X-Ray Mass Profiles from *Chandra* Galaxy Atlas

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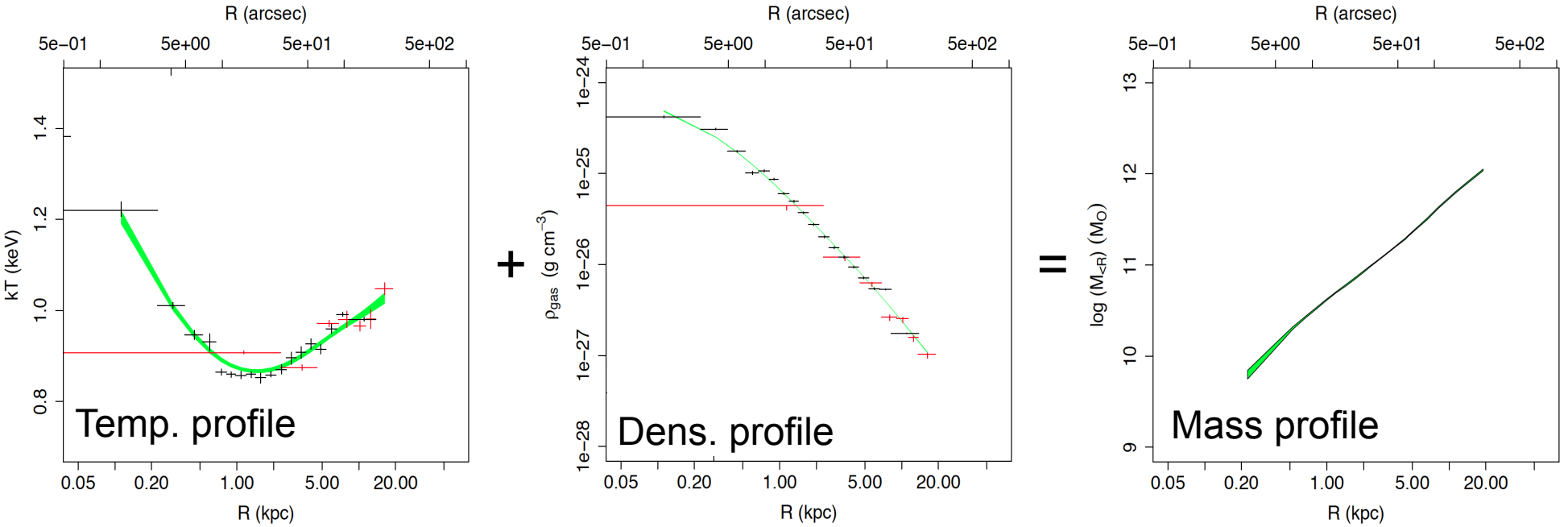
***Chandra* Science for the Next Decade - 8/18/2016**

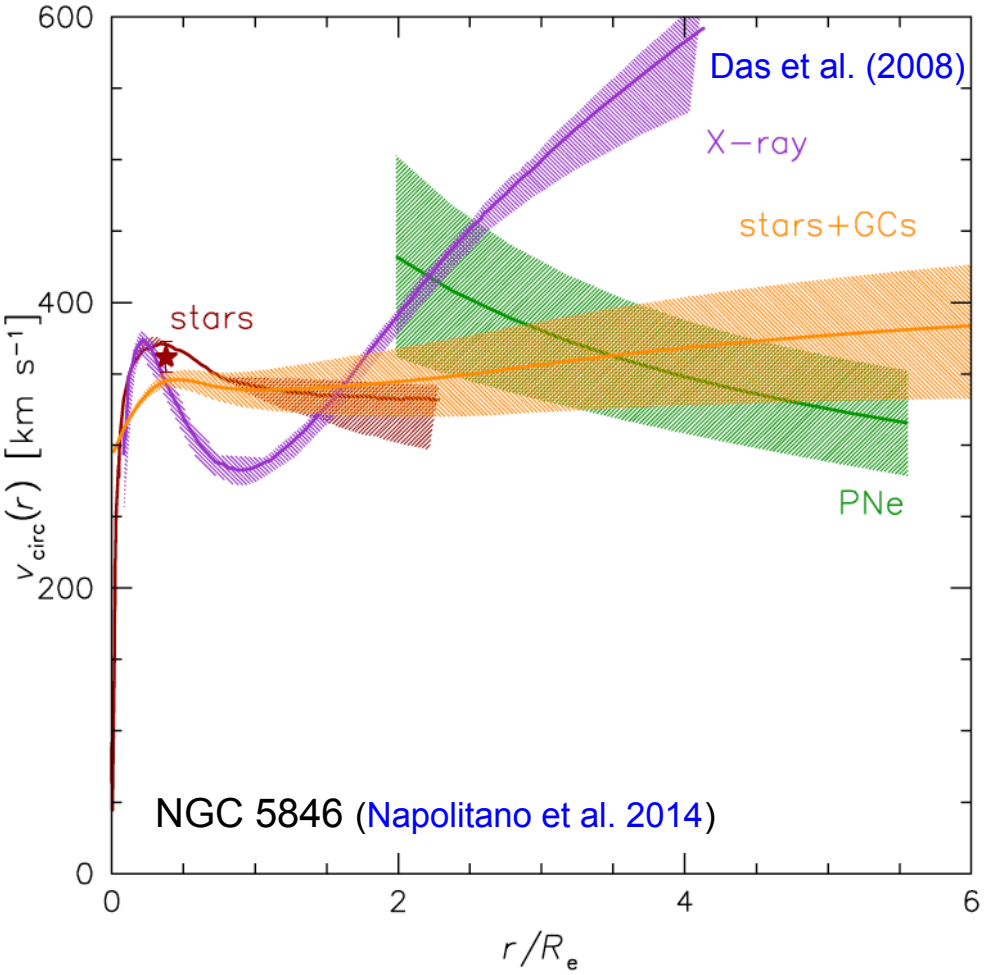
X-Ray Mass Profiles

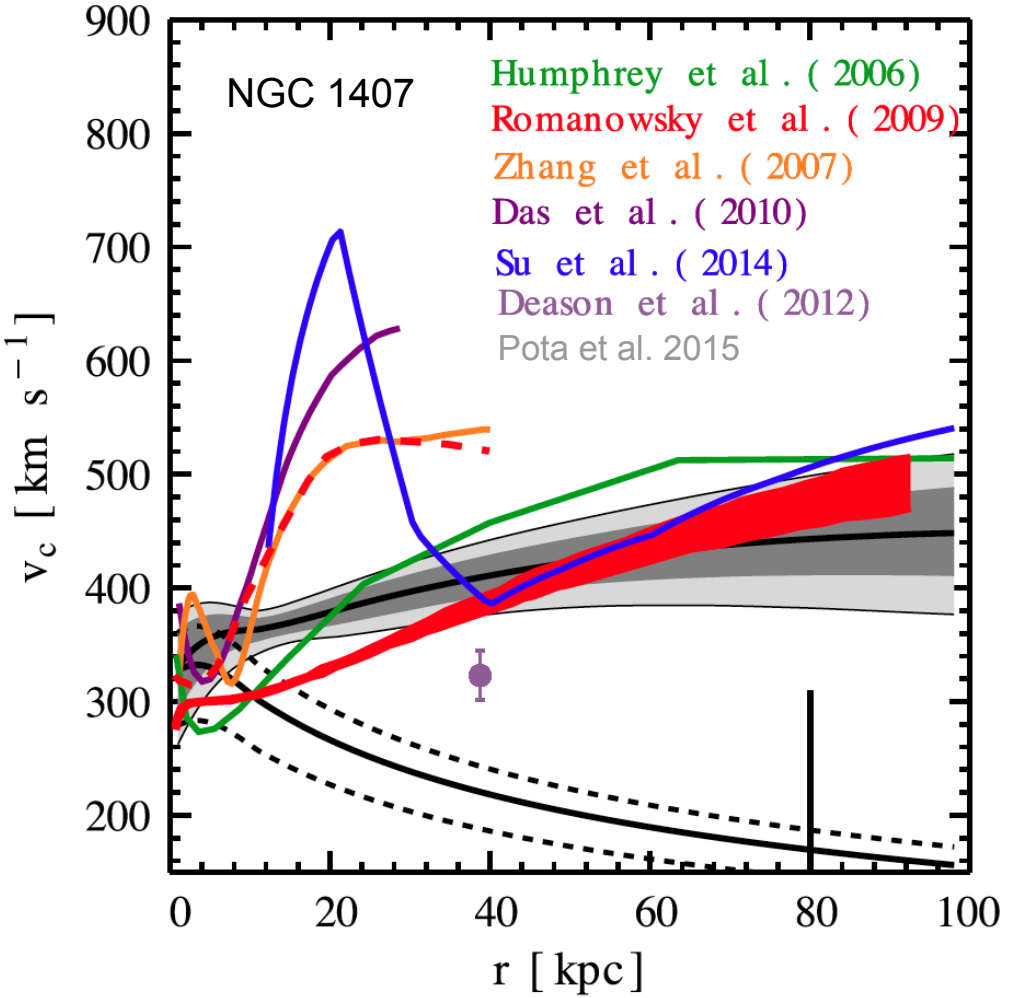
- X-ray observations of the hot ISM in galaxies give the total mass within a given radius assuming that the hot gas is hydrostatic equilibrium (e. g., Fabricant et al. 1984; Forman et al. 1985; Trinchieri & Fabbiano 1985; Fabbiano & Trinchieri 1987; Canizares et al. 1987; David et al. 1990, 1991; Kim et al. 1992a,b).



- *Chandra* angular resolution observations revealed an increasing number of structural features in the hot ISM (e.g., jets, cavities, cold fronts) also at the very small scales (e. g., Statler 2012; Buote & Humphrey 2012).

Deviations!





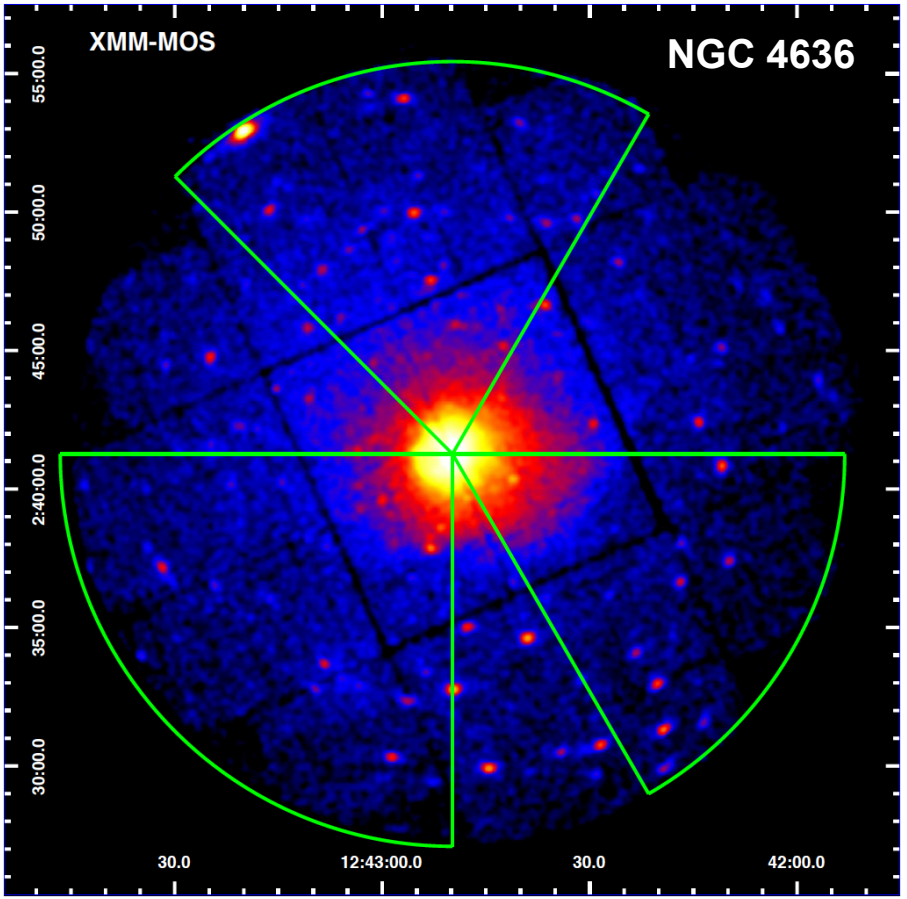
Deviations between X-ray and optical measurements of total mass profiles can be due to bulk gas motions (e. g. sloshing) or presence of non-thermal pressure (e. g., AGN activity) (Churazov et al. 2008; de Plaa et al. 2012; Humphrey et al. 2013).

How can we improve it?

***Chandra* Galaxy Atlas** (Kim et al. 2016)

- Uniform analysis of a sample of 137 ETGs from the *Chandra* archive ACIS imaging observations
- Combine with *XMM-Newton* data
- Spatial resolution of ACIS

  \+ large f.o.v. of EPIC-MOS
- Comparison with recent optical kinematics data of GCs and PNe (e. g. Cappellari et al. 2015, Alabi et al. 2016, Foster et al. 2016) in different azimuthal sectors



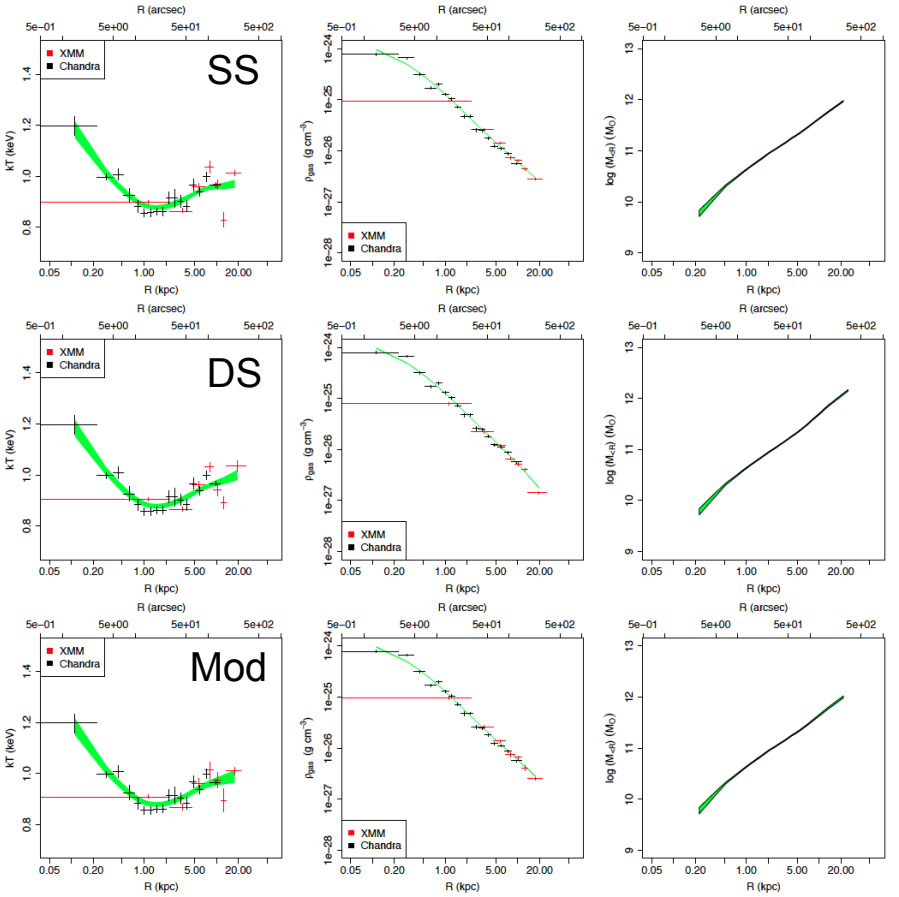
Refined X-Ray Mass Profiles

- Remove source detected on merged (ACIS/MOS) data
- Background:
  - *Chandra*: subtracted from "blank-sky" (Hickox & Markevitch 2006)
  - *XMM-Newton*:

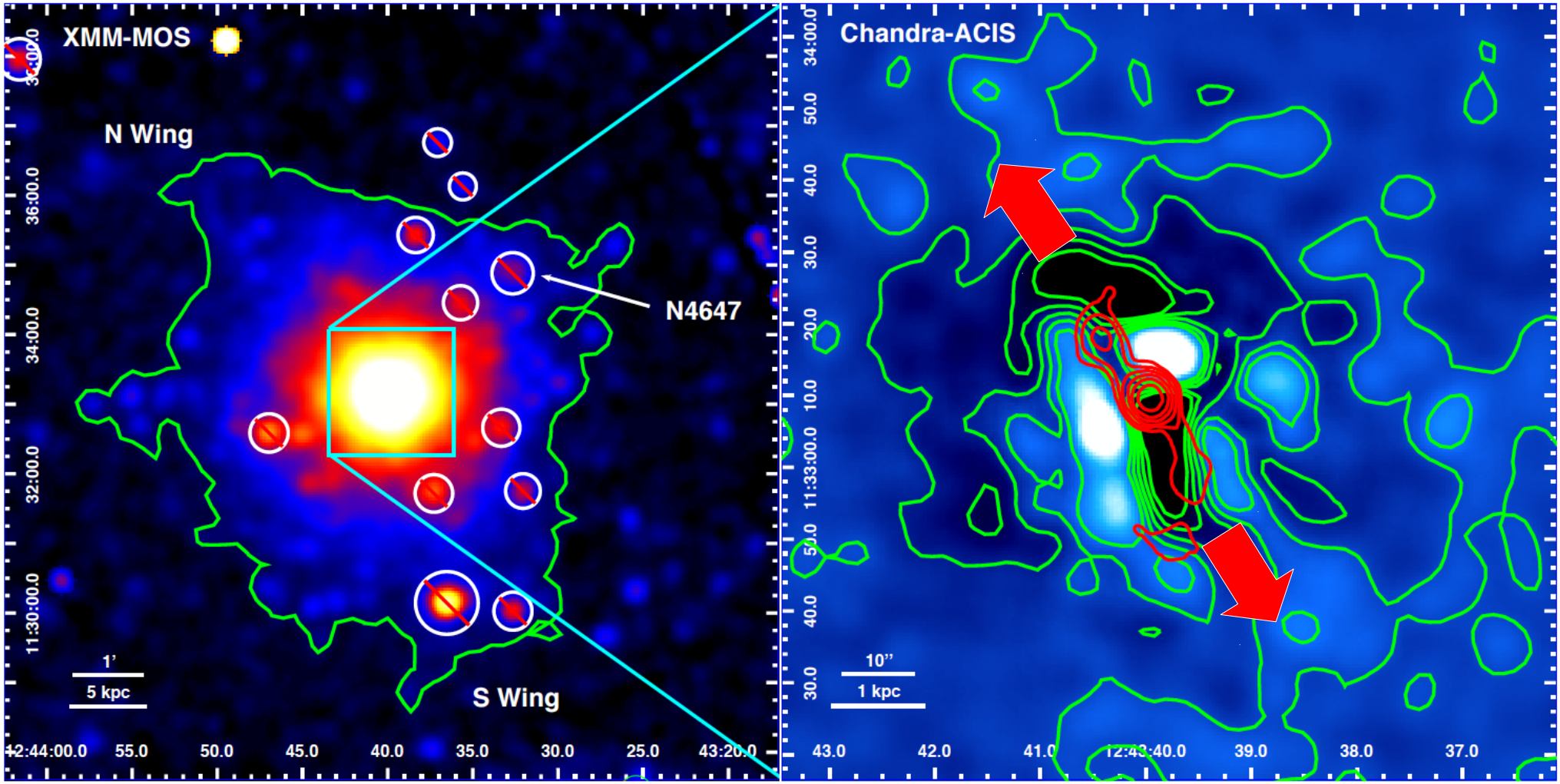
    a) Simple subtraction (Nevalainen et al. 2005)

    b) Double subtraction (Arnaud et al. 2001, 2002)

    c) Modeling (Snowden & Kuntz 2011)
- Concentric shells + 3D de-projection
- Variable element abundances
- T_{gas} + ρ_{gas} → mass profiles in azimuthal sectors

