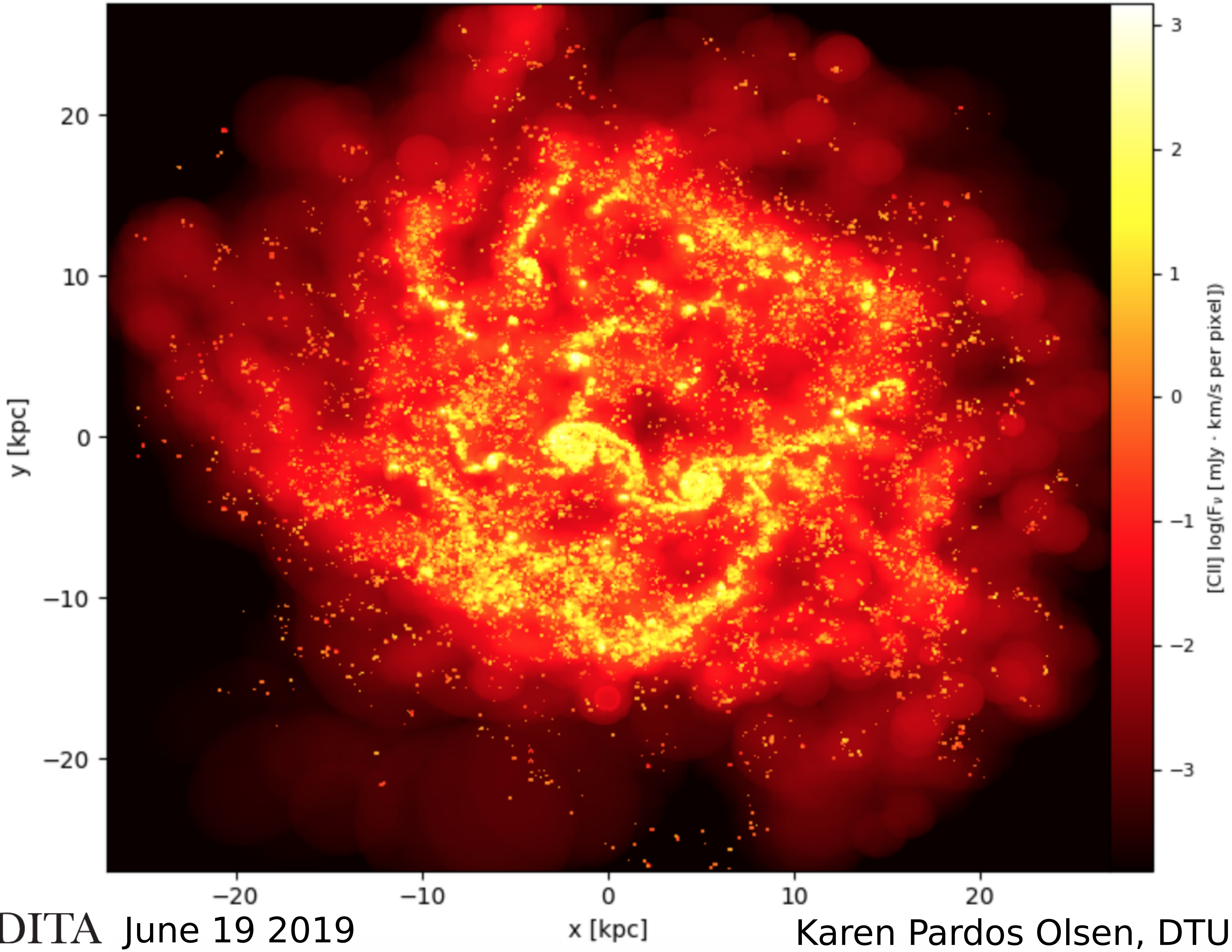
Reading between the lines

The benefits of modeling more than one emission line



Topics to cover

Background	- What can go wrong when we only model one line? - What science cases benefit from FIR line ratios?
SIGAME	- Brief description of SIGAME - https://kpolsen.github.io/SIGAME/index.html
Modeling line ratios at z~0	- Imitating *Herschel* - Line ratios as diagnostic tools of the ISM
	Suggestions for discussion…

Background

- Diagnostic FIR emission lines

The same galaxy with different glasses:

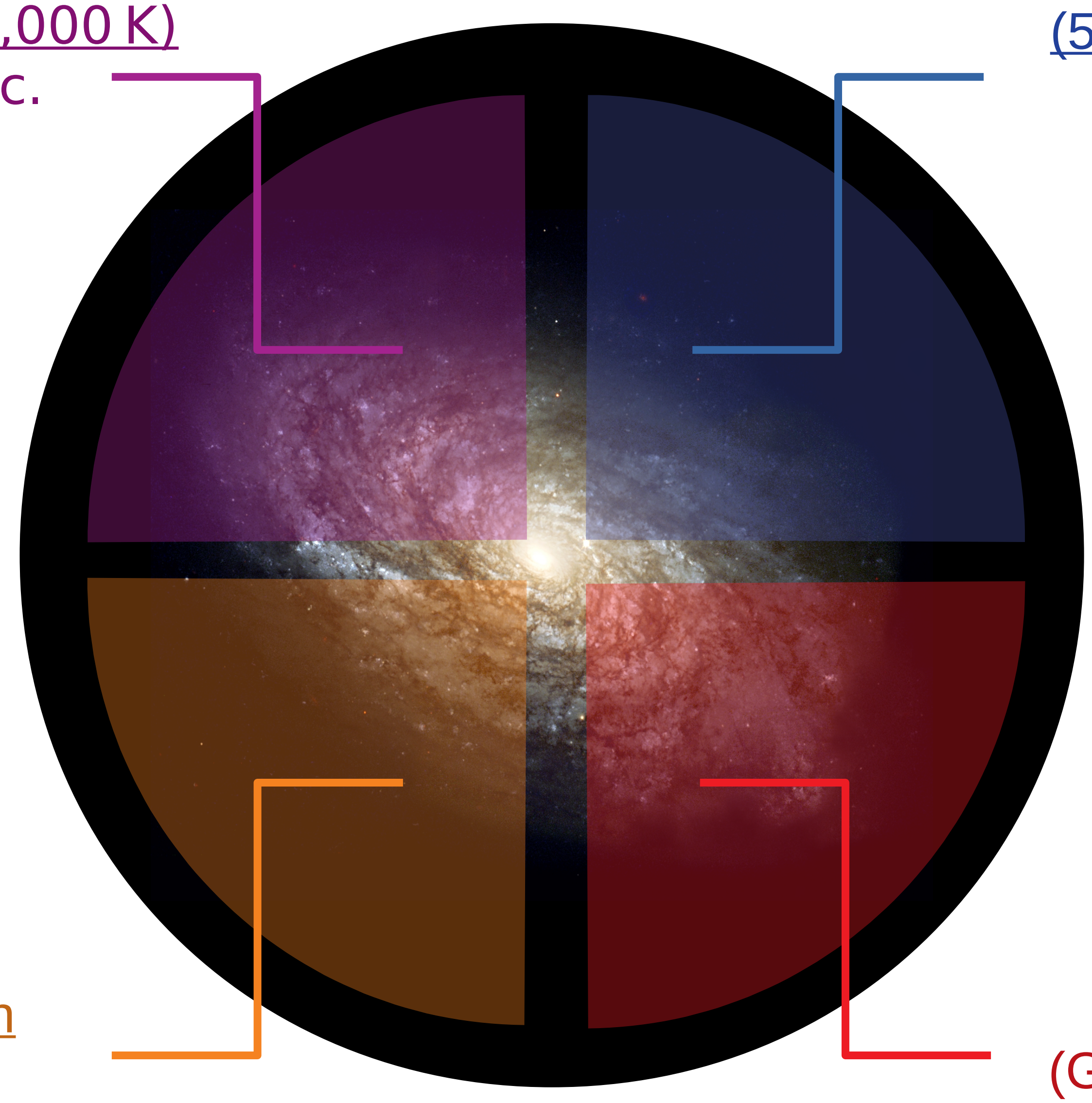
Background

- Diagnostic FIR emission lines

The same galaxy with different glasses:

Hot ionized ISM
(HII regions, ≈10,000 K)
[OIII], Lyα, Hα, etc.

