The formation of super-stellar clusters

François Boulanger
Institut d'Astrophysique Spatiale

Cynthia Herrera, Edith Falgarone, Pierre Guillard, Nicole Nesvadba, Guillaume Pineau des Forets

Outline

How do massive (globular-like) stellar clusters form ?

- ★ Background
  - Young massive clusters in starburst galaxies
  - H_2 and the JWST
  - Turbulence and star formation
- ★ Discovery of a massive H_2 luminous cloud in the Antennae
  - It is likely to be the first known progenitor of a massive ($>10^5$ $M_\odot$) stellar cluster
- ★ JWST will discover a large sample of such clouds in the local universe

Massive star clusters

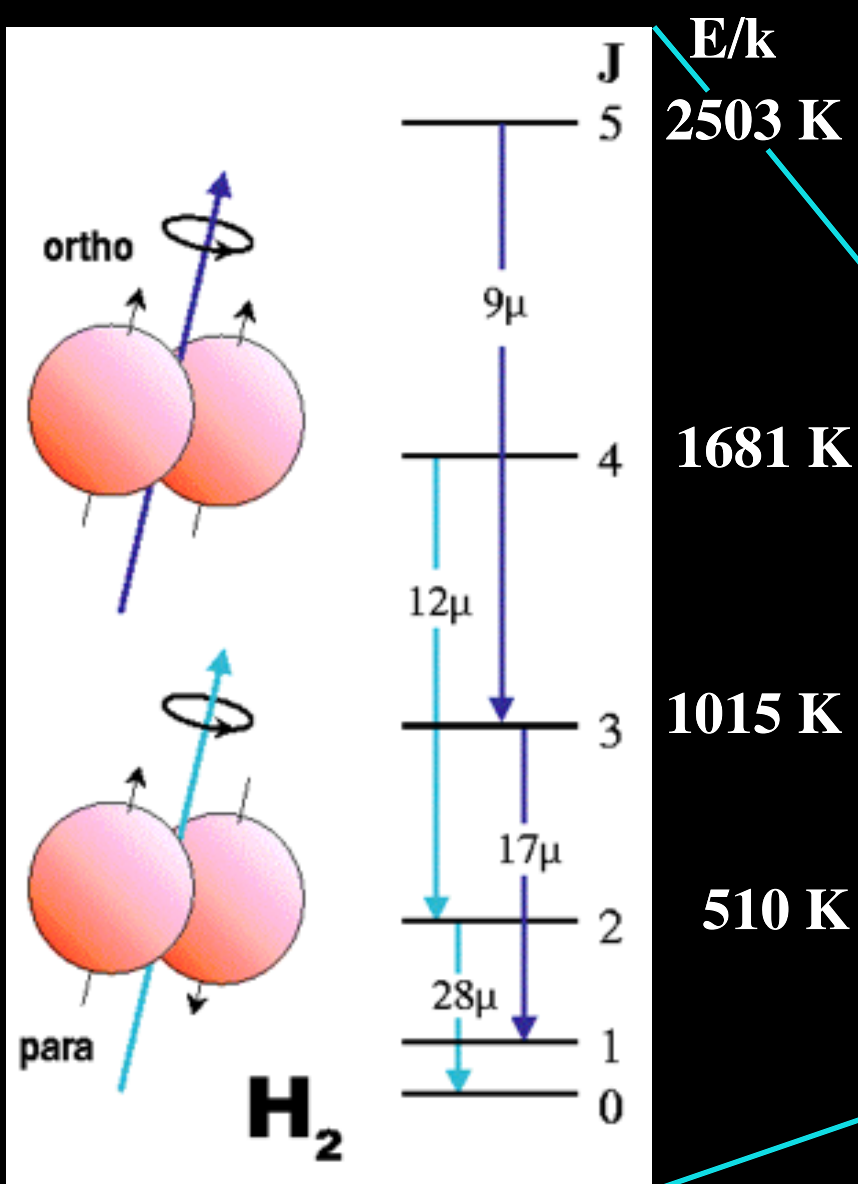
The Antennae by the HST

- ★ HST WFPC images of young massive clusters (YMCs) with half-light radii of a few pc and masses up to 10^6 Mo in virtually all the starburst galaxies observed, including dwarf galaxies.
- ★ The most massive are likely to be young globular clusters

