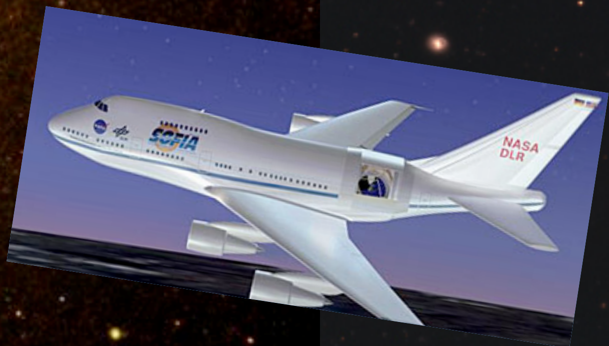
Elusive nature of the ISM and Star Formation in Low Metallicity Galaxies



Suzanne Madden, CEA Saclay, France and contributions from: Vianney Lebouteiller, Diane Cormier, Frederic Galliano, Sacha Hony, Maud Galametz, Aurelie Remy, SPIRE & PACS consortiua

Talk Outline

- Herschel surveys of low metallicity galaxies:
  - What are the goals
  - Herschel surveys: field dwarfs, cluster dwarfs &
  - Magellanic clouds

- Herschel results on dwarf galaxies:
  - PACS & SPIRE Photometry: dust SEDs of dwarfs
  - Herschel PACS spectroscopic results

- Molecular gas inventory in low metallicity gas:
- (CII+ CO) to H2 conversion factor ?

- Where Herschel leaves off –
  - What SOFIA might take over

The Dwarf Galaxy Survey – the Science

1. How do galaxies accumulate their metals?

2. How does the enrichment effect star formation processes?

Dust enrichment in primeval environments <----> essential for enhancement of SF activity

The distribution of dust and their properties ←--→ strongly influenced by SF activity

Understanding the heating and cooling processes in very low metallicity ISM

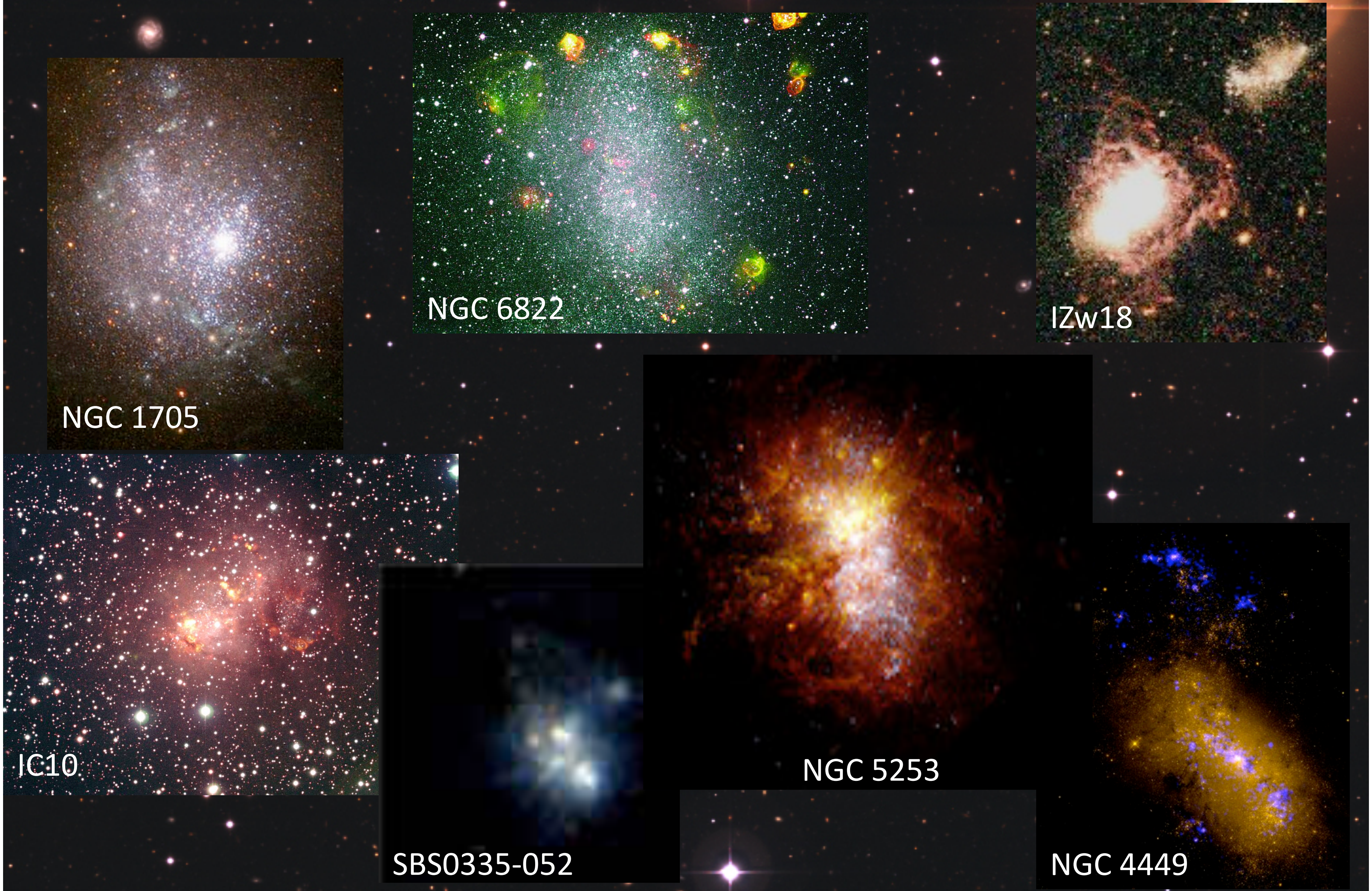
3. What galactic properties and processes control the dust and gas evolution? How are ISM structure, star formation activity, outflows and metallicity related? SEDs?

Local Universe dwarf galaxies are convenient labs to study of the evolution of the dust and gas properties

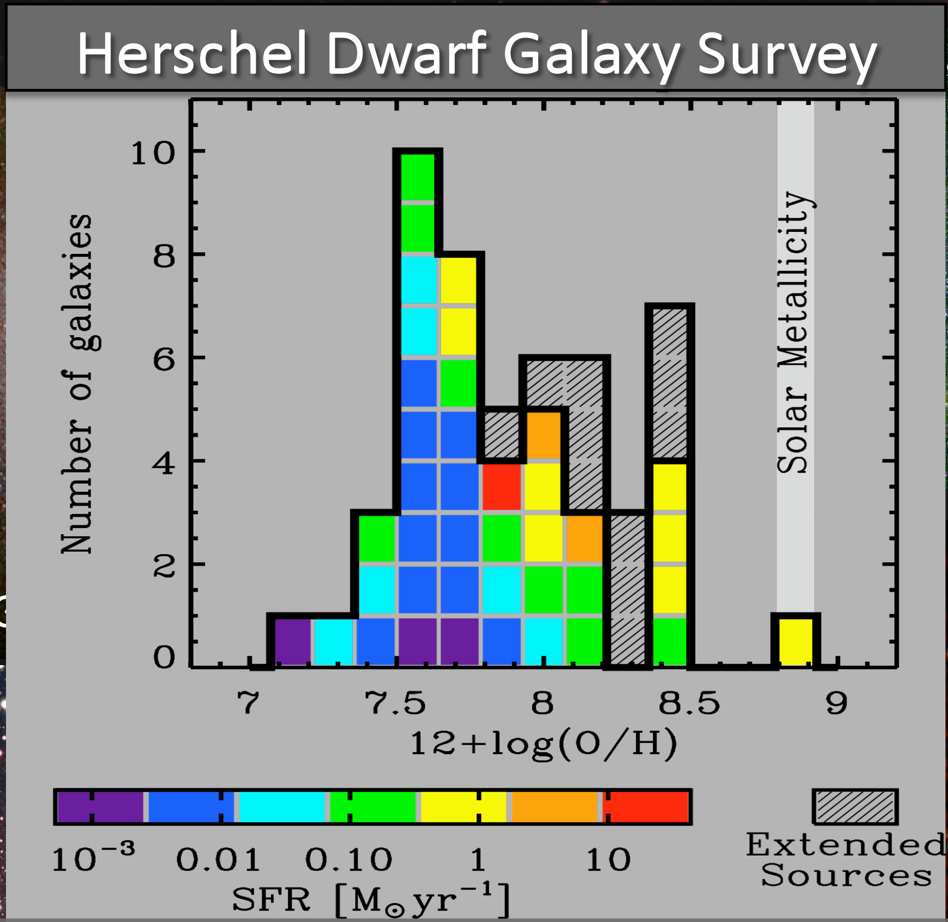
– *Requires a comprehensive program of FIR/submm*

– *photometry and spectroscopy along with other complementary data*

Zoo of dwarf galaxies in the local universe



Zoo of dwarf galaxies in the local universe



Source Selection

55 galaxies

Fill metallicity bins:

~ 5 to 9 galaxies in

7 bins where possible

Extremely low metallicity galaxies: 1/50 to 1/20

The well-known extended galaxies of the local group

All targets: Herschel FIR & submm photometry and FIR spectroscopy.

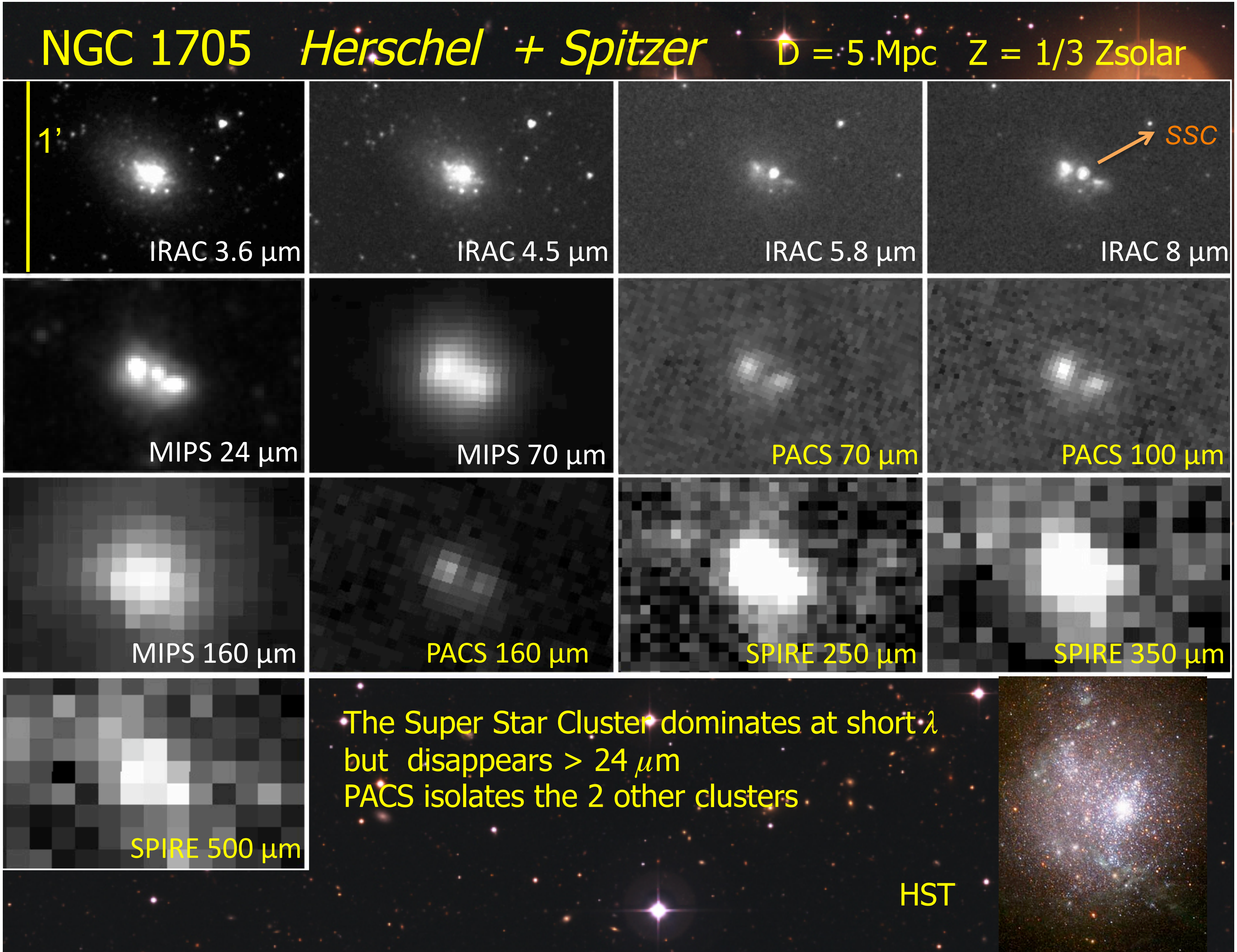
All targets: Spitzer MIR

NGC 5253

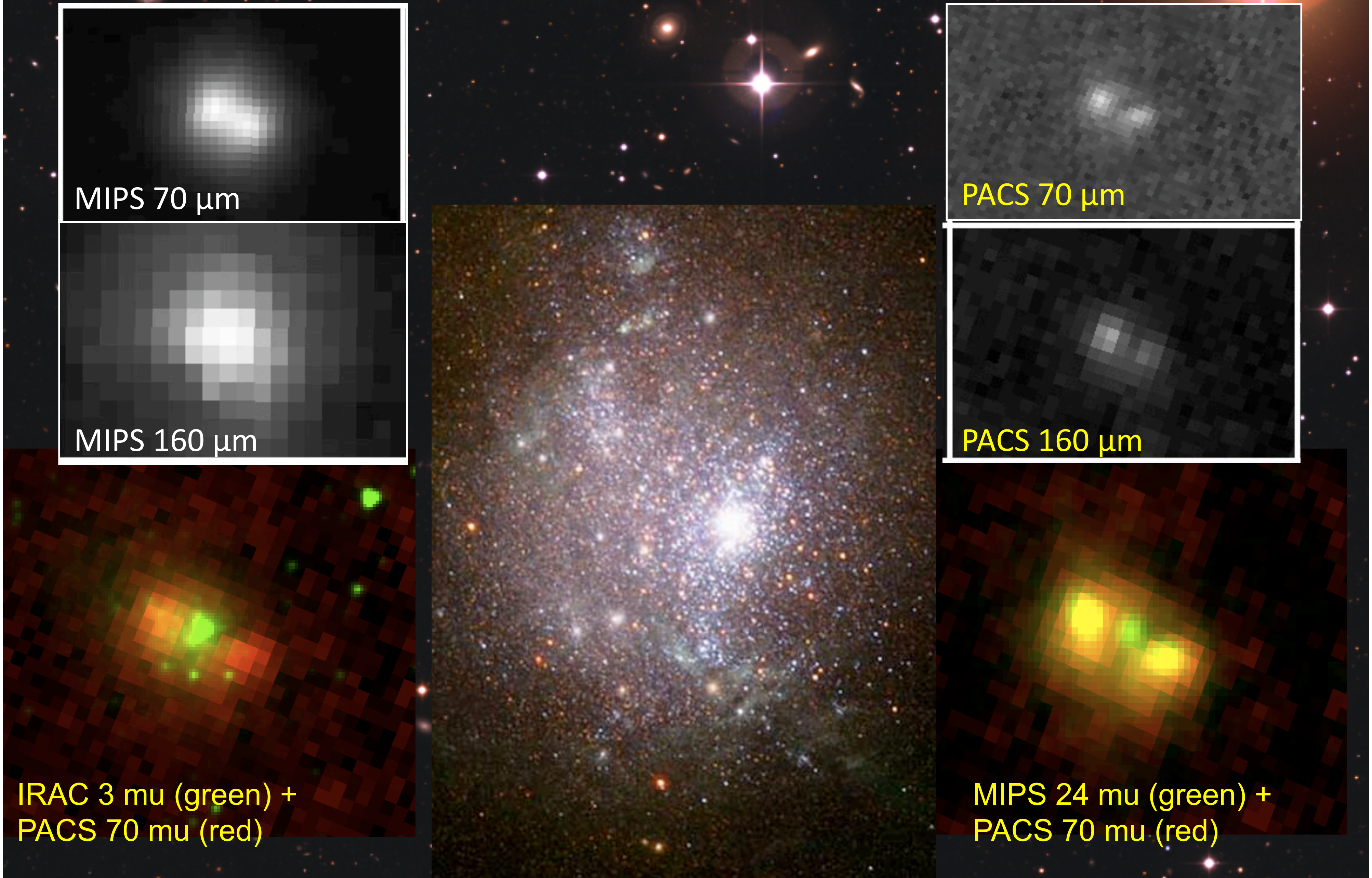
SBS0335-052

NGC 4449

NGC 1705 D = 5 Mpc Z = 1/3 Zsolar


NGC 1705 Herschel + Spitzer D = 5 Mpc Z = 1/3 Zsolar
1'
IRAC 3.6 µm
IRAC 4.5 µm
IRAC 5.8 µm
SSC
IRAC 8 µm
MIPS 24 µm
MIPS 70 µm
PACS 70 µm
PACS 100 µm
MIPS 160 µm
PACS 160 µm
SPIRE 250 µm
SPIRE 350 µm
SPIRE 500 µm
The Super Star Cluster dominates at short λ
but disappears > 24 µm
PACS isolates the 2 other clusters
HST

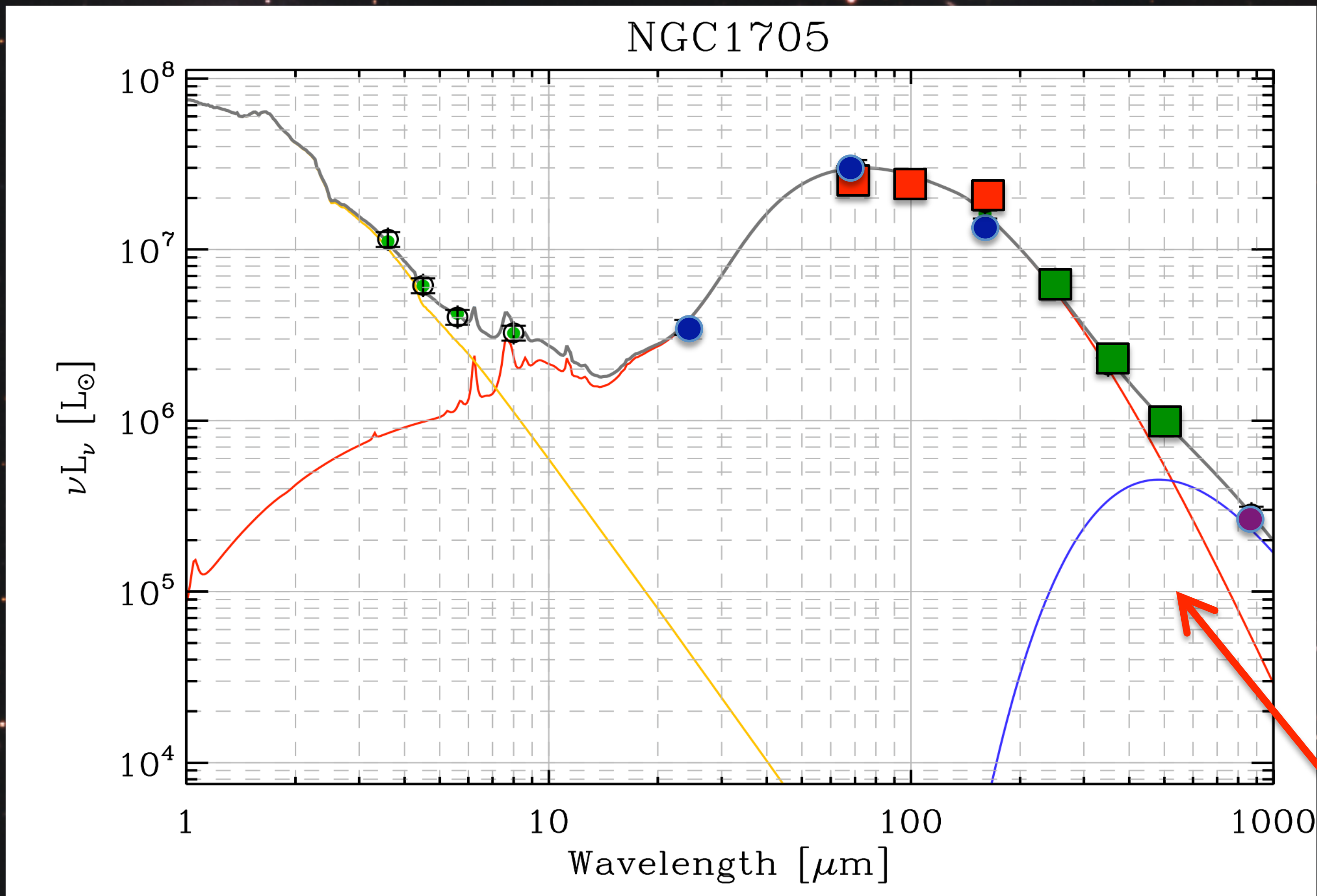
NGC1705: The Spatial Resolution of Herschel and SOFIA



