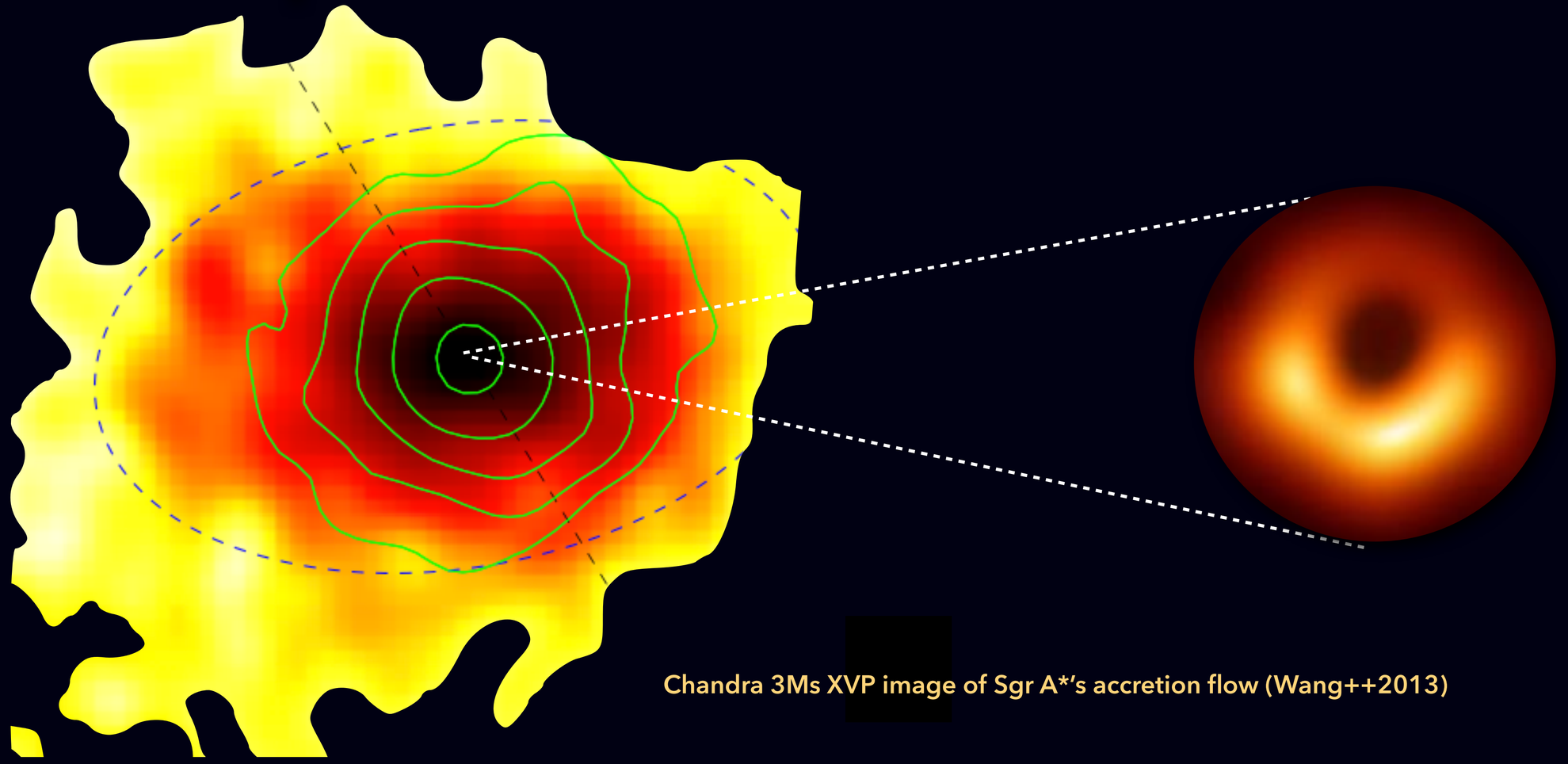
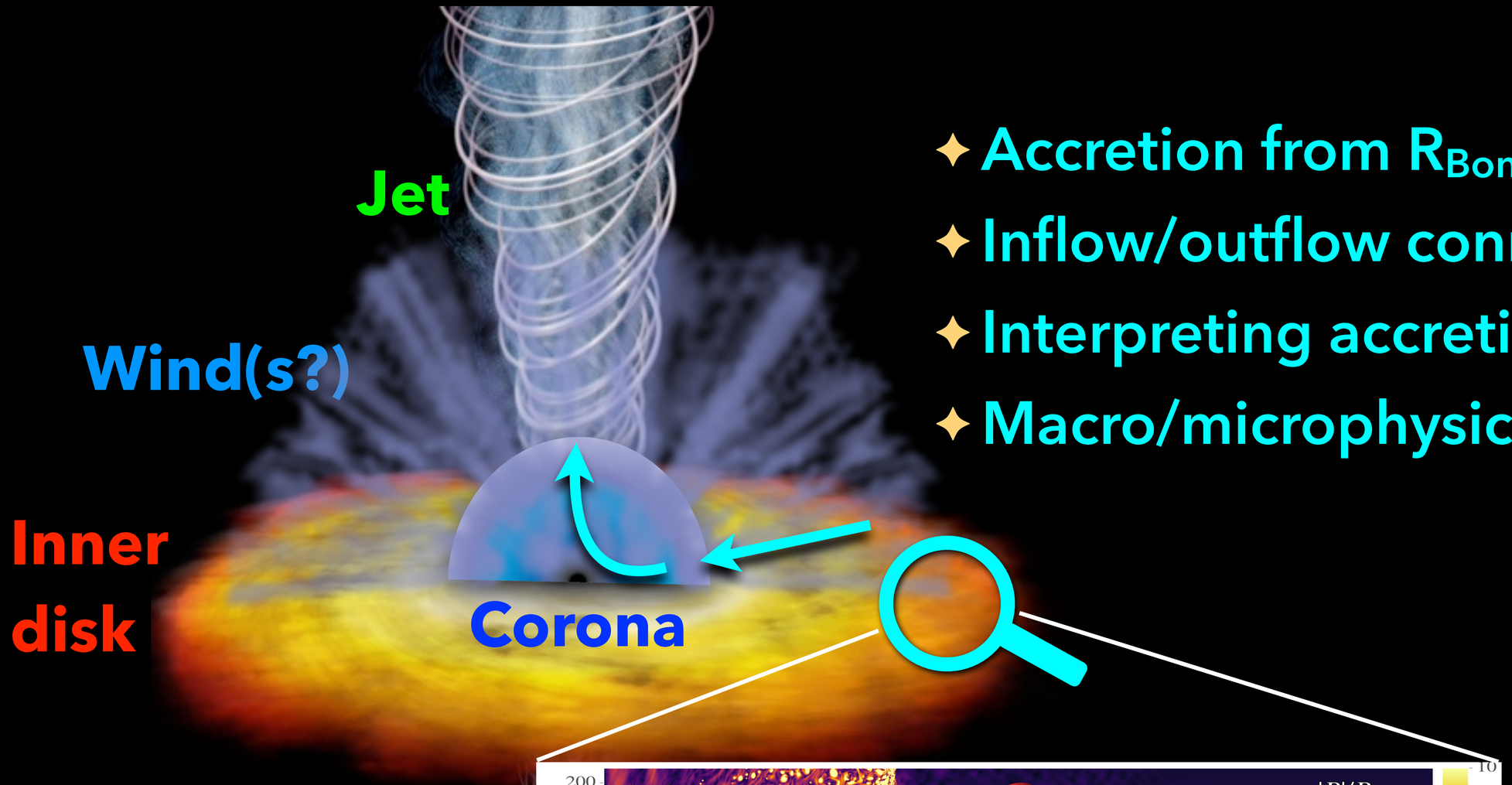
Chandra's exquisite view of the accretion processes around black holes



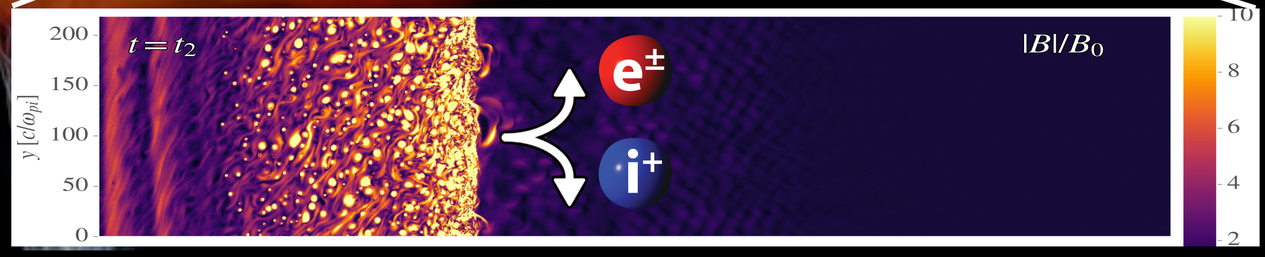
Chandra 3Ms XVP image of Sgr A*'s accretion flow (Wang++2013)

Sera Markoff (API/GRAPPA, University of Amsterdam + EHT collaboration]
...and a long list of collaborators, students and postdocs!!!

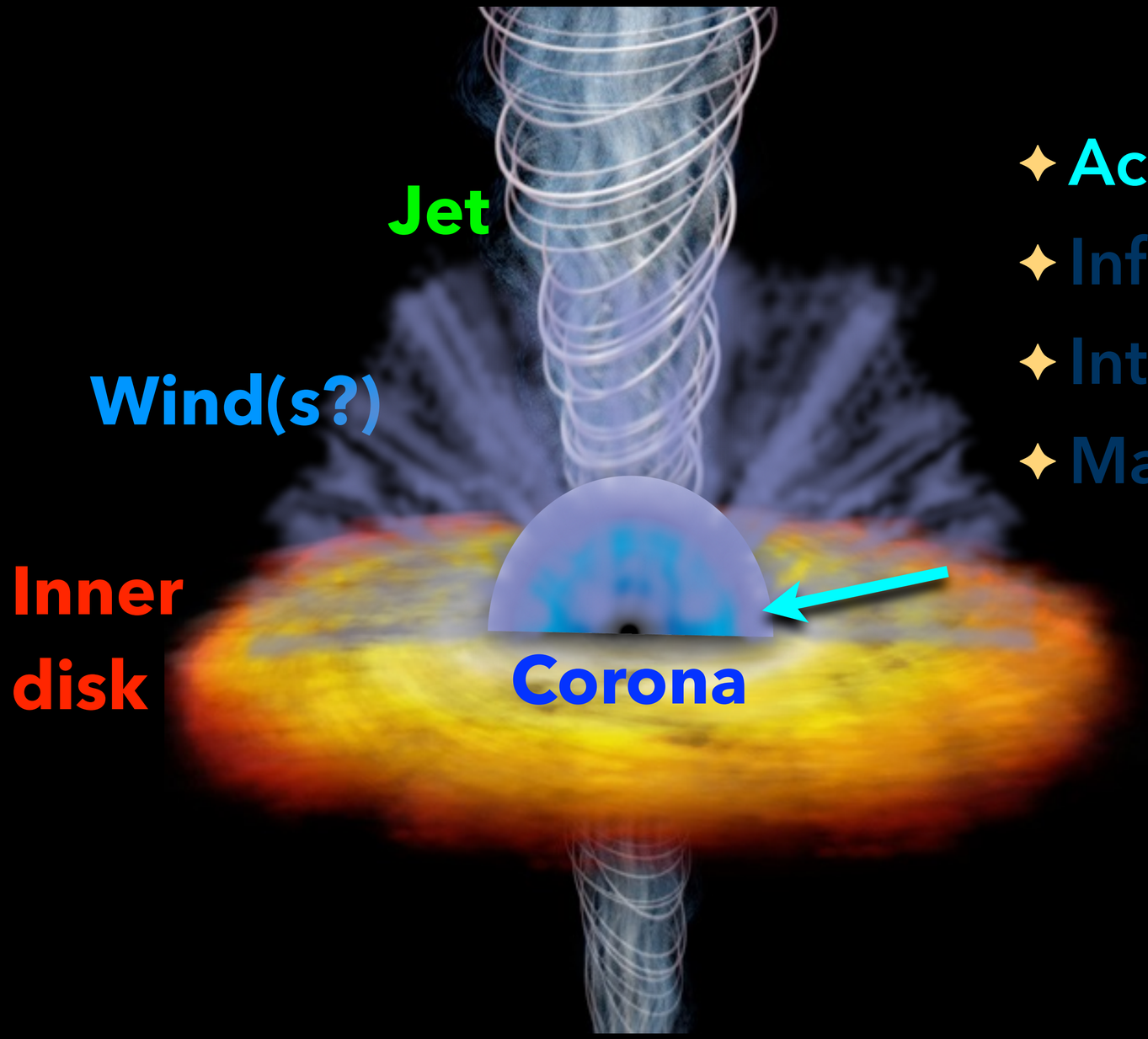
Schematic of inner ~100 R_g accretion "engine"



- Accretion from R_{Bondi} to R_g
- Inflow/outflow connection
- Interpreting accretion geometry
- Macro/microphysics connection



Schematic of inner ~100 R_g accretion "engine"



- Accretion from R_{Bondi} to R_g
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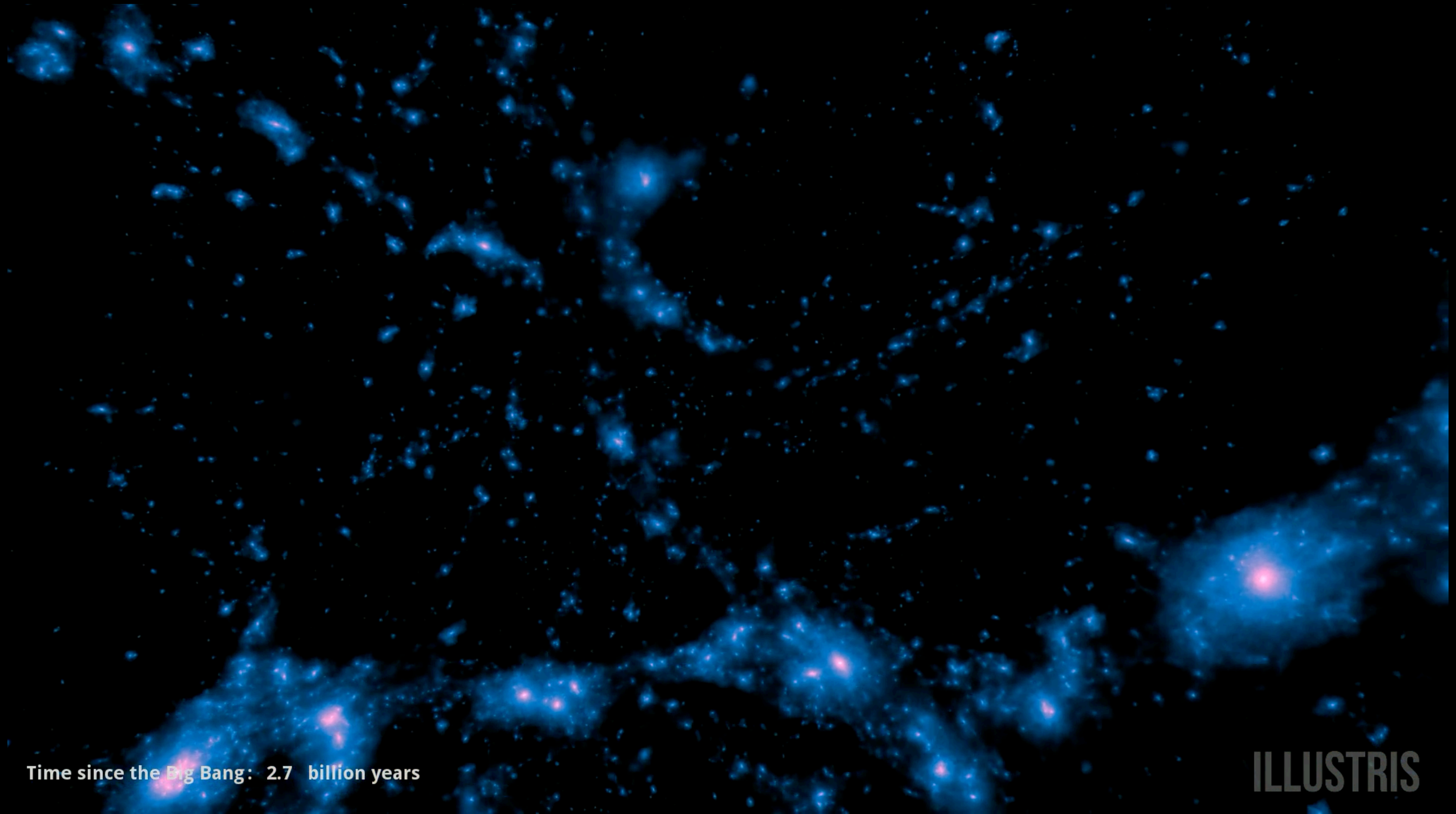
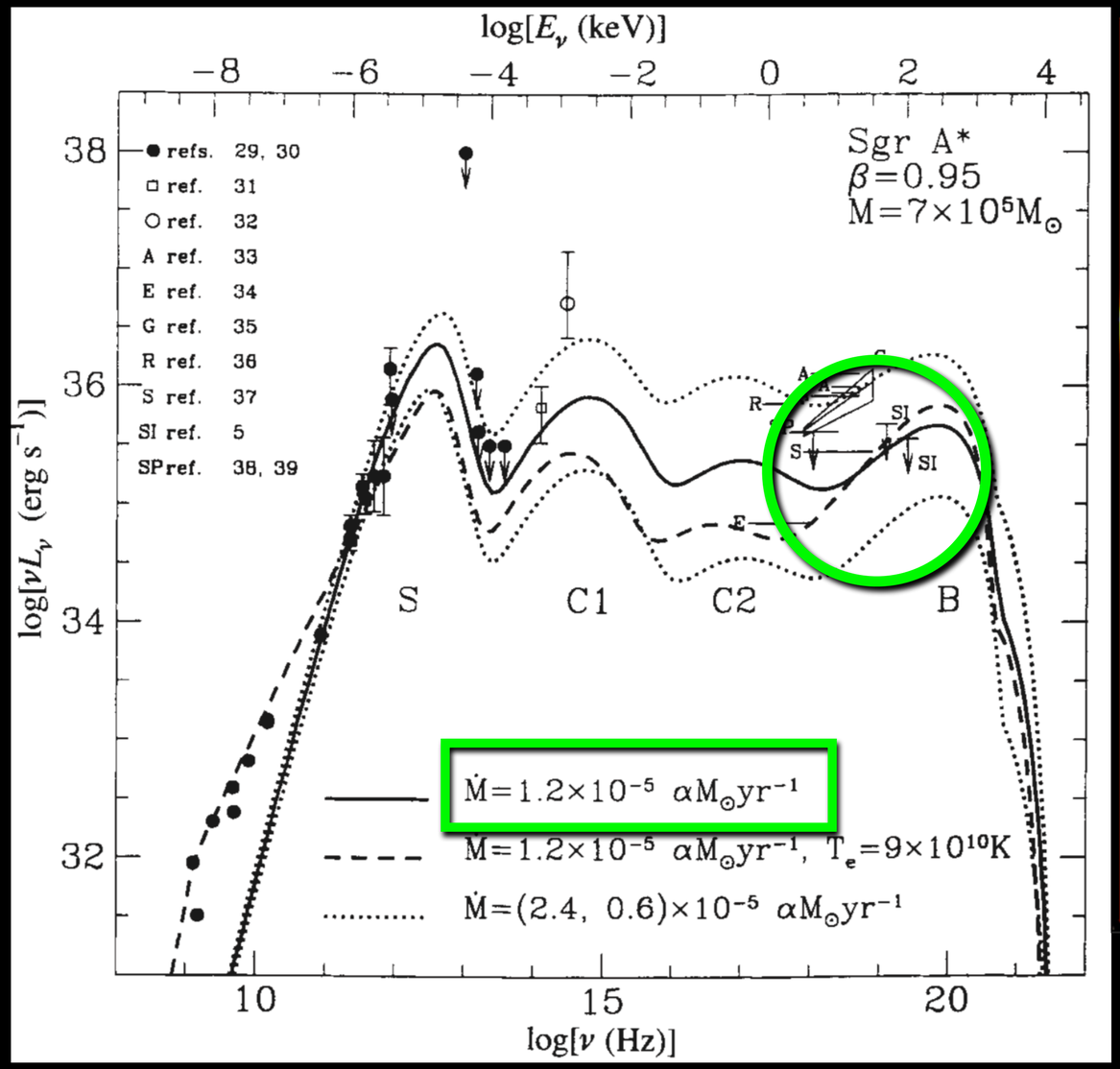
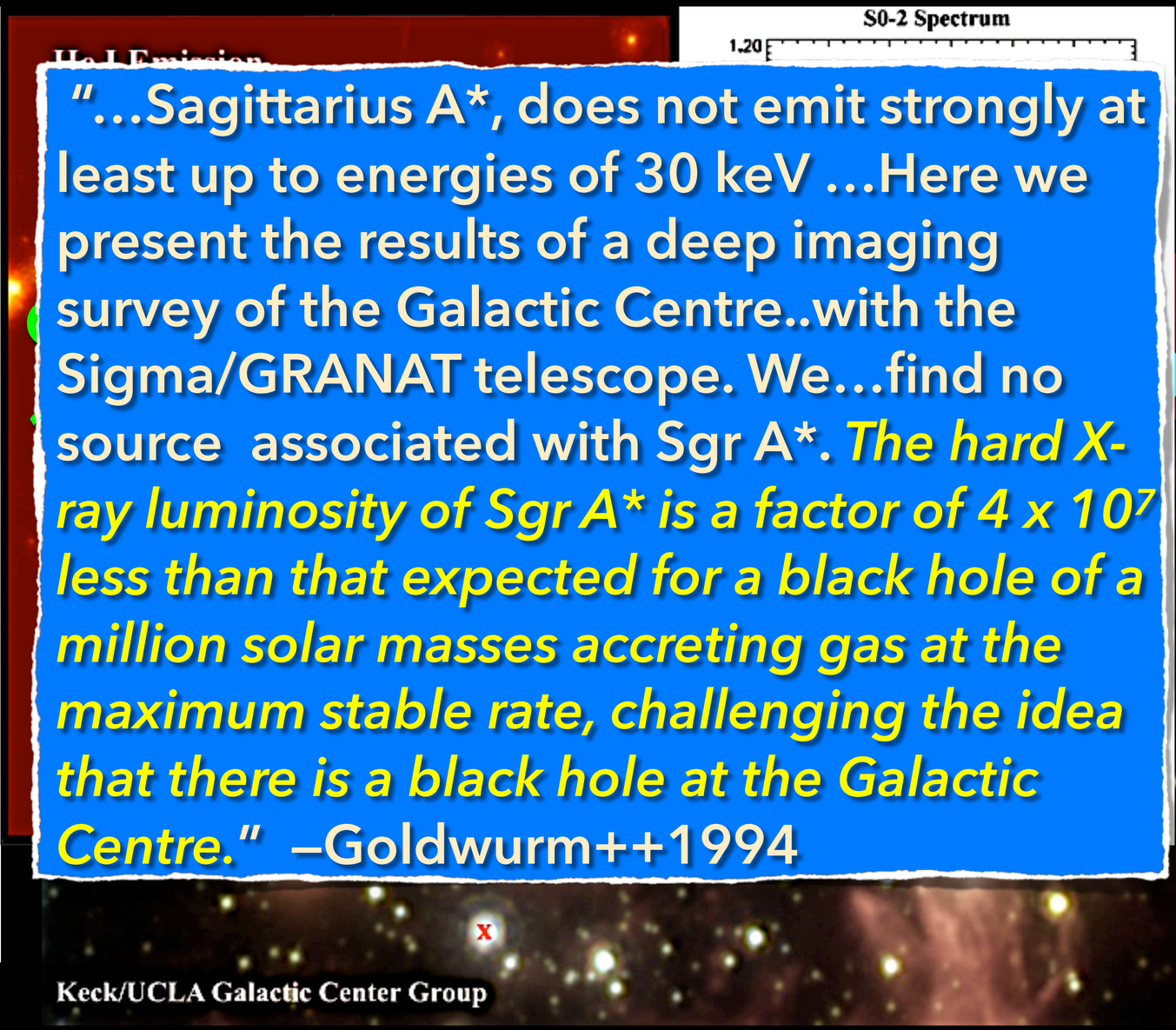
Black holes “redistribute the wealth” (with Bondi prescription…)