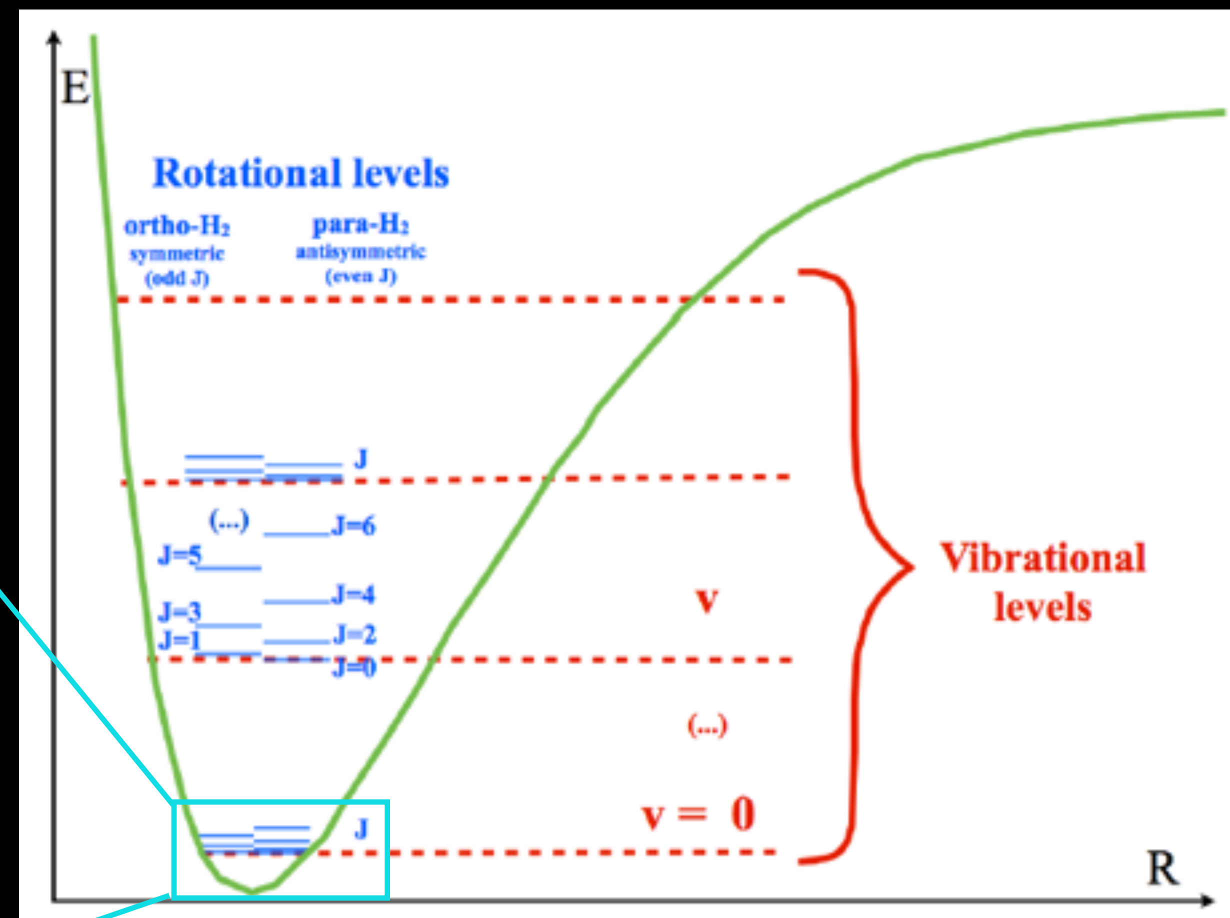
➡ **How do they form ?**

H_2 with the JWST

MIRI spectroscopy of H_2 rotational lines



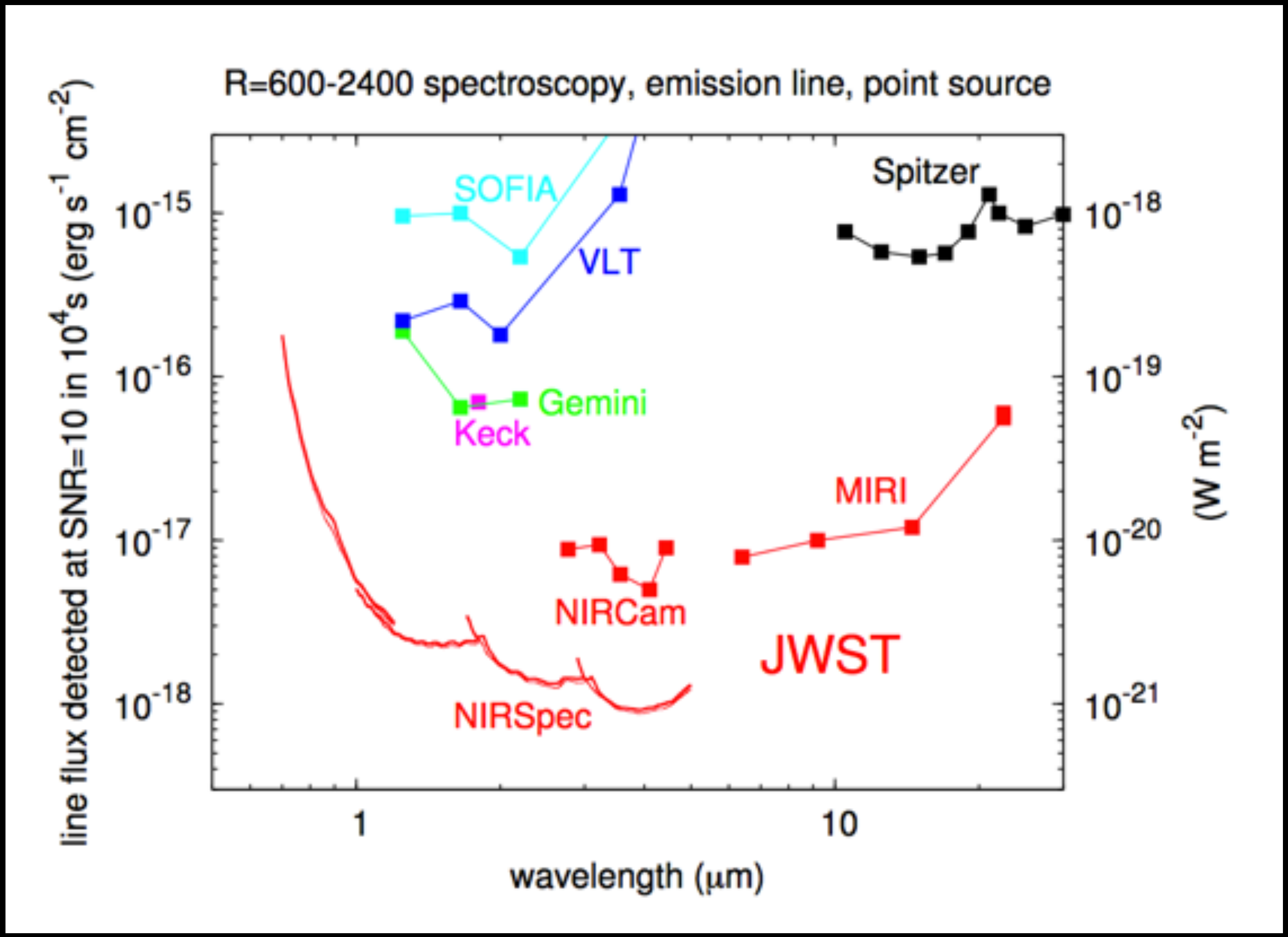
NIRSPEC spectroscopy of H_2 ro-vibrational lines

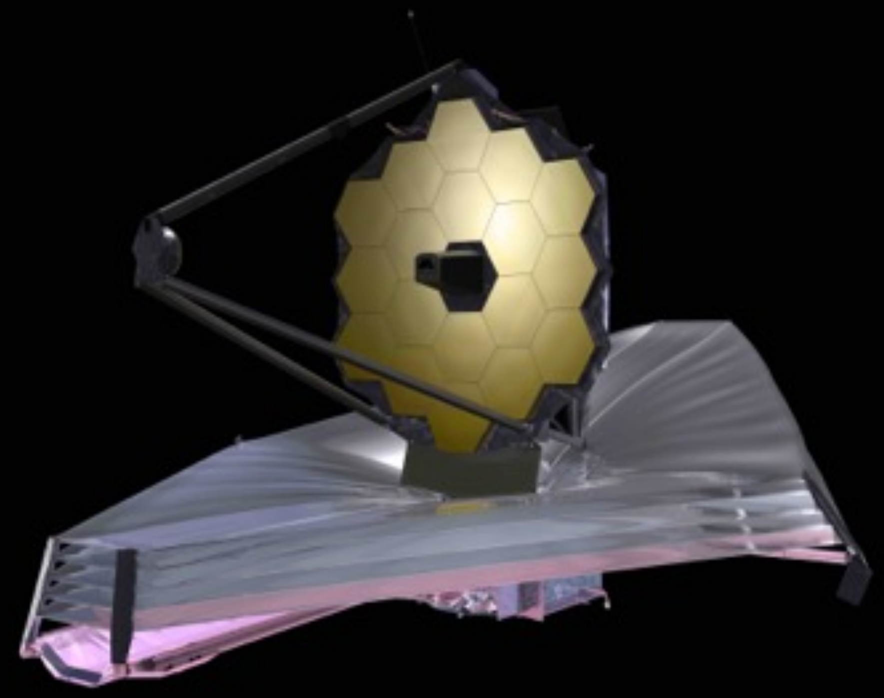


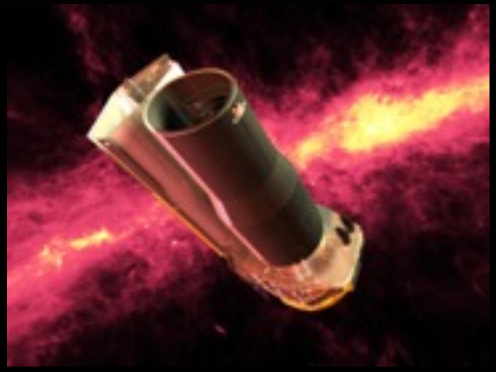
H_2 is the main coolant of molecular gas at $T \gtrsim 100$ K up to dissociation temperatures