Warm neutral medium
(5000 – 10,000 K)
[CII]



Photodissociation regions (PDRs)
[CII], [NII], [CI], [OI]

Molecular ISM
(GMCs, 10 – 50 K)
[CII], CO rotational lines

Background

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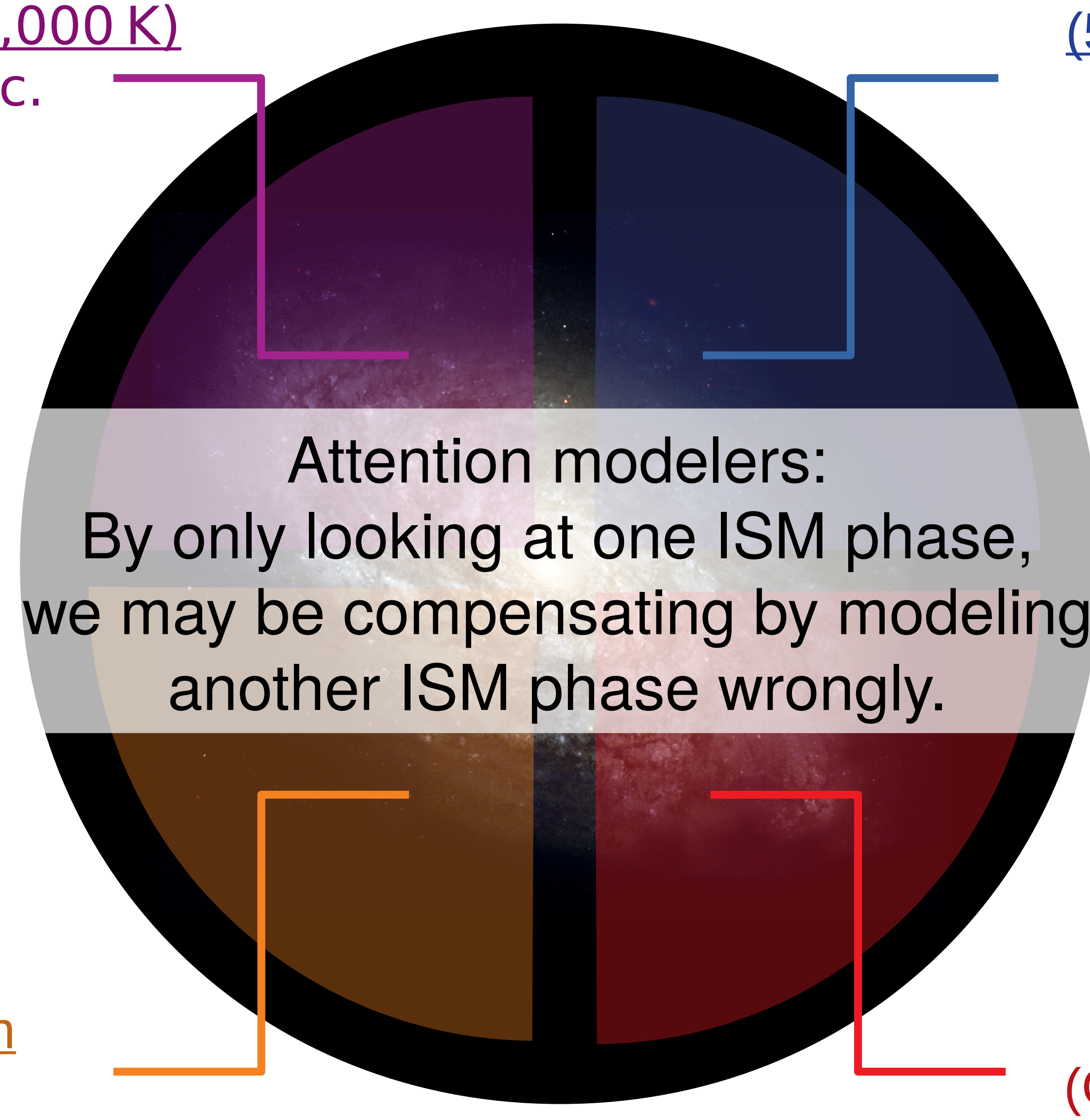


Photodissociation regions (PDRs)
[CII], [NII], [CI], [OI]

Molecular ISM
(GMCs, 10 – 50 K)
[CII], CO rotational lines

Background

- Diagnostic FIR emission lines
- Lessons from “Walking the Line workshop” last year

