A Deep *Chandra* Look at the Bondi Region of the Supermassive Black Hole in NGC 3115

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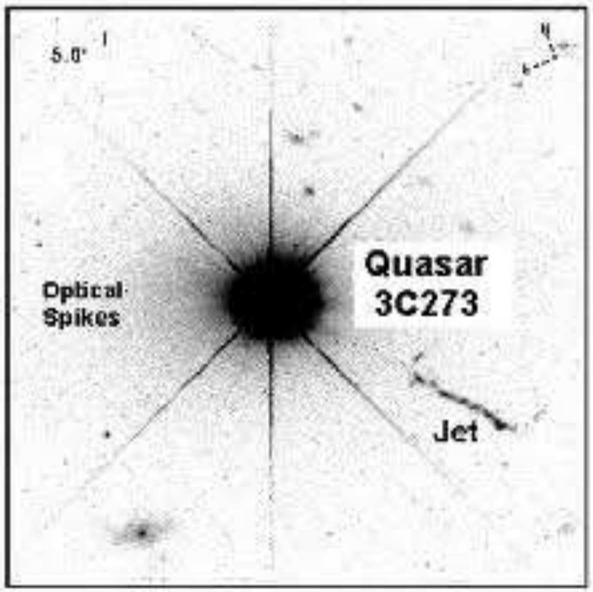
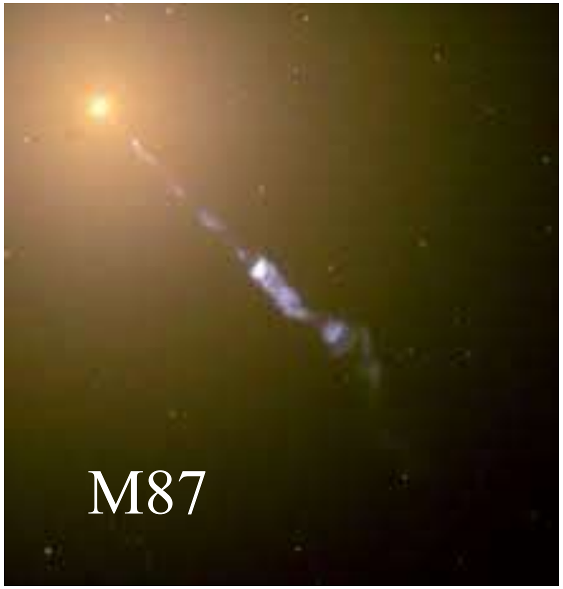
Accretion Onto Supermassive Black Holes

How does gas get to the event horizon of the black hole?

What determines how much mass gets to the event horizon and how efficiently the energy is radiated?

Quasars, AGN, and Quiescent SMBHs





Muno et al.

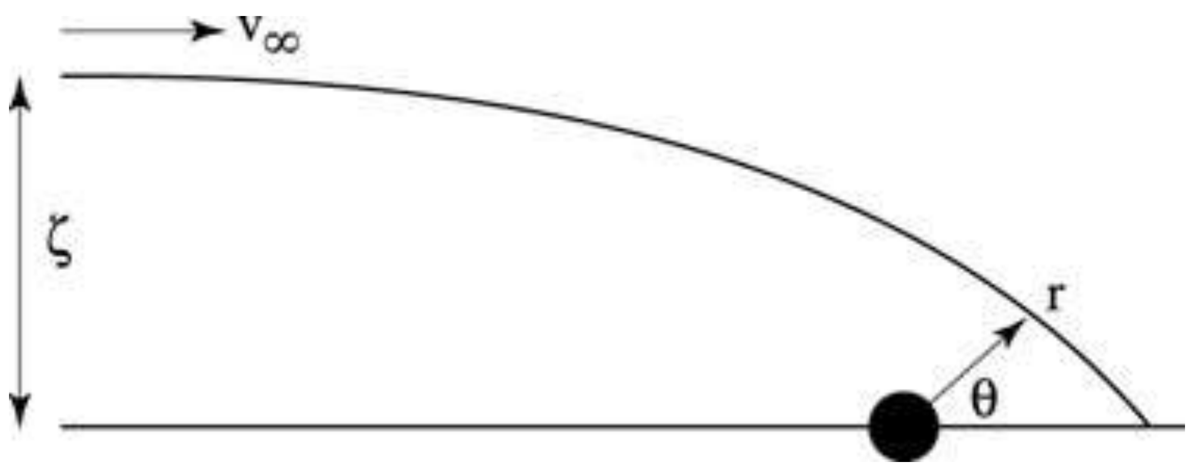
$L_{bol} \sim 10^{46}$ erg s^{-1}
$\sim 0.1\ L_{Eddington}$

$L_{bol} \sim 10^{42}$ ergs s^{-1}
$\sim 10^{-5}\ L_{Eddington}$

$L_{bol} \sim 10^{36}$ ergs s^{-1}
$\sim 10^{-8}\ L_{Eddington}$

Why are most SMBHs so radiatively inefficient?

Bondi Flows Around Black Holes



Edgar (2009)

The "sphere of influence" around a black hole is defined by its Bondi radius, $R_B = 2GM_{BH}/c_s^2$, where M_{BH} is the mass of the black hole, and c_s is the sound speed of gas near of the black hole.

For SMBHs in early-type galaxies, c_s assumed to be representative of the ambient hot ISM $\propto \sqrt{kT}$ of gas at R_B

$$R_B \sim 10^5 - 10^6 \; R_g \quad (\text{where } R_g = GM/c^2)$$

Gas Capture Rate and Efficiency

Bondi rate = $\dot{M}_B = 4\pi(GM_{BH})^2\rho/c_s^3 \sim 3 \times 10^{-6}\ M_\odot\ yr^{-1}$ for Sgr A*

→ predicts $L_{Bondi} \sim 10^{41}$ ergs s^{-1}

Why is material that is flowing through the Bondi radius only radiating a tiny fraction of its available energy?

Two general solutions:

(1) Material makes it to the event horizon, but energy is advected into the black hole without radiating (ADAF).

(2) Material does not make it to the event horizon, having been removed from the inner flow through either convection or outflow (CDAF, ADIOS).

Advection Dominated Accretion Flows

"Classical" ADAF (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994,1995)

Gas is hot and optically thin, with the ions carrying most of the thermal energy

→ gas is too low density to cool efficiently, so gas falls into the BH carrying most of the energy with it without radiating

Pure ADAFs predict:

$$\dot{M}(R) \propto \text{constant} \quad \text{and} \quad T(R) \propto R^{-1} \quad \text{and} \quad \rho(R) \propto R^{-3/2}$$

Works moderately well for Sgr A*, but fails to adequately describe radio flux or linear polarization.

Models With Mass Loss

CDAF (Convection Dominated Accretion Flow) (Narayan et al. 2000; Quataert & Gruzinov 2000; Abramowicz et al. 2002)

Gas circulates in convective eddies, removing gas from the inner accretion flow and redistributes it to larger radii within flow

$$T(R) \propto R^{-1} \text{ and } \rho(R) \propto R^{-1/2}$$

ADIOS (Advection Dominated Inflow Outflow Solution) (Blandford & Begelman 1999)

Strong wind carries away gas and energy, completely removing it from flow

$$\dot{M}(R) \propto R^{s} \text{ and } T(R) \propto R^{-1} \text{ and } \rho(R) \propto R^{-1/2+s}$$

Recent work by Begelman (2012) suggests $s \approx -1/2$, so $\rho(R) \propto R^{-1}$.

Summary of Accretion Flow Solutions

Recent work has focused on including effects of magnetic fields, gas cooling, conduction, rotation to make flows more realistic.

Yuan, Wu, & Bu (2012) summarized the current state of simulations among various groups. They find in general:

- $\dot{M}(R) \propto R^{s}$, where $s \neq 0$ (at least beyond $\sim 100\ R_S$)
- $\rho(R) \propto R^{-(1/2+p)}$ where $p = 0 - 1/2$

Yuan et al. (2012) simulations go out to $40{,}000\ R_g$ → close to area of flow that can realistically be probed by X-ray observations:

$\rho(R) \propto R^{-0.65}$ for $\alpha=0.001$

$\rho(R) \propto R^{-0.85}$ for $\alpha=0.01$

How Can We Constrain Accretion Flow Models Observationally?

Simulations converging on agreement that:

- $T(R) \propto R^{-1}$
- $\rho(R) \propto R^{-(1/2+p)}$ where $p = 0 - 1/2$

Can we spatially resolve the hot gas within the Bondi radius of a SMBH to derive $T(R)$ and $\rho(R)$ profiles?

