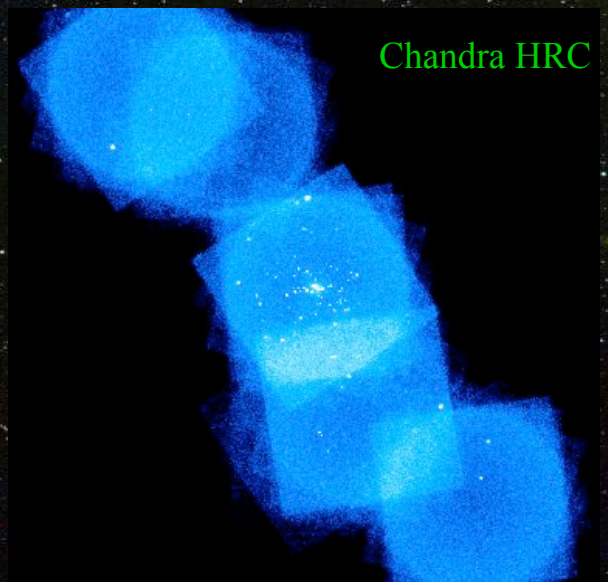
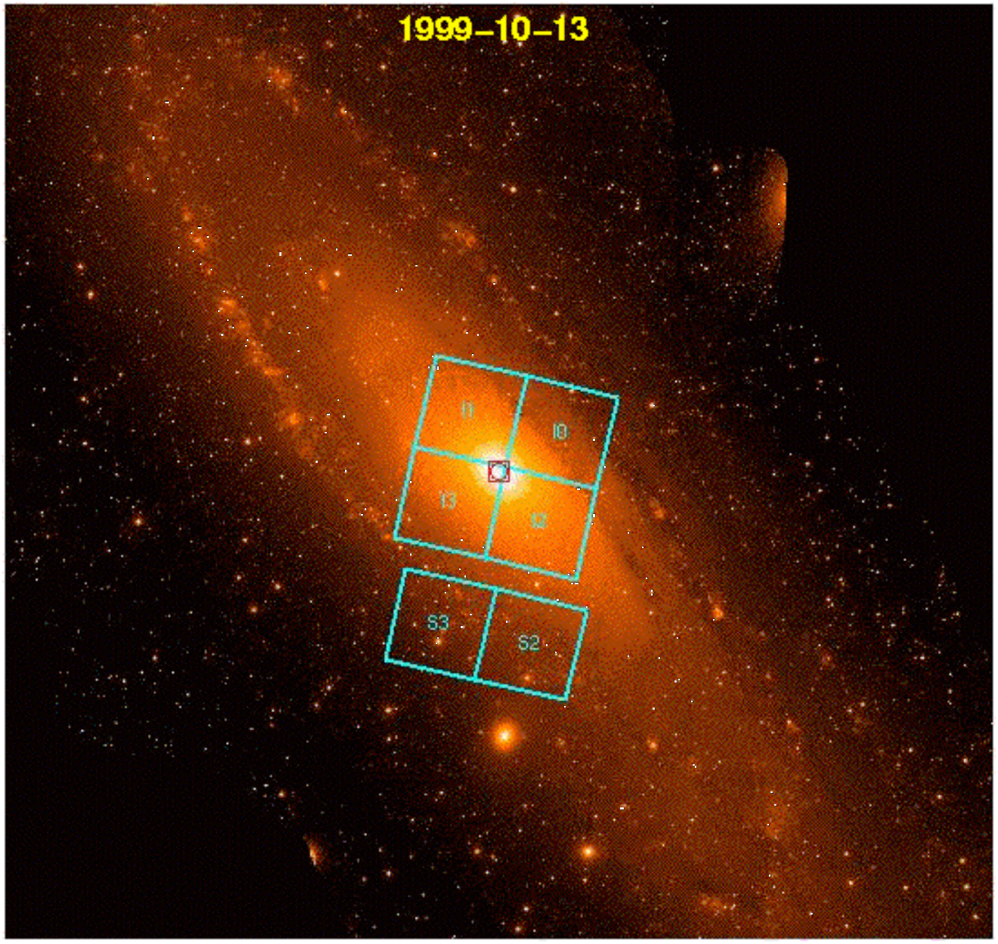
Our Chandra M31 Campaign
Some Surprises and M31*

Michael Garcia, Smithsonian Astrophysical Observatory

Ben Williams (Penn St), Albert Kong(MIT), Steve Murray (HRC/GTO),
Manuel Perez-Torres, Francis Primini

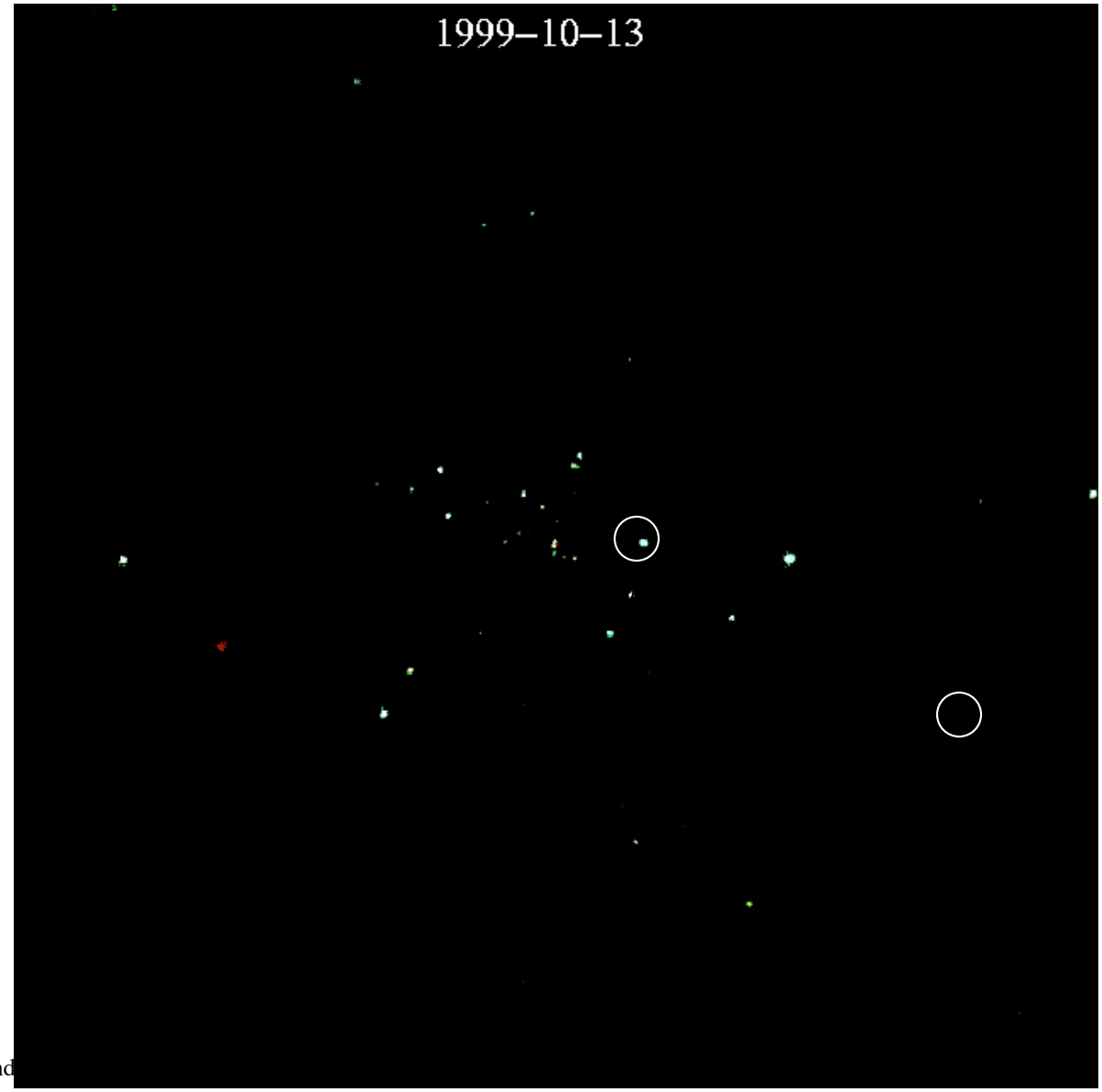


Our Campaign: ACIS Followup of Transients

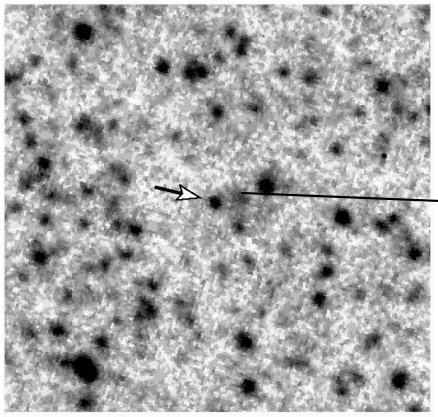


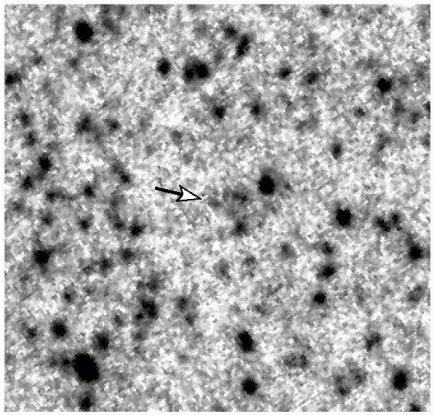
- Most transients in bulge, ACIS+HRC obs concentrated
- AO1,2,3,5,7… 107 separate obs, Σ=574ks! [141/814ks!!]
- Time 50/50 GO/GTO – multi-year program not possible w/o GTO time!
- 7 year span – yeilds numbers of SXT vs persistent, duty cycles.
- 574 ks – sensitive measure of M31*, LF, SNR, etc.

M31 ‘ACIS/ASM’ Movie



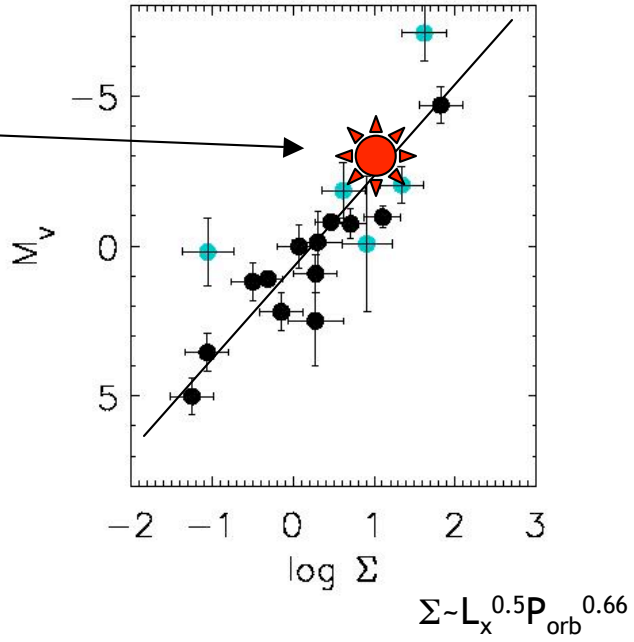
CXO+HST = RXTE/ASM + NOAO





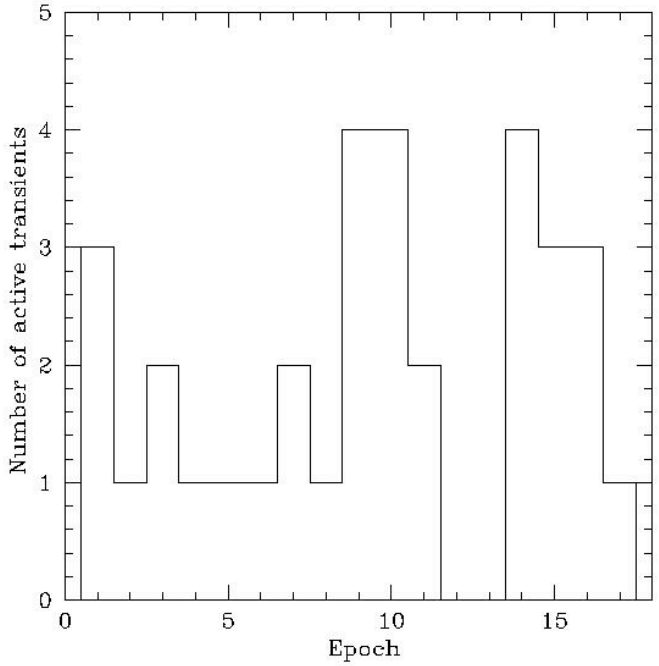
- AO3,5,(7)
- CXO SXT discovery, HST Optical ID
- Lx,Mv-> Porb (fundamental after population #s, -> a,evol,Mdot,XRT,etc.)
- 1, <1.6, <2.2, <2.3, 8, 23d
- MW, 0.15d<Porb<33d
- AO7, 2x deeper with HST

Van Paradijs & McClintock 94 +



Transients: Williams etal 2003 (surprise 1)

- Nov 99 – June 02, 2.5 years, HRC-I only - covering FULL disk
- 17 Transients in 17 Snapshots – concentrated in bulge
- 1 new source per obs, 100 persistent (NS) in bulge
- Transients concentrate in Bulge region – likely LM -> BH XRN?
- SURPRISE: IF Duty Cycle of BH ~1% (MW) -> similar # BH and NS
- Evolutionary calcs often predict #NS>>#BH ! (re-discovery of MW numbers)

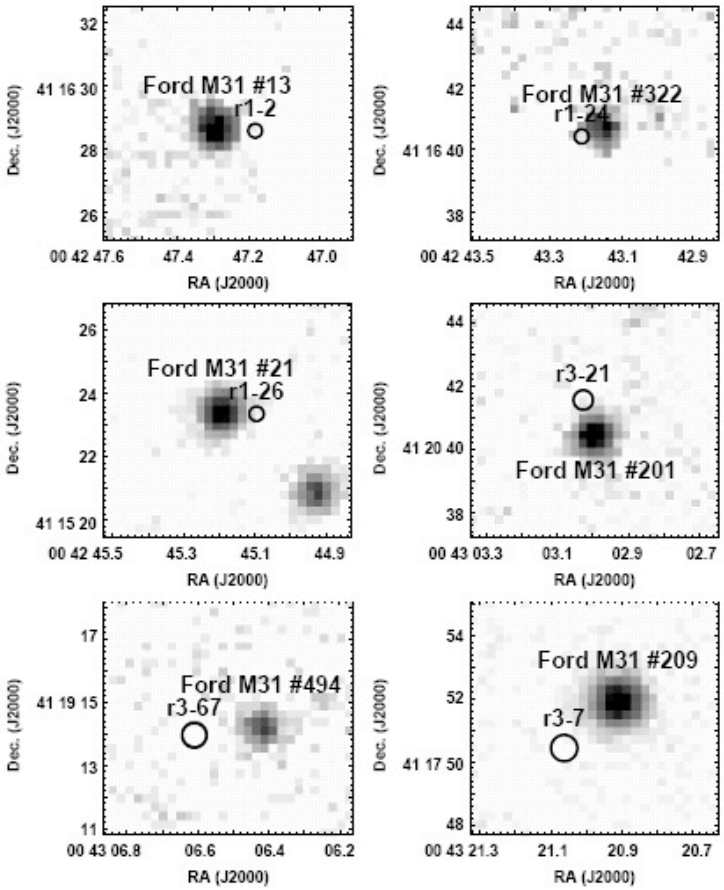


Williams 2005 ApJ submitted, 45(!) transients, ACIS, XMM, poster HERE

PN/SNR +XRB Associations (surprise 2)

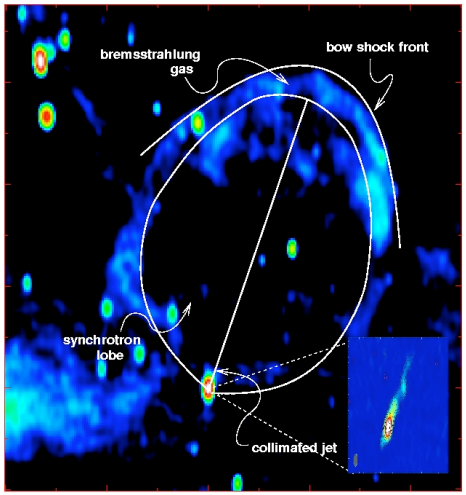
- Kong etal 2002 – 8 PNs w/ Lx~10^{37} (!)
- Williams etal 2004
- Register with LGS to 0.25'', O[III],S[II], Hα.
- NOT matches! Near misses – Prob 1%
- X-ray spectra/timing ~ XRBs
- What are they?
  - Probably NOT SNR – Lx < 10^{35}
  - Probably not Ejected XRB – V too high
- Don't Know! (survey eased in M31) optical spectra will help

O[III]

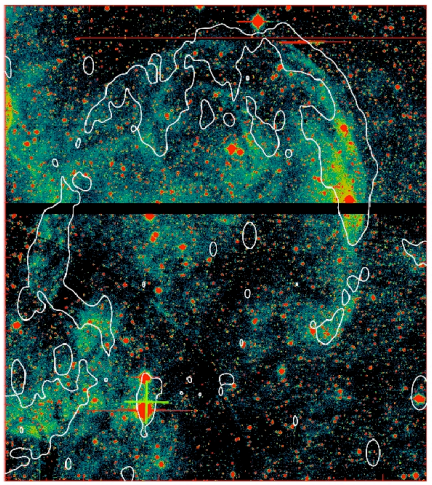


PN/SNR +XRB Associations (surprise 2)

Radio

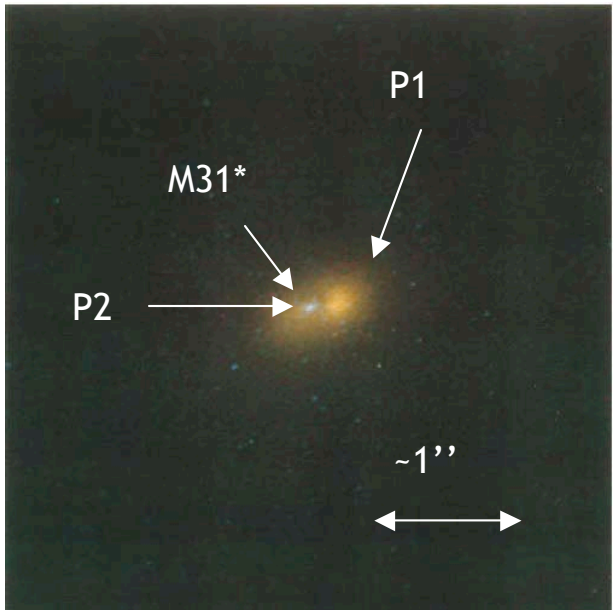


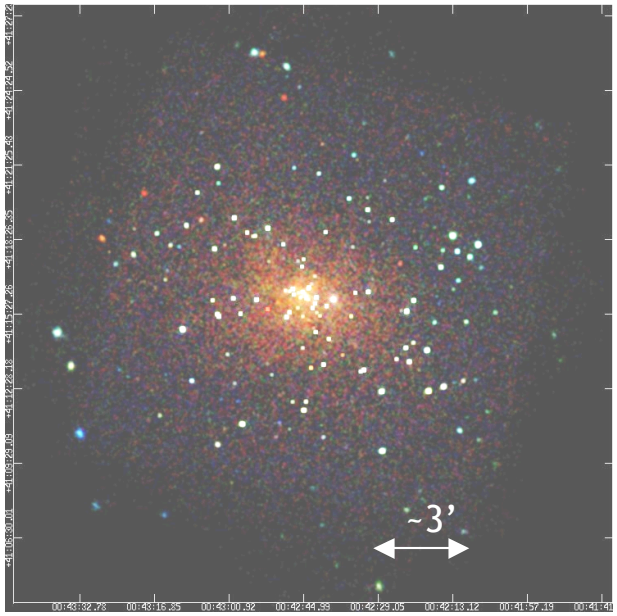
Optical w/ contours



- Gallo, Fender etal 2005 Nature
- Cyg X-1 radio/optical 'bubble' blown by jet
- Separation @M31 = 1 arcsec… as seen in PN/SNR + XRBs
- Optical spectra could tell!

