ブラックホール大研究会

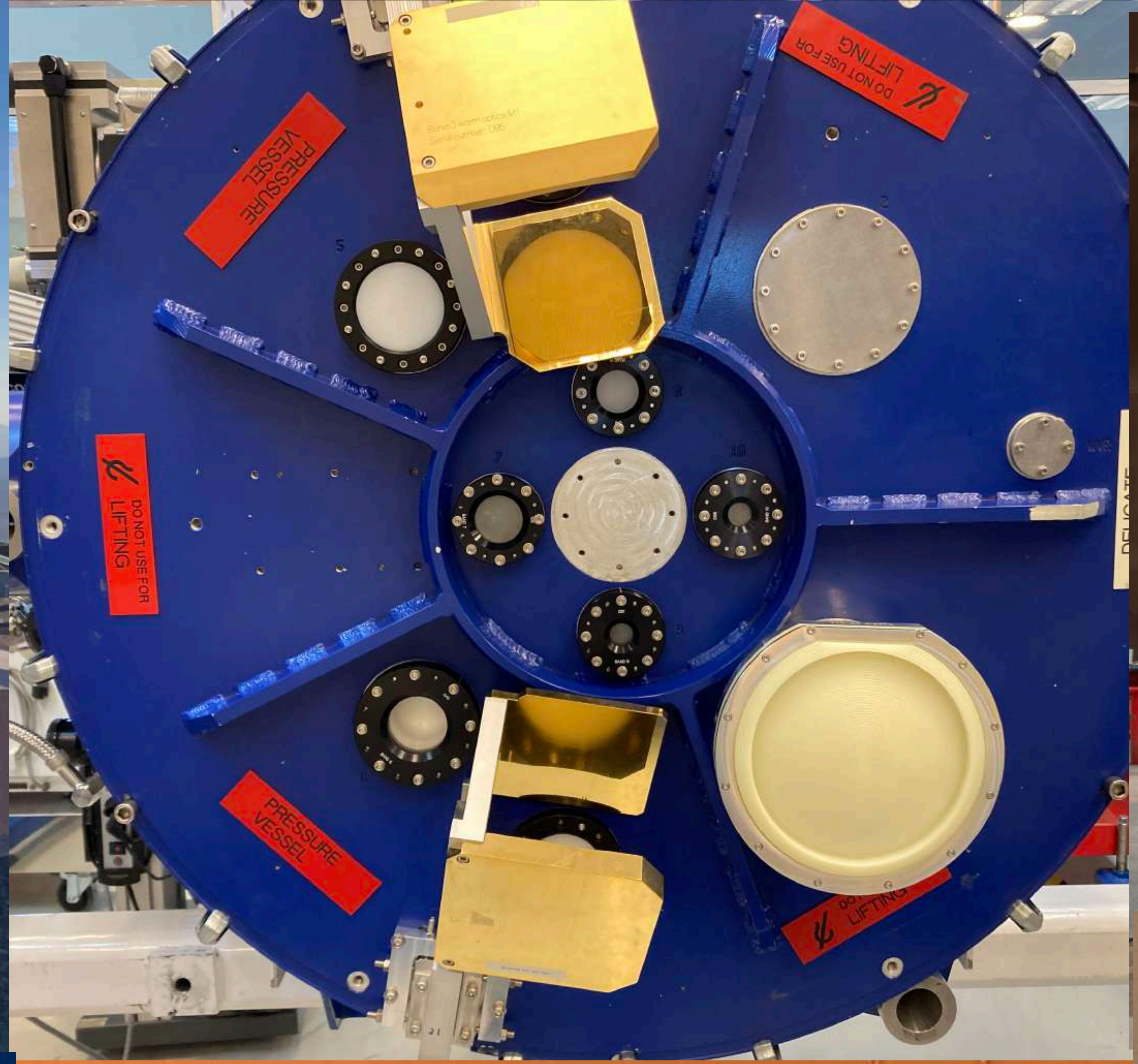
2024年2月28日~3月1日＠御殿場

ALMA望遠鏡が切り開いたAGN研究の最前線

泉 拓磨（国立天文台/総研大）

Atacama Large Millimeter/submillimeter Array

- World largest mm/submm interferometer at alt. 5000 m
- EA (incl. Japan), NA, EU, and Chile collaboration
- 50 × 12m antennas + ACA (12 × 7m + 4 × 12m antennas)
- Max. baseline: up to ~16 km (→ ~0.02”)
- Frequency coverage: 31 GHz - 950 GHz (Band 1 to 10)
- Antennas are reconfigurable


ALMA

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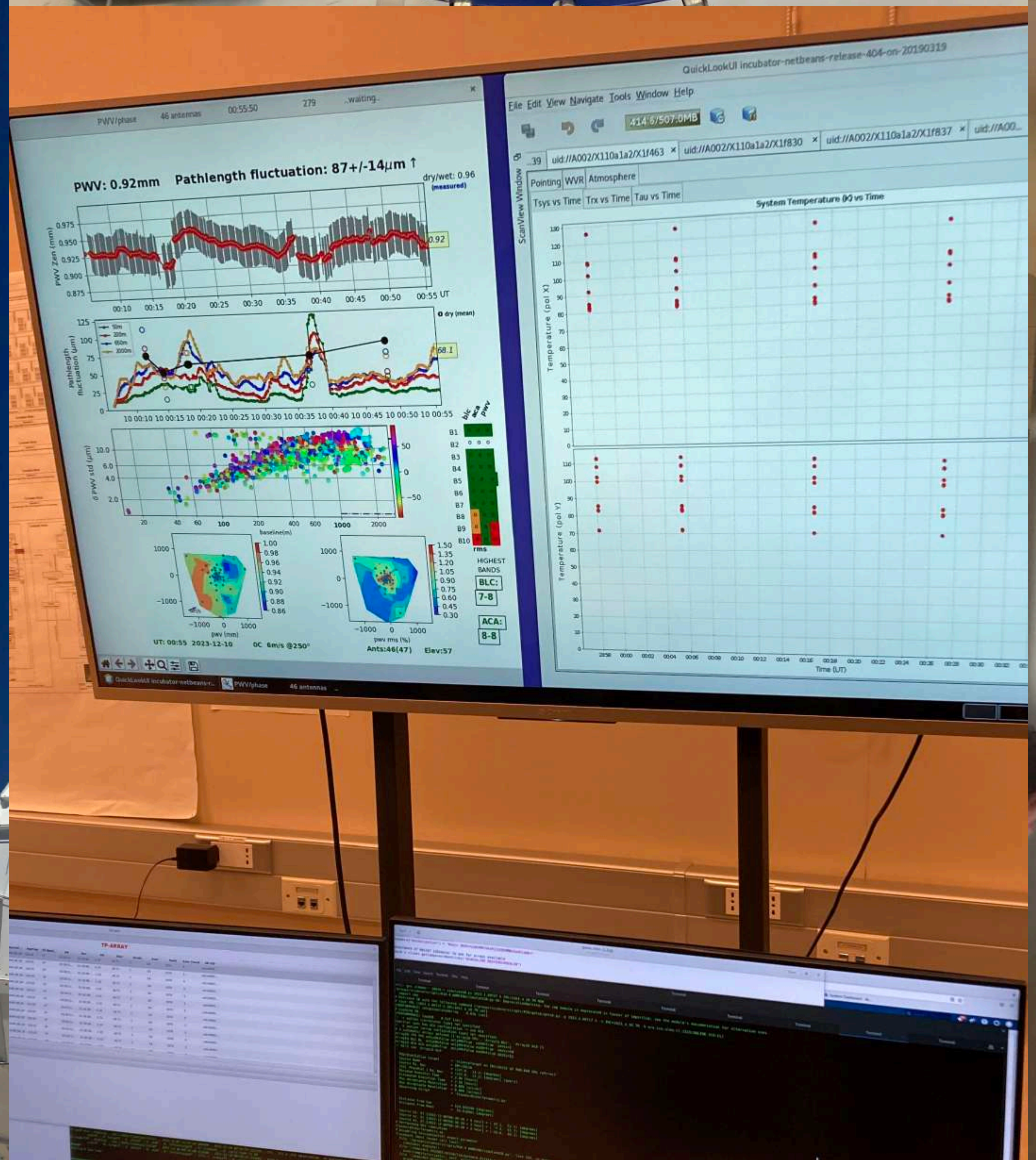
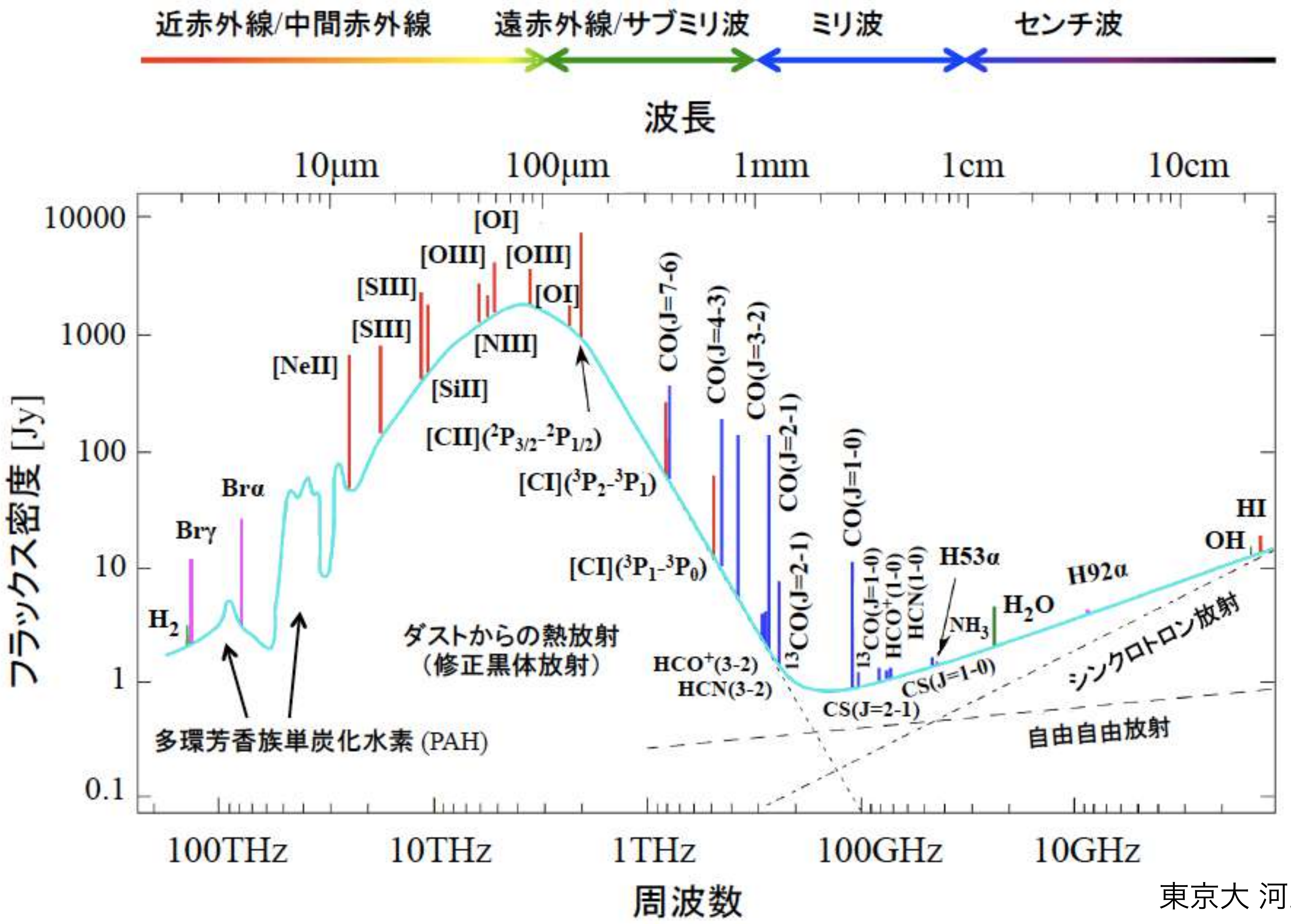
SCHEUERLE
ALMA


PWV: 0.92mm   Pathlength fluctuation: 87+/-14μm ↑
System Temperature (K) vs Time

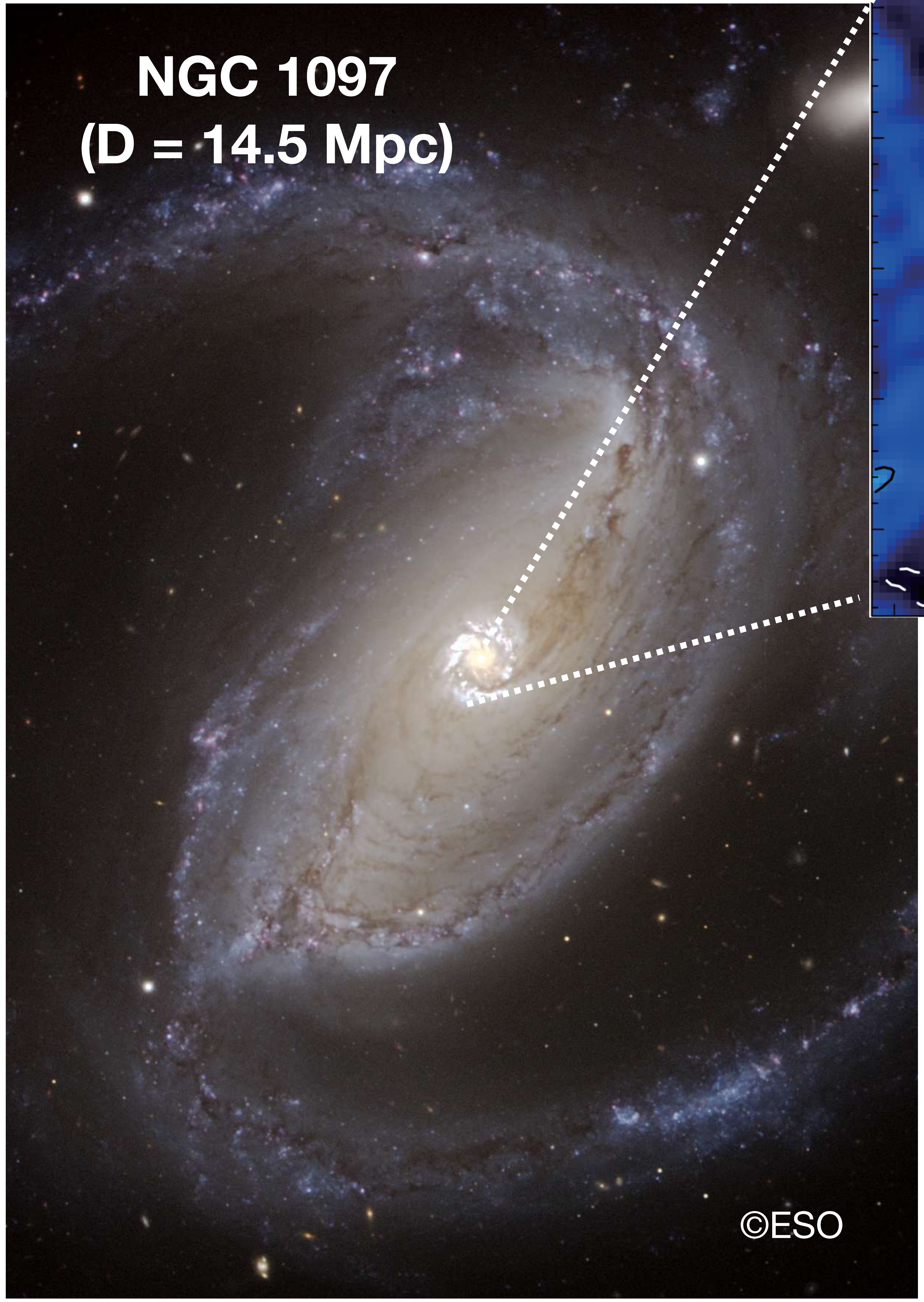

Basic observables

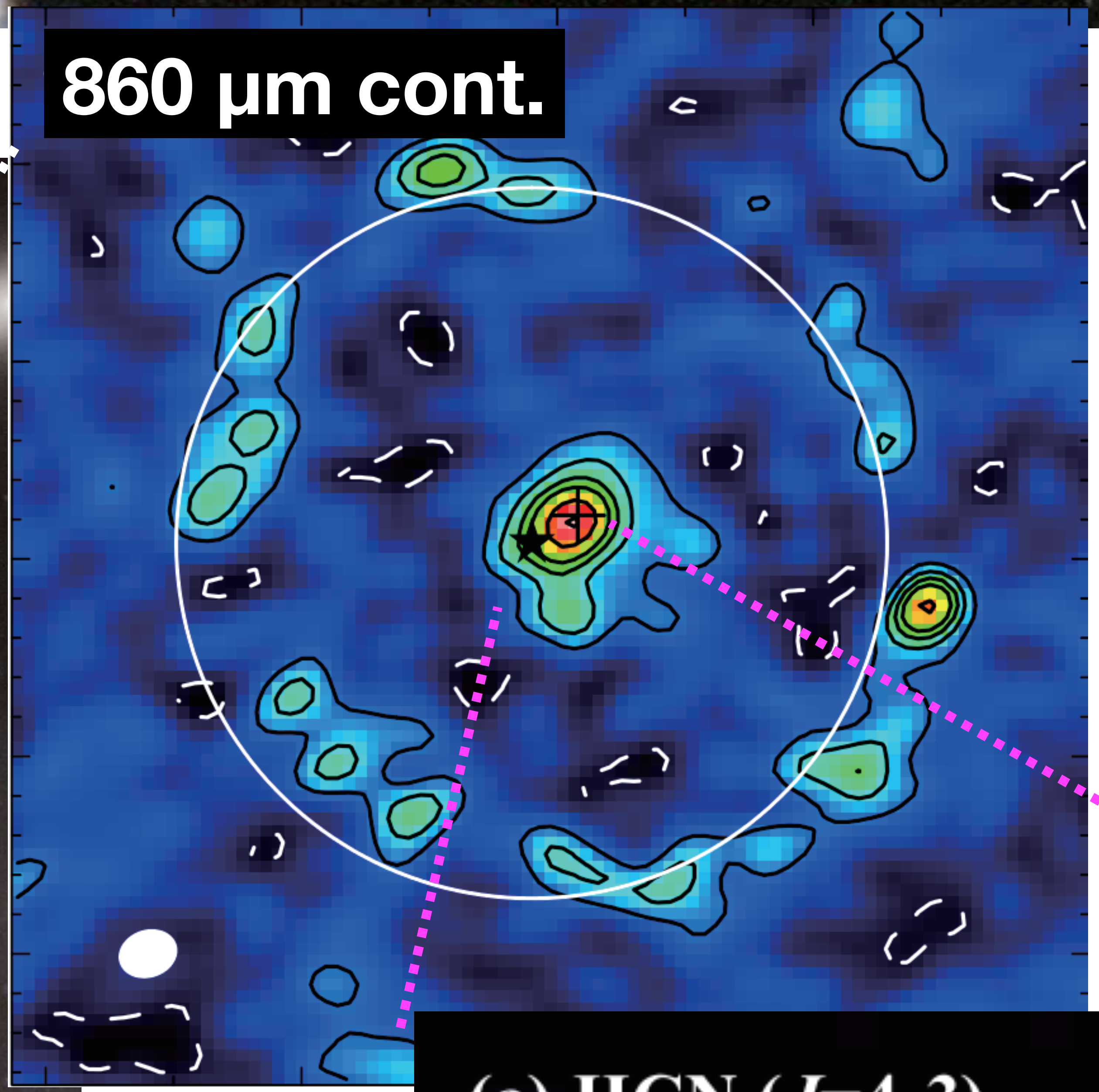


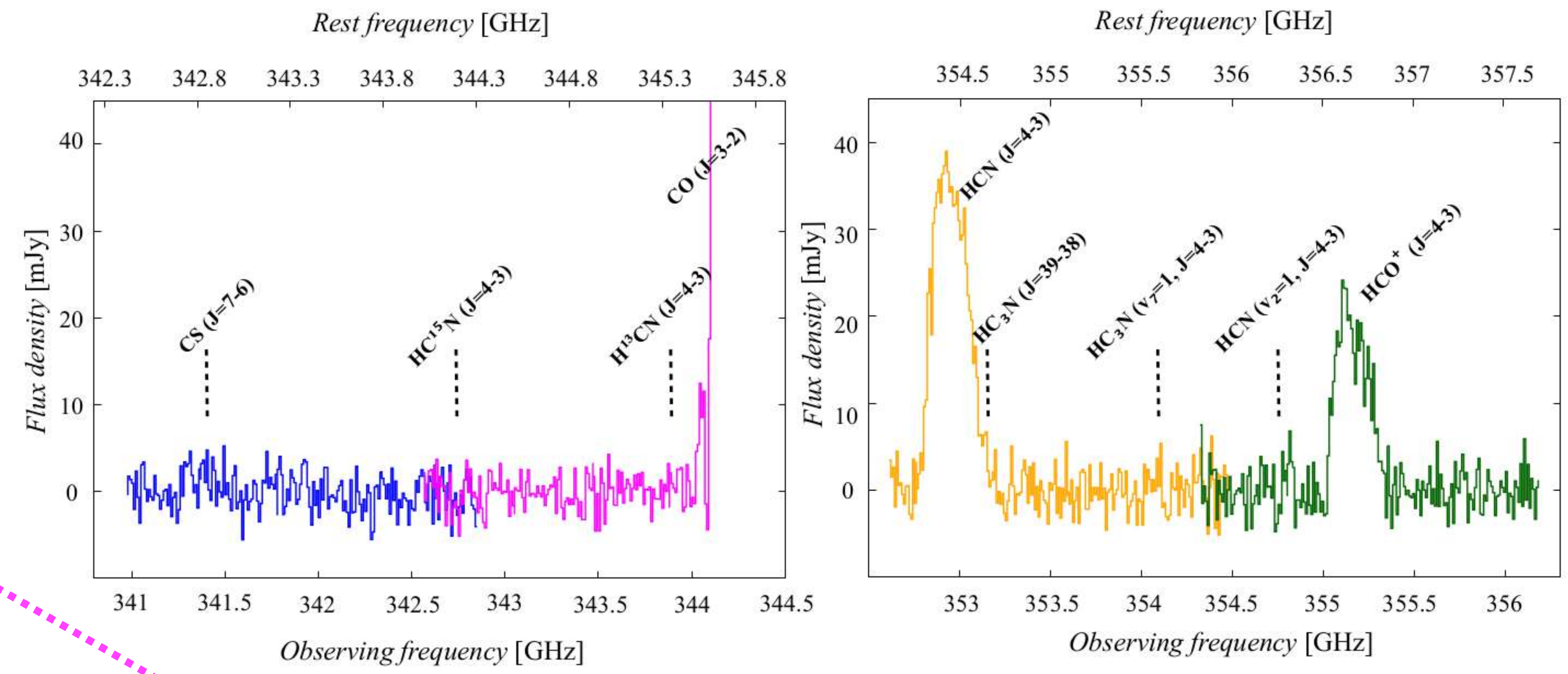
東京大 河野研究室HPより

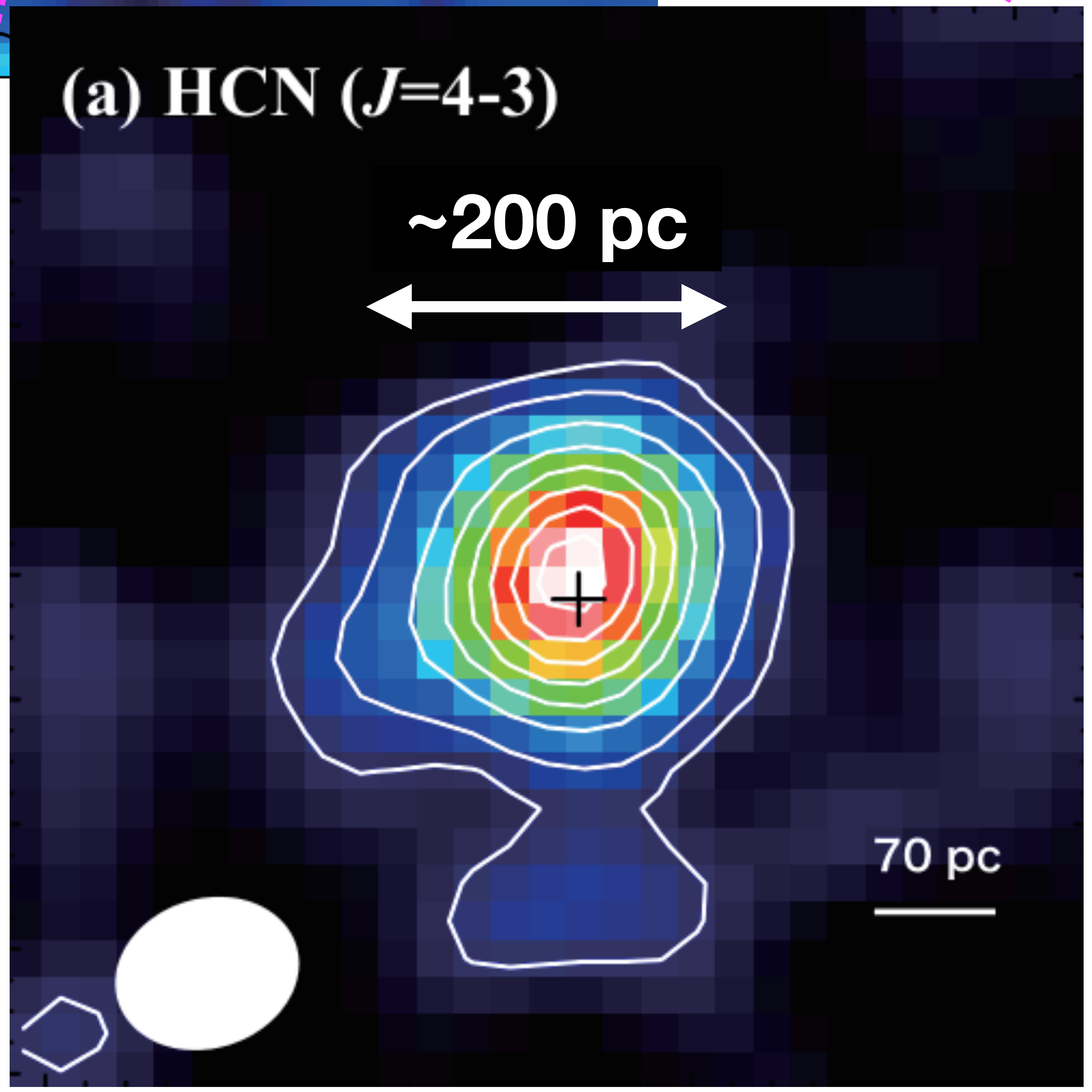
- Molecular rotational lines (CO, HCN, HCO+, …)
- Fine structure lines ([CII], [OIII], [OI])
- Hydrogen recombination lines (Hnα)
- Thermal dust continuum
- Synchrotron continuum
- Free-free continuum

My first paper (Izumi et al. 2013)



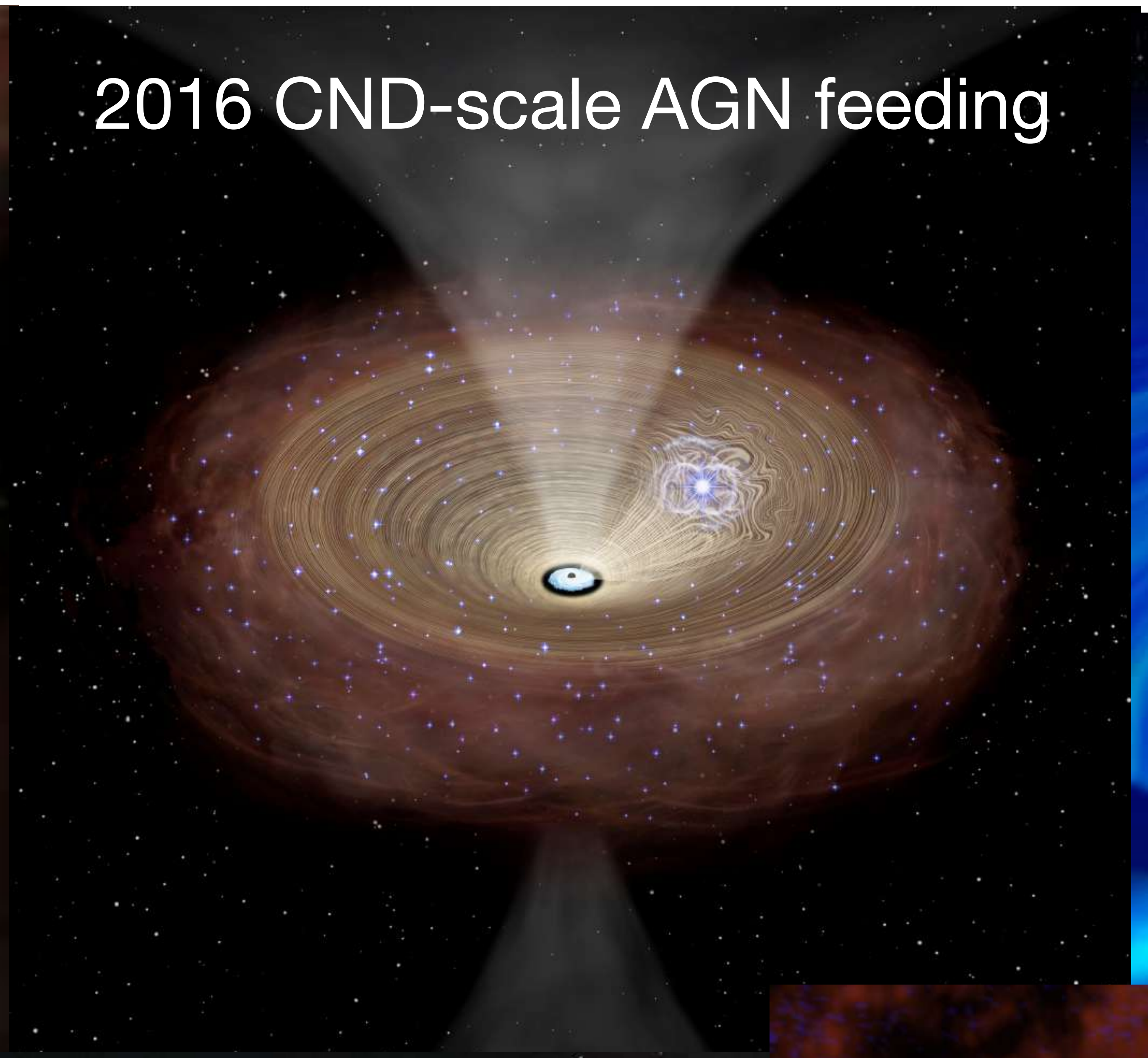


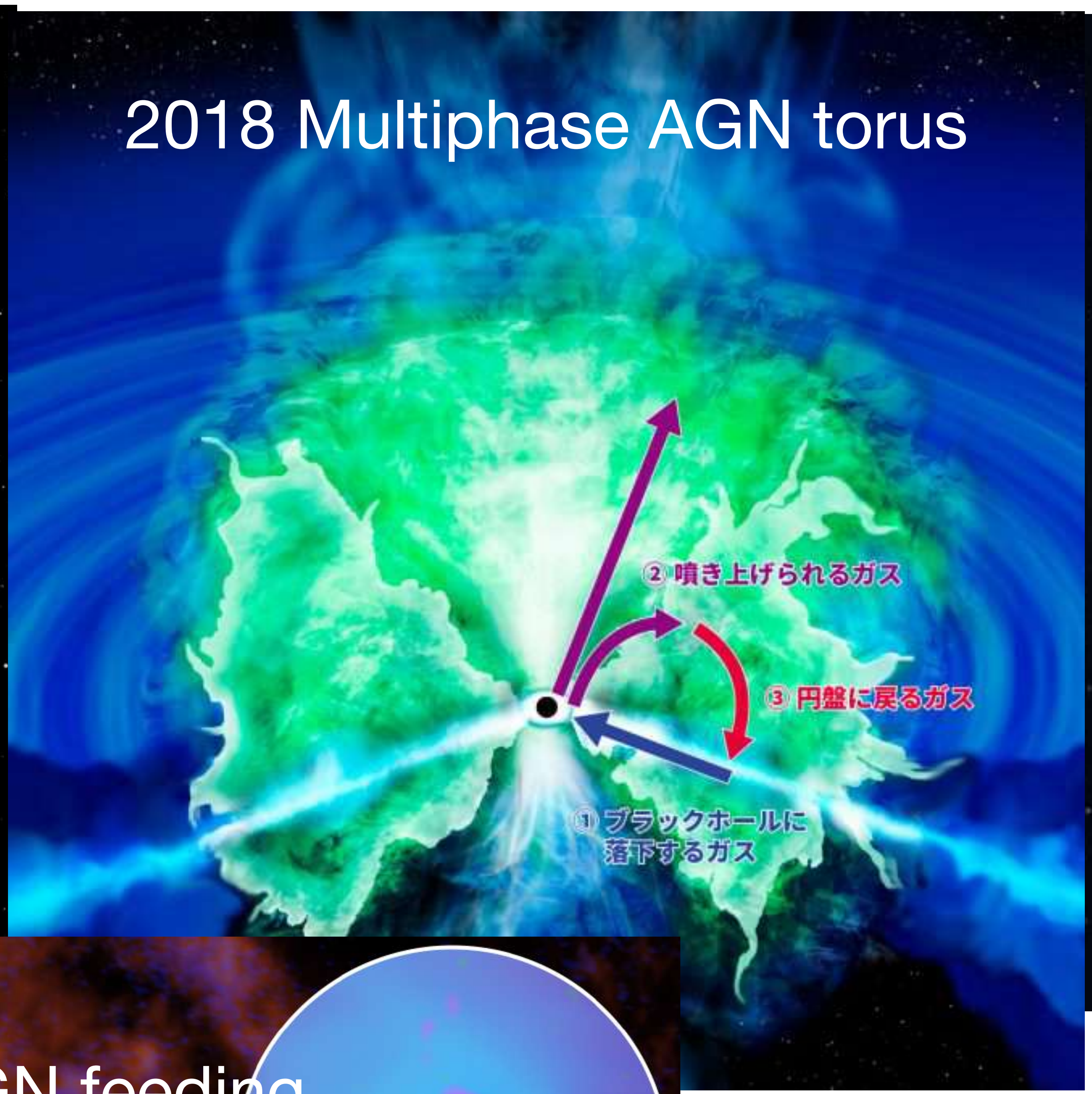


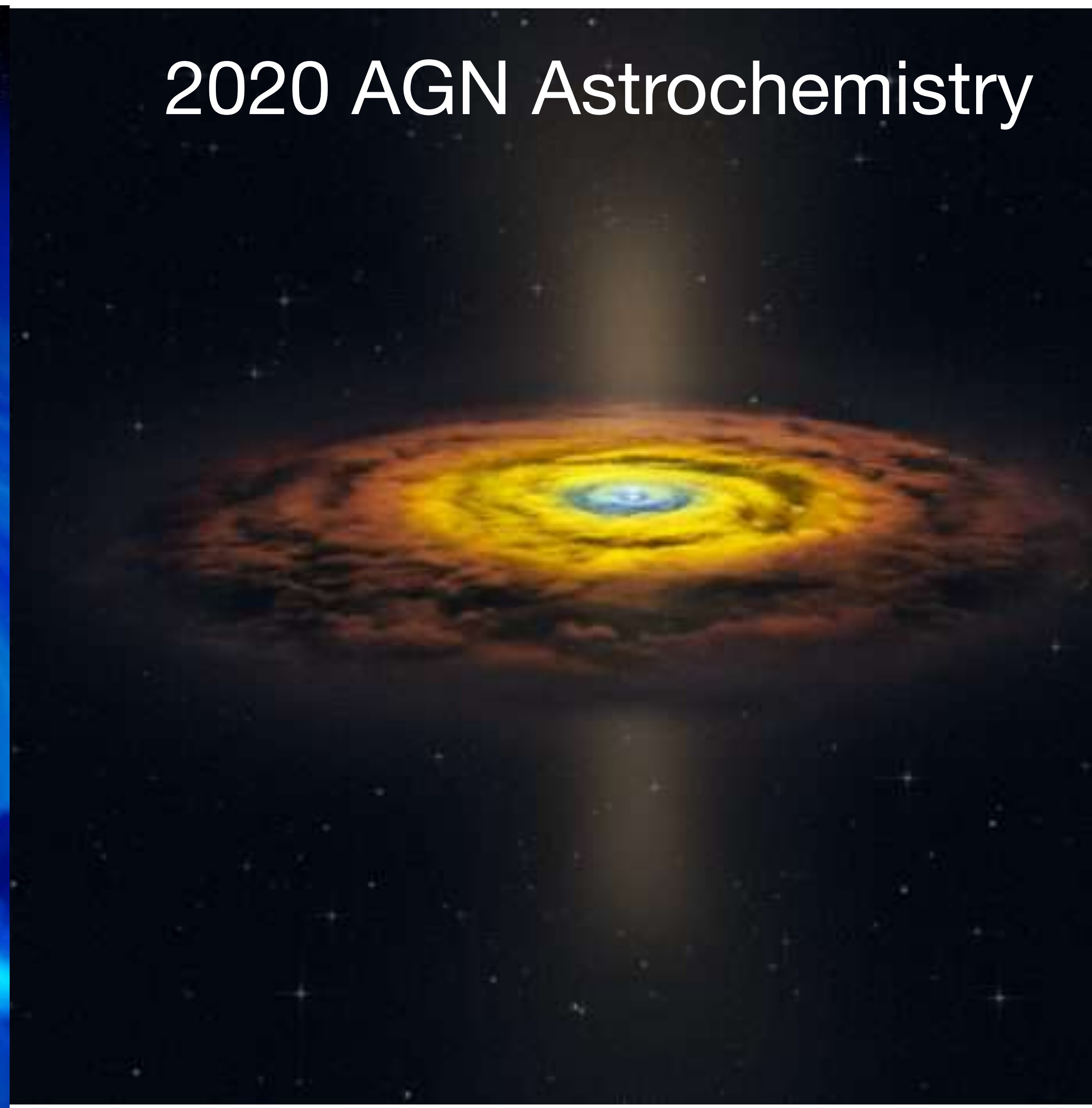


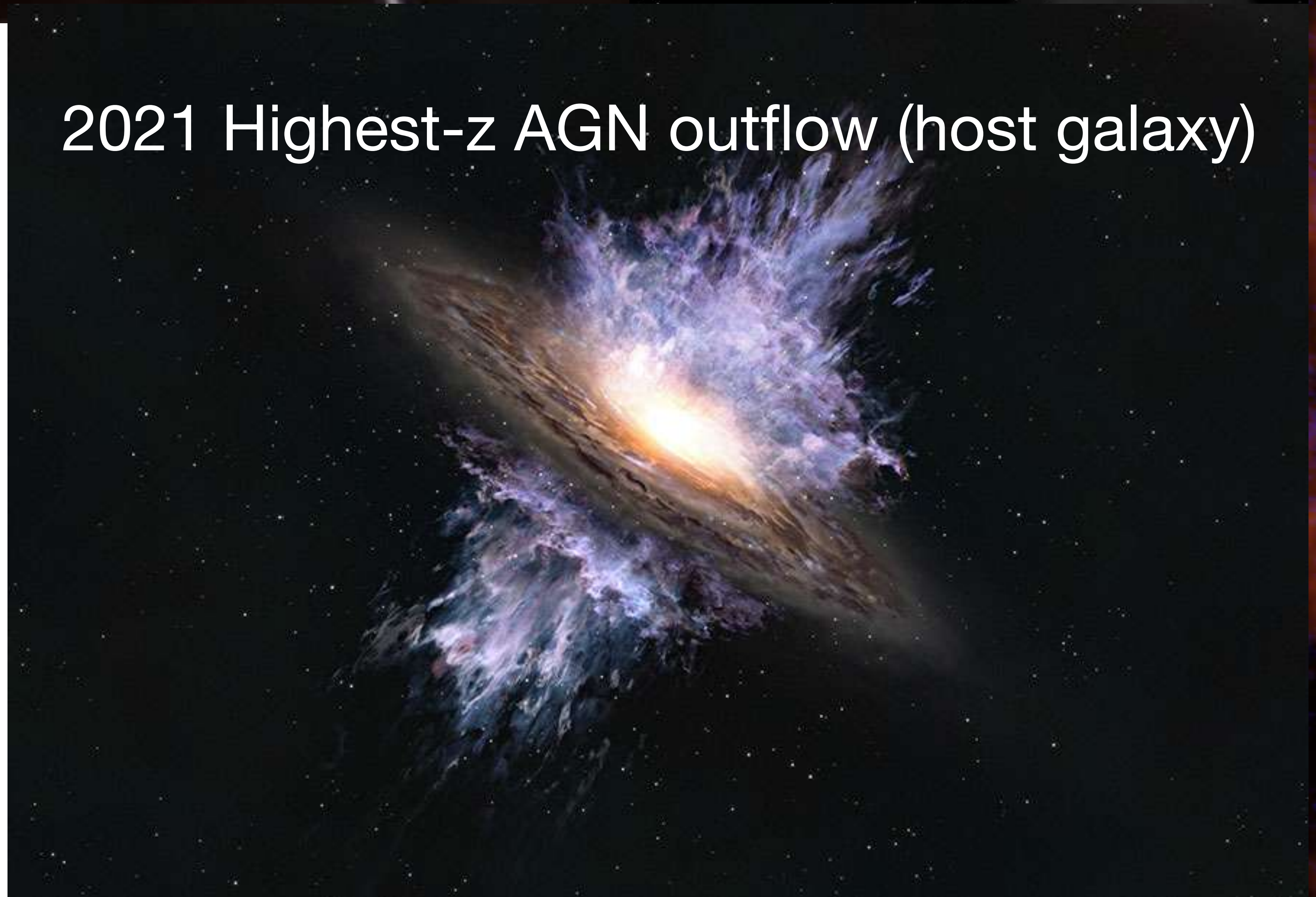
- ALMA Cycle 0 data (PI = K.Kohno)
- ~100 pc resolution dense molecular gas observations toward NGC 1097 (nearby LLAGN)
- Just ~1 hr on-source integration (→ ~week-level integration for NMA??)

