A Powerhouse of Star Formation: Parsec Scale Analysis of Emission from Vibrationally Excited Molecules of HC_3N in the NGC 253 Starburst Nucleus

Ashley Lieber

University of Kansas - Dr. Mills

April 13th, 2024 | PALOOZA 2024

MADISON & LILA SELF GRADUATE FELLOWSHIP

nearby galaxies lab

ESO

Our Neighbor, NGC 253

The Sculptor Galaxy

- Located 3.5 ± 0.2 Mpc away from the Milky Way (Rekola+2005, Newmann+2024)

- Barred Spiral, edge-on ($i \simeq 76$ degrees) (McCormick+2013)

  - Total Mass: $10^{11}\ M_{sun}$ (Karachentsev+2021)

- Starburst galaxy with no actively accreting black hole i.e. Active Galactic Nucleus (AGN) (Müller-Sánchez+2010)

ESO

Due to its proximity, NGC 253 is an ideal target for high resolution studies of the physics and chemistry of clustered star formation in starbursts

NGC 253

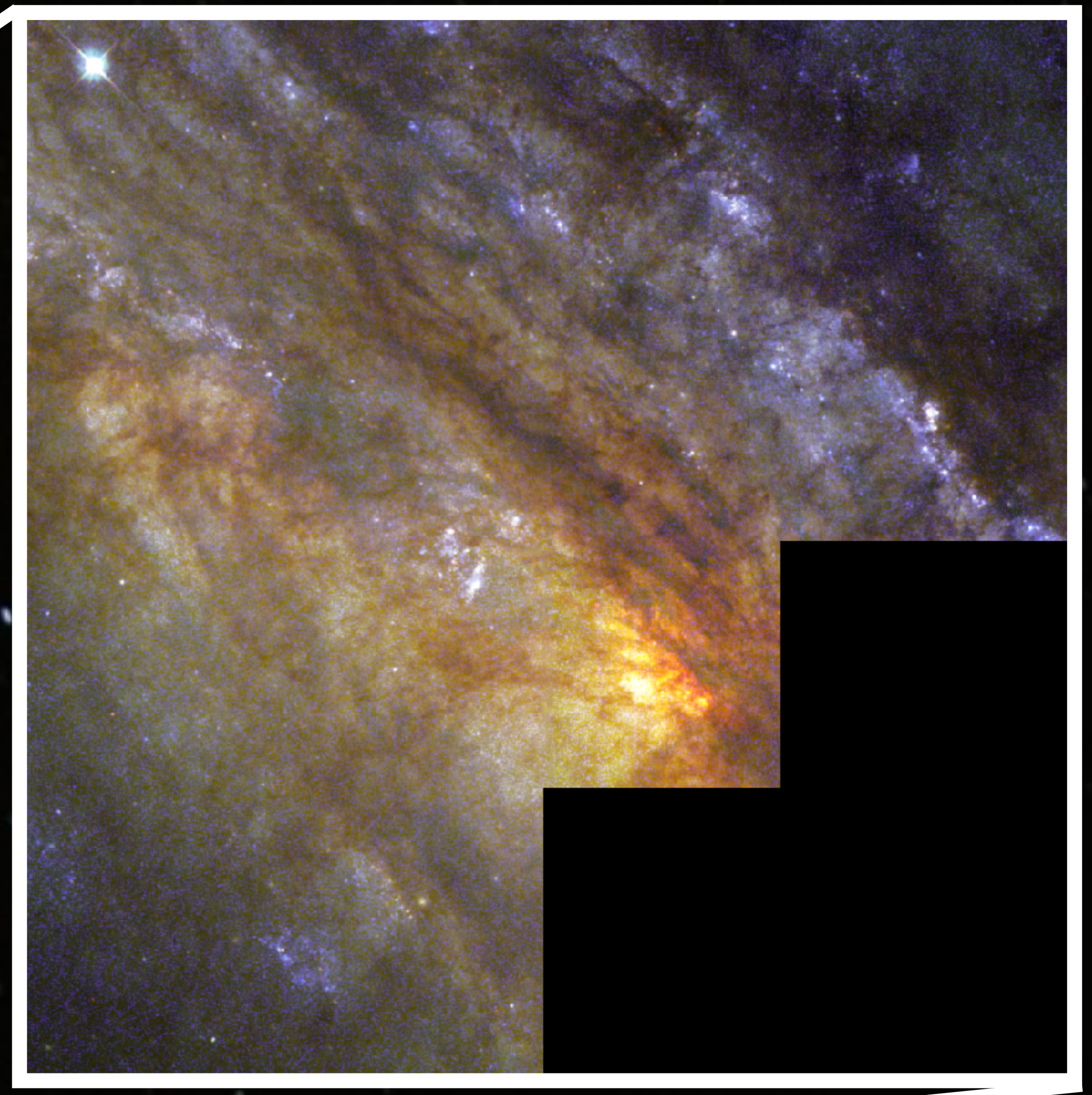
A prime candidate for study of gas in an extreme environment

ESO

NGC 253

A prime candidate for study of gas in an extreme environment

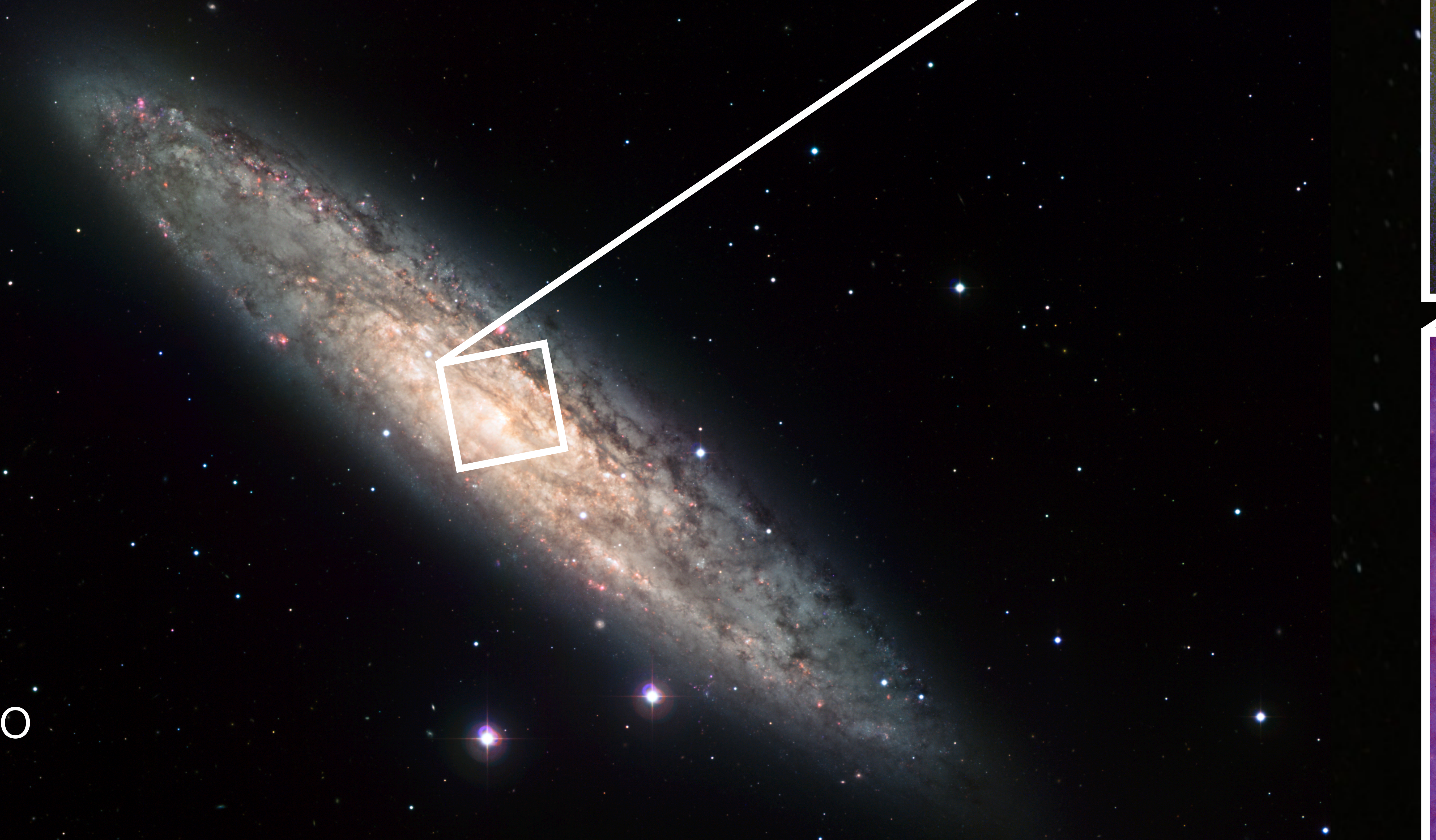
ESO



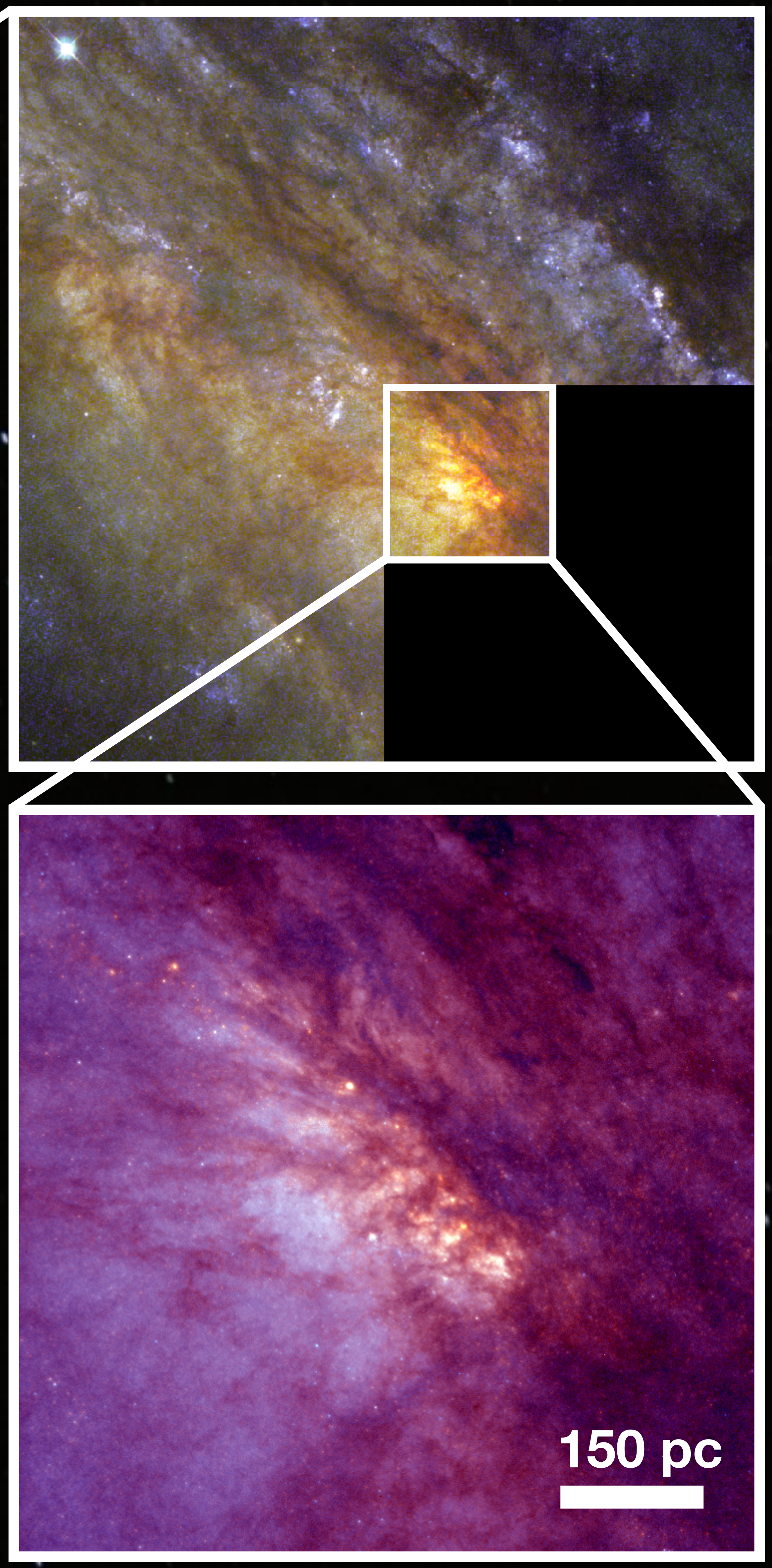
Hubble Heritage Team
(AURA/STScI/NASA/ESA)

