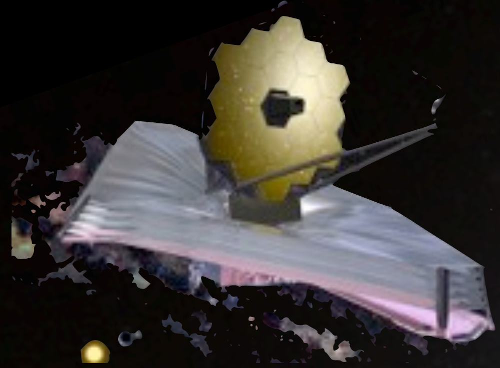
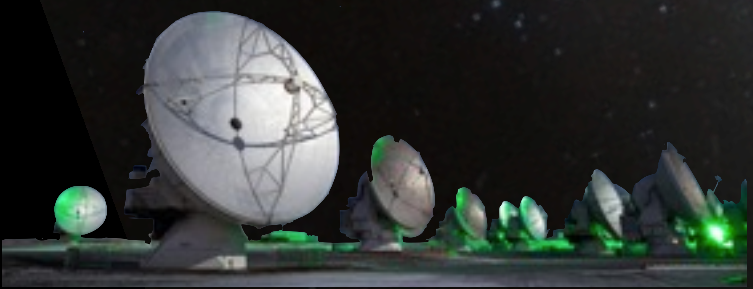


Formation of massive star clusters in mergers: Witnessing the dissipation of turbulent energy

Cinthya N. Herrera

François Boulanger, Edith Falgarone, Nicole Nesvadba, Guillaume Pineau des Forets, Santiago Garcia-Burillo, Daisuke Iono, Pierre Guillard

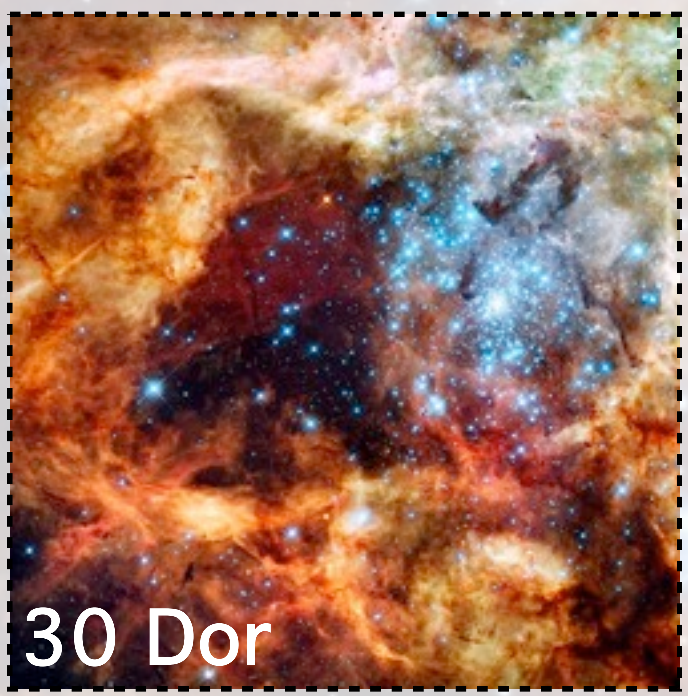


Super Star Clusters (SSCs)

One of the most extreme forms of star formation

- Massive ($>10^5\ M_\odot$) star clusters
- Compact (a few parsec)
- Thousands of O stars

... likely the progenitors of Globular Clusters



The number of such objects greatly increases in **galaxy interactions and mergers**, common phenomenon in the Universe.

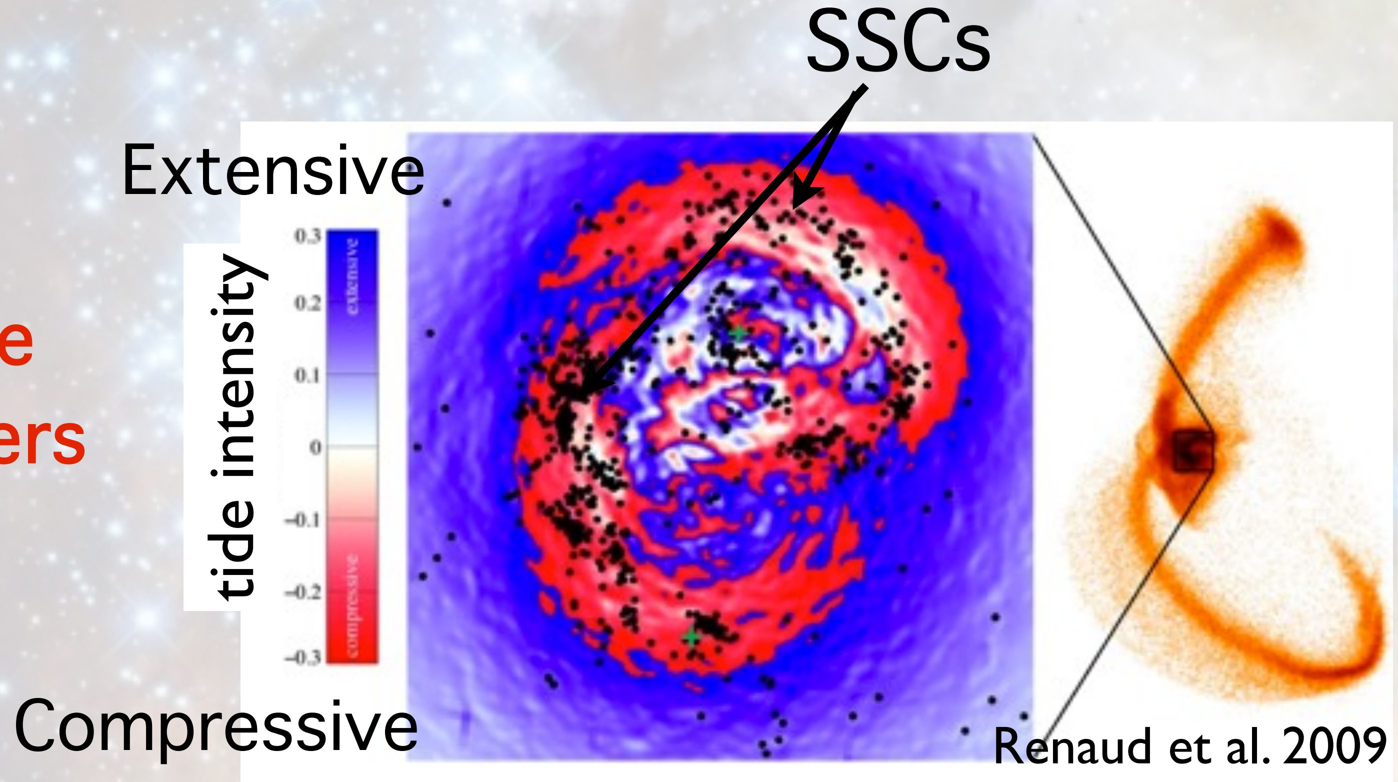
How do they **form** and early evolve?

Super Star Clusters (SSCs)

How galaxy interaction triggers the formation of SSC?

High gas densities and turbulence are probably key

- Large scale compression
- Mechanical heating → turbulence
- SF occurs in very massive clusters



Simulations of the Antennae galaxies: Compressive tides

Key idea: To search for early stages of massive cluster formation by combining tracers of gas mass AND turbulent energy dissipation

Super Star Clusters (SSCs)

How galaxy interaction triggers the formation of SSC?

High gas densities and **turbulence** are probably key

- Large scale compression
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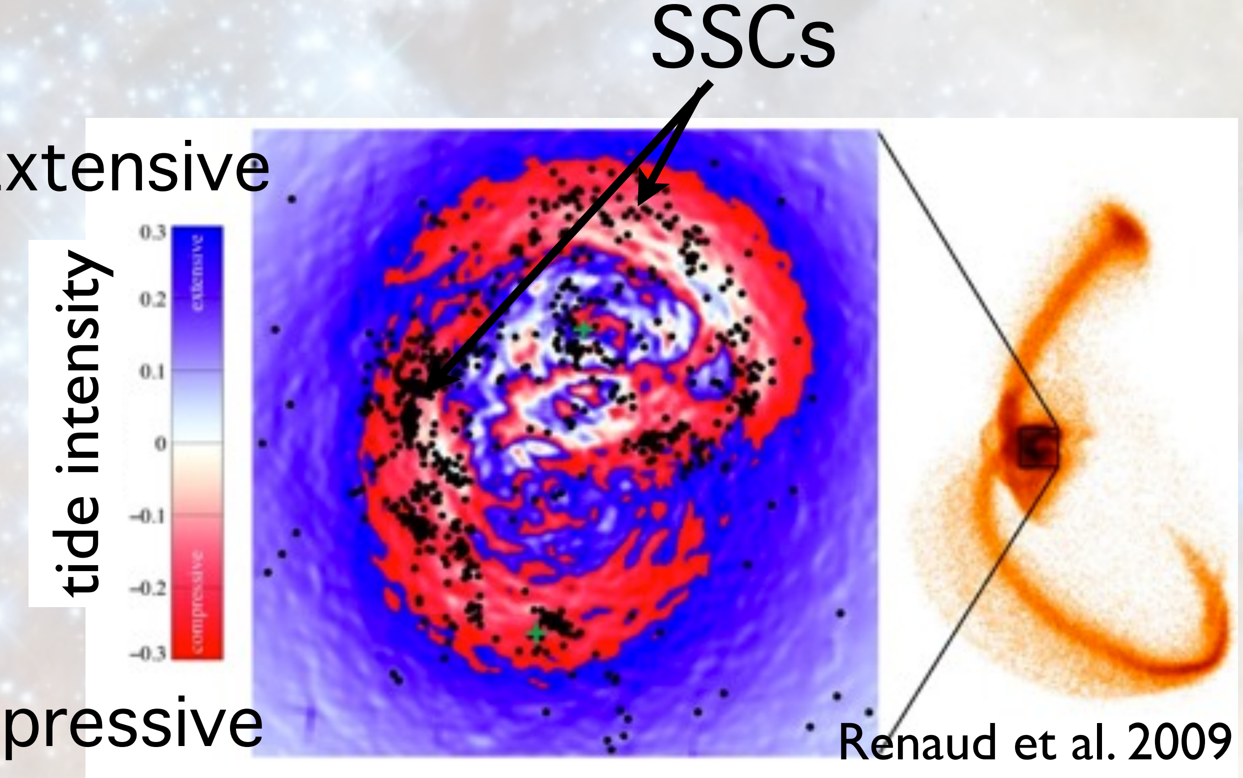
- SF occurs in very massive clusters



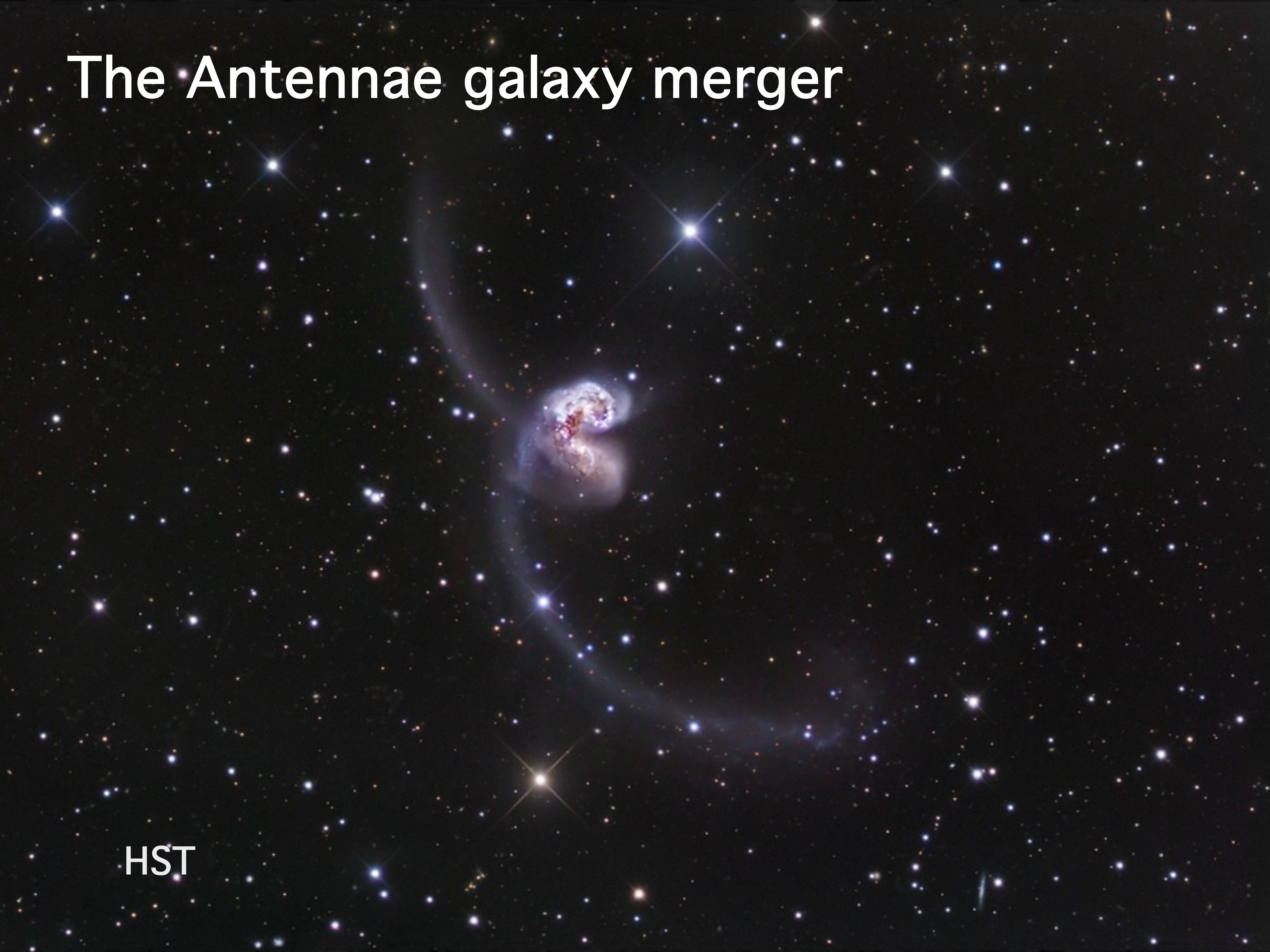
Simulations of the Antennae galaxies: Compressive tides

Key idea: To search for early stages of mas
formation by combining tracers o
AND turbul dissipation