Since $R_{Bondi} \propto M_{BH}/kT_{gas}$, need systems that have:

– large black hole mass
– cool ISM temperature
– small distance

Chandra X-ray Observatory

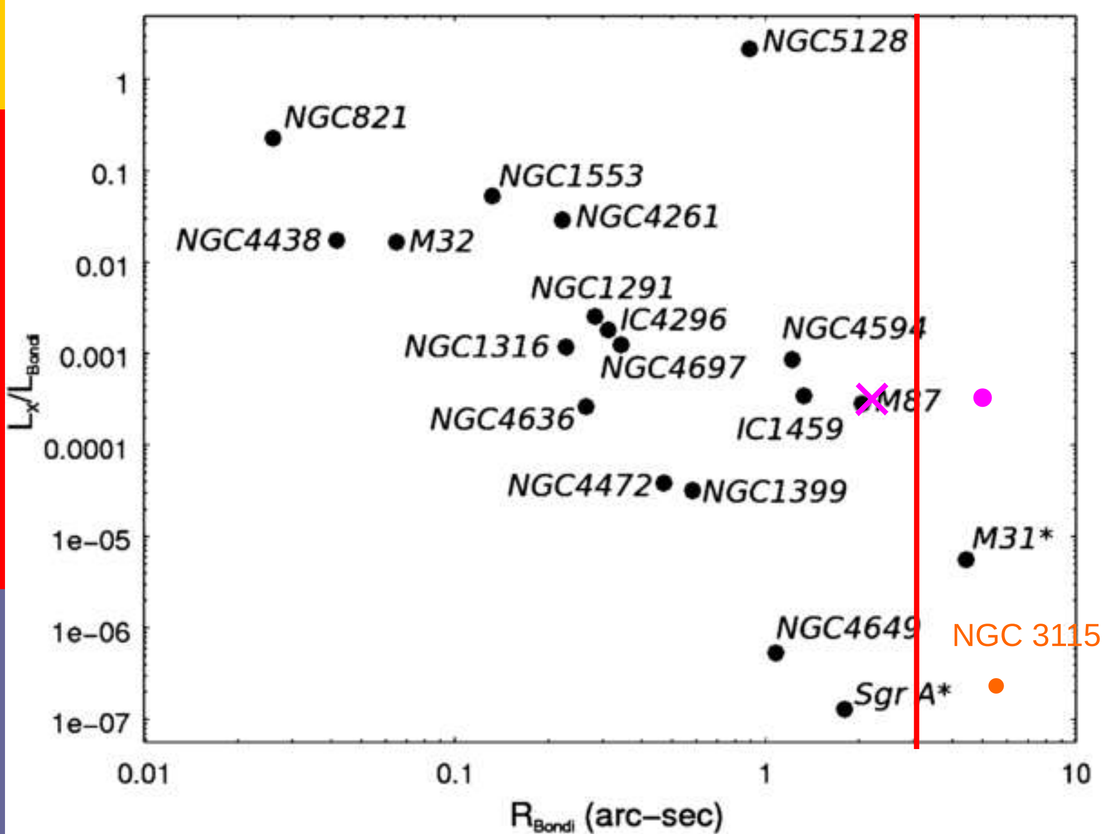
0.3 – 10 keV energy range

0.5” spatial resolution

Goal is to measure the radial temperature (and density) profiles of hot gas in the Bondi region of a SMBH from X-ray spectra.

Best Resolved Bondi Radius Candidates

Garcia et al. (2010)



If only *Chandra* had 0.1” spatial resolution!

Only reasonable candidates for deriving T(R) and ρ(R) are:

M87: extremely bright jet knot makes analysis frustratingly difficult

M31: low X-ray gas counts, luminous supersoft source within R_B

NGC 3115: low X-ray gas counts

The S0 Galaxy NGC 3115

ESO/VLT + *Chandra* (blue)

D = 9.7 Mpc (Tonry et al. 2001)

M_{BH} = 1-2 x 10^9 $M_\odot$ (Kormendy et al. 1996; Emsellem et al. 1999)

kT_{gas} ~ 0.35 keV (4 million K) (Wong et al. 2011)

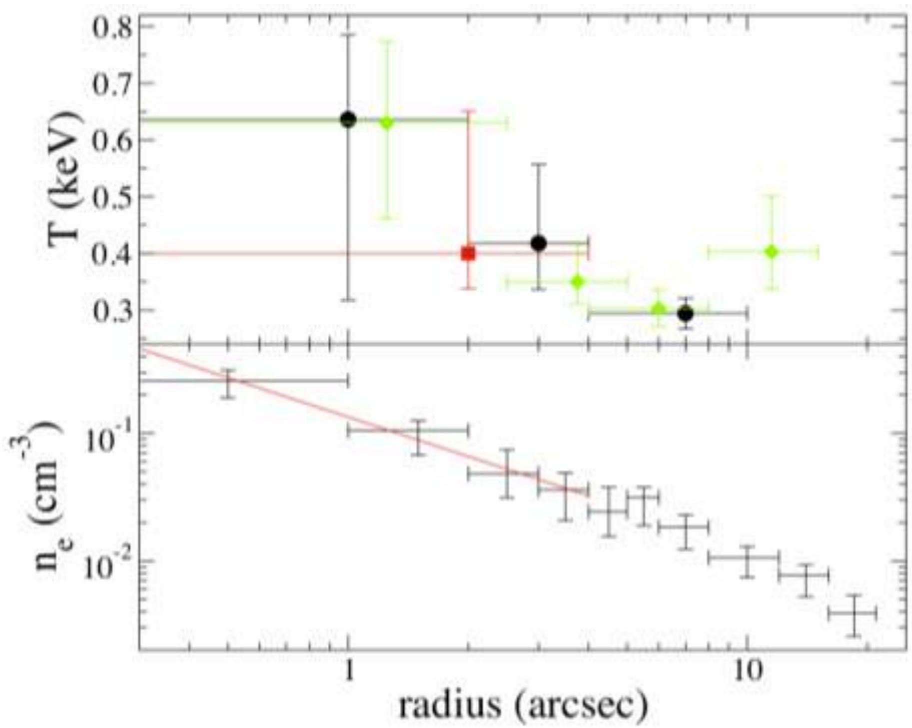
R_B = 2.5"-5"

No bright X-ray AGN/jet at its center

Very low radio flux

Previous Work on the Bondi Region of NGC 3115

Wong et al. (2011)



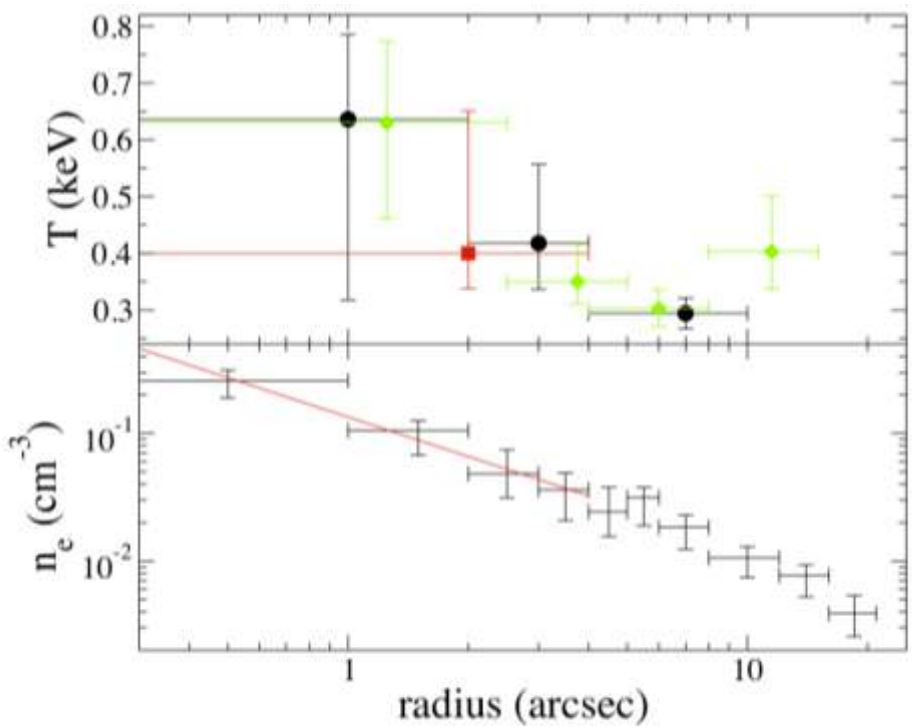
150 ksec of *Chandra* data from 2001/2010 hinted at a temperature increase inside the 5” (~240 pc) Bondi radius of its ~2 x10^9 $M_\odot$ black hole.

Hot gas density profile had a slope of $\rho(R) \propto R^{-p}$ $p=1.03^{+0.23}_{-0.21}$ inside 5”.

