Warm Molecular Hydrogen at high redshift with JWST

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Warm H_2 with JWST

Outline and take-home messages

1. Observations of warm H_2 in nearby and distant galaxies
   → a tracer of turbulent dissipation

2. Mapping the kinematics of warm H_2 gas with NIRSPEC and MIRI
   → unique capability up to z~2-3

3. What could we learn about galaxy formation?
   → Gas cooling in galaxy assembly. Physics worth exploring with JWST

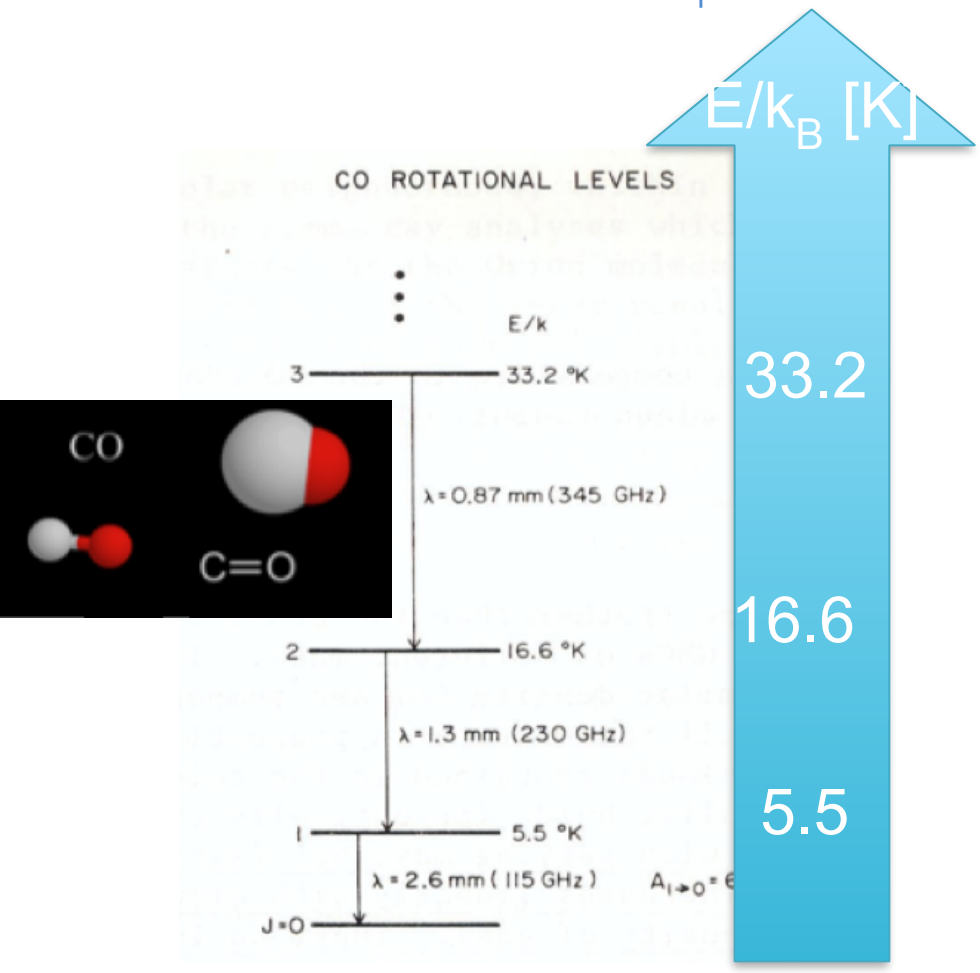
A small molecule with a wide range of diagnostics

H_2 Excitation:

1. collisional excitation with atoms and molecules (Flower1998, Le Bourlot 2002)
2. Absorption of UV photons + fluorescence (Gauthier 1976, Black & van Dishoeck 1987)
3. X-rays (Maloney et al. 1996, Tiné et al. 1997) + Cosmic Ray heating (Dalgarno et al. 1999)

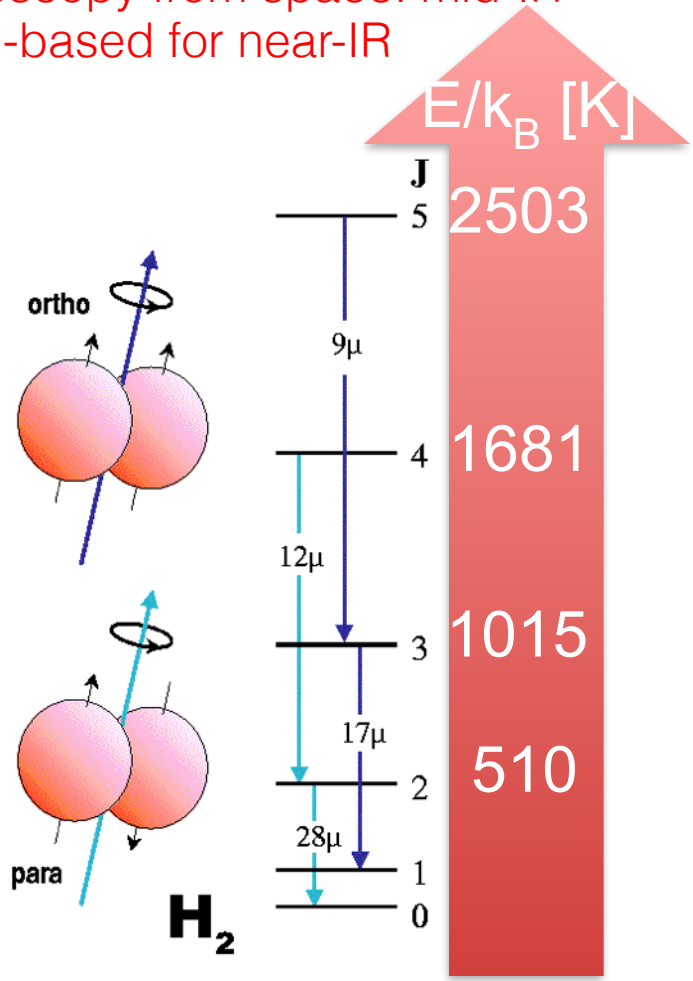
Why H_2?

