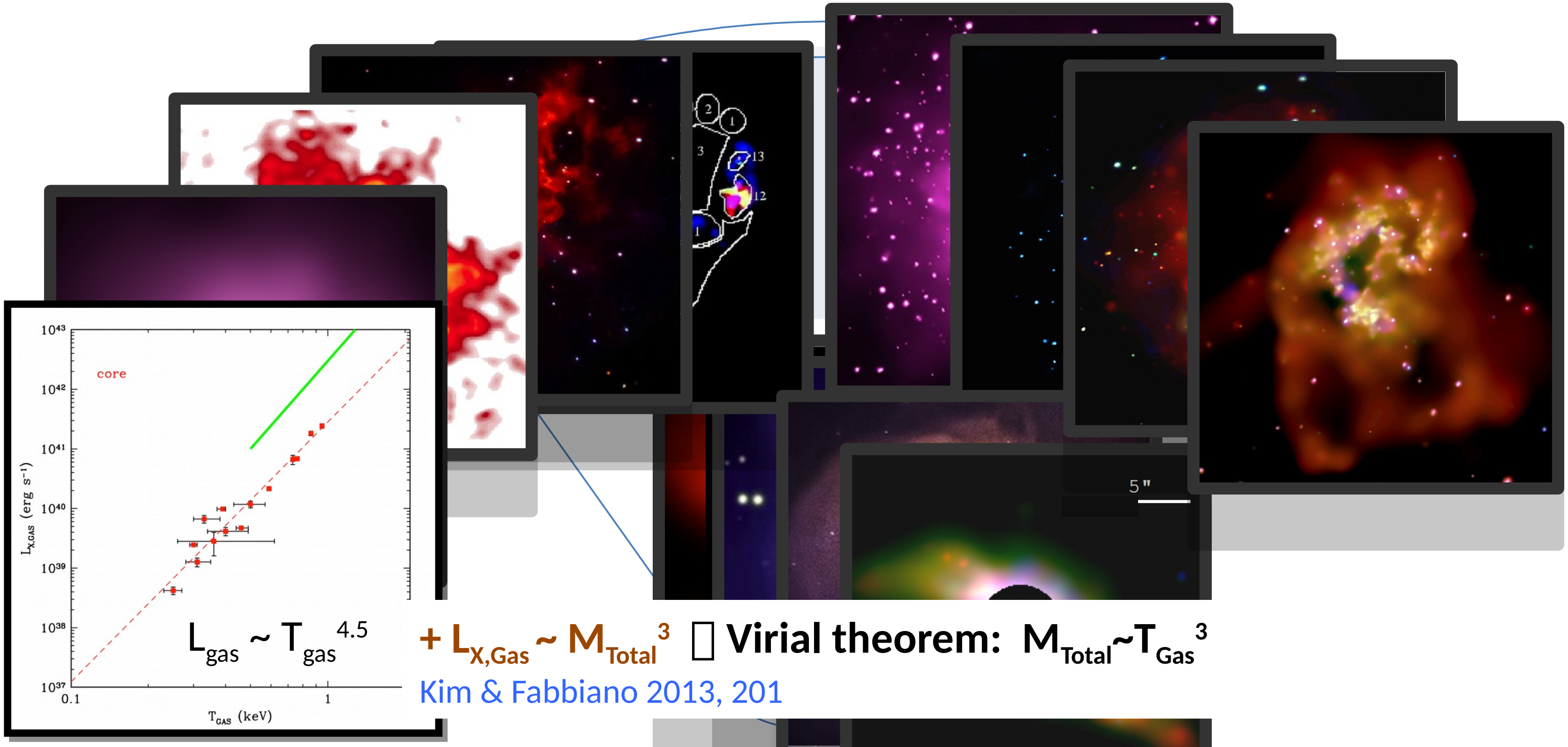
Chandra's Contributions to Galaxy Evolution

G. Fabbiano

Thanks to all, who have worked in this field

3 Areas of Chandra Observations Contribute to Galaxy Evolution



$L_{gas} \sim T_{gas}^{4.5}$ + $L_{X,Gas} \sim M_{Total}^{3}$ ⇒ **Virial theorem: $M_{Total} \sim T_{Gas}^{3}$**

Kim & Fabbiano 2013, 201

Galaxy evolution:

stellar, merging, chemical, outflow, equilibrium/mass

BH evolution:

stellar BH range, IMBH, BHs in obscured and merging galaxies

Feedback:

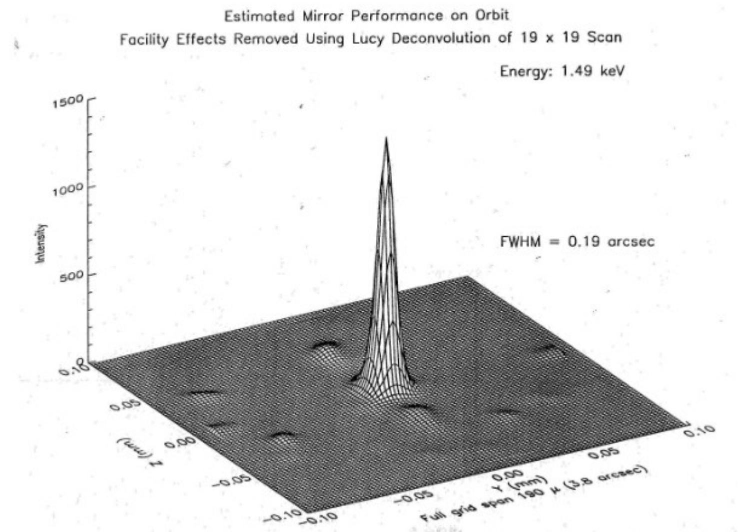
AGN: *Radio-mode* (halo cavities); *Quasar-mode* (interaction with ISM)

Stellar: XRB, SNR

Merging: energy & momentum transfer to hot halos

Chandra is unique

- **Angular resolution**
  - Sensitivity
  - Resolving confused regions
  - Resolving complex regions



+

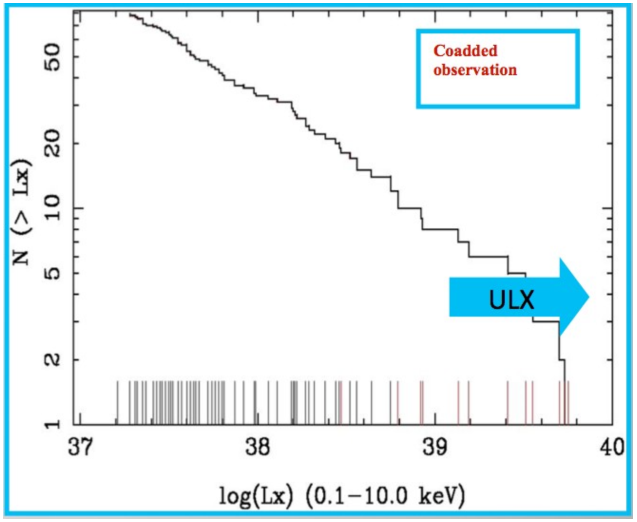
- **Spectral capabilities**
  - Characterization of sources and emission regions
  - Physical & chemical parameters

3 examples of the effect of these capabilities

1. Chandra's Sensitivity: going deep

The Hunt for IMBHs (10^{3-6} Msol)

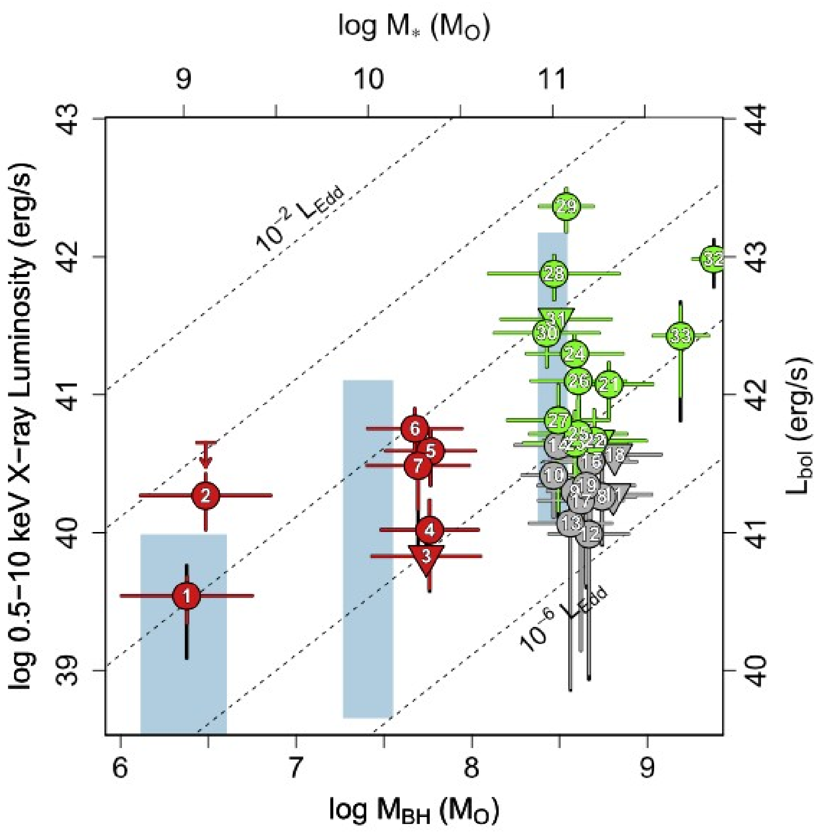
- **Chandra XRB population studies show that ULXs ($L_X > 10^{39}$ erg/s)** are not **IMBHs**



