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

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

Inner disk

Jet

Wind(s?)

Corona

\[ e^+ \pm e^\mp i \pm i \]
Schematic of inner $\sim 100 \, R_g$ accretion “engine”

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

Inner disk

Jet

Wind(s?)

Corona
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)

Keck HKL image w/some young, hot stars (field ~1pc across, courtesy Ghez++)

Combined wind loss ~few x $10^{-3} M_{\odot}$/yr!

"...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 $4 \times 10^7$ 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

(Narayan, Yi & Mahadevan 95; Goldwurm++1994)
Chandra confirmed ‘advective/inefficient’ accretion flows

\[ M = 1.2 \times 10^{-5} \alpha M_\odot \text{yr}^{-1} \]

(Narayan & Yi 94; 95)

Radio       submm   NIR    OPT    UV    X-rays

(Baganoff++ 01; 03)

Yuan et al. 2003
Repeat the mantra: Chandra’s resolution/sensitivity is key!!
(and a 3 Ms XVP doesn’t hurt…)

Yuan et al. 2003

Radio       submm   NIR    OPT      UV    X-rays

\( \theta \lesssim 0.5^\circ \) ~ \( 2R_{\text{Bondi}} \)

\( \hat{M}_{\text{Bondi}} \sim 10^{-6} - 10^{-5} \, M_\odot \)

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

\[ n(r) \sim r^{-1/2} \Rightarrow 99\% \text{ mass loss!} \]


(Wang, Nowak, SM++, Science, 2013)
Chandra + EHT cover $R_{\text{Bondi}}$ to $R_g$ for a few sources

(Garcia++, 2005, 2010)
An ‘almost’ complete picture of BH accretion from outside in

\[ M \approx 2.4 \times 10^{-8} M_{\odot}/yr \]

Outlook & questions:

- Bondi $10^{2-3}$x too high! Implications for local (hot winds) and $\Lambda$CDM/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 $\sim 100 \ R_g$ accretion “engine”

- Accretion from $R_{\text{Bondi}}$ 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

- B.C. (and sometimes still...): XRBs considered primarily interesting for understanding stellar evolution and local SFRs
- B.C., bright states thought likely IC from a hot 'corona' similar to Seyferts (e.g. Haardt & Maraschi 91, 93; Czerny++, 2003; Done++, Zdziarski++), but weak states controversial (e.g. Bildsten & Rutledge 2000)
- Chandra, with HETG for brighter states and ACIS for dimmer states, allowed the first studies of the full dynamical range of accretion states extending over 8 orders of magnitude!
- But something was missing from this paradigm... (Meyer & Meyer-Hofmeister)

(Done 2002) Quiescence
Low State
High State
Very High State

Advective flow collapses

MHD dynamo saturates

hard state

strong corona

hard photons

soft state

weak corona

soft photons

accretion disk

black hole

(Esin++1997)
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!

(46x12)(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

\[ \log L_X = (1.45 \pm 0.04) \log L_R - (0.88 \pm 0.06) \log M_{BH} - \text{const.} \]
The Fundamental Plane as a (rough) BH mass estimator

"...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

\[ \log M = 0.55 \pm 0.22 + (1.09 \pm 0.10) \log L_R + (-0.59^{+0.16}_{-0.15}) \log L_X \]
Mass scaling: “self-similar” models

\[(R_d, R_0) = (\zeta_d, \zeta_0)r_g\]

\[Z_{\text{acc}} = \xi r_g\]

\[Q_j = \eta \dot{m}_{\text{Edd}} c^2\]

\[U_p \sim U_B + U_e\]

\[U_B/U_e = k\]

\[T_d, T_e, \eta_{\text{acc}}\]

vary with mass/size

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 $\sim 100 R_g$ accretion "engine"

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

Jet

Wind(s?)

Inner disk

Corona
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)

Yes:
- 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)

Hmm, but theory predicts
- 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)

Connection to jets depends on driving mechanism (still debated): radiative/thermal (e.g., Higginbottom & Proga 15; Tomaru++19) vs. MHD (e.g. Chakravorty++16)
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 $R_{\text{Bondi}}$ to $R_g$
- Inflow/outflow connection
- Interpreting accretion geometry
- Macro/microphysics connection
Illustration of degeneracy introduced by 'adding' electrons = light

\( T_p/T_e = 5 \)

\( T_p/T_e = 15 \)

\( T_p/T_e = 25 \)

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

Yuan et al. 2003
(see Theory paper V; EHT Collaboration 2019. Slide courtesy A. Broderick)
Jet power estimated $\sim 10^{43} - 10^{45}$ erg/s (Forman, Allen, McNamara, Russell, Rafferty, Stawarz,++) on larger scales.

