Mass Estimates in Ultraluminous X-ray Sources

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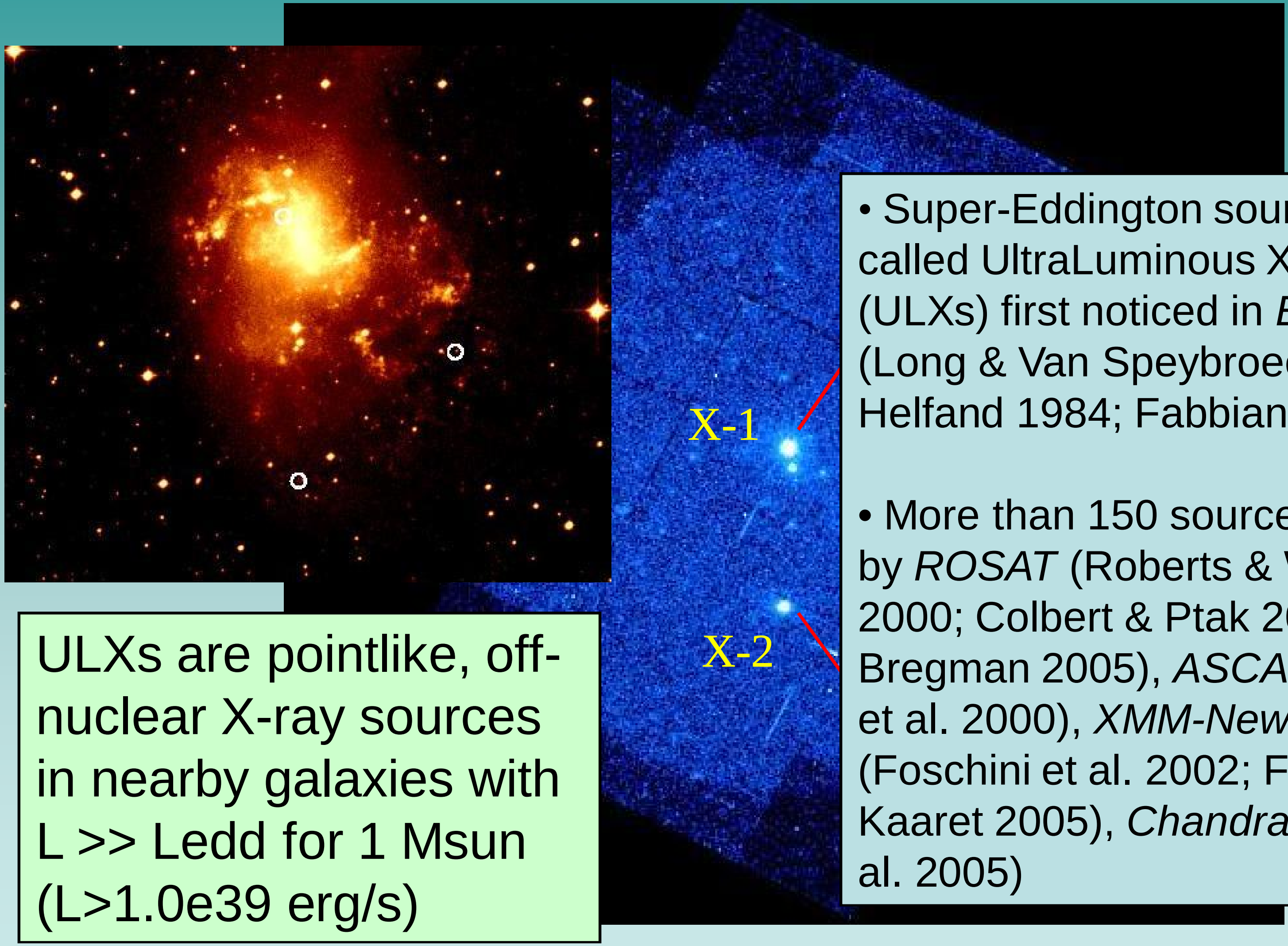
Outline

- What are Ultraluminous X-ray Sources (ULXs)
- Intermediate or stellar mass black holes?
- How to measure the mass of the black hole
- New approach for weighing BHs based on X-ray timing
- Revised estimates of M_{BH} from X-ray spectral fits
- Formation of black holes of 50-150 $M_{\odot}$ in ULXs
- Conclusions

What are Ultraluminous X-ray Sources

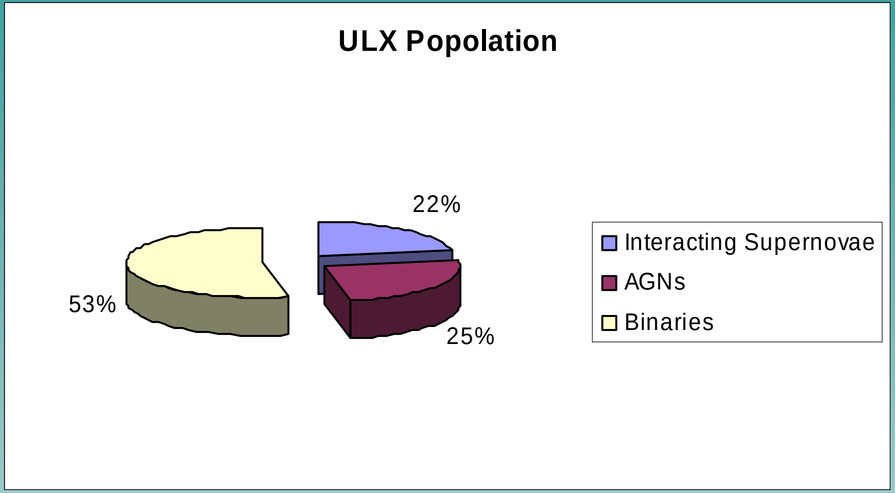


- Super-Eddington sources, later called UltraLuminous X-ray sources (ULXs) first noticed in *Einstein* data (Long & Van Speybroeck 1983; Helfand 1984; Fabbiano 1989)

- More than 150 sources observed by *ROSAT* (Roberts & Warwick 2000; Colbert & Ptak 2002; Liu & Bregman 2005), *ASCA* (Makishima et al. 2000), *XMM-Newton* (Foschini et al. 2002; Feng & Kaaret 2005), *Chandra* (Swartz et al. 2005)

ULXs are pointlike, off-nuclear X-ray sources in nearby galaxies with L >> Ledd for 1 Msun (L>1.0e39 erg/s)

What are Ultraluminous X-ray Sources



- **Background AGNs**:

  (a) optical spectroscopic identifications (Foschini et al. 2002b; Masetti et al. 2003)