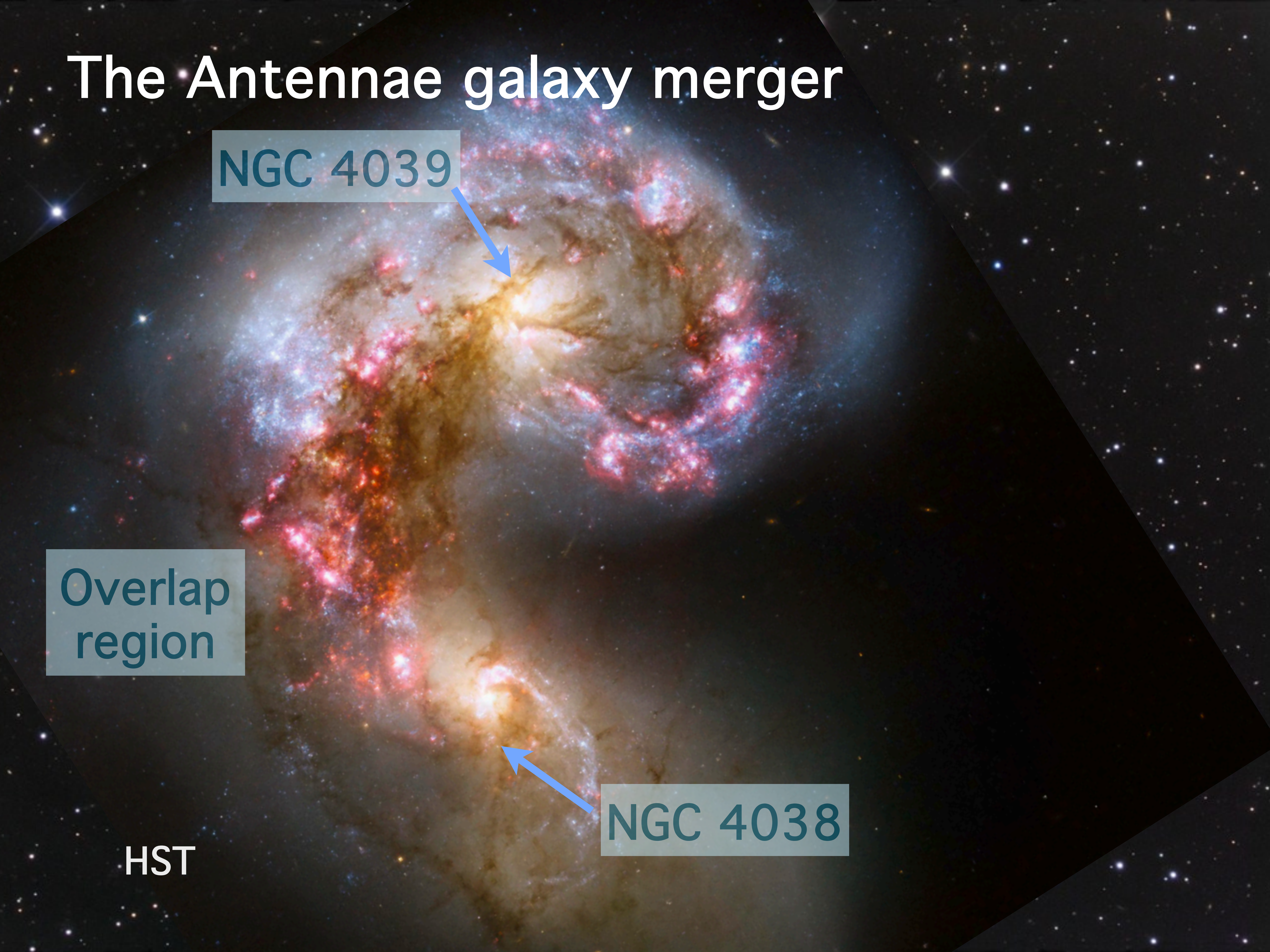
CO ALMA

H_2 JWST

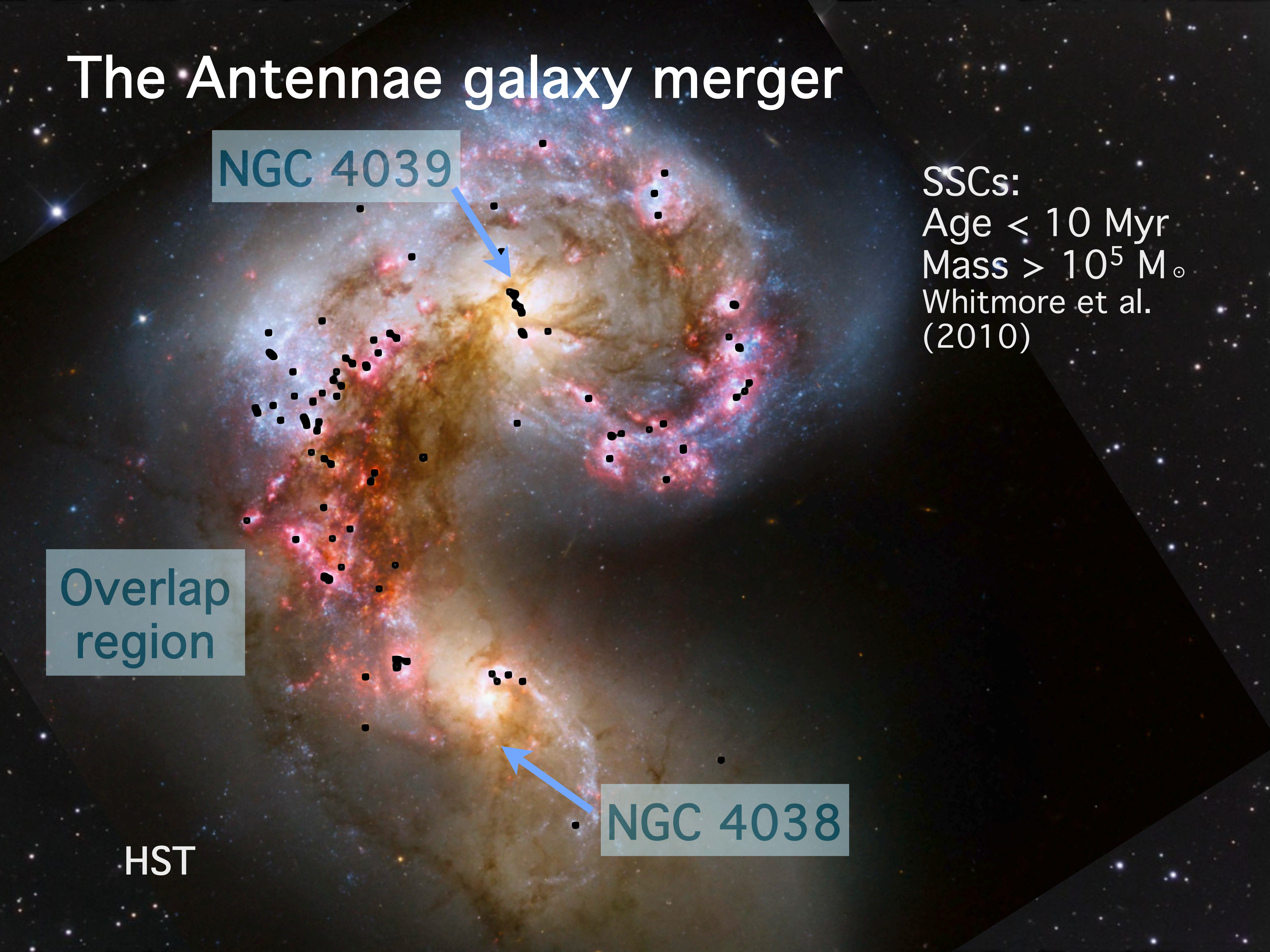
The Antennae galaxy merger



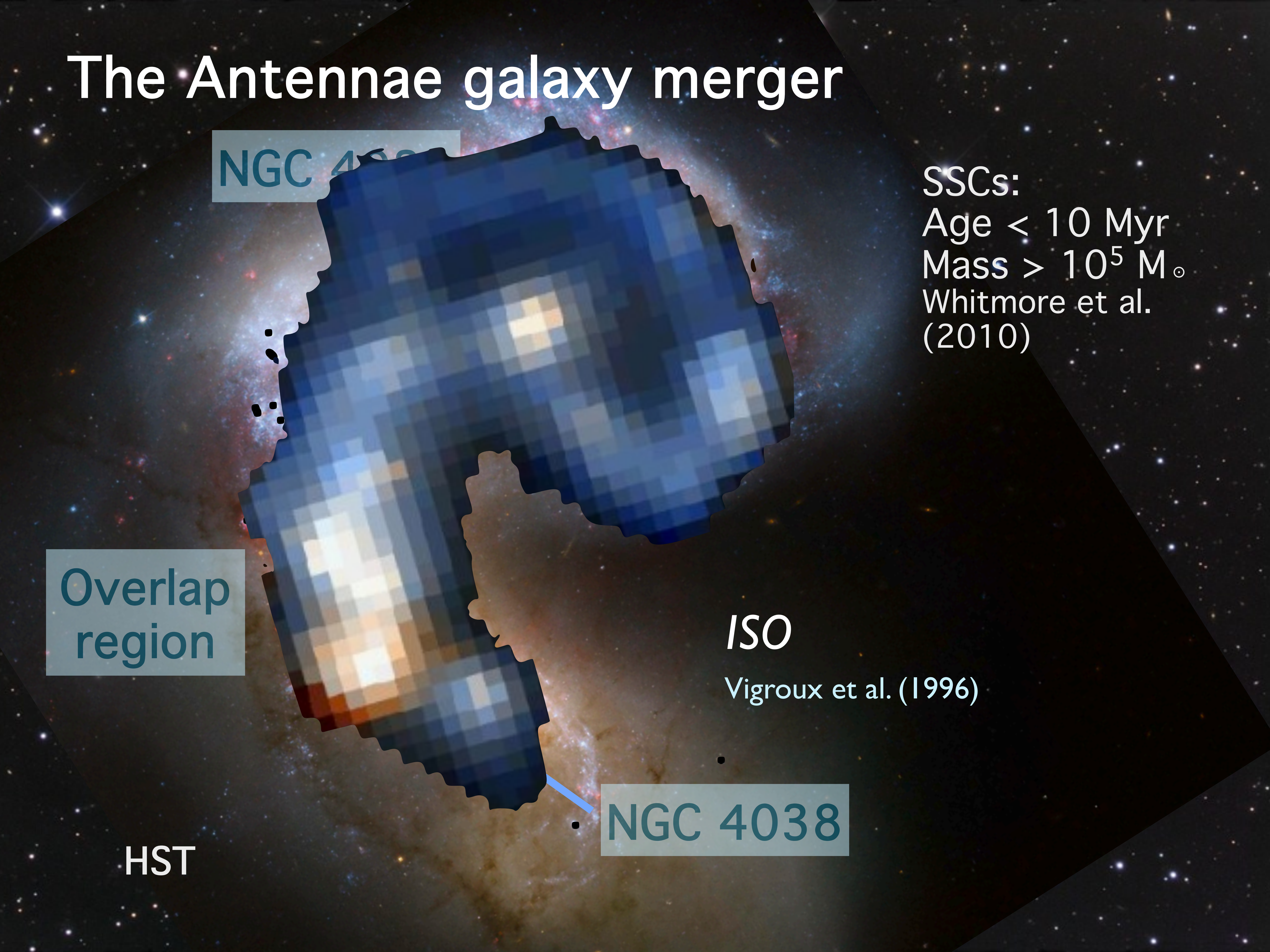
The Antennae galaxy merger

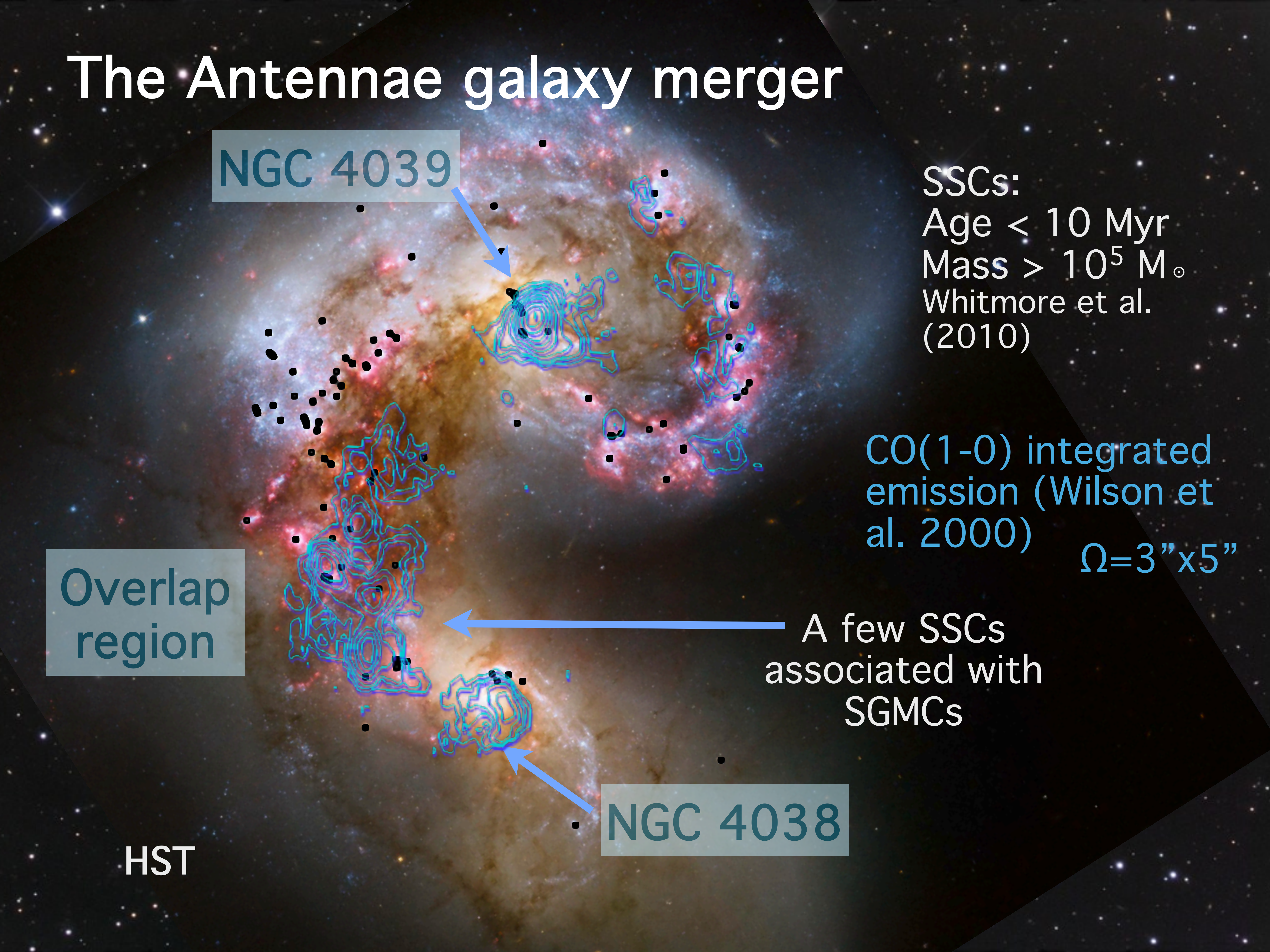


The Antennae galaxy merger

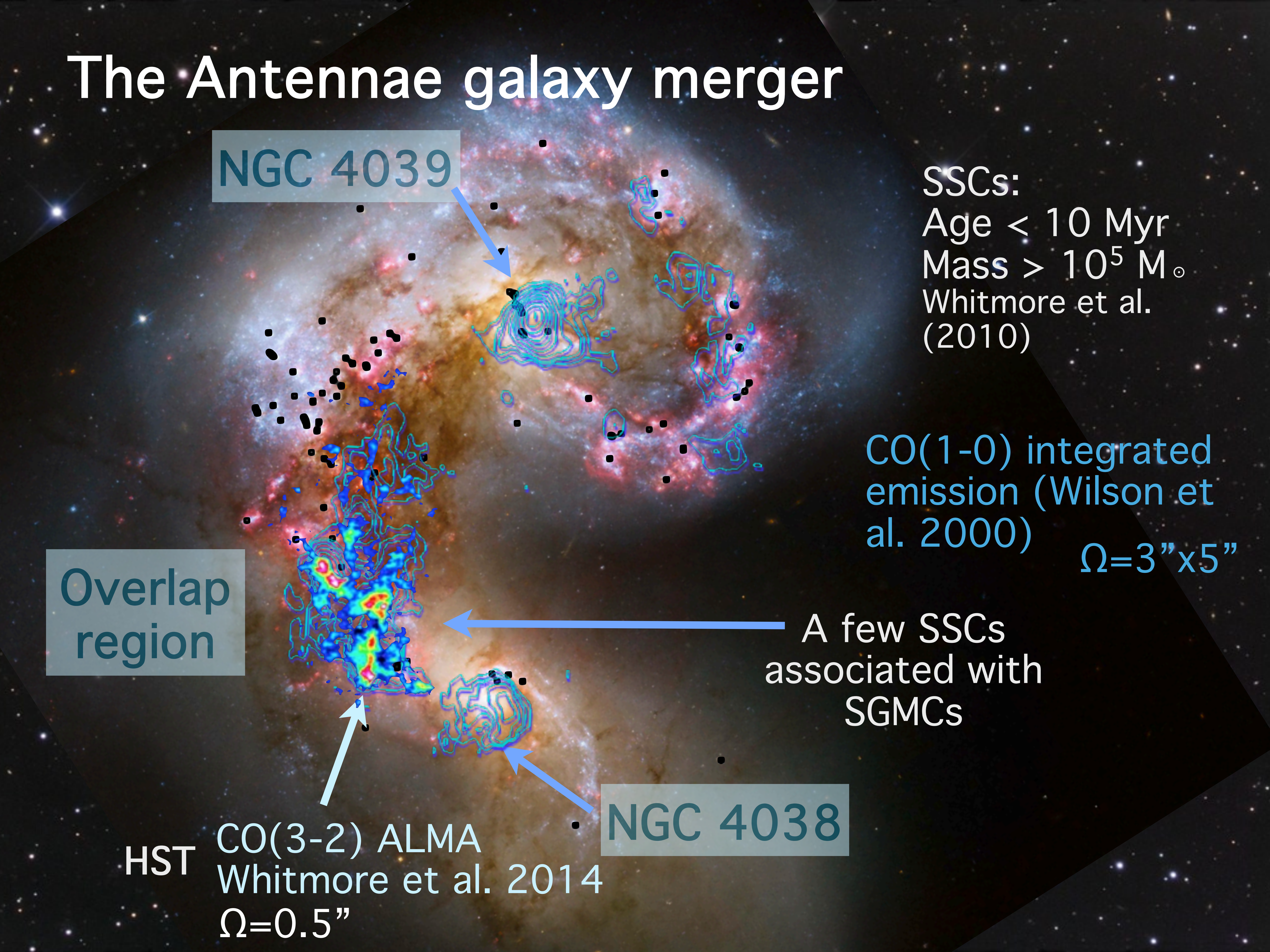


SSCs:
Age < 10 Myr
Mass > 10^5 $M_\odot$
Whitmore et al. (2010)

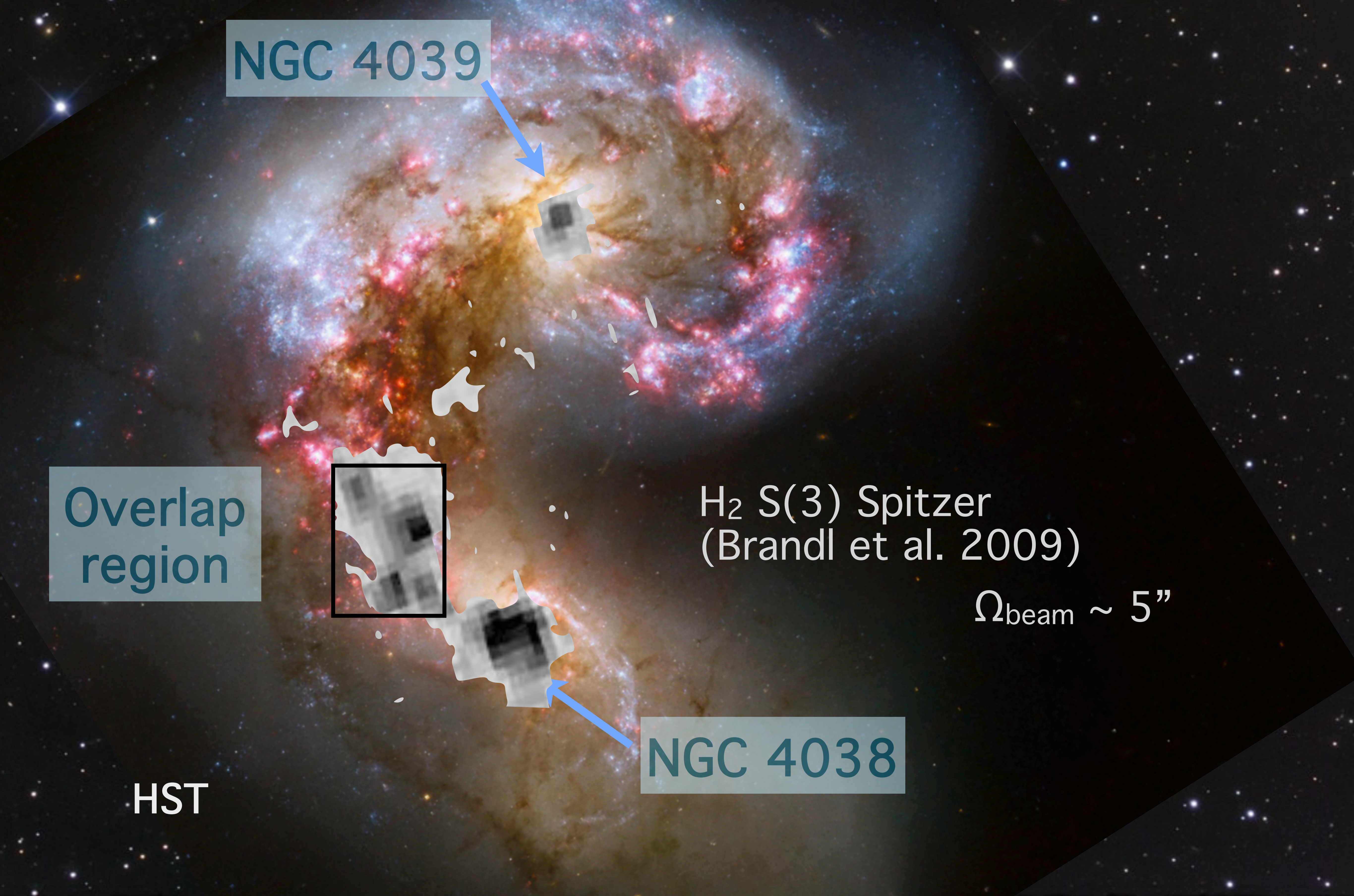

The Antennae galaxy merger
NGC 4
SSCs:
Age < 10 Myr
Mass > 10^5 $M_\odot$
