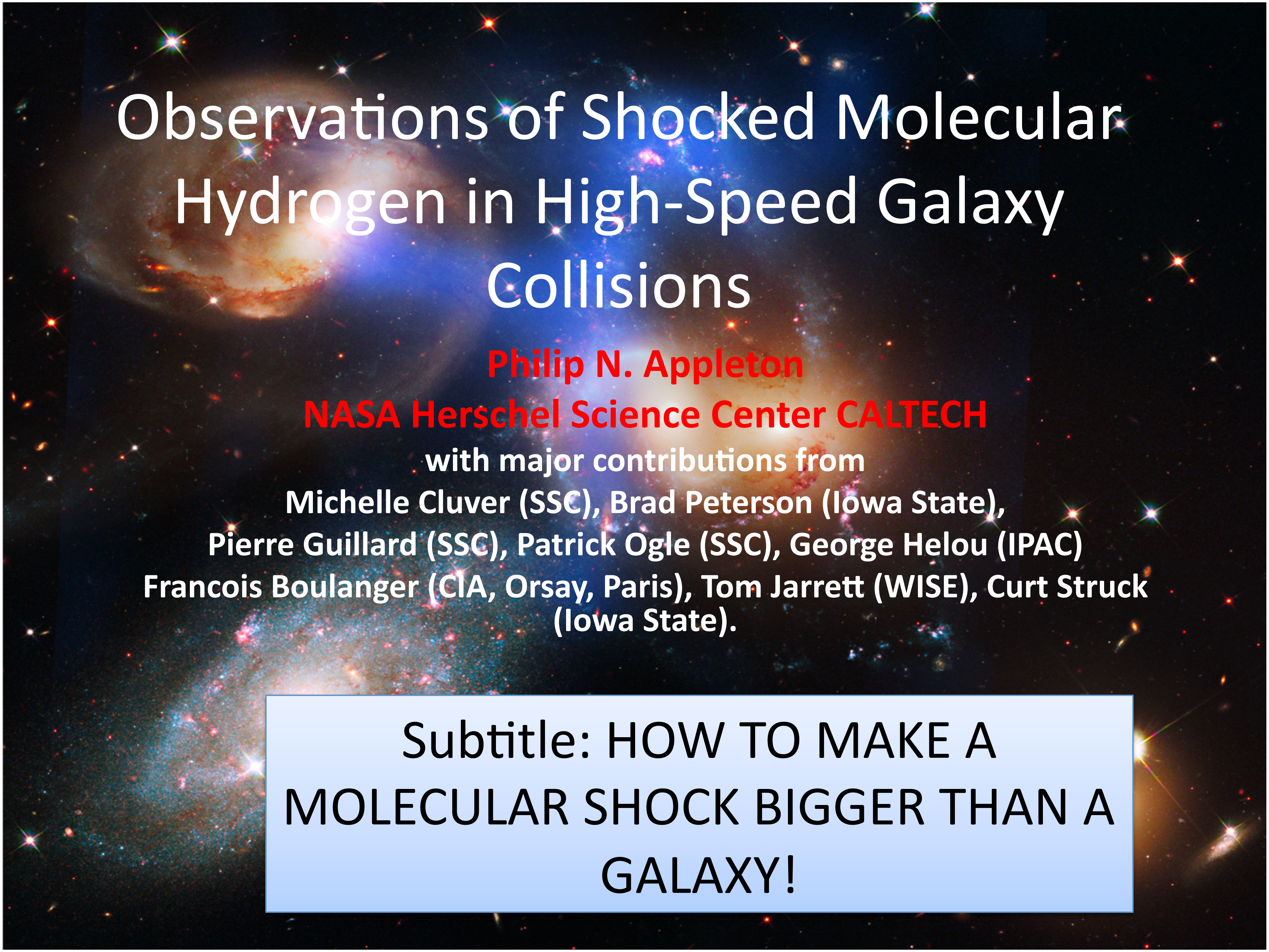


Observations of Shocked Molecular Hydrogen in High-Speed Galaxy Collisions

Philip N. Appleton

NASA Herschel Science Center CALTECH

with major contributions from

Michelle Cluver (SSC), Brad Peterson (Iowa State), Pierre Guillard (SSC), Patrick Ogle (SSC), George Helou (IPAC) Francois Boulanger (CIA, Orsay, Paris), Tom Jarrett (WISE), Curt Struck (Iowa State).

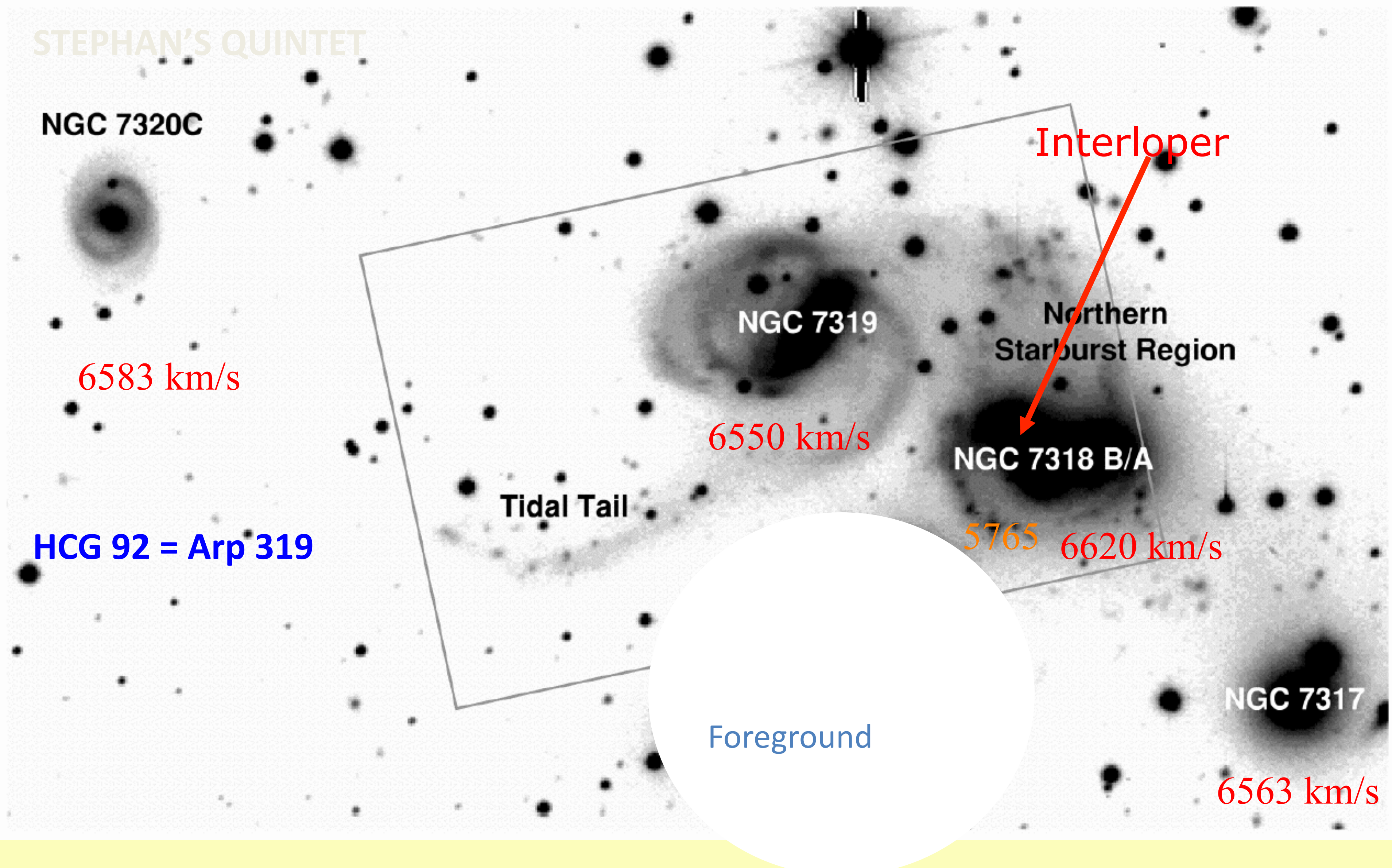
Subtitle: HOW TO MAKE A MOLECULAR SHOCK BIGGER THAN A GALAXY!

How to create a huge galaxy-sized molecule shock?

TRY 1:

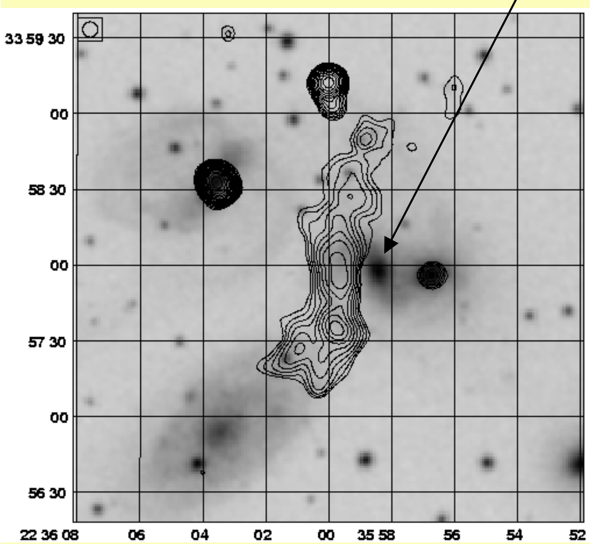
SLAM A GALAXY INTO
A Pre-existing TIDAL TAIL
AT > 700 km/s
and observe what happens!

PS—DO NOT TRY AT HOME!