NGC 1705 submm excess:

O'Halloran et al 2010 (see poster)

IRAC + MIPS + PACS + SPIRE + Laboca 870 mu



SED model Galliano et al & Galametz et al 2009

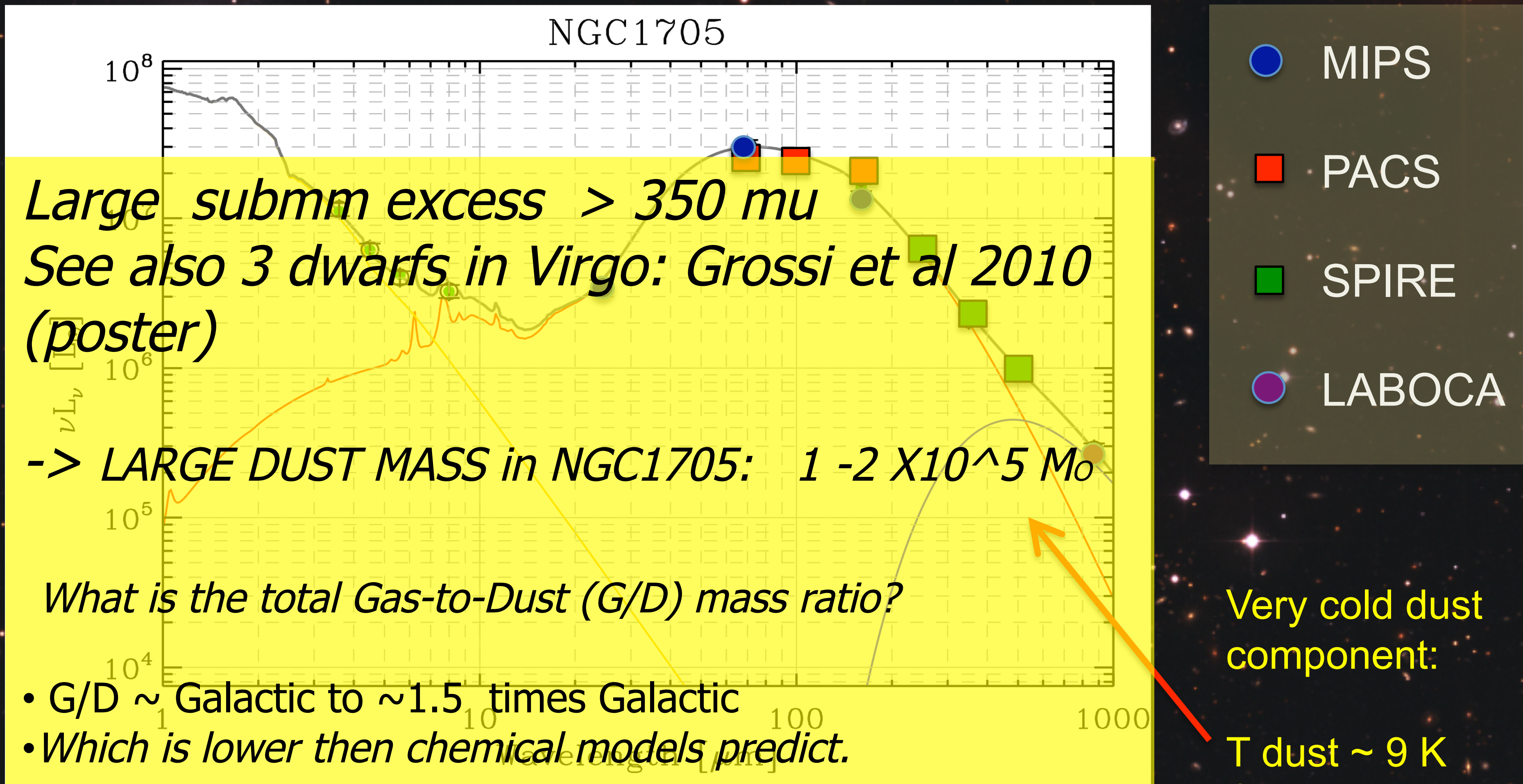
Very cold dust component:

T dust ~ 9 K
β = 1.0

NGC 1705 submm excess:

O'Halloran et al 2010 (see poster)

IRAC + MIPS + PACS + SPIRE + Laboca 870 mu



Large submm excess > 350 mu
See also 3 dwarfs in Virgo: Grossi et al 2010 (poster)

-> LARGE DUST MASS in NGC1705: 1 -2 X10^5 Mo

What is the total Gas-to-Dust (G/D) mass ratio?

- G/D ~ Galactic to ~1.5 times Galactic
- *Which is lower then chemical models predict.*

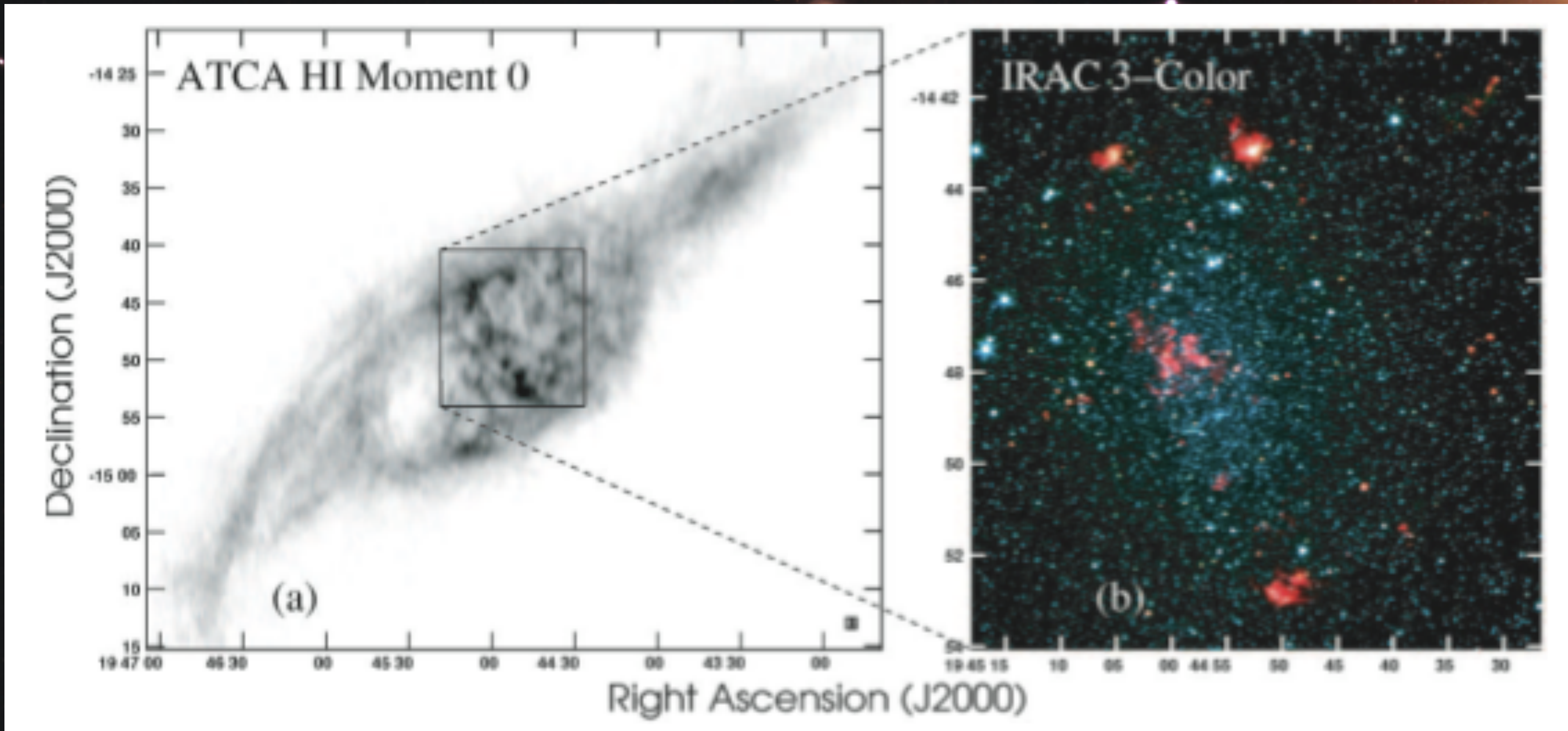
Very cold dust component:

T dust ~ 9 K
β = 1.0

SED model Galliano et al & Galametz et al 2009

NGC 6822:

Galametz et al 2010

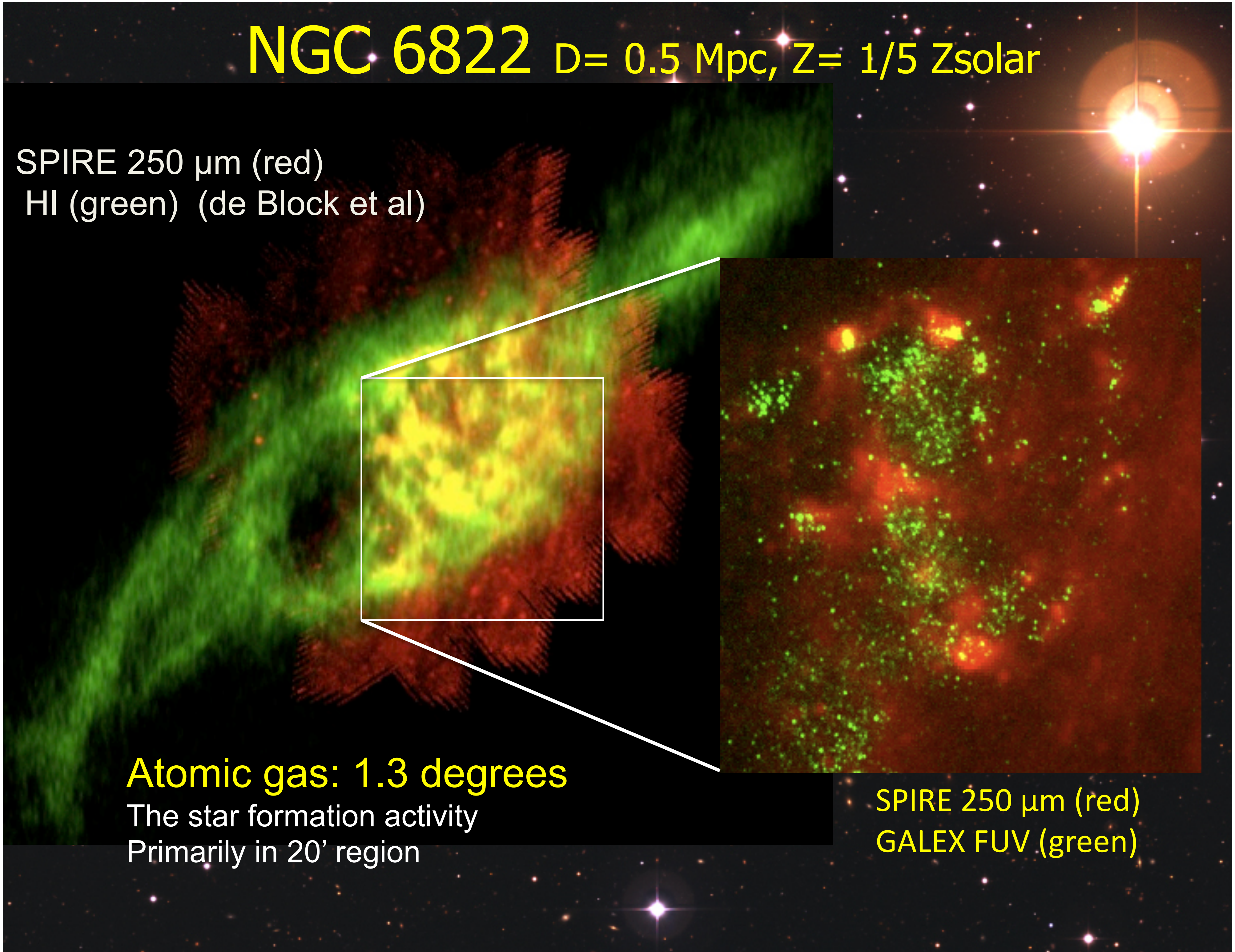


Cannon et al 2006

Atomic gas: 1.3 degrees

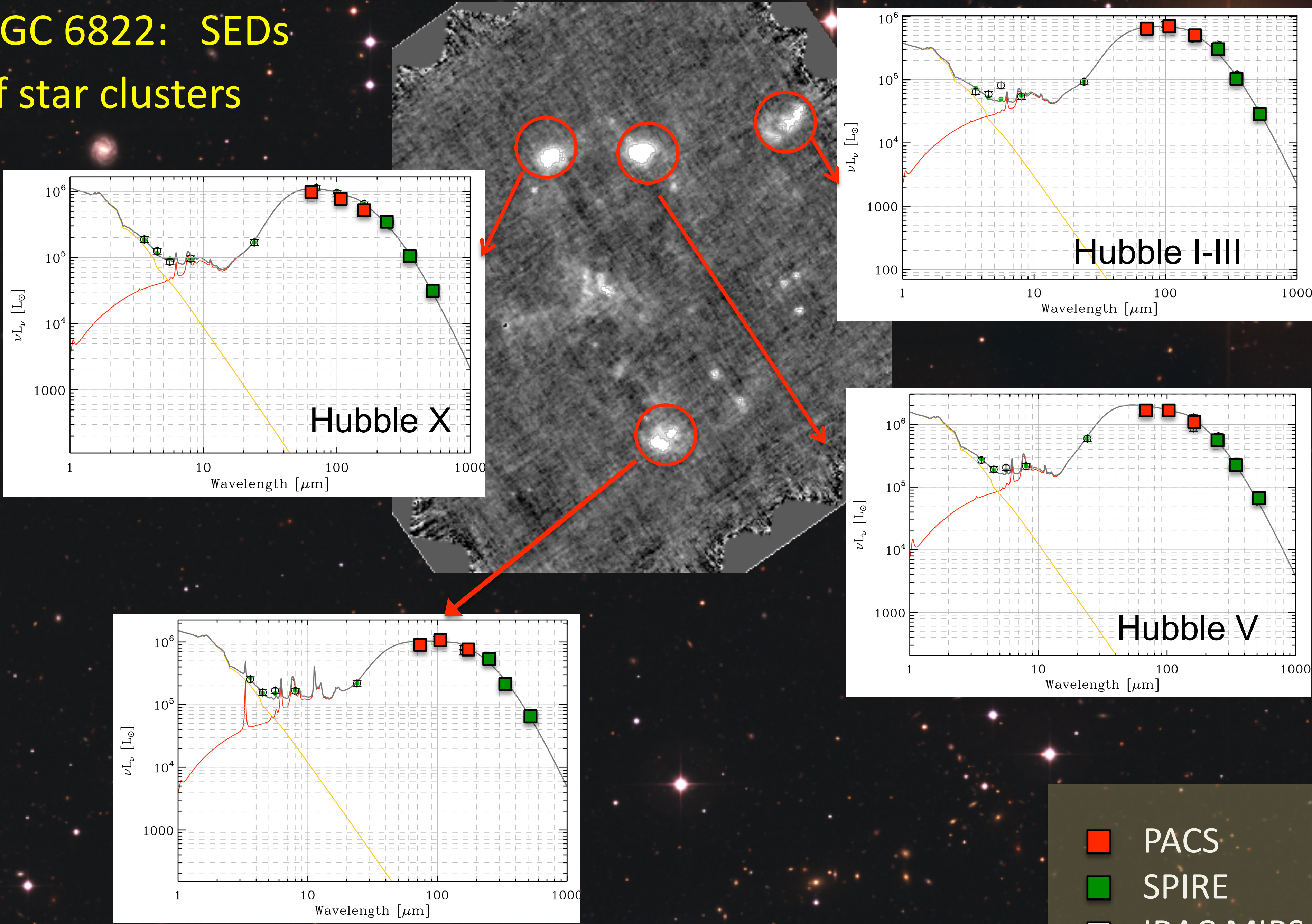
The star formation activity
Primarily in 20' region

D = 0.5 Mpc
Z = 1/5 Z solar



NGC 6822 D= 0.5 Mpc, Z= 1/5 Zsolar
SPIRE 250 μm (red)
HI (green) (de Block et al)
Atomic gas: 1.3 degrees
The star formation activity
Primarily in 20' region
SPIRE 250 μm (red)
GALEX FUV (green)

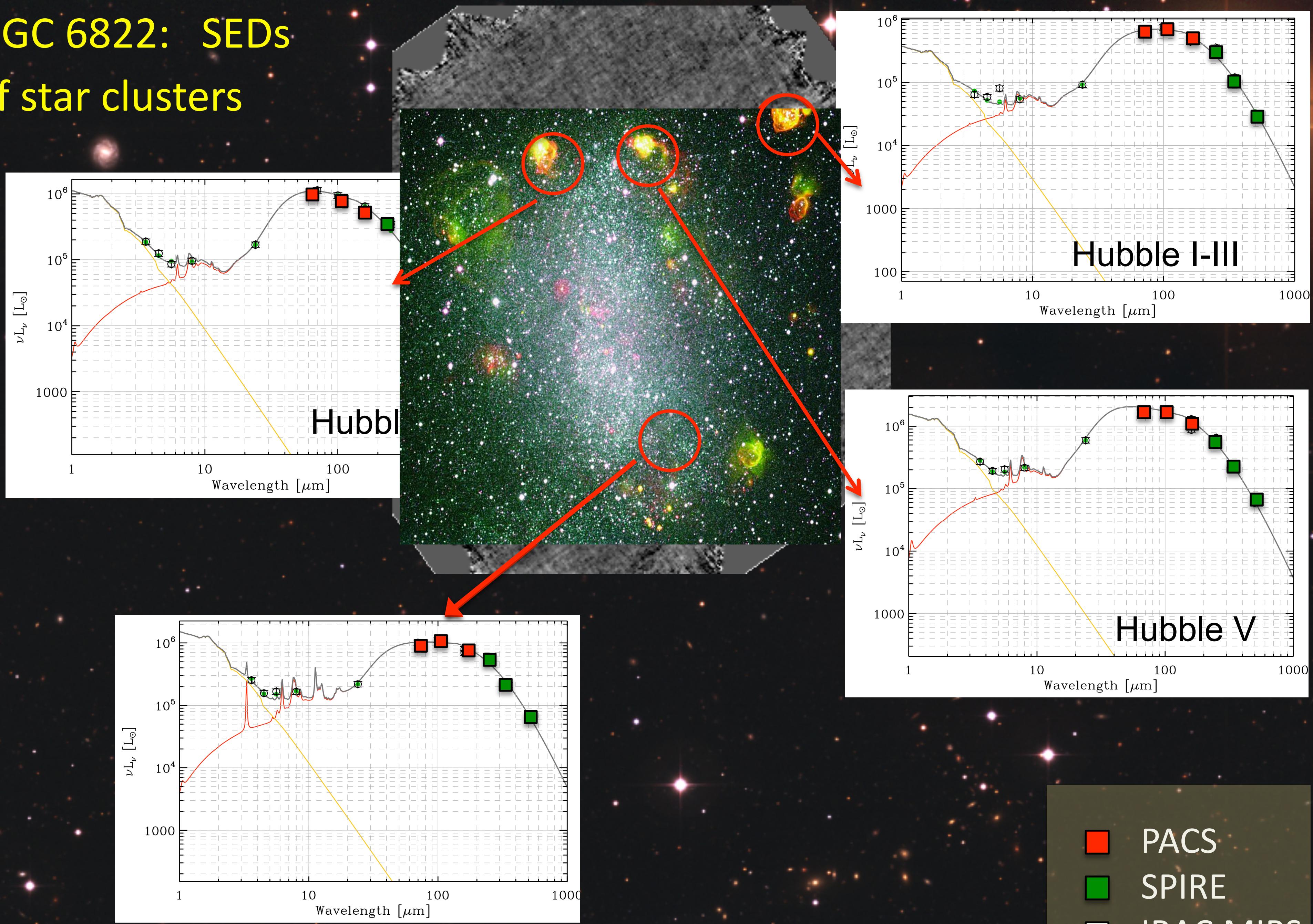
NGC 6822: SEDs of star clusters



Galametz et al (2010)