Taken at face value, ruled out classical Bondi/ADAF and CDAF models at ~2σ.

Previous Work on the Bondi Region of NGC 3115

Wong et al. (2011)



150 ksec of *Chandra* data from 2001/2010 hinted at a temperature increase inside the 5” (~240 pc) Bondi radius of its ~2x10^9 $M_\odot$ black hole.

$$\dot{M}_B = 2 \times 10^{-2}\ M_\odot\ yr^{-1}$$

$$L_{Bondi} \sim 10^{44}\ ergs\ s^{-1}$$

$$L_X/L_{Bondi} \leq \text{few} \times 10^{-7}$$

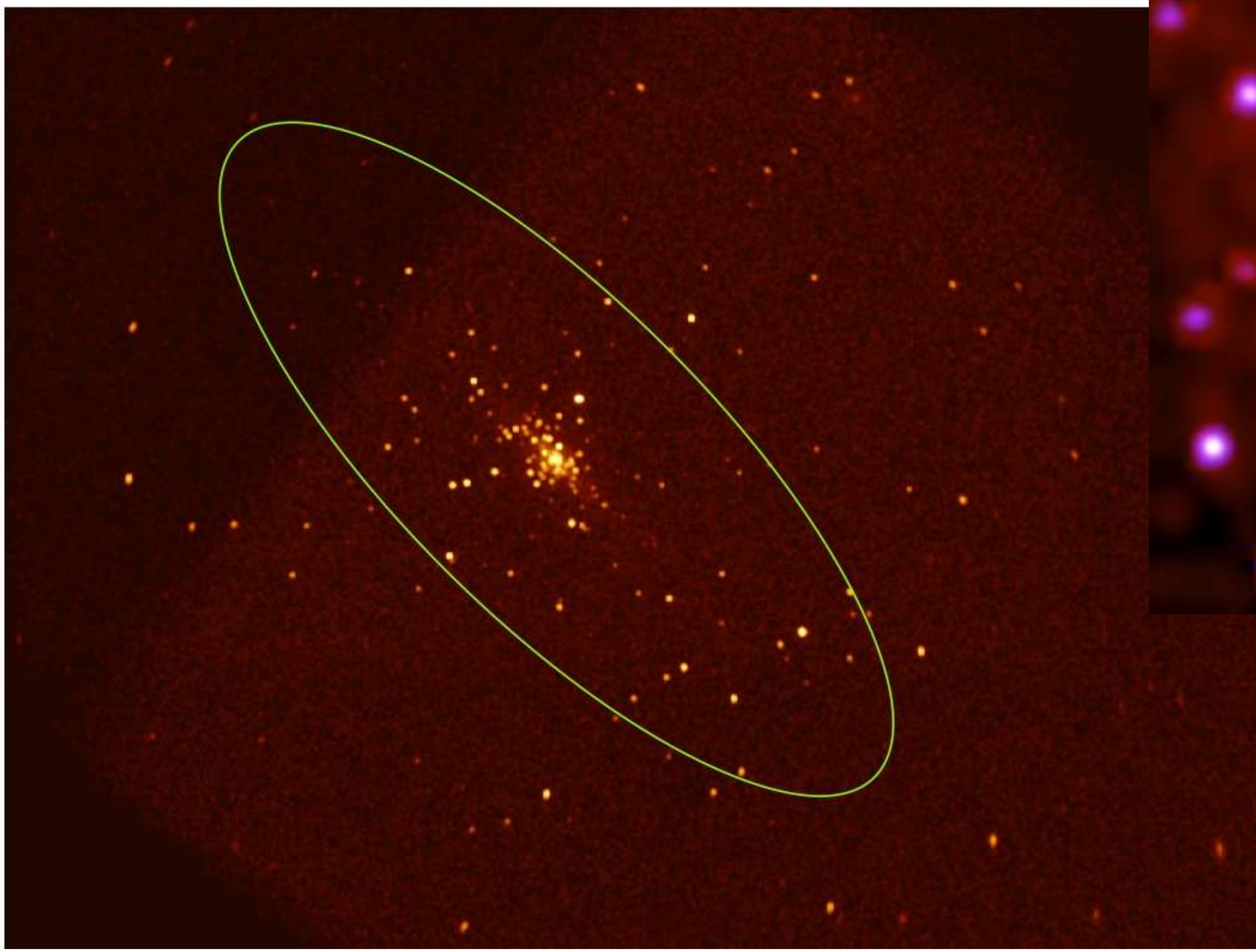
Chandra X-ray Visionary Projects (XVPs)

Due to *Chandra's* evolving orbit, observing efficiency has increased, leading to more available observing time

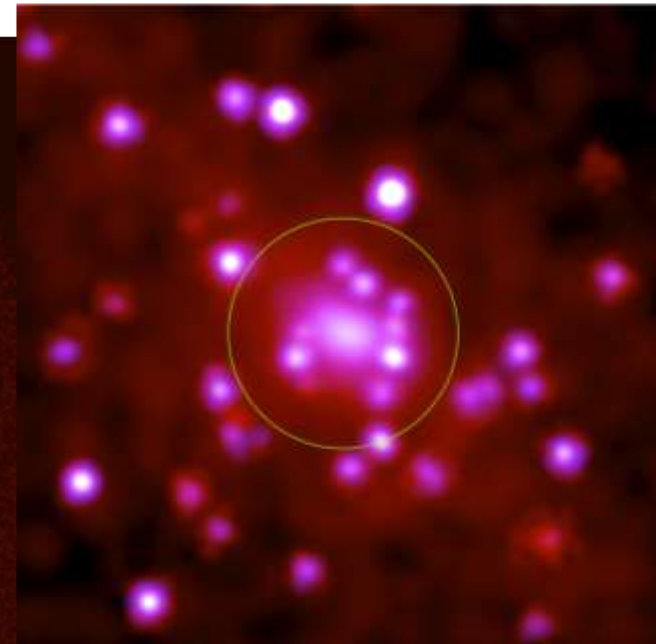
- new to Cycle 13 (continuing through Cycle 15)
- intended to address science that requires very long X-ray exposures (minimum 1 million seconds)

1 million second *Chandra* exposure of NGC 3115 was granted to obtain more accurate T(R) and ρ(R) profiles to confirm/constrain accretion flow theory.

1 Megasecond Chandra Image of NGC 3115



Green D25 contour



30” x 30”

Green 5”
Bondi radius

Multiple X-ray Components Within R_B

Central ~5” Bondi region is contaminated by diffuse emission from non-gaseous sources:

Unresolved X-ray binaries (XRBs): Observation resolved sources to $\sim 10^{36}$ ergs s^{-1}, although crowding raises this limit within R_B.

Solution: Assume sum of many XRBs can be fit with a $\Gamma=1.6$ power law spectrum, as in other early-type galaxies+M31 (Irwin et al. 2003)

Cataclysmic Variables/coronally Active Binaries (CV/ABs): large collection of dim ($\sim 10^{32}$ ergs s^{-1}) sources (Revnivtsev et al. 2007, 2008)

Solution: Assume CV/AB component scales with L_K stellar profile, normalized to L_X/L_K value for M32

