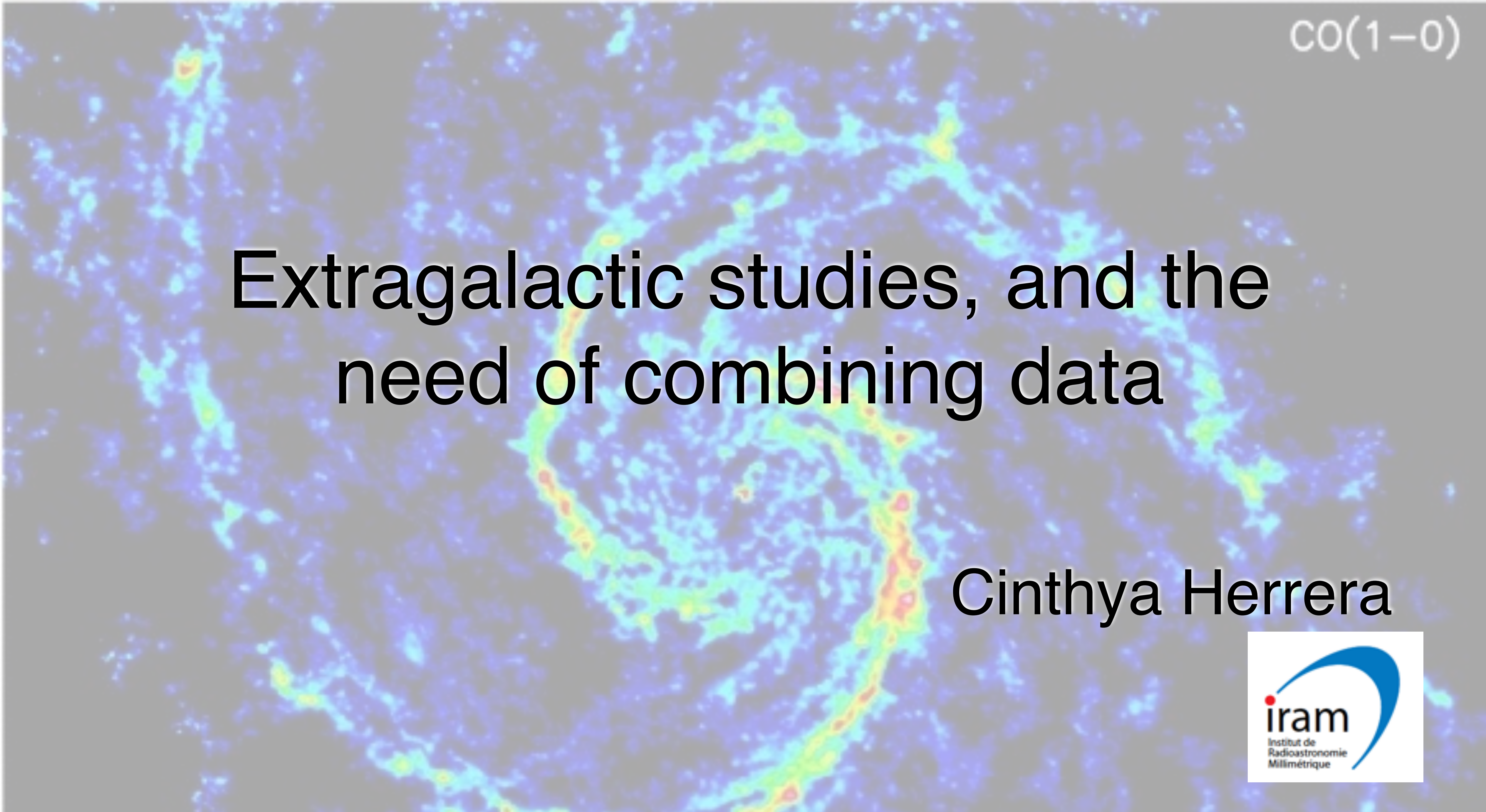
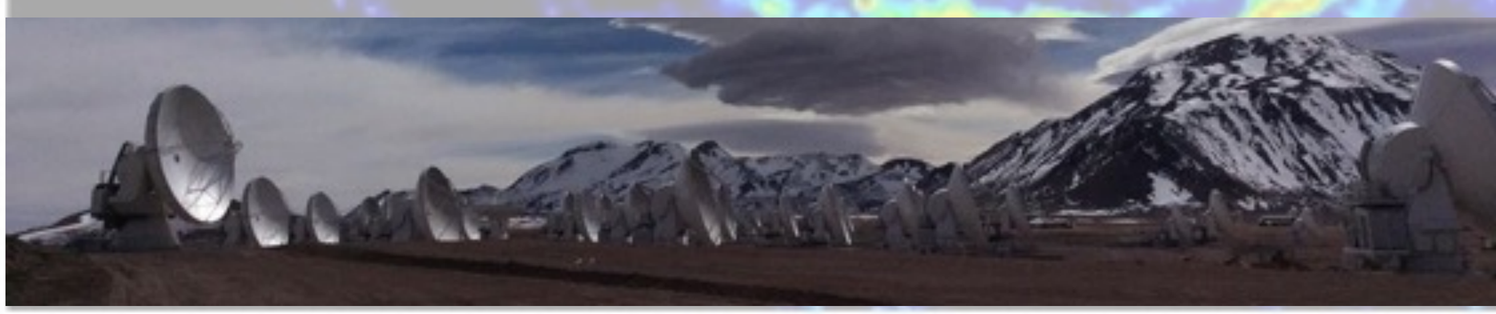


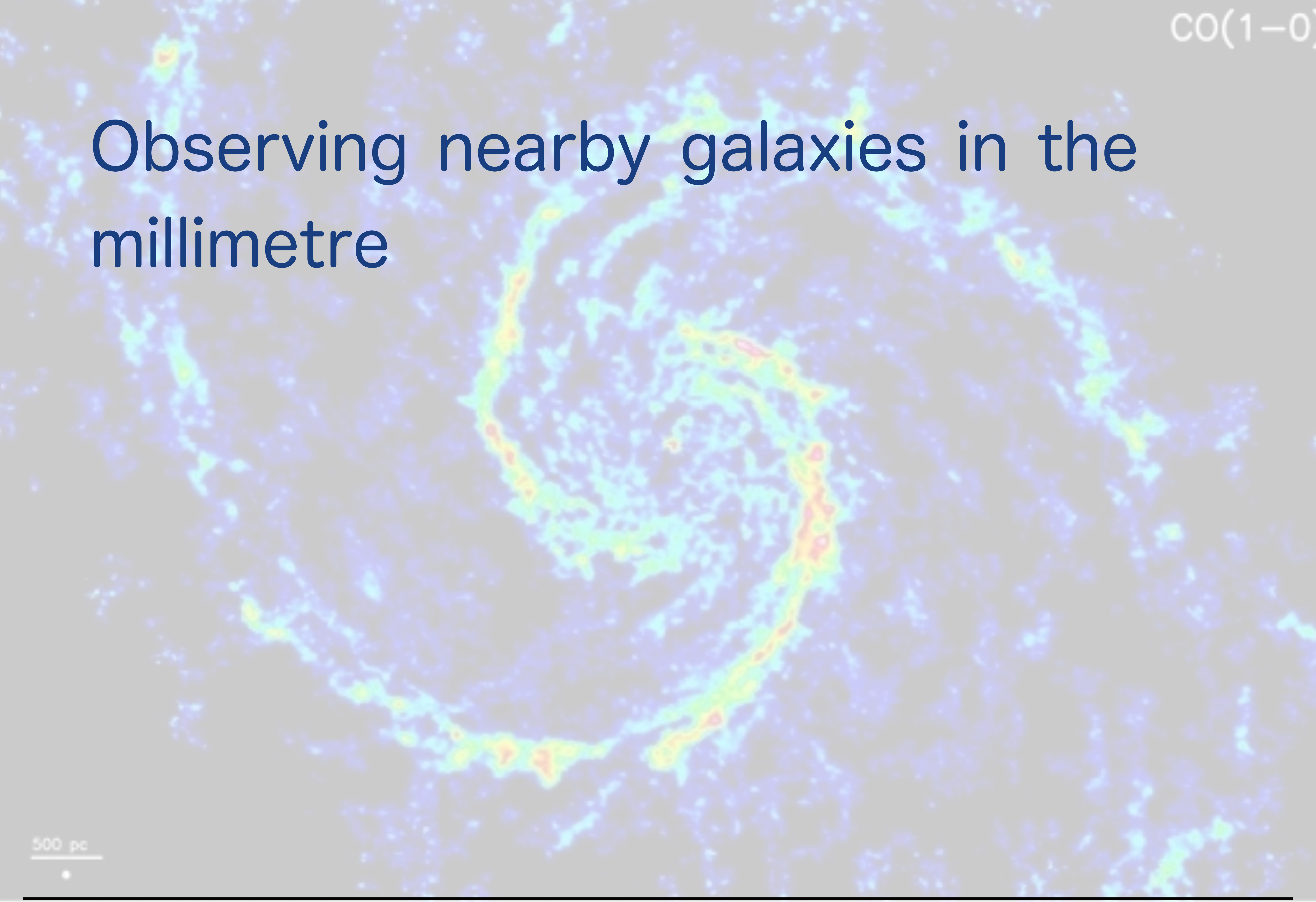
Extragalactic studies, and the need of combining data

Cinthya Herrera



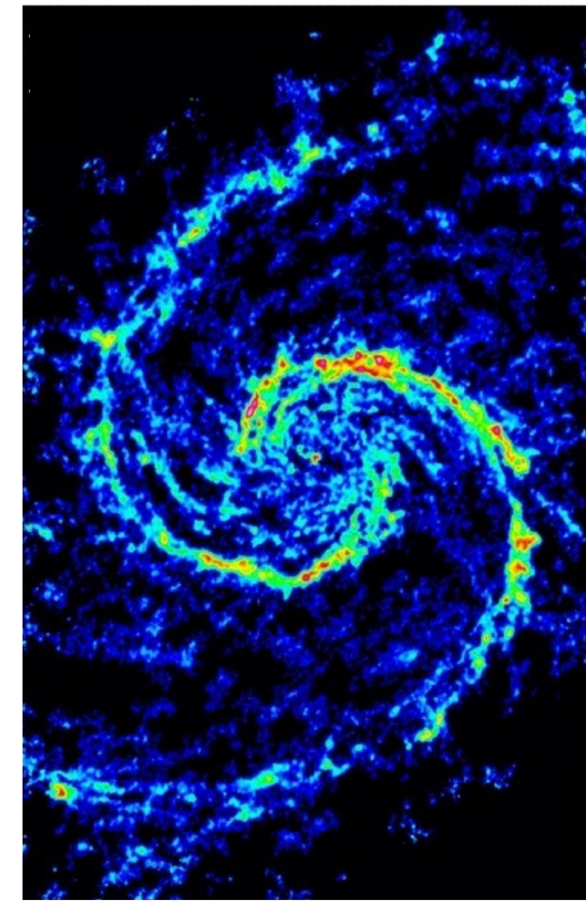
Improving Image Fidelity on Astronomical Data: Radio Interferometer and Single-Dish Data Combination
Leiden, August 12-16 2019

Observing nearby galaxies in the millimetre



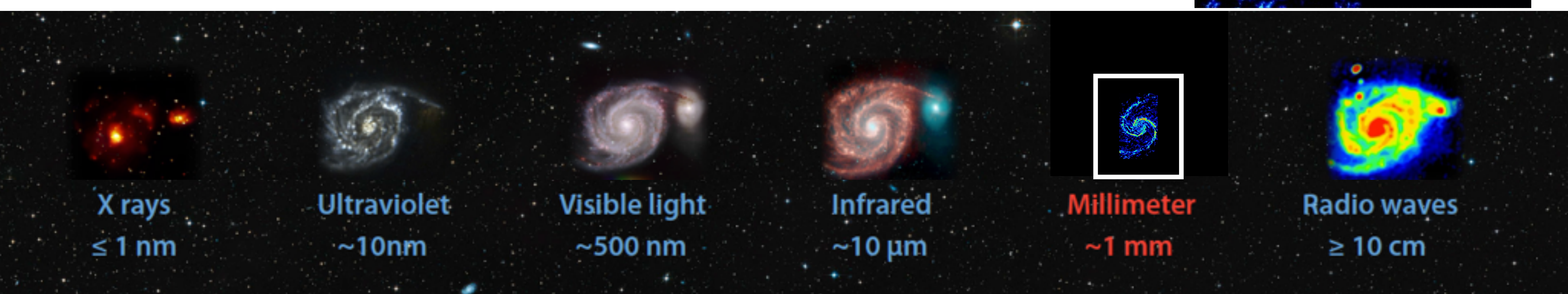
Observing nearby galaxies in the (sub)mm

Star formation occurs in molecular clouds, which are cold phases in the interstellar medium.



Millimetric telescopes are perfect tools for the **observation of the coldest regions in galaxies**, through the emission of molecular lines.

Detailed physics regulating star formation across nearby galaxies.



Observing nearby galaxies in the (sub)mm

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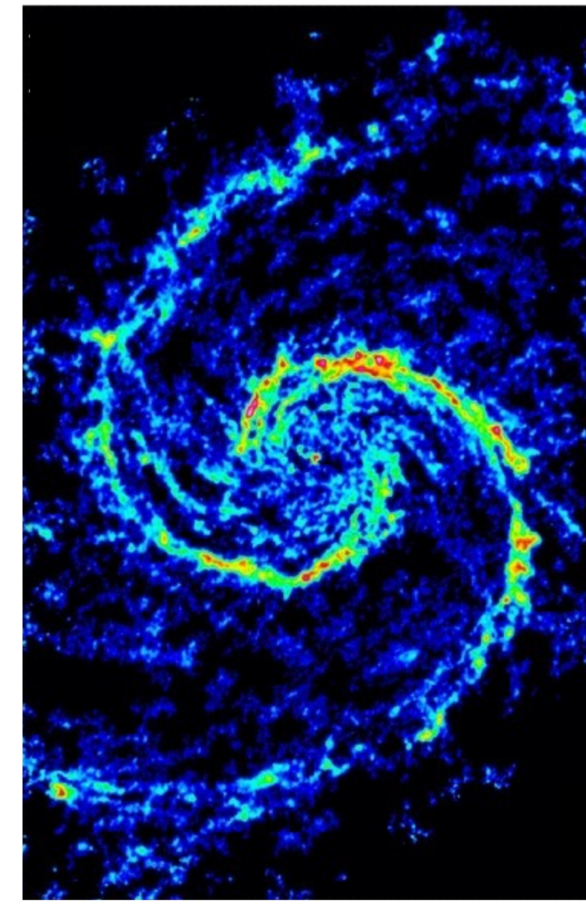

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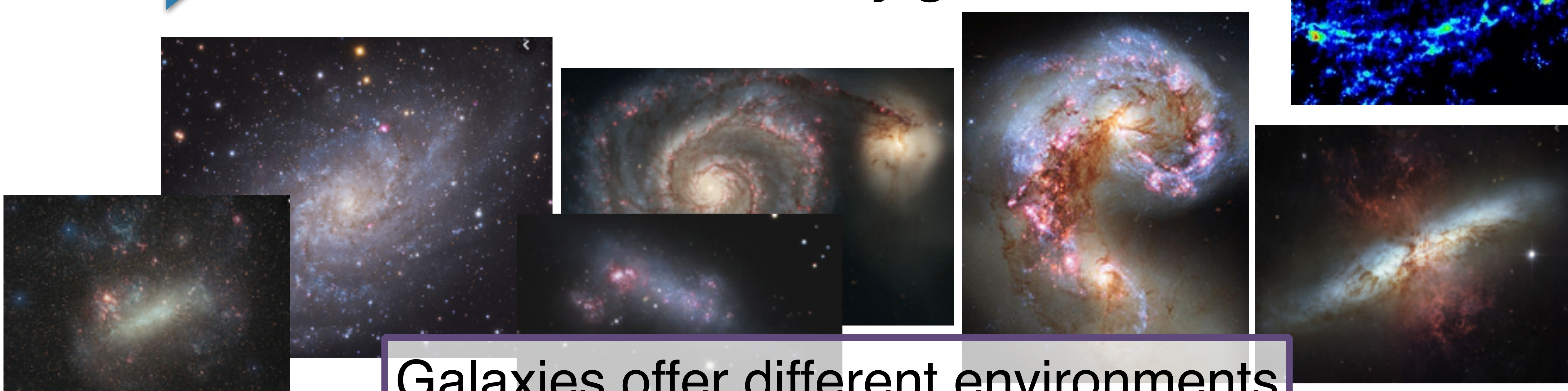


Galaxies offer different environments

Observing nearby galaxies in the (sub)mm

Studying the physics of the gas in galaxies.

<u>Cold gas</u>: main tracer of processes in galaxy evolution.

- **Gas properties close to black hole** (mass accretion, star formation, AGN). The mechanisms for jets and outflows.
- The **role of AGNs** in galaxy evolution?
- Is CO the **best tracer** of the gas in galaxies? Dependence on environment (metallicity, density, radiation field)
- **Star formation** in molecular clouds (SFR, lifetime of clouds, survival, dependence on environment).
- **Extragalactic vs Galactic** star formation and feedback processes?

Observing nearby galaxies in the (sub)mm

Studying the physics of the gas in galaxies.

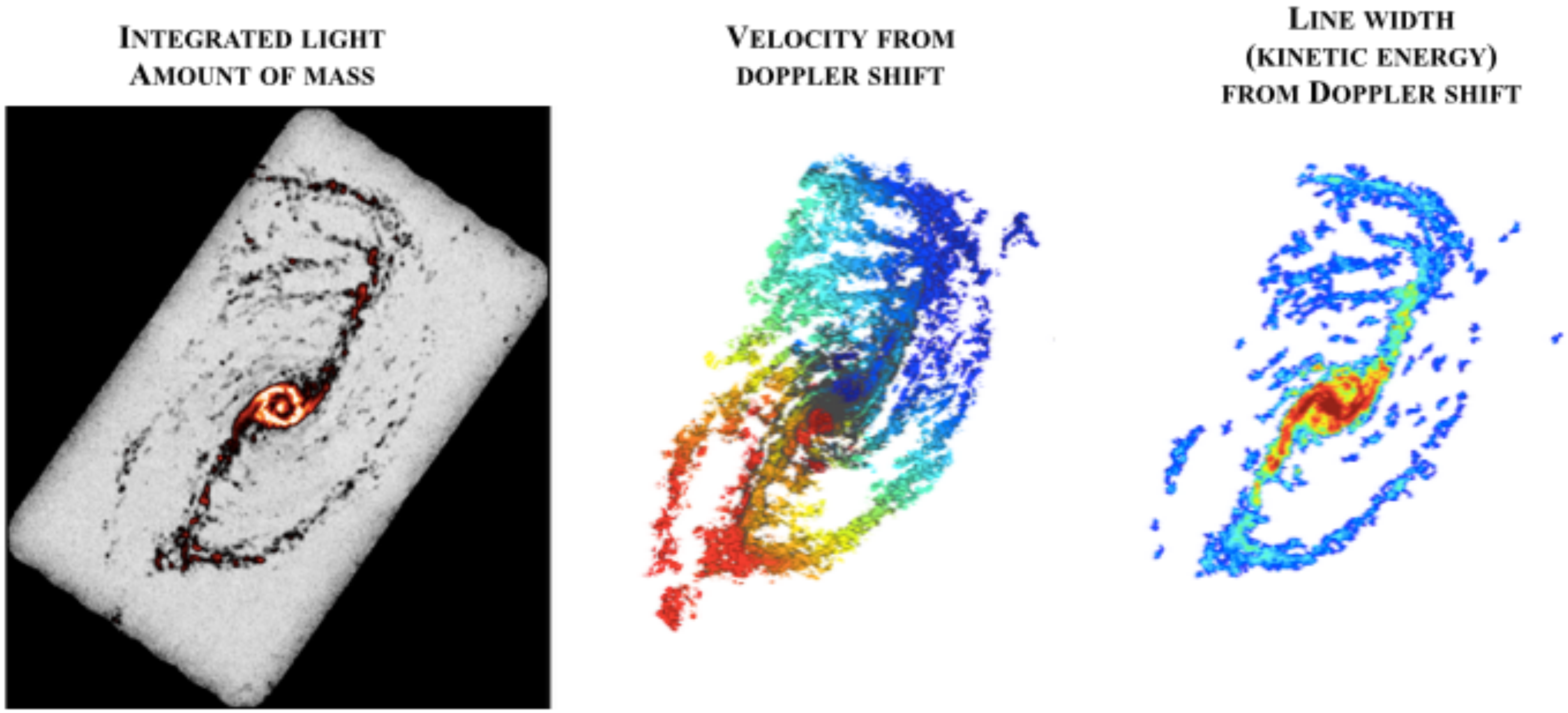
Cold gas: main tracer of processes in galaxy evolution.