STEPHAN'S QUINTET
NGC 7320C
6583 km/s
HCG 92 = Arp 319
NGC 7319
6550 km/s
Tidal Tail
Interloper
Northern
Starburst Region
NGC 7318 B/A
5765
6620 km/s
Foreground
NGC 7317
6563 km/s

Hypothesis: NGC 7318b is crashing into the rest of the group at V ~ 800 km/s : It is an interloper

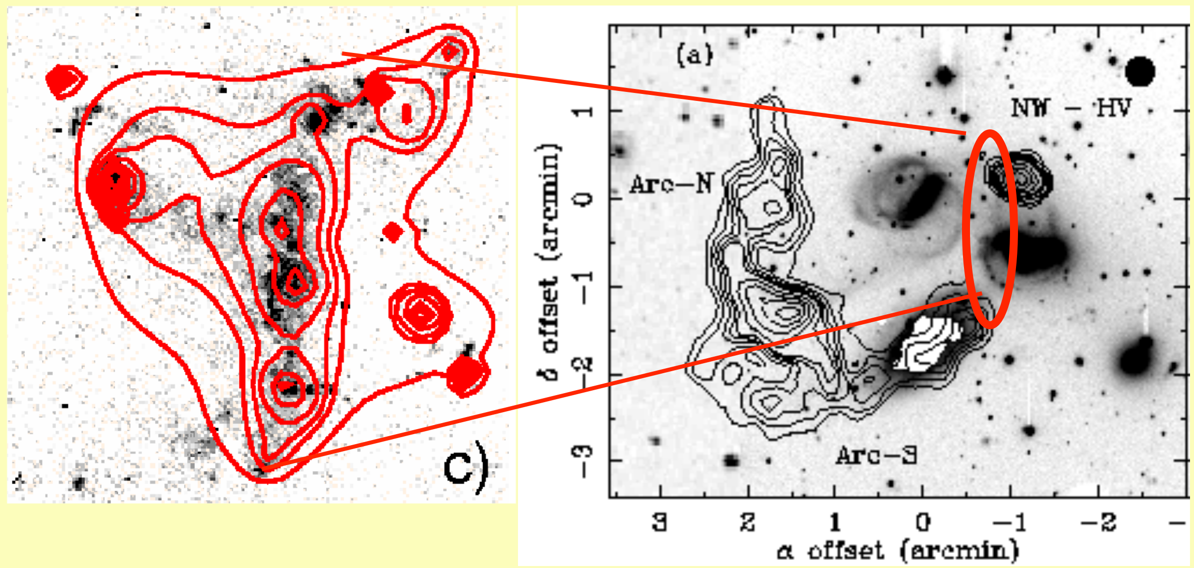
VLA Observations



20 cm Radio emission from between galaxies suggested an intergalactic shock (Allen & Hartzuiker 1972)

CHANDRA X-RAY TELESCOPE

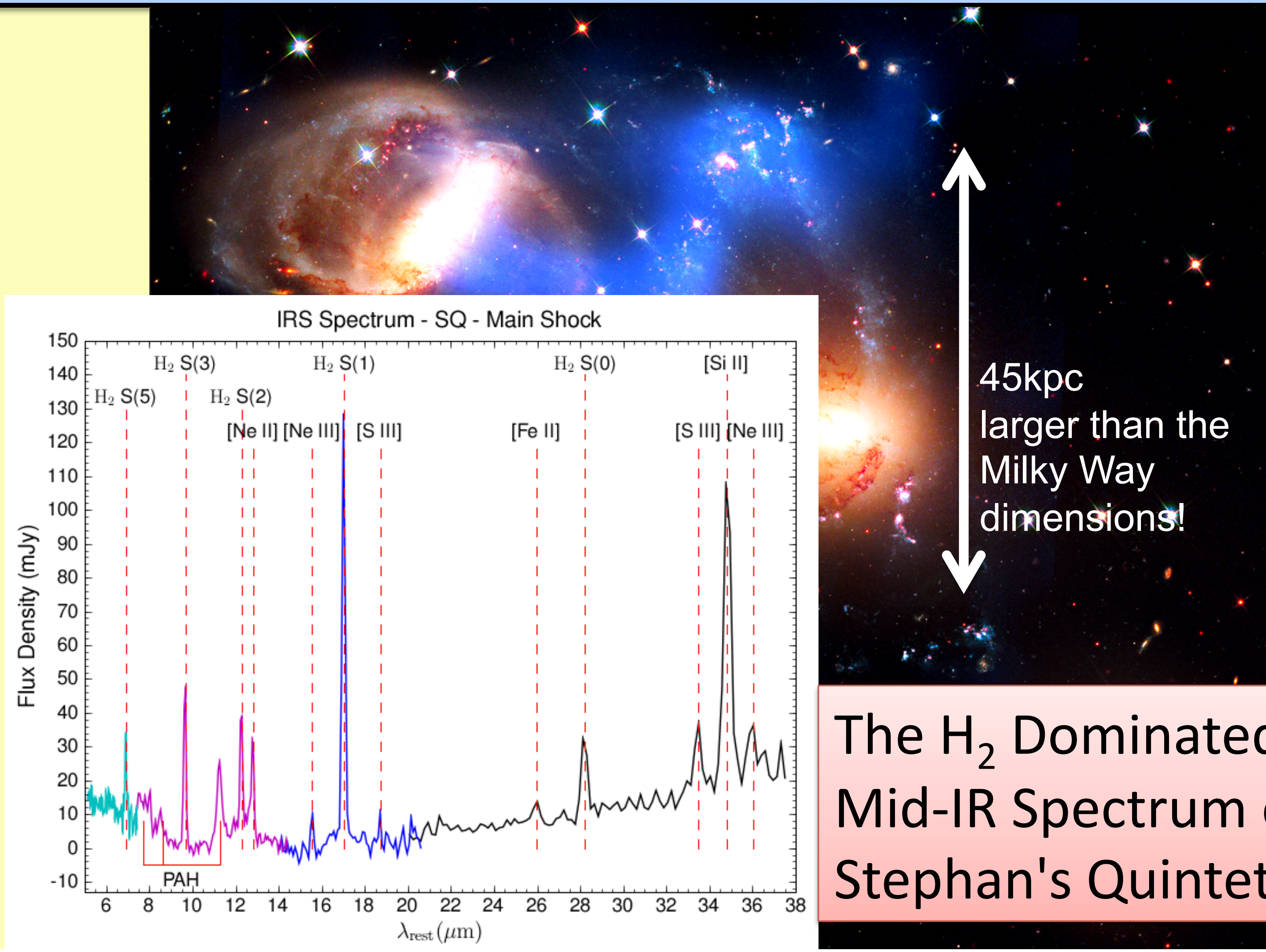
VLA Observations



Hot X-ray gas indicating powerful shock wave (Trinchieri et al. 2003)

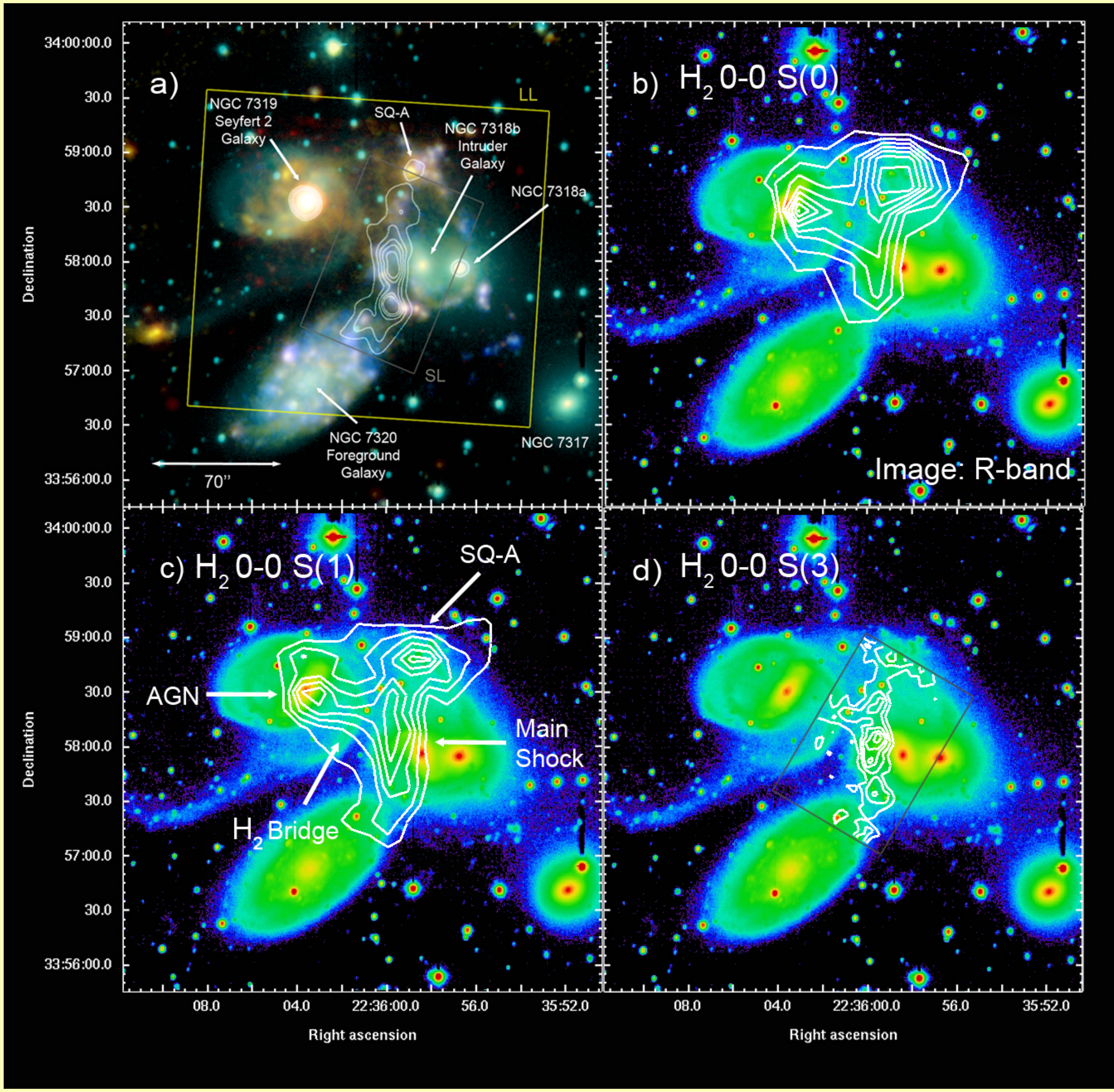
Neutral hydrogen Observations show "gap" in HI where Shock is observed

Spitzer IRS 0-0 S(1) Molecular Hydrogen in Stephan's Quintet (Cluver & Appleton et al. 2010)



The H_2 Dominated Mid-IR Spectrum of Stephan's Quintet

Extreme Rotational Mid-IR H_2 Line Cooling in Stephan's Quintet (Cluver et al. 2010)



Key Facts

$L(H_2) \sim 10^{35}$ W over whole group

$L(H_2)/L(\text{X-ray}) > 3$

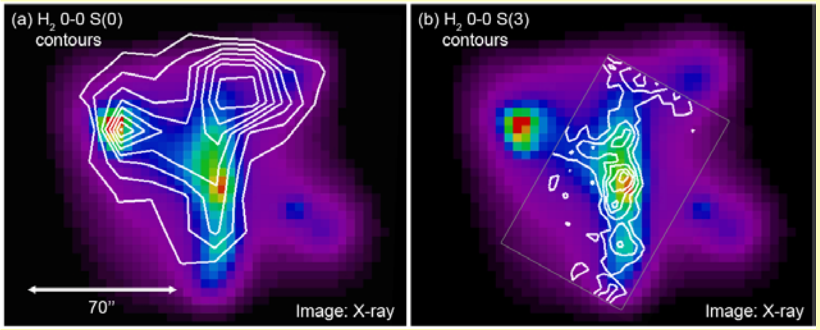
$L(H_2)/L([\text{SiII}]) = 10$

$L(H_2)/L(\text{IR}) \sim 0.3$
1000 X PDR Values!

