First results from the use of the relativistic and slim disc model SLIMULX in XSPEC

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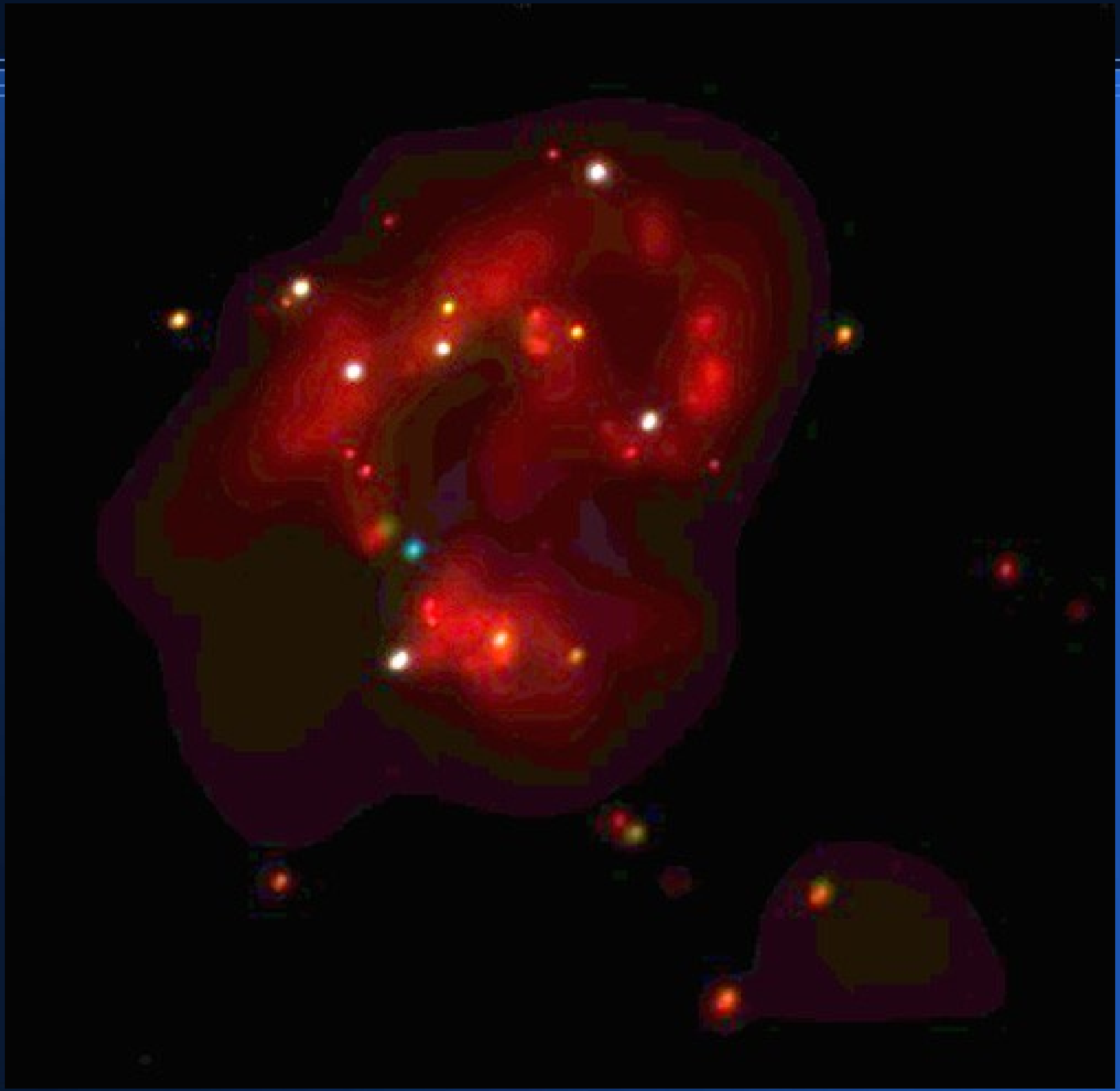
on behalf of a larger collaboration

Ultra-Luminous X-ray sources



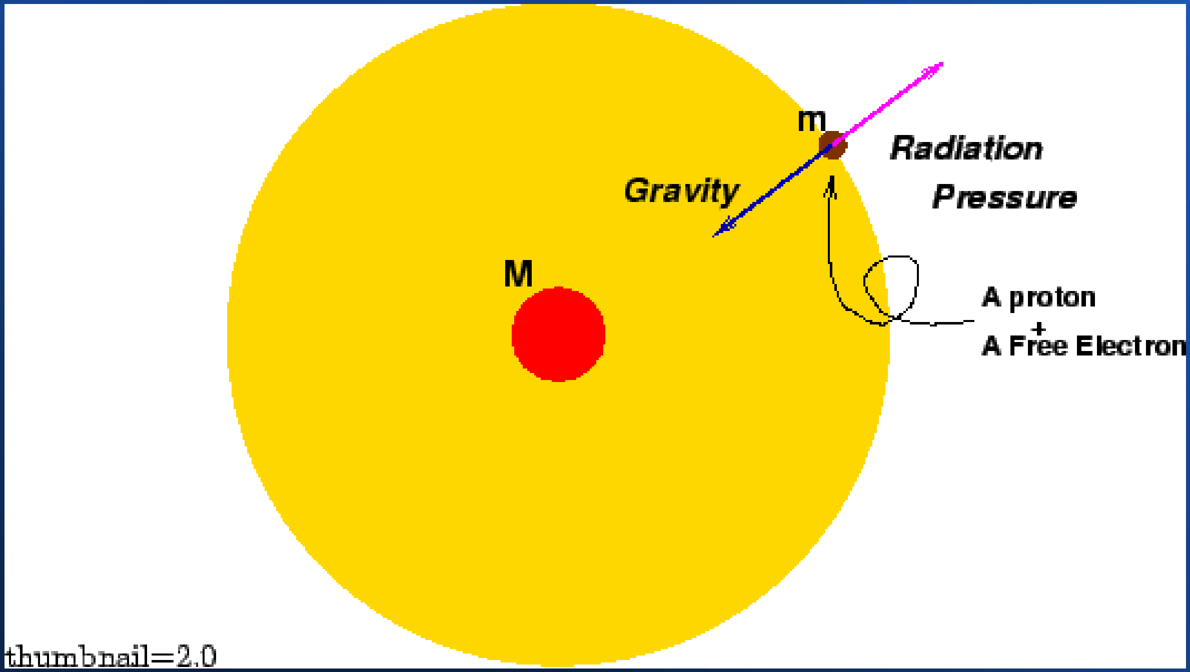
Chandra X-ray image of the Antennae galaxies (from Fabbiano et al. 2004)

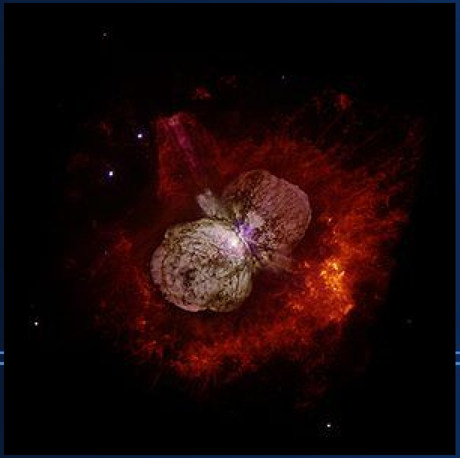
The Ultra-Luminous X-ray sources

- Ultra-Luminous X-ray (ULX) sources are point-like, off-nuclear sources observed in other galaxies, with ***total observed*** luminosities greater than the Eddington luminosity **for a stellar-mass black hole** ($L_X \sim 10^{38}$ erg/s).

