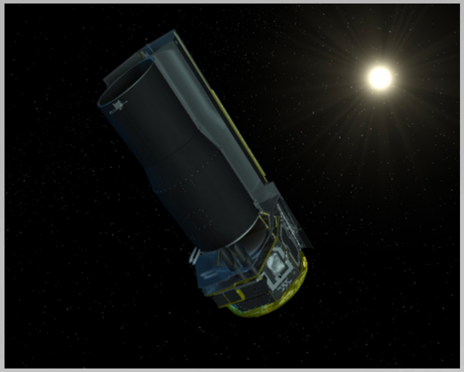
Warm Molecular Hydrogen as a Probe of Turbulence in the High-z Universe



Spitzer

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Herschel

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Francois Boulanger, Patrick Ogle, Lauranne Lanz+ many more

Heating and Cooling of gas in the Universe

Heat Sources

Radiation from Stars

- photoionizing radiation from young stars
- photoelectric heating in PDRs (grains+PAHs)
- dust/gas heating
- radiation from old stars
- gravitational heating

EM Radiation from AGN

- UV , X-rays and γ-rays

Cosmic Rays (SN,BHs,GRB)

Mechanical heating from Turbulence and Shocks

- stellar outflows in GMCs
- SB and AGN winds+ SN
- gas-rich galaxy collisions
- galaxy formation

FEEDBACK

Cooling

Adiabatic Cooling in Universe

X-ray and nebulae line cooling

Escape of CRs from galaxies

Cooling of the Dense ISM/High ioniz.

- [NII], CO (high J), [CII], [OI]

SMALL VOLUME HIGH DENSITY STARBURSTS

Cooling in the DIFFUSE ISM

- [CII], warm H_2, HD, [SiII] CO (low J)

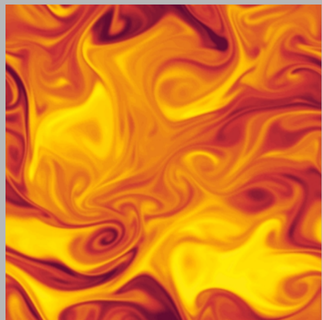
TODAY

LARGE VOLUME low density

Dust

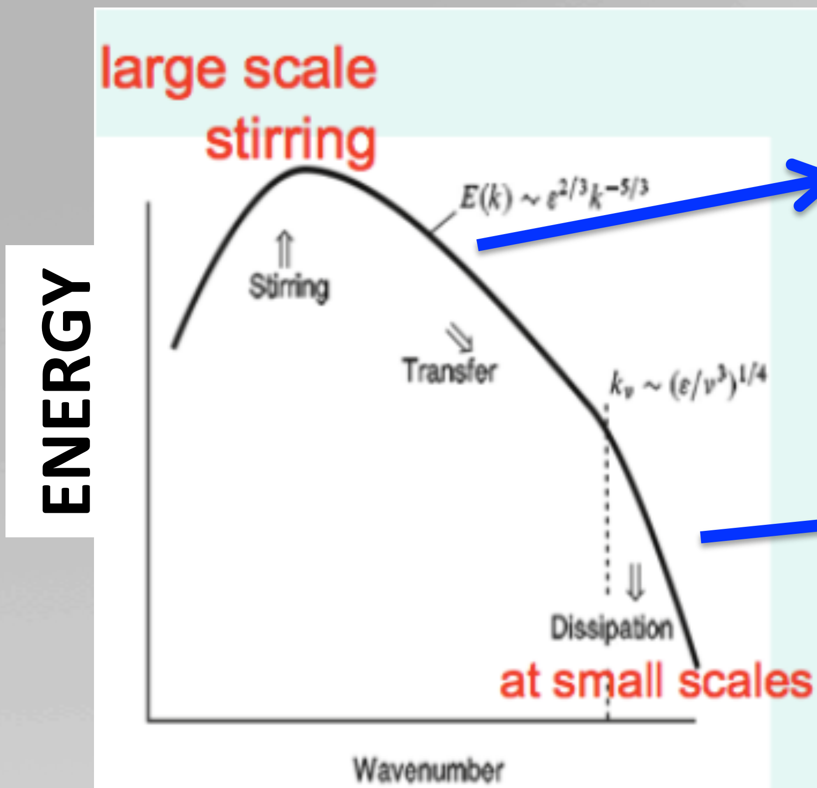
--Regulates gas phase abundances

-- can help cool X-ray gas by spluttering



Supersonic turbulence

Probing Turbulence Energy Dissipation in the local Universe



FAST SHOCKS and eddies from large-scale injection of kinetic energy

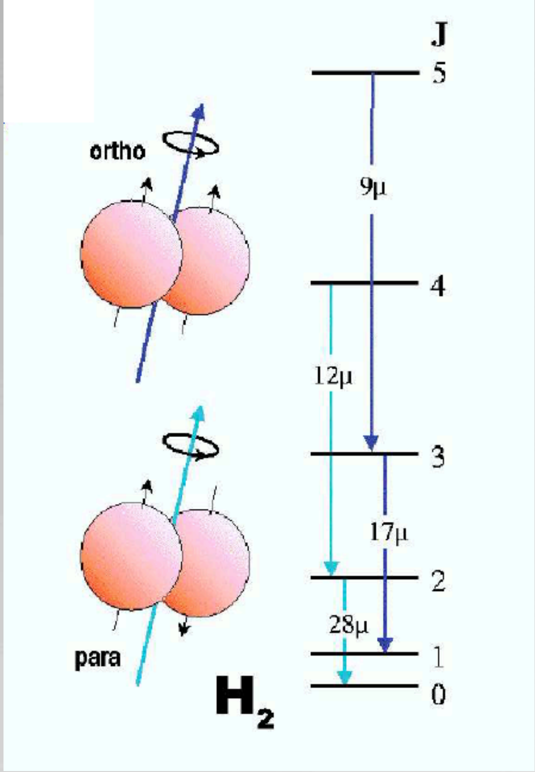
Rapid transfer to small scales

DISSIPATION OF SLOW SHOCKS— on small scales: most energy should be released here

Expect MANY low velocity shocks
Cooling lines associated with atomic and molecular gas

$$\Gamma_{\rm turb} = (3/2) \times 2m_{\rm H}(\sigma^2)/\tau_d$$

Warm Molecular Hydrogen in the Local Universe



DOMAIN OF MID-IR
AT LOW-z

Far-IR At high-z!

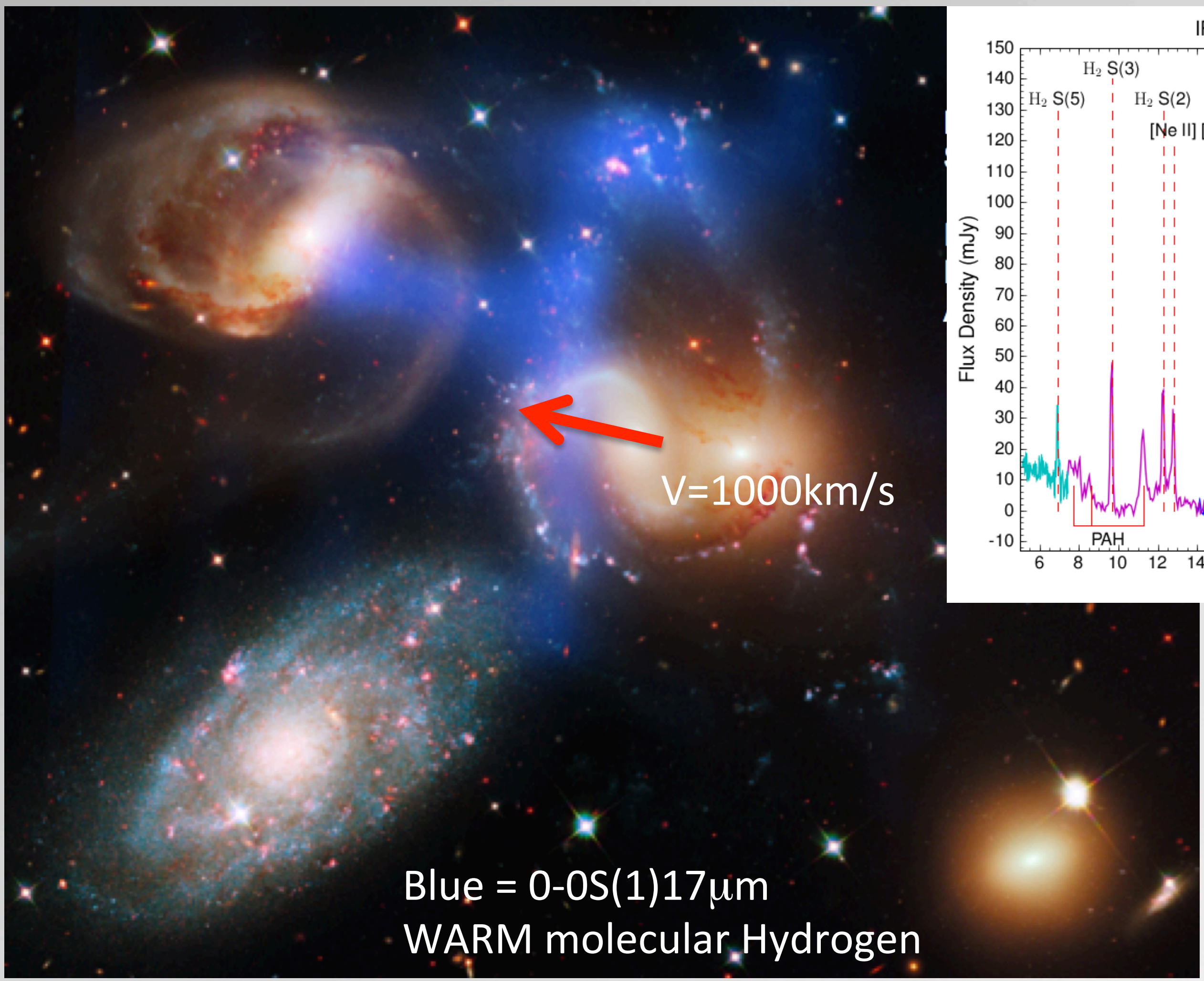
THIS IS PRIME
SURVEYOR MATERIAL!!