- **Gas properties close to black hole** (mass accretion, star formation, AGN). The mechanisms for jets and outflows.
- The
- Is C vironment (me
- **Sta** rvival, dependence on environment).
- **Extragalactic vs Galactic** star formation and feedback processes?

Studying nearby galaxies is key to understand the different processes in the formation and evolution of galaxies in the Universe.

Observing nearby galaxies in the (sub)mm

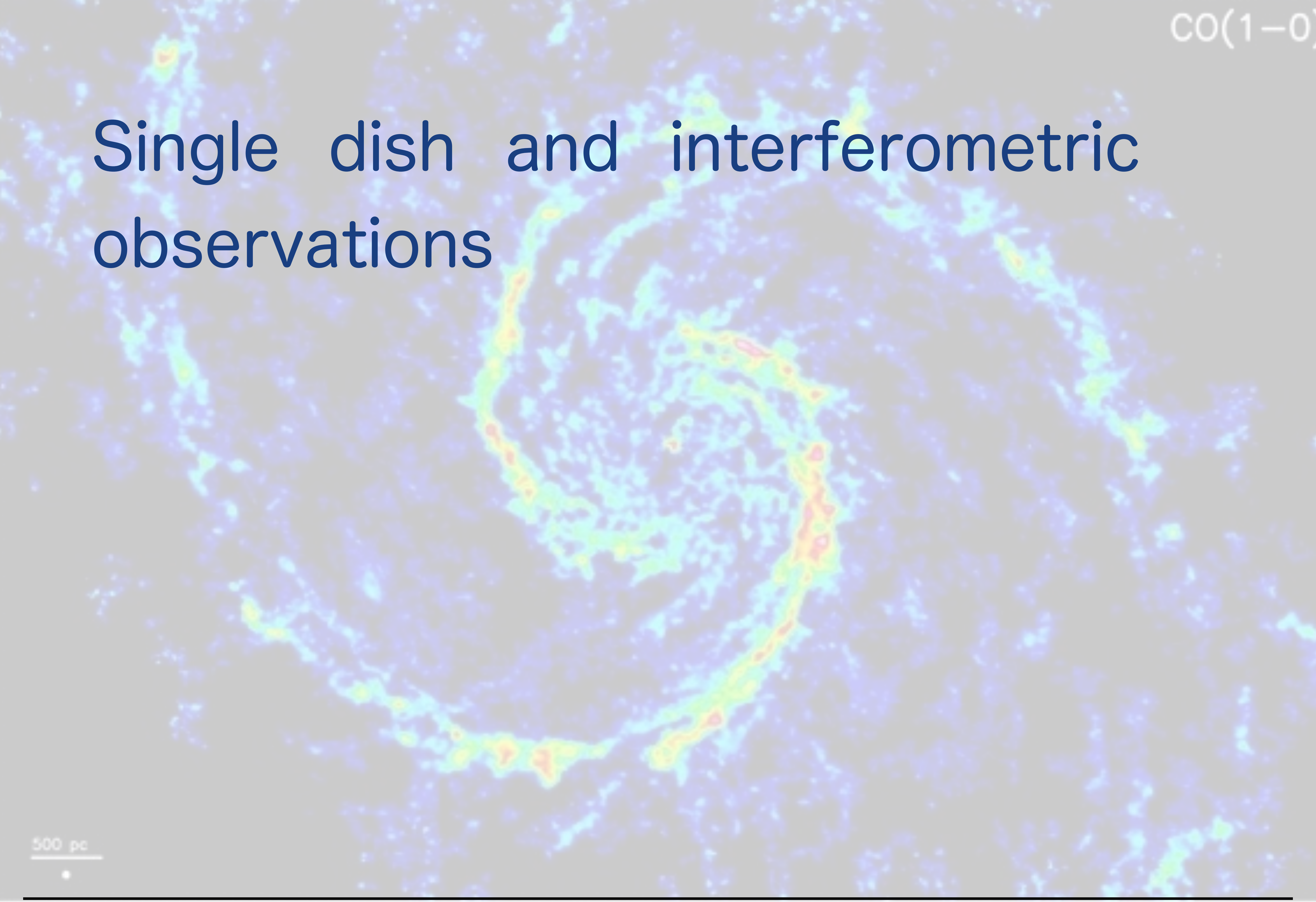
The ^{12}CO molecule second most abundant molecule in the Universe.
Physical conditions in the sites of star formation:
the distribution and mass of the gas, the motion of the gas (turbulence and bulk motion).



Leroy,..,Herrera et al. in prep

CO-TRACED DISTRIBUTION, BULK VELOCITY, AND LINE WIDTH FOR NGC 1097 FROM PHANGS-ALMA

Single dish and interferometric observations



SD and interferometric data

Single dish:

- One spectrum/pixel per pointing telescope
- Image resolution: primary beam size
  - ➡ Telescope resolution: ~λ/D

+ Recovery of **total flux**
+ On The Fly observation mode
- Beam dilution:
  No angular resolution to **resolve** the molecular gas content in nearby galaxies. Emission diluted in the beam.

SD and interferometric data

Interferometry:

- Several pixels per pointing telescope
- Field of View: primary beam size
- Image resolution: Synthesized beam

+ **High angular resolution**
+ Mosaicking
- Lost of short spacing: **total flux not recovered**. Also, negative lobes next to bright emission (i.e. spiral arms or nuclear regions)

SD and interferometric data

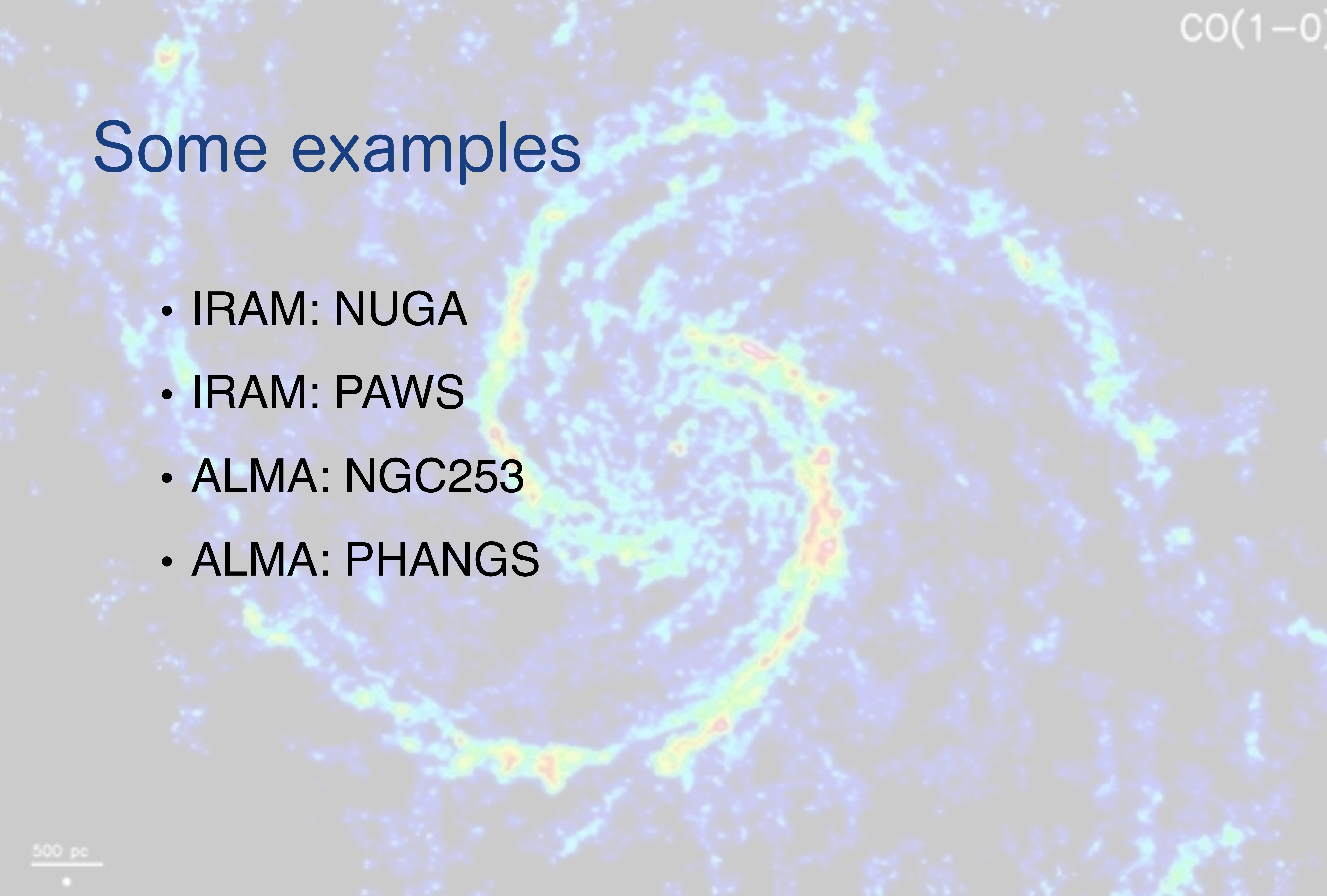
Resolving the molecular gas in nearby galaxies.

CO(2-1) @ 230.538 GHz line observed in different galaxies.

Galaxy distance	30-m **Ω=10.”7**	NOEMA A conf Ω=**0.”5**	ALMA ACA Ω=**5.5”**	ALMA C43-4 conf Ω=**0.”4**
1 Mpc	50 pc	2 pc	25 pc	2 pc
3 Mpc	160 pc	7 pc	80 pc	6 pc
20 Mpc	1 kpc	50 pc	530 pc	40 pc

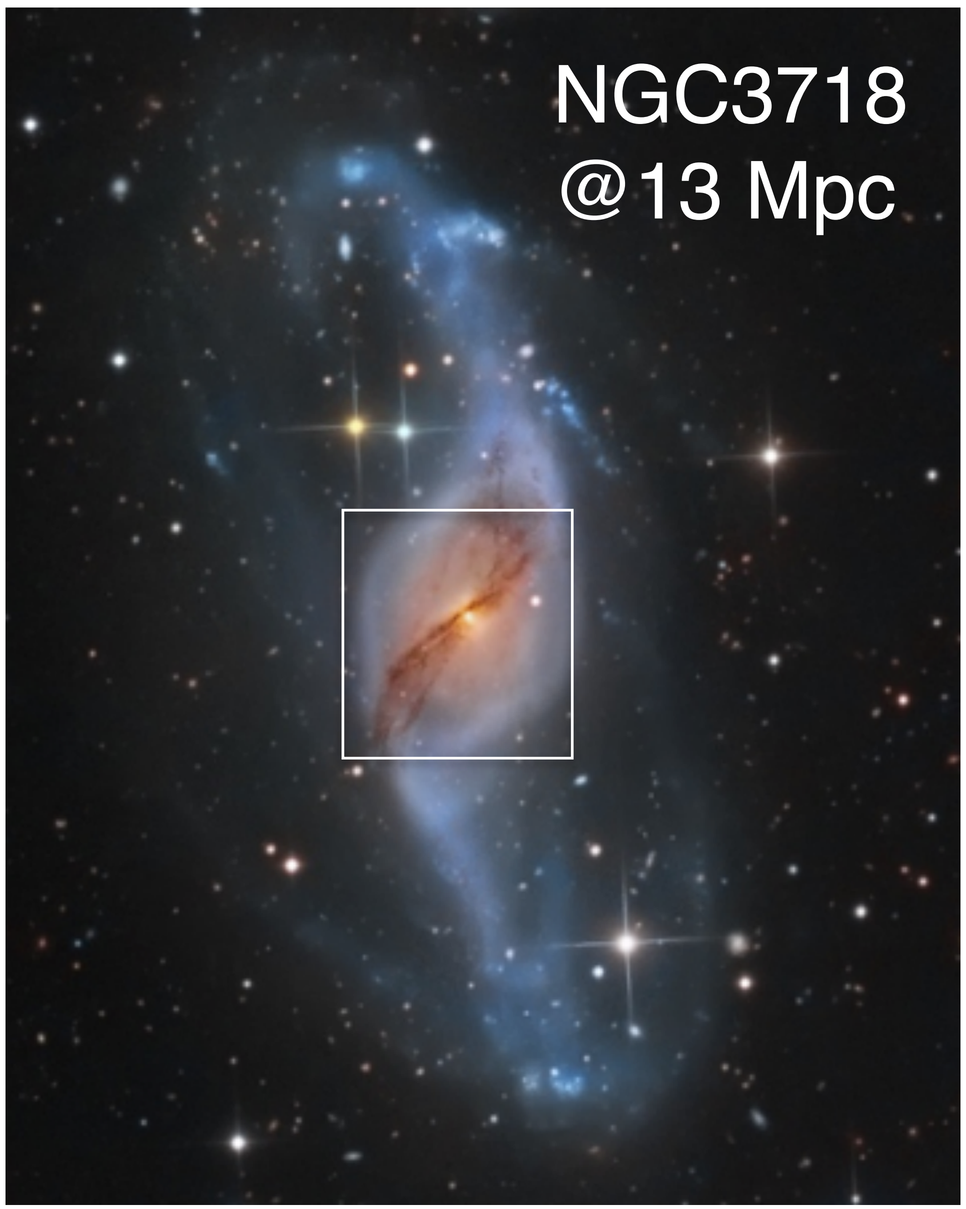
Some examples

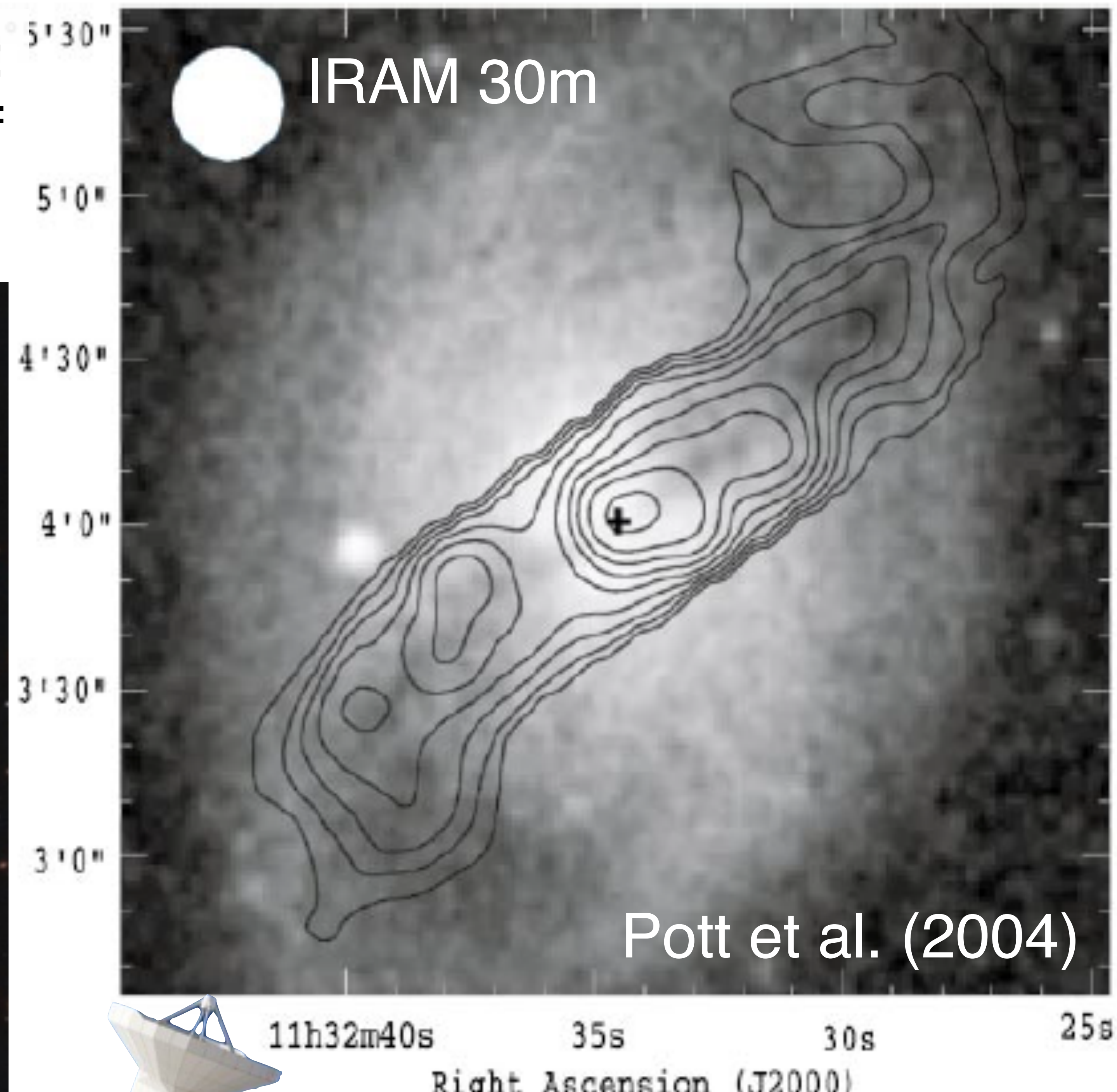
- IRAM: NUGA
- IRAM: PAWS
- ALMA: NGC253
- ALMA: PHANGS



NUGA

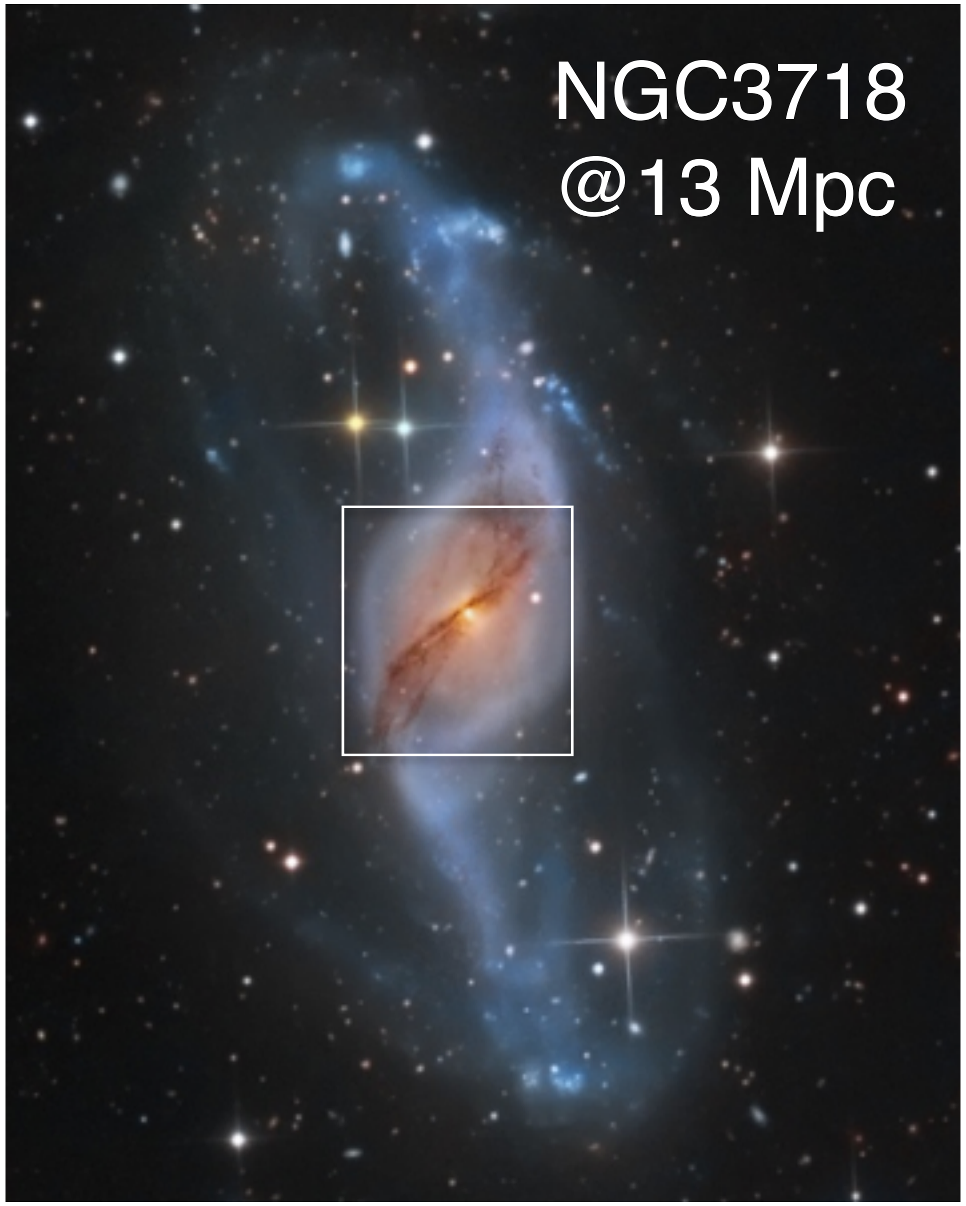
NUGA (NUclei of GAlaxies): investigate the processes of gas accretion onto AGNs.



