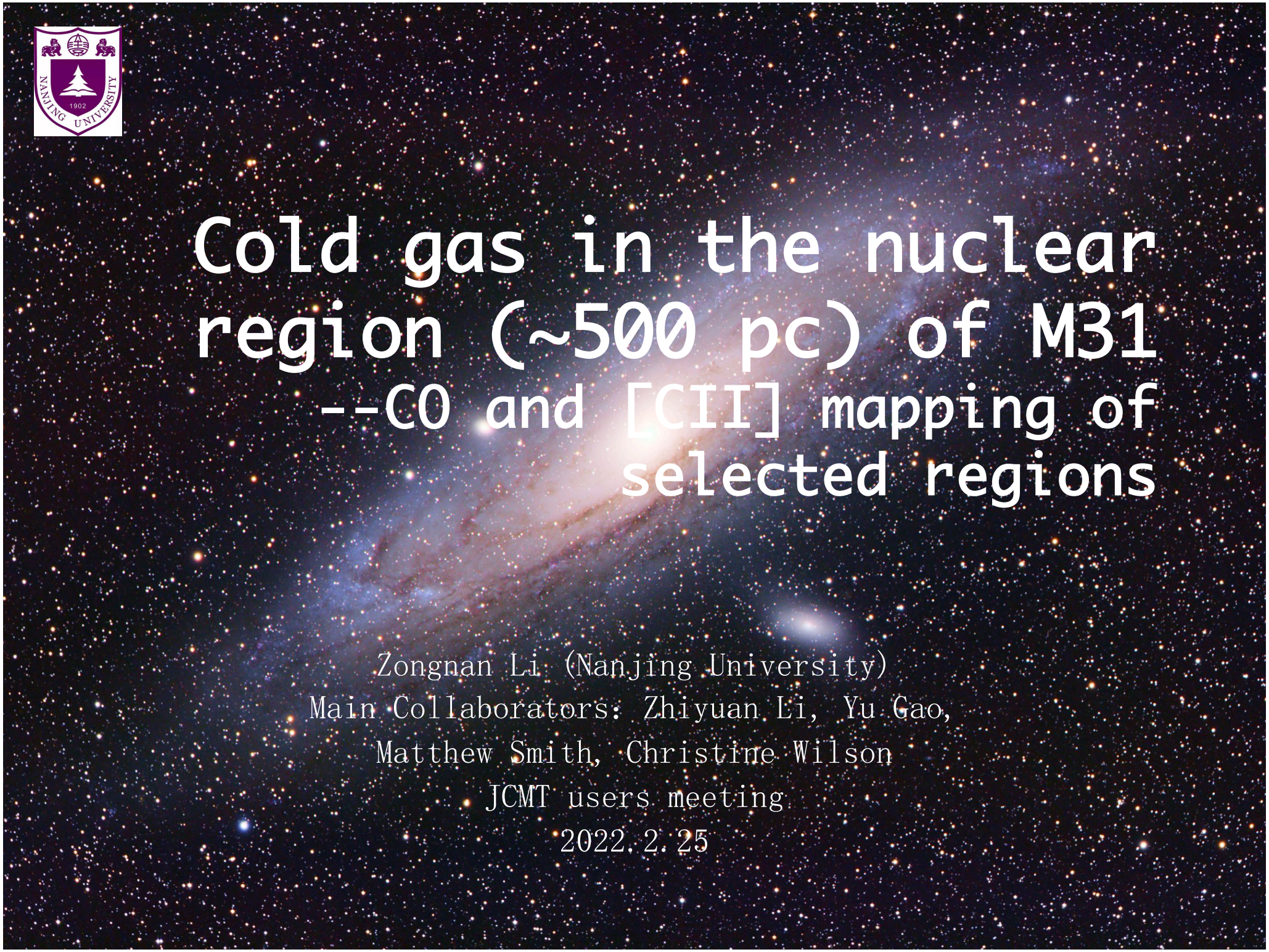


Cold gas in the nuclear region (~500 pc) of M31

--CO and [CII] mapping of selected regions

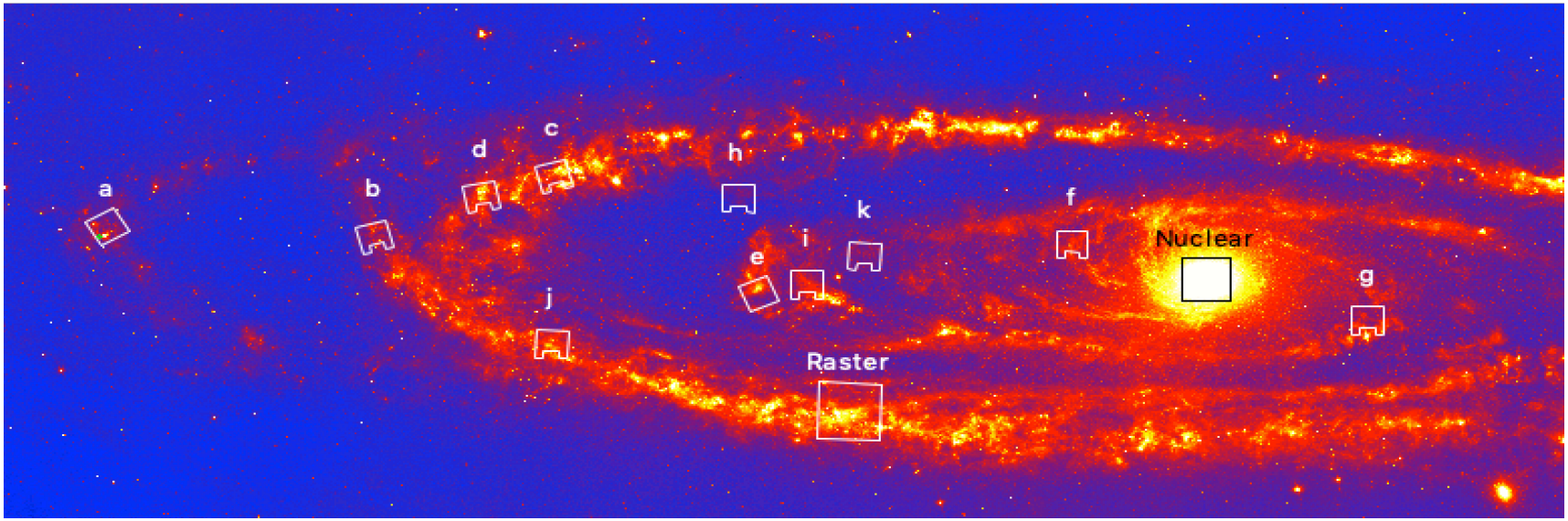
Zongnan Li (Nanjing University)
Main Collaborators: Zhiyuan Li, Yu Gao,
Matthew Smith, Christine Wilson

