frac{\dot{J}_\infty - 2a_* \dot{E}_\infty / M}{\langle \dot{M} \rangle_t}$$

Accretion efficiency

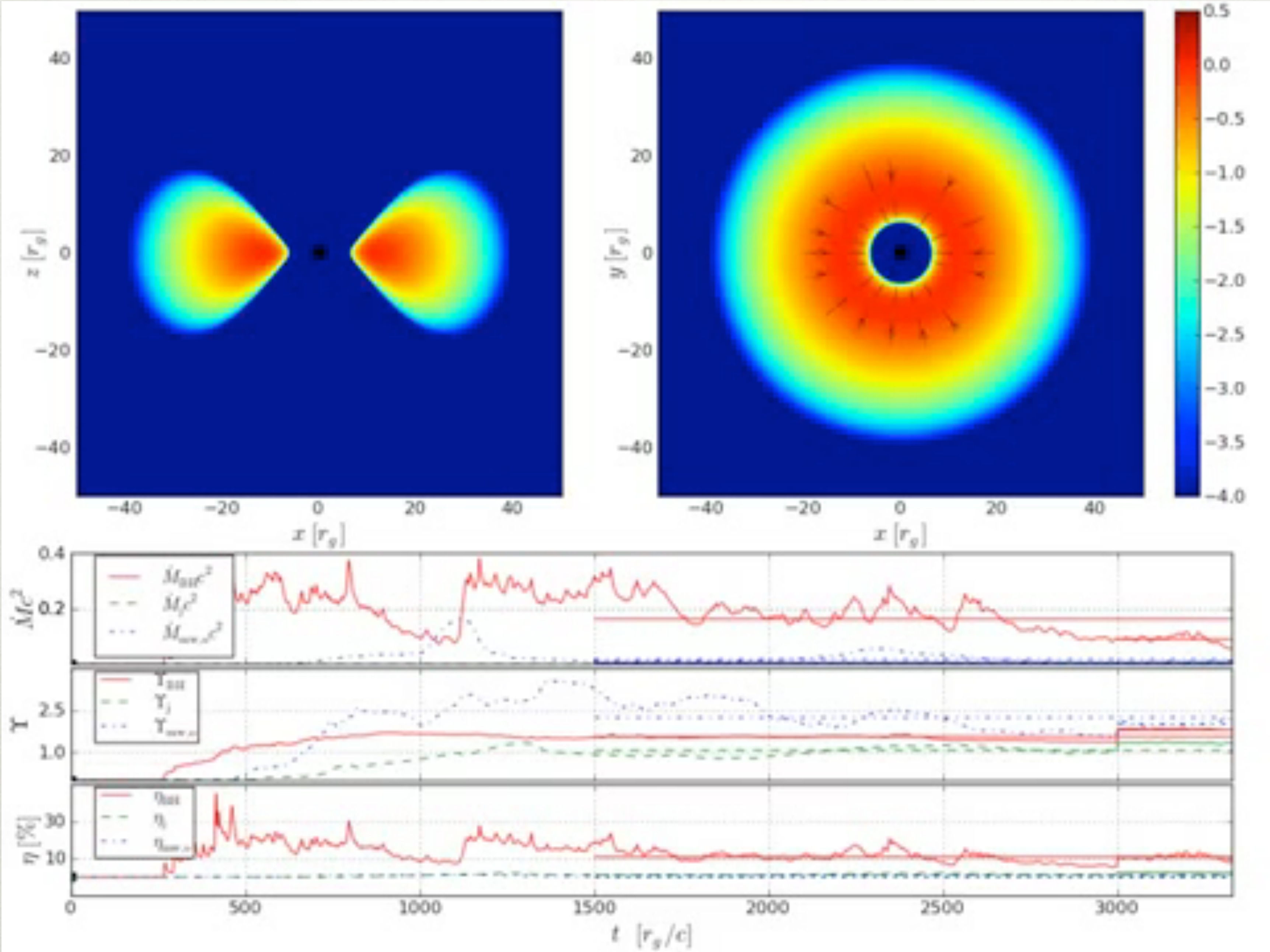
$$\eta \equiv \frac{\dot{M} - \dot{E}_\infty}{\langle \dot{M} \rangle_t} \times 100\%$$

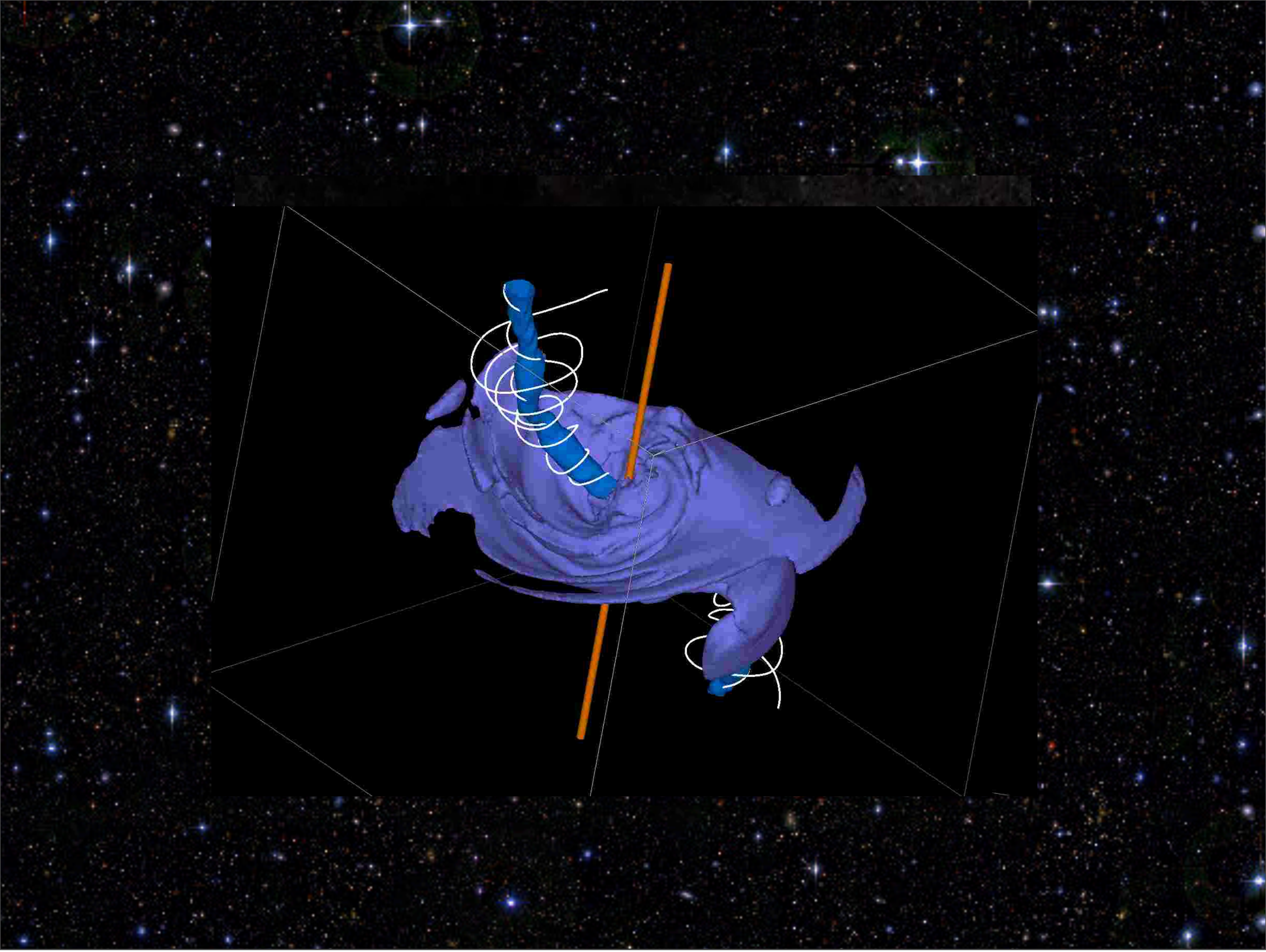
$$\frac{\dot{J}_\infty}{\langle \dot{M} \rangle_t} = s + 2a_* (1 - \eta)$$

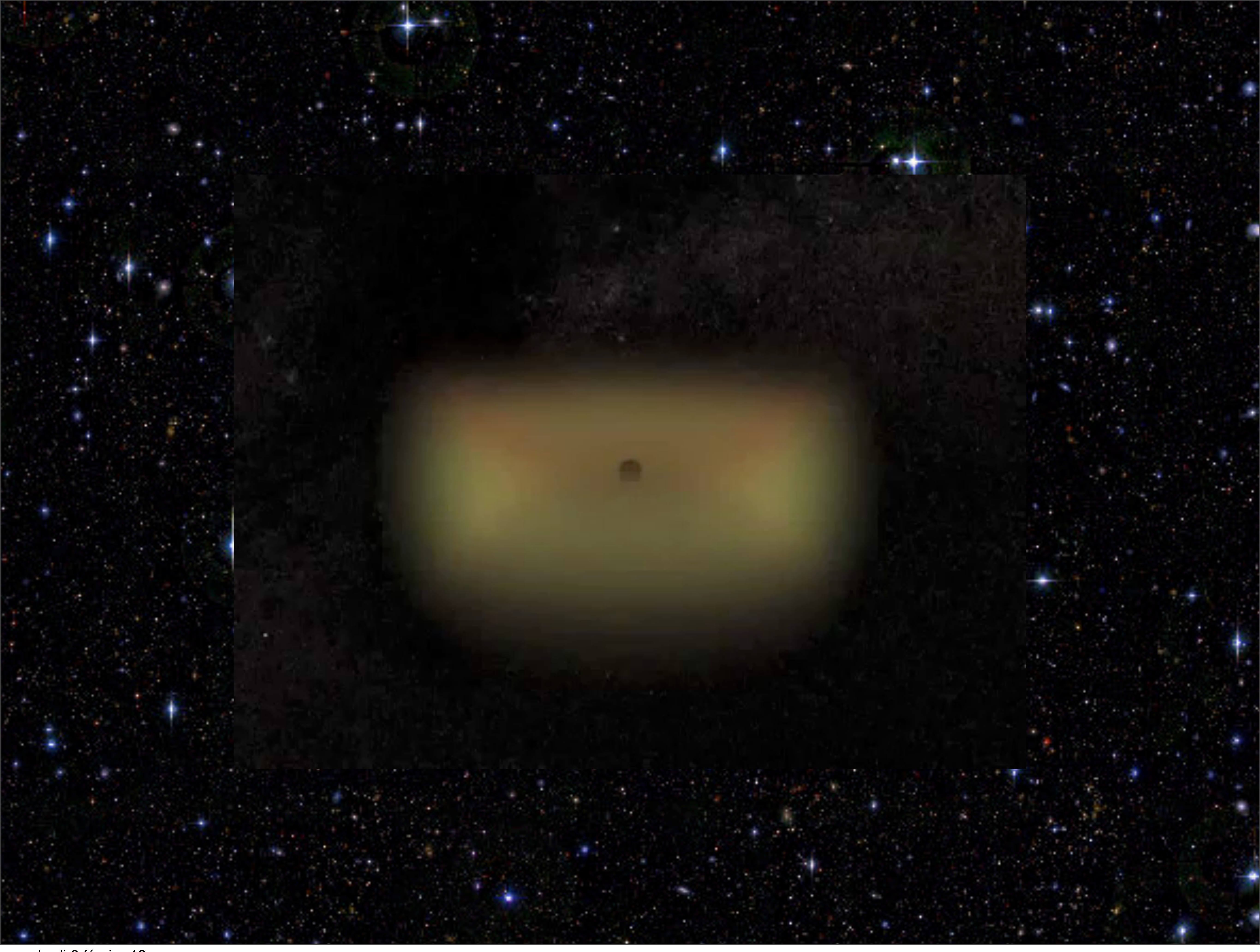
For $a_* > 0.1$: $\dot{J}_\infty < 0$

For $a_* > 0.9$: $\dot{E}_\infty < 0$

Efficiency depends on B-field configuration







ASTROPHYSICAL QUESTIONS:

Astrophysical questions:

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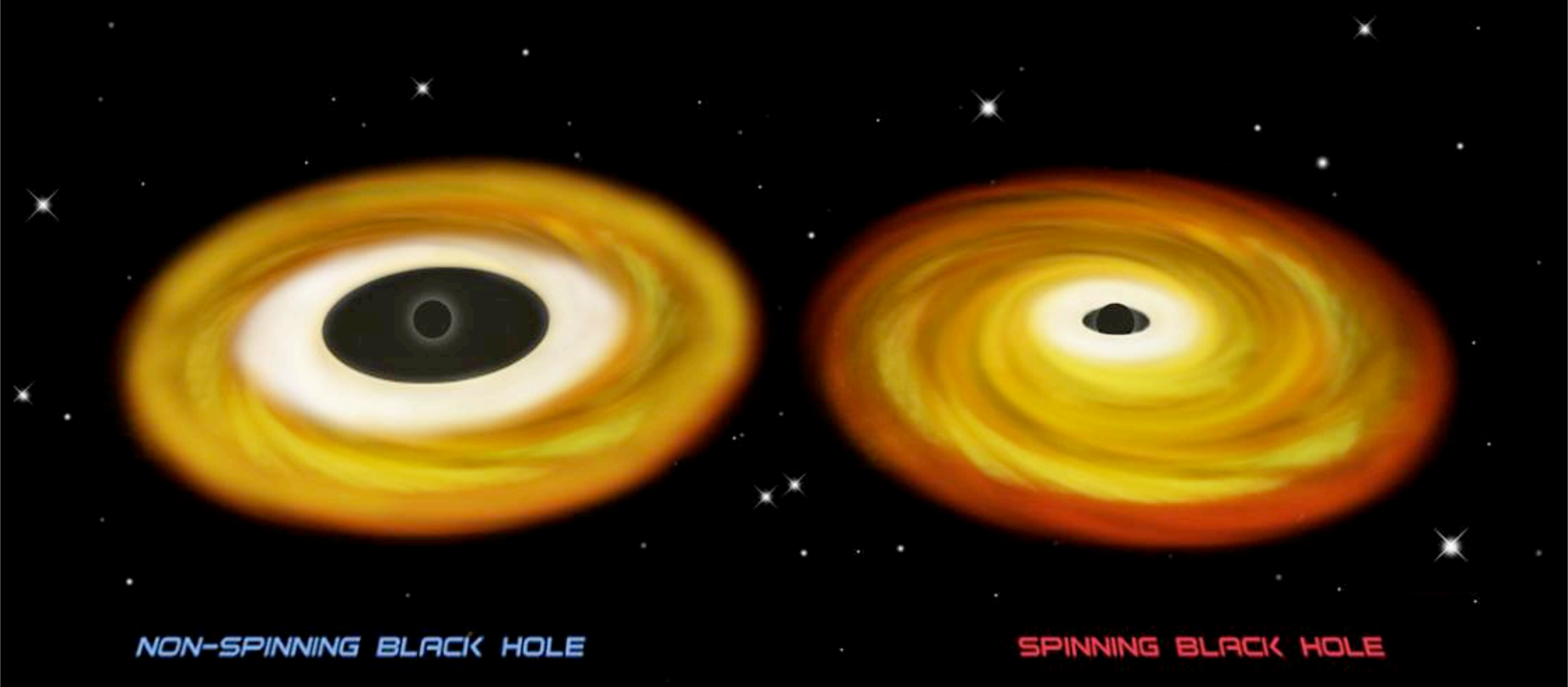
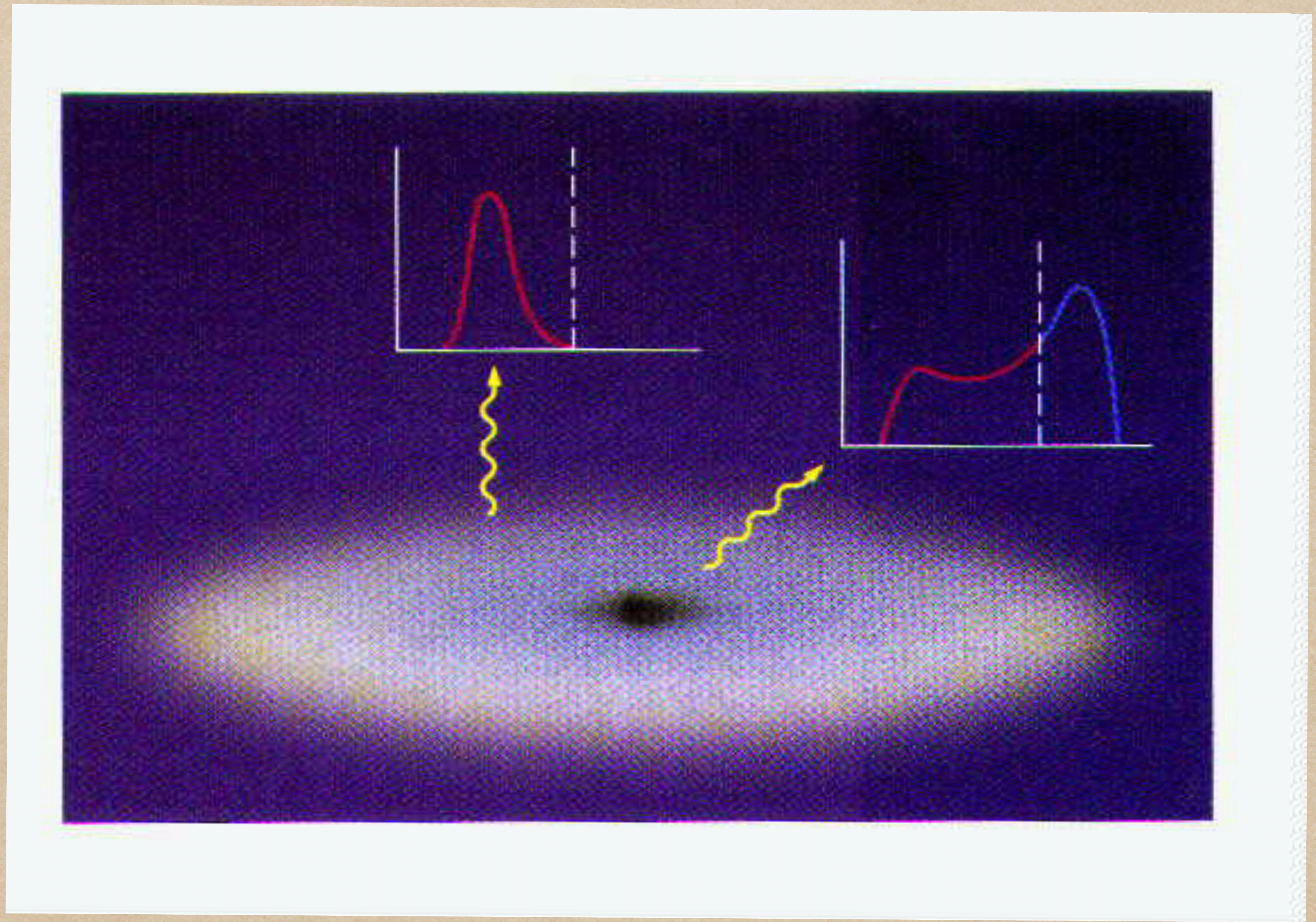
- Is jet production related to BH spin?
- If yes, how is it related?