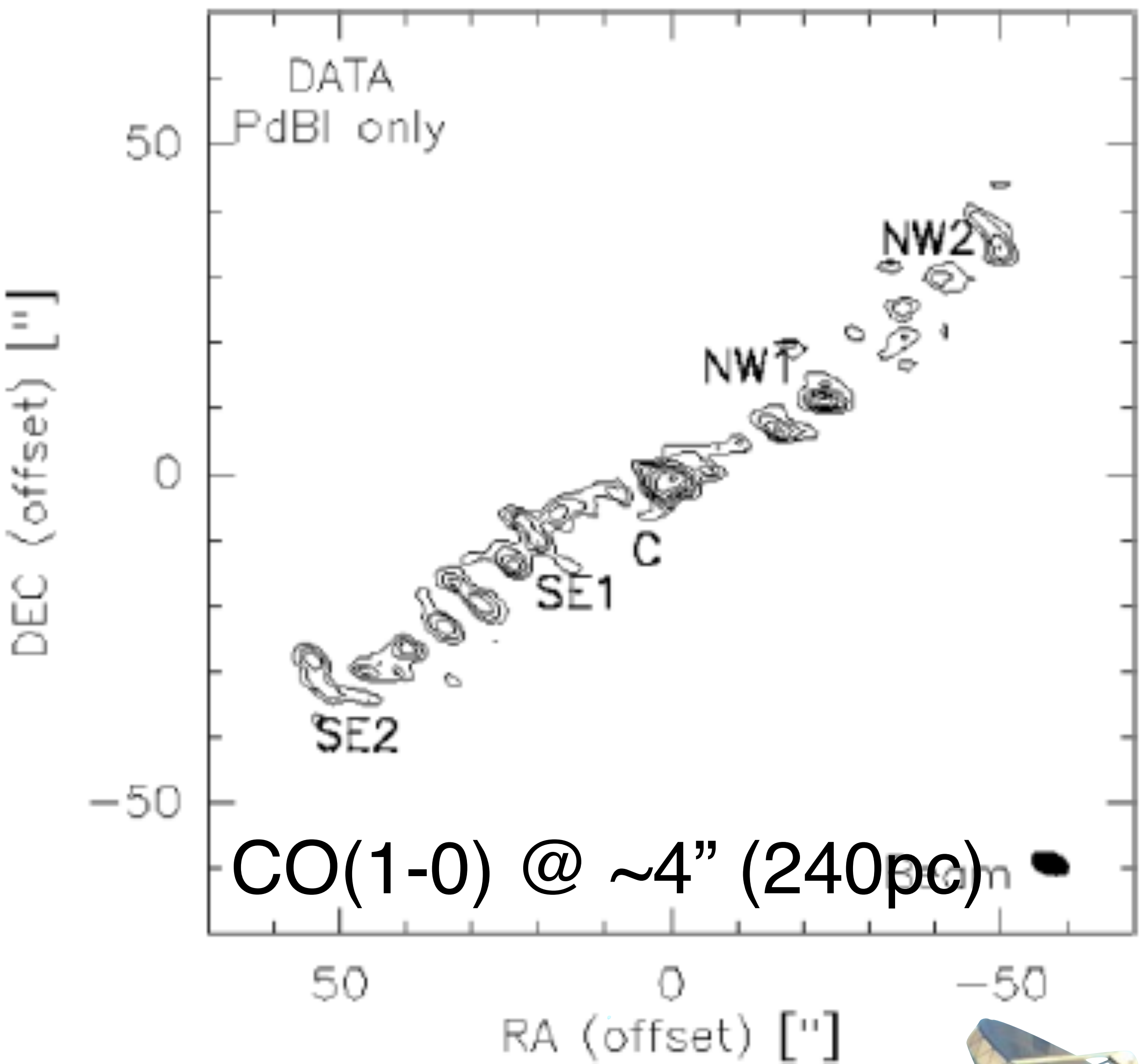


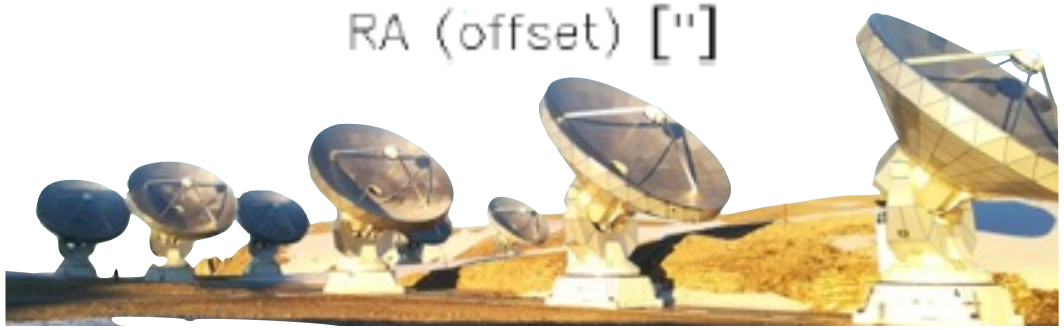
NUGA: SD + interferometric data

NUGA (NUclei of GAlaxies): investigate the processes of gas accretion onto AGNs.



Krips et al. (2005)





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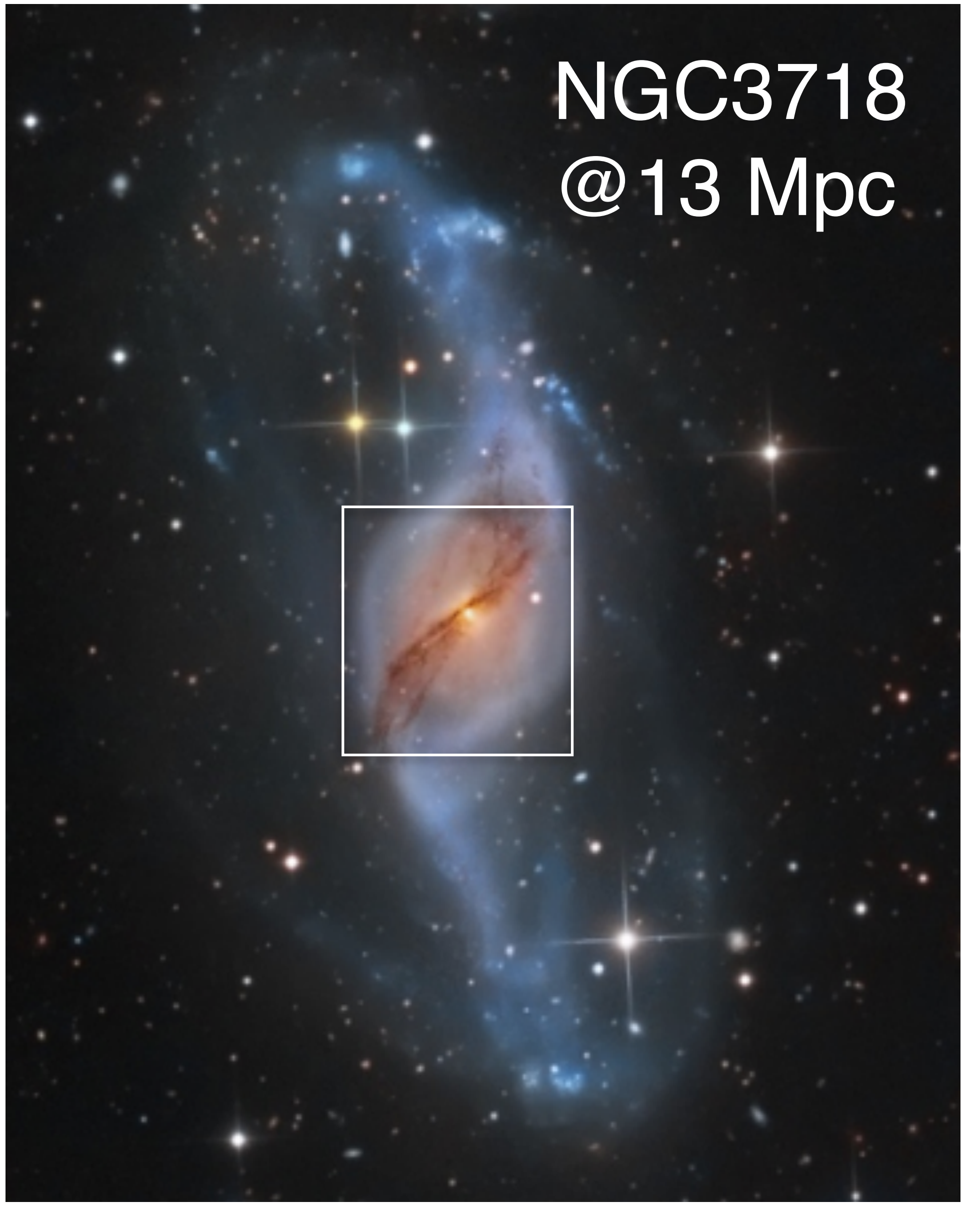

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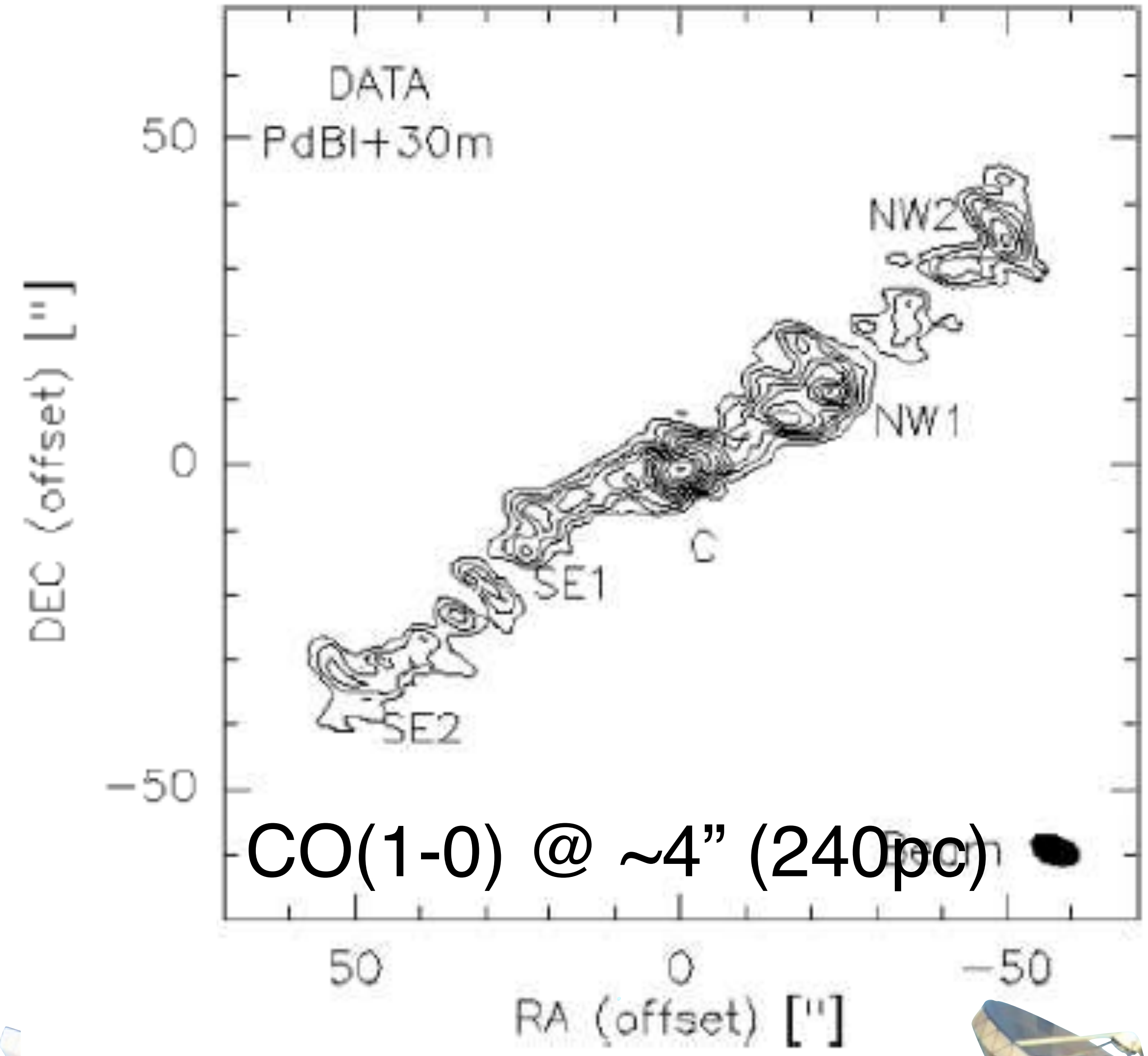
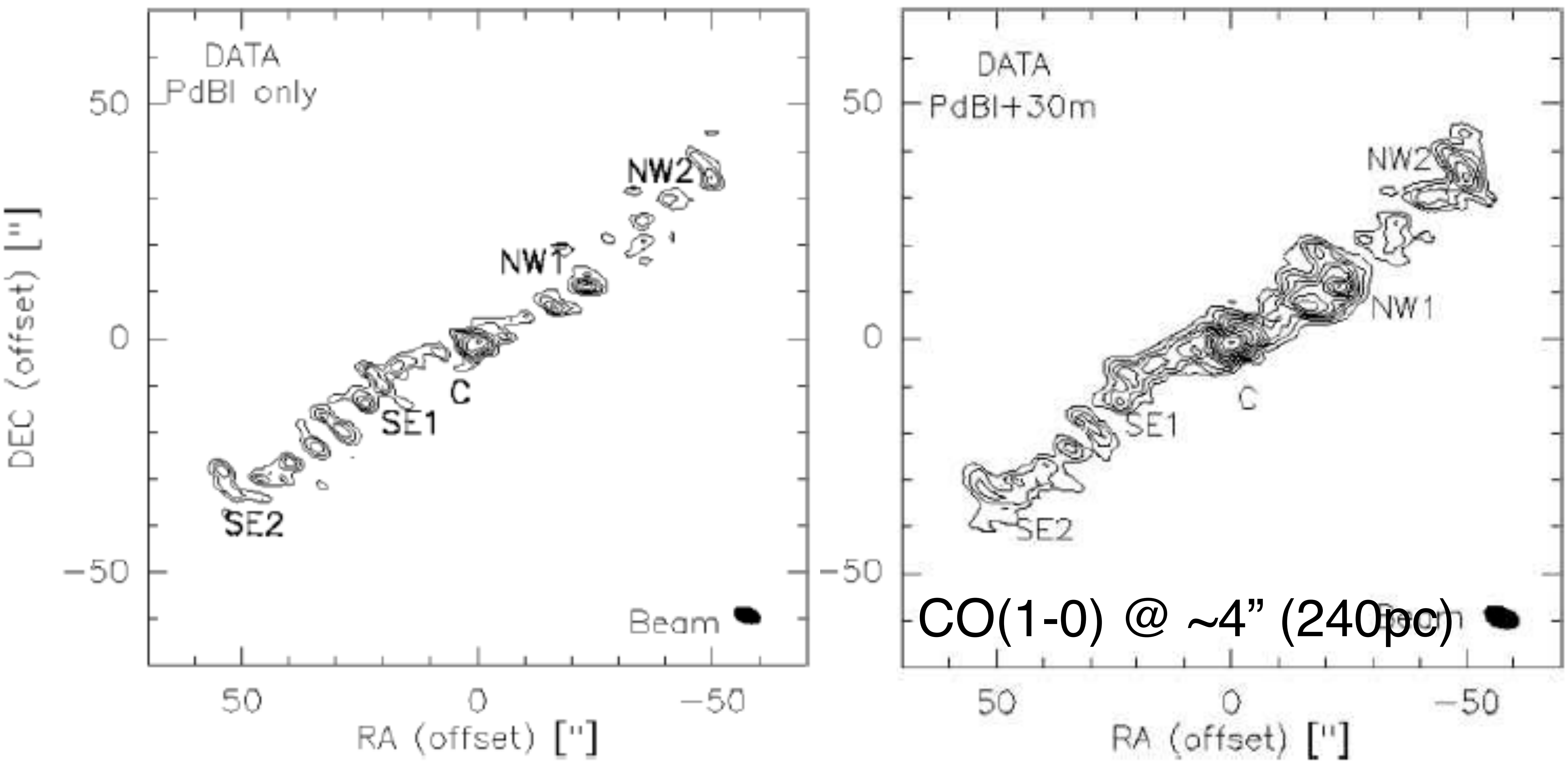


