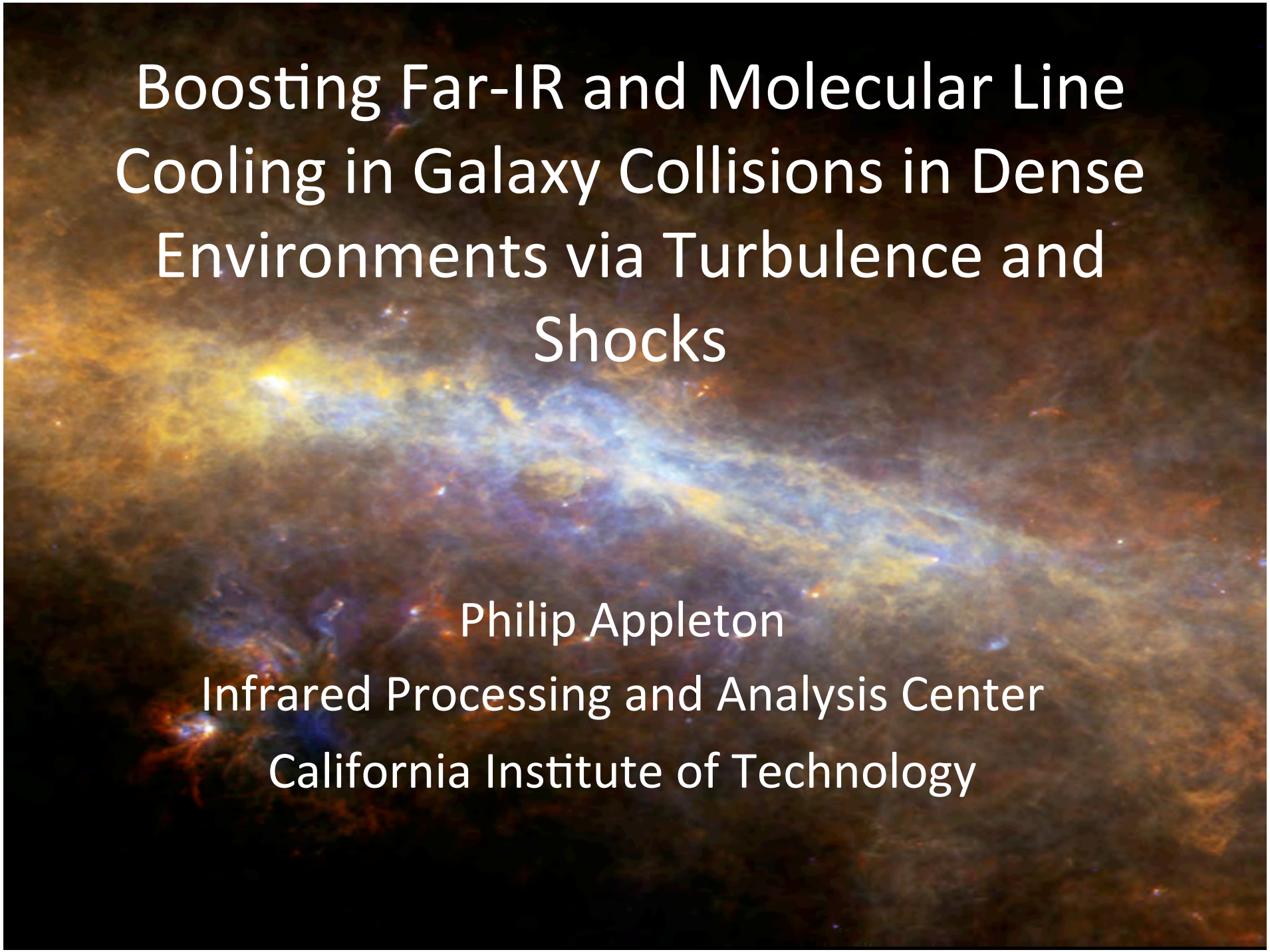


Boosting Far-IR and Molecular Line Cooling in Galaxy Collisions in Dense Environments via Turbulence and Shocks

Philip Appleton

Infrared Processing and Analysis Center

California Institute of Technology

Collaborators

SQ: Pierre Guillard and Francois Boulanger (IAS Paris), Michelle Cluver (AAO), Nanyao Lu (NHSC), Kevin Xu(NHSC), Edith Falgarone (Obs. de Paris), Eckhard Sturm (MPE), Paul van der Werf (Leiden), Ewan O'Sullivan (CfA), Guillaume Pineau des Forets (Paris), Patrick Ogle (NED)

HCG Groups: Katey Alatalo (Caltech), Pierre Guillard (IAS), Ute Lisenfeld (Granada), Michelle Cluver (AAO), Vassilis Charmandaris (Crete/Athens), Thodoris Bitsakis (Crete/Caltech), Patrick Ogle (NED) + the HCG team

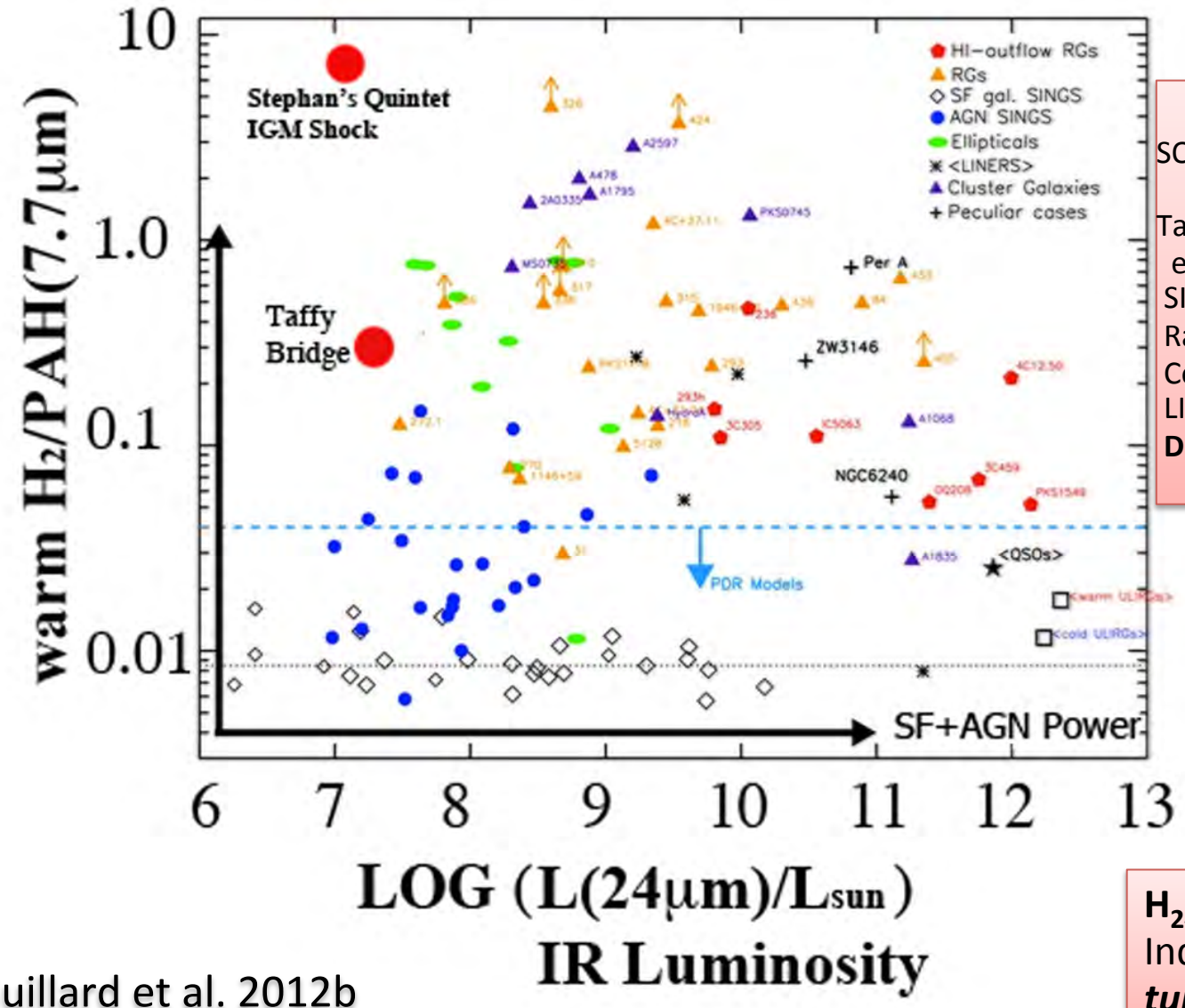
Taffy: Brad Peterson (U. Wisc), George Helou (IPAC), **Junfeng Wang** (Northwestern

Pierre and Francois skiing (whoops observing at IRAM)

Main Discussion points

- Shock-excited H_2 in nearby systems
- What we have learned from Herschel
  - C+ enhancements by shocks/turbulence?
- C+ and CO mapping of MOHEG Compact Group galaxies
- Implications for high-z system

There is a population of galaxies with extreme warm H_2/PAH emission based on Spitzer IRS observations



Guillard et al. 2012b

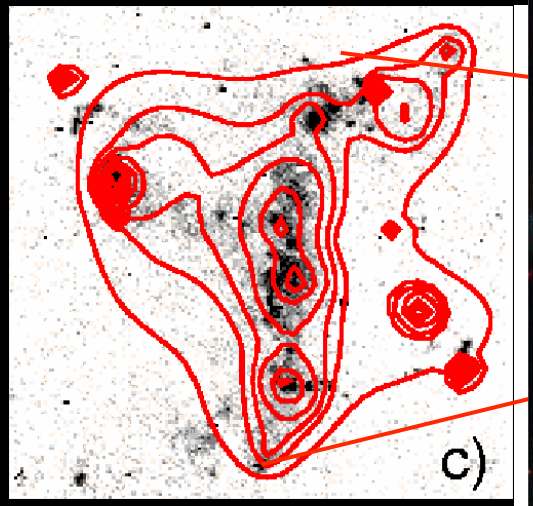
SQ Appleton et al (2006)
Cluver et al. 2010
Taffy Peterson & Appleton et al. (2012)
SINGS Galaxies (Roussel et al. 07)
Radio galaxies (Ogle et al. 10)
Cool core clusters (Egami 06)
LINERs, Seyferts (Roussel 07)
Dusty ellipticals (Kaneda 08).

