Fine-structure line diagnostics of the SFR and ISM conditions

Ilse De Looze[1], Diane Cormier[2,3], Suzanne Madden[2], Sacha Hony[3], Vianney Lebouteiller[2], Eric Pellegrini[3], with inputs of the Dwarf Galaxy Survey and KINGFISH teams

[1] University College London, UK
[2] Laboratoire AIM, CEA, Saclay, Paris
[3] Zentrum für Astronomie der Universität Heidelberg

Molecules and dust as fuel to star formation, KITP, Santa Barbara June 22nd 2016

Outline

- **Fine-structure lines to trace the SFR**

  - how is FIR line emission linked with SFR?

  - do we see the same trends across all metallicities and galaxy types?

  - which FIR line = best SFR indicator?

- **FIR line diagnostics of ISM conditions**

  - origin of [CII] deficit and other line deficits

  - multi-phase ISM modelling

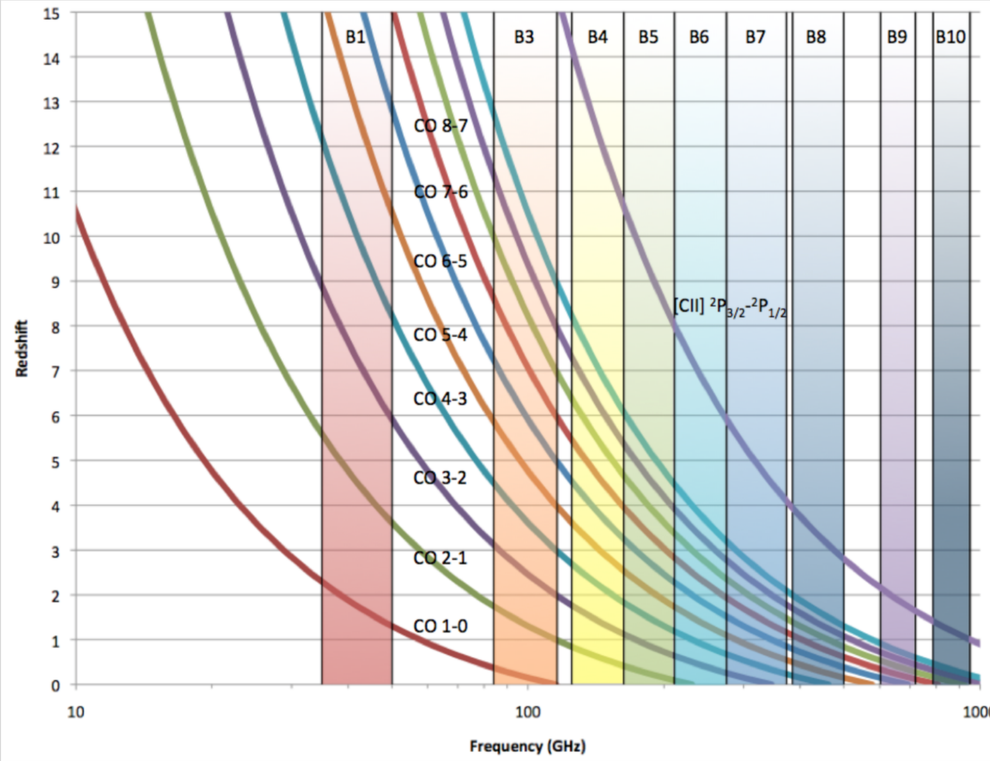
Why use FIR lines to trace the SFR?

- **C^+, O, O^{++}** are important **coolants** of the ISM
- strong line emission in star-forming galaxies
- Observable diagnostics at high redshift
  → line shifts to submm λ

(ALMA, IRAM, SMA, CARMA, …)

↓

Need to calibrate FIR lines
as SFR tracer in the local Universe
on metal-poor galaxies



Di Francesco+2013

Why use FIR lines to trace the SFR?

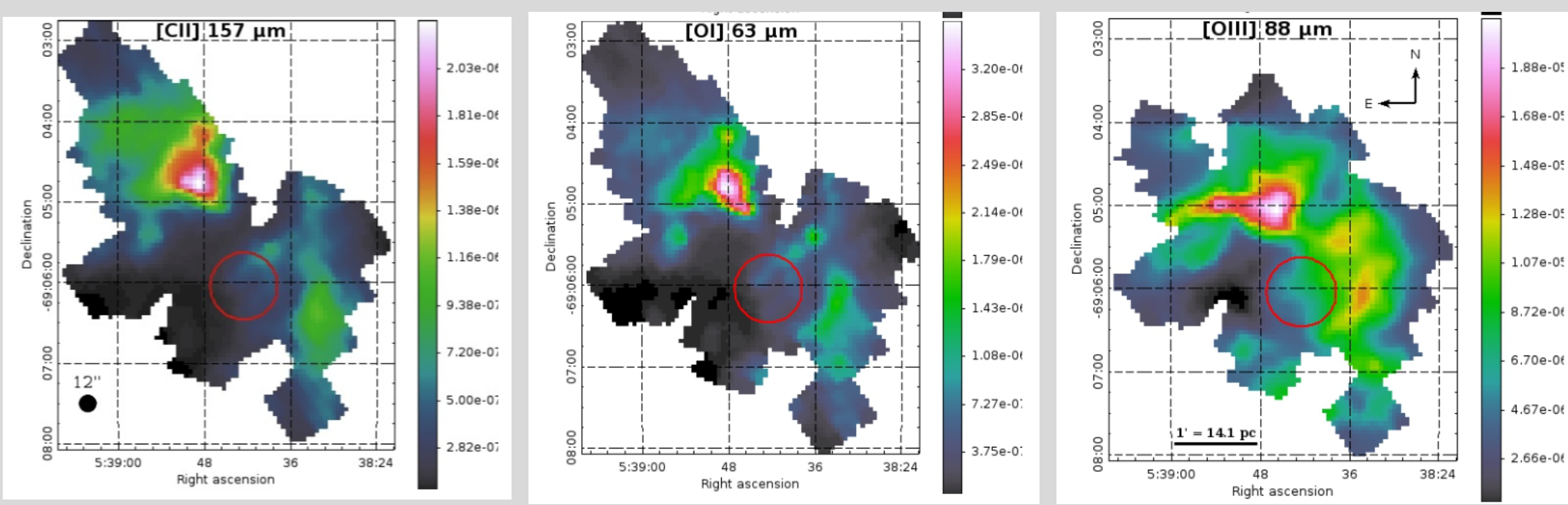
$[CII]_{158}$ → photo-dissociation regions (PDRs), diffuse HI clouds+ ionized media (due to low ionization potential)

$[OI]_{63}$ → warm and/or dense PDRs

$[OIII]_{88}$ → highly **ionised**, low-density gas

	$[CII]_{158}$	$[OI]_{63}$	$[OIII]_{88}$
$n_{cr}(cm^{-3})$	$3\text{-}5 \times 10^3$	$>10^5$	510
T_{exc} (K)	91	228	163
IP (eV)	11.3		35.1

FIR line view of 30 Dor (Chevance+ 2016):



Why use FIR lines to trace the SFR?

Good SFR tracers?

$[CII]_{158}$ → brightest FIR line (1% of TIR)
→ ambiguous origin (HII region, diffuse ionised, PDR)
→ [CII] line deficit

$[OI]_{63}$ → 2^{nd} brightest line in PDR
→ self-absorption, optical depth effects
→ possible shock excitation

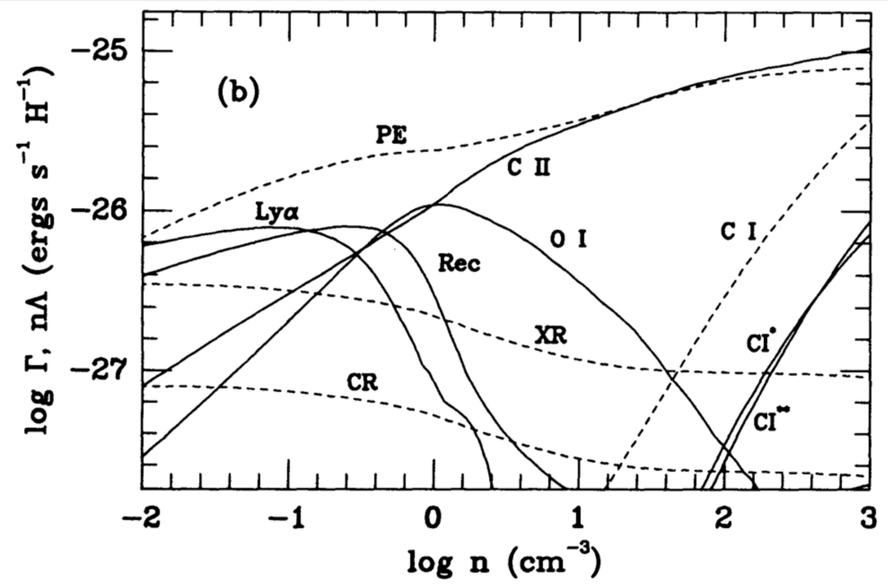
$[OIII]_{88}$ → brightest line towards low Z
→ line emission depends strongly on IP, electron density

In an ideal world…

Gas cooling (line emission) ⟷ **is linked to** ⟷ **star formation**

Higher SFR —> increased input to gas heating
—> need for more cooling through line emission

More efficient cooling —> easier contraction of molecular clouds
—> higher level of SF



Wolfire+ 1995

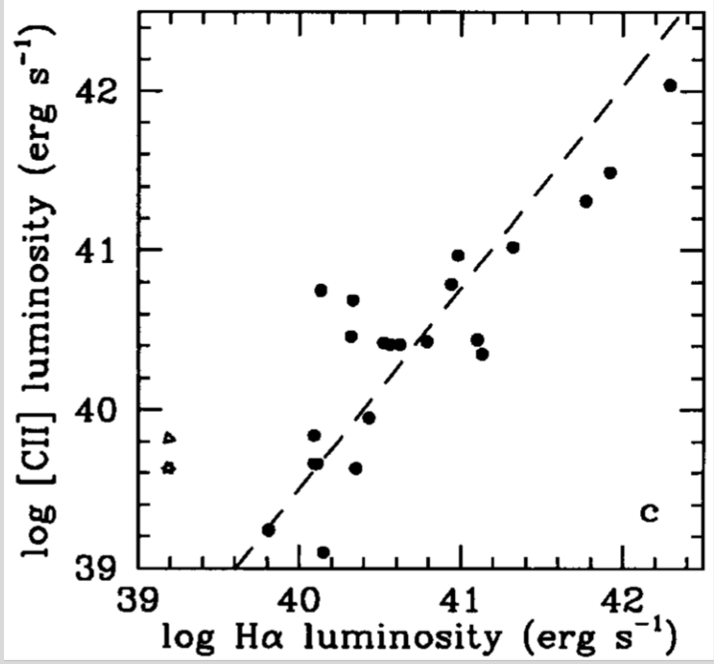
Previous [CII] calibrations

Boselli et al. (2002)

Calibration of SFR relation based on:
- Hα+[NII] lines
- ISO [CII] data

➔ dispersion $L_{H\alpha}$ – $L_{[CII]}$ relation: ≈ 3

➔ uncertainty on SFR estimate: ≈ 10

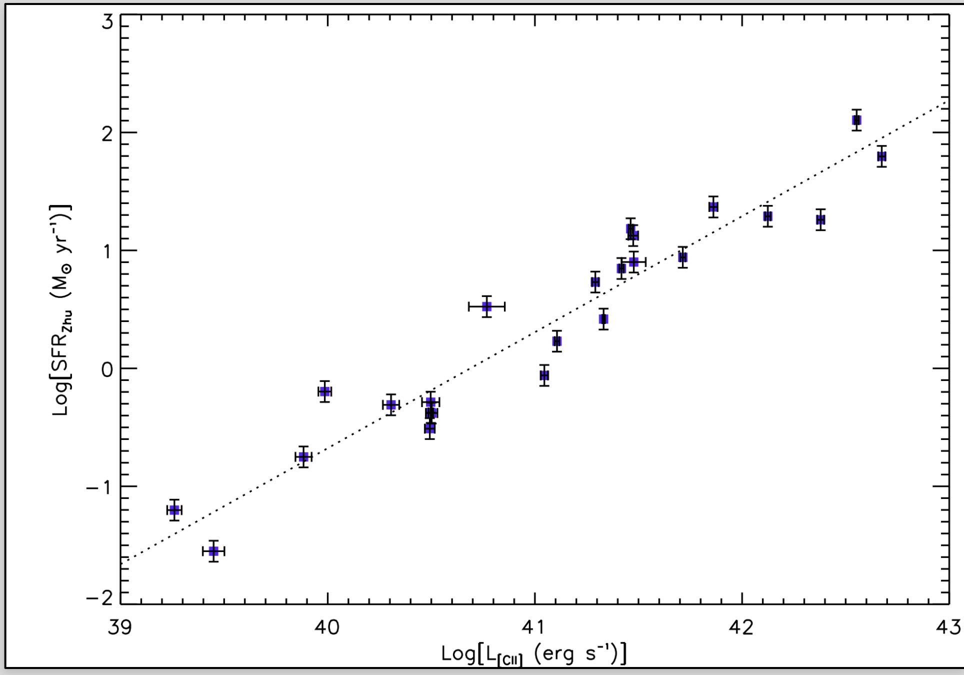


Conclusion: large dispersion in SFR-$L_{[CII]}$ relation due to different contributions to [CII] emission in galaxies

⟶ [CII] = poor SFR tracer?

BUT: large uncertainty on [NII] correction and Hα extinction

Previous [CII] calibrations



De Looze et al. (2011)

Calibration of SFR relation based on
- FUV+24 µm data
- ISO [CII] data (Brauher+ 2008)

➔ tight correlation: SFR and $L_{[CII]}$

Conclusion:

less dispersion (0.27 dex) than in Boselli et al.(2002)

BUT

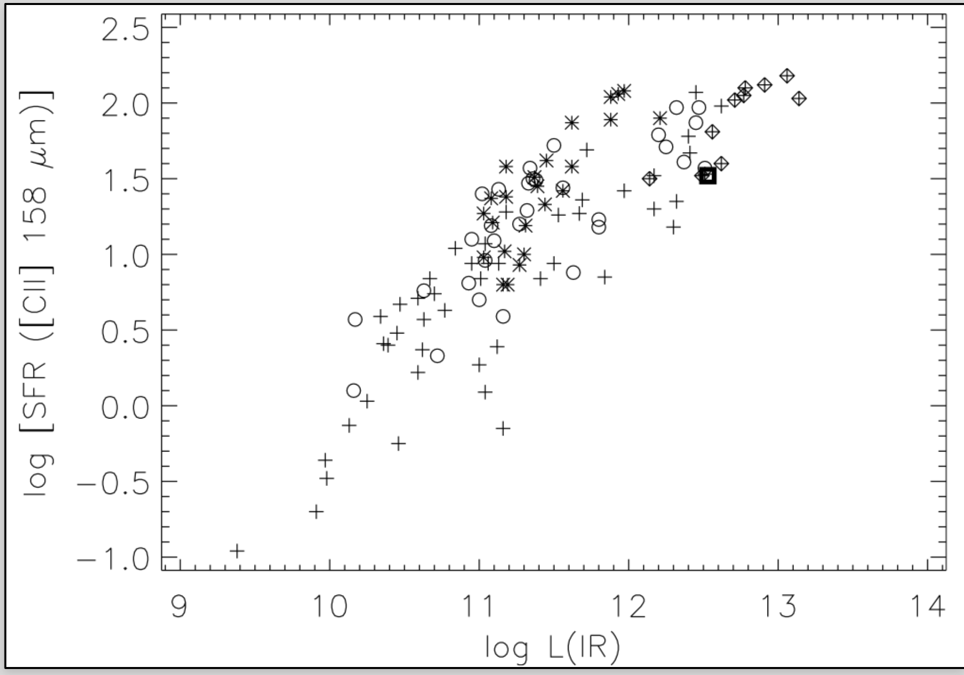
- Limited sample of merely metal-rich galaxies
- No spatially resolved observations → no constraint on origin of C^+

Previous [CII] calibrations

Sargsyan et al. (2012)

- [CII] can be used as SFR tracer in starburst galaxies

- deficit in [CII] for AGNs due to contribution from AGN to L_{IR}

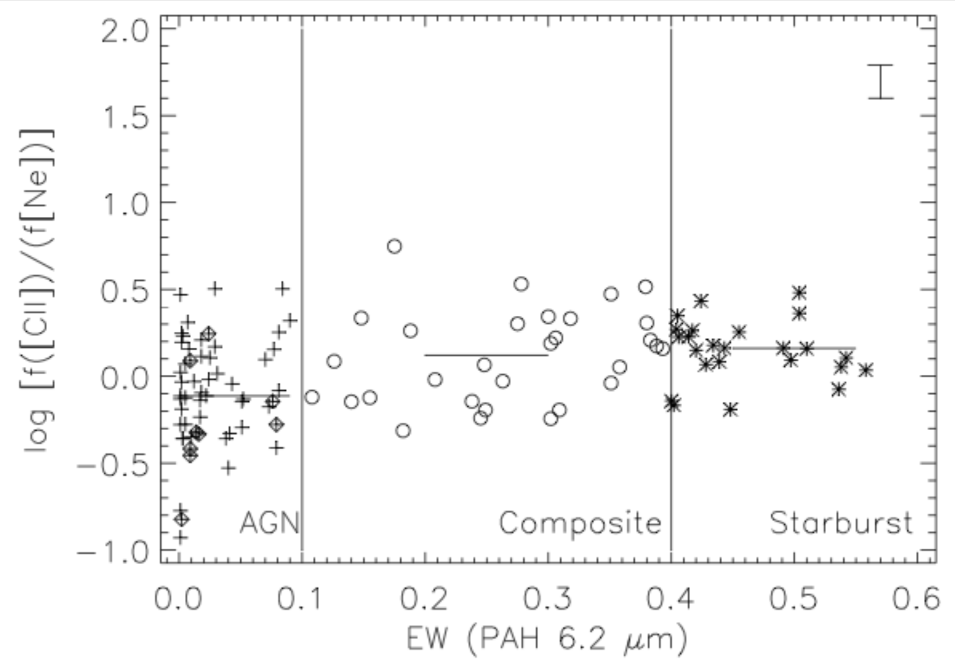


Conclusions: [CII] = reliable SFR indicator in normal star-forming galaxies, possibly also in AGNs