NUGA: SD + interferometric data

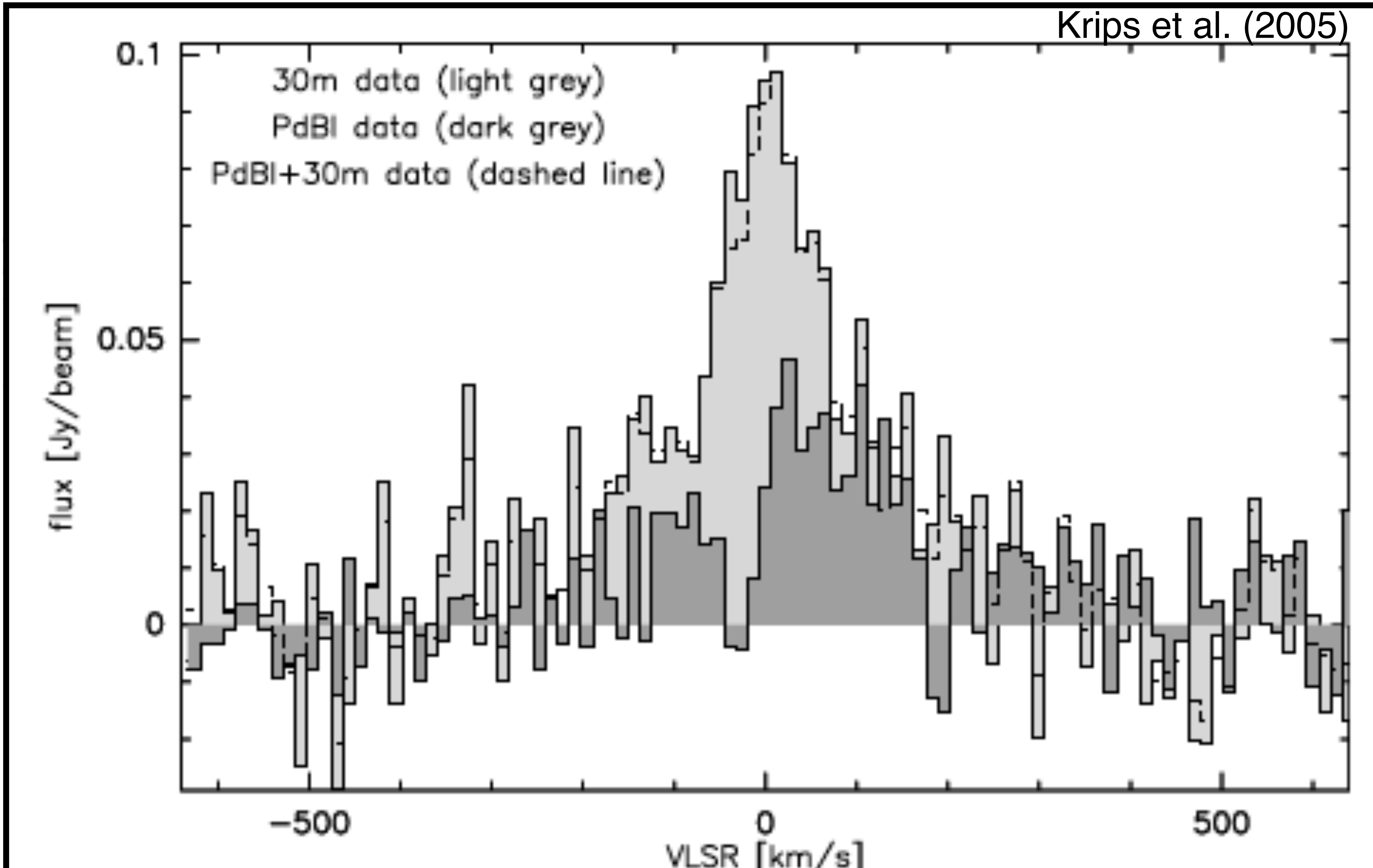
Krips et al. (2005)



CO(1-0) @ ~4” (240pc)

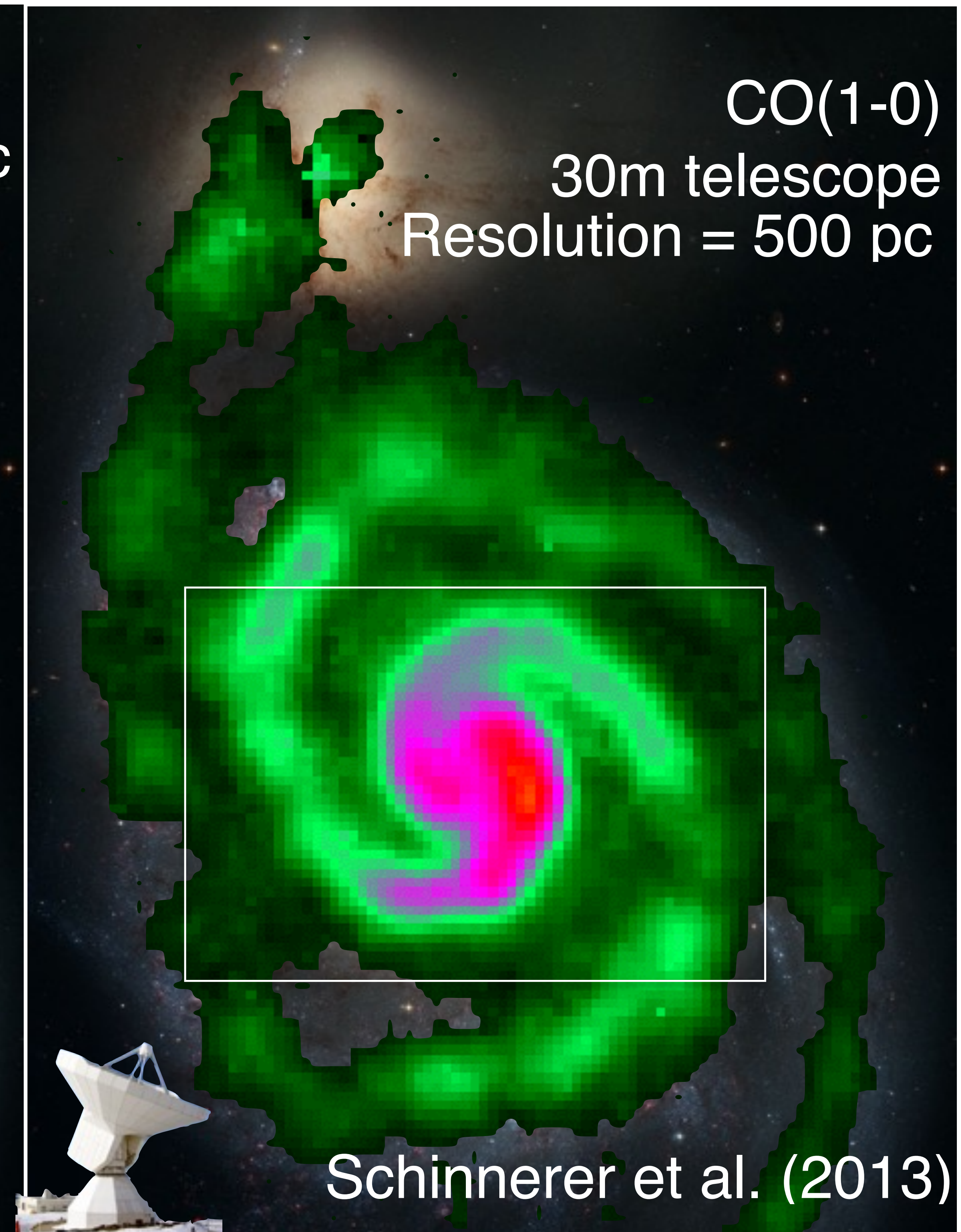
GILDAS/MAPPING

NUGA: SD + interferometric data



PAWS: SD + interferometric data

PAWS: PdBI Arcsecond Whirlpool Survey



PAWS: SD + interferometric data

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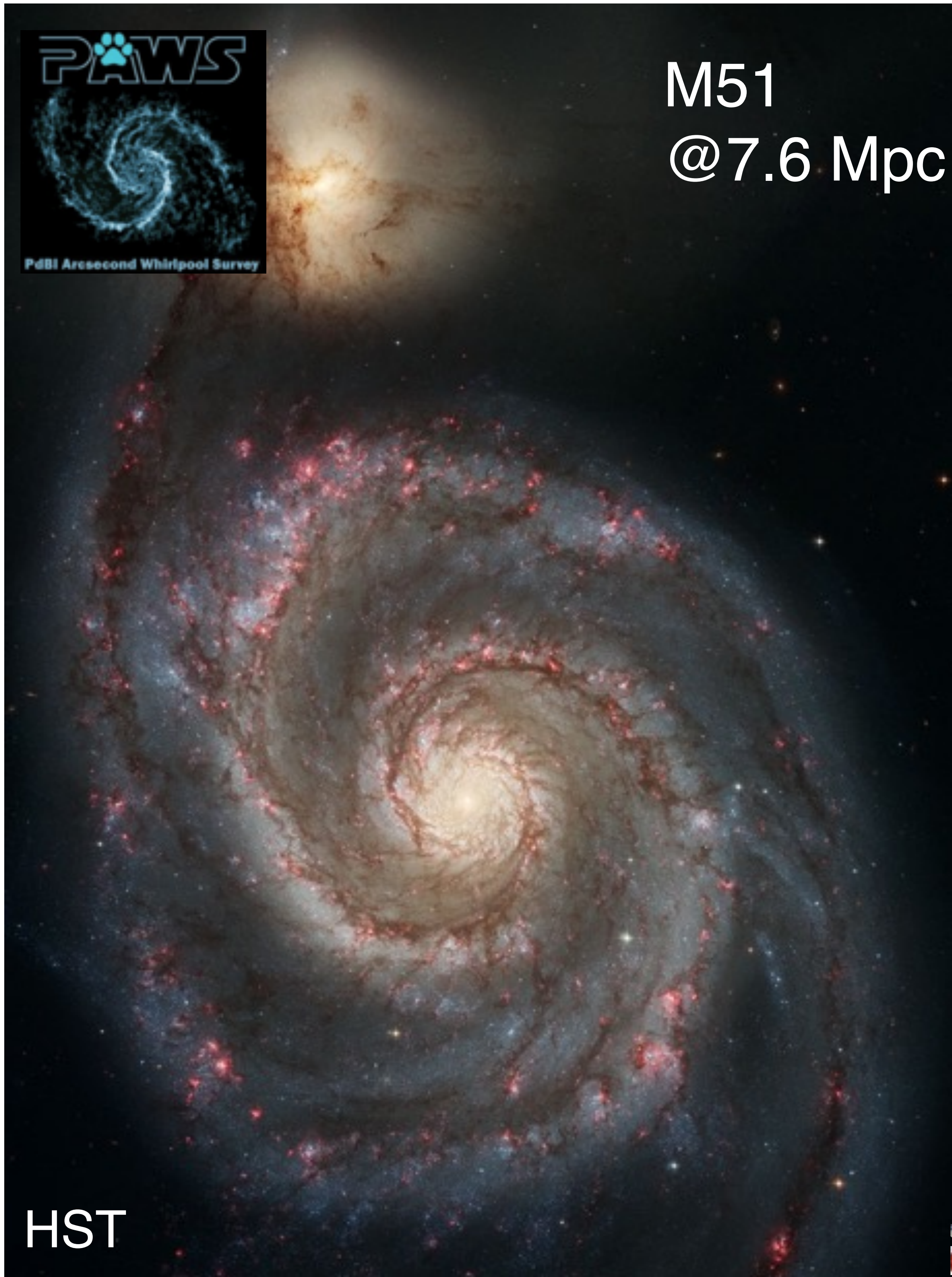
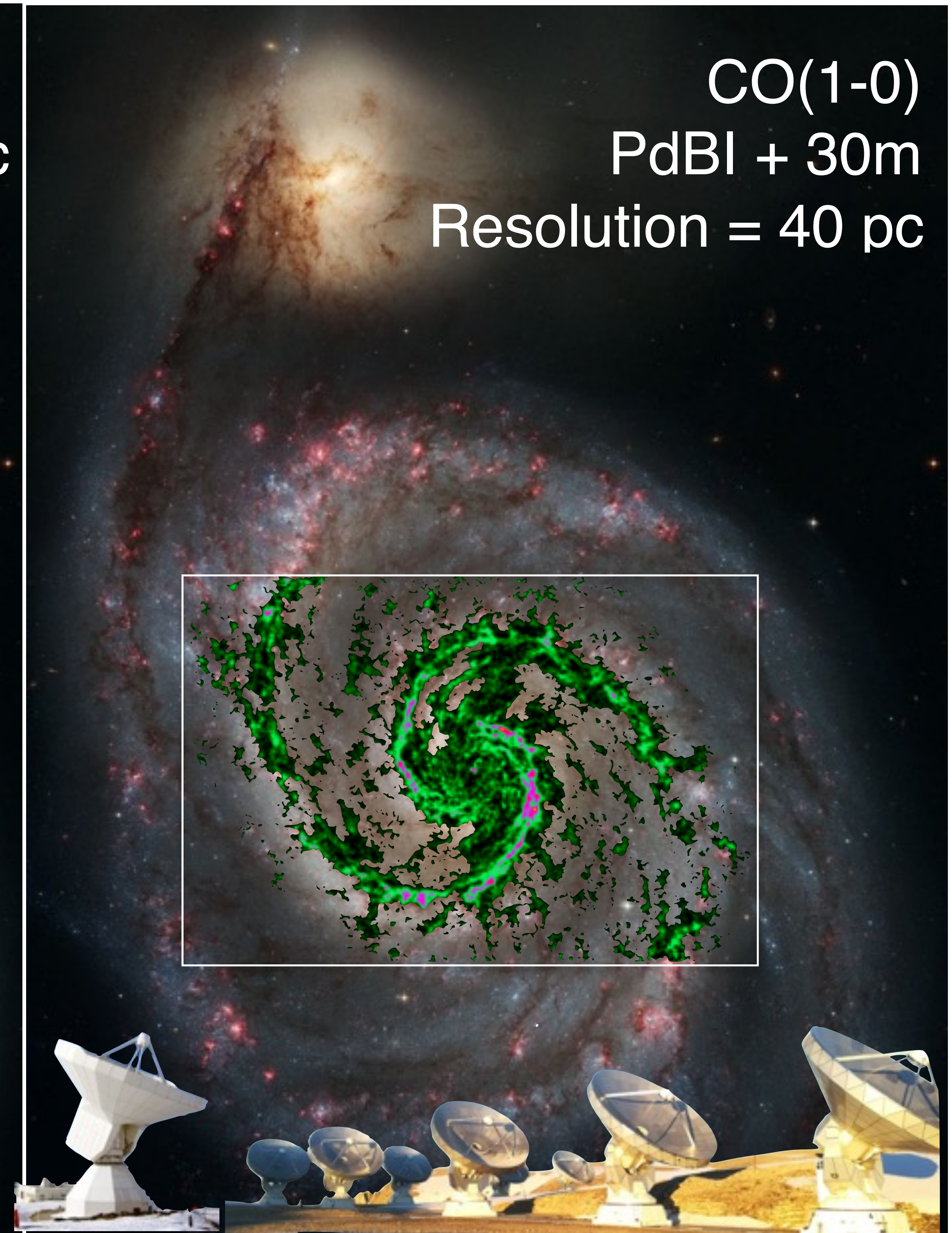
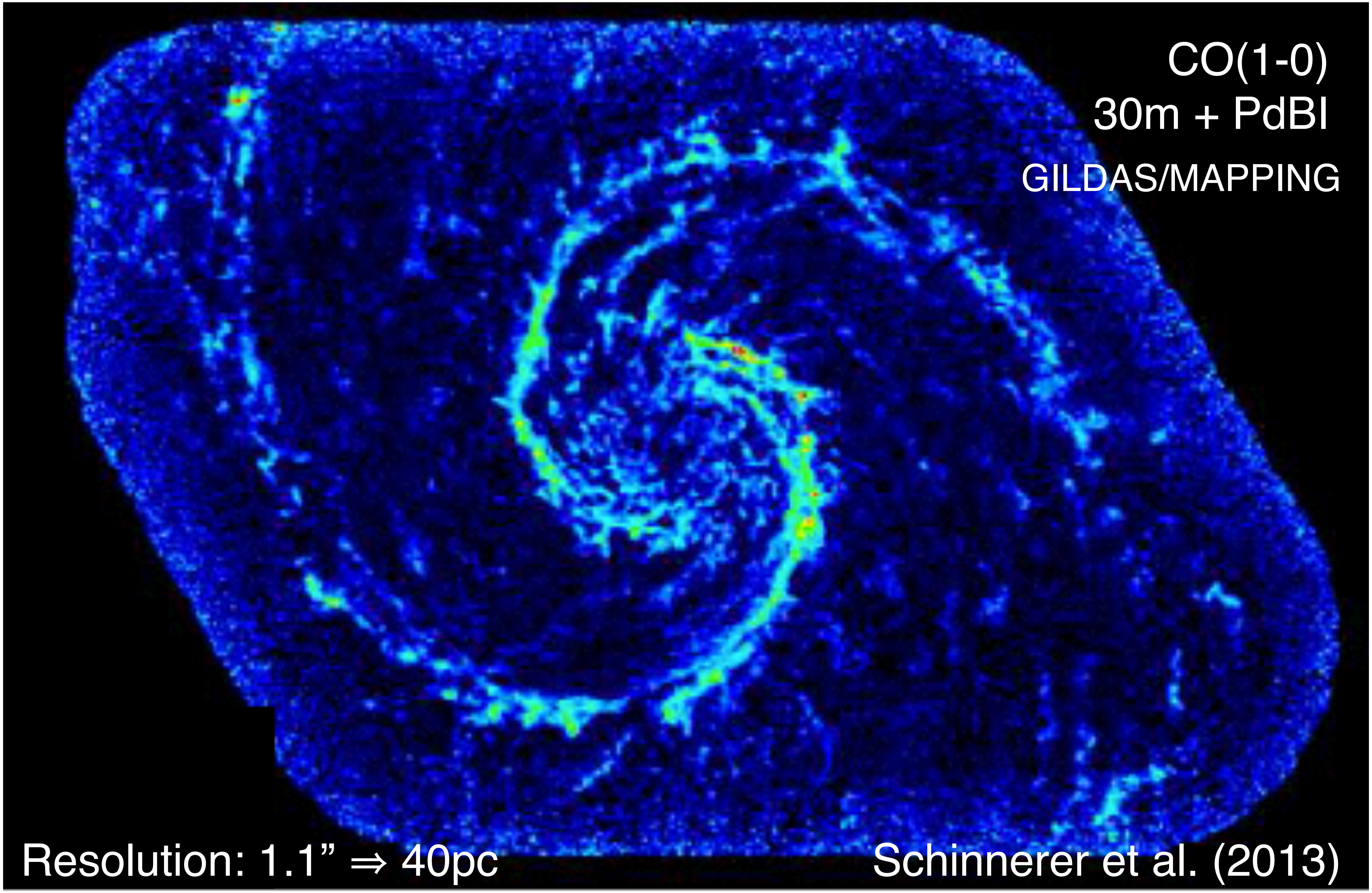
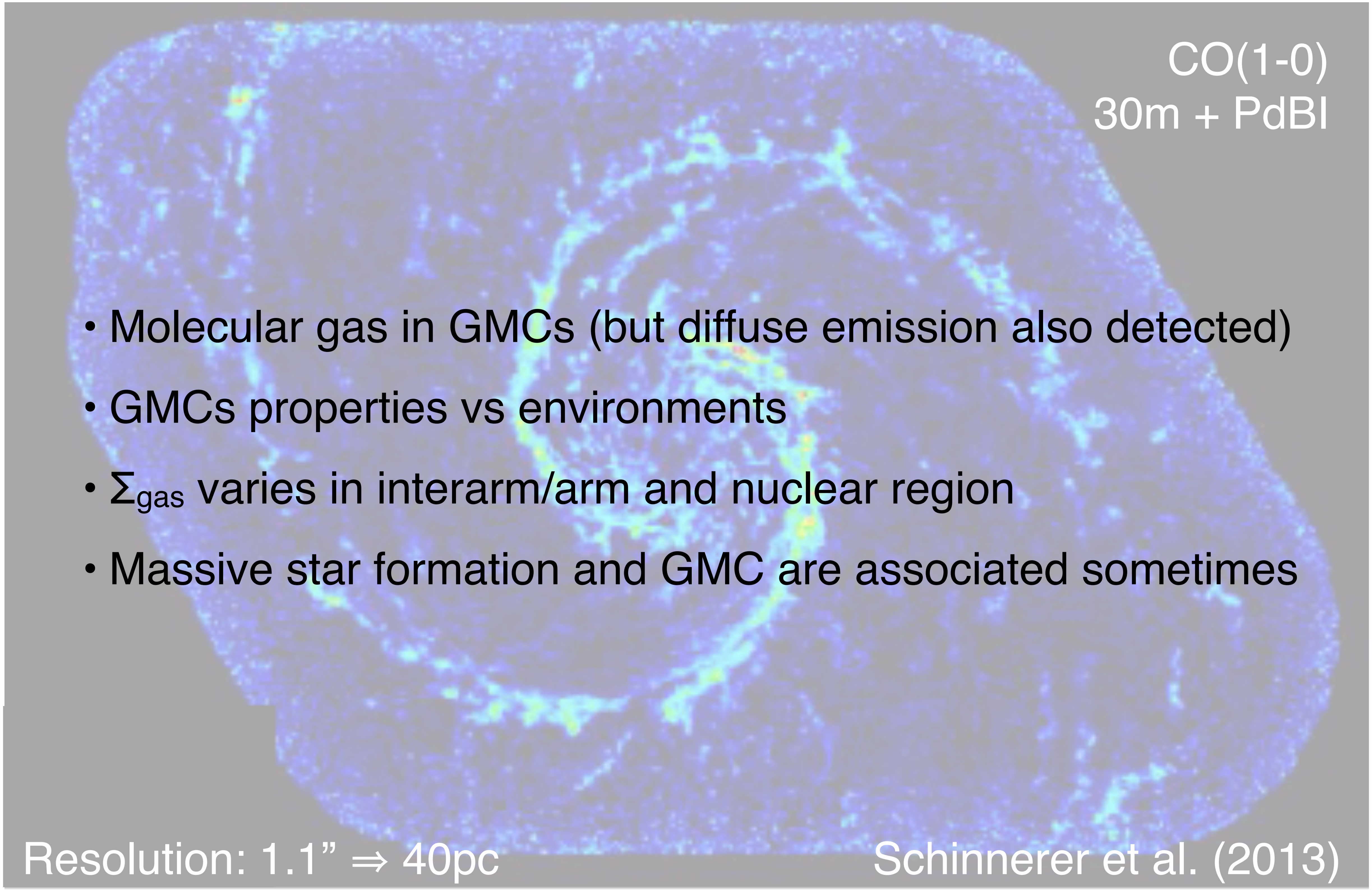