→ either the emission *is not isotropic* or the black hole has a higher mass ($M_{BH} \geq 20\ M_{\odot}$).

The Eddington limit





Eta Carinae (Eddington limit exceeded)

- Probably the maximum luminosity of a star.

$$\sigma_p \frac{L}{4\pi c r^2} \leq \frac{GMm_p}{r^2}$$

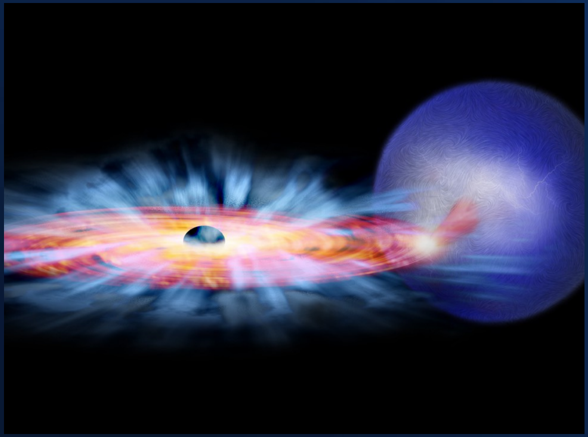
$$L \leq \frac{4\pi G m_p c}{\sigma_T} M \equiv L_{EDD}$$

$$L_{EDD} = 1.2 \times 10^{38} \left(\frac{M}{M_\odot}\right)$$

- It depends on the mass of the star.
- When the source emits isotropically. If not, this limit can be *exceeded*.

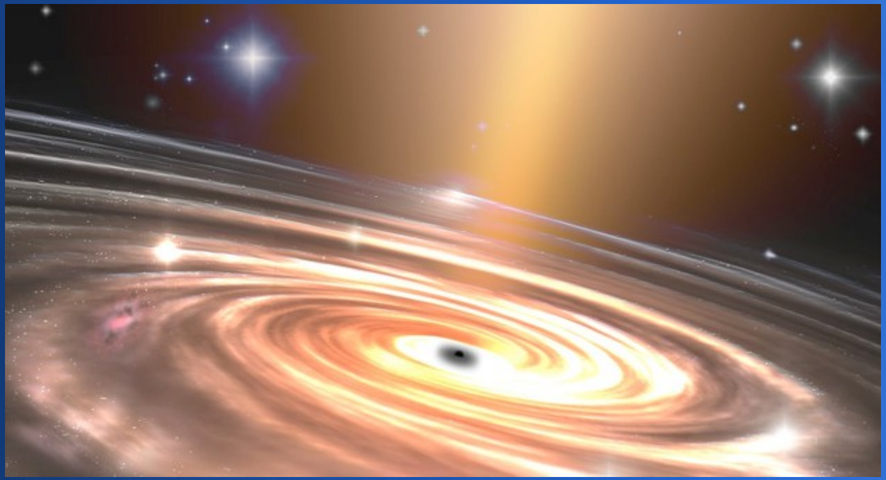
The Ultra-Luminous X-ray sources

- This opens a real possibility to the *existence of the InterMediate-Mass Black Holes* (IMBHs; $M_{BH} \geq 10^2$-10^4 $M_\odot$; Colbert & Mushotzky, 1999).
- The existence of these ULXs-IMBHs is controversial only few cases recently confirmed (ESO 243-49 HLX1, Farrell et al. 2011; see Sutton et al. 2012 for a few more candidates).



Stellar-mass Black Hole (BHB)

?



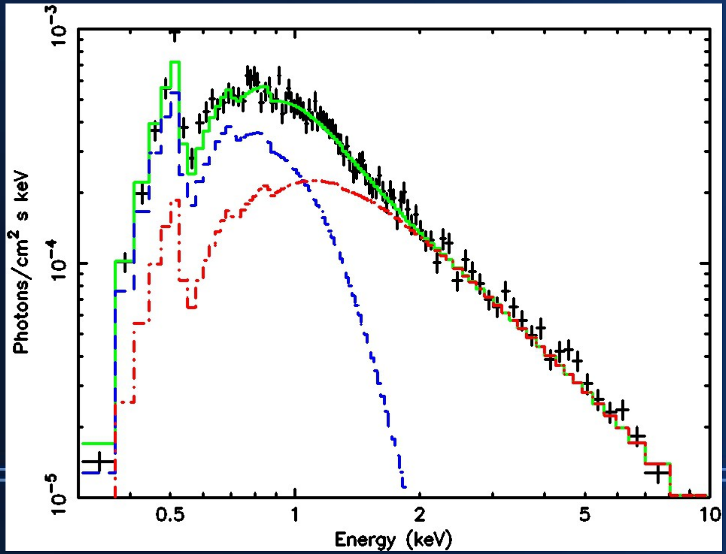
Supermassive Black Hole (AGN)

The Ultra-Luminous X-ray sources – the Standard (thin) Disc Theory

- **X-ray spectroscopy is useful. From the *Standard (Thin) Disc Theory* (applicable to sub-Eddington flows) the inner disk temperature scales with the mass of the BH as (Makishima et al. 2000)**