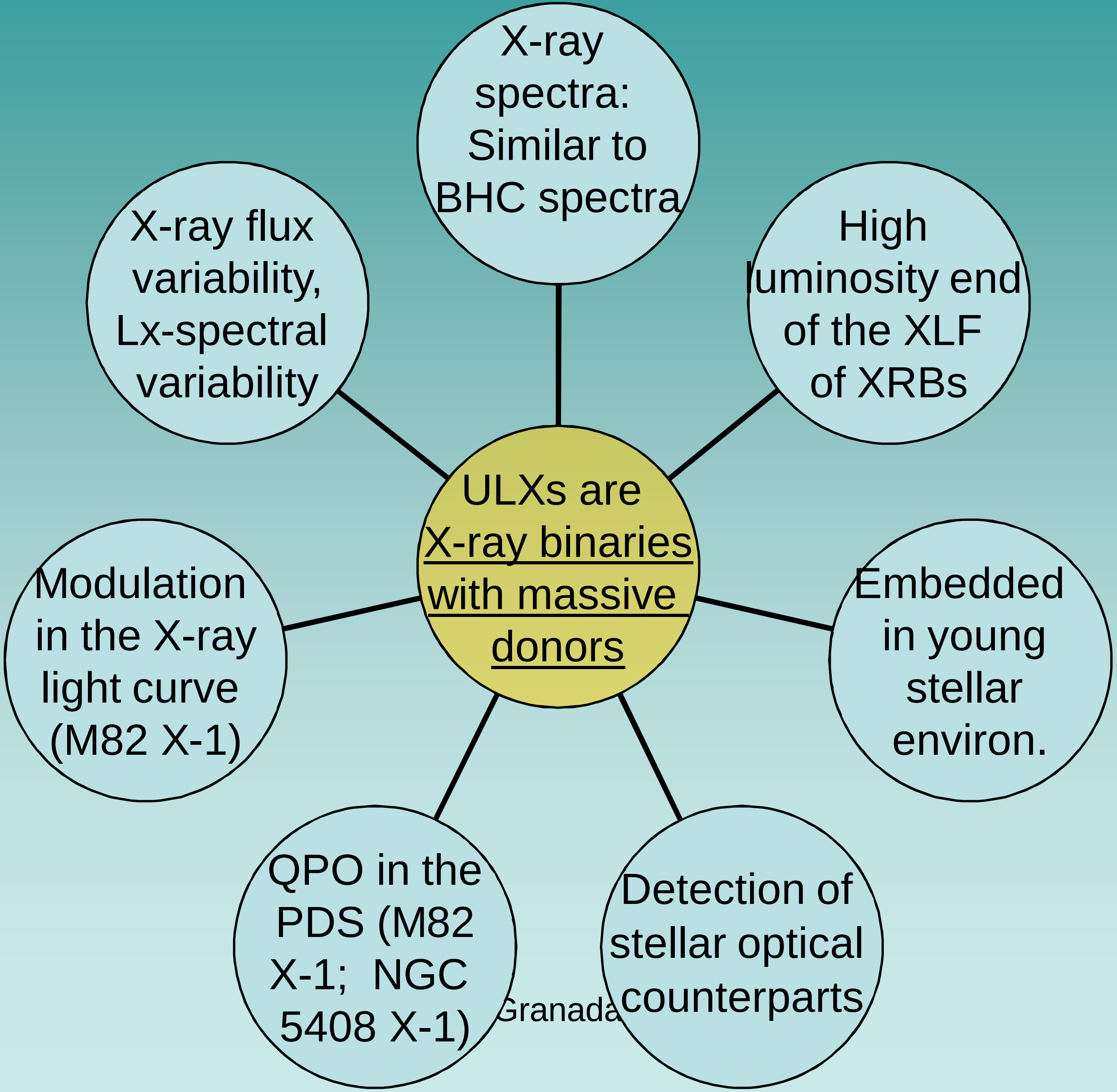
  (b) *Chandra* survey (Swartz et al. 2005): 25%, of which 44% in ellipticals and 14% in spirals

- **Interacting supernovae**:

  (a) we know of specific cases (e.g. SN 1978K, SN 1993J)

  (b) MEKAL spectra of some ULXs (Feng & Kaaret 2005; Swartz et al. 2005)

What are Ultraluminous X-ray Sources



ULXs are <u>X-ray binaries with massive donors</u>

X-ray spectra: Similar to BHC spectra

High luminosity end of the XLF of XRBs

Embedded in young stellar environ.

Detection of stellar optical counterparts

QPO in the PDS (M82 X-1; NGC 5408 X-1)

Modulation in the X-ray light curve (M82 X-1)

X-ray flux variability, Lx-spectral variability

Intermediate or stellar mass BHs?

What is the origin of the exceptionally high (isotropic) luminosity of ULXs?

Intermediate mass black hole (IMBH) interpretation

Mass estimates in excess of 100 $M_\odot$ are derived from the luminosity and the characteristic temperature/normalization of the soft X-ray component:

$L = 10^{39}$-10^{41} erg/s ⇒ from L=Ledd: $\mathbf{M_{BH}} > 75\ (L/10^{40}\ \mathrm{erg/s}) M_\odot$

$T_{MCD} = 0.1$-0.3 keV ⇒ from T_{MCD}=Tdisk: $\mathbf{M_{BH}} > 100\ (T_{MCD}/200\ \mathrm{eV})^{-4} M_\odot$

Problems with IMBHs >> 100 $M_\odot$ → Origin? Unbroken PL slope of the XLF up to 2×10^{40} erg/s? Star forming mass ending up in IMBHs?

Beamed X-ray Binary interpretation

Super-Eddington rates: may occur in particular conditions (e.g. Rappaport et al. 2005), when the donor has a radiative envelope and is more massive than the BH (thermal timescale mass transfer; King et al. 2001, King 2002)