JCMT users meeting

2022.2.25

Background

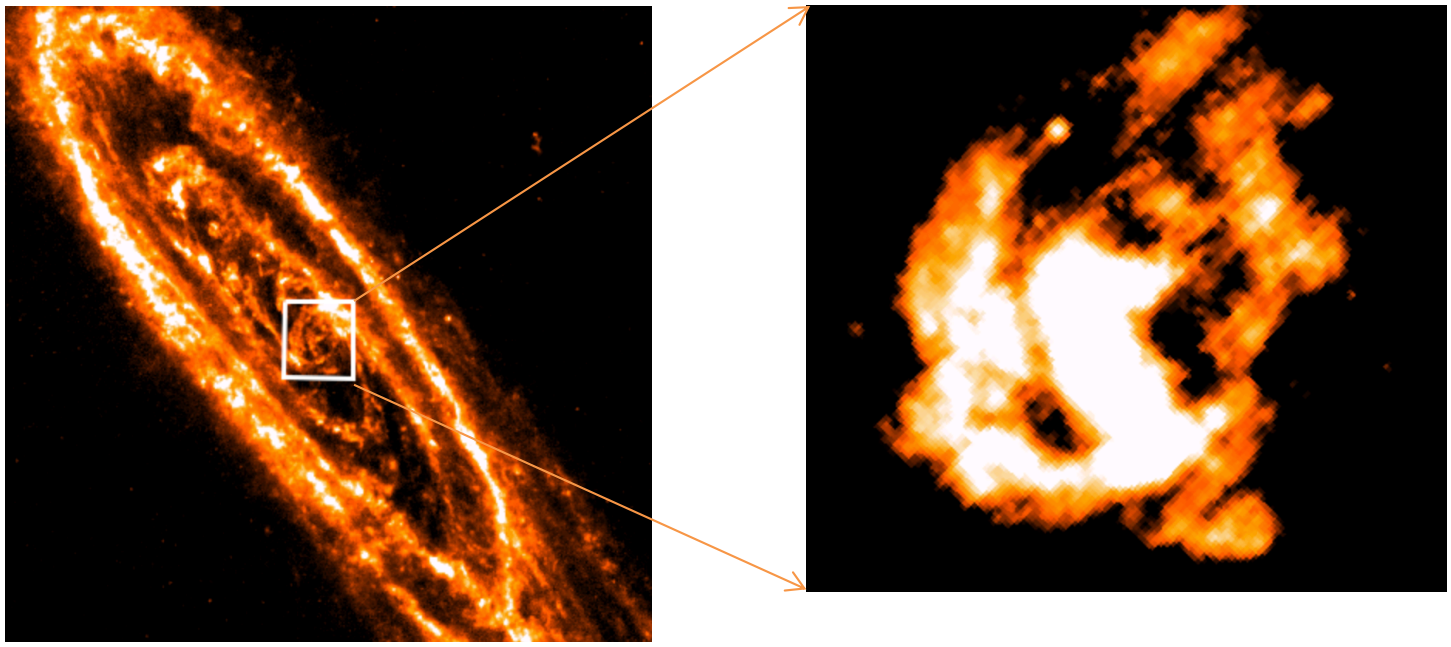
- Supermassive black hole (SMBH) and host galaxy coevolution: how does a SMBH influence the nuclear region? Physical properties of the interstellar medium (ISM).
- Why M31? Distance: 780 kpc, i.e. 1''≈ 4 pc: M31 is the nearest large spiral galaxy that can see the nuclear region from outside in detail.
- M31: similar to the Milky Way (MW), but has a much larger bulge and less obvious spiral arms, with most Star formation occurring in a 10 kpc ring. Good comparison to the MW.

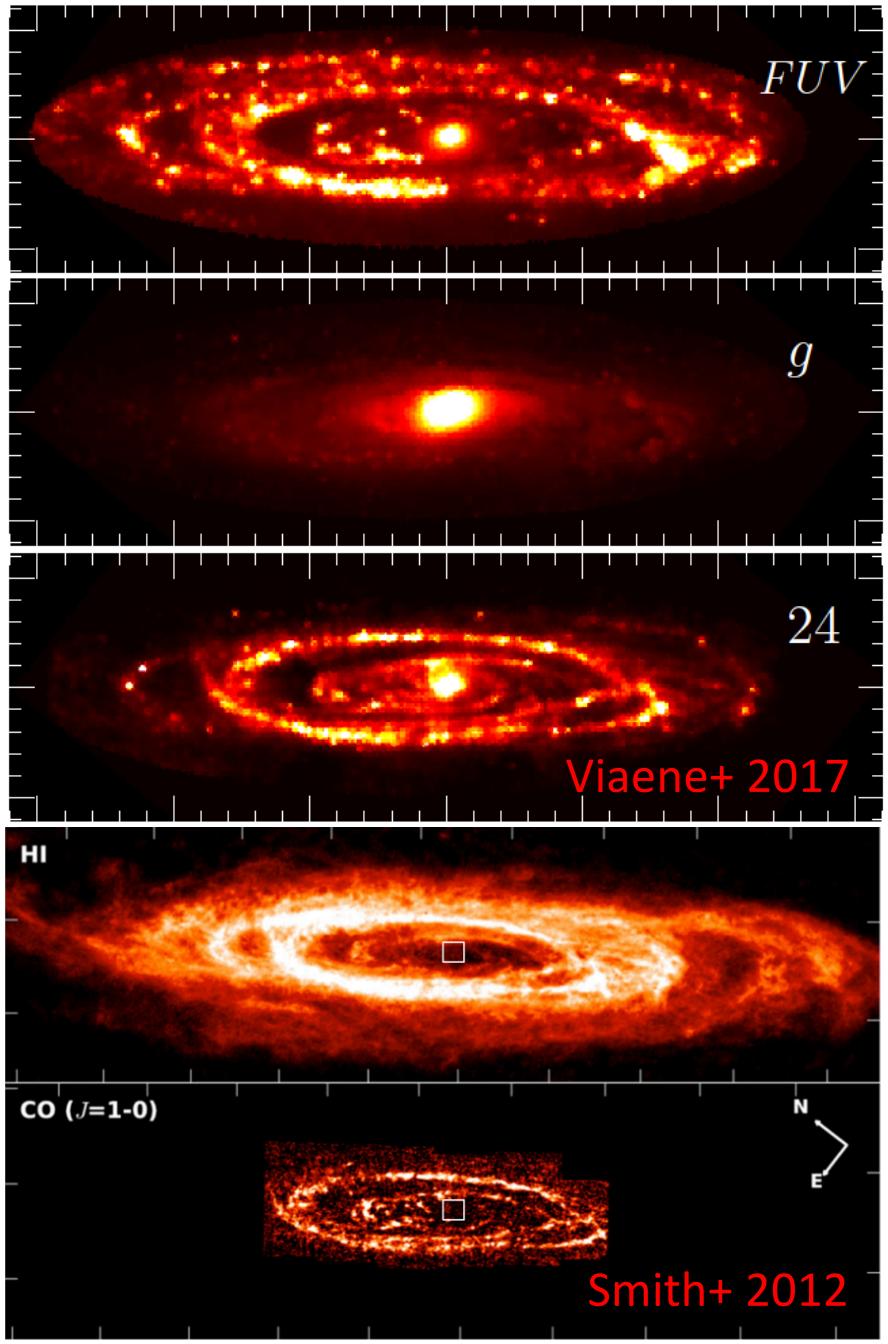


Nuclear region of M31

- A 1 kpc filament across the nucleus: nuclear spiral: how does it form? Interaction with other galaxy (e.g. M32, Block+ 2006) or bar resonance (Lewis+ 2015)?
- SMBH mass: ~ 10^8 $M_\odot$; luminosity: ~10^{-10} $L_{\rm Edd}$: little AGN activity
- Lack of recent SF and massive stars (Li+ 2009, Dong+ 2015)
- M31: the closest low-ionization nuclear emission line region (LINER): ionization mechanism?