$$kT_{in} \sim M^{-1/4}$$

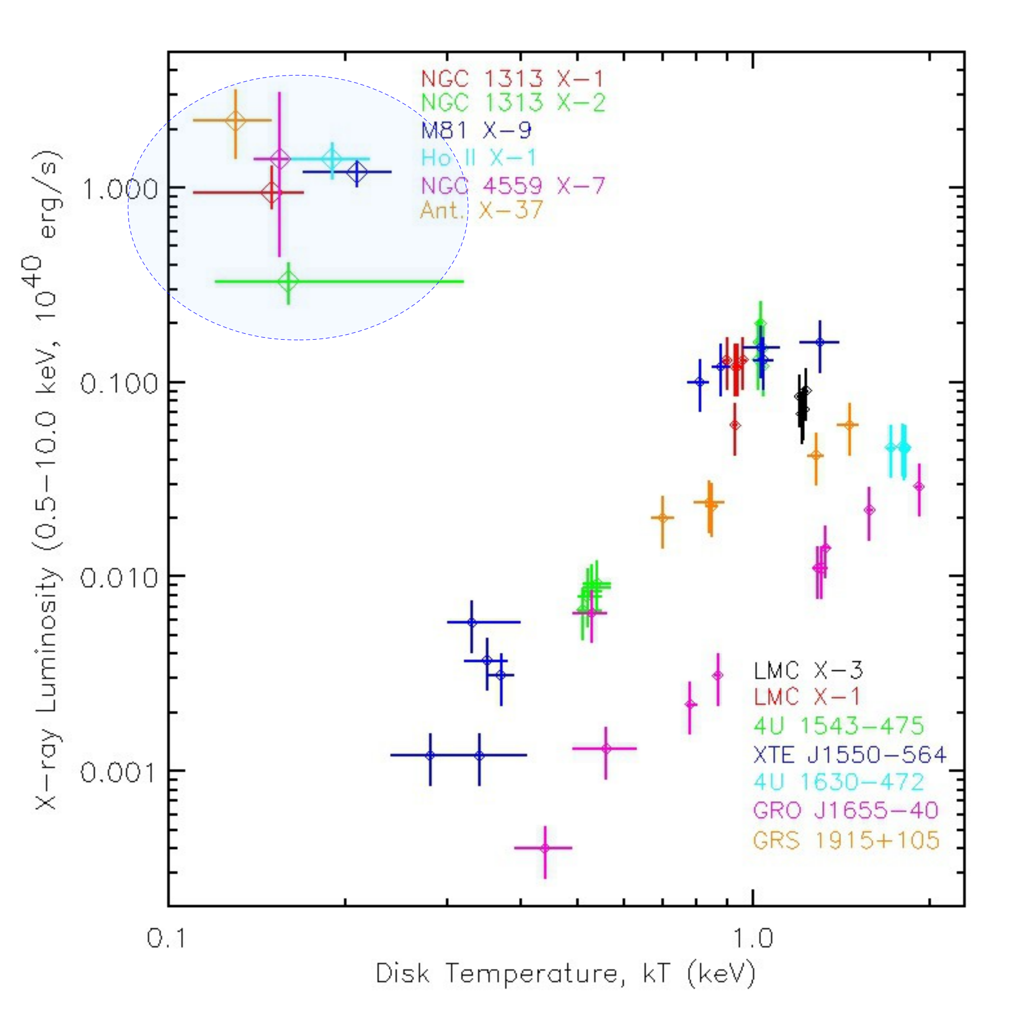
→ Inner disc t*emperatures found imply IMBHs for some ULXs (Miller et al. 2004).*



The XMM-Newton/EPIC-pn X-ray spectrum of NGC 1313 X-1 is shown (Miller, Fabian, & Miller 2004).

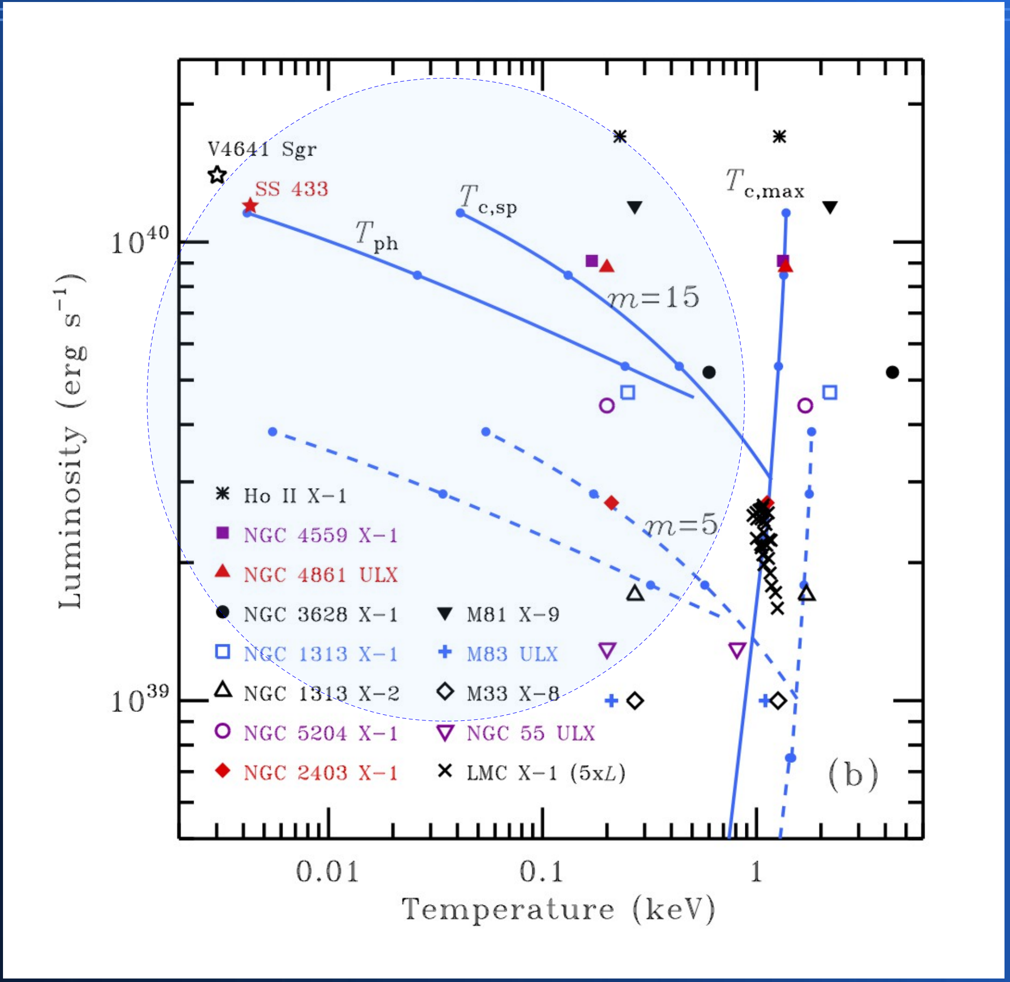
The need of slim-disc models

INNER DISC TEMPERATURE IS APPROX. "CONSTANT" (0.1-0.2 keV)



X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Miller, Fabian & Miller (2004).