In the years Before Chandra (B.C.) the hunt for Sgr A*

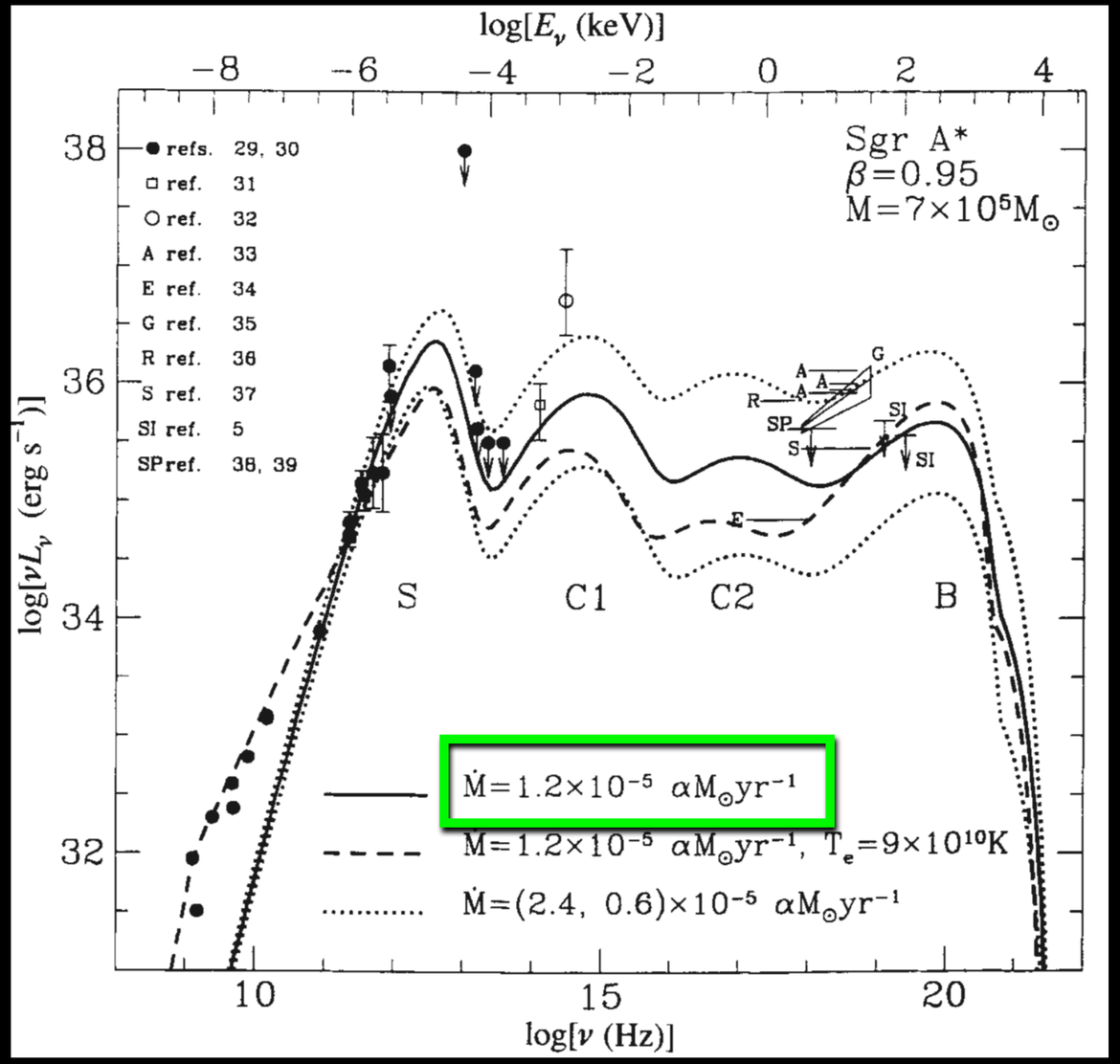


(Narayan, Yi & Mahadevan 95; Goldwurm++1994)

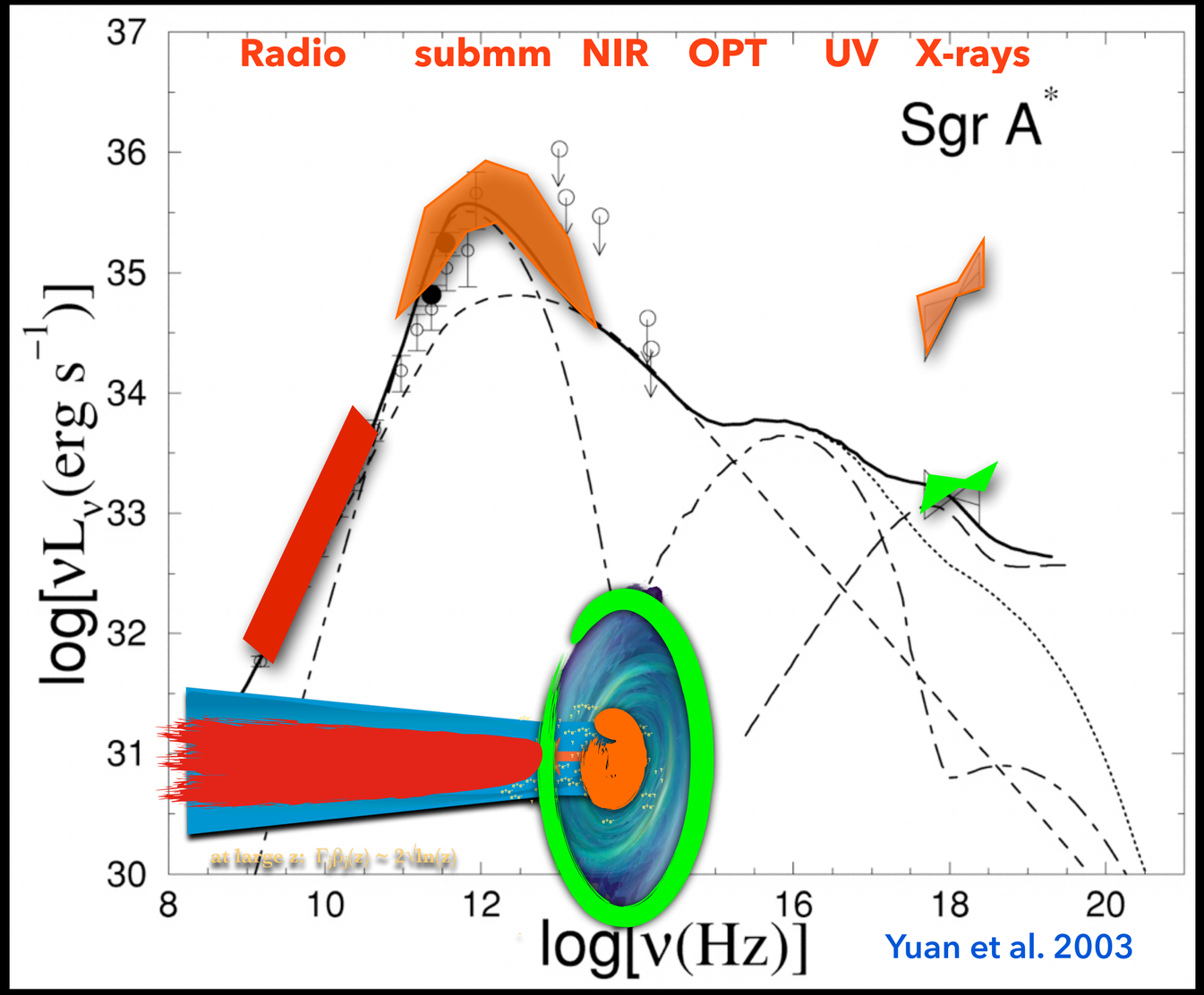


"…Sagittarius A*, does not emit strongly at least up to energies of 30 keV …Here we present the results of a deep imaging survey of the Galactic Centre..with the Sigma/GRANAT telescope. We…find no source associated with Sgr A*. *The hard X-ray luminosity of Sgr A* is a factor of 4 x 10^7 less than that expected for a black hole of a million solar masses accreting gas at the maximum stable rate, challenging the idea that there is a black hole at the Galactic Centre.*" –Goldwurm++1994

Chandra confirmed ‘advective/inefficient’ accretion flows



(Narayan & Yi 94; 95)

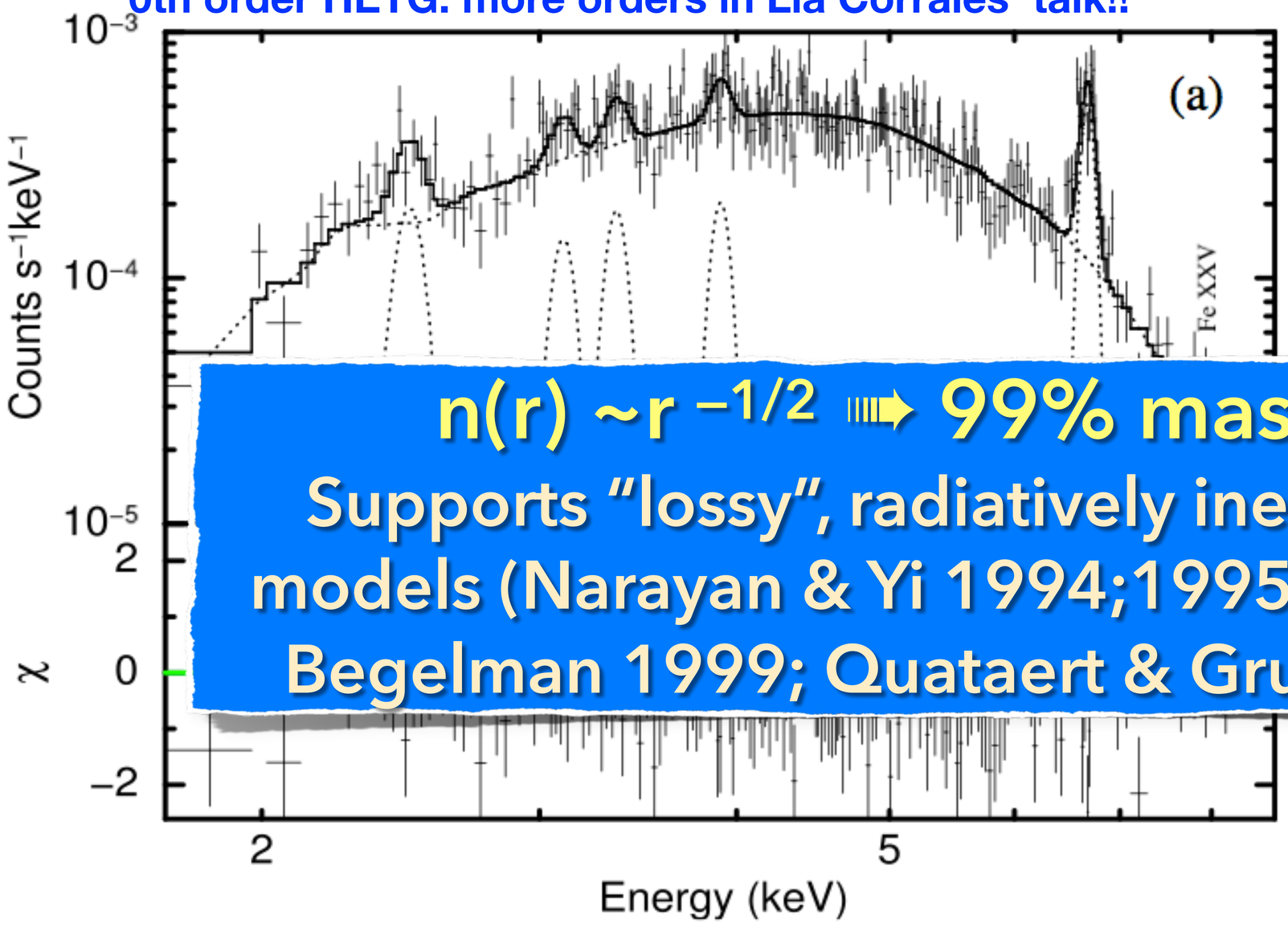


(Baganoff++ 01; 03)

Repeat the mantra: Chandra's resolution/sensitivity is key!!

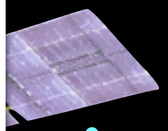
(*and a 3 Ms XVP doesn't hurt…*)

0th order HETG: more orders in Lia Corrales' talk!!

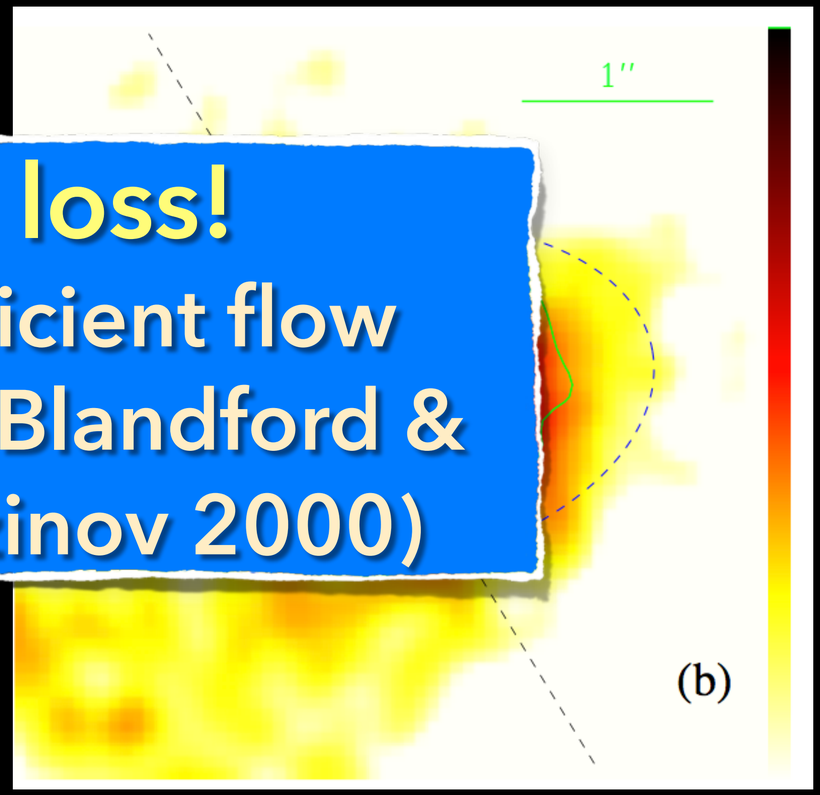


$n(r) \sim r^{-1/2}$ ➠ 99% mass loss!

Supports "lossy", radiatively inefficient flow models (Narayan & Yi 1994;1995; Blandford & Begelman 1999; Quataert & Gruzinov 2000)

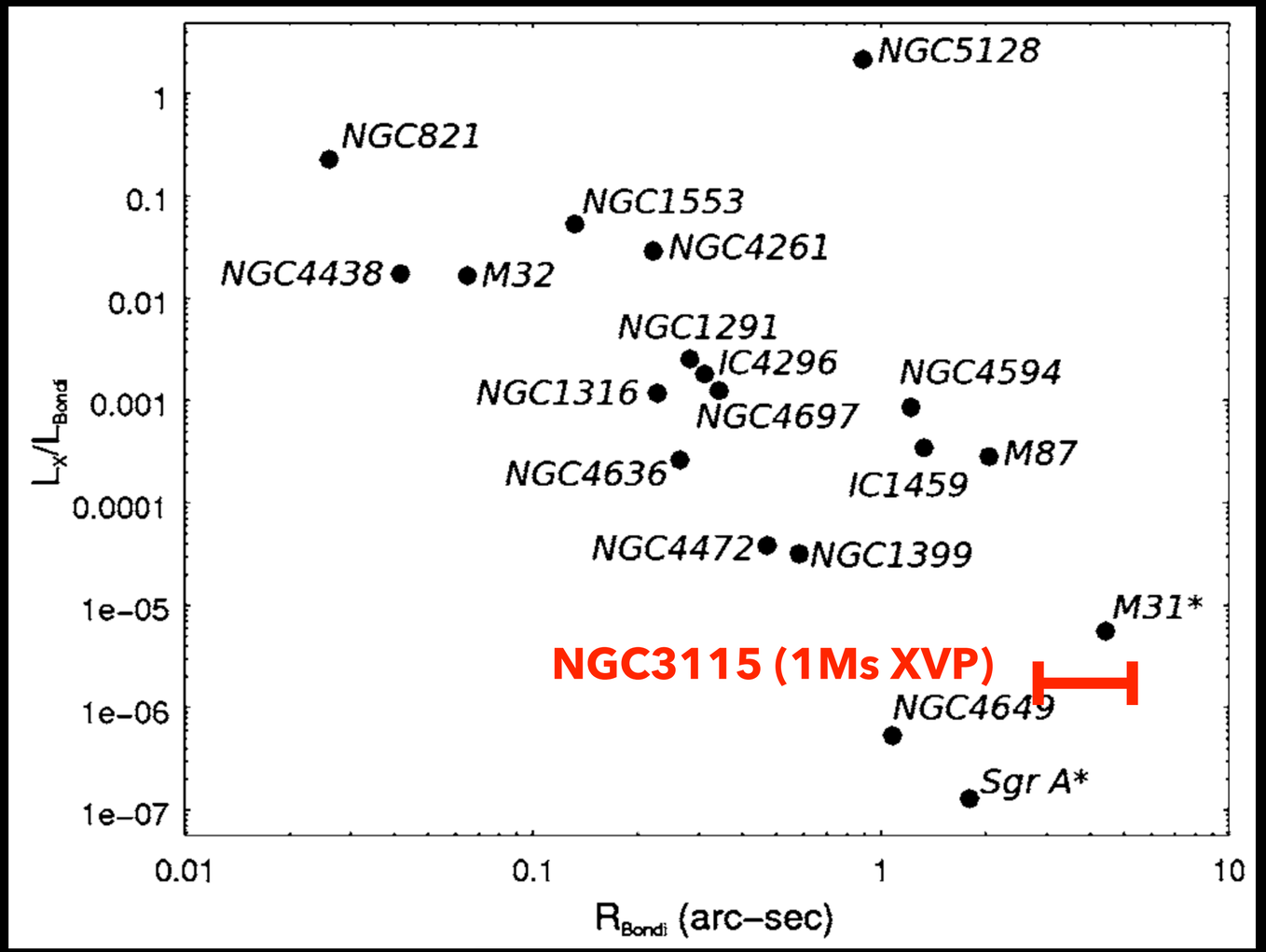


$\dot{M}_{Bondi} \sim 10^{-6} – 10^{-5}\ M_\odot$

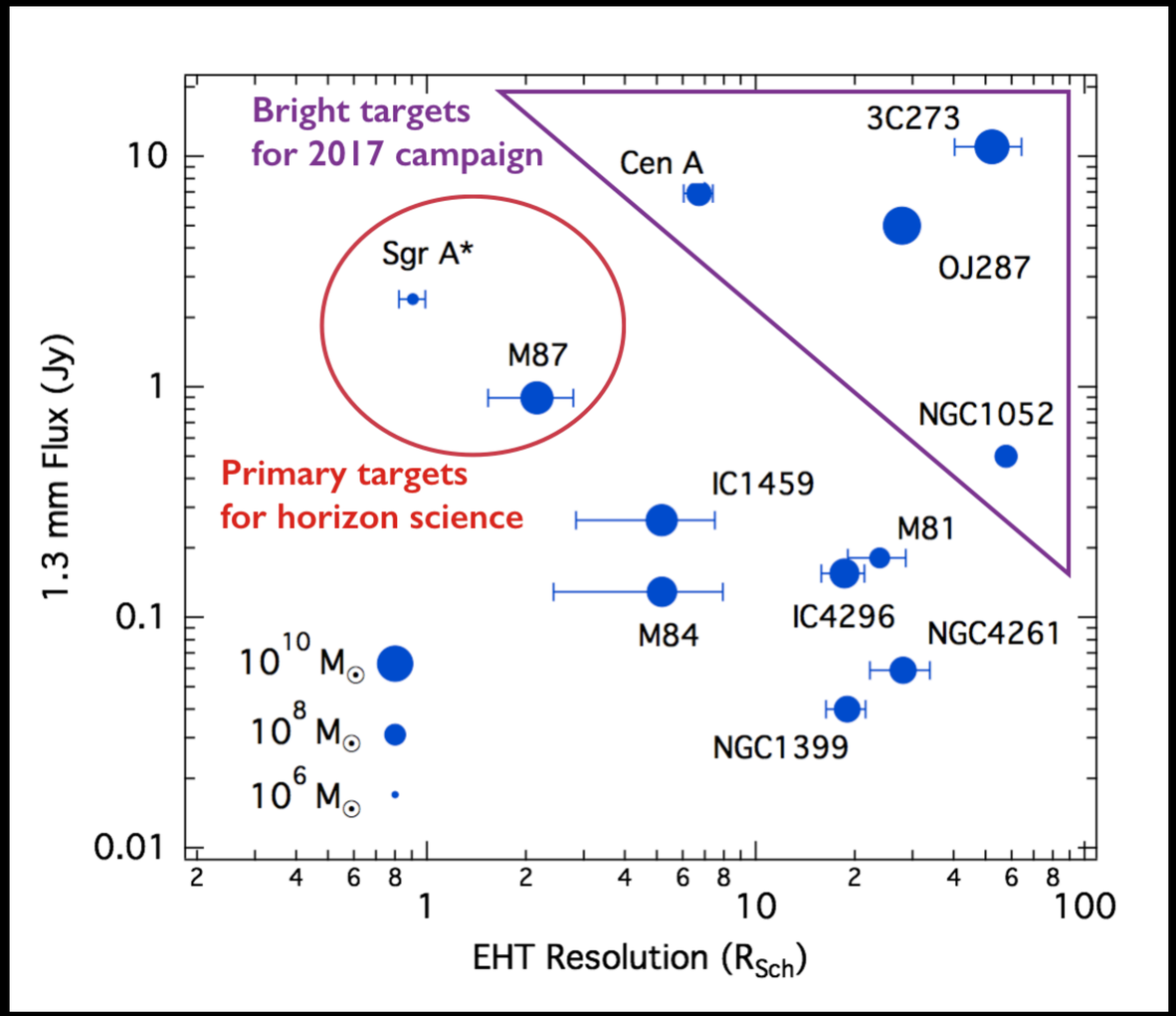


(Wang, Nowak, SM++, Science, 2013)