Phoenix, AZ March 2018

Walking the line

Simulating Line Emission from Galaxies

Conference Report

Challenges and Techniques for Simulating Line Emission

Karen P. Olsen [1,*], Andrea Pallottini [2,3], Aida Wofford [4], Marios Chatzikos [5], Mitchell Revalski [6], Francisco Guzmán [5], Gergö Popping [7], Enrique Vázquez-Semadeni [8], Georgios E. Magdis [9], Mark L. A. Richardson [10], Michaela Hirschmann [11] and William J. Gray [12]

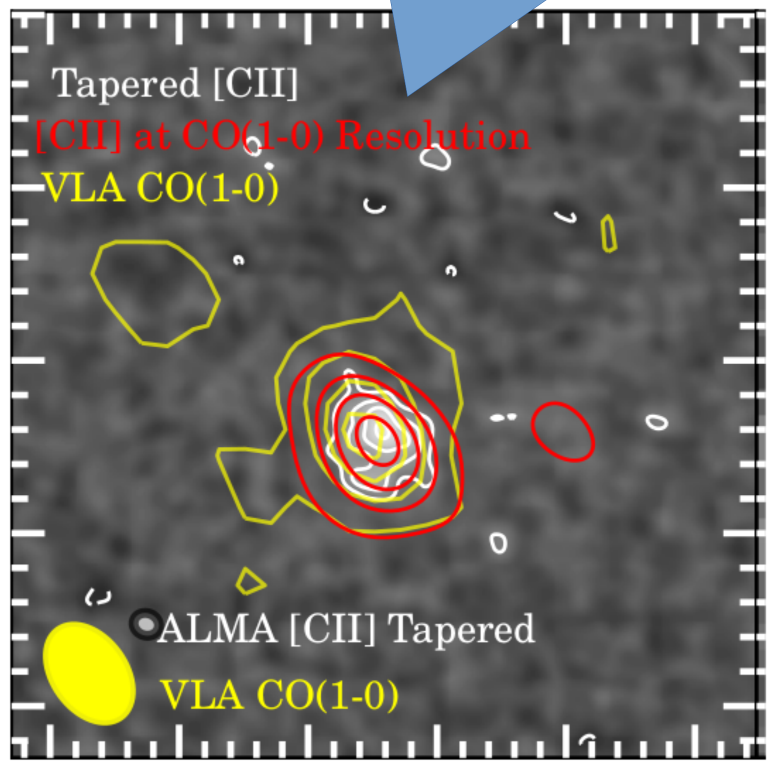
“One of the more valuable conclusions from the discussions on galaxy-scales simulations, was **the importance of simulating more than one emission line simultaneously**. By simulating different lines, arising in different ISM phases, and comparing with observations, one ensures that the post-process recipes not only satisfy what is seen in one ISM phase, but is **consistent across the entire galaxy**.”