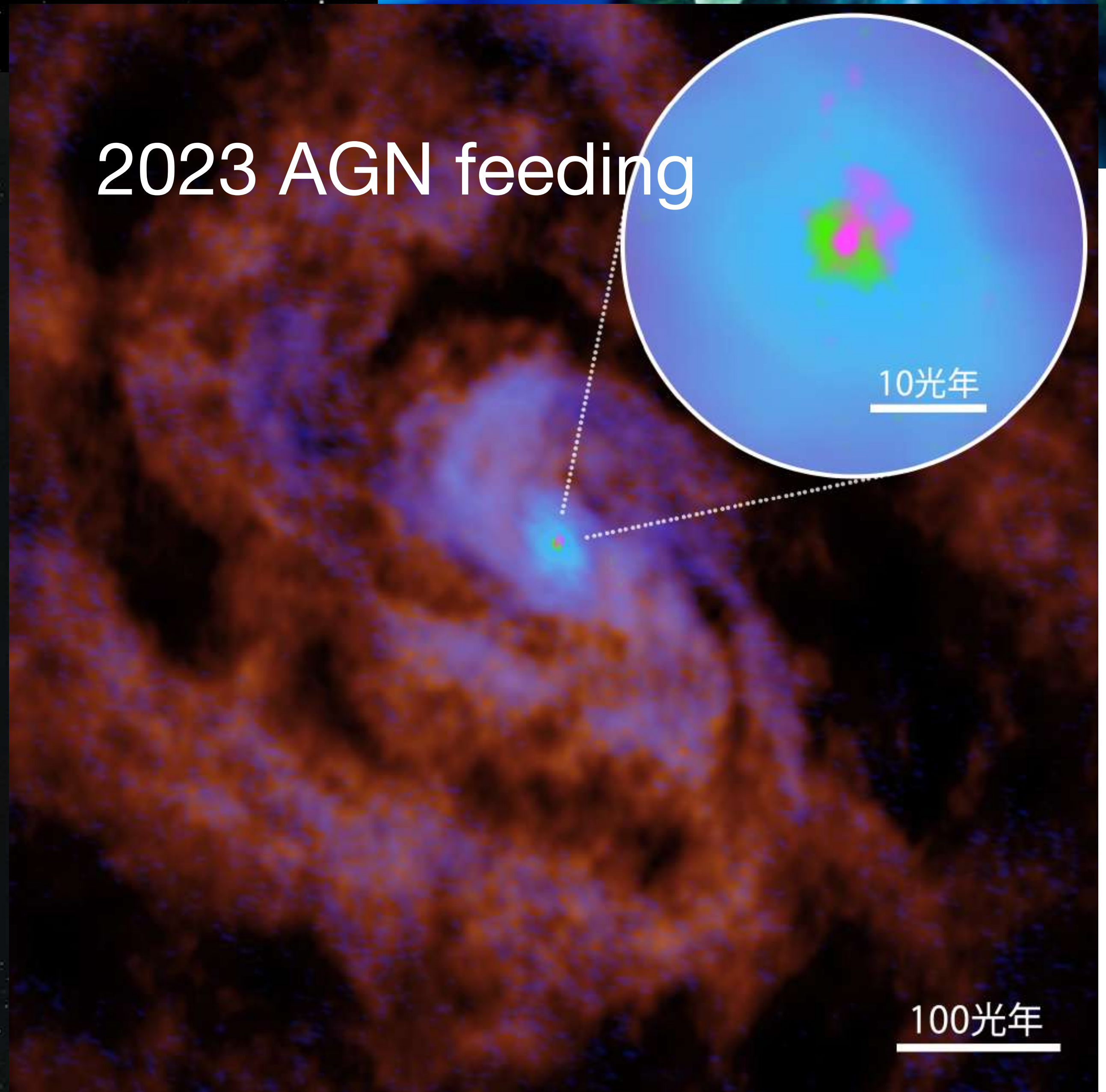
Active Galactic Nuclei (AGN) near and far











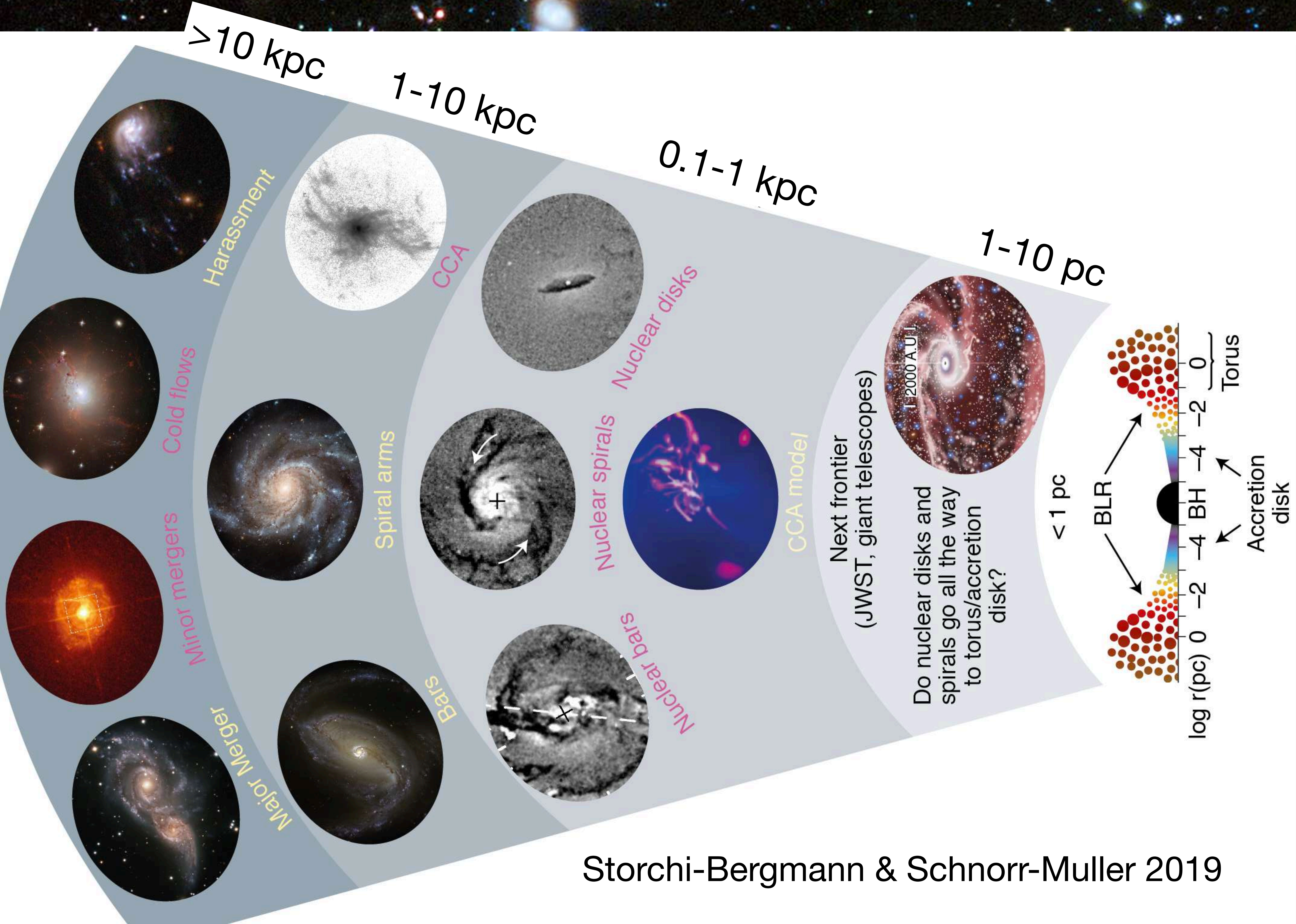
- By using ALMA, I've been studying (mainly cold/cool) ISM around AGNs
- From the central scale up to the host galaxy scale

Today's Contents

1. SMBH Feeding, Feedback, and Obscuration (torus) down to sub-parsec scales
2. Astrochemistry as a tool for astrophysics
3. Near-future works and beyond

1. SMBH feeding, feedback, and obscuration down to sub-parsec scales!

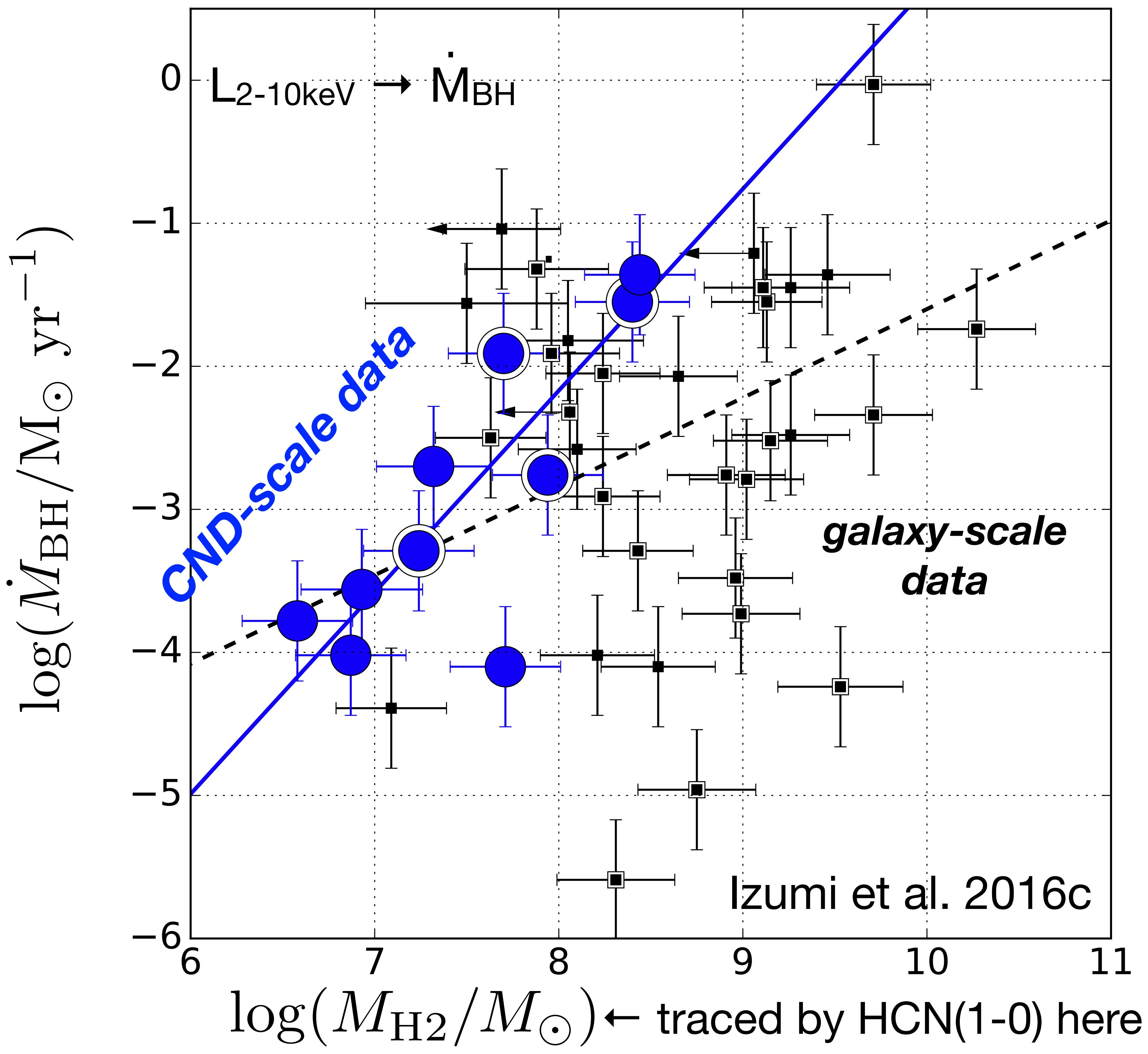
Supermassive black hole feeding



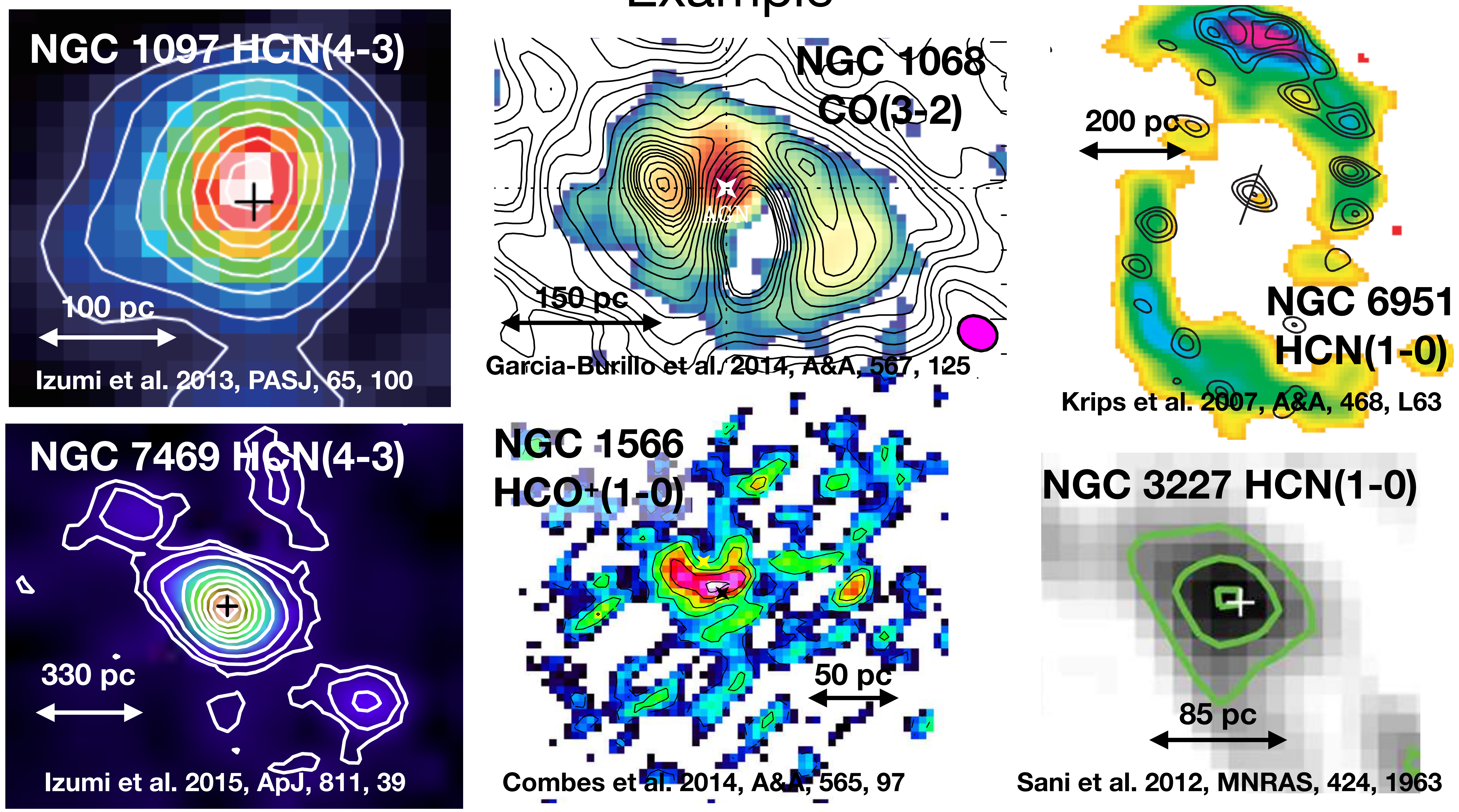
Storchi-Bergmann & Schnorr-Muller 2019

- Necessary to form supermassive black holes
- Major mergers, minor mergers, non-axisymmetric structures are the key at R > 100 pc
- Our knowledge at R < 100 pc is growing (HST, ALMA), but **little is known at r < 10 pc (frontier!)**
- What is the role of the (hypothetical) nuclear structure in SMBH feeding?? → **need high resolution at submm**

Striking Role of Circumnuclear Disk (CND)

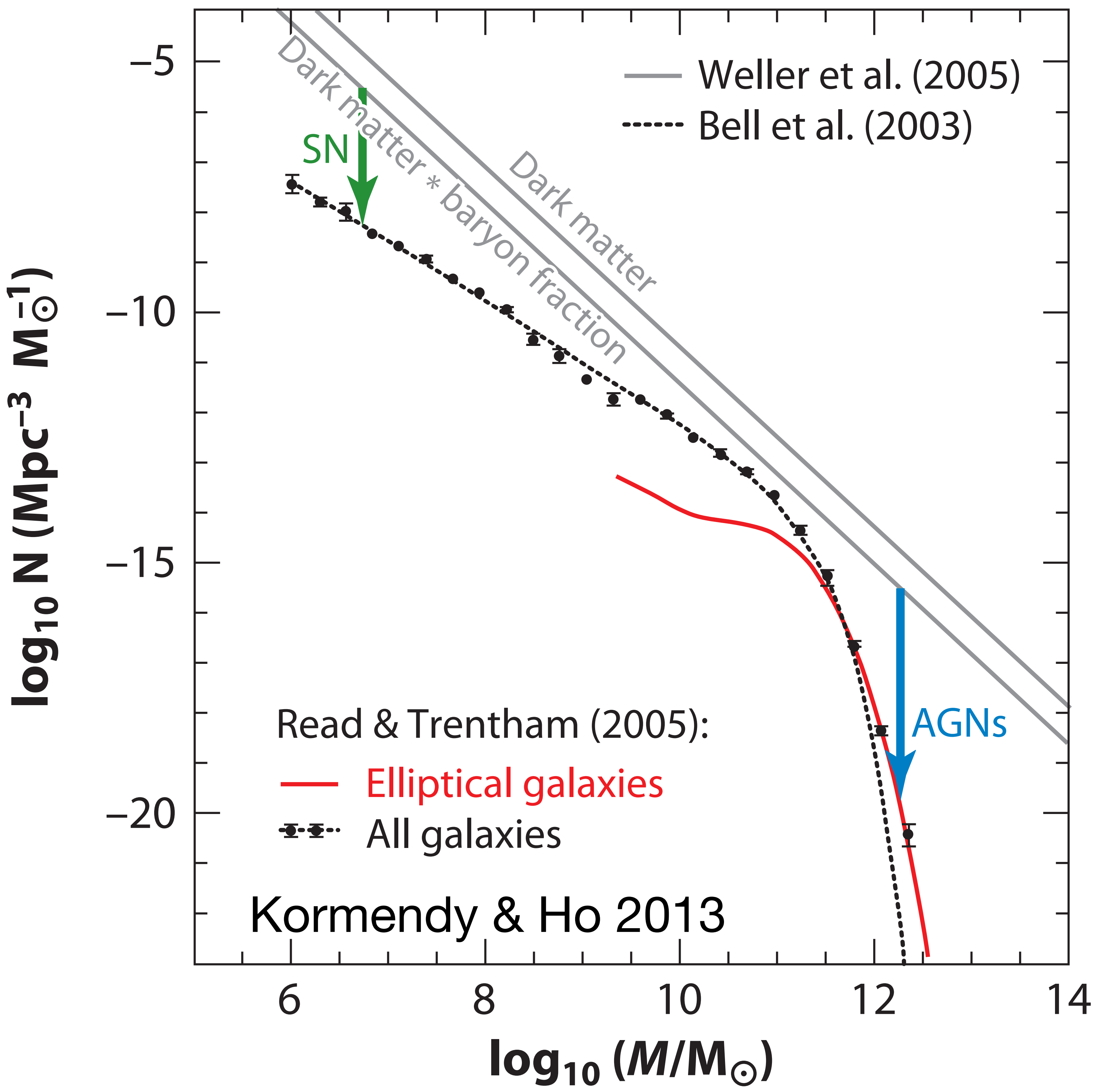


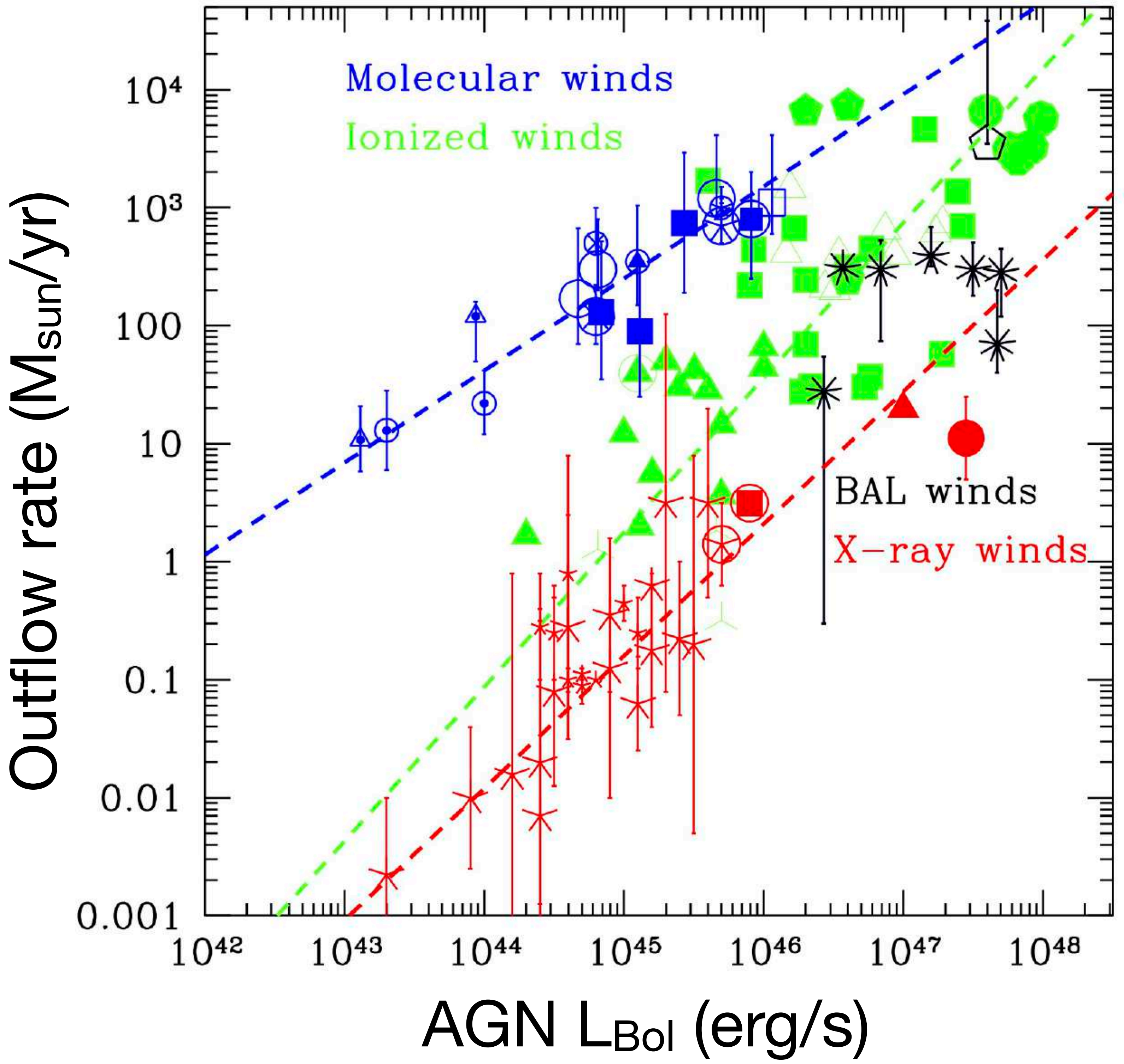
Example

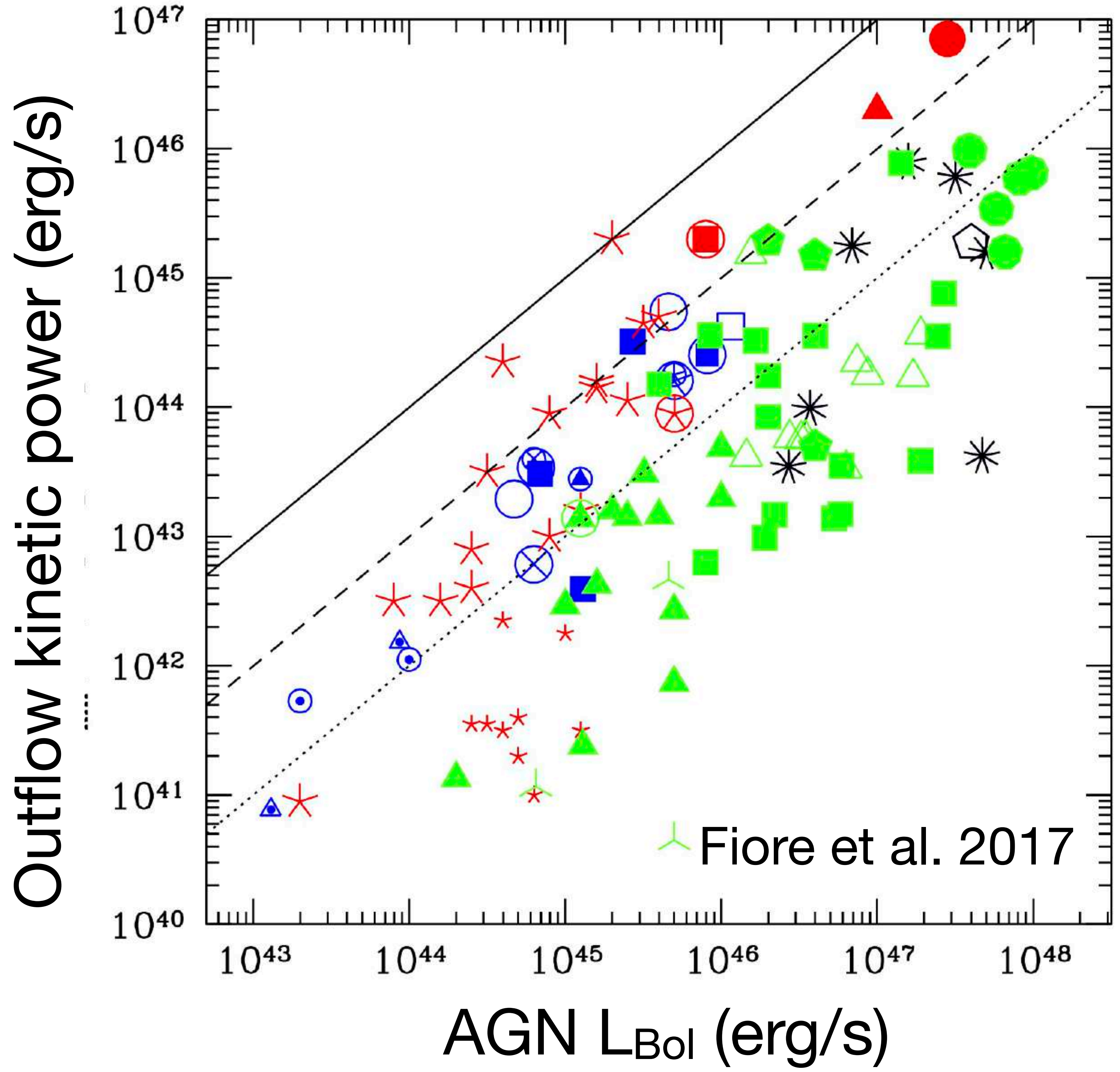


- We discovered a positive correlation between CND-scale dense molecular mass and AGN power, for the first time. **CND = direct reservoir of fuel for AGN**.
- Observationally indicate a key direction (= high resolution obs toward the CND-scale). Further higher resolution observations are needed to probe the innermost ~10 pc.

AGN-driven outflow: key ingredient for galaxy evolution

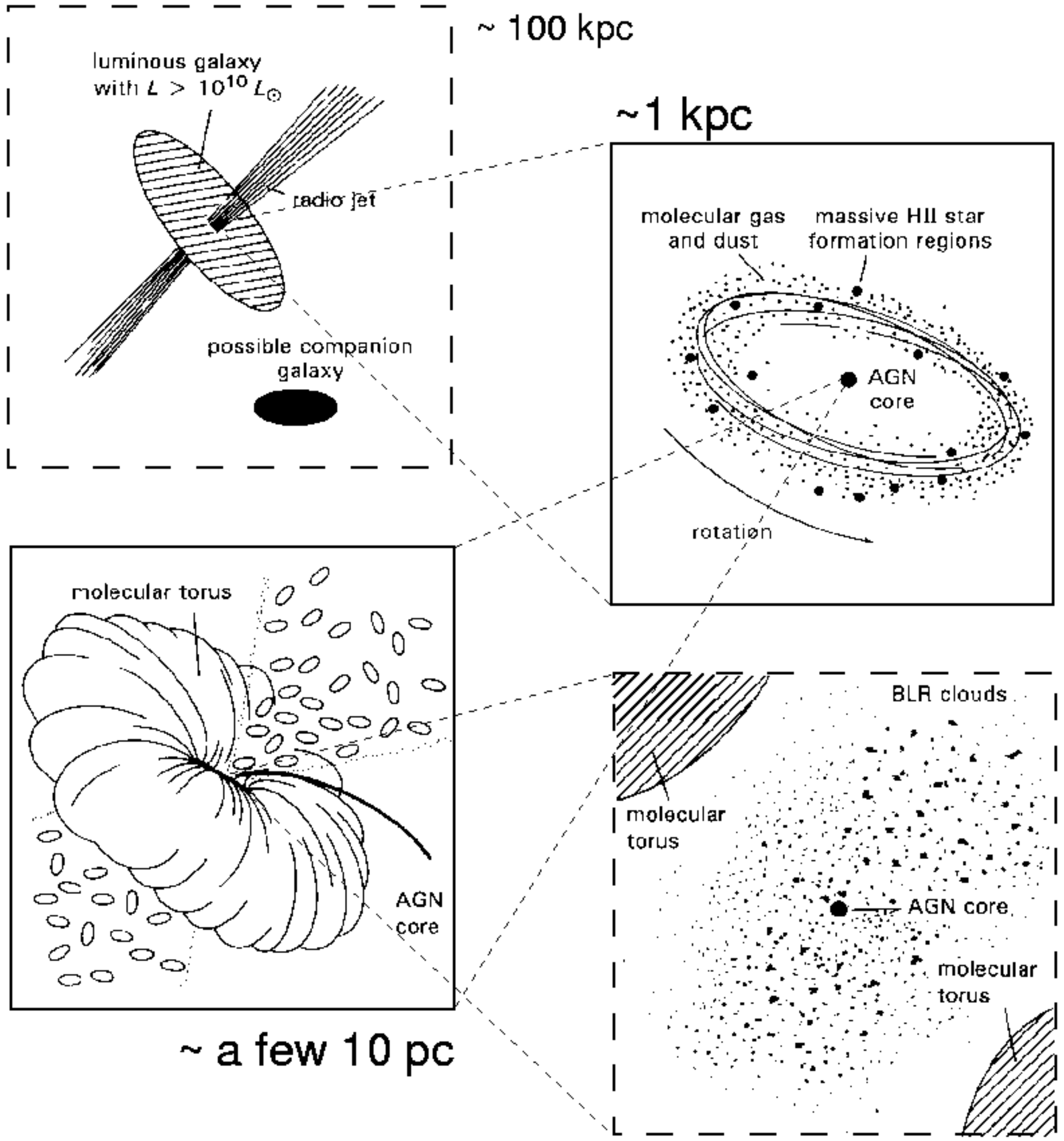




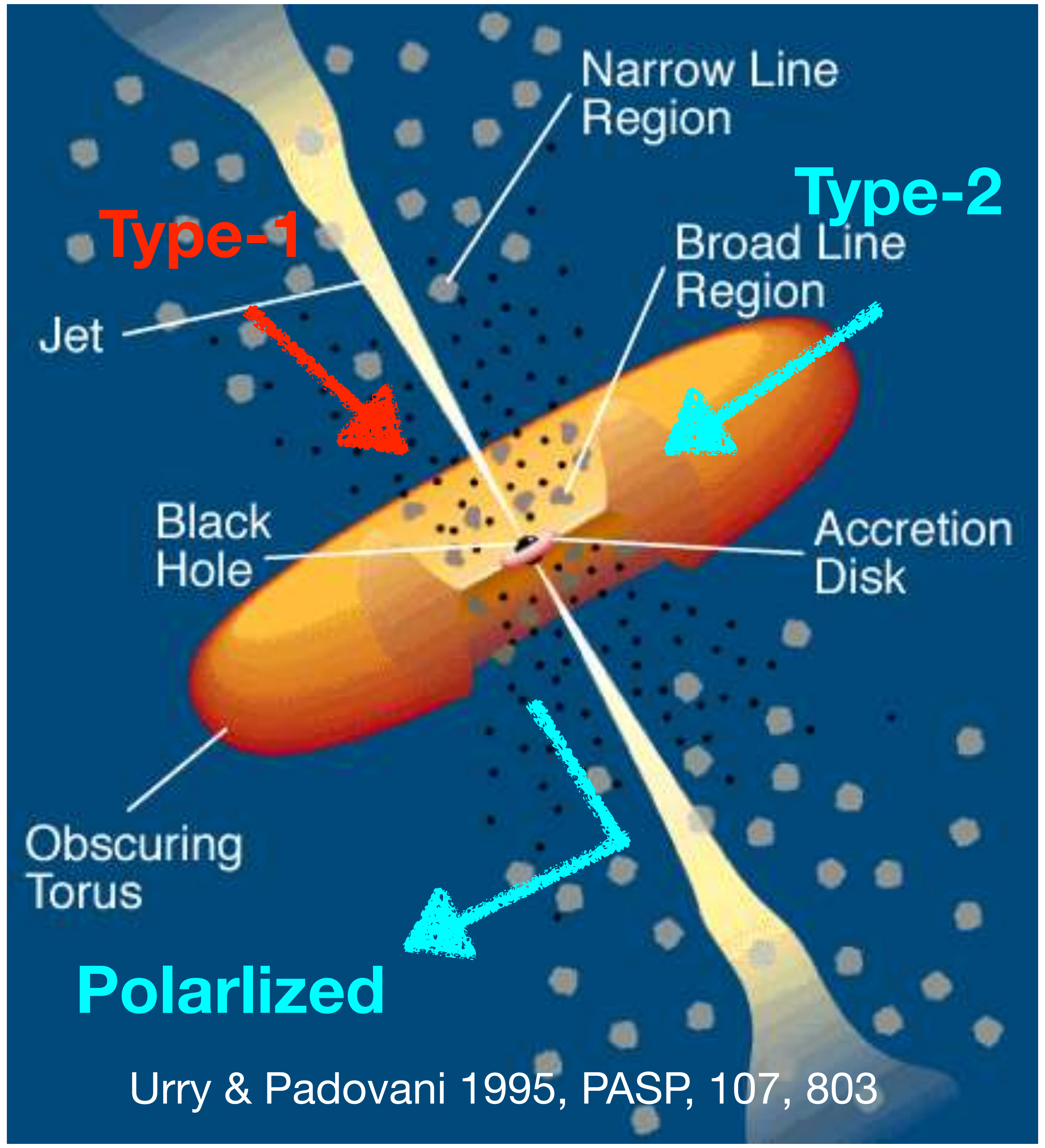


- One possible mechanism to regulate the growth of massive galaxies: **co-evolution**
- Multiphase (i.e., ion, atom, molecule) nature. Quantitative assessment of the coupling between AGN power and wind properties are investigated in various objects at various redshifts.
- **Little understanding at r < 10 pc (resolution + extinction) → High resolution at sub/mm**

Unite multiphase gas feeding, feedback, and obscuration



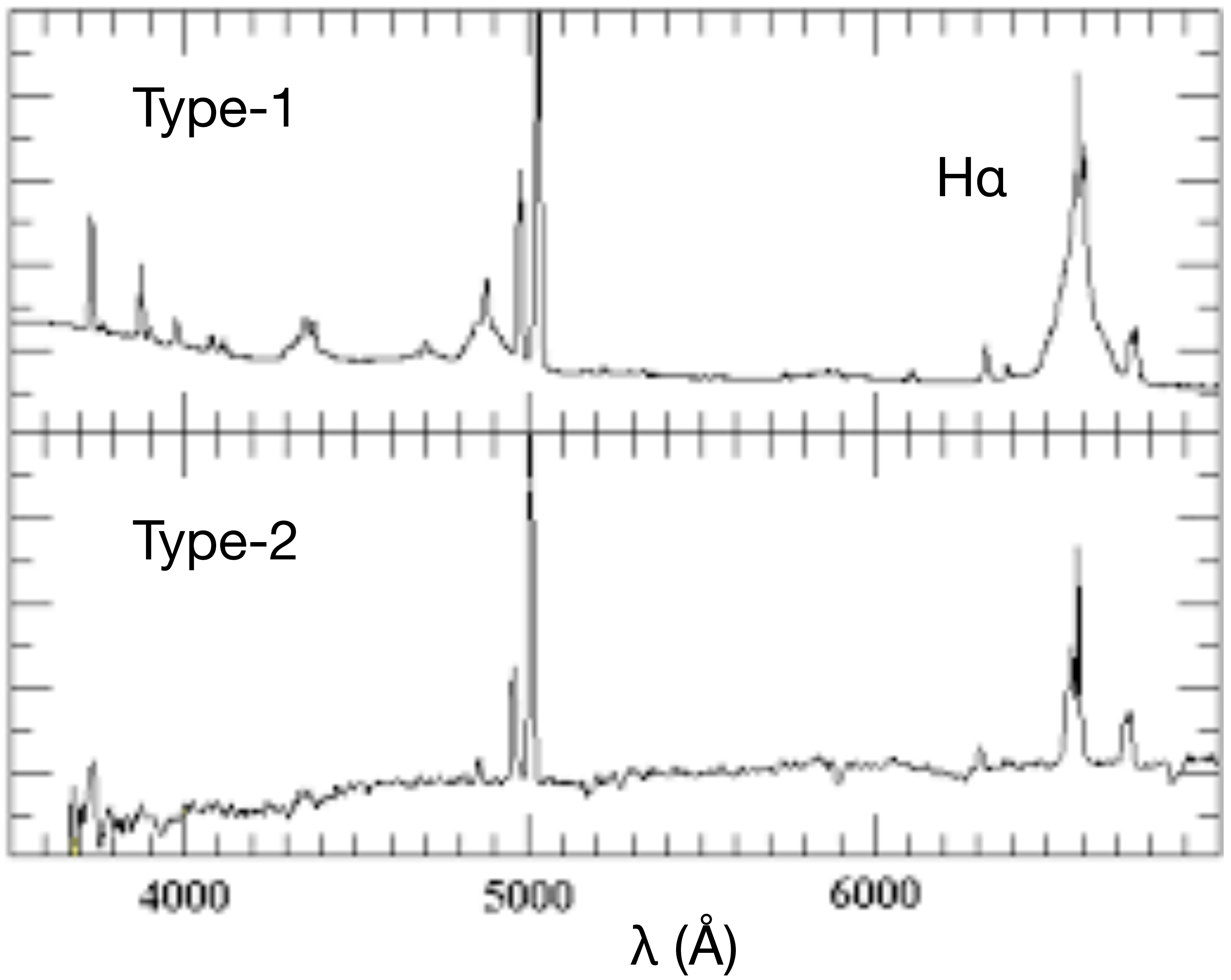
Robson 1996
"Active Galactic Nuclei"
p. 334



Urry & Padovani 1995, PASP, 107, 803

Unified scheme

(e.g., Antonucci 1993, ARA&A, 31, 473)

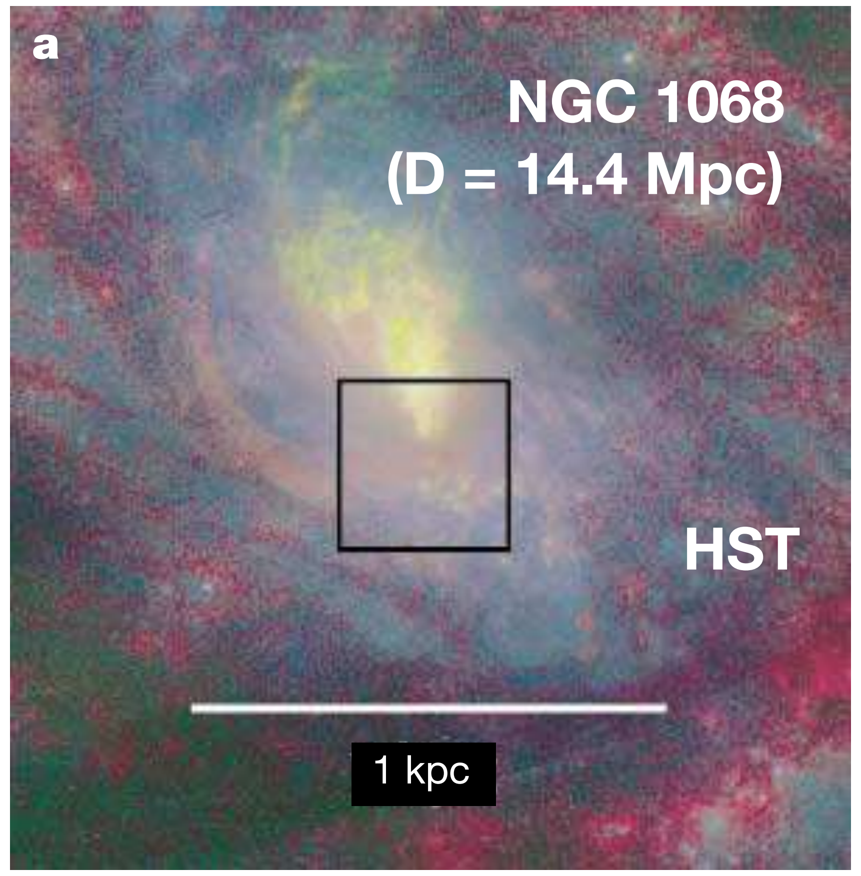


- Torus = immediate reservoir of fuel for SMBH growth: need to understand

- Torus = nice idea to understand the type-1 and type-2 variation of AGN appearance in a unified manner.

Progress of Torus observations

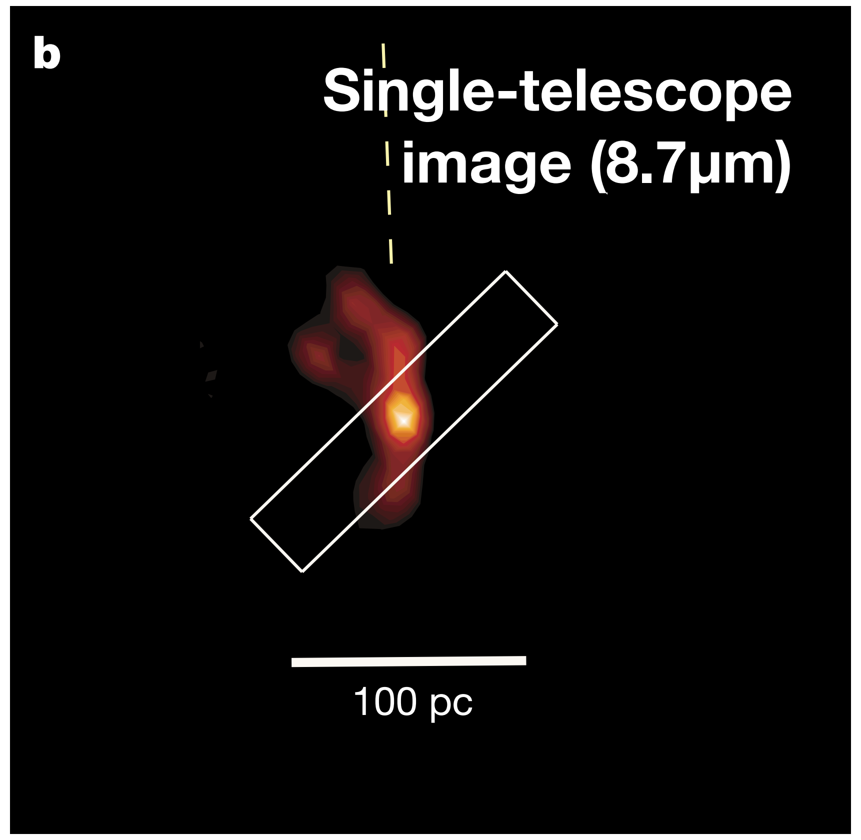
- NIR/MIR interferometry: direct imaging of compact tori
- Observed “visibility” + SED ⇄ Emission distribution model

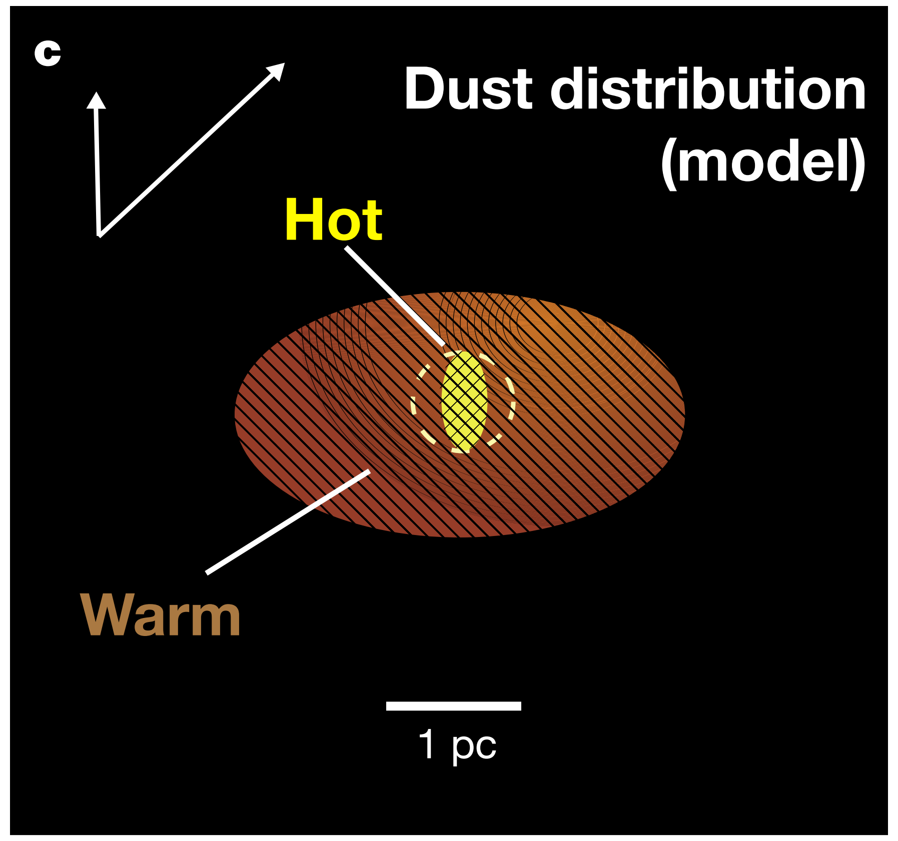


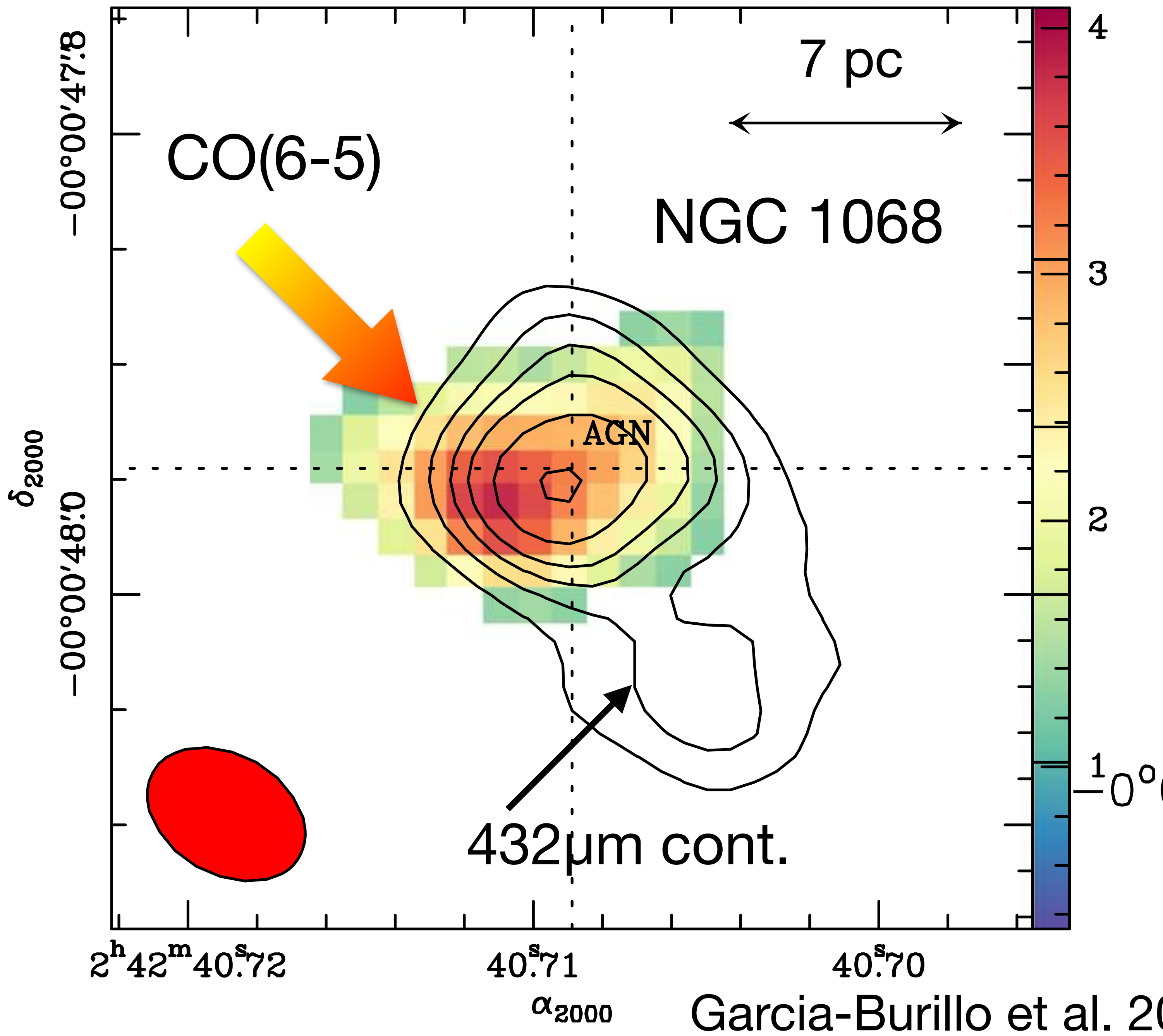
- 2-components fit → Hot (T > 800 K) & Warm (T = 320 K)
- Size (hot) < Size (warm)

Pc-scale structure!

