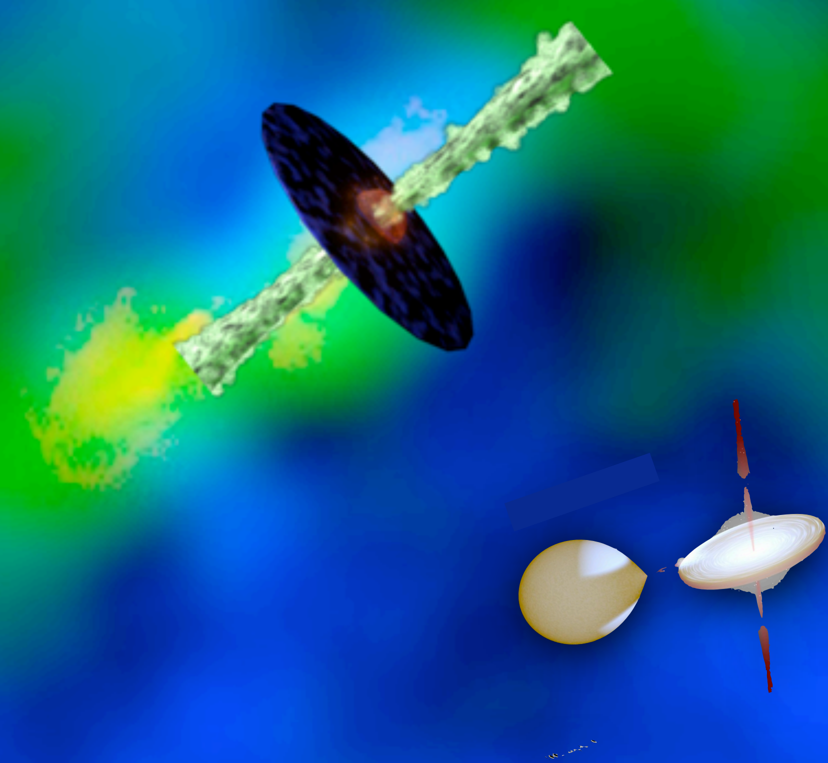
FROM QUASARS TO MICRO-QUASARS: INVESTIGATING MASS (AND POWER) SCALES IN ACCRETION PHYSICS



Sera Markoff (API, University of Amsterdam)

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(See also jobregister.aas.org)

*probably some postdocs too!

Outline

- Part I: General introduction to the concept of mass-scaling in accretion physics
- Part II: Summary of accretion states in XRBs and comparisons to AGN zoology
- Part III: Fundamental Plane of black hole accretion
- Part IV-- Advanced topics: what other things can we do?   What else do we see?

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Black holes are major engines in the universe

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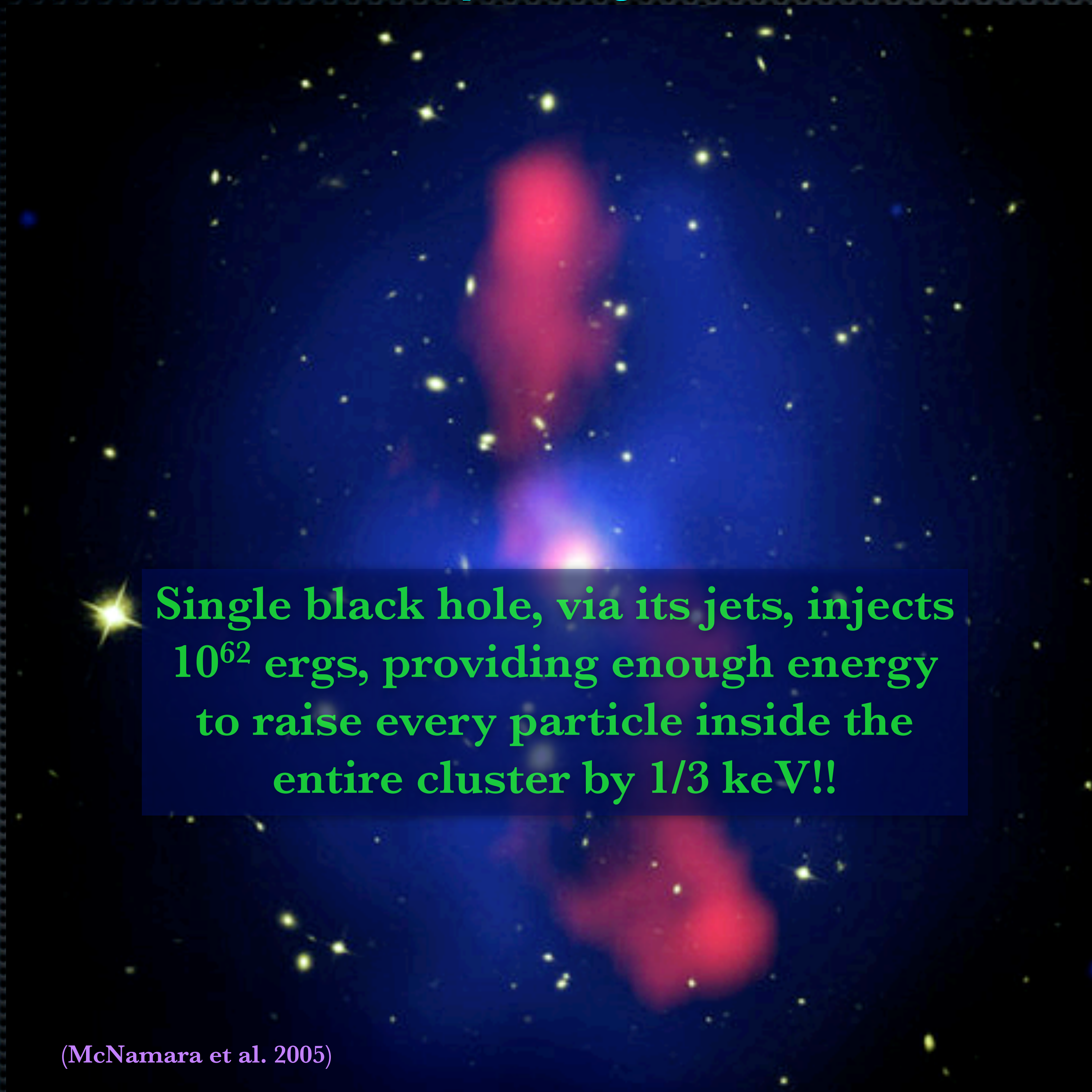
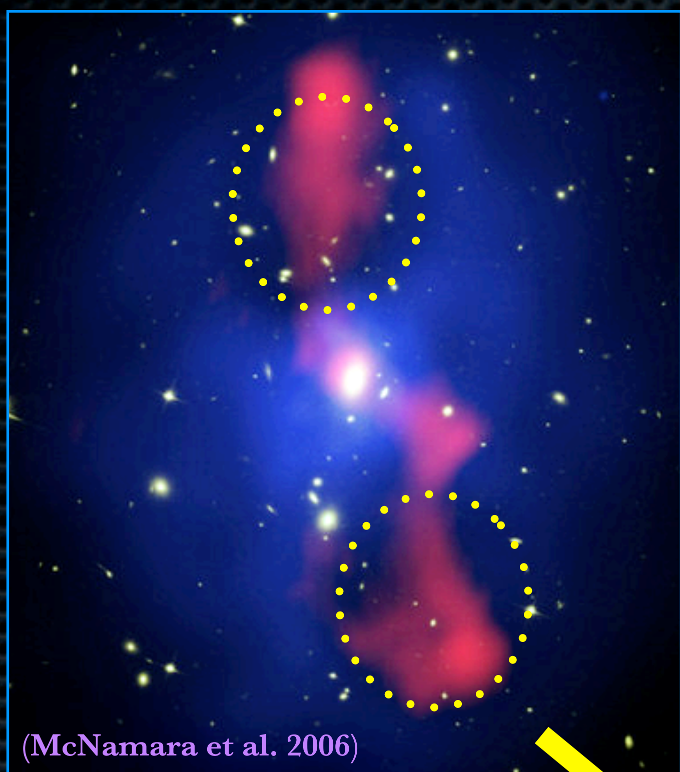
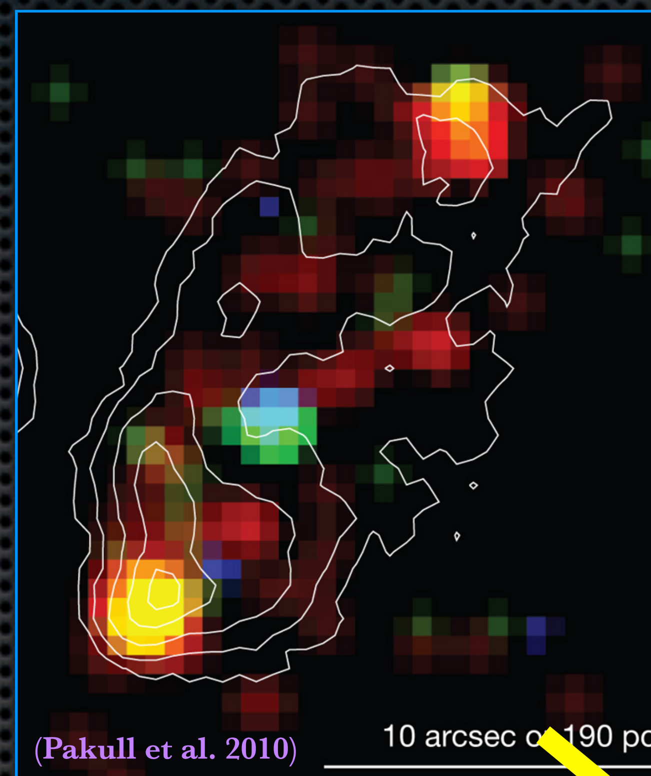


We need to understand the link between inner accretion flow and outflow properties in order to understand...

GALAXY EVOLUTION/ AGN FEEDBACK

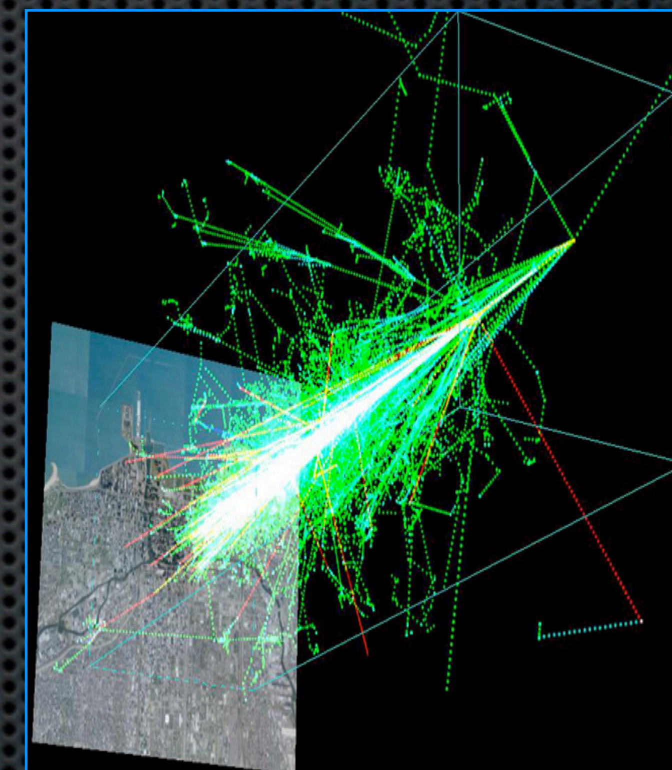

(McNamara et al. 2006)

IONIZATION OF SURROUNDING GAS

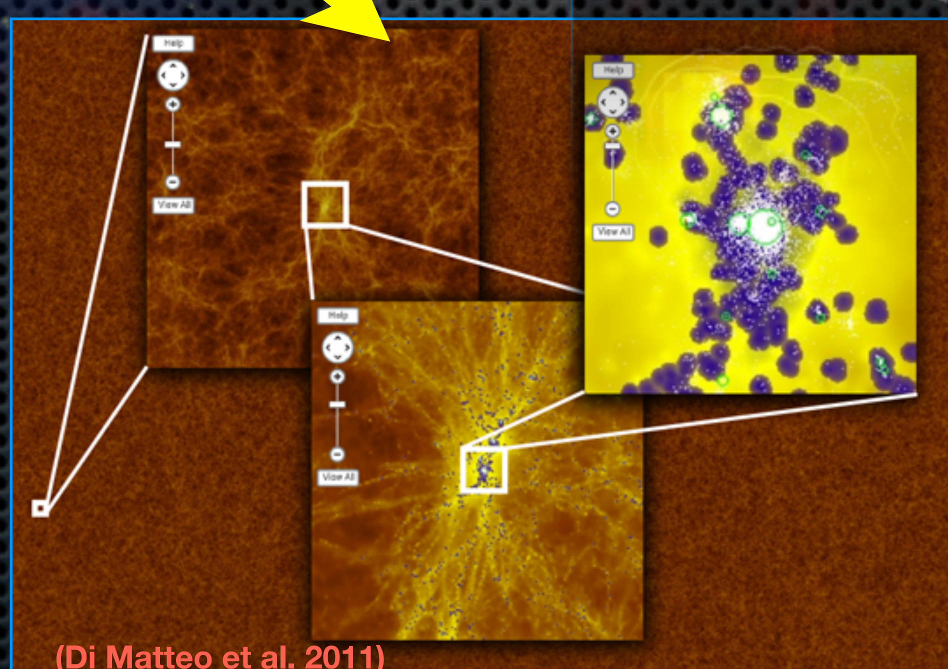


(Pakull et al. 2010)

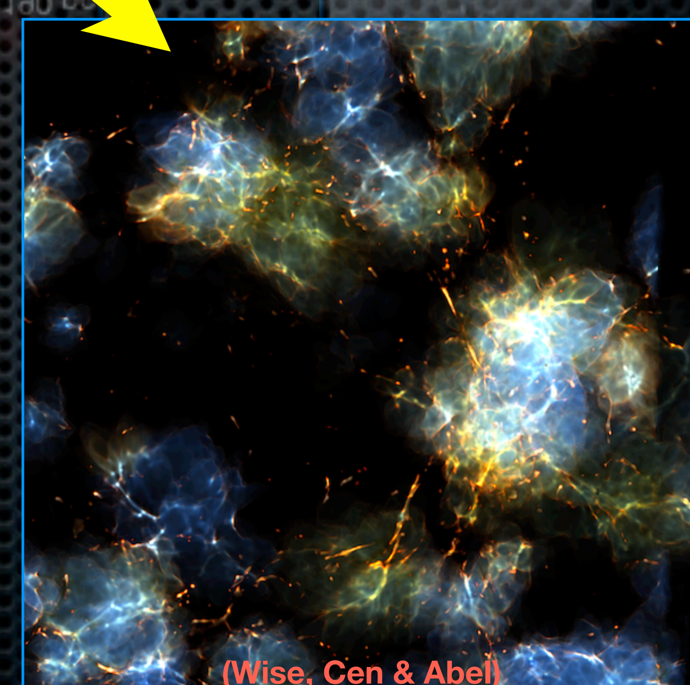
HIGH-ENERGY PARTICLE ACCELERATION



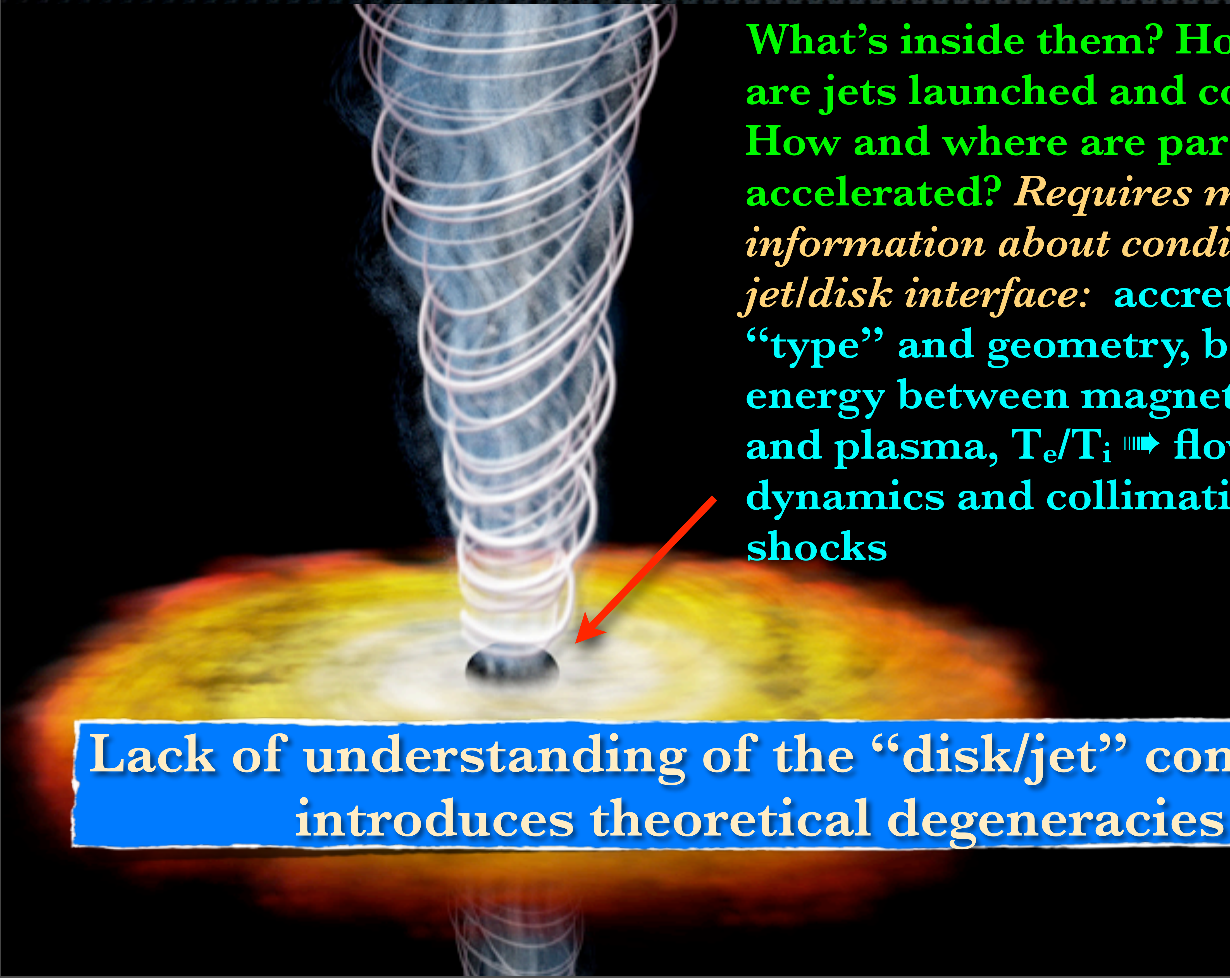
Cosmological Simulations:



(Di Matteo et al. 2011)


(Wise, Cen & Abel)

Immense power rooted in tiny scales

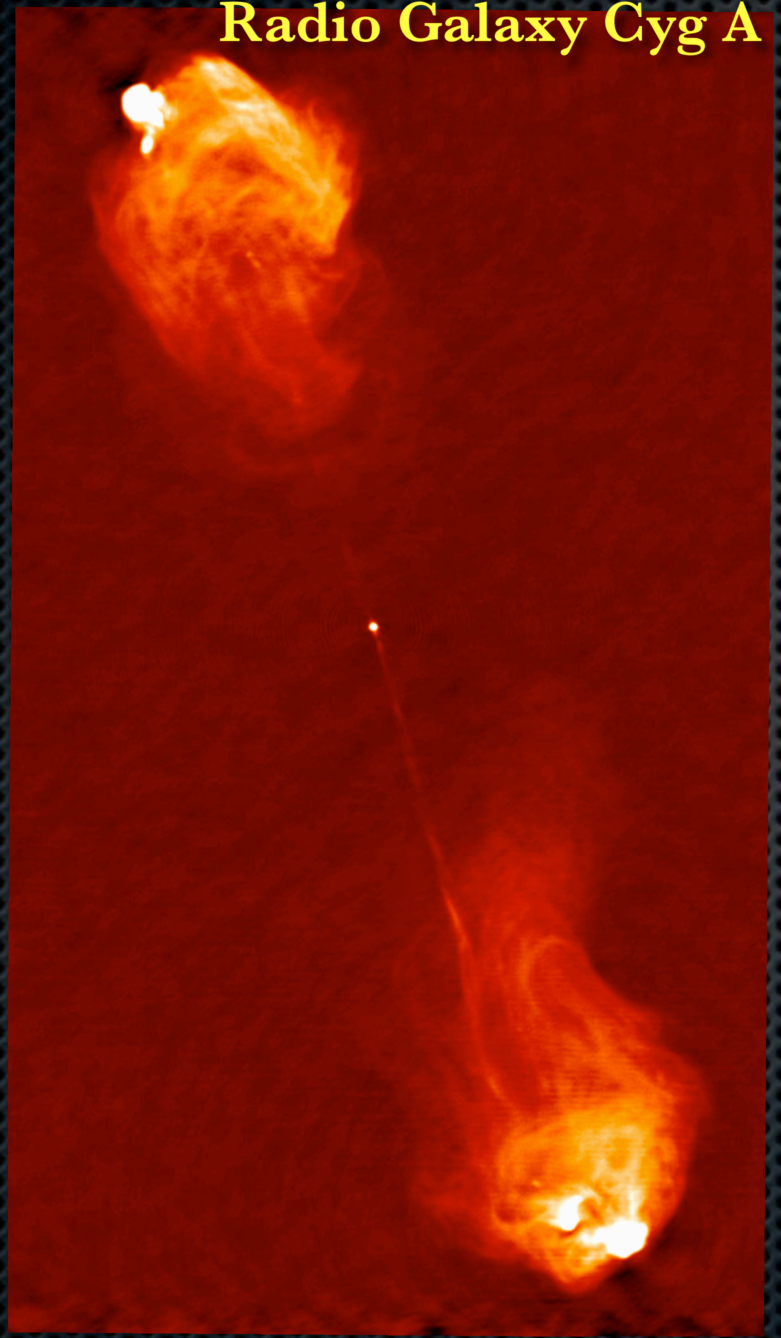


What's inside them? How and why are jets launched and confined? How and where are particles accelerated? *Requires more information about conditions near jet/disk interface:* accretion flow "type" and geometry, balance of energy between magnetic fields and plasma, T_e/T_i ➠ flow dynamics and collimation ➠ shocks

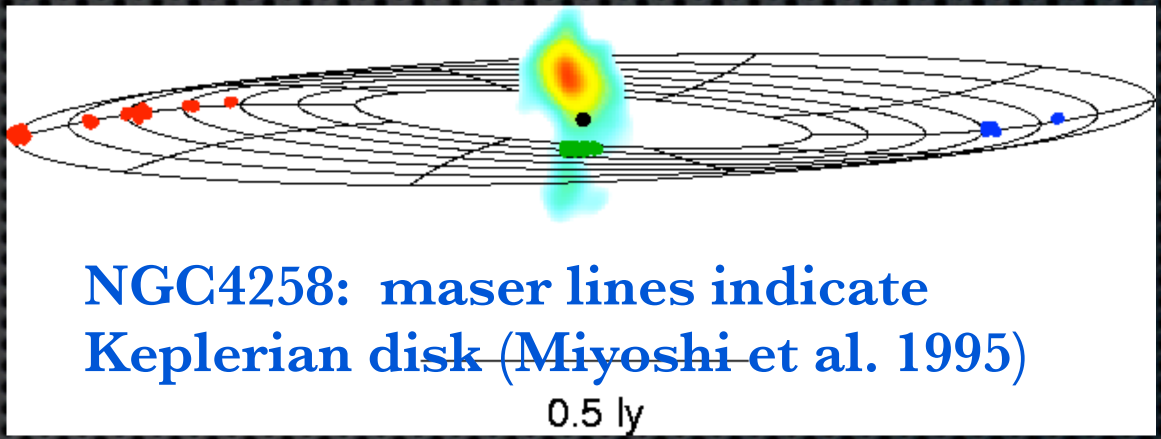
Lack of understanding of the "disk/jet" connection introduces theoretical degeneracies

Why is this so hard to figure out?

Jets are generally the only part of the system we can image directly:

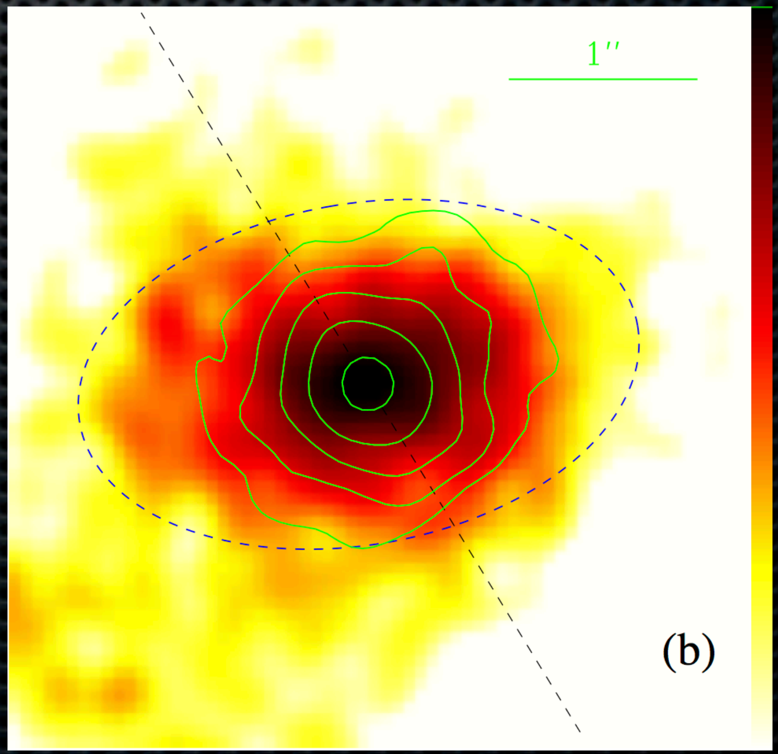


The accretion disk is mostly inferred, from indirect measures (multicolor blackbody, blue/redshifted lines)

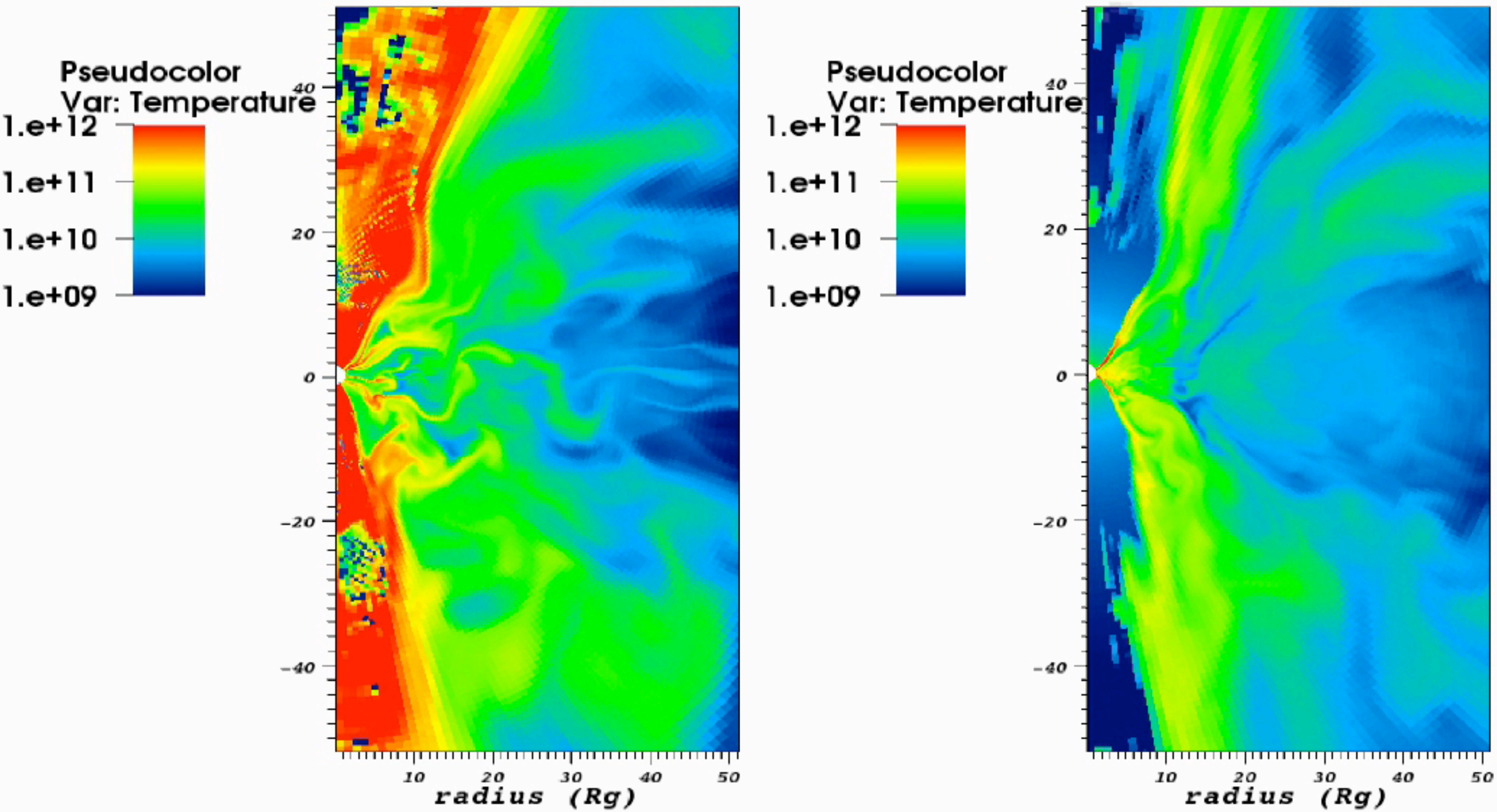


NGC4258: maser lines indicate Keplerian disk ~~(Miyoshi~~ et al. 1995)

Image of the accretion flow around Sgr A* in X-rays (Chandra; Wang, Nowak, SM et al. 2013)

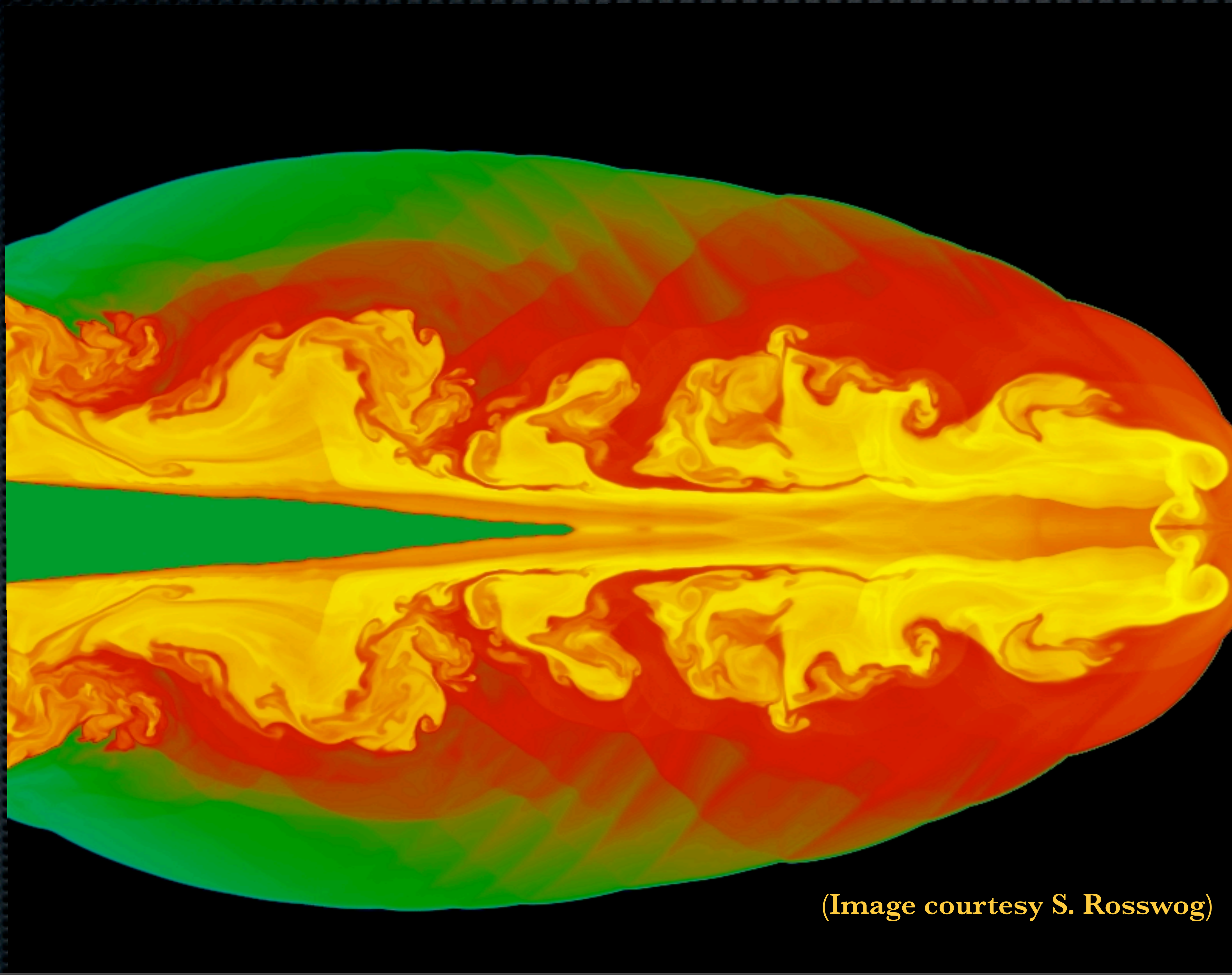


Simulations can help explore initial/boundary conditions



(Dibi et al. 2012)

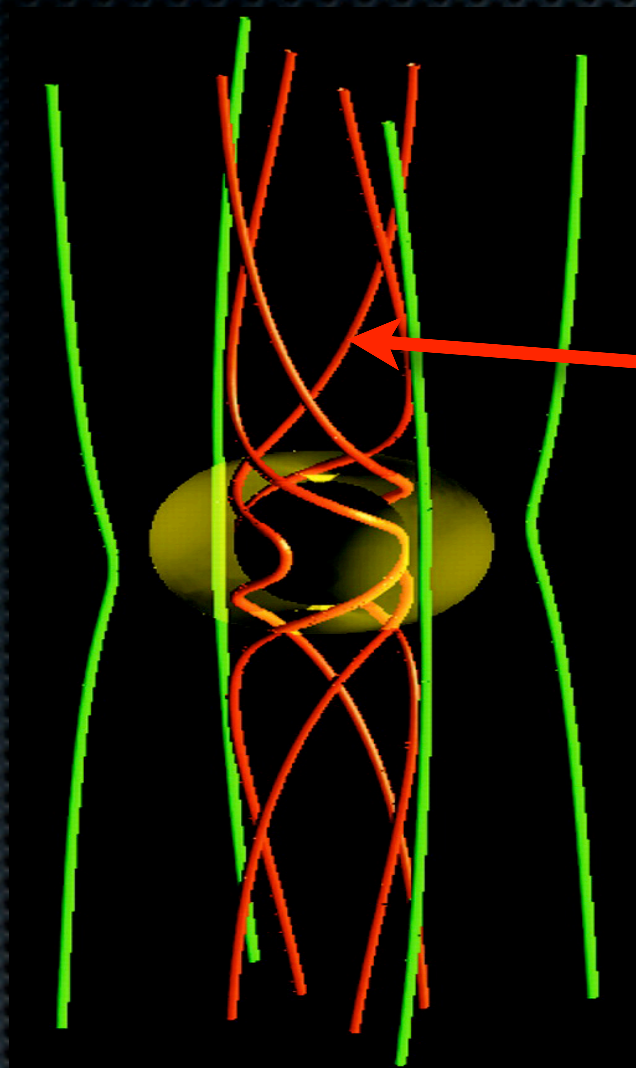
Other complications: what we observe may not be the most important part of the system

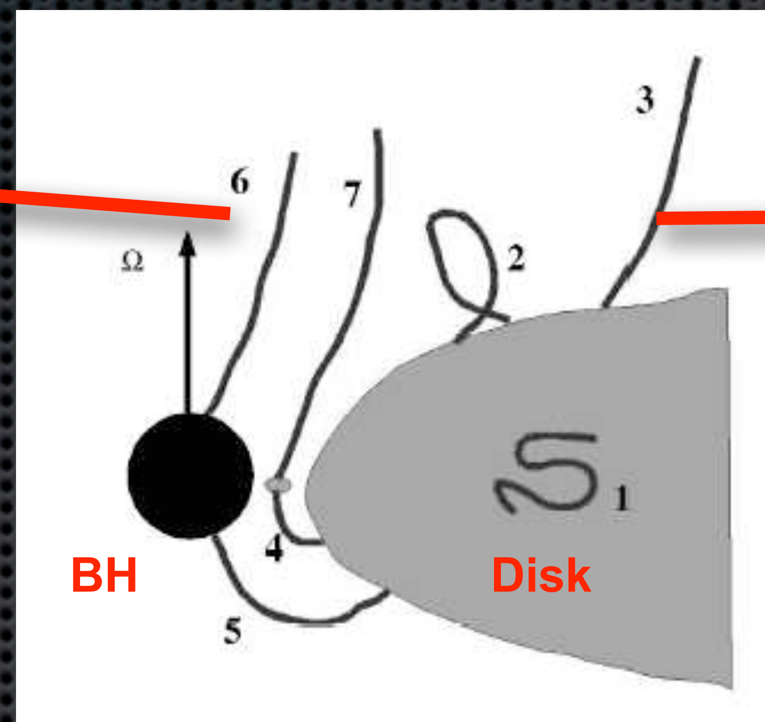


(Image courtesy S. Rosswog)

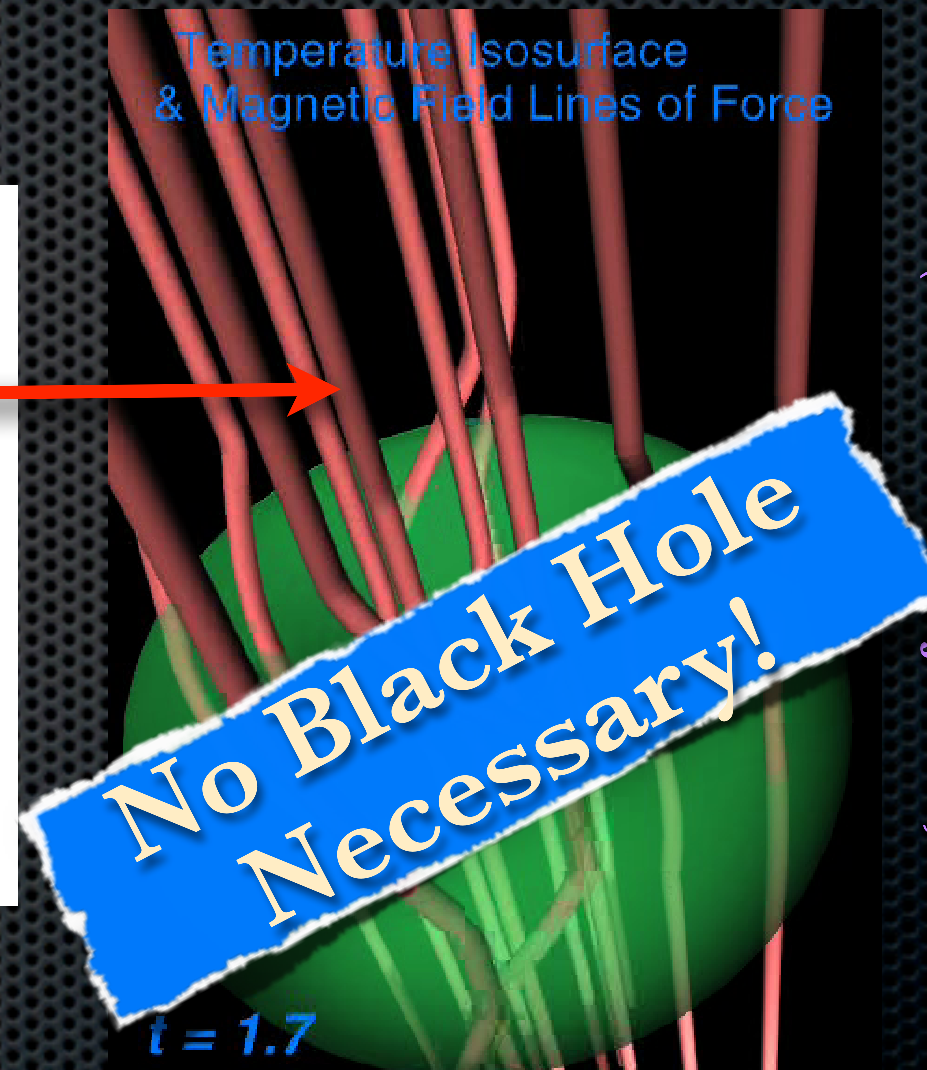
Jet power: two primary theoretical scenarios

Blandford-Znajek





Blandford-Payne



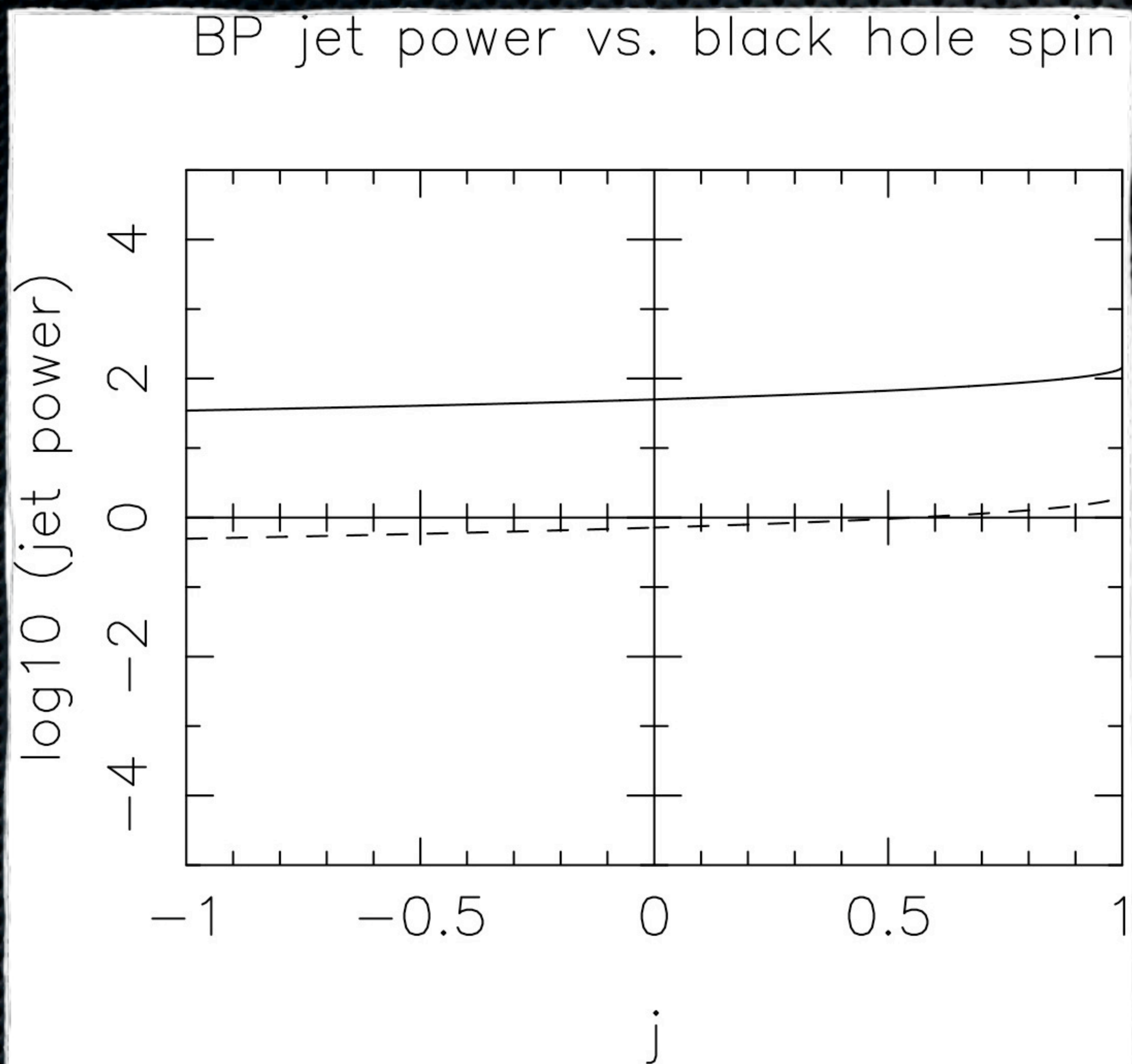
- Spin energy extracted from BH via magnetic fields
- Jets initiated as e^+e^- pairs, Poynting flux dominated

- Plasma accelerated up field lines from disk ("bead on wire")
- Jets loaded with neutral matter (ions, e^-s) from disk

(Blandford & Znajek 1977, Blandford & Payne 1982)

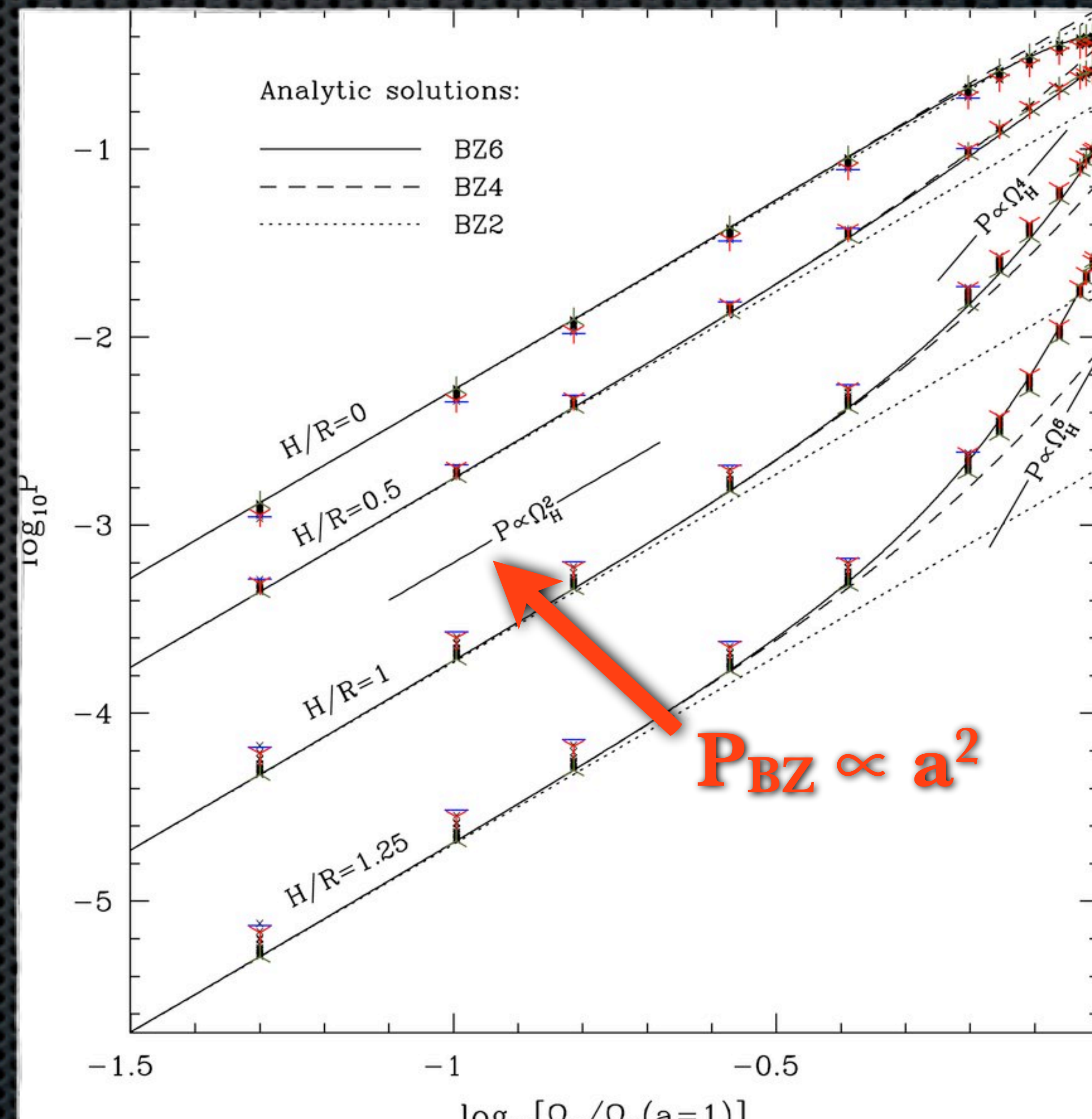
Jet power: dependence on spin

Blandford-Payne-like



(Meier 2001, Meier 2012)

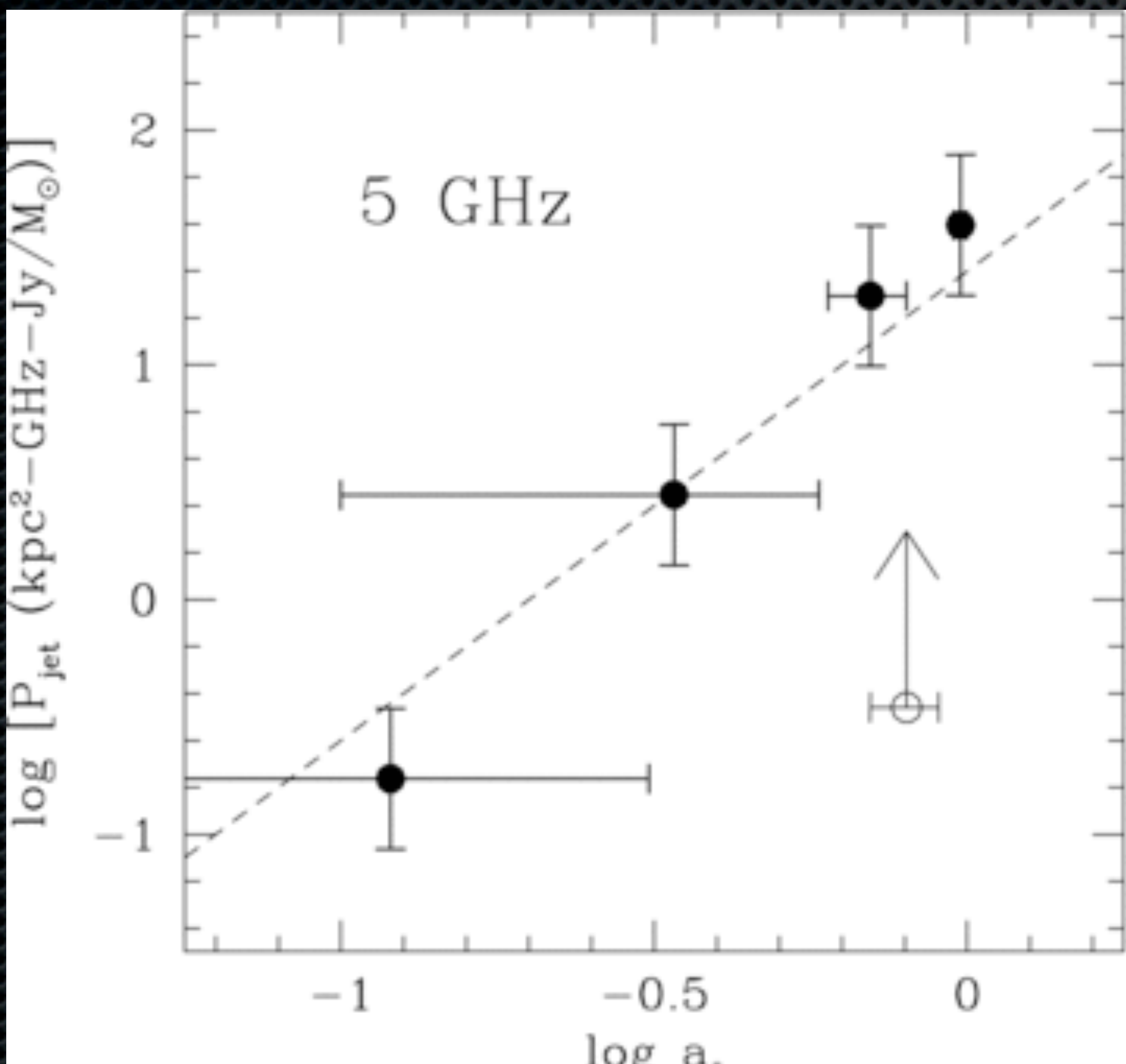
Blandford-Znajek-like



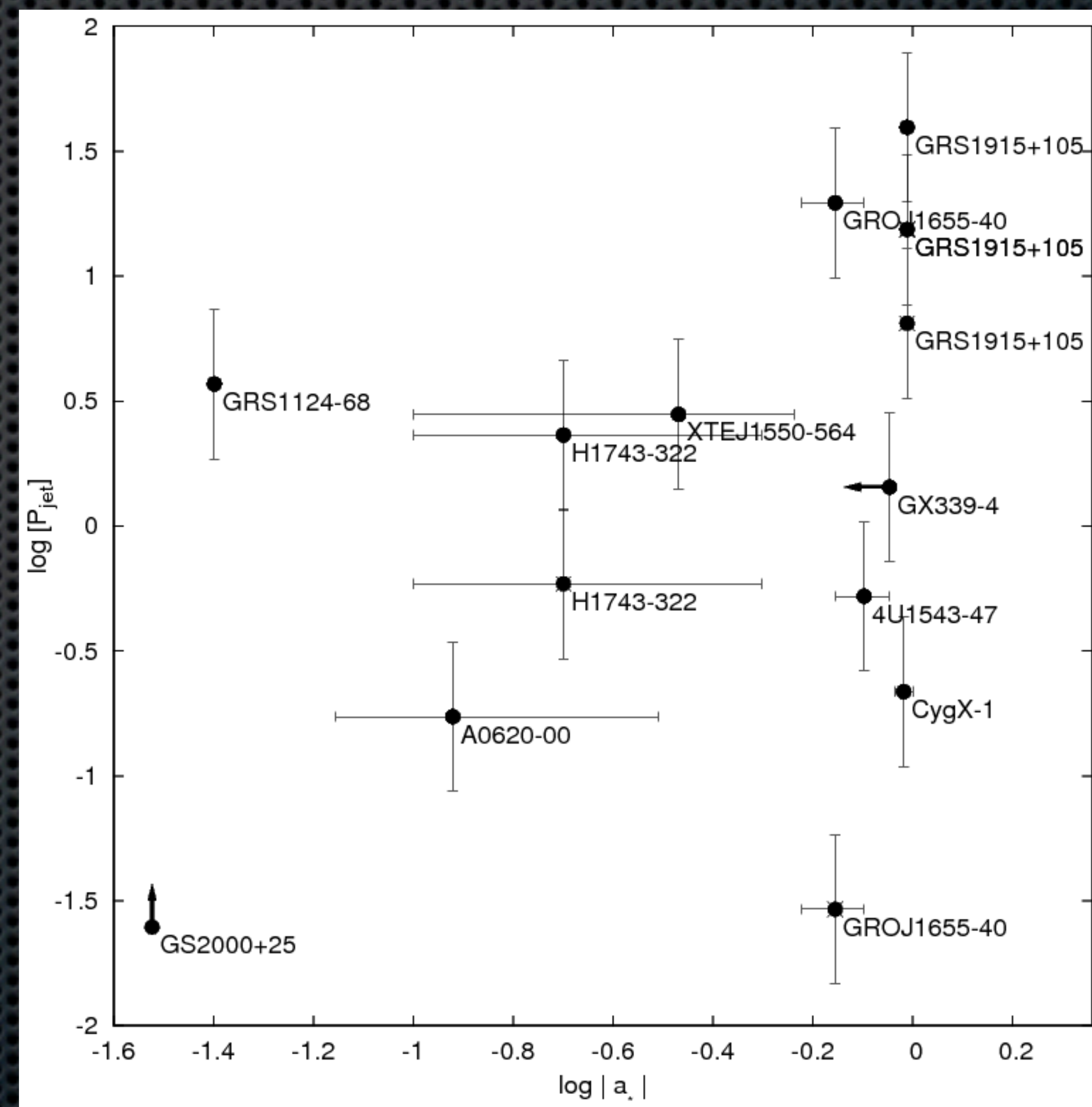
(Tchekhovskoy, Narayan & McKinney 2010)

But... spin definitively is still a problem

- Two groups are looking at this, without yet converging



(Narayan & McClintock 2012)



(Russell, Gallo & Fender 2013)

Thursday, 19 September 13

Any indication of BZ vs BP in XRBs?