Accretion disk geometrically thick

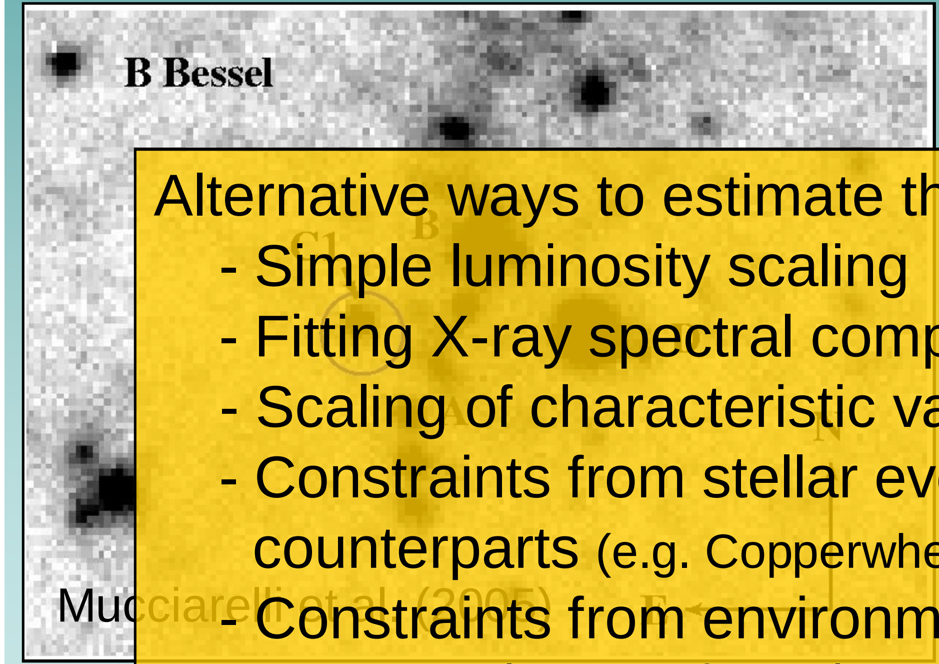
$\mathbf{M_{BH}} > 7.5\ (b/0.1)\ (L/10^{40}\ \mathrm{erg/s})\ M_\odot$

Problems → L > 10^{40} erg/s ULXs? Isotropically illuminated nebulae?

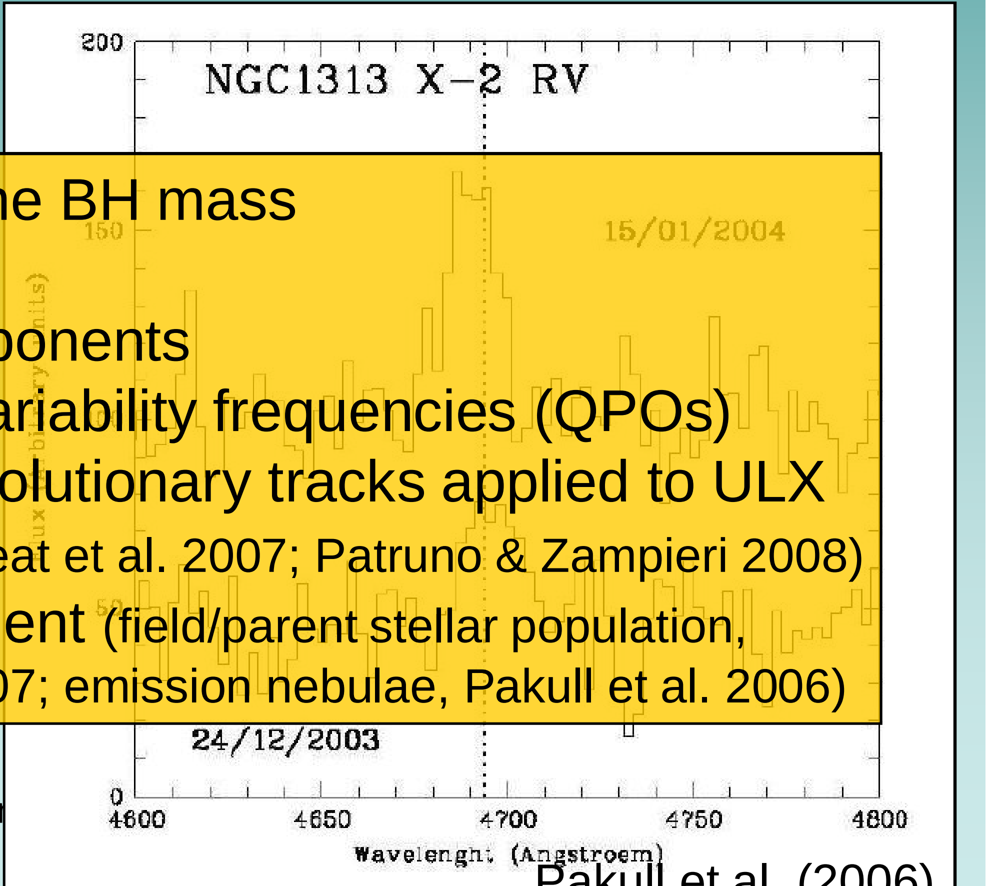
How to measure the mass of the BH?

Measurement of the dynamic mass function of some ULXs with optical counterparts (NGC 1313 X-2, NGC 4559 X-7): period, radial shift

→ Optical spectra at 8m class telescope needed (m_V~23)



Mucciarelli et al. (2005)



Pakull et al. (2006)

Alternative ways to estimate the BH mass

- Simple luminosity scaling
- Fitting X-ray spectral components
- Scaling of characteristic variability frequencies (QPOs)
- Constraints from stellar evolutionary tracks applied to ULX counterparts (e.g. Copperwheat et al. 2007; Patruno & Zampieri 2008)
- Constraints from environment (field/parent stellar population, Ramsey et al. 2006, Liu et al. 2007; emission nebulae, Pakull et al. 2006)