Sub-mm and mm radiotelescopes



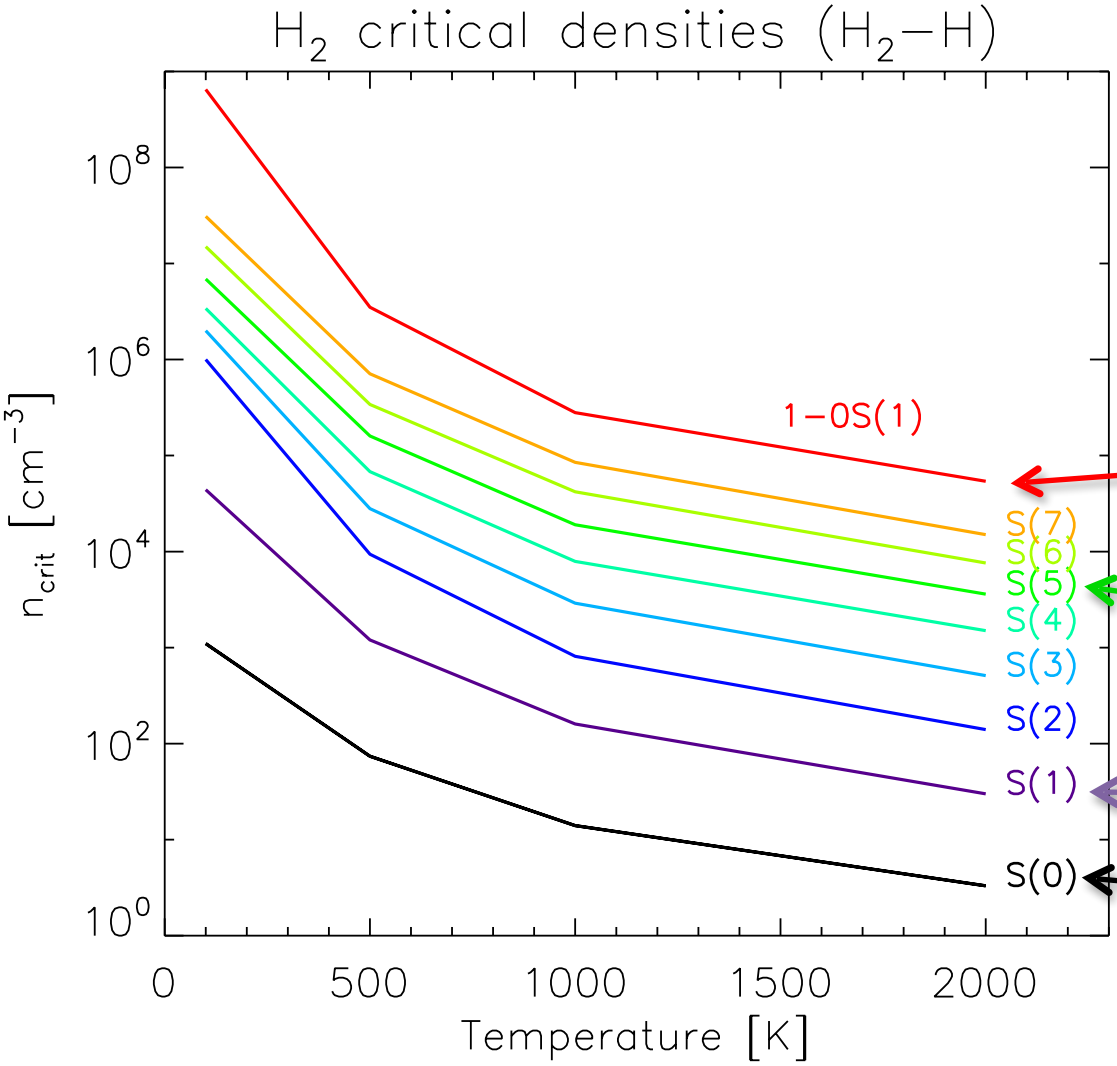
CO (cold H_2) : mass

Spectroscopy from space: mid-IR
Ground-based for near-IR



Warm H_2: energetics

Why H_2? A Thermometer



- Main lines are pure-rotational in the mid-IR and ro-vibrational in the Near-IR

2.12 μm

6.9 μm

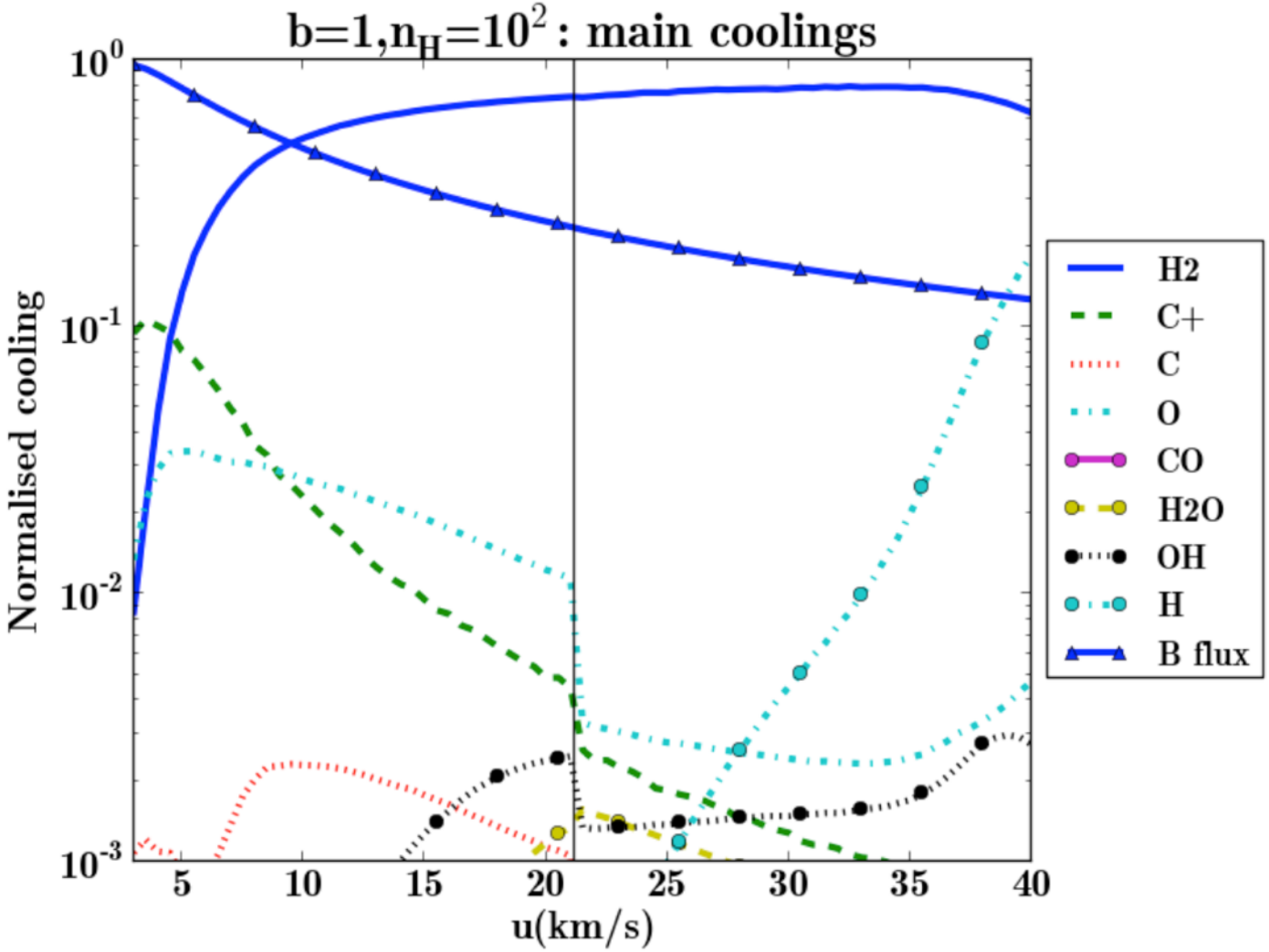
17 μm

28.2 μm

Wrathmall et al. 2007

Why H_2? A main coolant in shocks

- H_2 mid-IR lines are the main cooling lines of shocked molecular for $5 < V_s < 40$ km/s
- Shocks trigger the formation of H_2 gas if the gas is initially atomic provided that there is dust (Bergin+2007, Guillard+2009)



Flower et al. 2010, Lesaffre et al 2013

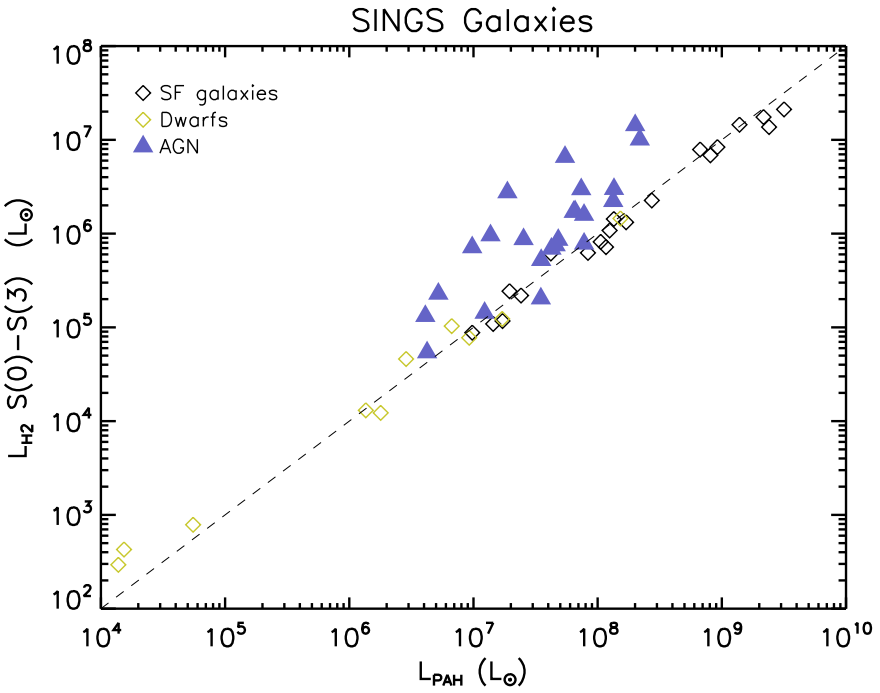
A small molecule with a wide range of diagnostics