H_2/PAH values may Indicate ***shock or turbulently heated*** **H_2**

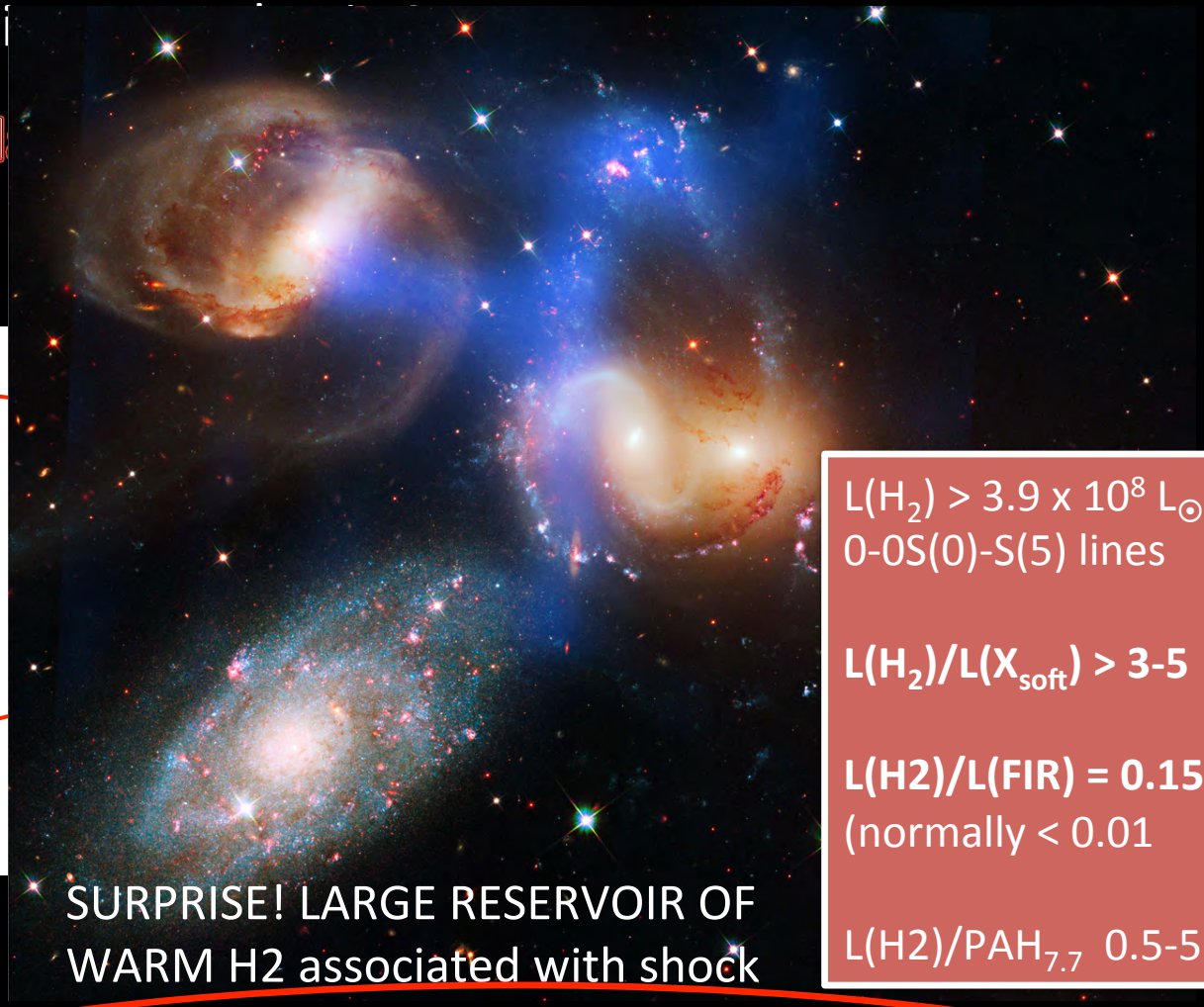
The case of Stephan's Quintet: A smoking gun for "Pure Shock" i

i.e. Take a tidal fil

CHANDRA X-RAY TELESCOPE



(Trinchieri et al. 2003 O'Sullivan 2009)



SURPRISE! LARGE RESERVOIR OF WARM H2 associated with shock

$L(H_2) > 3.9 \times 10^8 L_\odot$
0-0S(0)-S(5) lines

$L(H_2)/L(X_{soft}) > 3\text{-}5$

L(H2)/L(FIR) = 0.15
(normally < 0.01

$L(H2)/PAH_{7.7}$ 0.5-5!

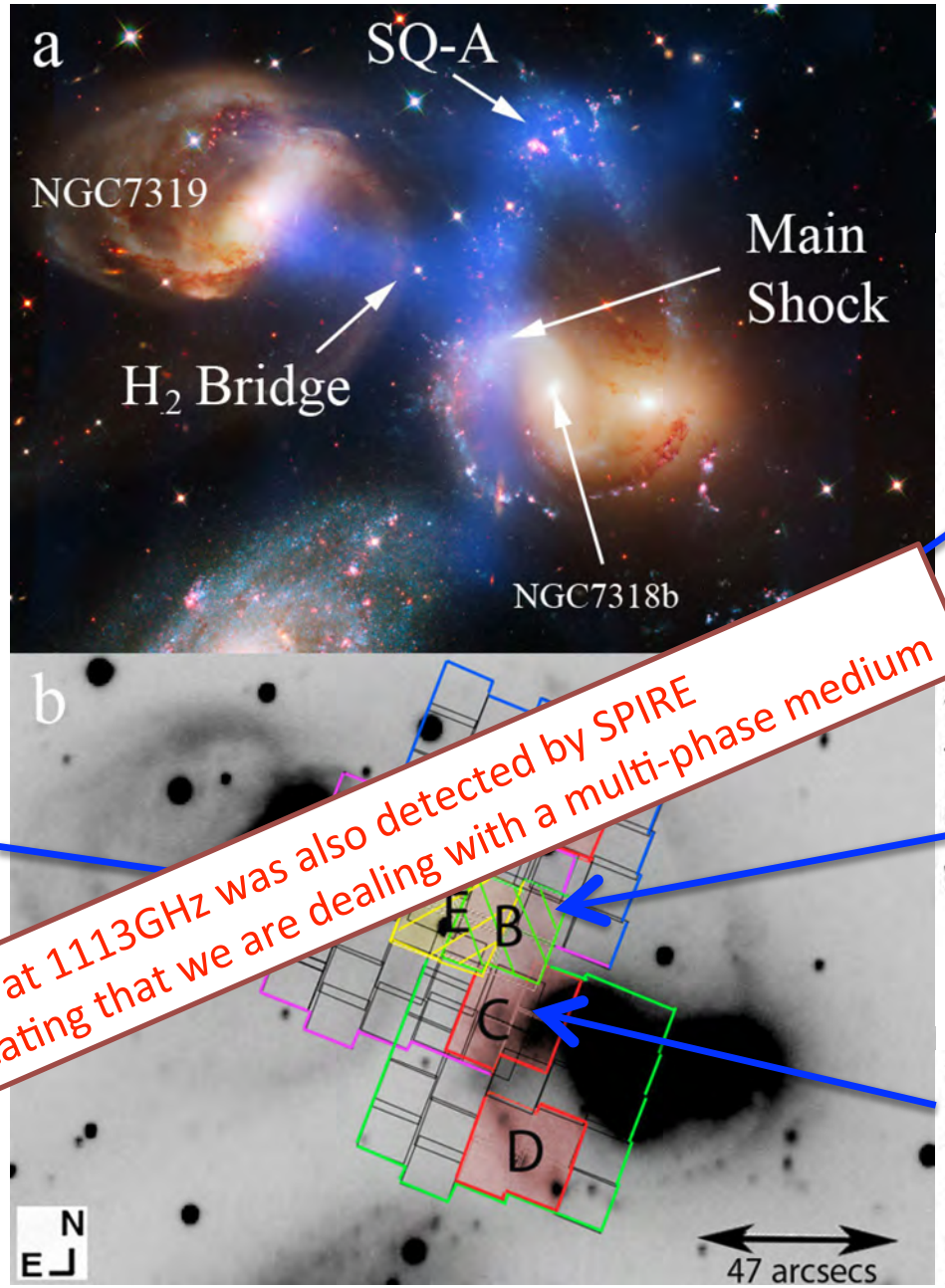
Mid-IR rotational H_2 lines were broadened to 780 km/s! Record for broadest line by IRS