https://walk2018.weebly.com/

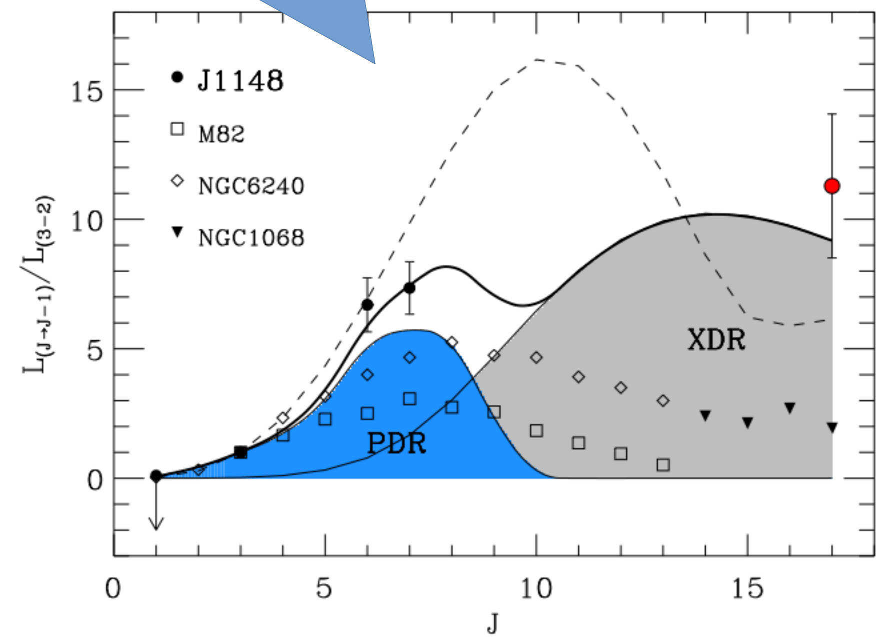
Background

- Diagnostic FIR emission lines
- Lessons from "Walking the Line workshop" last year
- Lessons from **this** workshop

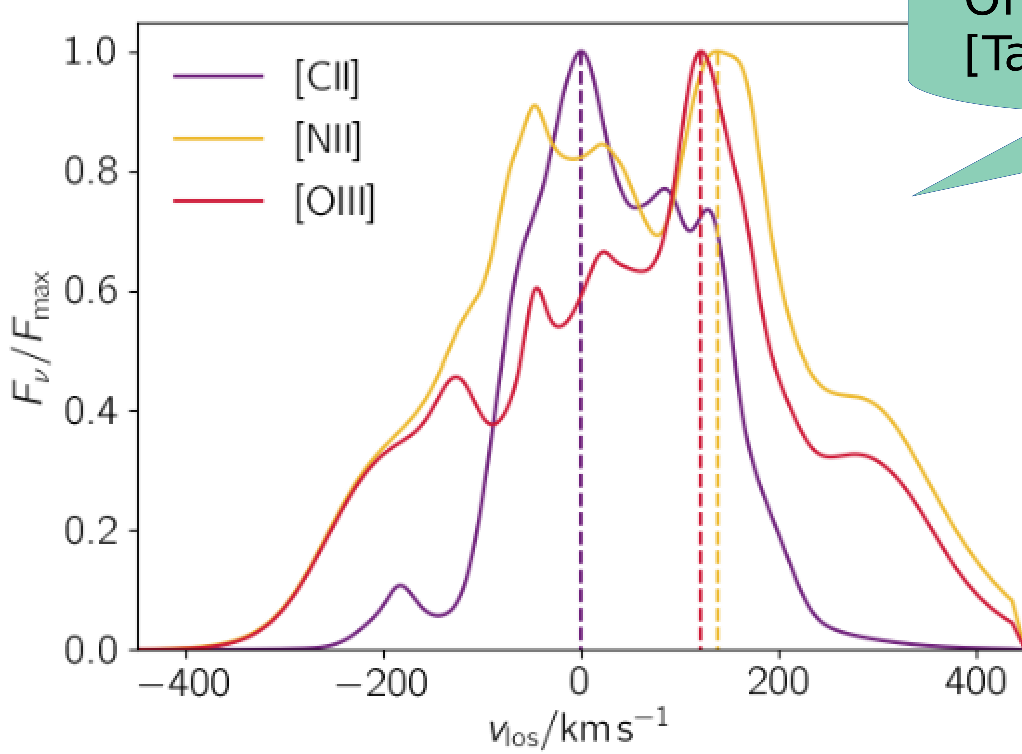
Spatial offsets (or not?) when switching line [Talk by Daisy Leung]



High vs low CO lines
[Talk by Simona Gallerani]



Offsets in velocity when switching line
[Talk by Andrea Pallottini]



SÍGAME

(=‘follow me’ in Spanish)