Fitting X-ray disc spectral components

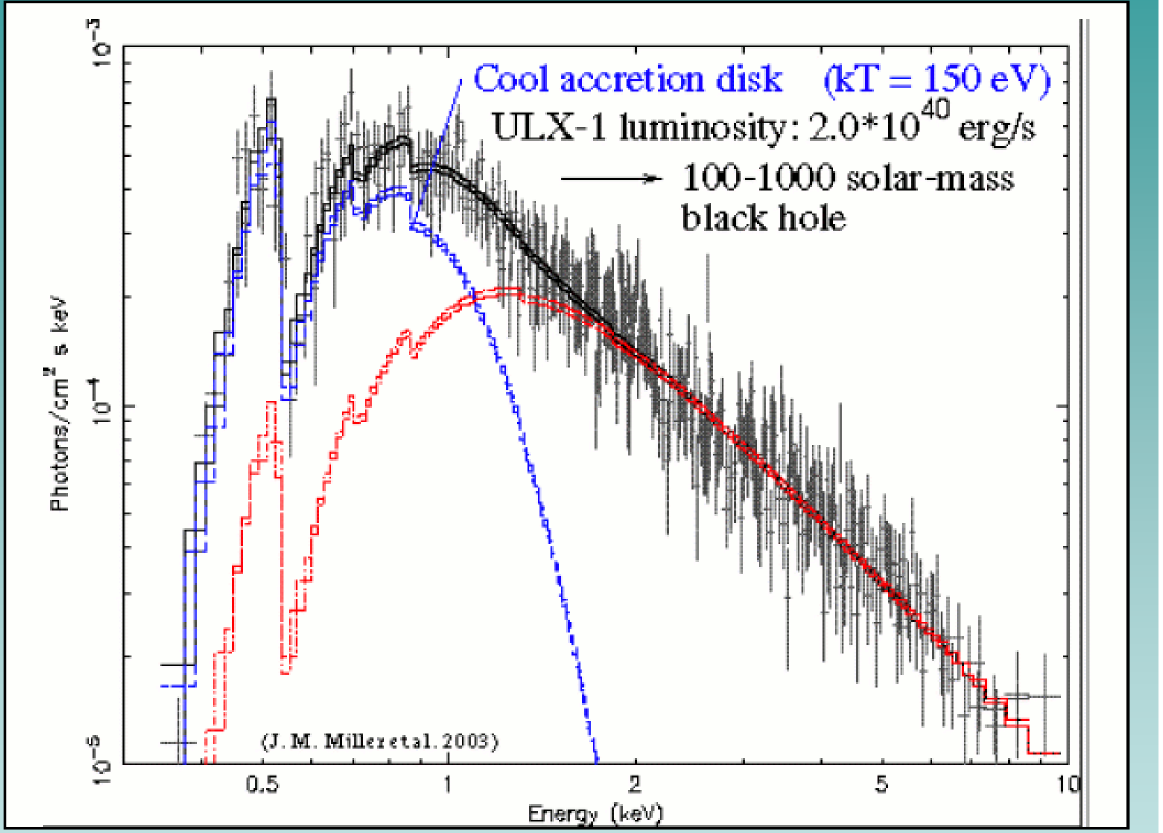
- MCD + PL (Miller et al. 2003, 2004): soft, low temperature (0.1-0.4 keV) MCD

→ **M_{BH}** =100-1000 $M_\odot$

Other models proposed (for ULX spectra with distinct curvature above 2 keV):

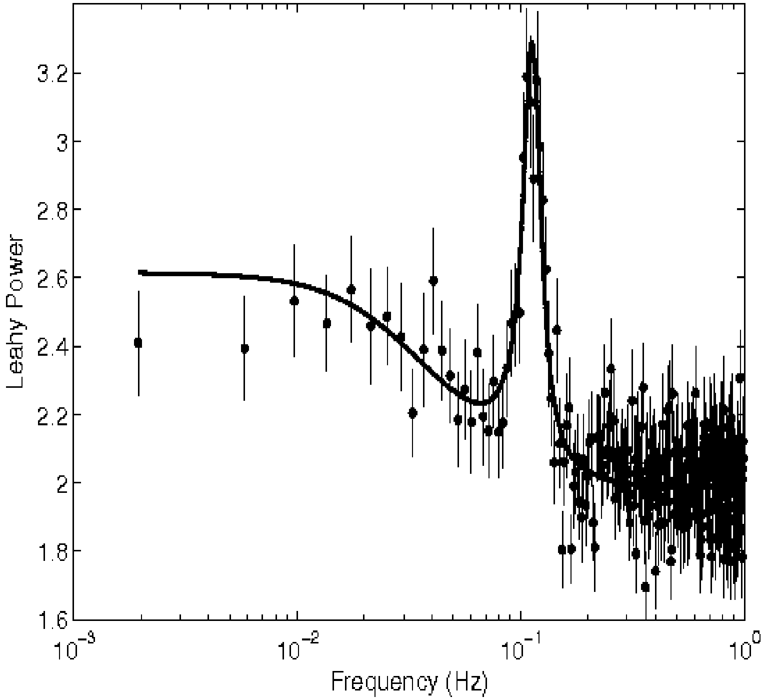
- MCD+Comptt or DISKPN+EQPAIR (Stobbart et al. 06)
- Fast ionized outflow (Goncalves & Soria 06)
- Slim disc and photon bubble models (Mizuno et al. 07; Finke & Bottcher 07; Vierdayanti et al. 08)

→ No constraint on **M_{BH}** or **M_{BH}**<100 $M_\odot$



Scaling of characteristic frequencies

(Mucciarelli et al. 2006)



QPOs detected in two ULXs (Strohmayer & Mushotzky 03; Strohmayer et al. 07**)**

M82 X-1: **ν_{QPO} = 54-166 mHz**
NGC5408 X-1: **ν_{QPO} = 20 mHz**

Properties (rms, coherence, noise, variability) similar to **Type C QPOs** in BHCs (0.1-15 Hz)