- Cir X-1 is a neutron star XRB and thus if BZ is the dominant force powering jets it should have weaker jets than BH XRBs, and yet…
  - To date it has the fastest jet measured in an XRB (though compact jet recently observed is slower)
  - X-rays detected from impact with ISM, constrain jet power to be 10^{35}-10^{37} erg/s, similar to what we find for black hole XRBs
- But 4U 0614+091 is also a NS XRB, whose jet break was explicitly detected with Spitzer
  - Definitely lower power than BH XRBs, for a comparable X-ray luminosity
  - Implies weaker jets, exactly as one might expect for a "missing" ingredient of Blandford & Znajek power

(Migliari ea 2006, Heinz ea 2007, Tudose ea. 2008, Soleri ea. 2009a, Soleri ea. 2009b, Sell ea. 2010, Miller-Jones et al. 2012)

Any indication of BZ vs BP in XRBs?

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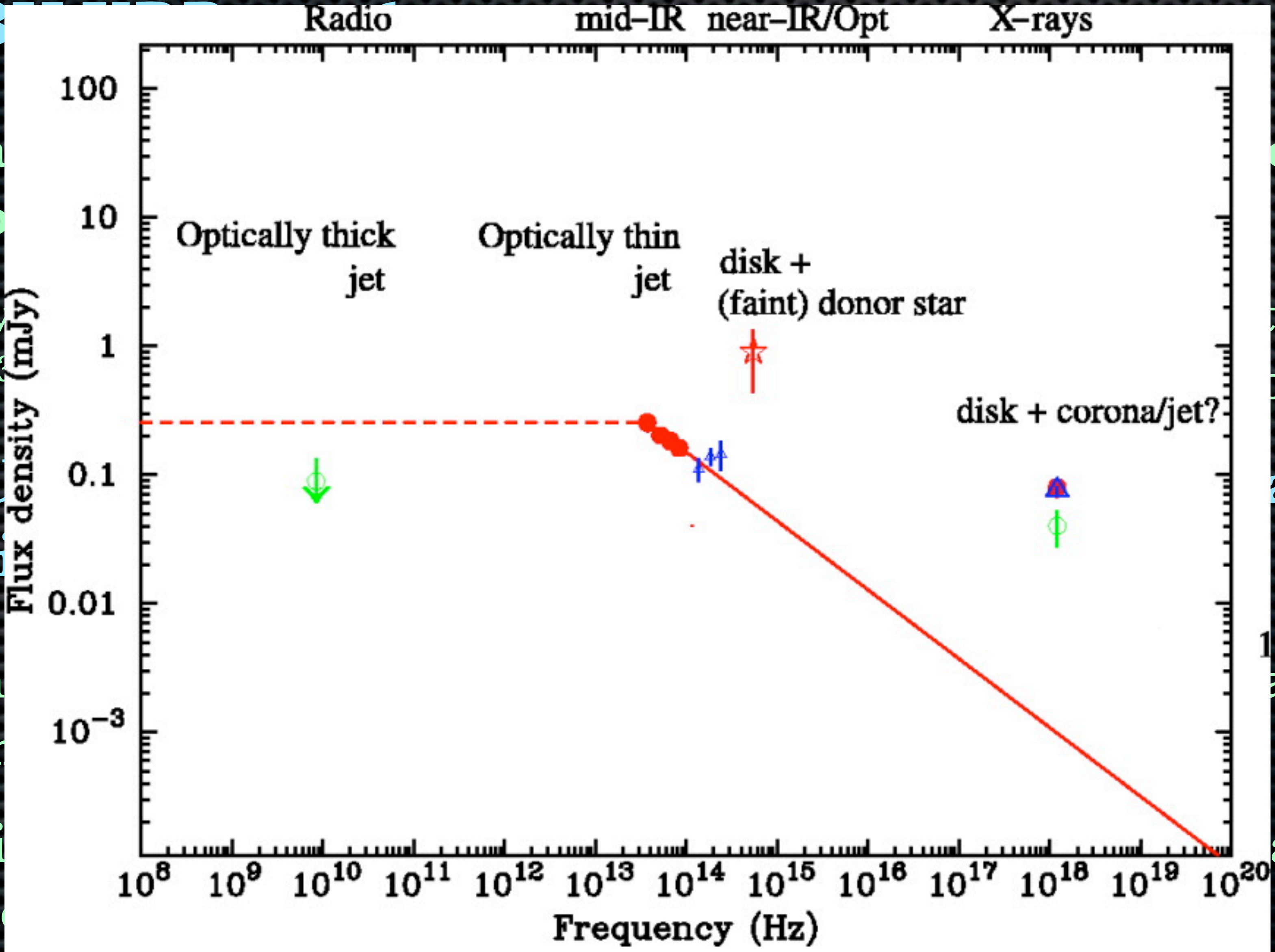

- To da … ough comp
- X-ray … power to be 10 … ble XRBs
- But 4U … ak was explici
- Defin … able X-ray lumin
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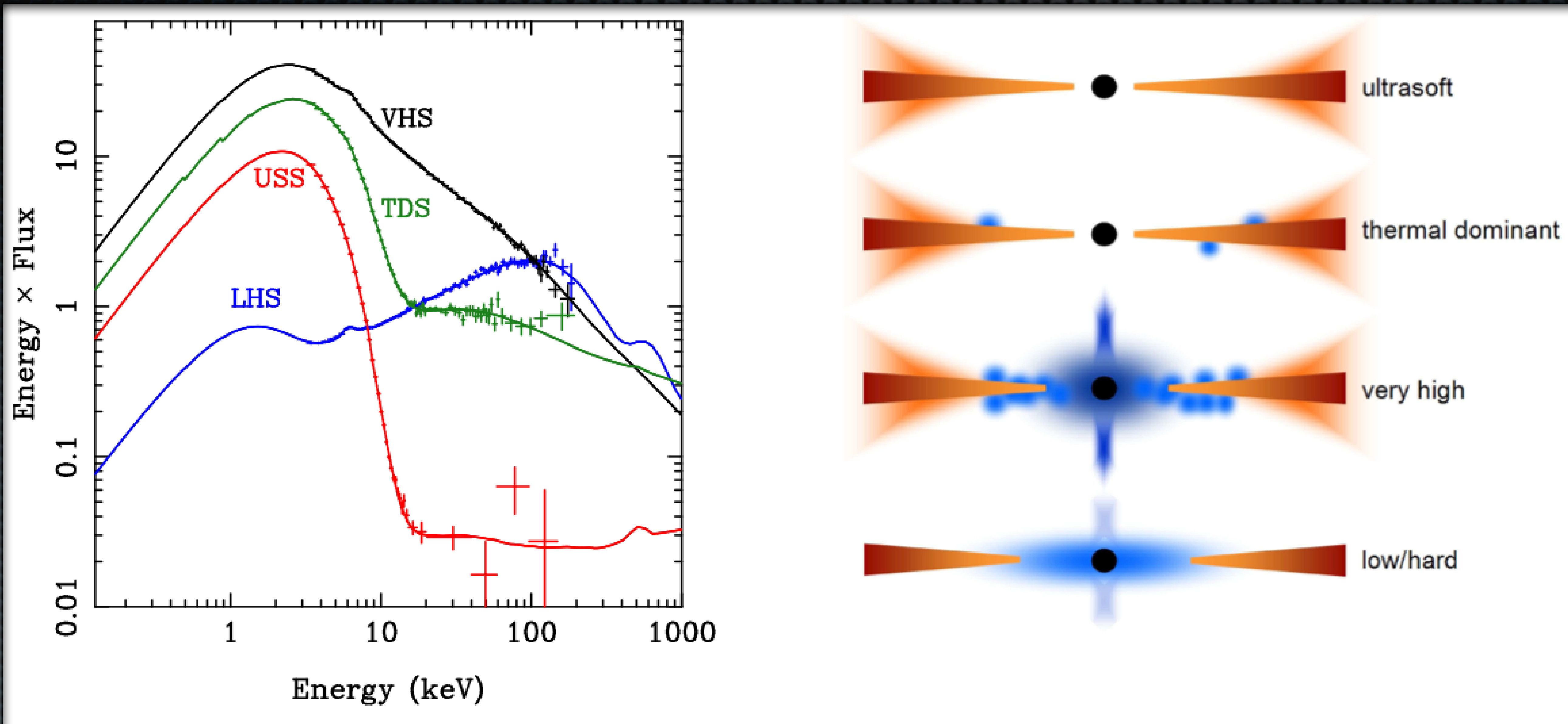
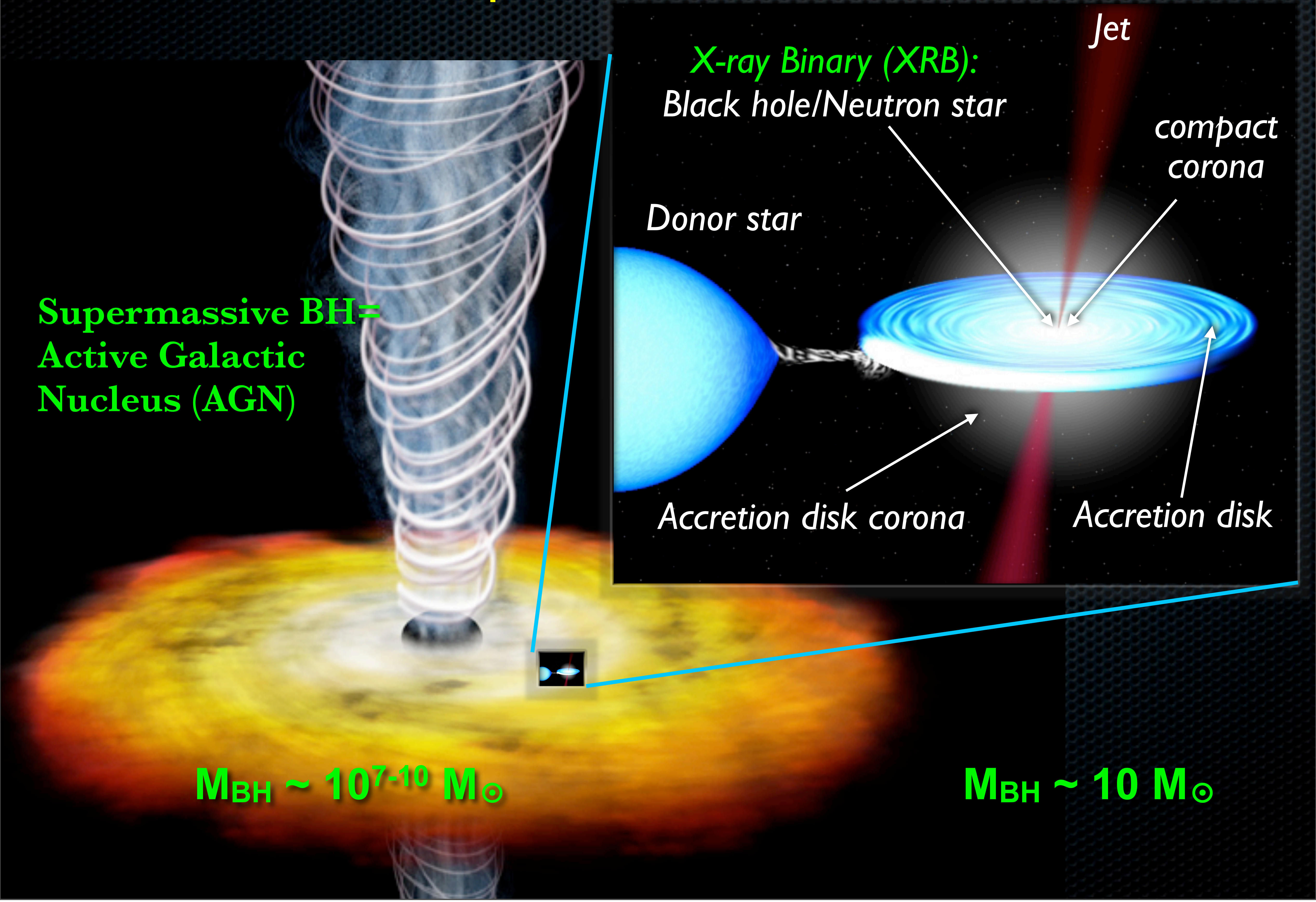
(Migliari ea 2006, Heinz ea 2007, Tudose ea. 2008, Soleri ea. 2009a, Soleri ea. 2009b, Sell ea. 2010, Miller-Jones et al. 2012)

Mostly we are left with indirect signals: spectra and lightcurves



(Esin et al. 1997; Done, Gierlinski & Kubota 2007)

Can we compare BHs across the mass scale?



Can we compare BHs across the mass scale?

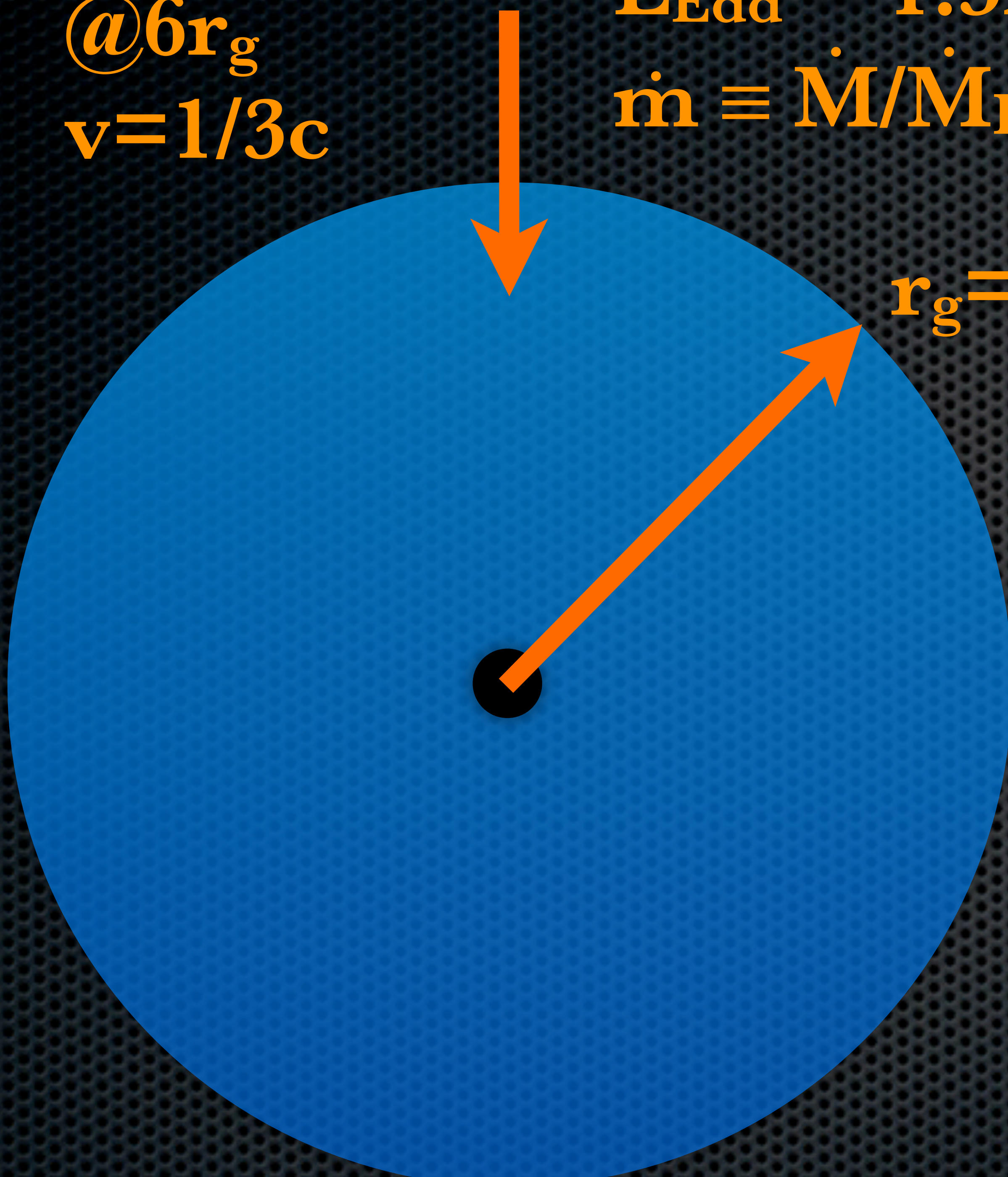
- **Differences in material accreted**
  - surrounding gas conditions (T,v) ➠ capture radius
  - angular momentum ➠ accretion inflow geometry
  - magnetic field ➠ carried in or amplified ➠ jets
- **Differences in the larger outer environment**
  - outer pressure gradient can affect disk/jets, influence their structures
- **Differences in the (accretion) history of the BH ➠ different accumulations of spin**
  - mergers can come in all directions, randomize the inflows
  - different modes of feeding: cold streamers or stellar winds
  - X-ray binaries: feeding off companion star generally spins up the black hole

Mass scaling units of size & power/efficiency

$L_{Edd} = 1.3\mathrm{x}10^{38}\ (M/M_\odot)$ erg/s$=\eta \dot{M} c^2$

$\dot{m} \equiv \dot{M}/\dot{M}_{Edd}$, where $L_{Edd} = 0.1\dot{M}_{Edd}\, c^2$

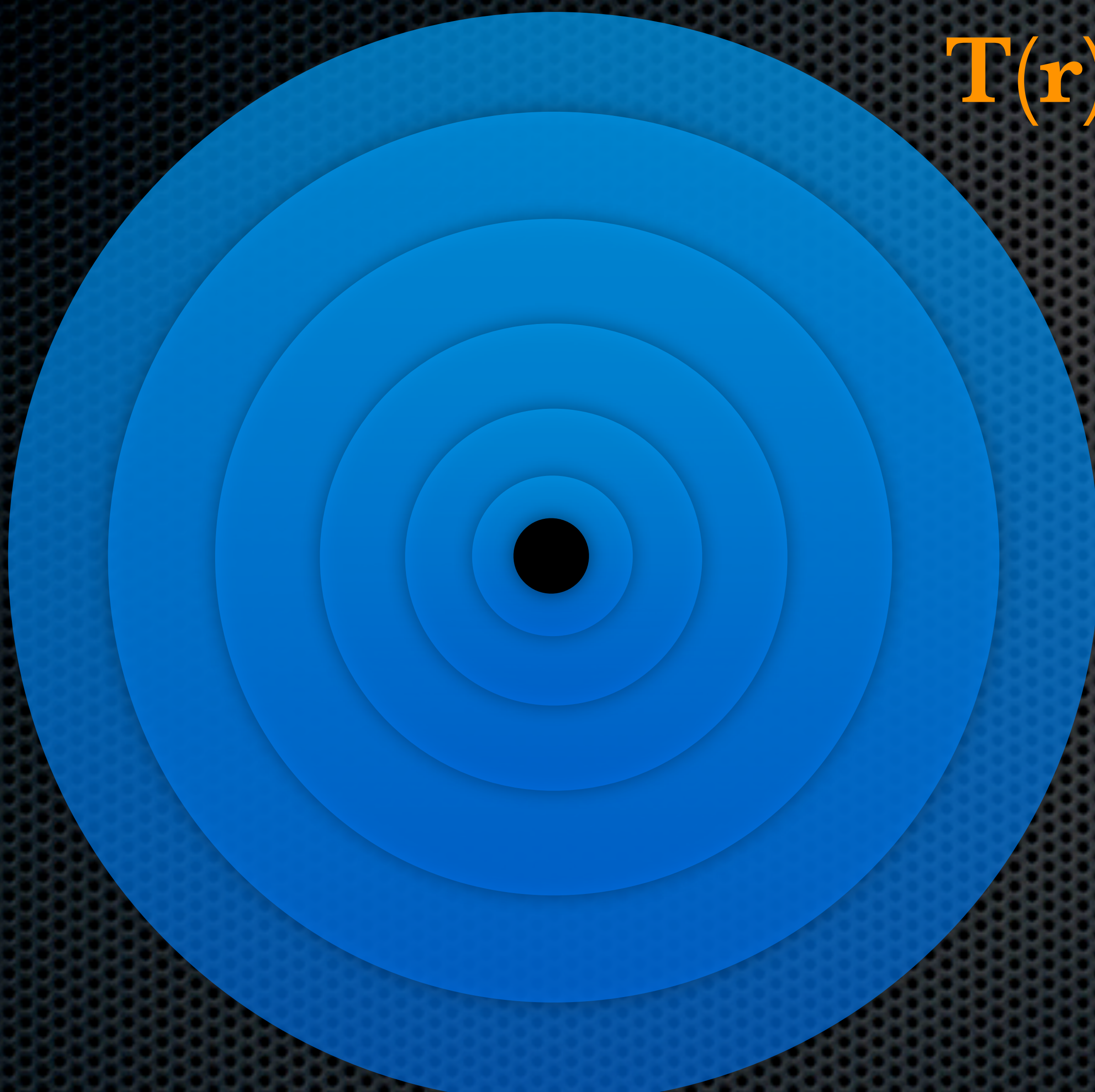
@$6r_g$
v=1/3c



$r_g = GM/c^2 = 1.5\mathrm{x}10^5\ (M/M_\odot)$ cm

But how different are the *physical* quantities? I.e., what's the difference in density at the ISCO ($6r_g$) between an XRB ($10M_\odot$) and a SMBH ($10^8M_\odot$) accreting at 1% of $\dot{M}_{Edd}$?

Application: multicolor blackbody (thin disk: Zezas' talk)

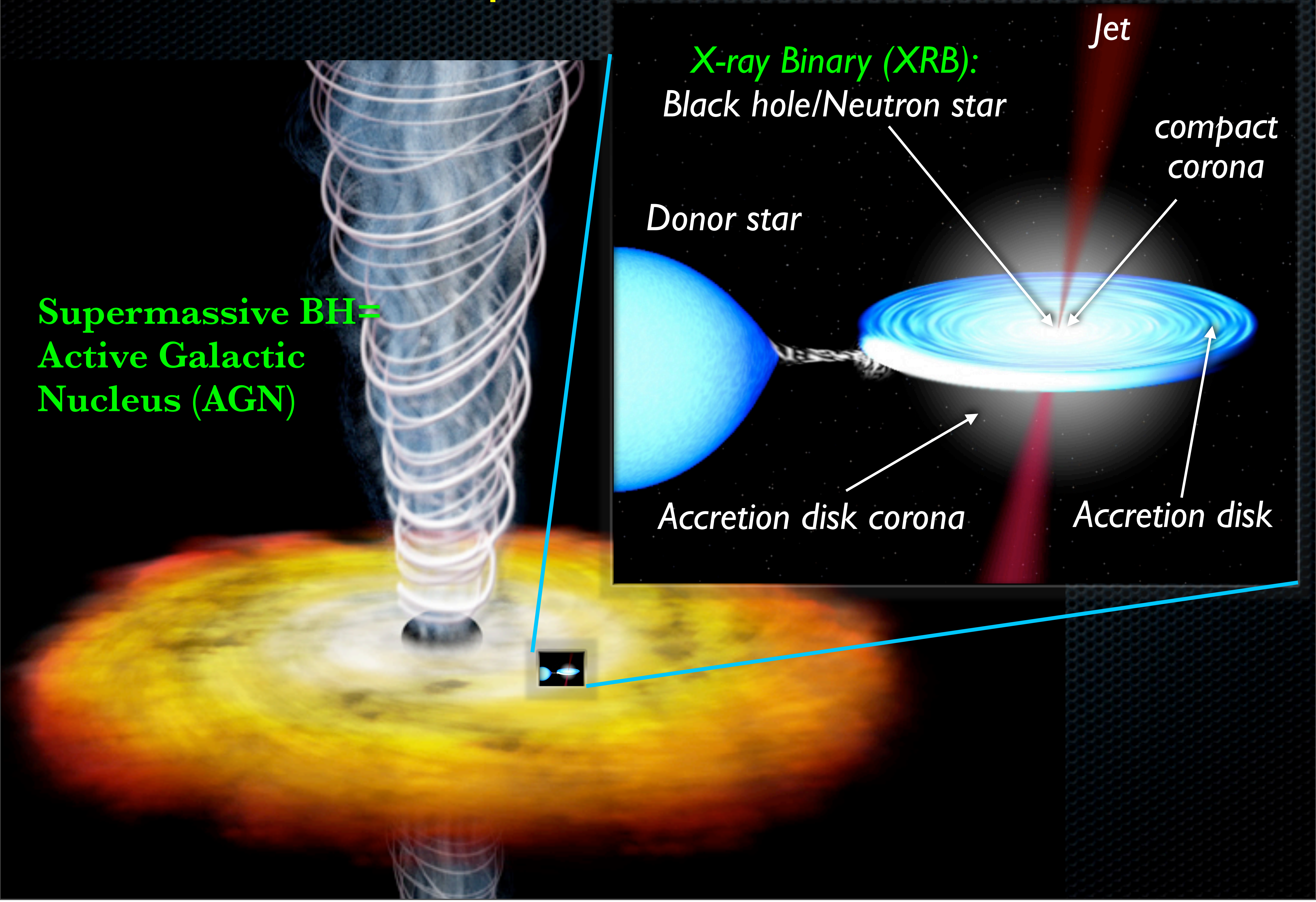


$T(r) \sim r^{-3/4}$

➠ $T_{SMBH}/T_{XRB} = (r_{SMBH}/r_{XRB})^{3/4} = (10^7)^{3/4} \sim 2x10^5$

I.e., the "big blue bump" associated with AGN accretion disk moves to the X-rays for X-ray binaries (thus the name!)

Can we compare BHs across the mass scale?



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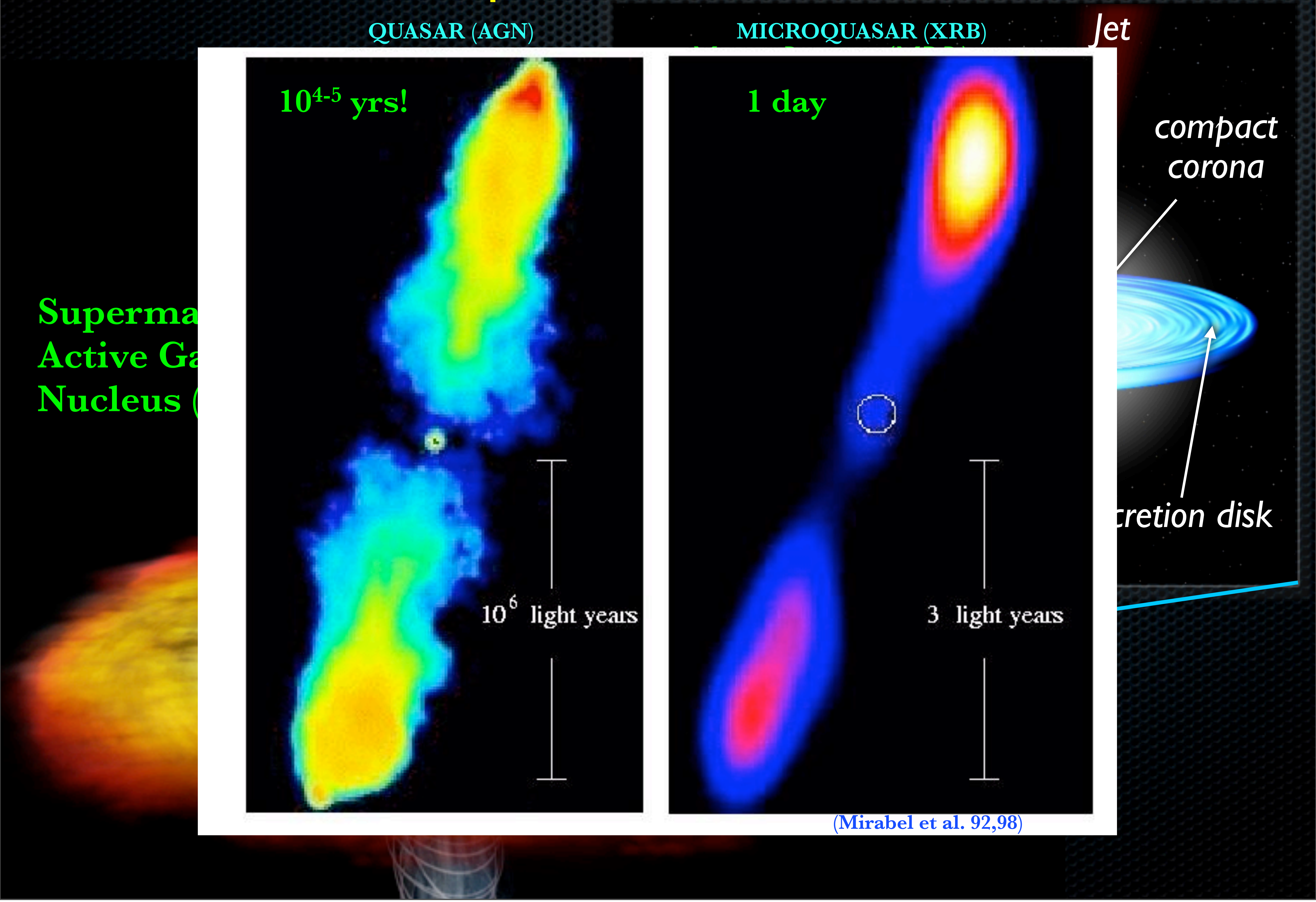

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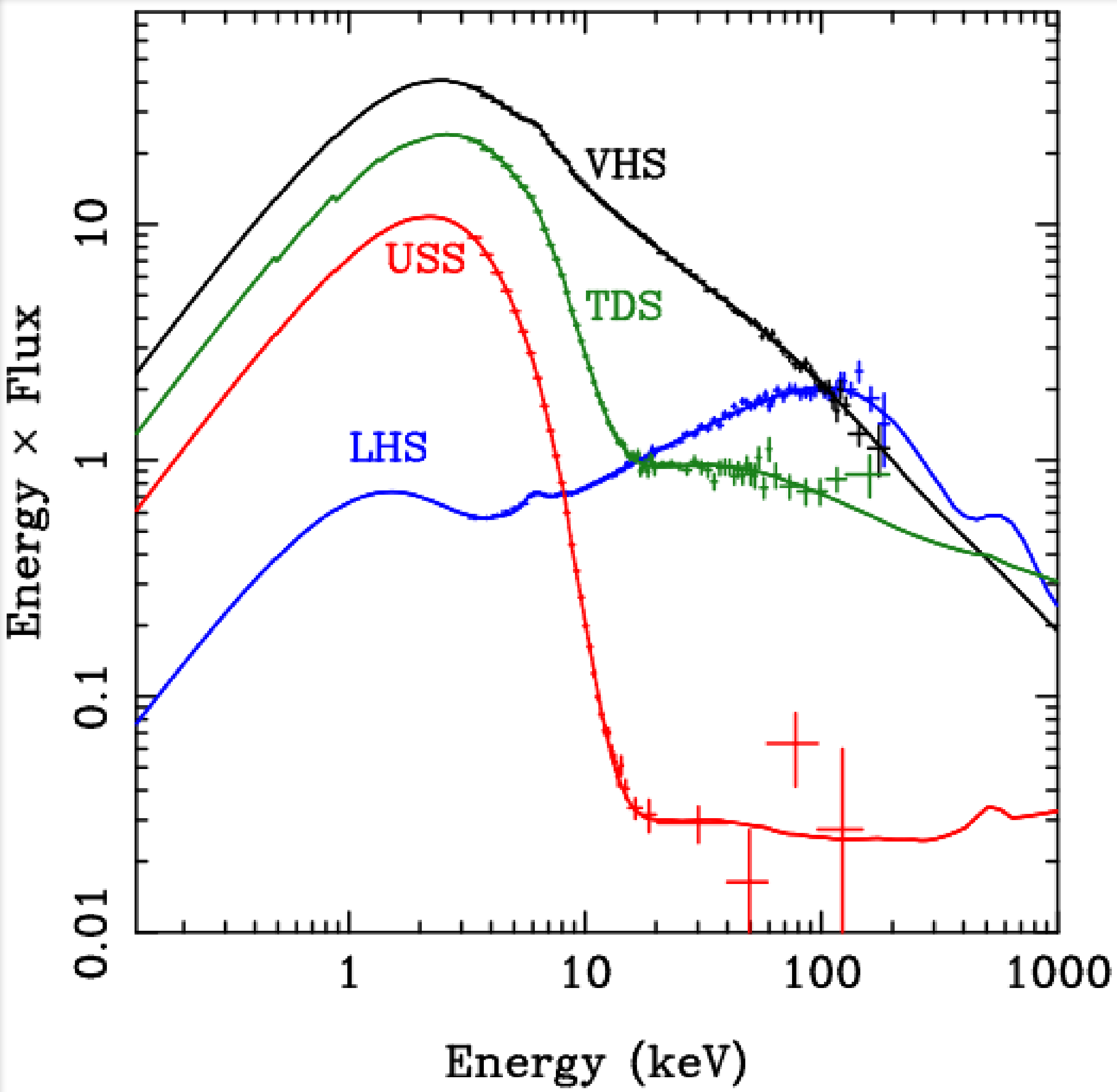
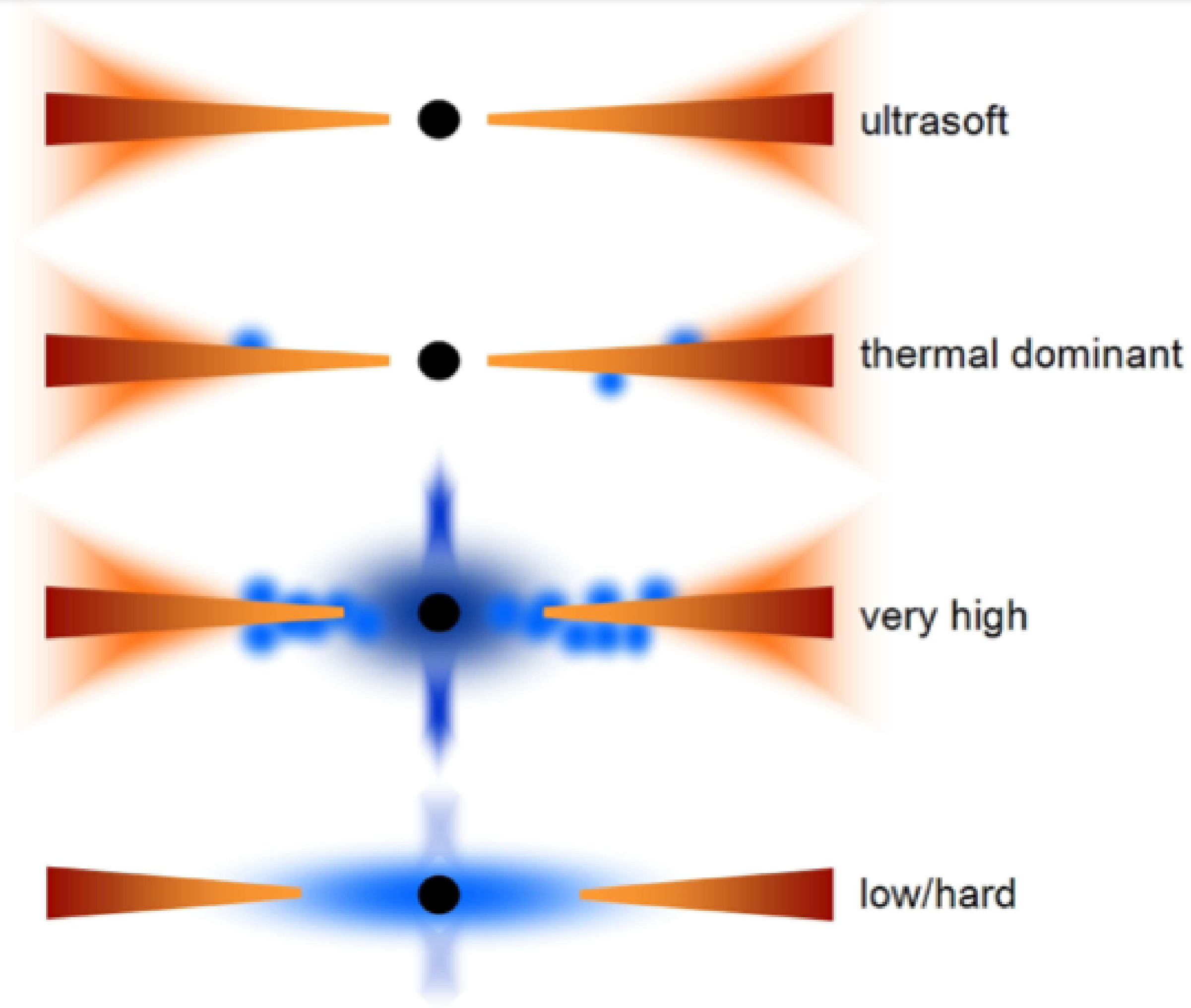
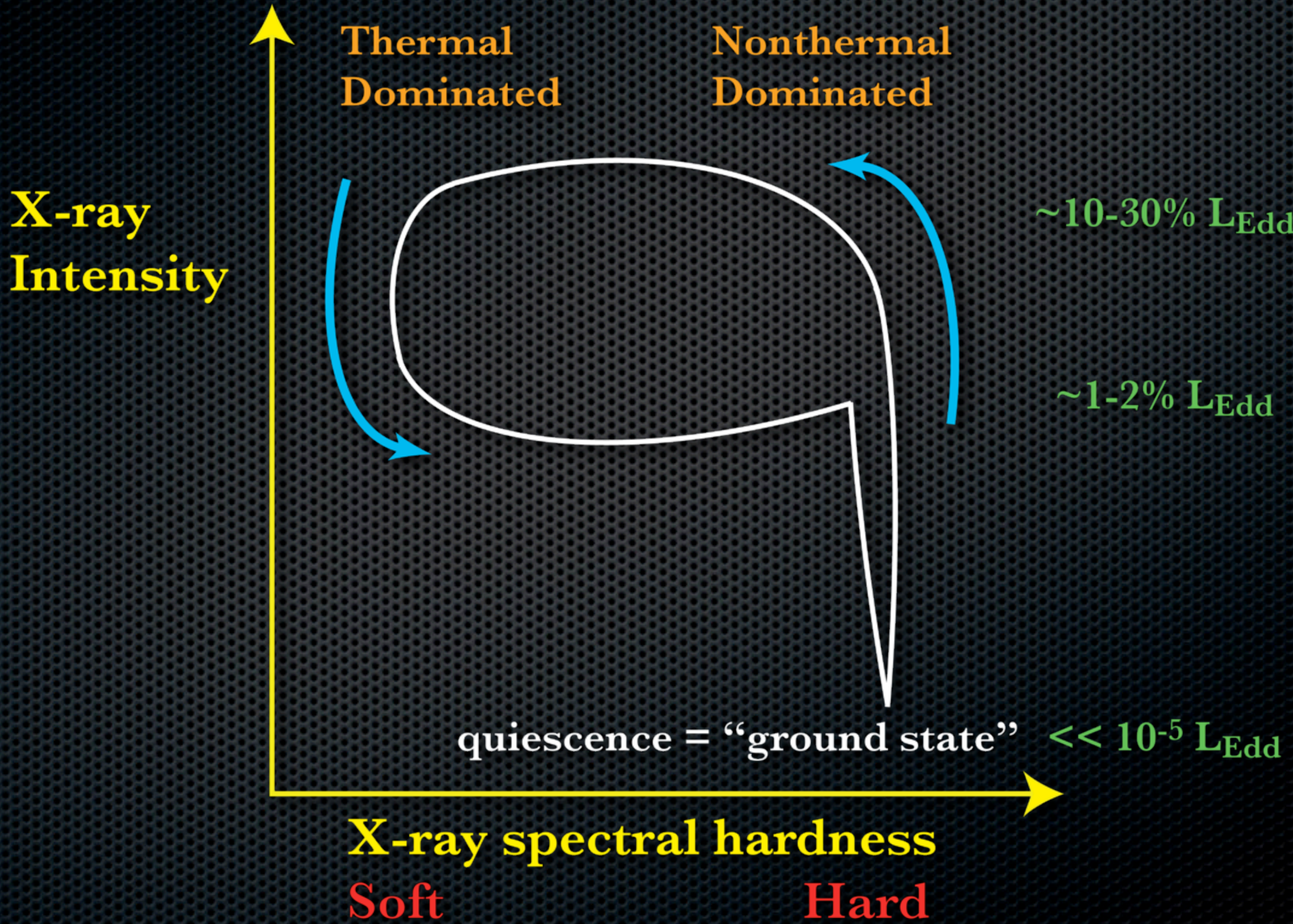
Time variable XRB behavior: The HID
Spectra and Interpretation



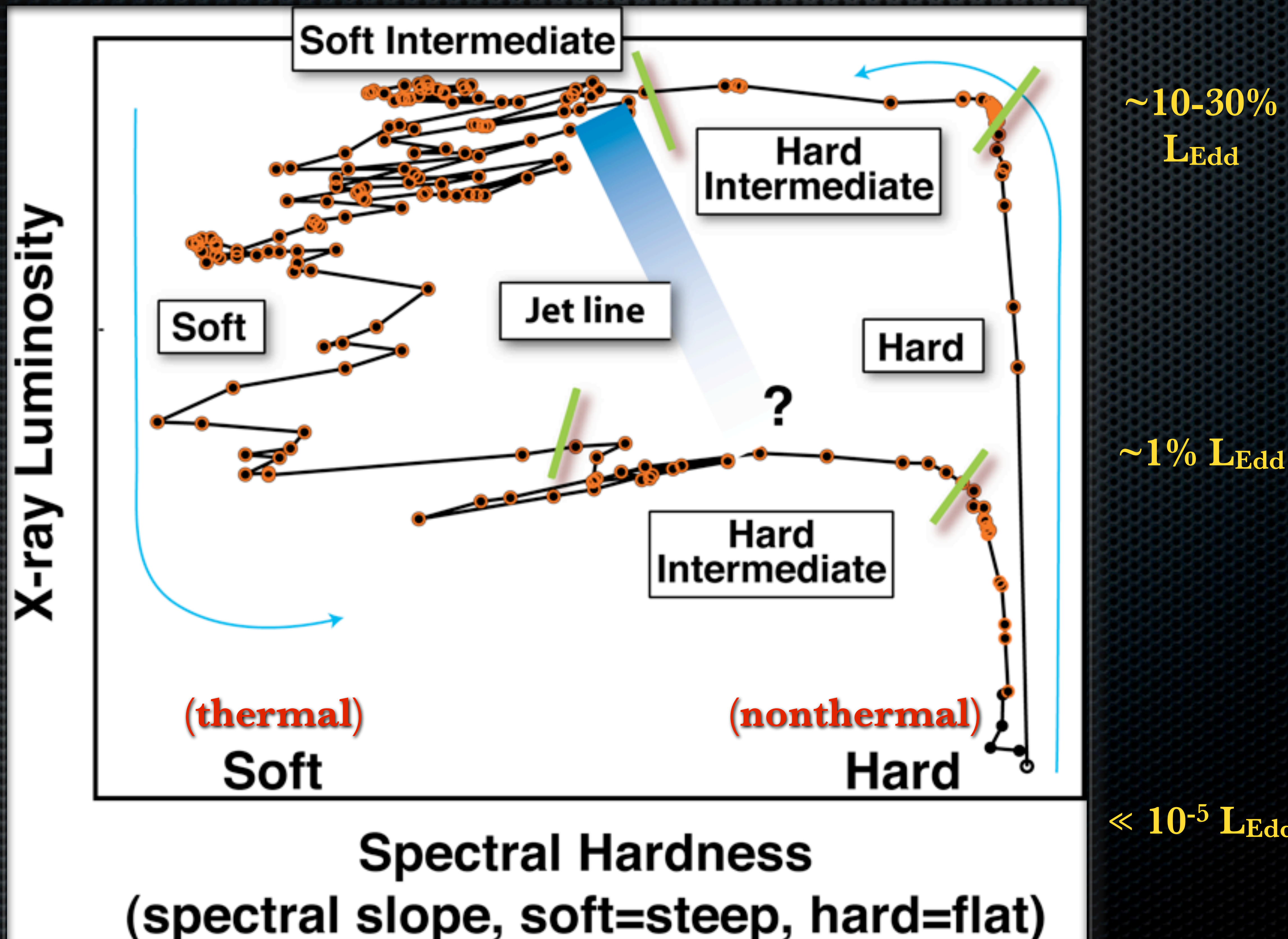


(Esin et al. 1997; Done, Gierlinski & Kubota 2007)

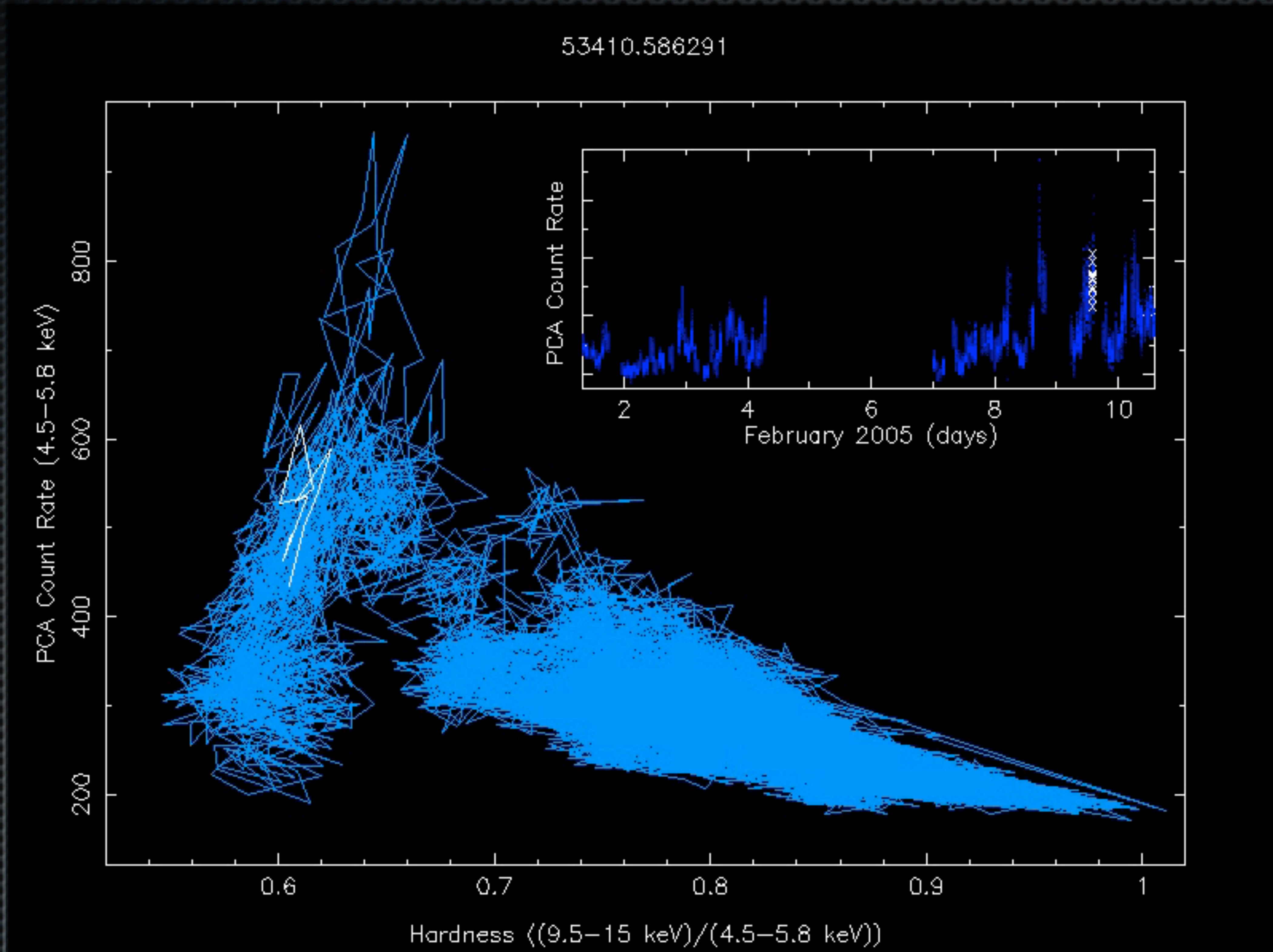
Time variable XRB behavior: The hardness-intensity diagram (HID): A schematic view