Previous calibrations

Sargsyan et al. (2014)

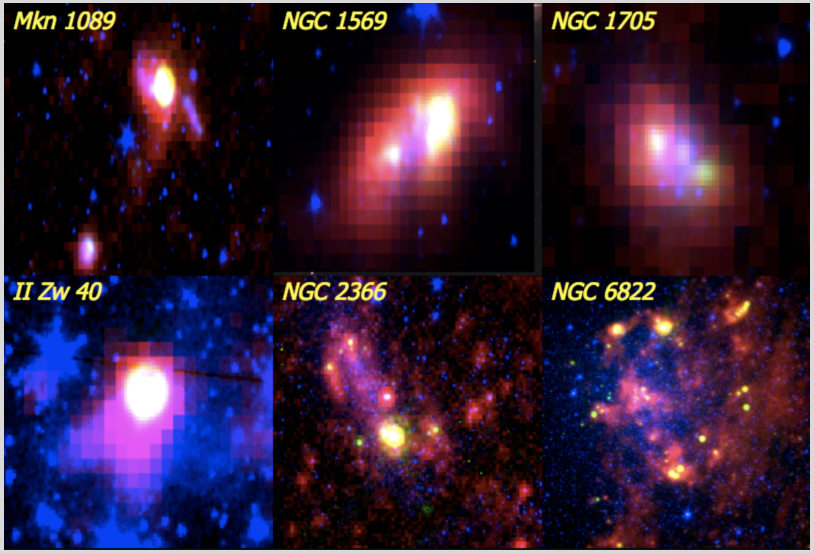
- enlarged sample compared to Sargsyan et al. (2012)
- SFR-[CII] calibration is similar using L_{IR} or [Ne II]+[Ne III] to trace the SFR



Conclusions: a.) [CII] is good SF diagnostic in starbursts,
b.) 158 µm continuum = reliable SF tracer, less affected by line deficits

FIR lines as SFR tracers:
effect of metallicity and galaxy type

Herschel program:
Dwarf Galaxy Survey
PACS/SPIRE phot+spec of 50 low-Z galaxies



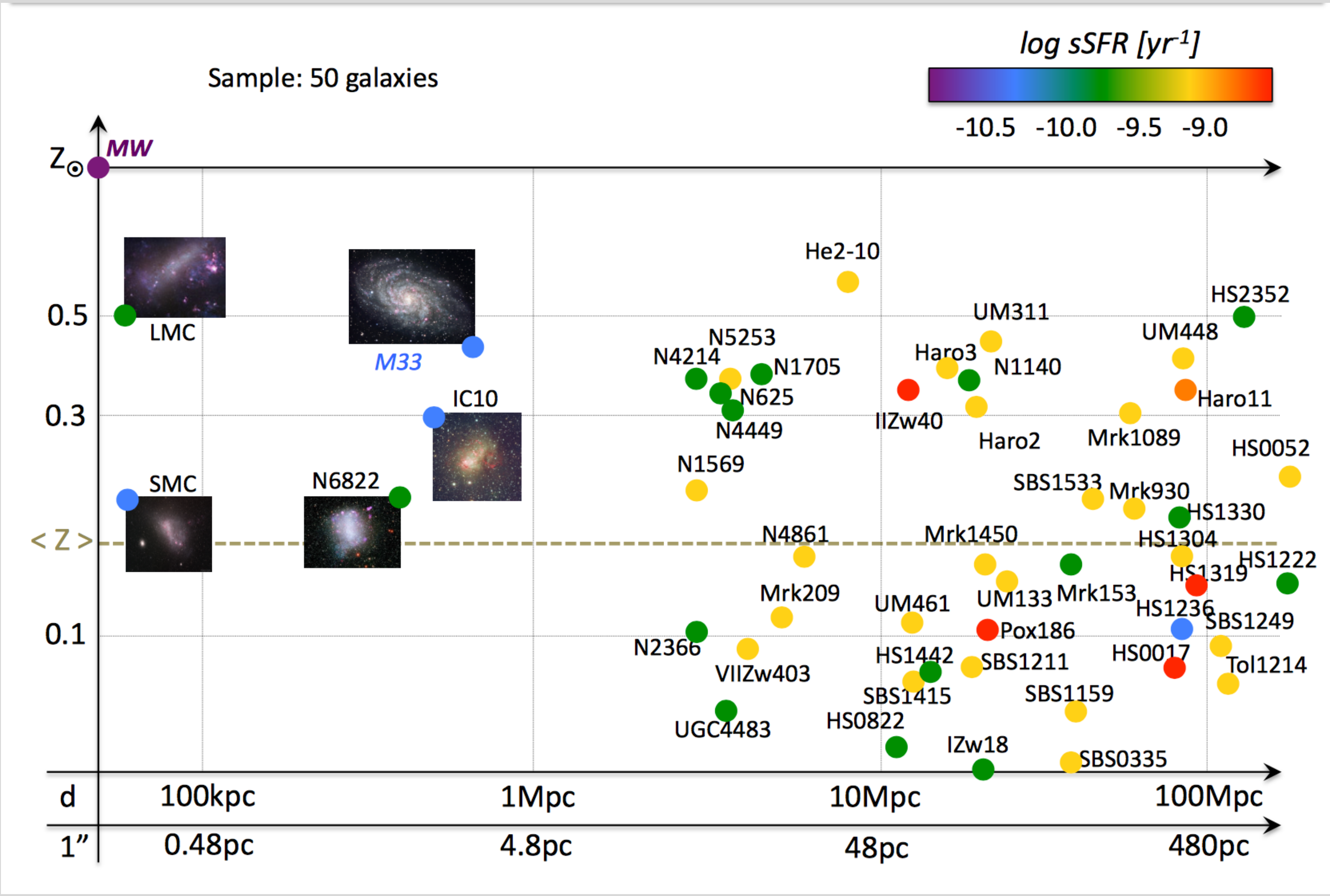
Literature sample of 530
- dwarfs
- starbursts
- AGNs
- ULIRGs
- high-redshift galaxies
with FIR line measurements

De Looze et al. (2014) A&A, 568, A62

Herschel Dwarf Galaxy Survey

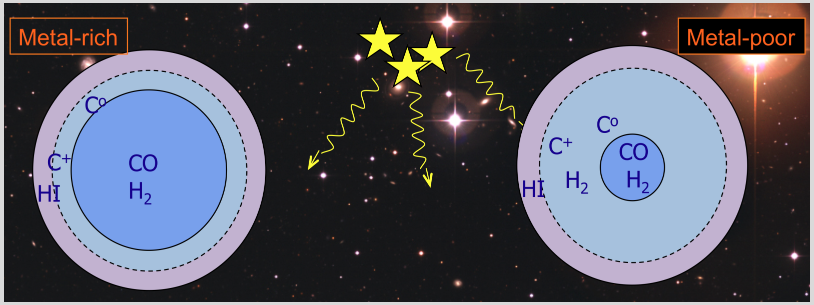
Madden+ 2013

- Sample of 50 dwarf galaxies
- Wide metallicity range: 1/50 $Z_{sun} \leq Z \leq Z_{sun}$

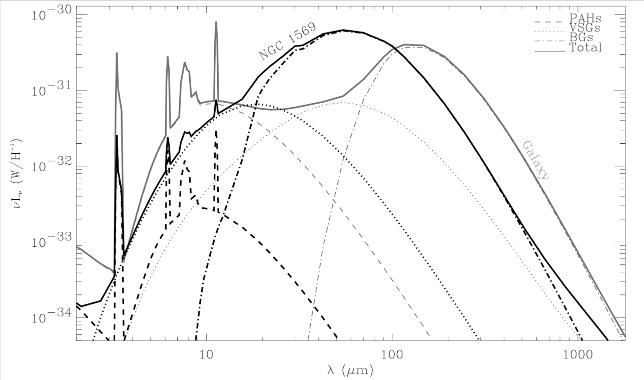


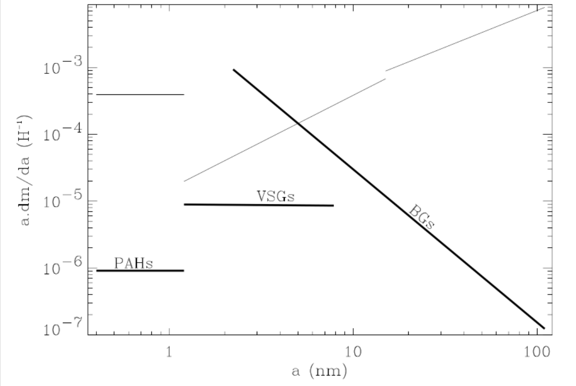
Influence of Z?

- Lower Z ⟶ less dust
  ⟶ longer free path lengths
  ⟶ photo-dissociation of CO
  ⟶ larger C^+ emitting zone



- Lower Z ⟶ peculiar grain properties
  ⟶ dearth of PAHs
  ⟶ high abundance of very small grains (VSGs)





Dust SED of dwarf NGC1569
Galliano+2003

PAHs/VSGs dominate photoelectric effect
⟶ influence on gas heating/cooling balance?

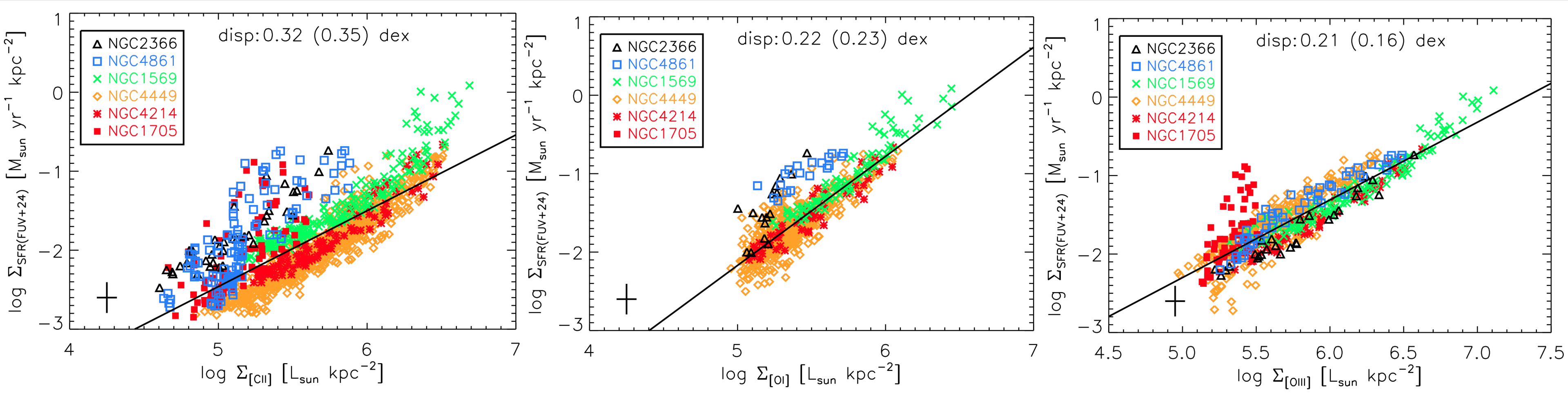
Spatially resolved SFR relations

- ❑ Offset between individual galaxies

⟶ dispersion in SFR relations = driven by diversity in ISM properties (e.g. Z, RF, ionisation, dust properties, heating mechanisms)?

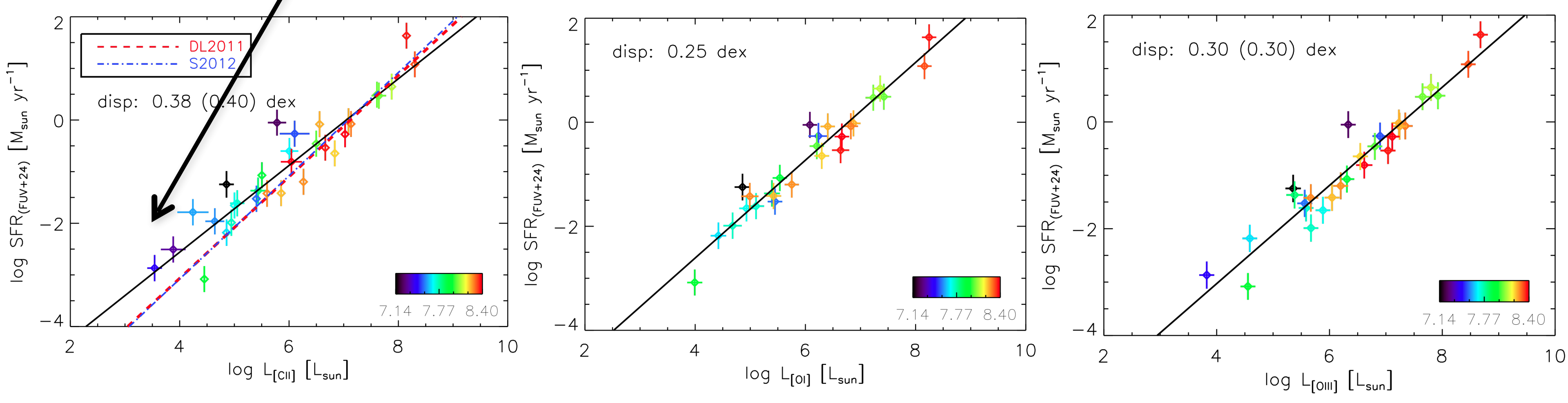
- ❑ Dispersion is largest for SFR-[CII] relation

⟶ [CII] = poor SFR tracer in metal-poor galaxies!



Global SFR relations

- ❑ [CII] = poor SFR tracer on global scales
- ❑ [OI] = most reliable SFR tracer in metal-poor dwarfs
- ❑ Weak [CII] emission towards lower metallicities
  Why?



Why [CII] = poor SFR tracer?

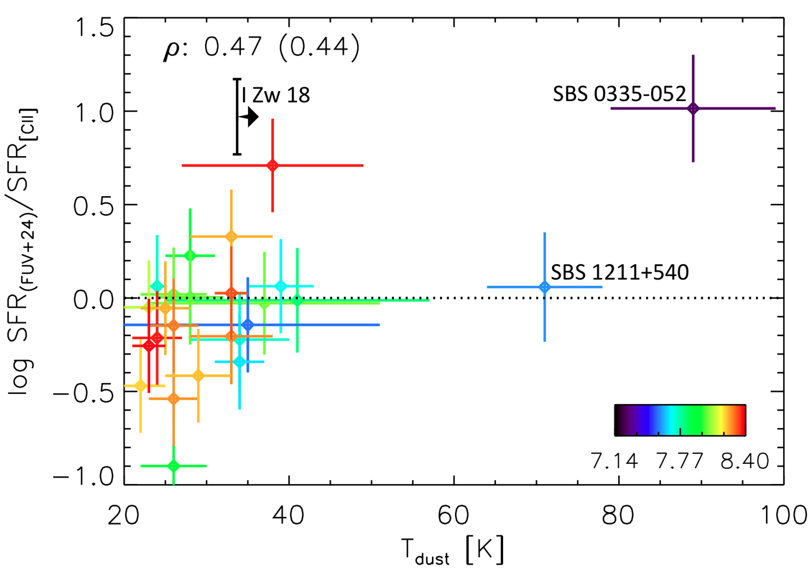
- **Hard radiation field** in low-Z galaxies

→ photo-electric efficiency drops due to **PAH destruction** (e.g. Boselli+ 2004, Engelbracht+ 2005, Jakcson+ 2006, Madden+ 2006, Draine+ 2007, Engelbracht+ 2008, Galliano+ 2008)

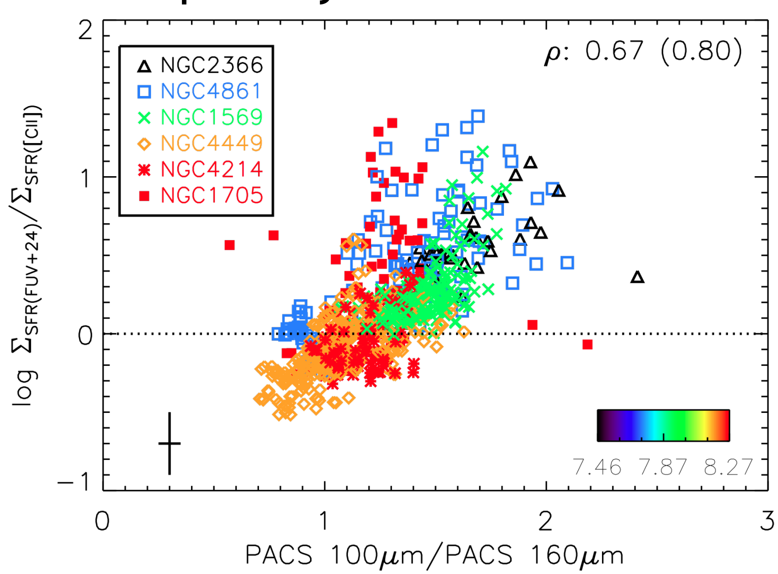
→ increase of **grain charging** parameter, lowers photo-electric efficiency (e.g. Tielens & Hollenbach 1985a, Malhotra+ 1997, Negishi+ 2001, Croxall+ 2012, Farrah+ 2013)

→ carbon might be locked in C^{++} rather than C^{+}

On global galaxy scales…



On spatially resolved scales…



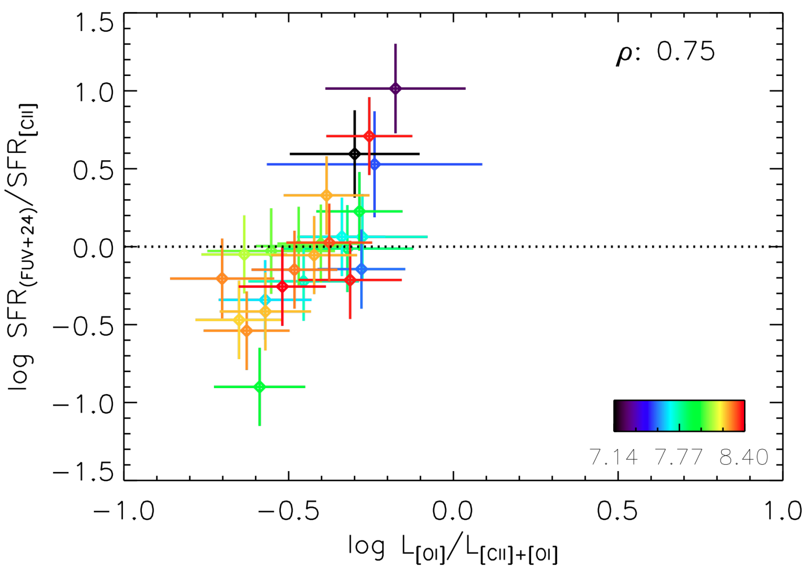
Why [CII] = poor SFR tracer?