Chandra + EHT cover R_{Bondi} to R_g for a few sources

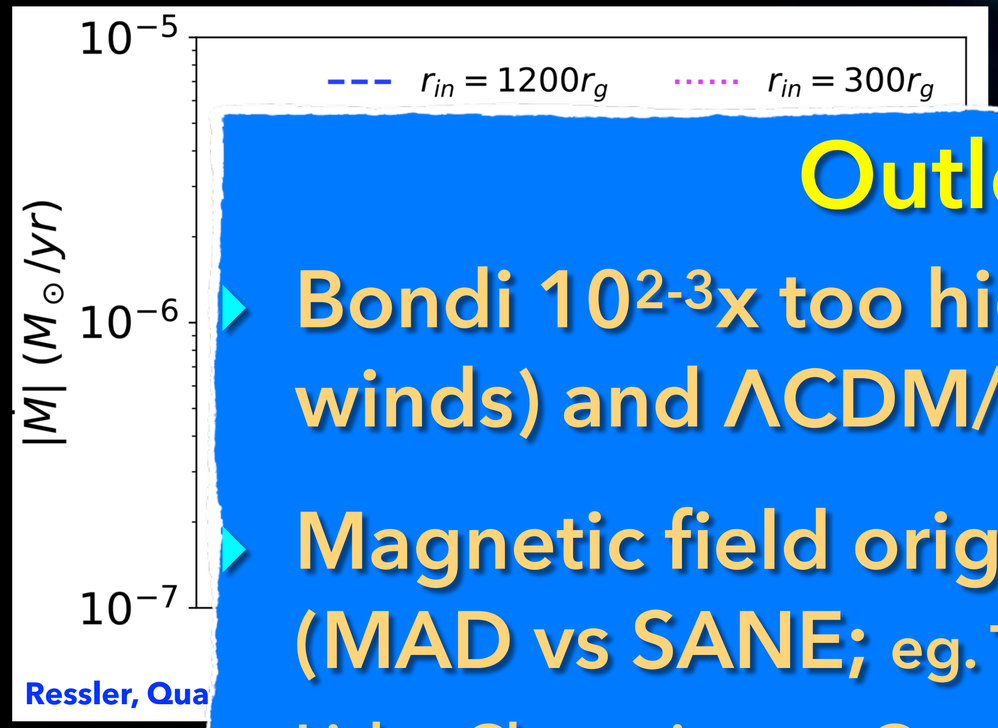


(Garcia++2005, 2010)



(Psaltis 2010)

An ‘almost’ complete picture of BH accretion from outside in



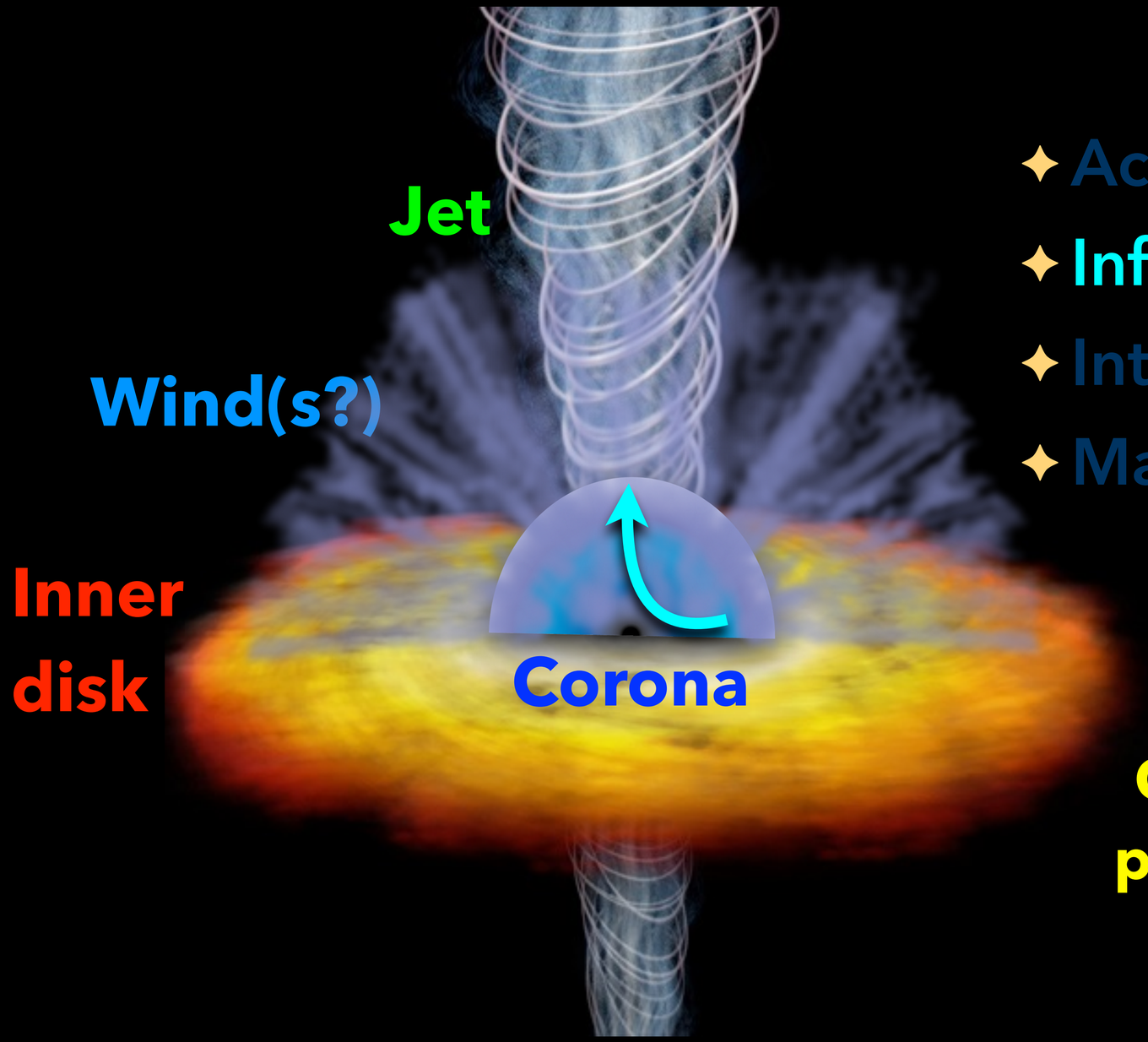
$\dot{M} \approx$

Outlook & questions:

- Bondi $10^{2\text{-}3}$x too high! Implications for local (hot winds) and ΛCDM/BH growth/feedback modeling?
- Magnetic field origins/seeding/configurations? (MAD vs SANE; eg. Tchekhovskoy++; McKinney++; Narayan++; Liska, Chatterjee++; Gammie++; Moscibrodzka++….)
- Connection between inflow properties and outflows?

(Coker & Melia++; Cuadra++; Ressler, Quataert++)

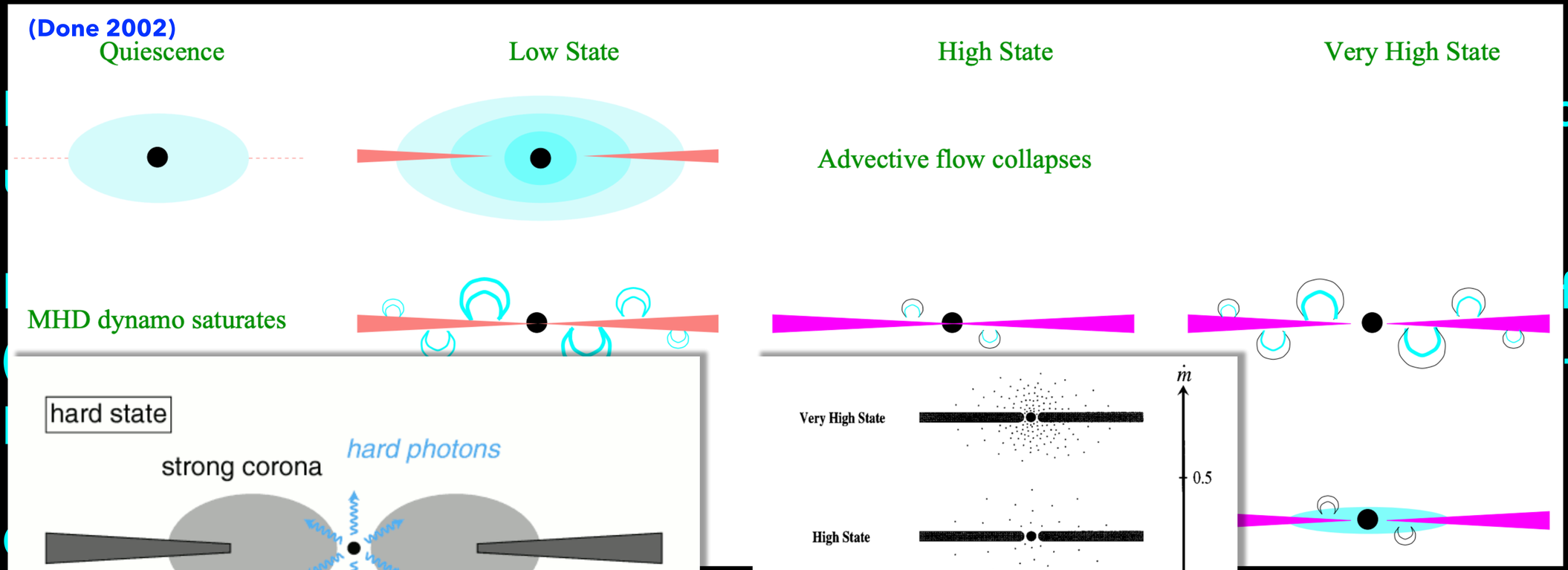
Schematic of inner ~100 R_g accretion "engine"

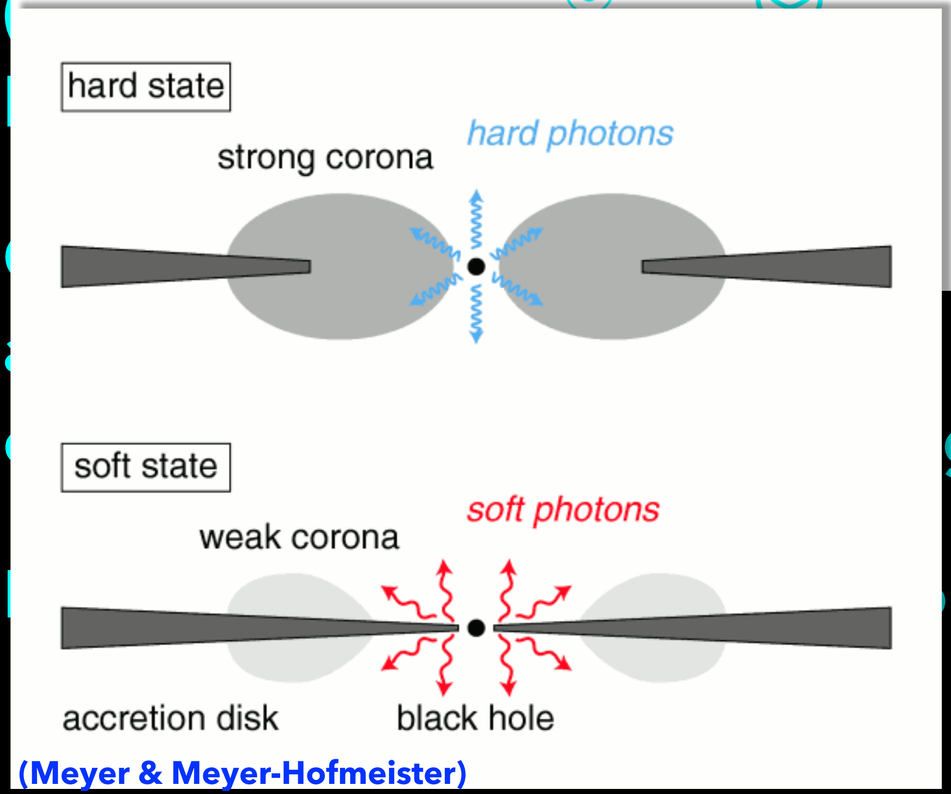


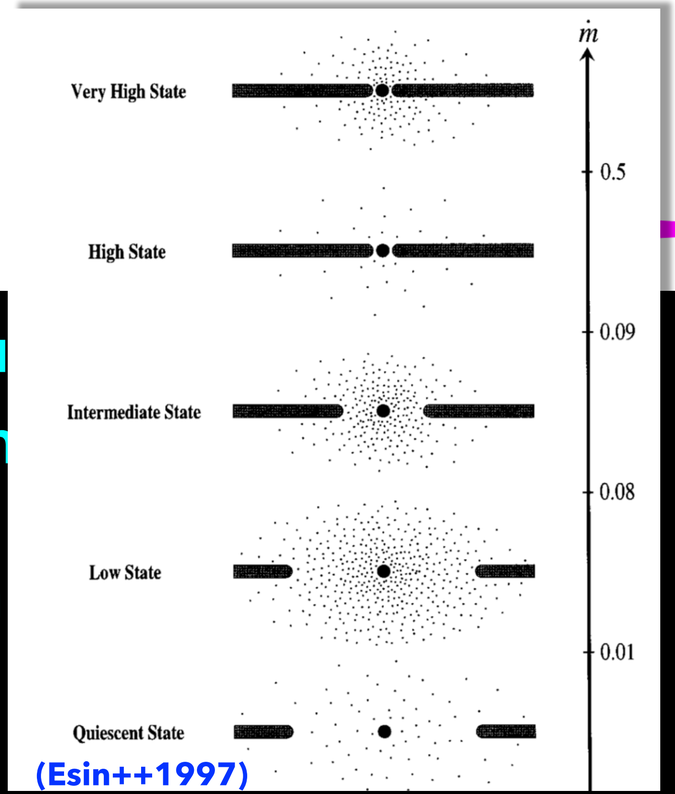
- Accretion from R_{Bondi} to R_g
- Inflow/outflow connection
- Interpreting accretion geometry
- Macro/microphysics connection

On the path towards a first-principles, predictive model!

XRBs show inflow/outflow coupling in human timescales

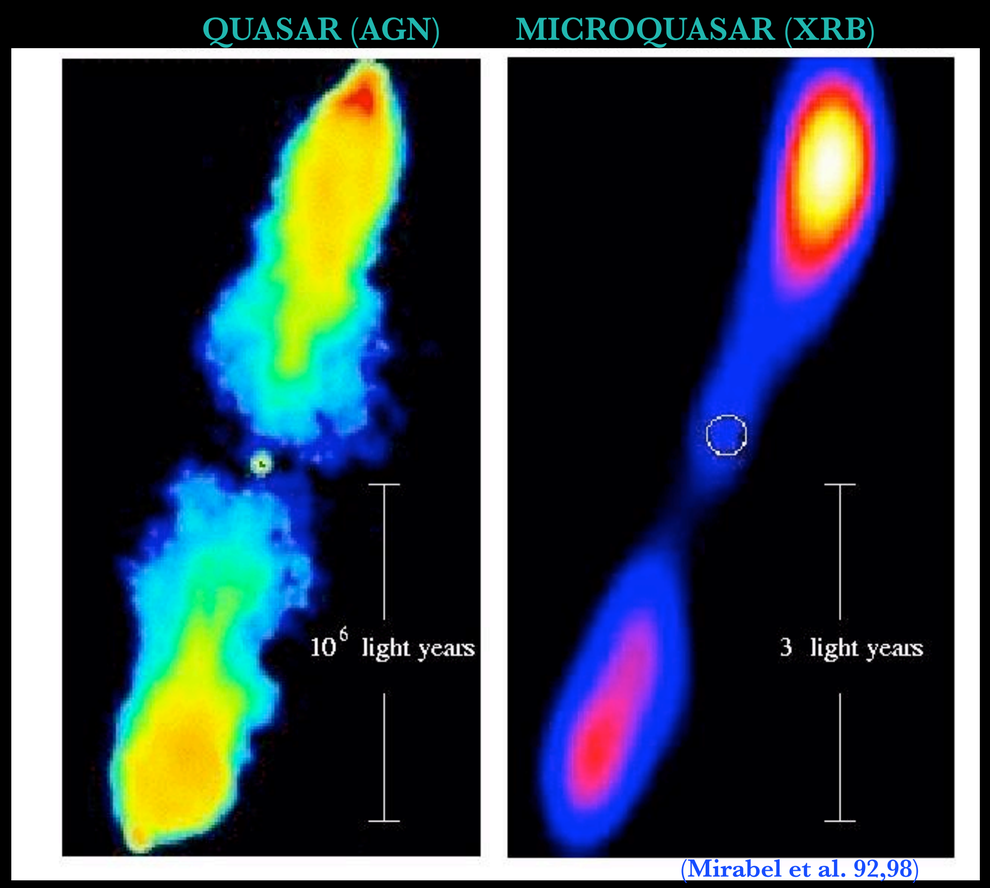


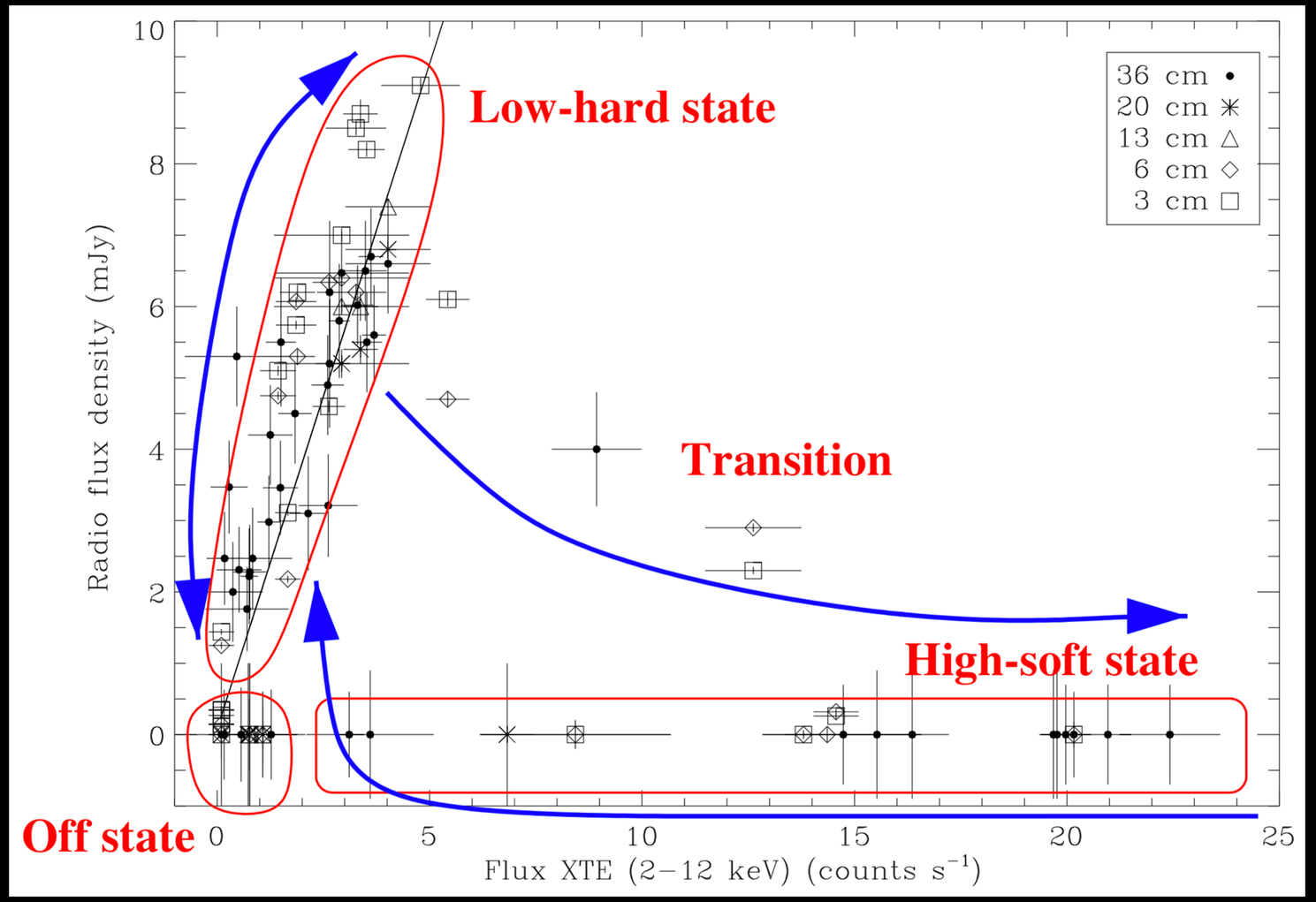




accretion states

Paradigm shift (just B.C.): XRBs as "microquasars"