PACS
SPIRE
IRAC,MIPS

NGC 6822: SEDs of star clusters



Galametz et al (2010)

PACS
SPIRE
IRAC,MIPS

NGC 6822: *What is the total Gas-to-Dust mass ratio?*

•Mdust = 6x10^5 Msolar using Draine & Lee silicate + graphite
• G/D ~ 100

• G/D ~ 200 using silicate + amorphous carbon of Rouleau & Martin 1991

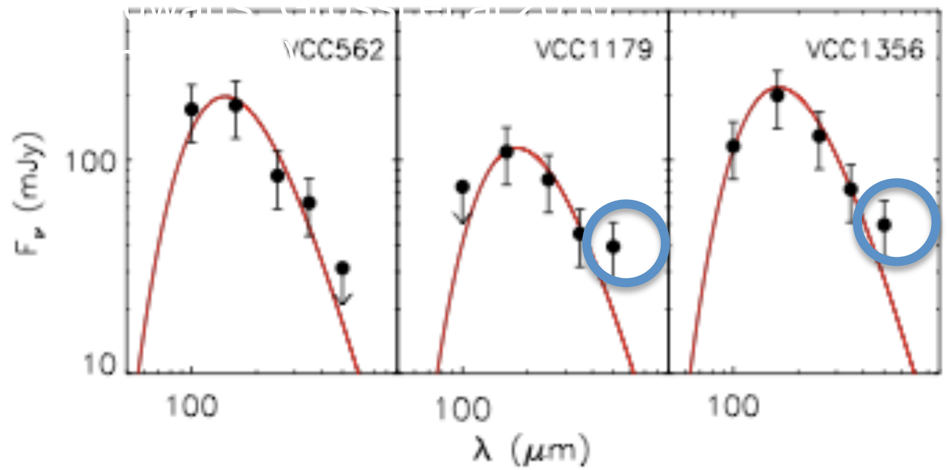
Less dust mass since amorphous carbons are more emissive (flatter submm slope) ➔ Higher G/D

Hubble V

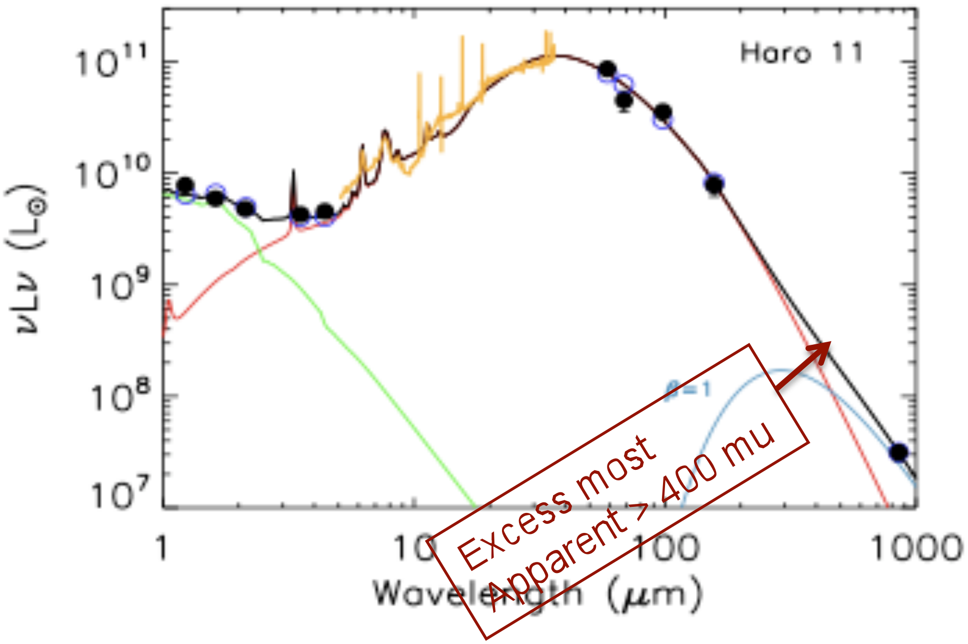
BUT G/D still lower than expected for its metallicity (1/5 Zsolar)
(G/D should be ~600 – 1000)

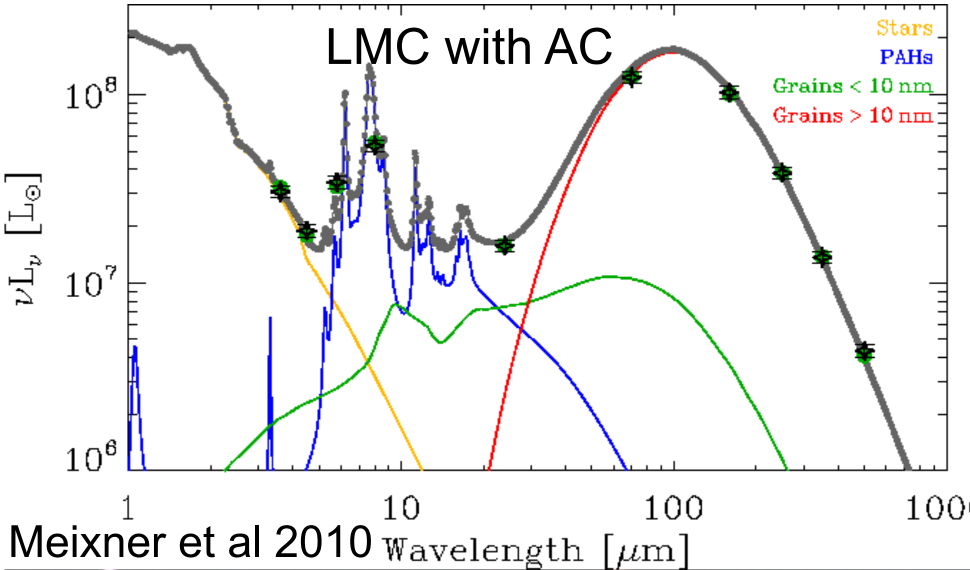
Dwarf Galaxies often show submm excess

Virgo dwarfs: Grossi et al 2010



Haro 11 Galametz et al 2009





Meixner et al 2010

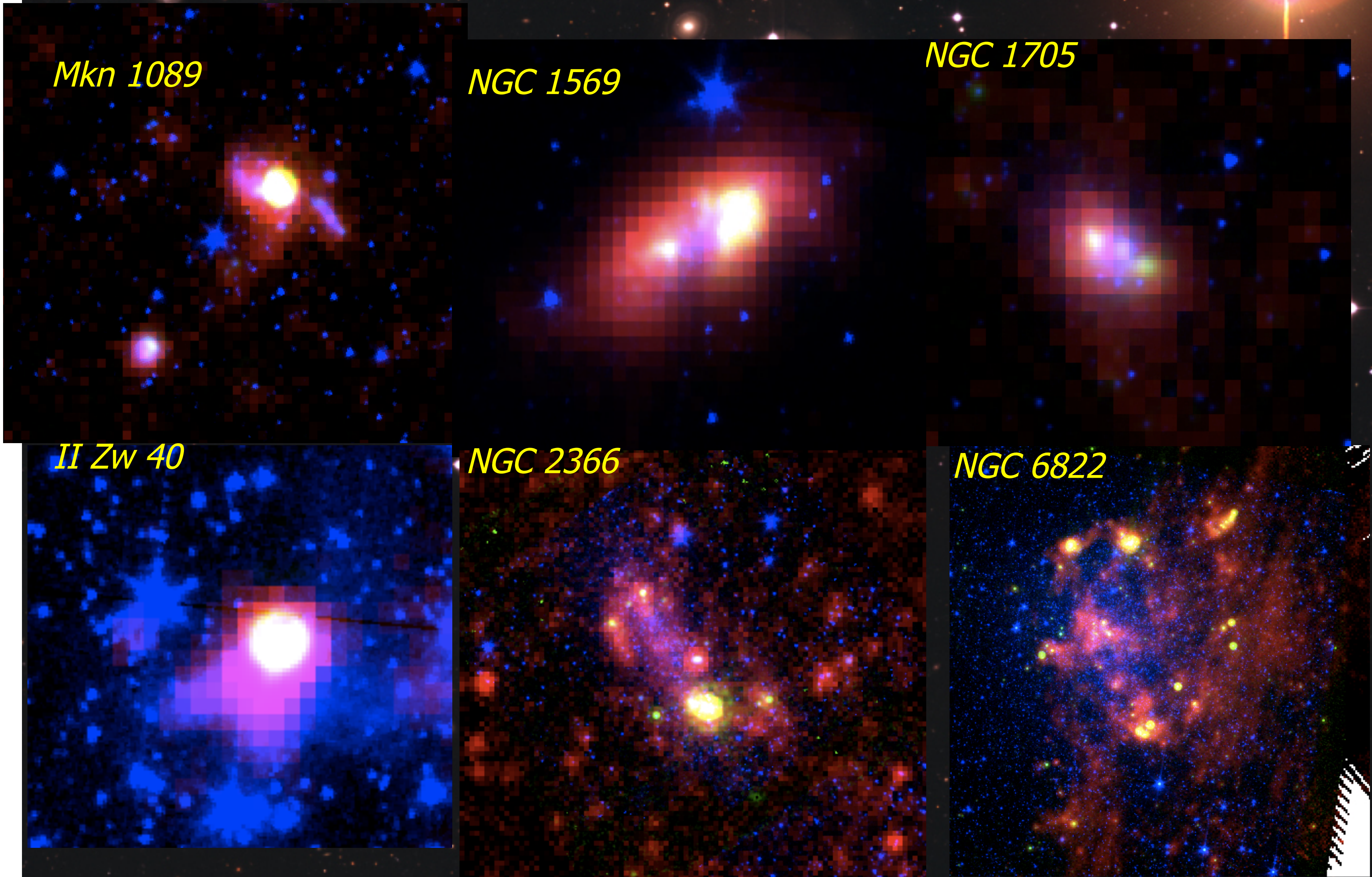
500 mu excess in the LMC with Herschel using graphite

Replacing graphite with amorphous carbon
Can give less dust mass (submm slope
Is flatter – more like a beta ~ 1 to 1.5)

Some other possibilities:
Lisenfeld et al hot fluctuating small grains (2001)
Spinning dust (Draine &Lazarian 1998; Hoang 2010; Ysard & Verstraete 2010; Bot et al 2010.)
Modified optical properties Inverse T – beta relationshp : (Meny et al 2007)

Dwarf Galaxies: Herschel-Spitzer 3-color images

Blue: 3.6 mu(stars) green: 24 mu (hot dust) red: 250 mu (cold dust)



1st summary (from photometry)

Dwarfs & Dust: the conundrum

1. submm excess (> 400 mu) common in dwarf galaxies - can imply very large dust masses – which give low G/D
2. Some dwarfs do not have submm excess, but still can have large dust masses when submm constraints exist.

Amorphous carbon instead of graphite can decrease the dust mass………. sometimes.
OR is the gas reservoir is not completely traced?

Hubble V

Such large dust masses giving low G/D not plausible for low metallicity galaxies

BUT

Do we know the total gas reservoirs in dwarfs?

The Dwarf Galaxy Survey – PACS Spectroscopy

Diagnostic tracers of HII regions, PDRs, Diffuse Ionised Medium =>

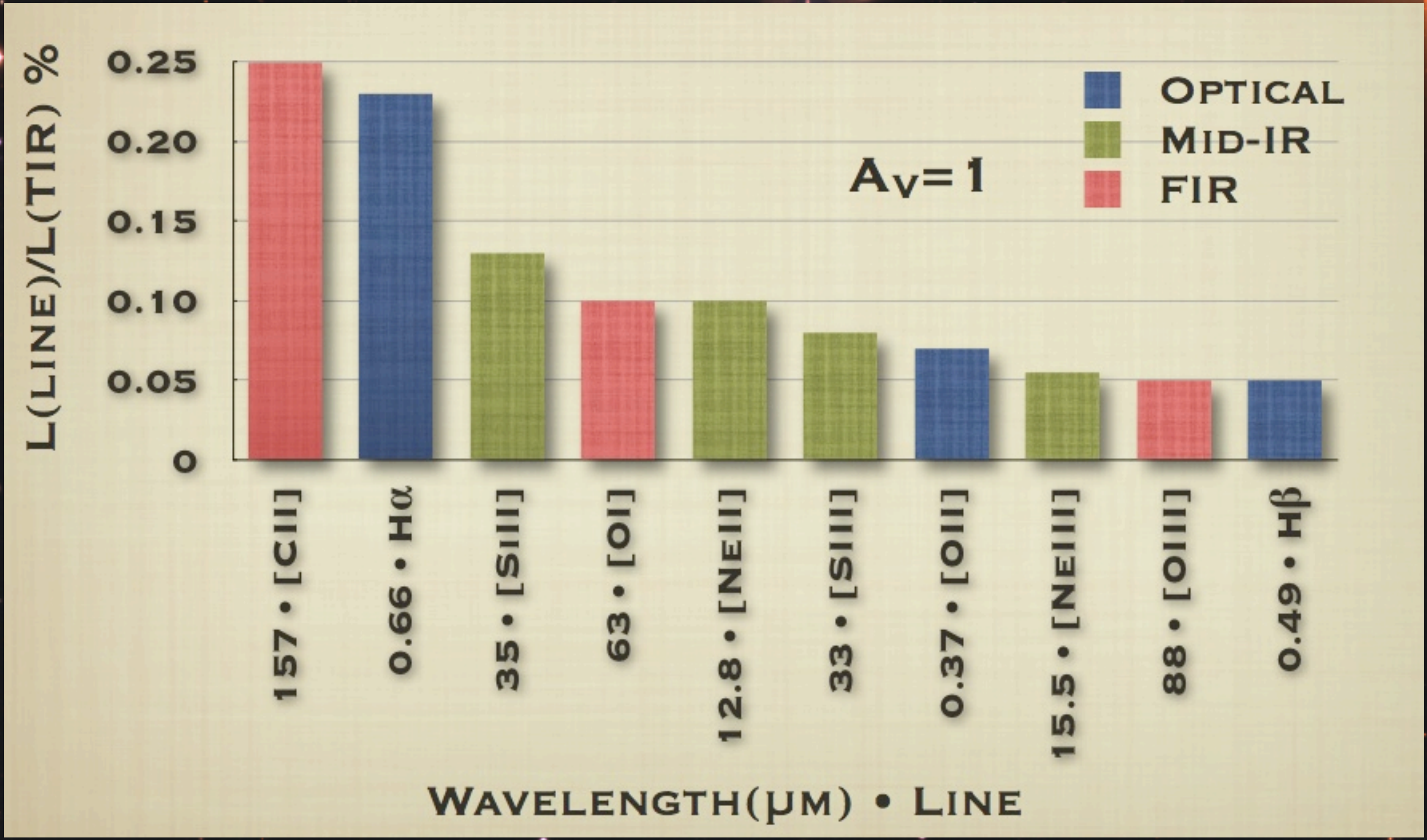
- *PACS spectroscopy + Spitzer IRS*

[CII]	158 µm	Most important cooling lines of the atomic gas.
[OI]	63 µm	Probes the conditions in PDRs - the largest fraction
[OI]	145 µm	of the neutral medium in a galaxy.

[NII]	122 µm	Conditions in the ionized medium. Diagnostics
[NII]	205 µm	of absolute level and excitation of star forming)
[NIII]	57 µm	activity and of n_e @ low density (< 10^3 cm^{-3}) DIM
[OIII]	88 µm	

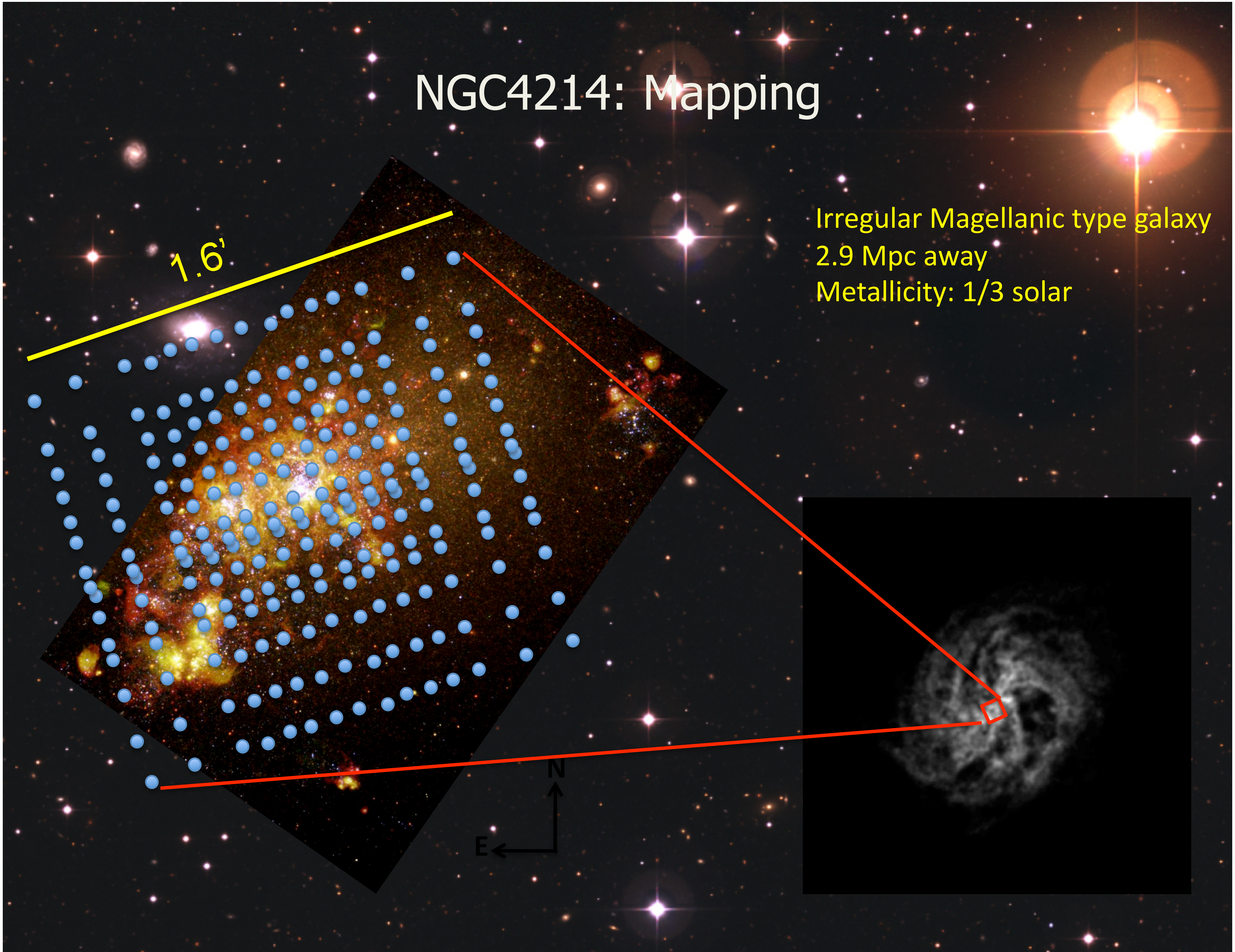
Abundances	***i.e. [NIII]/[OIII]***
Densities	***i.e. [NII], [OIII], [SIII] line pairs***
Gas pressure	***i.e. [OI] pairs***
UV hardness & intensity	***[NII]/[NIII]`. [SIII]/[OIII] pairs***
ISM filling factor	

How important are the MIR & FIR lines to the thermal budget?