M31* SMBH





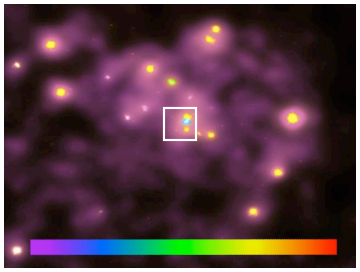
Kormendy and Bender 1999
Rare Double Nucleus, plus
3 x 10^7 Msun SMBH @P2

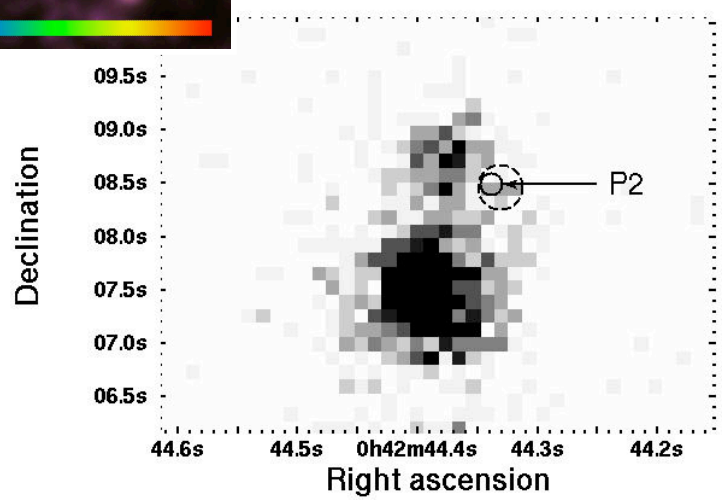
Kong etal 2002
ACIS Mosaic – Clear Diffuse emission
In central region

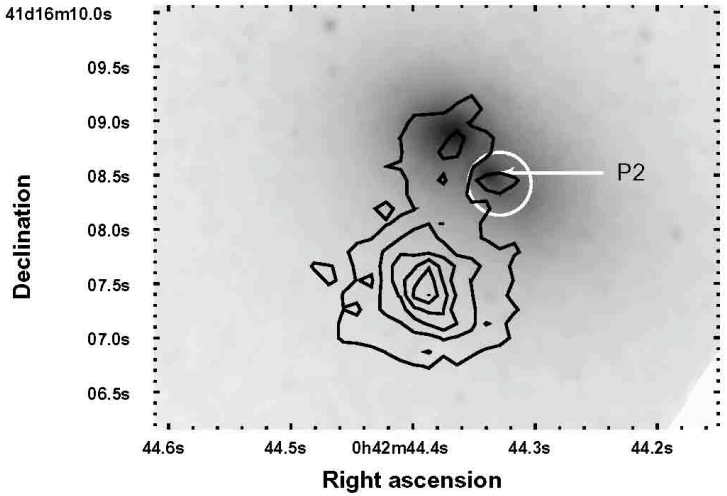
Bondi accretion rate? Bondi Radius? Accretion (radiation) efficiency? jets?
Position of Crane 1992 pt radio source? (within 0.5'', accurate to 0.15''…)

M31* - HRC and ACS to 0.1’’

Garcia etal 2005 ApJ







50ks HRC image

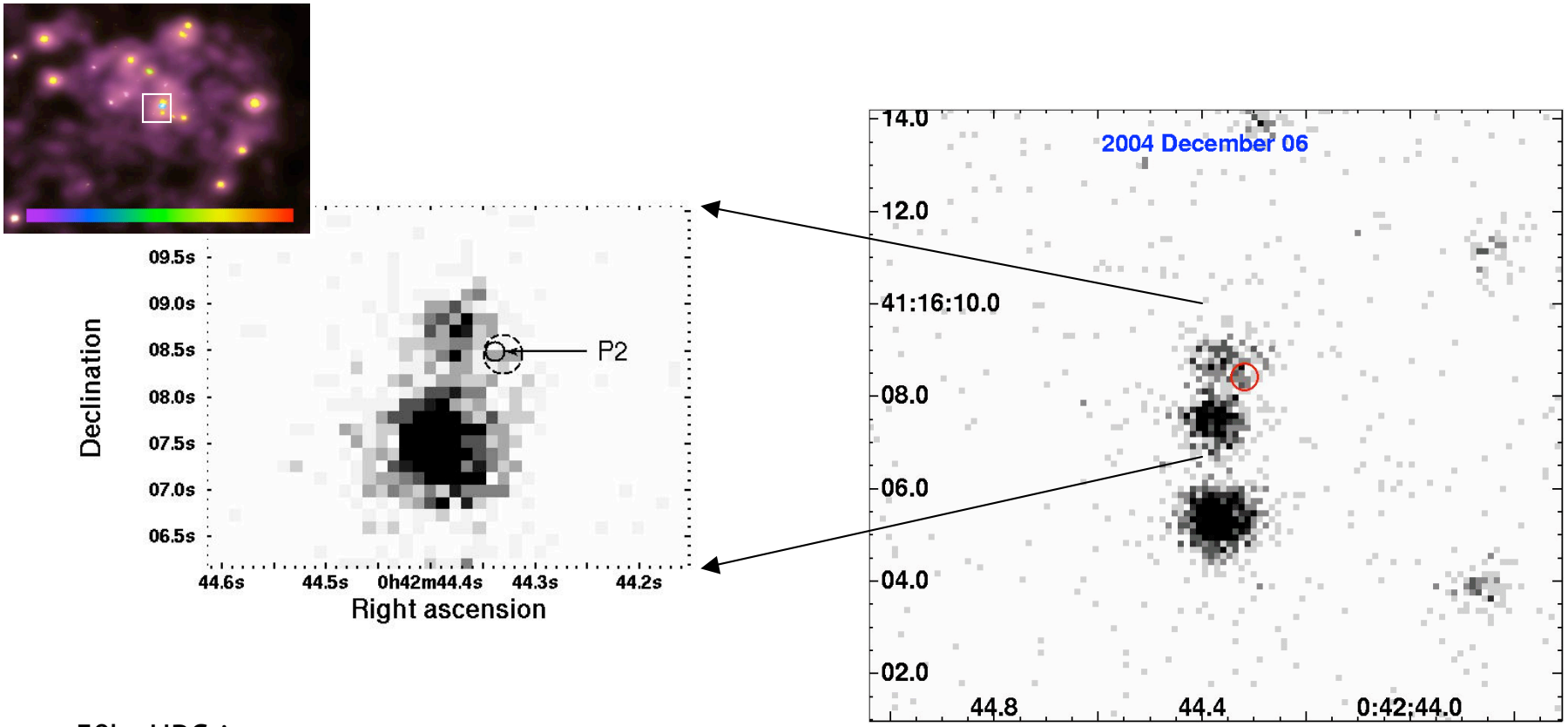
P1/P2 indicated schematically
M31* error circle = 0.1’’ radius
Dashed line = resolved source, 13 counts, 2.5σ
Above N1+SSS+diffuse
13 counts ~ 10^36 ergs/sec

ACS image, HRC contours

Separate (=resolved) contour at M31*

Radio pt source in white – predates
Discovery of double nucleus!

M31* - A06 HRC/VLA Movie



50ks HRC image

P1/P2 indicated schematically
M31* error circle = 0.1'' radius
Dashed line = resolved source, 13 counts, 2.5σ
Above N1+SSS+diffuse
13 counts ~ 10^36 ergs/sec

4 x 50 ks HRC images, simultaneous VLA

MUCH varaibility!

Radio/X-ray may distinguish Jets/ADAF

Summary: Chandra M31 Campaign, Some Surprises and M31*

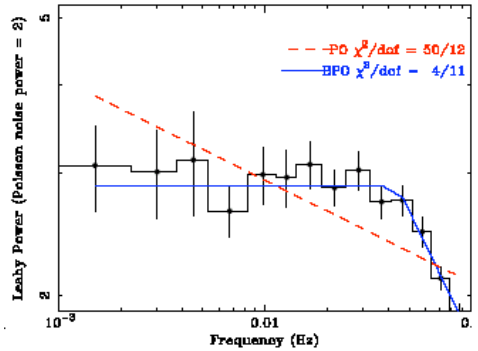
- 7 Year Synoptic program – Modest exposures, but sum 574ks, could obtain ~1 Msec if continued
- Many Transients found – 45 total, Williams 2005
- SXT Counterparts - 6 ORBITAL PERIODS, 5 more in AO7
- Surprises
  - N(NS) ~ N(BH) – expect N(NS) > N(BH)
  - X-rays near PNebula/SNR? Ejected XRBs? Jets?
  - Resolved SNR w/ embedded XRB
- M31* RBH resolved, 'Severe and Secure' constraints
- M31* X-ray/Radio Variablity – Jets or ADAF?

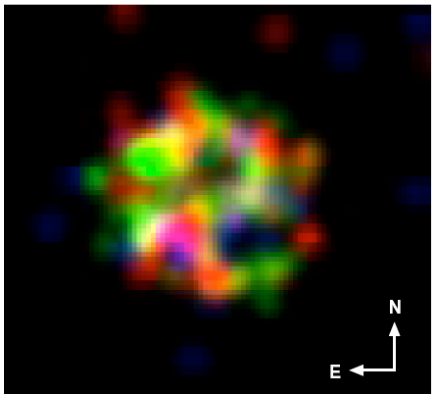
END – extra slides

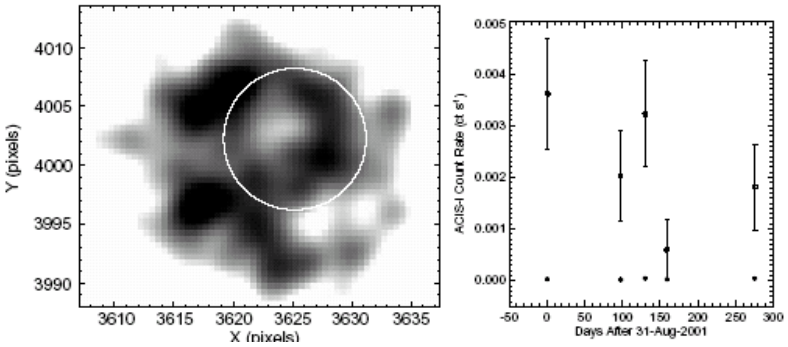
R3-63: A resolved SNR w/ XRB (surprise 3)

- Williams, Barnard etal 2005
- In MW, only SS433 (Cir X-1?)
- Highly Significant Variability detected in XMM PL+break = disk accretion
- SNR resolved with Chandra
- Low significance variability w/ Chandra in NW quadrant

- Maybe there are ejected XRBs?
- Optical spectra could ID SNRs

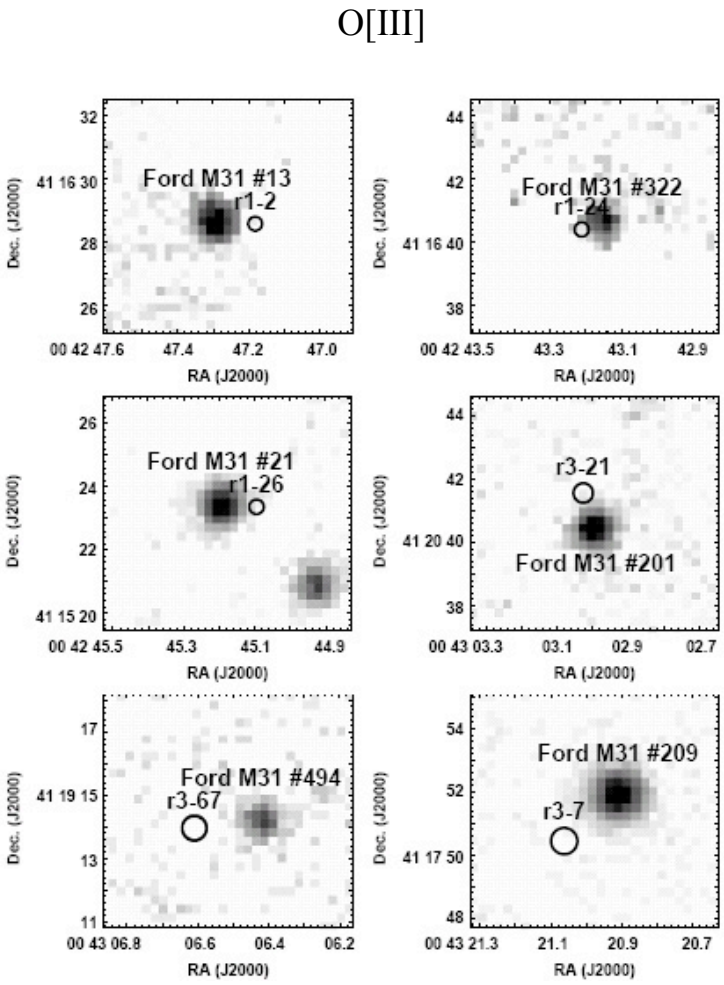






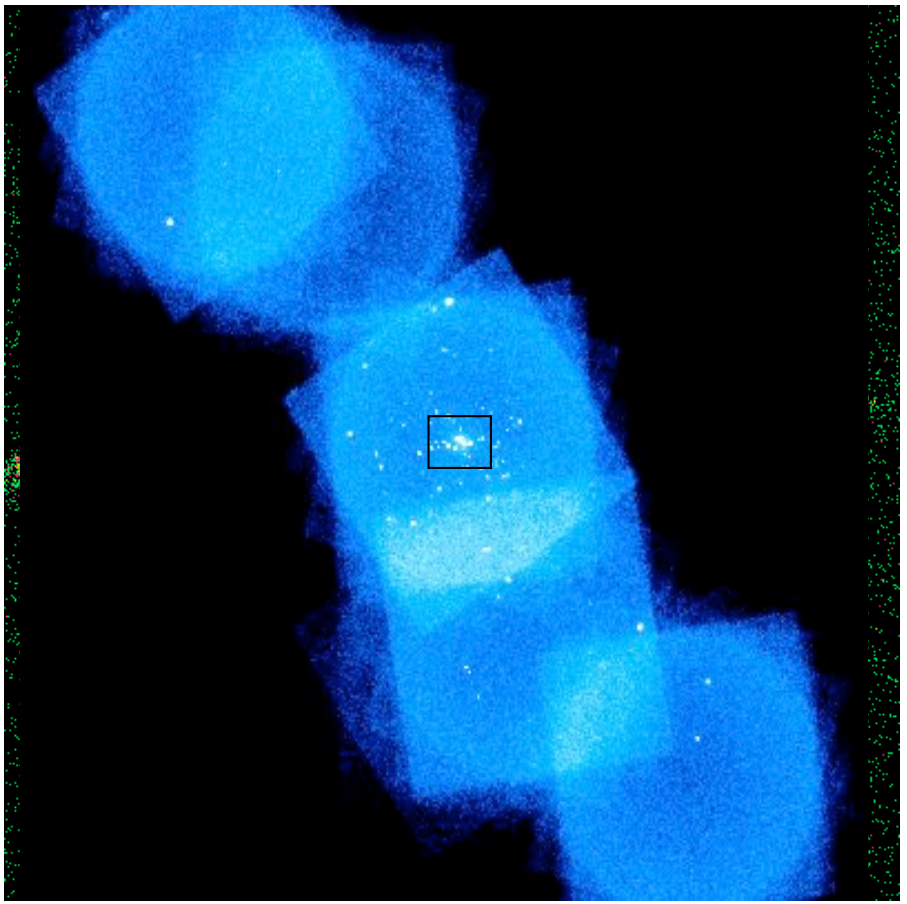
PN/SNR +XRB Associations (surprise 2)

- Kong etal 2002 – 8 PNs w/ Lx~10^{37} (!)
- Williams etal 2004
- Register with LGS to 0.25'', O[III],S[II], Hα.
- NOT matches! Near misses – Prob 1%
- Nebula Lx < 10^{35} not young SNR?
- Sizes < 1'' – Young SNR?
- 4 'PNebs' have S[II]/Hα ~ SNR, one does not, one unknown
- Low ISM Density SNR?
- 3 X-ray sources vary – all spectral ~ XRBs
- Ejected XRBs?? From SN Ia? (old)
  - Size < 1'' – Age < 1000 years
  - Ejection Velocity ~ 5000 km/sec
  - XRB orbital Velocity < 1000 km/sec
- Optical spectra will help….
- Don't Know! (survey eased in M31)



Chandra Observations of M31: Goals (outline)

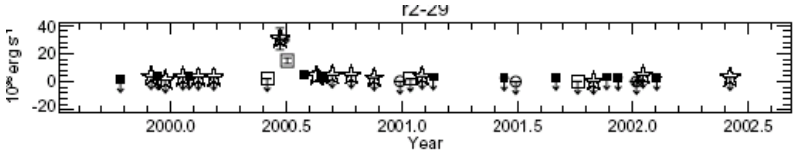
- Study Black Hole Nova. ~80% Galactic SXT=BH. Do ASM like Survey
- M31* = SMBH
- Population studies (HMXB, LMXB, SNR. helped by common D, low A_V
- Surprises!
- Separate bulge sources, resolve SNR- RESOLUTION Helps!

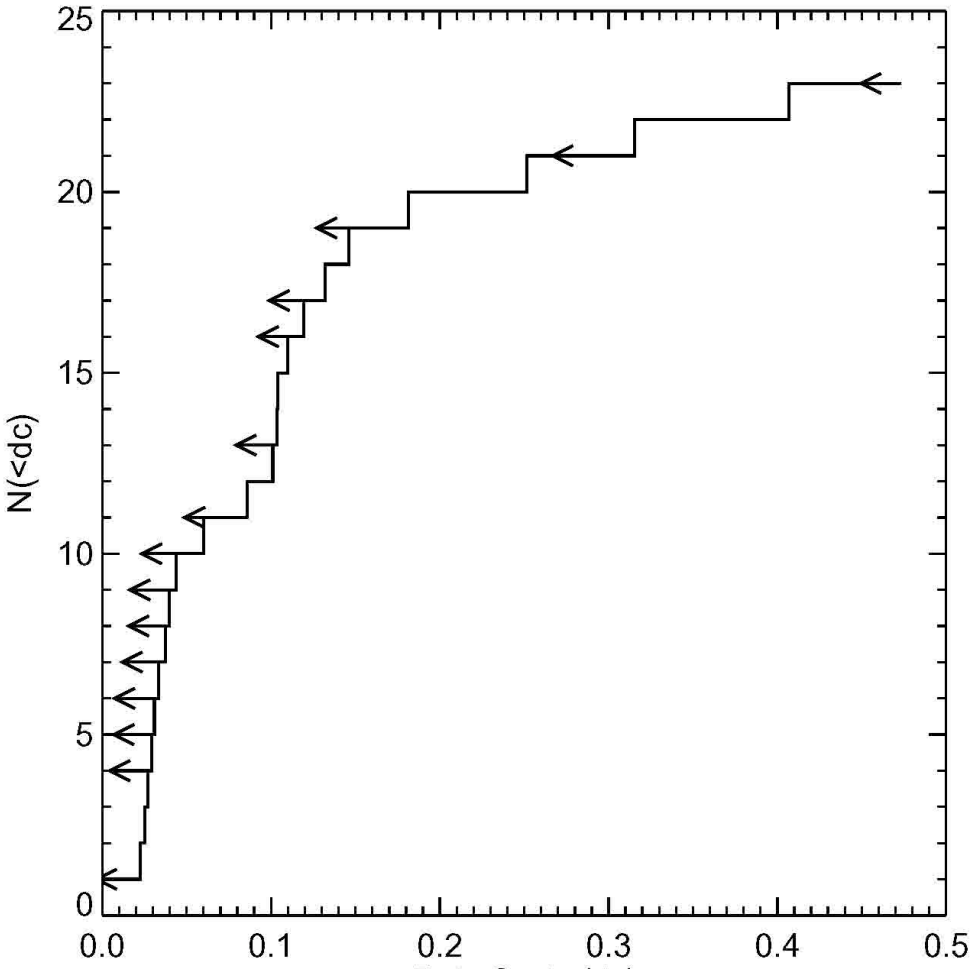


Duty Cycles (real measurments!)

Williams etal 2005 ApJ

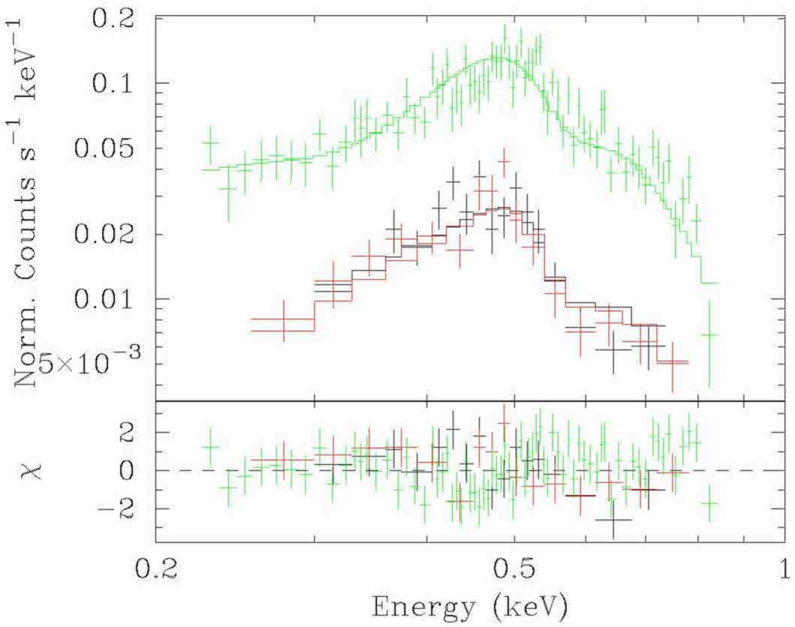
- 45 Transients
- First 2.8y ACIS+HRC +XMM
- Light curves, HID, spectra, decay times…
- High concentration in bulge
- Measurements, limits of duty cycles
- Lowest are 2% (vs 1% canoncial)



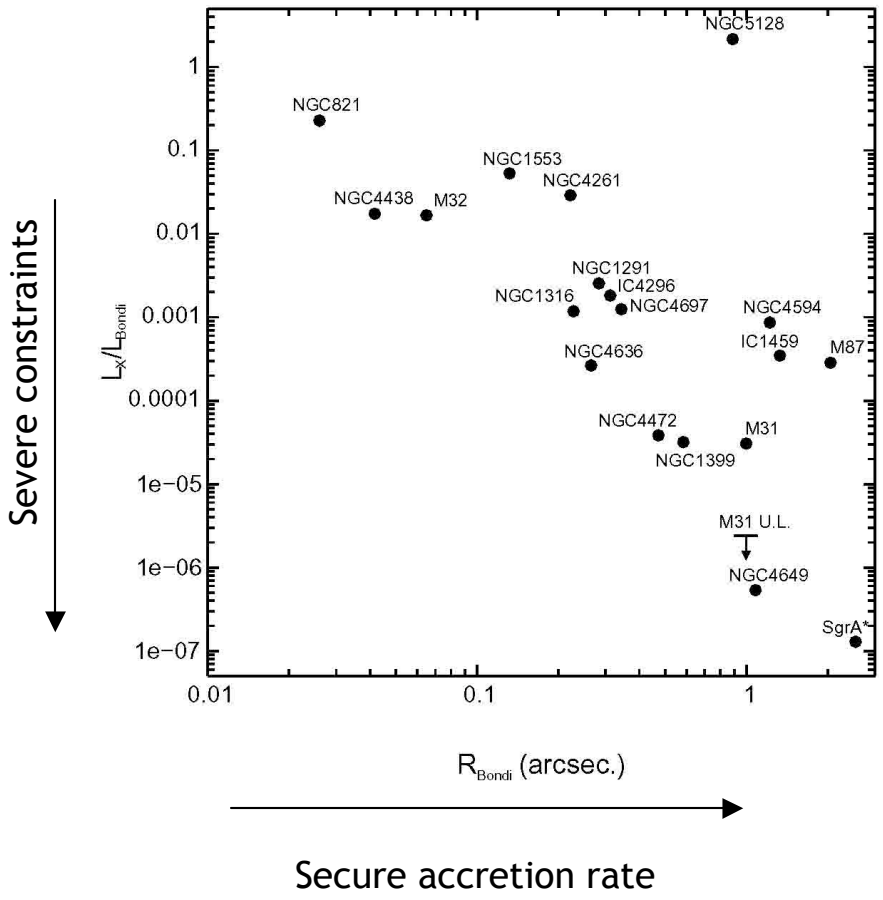


Transient NSA Sources

- 3 of 45 fit NSA, rest fit DBB/PL
- IF NS in M31 R>10^5 km – not in M31!
- If R=10km, d<100pc(!), Lx~10^{30}
- If WD, in MW Halo
- >1 deg^2
- Only repeated (107x !) survey to <10^{-13} $erg/cm^2/s$ (W.P.!)