Multiple X-ray Components Within R_B

Spectrum: hot gas + unresolved XRBs + CV/ABs

↑ thermal: free kT, norm

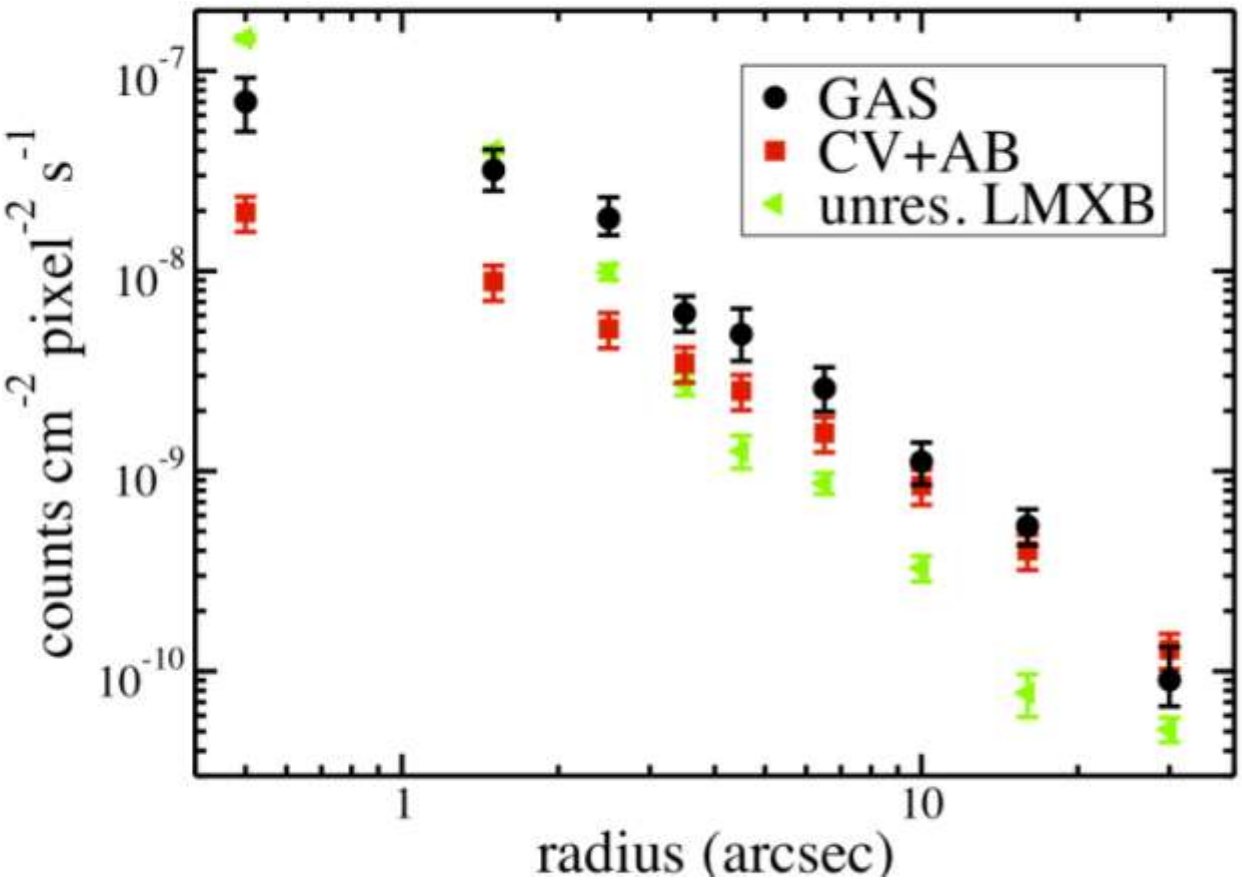
↑ Power law: free norm

↑ All components fixed, norm by L_K

All components absorbed by Galactic column density ($N_H = 4 \times 10^{20}$ cm^{-2})

Each region fit with XSPEC to obtain best-fit parameters, flux for each component + uncertainties.

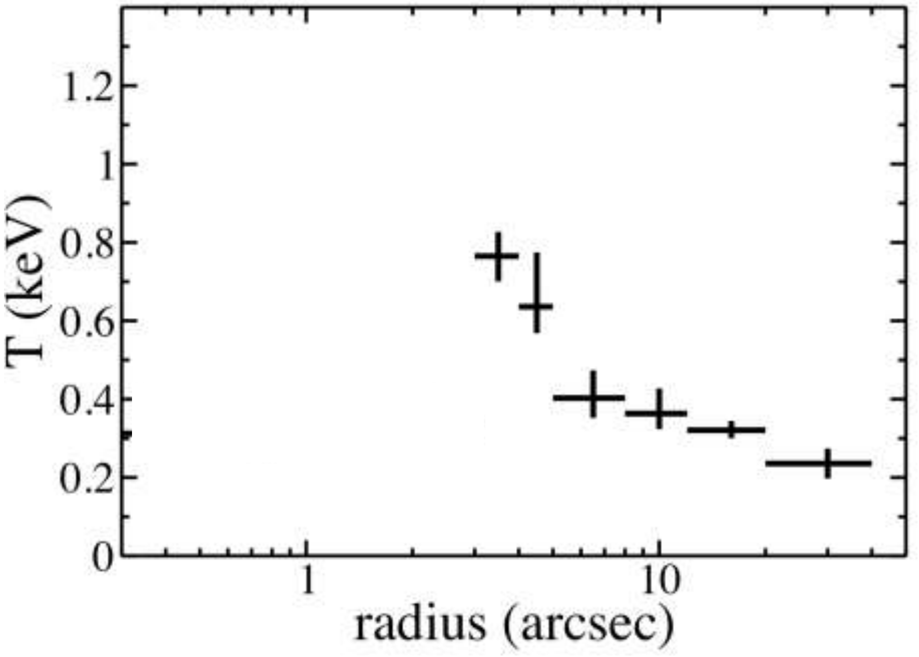
Surface Brightness Profiles of Components



1” = 47 pc @9.7 Mpc

Temperature Profile of Hot Gas Within NGC 3115

1-temperature thermal model



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Temperature Profile of Hot Gas Within NGC 3115

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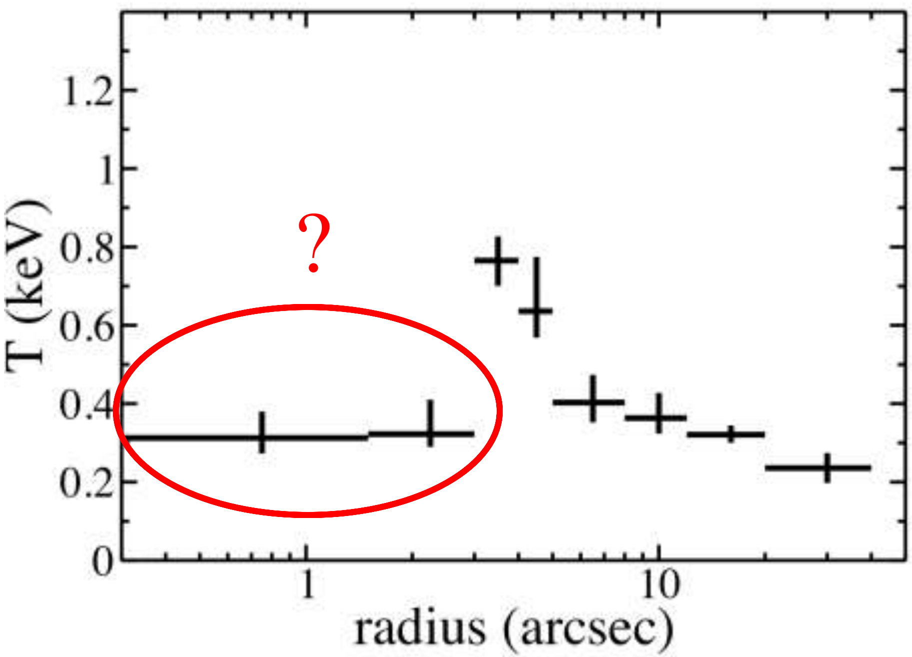
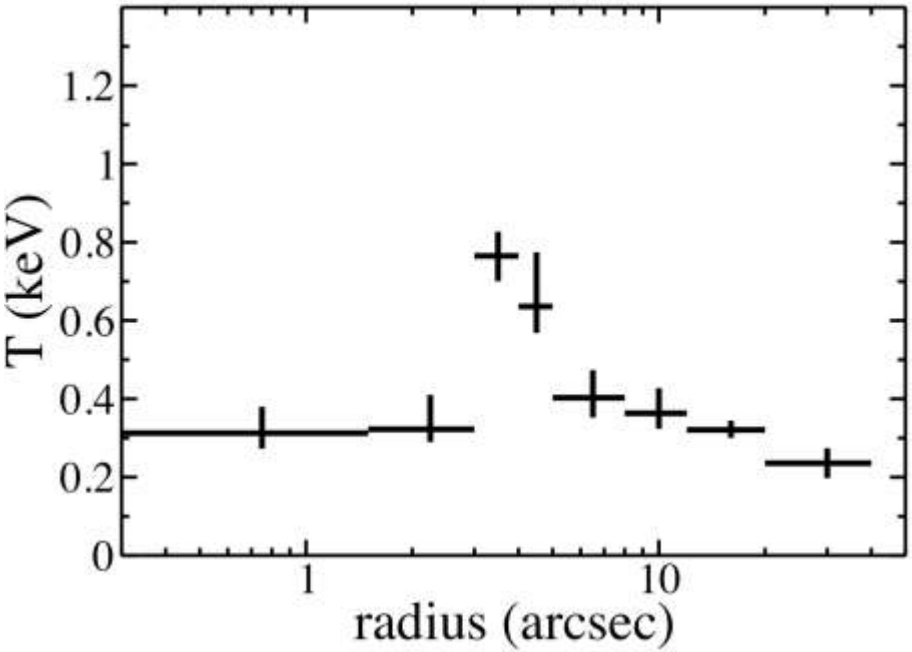


Inner 2” shows a decline, unlike an expected $T(R) \propto R^{-1}$ profile.