H_2 line emission ↔ the energetics of the cold (star forming) gas

The JWST jump forward







★MIRI vs Spitzer spectrometer:

A factor 100 in sensitivity, 10 in angular resolution, 5-60 in spectral resolution

★NIRSPEC vs VLT/SINFONI

A factor 100 in sensitivity and 10 in angular resolution

Spectral diagnostics

Spectral diagnostics and modeling tools are available to identify H_2 emission powered by **turbulent energy dissipation** rather than UV heating

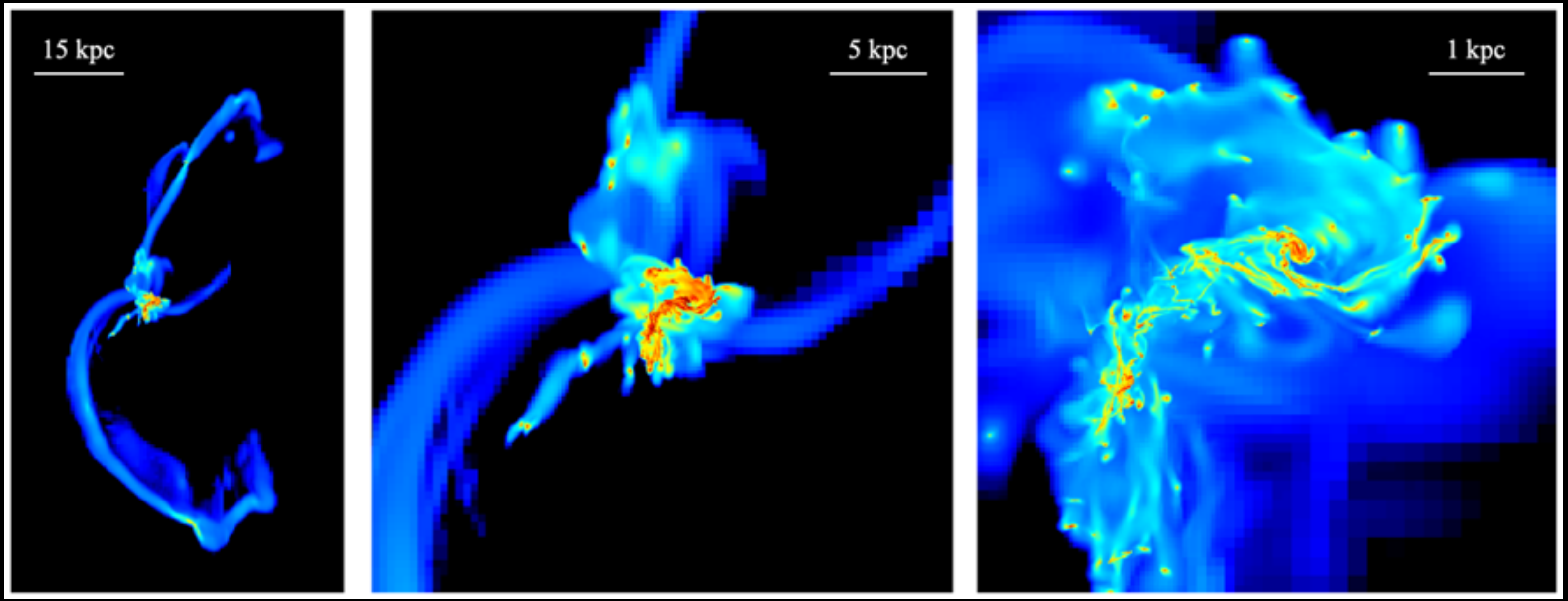
★ The JWST spectral range offers multiple diagnostics to assess H_2 excitation

- H_2 to PAH emission ratio (Pierre Guillard's talk)
- Intensity ratios of H_2 lines
- Ratios between H_2 and ionized gas lines

★ Much expertise and modeling tools available from the analysis of earlier data obtained with ISO and Spitzer

Turbulence in interacting galaxies

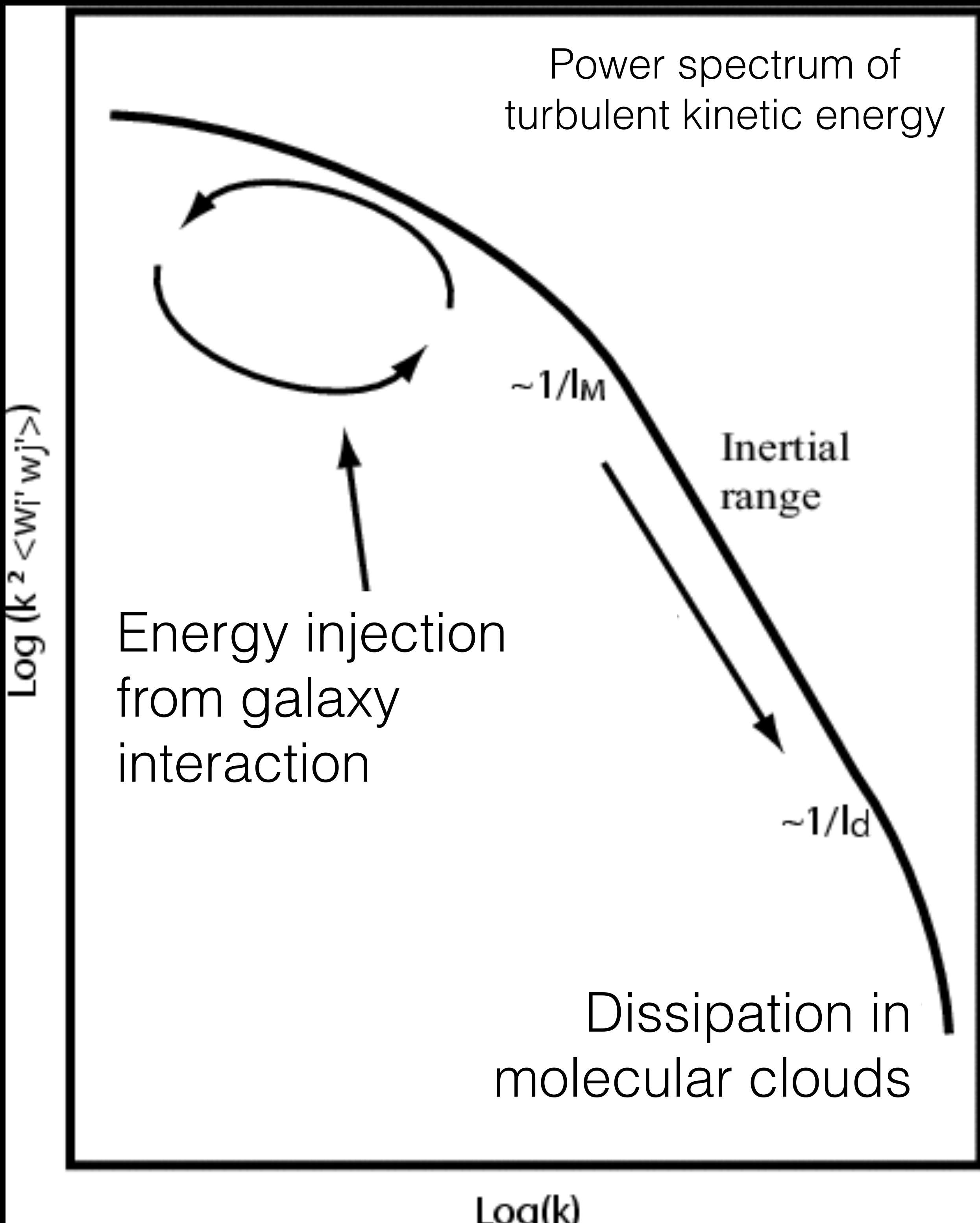
Snapshot of hydro simulations of the Antennae galaxies to 1pc resolution.