M31* Compared to Other Nearby SMBH



- Registration w/ GC+USNO confirms pt radio @M31* + Lx ~1e36
- "Extreme Quiescence"
- Starved or Inefficient??
- When R_{BH} ~ resolvable, cannot be Fuel Starved (Sgr A*, Baganoff etal)…
- M31* near to SgrA*, LR='secure and severe' constraints
- M31*/SgrA* Lx~1000, Lr~0.2
- ADAF, ADAF+winds, or convection, residual emission from flow or jets? (NT e-,Yuan 2005)
- X-ray vs Radio variability may tell jets from ADAF. AO6

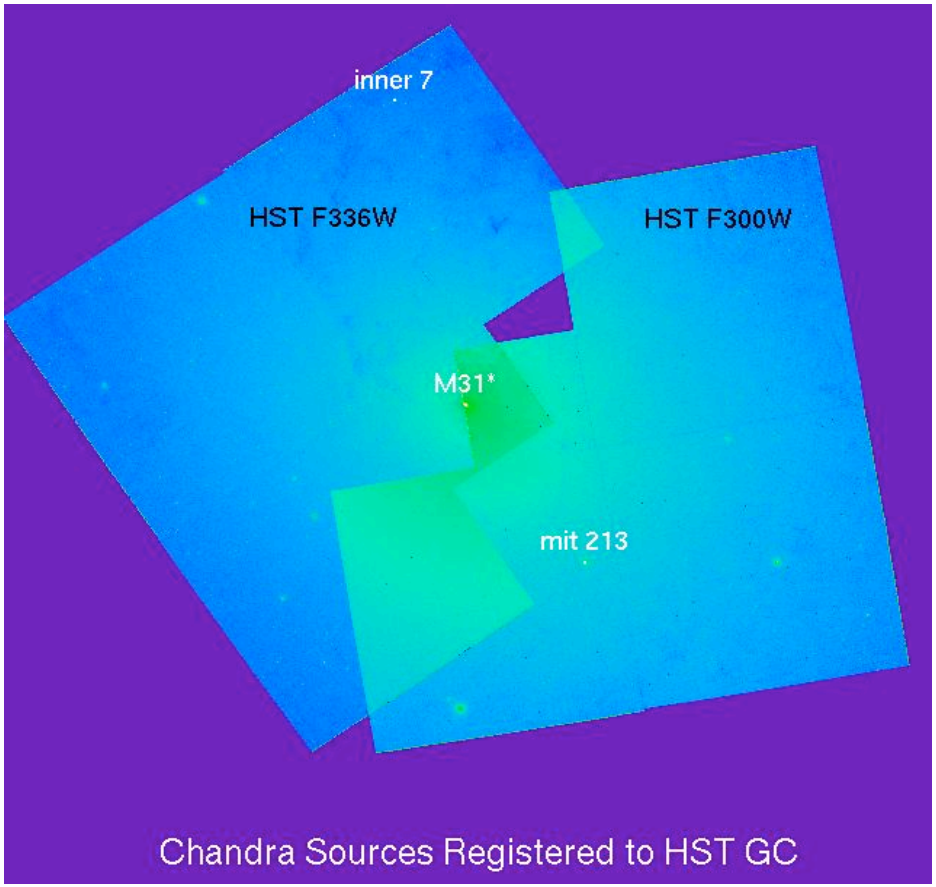
Surprise 2 in Summed Images of M31

Object	Catalogs	Number
X-ray	ROSAT HRI (PFJ93)	69
GC	Ba87, Ma94, & Barmby (2001)	21
SNR	DO80, BW83, & Ma95	2
PN	Ciardullo et al. (1989)	8
OB Assoc.	Magnier et al. 1993	0
Nova	IAUC	0
Extragalactic	NED and SIMBAD	1
Stars	Ha94 and SIMBAD	5

- Kong etal 2002
- Search Radius ~3”
- 8 PN IDs
- MW PN, Lx~10^{30}: these 10^{35}-10^{37} erg/s!
- PN ids O[III]/Hα
- Mis-IDed SNR?
- GX 13+1 unusual XRB: Mgiant, NS, symbiotic opt spect?
- Optical spectra can tell

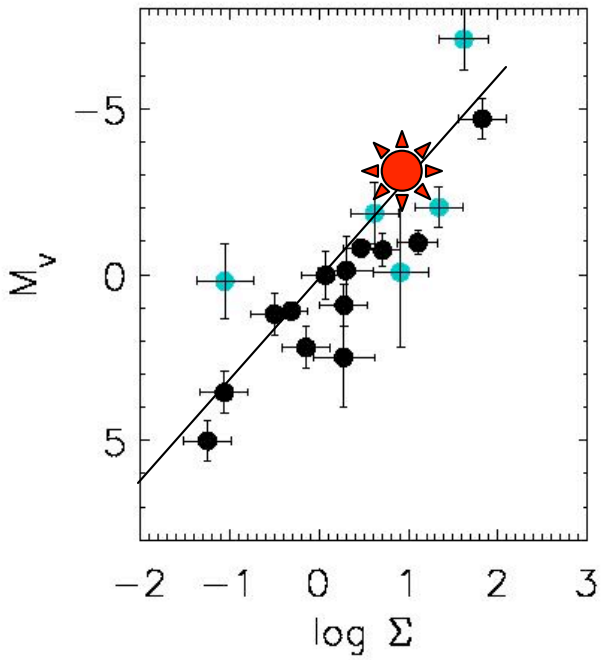
M31*

Two HST/Chandra Matches of Globular Clusters
MIT213 = Optically Bright
'inner 7' = new, Barmby, faint
Registration to ~0.1''



CXOM31 J004305.5+411703

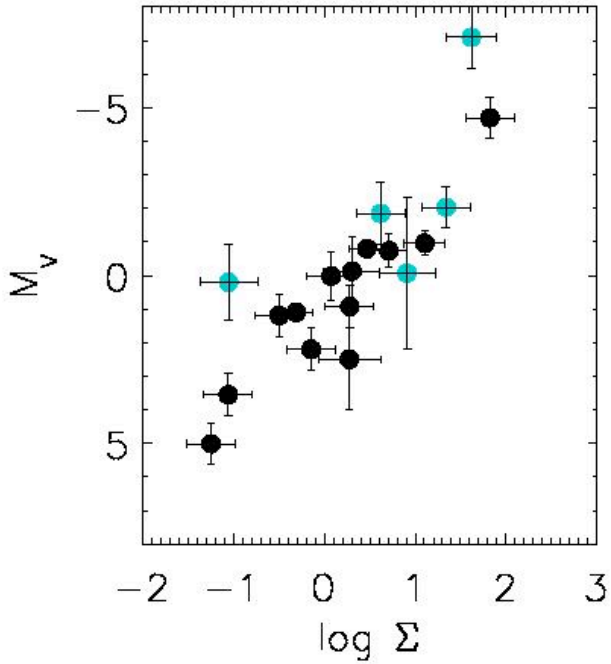
- u=22.3, $N_H=10^{21}$ $A_U=1.3$,
  U-V=-1, DM=24.5, M_V=-1.5,-2.9
- $\Sigma = (L_X/L_{Edd})^{1/2}\ (P/hr)^{2/3}$
- $L_X=3x10^{38} \sim L_{Edd}$ (1.4Msun)
- P_{orb} ~ 23 days (x2, colors, Av)
  V404Cyg=6.5d,GRS1915+105=33.5d
  U~V404 Cyg, Lx=0.1 V404 Cyg



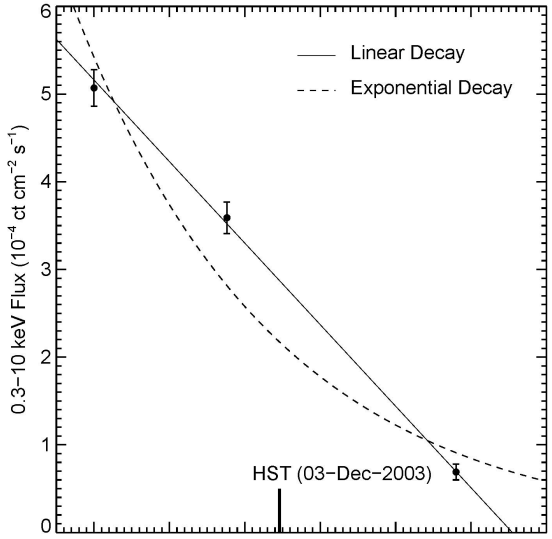
Van Paradijs & McClintock 94 +

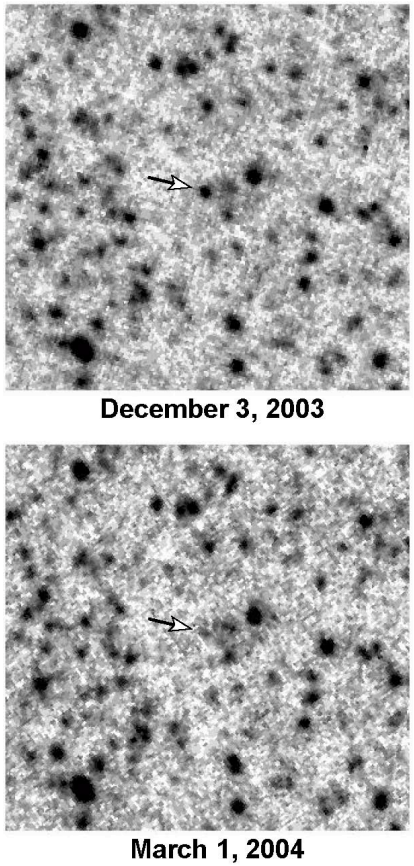
Transient Optical Followup Summary

- 3 counterparts, P_{orb}= 23, 1, 8 d
- Galactic BH XRT P_{orb} 0.17-33 d
- $M_B < 2.9$, may need 1 more magnitude (2 orbits, not 1)
- 3 more tries 'in the pipeline' (AO5/C10)
- Will try HST C12 – lost!
- Rumor of CXO C7 time with 2orbits



CXOM31 J004406.7+411220

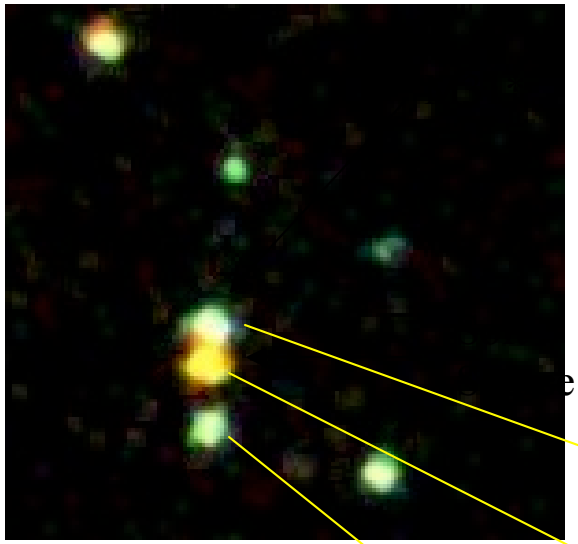




First obs with ACS. Limit B=27.8 4σ, M_B=2.9@M31
Lx(max) = 2.4x10^{38}, M_B(max) =25.75, Mv=-0.25
-> Porb ~ 1 day
T_decay – Linear – Long period (King & Ritter 1998) – Just consistent.

Williams etal 2004a

Locating M31* SMBH



M31* = CXOM31 J004244.2+411609 ?
Within 0.15" of SMBH between P1, P2
Registration of Chandra + HST to ~0.1"
Within 1.5σ of SMBH – HRC also

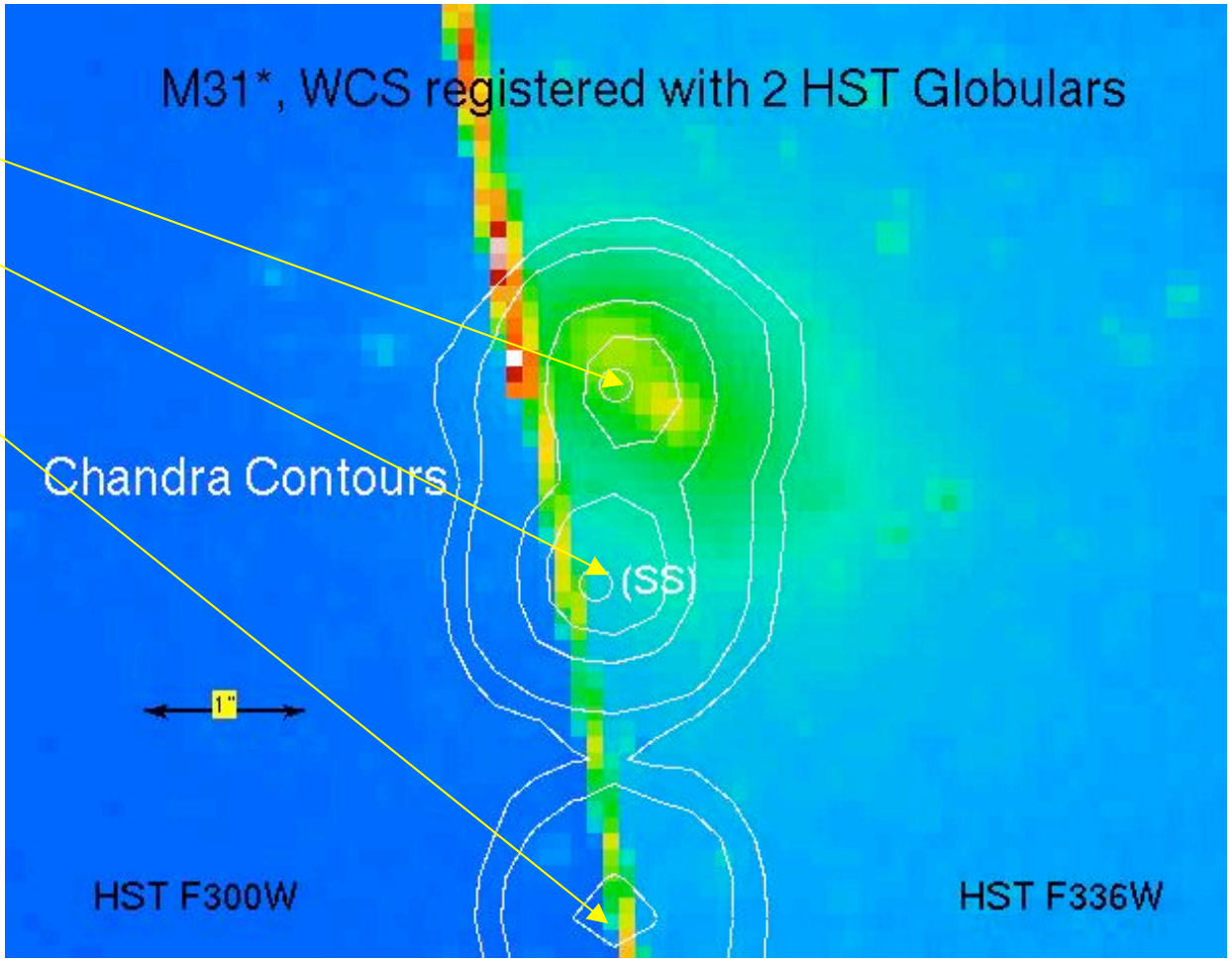
- M31* not SS source

(Garcia etal 2000)

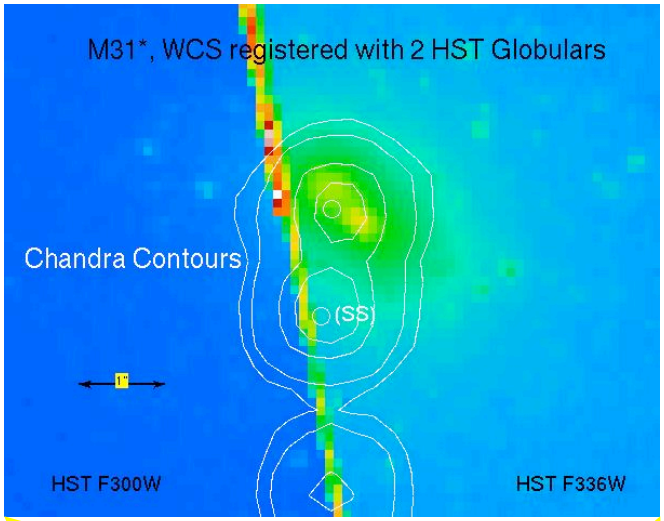
- Northern source

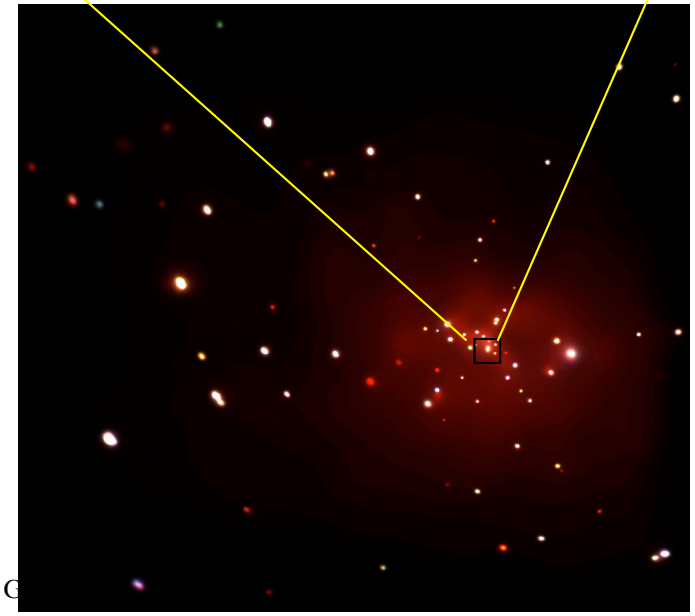
$L_x = 2x10^{37}$ ergs s^{-1}

$L_x = 5x10^{-9} L_{Edd}$



M31* SMBH: Diffuse Emission



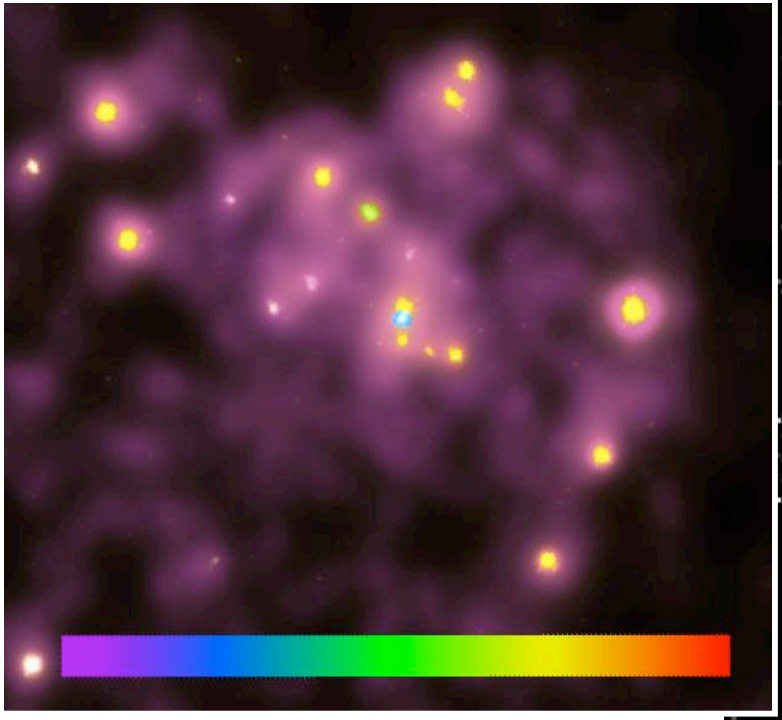


- M31* Embedded in Diffuse Emission
- kT ~ 0.35 keV (cool), ρ ~ 0.15 cm-3
- Will accrete if within gravitational radius, Bondi-Hoyle accretion
- R_{BH} ~ 0.6" (nearly resolvable!)
- M_{BH} ~ 2.4x10^{-4} M_{sun}/year
- E_{BH} ~ 2x10^{-5} – very inefficient (ADAF?)
- M31* Lx~other ~few M_{sun} Binaries, but M=3x10^{7} M_{sun} –"Embarrassingly Feeble"

M31*

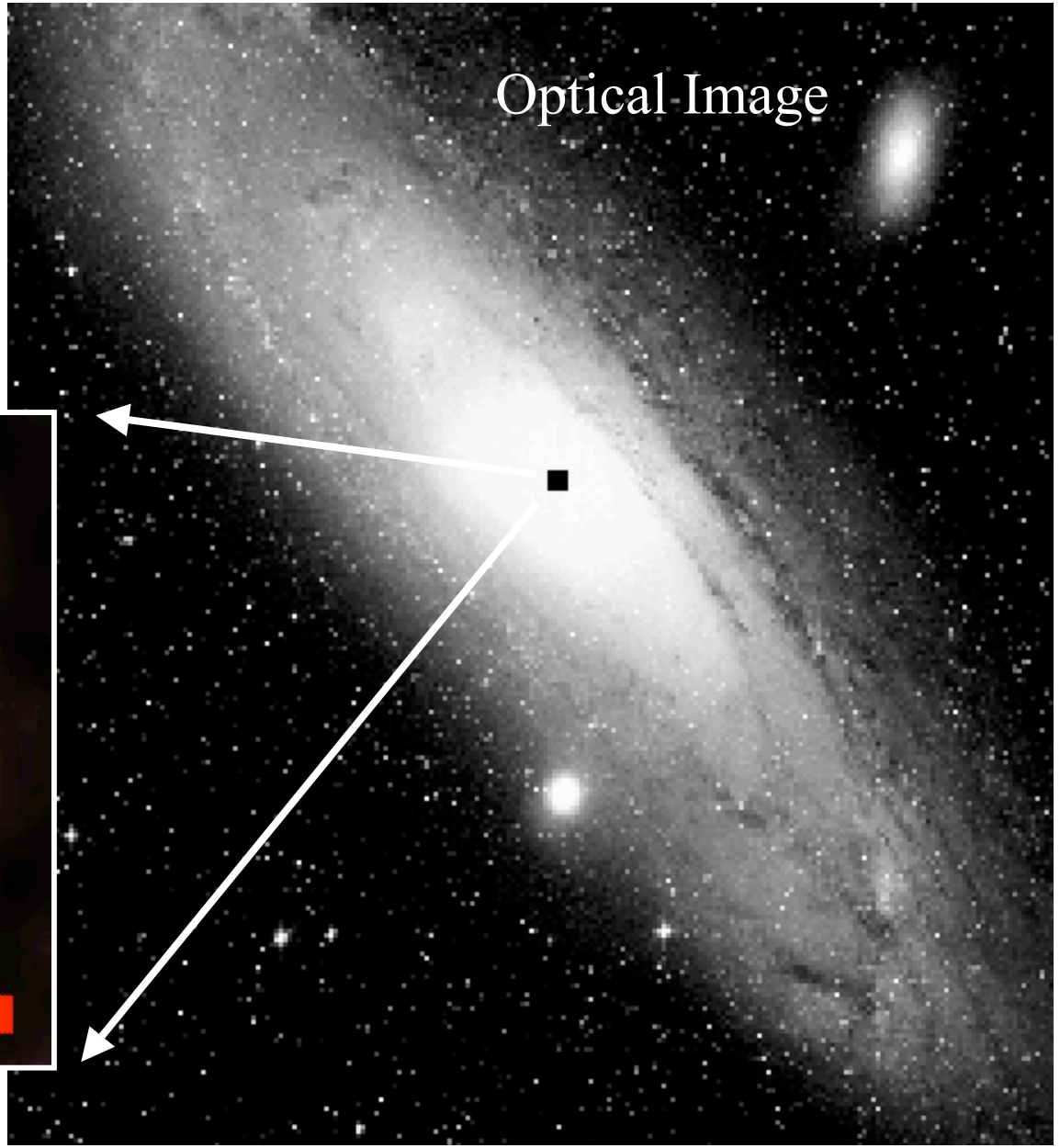
M31* = SS? 1’’
Garcia etal 2000 ApJ

Based on 1’’ HST/CXO
Aspect, rare SSS, but wrong

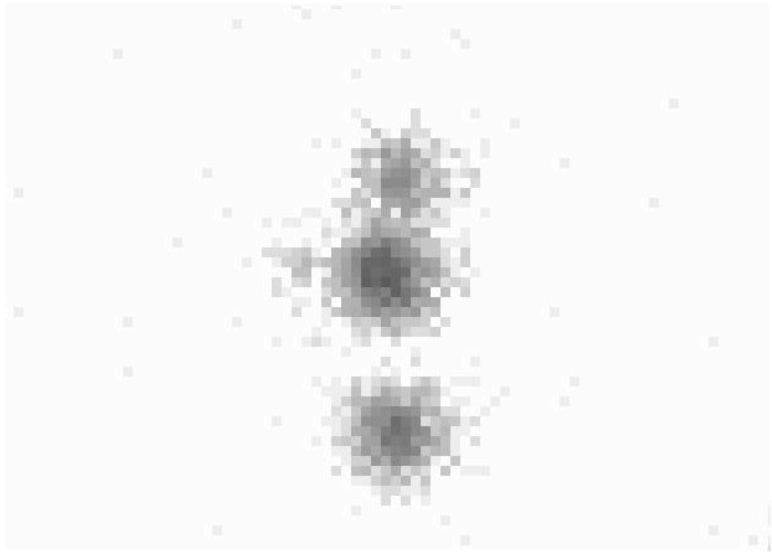


1 million K 20 million K

M Garcia, 6 Years of Chandra, Nov 4 2005

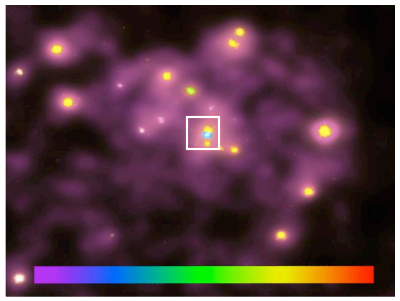


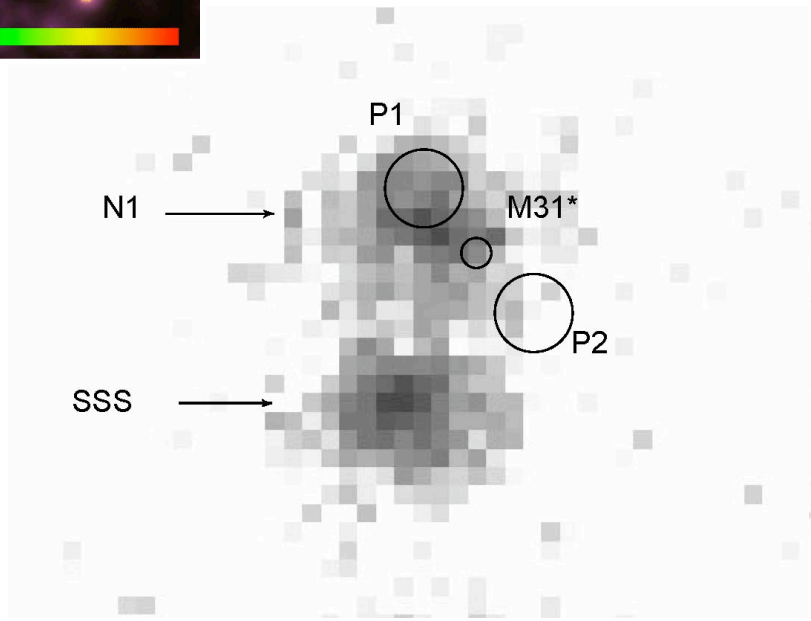
M31* AO6 Observations

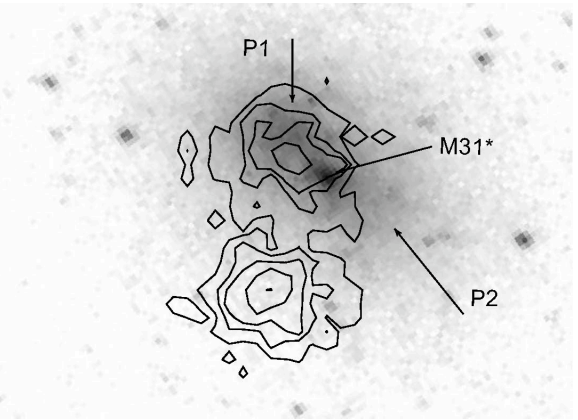


4x50 ks HRC, with VLA
M31* to West of Northern Source
MUCH variability in X-ray image
(Transient source to East)
VLA does show variability
Will be correlated w/ X-ray