- H_2 fuel for star formation: IR - H_2 correlation
  Main coolant to dissipate kinetic energy
  (**See F. Boulanger's talk tomorrow**)

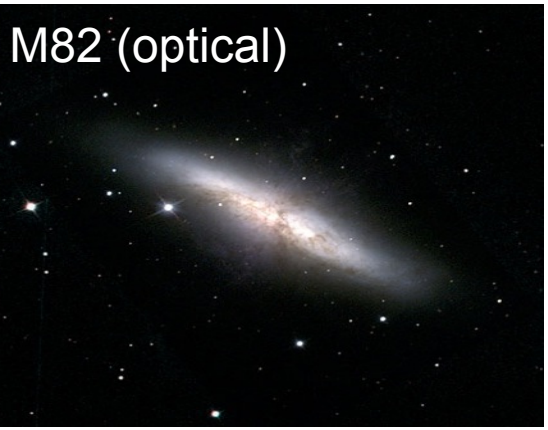
- H_2 influences the formation of cosmological structures (collapse of the first objects, Abel & Haiman 2000)

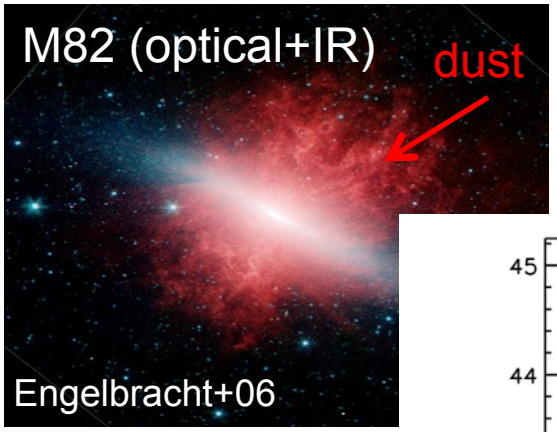
- Planet formation: formed in circumstellar disks made of 99% H_2 in mass.
  H_2 controls the thermodynamics of the disk
  H_2 observations help constraining scenarios for planet formation

- H_2 seed for molecular complexity (Herbst 1995, Cerniccaro et al. 2001)



Warm H_2 gas in the M82 outflow



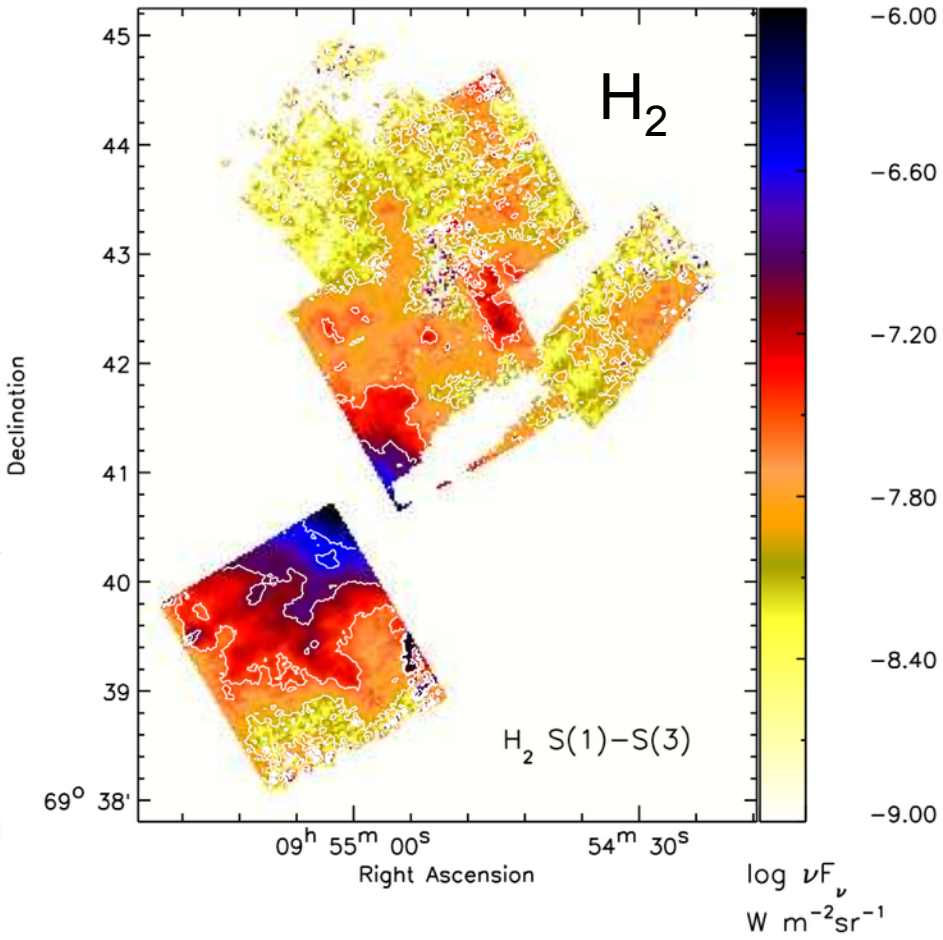


- Mass of warm H_2 ~ 10^7 M_o
- Spitzer spatial resolution ~ 35 pc
  No kinematical information

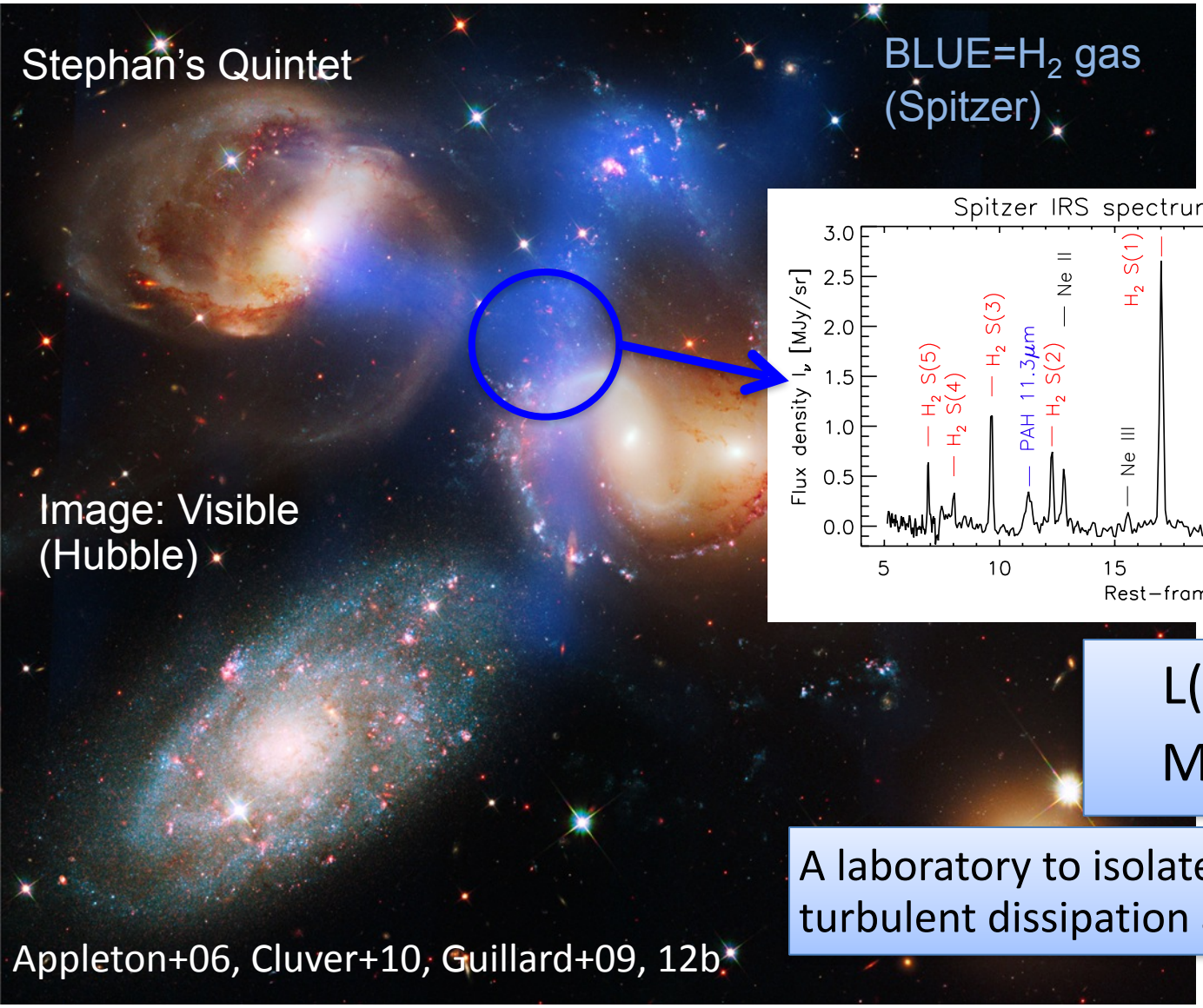
- What are the kinematics and small-scale structure of the warm H_2 ?
- What is the total outflow rate ?