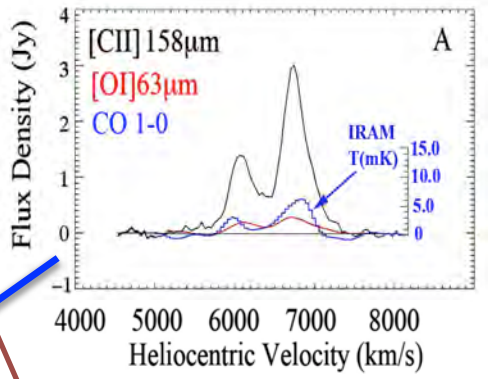
PACS SPECTROSCOPY

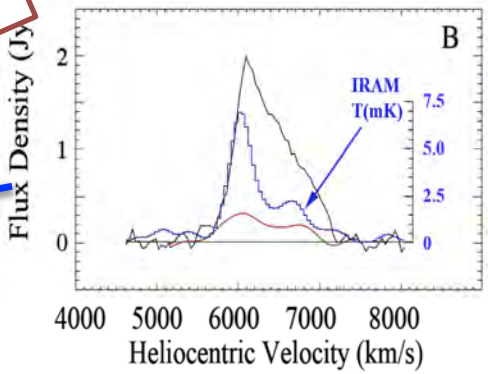
VERY STRONG C+
WEAKER [OI]63μm

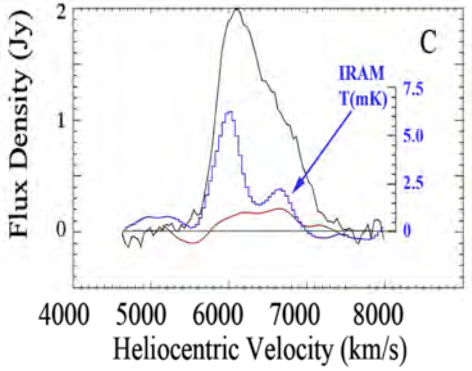
Common velocity
Signature to CO 1-0

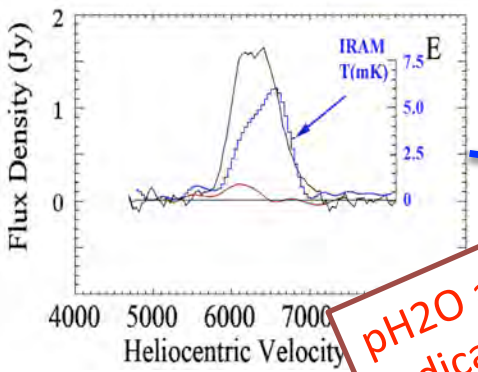
Appleton+ 2013
ApJ, Oct 20 2013
2013arXiv1309.1525A







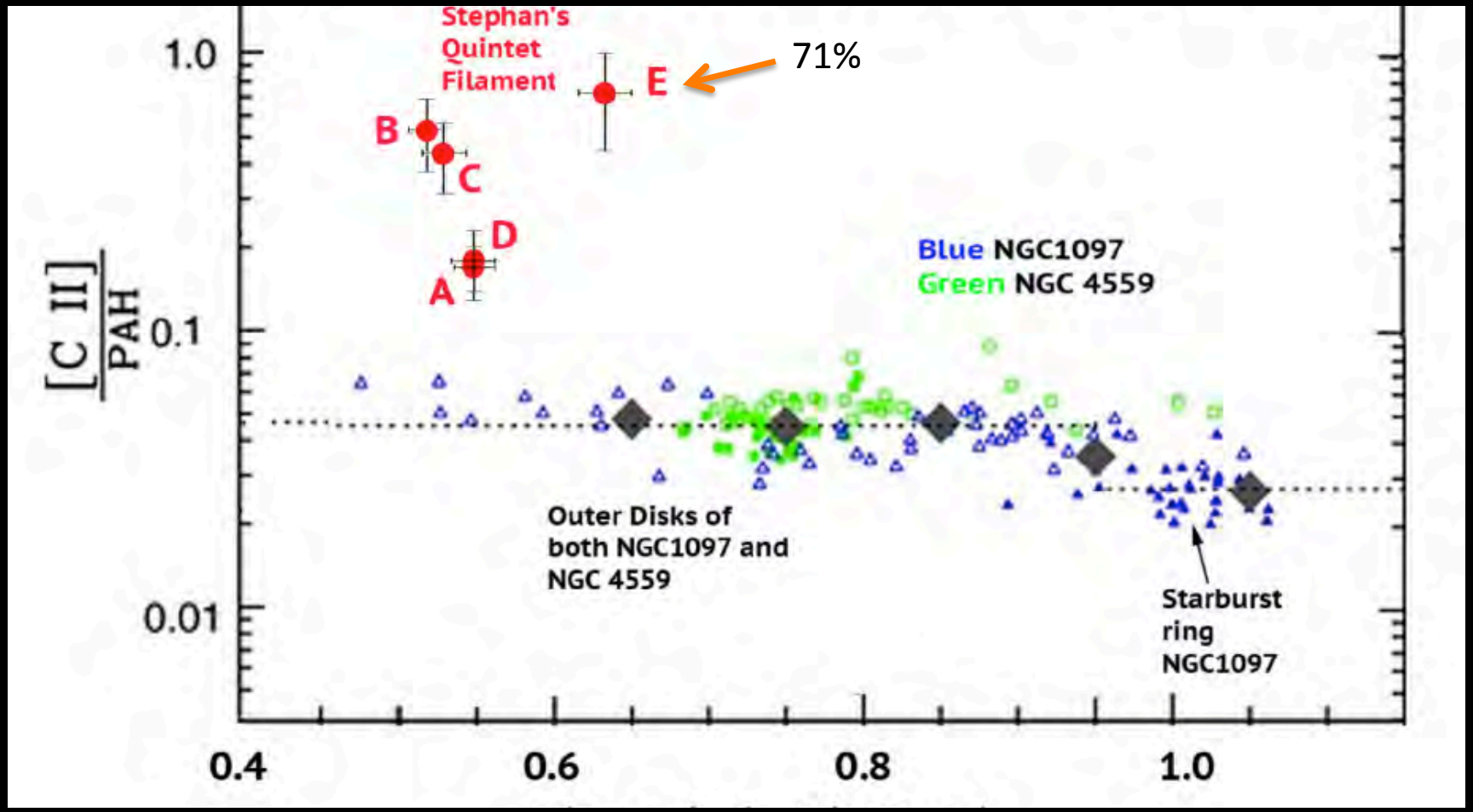




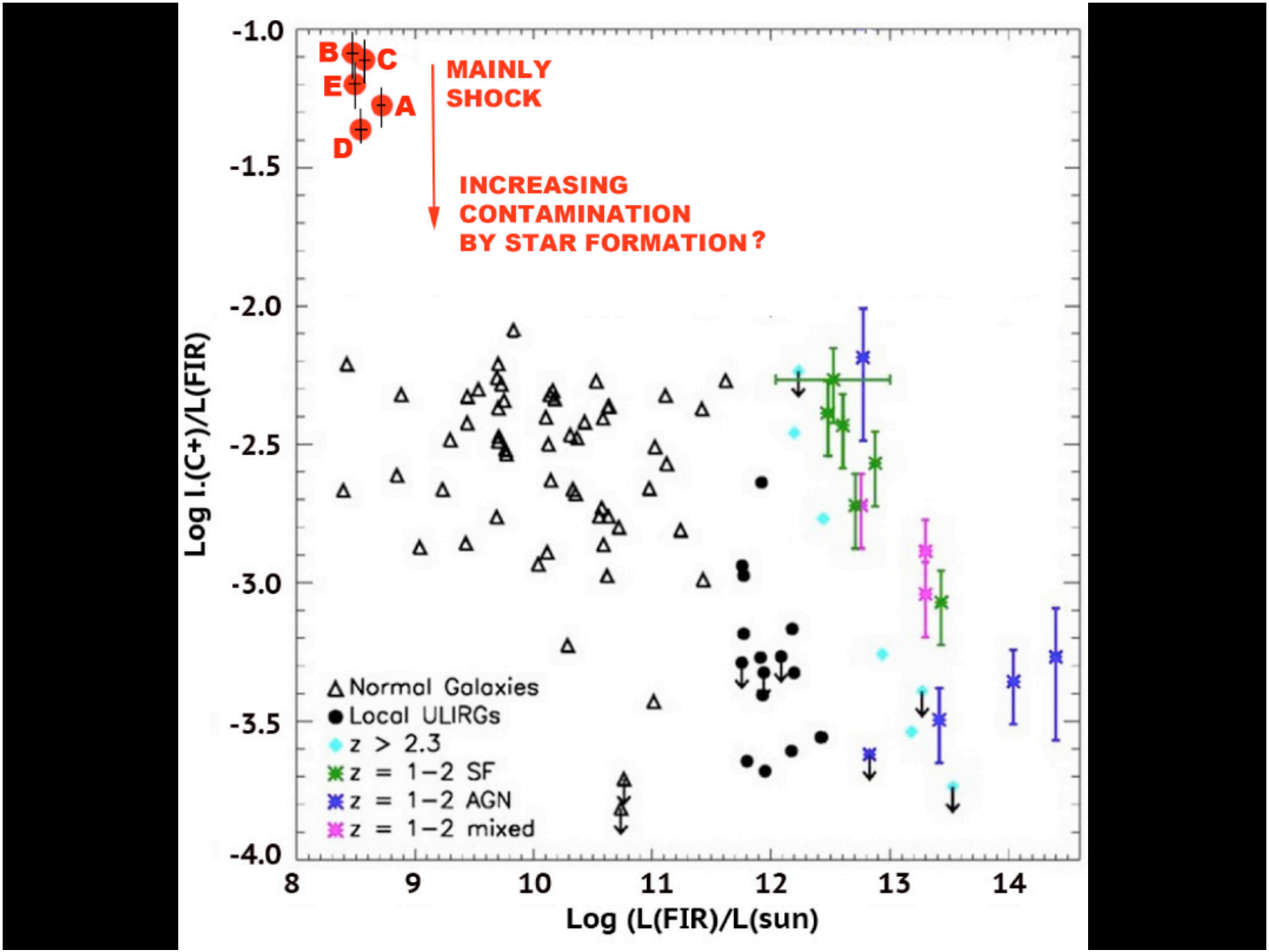
pH2O at 1113GHz was also detected by SPIRE indicating that we are dealing with a multi-phase medium

C+ and [OI]
VERY BROAD
(>1000 km/s)
3 components typically 400-800 km/s wide

Ridiculously high C+/PAH(6-16μm) ratios



Not shown are also similar large values found in 3CR MOHEG radio galaxies (Guillard, in preparation---See next talk!)