NGC 253

A prime candidate for study of gas in an extreme environment



ESO

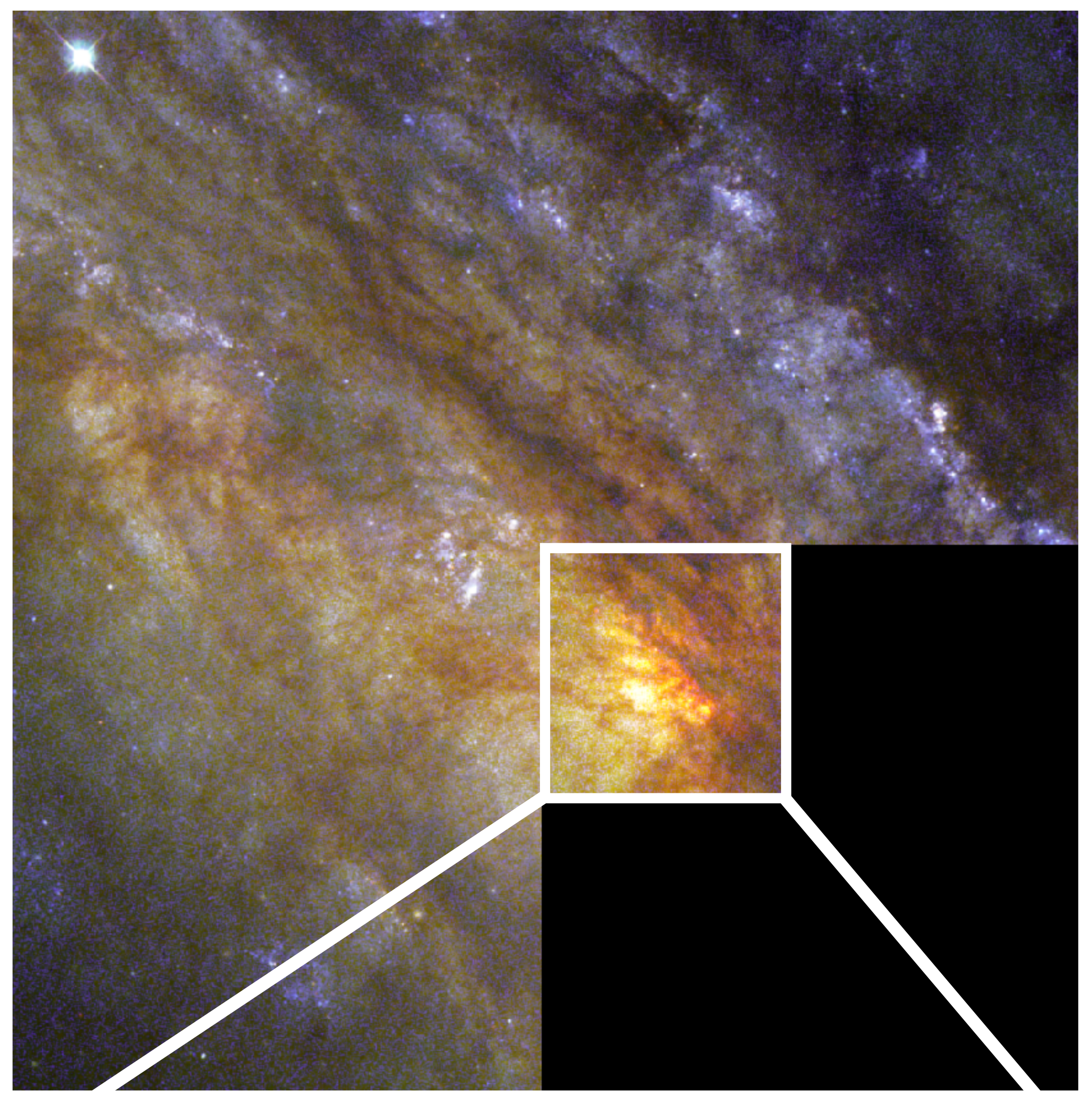


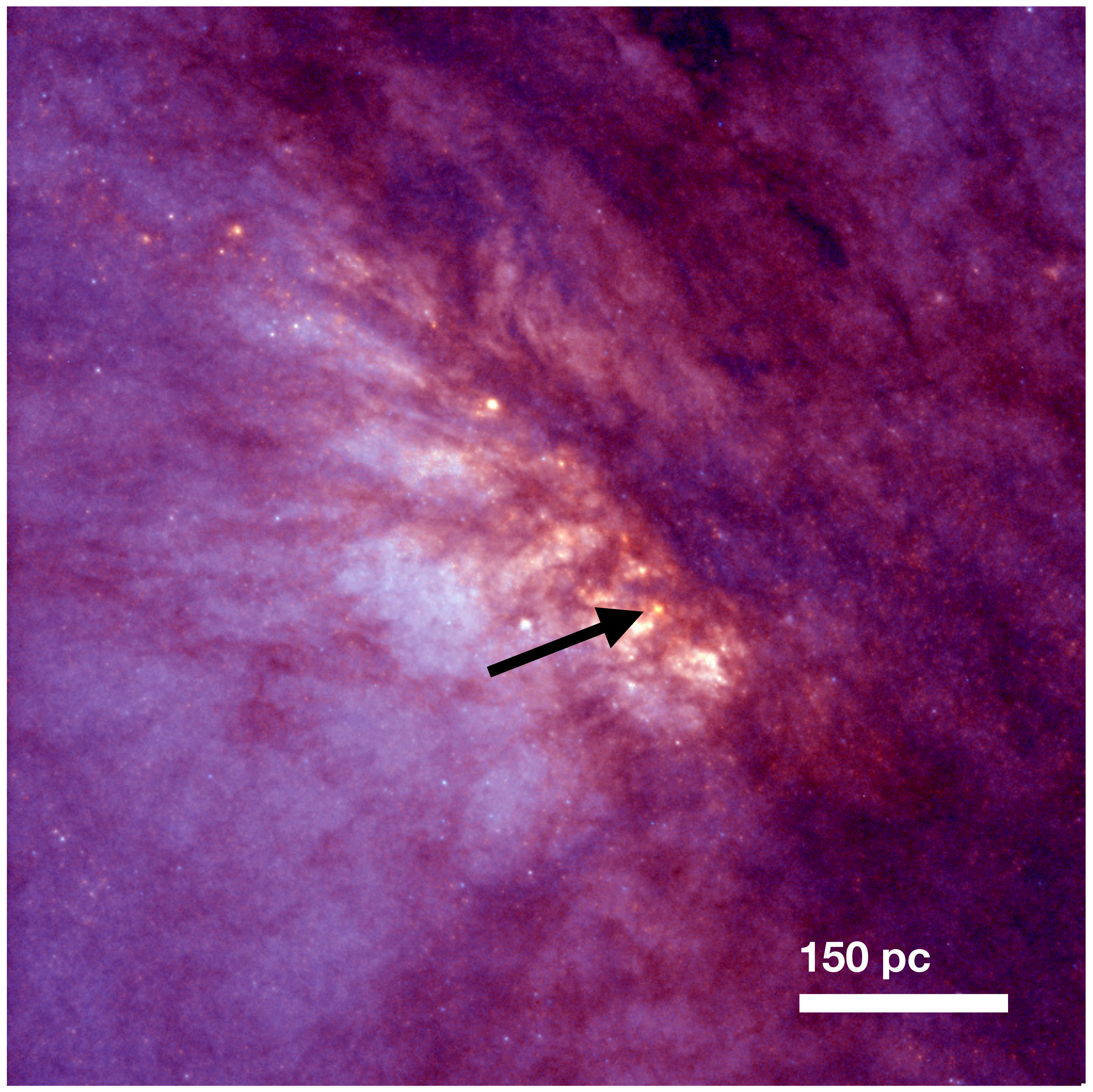
Hubble Heritage Team (AURA/STScI/NASA/ESA)

Carnegie Institution of Washington

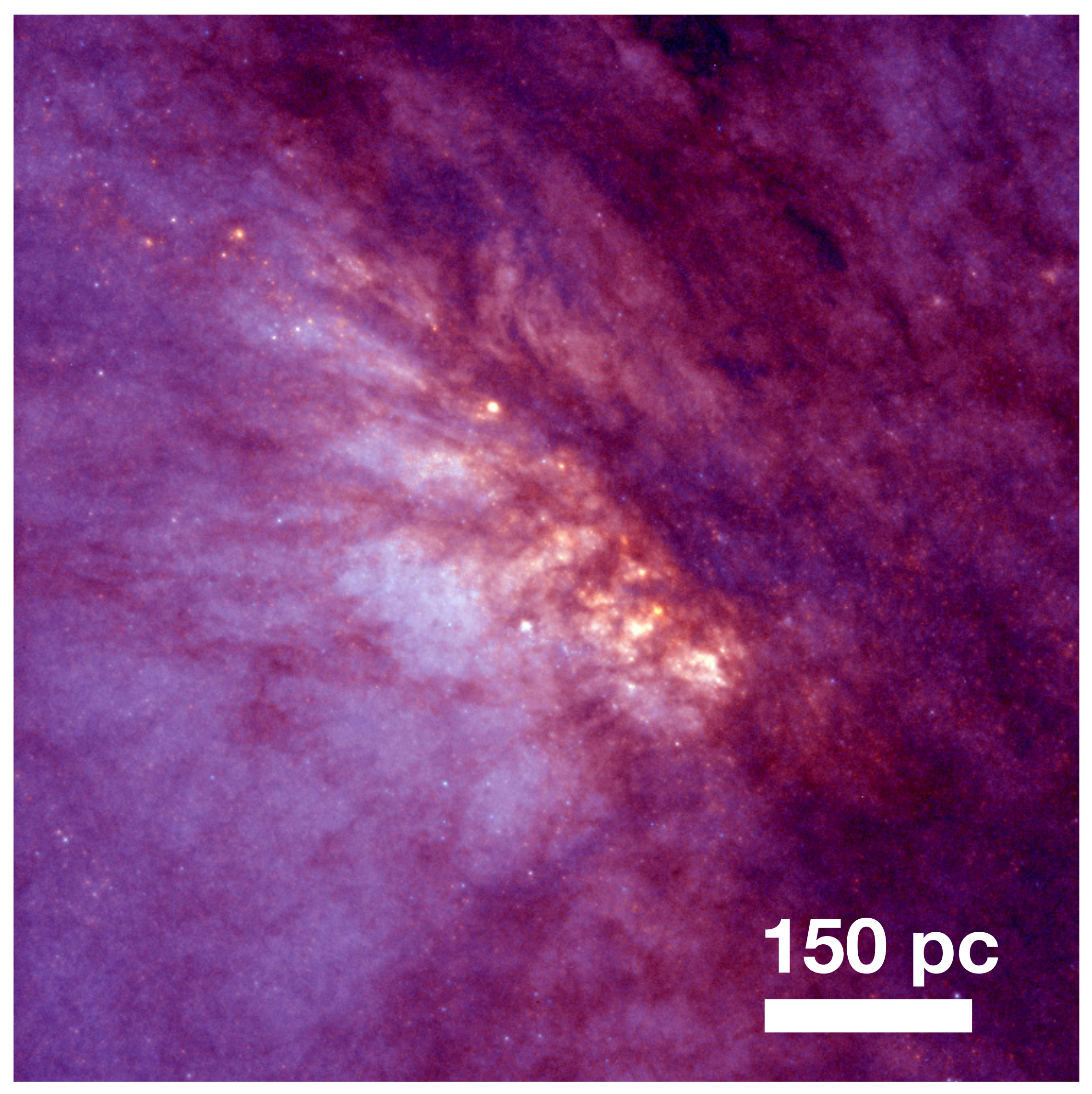
NGC 253: A Starburst Galaxy

Hubble Heritage Team
(AURA/STScI/NASA/ESA)