Key to these questions: multiphase ISM!



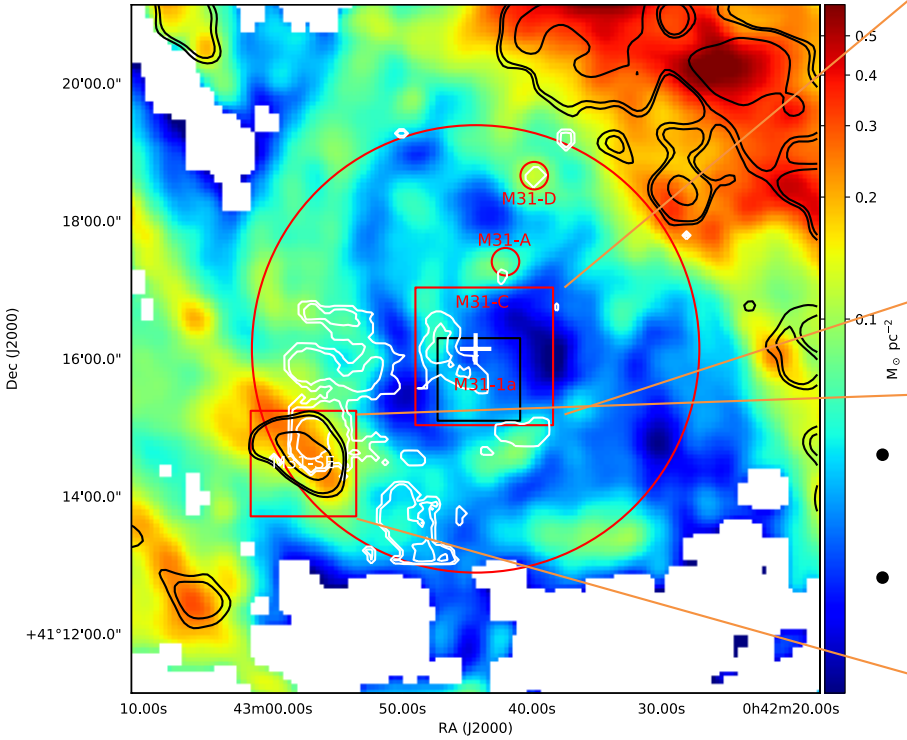


M31 in multiband

- Previous surveys show limited neutral gas detections in the circumnuclear region of M31. (e.g. Braun 2009, Nieten 2006)
- In comparison, the Milky Way has a central molecular zone (CMZ) that is rich in gas.

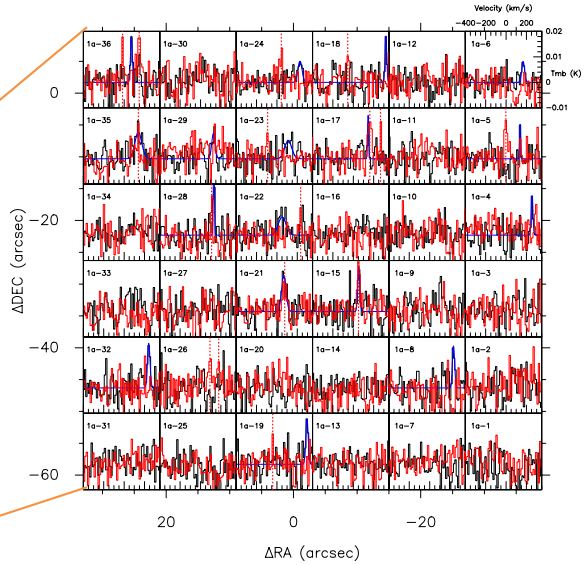
1. Molecular gas in the nucleus

- Deep CO(3-2) observations with 15 m JCMT/HARP raster mode (25 hrs):
- First CO(3-2) survey covering central ~ 3' radius

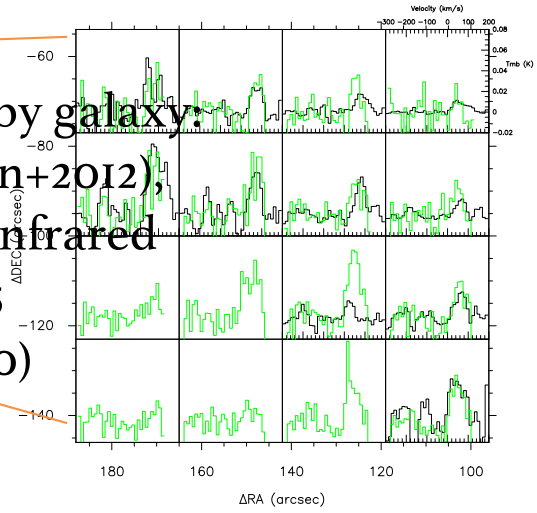


Color map: dust mass surface density.
White contour: CO(3-2). Black contour: CO(1-0).

CO(3-2)/CO(2-1)~0.8



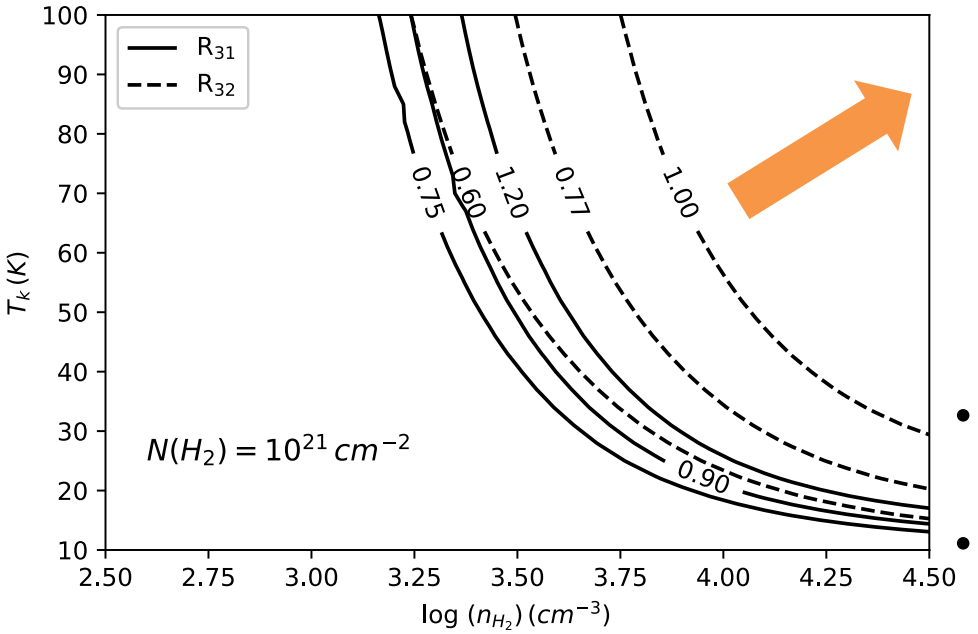
CO(3-2)/CO(1-0)~0.9



- Other nearby galaxy: ~0.2 (Wilson+2012),
- Luminous infrared galaxy: ~0.5 (Leech+2010)

