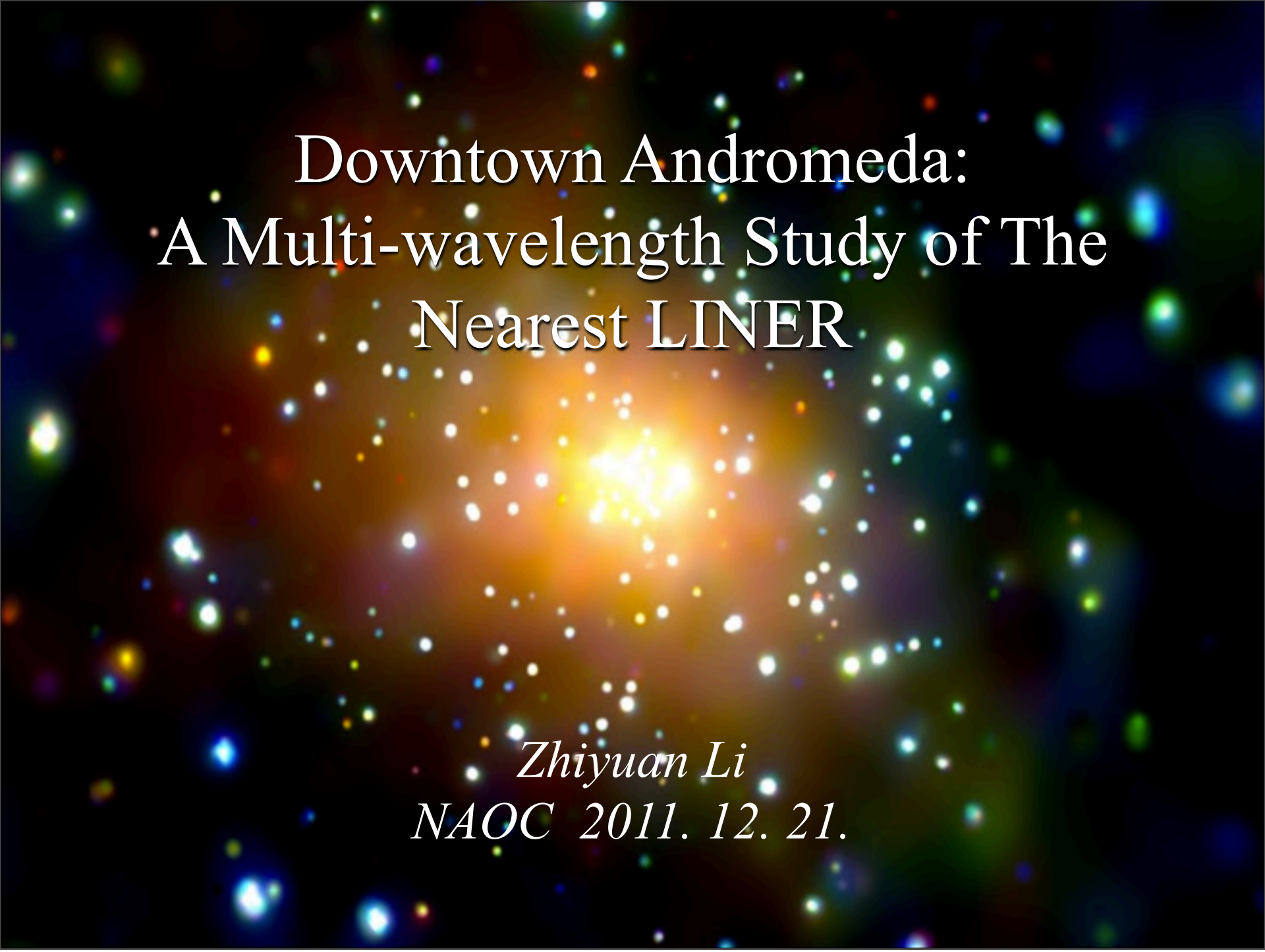
Downtown Andromeda:
A Multi-wavelength Study of The Nearest LINER
Zhiyuan Li
NAOC 2011. 12. 21.

Outline

- Overview of M31's circumnuclear region
- An on-going multi-wavelength study
- Future perspectives

Collaborators:

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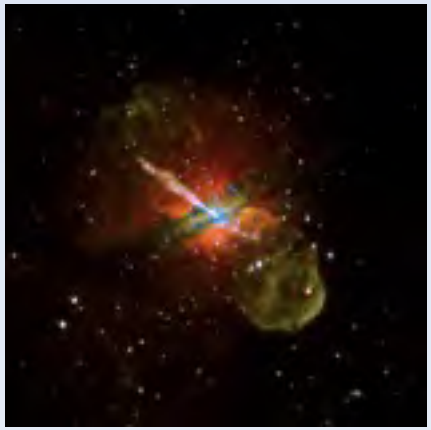
Galactic Circumnuclear Environments

- Interplay among the nuclear, stellar and interstellar components
  - The site of SMBH feeding and feedback
  - The site of active (sometimes violent) star formation
  - A multi-phase ISM: heating, cooling, ionization

- Origin of the SMBH-host galaxy relations; global evolution of the host galaxy



M31 - a unique laboratory

- The nearest (*D*=780 kpc) circumnuclear environment in a massive external galaxy -- highest linear resolution (after the Galactic Center)
- Little line-of-sight extinction -- transparent in almost all wavelengths -- allows to study nearly all stellar and interstellar components
- Hosts an extremely inactive SMBH and has no recent/current star formation -- a *quiescent* view of secondary effects

The nuclear spiral

- circumnuclear ionized gas detected in Hα, [N II], [S II], [O II], [O III] (Rubin & Ford 1971) -- the nearest LINER (Low-Ionization Nuclear Emission-line Region; Heckman 1996)
- filamentary, spiral-like morphology
  -- the *nuclear spiral* (Jacoby+ 1985)
- ~10^3 $M_\odot$ mass; low volume filling factor (<10^{-4})
- spatially coincident with dust emission
  -- ~10^6 $M_\odot$ neutral (probably molecular) gas, so far no direct direction
- probably formed in the triaxial bulge gravitational potential (Stark & Binney 1994)

Hα+[N II]; Devereux et al. 1994; 6'X6'

The nuclear spiral

• the ionizing source remains a puzzle (no young stars, no AGN!): Q(H) ~ 2x10^50 sec^-1

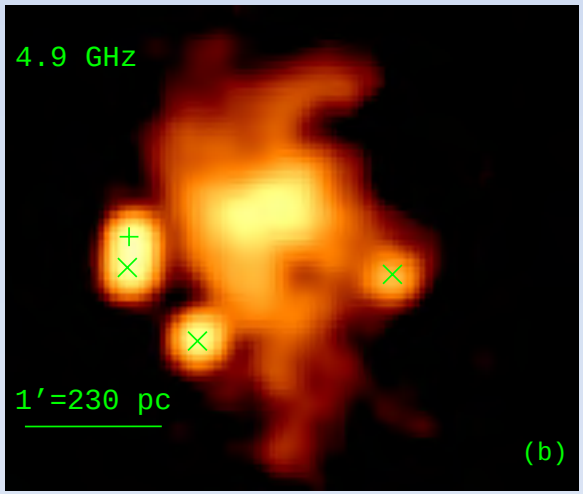
- post-AGB stars: models fall short to account for [N II]/Hα>~2 (Binette et al. 1994); M32 suggests a lack of pAGBs (Brown et al. 2008); *M31 under investigation (direct counting of UV stars)*
- X-ray binaries, hot gas, shocks ruled out (Li et al. 2009)

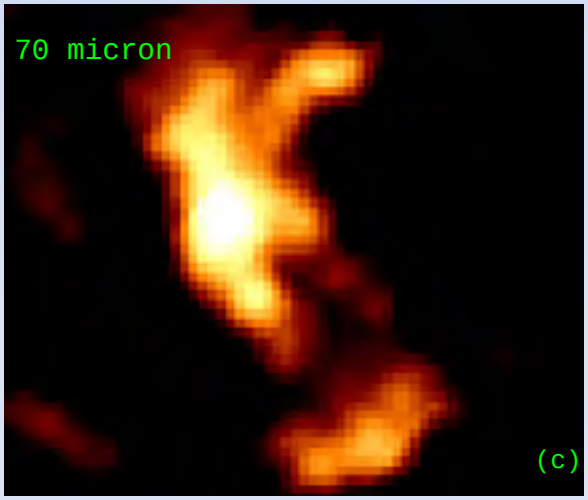
• *relativistic particles* most viable for the energetics ~ a few 10^{40} erg/s

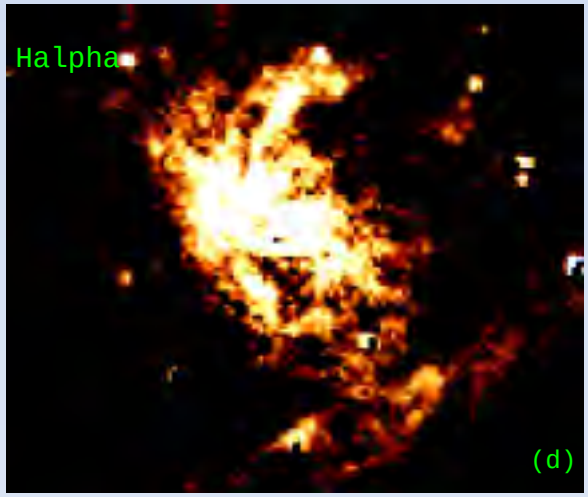
- **CRs both ionize and heat the gas**, resulting in an extended partially ionized zone => high [N II]/Hα, [S II]/Hα