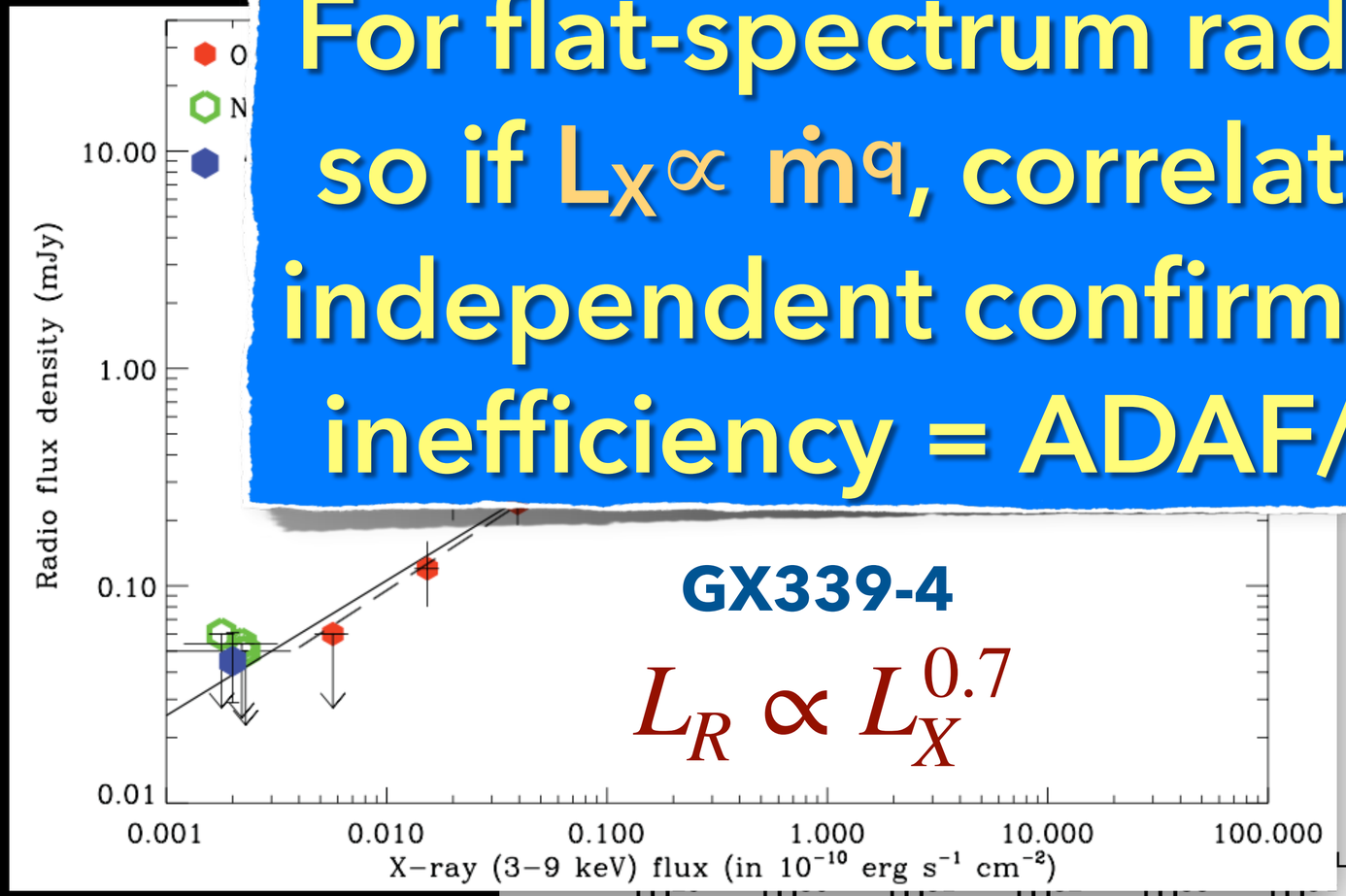




(Hannikainen++1998; Corbel++2000, radio + Xrays from RXTE)

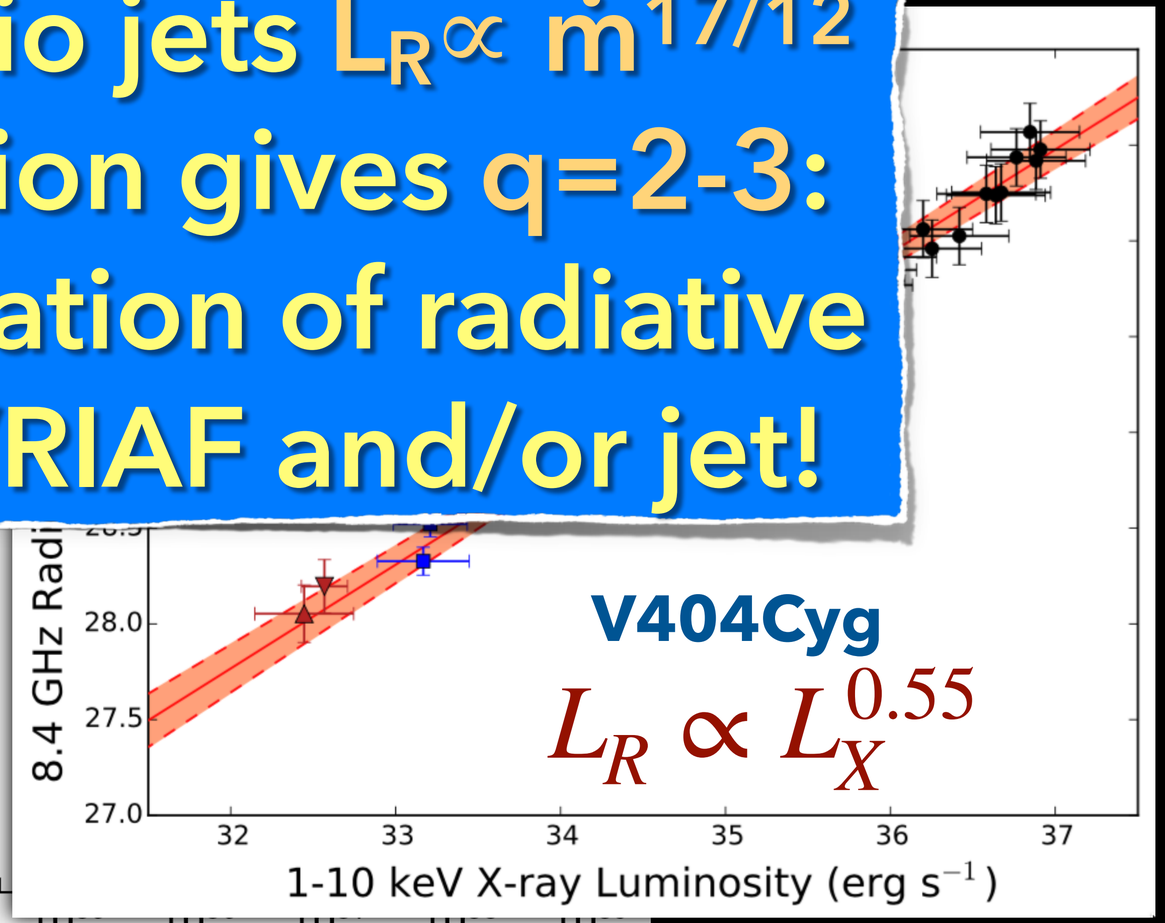
Chandra covers 8 $\mathcal{O}$ of magnitude in inflow/outflow coupling

For flat-spectrum radio jets $L_R \propto \dot{m}^{17/12}$ so if $L_X \propto \dot{m}^q$, correlation gives q=2-3: independent confirmation of radiative inefficiency = ADAF/RIAF and/or jet!



GX339-4

$$L_R \propto L_X^{0.7}$$

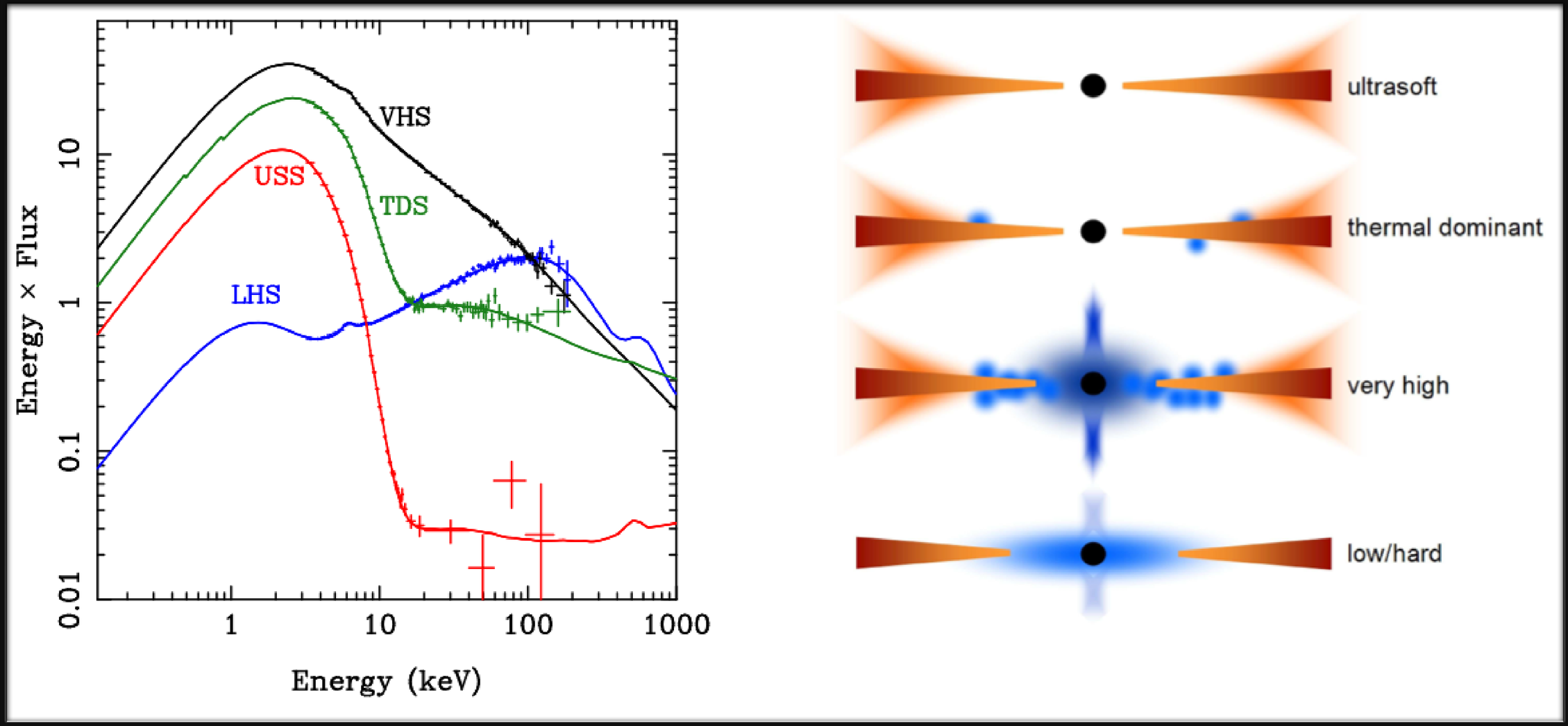


V404Cyg

$$L_R \propto L_X^{0.55}$$

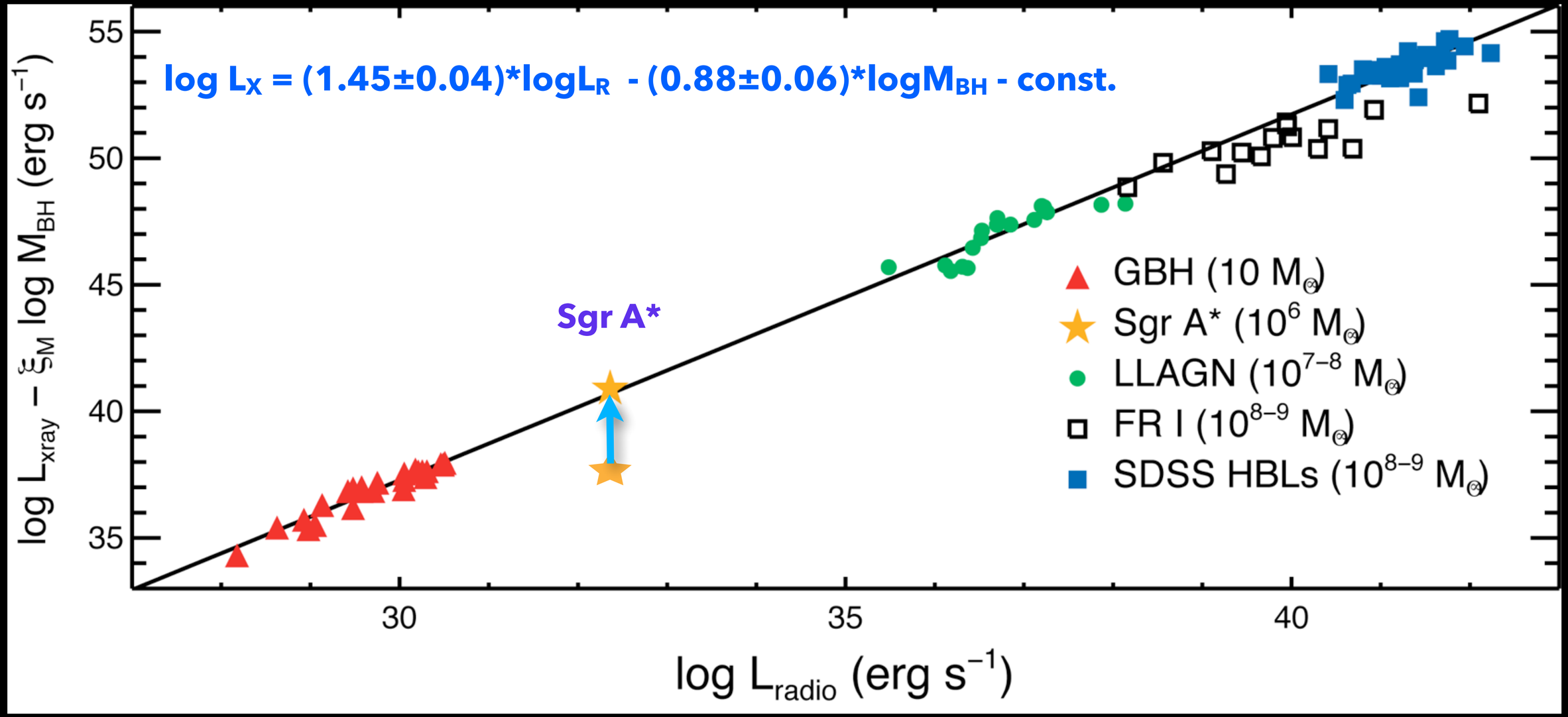
(SM++01,03,05; Corbel++2008; Hynes++2009; Corbel++2013; Rana++2016, Plotkin++2016, Bahramanian++ 2018)

Paradigm shift: jets dynamically important in state transitions



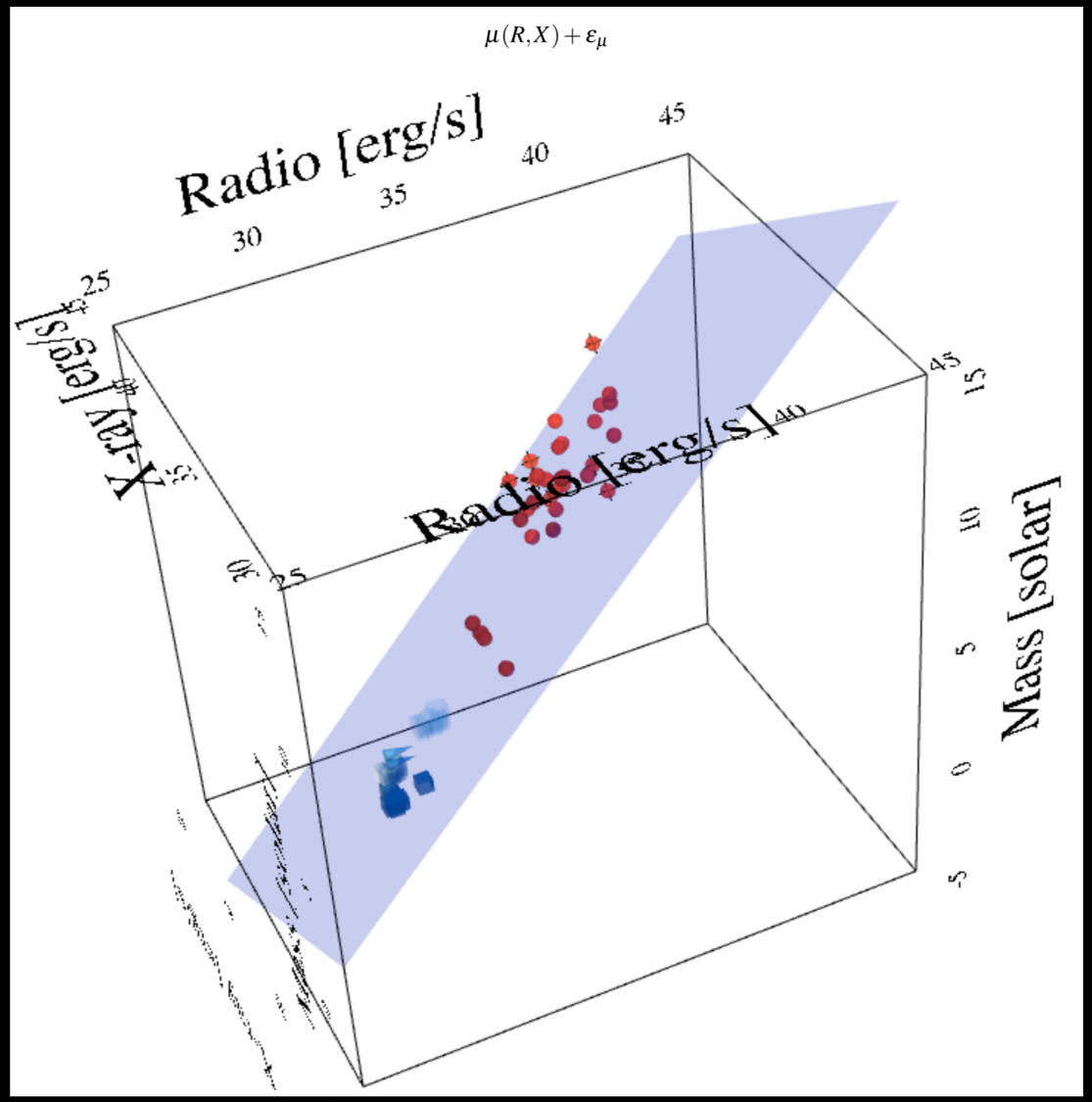
(Done, Gierlinski & Kubota 2007)

The Fundamental Plane of Black Hole Accretion



(SM++ 03; Heinz & Sunyaev 03; Merloni, Heinz & diMatteo 03; Falcke, Körding & SM 04; SM 05; Körding++06; Plotkin, SM ++ 12)

The Fundamental Plane as a (rough) BH mass estimator

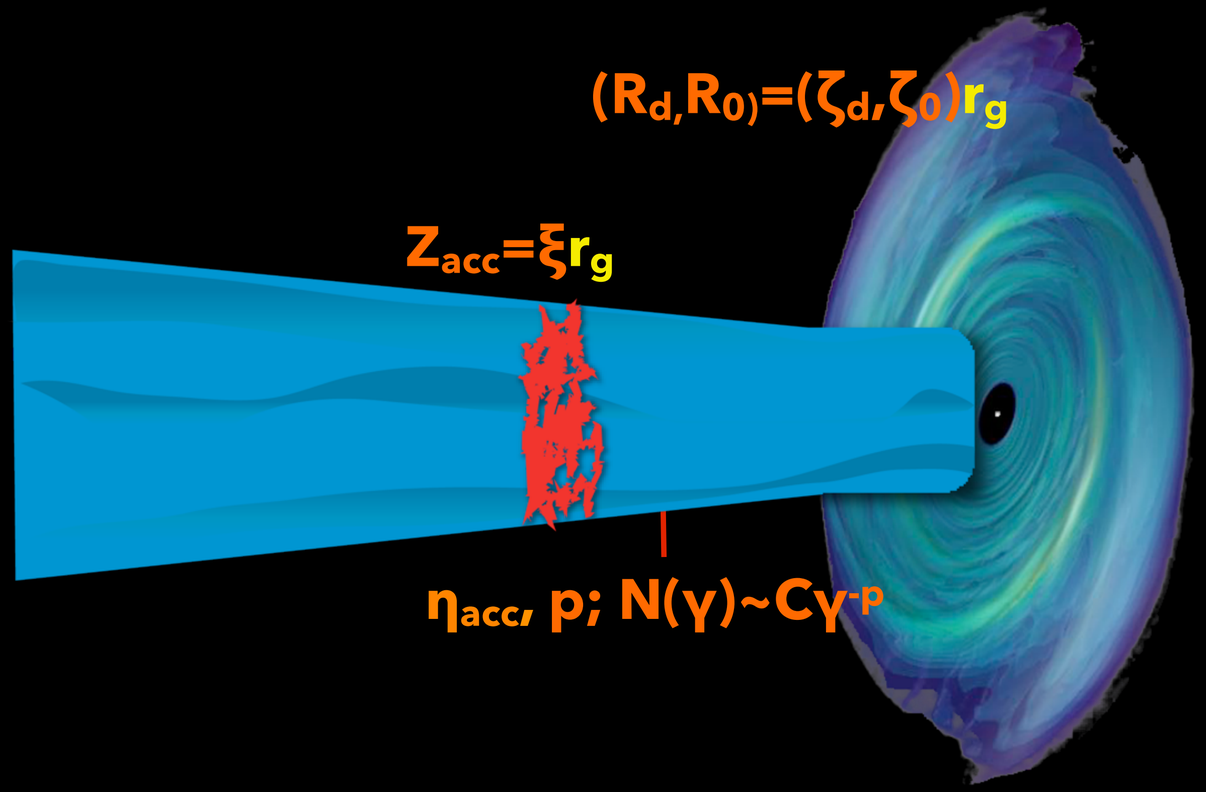


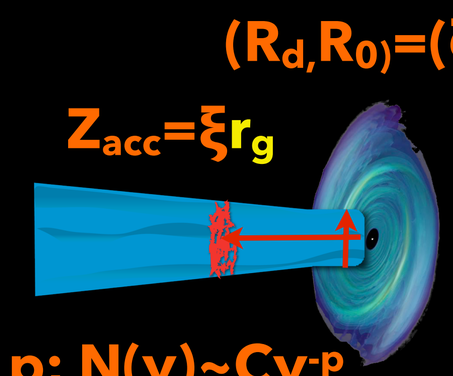
$$\log M = 0.55 \pm 0.22 + (1.09 \pm 0.10)\log L_R + (-0.59^{+0.16}_{-0.15})\log L_X$$