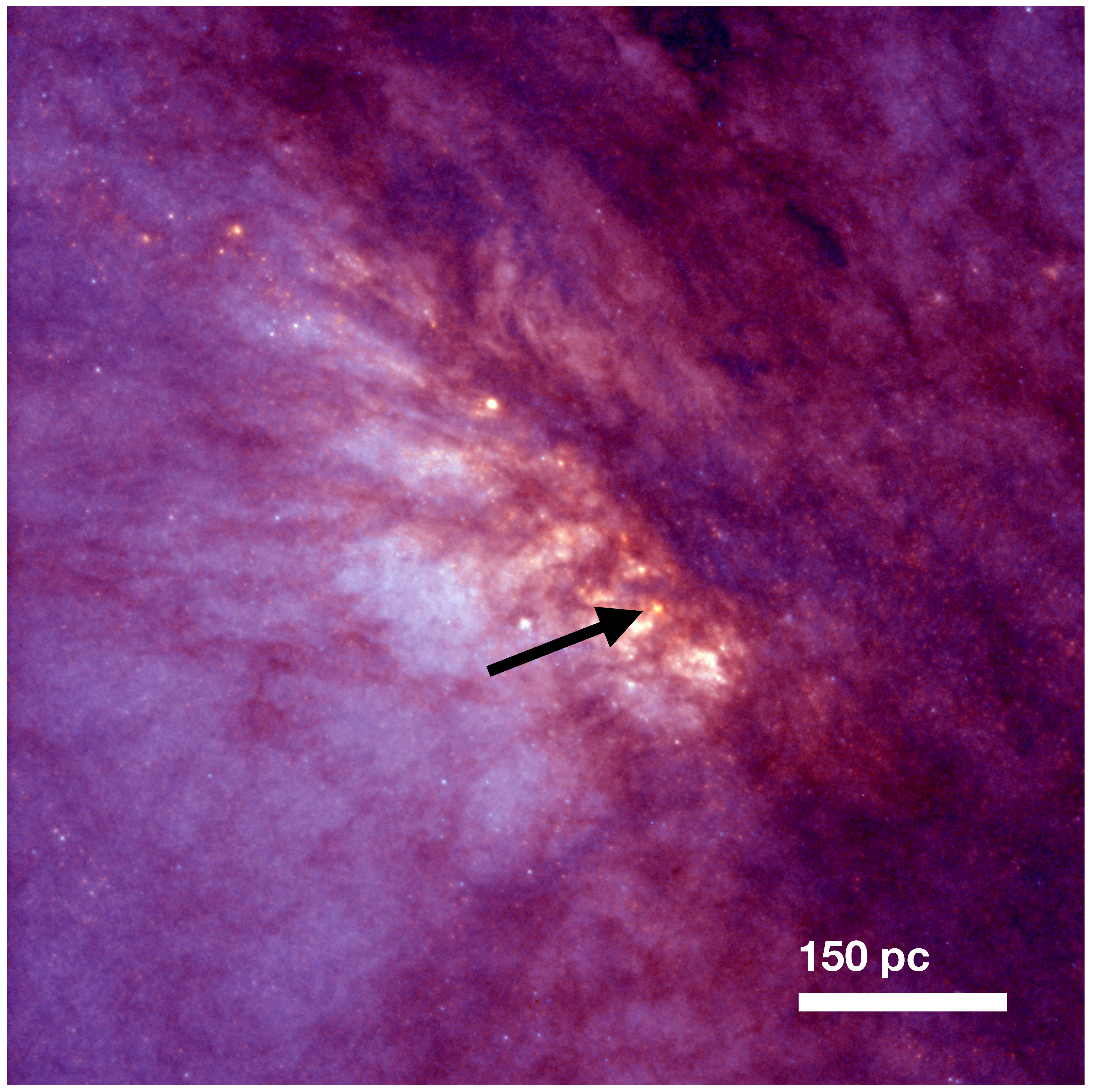




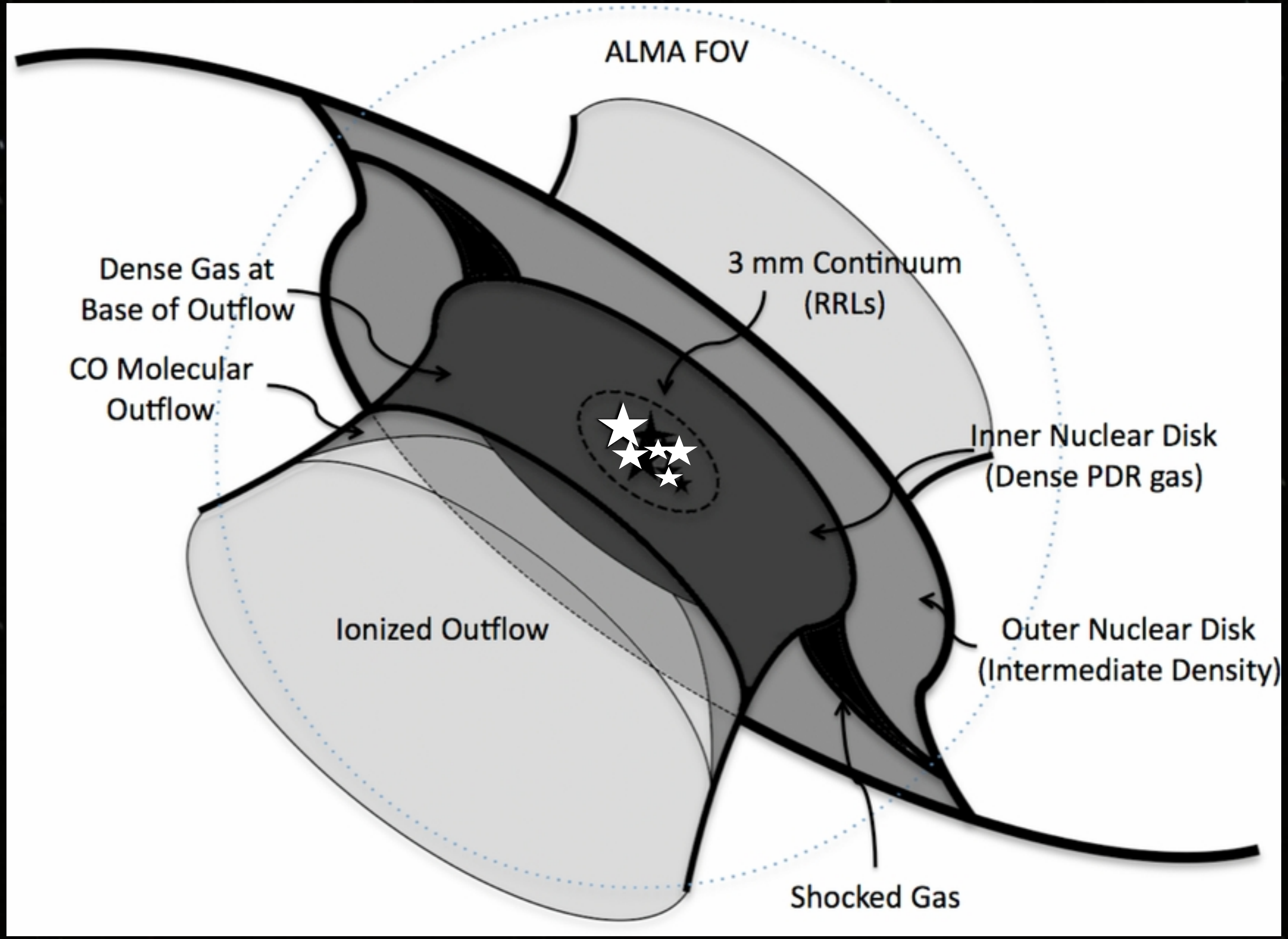
Carnegie Institution of Washington



NGC 253: A Starburst Galaxy



Carnegie Institution of Washington

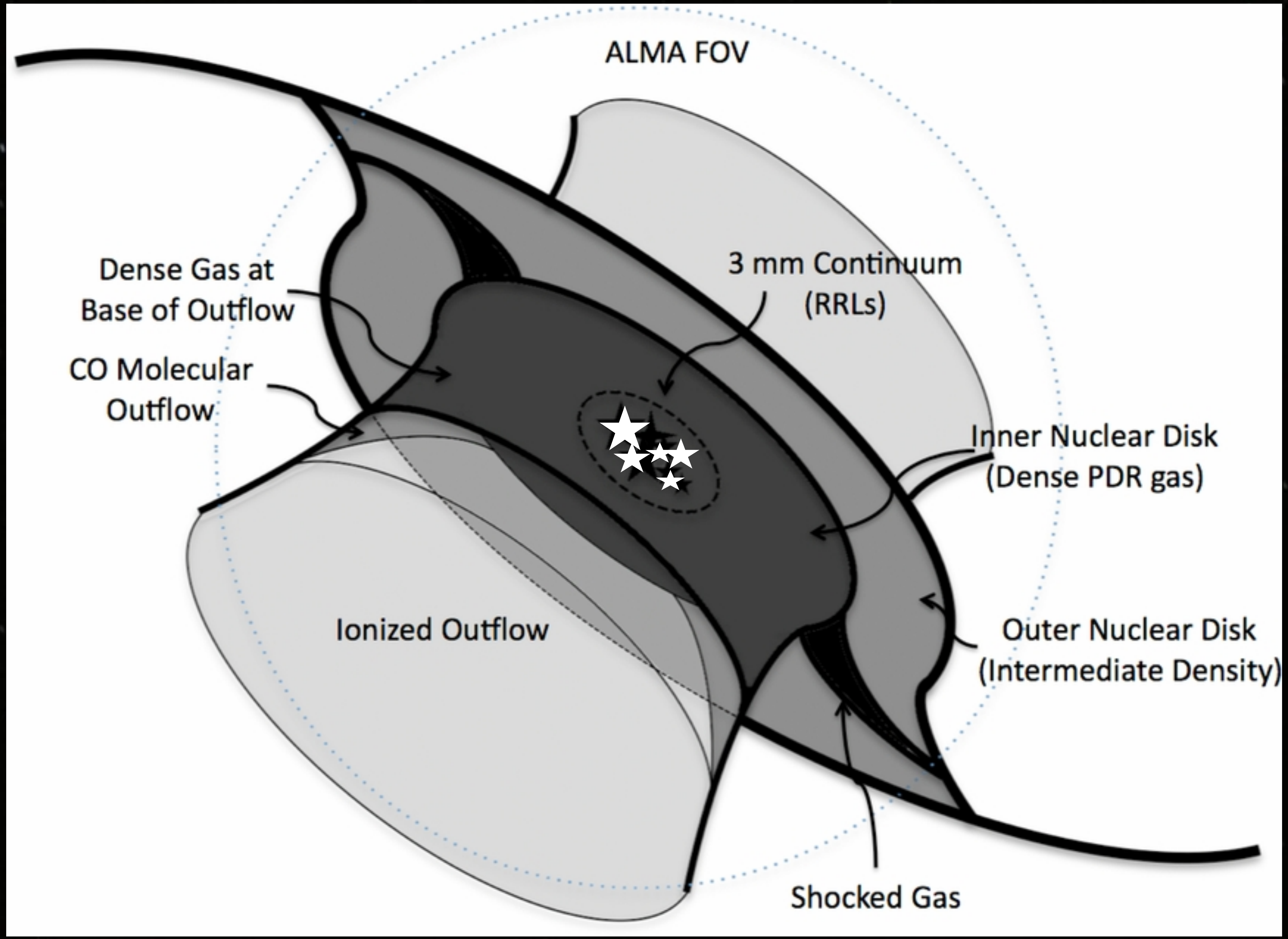


Schematic of the Central Starburst Region
Meier et al. 2015

NGC 253: A Starburst Galaxy

A powerhouse of star formation

- Entire galaxy: SFR = 5 $M_{solar} yr^{-1}$
  (Leroy+2015)
- Nucleus (~500pc): SFR ~ 2.8 $M_{solar}\, yr^{-1}$
  (Ott+2005, Bendo+2015)
- Starburst is fueled by a gas reservoir of mass $(2-4) \times 10^8\, M_{solar}$
  (Krieger+2019)
- The central concentration of star formation leads to the classification as a nuclear starburst



Schematic of the Central Starburst Region
Meier et al. 2015

What is a Super Star Cluster (SSC)?

A young, massive, & compact star cluster

SSCs in NGC 1569

NASA/HST

Massive

$M_\star \gtrsim 10^5 M_\odot$

Compact

R ~ 1 pc

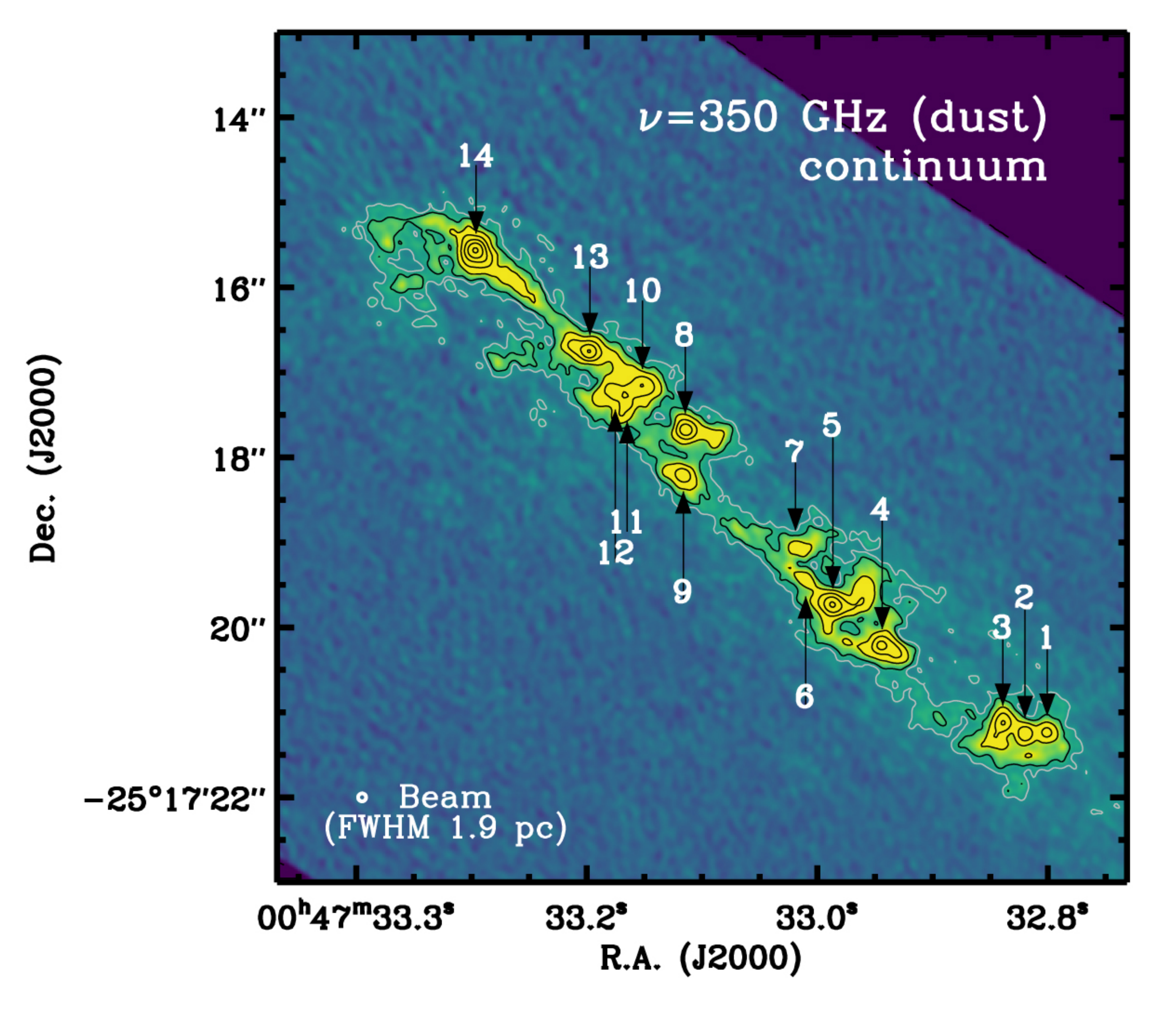
- Often found in starbursting systems
- Intense and efficient mode of star formation

(Wei et al. 2012, Beck 2015, Rebecca Levy)

ALMA reveals 14 SSCs in 253 Nucleus

Leroy et al. 2018

The clusters within NGC 253 are still forming which makes them ideal candidates to observe to understand the mechanisms behind SSC formation

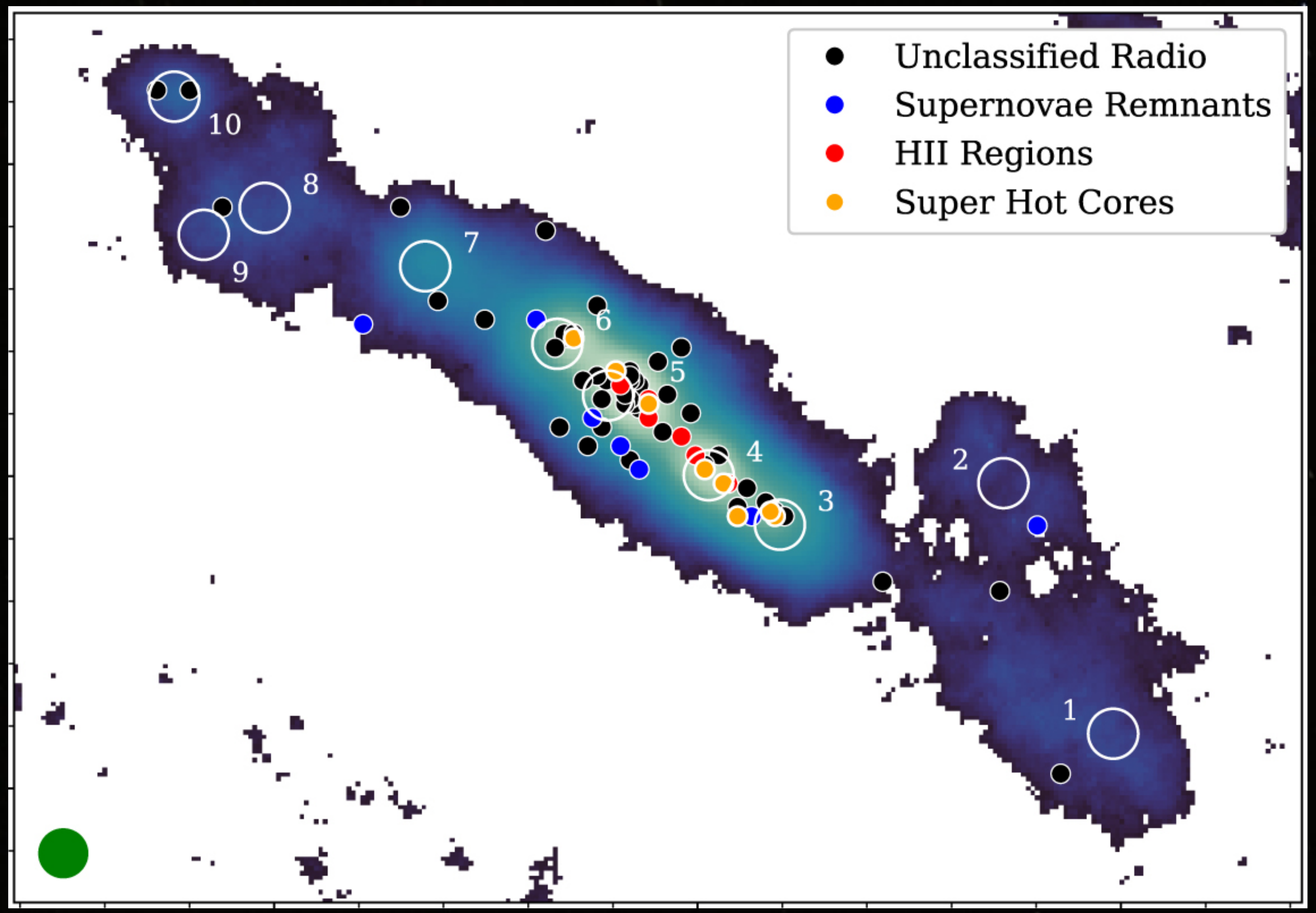


Location of Super Star Clusters
Leroy et al., 2018

Observing Super Star Clusters is Hard

- SSCs are deeply embedded — due to dust extinction these regions are invisible in the optical and nearly invisible in the near infrared (NIR).

- Clusters are compact and thus harder to resolve at greater distances

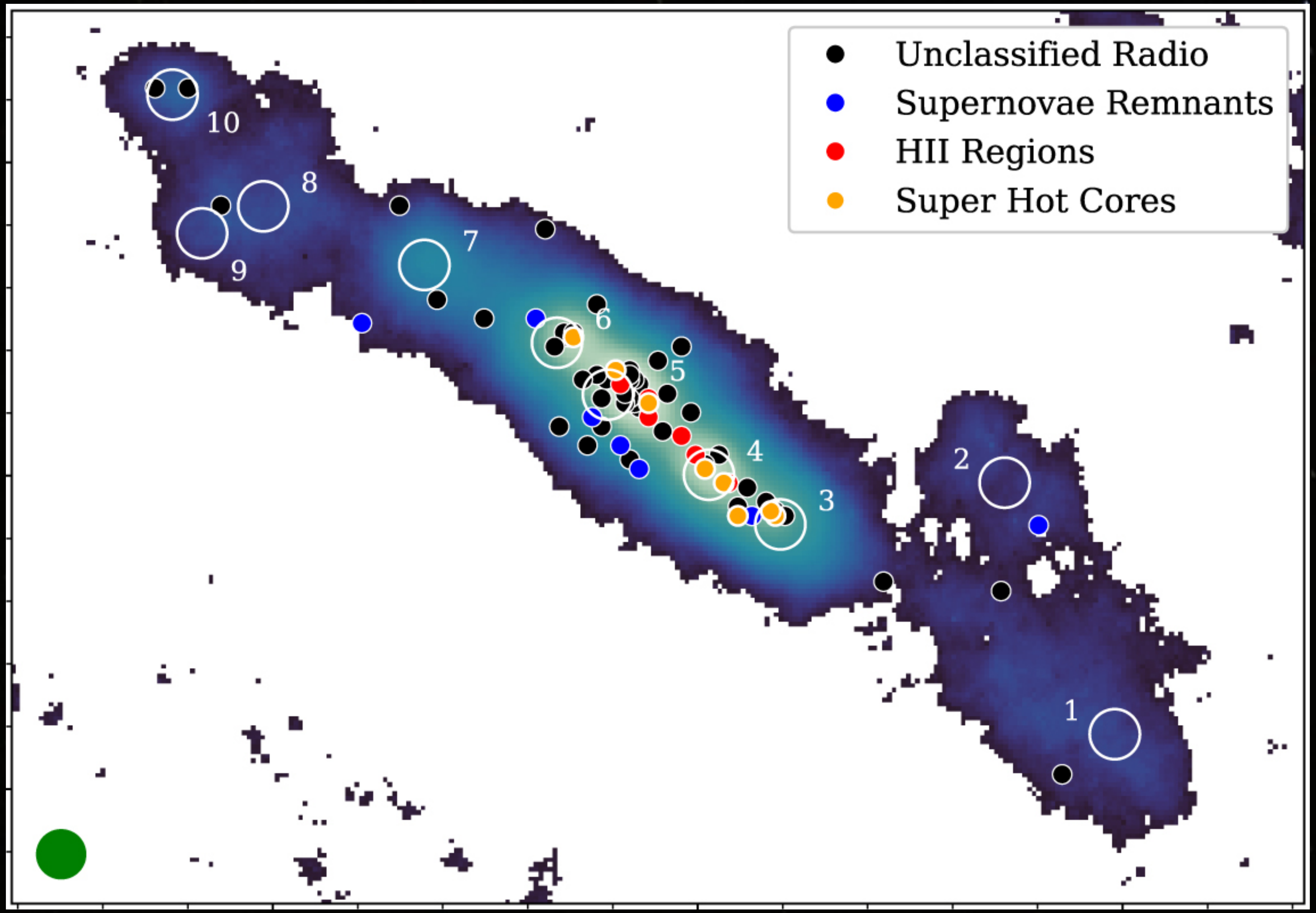


NGC 253 CMZ plotted over the 212 GHz ALCHEMI dust continuum emission. Numbered white circles indicate GMCs.
Behrens et al. 2022

Observing Super Star Clusters is Hard

- SSCs are deeply embedded — due to dust extinction these regions are invisible in the optical and nearly invisible in the near infrared (NIR).
- Clusters are compact and thus harder to resolve at greater distances

Observing at longer wavelengths using interferometry solves both of these challenges.