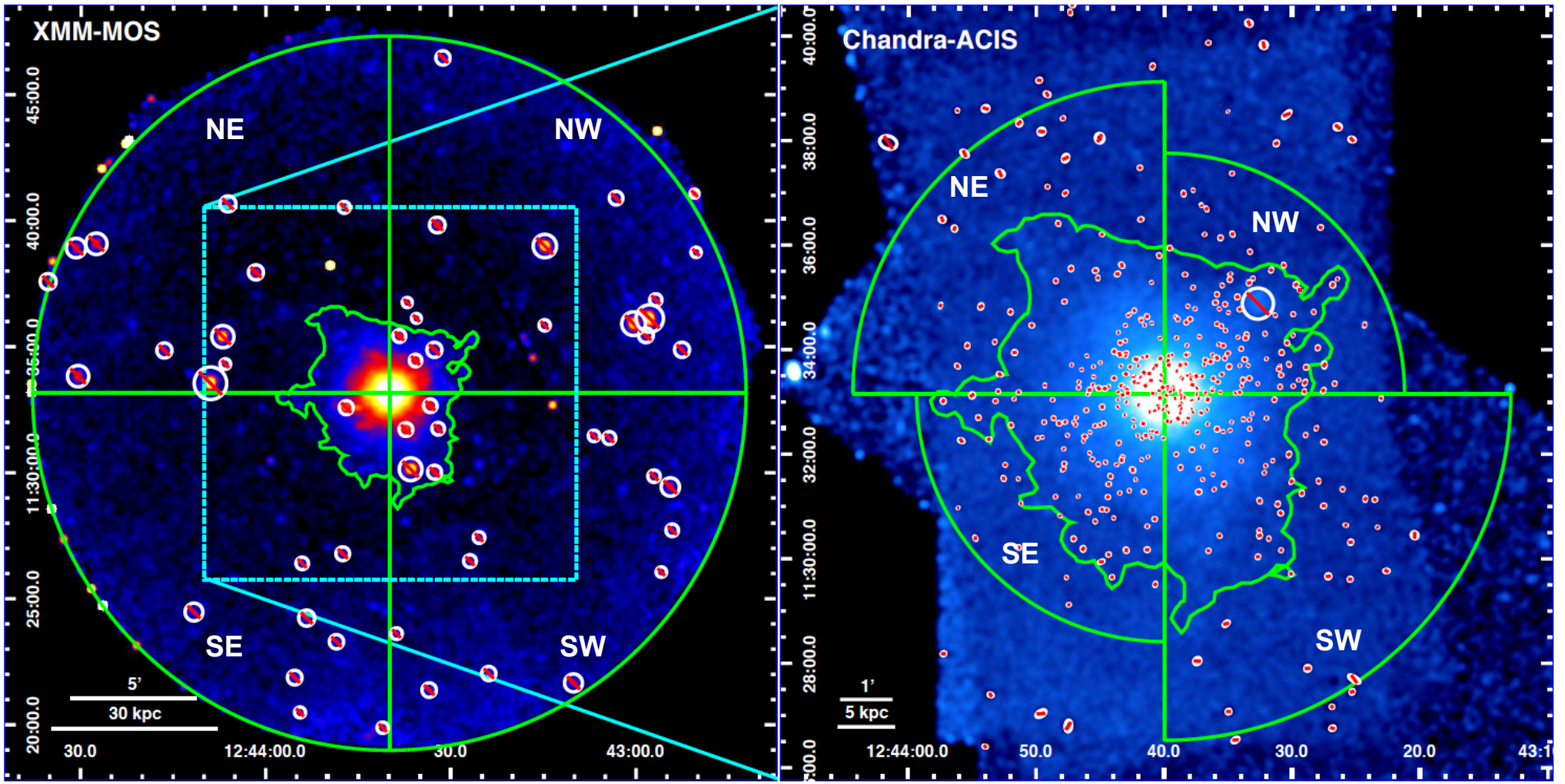


NGC 4649

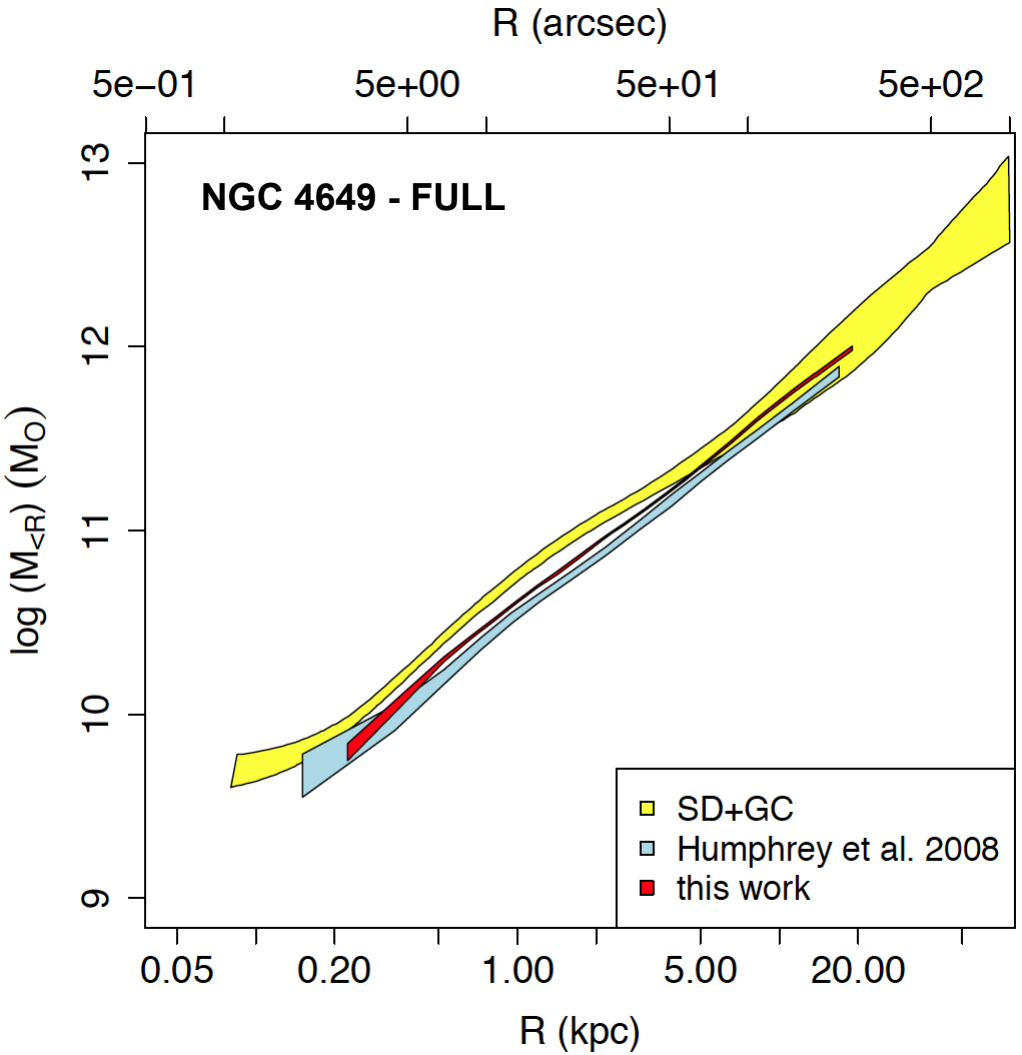


XMM-Newton MOS data show a generally relaxed large-scale morphology, with faint wing-like features (Wood et al. 2014) in NE and SW directions. In the central region *Chandra* ACIS data reveal cavities and ripples in the ISM that appear to be morphologically related with the central radio emission (Paggi et al. 2014).

Extraction Sectors



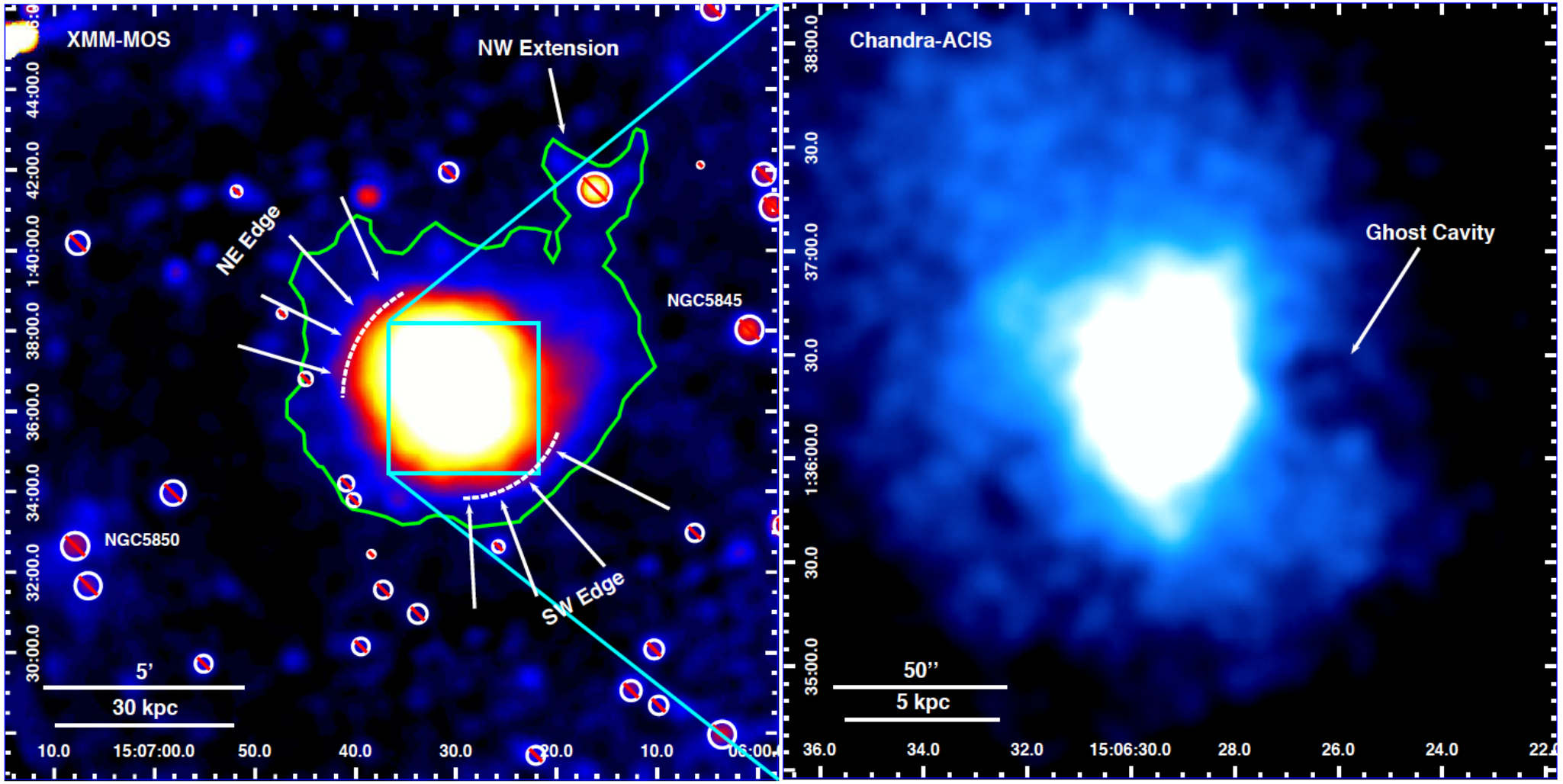
NGC 4649 Mass Profile



Mass profiles in different sectors are fairly similar and consistent with the optical profiles (Shen & Gebhardt 2010) → ISM is close to hydrostatic equilibrium or large scales.

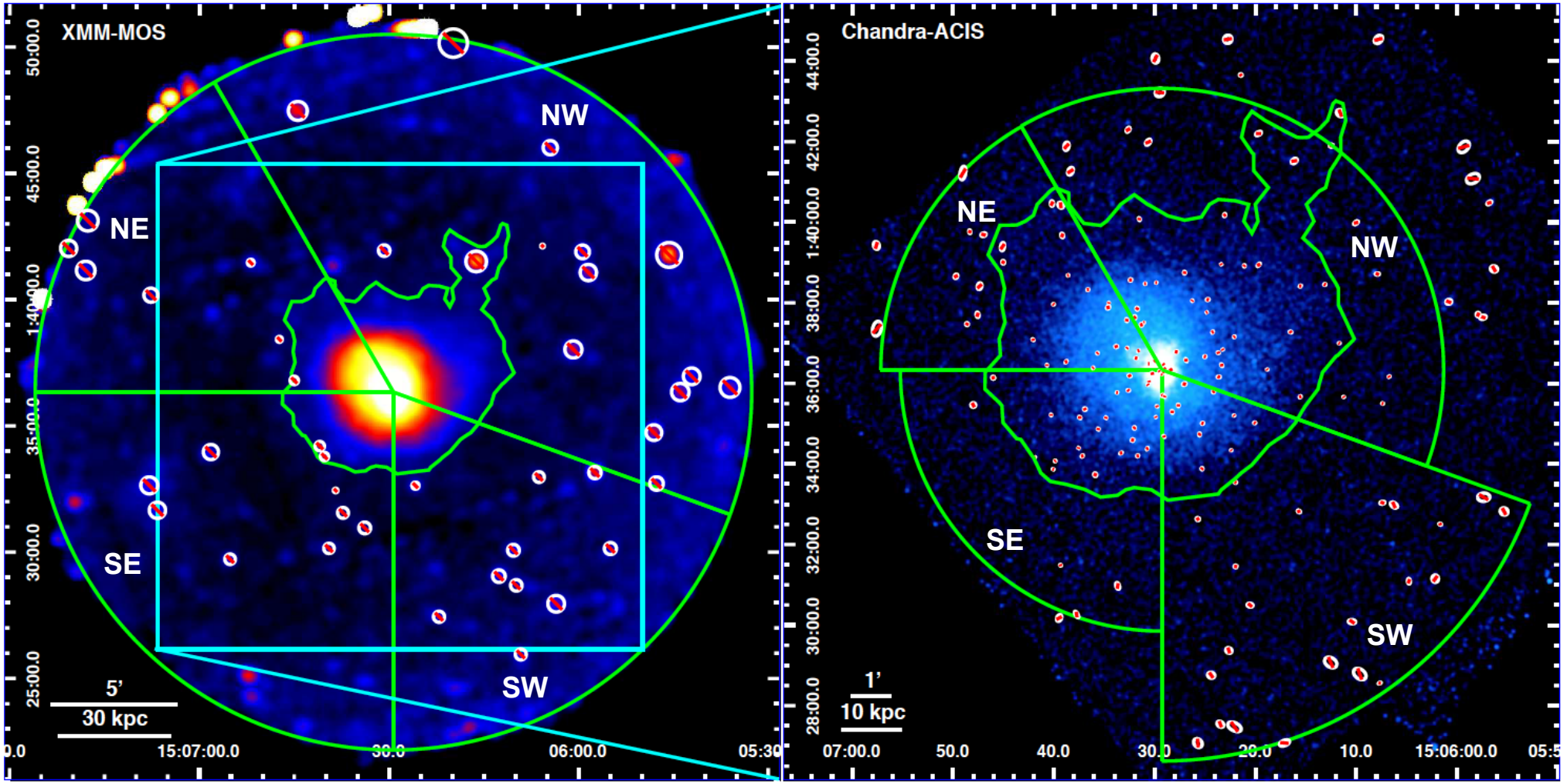
Deviations 0.5 kpc < r < 5 kpc are interpreted as non-thermal pressure connected with nuclear activity.

NGC 5846



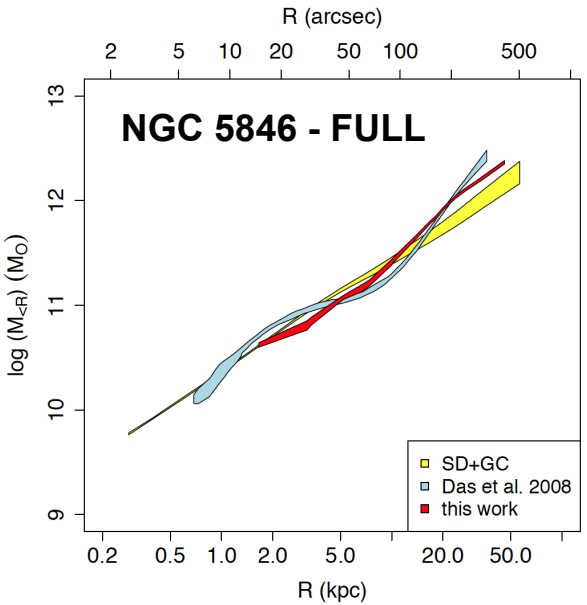
XMM-Newton MOS data show the edges in NE and SW direction likely due to interaction with NGC 5850 and the NW extension, while in the central region *Chandra* ACIS data reveal bubble and cavities related with recent AGN activity (Machacek et al. 2011).

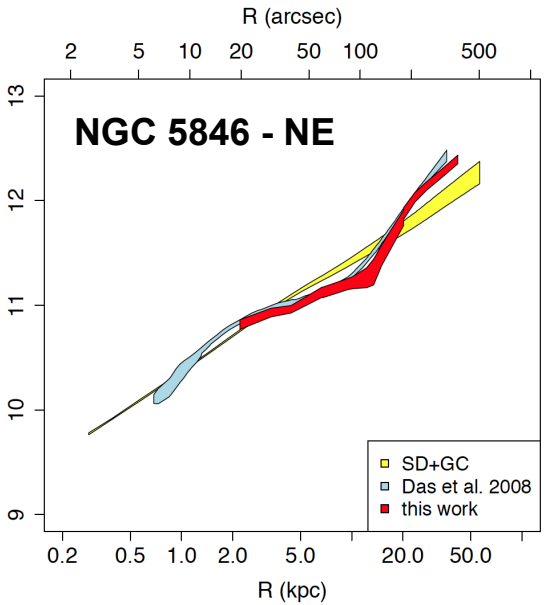
Extraction Sectors

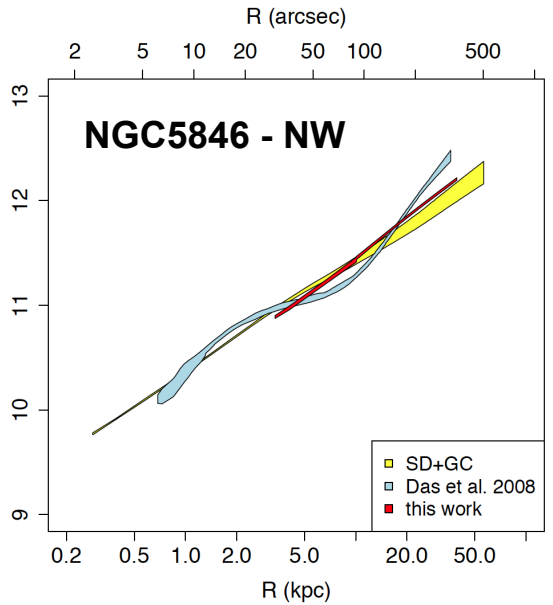


NGC 5846 Mass Profiles

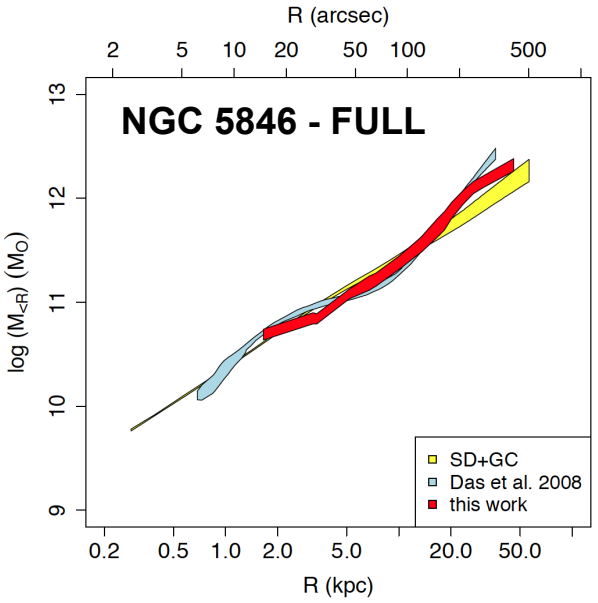
fixed abundances

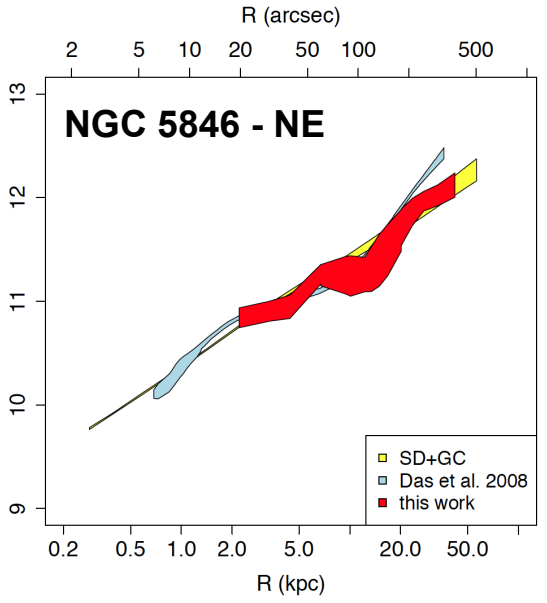


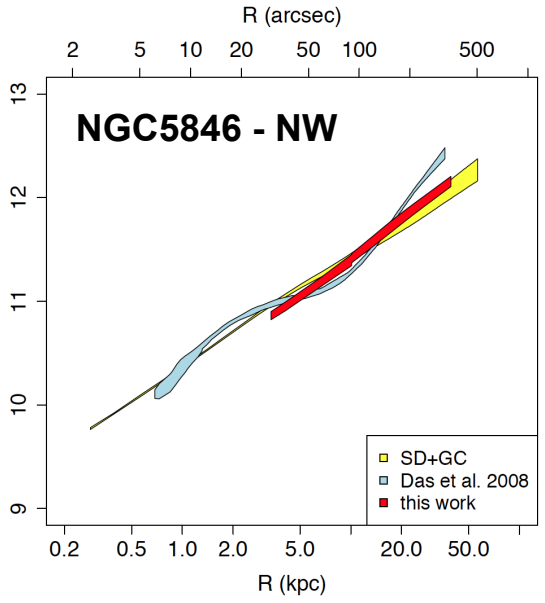




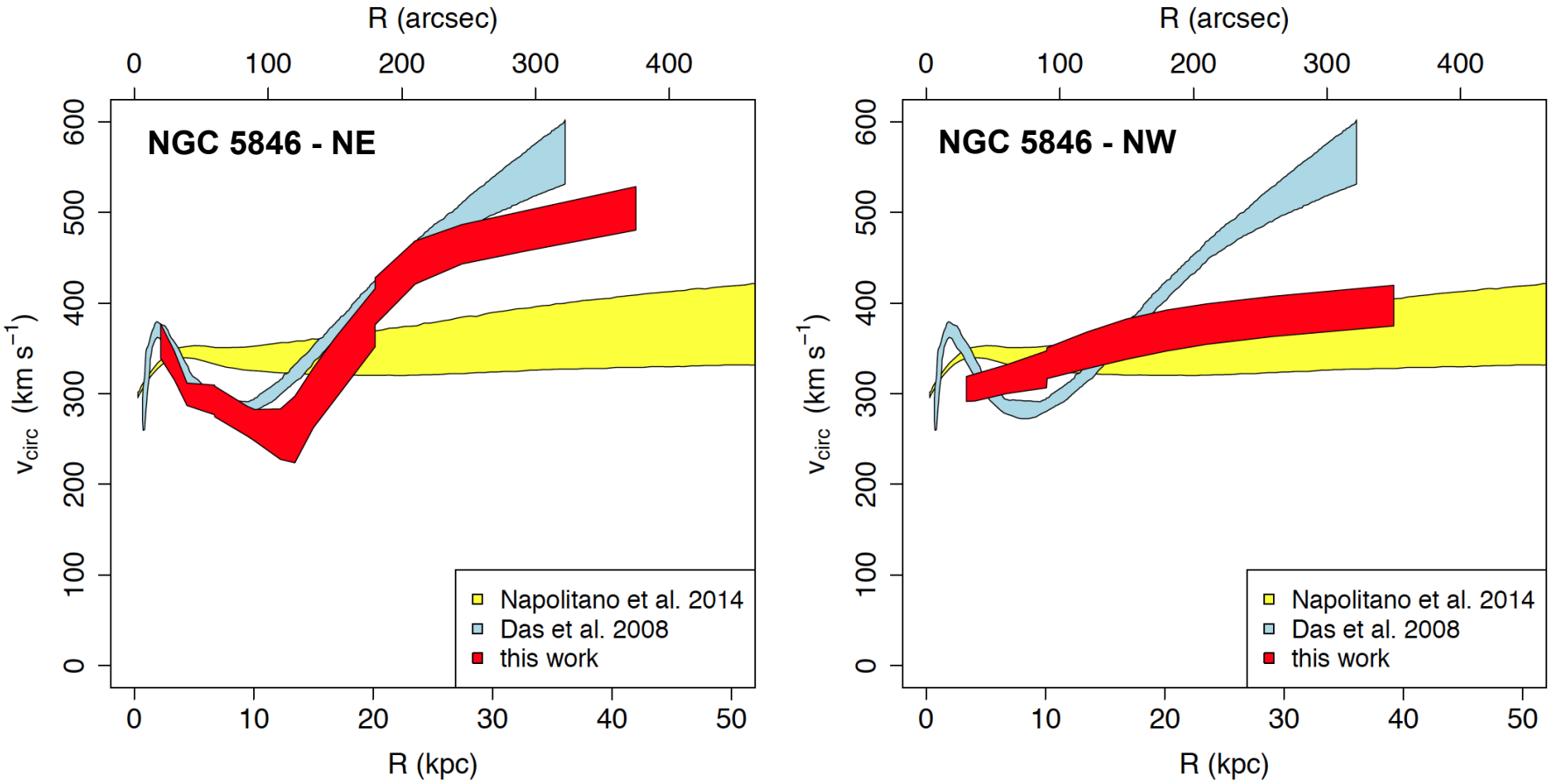
variable abundances







NGC 5846 Velocity Profiles



- On scales < 10 kpc the deviations from optical profiles are likely due to AGN activity.
- Gas sloshing connected to interaction with NGC 5850 on ~ 20 kpc scale in the NE sector.
- In the NW sector we obtain mass profiles consistent with the optical ones.

