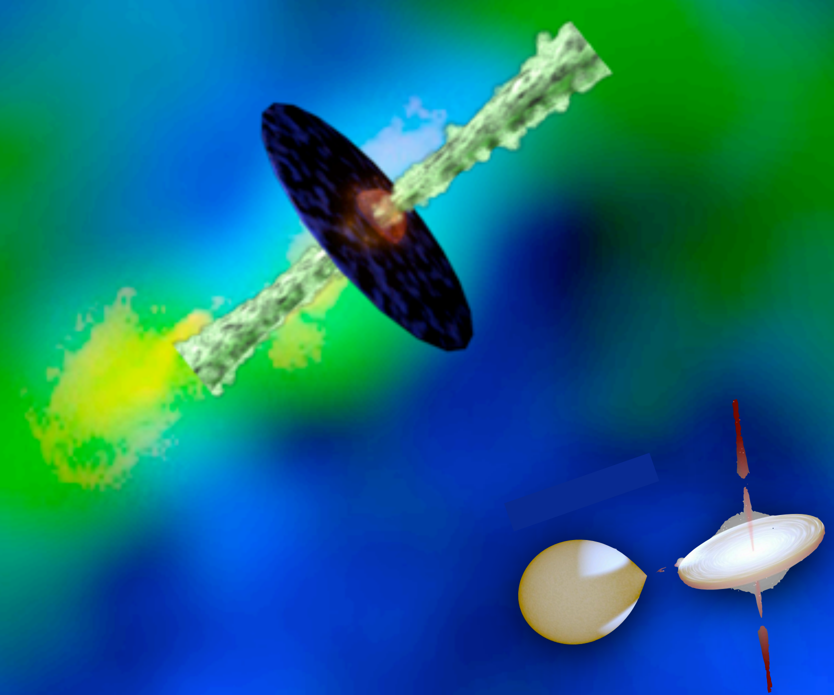
Jets across the black hole mass scale: new insights from X-ray binaries



Sera Markoff (API, University of Amsterdam)

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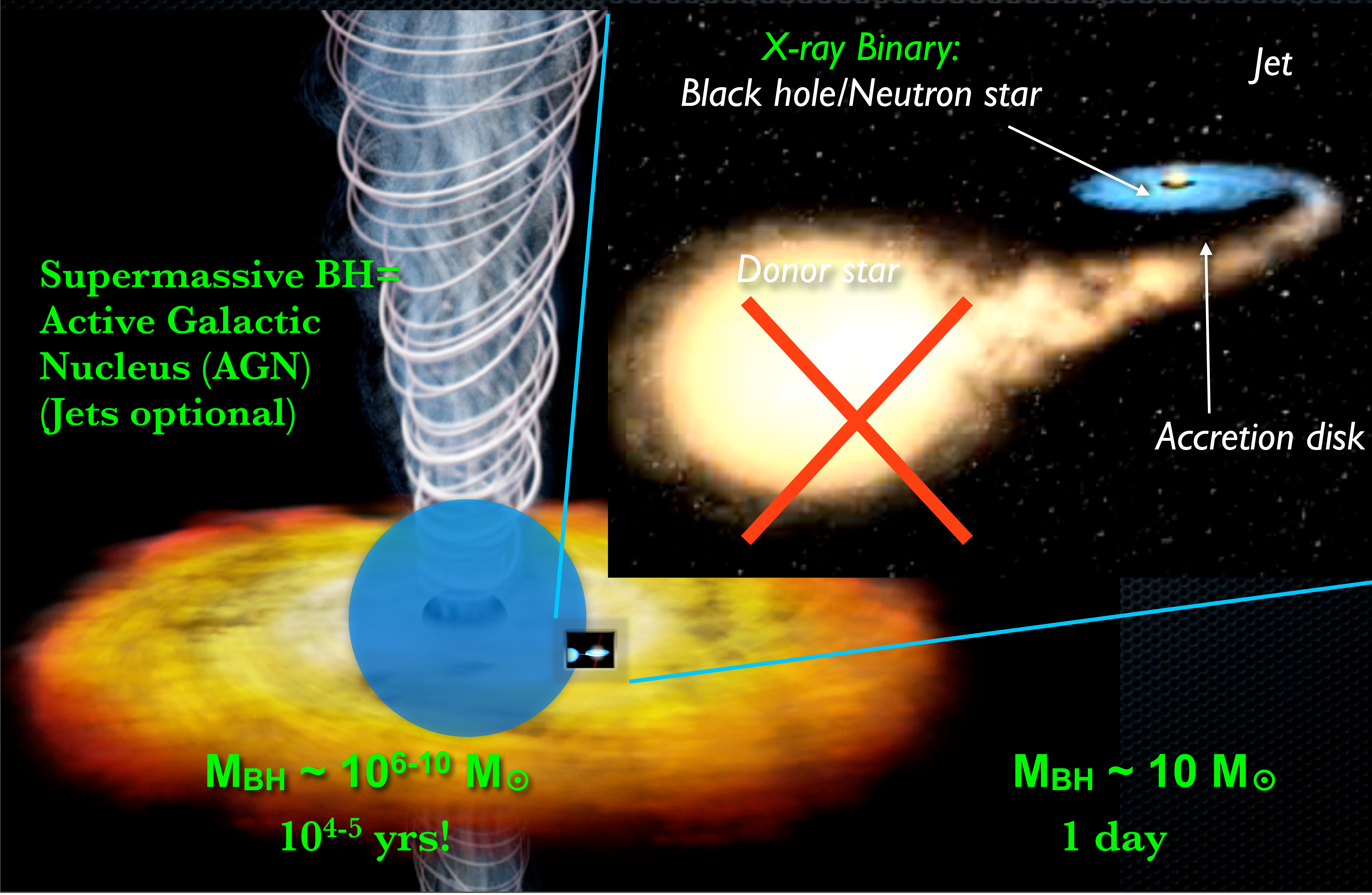
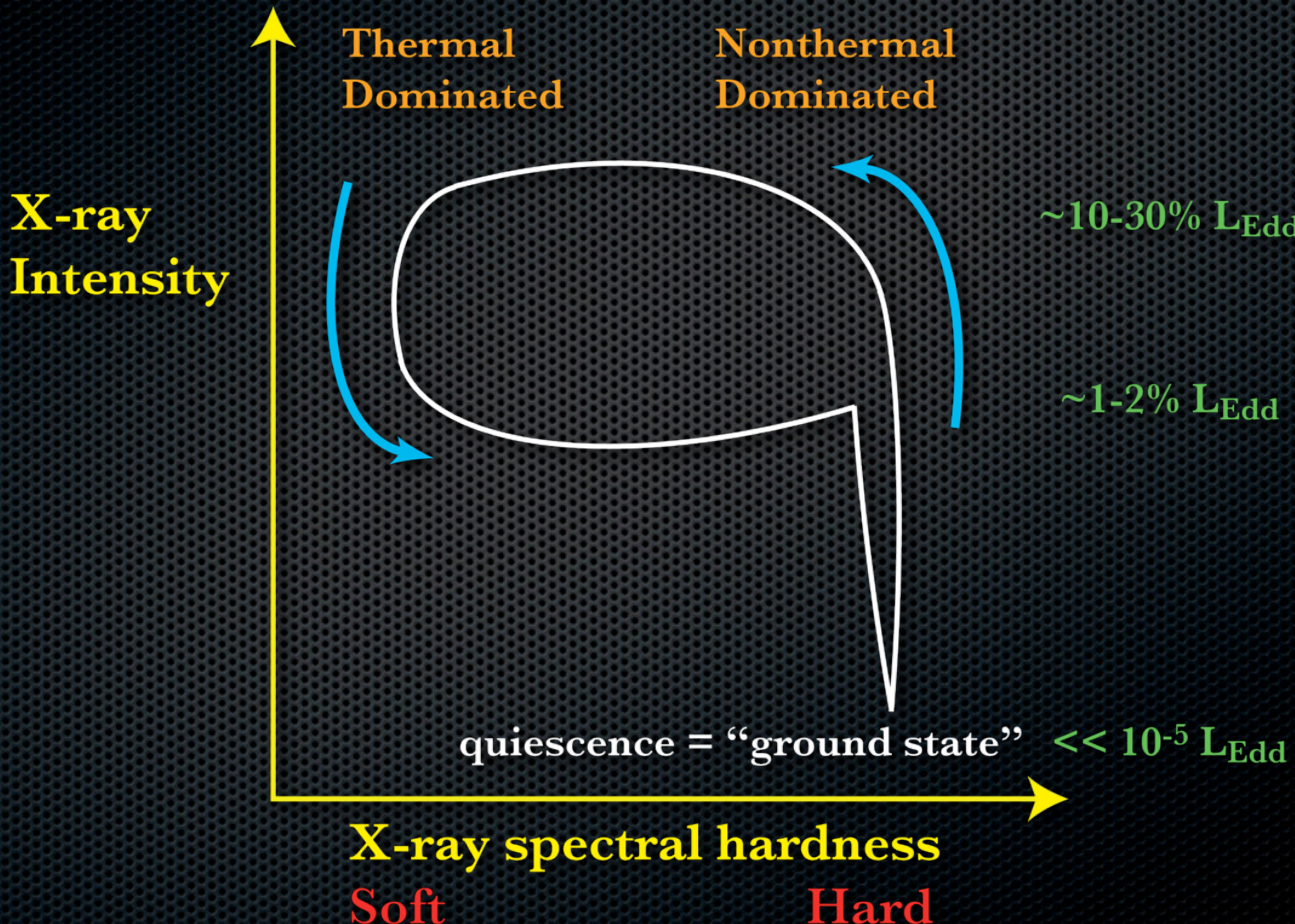
Can we compare black holes of differing mass/power?

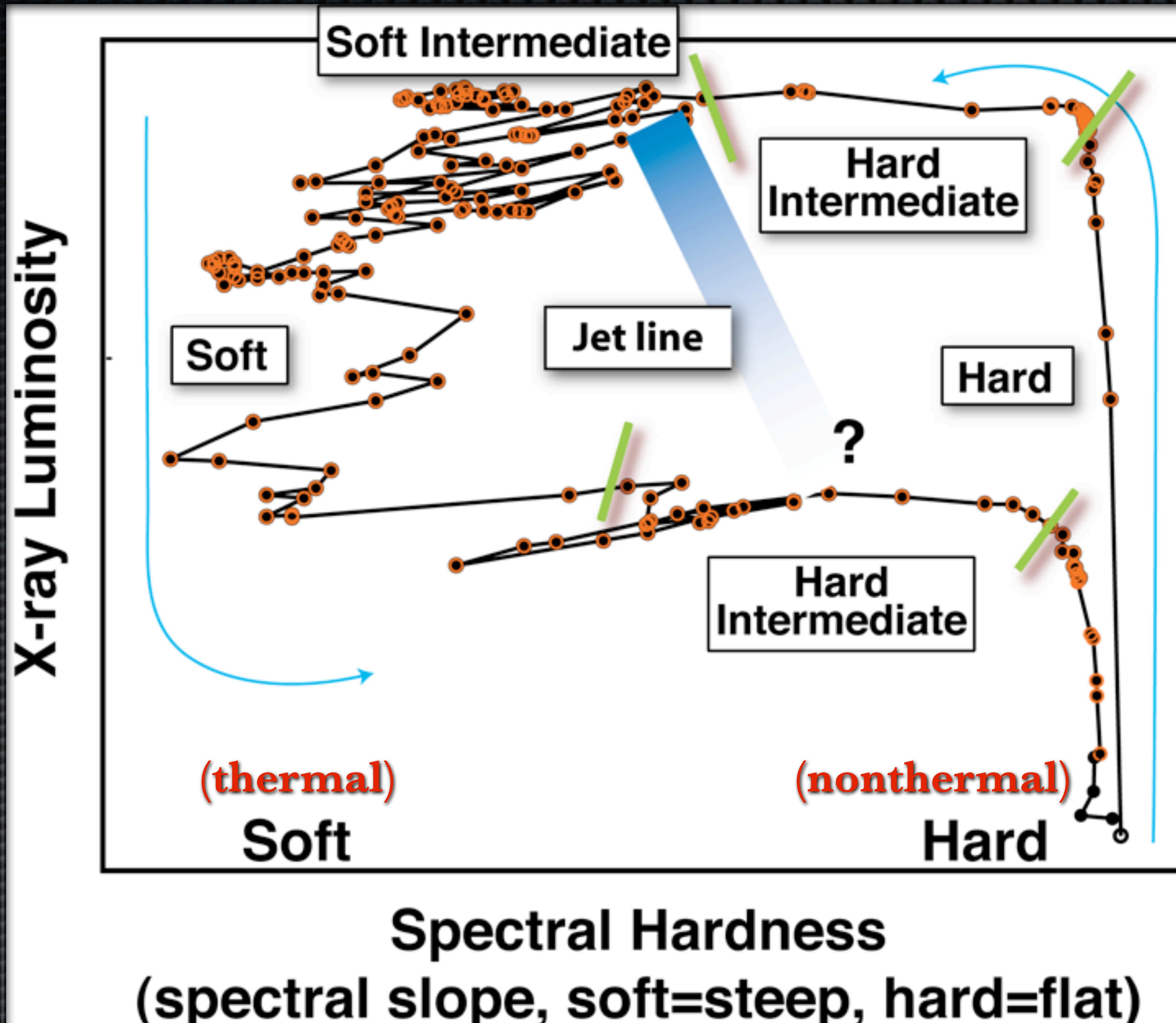


Time variable XRB behavior: The hardness-intensity diagram (HID): A schematic view



