Probing the State of Shocked Gas in Compact Group Galaxies

Phil Appleton

NASA Herschel Science Center

Caltech

With vital contributions from:

Pierre Guillard (IAP, Paris), Aditya Togi (U. of Toledo)

Katey Alatalo (Carnegie), Theo Bitsakis (UNAM), Guillermo Blanc (Chile)

Emily Freeland (U. of Stockholm)

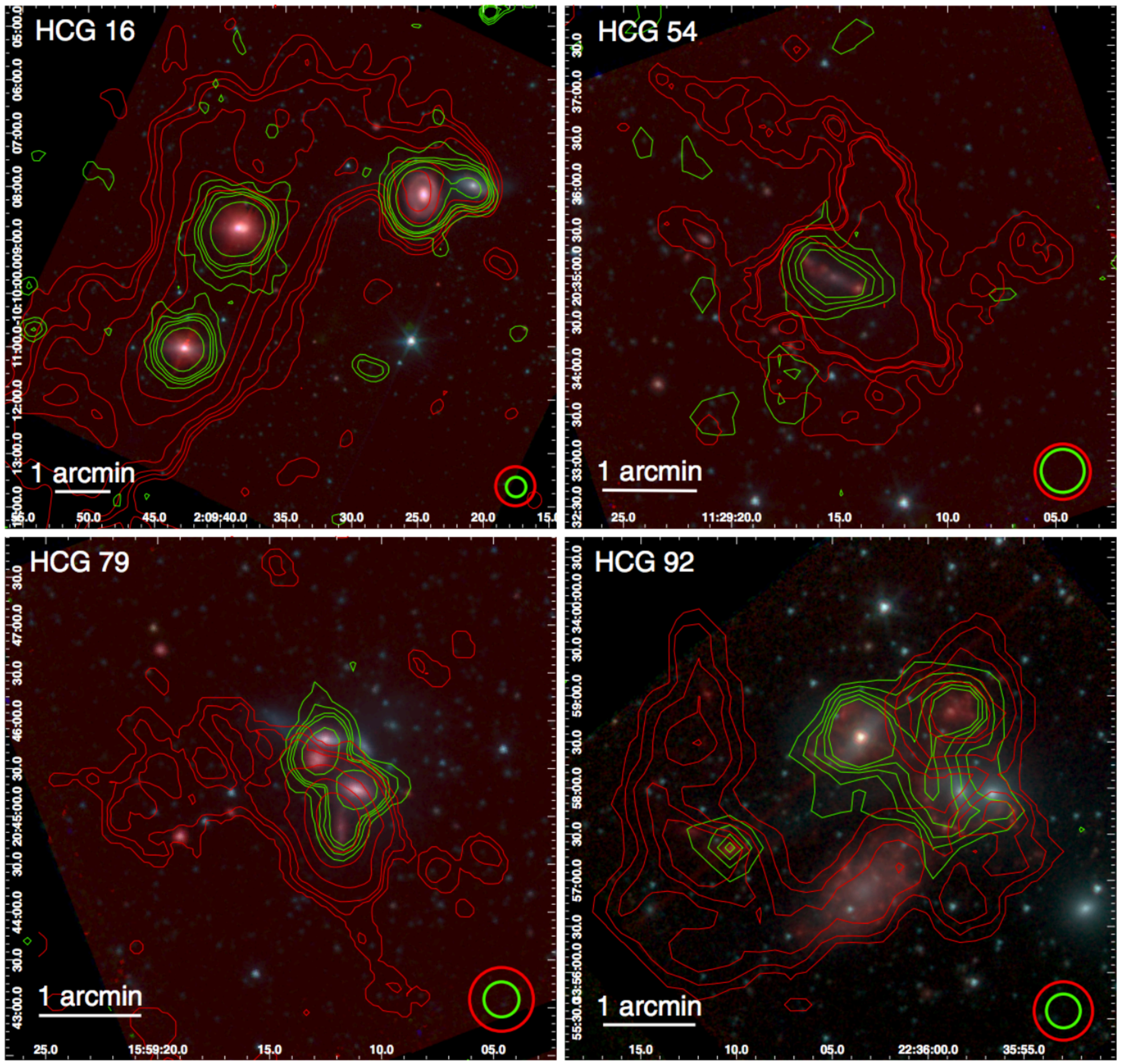
Michelle Cluver (U. of Western Cape), Ute Lisenfeld (Granada)

Vassilis Charmandaris (U. of Crete and Athens Obs),

Francois Boulanger (IAS, Paris), Pierre-Alain Duc (Saclay),

Min Yun (UMASS), Lourdes Verdes-Montenegro (Granada)

Groups are not isolated systems



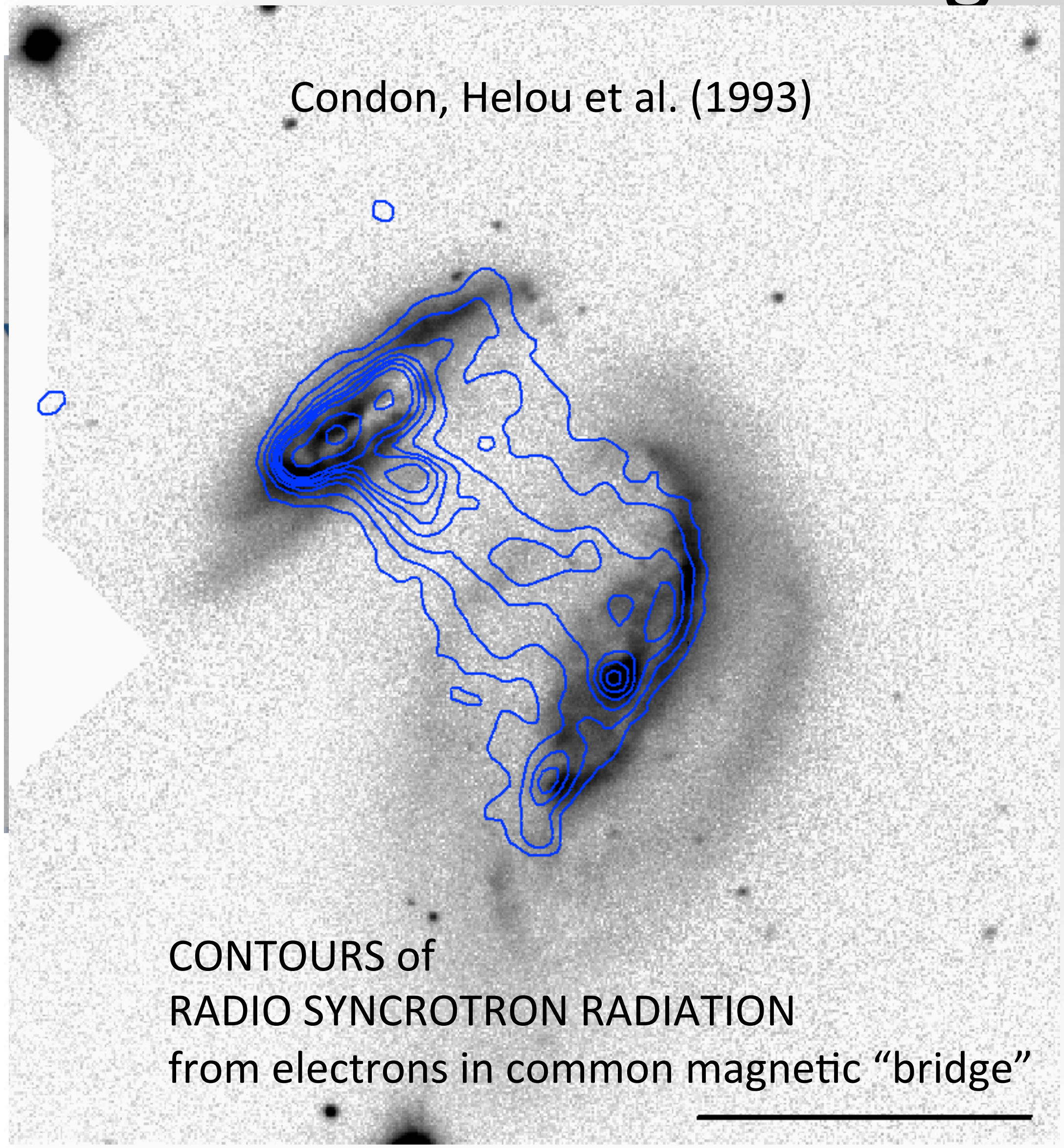
Bitsakis+14

Fair_IR Dust and HI

What this talk is about

- Shocks and Turbulence in few nearby shock-dominated systems
  – Stephan's Quintet, Taffy and Bridge
- Searching for clues as to the main heating source for warm H_2 in Group MOHEGs
  – Herschel and Optical IFU probes of gas excitation in a small sample of MOHEGs
- Can these effects suppress star formation and for how long? Are the MOHEG groups cause or effect?

Two well studied examples are in diffuse intergalactic gas!