Conclusions

- Refined ETGs X-ray mass profiles: background evaluation, azimuthal directions, etc.
- Combined *Chandra* + *XMM-Newton* data:
  - NGC 4649 → smooth profiles, ISM close to hydrostatic equilibrium on large scales
  - NGC 5846 → evidence of sloshing connected to galactic interaction
- We just got started! W. I. P.: NGC 4636 + NGC 1407
- *Chandra* Galaxy Atlas: **a resource for future *Chandra* science**

Backup Slides

X-Ray Spectral Extraction

- Lower limit on the annulus width to avoid strong mixing between spectra in adjacent annuli (1'' *Chandra*, 30'' *XMM-Newton*)
- Upper limit on the annulus width to reach minimum signal to noise (30, 50, 100)
- Spectral fitting: APEC (hot gas) + BREM (undetected LMXBs) + 3D de-projection → hydrostatic equilibrium equation:

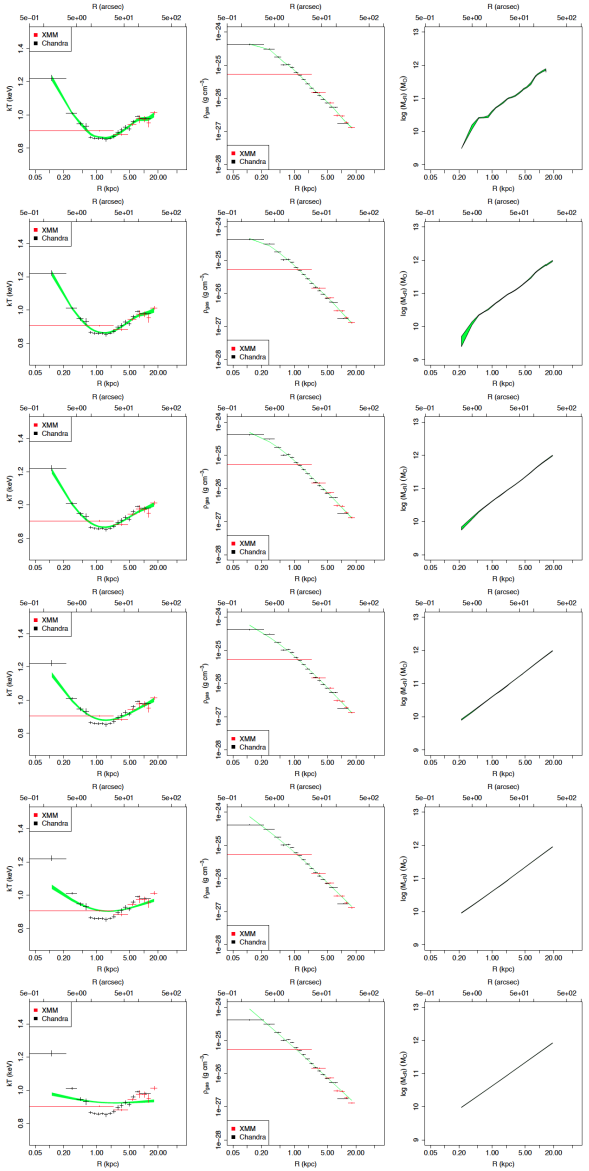
$$M(<R) = -R\,\frac{kT_g(R)}{G\mu m_p}\left(\frac{d\log\rho_g}{d\log R} + \frac{d\log T_g}{d\log R}\right)$$

- Fitting temperature and density gas profiles with a cubic smoothing spline (e. g., Johnson et al. 2009)
- Fixed and variable element abundances

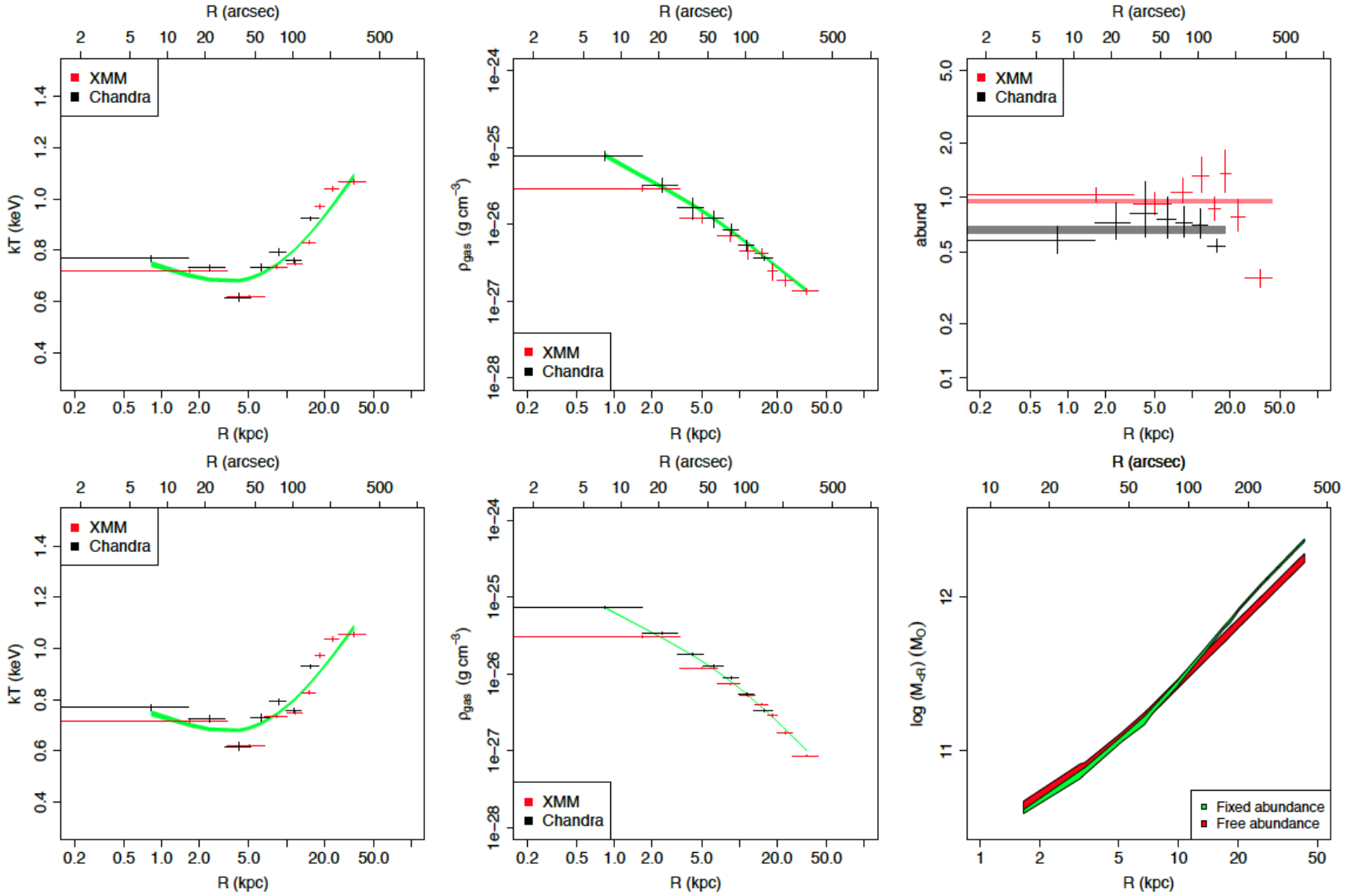
NGC 4649: a good example of a relatively relaxed system with symmetric and smooth X-ray mass profiles in fair agreement with optical measurements with only some small disturbances in the inner part of the galaxy

NGC 5846: a more disturbed system where sloshing introduces some measurable deviations in its mass profile from optical data both on small and large scales.

Profile fitting (smoothing)



Variable abundances



Source detection

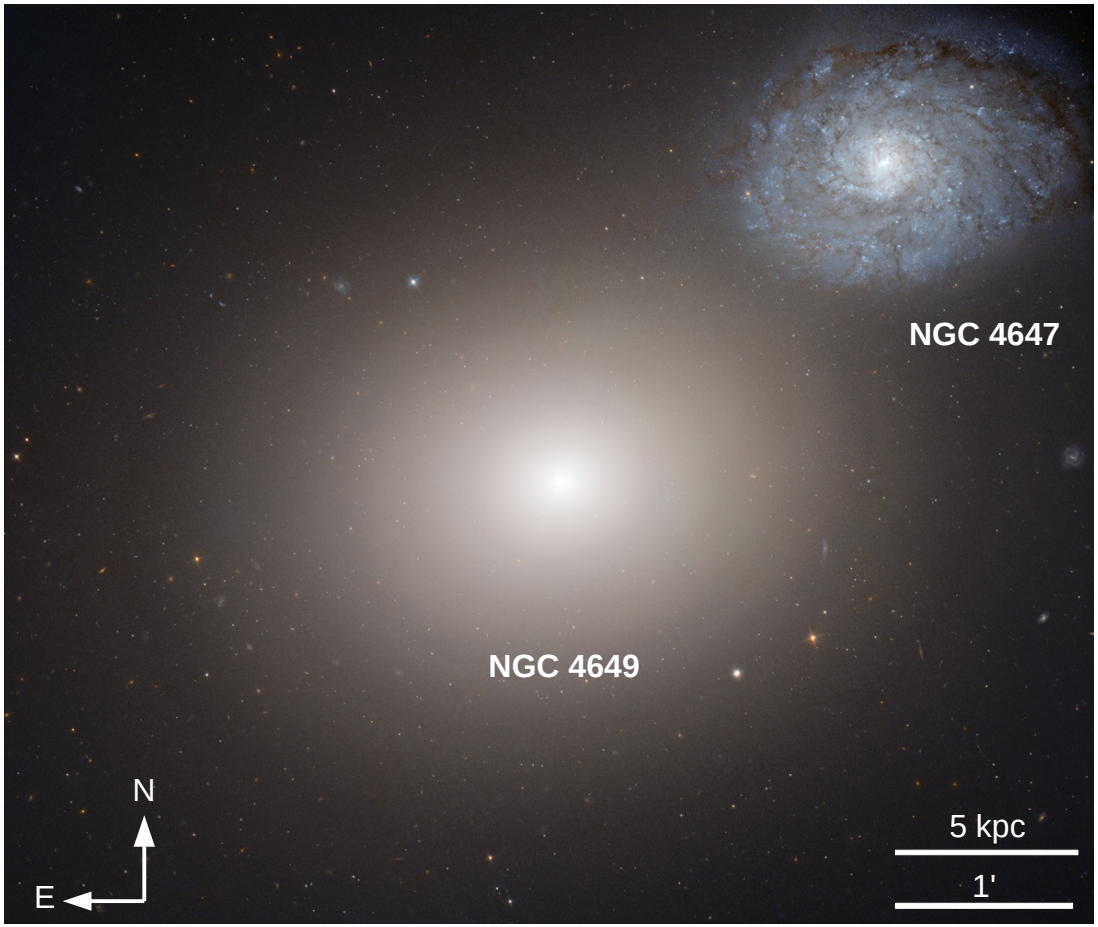
1) Sliding box with local background

2) Remove detected sources and create smooth background maps by fitting a 2-D spline to the images

3) Sliding box with background map

NGC 4649

- A.k.a. M60, nearby (~17 Mpc) X-ray bright, giant elliptical galaxy located in a group at the eastern edge of Virgo cluster.
- Faint radio source (Condon et al. 2002, Shurkin et al. 2008, Dunn et al. 2010).
- *Chandra* data indicate a generally relaxed X-ray morphology (Buote & Tsai 1995; Humphrey et al. 2008, 2013).
- But suggestions of AGN induced disturbances in the X-ray emitting gas (Randall et al. 2004, 2006; Shurkin et al. 2008; Dunn et al. 2010; Paggi et al. 2014).
- Companion spiral galaxy, NGC 4647 ~ 2.5' to the northwest from the center of NGC 4649



HST three color image (Credit: NASA, ESA, and Z. Levay STScI)

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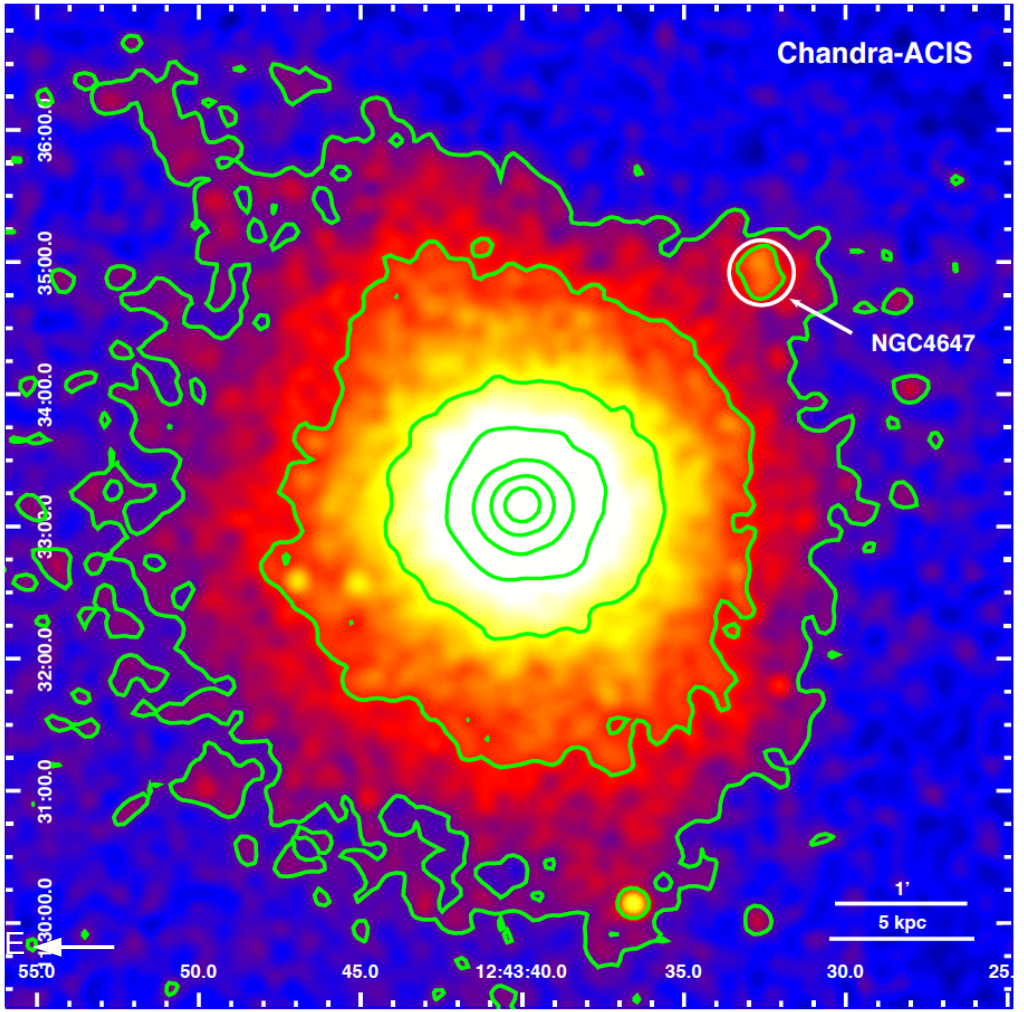
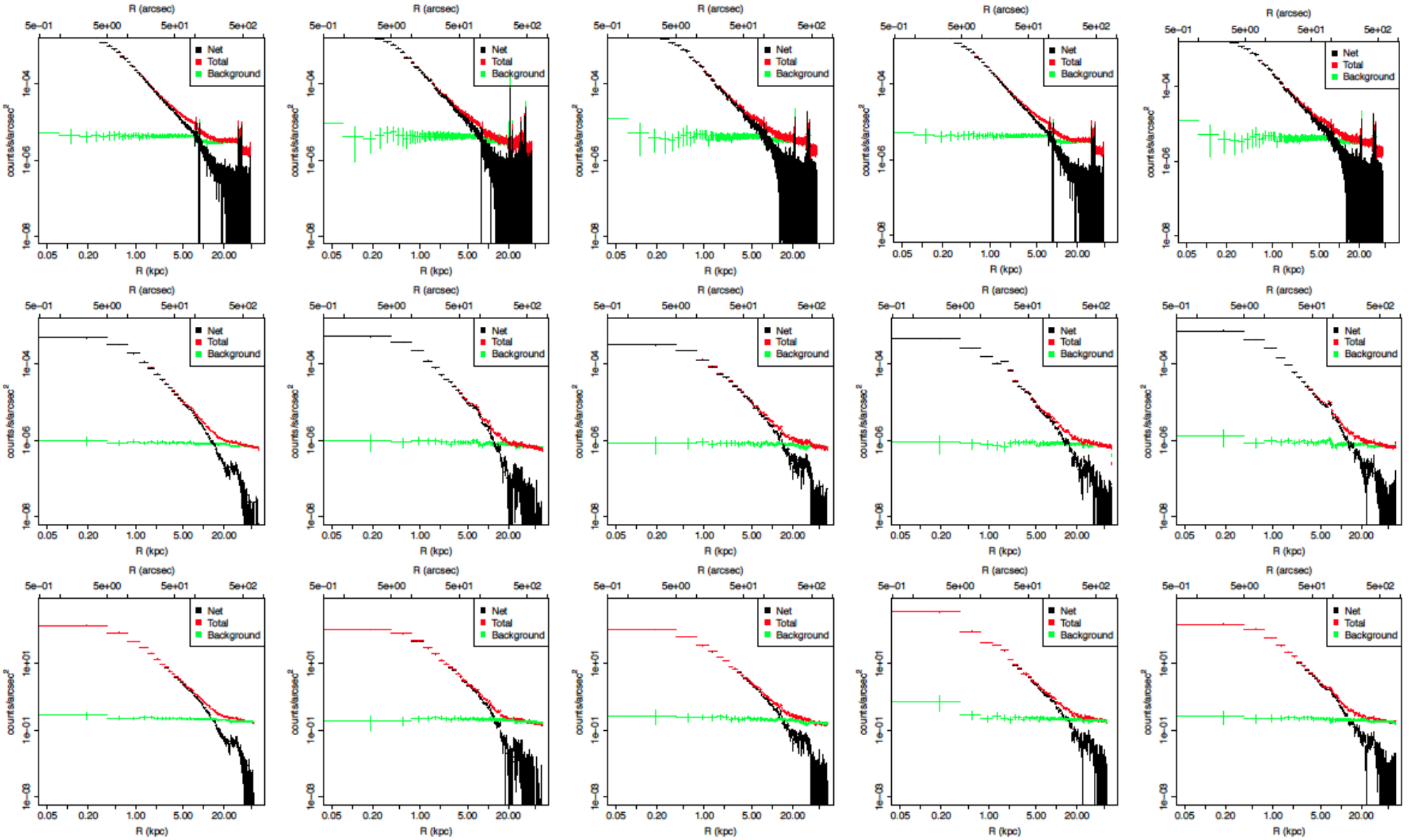
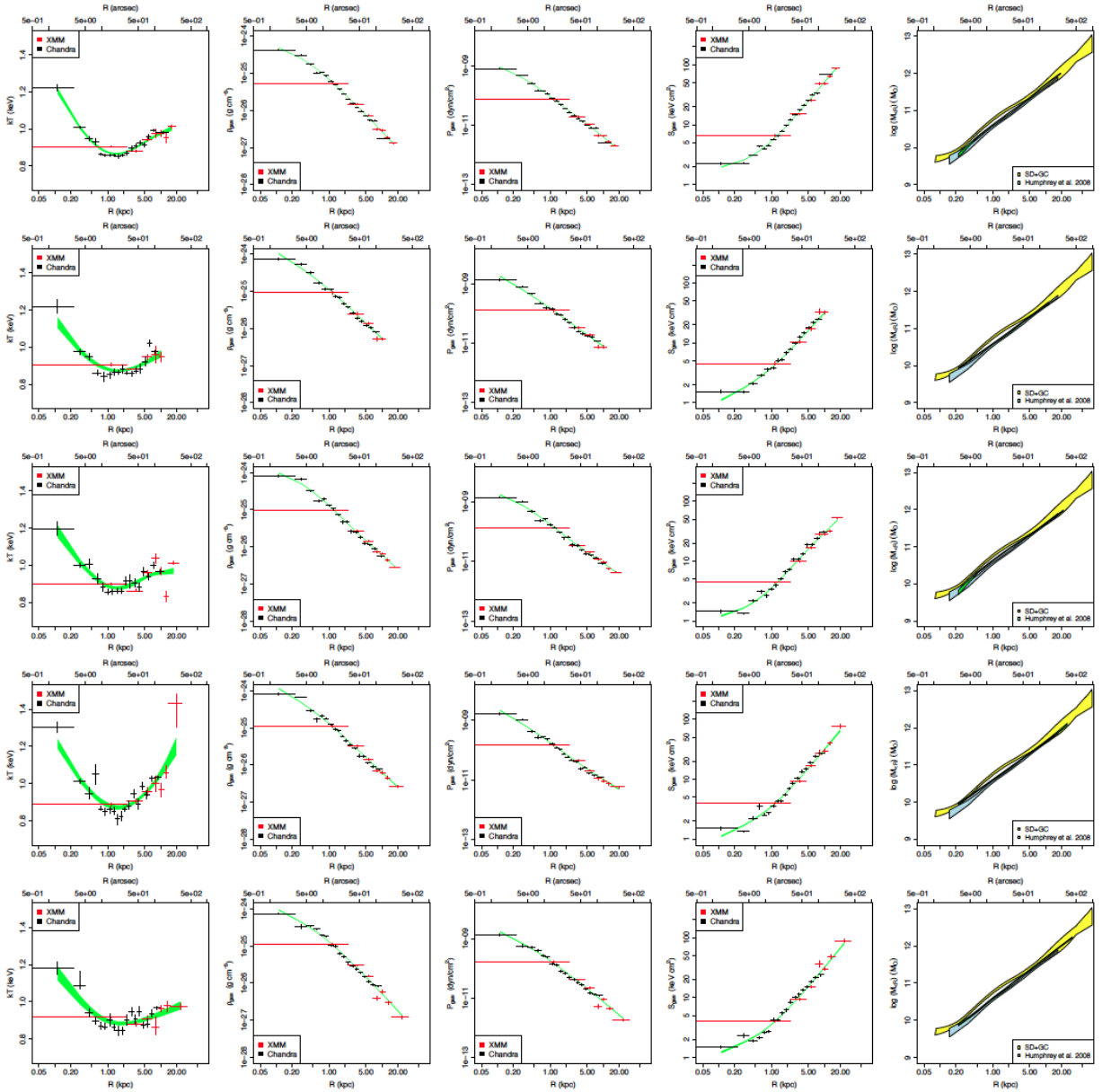