❑ **Different ISM structure** towards low Z

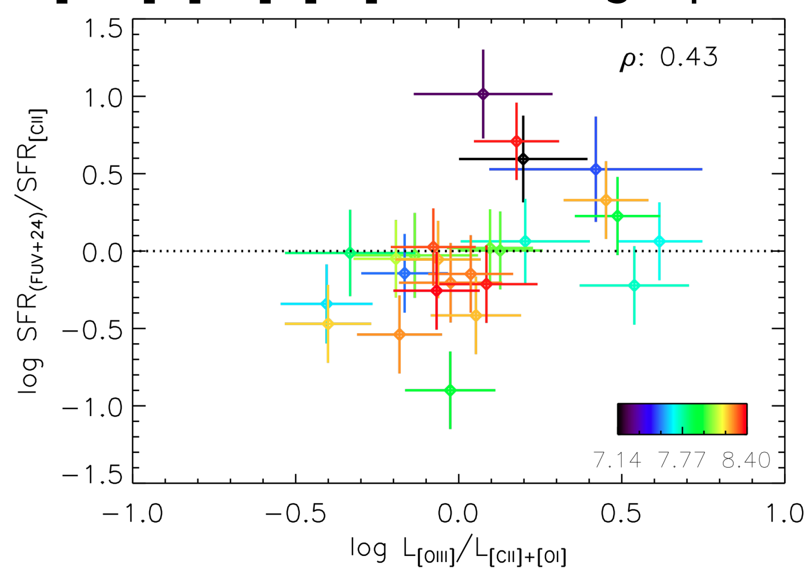
→ hard radiation + transparency of ISM
= large filling factor of ionised gas (Lebouteiller+ 2013,Cormier+ 2015)

→ @ extreme low Z (0.1 Z_{sun}): pseudo-PDRs dominated by soft X-ray heating (not photo-electric effect!) (Pequignot 2008, Lebouteiller in prep.)

[OI]/[CII]+[OI] = proxy warm/dense PDRs



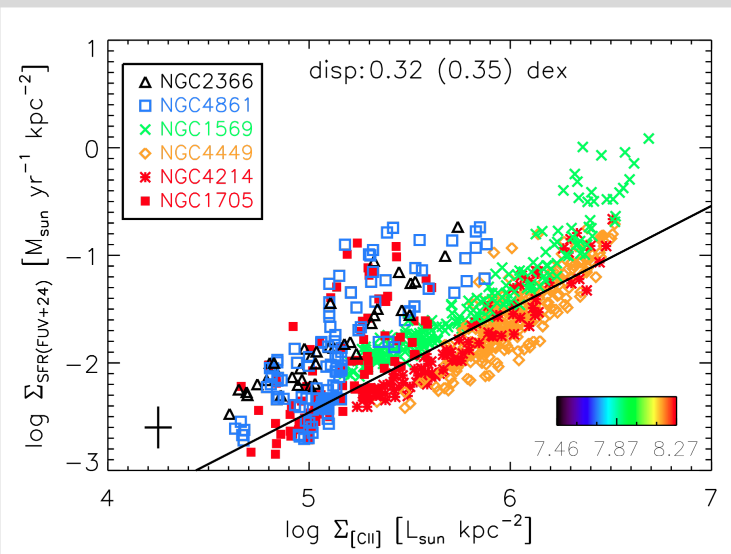
[OIII]/[CII]+[OI] = ionized gas phase

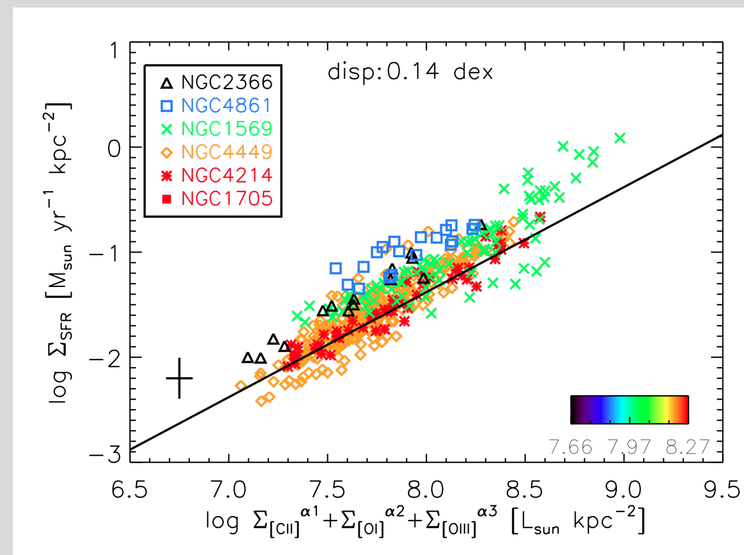


Combining $[CII]_{158}$, $[OI]_{63}$, $[OIII]_{88}$

In an ideal world… we combine FIR lines from different ISM phases

SFR-$L_{[CII]}$: 0.32 dex → SFR-$L_{[CII]+[OI]+[OIII]}$: 0.14 dex



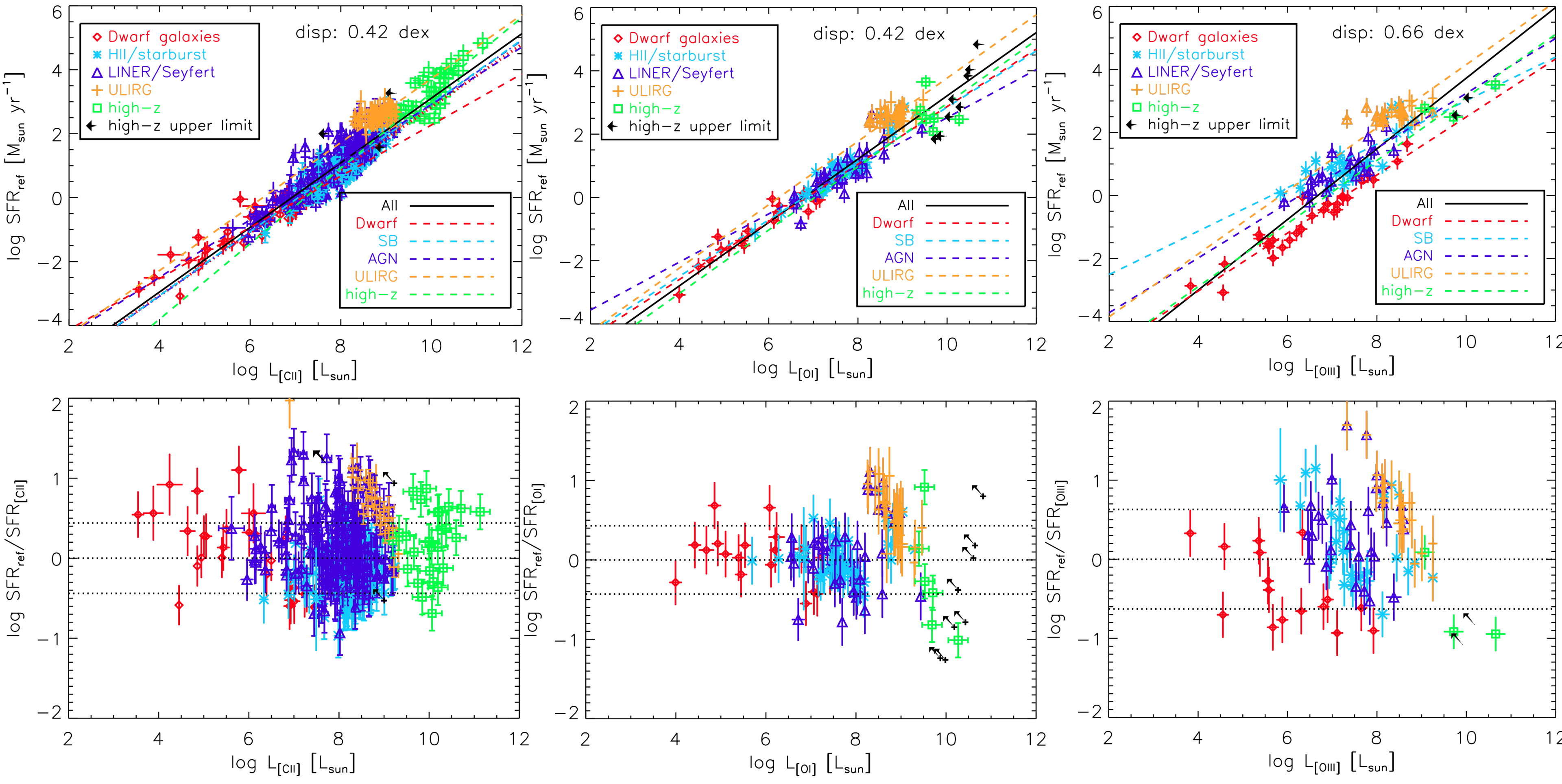


Significant ***reduction of scatter*** in SFR-L_{line} relation

—> other FIR cooling lines more important than C^{+} at low Z

Literature sample

◇ Sample consisting of dwarfs, starburst, AGNs, ULIRGs, high-redshift galaxies with [CII] (530), $[OI]_{63}$ (150) and $[OIII]_{88}$ (102)



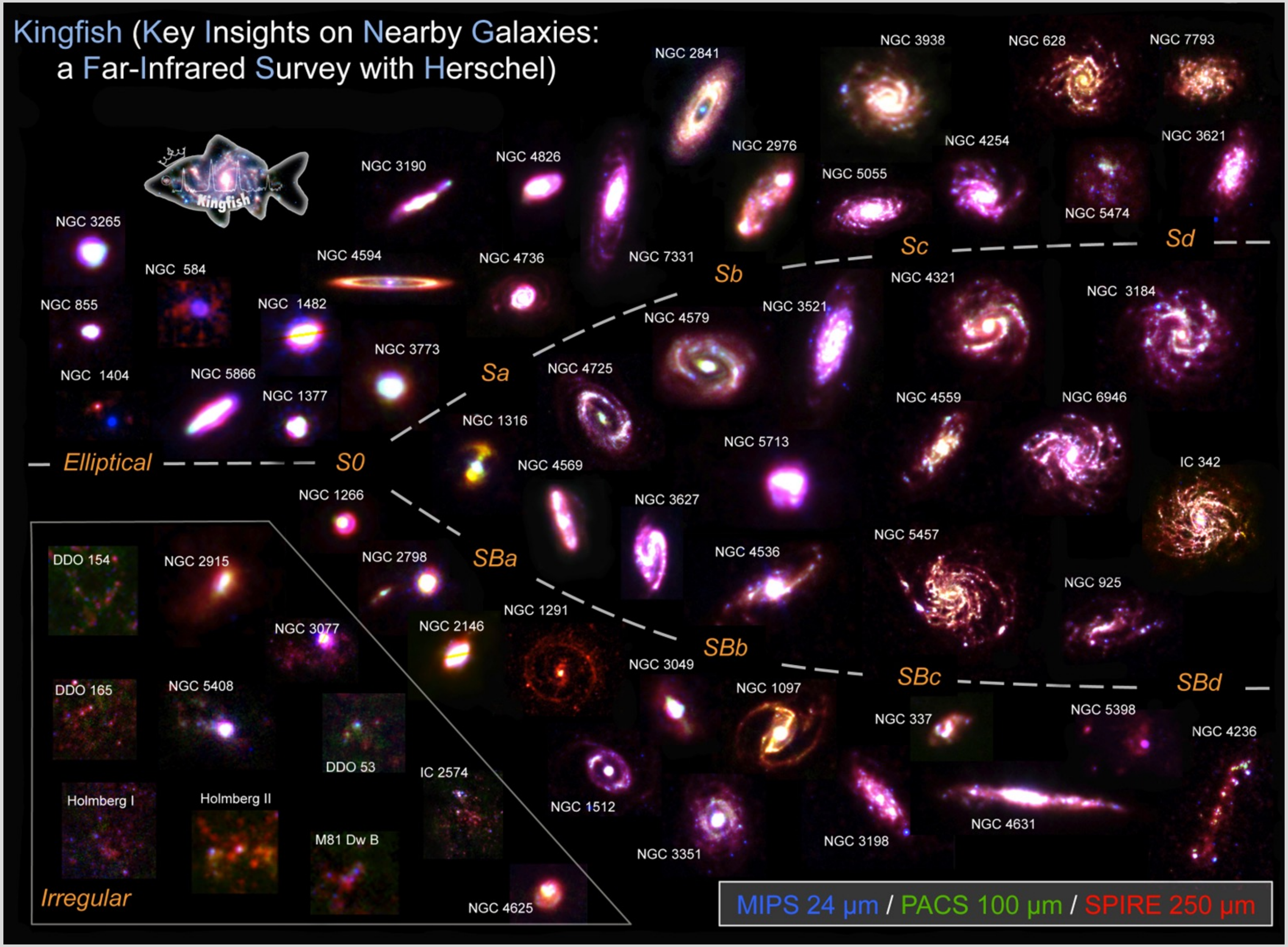
Literature sample

- $[OI]_{63}$, [CII] = most reliable SFR tracers, $[OIII]_{88}$ = unreliable SFR tracer
- Line deficit in ULIRGs causes offset in SFR calibrations
- [CII] = best calibrated SFR tracer @ high-redshift

Requirement: separate SFR calibrations + prescriptions per galaxy type

De Looze et al. (2014)

