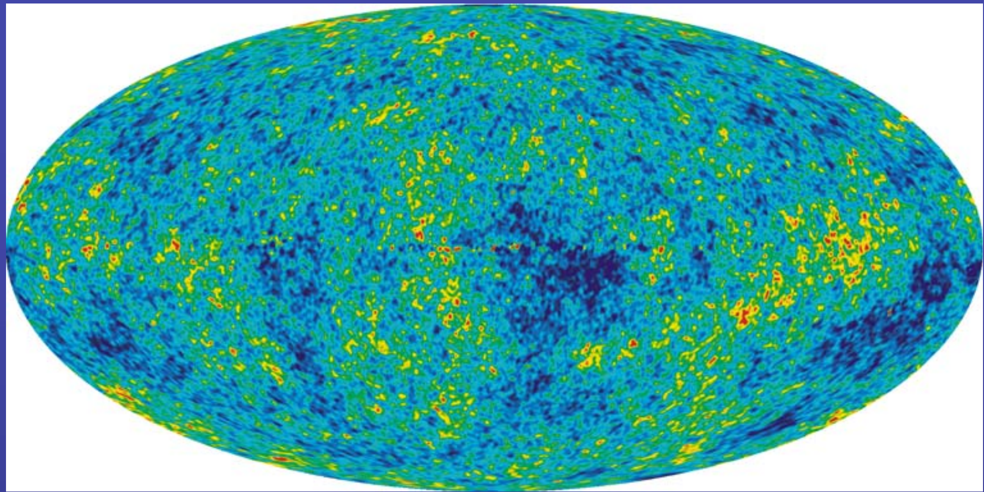


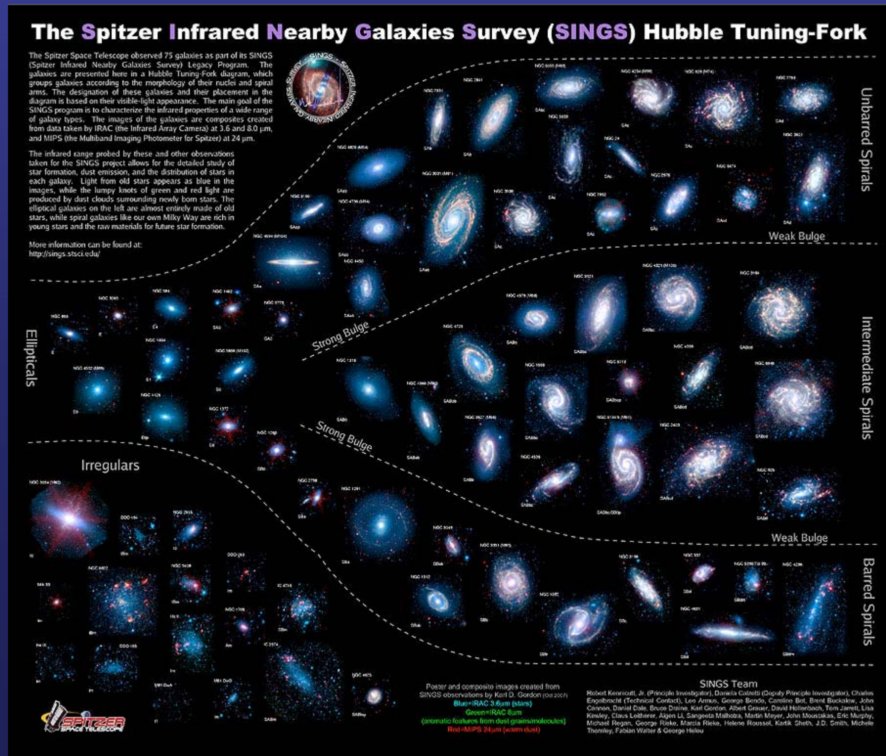
Universe

-13.7 billion years

WMAP → Planck

Galaxies today : IR Hubble tuning fork

Spitzer → Herschel



H_2 in Galaxy Formation

François Boulanger

IAS, Orsay

⟹ **H_2 spectroscopy from Space**

Outline

- ❑ H_2 and the energetics of Galaxy Formation
- ❑ What we are learning from Spitzer H_2 observations of Local Universe galaxies
- ❑ Beyond Spitzer:

The distance universe through the active era of galaxy build-up (z ~ 2) to the early steps (z > 5, Phil Appleton's talk) of galaxy formation

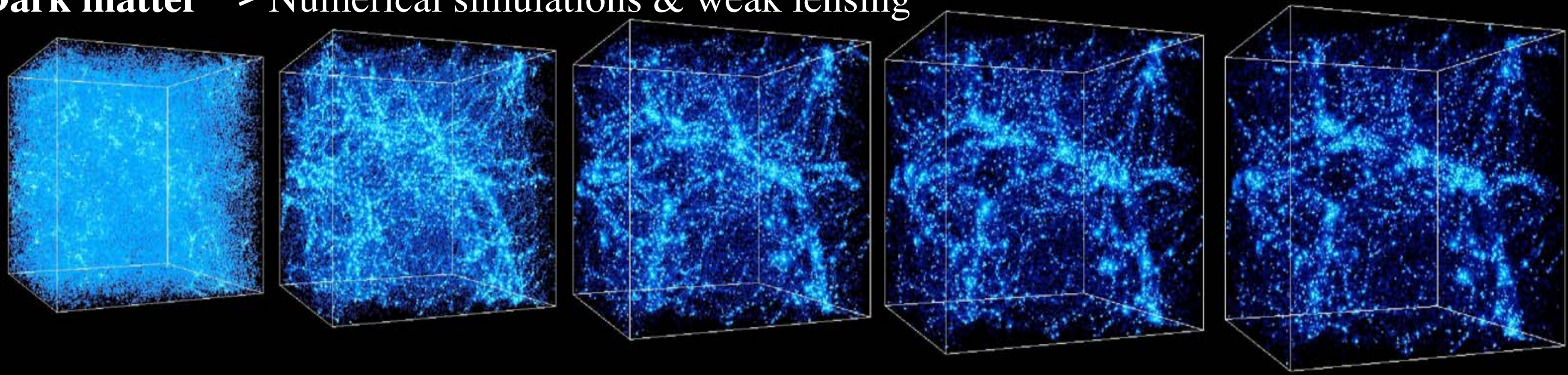
Collaborators:

P. Guillard (PhD student) , G. Pineau des Forets, N. Nesvadba (IAS, Orsay), E. Falgarone (Obs. Paris), L. Kristensen (Leiden)

P. Appleton (NSHC), P. Ogle (SSC) (see his poster)

Galaxies on the Cosmic Web

Dark matter → Numerical simulations & weak lensing



➢ Where and When do galaxies form ? ➜ Multi-wavelength photometric surveys

➢How ? ➜ Heating and cooling of baryons in relation with gas accretion, galaxies interaction/merging & star formation and AGN feedback

➜ Energetics of the cold gas which concentrates in galactic disks to form stars

Observations ➪ Questions

❖ Massive galaxies form early

❖ Their mass scales with that of their central Black Hole

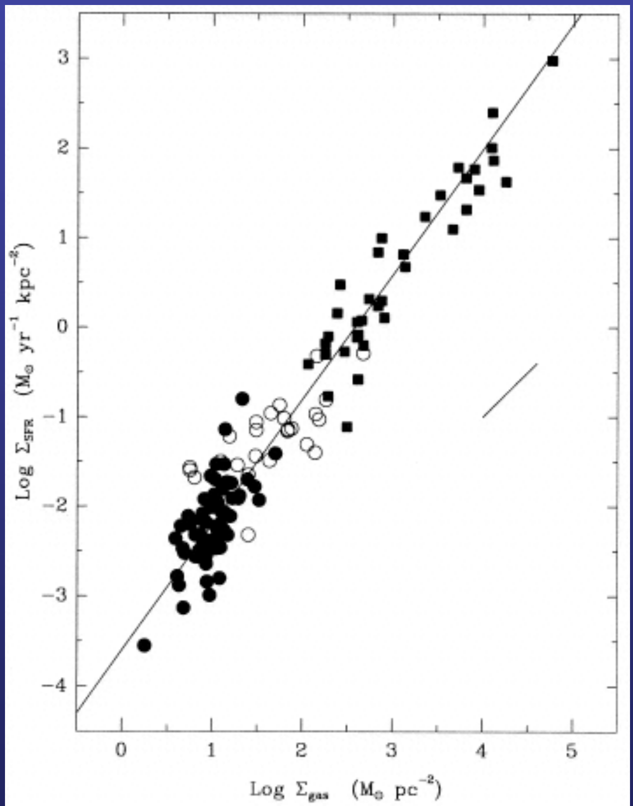
❖ Galaxy formation is inefficient

➢ Massive galaxies stop growing after concentrating a minor fraction of the available baryonic mass

➢ There are much fewer small galaxies than small dark matter halos

➢ Baryonic mass in galaxies is only 8 % of the total

Molecular Gas → Star Formation



Kennicutt et al. 1998

Global Schmidt law in star forming galaxies

- Star formation rate:

$\Sigma_{SFR} = 2.5\ 10^{-10}\ M_o\ yr^{-1}\ pc^{-2}\ (\Sigma_g/M_o\ pc^{-2})^{1.4}$

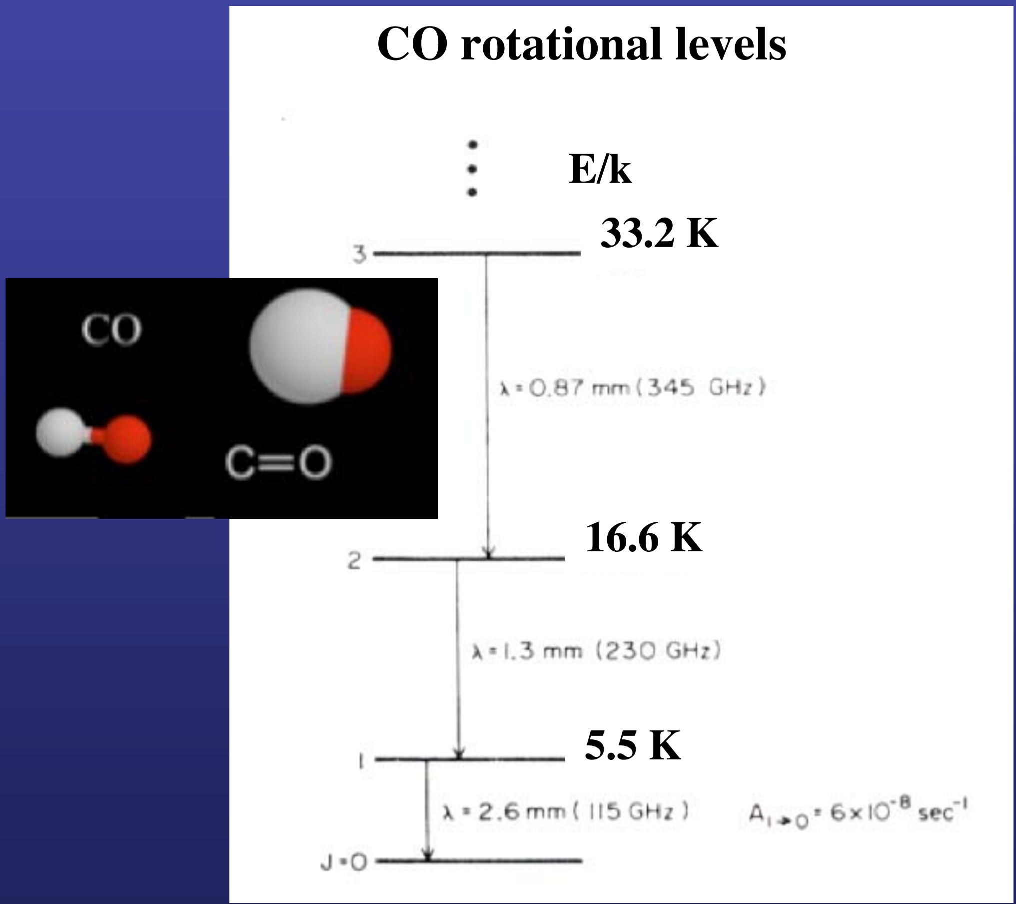
- Star formation time scale:

$t_{SF} = \Sigma_{g/}\ \Sigma_{SFR} = 10^9\ yr\ (\Sigma_g/\ 30\ M_o\ pc^{-2})^{\ 0.4}$

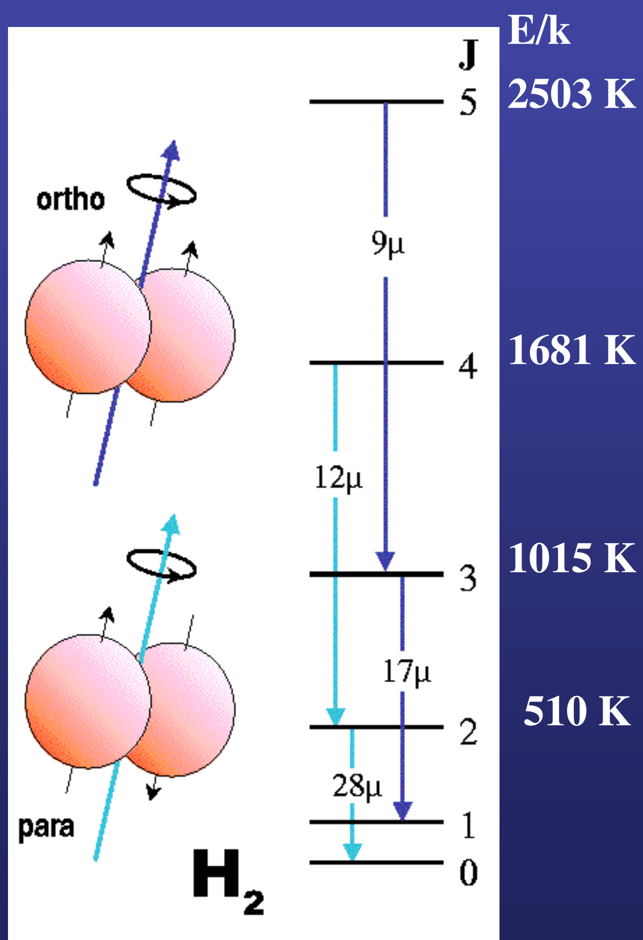
Miliky Way : $t_{SF} = 10^9$ yr

In ULIRGS : $t_{SF} < 10^8$ yr

Two distinct H_2 tracers



→ Cold H_2



→ Warm H_2

Observatories

CO

$R=10^7$

10-20''

1''

IRAM, CARMA … ALMA interferometer

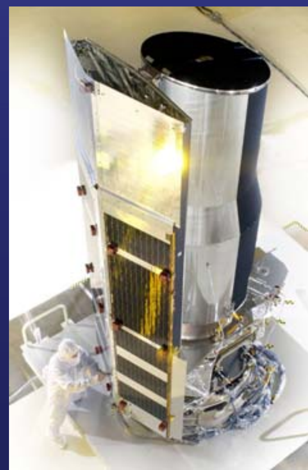
H_2

ISO

1995-1997

R=2000

20''



Spitzer

2003-2009

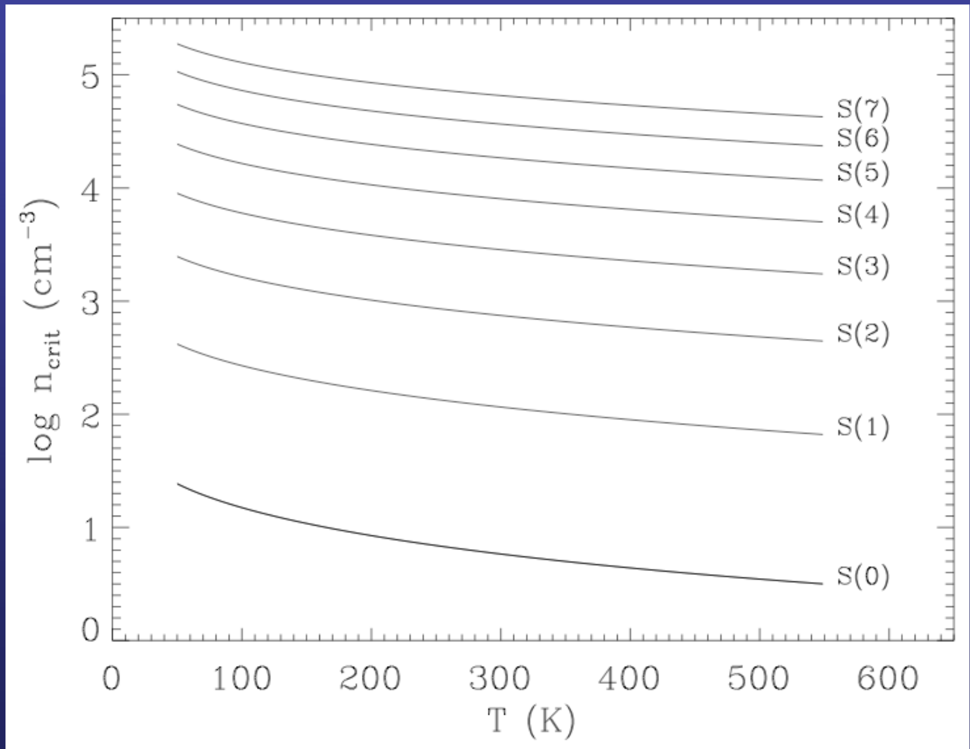
R=80 - 600

5-10''