Molecular hydrogen cooling very important in this galaxy-scale hi-speed shock!!

Appleton et al. 2006, Cluver et al. 2010

EVIDENCE FOR HIGH-SPEED SHOCK GOING INTO A MUTI-PHASE MEDIUM



Coexistence of Hot X-ray Gas and H_2 is this high-speed shock suggests the shock created by the intruder has collided with a multi-phase medium.

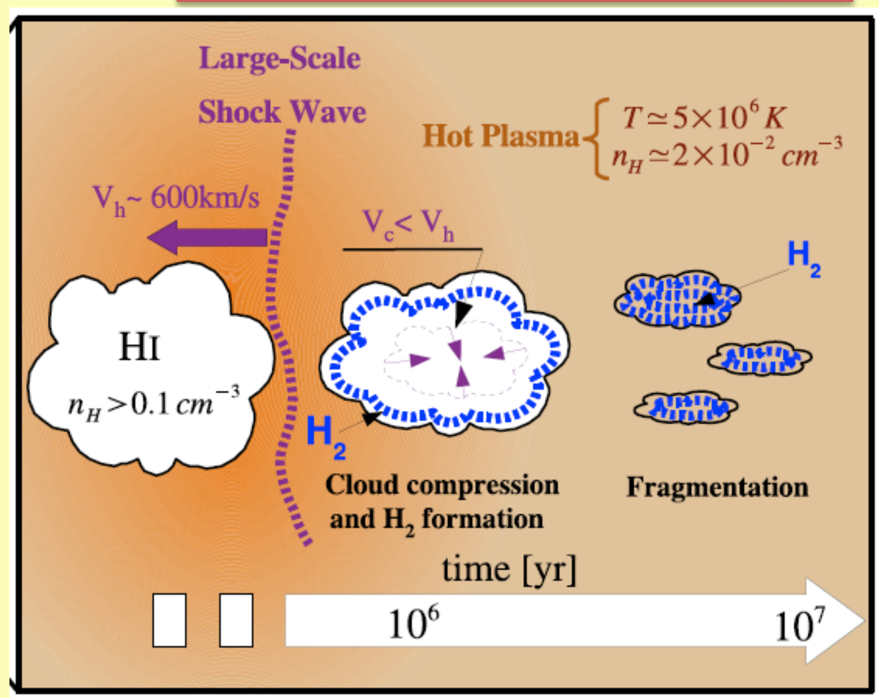
- X-rays emitted in the high-speed~600-700 km/s shocked low-density medium—dust destroyed

- WARM (3 temp) H_2 emitted in MHD dense molecular clumps entrained in the hot gas- dust survives (Guillard et al. 2009) Excitational diagram requires C- and J-shocks

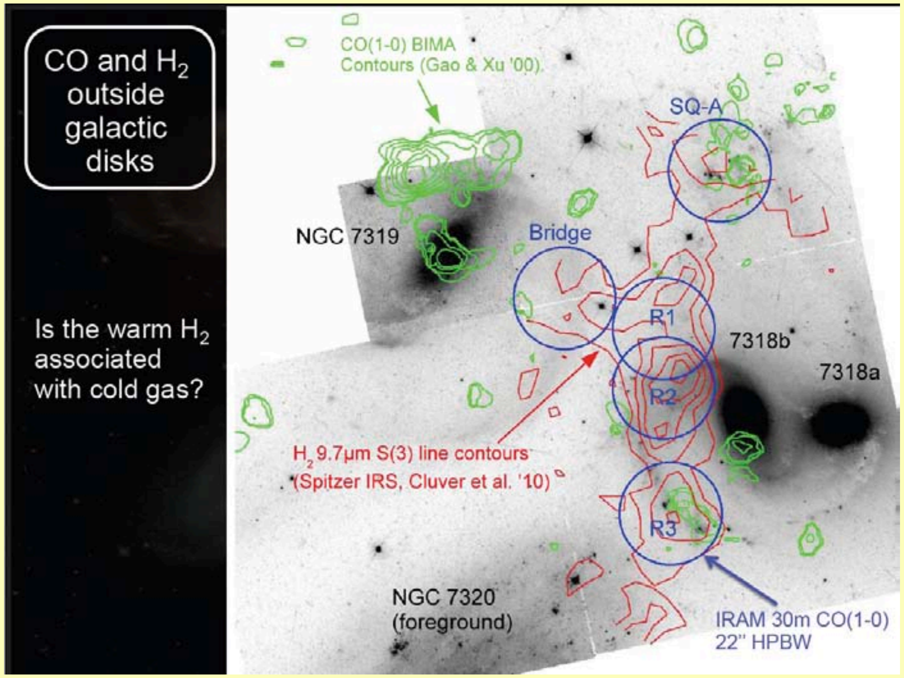
-strong [SiII] and weaker [FeII] detected in shock
----evidence of J-shocks! [NeIII]/[NeII] ratio
-consistent with V=100km/s shocks

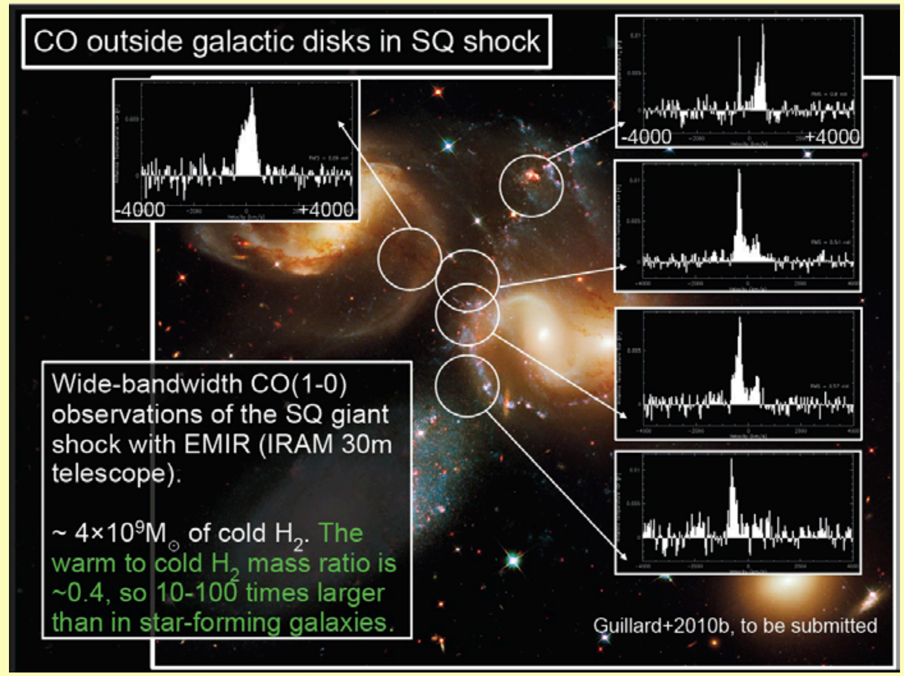
- discovery of 800 km/s wide CO(1-0) and (2-1) with 30m IRAM telescope implies denser, possibly colder gas present (Masers?? GBT)

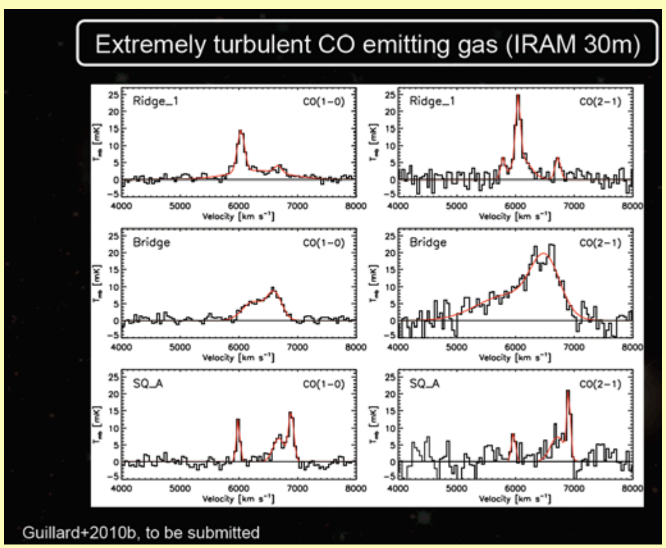
Models: Guillard et al. (2010)



CO J=1-0,2-1 Emission from shock (Guillard et al.)







Very deep IRAM 30m observations confirm the existence of broad (probably mainly cold) H2 emission in the shock and AGN bridge region (Guillard et al. in preparation). This confirms a multi-phase medium in the post-shocked gas.

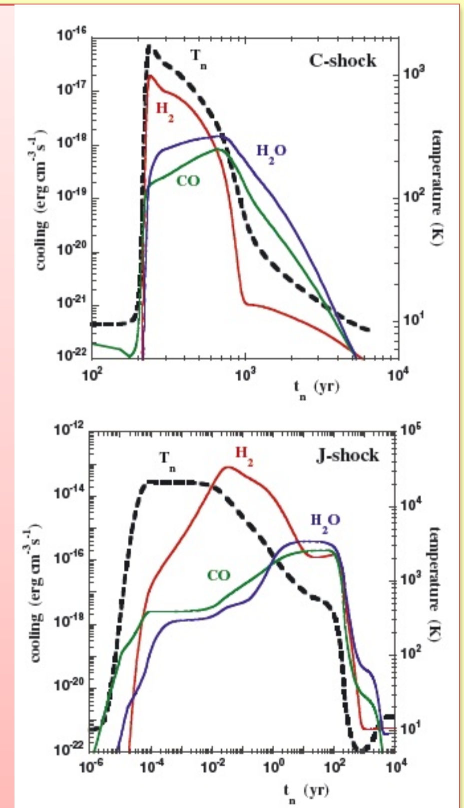
IT WORKED!!!
Collision created 2250 cubic kpc of warm H_2 in a compact group!