1) The Stephan’s Quintet Compact Group

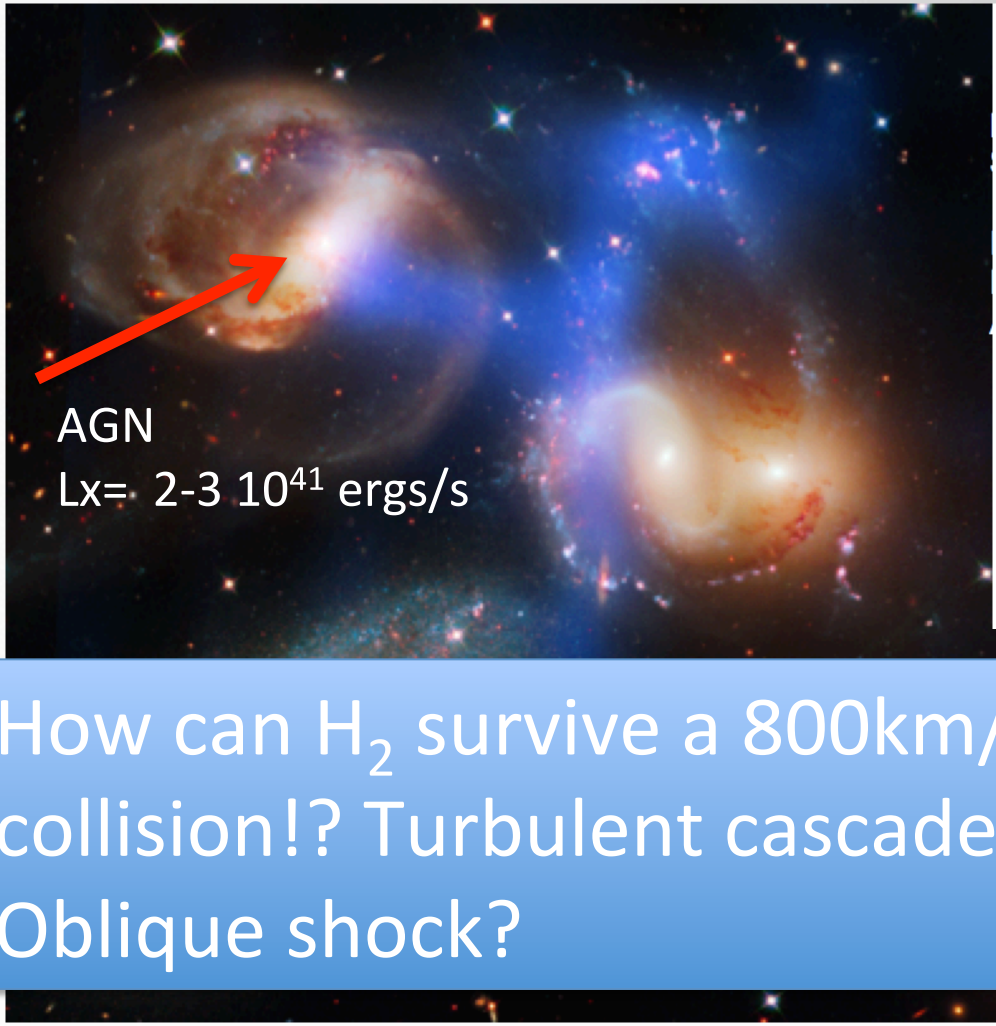
2) The Taffy Galaxies and Bridge

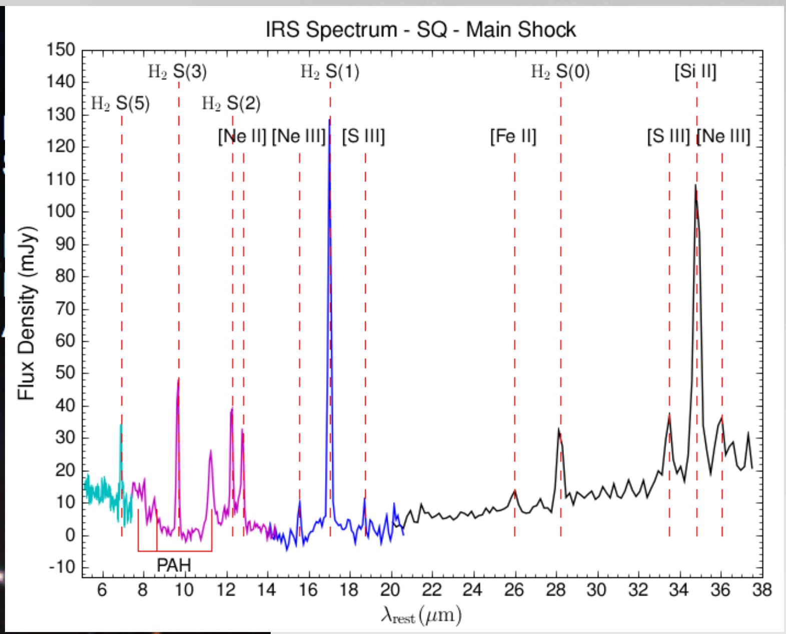
Galaxies having passed “ghost-like” through each (at over 600 km/s) other and have splashed gas into a bridge! (see later).

FAILED ULIRG? Or Pre-ULIRG?

Warm Molecular gas in Stephan's Quintet dominates cooling in giant shock

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





How can H_2 survive a 800km/s collision!? Turbulent cascade? Oblique shock?

H_2/PAH_tot Huge (10-110%!)

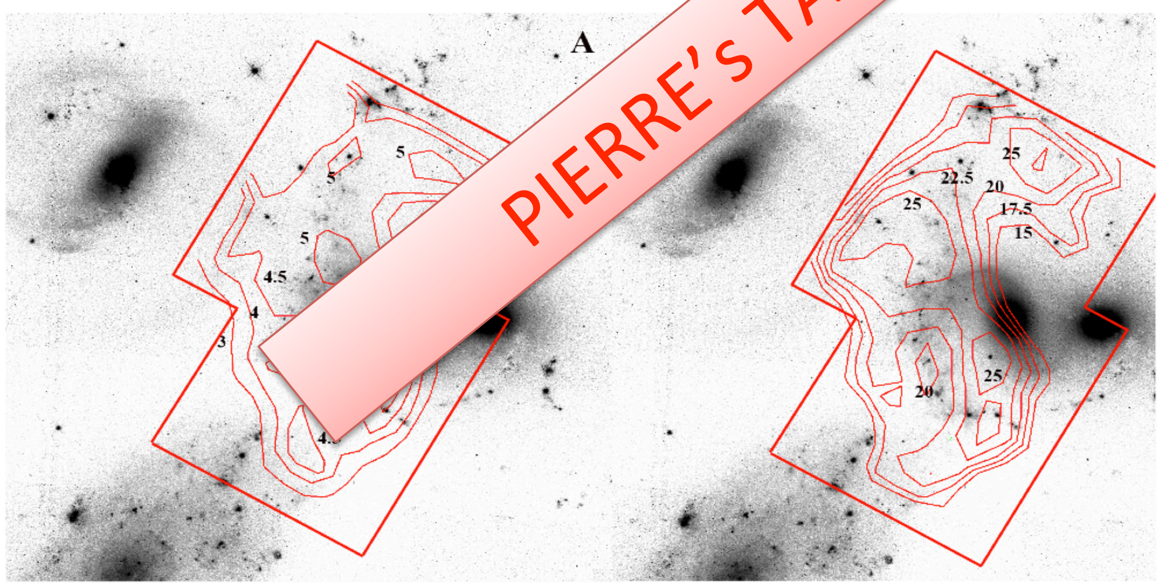
H_2/FIR > 10% in some regions

H_2 dominates cooling

We can fit the H_2 excitation with a physical shock model (Pierre's talk)

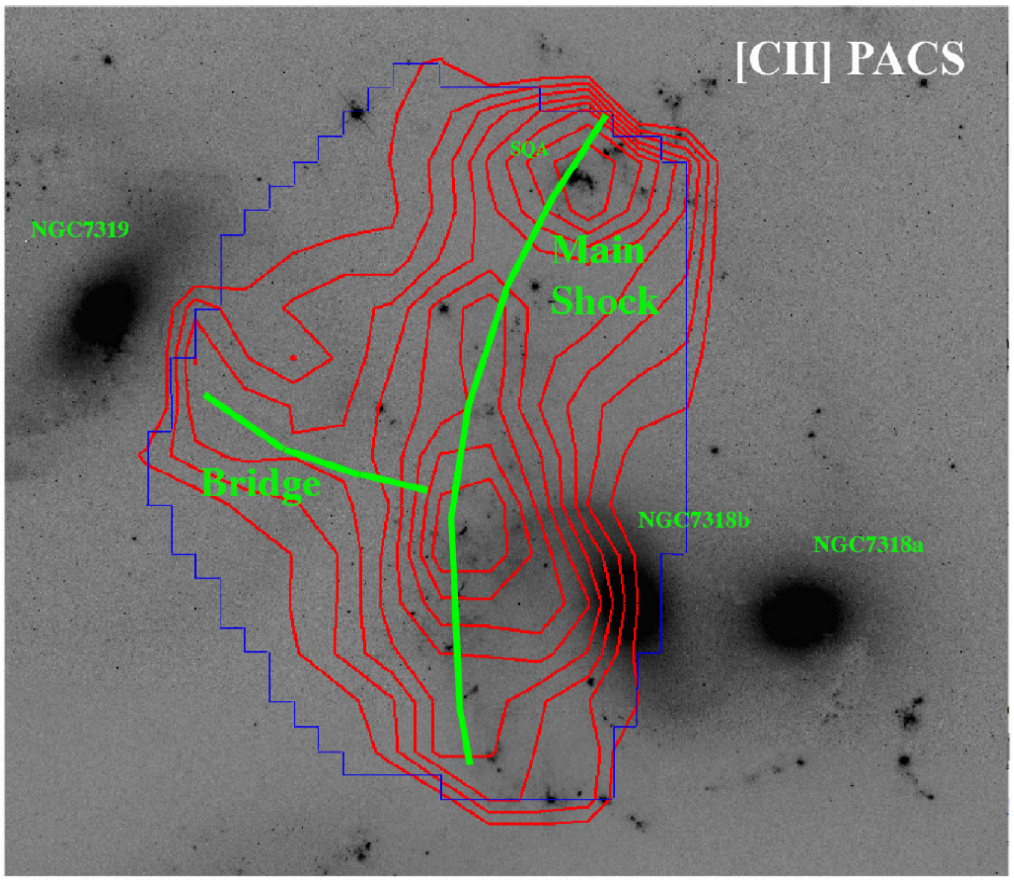
Guillard+09; Appleton, Guillard, Togi [illegible] 017)
(Guillard+16 based on models of [illegible] e_13)