Time variable XRB behavior: The HID
GX339-4 data with states indicated

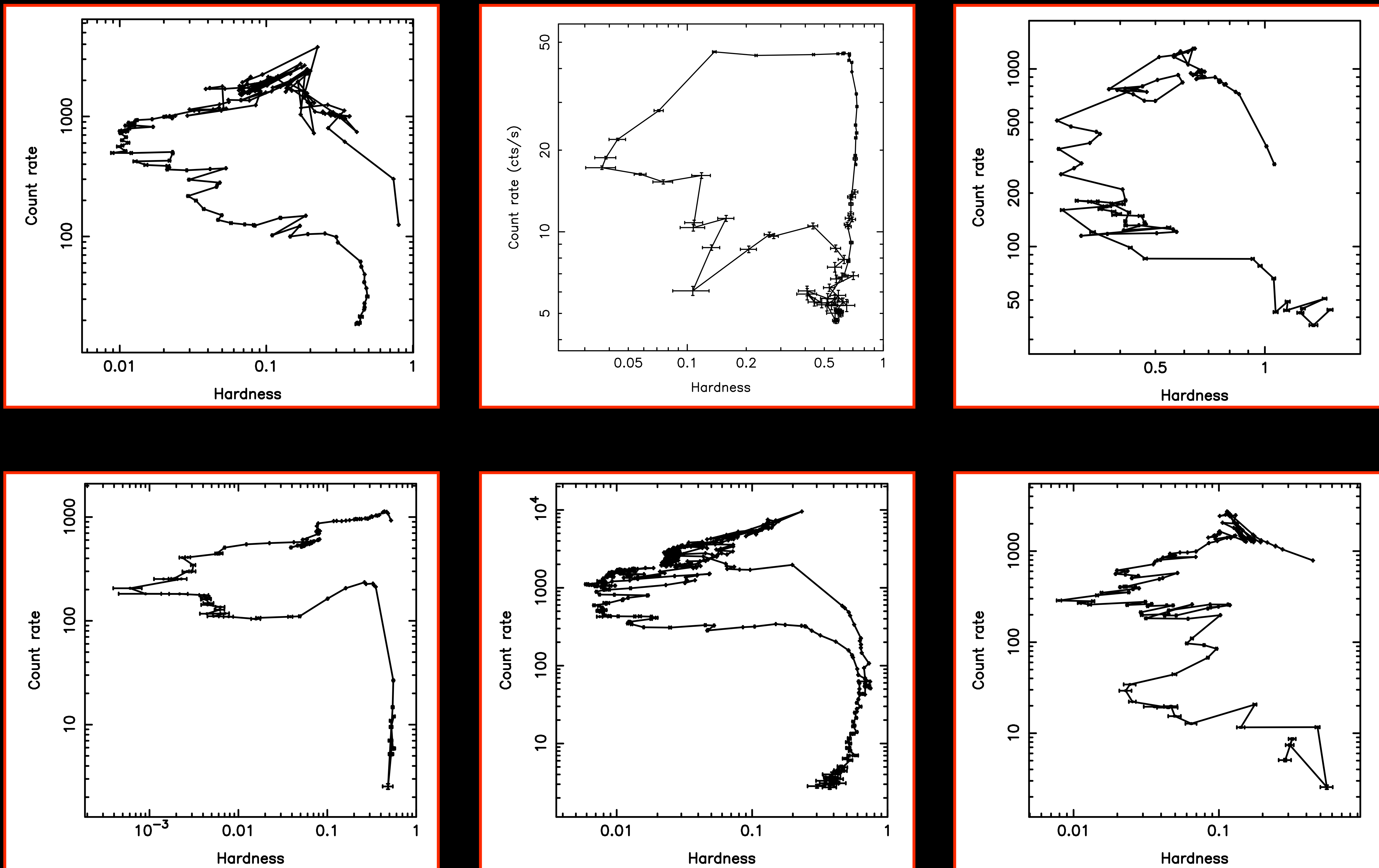


Time variable XRB behavior: The HID
Real data in real time: Cyg X-1



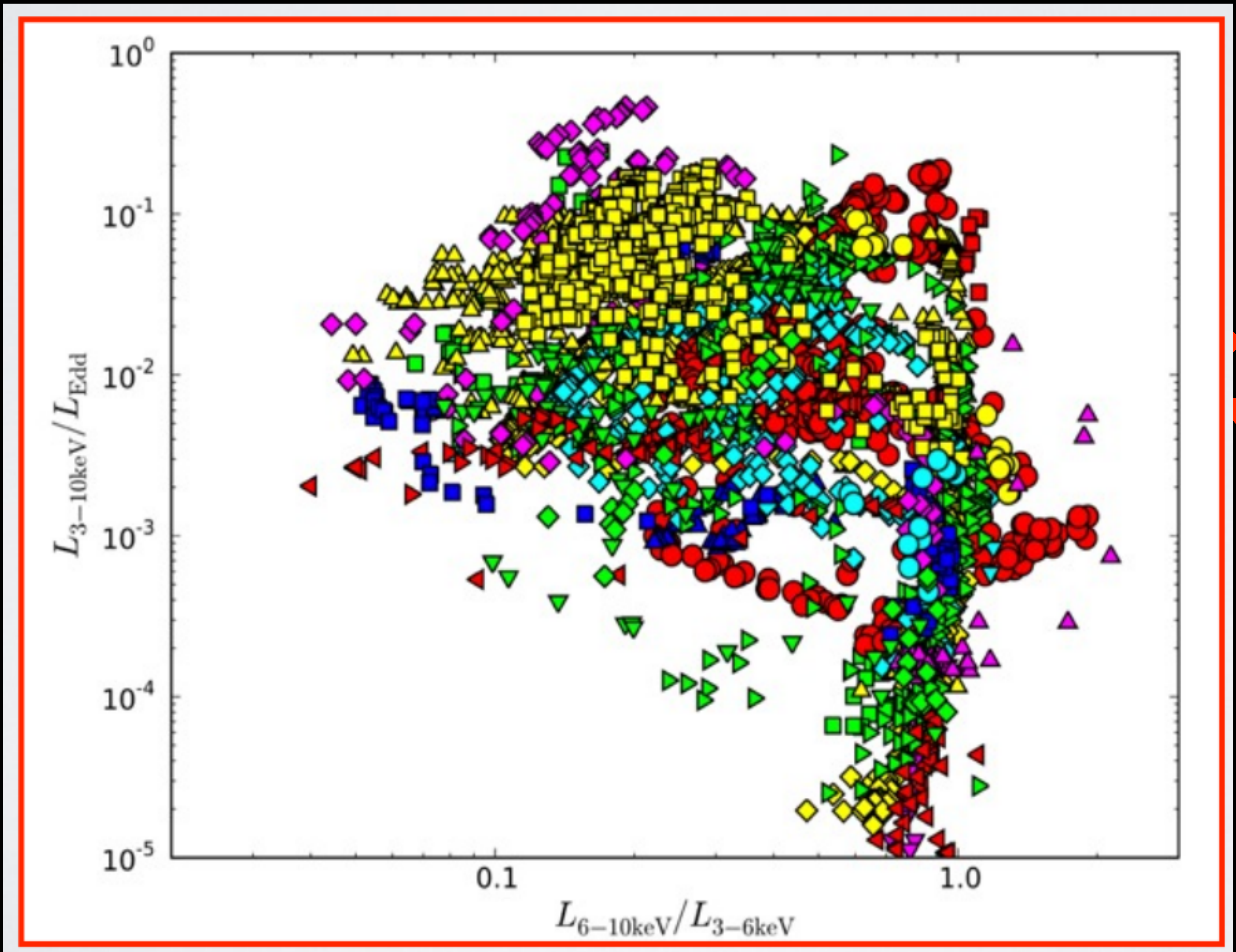
(Movie courtesy M. Böck, from monitoring campaign by Wilms, Nowak, Markoff, et al.)

hysteresis



(Figure from J. Homan)

variable transitions



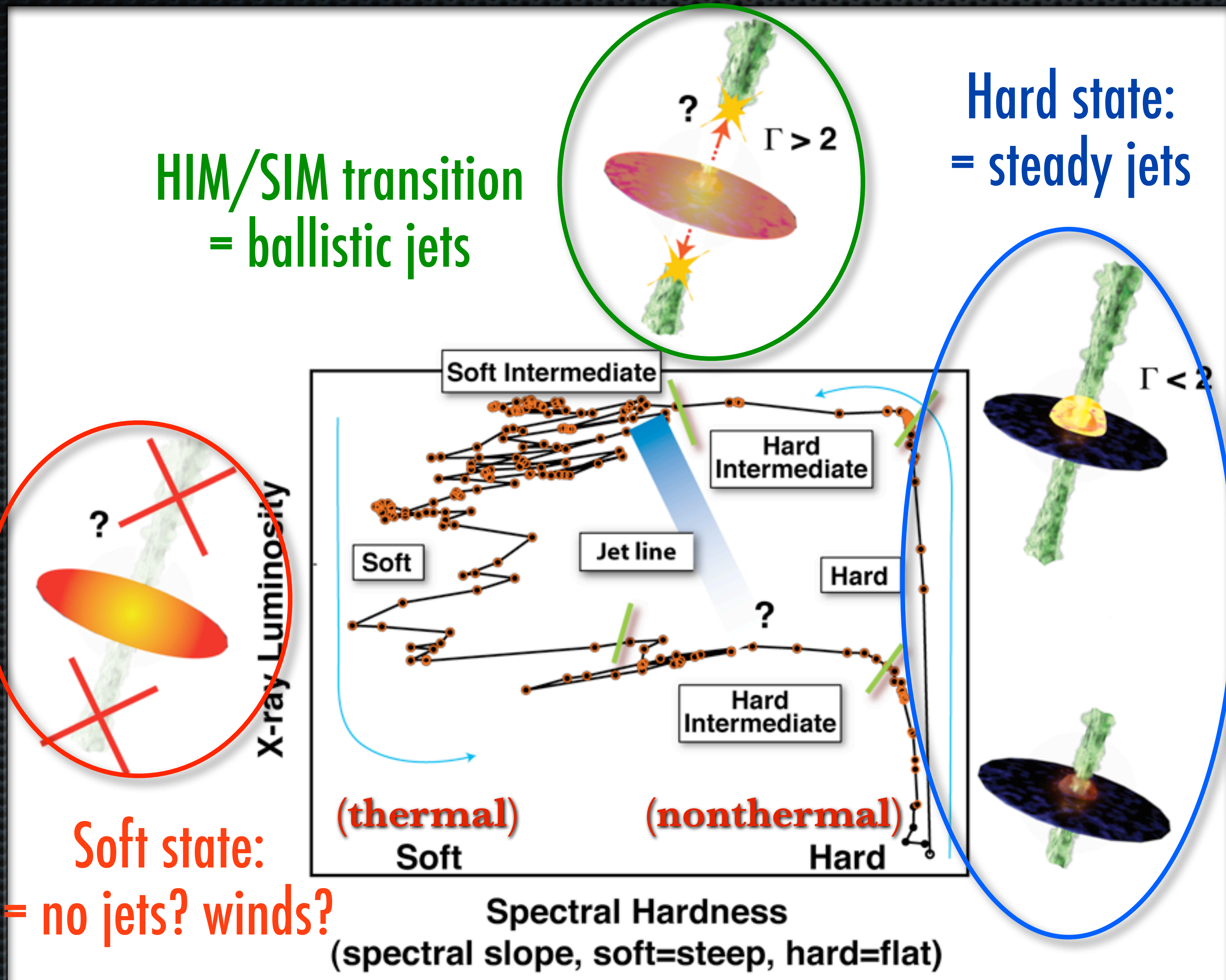
urce,

utburst

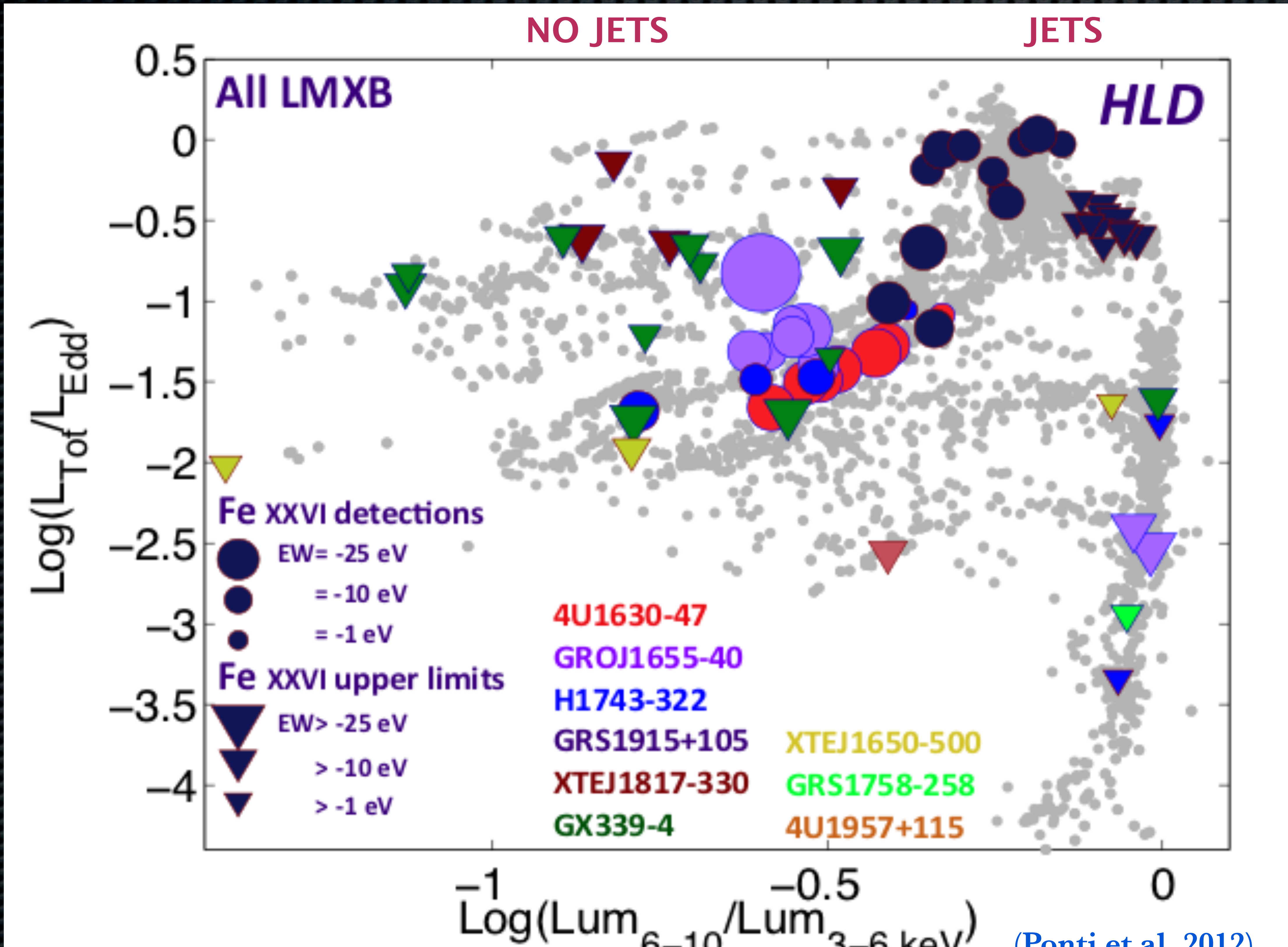
(Figures from J. Homan, Dunn et al. 2010)

Time variable XRB behavior: The HID

Complex cycle of different forms of power output

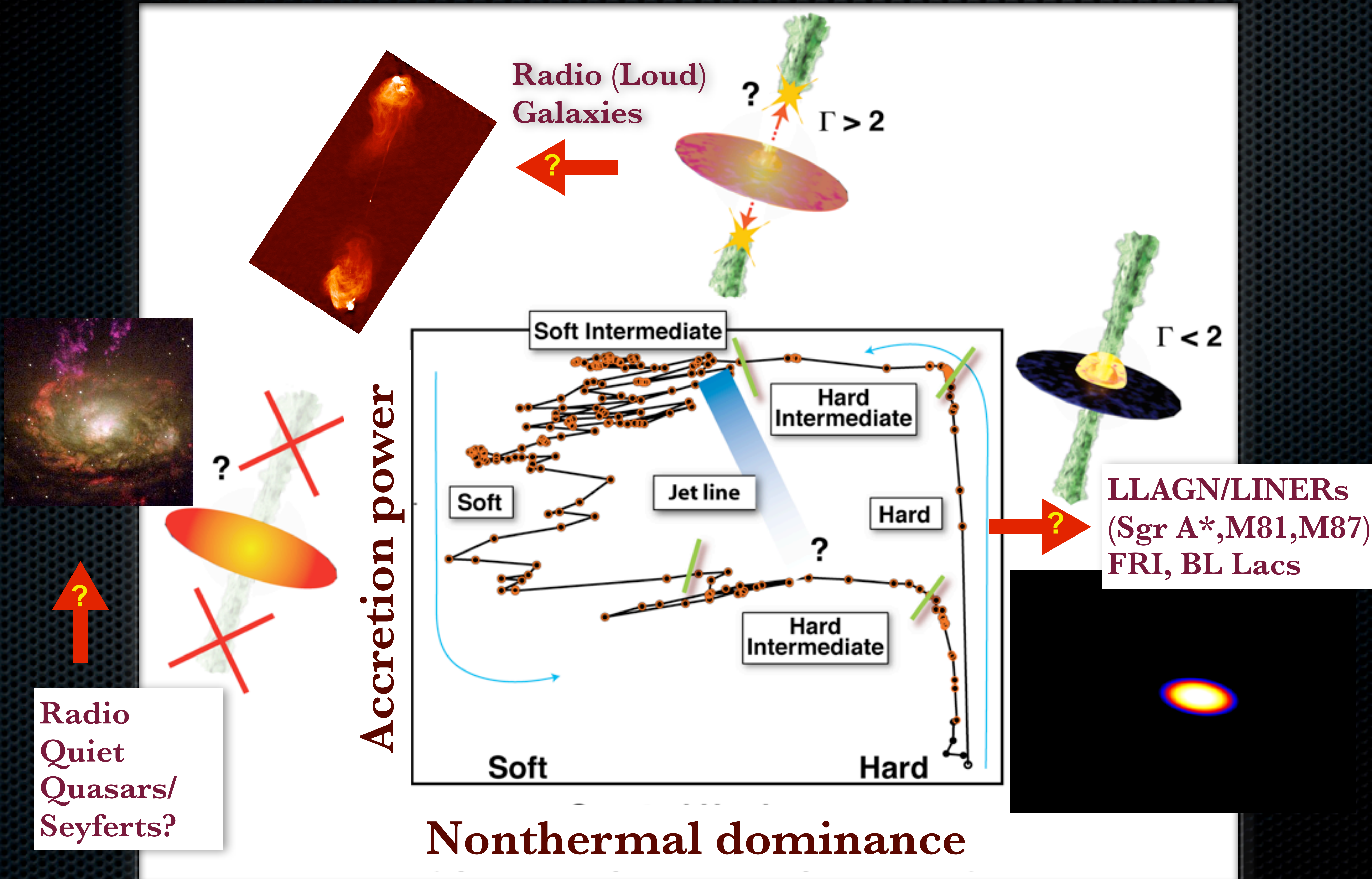


Time variable XRB behavior: The HID
There are also winds



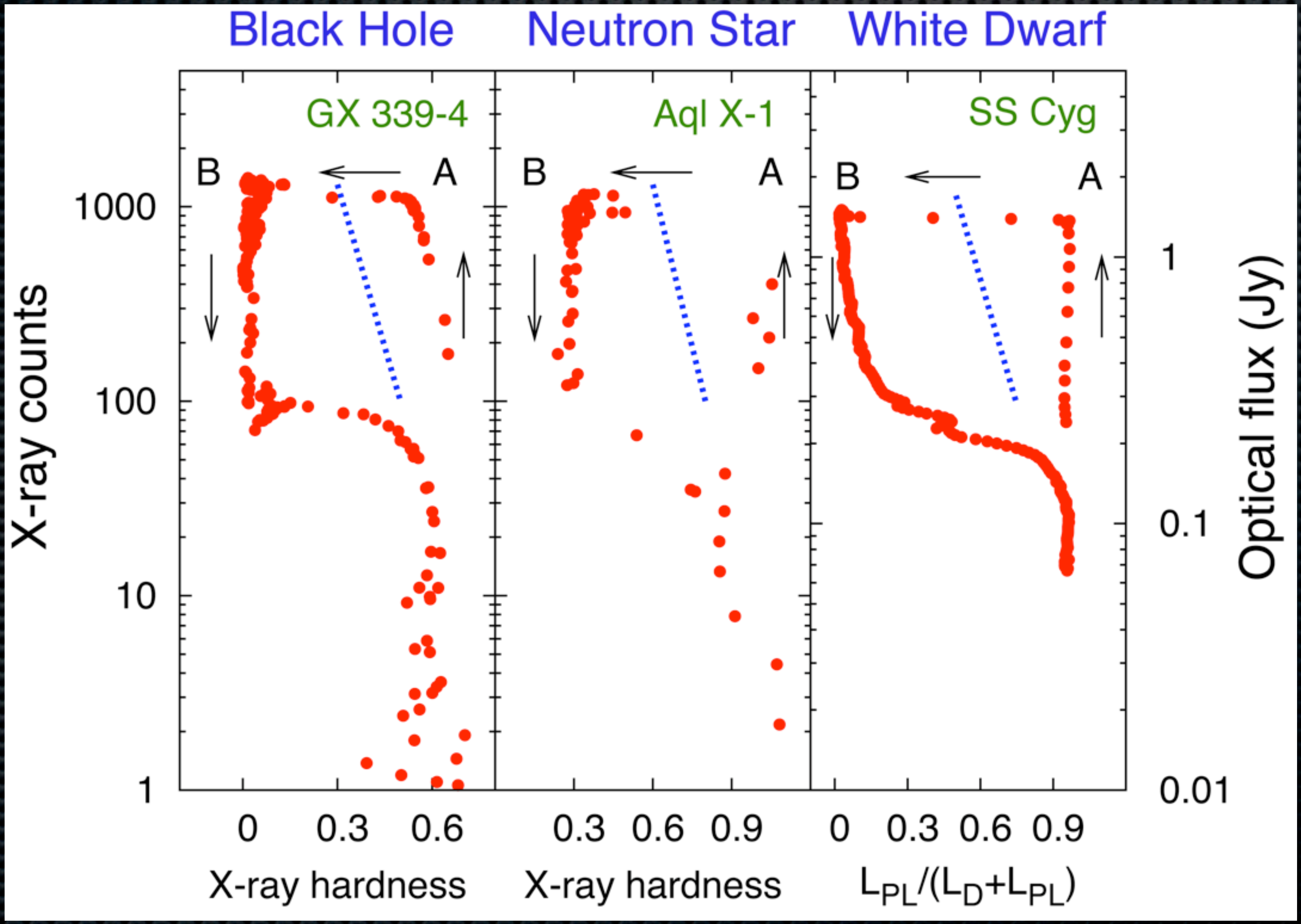
(Ponti et al. 2012)

Mapping XRB states ⇔ AGN classes?



Why might this be applicable to AGN?

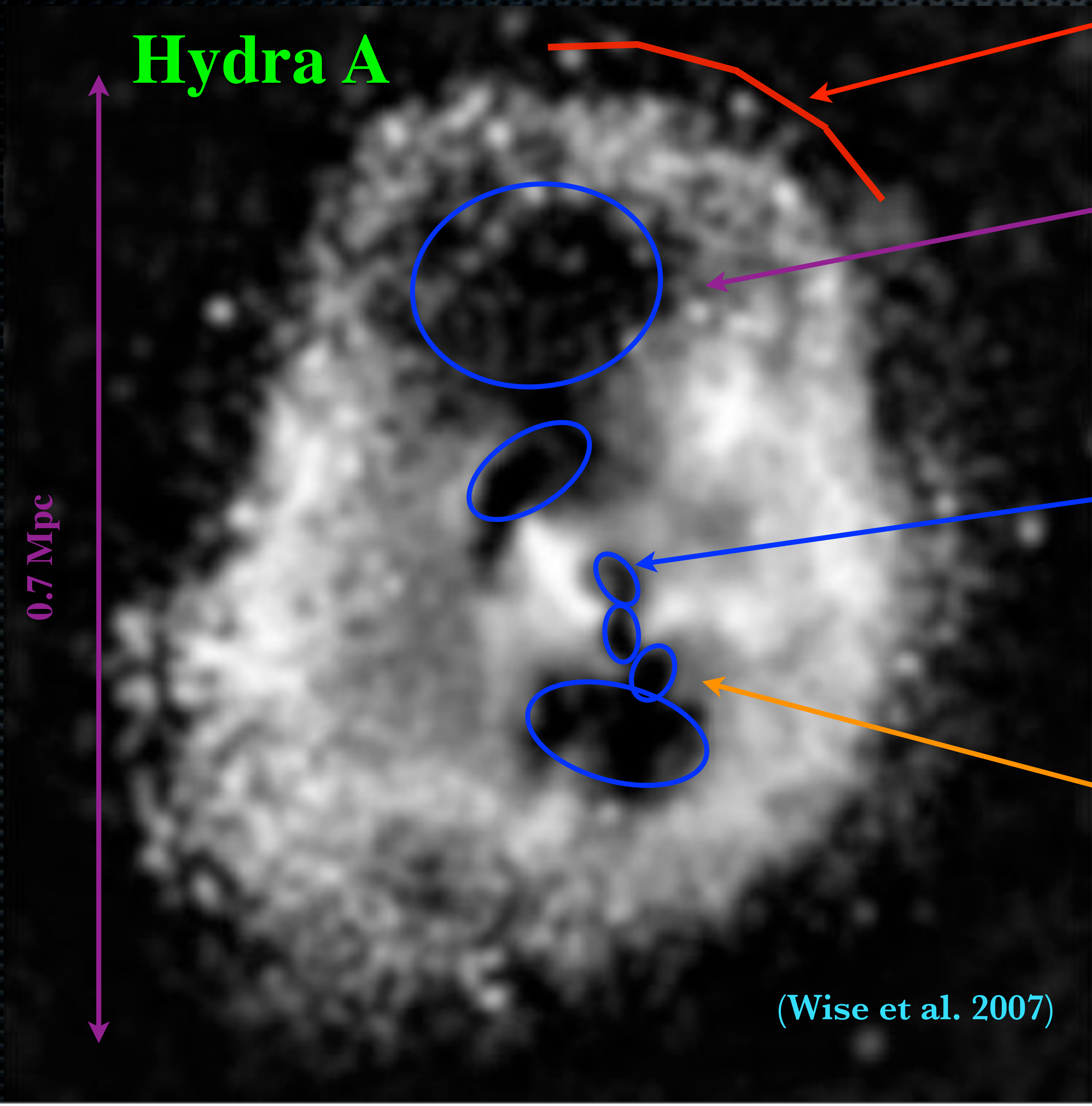
- Neutron stars and white dwarfs show a similar outburst evolution as XRB BHs!



(Körding et al. 2008, Science)

Why might this be applicable to AGN?

Shock

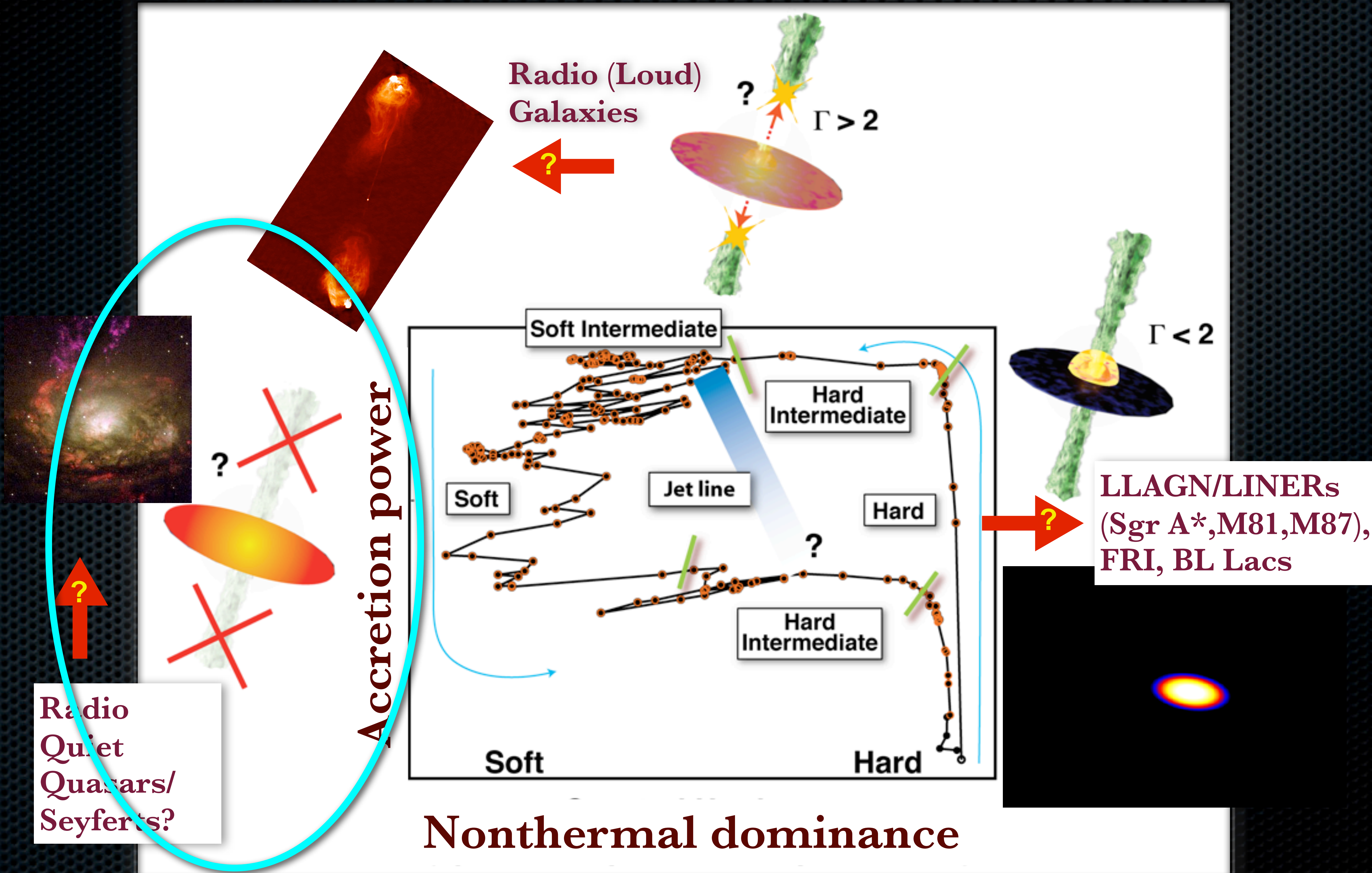


R ~ 100-225 kpc
D ~ 120-200 kpc
t > 200 Myr

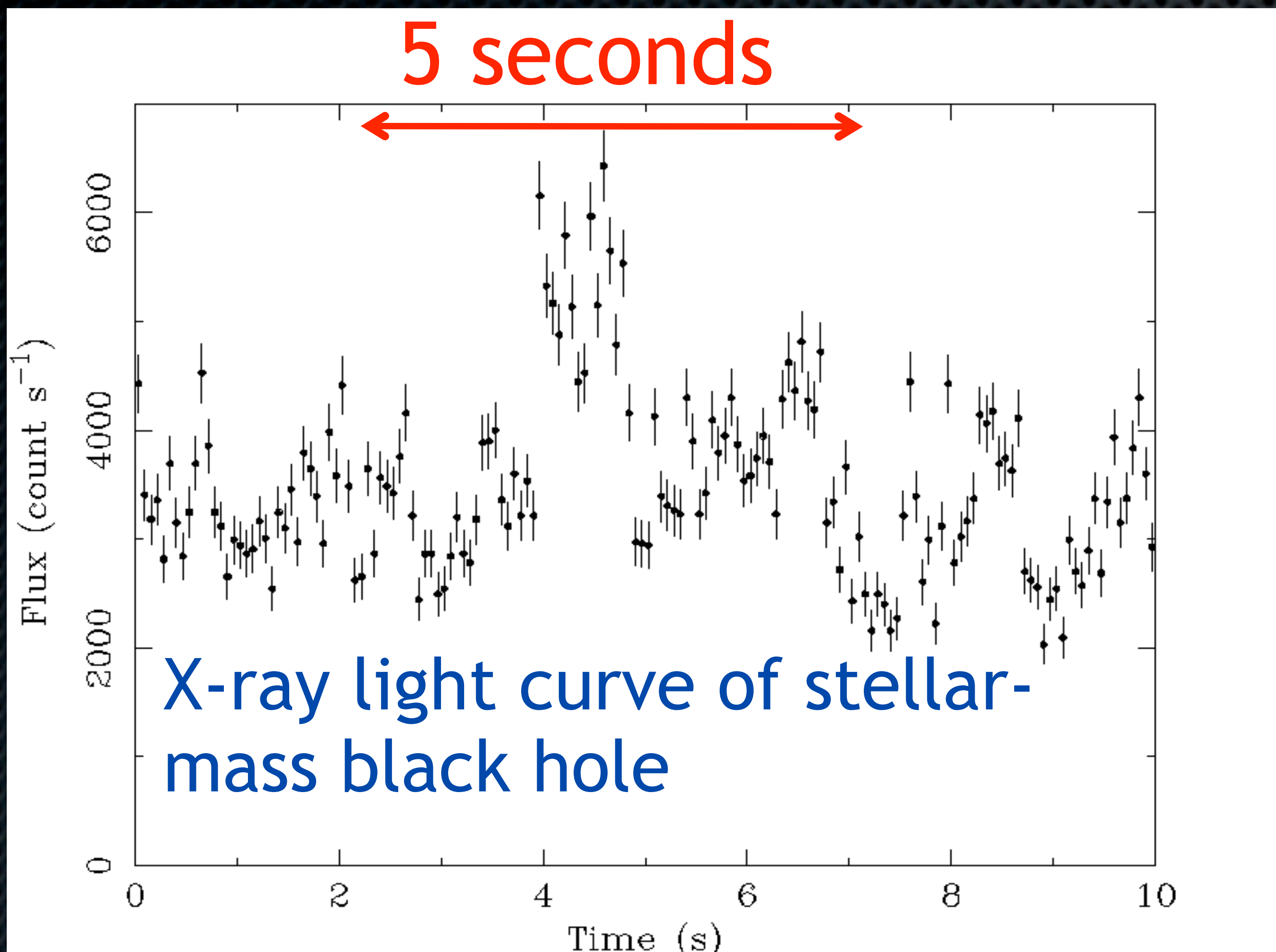
R ~ 30 kpc
D ~ 30-40 kpc
t ~ 50 Myr

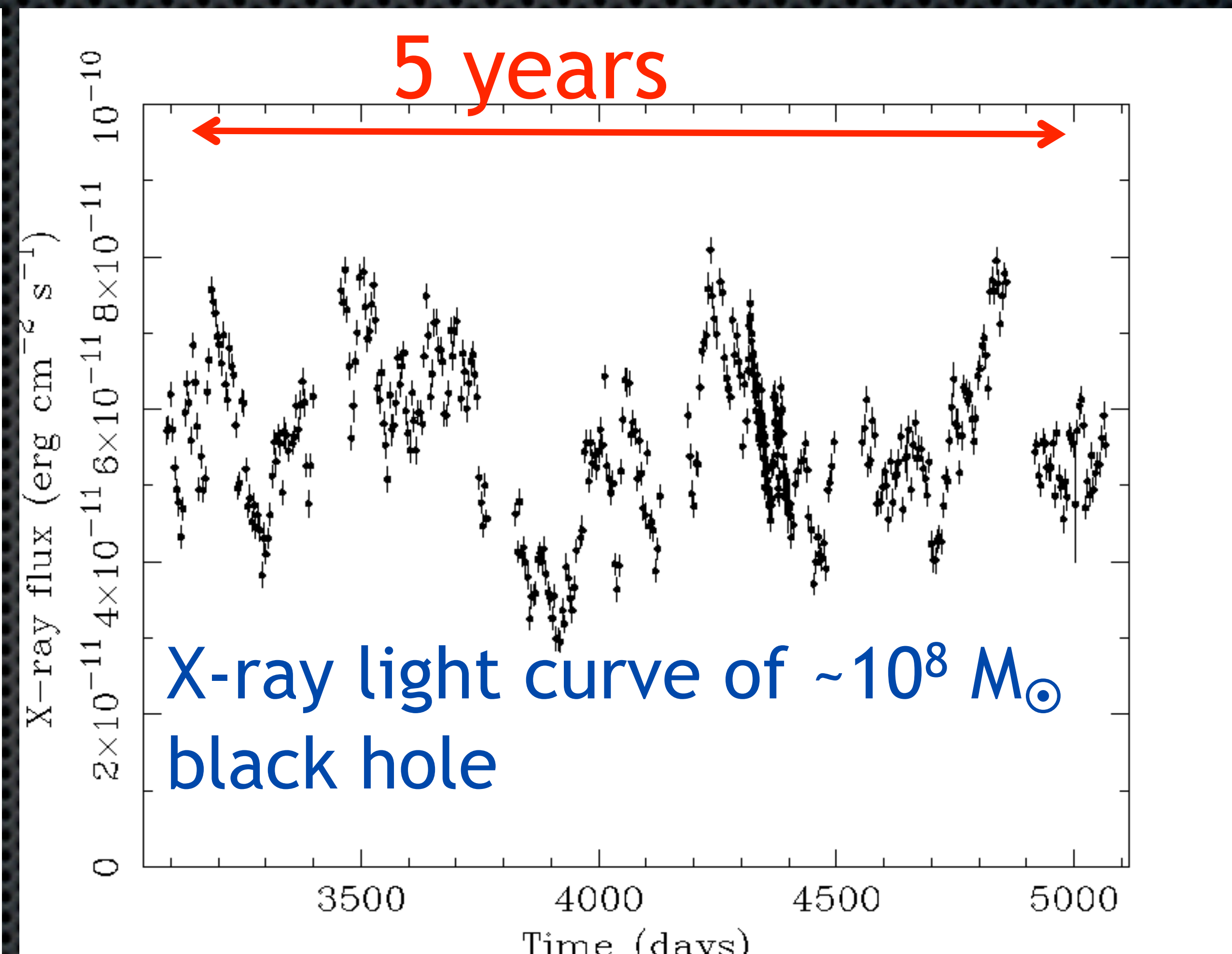
R ~ 60-100 kpc
D ~ 50-80 kpc
t ~ 100 Myr

Mapping XRB states ⇔ AGN classes?



Mass/power scalings in disk-dominated states – X-ray variability

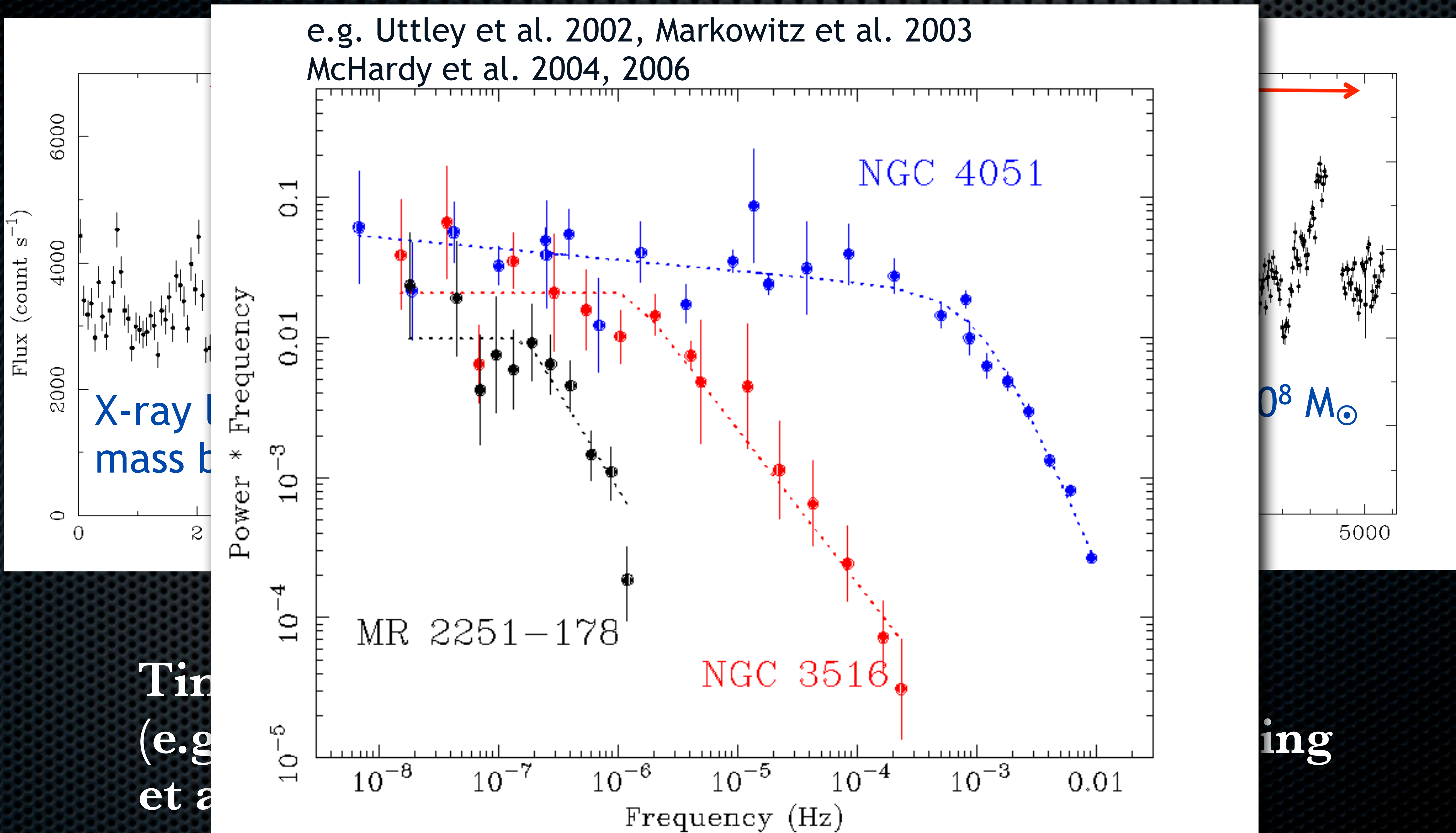




Time-scales scale linearly with BH mass (e.g. Uttley et al. 2002, McHardy et al. 2006, Körding et al. 2007)

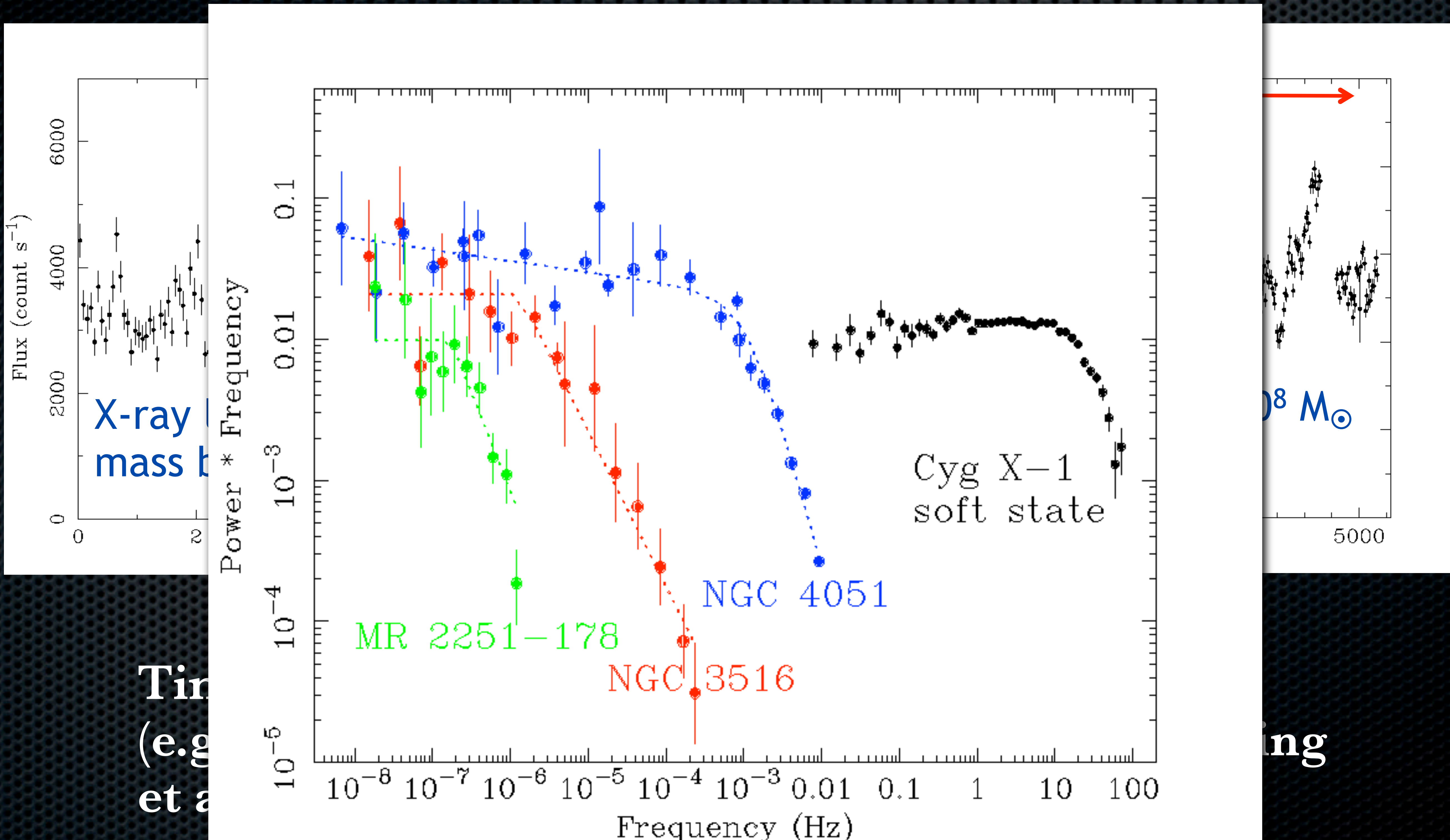
$>10^8\ M_\odot$ $\quad$ $4\times10^7\ M_\odot$ $\quad$ $10^6\ M_\odot$

Mass/power scalings in disk-dominated states – X-ray variability



$>10^8\ M_\odot$ $4\times10^7\ M_\odot$ $10^6\ M_\odot$

Mass/power scalings in disk-dominated states – X-ray variability



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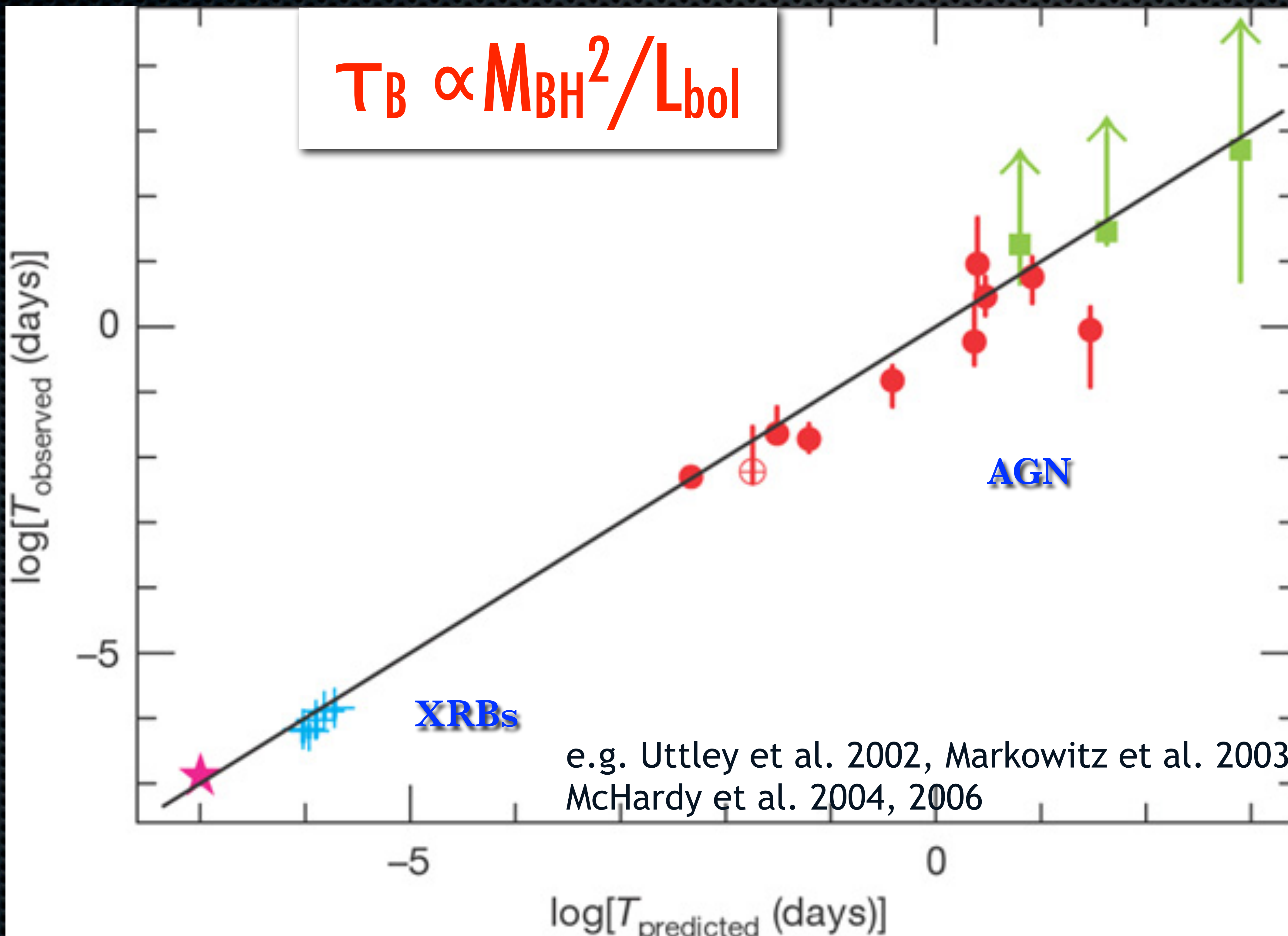
>10^8 M⊙ 4×10^7 M⊙ 10^6 M⊙