The need of slim-disc models

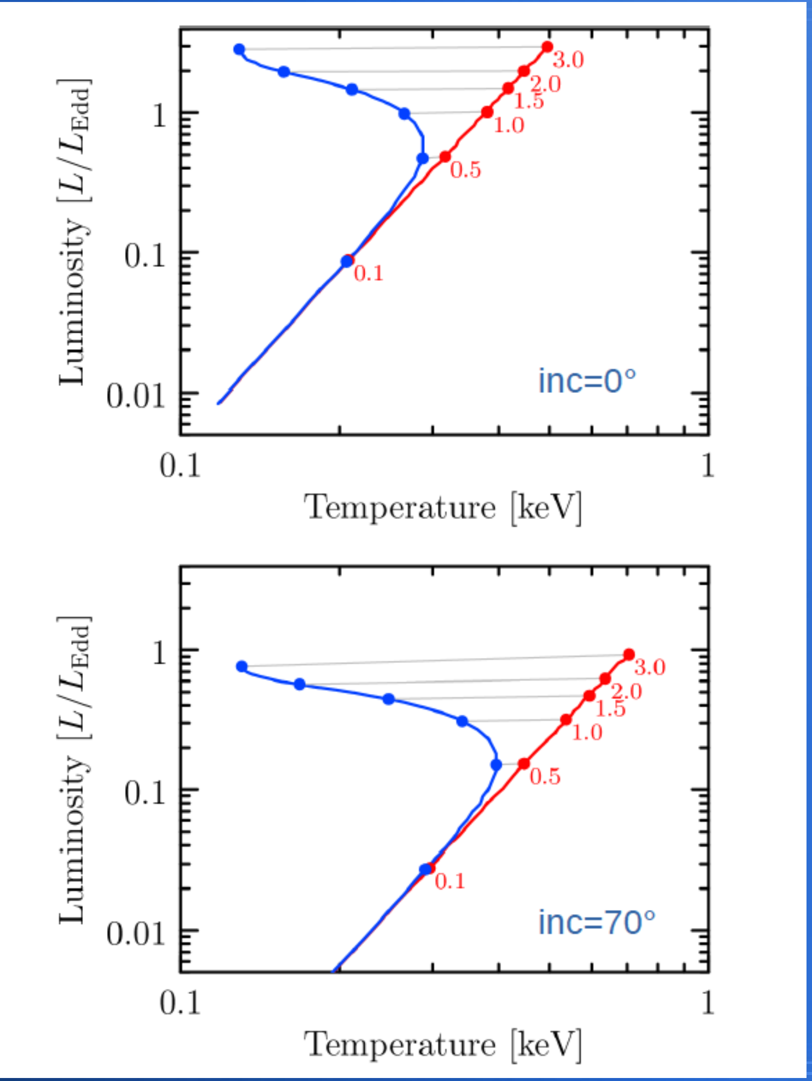


X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Poutanen et al. (2007).

The need of slim-disc models

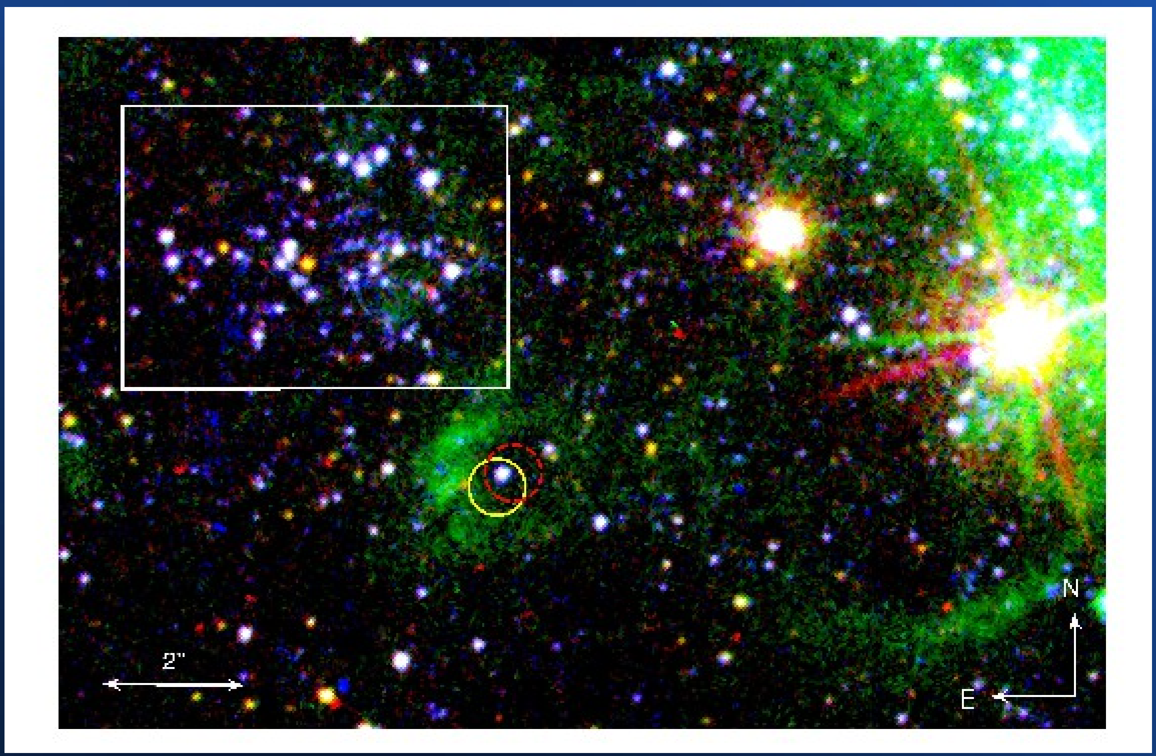
L-T plot in near-Eddington case

- Standard (thin) disc follows L~T^4 relation.
- Advection and obscuration effects cause *significant deviations from that relation in super-Eddington regime*.
- The effect is strong inclination dependent.
- Observed luminosity *can stay around Eddington* if mass accretion rate is high.



X-ray luminosity versus inner disc temperature for the standard (red) and the slim accretion disc (blue). Figure taken from Bursa (2016).