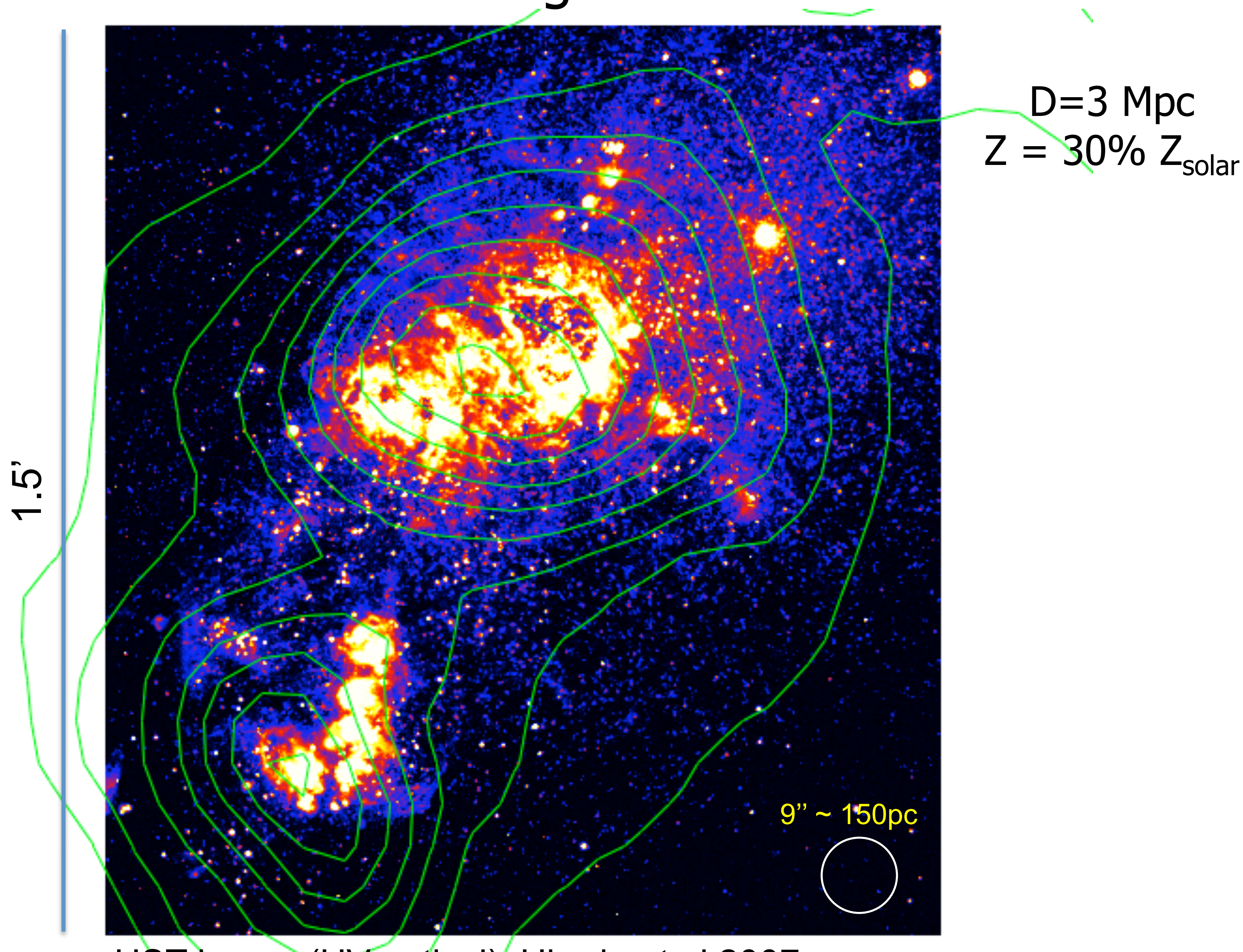


Slide from J.D. Smith

NGC4214: Mapping

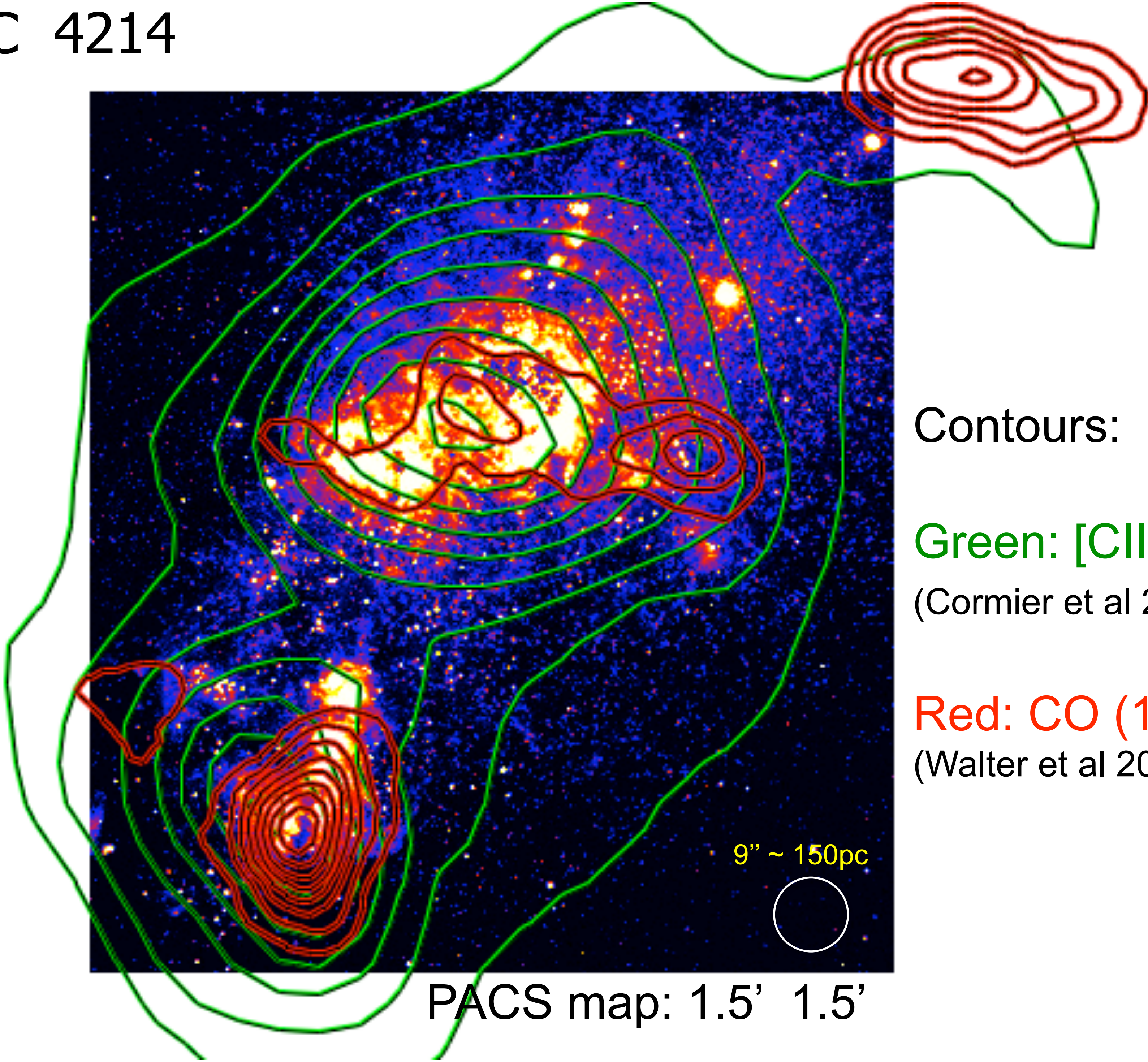


NGC 4214 HST image + PACS CII contours



HST image (UV-optical): Ubeda et al 2007
158 mu [CII] map: Cormier et al 2010

NGC 4214



PACS map: 1.5' 1.5'

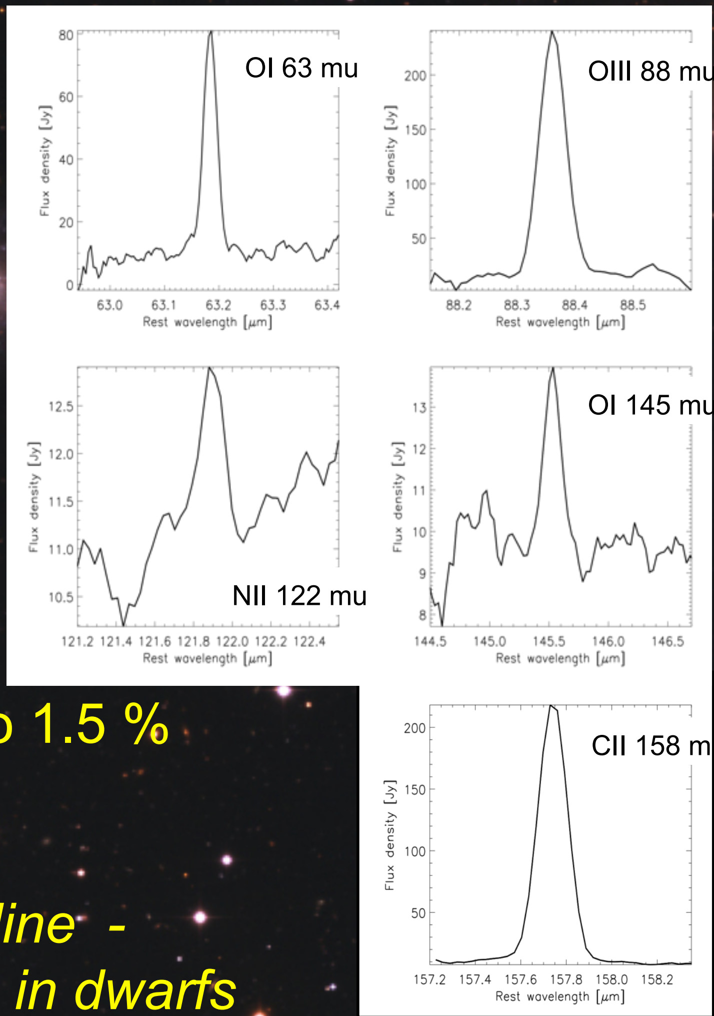
Contours:

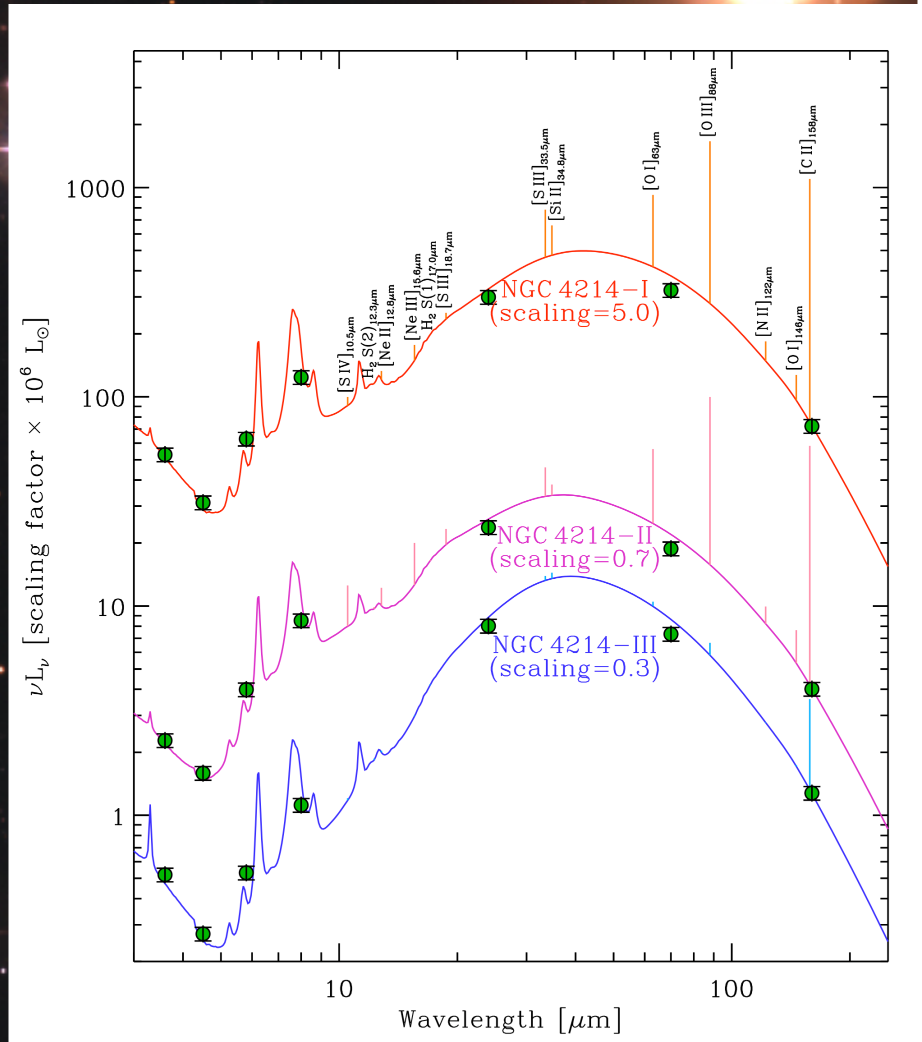
Green: [CII]
(Cormier et al 2010)

Red: CO (1-0)
(Walter et al 2001)

NGC 4214 d=3 Mpc $Z = 30\% Z_{solar}$

Map
5 FIR
PACS lines



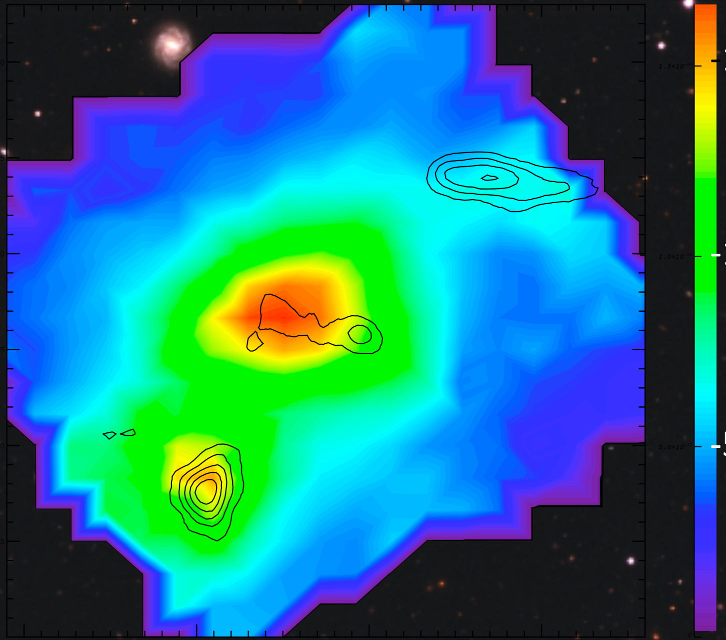


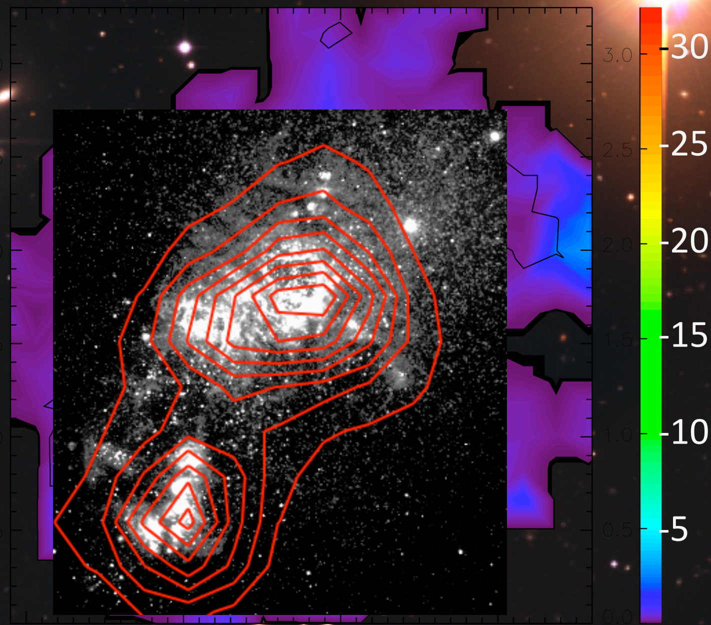
[CII] is 1% to 1.5 % of the L_{FIR}

[OIII] 88 mu line - brightest line in dwarfs traces the source of ionisation

All FIR lines ~ 2 to 4 % of L_{FIR}

NGC 4214 : mapping mode

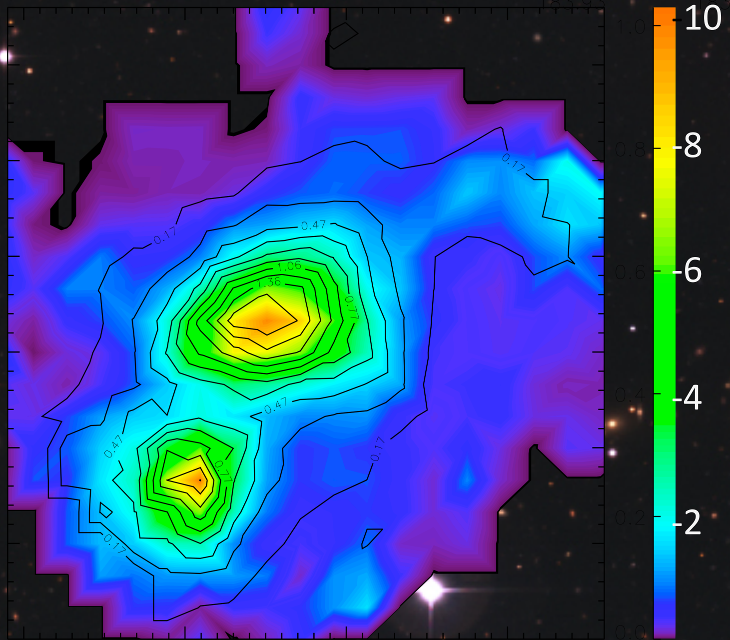




O III 88 μm

C II 158 μm

(CO contours: F. Walter)