M31* - ACIS and WF/PC2 to 0.1’’







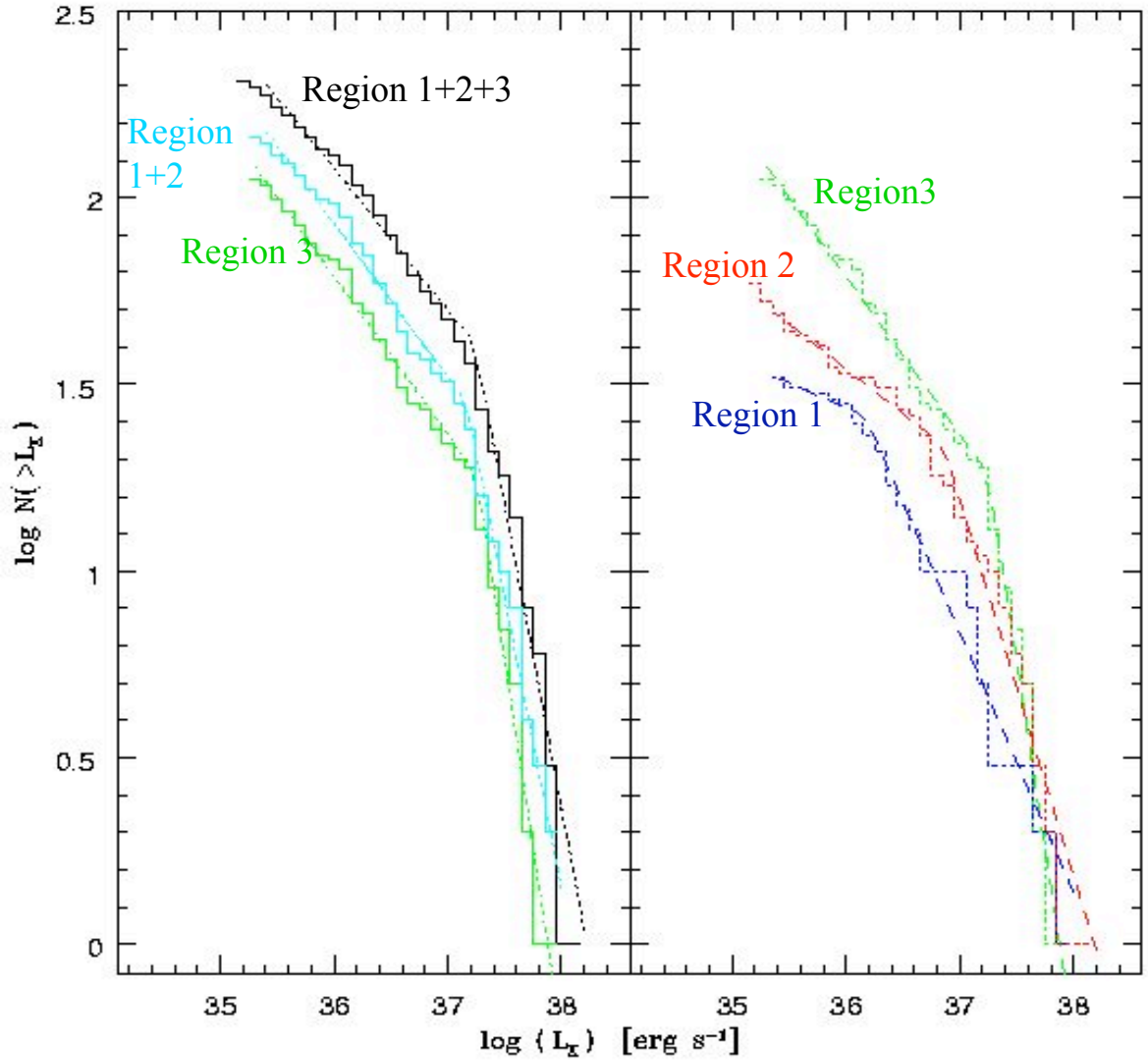
35ks merged ACIS image
P1/P2 indicated schematically
M31* position error w/ 0.1’’ radius

M31* NOT N1 or SSS, extension of N1
Towards M31*?

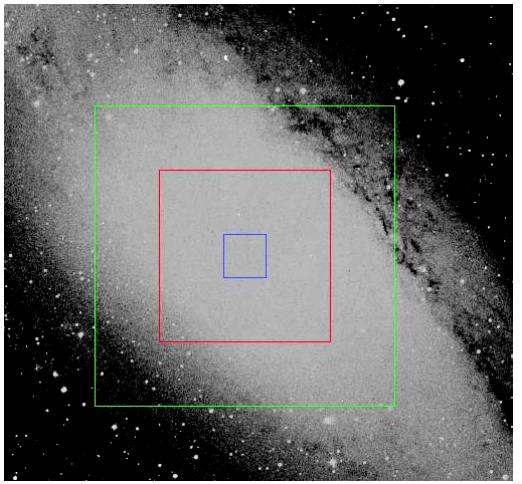
WF/PC2 image with ACIS contours

M31* (if emitting) not resolved from N1, but some extension?

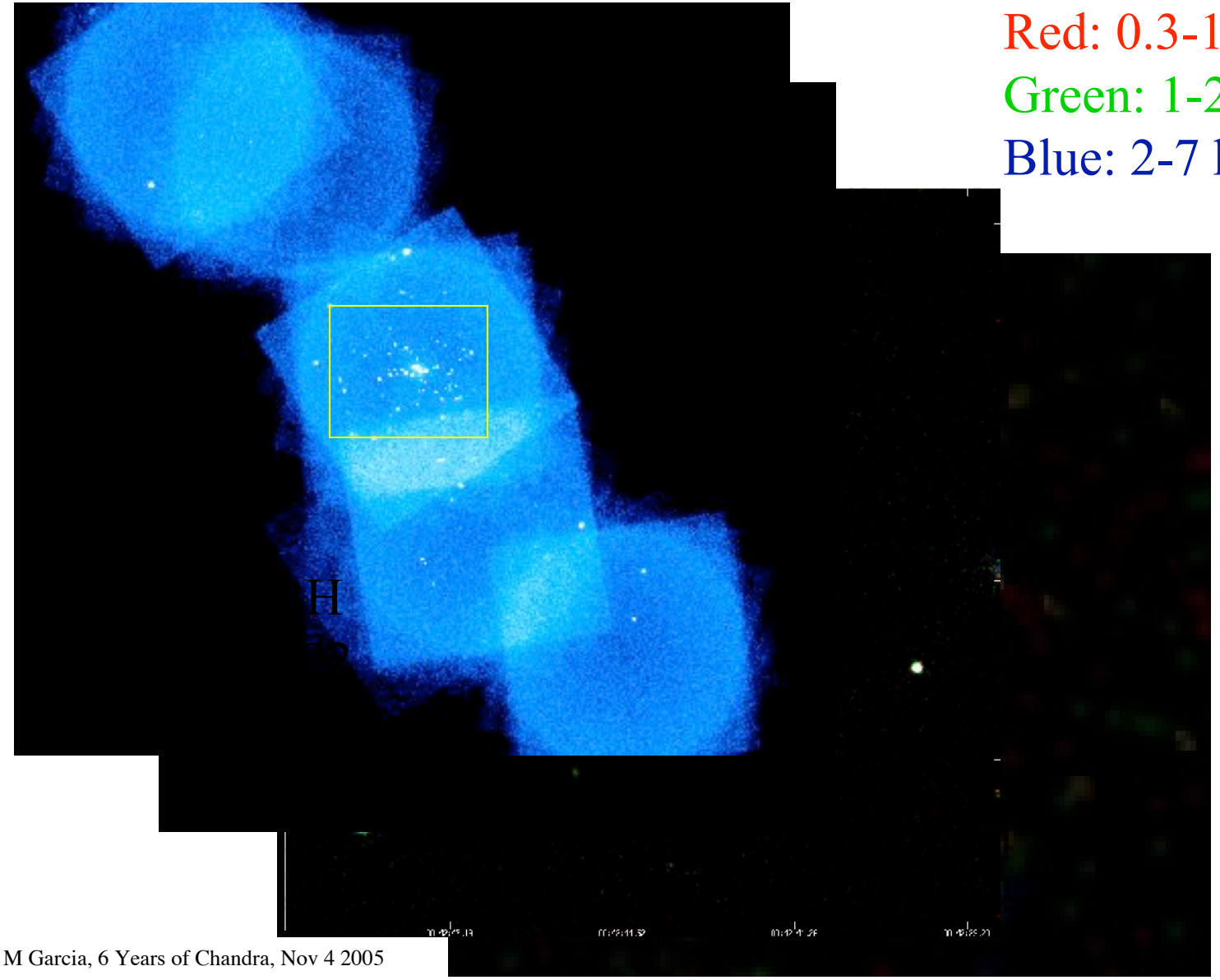
Surprises in Summed Images of M31



Luminosity Function vs. radius - Cutoff



Locating M31* SMBH

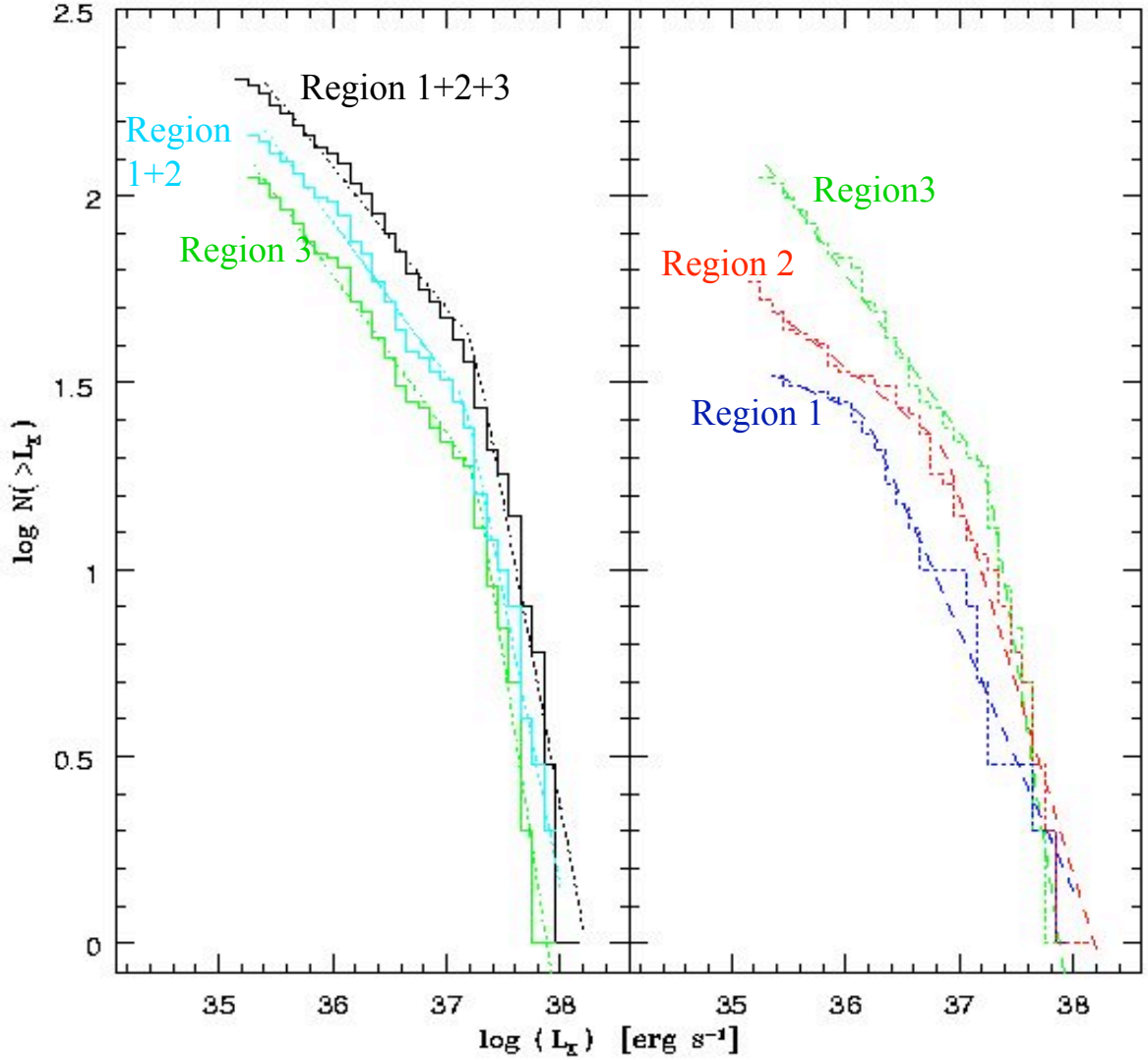


Red: 0.3-1 keV

Green: 1-2 keV

Blue: 2-7 keV

Surprises in Summed Images of M31

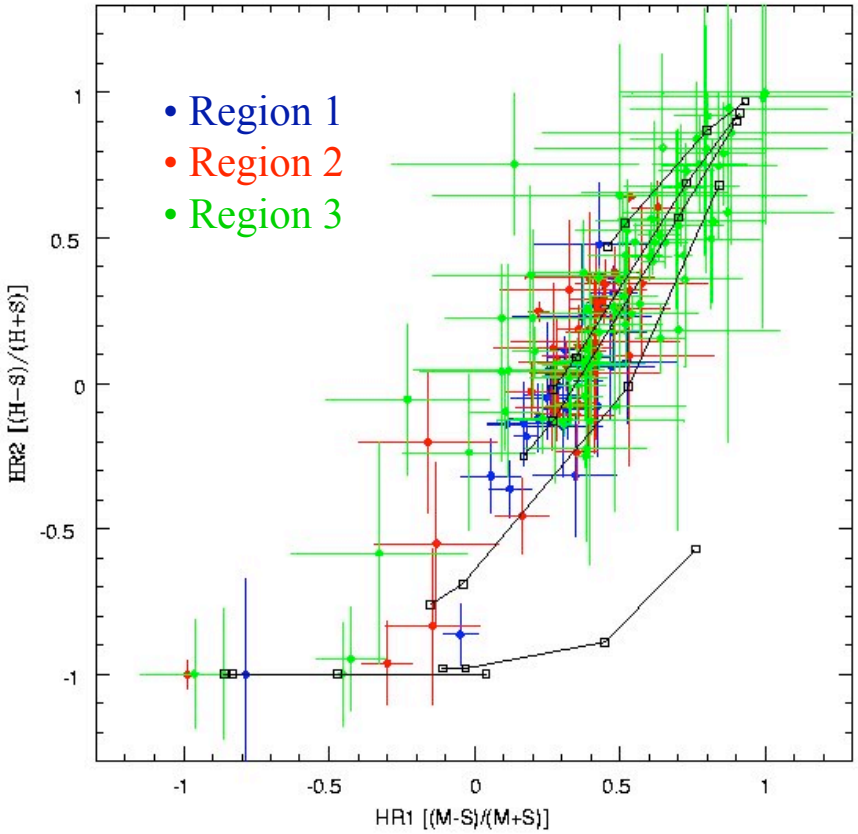


Luminosity Function vs. Radius – Slope

- Steepens with distance from nucleus, 0.14,0.22,0.4; 0.7, 0.9, 2.0
- Contamination by other sources?
- Background AGN have slope=1.5

M Garcia, 6 Years of Chandra, Nov 4 2005

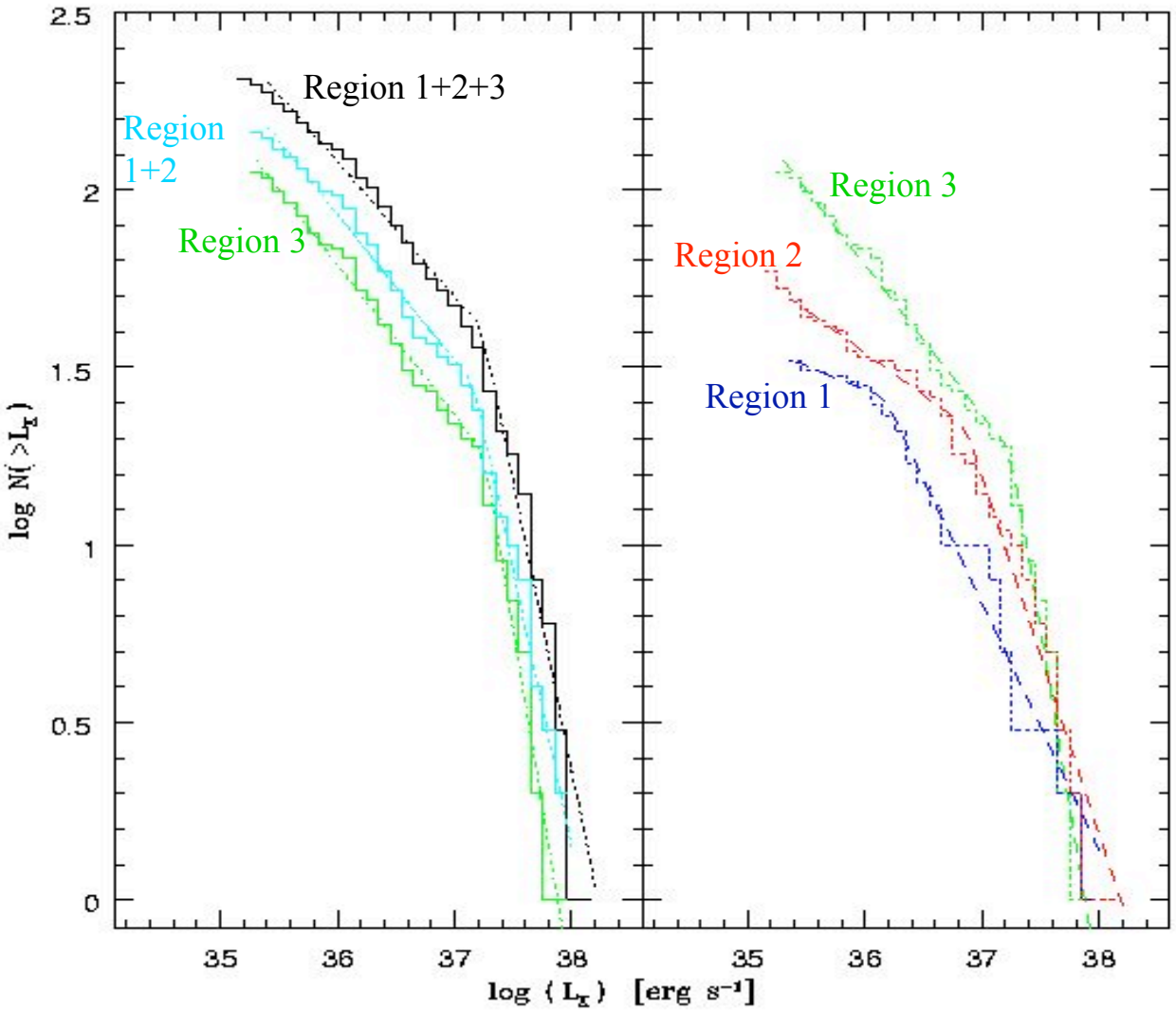
Surprises in Summed Images of M31



Luminosity Function vs. Radius - slope

- Contamination by other sources?
- Hint 1: Hardness vs radius
- Region 3 hard, cutoff – Background AGN may explain part of steepening slope.

Luminosity Function



Detection limit: ~$10^{35.2}$ erg/s

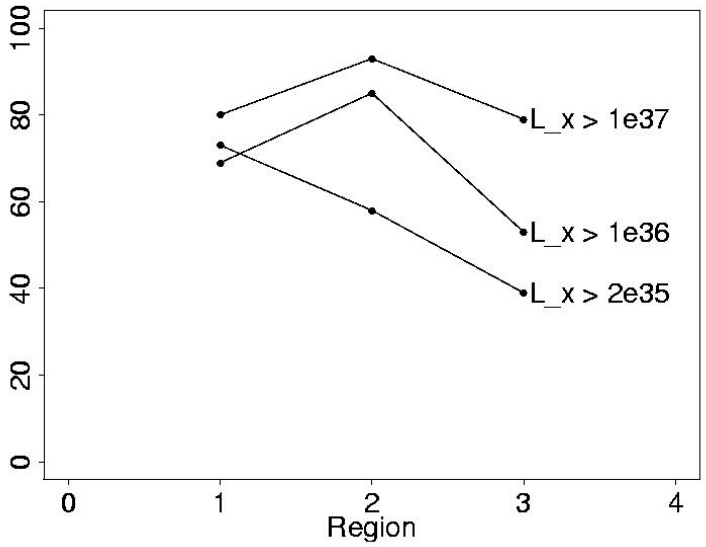
Break at ~$10^{37.3}$ erg/s for the whole field, and the r < 8'x8' and r > 8'x8' regions

Difference becomes apparent for the inner bulge (1) and outer bulge (2); may be seen in the Einstein data (TF91)

Different star-formation history and stellar evolution?