Mass/power scalings in disk-dominated states – X-ray variability



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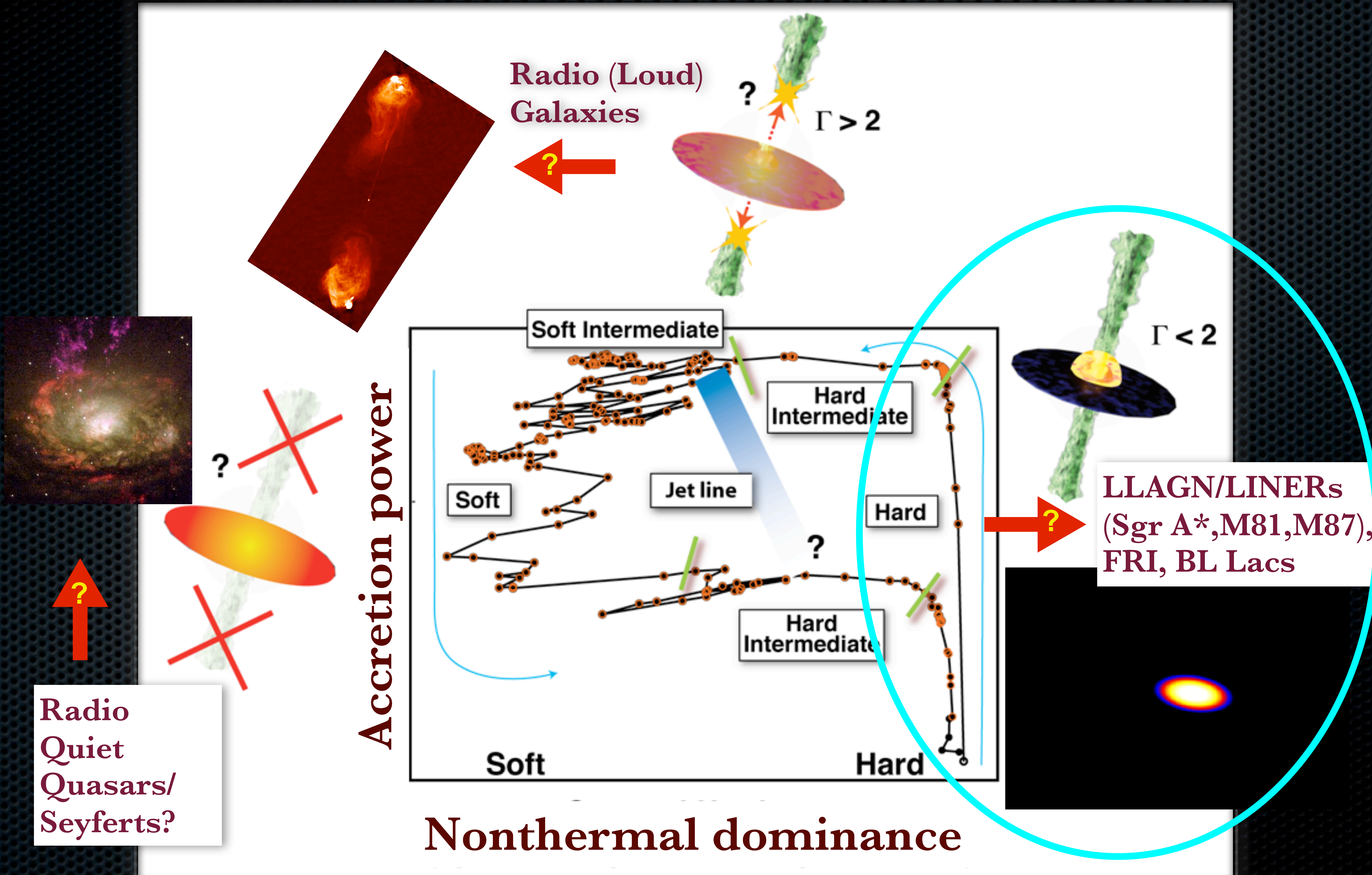
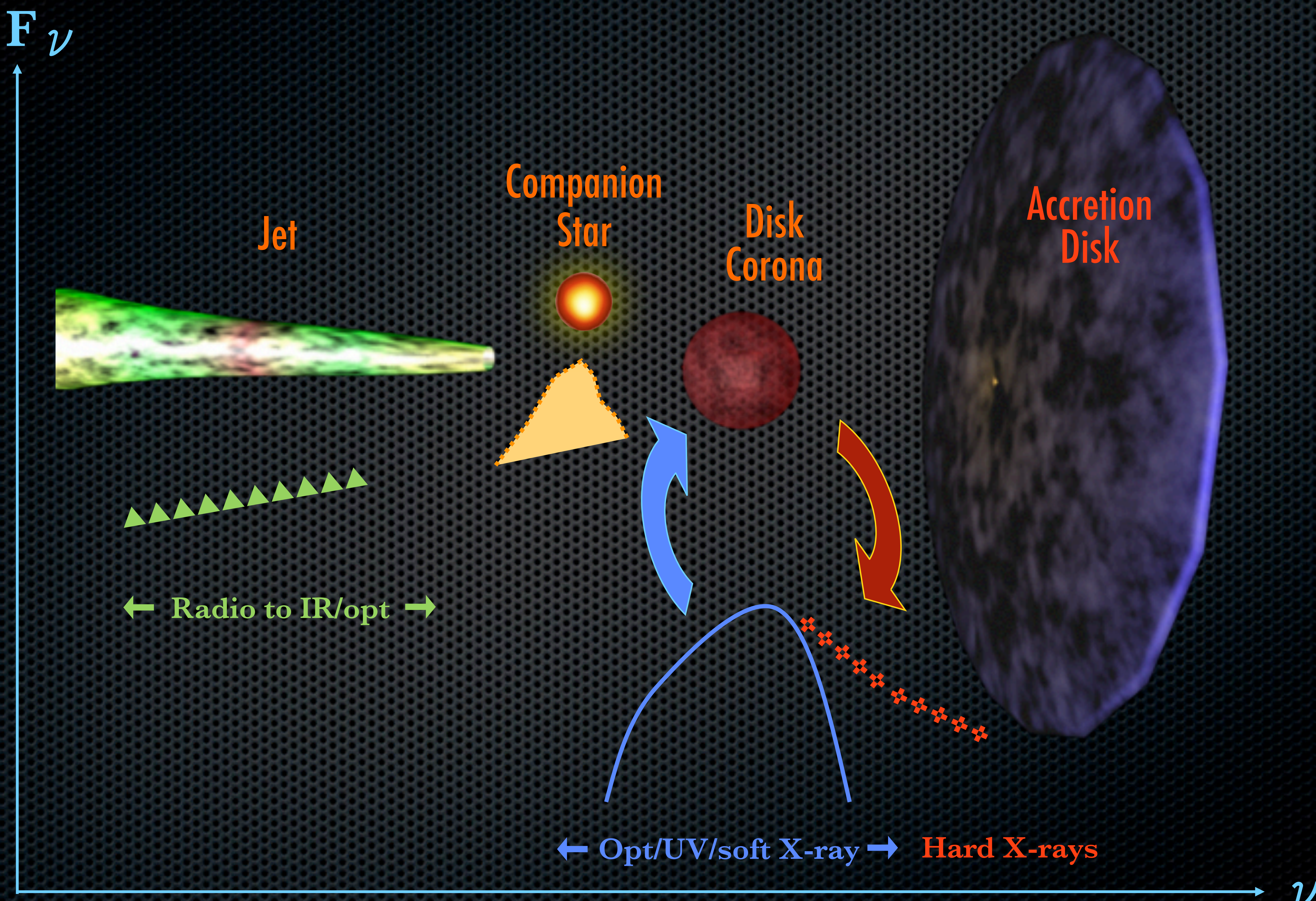


Decomposition of hard/jet-dominated XRB state



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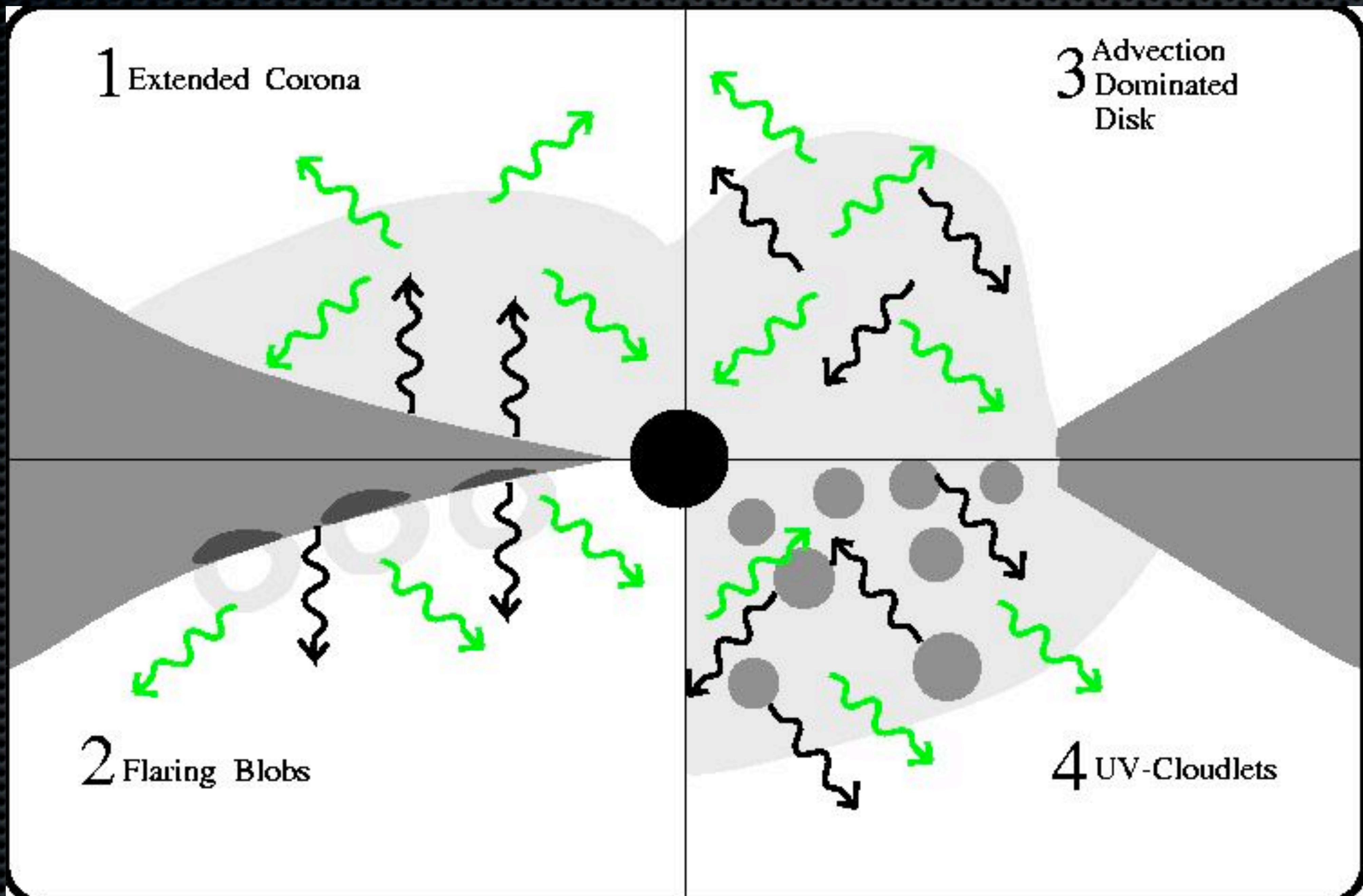
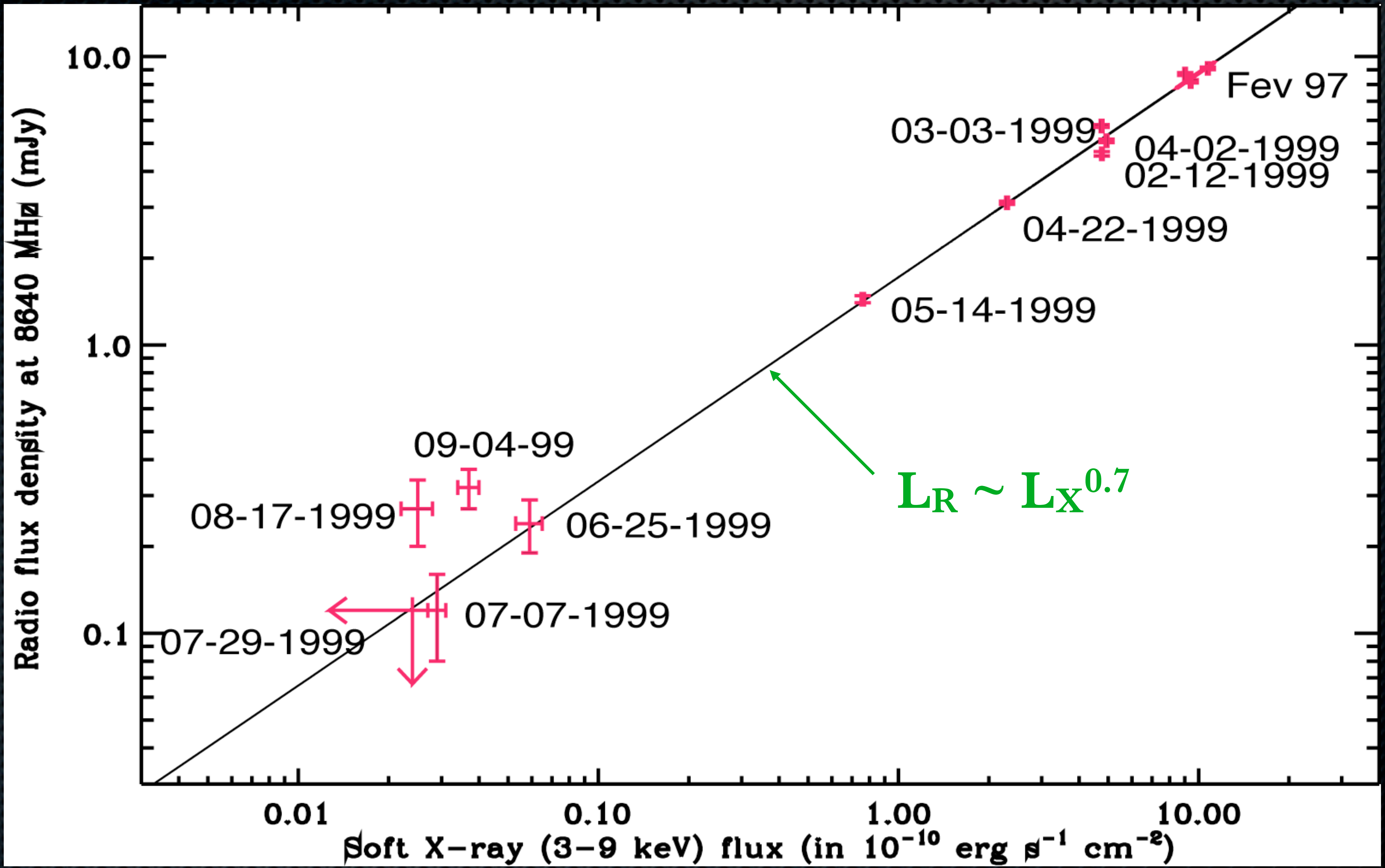


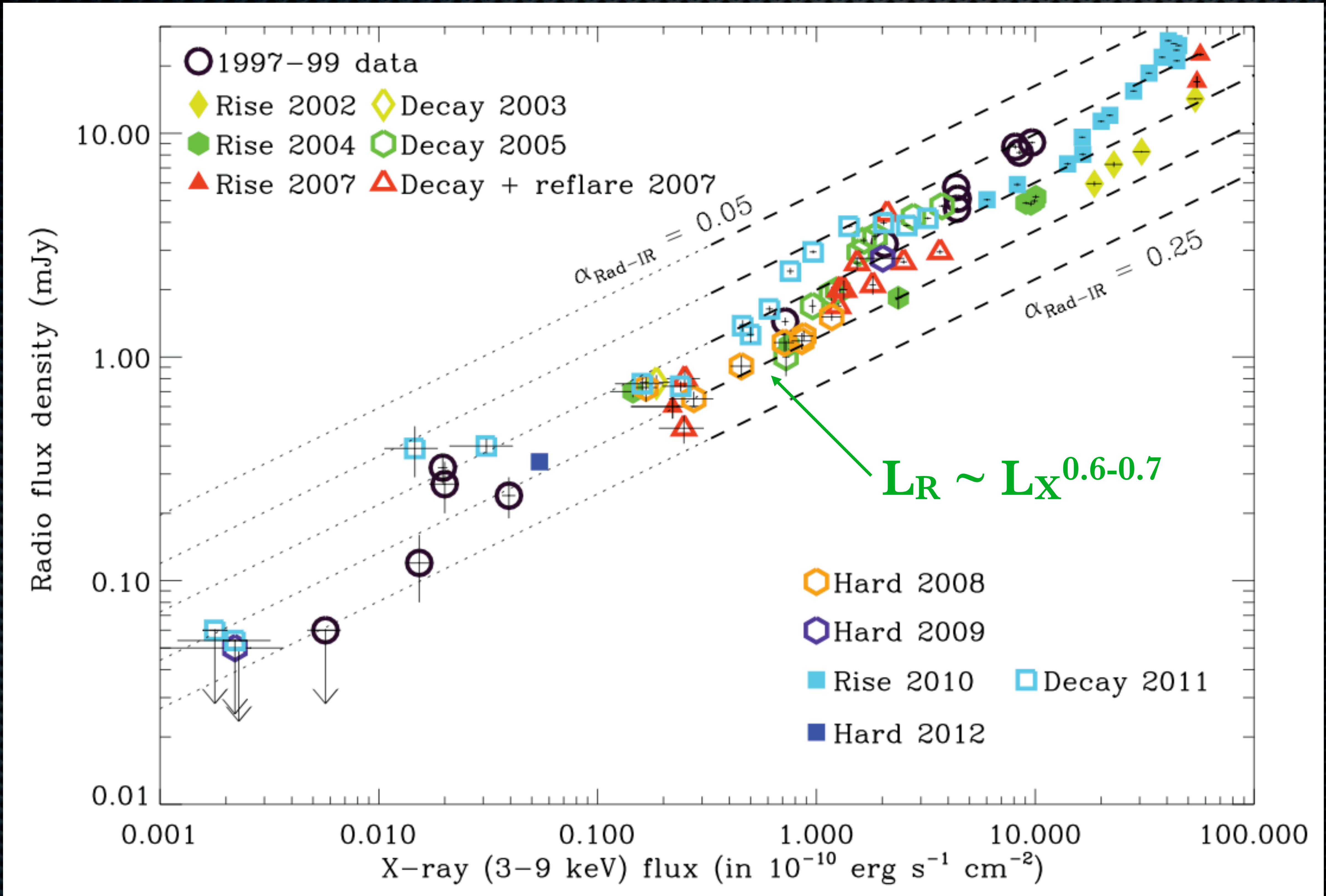
(e.g., Haardt & Maraschi 1991; Magdziarz & Zdziarski 1995; Haardt 1997; Esin et al. 1997)

XRB hard state -- "Universal" Radio/X-ray Correlation



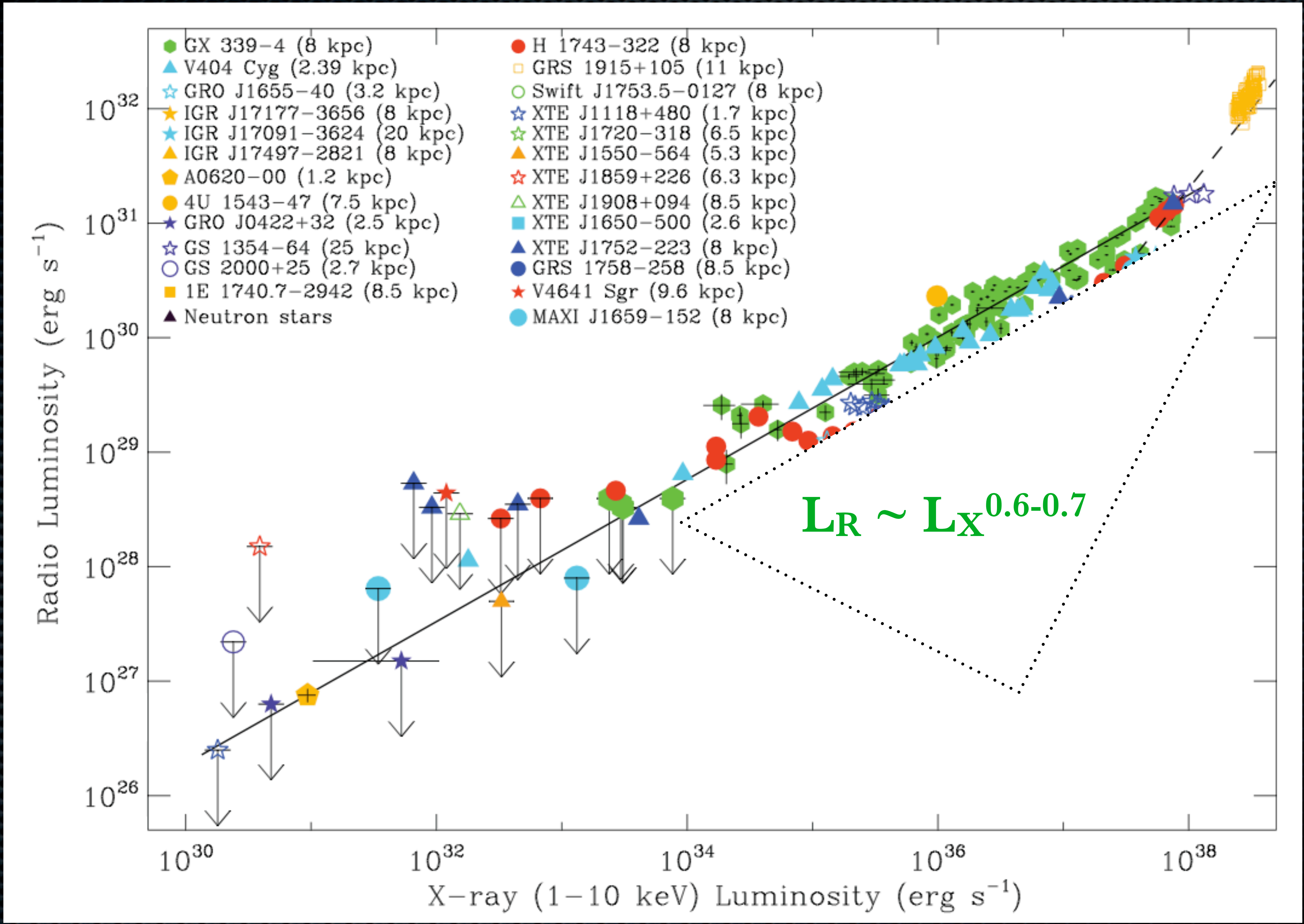
(Corbel et al. 2000, 2003; Markoff et al. 2003)

XRB hard state -- "Universal" Radio/X-ray Correlation



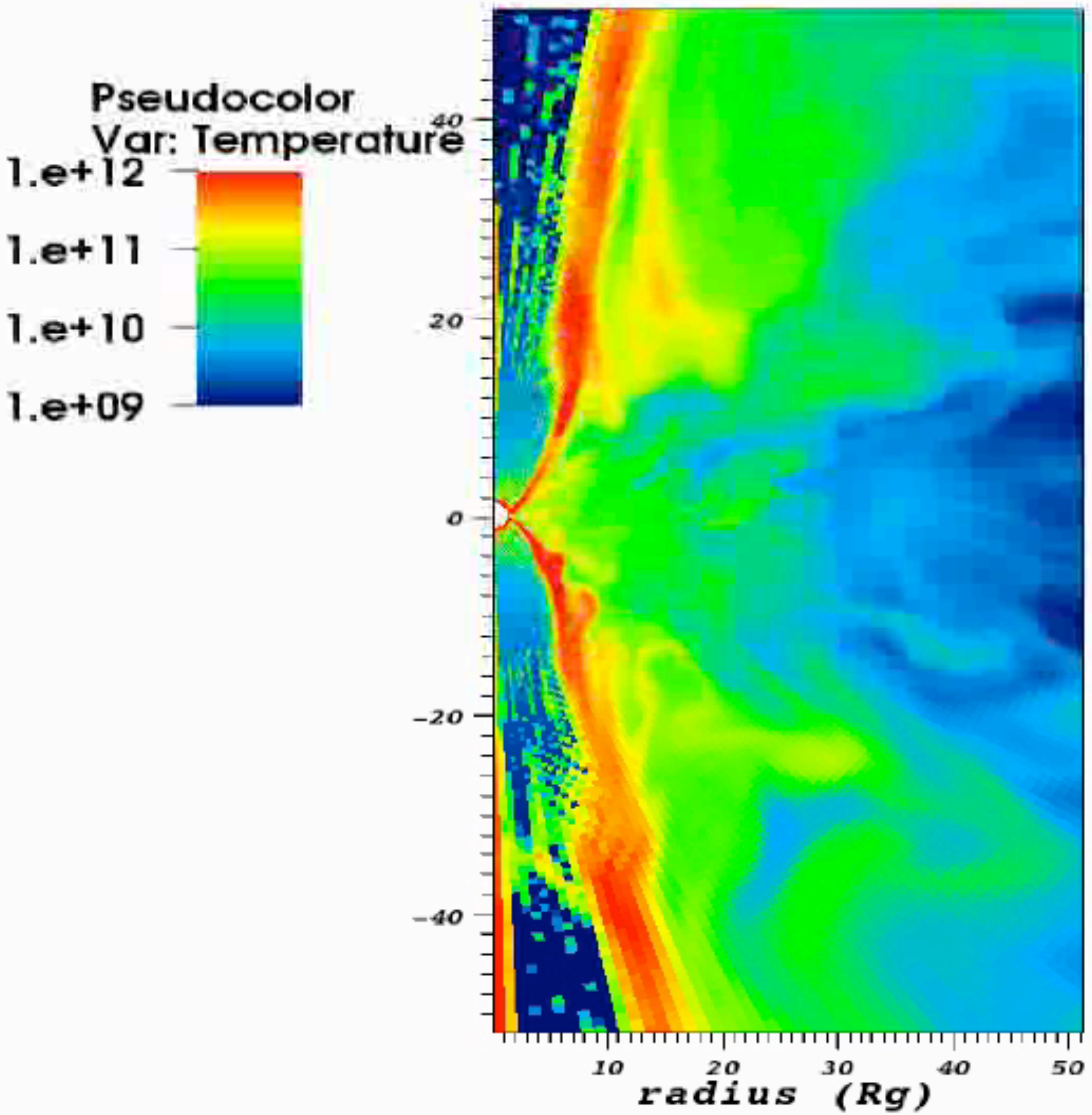
(Corbel et al. 2013)

XRB hard state -- “Universal” Radio/X-ray Correlation



(Corbel et al. 2013)

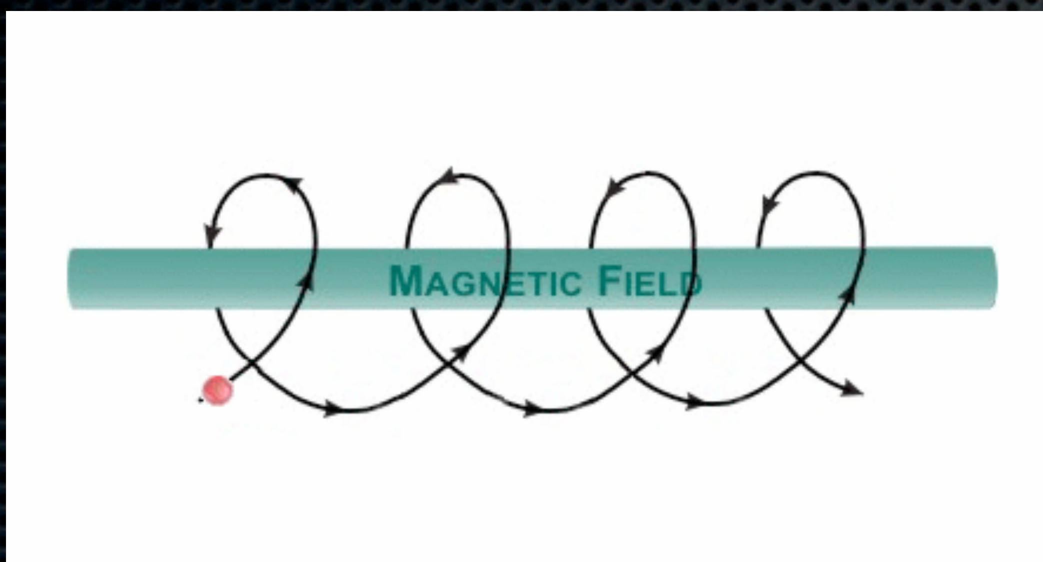
XRB hard state -- Reveals role of magnetic fields?

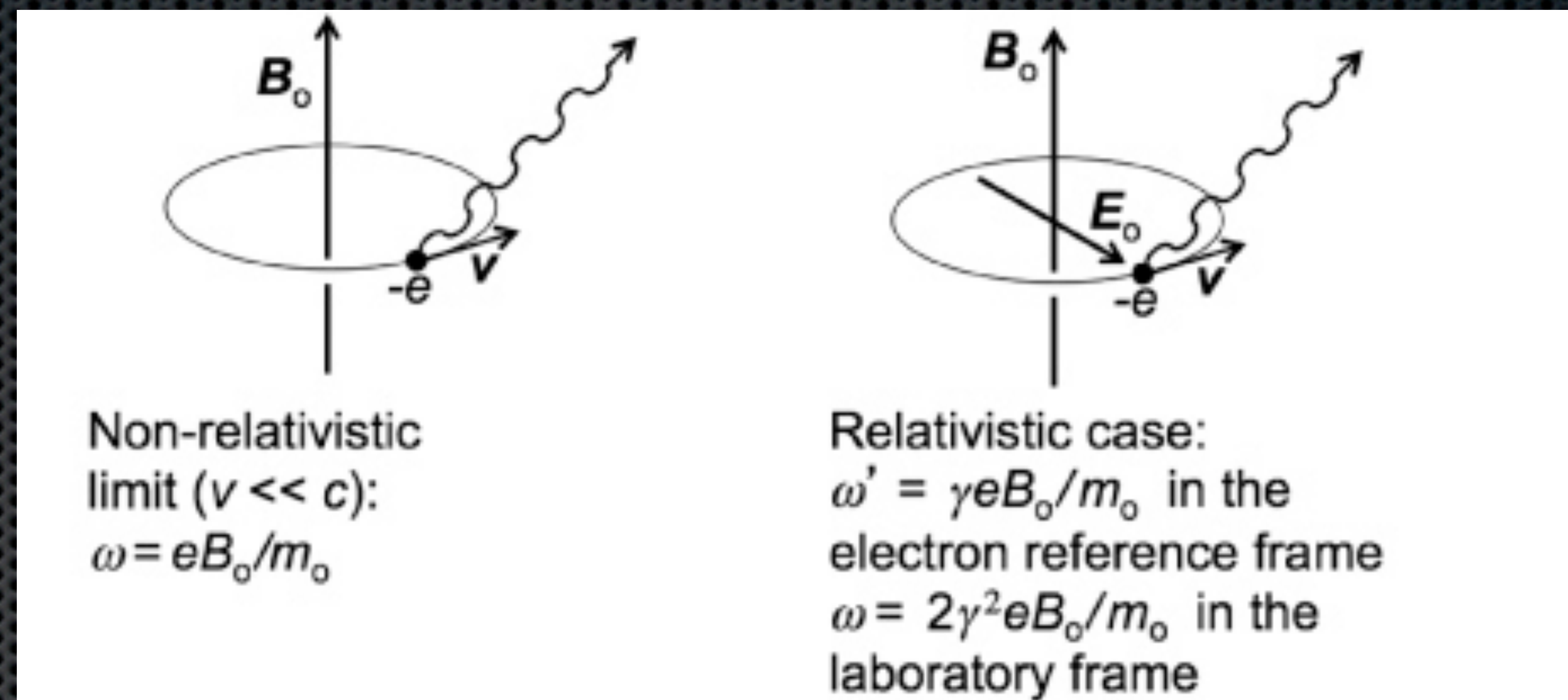


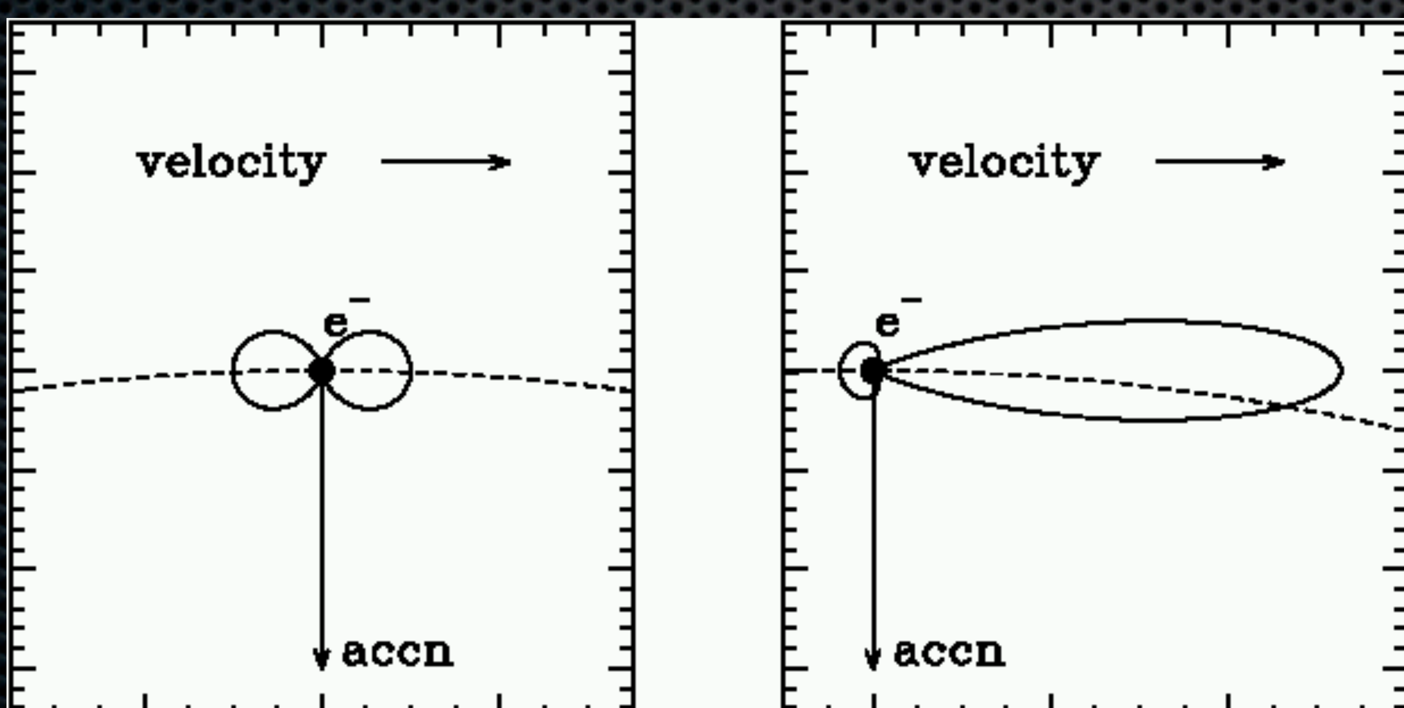
Quick and dirty synchrotron theory

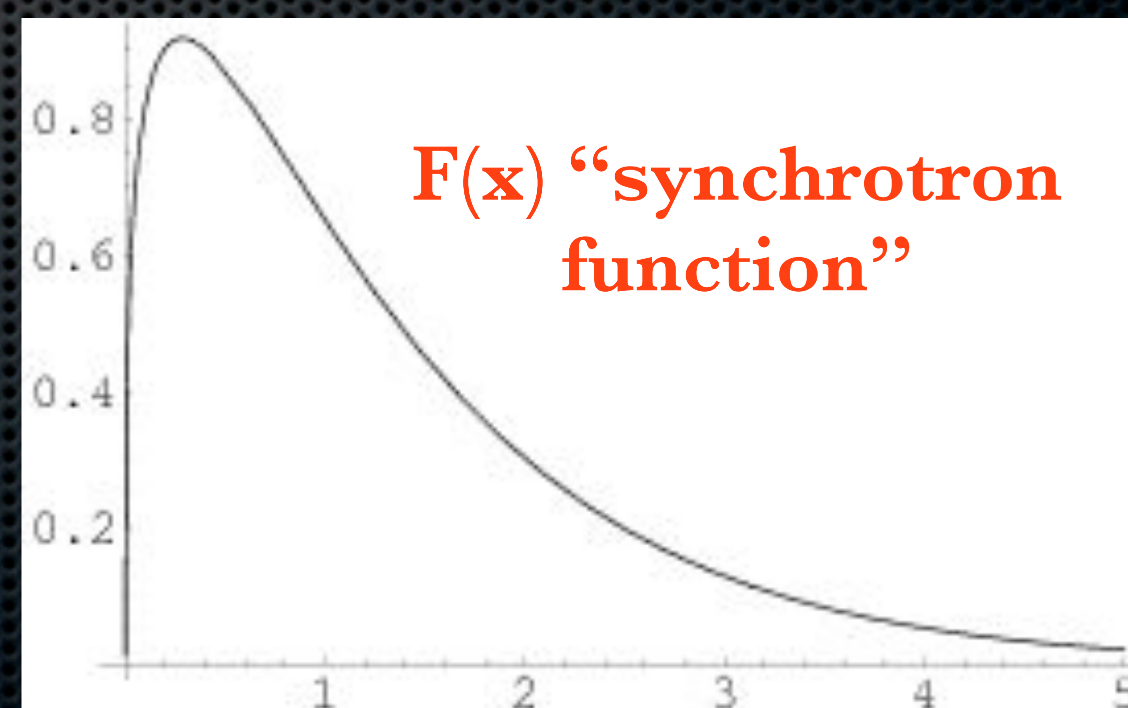
a) How does a single electron moving in a magnetic field emit?

F=ma=e/c (v x B)



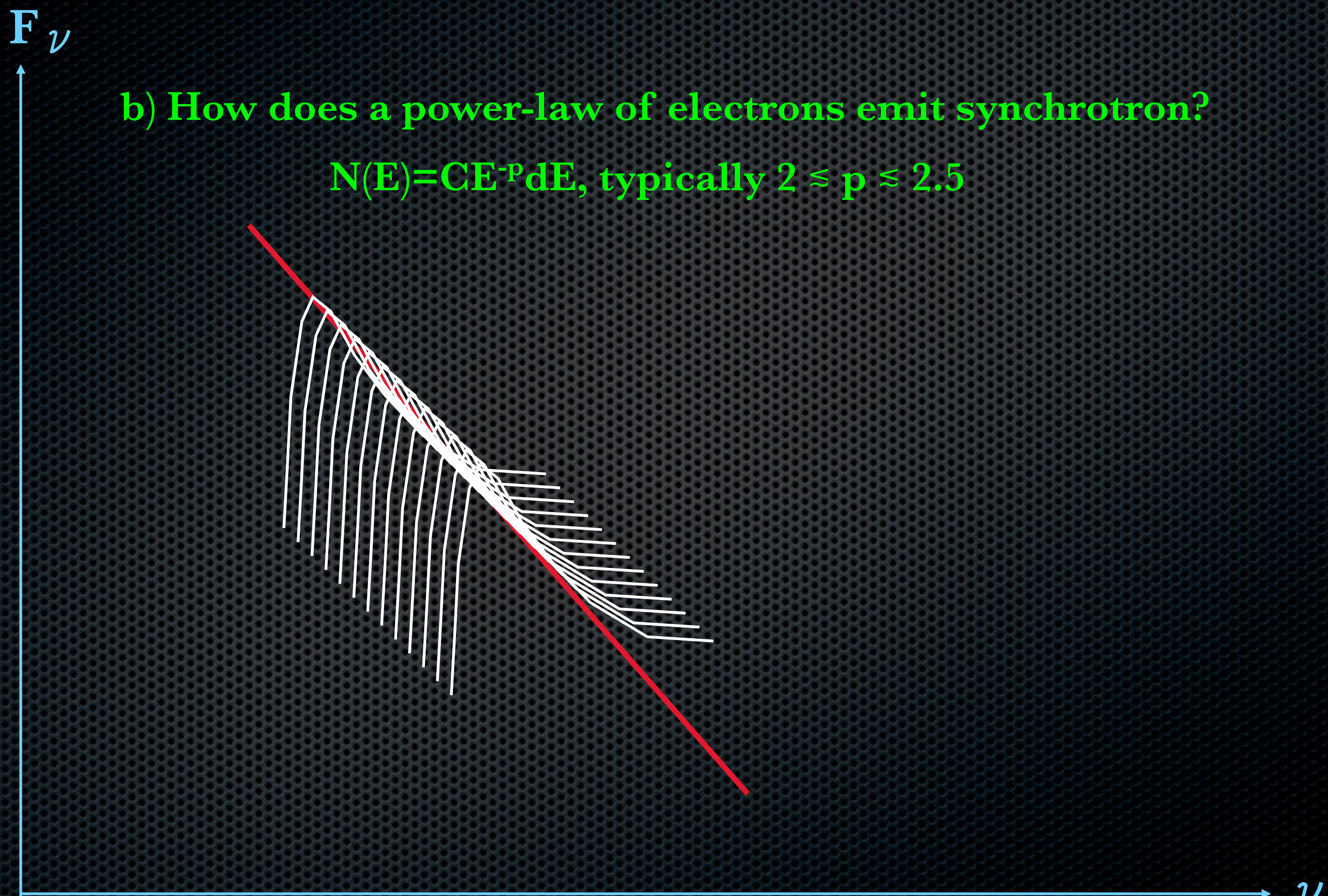






(See, e.g., Rybicki & Lightman 1979)

Quick and dirty synchrotron theory



b) How does a power-law of electrons emit synchrotron?

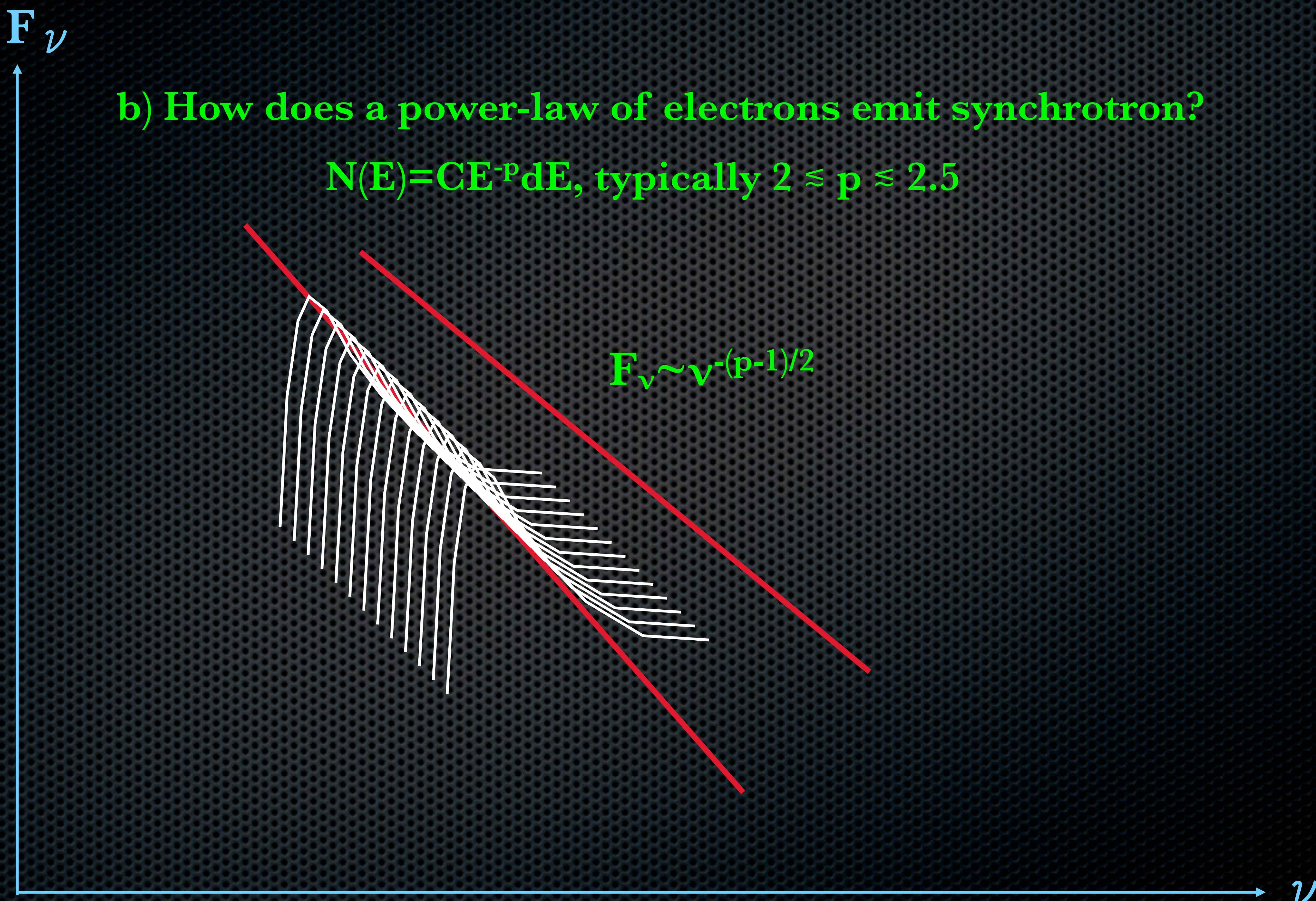
$N(E)=CE^{-p}dE$, typically $2 \lesssim p \lesssim 2.5$

(See, e.g., Rybicki & Lightman 1979)

Quick and dirty synchrotron theory

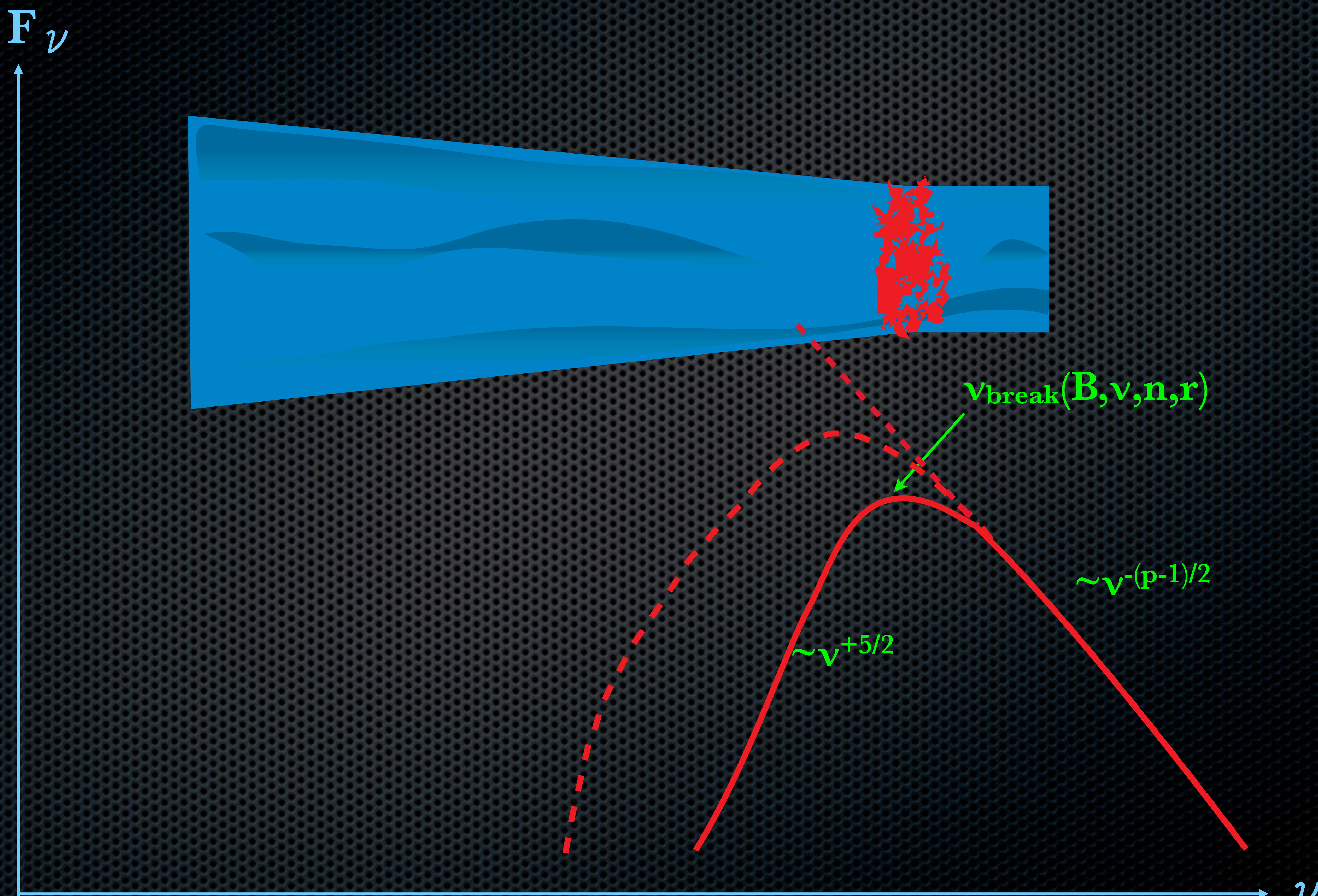
b) How does a power-law of electrons emit synchrotron?

$N(E) = CE^{-p}dE$, typically $2 \lesssim p \lesssim 2.5$



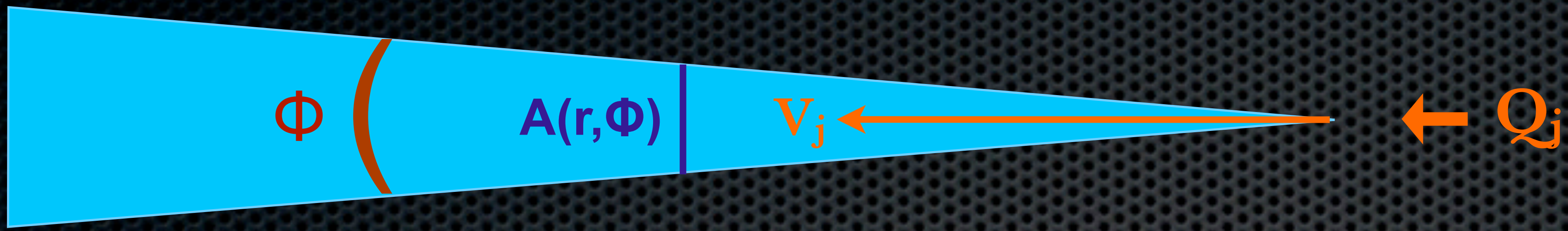
(See, e.g., Rybicki & Lightman 1979)

Synchrotron emission in an optically thick (compact) jet



(Blandford & Königl 1979)

So how does a flat/inverted synchrotron spectrum arise?