Renaud+15: Gas density 6 Myr after the second pericenter passage

Gas dynamics in interacting galaxies => Large scale compression and turbulence, which set the physical conditions for formation of massive clusters

Turbulent energy dissipation



- ★ Energy injection on galaxy-wide scales from the large gas dynamics
- ★ The gas flows have a high Reynolds number => they drive turbulence
- ★ The energy cascade from large to small scales drives supersonic turbulence in cold (molecular) gas => shocks
- ➡ Dissipation occurs mainly within molecular gas => H_2 line emission is a main tracer of turbulence dissipation

Turbulence and star formation

★Turbulence creates a range of density structures in interstellar matter and locally the initial conditions for star formation

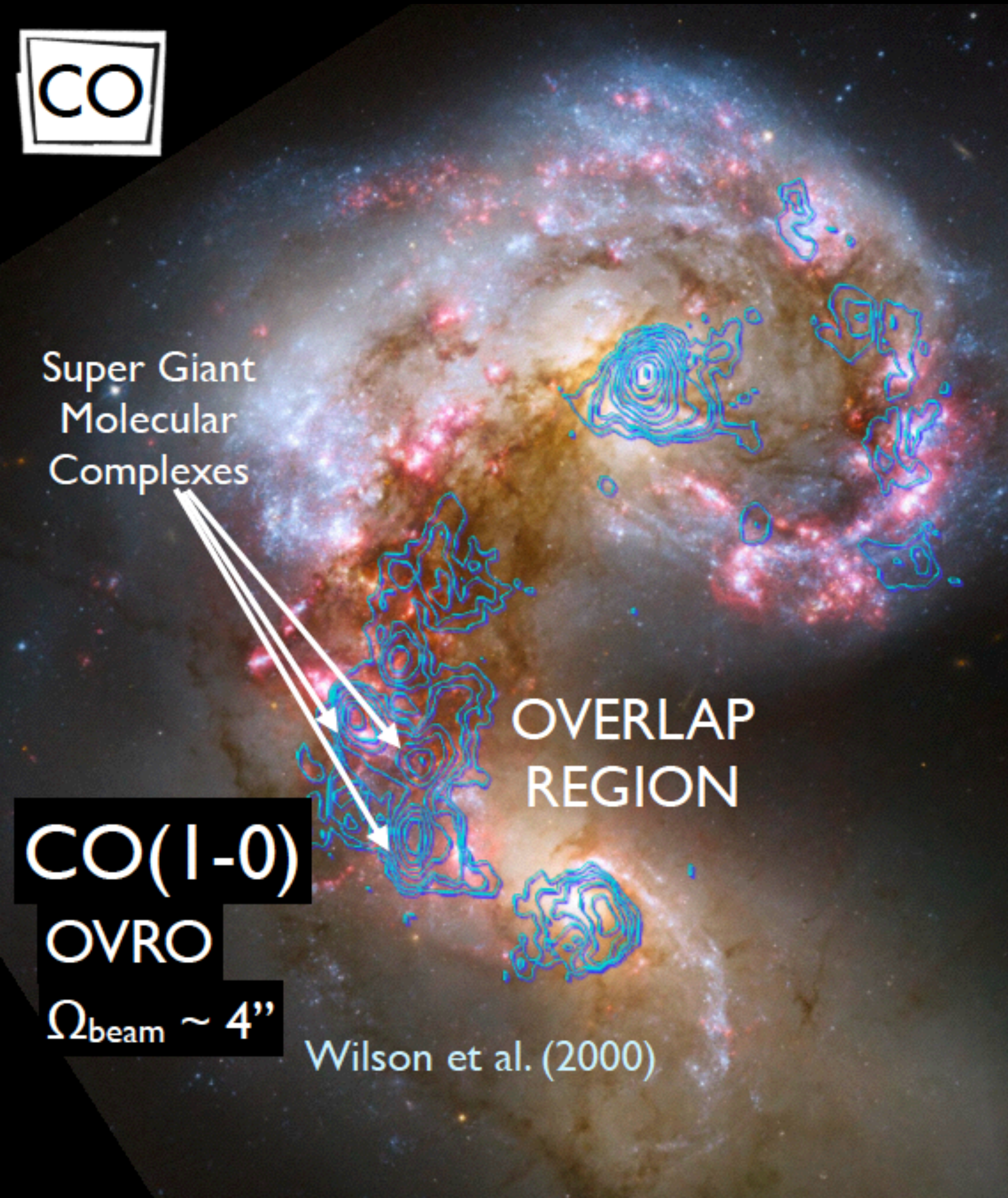
★ The masses and sizes of clouds which become gravitationally bound depend on the turbulence amplitude ($\boldsymbol{\sigma}_{\mathrm{v}}$) and the ISM pressure ($P_{\mathrm{ext}}$)