… SPICA, CALISTO, SAFIR

Warm H_2 thermometer

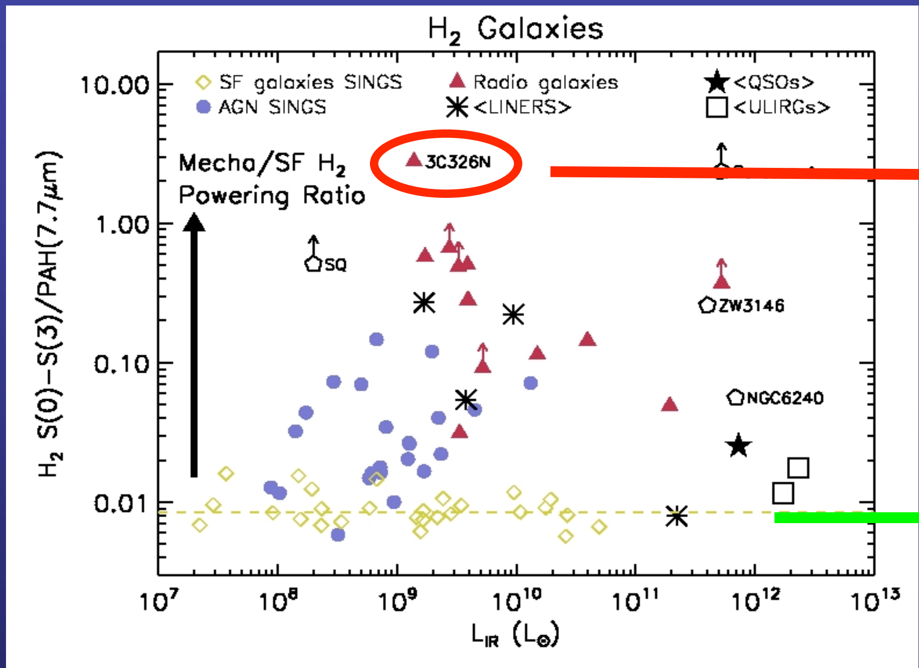
Critical density H_2 rotational lines

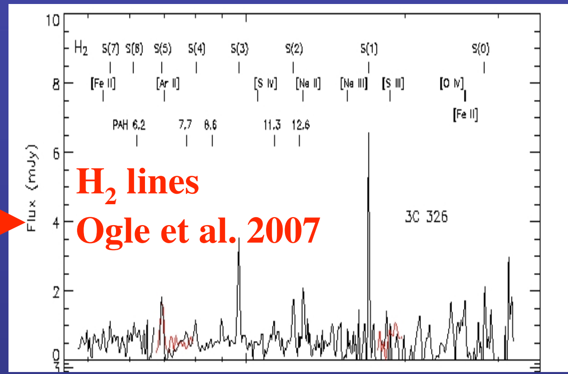


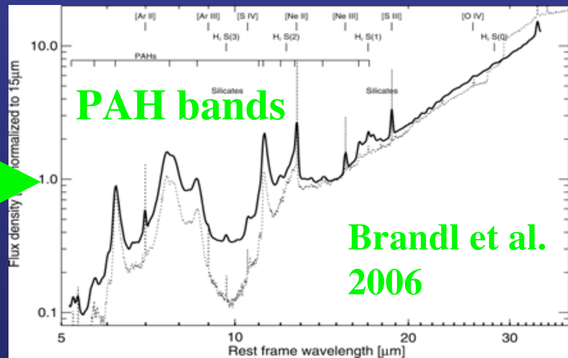
- The lowest J transitions are thermalized at molecular cloud densities

→ They trace molecular gas energetics

H_2 Luminous Galaxies







➔ Population of **H_2 luminous galaxies with no or relatively weak star formation** that includes AGNs, radio galaxies, cooling flows in clusters, ellipticals, interacting/merging systems

From 10^7 to 10^{10} $M_\odot$ of warm (T ≥150 K) H_2

H_2 in Galactic winds

M82: Optical

Spitzer, 3.5 - 8μm

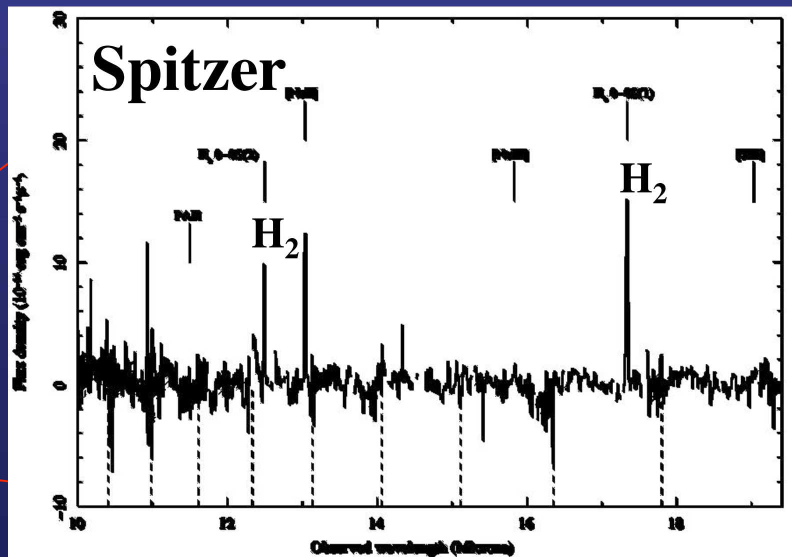
➜ M82 wind holds dust and H2 gas (Engelbracht et al. 2006 & Armus et al/)