B
C
E
A
D
MAINLY SHOCK
INCREASING CONTAMINATION BY STAR FORMATION?
Normal Galaxies
Local ULIRGs
z > 2.3
z = 1–2 SF
z = 1–2 AGN
z = 1–2 mixed
Log l.(C+)/L(FIR)
Log (L(FIR)/L(sun))
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
8
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14

MORE EXAMPLES:

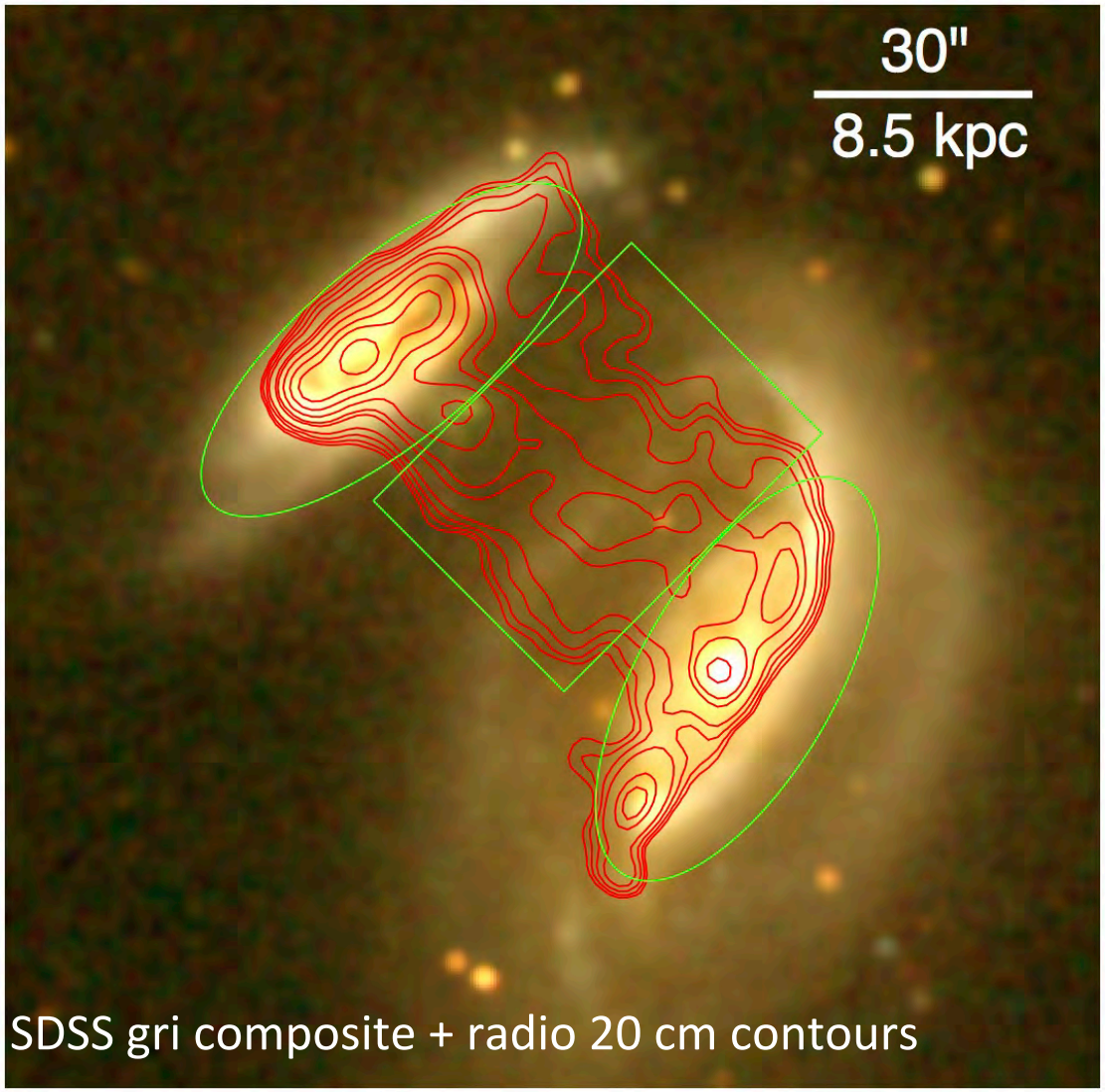
Another “Tidally Induced Shocked Region”

Junfeng Wang, Phil Appleton, Bradley Peterson et al. in prep.

The Taffy Galaxies
(Condon et al. 1993)

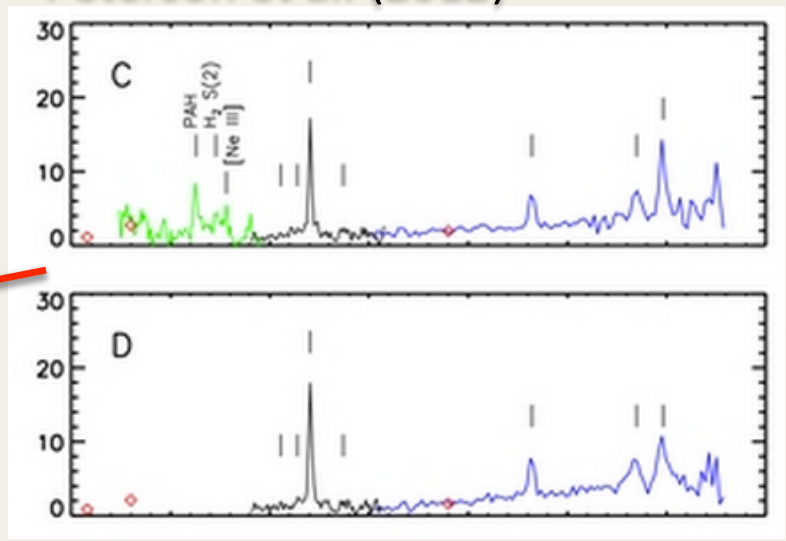
The aftermath of a head-on collision

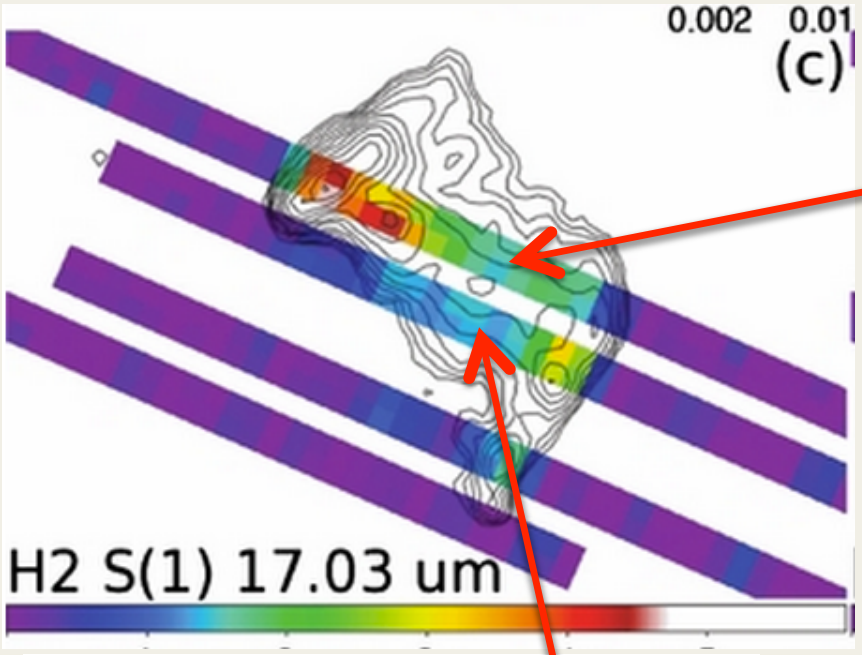
Radio continuum likely from shock accelaration in "splash bridge" (Lisenfeld & Völk 2009)

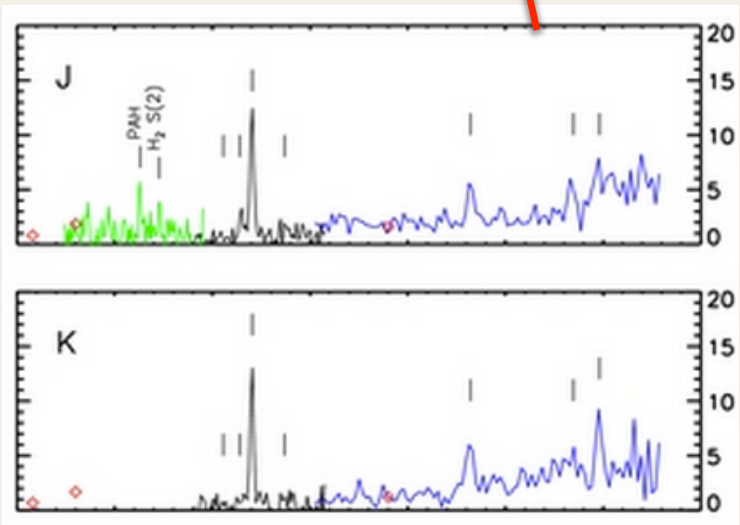


Warm H_2 in Taffy Bridge with *Spitzer*

Peterson 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))!