Time variable XRB behavior: The HID

GX339-4 data with states indicated

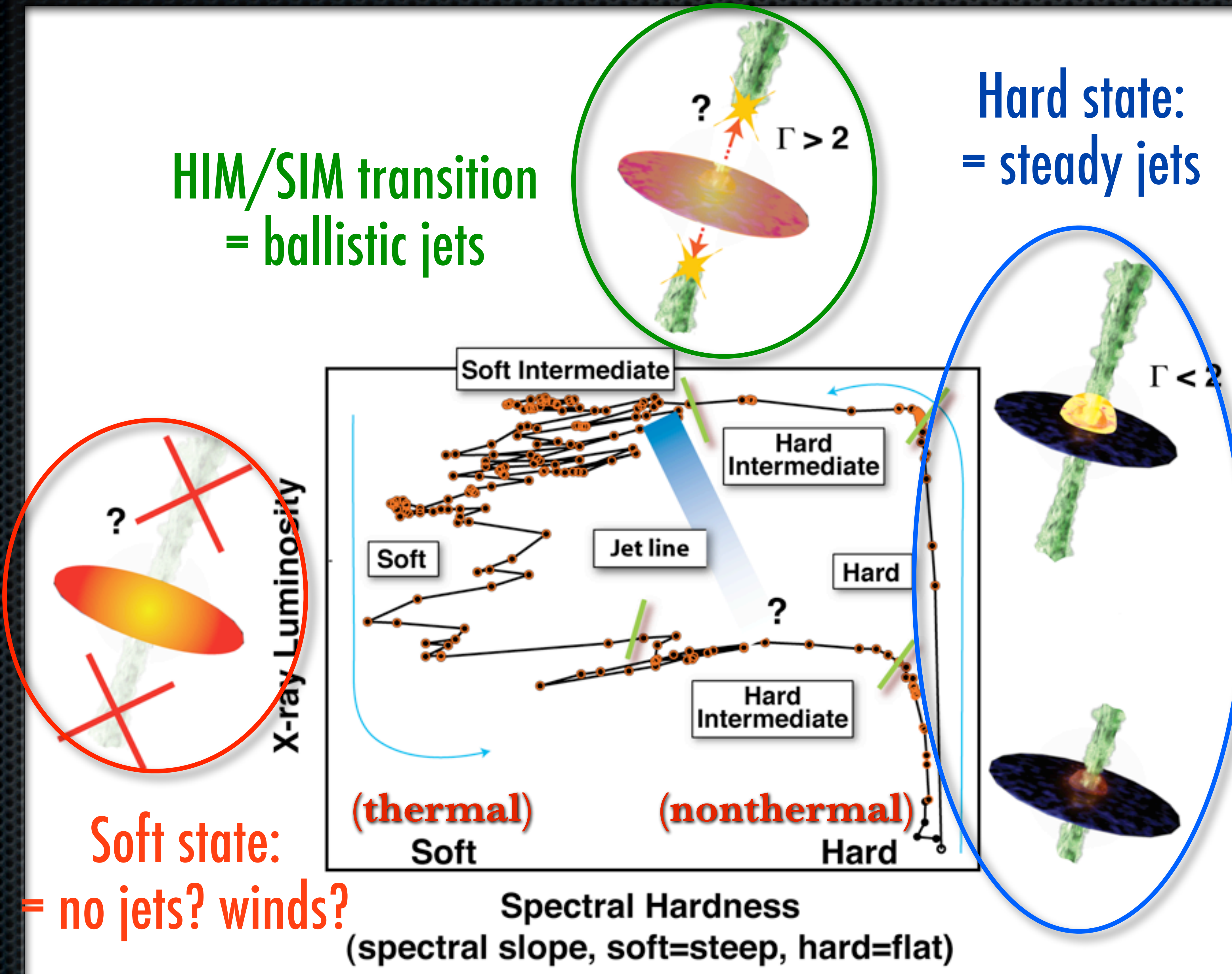


~10-30% L_{Edd}

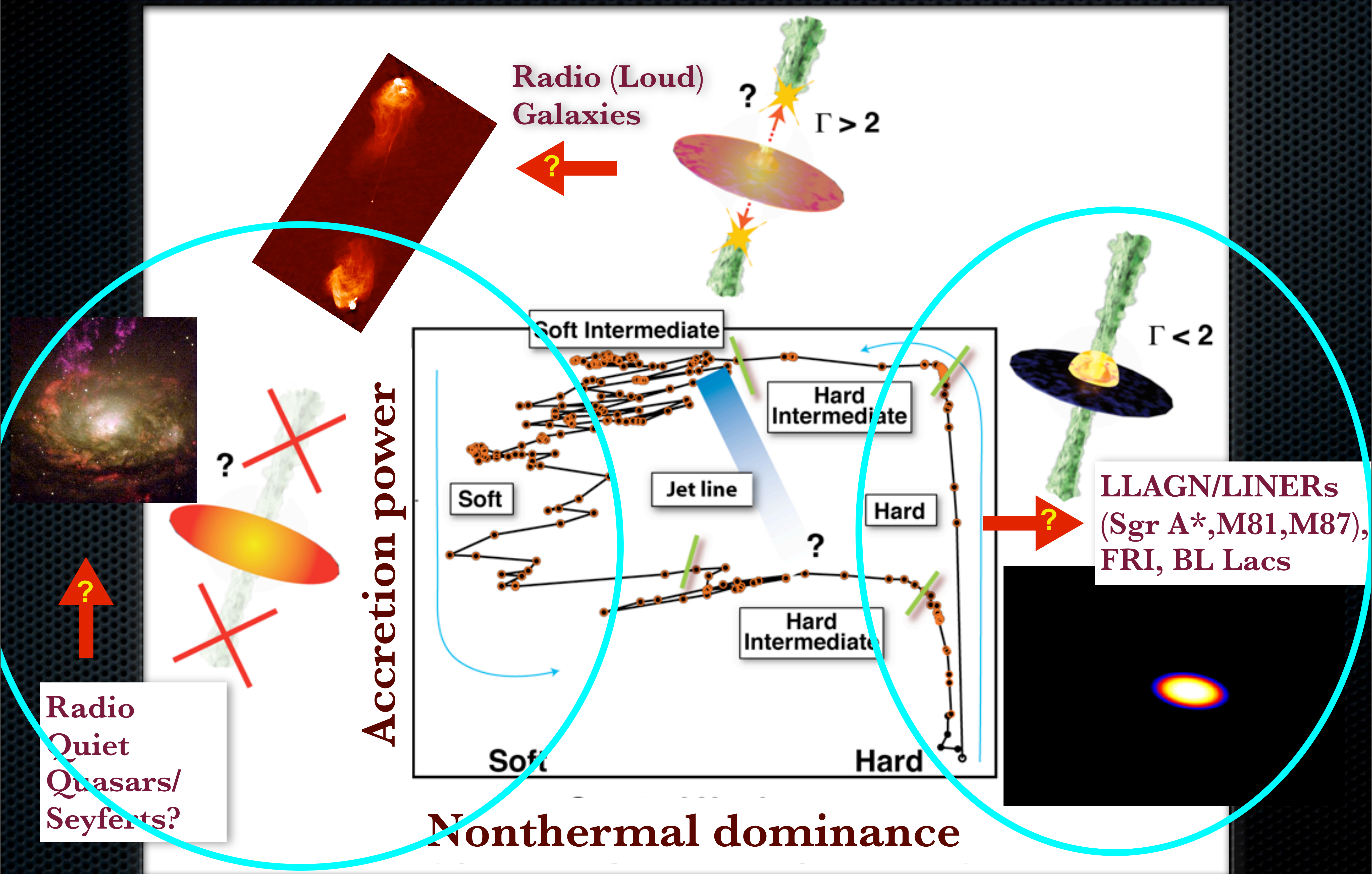
~1% L_{Edd}

≪ 10^{-5} L_{Edd}

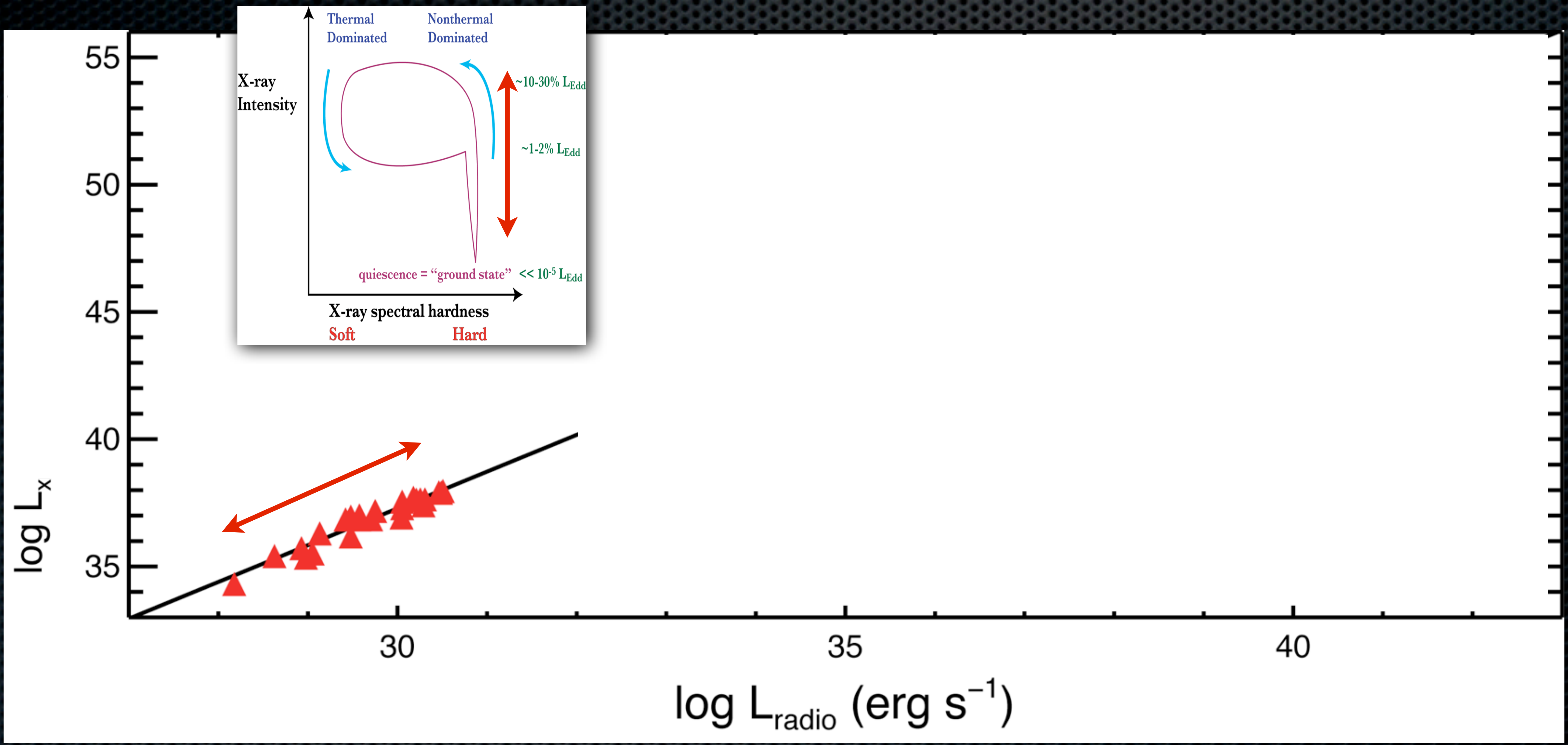
Time variable XRB behavior: The HID
Complex cycle in disk/jet dominance



Mapping XRB states ⇔ AGN classes?



Mass/power scalings (XRB ⇔ AGN)
The "Fundamental Plane" of BH accretion



(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)

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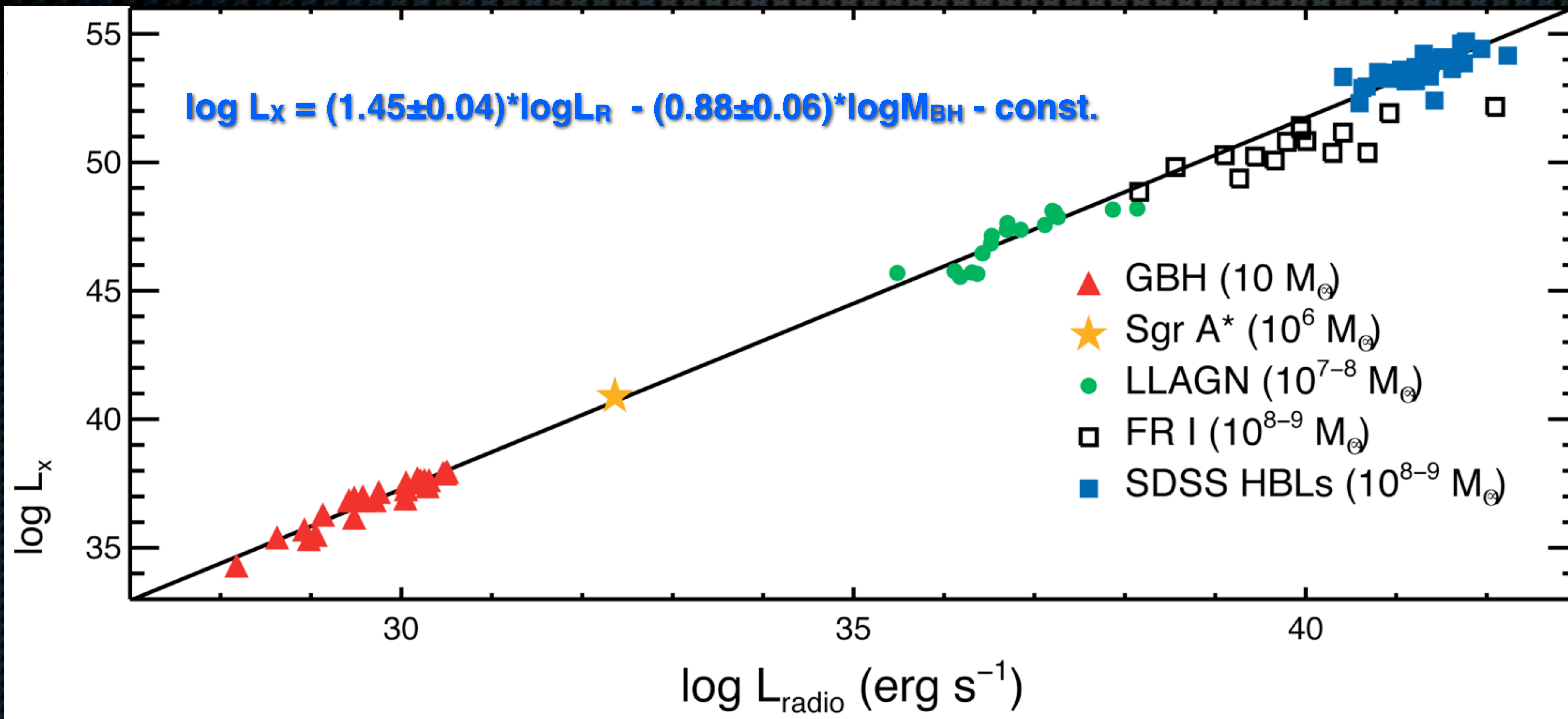

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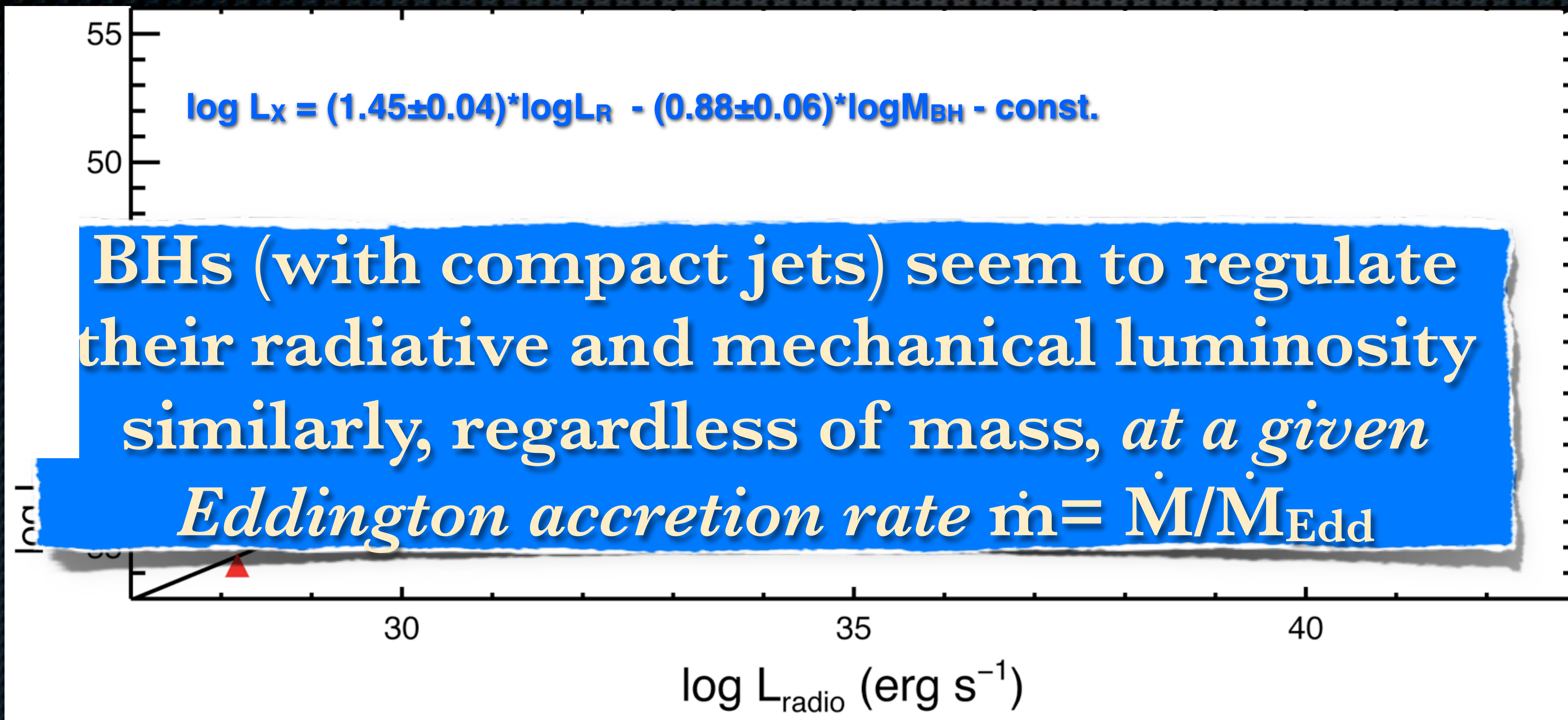


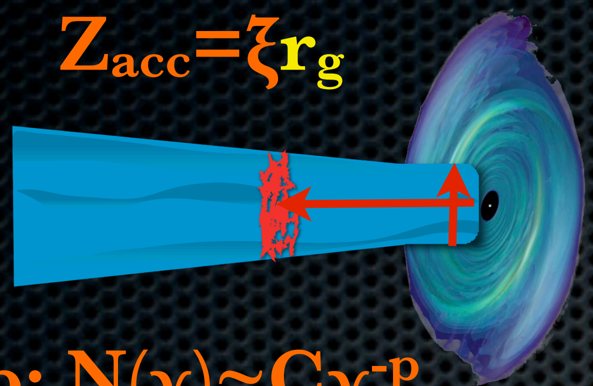
BHs (with compact jets) seem to regulate their radiative and mechanical luminosity similarly, regardless of mass, *at a given Eddington accretion rate* $\dot{m} = \dot{M}/\dot{M}_{Edd}$

(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)

Mass/power scaling models (synchrotron example)

$(R_d, R_0) = (\zeta_d, \zeta_0) r_g$

$Z_{acc} = \xi r_g$



p; $N(\gamma) \sim C\gamma^{-p}$

← $Q_j = \eta \dot{M} c^2 = \eta \dot{m} M c^2$
$U_B/U_e = k$

- You can also do similar analysis for direct feeding from various known accretion flow
- This assumption is equivalent also to RIAF launching

★ $C \propto B^2$ (fixed partition of energy), in disk launching $P, \rho \propto \dot{m}/M$, $B^2 \sim P, \rho$, or $B^2 \propto Q_j/(R^2 c) \propto \dot{m}/M$

★ Synchrotron self absorption:

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

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

$$\tau = R_j \alpha_\nu \qquad R_j \propto M$$

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

★ Consider (self-absorbed) flux from contributing τ=1 surfaces at some ν:

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

★ Derive expected scalings i.e.,

$$\nu_{SSA} \propto \left(M \phi_c \phi_B^{(p+2)/2} \right)^{2/(p+4)}$$

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

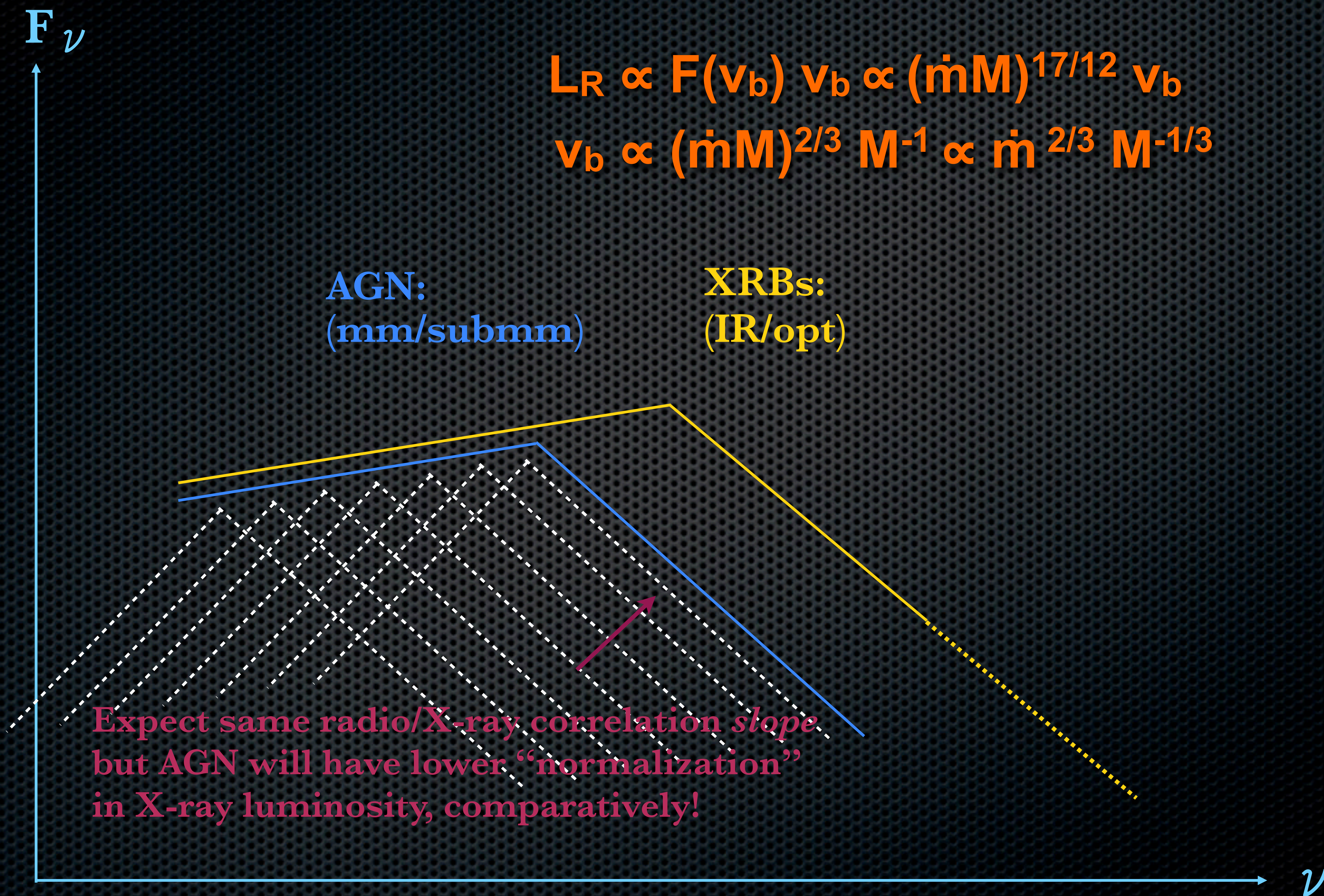
$$\sim \dot{m}^{2/3} M^{-1} = \dot{M}^{2/3} M^{-1}$$