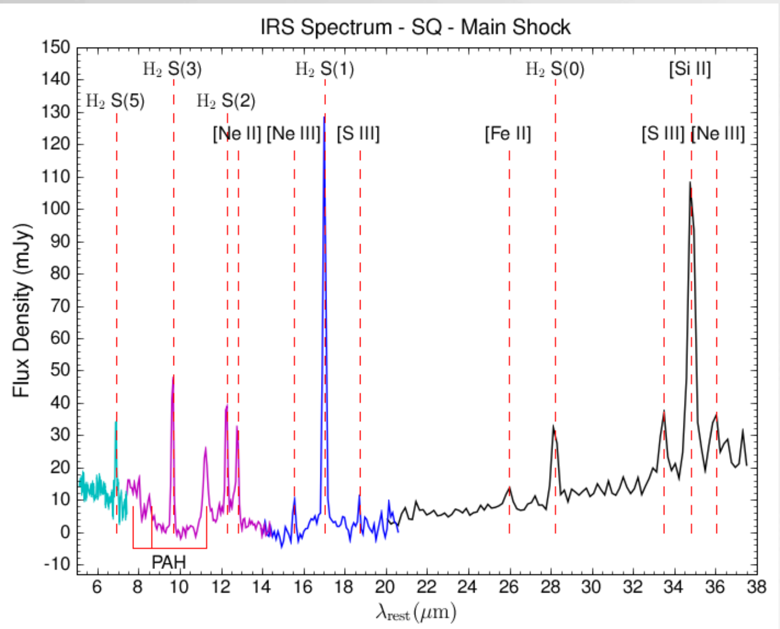
IT CANNOT BE DONE
At z < 12 by ALMA

Local Universe holds some surprises! Spitzer discovery of GROUP-wide WARM H_2

Stephan's Quintet

Appleton+06, Guillard+09, Cluver+10, Appleton+13



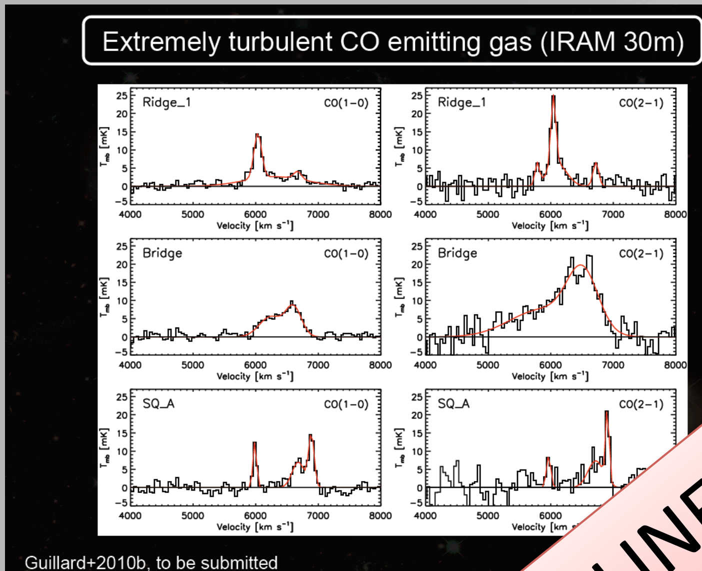


$L(H_2)/L(PAH_{tot})$= 10-110%!

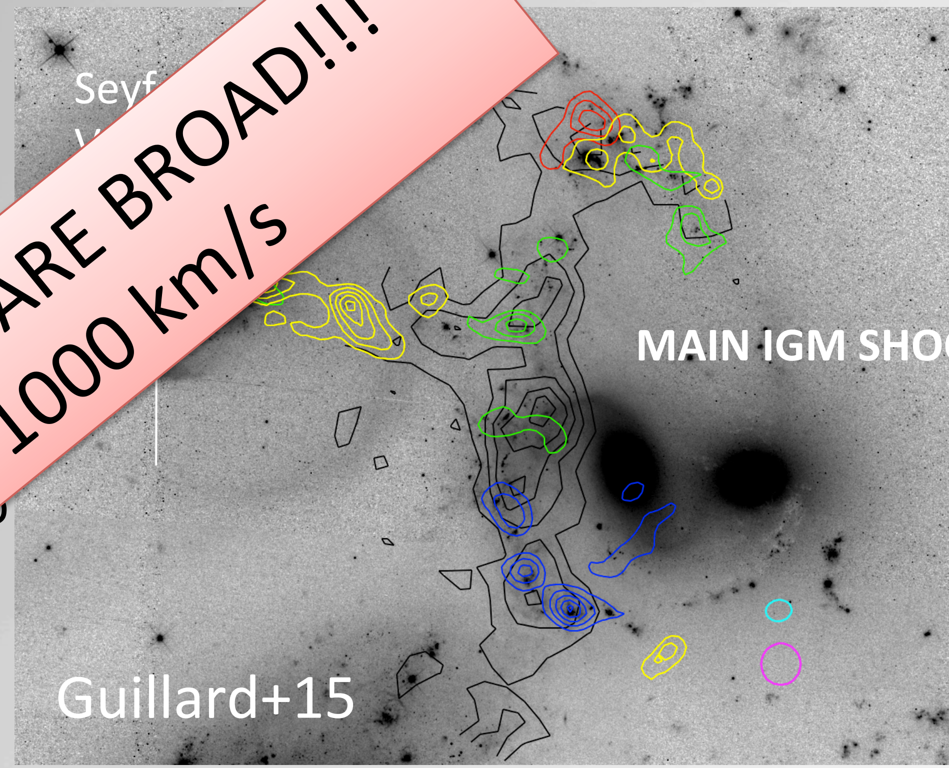
$L(H_2)/L(FIR)$ > 10% in some regions

SHOCK EXCITED H_2

Diffuse CO emission has very high velocity dispersion: Large turbulent mass:



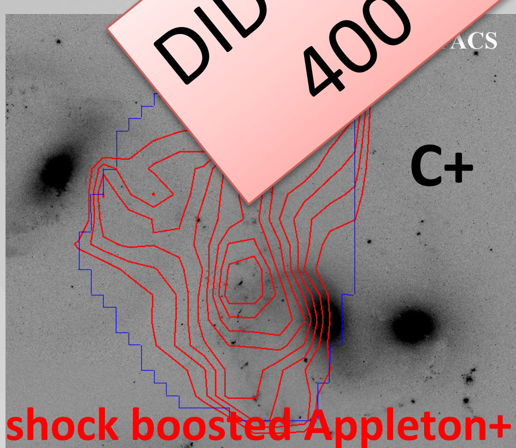
IRAM 30-m a... and CARMA inteferemeter



Very broad CO lines ...
1000 km/s and i... ps
400 km/s in ...

DID I SAY THE LINES ARE BROAD!!!
400 < FWHM < 1000 km/s

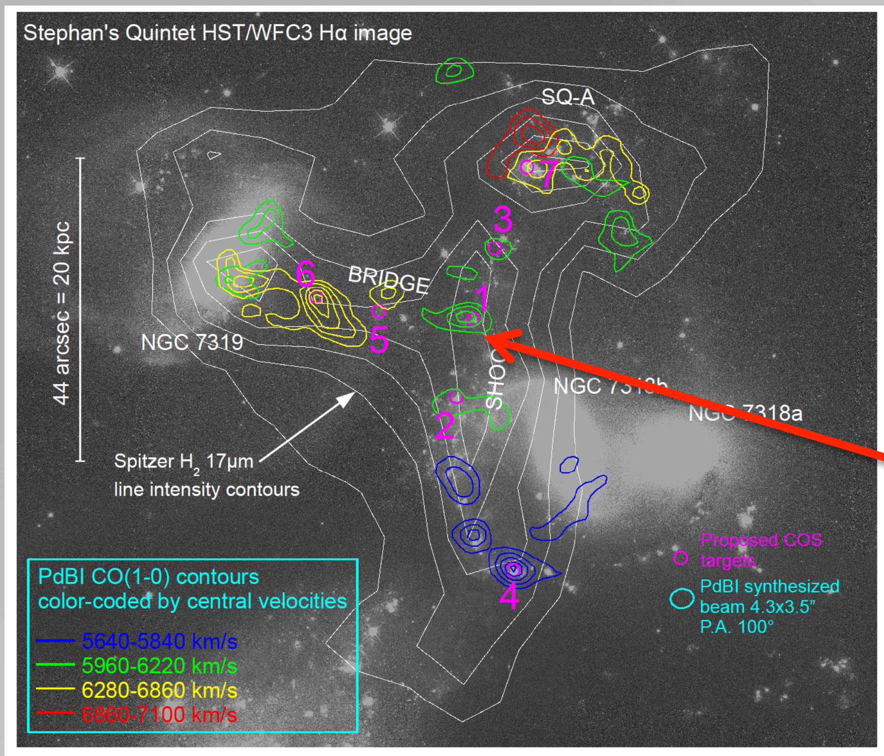
High H2/PAH and H2/FIR ratio
High C+/PAH and C+/FIR ratios
Low [OI]/C+ T~150-200K density = 10^3 cm^{-3}



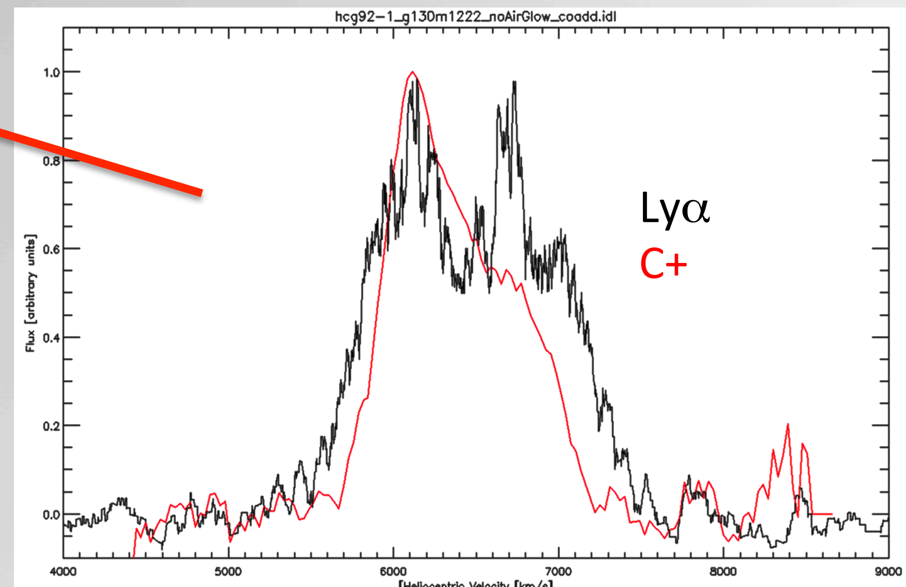
C+ is shock boosted Appleton+13

Diffuse turbulent gas fills large part of intra-group medium>> Mechanical energy from collision drives turbulents and shocks

Detection of Ly-α with COS/HST : Strong Evidence for Turbulent Cascade (Guillard+Appleton+15)