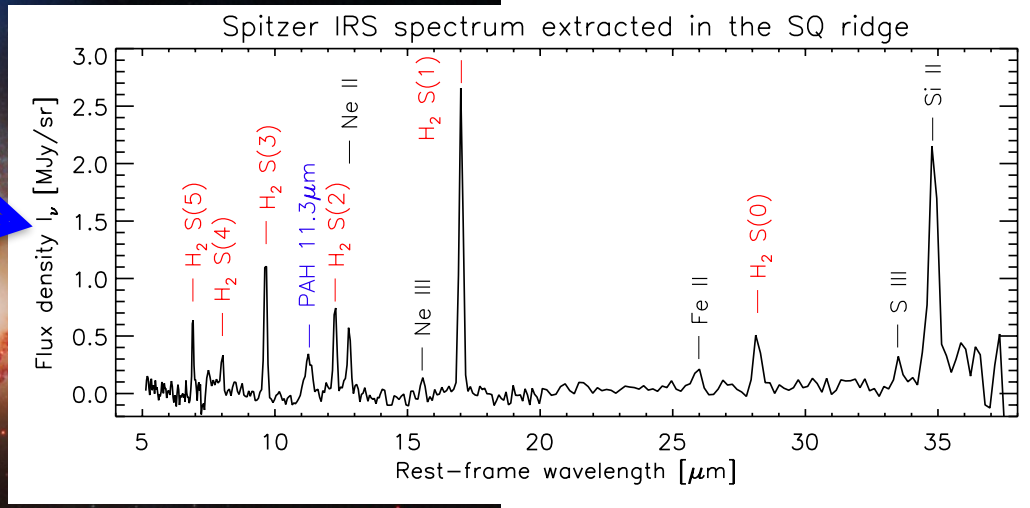
MIRI can (locally) map the morpho-kinematics at a spatial resolution of 1.5 pc !

Warm H_2 gas far out of the disk (Beirao et al. 2015)



Shock-powered H_2 emission in galaxy interactions



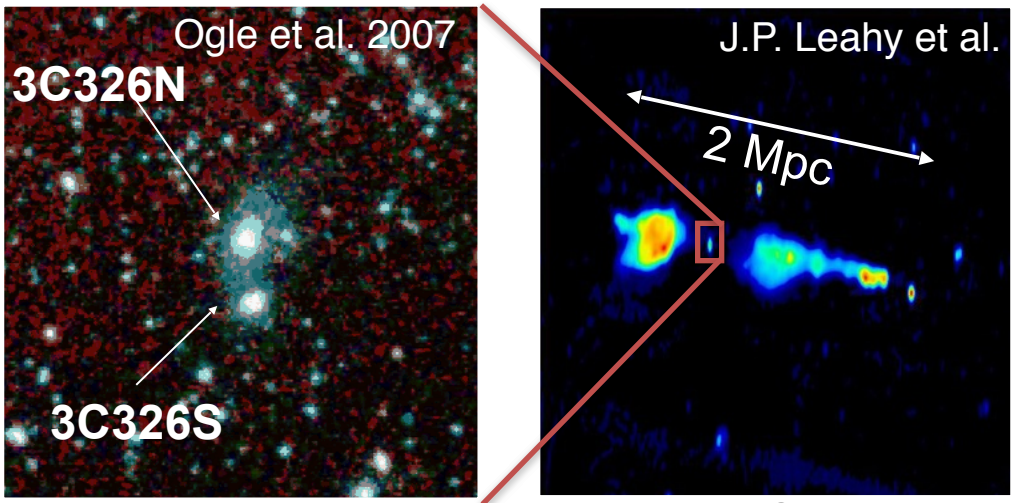


$L(H_2) = 3\ L(\text{X-rays})$

$M(H_2) = 5\text{x}10^9\ M_\odot$

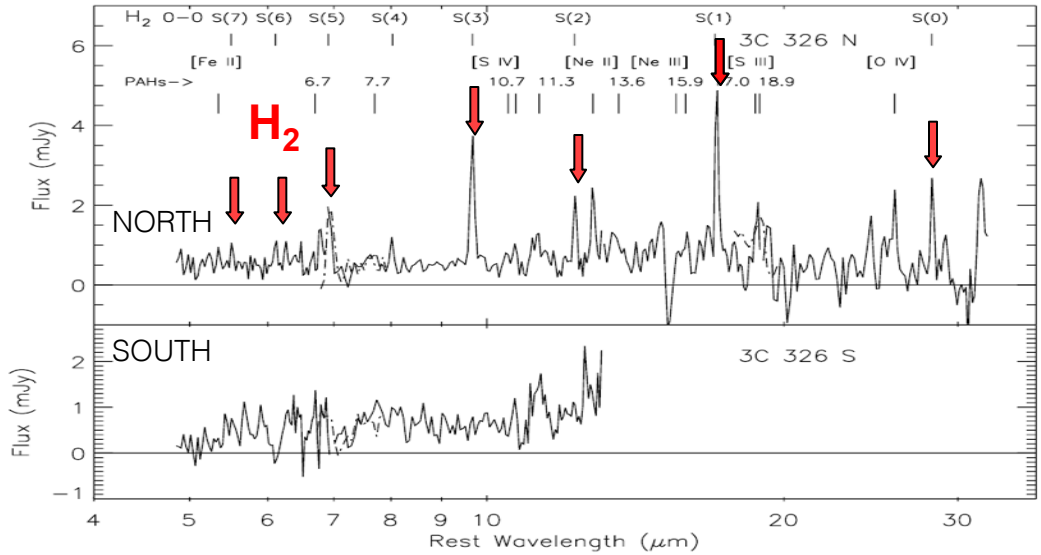
A laboratory to isolate the physics of turbulent dissipation against the dark sky