NGC 253 CMZ plotted over the 212 GHz ALCHEMI dust continuum emission. Numbered white circles indicate GMCs.
Behrens et al. 2022

ALMA Dataset

Atacama Large Millimeter/submillimeter Array

- <5 pc (~0.29”) resolution
- ALMA observations at multiple frequencies
    - Band 3 (84 GHz)
- ALMA provides the necessary high resolution and sensitivity needed to peer into the heart of these SSCs

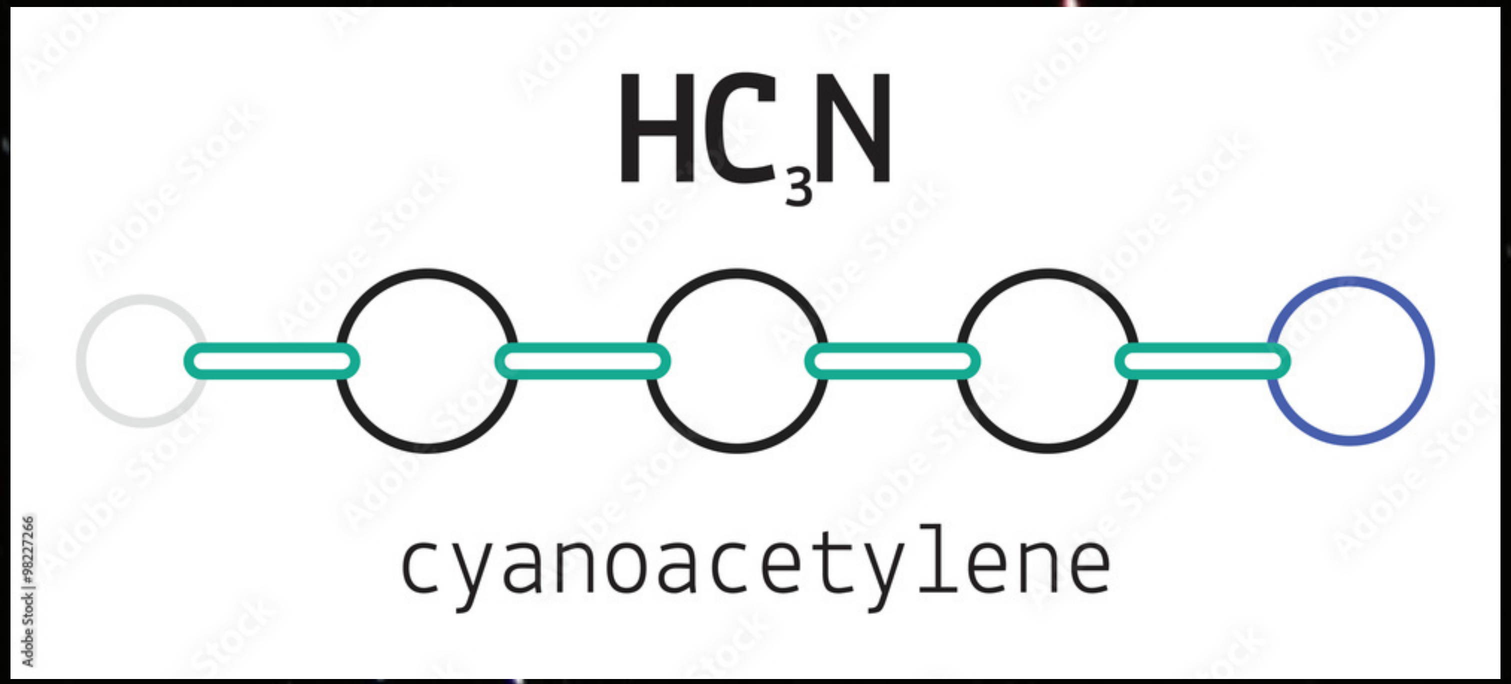
ESO/José Francisco Salgado

The Key to Peering through Obscuration

HC_3N emission is used to probe high density and hot material

- Rotational and virbational emission of HC_3N is virtually **unaffected** by dust extinction in the (sub)millimeter range and allows us to probe the deeply embedded regions (Rico-Villas et al. 2020)

- Study of multiple vibrational transitions allows us to better understand their:
  - physical properties
  - thermal and density structures
  - kinematics of the material heated by the protostars

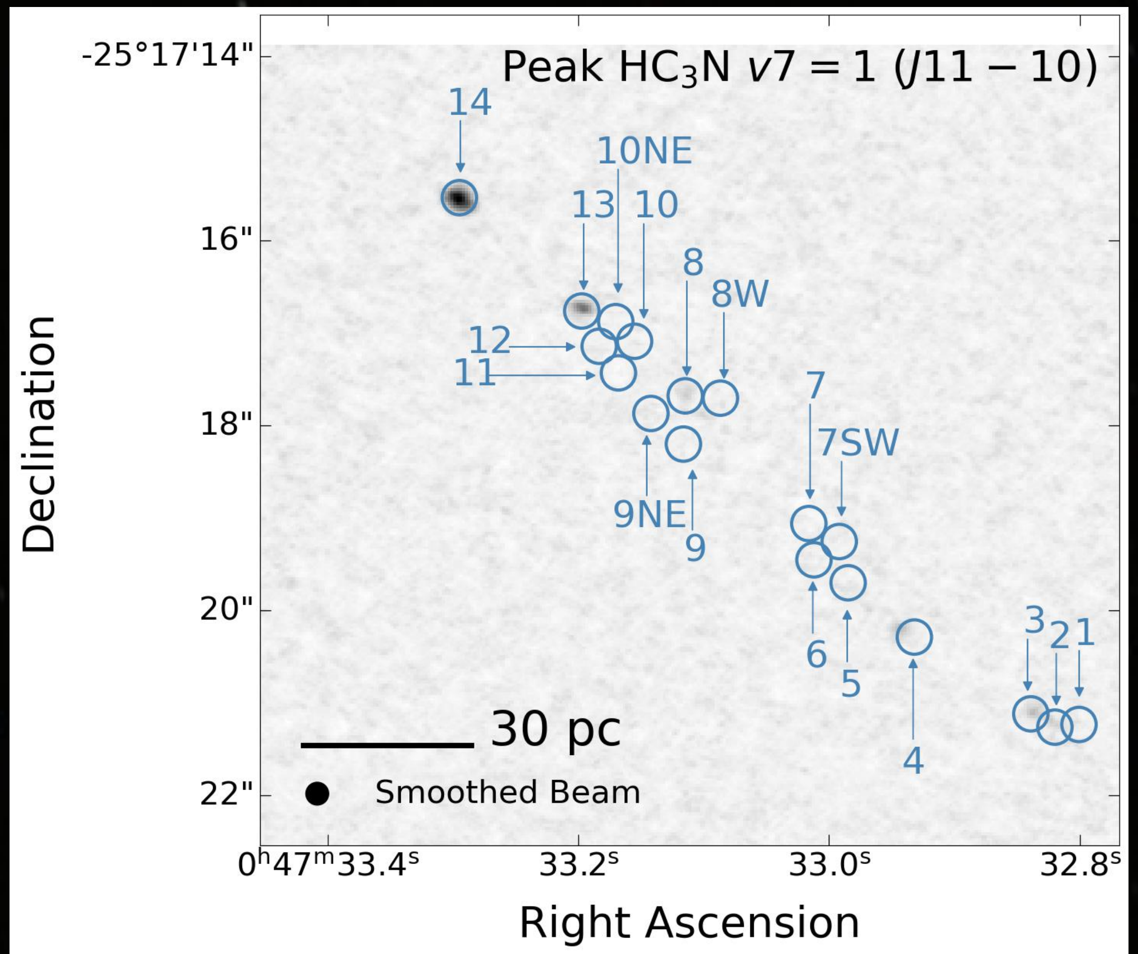


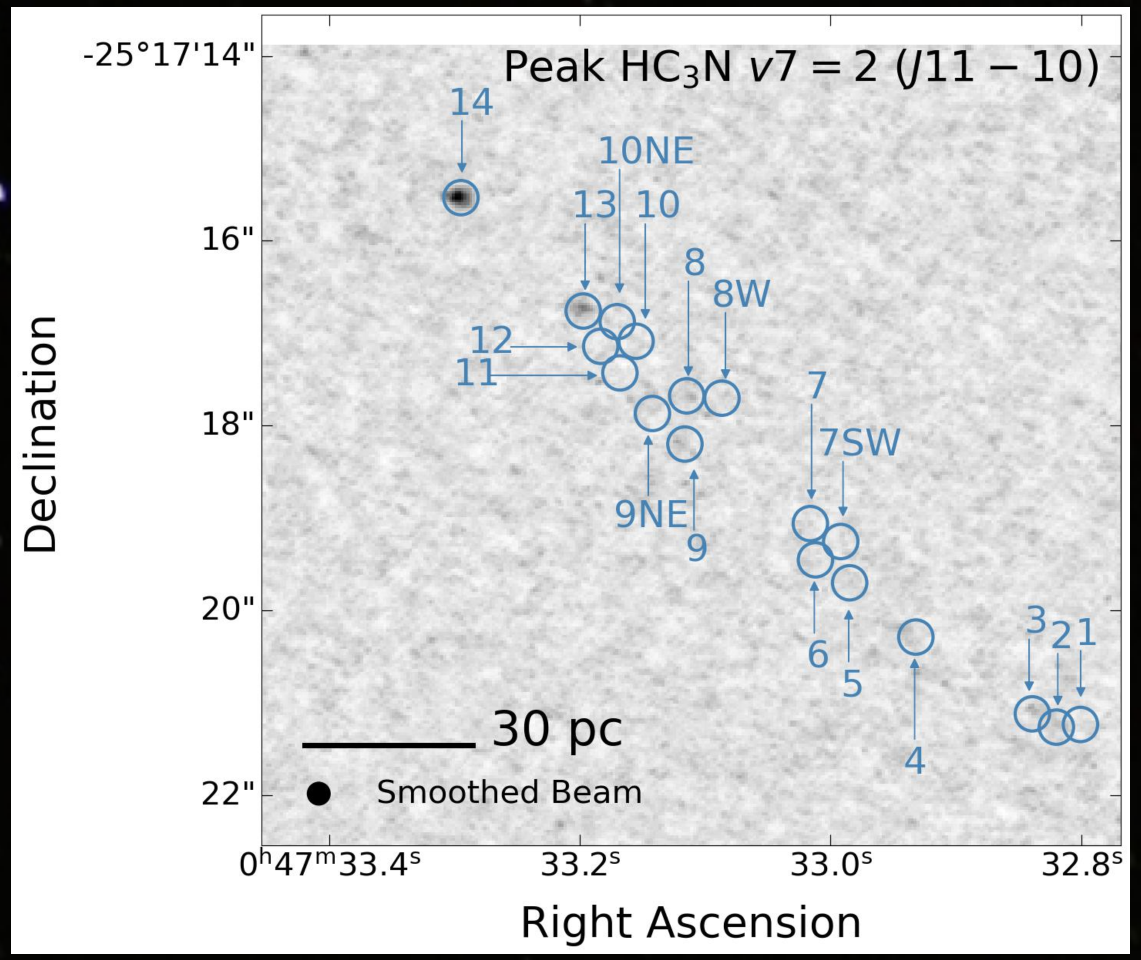
Emission from SSCs

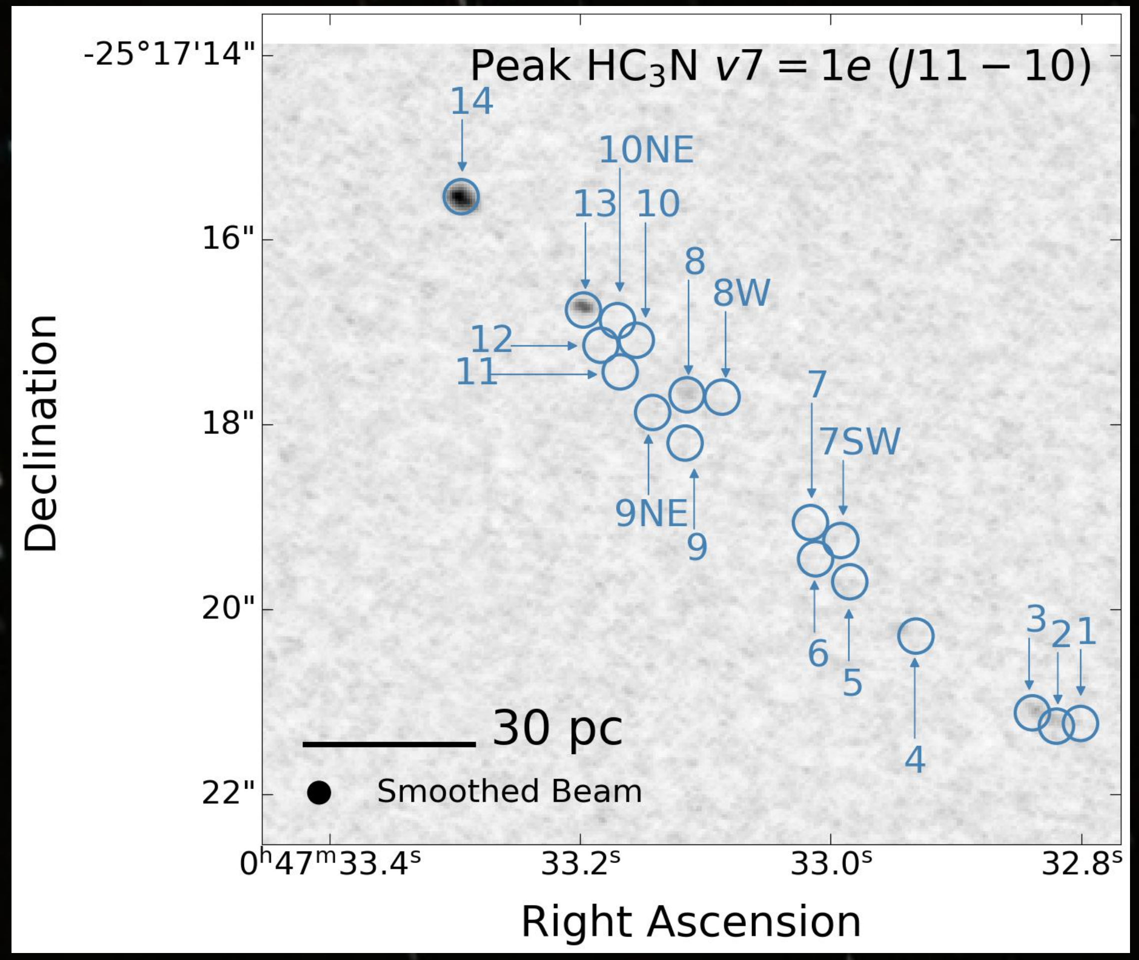
Look at several vibrational transitions of HC3N