Rich laboratories for interstellar/IGM chemistry

What we don't know is:

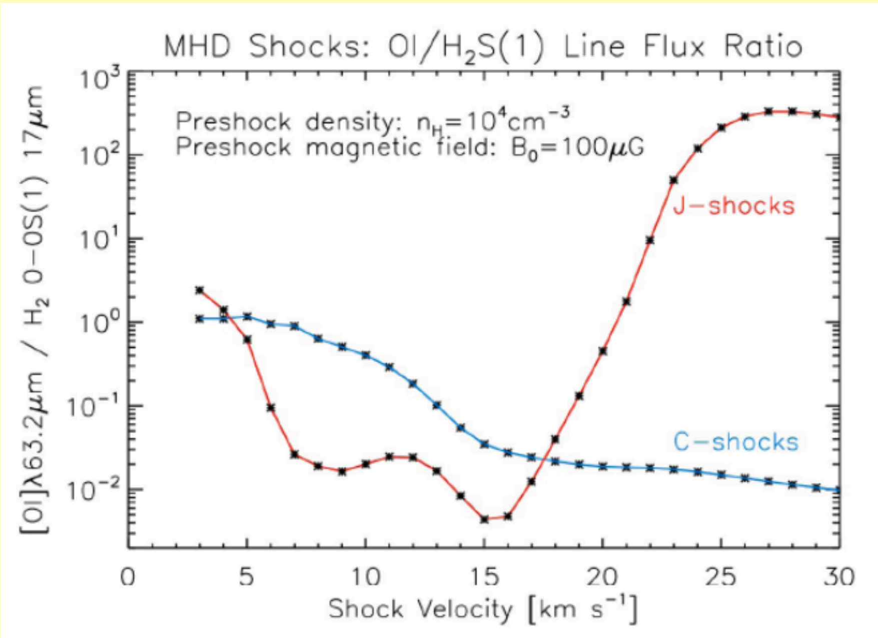
-Do the J-shocks create lots of H_2O?
-What does the CO ladder look like?
Is Cosmic Ray heating important?

Draine,Roberge and Dalgarno (1983)
Hollenbach & McKee (1989)
Kaufman & Neufeld (1996a,b)

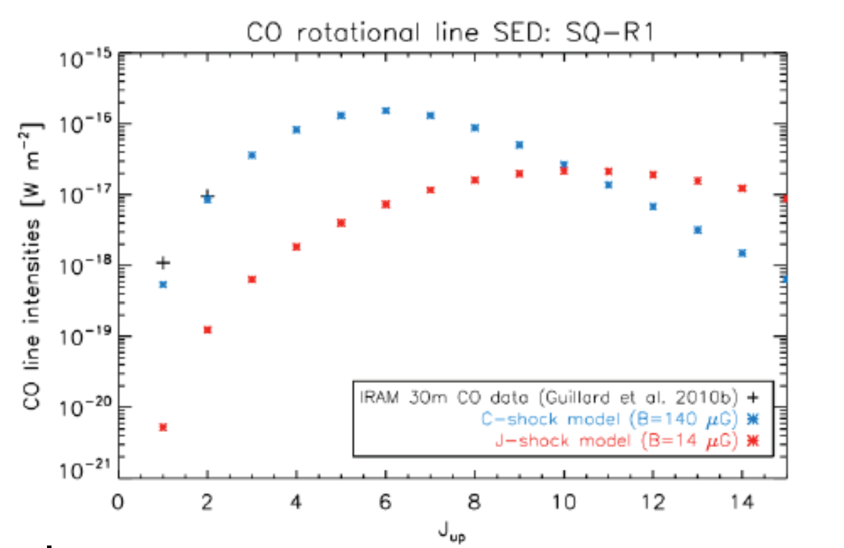


Flower & Pineau des Floret 2010

Herschel can help break the degeneracy between C and J-shocks



[OI]/H2 ratio sensitive to J-shocks
Release of Oxygen can enhance H2O formation also.
H2O can be very strong in J-shocks as can Ly-alpha from H2 dissociation



CO ladder can provide information about warm H2 component
Shocks can heat the gas to higher temperatures and populate the high-J levels

How to create a huge molecule shock!

Try 2

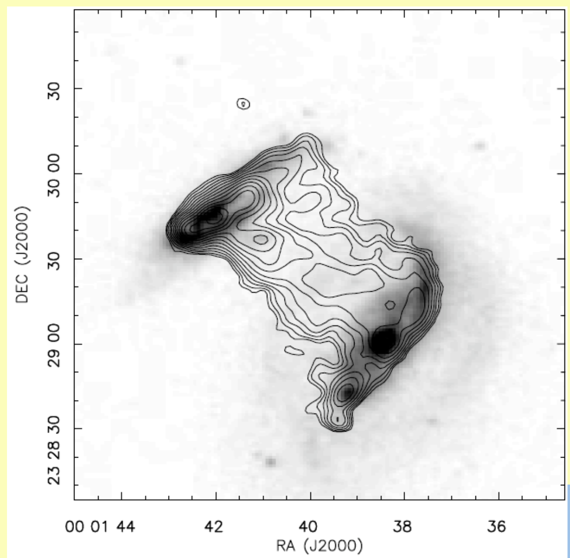
Take two galaxies and collide them Head ON!

DO NOT TRY THIS!

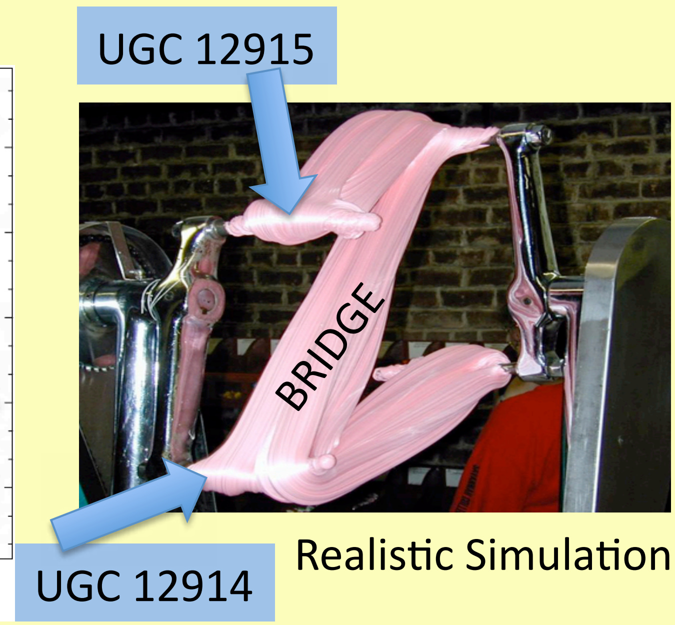
The "Taffy" Galaxies

- Effect discovered by Condon and Helou the 1990's
  - Head-on collision between two galaxies creating a common radio halo
  - Magnetic field of galaxies pulled out like Taffy!

R-band (Red) with H-alpha (Blue)

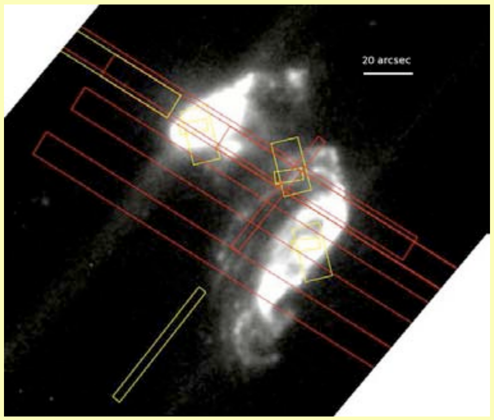


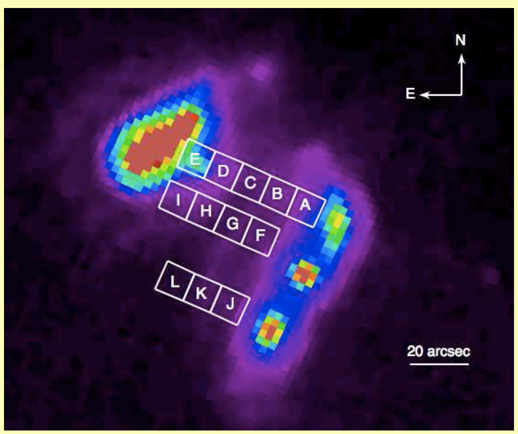
1.49 GHz contours from Condon et al. (1993) overlaid on DSS image (Jarrett et al. 1999)