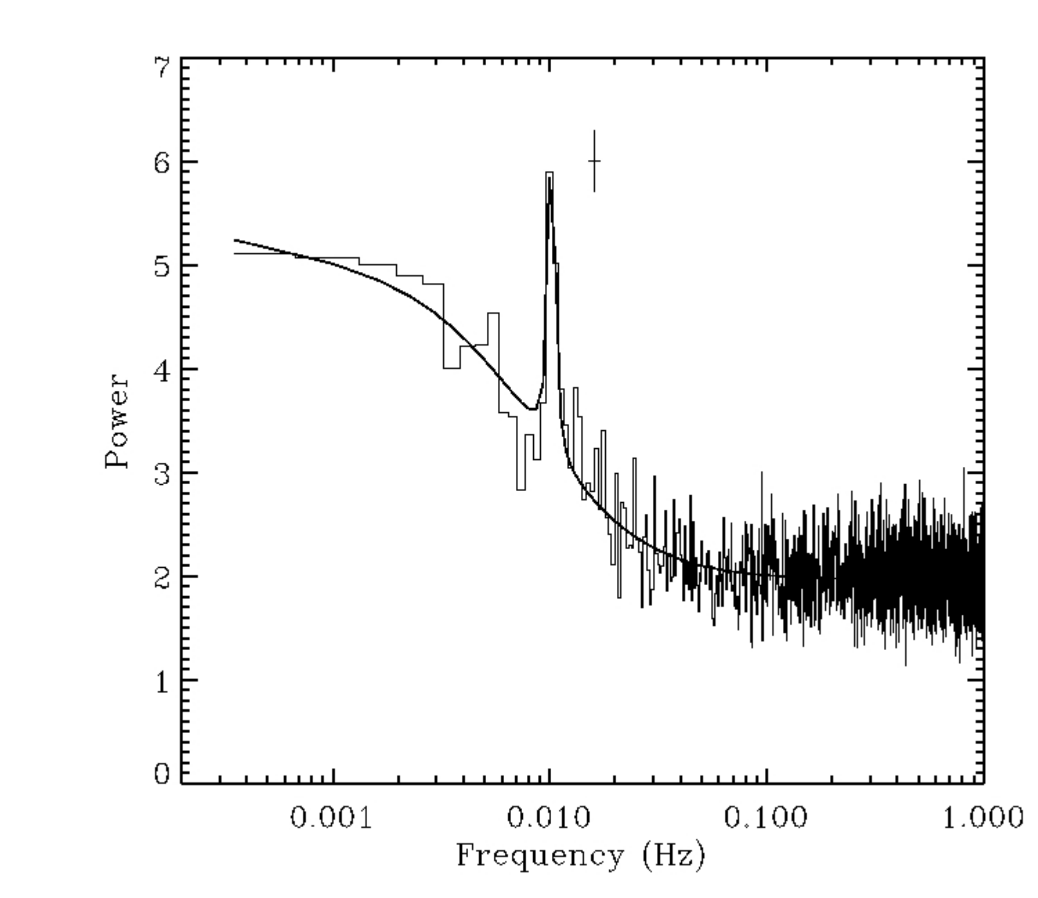
NGC 5408 X-1



HST image (blue - F225W, green - F502N, red - F845M) of ULX NGC 5408 X-1 (circled), the surrounding field and a nearby stellar association (box) (from Grise et al. 2012)

- Nearby (D=4.8 Mpc)
- Peak (*RXTE*, 0.3-10 keV, 2008-2009) X-ray luminosity of $L_X=2\times10^{40}$ erg/s (Strohmayer, 2009).
- Strohmayer & Mushoztky (2009) estimated a BH mass of $M=10^3$-10^4 $M_\odot$
- 6-Long 100 ks observations with XMM-Newton performed in 5 years (2006-2011).
- *X-ray timing and spectral analysis* reported in Strohmayer et al. (2007), Strohmayer & Mushotzky (2009), Dheeraj & Strohmayer (2012), Caballero-Garcia et al. (2013).

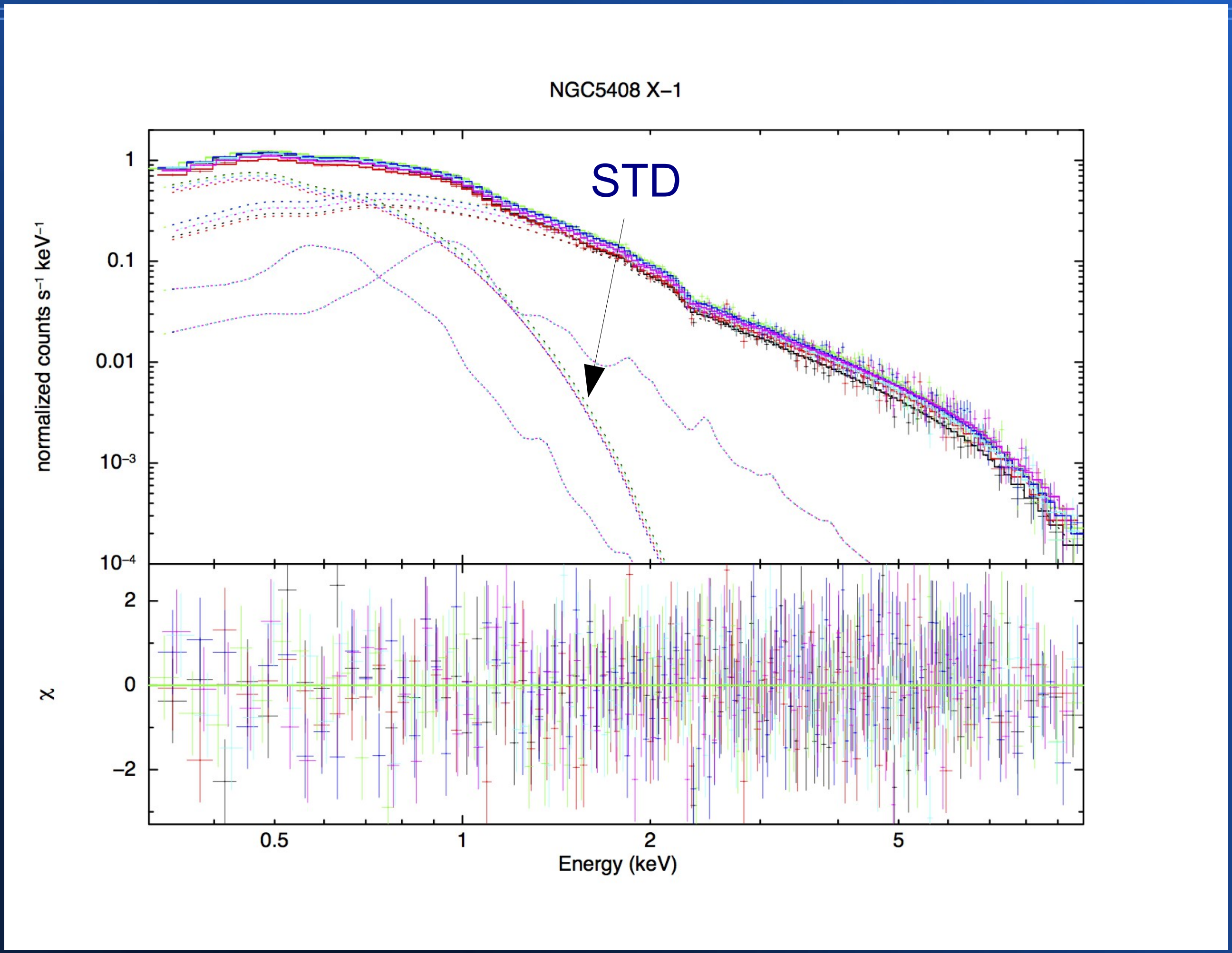
NGC 5408 X-1 – X-ray timing



Average PDS of NGC5408 X-1 (from Strohmayer & Mushotzky, 2009)

- BH masses scale with the break frequency of their Power Density Spectrum (PDS; McHardy et al. 2006; Kording et al. 2007). This relation holds over six orders of magnitude in mass, i.e., from Black Hole Binaries (BHBs) to Super-Massive Black Holes (SMBHs).
- PDS and the energy spectrum of NGC 5408 X-1 are *very similar to that of BHBs in the Steep Power-law (SPL) state. BUT the* characteristic timescales within the PDS are lower by a factor of ≈100 and X-ray luminosity is higher by a factor of a few ×10, when compared to BHBs.