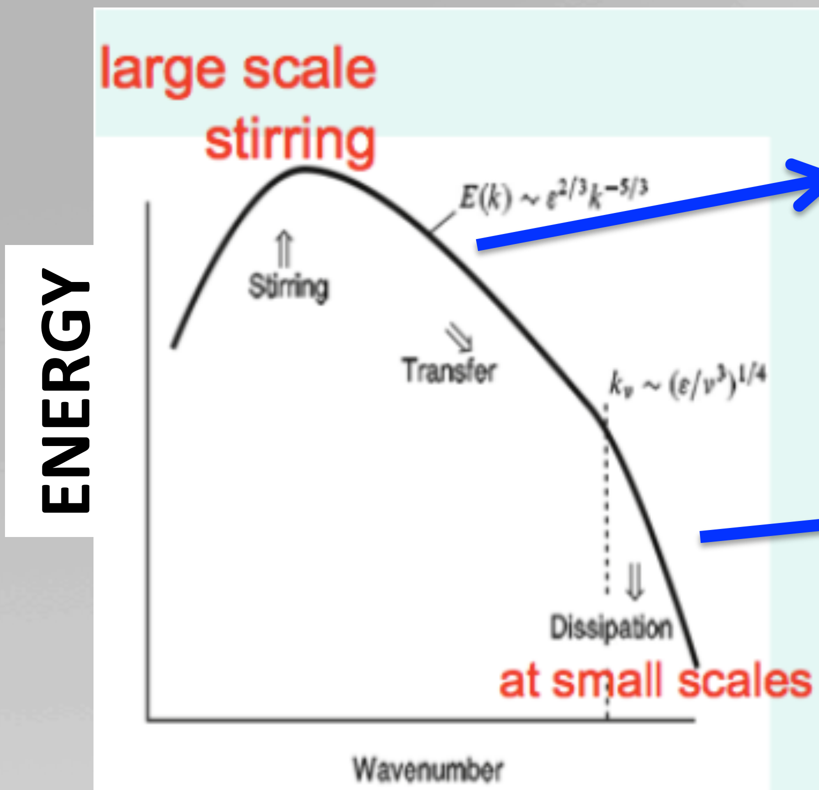


We targeted small areas r = 1.5 arcsecs in various parts of the **main shock (corresponding to 600 pc).**



VERY BROAD Ly-α LINES SEEN near center of shock ~ 1600 km/s in 600pc region!

The Group-wide gas in SQ is a perfect example of supersonic turbulence on 40-50kpc scale with micro-effects at << kpc scales



Networks of FAST SHOCKS from large-scale Collision (100-300 km/s shocks) predicted to radiate in Ly-α—spread over full dispersion

Detected by HST COS

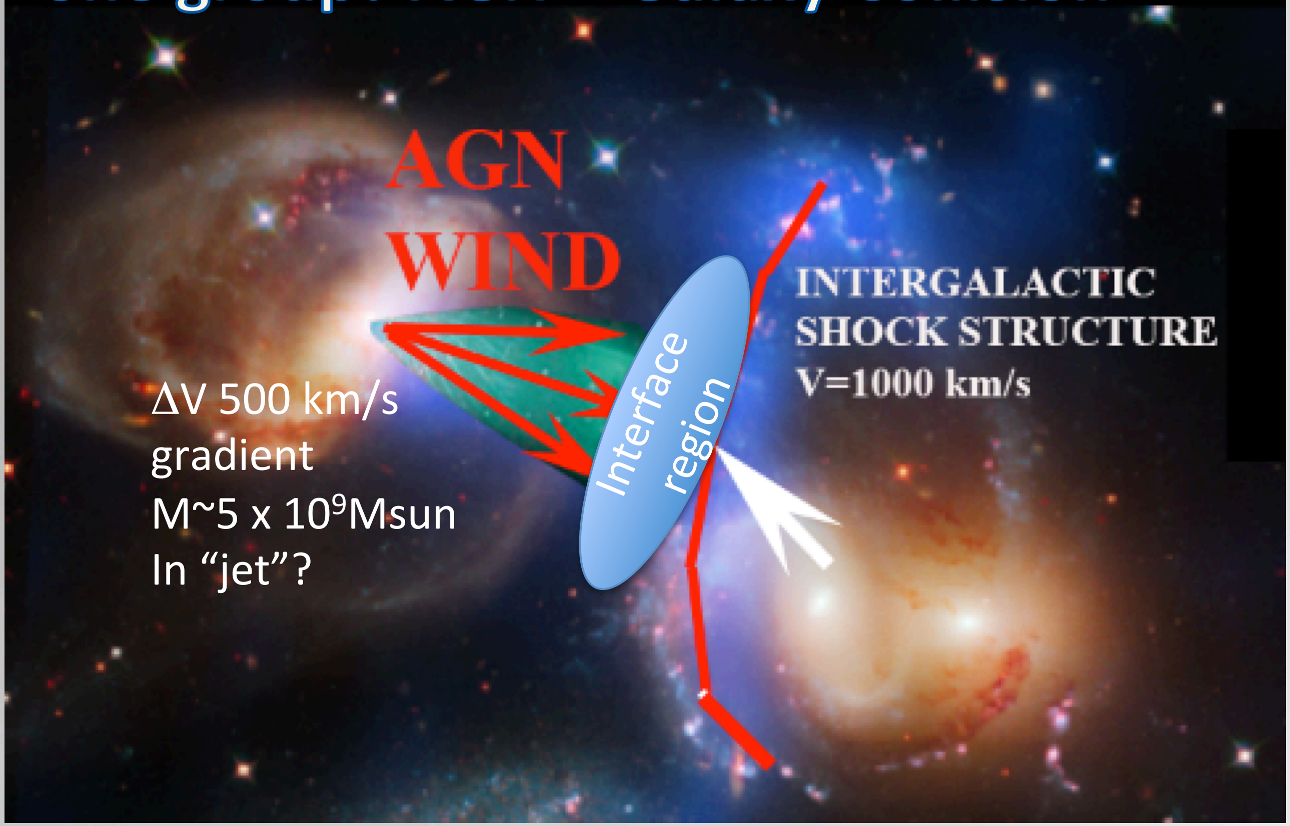
have 10% cooling rate of H2 and C+ lines

SLOW SHOCKS (Main Dissipation)
SPITZER/HERSCHEL

H_2, C+ have 90% of cooling rate

Low-velocity molecular shocks (mix of C and J shocks) can explain Excitation of both species very well

Two different processes in one group? AGN + Galaxy Collision



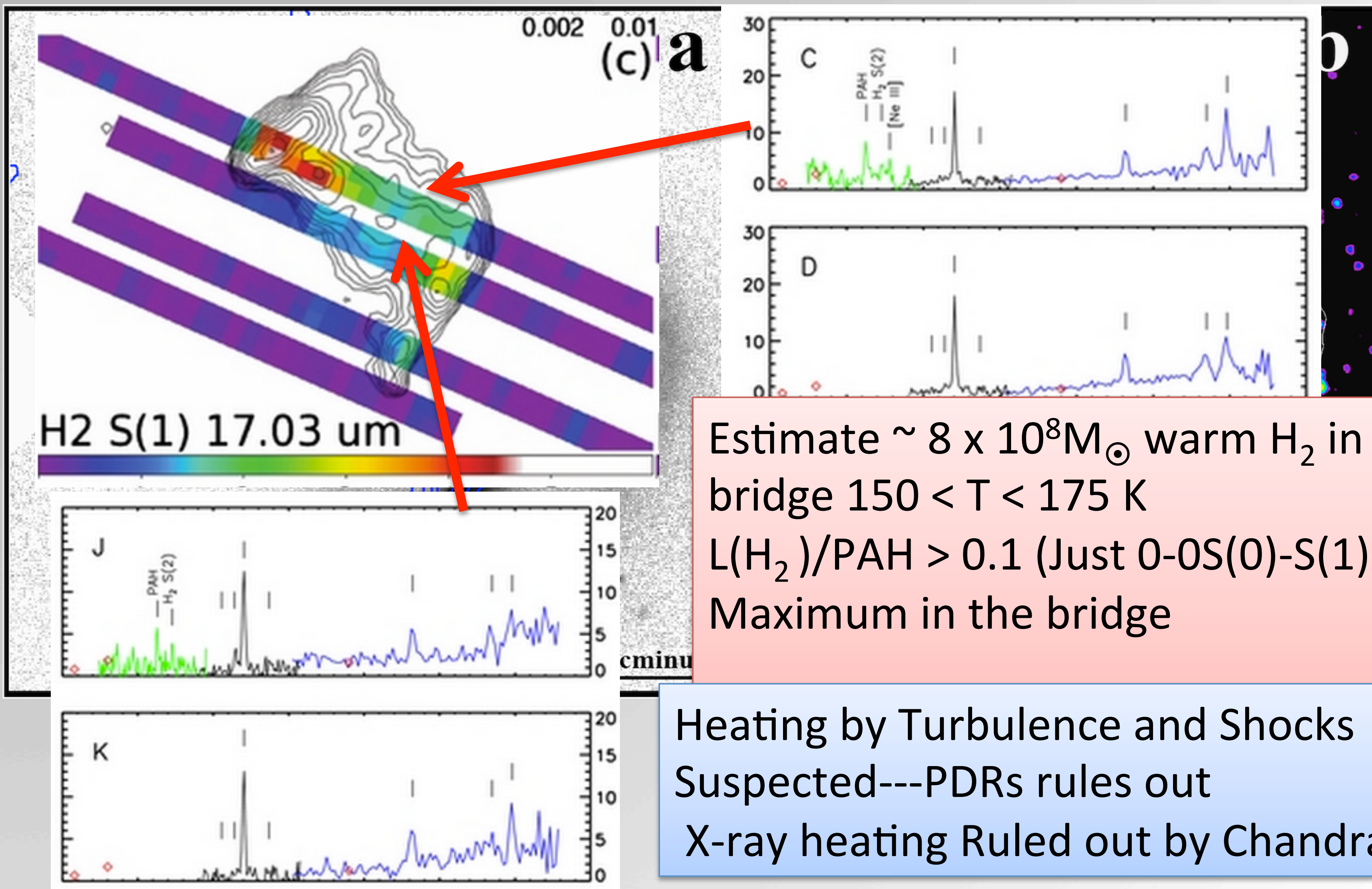
In Stephan’s Quintet (HCG92) we seem to be see the effects of two types of large-scale shocks—a possible AGN WIND AND Galaxy-collisional shocks

The gas in Compact Groups seems excited by a variety of complex processes!