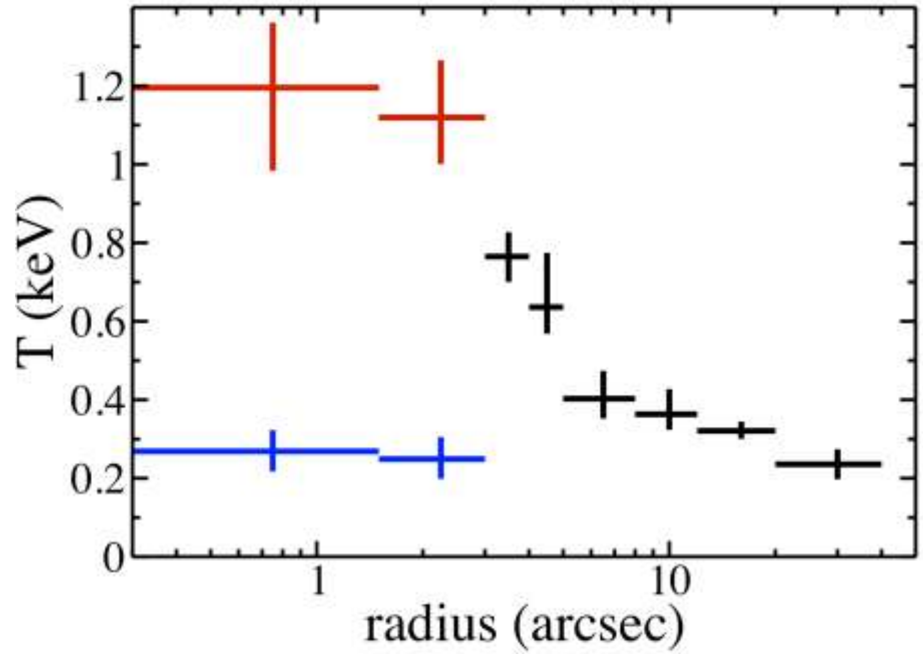
1” = 47 pc @9.7 Mpc

Temperature Profile of Hot Gas Within NGC 3115

1-temperature thermal model



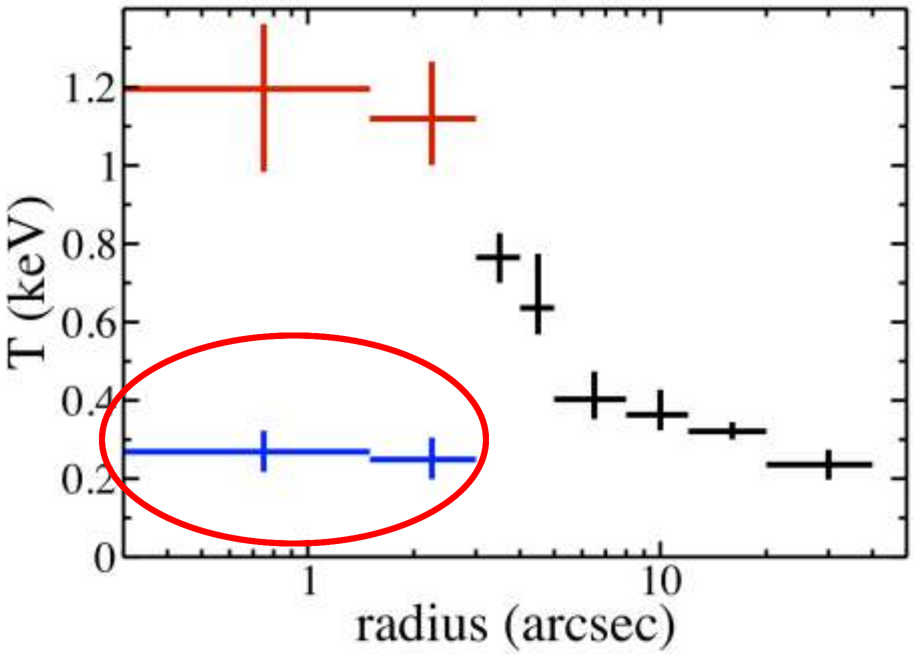
2-temperature thermal model



Use two thermal models for inner two spatial bins

1" = 47 pc @9.7 Mpc

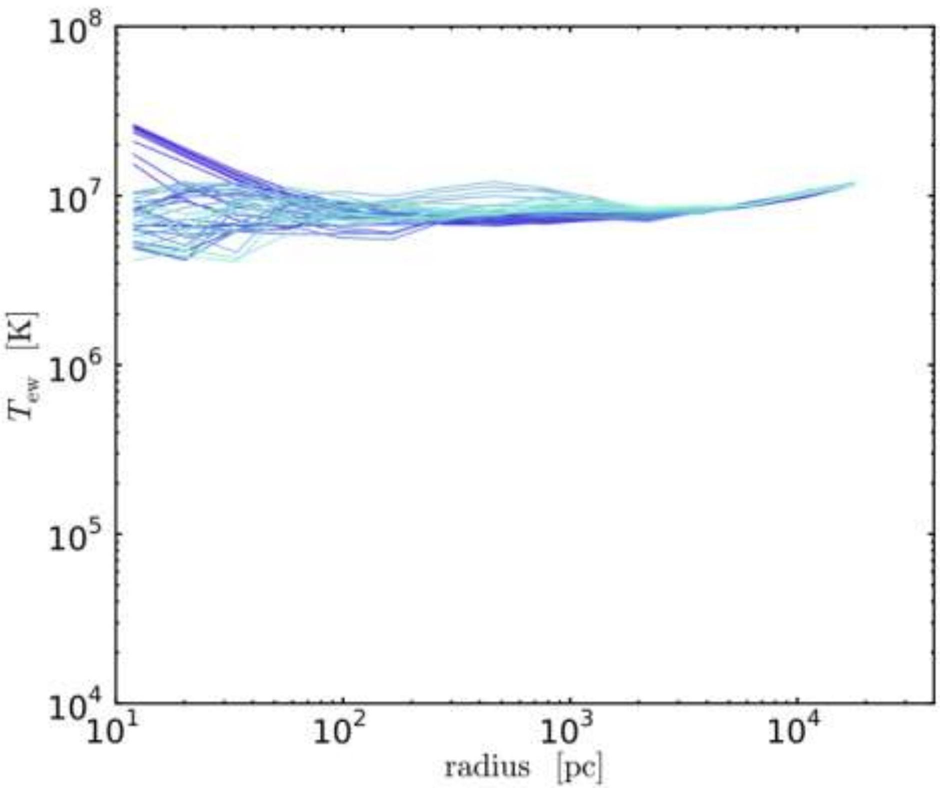
Cooler Component a Result of Projection?



Could cooler gas from larger radii projected in front of/behind the inner two bins be responsible for cooler component (blue data points)?

An elliptical de-projection of the surface brightness indicates only 60%-70% of soft component can be from projection (at most).

Cooler Component a Result of Multi-Phase Gas?



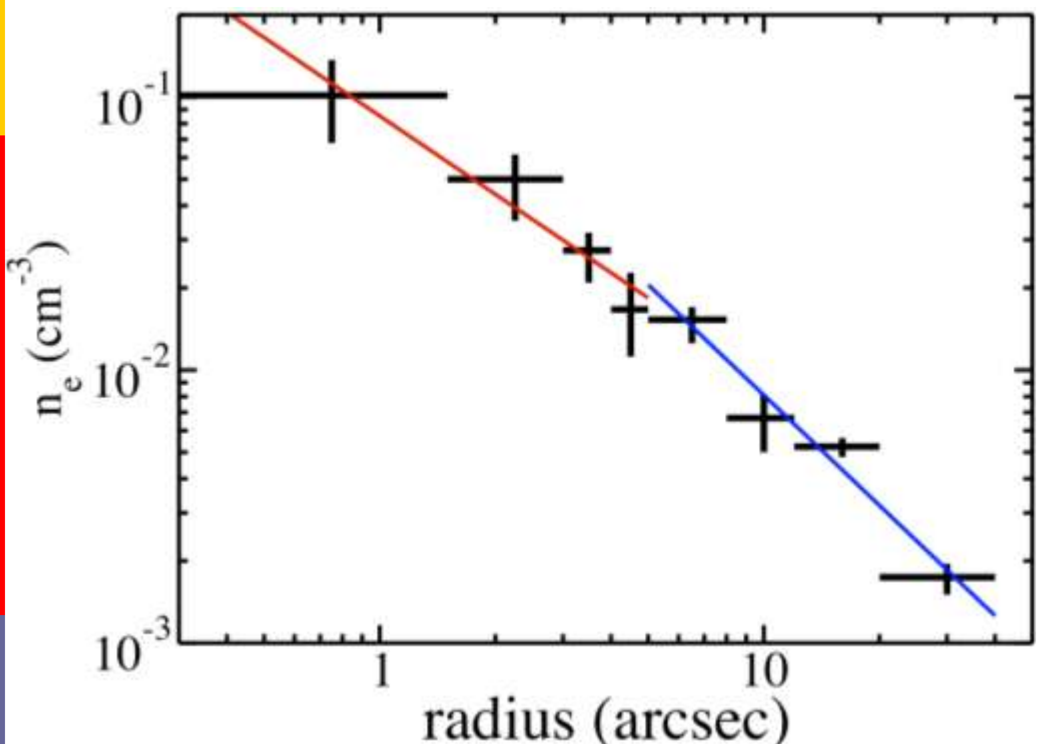
Gaspari et al. (2013)

Recent realistic by Gaspari et al. (2013) indicate that hot gas is thermally unstable to cooling if $t_{cool} \leq 10\ t_{freefall}$

Predicts multi-phase gas, and cold mode accretion.