"…there is substantial intrinsic scatter ….This makes it a relatively crude tool for black hole-mass estimation, *but if it is the only tool available, it will be the best tool available.*"
–Kayhan Gültekin ++ 2019

(Sample w/ only well-determined dynamical masses and Chandra measurements of the X-ray to isolate the core; Gültekin++19)

Mass scaling: "self-similar" models

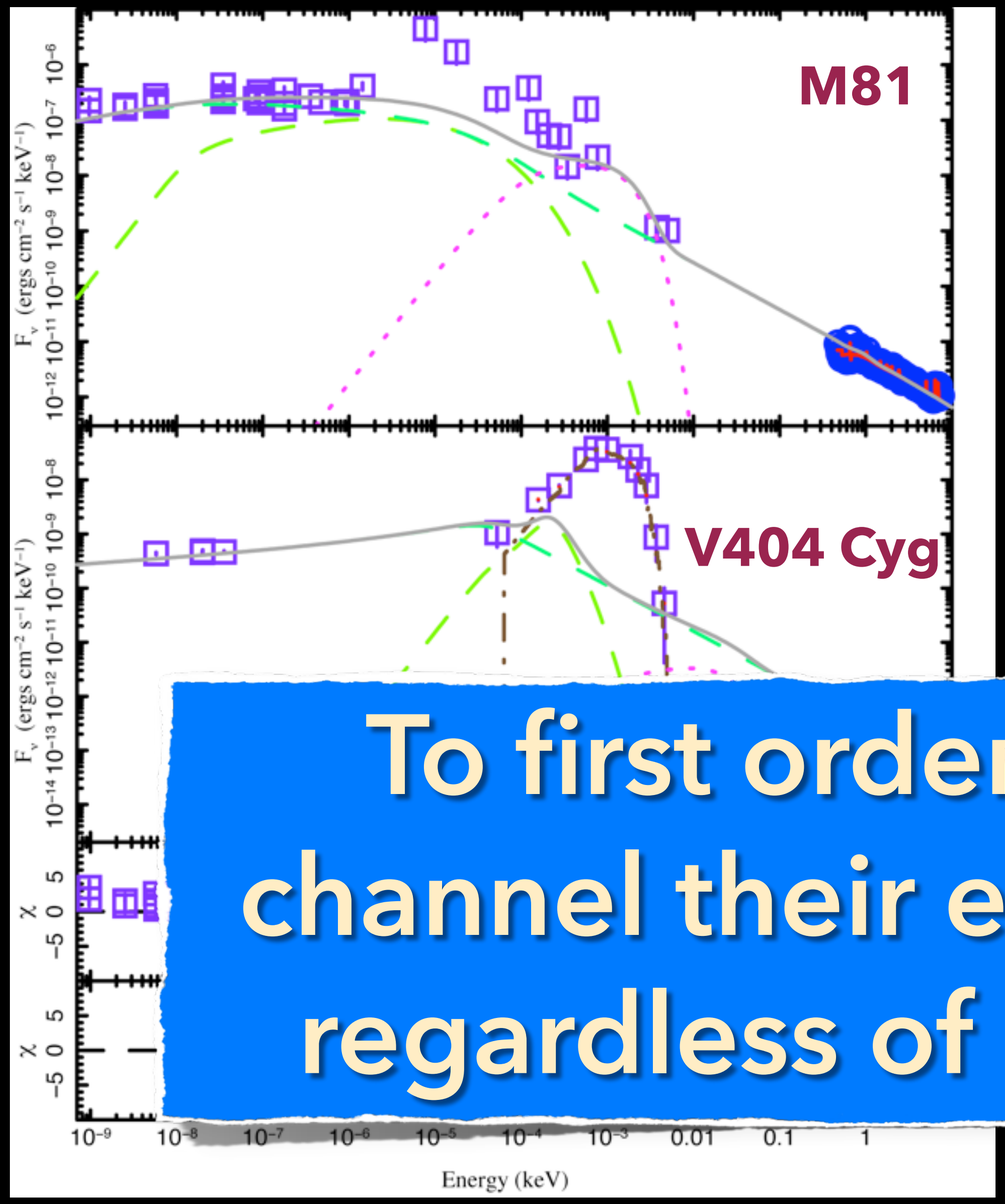


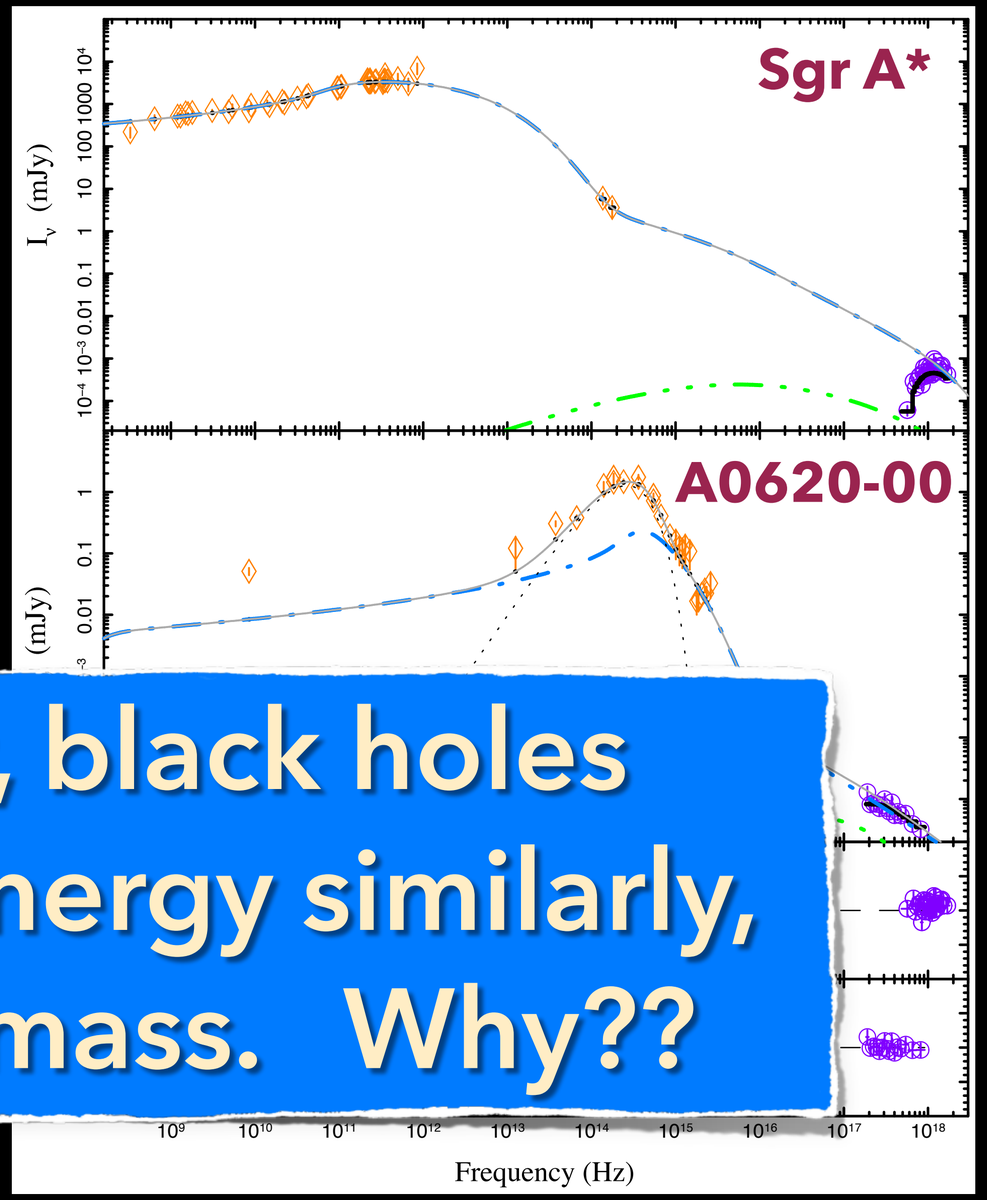


T_d, T_e, η_{acc}
vary with mass/size

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

Quasi-simultaneous Chandra + MWL: joint fits across $10^{6\text{-}7}$ in mass

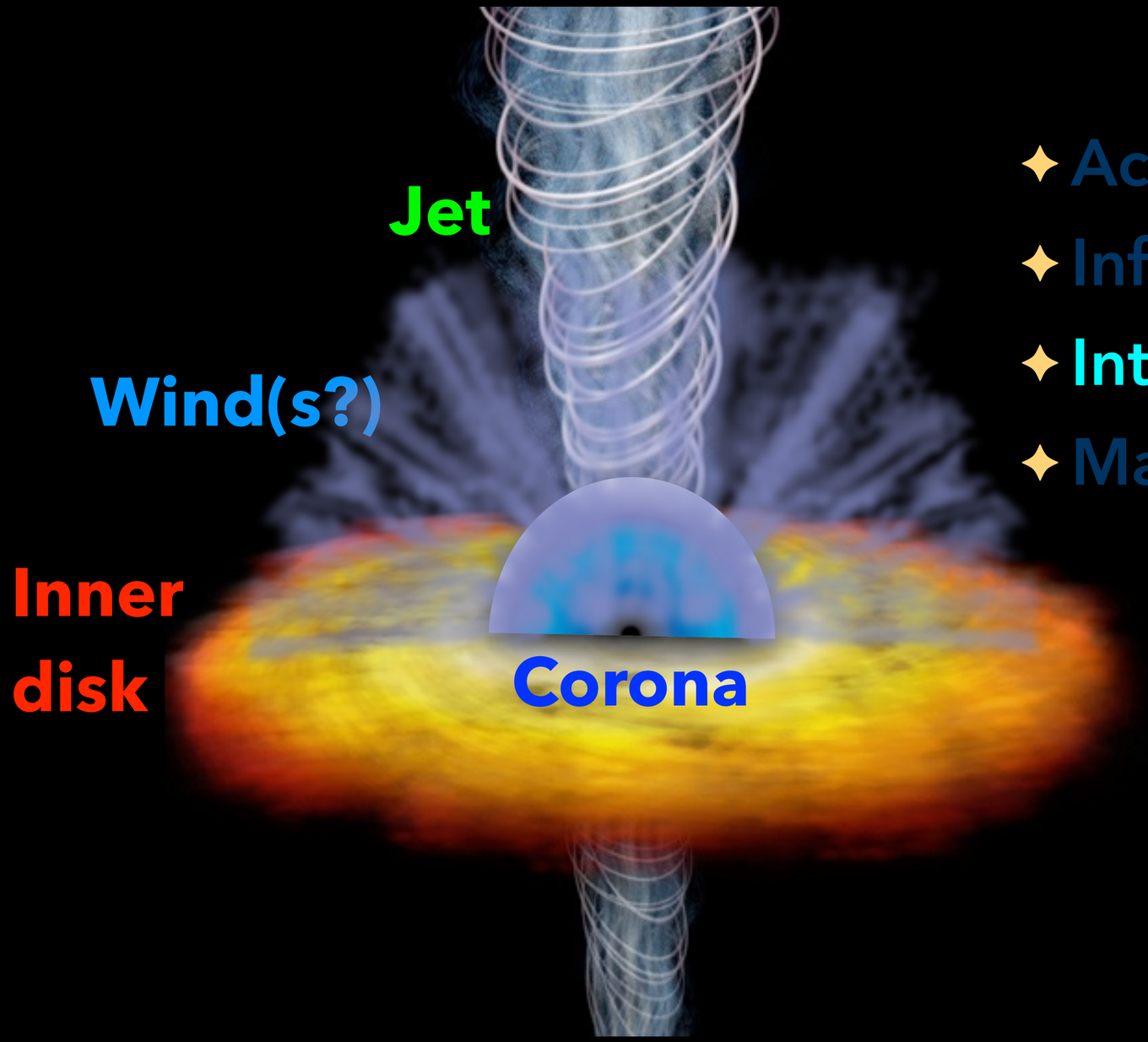




To first order, black holes channel their energy similarly, regardless of mass. Why??

(SM, Nowak++2008; SM, Nowak++ 2015; Connors, SM, Nowak++2017)

Schematic of inner ~100 R_g accretion "engine"



- Accretion from R_{Bondi} to R_g
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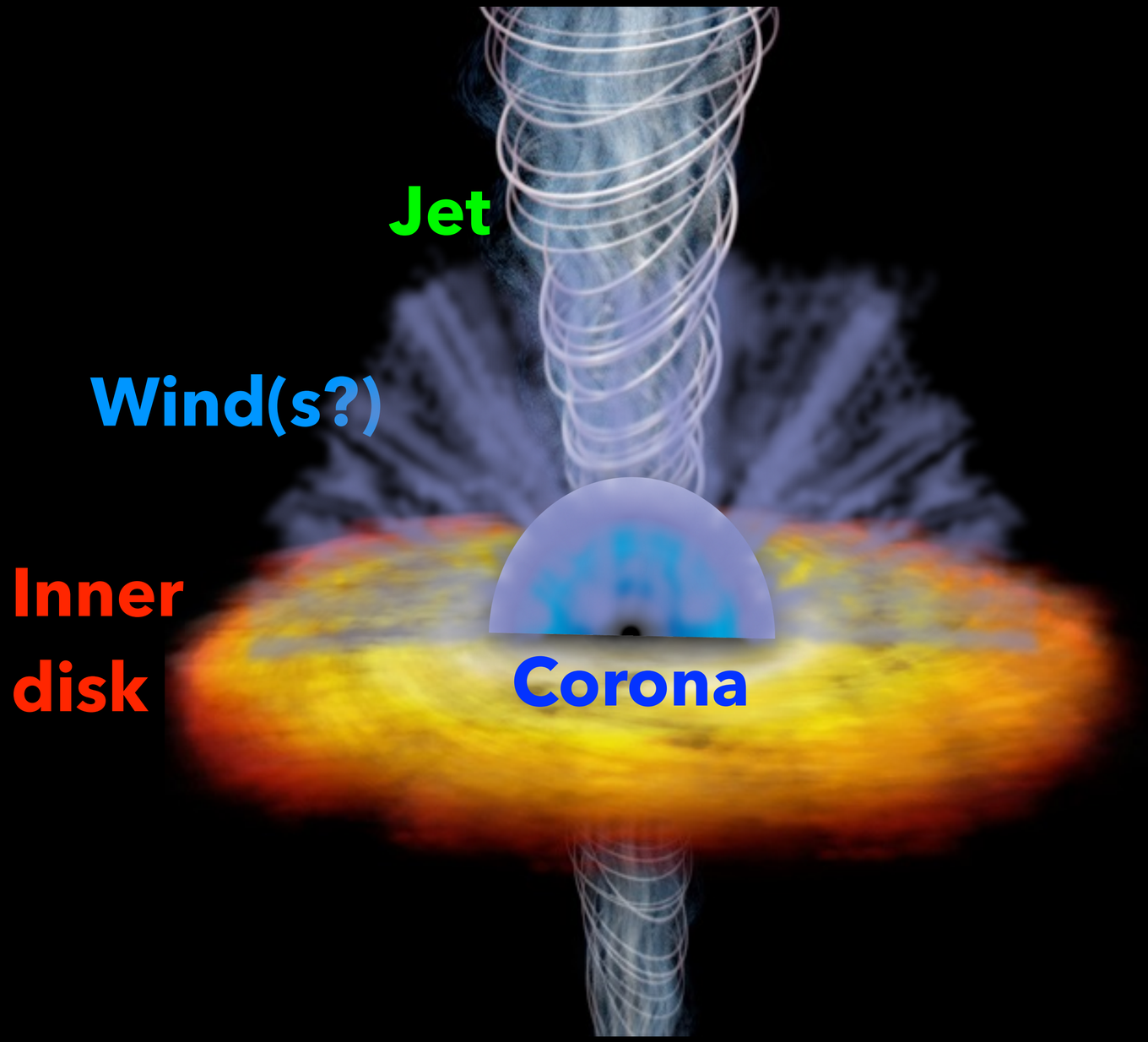
Many open questions for modeling "central engine"



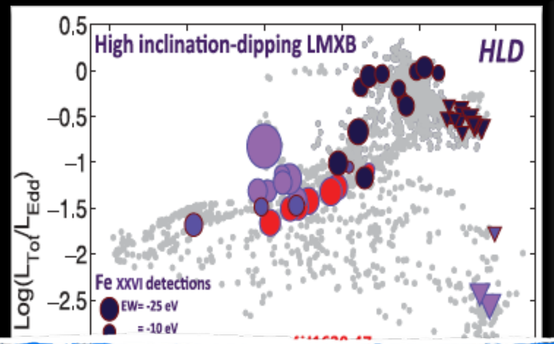
Mapping these components to SED still degenerate/unclear:

- Corona =? = ADAF/RIAF =? = jet base??
- Are winds related to disk or outer part of jets?

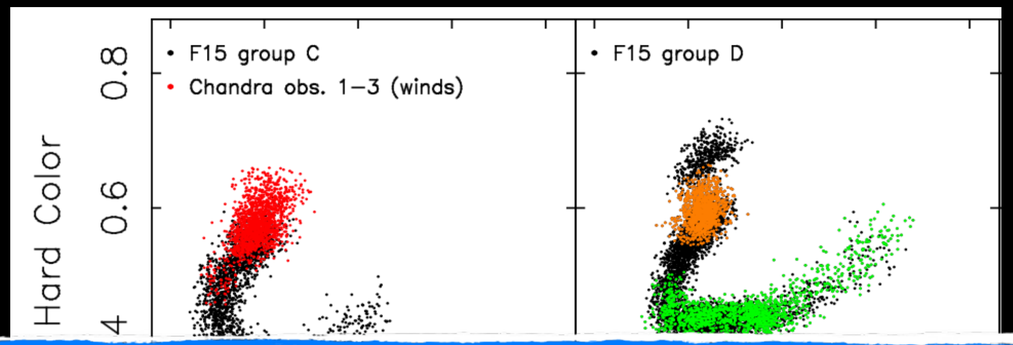
Wind/jet relationship: dichotomy or coexistence?

"Winds present only when jets are absent" (via mass depletion; Neilsen & Lee 2009)

Yep:



Hmm, but theory predicts

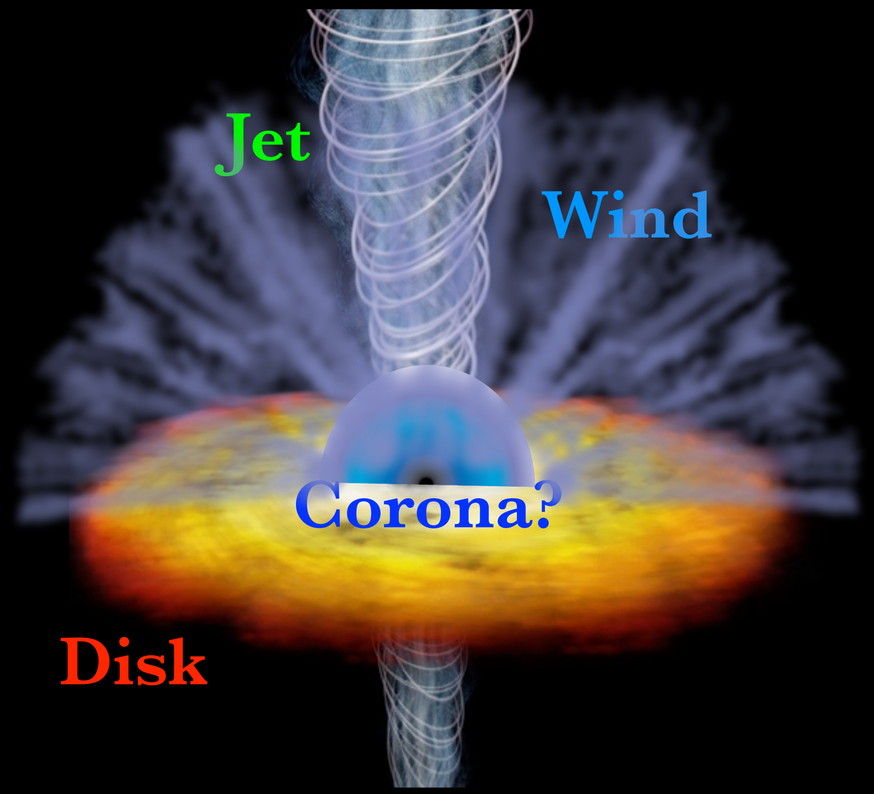


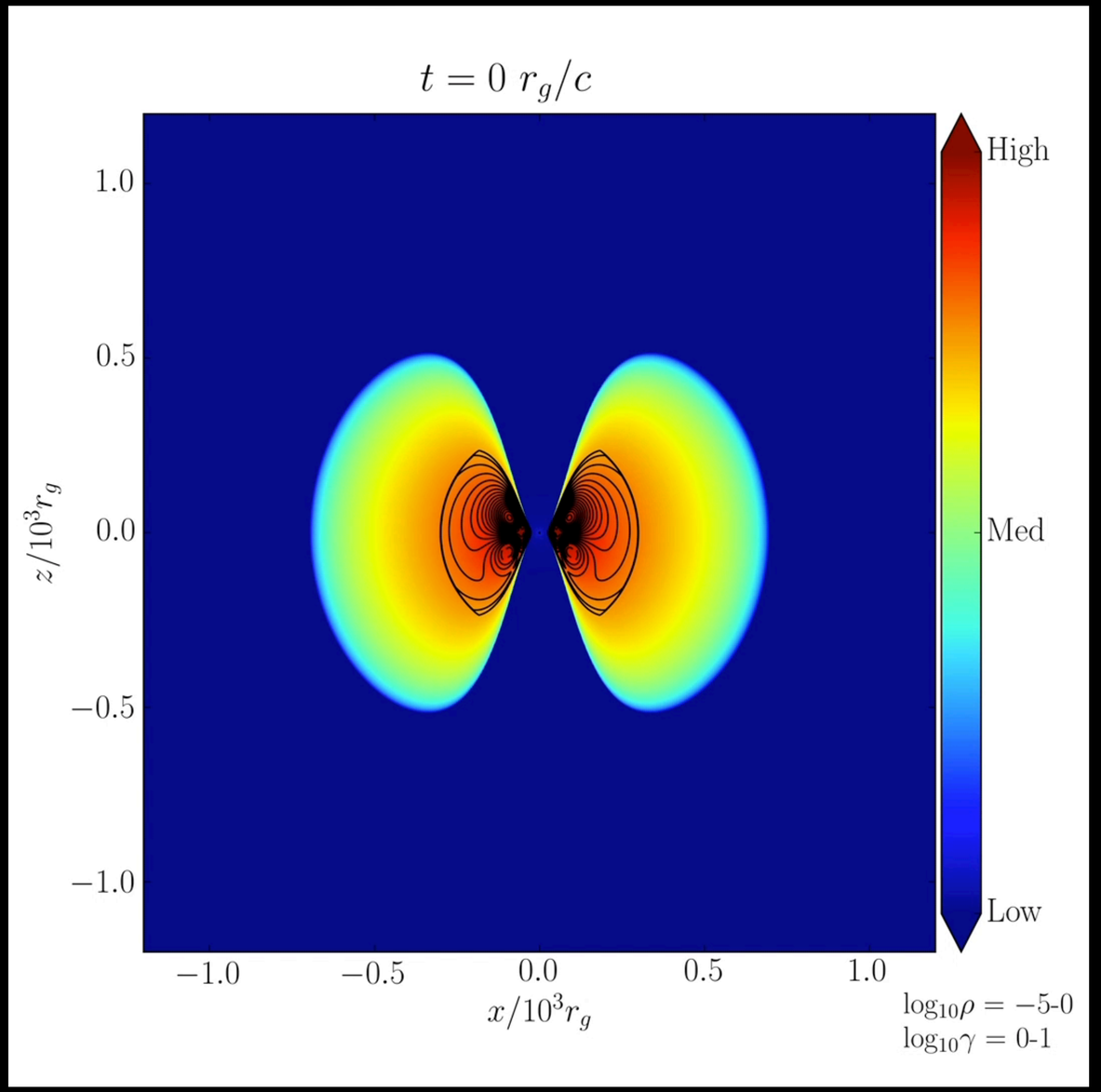
Connection to jets depends on driving mechanism (still debated): radiative/thermal (e.g., Higginbottom & Proga 15; Tomaru++19) vs. MHD (e.g. Chakravorty++16)