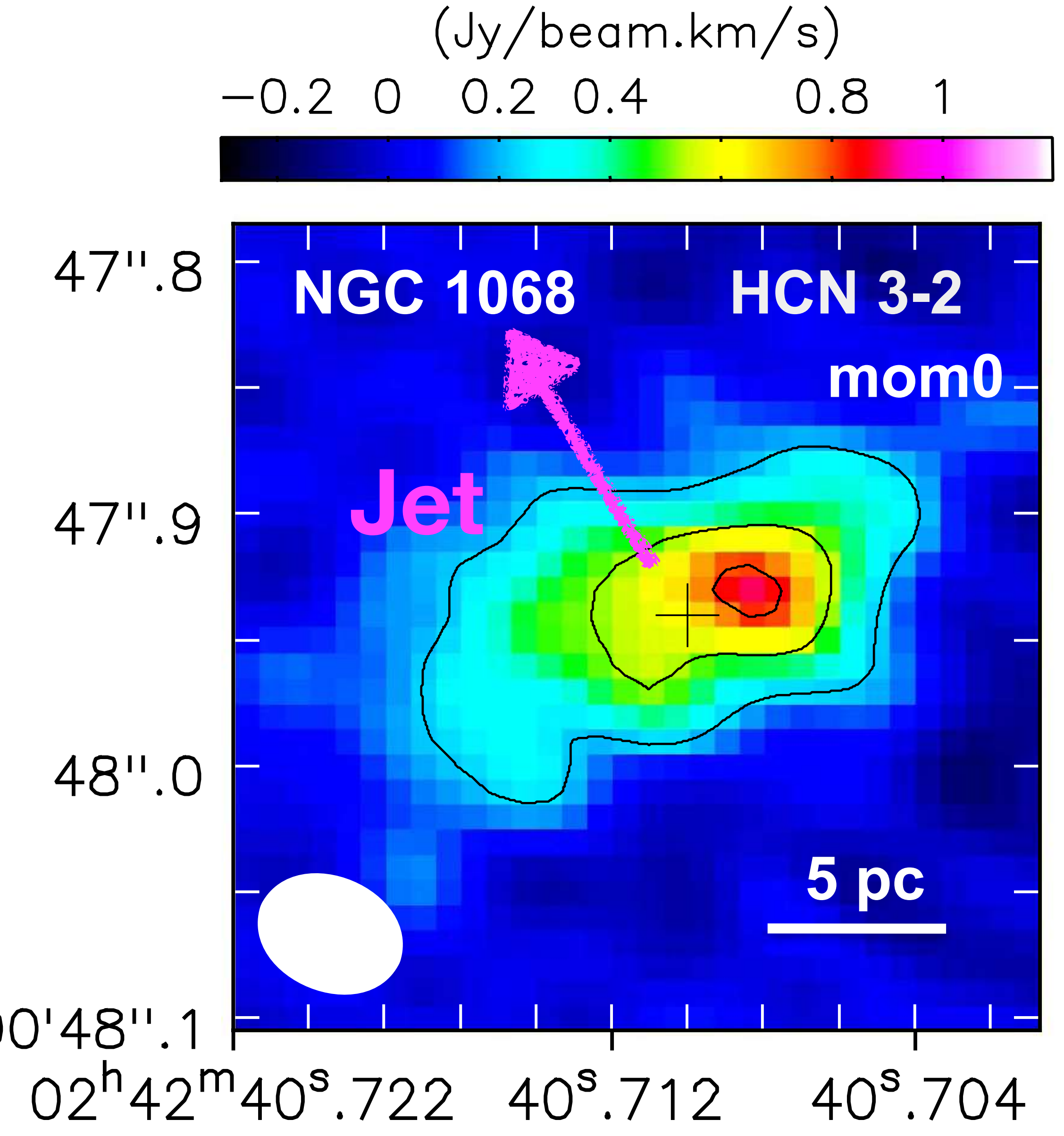
Jaffe et al. 2004, Nature



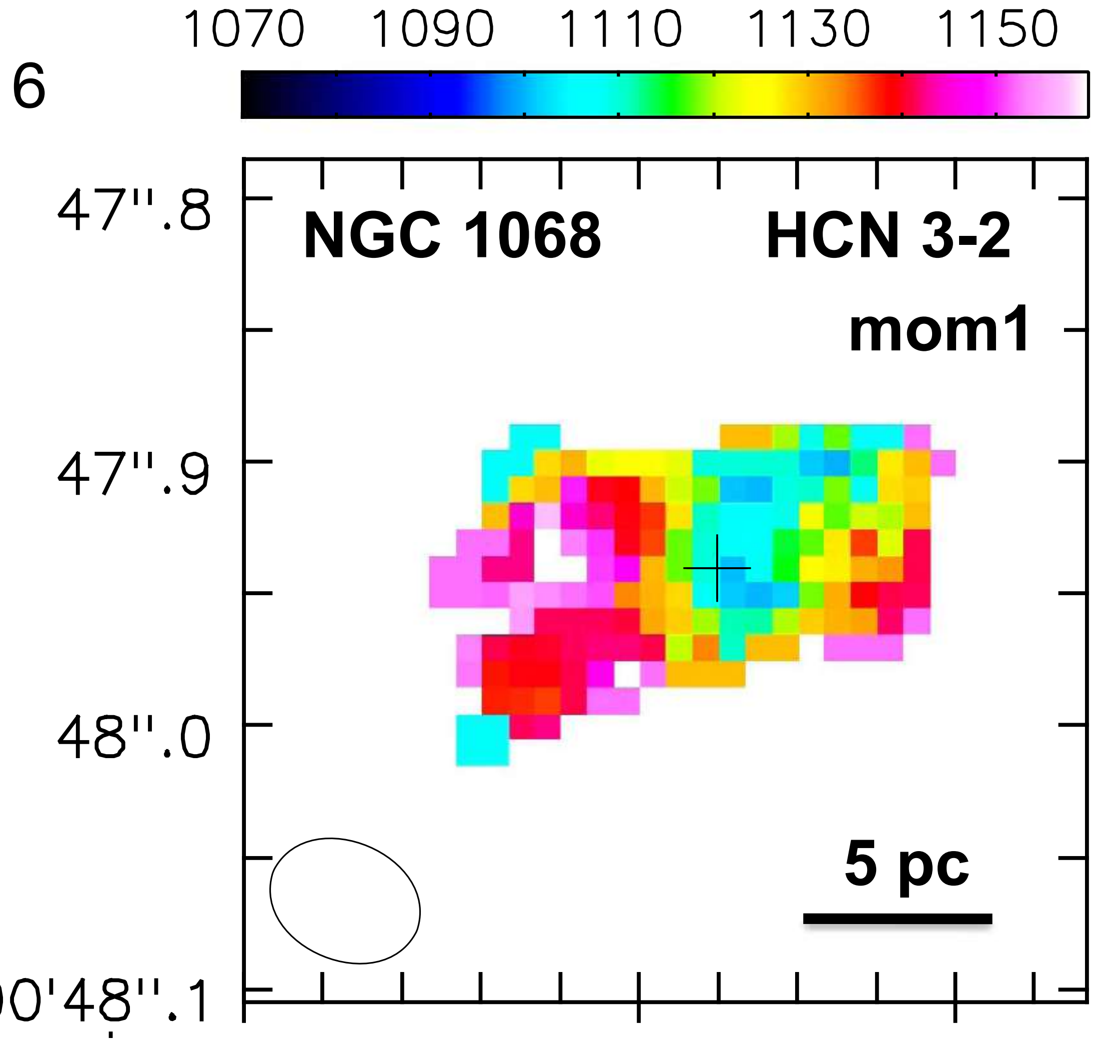




Garcia-Burillo et al. 2016



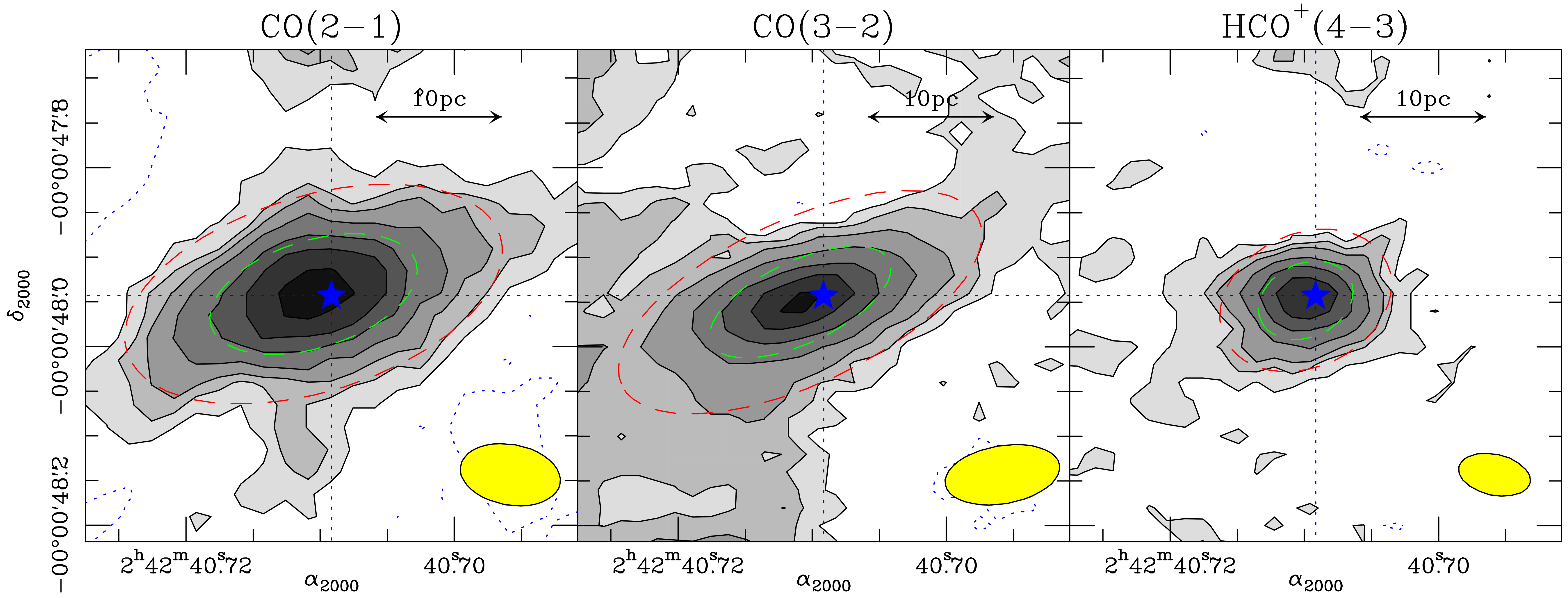
- Finally, ALMA started to detect cold parts of tori (line + continuum)!
- More extended (~10 pc) than the hot/warm components → *T*-dependence
- Rotation motion was also detected



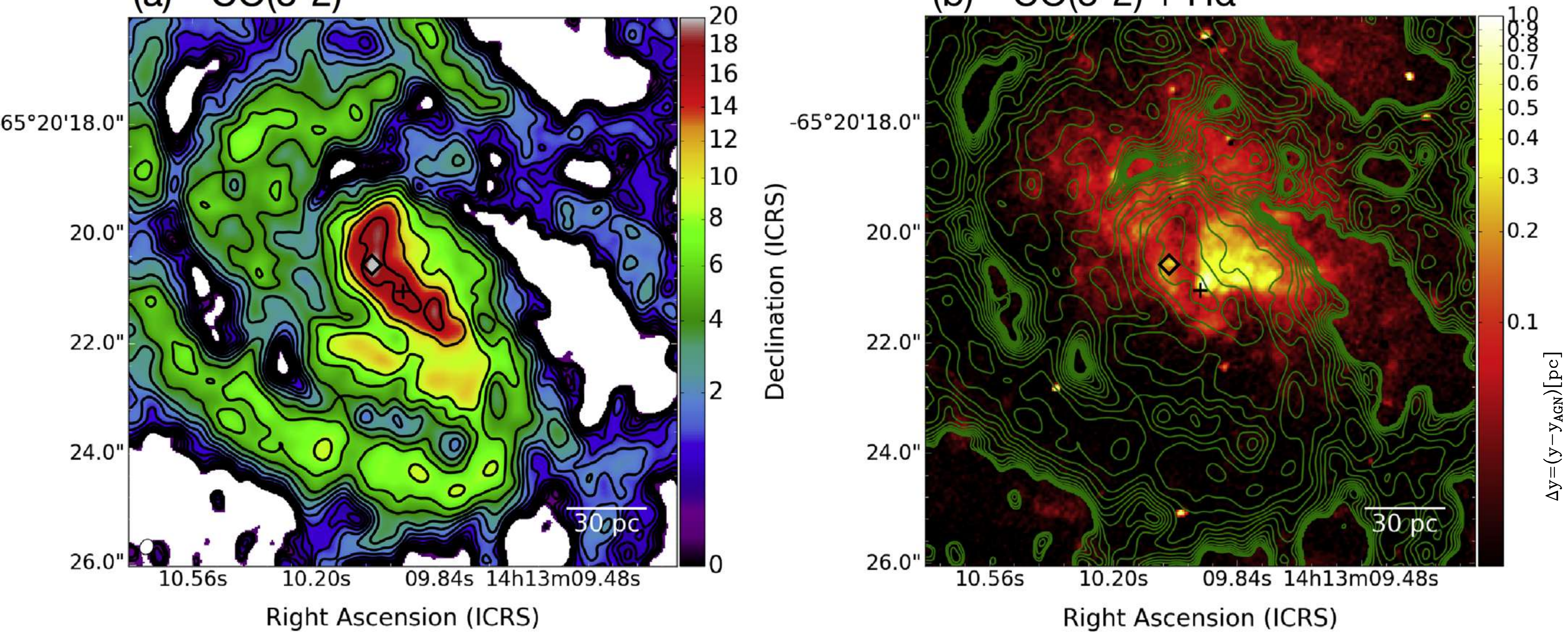
Imanishi et al. 2018

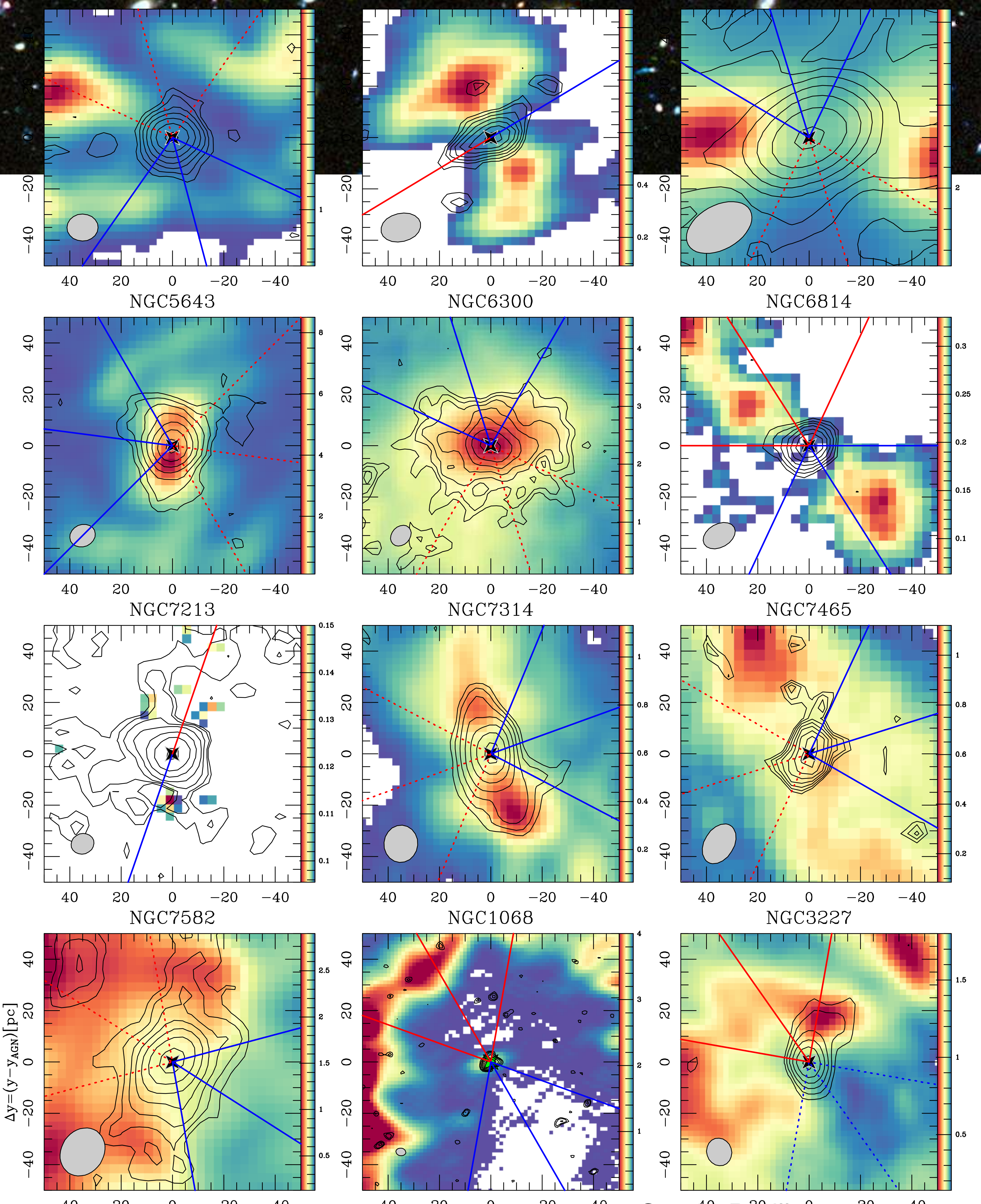
Progress of Torus observations

Garcia-Burillo et al. 2019



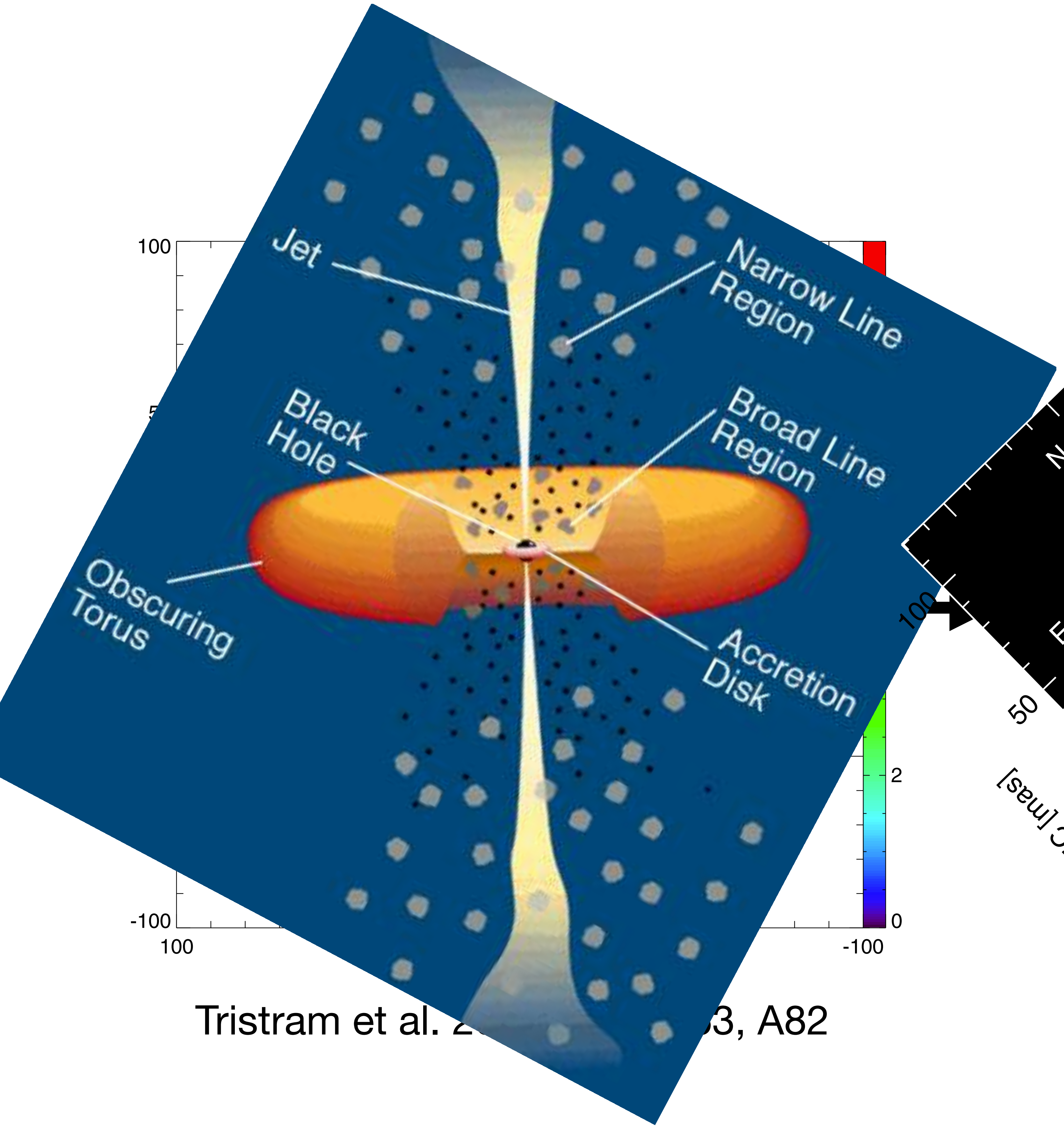
Izumi et al. 2018



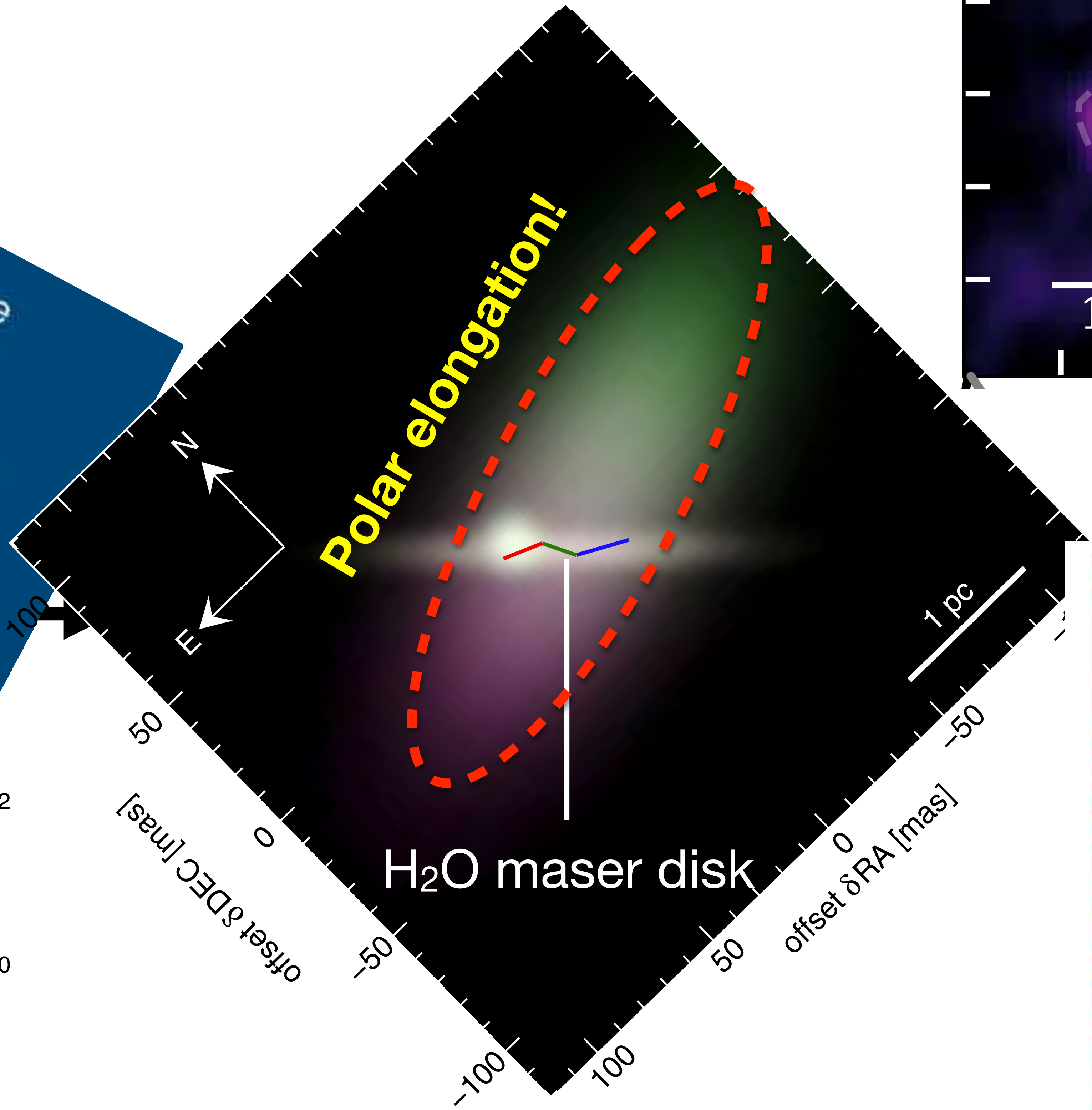


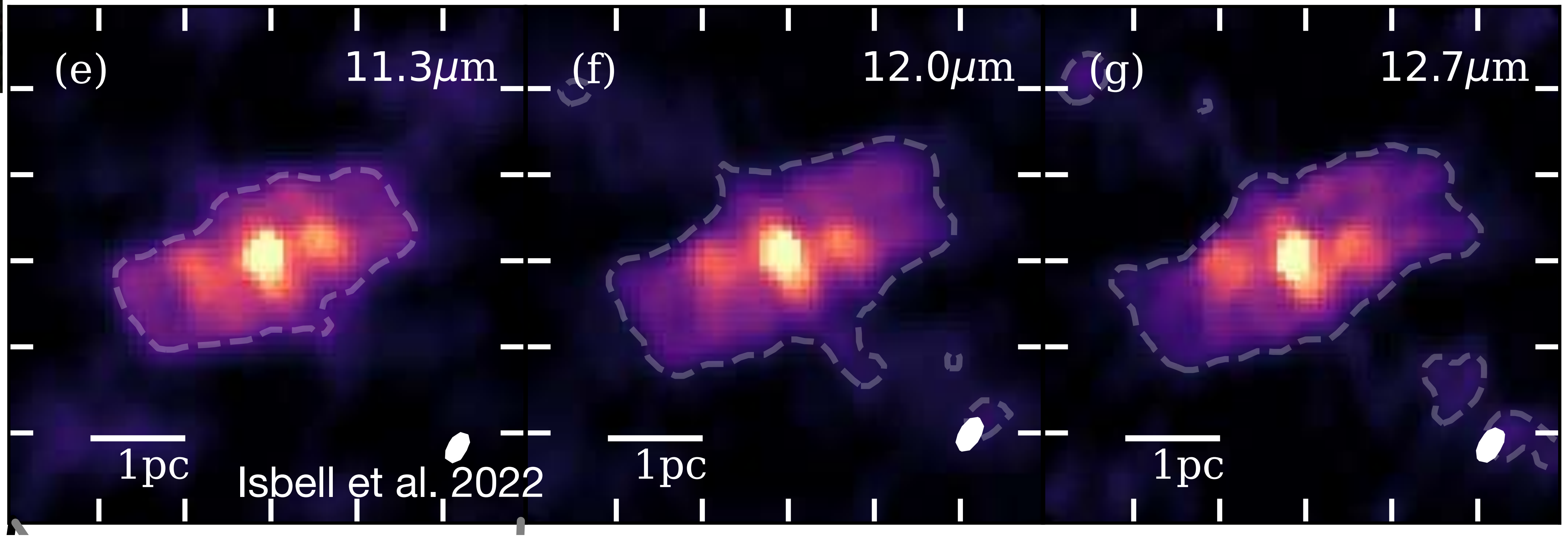
Garcia-Burillo et al. 2021

Big Challenge: polar dust component

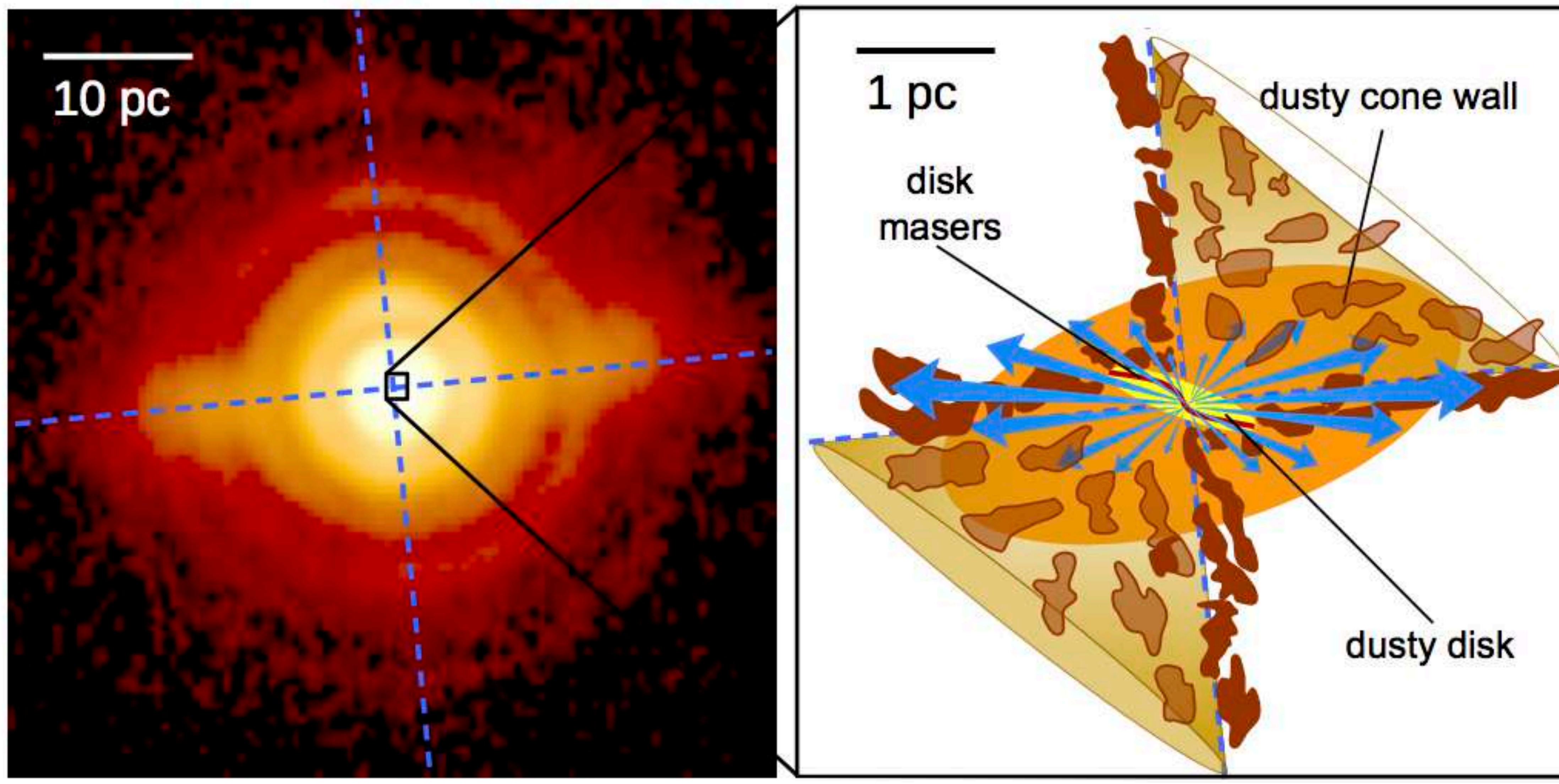


Tristram et al. 2 … 3, A82





Stalevski et al. 2017

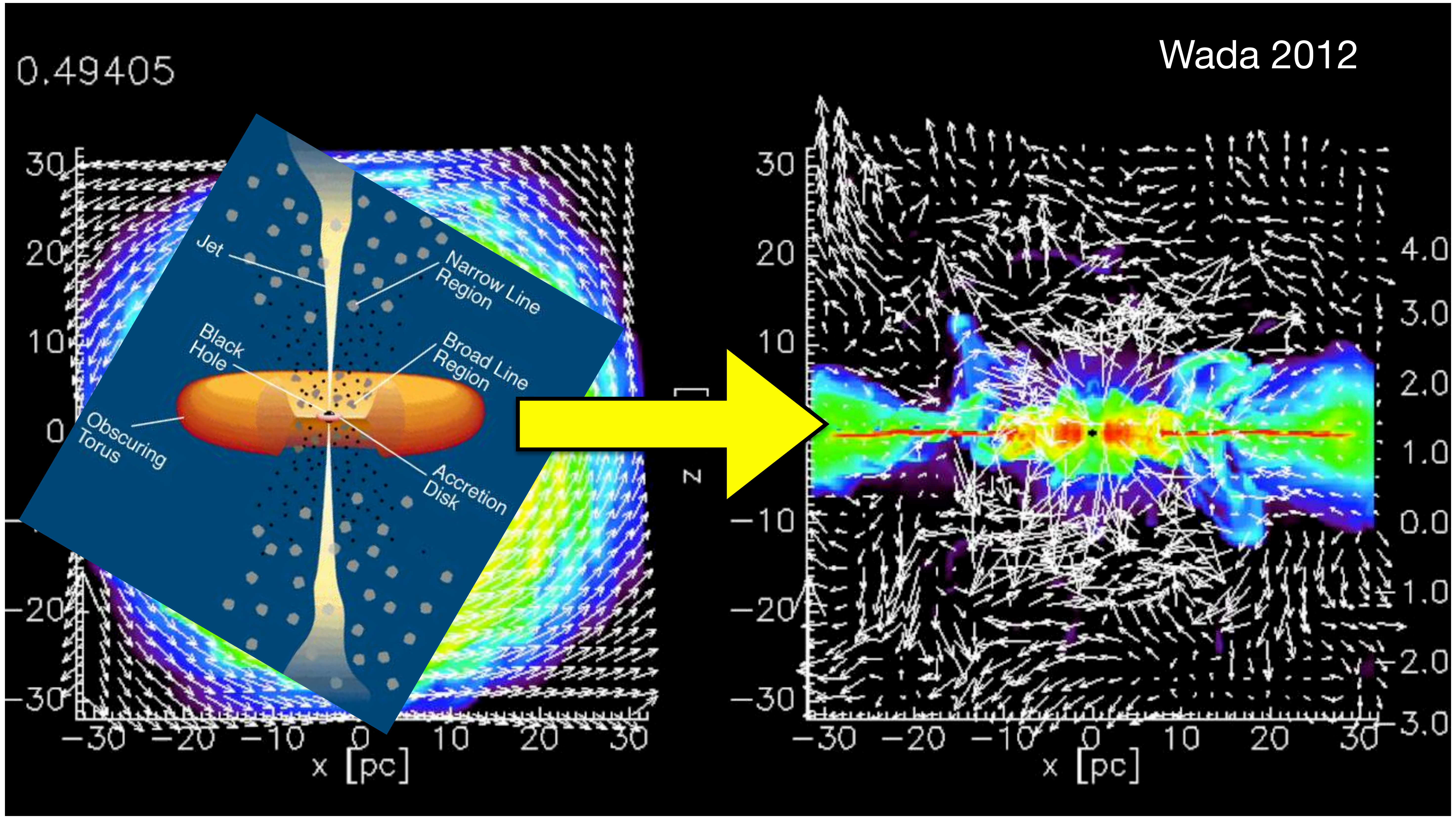


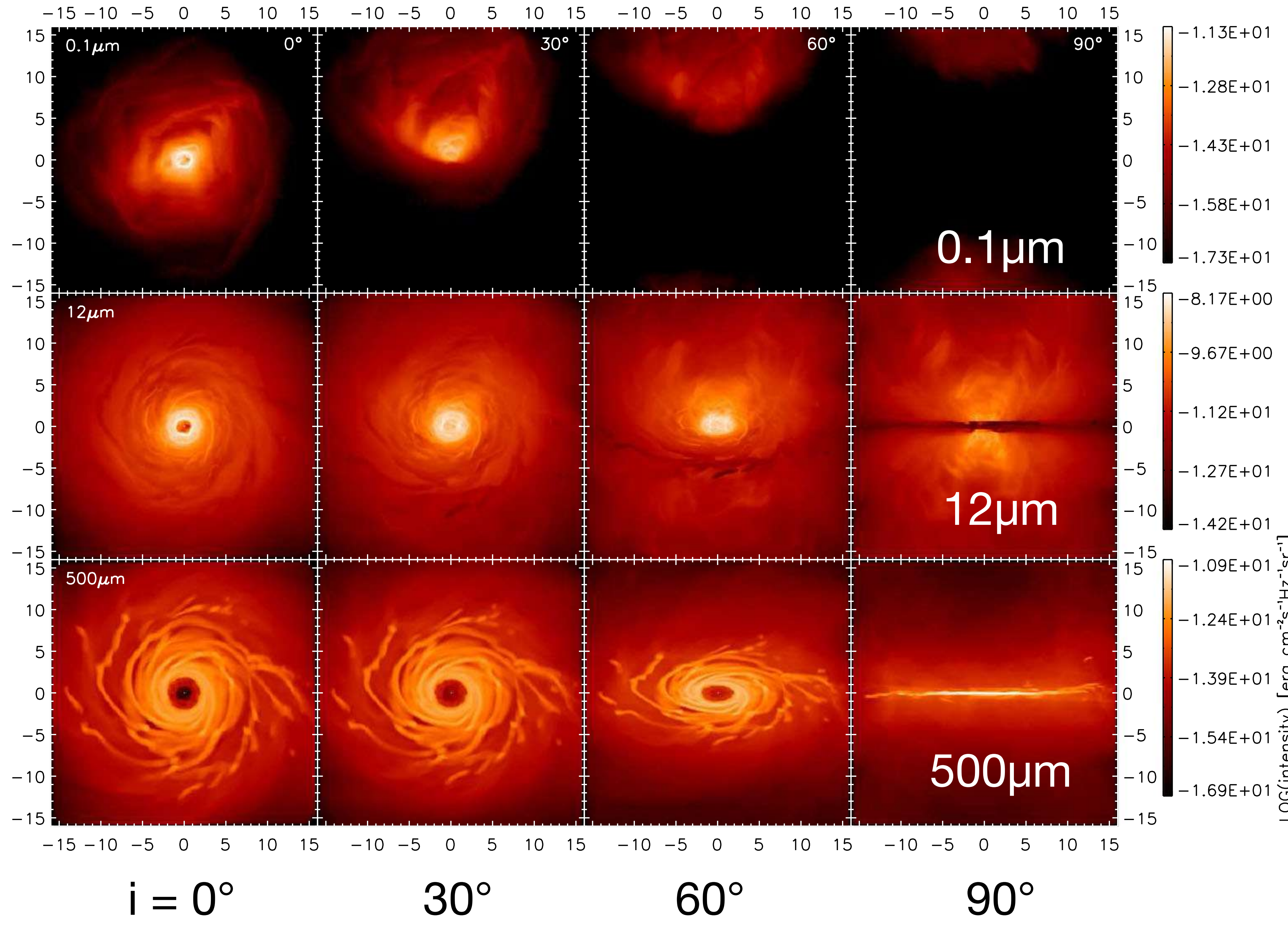
- Polar elongation@MIR continuum!?
  → Inconsistent with the postulated equatorial distribution in the torus
- Statistical confirmation (e.g., Lopez-Gonzaga et al. 2016)
- See more recent images by VLTI/MATISSE

- Dusty cone can reproduce the observed MIR distribution → How to make this vertical structure??