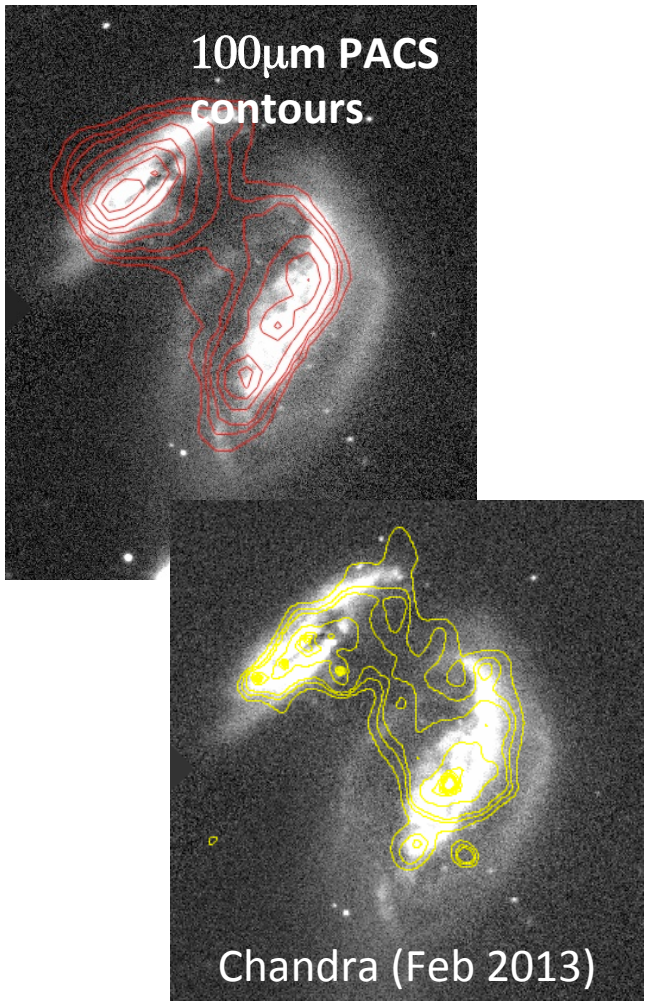
Maximum in the bridge

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

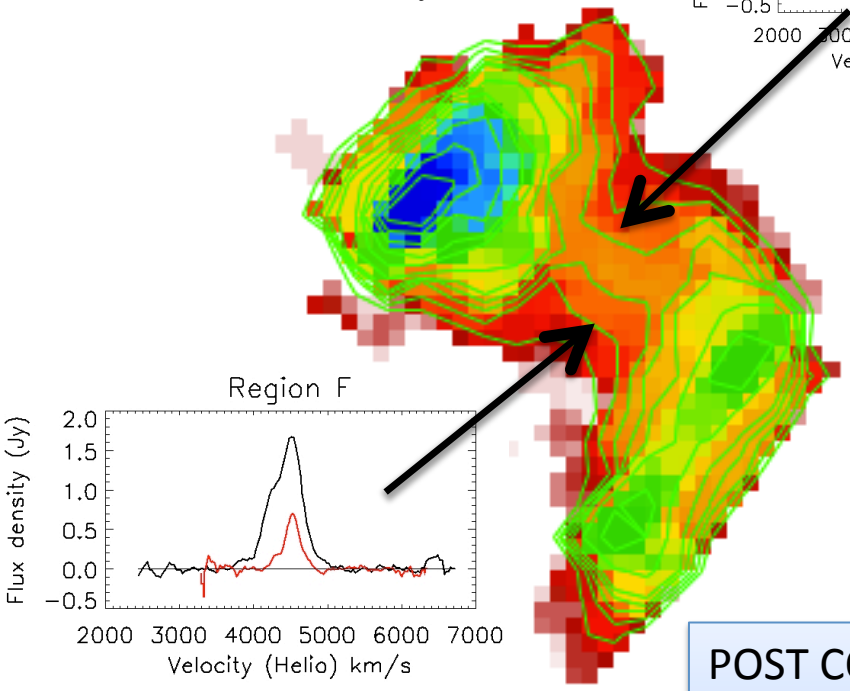
X-ray heating now ruled out

Herschel/CHANDRA of TAFFY BRIDGE: Strong similarities to Stephan's Quintet

(Wang, Appleton et al.; Peterson et al, 2013)



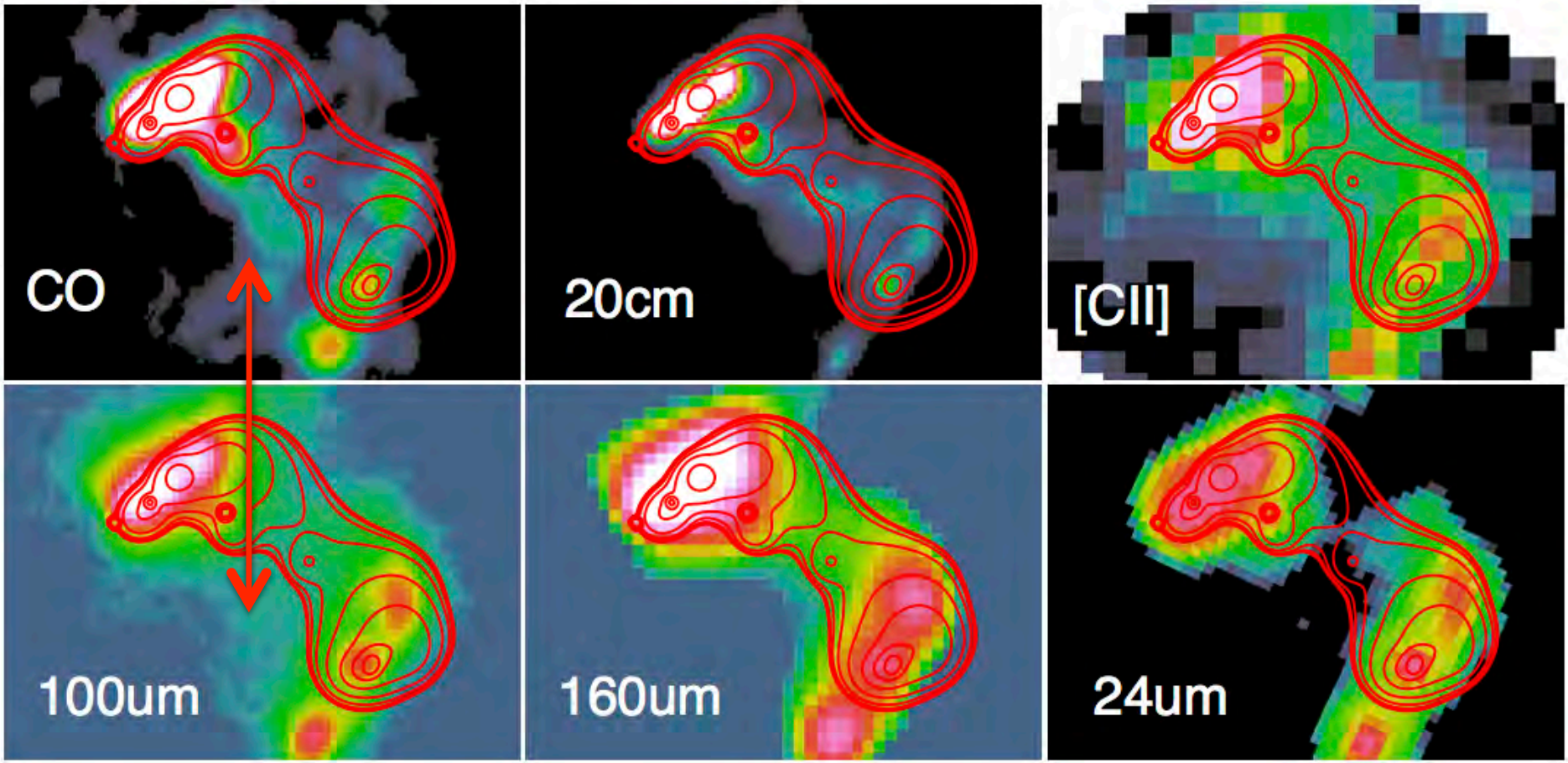
[CII]157.7μm



[CII] and [OI]63mm show considerable structure

POST COLLISION GAS IN HIGHLY TURBULENT STATE BETWEEN GALAXIES

Chandra soft X-ray (contours) define where the current energy is being dissipated (with C+, FIR)



Huge variation in gas to dust ratio—Mismatch of
Herschel cool dust/C+/X-ray and CO 1-0 suggests dust destruction.
Shock structure could appear transverse because of counter-rotation of 2 galaxies

Sample of 23 Hicson Compact Groups studied by *Spitzer* IRS show enhanced H_2

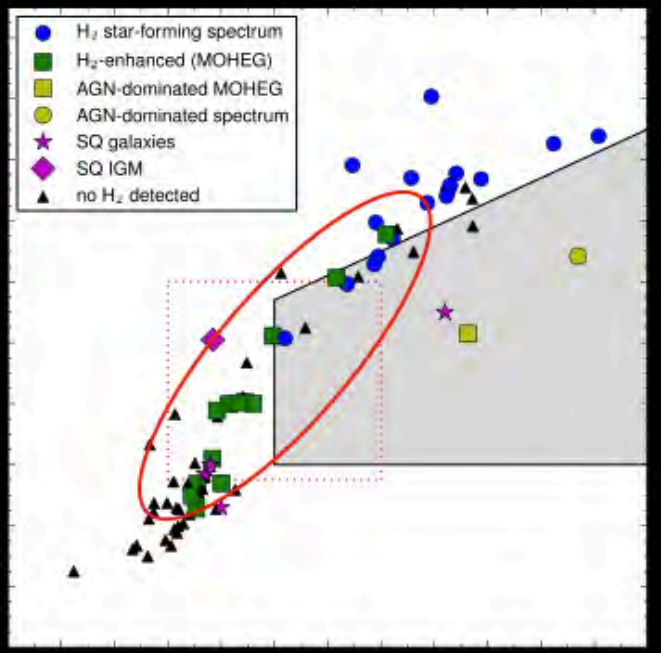
$H_2/7.7\mu\mathrm{m}\ \mathrm{PAH} \geq 0.04$ Cluver et al. (2013)

14/78 galaxies showed H_2 emission too strong to be energized solely by photon-dominated regions (PDRs). Those 14 tend to sit in the IR gap that some associate with rapid evolution from blue cloud to red-sequence. Most lie in the Green Valley

