An upper limit on the black hole mass for optically dark X-ray bright sources in nearby galaxies

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INTRODUCTION

- **Compact, off-nuclear X-ray point sources in nearby galaxies, with luminosities 10^{39}-10^{41} ergs s^{-1} are referred as Ultra-luminous X-ray sources (ULXs).**
- **The observed luminosities of ULX sources exceeds the Eddington limit for a $10M_{\odot}$ black hole. Since ULXs are off-nuclear sources, their masses must be $< 10^5 M_{\odot}$ from dynamical friction arguments [1].**
- **Thus the allowed black hole mass range for X-ray sources in nearby galaxies span five orders of magnitude ($10M_{\odot} < M < 10^5 M_{\odot}$) and it is important to obtain tighter constrains.**

OBSERVATIONS AND DATA REDUCTION

- We selected a sample of 13 galaxies from *Devi et al.* [2] and *Swartz et al.* [3] (See Table 1). The Optical study was carried out using the Advanced Camera Survey (ACS) and Wide Field Planetary Camera 2 (WFPC2) that are available in the *HST* data archive.
- Most of the optical sources are too faint to be detected against the dominant galaxy light that fills most of the *HST* images. To enhance the contrast, and aid in the detection of point sources in the image, the galaxy light was modelled based on the isophotes obtained using the ellipse task in *IRAF/STSDAS* software.
- The residual image was obtained by subtracting the model image from the observed galaxy image. The object extraction was done on the residual image using *SEXTRACTOR* with a threshold level of 3 sigma.
- On visual inspection, many of the *Chandra* X-ray sources have counterparts within a positional off-set of less than a few arc-seconds. This constant off-set was applied for the galaxy to match the *Chandra* sources to the optical sources in the *SEXTRACTOR* catalog.

RESULTS

- A total of 84 point sources were analyzed in 13 elliptical galaxies. Fifty six of them are having possible optical counterparts in their respective position. Twenty eight sources have no optical counterparts and named as **optically dark** or **field** X-ray sources.
- These optically dark sources are X-ray bright compared to their optical emission and hence are not foreground stars and are unlikely to be background AGNs.
- This can be further quantified by estimating X-ray-to-optical flux ratio. This ratio ranges from 0.1 to 50 for AGNs including BL Lacs. In contrast, the estimated lower limits for the optically dark sources in the sample is significantly larger. Thus we can conclude that these sources are not background AGNs.
- These sources are most likely to be bright X-ray binaries (or at least accreting systems) within the galaxy. An accretion disk around a compact object should also produce optical emission whose flux can be estimated by the standard accretion disk theory [4]. The observed flux from the disk at a frequency ν is given by,

$$F_\nu = \frac{\cos i}{D^2} \int_{R_{in}}^{R_{out}} B_\nu(\nu, T(R))\, 2\pi R dR$$

- Assuming that most contribution to F_ν arises from the region in the disk that are far away from the inner and outer radii, the expected observed flux can be written as,

$$F_\nu \sim 7 \times 10^{-31} \text{ ergs s}^{-1}\text{cm}^{-2}\text{Hz}^{-1} \left(\frac{\lambda}{5000A}\right)^{-1/3} \left(\frac{\eta}{0.1}\right)^{-2/3} \times \left(\frac{L_x}{10^{39} \text{ergs } s^{-1}}\right)^{2/3} \left(\frac{D}{10\text{Mpc}}\right)^{-2} \left(\frac{M}{1000 M_{\odot}}\right)^{2/3}$$

- For optically dark sources, the predicted accretion flux should be less than the measured upper limit $F_{\nu,max}$. Thus one can estimate an upper limit on black hole mass as

$$M_U < 1000\ M_{\odot} \left(\frac{F_{\nu,max}}{7 \times 10^{-31} \text{ ergs s}^{-1}\text{cm}^{-2}\text{Hz}^{-1}}\right)^{3/2} \times \left(\frac{\lambda}{5000A}\right)^{1/2} \left(\frac{\eta}{0.1}\right) \left(\frac{L_x}{10^{39} \text{ergs } s^{-1}}\right)^{-1} \left(\frac{D}{10\text{Mpc}}\right)^{3}$$

- For each source, we estimated this upper limit on the black hole mass and the ten best cases in ascending order of black hole mass limit is listed in the Table 2. The best case is for the ULX in NGC 4486, for which $M_U = 1244 M_{\odot}$.