Higher the spin, closer to BH the inner disc

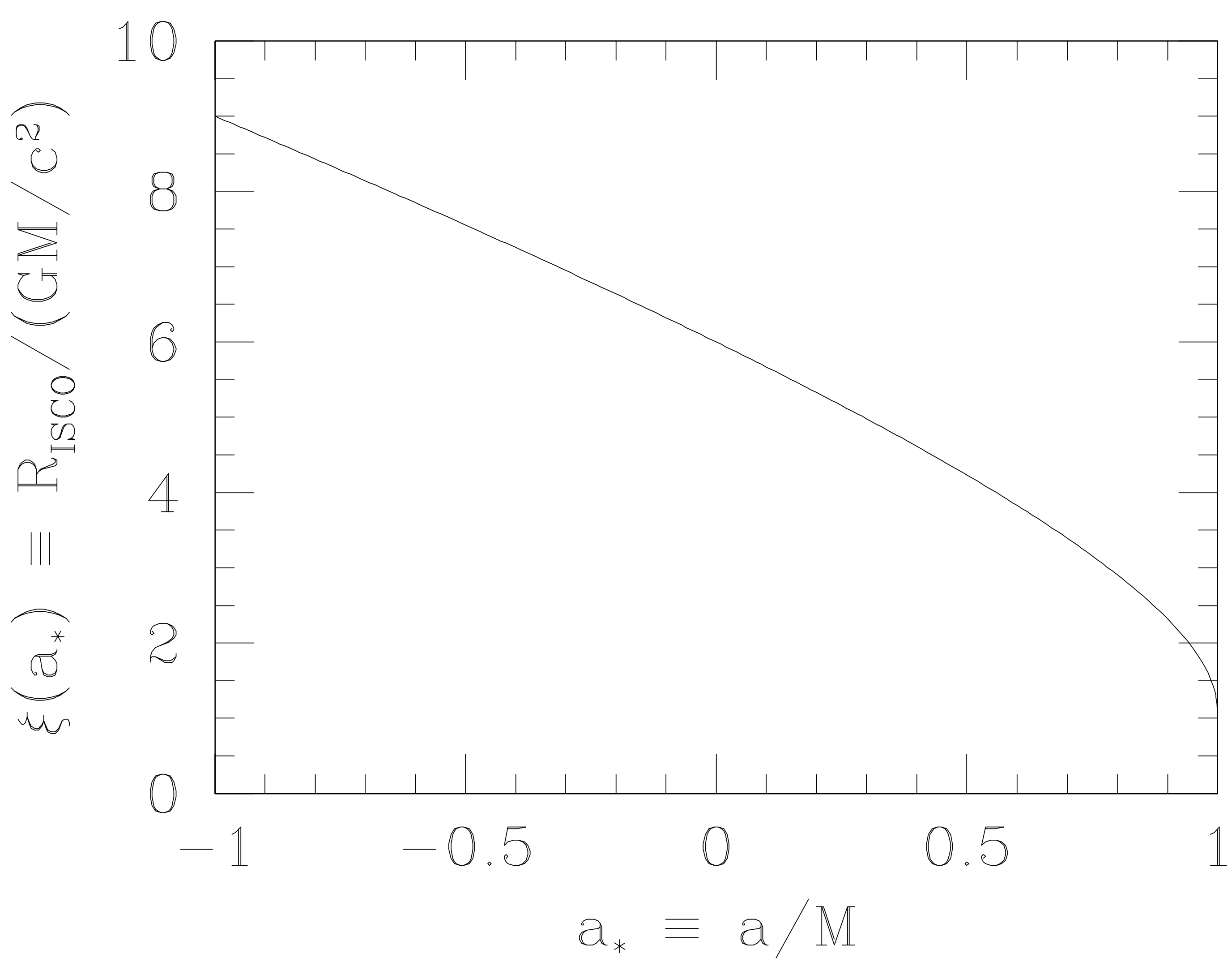


Emission line width



Measuring R_{ISCO} gives directly the value of a_*

$$r^{\pm}_{\rm ISCO} = M\{3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2}\},$$
$$Z_1 = 1 + \left(1 - a^2/M^2\right)^{1/3}\left[(1 + a/M)^{1/3} + (1 - a/M)^{1/3}\right],$$
$$Z_2 = \left(3a^2/M^2 + Z_1^2\right)^{1/2}.$$



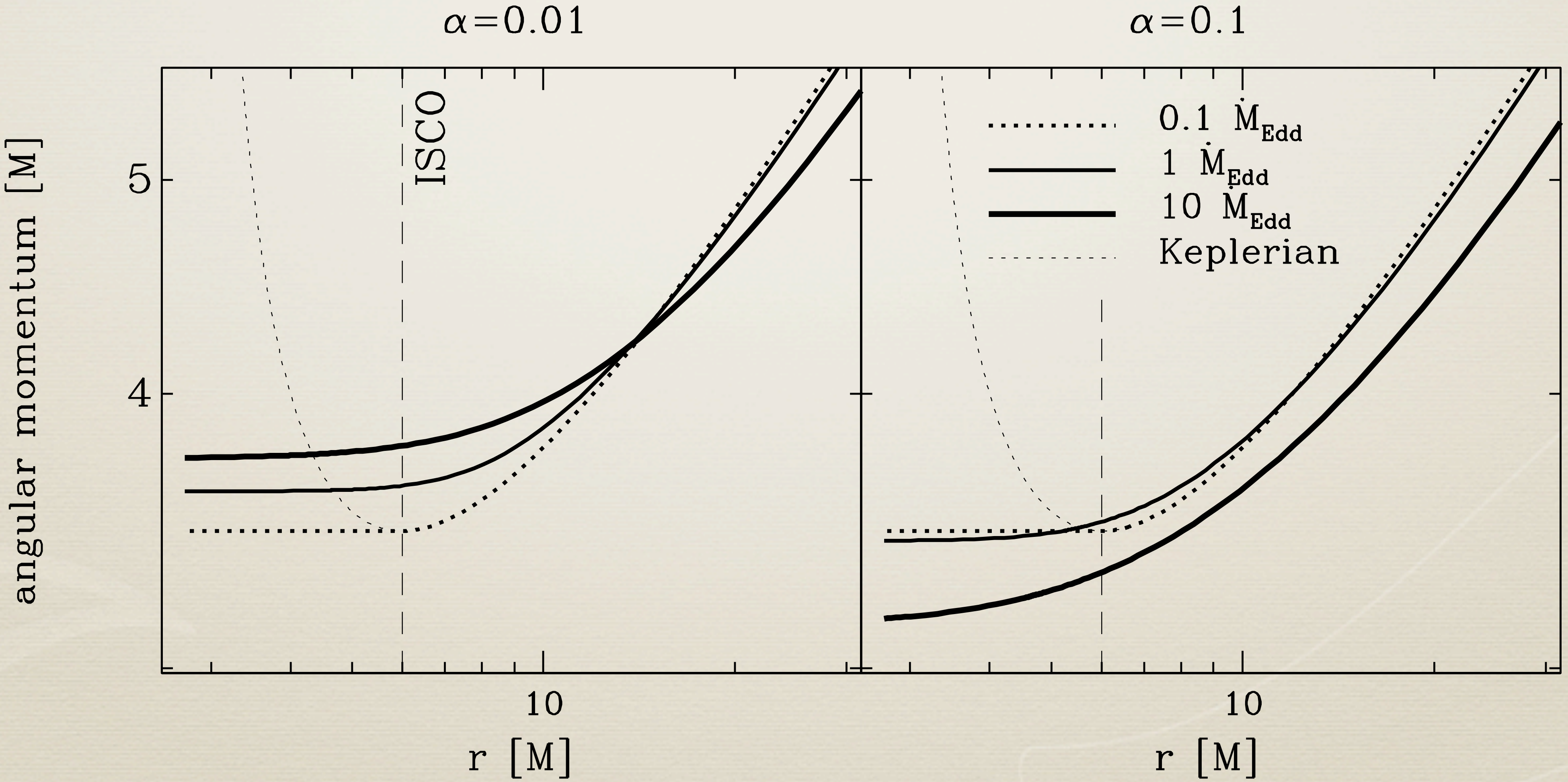
BH spin-up from ISCO

$$a = \frac{r_{\rm ISCO}^{1/2}}{3}\frac{M(t)}{M(t+\Delta t)}\left[4 - \left(\frac{3M(t)^2}{M(t+\Delta t)^2}r_{\rm ISCO} - 2\right)^{1/2}\right]$$

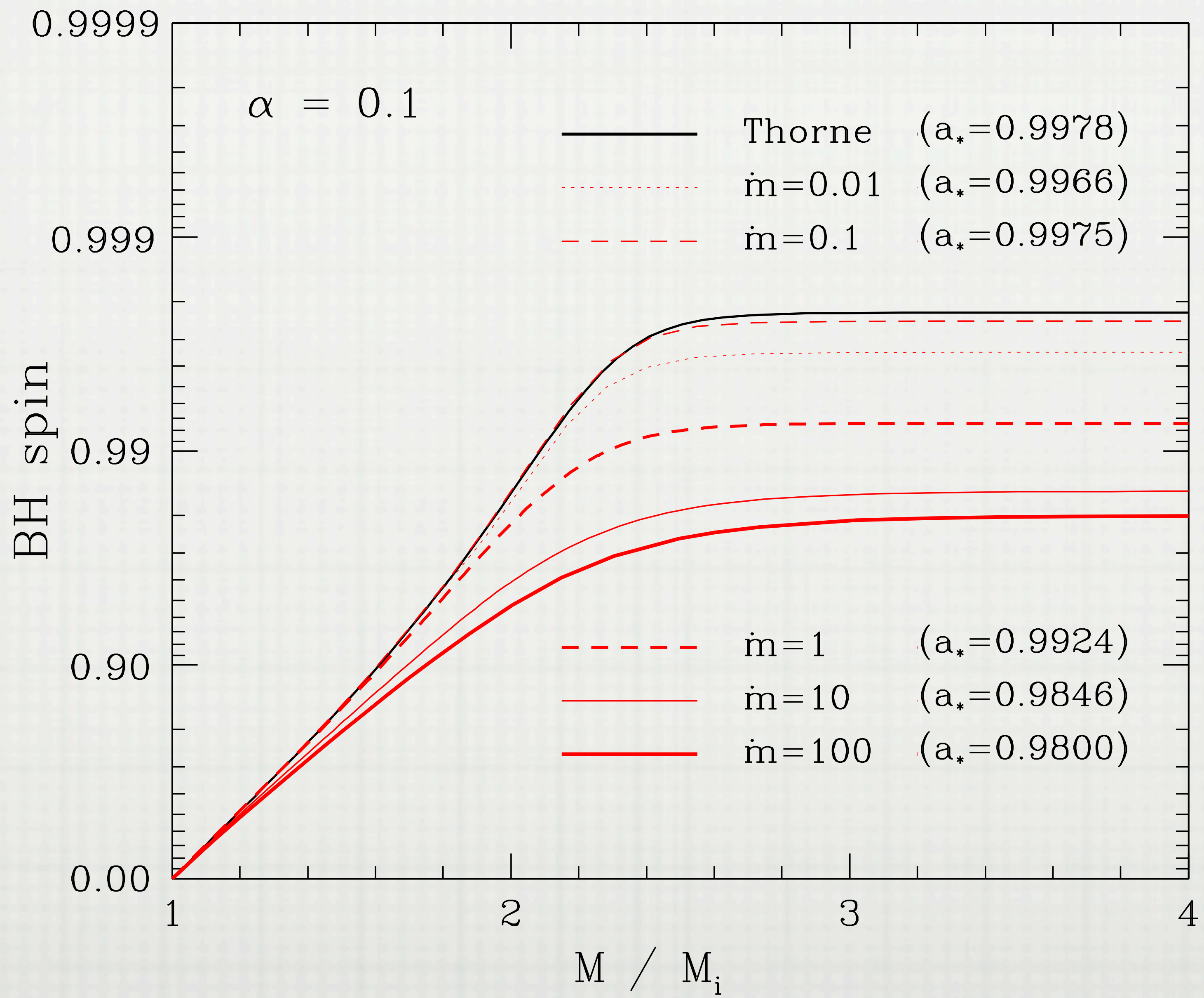
$$\text{for } \frac{M(t+\Delta t)}{M(t)} \leq r_{\rm ISCO}^{1/2},$$