PIERRE's TALK



(from Appleton, Guillard, Togi+16)

Herschel Observations of C+(157.7μm line) (Appleton and Guillard et al. 2013)



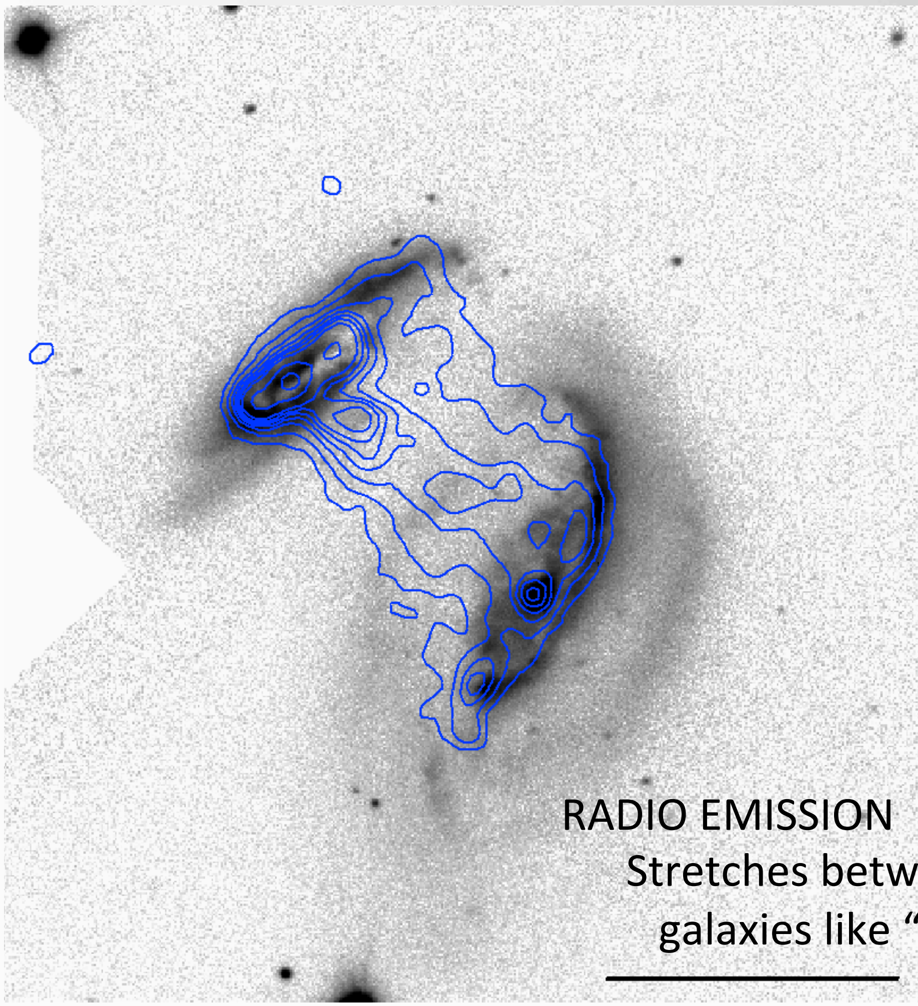
Power in 0-0S(1)17μm
And C+ quite similar

This is exactly what the
magnetic shocks predict
for v = 5 km/s.

Models of Lesaffre et al. 2012
And hints from broad-band
Images from Akari suggested
C+ may be important in SQ.