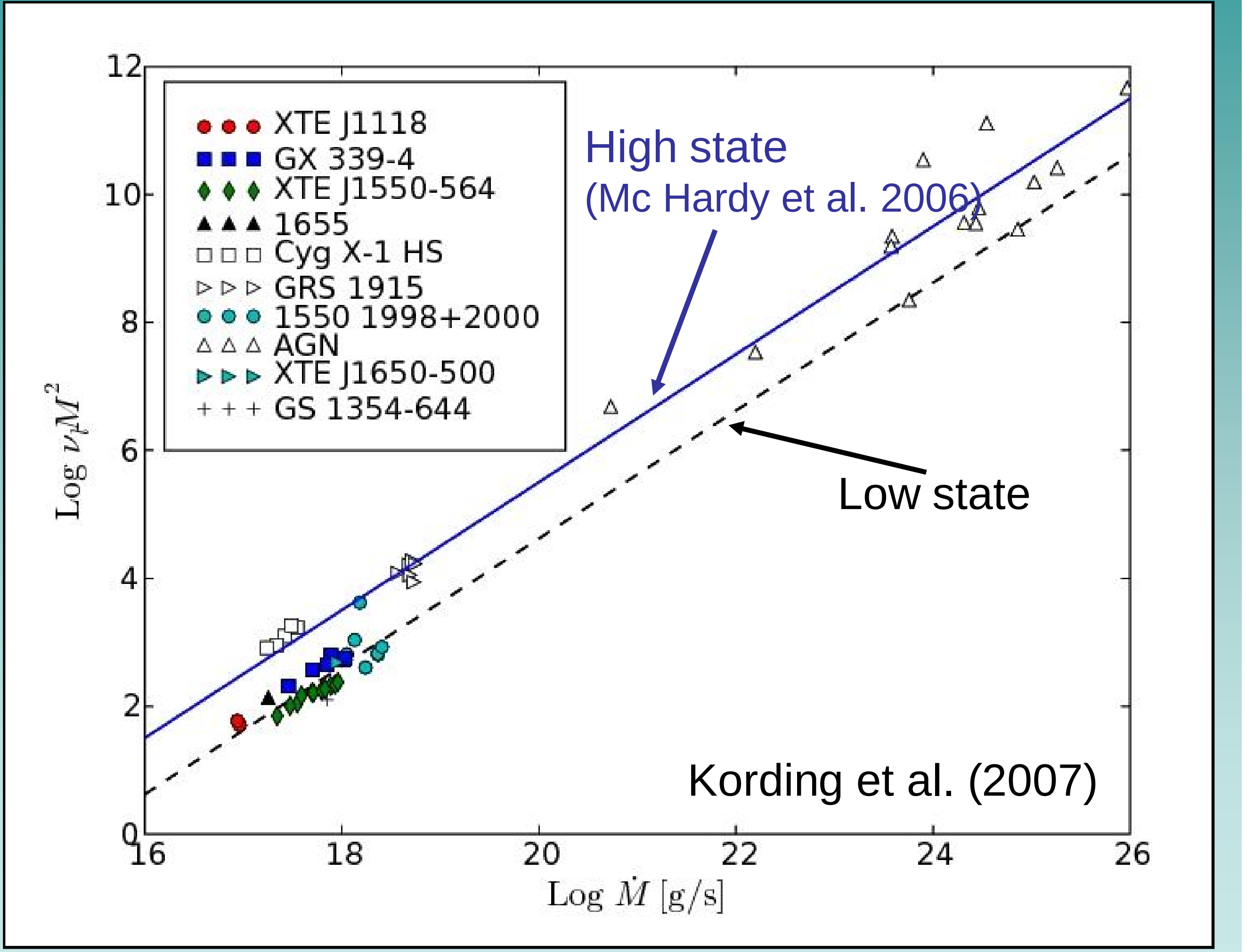
⬇

Extrapolating correlations known to exist for BH binaries and assuming that ν_{QPO} scales inversely to **M_{BH}** (Fiorito & Titarchuk 04; Mucciarelli et al. 06; Strohmayer et al. 07; Feng & Kaaret 07):

M82 X-1 → M_{BH} ~ 10-1000 $M_{\odot}$
NGC5408 X-1 → M_{BH} ~ 600-5000 $M_{\odot}$

Weighing BHs through X-ray timing

- **Variability plane:** BHCs and AGNs populate a plane in the parameter space defined by M_{BH}, μ and v_l, meaning that <u>BH accretion is scale invariant</u>
- If the accretion flow in ULXs behaves in a similar way → M_{BH}
- No extrapolation outside its range of validity



High state
(Mc Hardy et al. 2006)

Low state

Kording et al. (2007)

Weighing BHs through X-ray timing

- ν_l (lower frequency Lorentzian) → extrapolation of the Belloni et al. (2002) relation for BHCs: $\nu_l \sim 12.37\ \nu_{QPO}^{1.023}$

  Extension less critical as the relation appears rather tight over a very broad range of frequencies, which includes the frequencies of the QPOs observed in M82 X-1
- Estimate of μ:

  * efficient accretion → $\mu \sim Lx/0.1\ c^2$

  * inefficient accretion: ‘fundamental plane’ (Merloni et al. 2003; Falcke et al 2004) and Lradio-μ relation (Kording et al. 2006) → $\mu \sim 0.1\ Lx^{0.5}M^{0.43}$ g/s

	Lx (erg/s)	ν_{QPO} (mHz)	M_{BH} ($M_\odot$)
M82 X-1	$(1.3-1.7)\times10^{40}$	54-113	**95-1300**
NGC 5408 X-1	3×10^{39}	20	**115-1300**

Casella et al. (2008)

X-ray fits with 'physical' disk models

- Soft component modeled as emission from an accretion disk
- The MCD (Mitsuda et al. 1984) is an approximation of a newtonian, standard disk in which the effects of the viscous torque at the inner boundary are neglected
- Spectra of standard (Shakura & Syunyaev 1973) and
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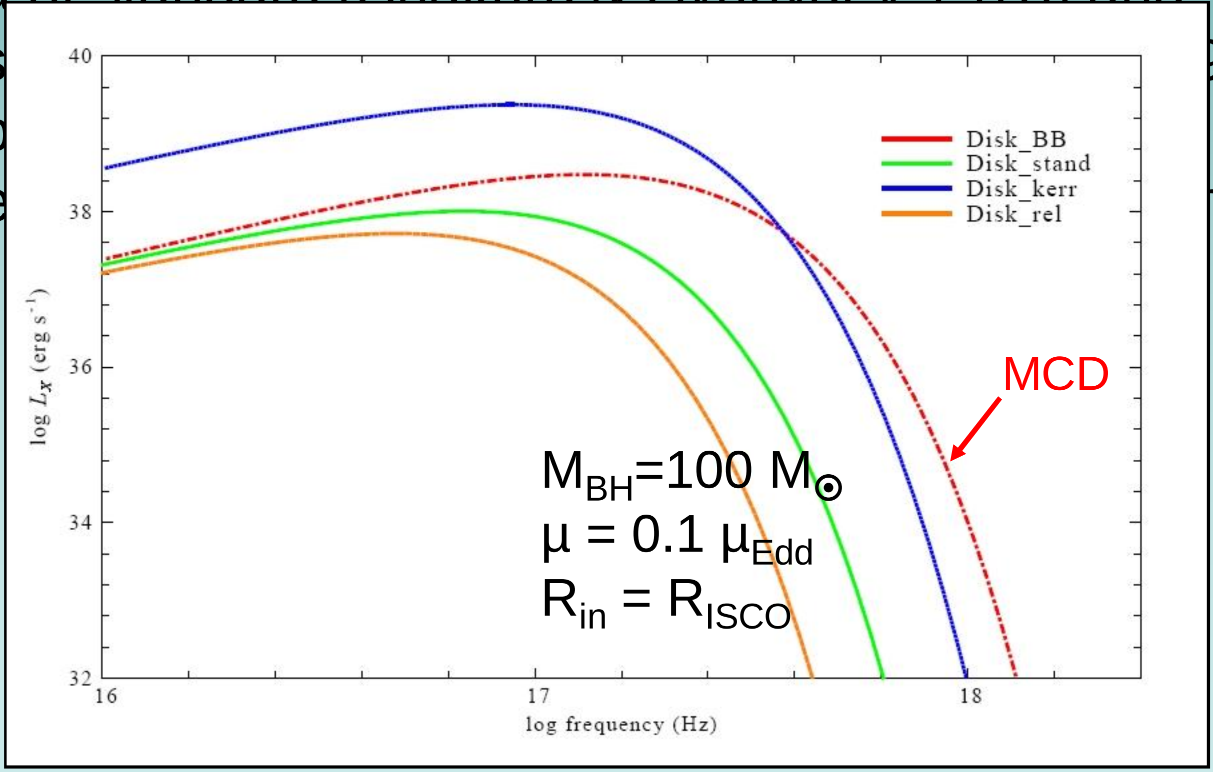