Hα+[N II]; Devereux et al. 1994

CRs and magnetic fields

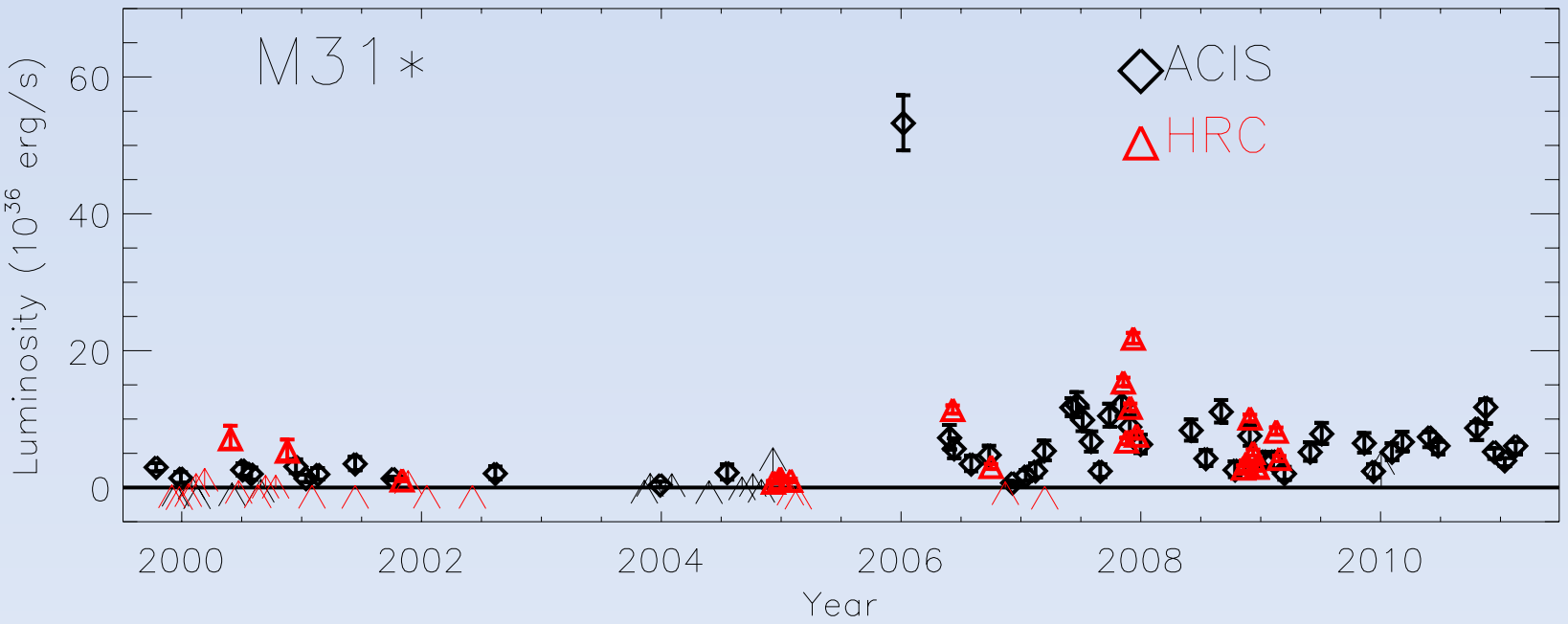




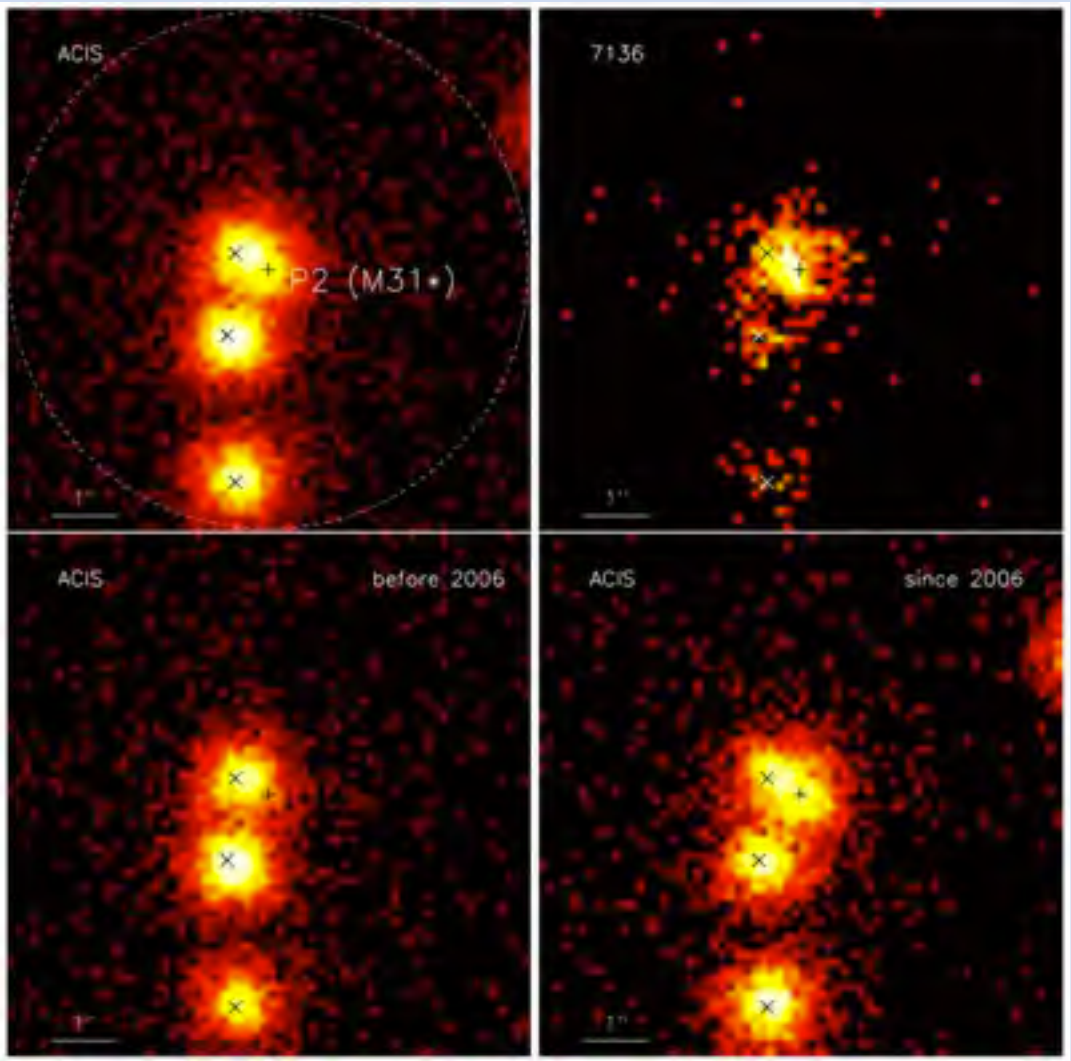


- Extended radio continuum emission *traces* the nuclear spiral; primarily non-thermal (Walterbos & Grave 1985)
- The regular magnetic field is oriented along the nuclear spiral; ~10 μG; ~ 0.5 f^(-4/7) eVcm^-3; ~ 3E50 f^(3/7) ergs
- Source of CRs: SMBH or SNe? -- A radial trend seen in the spectral index indicates the aging of CRs (Hoernes+98)
- New *EVLA* mapping of the polarized emission from the nuclear spiral (PI: ZL)

The SMBH - M31*

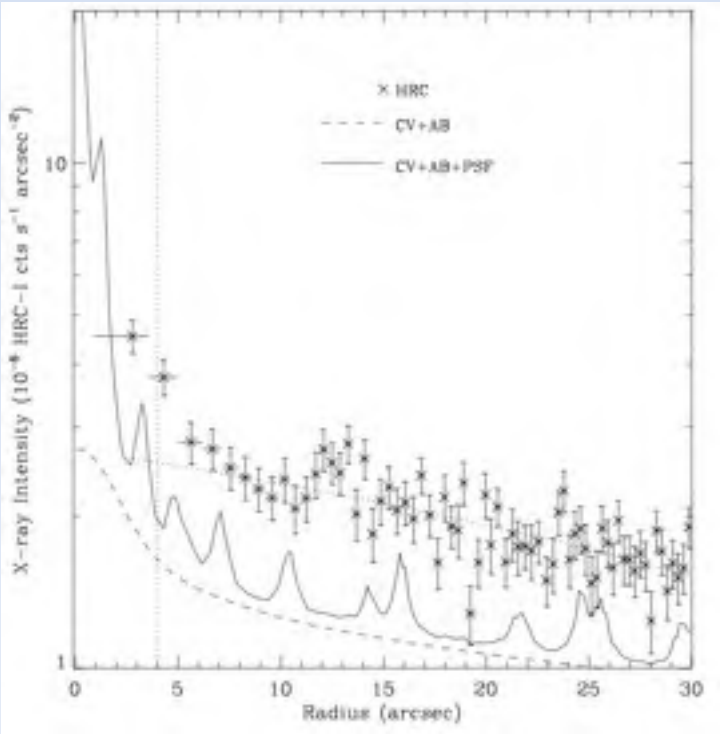


- M31*: an extremely quiescent state ($\leq 10^{-10}$ L_{Edd}) before 2006; an X-ray outburst occurred on Jan. 6, 2006 (~100X flux); a more active state since 2006 (~10X flux) -- analogy to Sgr A* flares (Li et al. 2011)
- Jet-ADAF models predict the ejection of relativistic particles (Yuan et al. 2009) into the ISM (no jet-like feature observed yet)
- New joint Chandra/EVLA monitoring of M31* (PI: ZL)
- Upcoming joint *Chandra/HST/EVLA* observations of M31* (PI: M. Garcia)