Surprises in Summed Images of M31

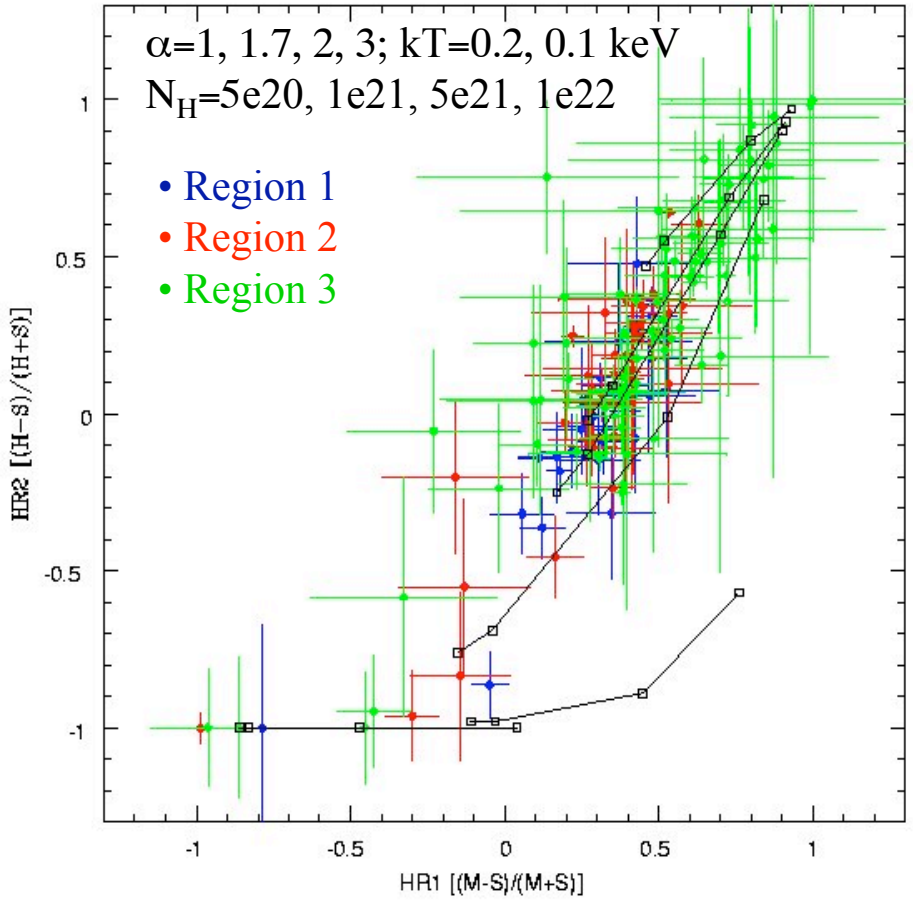
$$S(F_{max} - F_{min}) = \frac{|F_{max} - F_{min}|}{\sqrt{\sigma^2_{F_{min}} + \sigma^2_{F_{max}}}} > 3$$



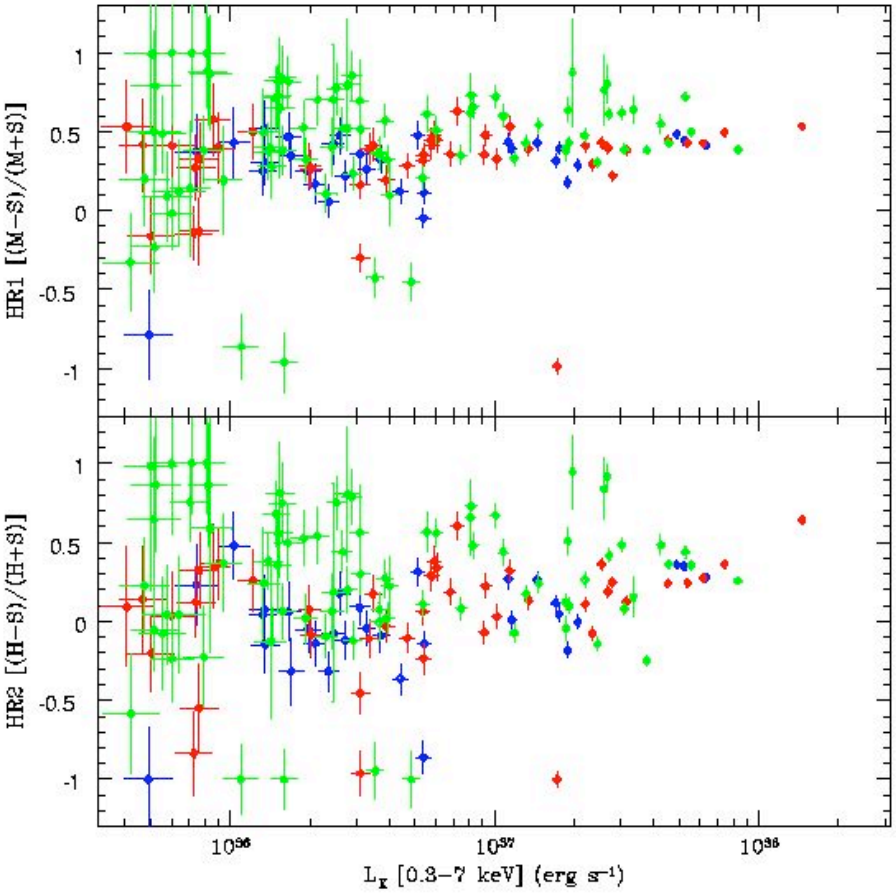
Luminosity Function vs. Radius – Slope

- Contamination by other sources?
- Hint 2: varaibility vs. radius
- Optical spectroscopy of ~40 M31 sources could tell…..

Color-color diagram



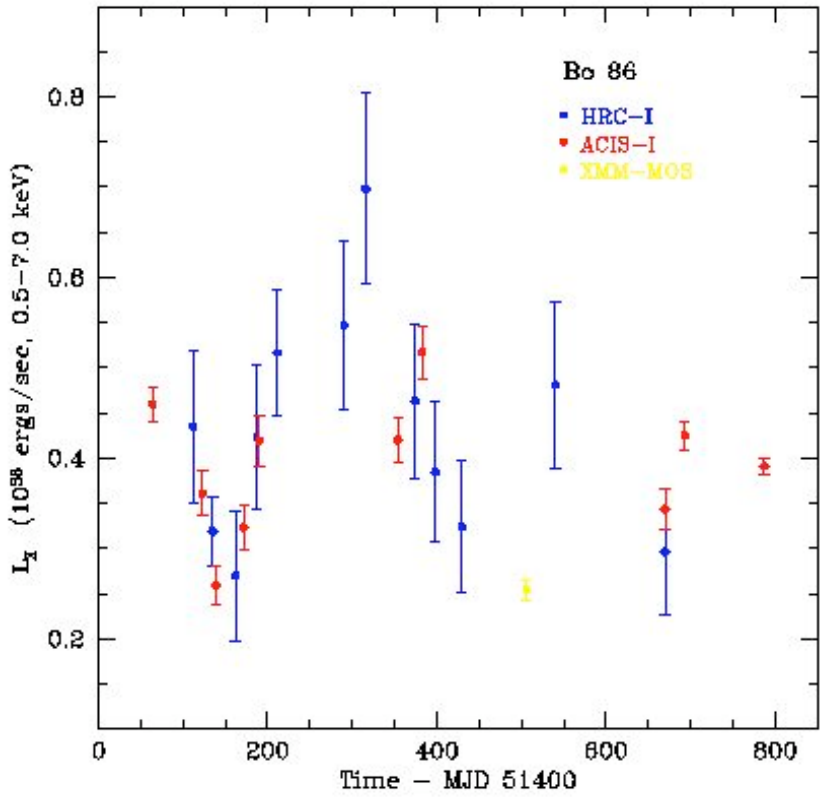
Hardness-intensity diagram

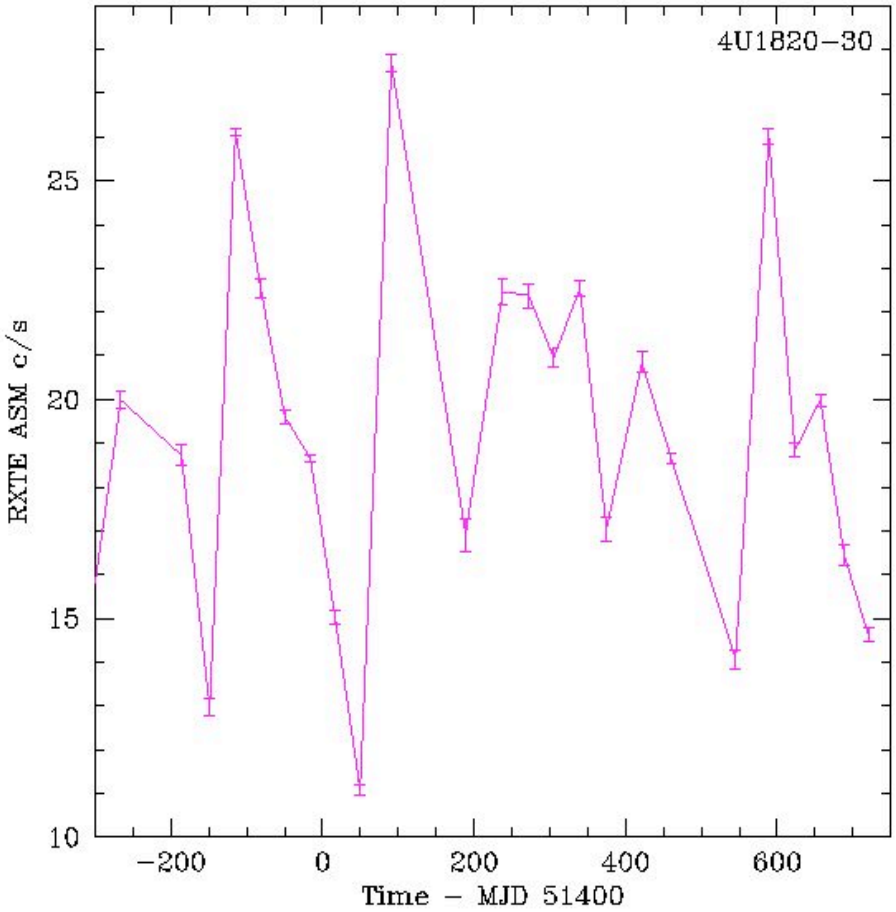


Region 2: outer bulge Region 3: disk

Light curves of X-ray sources

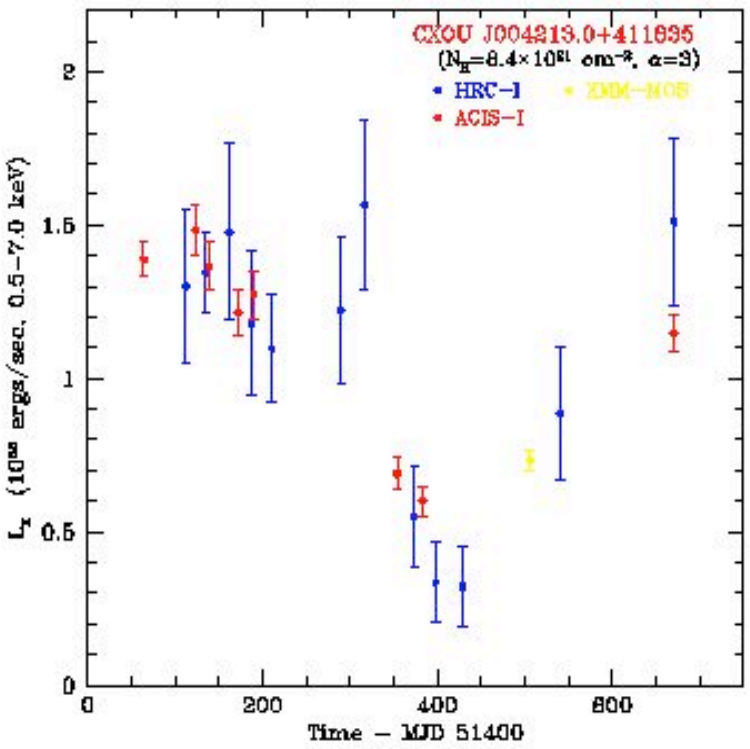
~200 d variability? (c.f. 4U1820–30)

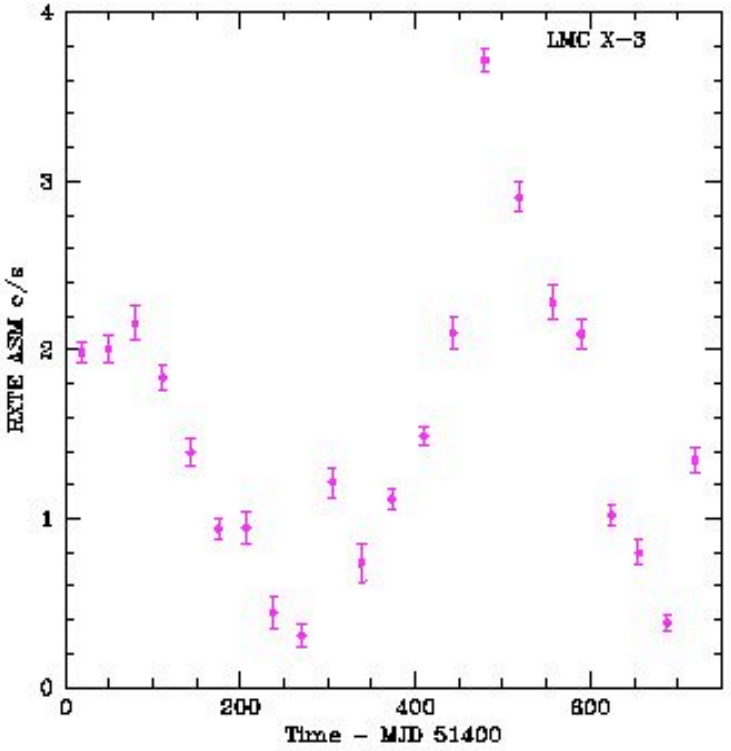




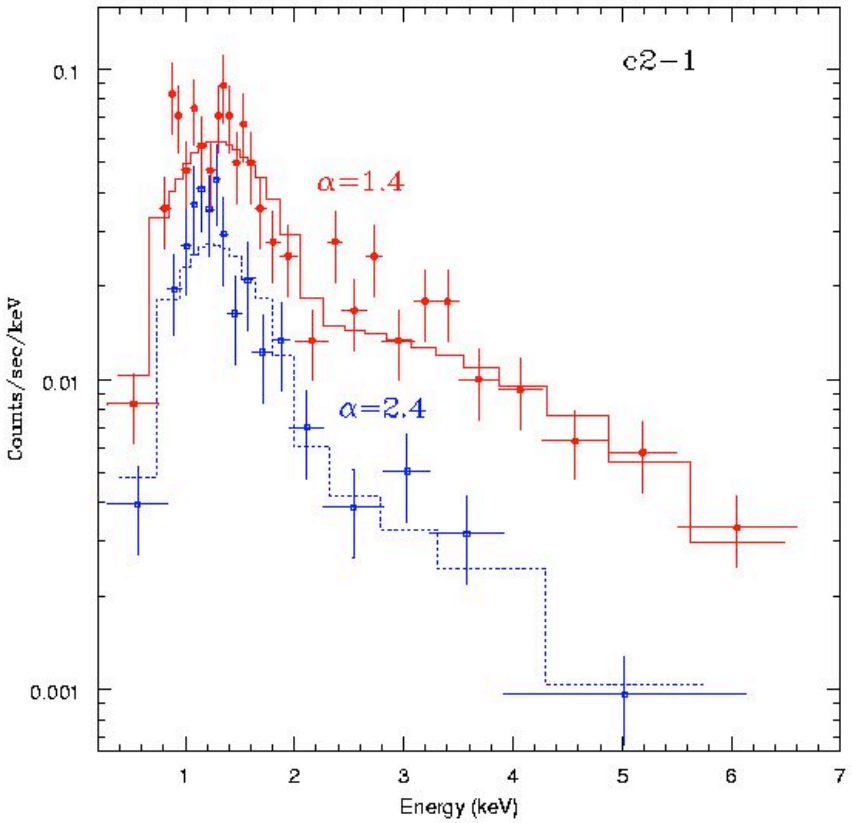
Light curves of X-ray sources

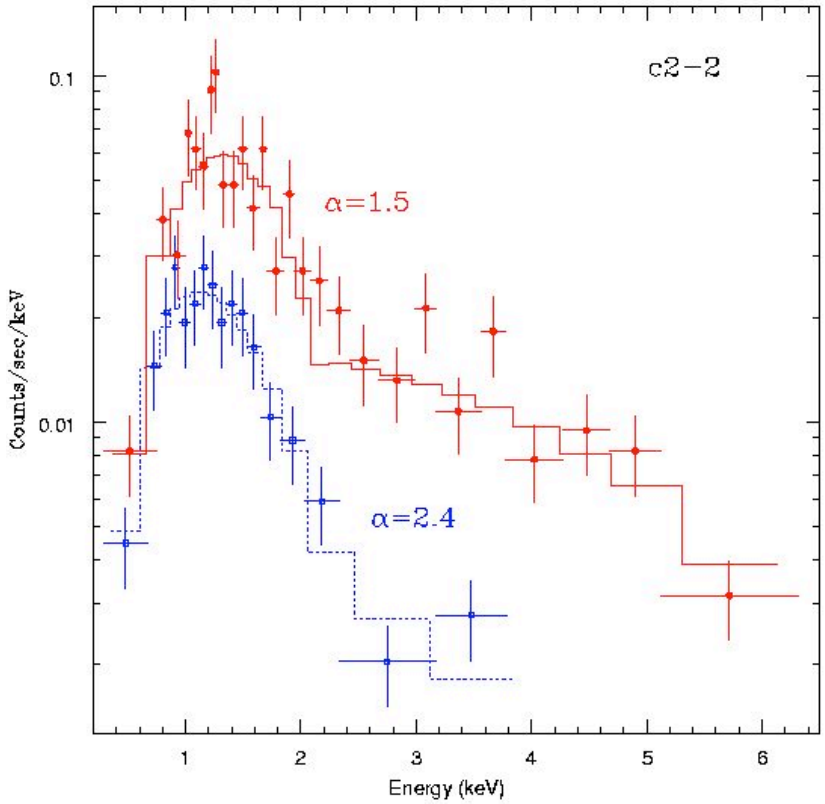
Highly variable source: HMXB?





Spectral variability





From low/soft state to high/hard state

$L_X = (0.5\text{-}1) \times 10^{38}$ erg/s

Z source moving along the Normal Branch ?

Variable sources in M31

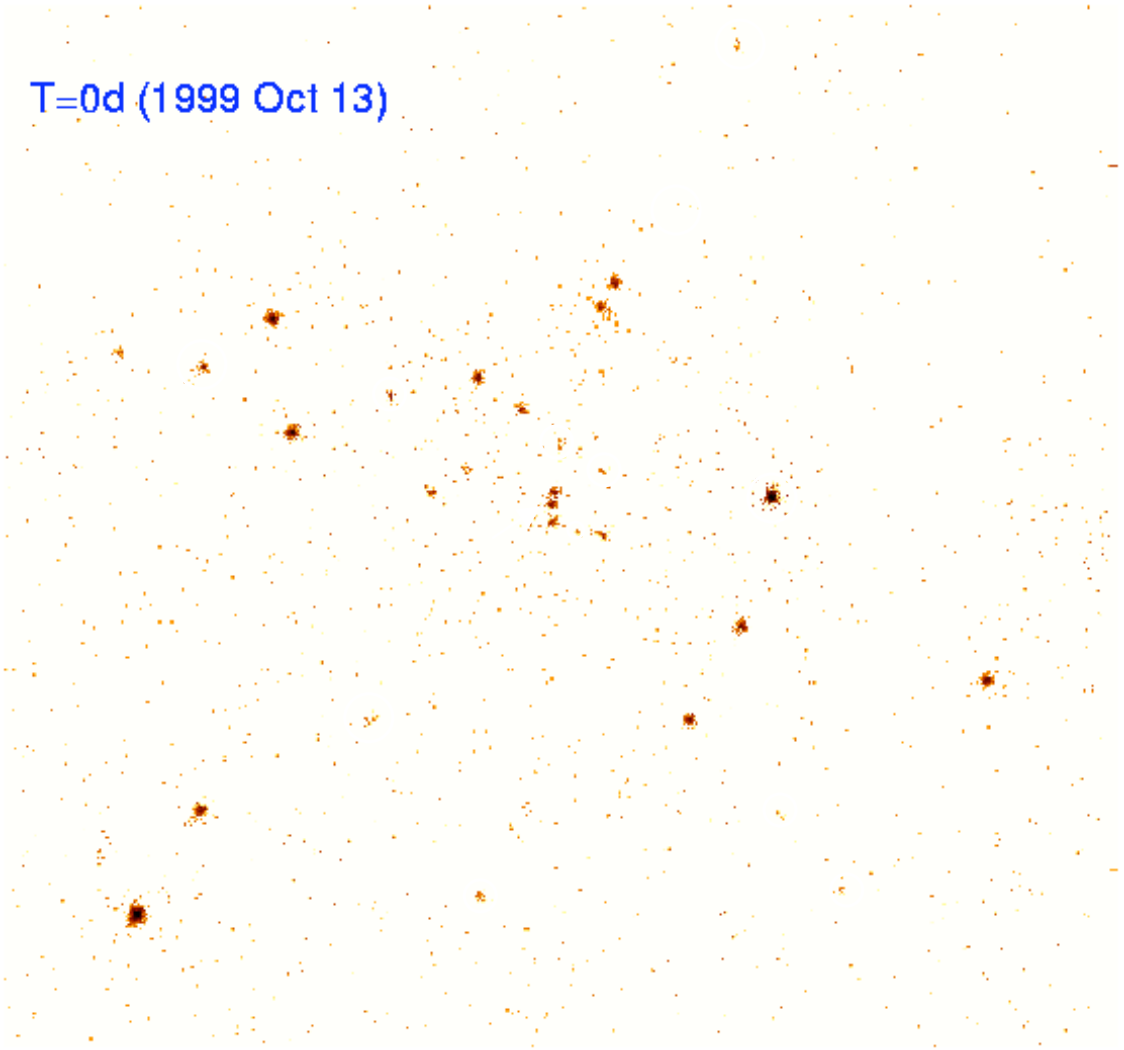
	Number	Fraction
Variables	99	50%
Spectral variables	12	6%
Transients	13	6%

$$S(F_{max} - F_{min}) = \frac{|F_{max} - F_{min}|}{\sqrt{\sigma^2_{F_{min}} + \sigma^2_{F_{max}}}} > 3$$