Unite multiphase gas feeding, feedback, and obscuration

X-ray + Radiation pressure → Multi-phase Outflow → Failed wind

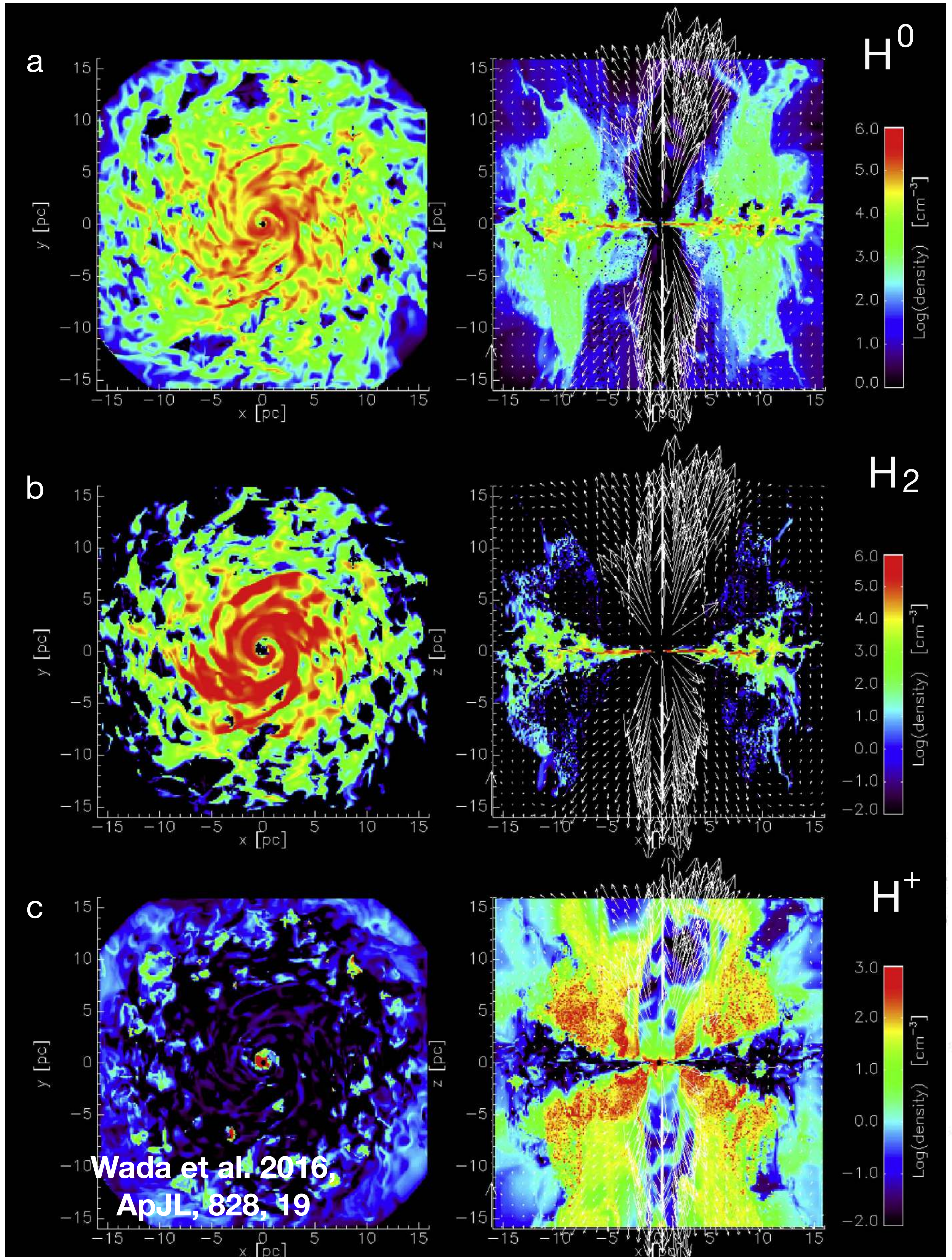




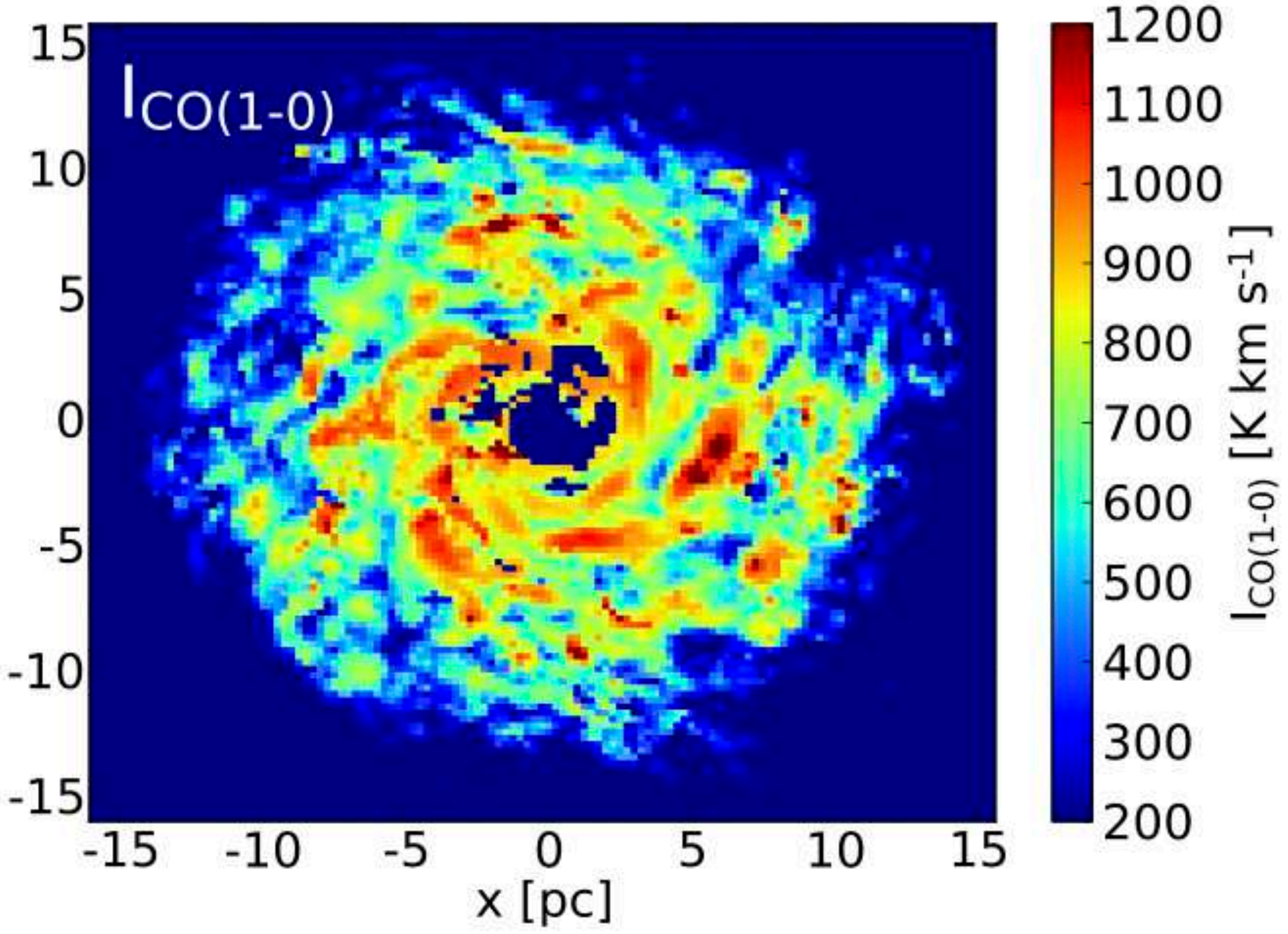
Schartmann et al. 2014

- Radiation-driven fountain flows can naturally provide a geometrically thick obscuration.
- MIR polar elongation is also reproduced (due to dusty warm outflows)

Our previous work: Multiphase Gas Distribution

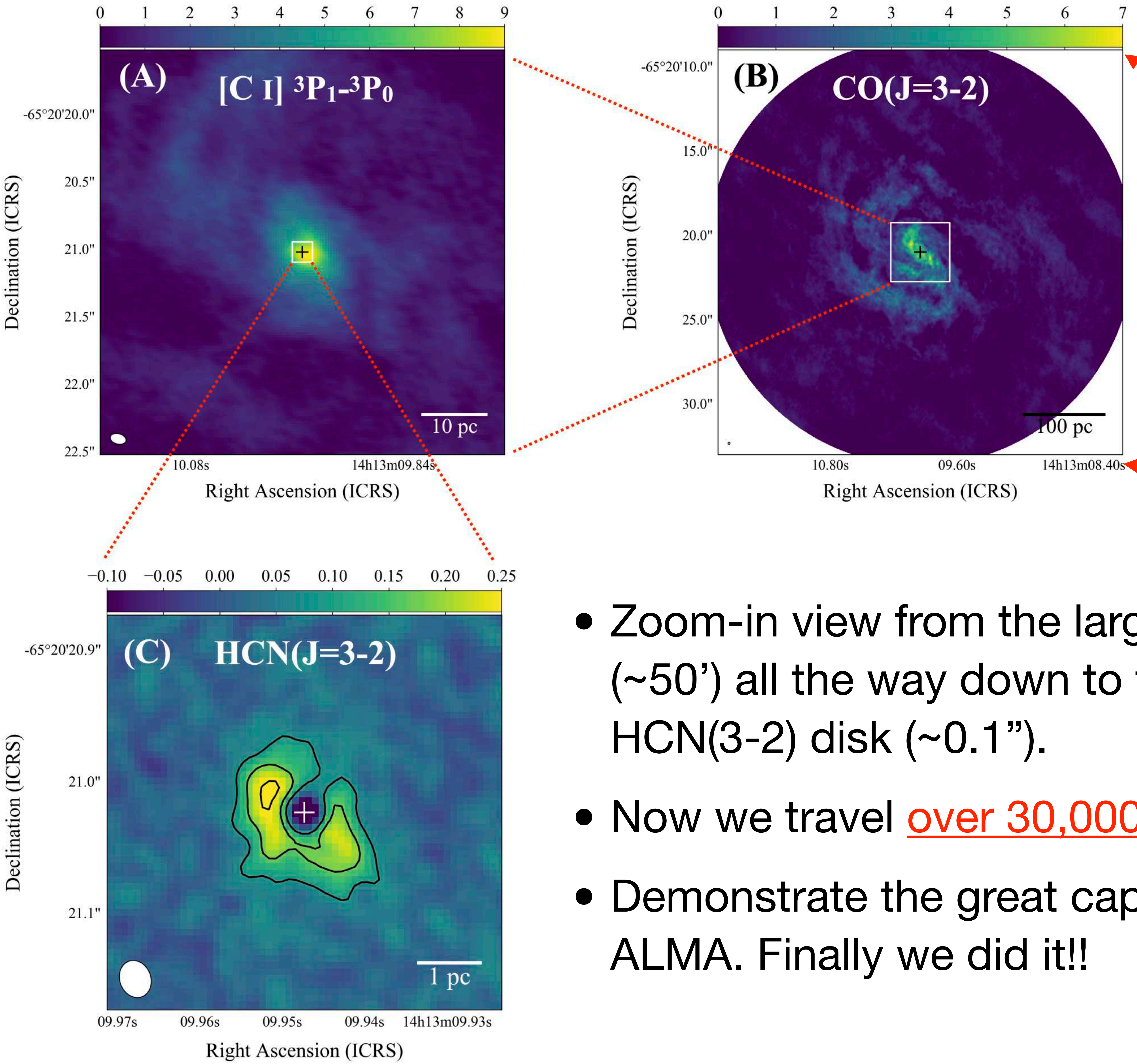


Wada, Fukushige, TI, et al. 2018

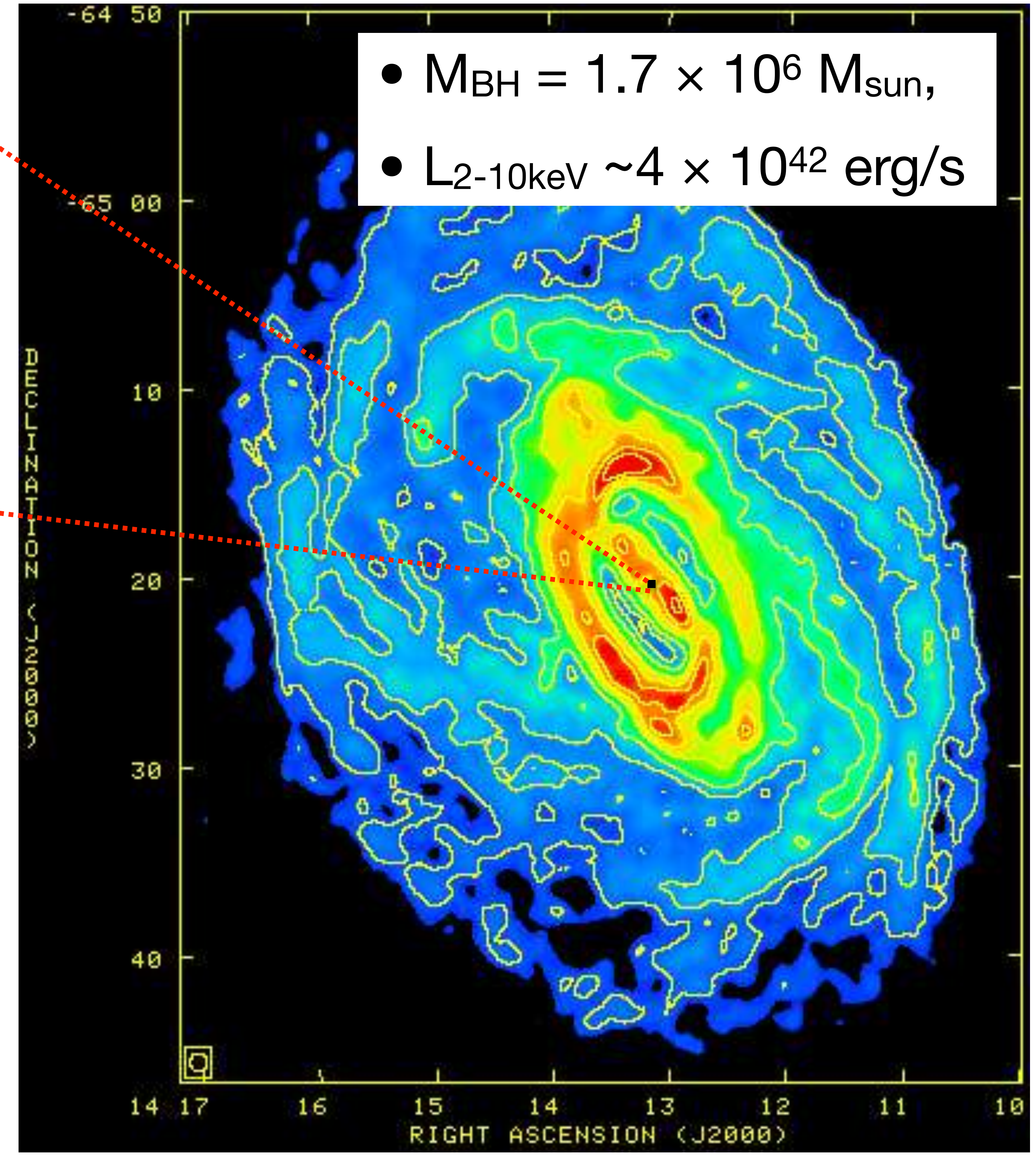


- Target: <u>Circinus galaxy</u> (D = 4.2 Mpc; 1” = 20 pc)
- M_{BH}, λ_{Edd}, CND-scale M_{gas}: matched to the values of Circinus
- **Hydrodynamic simulation + XDR chemistry + radiative transfer**
- NAOJ’s supercomputer “ATERUI”
- Prepared for ALMA observations by post-processed radiative transfer calculations.

Spatially Resolved Picture of the Circinus Galaxy



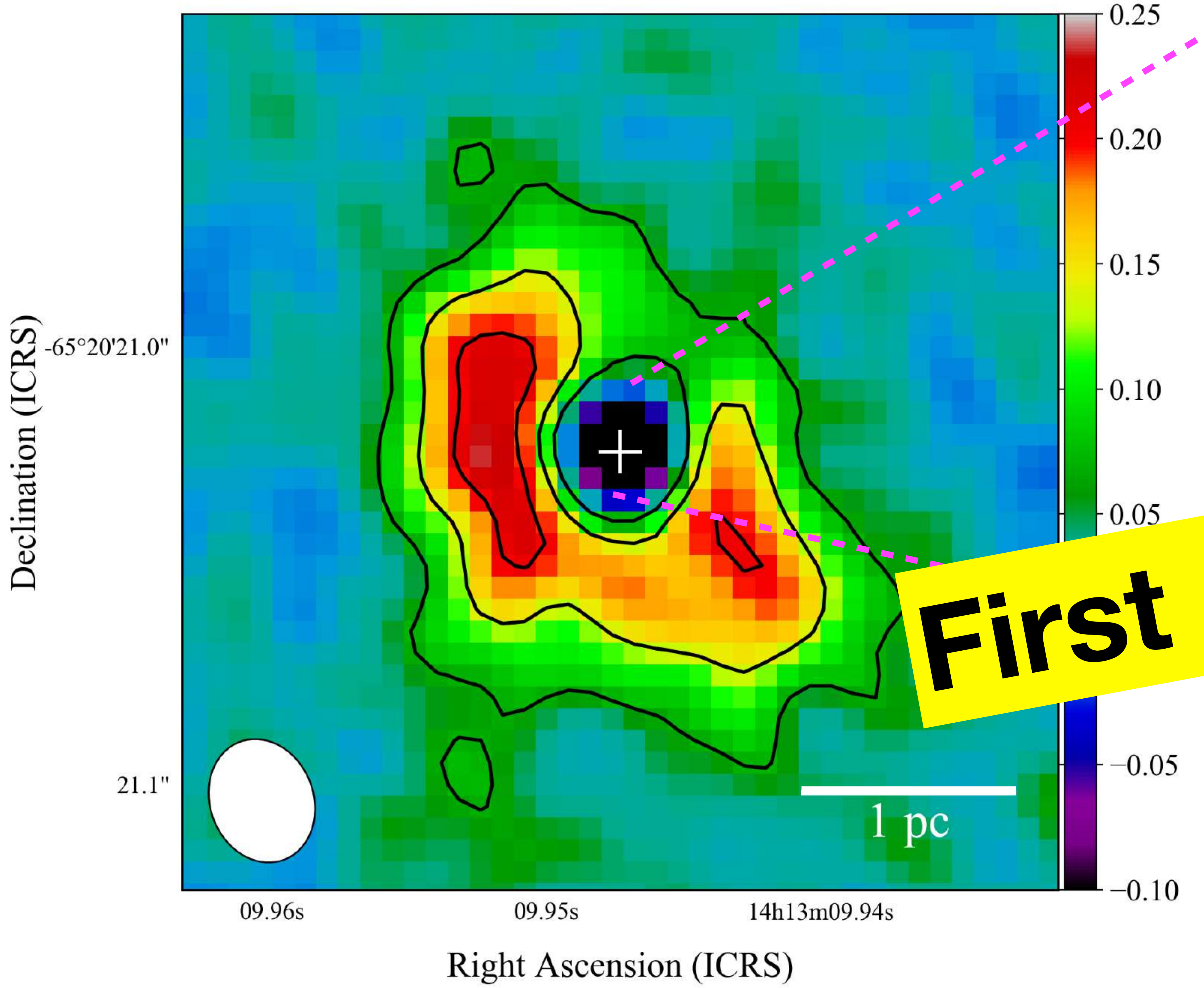
ATCA HI map (Jones et al. 1999)

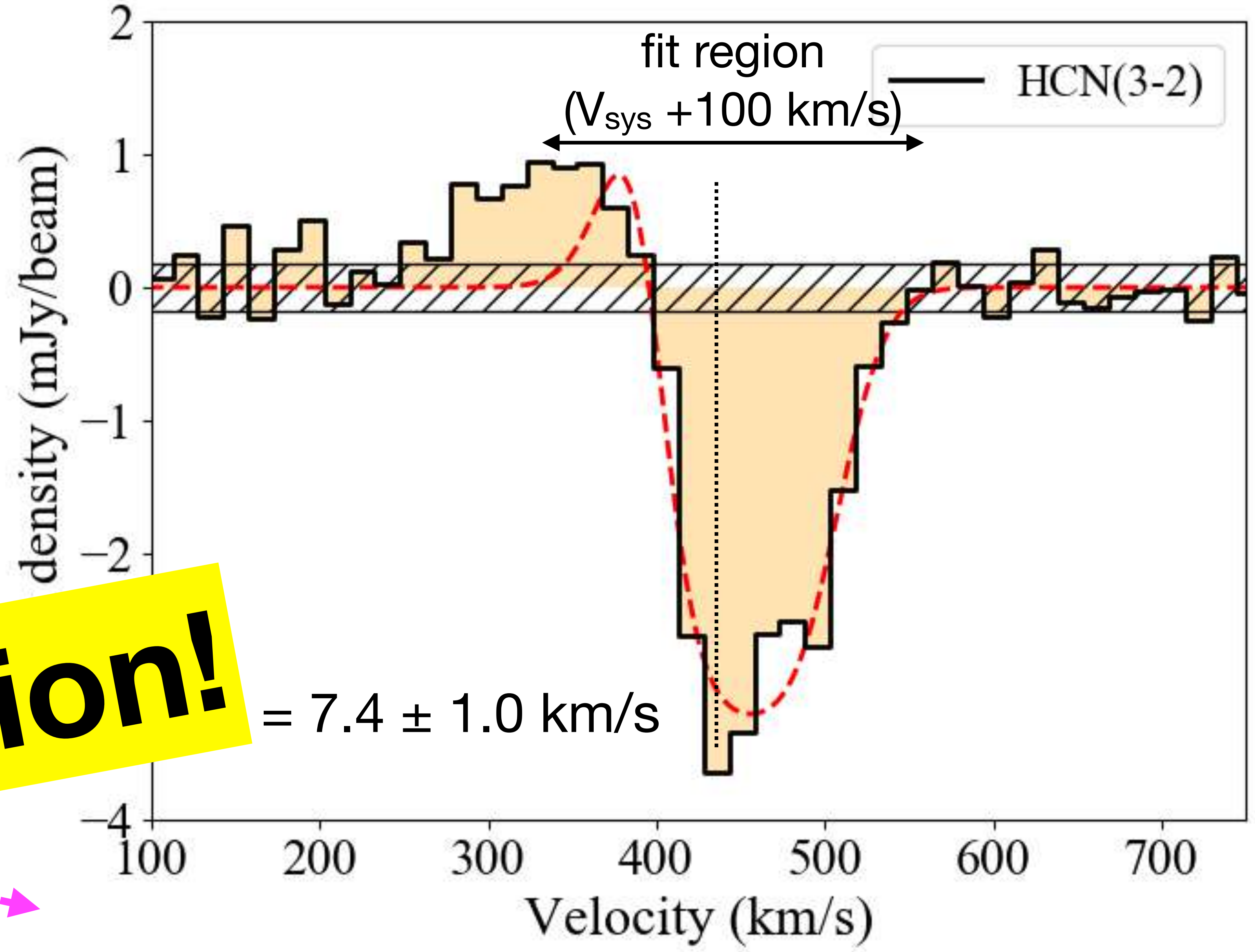


- $M_{BH} = 1.7 \times 10^6\ M_{sun}$,
- $L_{2\text{-}10keV} \sim 4 \times 10^{42}$ erg/s

- Zoom-in view from the large HI disk (~50’) all the way down to the central HCN(3-2) disk (~0.1”).
- Now we travel over 30,000× scales!
- Demonstrate the great capability of ALMA. Finally we did it!!

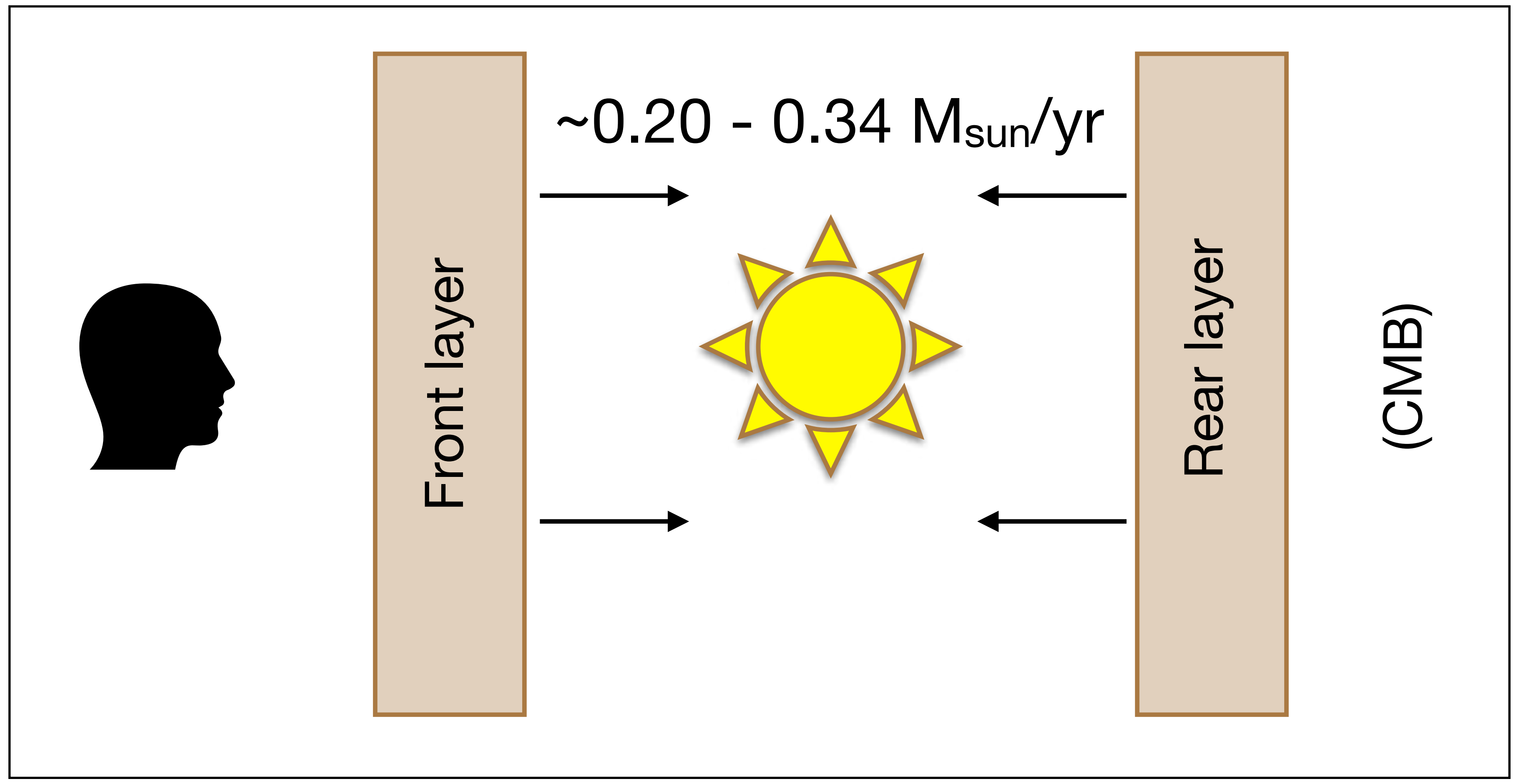
Dense Molecular Gas: HCN(3-2)



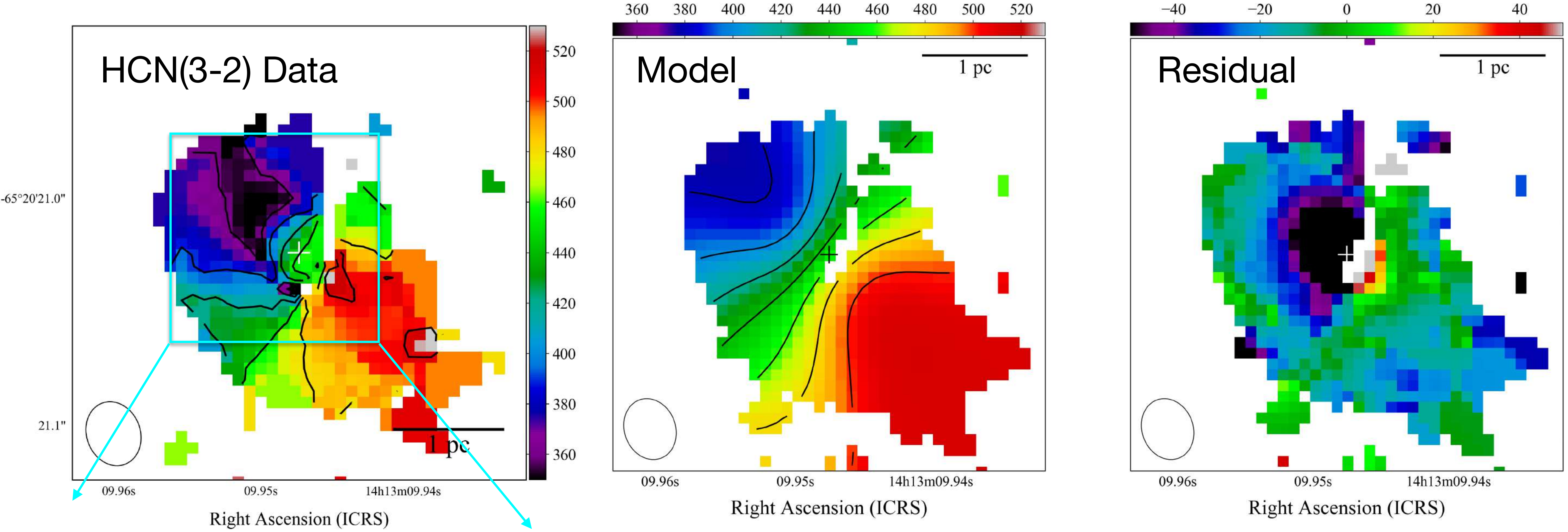


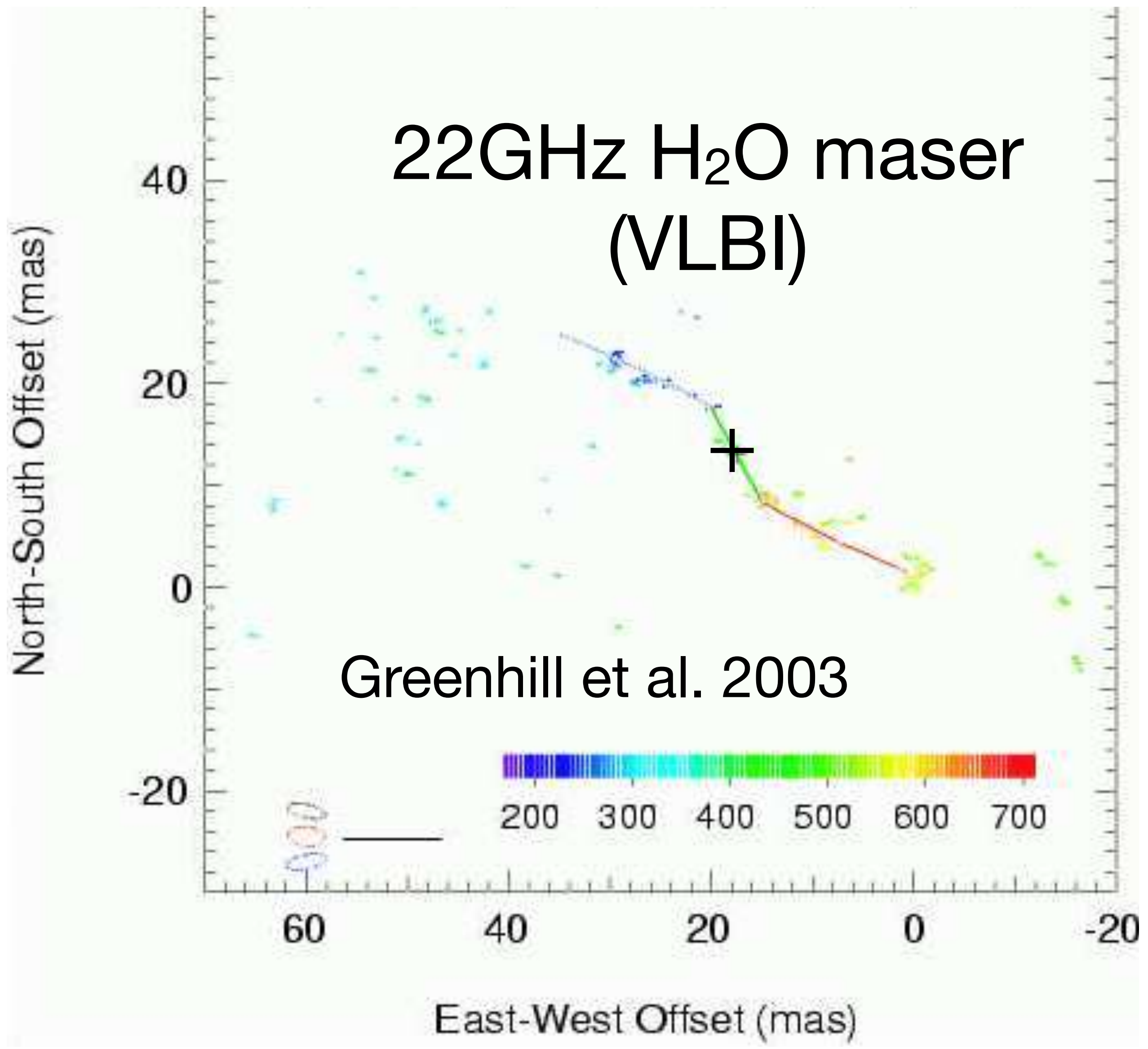
First detection!

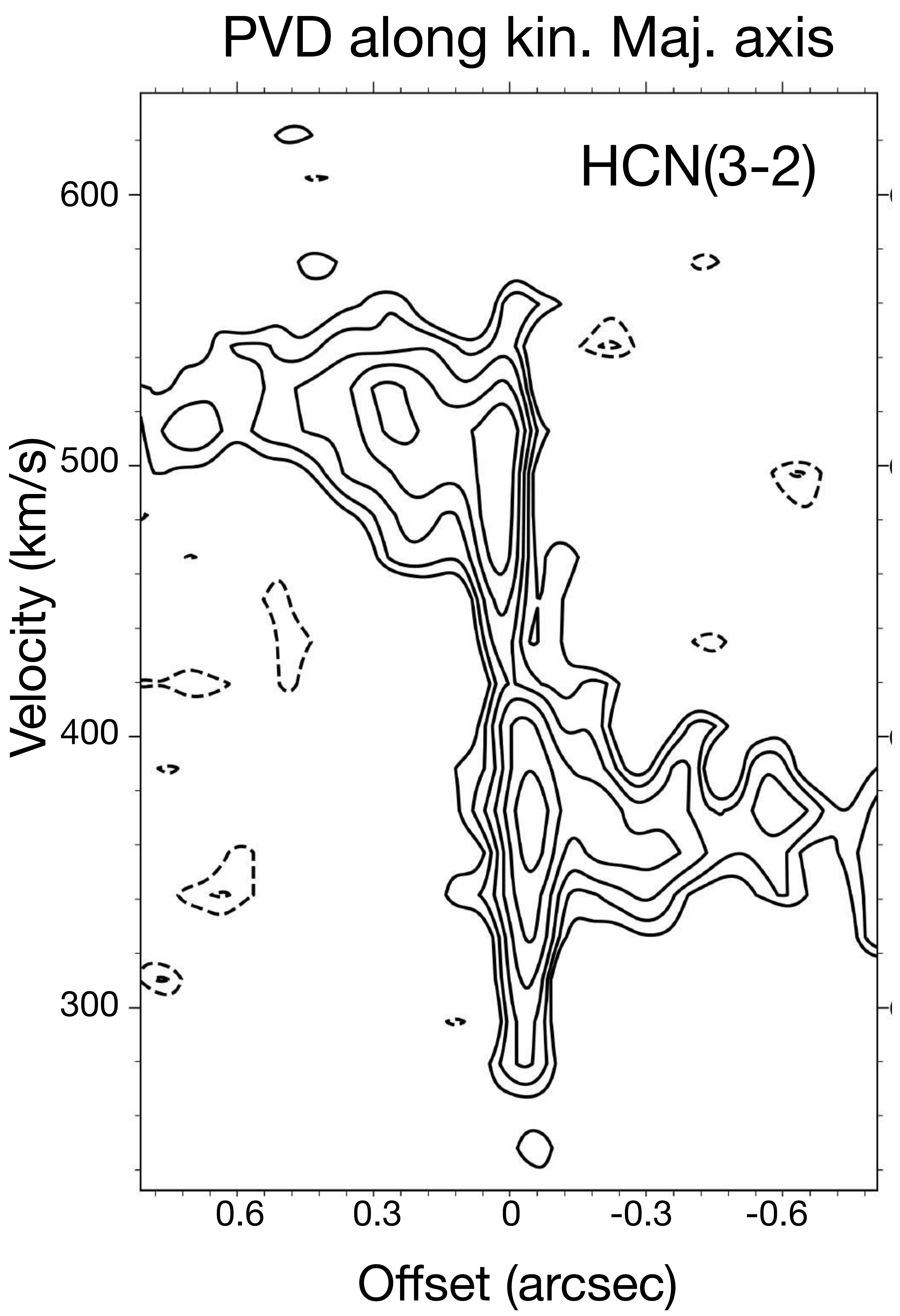
- Deep cont. absorption → "**inverse P-Cygni**" profile = **inflow**!
- Simple two-layer model indicates V_{in} = 7.4 ± 1.0 km/s
- $M_{dot,in}$ ~ 0.20 - 0.34 M_{sun}/yr (assumed density = n_{crit})
- c.f. $M_{dot,BH}$ = 0.006 M_{sun}/yr (from 2-10 keV X-ray): **~3% of $M_{dot,in}$**



3D Modeling of Gas Dynamics (tilted ring scheme)

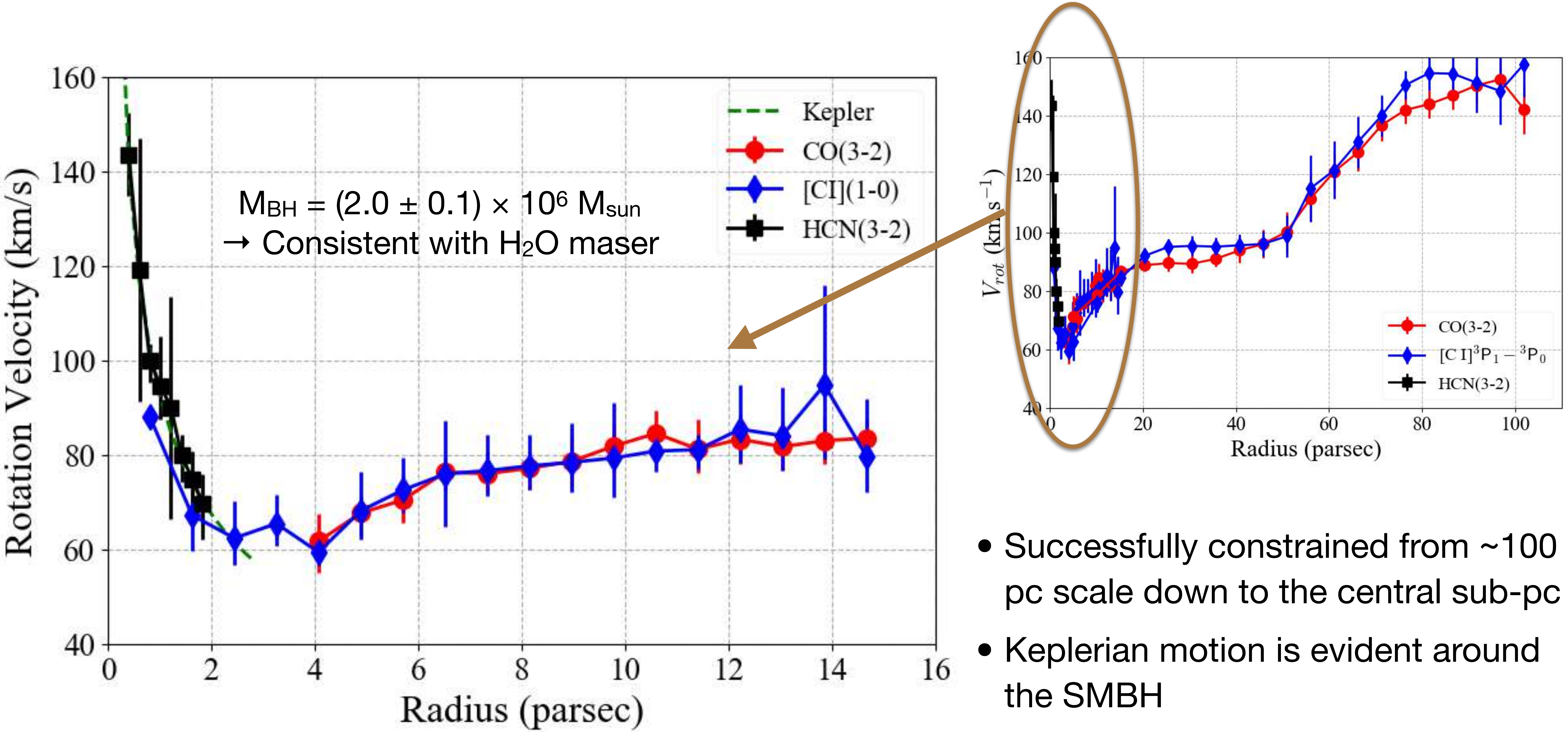






- Tilted-ring model (^{3D}Barolo; Di Teodoro & Fraternali 2015)
  → Decompose V_{rot} and σ_{disp}
- HCN(3-2) clearly shows Kepler motion that is consistent with the H_2O maser dynamics.