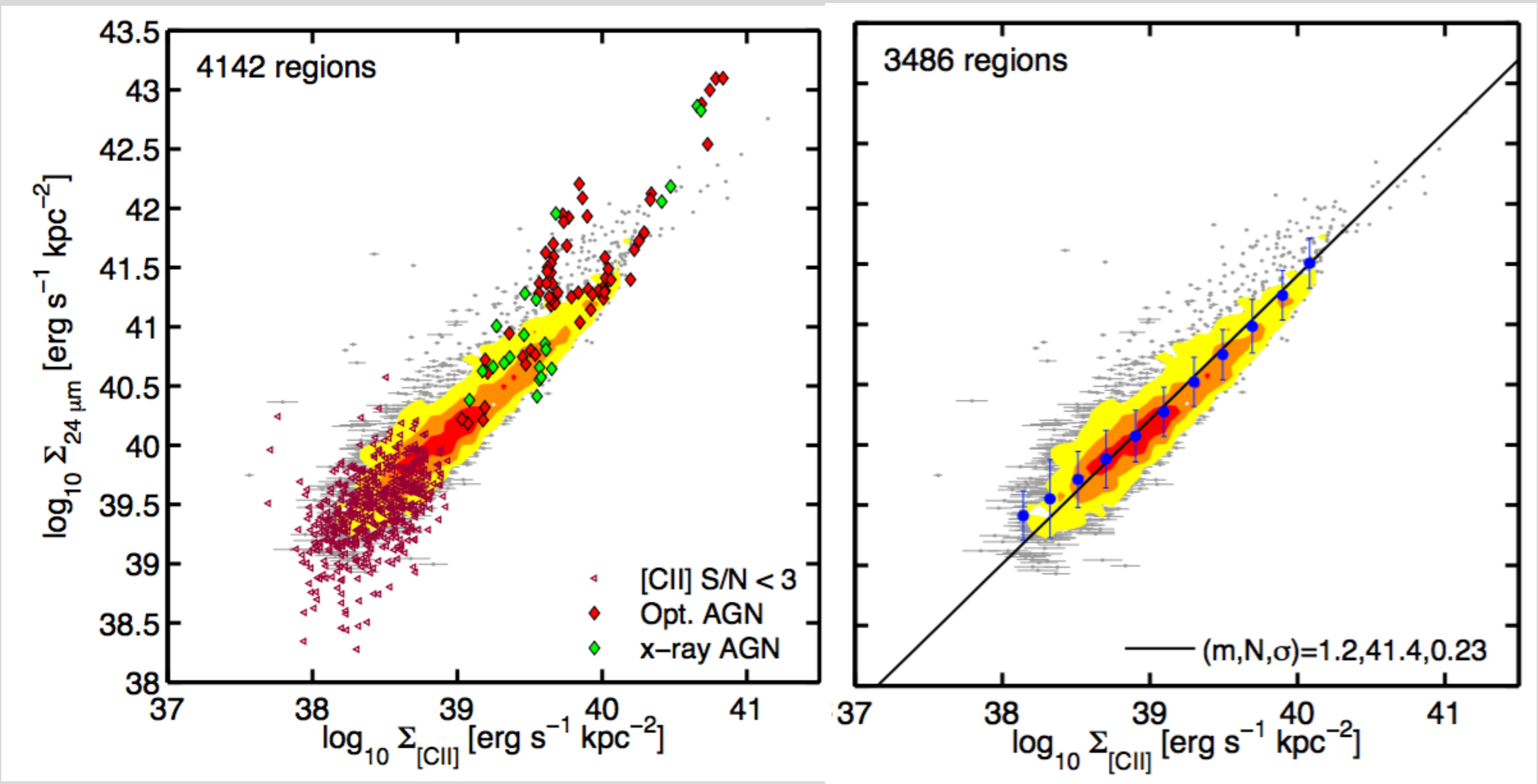
KINGFISH sample



Kennicutt+ 2011

KINGFISH sample

Correlation between [CII] and SFR surface densities $\Sigma_{[CII]}$-Σ_{SFR}

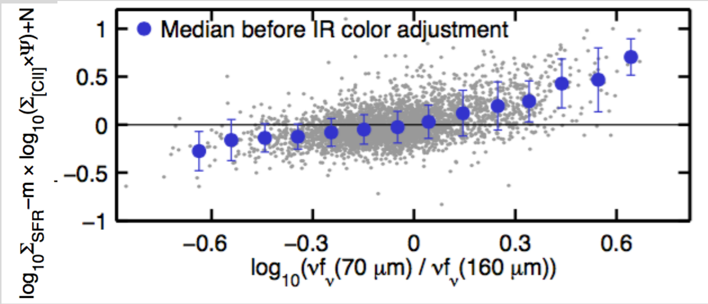


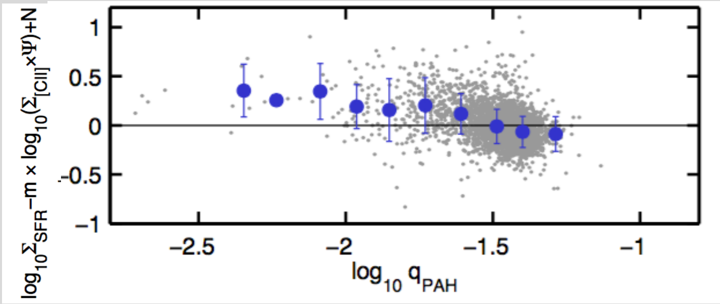
Offset for galaxy centers in MIPS 24-[CII] relation

Herrera-Camus+ 2014

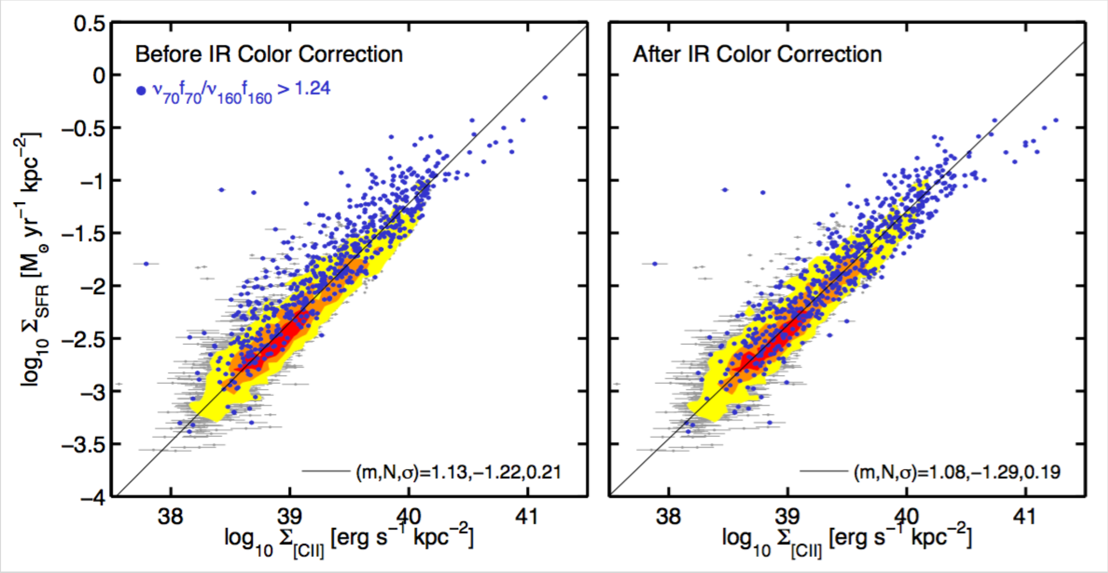
KINGFISH sample

Residuals in $\Sigma_{[CII]}$-Σ_{SFR} relation correlate with IR color, not q_{PAH}





→ SFR-[CII] relation with **IR color as secondary parameter**

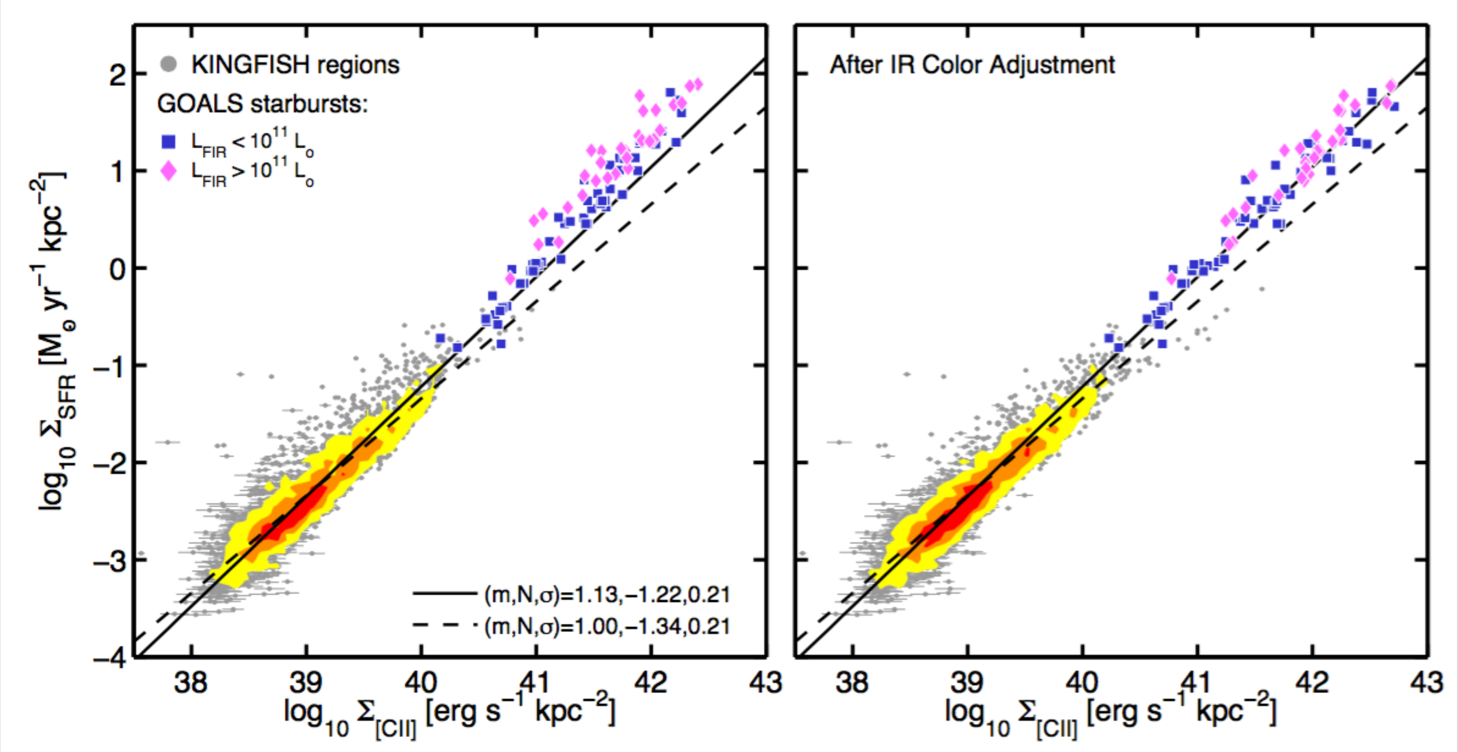


Herrera-Camus+ 2014

KINGFISH sample

Can be applied to normal SF galaxies and non-AGN LIRGs:

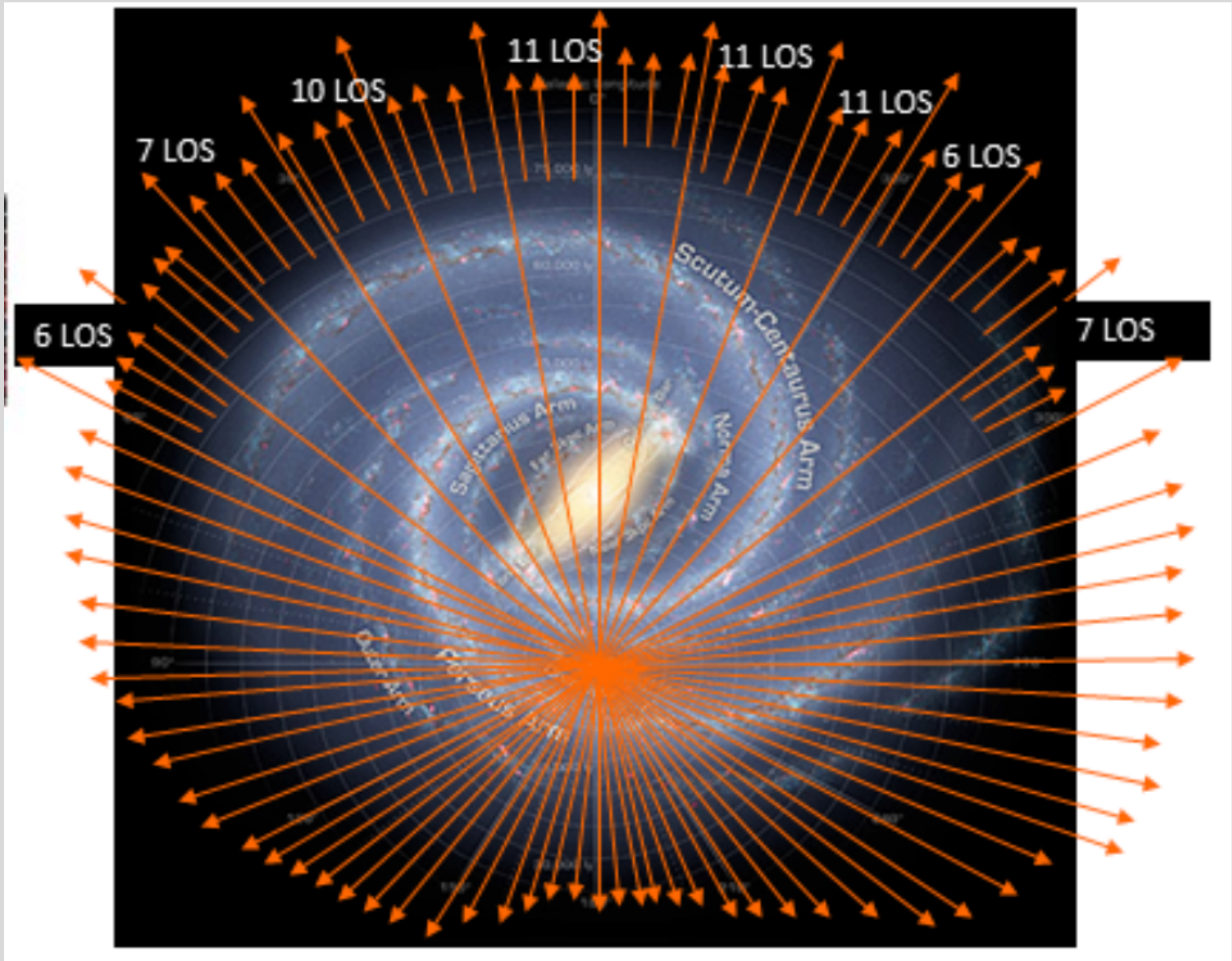
$$\log_{10}(\Sigma_{\mathrm{SFR}}) = m \times (\log_{10}(\Sigma_{[\mathrm{CII}]} \times \Psi(\gamma)) - 40) + N$$



Herrera-Camus+ 2014

GOT C+ Survey

Herschel HIFI observations along 500 sight-lines in the Milky Way



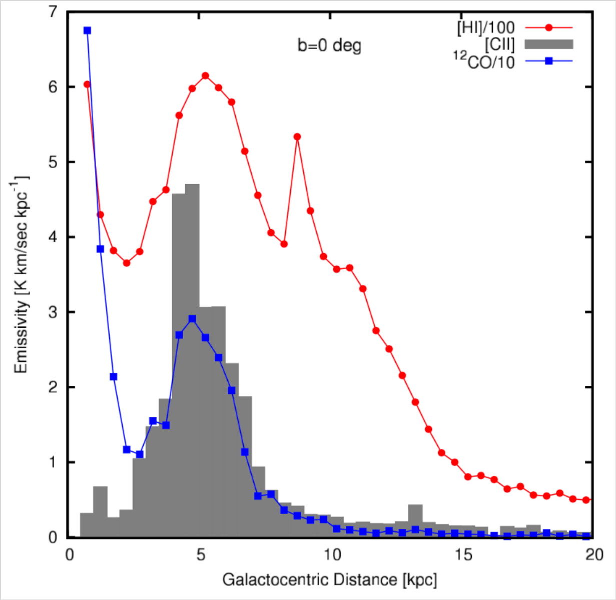
Langer+ 2011

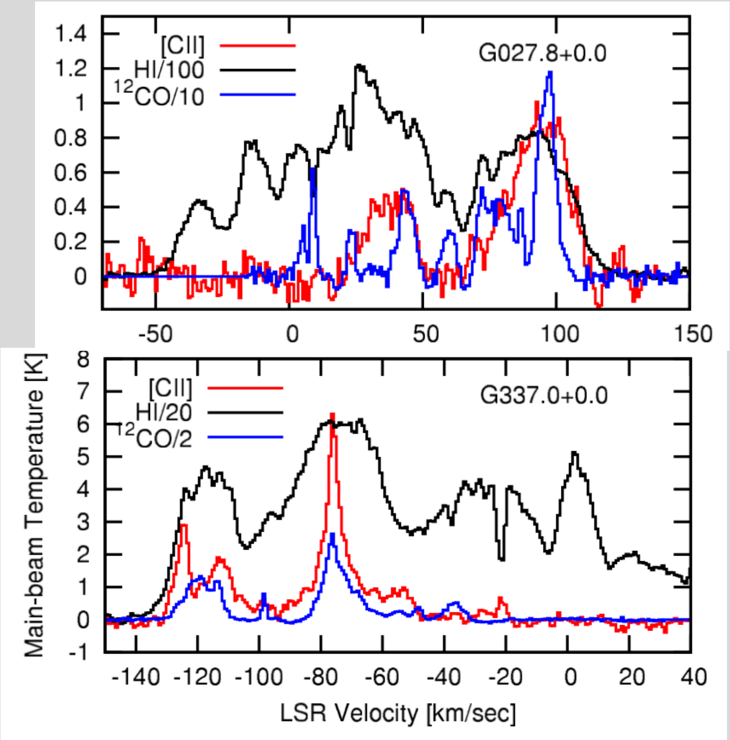
GOT C+ Survey

Separate [CII] emission from different ISM phases

→ compare [CII] velocity profiles/spatial distribution with HI, ^{12}CO, ^{13}CO

Pineda+ 2013





→ most [CII] emission at radii 4-11 kpc, associated to spiral arms

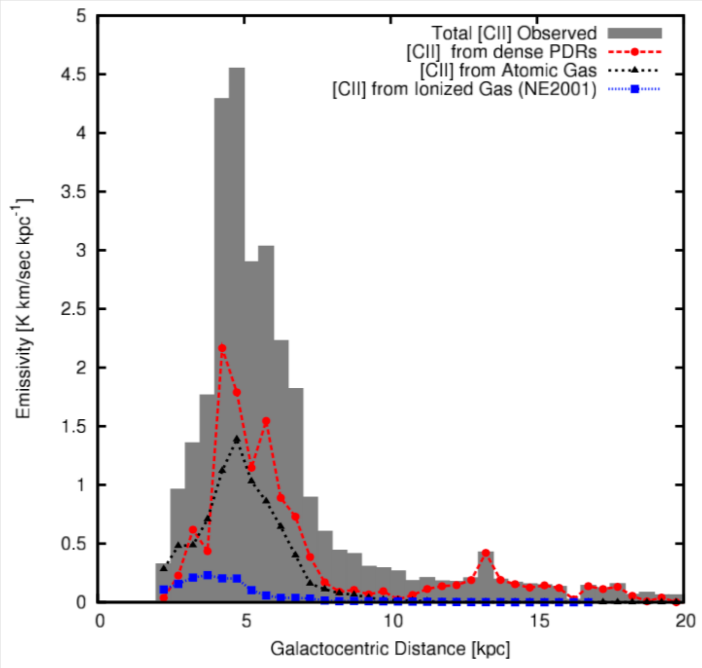
→ traces ISM phase intermediate extended HI and dense CO clouds