An H_2-rich radio-loud AGN with extremely weak star formation



VLA 1.4 GHz image

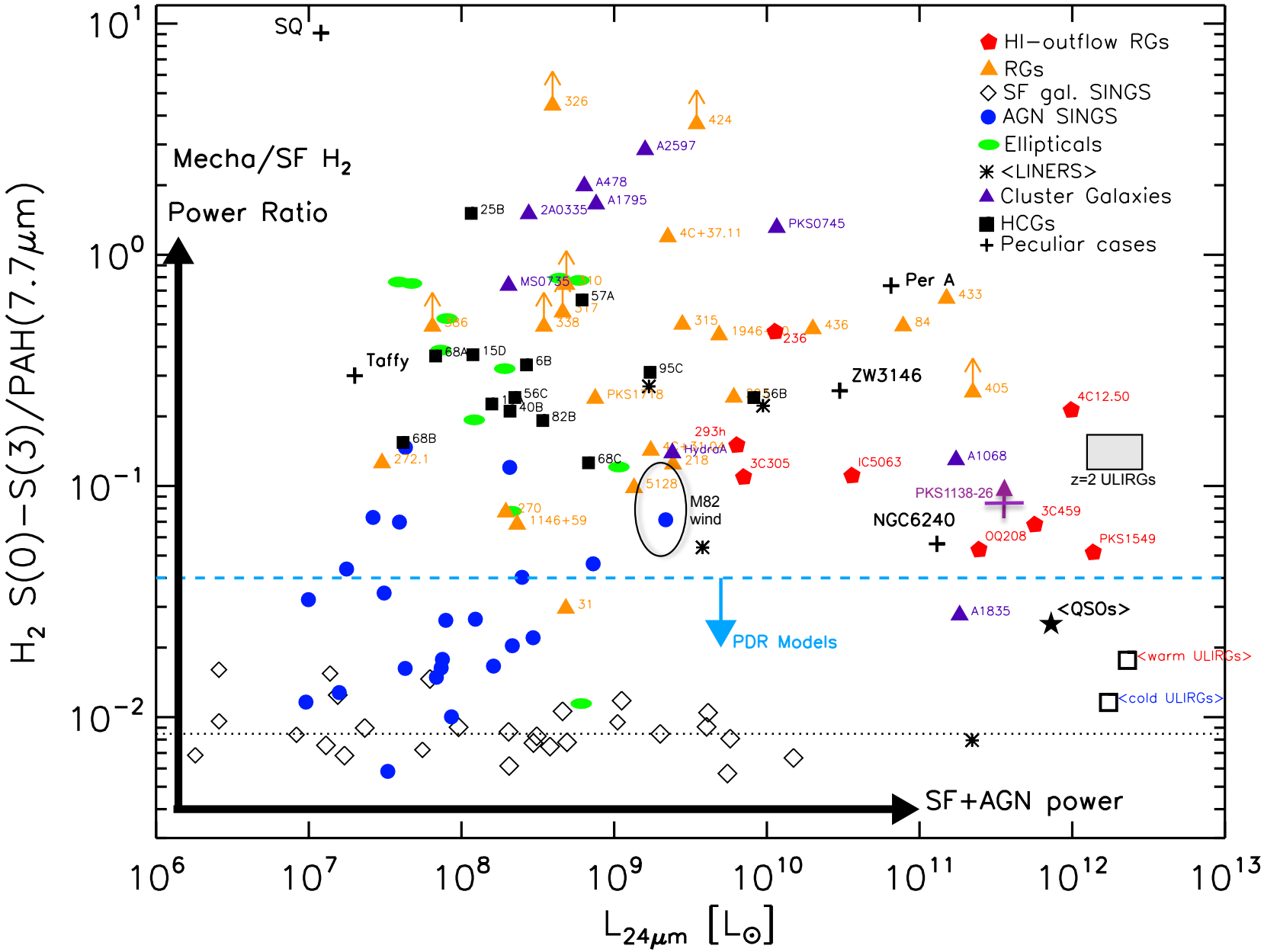
- Pair of galaxies 3C 326N & S at z=0.089



- $L(H_2)=8x10^{41}$ erg/s
- 10^9 $M_\odot$ of warm H_2
- SFR < 0.07 $M_\odot$ yr^{-1}
- $L(H_2)/L(IR)$ ~ 0.2 !!

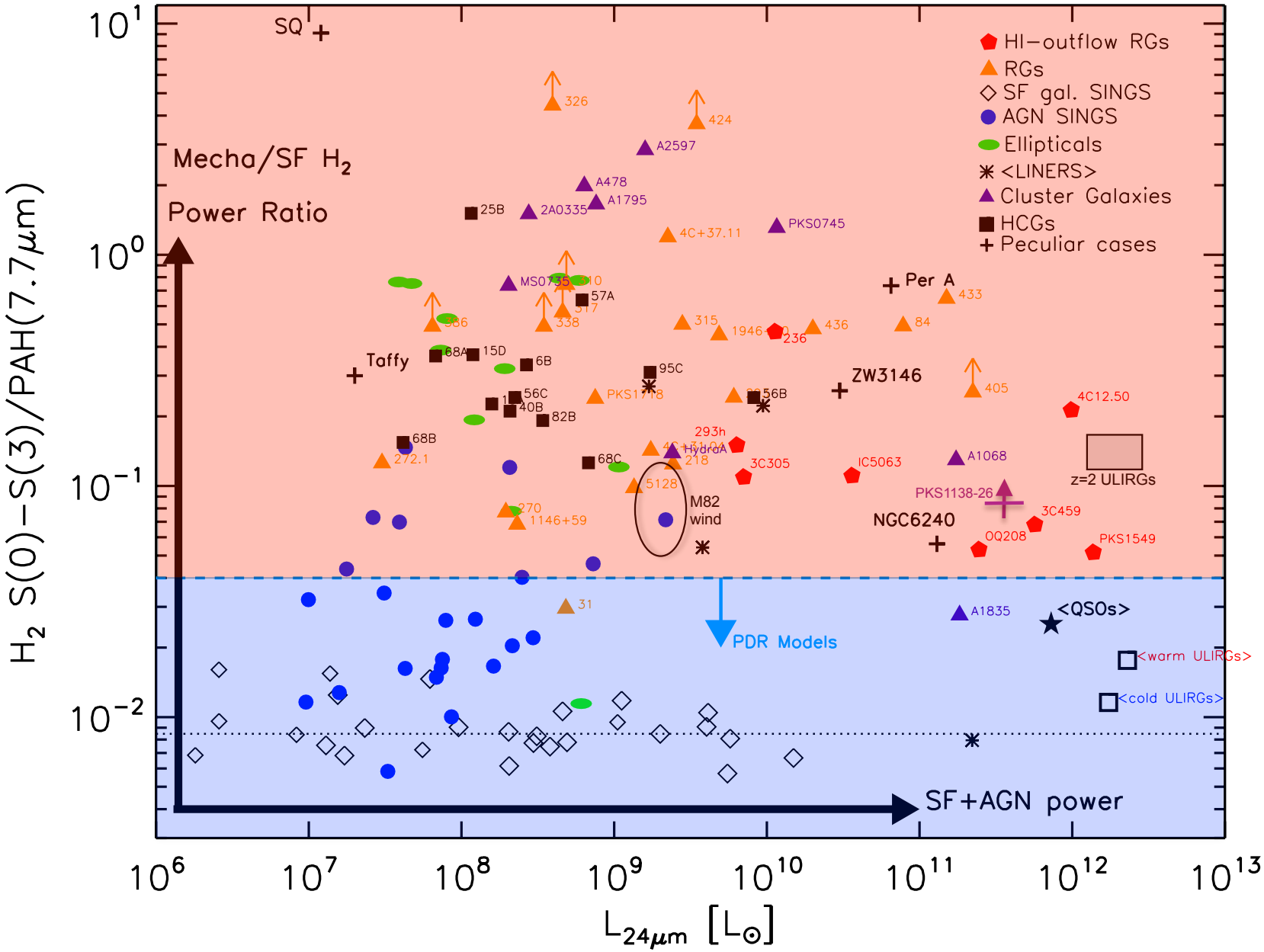
H_2/PAH flux ratio: diagnostic of kinetic VS UV heating of the gas (Ogle+10, Guillard12a, 15)

H_2 line emission in galaxies (Spitzer)