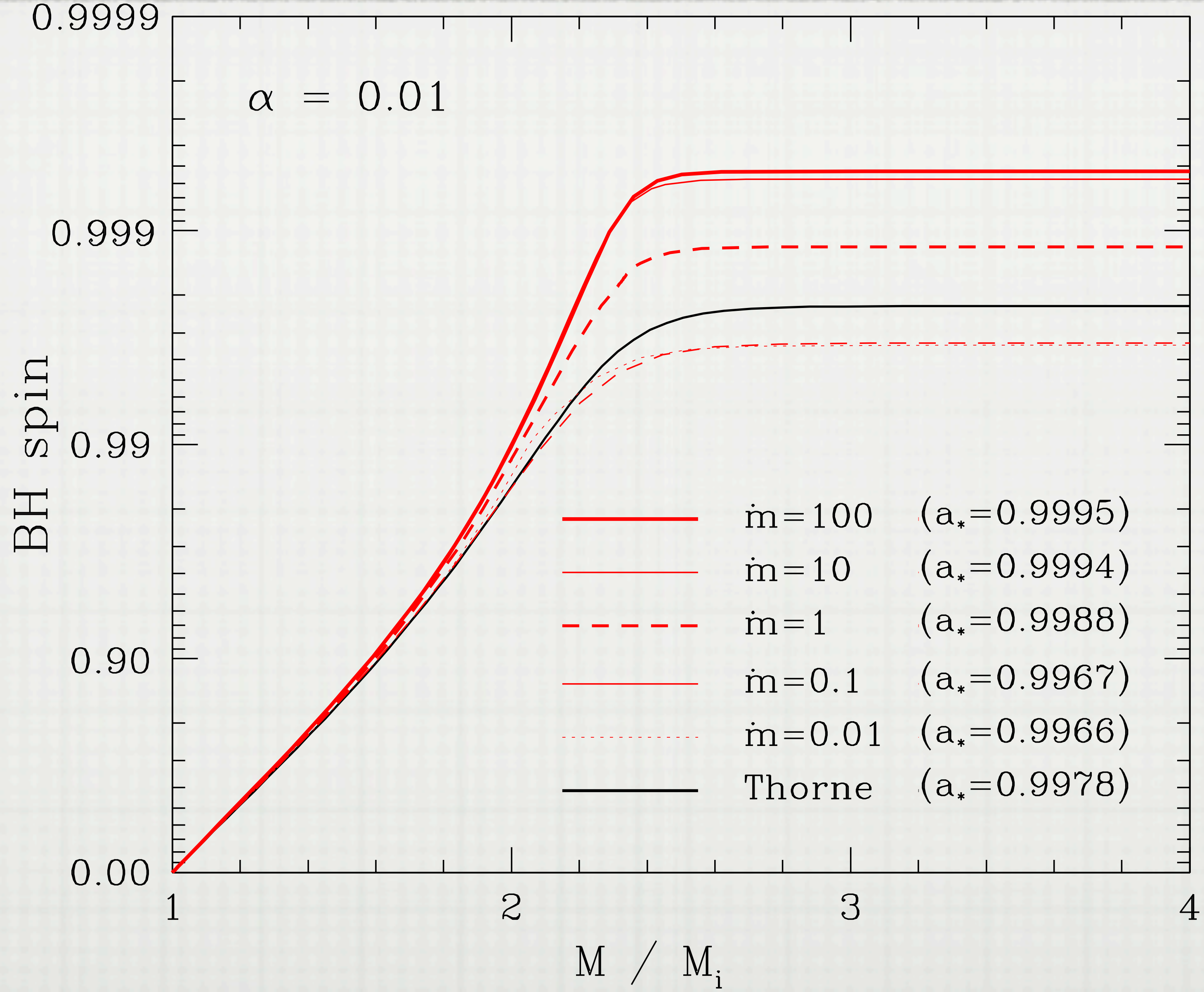
$$a = 0.998 \quad \text{for } \frac{M(t+\Delta t)}{M(t)} \geq r_{\rm ISCO}^{1/2}$$

but for high accretion rates the inner disc is not at ISCO

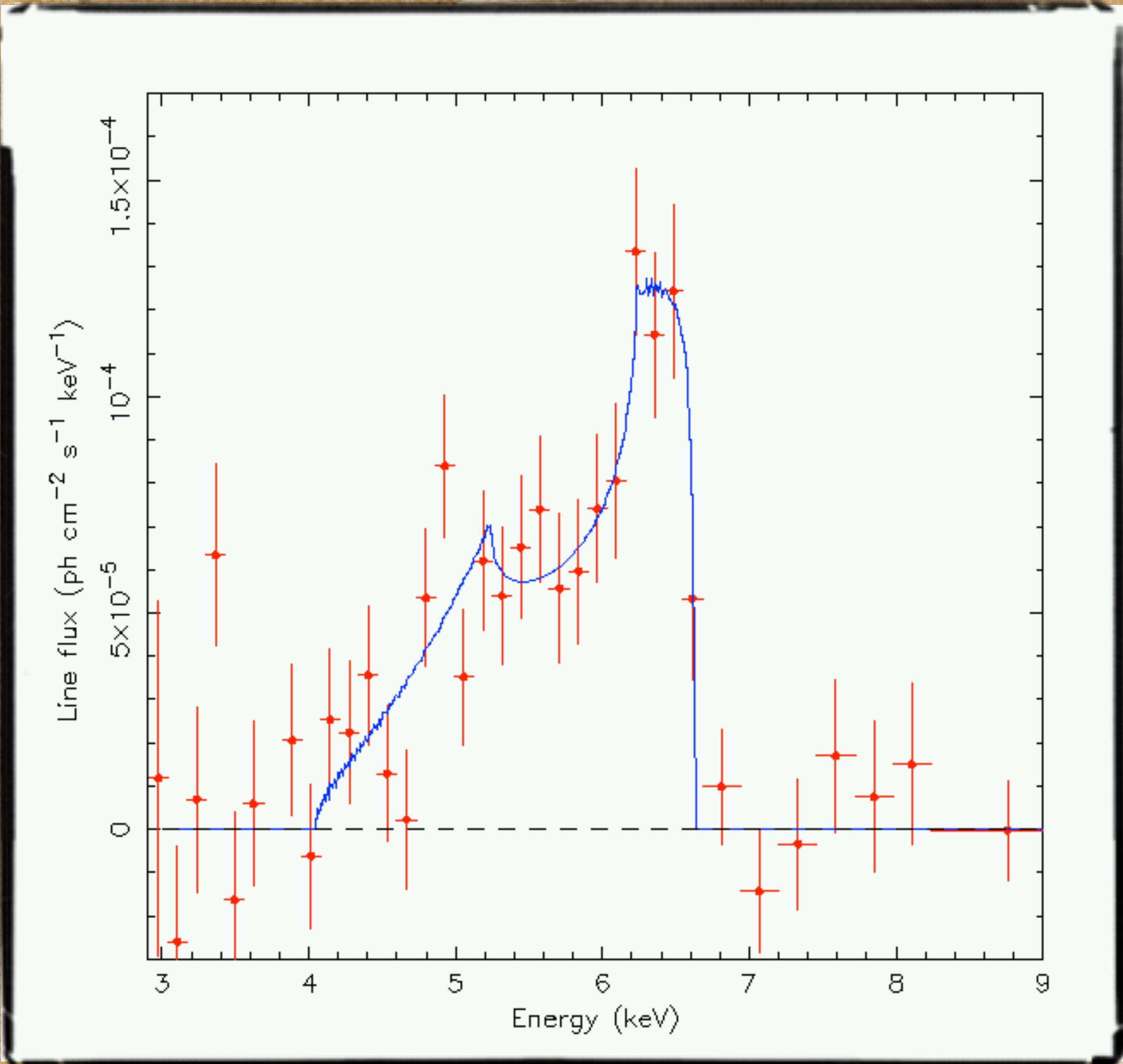


FOR ACCRETION FROM A THIN DISC THE MAXIMUM VALUE OF BH SPIN IS $a_*=0.9978$ (Thorne)





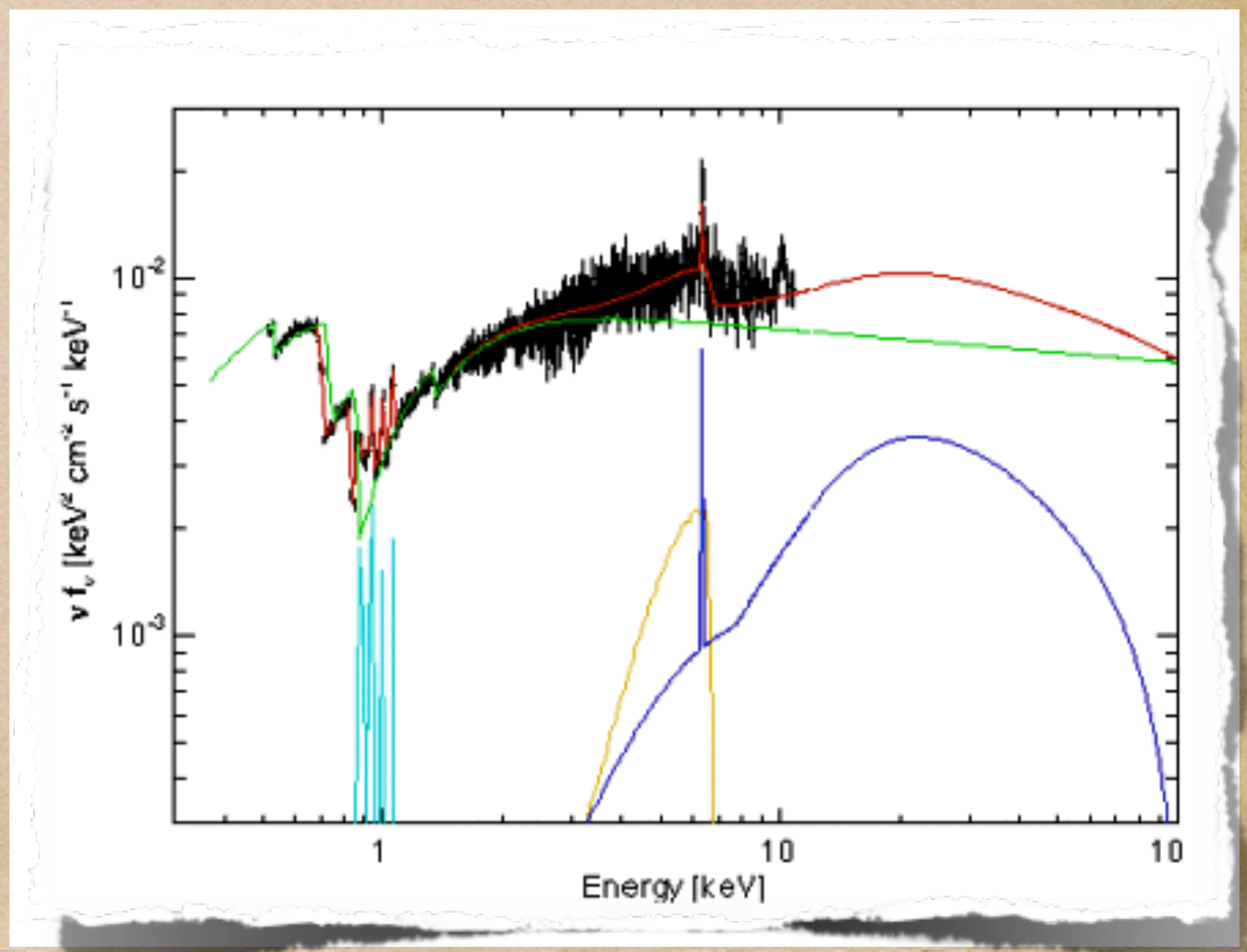
Sądowski et al. 2011



ASCA

MCG-6-30-15

XMM-Newton



XTE J1550–564 (micro-quasar)

Continuum fitting

Fe line fitting

Steiner et al. 2011

XTE J1550−564 (micro-quasar)

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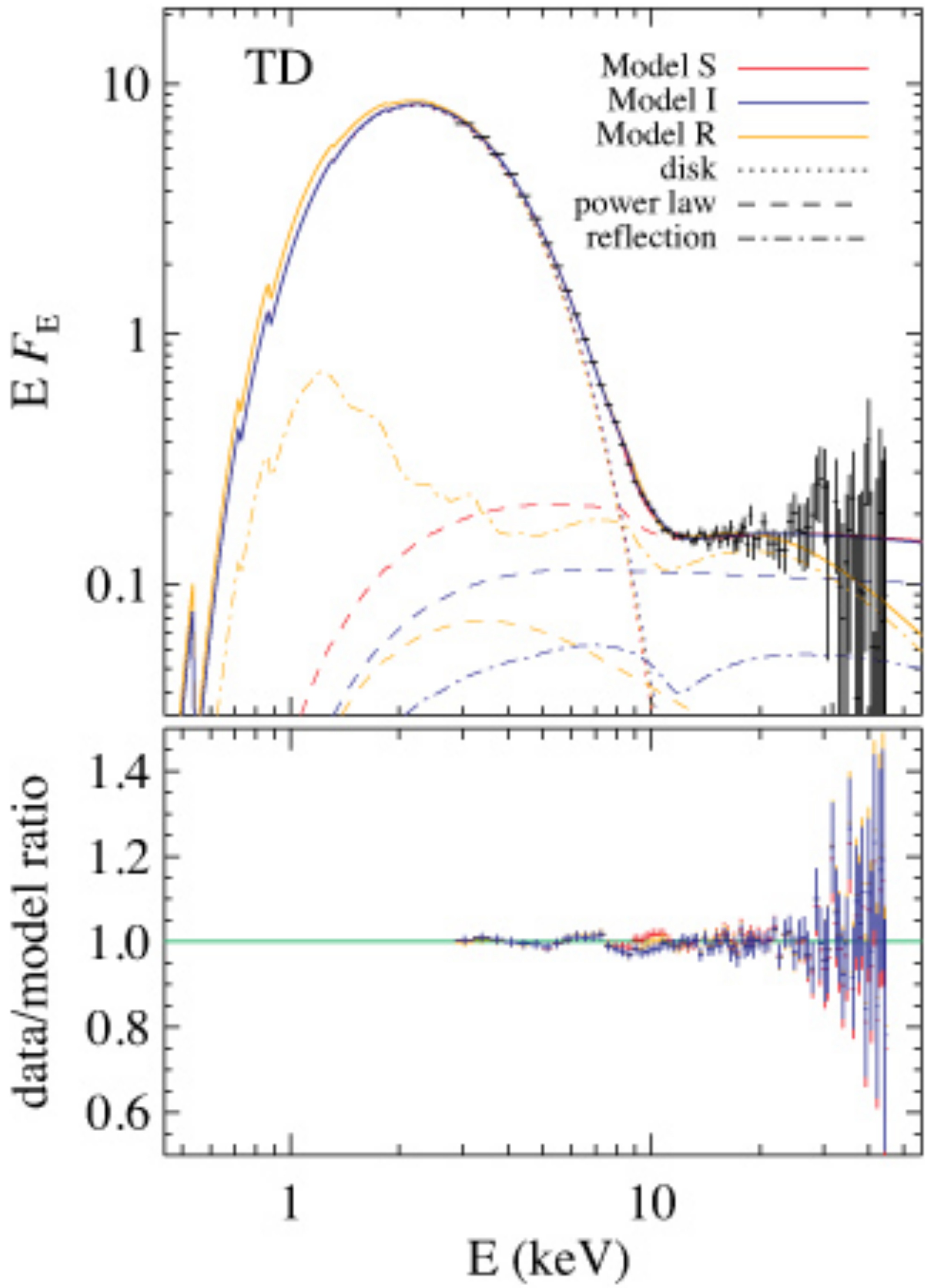