M_{BH}=100 $M_{\odot}$
$\mu = 0.1\ \mu_{Edd}$
$R_{in} = R_{ISCO}$

X-ray fits with 'physical' disk models

- Fits of ‘physical’ disks with a MCD performed for small inclinations in order to obtain correction factors for M_{BH} and μ (e.g. Ebisawa et al. 91; Kubota et al. 05)
- We did similar fits but fixing M_{BH} or μ
- Acceptable fits with different best-fit values of R_{inBB}. For fixed M_{BH}:

  * *standard* (e.g. Kubota et al. 1998):

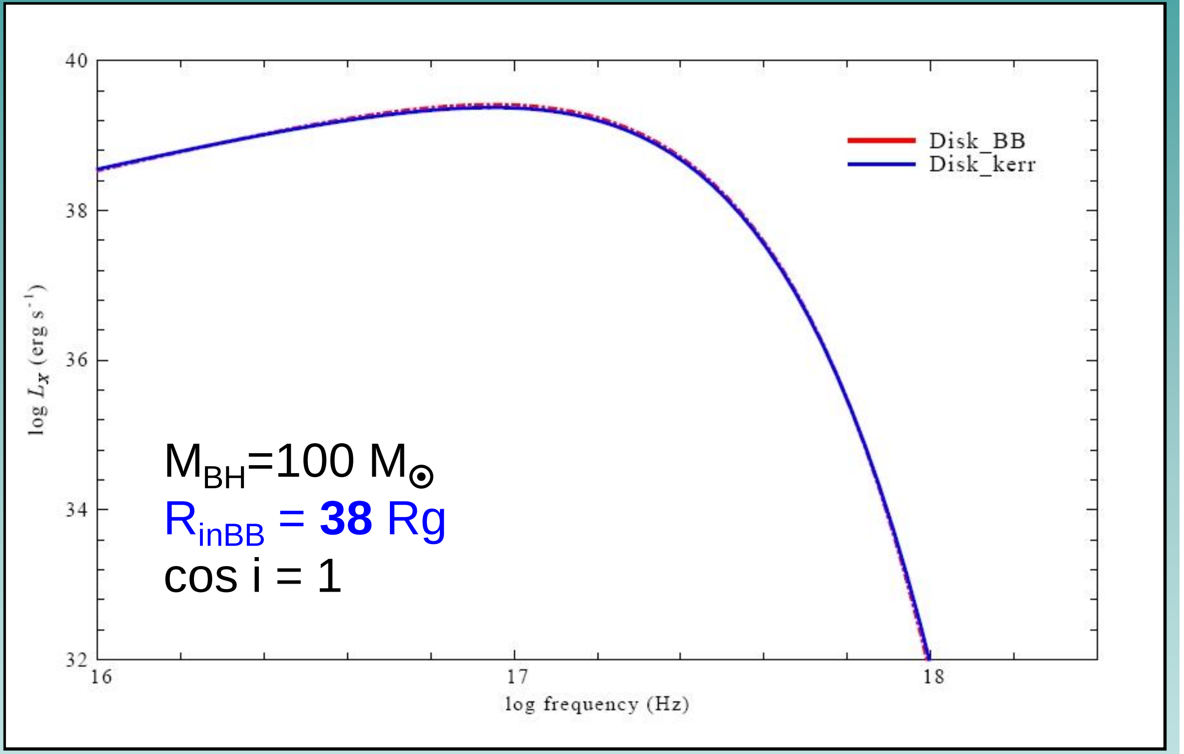
  R_{inBB} = **13** Rg

  * *Schwarzschild*:

  R_{inBB} = **19** Rg

  * *Kerr* (max rotat.):

  R_{inBB} = **38** Rg



M_{BH}=100 $M_\odot$

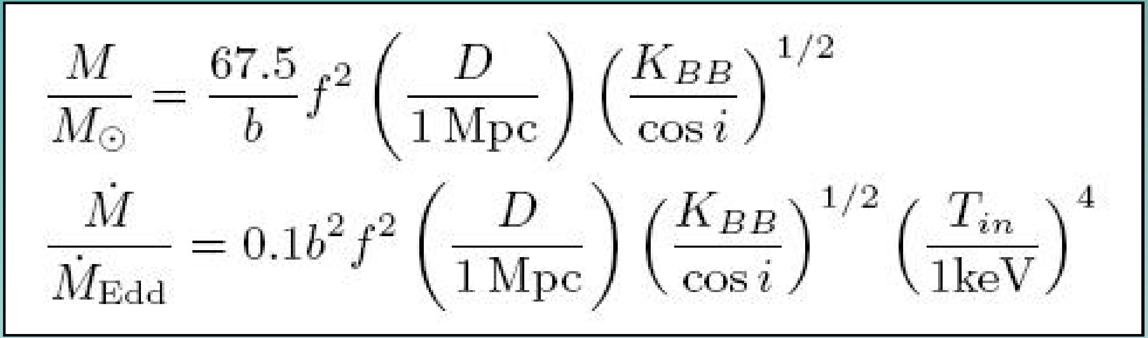
R_{inBB} = **38** Rg

cos i = 1

Lorenzin & Zampieri (2008)

X-ray fits with 'physical' disk models

- Adopting the appropriate value of **$b = R_{inBB}/Rg$**, it is possible to revise estimates of M_{BH} based on MCD spectral fits of ULXs