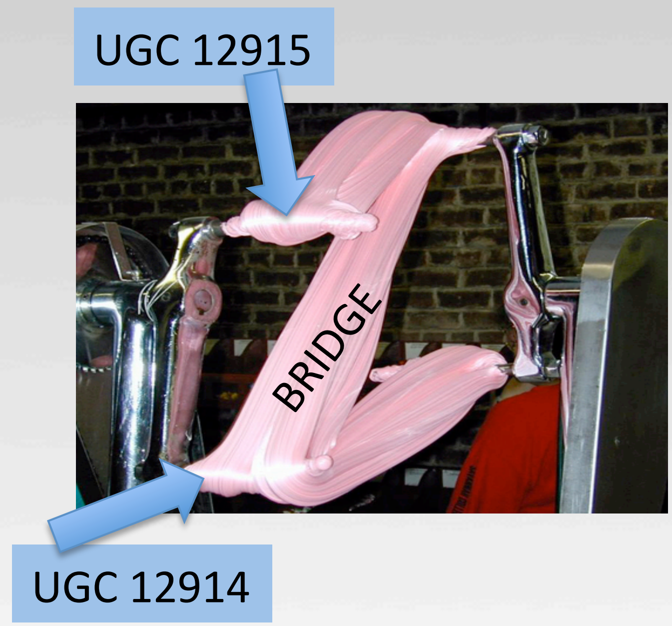
The “Taffy” Galaxies Discovered

- Condon and Helou the 1993

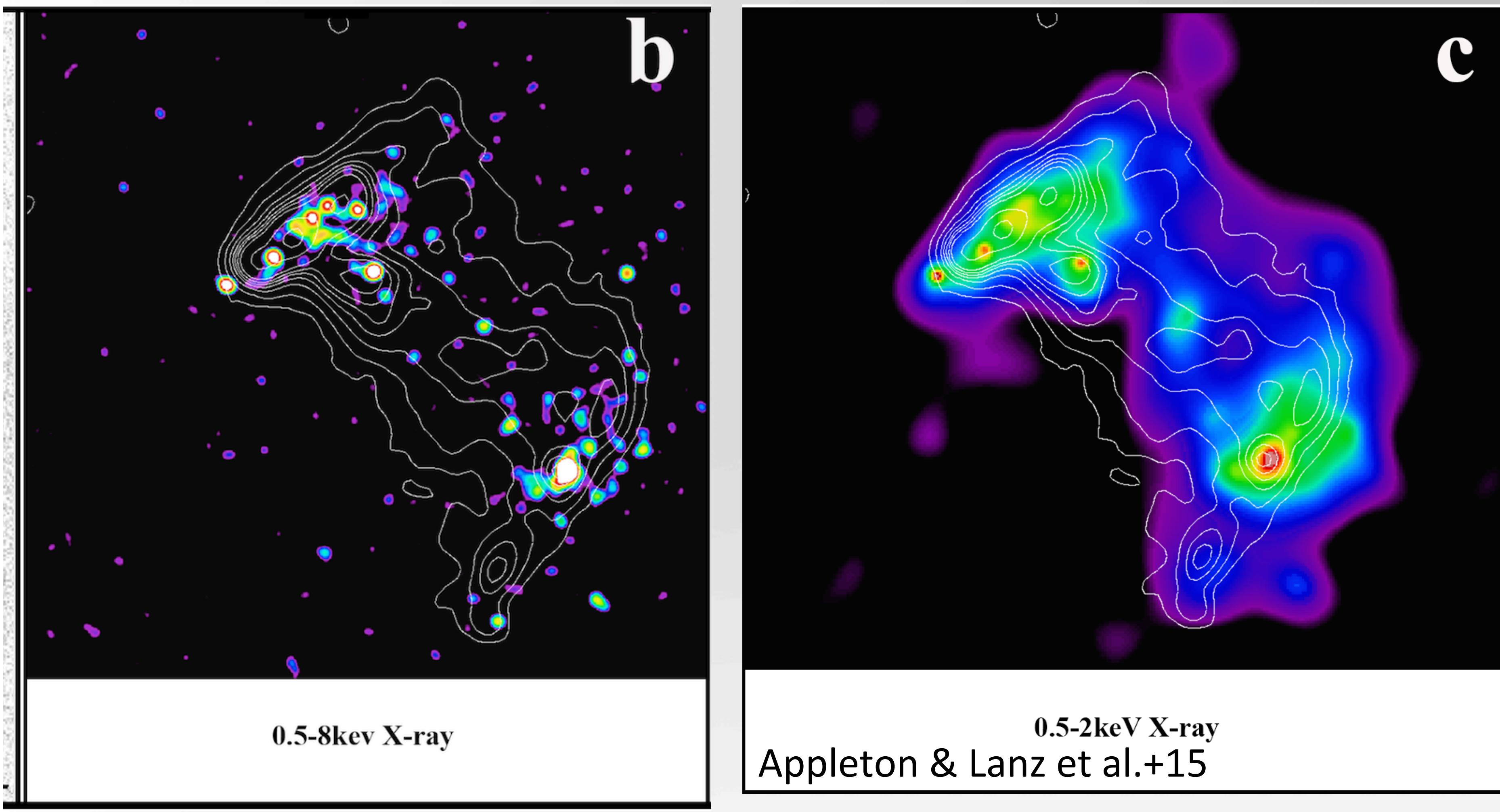


Realistic Simulation

SALT WATER TAFFY

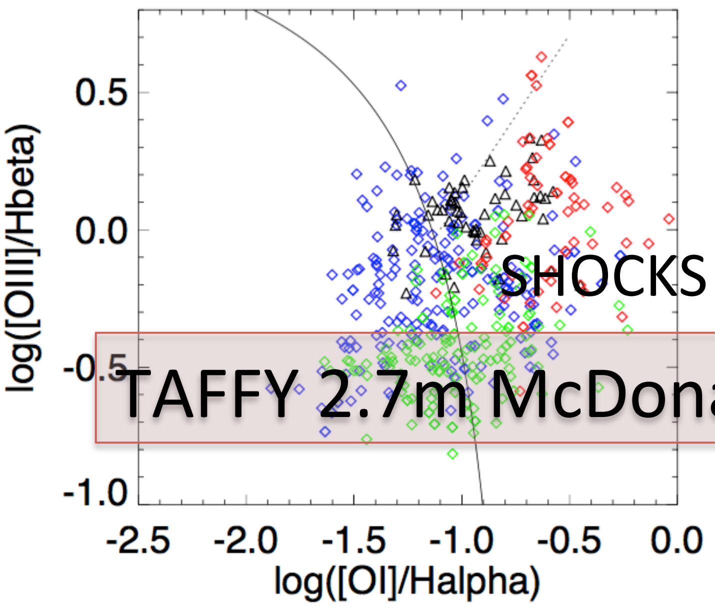


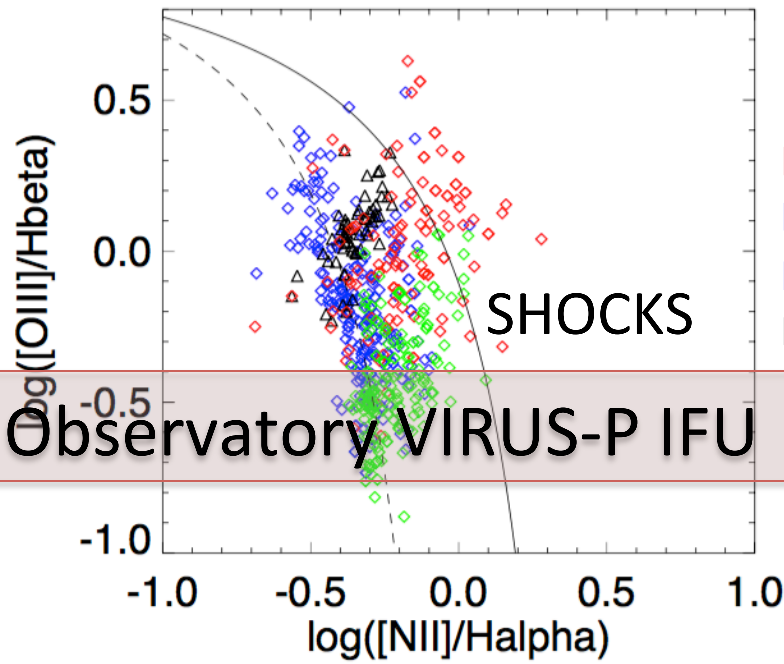
Taffy in X-rays (Soft Extended)



Appleton & Lanz et al.+15

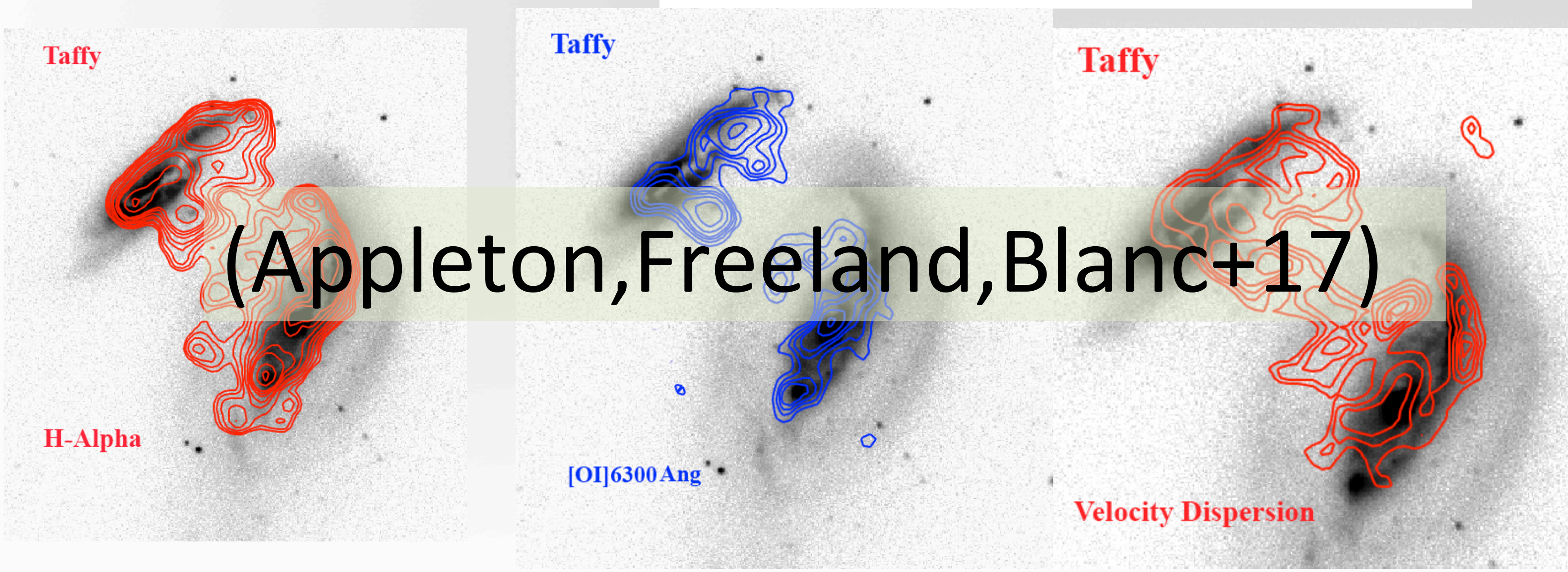
Diffuse X-ray luminosity 1/42 power in L(warm H_2) lines!
X-rays cannot be the source of heating of warm gas





RED=BRIDGE
Blue/green
N S Galaxies
Black=XHII

TAFFY 2.7m McDonald Observatory VIRUS-P IFU



(Appleton,Freeland,Blanc+17)

What could heat ~ $10^9\ M_\odot$ of H_2 to 150-700K and keep it warm for tens of millions of years?

- Photo-electric heating from PAHs and small grains bathed in UV from stars?

  NO—H_2/PAH ratios too high!

- Heating from X-rays or Cosmic Rays?

  NO --$L(H_2)/L(x)$ to high; Not enough X-rays!!

  Cosmic Rays may be important in MOHEG radio galaxies, but not in SQ and Taffy (Guillard++12)

- Shocks and Turbulence?

Likely: Plenty of available energy from galaxy collisions—but initially not proven…

How can we test?

Extension to a larger sample of Hickson Compact Groups

We have studied a dozen HCGs with

Sample: Drawn from 24 HI deficient compact groups (78 galaxies) from Cluver et al. (2013).

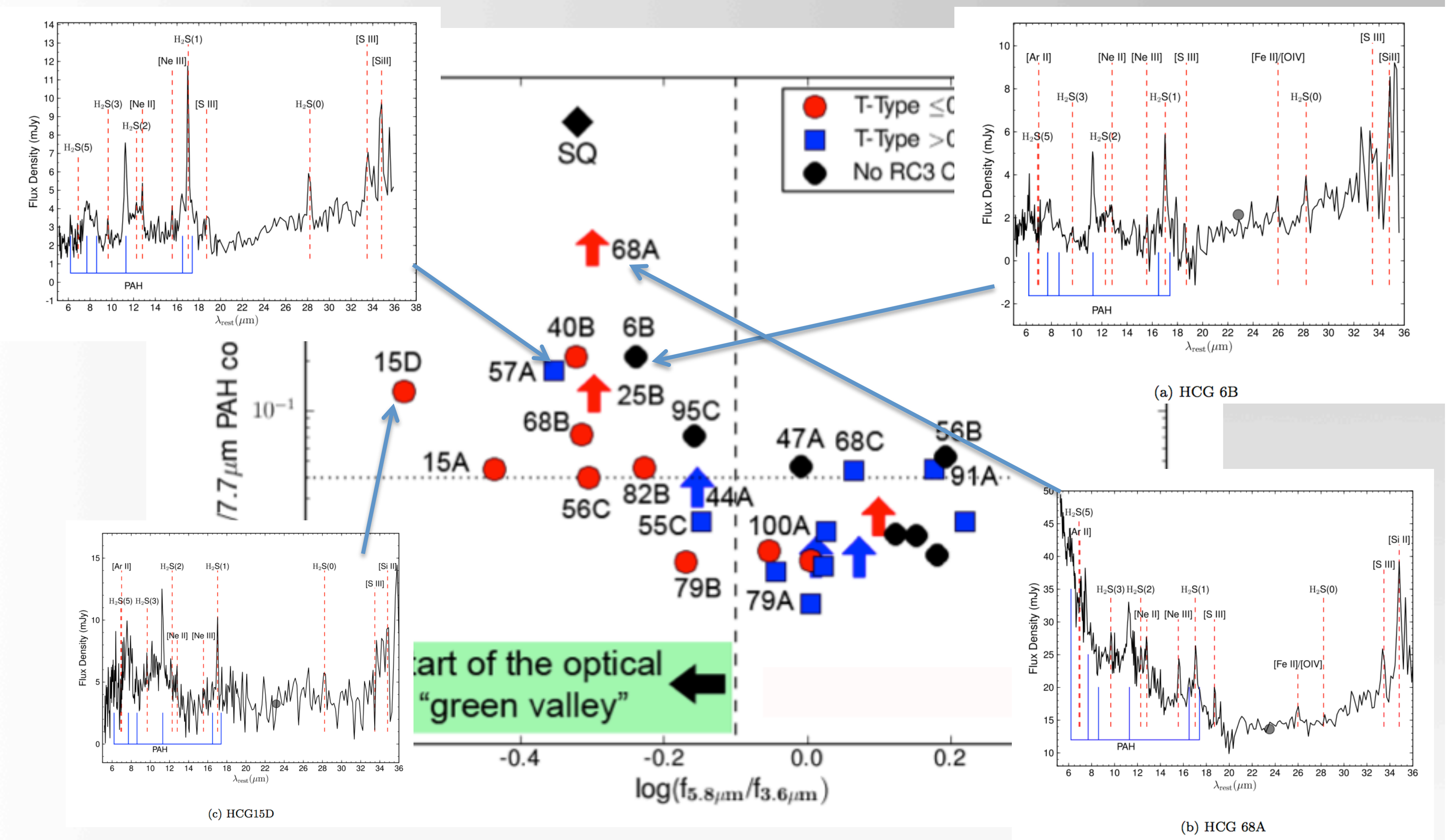
Herschel **PACS IFU Spectrometers (In [CII]157μm and [OI]63μm**