H α image Conselice et al. 2001

Perseus cluster cooling flow

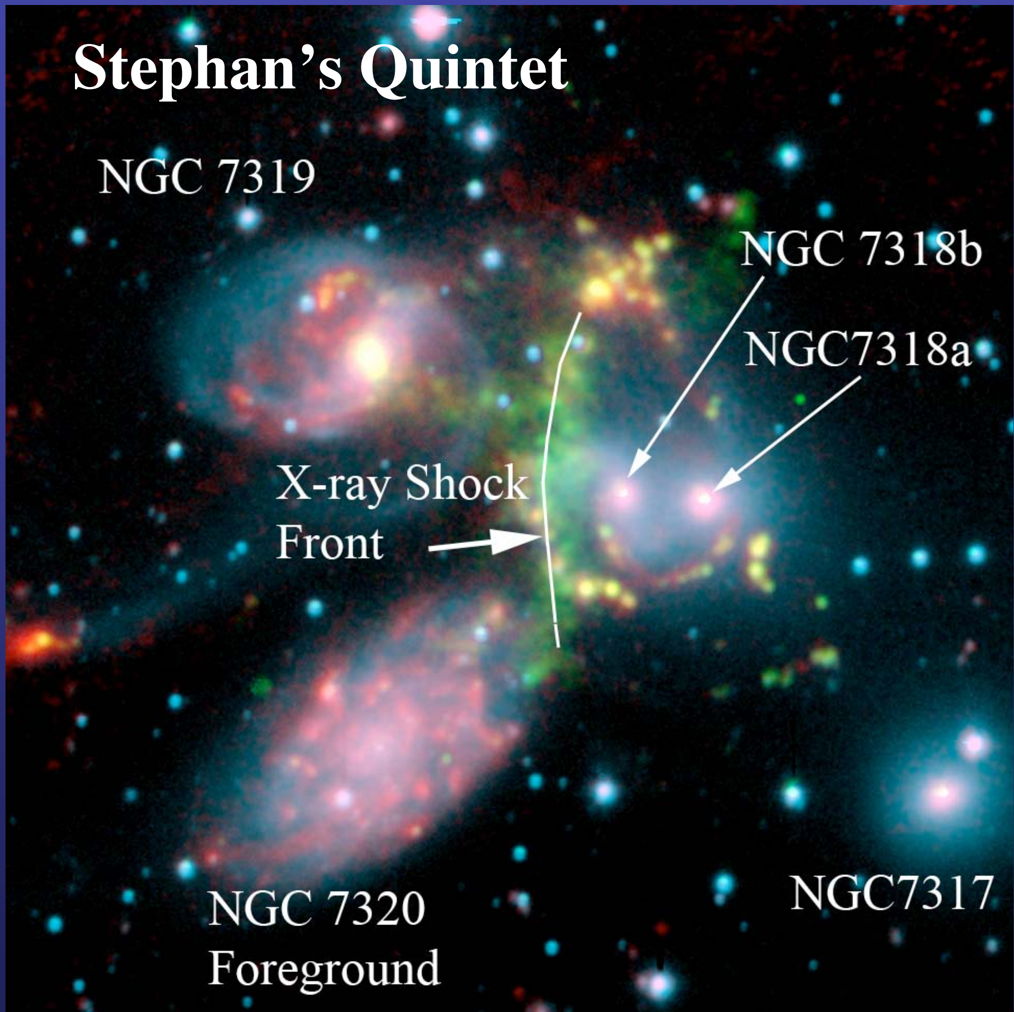
3’