(Falcke & Biermann 1995; SM et al. 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding, SM 2004; Heinz & Sunyaev 2003)

Compact jets: optical depth effects dominate scalings

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

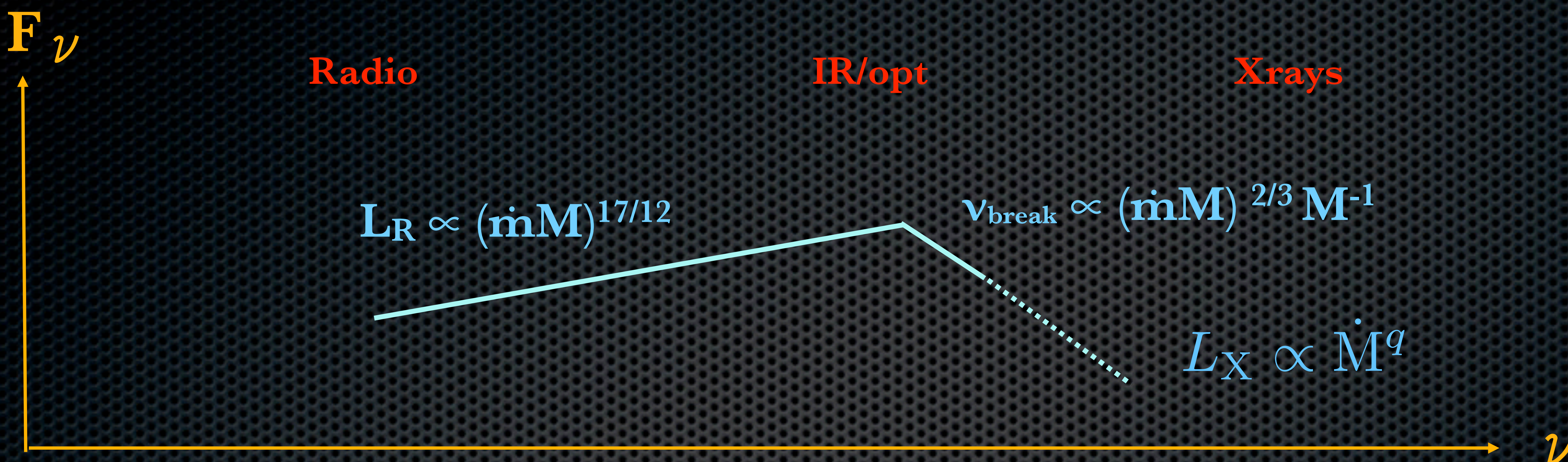
$$\nu_b \propto (\dot{m}M)^{2/3}\,M^{-1} \propto \dot{m}^{2/3}\,M^{-1/3}$$



Expect same radio/X-ray correlation *slope*
but AGN will have lower "normalization"
in X-ray luminosity, comparatively!

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

Constraining accretion physics with radio/X-ray correlations



For objects with the *same* mass:

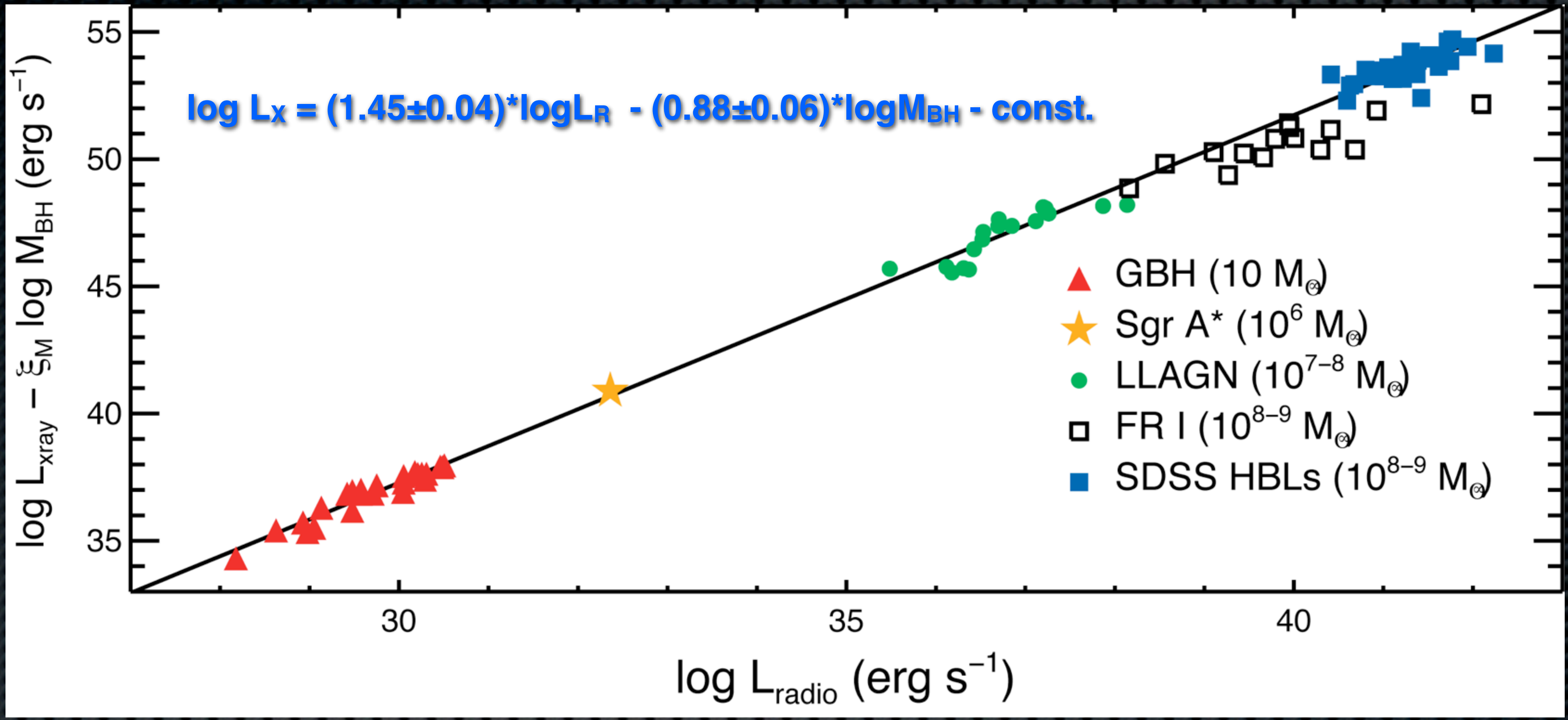
$$L_R \propto L_X^m \qquad m = \frac{\frac{17}{12} - \frac{2}{3}\alpha_R}{q} \approx \frac{1.4}{q}$$

Synchrotron: q=2, ADAF/RIAF: q=2-2.3,

Radiatively efficient disk/corona: q=1 ➠ problematic

(Falcke & Biermann 1995; SM et al. 2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding & SM 2004; Heinz 2004; Körding et al. 2006; Plotkin, SM et al. 2012)

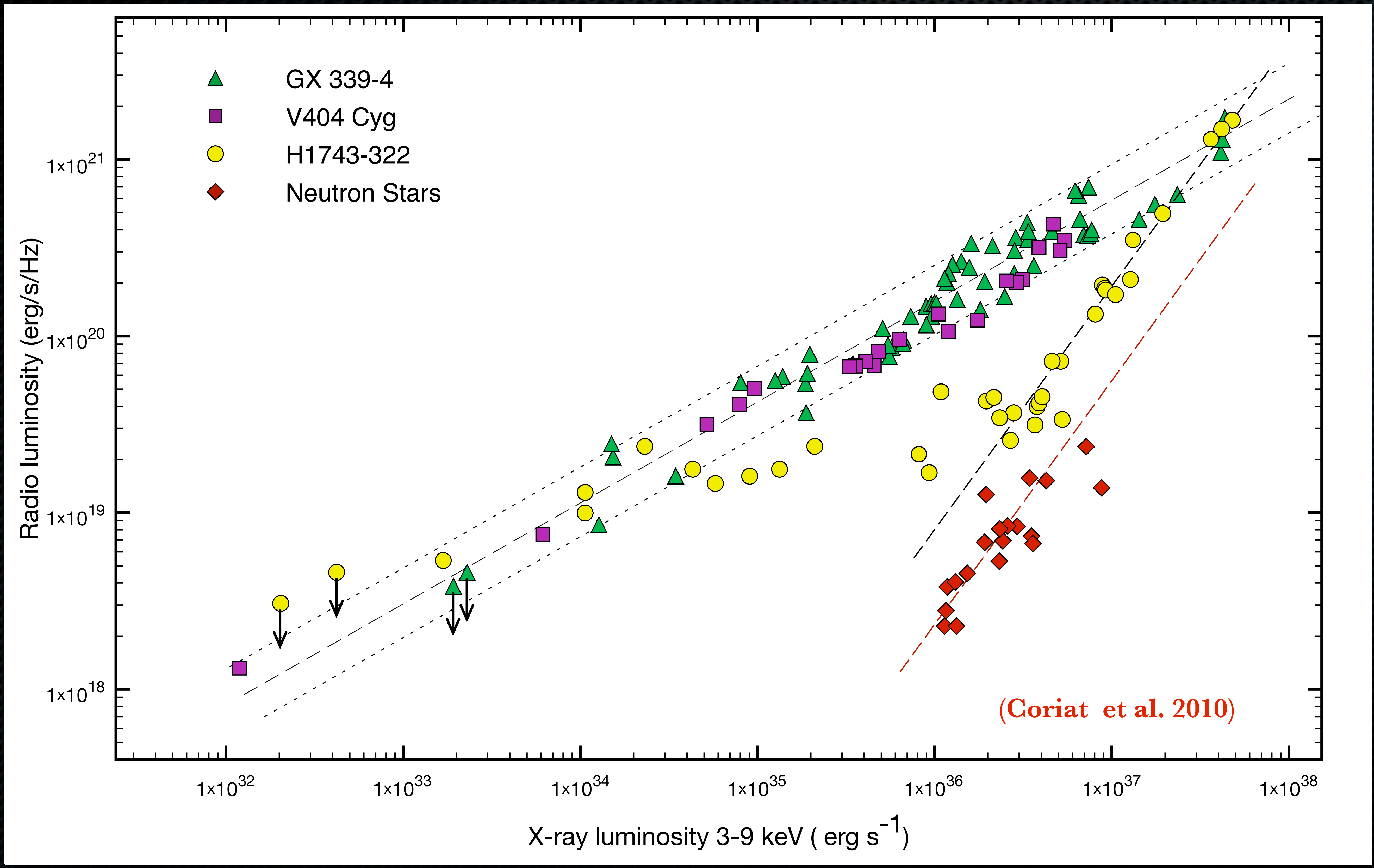
Conclusions from the "Fundamental Plane" body of work



- Strong evidence for shared physics across BH mass scale for "steady, compact jet" states (XRBs: hard state; AGN: LLAGN, FRI, BL Lacs)
- Location of jet break seems to be a key pivot point, either linking radio/Xray via synchrotron or otherwise setting scales

But, like all good stories, there are always complications….

New: RL/RQ/multi-efficiency states seen in single XRBs!



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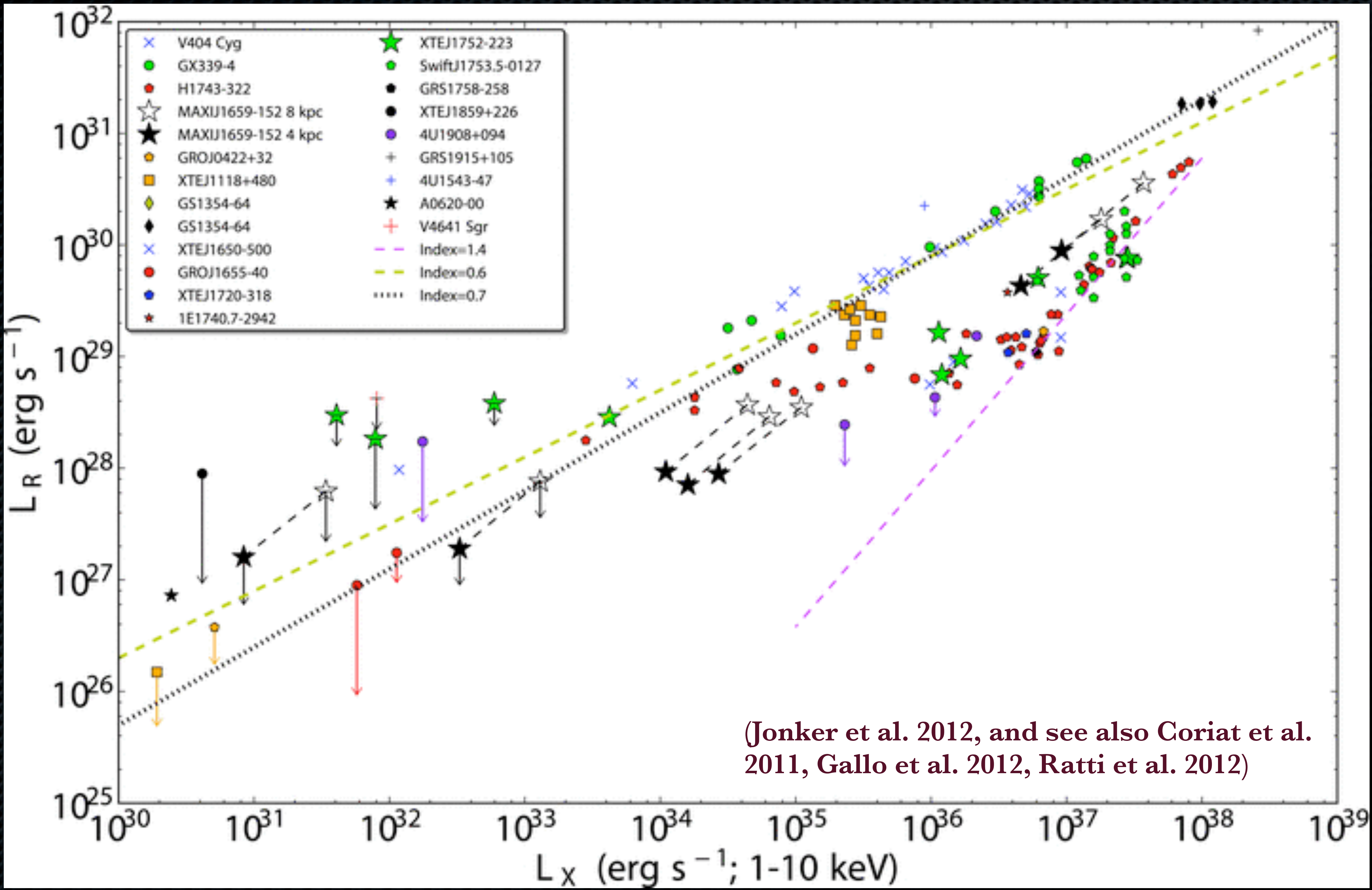
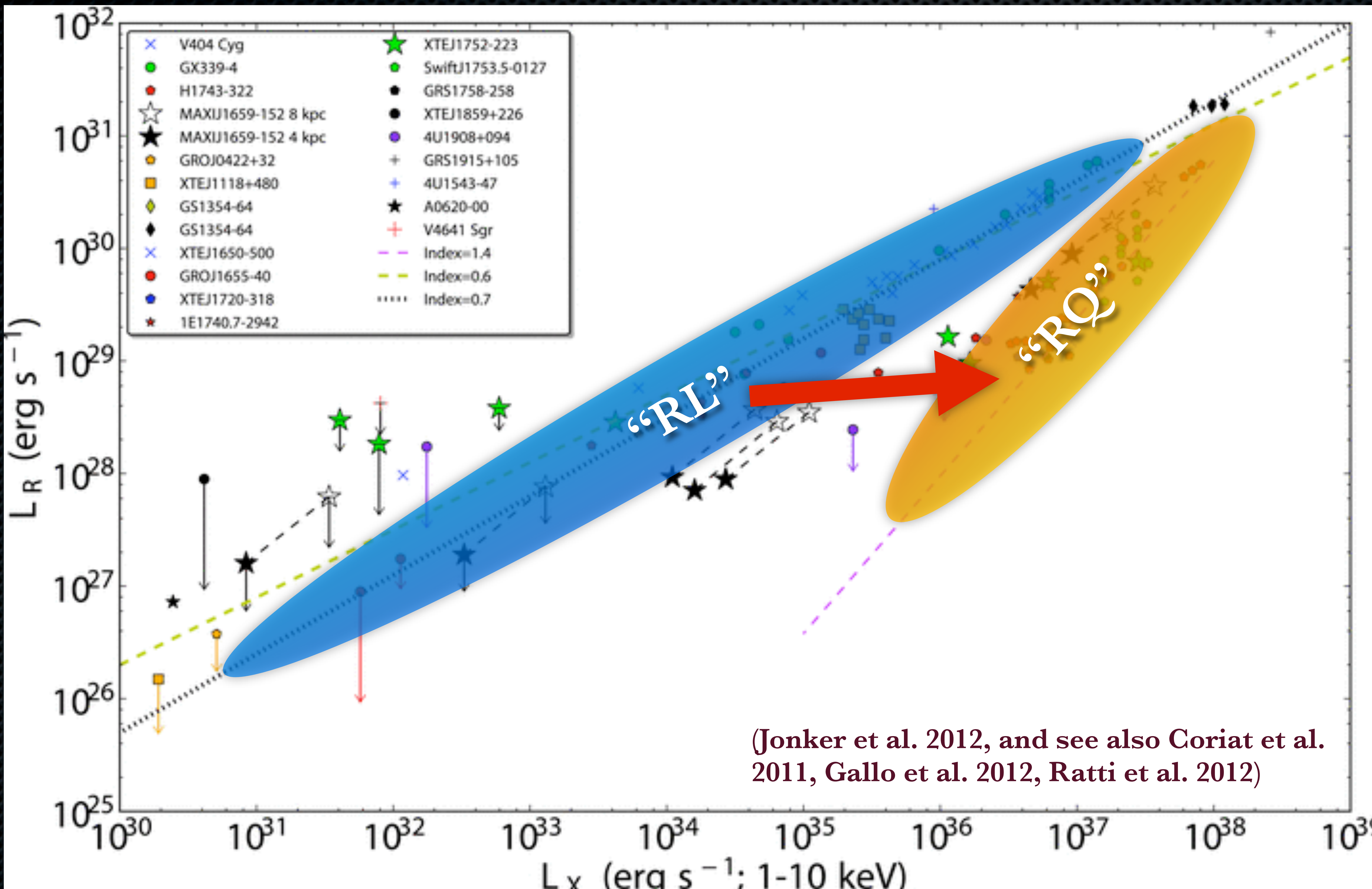
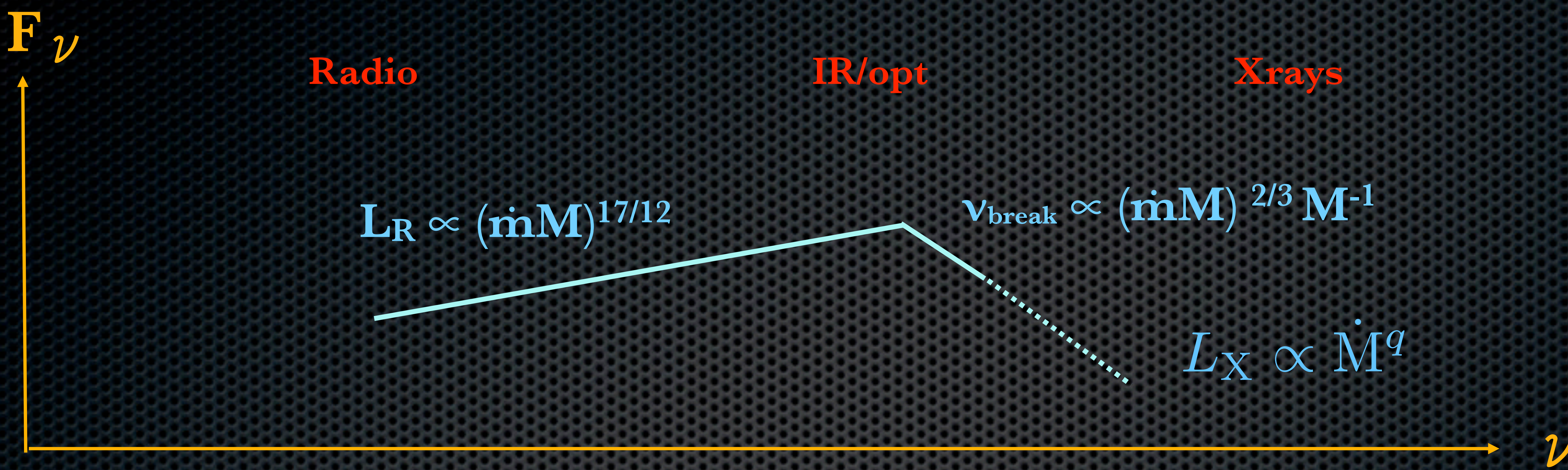