$$M_c \, \alpha \, \sigma_v^4 \, P_{ext}^{-1/2}$$ Maximum mass in equilibrium

$$R_c \, \alpha \, M_c^{1/2} \, P_{ext}^{-1/4}$$ Corresponding radius

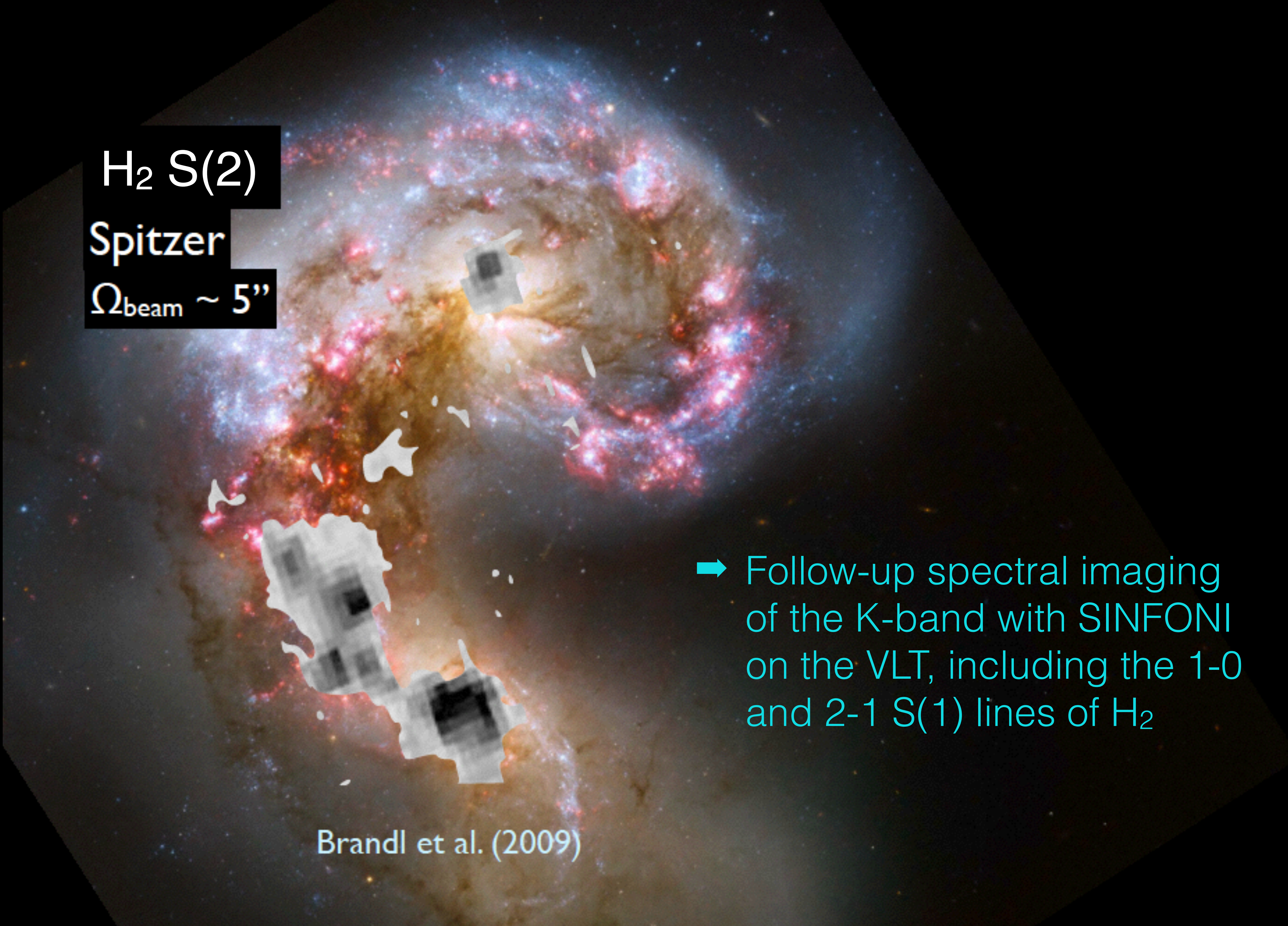
Ebert-Bonner relations

With H_2 spectroscopy we probe the turbulent energy dissipation associated with the formation of ISM structures



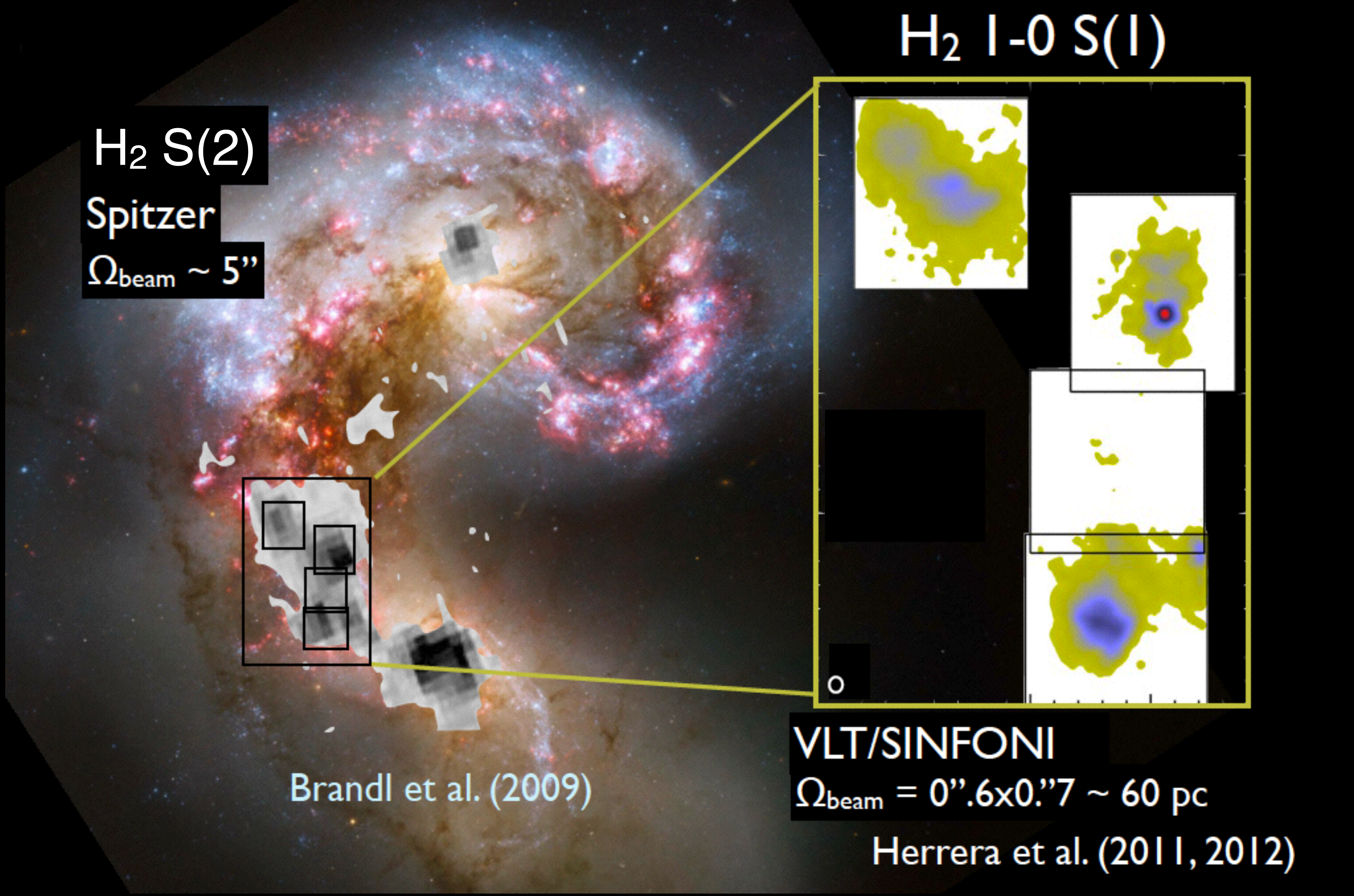
Much of the YMCs are found in the overlap region where CO observations have revealed the presence of super GMC (SGMCs) with masses of a few 10^8 M_o and large velocity dispersions ($\Delta v \sim 100$ km/s)