Taffy with Spitzer IR Spectrograph : Another example

LOTS OF WARM MOLECULAR HYDROGEN

(Peterson \& Appleton et al. 2012)



Estimate ~ 8 x $10^8 M_\odot$ warm H_2 in bridge 150 < T < 175 K

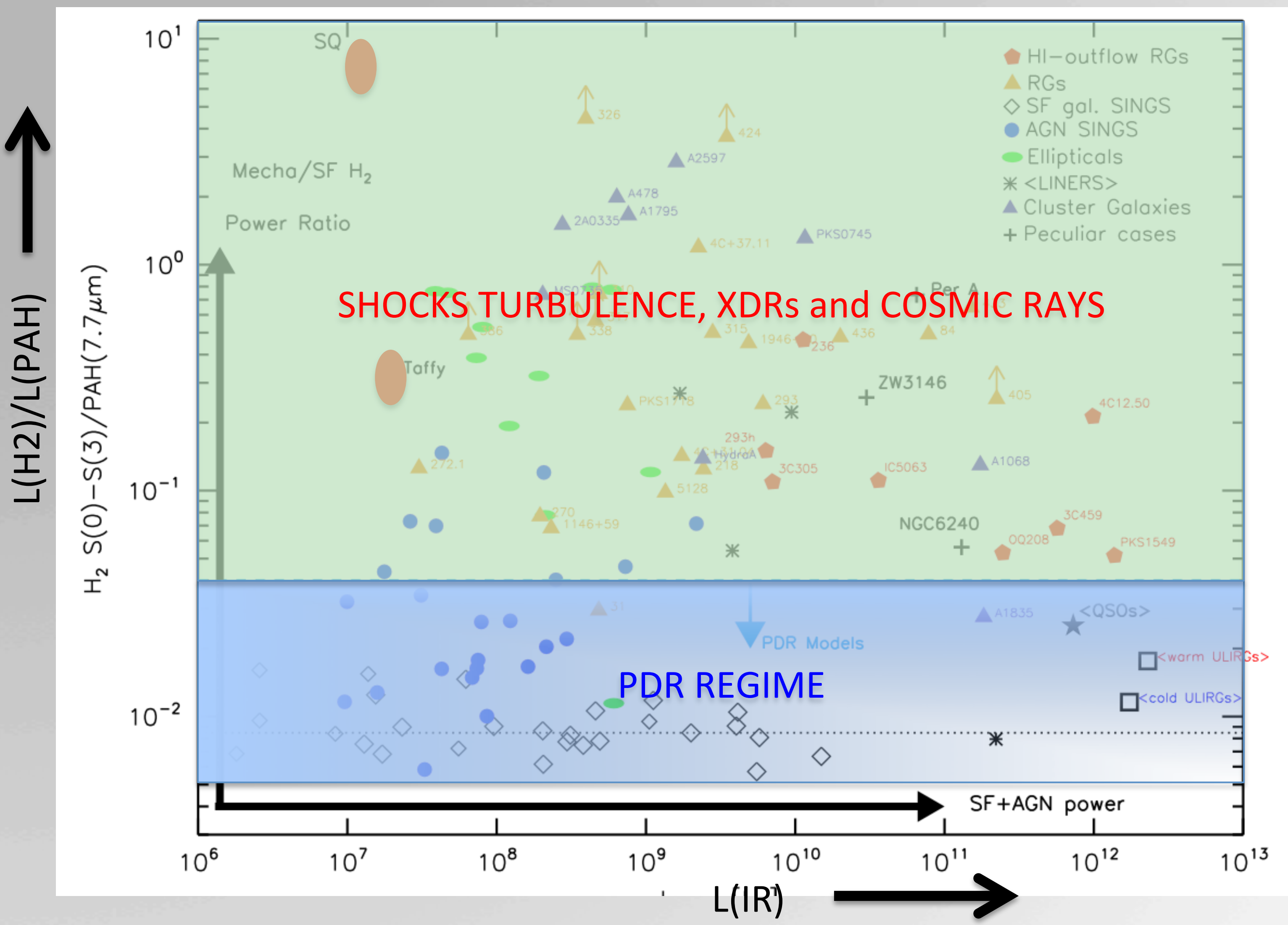
$L(H_2)/PAH > 0.1$ (Just 0-0S(0)-S(1))!

Maximum in the bridge

Heating by Turbulence and Shocks Suspected---PDRs rules out

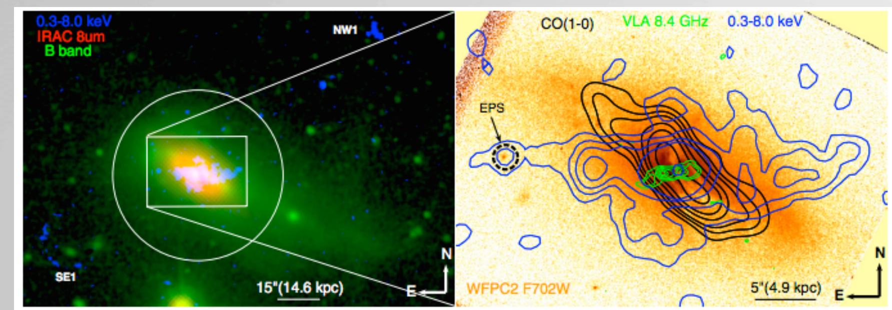
X-ray heating Ruled out by Chandra

SINCE THAT TIME MANY EXAMPLES OF LIKELY SHOCK EXCITED H_2 emission have been found in local universe

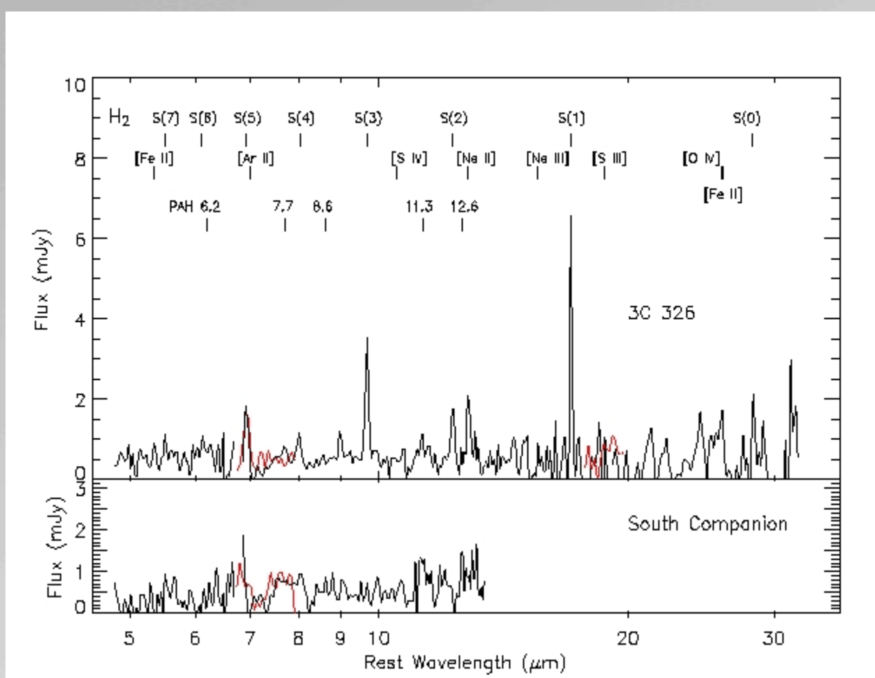


There is a whole group of H_2-bright systems associated with radio-mode feedback Ogle et al. (2007; 2010), Lanz+14,15

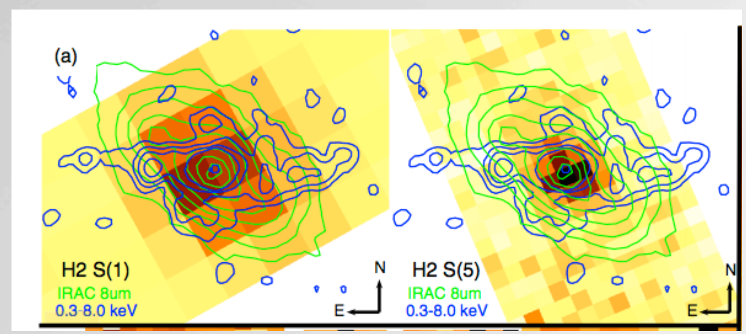
20% of a sample of 3CR radio galaxies studied by Ogle et al. have H2 dominated spectra
L(H2) typically ~ 1 x 10^{42} ergs/s
Very Low Mid-IR continuum and SFR



e. g. Radio Galaxy 3C 326 (z=0.089)



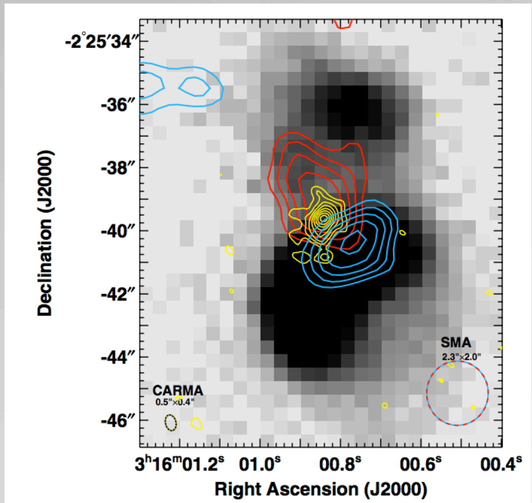
3C 293 (Lanz+15)

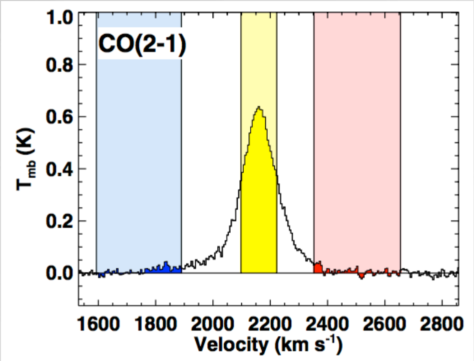


Take-away point:
AGN at high-z could also impact H2 Excitation

What is causing the H_2 emission?

- Large-scale collisional shocks -Requires high speed motions and colliding filaments/objects in rapid motion
- Shocks in Cooling Flows? Accretion shock onto central object?
- AGN Jet/IGM Shocks: May explain some of RGs
- Shocks from Starburst Winds/IGM? e. g. NGC 6240 analogs



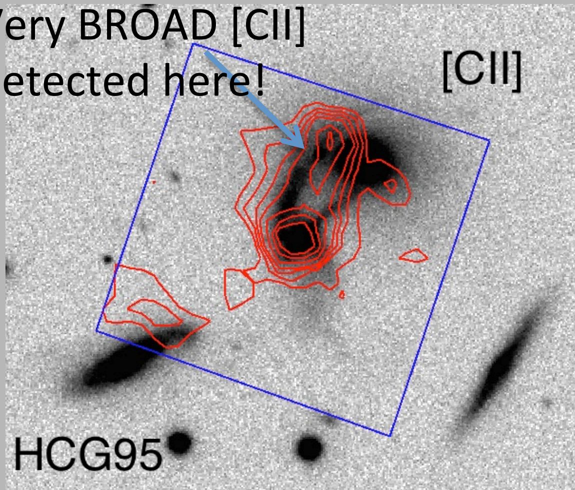


NGC 1266
SINGS H2/PAH luminous
Alatalo+11,+14
Shows Bipolar outflow
Triggering shocks
MAJOR SUPRESSION OF
STAR FORMATION

We followed up many H_2-bright systems in Compact Groups with Herschel/ CARMA to look at C+, [OI] and CO

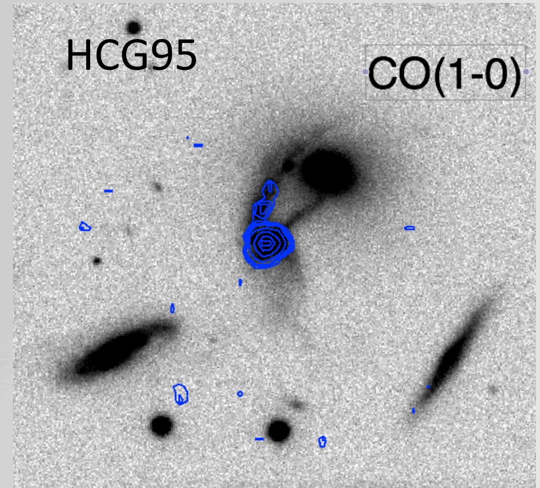
There is a connection with transition of galaxies from blue to red sequence

(Another talk!)