Fits to Chandra-isolated core + MWL gives $P_{\text{jet,rad}} \lesssim 10^{42}$ erg/s, and total power $P_{\text{jet}} < \text{few } x 10^{43}$ erg/s (Lucchini, Krauss & SM 2019).

Conservative constraint $P_{\text{jet}} > P_{\text{jet,rad}}$ rejects ~half of our simulations, including all spin=0 models! (proof of Blandford-Znajek mechanism?)

Only high-spin ($a \sim \pm 1$) SANE models (non-magnetically arrested; MAD) survive.

Simultaneous Chandra/NuSTAR observations give $L_{\text{X}} (2-10 \text{ KeV}) = (4.4 \pm 0.1) \times 10^{40}$ erg/s, used to rule out models that consistently over-predict that flux.

X-ray data not yet fully exploited for EHT, but as GRMHD + radiation codes develop, Chandra will be crucial for interpreting EHT results (M87, SgrA*,++, Paper V; EHT Collaboration 2019).

**Table 2. Rejection Table**

<table>
<thead>
<tr>
<th>flux</th>
<th>$\alpha$</th>
<th>$R_{\text{mag}}$</th>
<th>AIS</th>
<th>$c^5$</th>
<th>$L^6$</th>
<th>$P_{\text{jet}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>1</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>10</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>20</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>40</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>80</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.94</td>
<td>160</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>1</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>20</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>40</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>80</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>-0.5</td>
<td>160</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>1</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>20</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>40</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>80</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>0</td>
<td>160</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>1</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>10</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>20</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>40</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>80</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.5</td>
<td>160</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>1</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>20</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>40</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>80</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>SANE</td>
<td>+0.94</td>
<td>160</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>1</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>20</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>40</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>80</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.94</td>
<td>160</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>1</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>10</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>20</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>40</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>80</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>-0.5</td>
<td>160</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>1</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>10</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>20</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>40</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>80</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>0</td>
<td>160</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>1</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>10</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>20</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>40</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>80</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.5</td>
<td>160</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>1</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>10</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>20</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>40</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>80</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>MAD</td>
<td>+0.94</td>
<td>160</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
</tbody>
</table>

1. flux: net magnetic flux on the black hole (MAD, SANE).
2. $\alpha$: dimensionless black hole spin.
3. $R_{\text{mag}}$: electron temperature parameter, see equation (8).
4. Average Image Scoring (THIEMS-AIS), models are rejected if $p \leq 0.01$, see Section 4 and Table 1.
5. $c$: radiative efficiency, models are rejected if $c$ is larger than the corresponding thin disk efficiency, see Section 6.1.
6. $L_X$: X-ray luminosity; models are rejected if $(L_X) > 4.4 \times 10^{40}$ erg s$^{-1}$. See Section 6.2.
7. $P_{\text{jet}}$: jet power, models are rejected if $P_{\text{jet}} < 10^{42}$ erg s$^{-1}$, 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 GMRHID 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!!

Expected shadow size

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

- 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

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

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

(Chandra reveals low-luminosity AGN:)

- Sgr A*: $M = 7 \times 10^6 M_\odot$
- M81*: $M = 1.2 \times 10^{-5} \alpha M_\odot \text{yr}^{-1}$

\[
\text{log}[E_\gamma (\text{keV})] = \begin{cases} 
38 & \text{ref.} 29, 30 \\
36 & \text{ref.} 31 \\
34 & \text{ref.} 32 \\
32 & \text{ref.} 33 \\
29 & \text{ref.} 34 \\
27 & \text{ref.} 35 \\
24 & \text{ref.} 36 \\
21 & \text{ref.} 37 \\
18 & \text{ref.} 5, \text{SRef.} 36, 39 \\
\end{cases}
\]

\[
\text{B: } M = (2.4, 0.6) \times 10^{-5} \alpha M_\odot \text{yr}^{-1}
\]

\[
\text{M81*: } M = 1.2 \times 10^{-5} \alpha M_\odot \text{yr}^{-1}, T_e = 9 \times 10^{10} \text{K}
\]

\[
\text{Sgr A*: } M = 1.2 \times 10^{-5} \alpha M_\odot \text{yr}^{-1}
\]

(Narayan & Yi 94; 95)

(Ho++ 99, Baganoff++ 01, 03; SM, Nowak++ 08)
Evidence for a thermal ‘corona’ from low accretion rate sources

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

(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?

“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?

\[
\log_{10} L_X + 0.6934 \log_{10}(M/M_\odot) (\text{erg/s})
\]

\[
\log_{10} L_R (\text{erg/s})
\]

NGC 4258
M81
GX 339-4
Sgr A*

Quiescent state
Flares