NGC5408 X-1 X – X-ray spectroscopy



XMM-Newton fitted-spectra from the 6 observations (from Caballero-Garcia et al., 2013)

- Little spectral evolution (slight spectral hardening), in spite of the observations spread in 5 yr.
- Fit with several phenomenological models (*diskbb* or *diskpn* for the soft X-rays and *powerlaw* or *compTT* for the high-energies; 2 *apec* for the diffuse emission).
- Steep spectra ($\Gamma \approx 3$) and cold (and constant) inner disc temperature ($kT_{in} \approx 0.17$ keV) → $M = 2 \times 10^3 M_{\odot}$; $\eta = 10^{-1}$

Does it mean that we have found one of the IMBHs proposed to exist as cosmological seeds of current galaxies by Madau & Rees (2001)

?!

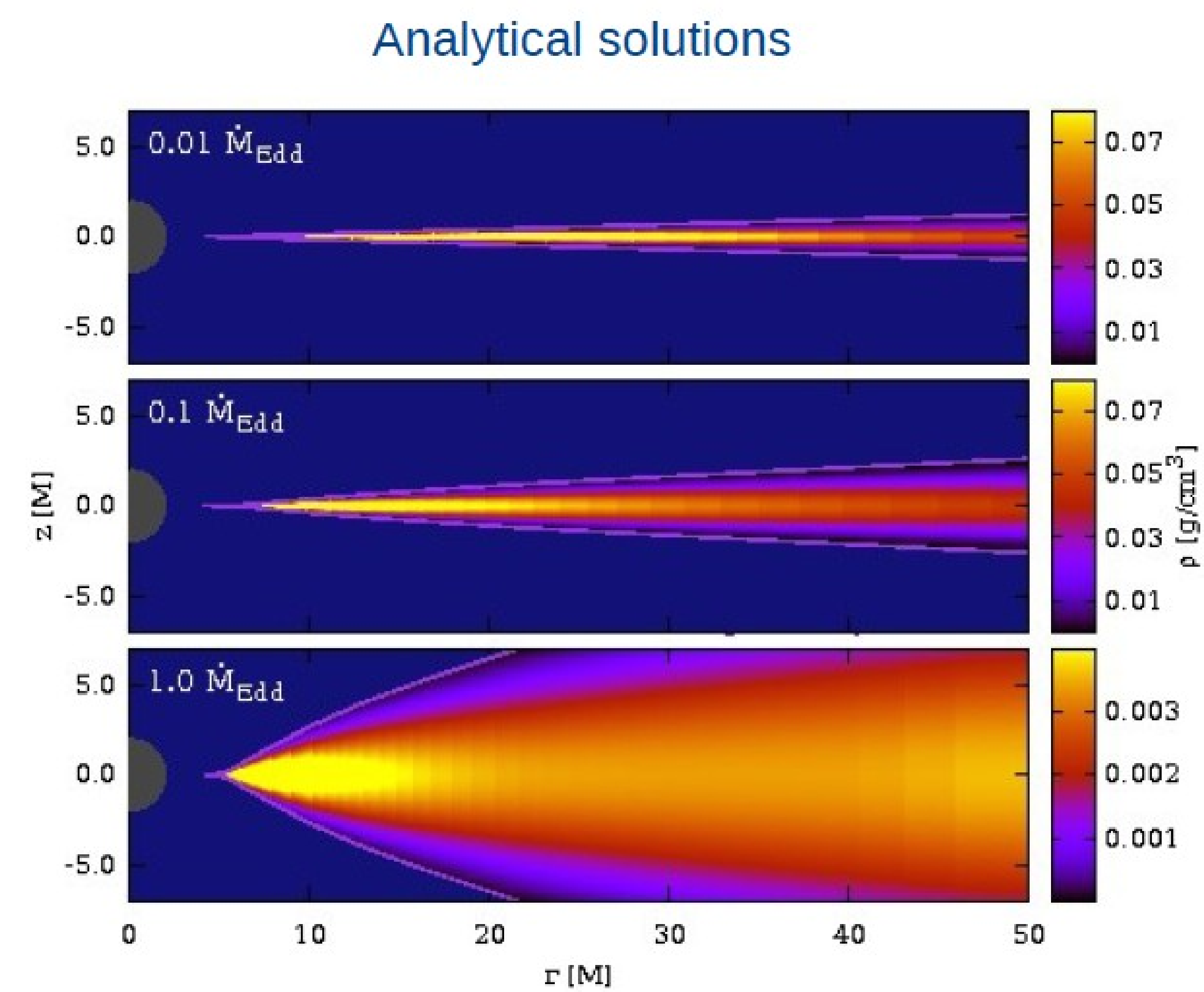
Very likely not

The SLIMULX model

[*It is a thermal disc model (effects from the corona not taken into account)*]