TABLE 1:
Sample Galaxy Properties

Galaxy	Distance (Mpc)	N_x	N_d
NGC 1399	18.3	26	4
NGC 4649	16.6	12	5
NGC 4697	11.8	11	3
NGC 1291	8.9	5	1
NGC 4365	20.9	4	3
NGC 1316	17.0	7	3
NGC 4125	24.2	3	3
NGC 3379	11.1	3	1
NGC 4374	17.4	2	1
NGC 4486	15.8	5	2
NGC 4472	15.9	1	0
NGC 1407	17.6	2	2
NGC 4552	15.9	3	0

NOTE. — (1) Host galaxy name; (2) Distance to the galaxy ; (3) Number of X-ray sources within HST field of view; (4) Number of X-ray sources without optical counterparts

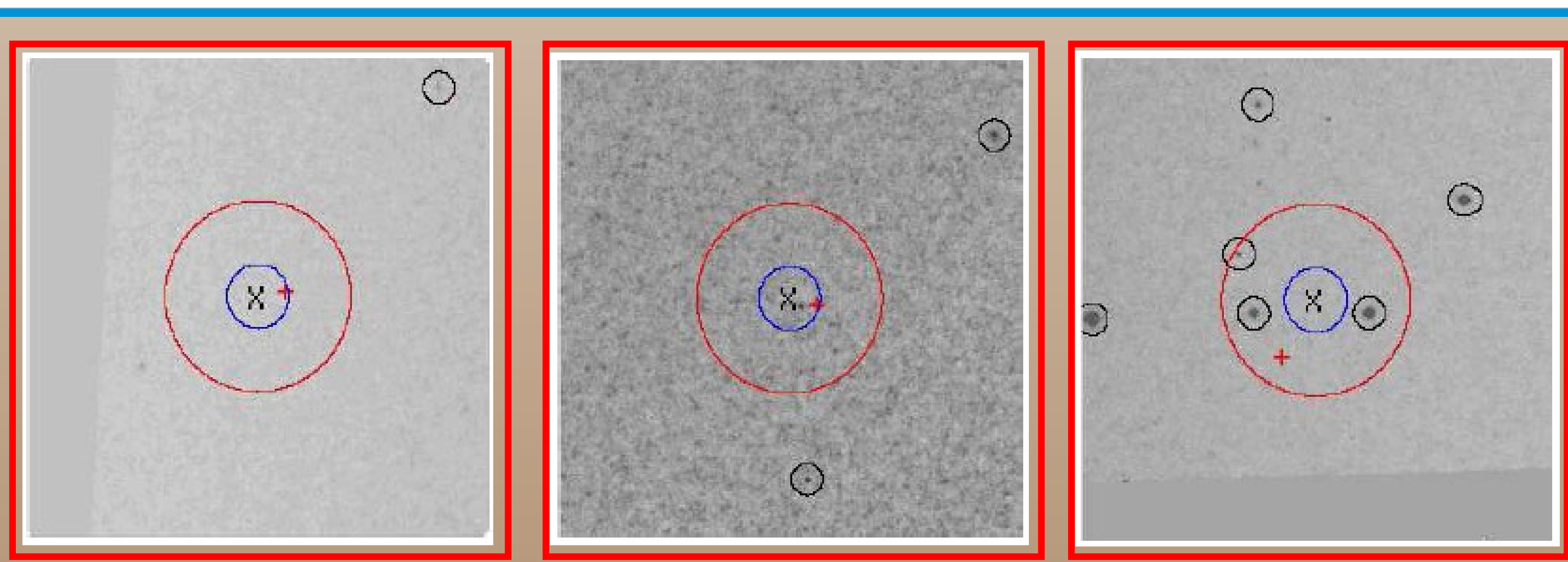
CONCLUSIONS

- **These optically dark X-ray sources cannot be foreground stars and are highly unlikely to be background AGNs.**
- **The non-detection of optical emission impose an upper limit on the black hole mass M_U. For ten sources $M_U < 10{,}000 M_{\odot}$ and for one of the bright ULX sources in NGC 4486, the black hole mass is smaller than $1244 M_{\odot}$.**
- **This is two order of magnitude smaller than the constrain obtained from dynamical friction arguments, $10^5 M_{\odot}$.**