The Antennae Galaxies in H_2 emission



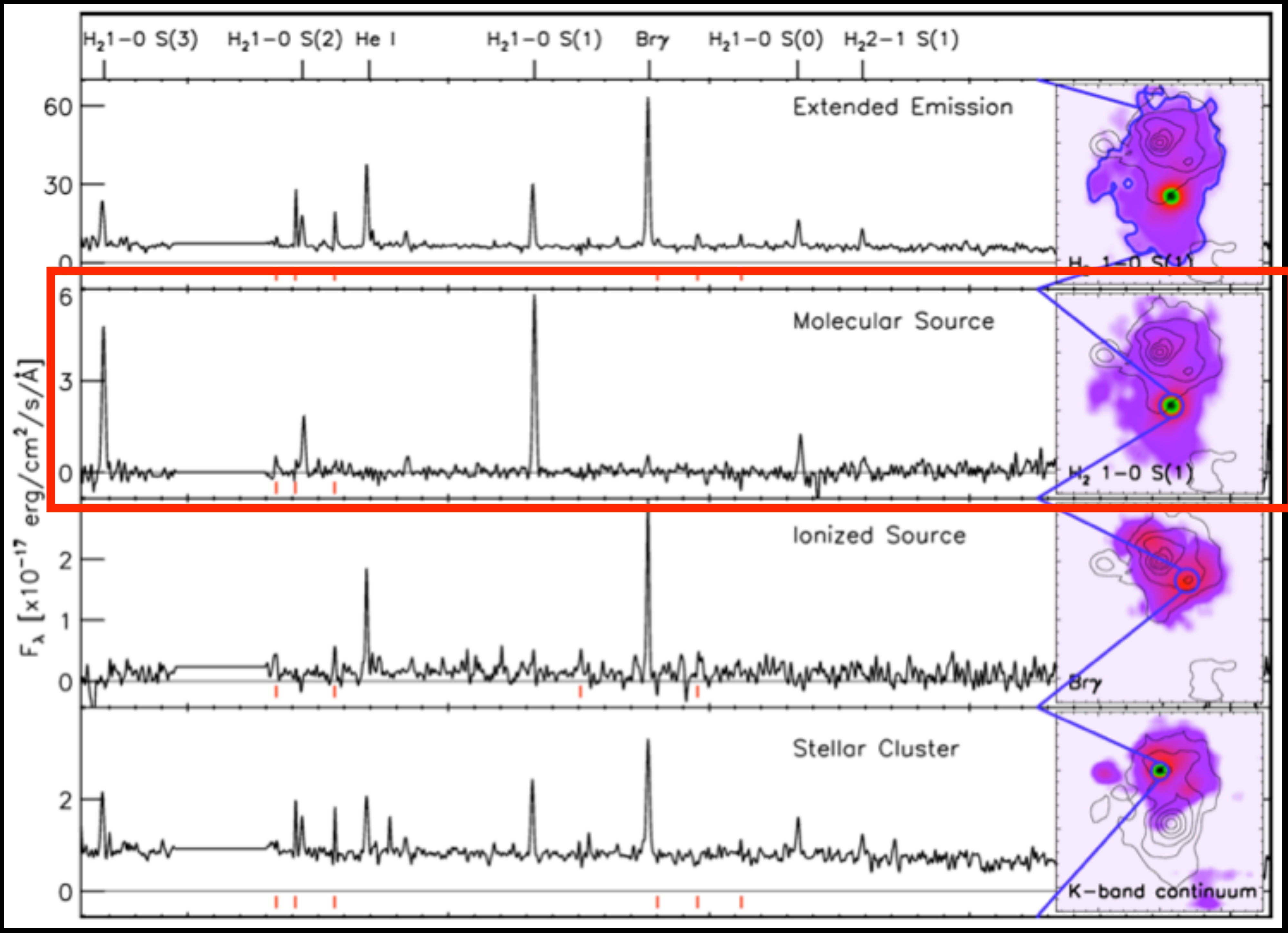
- ➡ Follow-up spectral imaging of the K-band with SINFONI on the VLT, including the 1-0 and 2-1 S(1) lines of H_2