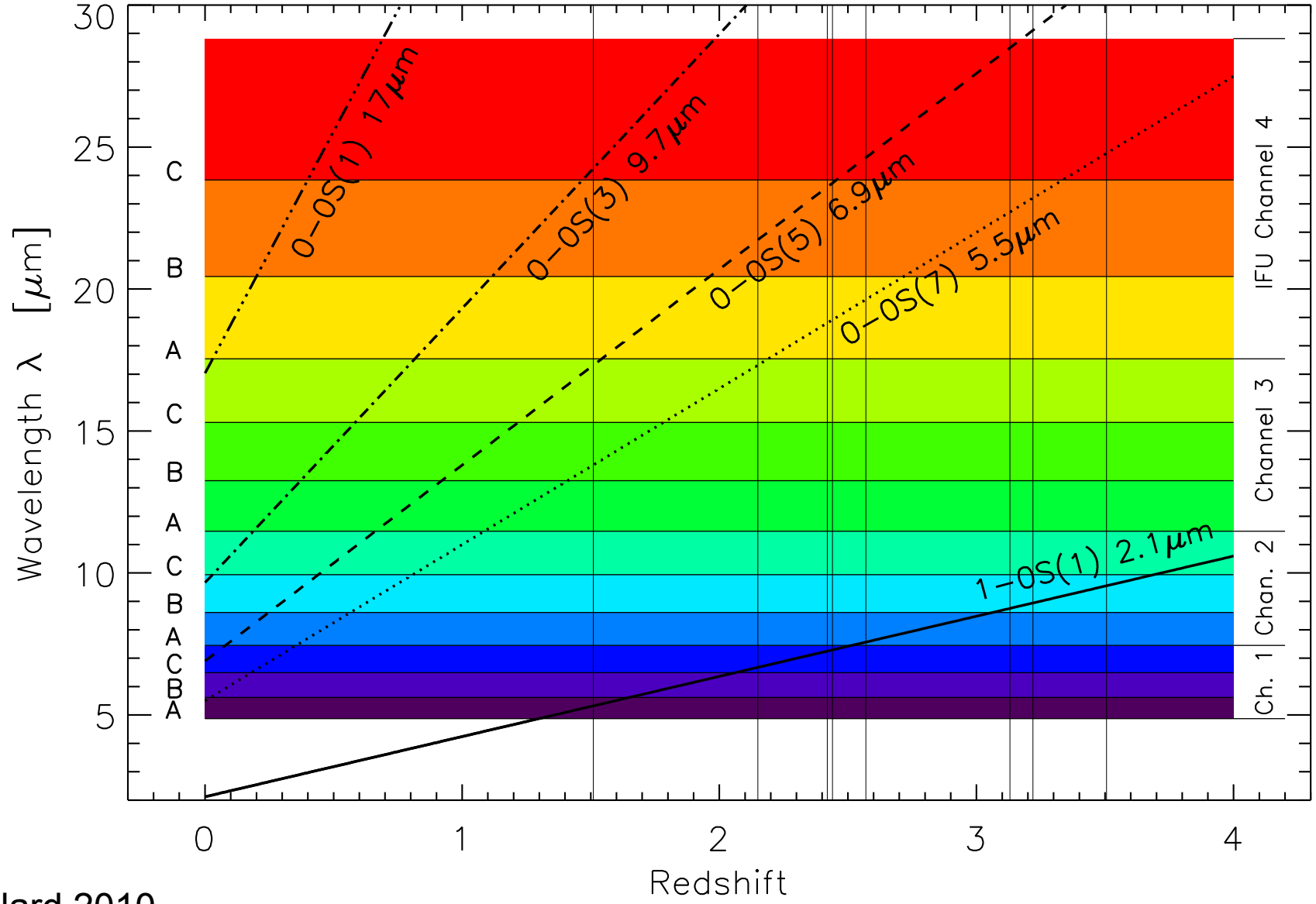
Updated from Guillard et al. 2012a

H_2 line emission in galaxies (Spitzer)

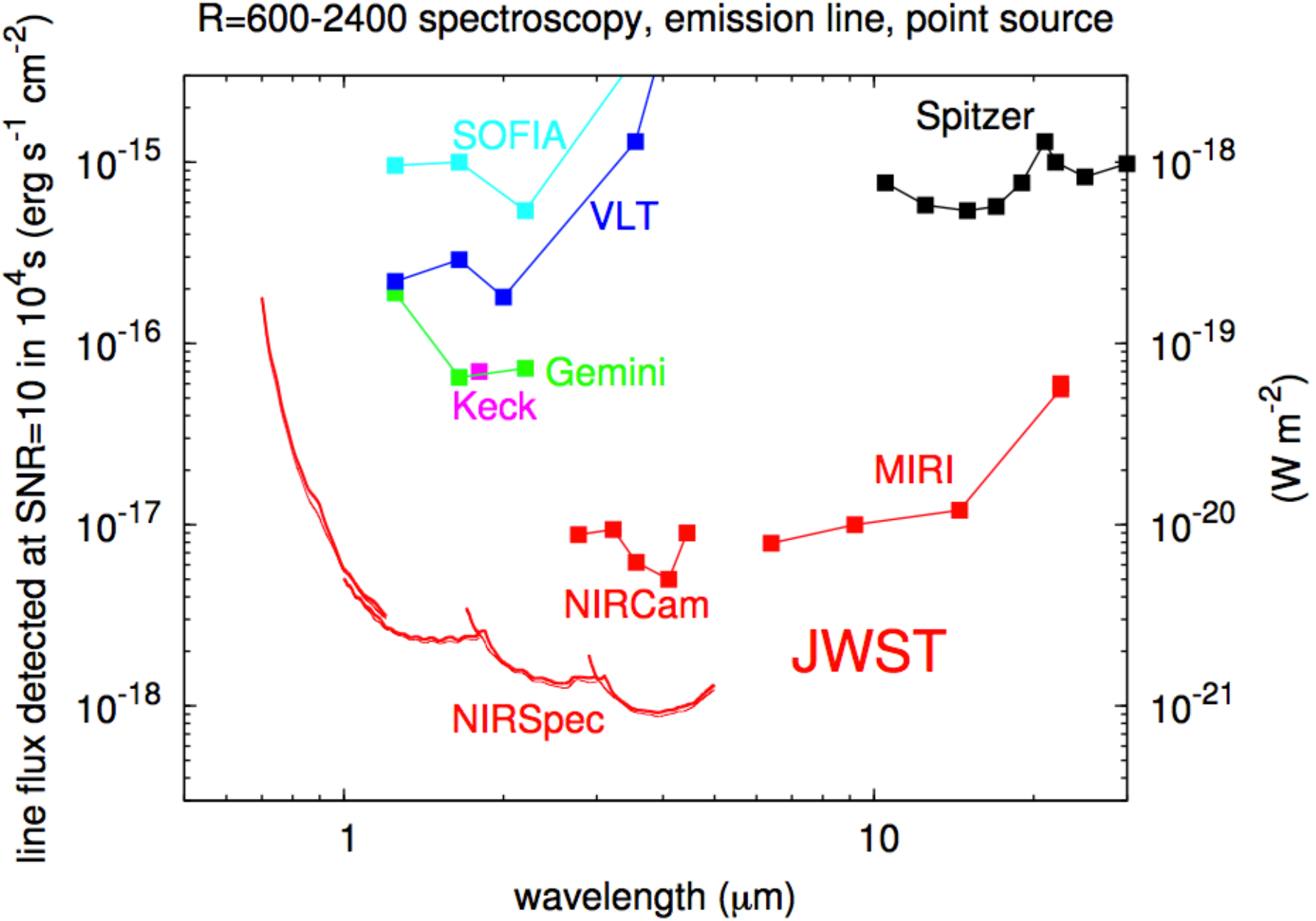


After *Spitzer IRS*, *NIRSPEC* and *MIRI* are the next-generation instruments to observed rotation-vibration H_2 lines