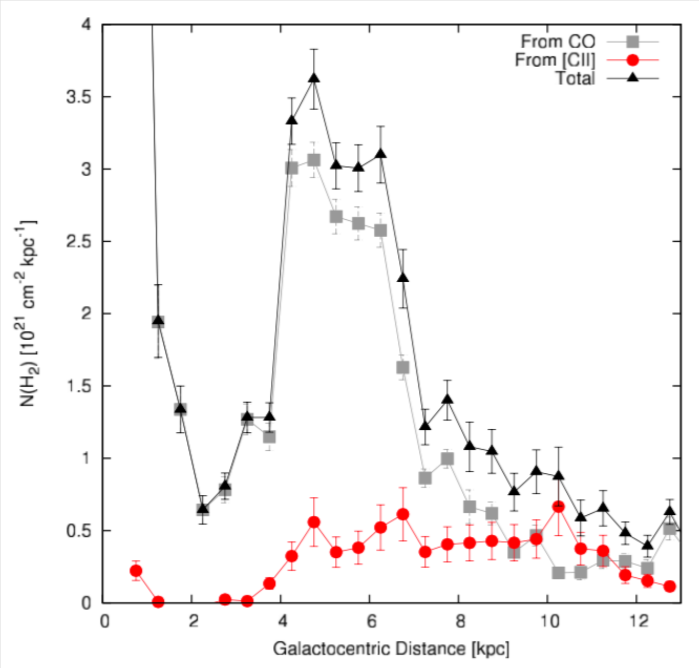
GOT C+ Survey

Separate [CII] emission from different ISM phases

→ [CII] originates from: PDRs (47%), CO-dark H_2 (28%), cold atomic gas (21%), ionised gas (7%)

Pineda+ 2013





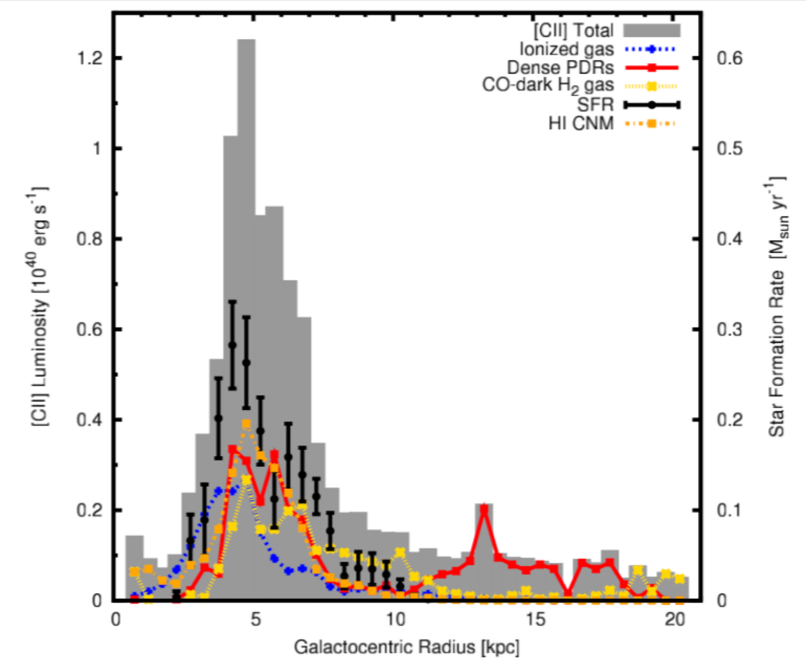
→ fraction of CO-dark gas increases with Galactocentric radius

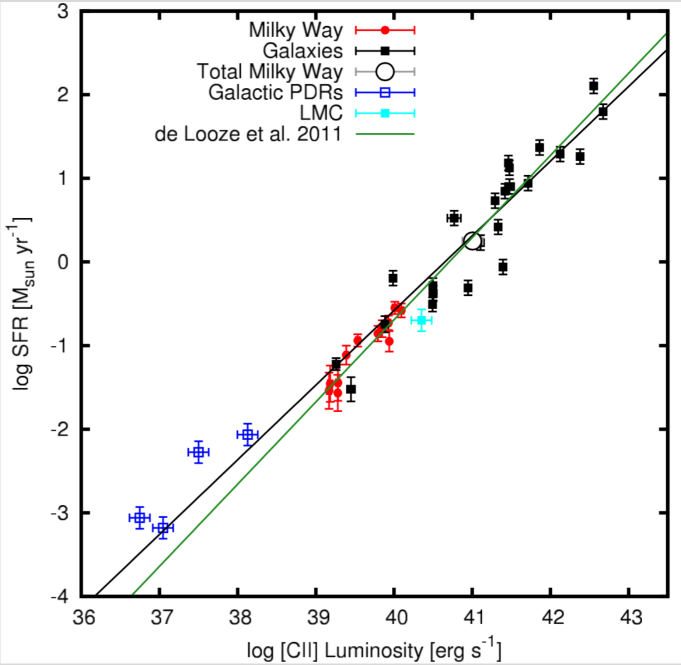
GOT C+ Survey

How does SFR relate to [CII] emission in our Milky Way?

⟶ SFR derived from radio observations (free-free emission)

Pineda+ 2014





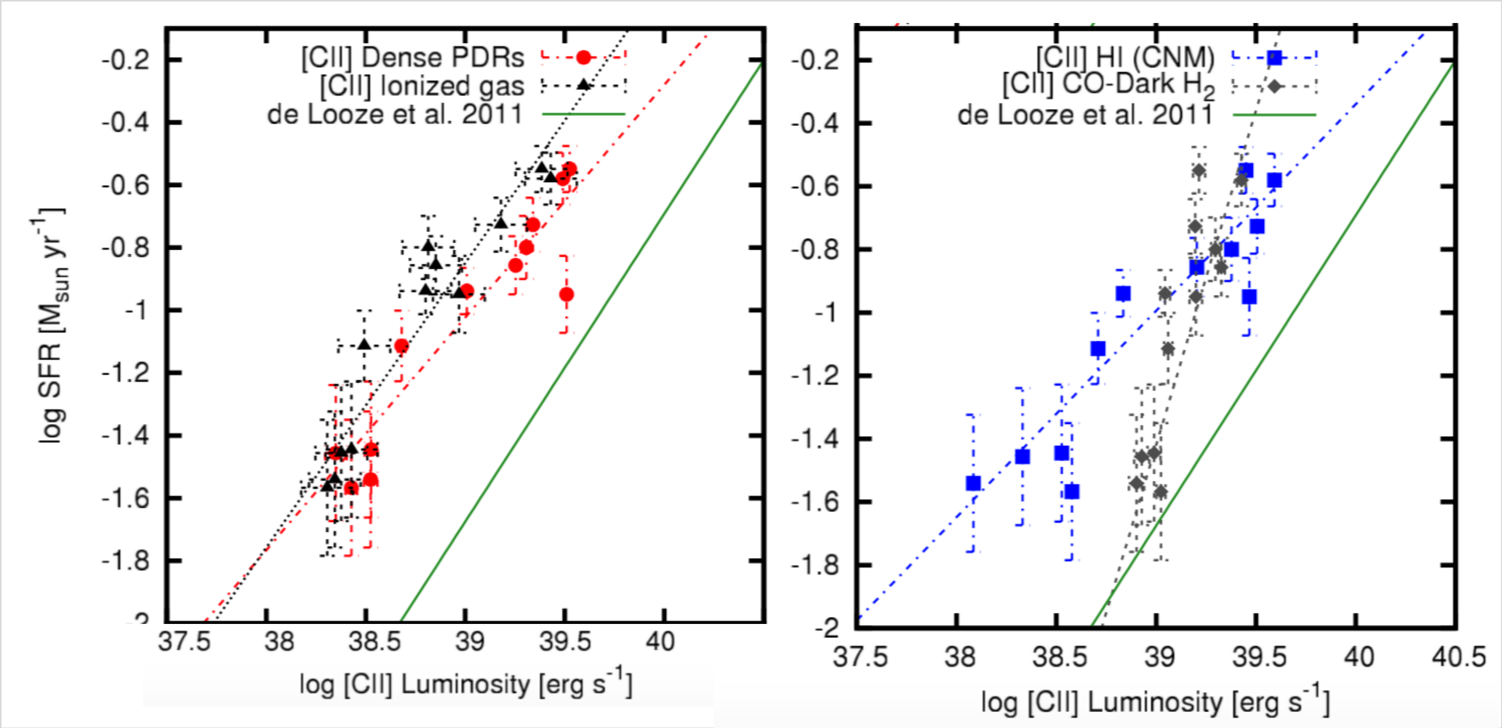
⟶ SFR-[CII] relation holds over six orders of magnitude

GOT C+ Survey

How does SFR relate to [CII] emission in our Milky Way?

→ SFR-[CII] relation behaves different in various ISM phases

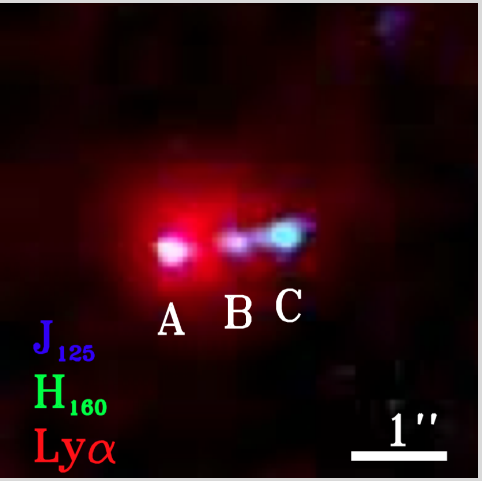
Pineda+ 2014



→ only global SFR-[CII] relation consistent with other galaxies

[CII] as SFR tracer @ high redshift?

◇ Himiko (z=6.6, Ouchi+2013, see also González-López+ 2014)



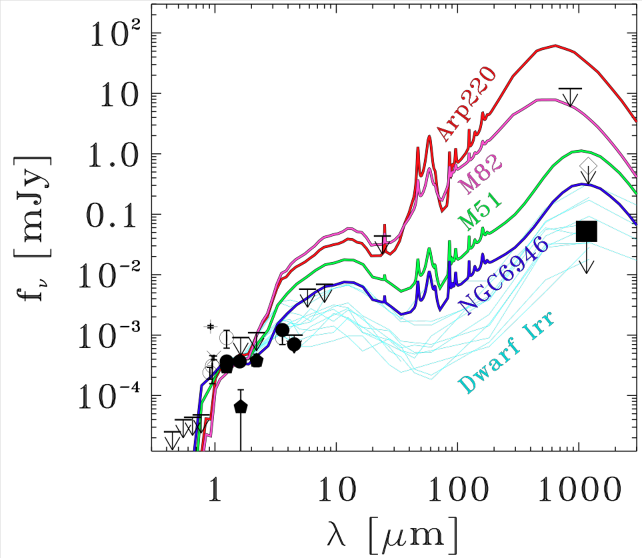
Bright HST source → SFR ≈ $100 M_{\odot}/yr$

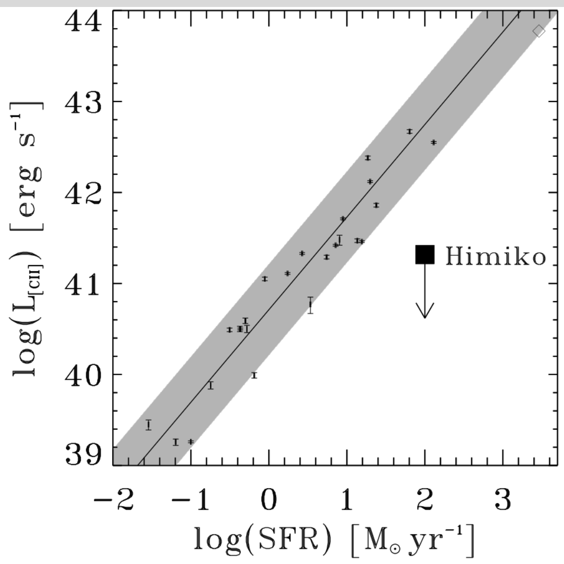
No FIR and [CII] detection

→ low metal content!

→ other cooling mechanisms (e.g. Lyα)

[CII] is NOT good SFR tracer in those objects!





[CII] as SFR tracer @ high redshift?

◇ IOK-1 (z=6.96, Ota+2014)

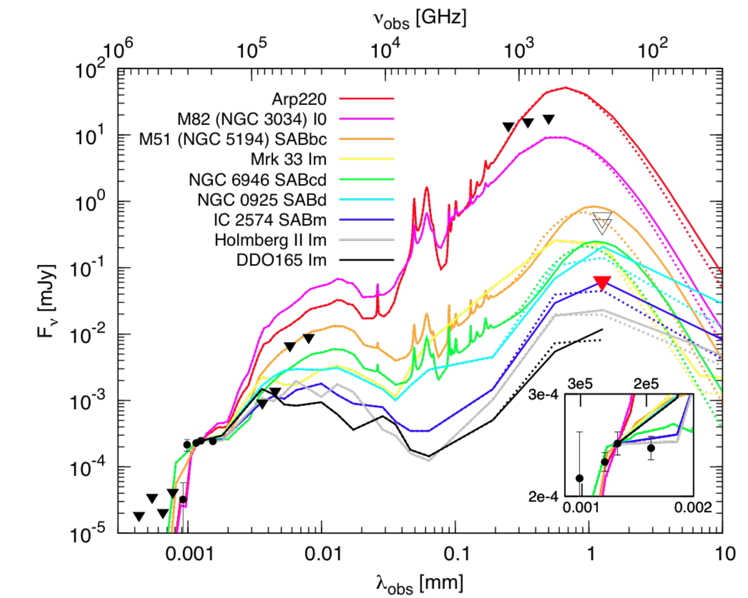
- Similar properties as Himiko
- Mostly unobscured SF (SFR ≈ 29 $M_\odot$/yr)

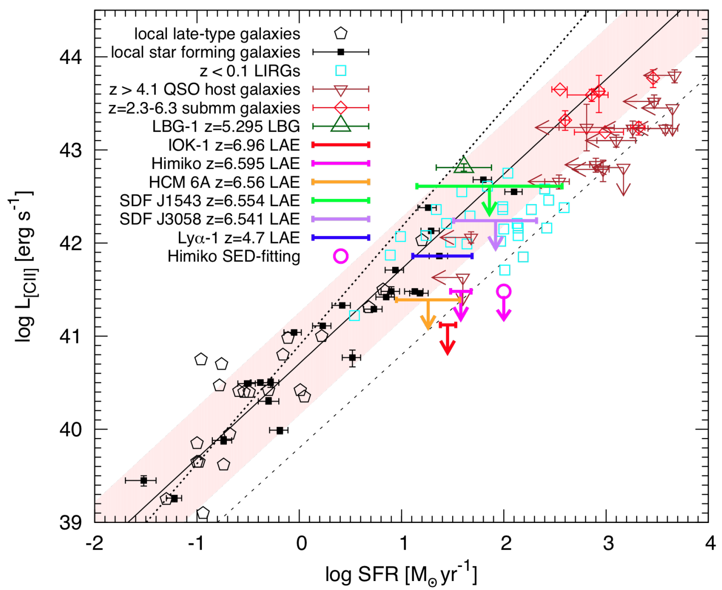
+ no [CII] detection → low metal content!

SED similar to local dwarf irregulars
⟶ local dwarfs are important study cases!

[CII] is NOT good SFR tracer in objects that have just started forming stars after cosmic re-ionization!

How unique are objects as Himiko, IOK-1?
⟶ not many [CII] detections @ z ≥ 6





Conclusions: Part I

Which FIR lines to use as SFR tracers?

1.) <u>Effect of ***metallicity***</u>

- ◇ [CII] = **poor** SFR tracer
  - at low metallicities
  - at warm IR colours ([CII] deficit!)
  - → other cooling lines dominate @ ≠ *gas density/ionisation state*

2.) <u>Effect of ***galaxy type***</u>

- ◇ Need for separate calibrations per galaxy type (ULIRGs!)

3.) <u>Best SFR indicator</u>

- ◇ [OI] shows tightest correlation with SFR, but is weaker than [CII]
- ◇ Use galaxy-specific or colour-based SFR relation for [CII]

Guideline: Without info on metallicity/galaxy type/IR colour:
$[OI]_{63}$=best SFR tracer

Outline

- **Fine-structure lines to trace the SFR**

  - how is FIR line emission linked with SFR?

  - do we see the same trends across all metallicities and galaxy types?

  - which line = best SFR indicator?