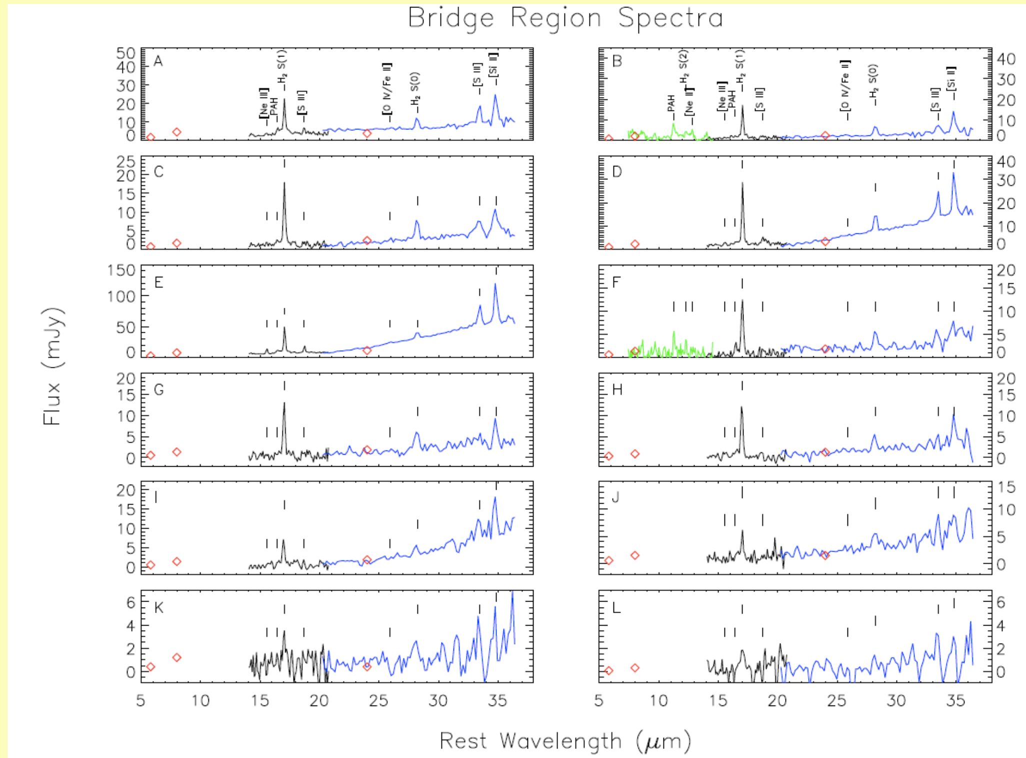


Realistic Simulation

Spitzer IRS Spectroscopy



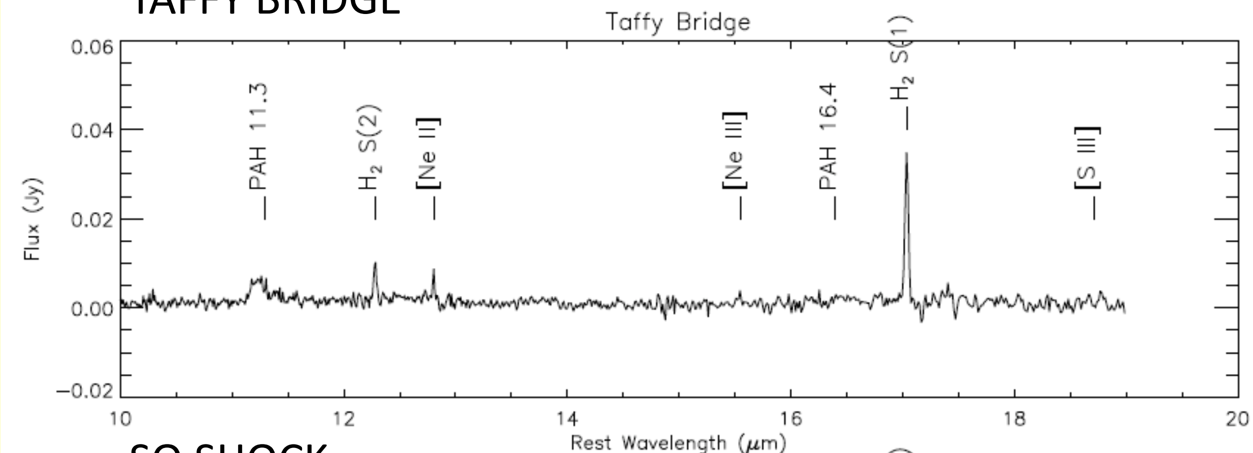




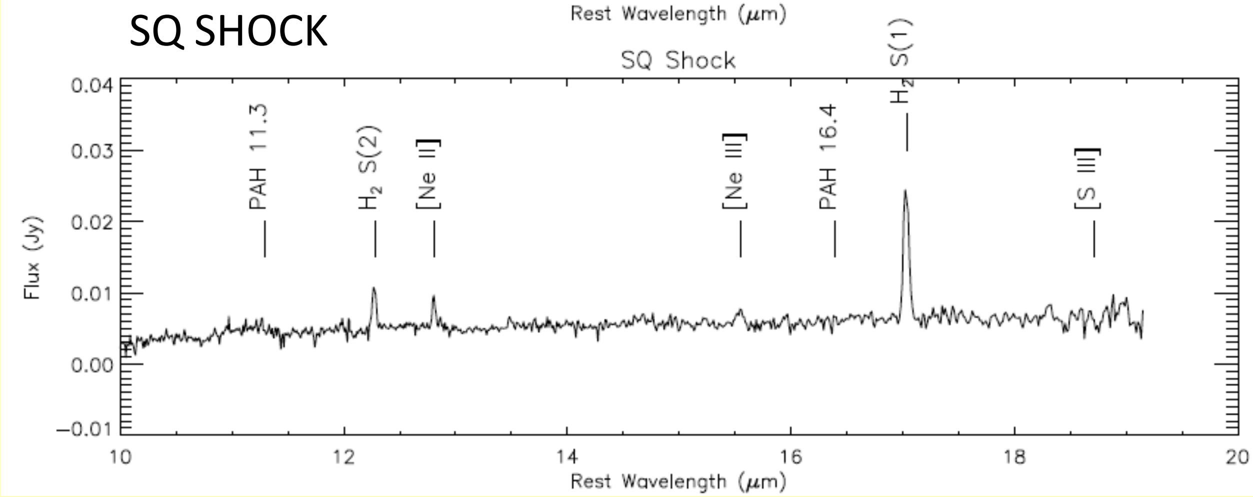
SPECTRA SHOW VERY STRONG H2 Emisson
from bridge! Look very similar to Stephan's Quintet

Taffy Bridge vs. SQ
(Brad Peterson (ISU), Appleton, Helou + 2010)

TAFFY BRIDGE



SQ SHOCK



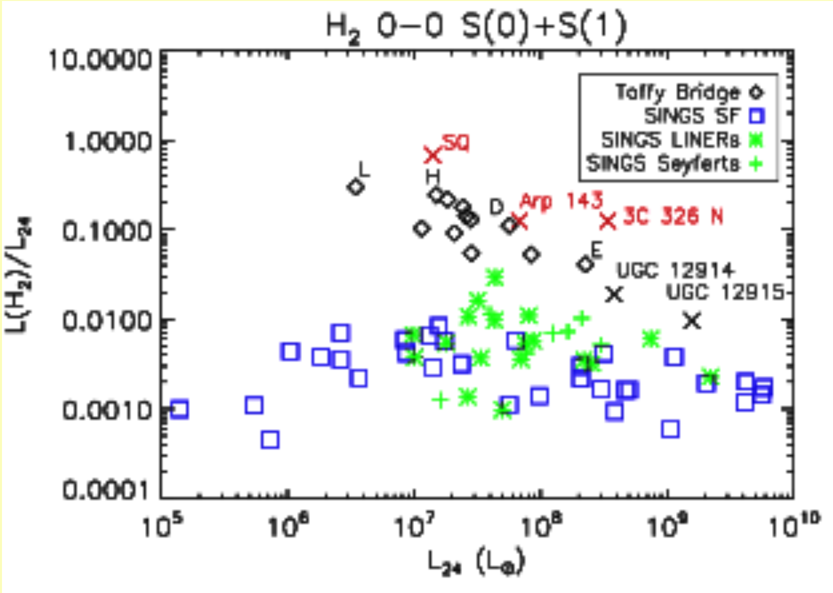
IRS SH

SQ data from Cluver et al. (2010)

- **Taffy has IRS**
- **spectrum almost identical to Stephan's Quintet shock**

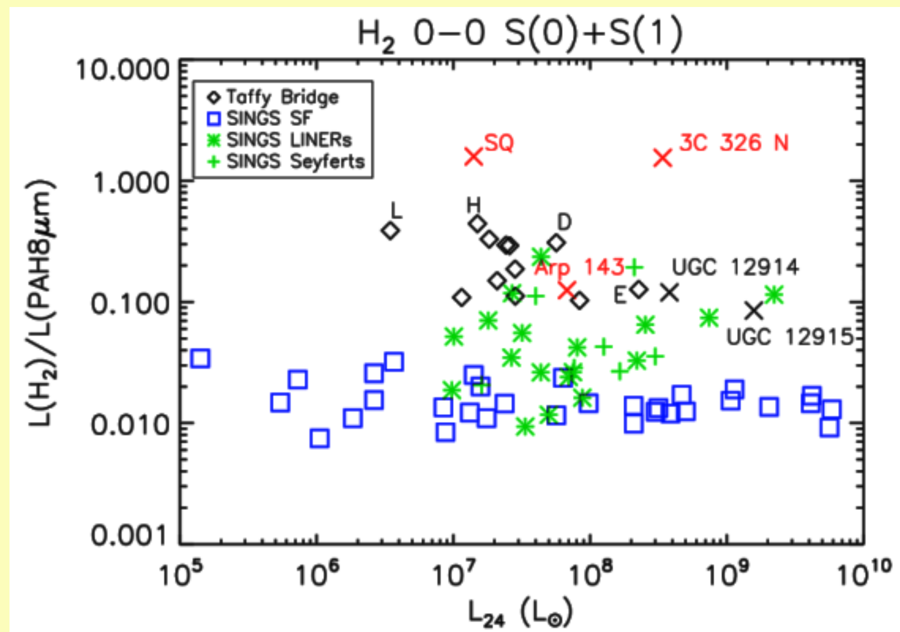
- **SQ has broader more powerful lines (σ ~ 870 km/s!)**

What Powers the H_2 in Taffy Bridge?

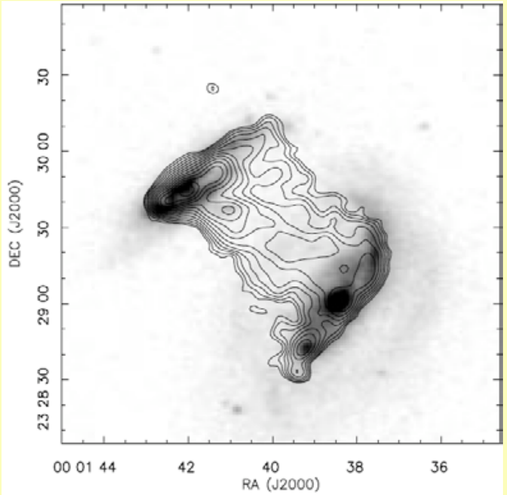


PDRs (Not enough UV)
XDRs (Not enough X-ray emission)
Cosmic Rays (probably not)
Magnetic Reconnection ?
Shocks—Very likely

TAFFY BRIDGE OCCUPIES REGION OF H2-POWER OCCUPIED BY MOHEGS AND Stephan's Quintet. It is inconsistent with PDR heating by factor of 100.



1-10 Mev Cosmic Ray Heating in Taffy Bridge?



Based on radio continuum can estimate the Magnetic Field strength and energy density assuming minimum equipartition between magnetic field and CRs The lower-energy CR are the ones that heat the H_2 (inefficiently).