Steiner et al. 2011

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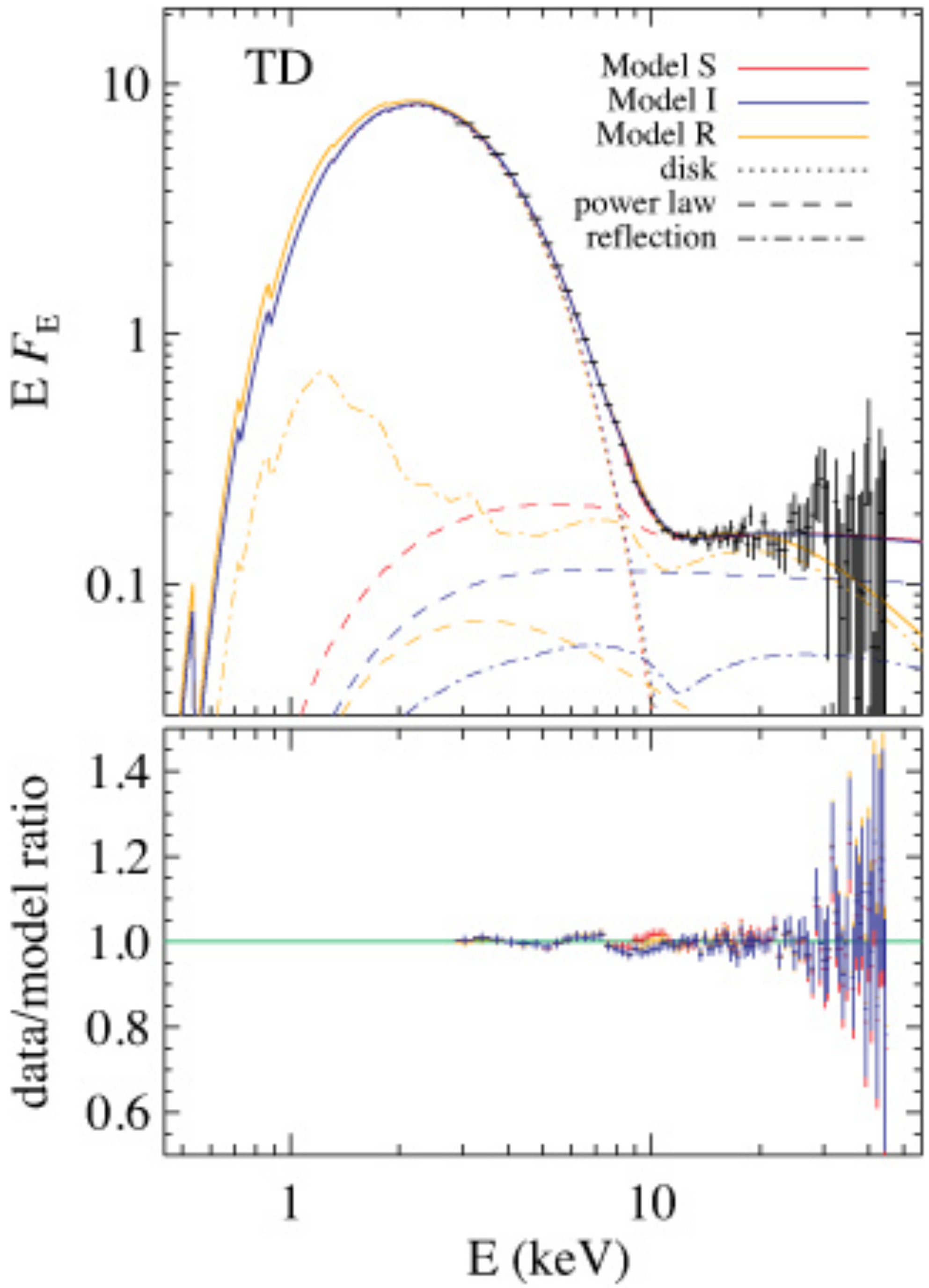

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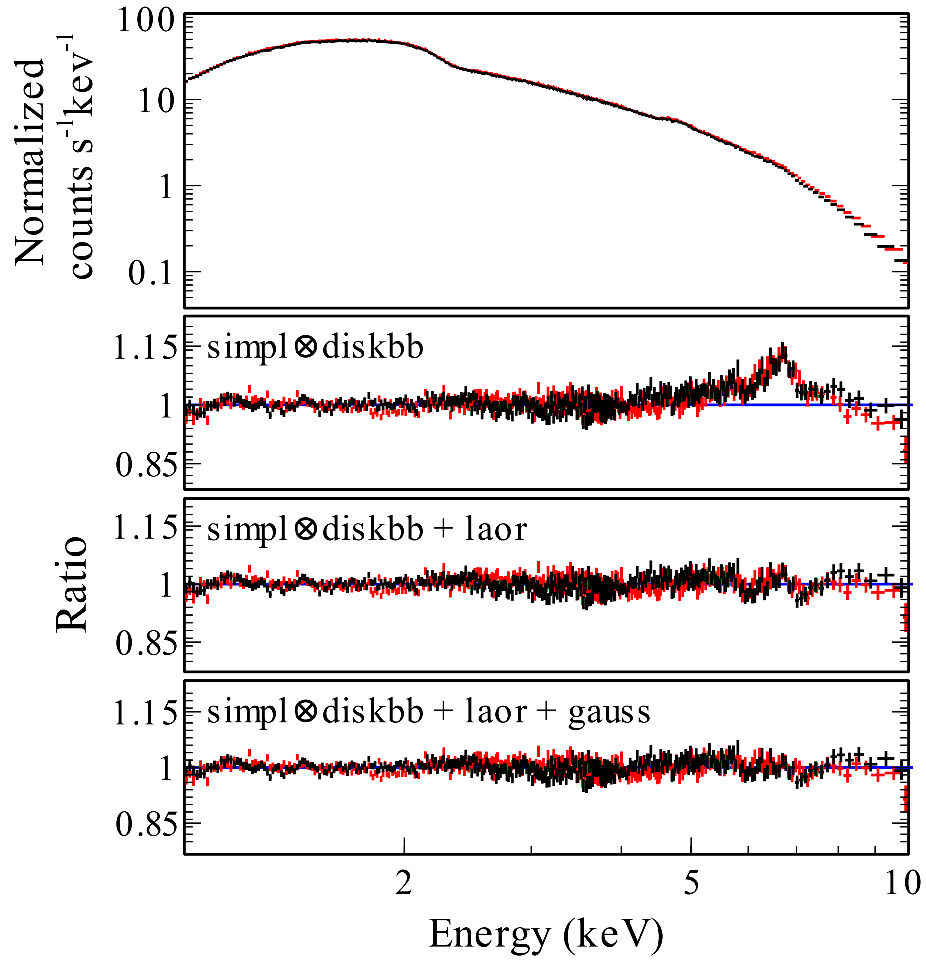

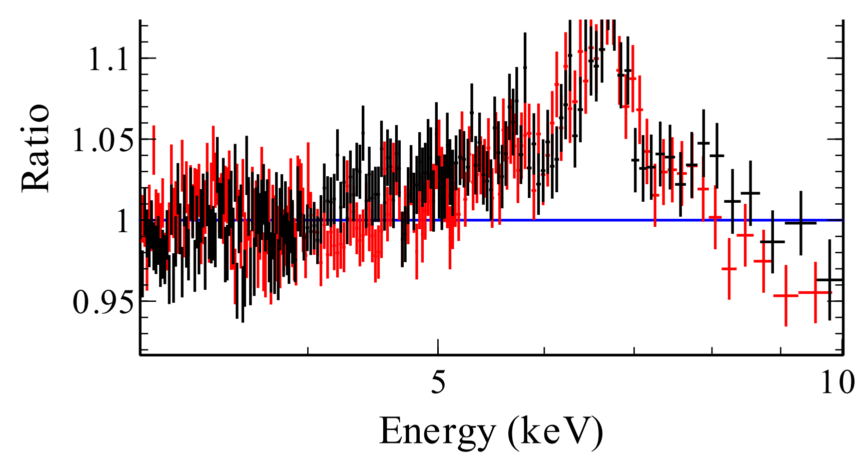

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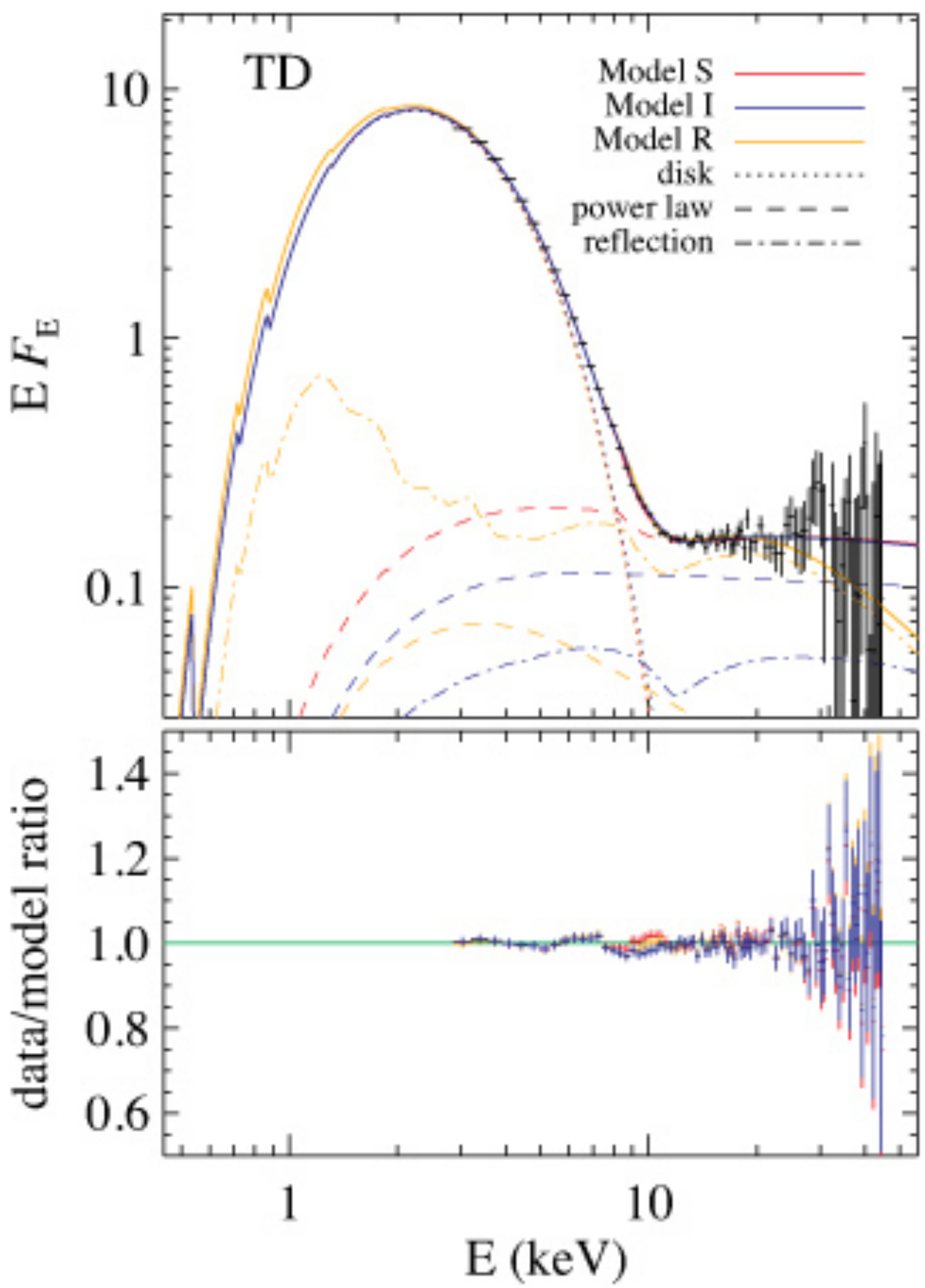
$a_* = 0.34$



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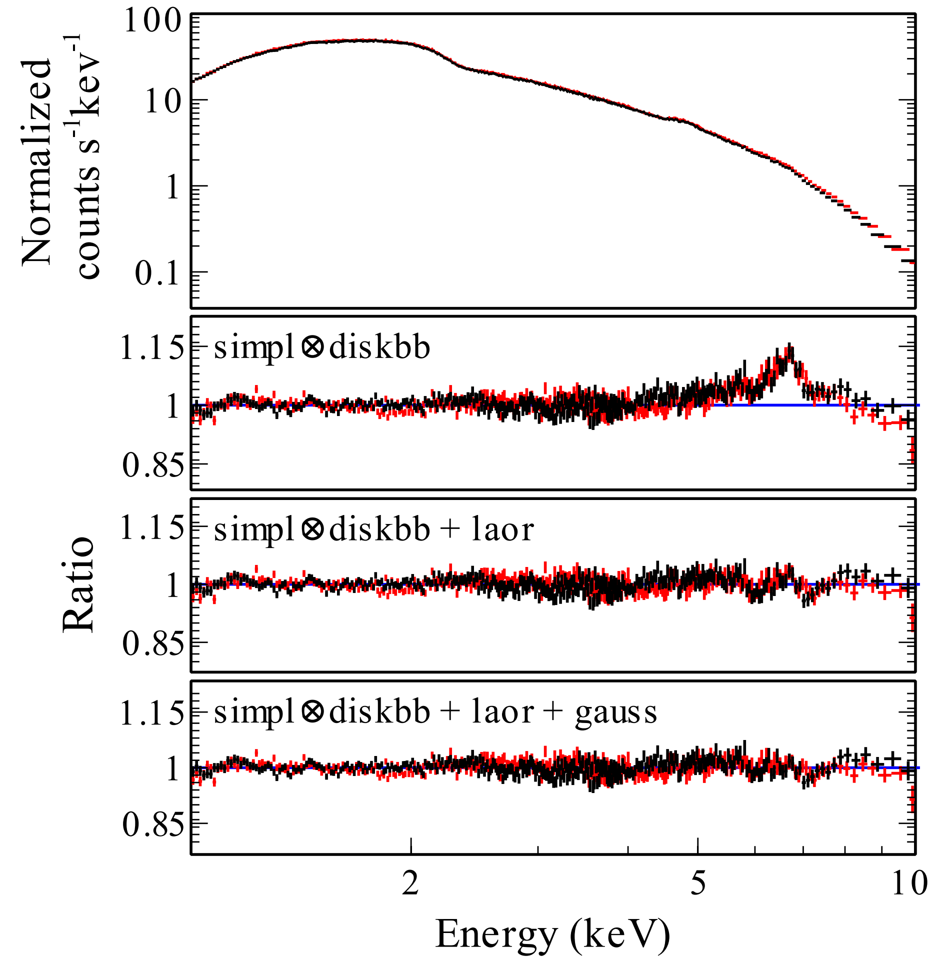