XLF of the HMXB population in a star-forming galaxy: The Antennae (Zezas et al 2007)

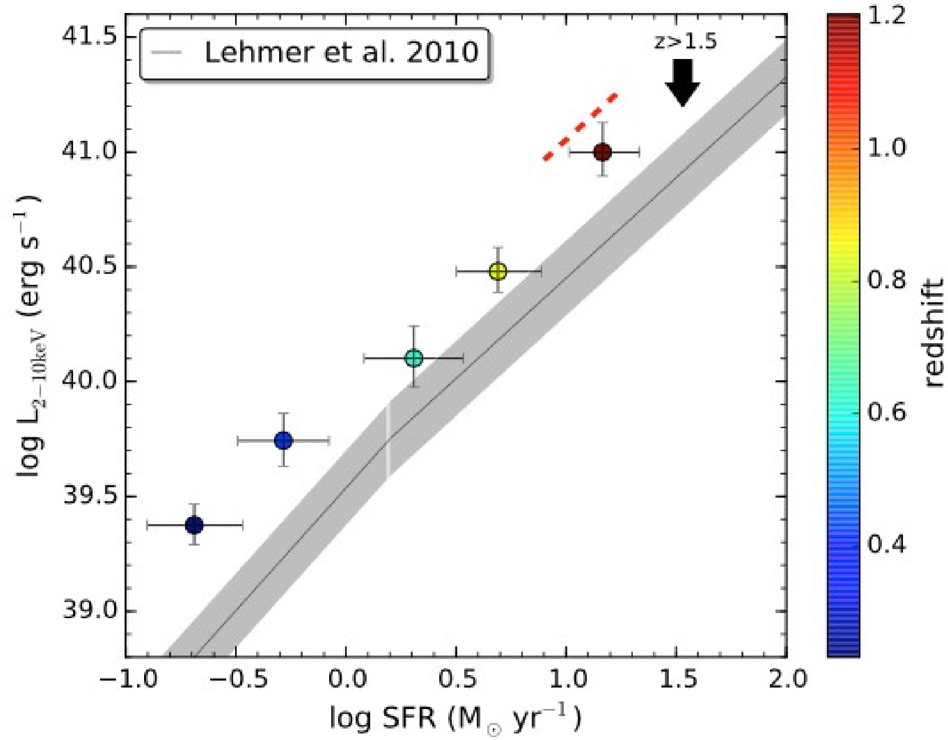
- **Are there IMBHs in dwarf galaxy nuclei?**
- **Scaling relations from the study of nearby galaxies** can be used to derive non-XRB X-ray emission of galaxies (Nuclei and Hot Halos)
- **Application to stacking of COSMOS survey data provide evidence of nuclear IMBHs**

Stacking Analysis of the COSMOS survey:
low-luminosity AGN emission from lower-mass SMBH / IMBH in Early-type Galaxies (ETG) up to z=1.5



6388 stacked – LMXB subtracted - ETG (Paggi et al 2016):
results compare well with Volonteri (2011) models of accretion of stellar outgassing onto nuclear SMBH

Stacking Analysis of the COSMOS survey:
low-luminosity AGN emission from IMBH in dwarf ($M_* < 3 \times 10^9$ Msol) star-forming galaxies (DSFG)

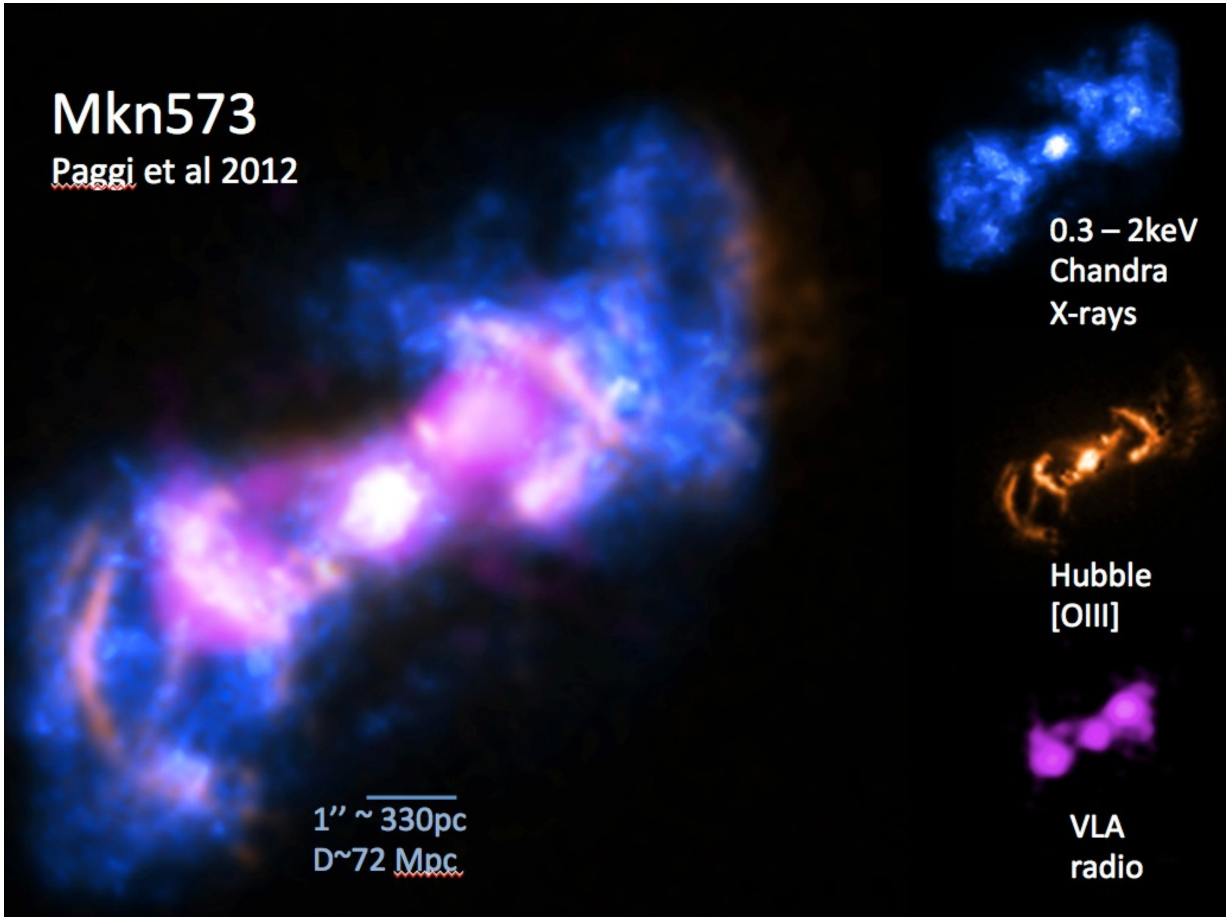


50,000 stacked DSFG compared with XRB emission (Mezcua et al 2016)
Luminosities consistent with sub- Eddington accreting rates of $\sim 10^{-3}$ and BH masses $1–9 \times 10^5$ Msol