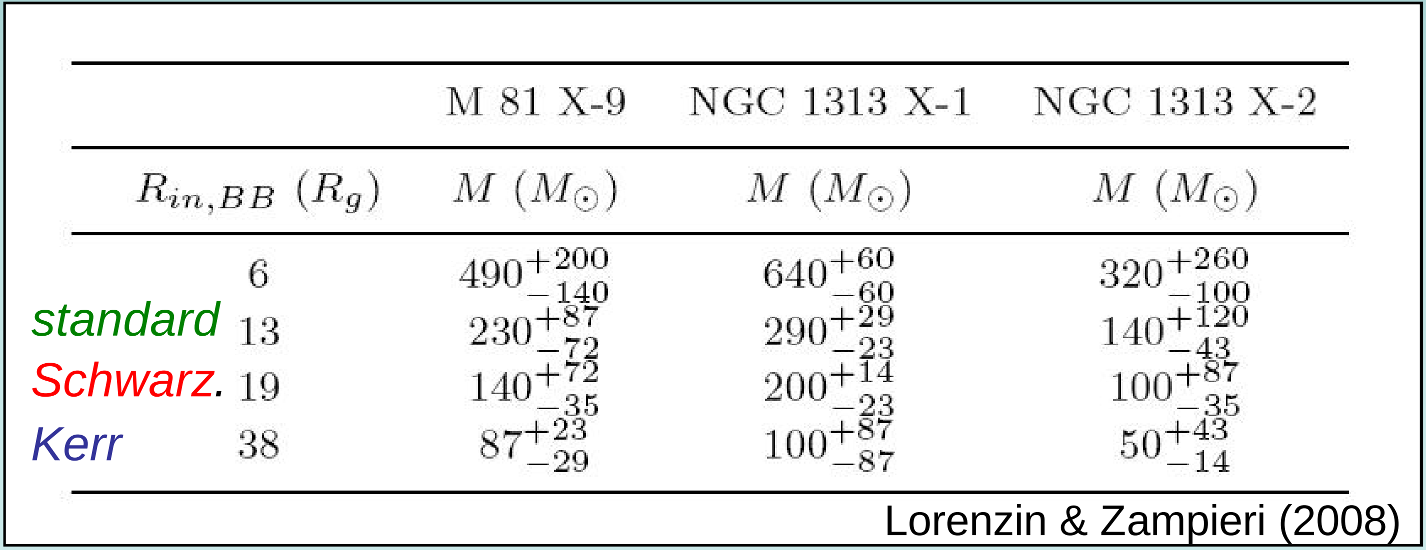


$$\frac{M}{M_\odot} = \frac{67.5}{b} f^2 \left(\frac{D}{1\,\mathrm{Mpc}}\right)\left(\frac{K_{BB}}{\cos i}\right)^{1/2}$$

$$\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} = 0.1 b^2 f^2 \left(\frac{D}{1\,\mathrm{Mpc}}\right)\left(\frac{K_{BB}}{\cos i}\right)^{1/2}\left(\frac{T_{in}}{1\mathrm{keV}}\right)^4$$

KBB, Tin → MCD fitting parameters

f~1.7 color correction factor (Shimura & Takahara 1995)



		M 81 X-9	NGC 1313 X-1	NGC 1313 X-2
	$R_{in,BB}$ (R_g)	M $(M_\odot)$	M $(M_\odot)$	M $(M_\odot)$
	6	490^{+200}_{-140}	640^{+60}_{-60}	320^{+260}_{-100}
standard	13	230^{+87}_{-72}	290^{+29}_{-23}	140^{+120}_{-43}
Schwarz.	19	140^{+72}_{-35}	200^{+14}_{-23}	100^{+87}_{-35}
Kerr	38	87^{+23}_{-29}	100^{+87}_{-87}	50^{+43}_{-14}

Lorenzin & Zampieri (2008)

X-ray fits with 'physical' disk models

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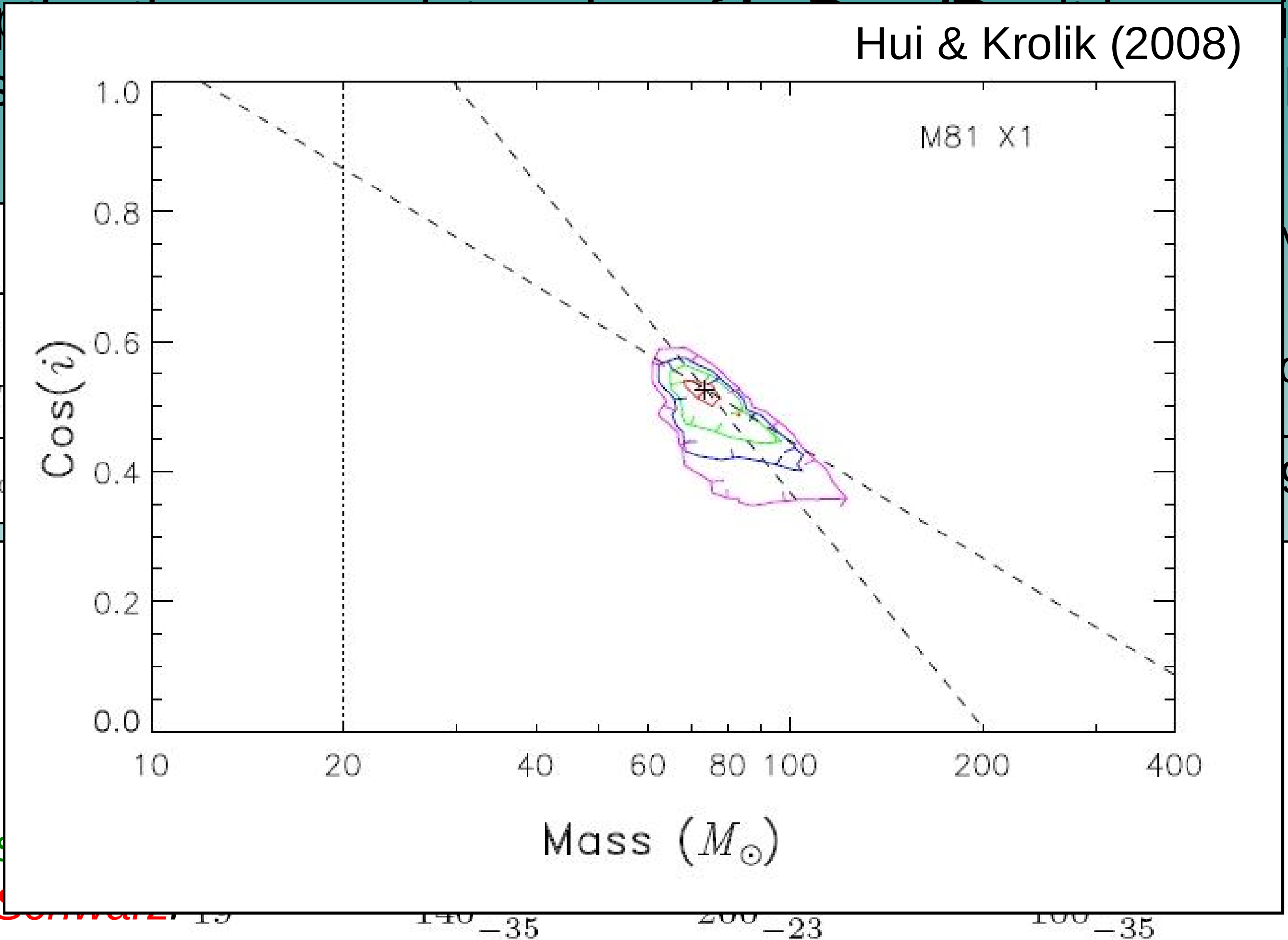
Hui & Krolik (2008)

MCD fitting

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$\frac{M}{M_\odot}$

$\frac{\dot{M}}{\dot{M}_{\mathrm{Ed}}}$

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Schwarz.	19	140_{-35}	200_{-23}	100_{-35}
Kerr	38	87^{+23}_{-29}	100^{+87}_{-87}	50^{+43}_{-14}

Lorenzin & Zampieri (2008)

Black holes of 50-150 $M_{\odot}$ in ULXs?