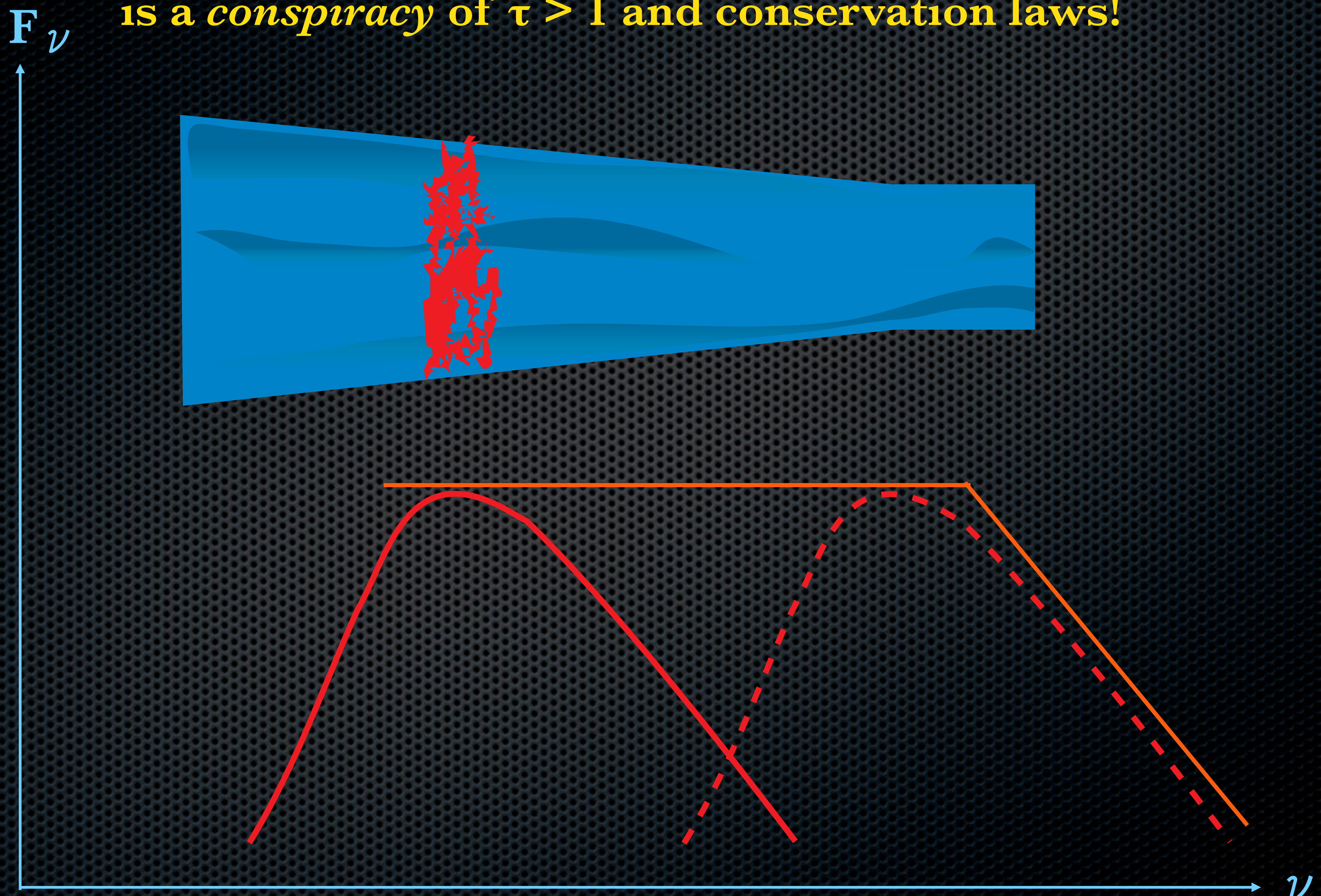
- Convert input power into energy density: $\dfrac{Q_j}{\pi r_0^2 \beta_j \gamma_j c} = U_B + U_p + U_e$
- Make a choice about energy partition (and fix it, e.g.): $U_p = U_B + U_e$
  - Conservation of particle and magnetic fluxes ➠ $B \propto r^{-1}$, $n \propto r^{-2}$
  - Assume particles have PL: $N(E) \sim CE^{-p}$, fixed energy partition ➠ $C \propto n \propto B^2$
- Assume optically thick, for PL of electrons: $\alpha_\nu \propto CB^{(p+2)/2}\nu^{-(p+4)/2}$
- The part we see is at photosphere where $\tau \sim \alpha_\nu r = 1 \Rightarrow \alpha_\nu \propto 1/r$
- Assume "canonical" PL index $p=2$, substitute C, B in α_ν in terms of r:

$$\frac{1}{r} \propto \left(\frac{1}{r}\right)^2 \left(\frac{1}{r}\right)^2 \nu^{-3} \Longrightarrow r \propto \nu^{-1}$$

☛ $$F_\nu \propto CB\left(\frac{\nu}{B}\right)^{-(p-1)/2} r^3 \propto (r\nu)^{-0.5} \propto \text{constant!}$$

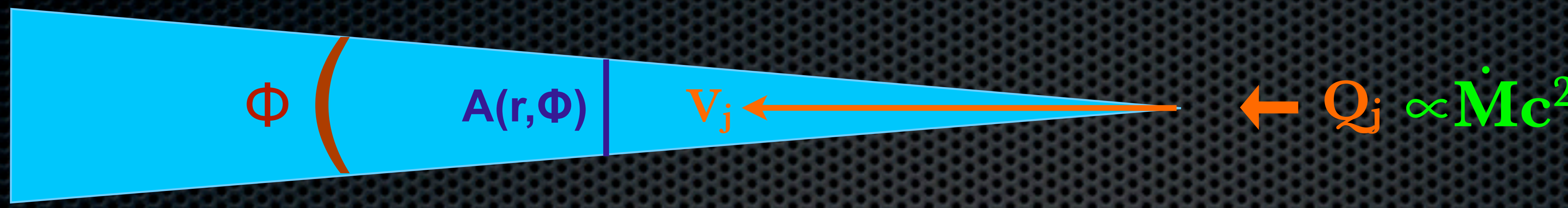
(Blandford & Königl 1979; Rybicki & Lightman 1979)

"Signature" flat(ish) emission of compact jets ("cores") is a *conspiracy* of $\tau > 1$ and conservation laws!



(Blandford & Königl 1979)

Deriving the “Blandford Königl” jet dependence on $\dot{M}$



$$\frac{Q_j}{\pi r_0^2 \beta_j \gamma_j c} = U_B + U_p + U_e \quad \Longrightarrow \quad C \sim n \sim B^2 \propto \dot{M}/M^2$$

$$U_p = U_B + U_e$$

$$j_\nu \propto C B^{(p+1)/2} \nu^{-(p-1)/2} \qquad \alpha_\nu \propto C B^{(p+2)/2} \nu^{-(p+4)/2}$$

$$S_\nu \propto \xi(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu$$

$$F_\nu = \int_{r_g}^{\infty} dr R_r S_\nu(r) = F_\nu(M, \dot{m}, a, \nu, \theta)$$

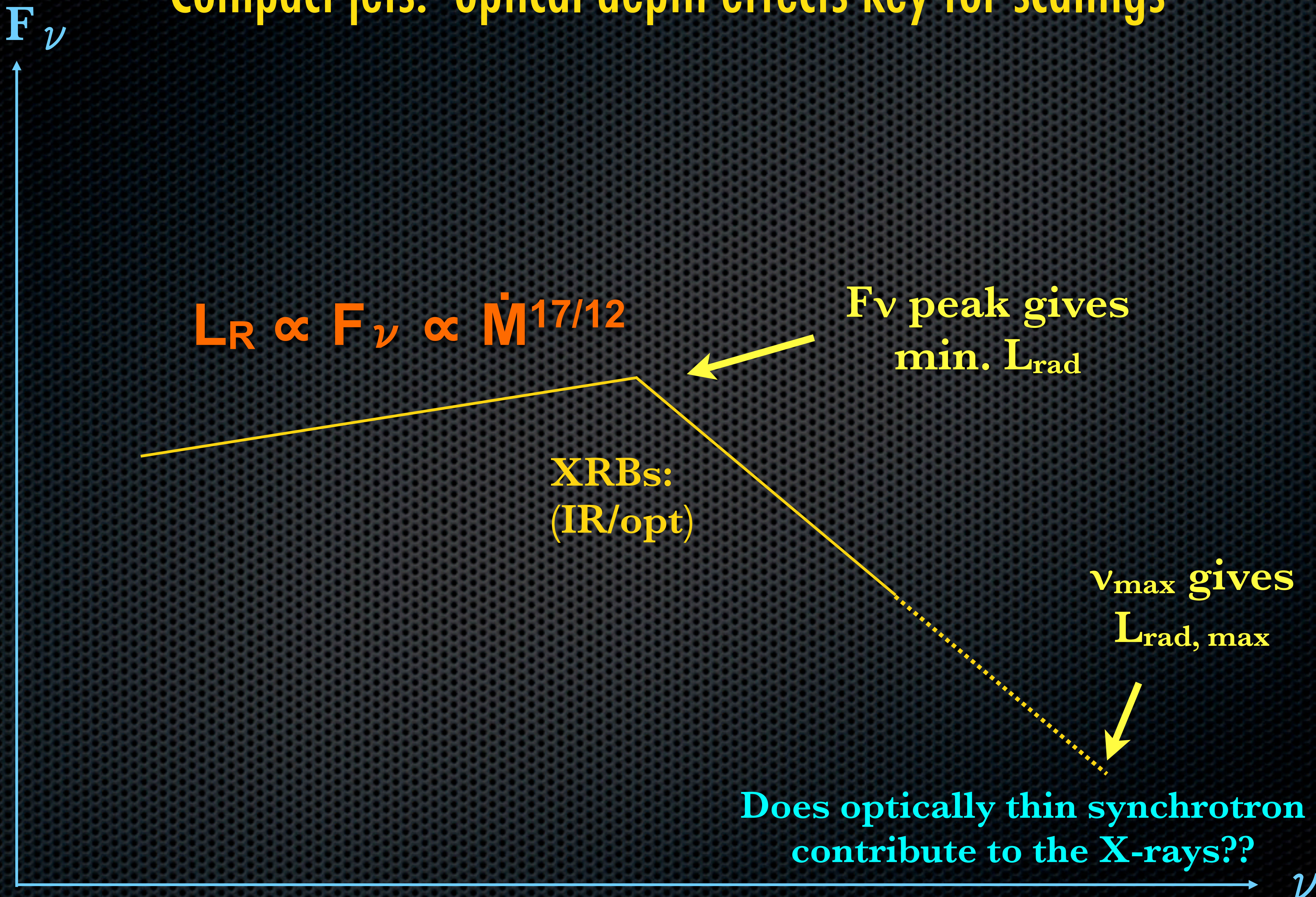
(taking p=2)

If perfectly “flat”

$$\frac{\partial \ln F_\nu}{\partial \ln \dot{m}} \equiv \xi_{\dot{m}} = \frac{2p + (p+6)\alpha_{RIR} + 13}{2(p+4)} \sim \frac{17}{12} + \cancel{\frac{2}{3}\alpha_{RIR}}$$

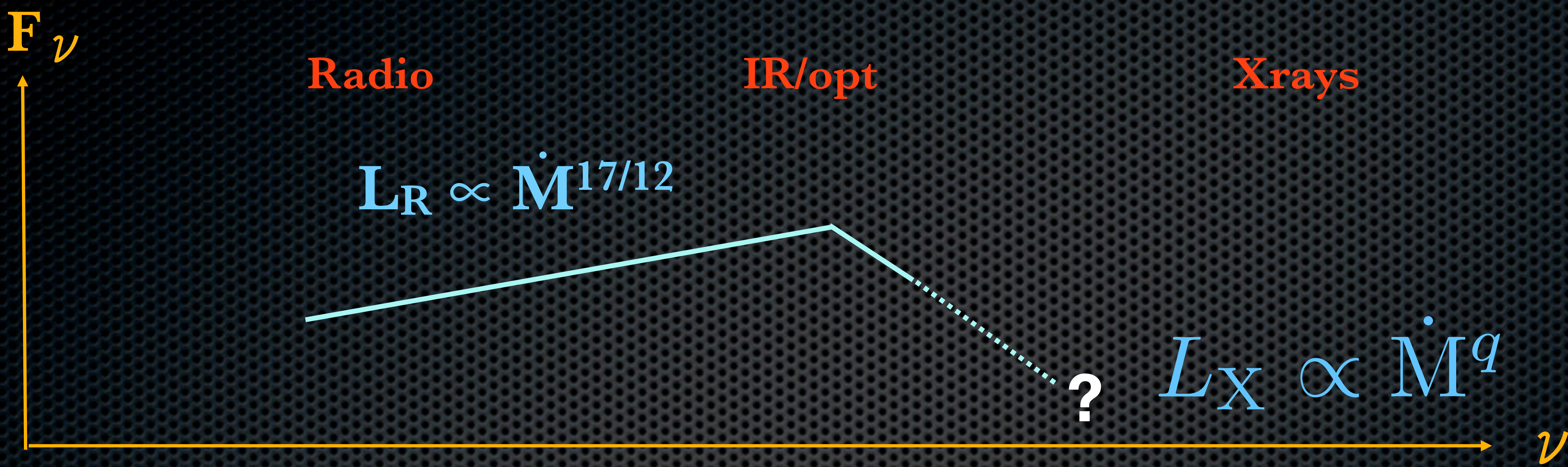
(Blandford & Königl 1979; Rybicki & Lightman 1979; Falcke & Biermann 1995; SM et al. 2003; Heinz & Sunyaev 2003)

Compact jets: optical depth effects key for scalings



(Blandford & Königl 1979, Falcke & Biermann 1995, SM et al. 2003, Heinz & Sunyaev 2003)

Radio/X-ray correlations constrain accretion efficiency!!



For objects with the *same* mass, i.e. ~XRBs:

$$L_\mathrm{R} \propto L_\mathrm{X}^m \qquad m = \frac{\frac{17}{12} - \frac{2}{3}\alpha_\mathrm{R}}{q} \approx \frac{1.4}{q}$$

Synchrotron: q=2, radiatively inefficient disks: q=2-2.3 (RIAFS= ADAFs, CDAFs, ADIOS: “puffy” gas pressure dominated accretion flows)

Radiatively efficient disk/corona: q=1 ➠ problematic

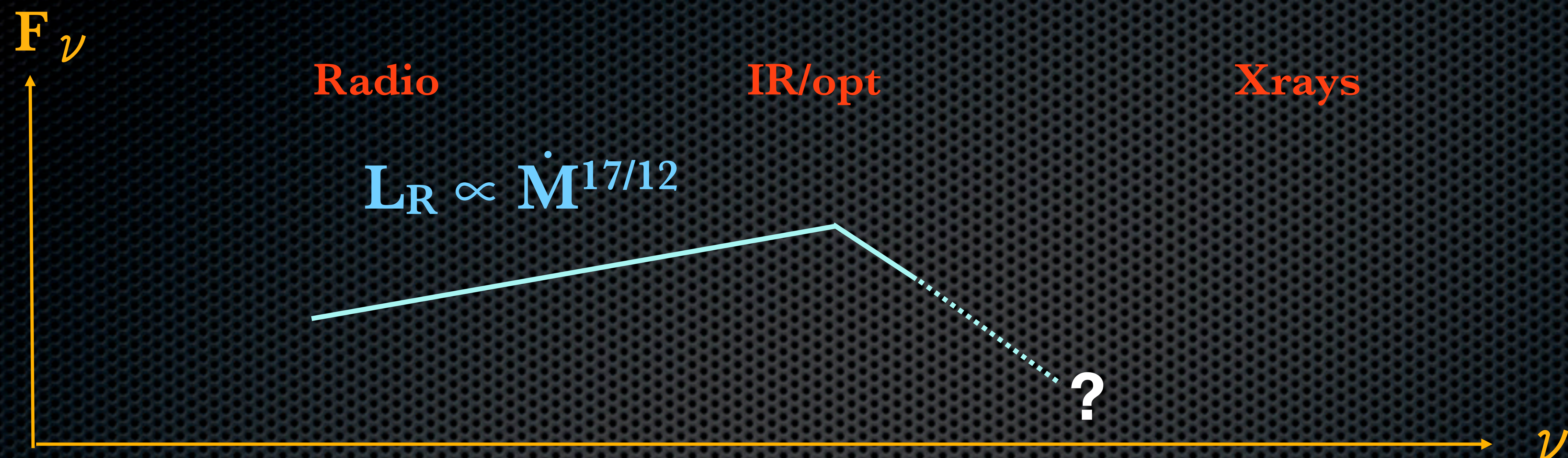
Cooling-dominated synchrotron, q=1 ➠ problematic

(Falcke & Biermann 1995, SM et al. 2003, Heinz & Sunyaev 2003)

Radio/Xray correlations turn out to be extremely revealing about the physical processes very close to the black hole...more so than the X-rays themselves, which was surprising!

How might the mass of the BH come into play here?

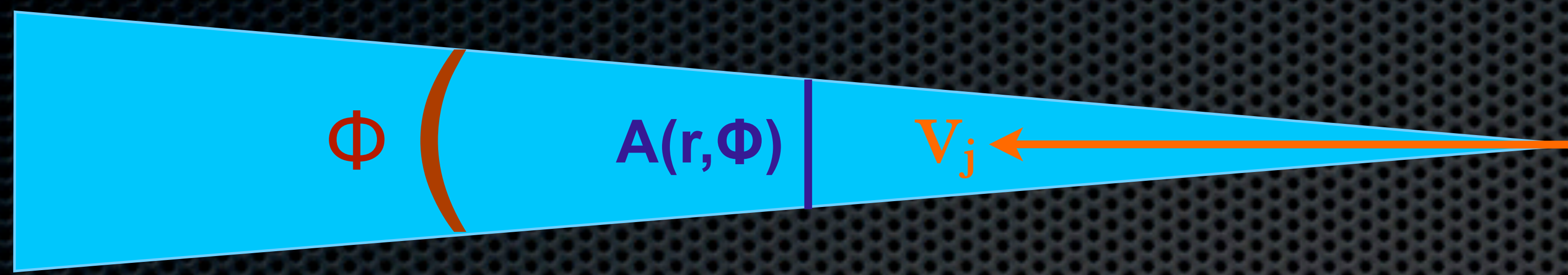
What do we expect the effect of mass to be??



- Think about switching to $\dot{m}=\dot{M}/\dot{M}_{Edd} \propto \dot{M}/M$!
- I.e., if we now think about an AGN with a mass 7 orders of magnitude higher, but at the same $\dot{m}_{Edd}$, and remembering that synchroton "peak" frequency $\nu_c \propto B$ …

Will the flux/break frequency be higher or lower?

Deriving the "Blandford Königl" jet dependence on M



← $Q_j \propto \dot{M}c^2$

$$C \sim n \sim B^2 \propto \dot{M}/M^2 \qquad j_\nu \propto C B^{(p+1)/2} \nu^{-(p-1)/2}$$

$$\alpha_\nu \propto C B^{(p+2)/2} \nu^{-(p+4)/2} \qquad S_\nu \propto \xi(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu$$

$$F_\nu = \int_{r_g}^{\infty} dr R_r S_\nu(r) = F_\nu(M, \dot{m}, a, \nu, \theta)$$

(taking p=2)

$$\nu_{SSA} \propto \left(M \phi_c \phi_B^{(p+2)/2} \right)^{2/(p+4)} \sim \dot{m}^{2/3} M^{-1/3} = \dot{M}^{2/3} M^{-1}$$

$$\frac{\partial \ln F_\nu}{\partial \ln M} \equiv \xi_M = \frac{2p + 13 + 2\alpha_{RIR}}{p+4} - \frac{1}{2}\left[\frac{2p + 3 + (p+2)\alpha_{RIR}}{p+4}\right] - \frac{5 + 2\alpha_{RIR}}{p+4}$$

$$\sim \frac{17}{12} - \cancel{\frac{\alpha_{RIR}}{3}}$$

If perfectly "flat"

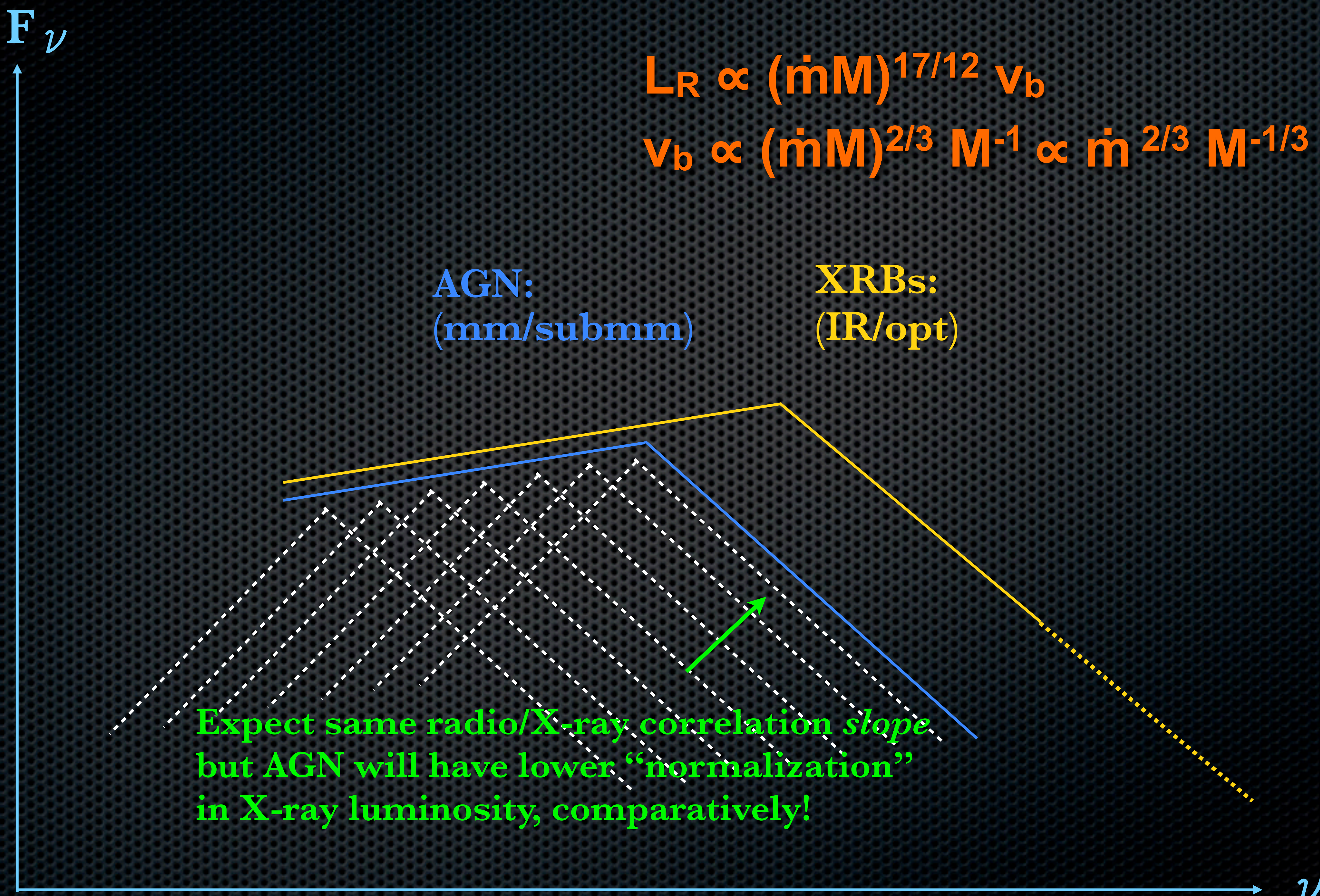
(~5/4 if optically thin)

(Blandford & Königl 1979; Rybicki & Lightman 1979; Falcke & Biermann 1995; SM et al. 2003; Heinz & Sunyaev 2003)

Compact jets: optical depth effects dominate scalings

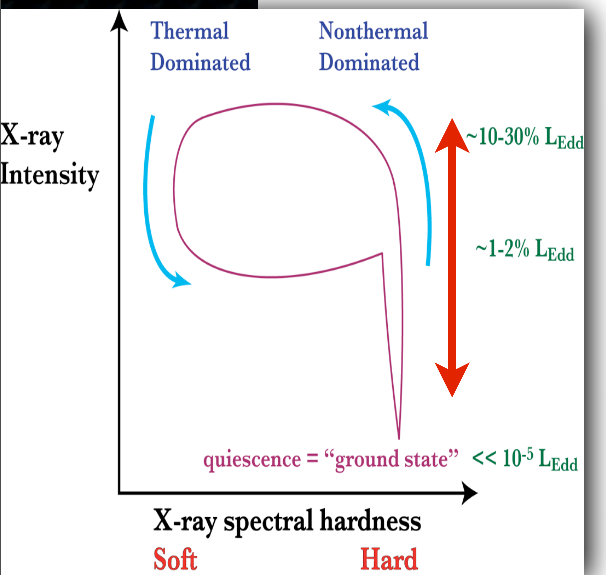
$L_R \propto (\dot{m}M)^{17/12}\, \nu_b$

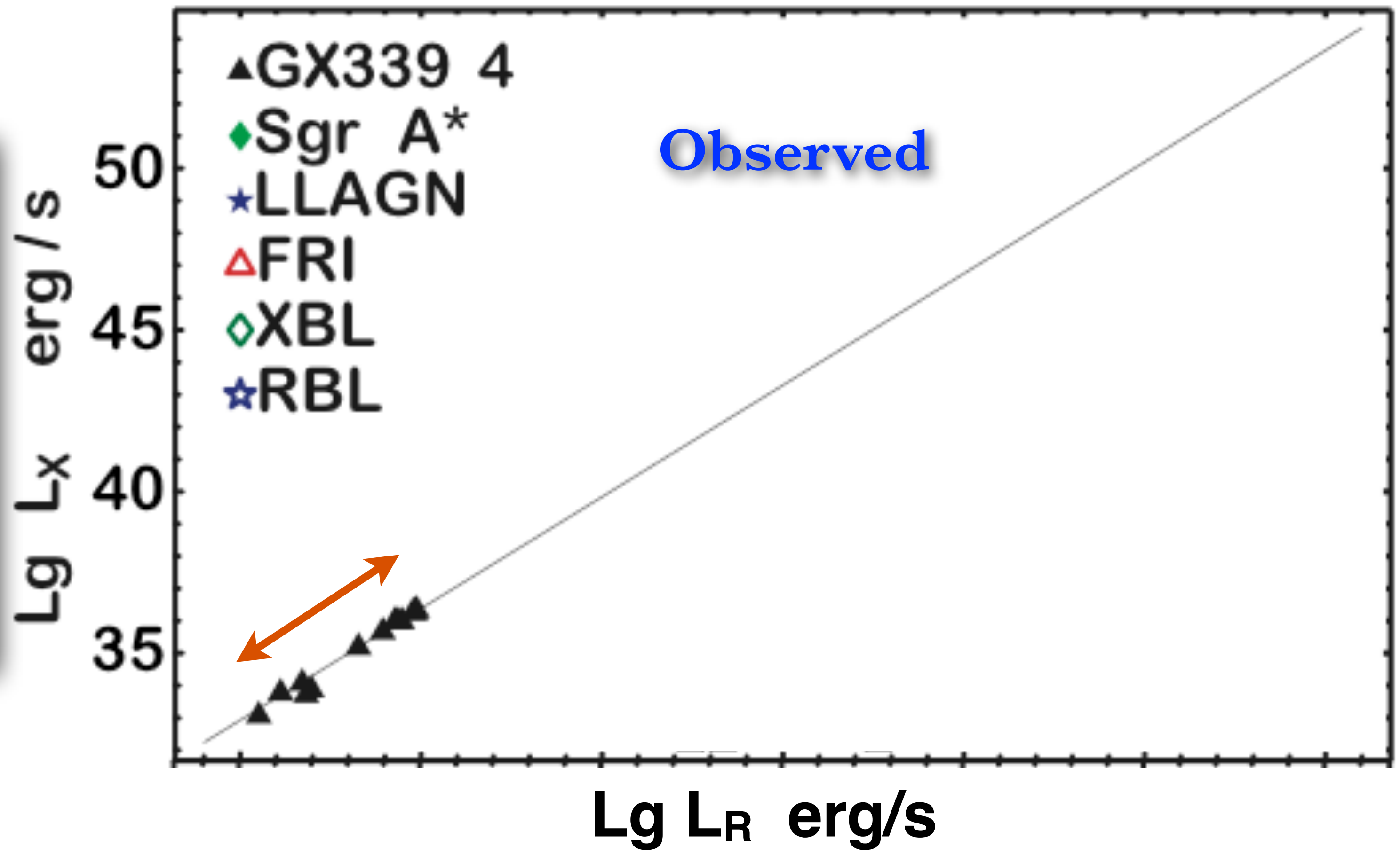
$\nu_b \propto (\dot{m}M)^{2/3}\, M^{-1} \propto \dot{m}^{2/3}\, M^{-1/3}$



(Blandford & Königl 1979, Falcke & Biermann 1995, SM et al. 2003, Heinz & Sunyaev 2003)

“Fundamental plane of BH accretion”

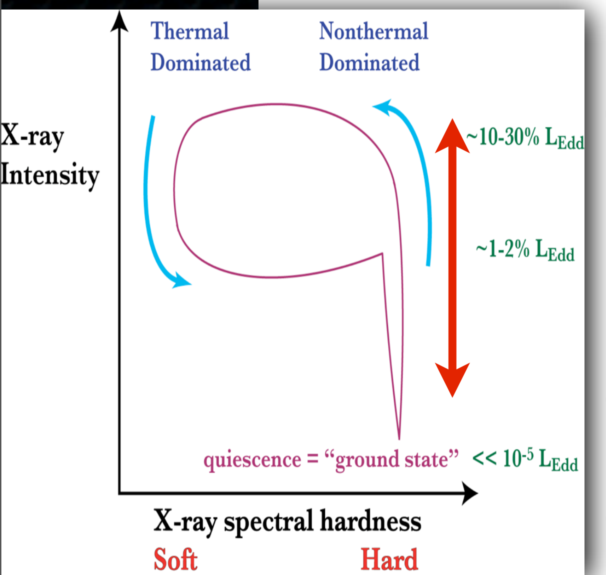


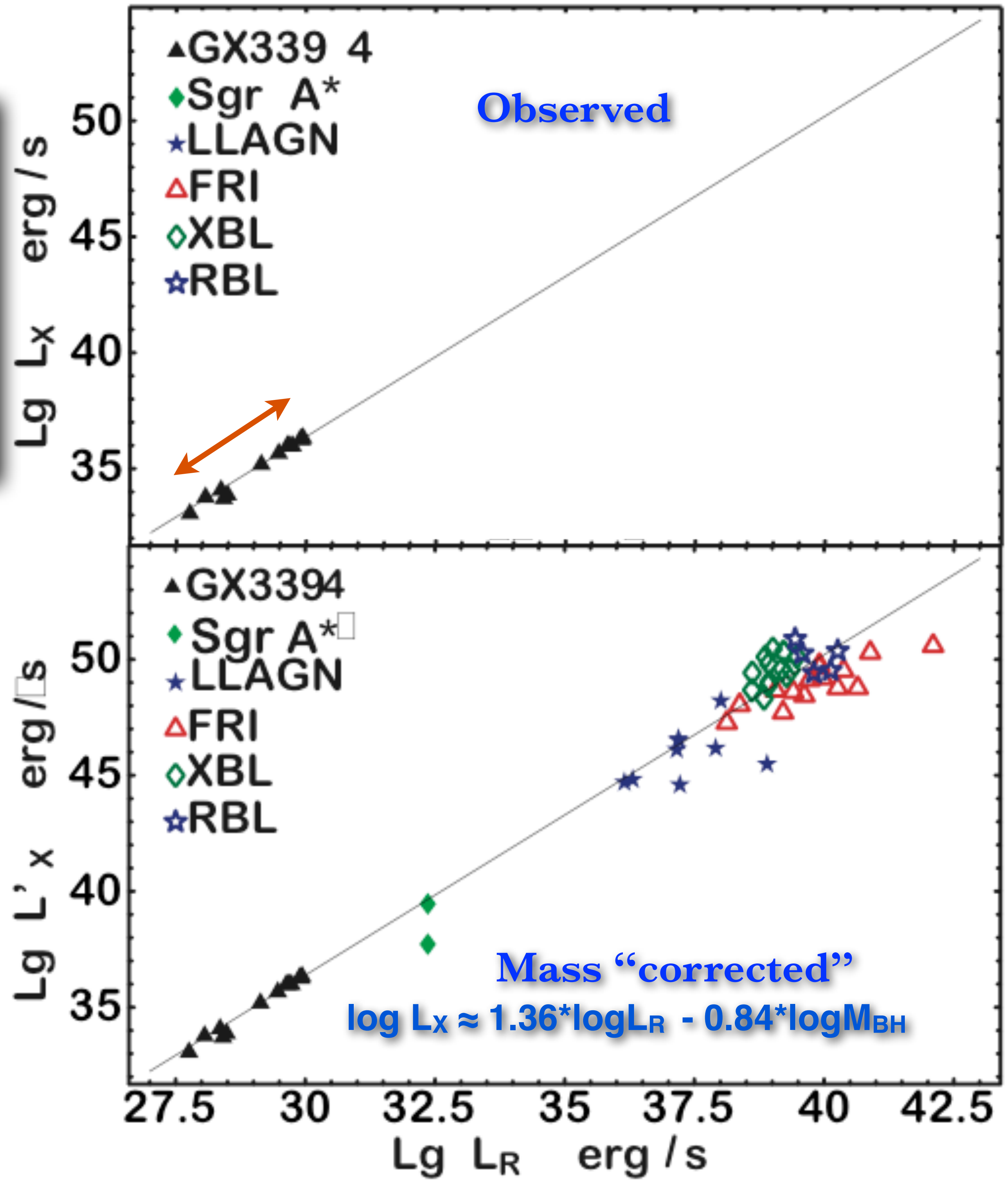


(SM et al. 2003, Merloni,Heinz & diMatteo 2003, Falcke, Körding & SM 2004, SM 2005, Merloni et al. 2006, Kording et al. 2006)

$$\log L_X \approx 1.36*\log L_R - 0.84*\log M_{BH}$$

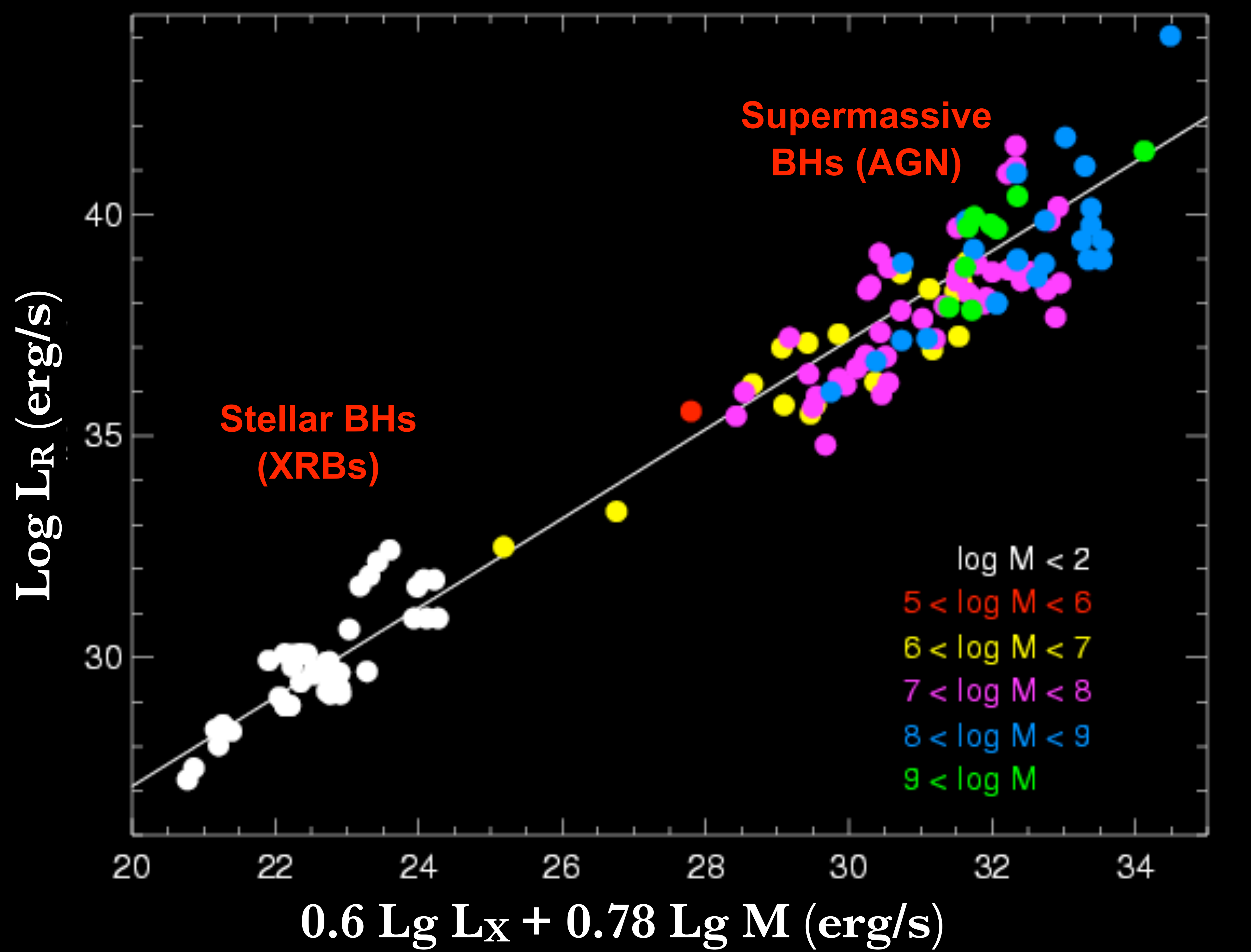
"Fundamental plane of BH accretion"





(SM et al. 2003, Merloni,Heinz & diMatteo 2003, Falcke, Körding & SM 2004, SM 2005, Merloni et al. 2006, Körding et al. 2006)

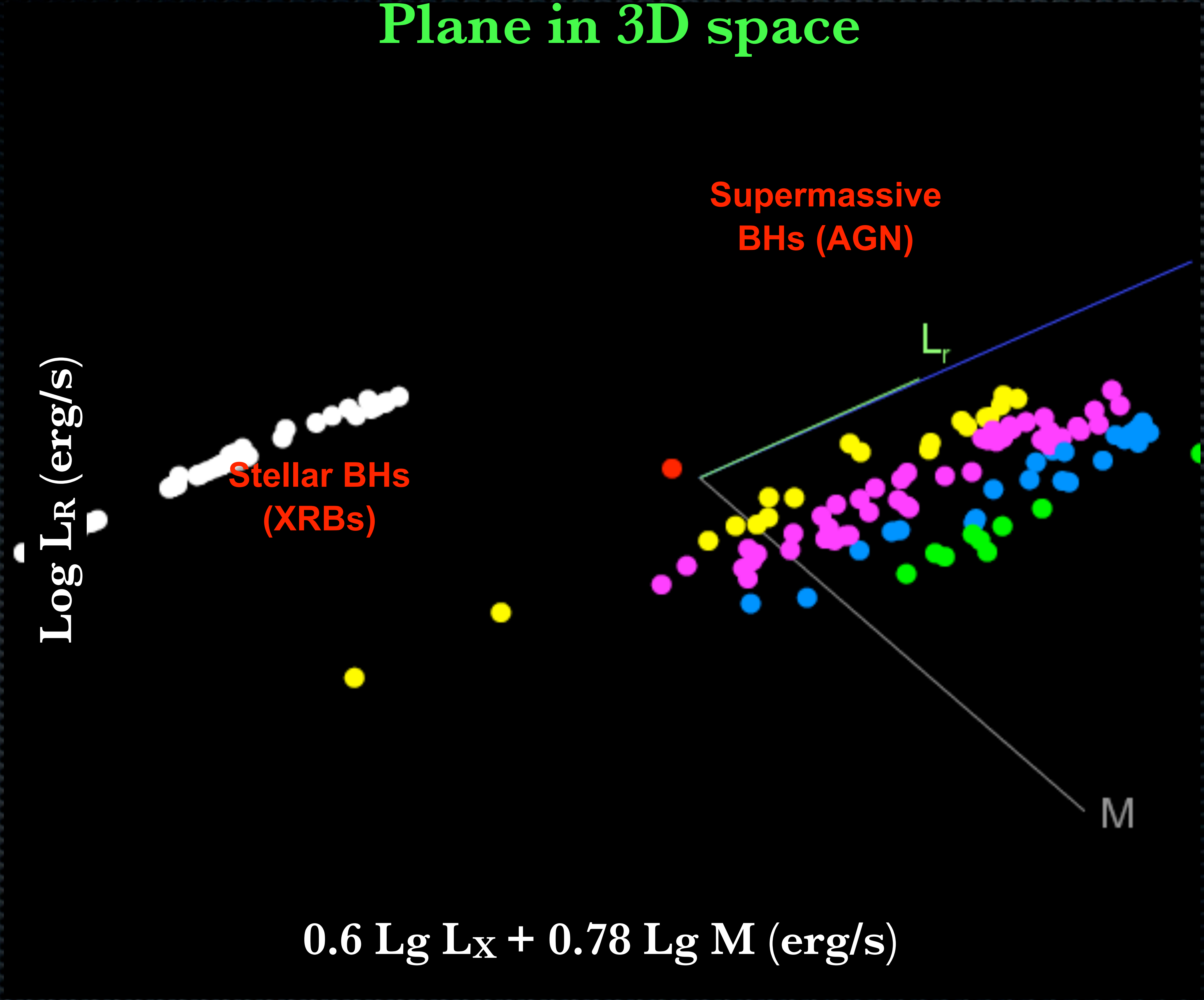
Fundamental plane of BH accretion: Plane in 3D space



(SM et al. 2003; Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; SM 2005; Merloni et al. 2006; Körding et al. 2006; Gültekin et al. 2009; Plotkin, SM et al. 2011)

(movie courtesy of S. Heinz)

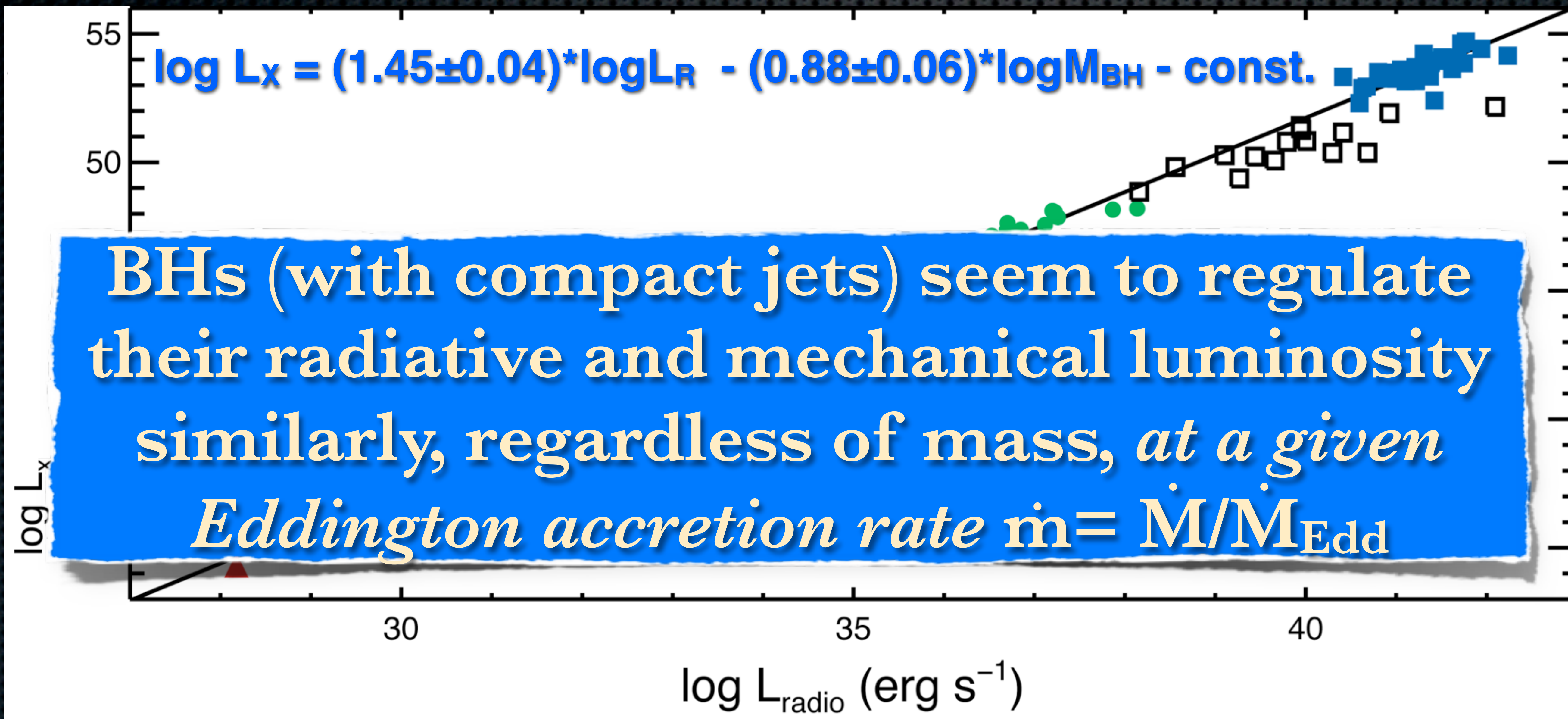
Fundamental plane of BH accretion: Plane in 3D space



(SM et al. 2003; Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; SM 2005; Merloni et al. 2006; Kording et al. 2006; Gültekin et al. 2009; Plotkin, SM et al. 2011)

(movie courtesy of S. Heinz)

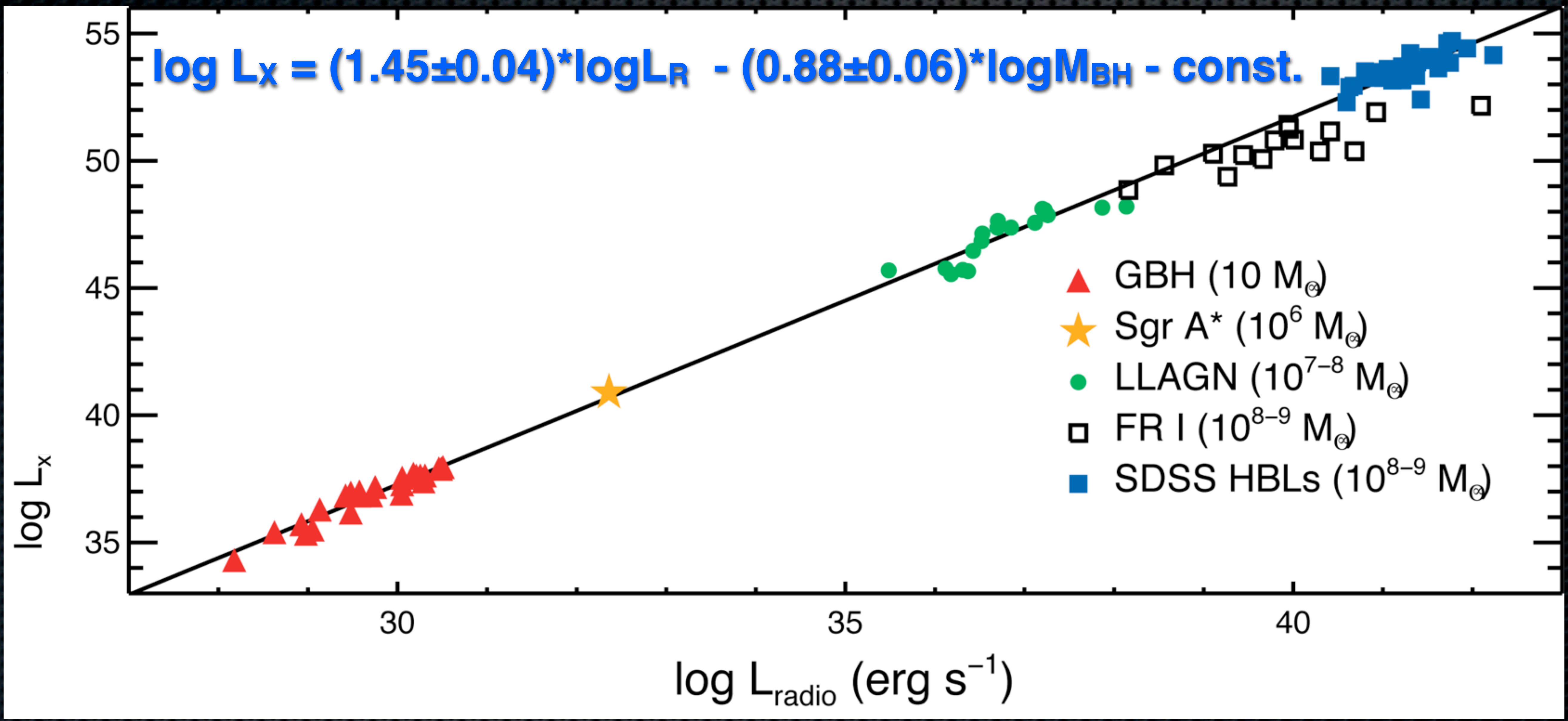
Fundamental Plane of Black Hole Accretion: XRBs ⇔ AGN



BHs (with compact jets) seem to regulate their radiative and mechanical luminosity similarly, regardless of mass, *at a given Eddington accretion rate* $\dot{m} = \dot{M}/\dot{M}_{Edd}$

(Corbel ea. 2003; SM ea. 2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding, SM 2004; SM 2005; Körding et al. 2006; Plotkin, SM, Kelly, Körding & Anderson 2012)

Fundamental Plane of Black Hole Accretion: XRBs ⇔ AGN



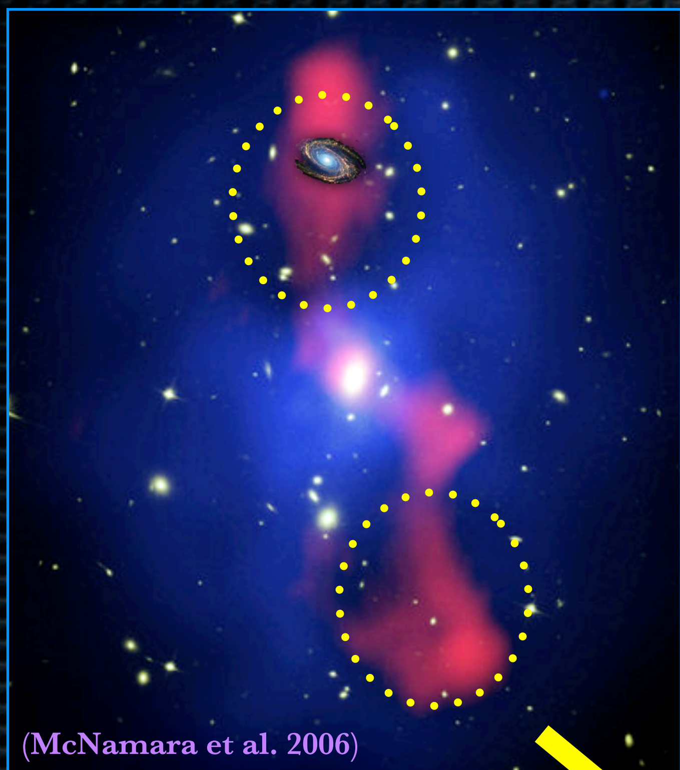
(Corbel ea. 2003; SM ea. 2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding, SM 2004; SM 2005; Körding et al. 2006; Plotkin, SM, Kelly, Körding & Anderson 2012)

Outline

- Part I: General introduction to the concept of mass-scaling in accretion physics
- Part II: Summary of accretion states in XRBs and comparisons to AGN zoology
- Part III: Fundamental Plane of black hole accretion
- Part IV-- Advanced topics: what other things can we do? What else do we see?