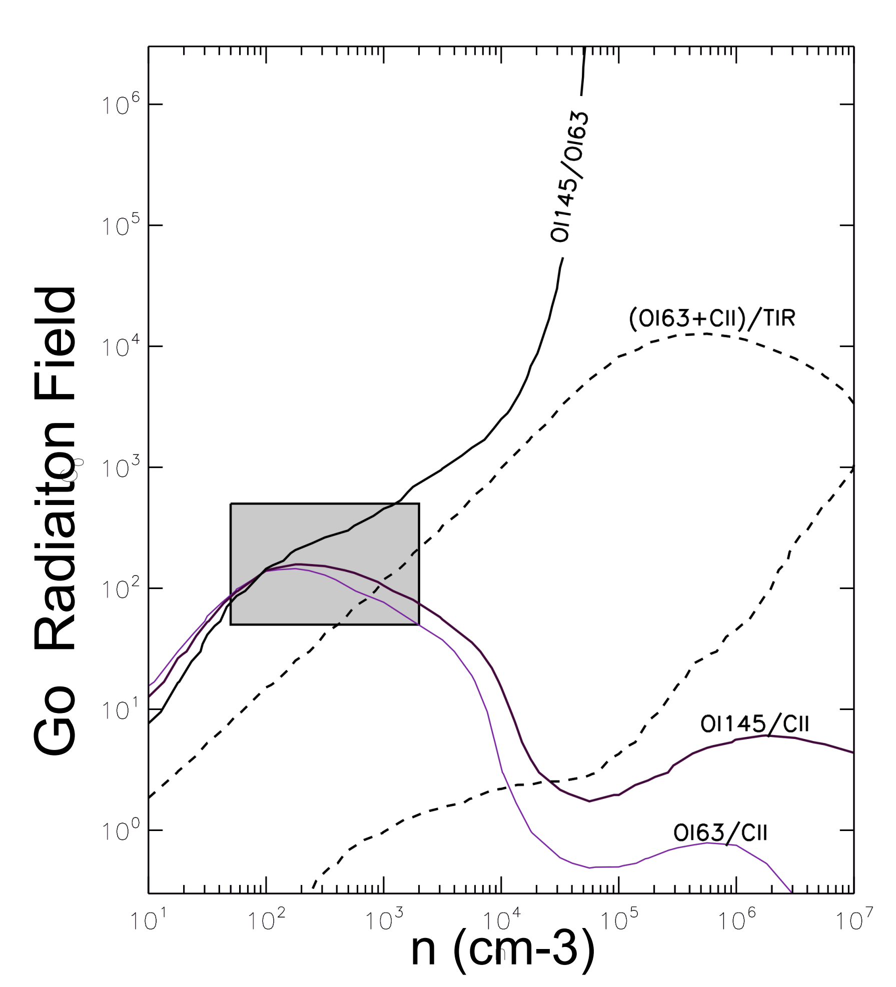
O I 63 μm

Other lines:
- O I 145 μm
- N II 122 μm
- N II 205 μm

Cormier et la 2010

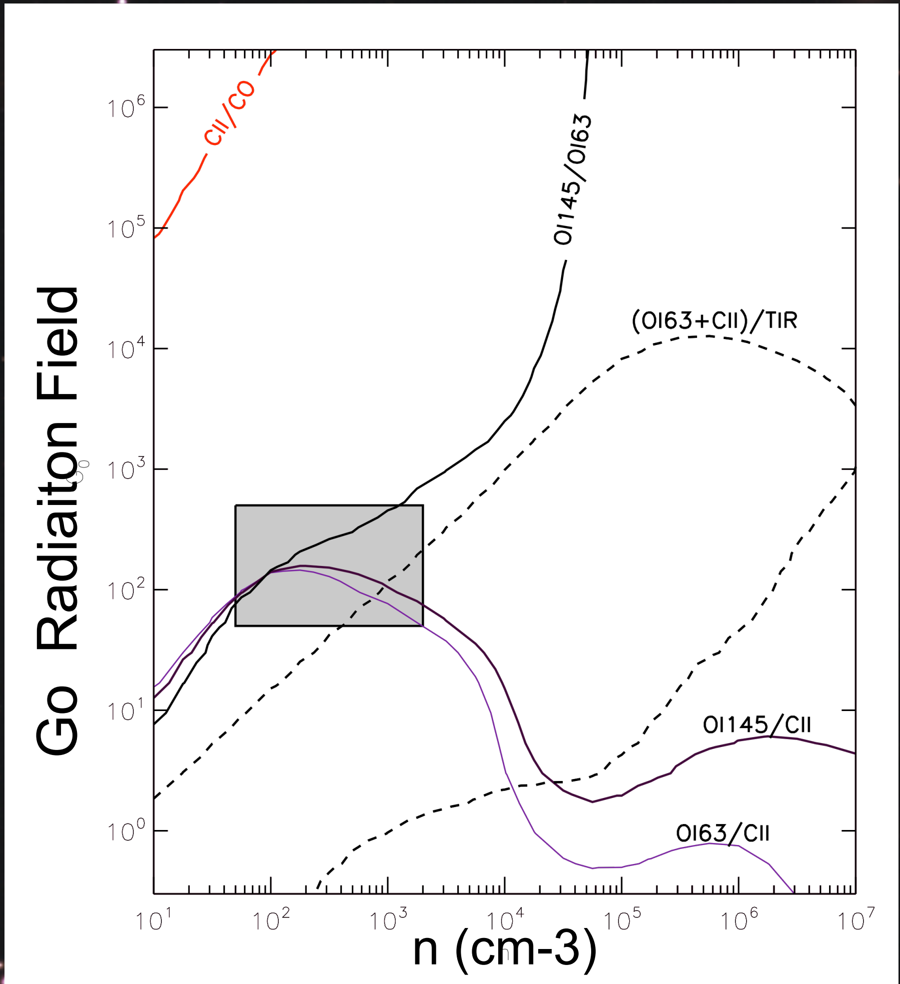
NGC 4214 d=3 Mpc $Z = 30\% Z_{solar}$

Kaufman et al PDR plots



NGC 4214 d=3 Mpc $Z = 30\% \, Z_{solar}$

Kaufman et al PDR plots:
Problem of slab geometry - CII/CO



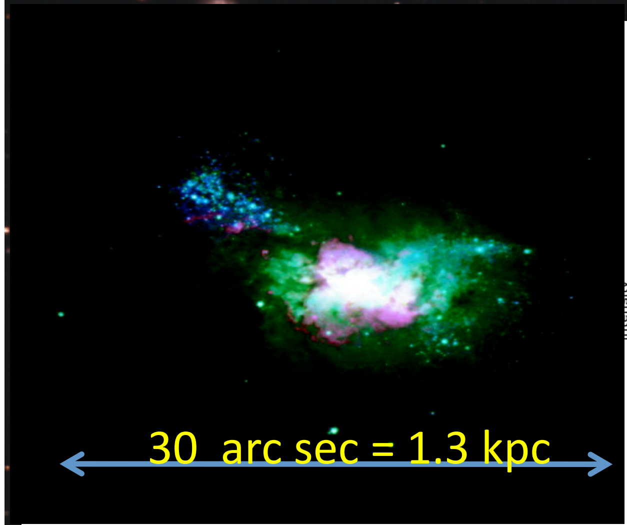
[CII]/CO = 4 000 to 75 000
(galaxy average: 30 000)

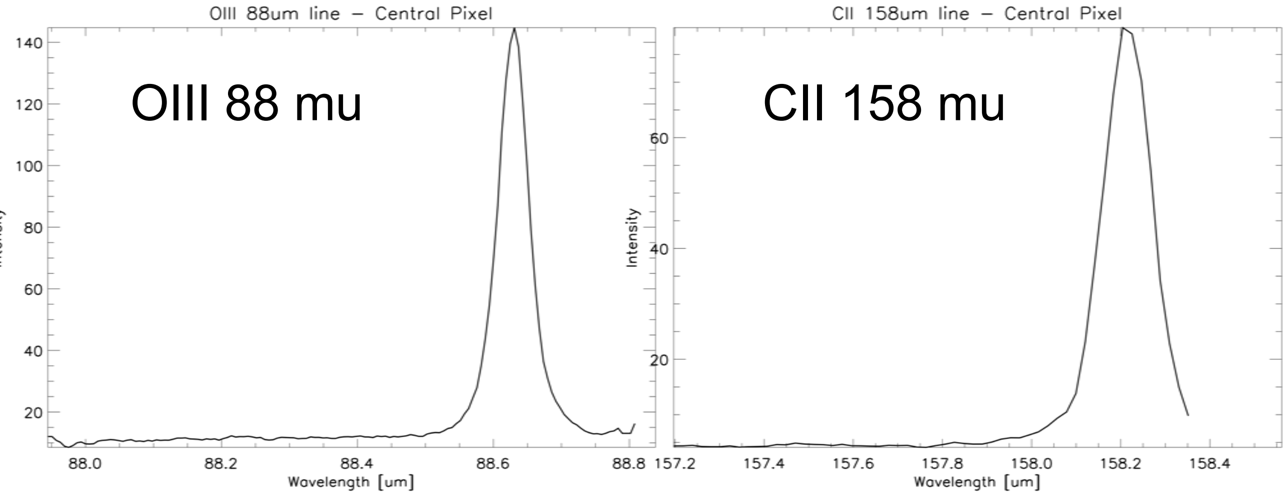
'Hidden' molecular gas traced by C+ (CO-free zone) up to 20 times that traced by CO

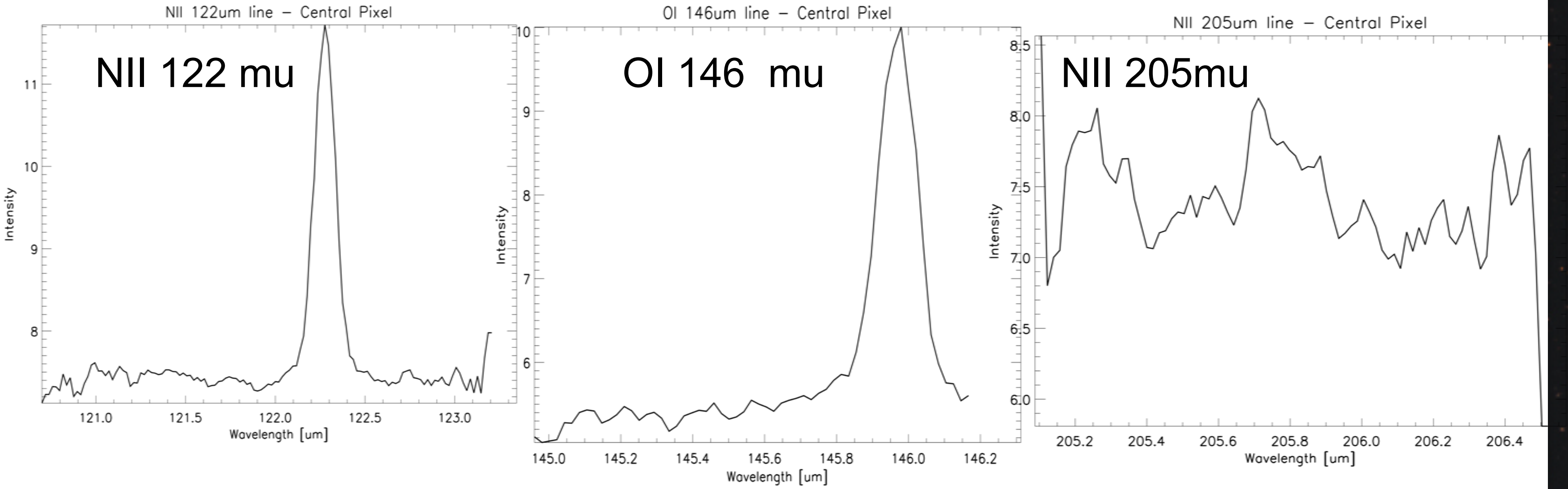
IC10: 50 to 100 x more H_2 Than that traced by CO. Mapped in CII (Madden et al 1997)

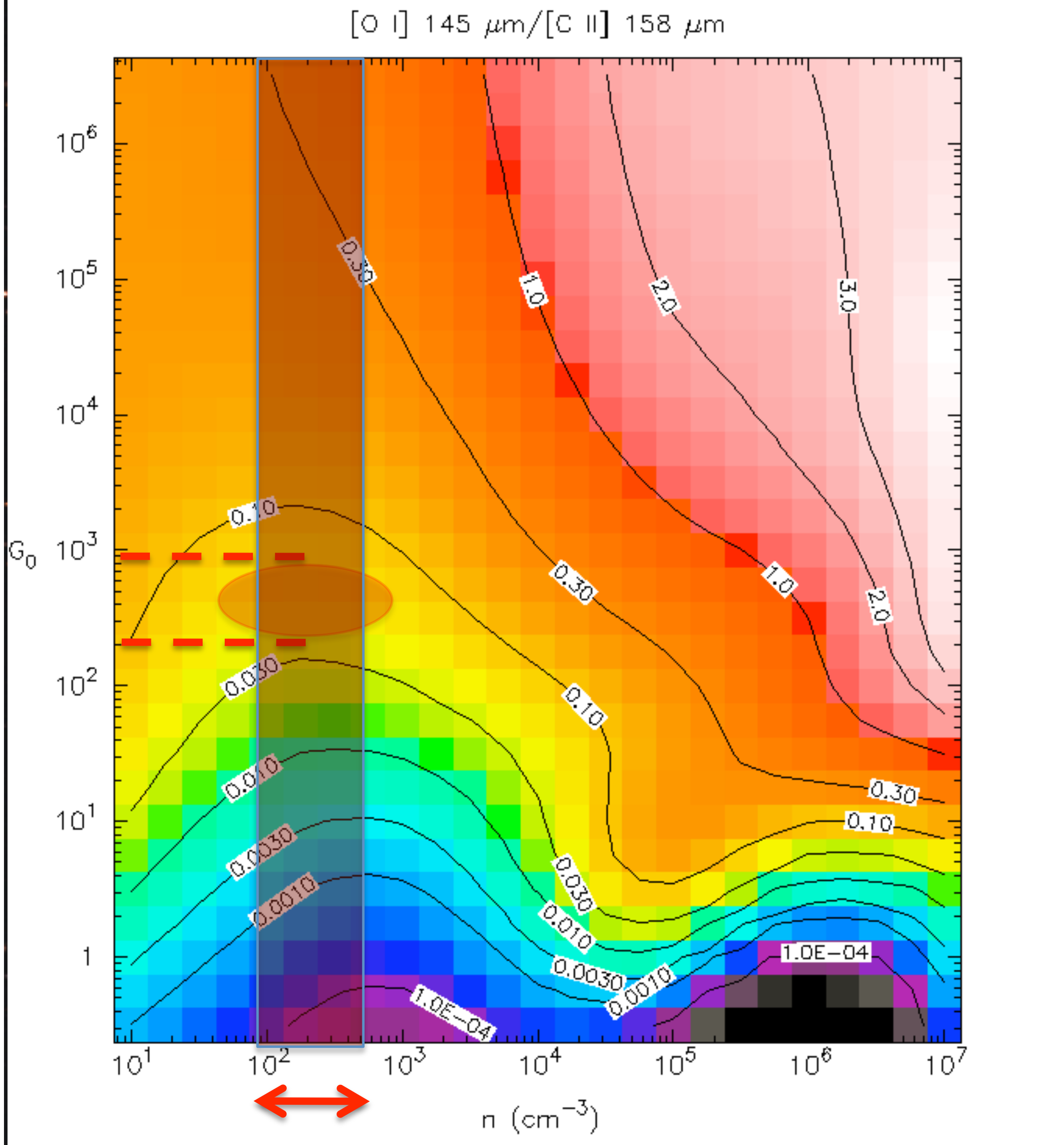
Also: Stacey et al 1991; Poglitsch et al 1995; Madden et al 1997; Madden et al 2000;
Models: Roellig et al 2006; Wolfire et al 2010

He 2-10 (D=9 Mpc)


30 arc sec = 1.3 kpc


OIII 88um line – Central Pixel
OIII 88 mu
CII 158um line – Central Pixel
CII 158 mu
Intensity
Wavelength [um]


NII 122um line – Central Pixel
NII 122 mu
OI 146um line – Central Pixel
OI 146 mu
NII 205um line – Central Pixel
NII 205mu
Intensity
Wavelength [um]



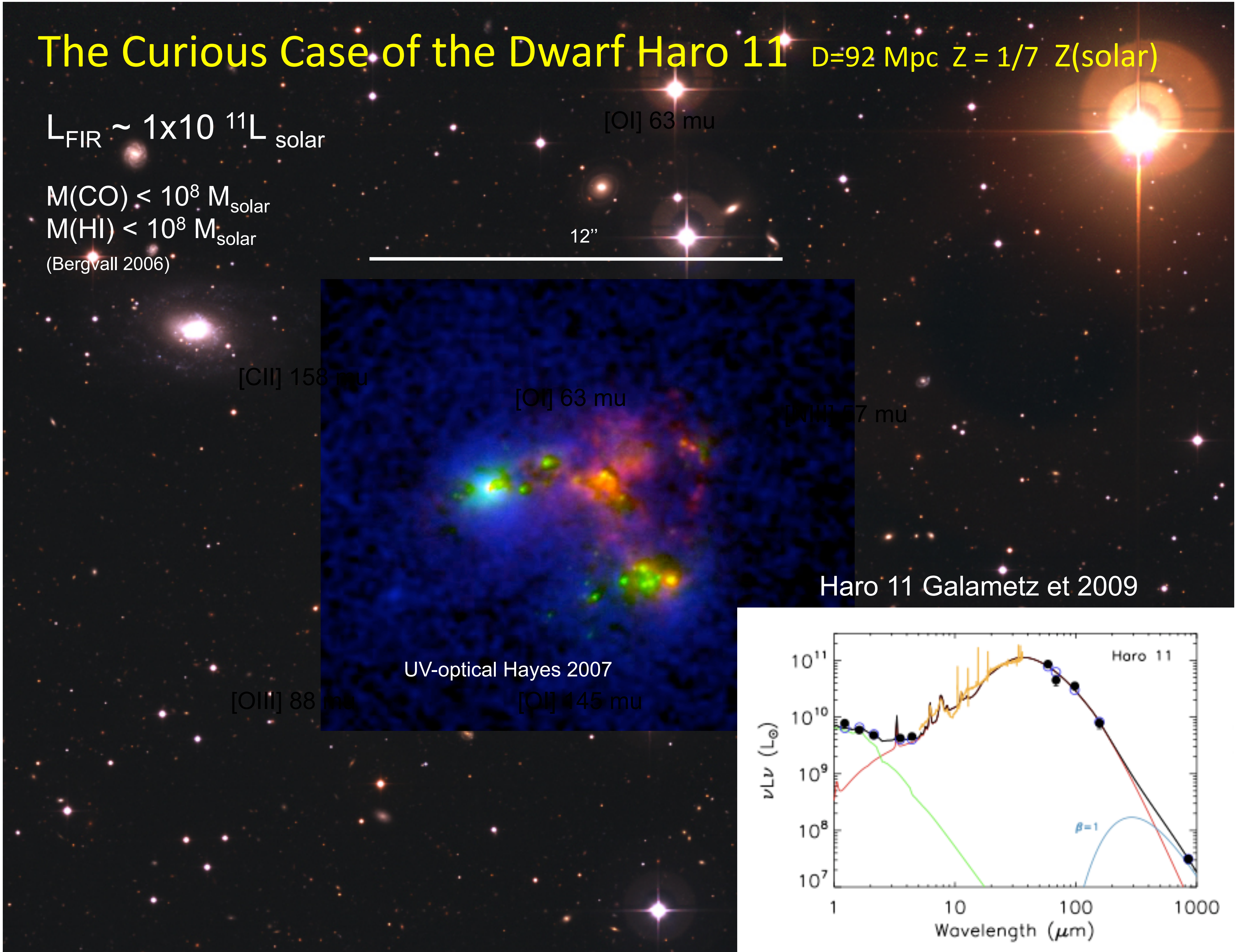
He 2-10 *preliminary* PDR modelling

I (OI 146um)/I (CII 158um) = 0.06

CO (1-0) = 1.0 e-22 W cm-2

600 < G0 < 1000
80 < n < 500

CII / CO = 10e^4 for He2-10

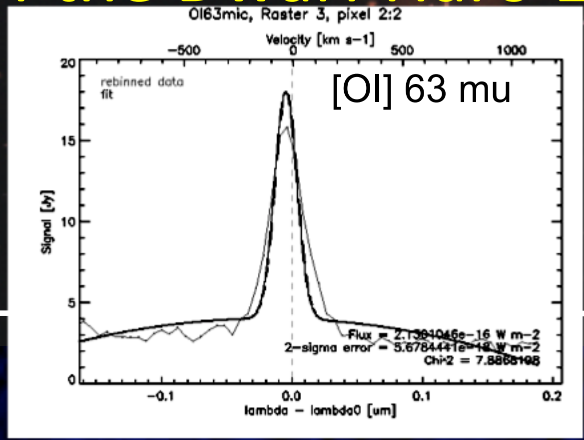

The Curious Case of the Dwarf Haro 11 D=92 Mpc Z = 1/7 Z(solar)
L_FIR ~ 1x10 ^11 L solar
M(CO) < 10^8 M_solar
M(HI) < 10^8 M_solar
(Bergvall 2006)
[OI] 63 mu
12''
[CII] 158 mu
[OI] 63 mu
UV-optical Hayes 2007
[OIII] 88 mu
[OI] 145 mu
Haro 11 Galametz et 2009
Haro 11
β=1
νLν (L)
Wavelength (μm)
1
10
100
1000
10^11
10^10
10^9
10^8
10^7

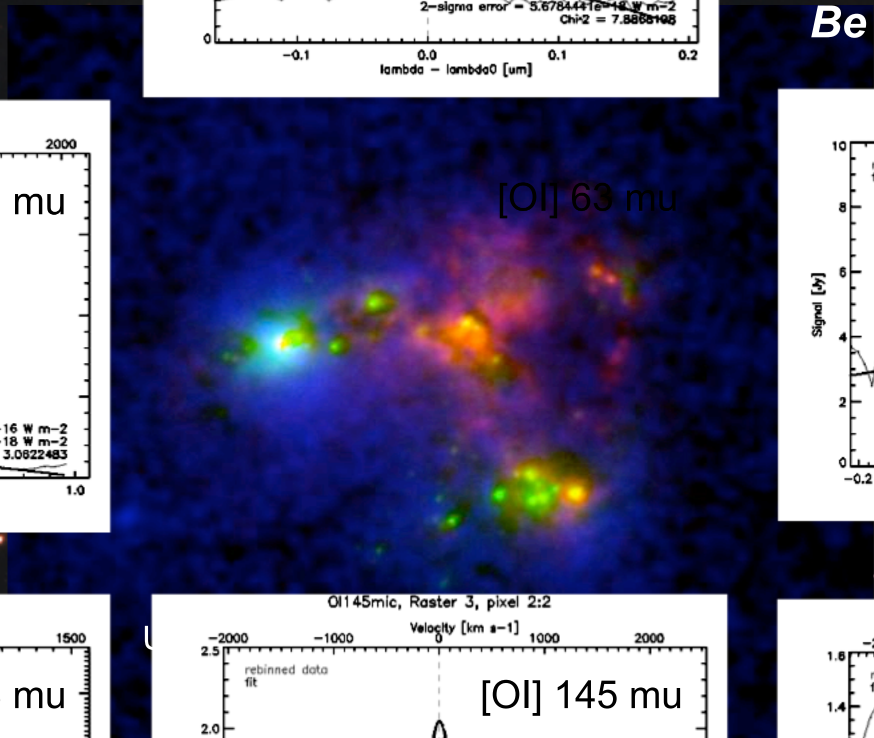
The Curious Case of the Dwarf Haro 11 D=92 Mpc Z = 1/7 Z(solar)