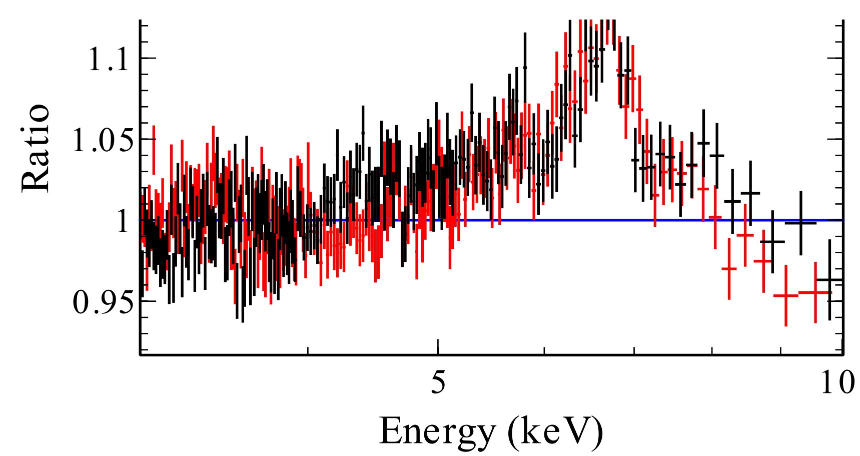

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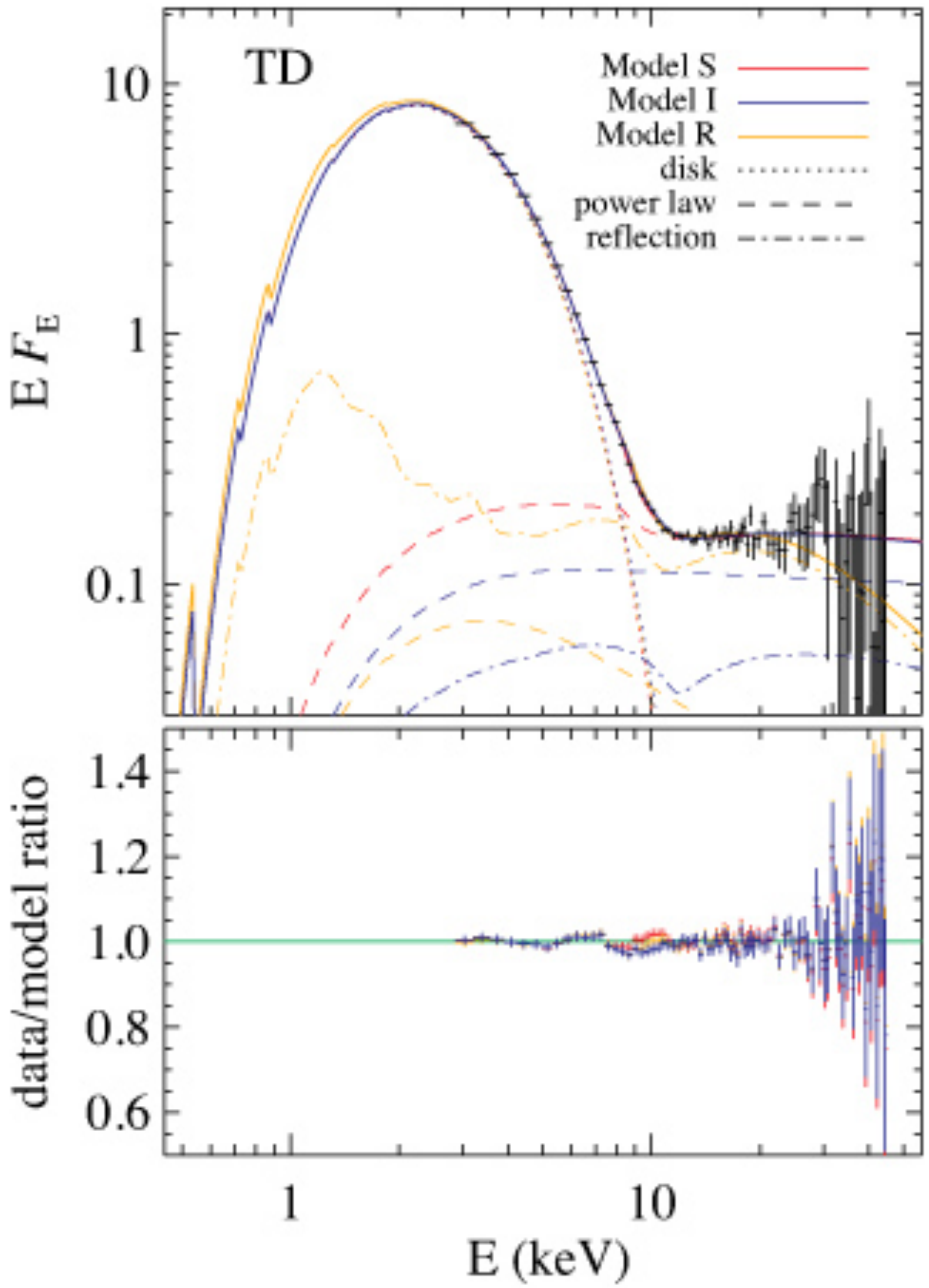
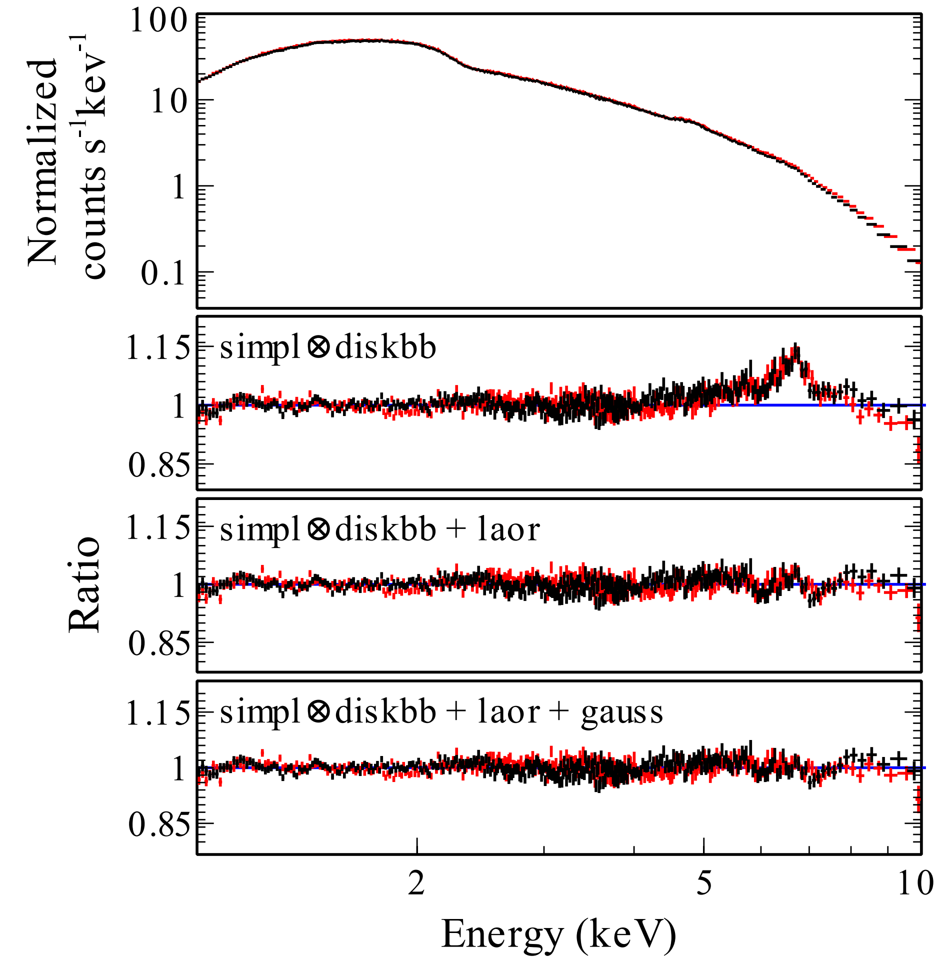
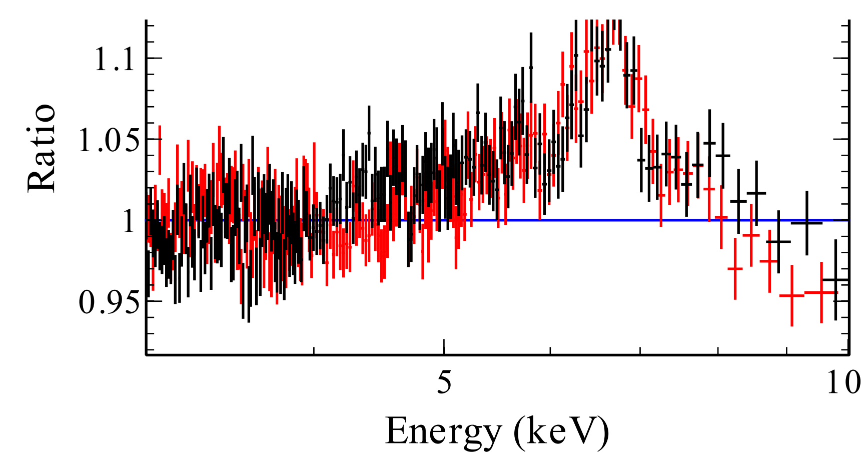