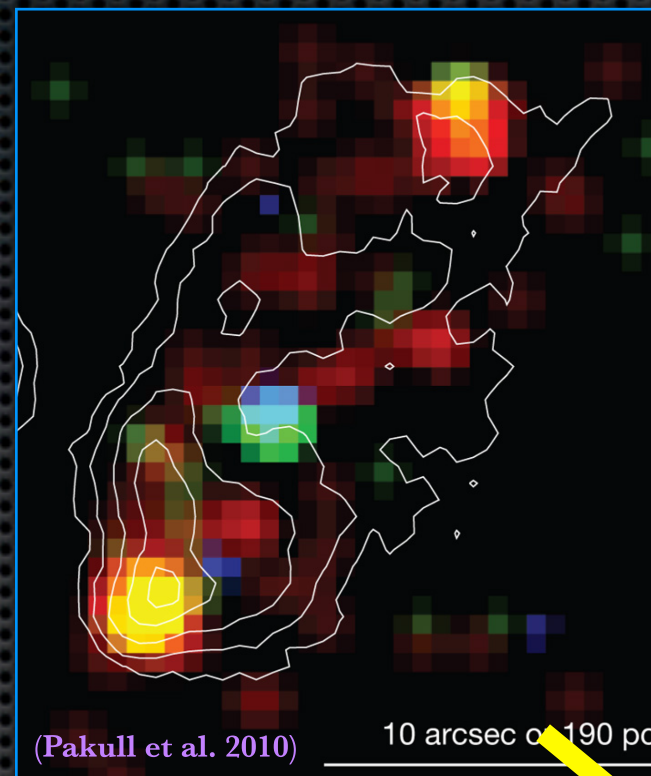
Black holes drive several major processes in the universe

GALAXY EVOLUTION/ AGN FEEDBACK



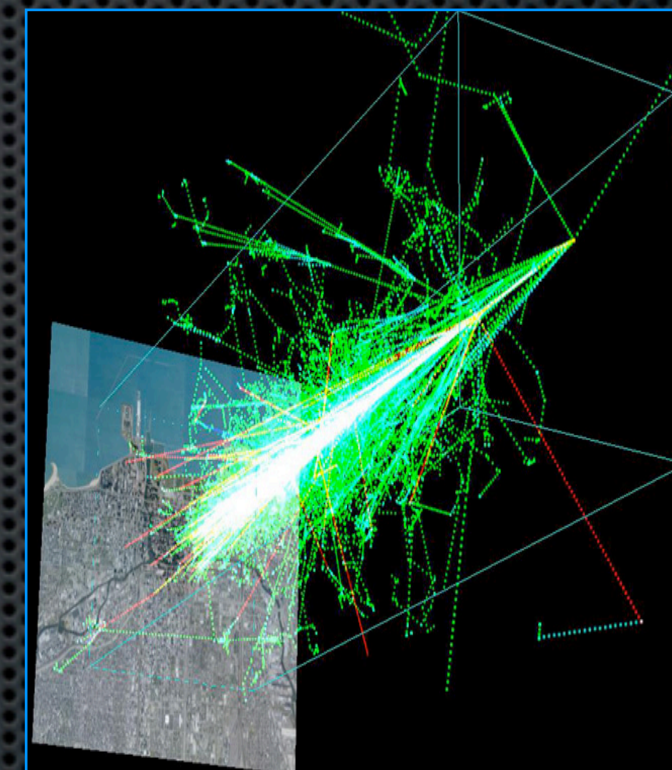
(McNamara et al. 2006)

IONIZATION OF SURROUNDING GAS

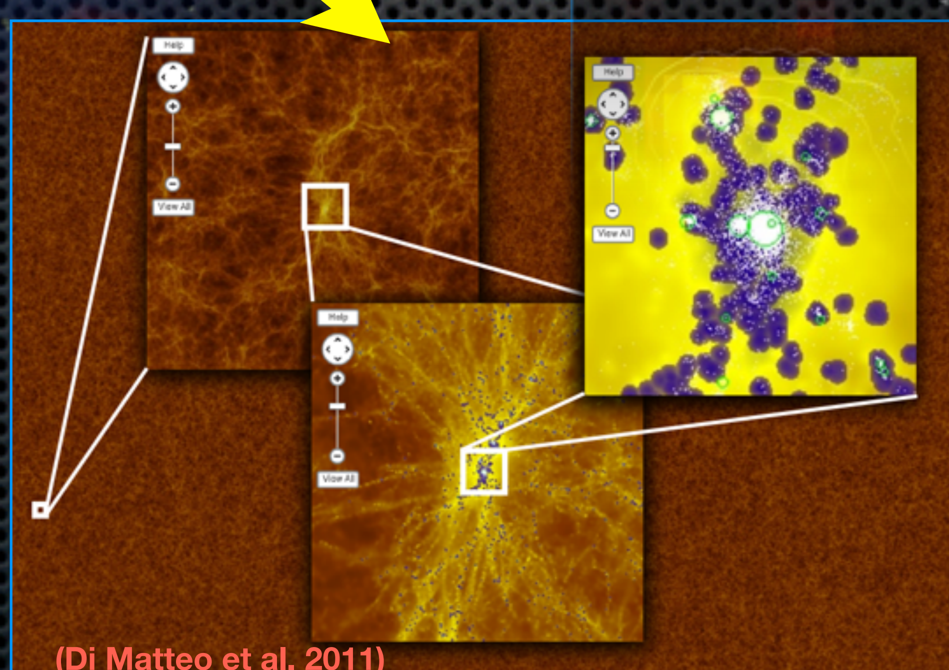


(Pakull et al. 2010)

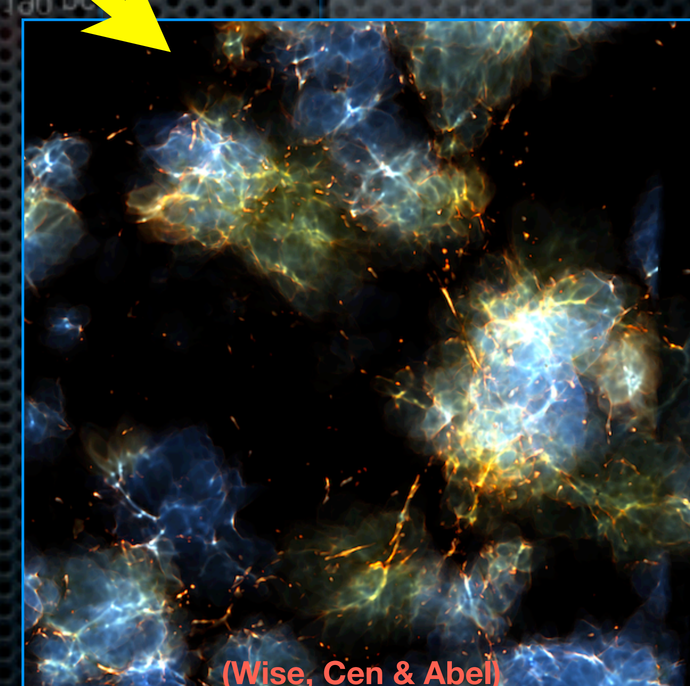
HIGH-ENERGY PARTICLE ACCELERATION



Cosmological Simulations:



(Di Matteo et al. 2011)



(Wise, Cen & Abel)

Black holes drive several major processes in the universe

GALAXY EVOLUTION/ AGN FEEDBACK

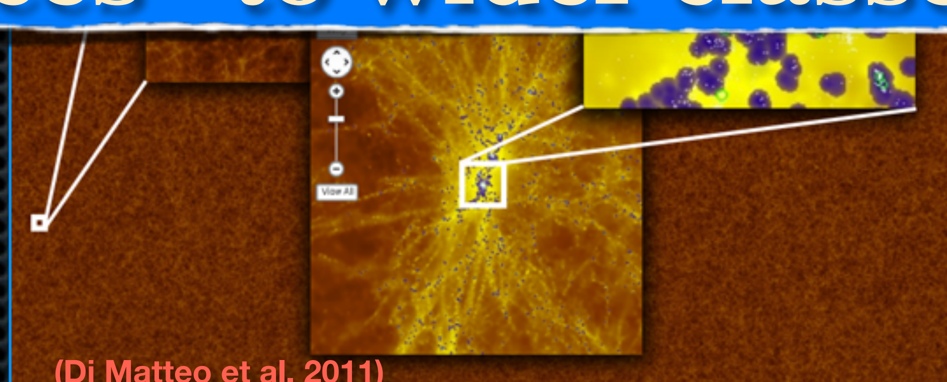
IONIZATION OF SURROUNDING GAS

HIGH-ENERGY PARTICLE ACCELERATION

If XRBs "scale" to SMBHs in AGN we get:

- a better understanding of jet/disk coupling in AGN
- a better sense of what type of feedback (radiation/wind/jet/CRs) dominates when
- the potential for "generic" BH physical models
- the potential to extend knowledge from "special sources" to wider classes of objects

Simulations:

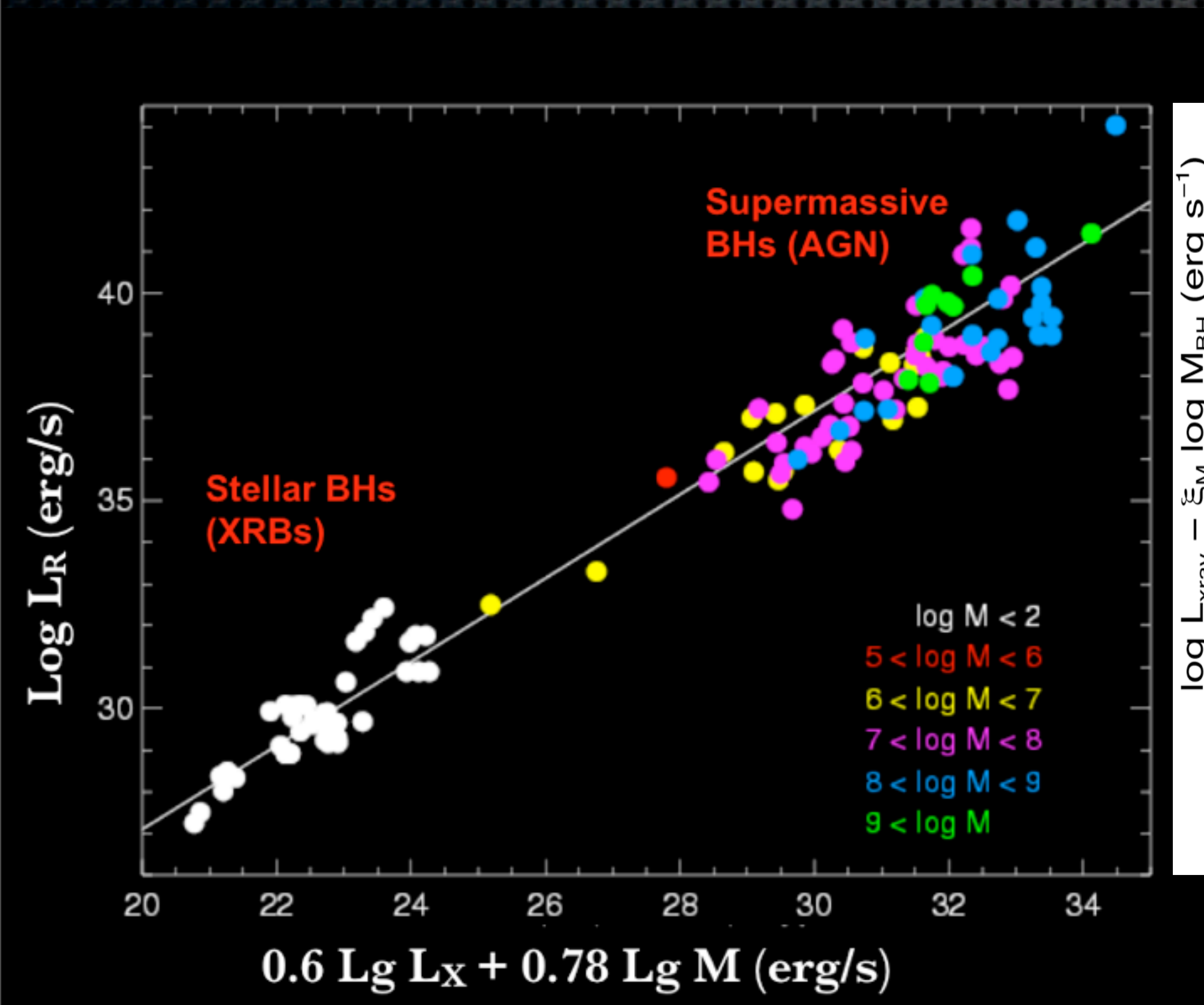


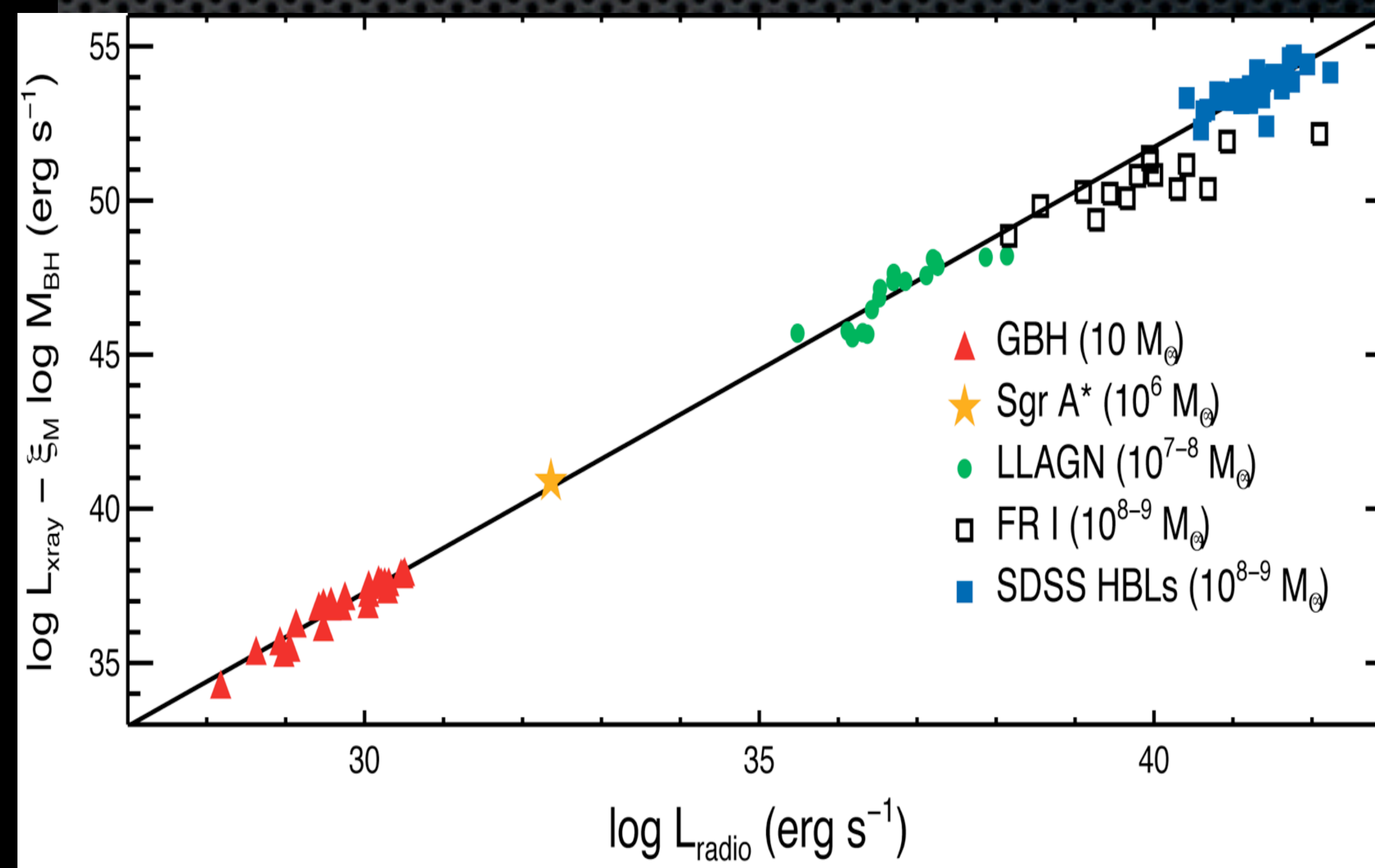
(Di Matteo et al. 2011)

(Wise, Cen & Abel)

Refining the FP: sources of scatter?

- Comparative scatter: ~0.65 vs. 0.25 dex, due to inclusion of Seyferts, or other factors like mass/distance Δ's?

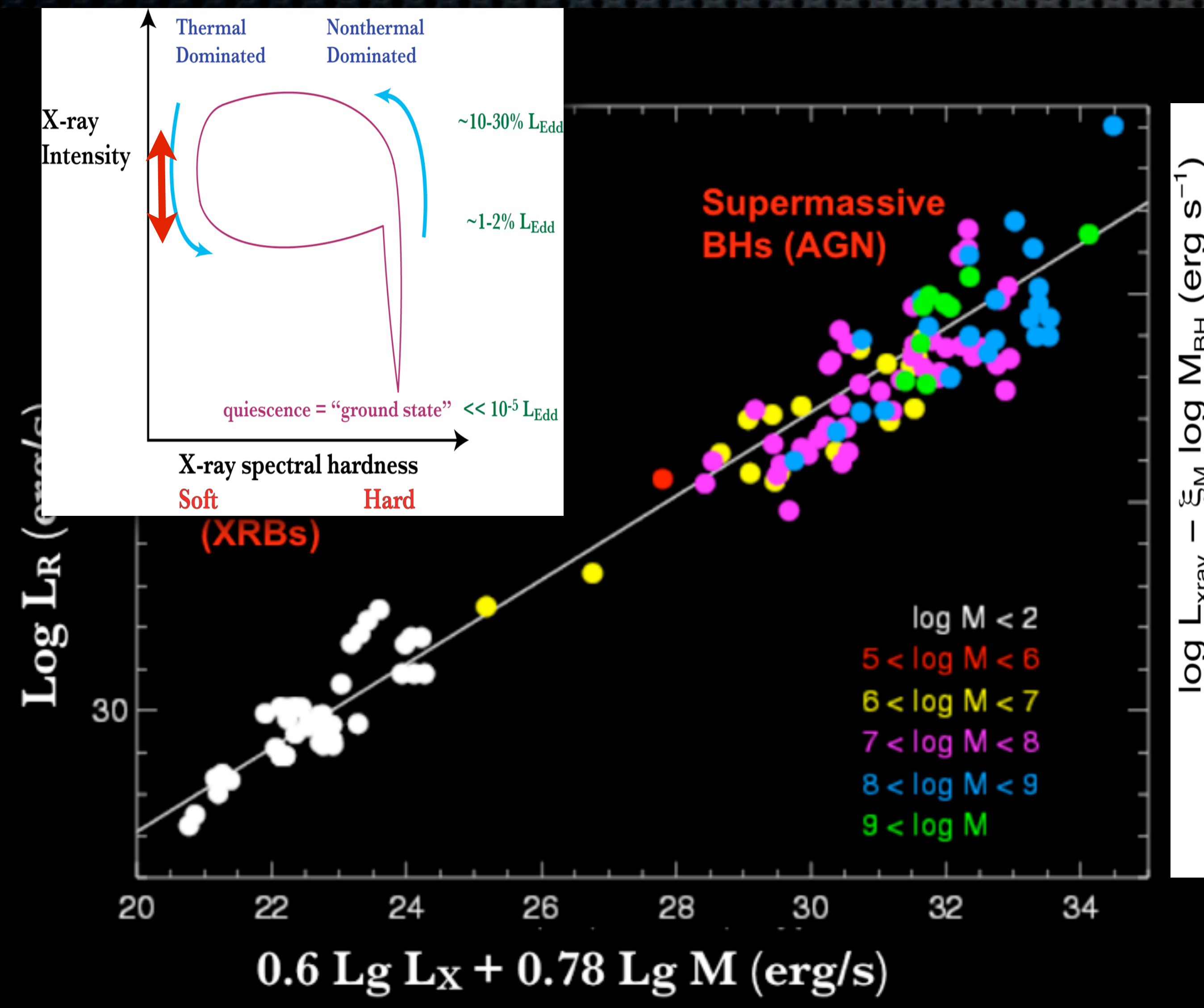


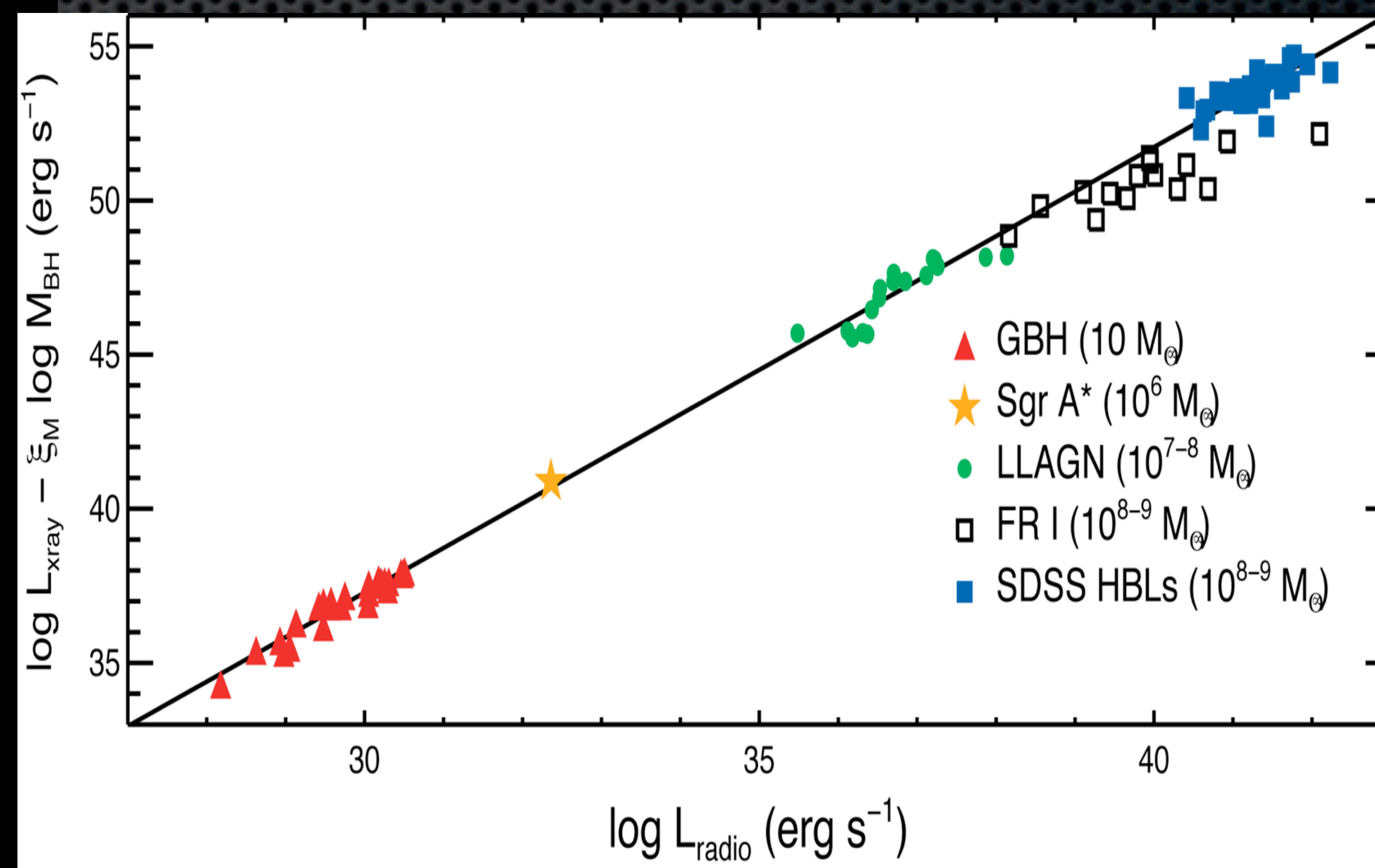


(Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; Plotkin et al. 2012)

Refining the FP: sources of scatter?

- ★ Comparative scatter: ~0.65 vs. 0.25 dex, due to inclusion of Seyferts, or other factors like mass/distance Δ's?

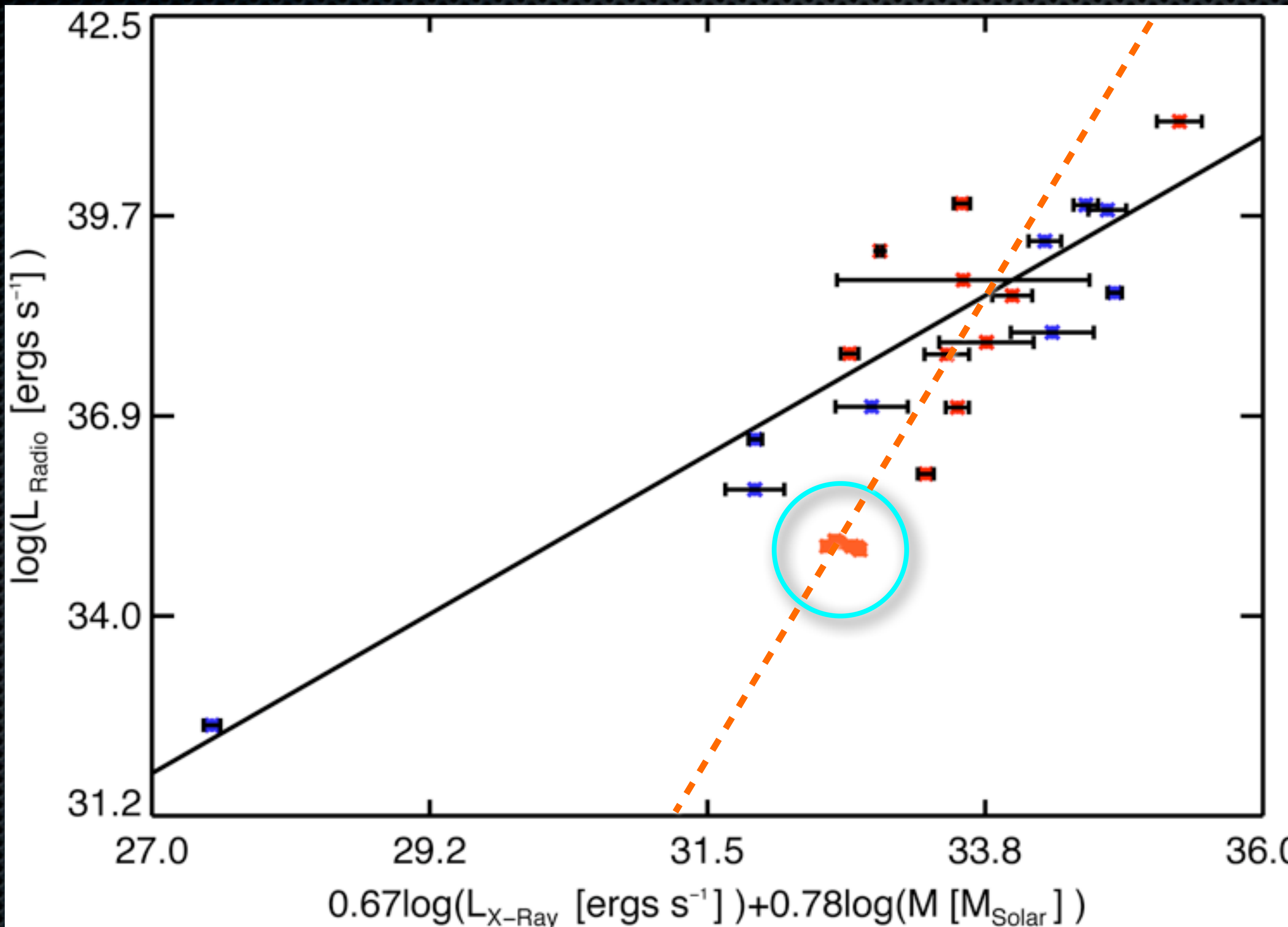




(Merloni, Heinz & diMatteo 2003; Falcke, Körding & SM 2004; Plotkin et al. 2012)

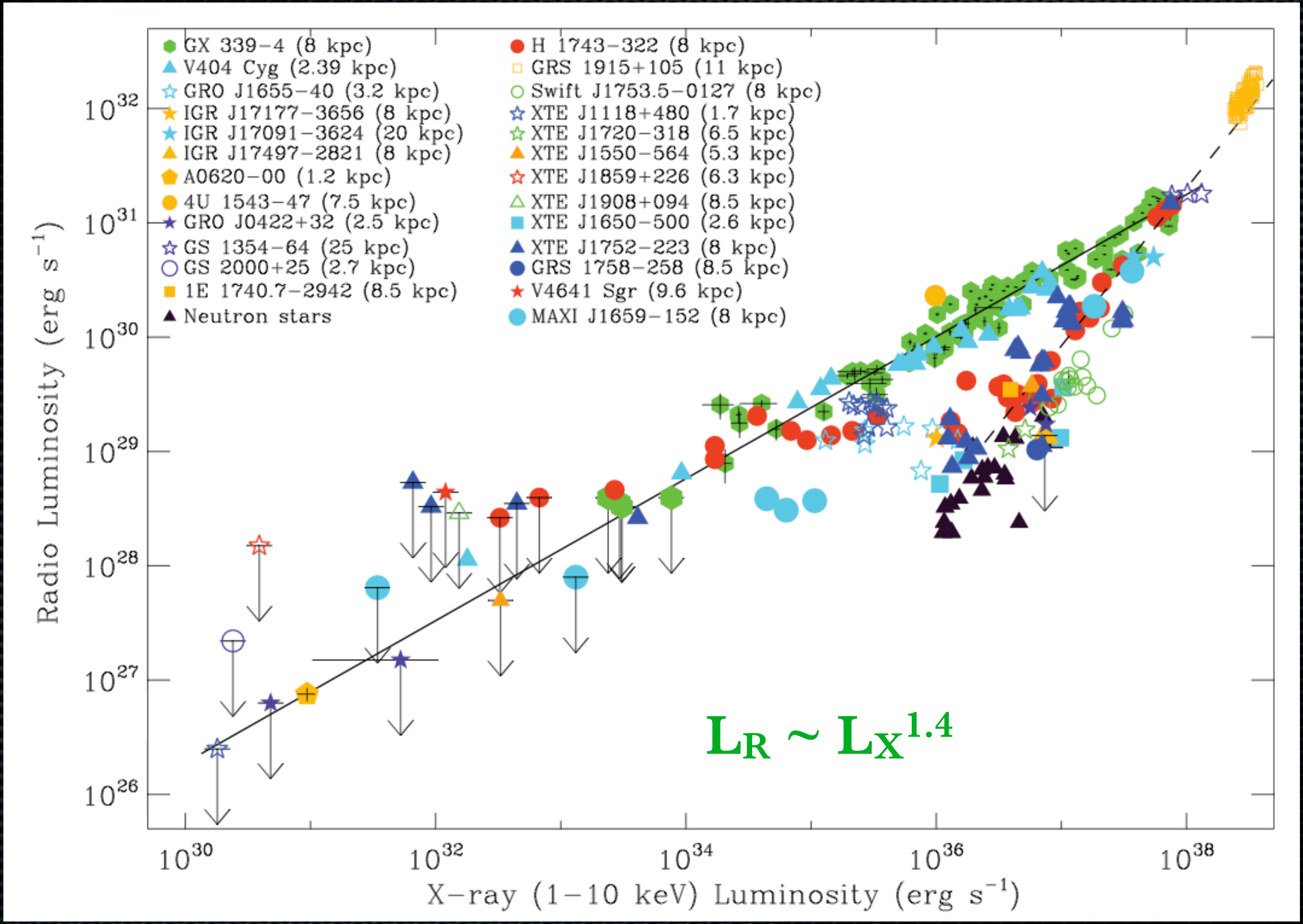
Evidence for a new “FP” in AGN as well?

Seyferts, M-σ sources only:



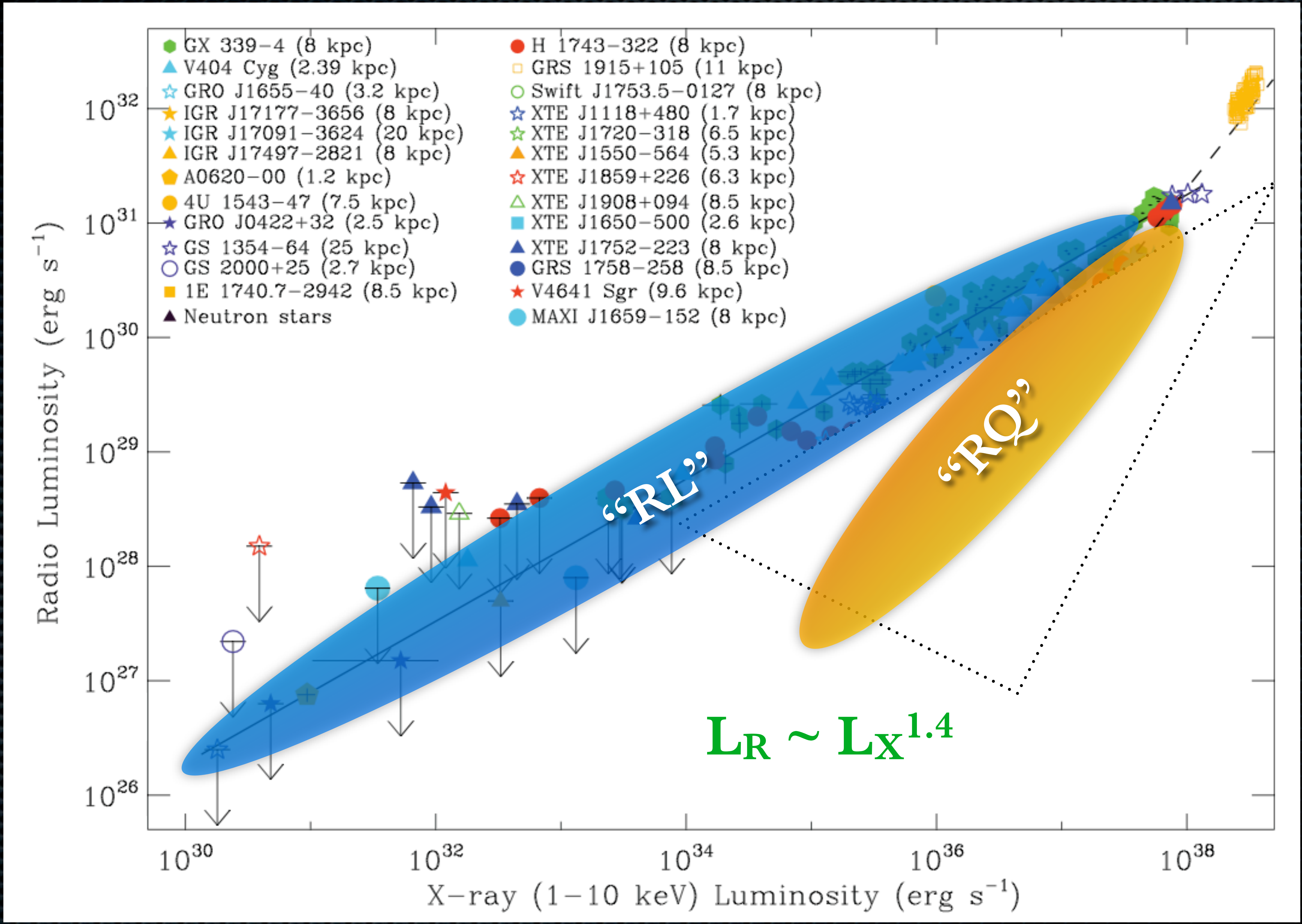
(Gültekin et al. 2009, King et al. 2011)

XRB hard state -- New Branch in Radio/X-ray Correlation



(Corbel et al. 2013)

XRB hard state -- New Branch in Radio/X-ray Correlation



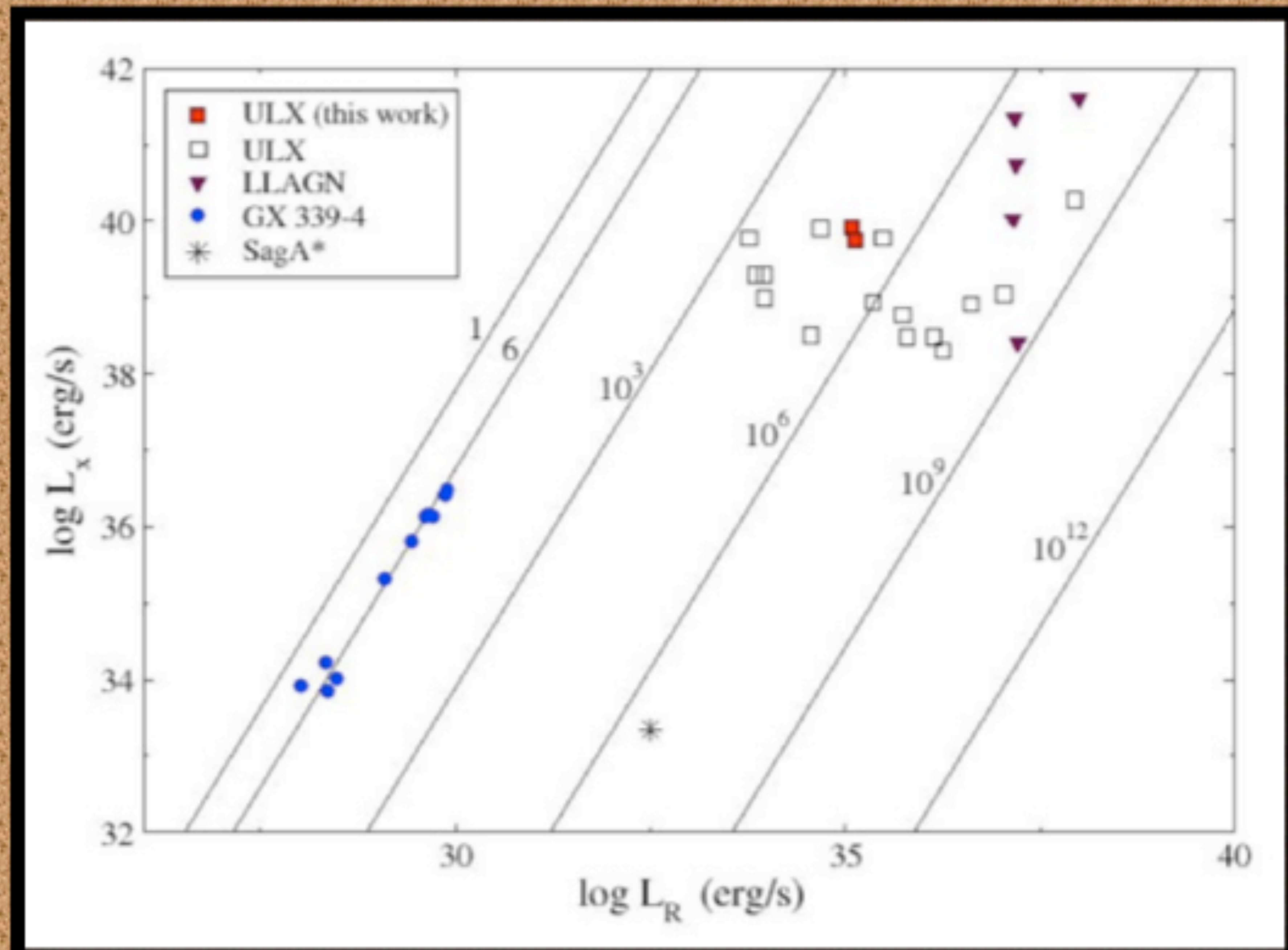
(Corbel et al. 2013)

Using the Fundamental Plane to Constrain BH mass?

- Several groups lately are starting to use the Fundamental Plane to constrain the mass of sources with L_R and L_X measurements
- Can you think of any important caveats (things to be careful about)??

Using t[...] mass?

- Several [...]ental Plane t[...] L_X measu[...]
- Can yo[...] careful about)?



Fundamental plane. Location in the fundamental plane of the ULXs N4088-X1 and N4861-X2 (this work, red squares) and of other ULXs with radio counterparts (open squares). The parallel lines correspond to the labeled BH mass relative to that of the Sun. We show for comparison the Corbel et al. (2003) data for the X-ray binary GX 339-4 (filled circles), and the Merloni et al. (2003) data for some Low Luminosity AGN (inverted triangles).

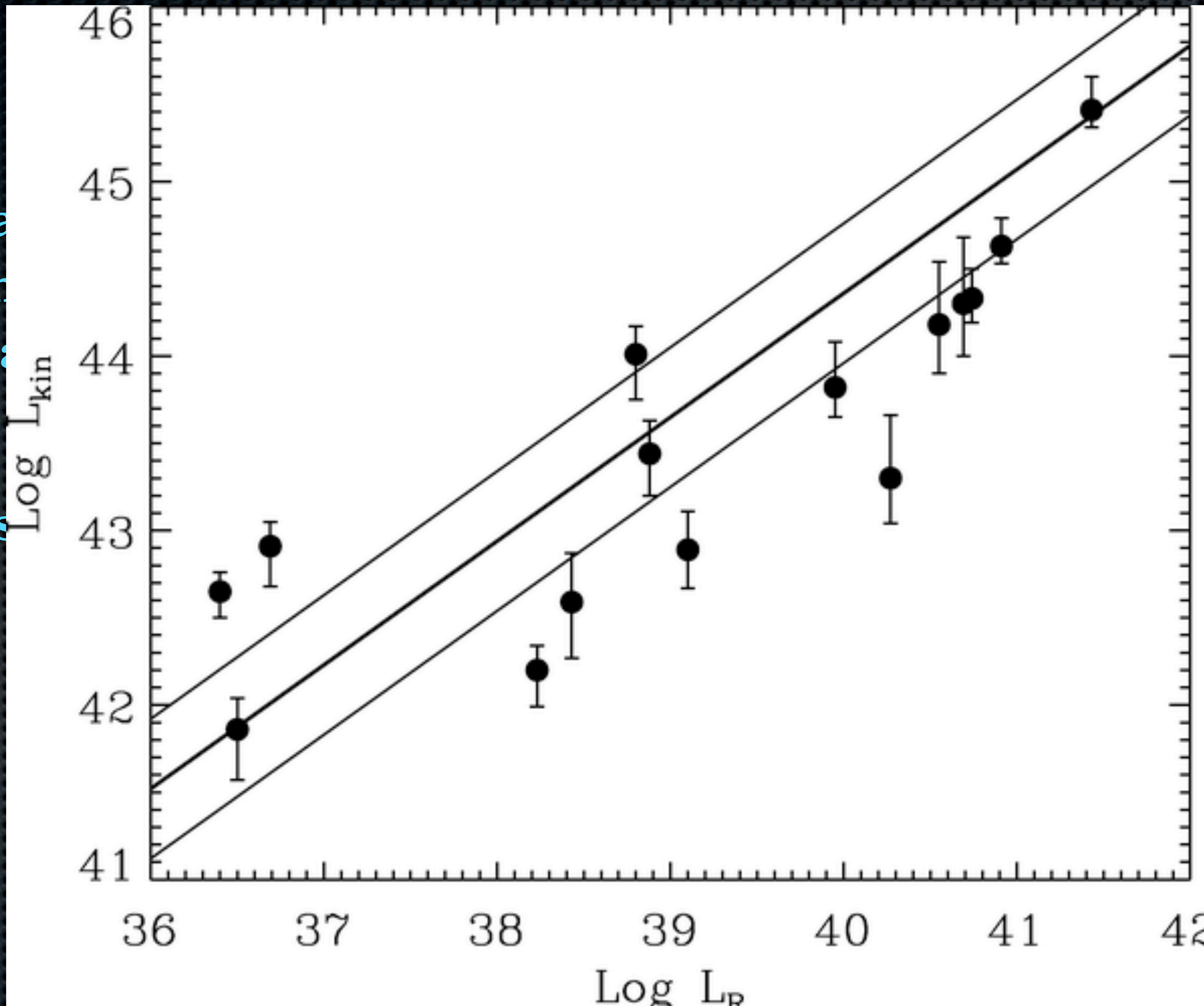
Using the Fundamental Plane to create templates for AGN feedback

- One can turn around the $L_R \sim \dot{M}^{17/12}$ to convert observations of samples of AGN into estimates of kinetic power associated with jet "mechanical feedback"
- There is a long way to go however, since we do not yet understand the duty cycle of the different states, or the power channels in all the various states, or even which XRB states actually map

(e.g., Heinz, Merloni & Schwab 2007

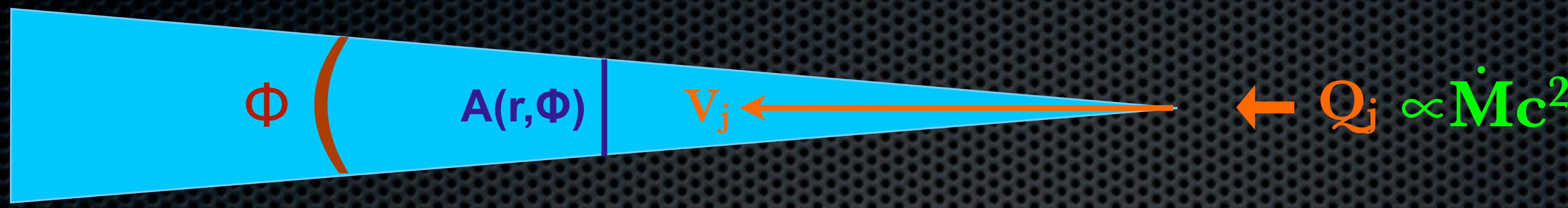
Using the Fundamental Plane to create templates for AGN feedback

- One ca… vations of sam… associ…
- There … et unders… the power … ch XRB states …



(e.g., Heinz, Merloni & Schwab 2007

Are the break locations determined by pure scaling?



$$C \sim n \sim B^2 \propto \dot{M}/M^2 \qquad j_\nu \propto C B^{(p+1)/2} \nu^{-(p-1)/2}$$

$$\alpha_\nu \propto C B^{(p+2)/2} \nu^{-(p+4)/2} \qquad S_\nu \propto \xi(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu$$

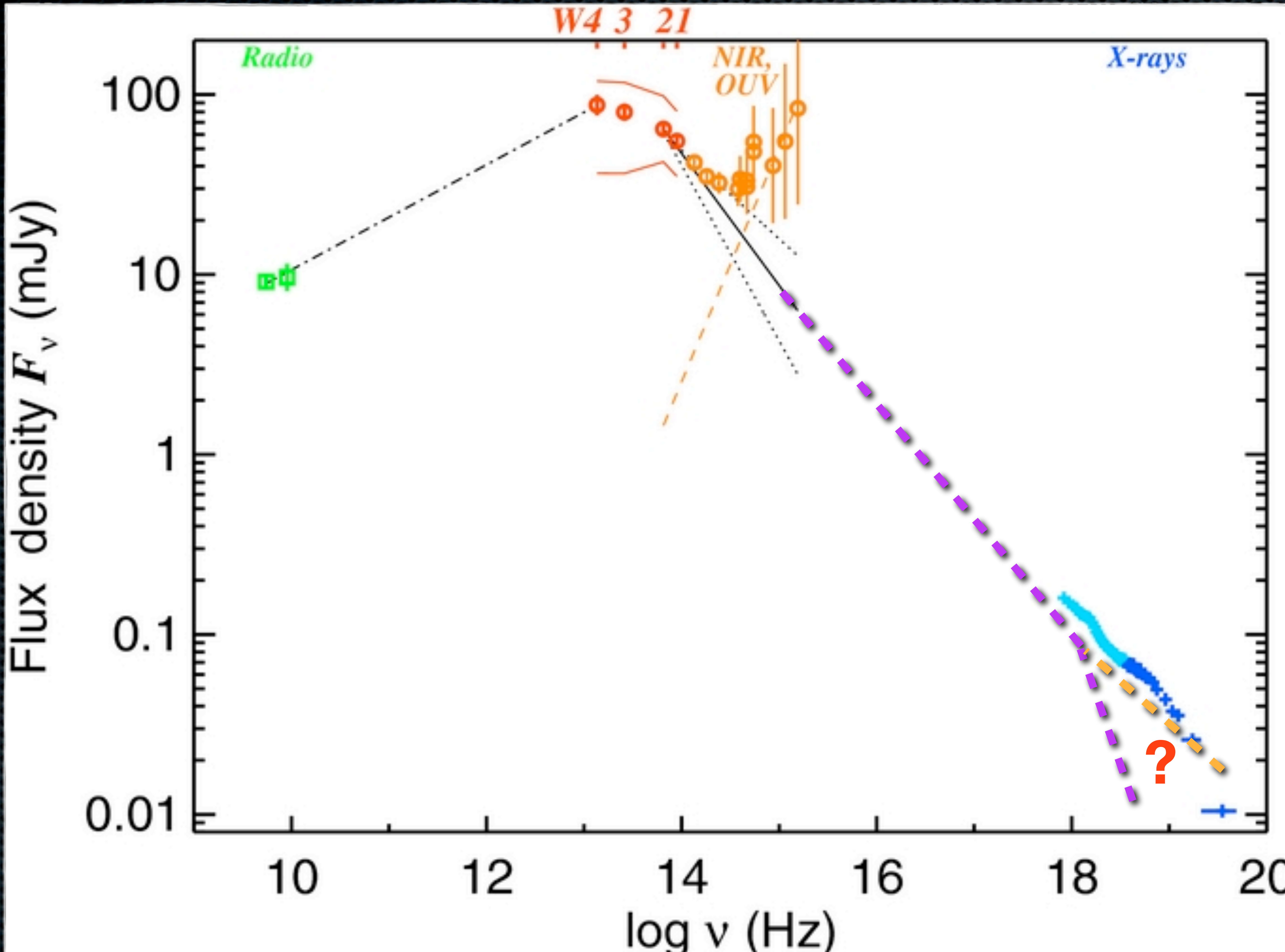
$$F_\nu = \int_{r_g}^{\infty} dr R_r S_\nu(r) = F_\nu(M, \dot{m}, a, \nu, \theta)$$

(taking p=2)

- $\nu_{SSA} \propto \left(M \phi_c \phi_B^{(p+2)/2}\right)^{2/(p+4)} \sim \dot{m}^{2/3} M^{-1/3} = \dot{M}^{2/3} M^{-1}$

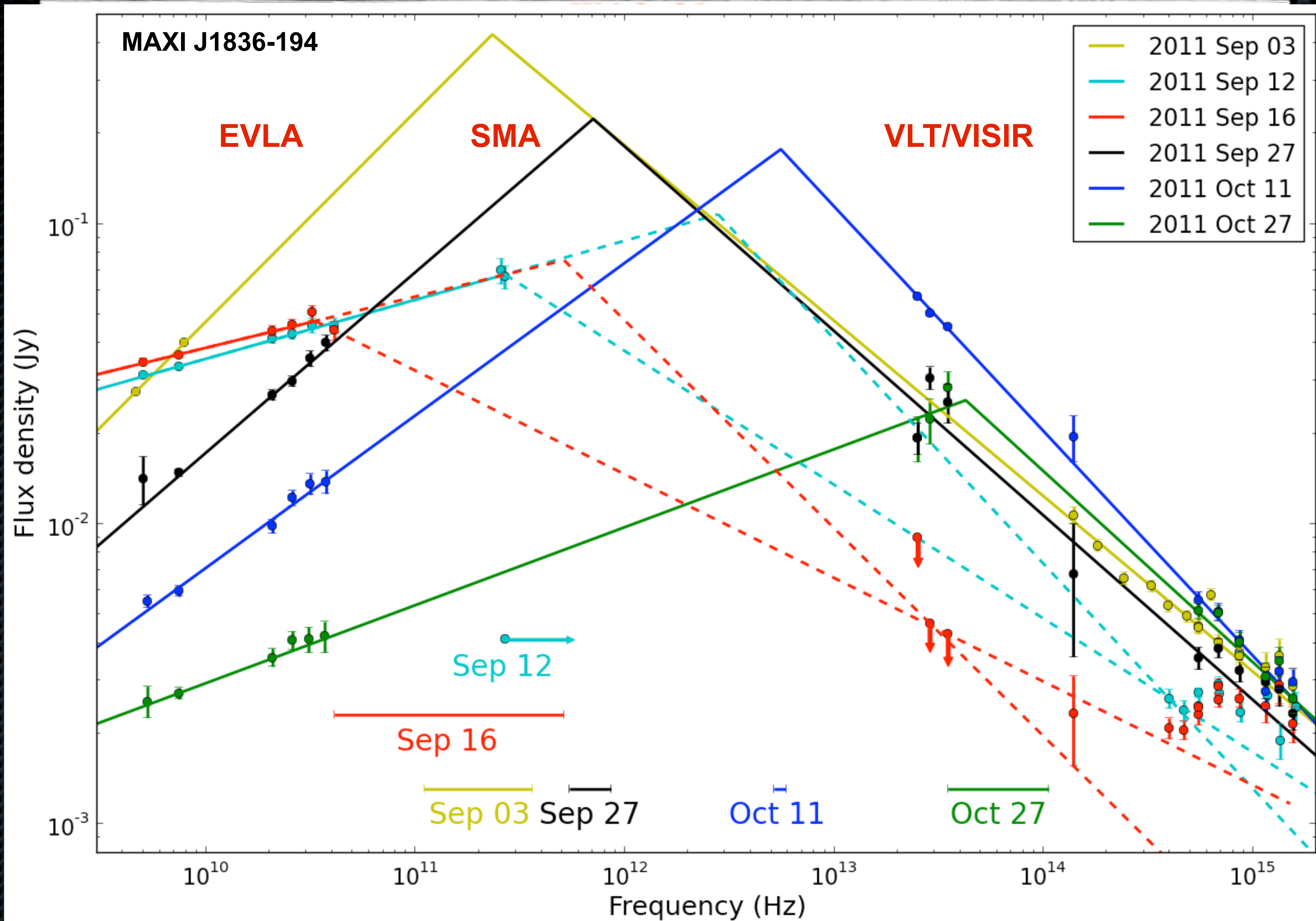
(Blandford & Königl 1979; Rybicki & Lightman 1979; Falcke & Biermann 1995; SM et al. 2003; Heinz & Sunyaev 2003)