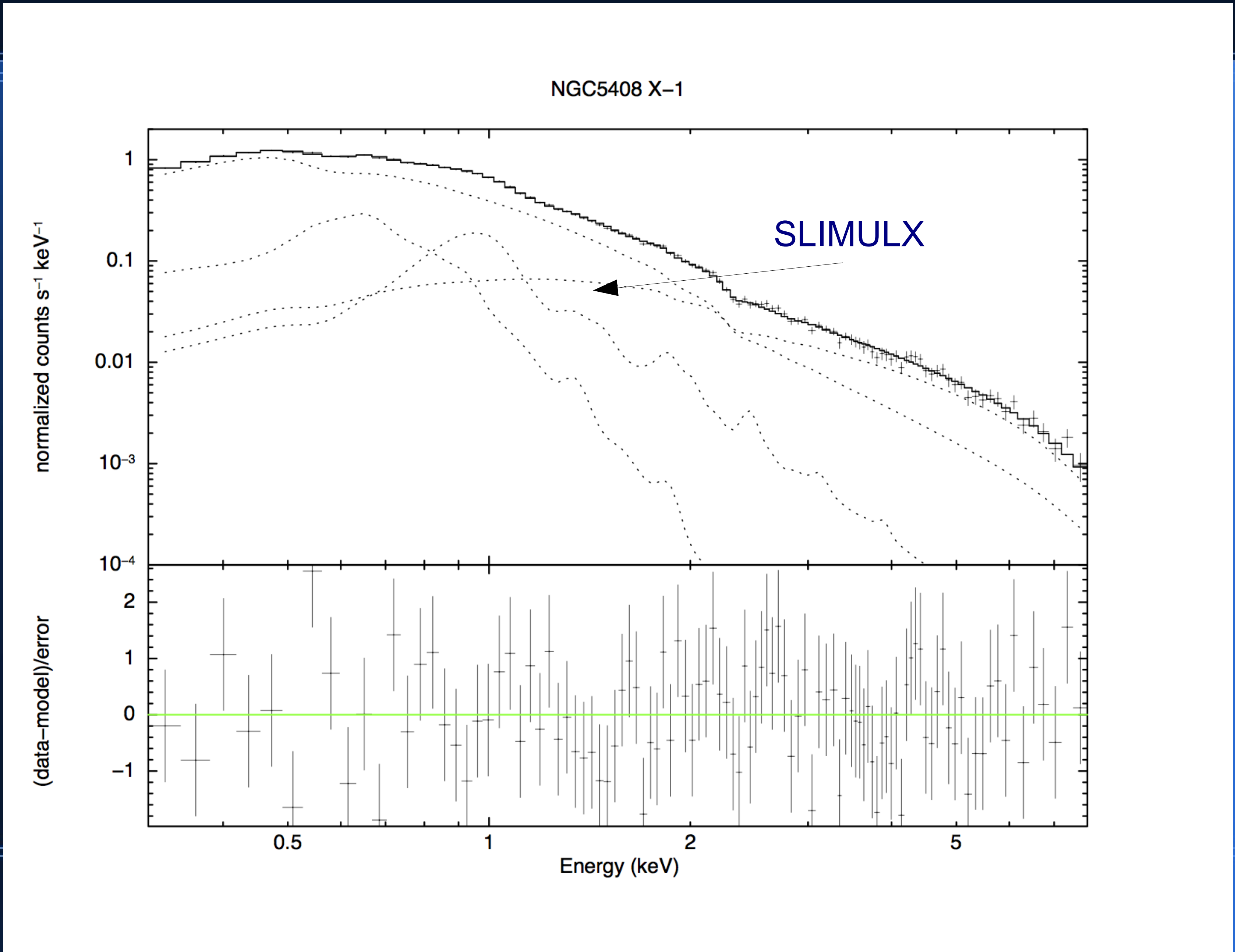
- Thin disc model is inaccurate for L>0.3 L_{EDD}.
- Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).
- Standard (thin) discs follow $L \sim T^4$ relation.
- Advection and obscuration effects cause significant deviations from that relation in super-Eddington regime.
- The effect is strongly inclination dependent.
- Observed luminosity can stay around Eddington even if mass accretion rate >> 1 → *Reduces inferred BH mass* !!!!!
- General Relativistic effects are fully consistently taken into account.

The SLIMULX model



Sadowski+2009

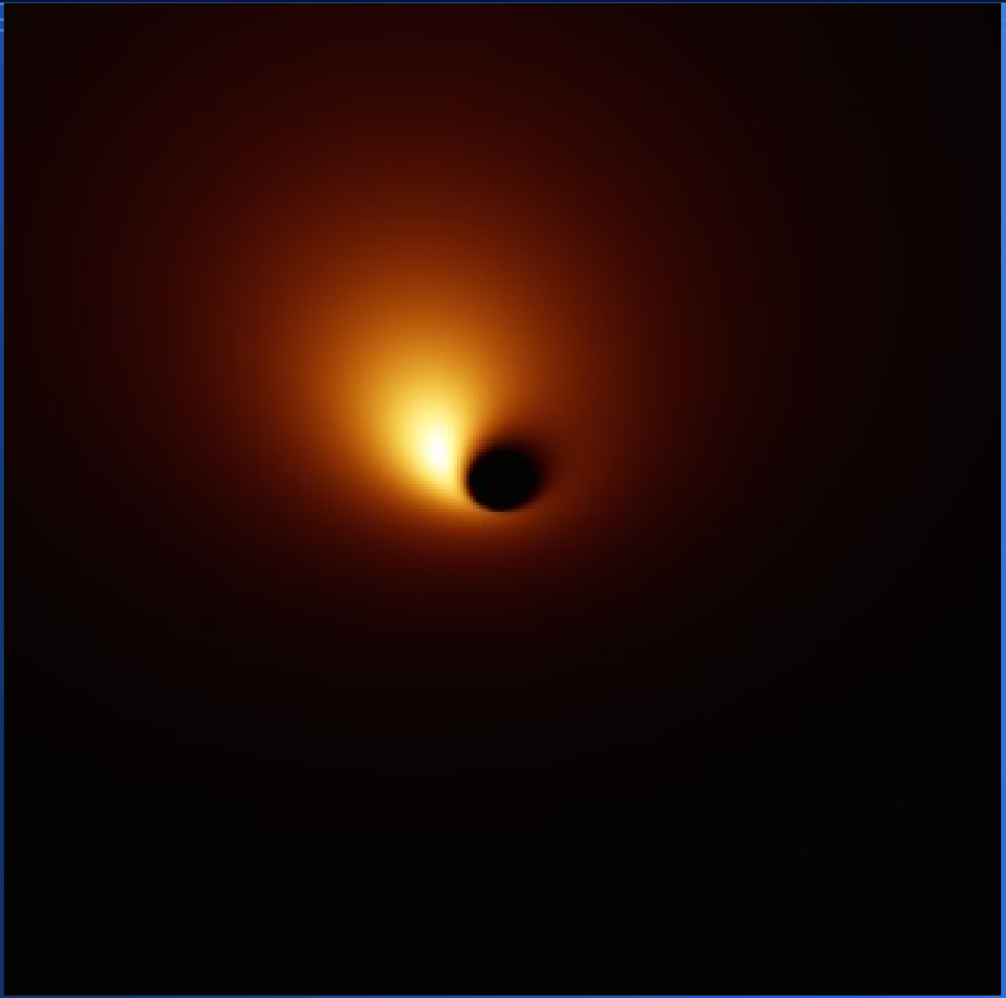
NGC 5408 X-1 spectrum fitted with SLIMULX