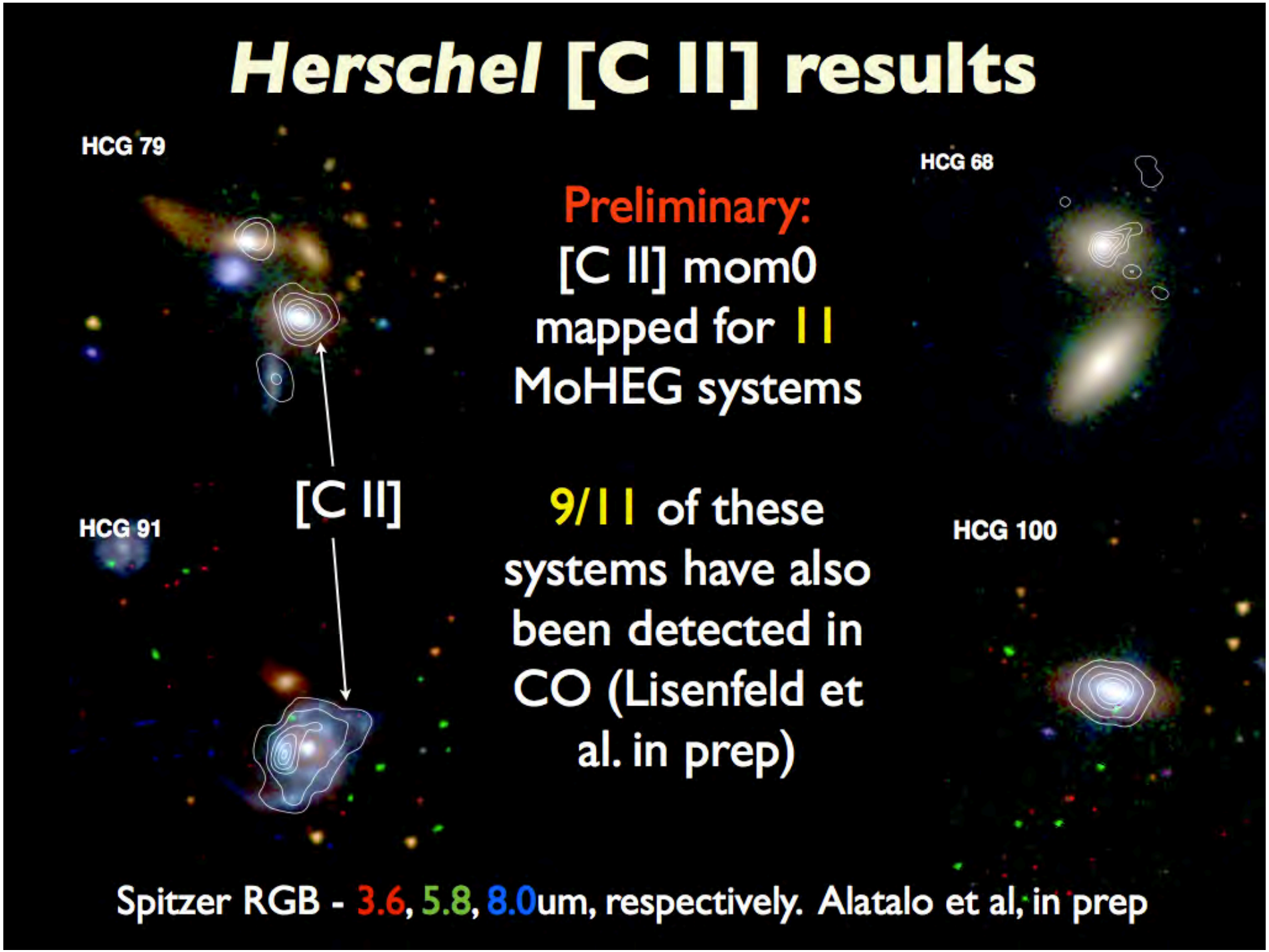
We observed 9 systems with most extreme H2/PAH ratios with Herschel PACS Spectometer and CARMA CO 1-0 spectral imaging.

Aim is search for clues to enhanced ratios

Cluver et al. 2013



Herschel [C II] results

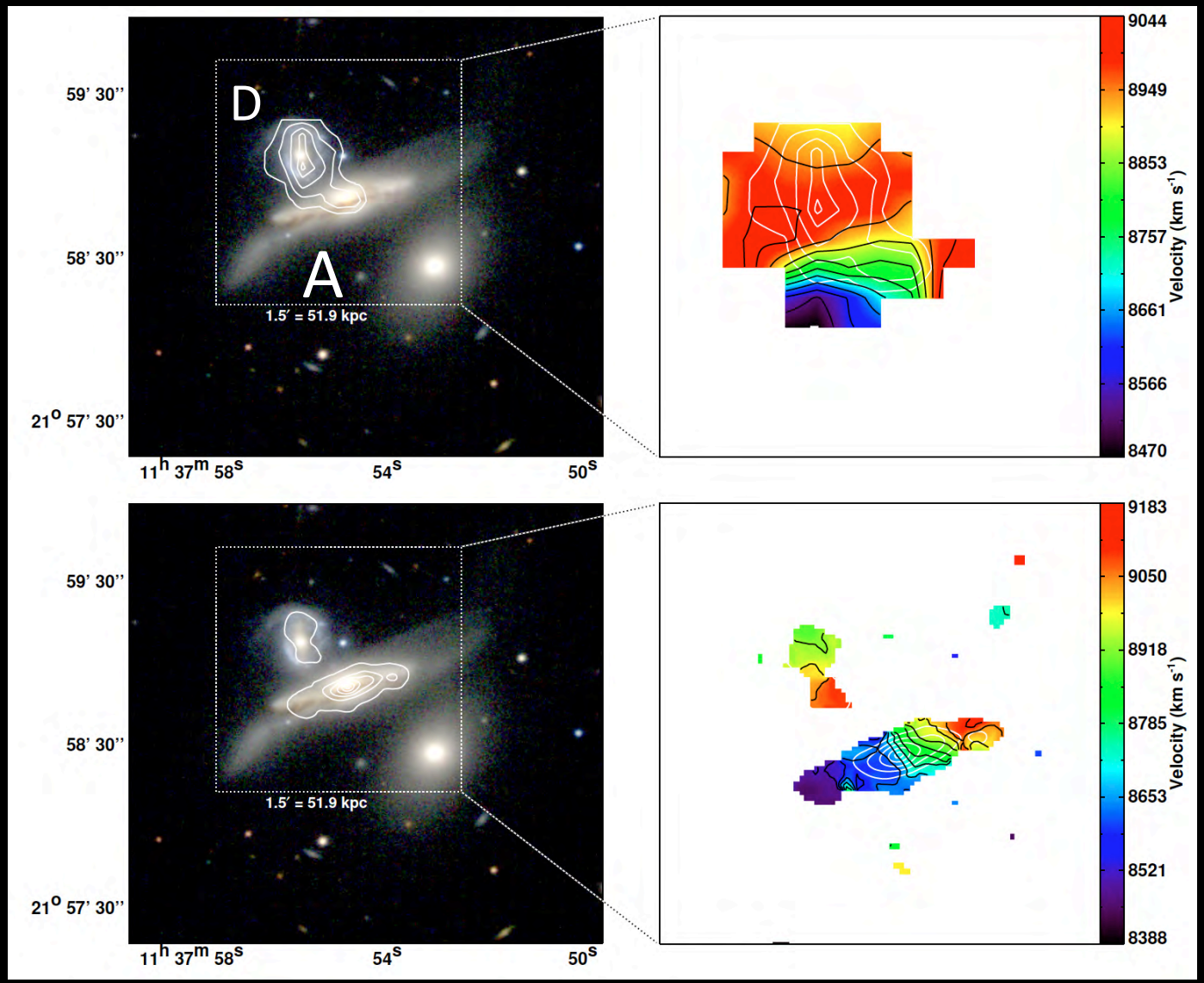


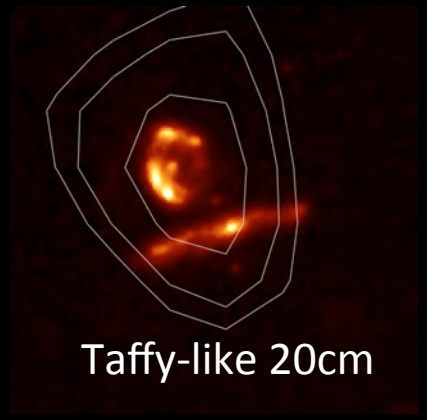
Preliminary:
[C II] mom0 mapped for 11 MoHEG systems

9/11 of these systems have also been detected in CO (Lisenfeld et al. in prep)