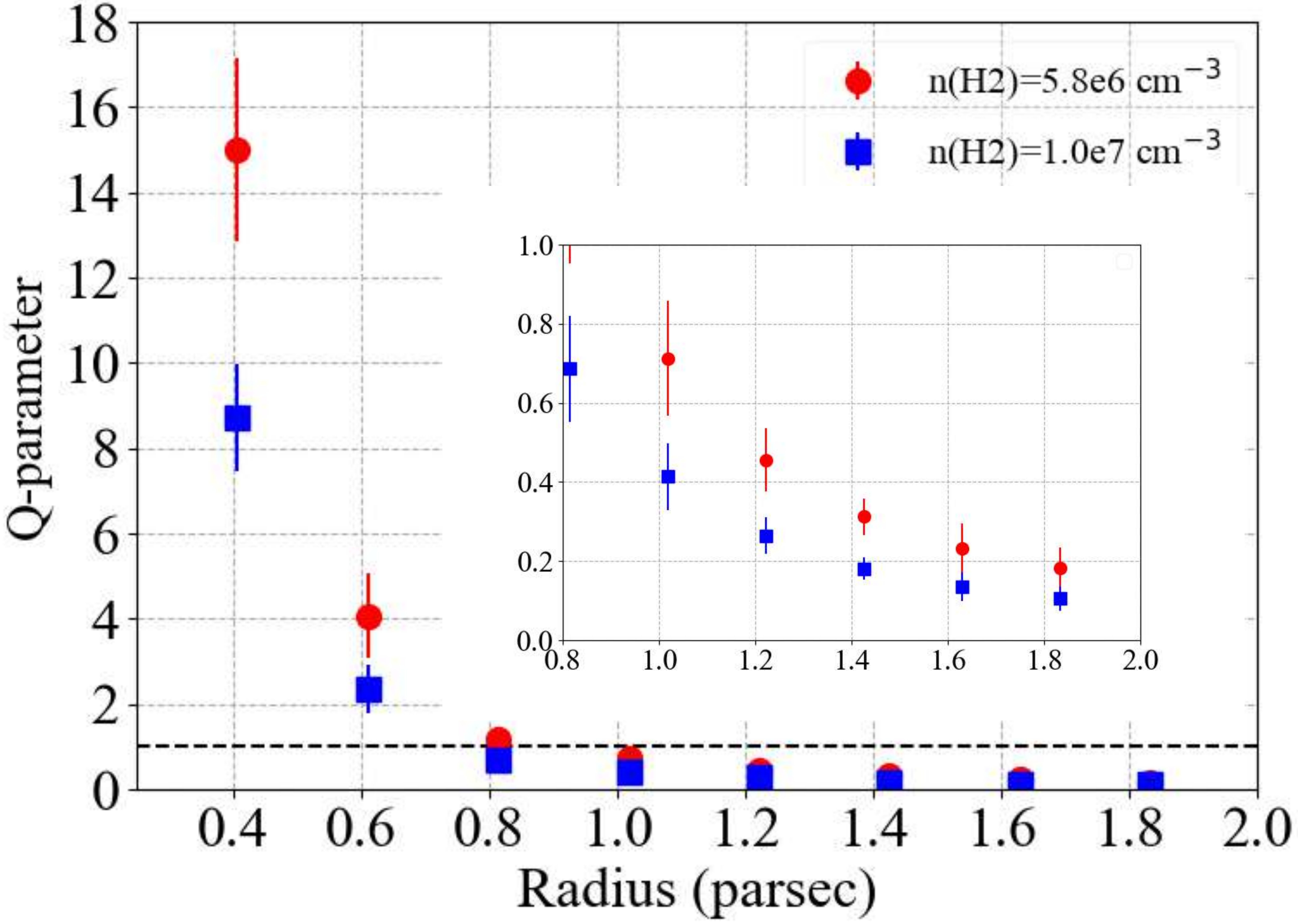
Rotation Curve



$M_{BH} = (2.0 \pm 0.1) \times 10^6\ M_{sun}$
→ Consistent with H_2O maser

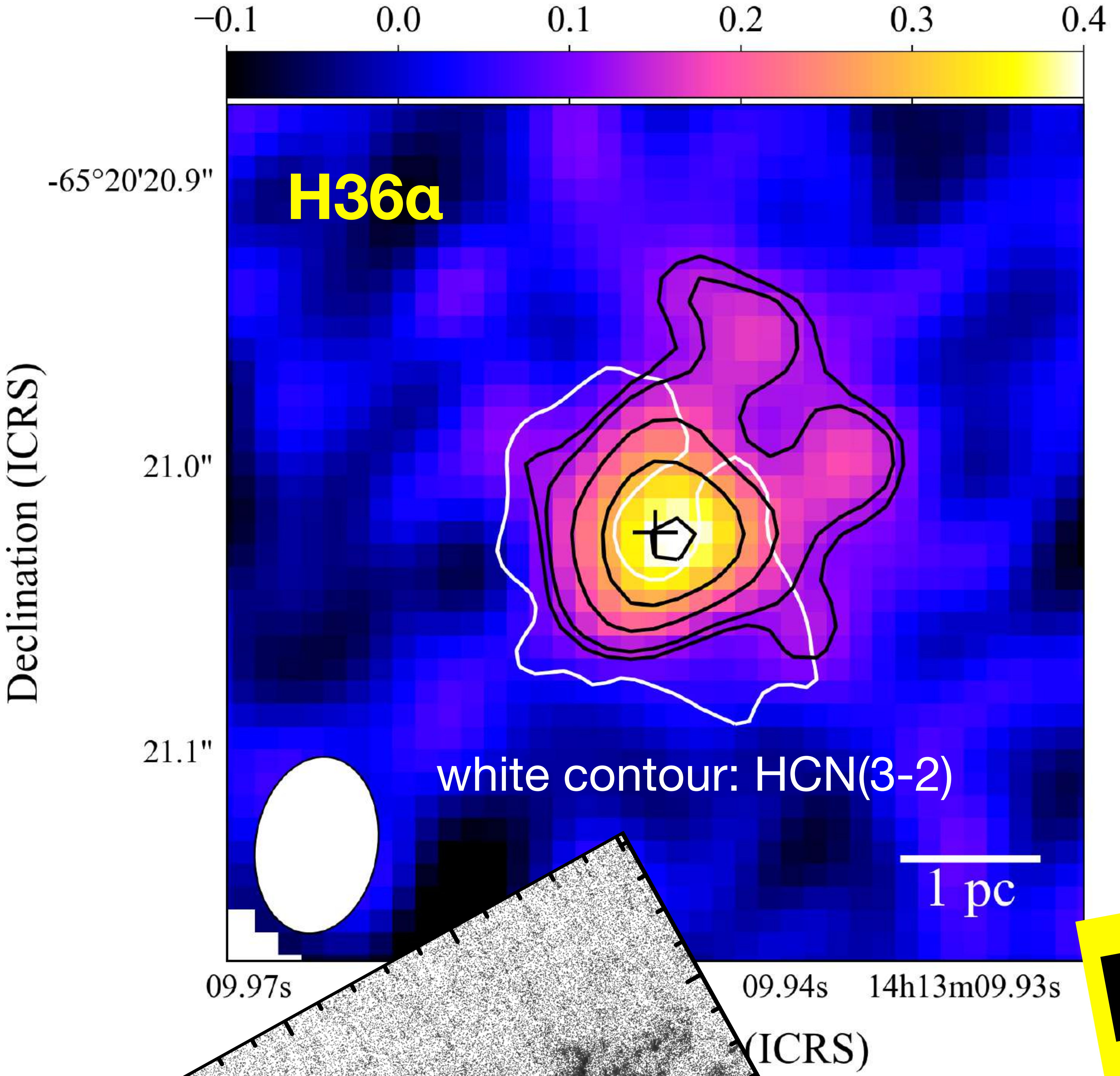
- Successfully constrained from ~100 pc scale down to the central sub-pc
- Keplerian motion is evident around the SMBH

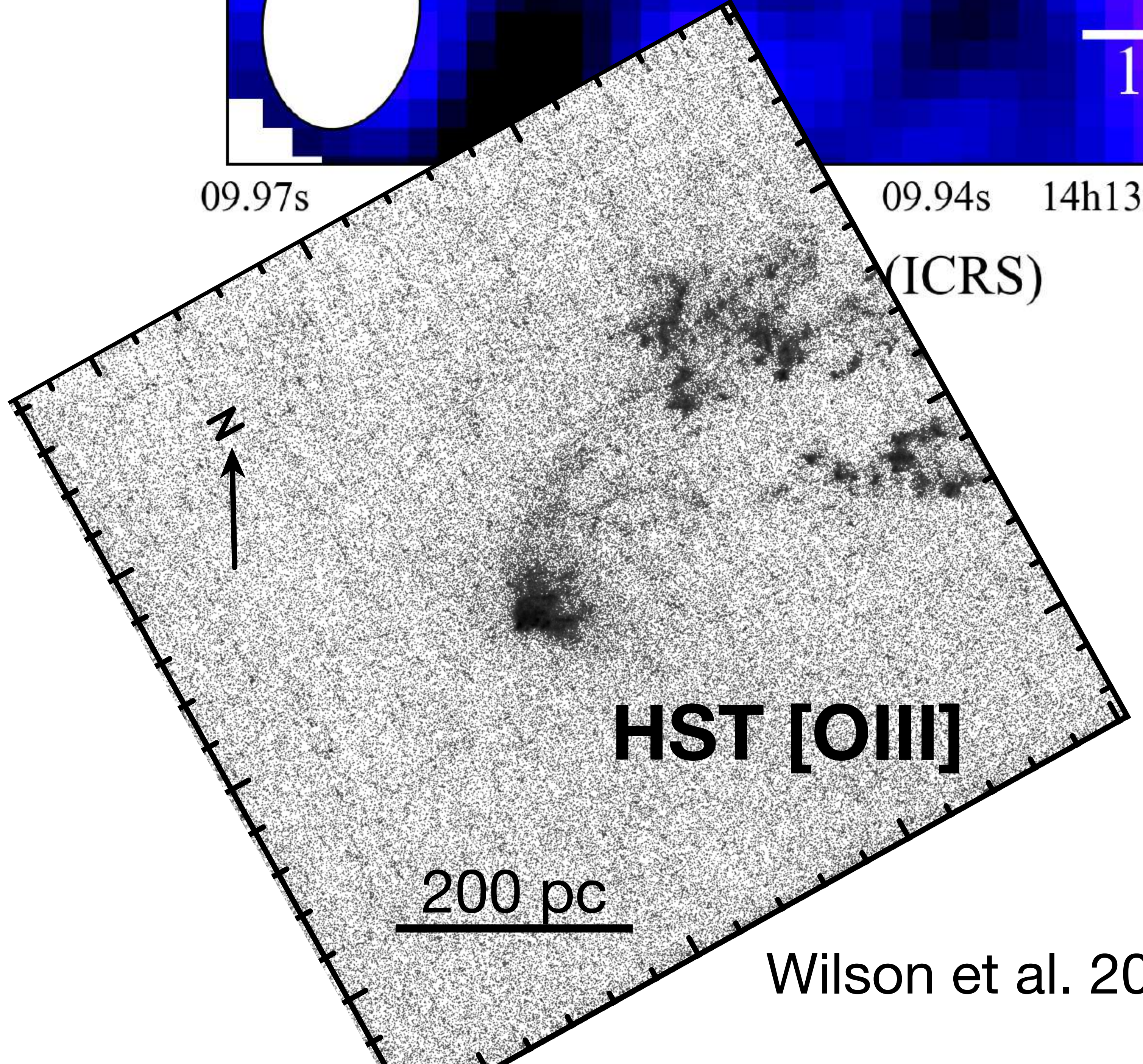
Gravitational Instability Drives Accretion!



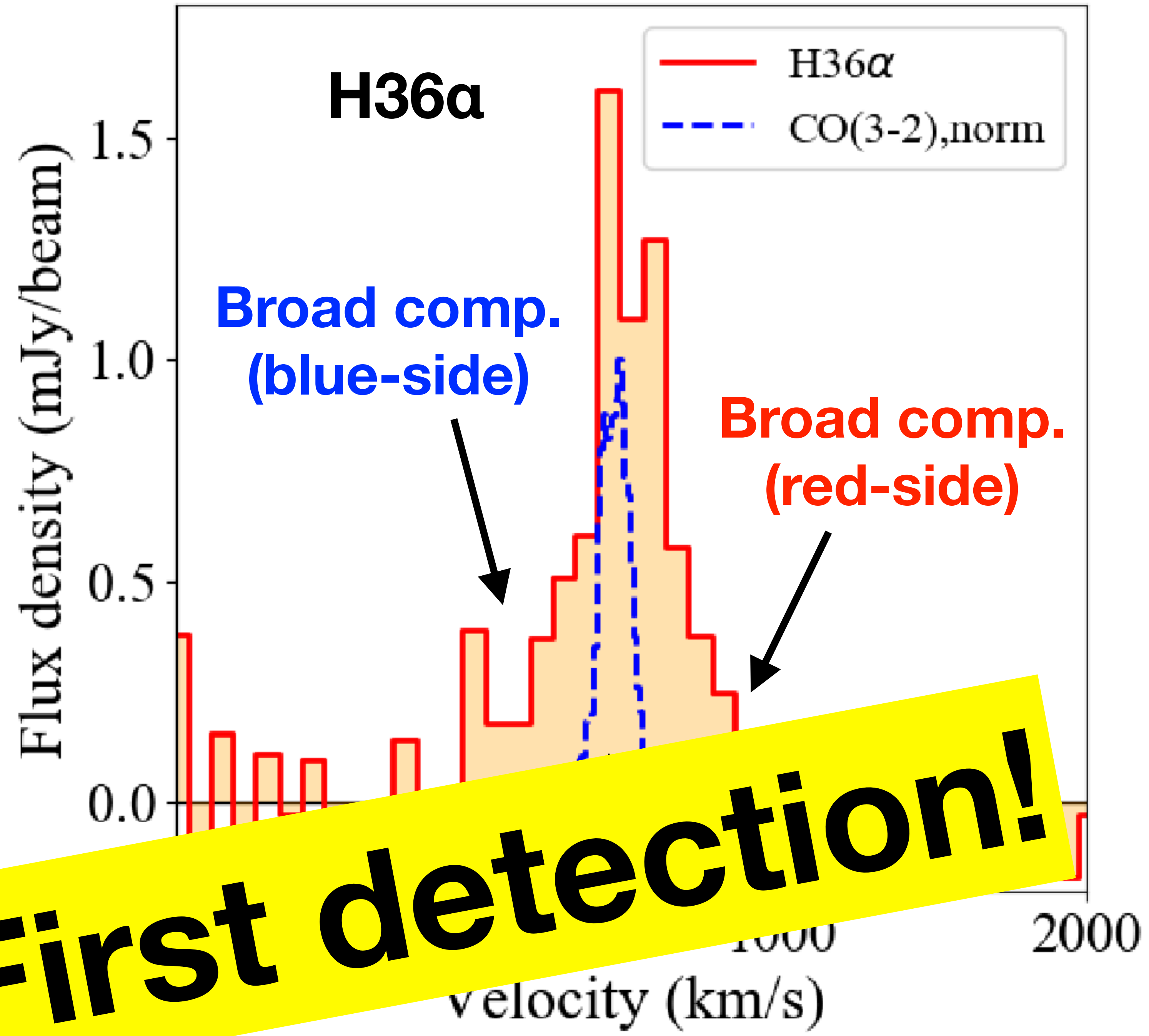
- Gas mass: from HCN(3-2) critical density
- Gas velocity: from V_{rot} curve
- Disk geometry: from σ/V_{rot}
- Toomre-Q < 1 at r > 1 pc: **gravitational instability** can drive the accretion
- But it is NOT sufficient at r < 1 pc!
- Maybe, a very dense ($n > 10^8$ cm^{-3}) disk is not well captured by HCN(3-2).

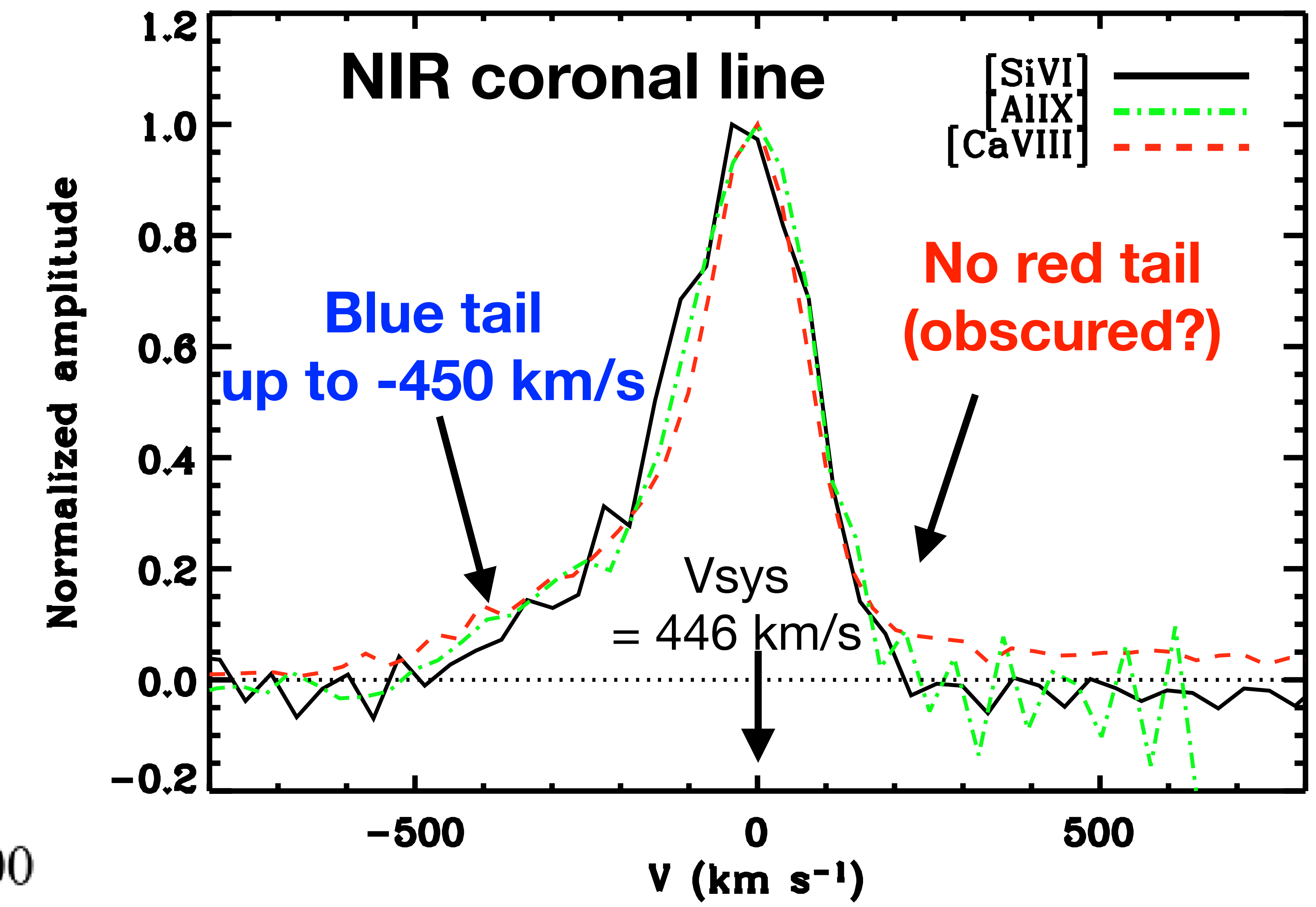
Parsecs-scale Ionized Gas: H36α





Wilson et al. 2000



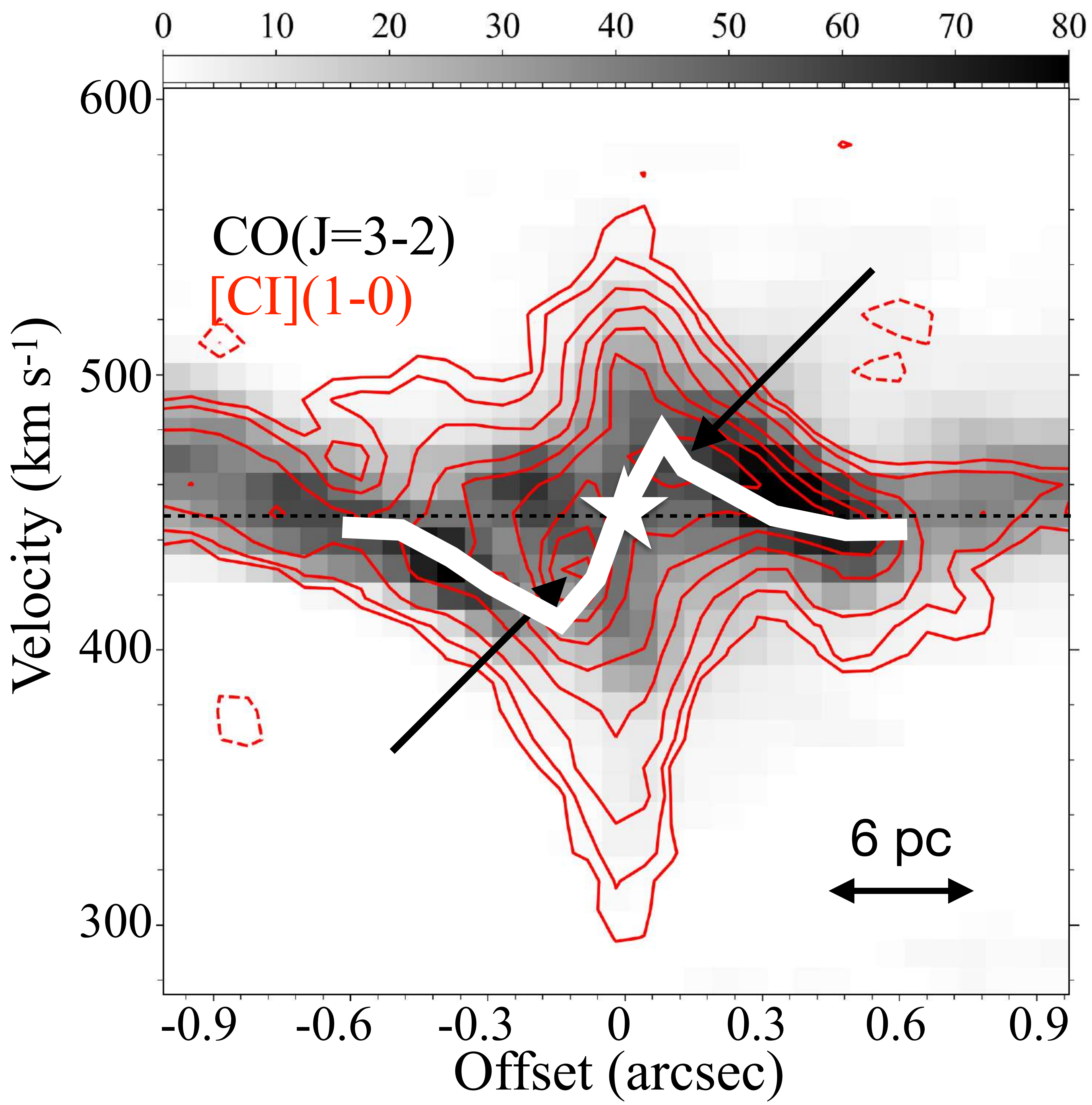


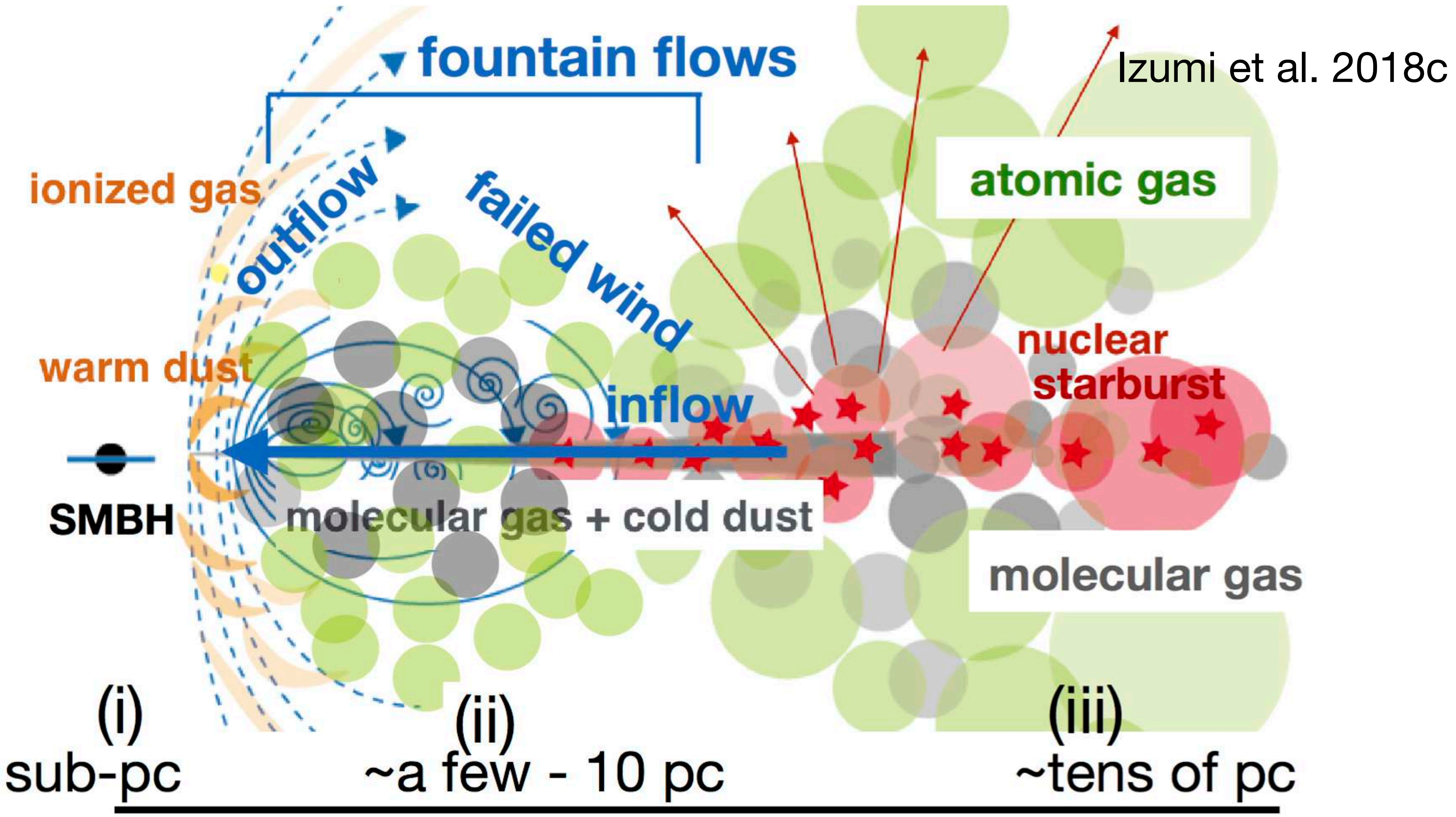
First detection!

- Conical distribution is found, consistent with [OIII] and Hα.
- H36α is very broad → innermost part of the **ionized outflow**!
- Almost symmetric profile, which is not the case for NIR coronal lines → Submm-RLs as an **extinction-free probe** of ionized gas!
- Ionized outflow rate ~ 0.04 M_{sun}/yr (w/ LTE) (c.f., $M_{dot,in}$ ~ 0.20-0.34 M_{sun}/yr, $M_{dot,BH}$ = 0.006 M_{sun}/yr)

Where is the Remaining Mass? Atomic-dominant Outflow

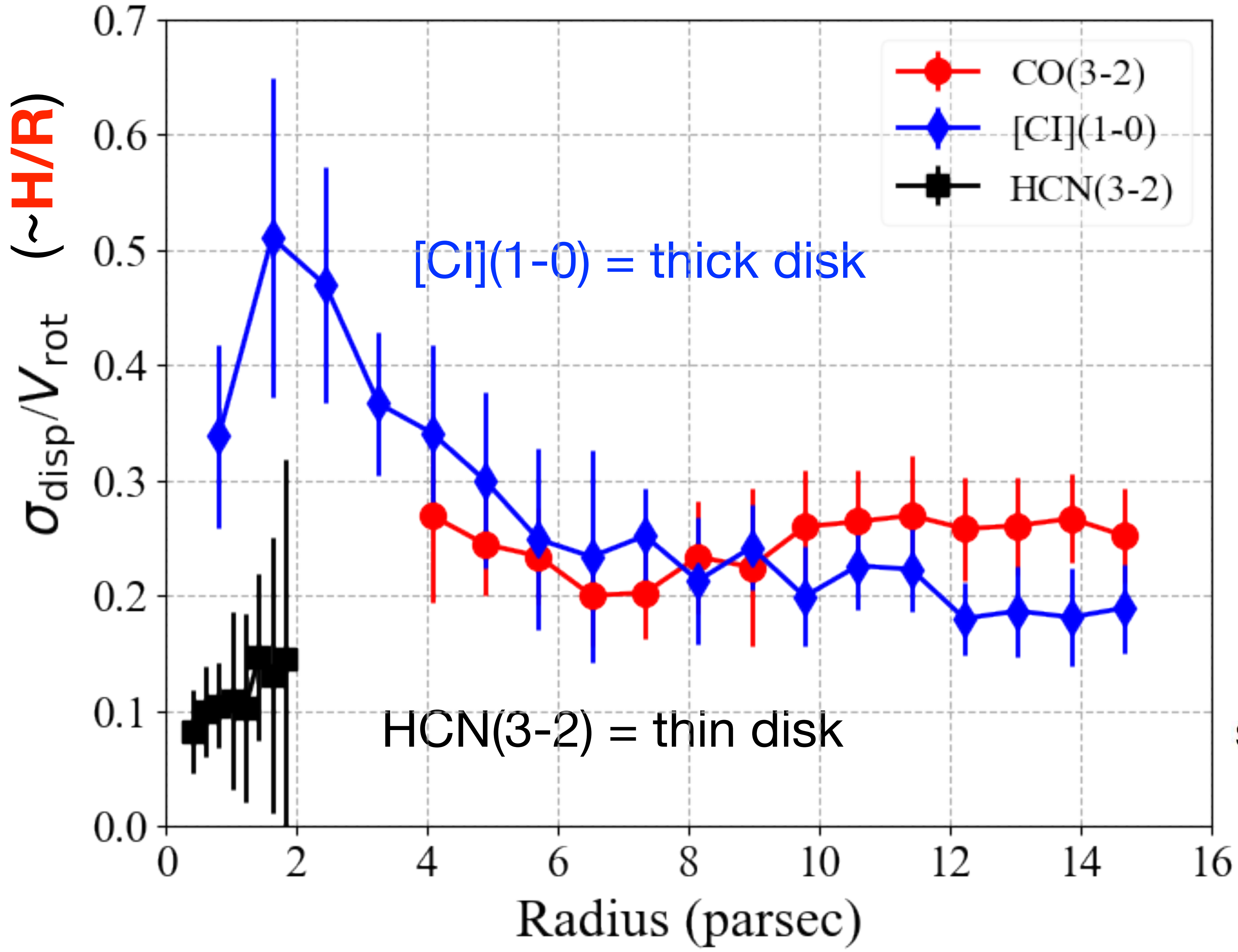
PVD along kin. min. axis

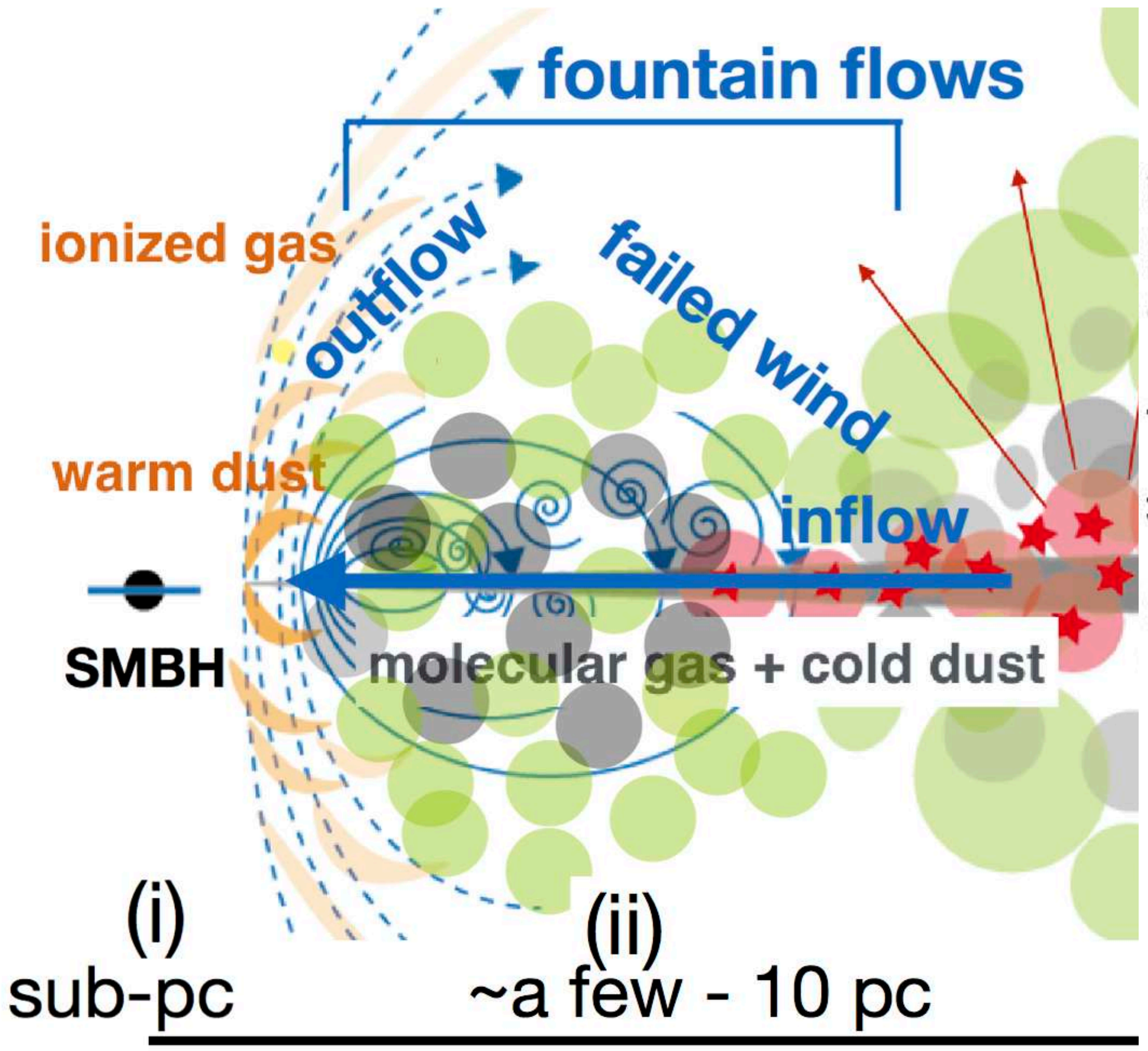


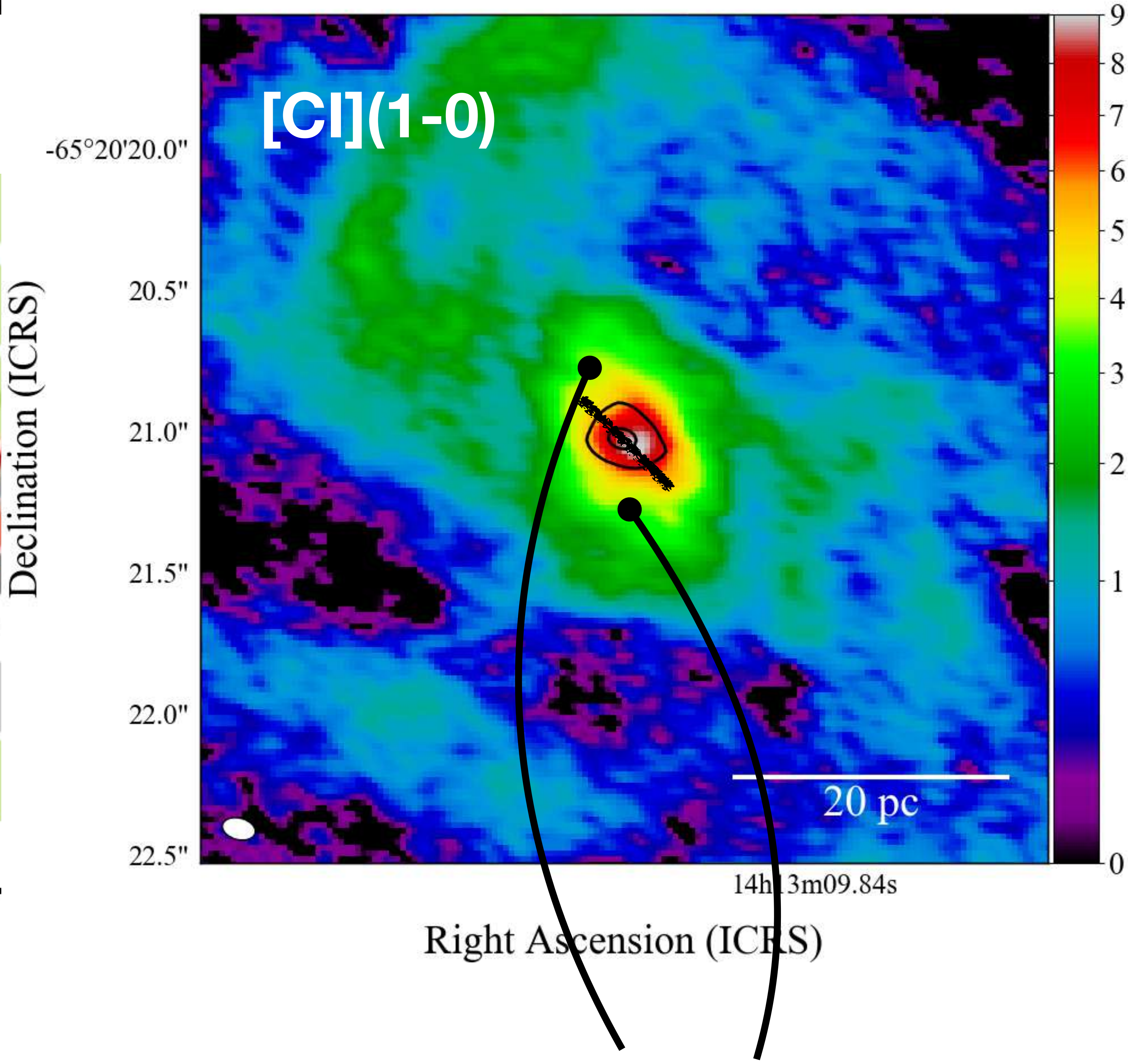


- Offset peaks in the minor axis PVD: prominent in [CI]
  → indication of **atomic-dominant outflow**!
- Geometry is unresolved, but is well-constrained by H36α cone.
  → Atoms reside outside of the ionization cone
- Outflow velocity <u>< 40 km/s @r~1-2 pc</u> (slow)
  → **Backflow to the disk (circulation)**

Multiphase Torus Geometry





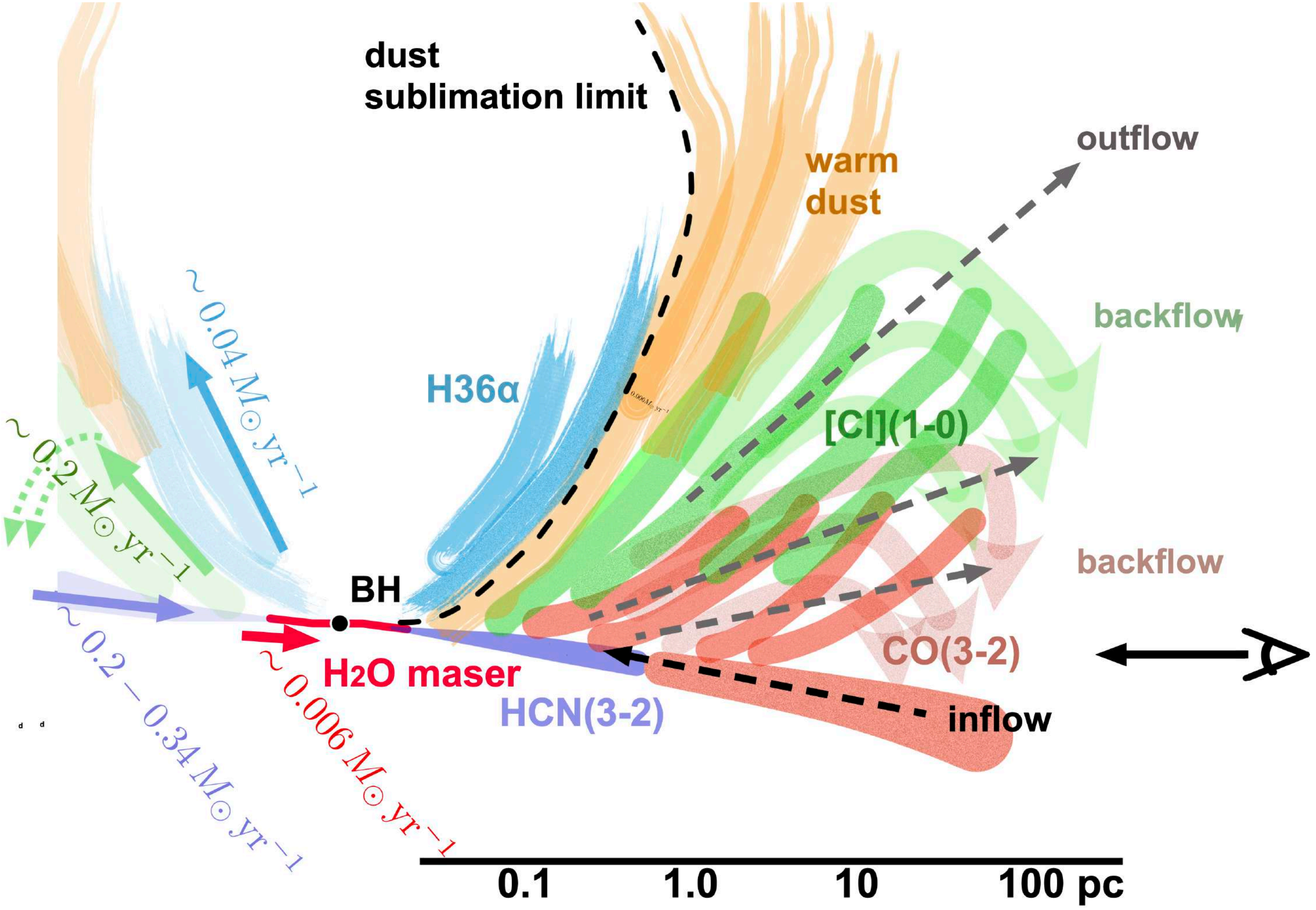


- Geometrical structure, or disk **scale height/ radius**, depends on the phase/density of the gas → **multiphase obscuring structure!**
- Turbulence induced by the backflow would support the thickness of the CI disk.

- Expected H-column density and/or A_V above the nearly edge-on disk (LTE) → N_H = (4–9) × 10^{23} cm^{-2} or **A_V = 210—440 mag**.
- This thick disk provides a **substantial obscuration = obscuring torus**.