2. Chandra's Sub-Arcsec Spatial Resolution

AGN – galaxy interaction

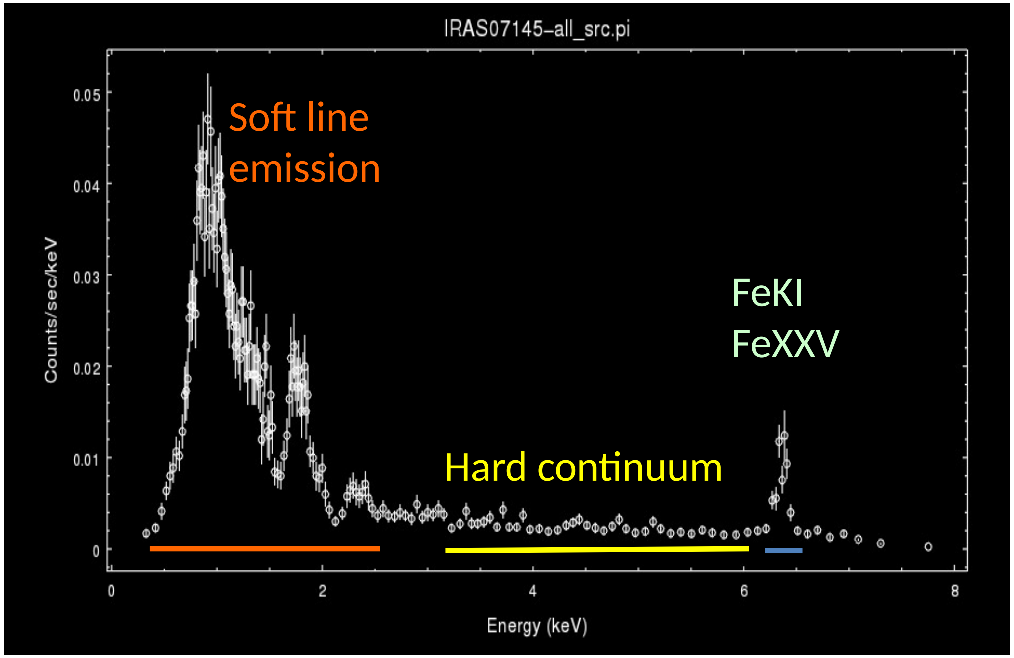
- **Resolving ~70 - 100 pc features in circum-nuclear regions** matching HST and radio observations



3. Chandra's Joint Spatial & Spectral Resolution

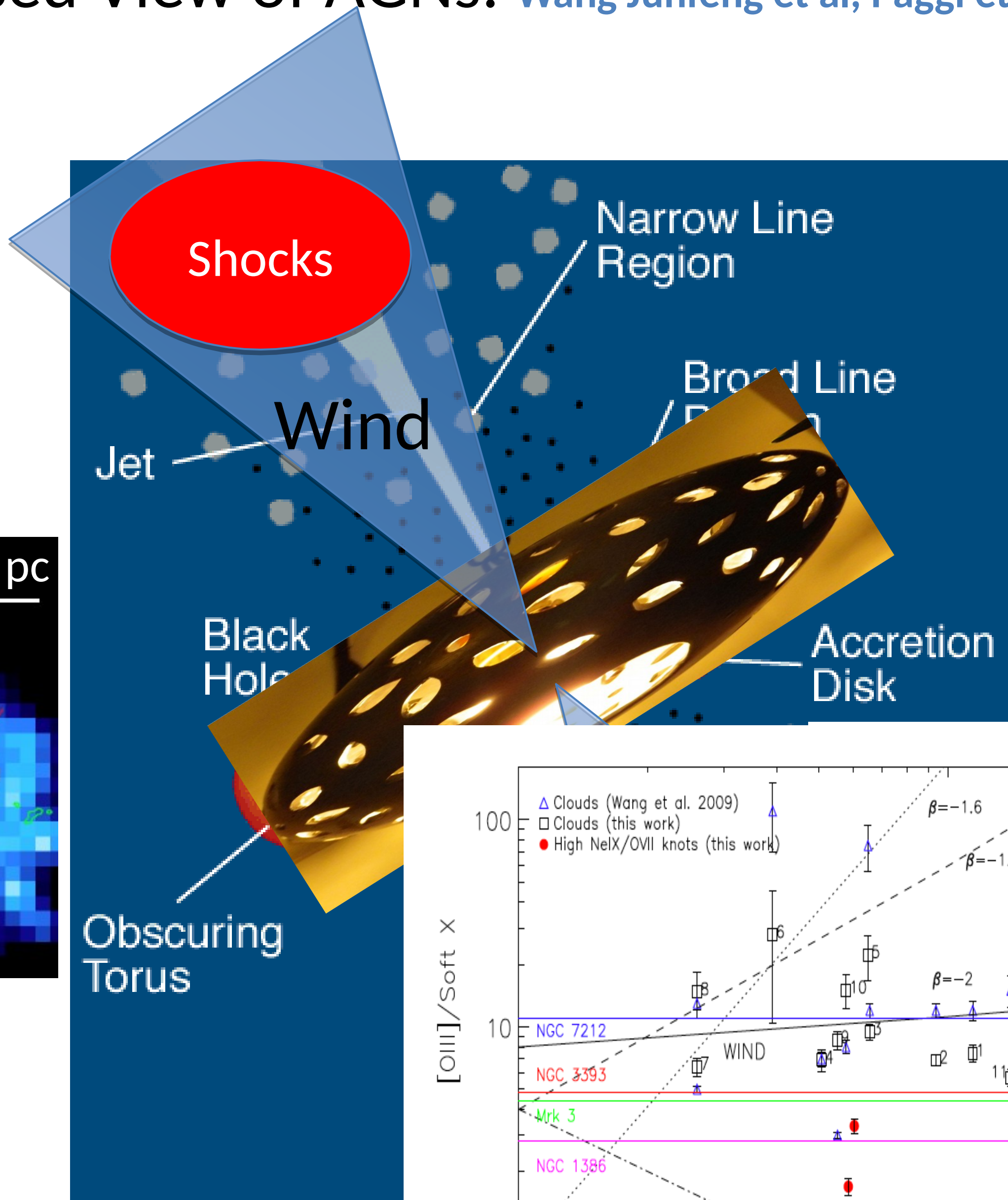
AGN – galaxy interaction

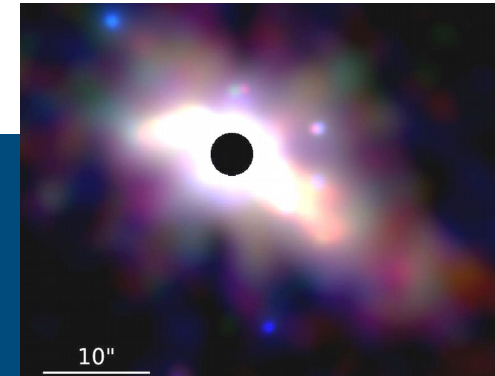
- **Imaging in spectral bands shows different X-ray lines in clouds** and identifies regions of photo and collisional ionization

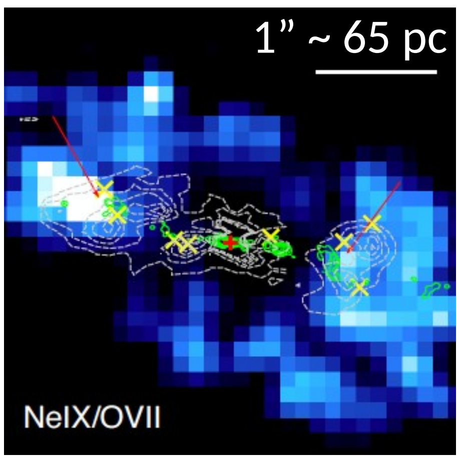


- **These high resolution studies are significantly modifying our mental picture of AGNs**

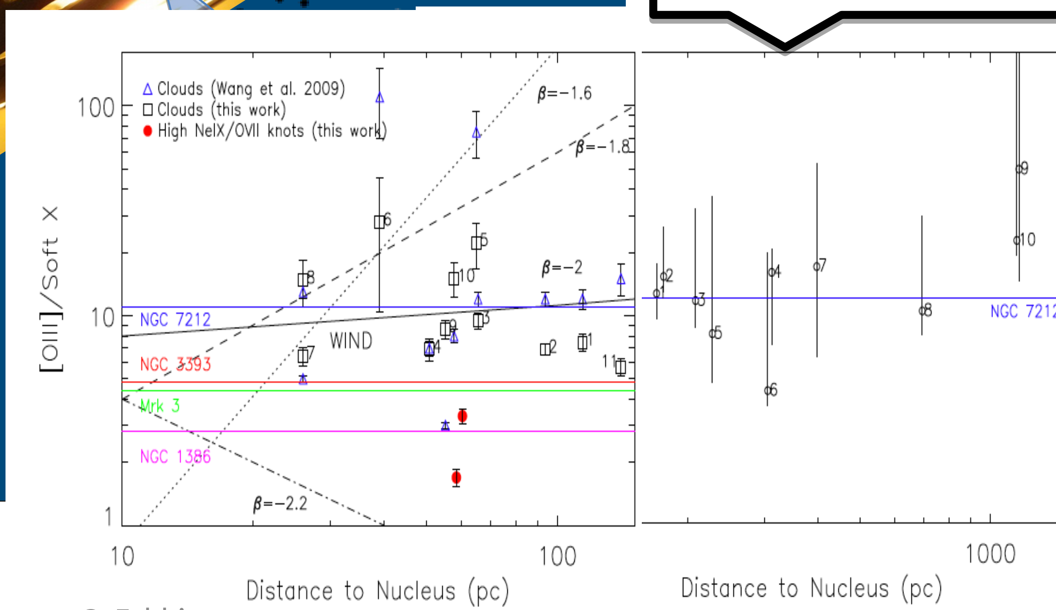
A Revised View of AGNs: Wang Junfeng et al, Paggi et al, Maksym et al