v7=2

v7=1

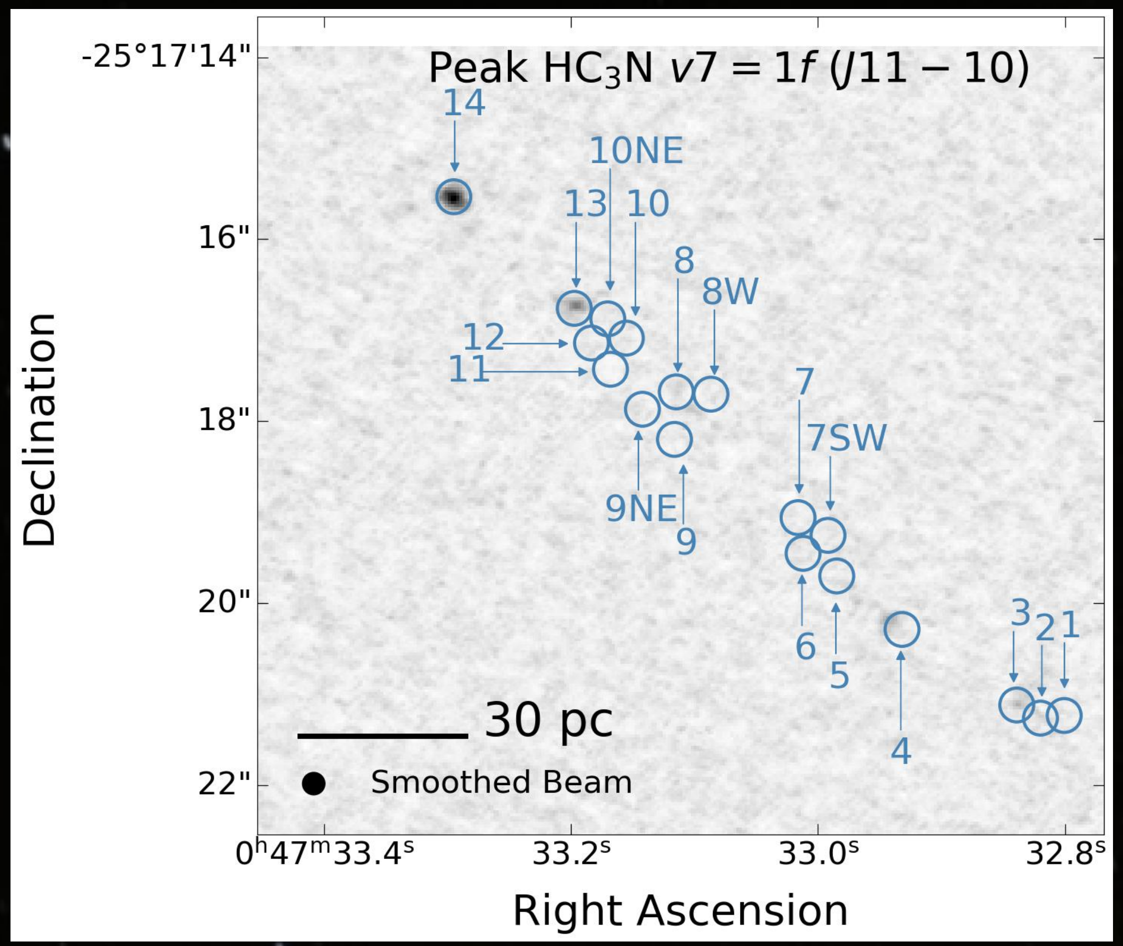


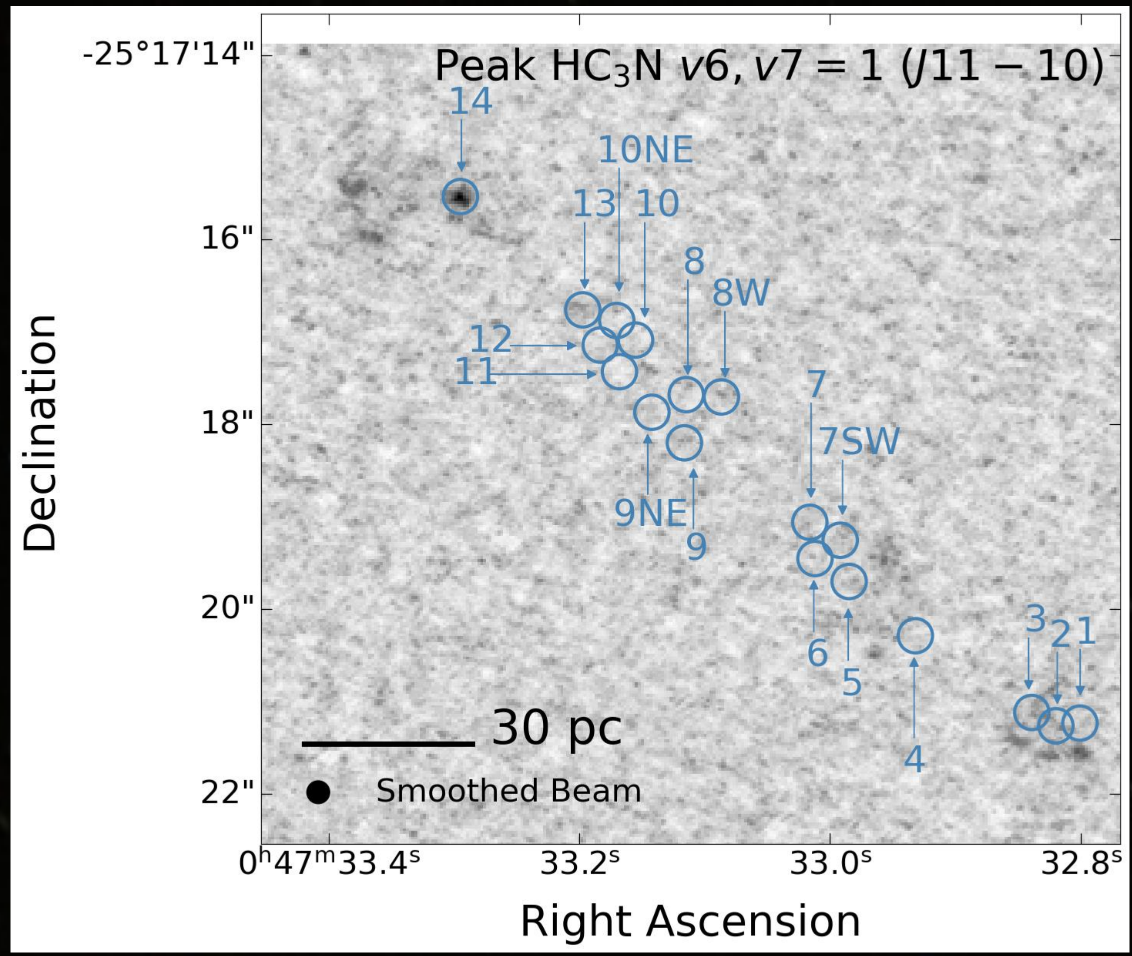




v7=1e

v7=1f

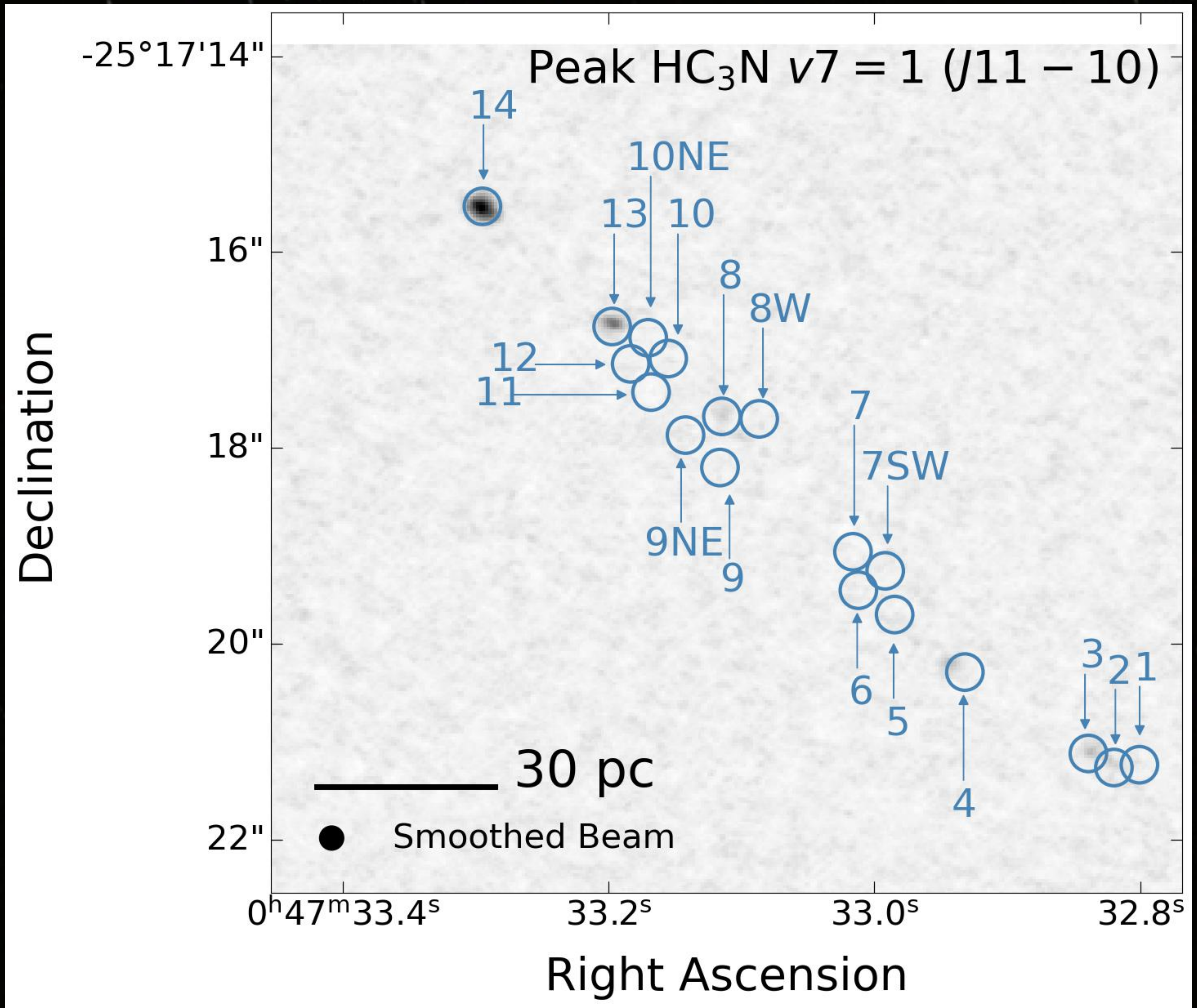




v6=1
v7=1

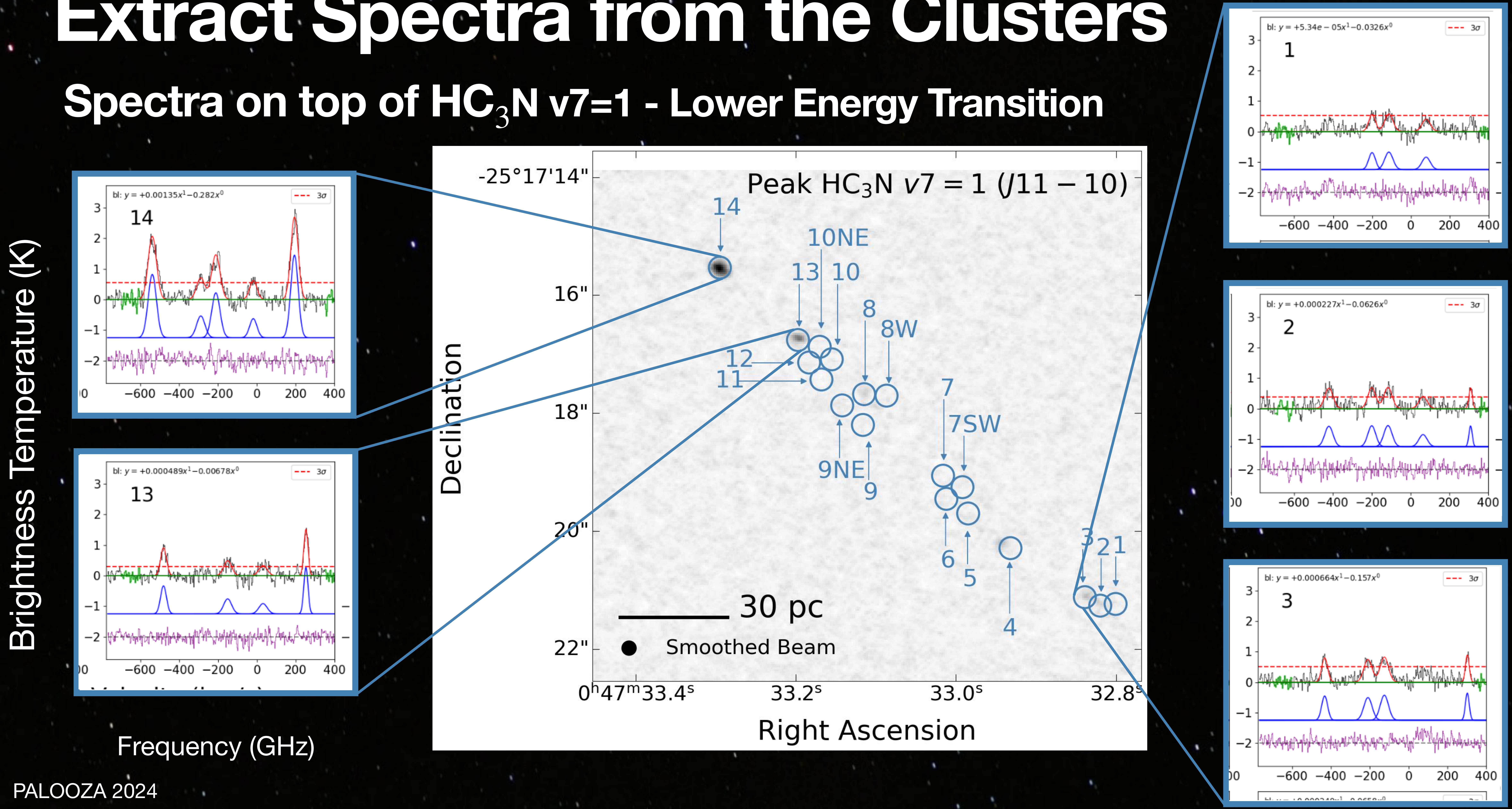
Extract Spectra from the Clusters

HC_3N v7=1 - Lower Energy Transition



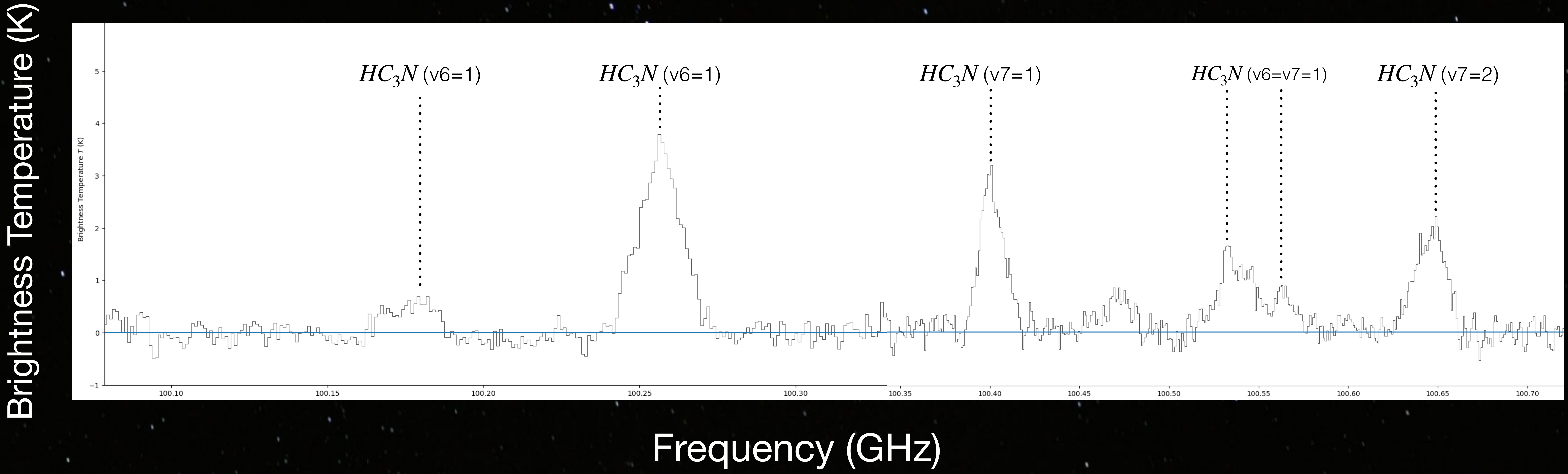
Extract Spectra from the Clusters

Spectra on top of HC_3N v7=1 - Lower Energy Transition



Lines Present in the Starburst Nucleus

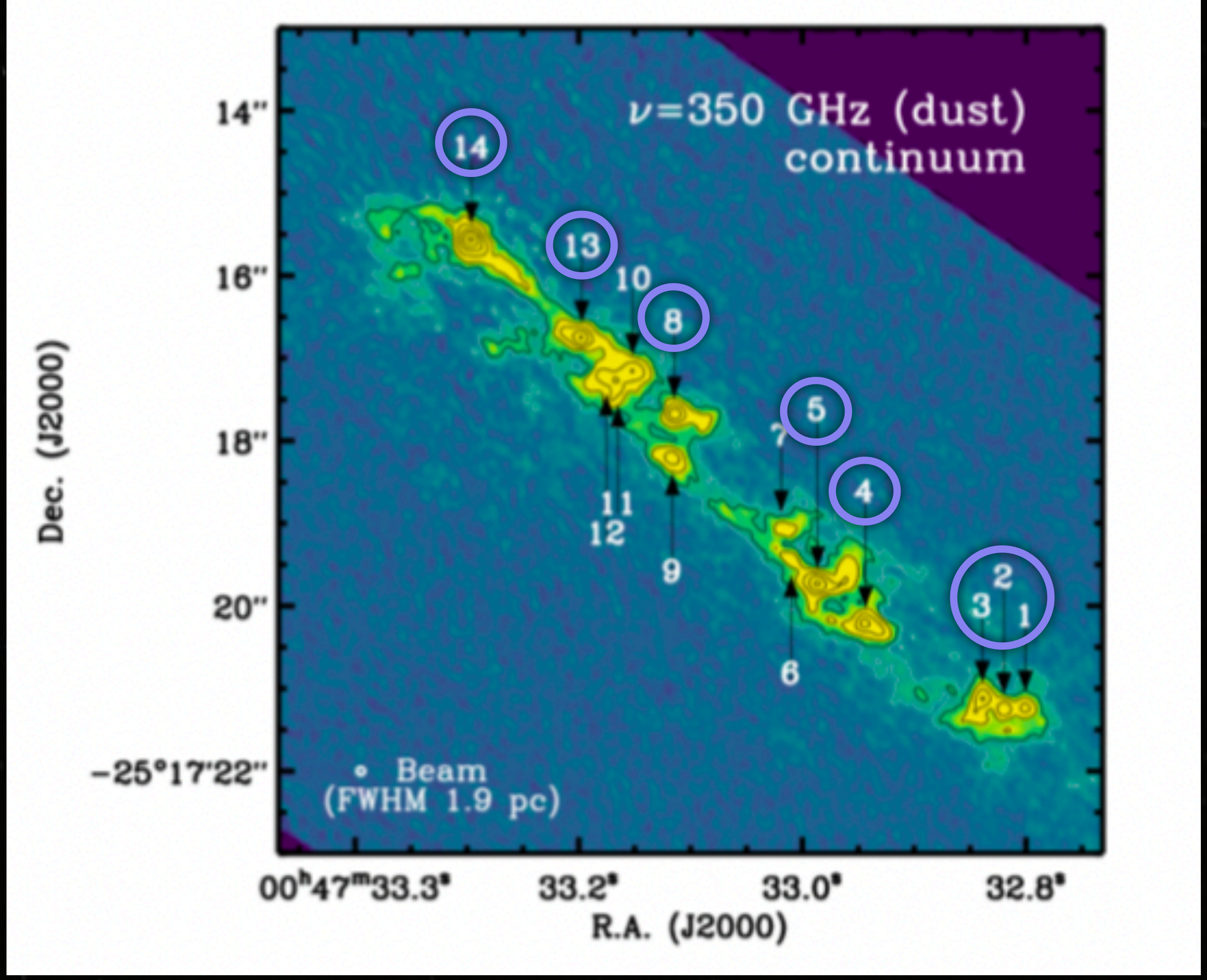
Strongest detection found in SSC 14



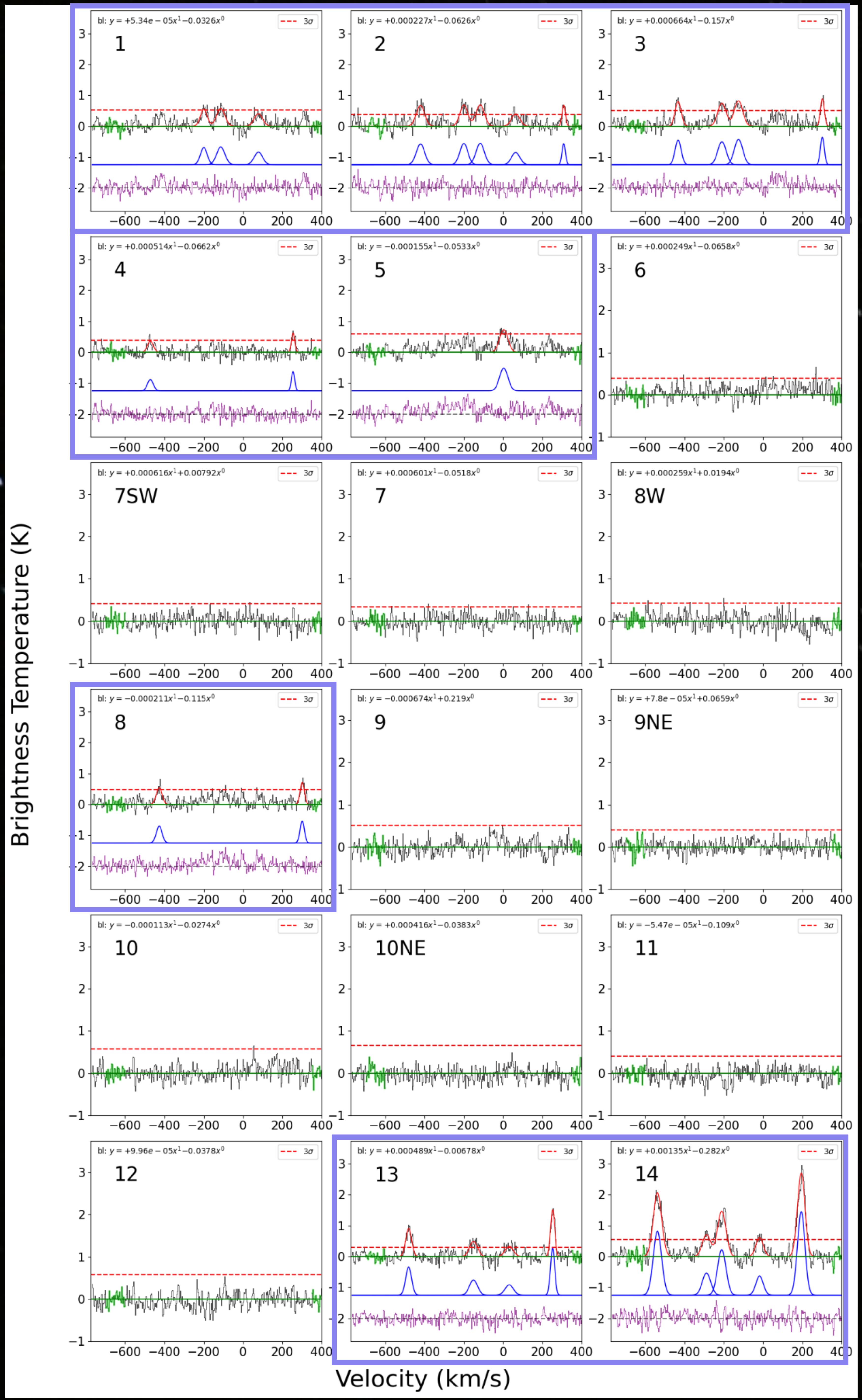
Detections Vary by SSC