Circumnuclear multiphase gas flows

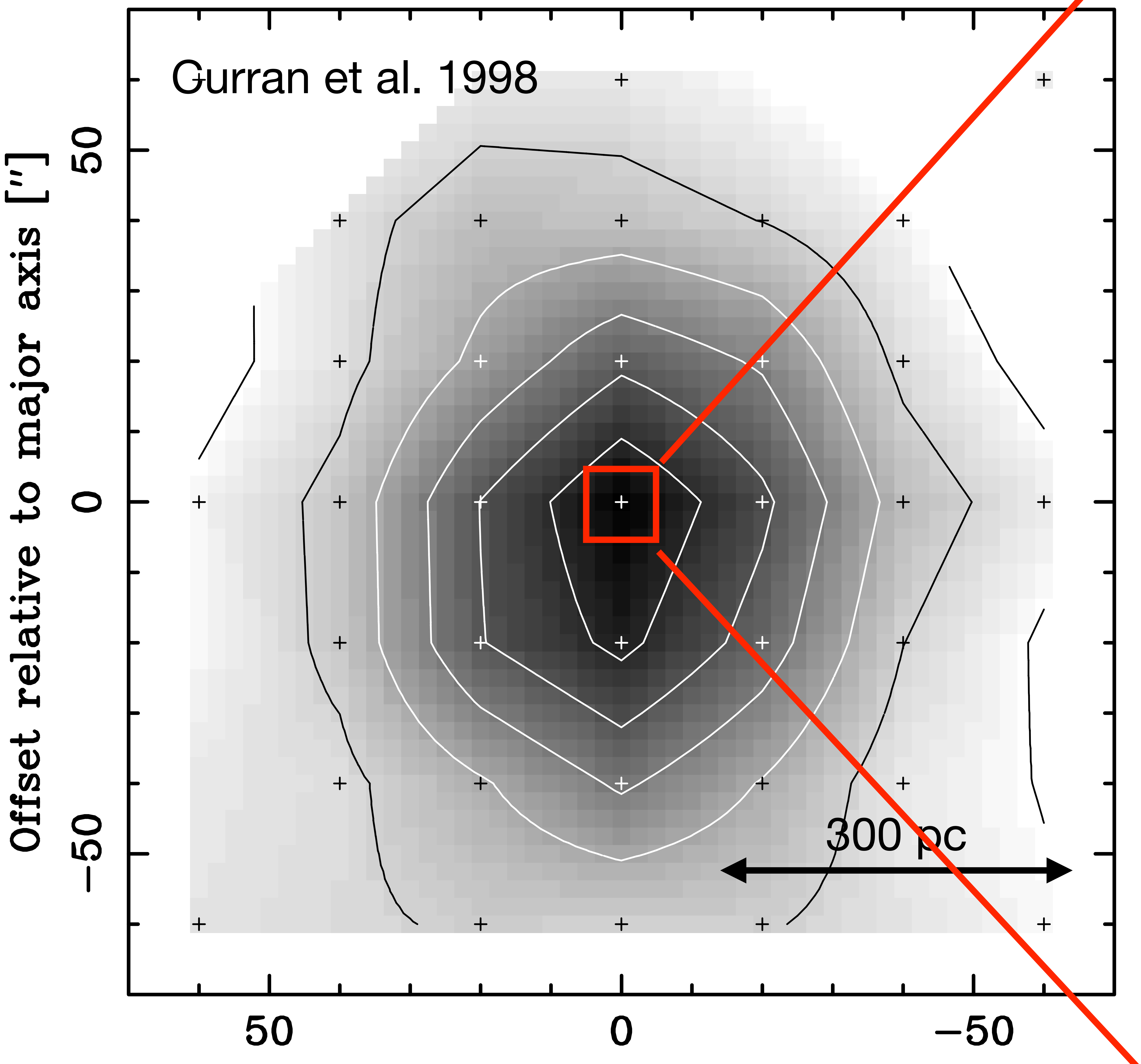
Izumi et al. 2023

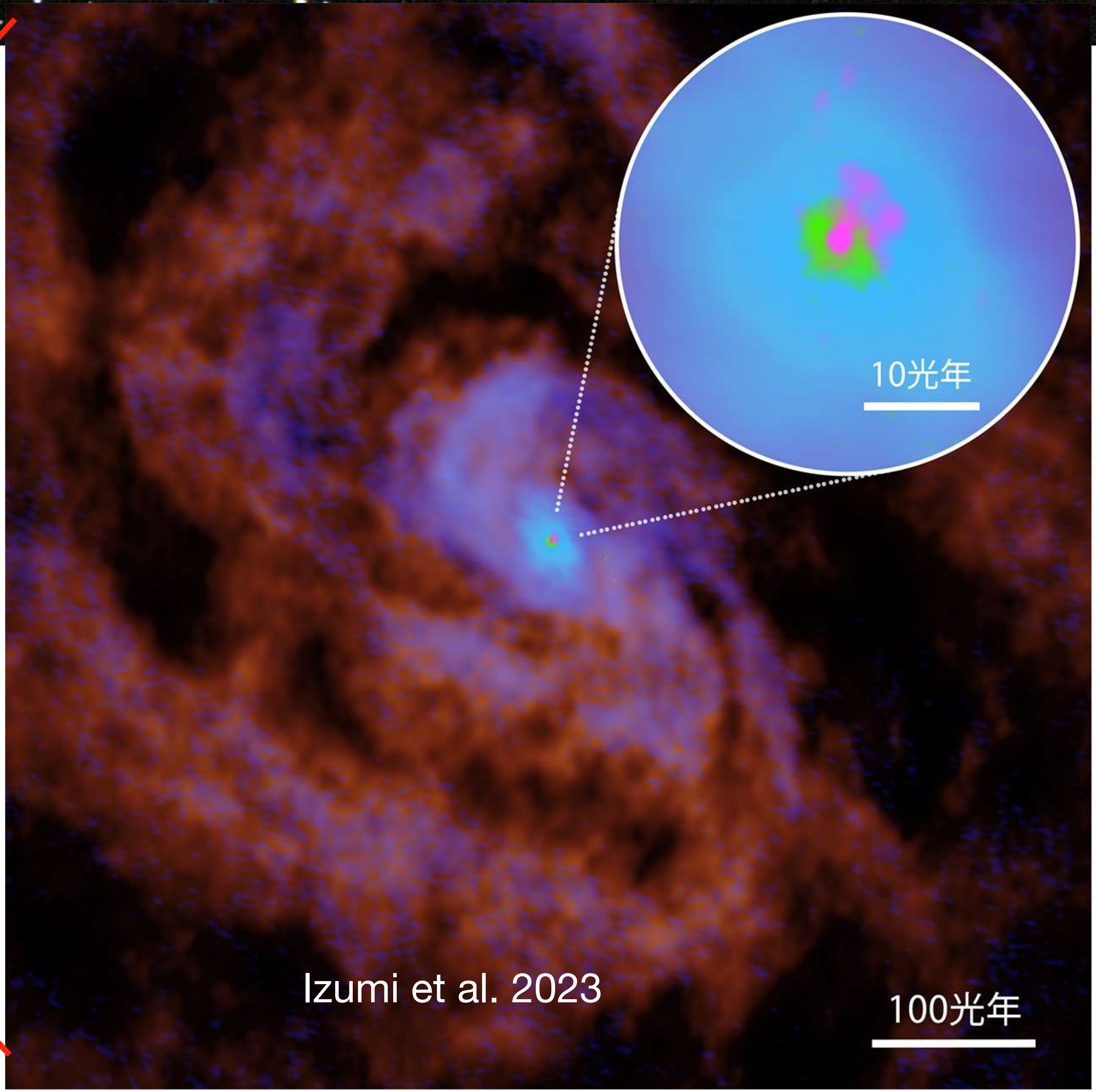


In AGN:

- We have for the first time ever detected the **pc-scale dense molecular inflow**.
- Only a tiny portion (< 3%) of this inflow is consumed as the actual SMBH growth.
- We have for the first time ever detected **pc-scale ionized outflows** w/o severe dust extinction: root-part of outflows
- A bulk portion of the inflow must be carried by **atomic (+ molecular) outflows:** eventually become backflows.
- Atomic gas forms a geometrically thicker volume than dense molecular disk → **multiphase** nature of obscuration (torus)

Significant Advancement over the past ~25 yrs

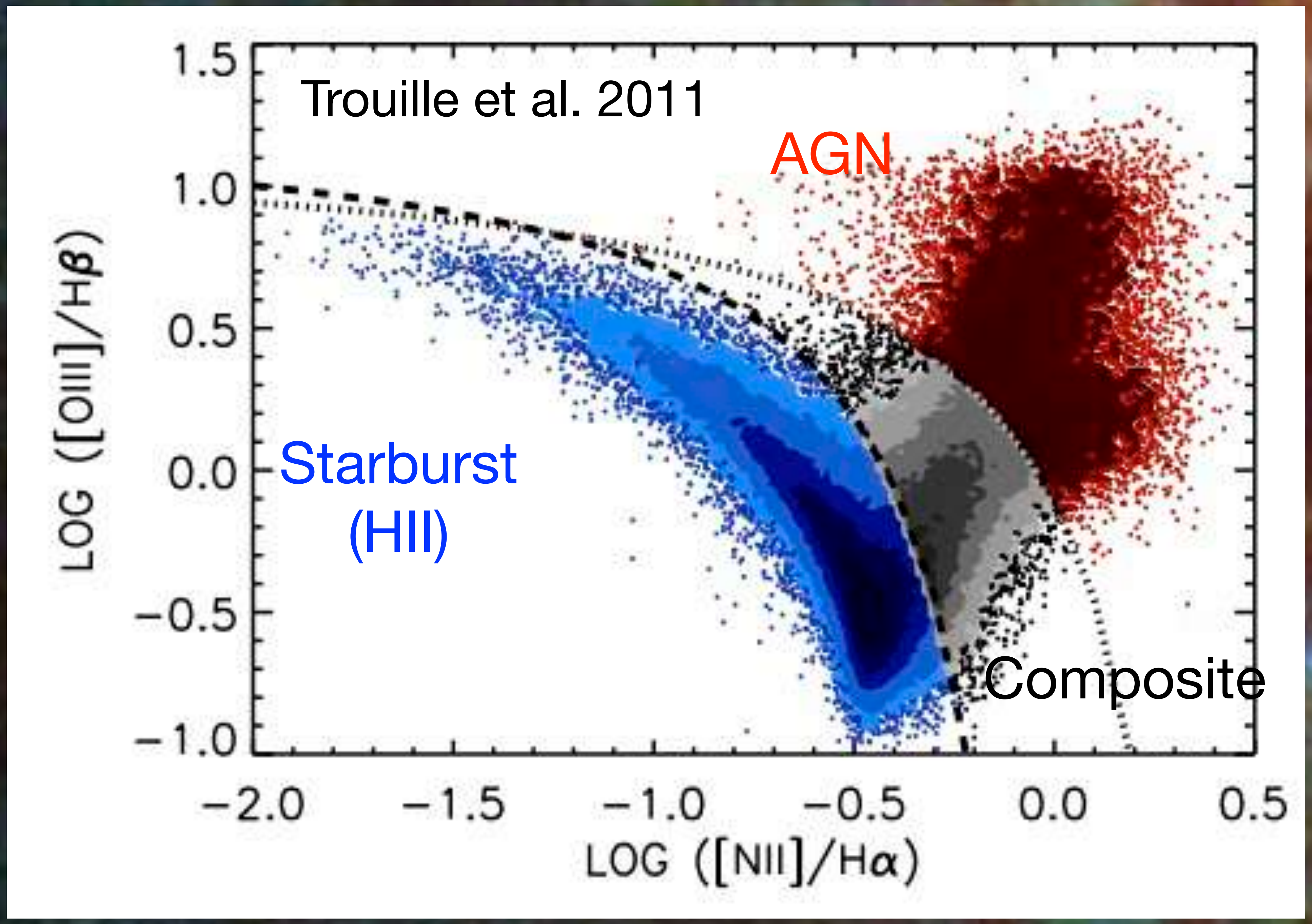




2. Astrochemistry as a tool for Astrophysics

My motivation: to identify the obscured activity

A_V ~ 2000 mag (!?)



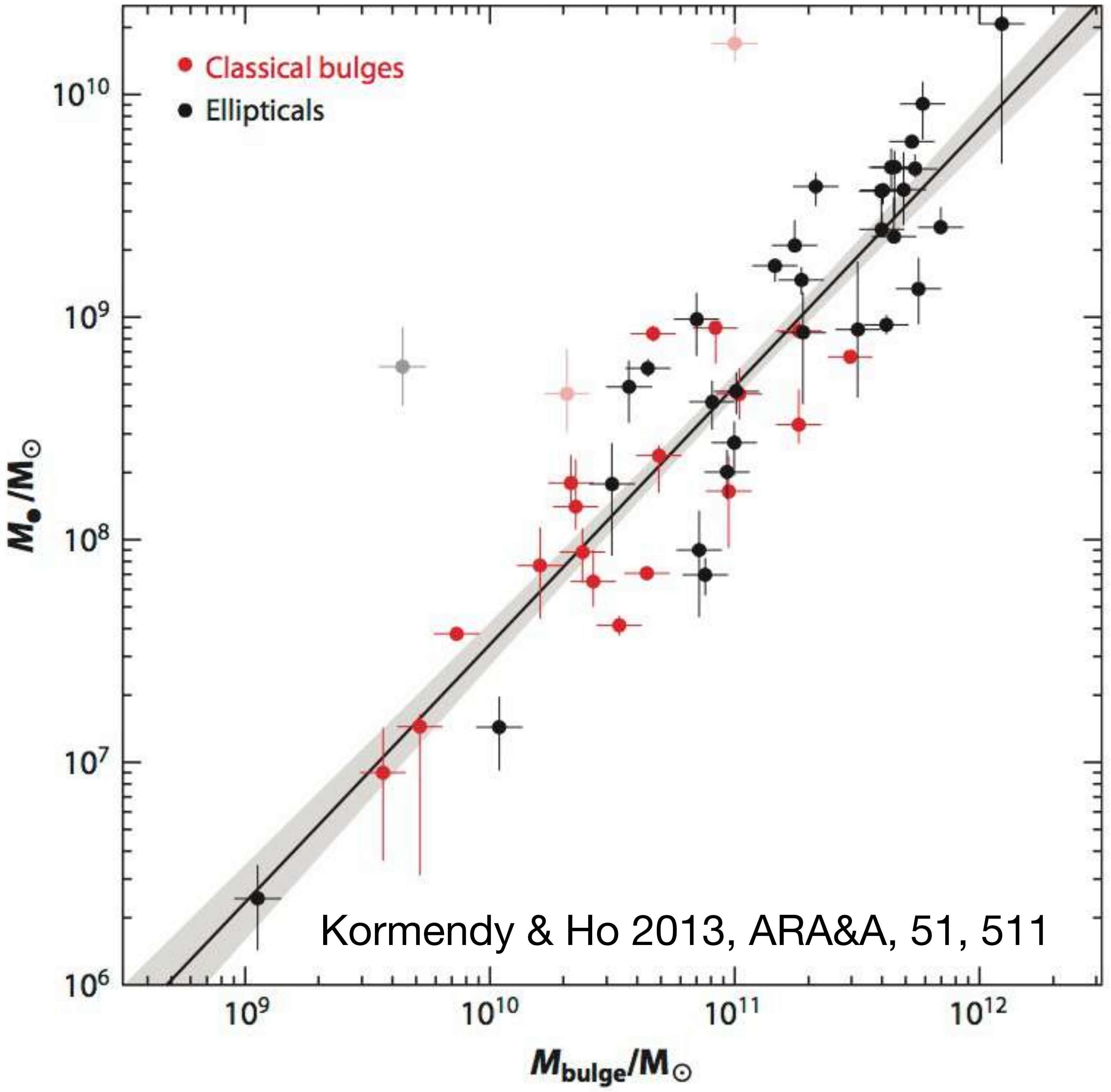
Arp220 / NASA, ESA, and C.Wilson

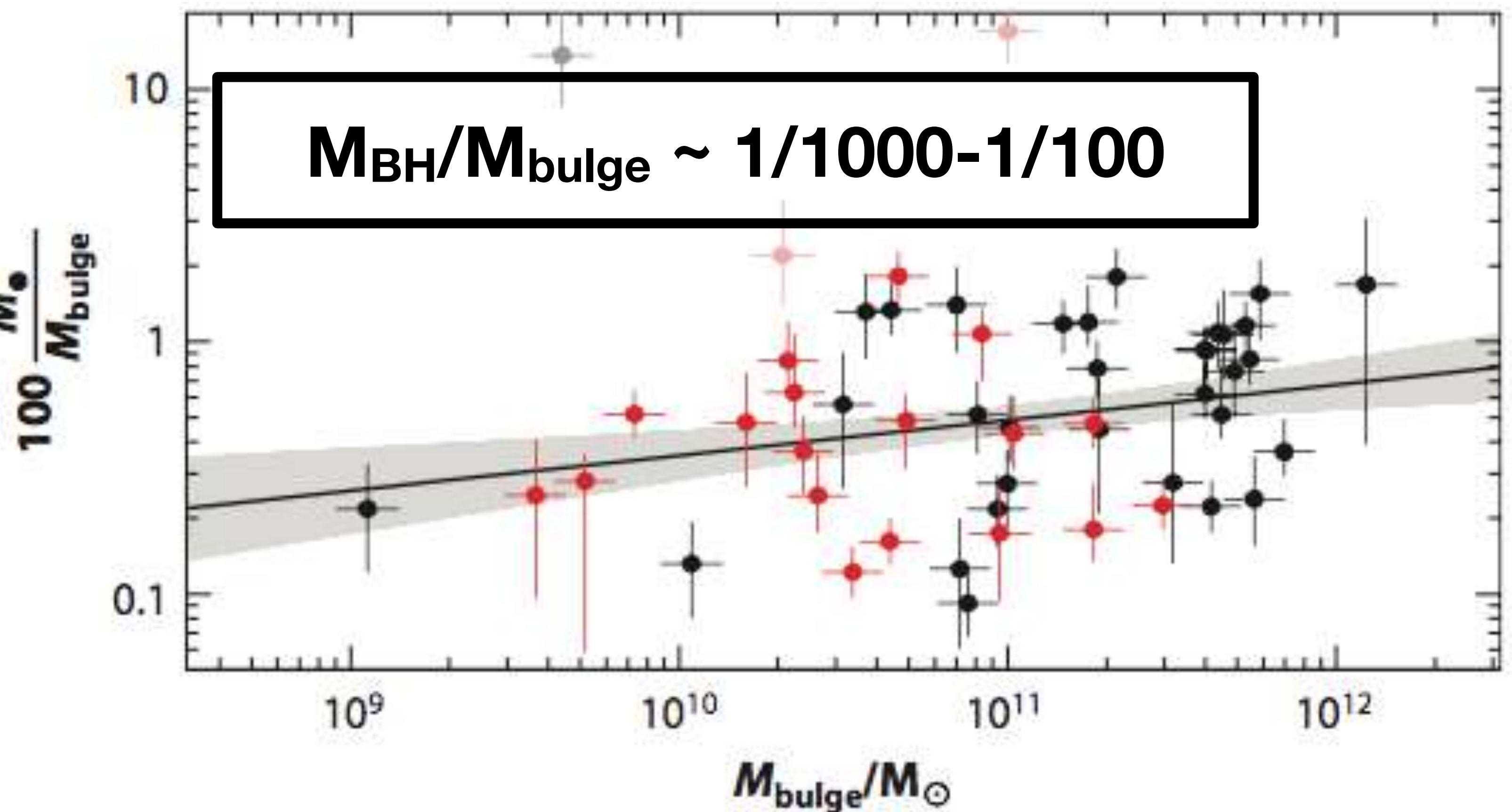
Toward a diagnostic method of nuclei behind the curtain of dust

- Different heating mechanisms (AGN, starburst) will produce different signature on ISM
- **Photo dissociation region (PDR)**, **X-ray dominated region (XDR)**, **Cosmic-ray**, **Mechanical heating**
  → ***chemical feedback***

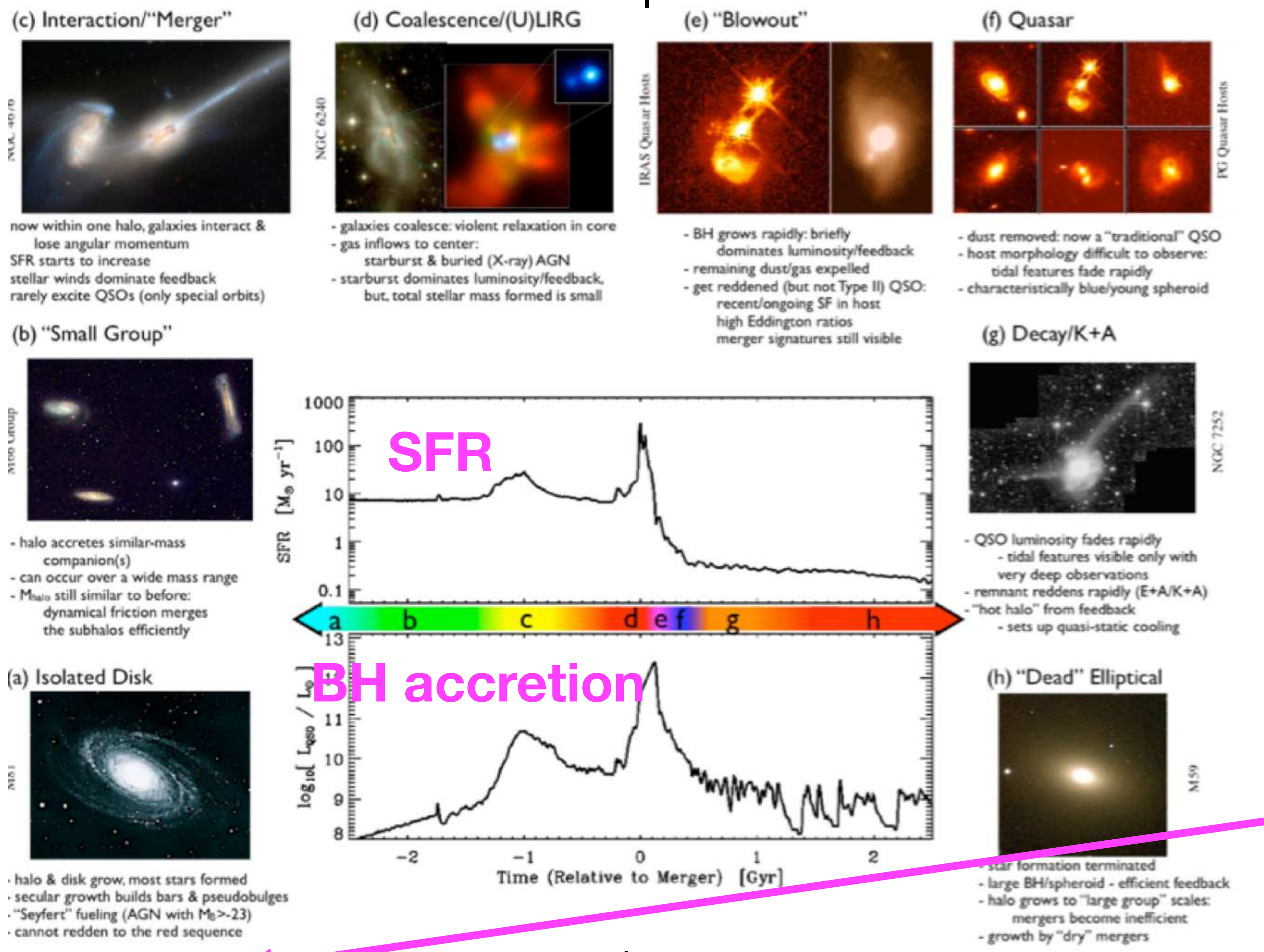
Arp220 / NASA, ESA, and C.Wilson

Role of Obscured AGN in the cosmological SMBH growth?

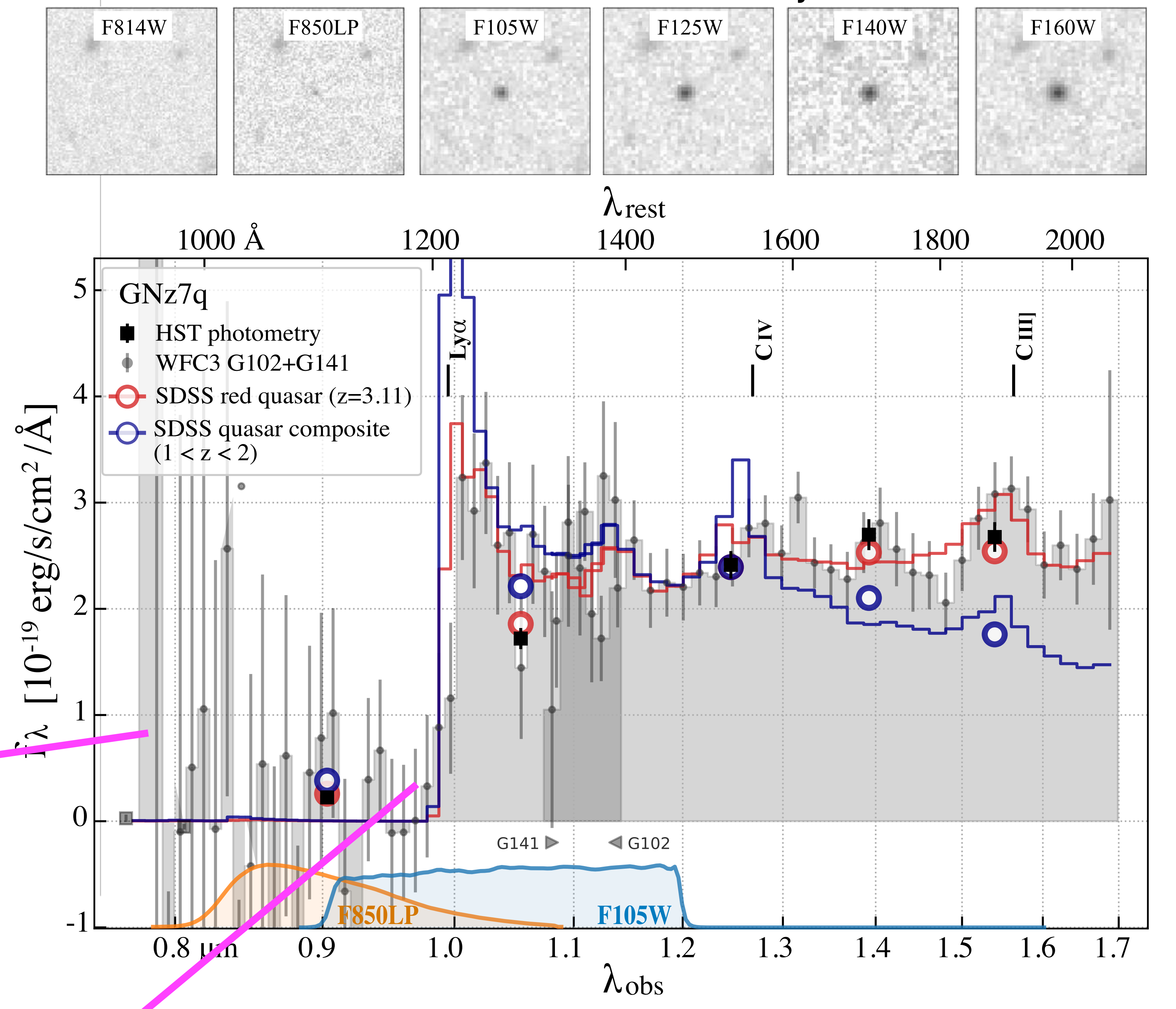


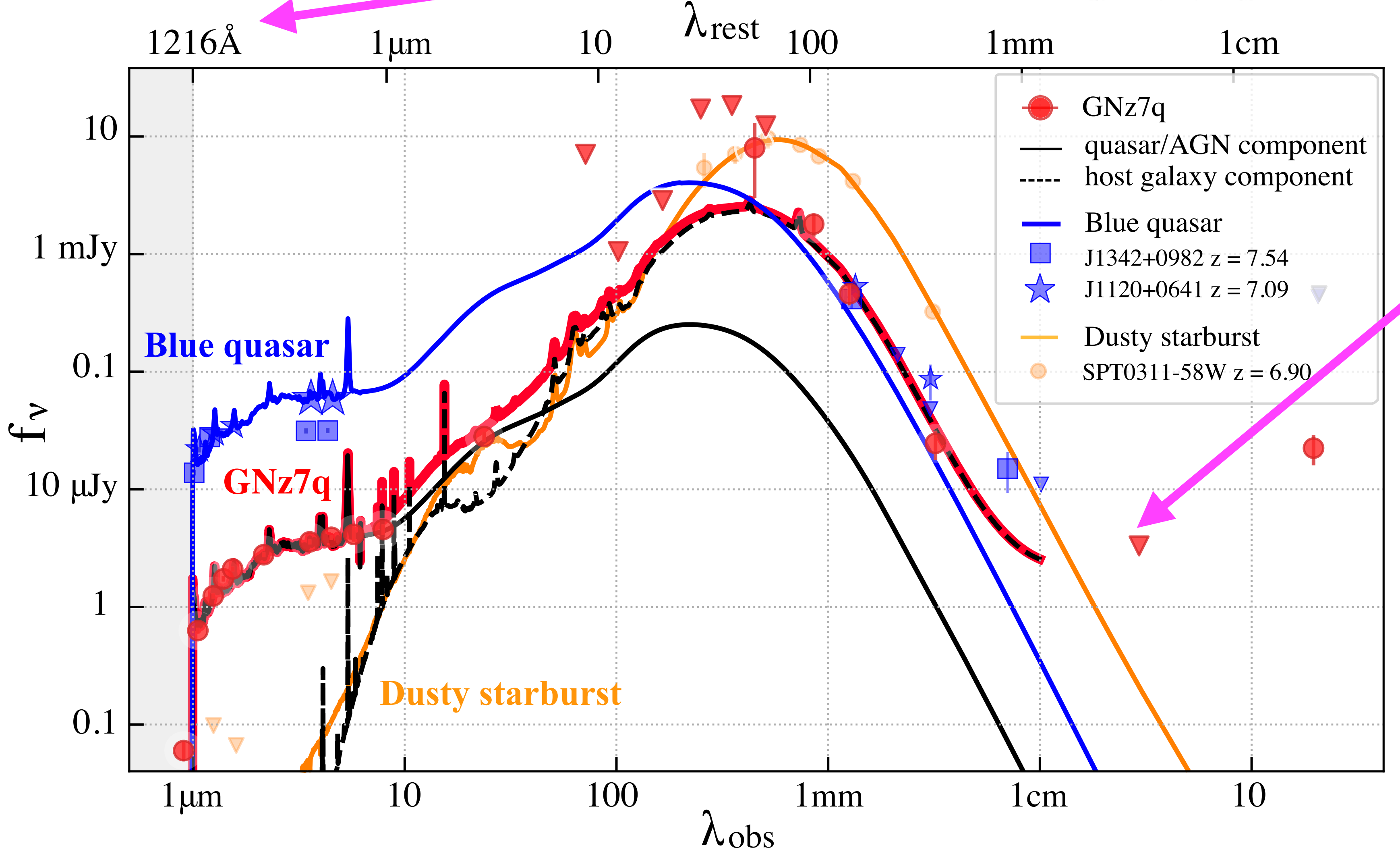


Hopkins et al. 2008



Fujimoto et al. 2022

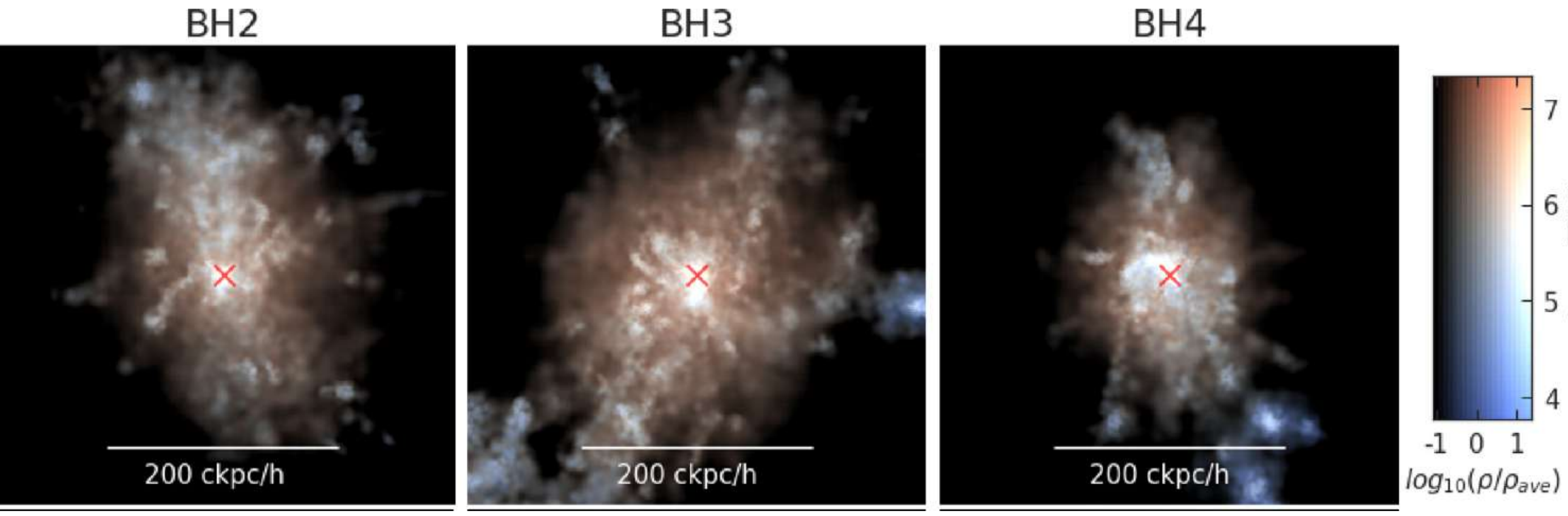


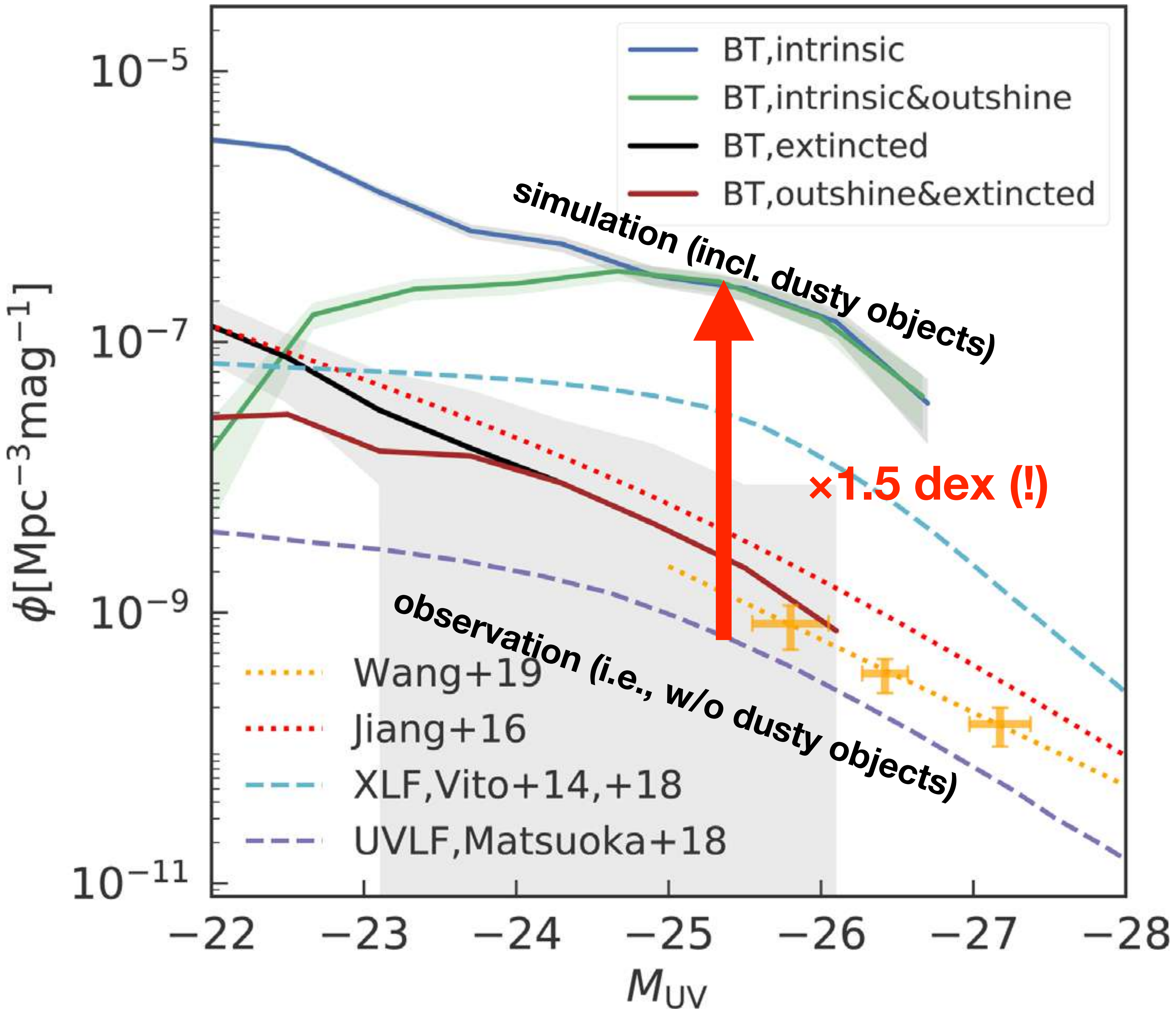


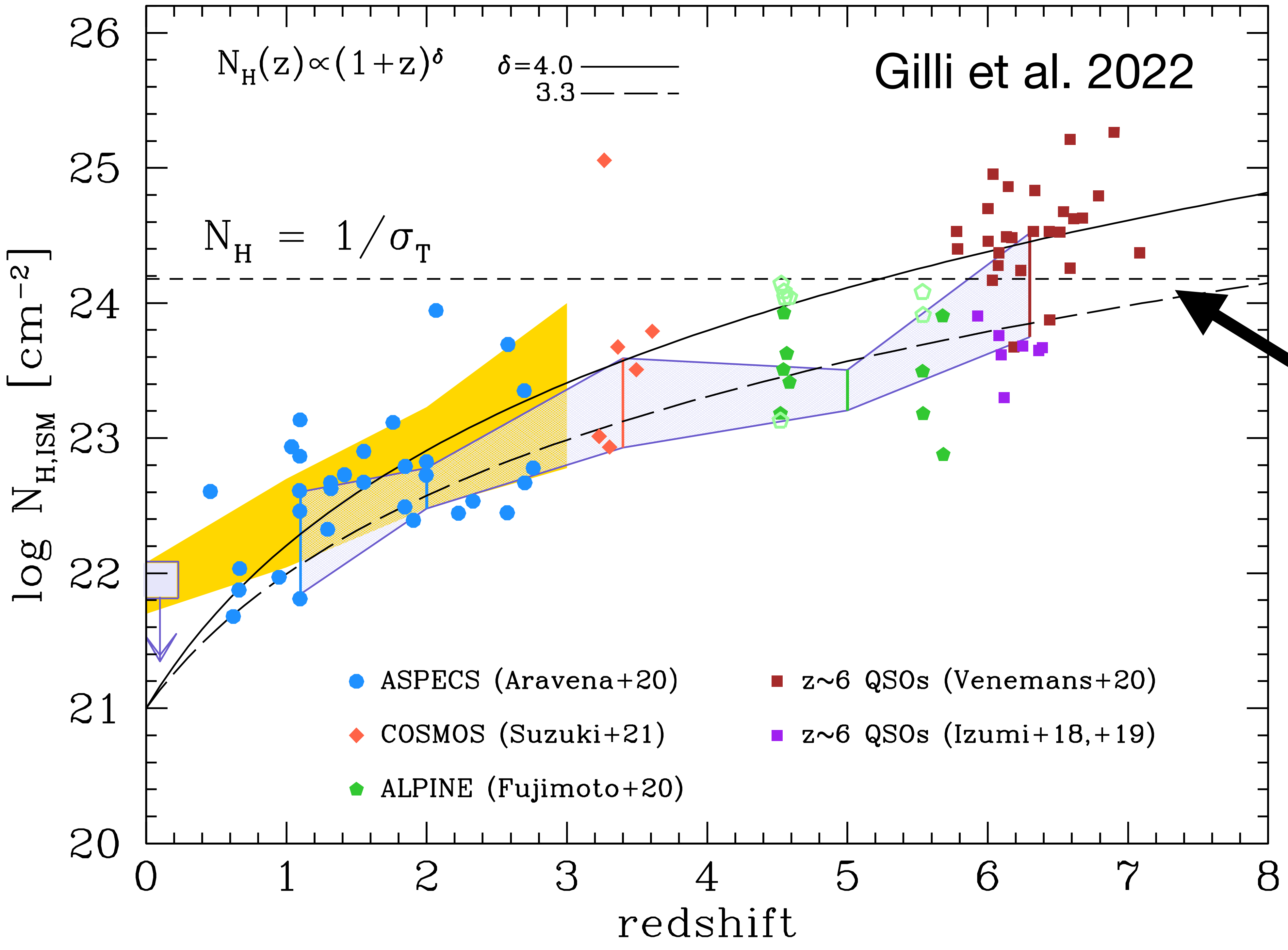
- Obscured, rapid growth phase in the co-evolution of SMBHs and galaxies.
- Now we see this class of object even at z > 7 (Fujimoto+22)

Role of Obscured AGN in the cosmological SMBH growth?

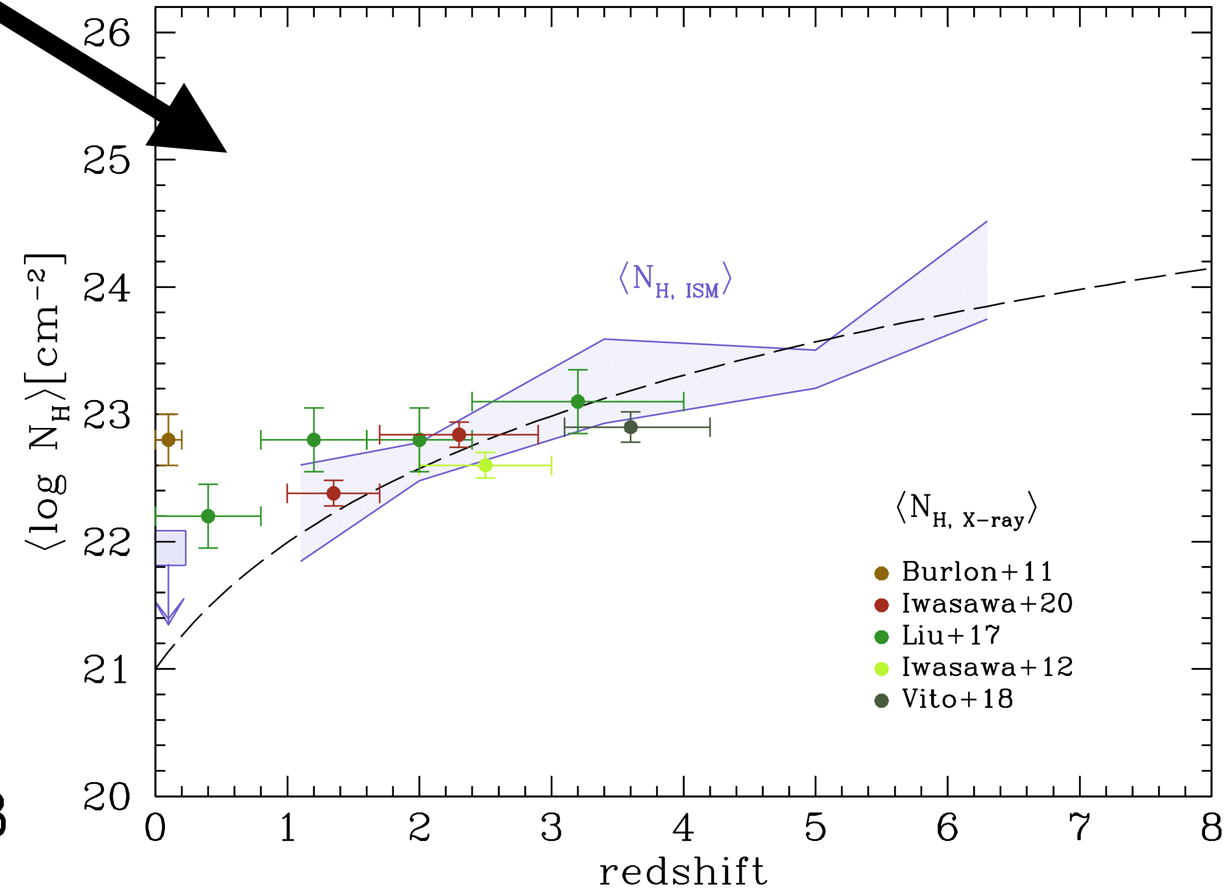
Ni et al. 2020





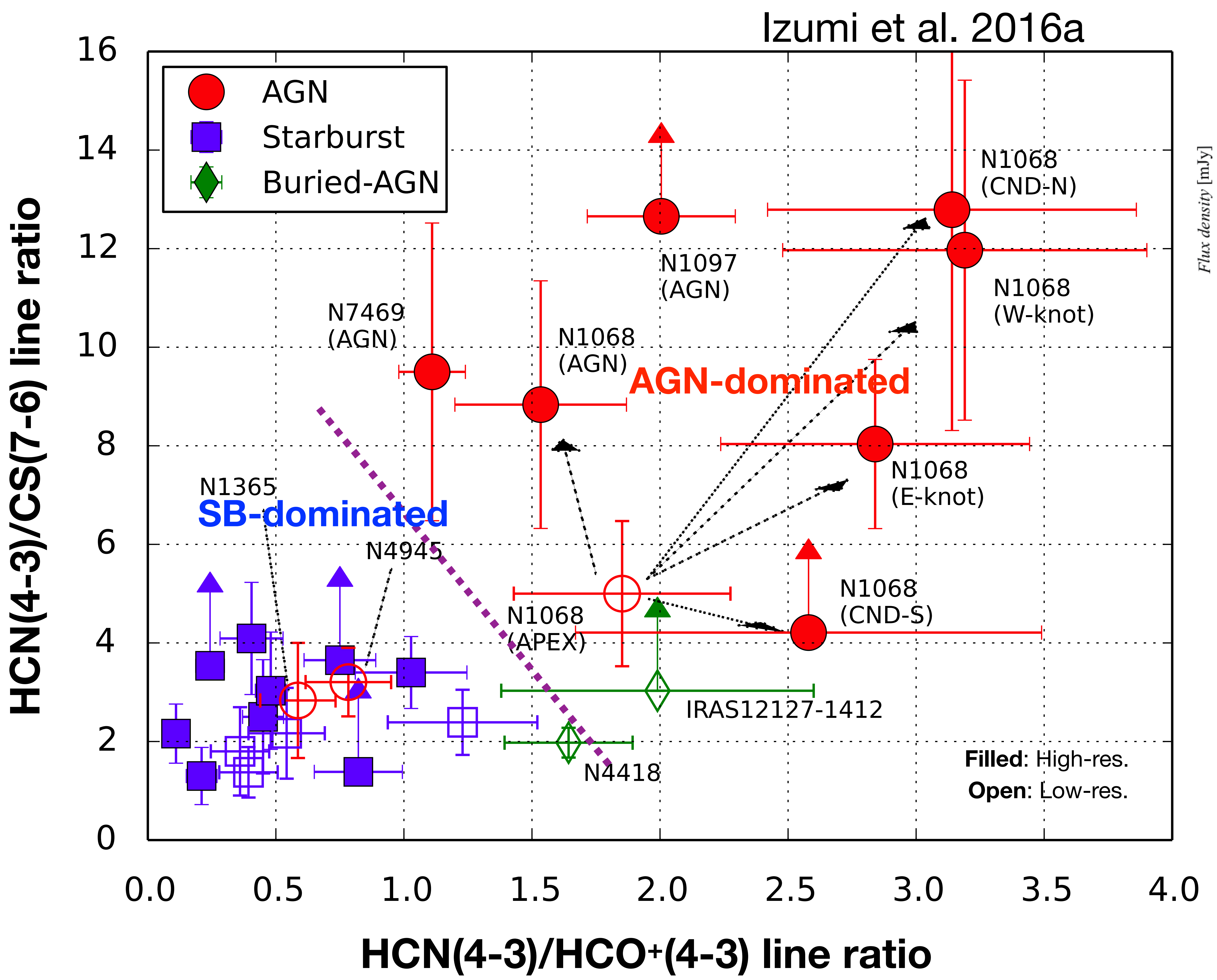


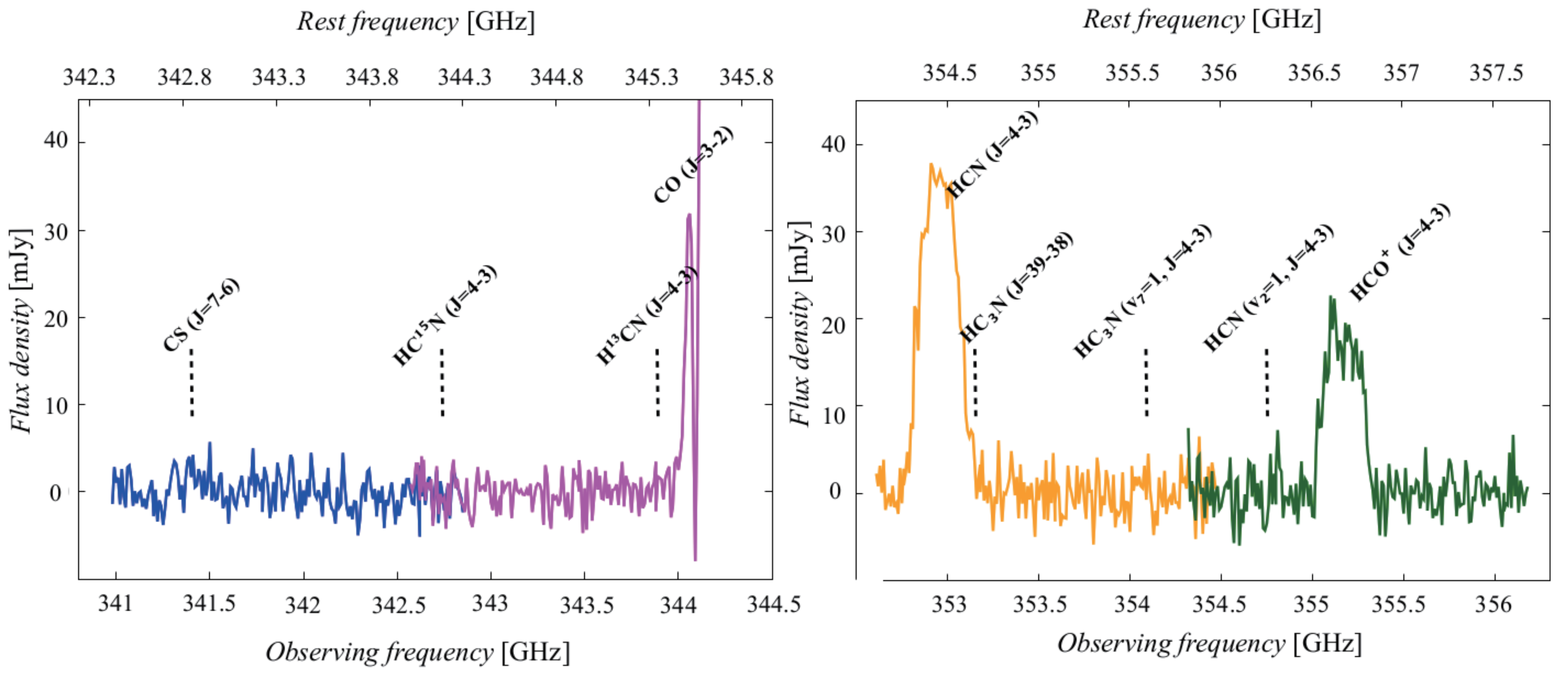
On average $N_H > 10^{23}$ cm^{-2} at z > 3? Host galaxy-scale obscuration must happen.