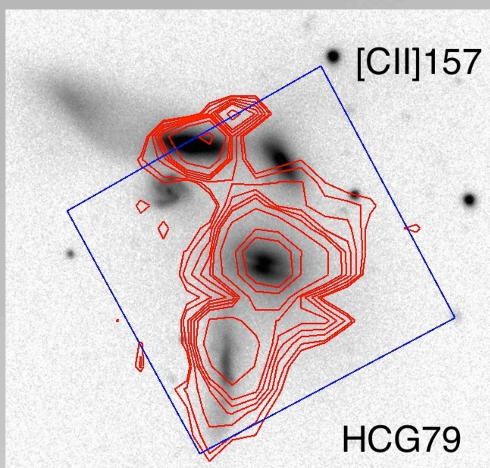


PACS
[CII] 157.4

CO 1-0

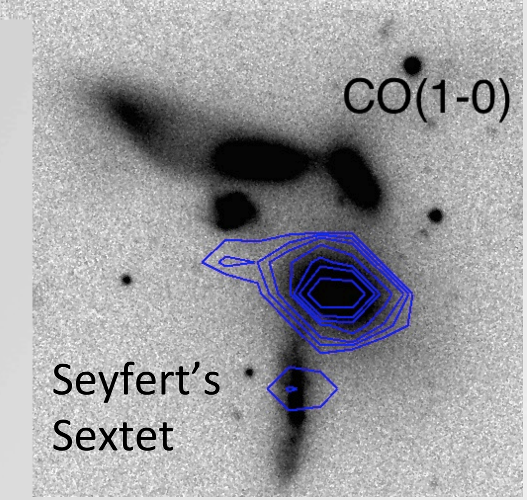


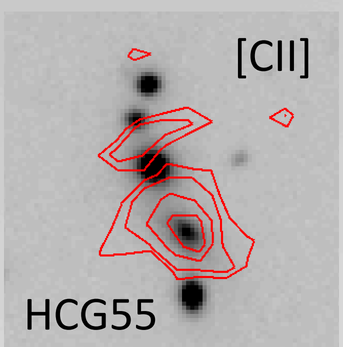
Alatalo+14,15
Appleton+15



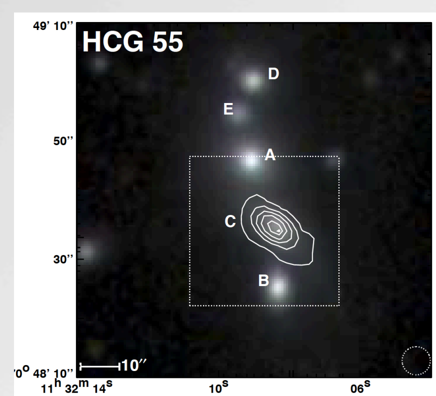
HERSCHEL

CARMA



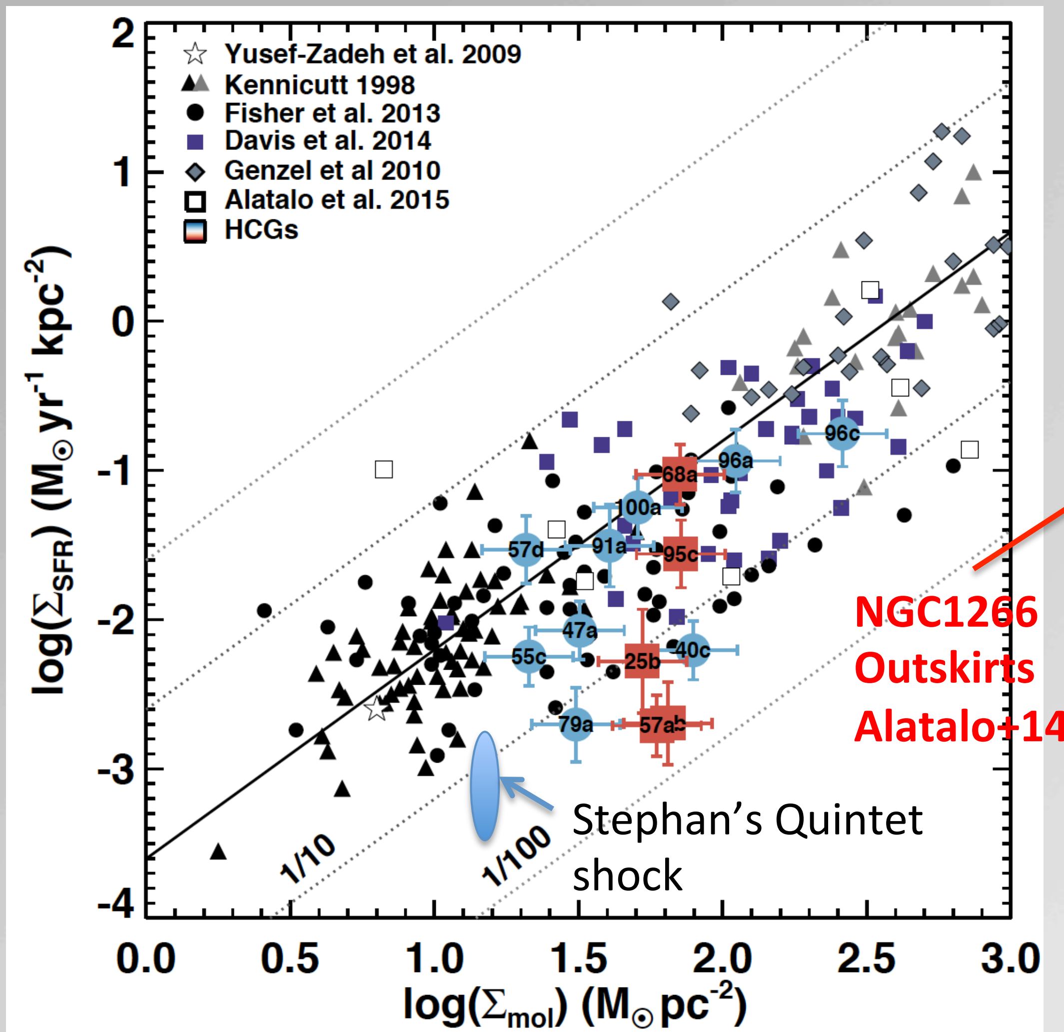


SOME
EXAMPLES
Of H_2 bright
HCG galaxies



These H_2-luminous galaxies seem to show SF suppression (Cluver+13; Alatalo& Appleton+15)

Depletion times of gas > Age of Universe!!



Many Hickson Compact Group Galaxies fall on the lower end The S-K relationship (Alatalo+15)

This despite having normal gas to dust ratios as measured by Herschel and CARMA/IRAM-30m. Some of the suppressed HCGs are relatively massive (~ 10^{11} $M_{\odot}$) >> high metallicity—so a high α_co is probably not the culprit.

The results imply that some of the galaxies are suppressing stars by a significant amount

A result of turbulence?

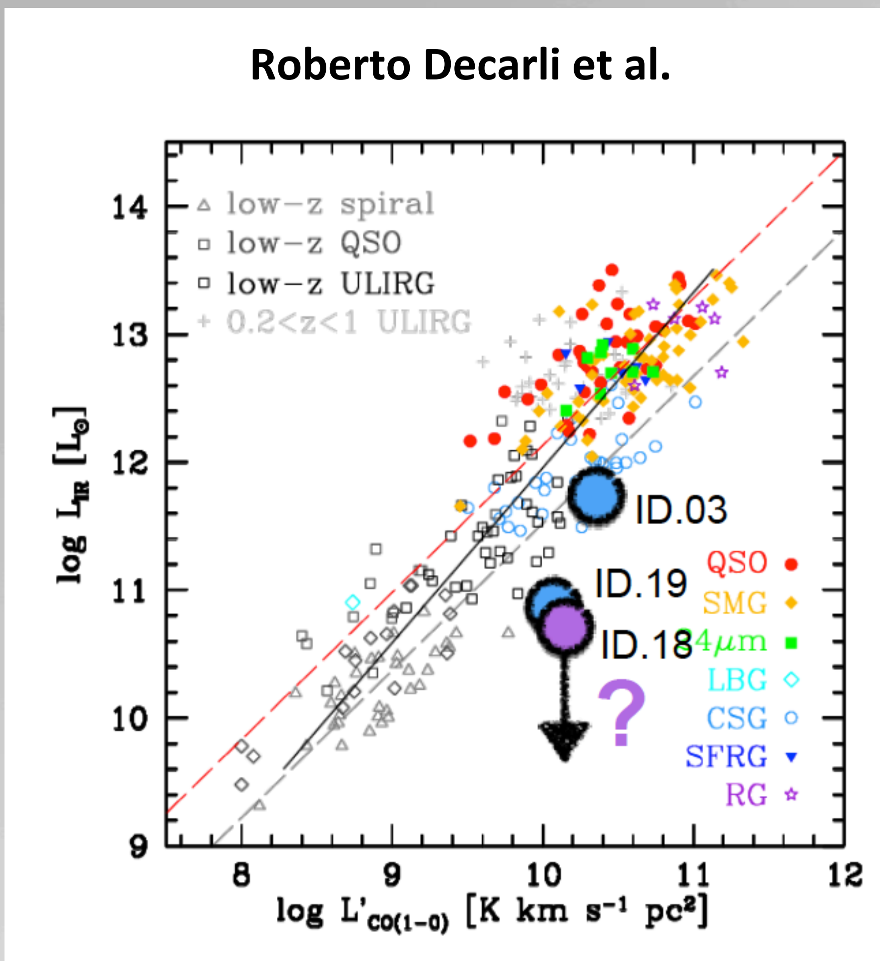
Spitzer was essentially blind above z > 2.5 to strong H_2