Constant
Ionization Parameter
n ~ r $^{-2}$

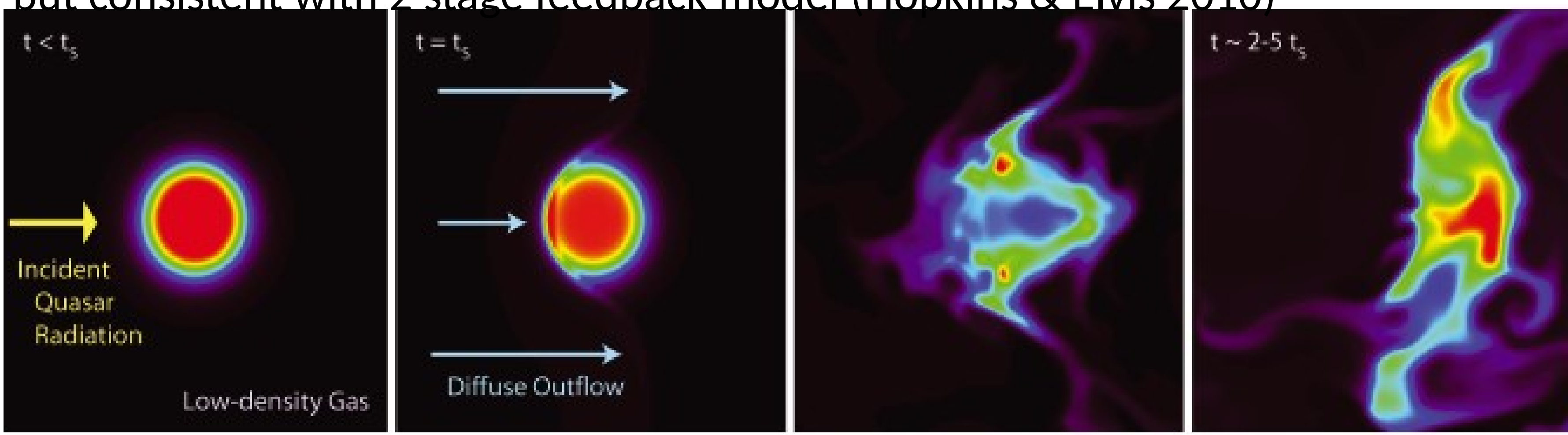


Implications for Feedback from cloud modelling

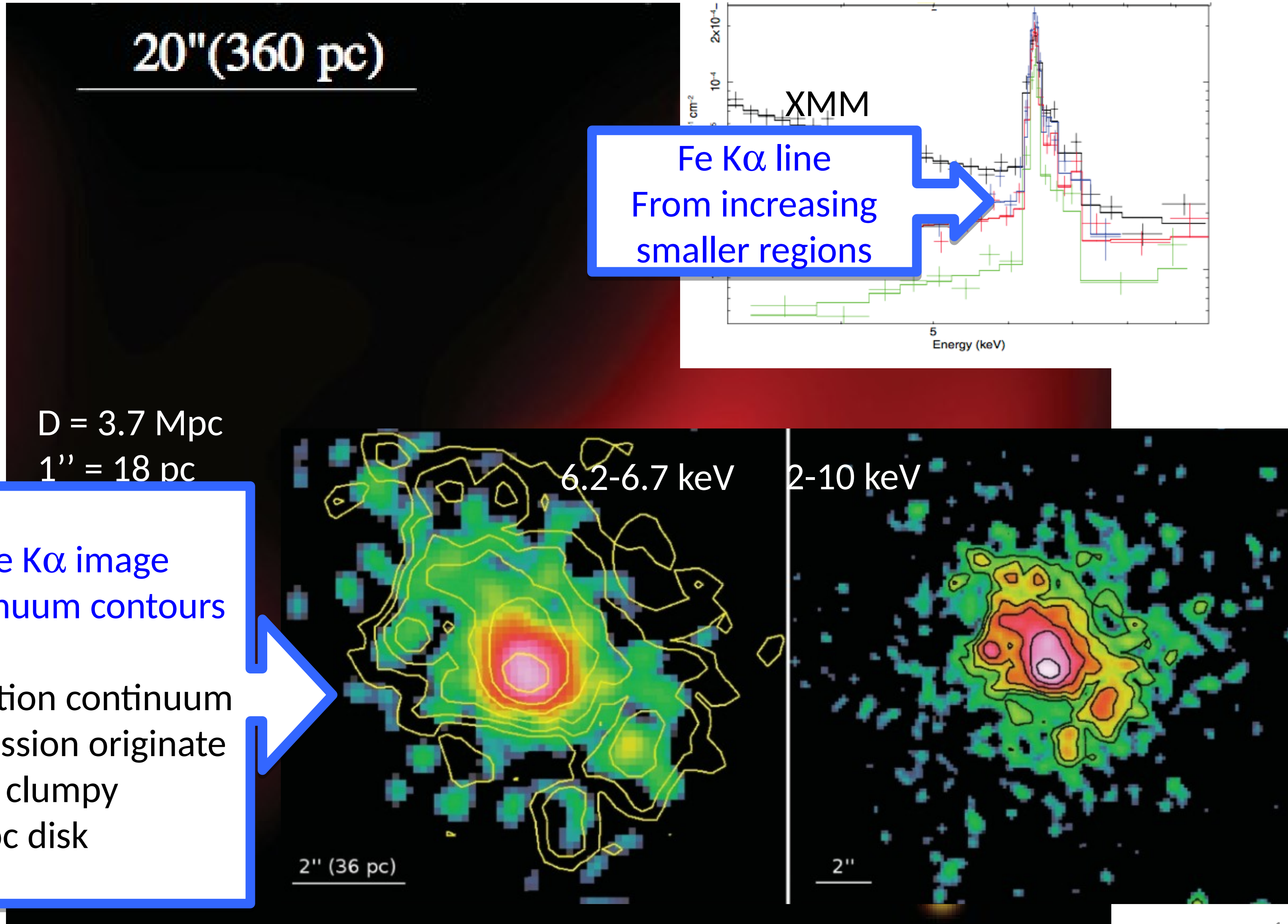
Wang et al 2011c

From CLOUDY photoionization modeling of clouds 1 and 2 in NGC4151
Log n_H = 2.9 +/- 0.5 cm^{-3}

□ dM/dt ~ 2.1 $M_{\odot} yr^{-1}$ comparable with NIR (Storchi-Bergmann et al 2010)
➔$L_{outflow}$ = ½ dM/dt v^2 = 1.7×10^{41} erg s^{-1} ~ 0.2% of accretion power
<< than most feedback models
but consistent with 2 stage feedback model (Hopkins & Elvis 2010)



Resolving Hard Continuum and Fe Kα emission in obscured AGN: NGC4945 - Marinucci et al 2012



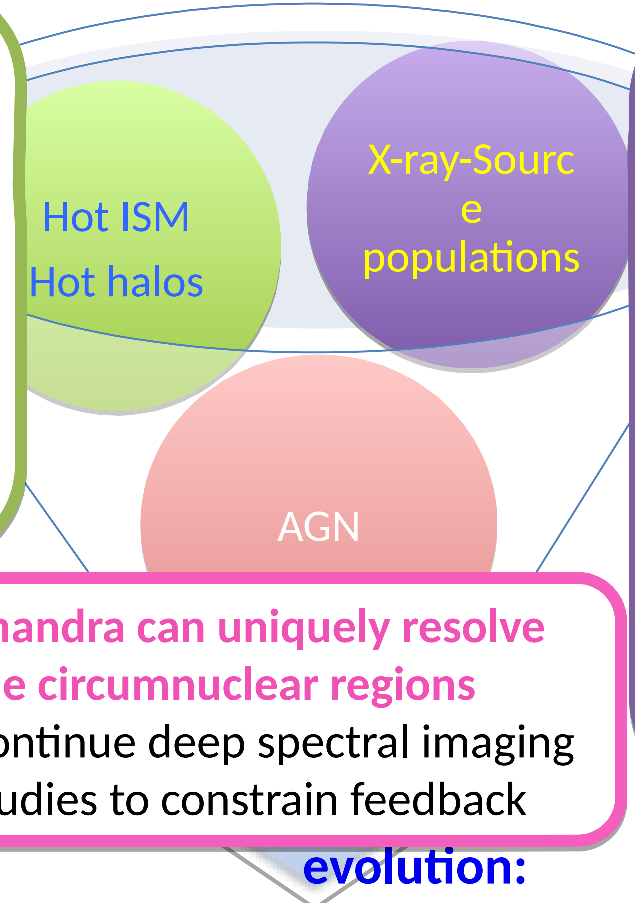
Fe Kα line
From increasing
smaller regions

Chandra Fe Kα image
Hard continuum contours

Cold reflection continuum and Fe emission originate from same clumpy ~200x100pc disk

Next 10 years? Exploit sub-arcsec resolution!