(Jonker et al. 2012, and see also Coriat et al. 2011, Gallo et al. 2012, Ratti et al. 2012)

New: RL/RQ/multi-efficiency states seen in single XRBs!



Constraining accretion physics with radio/X-ray correlations



For objects with the *same* mass:

$$L_R \propto L_X^m \qquad m = \frac{\frac{17}{12} - \frac{2}{3}\alpha_R}{q} \approx \frac{1.4}{q}$$

Synchrotron with cooling break: q=1

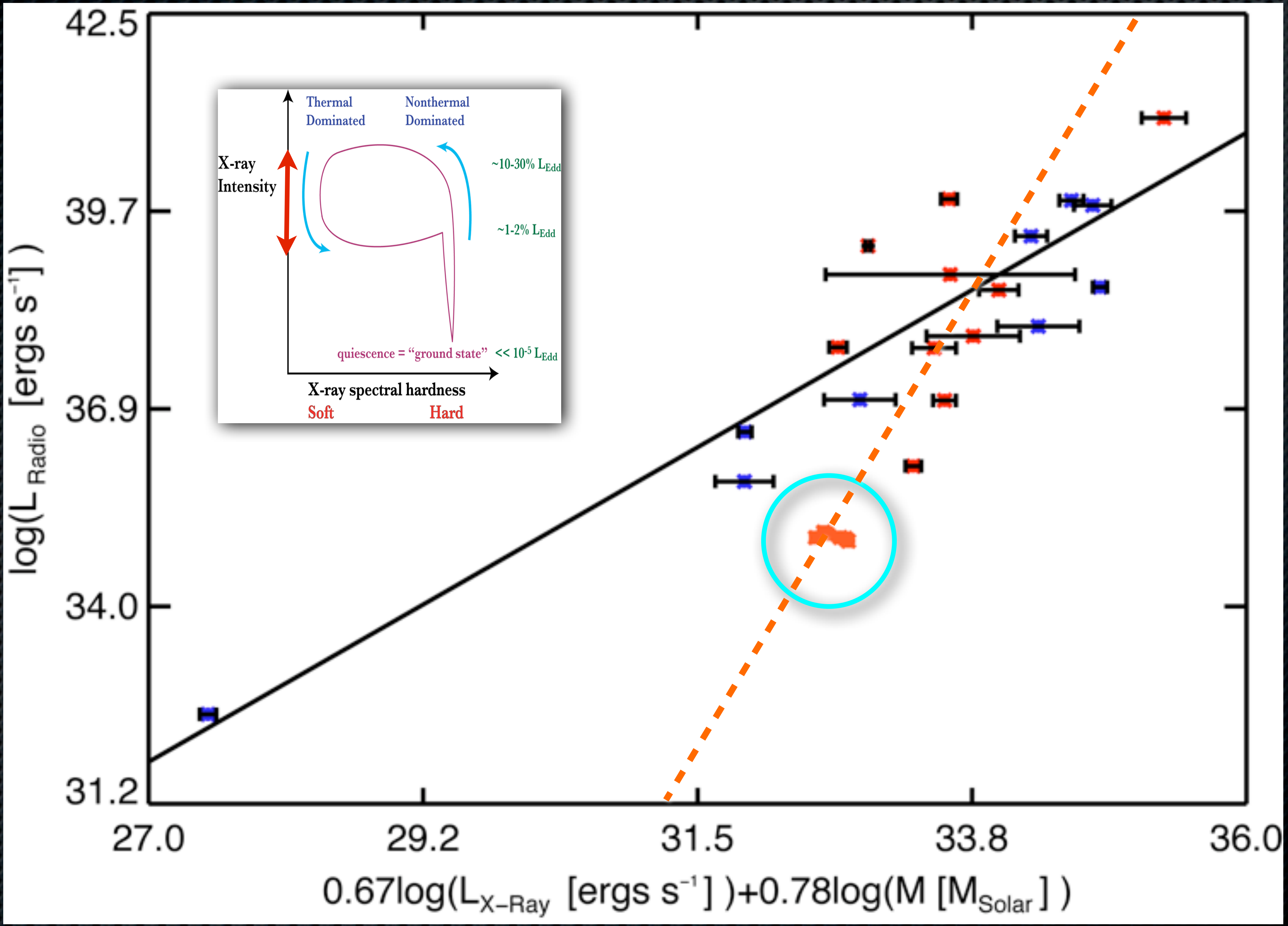
or radiatively efficient X-ray production ($L_X \propto \dot{M}$)

or jets not the same as in “classic” hard state

(Falcke & Biermann 1995; SM et al. 2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding & SM 2004; Heinz 2004; Körding et al. 2006; Plotkin, SM et al. 2012)

Evidence for a new, high-efficiency "FP"?

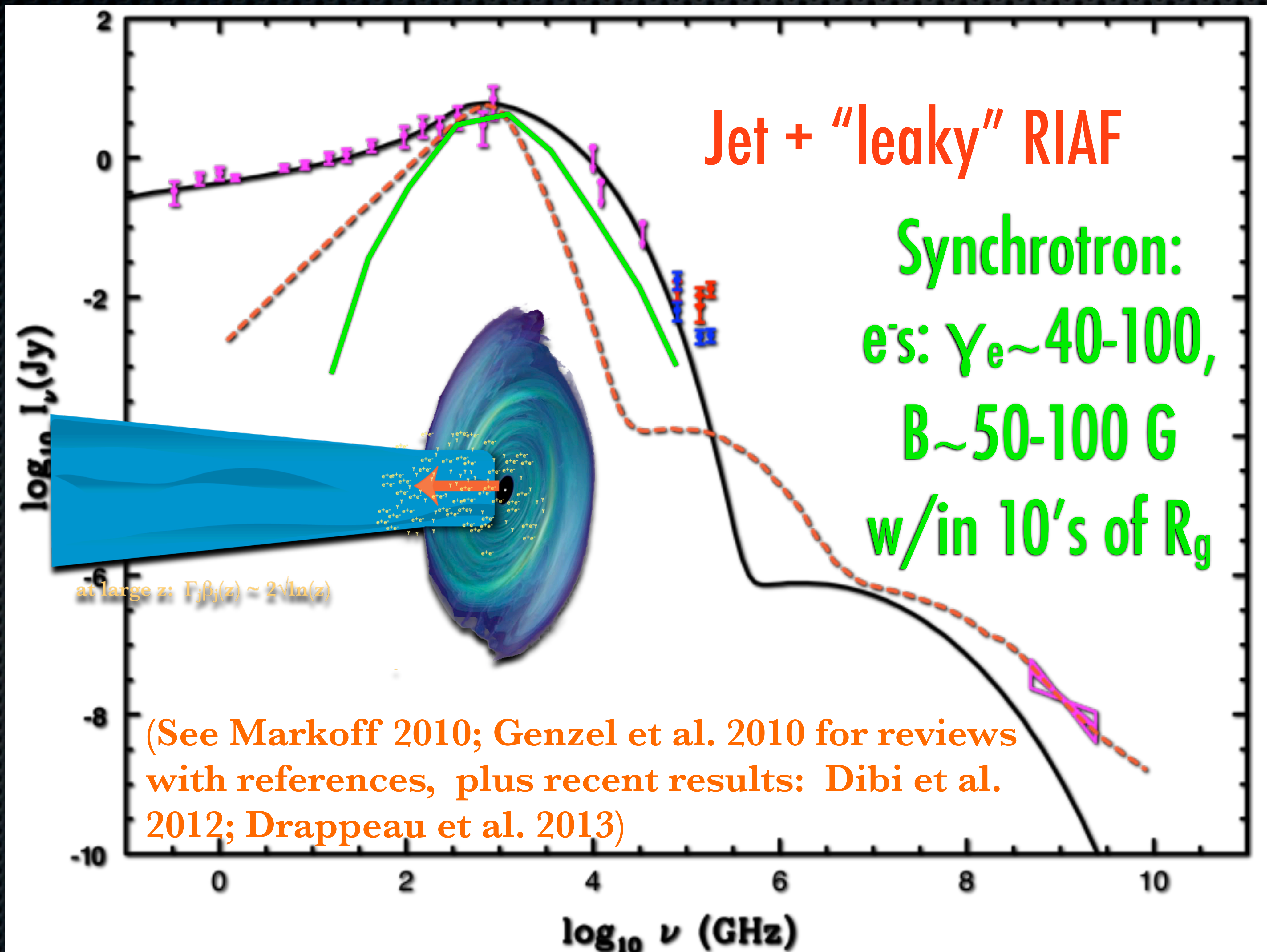
Seyferts, M-σ sources only:



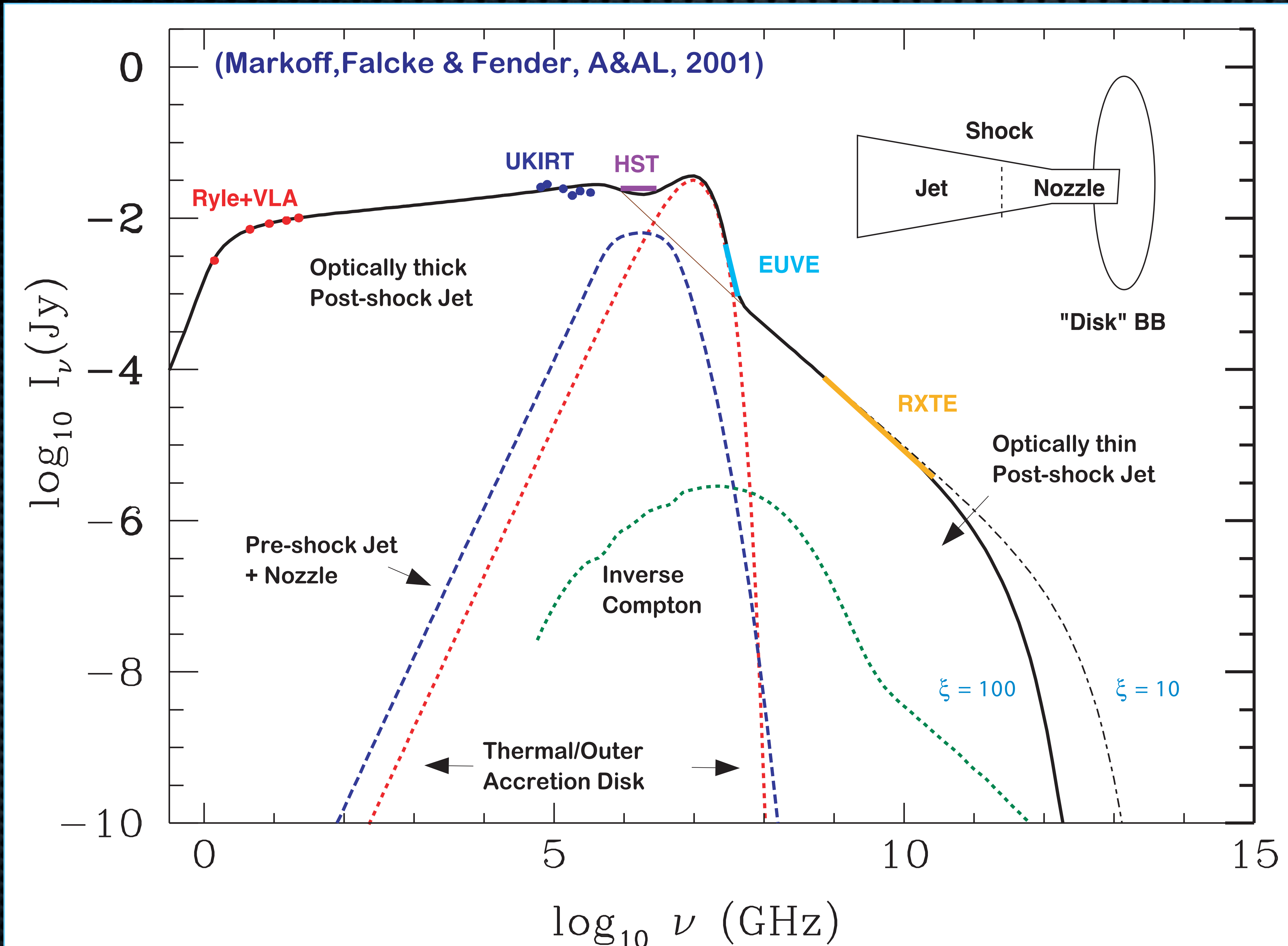
(Gültekin et al. 2009, King et al. 2011)

Beyond correlations: modeling spectra and jet breaks

Sgr A* – best understanding of plasma conditions within $10R_g$ for any black hole!



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)

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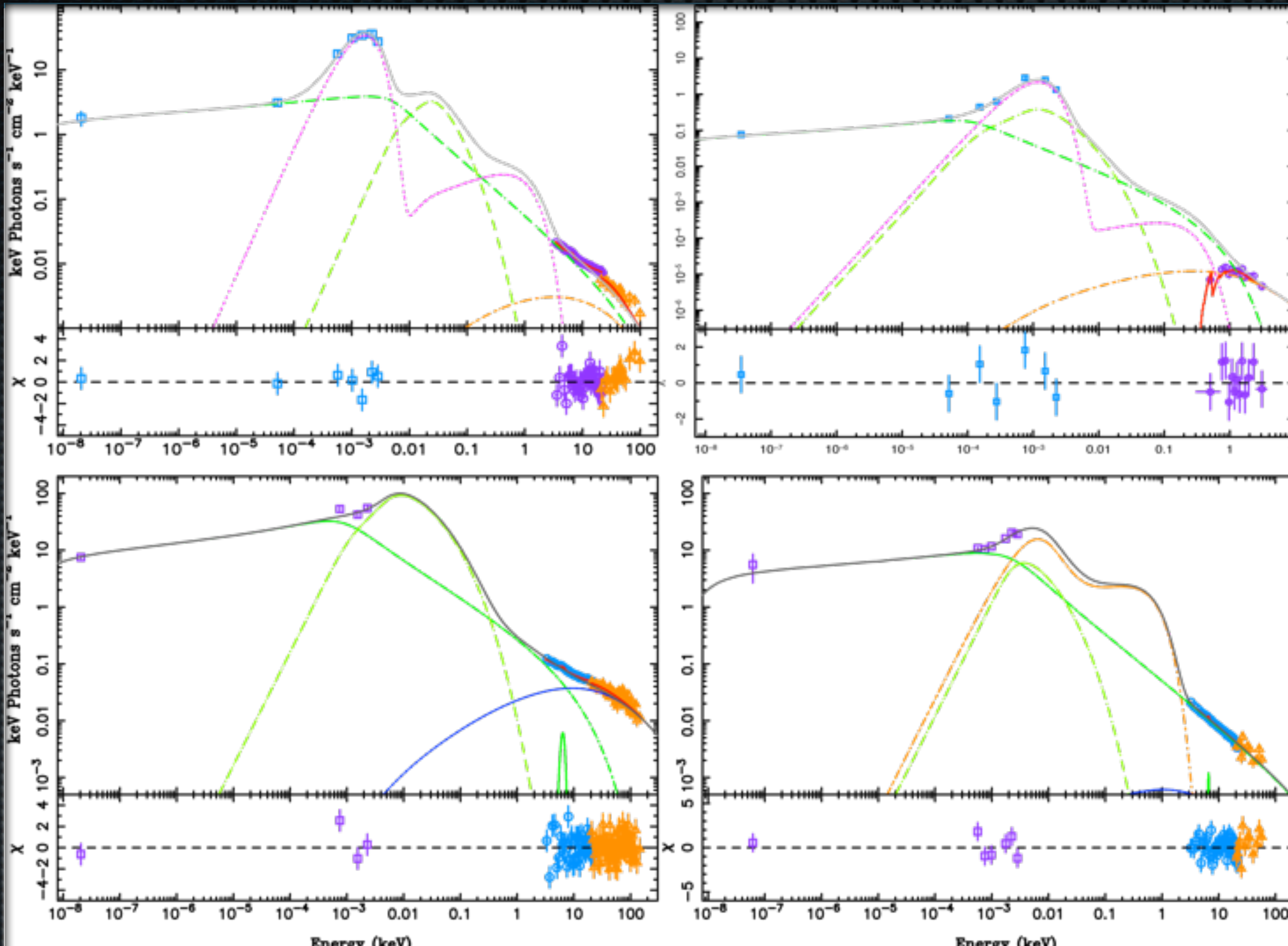

