Super-Eddington Accreting Black Hole Systems

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Bamberg Black Hole Workshop

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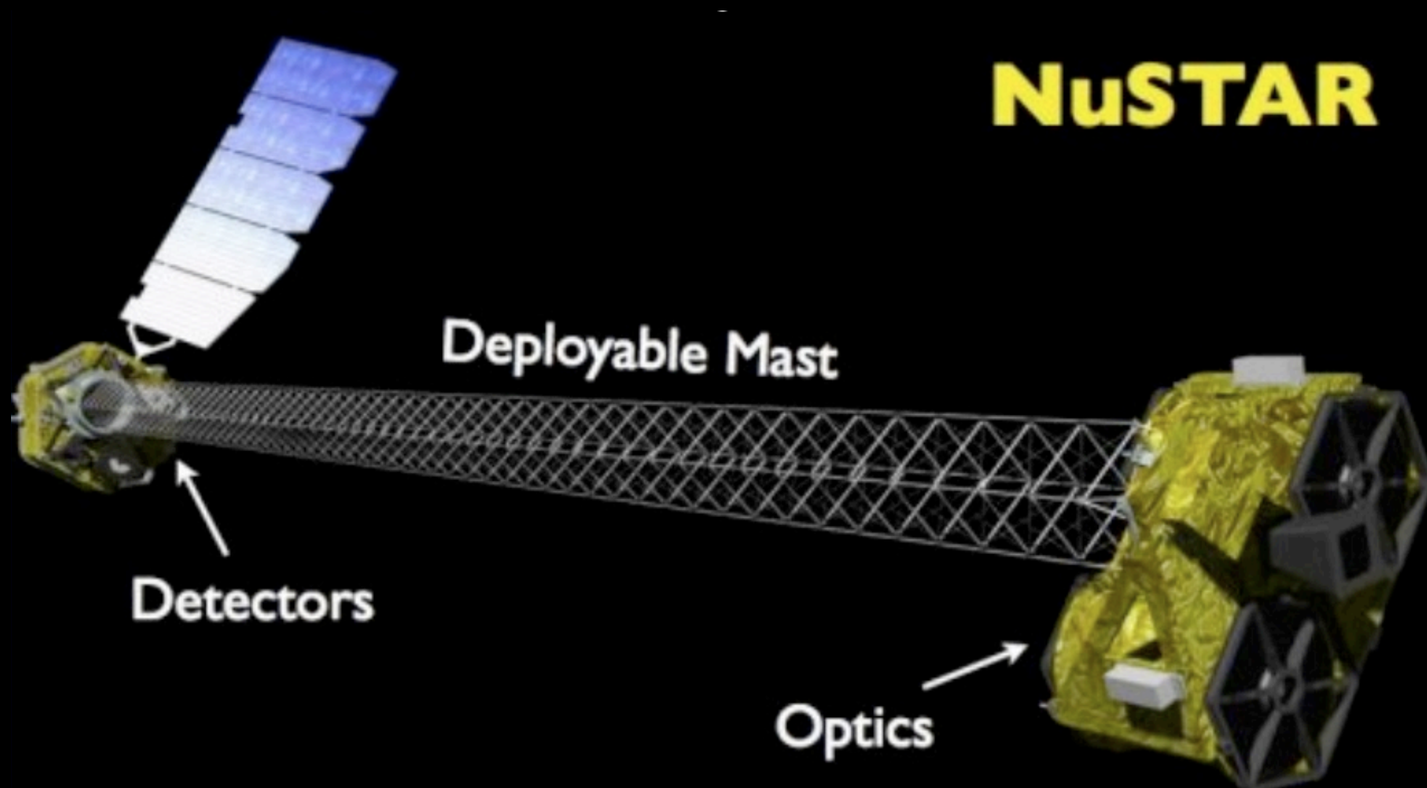
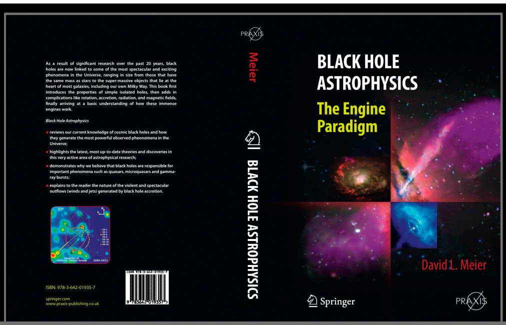
Launched Successfully 13 June!