The SLIMULX model

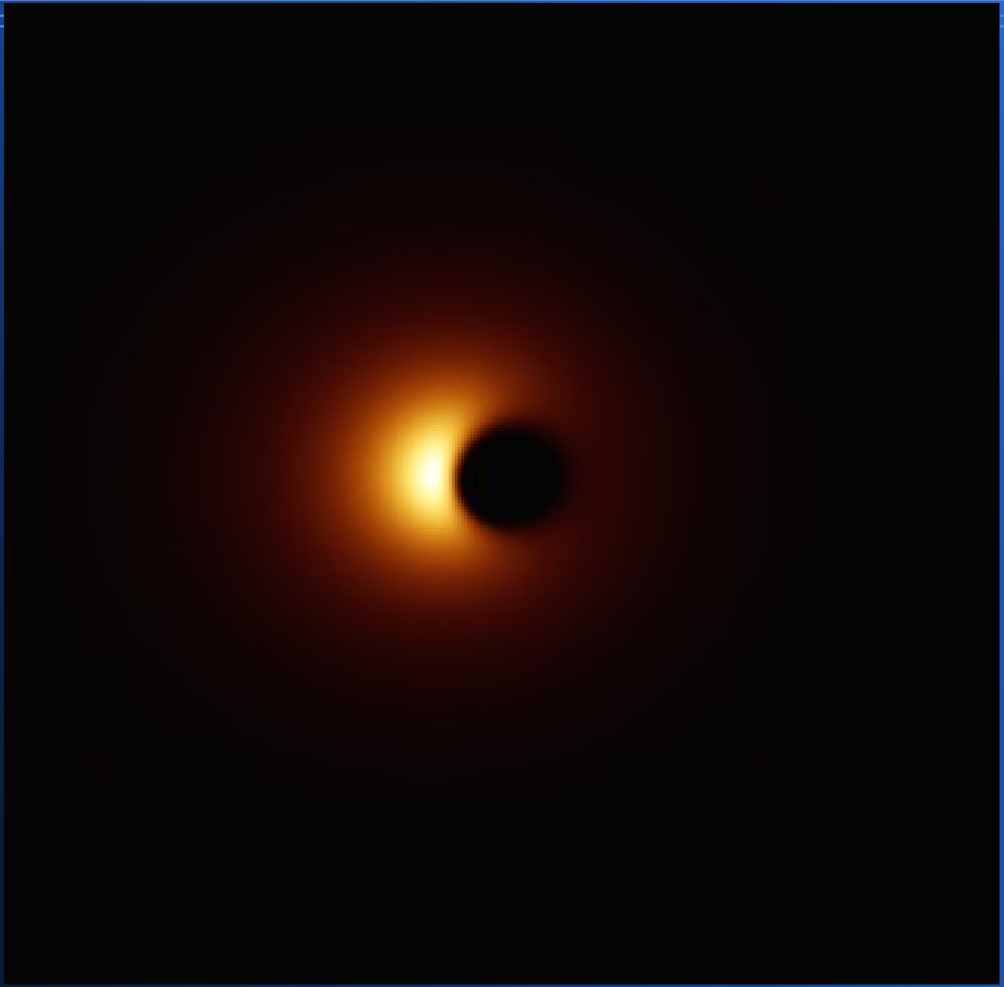
Obtained parameters

- $M_{BH} = 5.7 \pm 0.2\ M_{\odot}$
- $a = 0.99$
- $L = 3.2 \pm 0.3\ L_{EDD}$
- $i \leq 30$ deg.
- h (disc thickness)= 1



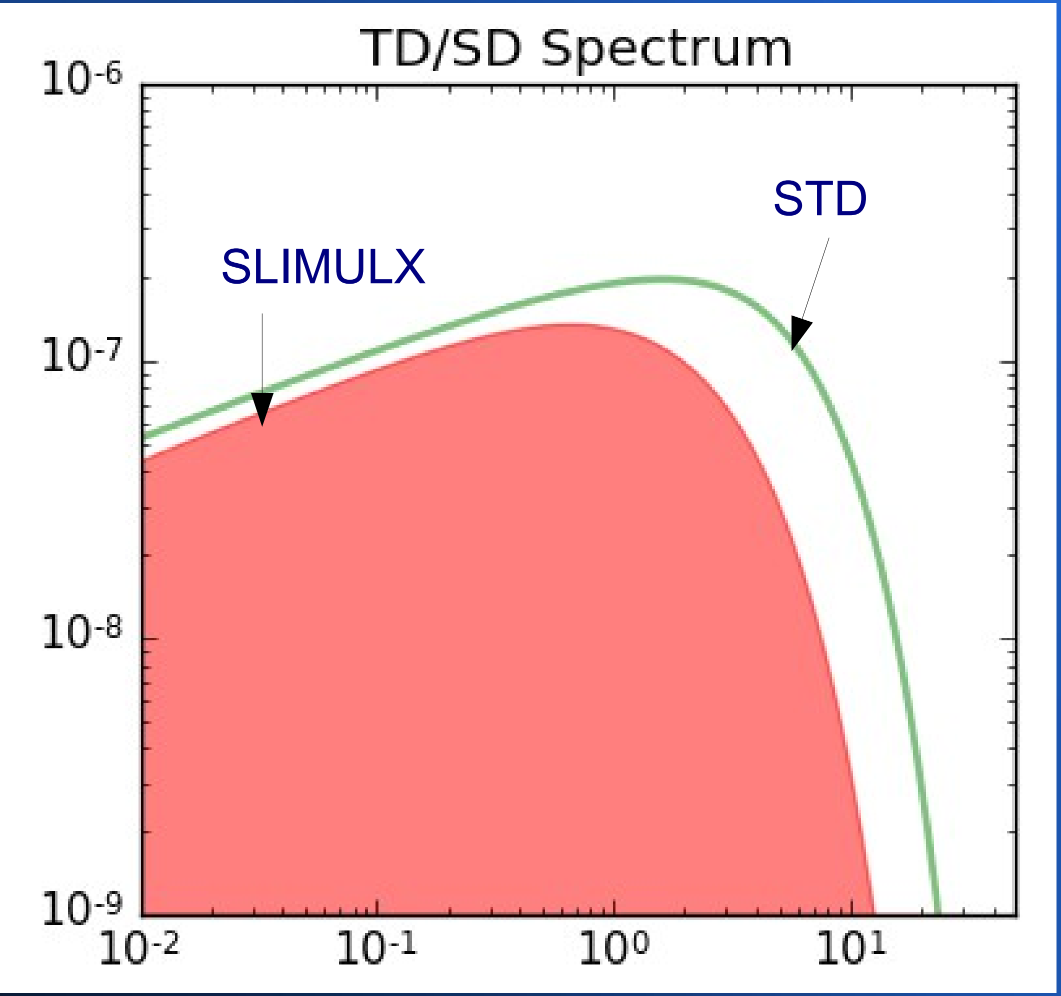
Accretion disc as seen from an observer located at inf nity (credits: M. Bursa)

Standard (thin) Disc Theory



Standard accretion (thin) disc as seen from an observer located at inf nity (credits: M. Bursa)

Standard (thin) vs. Slim Disc Spectra



(Credits: M. Bursa)

Summary and Conclusions

- Standard (thin) disc model is inaccurate for $L_{disc} > 0.3\ L_{EDD}$.
- Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).
- Standard (thin) accretion disc theory is not enough → need to move on to *slim-discs*.
- For the case of NGC 5408 X-1 ***a maximally rotating, of 5*** $M_{\odot}$ ***BH*** is inferred.
- No need of IMBH for NGC 5408 X-1 (prototype of the ULX classification).

Acknowledgements

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STRONGGRAVITY

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