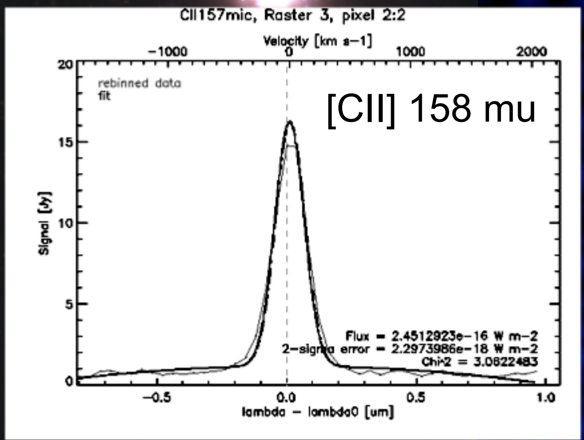
$L_{FIR} \sim 1x10^{11} L_{solar}$

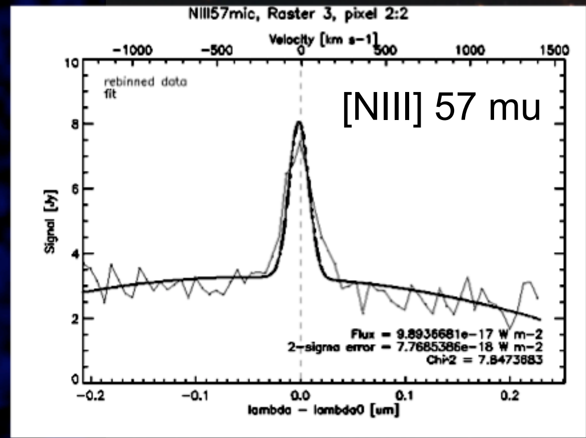
$M(CO) < 10^8 M_{solar}$
$M(HI) < 10^8 M_{solar}$
(Bergvall 2006)

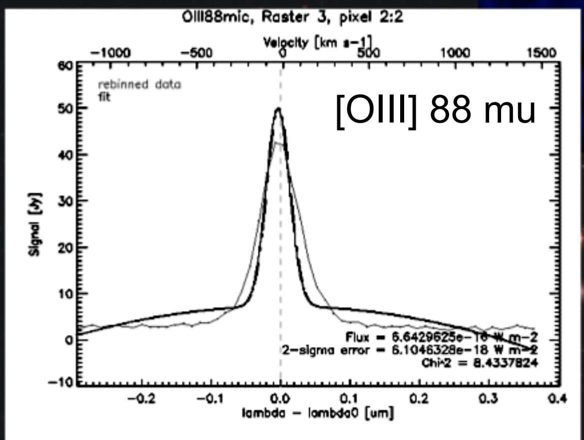
L(CII)/L(CO) > 50 000 !!
A large fraction of
the H_2 gas could
Be in the PDRs

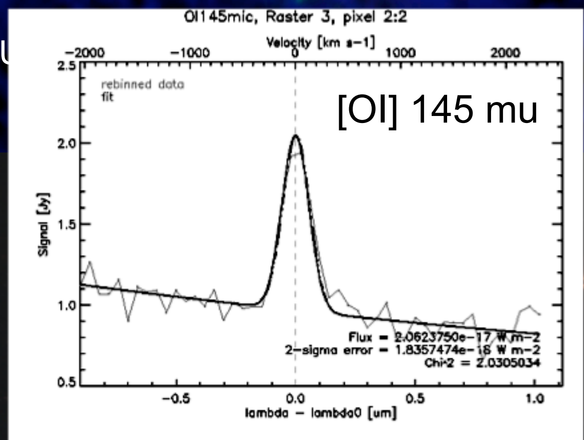


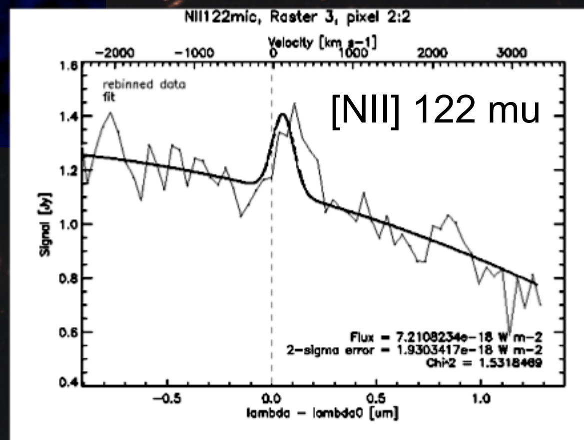




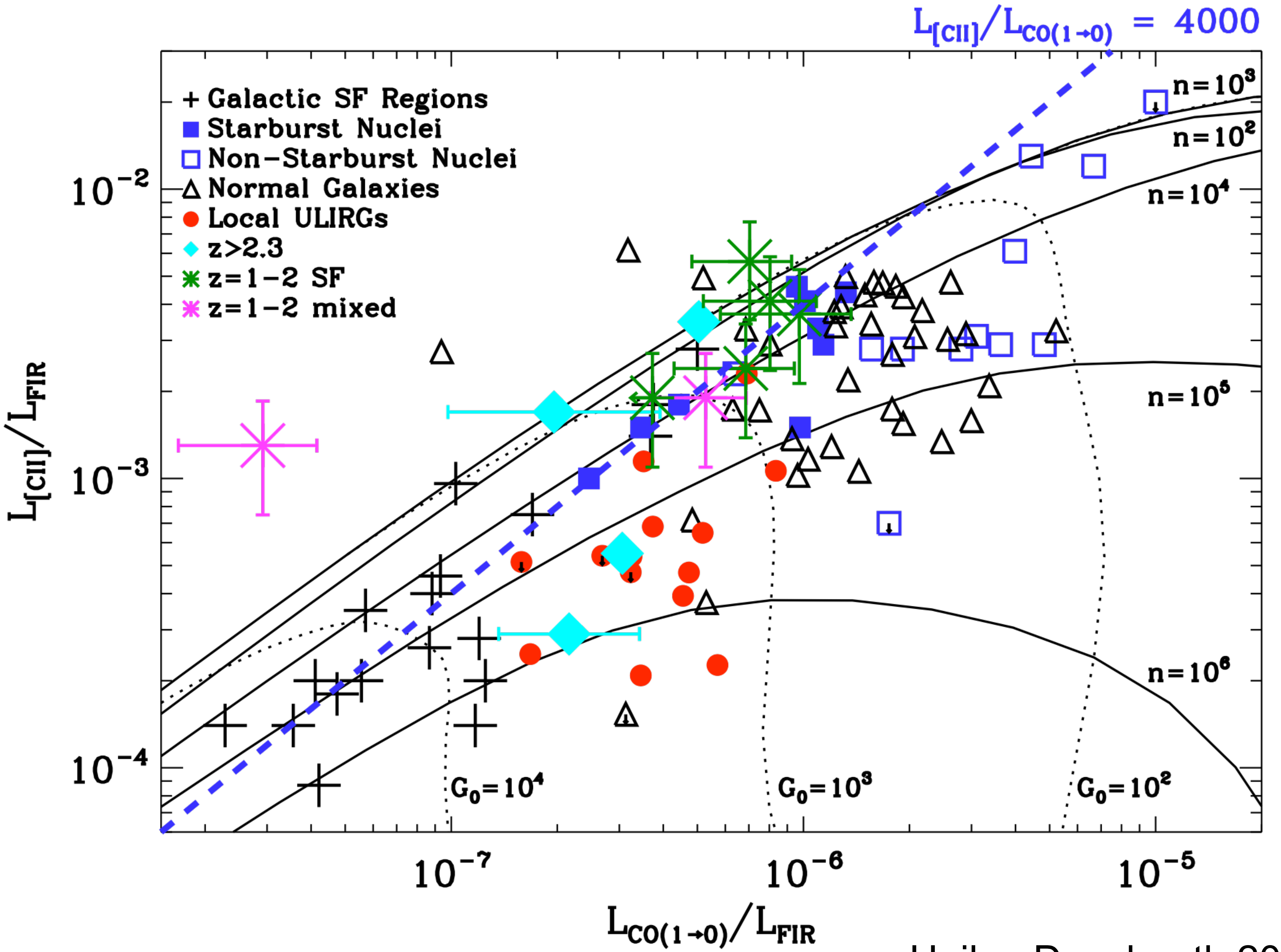






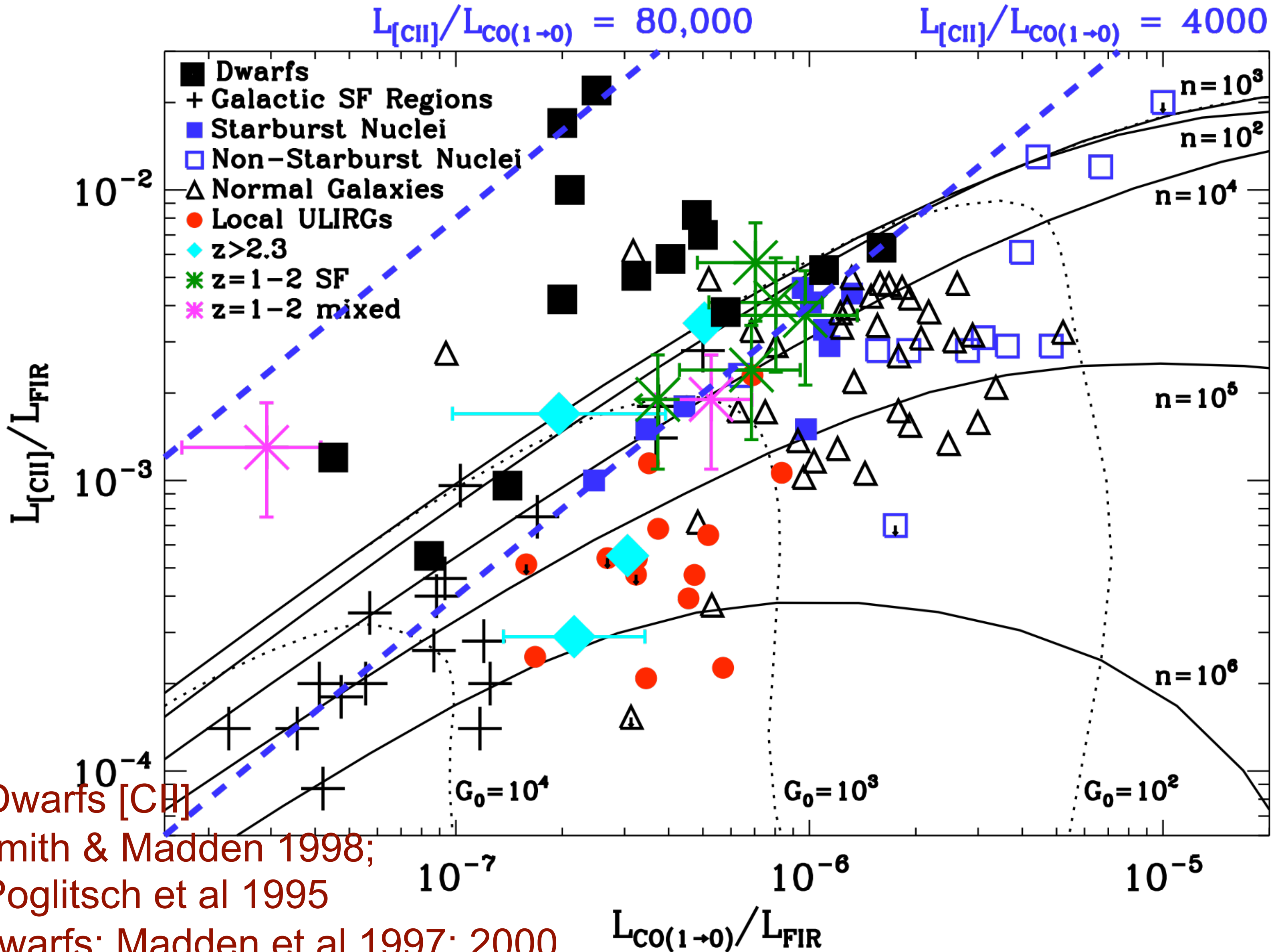


[CII]/FIR & [CII]/CO in Galaxies - local and high-z



Hailey-Dunsheath 2010

[CII]/FIR & [CII]/CO in Galaxies - local and high-z

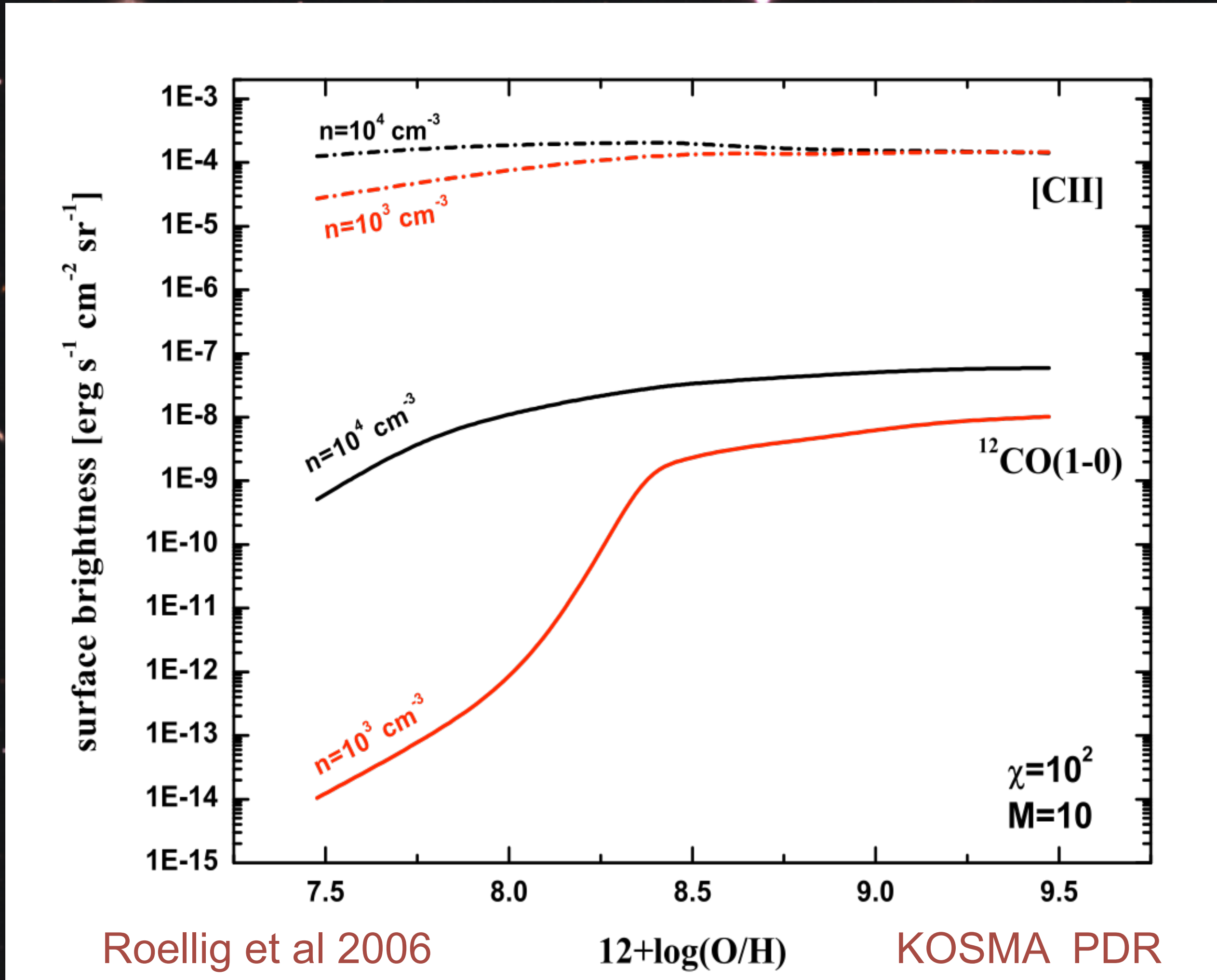


(Dwarfs [CII]
Smith & Madden 1998;
Poglitsch et al 1995
Dwarfs: Madden et al 1997; 2000
Cormier et al 2010
Stacey et al 2010, Madden 2011, adapted from Hailey-Dunsheath et al 2010)

Effects of decreasing metallicity to explain high I[CII]/I(CO) :
Normal metallicity clouds – PDR a *thin* shell around H_2
Decreased in metallicity – decrease in dust – lower photon attenuation in cloud

CO more easily destroyed – deeper PDR around smaller CO
Total $N(C^+)$ the same ; $N(H_2)$ is the same (self-shielding of H_2)
Very different C+ & CO filling factors
M(H2) conversion factor which includes I[CII] to trace 'hidden' H_2 ie IC10 – 100 time more H_2 than seen in CO (Madden et al 1997)

PDR modeling and Metallicity



CO-free zone
H2- dark zone
Traced by [CII]

Critical parameter:
Shielding of H2 determines
HI/H2 transition -
depends on
Go/n vs
dust extinction of FUV

Close to the clump surface?
Or close to the
C+/C/CO interface?