CARMA/PdB CO 1-0 mapping (Alatalo & Appleton+15 for CO results)

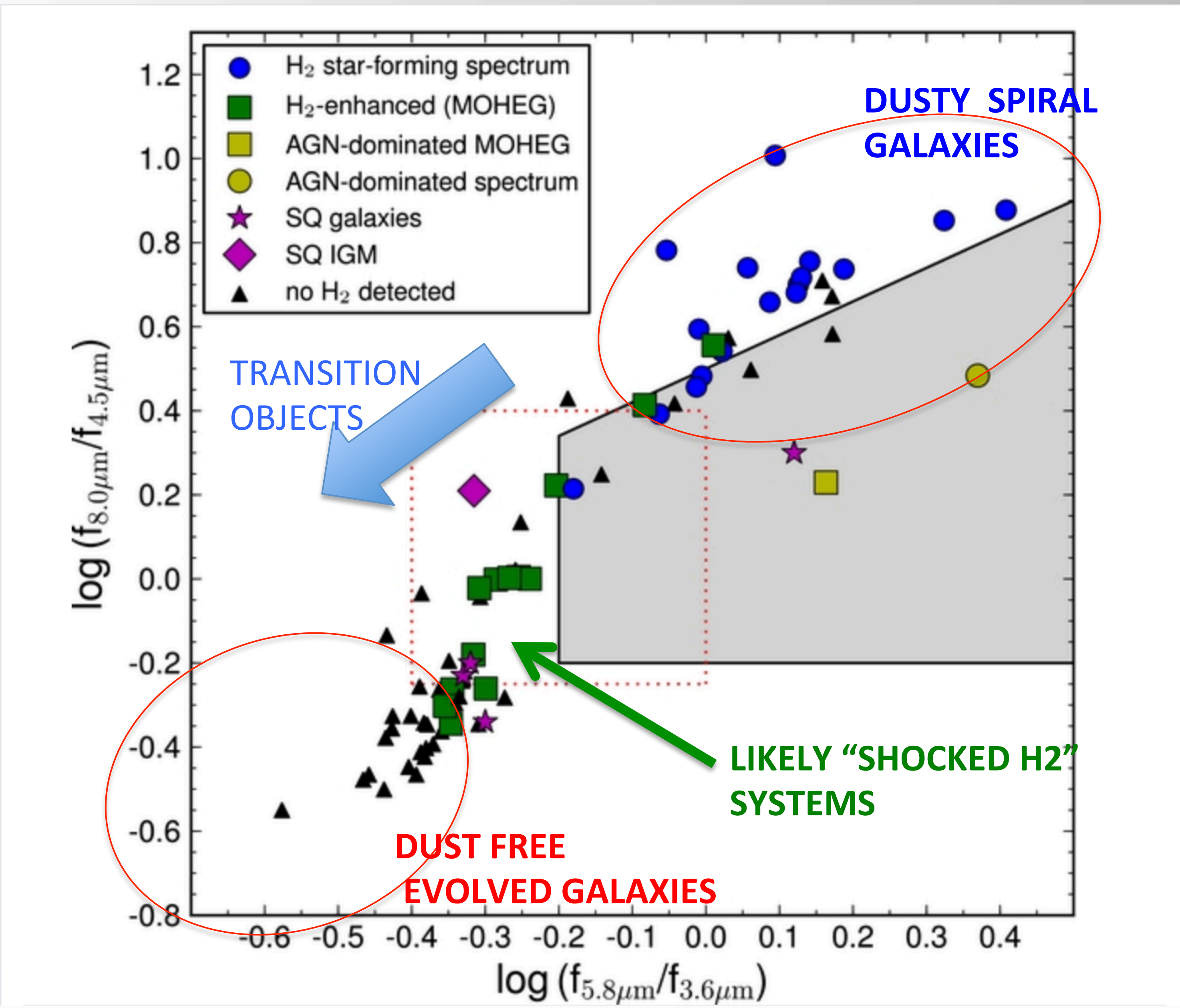
2.7-m McDonald Obs Optical IFU (VIRUS-P) mapping of bright emission lines

HCG with Extreme H_2/PAH ratios

(Ogle defines a MOHEGs L(H2/PAH> 0.04)



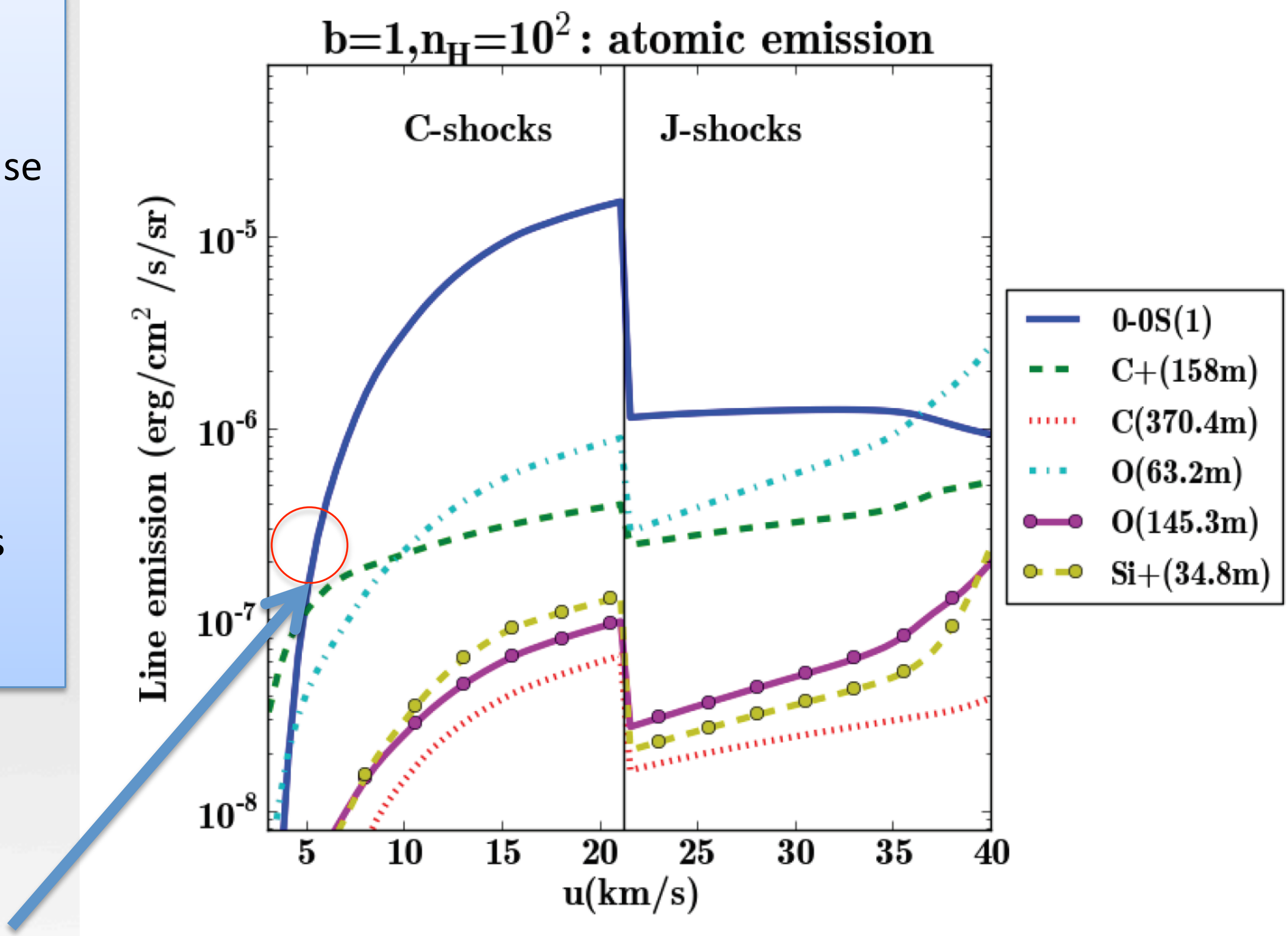
Warm H_2 Galaxies (MOHEGS) lie in IRAC Color Valley



Additional constraints come from model that incorporate both H_2 and far-IR cooling lines: Predictions; Flower & Pineau des Forets+10: Lesaffre+13

Magnetic C-shocks
MHD Molecular gas
PAHs, atomic and mole
Gas in presence of diffuse
UV radiation

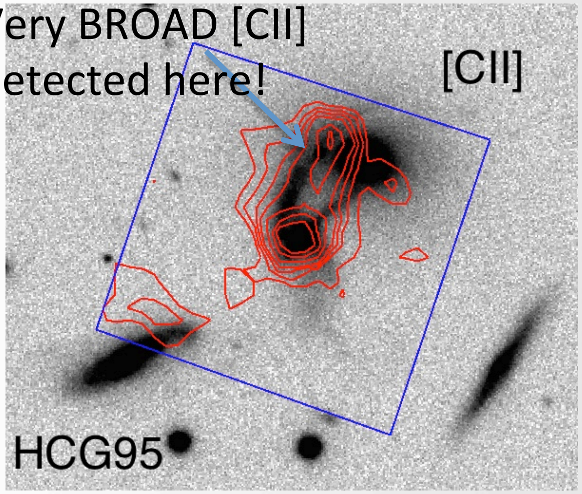
PREDICTS STRONG H2
And shock-heated C+
Emission
[OI]63 dominates in
higher-velocity J-shocks