- **FIR line diagnostics of ISM conditions**

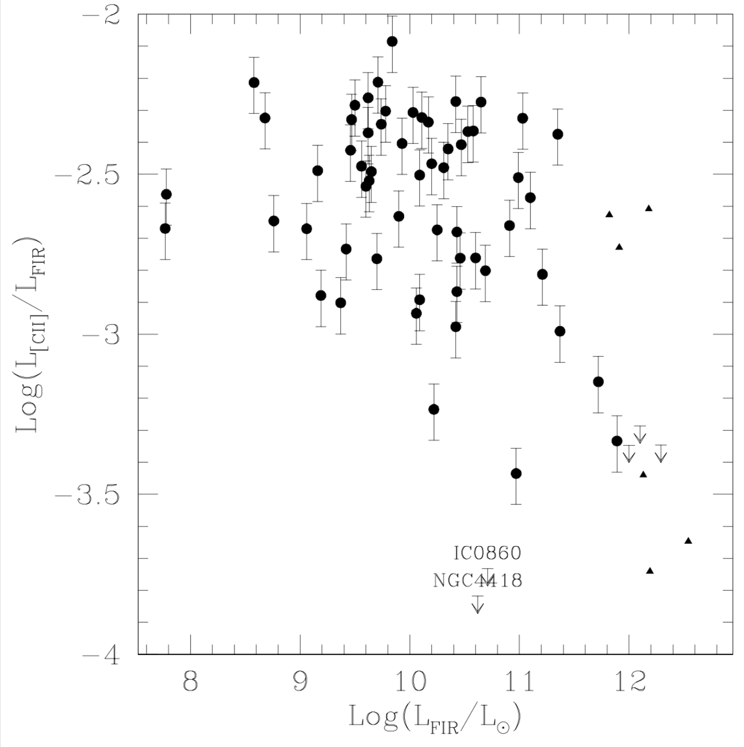
  - origin of [CII] and other line deficits

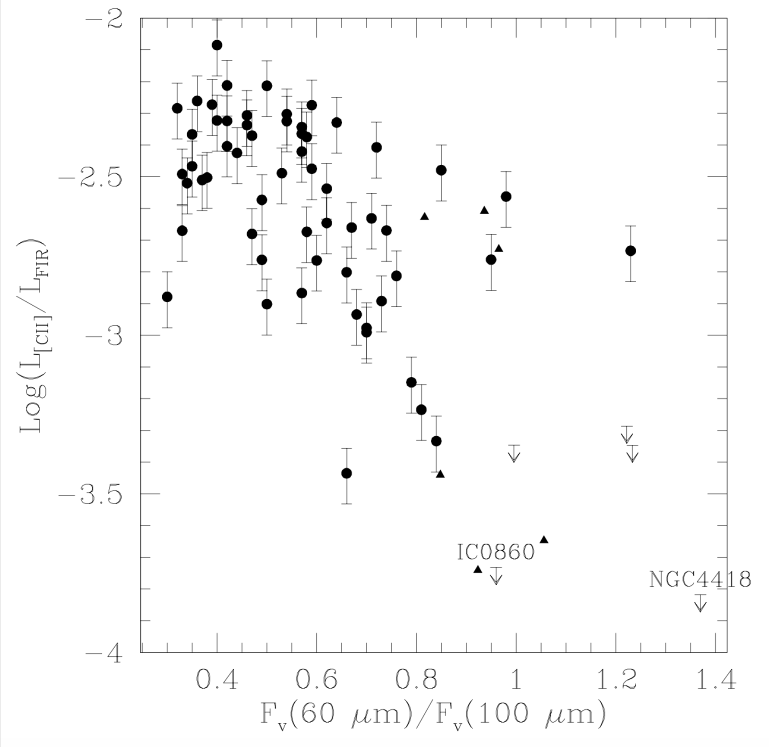
  - multi-phase ISM diagnostics

Origin of [CII] (line) deficit

What?

- Drop in [CII]/FIR ratio with increasing FIR
- [CII] line deficit seems to correlate with IR colours



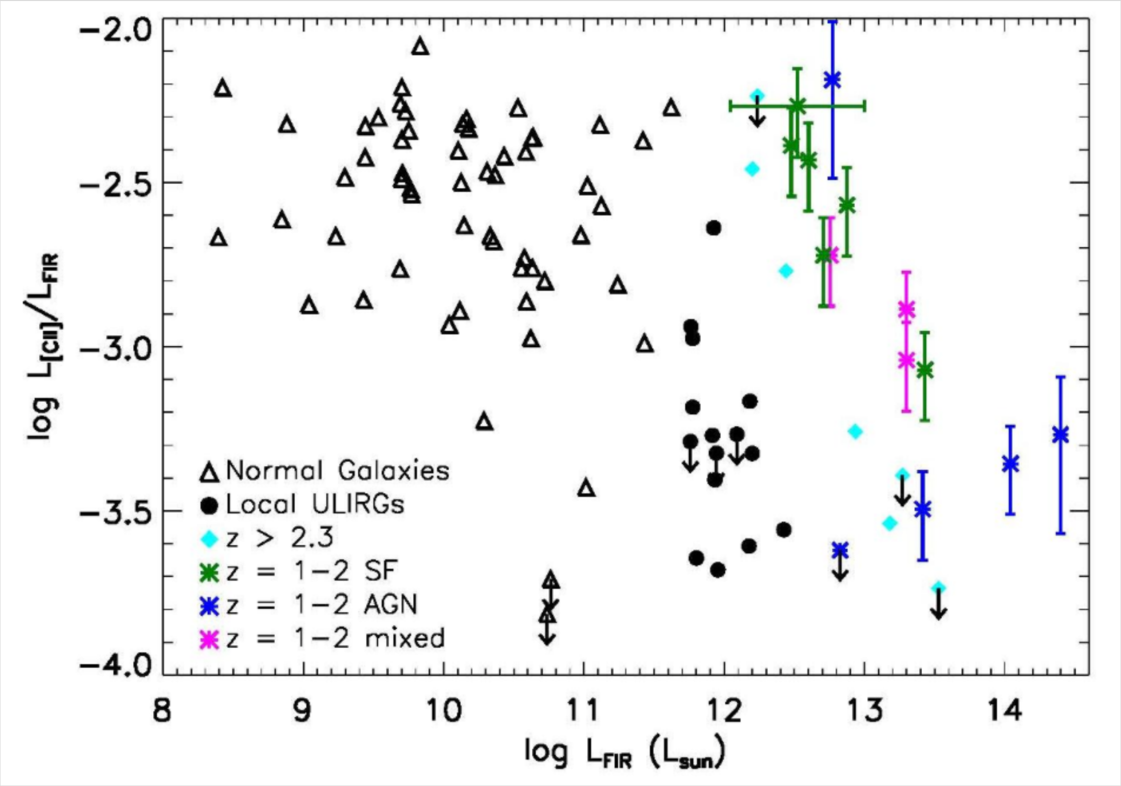


Malhotra+ 2001

Origin of [CII] (line) deficit

At high-redshift:

- no continuation of line deficit
- trend = more dispersed trend



Stacey+ 2010

Origin of [CII] (line) deficit

Possible explanations?

1.) self-absorption of C^+ line emission

2.) saturation of [CII] line flux above n_{crit}

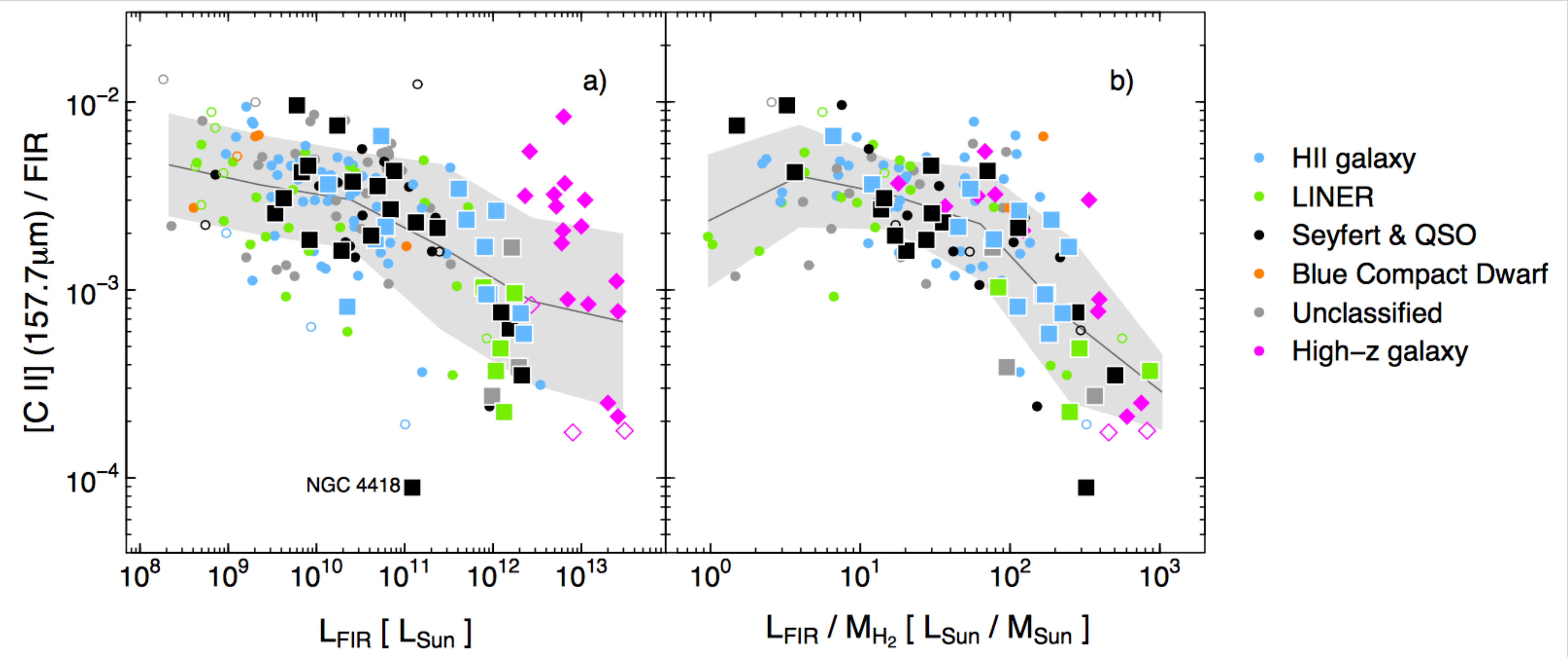
3.) charging of dust grains —> drop in photo-electric efficiency (no decrease in dust emission)

4.) high dust-to-gas opacity due to high ionisation parameter

5.) AGN contribution

Origin of [CII] (line) deficit

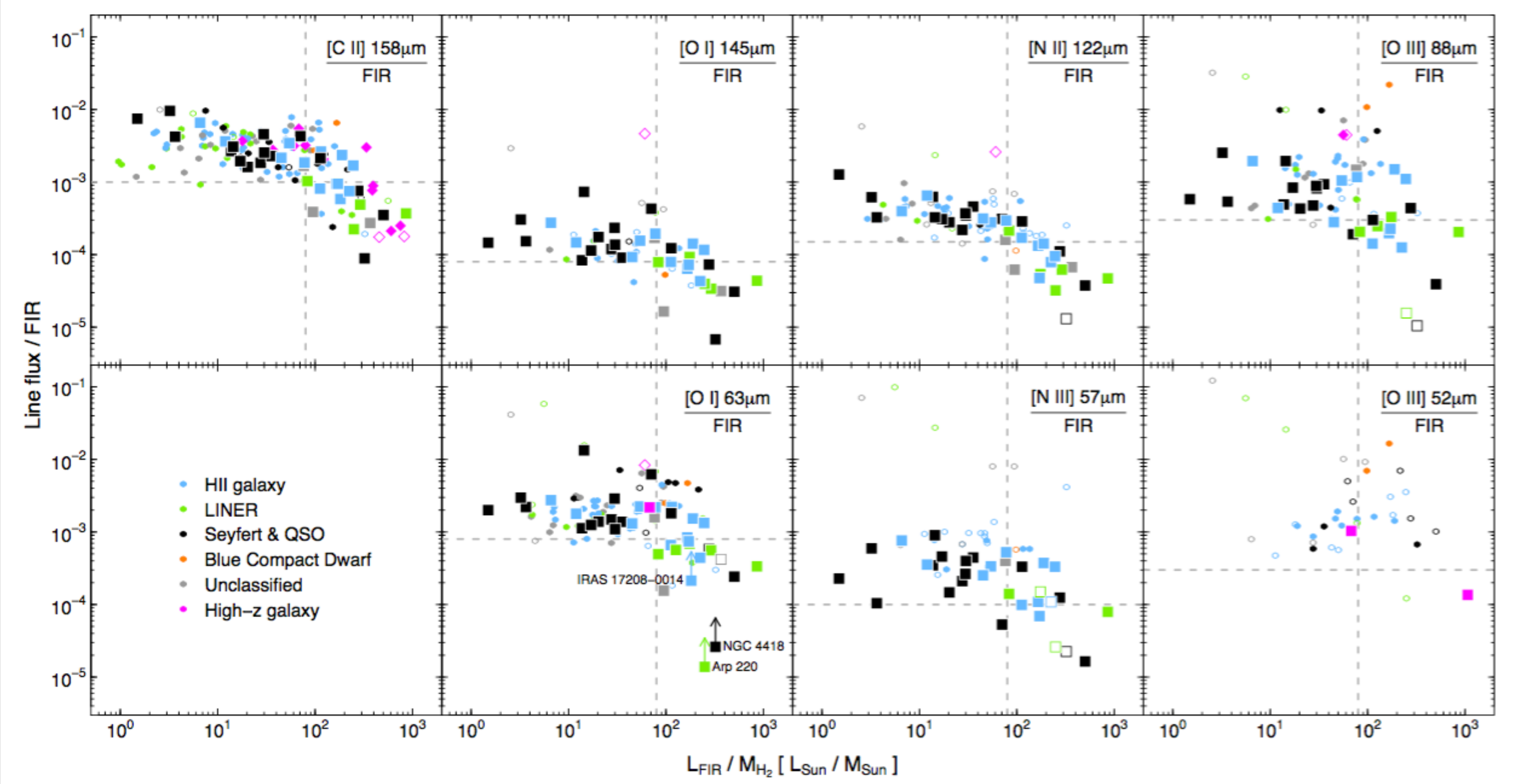
- Herschel SHINING program (local starbursts, Seyferts, low-metallicity galaxies, (U)LIRGS at low/high redshift)
- [CII]/FIR —> correlates better with L_{FIR}/M_{H2}



Gracia-Carpio+ 2011

Origin of [CII] (line) deficit

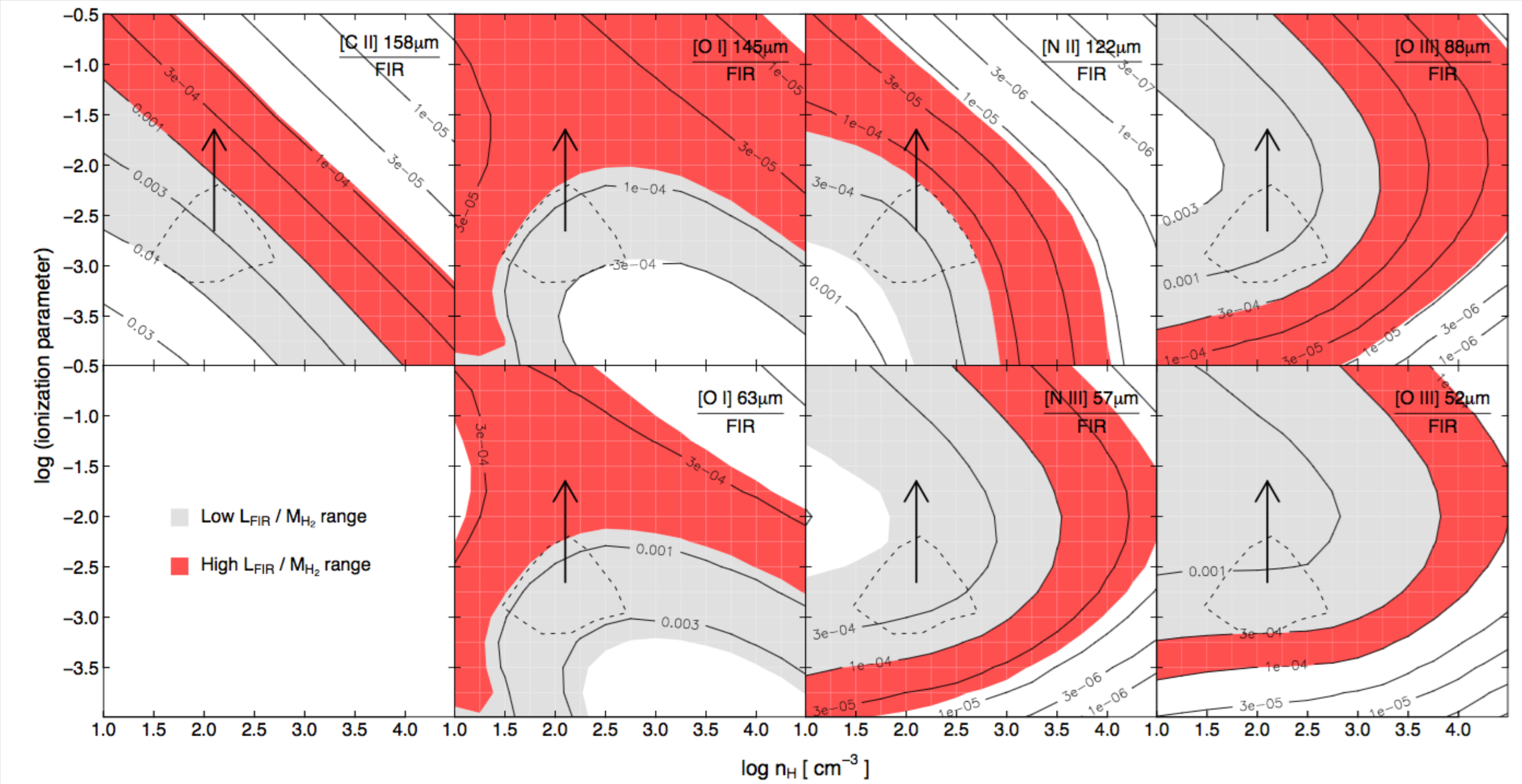
- Herschel SHINING: line deficits detected for [CII]158, [OI]145, [NII]122, [OIII]88, …
  —> mechanism that causes deficit not restricted to PDRs