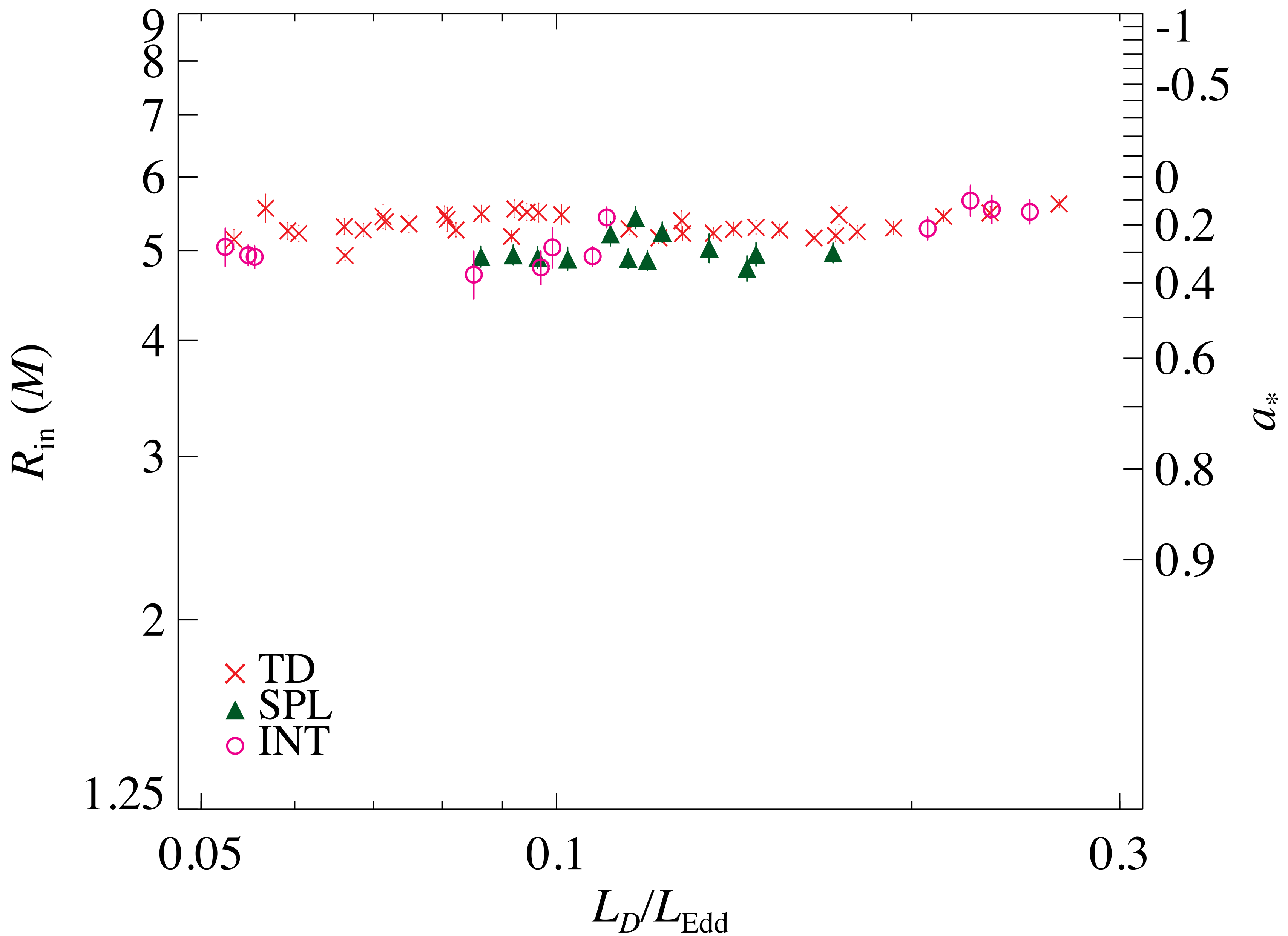
Fe line fitting

$a_* = 0.55^{+0.15}_{-0.22}$





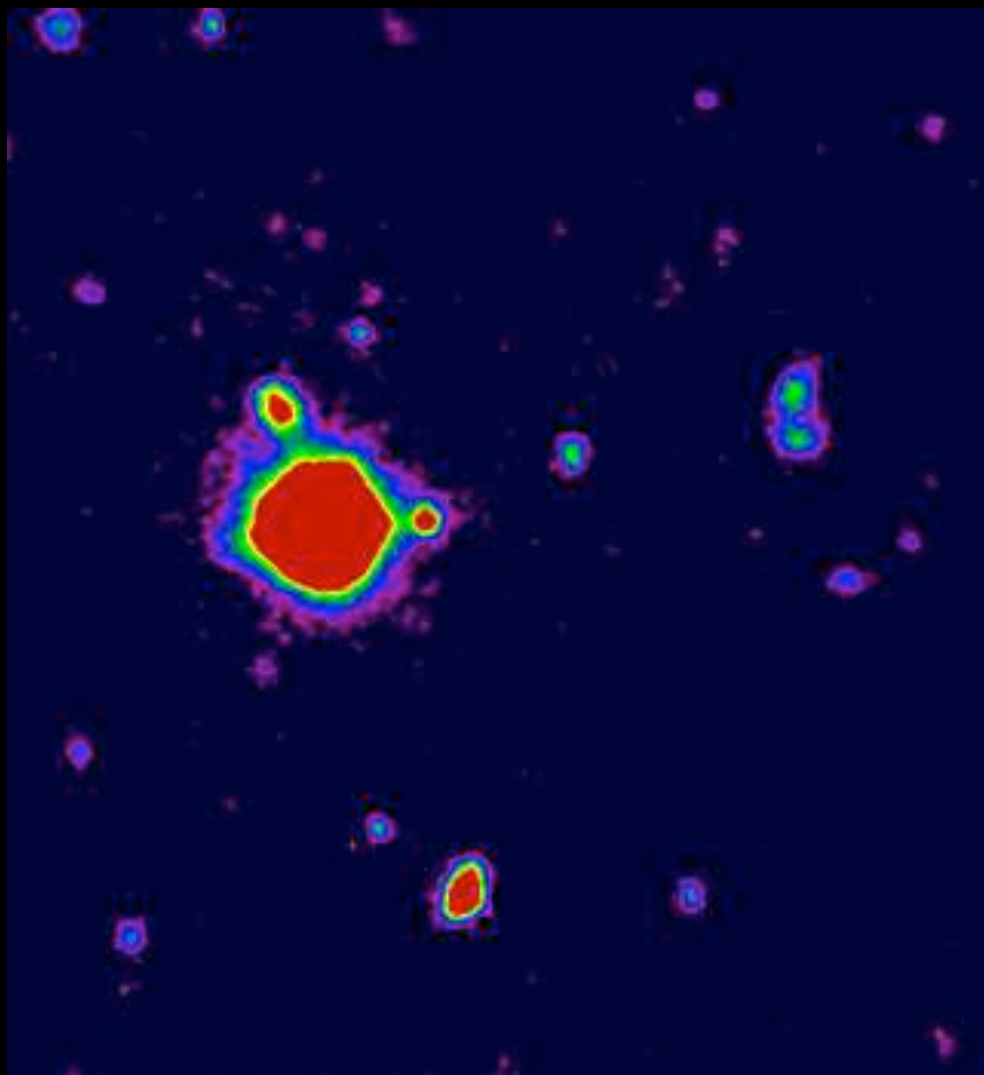
Steiner et al. 2011

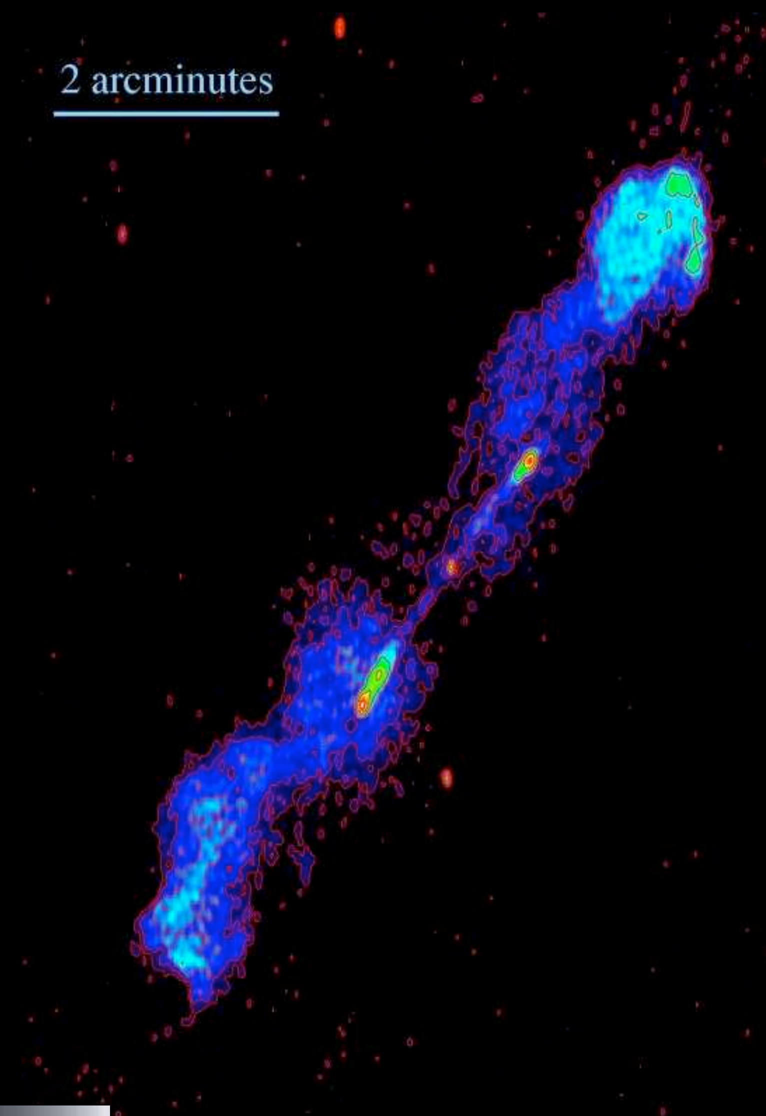


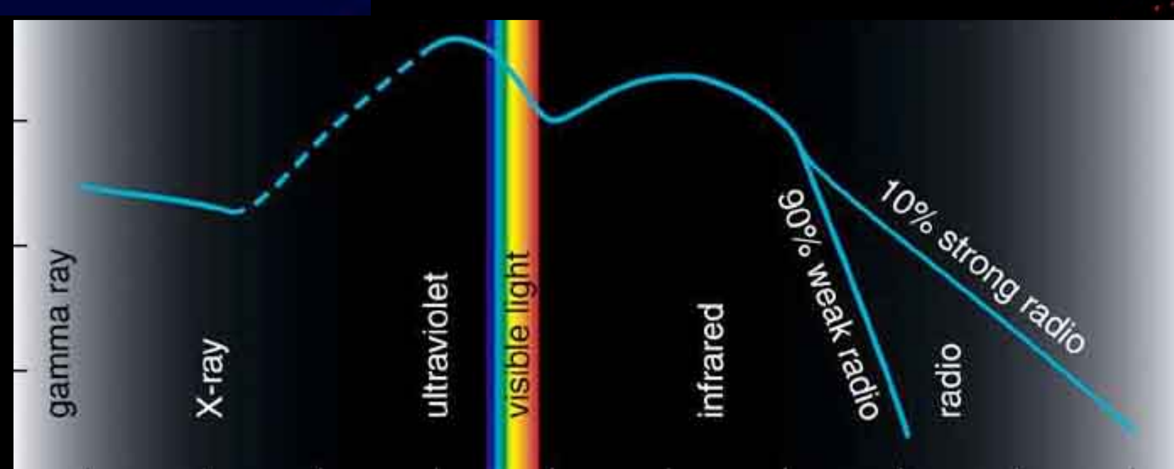
CF simple but requires mass and distance; LF weak signal, problem with (where is ?) the continuum.

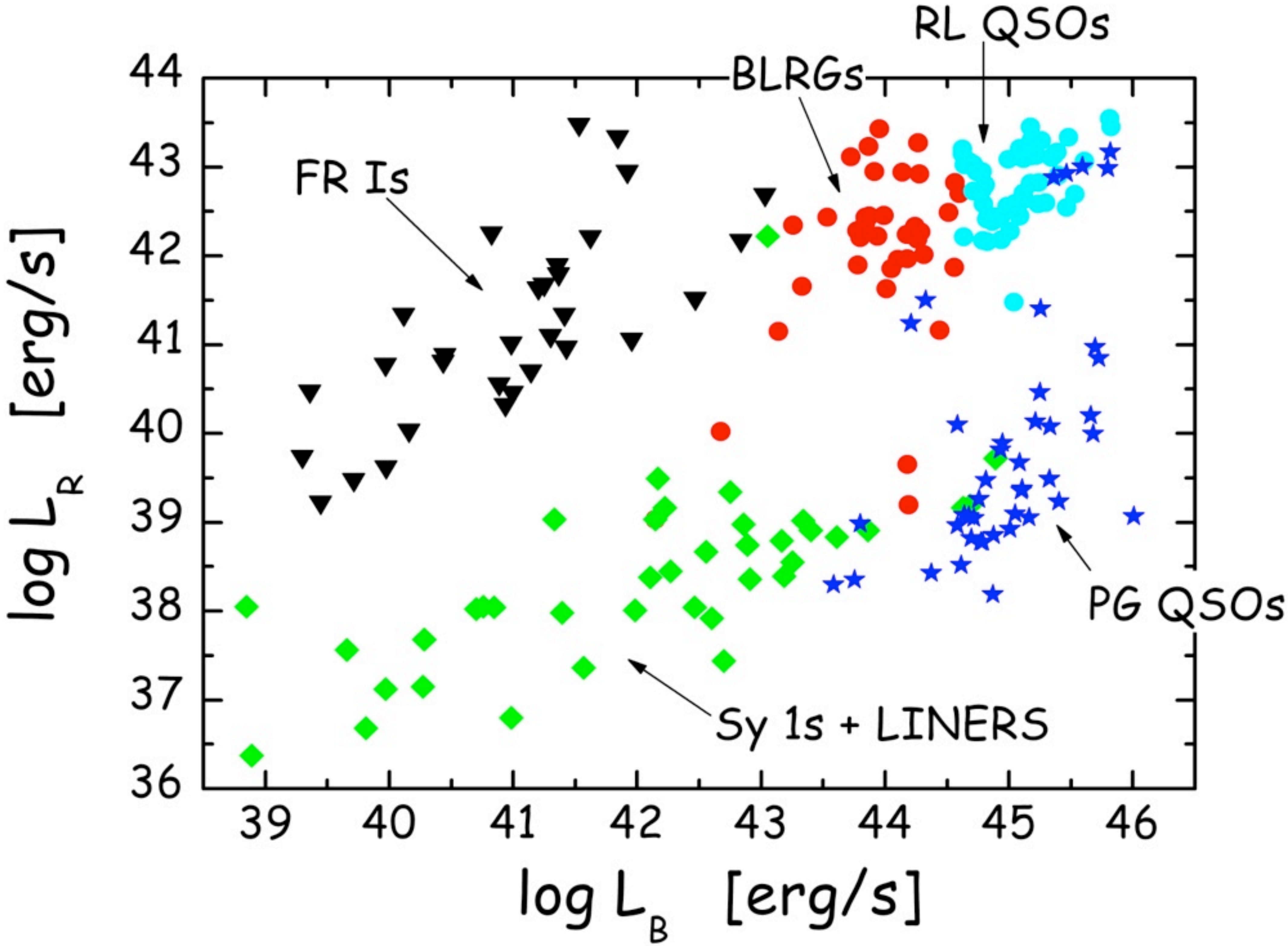
Steiner et al. 2011

Radio-quiet vs radio-loud AGN

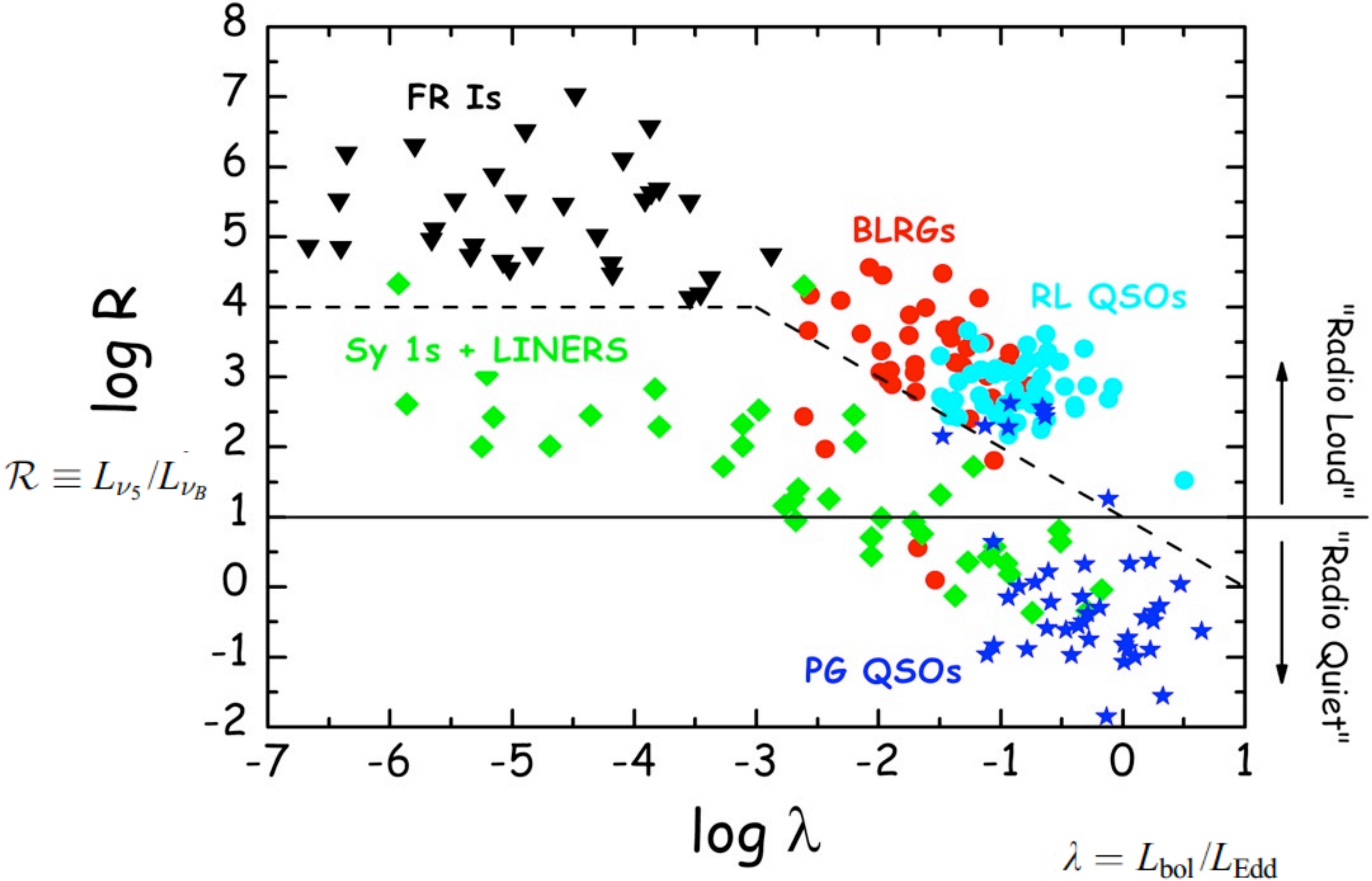




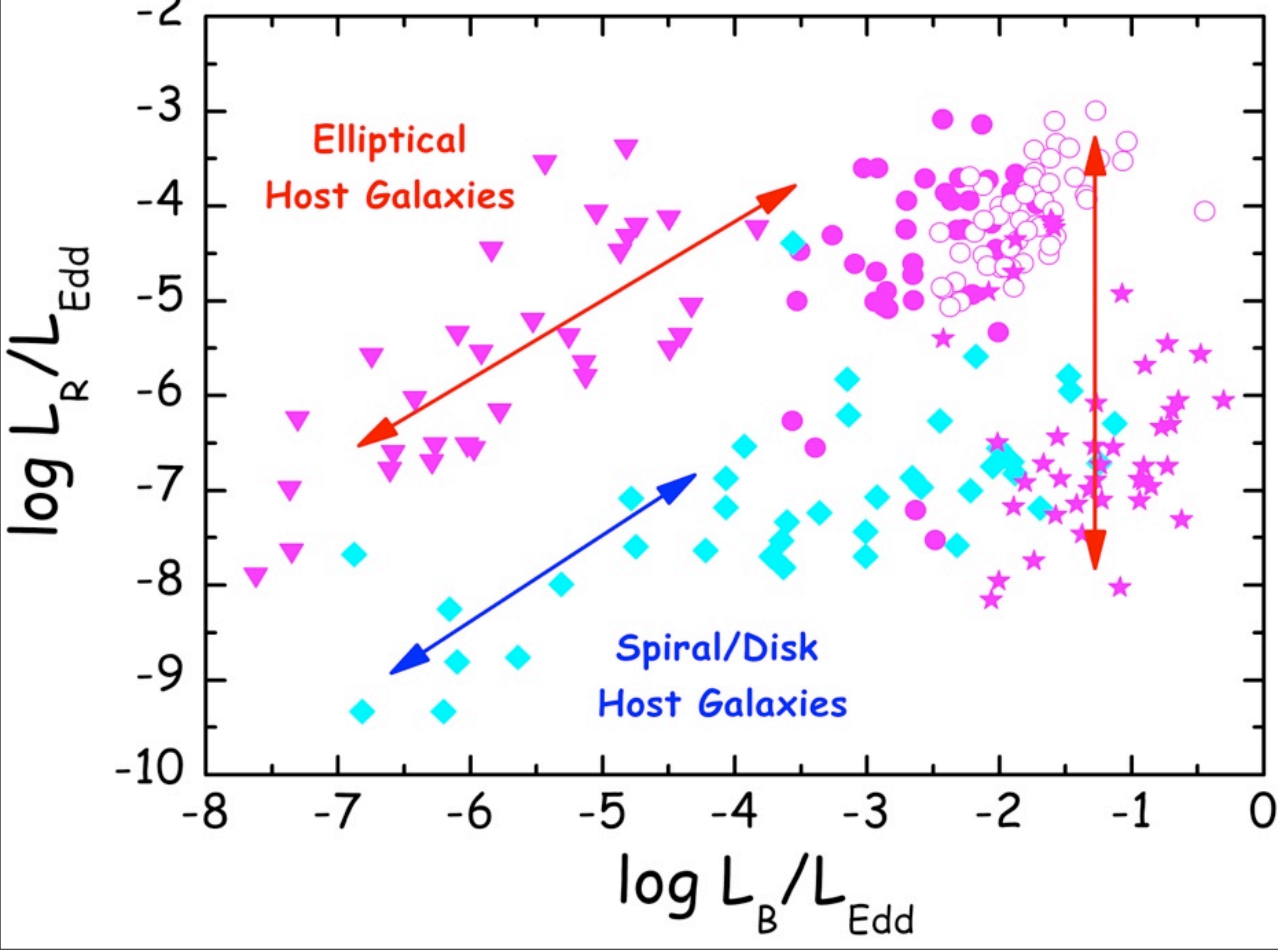




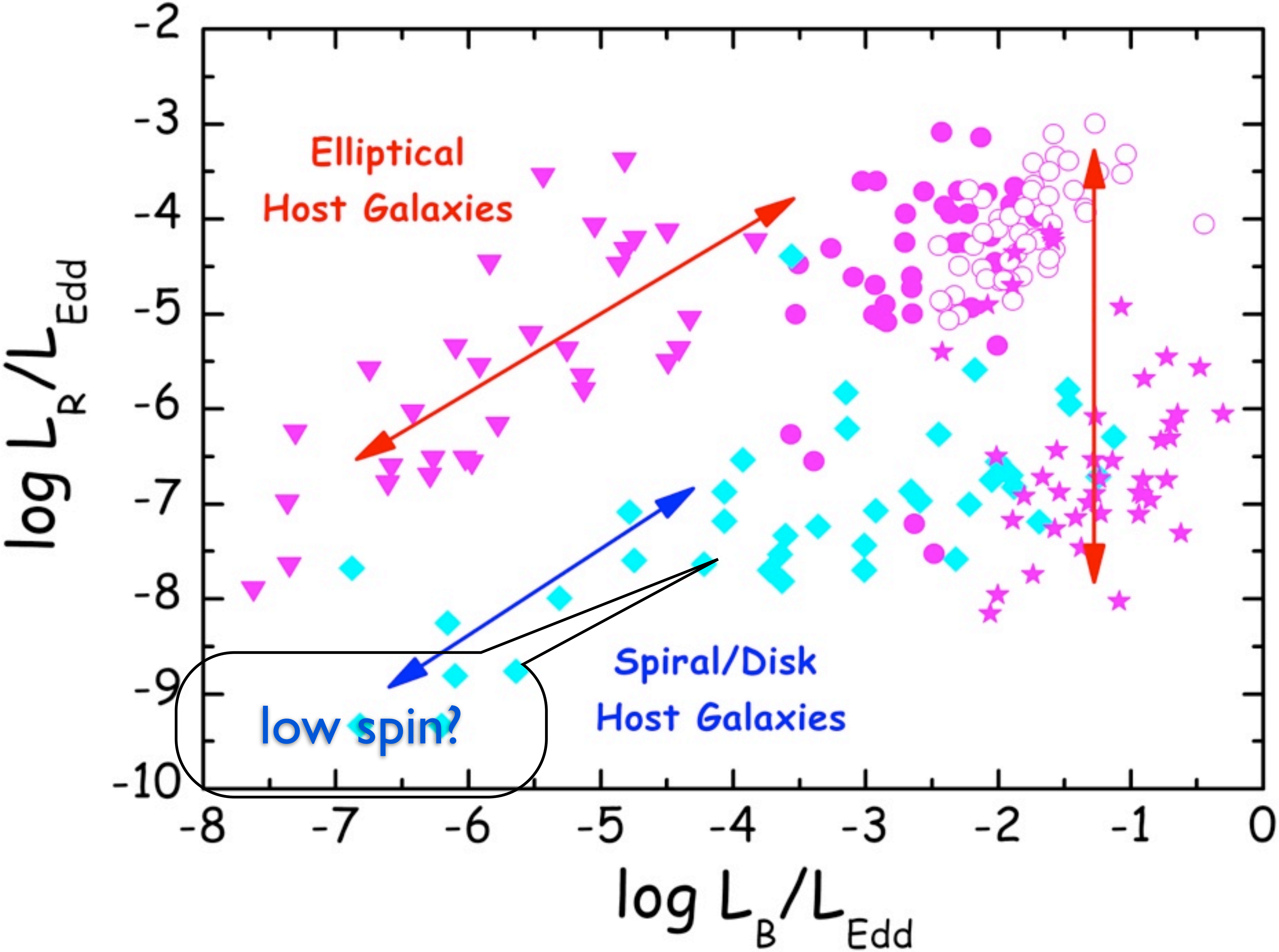
Sikora, Stawarz, Lasota 2007



Sikora, Stawarz, Lasota 2007



Elliptical
Host Galaxies
Spiral/Disk
Host Galaxies
log L_R/L_{Edd}
log L_B/L_{Edd}
-2
-3
-4
-5
-6
-7
-8
-9
-10
-8
-7
-6
-5
-4
-3
-2
-1
0