Clusters are not uniform

- Emission detected in 8 of the SSCs
- Prevailing theory is that this aligns with the subset of clusters that are younger



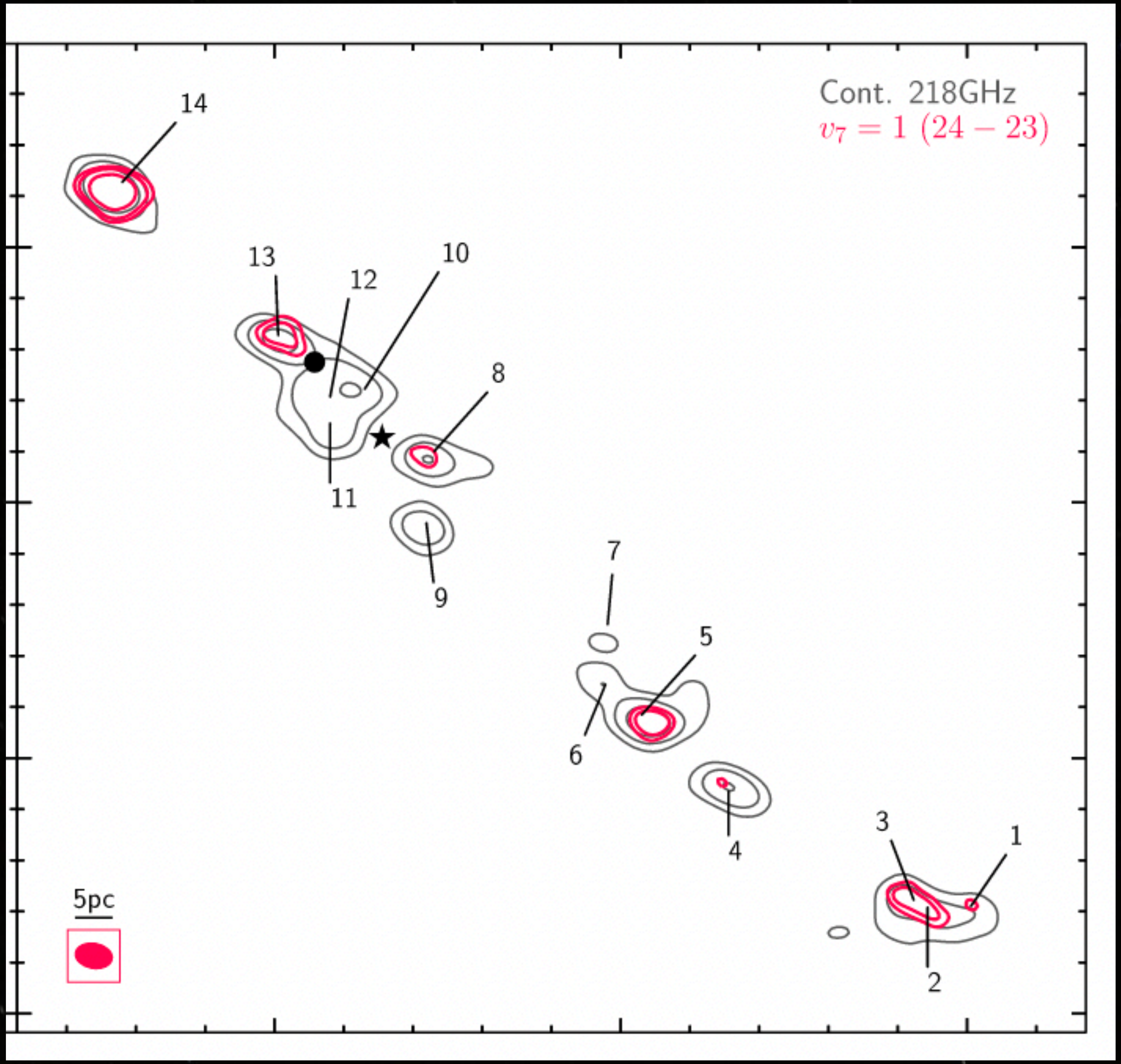
Detections



Does this align with previous findings?

- In 2020, the Rico-Villas team presented which clusters they found HC_3N^* emission in in ALMA Band 6 (211 – 275 GHz) & 7 (275 – 373 GHz) at ~3pc resolution
- They found HC_3N^* emission in 8 SSCs in the nucleus region of NGC 253

Yes, we see clear detections in the same 8 SSCs!

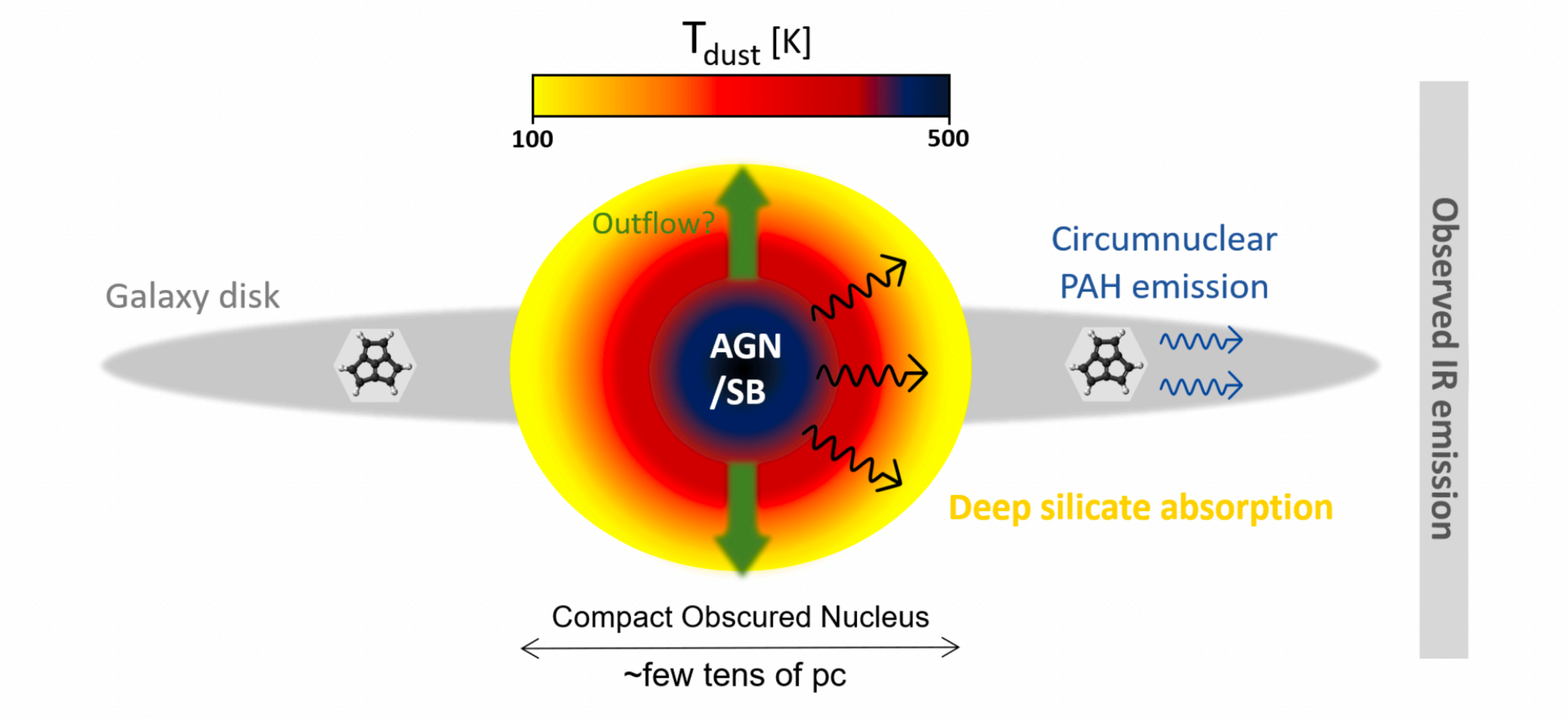


(Rico-Villas et al. 2020)