Mast Deployment Scheduled for 21 June; image formation and adjustments to follow

New Book (Springer-Praxis)

Black Hole Astrophysics: The Engine Paradigm



- Part I: Observations of Black Hole Engines
  - Recognizing Black Holes
  - Macroquasars
  - Microquasars
  - Miniquasars
- Part II: Physics of Black Hole Engines
  - Review of Newtonian Mechanics
  - Special Relativity
  - General Relativity and Black Holes
  - Gravitational Waves and Collapse
  - Nuts & Bolts of the Black Hole Engine: General Relativistic Mechanics
- Part III: Astrophysics of Black Hole Engines
  - Assembling the Engine Block: Black Hole Formation
  - Fueling and Carburetion
  - The Combustion Chamber: Spherical and Disk Accretion
  - The Thermal Exhaust System: Radiation- and Thermally Driven Winds & Jets
  - The Non-Thermal Exhaust System I. Rotating Magnetospheres
  - The Non-Thermal Exhaust System II. Magnetic Winds & Jets
  - Putting it all Together: Black Hole Engines of All Sizes
- Seven Appendices (GR kinetic theory/MHD, stellar structure, FFDE, stationary jet MHD)

NOTES:
950 pages; 204 figs; 640 refs.
Mid-level:
 Late undergrad, early grad
 Observers, PhD engineers
 Budding theorists
Not for professional theorists (maybe a little)
Not for the layperson
Available mid-July, 2012 (<1 month delay)
10% discount for meeting attendees

PRICES:

Amazon.com:	$118.58 = 94 €
BHU Flyer BP:	81 £ = 100 €
BHU Flyer (euro):	90 €

What Does "Super-Eddington" Accretion Mean?

Super-Eddington accretion is DEFINED as $\dot{m} \equiv \dot{M} / \dot{M}_{Edd} > 1$

$\dot{M}_{Edd} = 4\,\pi\, GM / \kappa_{es}\, c\, \varepsilon$ and $\varepsilon \approx 0.1$ is the accretion efficiency.

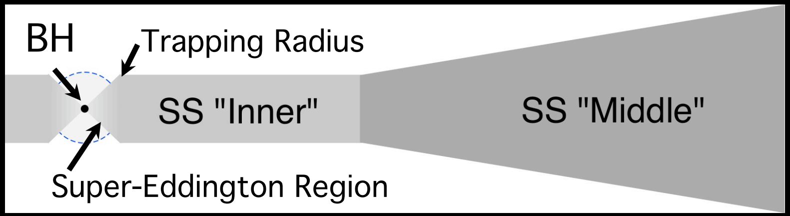
But, super-Eddington accretion can drive strong winds that reduce $\dot{m}$.

So, where in the accretion flow parameter $\dot{m}$

Answer: same as before, in the sub-Eddington portion of the disk

- In SS "Middle" region: $\dot{m}$ is steady (and same outside that region)
- In SS "Inner" region: $\dot{m} = \langle \dot{M} / \dot{M}_{Edd} \rangle$ (may be unsteady)

The Shakura & Sunyaev "inner" region spherizes ($H \approx r$), at the "trapping radius":