Simultaneous radio-X-ray spectra ➠ strong constraints on jet physics



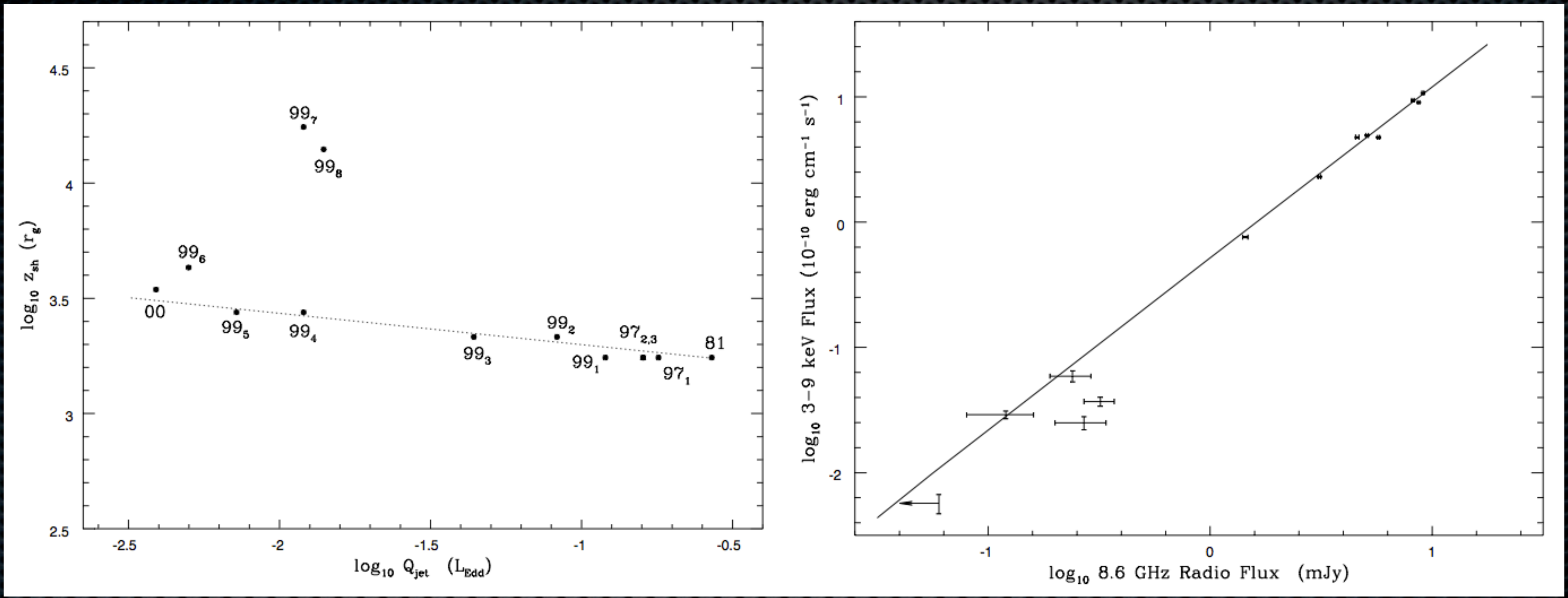
(Corbel & Fender 2002, SM ea. 2003, Heinz & Sunyaev 2003, Gandhi ea. 2011, Russell et al. 2013ab)

Simultaneous radio-X-ray spectra ➟ strong constraints on jet physics



(Corbel & Fender 2002, SM ea. 2003, Heinz & Sunyaev 2003, Gandhi ea. 2011, Russell et al. 2013ab)

We didn’t see the predicted scaling in the GX339-4 correlations

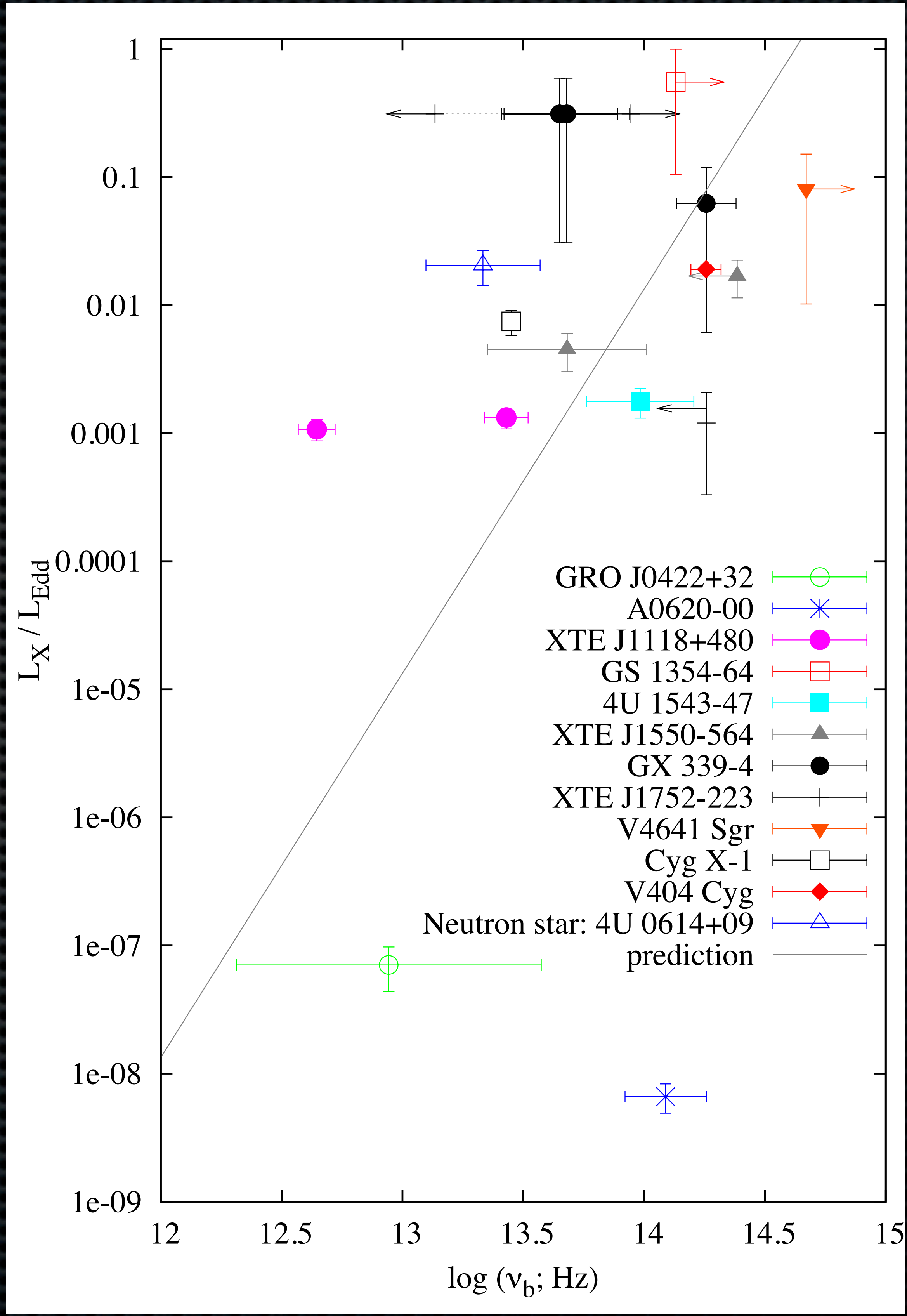


$$z_{acc} \propto Q_j^{-0.135} \sim \dot{M}^{-0.135}$$ **(not $\dot{M}^{2/3}$!)**

(SM et al. 2003)

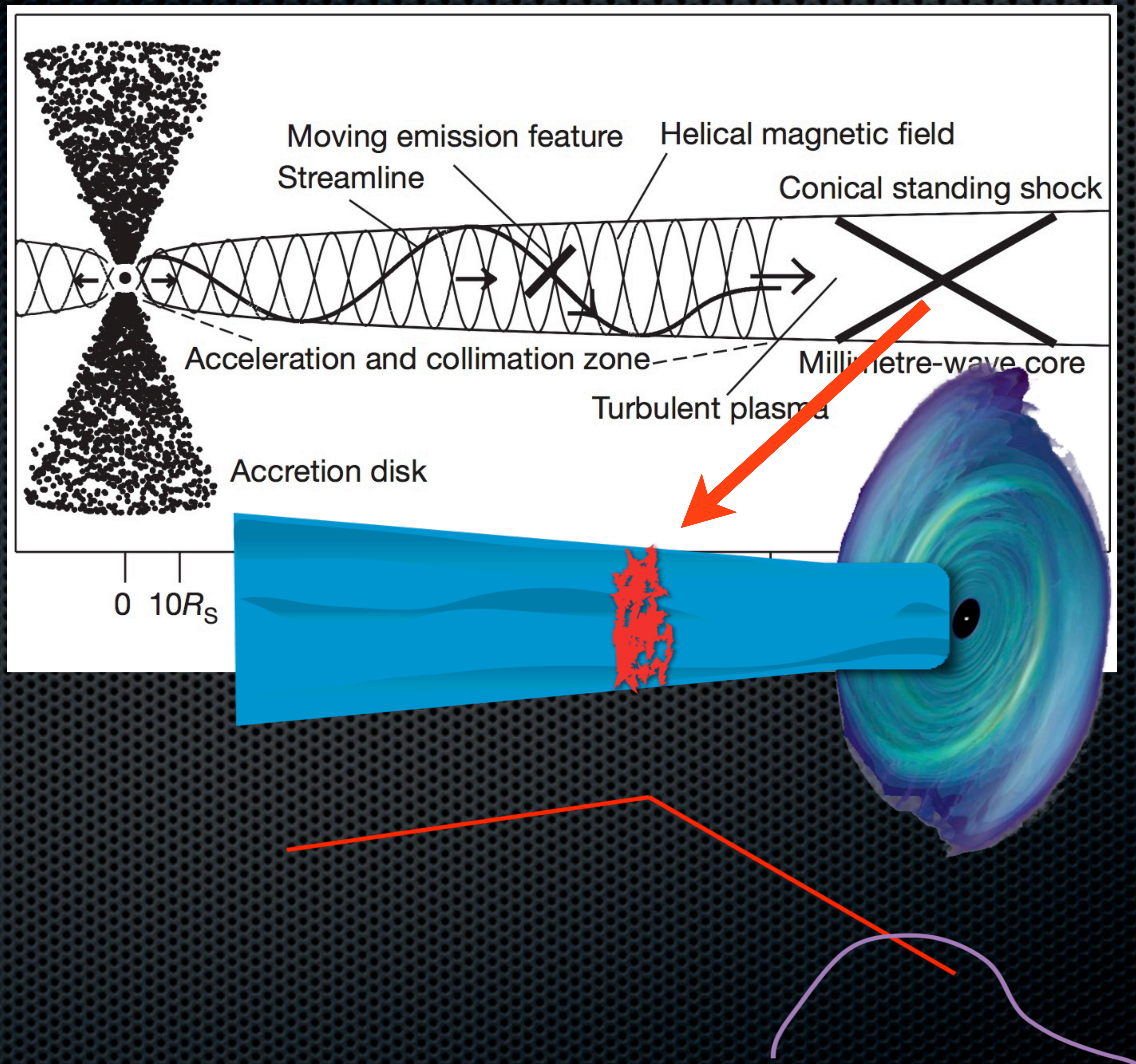
Simultaneous radio-X-ray spectra ➠ strong constraints on jet physics

- Now we're starting to observe/constrain the breaks in many XRBs during outbursts, and we don't see $\dot{M}^{2/3}$ scaling
- What does this tell us? Basically there's another variable driving the location where particle acceleration starts in the jets! Something that is likely determined by magnetohydrodynamical processes (Vlahakis' talk...)

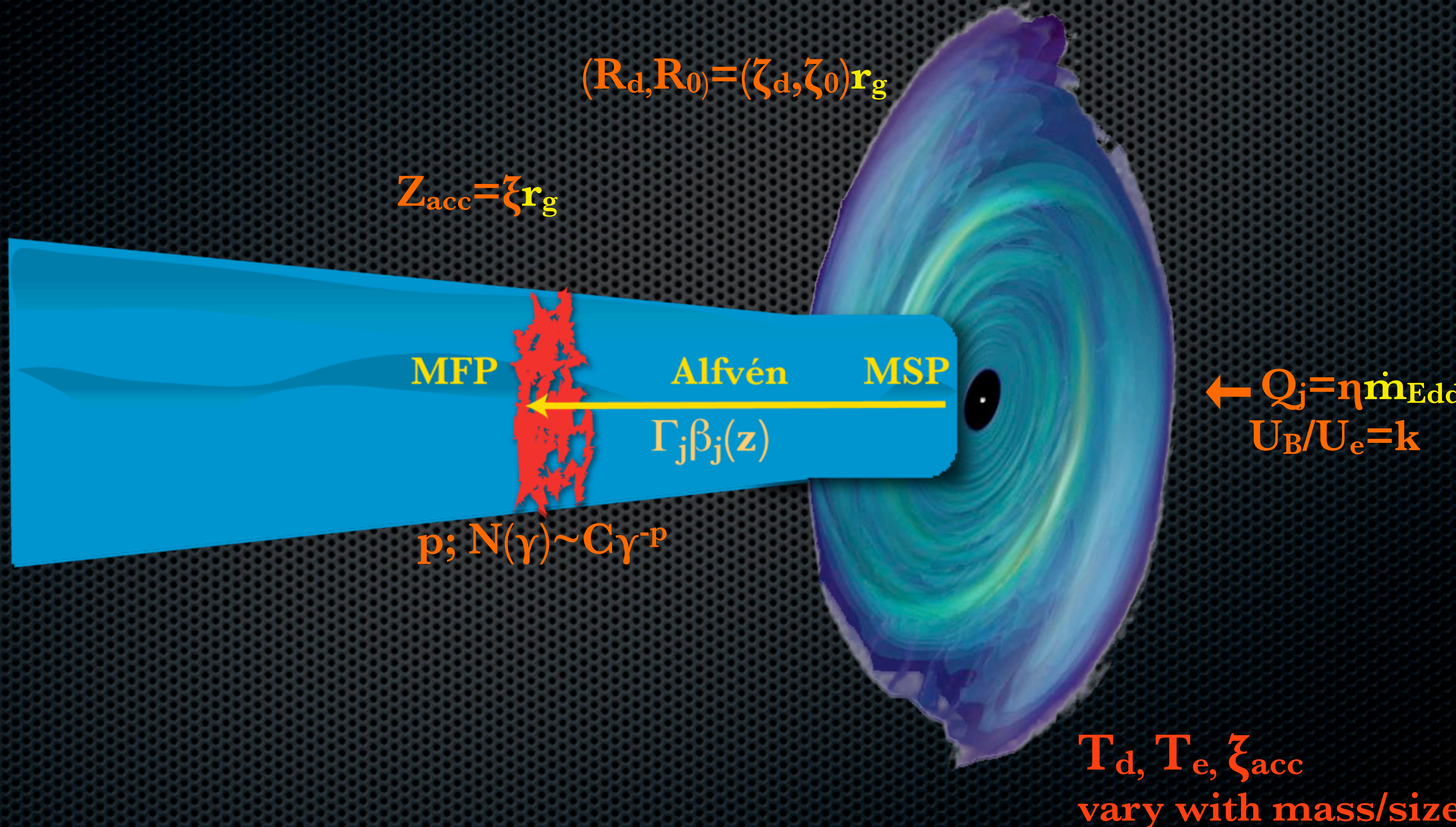


(Russell et al. 2013ab)

"Deeper" meaning of the break frequency

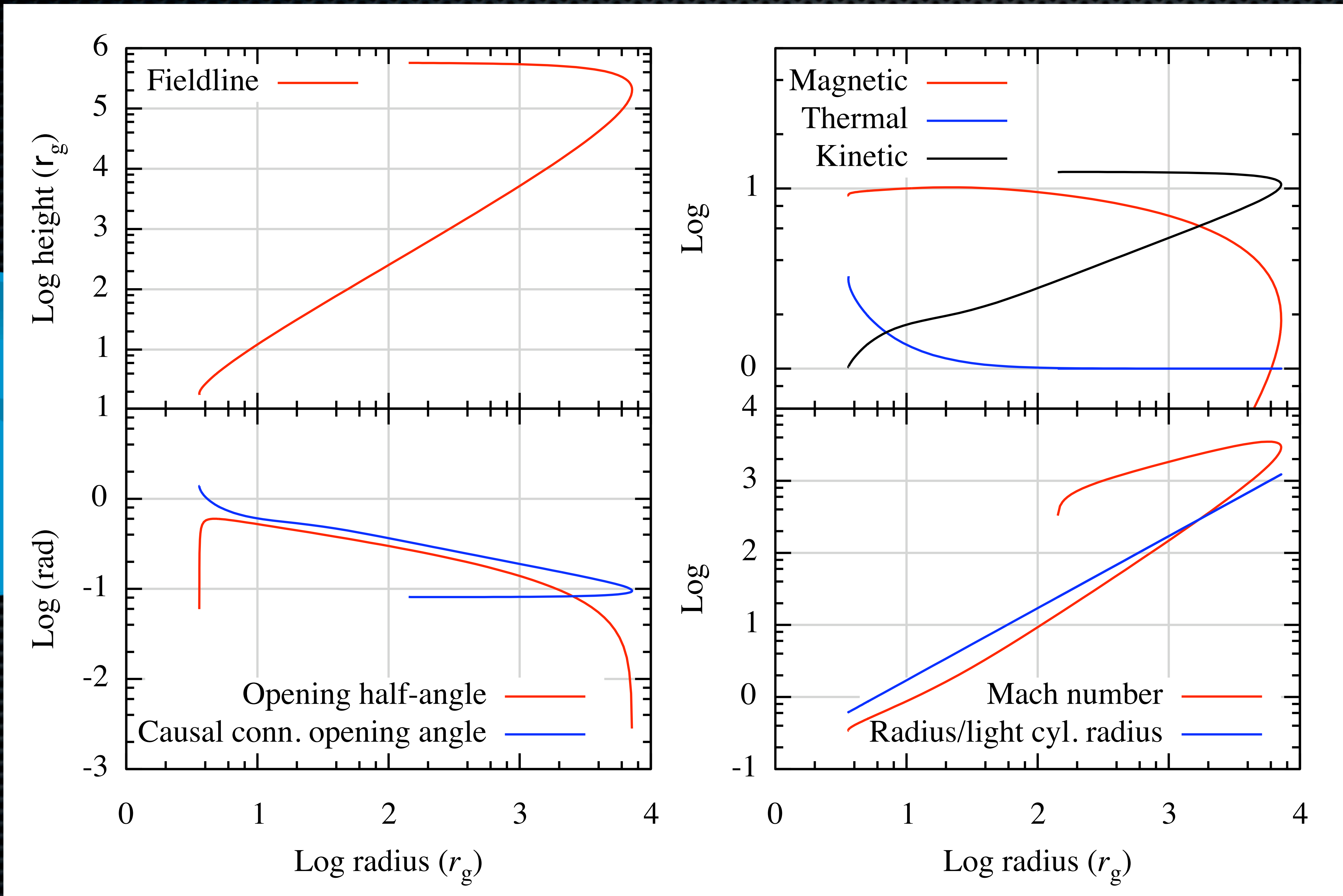


Mass scaling compact jets ➠ new relativistic MHD model to try to understand these trends



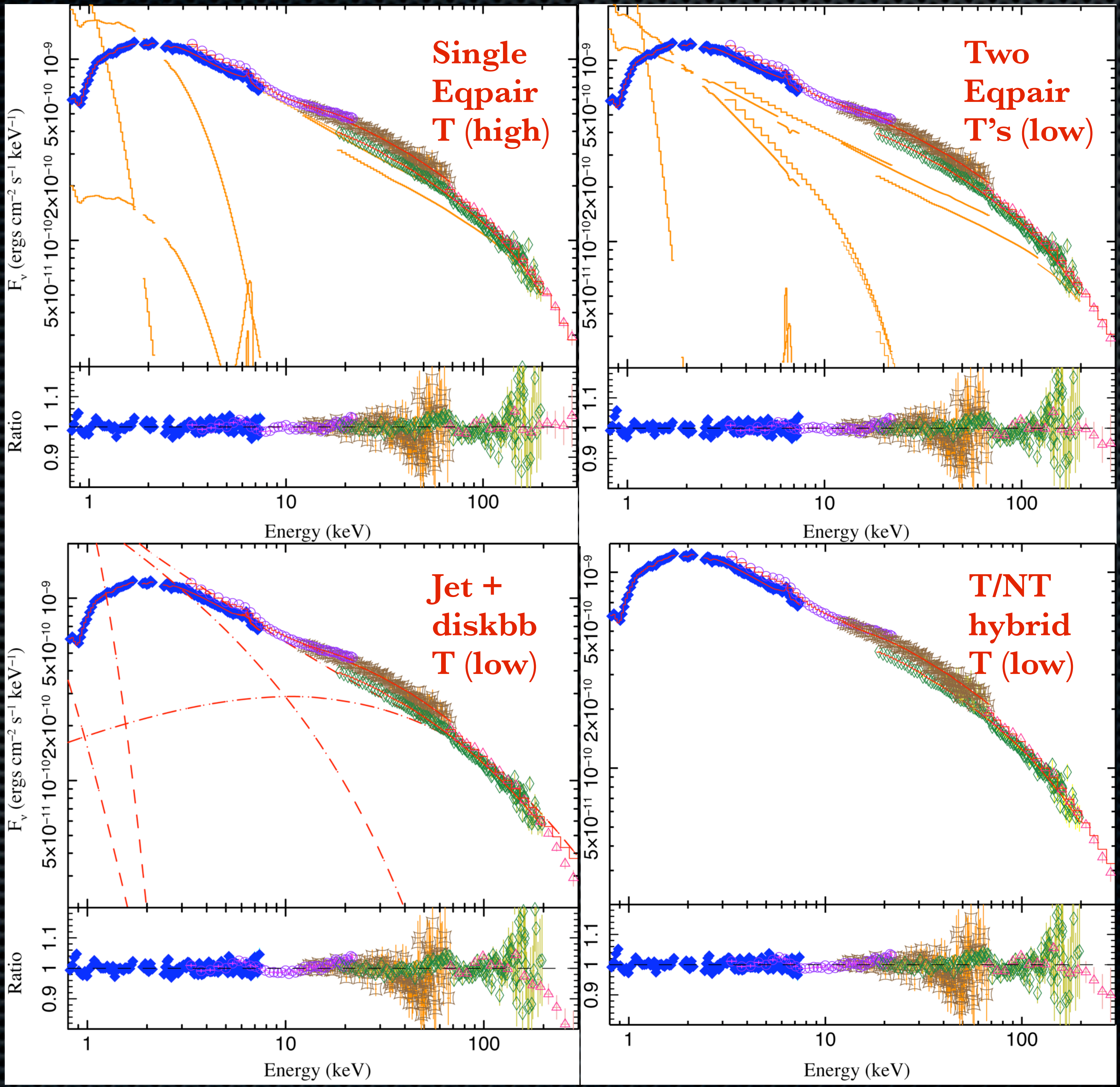
(Polko, Meier & SM 2010, Polko, Meier & SM 2012a, Polko, Meier & SM, subm.)

Mass scaling compact jets ➠ new relativistic MHD model to try to understand these trends



(Polko, Meier & SM 2010, Polko, Meier & SM 2012a, Polko, Meier & SM, subm.)

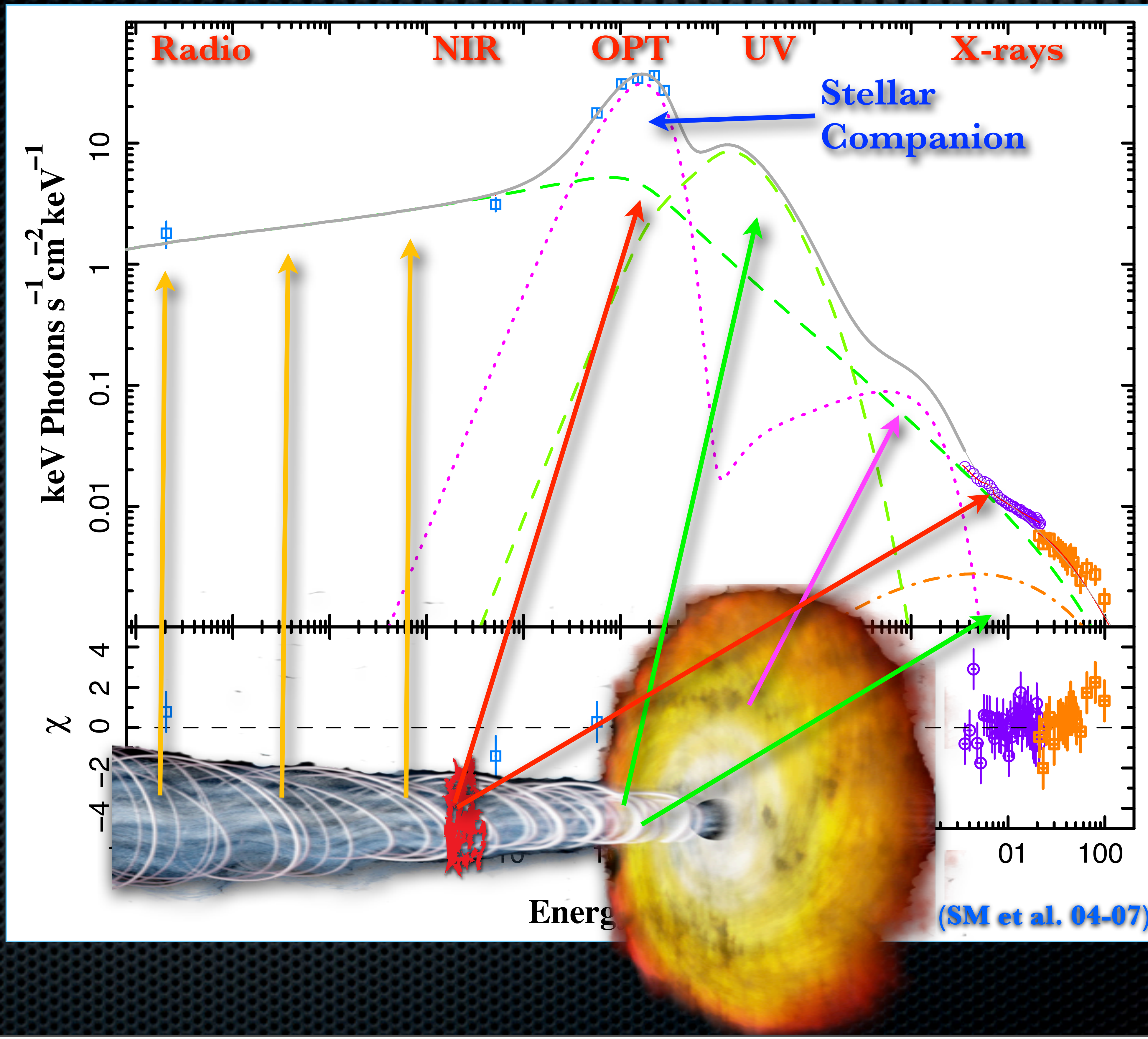
Breaking theoretical degeneracies:



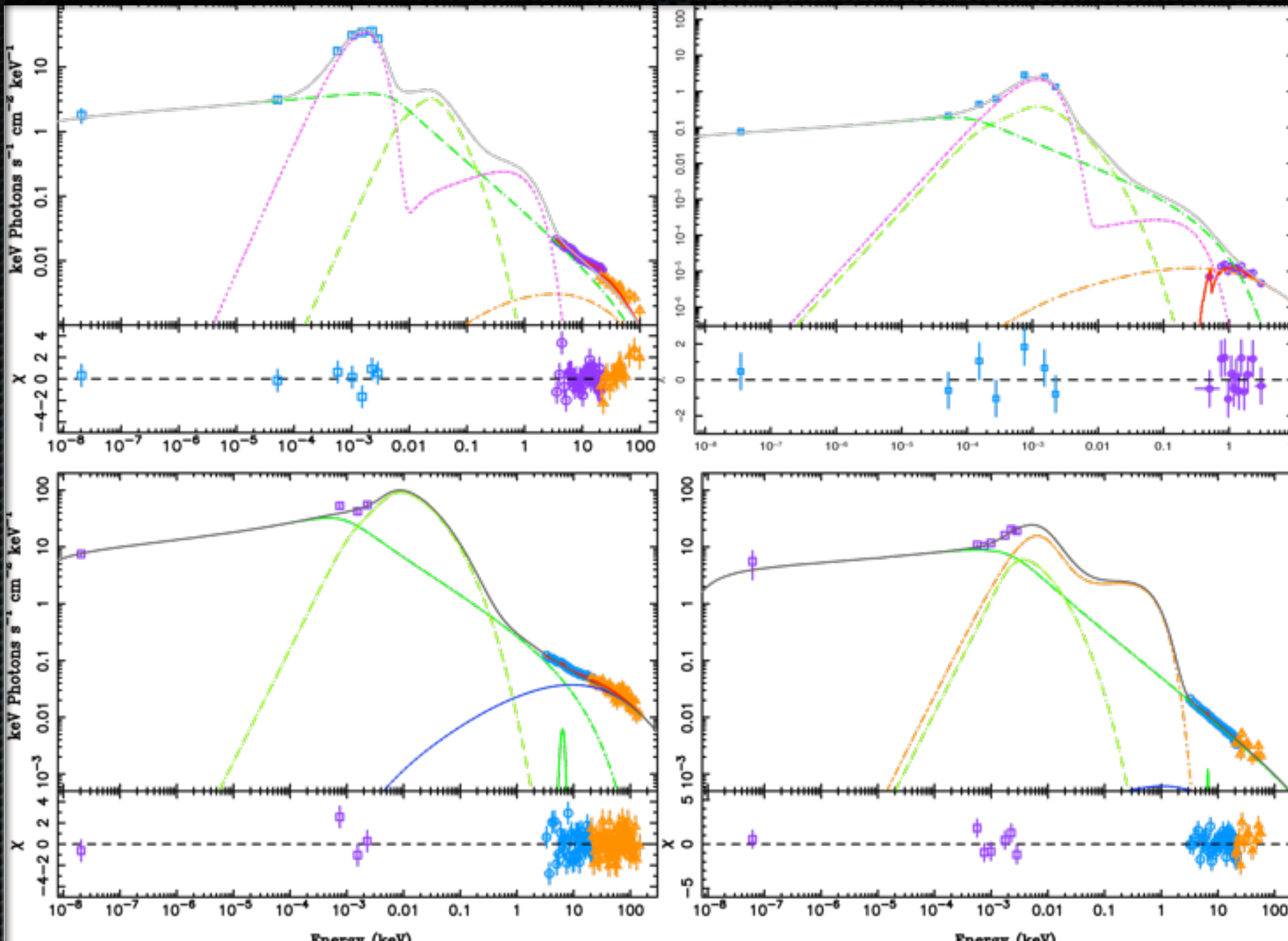
(Nowak et al. 2011)

+ Jet
Radio/IR
correla-
tions

Modeling "hard state" (steady jet) black hole XRBs

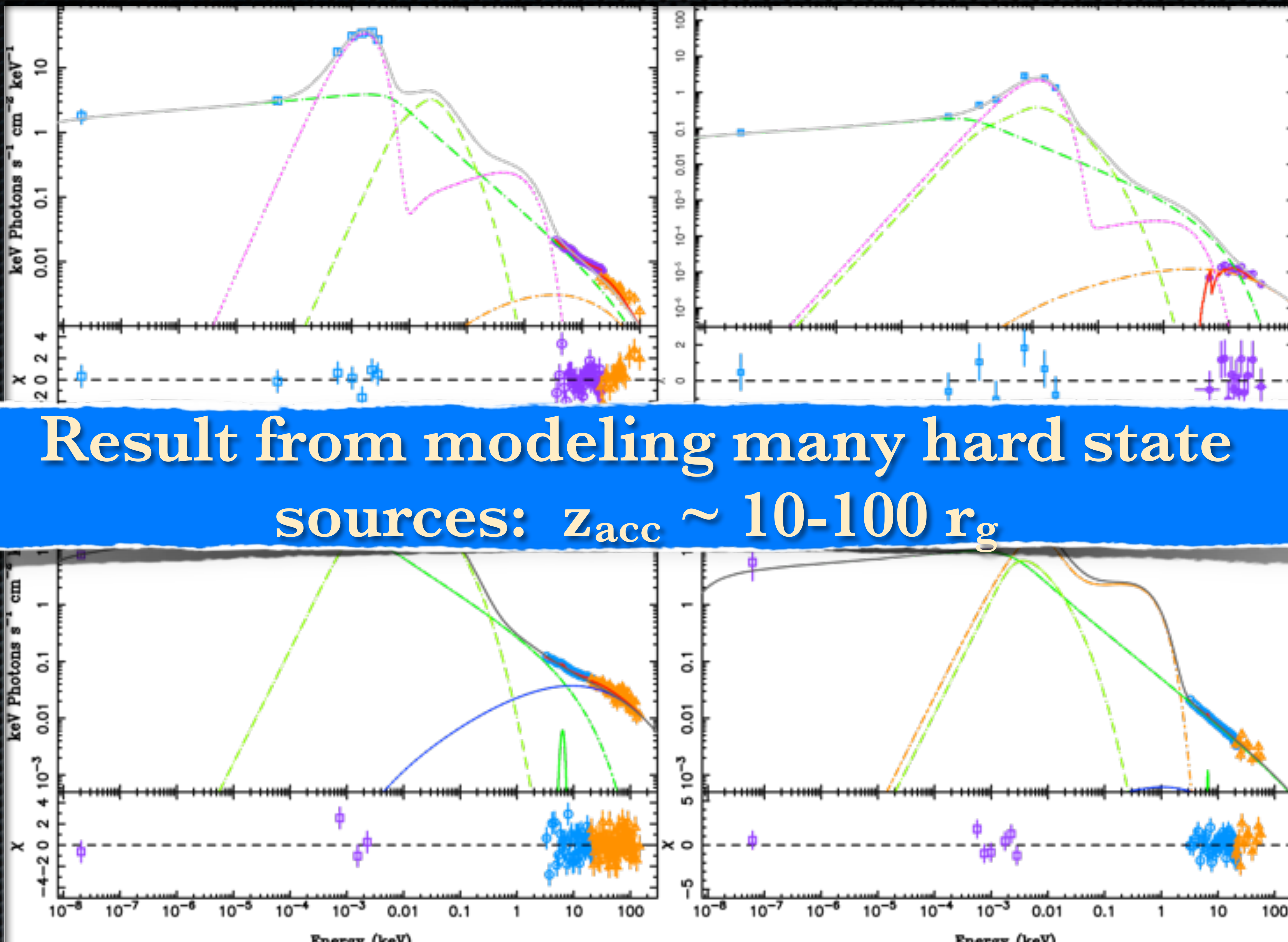


Application to multiple black hole XRBs: simultaneous MW data



(SM ea. 01, SM ea. 03, SM, Nowak & Wilms 05, Migliari ea. 07, Gallo ea. 07, Maitra ea. 09)

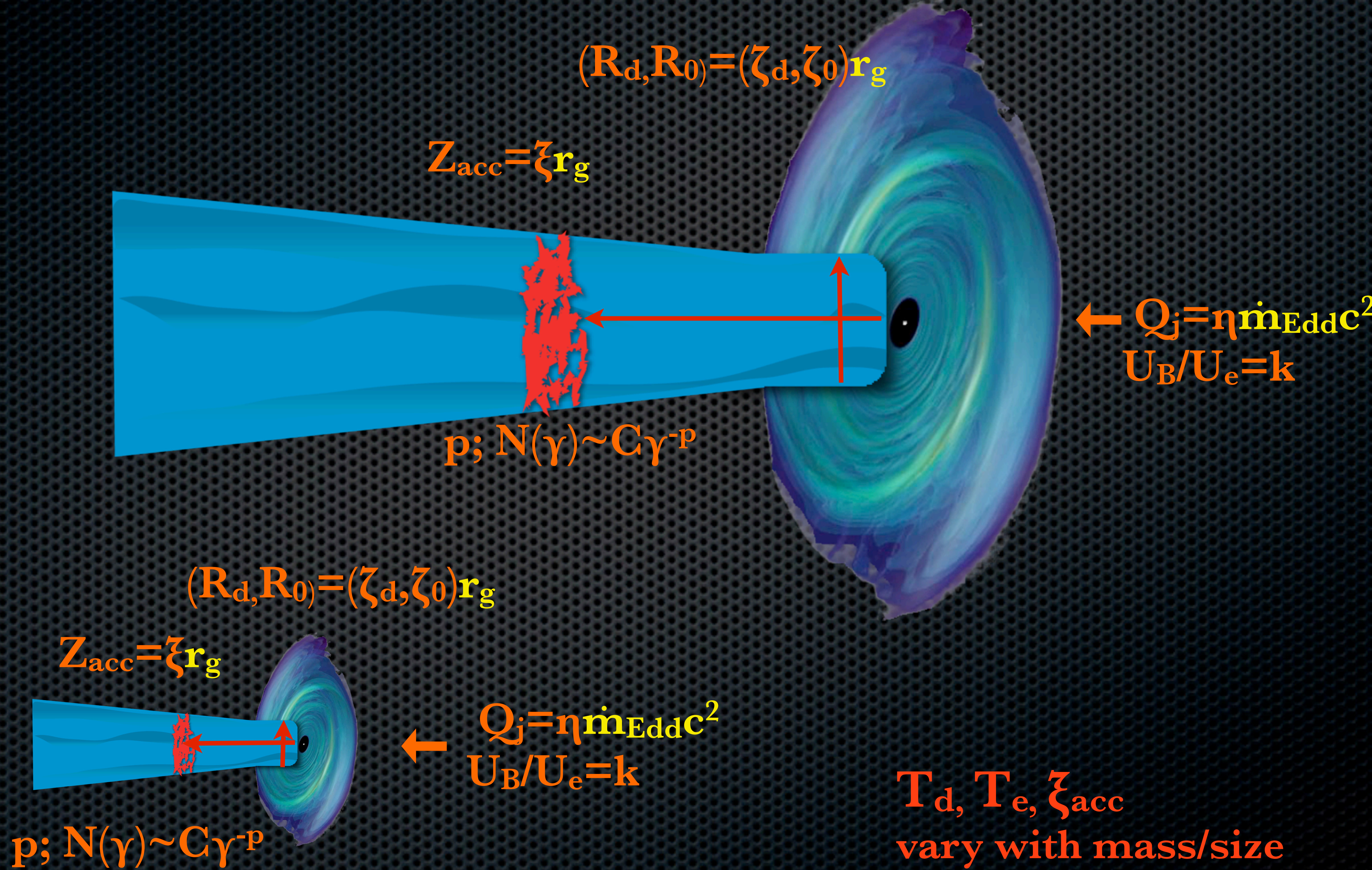
Application to multiple black hole XRBs: simultaneous MW data



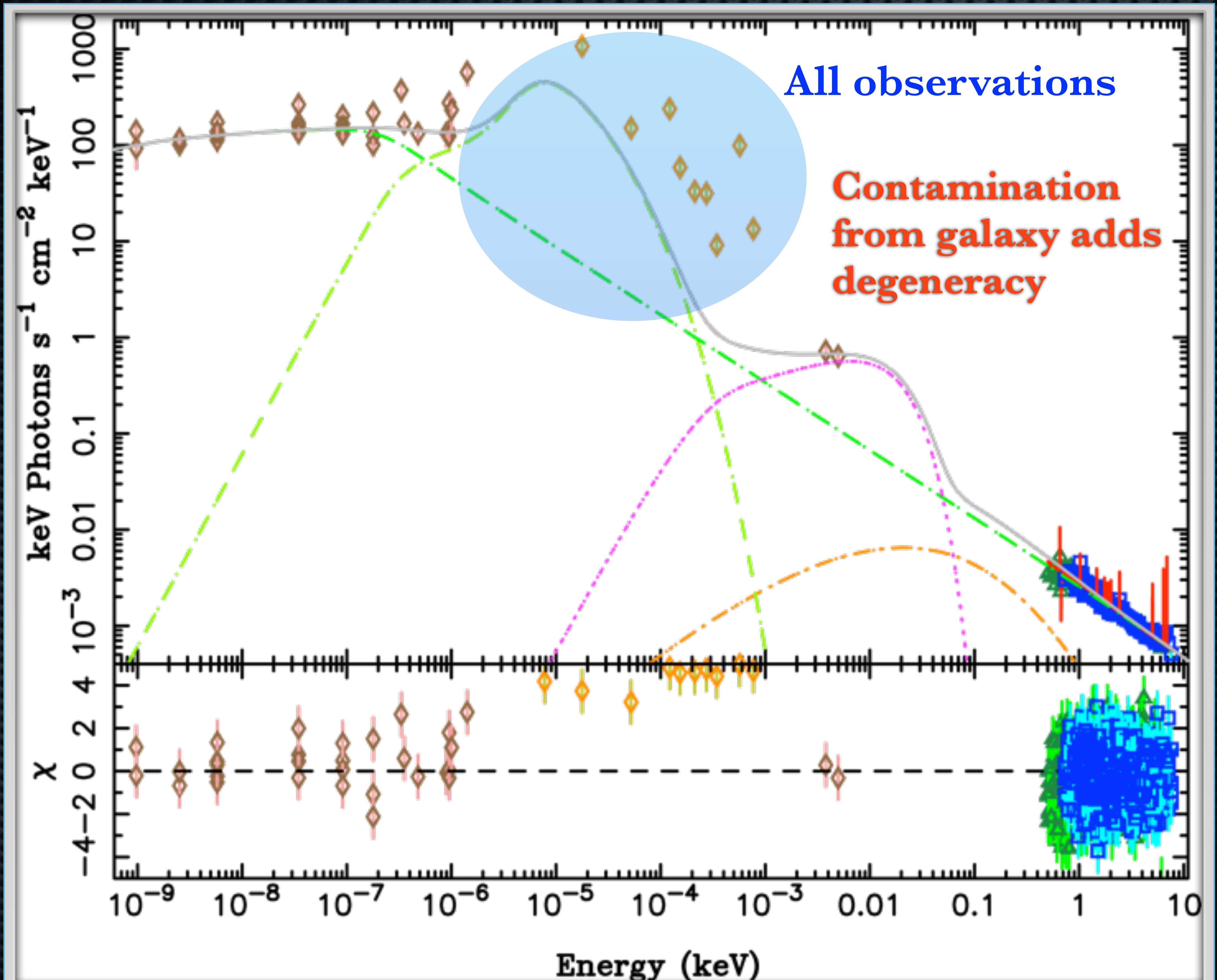
Result from modeling many hard state sources: $z_{acc} \sim 10\text{-}100\ r_g$

(SM ea. 01, SM ea. 03, SM, Nowak & Wilms 05, Migliari ea. 07, Gallo ea. 07, Maitra ea. 09)

How far can mass/power scaling go? Can we fit the broadband SED of an AGN and XRB with one model??



M81*: seems like "scaled up" XRB in hard state...?



(SM et al. 2008)

XRB/LLAGN model comparisons

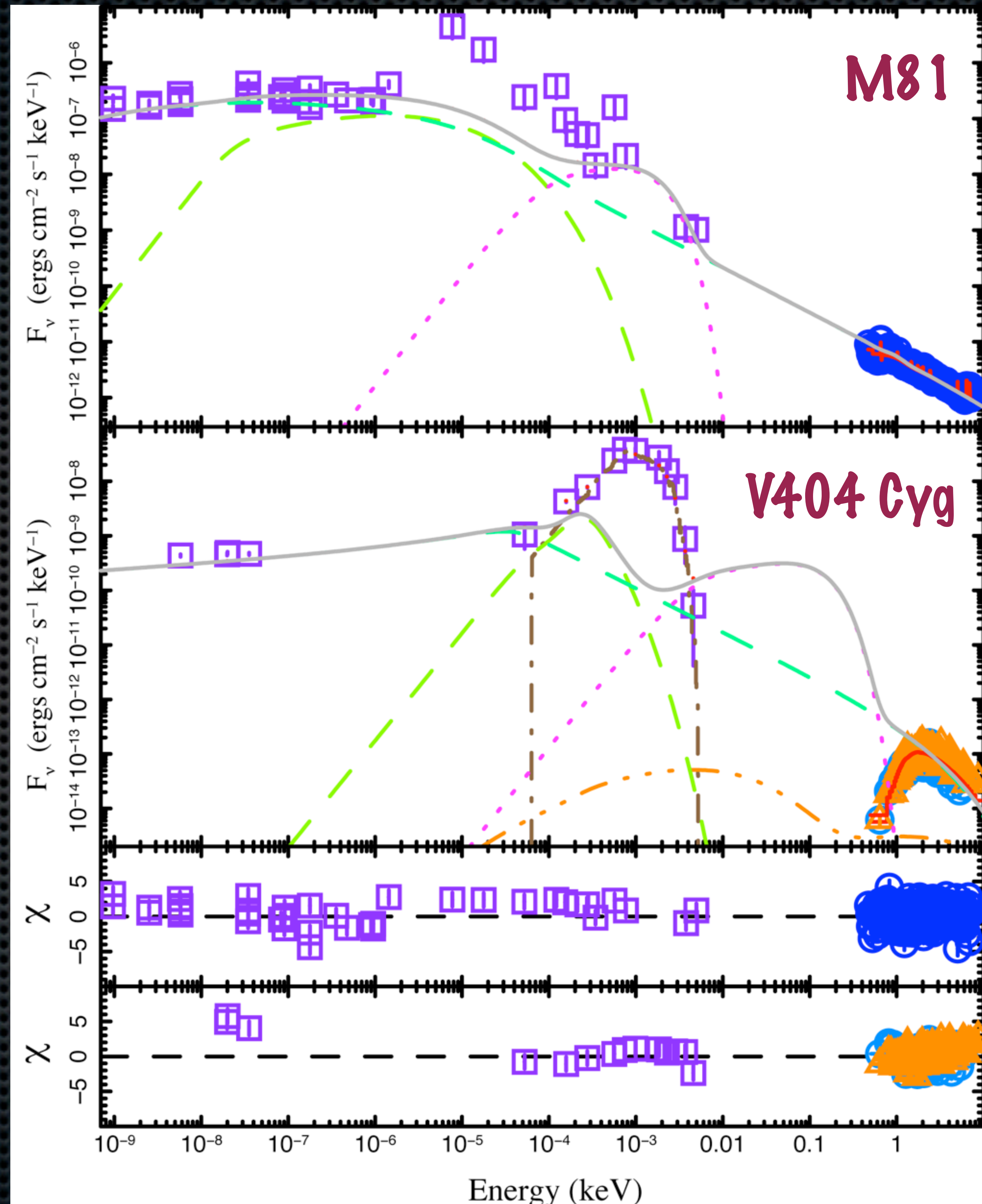
Parameter	meaning	HS-XRBs	M81
M ($M_\odot$)	BH mass	~10	7×10^7
Q_{jet} (L_{Edd})	norm'd power	10^{-5} – 10^{-1}	10^{-5}
R_0 (R_g)	radius jet base/corona	2–20	2.4
z_{acc} (R_g)	location of start of particle accel in jets	10–400	144
p_{elec}	electron PL index	2.4–2.9	2.4
PL frac	fraction of particles accelerated into PL at z_{acc}	0.6*	0.6*
T_e (K)	Thermal electron temp	$2–5\times10^{10}$	1×10^{11}
equip ($1/\beta$)	magnetic/thermal gas pressure ratio	1–5	1.4

(SM, Nowak & Wilms 2005, Migliari et al. 2007, Gallo et al. 2007, SM, Bower & Falcke 2007, SM et al. 2008, Maitra et al. 2009, van Oers, SM et al., 2010, Nowak et al. 2011)

Mass-scaling physical models: M81 ⇔ V404 Cyg ($L_x \sim 10^{-7}$ - 10^{-6} L_{Edd})

★ Tied parameters:

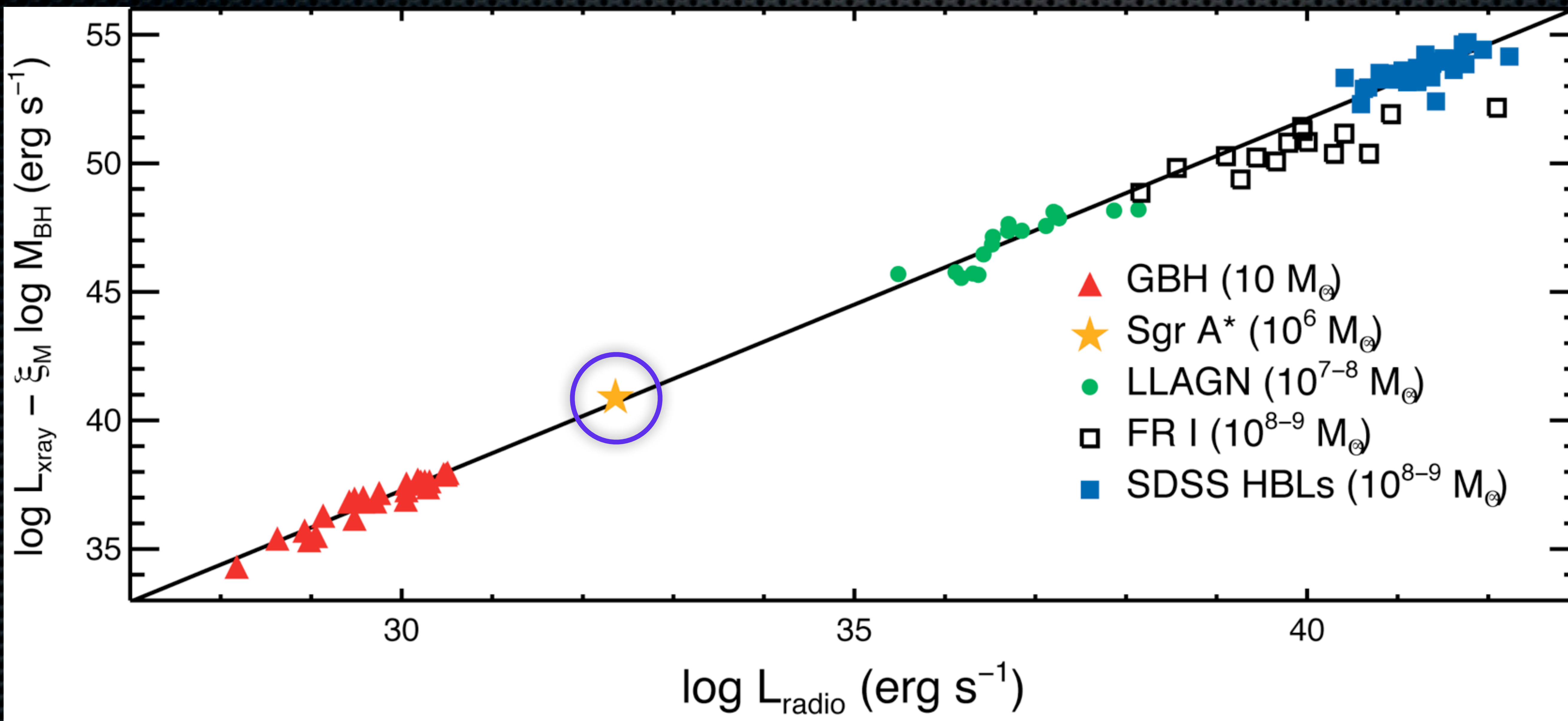
- R_{in} (BB disk)
- R_0 ("corona")
- z_{acc}
- p (e^- PL)
- U_B/U_{e-}



(SM, Nowak, Houck, Davis, Gallo, Hynes et al., in prep.)