- **Only a few in-depth halo study exist**
- Deep observations are needed for spatially resolved spectral studies
- Chandra's resolution needed to 'clean' the halos and avoid spectral confusion



- **We have a basic understanding of the XLFs**
- 'Local' detailed relation with the underlying stellar population (age, metallicity)
- Stacking studies with z and type to explore XLF/XRB evolution
- 2D LMXB distributions in ETG as indicators of merging history (D'Abrusco et al)

- **Chandra can uniquely resolve the circumnuclear regions**
- Continue deep spectral imaging studies to constrain feedback

Galaxy evolution:
stellar, chemical, infall /outflow, equilibrium/mass, merging

BH evolution:
stellar BH range, IMBH, BHs in obscured and merging galaxies

Feedback:
AGN: *Radio-mode* (halo cavities); *Quasar-mode* (interaction with ISM)
Stellar: XRB, SNR
Merging: energy & momentum transfer to hot halos

Next 10 yrs?

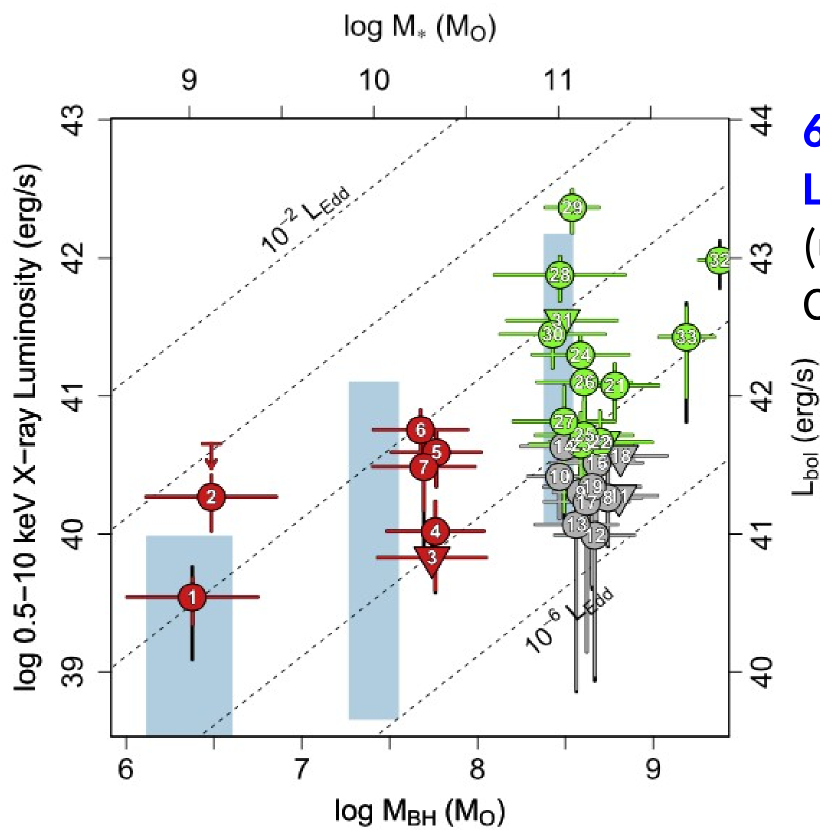
What is needed to support the observations?

- Prioritize soft-band observations (ACIS soft band response will degrade)
- Additional Calibrations (see M. Karovska's poster)
  - 2D HRMA + Instrument calibrations of the PSF for sub-pixel work
    - » With energy up to the FeK band
    - » Include 0^{th} order of grating
  - HRC (soft) + ACIS cross-calibration
- The Chandra Source Catalog will provide increasing larger data sets
  - Increase emphasis on multi-wavelength studies
  - Tools: advanced fitting, data mining
- **Work to make the X-Ray Surveyor a reality!**

The End

Stacking Analysis of the COSMOS survey:
low-luminosity AGN emission from lower-mass SMBH / IMBH in Early-type Galaxies (ETG)

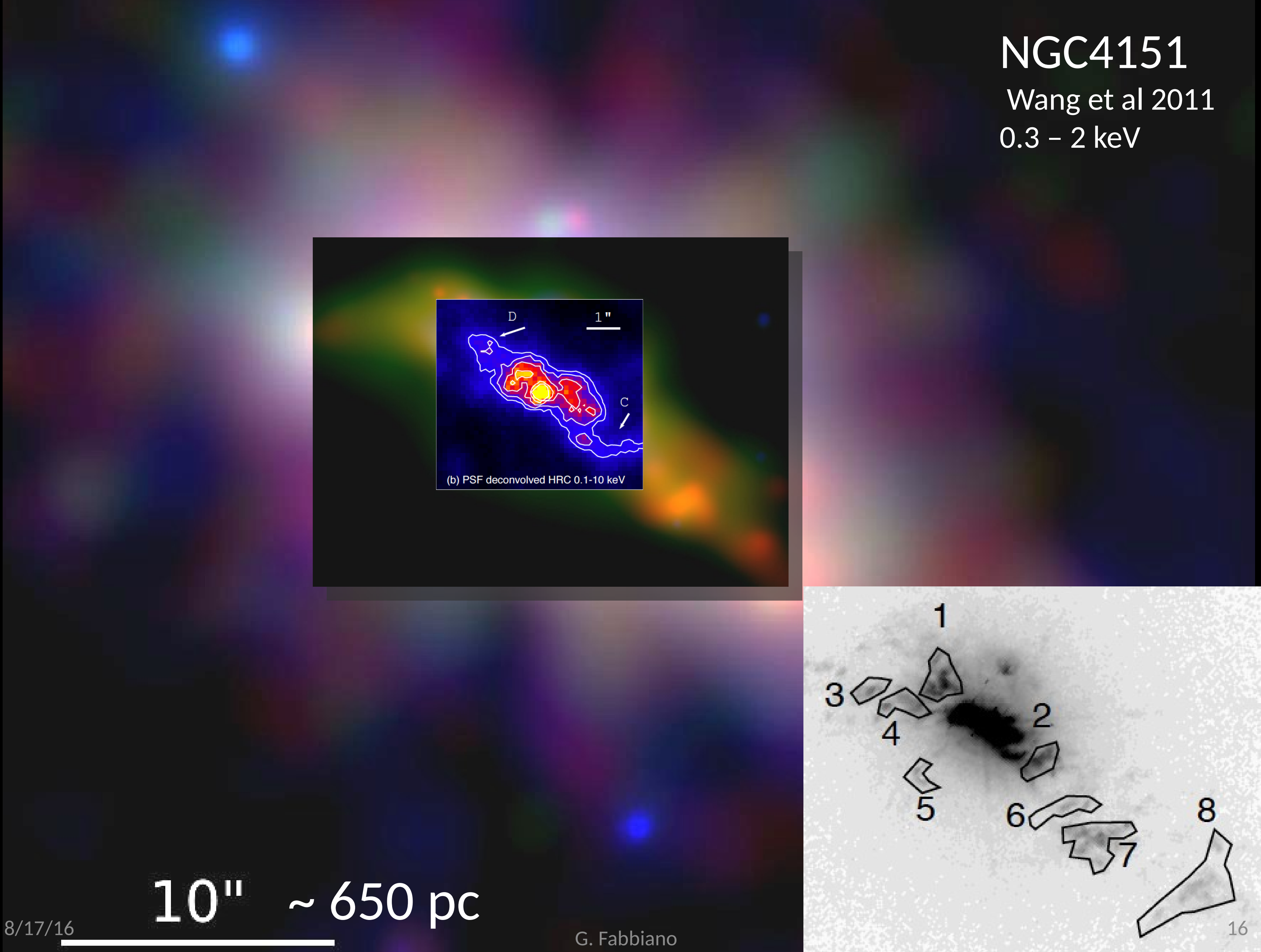
6388 stacked ETG LMXB subtracted: luminosity and hardness ratios (**Paggi et al 2016**) Hard ratios suggest AGN