PAWS: SD + interferometric data



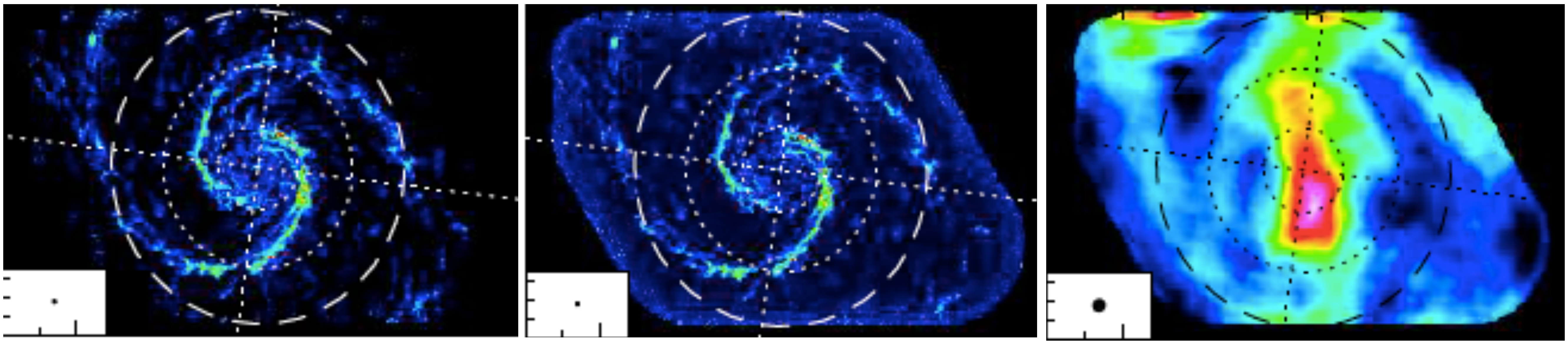
PAWS: SD + interferometric data

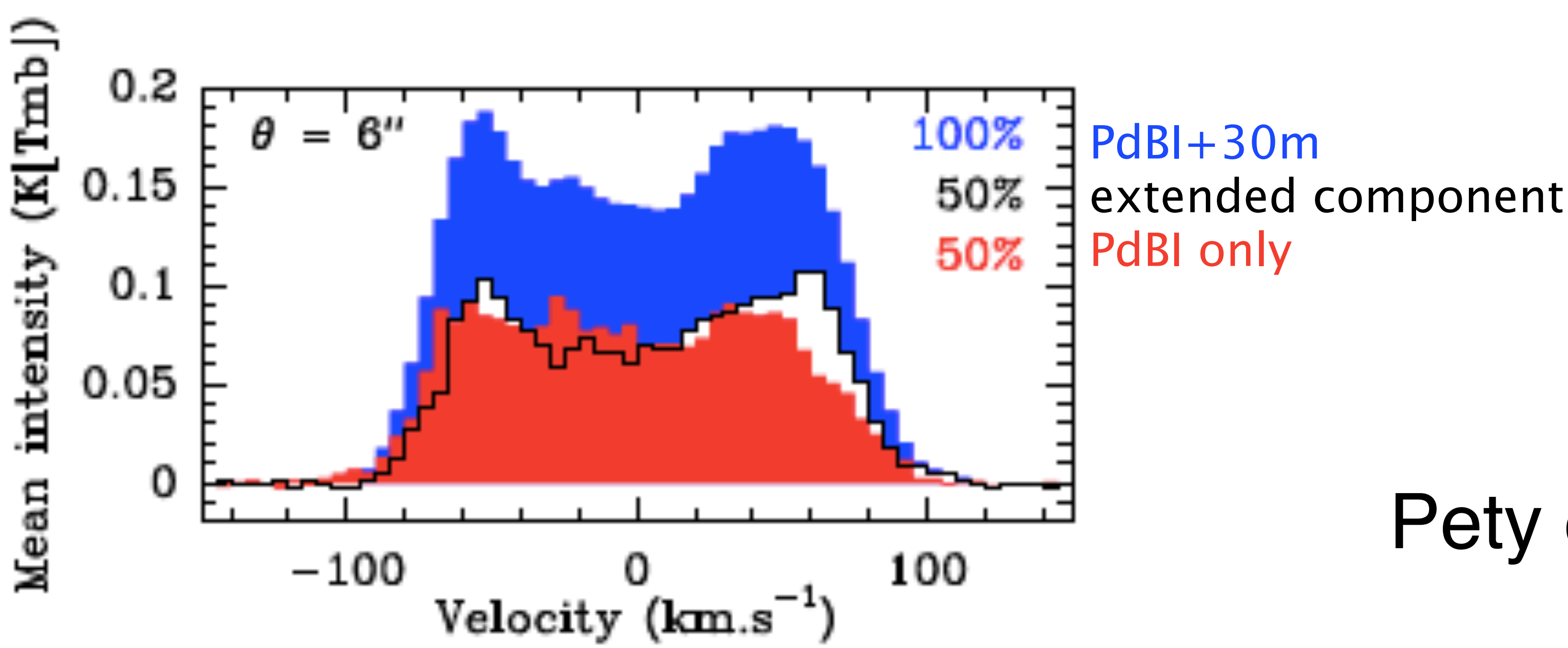


- Molecular gas in GMCs (but diffuse emission also detected)
- GMCs properties vs environments
- Σ_{gas} varies in interarm/arm and nuclear region
- Massive star formation and GMC are associated sometimes

PAWS: SD + interferometric data

PdBI+30m | PdBI only | Extended component (6")

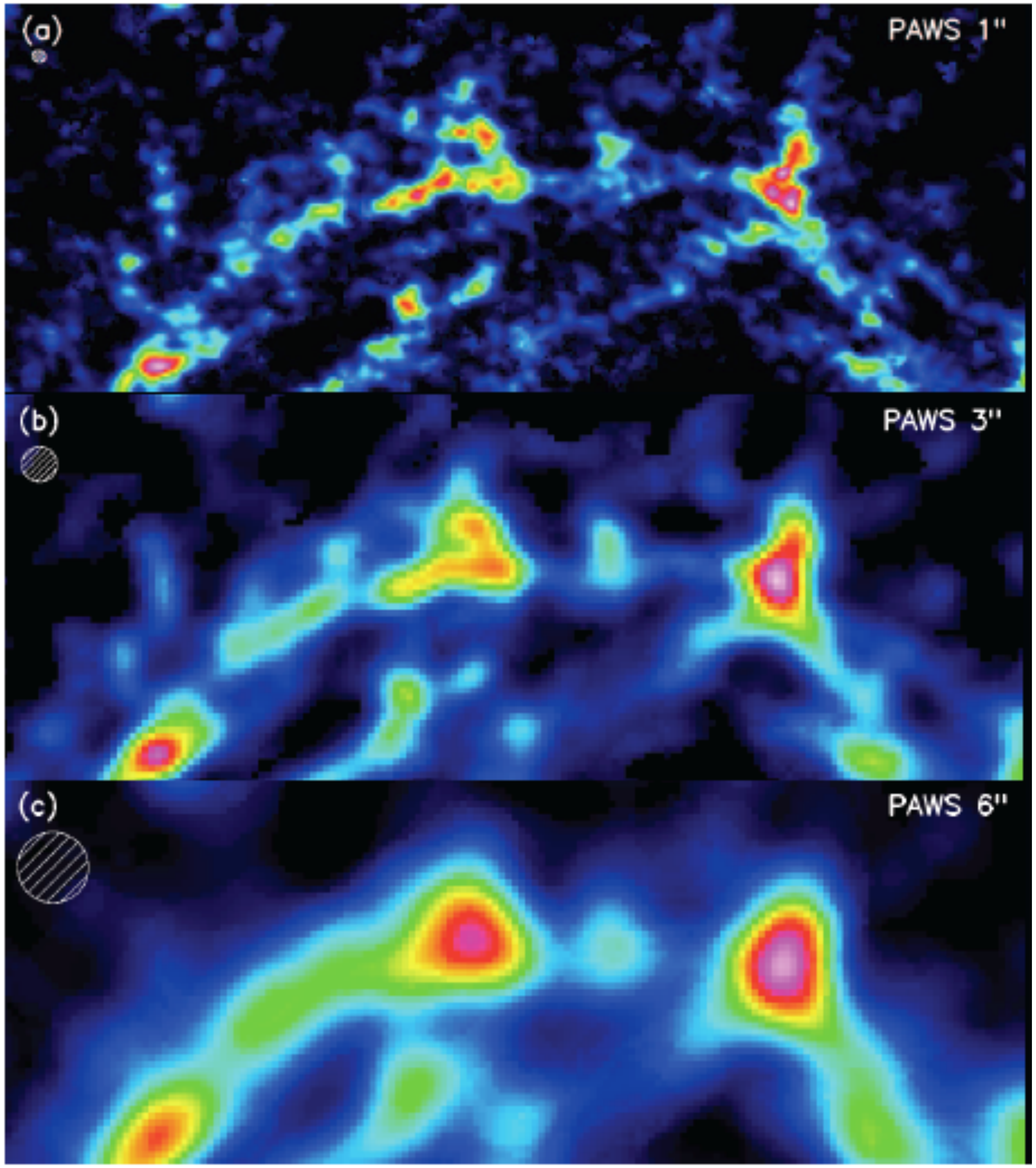




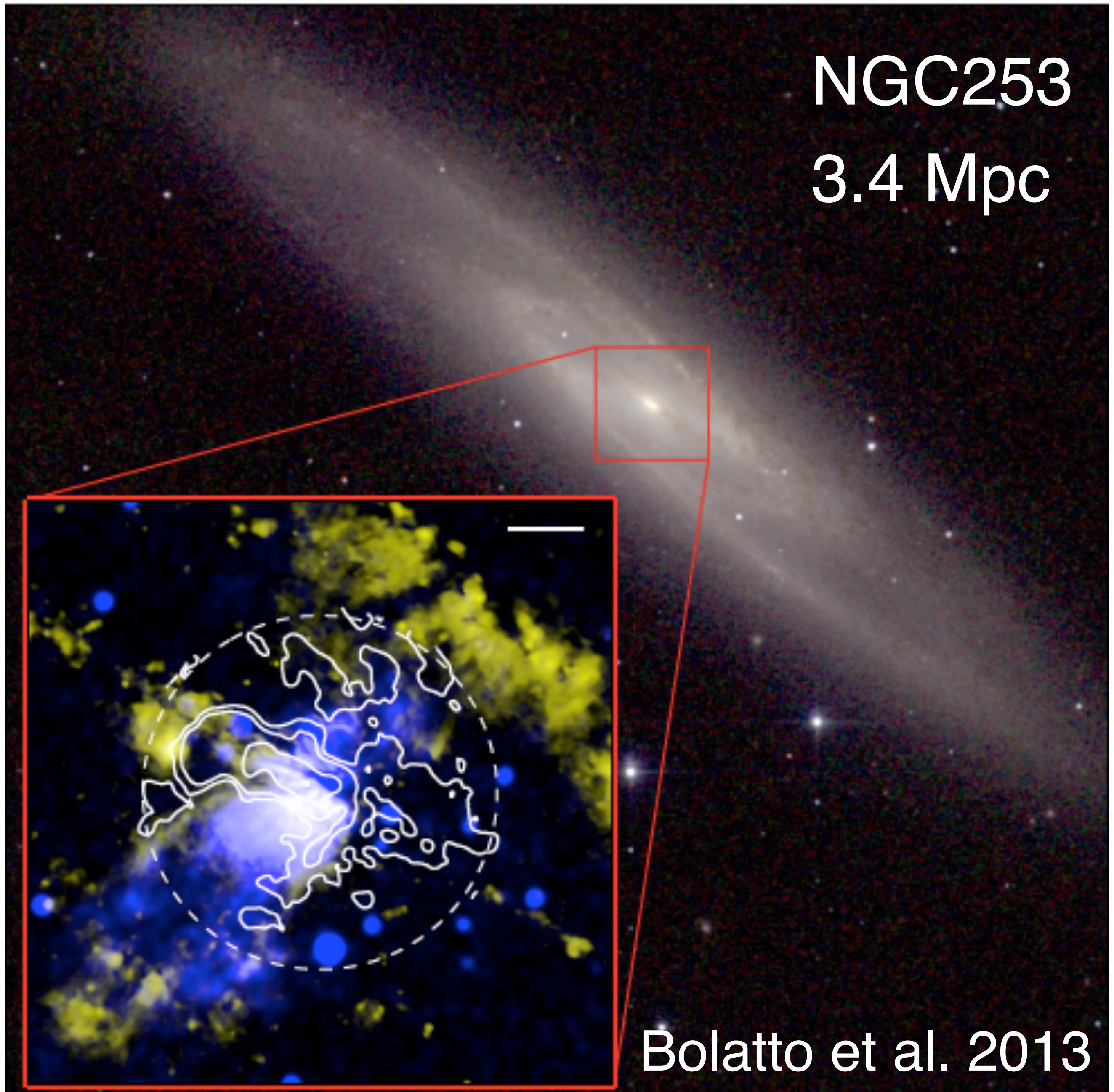
Pety et al. (2013)

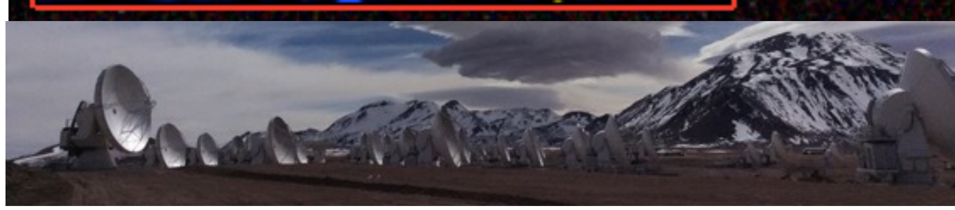
- A CO diffuse thick disk, typical scale of 200 pc.
- ~50% of the flux is resolved at scales >36" (1.3kpc)

PAWS: SD + interferometric data



ALMA: SD + interferometric data

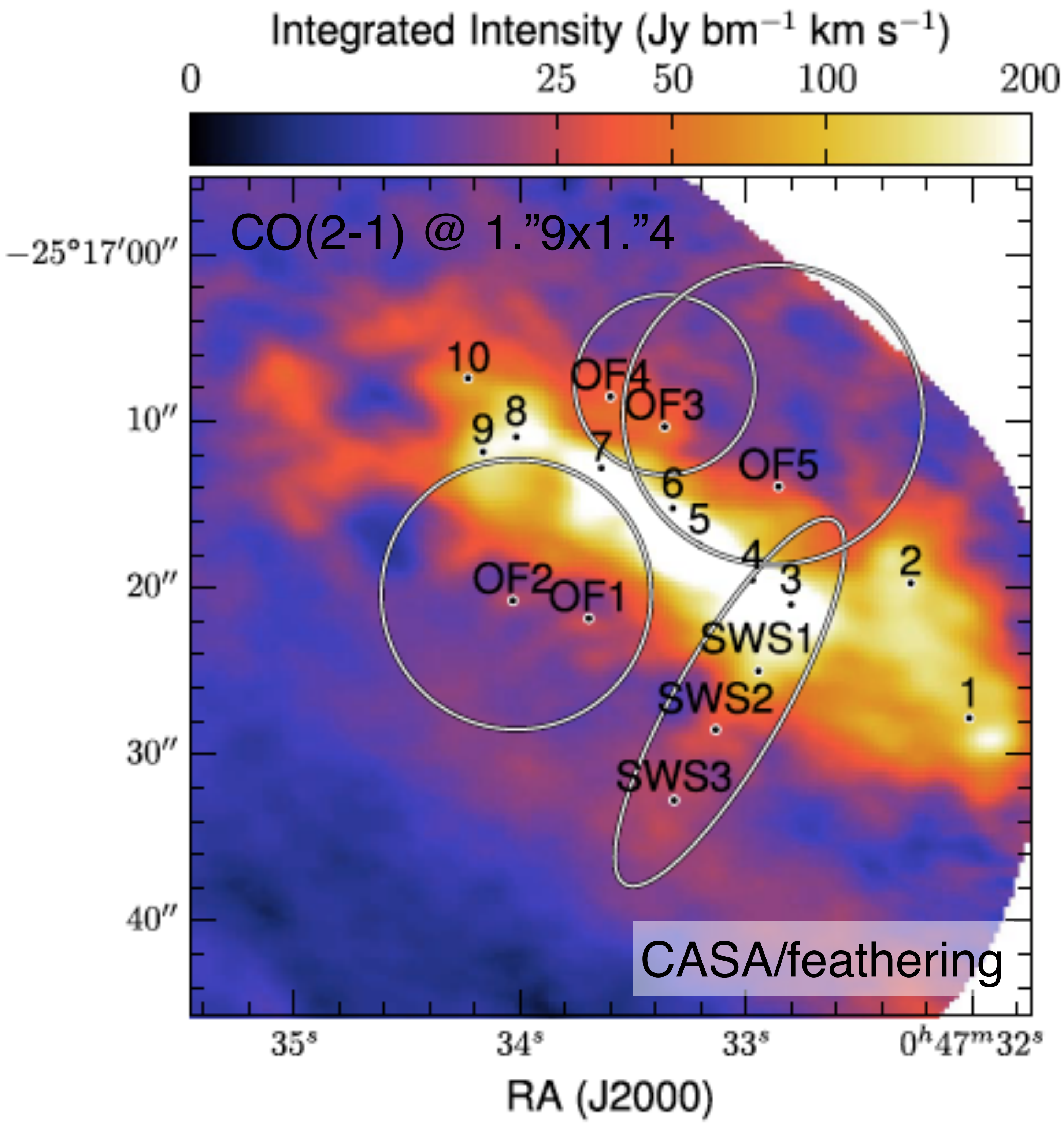




Nuclear starburst galaxy hosting a starburst-driven molecular outflow

- $\dot{M}_{outflow} \sim SFR_{global}$
- But $\dot{M}_{outflow}$ is a lower limit, because its calculation assumed optically thin CO emission