Spitzer RGB - 3.6, 5.8, 8.0um, respectively. Alatalo et al, in prep

The Peculiar Case of HCG57





HERSCHEL PACS
C+ LINE

CARMA
CO 1-0 Line

HCG57 A/D Peculiar CO Kinematics

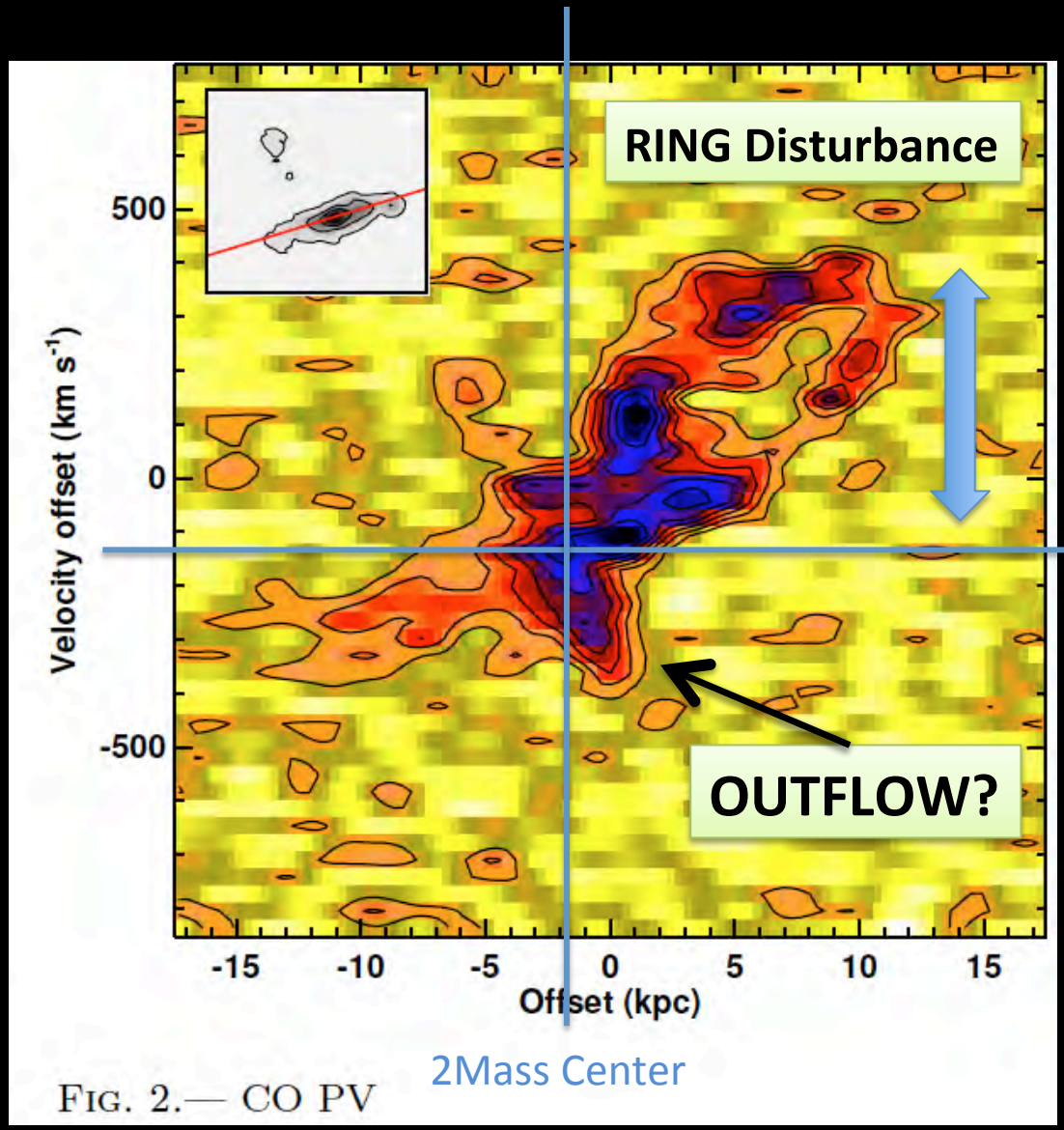


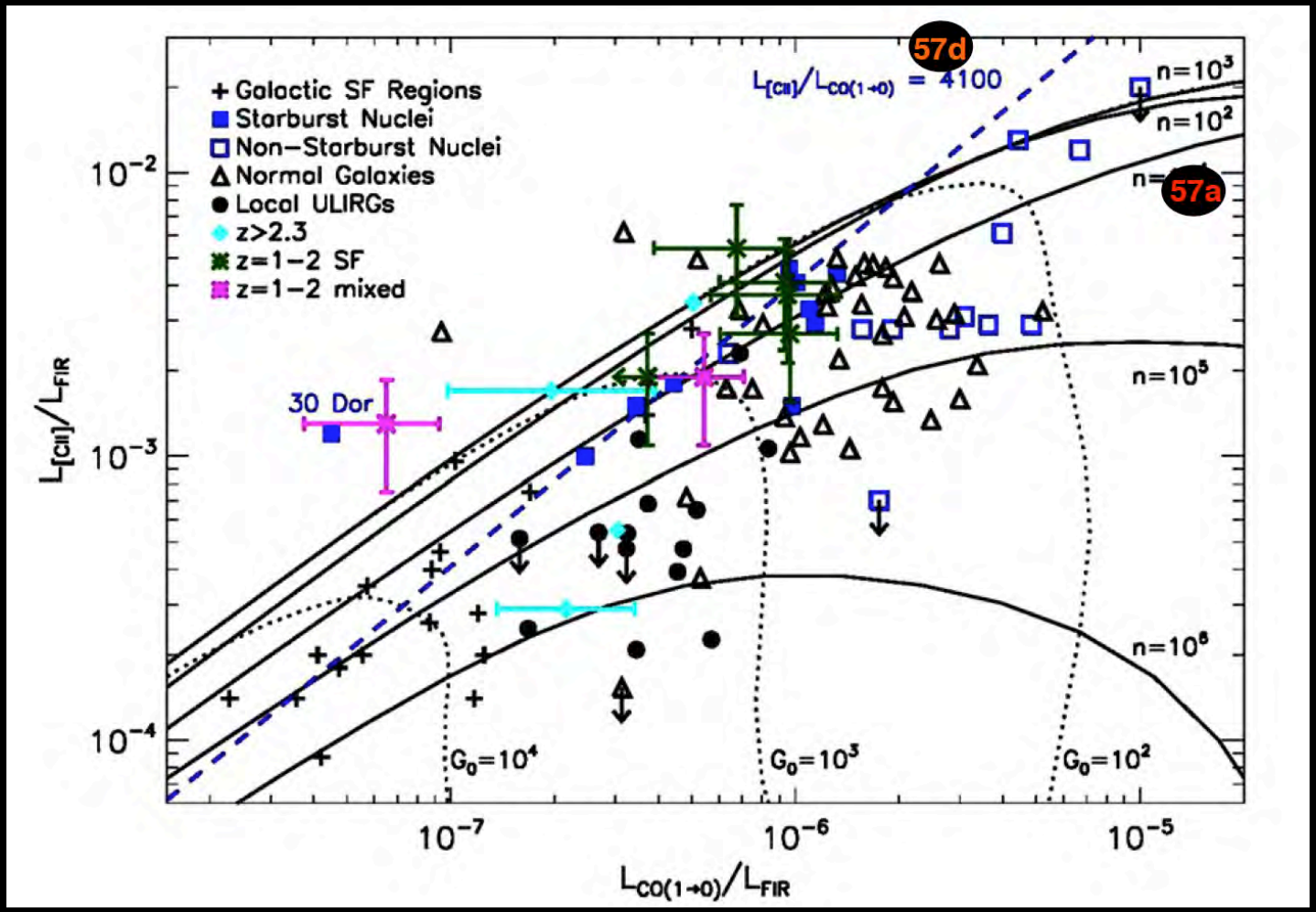
FIG. 2.— CO PV

Two peculiar features in HCG 57A

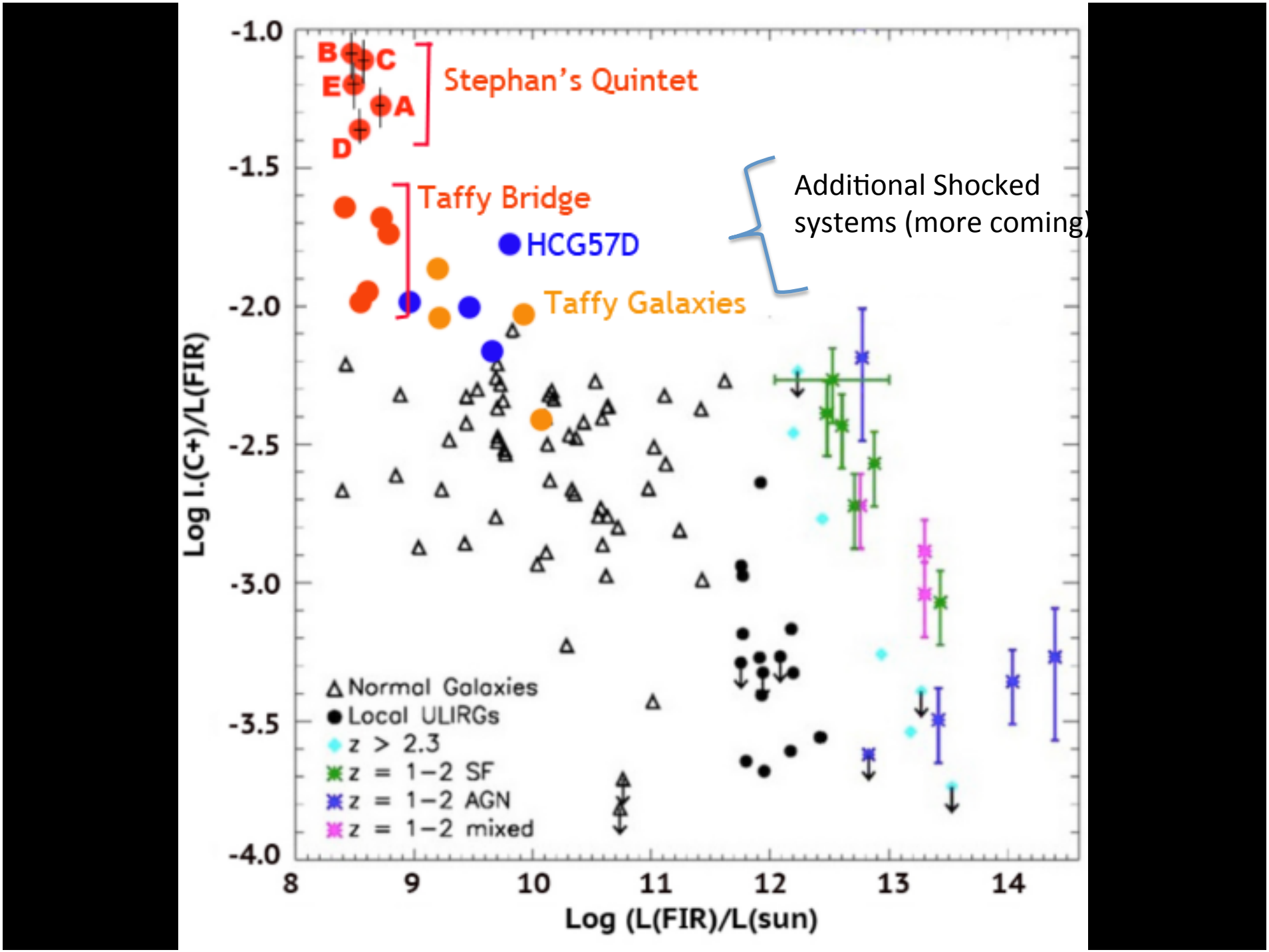
1) Possible outflow?
2) Possible asymmetri kinematic disturbance (off-center ring?)

Is HCG57A/D another head-on collision product?