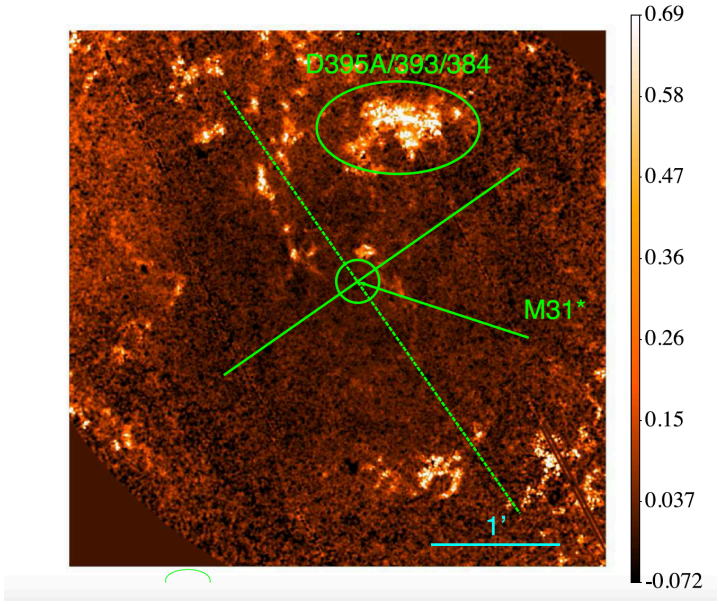
Molecular gas properties

- Large velocity gradient (LVG) assumption with RADEX code:
- CO(3-2)/CO(1-0) (R_{31}) ~ 0.90: T_k > 20 K and n(H_2) > 4 x 10^3 cm^{-3};
- CO(3-2)/CO(2-1) (R_{32}) ~ 0.8 : T_k > 30 K and n(H_2) > 2 x 10^3 cm^{-3}.



HST extinction map (A547M, Dong+ 2016):

- A<1 -> low column density.
- Rotation pattern, nuclear disk -> low density: n(H_2)~ 10^3 – 10^4 cm^{-3}.

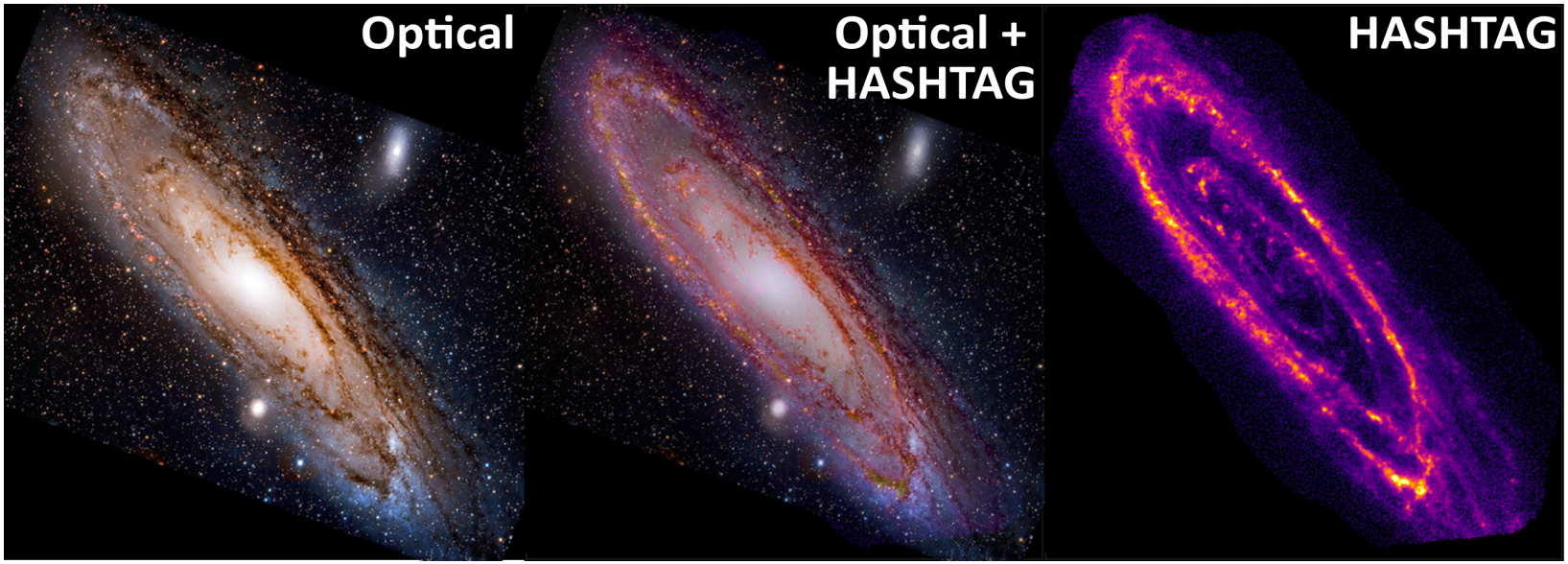


- Molecular gas mass: 3.7 x 10^5 $M_\odot$, compared to ~ 10^7 $M_\odot$ in Milky Way CMZ.
- H_2/dust ratio: ~ 30 in the central region: higher metallicity (Draine+ 2014)

2. HARP and SCUBA-2 High-Resolution Terahertz Andromeda Galaxy Survey (HASHTAG)

- JCMT large program: first ground-based submillimeter continuum survey of the Andromeda. (273.6 hr)
- SCUBA-2: 450 μm (25 pc) and 850 μm (50 pc) very cold dust survey for entire M31.

PI: Matthew Smith
Observing Manager: Yu Gao
Spectroscopy data reduction lead: Zhiyaun Li & I