ALMA: SD + interferometric data

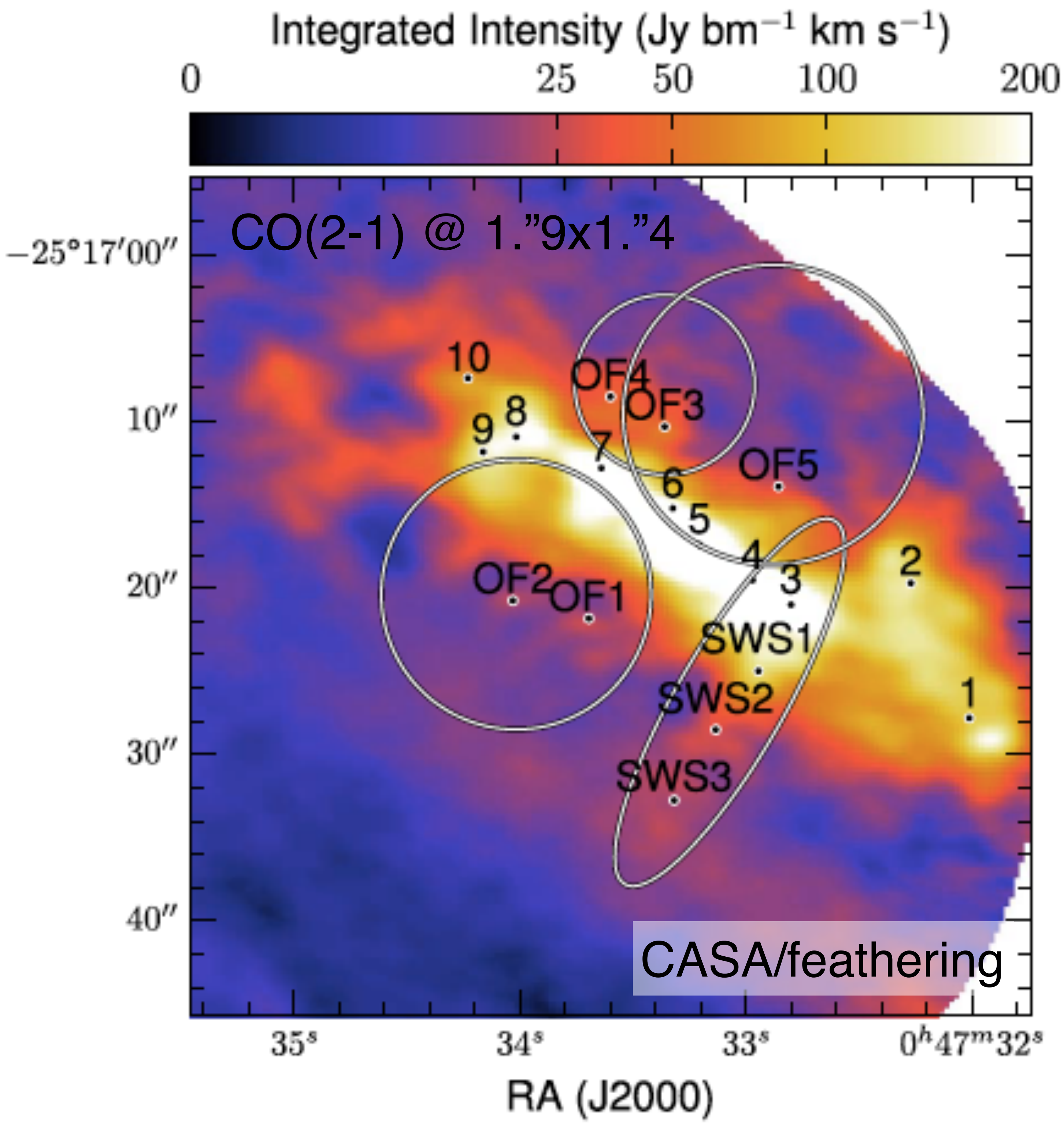


CO(2-1)/CO(1-0)

Region	No SD	With SD	Difference
1	0.51^e	0.51	1%
2	0.67^e	0.66	2%
3	0.82	0.84	3%
4	0.83	0.86	3%
5	1.01	1.05	4%
6	0.95	1.04	9%
7	0.93	0.95	3%
8	0.85	0.92	7%
9	0.72	0.79	6%
10	0.75	0.81	7%
SW streamer 1	0.79	0.84	6%
SW streamer 2	0.78	0.49	46%
SW streamer 3	0.83	0.67	22%
Outflow 1	0.91	0.95	5%
Outflow 2	0.60	0.62	2%
Outflow 3	0.65^e	0.77	18%
Outflow 4	0.55^e	0.61	9%
Outflow 5	0.70^e	0.89	24%

Zschaechner,..,Herrera et al. 2018.

ALMA: SD + interferometric data



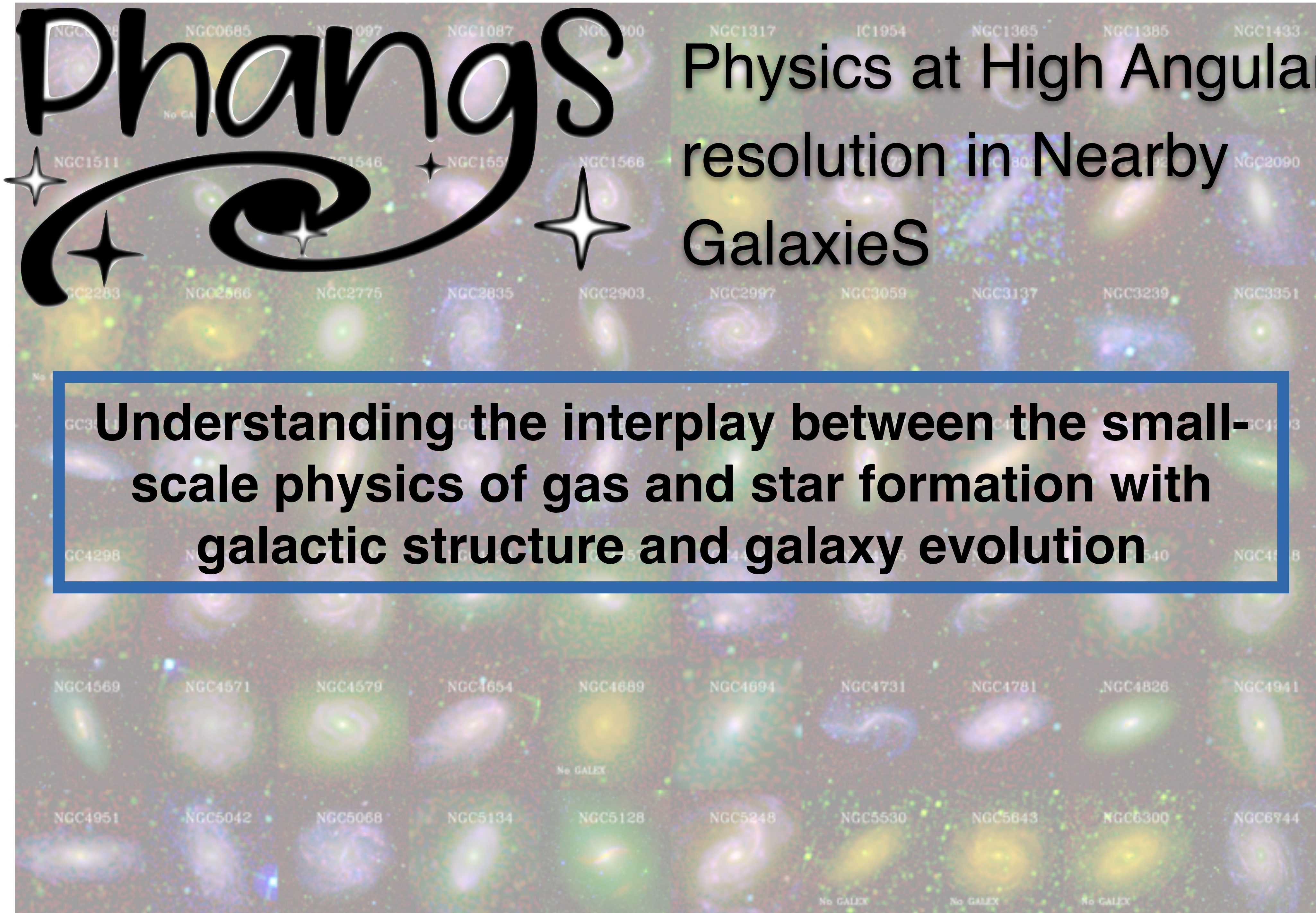
SW streamer 1	6%
SW streamer 2	46%
SW streamer 3	22%
Outflow 1	5%
Outflow 2	2%
Outflow 3	18%
Outflow 4	9%
Outflow 5	24%

Zschaechner,..,Herrera et al. 2018.

CO ratios ⇒
Optically thick CO gas in the outflow and in the starburst.

Molecular outflow mass is 3-6 times larger than previously reported (~10-20 larger than SFR in NGC 253).

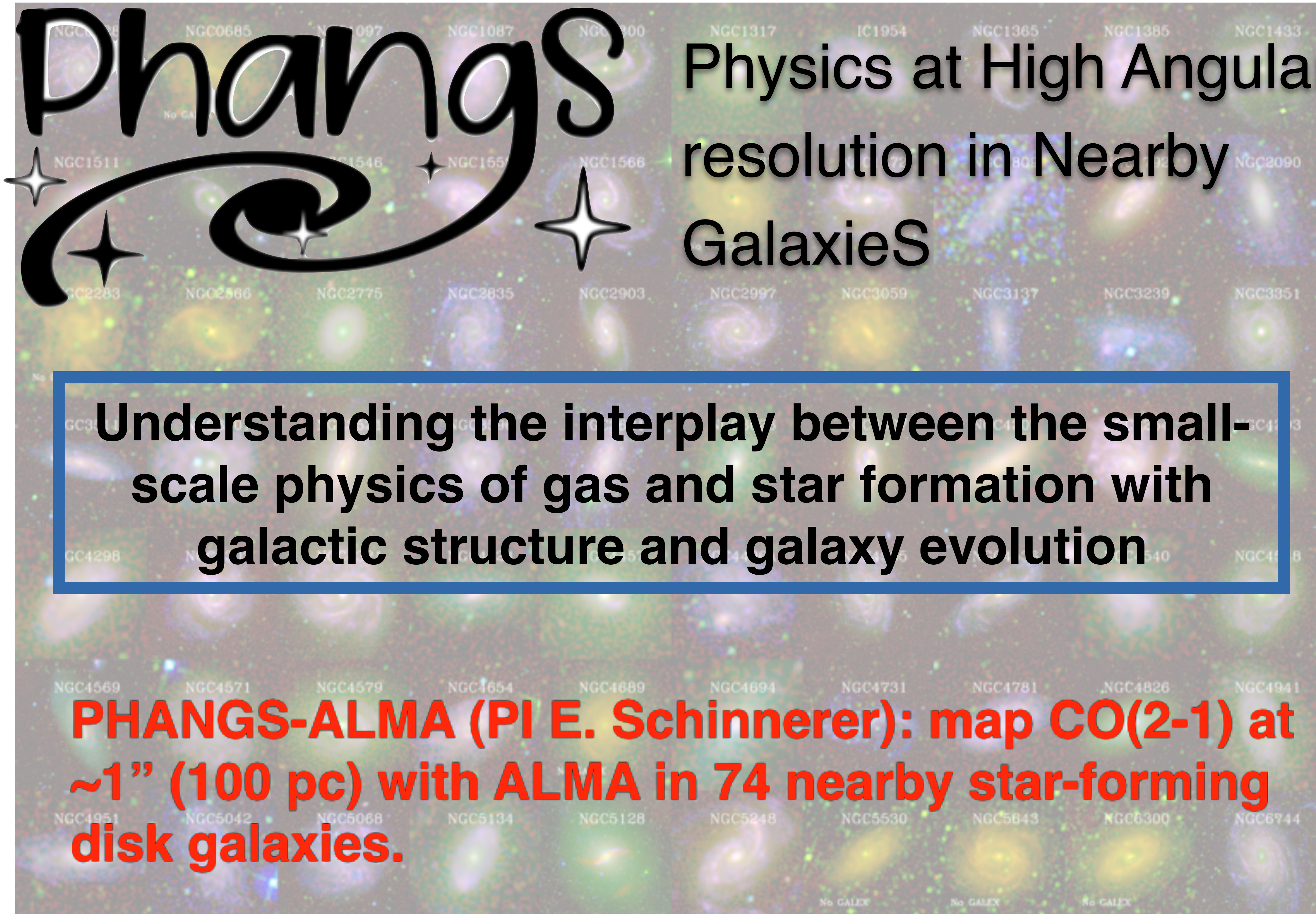
ALMA: PHANGS



Physics at High Angular resolution in Nearby GalaxieS

Understanding the interplay between the small-scale physics of gas and star formation with galactic structure and galaxy evolution

ALMA: PHANGS



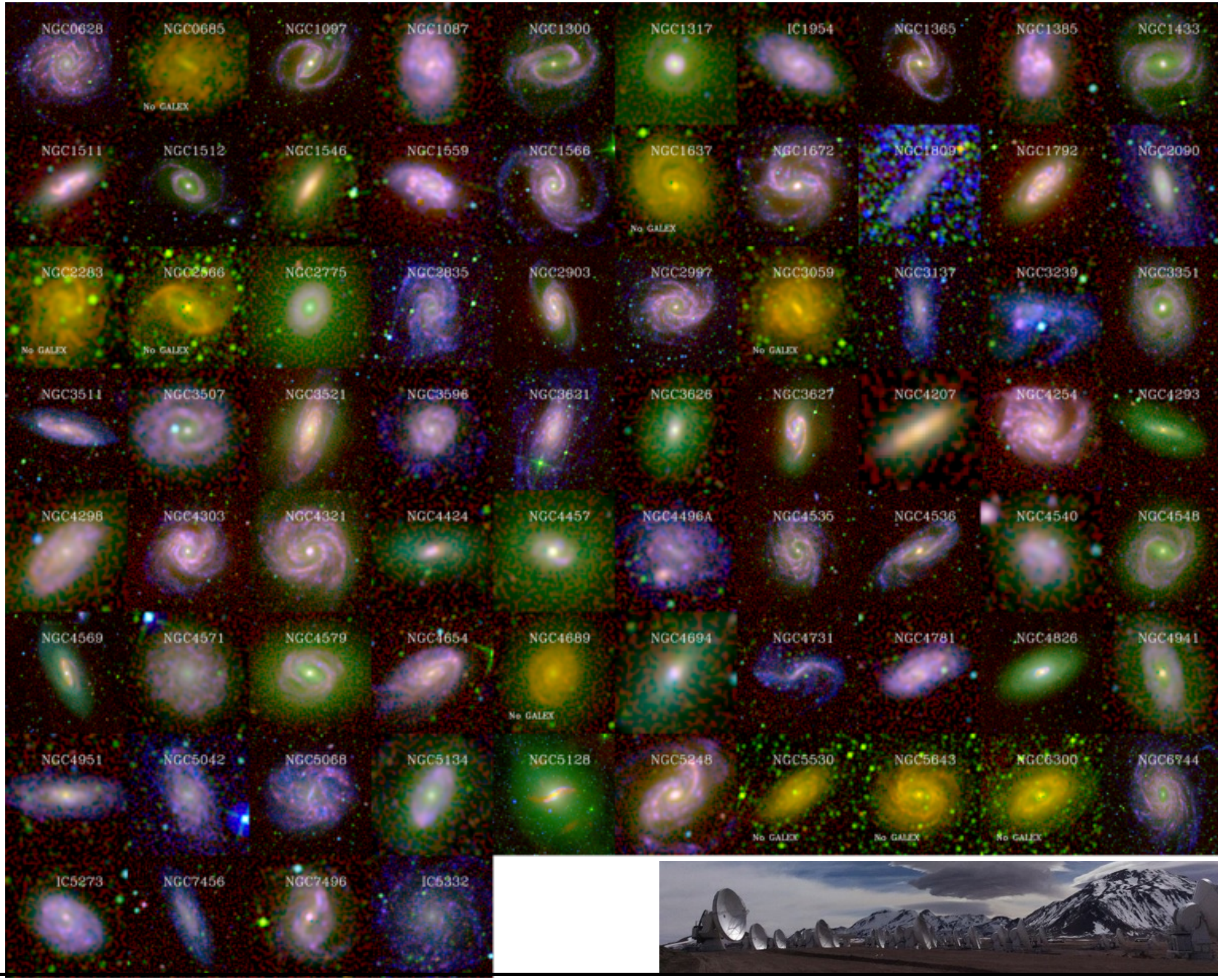
Phangs

Physics at High Angular resolution in Nearby GalaxieS

Understanding the interplay between the small-scale physics of gas and star formation with galactic structure and galaxy evolution

PHANGS-ALMA (PI E. Schinnerer): map CO(2-1) at ~1” (100 pc) with ALMA in 74 nearby star-forming disk galaxies.