Molecular gas filaments are formed in cooling flows



Johnstone et al. 2007

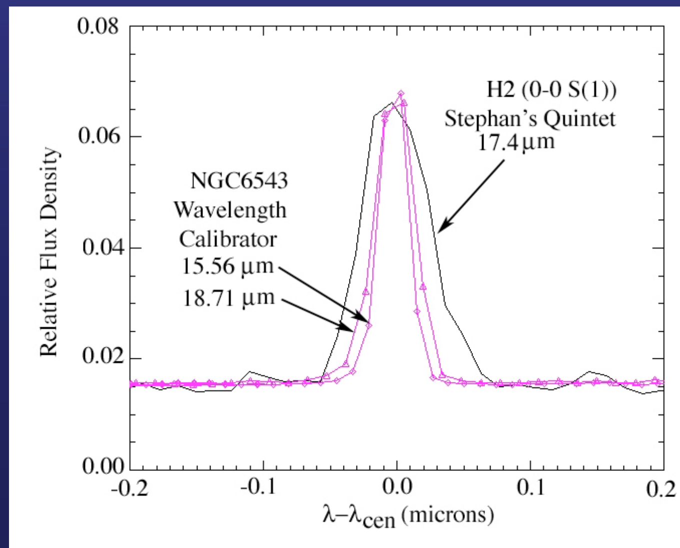
Galaxy Collision



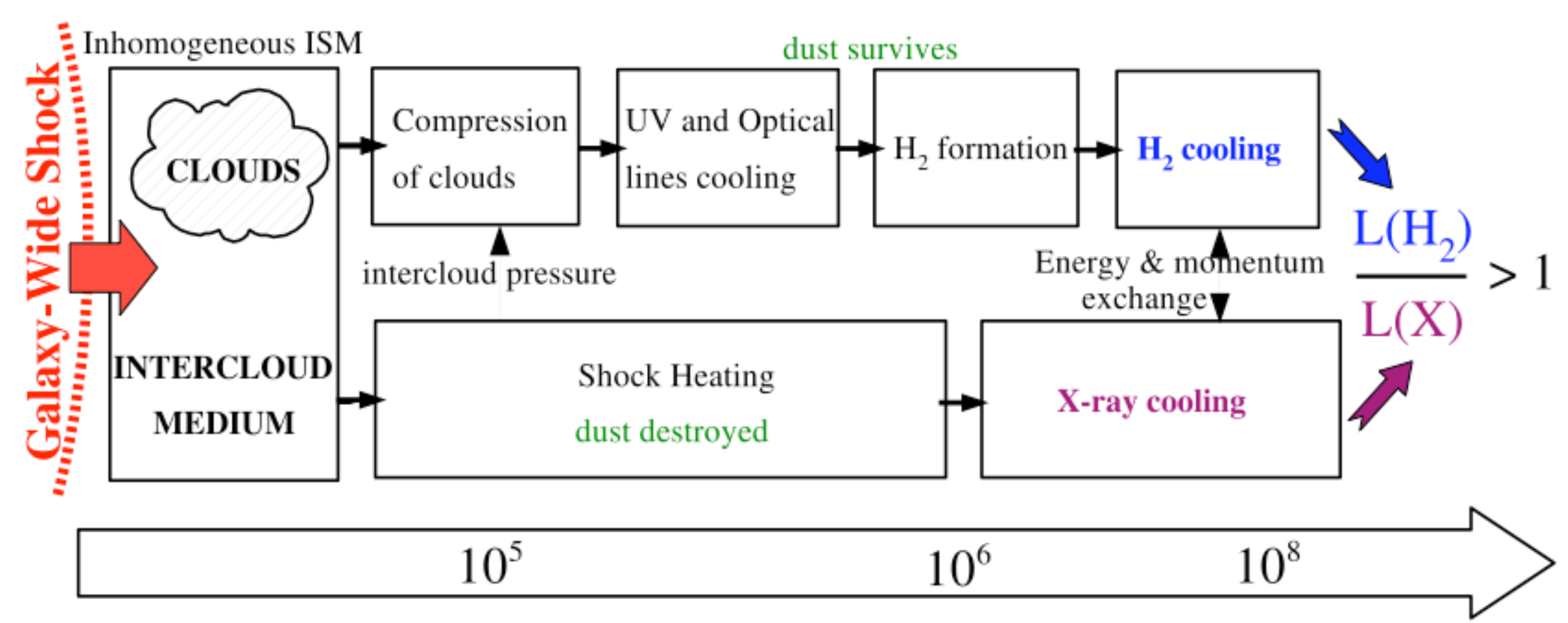
Galaxy-wide shock created by a 1000 km/s collision betweena galaxy and a tidal tail

- $L_{H2} > L_{X\text{-}ray}$
- H_2 line width ~ 1000 km/s

Appleton et al. 2006



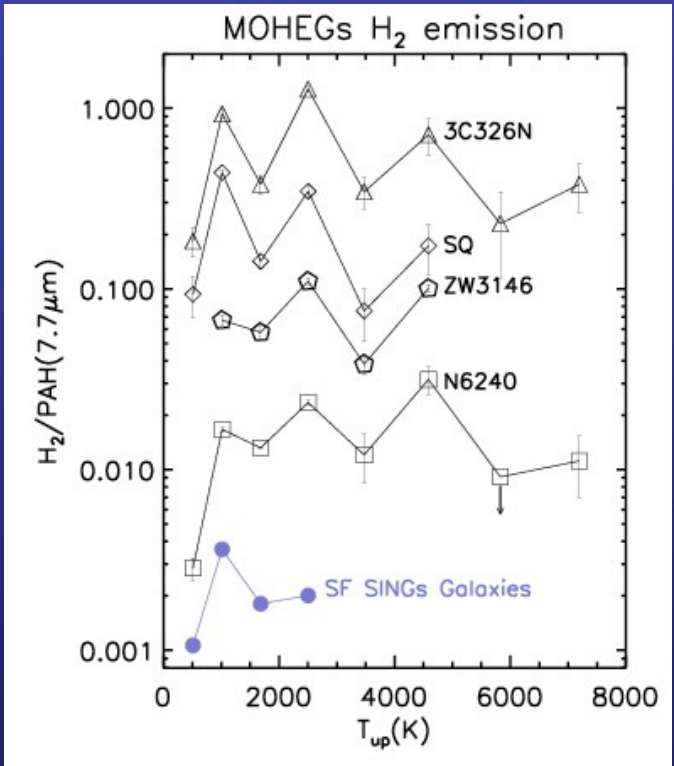
Galaxy wide shocks

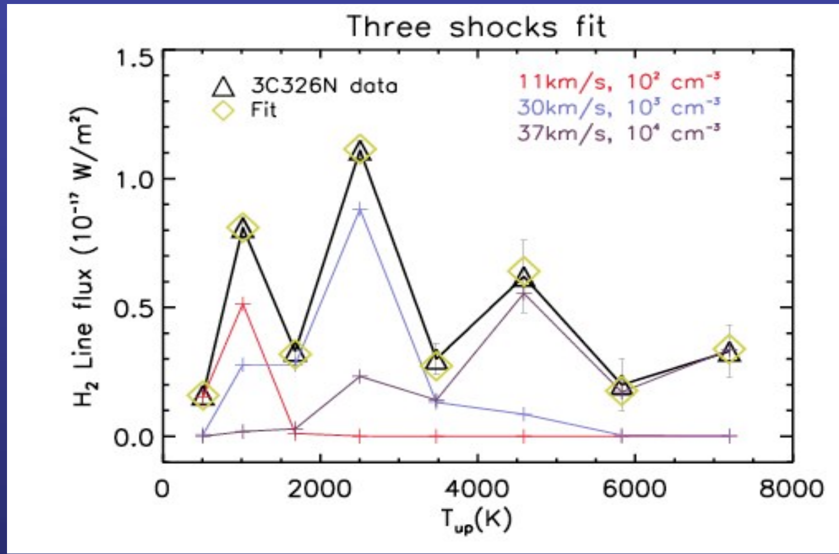


Guillard et al. 2008

➞ Galaxy wide shock create a multiphase medium with H_2 gas embedded in hot X-ray emitting plasma