"The Dark Molecular Gas ": Grenier et al 2005
Wolfire et al 2010

Preliminary Hershcel results summary

- *Submm excess observed in dwarf galaxies*
  - Is this due to a v. large cold dust mass?
  - Using amorphous carbons instead of graphite can ameliorate this
  - Can still find large dust masses sometimes - *low gas-to-dust mass ratio*
- *'Missing' Molecular Gas in low metallicity galaxies?*
  - *L([CII]/L(CO) >> than dusty star burst galaxies - tracing the H_2 gas not traced by CO*
  - [CII] widely distributed throughout low metallicity galaxies – very clumpy?
  - L([CII]/LFIR 0.5% to 2%
  - OIII/CII > 2 on galactic scale (like giant HII regions). OIII may be a workhorse diagnostic for high z, low Z galaxies with ALMA

Molecular reservoir:

([CII] + CO) -to-H_2 conversion factor

The total dust mass issue - needs the gas inventory

Herschel to SOFIA

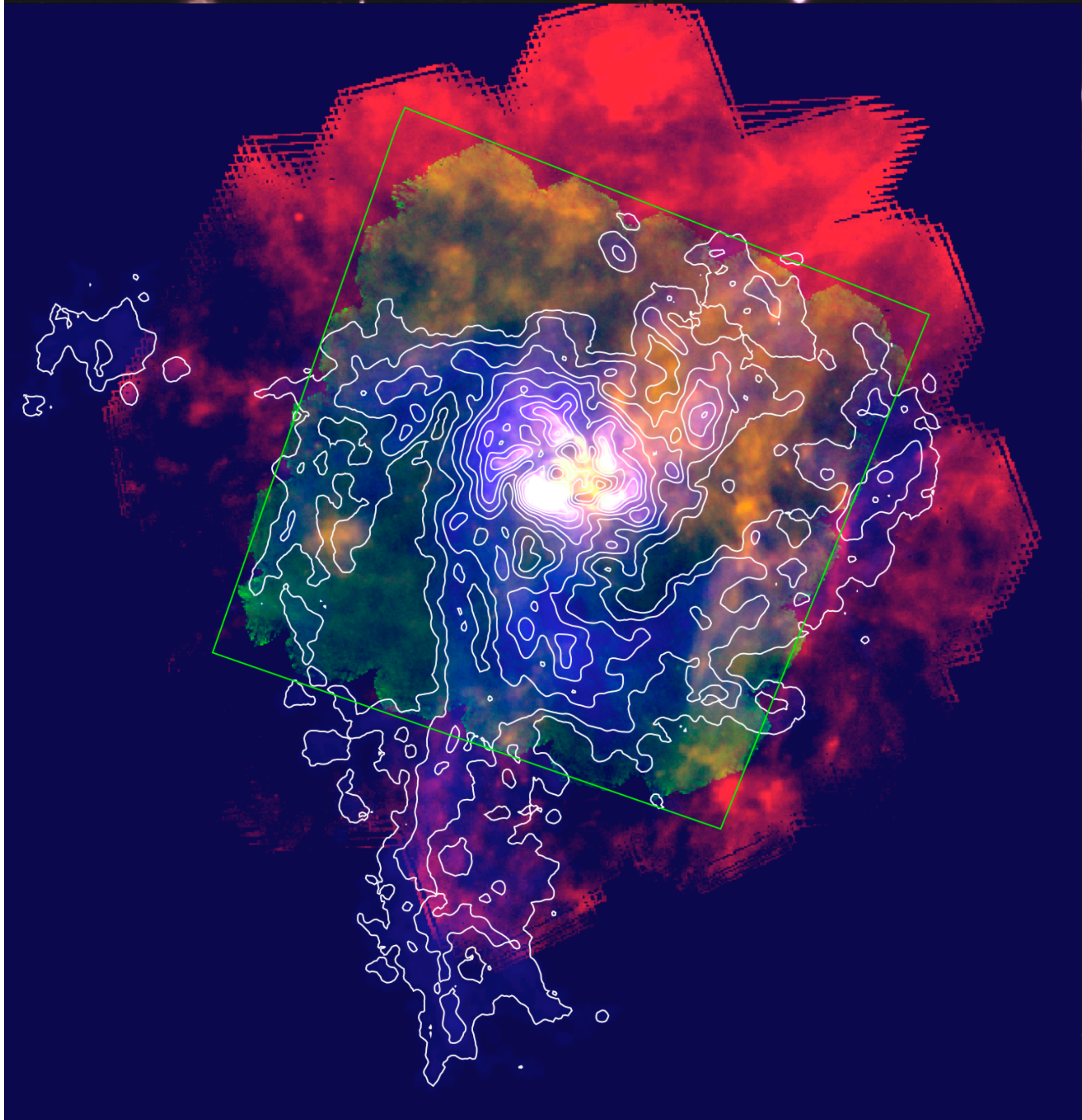
Spectrosocpic mapping: GREAT & FIFI-ls limitations:
CII – the most important coolant in galaxies: sensitive CII/OI mapping of large Local Group Dwarf galaxies. Need fast mapping capability to cover large (30' to degrees) galaxies. How to map CII in the LMC? Frequency-switching? On the fly line mapping?

Dust imaging Large field of view - trace the submm excess?excess begins at 500 mu: for now, it looks to be sitting in the **DIFFUSE** ISM – avoiding the compact, SF sites. Perhaps not idea for ALMA? Ground-based bolometers tough to do extended emission.

Dwarf galaxies peak of luminosity from 20 to 60 mu:
Wavelength dessert from to 60 mu imaging
(Forcast goes to 40 mu – grism capabilities moderate resolution spectroscopy SEDs (R~100)

High-z Low Z galaxies: OIII and OI with SOFIA

Local Group: IC10 Z~1/6 solar



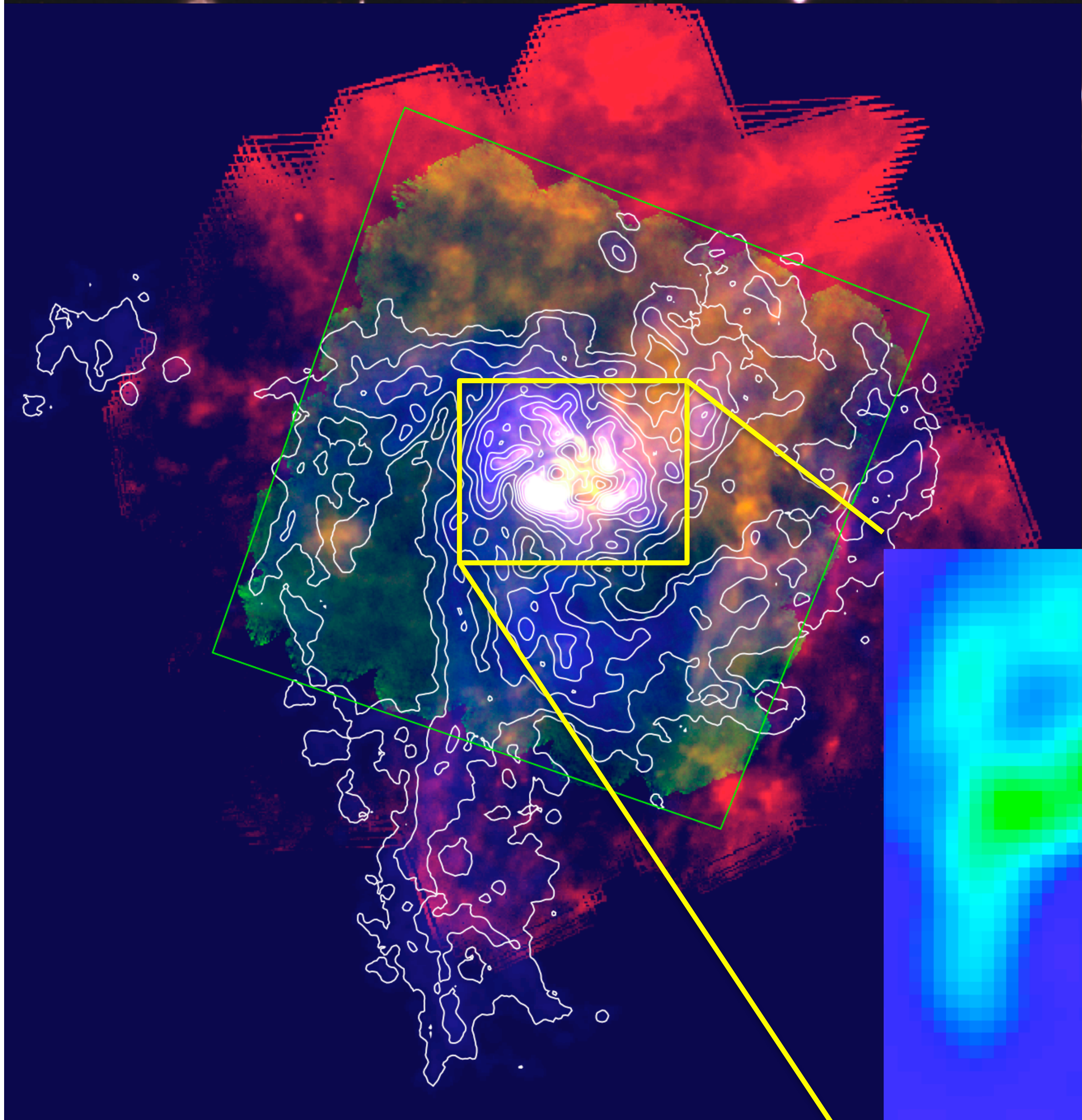
20’

D= 800 kpc

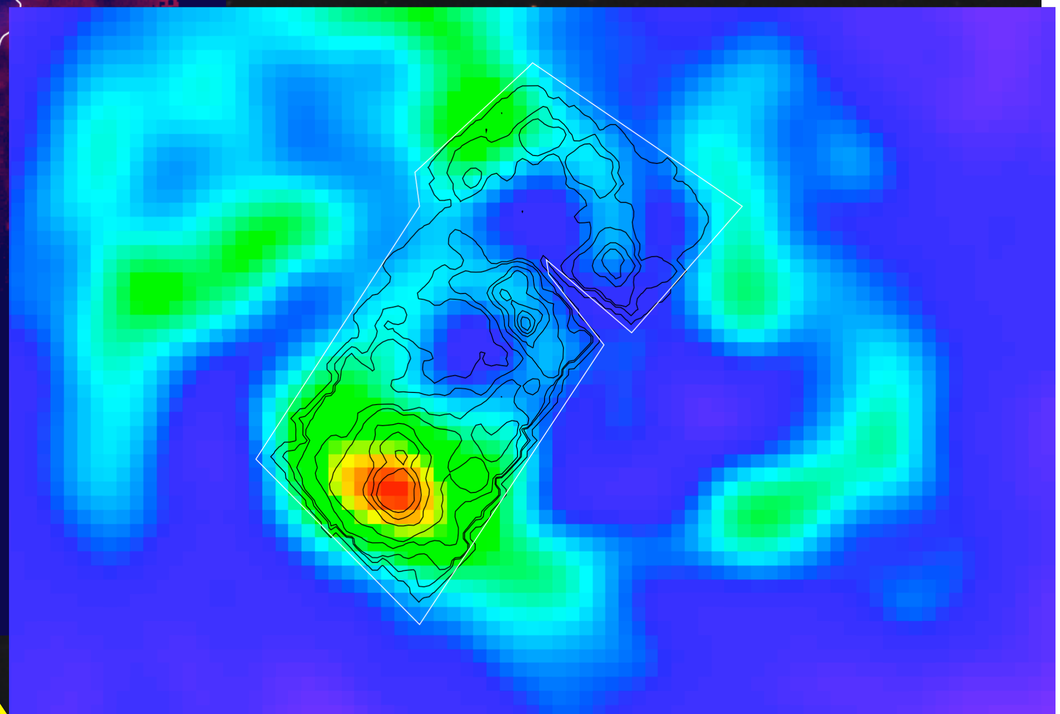
HI: 2x10^10 M(solar)

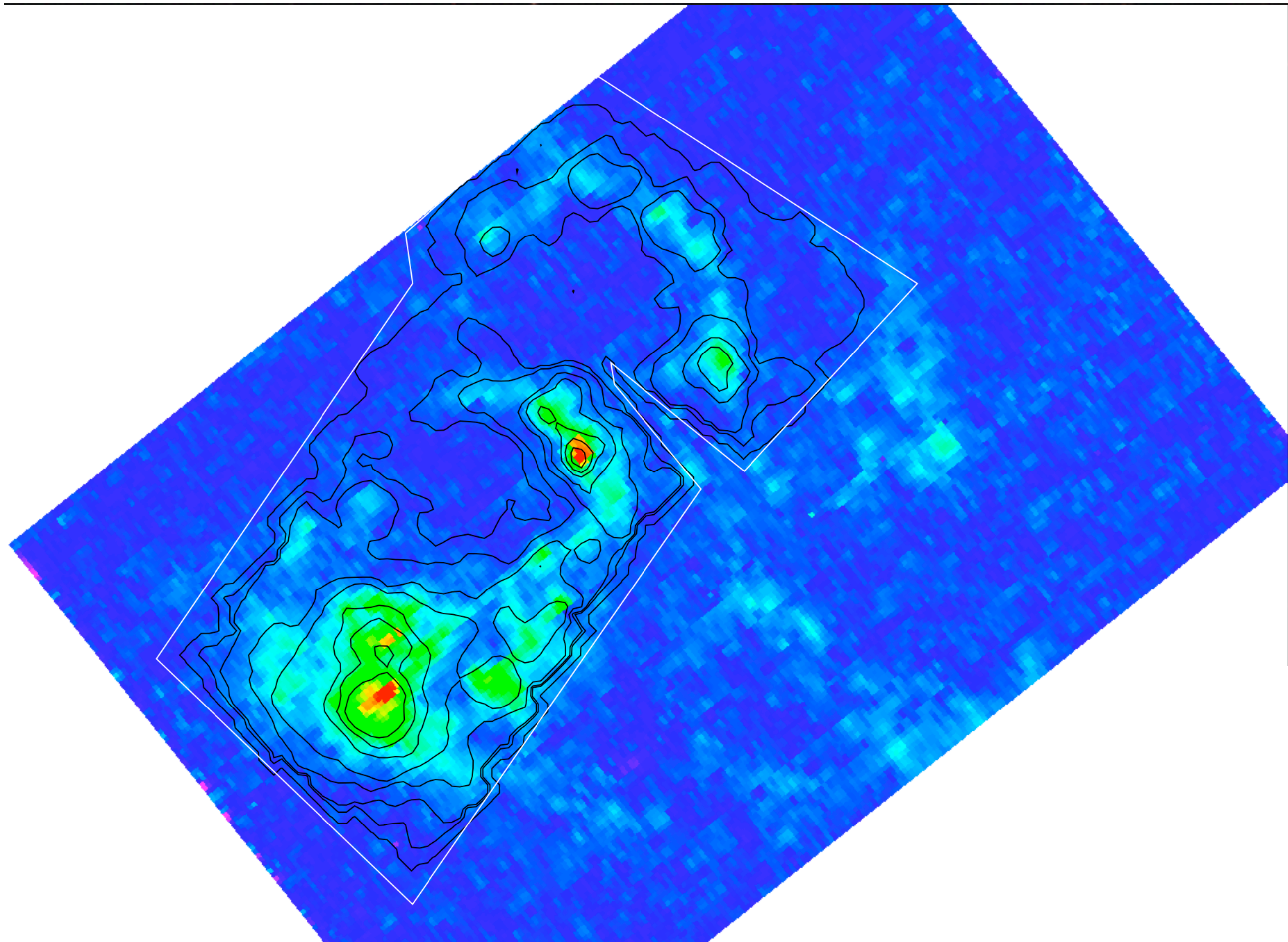
(Wilcots & Miller 1998)

Local Group: IC10 Z~1/6 solar

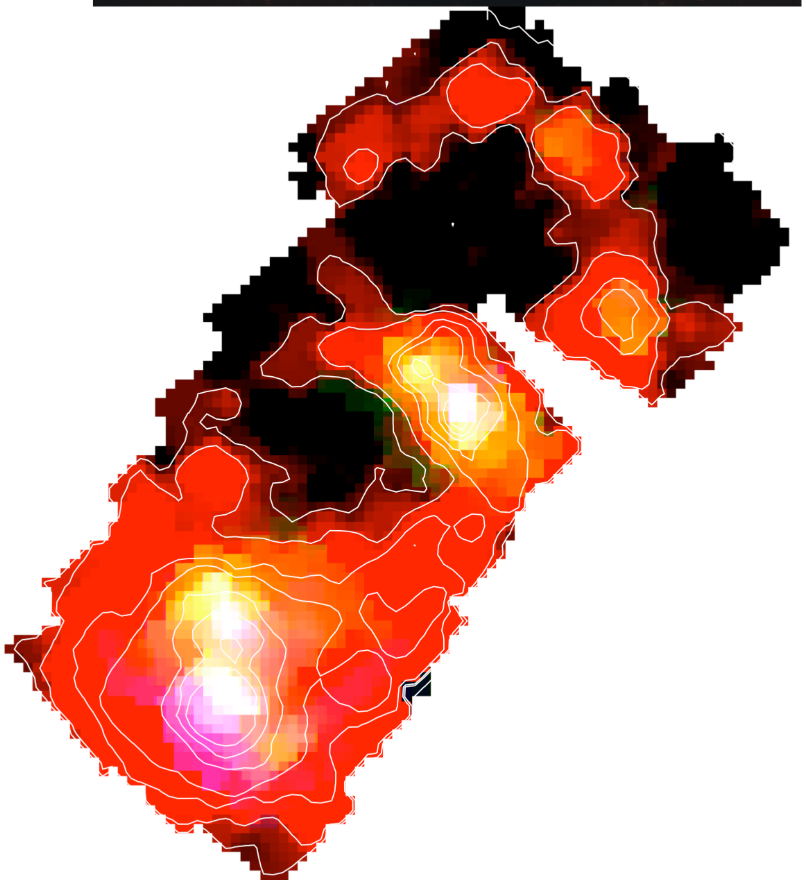


PACS CII map:
2’ x 6’



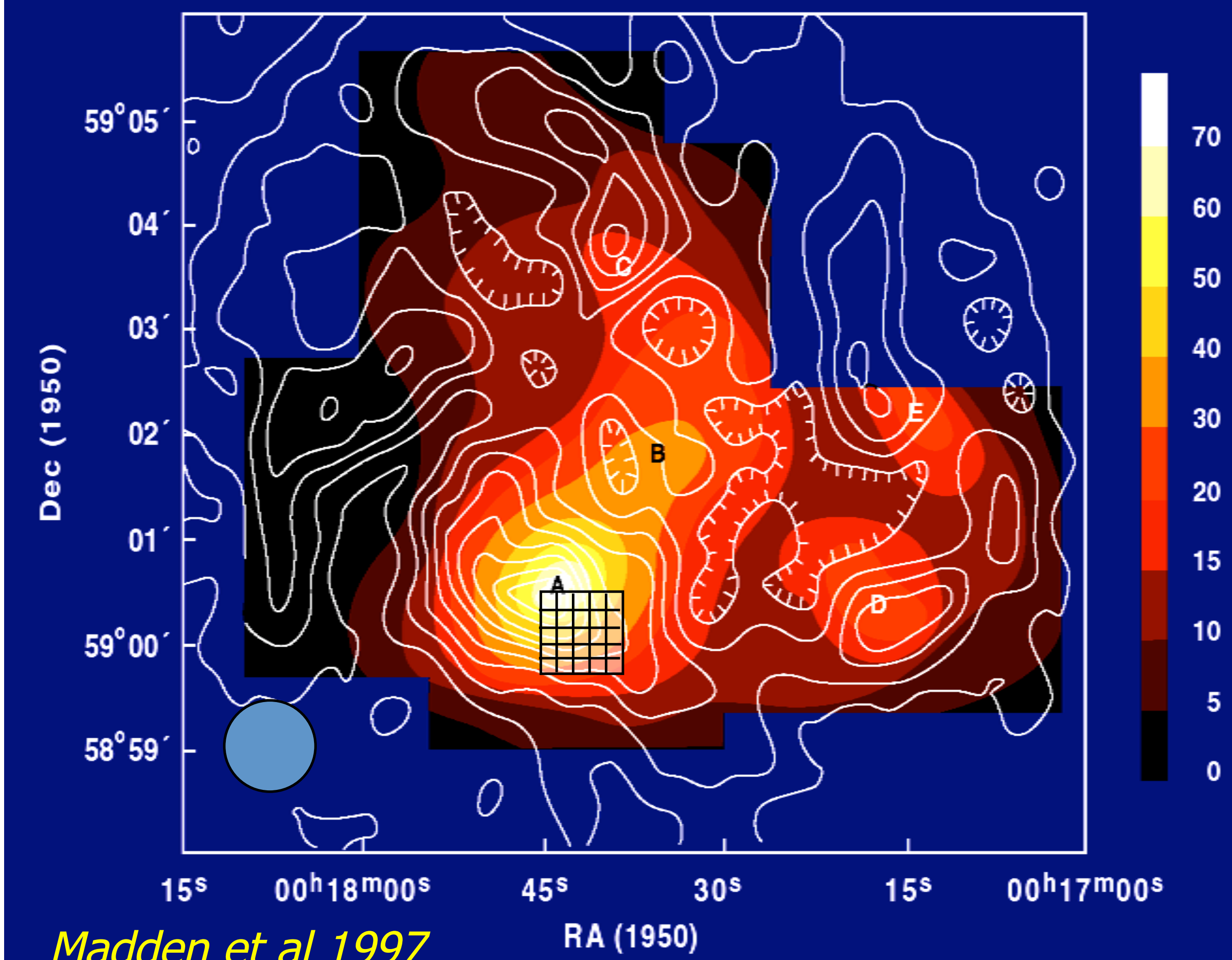


IC10: PACS CII
on IRS: PAH map
(Lebouteiller et al)



IC10: CIIPACS maps:
red: CII
green: OI63mu
Blue: OIII 88mu

[CII] Map in IC10 (D ~ 1Mpc)