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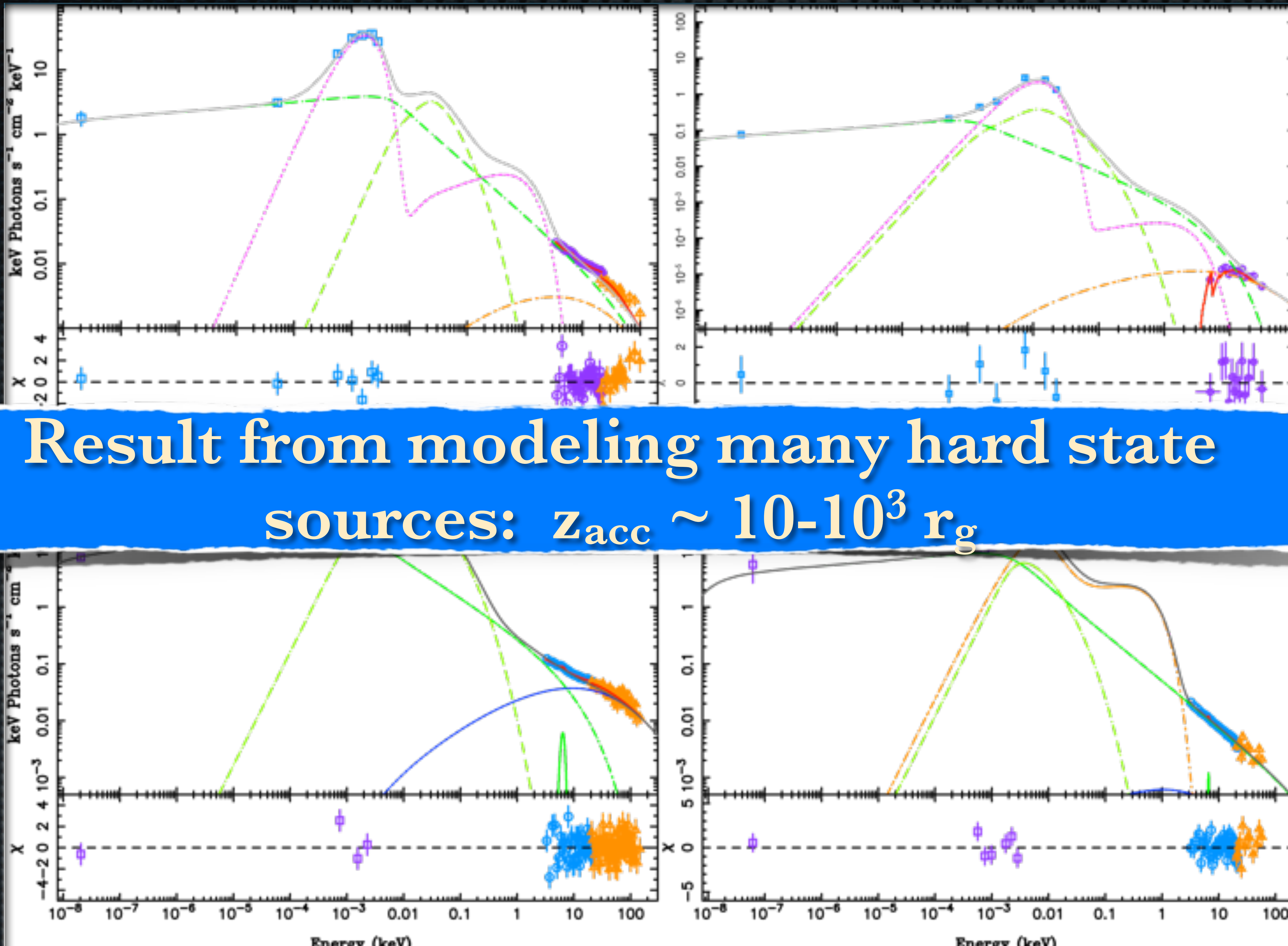
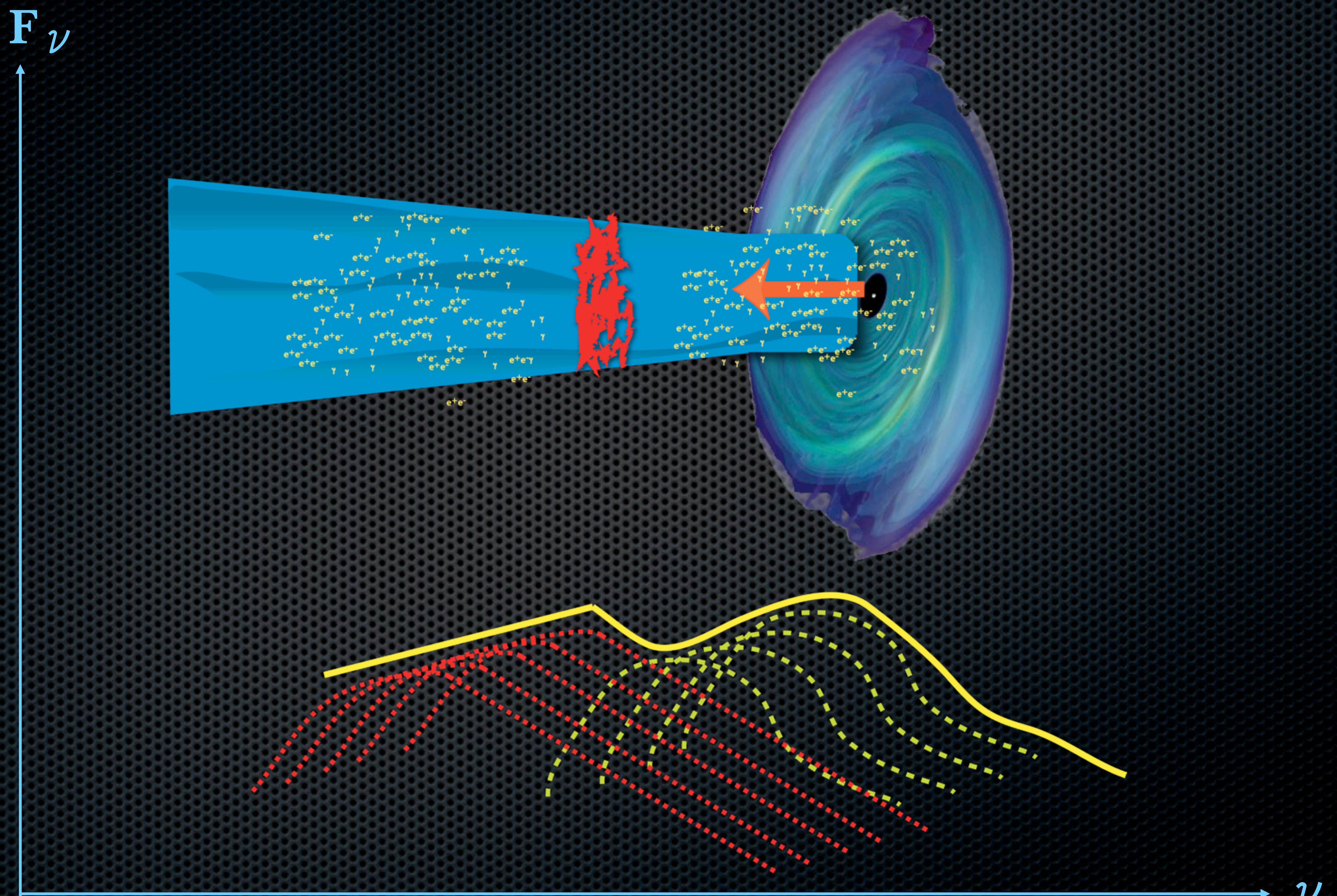


Result from modeling many hard state sources: $z_{acc} \sim 10\text{-}10^3\ r_g$

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

(Poor) artist's impression of thermal + nonthermal model



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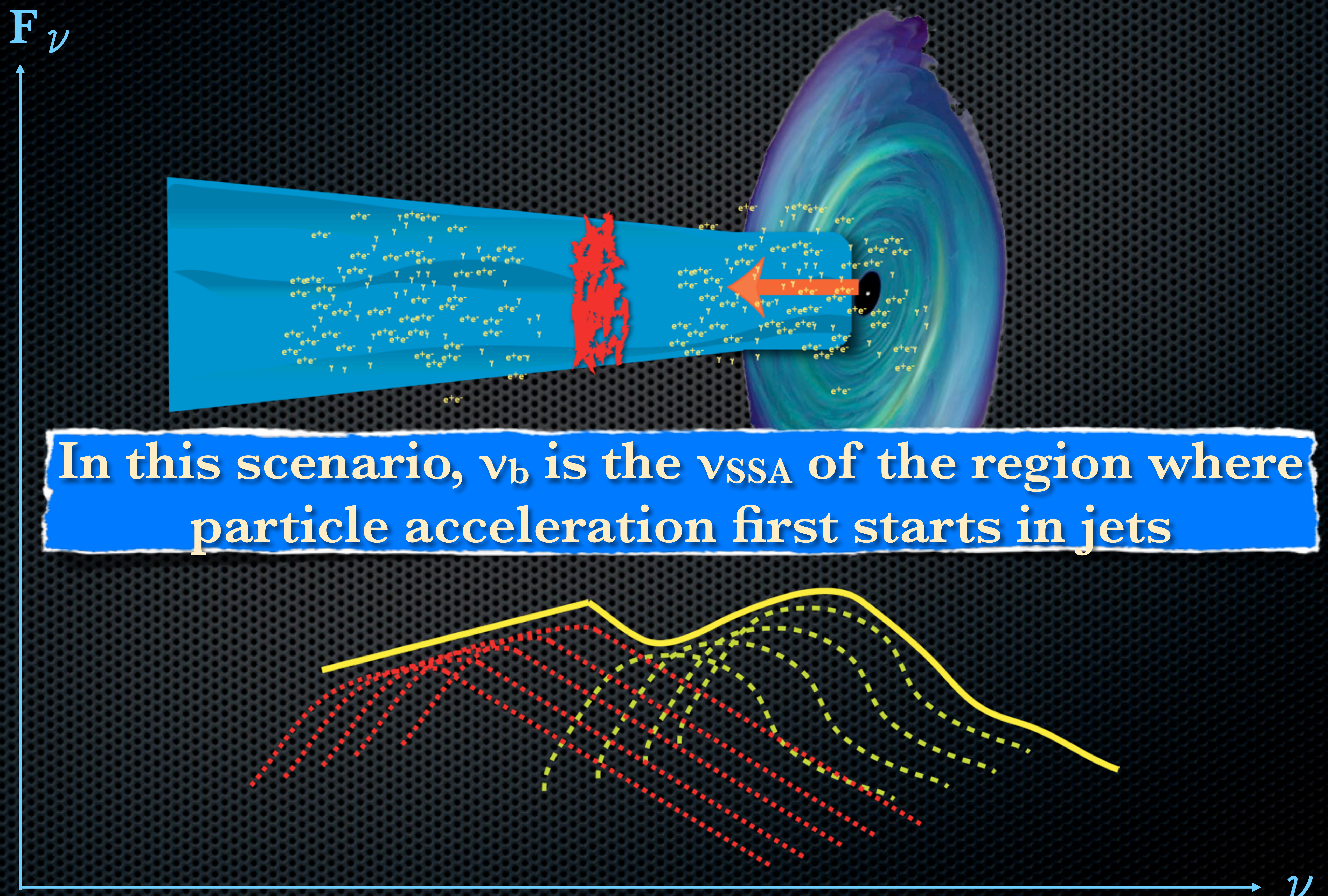
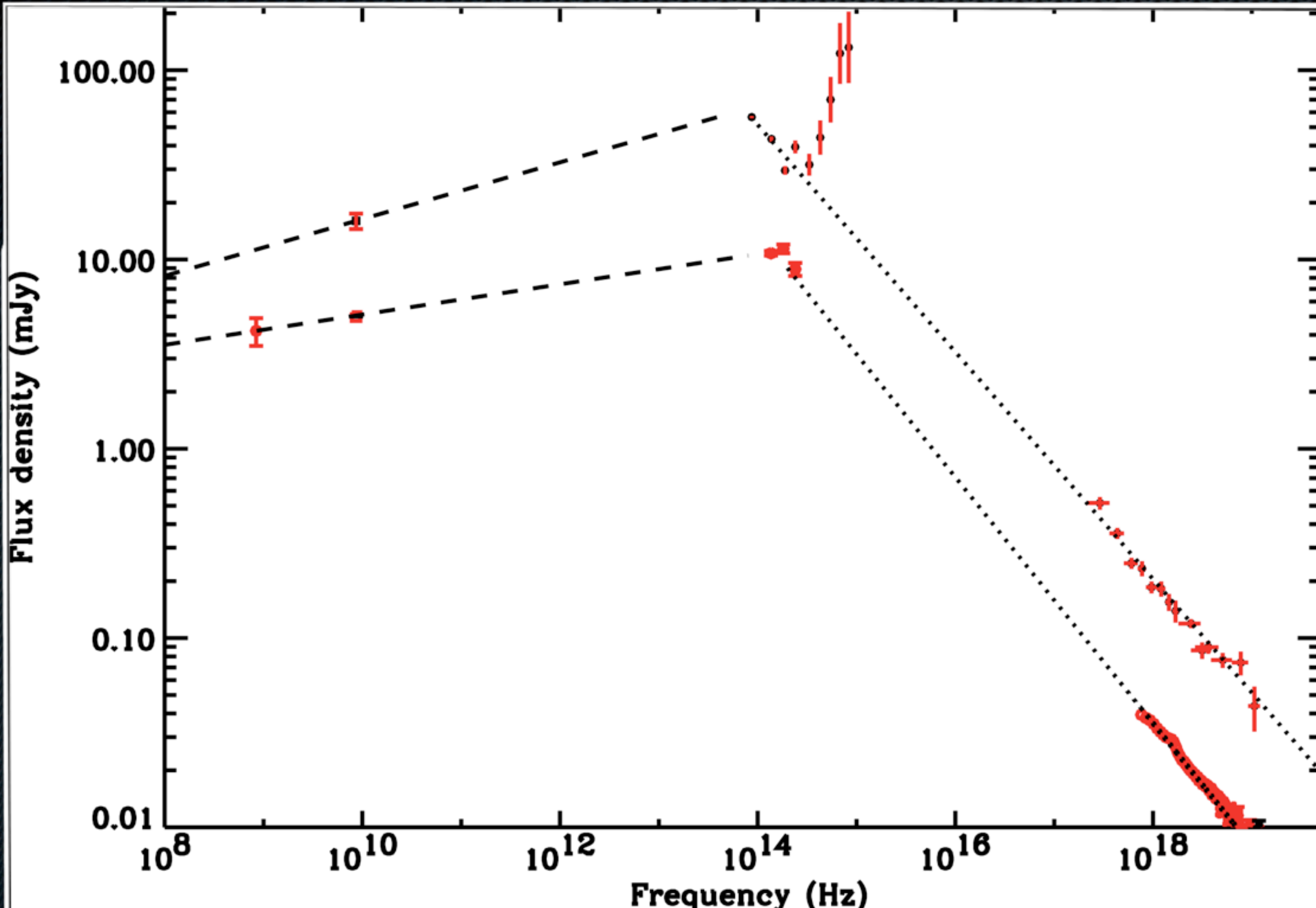


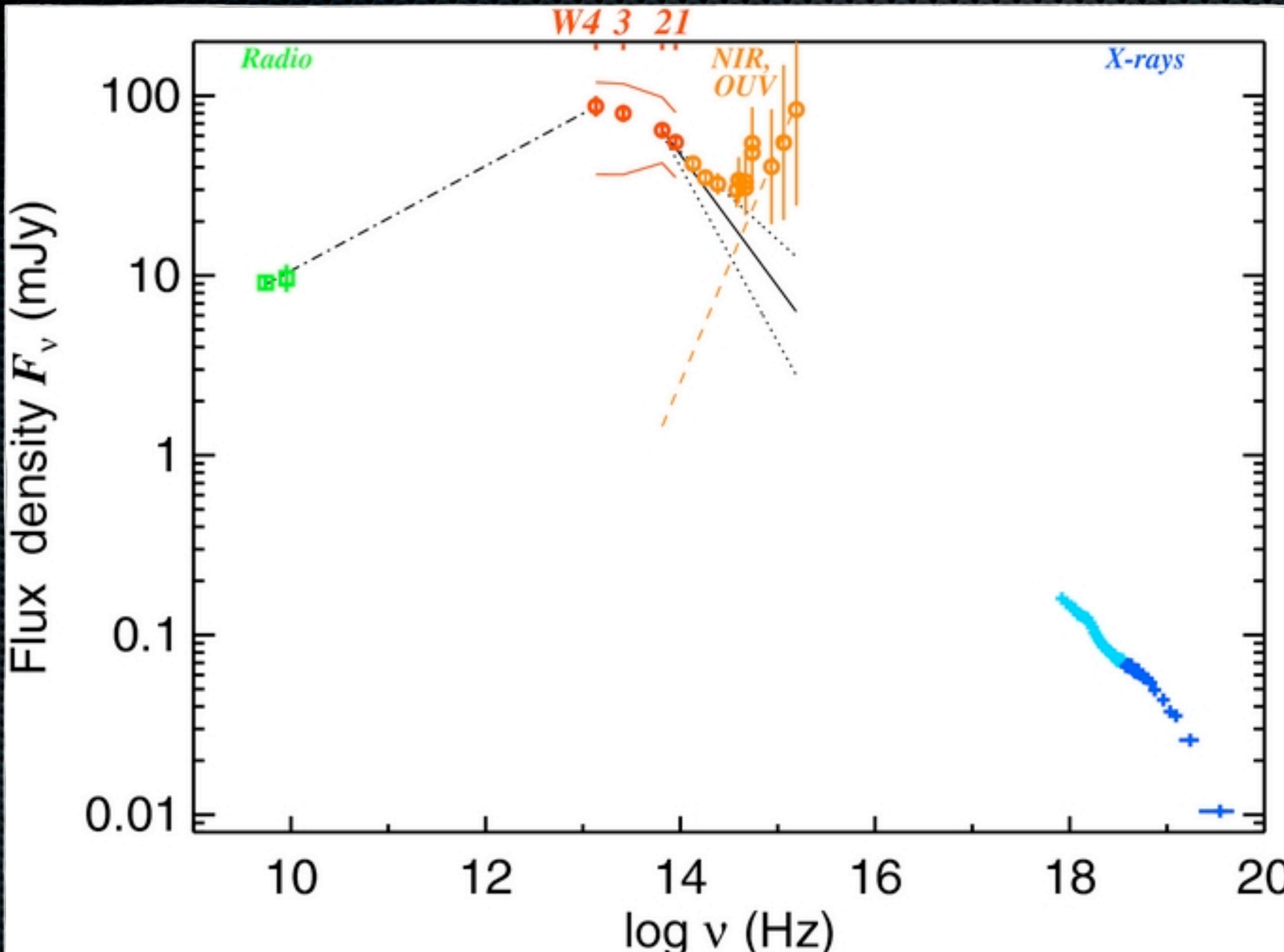
In this scenario, ν_b is the ν_{SSA} of the region where particle acceleration first starts in jets