Powering the H_2 emission

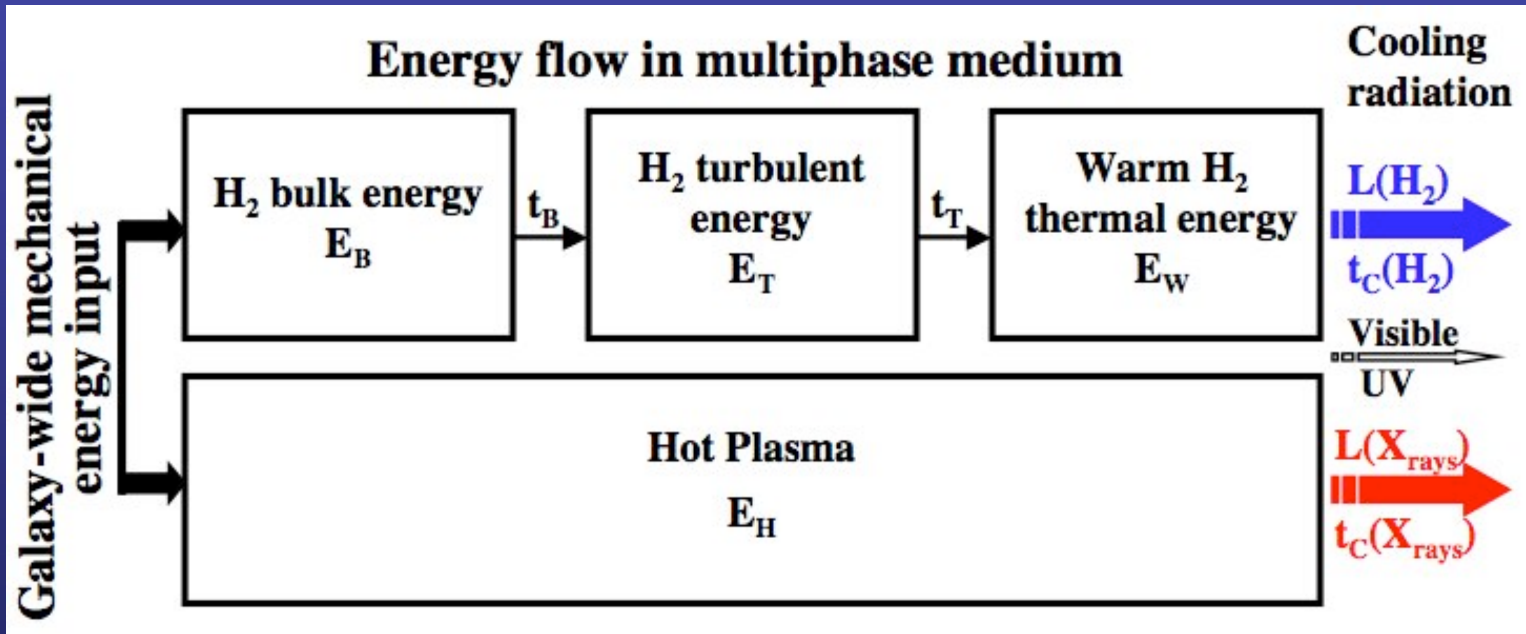




➜ Cooling time of warm H_2 is ~10^4 yrs => Need continuous energy supply

➜ Distinct H_2 luminous galaxies have similar H_2 SEDs

Energy flow in multiphase medium



- ❑ Bulk kinetic energy reservoir $E_B >> E_T$, $E_W => t_B >> t_T$, t_C
- ❑ In Stefan's quintet:
  - $E_B \sim E_H$ and $L(H_2)$ is a few times $L(X_{rays})$
  - H_2 gas and hot plasma « cooling time » $t_C \sim 10^8$ yrs

H_2 in galaxy build-up

Elementary steps in galaxy evolution

- **Accretion**: from the intergalactic medium/galaxy halo
- **Feedback**: Gas ejection powered by star formation and the central black hole
- **Galaxy interactions**: collisions and merging

→ Multiphase medium with H_2 gas embedded in hot plasma

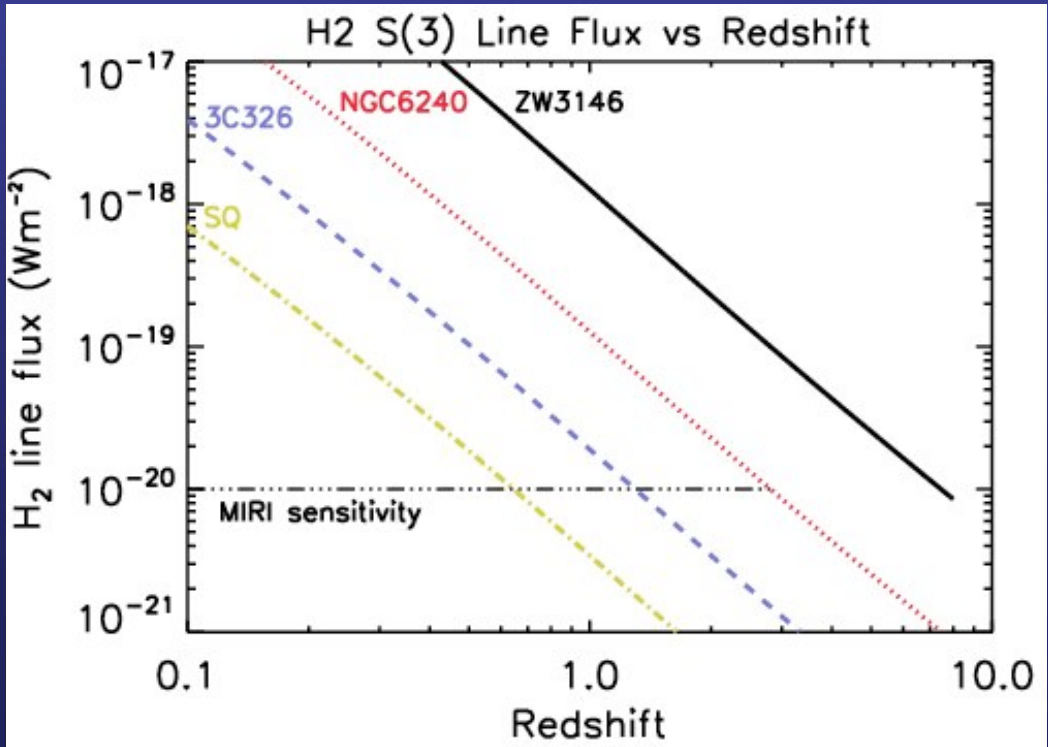
→ The gas bulk kinetic energy sustains molecular gas turbulence