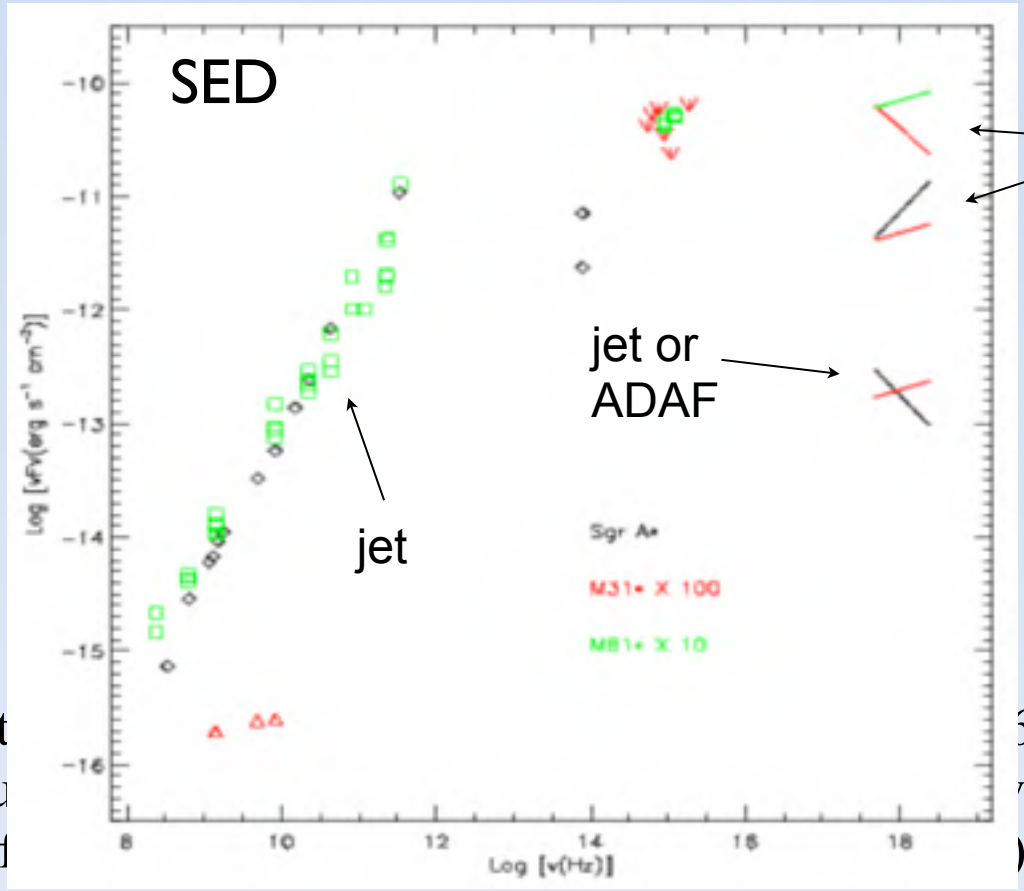


Li et al. 2011

The largest angular *Bondi radius* ~ 4” (~15 pc) -- a great potential for studying the accretion flow



The SMBH - M31*



- M31*: an ext ; an X-ray outburst occu e state since 2006 (~10X f)
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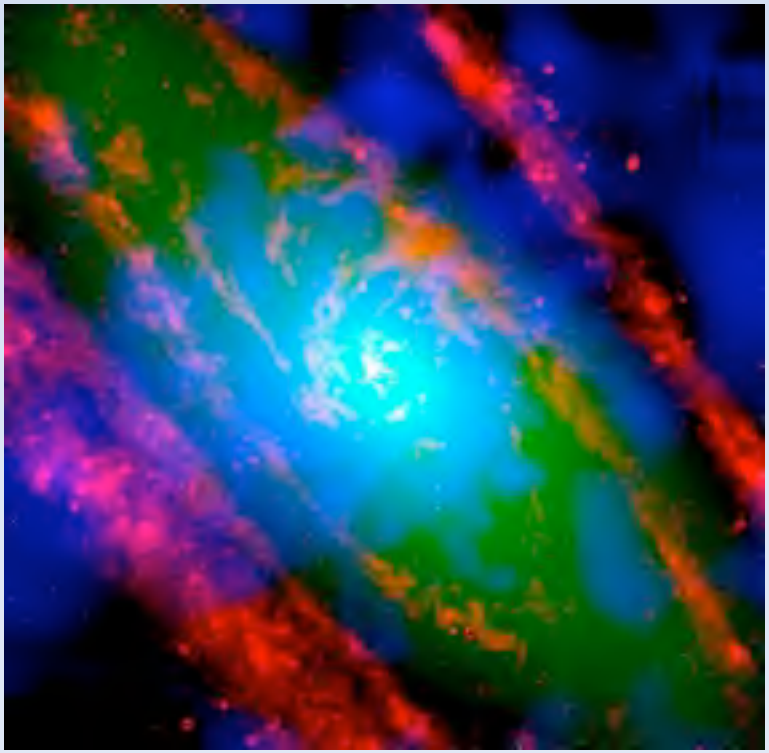
The hot gas

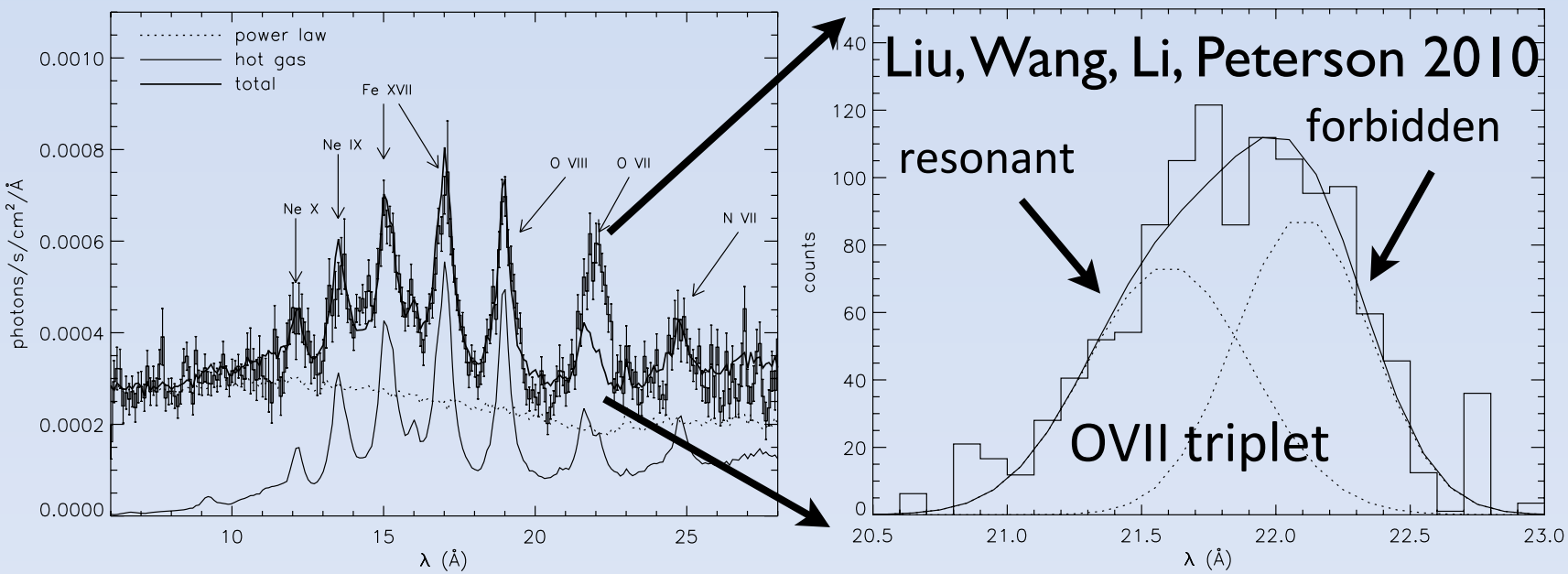
- diffuse hot gas within 300 pc: $L_X \sim 7 \times 10^{37}$ erg/s vs. *SNe Ia* heating rate $\sim 5 \times 10^{39}$ erg/s; $M_X \sim 10^5\ M_\odot$ vs. stellar mass loss rate 0.01 $M_\odot$/yr
- *missing stellar feedback*! – transported by an outflow of hot gas (Li & Wang 2007)
- *however*, both T (~0.3 keV) and Z_Fe (~solar) appear lower than expected from stellar feedback (3 keV; a few solar) -> additional mass input

0.5-2 keV X-ray, K-band, 24 μm



Diffuse X-ray emission--elongated morphology --a bulge outflow, likely a generic component in intermediate-mass early-type galaxies

XMM-Newton/RGS spectrum of the inner bulge



excess in the O VII forbidden line: observed G = $(f+i)/r \sim 1.5$, while G ~ 0.7 for a 0.3 keV gas; G ~ 2.2 for *charge exchange emission* (CXE)
-> evidence for a significant contribution from CXE