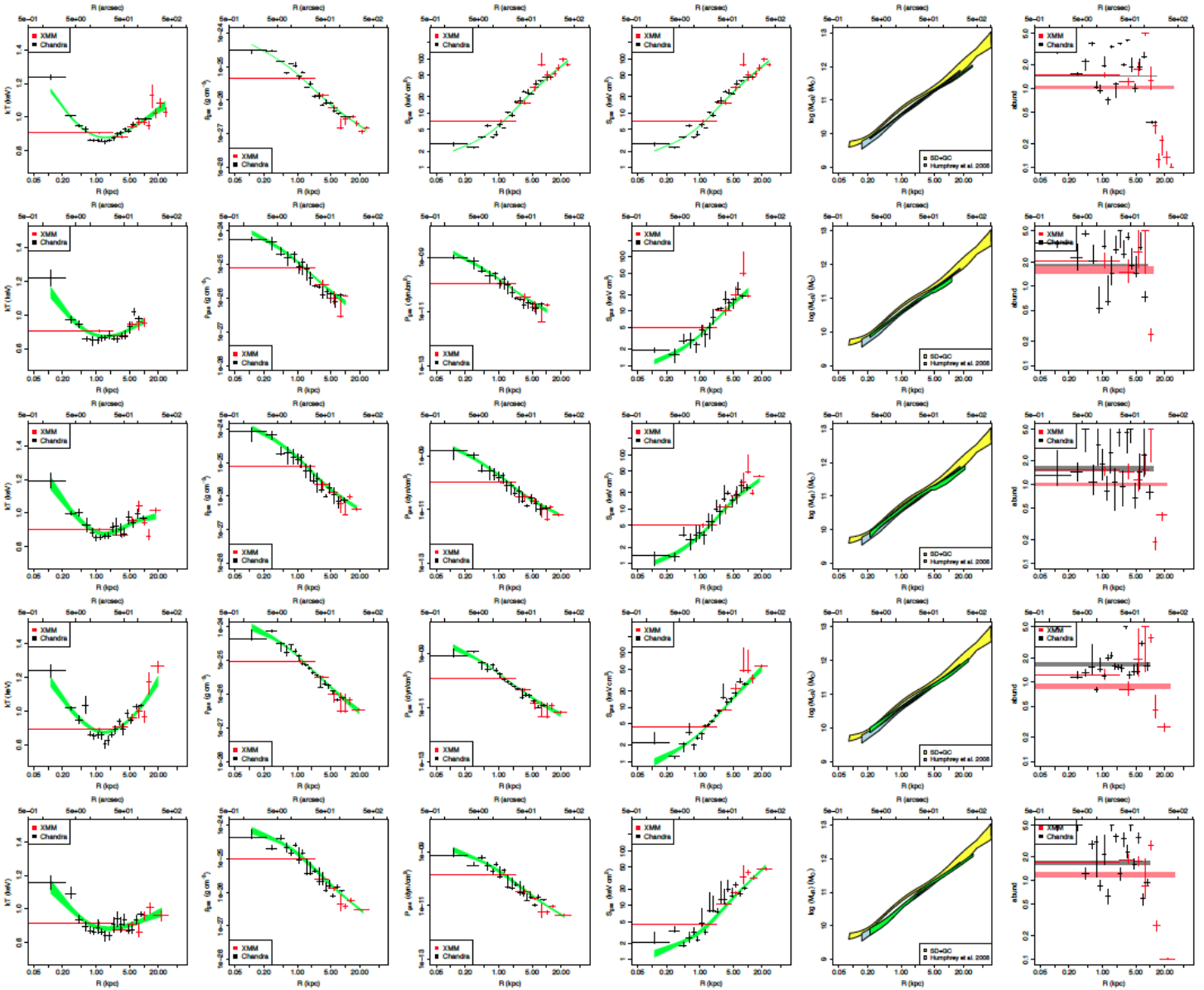
Surface Brightness Profiles



Gas Profiles (fixed abund.)



Gas Profiles (var. abund.)



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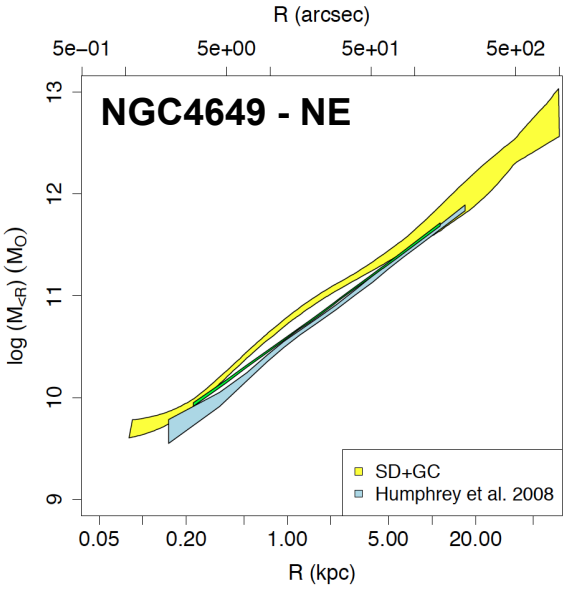
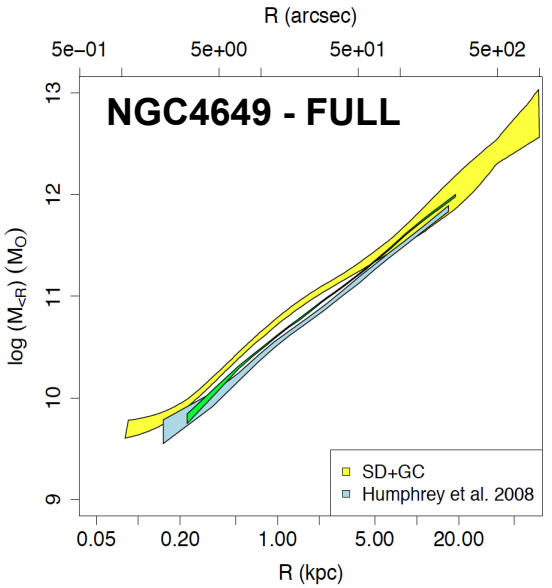
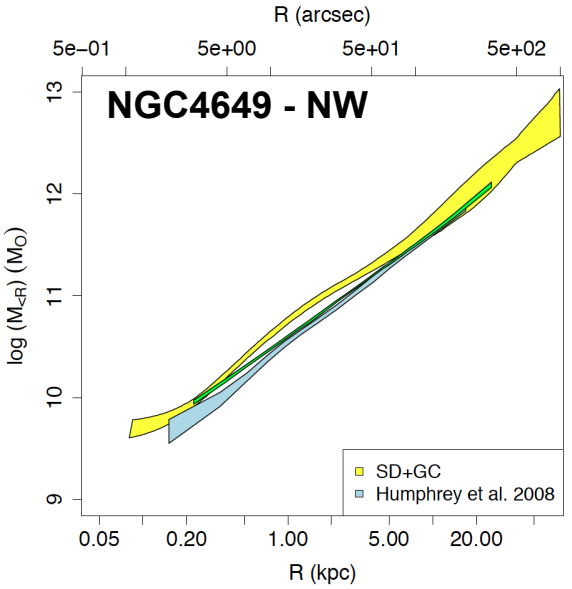
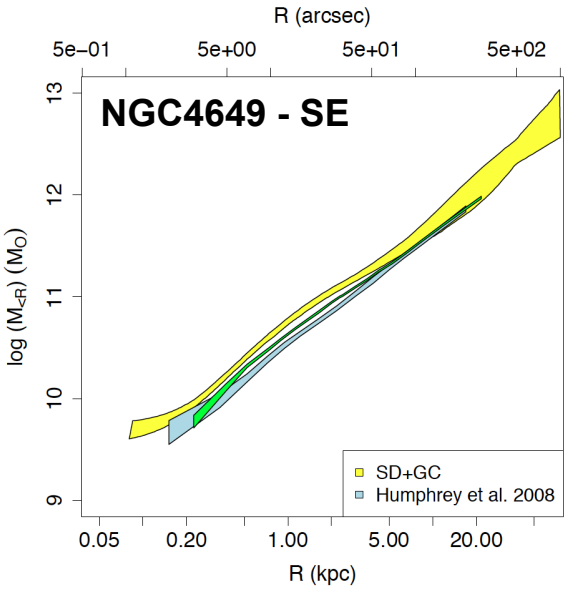
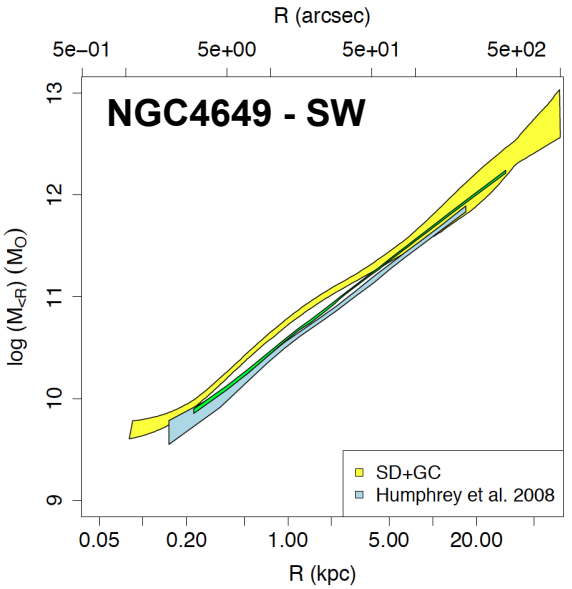


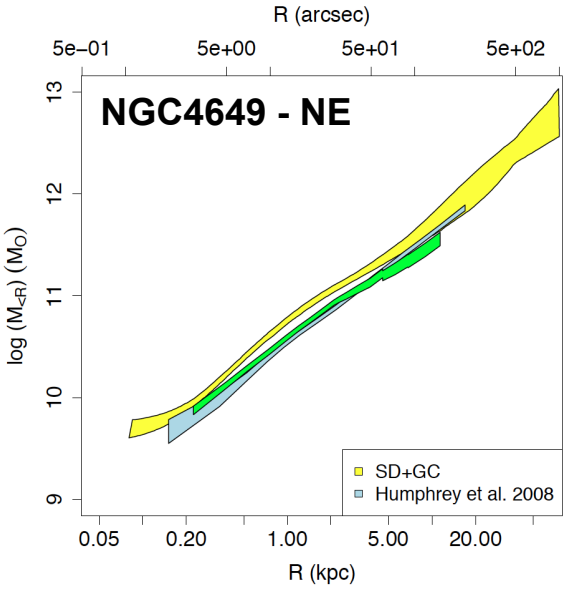


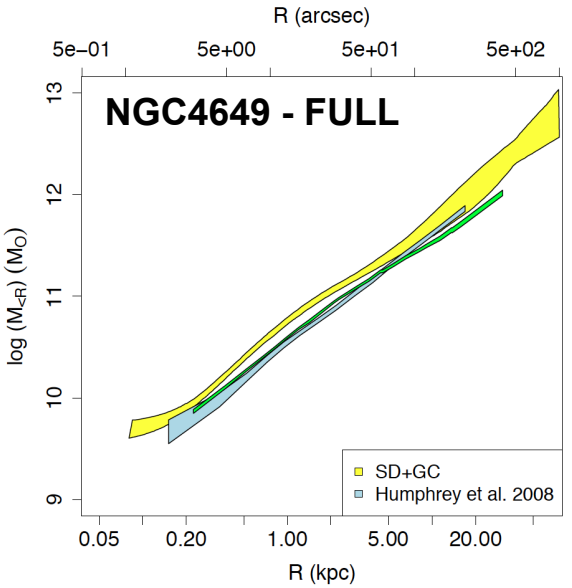


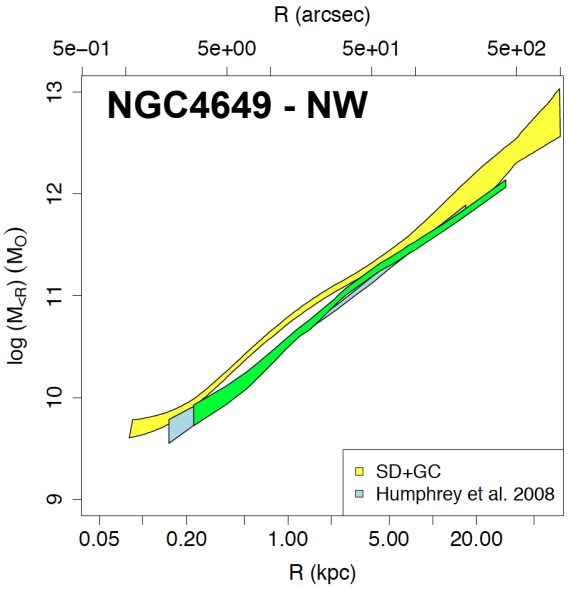


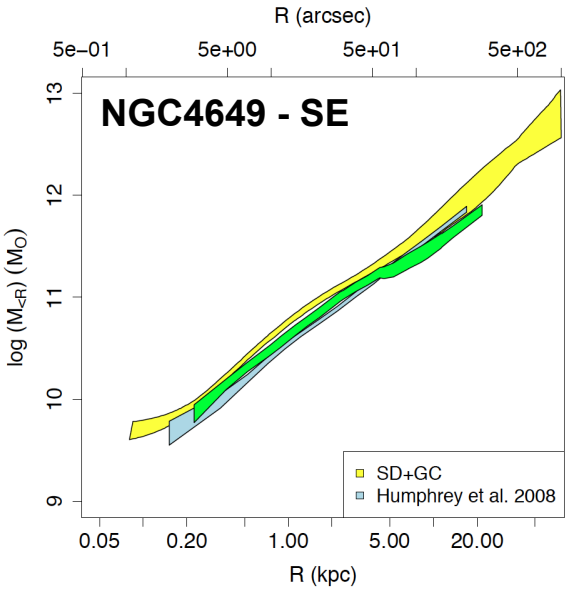


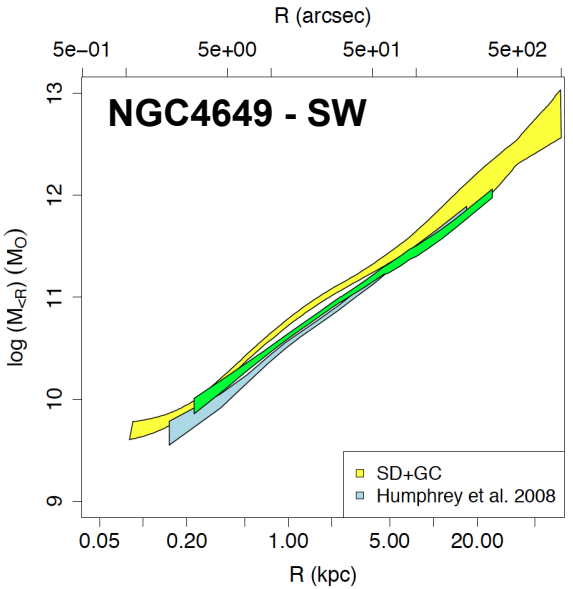
Mass Profiles (var. abund.)