Whitmore et al.
(2010)
Overlap
region
ISO
Vigroux et al. (1996)
NGC 4038
HST


The Antennae galaxy merger
NGC 4039
SSCs:
Age < 10 Myr
Mass > 10^5 $M_\odot$
Whitmore et al. (2010)
CO(1-0) integrated emission (Wilson et al. 2000)
Ω=3”x5”
Overlap region
A few SSCs associated with SGMCs
NGC 4038
HST

The Antennae galaxy merger

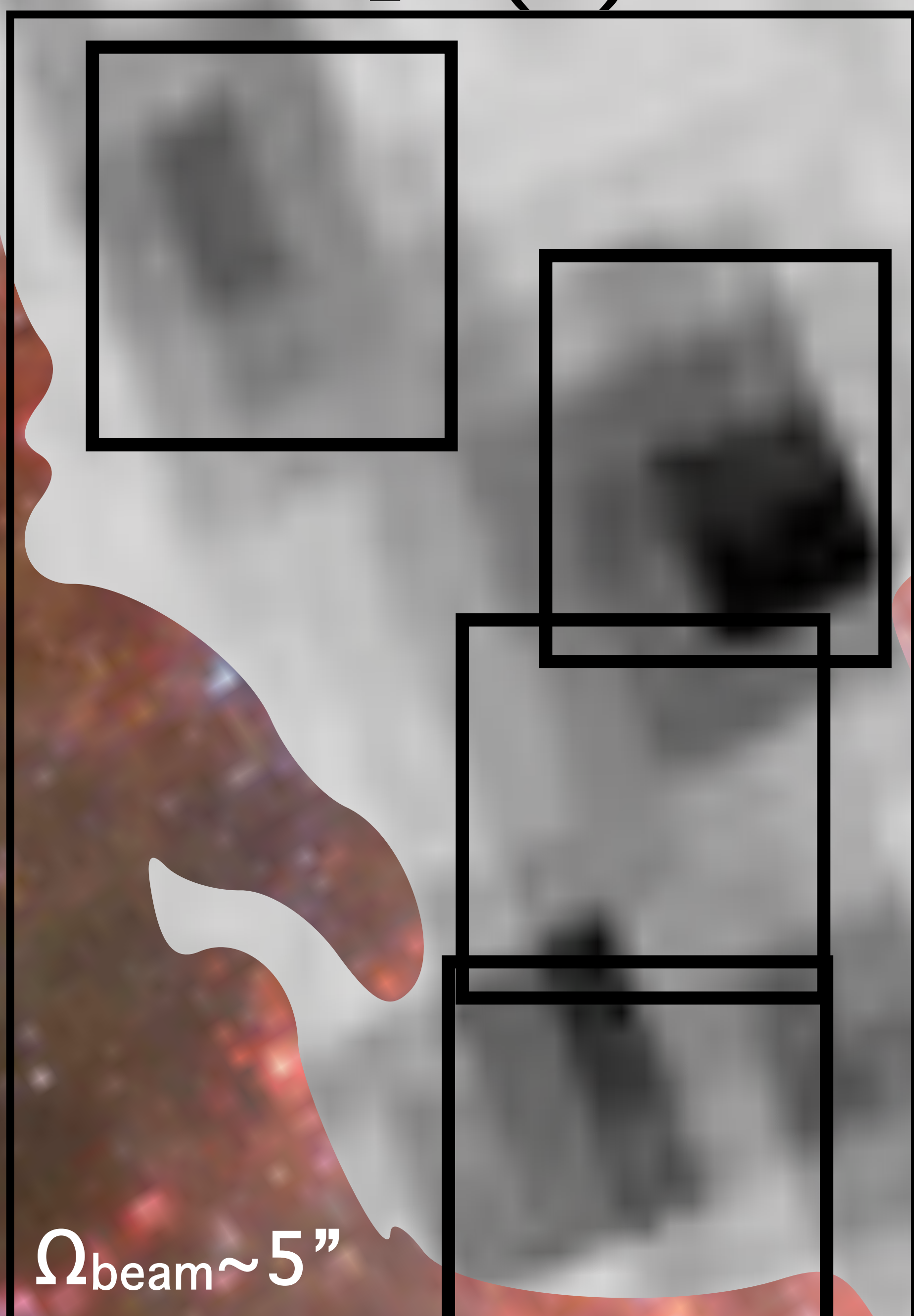


The Antennae galaxy merger



The Antennae galaxy merger

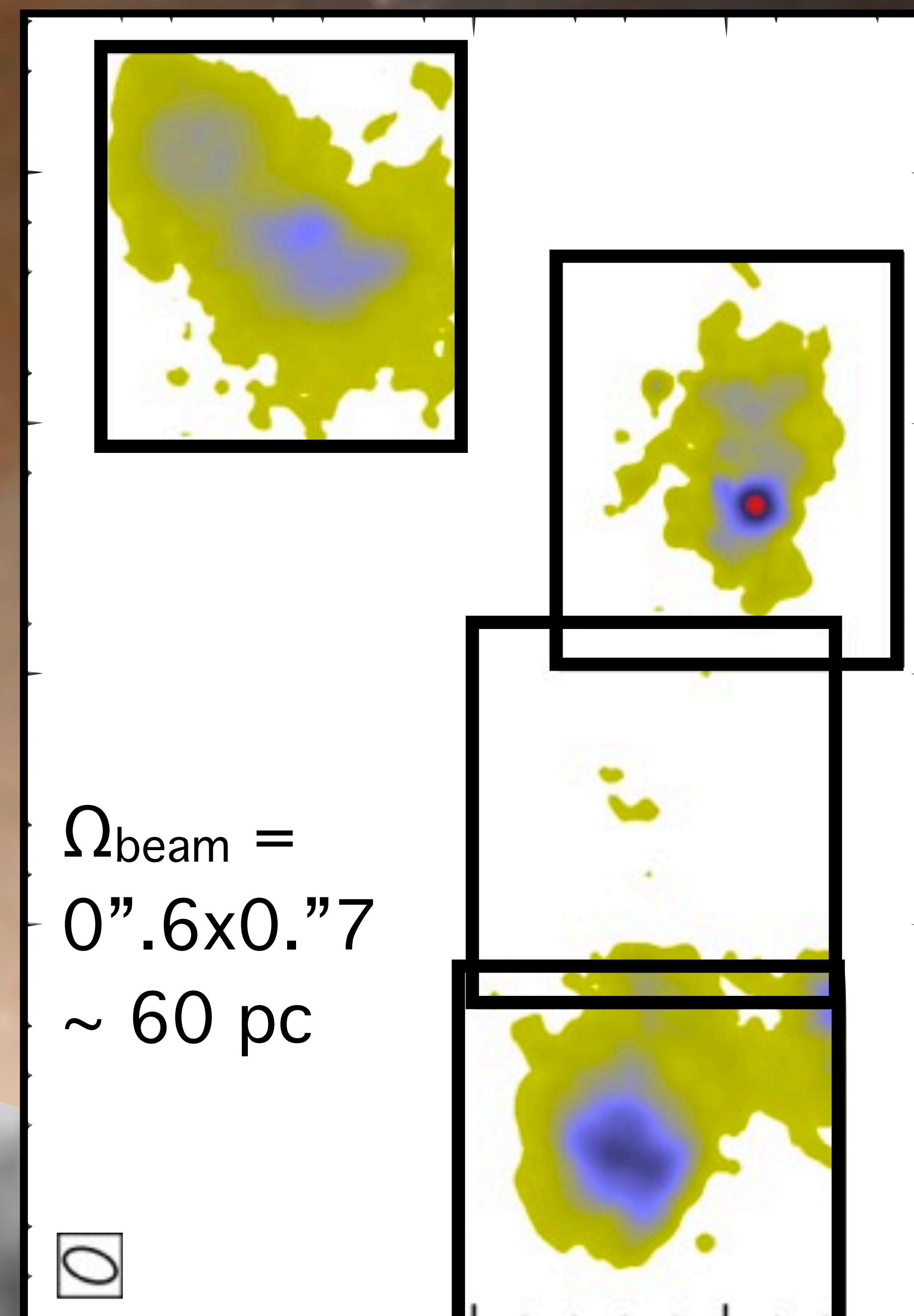
H_2 S(3)