Broader Connections

Adding clarity to the observations of galaxy centers

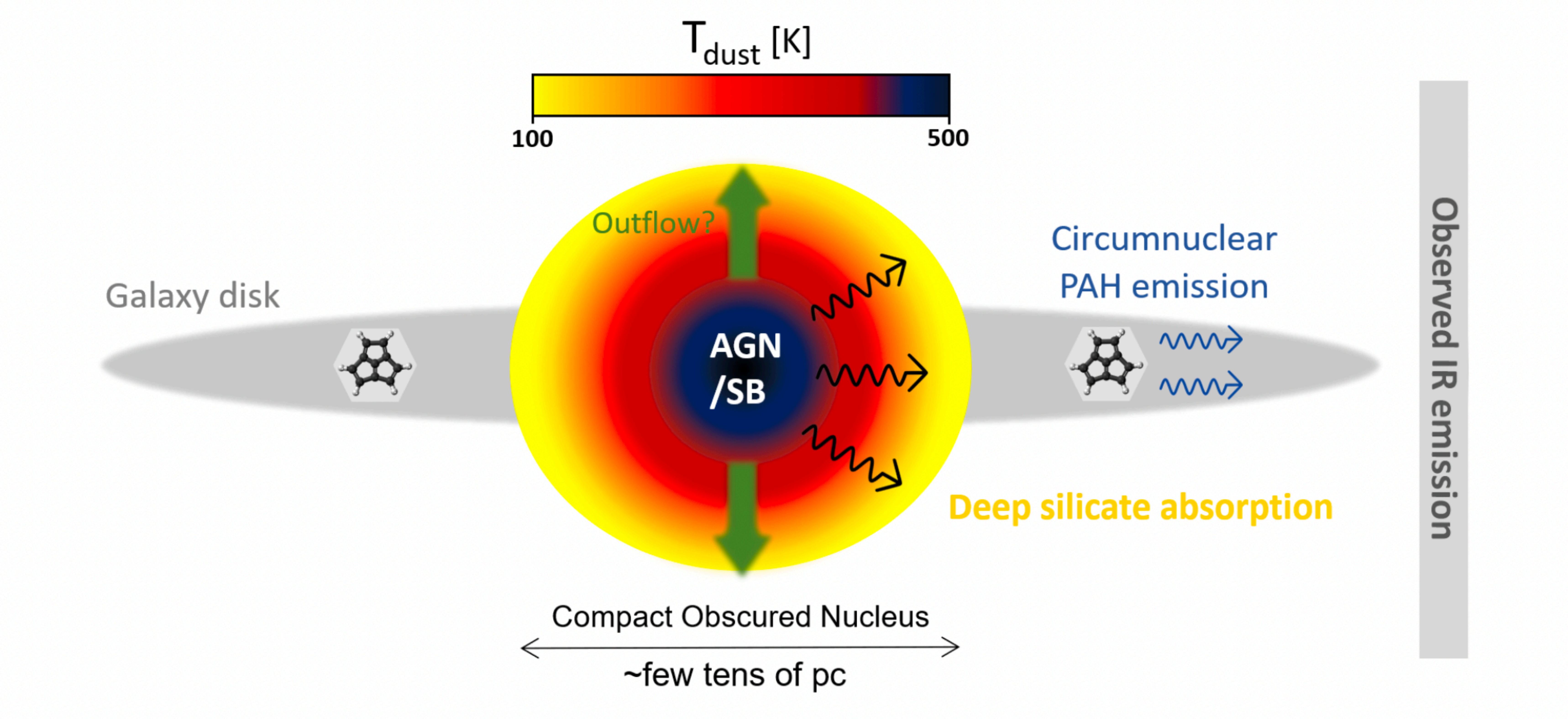
- There is contention around whether or not compact obscured nuclei at the centers of galaxies require active supermassive black holes (AGNs).



García-Bernete et al. 2022

Broader Connections

An analog to star formation in the past



We can think of a compact nucleus as a mega-SSC.

SSC allow us to observe local, less extreme analogs and to refine our observational techniques.

García-Bernete et al. 2022

Summary

Analysis of Emission from Vibrationally Excited Molecules of HC_3N in NGC 253

- Due to its proximity, NGC 253 is the optimal candidate for studying the star forming gas in nuclear starbursts
- Focusing on vibrational transitions of HC_3N allow us to peer deeper into the inner workings of the super star clusters (SSCs) with the help of ALMA
- Preliminary spectra from these SSCs match previous findings for what SSCs see lines
- Setting the stage for future radiative transfer analysis in which we will be able to place constraints on the physical conditions and environments we are observing

Thank you!

Ashley Lieber
Dr. Elisabeth Mills Nearby Galaxies Lab
University of Kansas
ashleylieber@ku.edu