- Winds carry away a lot of mass (e.g., Neilsen++11; 16)
- Normally seen after jets vanish (e.g., Miller+ +08; Neilsen & Lee 09; Ponti++12;)
- Winds disappear before jets appear (e.g. Diaz Trigo++14; Gatuzz++19)

- Winds (X-ray) and radio flare/jet (e.g. Lee+ +02; Kalemci++16)
- Winds (optical) and radio jets (e.g. Wu++01, Rahoui++14, Munoz-Darias++19)
- Low ionisation X-ray absorption in hard states of XRBs (Diaz Trigo++06, Shidatsu 13)

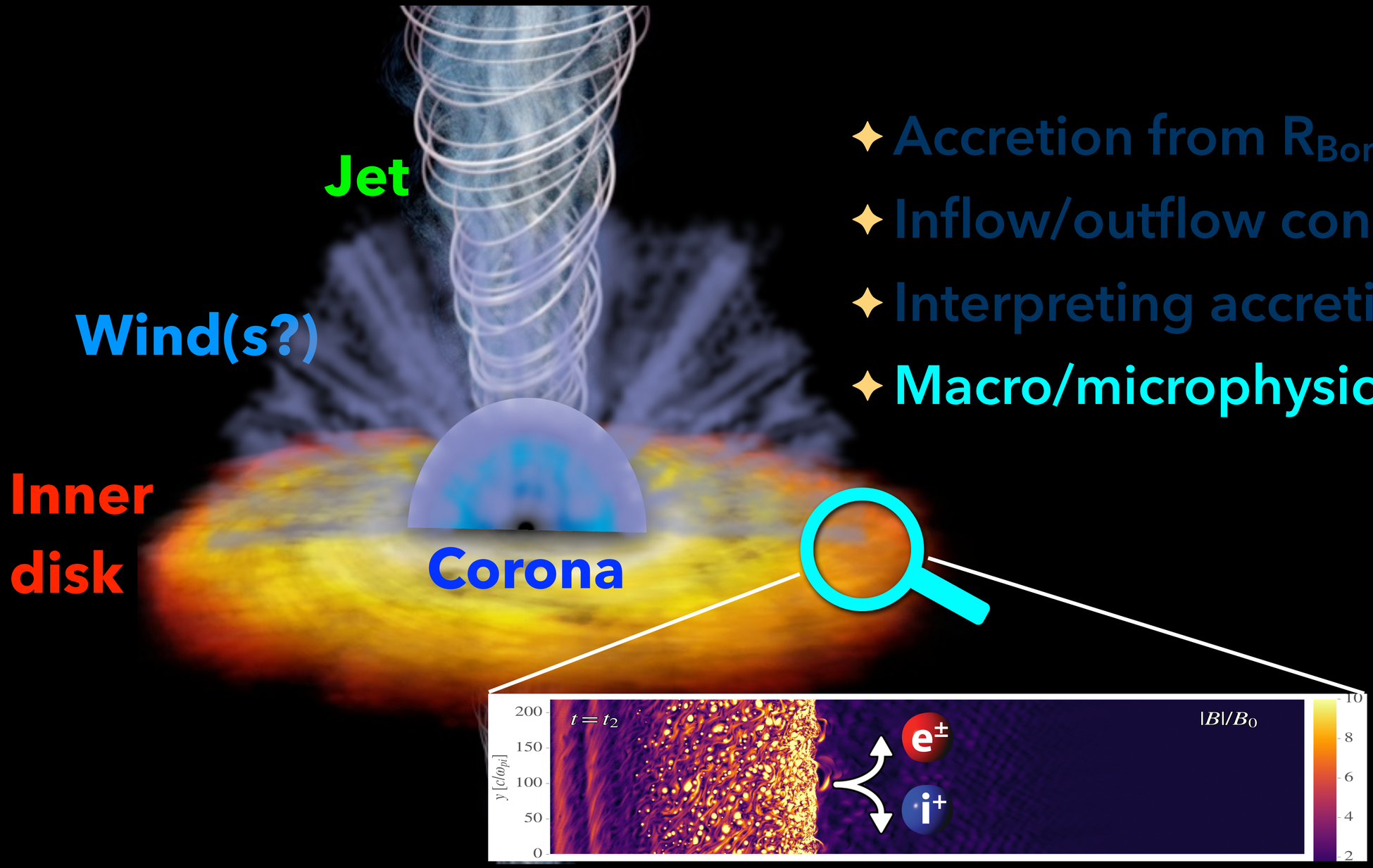
Does the old phenomenology still make sense??





(2D 6000x800x1 resolution with H-AMR: Chatterjee, Liska, Tchekhovskoy & SM 2019)

Schematic of inner ~100 R_g accretion "engine"



- Accretion from R_{Bondi} to R_g
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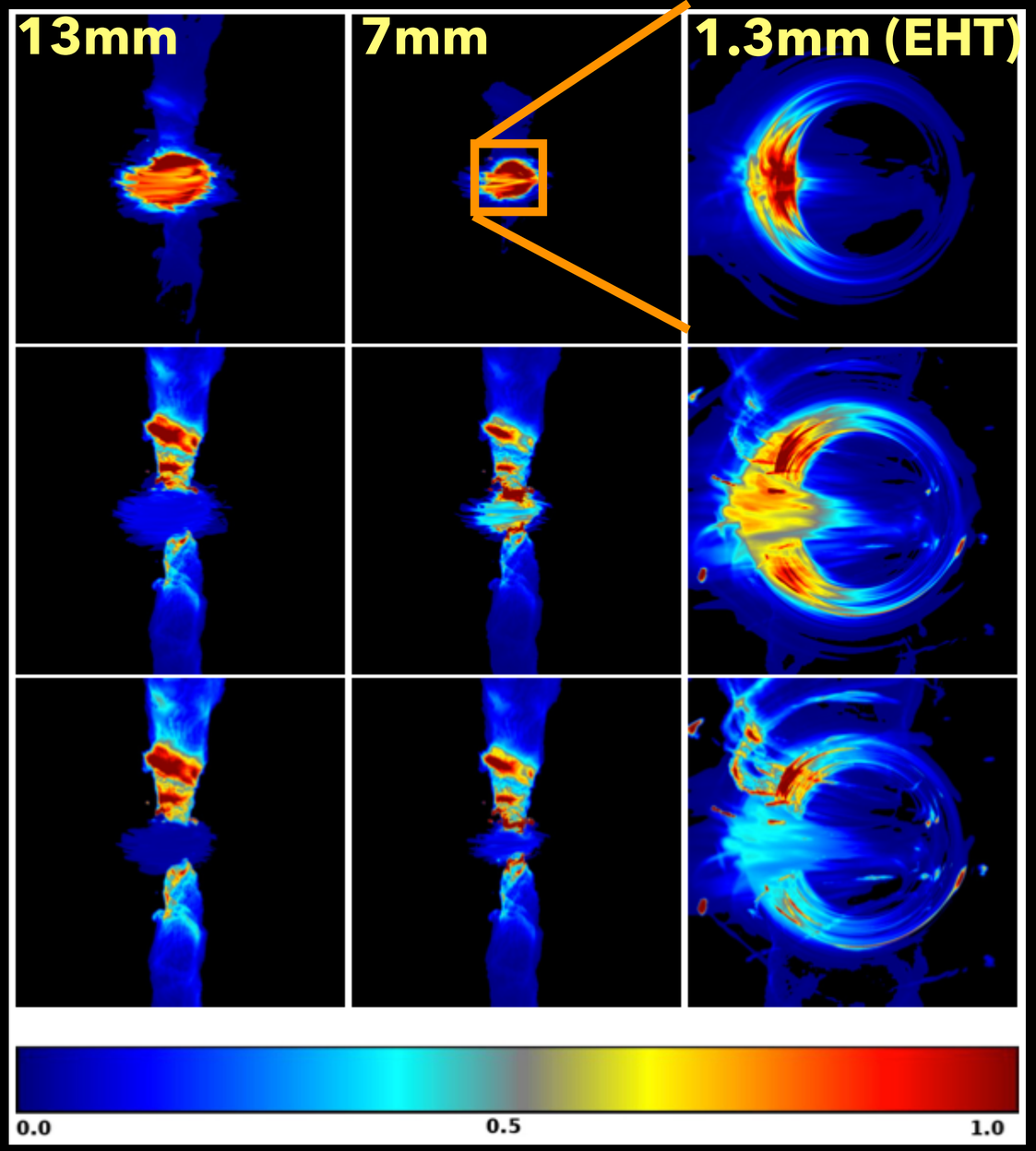
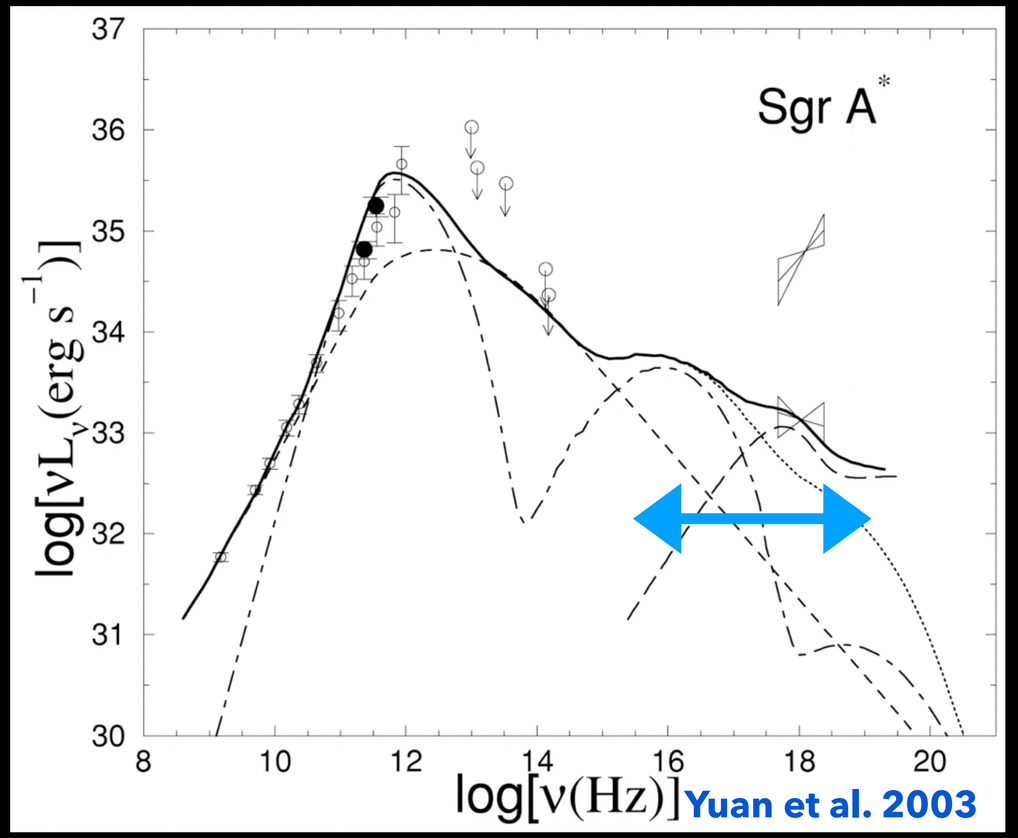
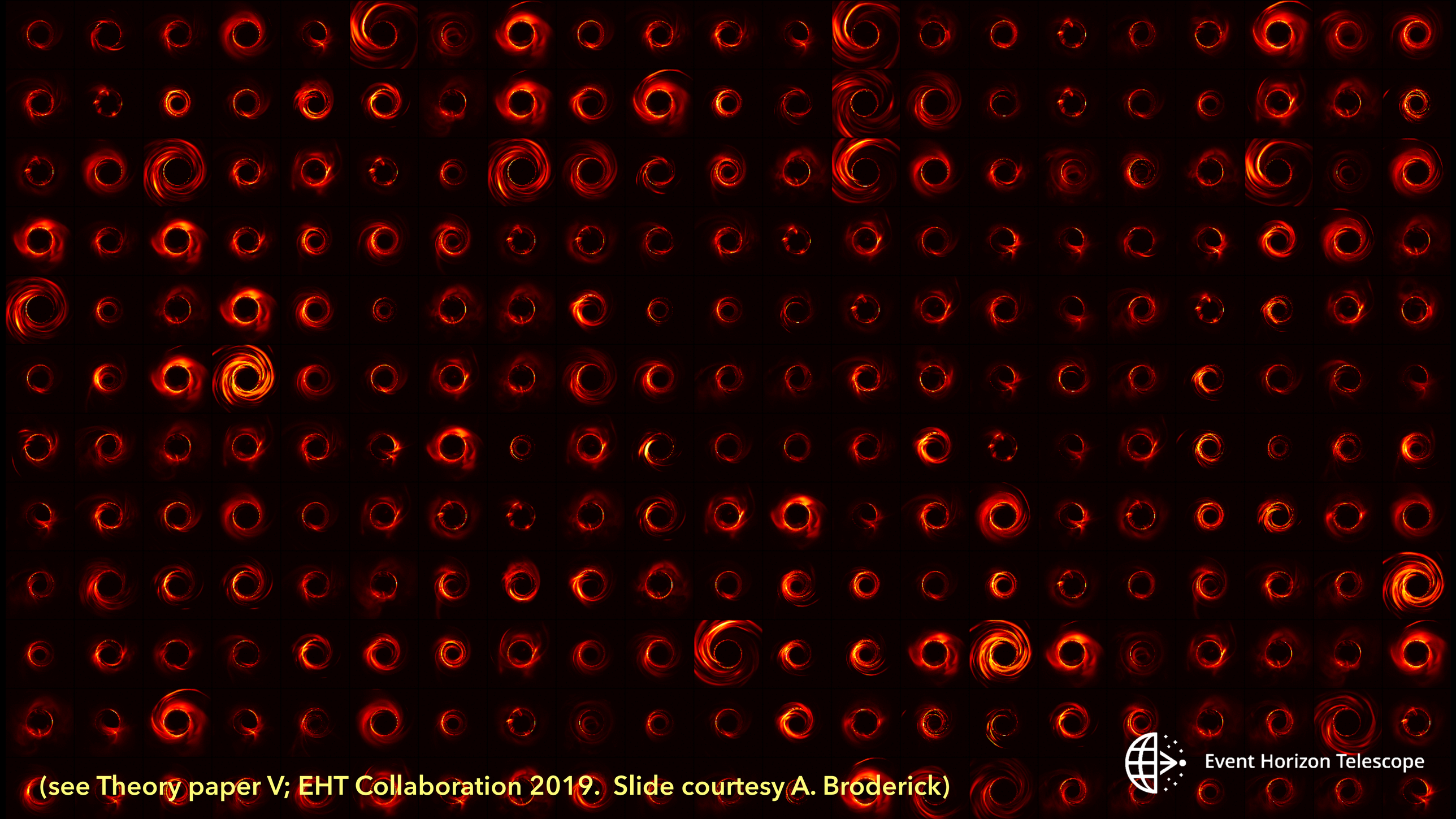
- Macro/microphysics connection

Illustration of degeneracy introduced by 'adding' electrons = light





(Moscibrodzka, Falcke, Shiokawa & Gammie 2014; see also Ressler++15,17; Chael++18; Ryan++18)



(see Theory paper V; EHT Collaboration 2019. Slide courtesy A. Broderick)

Event Horizon Telescope

Chandra crucial … M87, SgrA*,++)

- Jet power estimat… …ra, Russell, Rafferty, Stawarz,++) on lar…
- Fits to Chandra-iso… …nd total power P_{jet} < few x 10^{43} erg/s (L…
- Conservative const… …ons, *including all spin=0 models!* (p…
- Only high-spin (a~… …d; MAD) survive
- Simultaneous *Char*… …4.4 ± 0.1) × 10^{40} erg/s, used to rule… …t flux
- X-ray data not yet … …ation codes develop, Chandra … …odel space

(Paper V; EHT Collaboration 2019)

Table 2. Rejection Table

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
SANE	-0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	-0.94	10	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	20	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	40	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	-0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	-0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	+0.94	160	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.94	1	Fail	Fail	Pass	Pass	Fail
MAD	-0.94	10	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	20	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	40	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	80	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	160	Fail	Pass	Pass	Pass	Fail
MAD	-0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	-0.5	10	Pass	Pass	Pass	Fail	Fail
MAD	-0.5	20	Pass	Pass	Pass	Pass	**Pass**

Table 2 *(continued)*

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
MAD	-0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	160	Pass	Pass	Pass	Pass	**Pass**

[1] flux: net magnetic flux on the black hole (MAD, SANE).

[2] a_*: dimensionless black hole spin.

[3] R_{high}: electron temperature parameter, see equation (8).

[4] Average Image Scoring (THEMIS-AIS), models are rejected if $p \leq 0.01$, see Section 4 and Table 1.

[5] ϵ: radiative efficiency, models are rejected if ϵ is larger than the corresponding thin disk efficiency, see Section 6.1.

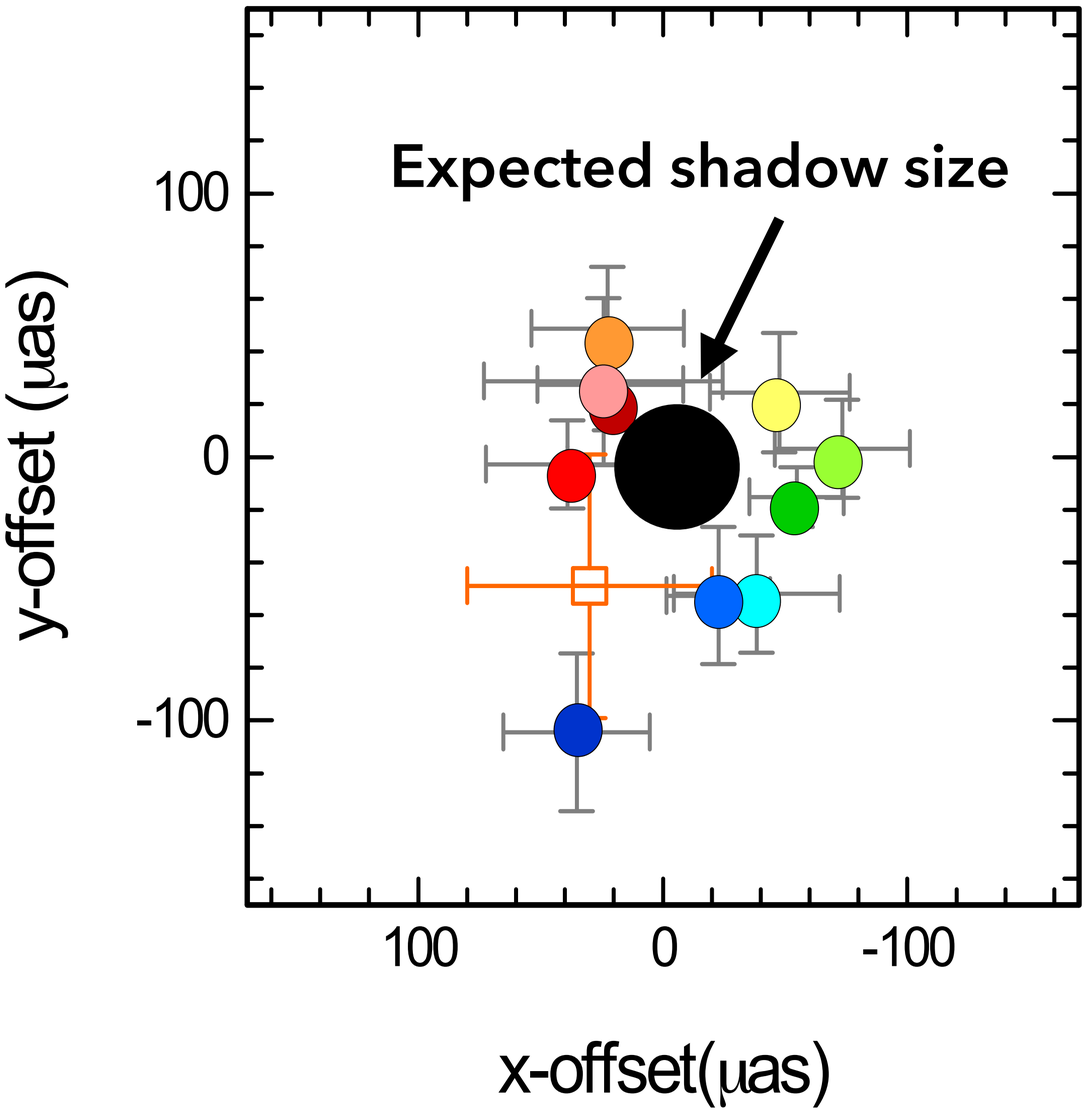
[6] L_X: X-ray luminosity; models are rejected if $\langle L_X \rangle 10^{-2\sigma} > 4.4 \times 10^{40}\,\mathrm{erg\,sec^{-1}}$. See Section 6.2.