Brandl et al. (2009)

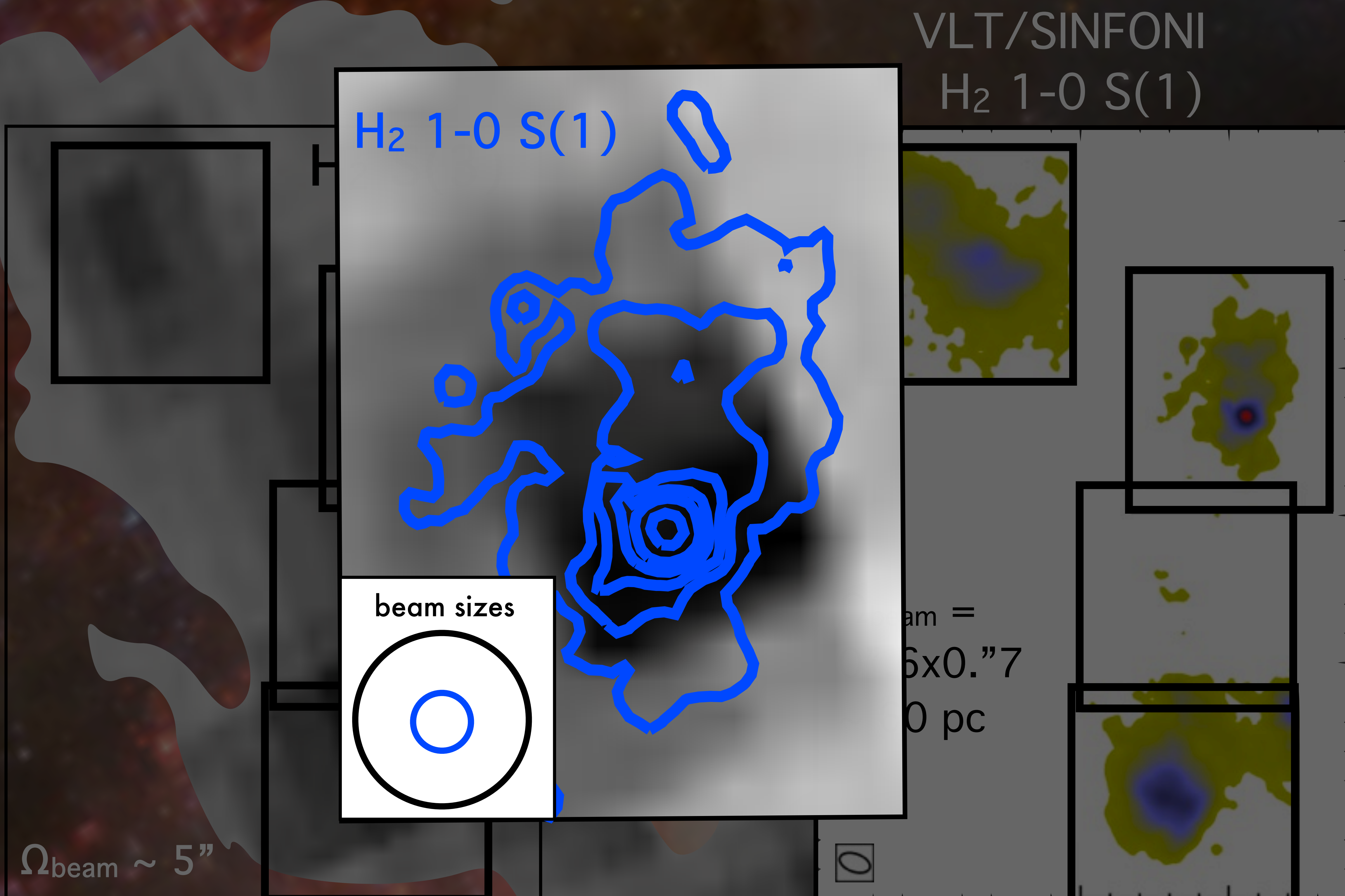
VLT/SINFONI

H_2 1-0 S(1)



Herrera et al. (2011, 2012)

The Antennae galaxy merger



Brandl et al. (2009)

Herrera et al. (2011, 2012)

Nature of the H_2 emission

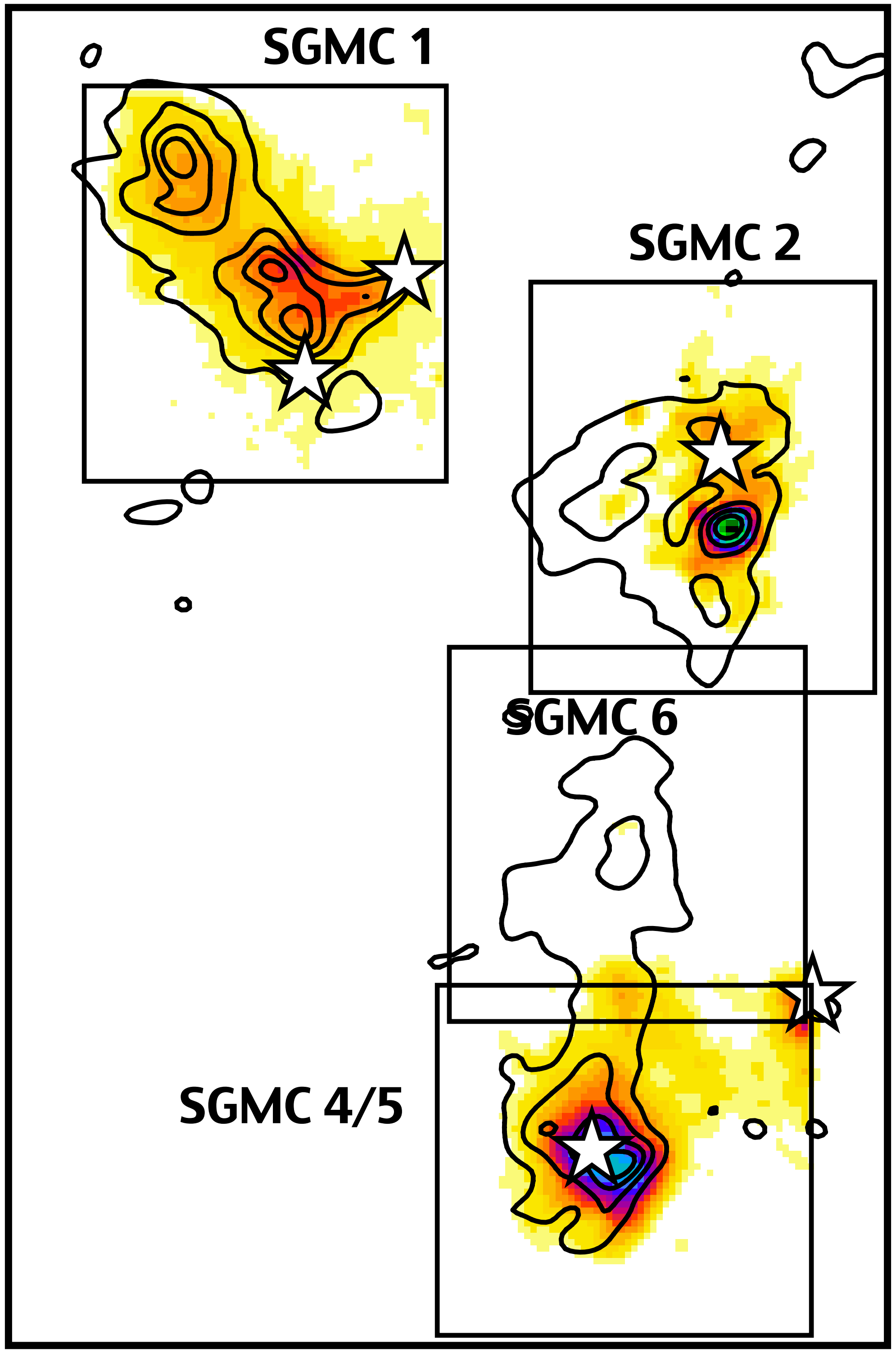


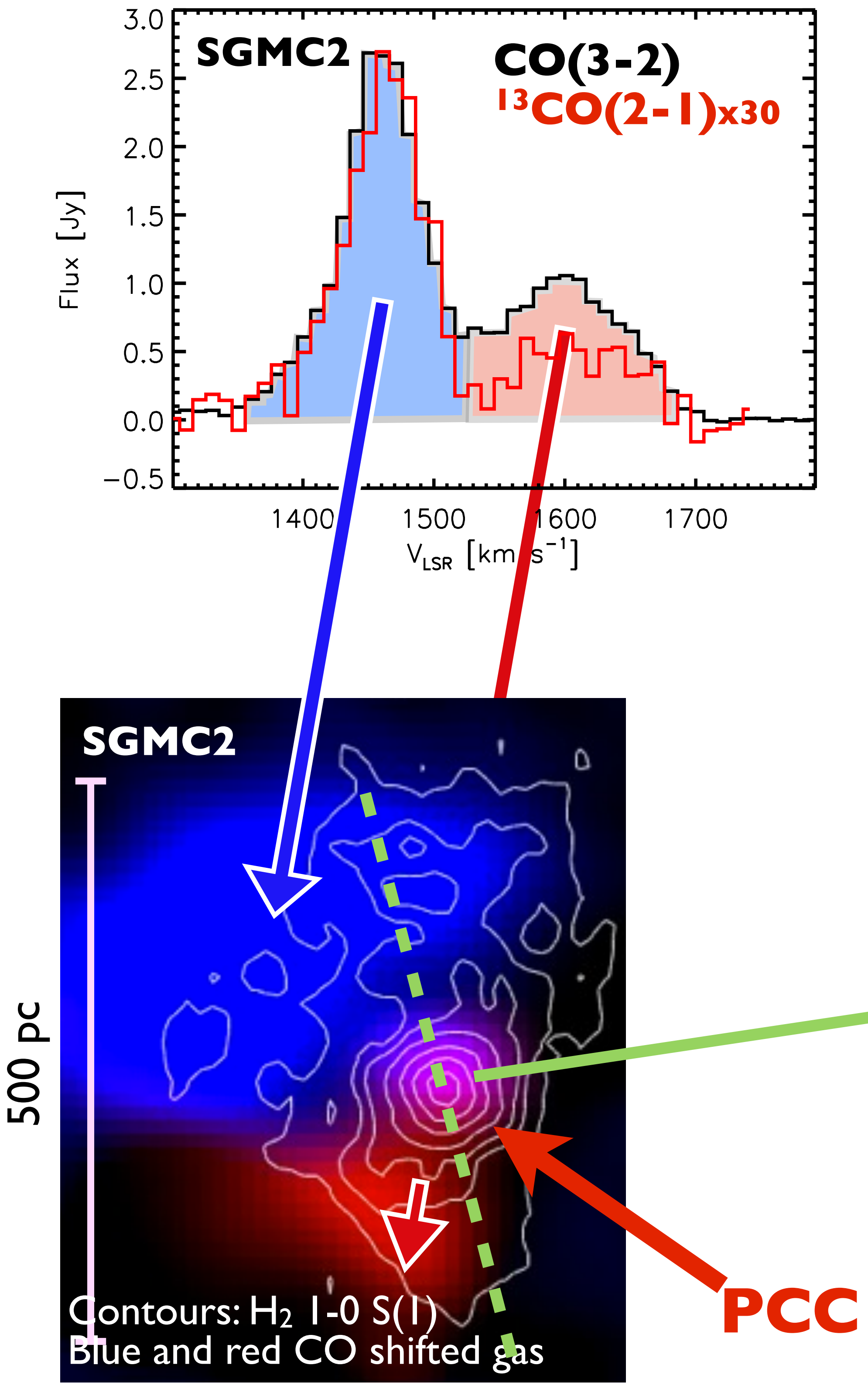
Image: H_2 1-0 S(1)
Contours: CO(3-2)

- Near-IR H_2 emission is bright and diffuse and associated to SGMCs.
- Extinction-independent diagnostics H_2 2-1/1-0 S(1), H_2 1-0 S(1)/ Brγ
  ➜ H_2 emission is shock excited

H_2 emission is tracing the dissipation of the mechanical energy of the gas driven by the galaxy interaction (Herrera et al. 2011).

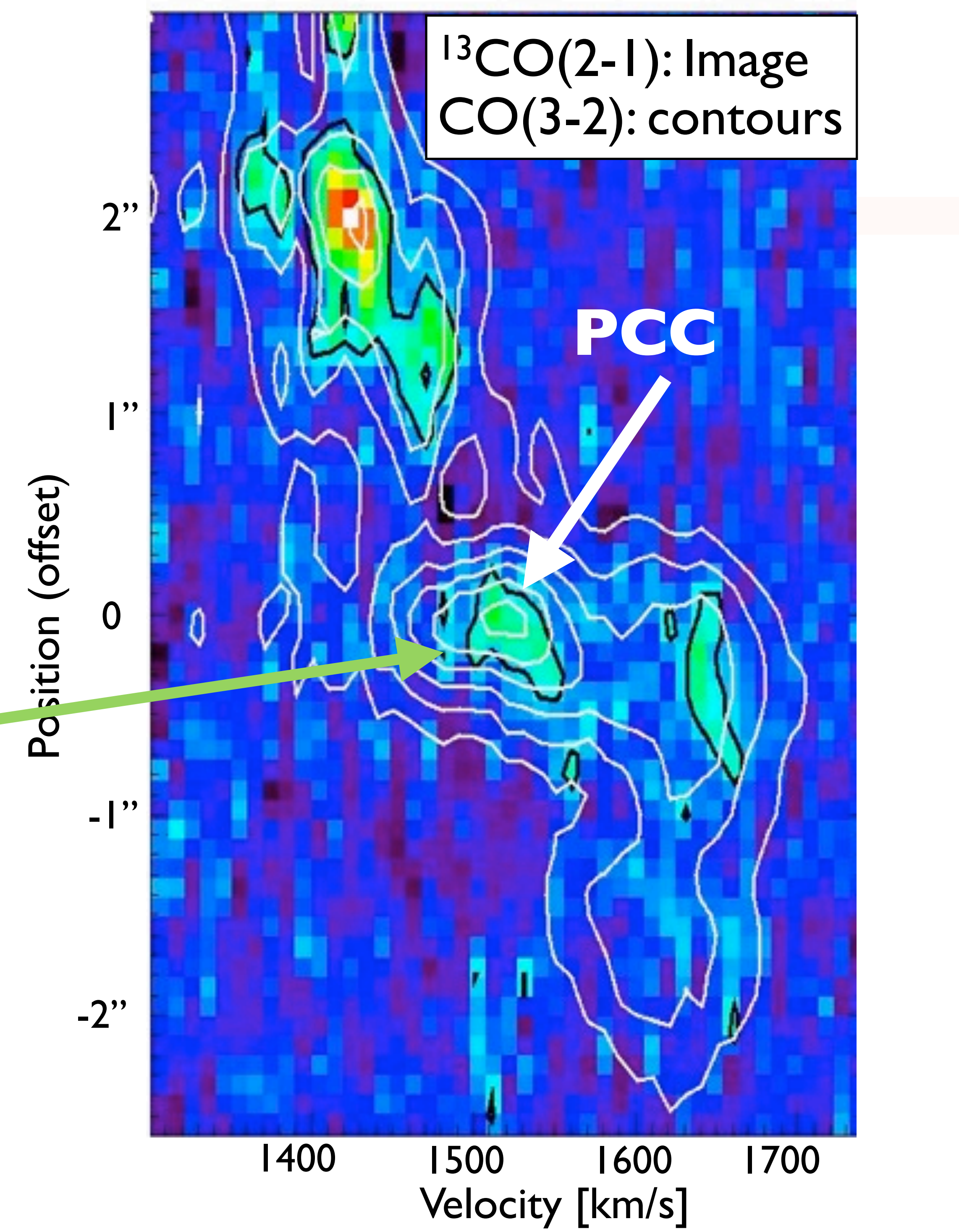
There is a **unique** source where the H_2/CO ratio is the largest. **Localized mechanical energy dissipation.**