MARAC 2023

KU | MADISON & LILA SELF GRADUATE FELLOWSHIP

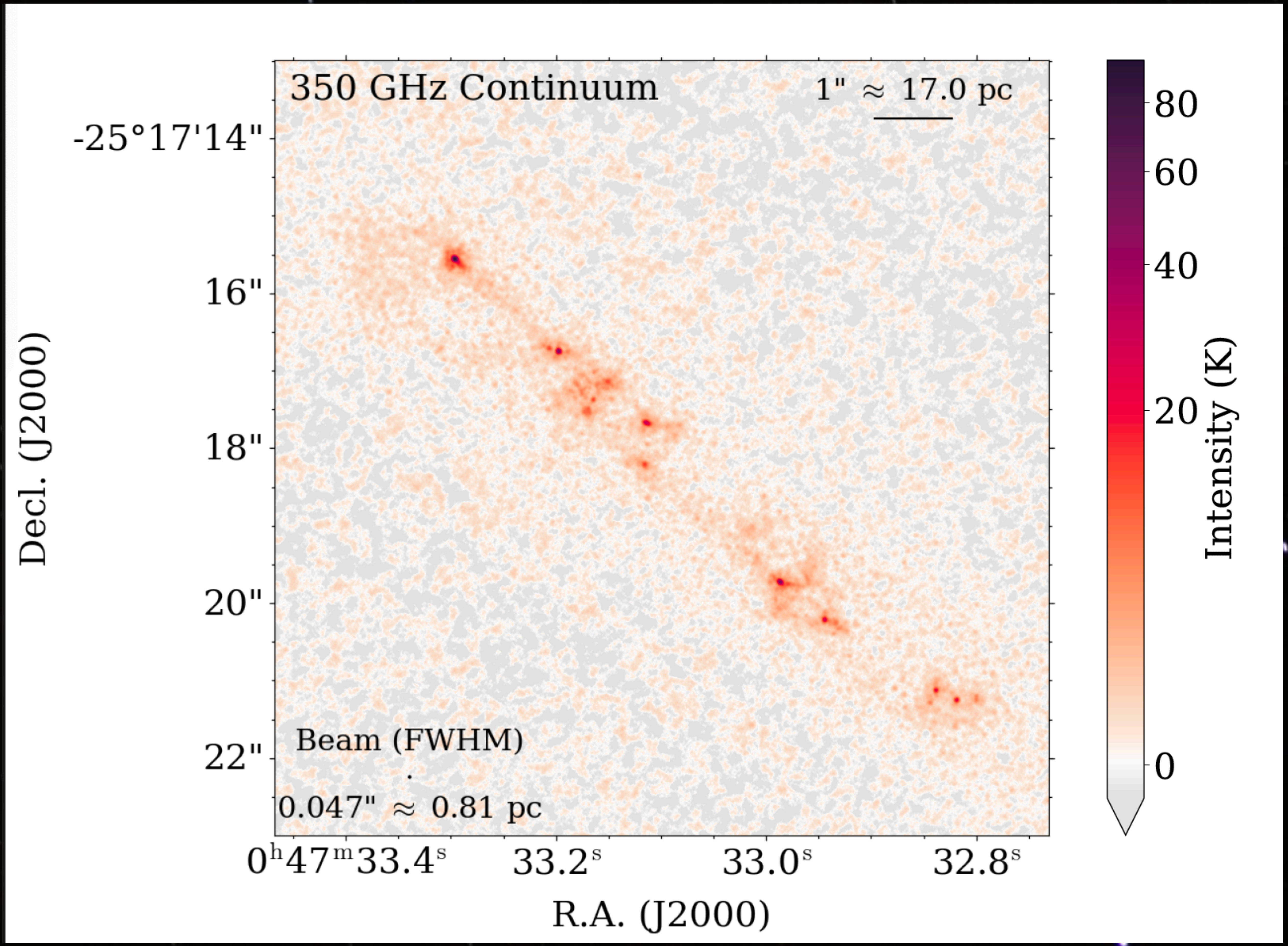
nearby galaxies lab

ESO

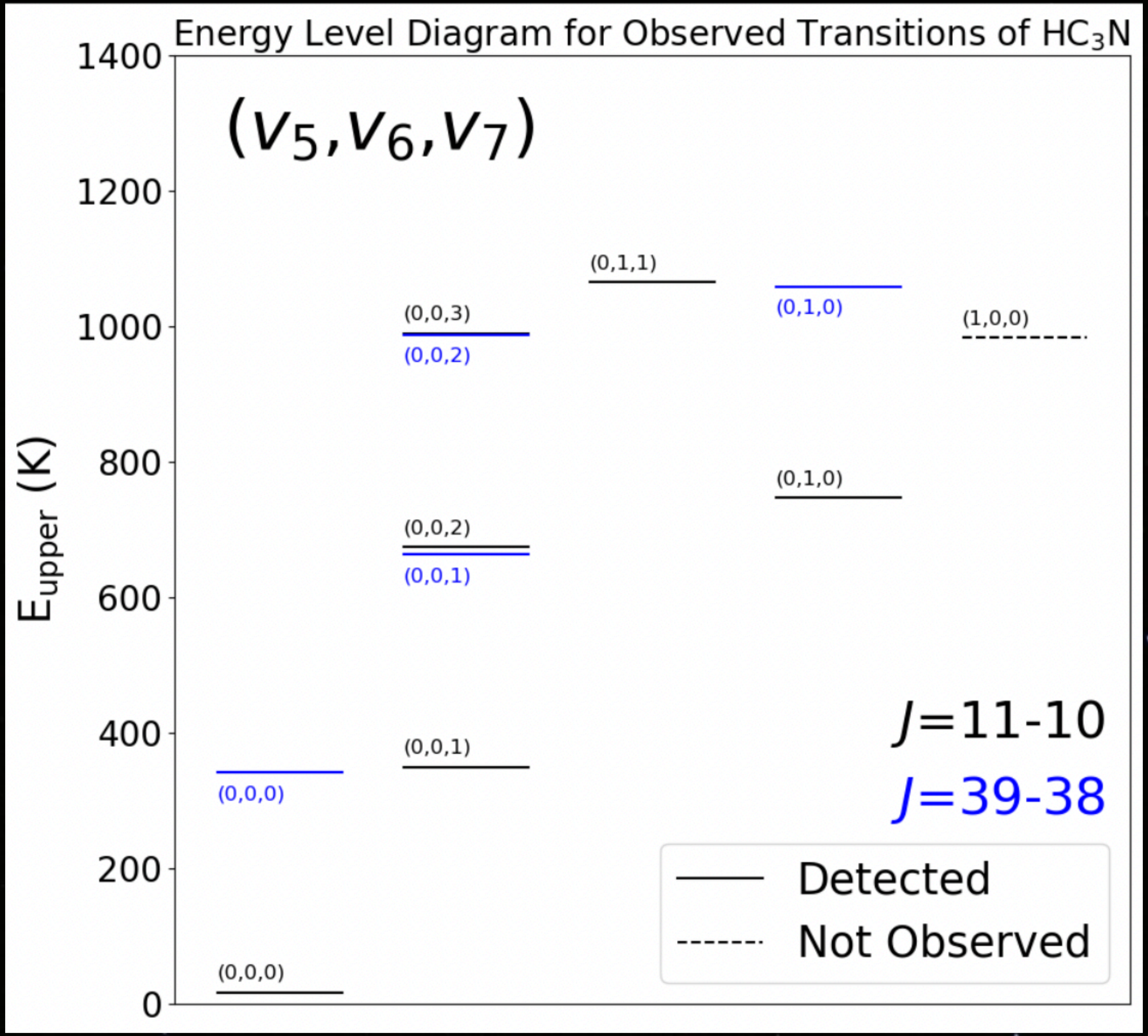
Backup Slides

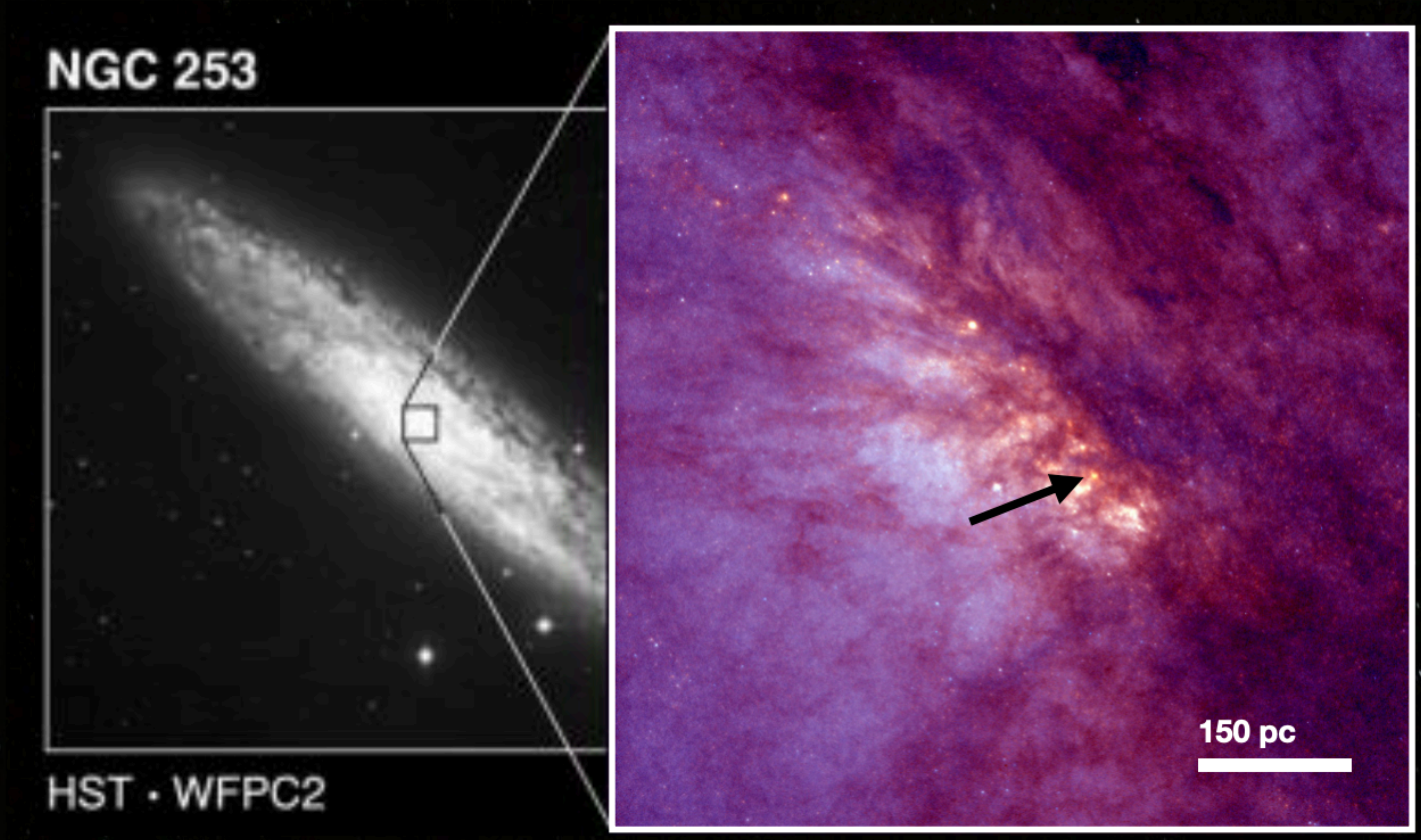
Higher Resolution Observations

Clear Separation of some potential SSCs

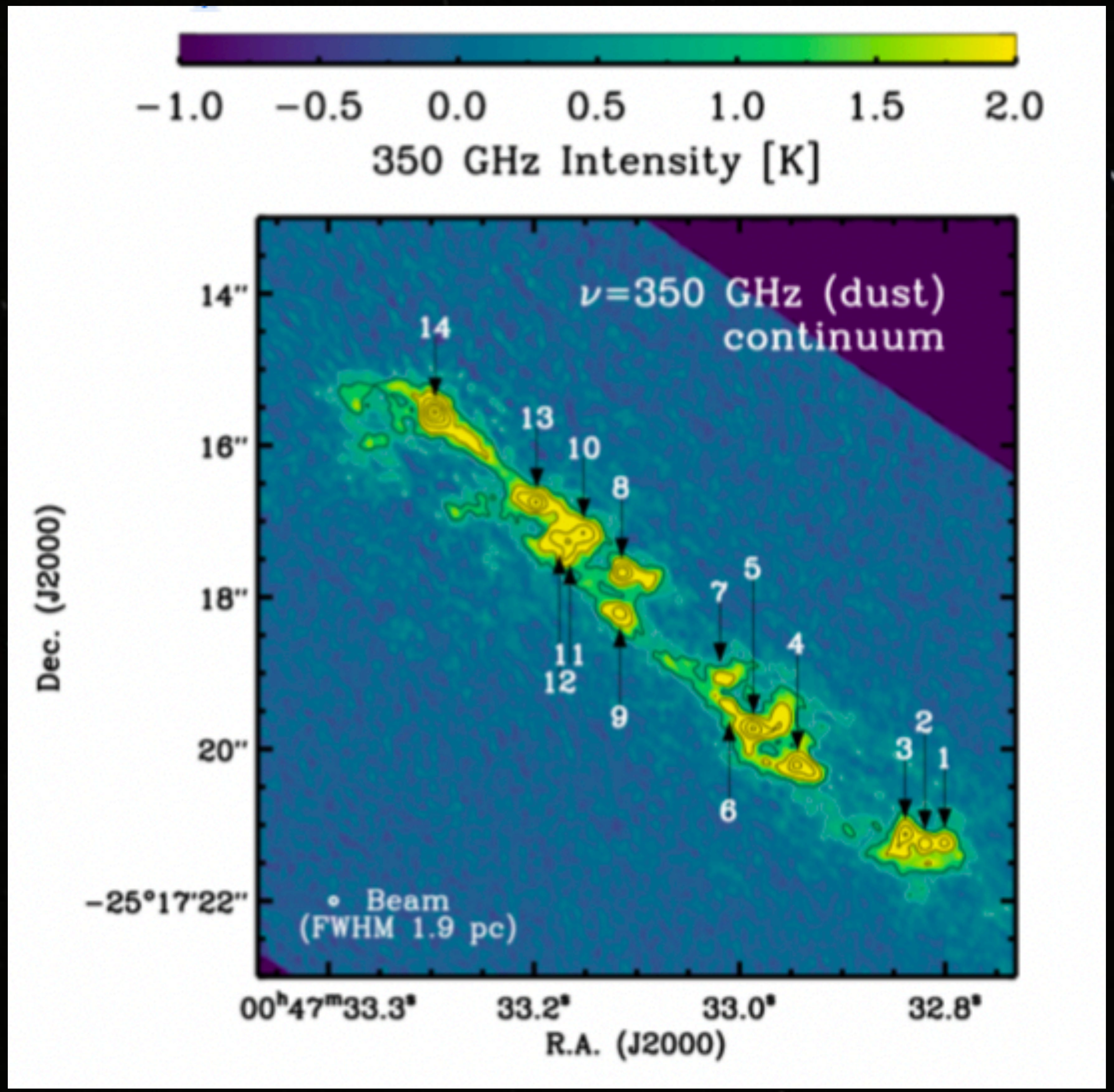


Energy Level Diagram

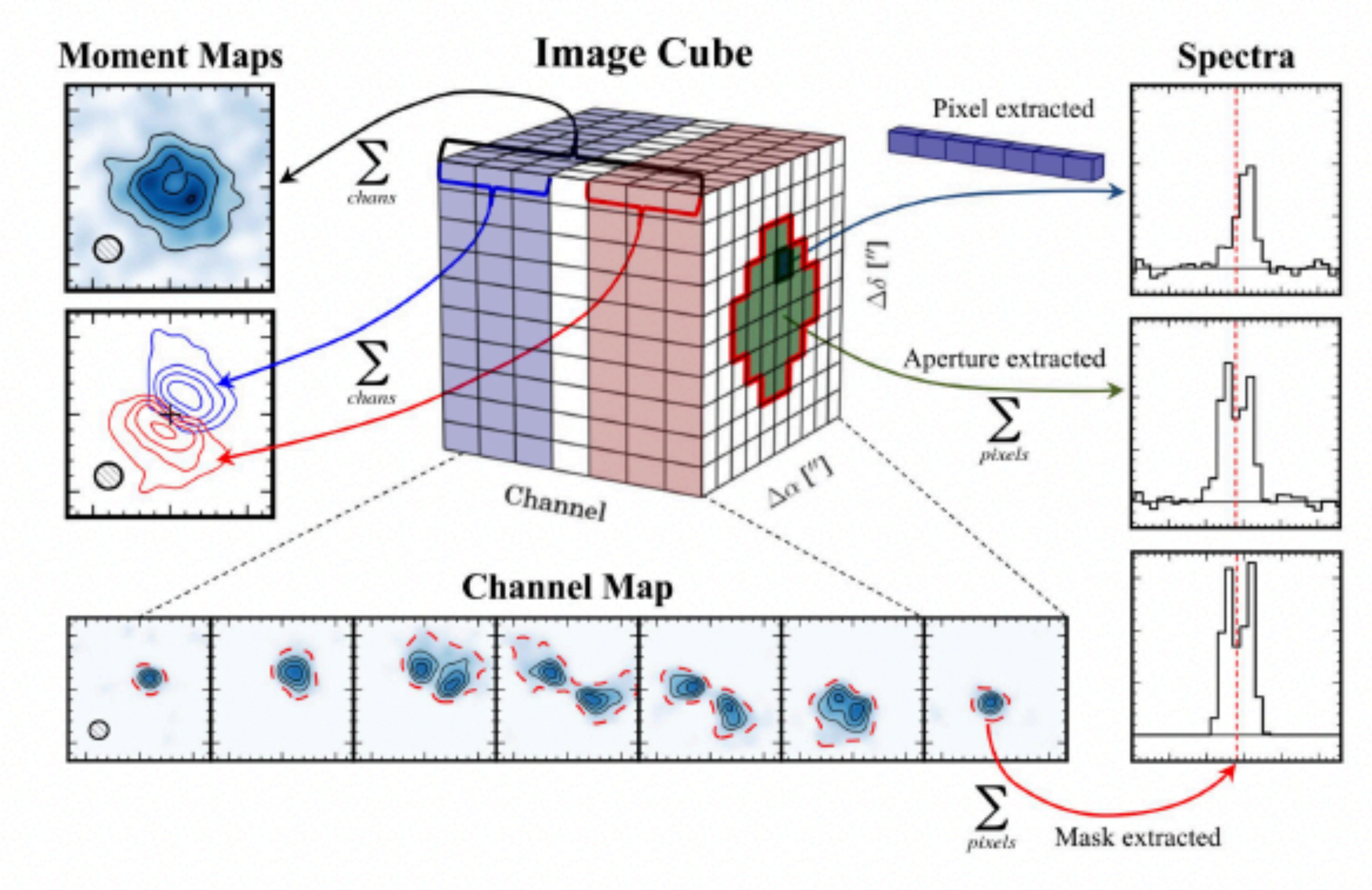




Carnegie Institution of Washington

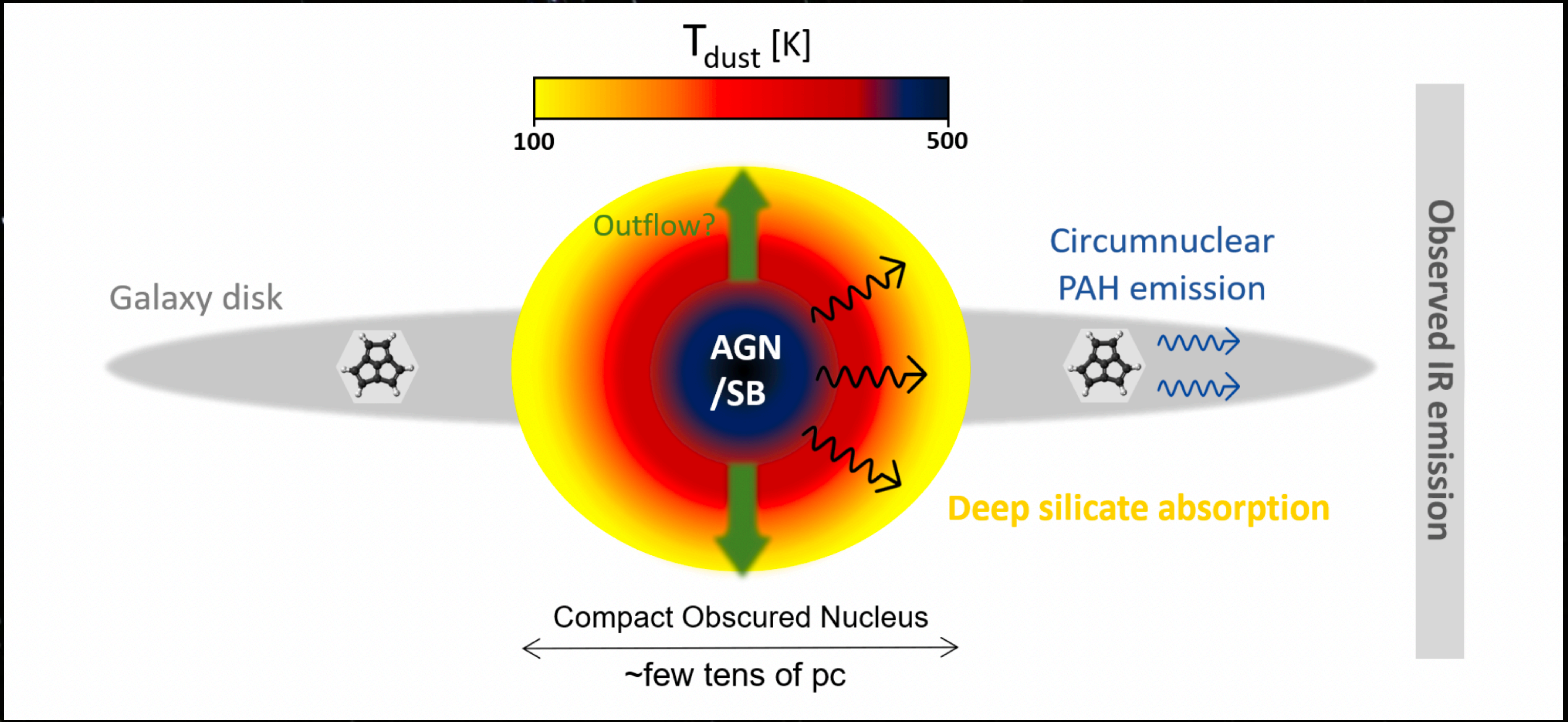


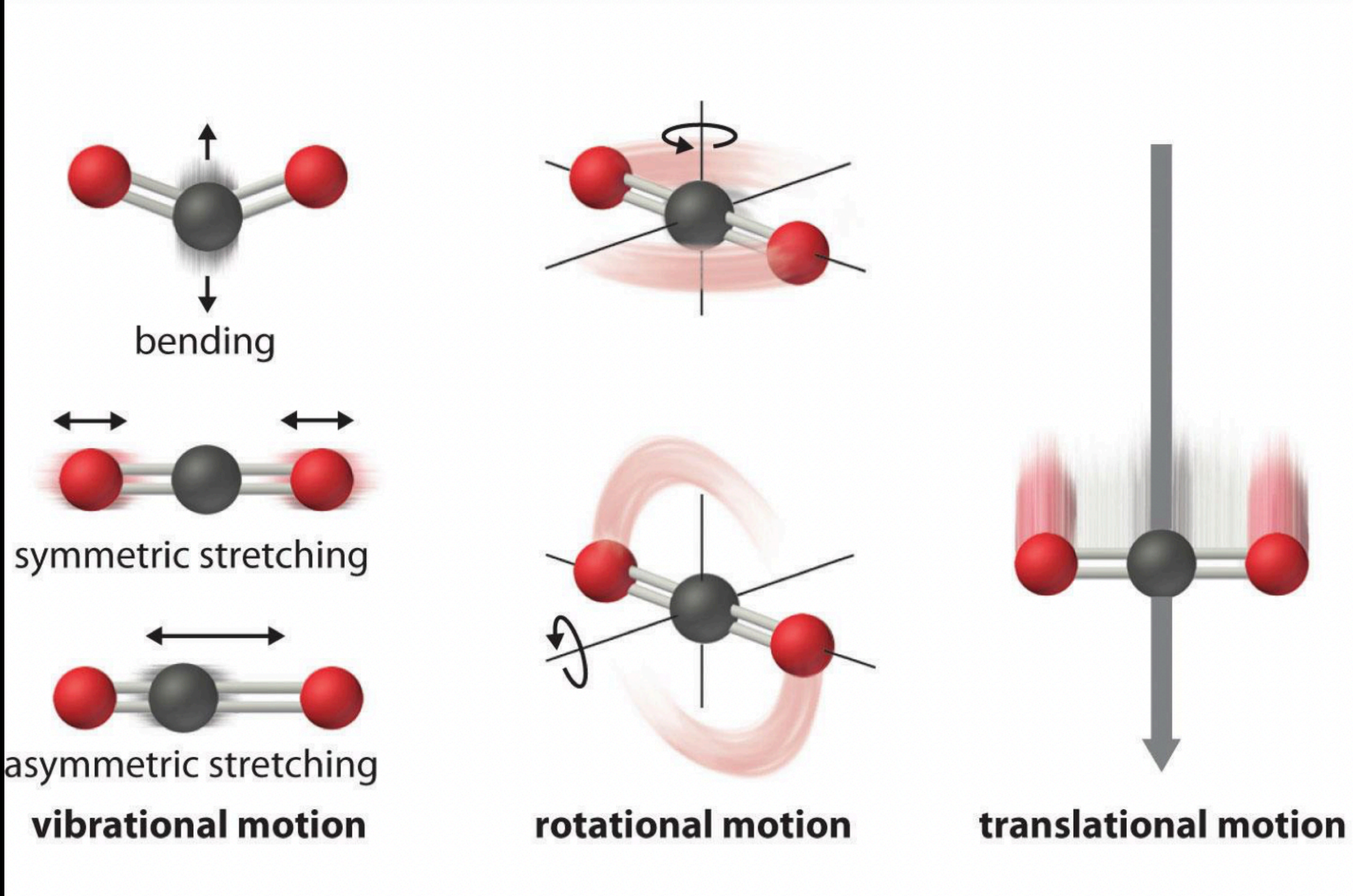
Anatomy of a Datacube



A Glimpse into the Obscured

Compact Obscured Nuclei




bending
symmetric stretching
asymmetric stretching
vibrational motion
rotational motion
translational motion

Broader Connections

An analog to star formation in the past

- The extreme star formation found in these SSCs is rare today, but that wasn't always the case.
- This is much more common of the epoch of star formation in our Universe's history called Cosmic Noon which was a period of massive star formation.
-