- Recent hydro simulations indeed predict such obscured growth phase → 「**Obscured AGN/quasar**」
- BLUETIDES simulation predicts <u>1.5 dex more abundant</u> obscured AGNs than non-obscured normal AGNs.（Subaru/HSC survey finds n ~0.1/deg² unobscured quasars at z > 6. Hence there could be **~1/deg² obscured quasars**)

Submm-HCN Diagram (ALMA Band 7)





Izumi et al. 2013

PASJ: Publ. Astron. Soc. Japan **65**, 100, 2013 October 25

Submillimeter ALMA Observations of the Dense Gas in the Low-Luminosity Type-1 Active Nucleus of NGC 1097

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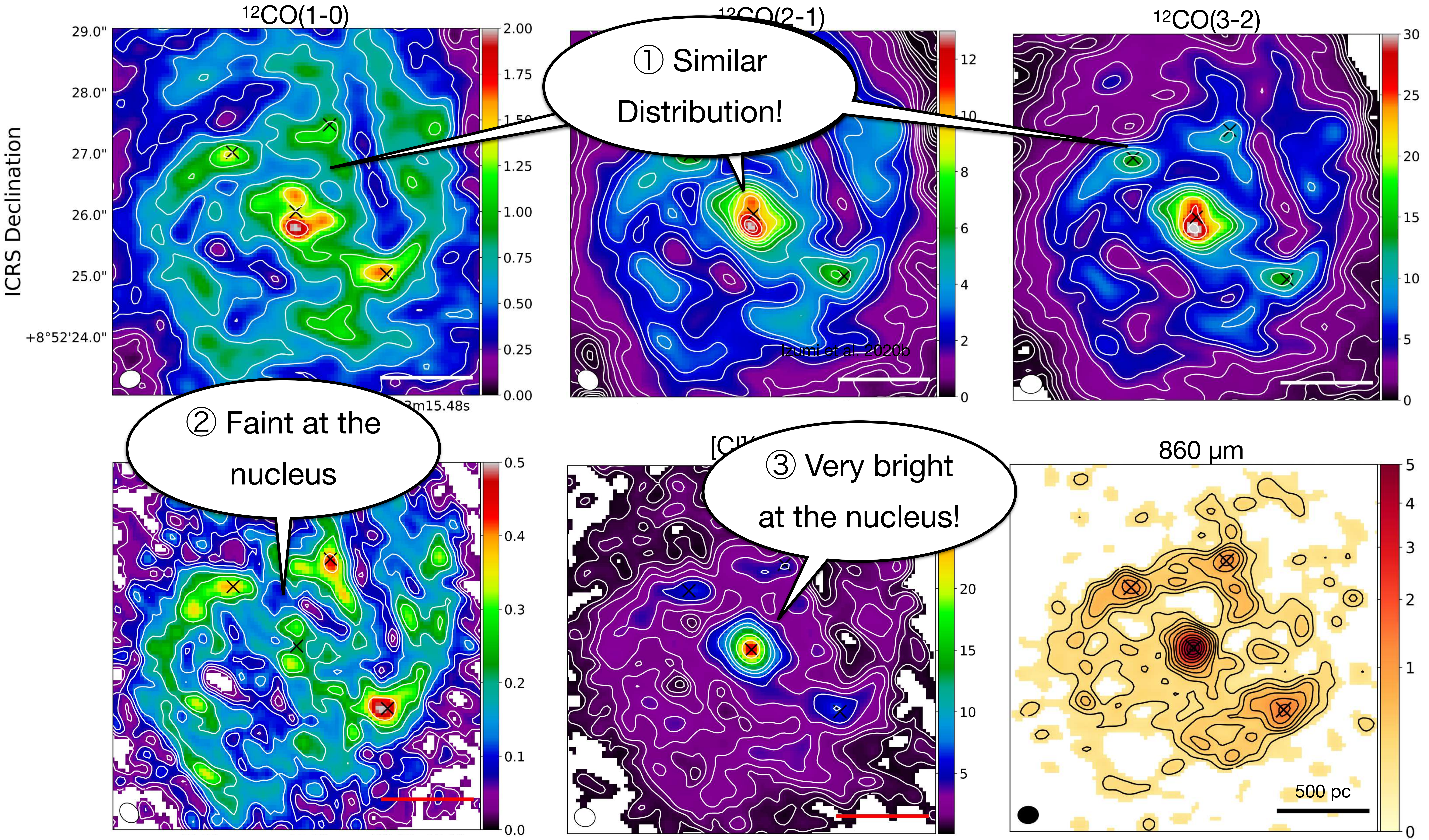
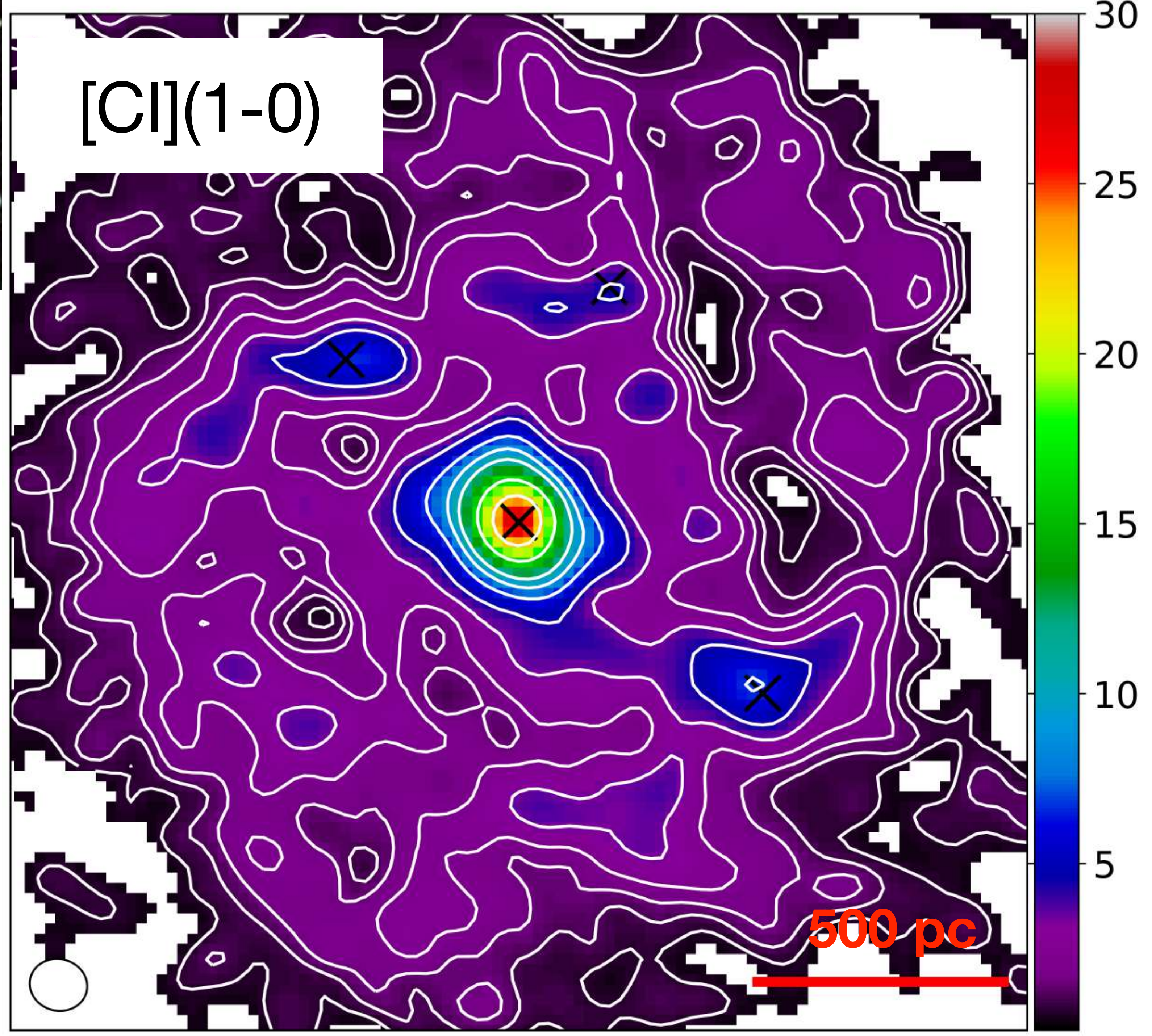
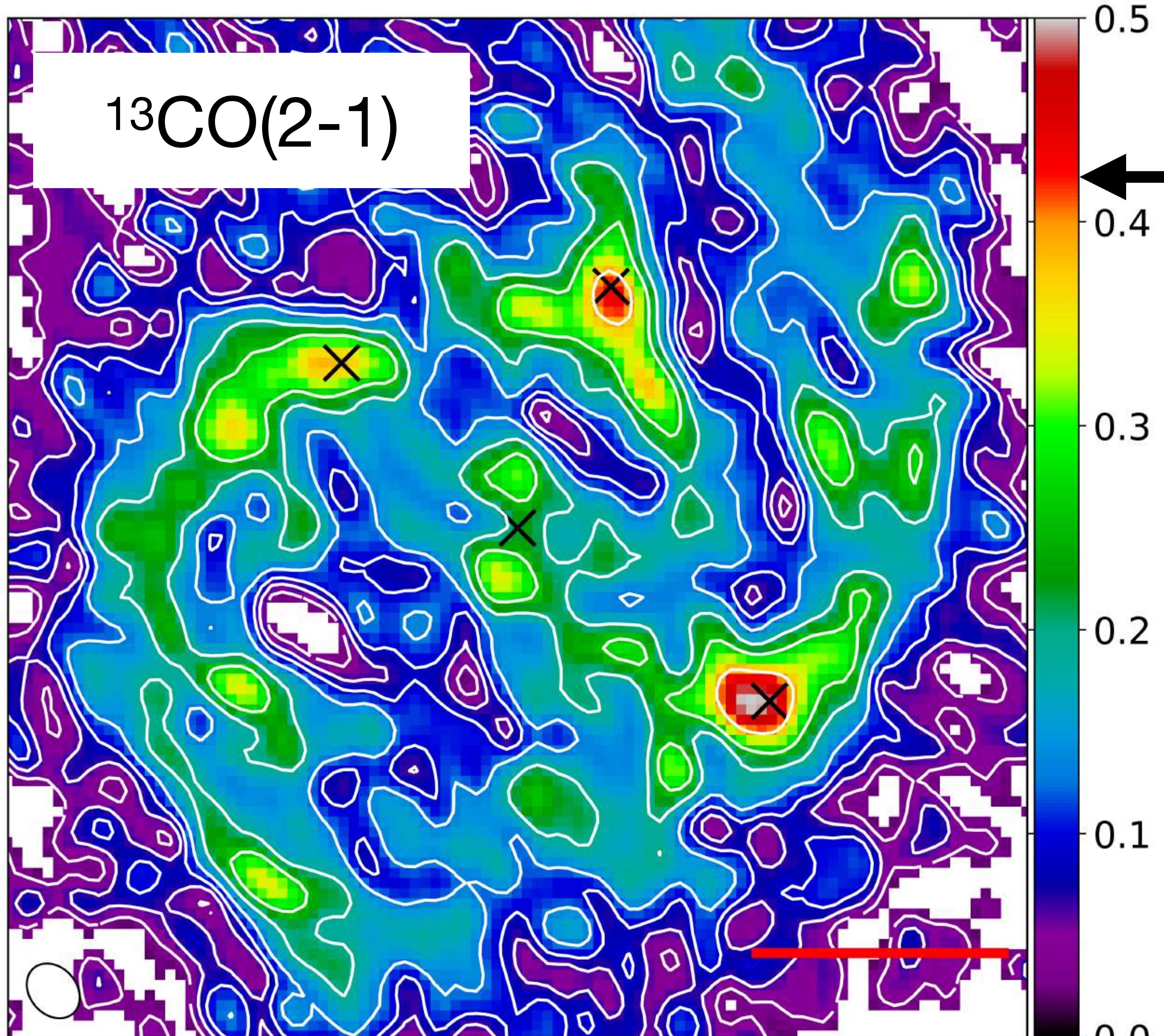
Gas spatial distributions in NGC 7469



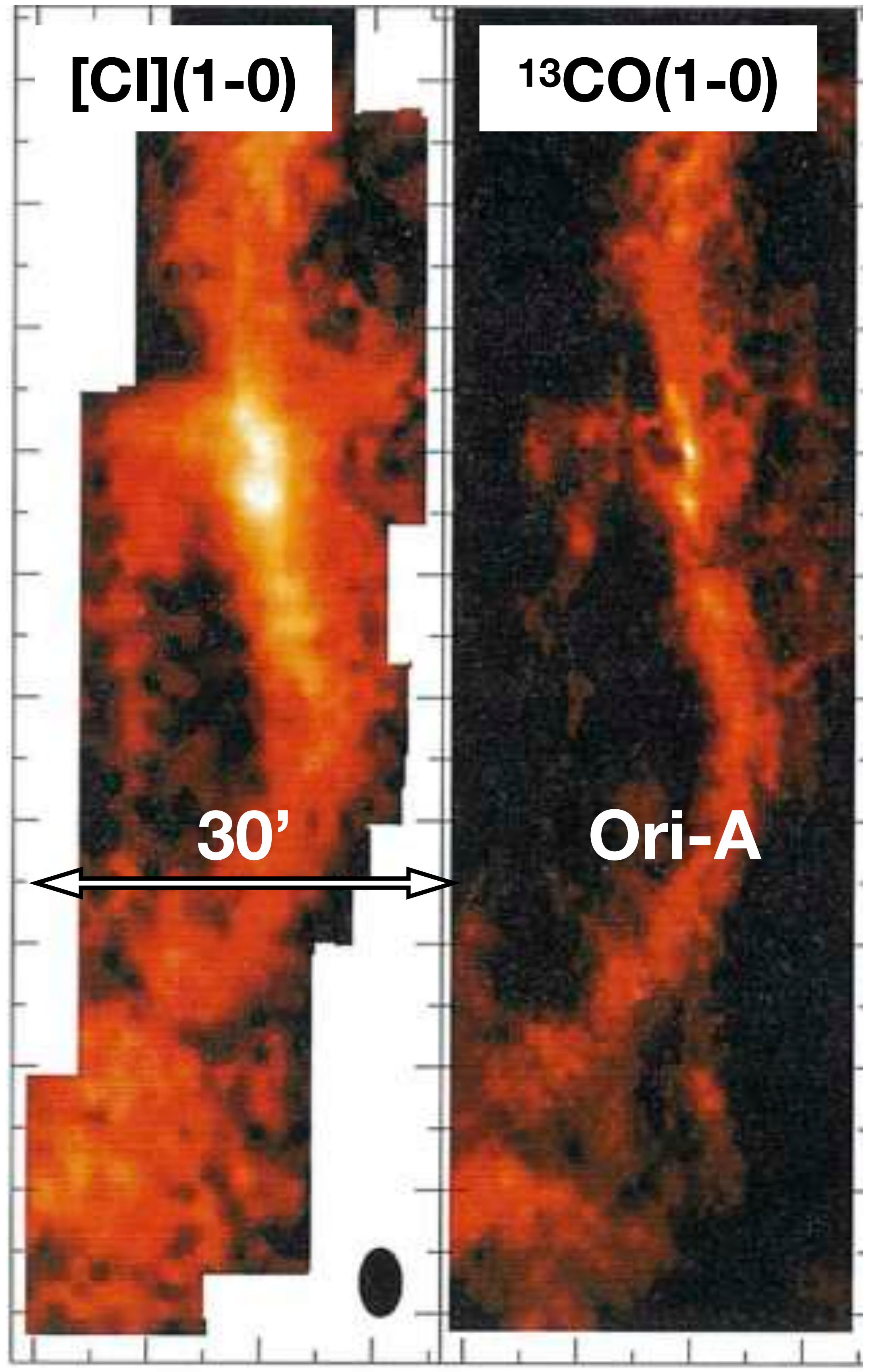
[CI](1-0) vs CO(2-1) distributions

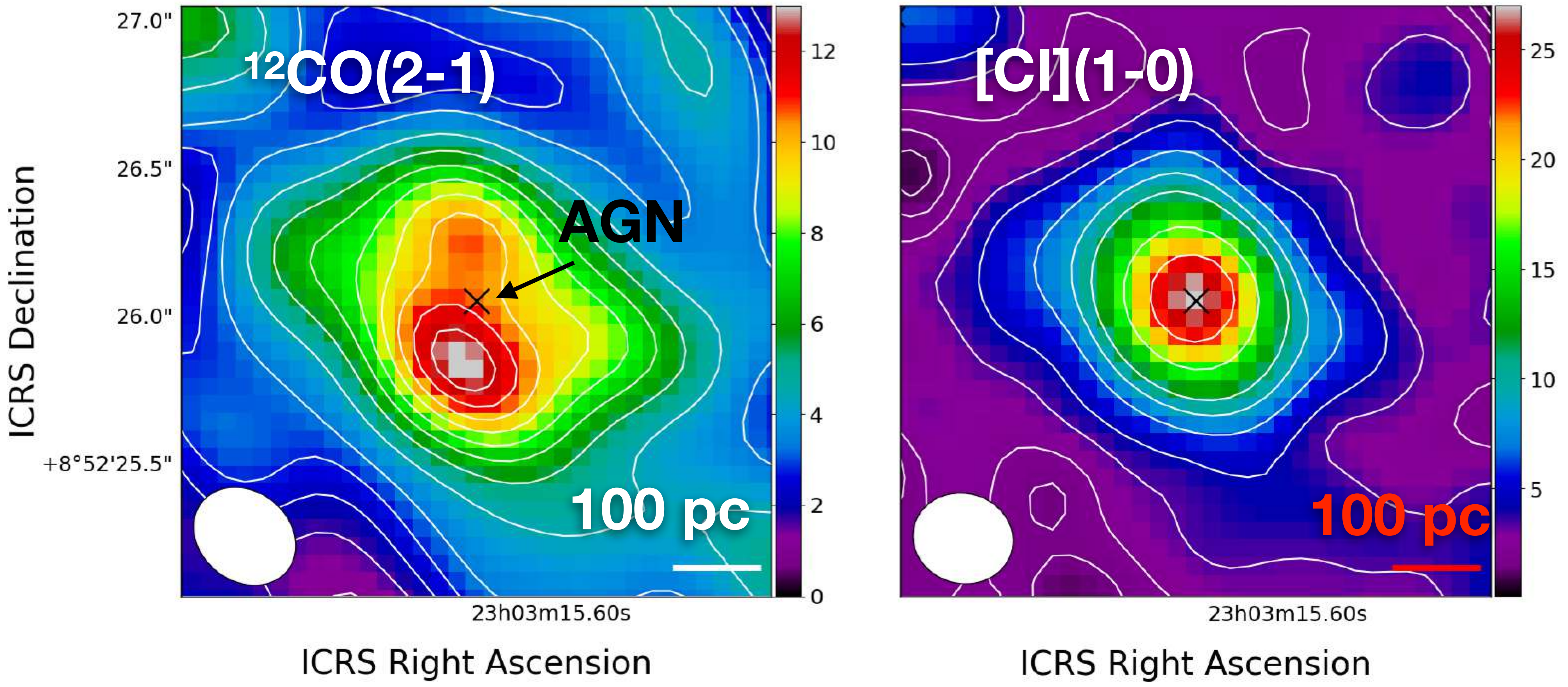




- A sort of spatial “**anti-correlation**” between [CI](1-0) and ^{13}CO(2-1)
- Not the case in Galactic molecular clouds (e.g., Orion-A).

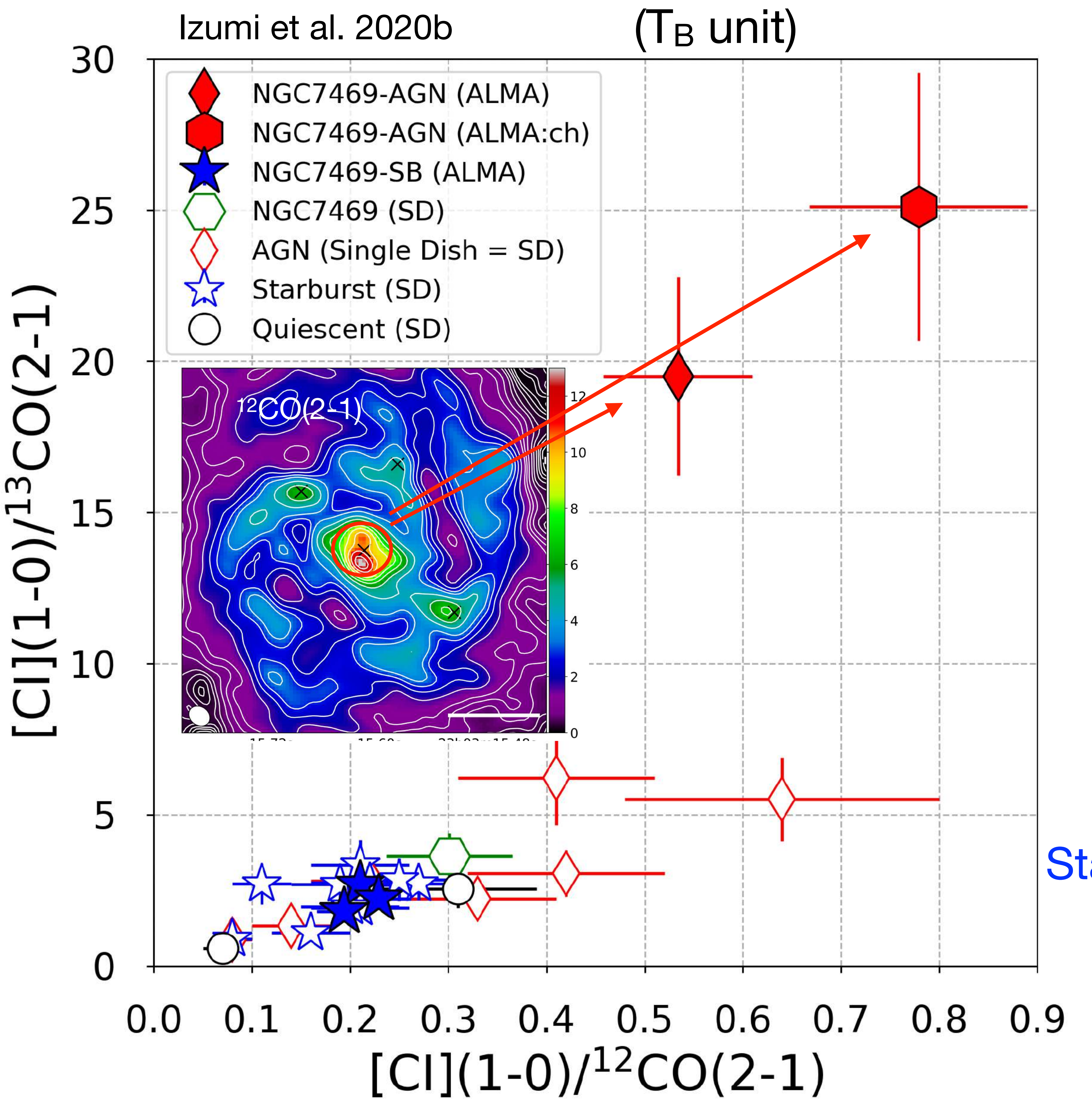
vs

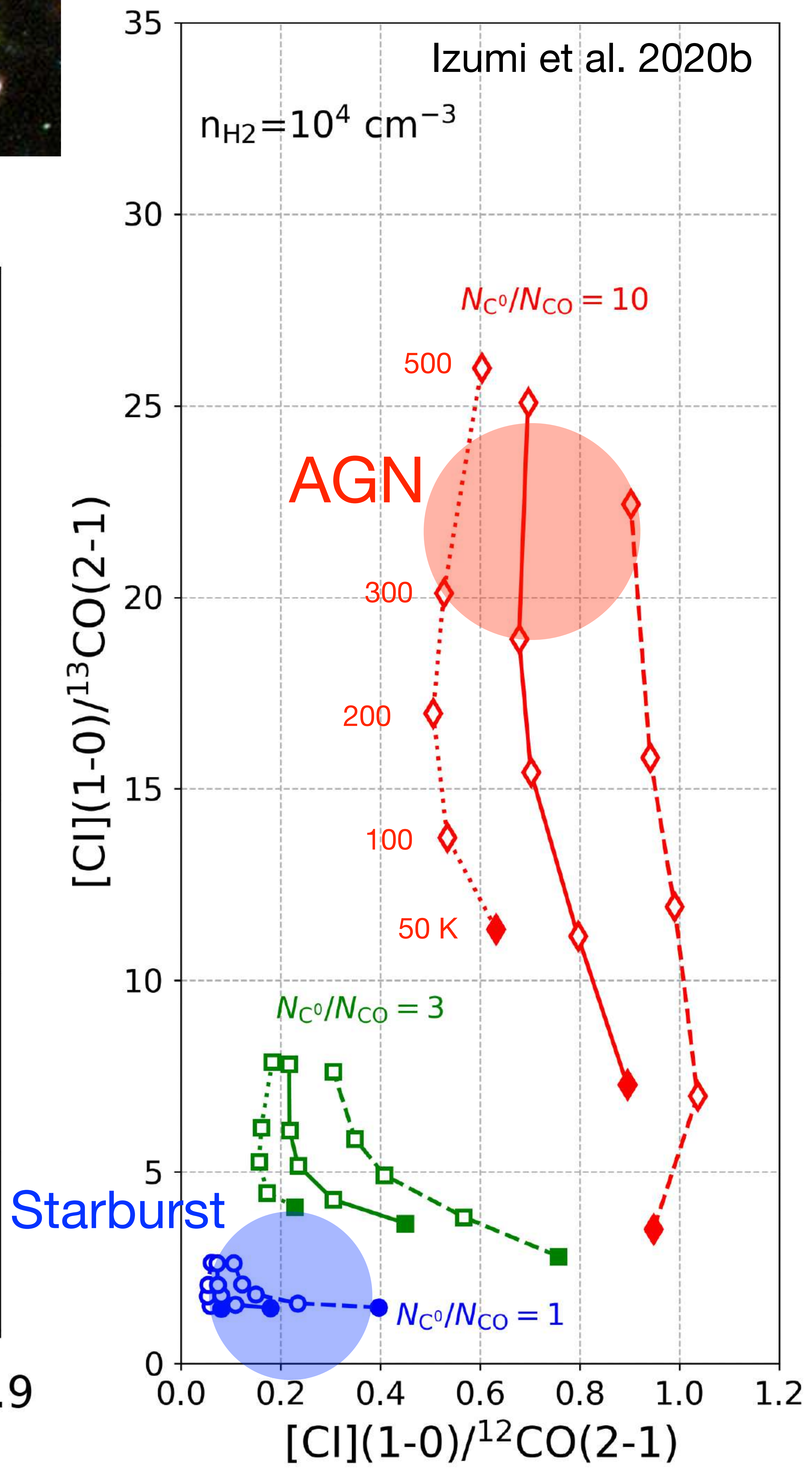




- CI probes a closer vicinity of AGN than CO.
- [CI](1-0) luminosity > ^{12}CO(1-0) + (2-1) + (3-2) + ^{13}CO(2-1) luminosity.
  → Very important ISM coolant around this AGN.

[CI](1-0) diagnostics



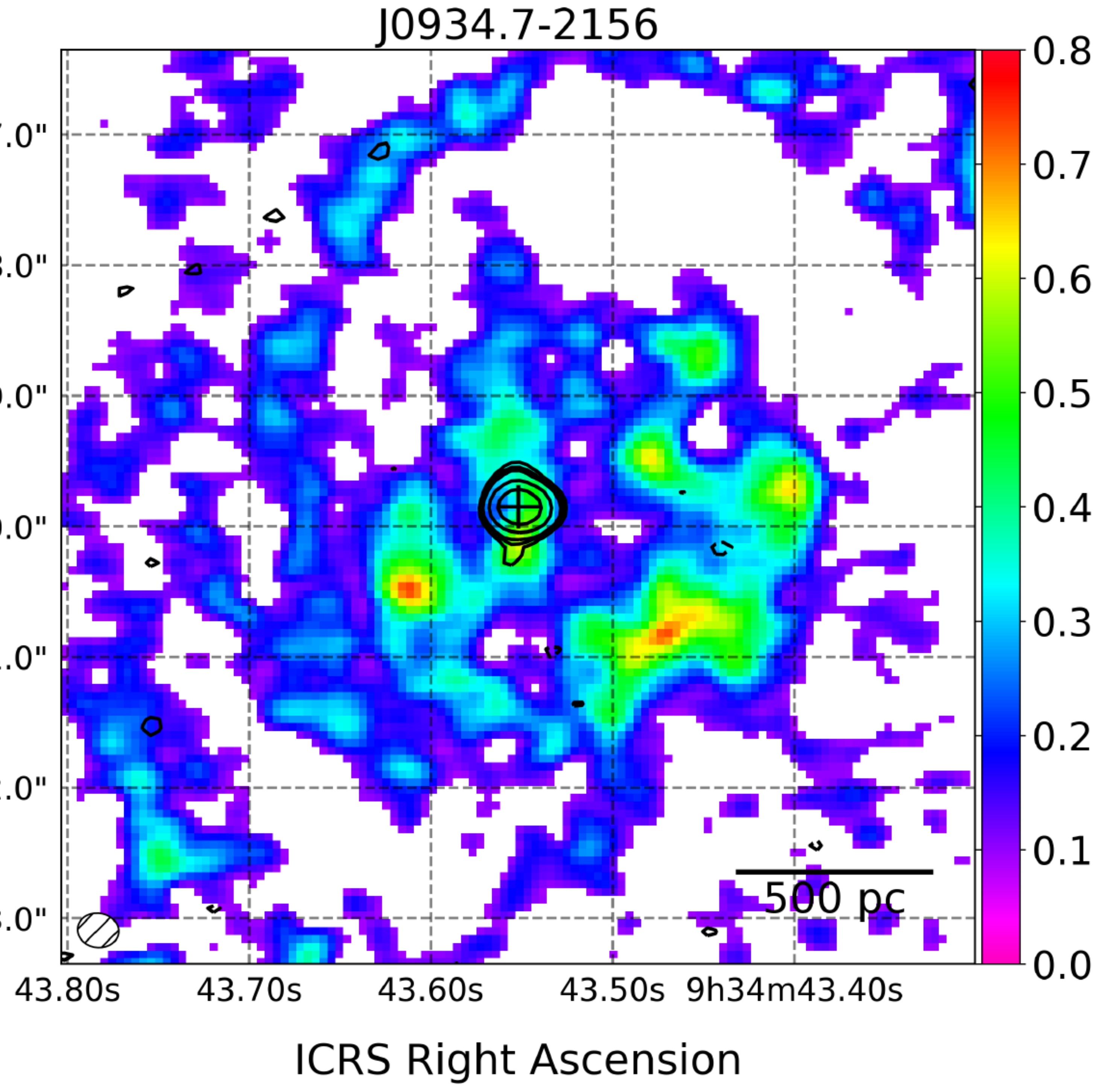


- Extremely high [CI](1-0)/ ^{13}CO(2-1) ratio at the NGC 7469's AGN is found, when spatially resolved.
- No single dish data shows this high ratio. → Thanks to the high resolution of ALMA.
- AGN's joint influence (XDR):
  i) Super-high excitation (high-T)
  ii) CO dissociation

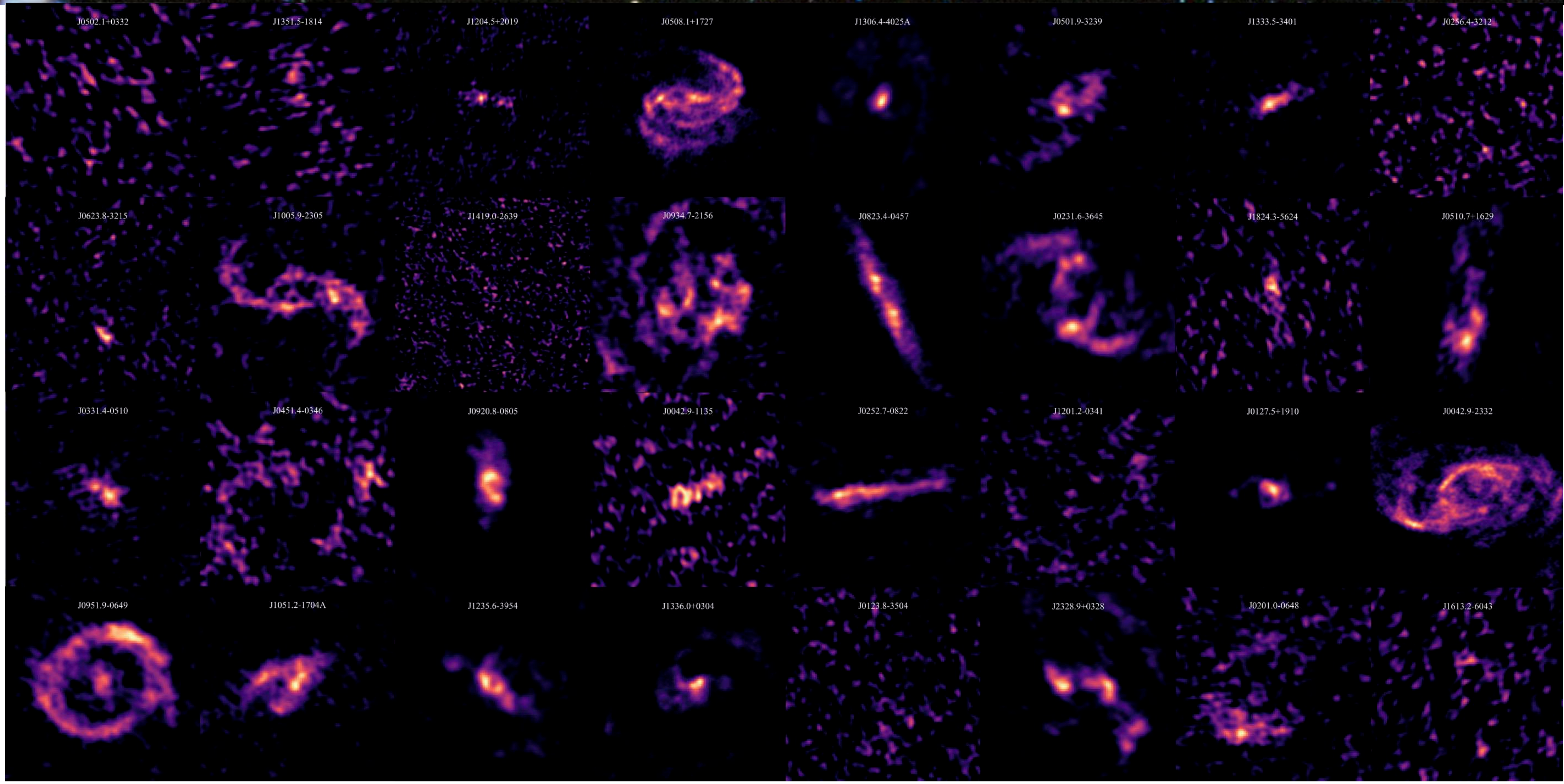
3. Near-future works and beyond

(part of this section is confidential!!)

Systematic Survey of Molecular Gas



Color: CO(2-1) in Jy/b*km/s,
Contour: Band 6 continuum

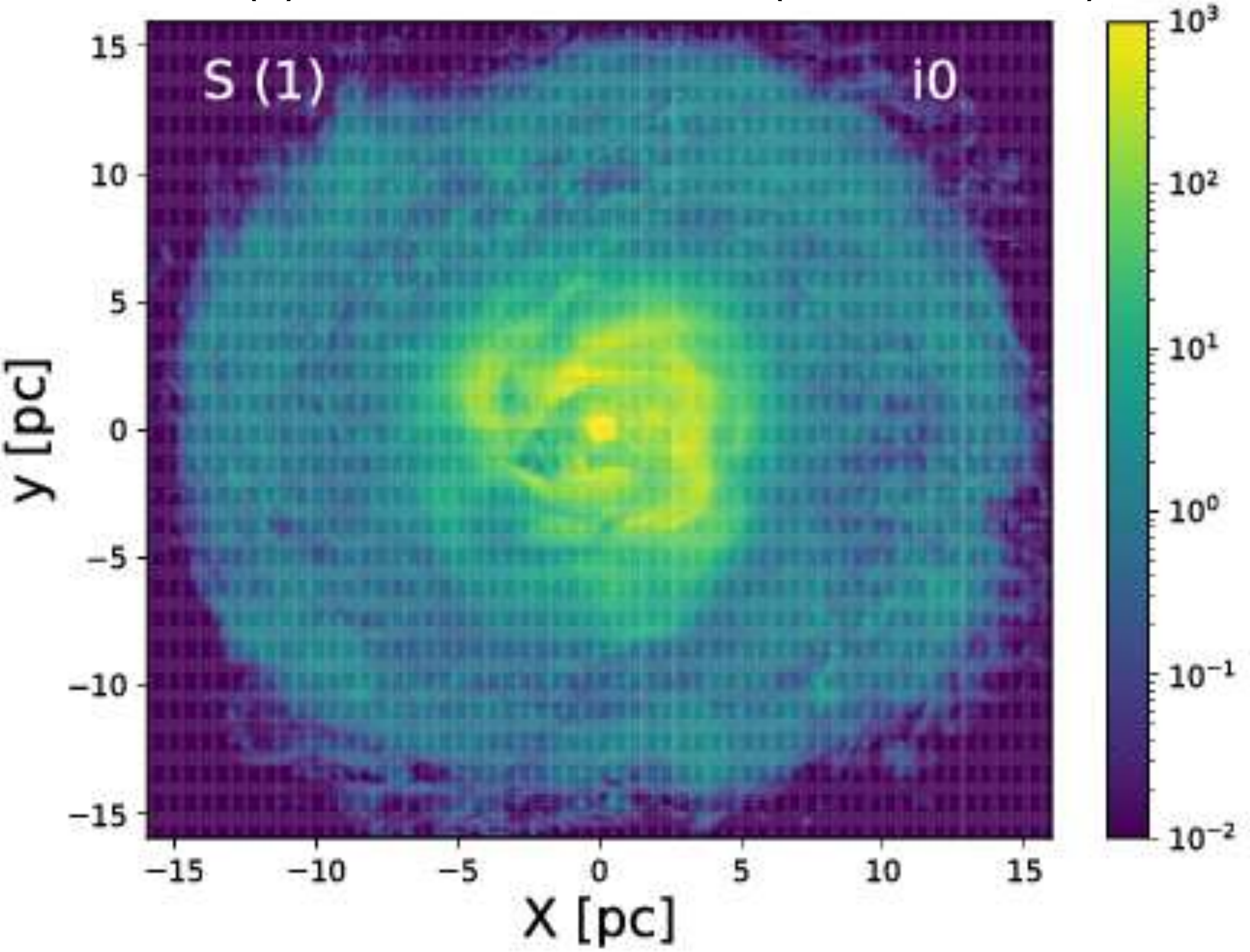


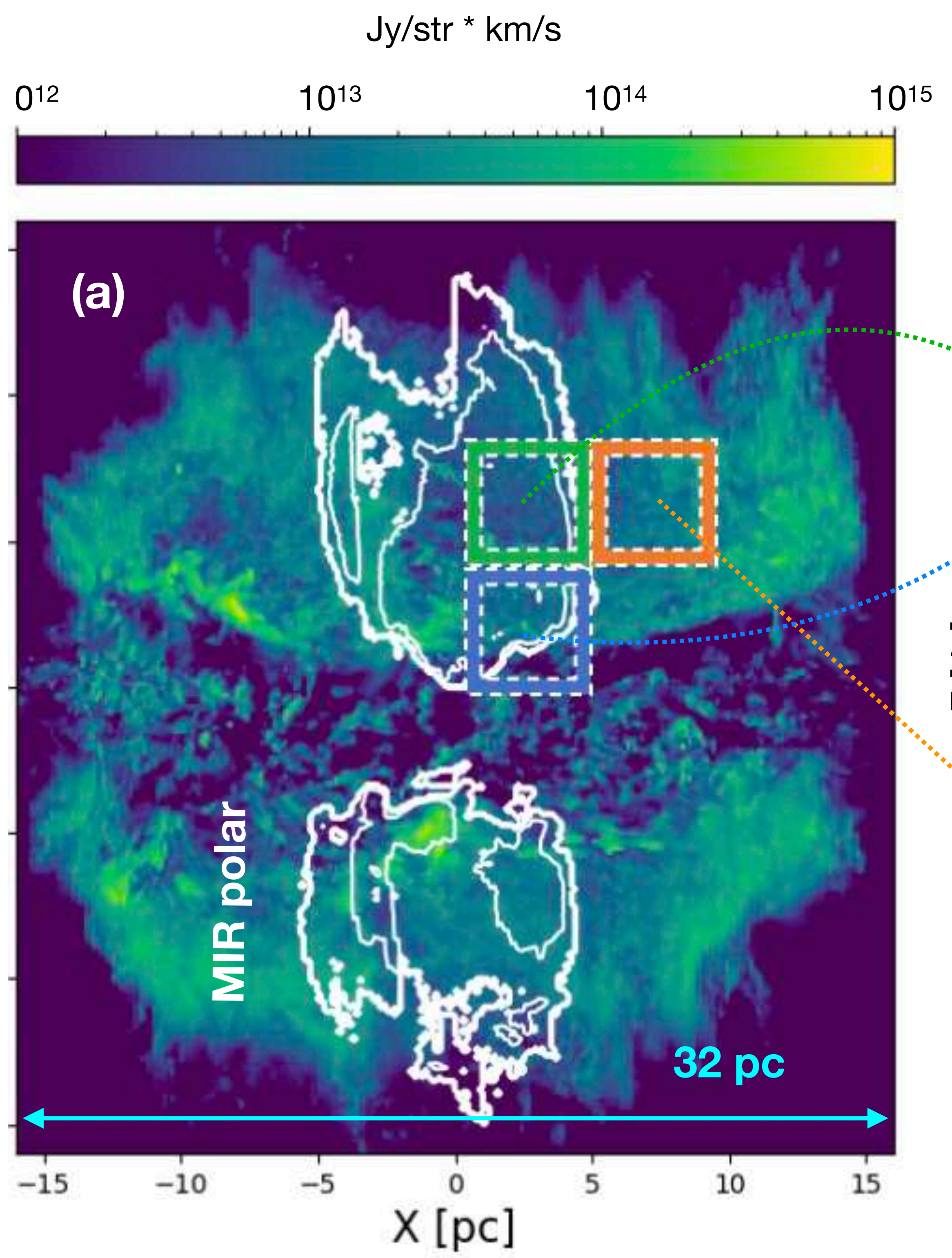
- CO(2-1) survey toward 32 nearby luminous Swift/BAT AGNs ($L_{Bol} > 10^{44}$ erg/s)
- Resolution ~ 100 pc (0.2”-0.3”): largest high resolution CO survey toward AGNs
- Scope = Feeding from the CND, Feedback (outflow) from the AGN…in a **statistical** manner!