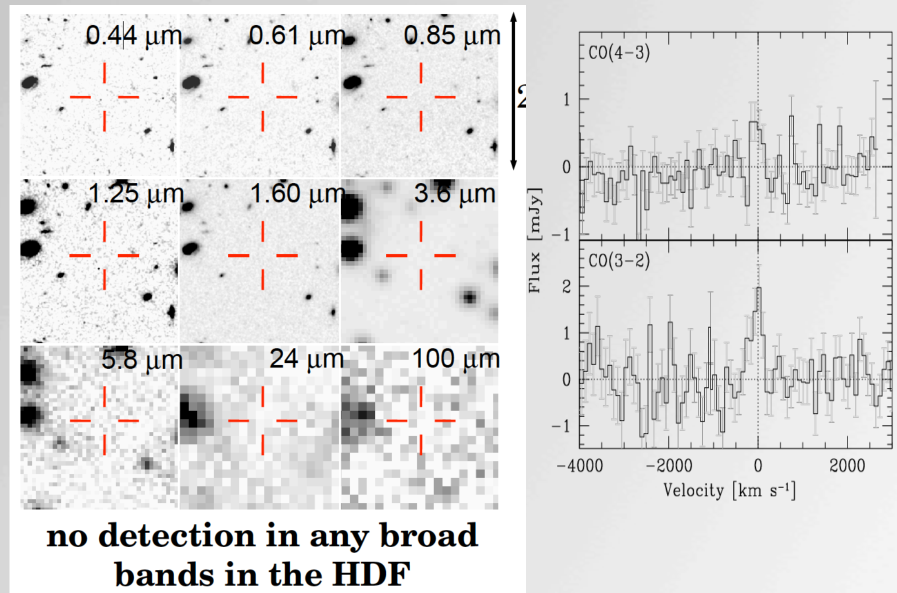
High redshifts almost certainly will bring surprises

New science from deep exploration of phase space

Hard to guess where new discoveries will come

New results from Blind ALMA surveys--- "Dark" molecular-rich Galaxies at z = 2





What is the nature of this gas-rich Object? Suppressed SF ??? Could objects like this be potential HD and H2 targets?

Very few high-z galaxies were observed by Spitzer IRS

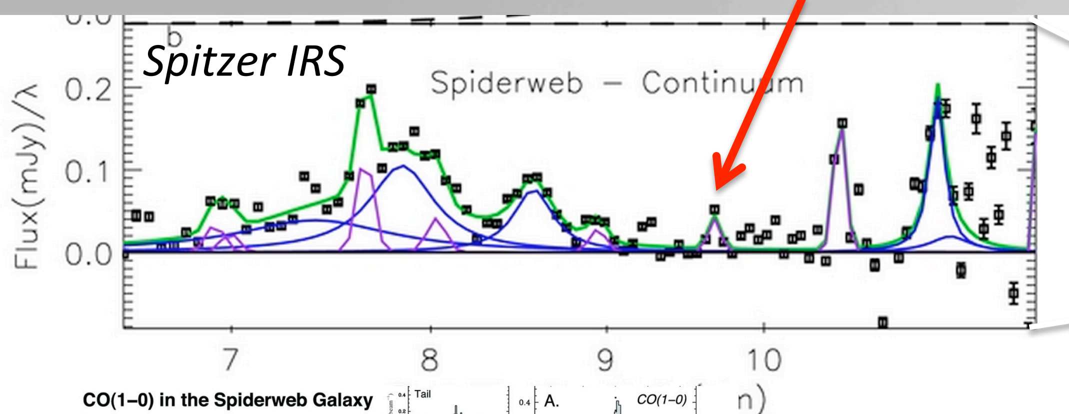
Few found almost by accident

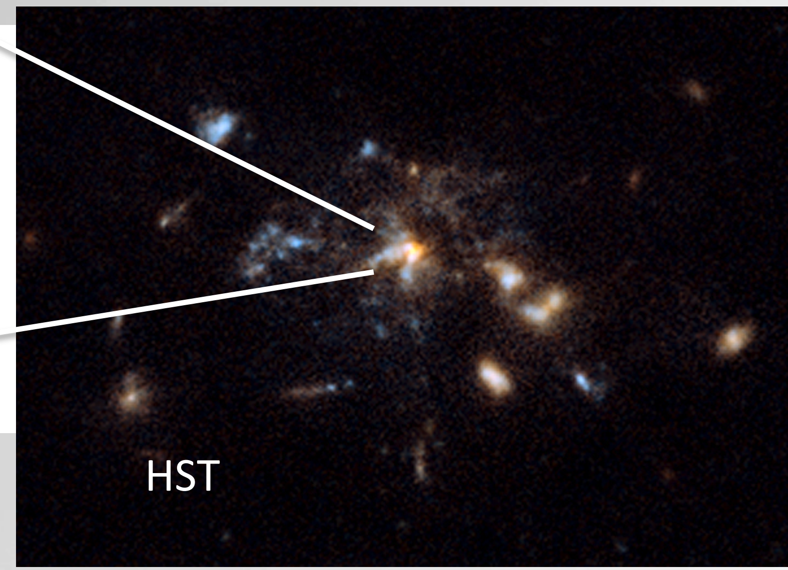
One of the most dramatic is the Spiderweb Radio Galaxy z = 2.16

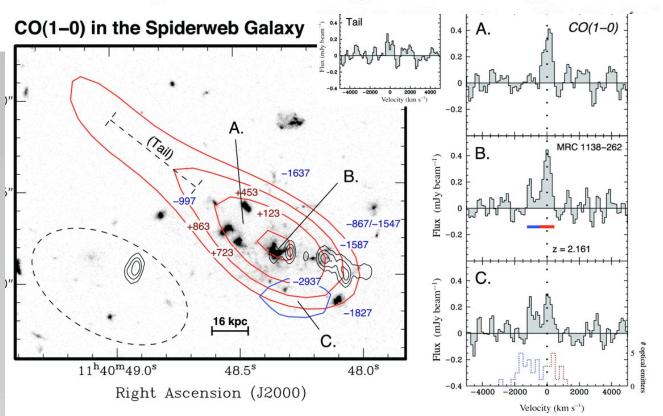
PKS 1138-26 Ogle et al. (2012)

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

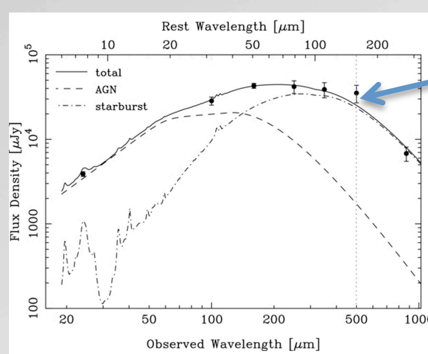
Ogle et al. (2012)







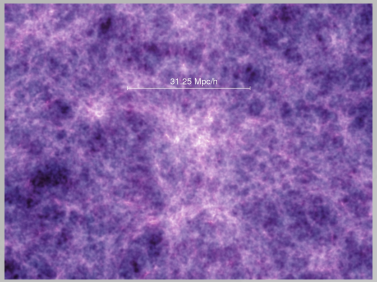
Emonts et al. (2013) ATCA CO



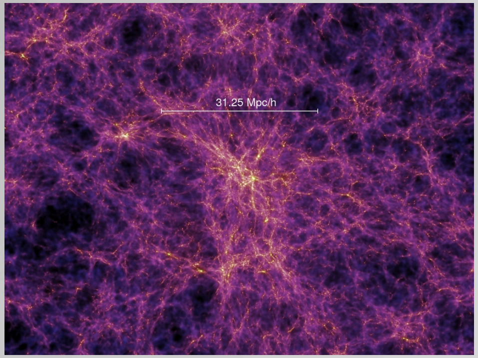
Seymour et al. claim Detection of [CII] with C+/FIR = 2% based on SED detection. Could some of this be shocked gas??

Universe at High z

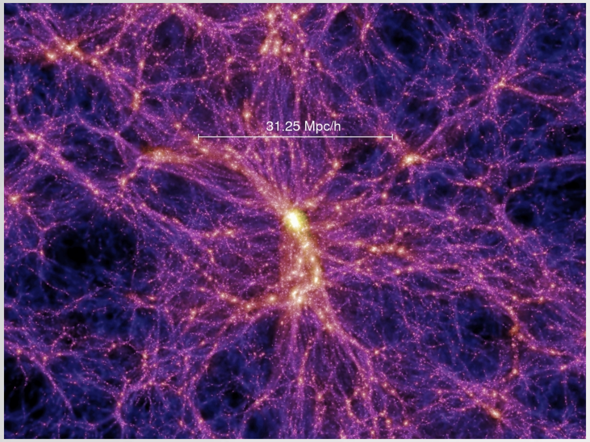
Dark matter distributions from Millenium Simulation
Ω_Λ=0.7, Ω_Λ=0.7 Ho=70