For NGC 3115, $t_{cool} \sim 20\ t_{freefall}$. Is this close enough to cooling criteria?

De-projected Density Profile of Hot Gas Within NGC 3115



n_e only weakly dependent on assumed temperature

ρ at each radius determined from emission measure:

$EM = \int n_e n_h \, dV / 4\pi D^2$

→ Determine n_e profile, and de-project

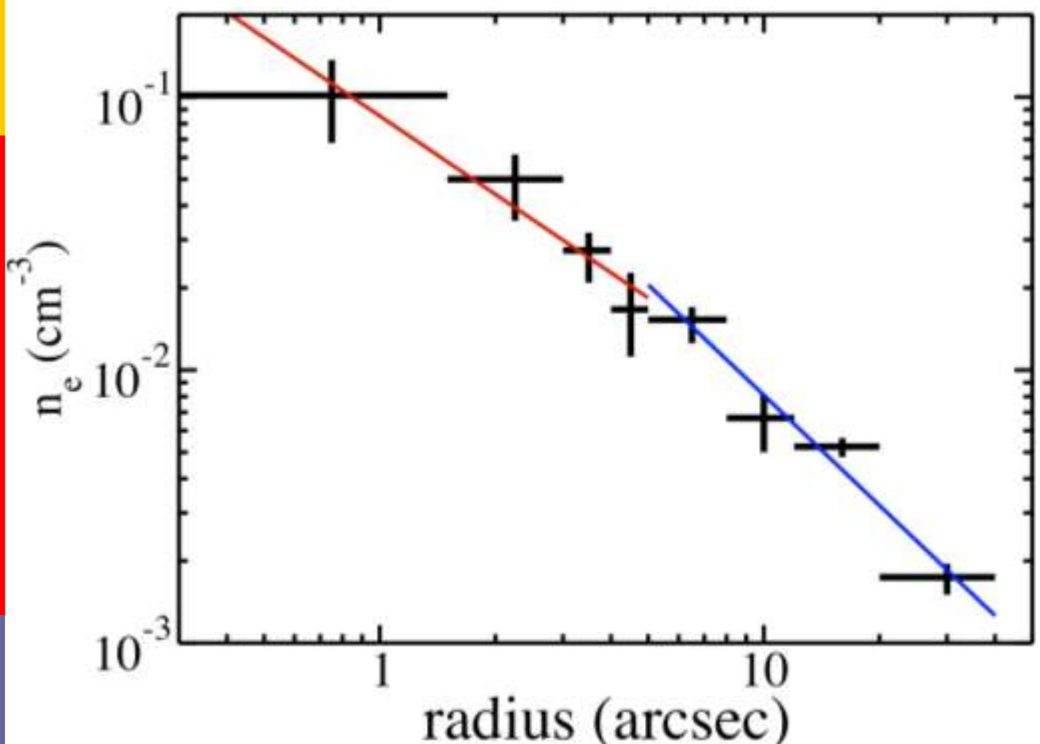
From 5”-40” (outside R_B)

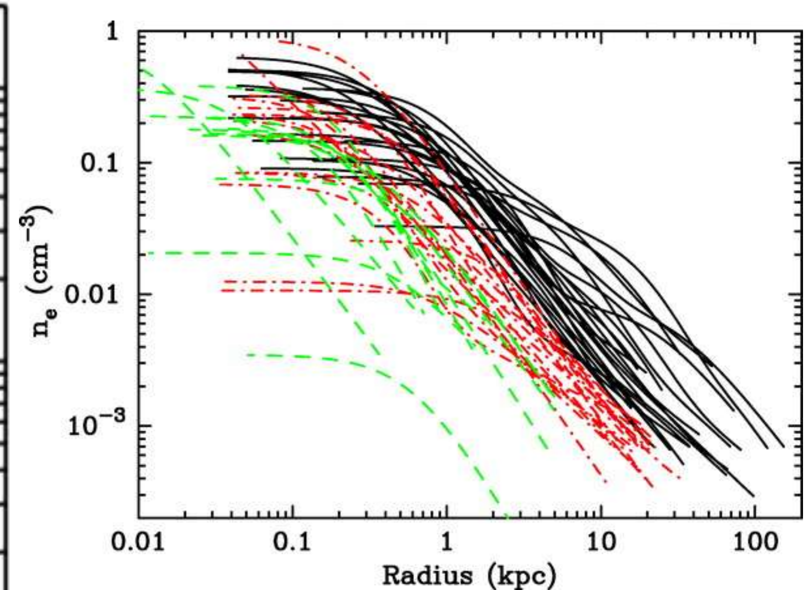
$\rho(R) \propto R^{-s}$ $s = 1.34^{+0.09}_{-0.15}$

Within 5” Bondi radius R_B

$\rho(R) \propto R^{-s}$ $s = 0.95^{+0.24}_{-0.24}$

Comparison to Other Galaxies



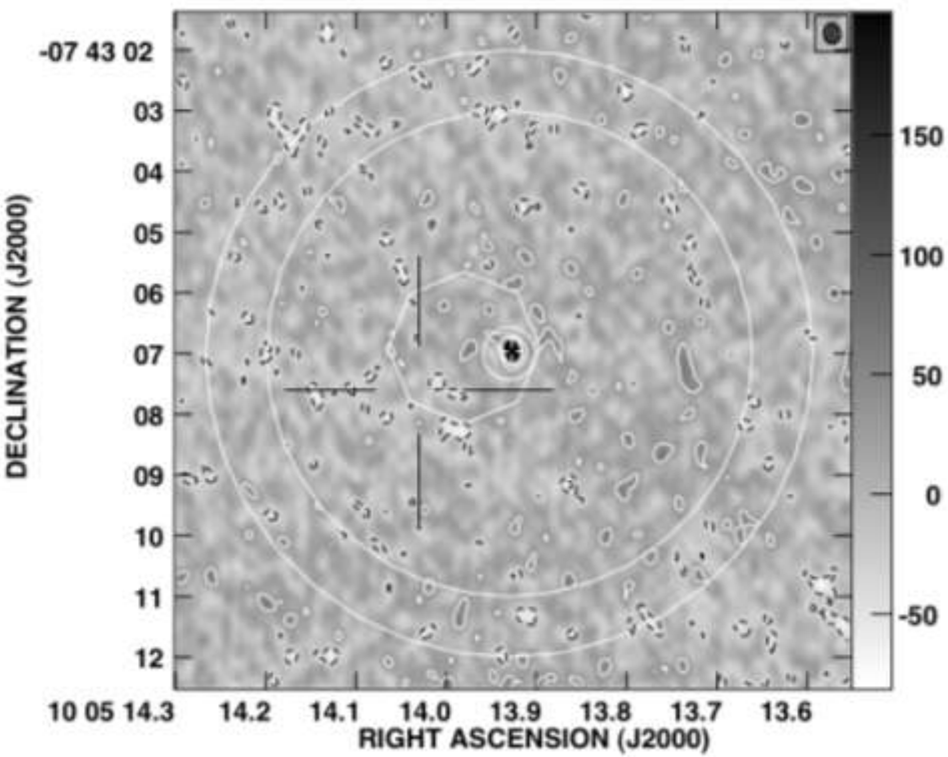


Fukazawa et al. (2006)

1” = 47 pc @9.7 Mpc

Other galaxies have very flat density profiles inside 250 pc

Radio Emission from NGC3115



Recently, Wrobel & Nyland (2012) found an unresolved (< 0.17") radio source in the nucleus of NGC3115

νL_ν(8.5 GHz) = 3.1 x 10^{35} ergs s^{-1}

with a flat spectrum $\alpha = -0.23$

Shcherbakov et al. (2013, in prep.) used this radio flux to derive a density near the event horizon – coupled with density near R_B from X-ray data derive a density relation $\rho(R) \propto R^{-p}$ p= 0.7–0.8

Summary

Our Megasecond *Chandra* observation of the Bondi region of the $2 \times 10^9\ M_\odot$ SMBH of NGC3115 has so far revealed:

1) First temperature/density profile of hot gas within the Bondi radius of a supermassive black hole.