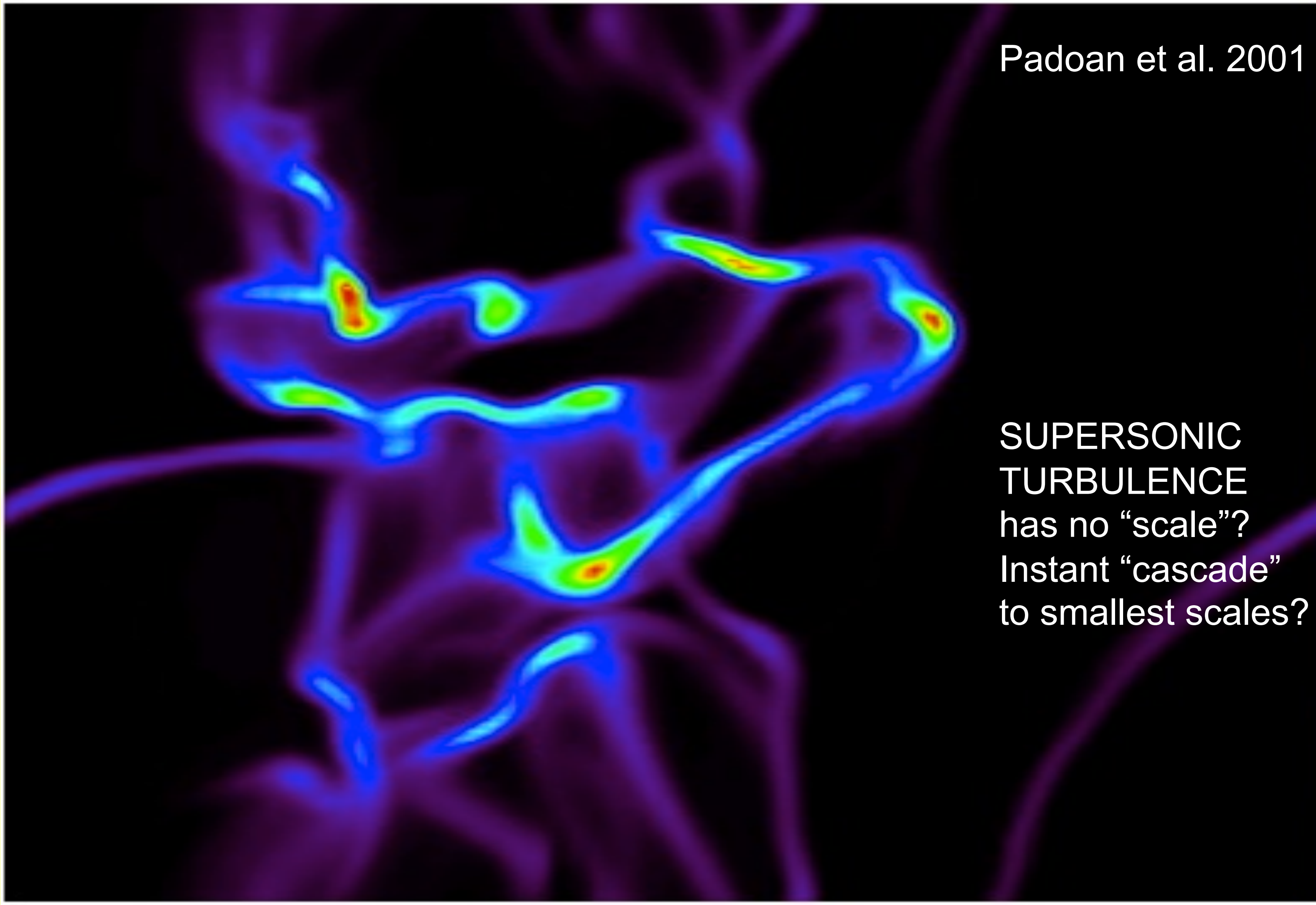
B_{min} = 4.5 – 8 μG and $<\mu_{Bmin}> \sim 2 \times 10^{-12}$ ergs/cm^3

assuming $<\mu_{Bmin}> \sim <\mu_{CR}> = 2 \times 10^{-12}$ ergs/cm^3

ENERGY ARGUMENT (HUGE EXTRAPOLATION FROM RADIO SYNCHROTRON to ~Mev)
To heat the H_2 to a luminosity density of 1.2×10^{32} W/kpc^2 required from the observations would require VERY HIGH HEATING EFFICIENCY ~ 100% over lifetime of collision. Alternatively equipartition may be invalid, and therefore CR energy density could be much higher, but what would balance the increased pressure implied by this?

IONIZATION ARGUMENT: CR heat H_2 by ionization. How many ionization/s are needed to balance cooling rate L(H2) per H_2 molecule. Cooling rate ~ 4×10^{-32} W/mol . To balance ionization will require ionization rate $X\iota \sim 10^{-14}$ s^{-1} This ionization rate 50-100 x higher than diffuse clouds in our own galaxy and ~10 higher than in vicinity of nearby SNR. (See talk by Indriolo with H3$^+$ argument). However this rate has not been measured in Taffy.

Most Likely Turbulence and Shocks provide the heating as in Stephan's Quintet



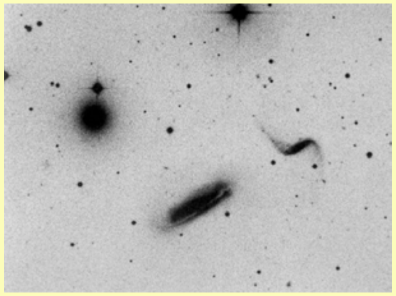
00

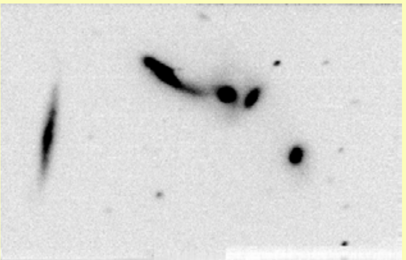
How to create a huge molecule shock?

Try 3

Compact Groups: "Death by Debris"

Run the galaxy through an ocean of discrete HI clouds and shock-heat the whole galaxy for a short period until the galaxy has had enough and becomes gas poor!

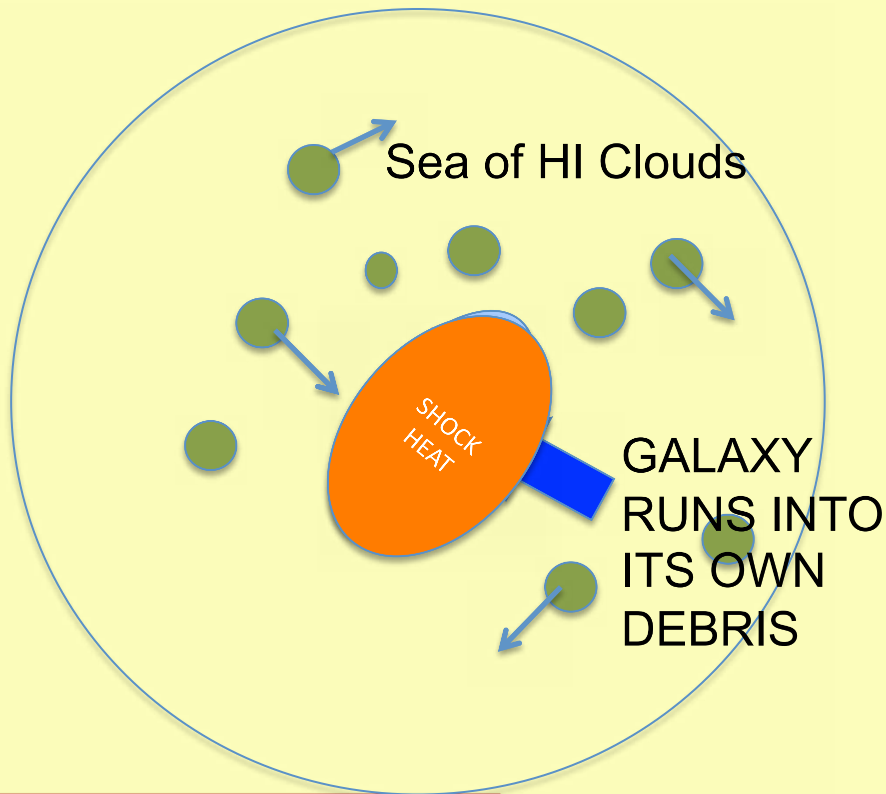




Method:

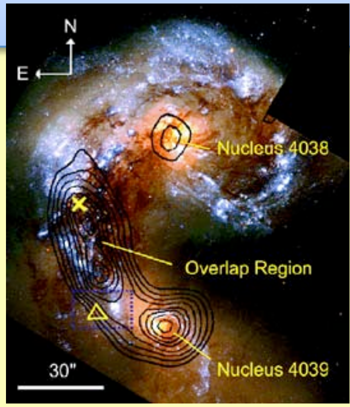
Need at home---

- One Compact Group
- One moving gas-rich galaxy
- a set of roughly virialized HI clouds moving in group



SEE MICHELLE CLUVER's POSTER FOR HANDS-ON DEMO!

Growing Number of Resolved H_2-bright Systems

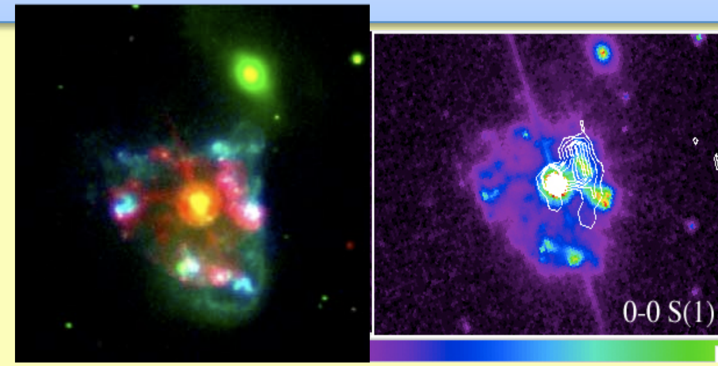


ISO Observation of 0-0 S(3)

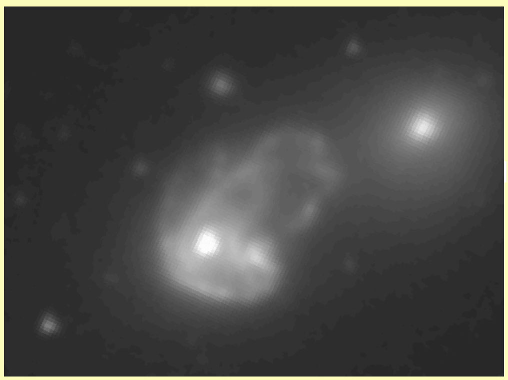
THE ANTENNA
Haas et al. 2005
Brandl et al. 2009

Strong H_2 in overlap region

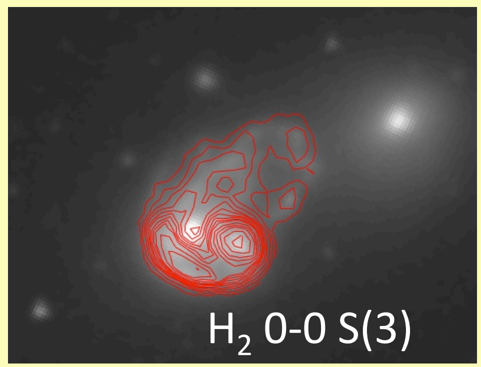
ARP 143



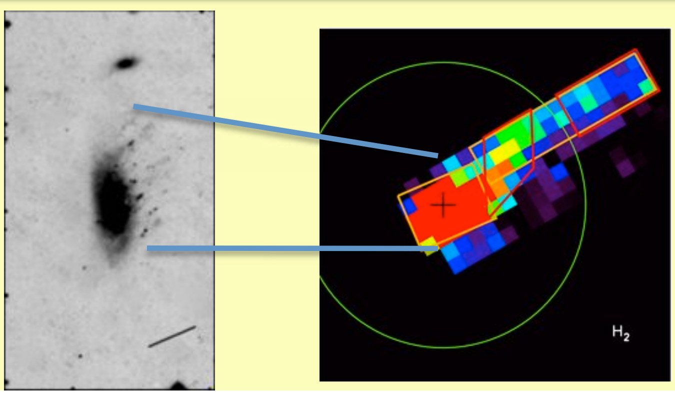
Beirao, Appleton et al. (2009)



ARP 118
Appleton et al.
In prep.