(a) Revised fits with relativistic disk models

→ M_{BH} ~50-200 $M_{\odot}$

(b) Fits with a slim disk (Vierdayanti et al. 2006, 2008) and/or a dominant comptonizing corona (Done & Kubota 2006, Stobbart 2006), and comparison with very-high state of BHCs (Soria 2008)

→ M_{BH} ~50-100 $M_{\odot}$

- Many ULXs (apart from M82 X-1 and NGC 5408 X-1) may not contain ~1000 $M_{\odot}$ black holes, but BHs with mass ~50-150 $M_{\odot}$

- **How can these “small” IMBHs (e.g. Roberts 2007) form?**

- No exotic channel required. From stellar evolution of massive stars up to the pre-supernova stage (e.g. Heger et al. 2003):

BHs may form direct core collapse from a very massive progenitor (50-150 $M_{\odot}$) in a low metallicity environment (e.g. Cropper et al. 2004; Zampieri et al. 2004)

Black holes of 50-150 $M_\odot$ in ULXs?

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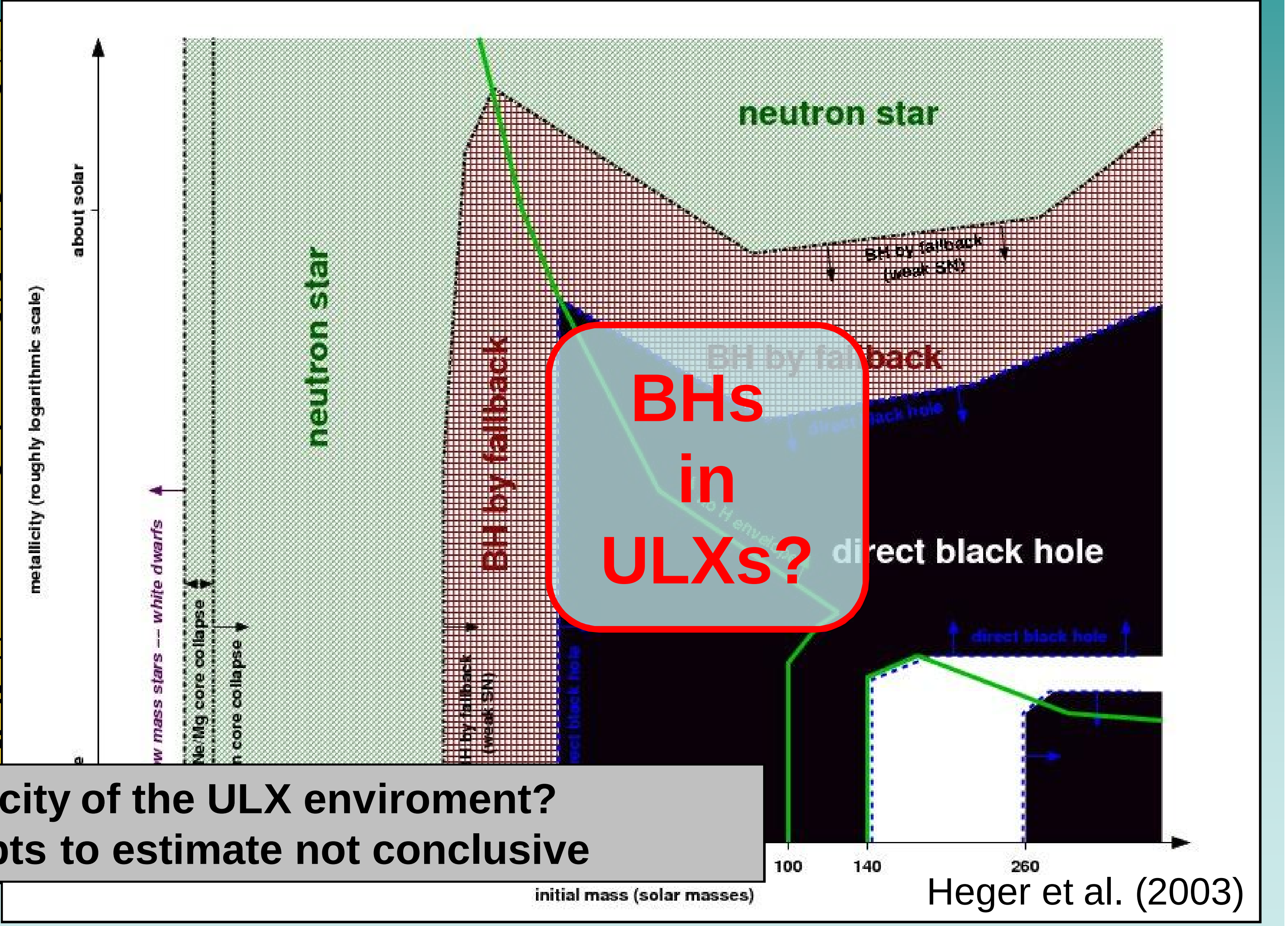

BHs in ULXs?

Heger et al. (2003)

Metallicity of the ULX enviroment?
Attempts to estimate not conclusive

Conclusions

- Presented estimates of BH masses in ULXs based on the “variability plane”: M82 X-1, NGC5408 X-1 → M_{BH} ~ 100-1000 $M_\odot$
- Compared the temperature profiles and spectra of standard and relativistic accretion disks with those of a MCD model → revision of the MCD estimates of M_{BH} (max rotating Kerr has M_{BH} 6 times lower)

→ May ULXs host BHs with masses ~50-150 $M_\odot$?

→ **Formation via direct core collapse from a very massive progenitor (50-150 $M_\odot$) in a low metallicity, clustered environment**

Future perspectives:

* Measurements of the dynamical mass function from spectral lines

* Very long X-ray observations of selected ULXs (timing, high counting statistics spectra)

* Monitoring of ULXs with known QPOs

* Detailed investigation of the environment (metallicity, parent population) → IR, UV?

* Theoretical models of disc spectra at high Mdot