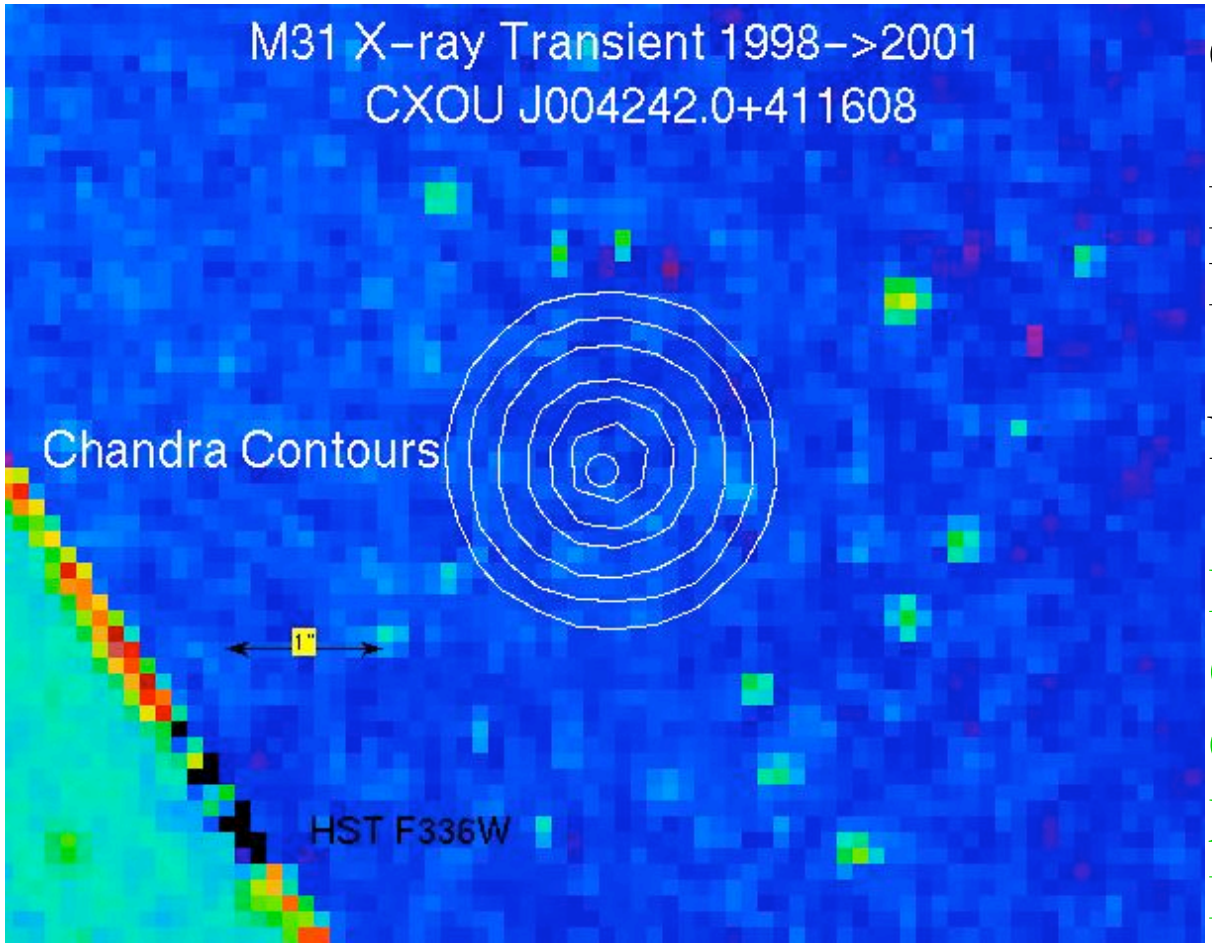
See Primini, Forman, & Jones (1993)

X-ray Variability in M31

Central 2’ x 2’ region



Searching X-ray transients in M31



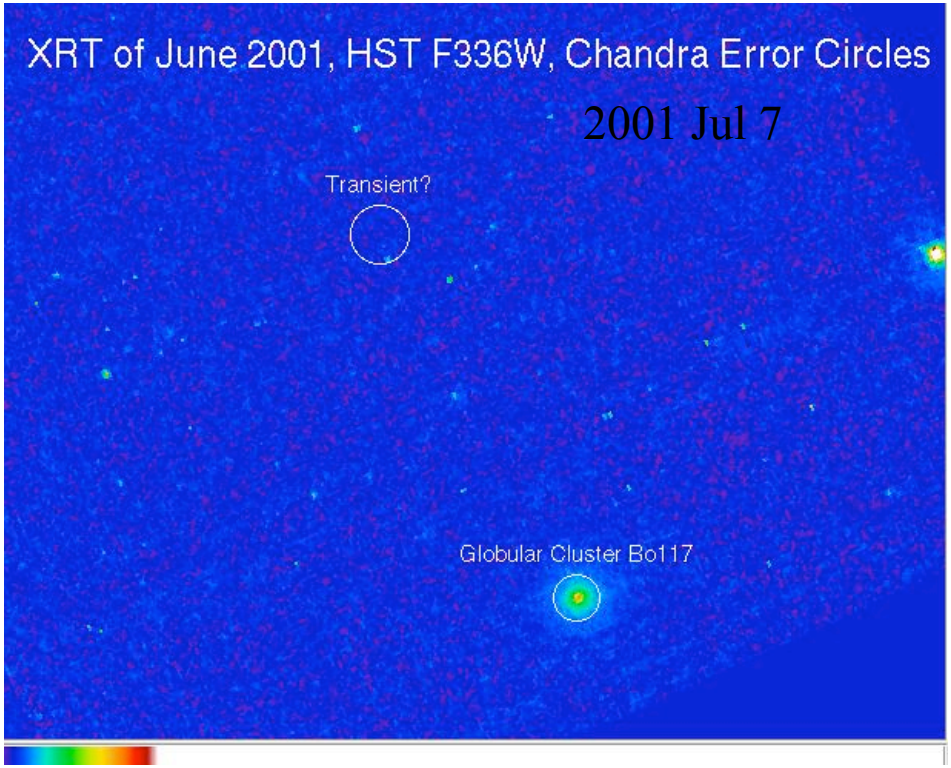
Our first try: 2000 Feb 25

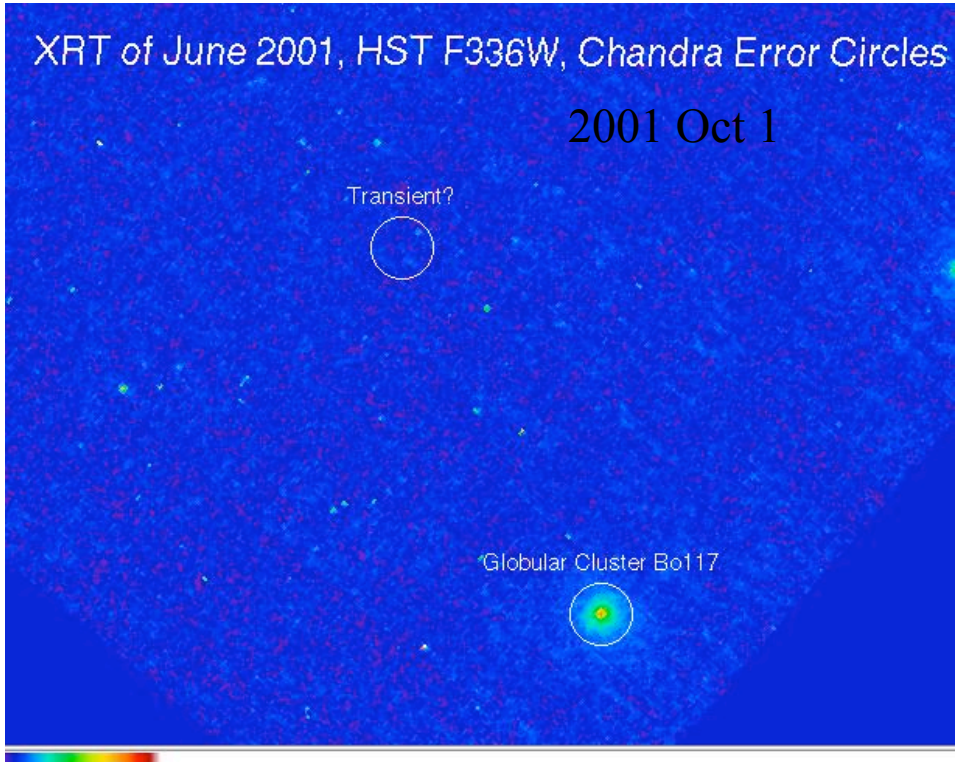
Brightest star U~22
Faintest star U~24

NO candidates to U~24!

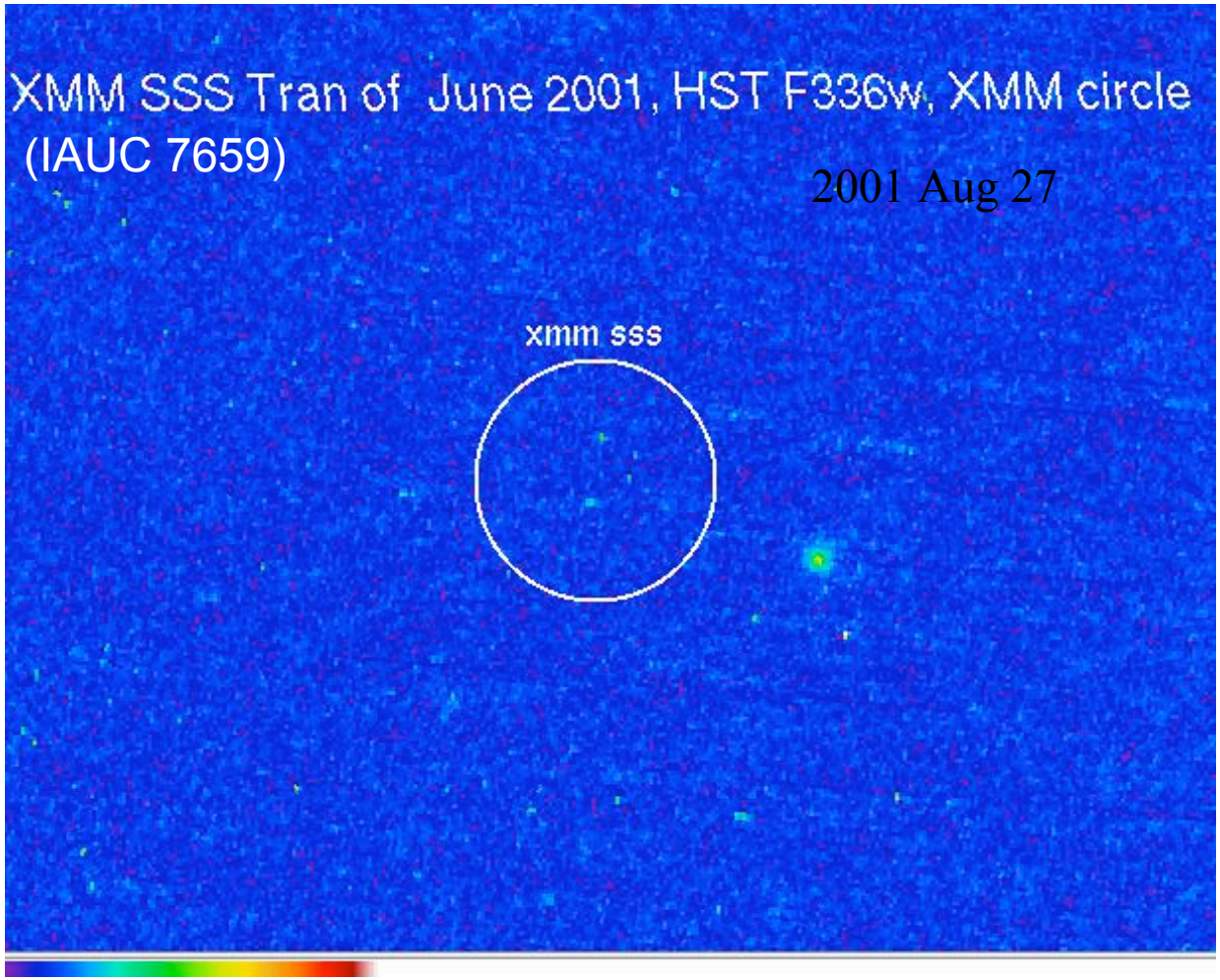
More chances…..
6 pairs of HST C10 +
Chandra AO2-3 +
XMM AO1
Plus KAIT ?

Searching X-ray transients in M31

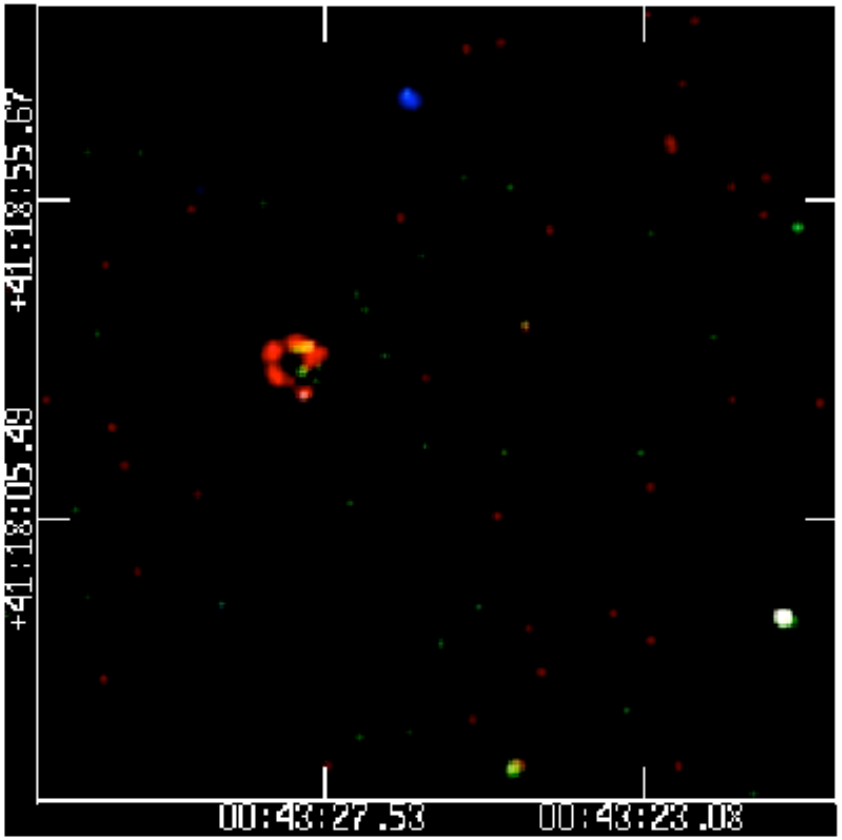


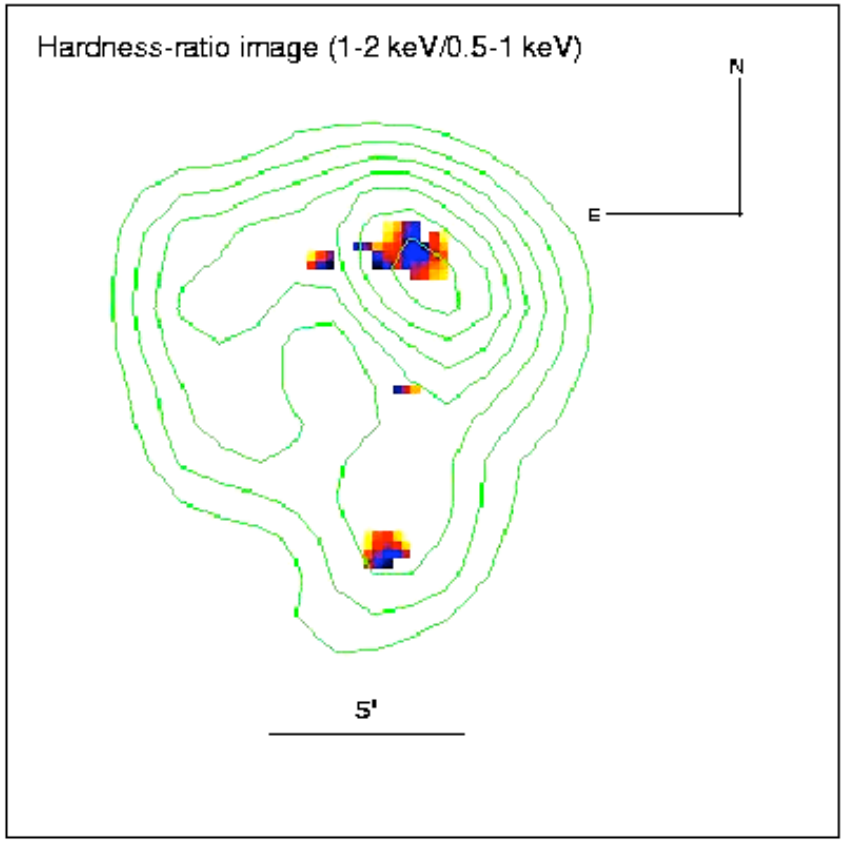


Searching X-ray transients in M31

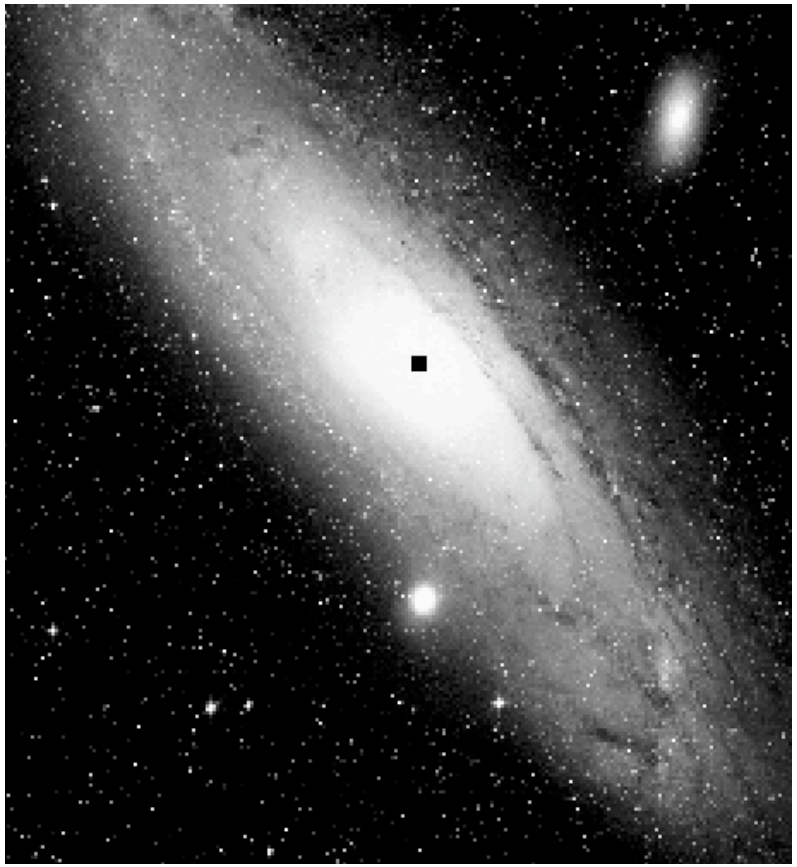


The first resolved SNR in M31





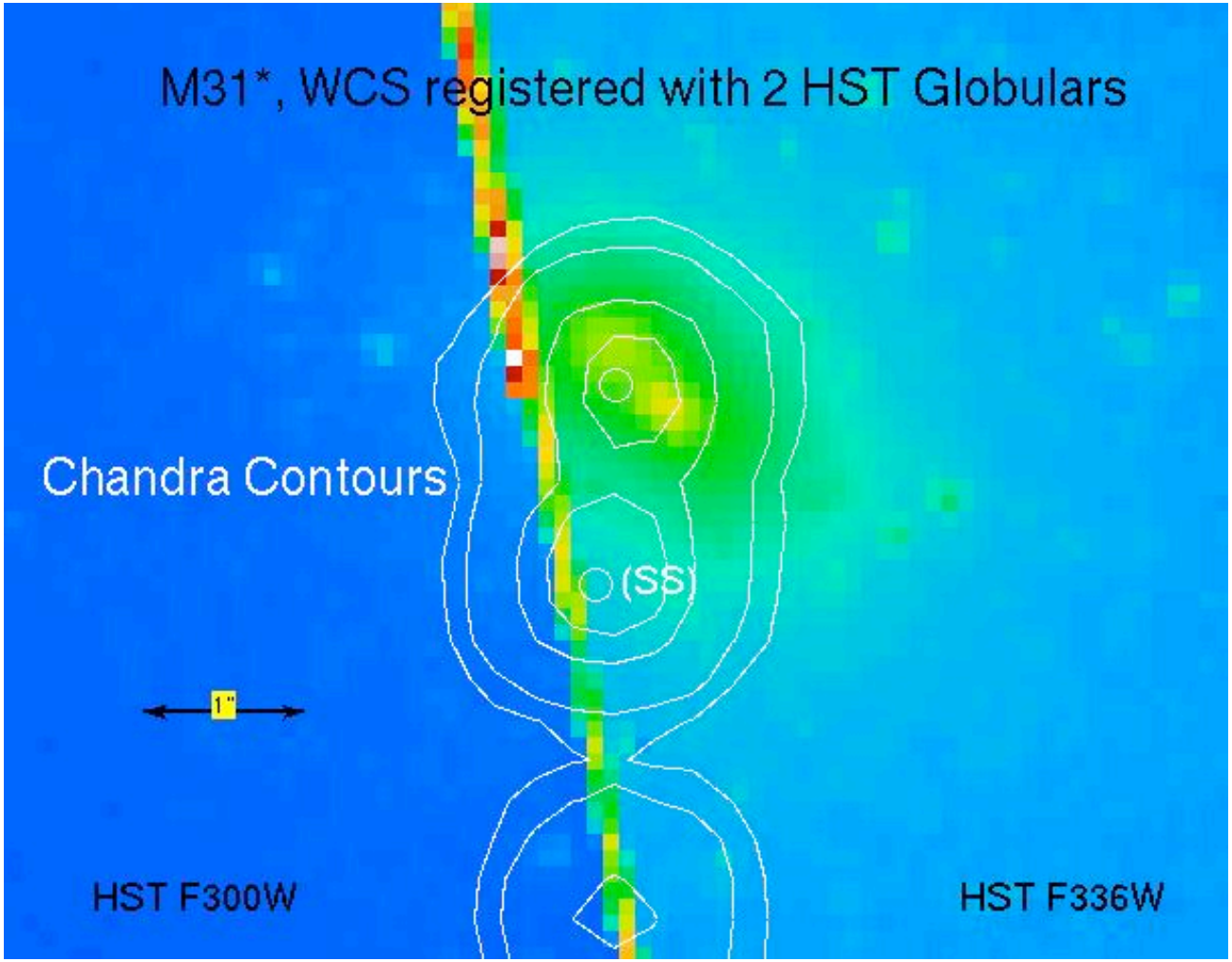
Next Nearest Black Holes: M31



* BHXN, XRB Easily detectable in 5ks, 100 cts at 10e37 ergs/sec
- If like A0620-00, U~22: Well within HST range!
- Monitoring with Chandra+HST:
- First Step in Extending 'galactic' BHXN studies to other galaxies!
- M31*: SMBH 3e7 Sun
- (Sgr A*: SMBH 3e6 Sun)