Redshifted H_2 lines with MIRI



Guillard 2010


R=600-2400 spectroscopy, emission line, point source
line flux detected at SNR=10 in 10^4s (erg s^-1 cm^-2)
(W m^-2)
wavelength (μm)
SOFIA
VLT
Spitzer
Gemini
Keck
MIRI
NIRCam
JWST
NIRSpec
10^-15
10^-16
10^-17
10^-18
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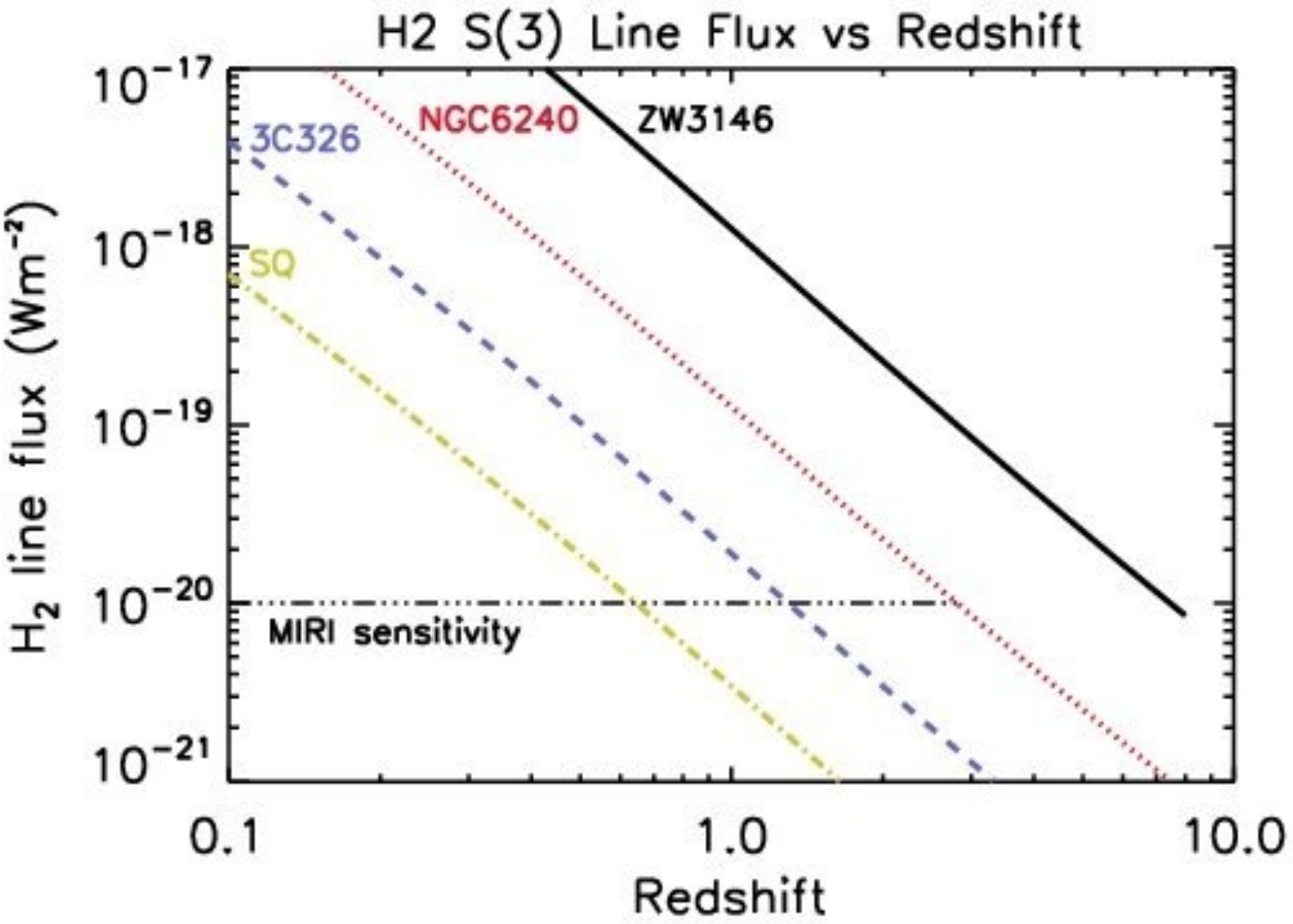
10^-20
10^-21
1
10

H_2 lines at high redshift with MIRI

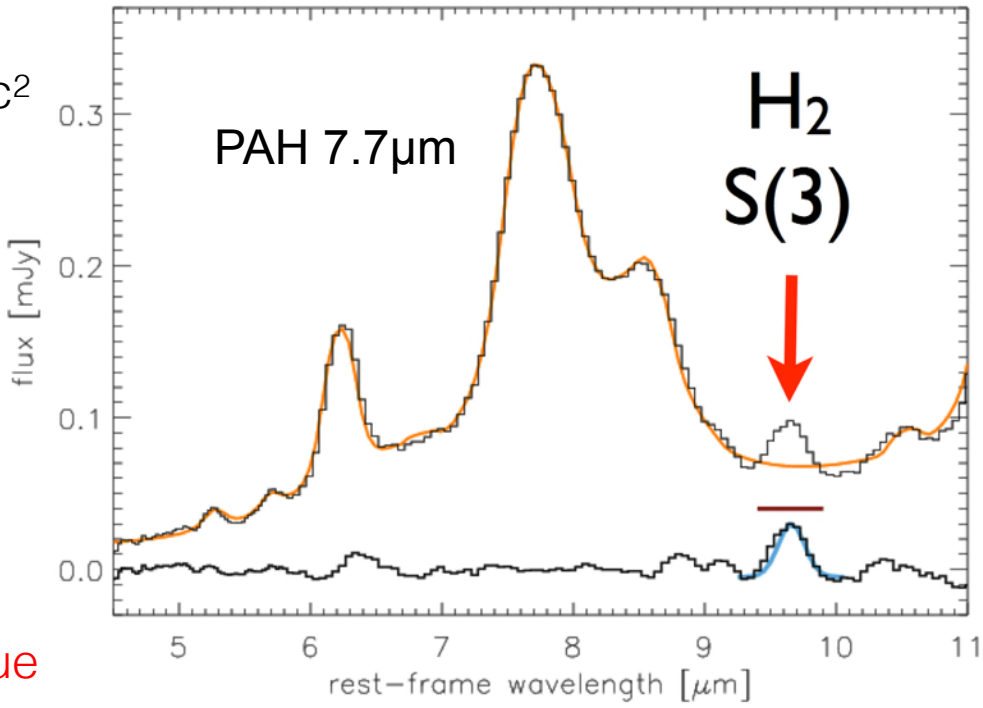


H_2 cooling in high-z starbursts

- 16 Spitzer-selected galaxies at z~2
  IRAC photometry: $<M_\star> = 1.5\times10^{11}\ M_\odot$
  Mid-IR spectroscopy: $<SFR> \sim 1000\ M_\odot/yr$
  Sub-mm photometry: $M_{gas} \sim 5\times10^{10}\ M_\odot$
  $\Sigma_{gas} \sim 2000\ M_\odot/pc^2$

- $L_{H2}(S(3)) = 1.5\ 10^9\ L_\odot$
- Based on spectra of local H_2 luminous galaxies:
  $L_{H2}(S(0)\text{-}S(5)) \sim 6\ 10^9\ L_\odot$
  $M_{H2}(T>150K) \sim 10^{10}\ M_\odot$: 20% M_{gas}
  $L_{H2}/M_{gas} \sim 0.12\ L_\odot/M_\odot$
  $\equiv 4\ 10^{-25}$ erg/s/H
  ~ 500 times the Milky Way value

Stacked IRS spectrum (Fiolet+10)

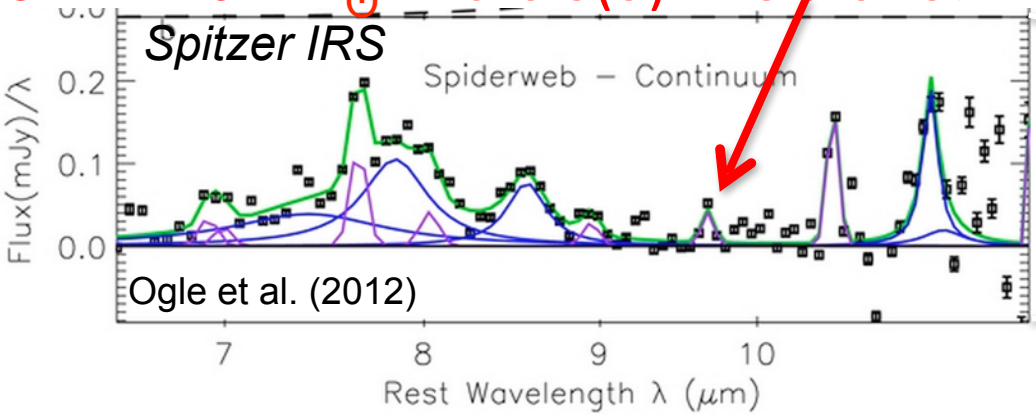


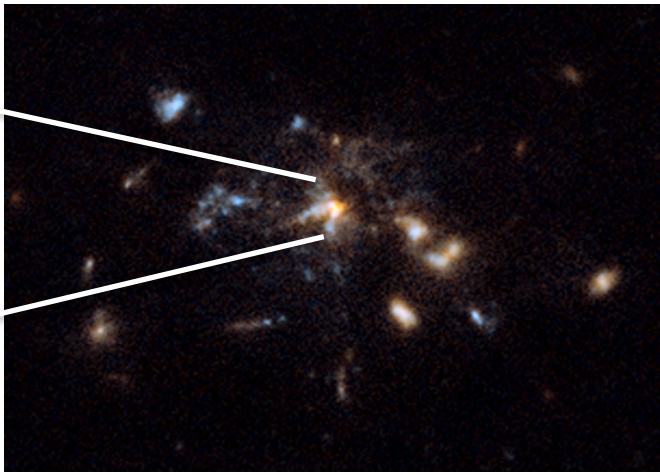
H_2/PAH ratio above what may accounted by UV heating of molecular clouds based on CO, FIR, [CII]λ158μm (Stacey+10)