H_2 compact source

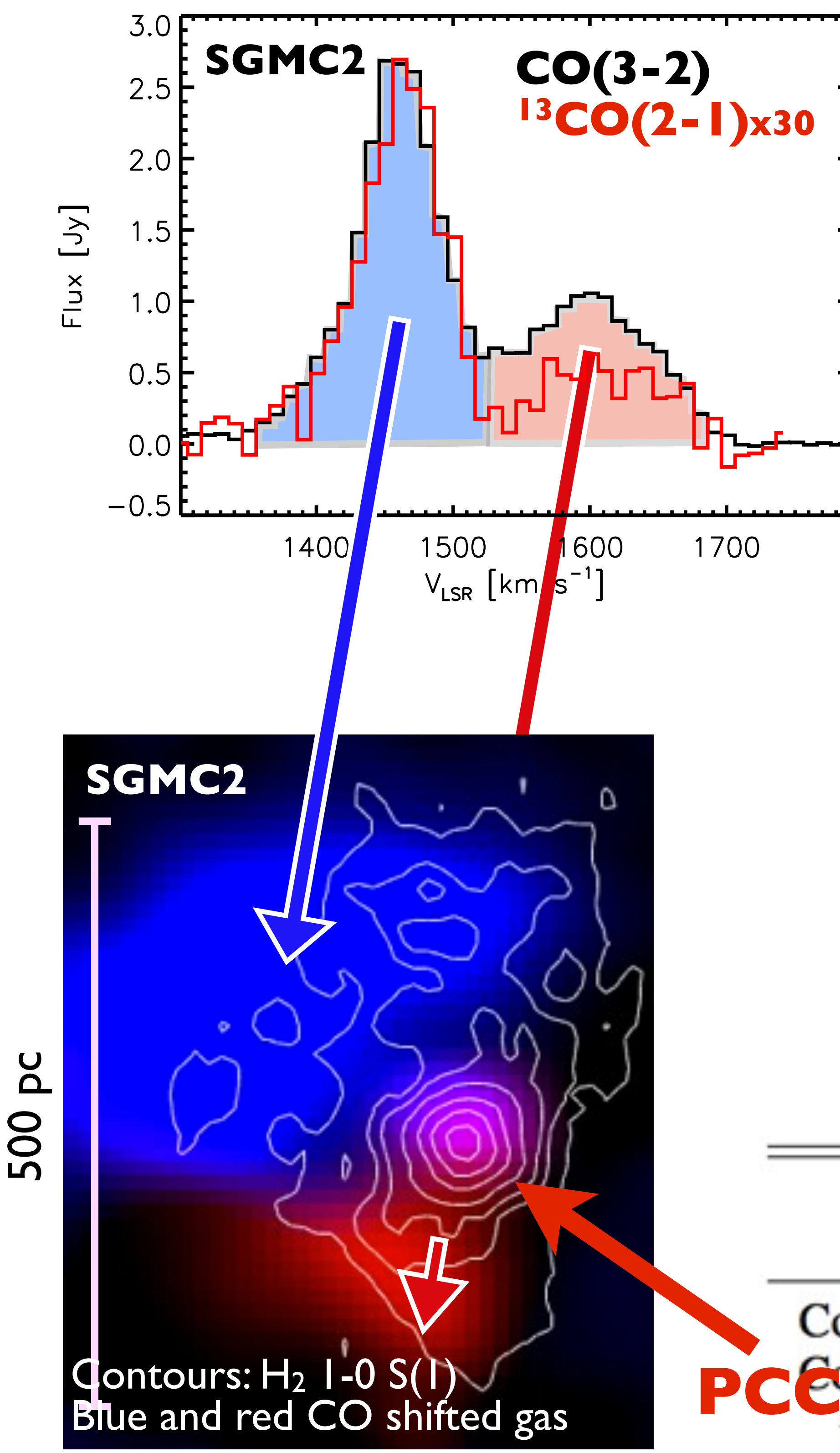


Herrera et al. (2012)

- Located in the SGMC2, where the velocity gradient is the steepest, at the interphase of blue and red shifted gas.



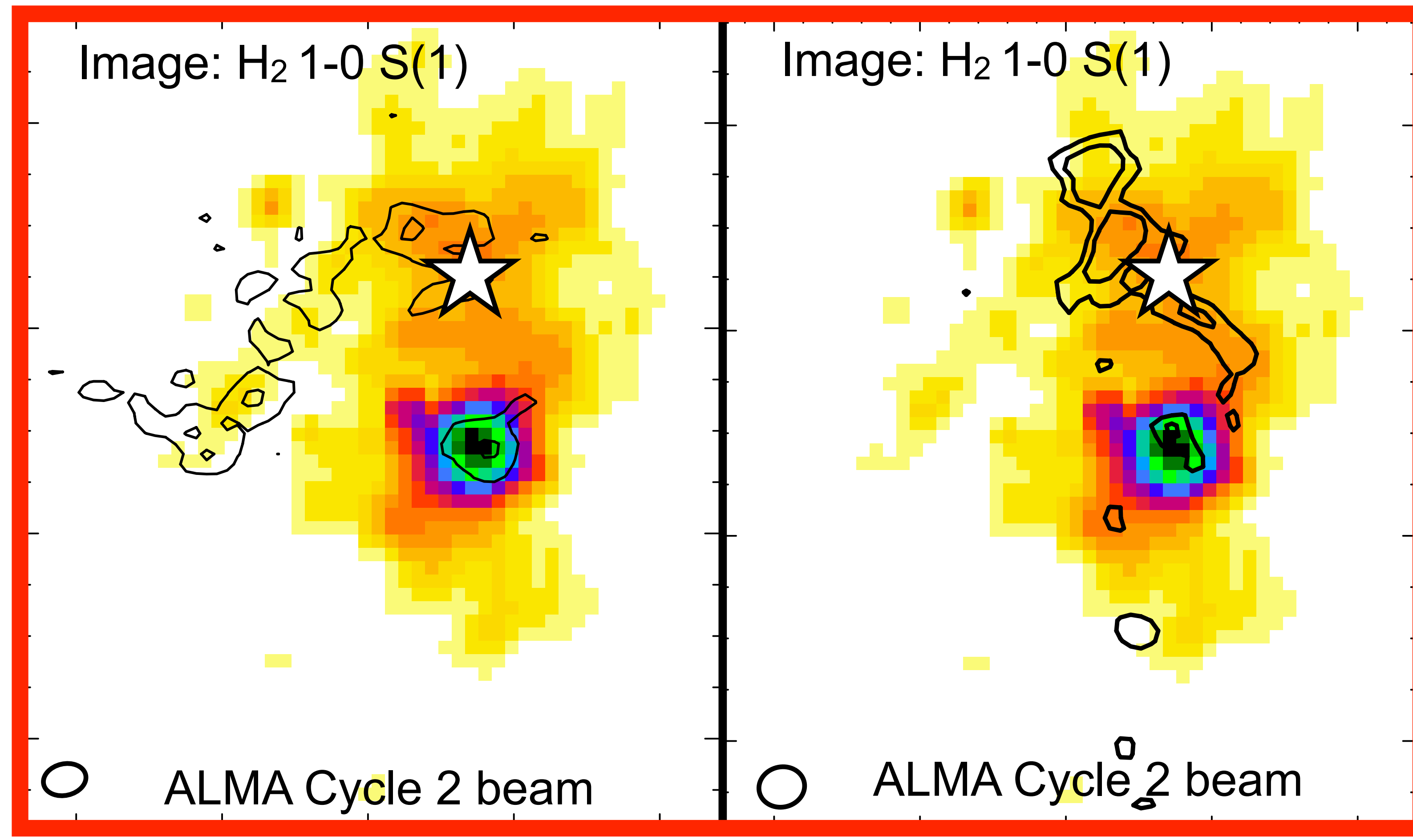
H_2 compact source



Herrera et al. (2012)

- Very bright in H_2, $L_{H2} = 2 \times 10^6\ L_\odot$
- Source is compact ($\lesssim$50 pc)