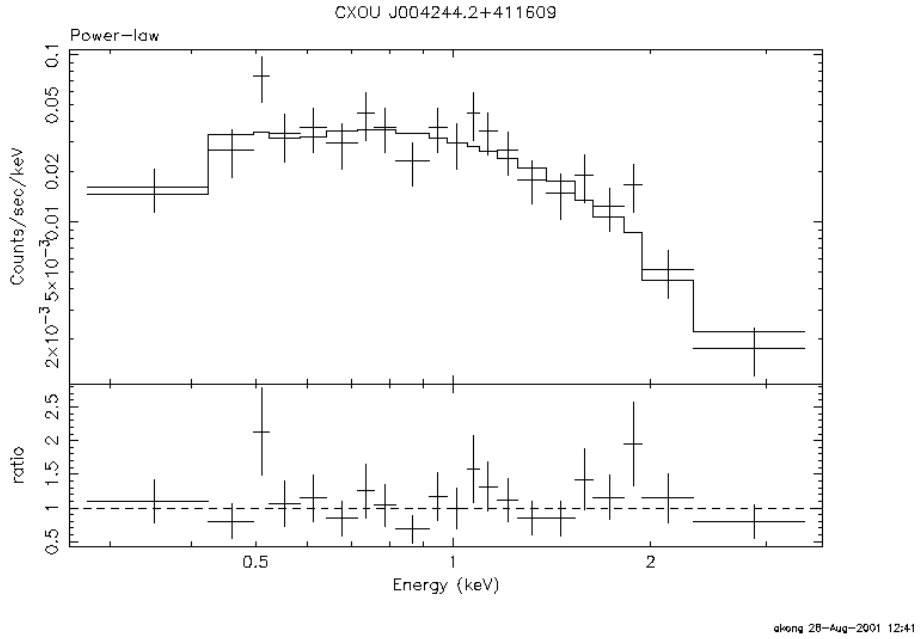
M31: The Andromeda Galaxy

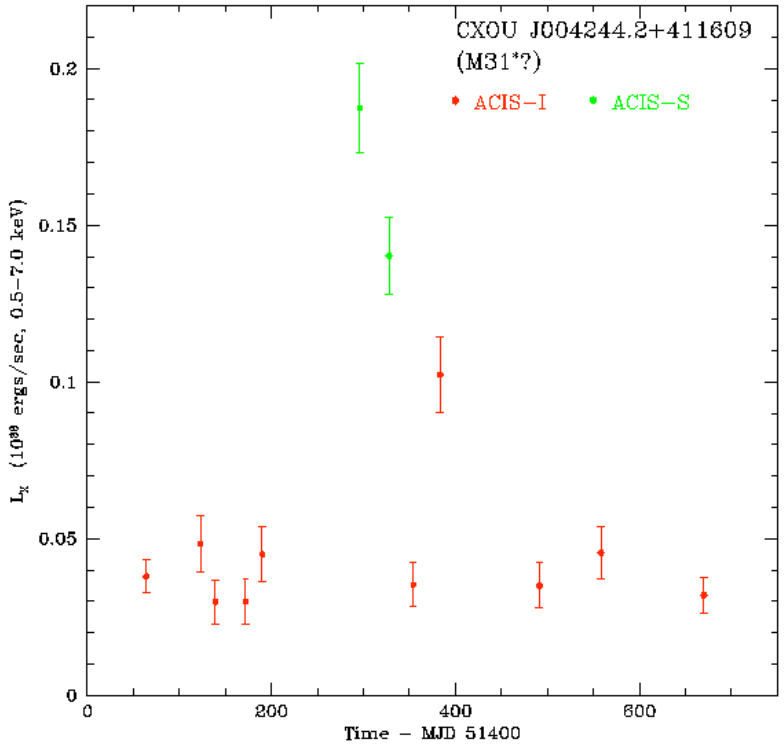
M31* = CXOU J004244.2+411609?
0.15'' from M31*, error = 0.07'' or 0.14'' (correlated)



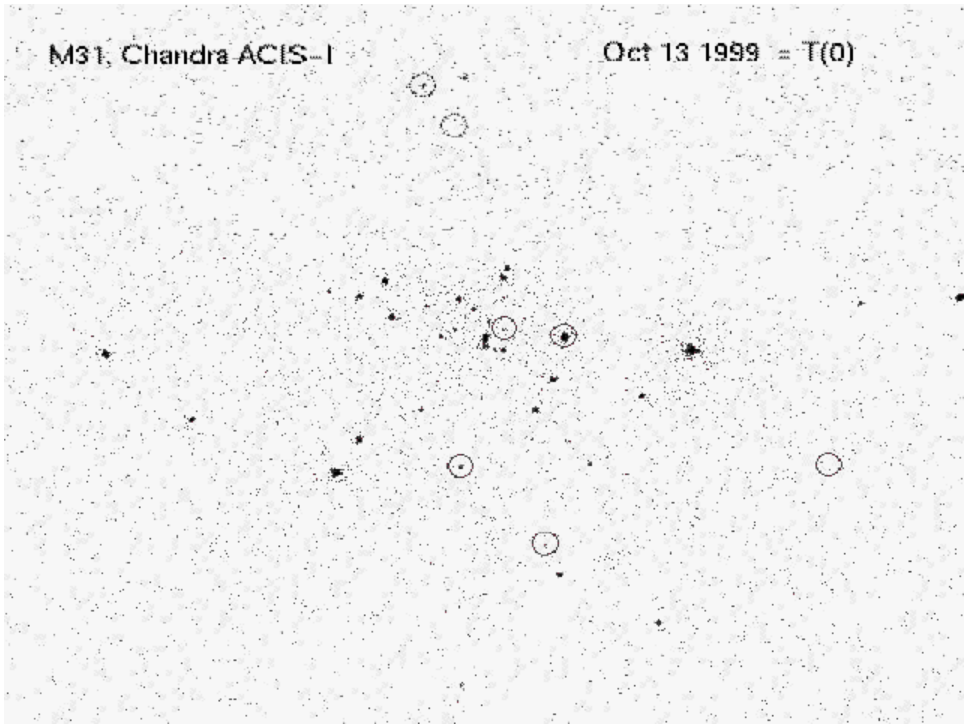
M31: The Andromeda Galaxy

M31* = CXOU J004244.2+411609?
PL with a=2.3 +/- .45, N(H)=1.5+/-0.8e21, Lx=2.4e37(max)
(Brems, R/S also fit)





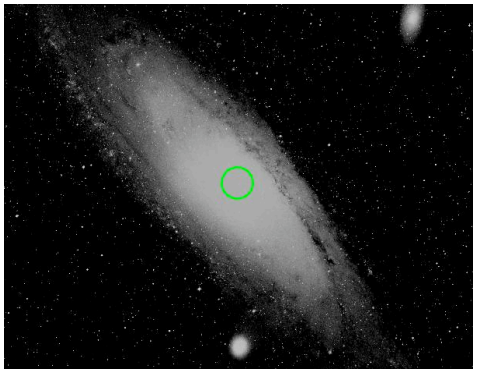
Many Transients in M31:

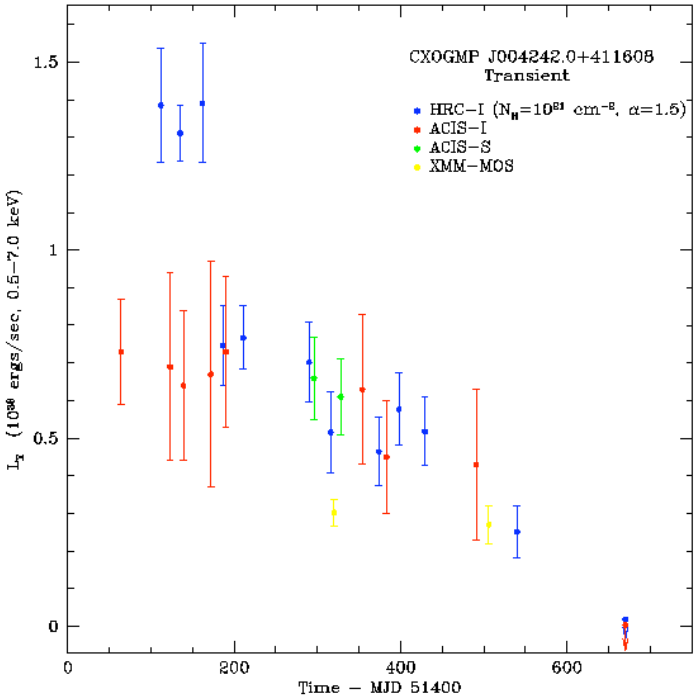


- Every 5ks ACIS image finds ~>1 new 10e37 source
- HRC monitoring (1.25y) has NOT found >1e38 transient: might expect 1+
- Search for HST Counterparts……..

Garcia etal 2001 IAUS 205

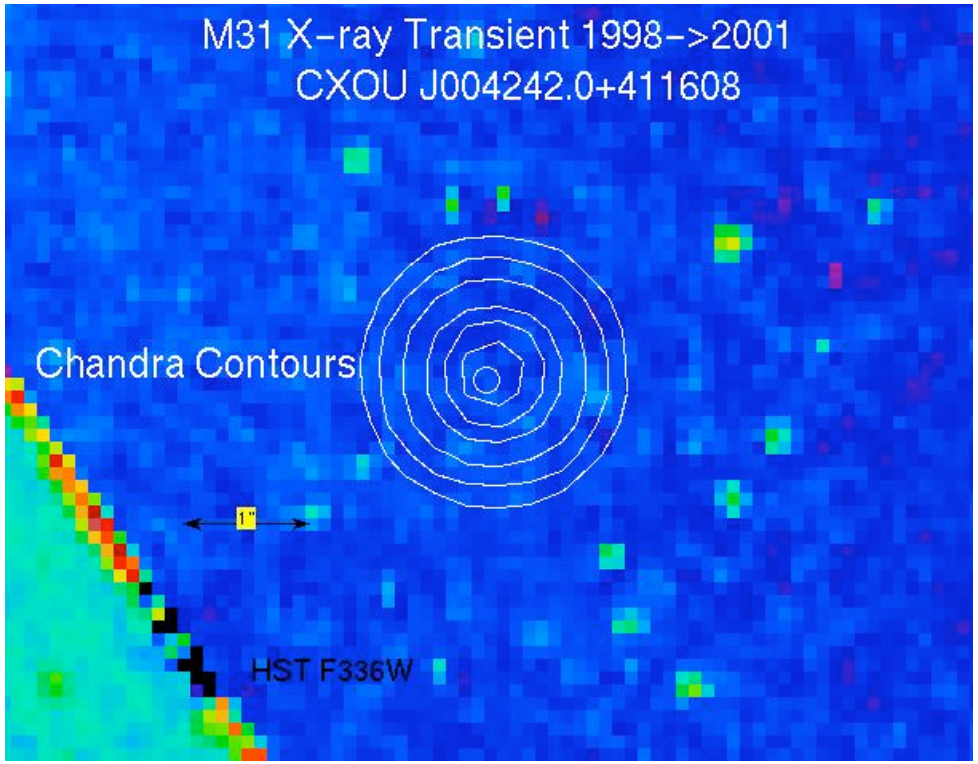
First Try at HST Detection of M31 XRN





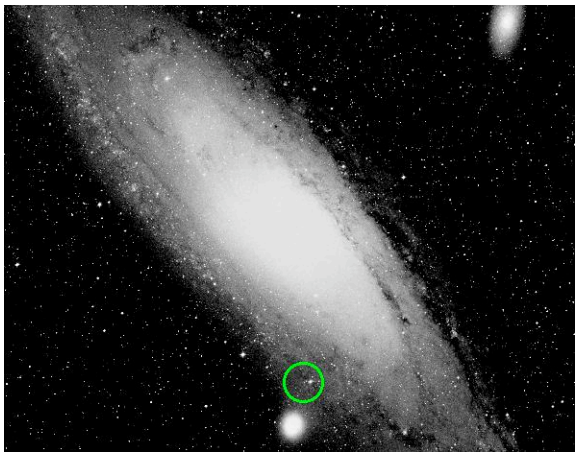
- Discovered in First Chandra Image, Oct 99, 26'' west of Nucleus
- After 2 years, now off! (unusually long…)
- IF like A0620-00, expect U~22 at M31 at peak

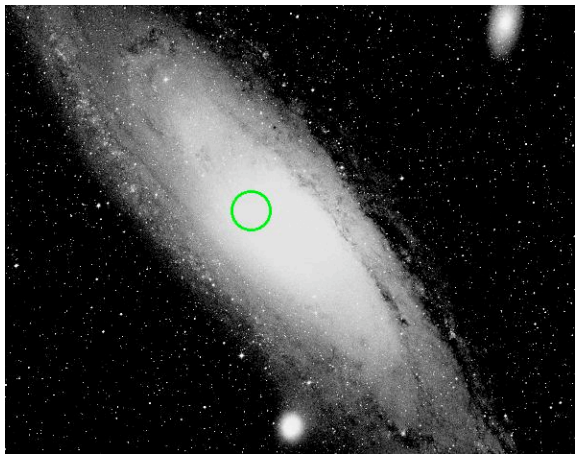
First Try at HST Detection of M31 XRN



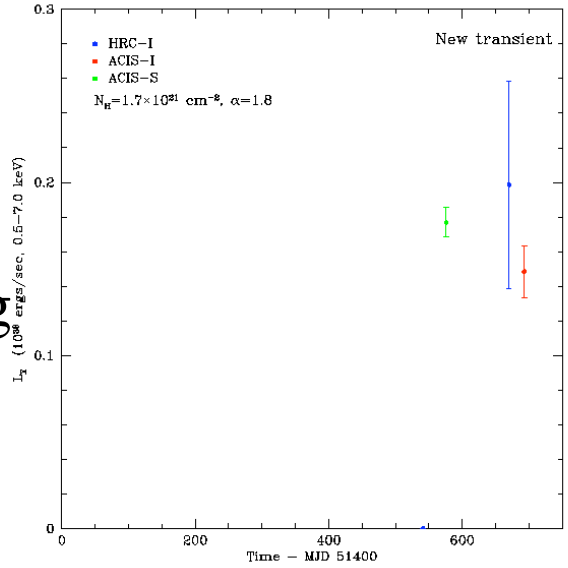
- HST WF/PC2 U-band image including Lx=37.8 transient
- White Circle = 0.1'' radius, using GC Registration. (needed!)
- Brightest stars U~22, faintest U~24
- NO CANDIDATES to U~24. A_U ~ 1.5?,Lx<e39?
- Many other chances! 6 on/off pairs with HST C10 + Chandra AO3 + XMM AO1

Two More Recent HST Followups within last month





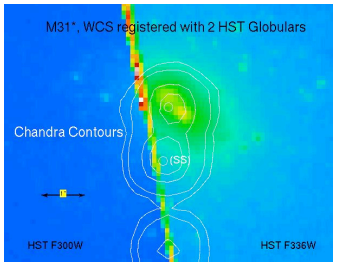
A XRN
Found by
HRC
Monitoring



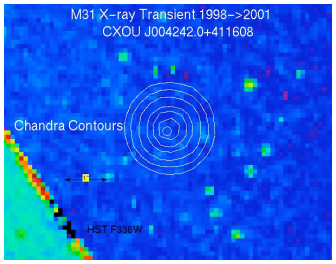
A SSS found
By XMM June 29
IAUC 7659 (Shirey etal),

Analysis of HST WFPC2 images in Progress…..

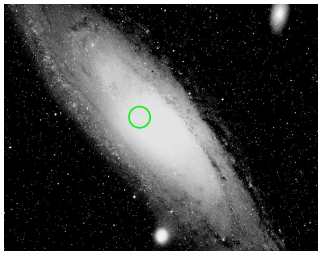
SUMMARY

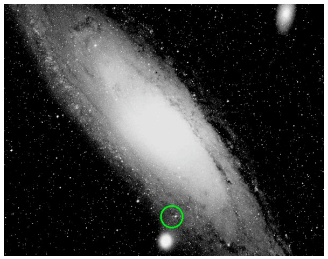


M31* = CXOU J004244.2+411609?
Lx = 2e37, alpha = 2.3, Variable ~ month



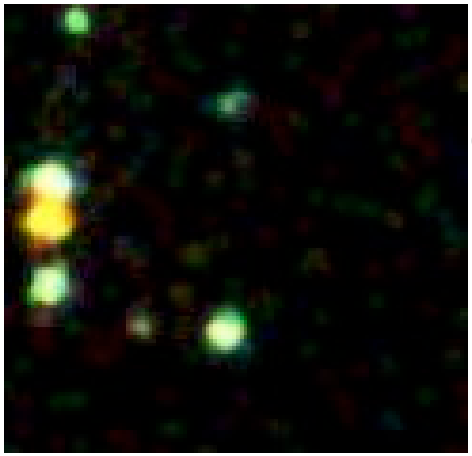
CXOU J004242.0+411608 = 2 year Transient
Lx=e37.8 U>24…. Why? Av = 1.5, U = 22+2?





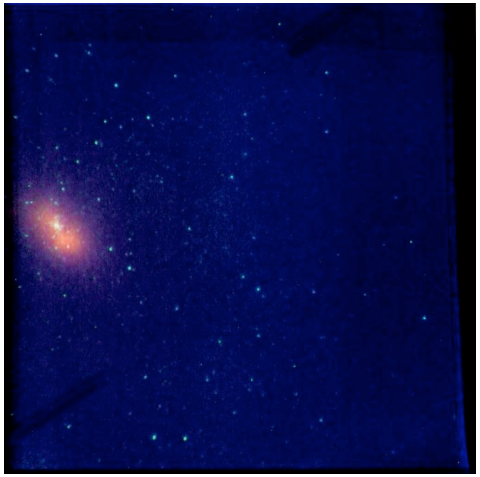
ASM + G.B. in MW = Chandra+HST in M31
Recent Followups:
At lower Av, on/off images, 1 mag deeper

qSMBH: M31*



Albert Kong, 'True Color' X-ray Image 37.5ks ACIS

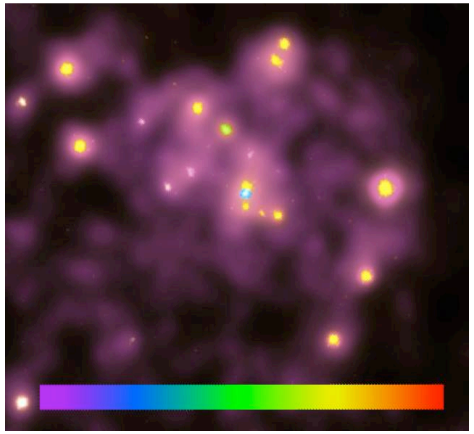
----------14'' ----------



Brown etal 1998 HST FOC 1750/2750/5500

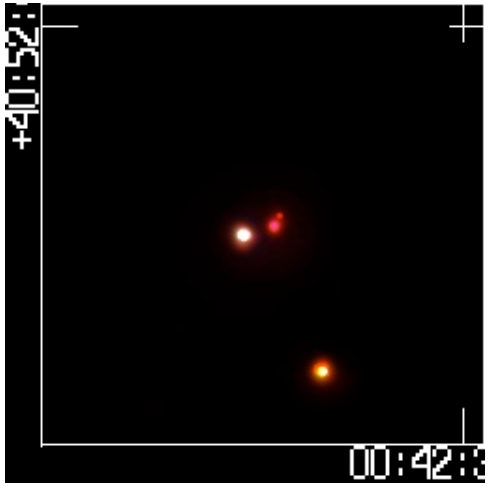
- M31*: Between P1/P2, 0.5" separation
- Chandra position ~1"
- Garcia etal 2000 ApJ: M31* = SSS?
- Garcia etal (IAUS 205): M31* = Northern Source?
- NEW: Second GC from Barmby's catalog: M31* = Northern source? Lx =2e37 ergs/s.

qSMBH: M31*, Sgr A*, M32*

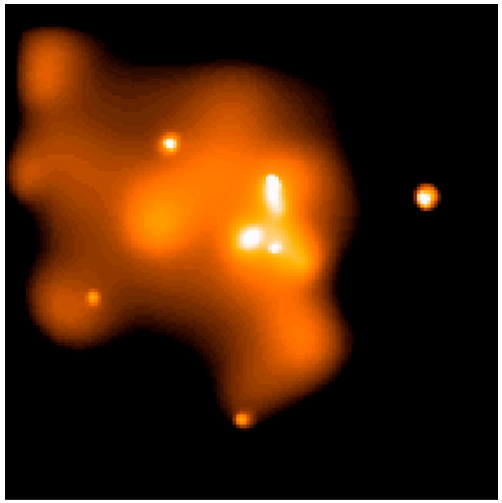


Garcia etal 2000
ApJ Lett

- M31*: Lx =2e37, 5e-9 L(E)
- Sgr A*:Lx=2e33 , 7e-12 L(E)
- M32*: Lx<3e36, 1e-8 L(E)
- Some much fainter than qBHXN (1e-8->1e-6 L(E)), but Mdot unknown.