ALMA: PHANGS


NGC0628
NGC0685
No GALEX
NGC1097
NGC1087
NGC1300
NGC1317
IC1954
NGC1365
NGC1385
NGC1433
NGC1511
NGC1512
NGC1546
NGC1559
NGC1566
NGC1637
No GALEX
NGC1672
NGC1809
NGC1792
NGC2090
NGC2283
No GALEX
NGC2566
No GALEX
NGC2775
NGC2835
NGC2903
NGC2997
NGC3059
No GALEX
NGC3137
NGC3239
NGC3351
NGC3511
NGC3507
NGC3521
NGC3596
NGC3621
NGC3626
NGC3627
NGC4207
NGC4254
NGC4293
NGC4298
NGC4303
NGC4321
NGC4424
NGC4457
NGC4496A
NGC4535
NGC4536
NGC4540
NGC4548
NGC4569
NGC4571
NGC4579
NGC4654
NGC4689
No GALEX
NGC4694
NGC4731
NGC4781
NGC4826
NGC4941
NGC4951
NGC5042
NGC5068
NGC5134
NGC5128
NGC5248
NGC5530
No GALEX
NGC5643
No GALEX
NGC6300
No GALEX
NGC6744
IC5273
NGC7456
NGC7496
IC5332

ALMA: PHANGS

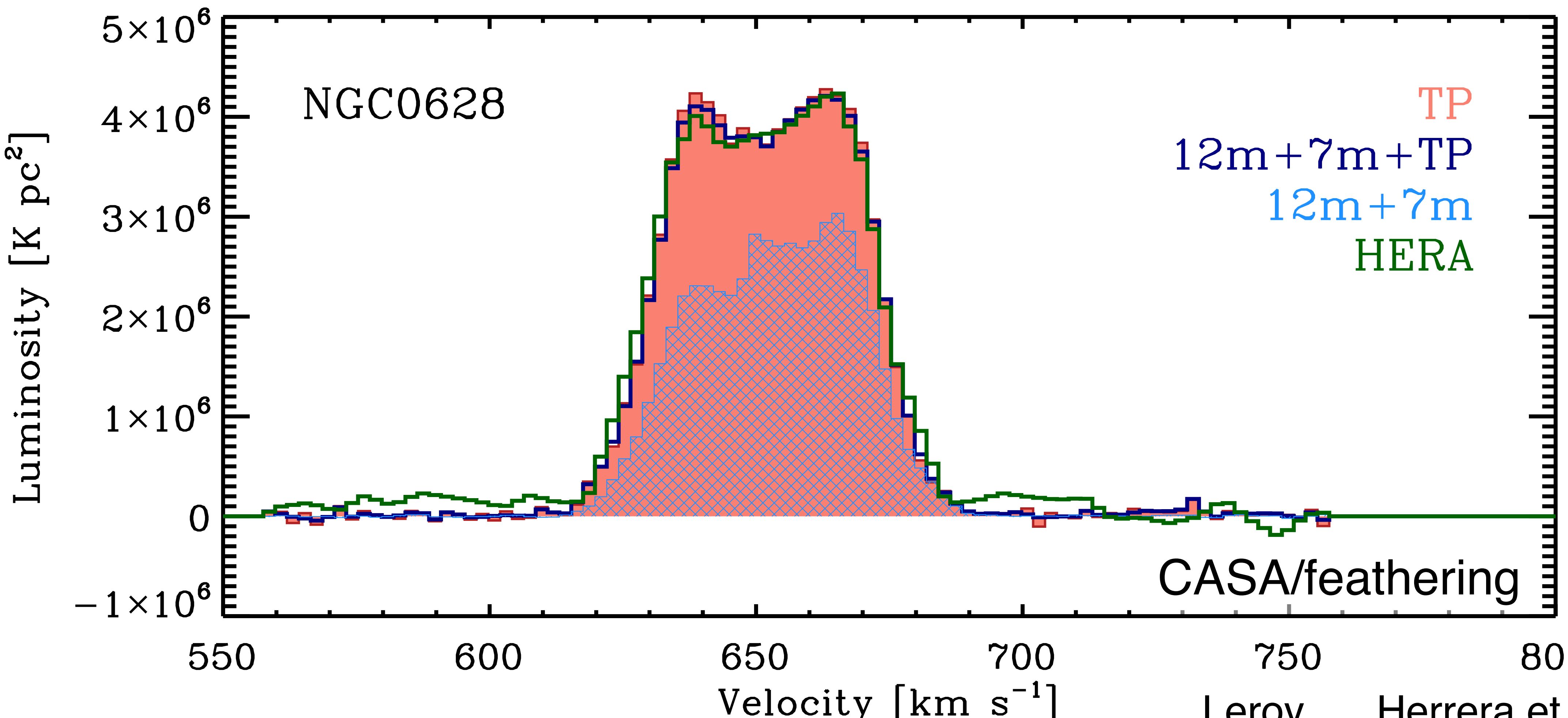
Physics at High Angular resolution in Nearby GalaxieS

Molecular Clouds - Star Formation - Timescales

- How do local ISM conditions depend on galactic environment?
- How do cloud-scale conditions in the gas affect the ability of gas to form stars and clusters
- What are the timescale and efficiencies for evolution of the molecular ISM?

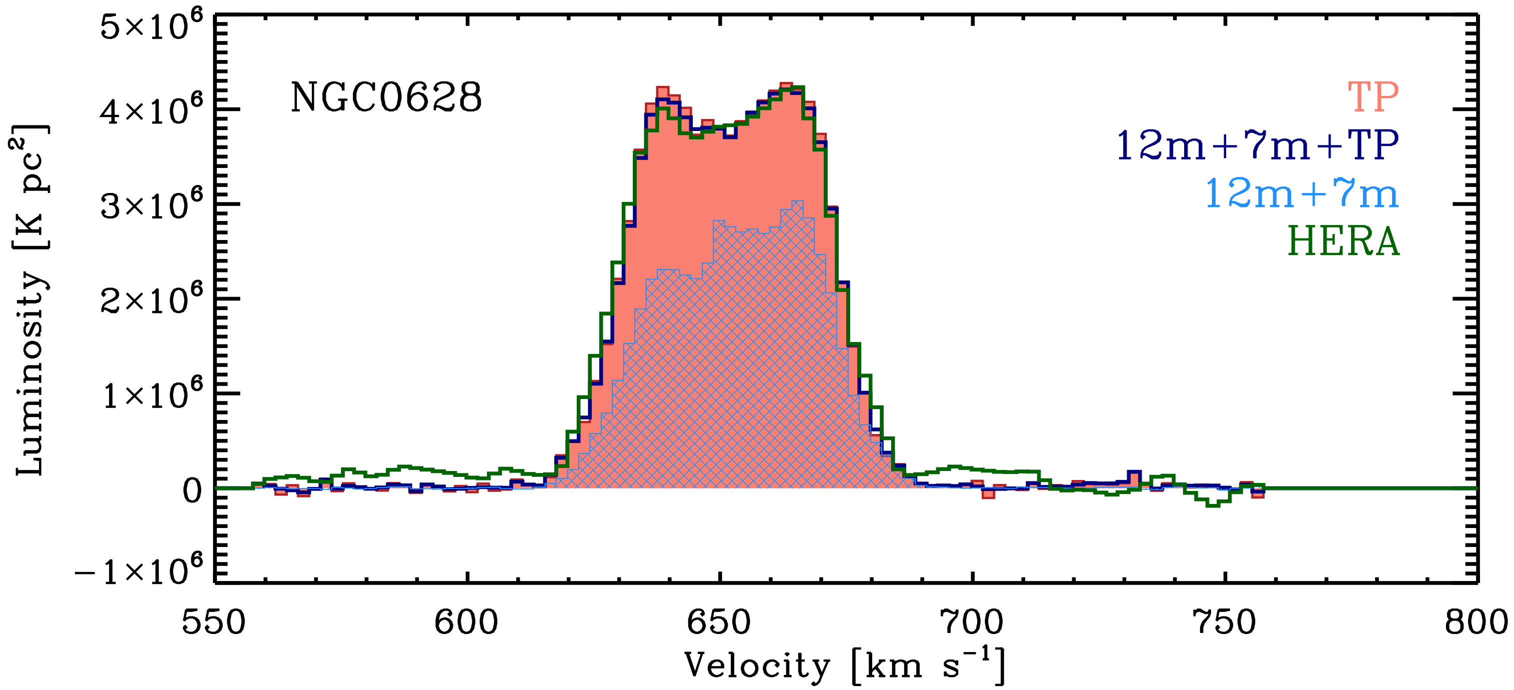
ALMA: PHANGS

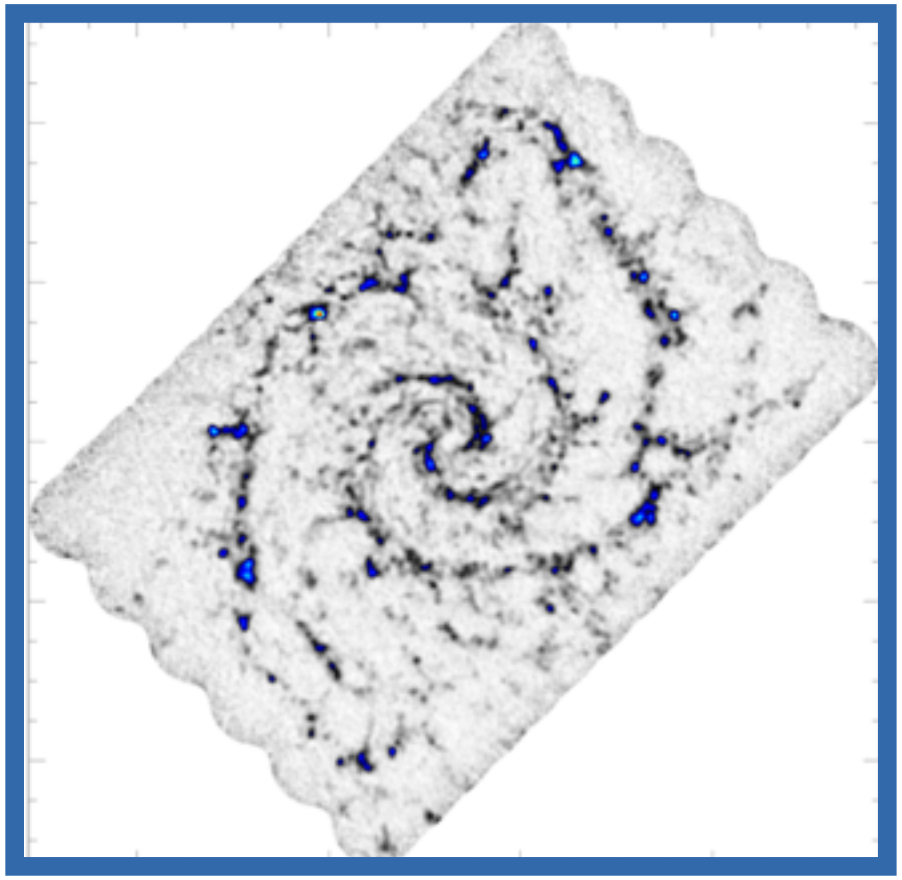
The short and zero spacing information is essential to make any complete survey of cold gas in a galaxy.

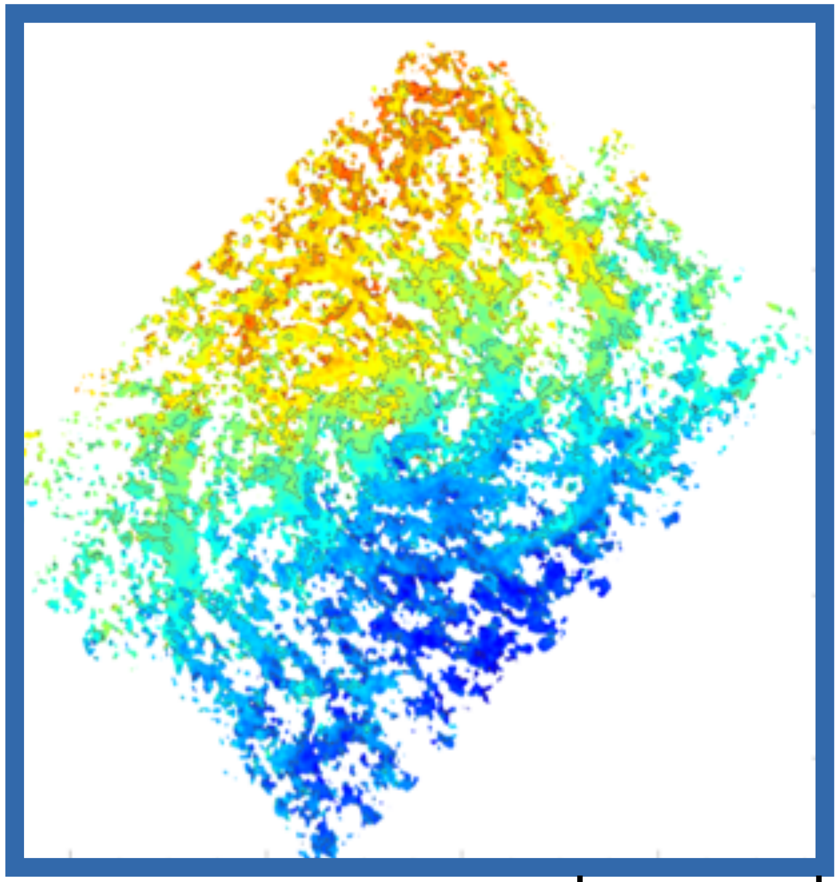


Leroy,..., Herrera et al. in prep.

ALMA: PHANGS

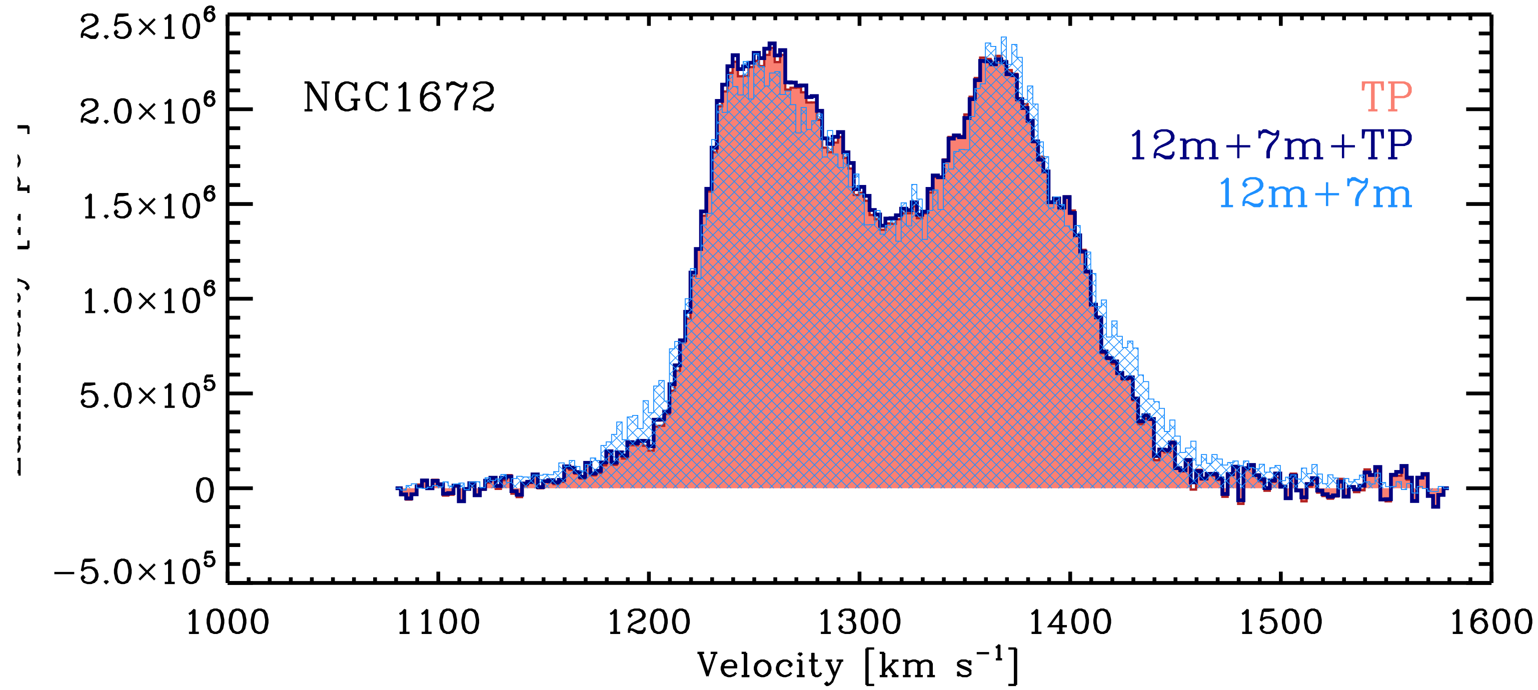


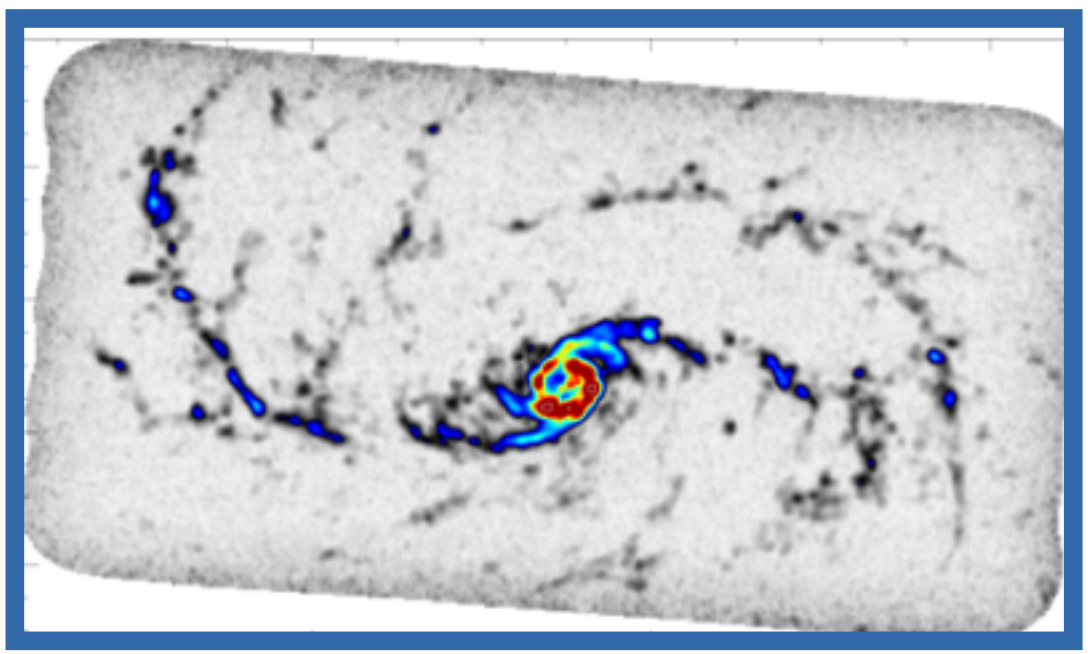


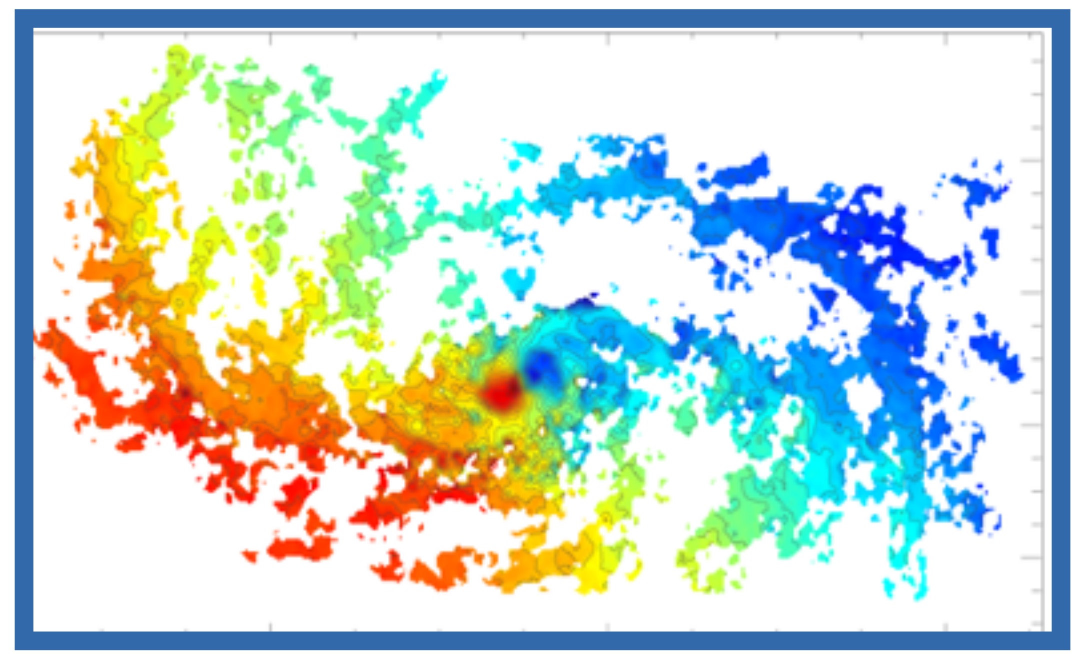


Leroy,…, Herrera et al. in prep.