Diagnostics



From Stacey+10


-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
8
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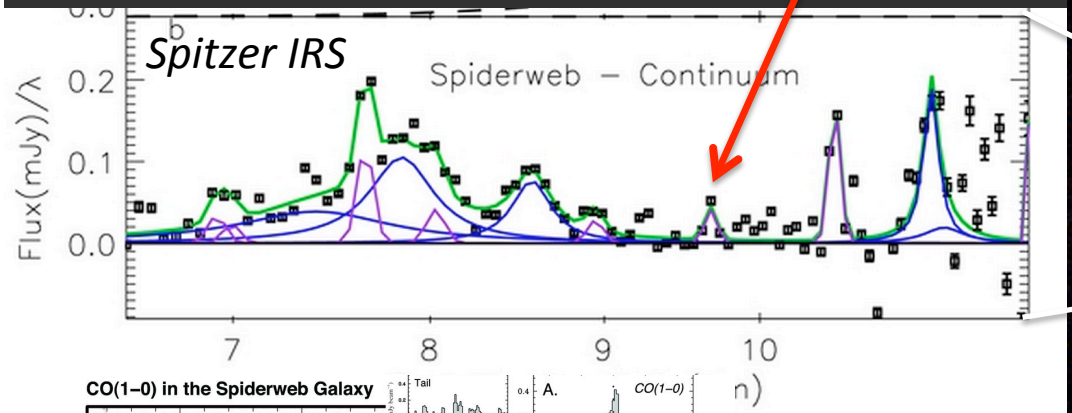
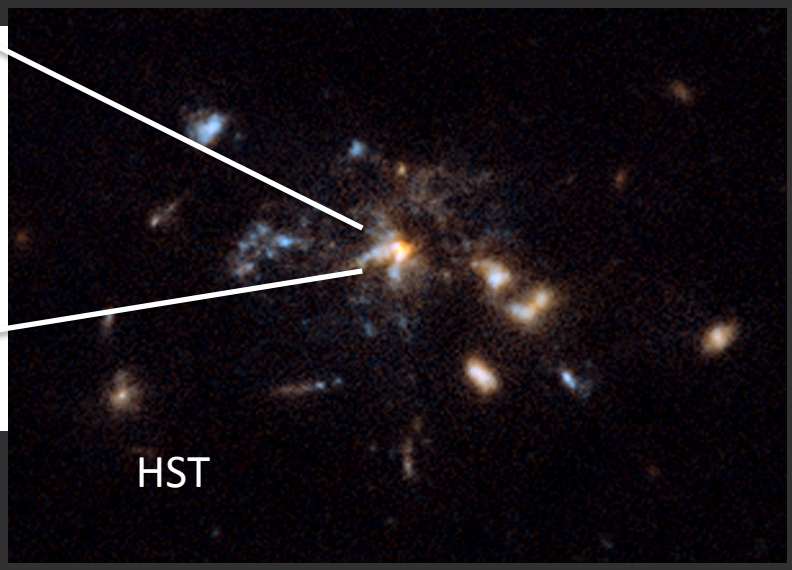
14
Log I.(C+)/L(FIR)
Log (L(FIR)/L(sun)
B
C
E
A
D
Stephan's Quintet
Taffy Bridge
HCG57D
Taffy Galaxies
Additional Shocked systems (more coming)
Normal Galaxies
Local ULIRGs
z > 2.3
z = 1–2 SF
z = 1–2 AGN
z = 1–2 mixed

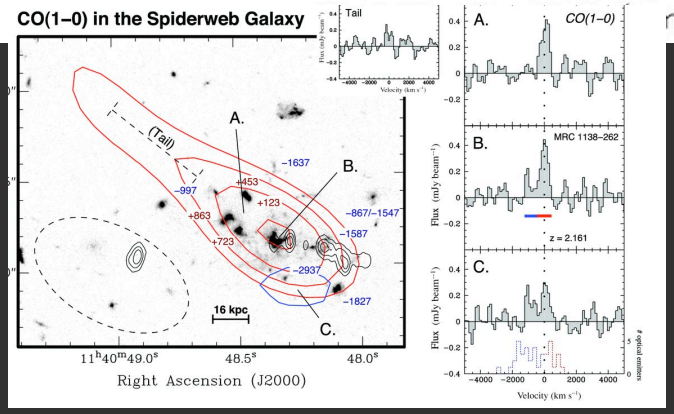
Scaling up from Stephan's Quintet
The Spiderweb Radio Galaxy z = 2.16?

PKS 1138-26 Ogle et al. (2012)

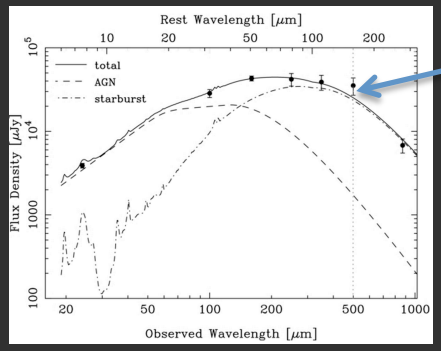
3.7 x 10^{10} $L_{\odot}$ in 0-0 S(3) line alone!



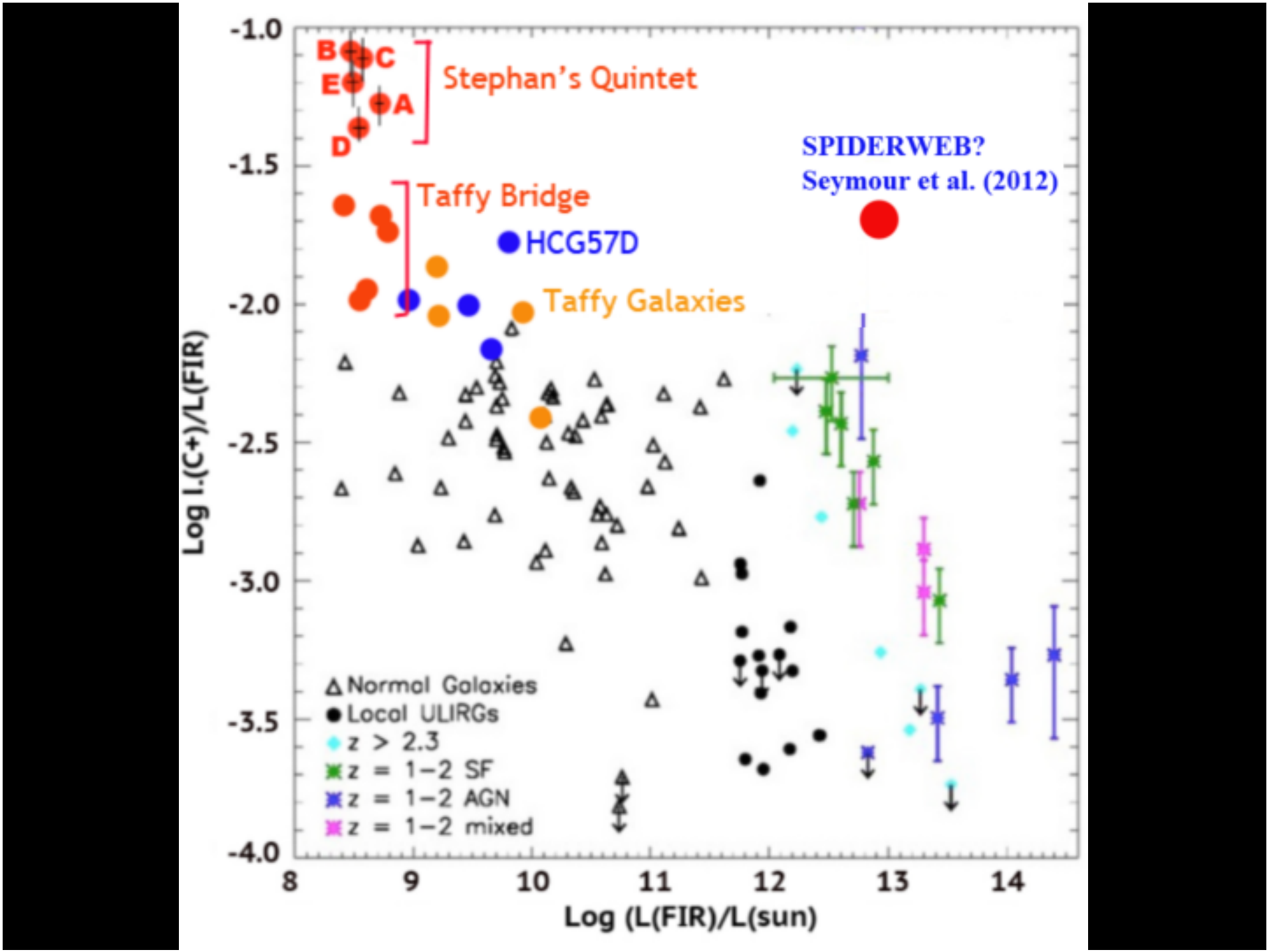




Emonts et al. (2013) ATCA CO



Seymour et al. claim Detection of [CII] with C+/FIR = 2% based on SED detection. Could some of this be shocked gas??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SPIDERWEB?
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Normal Galaxies
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z > 2.3
z = 1–2 SF
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Log I.(C+)/L(FIR)
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8
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14

Conclusions

- Observations of giant extragalactic SQ "shock" reveal extreme H2/PAH AND C +/PAH ratios inconsistent with photoelectric heating (no small grains either) extreme values of C+/PAH = 71% IN ONE REGION! Taffy bridge shows similar behavior but less extreme. Large dust to gas ratio changes seem evident.
- C+/FIR also boosted to extreme edge of PDR models (7%)-Metallicity is not a factor in either SQ, Taffy nor HCG 57D
- Preliminary studies of H_2-enhanced HCG systems suggest peculiar kinematics in some systems which may be related to shock heating? Optical IFU follow up may also help determine where shocks are dominant.
- High C+/PAH and C+/FIR found in collisional systems which require ADDITIONAL HEAT SOURCE for Spitzer WARM H2. SOURCE OF HEATING OF C+ LIKELY WARM H_2 itself!
- Shock or Turbulence is VIABLE heat source C+—warm diffuse gas can look a lot like diffuse PDR but without enough UV (or/CR/Xrays)
- Kinetic energy dissipation may be an important source of C+ emission in massive protogalaxy systems at high-z but may well be masked by star formation effects. Future observations by SPICA and JWST may help.