→ Turbulence dissipation powers H_2 emission

→ Dissipation controls the H_2 gas evolution towards star formation

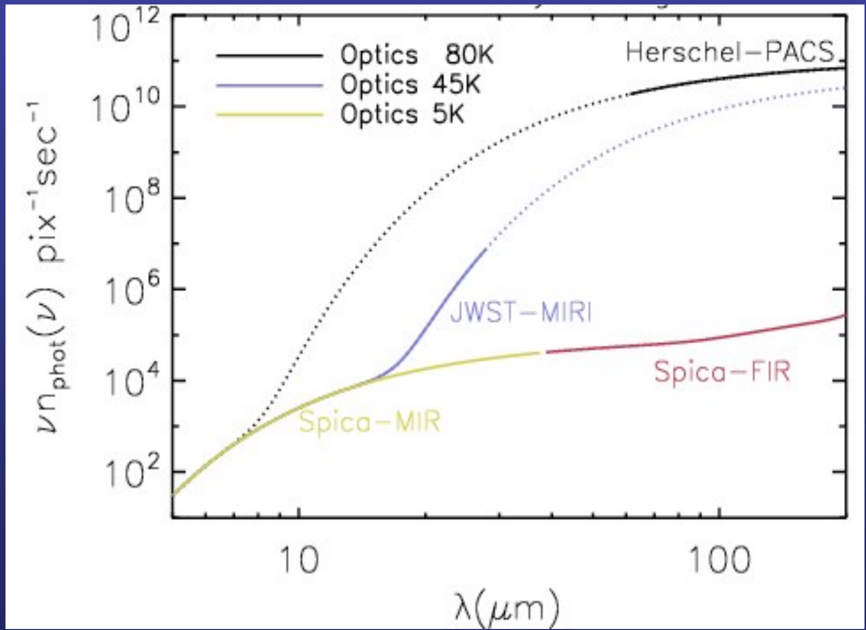
H_2 beyond Spitzer

➜ Tracing the energetics of Galaxy Formation through the active galaxy build-up era (z~2) to the early steps at z>5

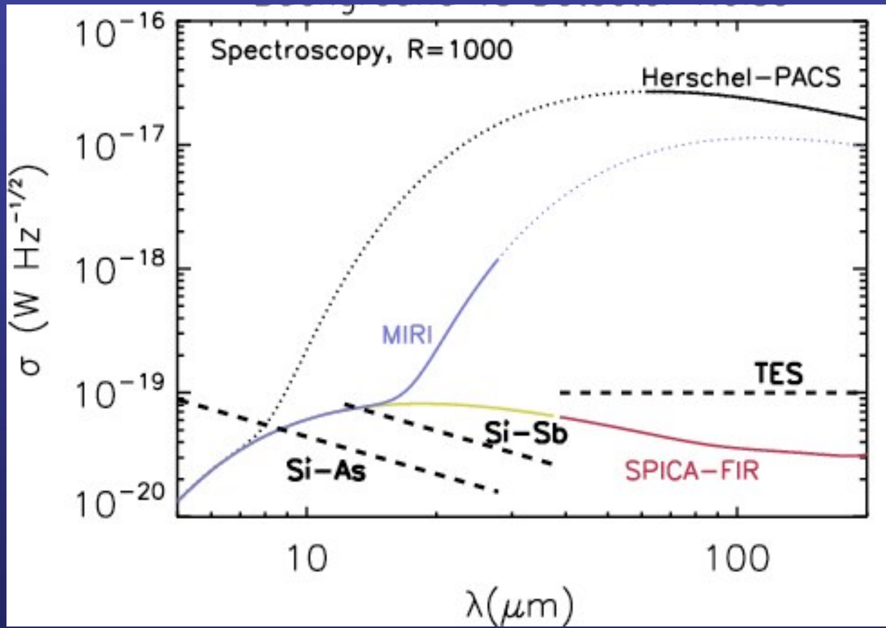


Background sensitivity limit

Diffraction limited sky background



Background noise



➜ Sensitivity of 10^{-21} W/m^2 achievable with SPICA with 10^{-19} W/Hz$^{0.5}$ NEP detectors

Conclusions

❖ H_2 Spitzer observations reveal large quantities of dynamically energized molecular gas out of star forming galactic disks, powered by gas accretion, star formation and AGN feedback, and galaxy interactions.

❖ H_2 rotational line emission is a unique tracer of **Galaxy Formation Energetics**: the energy released by accretion and feedback & its dissipation

❖ Observation of redshited H_2 lines is a main science driver for future far-IR Space missions

❖ Active telescope cooling and a new generation of sensitive far-IR detectors (NEP < 10^{-19} W/Hz$^{0.5}$) will provide the needed sensitivity ➜ SPICA, CALISTO, SAFIR …