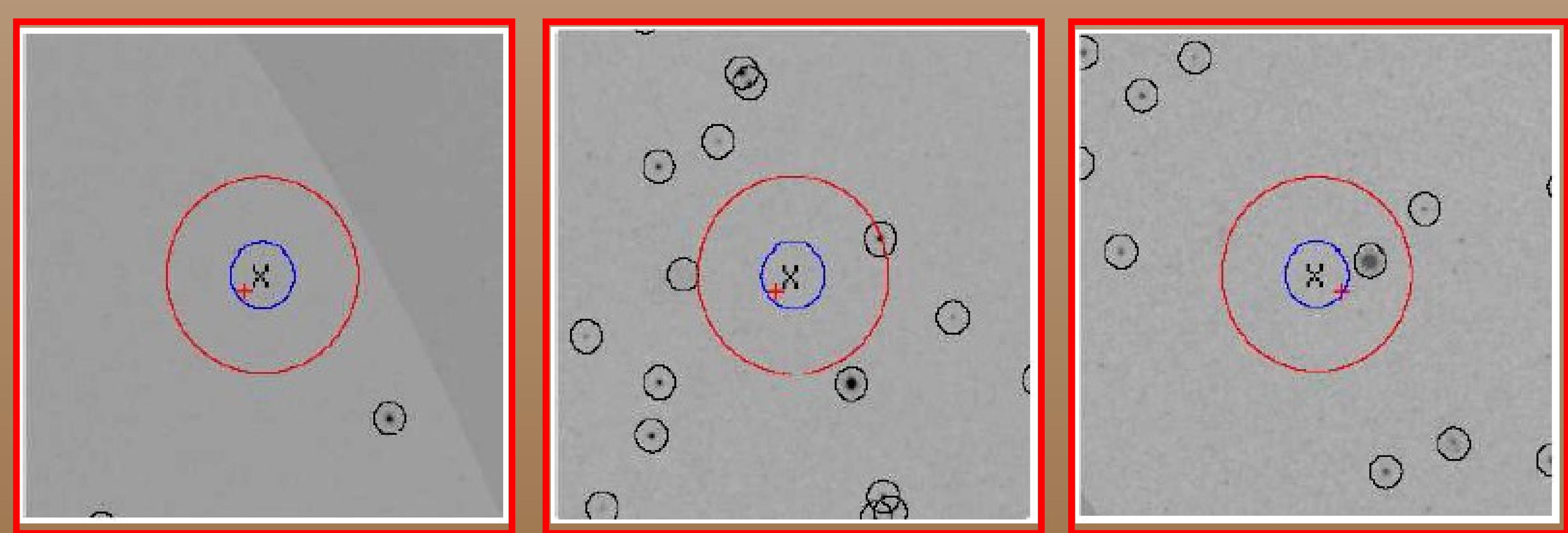
TABLE 2:
The Upper limit of Black hole Mass of Ten Optically Dark X-ray Sources

Galaxy	*R.A*(*J*2000)	*Decl.*(*J*2000)	log L_x	HST Filter	$F_\nu \times 10^{-30}$	F_X/F_O	$M_U(M_{\odot})$
NGC4486	12 30 50.82	+12 25 02.66	$39.17^{+0.05}_{-0.04}$	F475W	0.409	533	1244
NGC4697	12 48 33.20	-05 47 41.17	$38.84^{+0.06}_{-0.05}$	F475W	0.752	243	2890
NGC4649	12 43 41.90	+11 34 33.83	$38.91^{+0.47}_{-0.11}$	F475W	0.402	164	3073
NGC4374	12 25 01.54	+12 52 35.59	$39.10^{+0.67}_{-0.22}$	F475W	0.441	347	3378
NGC1399	3 38 25.92	-35 27 42.37	$38.62^{+0.12}_{-0.09}$	F606W	0.370	228	3927
NGC1316	3 22 36.46	-37 13 24.68	$38.80^{+0.23}_{-0.08}$	F475W	0.449	179	4780
NGC1316	3 22 35.58	-37 13 14.10	$38.78^{+0.40}_{-0.07}$	F555W	0.520	287	6366
NGC1399	3 38 32.33	-35 26 45.73	$38.54^{+1.13}_{-0.41}$	F606W	0.377	186	7829
NGC1399	3 38 27.62	-35 26 48.76	$39.42^{+0.16}_{-0.14}$	F606W	0.766	702	7829
NGC4649	12 43 34.17	+11 33 41.93	$39.04^{+0.10}_{-0.11}$	F475W	0.912	97	8073

NOTE. — (1) Host galaxy name; (2) Right Ascension of shifted position in hours, minutes and seconds; (3) Declination of shifted position in degrees, arcminutes and arcseconds; (4) log of X-ray luminosity in *ergs/s*; (5) HST filter for which the upper limit on flux and the black hole mass limit is calculated; (6) Upper limit on Optical flux in ergs/s/cm^2/Hz; (7) Lower limit on ratio of X-ray to optical flux; (8) M_U, Upper limit on black hole mass.



(a)NGC 4486 (b)NGC 4697 (c)NGC 4649



(a)NGC 4374 (b)NGC 1399 (c)NGC 1316

Fig 1 : The HST image of the first six X-ray sources listed in the table 2. Overlaid are 1" and 3" circles centered on the shifted *Chandra* positions. The plus sign marks the original *Chandra* positions. Note that for four of the images, there are no optical sources even within 3" of the X-ray position.

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