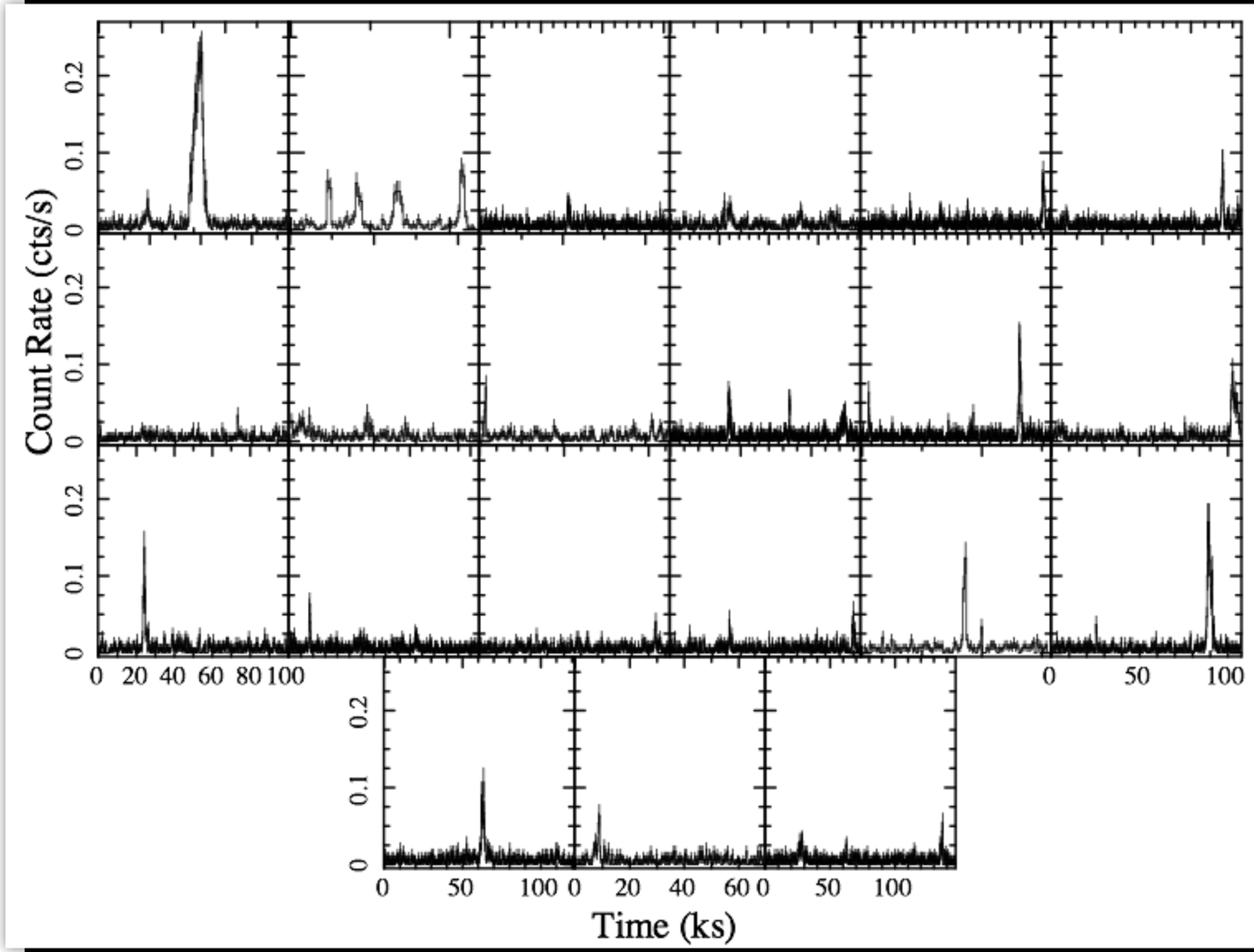
[7] P_{jet}: jet power, models are rejected if $P_{jet} \leq 10^{42}\,\mathrm{erg\,sec^{-1}}$, see Section 6.3.

7. DISCUSSION

We have interpreted the EHT2017 data using a limited library of models with attendant limitations. Many of the limitations stem from the GRMHD model, which treats the plasma as an ideal fluid governed by equations that encode conservation laws for particle number, momentum, and energy. The eDF, in particular, is de-

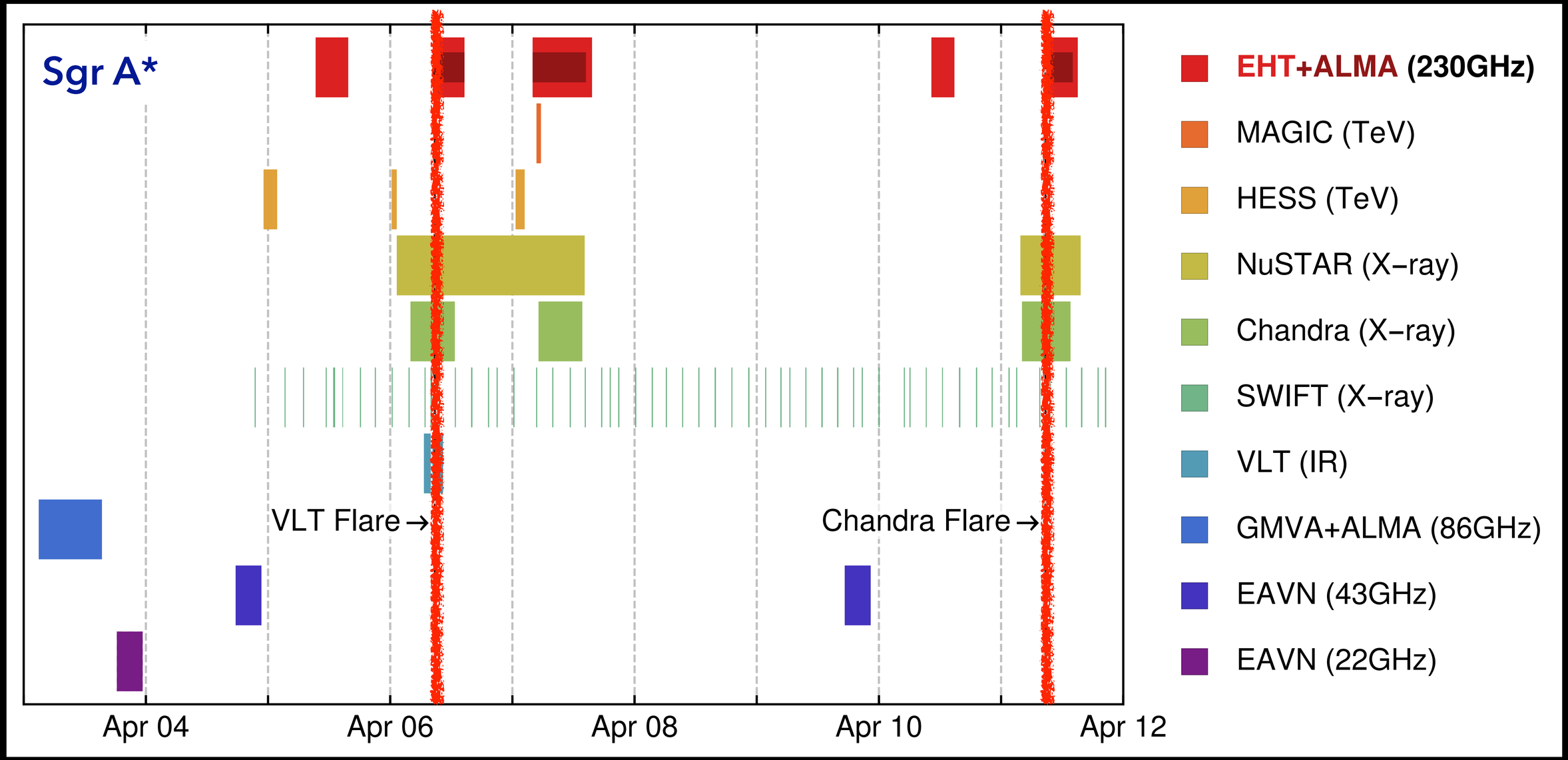
Sgr A*: EHT + Chandra + GRAVITY in 2020!!





(GRAVITY++2018) (Dodds-Eden 2009; Witzel++ 2012; 18; Nielsen++ 2013, Nielsen, SM++ 2015; Nielsen++2016; Haggard++2019)

Thank you Belinda and Chandra scheduling team!!!

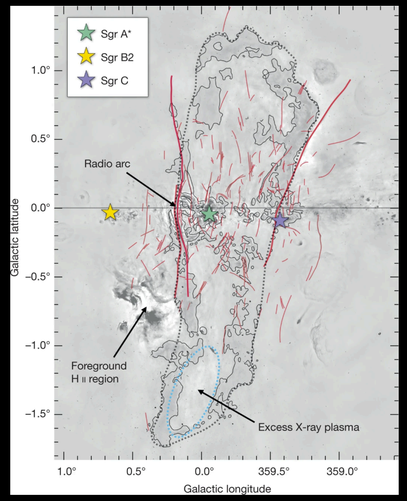


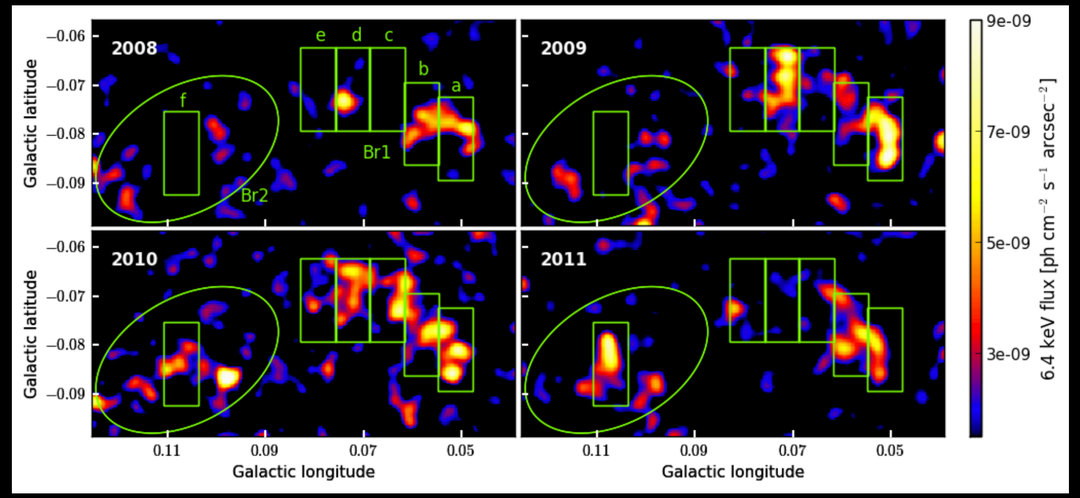
(J. Farah, M. Johnson, for EHT MWL WG)

Frontiers for the coming decade(s)

- Chandra + MWL + EHT + GRMHD/PIC: capture the full dynamical range of processes from particle acceleration to kpc scale jets
- BH spin/power, regulation of winds vs jets, activity duty cycles
- Polarization and pair/hadronic content

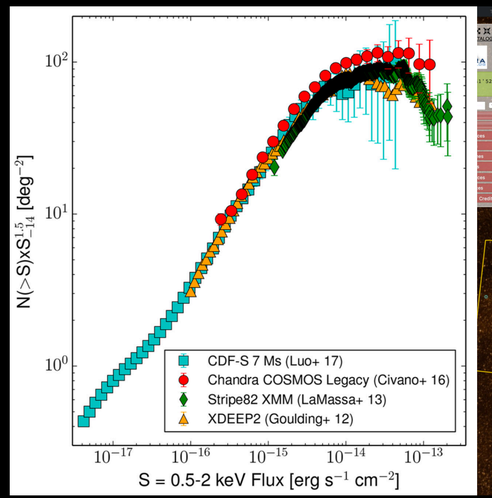
Accurate model of Sgr A*'s past activity ⇔ M87

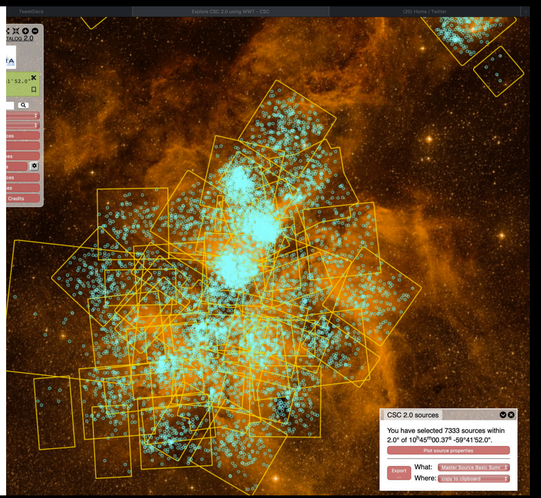




(MeerKAT radio bubbles; Heywood++2019 + X-ray reflection "waves": Muno++, Ponti++, Clavel++)

Populations ⇔ BH Feedback



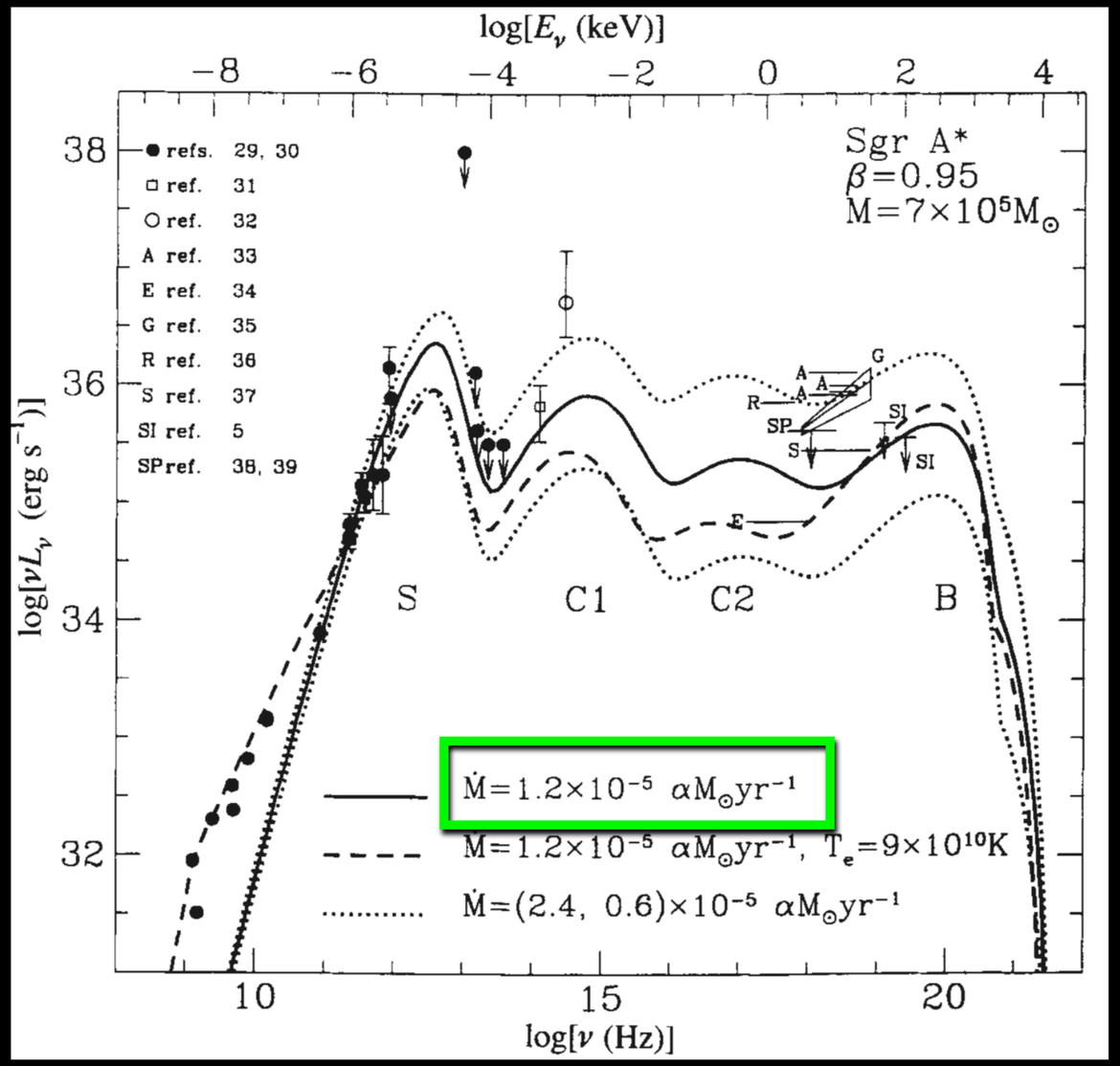


CSC++, Civano++2016; e.g., Wednesday's talks, Cooper, Gaggero, SM & Zhang, subm.

Thanks to Chandra we have…

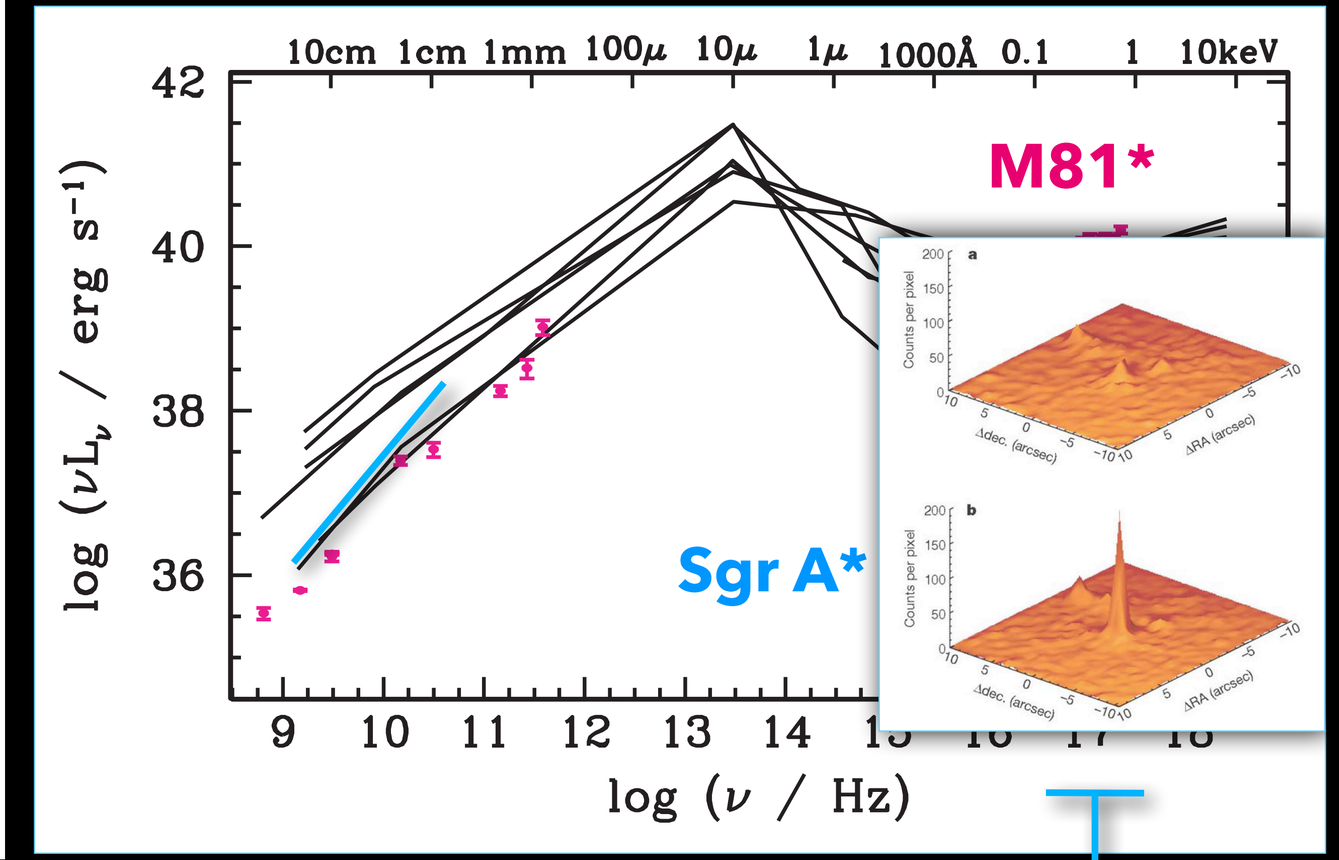
- …revolutionised our understanding of the dominant, state of black hole accretion in the Universe (and the radio/mechanical feedback mode!!)
- …seen Sgr A* in the X-ray, including flares = major clue for microphysics of particle acceleration in hot, magnetized plasmas
- …resolved sub-Bondi accretion flows in nearby galaxies and their plasma properties ➠ major step towards complete picture of accretion, esp. w/ EHT!
- …, together with MWL, revealed 8 orders of dynamic range in inflow/outflow coupling in XRBs, quantitatively establishing XRBs as AGN analogs (FP)
- …better population/evolution models ➠ paves way for accurate cosmological ‘calibration' of black hole growth and influence on all scales

Chandra confirmed ‘advective/inefficient’ accretion flows



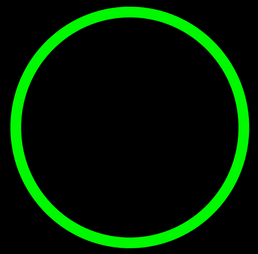
(Narayan & Yi 94; 95)