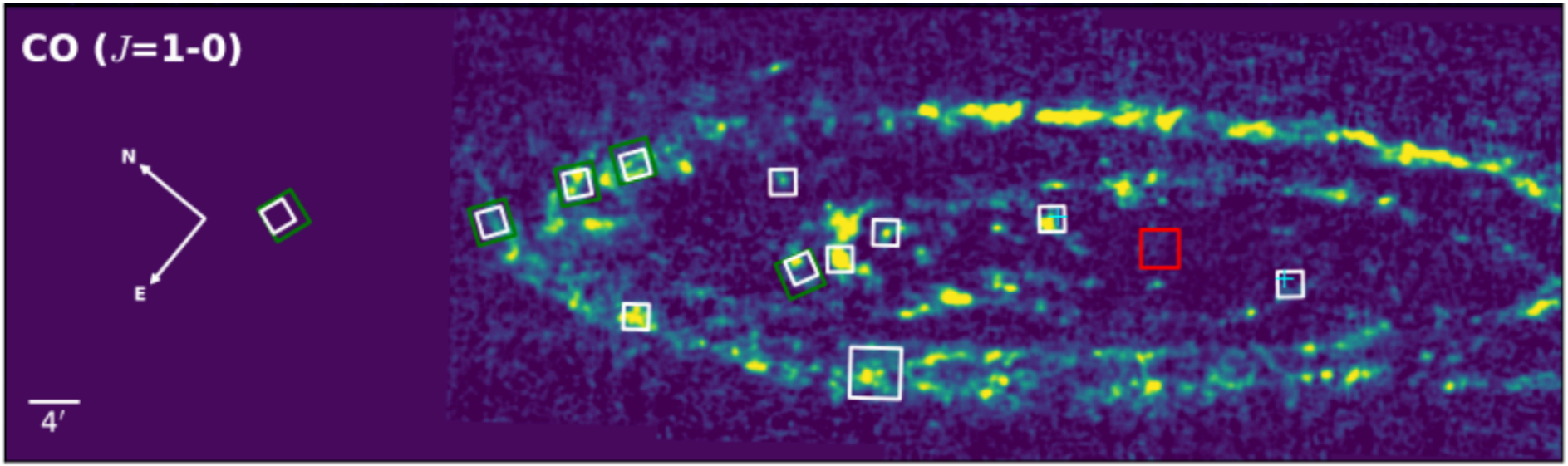


HARP CO observations

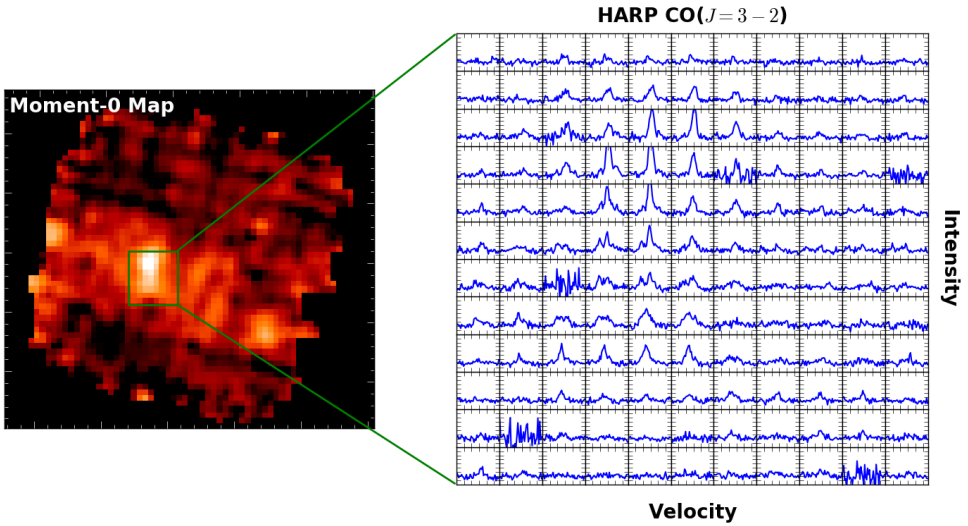
- HARP CO(3-2) observations: Eleven 2’ x 2’ jiggle fields, one 4’ x 4’ raster field (55.3 hours in total). Mean rms: 0.013 K T_A^*

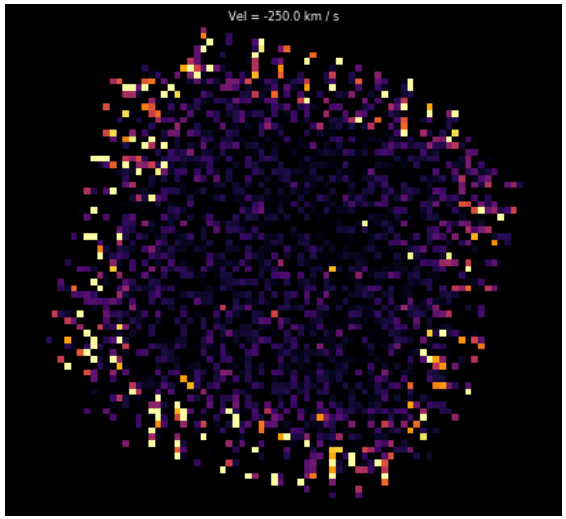
1. Five regions covered by Herschel and optical IFU spectroscopy
2. Two regions where it has been suggested to have a component of very cold gas
3. Four in the area observed by PHAT, CARMA and the IRAM CO(1-0)/CO(2-1)

- For now: focusing on the CO(3-2)/CO(1-0) ratio.



CO(3-2) in the disk

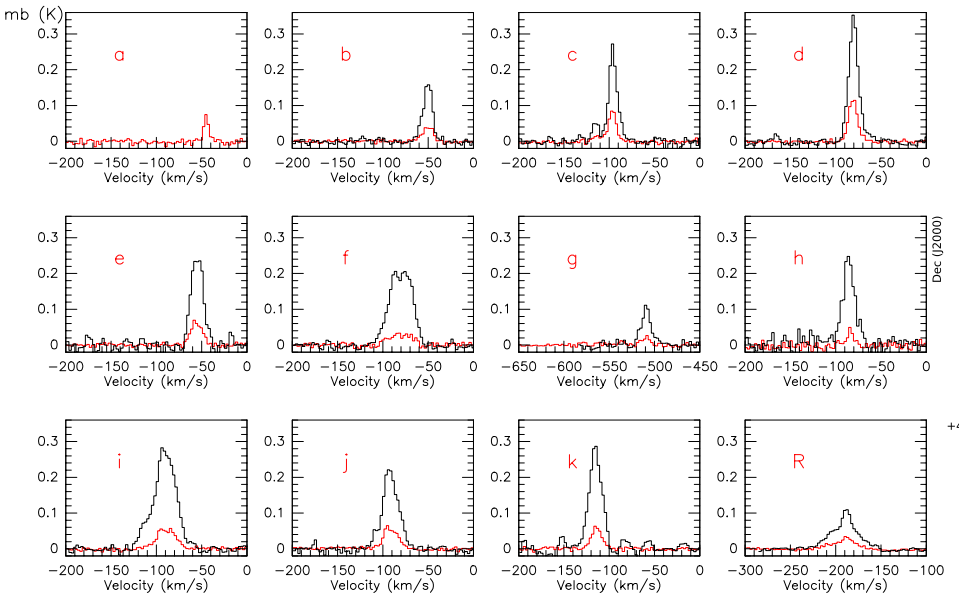


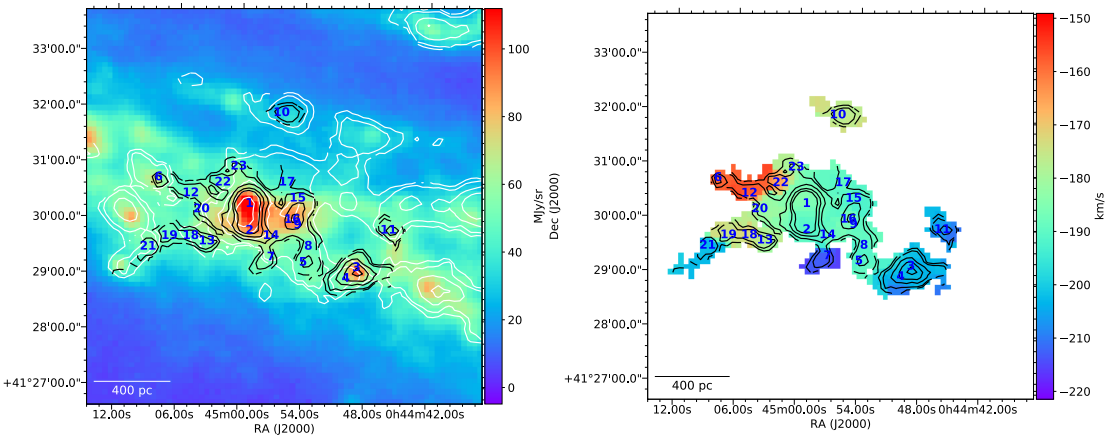


Black: CO(1-0), red: CO(3-2)