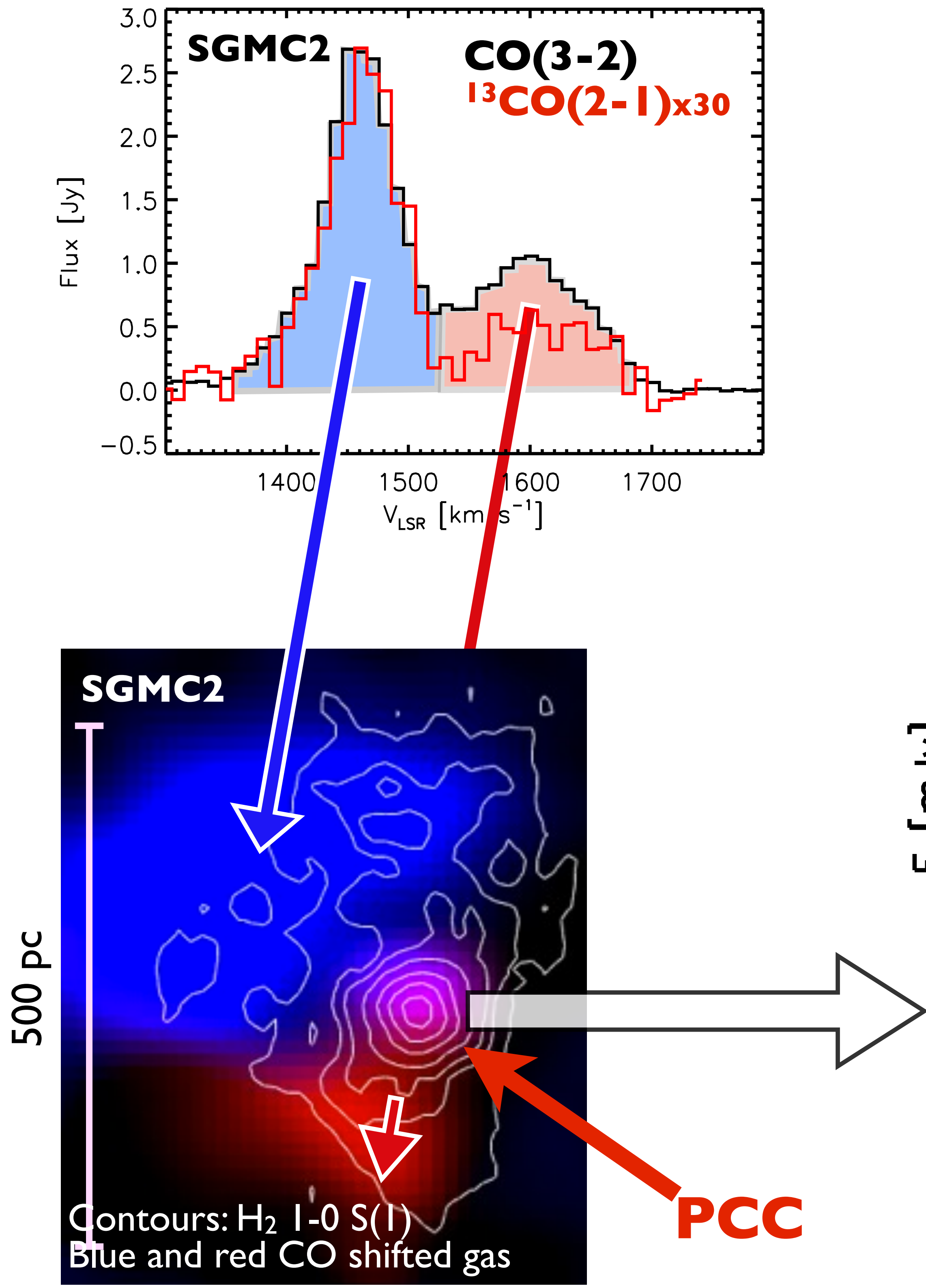
$^{13}CO(2\text{-}1)$ Continuum



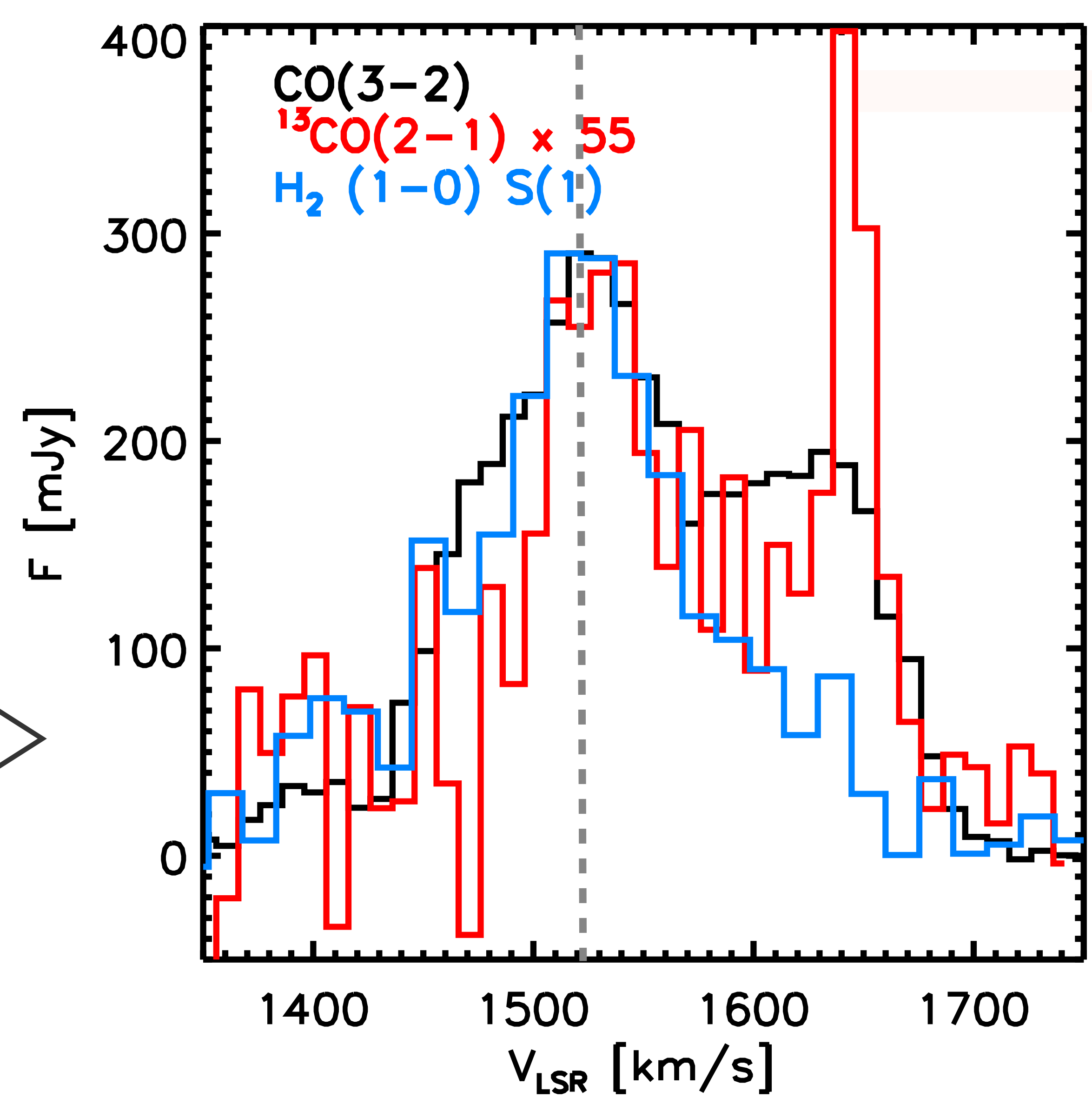
Line	Geometric Size FWHM	Geom. Ω_{beam}		Deconvolved source size	
Cont 217 GHz	0″.55±0.03	0″.42	45 pc	0″.37±0.03	40±6 pc
Cont 348 GHz	0″.44±0.02	0″.47	50 pc	beam limited	50 pc
$^{13}CO(2\text{–}1)$	0″.52±0.03	0″.36	38 pc	0″.37±0.03	40±3 pc
$^{12}CO(3\text{–}2)$	0″.68±0.002	0″.49	52 pc	0″.47±0.002	50.4±0.2 pc

H_2 compact source

- FWHM of H_2 and CO lines are ~90 km/s.
- $M_{vir} = 5R\sigma^2/G \sim 4\times10^7 \ M_\odot$

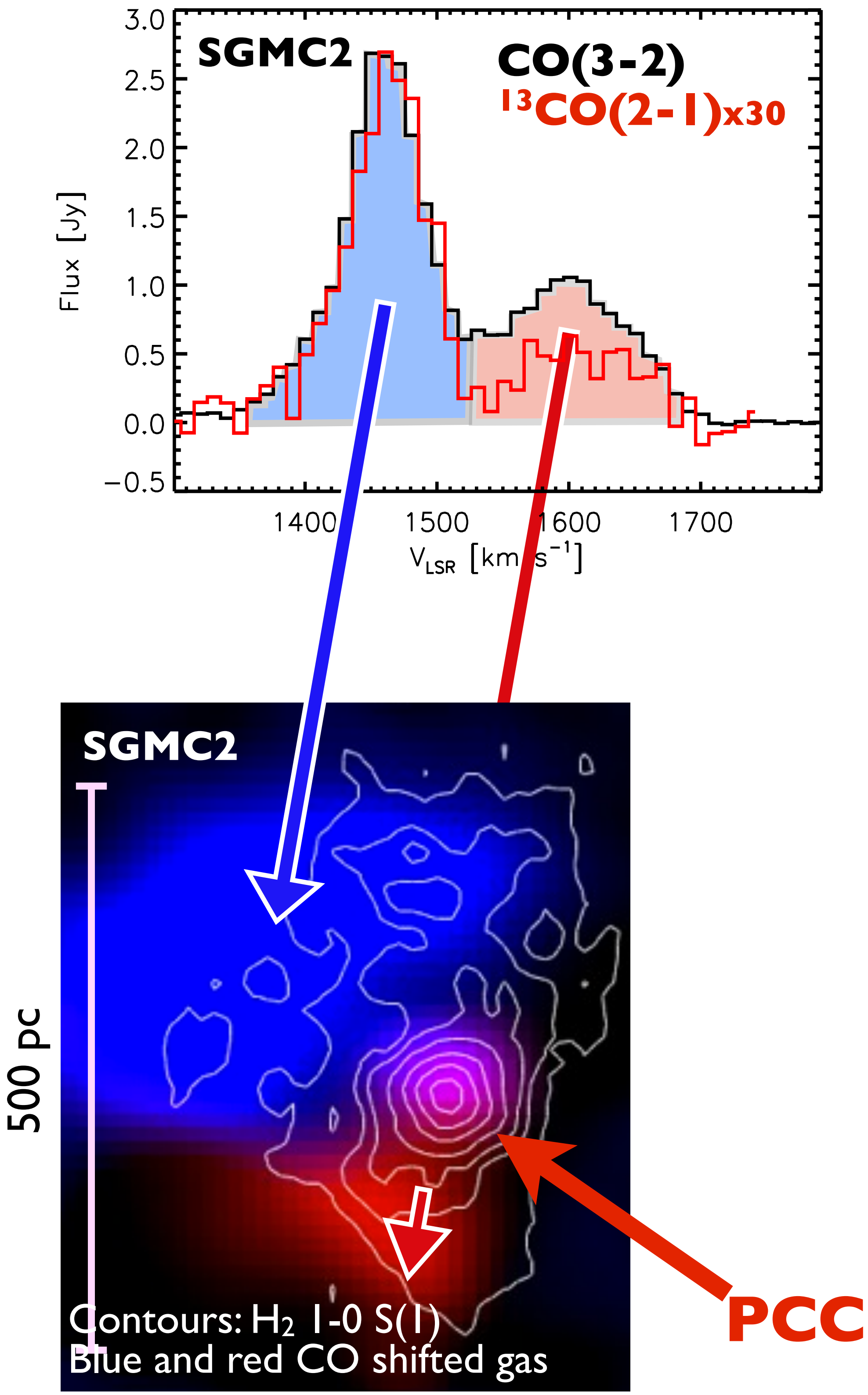


Herrera et al. (2012)

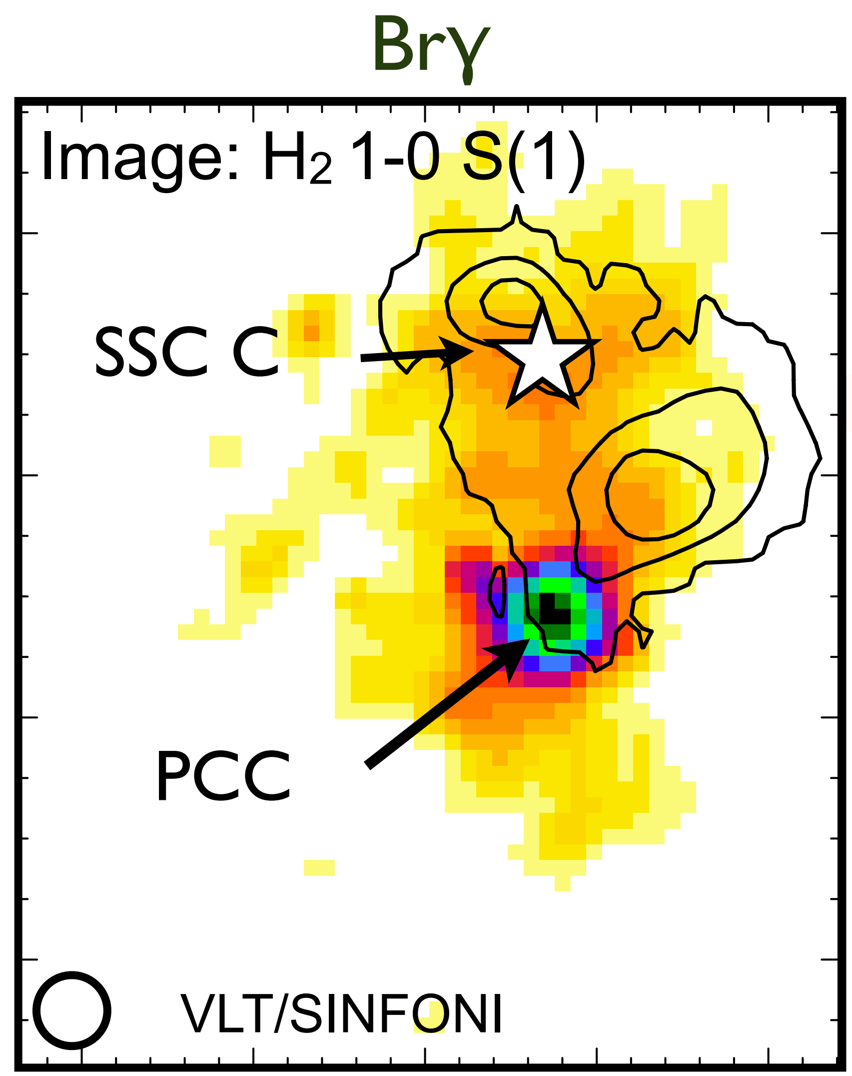


H_2 compact source

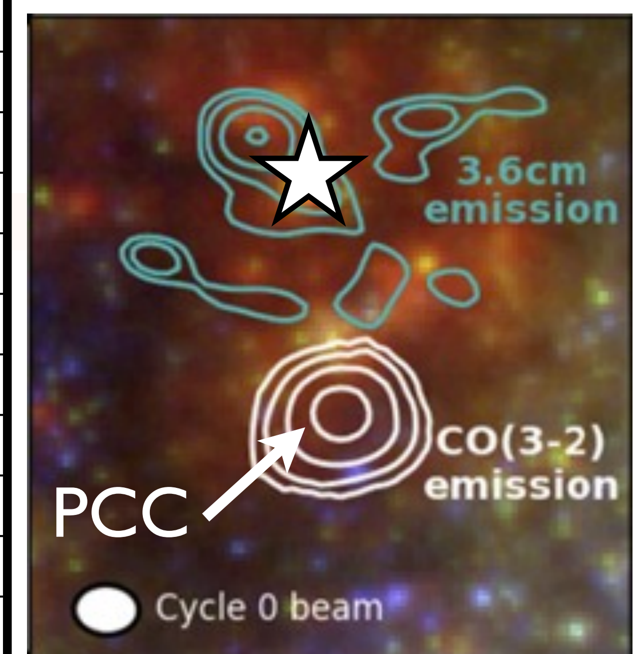
- Very little star formation (from no detection in Paα and radio obs.) $M_\star < 10^4\ M_\odot$ (Johnson et al. 2015).



Herrera et al. (2012)

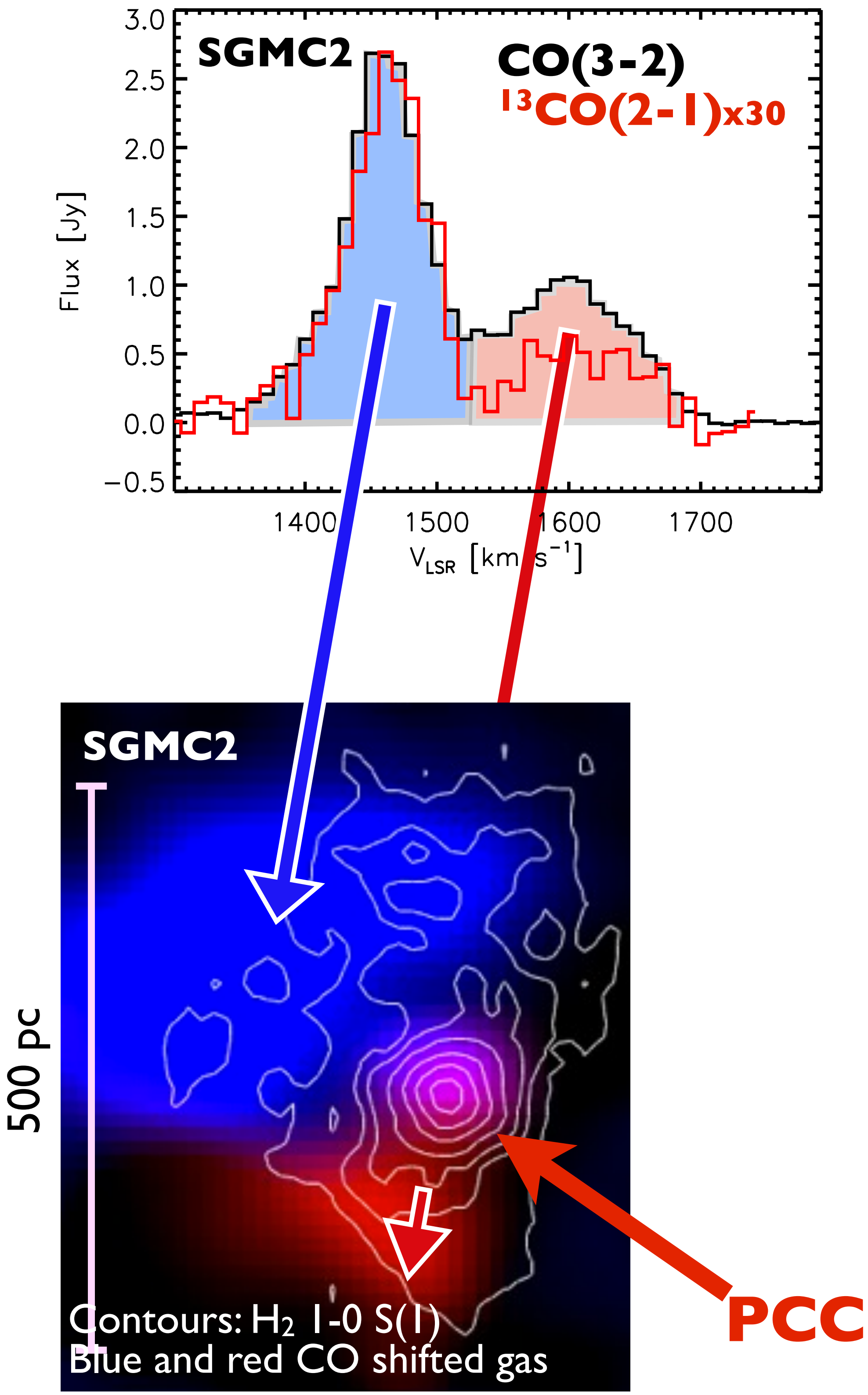


Herrera et al. 2011



Johnson et al. 2015

H_2 compact source



Herrera et al. (2012)