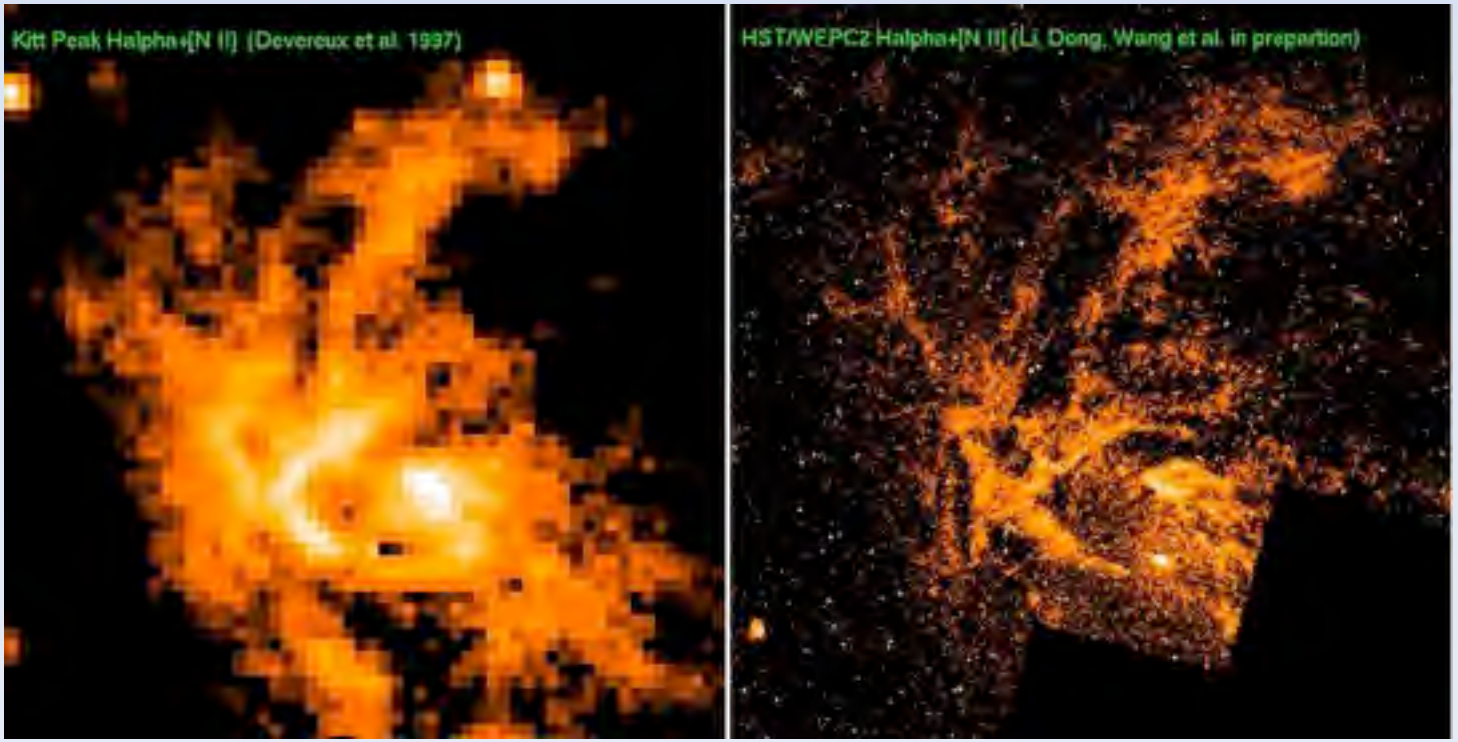
the O VII excess is spatially coincident with the so-called nuclear spiral
-> from the interface of hot gas and cooler gas -- ***gas evaporation***
(see also Liu,Wang & Mao 2011a,b for CXE in star-forming galaxies)

Evaporation of the nuclear spiral

- important regulation mechanism for the nuclear region

(i) a mass-loaded hot gas with lower T and diluted Z; (ii) the dearth of cold gas, despite the presence of an in-disk inflow; (iii) the starved SMBH

- the inferred evaporation rate (accounting for T and Z) implies *clouds of sub-parsec sizes* -> the need for HST imaging (0.1"=0.4 pc) !



Multi-wavelength data

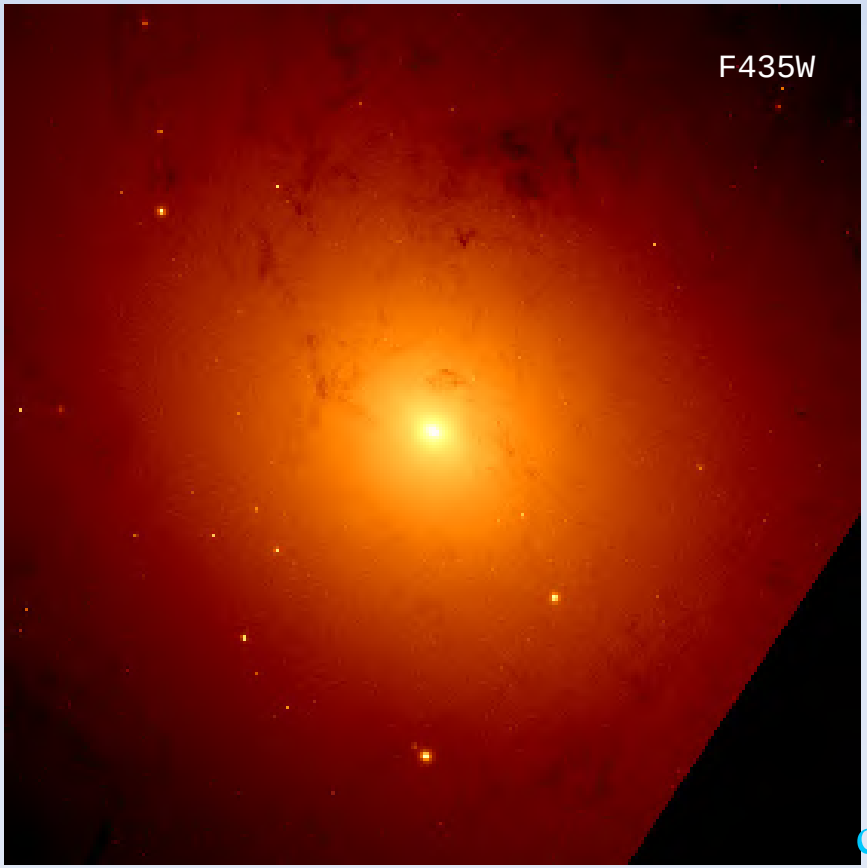
- An *HST*/WFC3 mapping of the nuclear spiral: [O II]3727, [O III]5002, Hα, [N II]6583 (PI: ZL)
- *HST*/WFC3 and *HST*/ACS mapping of the circumnuclear dust extinction: F275W, F336W, F475W, F814W, F110W, F160W (PI: J. Dalcanton), F435 W (PI: M. Garcia), F390M, F547M, F665N (PI: ZL)
- *Spitzer*/IRS mapping of the nuclear spiral (PI: C. Joblin)
- *Chandra*/ACIS observations of the M31 bulge (PI: M. Garcia, S. Murray): 600 ks ACIS-I + 400 ks ACIS-S (upcoming)
- Upcoming *Herschel* mapping of the nuclear spiral: [C II]152 micron, [O I] 63 micron, [O III]88 micron (PI: ZL)
- Upcoming *EVLA* mapping of the polarized radio continuum (PI: ZL)

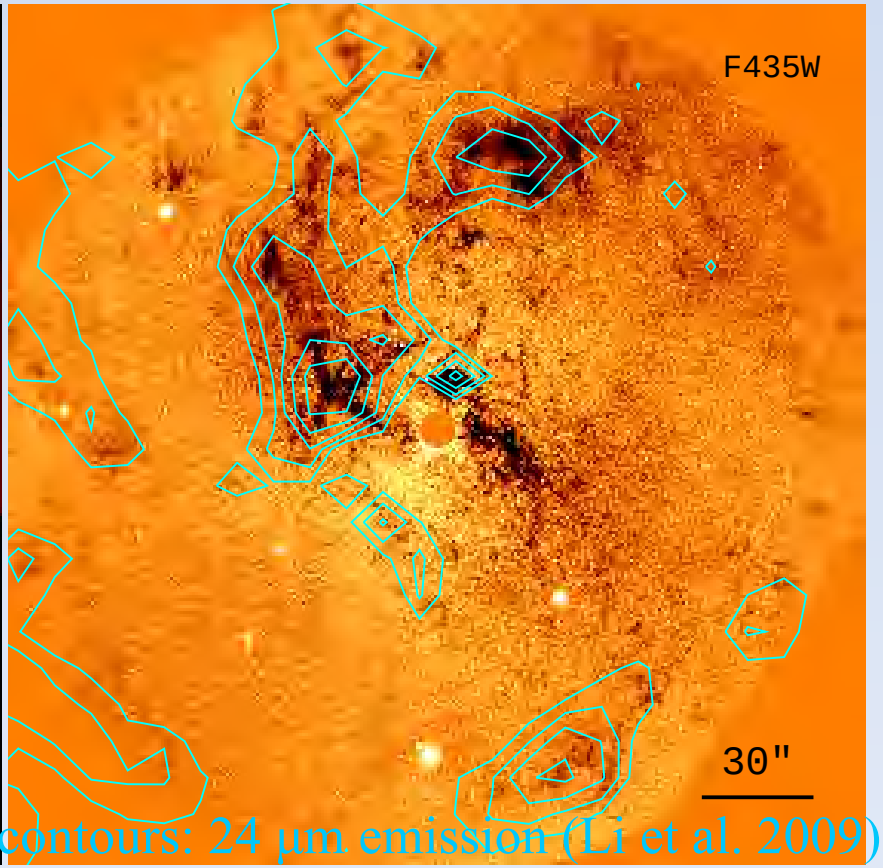
Outstanding questions:

(i) ionization/heating mechanism(s) of the nuclear spiral;

(ii) regulation of the circumnuclear ISM and the feeding/ feedback of the SMBH

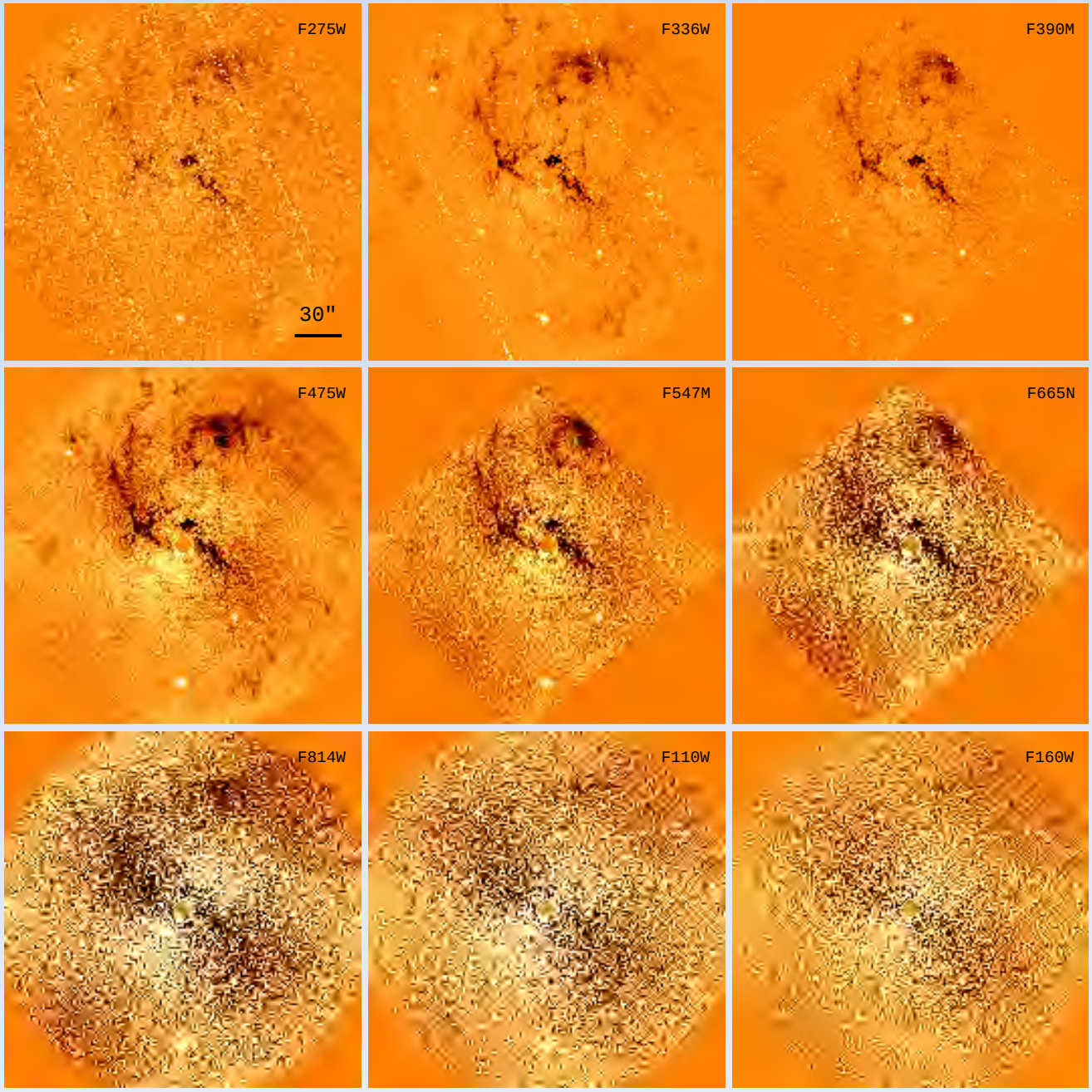
The circumnuclear dust extinction



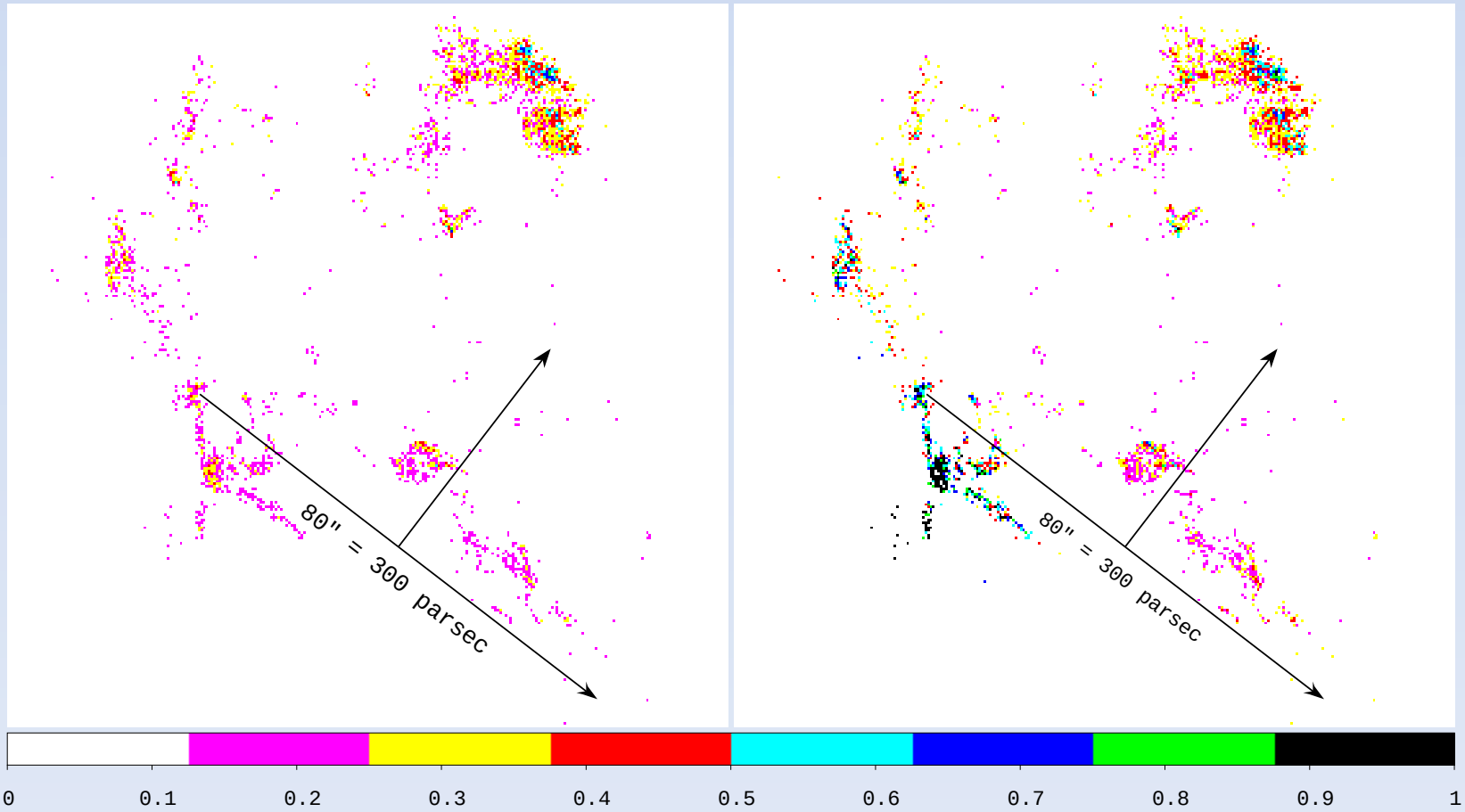


- 2-D fit of the smooth starlight (GALFIT, a *Sersic* model)
- Residual map = Observed map - model map