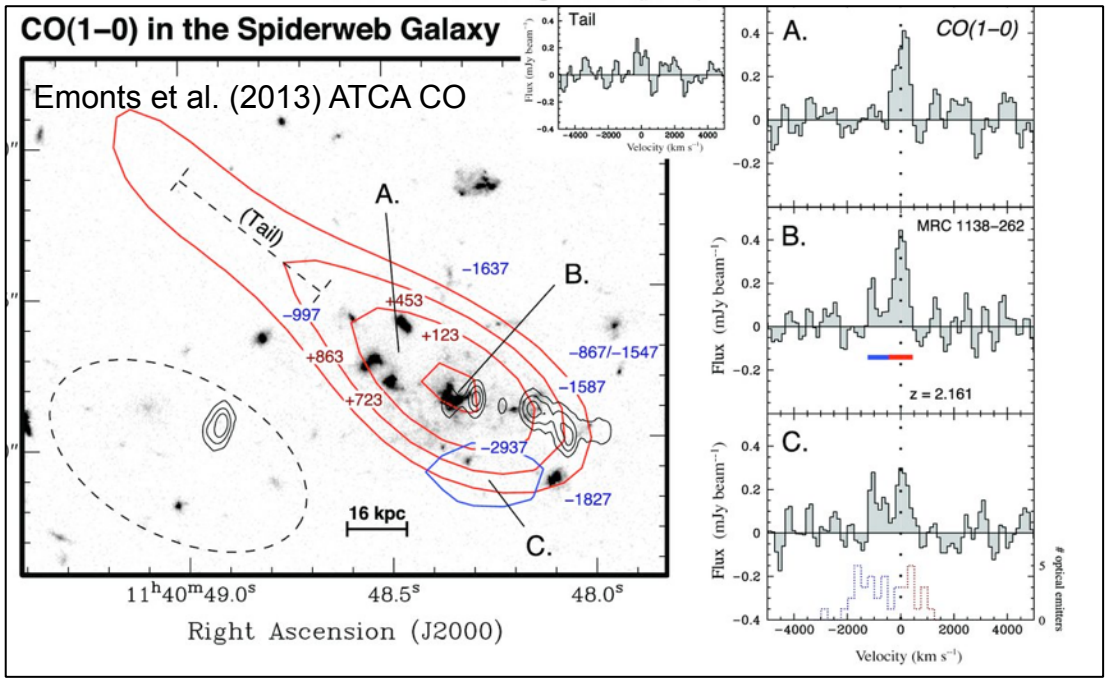
H_2 may be powered by dissipation of turbulence (possible sources: SN, radiation pressure, gas accretion)

The Spiderweb Radio Galaxy z = 2.16

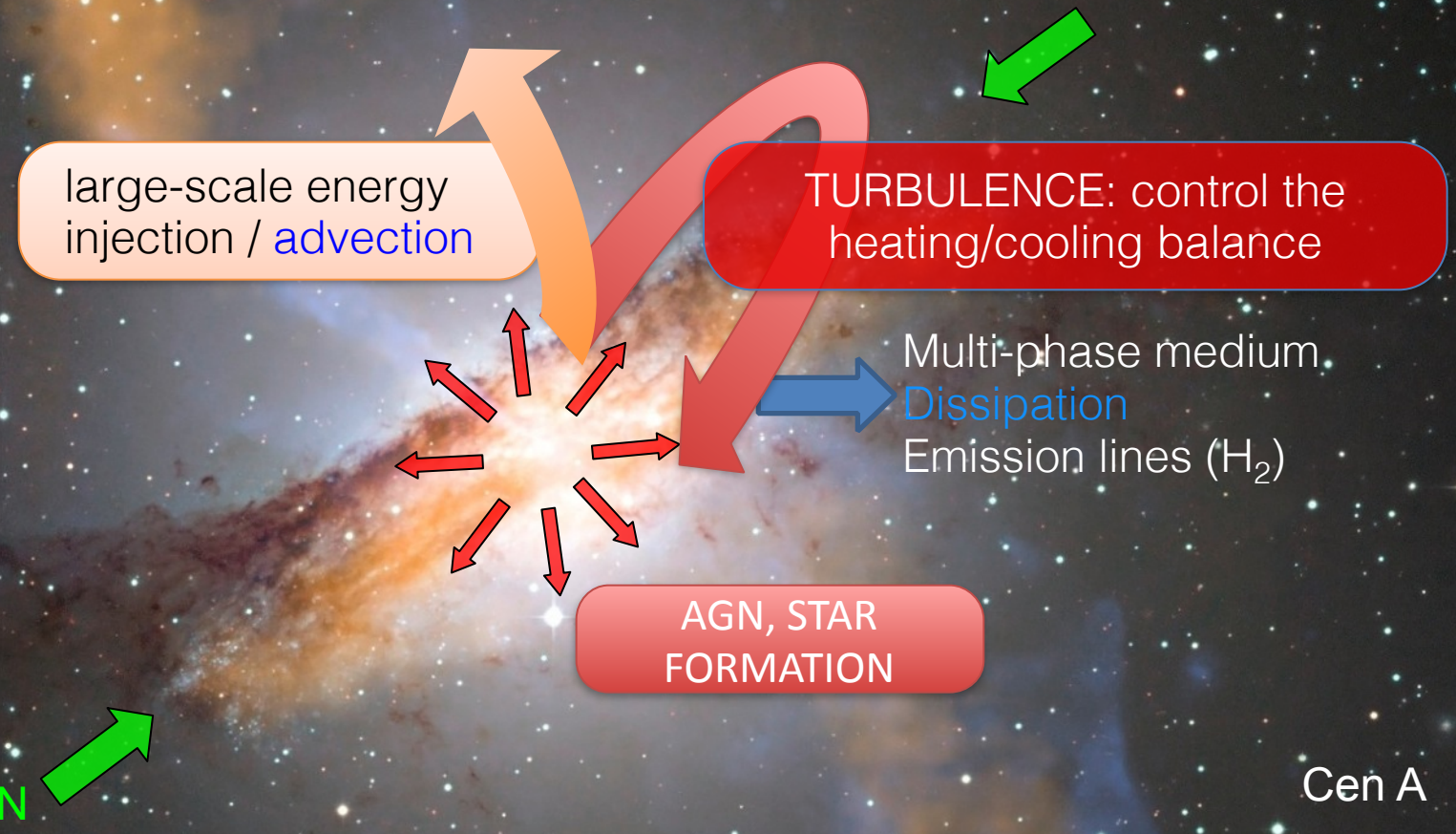
3.7 x 10^{10} $L_\odot$ in 0-0 S(3) line alone!







Gas Heating and Cooling in galaxy assembly



JWST obs: cooling, dissipation & dynamical timescales

Warm H_2 with JWST

To take-away:

⟶ *Cooling of multiphase ISM through H_2 lines. A tracer of the dissipation of turbulence.*

⟶ *H_2 lines are expected to be enhanced in high-z turbulent galaxies*

⟶ *NIRSPEC and MIRI will allow to map the kinematics of warm H_2 gas at high spatial resolution up to z~2-3*

⟶ *Tracing the turbulent energy cascade associated with feedback processes, shedding light on the self-regulation of star formation*

⟶ *What is the role of H_2 as a gas coolant at the peak of the star forming activity of the Universe?*

Extras

After JWST? Witnessing galaxy mass build-up?

- Energetics of galaxy build-up
- ALMA Band 10 (850 GHz): a few 10^{-20} W/ m^{-2} in 5h…but… requires precise target location and redshift!!
- Need large field of view and large fractional bandwidth