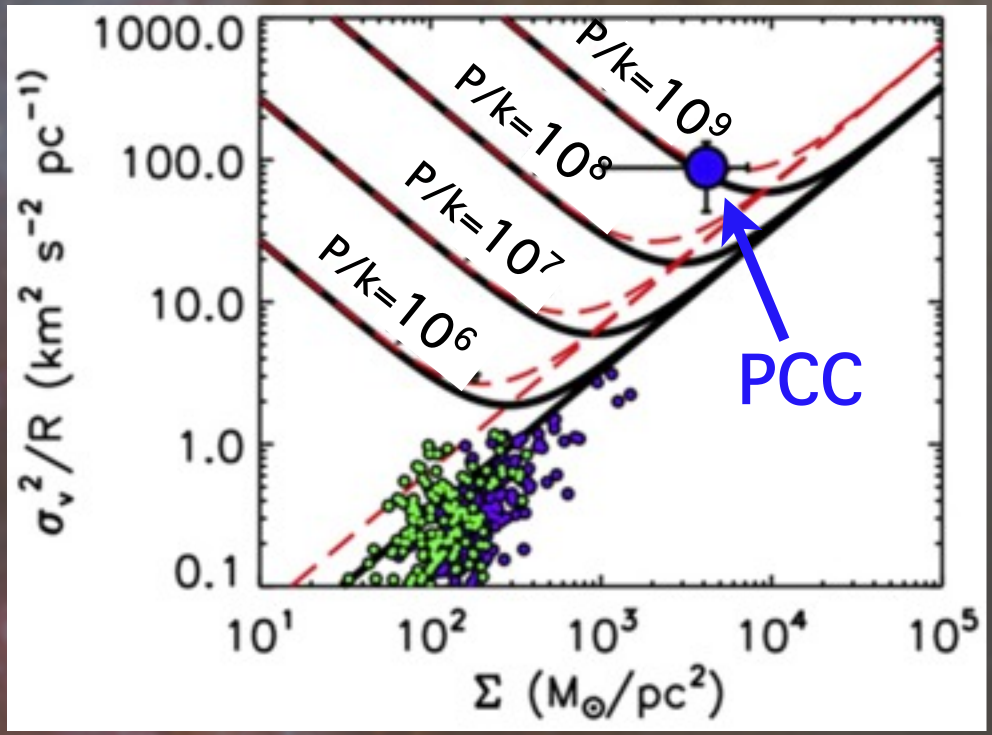
- Source is compact ($\lesssim$50 pc)
- Very bright in H_2, $L_{H2} = 2\times10^6\ L_\odot$
- Located at the interphase of blue and red shifted gas.
- FWHM of H_2 and CO lines are ~90 km/s.
- $M_{vir} = 5R\sigma^2/G \sim 5\times10^7\ M_\odot$
- Very little star formation ($M_\star<10^4\ M_\odot$)

Have we discovered a massive cloud which will form a SSC as the gas turbulent energy dissipates?

H_2 compact source: Dynamical state?

$M_{1.3mm} = 3.7 \pm 1.6 \times 10^6\ M_\odot \ll M_{dyn} \sim 4 \times 10^7\ M_\odot$

The source is not a gravitationally bound cloud



→ bound by external pressure?

(Johnson et al. 2015)

It needs $P_{ext} \sim 10^9$ K cm^{-3}

Overlap region:

- 5 massive ($>10^5\ M_\odot$) and young (<5 Myr) SSCs (Whitmore et al. 2010).
- 1 Pre-cluster cloud

We have identified a short evolutionary stage in the formation of SSCs.

$\tau_{diss} \sim \tau_{cross} \sim 1$ Myr

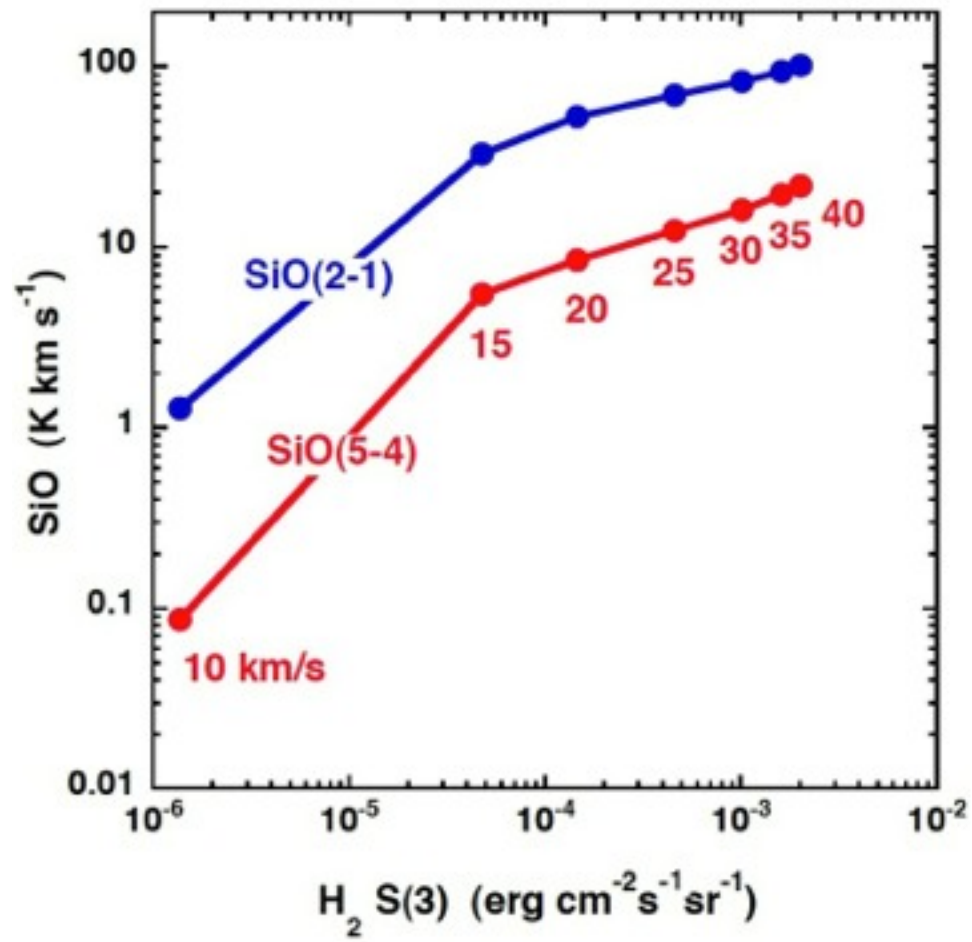
H_2 exquisite dissipation tracer in starbursts

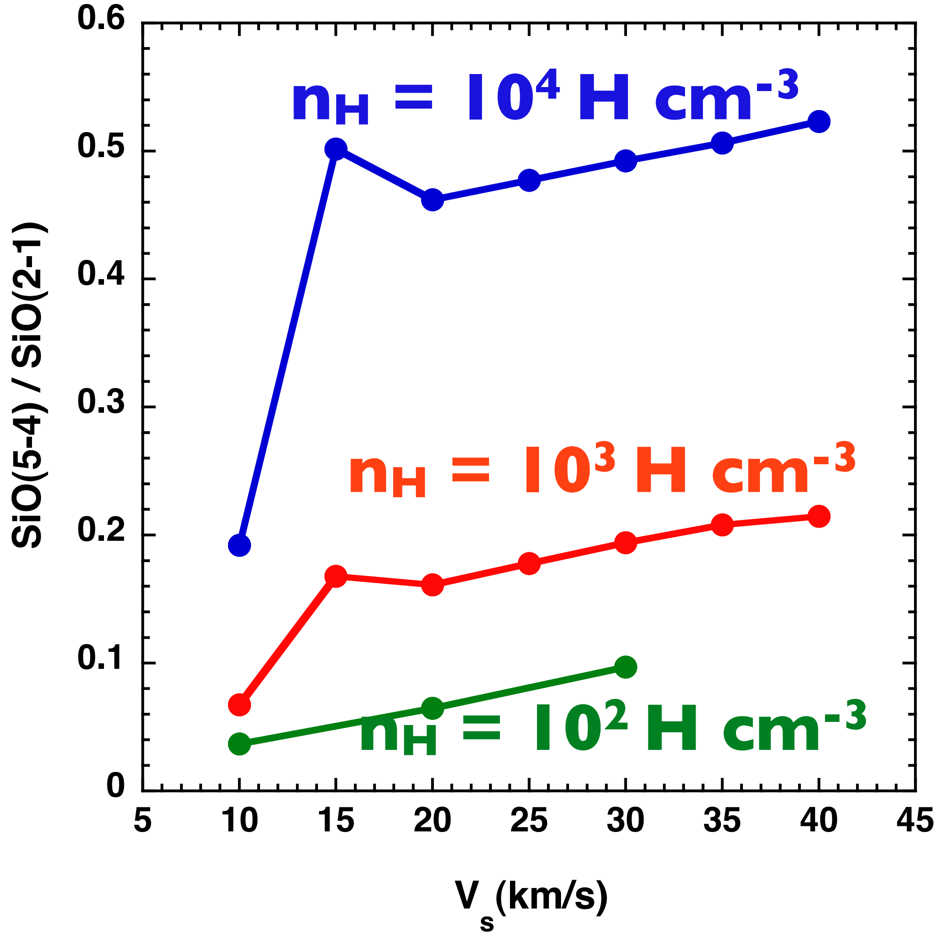
H_2 is tracing the dissipation of energy and is powered by shocks.

$n_H = 10^3$ H cm^{-3}

C-shocks
SiO on mantles (8% of [Si])

MHD shock models
(Flower & Pineau des Forets 2010)





But, no detection of SiO(2-1) nor SiO(5-4) with ALMA. Background radiation field of ~10^3 G_0 may destroy this molecule (P. Lessafre priv. comm.).

In starbursts galaxies we NEED to look at H_2!

Plans with the JWST

H_2 line emission are exquisite tracers of the dissipation of kinetic energy in the cold ISM of the Antennae through shocks.

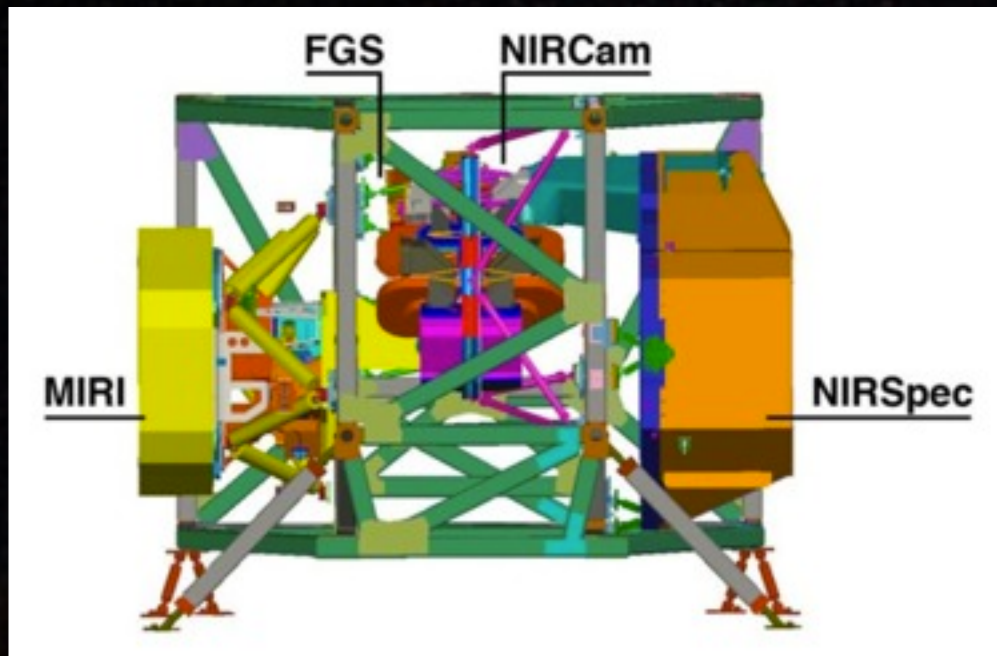
With the JWST we will look for PCC-like sources in starburst galaxies

- Compact sources (<50pc) → 0.”2 @ 50 Mpc
  0.”3 @ 34 Mpc
- H_2 luminous ($>10^6\ L_\odot$)

We will complement JWST (H_2) with ALMA (CO)

- Survey of H_2 emission in large sample.
- Statistics to constrain the evolutionary timescale of SSC progenitors.
- With spectroscopy, study their velocity structure: dynamics!

Plans with the JWST



MIRI IFU:

Medium Resolution Spectrograph

4 IFUs to cover 5-28 μm

FOV:

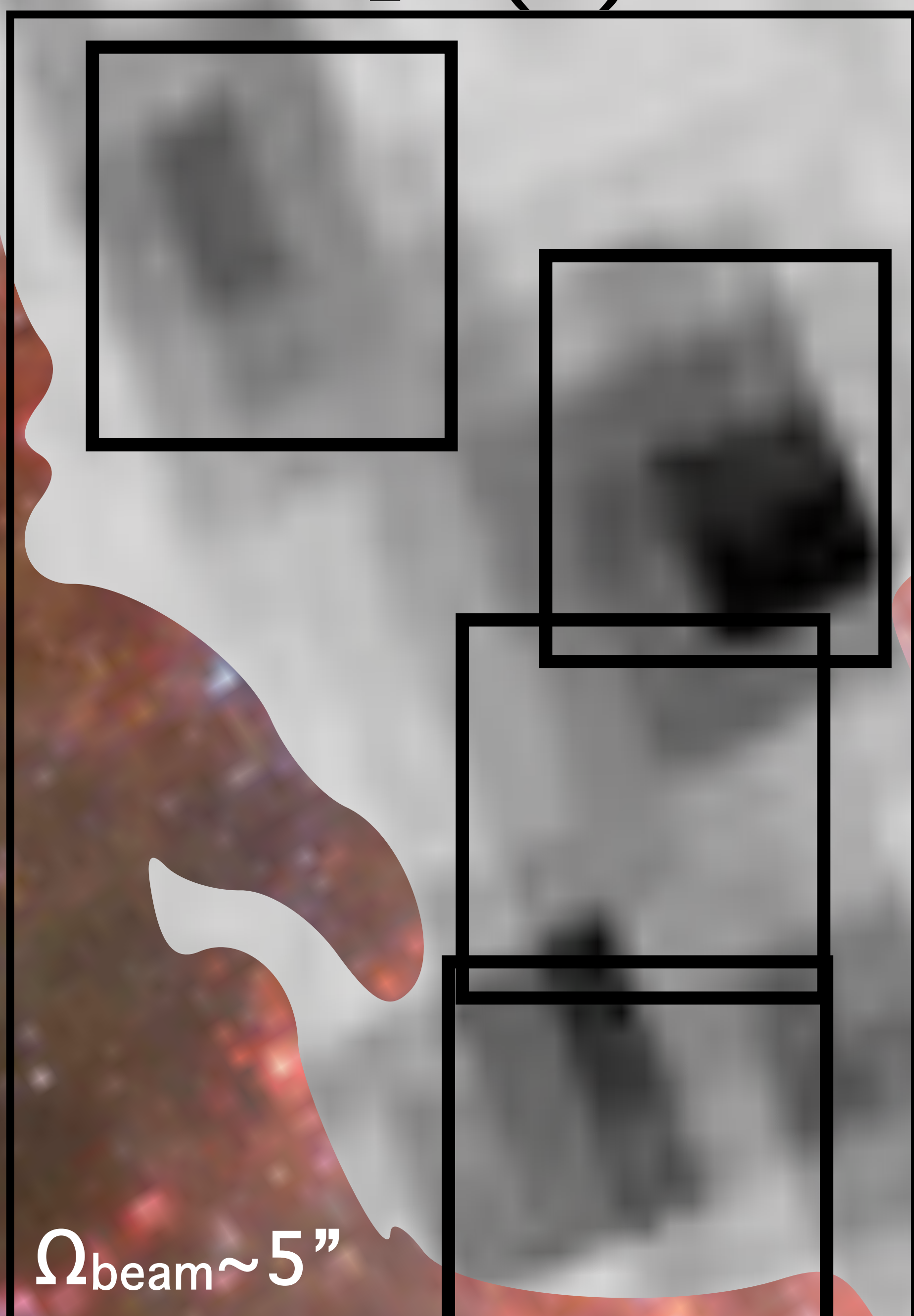
3.”6x3.”6 to 7.”6 x 7.”6 (~6”x6” for H_2 S(2)).