All involve contact systems with potentially high-speed collisions



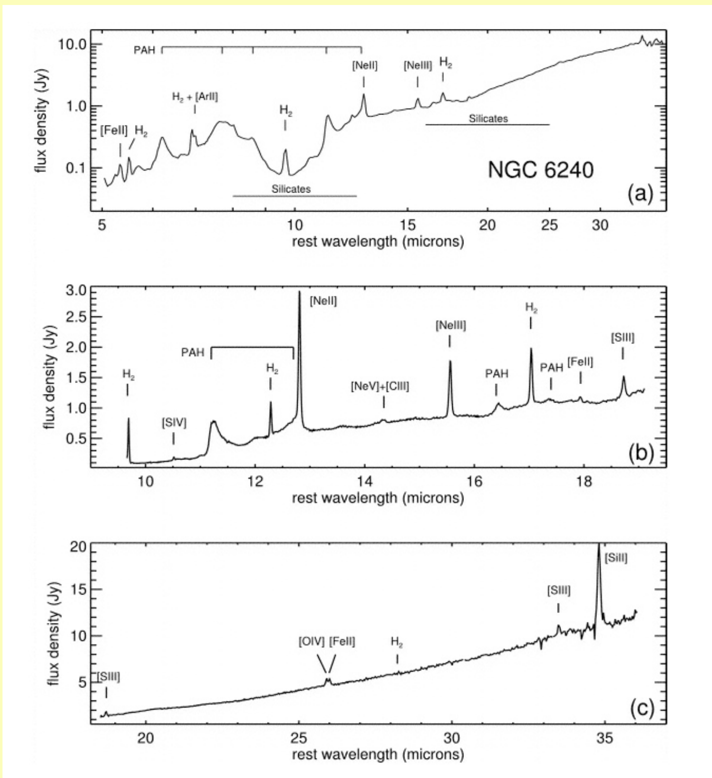
Hi-Speed GALAXY-IGM INTERACTION

The H_2 excited "TAIL" of cluster galaxy **ESO 137-01** in Abell 3627 (Silvanandam, Rieke & Rieke 2010)

ULIRGs show powerful H_2 emission--it may be extended on large scales? Emission swamped by Star formation or AGN activity

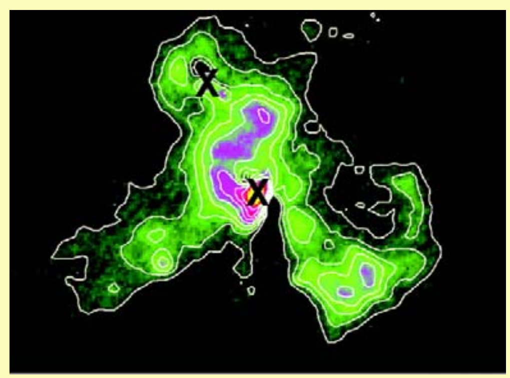
Armus et al. (2006)

The Case of NGC 6240



L_{H2} ~ 10^{42} ergs/s
Strong IR continuum
Multi-temp fit

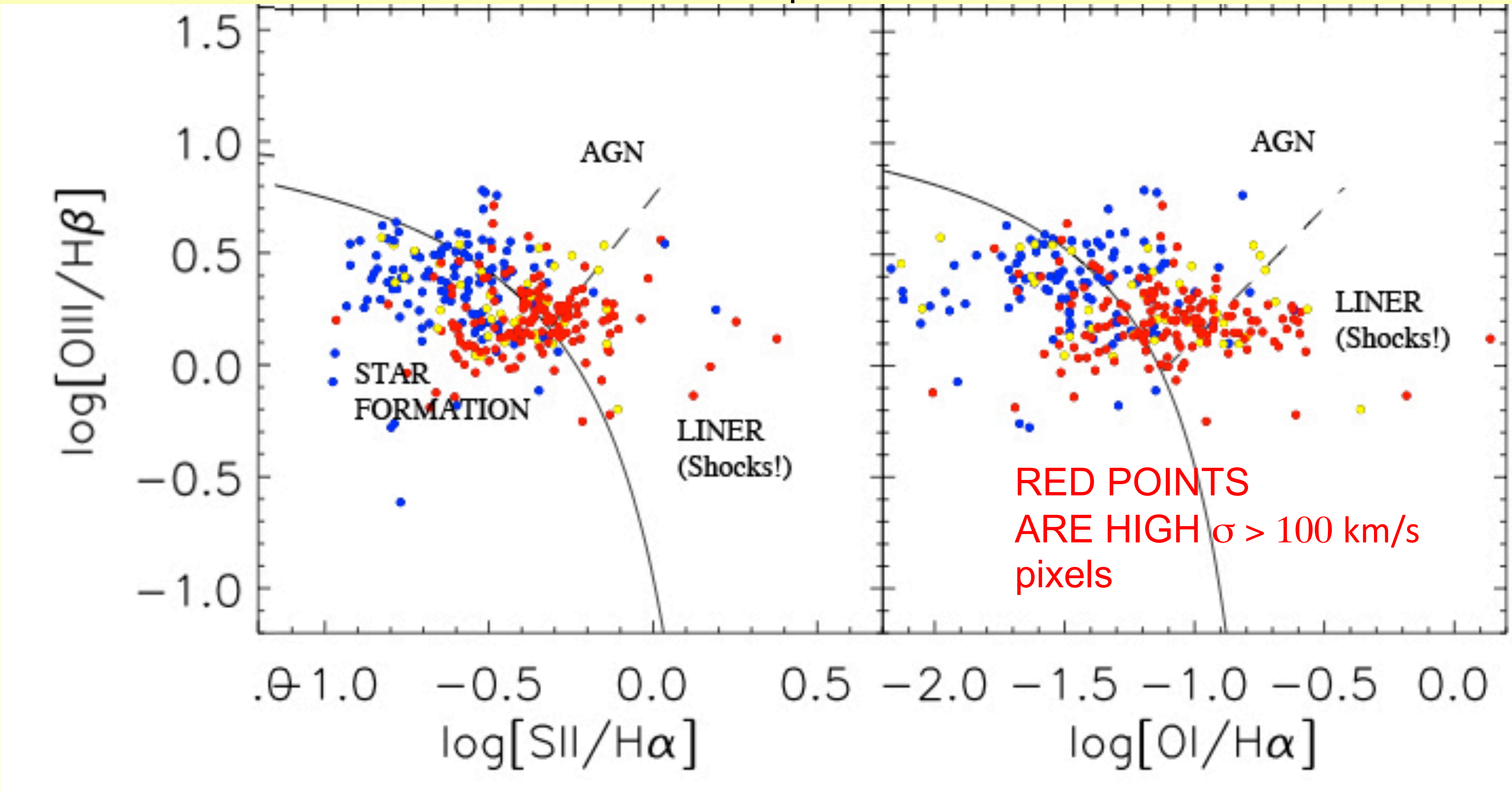
Higdon et al. 2006
Zakamska 2010
(H2 and PAH
not at same location)



H_2 1-0 S(1)
Max et al. (2005)
Keck AO image

New IFU data on shocks in (U)LIRGS

Mike Dopita/Jeff Rich et al. 2010: WIFeS ARRAY



shows HII region-like line ratios

shows LINER spectra

Common Factors in Collisional MOHEGS?

- Warm molecular hydrogen is VERY luminous

  $10^{41} < L(H_2) < 10^{43}$ ergs/s in lines and extended over large scales. H2 >> Mid-IR Fine Structure line cooling e. g. [SiII]. Far-IR cooling?????

- High-speed galaxy collisions seem to be needed to generate energy needed to power H_2

- Cascade of mechanical energy required to funnel power from high-speed shocks to low-velocity C- and J-shocks