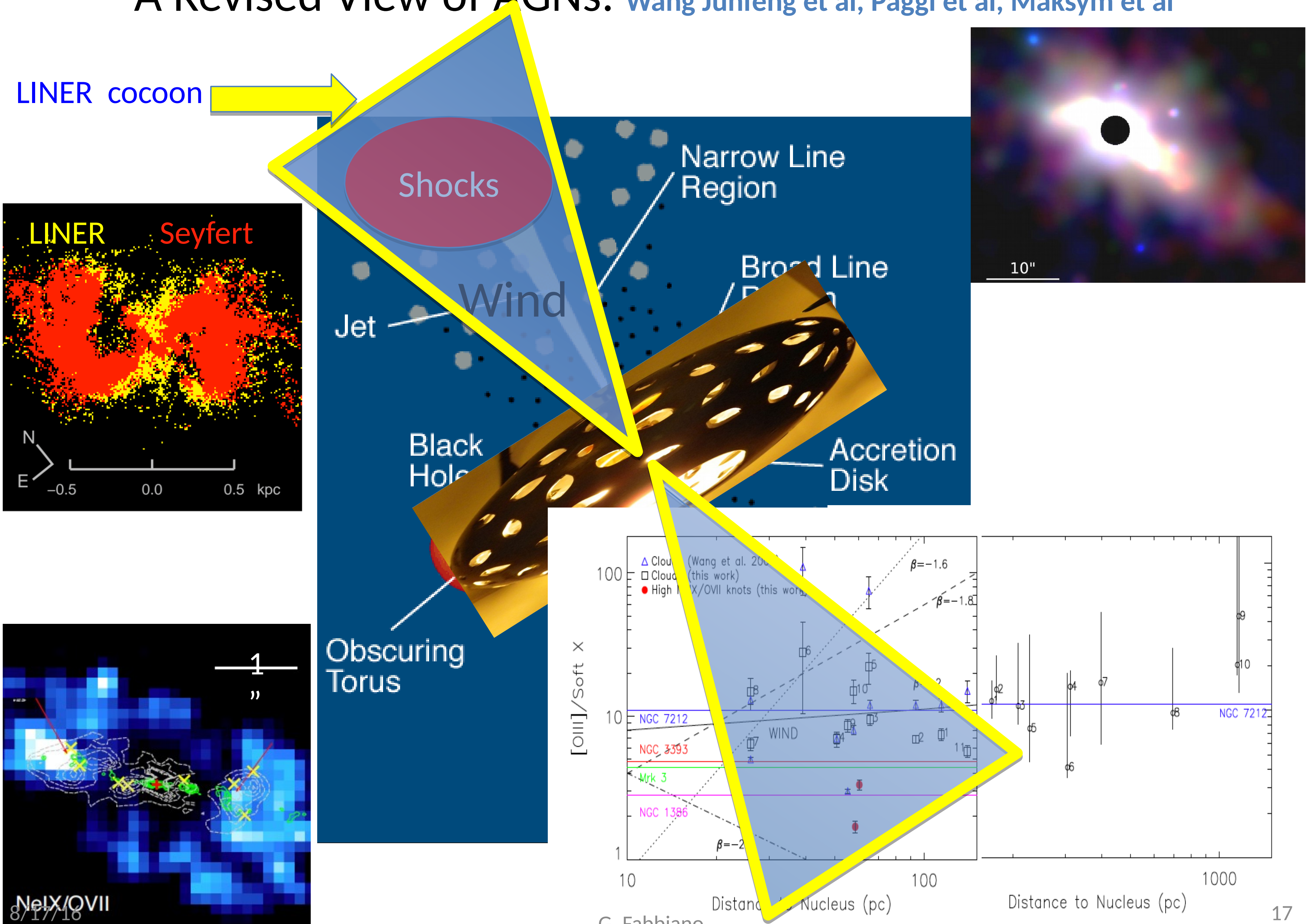
69 COSMOS detected ETG LMXB subtracted (up to z=1.5; Civano et al 2014)

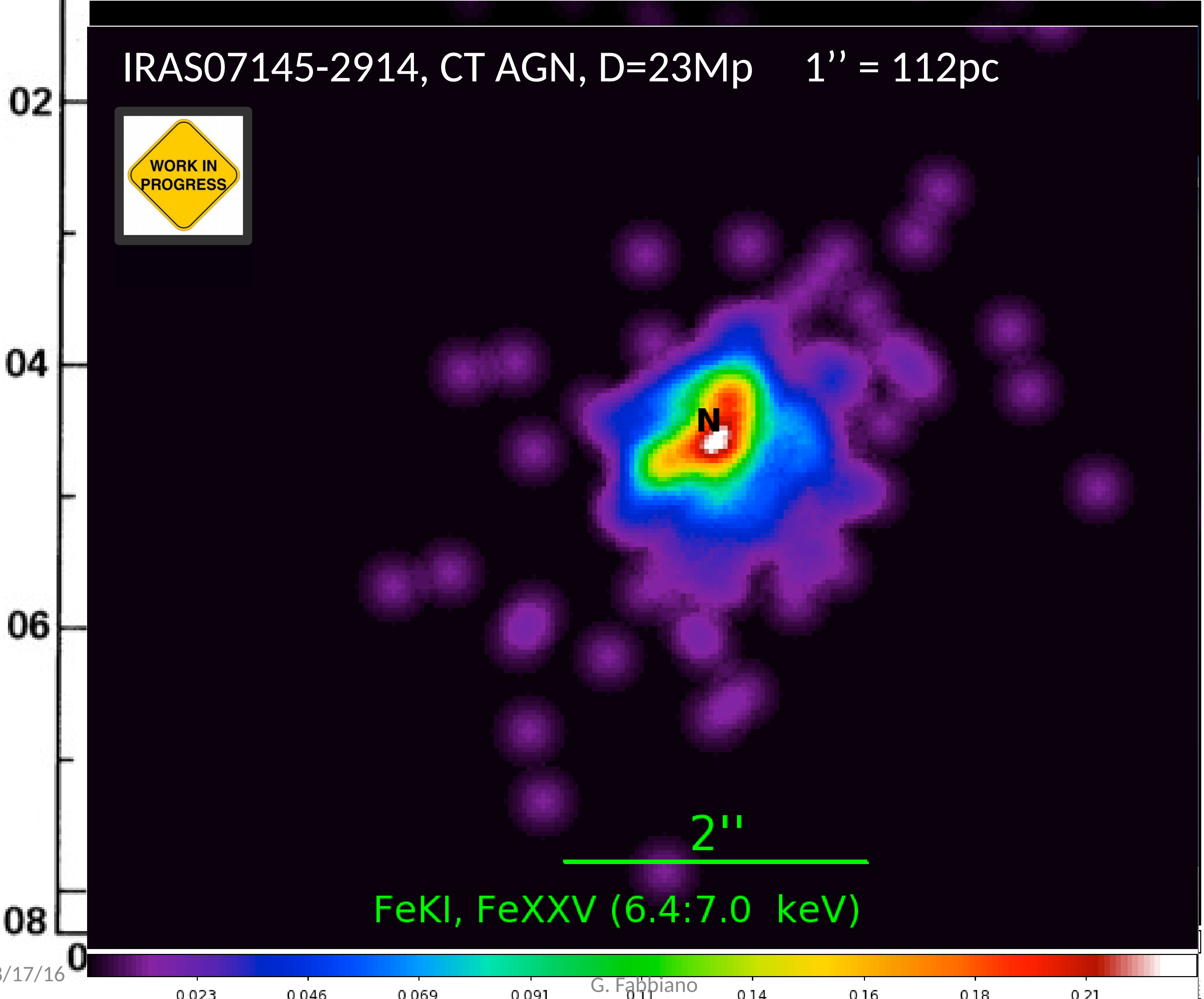
nearby ETG LMXB subtracted ('virialized halos'; Boroson, Kim & Fabbiano 2011)

6388 stacked ETG: results compare well with Volonteri (2011) models of accretion of stellar outgassing onto nuclear SMBH


NGC4151
Wang et al 2011
0.3 – 2 keV
D
1"
C
(b) PSF deconvolved HRC 0.1-10 keV
1
2
3
4
5
6
7
8
10"
~ 650 pc