The Antennae Galaxies in H_2 emission



H_2 luminous source in one of the SGMCs

SINFONI K-band spectra from Herrera+ 2011



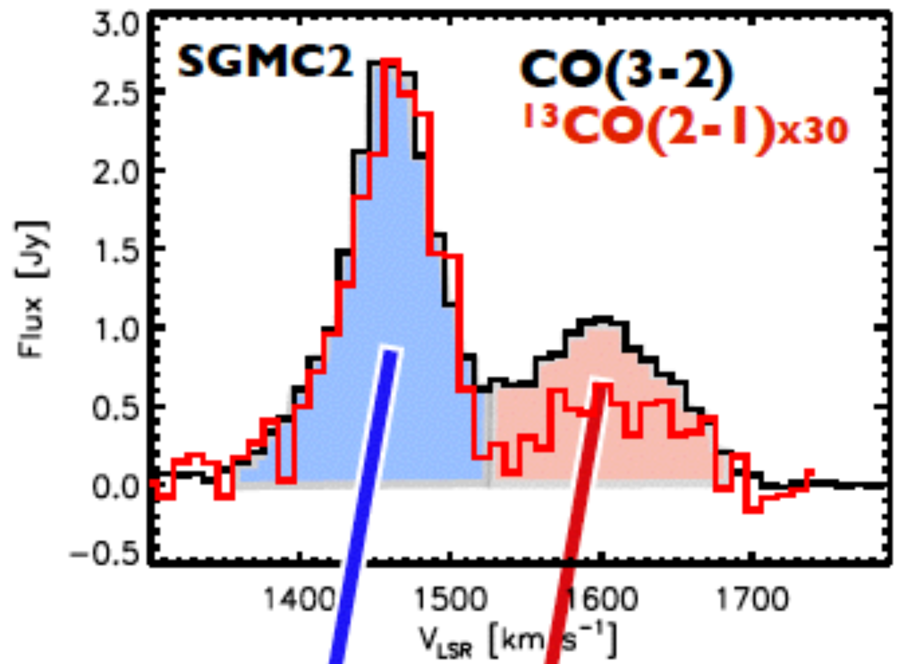
Point-like H_2 luminous source

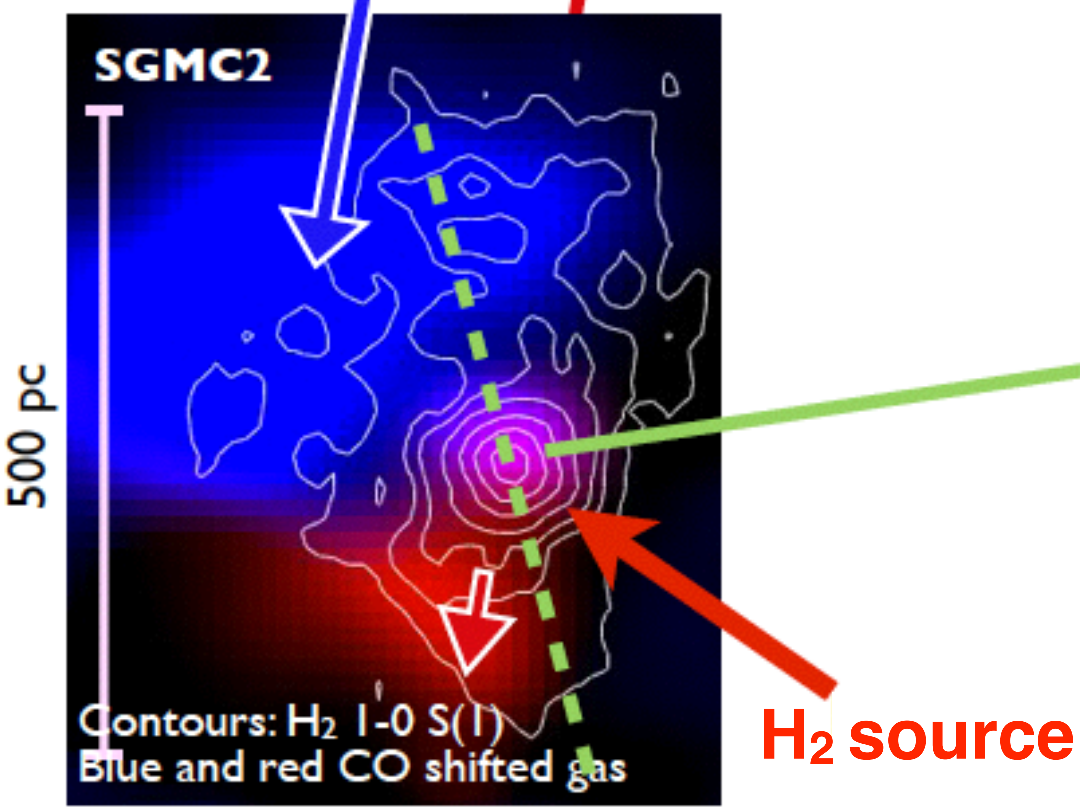
Have we discovered the progenitor of a massive cluster?
=> ALMA follow-up