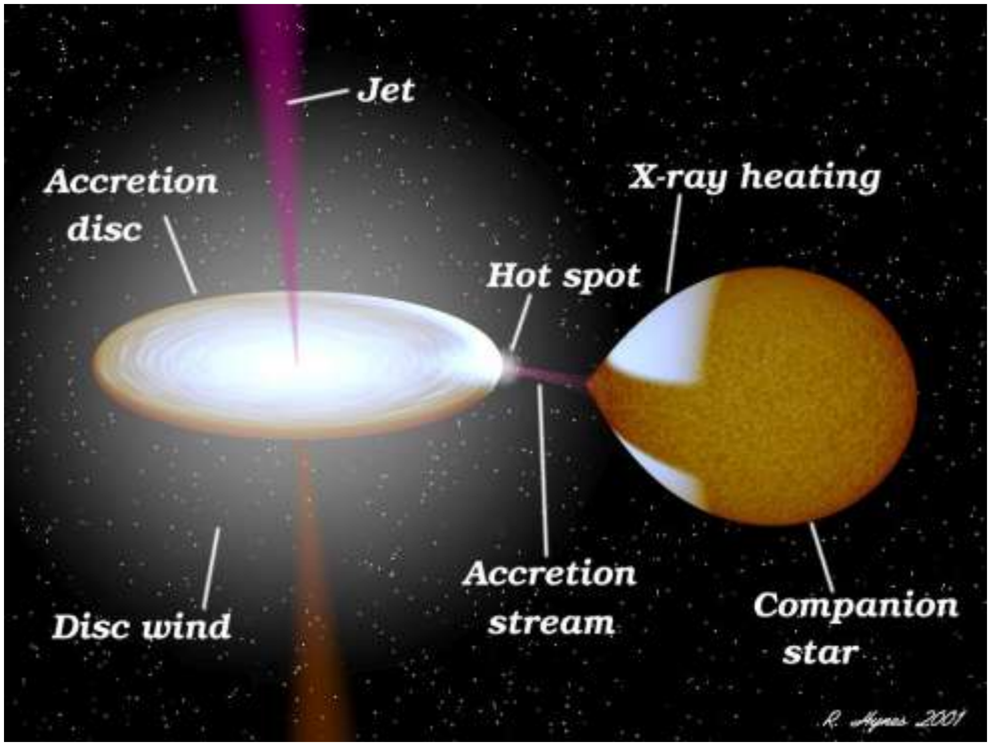
2) Evidence that temperature increases inside Bondi radius, as expected, but also a cooler component inside 3". Projection (probably not) or mixed phases? New physics?

3) Density profile within 5": $\rho(R) \propto R^{-s}$, $s = 0.95^{+0.24}_{-0.24}$, in line with many simulations (but not a pure ADAF nor CDAF).

More work to do!

Bonus Science!

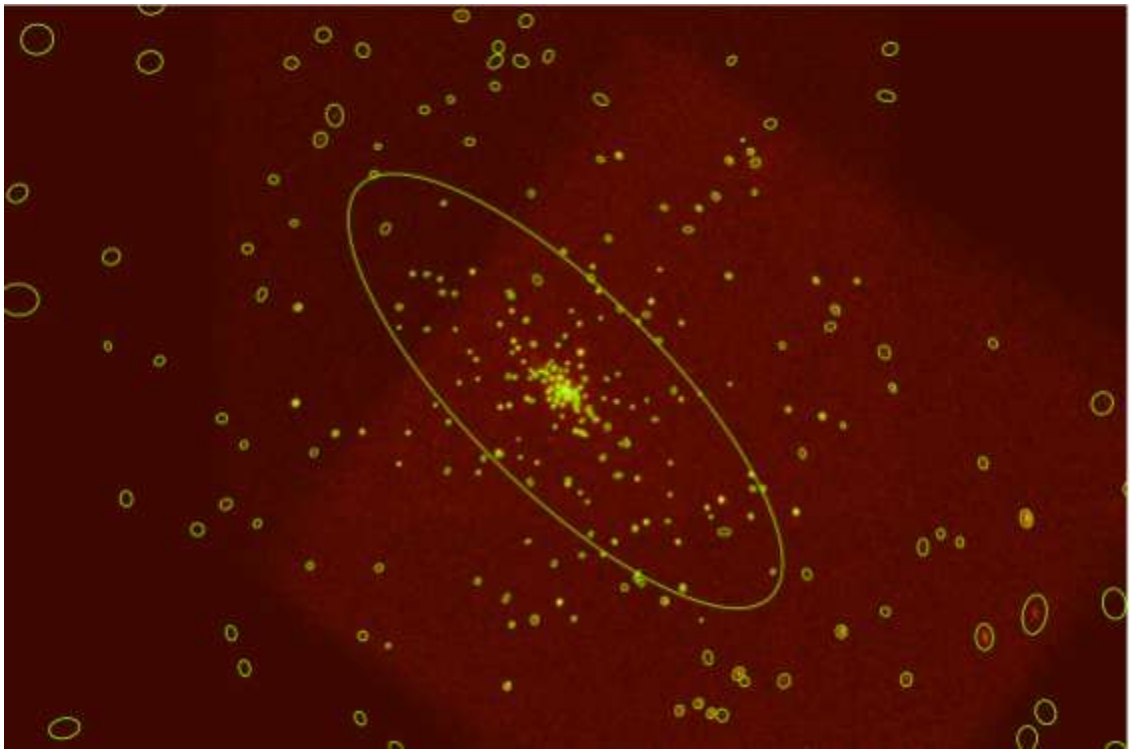
Our Megasecond *Chandra* observation of NGC 3115 also provides us with the deepest look to date at the X-ray low-mass binary population of a "normal" early-type galaxy.



Courtesy Rob Hynes

In an old stellar population X-ray binaries are exclusively of the low-mass (companion) type → neutron star/black hole is fed by Roche lobe overflow (and not stellar winds).

Bonus Science!



453 total sources detected in all observations

~150 sources detected within one D25 contour (green ellipse)

Limiting luminosity of ~10^{36} ergs s^{-1}

Observation Log

Timing scheme was chosen to get as close to continuous coverage as possible for a 1 million second exposure (11.6 days).

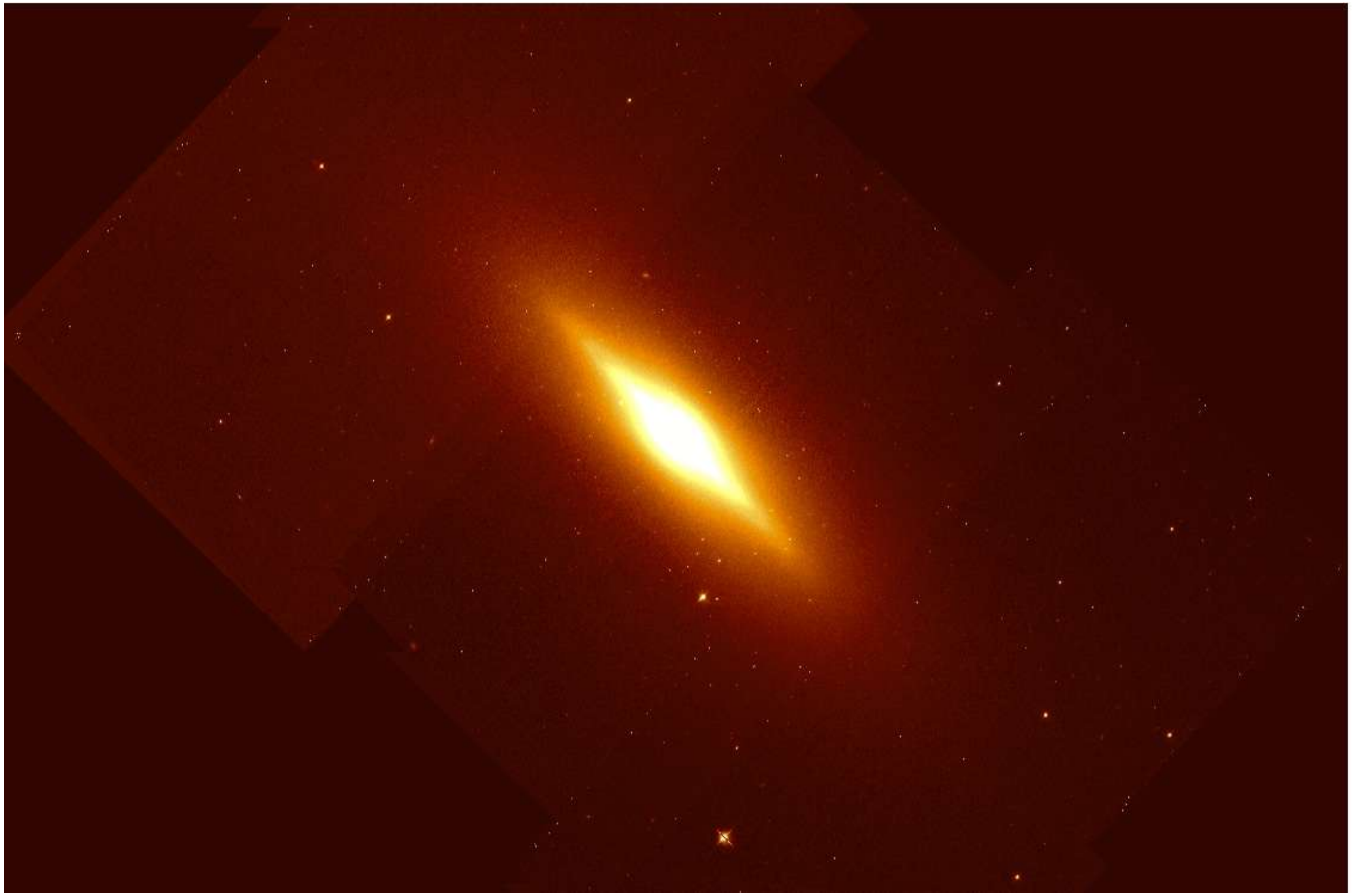
Epochs (2012):