Credit: Matt Smith

Findclump to label clumps in 3D

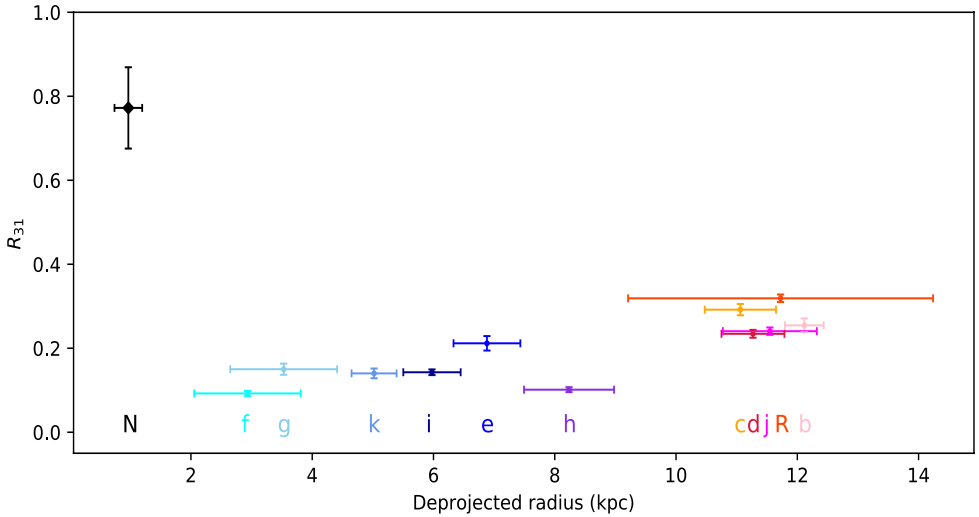




Color map: dust, black contour: CO(3-2), white contour: CO(1-0)

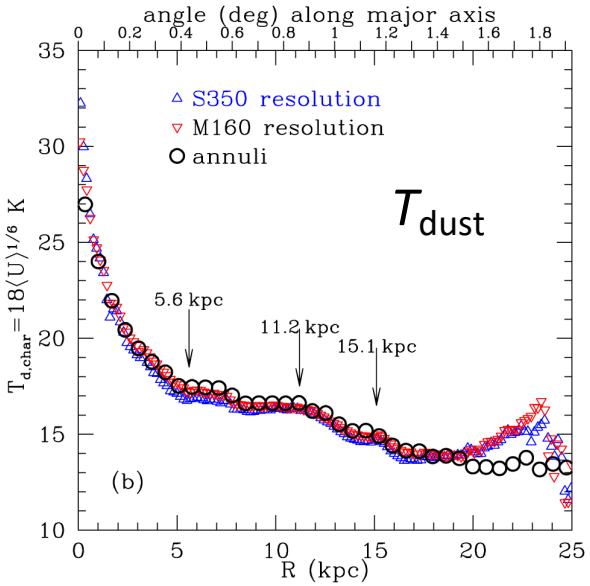
CO(3-2)/CO(1-0) ratio (R_{31})

- Nuclear region: ~0.8
- Mean ratio of the 10 kpc ring: 0.27
- Mean ratio of the inner disk: 0.14

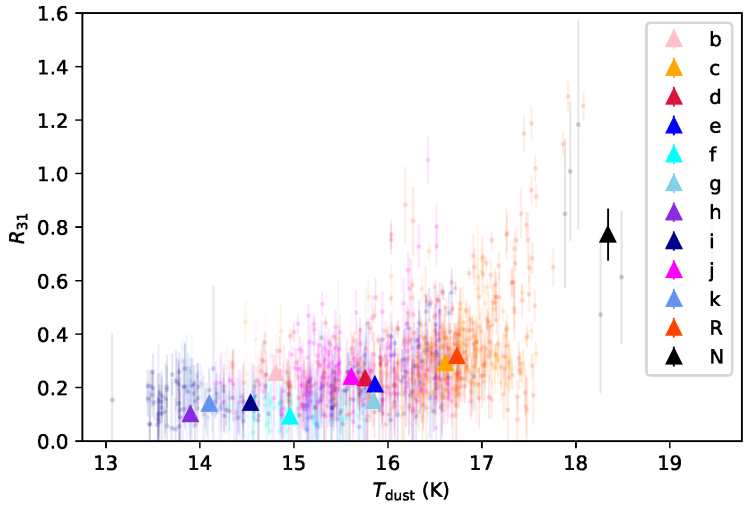


- M31 Nucleus: ~0.8, Disk: ~0.23.
- Galactic center: ~0.7, Galactic disk: ~0.4 (Oka et al., 2012)

- LVG model: The lowest value 0.14 only requiring a kinetic temperature > 5 K.



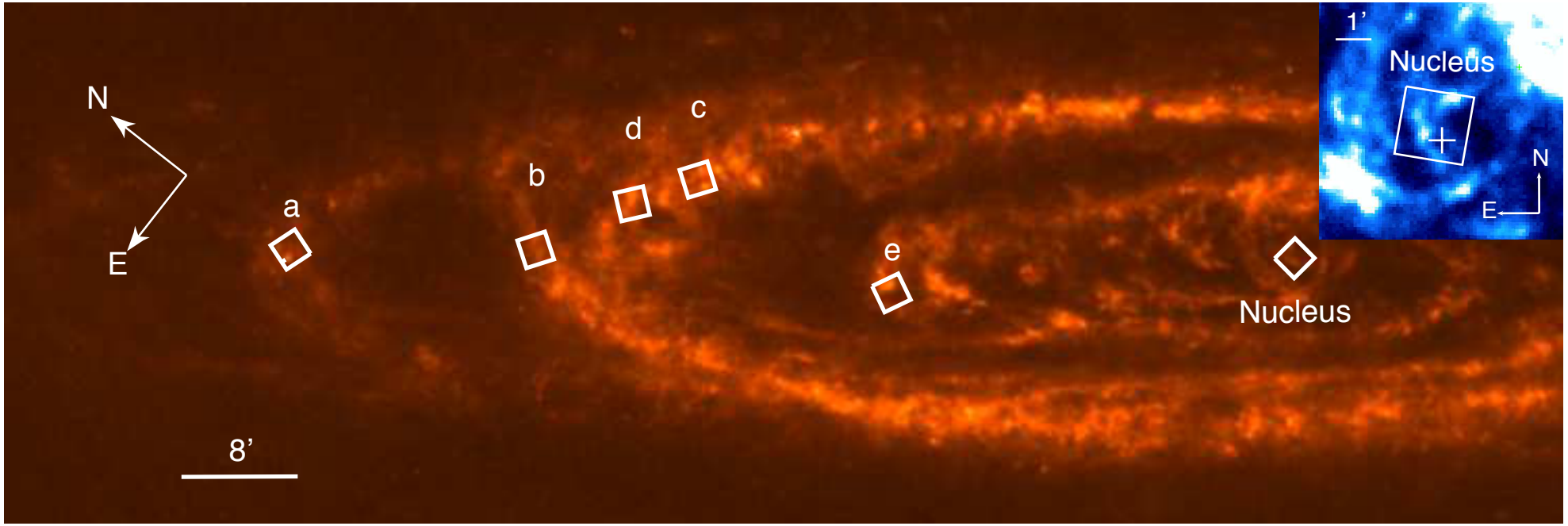
Draine et al. 2014



- Dust temperature – R_{31}: Spearman's rank correlation coefficient ρ: 0.55, p-value: < 0.001