Near-UV



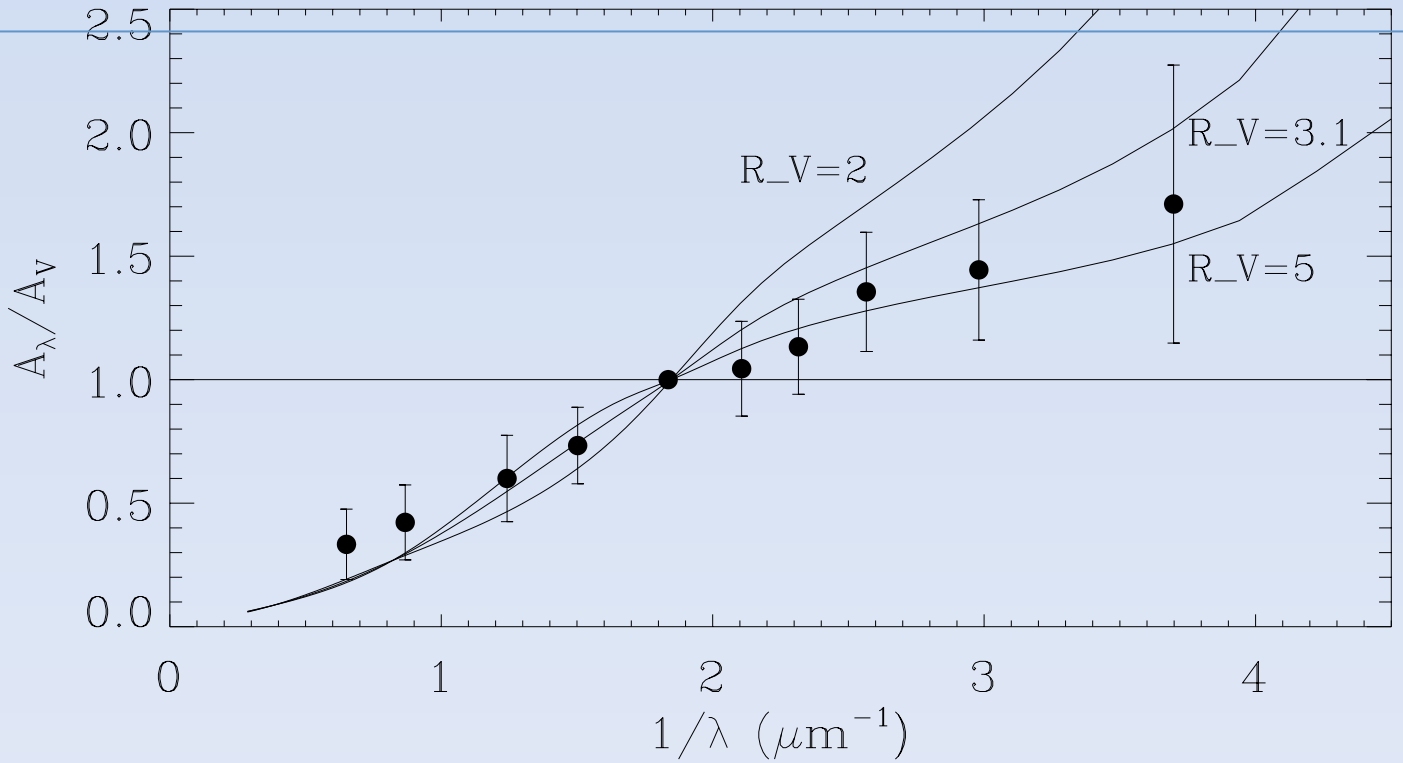
Near-IR



- convert the *apparent* (left) B-band extinction to the *intrinsic* (right) extinction, assuming: (i) ellipsoidal bulge and (ii) clouds in the thin tilted plane *to calculate the obscured fraction of the bulge starlight*
- A_V ~ 0.2 - 1 mag => N_H ~ 3.5-17.5 E20 cm^-2

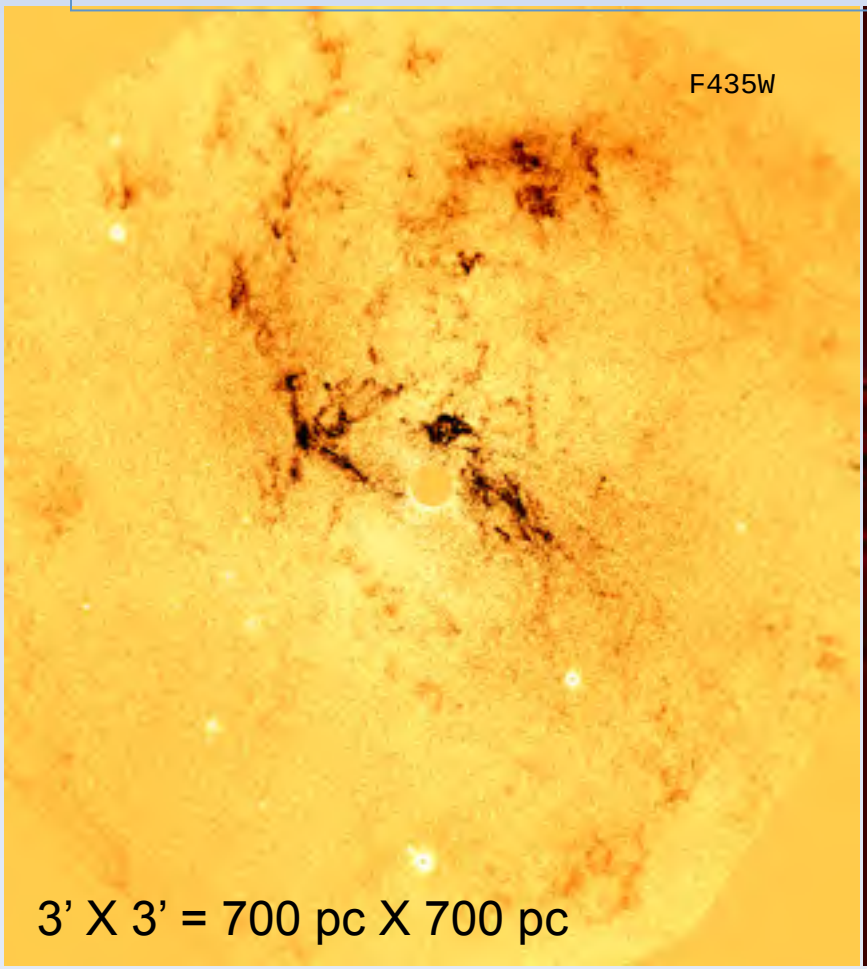
  => n ~ 250-1250 cm^-3 (assuming cloud size = 0.5 pc)

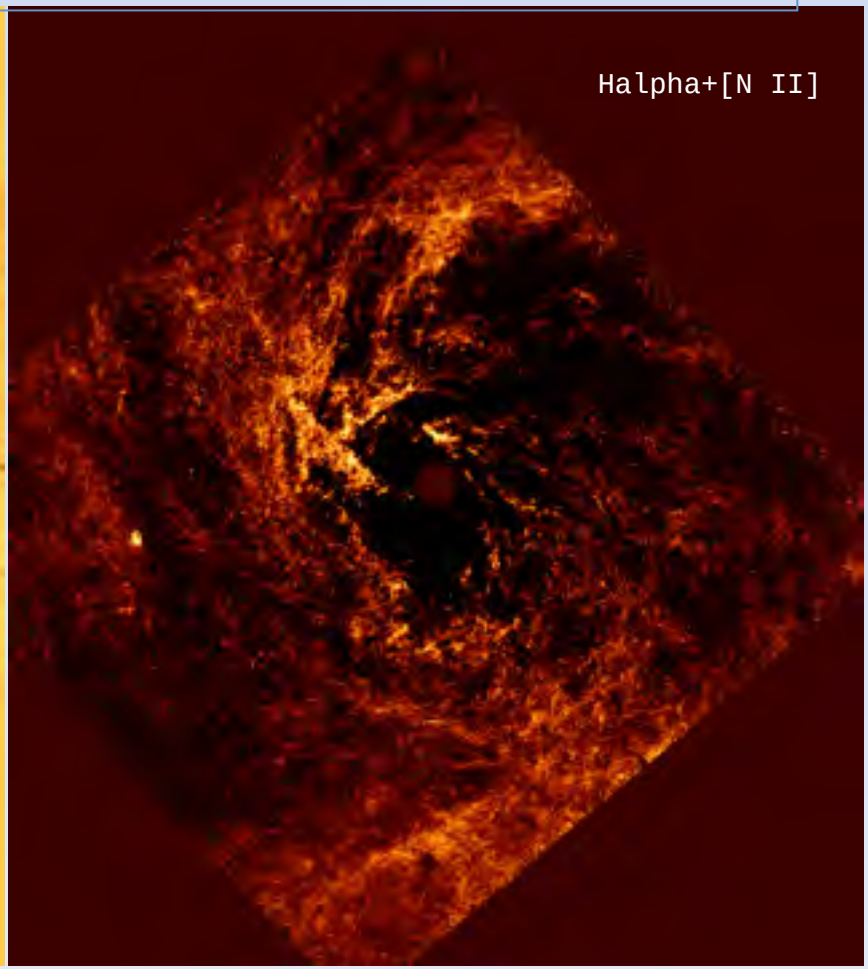
First NIR-NUV extinction curve of circumnuclear dust