Elliptical
Host Galaxies
Spiral/Disk
Host Galaxies
low spin?
log L_R/L_{Edd}
log L_B/L_{Edd}
-2
-3
-4
-5
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-8
-7
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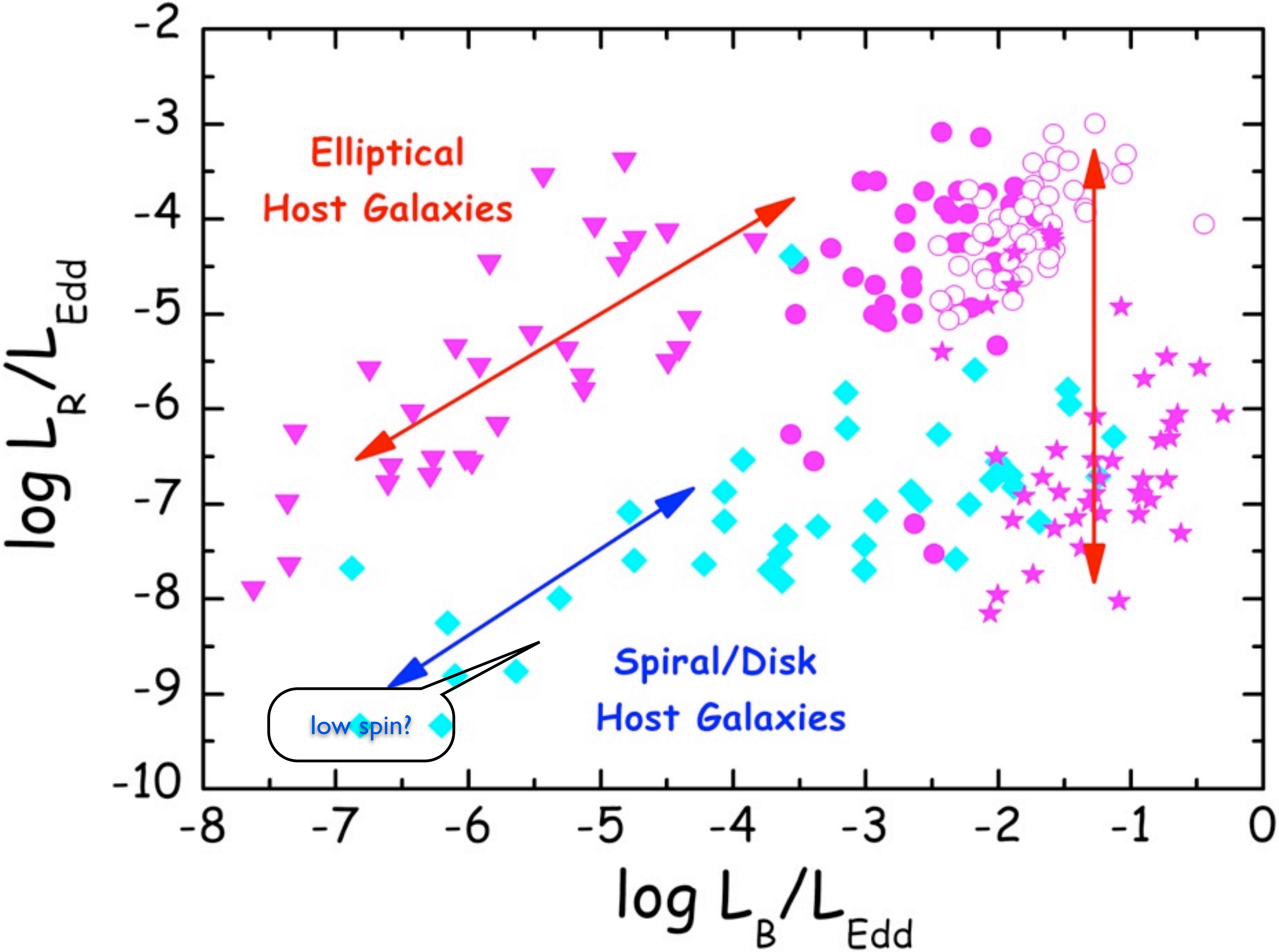
-5
-4
-3
-2
-1
0



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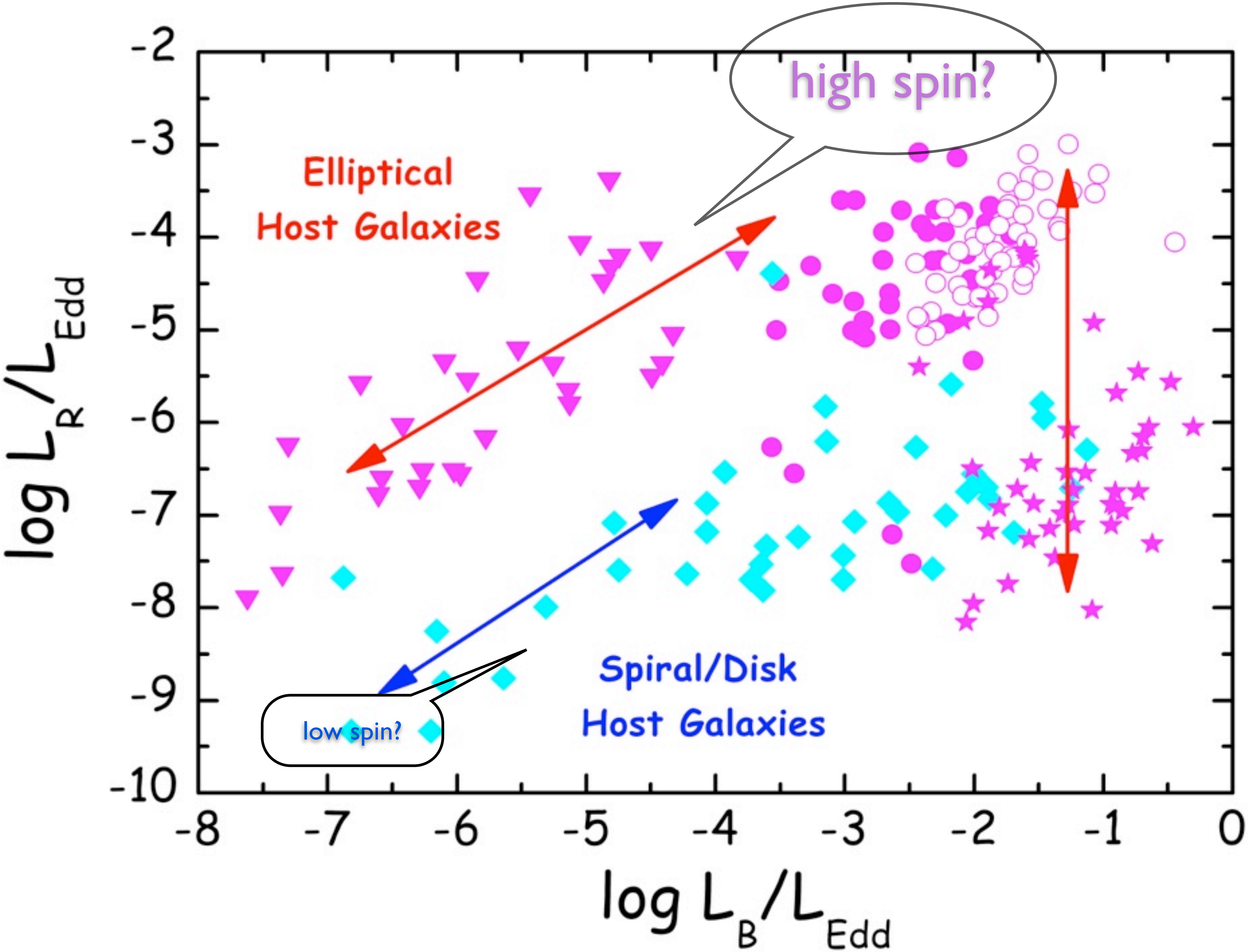
high spin?
Elliptical
Host Galaxies
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Host Galaxies
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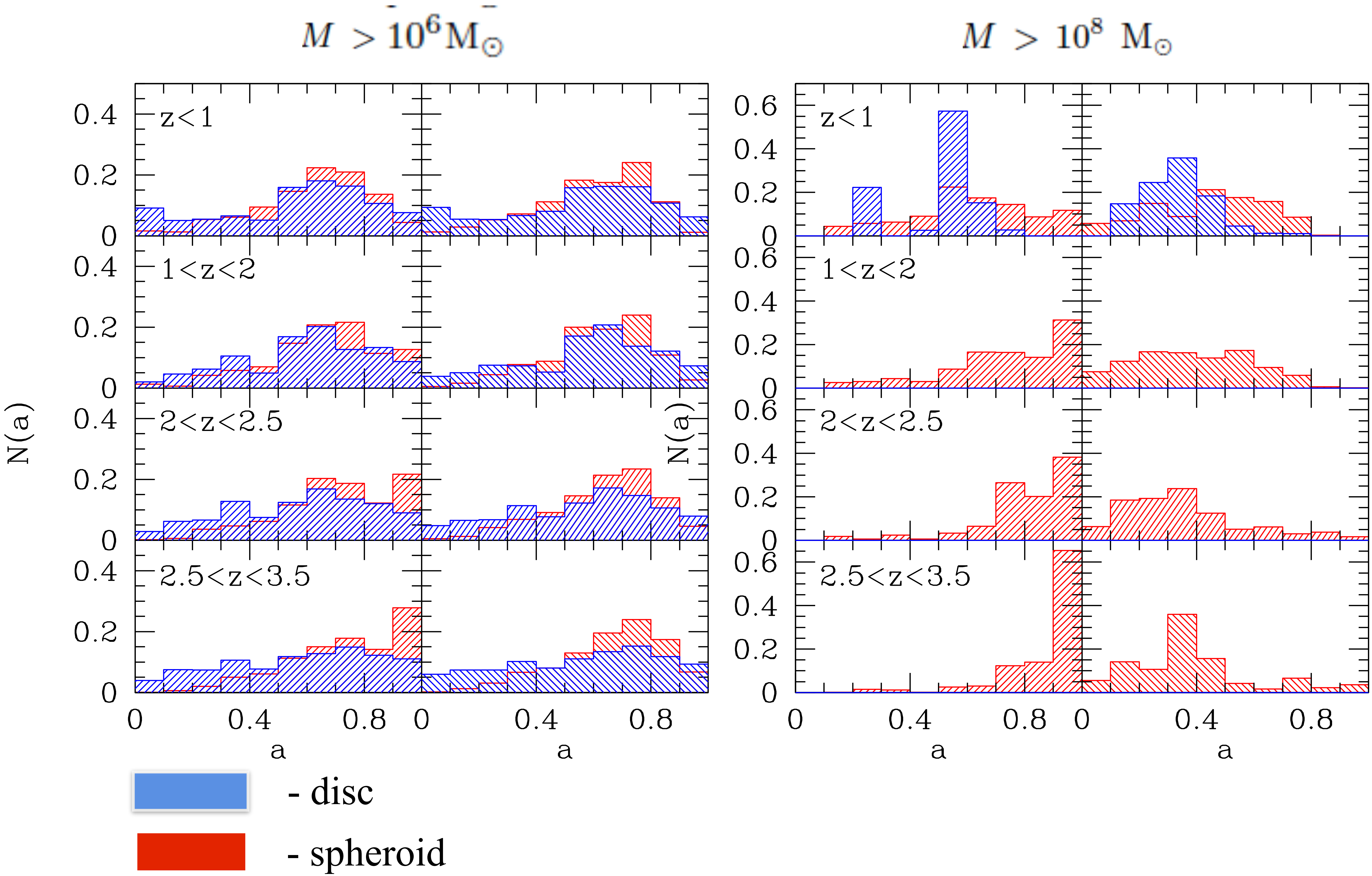
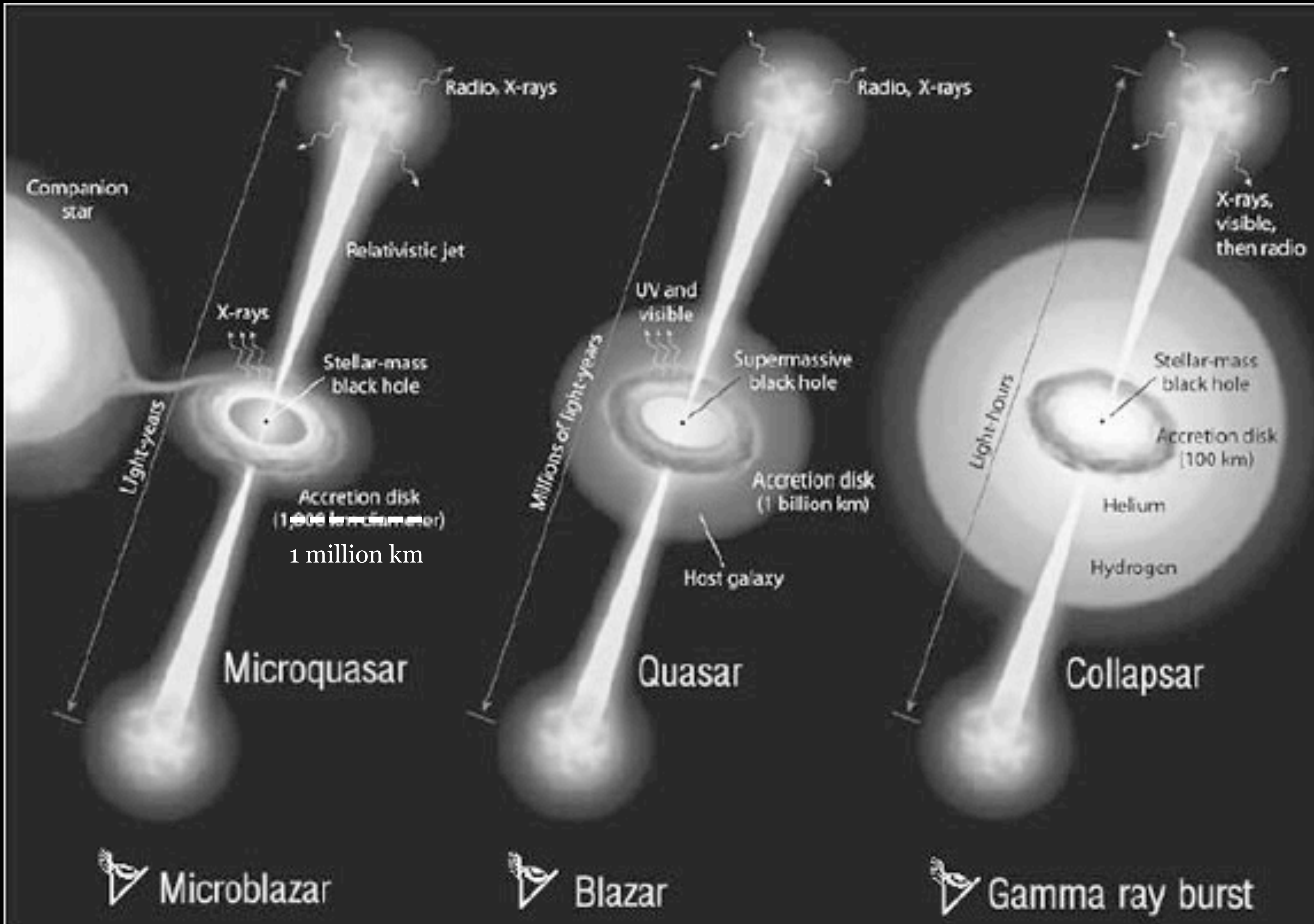