H_2 compact source: Characteristics

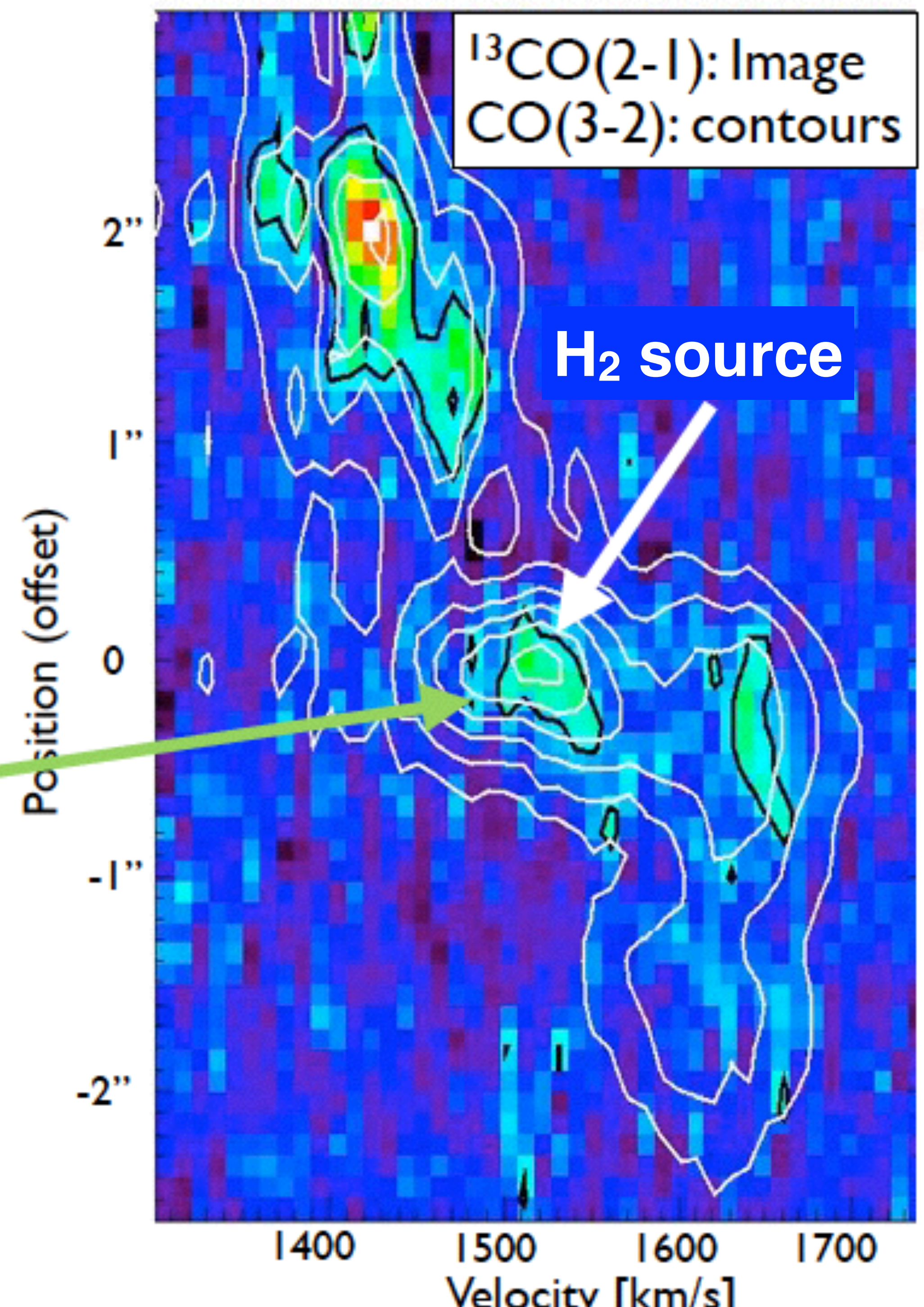
ALMA observations

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

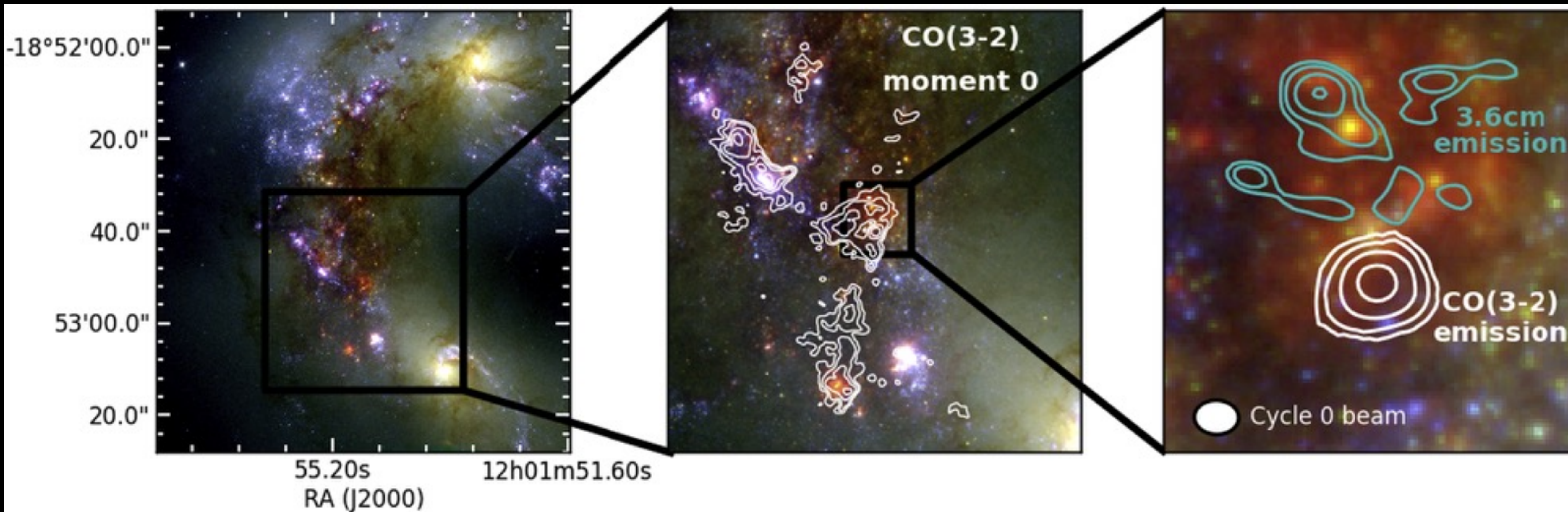




Herrera et al. (2012)



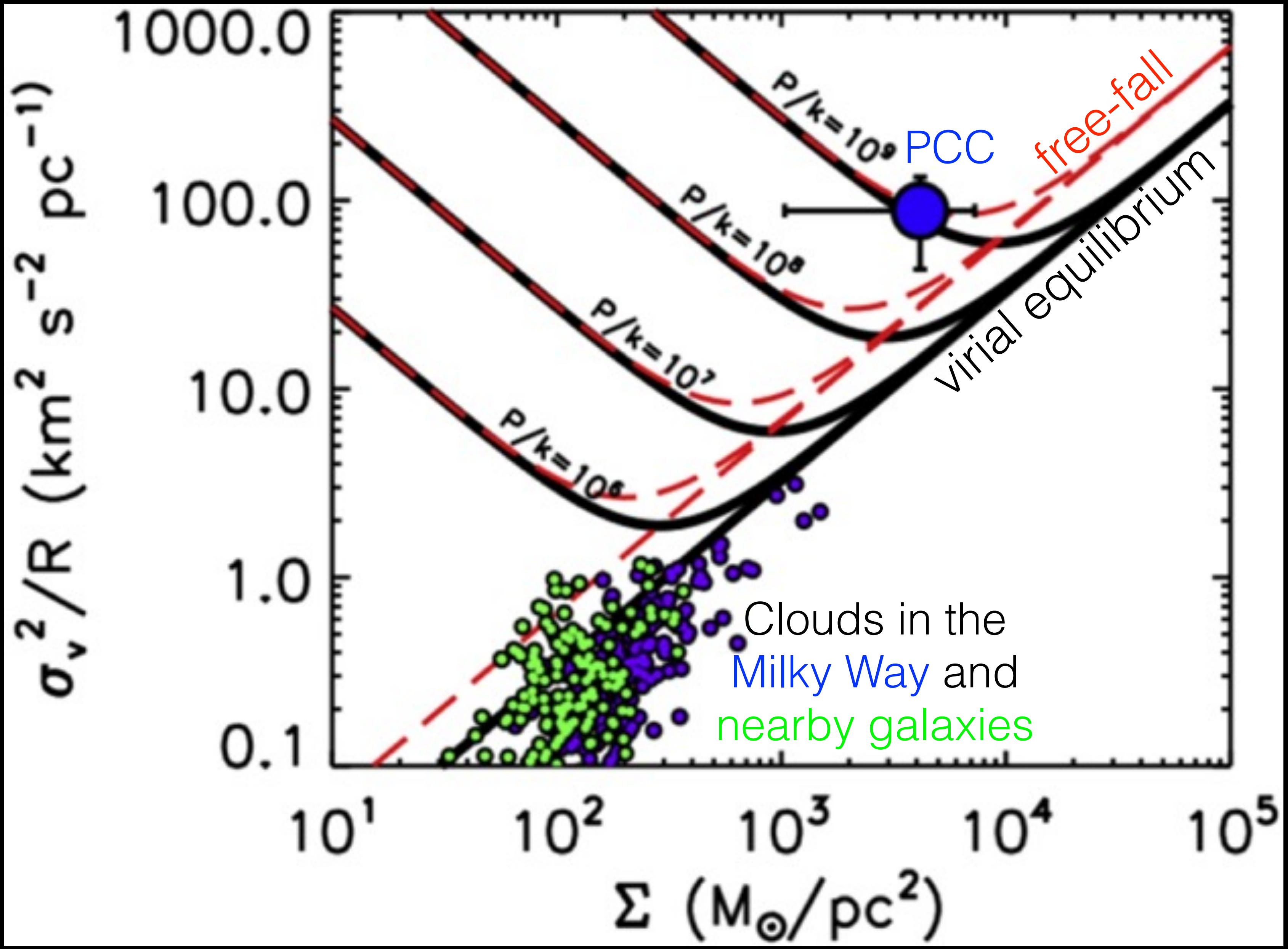
No radio counterpart



Johnson+2015

- ★ The H_2 luminous source discovered with SINFONI has now been detected with ALMA in CO, 13CO, and dust continuum
- ★ It is a massive ($5\ 10^6$ Mo) and compact (radius < 25pc) cloud with a velocity dispersion $\boldsymbol{\sigma}_V$=50 km/s (FWHM = 115 km/s).
- ★ The virial mass is one order of magnitude larger than the mass inferred from the CO and dust emission

Dynamical state



Johnson+2015

A high pressure (p/k ~10^9 K cm^{-3}) is necessary to bind the cloud

This pressure may be accounted for by the turbulent pressure of the H_2 emitting gas

This implies a short dissipation time of turbulence, i.e. the cloud evolutionary time

$$\tau_d = R_c/\sigma_v \,\alpha\, M_c^{1/4} P_{ext}^{-3/8}$$

The antennae source is so far unique => it must trace a short (≲10^6 yr) evolutionary stage in the formation of YMCs

What can JWST do?

- ★ Search for cluster progenitors more efficiently and to a much larger (a factor 10) distance
- ★ A survey for H_2 luminous sources in starburst galaxies, including ultra luminous IR galaxies with an SFR one order of magnitude larger than that of the Antennae, will yield a significant sample of detections
- ★ It will provide the statistics needed to determine the evotulionary timescale of YMCs' progenitors
- ★ JWST will also characterize the progenitor clouds by resolving and imaging their H_2 emission.

Summary

- ★ JWST will improve the sensitivity, and the angular and spectral resolution, of Spitzer and VLT H_2 spectral imaging observations by one to two orders of magnitude
- ★ This jump forward will open an immense discovery space.
- ★ JWST will unveil how massive (globular-like) stellar clusters form by discovering and characterizing their progenitor clouds
- ★ H_2 lines will also be detected in many JWST spectroscopic observation in galaxies (local to high z: Pierre Guillard's talk), star forming clouds, the diffuse ISM, young stellar objects, proto-planetary disks, evolved stars …

What will be learned from H_2 spectroscopy will be a main and unique scientific outcome of the JWST.