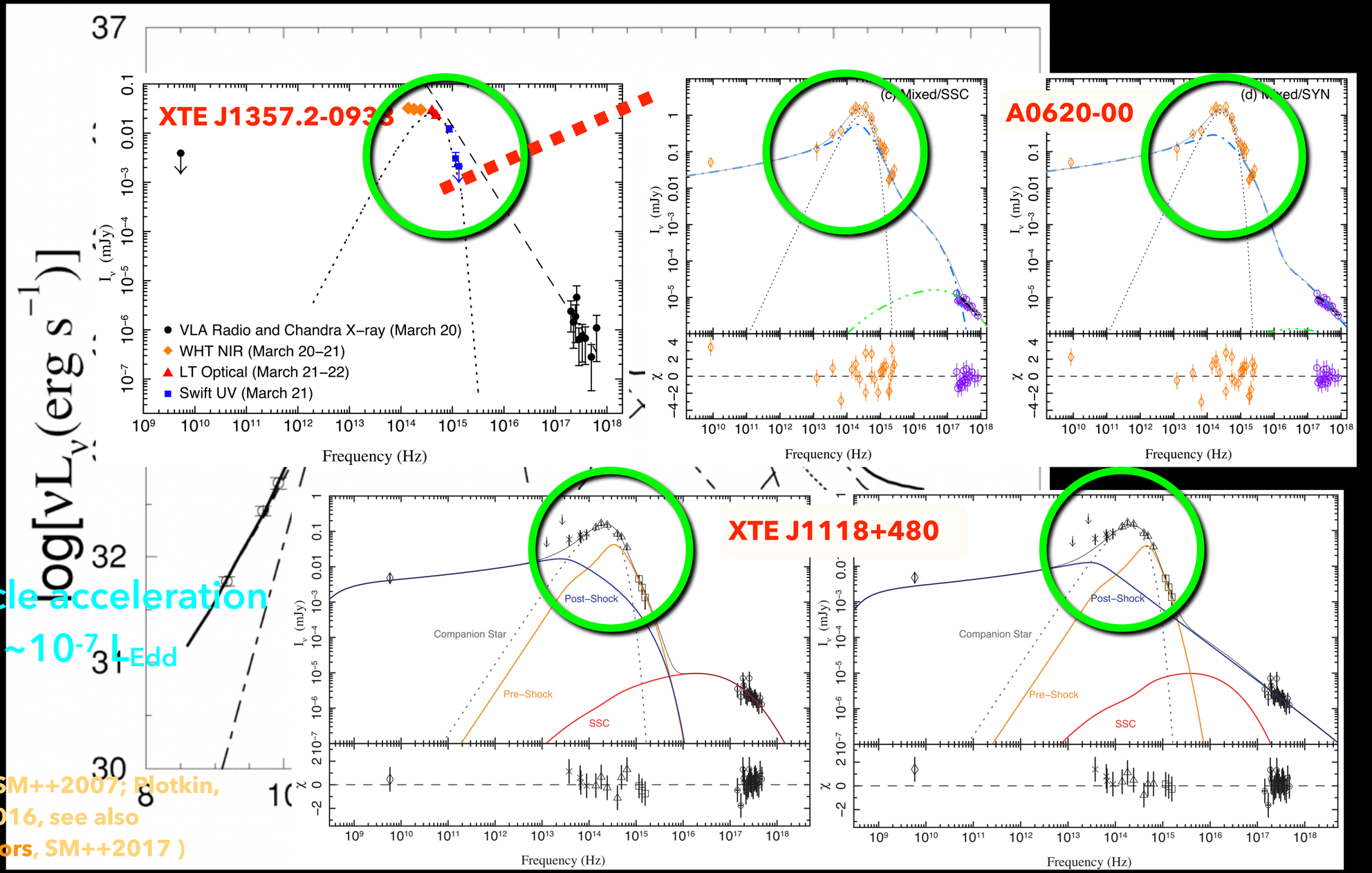
Chandra reveals low-luminosity AGN:



(Ho++ 99, Baganoff++ 01; 03; SM, Nowak++ 08)

Evidence for a thermal ‘corona’ from low accretion rate sources

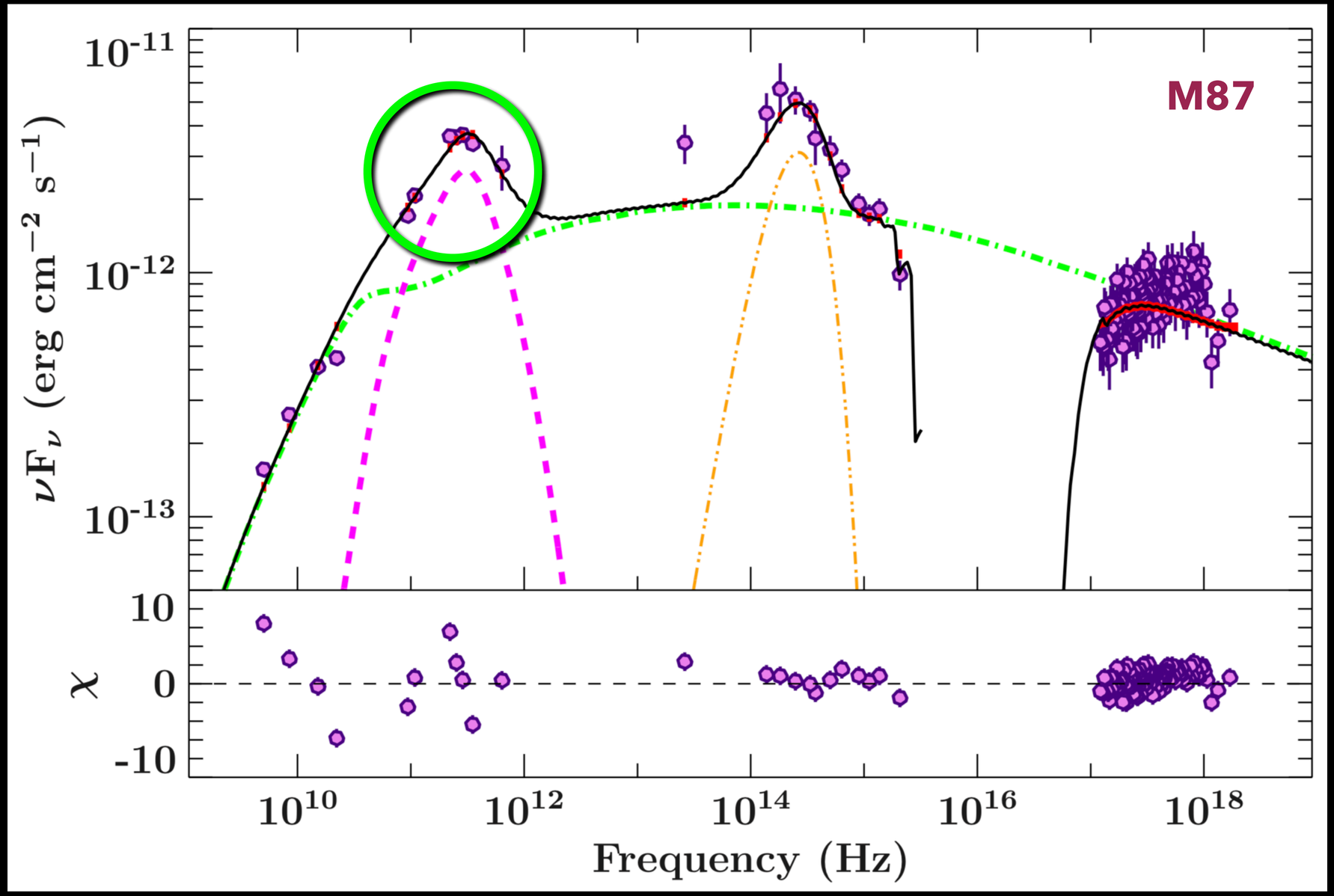




General trend: particle acceleration fizzles below $L_x \sim 10^{-7} L_{Edd}$

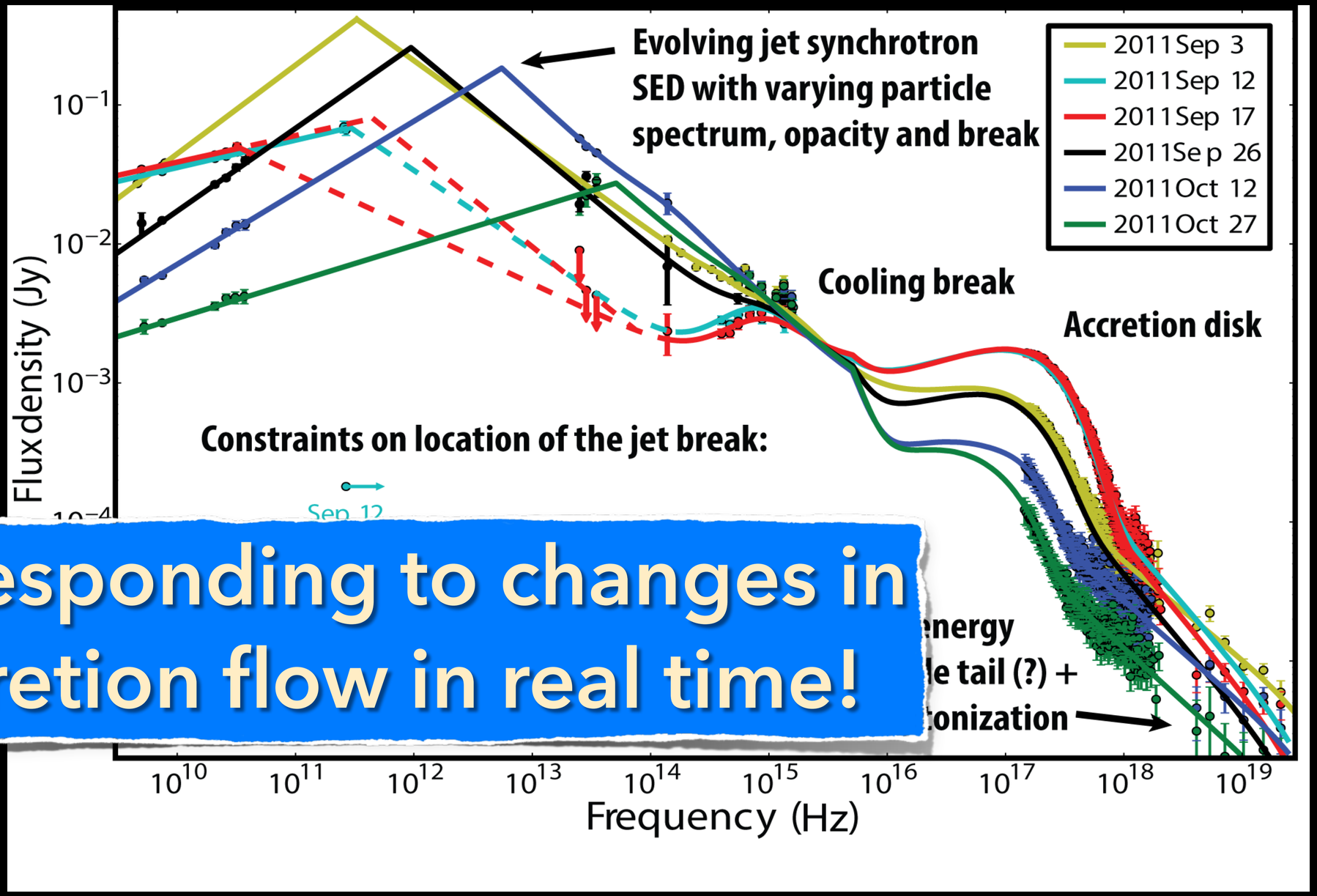
(Yuan++2003; Gallo, Migliari, SM++2007; Plotkin, Gallo, SM++2015; Plotkin++2016, see also Shahbaz & Russell 2013; Connors, SM++2017)

Also M87: something we can test with EHT?



(Prieto, Fernandez-Ontiveros, SM & Espada 2016; Lucchini, Krauss & SM 2019)

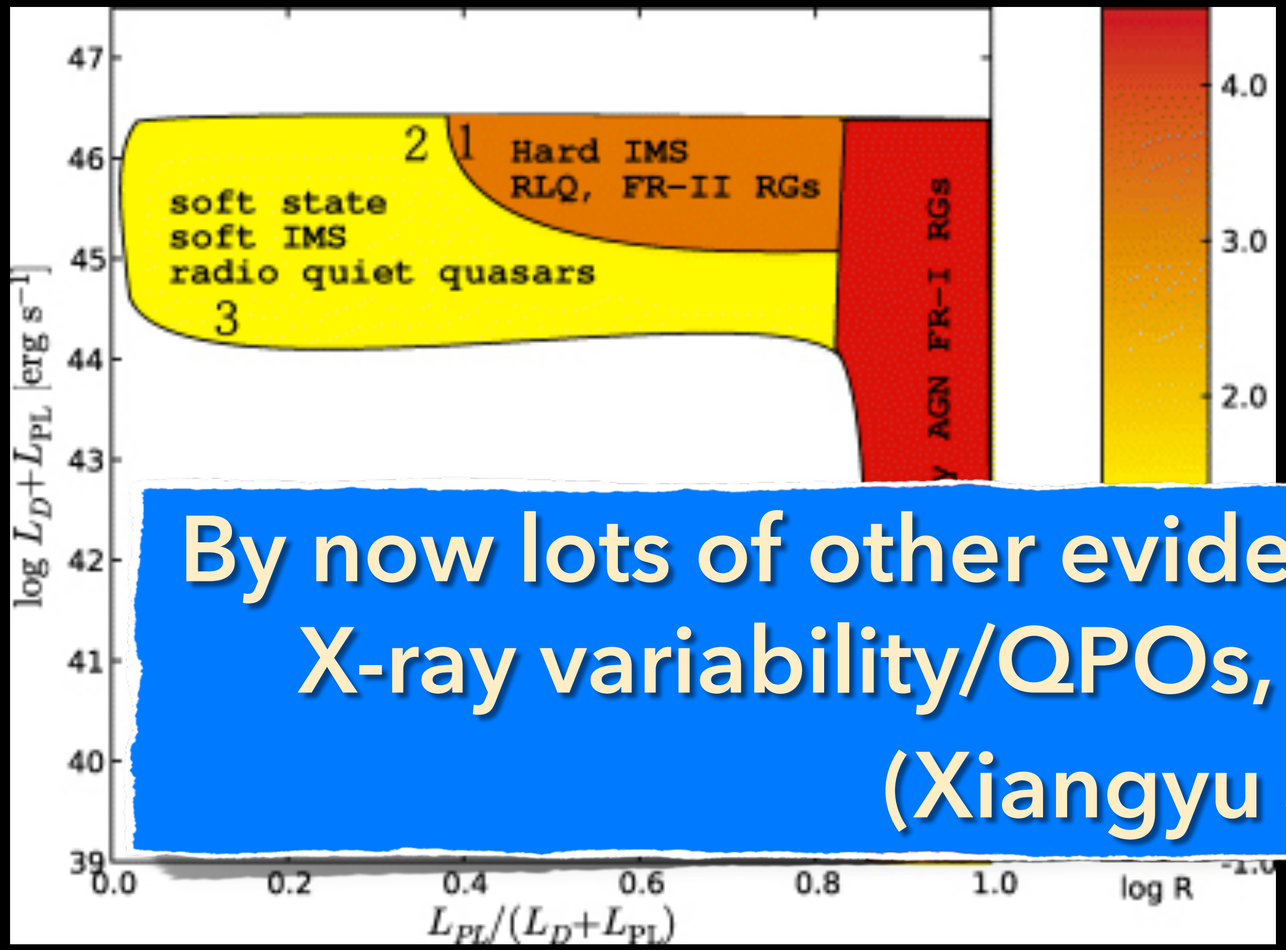
"Next gen" XRB monitoring campaigns: MAXI J1836-194

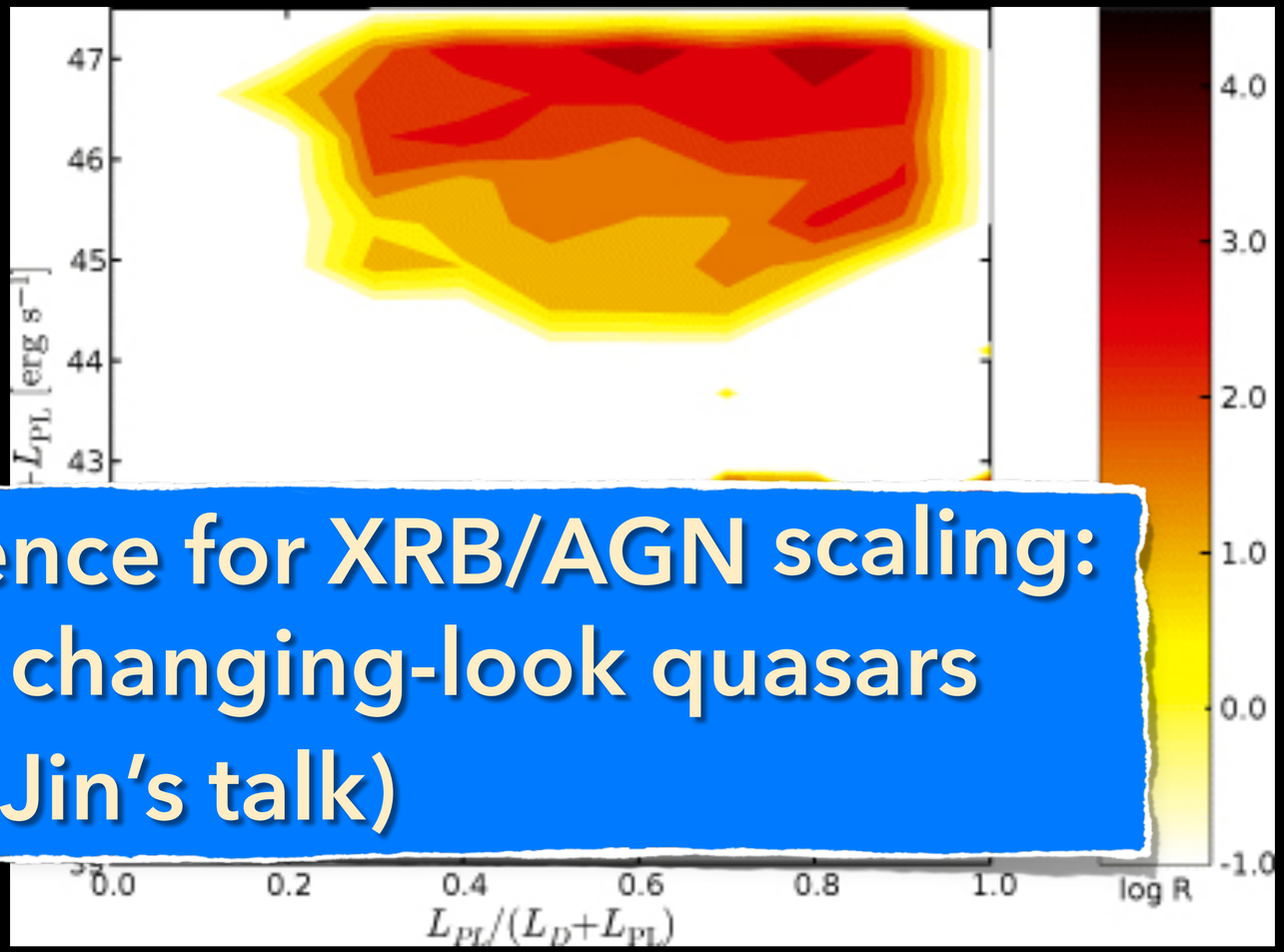


Jet responding to changes in accretion flow in real time!

(TRussell, Miller-Jones,++ 2014; TRussell, Lucchini ++ in prep.; see also DRussell++13; Koljonen++ 2015)

XRBs as "Quasars for the impatient" –Blandford

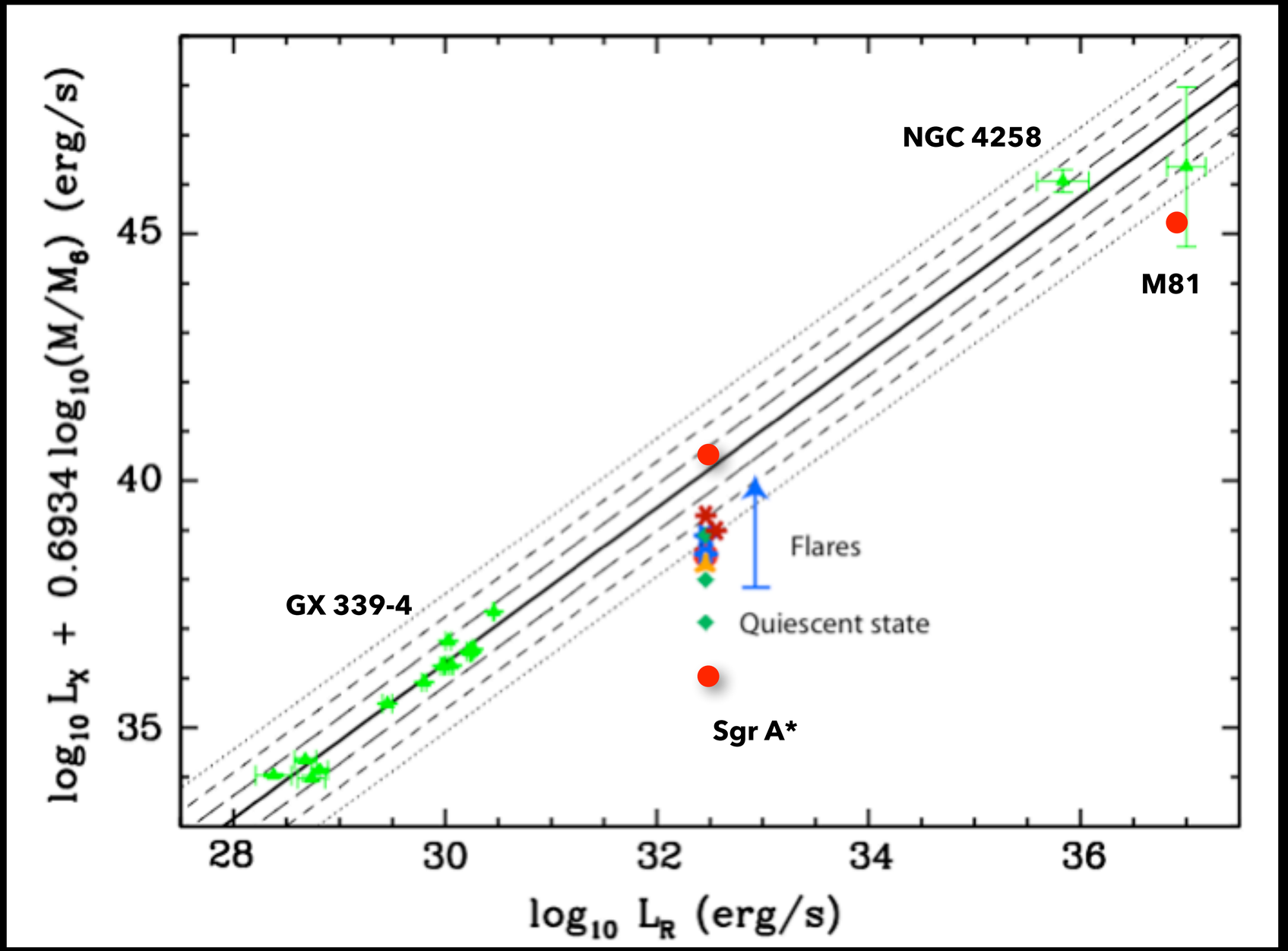




By now lots of other evidence for XRB/AGN scaling:
X-ray variability/QPOs, changing-look quasars
(Xiangyu Jin's talk)

(Körding++2006)

Sgr A*'s flares and the Fundamental Plane?



(SM 2005; Nowak, Neilsen, SM++ 2012; Neilsen++2013;2015; Ponti++2017; Yuan & Wang 2018; Boyce, Haggard++ 2018; Haggard++2019)