January 18: 174 ksec
January 21: 162 ksec
January 26: 77 ksec
January 31: 187 ksec

February 3: 160 ksec
April 4: 121 ksec
April 5: 47 ksec
April 6: 71 Ksec

Only 1.5% (15 ksec) lost due to flaring ☺

HST *z* Band Image of NGC 3115



To Do List

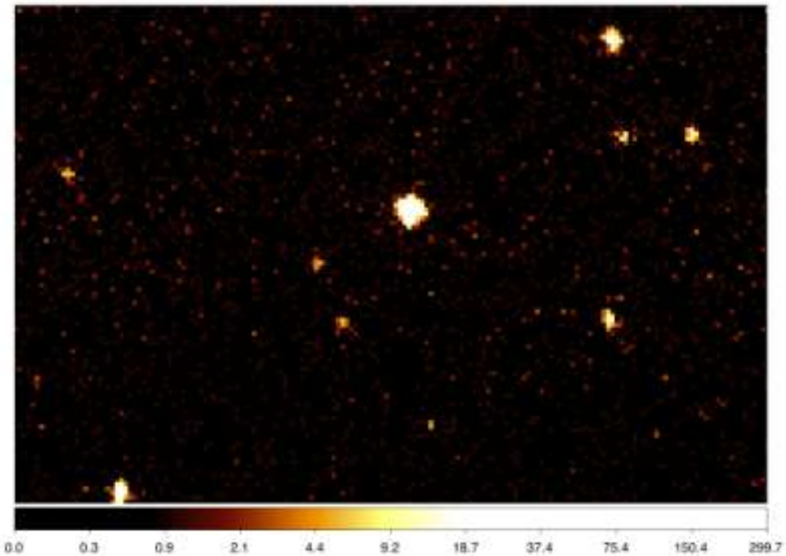
<u>Our Goals</u>

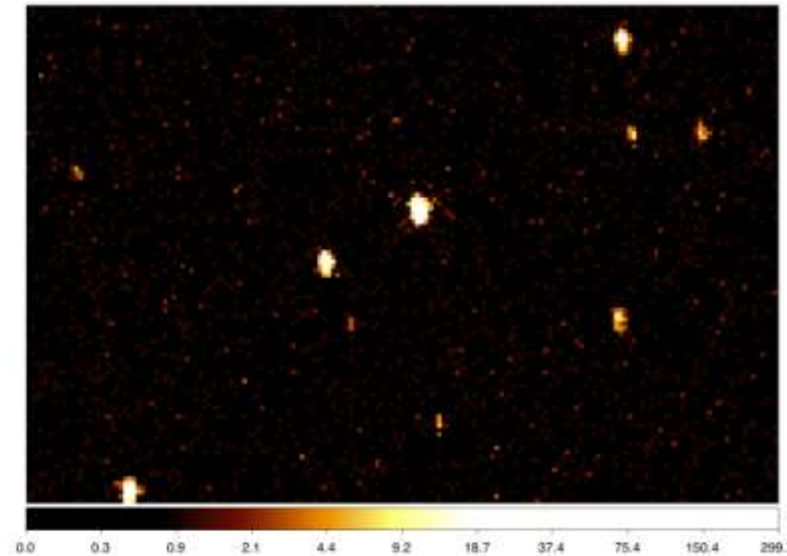
1) Short-time scale variability (< 16 day + 2.5 month) of a large number of LMXBs to constrain duty cycles, outburst duration, and recurrence times of accreting neutron stars and black holes.

2) Connection to globular clusters (HST *g* and *z* band mosaic)

3) Luminosity functions, and more.

An Interesting X-ray Source





"low" state (575 ksec)

"high" state (423 ksec)

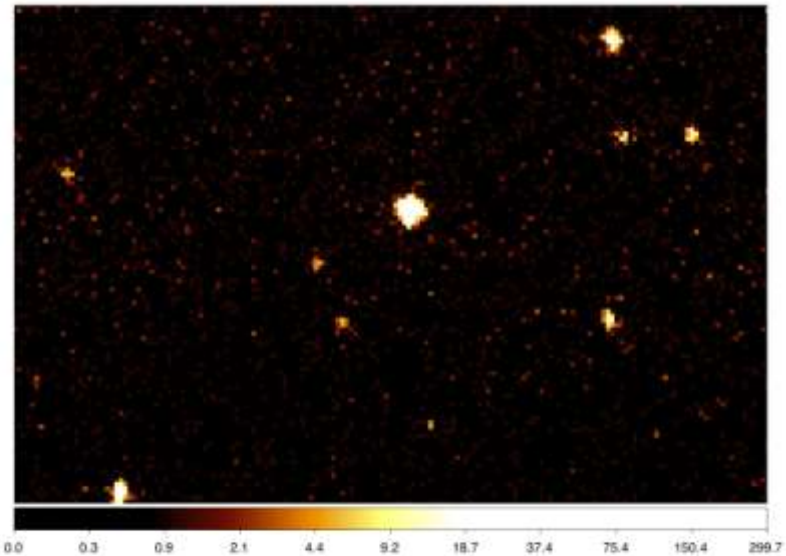
Jan. 18, Jan. 21
April 4, April 5, April 6

Jan. 26, Jan. 31, Feb. 3

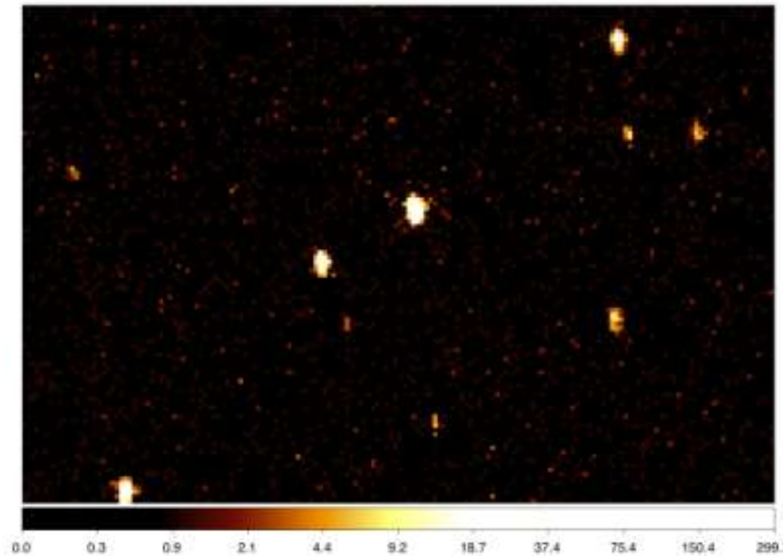
$L_X \sim 4 \times 10^{36}$ erg s^{-1}

$L_X \sim 8 \times 10^{37}$ ergs s^{-1}

An Interesting X-ray Source



"low" state (575 ksec)



"high" state (423 ksec)

$\Gamma = 1.62 \pm 0.17$ *or*

$\mathbf{kT_{diskbb} = 0.87 \pm 0.14}$ **keV**

S: 18 M: 5 H: 0

S: 77 M: 194 H: 54

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