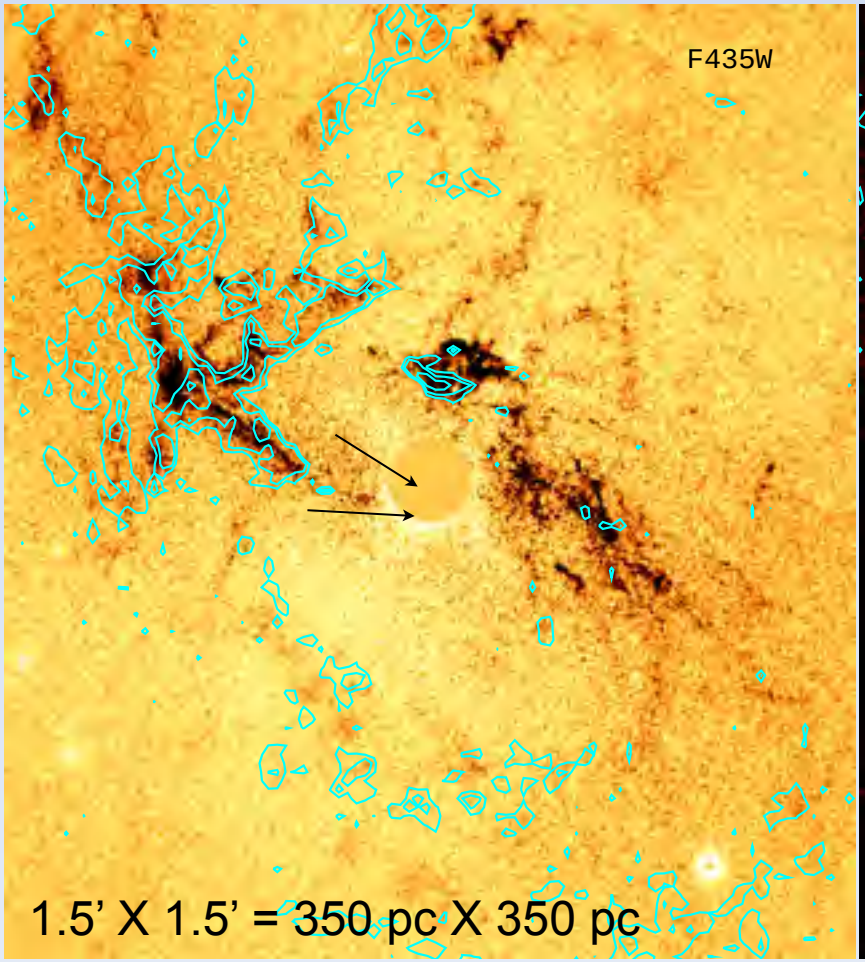


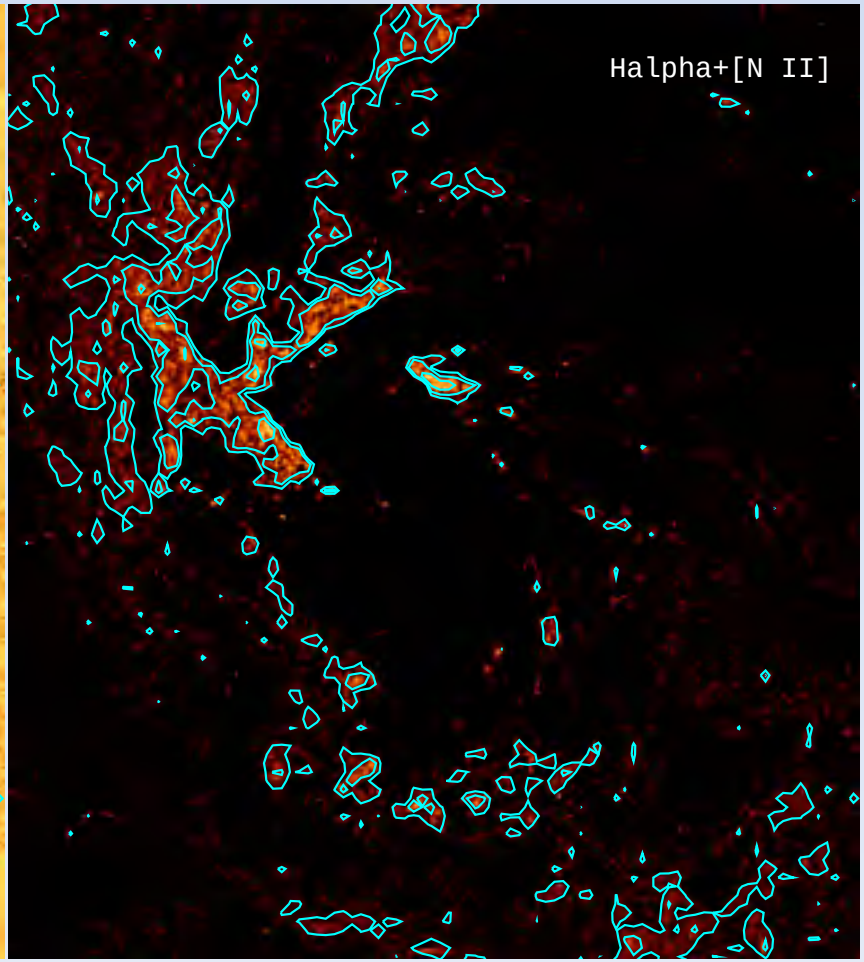
Alternatively approach of mapping (the 3-D distribution of) dust with multi-band SED fitting (Dong et al. in preparation)
working assumption: stellar population synthesis models (but no geometrical assumptions, hence complementary to imaging fitting)

Morphologies of dust and ionized gas

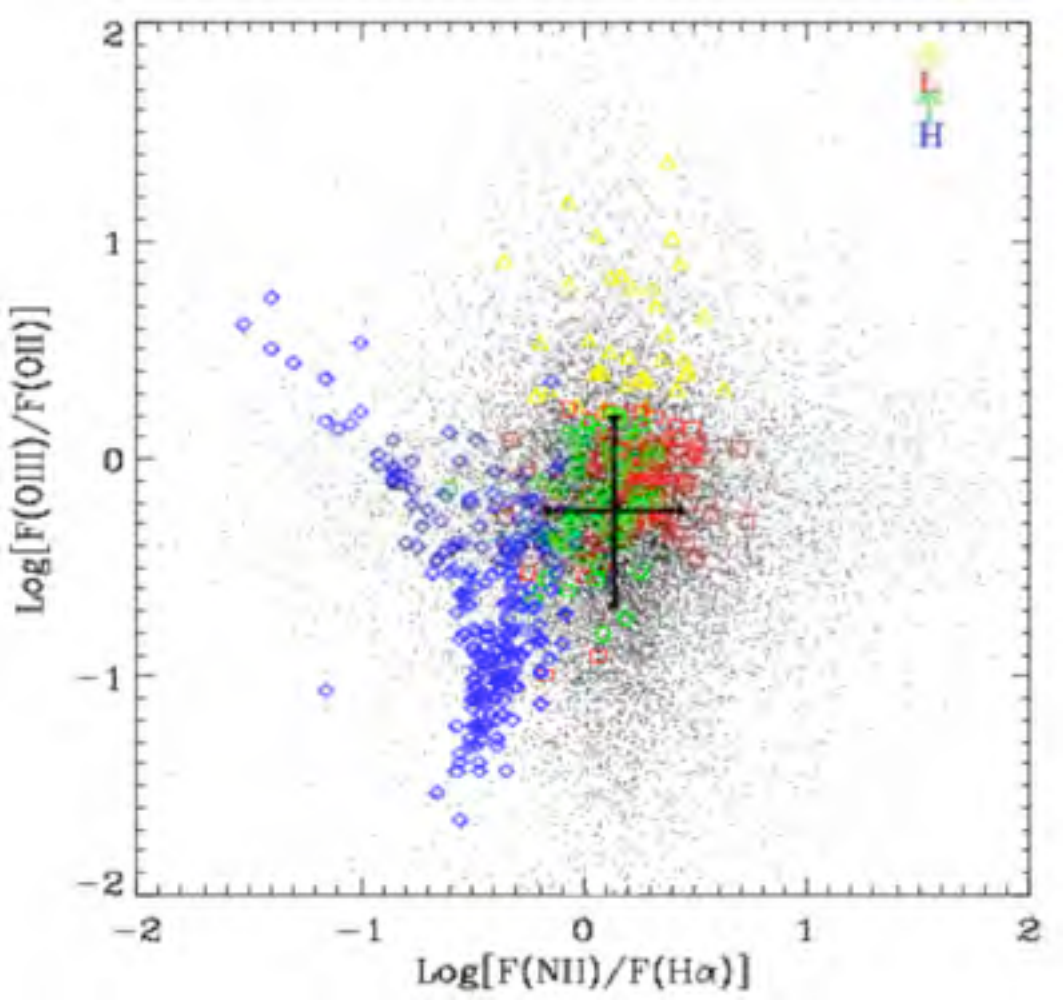





F435W
1.5’ X 1.5’ = 350 pc X 350 pc


Halpha+[N II]

BPT-type diagram



Palomar survey (Ho et al. 1997)