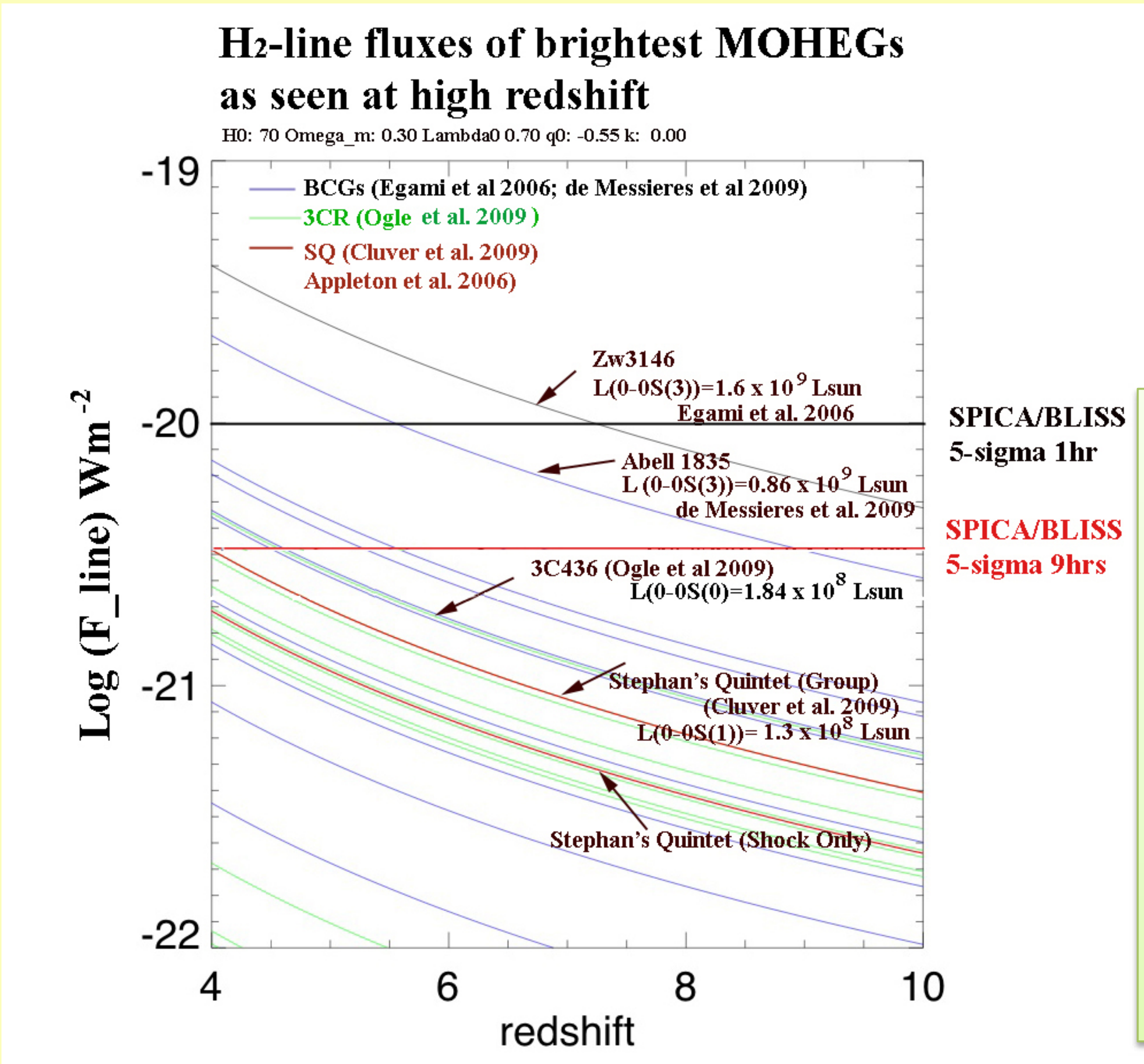
  Details are not well understood!

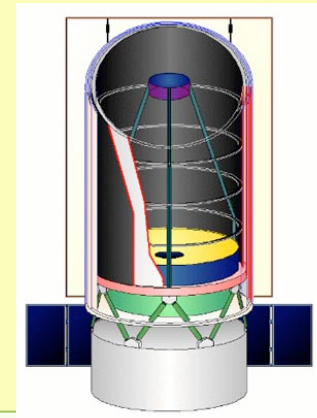
Conclusions

- High-speed collisions involving large-scale shocks in galaxies seem to drive ultra-powerful molecular hydrogen emission (MOHEGS). Need energy cascade to small scales. $L_{(H2)}$~$0.1L_{(Mech)}$
- Emission seen in variety of collisional scenarios, from collisions between galaxies and tidal debris, to direct galaxy-galaxy collisions.
- Stripping of gas in "shock heated" phase may provide a route to "dry merger" in groups and clusters (See M. Cluver's poster). H_2-bright phase is new signpost of stripping in action!
- If galaxies are more gas-rich at high-redshift, we can expect to see more shock-induced H_2 cooling in systems with high gas streaming velocities (pre-quasar dark-matter halos). These may be work looking for at high-z with next generation of IR space observatories (e. g. SPICA/BLISS)

THE END

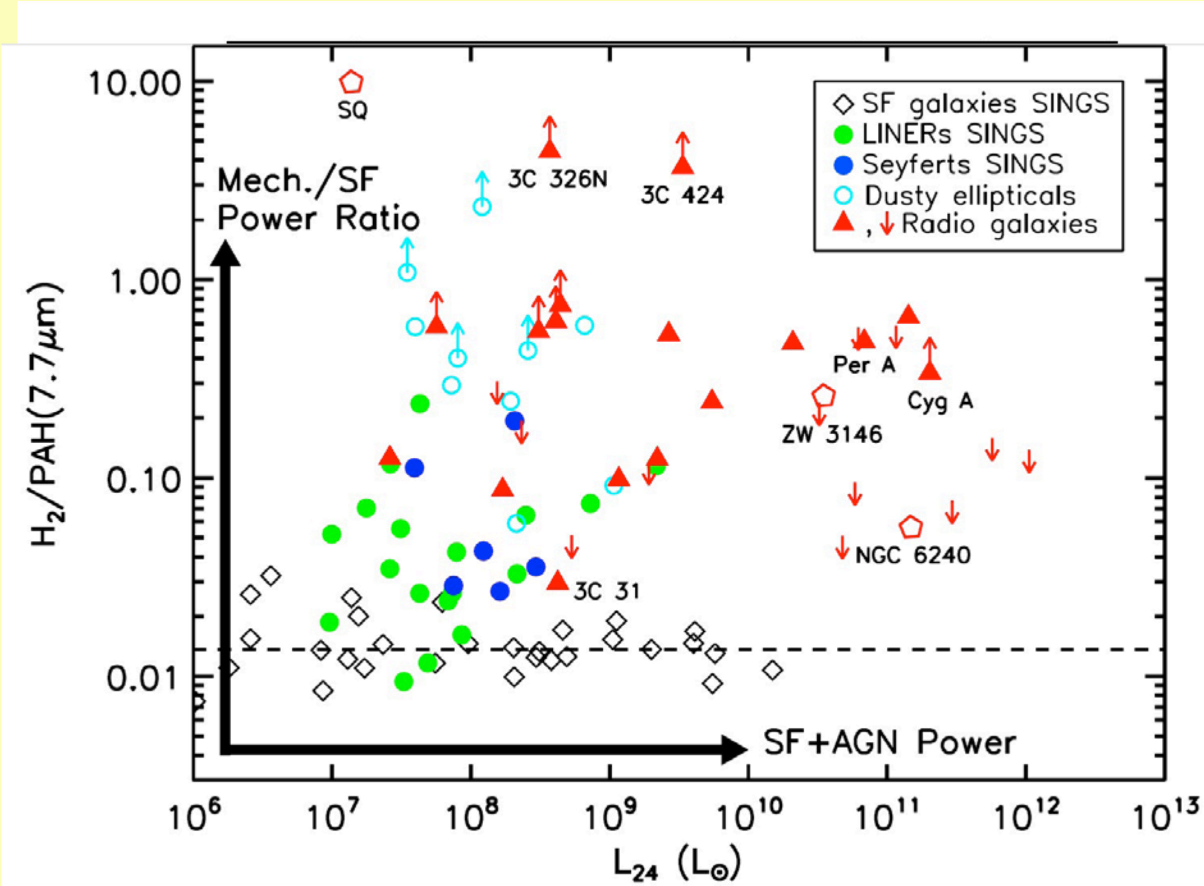
MOTIVATION FOR SPICA/BLISS AND PROBING TO HIGH-z





The SPICA (Space Infrared Telescope for Cosmology and Astrophysics), which is a Japanese astronomical infrared satellite project with a 3.5-m telescope, is scheduled for launch in ~ 2018. The SPICA/ BLISS system will allow us to explore H2 emission to high redshift—this is not possible with ALMA

MOlecular Hydrogen Emission-line GalaxieS (MOHEGS) Patrick Ogle et al. (2010)



Infrared Luminosity

H_2 measured from 0-0 S(0) to 0-0 S(5) lines

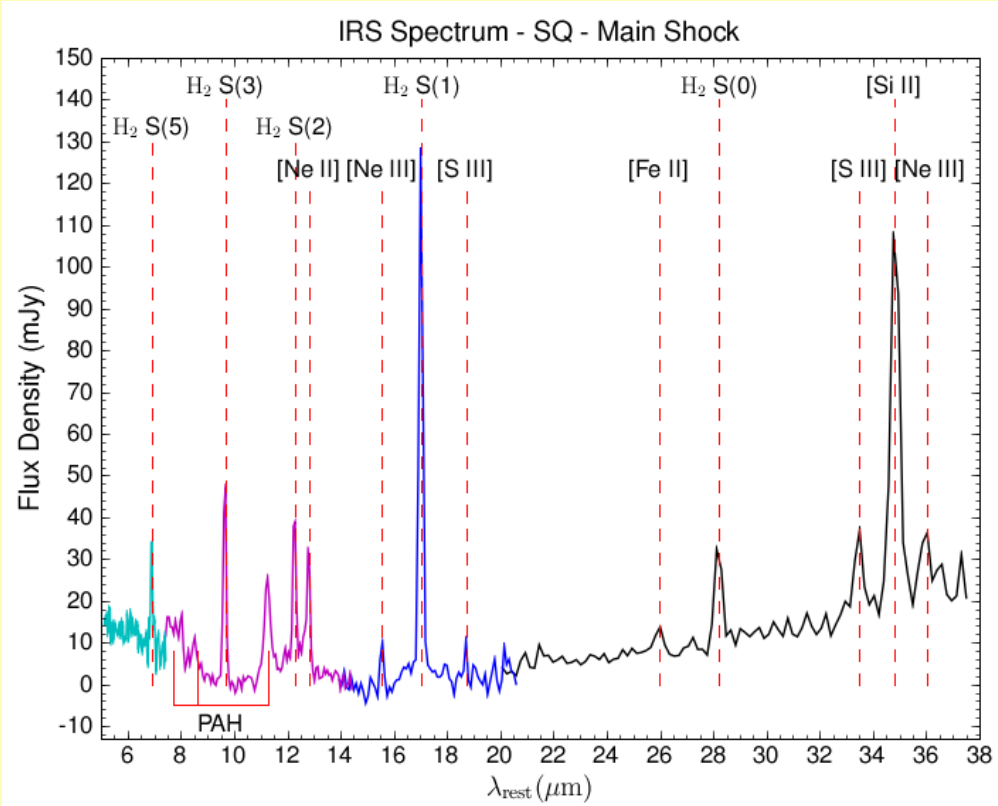
Star forming galaxies have $L(\mathbf{H_2})/L(7.7\ \mu m\ \mathbf{PAH}) \sim 4\text{-}8\times10^{-3}$

MOHEGS have extreme **H_2/PAH values** and may indicate ***shock heated* H_2** in:

-Radio galaxies (Ogle et al. 10)
-Cool core clusters (Egami 06)
-LINERs, Seyferts (Roussel 07)
-Dusty ellipticals (Kaneda 08).

Very large L(H2)/L(IR) ratios imply
H_2 is enhanced by large factors

Shocks implicated--RG sample
likely connection to Radio-Jet Feedback



The H_2 Dominated Mid-IR Spectrum of Stephan's Quintet

(Cluver & Appleton et al. 2010)

Do we find this kind of spectrum elsewhere?

Yes in many different situations