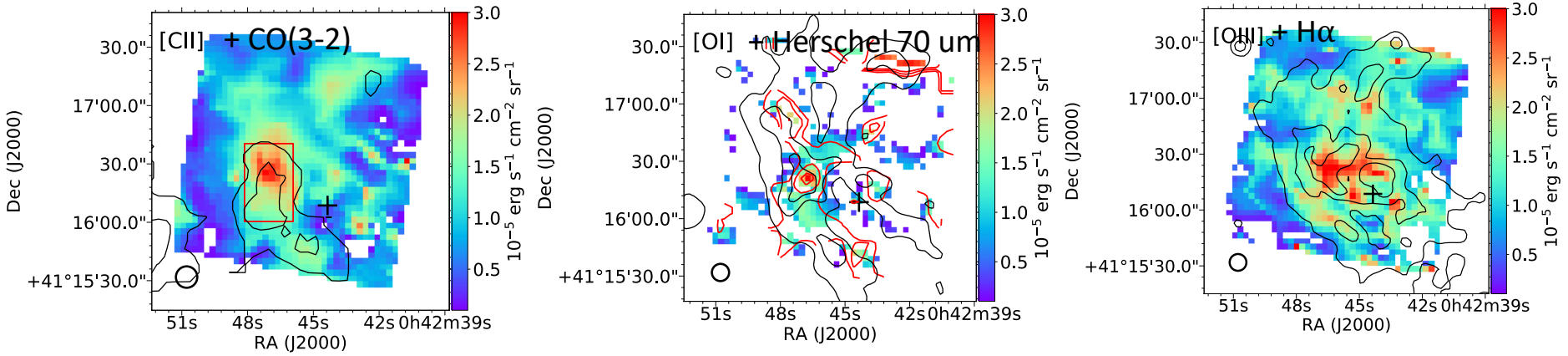
3. FIR lines in the circumnuclear region of M31

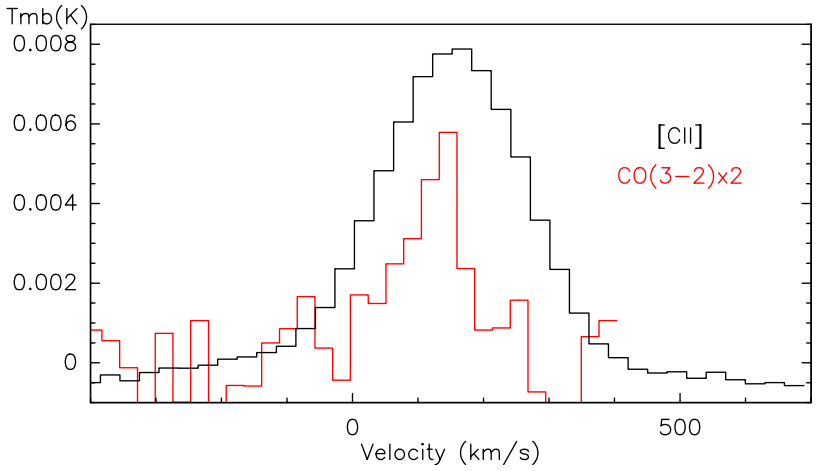
- Herschel PACS observation of [CII] 158 μm, [OI] 63 μm and [OIII] 88 μm, covering a 2’ x 2’ region in the center (‘Nucleus’).
- O++: ionized gas; C+: exists in ionized, atomic, molecular gas; O: neutral gas -> physics in photodissociation region (PDR)
- Five 3’ x 3’ fields on the disk, from Kapala et al. (2015), mainly [CII]. (‘a-e’)

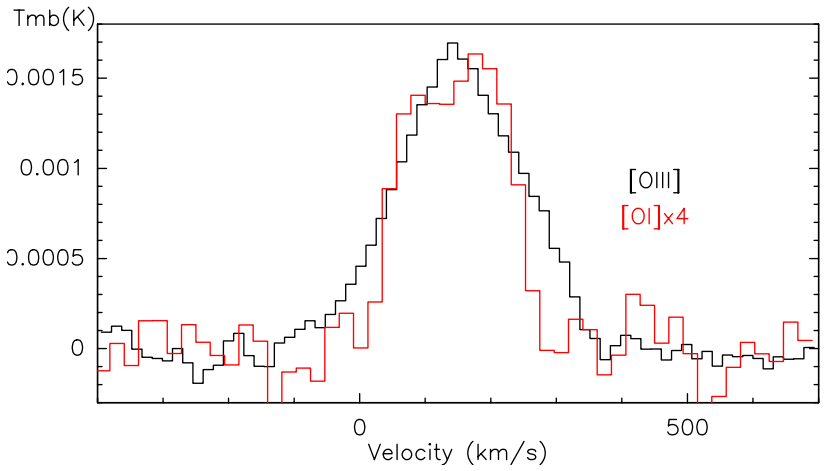


Morphology and kinematics

- [CII], [OI] consistent with CO and dust emission
- [OIII] consistent with Hα emission
- [OI] has double components: from two different arms