ALMA: PHANGS

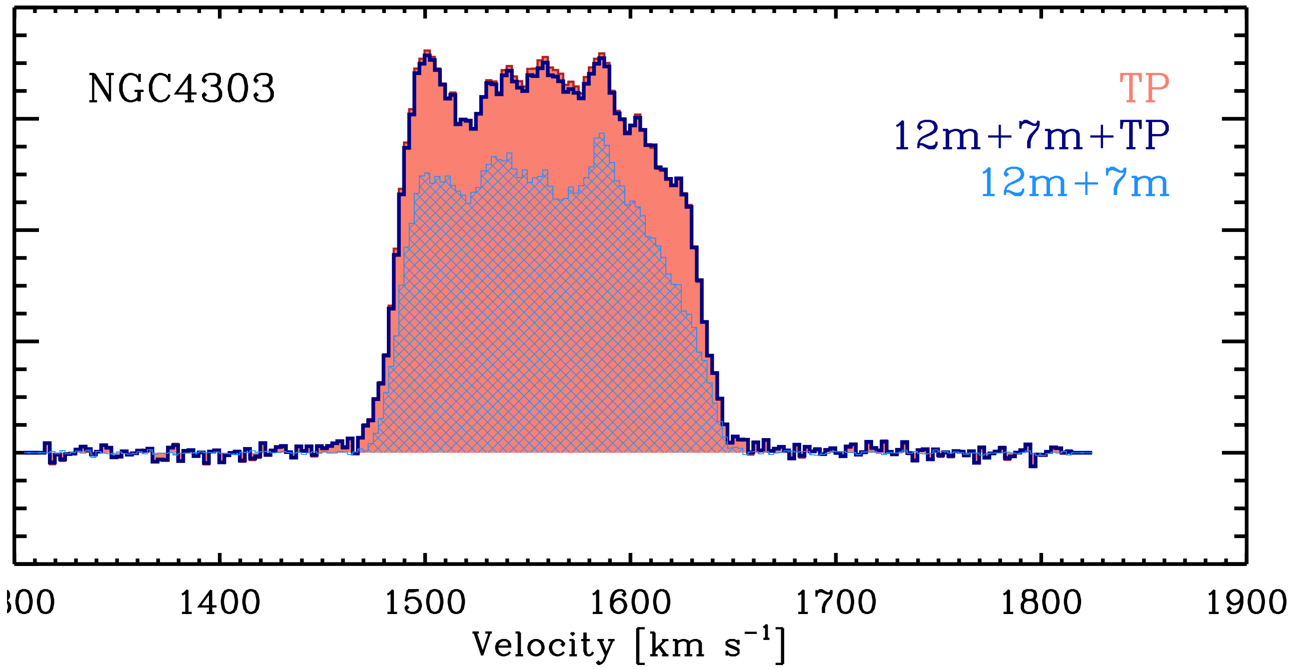


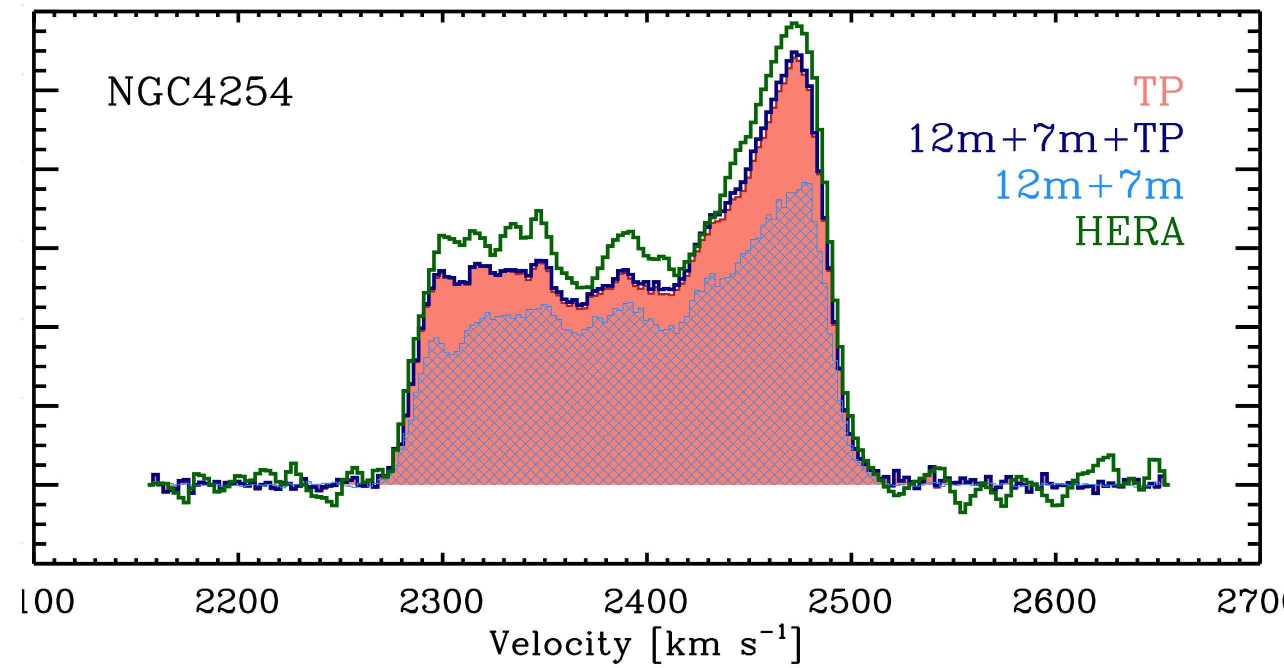


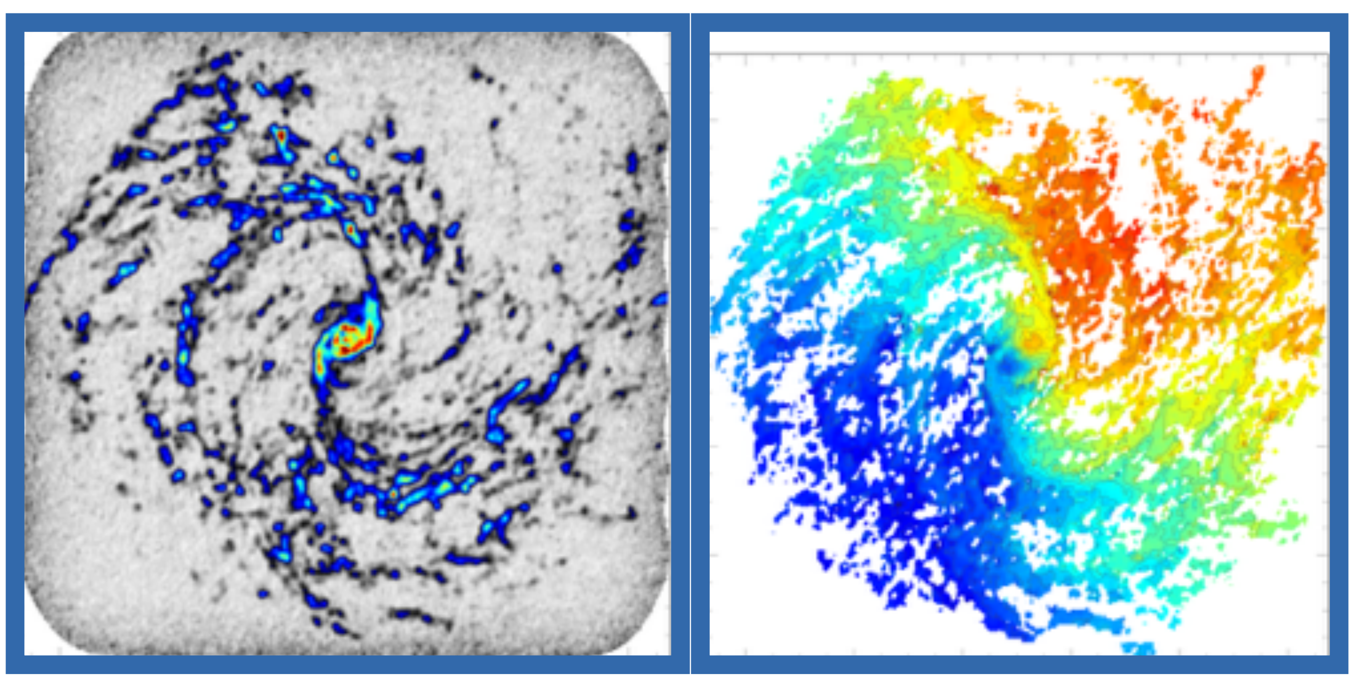


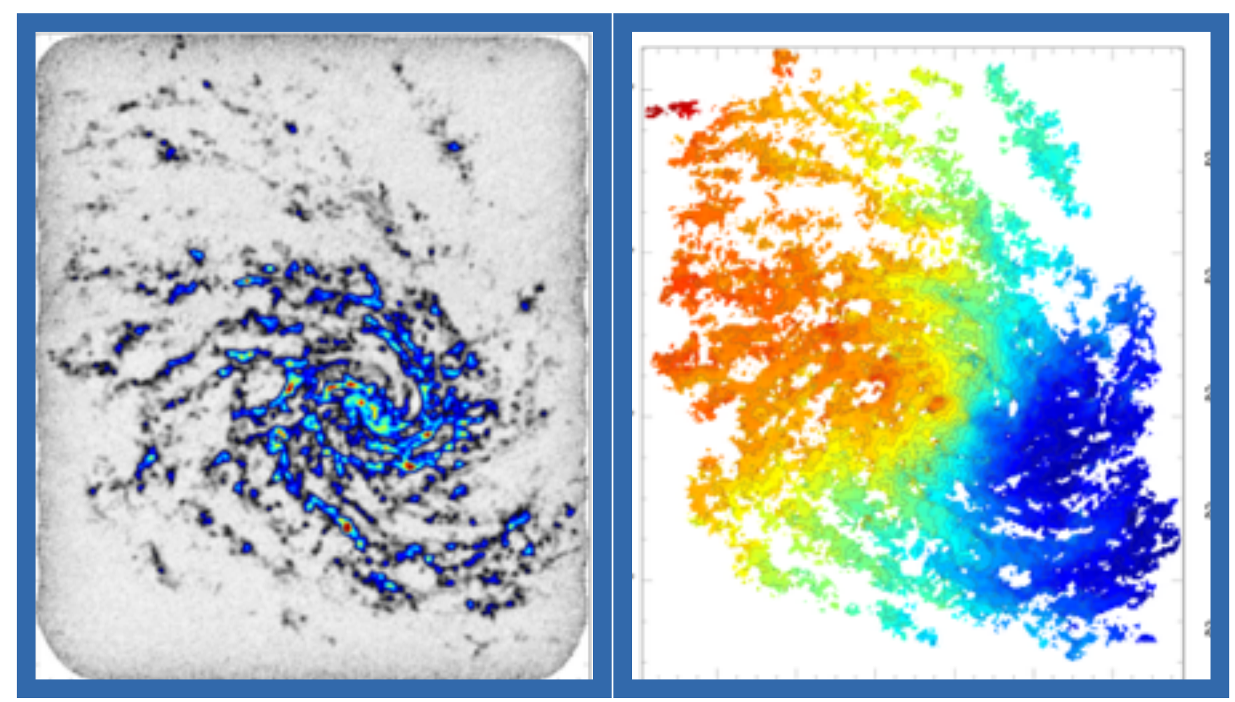
Leroy,…, Herrera et al. in prep.

ALMA: PHANGS







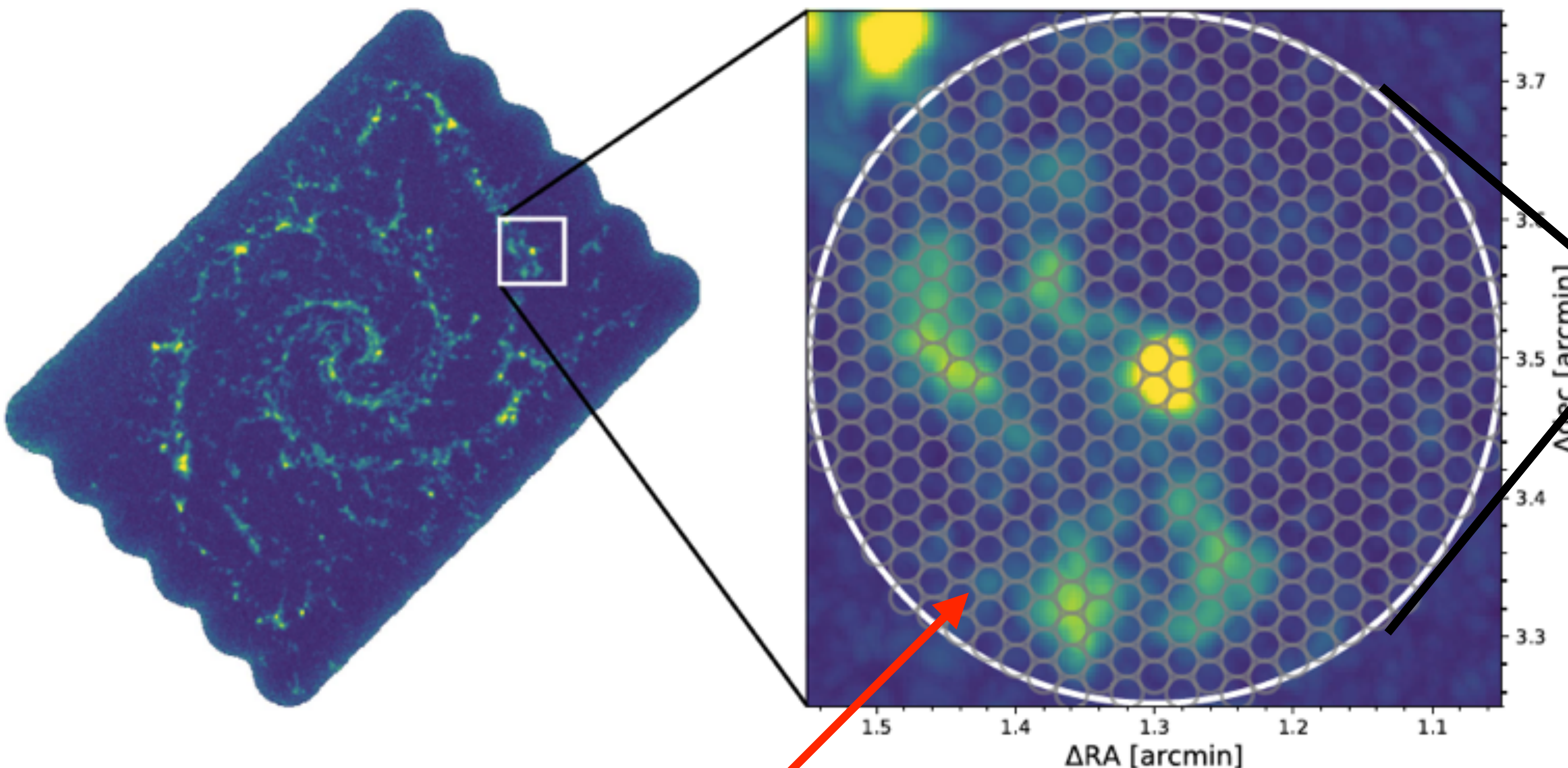


Leroy,…, Herrera et al. in prep.

ALMA: PHANGS

Statistical studies of the cold molecular gas in our galaxy sample.

Star formation efficiency per gravitational free-fall time at 60– 120 pc resolution



Large-scale measurement of SFR, M_{gas}, t_{dep} at 1 kpc, assuming equilibrium.

$SFR/M_{gas} = t_{dep}$

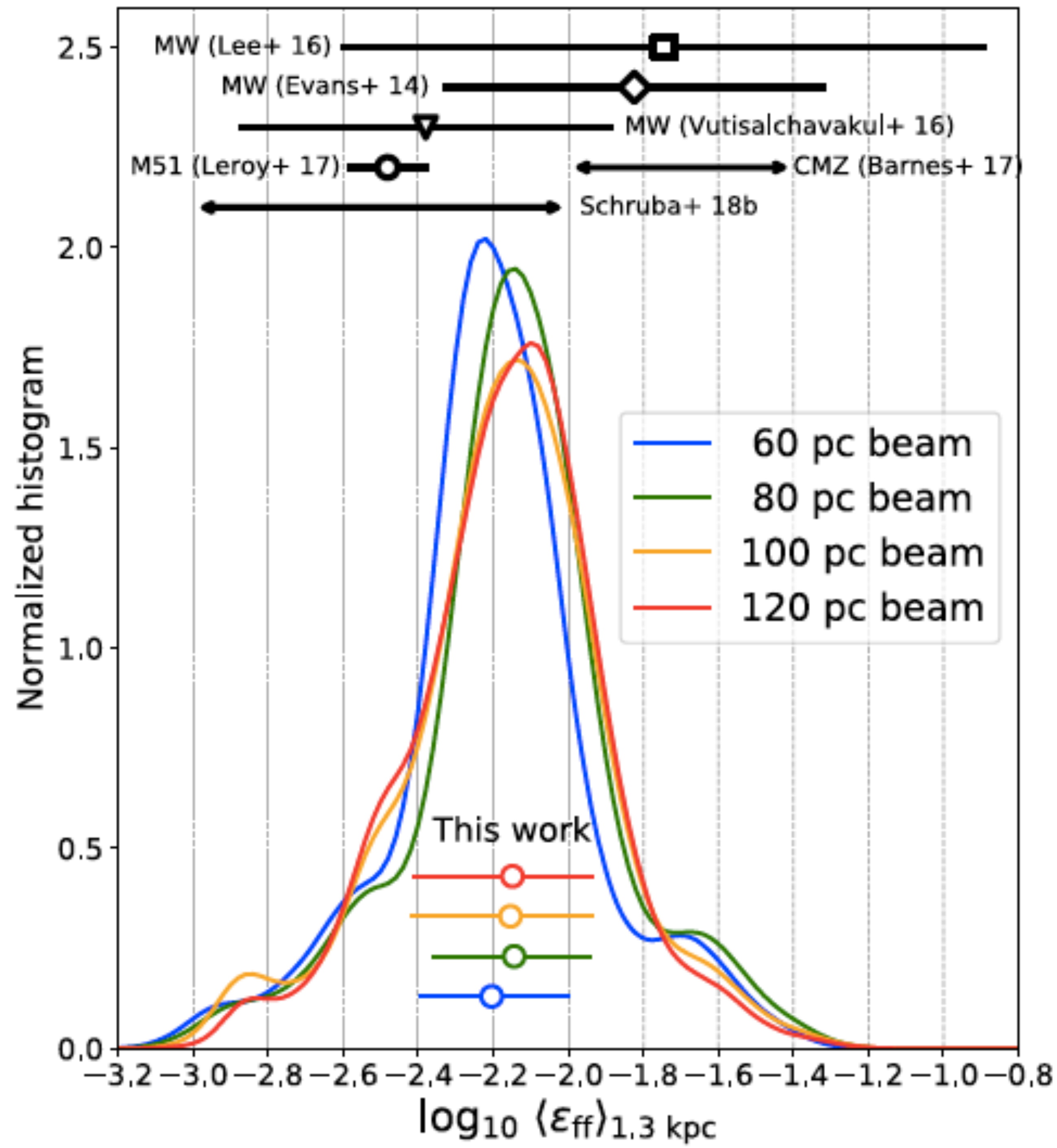
Cloud-scale measurement of Σ_{mol} and t_{ff} at 60 pc weighted by luminosity

$SFR/M_{gas} = \varepsilon_{ff}/t_{ff}$

Utomo,..,Herrera et al. 2018

ALMA: PHANGS

- Median value in our sample is 0.7%.
- Comparable to the theoretical value of 1%
- We find a mild scale dependence, with higher ε_{ff} measured at coarser resolution.
- Individual galaxies show different values of ε_{ff} (0.3% - 2.6%).
- Highest ε_{ff} for our lowest-mass targets, reflecting both long t_{ff} and short t_{dep}.



Utomo,..,Herrera et al. 2018

Conclusions

- Studying nearby galaxies is key to understand the different processes in the formation and evolution of galaxies in the Universe.
- We need observations providing information on both the diffuse, extended emission and compact, localized objects.
- Combining single dish and interferometry data is key to trace all spatial scales of the molecular gas.
- Large programs are essential for statistical analysis, providing public database.