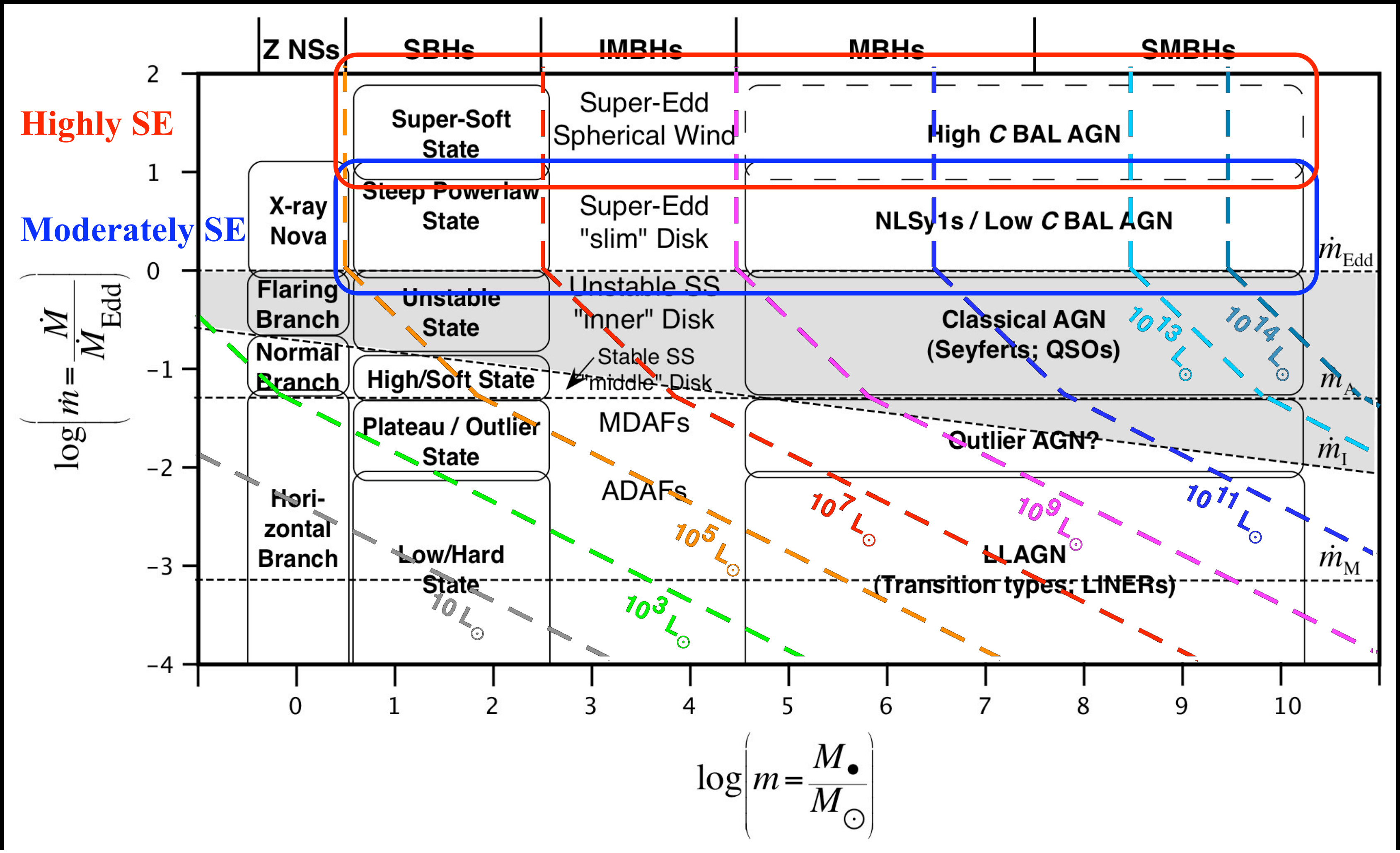
$$r_t = \dot{m}\ (r_g / \varepsilon)$$

Inside r_t, the accretion rate may not be constant with radius

What Does "Super-Eddington" Accretion Mean (cont.)?

The Eddington-scaled luminosity $l \equiv L_{bol} / L_{edd}$ is NOT necessarily equal to $\dot{m}$

- For RIAFs $\dot{m} << 1$, $L_{bol} \propto \dot{m}^2 m$ and $l = \dot{m}^2 / \dot{m}_A$
- For thin disks $\dot{m} \leq 1$, $L_{bol} \propto \dot{m}\, m$ and $l = \dot{m}$
- For SE flows $\dot{m} > 1$, $L_{bol} \propto m$ and $l \approx 1$



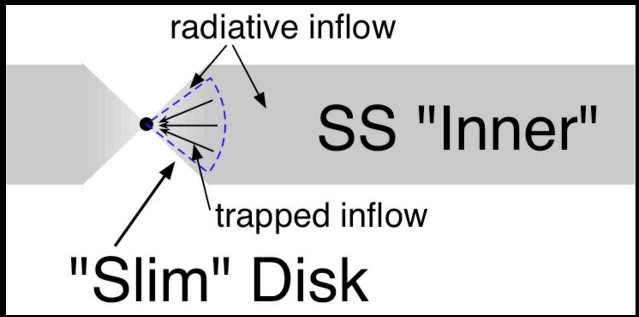
Eddington and
<u>Moderately</u> Super-Eddington Accretion:

High-Luminosity X-ray Sources

"Slim" Disk Model for
Moderately Super-Eddington Accreting Black Holes

From an accretion theory point-of-view, the "slim" disk model* is the appropriate model for super-Eddington accretion –
at least for $1 < \dot{m} < \sim 10$ or so.

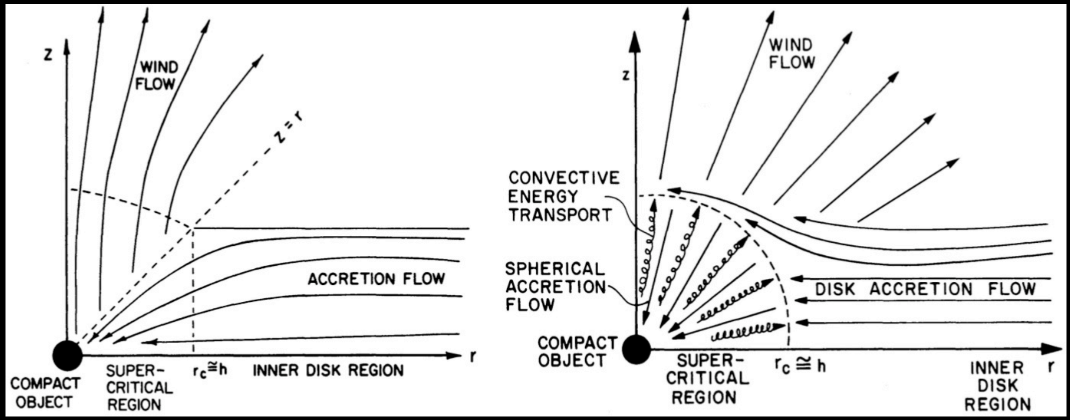
*Begelman & dlm (1982); Abramowicz et al. (1988); Chen et al. (1995)