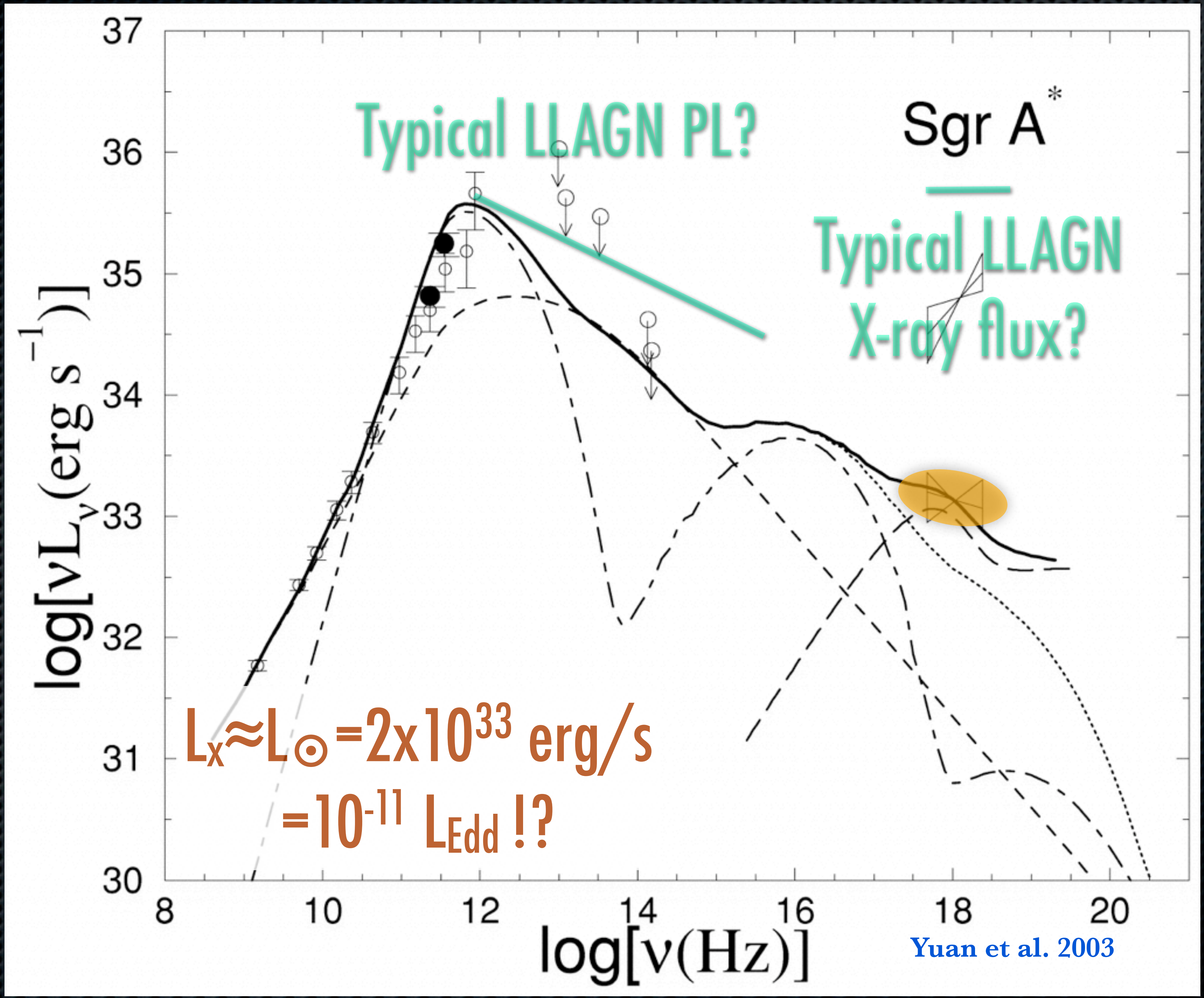
Sgr A* in context: a weak AGN or something else?:

Sgr A* sits on the FP...but only during flares!



(SM 2005; Plotkin, SM, Kelly, Körding & Anderson 2012)

Sgr A* quiescent spectrum – Very weak!



General trend: particle acceleration fizzles at very low $\dot{m}$

L < 10^{-7} L_{Edd}

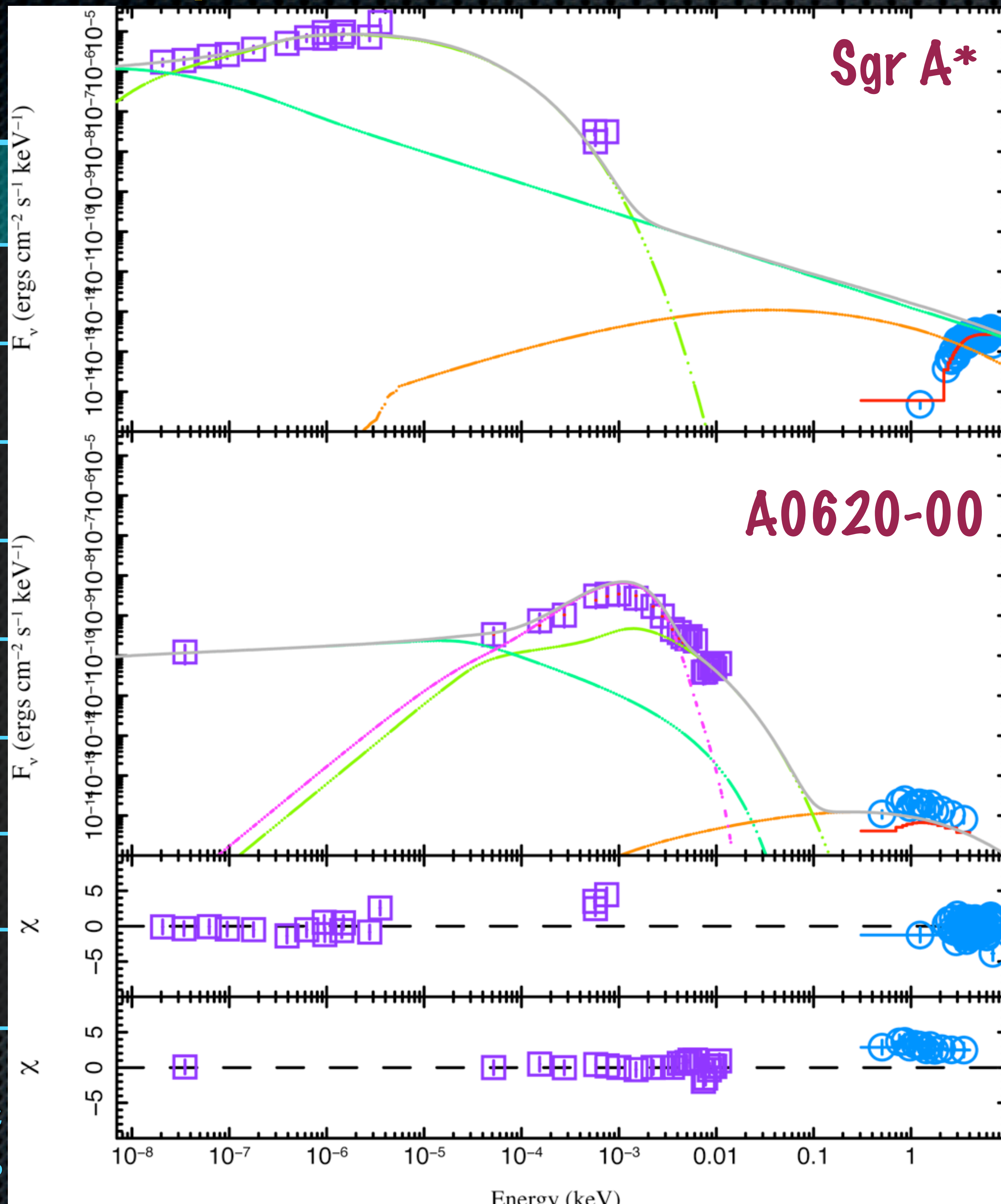
Parameter	HS-XRBs	M81	A0620	Sgr A*
M ($M_\odot$)	~10	7×10^{7}	~10	4×10^{6}
Q_{jet} (L_{Edd})	10^{-5} – 10^{-1}	10^{-5}	10^{-7}	10^{-9}
R_0 (R_g)	2–20	2.4	2–7	2.5
z_{acc} (R_g)	10–400	144	1250	$>10^{4}$
p_{elec}	2.4–2.9	2.4	3.4	>3.8
PL frac	0.6*	0.6*	<0.6	<0.01
T_e (K)	2–5×10^{10}	1×10^{11}	2×10^{10}	1×10^{11}
equip ($1/\beta$)	1–5	1.4	1.5	>10

(SM, Nowak & Wilms 2005, Migliari et al. 2007, Gallo et al. 2007, SM, Bower & Falcke 2007, SM et al. 2008, Maitra et al. 2009, van Oers, SM et al., 2010, Nowak et al. 2011, SM ea. in prep.)

General trend: particle acceleration fizzles at very low $\dot{m}$

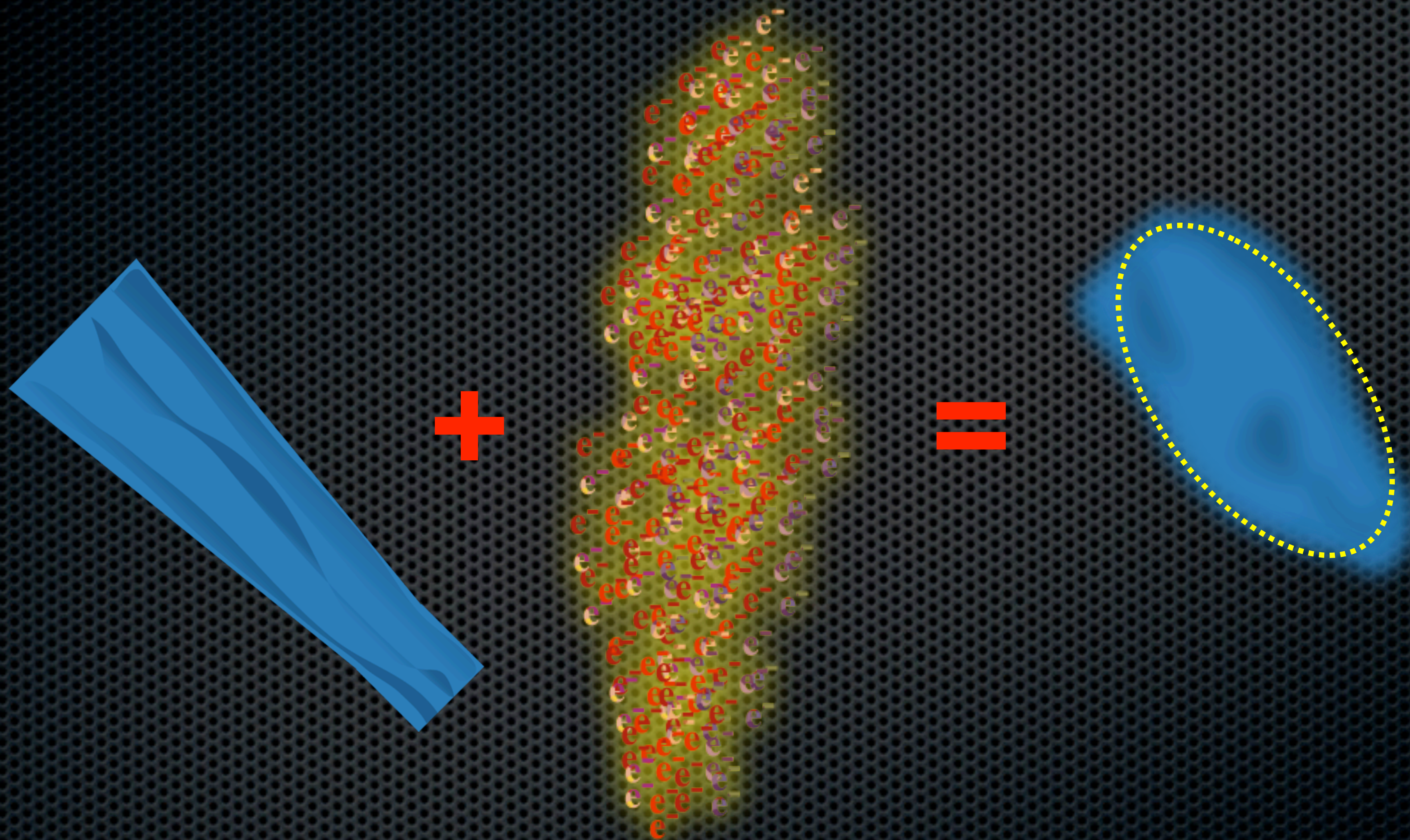
0^{-7} L_{Edd}

Parameter	Sgr A*
M ($M_\odot$)	4×10^6
Q_{jet} (L_{Edd})	10^{-9}
R_0 (R_g)	2.5
z_{acc} (R_g)	$>10^4$
p_{elec}	>3.8
PL frac	<0.01
T_e (K)	1×10^{11}
equip ($1/\beta$)	>10



(SM, Nowak & ... & Falcke 2007, SM et al. 2008, ... 11, SM ea. in prep.)

Scattering by intervening e-'s can hide Sgr A*'s jets!



(SM, Bower & Falcke 2007)

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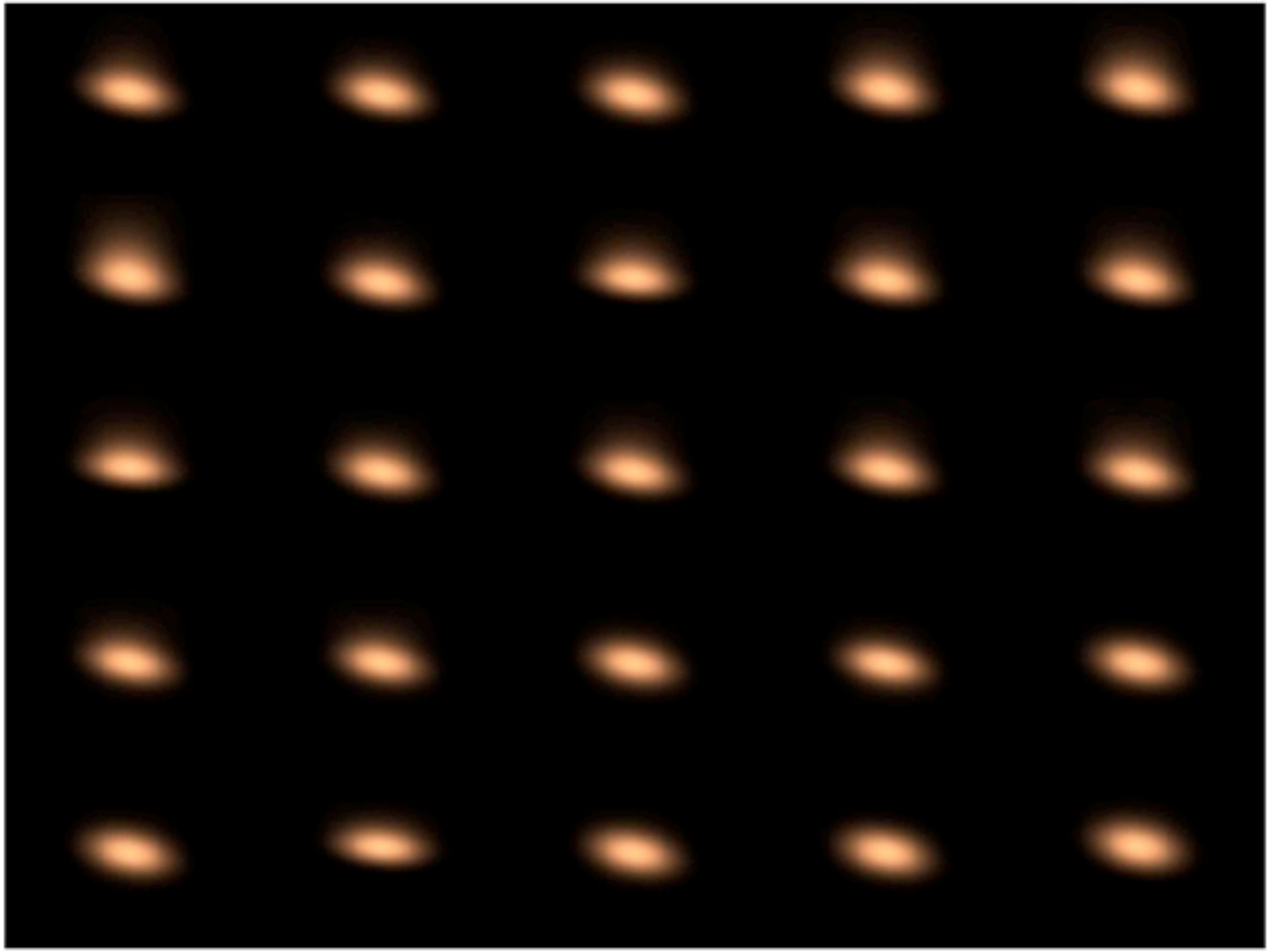
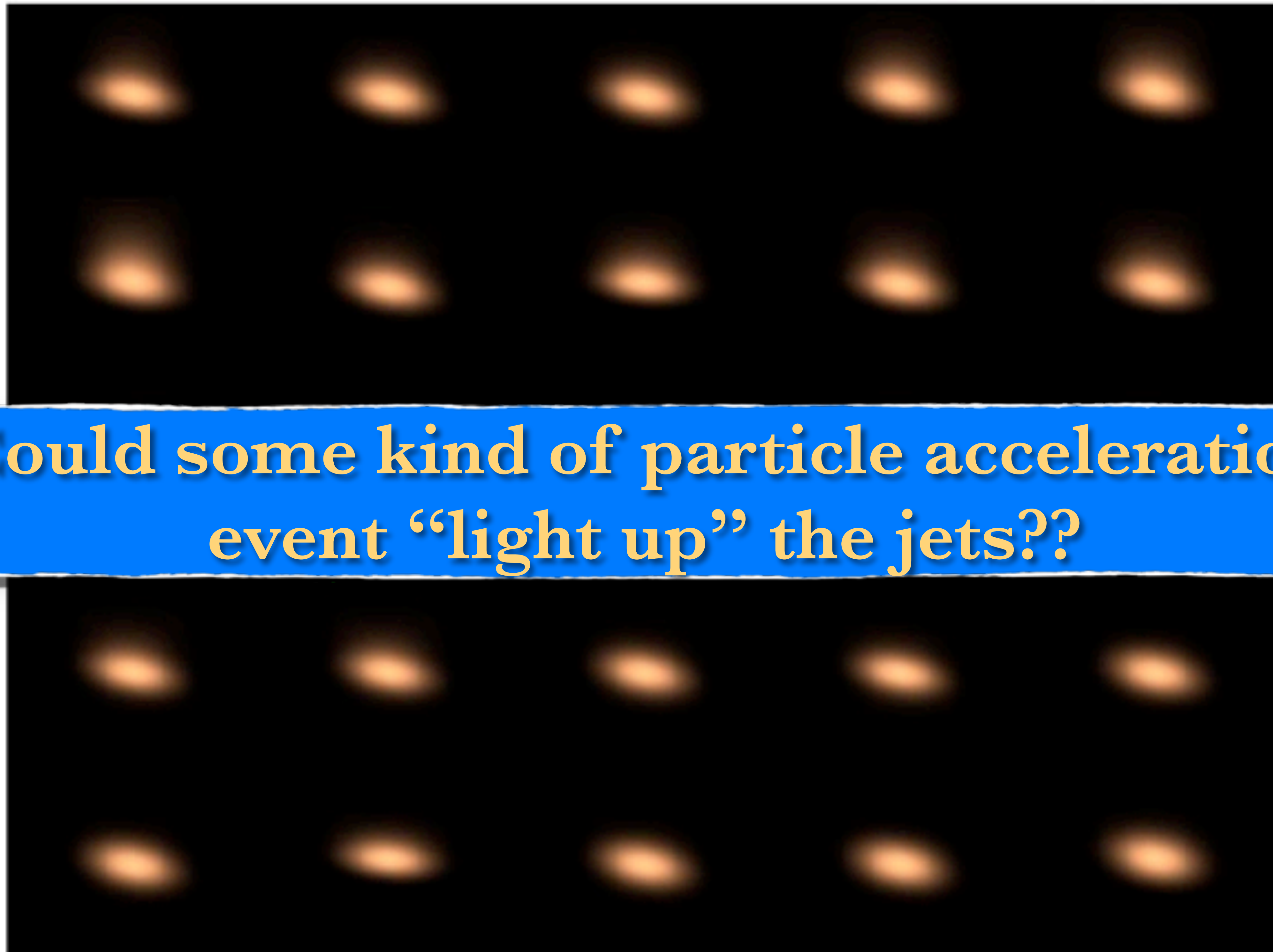


(SM, Bower & Falcke 2007)

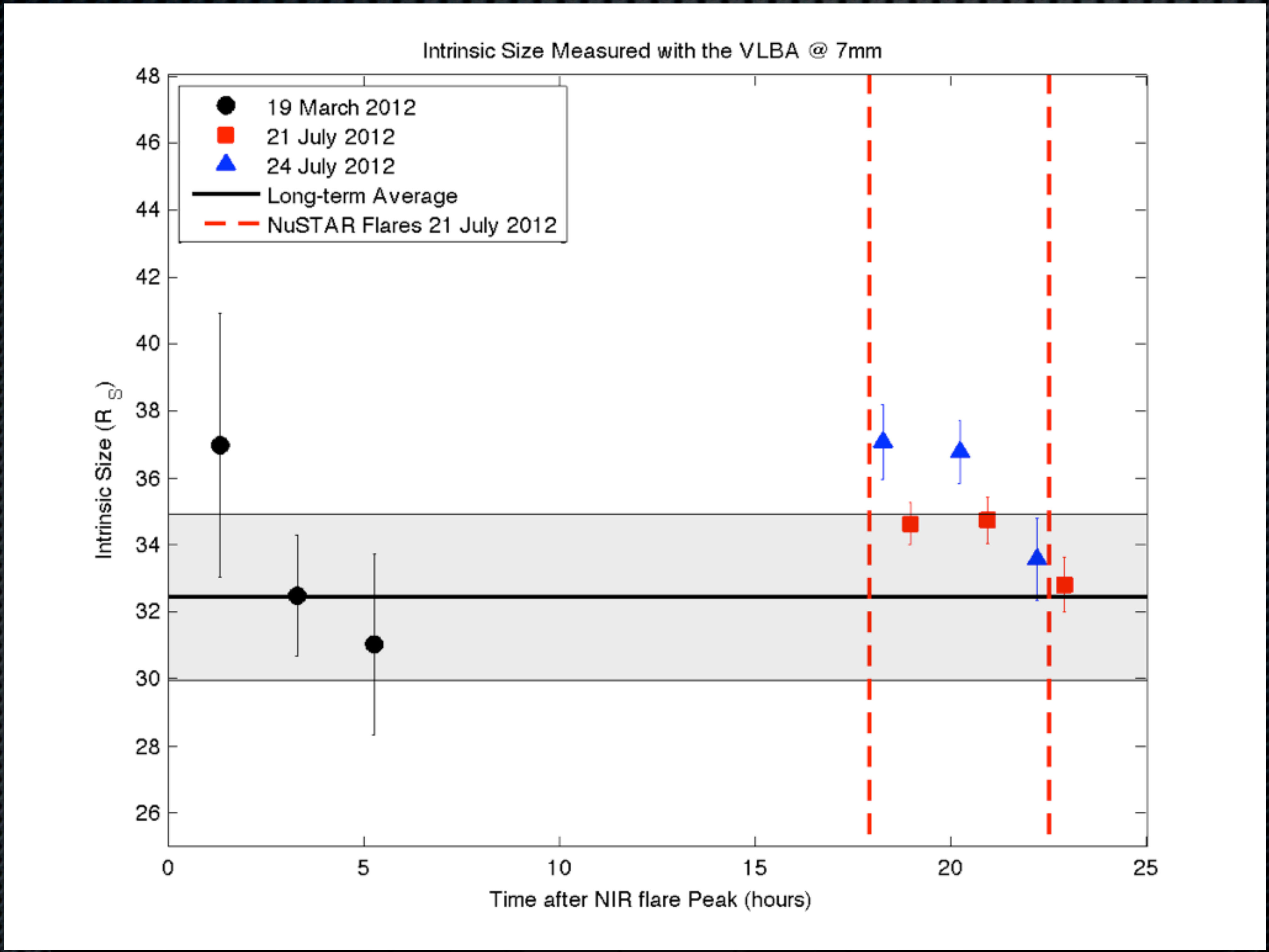
Scattering by intervening e-'s can hide Sgr A*'s jets!



Could some kind of particle acceleration event "light up" the jets??

(SM, Bower & Falcke 2007)

What might flares trigger for jets?
VLBA observations triggered from IR



(Bower, SM, et al., subm.)

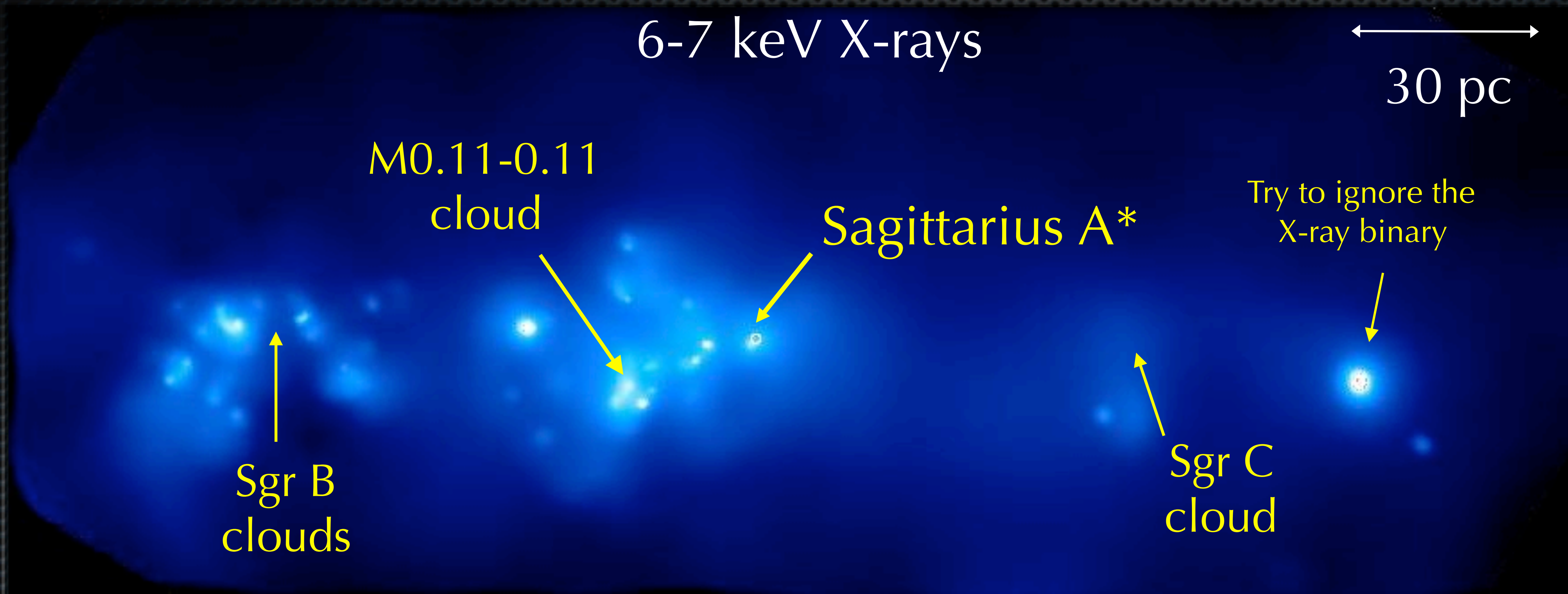
Prediction: the next push in constraining the MHD models of jets, and jet/disk connetions will be self-consistent determinations of the acceleration zone, and interpretation of VLBI observations, in the context of semi-analytical models and GRMHD simulations

Summary & Outlook

- XRBs are key for jet studies at all scales: predictable scaling of accretion physics with BH mass, realtime evolution offers a view of longterm processes in AGN ("Fundamental Plane" is one example)
- XRBs reveal the coupling between jet powering and particle acceleration: we see buildup from launch to onset of particle distribution, can localize acceleration regions ☛ key constraints for physical models
- XRB jets contribute to Galactic CR population: X-ray and γ-ray flares, polarized soft γ-rays, jet break constraints ➠ TeV-PeV CRs
- Jet power vs. spin: It's complicated! Roll of spin not yet isolated from "astrophysics"
- Outlook:
  - ➠ Improved models: new MHD models/simulations explore links between accretion inflow, jet dynamics and particle acceleration
  - ➠ New facilities: Era of "transient factories": LOFAR/MeerKAT/ASKAP/LSST, NuSTAR, CTA
  - ➠ XRB jet feedback: ionization, Galactic/low-energy cosmic rays ➠ burgeoning field: with transient monitoring studies paves the way towards understanding the effect on the Galaxy/star formation

Extra slides

Was Sgr A* more active in the past?



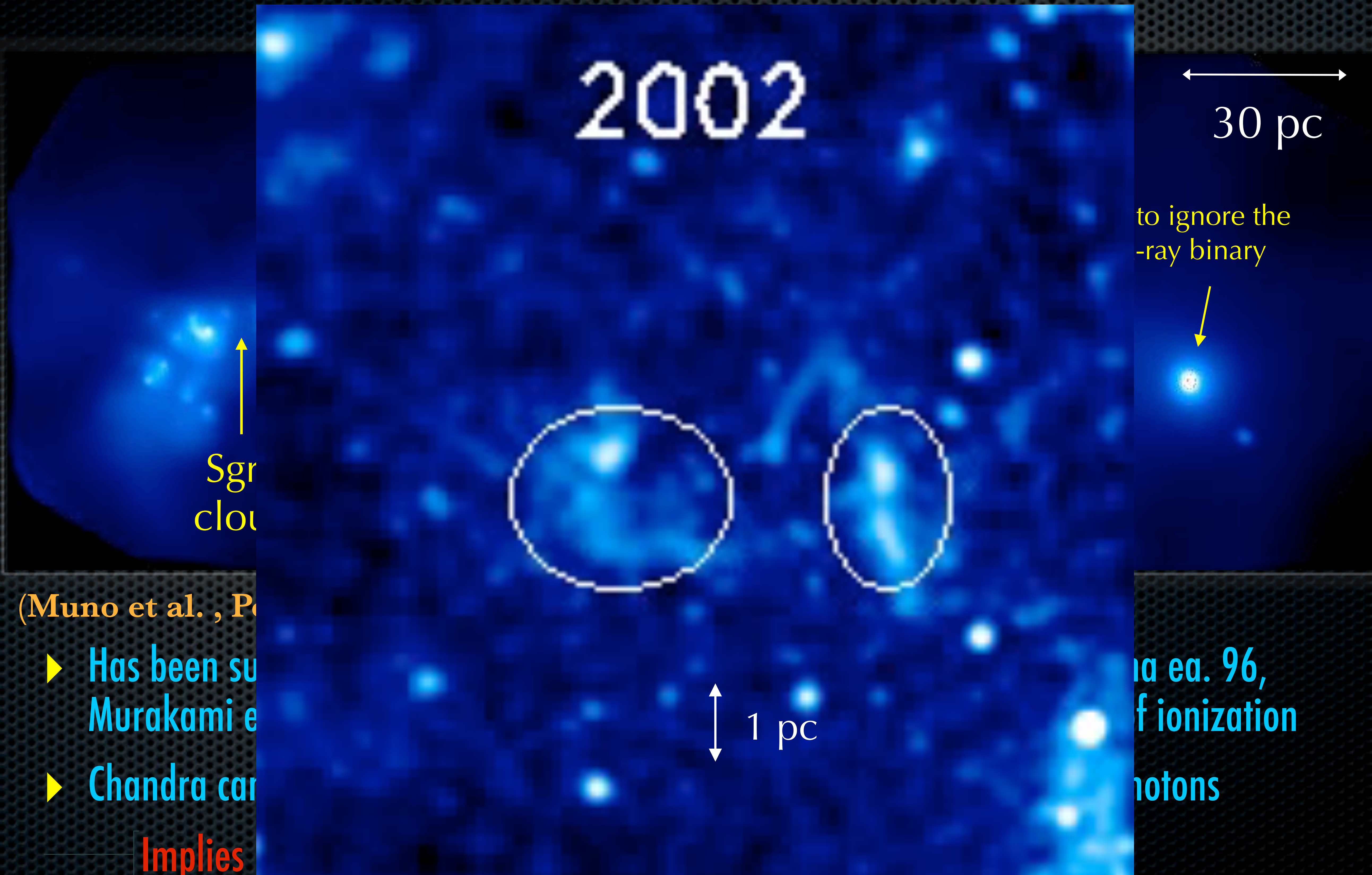
(Muno et al. , Ponti et al. etc.)

- Has been suggested that the best source is prior activity of Sgr A* (Koyama ea. 96, Murakami ea 00, Revnivtsev ea. 04) but some controversy about source of ionization
- Chandra can actually resolve the "wave" of fluorescence, must be hard photons

1 pc

Implies $L \leq 10^{39}$ erg/s outburst lasting ~10 yrs, about 100 years ago!

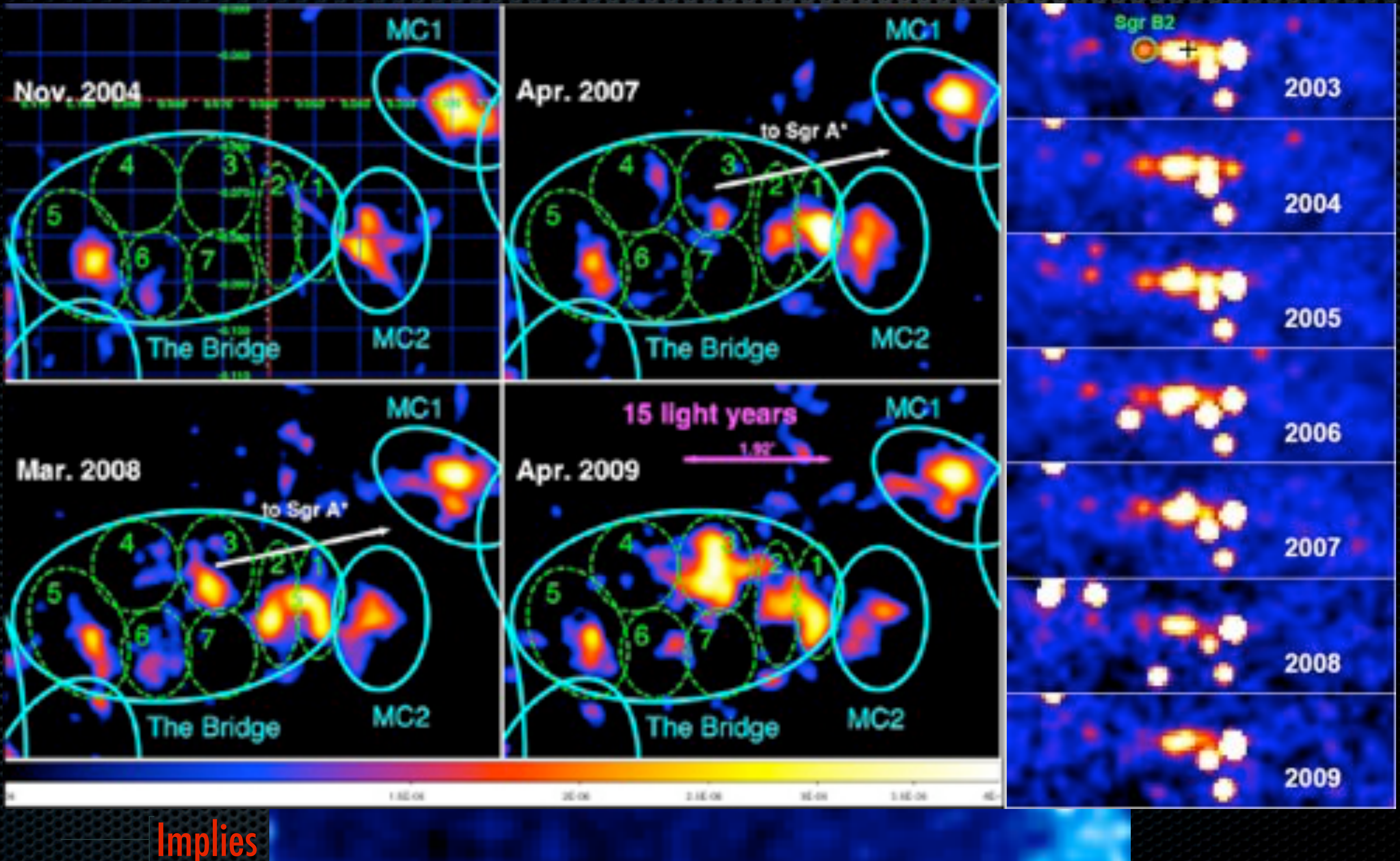
Was Sgr A* more active in the past?



(Muno et al. , P

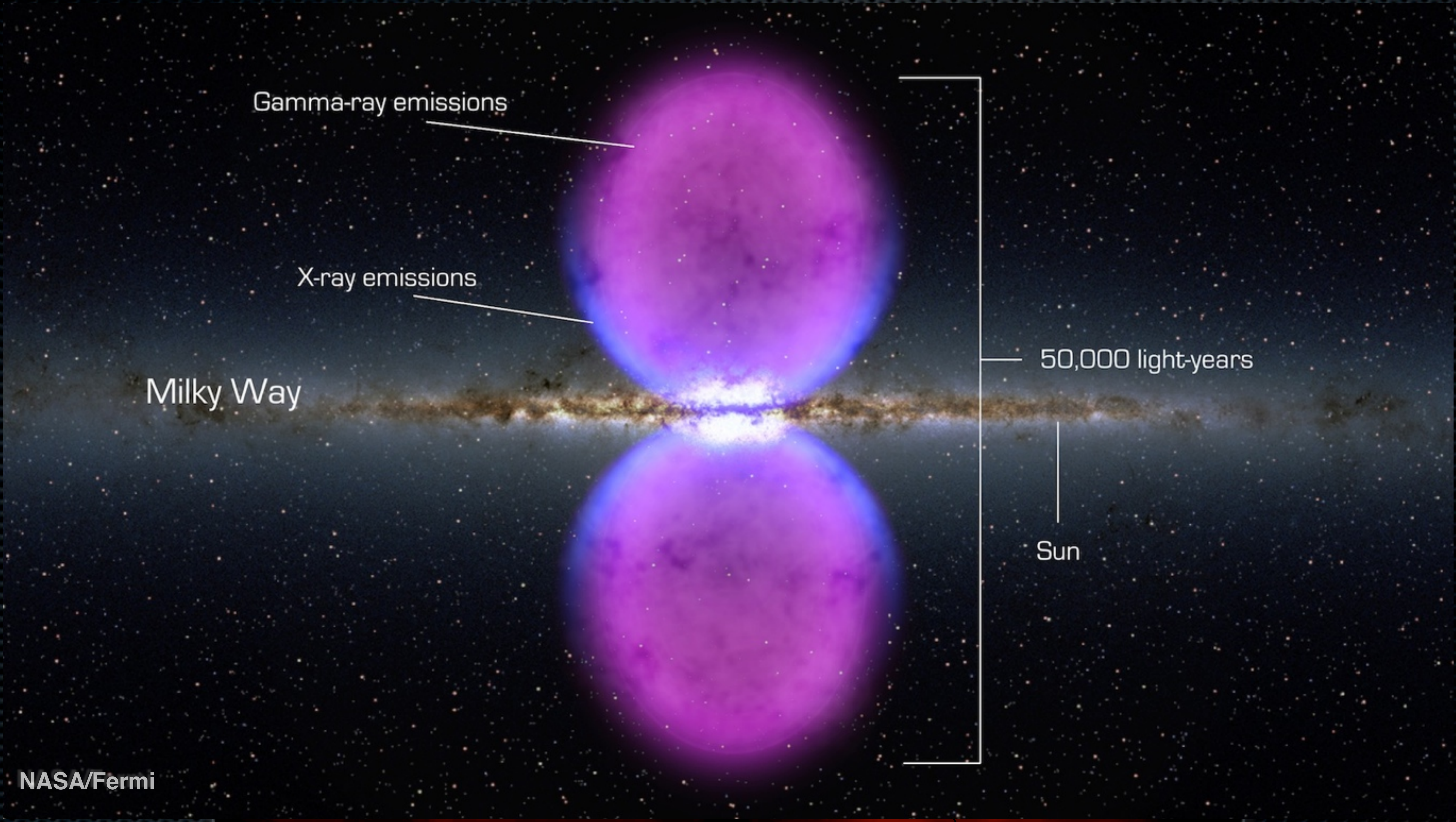
- Has been su ... a ea. 96,
  Murakami e ... f ionization
- Chandra ca ... otons
  - Implies

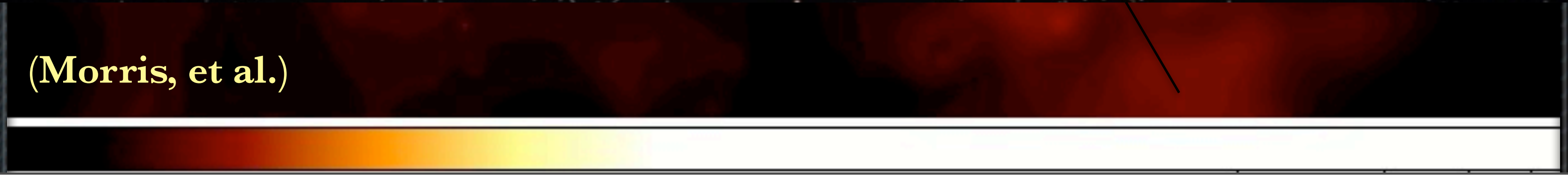
Was Sgr A* more active in the past?



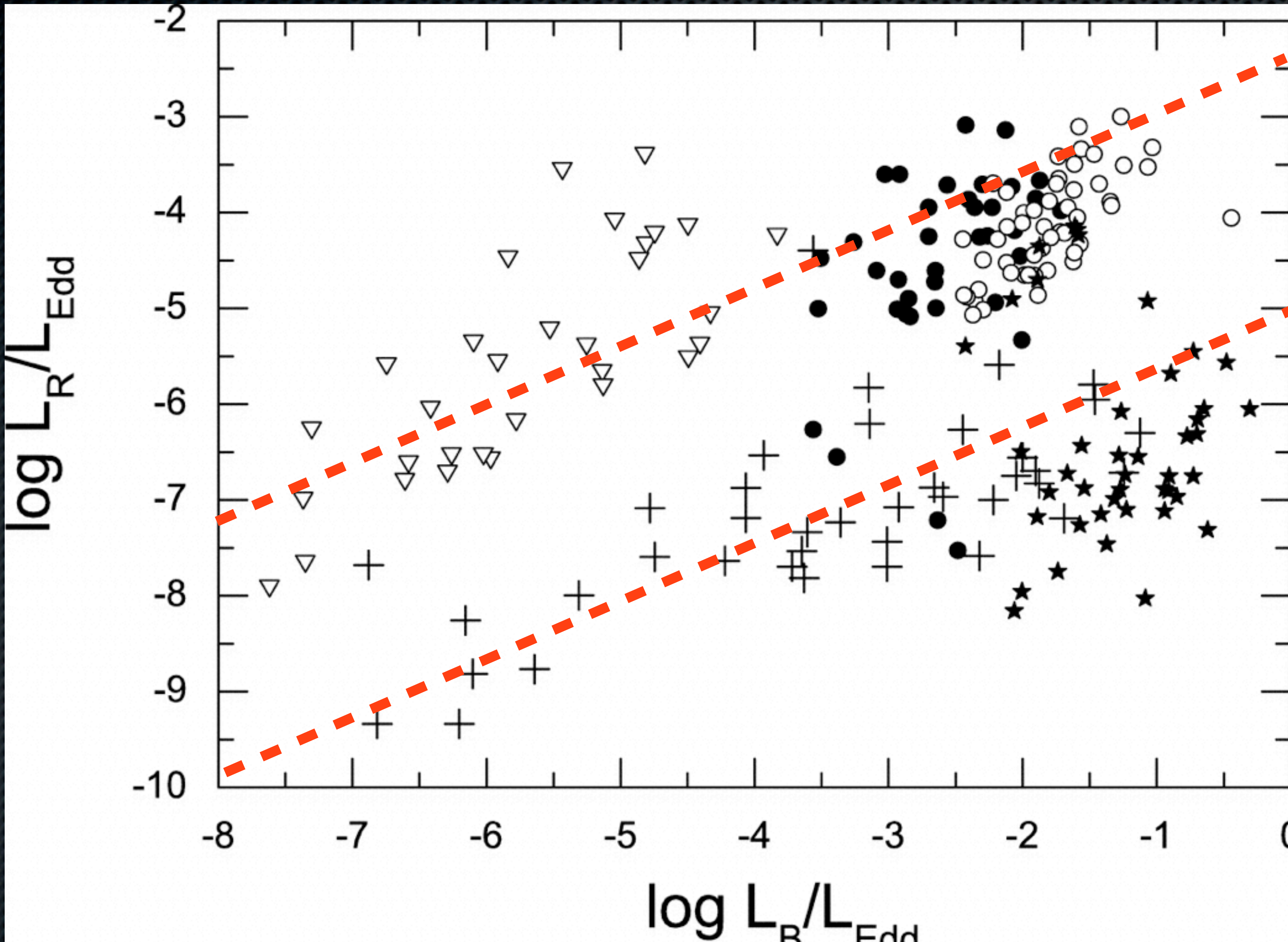
Implies

Was Sgr A* more active in the past?



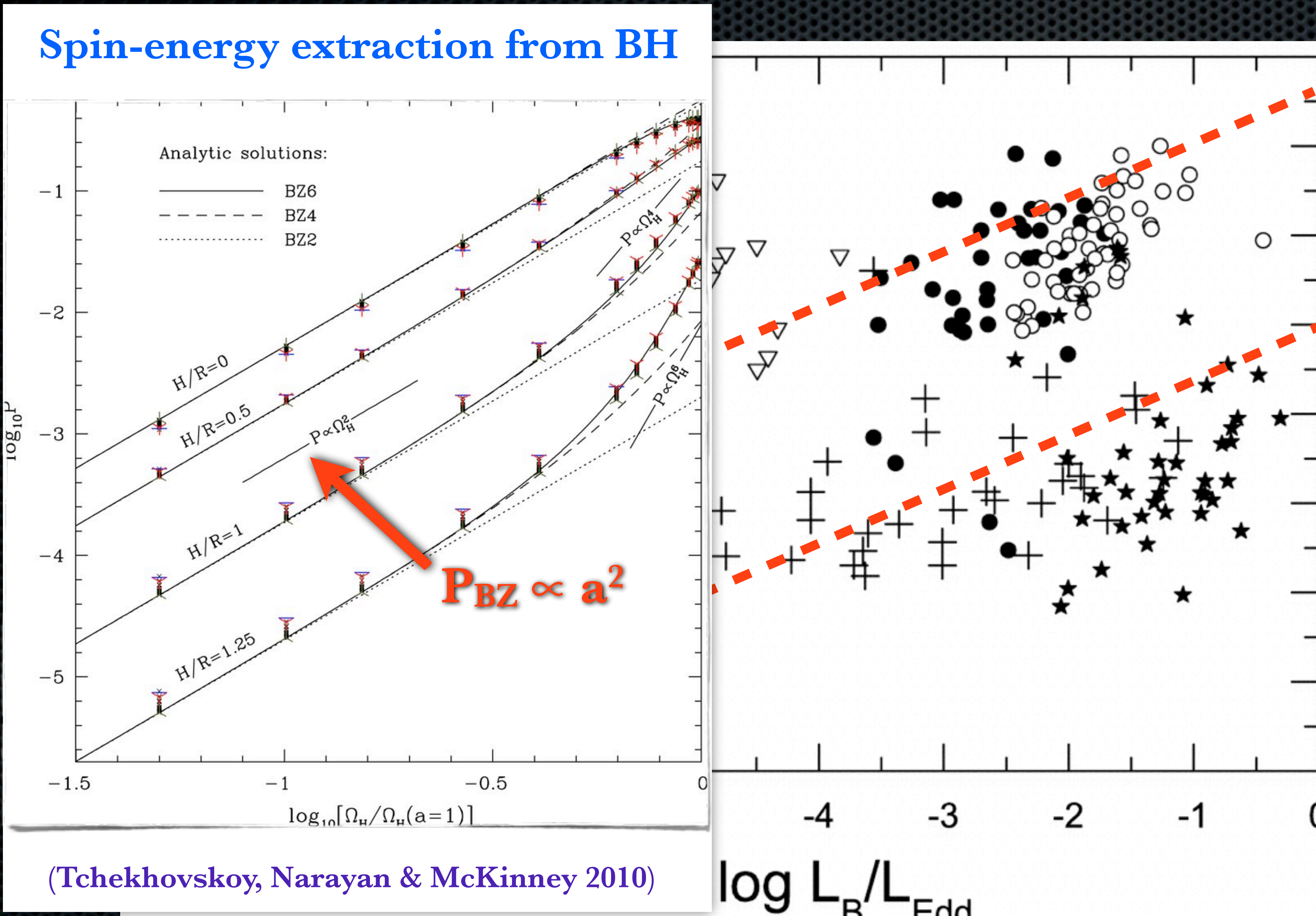


Jet power: RL/RQ dichotomy in AGN populations?



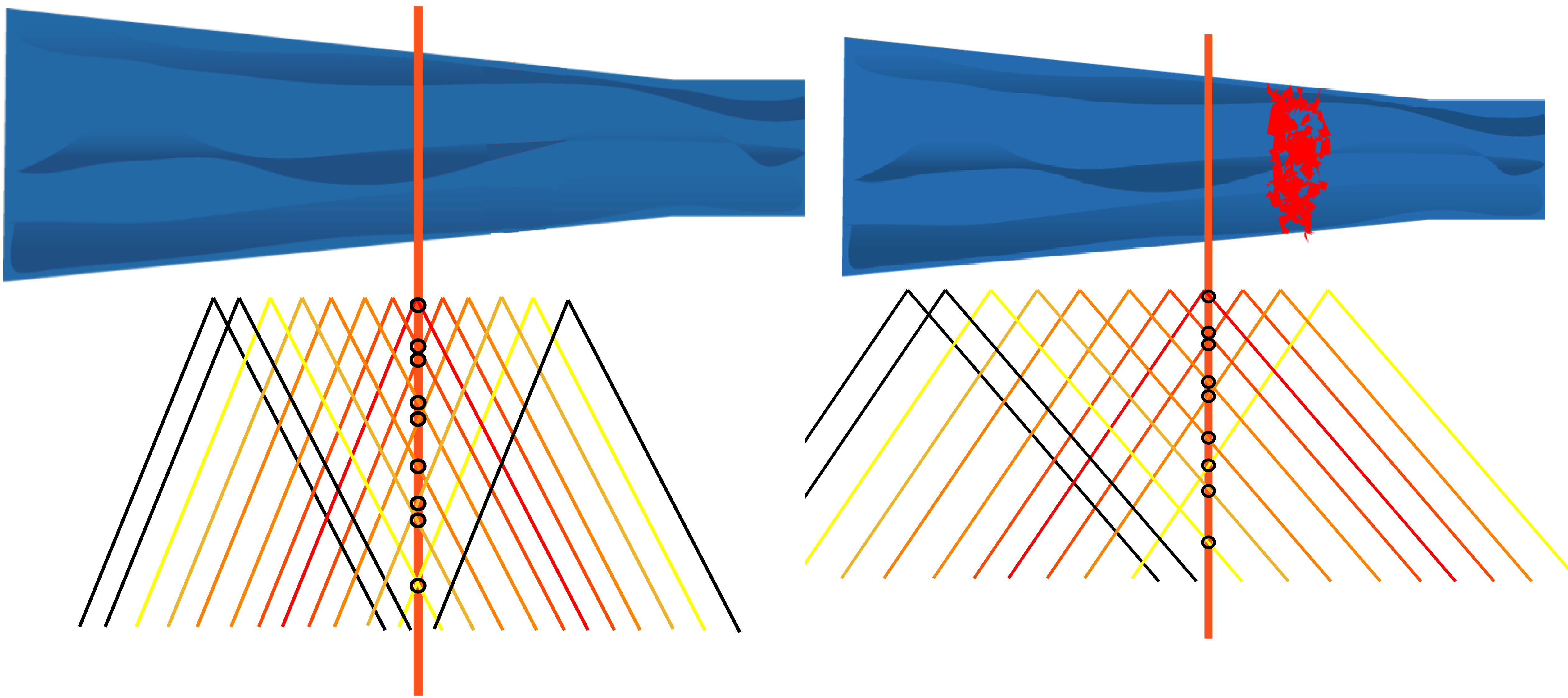
(Sikora, Stawarz & Lasota 2007)

Jet power: RL/RQ dichotomy in AGN populations?



(Sikora, Stawarz & Lasota 2007)

Particle acceleration increases jet "footprint" on sky



Particle acceleration increases jet “footprint” on sky