Gracia-Carpio+ 2011

Origin of [CII] (line) deficit

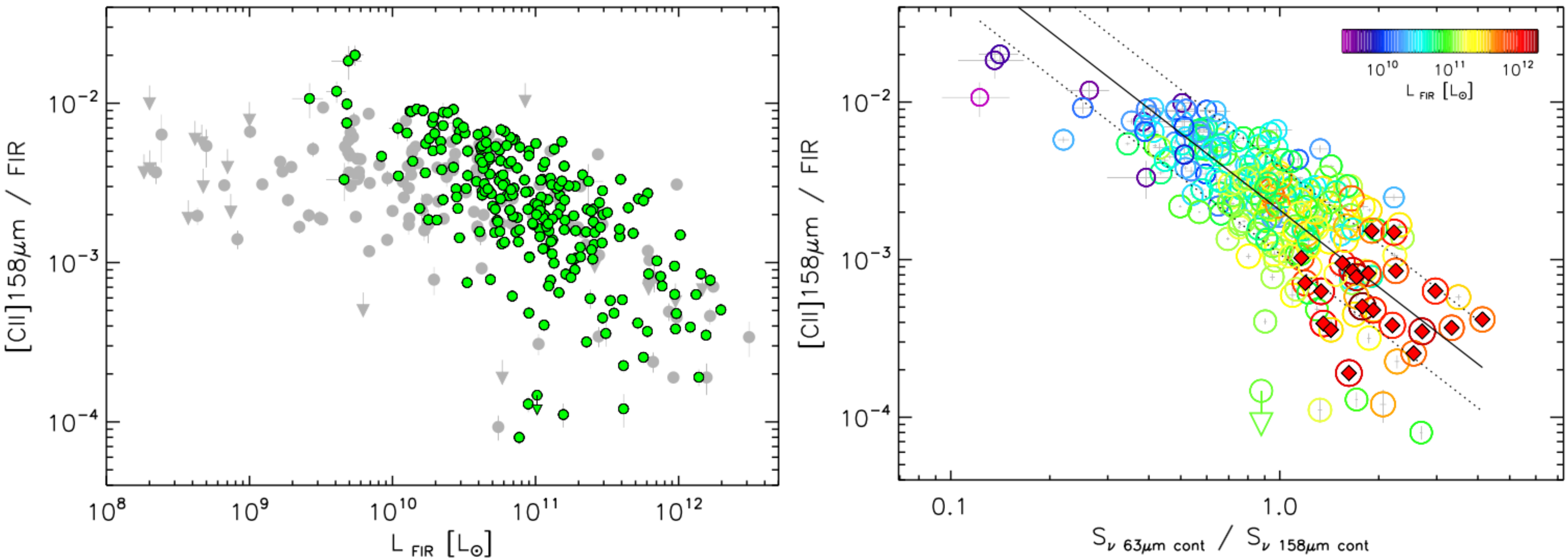
- L_{FIR}/M_{H2} separates galaxies in two SF modes
- Line deficit occurs @ high ionisation parameter / high SFE



Gracia-Carpio+ 2011

Origin of [CII] (line) deficit

- Herschel GOALS: sample of 202 LIRGs + ULIRGs
- Most galaxies show line deficit
- [CII] deficit correlates with IR colour



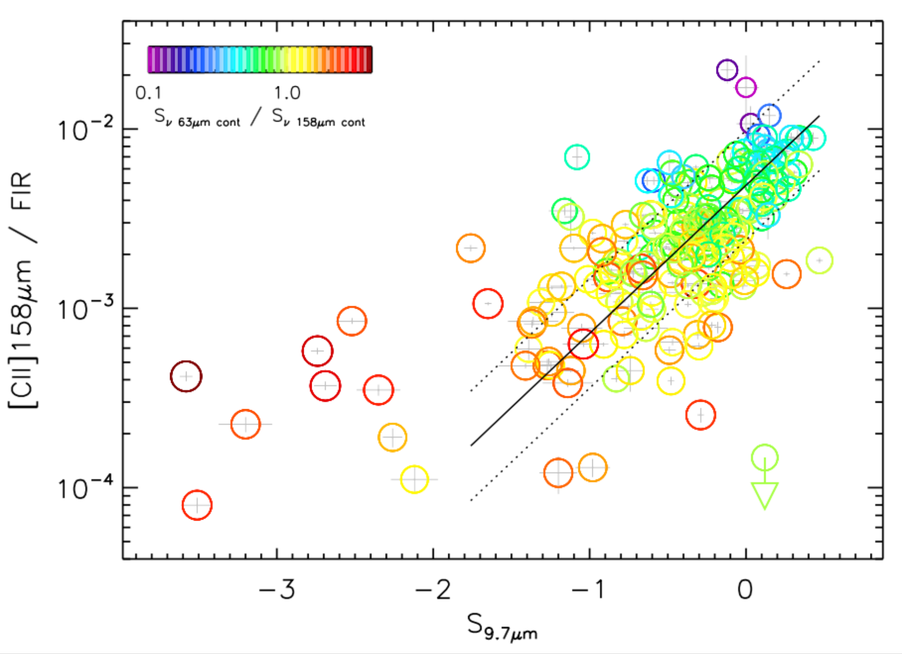
Diaz-Santos+ 2013

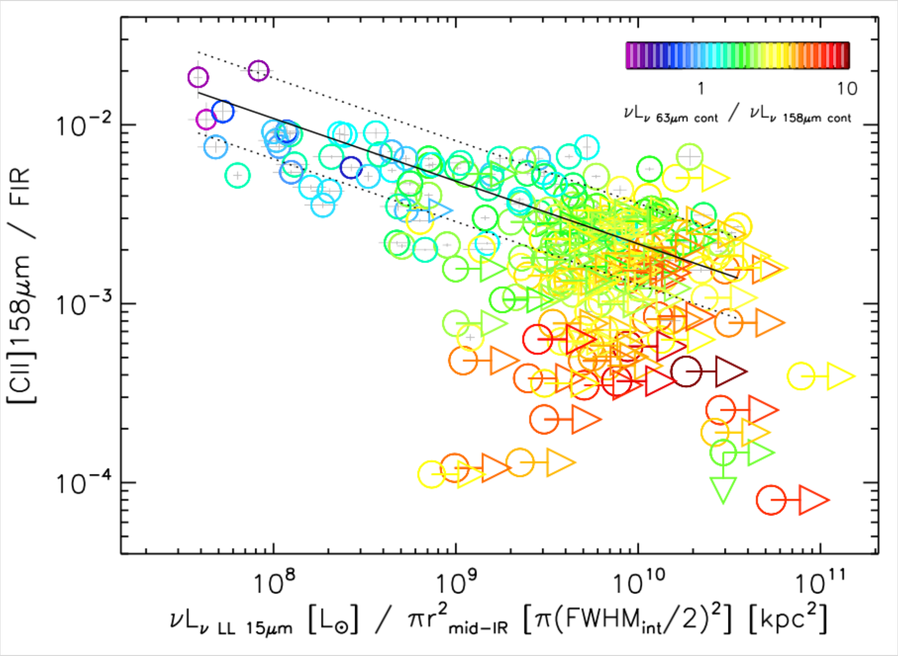
Origin of [CII] (line) deficit

Herschel GOALS: [CII] deficit correlates with

- 9.7 μm silicate absorption feature
- mid-IR luminosity surface density (Σ_{MIR})

—> line deficit occurs in warmer, more compact starbursts

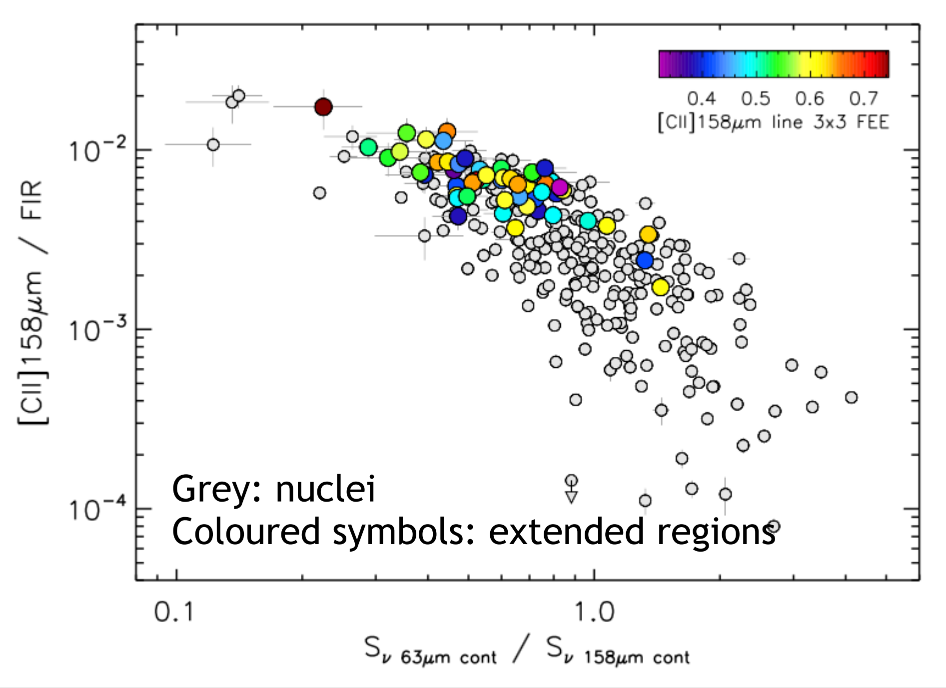




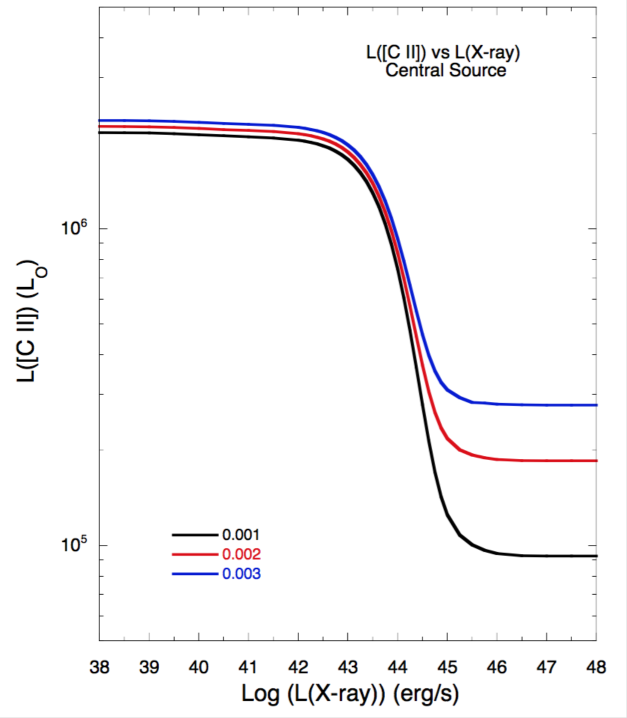
Diaz-Santos+ 2013

Origin of [CII] (line) deficit

Herschel GOALS: resolving the emission of nuclei and disk:
—> nuclei show the strongest deficits
—> models attribute deficit in nuclei to lower C^+ abundance in the presence of X-rays, when L(X-ray) >10^{43} erg/s



Diaz-Santos+ 2014

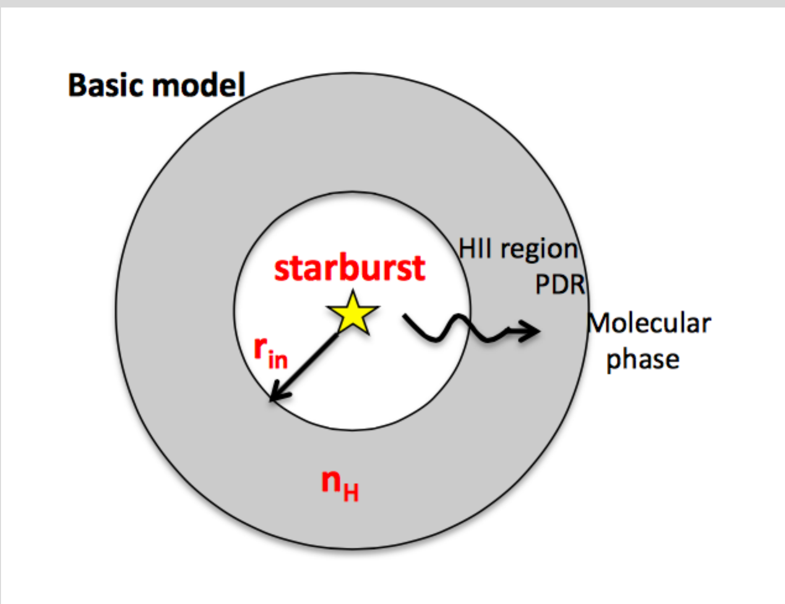


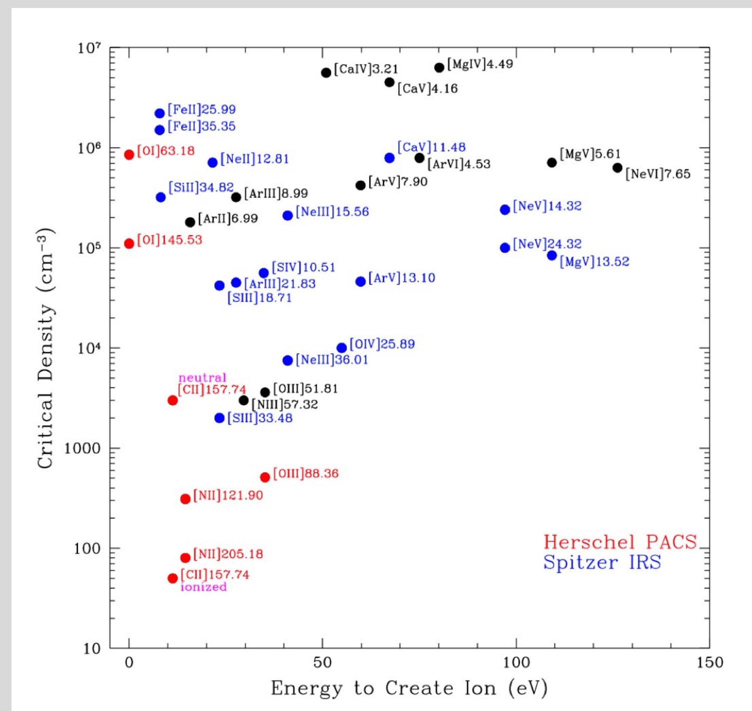
Langer&Pineda 2015

Multi-phase ISM conditions

<u>Multi-phase ISM model</u> = the only way to constrain

- origin of [CII] emission/deficit
- SFR calibrations (for different metallicities, galaxy-types)
- FIR lines as gas mass tracers (K-S law!)