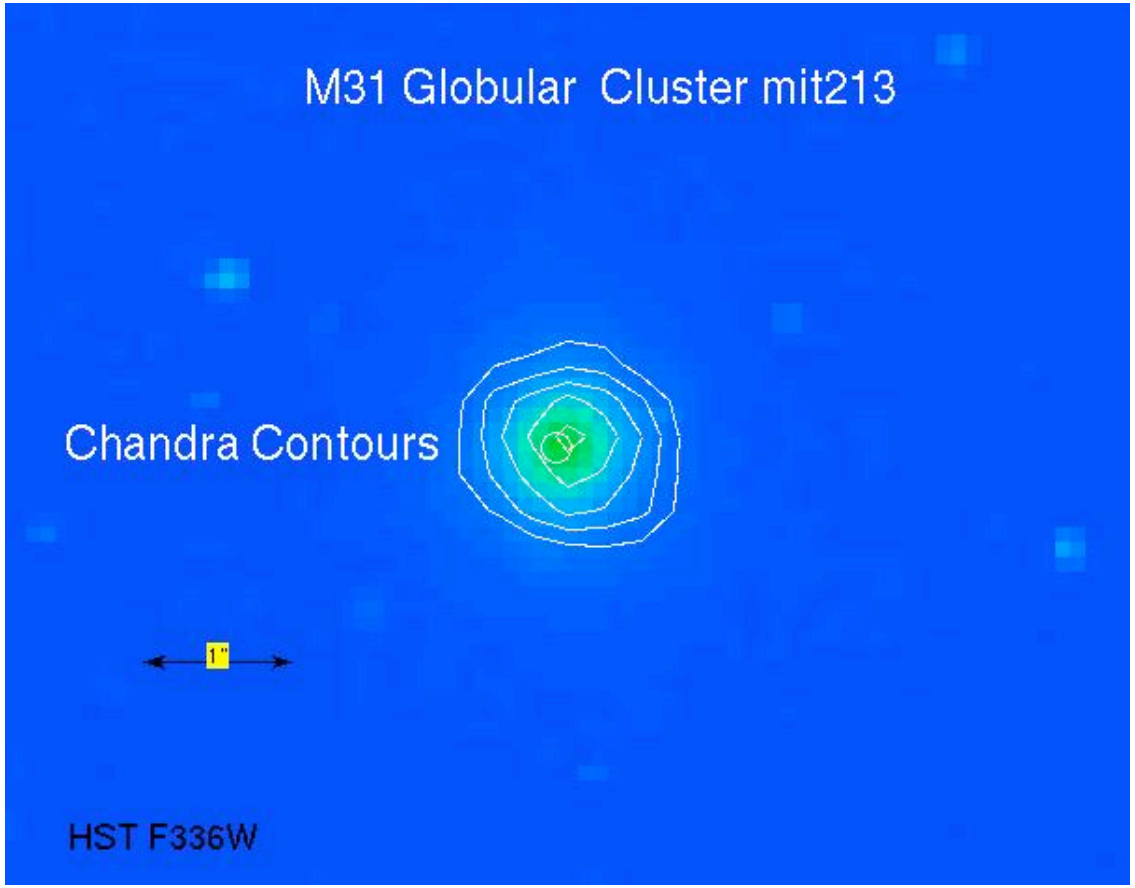
Primini etal 2001
In prep



Baganoff etal 2001
Astroph/0102151

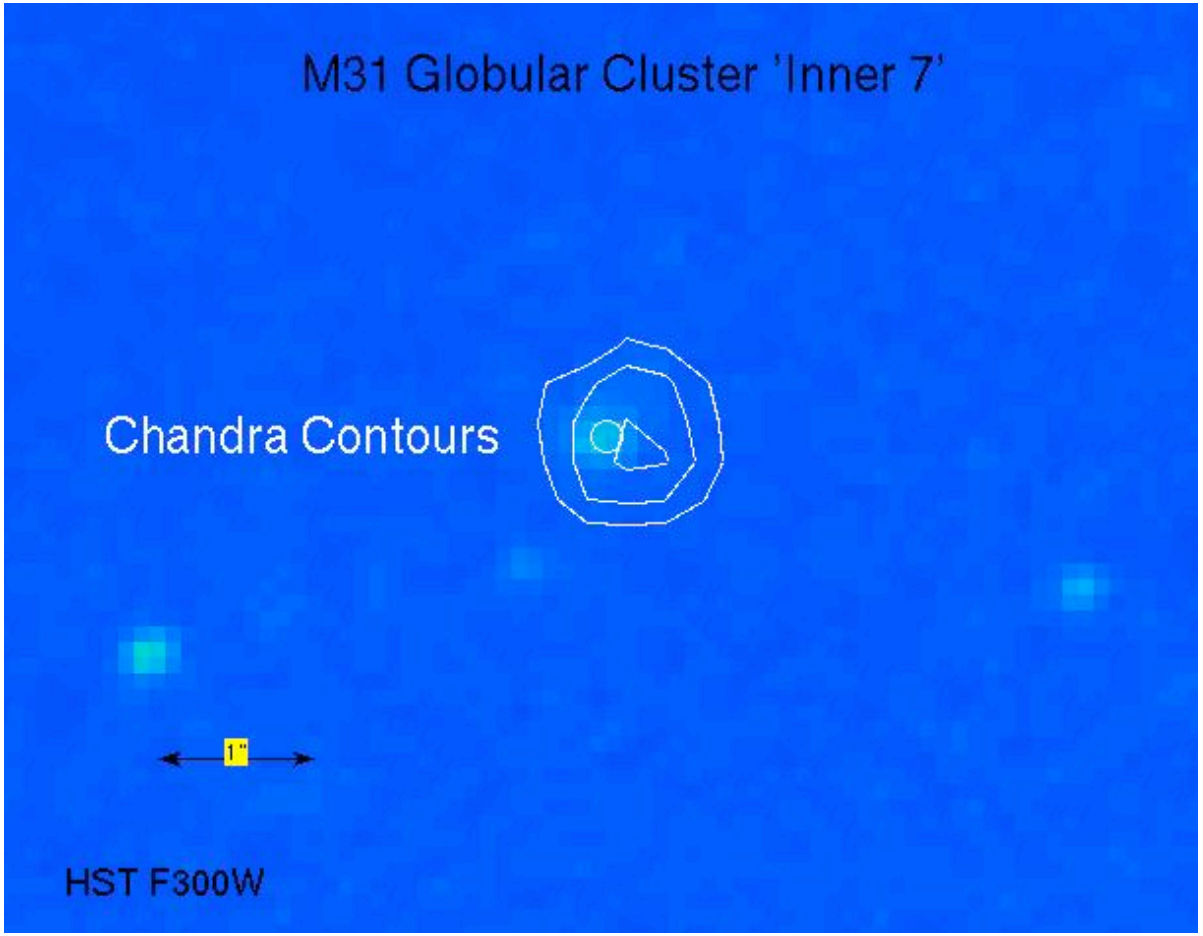
M31: The Andromeda Galaxy

MIT213: Chandra Contours on Registered HST Image
Inner circle = 0.1”
60 X-ray Counts



M31: The Andromeda Galaxy

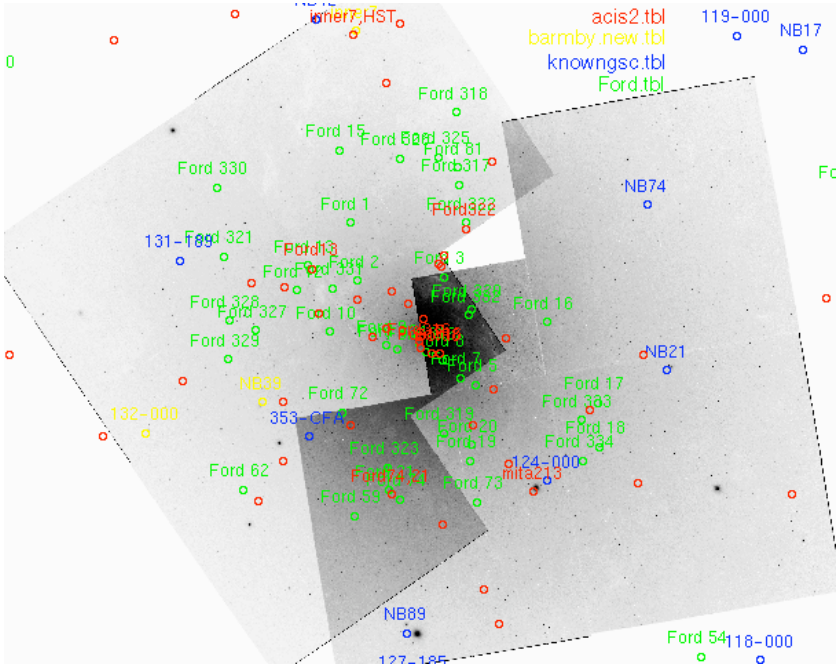
Inner 7: Chandra Contours on Registered HST Image
central circle = 0.1”
40 X-ray Counts



M31: The Andromeda Galaxy

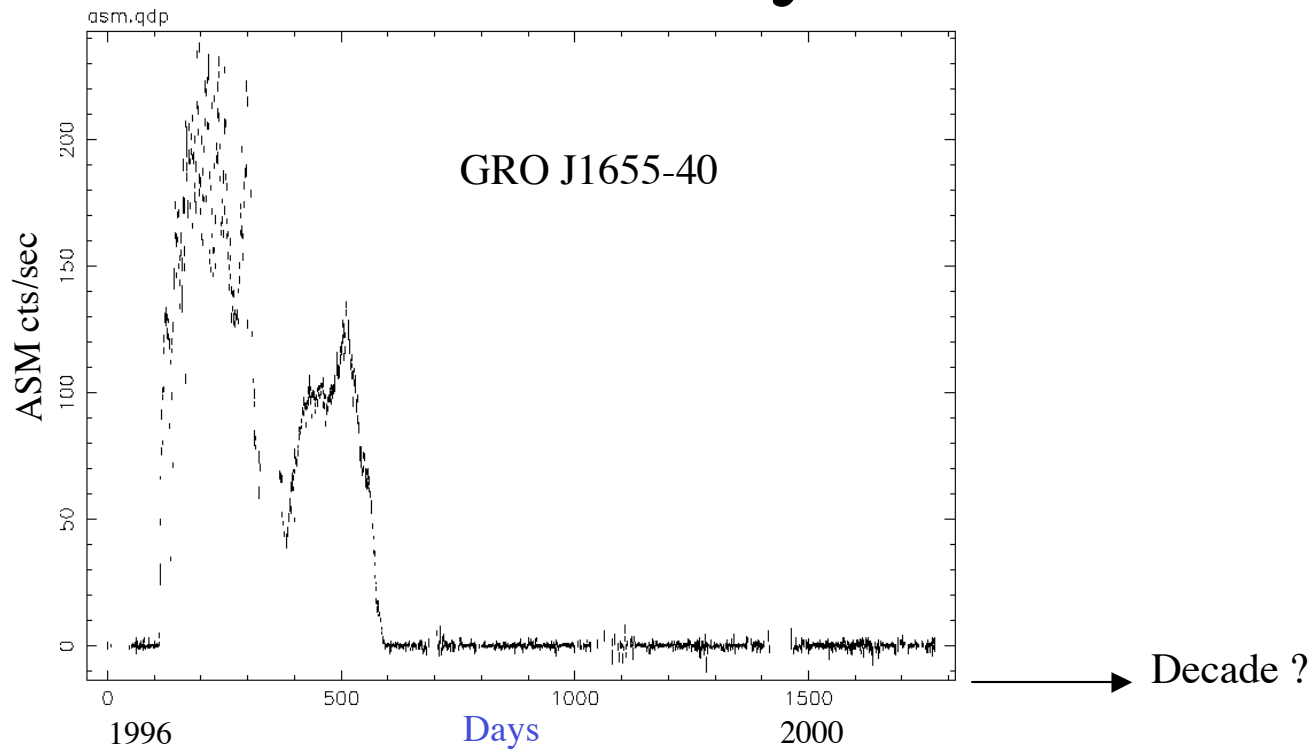
Registation of HST/Chandra Images:
Absolute Positions good to ~1''
FOVs Divergent: ACIS=16', WFPC2=2'
Mosaic WFPC2, match Sources!

~100 matches in
HST F300W/F336W
rms =0.05''



ACIS Sources
Barmby GC
MIT/Bolg GC
Ford PN

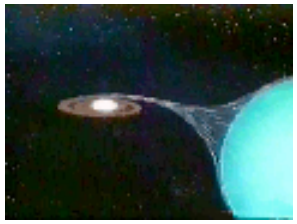
Q:What is an X-Ray Nova?



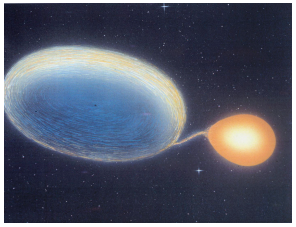
- An **X-ray Nova (XN)** is a NOVA, found via X-ray outburst (RXTE/ASM, CGRO/BATSE) Delta Fx>1e6, Delta V>6
- An XRN has two states: a bright state and a dormant state

A: Secure Black Hole

- "Some of Most Secure BH Known": Why?
- Lx > 10^38 erg/sec in outburst, t~1msec: heavy and small
- f(m) > 3 Suns, Mx > 3 Suns
- GR: M(NS) < 3 Suns, Therefore f(m) > 3Sun: BH!
- Cyg X-1 f(m)=0.24 Suns: HM less secure than LM

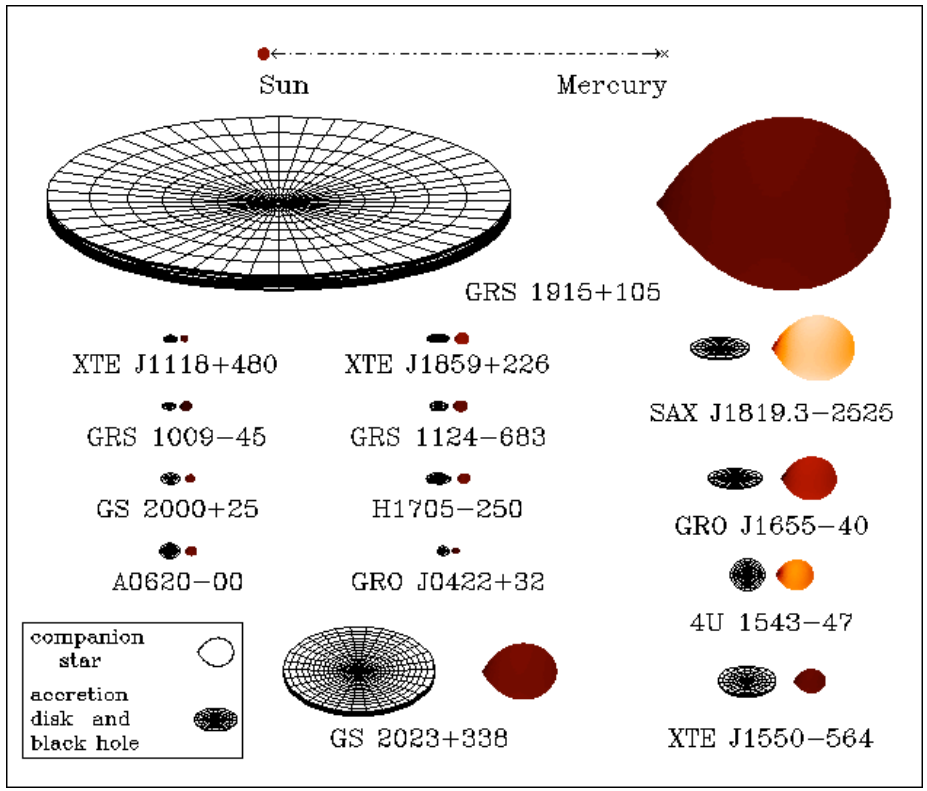


VS.



NB: Process of Elimination not EH or Singularity

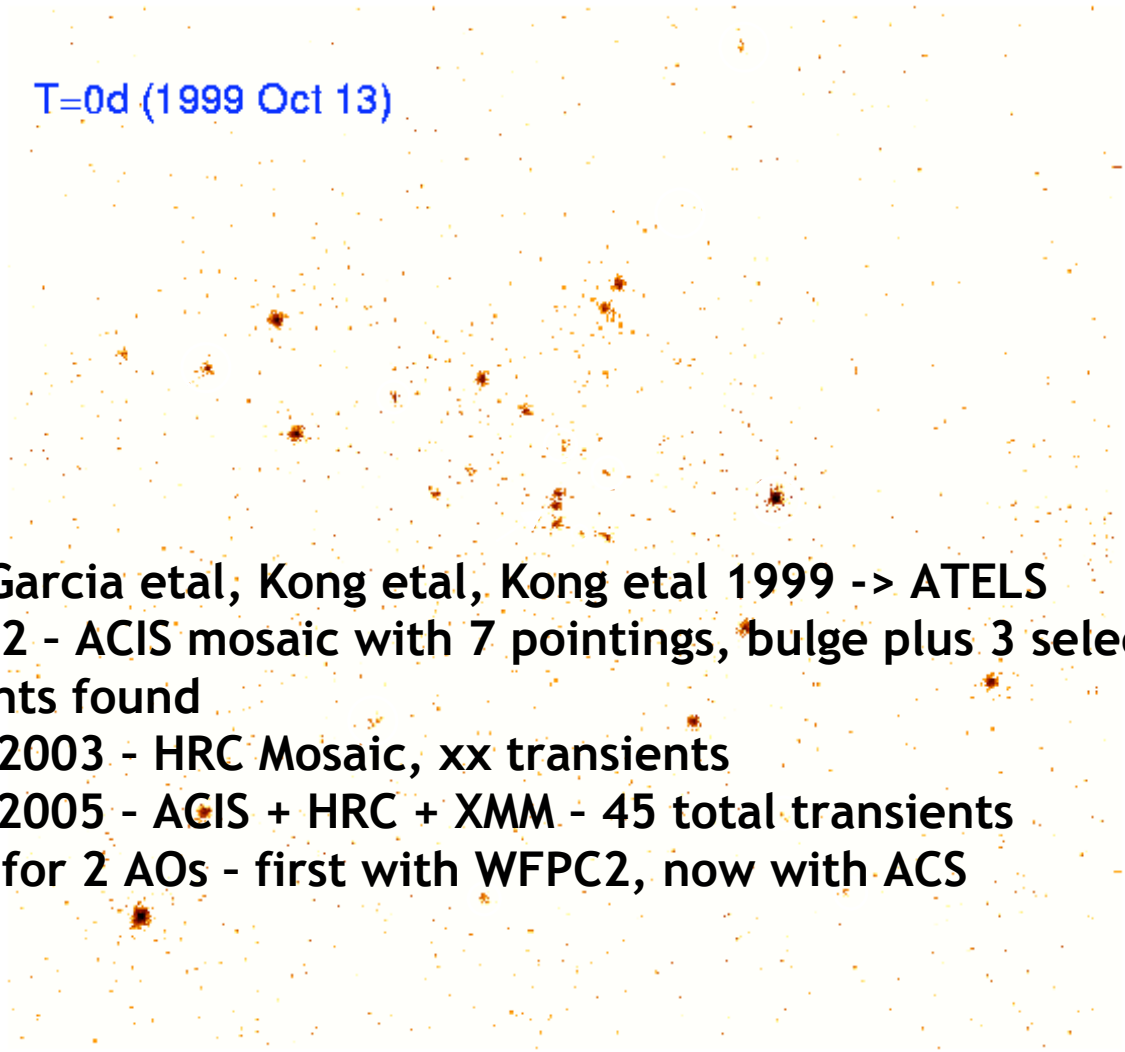
Why Might These M31 XRT be Black Holes?



Jerry Orosz, Utrect

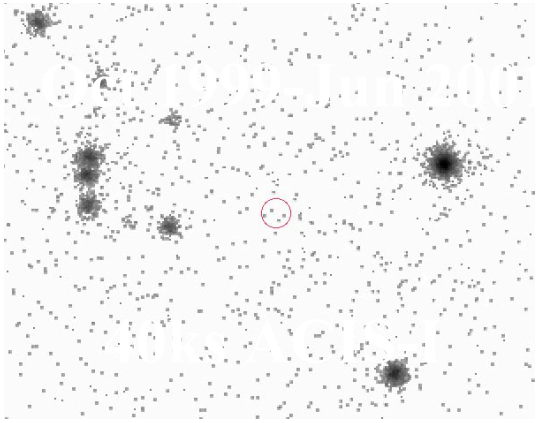
Synpotics Observations of M31: Goals?

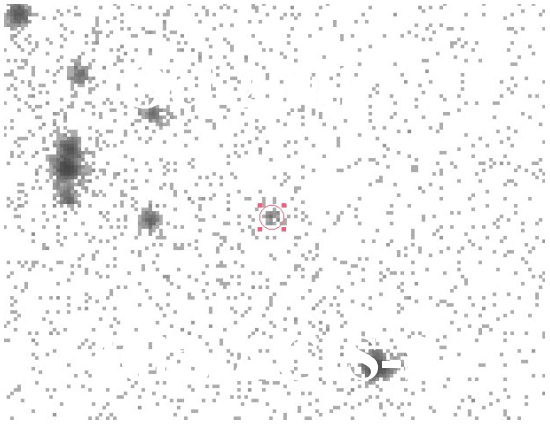
Transients

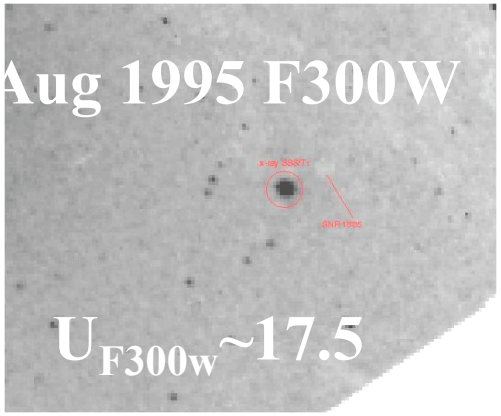


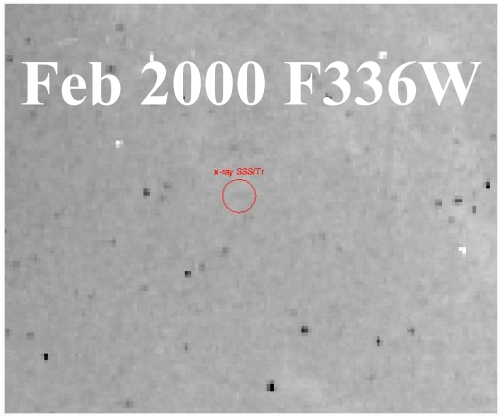
- Murray etal, Garcia etal, Kong etal, Kong etal 1999 -> ATELS
- Kong etal 2002 – ACIS mosaic with 7 pointings, bulge plus 3 selected regions, 13 transients found
- Williams etal 2003 – HRC Mosaic, xx transients
- Williams etal 2005 – ACIS + HRC + XMM – 45 total transients
- HST followup for 2 AOs – first with WFPC2, now with ACS

CXOM31 004243.1+411604 -Nova?

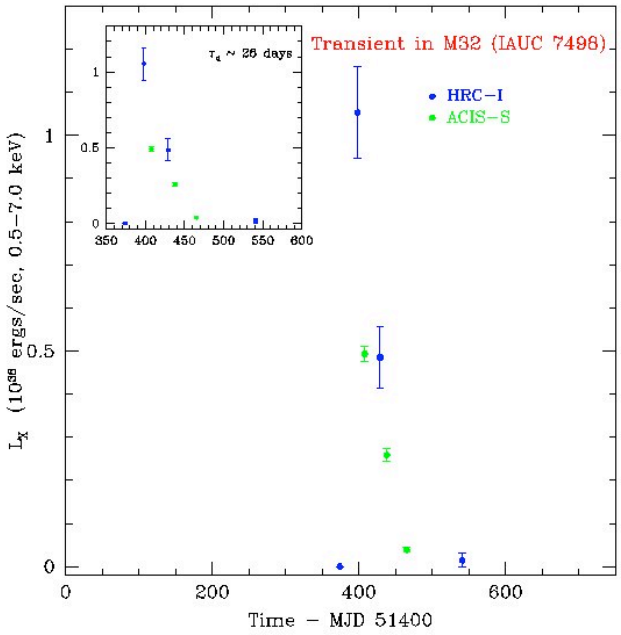


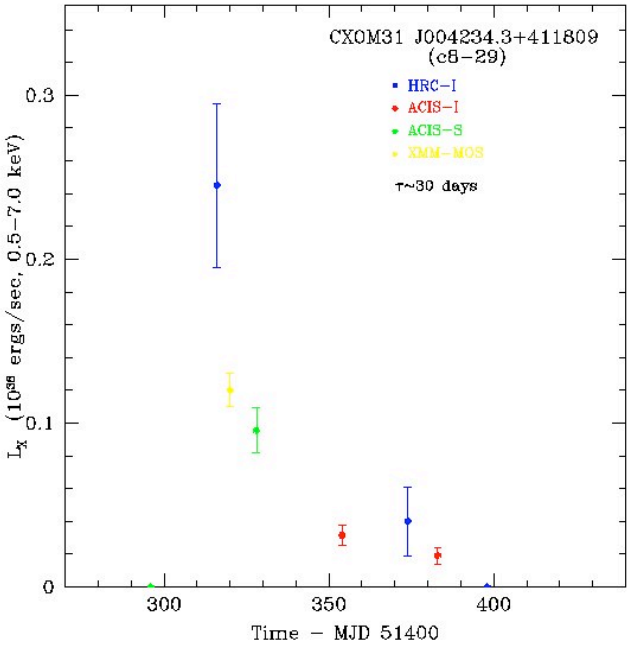


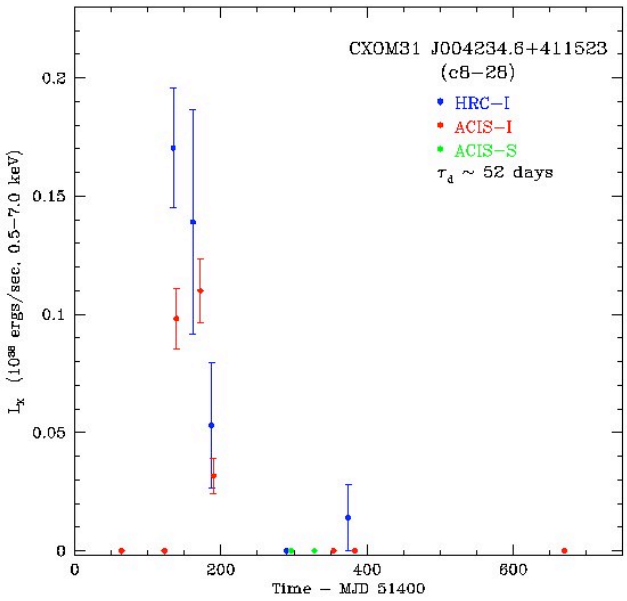




Light curves of X-ray sources







Fast-rise-exponential-decay light curves

Light curves of X-ray sources