Simultaneous radio-X-ray spectra ➠ strong constraints on acceleration



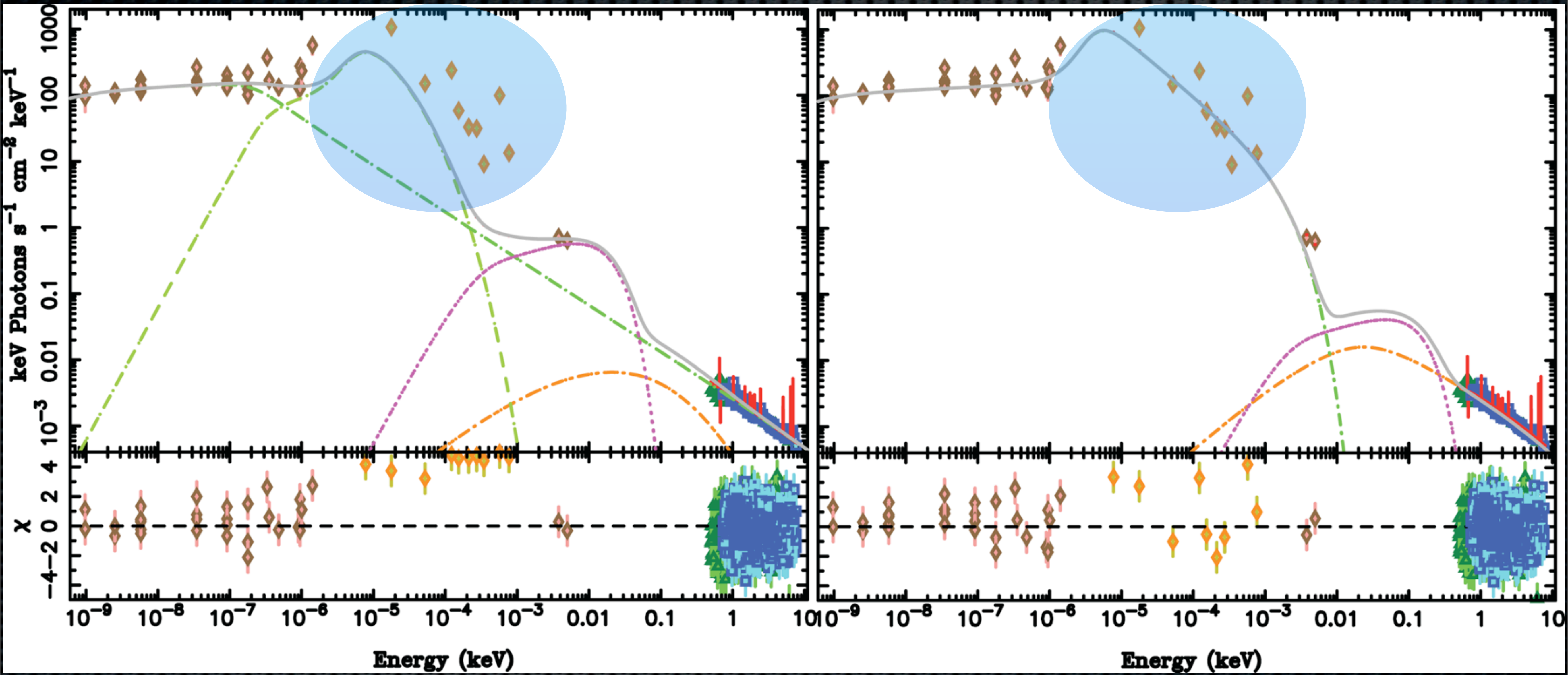
(Corbel & Fender 2002, SM ea. 2003, Gandhi ea. 2011)

Simultaneous radio-X-ray spectra ➠ strong constraints on acceleration



(Corbel & Fender 2002, SM ea. 2003, Gandhi ea. 2011)

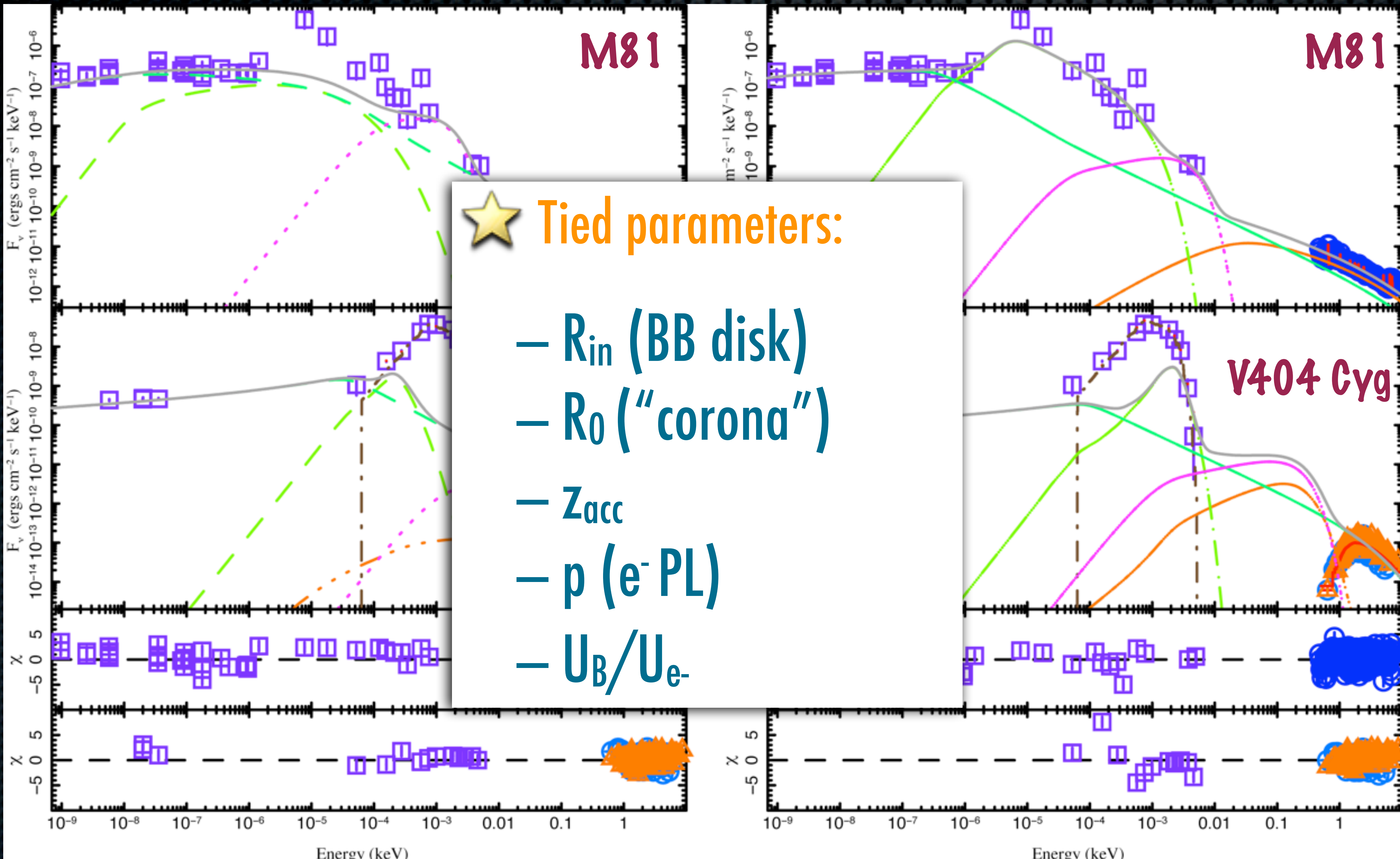
M81*: XRB model applied to supermassive BH



- Contribution from host galaxy creates degeneracy in modeling
- Synchrotron dominated model is quantitatively a scaled up (in mass) XRB hard state, z_{acc}~150-300r_g

(SM, Nowak, Young et al. 2008)

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, et al., in prep.)

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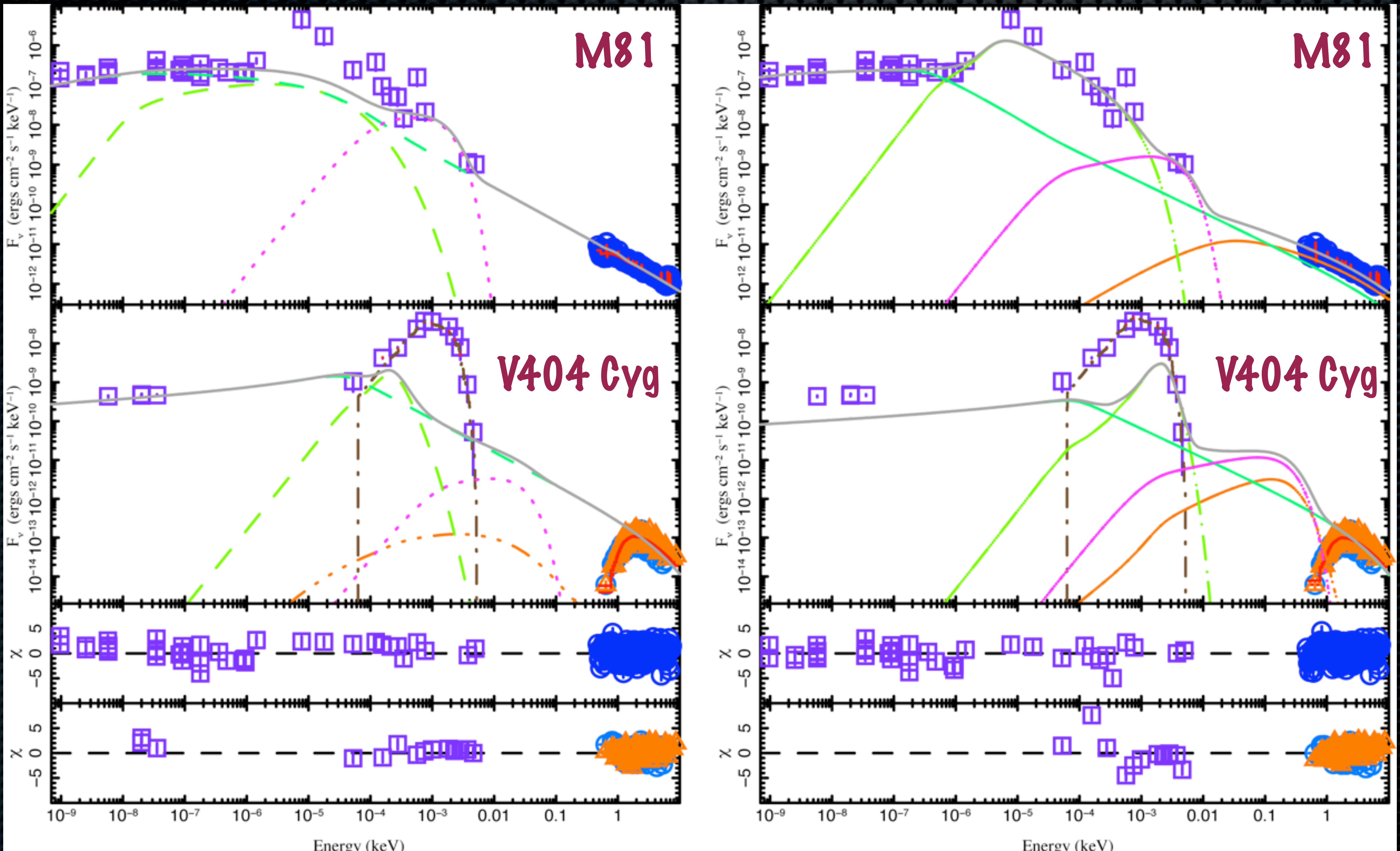
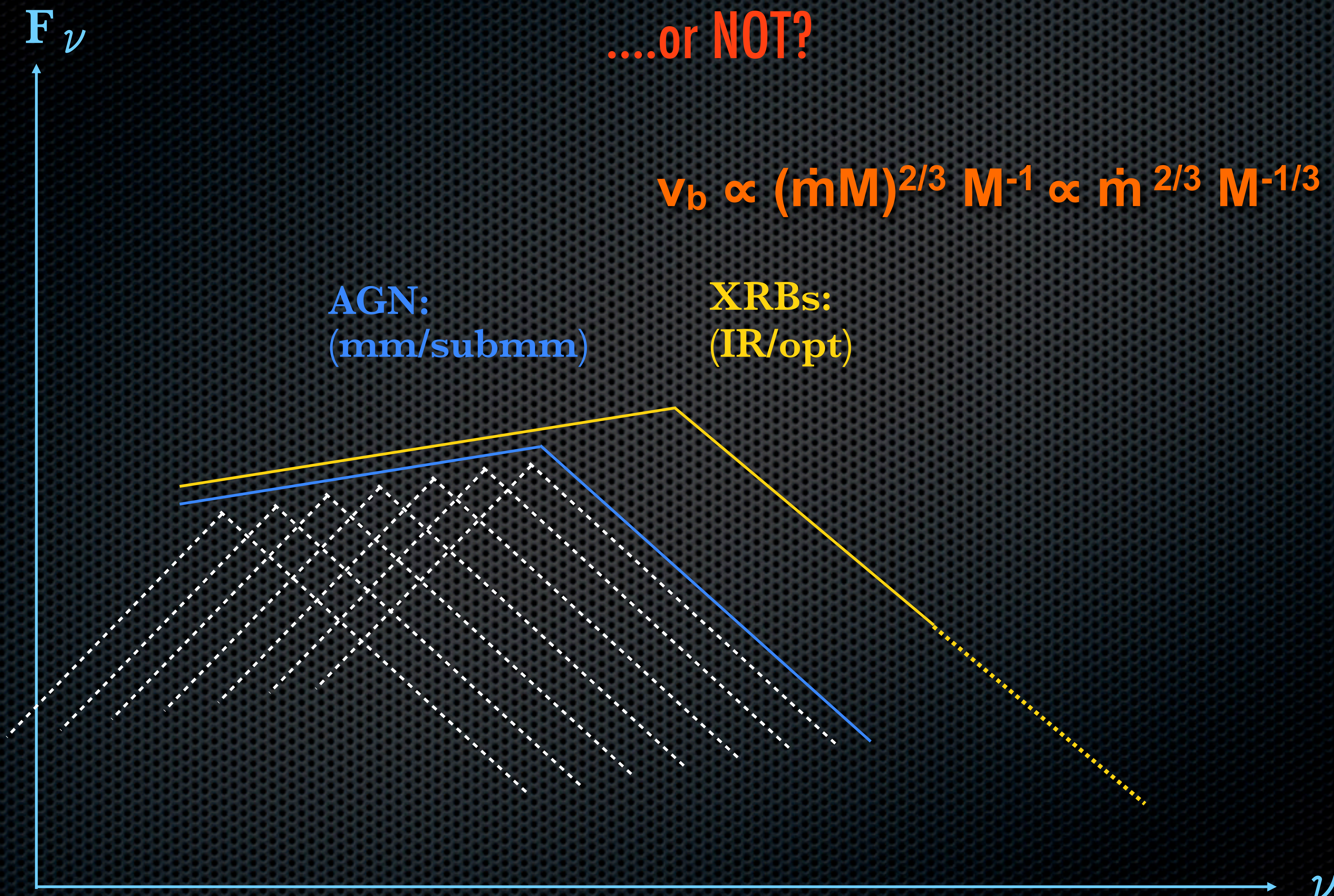


(SM, Nowak, et al., in prep.)

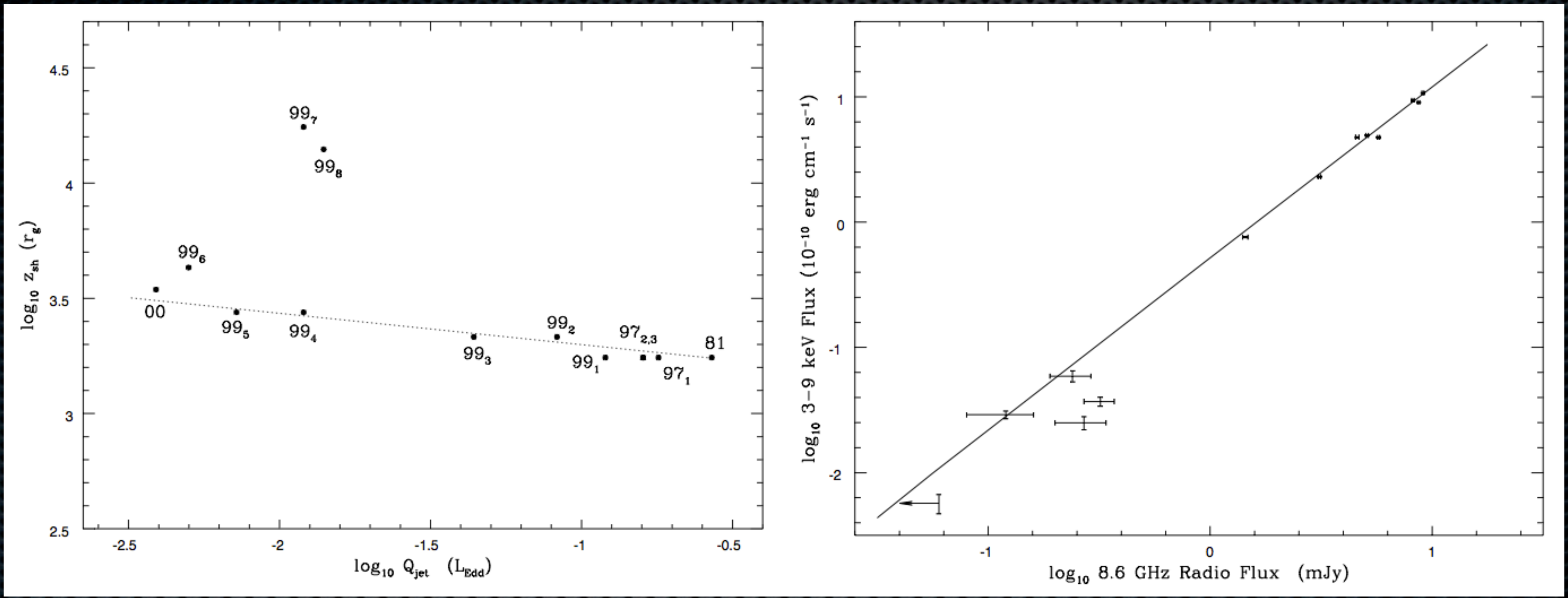
Compact jets: optical depth effects dominate scalings
....or NOT?