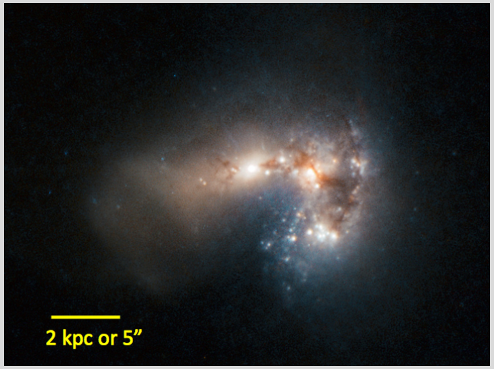
Kennicutt+ 2011

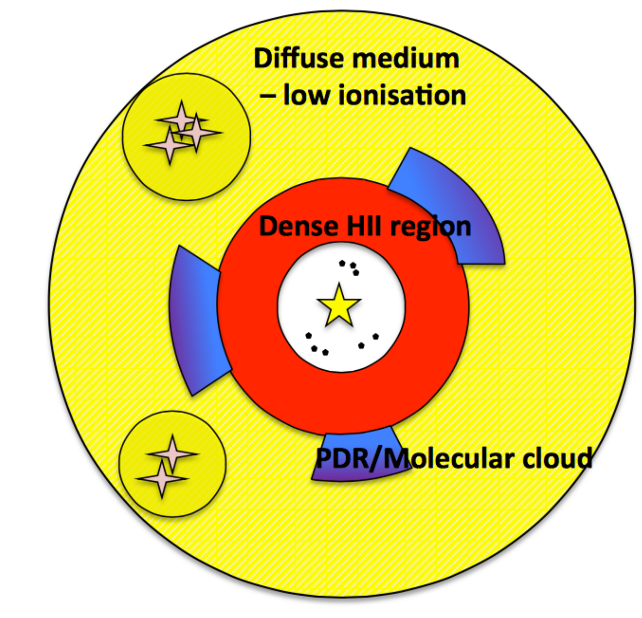
Multi-phase ISM conditions

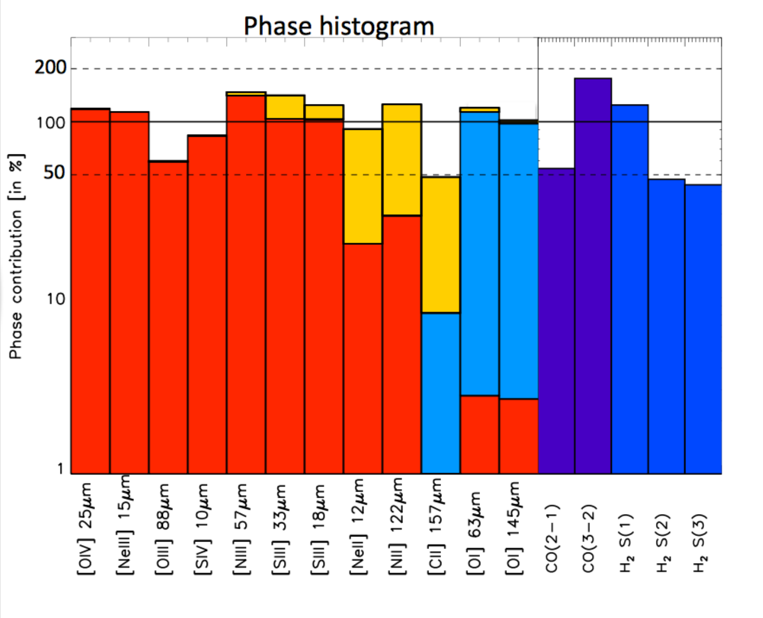
Multi-phase ISM model Haro 11:

Compact HII region: $n_H = 10^3\ cm^{-3}$, $A_{burst} = 4$ Myr
Dense PDR model: $n_H = 10^5\ cm^{-3}$, $G_0 = 10^3$ Habing
Diffuse medium: $n_H = 10\ cm^{-3}$, $T_{eff} = 35\,000$ K

D = 84 Mpc
LIR = 1.6x1011Lsun
Z=0.3Zsun
SFR=22Msun/yr







Cormier+ 2012

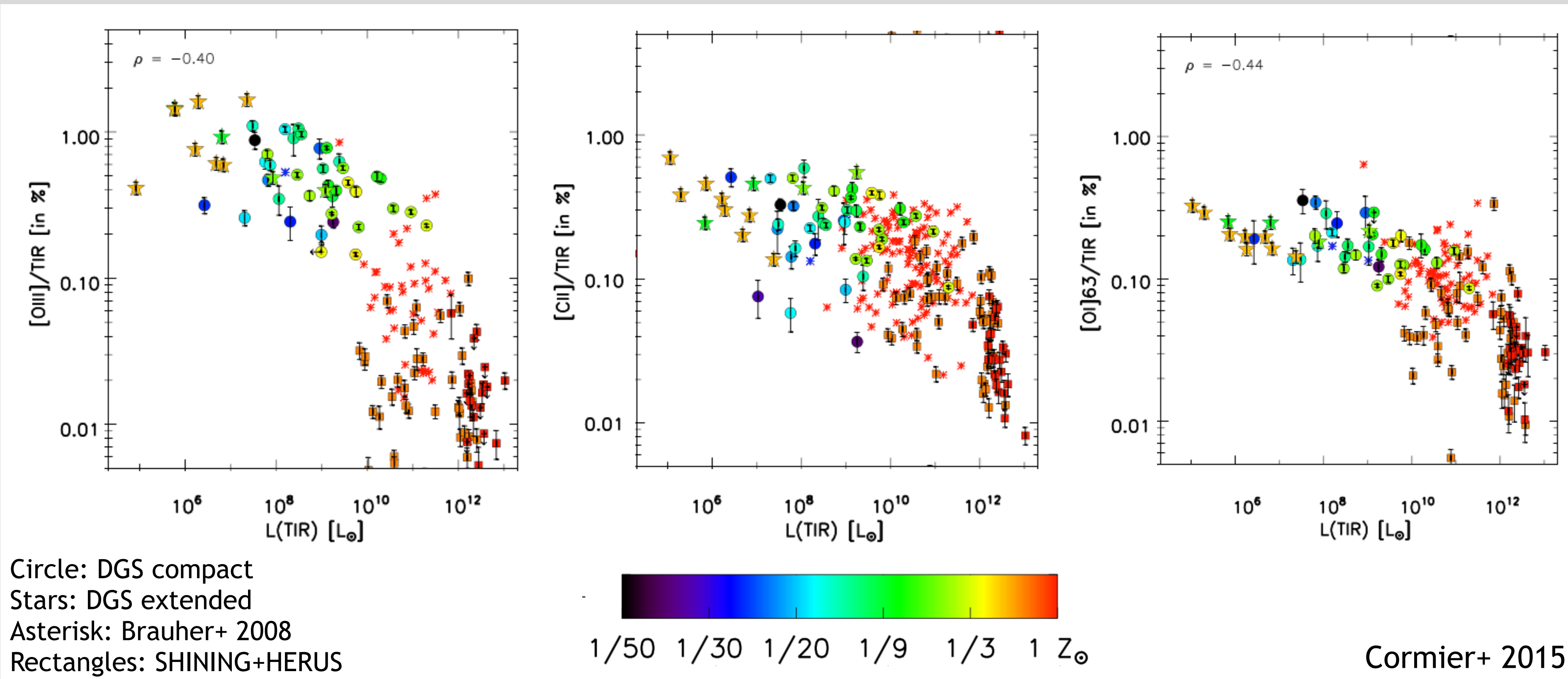
—> 40% of the [CII] emission comes from ionised gas, 60% from PDR

Multi-phase ISM conditions

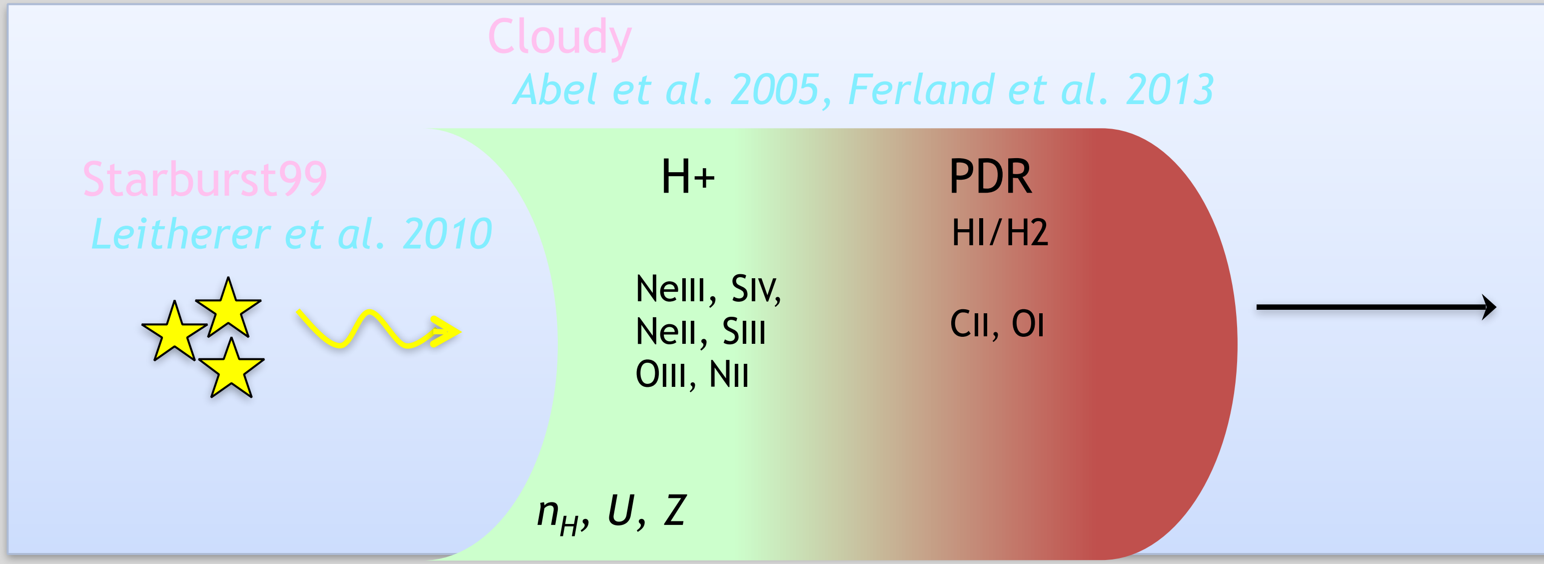
<u>Dwarf Galaxy Survey</u>

How different is the ISM at low-metallicity?

- <u>No line deficits!</u> (even enhanced gas cooling!)



Multi-phase ISM conditions



Model setting:

Continuous SF
ISM abundances
Grids varying: n_H and U
Z = 0.05, 0.1, 0.25, 0.5, 1.0 Zo

1) Derive the best fit model for HII region
2) Next predict PDR phase – pressure equilibrium throughout

Diagnostics:

[SIII]18/33 => HII region electron density

[NeIII]/[NeII]
[SIV]/[SIII]18 => radiation field hardness
[OIII]/[NII]

[OI]/[CII] => PDR temperature, density
[CII]/L(TIR)
[CII]/CO => Av

Multi-phase ISM conditions

Model comparison:

low-metallicity dwarfs	vs	normal SF galaxies

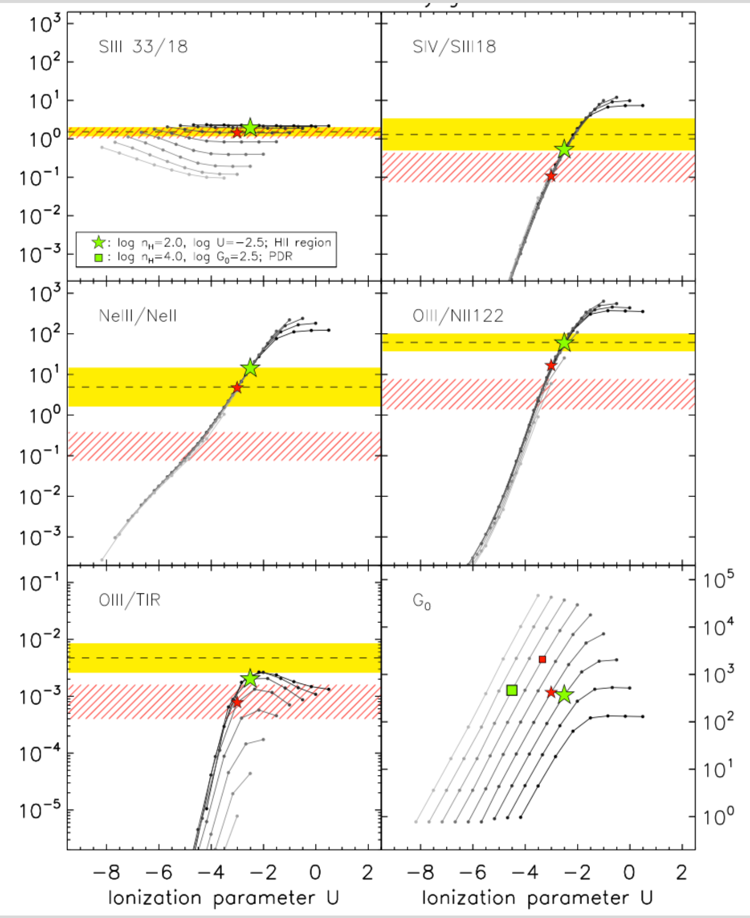
<u>HII region:</u>

	Low-Z dwarfs	High-Z SF gal
n_e [cm^{-3}]	$10^{2.0}$	$10^{2.5}$
log U	-2.5	-3.0
$R_{S,eff}$ [pc]	46	16

↓

At low metallicity:
- Harder RF
- Dilution of UV field

Cormier+ 2015



Multi-phase ISM conditions

Model comparison:

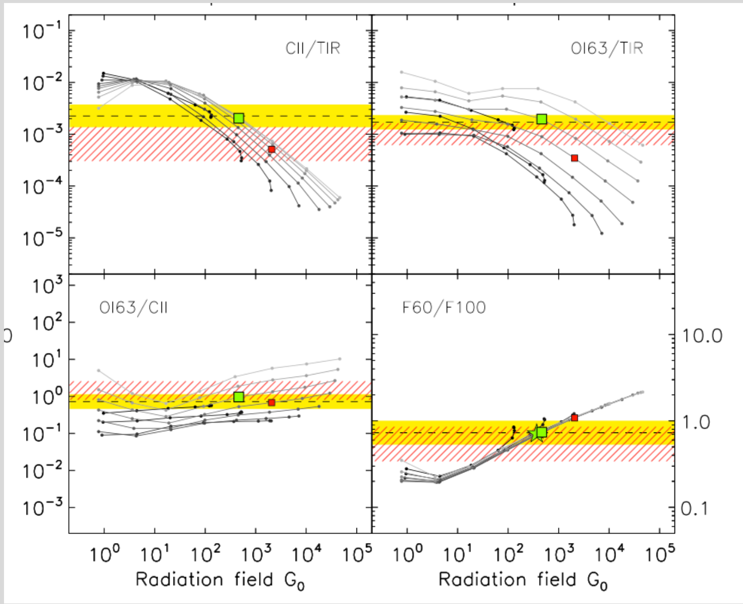
low-metallicity dwarfs	vs	normal SF galaxies

Photo-dissociation region:

	Low-Z dwarfs	High-Z SF gal
n_H [cm^{-3}]	$10^{4.0}$	$10^{3.5}$
log G_0	2.7	3.3

↓

Cormier+ 2015



At low metallicity:
- We need to reduce PDR covering factor is lower by factor of ~3 to reproduce line-to-IR ratios.

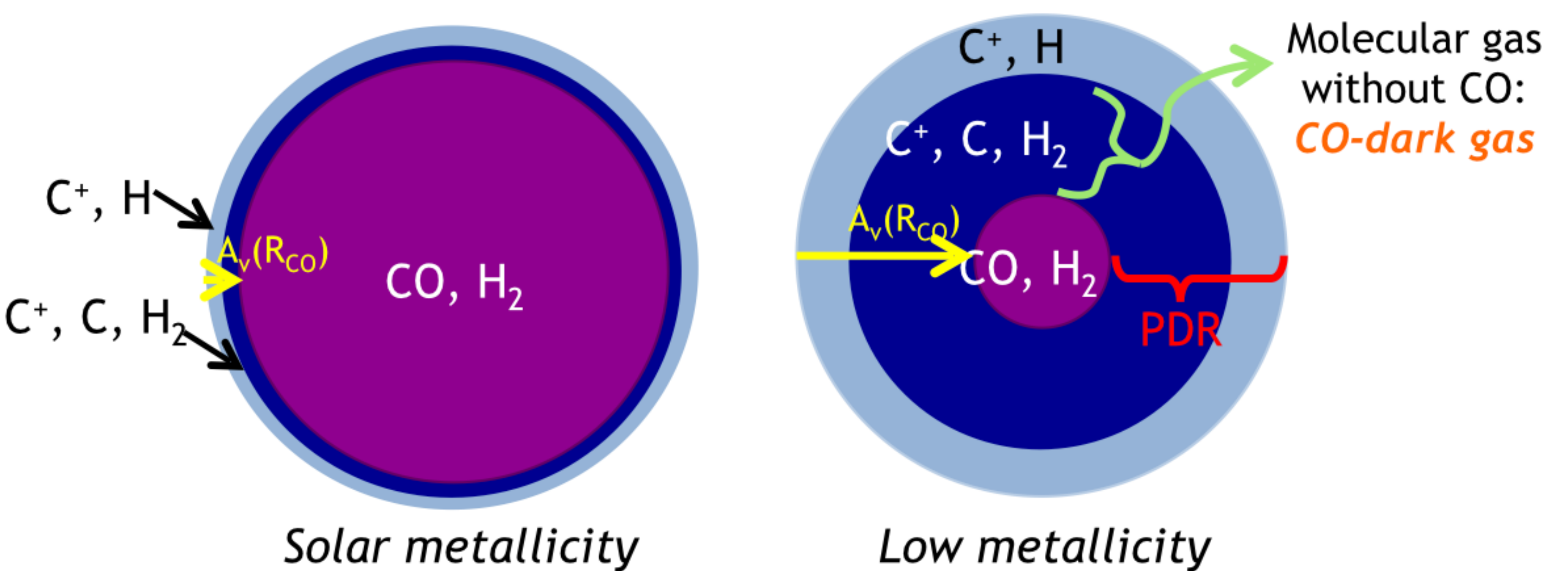
Multi-phase ISM conditions

Low-metallicity dwarf galaxies

—> <u>very different ISM structure</u>:

1. volume-dominated by diffuse high-ionisation gas
2. small filling factor of PDRs

⟶ **!problem!** CO = not good tracer of molecular gas!



Conclusions: Part II

Multi-phase ISM conditions

1.) [CII] and other line deficits

- ◇ Drop in [CII]/TIR in local (U)LIRGs
- ◇ Wide spread in [CII]/TIR at high redshift
- ◇ Significant drop in galaxy nuclei (AGN and SB)
- ◇ Origin = unclear: - dusty, more compact HII regions,
  - X-ray ionisation —> C in higher ionisation states
  - photo-electric efficiency affected by grain abundance, grain charging

—> might be a *mixture of effects at play in different environments*

2.) Multi-phase modelling

- ◇ Unique tool to constrain how ISM conditions change (at low metallicity)
- ◇ Models can help to constrain CO-dark gas fraction (e.g., [CII]/CO)