Z=18

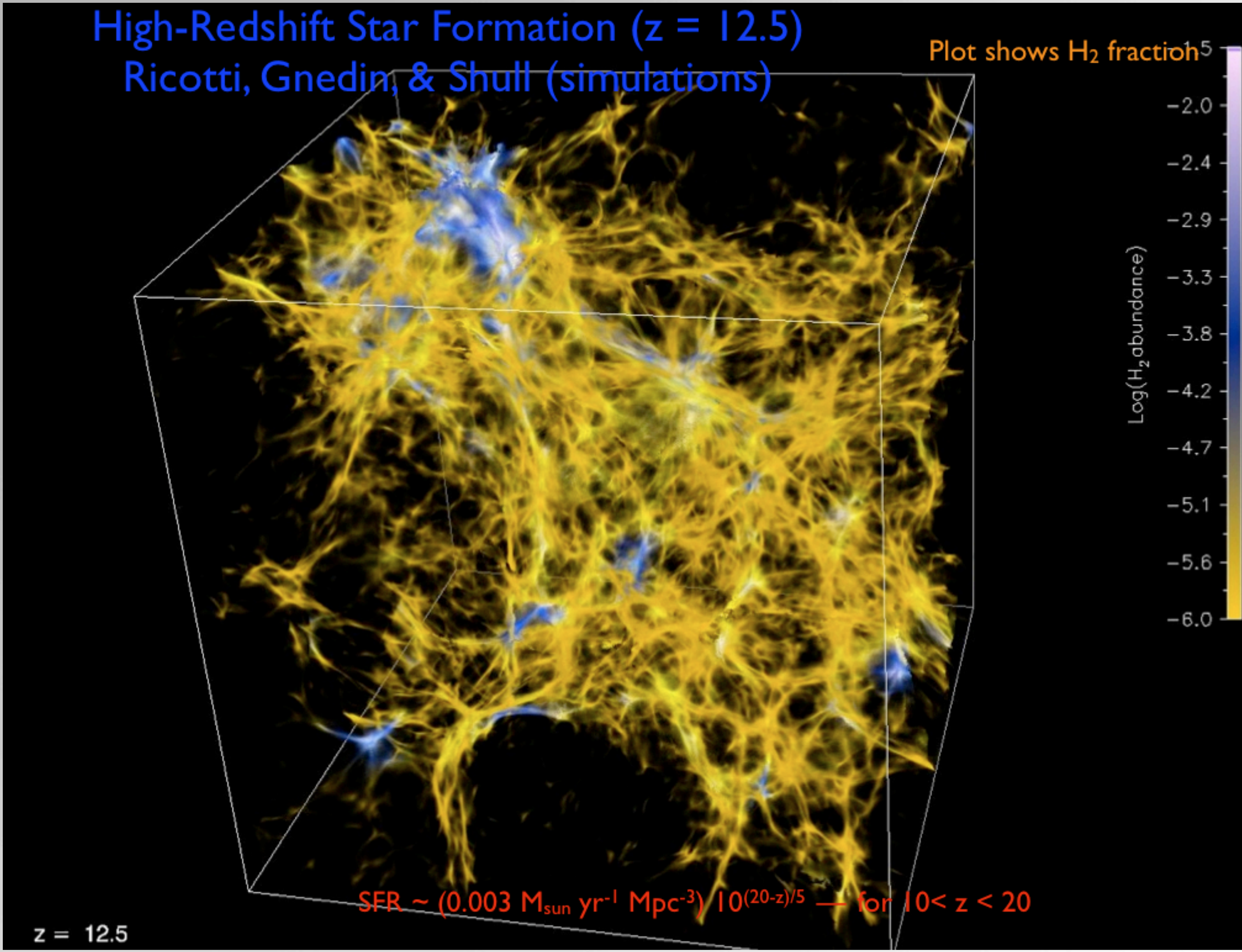


Z=6



Z~0

- At z = 6-20 lots of large-scale evolution in filaments--good chance of shock-driven H_2 emission due to collapse of filaments
- Mini-quasars may drive jets into surrounding H2 clouds--analogs to the 3C radio galaxies--if more than 1 per beam--or brighter than local analogs--might be detectable at 3-sigma peaks



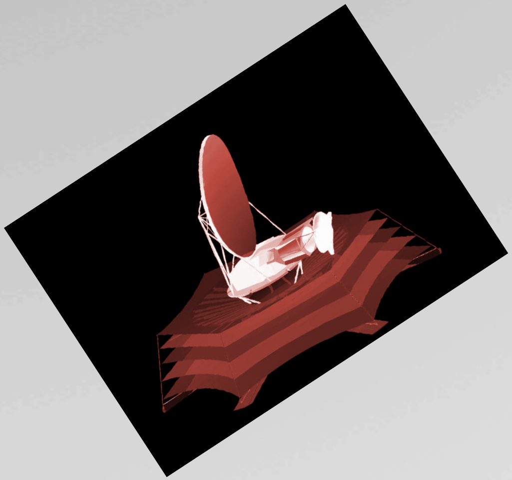
High-Redshift Star Formation (z = 12.5)
Ricotti, Gnedin, & Shull (simulations)
Plot shows H_2 fraction
Log(H_2 abundance)
−2.0
−2.4
−2.9
−3.3
−3.8
−4.2
−4.7
−5.1
−5.6
−6.0
SFR ~ (0.003 M_{sun} yr^{-1} Mpc^{-3}) $10^{(20-z)/5}$ — for 10< z < 20
z = 12.5

Can we detect H_2 emission from protoclouds at high-z?

Wavelength range for key rotational line puts detection in FIR-SPACE MISSION

0-0 S(3) 9.66um	z = 6-15	68-154 μm
0-0 S(1) 17.08um	z = 6-15	119-272 μm
0-0 S(0) 28um	z = 6-15	196-448 μm

Strongest X_{gal} lines



Note: ALMA will be blind to these unless significant emission at z > 10.5 tiny beam and small fractional bandwidths

How does it form at high-z?

Two main ways to make H_2 (see Cazaux & Spaans 2004)

H^- (pure gas route)

$H + H^- = H_2 + e^-$

H^- abundance depends critically on the electron abundance $\varepsilon_e = n_e/n_h$ because it forms at a rate $R_g = k_1 n_h^2 \varepsilon_e$

Formation on grains (dust route)

Dust cross-section

Efficiency

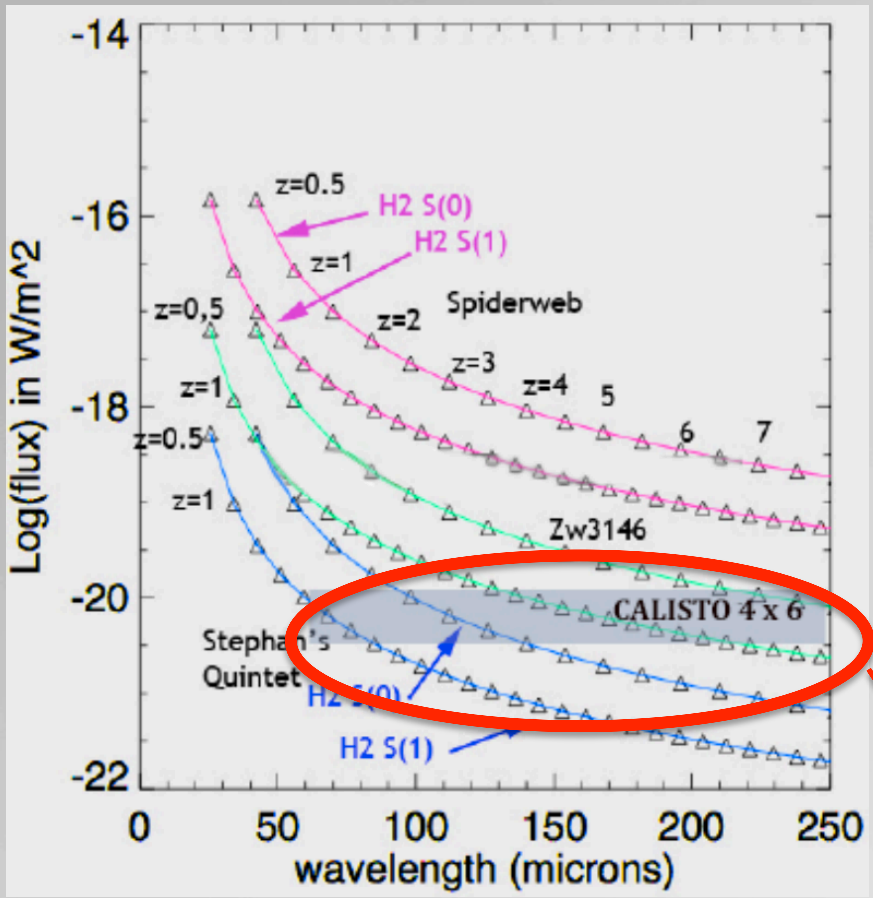
Sticking coeff. (very T sensitive)

Formation rate $R_d = 1/2\, n(H) v_H\ (n_d \sigma_d)\ \varepsilon_{H2}\ S_H(T_d T_g)$

$\approx k_2\ \varepsilon_{H2} S_H\, n(H) \varepsilon_d\, n_h$ where ε_d=dust/gas ratio n_d/n_h

At z ~ 15, $T_{dust} = T_{cbr} = 2.9\,(1+z) = 48K$. At this temperature and below, dust formation dominates over H- route, and formation depends critically on GDR at that z! Generally H_2 forms rapidly in low-velocity shocks.

Prospects of detection at high-z



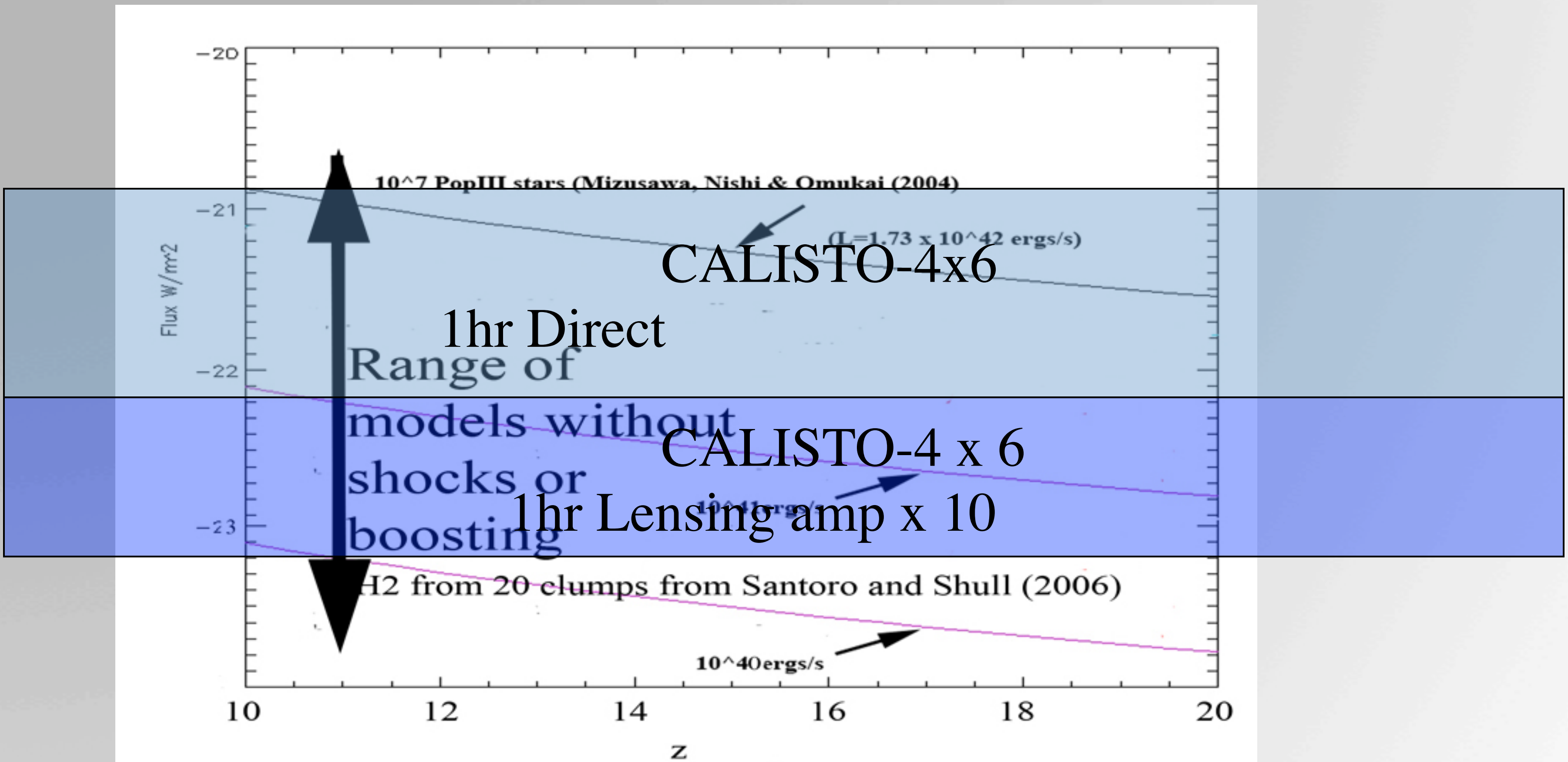
Calisto is very sensitive
At high-z

It could detect H2 from most
Powerful cluster sources to
Z ~ 6 or above

Such sources are not likely at
these redshifts

Regime of single filled aperture
Targets:

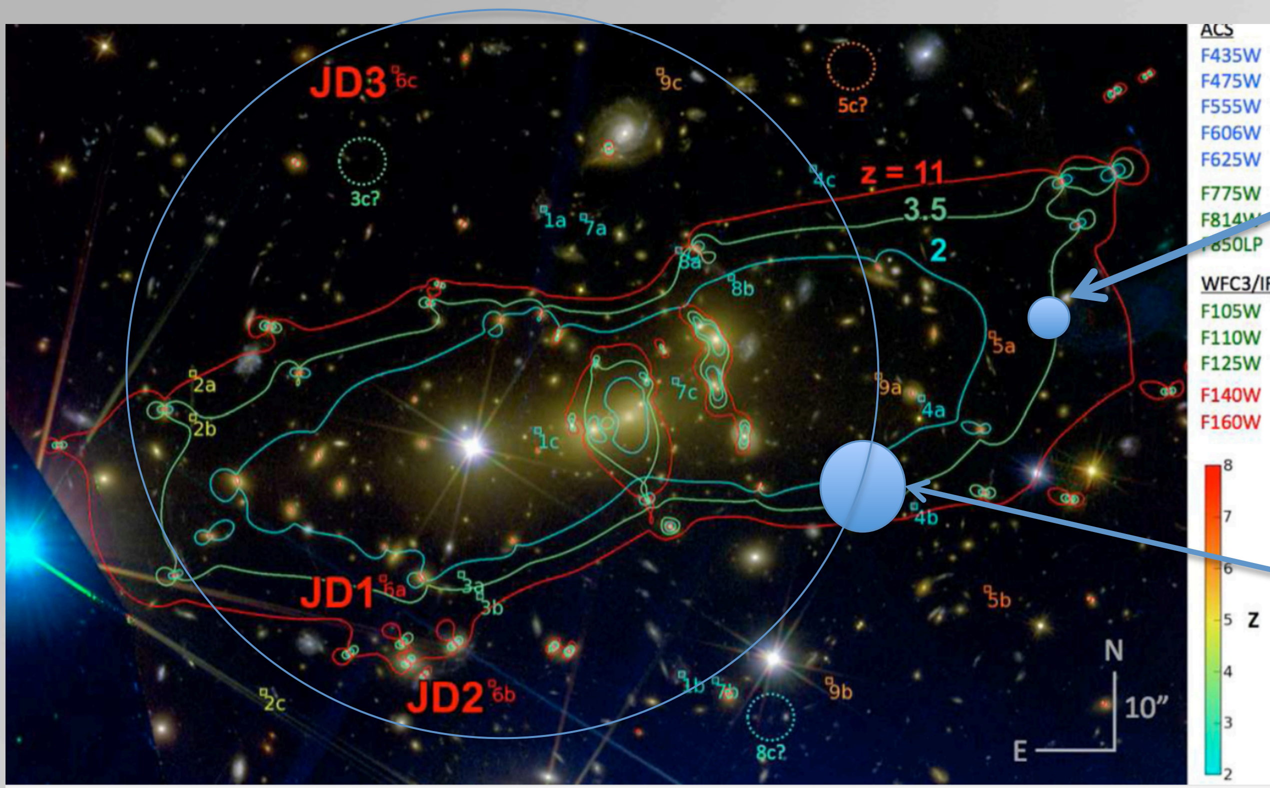
Huge range in model predictions for primordial gas



Individual clumps—hard but lot of unknowns in dissipation time scales and H2 formation Processes---- WE SHOULD STILL TRY!

Search Strategy for strong lensing clusters: Either make deep map or search along caustics--

SPIRIT CONCEPT—NICE BUT NOT DEEP ENOUGH



BAND 10
ALMA 12m
primary beam
@ 850GHz
(0-0S(0) @ z = 11)

CALISTO 5-m
BEAM @200μm
0-0S(0) @ z ~ 6
or 0-0S(1) @ z = 11
Multiple lines VITAL

MACSJ0647.7+7015 (Coe et al. 2013) and lensing model showing critical caustics

Conclusions

- **H_2 emission is common DIFFUSE GAS in low-z galaxies** but discovery of turbulent/shock systems came too late for major follow up with Spitzer
  - **NO Spitzer detections z > 2.1** (where 0-0S(3) line fell out of band)
  - **H2/PAH ratio > 4% indicative of shocks/turbulence**—often BROAD (300-1000km/s wide)
  - MEASURMENT OF LINE POWER == TURBULENT ENERGY DISSIPATION MEASUREMENT Kinematics can be obtained from other diagnostics (C+, CO etc).

- **Some follow up possible with JWST** but most mass in COLD gas **(HD and lower-level H_2 rotational lines) ONLY POSSIBLE WITH Far-IR telescope**

- **Line strengths and broad lines conducive to LARGE APERTURE COLD TELESCOPE** and R > 400-600 spectral resolution desirable (more is better).

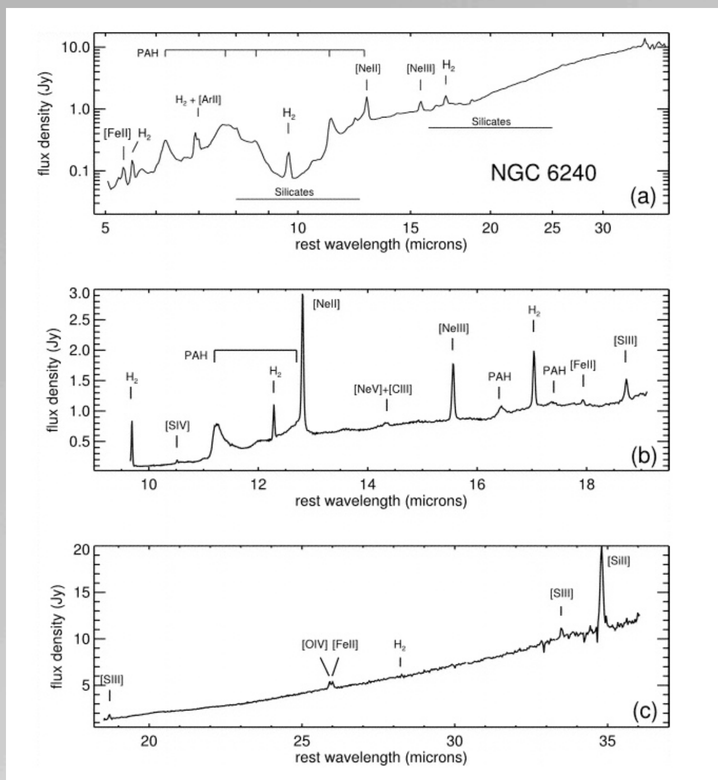
- **Although direct detection of protogalaxies very challenging**, there are enough uncertainties in the turbulent dissipation times and H_2 formation rates/Mini-AGN at high-z to make **searches worthwhile (big payoff if detected).** Using strong lenses to search for massive halos doable with large beams of CALISTO-like telescope. FIR Interferometer very nice but sensitivity not good enough despite nice large primary beam. Next-generation FIR interferometer would be needed.

KEY POINT DEEP FAST MAPPING IS NEEDED TO FIND RARE DM Halos at High-z

Extras

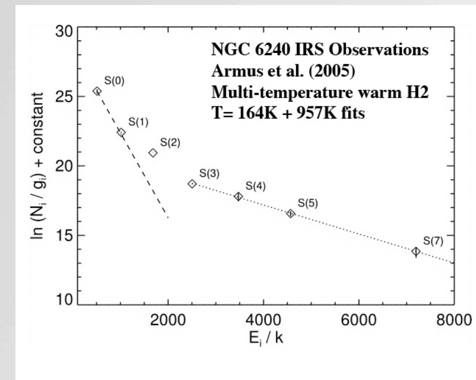
ULIRGs show powerful H_2 emission--it may be extended on large scales?

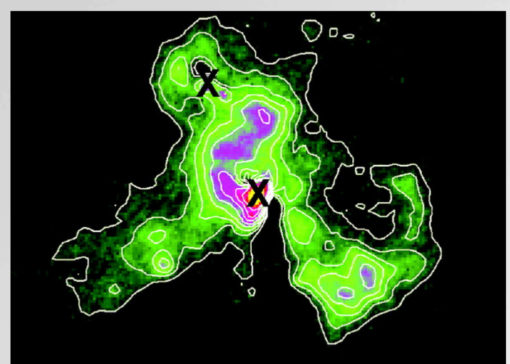
Armus et al. (2006)



The Case of NGC 6240

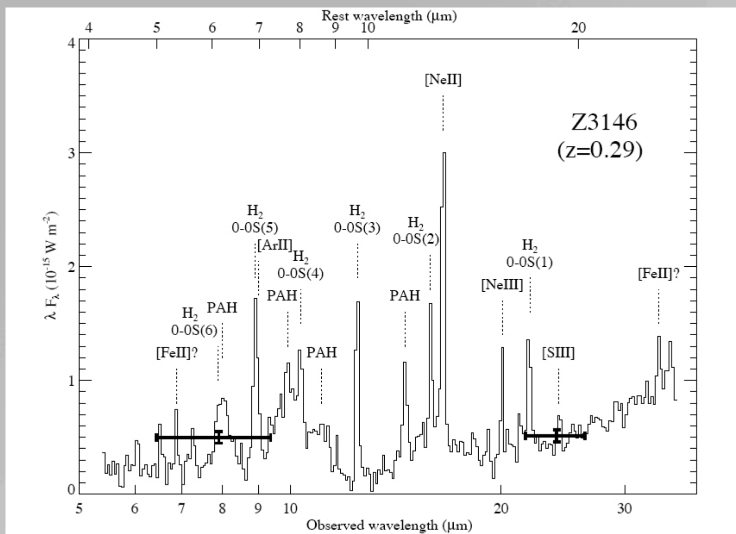
L_{H2} ~ 10^{42} ergs/s
Strong IR continuum
Multi-temp fit





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

Even more powerful H_2 discovered in X-ray-luminous cluster Zw 3146 (Egami et al. 2006)



SPITZER IRS RESULTS

L_{H2} ~ 6 x larger than NGC 6240!

L(0-0S(3) alone = 6 x 10^{42} ergs/s)

L_{H2}/L_{FIR} = 0.3

JUST LIKE Stephan's Quintet

but 60 x brighter!)

- z = 0.29

SHOCKS IMPLICATED:

H_2 strength seems to scale with size or mass of system.... Centrally concentrated--