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



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

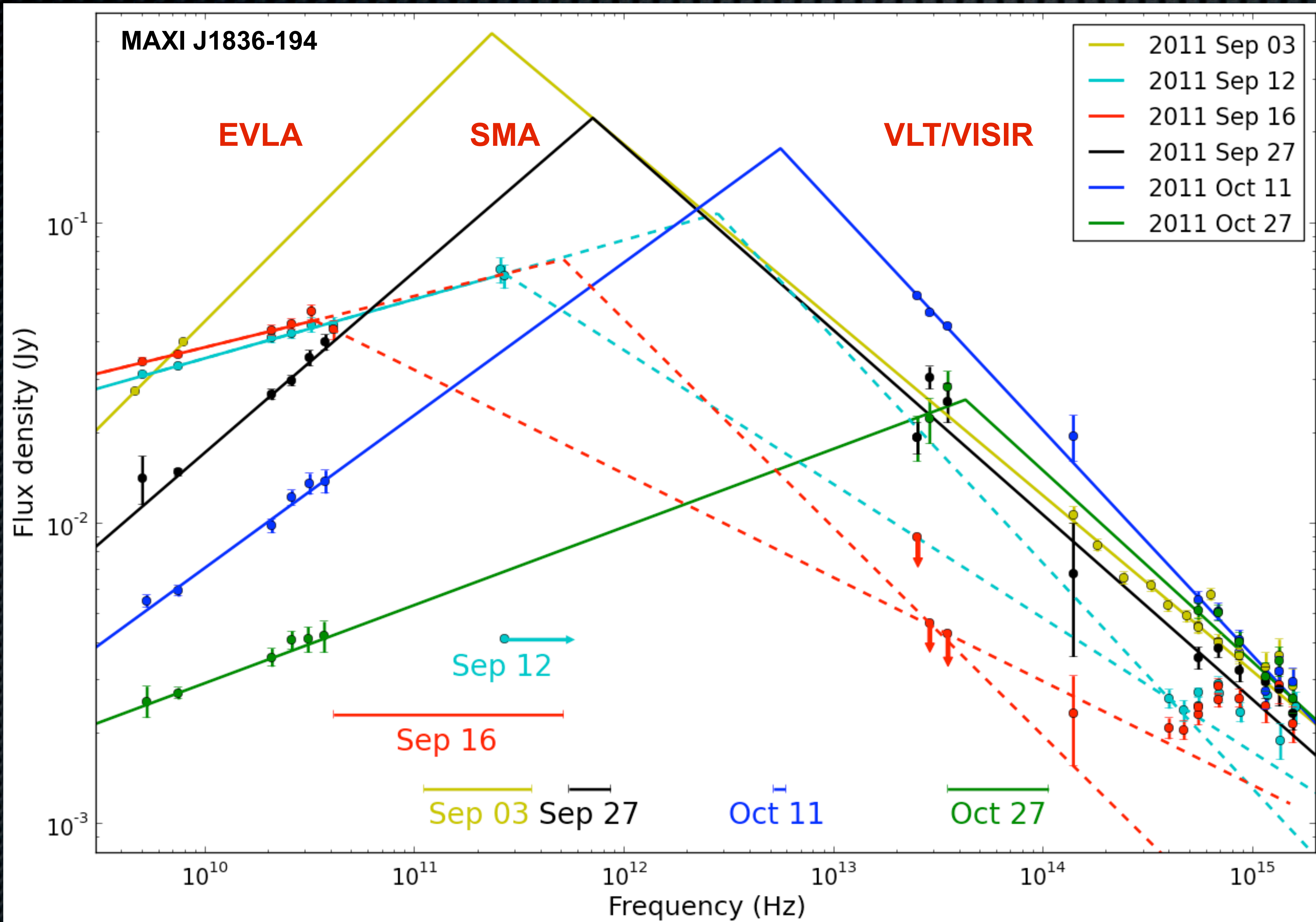
We didn't see this scaling in the original GX339-4 correlations



$$z_{acc} \propto Q_j^{-0.135} \sim \dot{M}^{-0.135}$$

(SM et al. 2003)

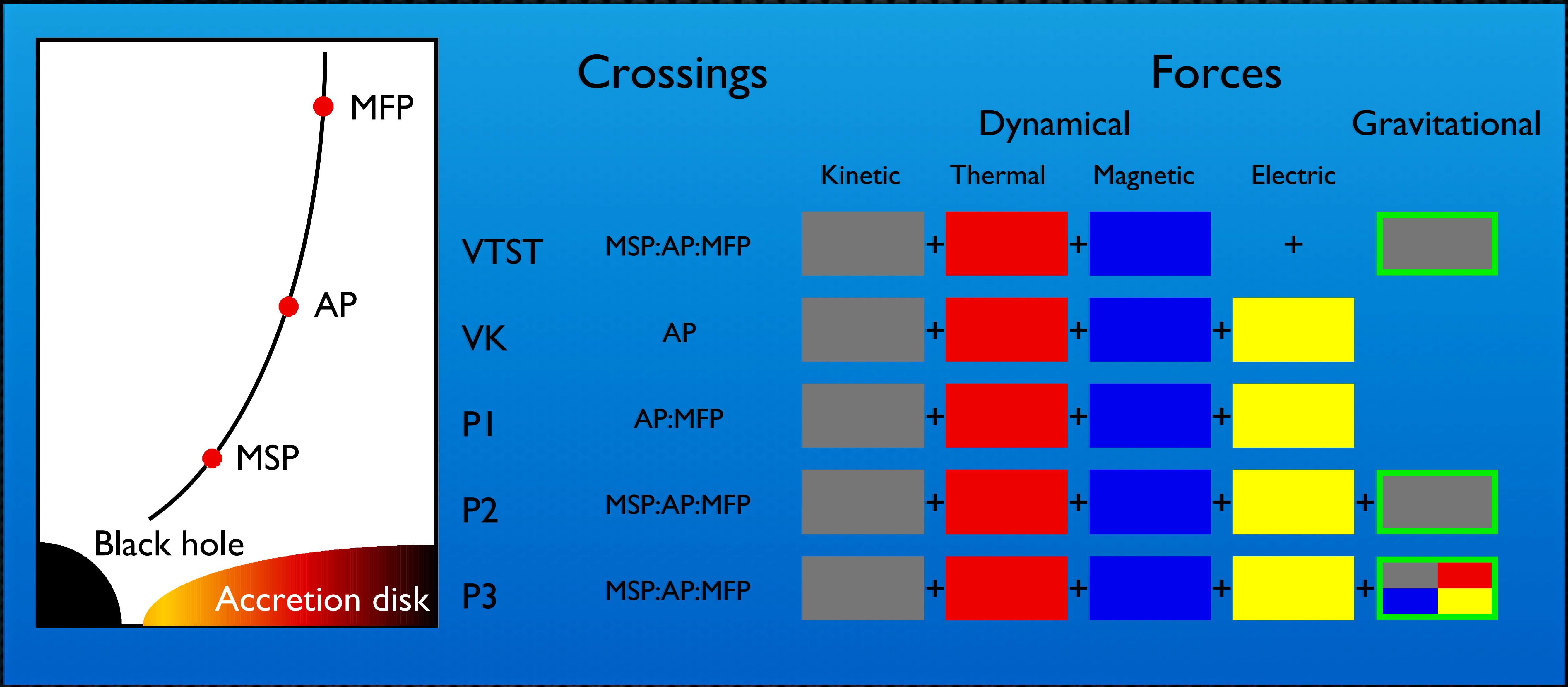
Simultaneous MW spectra ➠ jet break evolution



(Russell et al. 2013ab)

Some newer work and some questions

Outlook: location of acceleration and jet dynamics linked explicitly to conditions in inner accretion flow (breaks degeneracies)



(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013a,b)

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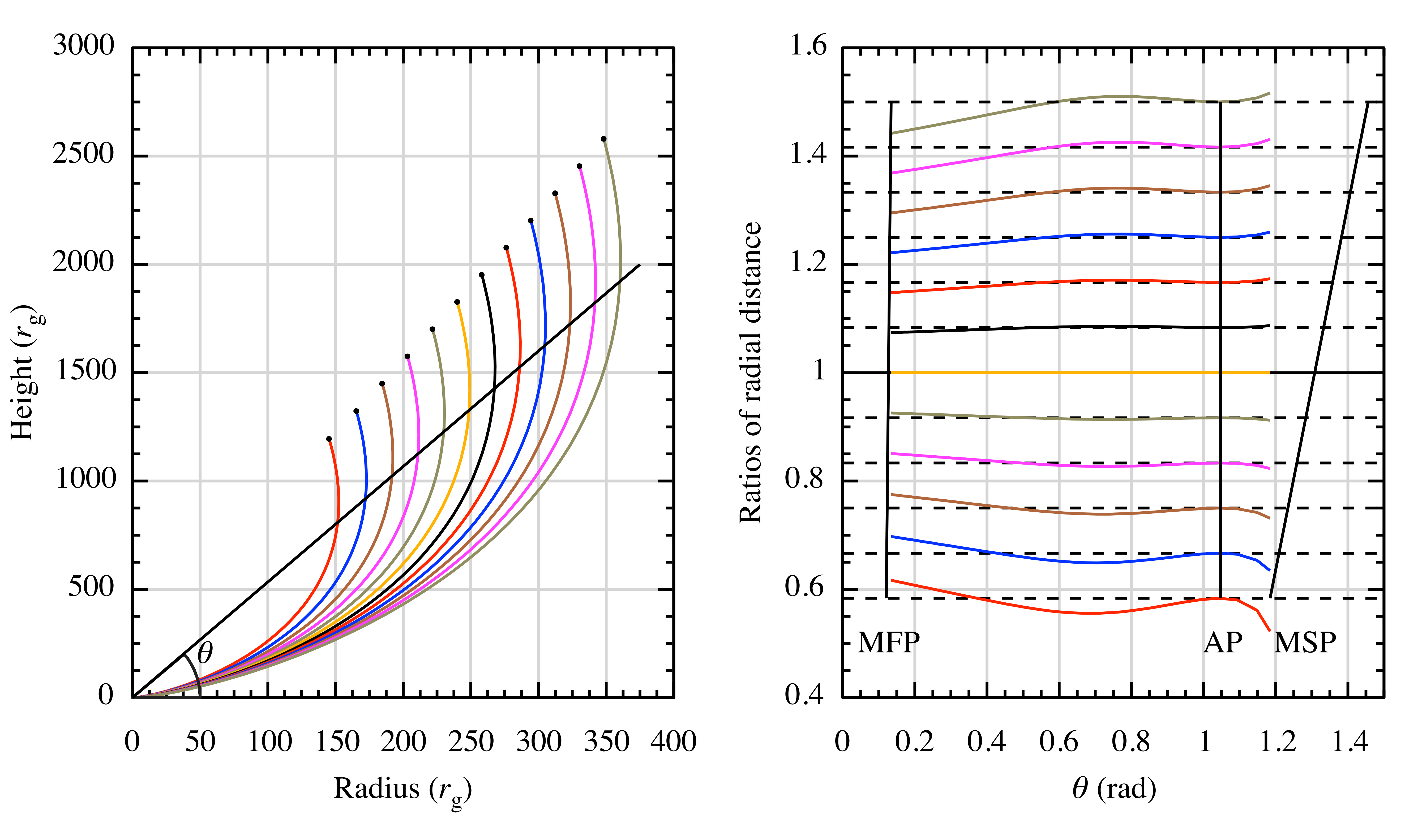

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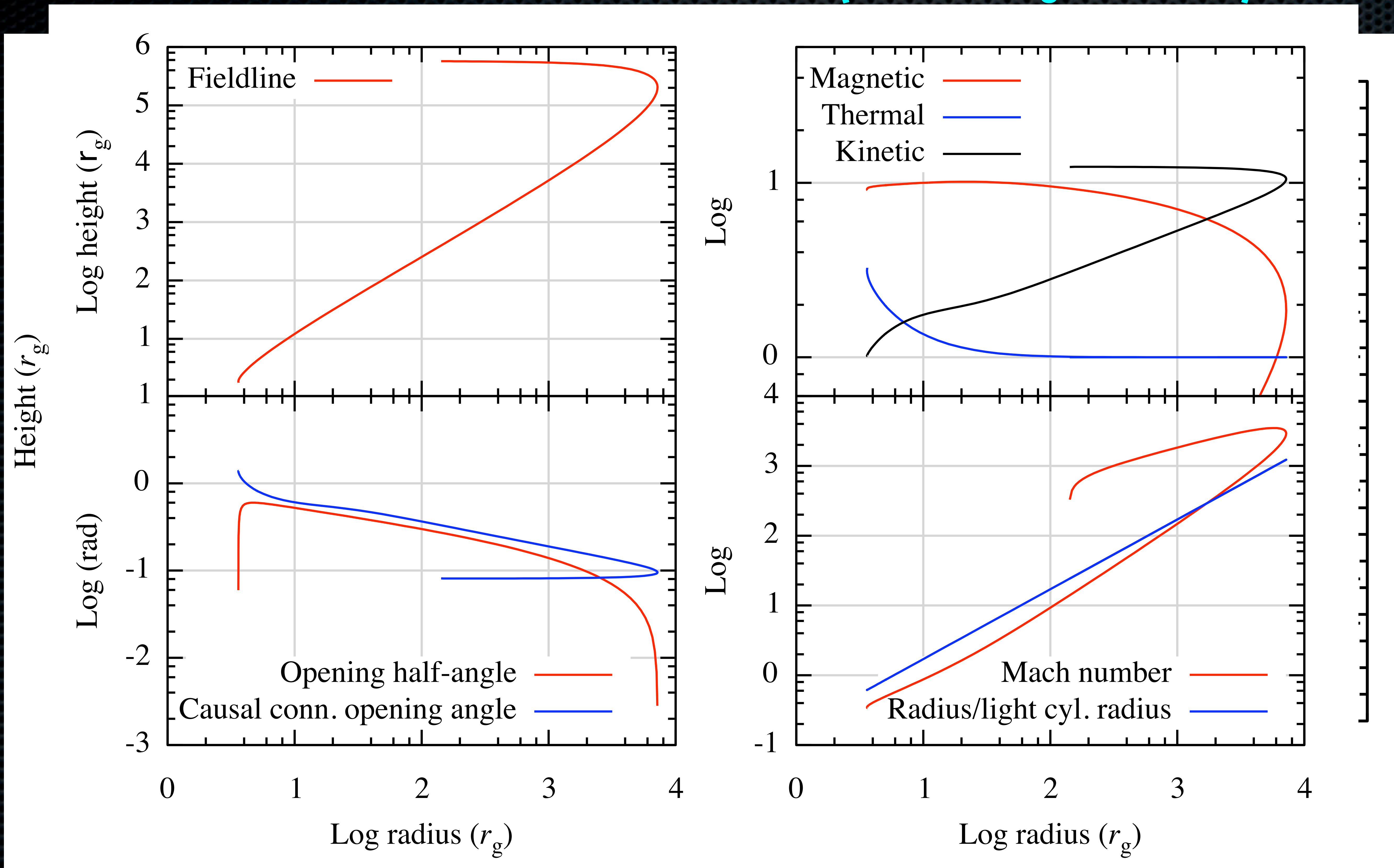

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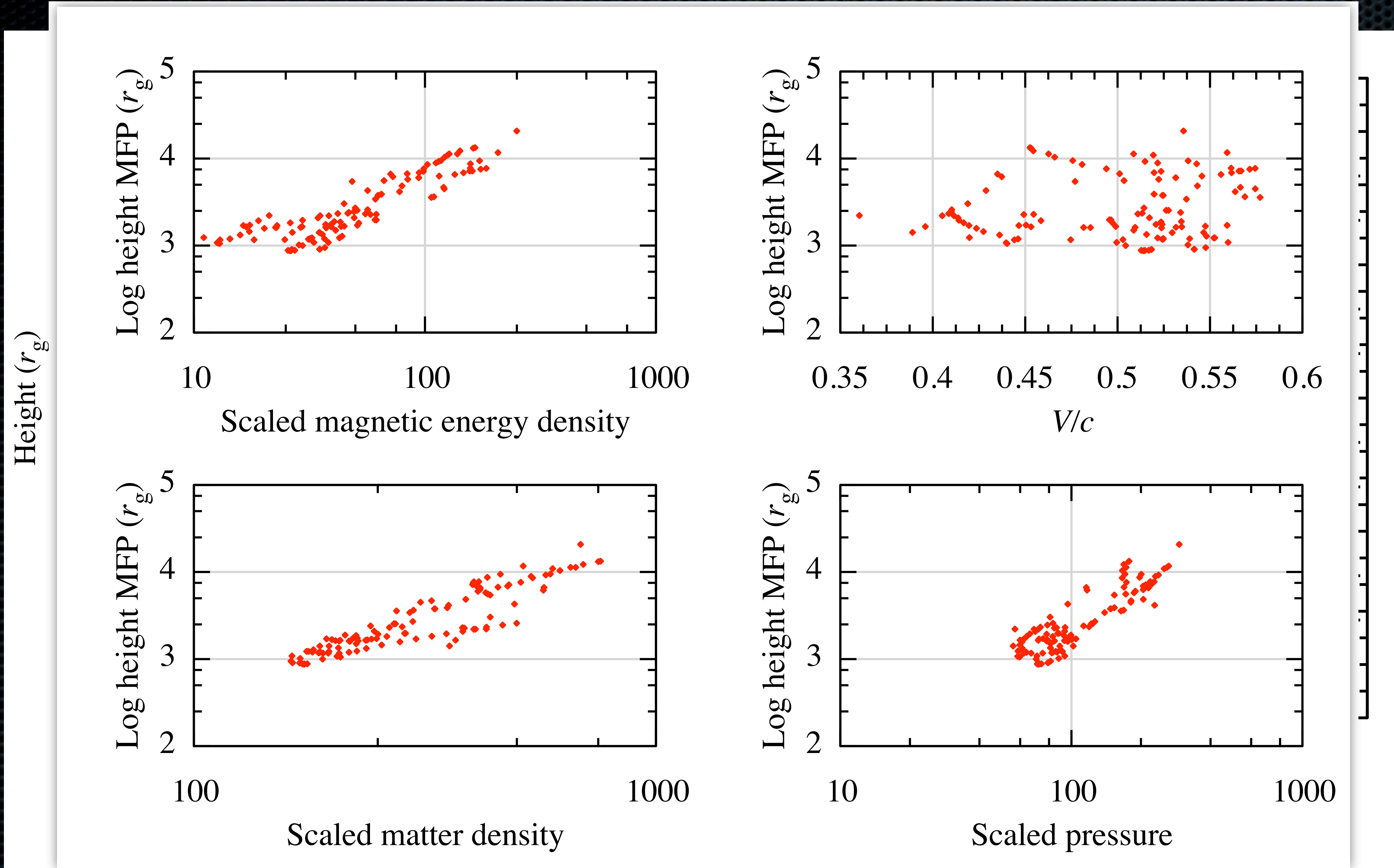