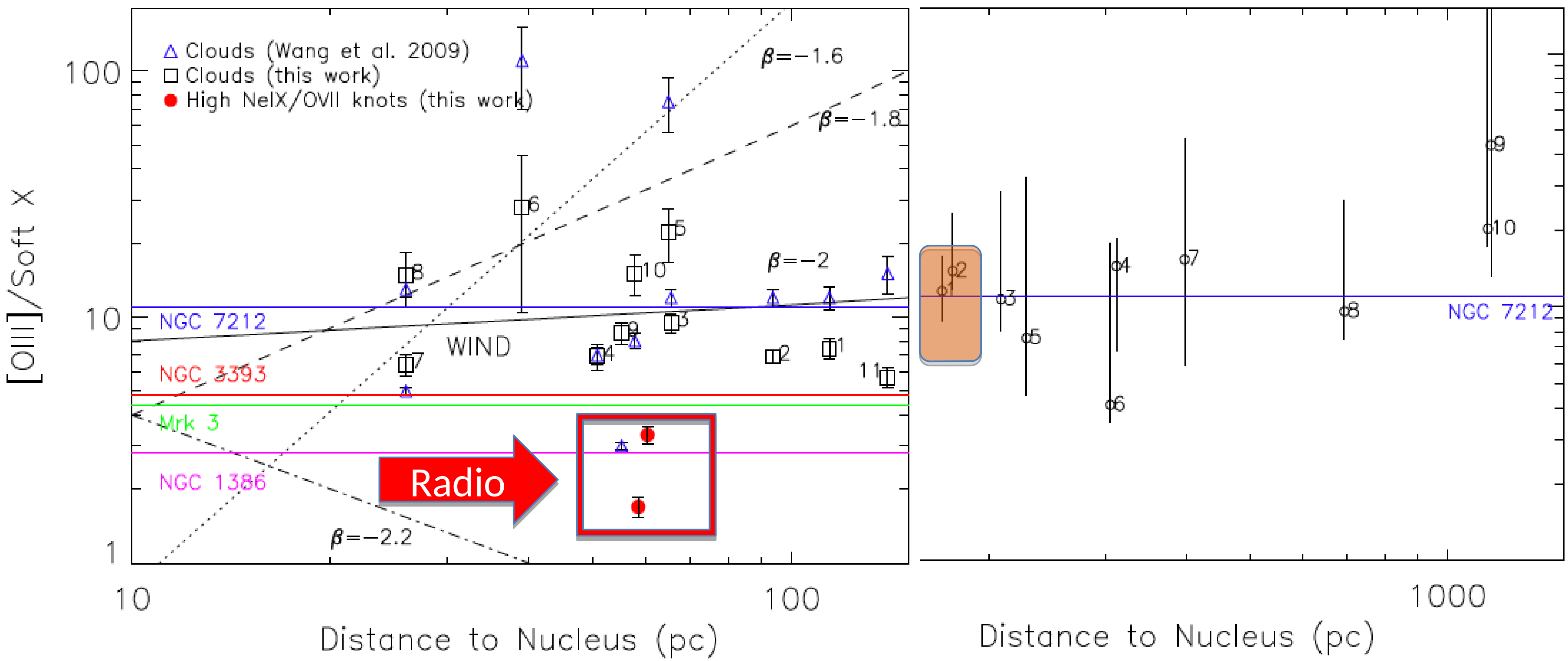
A Revised View of AGNs: Wang Junfeng et al, Paggi et al, Maksym et al




IRAS07145-2914, CT AGN, D=23Mp 1'' = 112pc
WORK IN PROGRESS
N
2''
FeKI, FeXXV (6.4:7.0 keV)
02
04
06
08
0.023
0.046
0.069
0.091
0.11
0.14
0.16
0.18
0.21

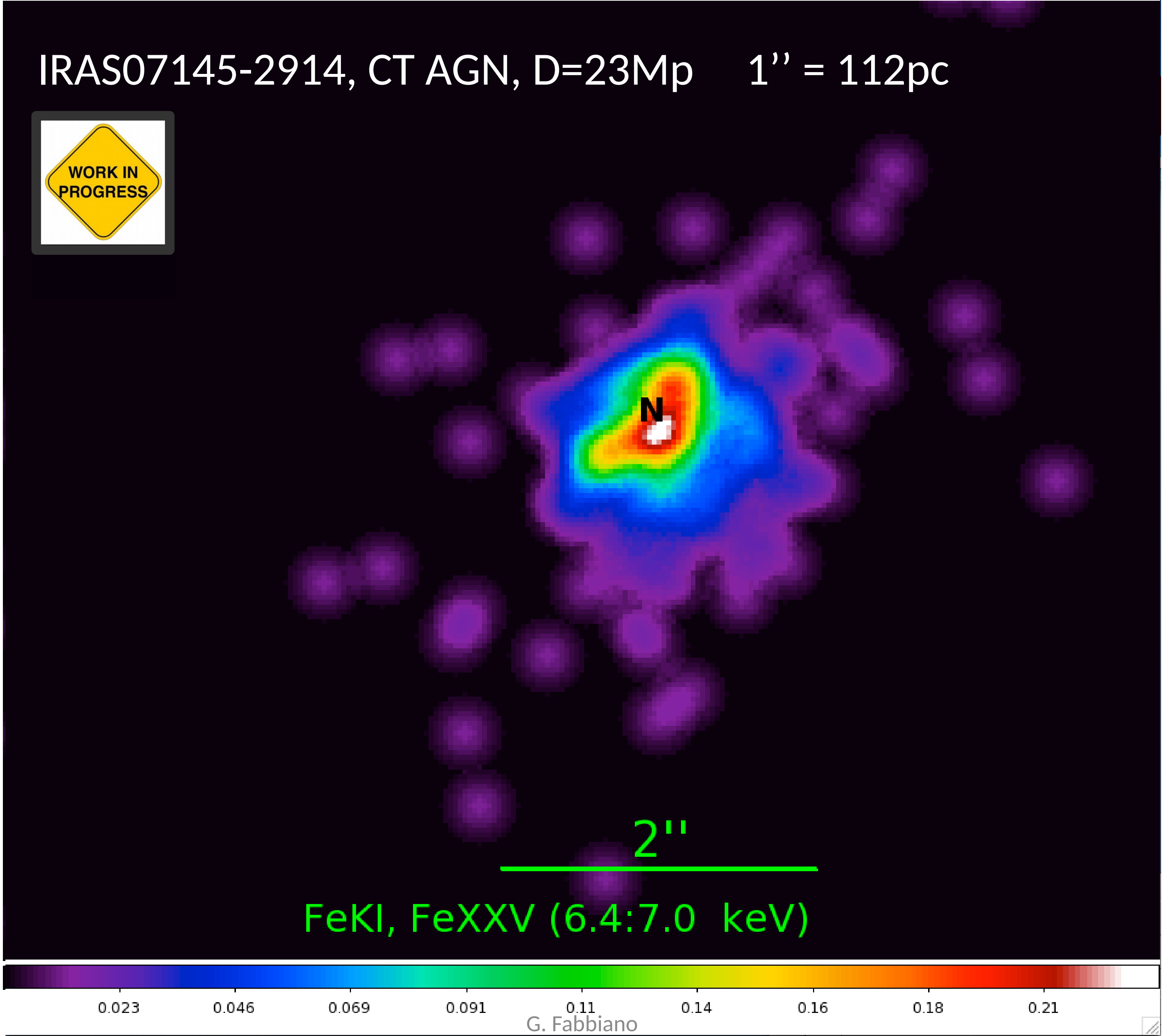
Constant Ionization Parameter *n~r* -2 – nuclear wind