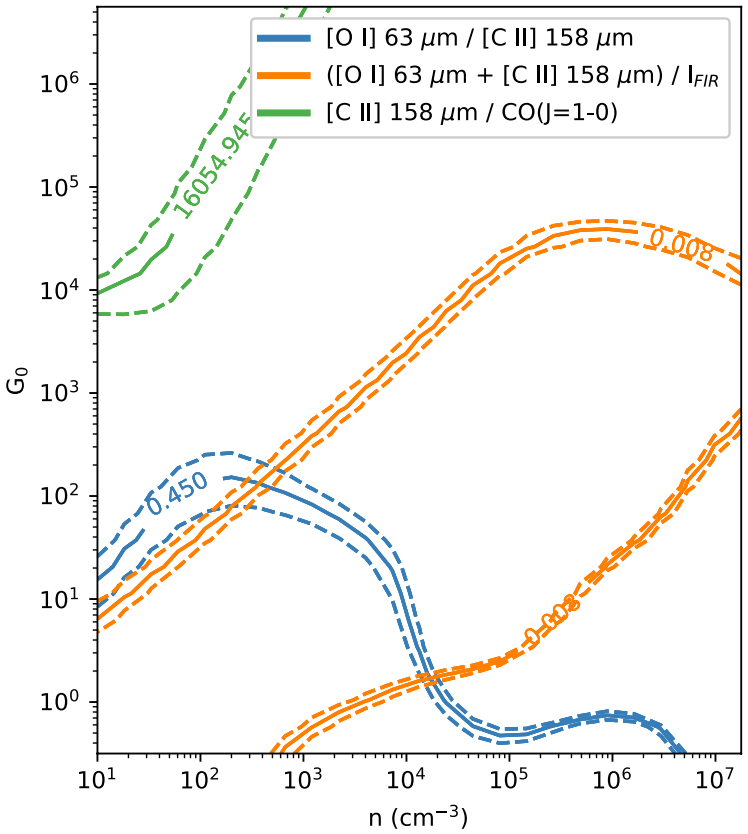




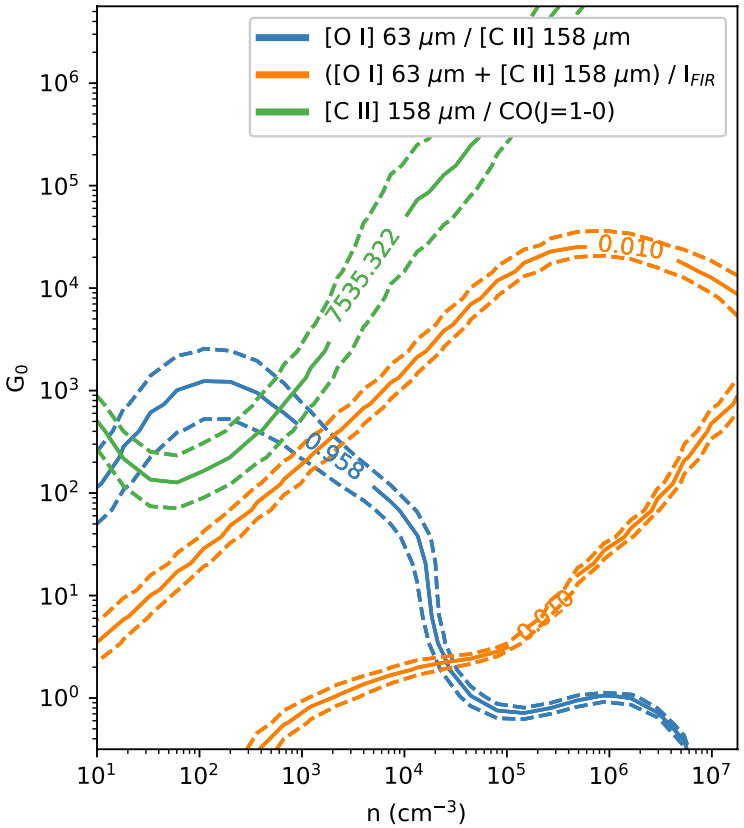
PDR modeling

- Photo Dissociation Region Toolbox (PDRT; Pound & Wolfire 2008; Kaufman et al. 2006): 2D slab PDR illuminated by FUV from one side.
- [OI]/[CII], ([OI]+[CII])/FIR, [CII]/CO(1-0) ratios as diagnostics to constrain gas density n (cm^{-3}) and incident FUV intensity G0 (1.6×10^{-3} erg cm^{-2} s^{-1}).

Uncorrected



Corrected:
53% [CII] from ionized gas (Lapham et al. 2017)
Illuminated from both sides: FIR/2



Best-fit:
n: 10^3
G0: 3.16×10^2

Milky Way:
n: $10^{3.5\text{-}4}$
G0: 1-30
(Pineda et al. 2013)

Take home messages

- R_{31} ratio is higher in the central region (0.8) than in the disk (0.14), and rise again in the 10 kpc ring (0.27).

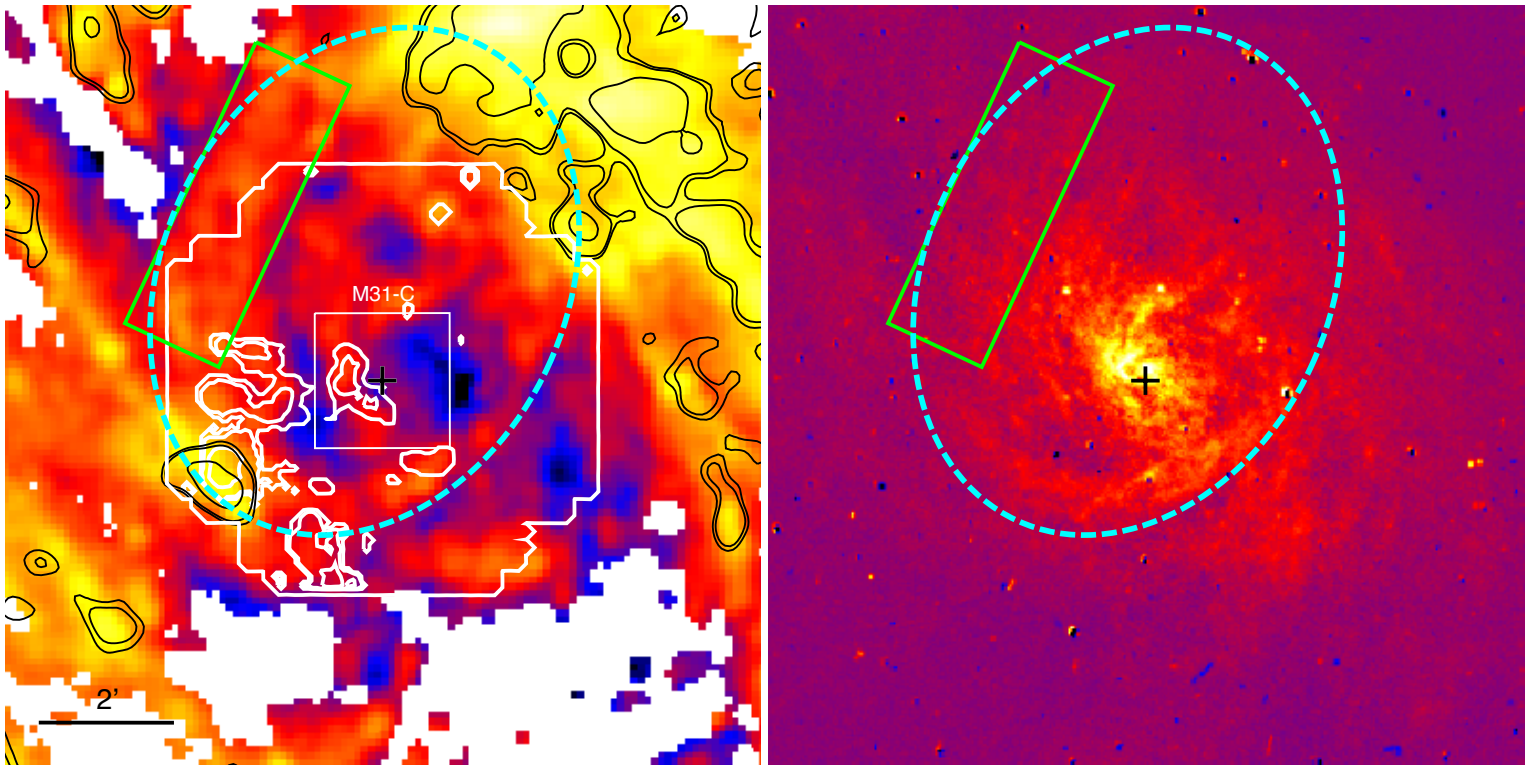
- From PDR modeling, we can derive gas density n ~ 10^3 cm^{-3} and FUV intensity G0 ~ 3.16 x 10^2 (in units of 1.6 x 10^{-3} erg cm^{-2} s^{-1}).

Cold gas in the circumnuclear region is little but hot, and suffered from a high radiation field!

Follow-up programs

Follow-up IRAM 30m CO(1-0) and JCMT CO(3-2) mapping of the nuclear region:

- Help reveal the origin of the nuclear spiral.
- Complementary of HASHTAG CO observations.



Left: dust surface density map (Groves 2012). Right: Hα map. Dashed ellipse marks the nuclear ring.