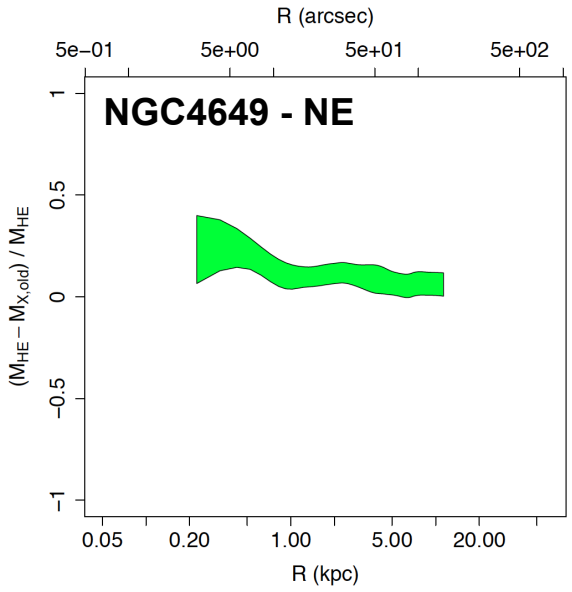


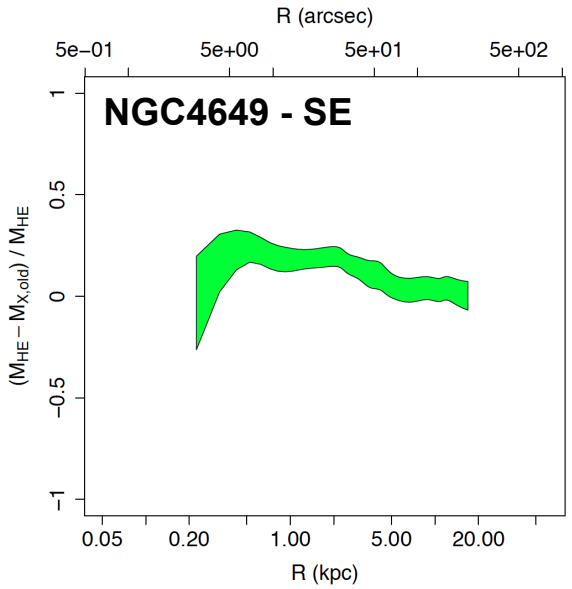


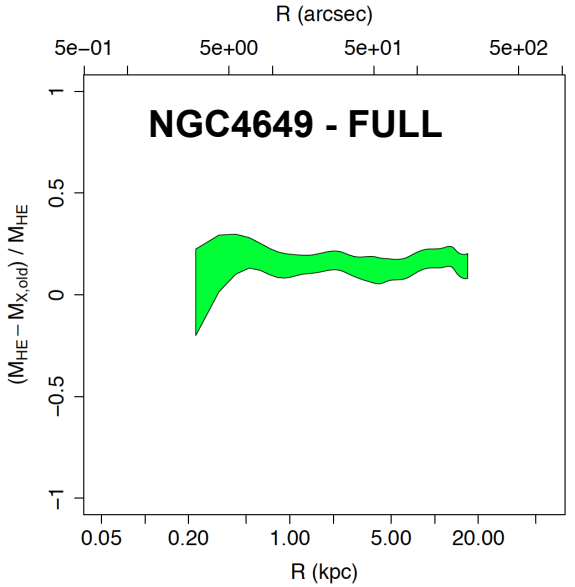


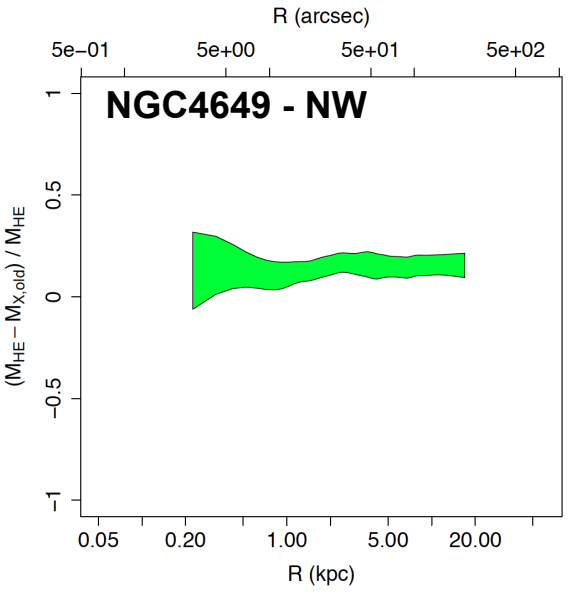


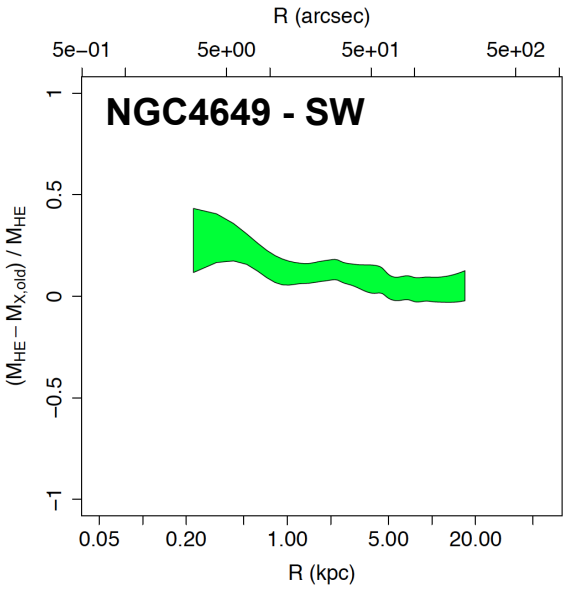
X-Ray Profile Comparison



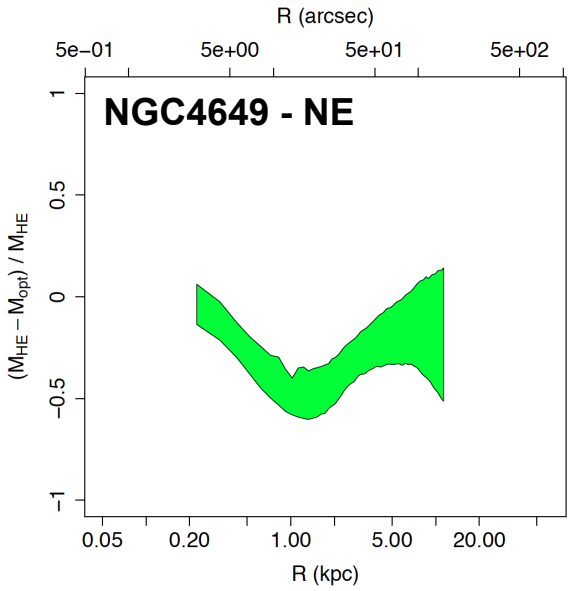


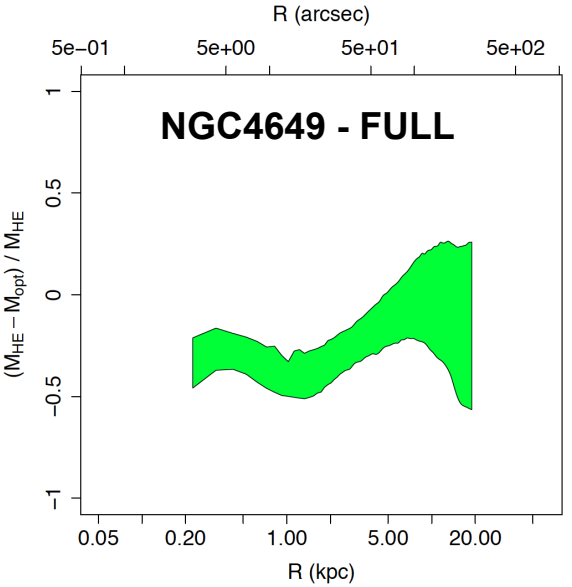


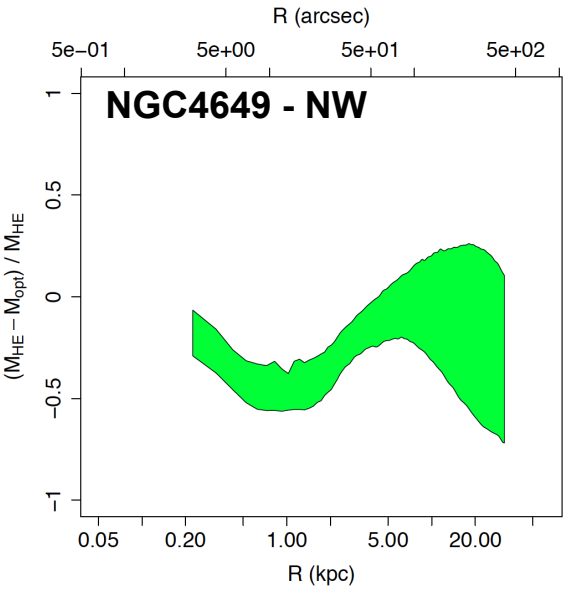


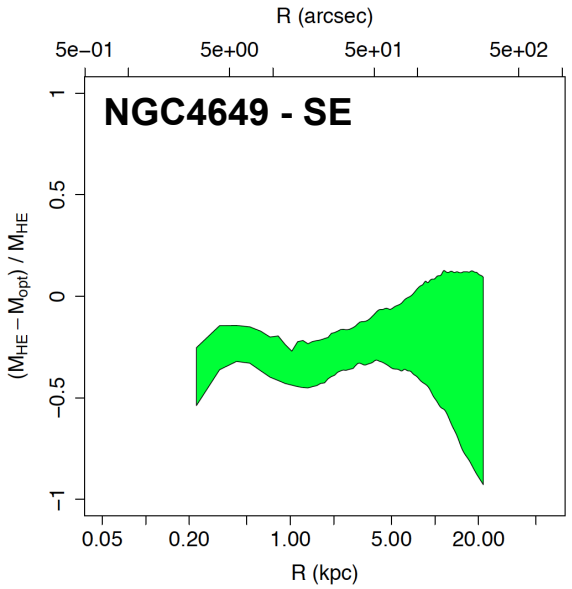


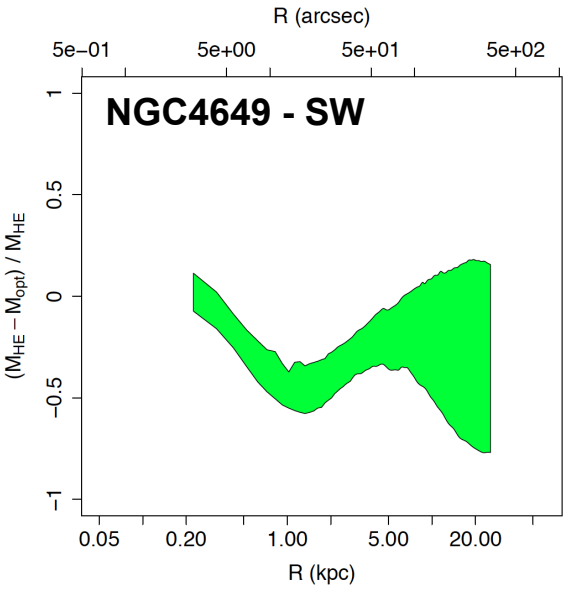
Optical Profile Comparison





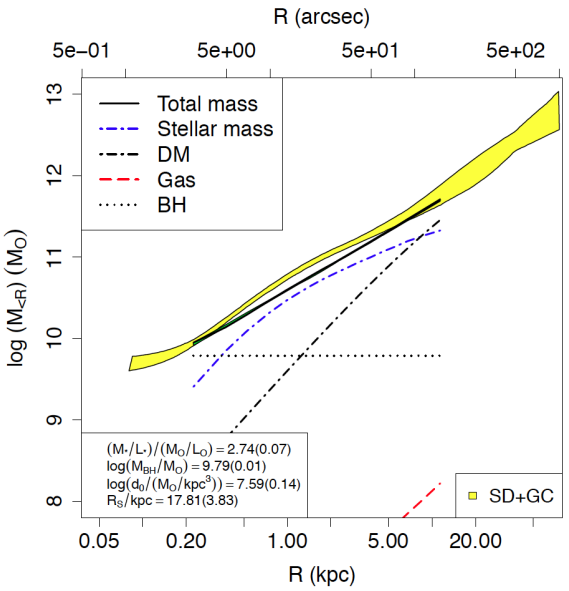




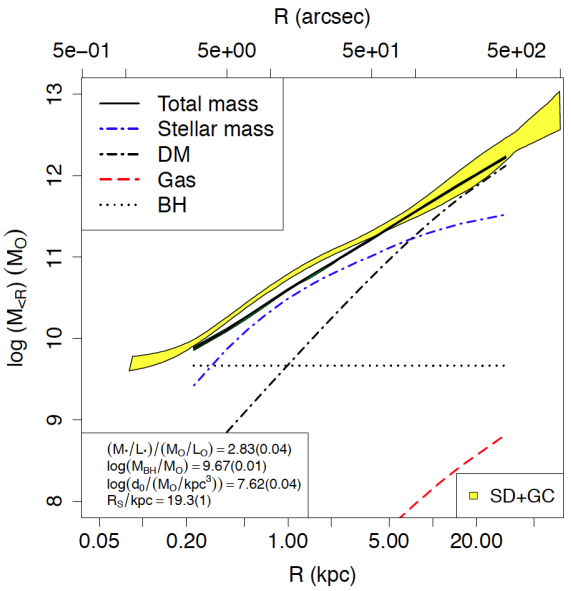


Mass Fits (fixed abund.)

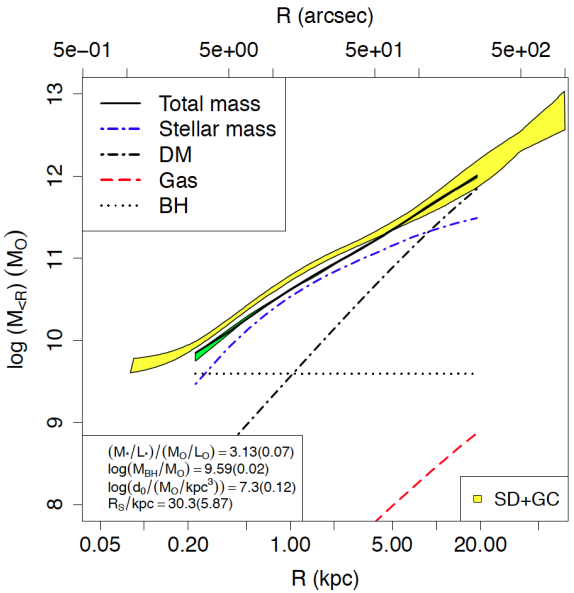
NGC4649 - NE



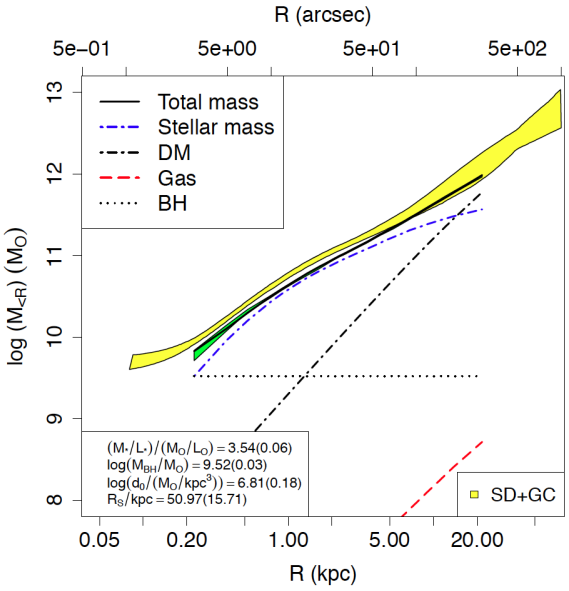
NGC4649 - NW



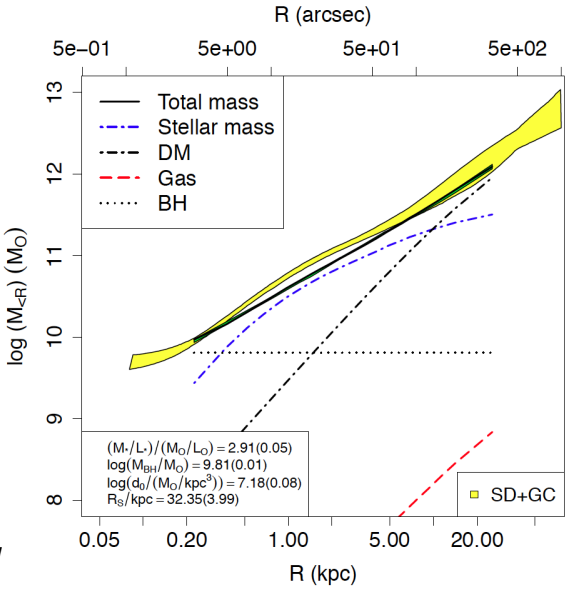
NGC4649 - FULL



NGC4649 - SE

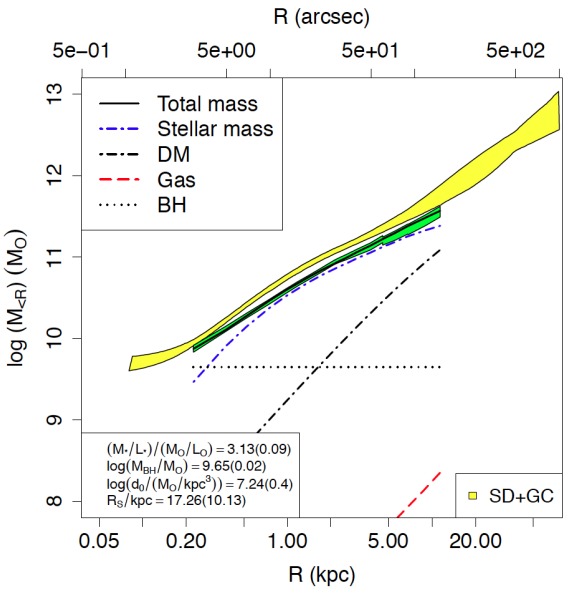


NGC4649 - SW

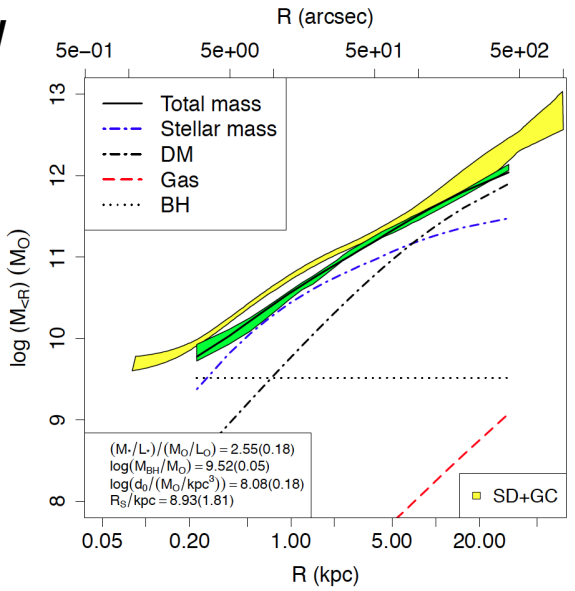


Mass Fits (variable abund.)

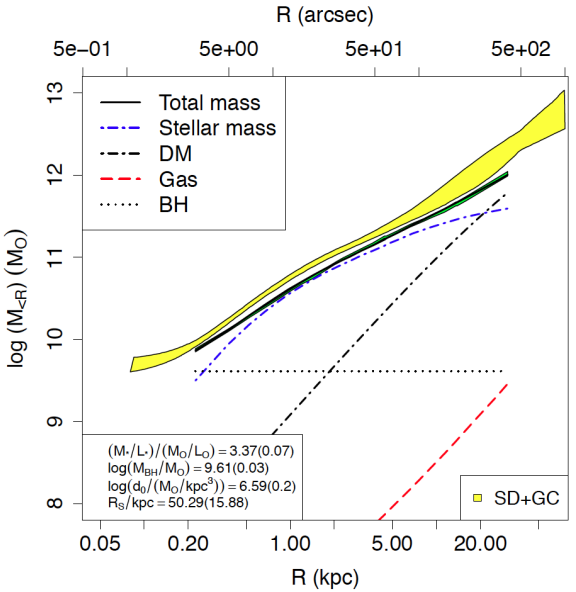
NGC4649 - NE



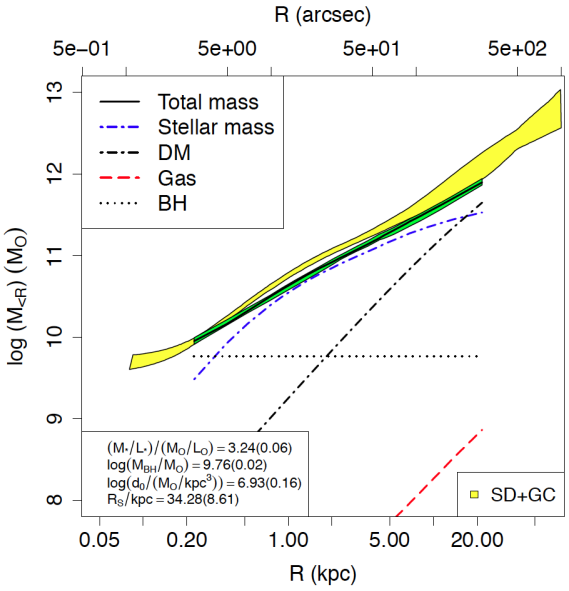
NGC4649 - NW



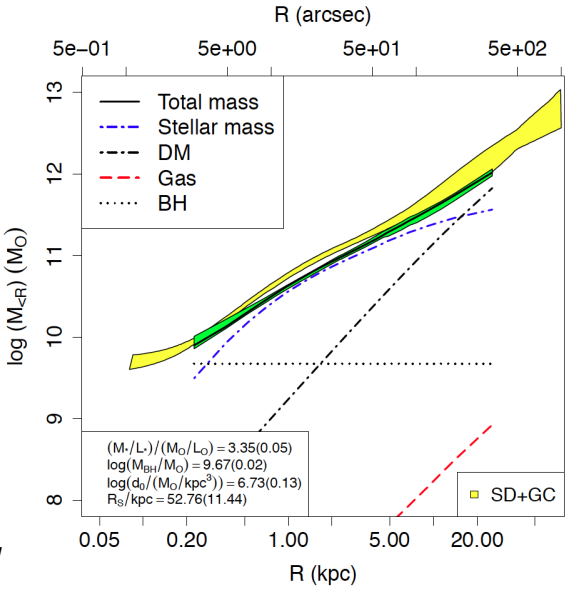
NGC4649 - FULL



NGC4649 - SE

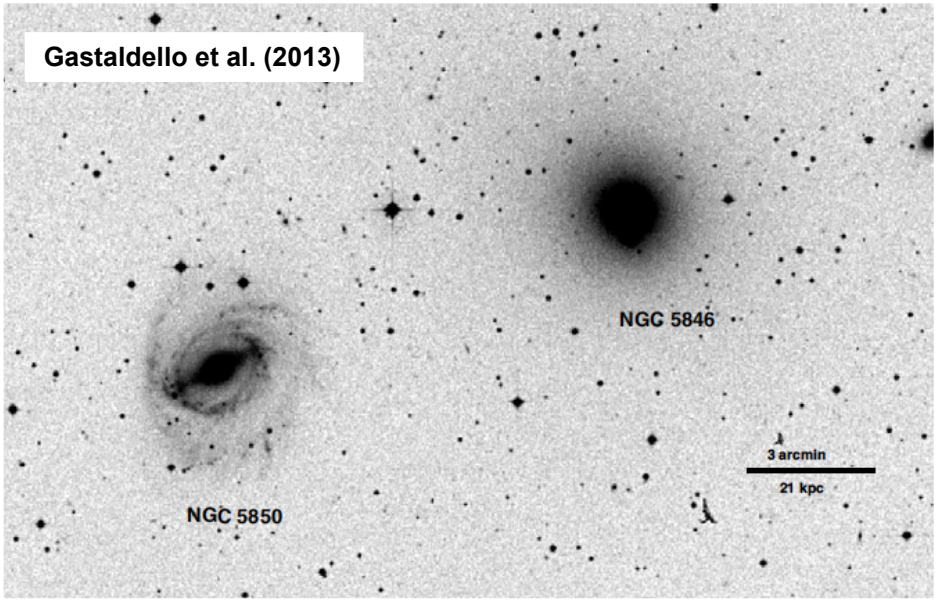


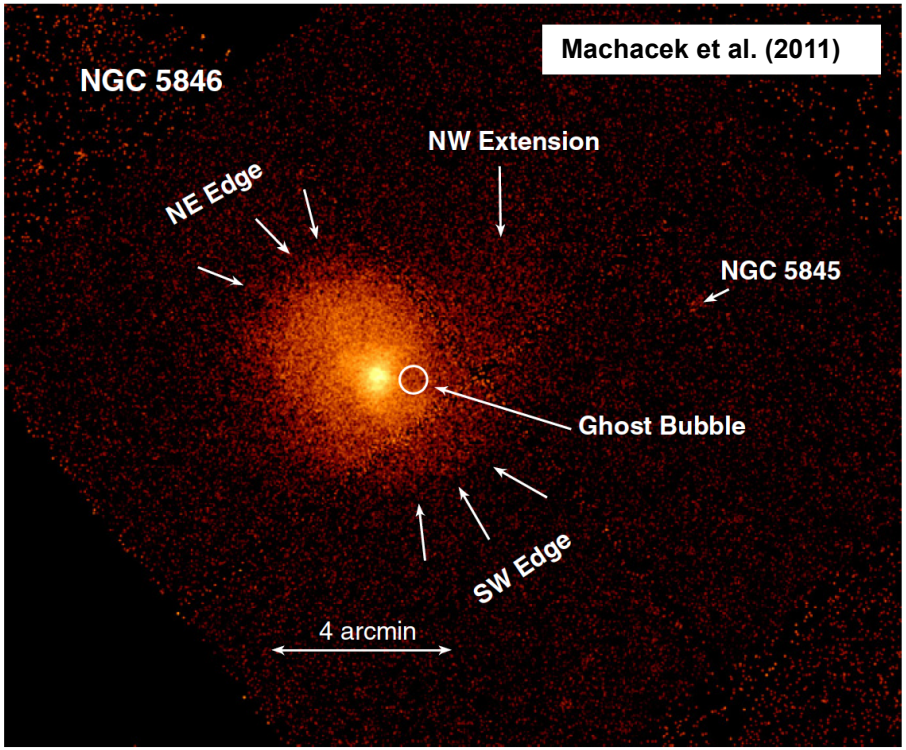
NGC4649 - SW



NGC 5846

- NGC 5846 is a nearby group (z = 0.0056) with evidence for gas sloshing with multiple cold fronts in *Chandra* data (Machacek et al. 2011)
- A likely perturber is the big spiral galaxy NGC 5850 located 10' (71 kpc) in projection to the east of NGC 5846 (Machacek et al. 2011)