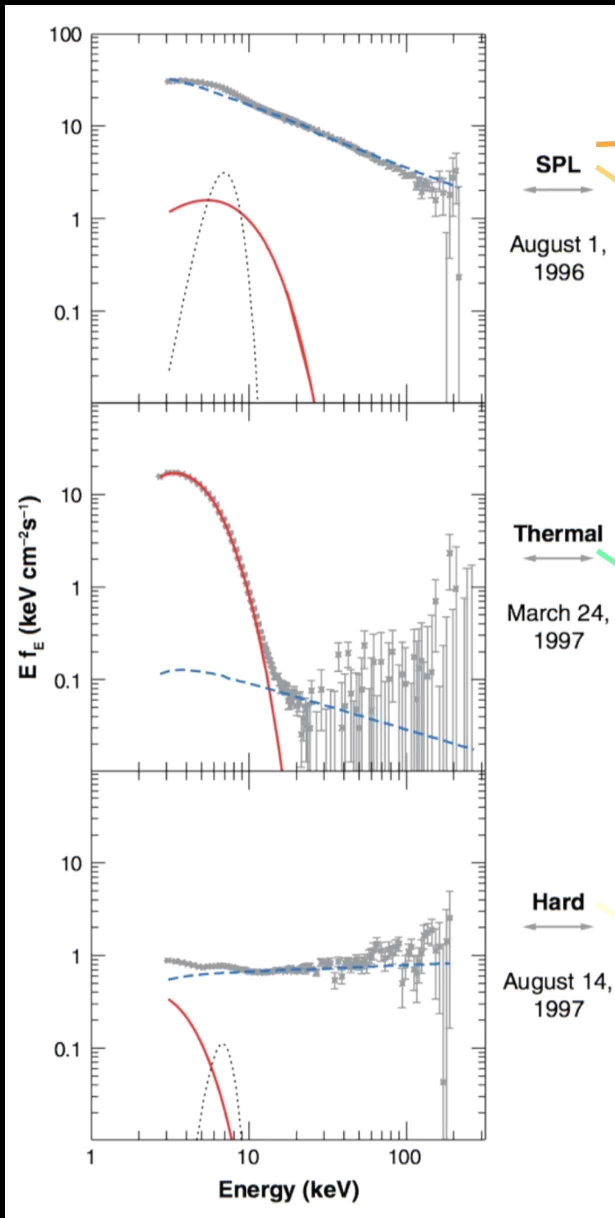
Properties of "slim" disks:

- Geometrically thick (H ~ r)
- Radiative inflow along surface
- Trapped, advective core inflow (~ADAF; drags photons toward BH)
- Core inflow is convectively unstable (Begelman & dlm 1982)
- Possibility of significant outflow (~ADIOS)
- Possible models:
    - #1: ADIOS-like
    - #2: convective transport to radiative regions
    - #3: combination of #1 & #2

dlm (1979)



Accretion Models for Steep Power-Law Sources



Remillard & McClintock (2006)

Two Types of SPL Sources

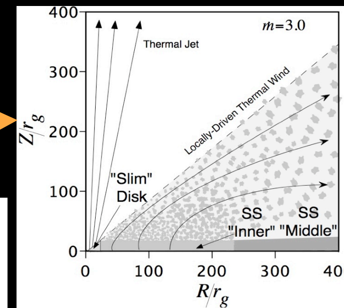
Weak thermal, no QPOs

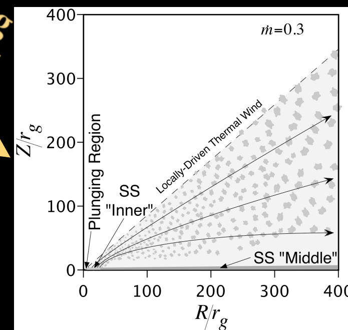
Strong thermal and QPOs

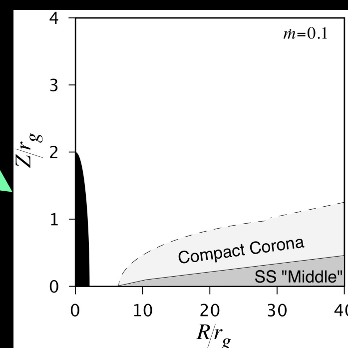
SS “inner” disk with corona + thermally instability

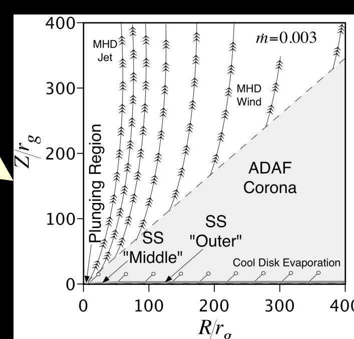
SS “middle” disk with compact corona

ADAF + weak thin disk









“slim” disk with corona

$T_* =$ 1.3 keV $m_{10}^{-1/4}\ \dot{m}_{10}^{1/4}$

$T_* =$ 0.7 keV $m_{10}^{-1/4}\ \dot{m}^{1/4}$ for <u>all</u> thermal models

NOTE

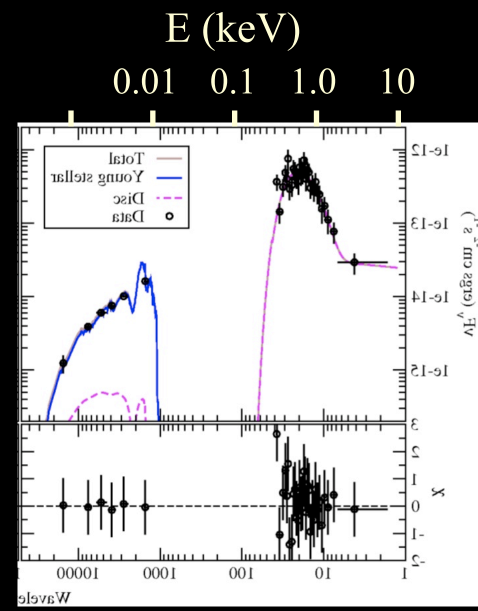
A geometrically thick accreting “slim” disk (H ~ R) should have a shallow power law spectrum also (Γ ~0.5), like an ADAF.