Volonteri, Sikora, Lasota, Merloni 2012

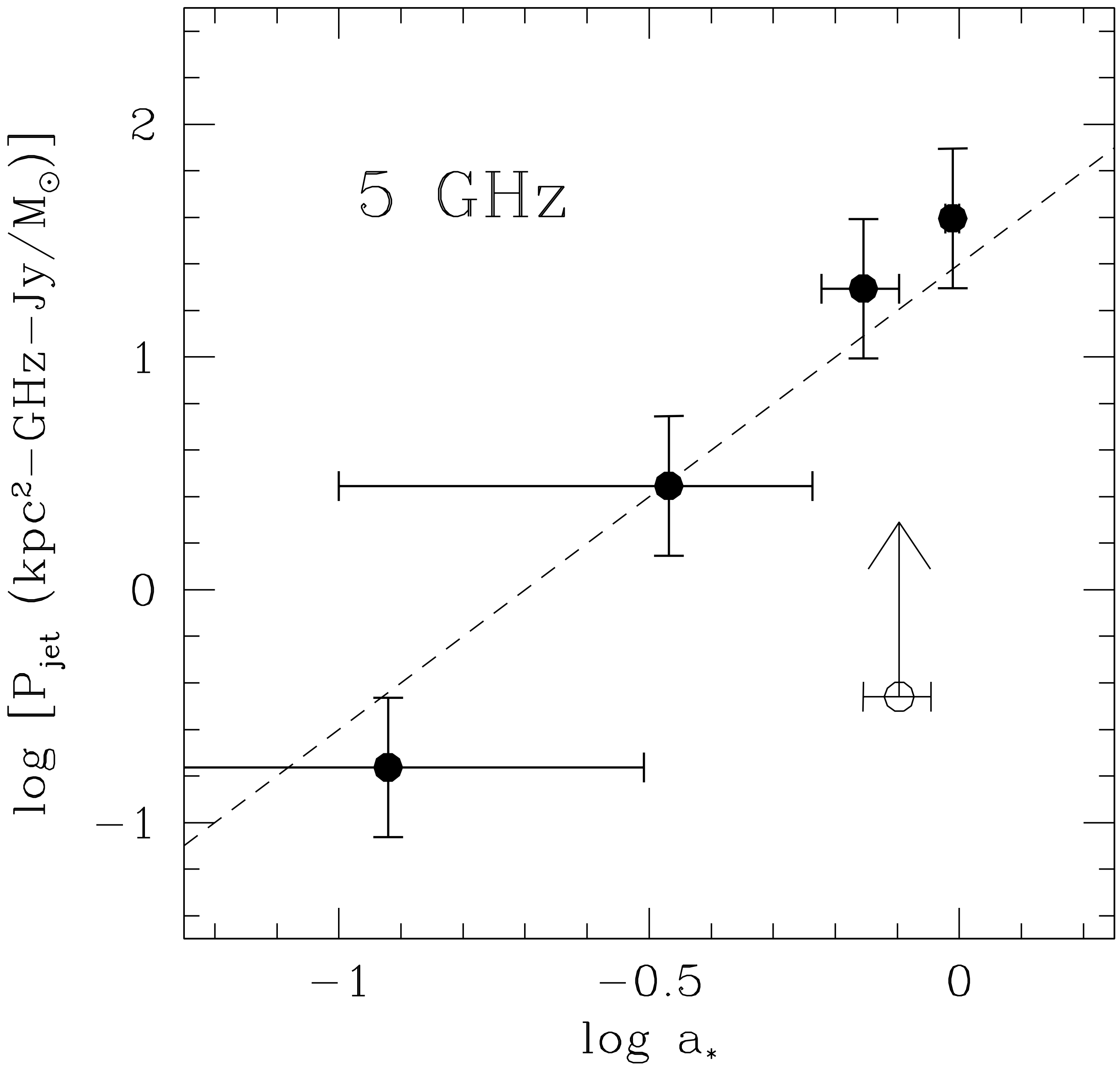
Magnetic field more «important» than spin ?

The magnetic flux threading the black hole, rather than black hole spin or Eddington ratio, is the dominant factor in launching powerful jets and thus determining the radio loudness of active galactic nuclei (AGN). Most AGN are radio quiet because the thin accretion disks that feed them are inefficient in depositing magnetic flux close to the black hole. Flux accumulation is more likely to occur during a hot accretion (or thick disk) phase, and we argue that radio-loud quasars and strong emission-line radio galaxies occur only when a massive, cold accretion event follows an episode of hot accretion. Such an event might be triggered by the merger of a giant elliptical galaxy with a disk galaxy.

Sikora & Begelman 2013


Radio, X-rays
Companion star
Relativistic jet
X-rays
Stellar-mass black hole
Light-years
Accretion disk
1 million km
Microquasar
Microblazar
Radio, X-rays
UV and visible
Supermassive black hole
Millions of light-years
Accretion disk (1 billion km)
Host galaxy
Quasar
Blazar
X-rays, visible, then radio
Stellar-mass black hole
Light-hours
Accretion disk (100 km)
Helium
Hydrogen
Collapsar
Gamma ray burst

Microquasar jet power as a function of BH spin



Narayan & McClintock 2012

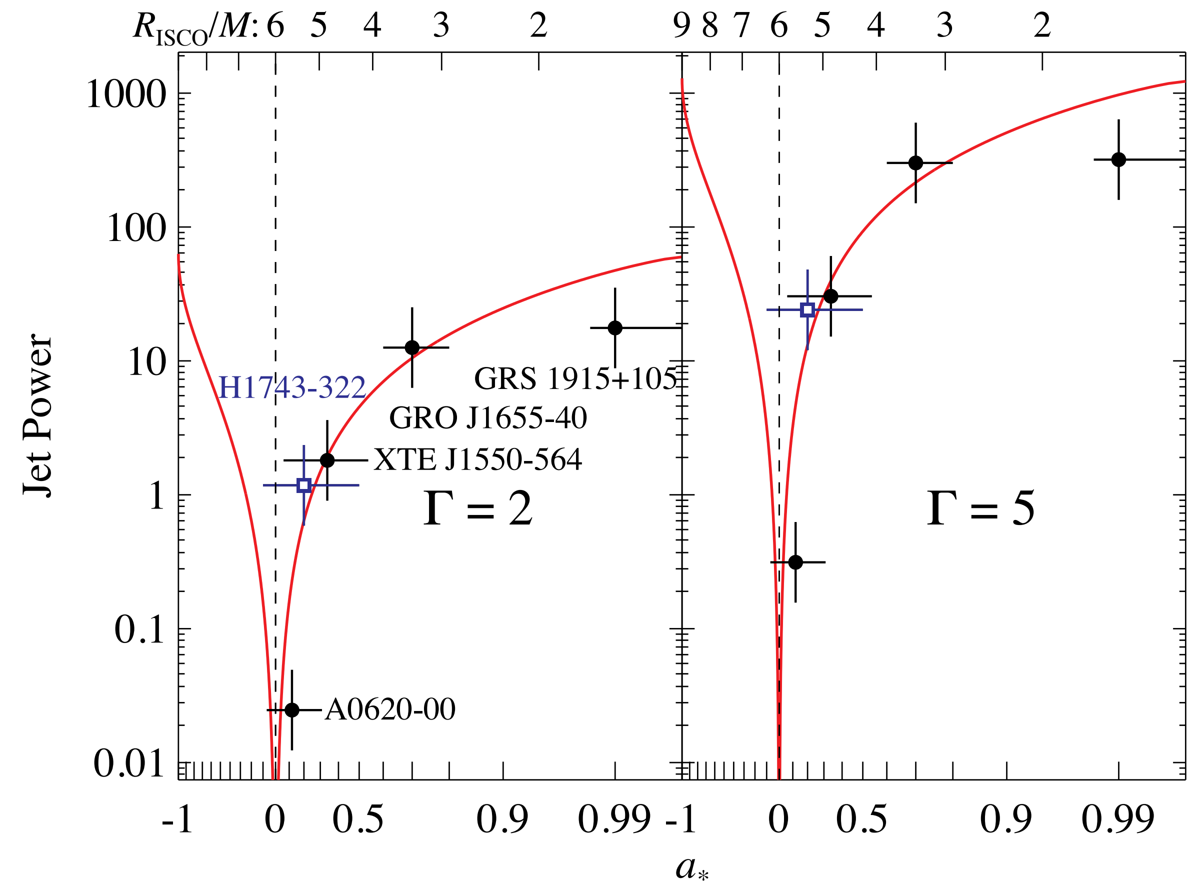
The NM12 model

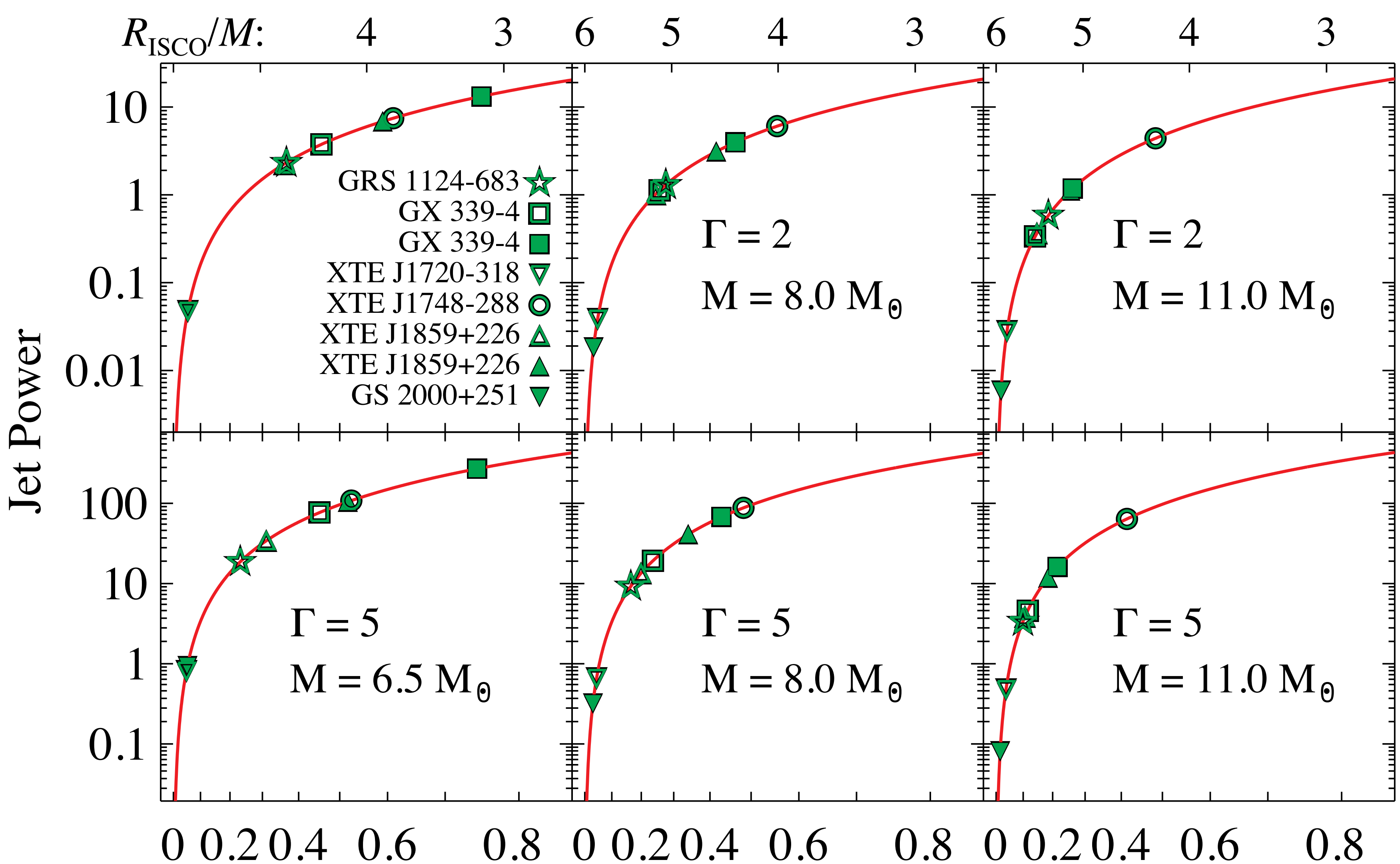
$$P_{\rm jet} = \left(\frac{\nu}{5\ {\rm GHz}}\right)\left(\frac{S^{\rm tot}_{\nu,0}}{\rm Jy}\right)\left(\frac{D}{\rm kpc}\right)^2\left(\frac{M}{\rm M_\odot}\right)^{-1}$$

with the fit:

$$S^{\rm tot}_{\nu,0} = \left(\frac{a_*}{1+\sqrt{1-a_*^2}}\right)^2\left(\frac{M}{\rm M_\odot}\right)\left(\frac{D}{\rm kpc}\right)^{-2}\left(\frac{\nu}{5\ {\rm GHz}}\right)^{-1}\ {\rm Jy}$$

$$\times\begin{cases}{\rm Exp}(4.2\pm0.5), & \Gamma=2\\ {\rm Exp}(7.2\pm0.5), & \Gamma=5.\end{cases}$$





Dichotomy between persistent & transient systems

System	Spin a_*	$M/M_\odot$	Reference
Persistent	$a^* > 0.8$	$M = 11\text{-}16\ M_\odot$	*Large mass & high spin*
Cygnus X-1	> 0.95	15.8 ± 1.0	Gou+ 2011; Orosz+ 2011
LMC X-1	0.92 ± 0.06	10.9 ± 1.4	Gou+ 2009; Orosz+ 2009
M33 X-7	0.84 ± 0.05	15.7 ± 1.5	Liu+ 2008; Orosz+ 2007
Transient	$a^* < 0.8$	$M = 7.8 \pm 1.2\ M_\odot$	Ozel et al. 2010
GRS 1915+105	> 0.95	10.1 ± 0.6	McClintock+ 2006; Steeghs+ 2013
4U 1543-47	0.8 ± 0.1	9.4 ± 1.0	Shafee+ 2006; Orosz+ 2003
GRO J1655-40	0.7 ± 0.1	6.3 ± 0.5	Shafee+ 2006; Greene+ 2001
XTE J1550-564	0.34 ± 0.24	9.1 ± 0.6	Steiner+ 2011; Orosz+ 2011
LMC X-3	< 0.3	7.6 ± 1.6	Davis+ 2006; Cowley+ 1983
H1743-322	0.2 ± 0.3	≈ 8	Steiner+ 2012; Ozel+ 2010
A0620-00	0.12 ± 0.19	6.6 ± 0.3	Gou+ 2010; Cantrell+ 2010

McClintock 2013

Conclusions:

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