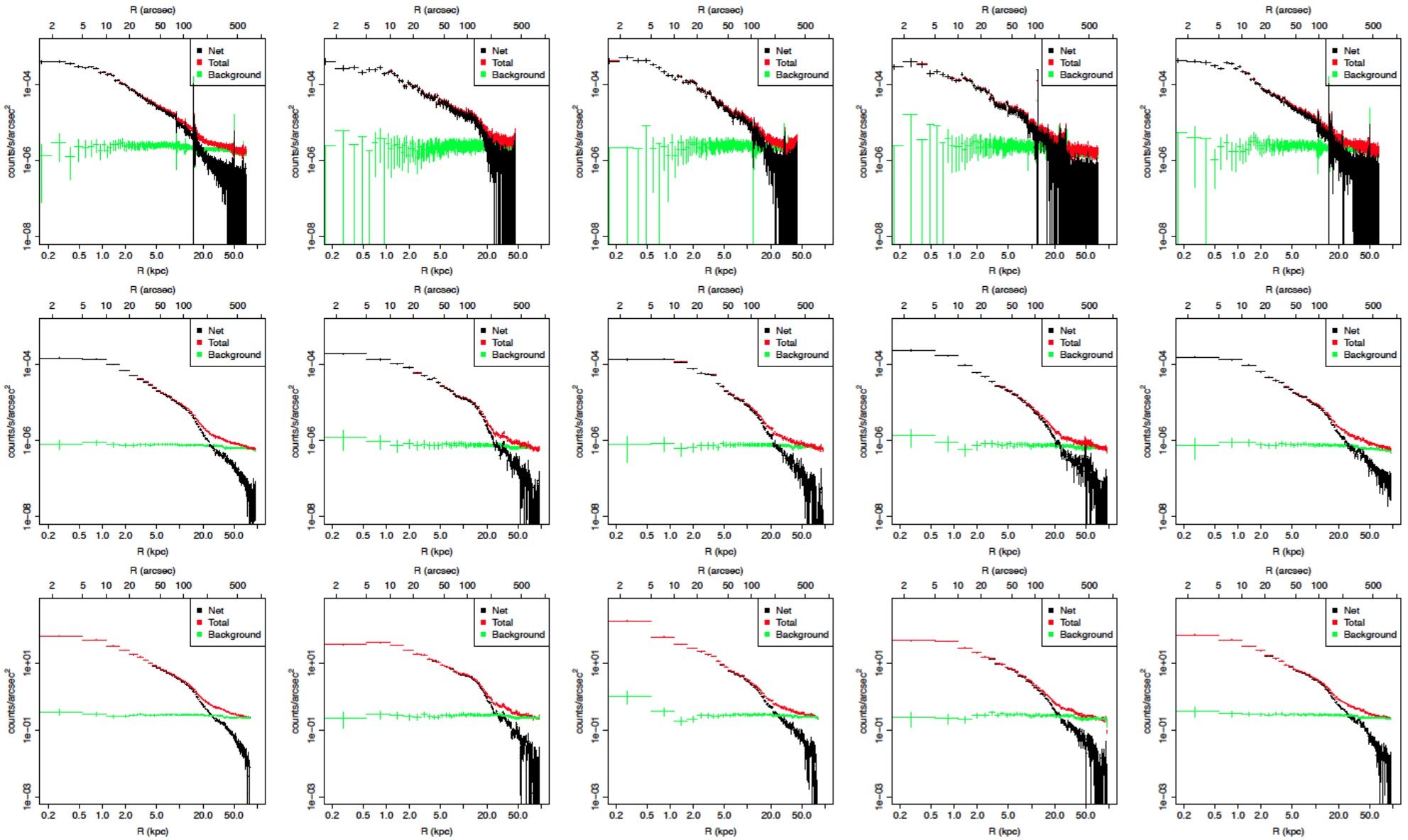




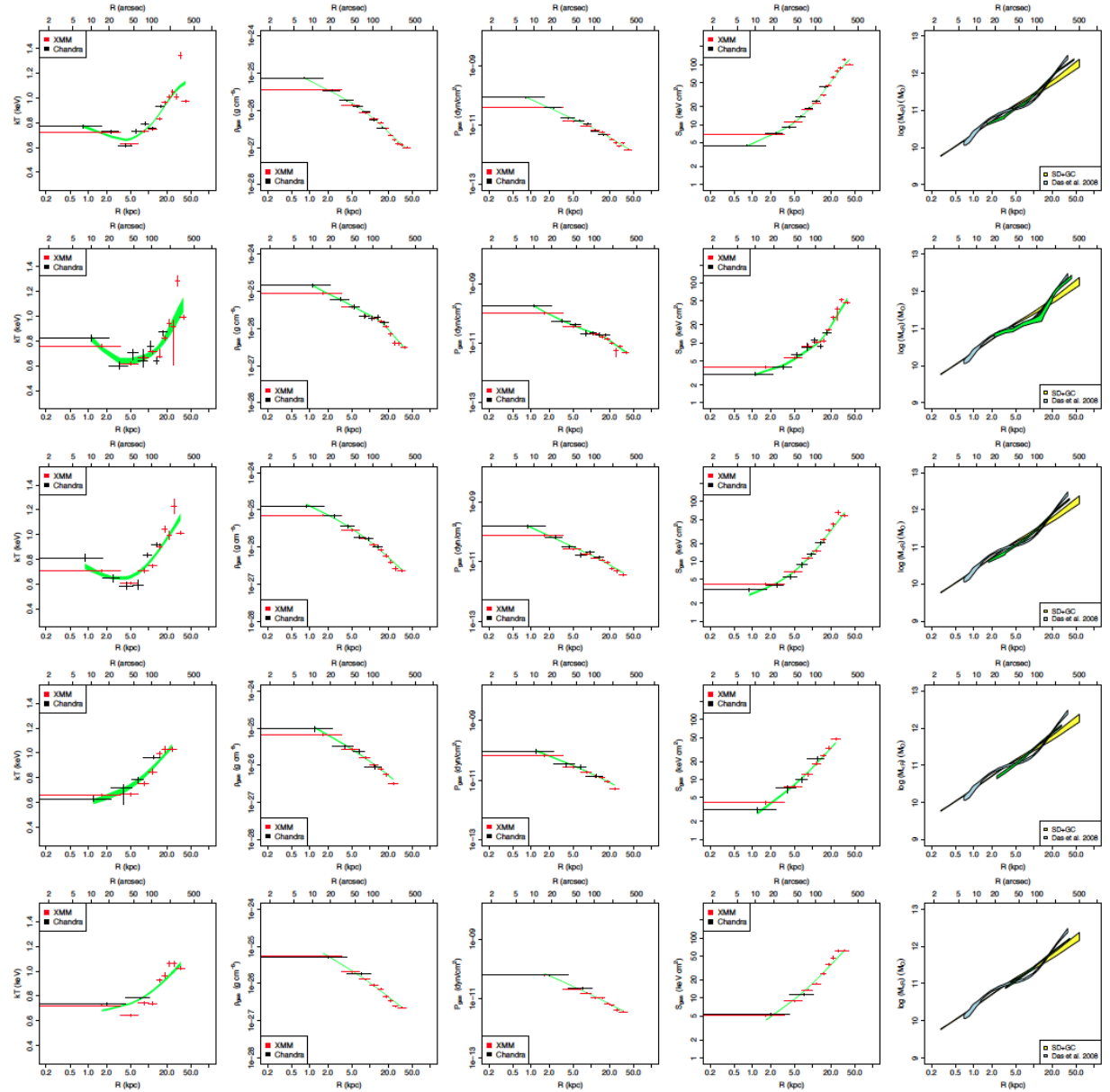
Chandra background-subtracted, exposure-corrected, merged 0.75–2.0 keV image of the diffuse gas in the outer regions of NGC 5846 (Machacek et al. 2011)

- Evidence for recent AGN activity in NGC 5846 (bubbles and cavities, Machacek et al. 2011)

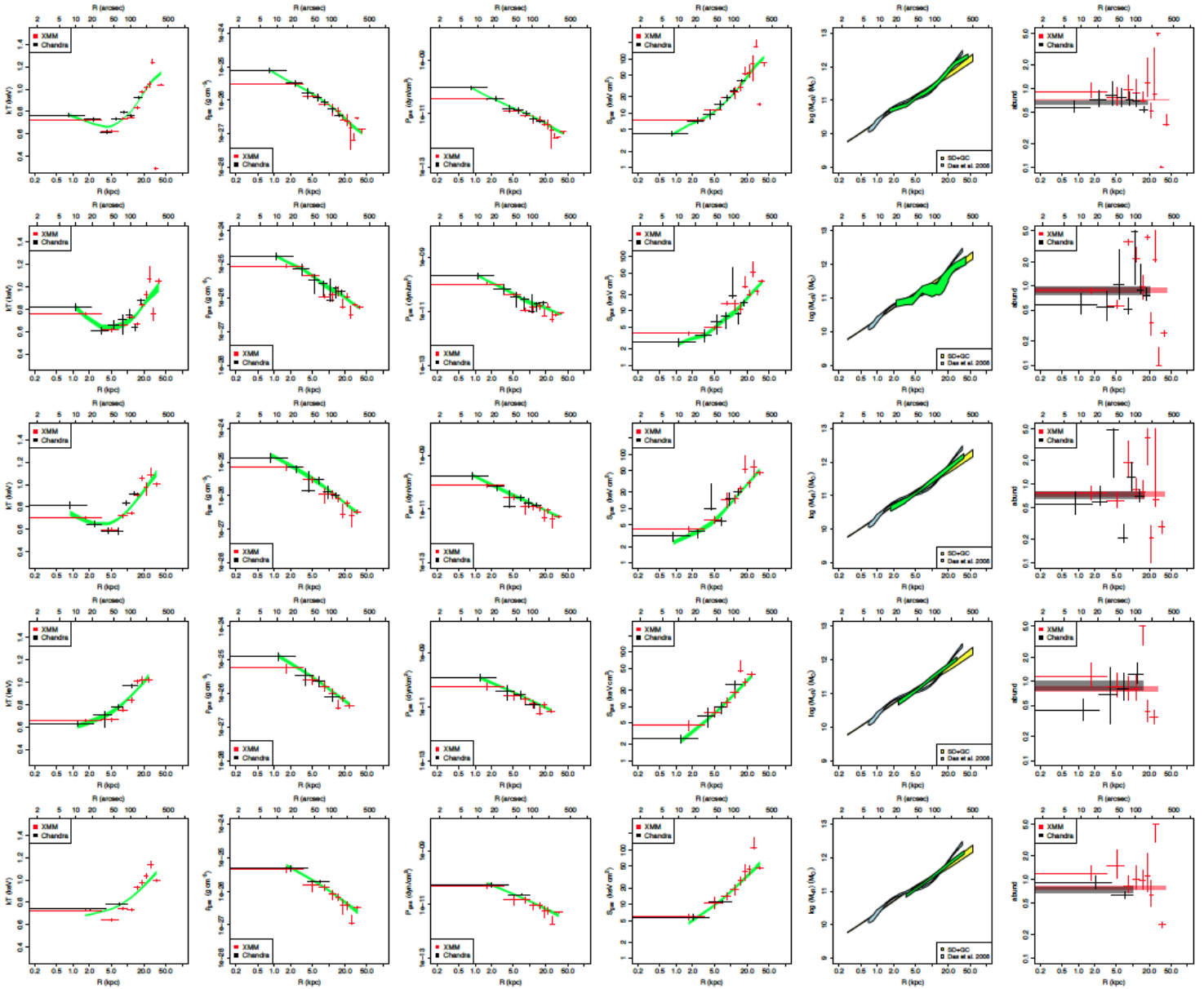
Surface brightness profiles



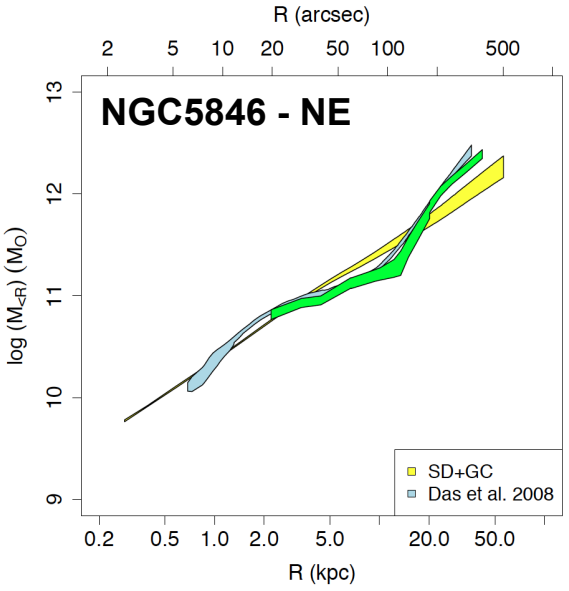
Gas Profiles (fixed abund.)

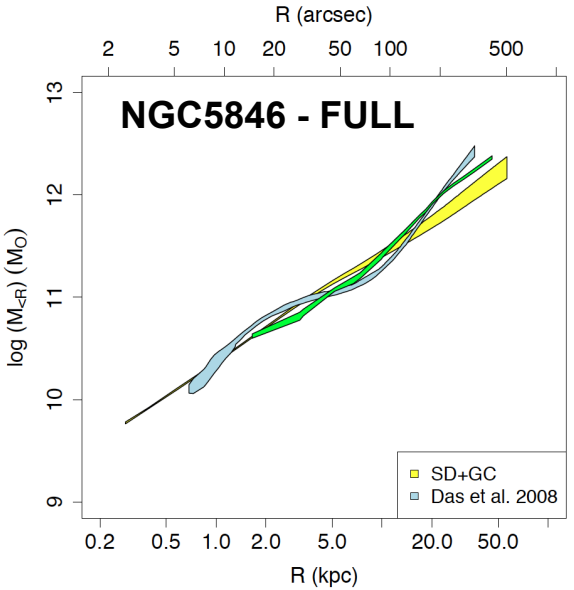


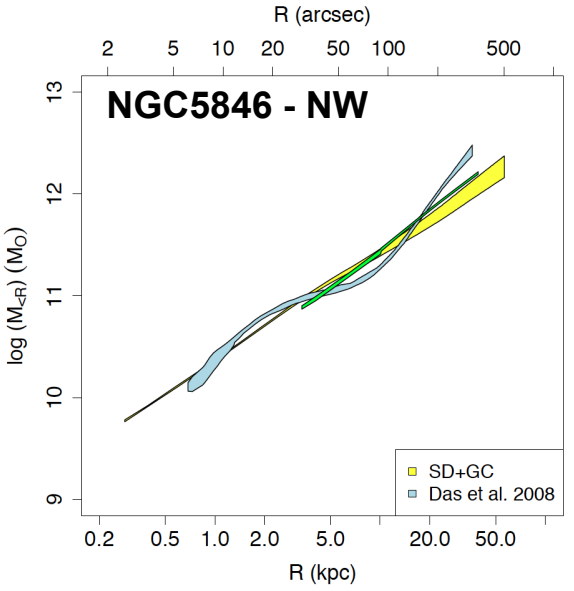
Gas Profiles (var. abund.)

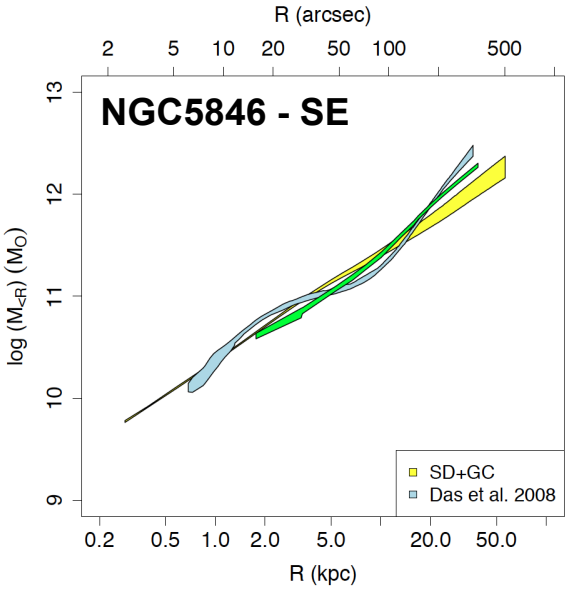


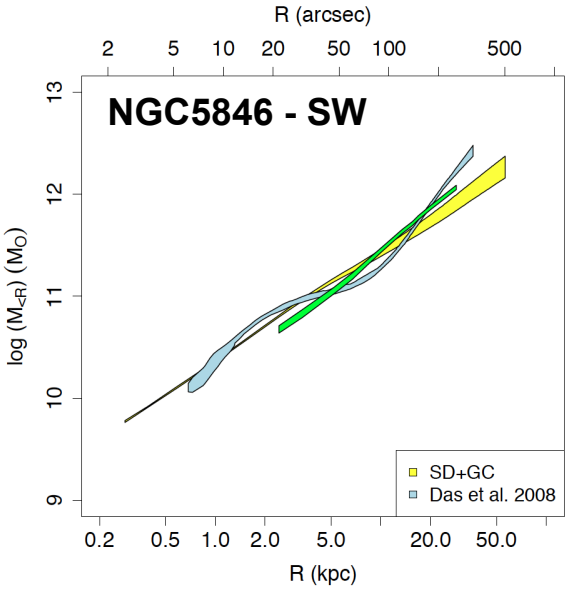
Mass Profiles (fixed abund.)



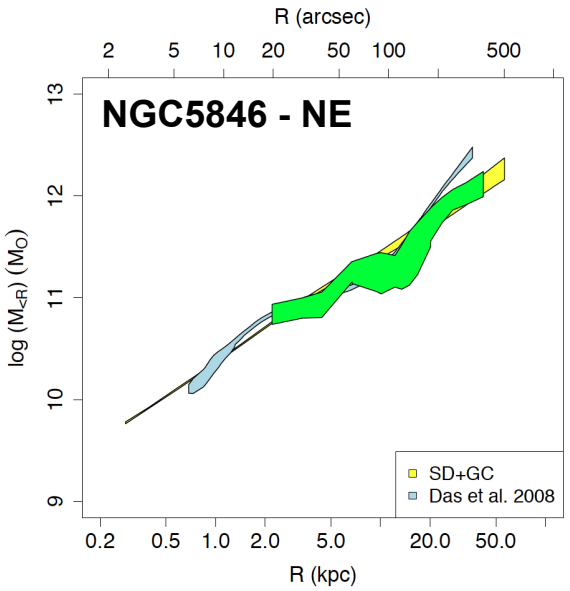


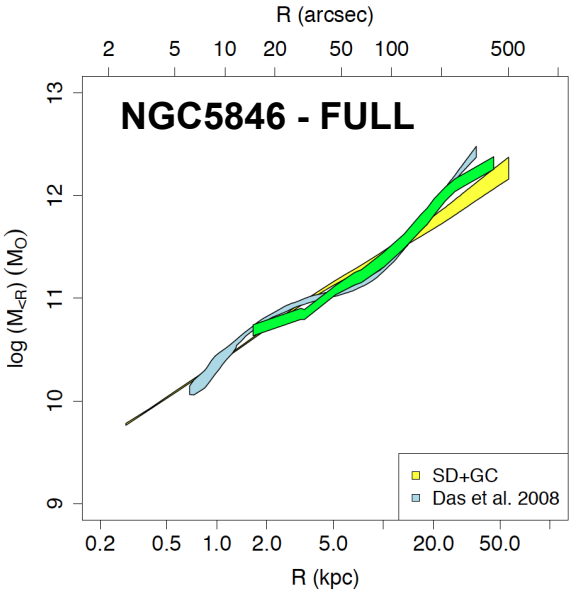


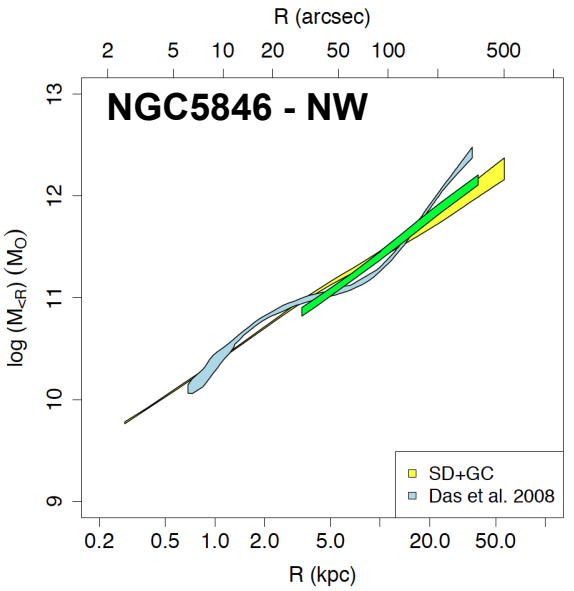


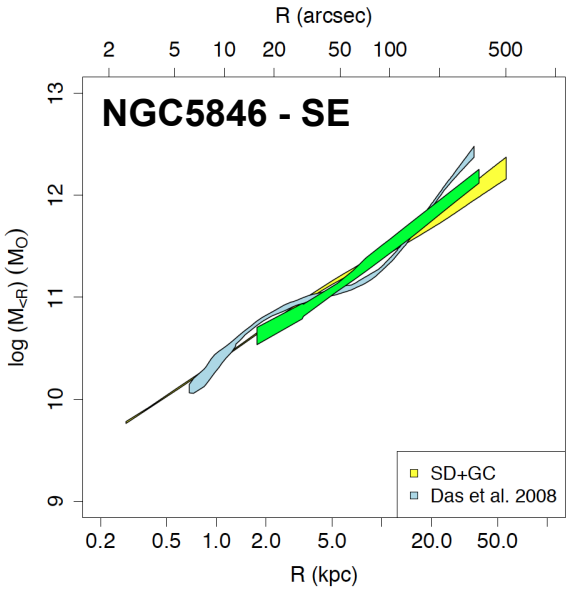


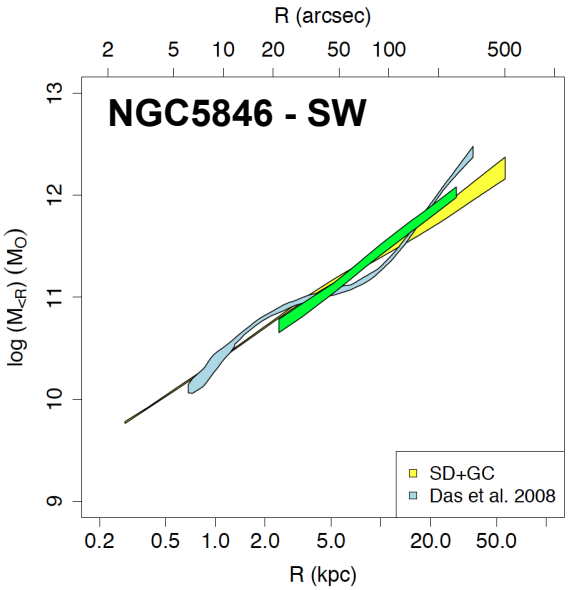
Mass Profiles (var. abund.)