<u>However, if the “slim” disk is losing mass in its interior</u> ($\dot{M} \sim R^{1/3} - R^{1/2}$), it will have a steep spectrum instead ($\Gamma > 2.4$).

Slim Disk Models for the Source ESO 243-49 HLX-1

ESO 243-49 HLX-1 is a strong candidate for a Portegies Zwart & McMillan-type young cluster that forms an Intermediate Mass Black Hole

- Disk properties:
  - Thermal component temperature: $T_* = 0.2$ keV
  - Bolometric luminosity: $L_{bol} = 1.1 \times 10^{42}$ erg s^{-1} = $10^{8.5}$ $L_\odot$
- Cluster mass: $(4 - 6) \times 10^6\ M_\odot$
- Black hole mass from
  - Slim disk accretion models of L_{bol} and T_*: $8800 - 15{,}000\ M_\odot$
  - Magorrian relation for cluster mass: $5200 - 7800\ M_\odot$
- Black hole accretion rate from:
  - Slim disk accretion models of L_{bol} and T_*: $(0.6 - 5)\ \dot{M}_{Edd} = 10^{22-23}$ g s^{-1}
- Power law index poorly constrained:
  - Farrell *et al.* used $\Gamma = 2.1$
  - Easily could be an SPL source ($\Gamma > 2.4$)



Farrell *et al.* (2012)

BOTTOM LINE

Near- and moderately super-Eddington sources should have significant emission above 2 keV AND display a (possibly steep) power-law component that extends toward 10 keV and beyond.

<u>Highly</u> Super-Eddington Accreting Black Holes:

"Cygnus X-1s on Steroids"

Super-Eddington Wind Model for Highly Super-Eddington Accreting Black Holes

Unlike ADIOS winds, when a super-Eddington accretion flow produces outflow, it will be optically thick – VERY optically thick.

Under these conditions (e.g., $\dot{m} >> 10$ or so) for observations we can ignore the details of the accretion flow, deal just with the wind, and assume that the mass loss rate $\Delta\dot{m} \approx \dot{m}$.

Early history of super-Eddington winds:

- Shakura & Sunyaev (1973):
  - Constant-velocity wind model (not detailed enough for analyzing observations)
- dlm (1977, 1979, 1982a, b, c):
  - Accelerating, radiatively-driven wind
  - With sonic point, photosphere formation, etc.
  - Relative positions of various important radii affect wind dynamical and thermal properties:
    - Sonic points (gas pressure, radiation pressure)
    - "Adiabatic radius" (where outflow transitions from adiabatic to radiative)
    - Photosphere
  - Generated many very complicated sets of algebraic equations

Super-Eddington Wind Model for Highly Super-Eddington Accreting Black Holes (cont.)

The complex set of equations can be inverted into a fairly simple set, based on observed L_{bol} and T_*.

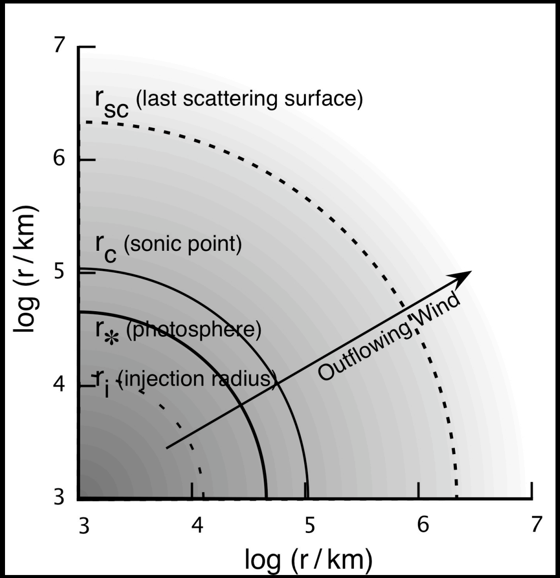
$$m = \frac{L_*}{1.25 \times 10^{38}\,\mathrm{erg\,s^{-1}}}$$

$$\begin{array}{lcllll} r_i &=& 1.01 \times 10^9 & \mathrm{cm} & \alpha^{2/5} & m^{19/25}\,T_{*6}^{-28/25} \\ r_* &=& 2.2 \times 10^9 & \mathrm{cm} & & m^{3/5}\,T_{*6}^{-17/10} \\ r_c &=& 1.43 \times 10^9 & \mathrm{cm} & \alpha^{-1/10} & m^{19/25}\,T_{*6}^{-28/25} \\ r_{sc} &=& 1.36 \times 10^{11} & \mathrm{cm} & \alpha^{1/10} & m^{16/25}\,T_{*6}^{-42/25} \\ V_\infty &=& 3.7 \times 10^8 & \mathrm{cm\,s^{-1}} & \alpha^{3/10} & m^{3/25}\,T_{*6}^{14/25} \end{array}$$

$$\dot{m} = 1.22 \times 10^3\,\alpha^{2/5}\,m^{-6/25}\,T_{*6}^{-28/25}$$

Properties of super-Eddington winds:

- L_{bol} remains near L_{edd}, regardless of $\dot{m}$
- Very extended: last scattering surface $r_{sc} > 100\ r_i \approx r_t$
- Spectrum formed deep in wind: photosphere $r_* << r_{sc}$
- Photosphere can be below or above sonic point r_c
- However, lower $\dot{m}$ produces hotter spectrum T_* (just like a classical nova)



Super-Eddington wind model:

$M = 25\ M_\odot$

$\dot{M} = 2 \times 10^{21}$ g s^{-1}

$T_* = 0.17$ keV

$V_{wind} = 2800$ km s^{-1}

BOTTOM LINE

Highly super-Eddington sources should be very cool

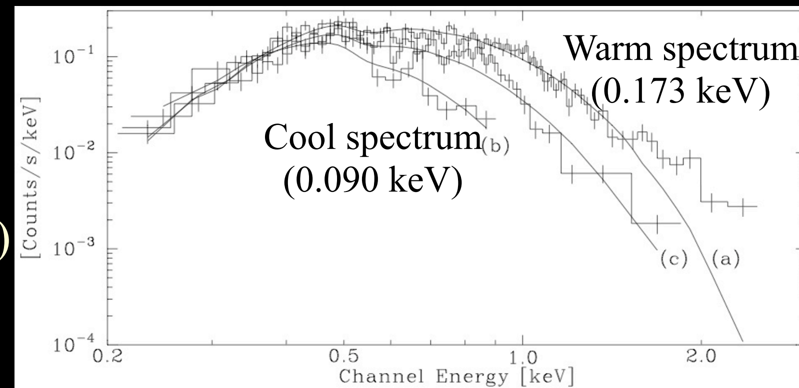
$$T_* = 1.1\ \mathrm{keV}\ m_{10}^{-0.21}\ \dot{m}_{10}^{-0.89}$$

with little or no emission above 1 – 2 keV.

Super-Eddington Wind Models for Super-Soft ULX Sources

Some well known super-soft ULXs:

- P098 in M101 (Pence *et al*. 2001; Mukai *et al*. 2003)
- N1 in M81 (Swartz *et al*. 2002)
- ULX in GC RZ 2109 in NGC 4472 (Zepf *et al*. 2008)
- SS 433 (?)

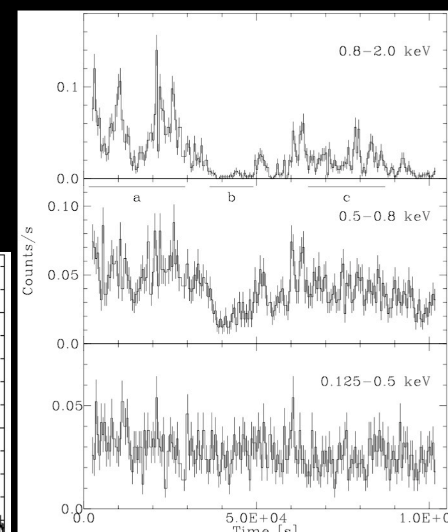


P098 spectral variability …

Basic properties of super-soft ULXs:

- L_{bol} > 10^{39} erg s^{-1}
- T_* < ~ 0.2 keV
- Little detectable emission above ~2 keV

… and light curves



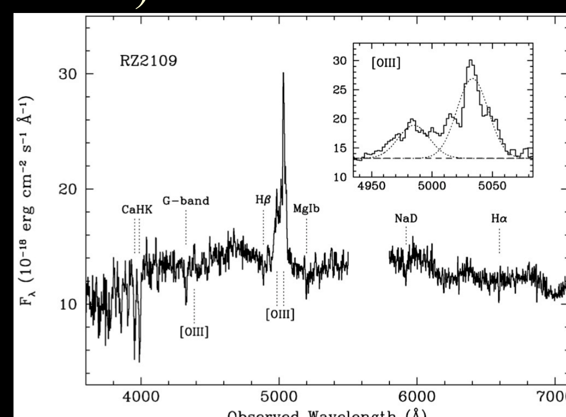
Mukai *et al*. (2003)

Important properties of P098:

- Highly variable
- But variability is only in T_* (0.090 – 0.173 keV)
- L_{bol} remains constant at ~3 × 10^{39} erg s^{-1} (just like a classical nova)

Important properties of RZ 2109 ULX:

- L_{bol} ~ 4 × 10^{39} erg s^{-1}
- Estimated mass of BH ~ (10 – 35) $M_\odot$
- V_{wind} ~ 2000 km s^{-1}



Zepf *et al*. (2003)

Super-Eddington Wind Model for ULX P098 in M101

We can use the previous set of equations to determine the following about P098 in M101, under the SE wind model:

- Mass of BH ~ 25 $M_\odot$
- Accretion rates of (4 – 7) × 10^{-5} $M_\odot$ yr^{-1}

Table 16.4: Models of P098 at two different color temperatures

Parameter	Symbol	Cool spectrum	Warm spectrum
Color temp.	T_*	0.090 keV	0.173 keV
Accretion rate	$\dot{m}$	130	63
Mass-loss rate	$\Delta\dot{M} \approx \dot{M}$	4.6×10^{21} g s^{-1}	2.2×10^{21} g s^{-1}
Injection radius	r_i	27,000 km	13,000 km
Photosphere	r_*	141,000 km	46,000 km
"Sonic" radius	r_c	223,000 km	107,000 km
Scattersphere	r_{sc}	7×10^6 km	2.2×10^6 km
Wind speed	V_∞	1950 km s^{-1}	2800 km s^{-1}

What kind of mass transfer could produce such high accretion rates?:

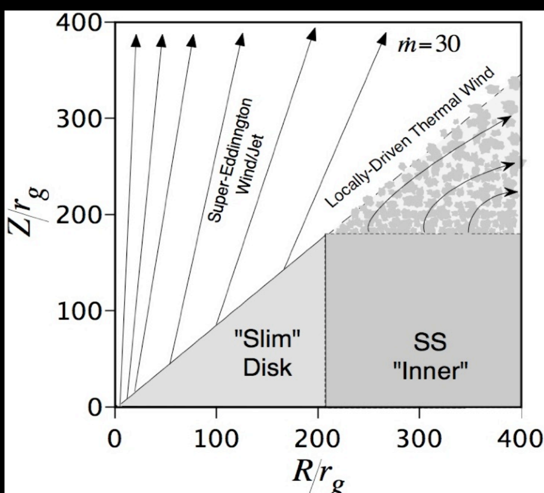
- Roche lobe overflow on a thermal time scale

$$\dot{M}^{\star}_{\mathrm{th}\bullet} \approx \frac{M_\star}{\tau^\star_{\mathrm{th}}} = 2.0 \times 10^{18}\,\mathrm{g\,s^{-1}} \left(\frac{M_\star}{\mathrm{M}_\odot}\right)^{3.5}$$

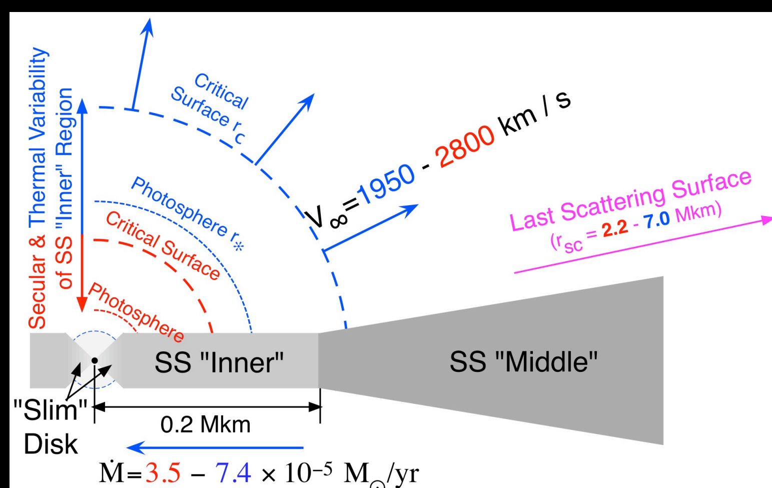
  from an ~ 8 $M_\odot$ B star companion

- Variability time scales (8 min – 15 hr) are similar to the thermal and secular time scales in the "inner" region

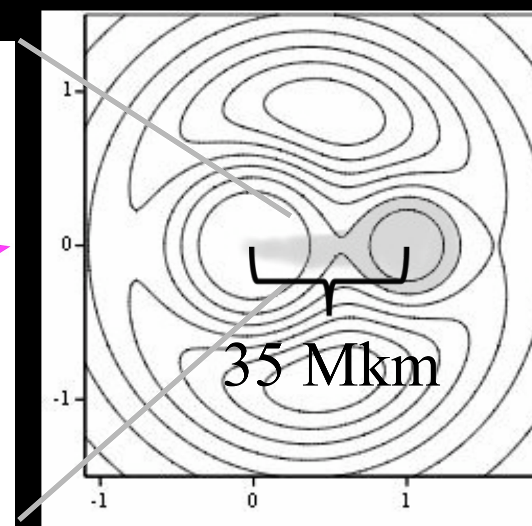
- Prediction: P098 should show outflow between 2000 – 3000 km s^{-1}



Schematic diagram



Accretion Model for Two Temperatures T_*



Introduction to SuperMassive Super-Eddington Sources:

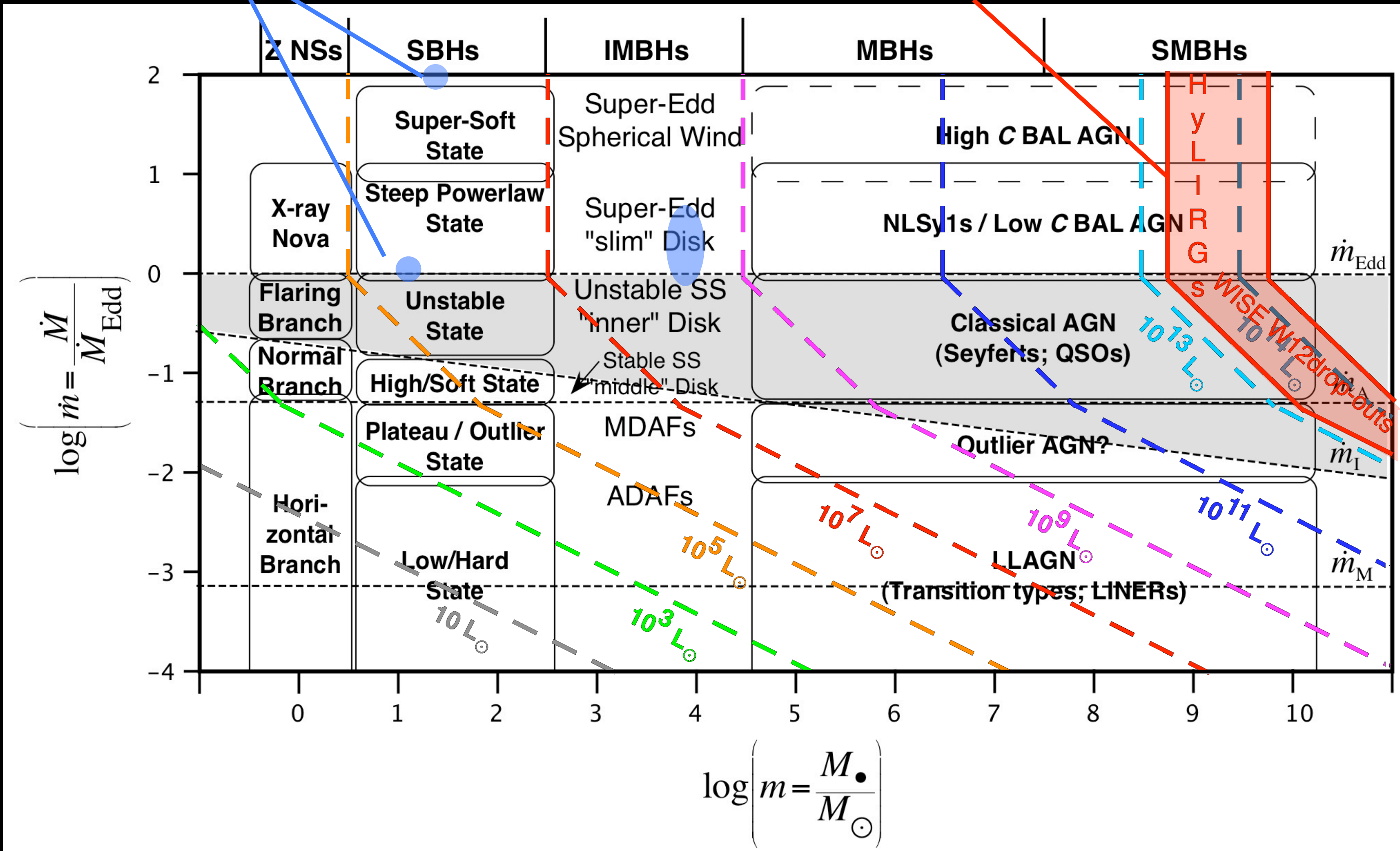
NLSy1s, BAL Quasars, ULIRGs, and HyLIRGs

SuperMassive Super-Eddington Sources: An Introduction

Any source that hovers near its Eddington luminosity (or more) is a SE candidate

SPL and Super-Soft sources

WISE-selected HyLIRGs (60% Type 2 opt spectra) (Eisenhardt et al.; Jingwen et al 2012)



Conclusions

1. ULXs are good candidates for stellar-mass and IMBH super-Eddington sources:
   - ULXs having significant emission above 2 kev: moderately ($1 < \dot{m} < 10$) SE SPL sources, esp. if $\Gamma > 2.4$
   - Super-soft ULXs with little emission above 2 kev: highly SE accreting objects ($\dot{m} >> 10$)

2. WISE-selected W12dropouts are good candidates for extreme SMBH super-Eddington sources:
   - Have Type 2 optical/UV spectrum ➔ large dusty torus
   - Dark at 3 & 5 μm, bright at 12 & 22 μm ➔ torus very opt thick

3. Others (NLSy1s, BAL QSOs, etc.) possible but not discussed

4. Some high covering factor BAL QSOs also may exist