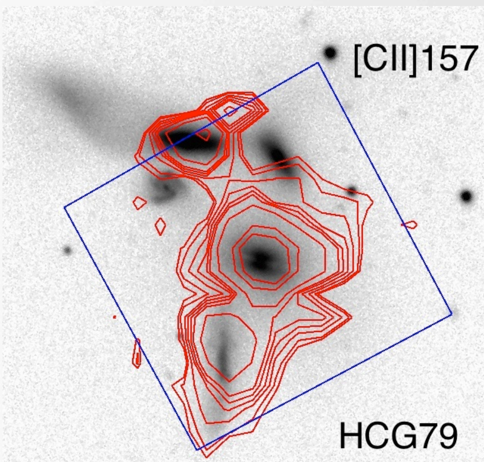


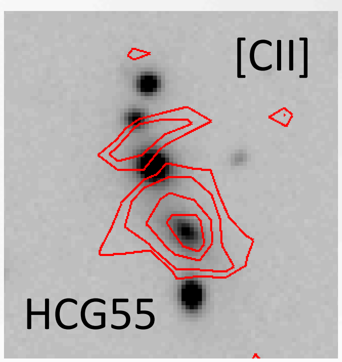
0-0S(1) H2 and C+ equal in low velocity shocks

PACS
[CII] 157.4

HERSCHEL

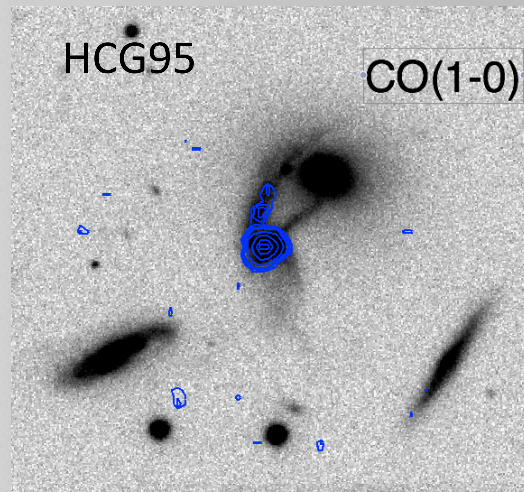


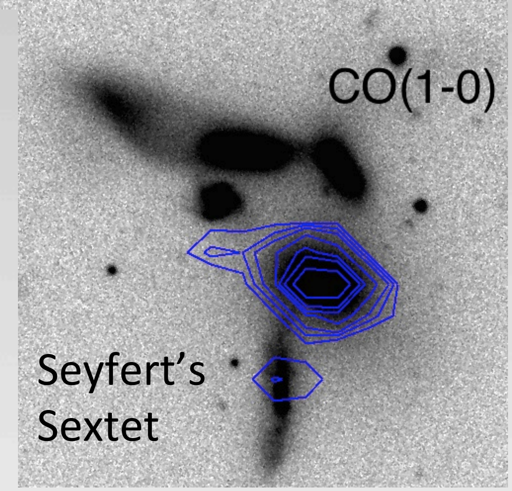


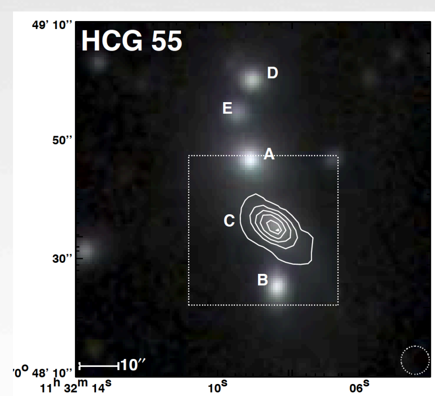


CO 1-0

CARMA

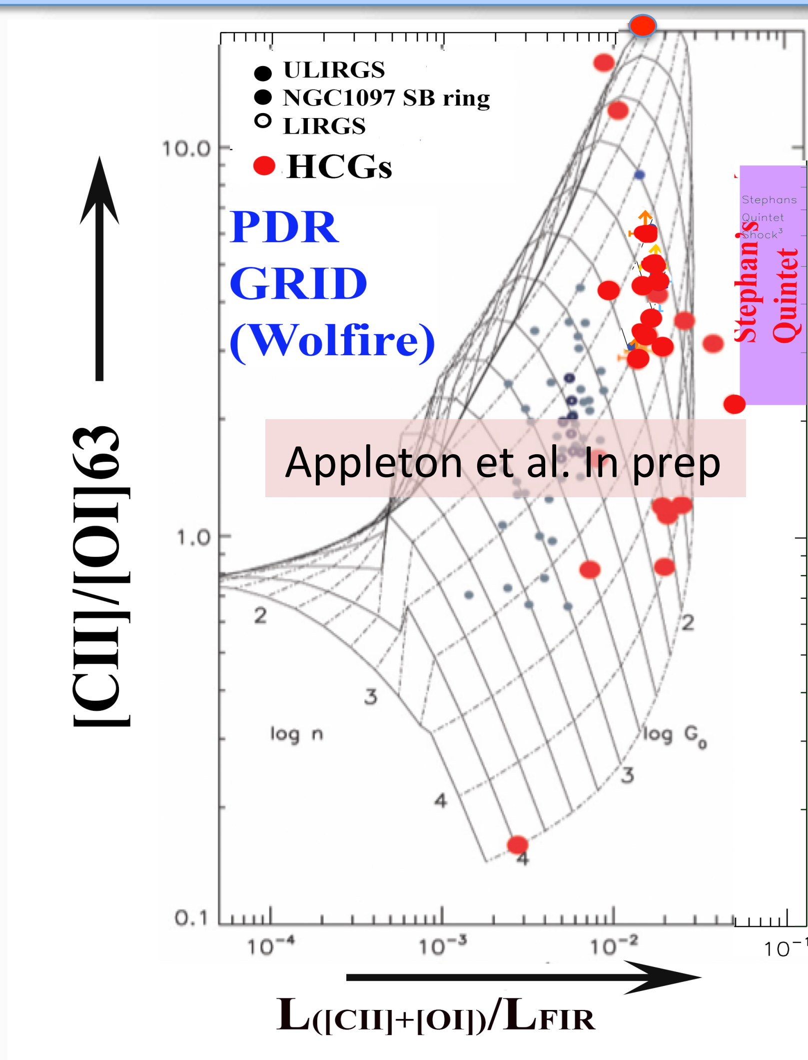






SOME EXAMPLES

Far-IR Fine Structure lines can provide a diagnostic of diffuse gas conditions
How strong is the cooling through C+157μm and [OI]63μm?



The FIR can allow another view of the diffuse ISM. (e. g. comparisons with L_FIR and L_PAH

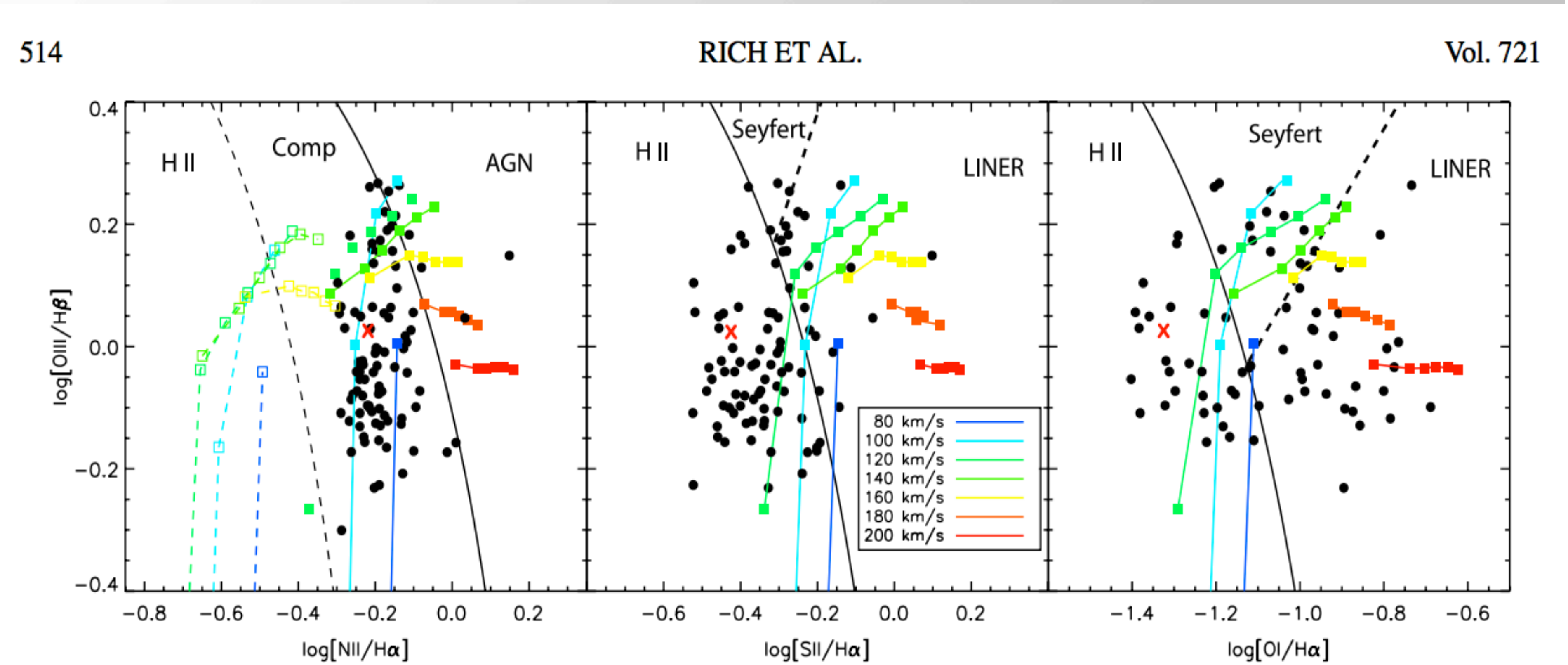
Although many systems
look like low-density PDR systems
--shocks can produce conditions similar to low-density PDRs