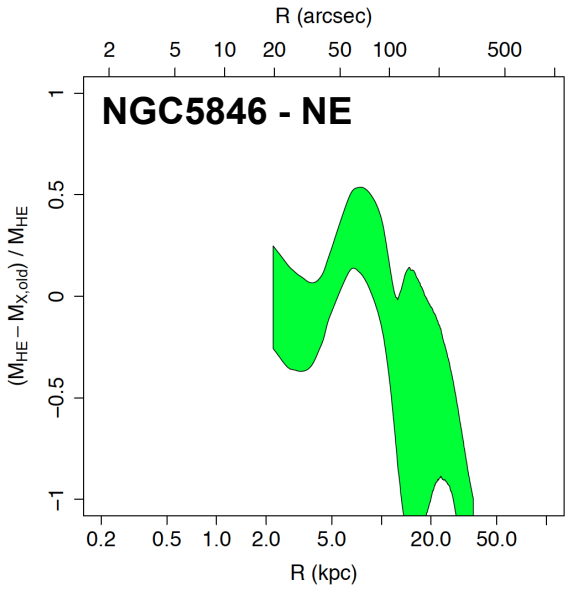


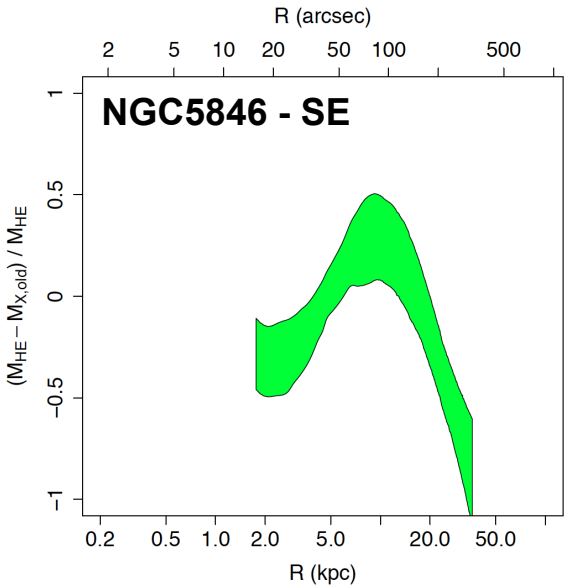


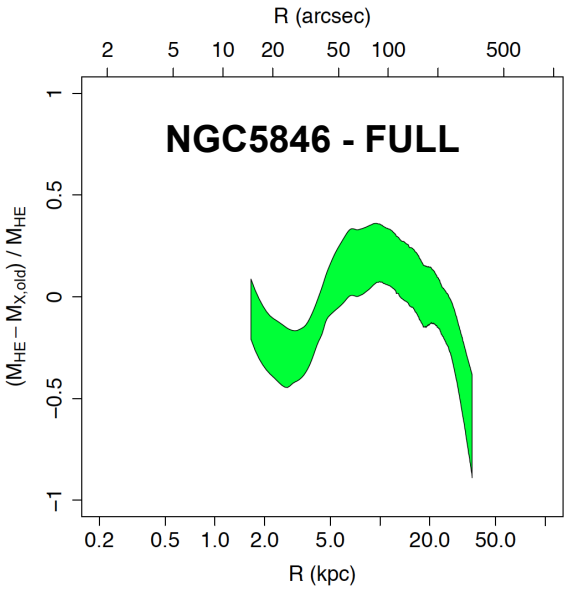


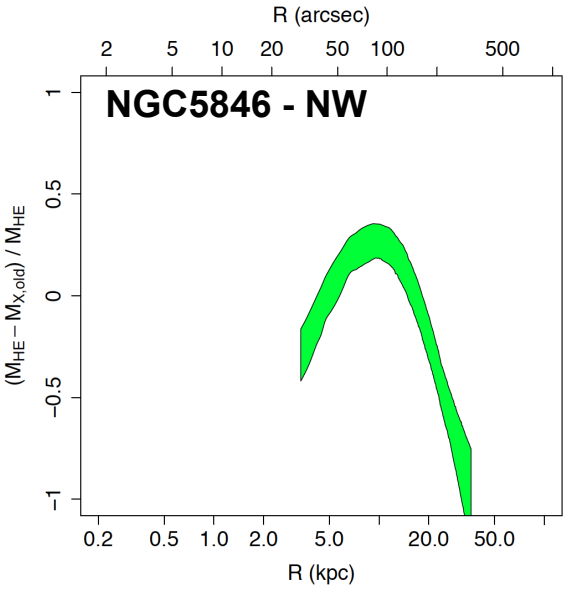


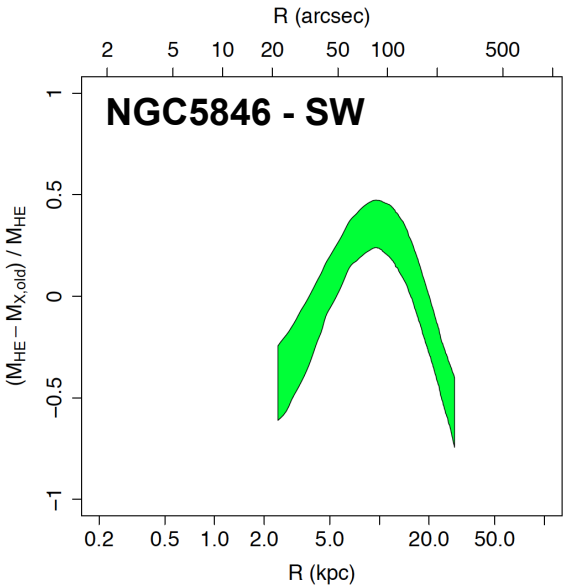
X-Ray Profile Comparison



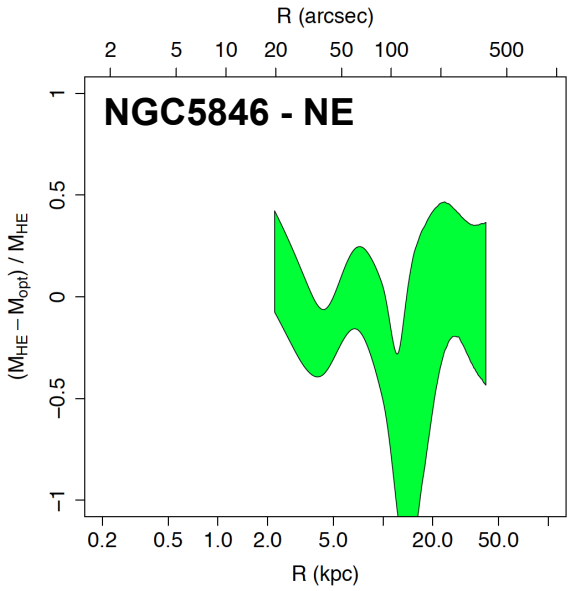


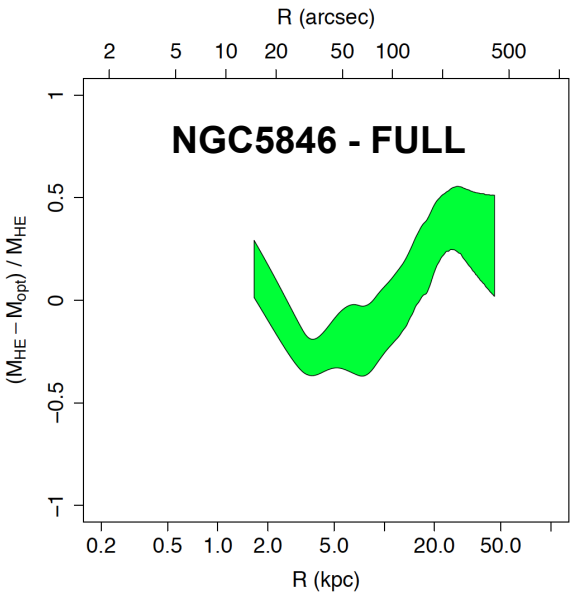


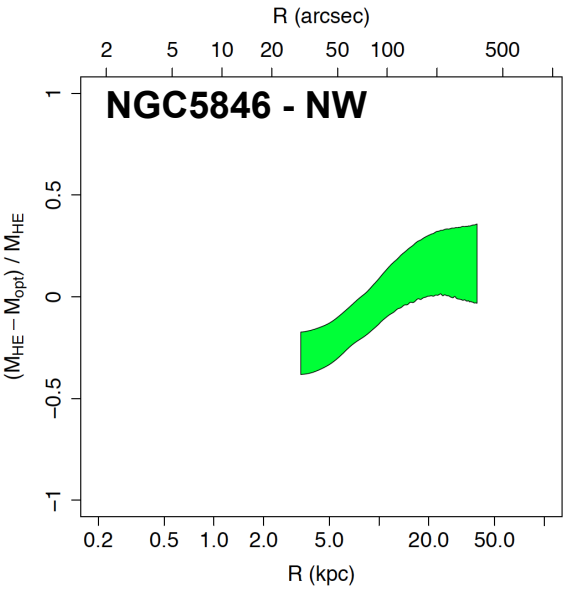


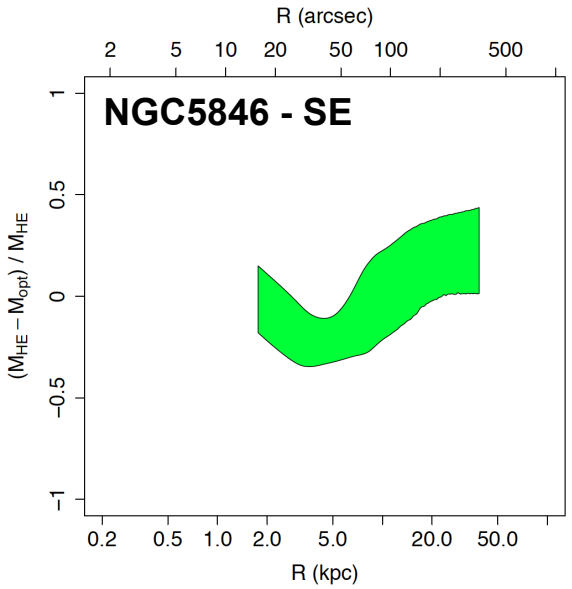


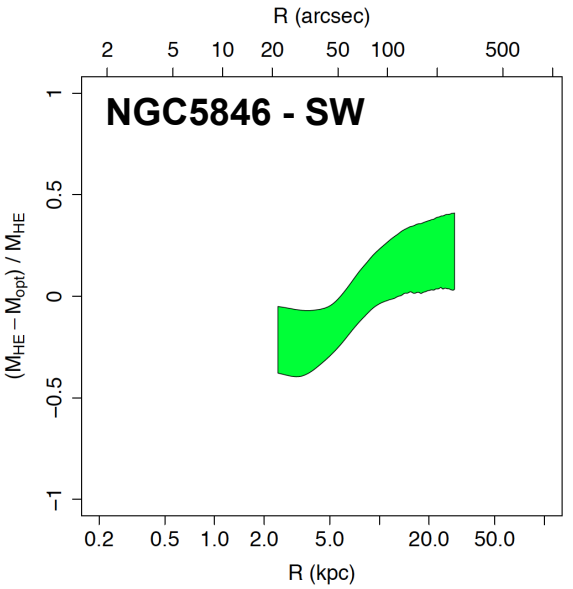
Optical Profile Comparison





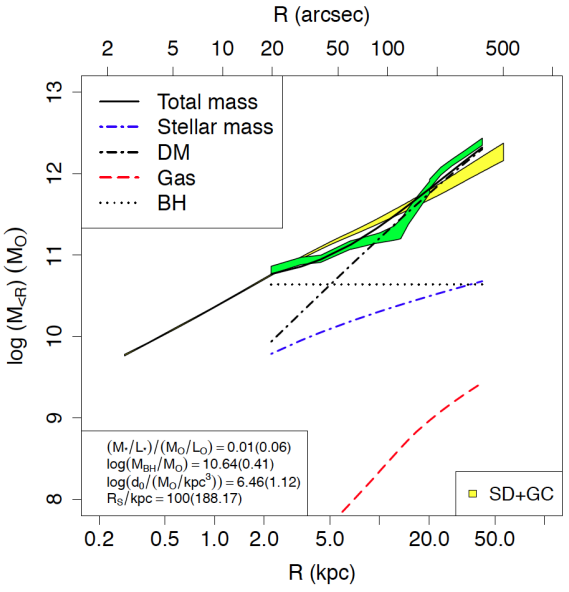




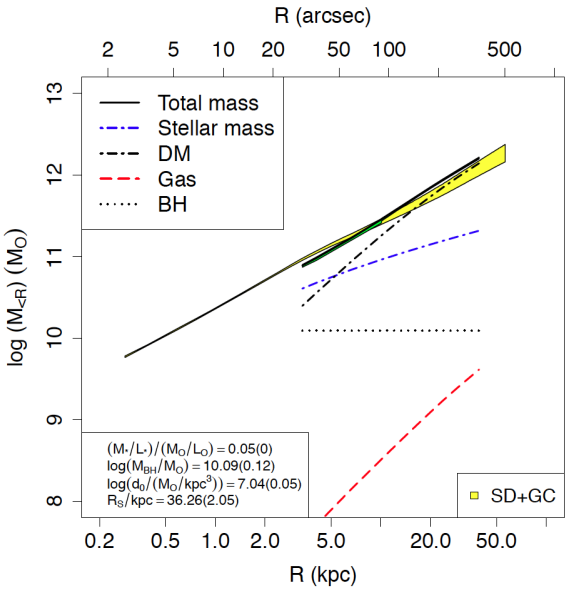


Mass Fits (fixed abund.)

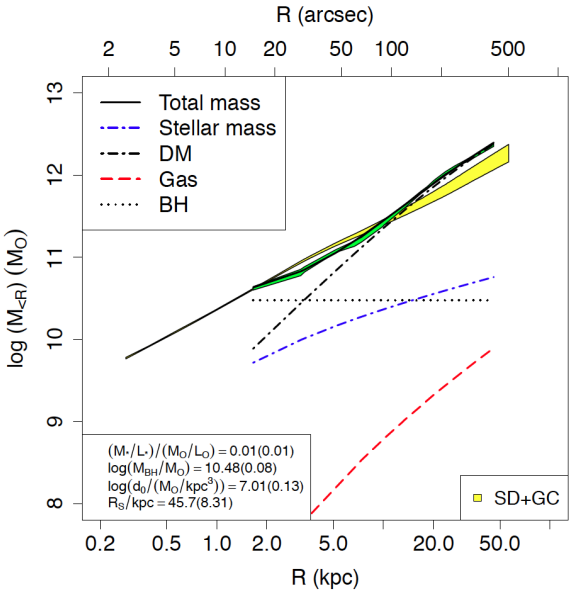
NGC5846 - NE



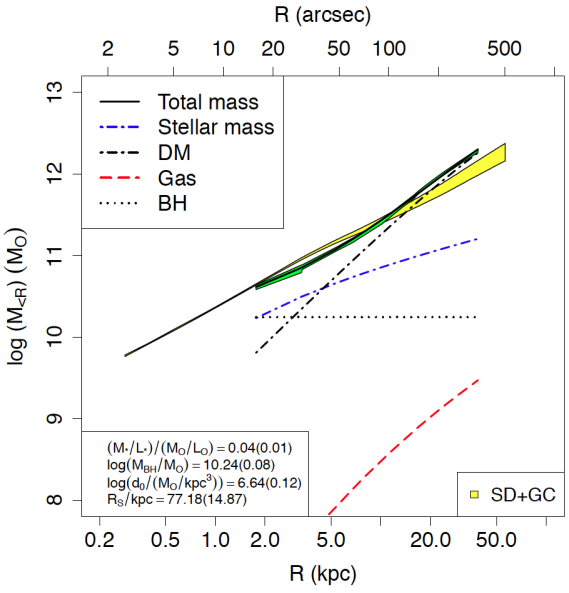
NGC5846 - NW



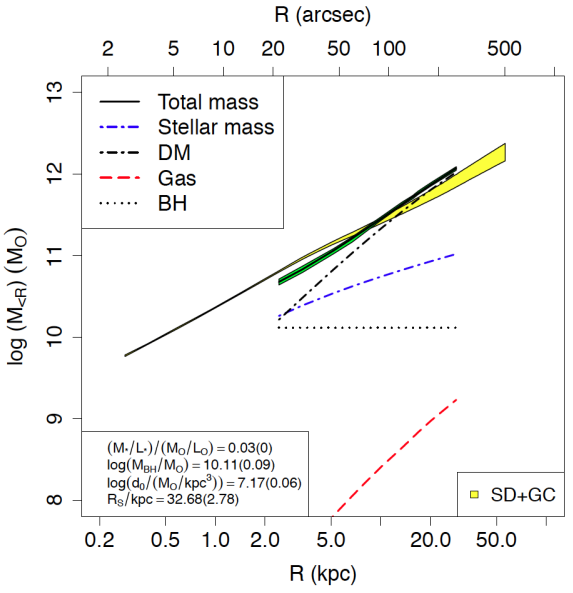
NGC5846 - FULL



NGC5846 - SE

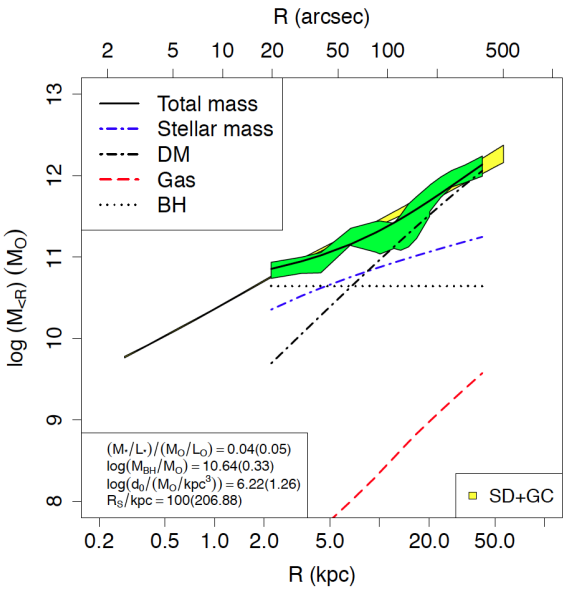


NGC5846 - SW

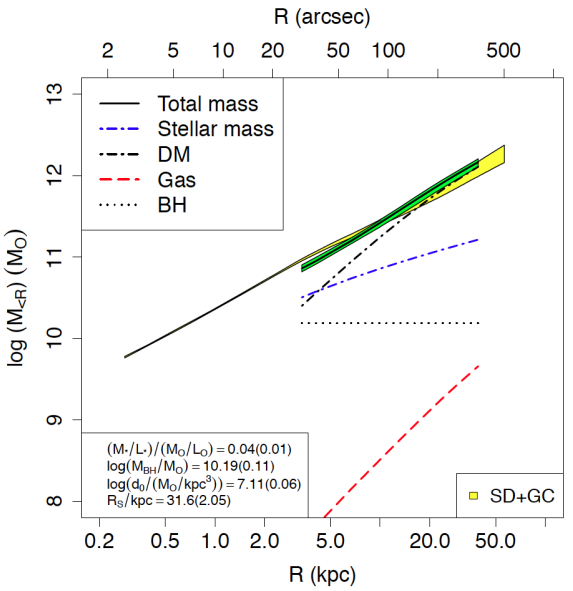


Mass Fits (var. abund.)