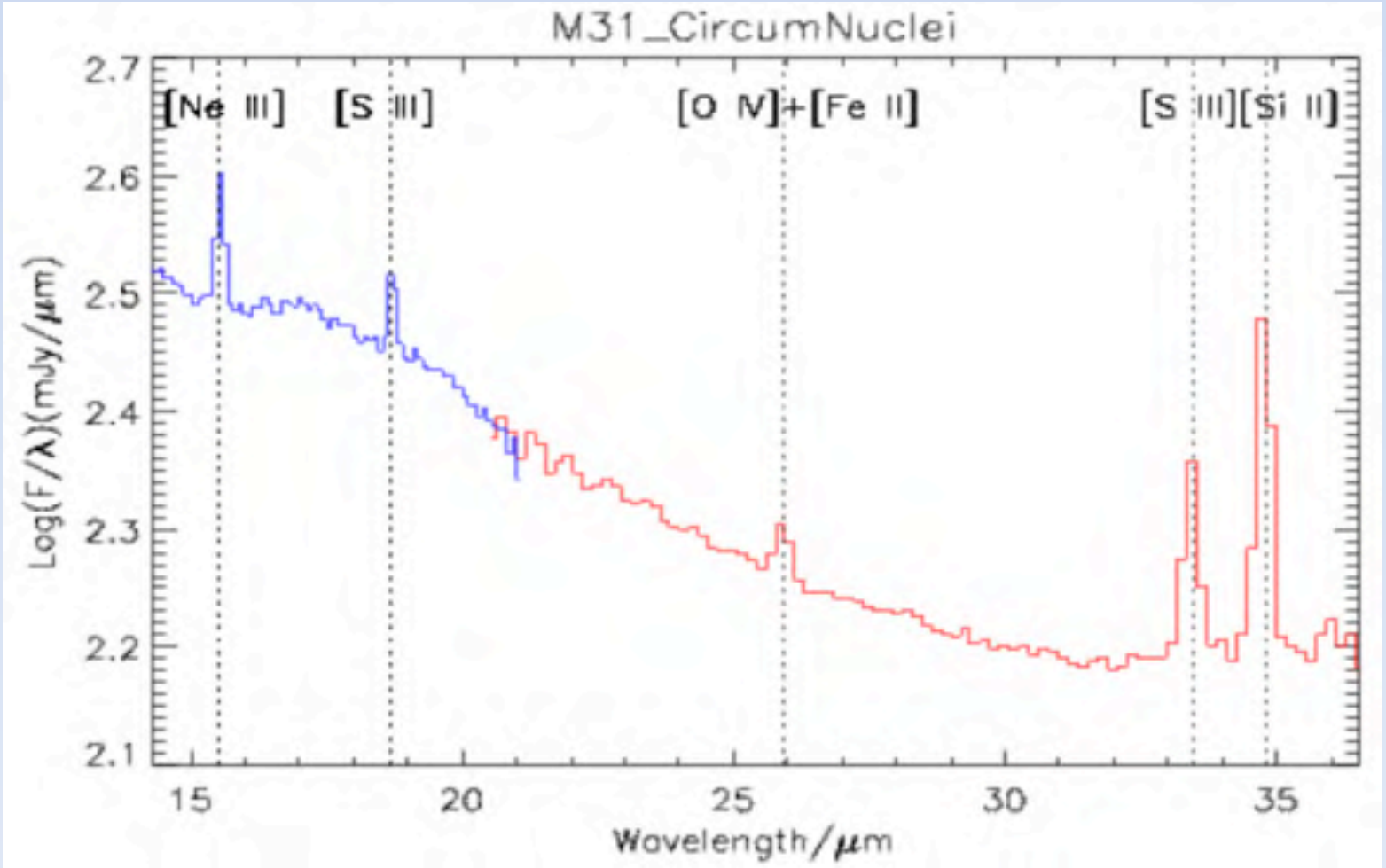
S = Syfert T = Transition

L = LINER H = H II region

vs.

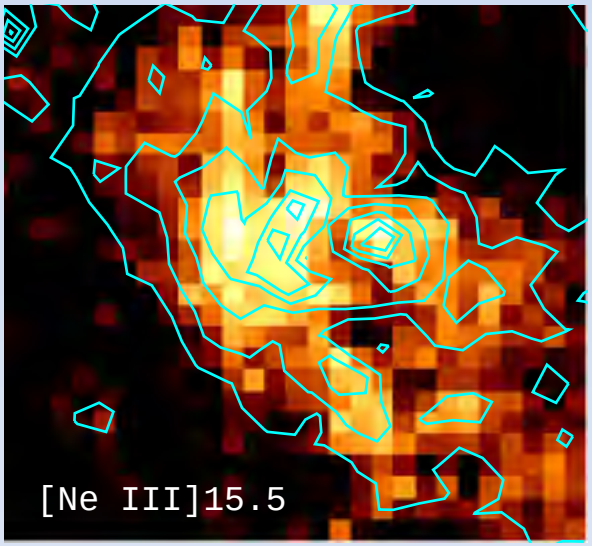
individual clouds in the nuclear spiral

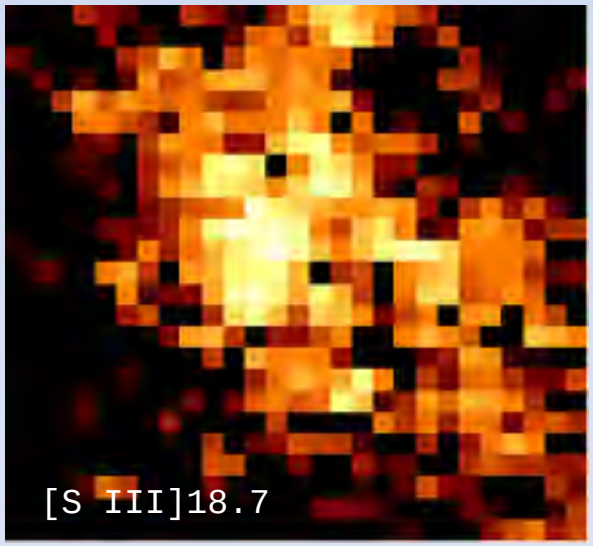
the nearest LINER

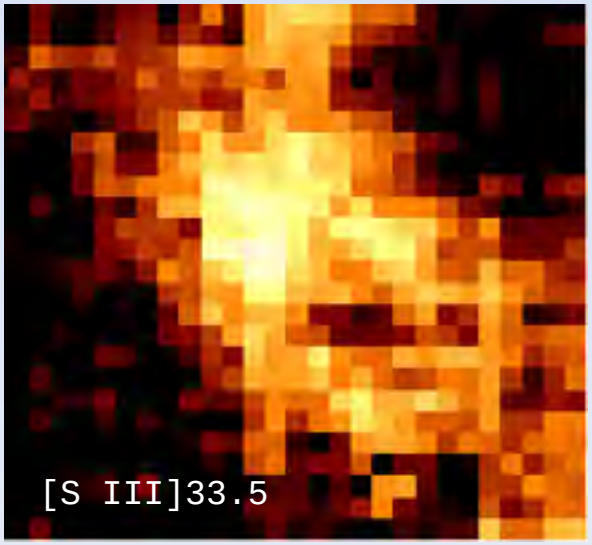


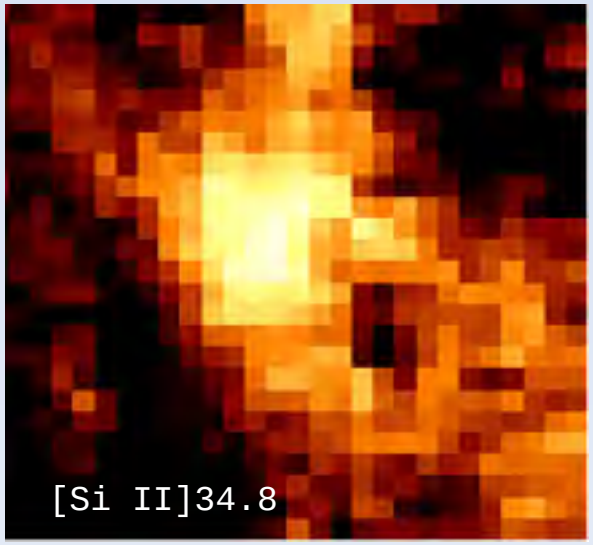
- *Spitzer*/IRS Long-Low spectrum
- [Ne III]15.5 (40.96 eV), [S III]18.7, 33.5 (23.33 eV), [Si II]34.8 (8.15 eV) detected
- [O IV]+[Fe II] blended (54.9 eV for O IV, unlikely)

contours: Hα+[N II] emission



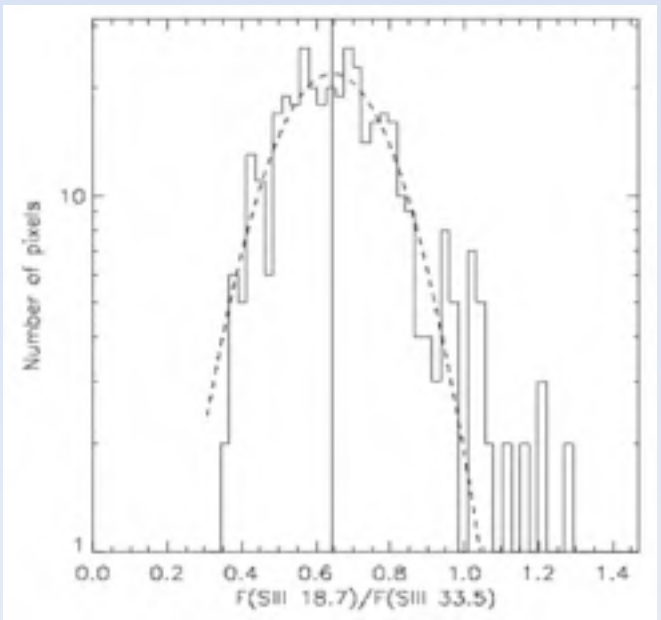






~20 pc resolutions

- n_e ~ 200 cm^-3 (from [S III]18.7/[S III]33.5), lower limit for the clouds



M31's circumnuclear environment: summary and prospects

- Two outstanding questions: (i) ionization/heating mechanism(s) of the nuclear spiral; (ii) regulation of the circumnuclear ISM, feeding and feedback of the SMBH
- Work in progress: (i) mapping of magnetic fields and CRs; (ii) cosmic-ray heating model with CLOUDY; (iii) population analysis of the circumnuclear low-mass hot stars
- Complementary info needed: distribution and kinematics of molecular gas (mapping of CO; *formation mechanism*) and atomic gas (mapping of [C II] and [O I] FIR lines with *Herschel*; *heating mechanism*)
- Observational constrains and modeling of the accretion flow and mechanical feedback of M31*