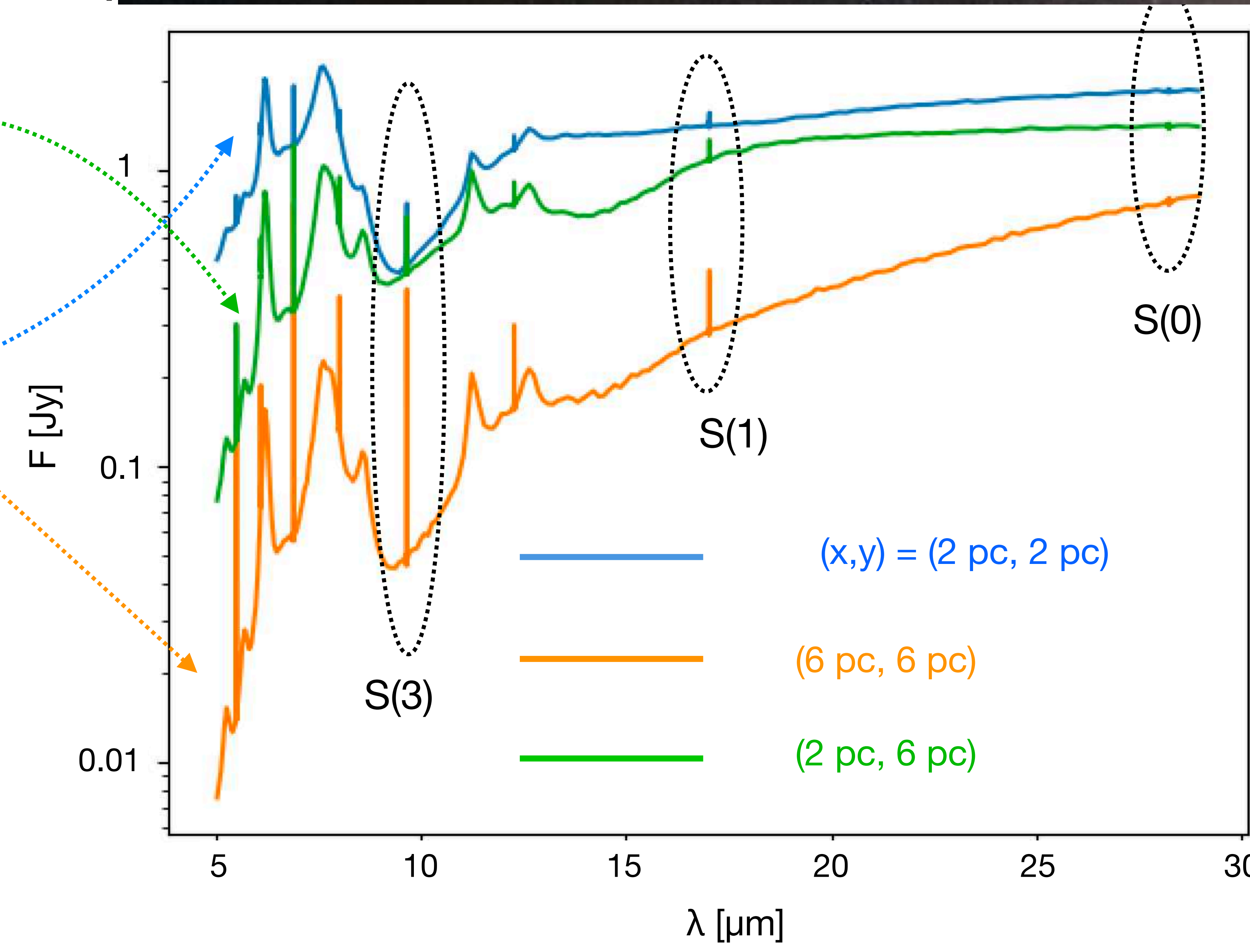
Yu Ikeda, TI+ in prep.

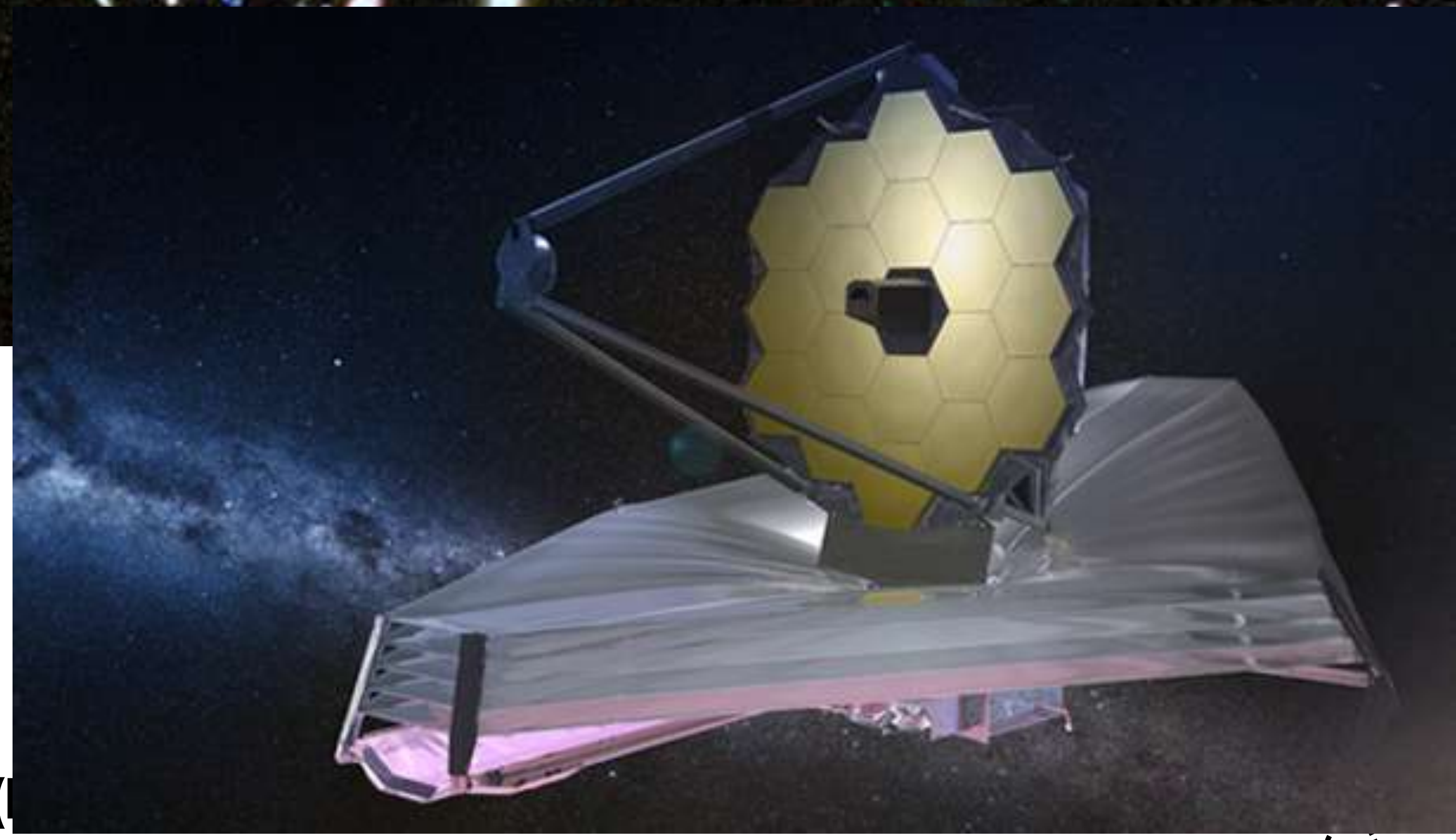
JWST observations of warm torus

H_2 S(1) + MIR continuum (rad. transfer)







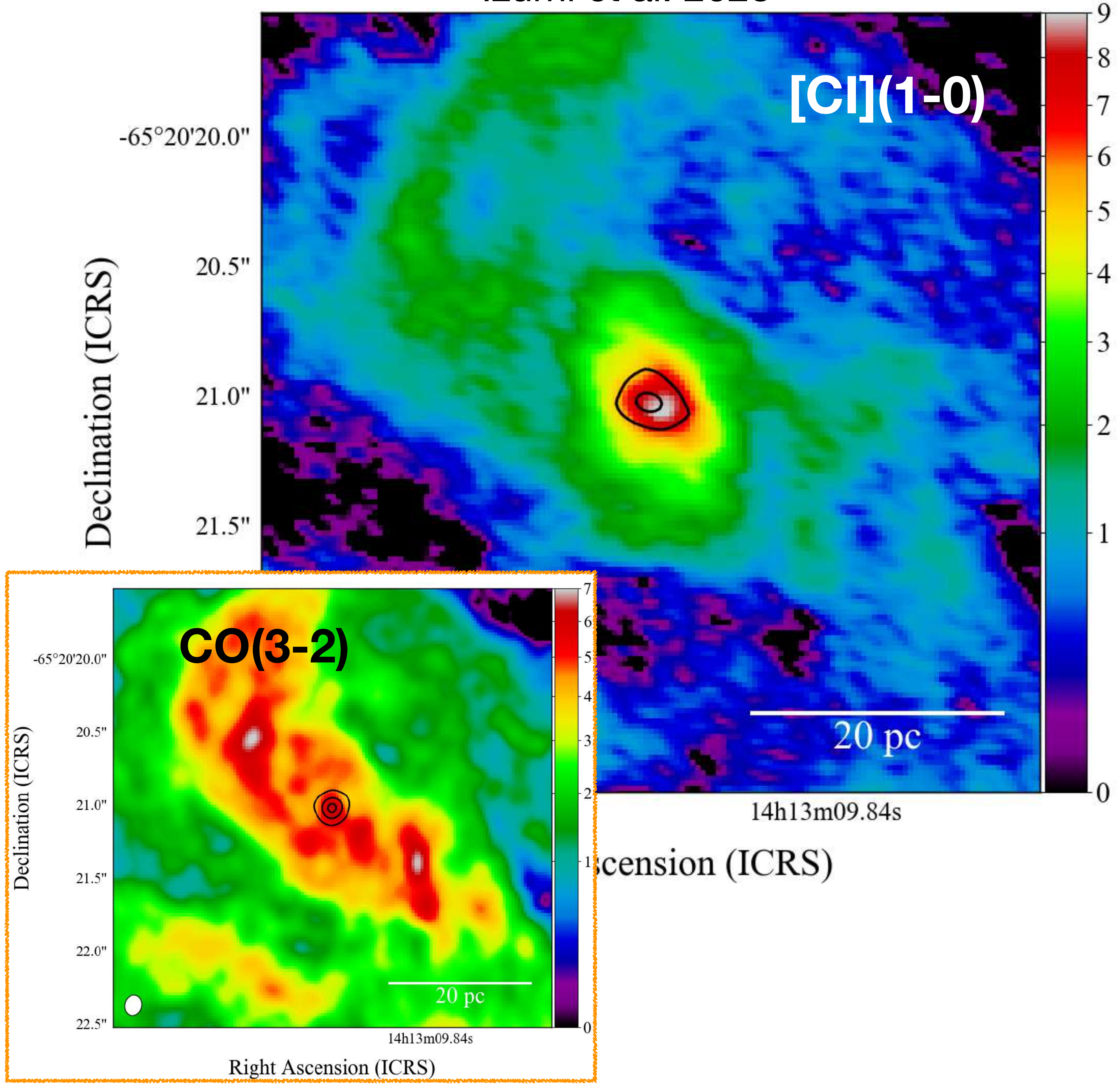


→ T. Izumi et al. JWST Cycle 2 GO (ID4225)

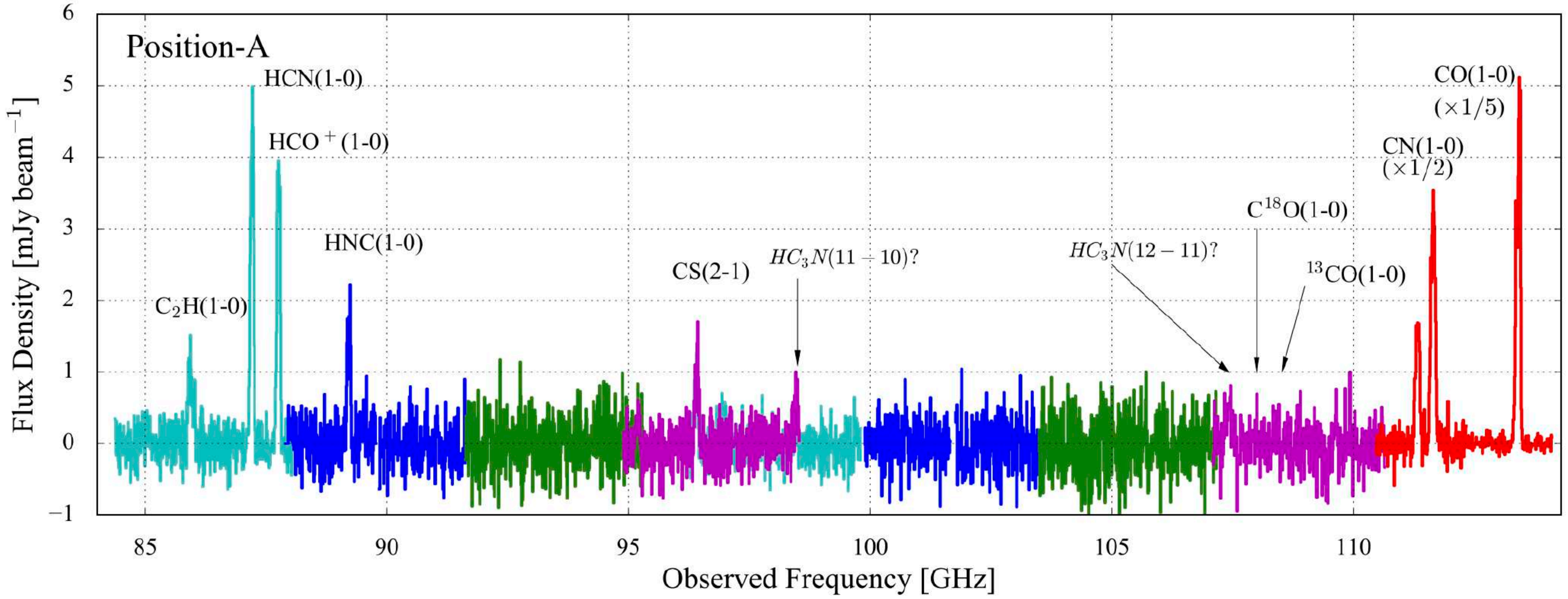
- MIRI MRS observation of various molecular/atomic/ionized lines
- To detect warm part of the torus (H_2 mass, warm mol. outflow, extinction)

Spatially resolved study of XDR

Izumi et al. 2023

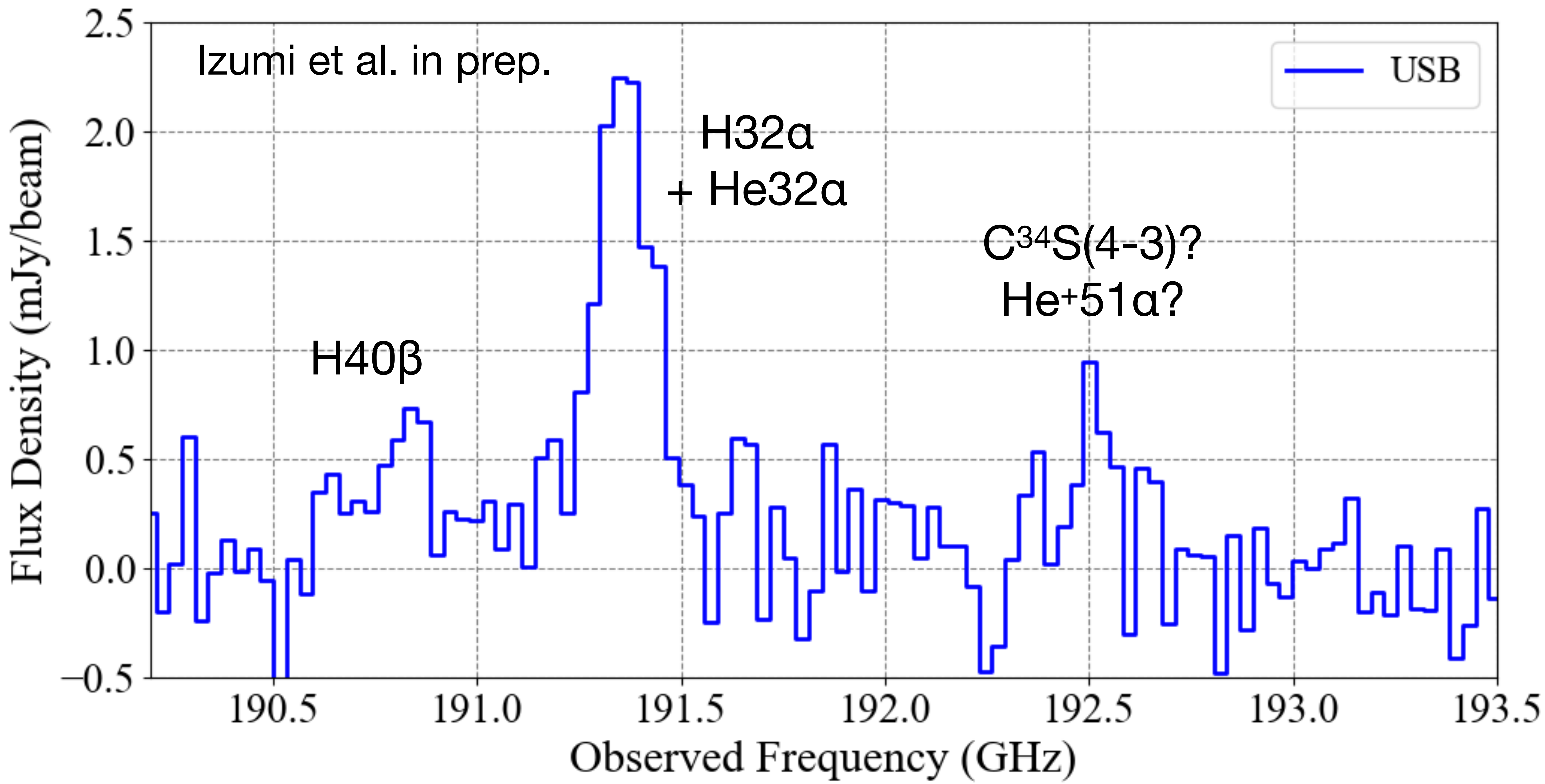


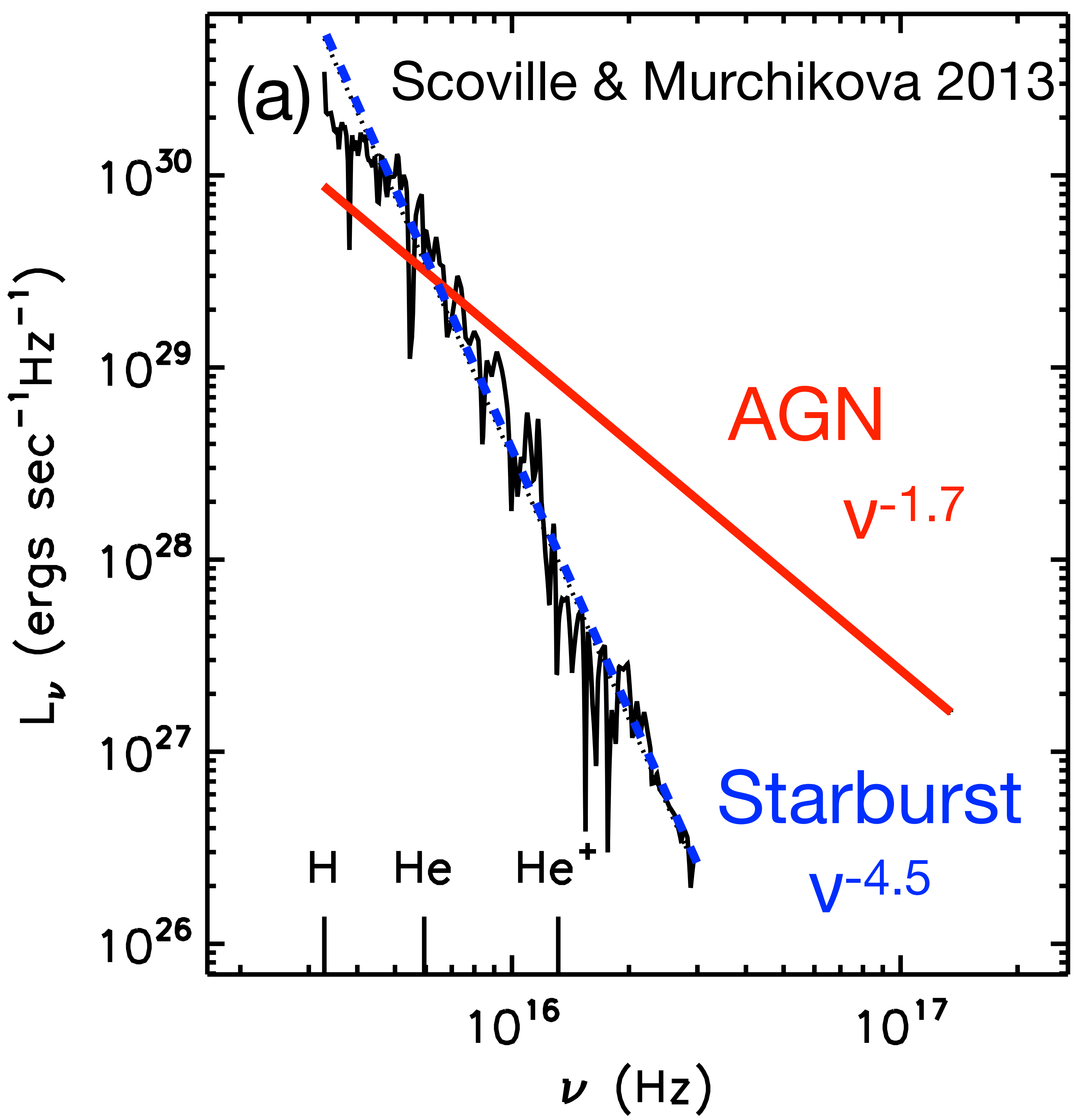
Izumi et al. in prep.



- Now we can spatially isolate and resolve X-ray dominated region (XDR), where gas physics & chemistry are governed by X-ray radiation.
- What is the characteristic feature there??
  → Interplay of astronomy and chemistry

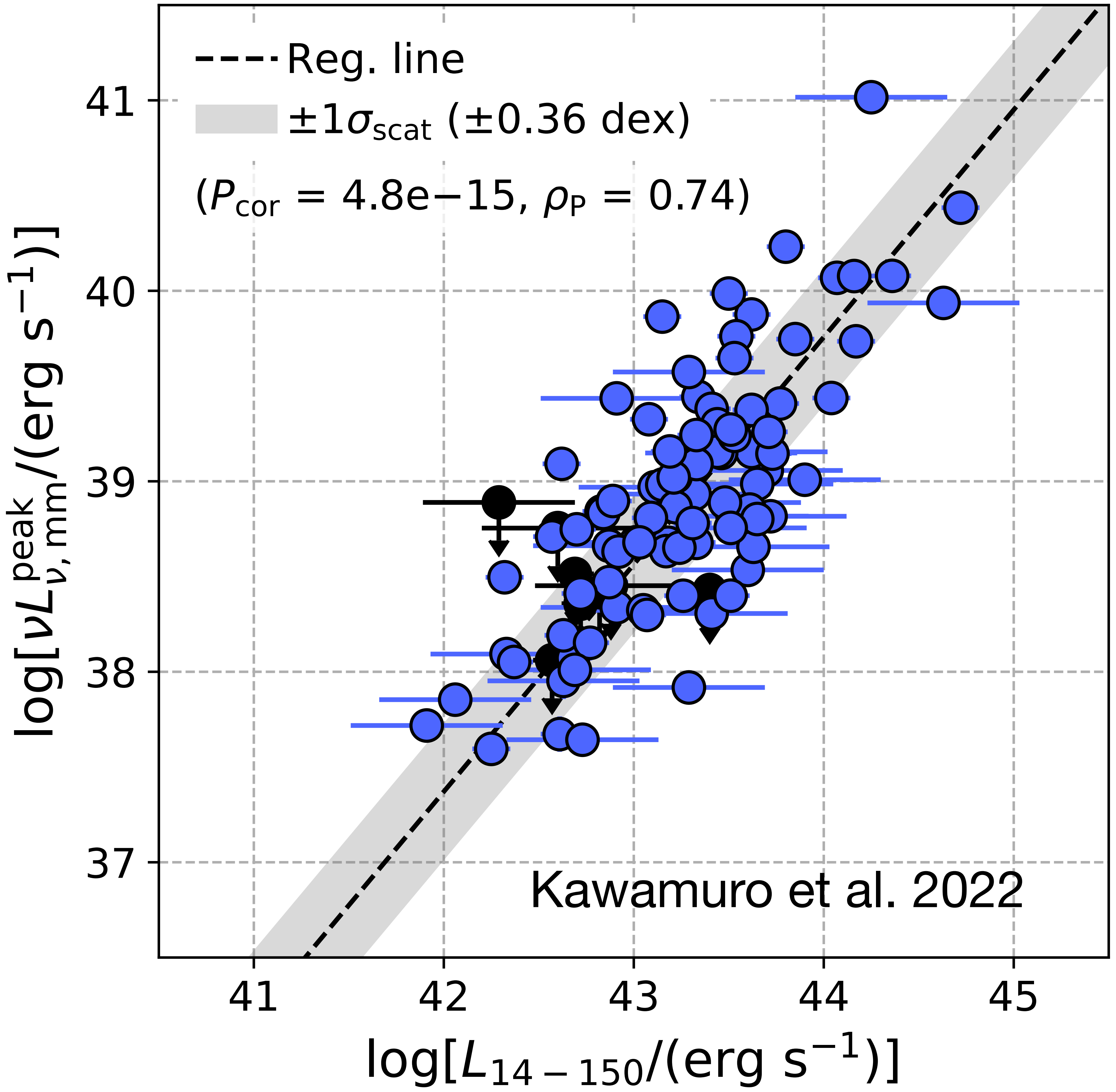
Sub/mm recombination lines



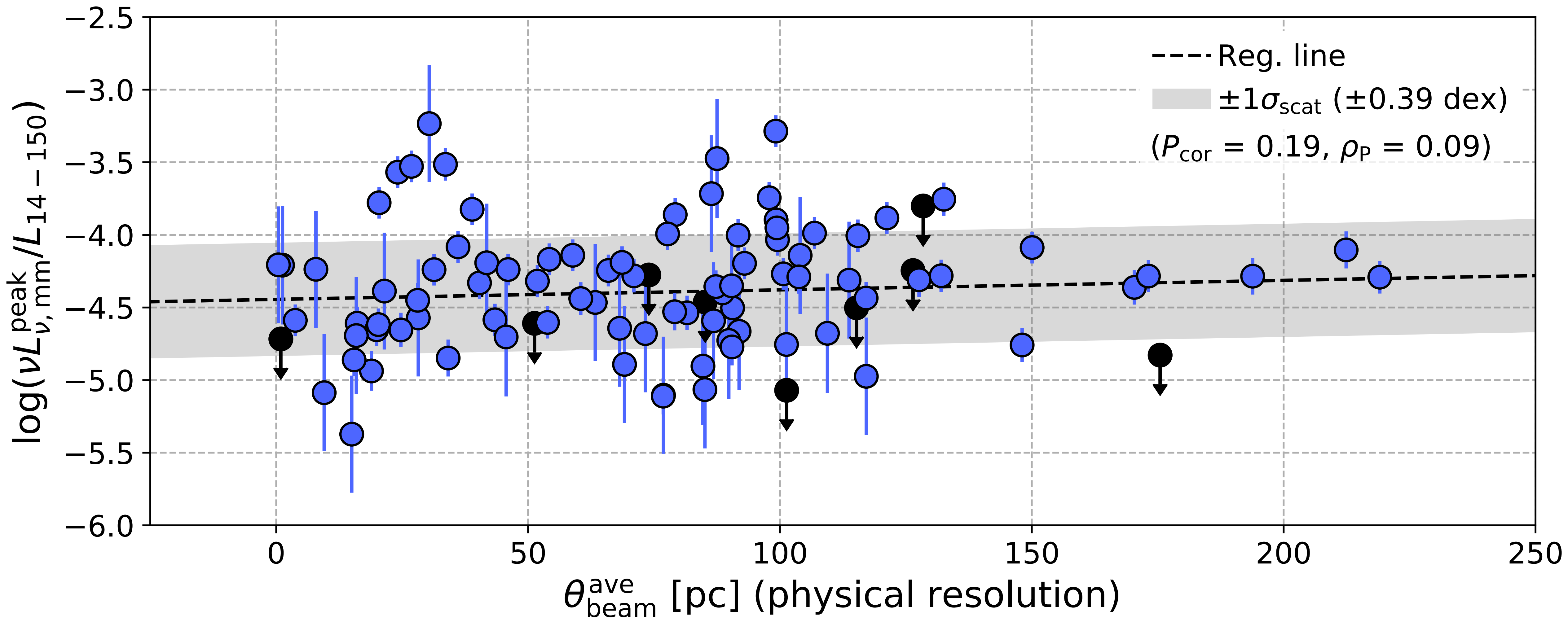


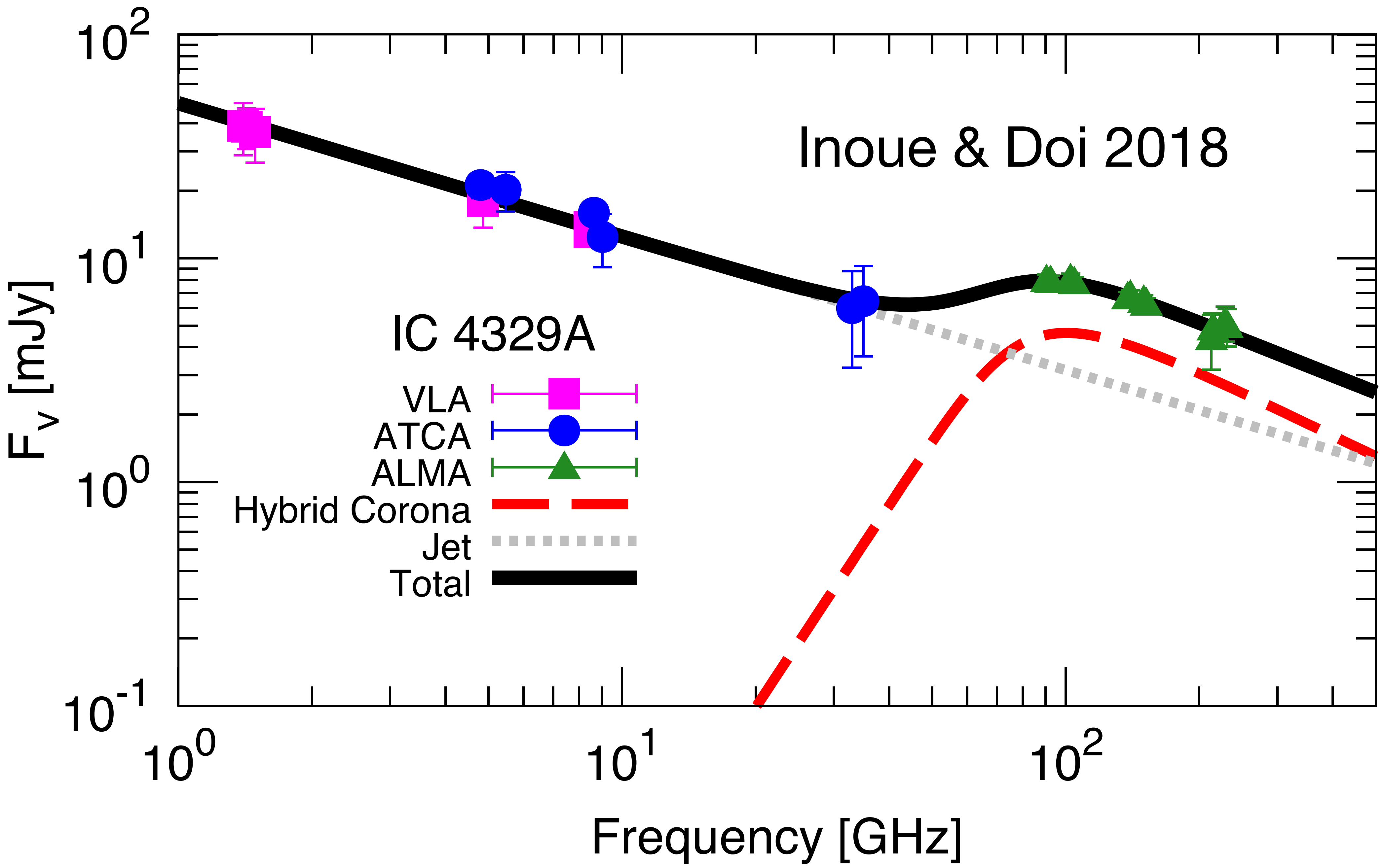
- Clear detections of Hnα and Hnβ lines. And possible detection (or upper limit) on He+ line.
- In principle, He+/H ratio depends on the hardness of the FUV radiation.
  → Extinction-free constraint on the shape of the FUV SED!

Synergy with hard X-ray obs.



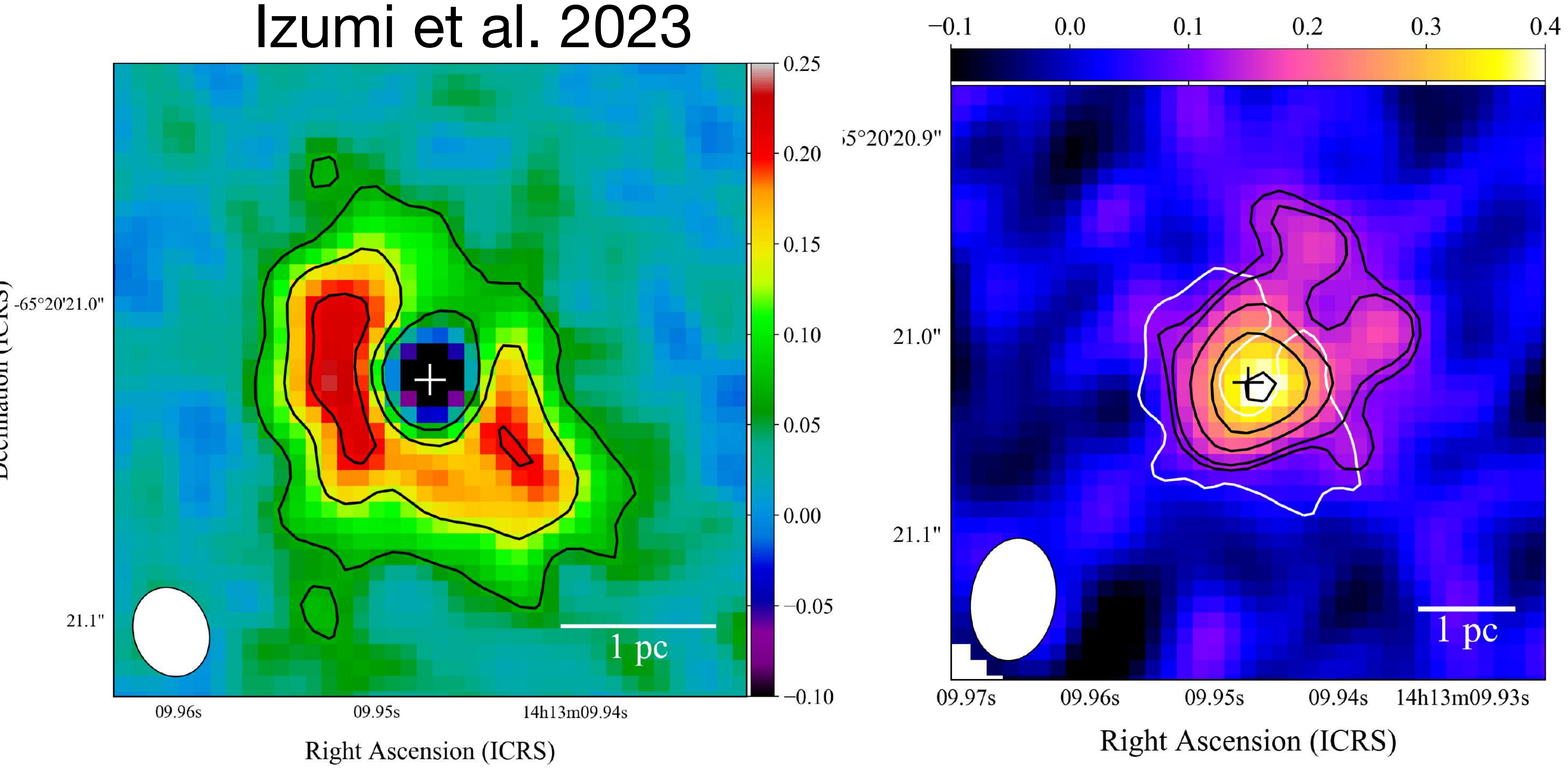
- Strong positive correlation between hard X-ray luminosity and mm continuum luminosity
  → same physical origin??
- Candidate physical origin = AGN corona (synchrotron)
- SED analysis also supports this idea (although there are numerous free parameters)



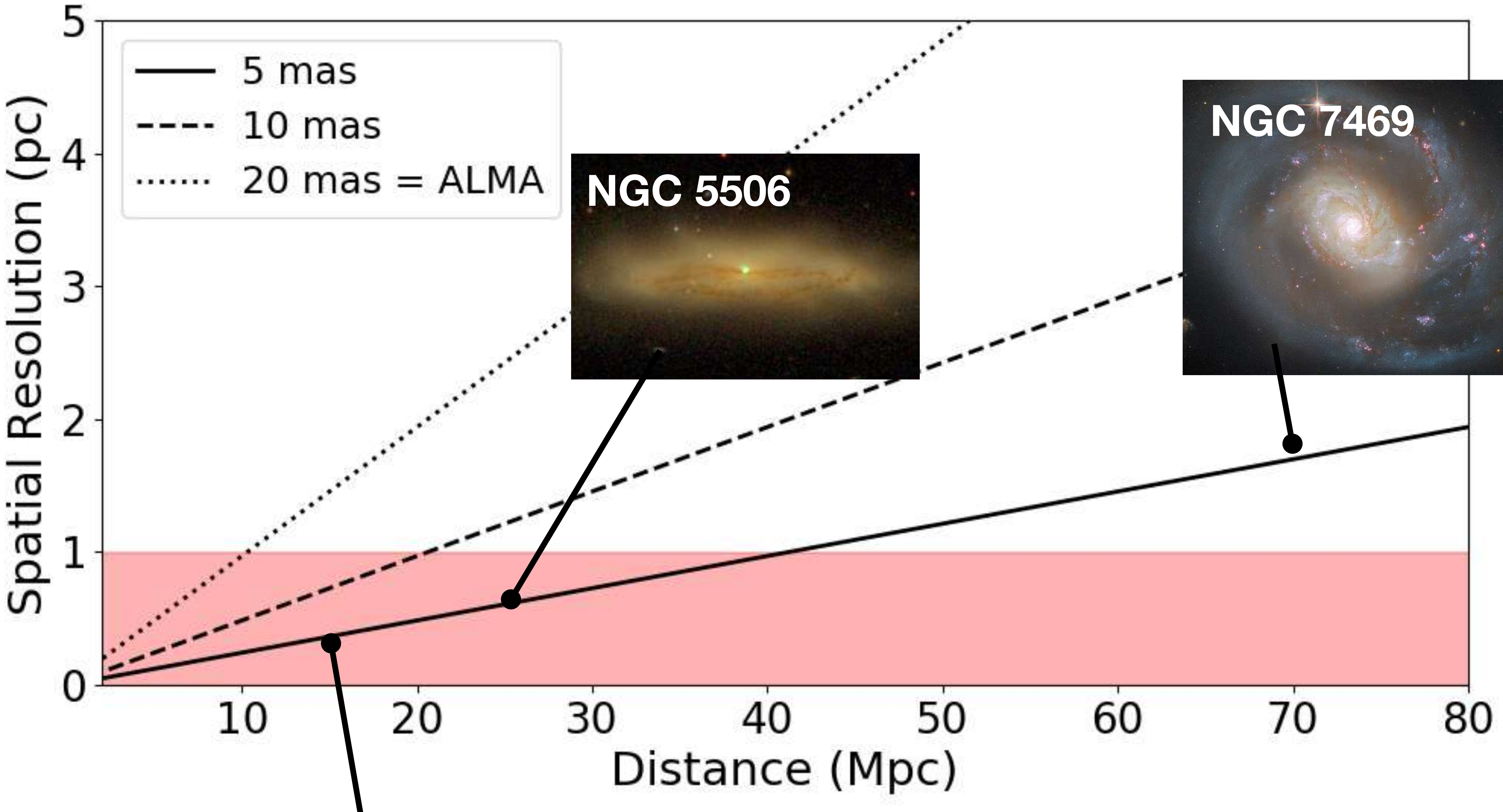


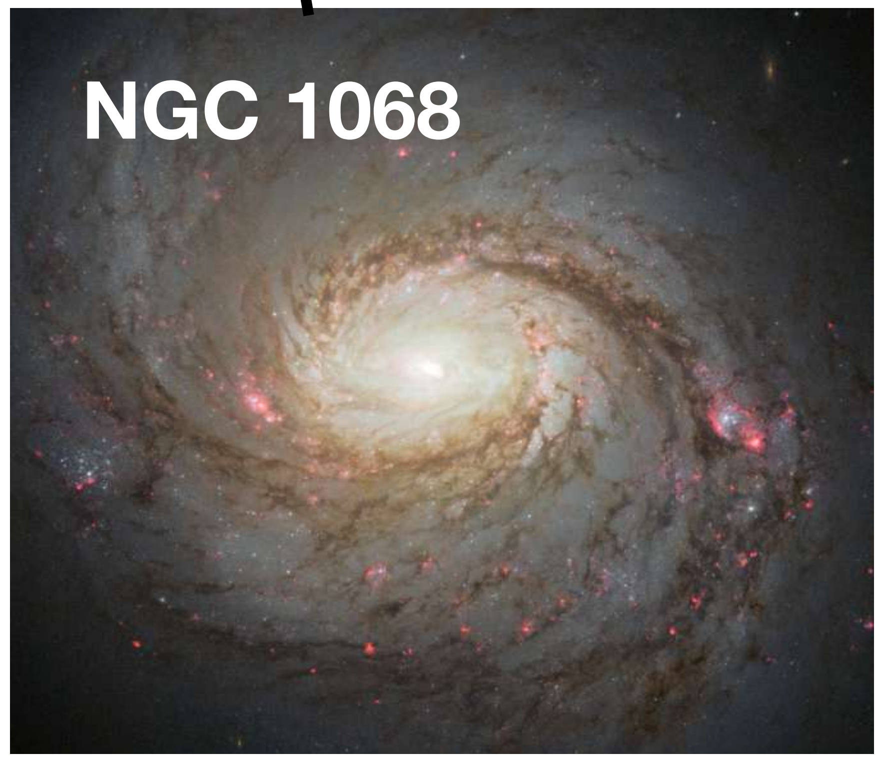
Key element for (nearby) AGN study: high resolution!

Izumi et al. 2023



- We need pc-scale resolution (< 20 mas) to detect inflows via absorption. (note: more compact AGN itself is the background continuum source)
- We need pc-scale resolution & high sensitivity to probe the innermost part of the AGN-driven outflow
- **Future ALMA upgrade and/or ngVLA?**





- Expand the pc-scale exploration to many more AGNs.
- *Resolution matters, always*.

Summary (ALMA nearby AGN studies; my works-only)

- ALMA plays a key role in studying various aspects of nearby AGNs.
- Feeding and feedback are now considered in a unified manner
  → Circumnuclear multiphase gas flows that form different dynamical structures
- ISM properties in extreme environments start to be revealed at sub/mm
  → An ideal laboratory to study XDR chemistry, for example.
- Further progress focusing on new aspects of AGN can be anticipated!
  + Sub/mm recombination line
  + Time variability
  + etc
- But we are also aware of possible limitations of the current facility.
  → Strong demand for the next-generation radio interferometers!

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