OPTICAL IFU VIRUS-P 2.7-m McDonald Observatory Telescope

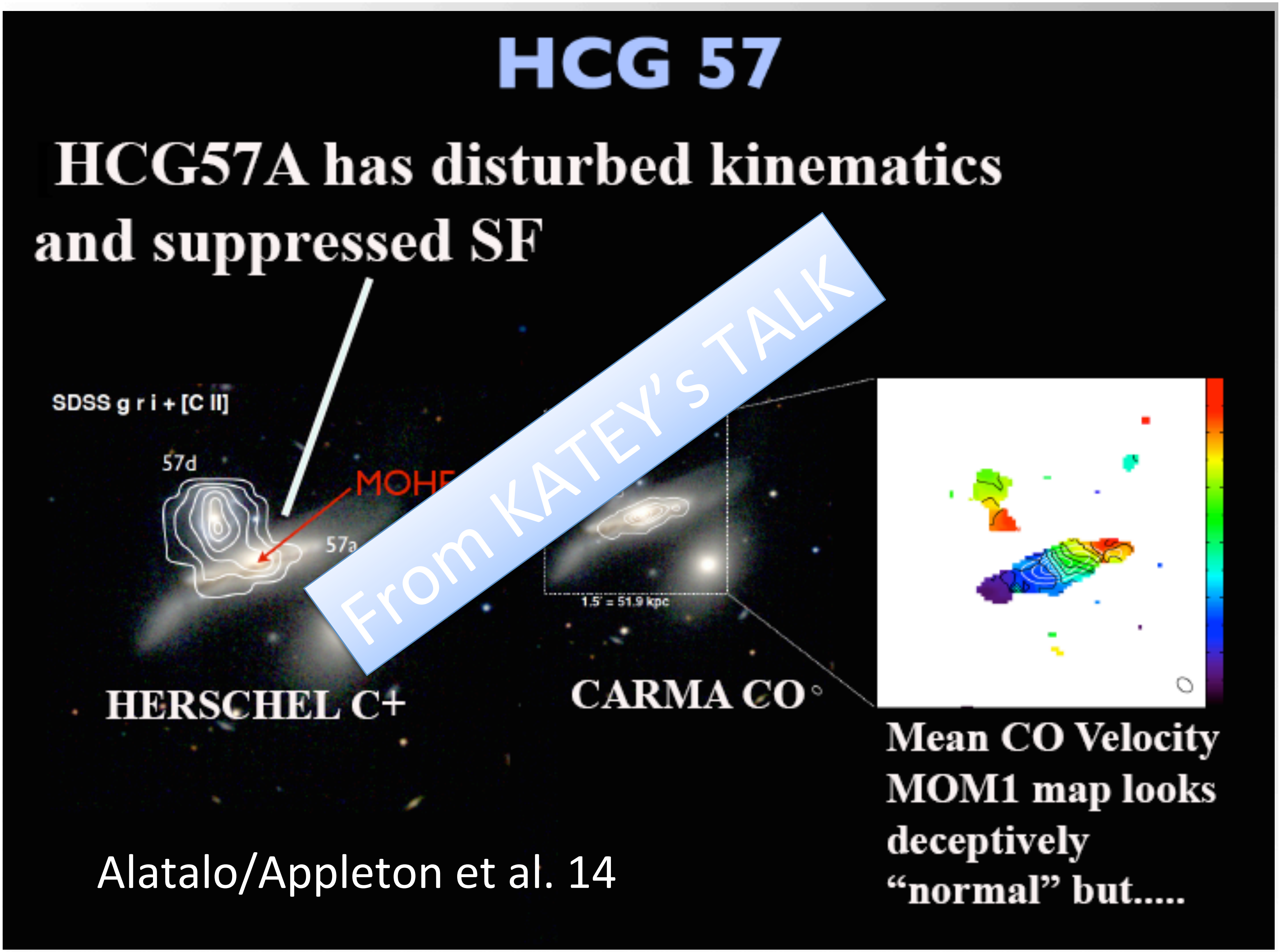
(with Emily Freeland formerly of Texas A&M)

Here are some small examples of MOHEG HCG Galaxies
More coming soon

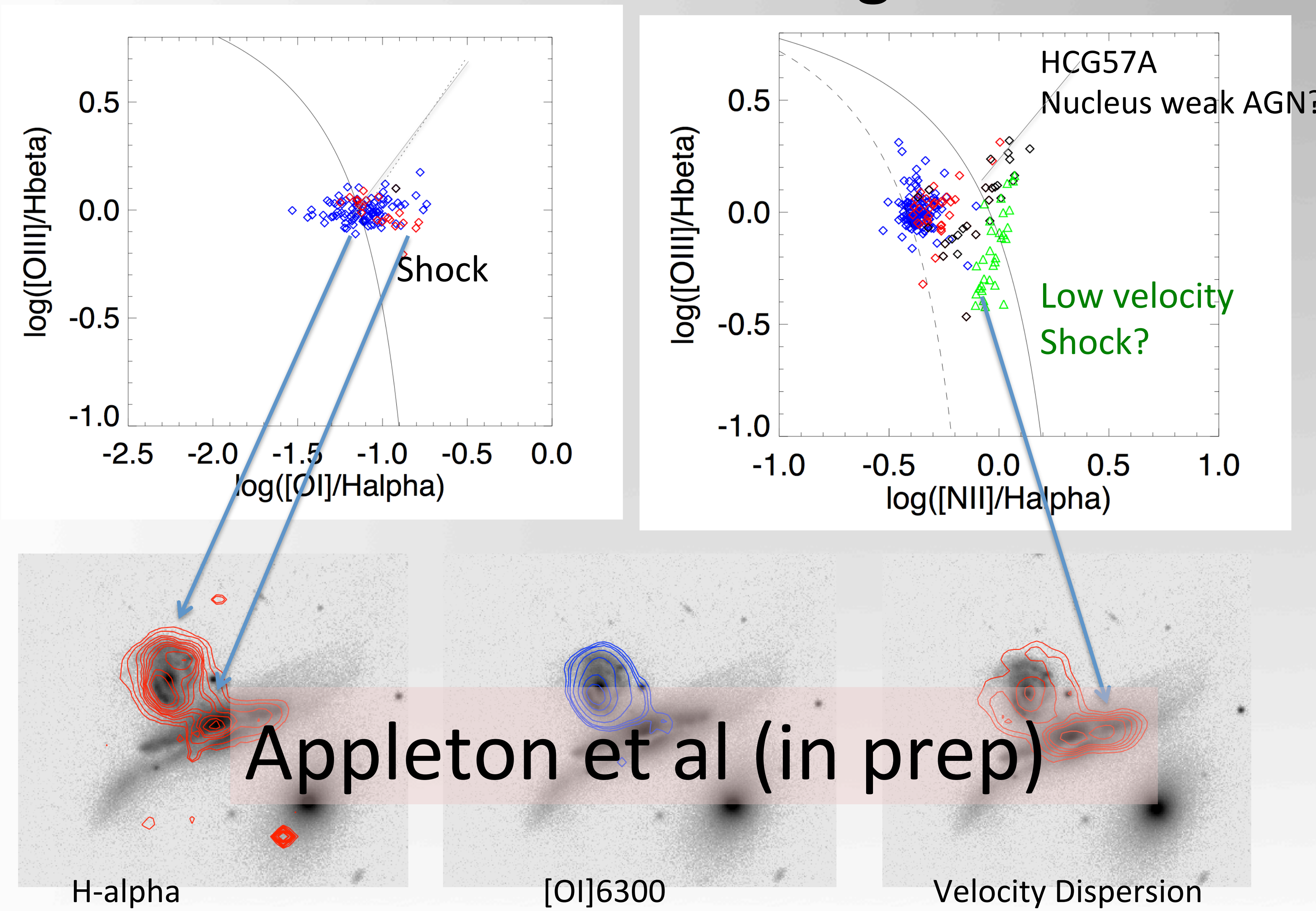
Optical Gas Excitation Diagnostics Evidence of fast shocks (100-300 km/s)



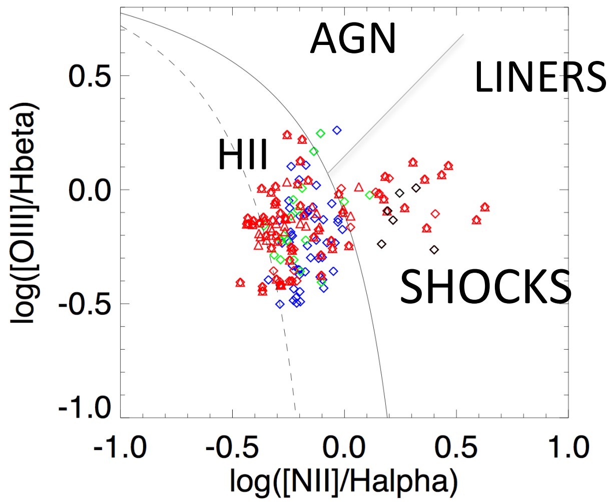
The same diagram can be used to diagnose shocks (Black dots are Is the superwind in LIRG NGC 389) (e. g. Rich et al. 2010) (Using Mappings III and assuming B=5μG, nc=10cm-3 Z=1 to 2) (Dopita and Sutherland, 1993)Pure radiative shock L ~k Vs^3 but much of energy comes in UV –see later! Only 1-5% in visible lines. Dots indicate assumed pre-ionization level.