Angular resolution:

0.”2x0.”2 to 0.”6x0.”3 (0.”4x0.”2 for H_2 S(2))

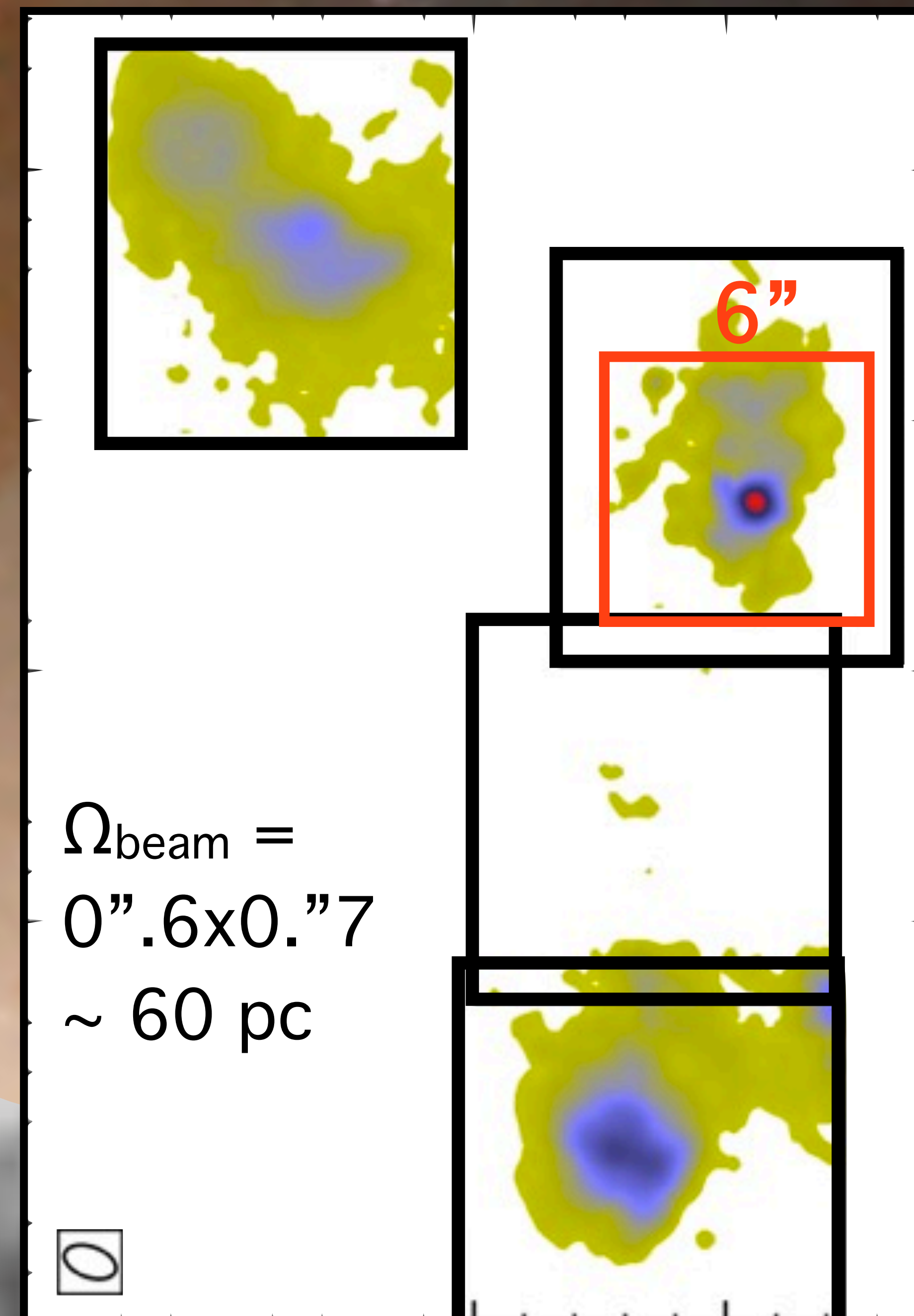
The Antennae galaxy merger

H_2 S(3)



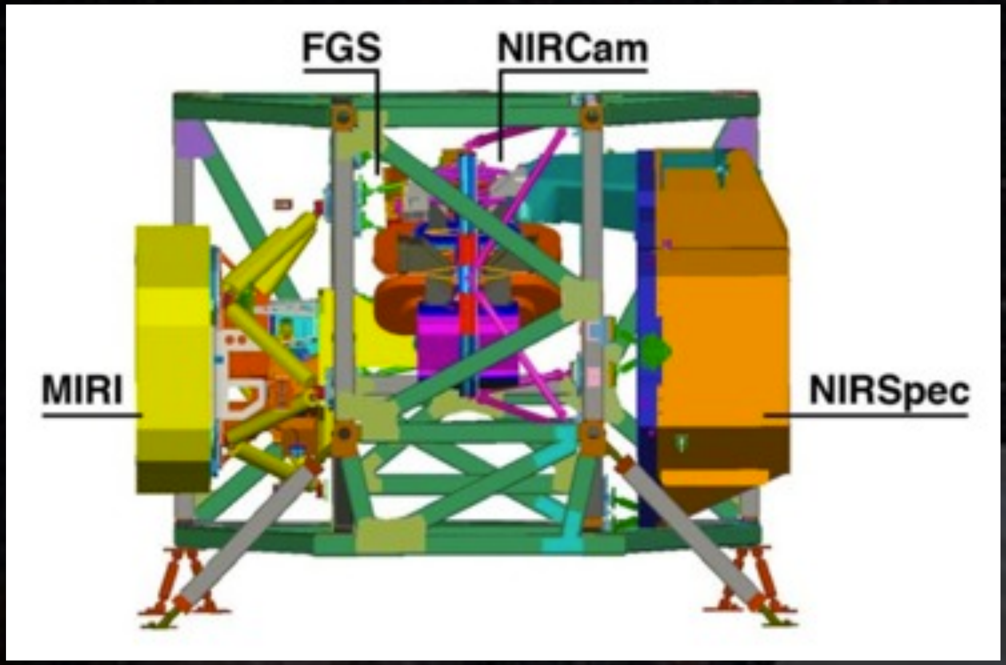
Brandl et al. (2009)

VLT/SINFONI
H_2 1-0 S(1)



Herrera et al. (2011, 2012)

Plans with the JWST



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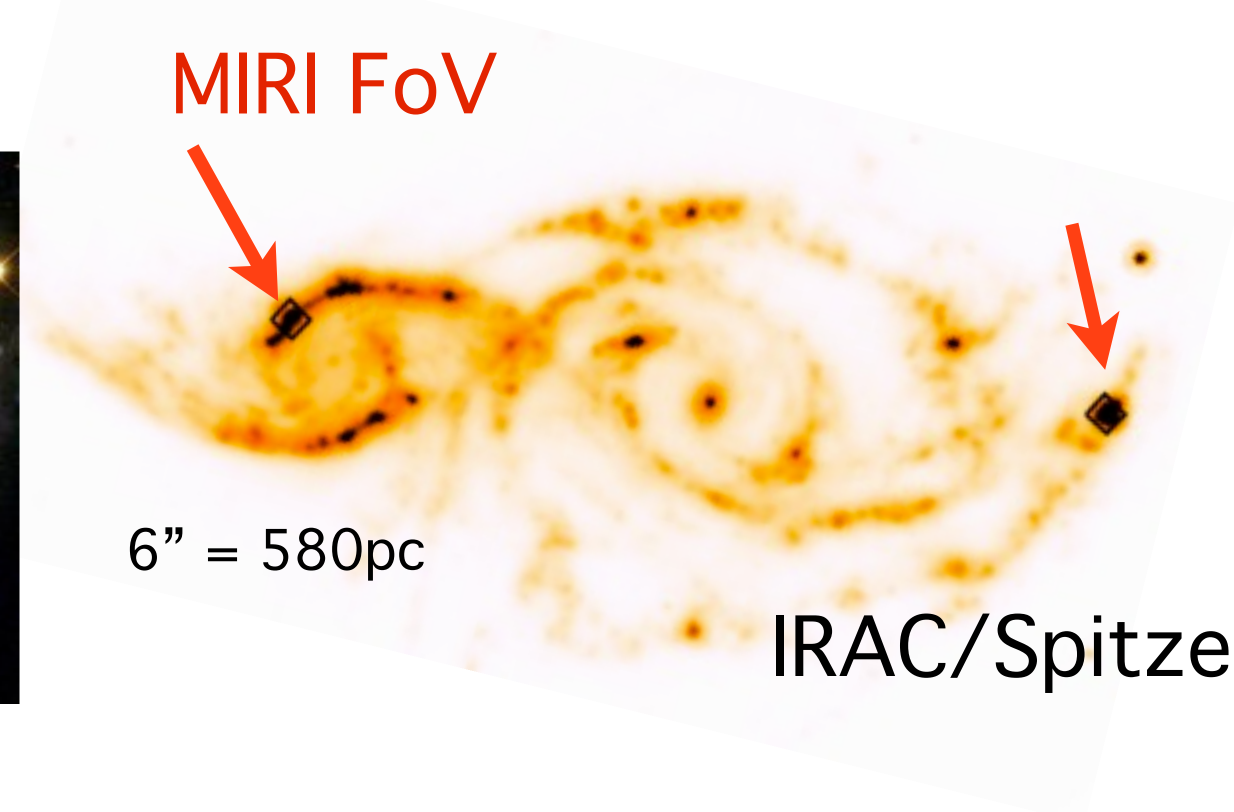
Angular resolution:
0.”2x0.”2 to 0.”6x0.”3 (0.”4x0.”2 for H_2 S(2))

En 2.7h, S/N=10, ➜ **sensitivity:** 1 - 6x10^{-20} W/m^2

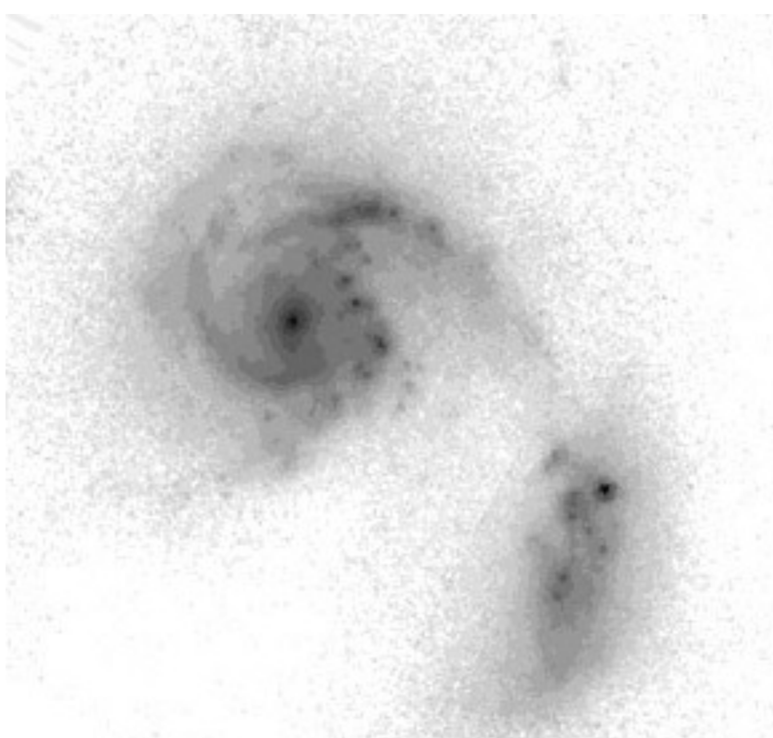
For PCC-like sources, 2x10^{-16} W/m^2

vs ~10h imaging H_2 S(2)
VISIR/VLT

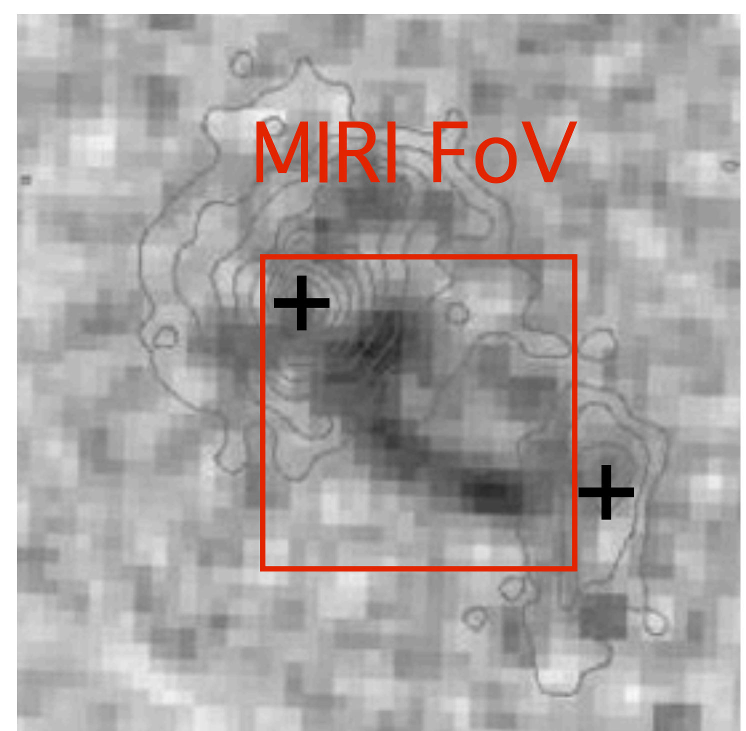
Galaxies @ 20Mpc



Galaxies @ 120 Mpc



NGC6090



NGC6090

6” = 3.5 kpc

Image: H_2
Contour: K-band

Summary

- Discovery of early steps in the formation of super star clusters by looking at H_2 as tracer of energy dissipation.
- The non-detection of SiO tell us that, in starbursts, H_2 line emission are exquisite tracers of the dissipation of kinetic energy in the cold ISM through shocks.
- JWST reaches resolutions to do complementary studies with ALMA (cold molecular component).
- With the JWST, we will be able to study the formation of massive star cluster by discovering and characterizing their progenitor clouds.