Wang et al 2011c



NGC 4151 – constant [OIII] / X ratio from ~20 to 1000 pc

NGC 1068 – constant ratio ~10-200 pc (Wang et al 2012)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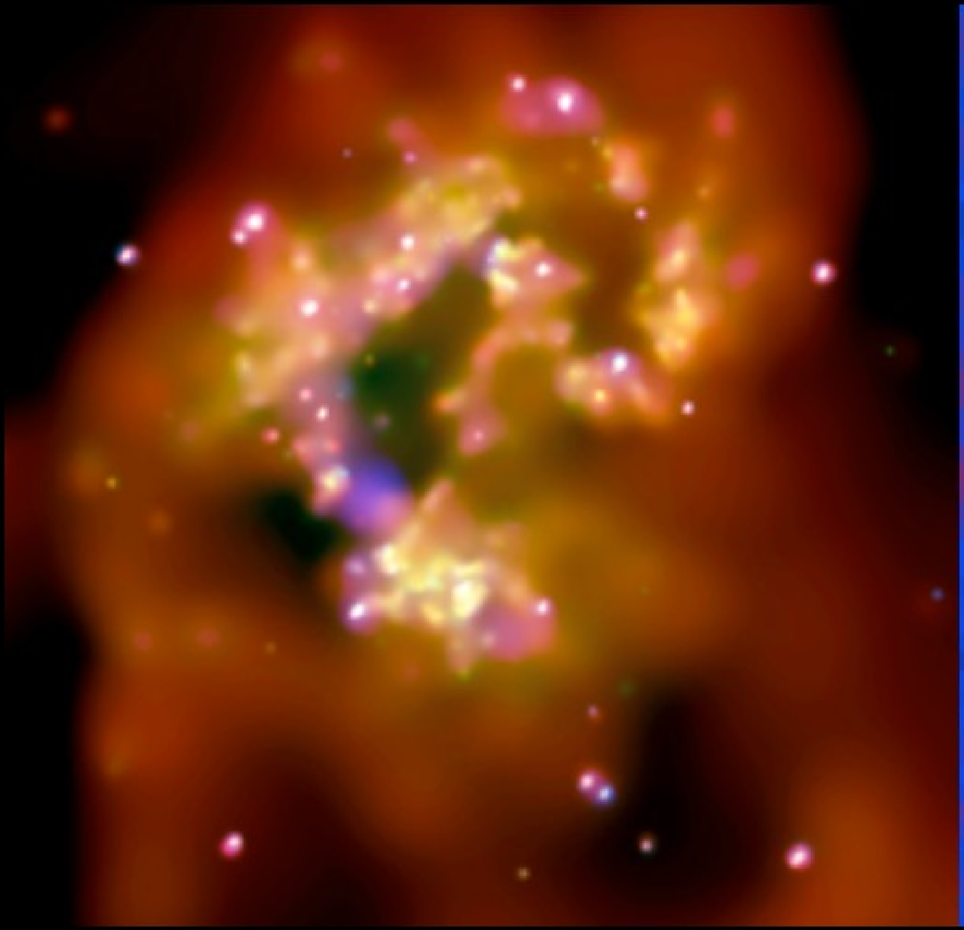
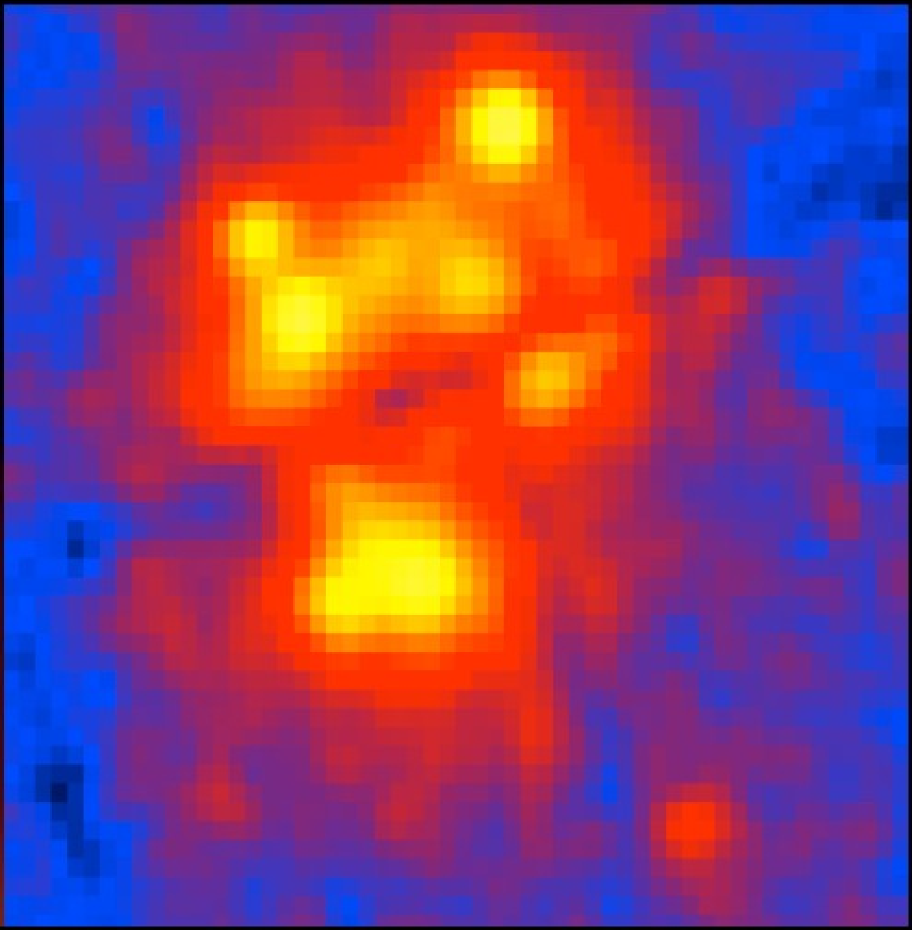
Why *Chandra*? Angular resolution is essential

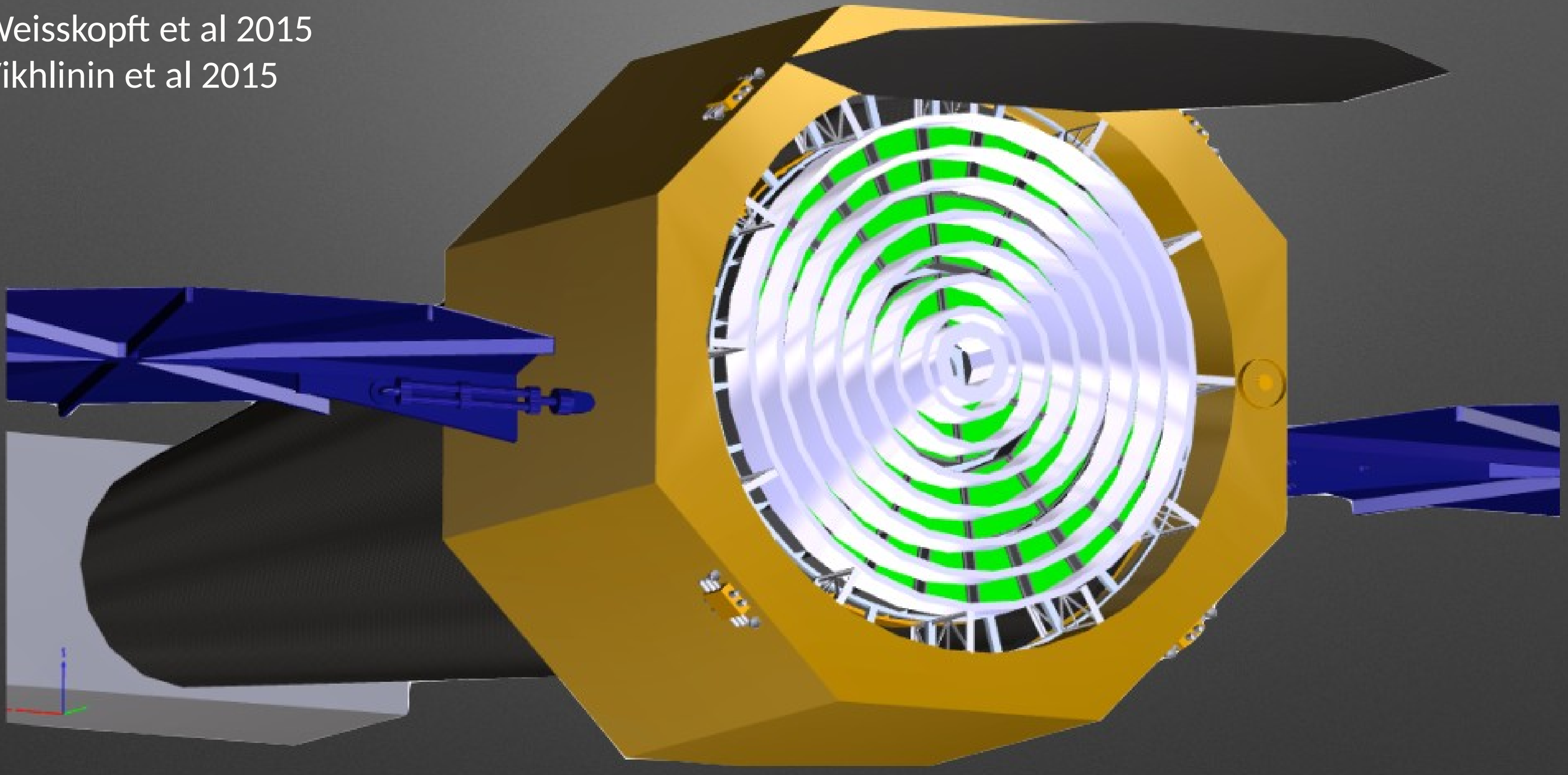




- The Antennae galaxies – *Chandra* versus *XMM-Newton*

Leap in sensitivity:
High throughput with sub-arcsec resolution

Weisskopft et al 2015
Vikhlinin et al 2015



- ×50 more effective area than *Chandra*. 4 Msec *Chandra* Deep Field done in 80 ksec. Threshold for blind detections in a 4Msec survey is ~ 3×10^{-19} erg/s/cm^2 (0.5–2 keV band)
- ×16 larger solid angle for sub-arcsec imaging — out to 10 arcmin radius
- **×800 higher survey speed at the *Chandra* Deep Field limit**