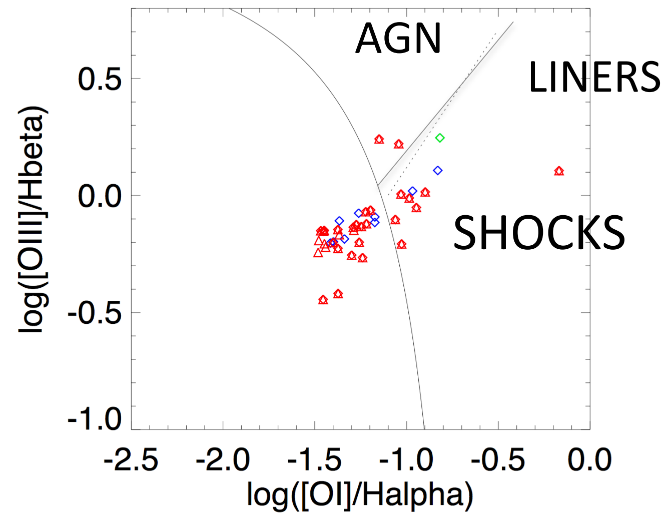

HCG 57
HCG57A has disturbed kinematics and suppressed SF
SDSS g r i + [C II]
57d
57a
1.5′ = 51.9 kpc
HERSCHEL C+
CARMA CO
From KATEY's TALK
Mean CO Velocity MOM1 map looks deceptively "normal" but.....
Alatalo/Appleton et al. 14

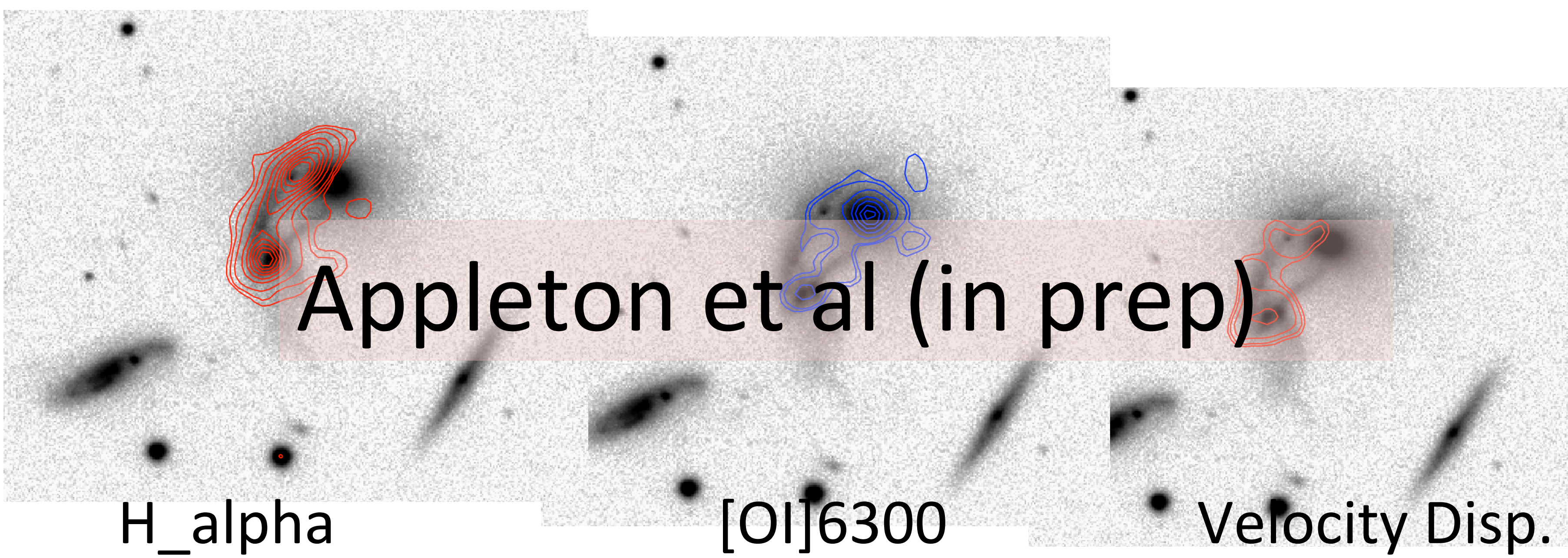
HCG57 Visible Light



HCG95C


AGN
LINERS
HII
SHOCKS
0.5
0.0
-0.5
-1.0
log([OIII]/Hbeta)
-1.0
-0.5
0.0
0.5
1.0
log([NII]/Halpha)


AGN
LINERS
SHOCKS
0.5
0.0
-0.5
-1.0
log([OIII]/Hbeta)
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
log([OI]/Halpha)


Appleton et al (in prep)
H_alpha
[OI]6300
Velocity Disp.

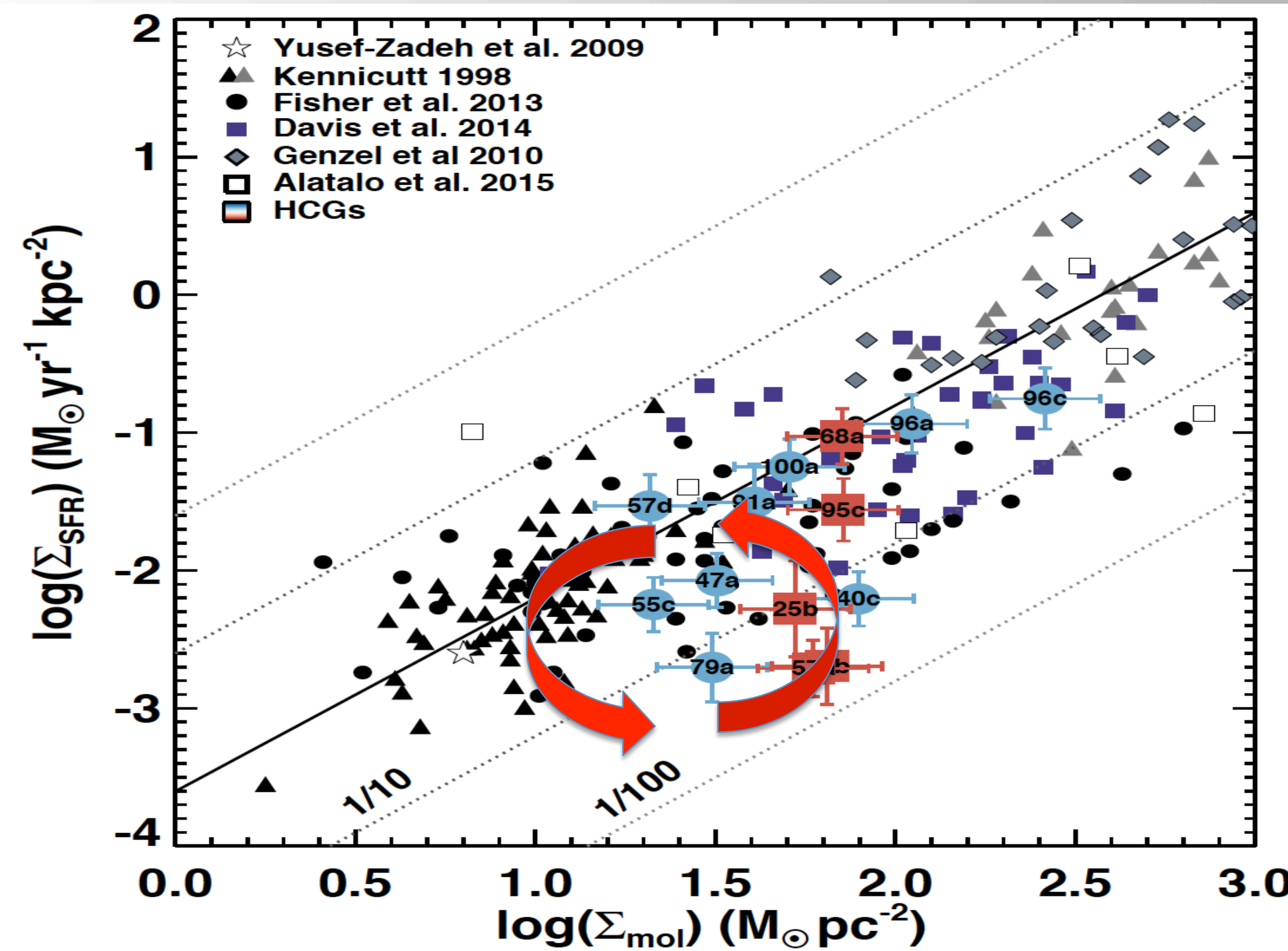
Summary of Optical IFU Study

Work is ongoing but so far:

1) We are finding optical IFU data shows MOHEGS systems contain shocked gas correlated with high velocity dispersion
   Evidence of shocks (Rich+10)—not always 100% correlated with warm H_2? More analysis is needed)
2) Some systems show enhanced C+ emission that is not consistent with PDR models
   --shocks/turbulent heating of H_2>>C+
   --could there be enhanced ionized gas?
   --What about the role of HI in C+ emission?

If infall onto central galaxy from tidal tails is both source of gas and heating

- How much mass is involved (Arp 94—see Appleton +13 for similar case)
- Can high infall rates be sustained? Energy rate 1/2 (dM/dt) v_{infall}^2 L(H_2) ~ 10^{40} 10^{42} erg/s in most MOHEGS
- Turbulent dissipation timescales are very short so the process itself must sustain the turbulence and shock heating. H2 cooling times are ~1000 yrs.


Yusef-Zadeh et al. 2009
Kennicutt 1998
Fisher et al. 2013
Davis et al. 2014
Genzel et al 2010
Alatalo et al. 2015
HCGs
log(Σ_SFR) (M⊙ yr⁻¹ kpc⁻²)
log(Σ_mol) (M⊙ pc⁻²)
1/10
1/100
96c
96a
68a
100a
57d
95c
47a
40c
55c
25b
79a
2
1
0
-1
-2
-3
-4
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Take away Summary

Shocks and Turbulence in Galaxy Collisions and Outflows (or inflows) have a complex effect on Multi-phase ISM and IGM of galaxies in Compact Groups

- Can Induce **PHASE TRANSITIONS** (e. g. HI > warm H2 and X-rays (Guillard+09)
- TURBULENT CASCADE can **funnel energy to small scales** and low velocities where most of KE in dissipated
- **Mid-IR H_2 and far-IR cooling (C+ and [OI]) carries away largest power** from shocks allowing measurement of kinetic energy dissipation more directly than less energetically important optical lines and X-ray emission