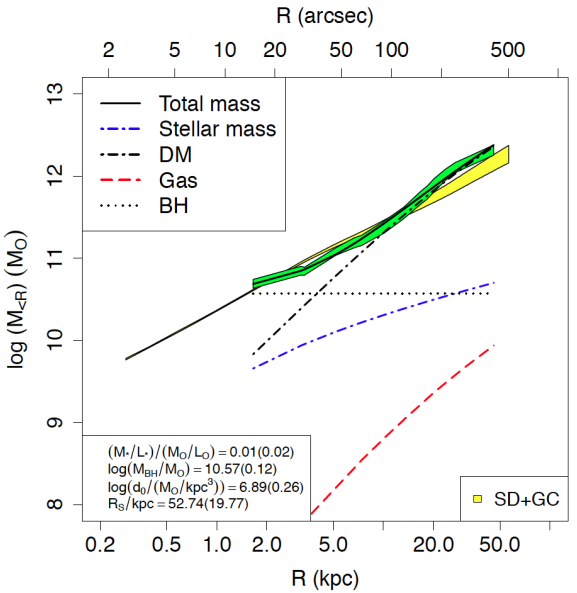
NGC5846 - NE



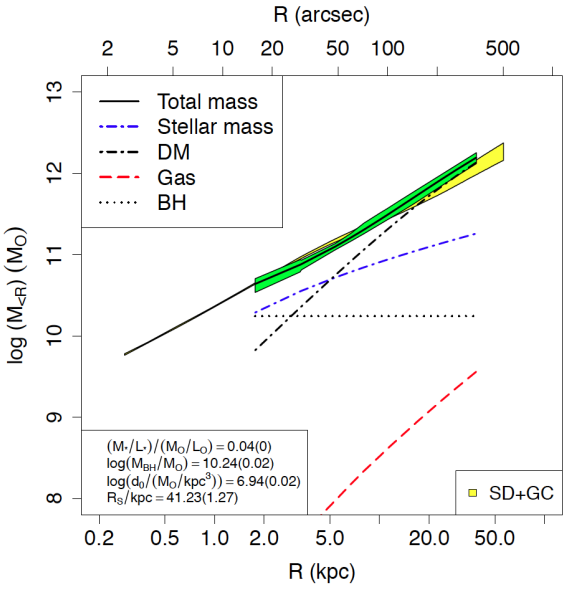
NGC5846 - NW



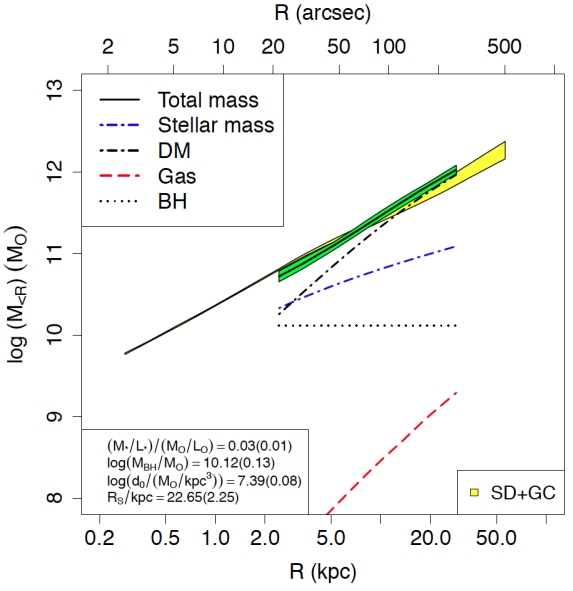
NGC5846 - FULL



NGC5846 - SE



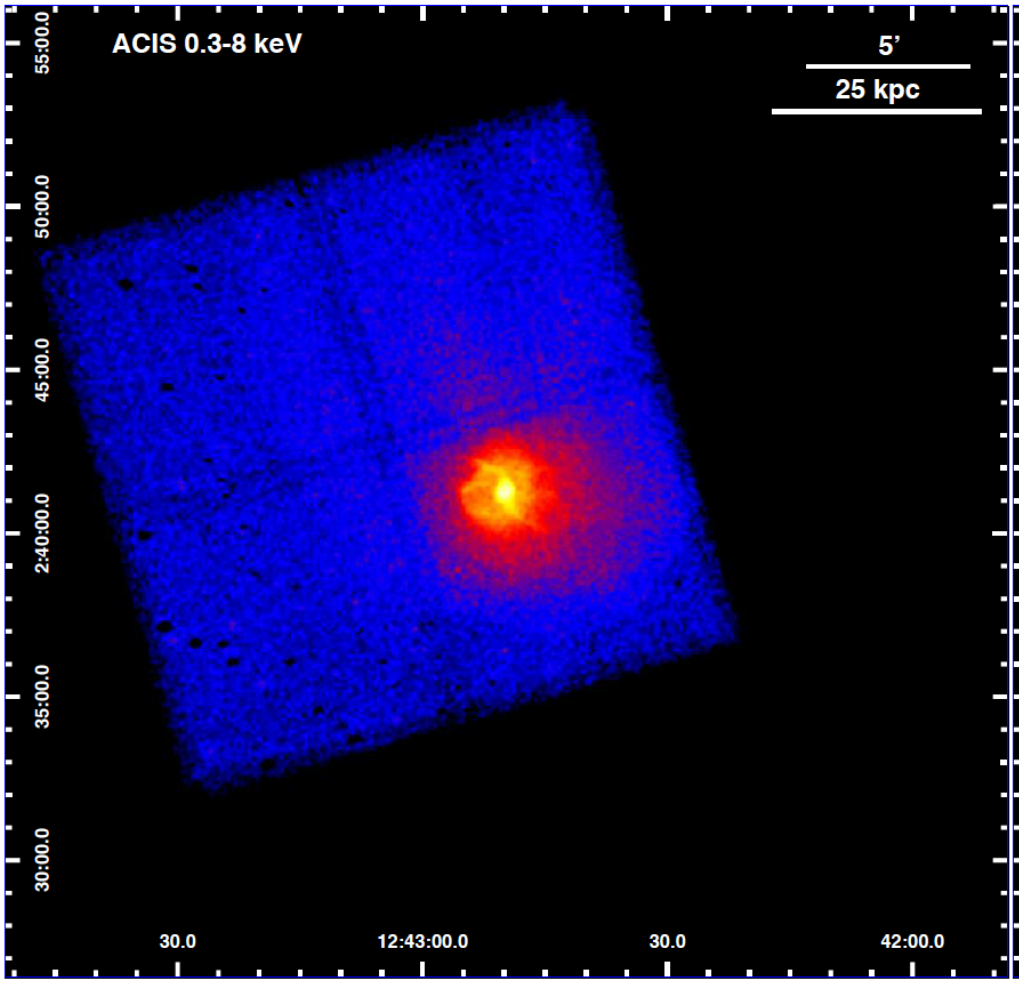
NGC5846 - SW

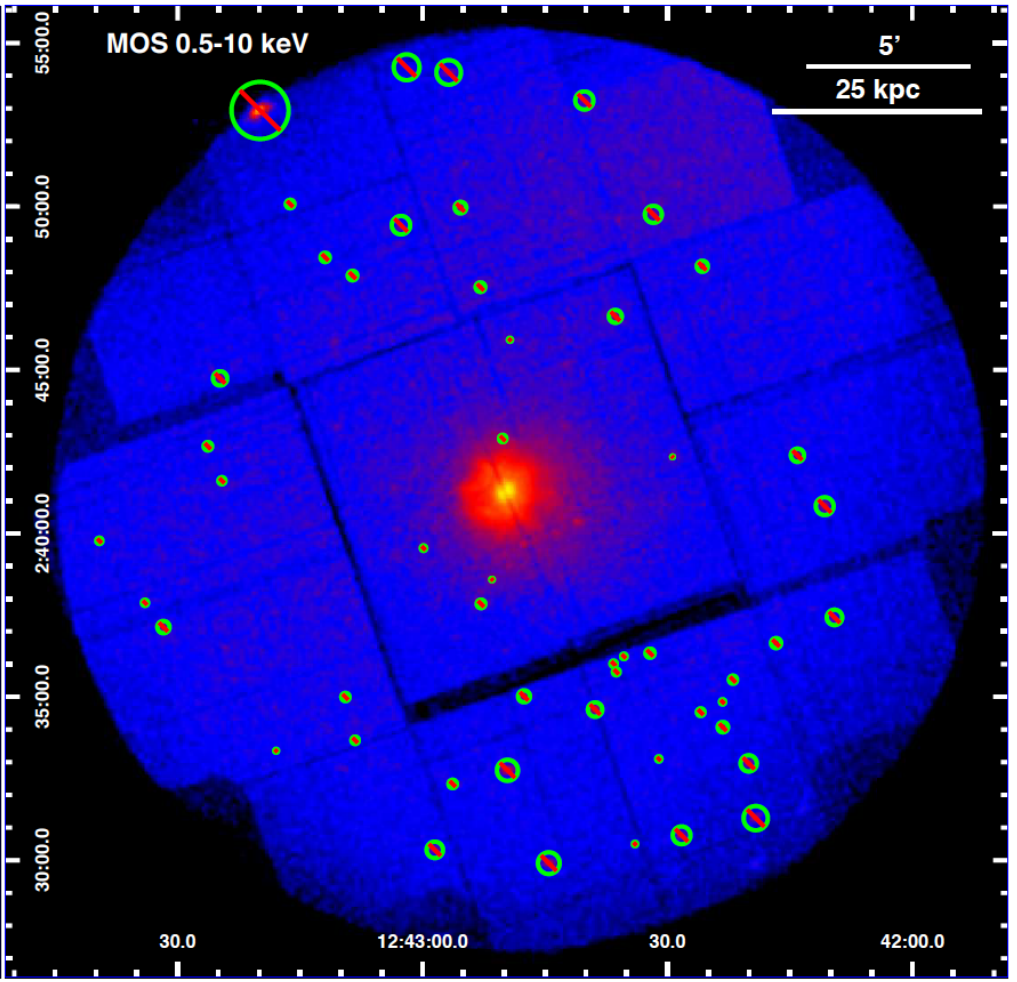


NGC 4636

- NGC 4636 is situated in a group at the edge of the Virgo cluster.
- ROSAT observations have shown the galaxy to have extended X-ray emission (Trinchieri et al. 1994).
- The central regions of the galaxy have been studied in detail using *Chandra* data by Jones et al. (2002), who identified the presence of shocks caused by recent AGN activity.
- The X-ray mass profile of the system has been studied by Loewenstein & Mushotzky (2003), who found an enclosed mass at 35 kpc of ~ 1.5 x 10^{12} M_O, strong evidence for a massive dark matter halo in this system.
- Analysis of *Chandra* data (~75 ks) by Johnson et al. (2009) shown discrepancies between the X-ray an GC mass profiles at radii smaller than 10 kpc and larger than 30 kpc (gas inflow, non-thermal pressure).

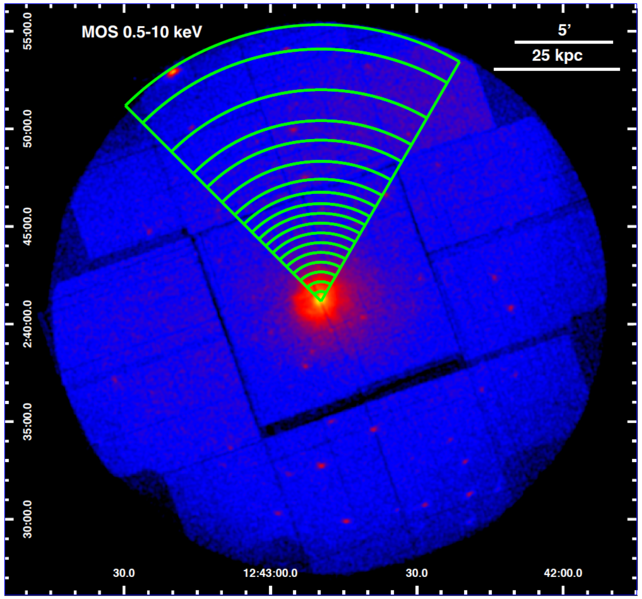
Merged MOS data

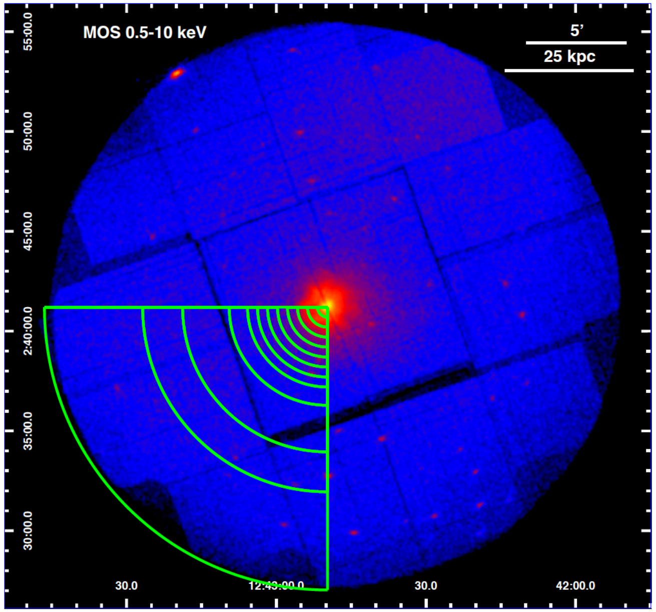


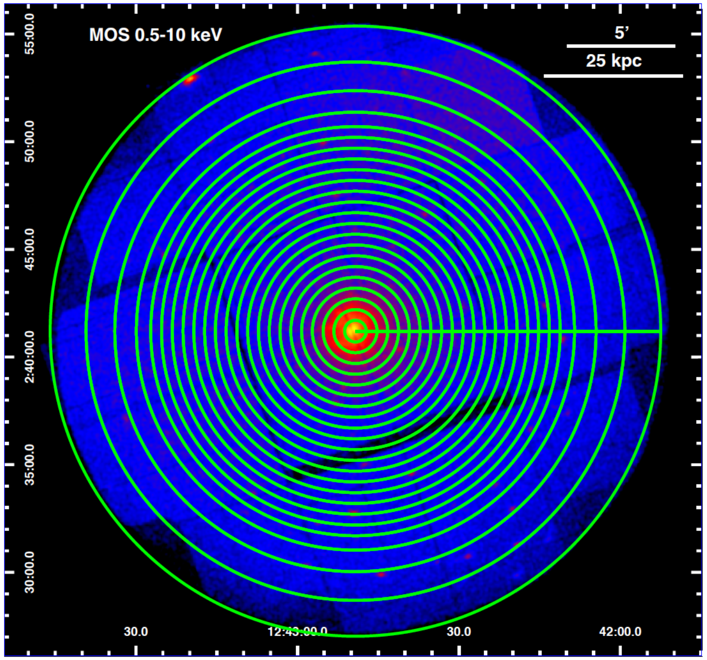


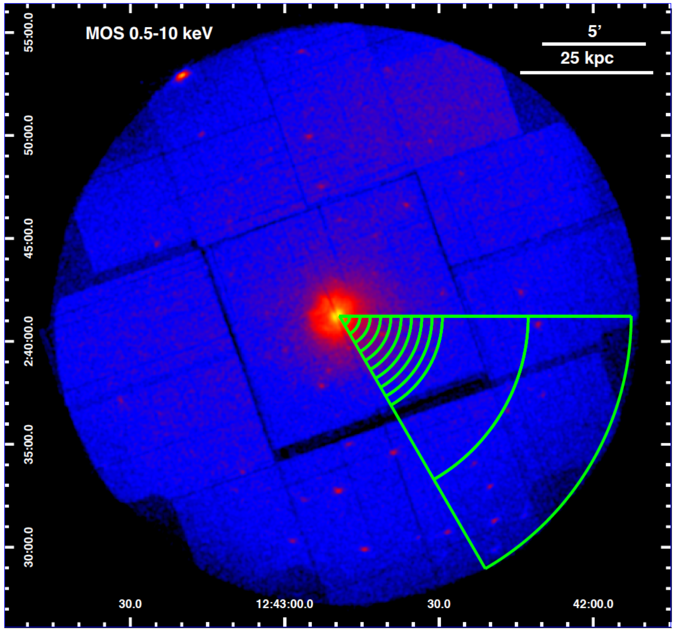
Total MOS exp. ~ 65 ks + total ACIS exp. ~ 210 ks

Extraction regions

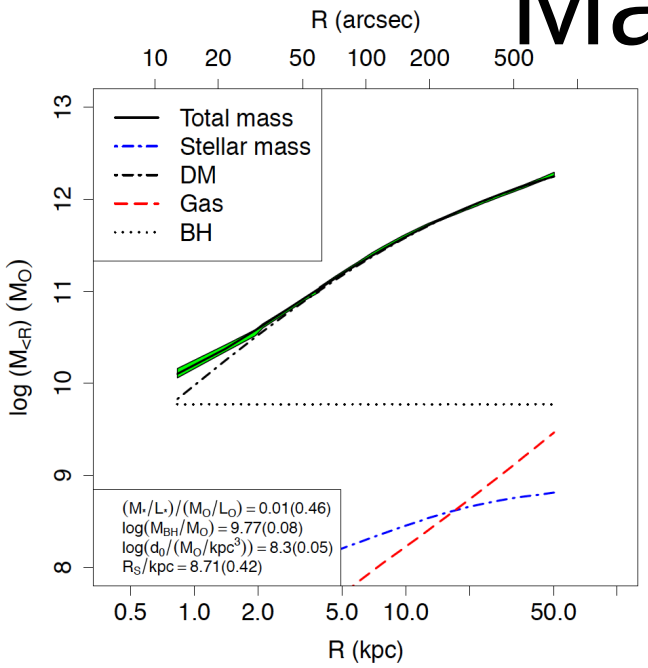


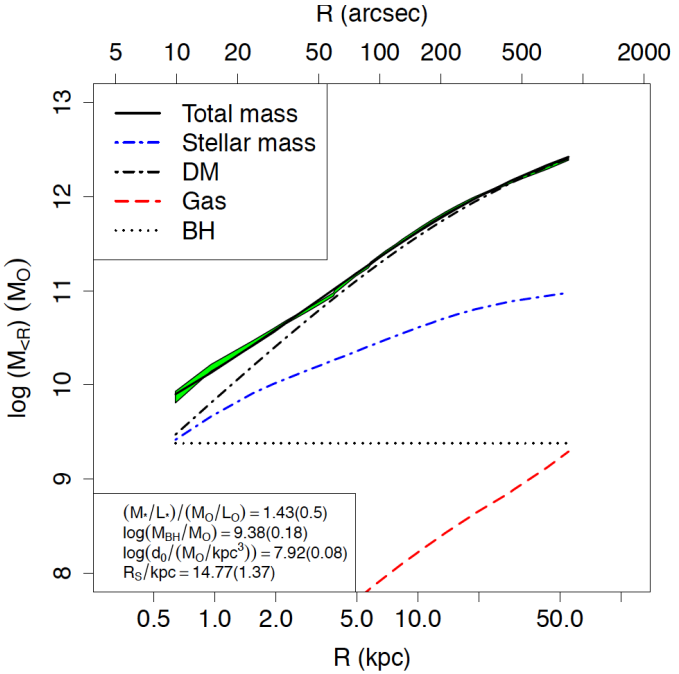


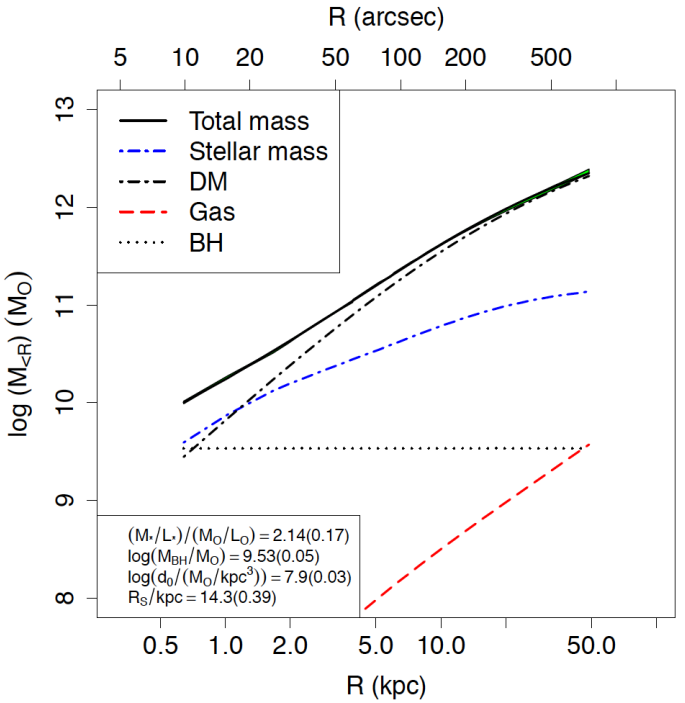


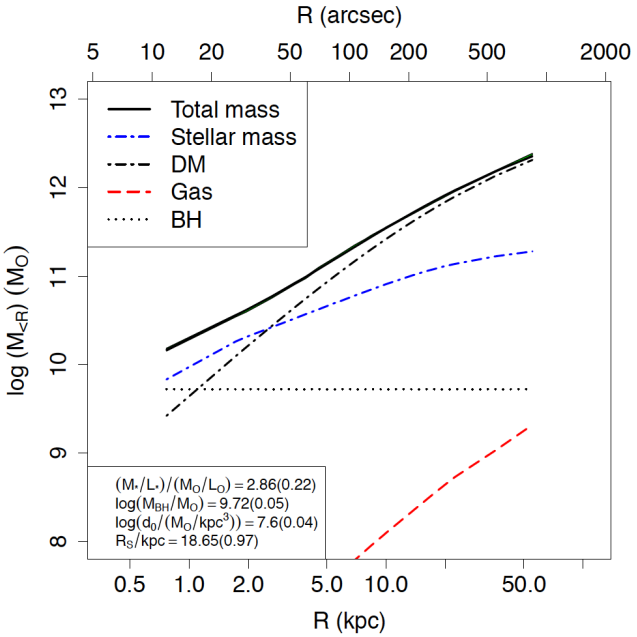


Mass Profiles (prel.)



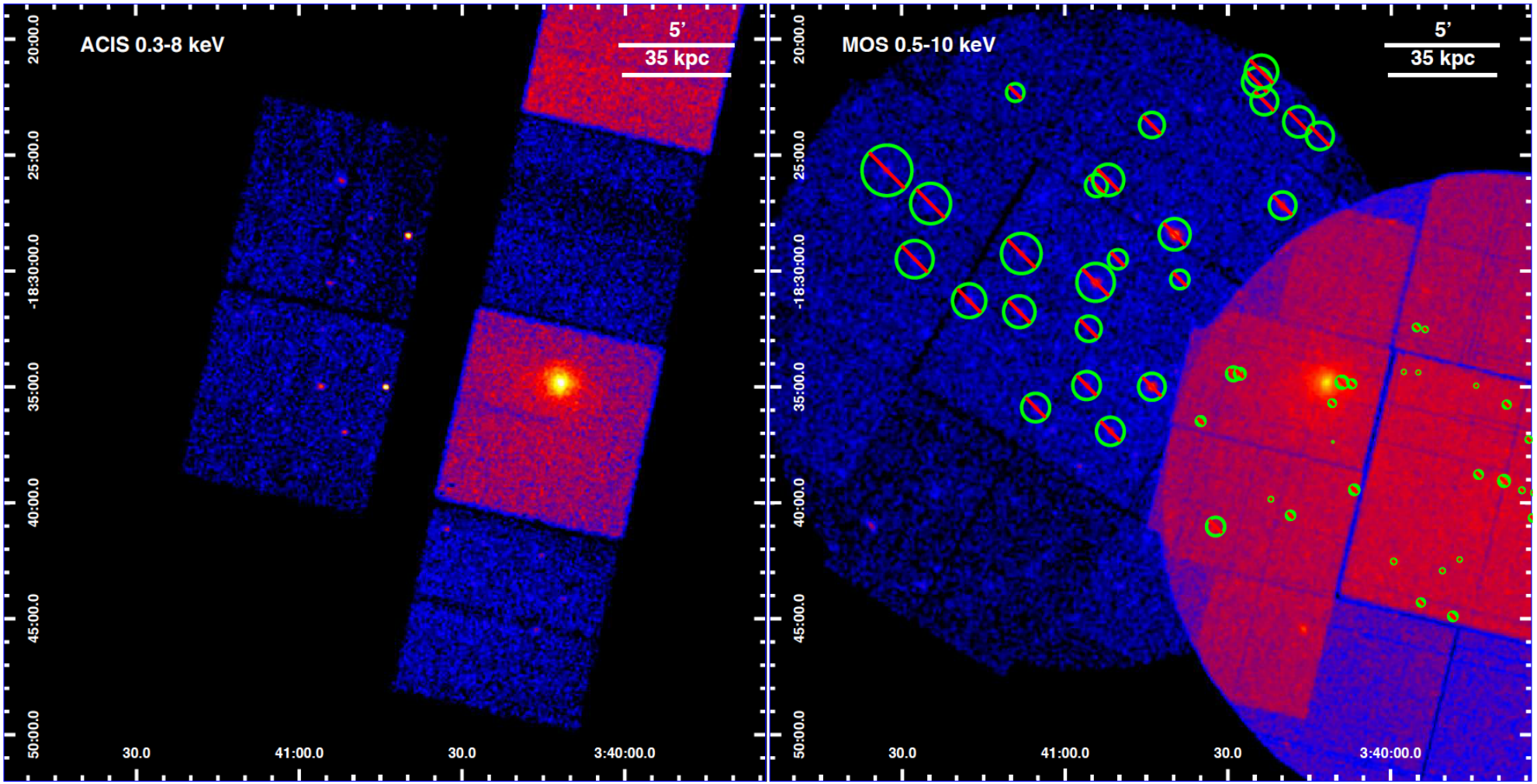






Comparison with optical data (Park et al. 2012, Schuberth et al. 2012).

NGC1407



Total MOS exp. ~ 70 ks + total ACIS exp. ~ 50 ks (Su et al. 2014)