Madden et al 1997

KAO FIFI (55″)
~ 6′ x 5′ map
~7h

Total [CII] luminosity:
1.5 10 ⁶ Lo

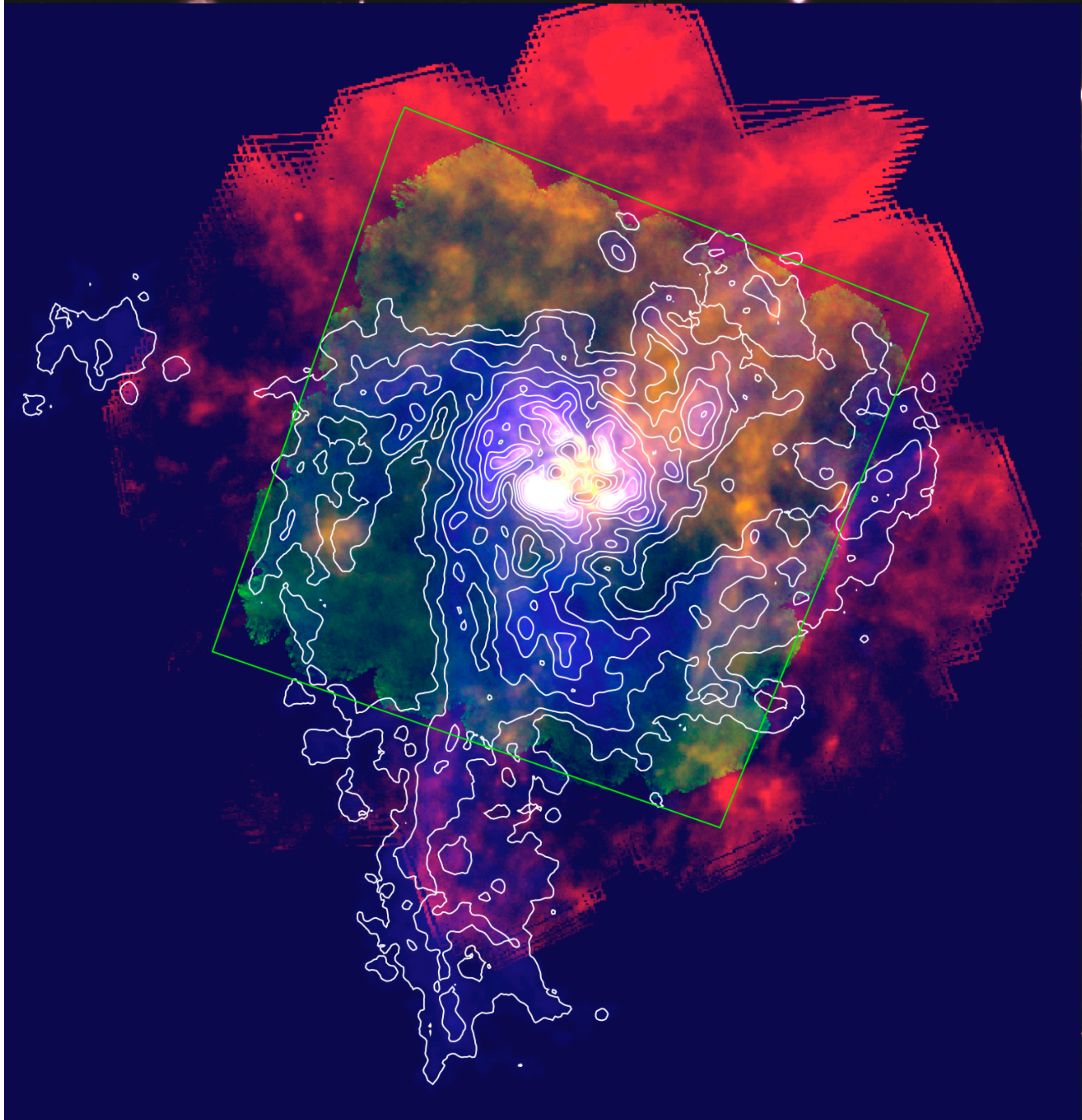
To reconcile cooling
Rates from [CII] and
Column densities =>

100 times more
Molecular mass
Traced by [CII]
Than using CO alone.

*Need [CII] measurements for **total** gas inventory*

PACS &
FIFI-ls
array

Local Group: IC10 Z~1/6 solar



20'

D= 800 kpc
2x10^10 M(solar)
(Wilcots & Miller 1998)

CII expected from most of HI

How long would it take make a 10' x 10' CII map with SOFIA down to 5x10^-18 or 19-17 W/m2 ?

The Magellanic Clouds

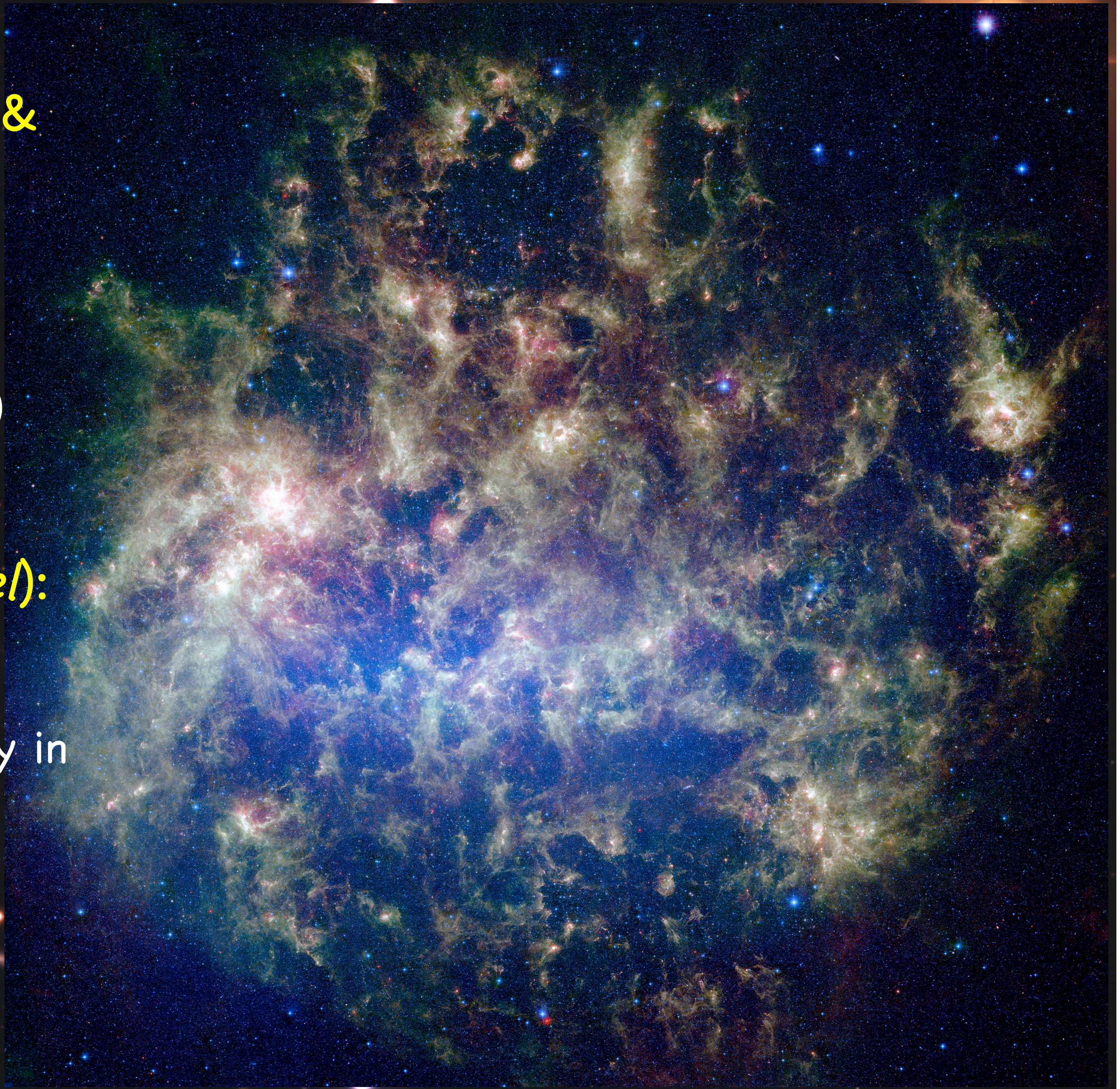
SAGE (*Spitzer*):
Mapped with IRAC & MIPS 8° × 8°

- ✓Green: PAHs (3.6 μm)
- ✓ Blue: stars (4.5 μm)
- ✓Red: hot dust (24 μm)

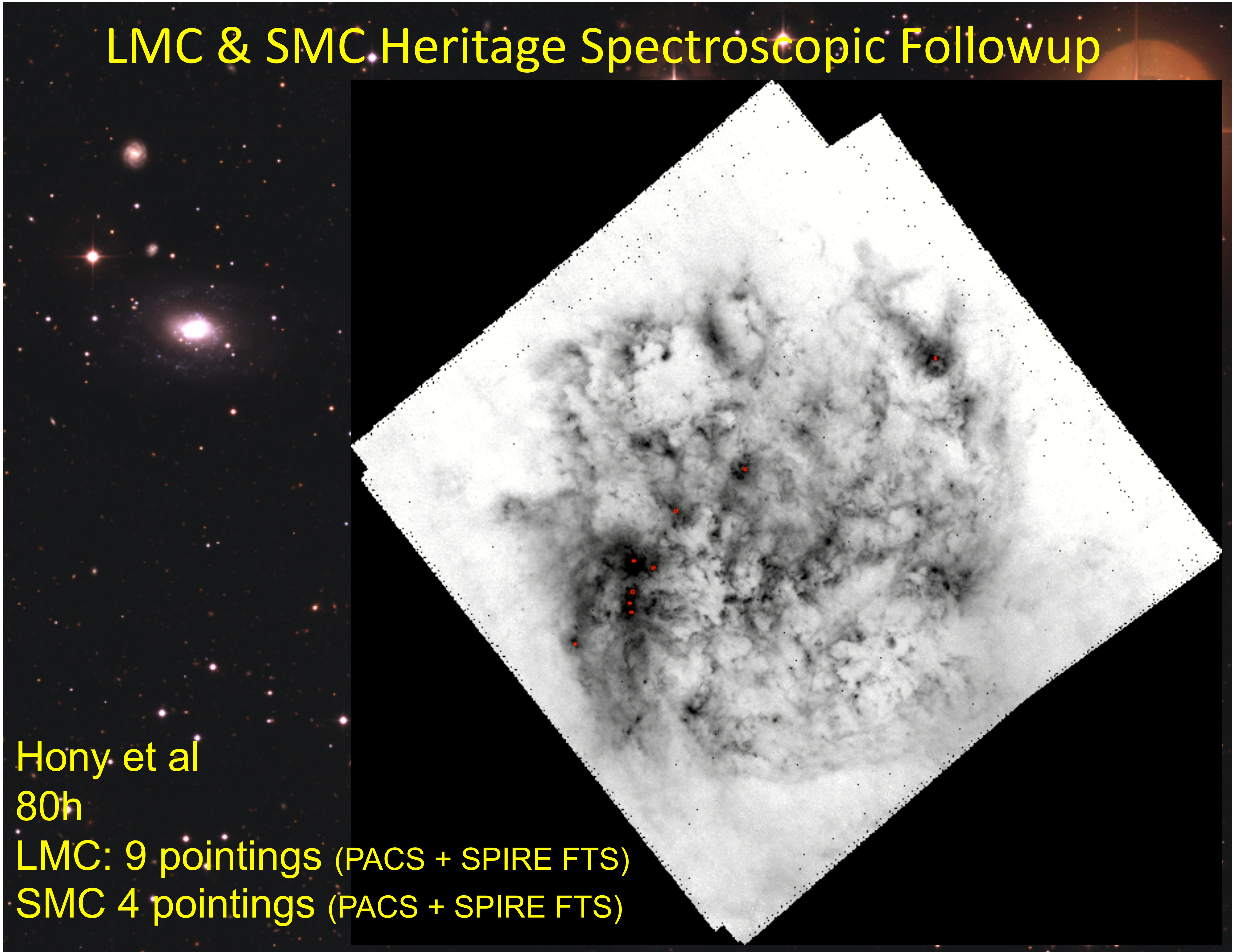
(Meixner *et al.*, 2006)

HERITAGE (*Herschel*):
PACS & SPIRE mapping

Hony et al Spectroscopy in LMC & SMC 80h

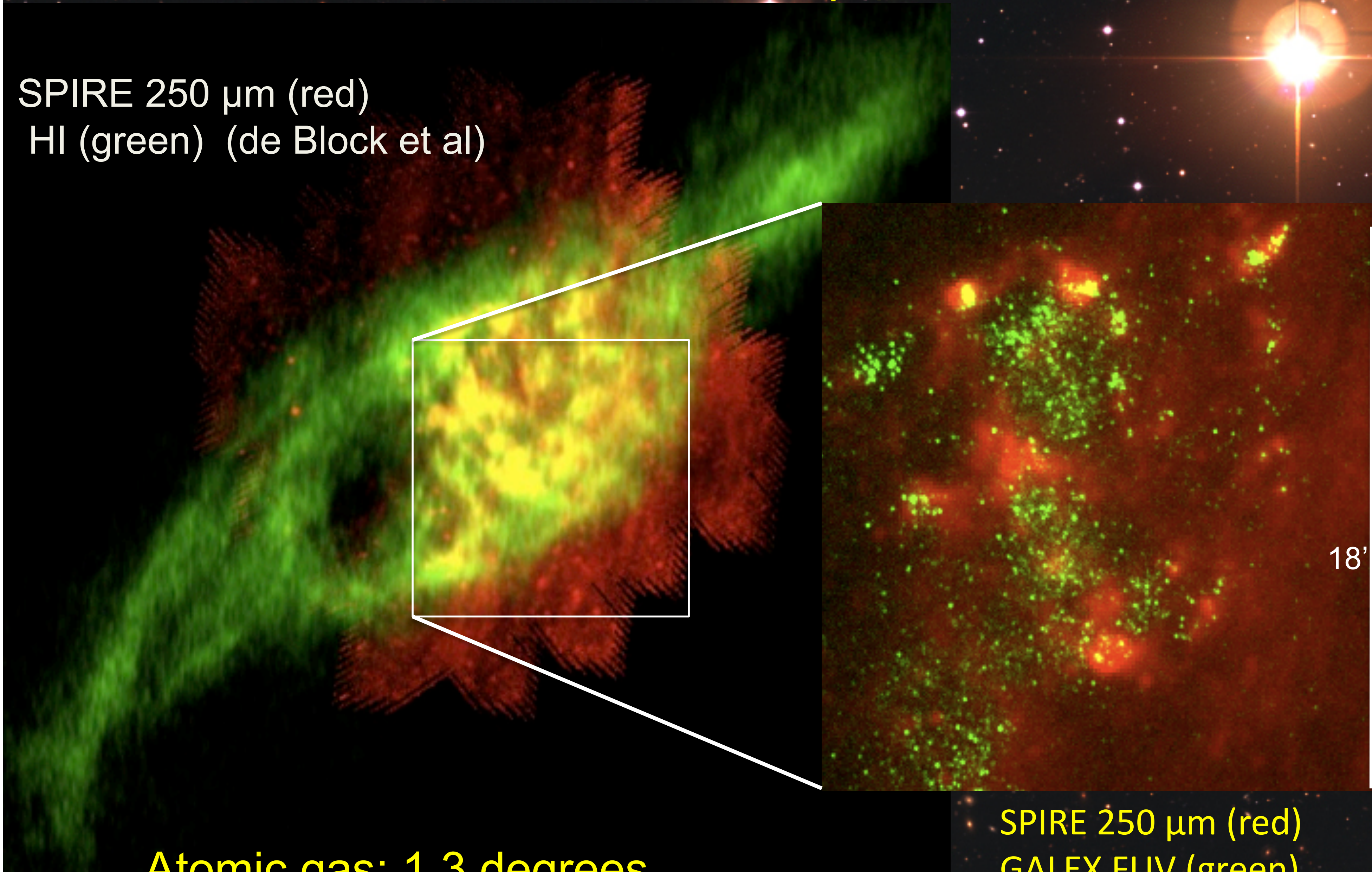


LMC & SMC Heritage Spectroscopic Followup



Hony et al
80h
LMC: 9 pointings (PACS + SPIRE FTS)
SMC 4 pointings (PACS + SPIRE FTS)

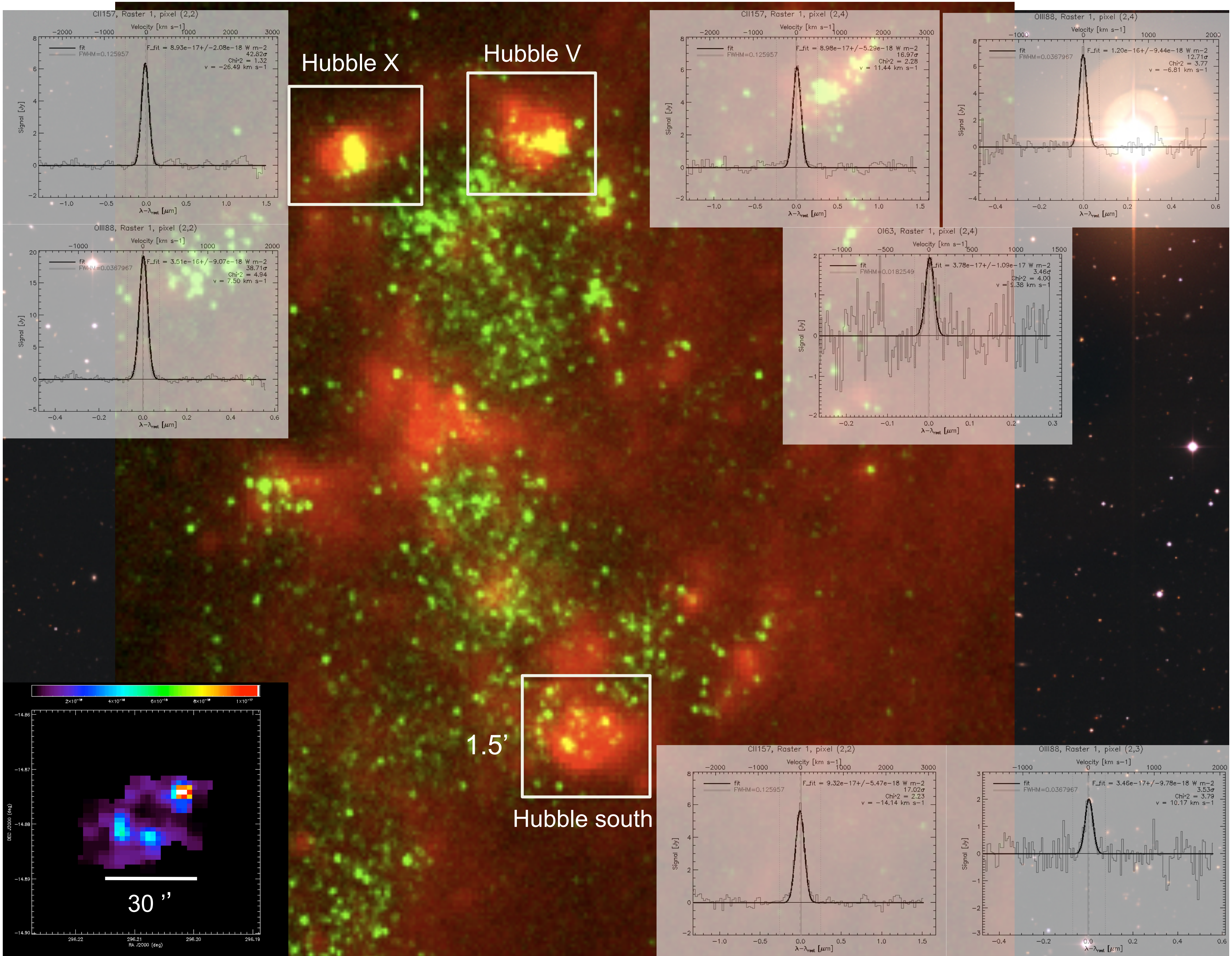
NGC 6822 D= 0.5 Mpc, Z= 1/5 Zsolar



SPIRE 250 μm (red)
GALEX FUV (green)

Atomic gas: 1.3 degrees

The star formation activity
Primarily in 18' region



Hubble X
Hubble V
Hubble south
1.5'
30 ''
CII157, Raster 1, pixel (2,2)
OIII88, Raster 1, pixel (2,2)
CII157, Raster 1, pixel (2,4)
OIII88, Raster 1, pixel (2,4)
OI63, Raster 1, pixel (2,4)
CII157, Raster 1, pixel (2,2)
OIII88, Raster 1, pixel (2,3)

Herschel and Beyond: Multiphase and Multiscale modeling of galaxies