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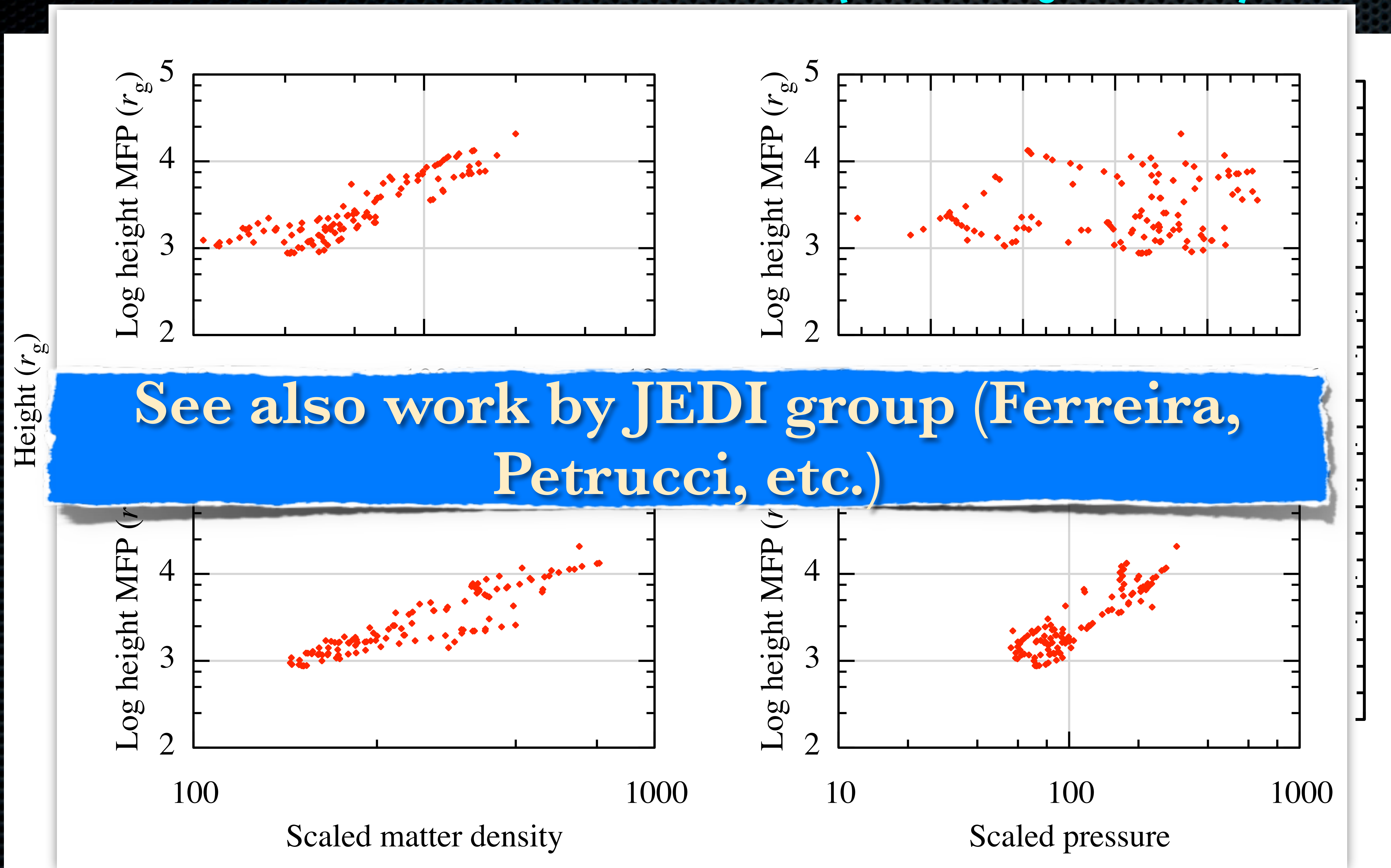
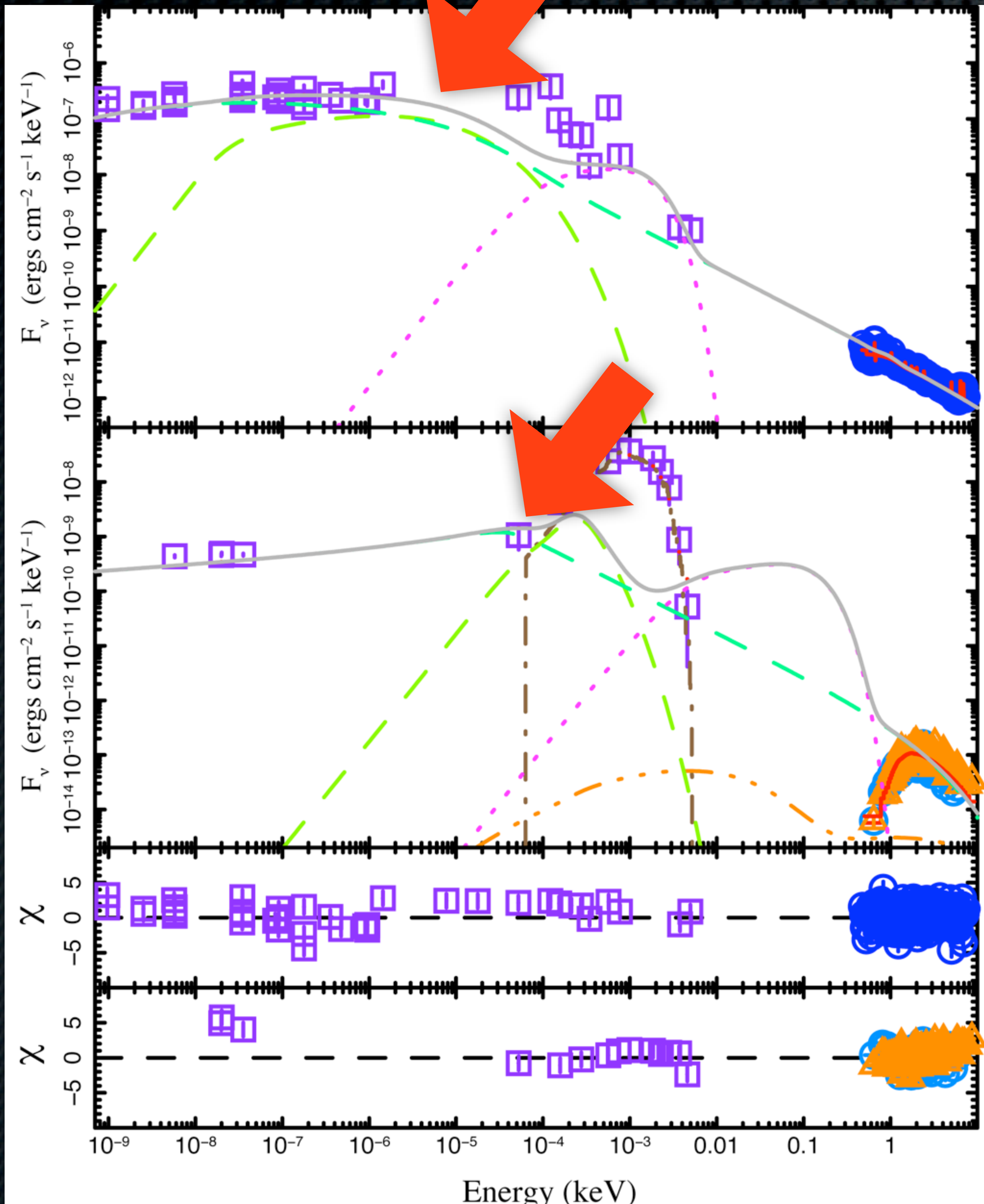


See also work by JEDI group (Ferreira, Petrucci, etc.)

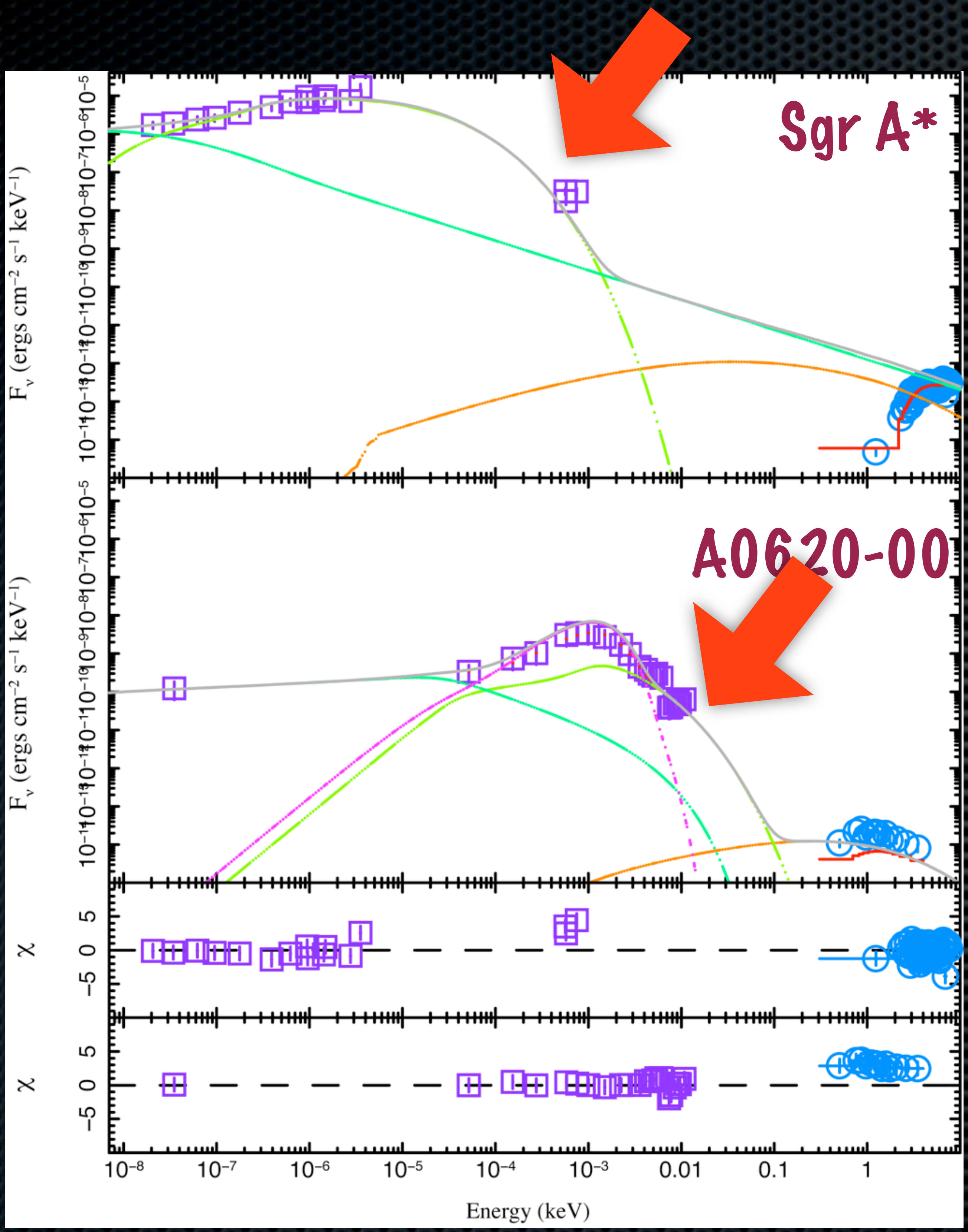
(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013a,b)

Questions raised for me by this meeting so far...



- Jet breaks fall within a relatively narrow range for black holes of all masses ➠ stable feature?
- Don't follow ~$\dot{m}^{2/3}$ scaling for ν_{SSA} ➠ within our model, because associated with a new component (particle accel)
- I had associated this with MFP/ recollimation shock (see Polko ea.)
- But M87 scales of jet base/launch zone similar, and HST-1 much further out (RCS)??
- Question: what accelerates the particles before the recollimation shock, and do we expect the resulting spectra to be different before and after???

Questions raised for me by this meeting so far...

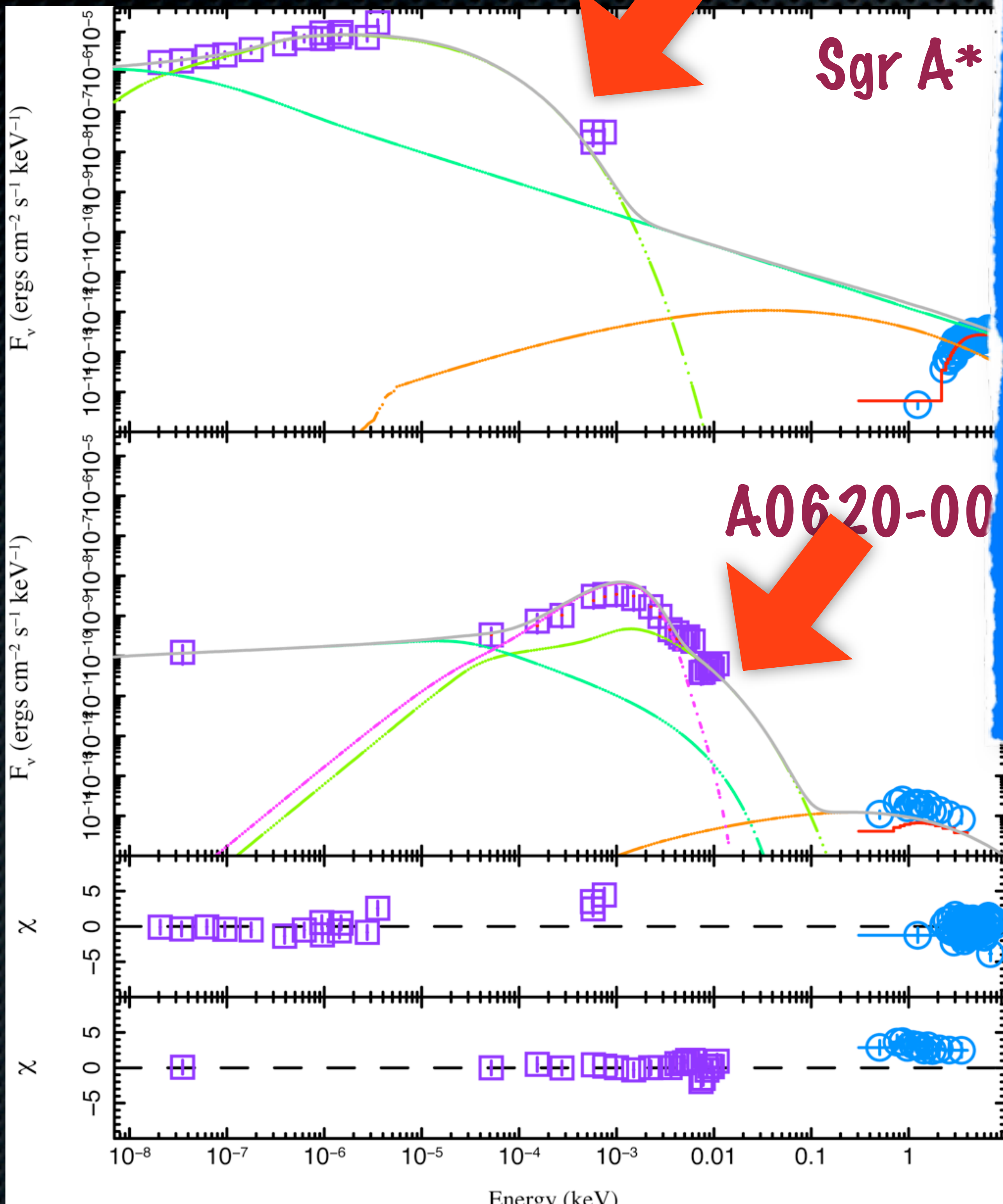


- "ultraweak" black hole Sgr A* show evidence for very weak, sporadic particle acceleration during flares (puts it on FP)
- Same scenario matches quiescent XRB A0620-00: below $\sim 10^{-7}$ L_{Edd}, the power-law fades away:

  → acceleration zone further down jets?

  → less efficient acceleration/ lower cutoff?
- Question: do we expect a jet power threshold below which structures for particle acceleration won't form or will be less efficient?

Questions raised for me by this meeting so far...



NEW! Poster by Tariq Shahbaz, Dave Russell et al.: Swift J1357.2-0933 in quiescence has slope too steep to be from particle acceleration (even cooled)! Maybe relevant for Juan Fernandez Ontiveros' steep LLAGN as well??

lower cutoff?

- ★ **Question: do we expect a jet power threshold below which structures for particle acceleration won't form or will be less efficient?**

Summary & Outlook: XRBs are very relevant for AGN!

- XRBs display a range of disk/jet configurations, so do AGN (though not in realtime): sub-Eddington accretion state with compact jets scales with M_{BH} (hard state ⇔ LLAGN/FRI/BL Lac) [+ disk-dominated state…]
- Beyond correlations in accretion output (Fundamental Plane): most recent work suggests full physical models can be scaled in M, $\dot{m}$ over 7 $\mathcal{O}$(mag)!
- Jet breaks are a key feature: Lack of strong scaling with M or $\dot{m}$ hints at stable/self-similar feature ➟ MFP/recollimation shock? If so, why so close compared to M87/BL Lac? If not, what other MHD feature could produce the break? *XRBs critical for developing/testing these ideas!*
- Increasing signs that below ~10^{-7} L_{Edd}, jets experience less efficient (or no) particle acceleration: Does this fit into the emerging views presented here?
- Outlook:

➡ Improved models: One size does not fit all! New SA-models with MHD-consistent "backbones" ➟ reduce degeneracies, provide link to simulations

➡ New simulations: GRMHD + rad. transfer, including particle acceleration?

➡ New facilities: Era of "transient factories": LOFAR/MeerKAT/ASKAP/LSST will discover more XRBs and TDEs to test models of realtime jet evolution