- Started during PhD at Dark Cosmology Centre in Copenhagen

SImulator of GAlaxy Millimeter/submillimeter Emission

SÍGAME

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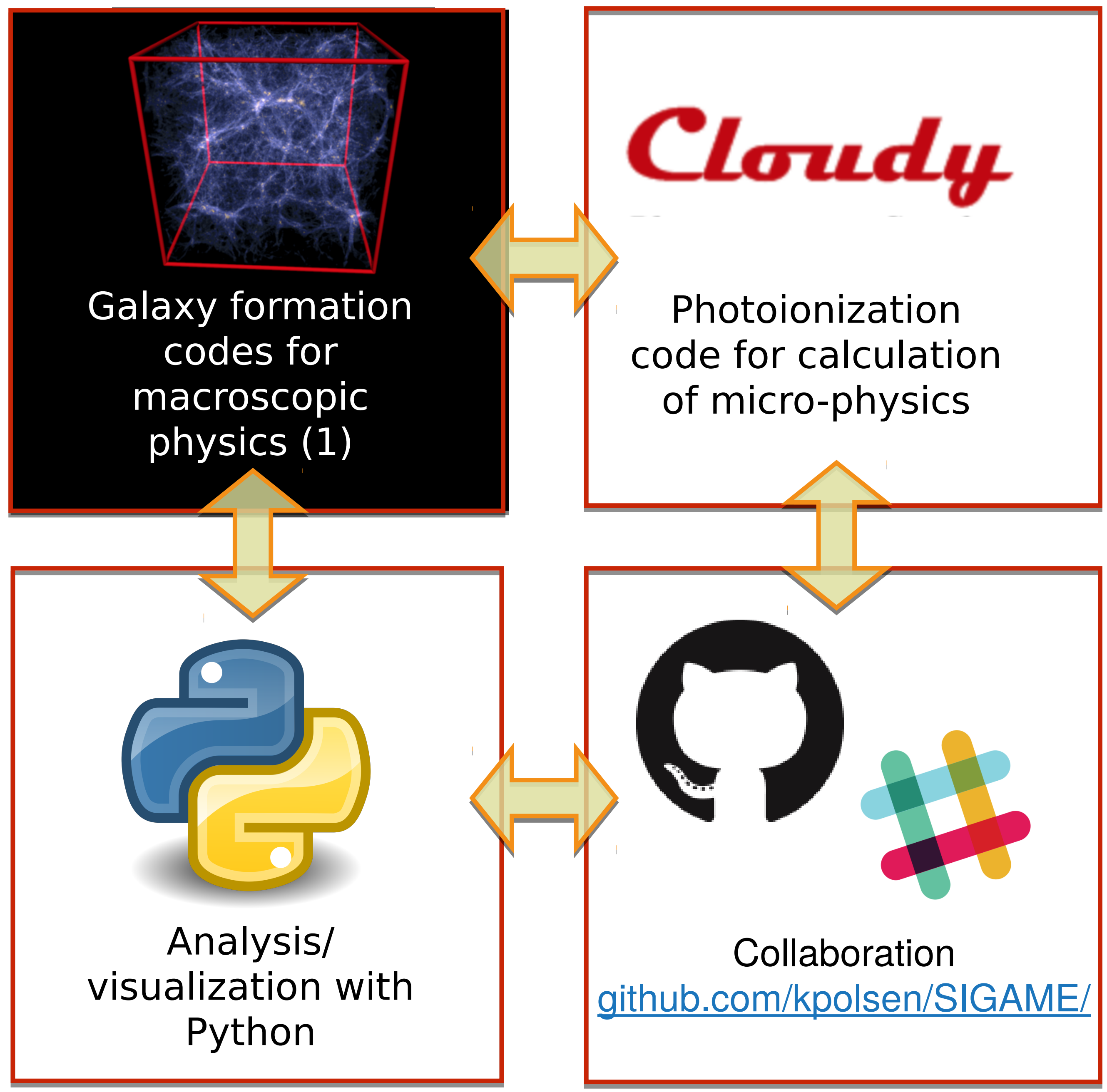
- Now a project that combines...

SImulator of GAlaxy Millimeter/submillimeter Emission



(1) Springel V., Hernquist L., 2003, MNRAS, 339, 312.

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- Now a project that combines…

We chose cosmological simulations…

cf. talk by Josh Borrow!

SÍGAME

(='follow me' in Spanish)

- Started during PhD at Dark Cosmology Centre in Copenhagen

- Now a project that combines…

cf. talk by Josh Borrow!

We chose cosmological simulations…

… for the sample size and cosmological variance.

- Hydrodynamics solver: meshless finite mass (MFM)

- SPH fluid element approach
  Gizmo → **Mufasa (zoom-ins)** → Simba

- Mass resolution:
  $m_{DM} = 10^6\ h^{-1}$Msun, $m_{gas} = 1.9 \times 10^5\ h^{-1}$Msun

- Tracking 10 elements in addition to Hydrogen

- Stellar winds from young stars from fit to FIRE simulations
  (Feedback in Realistic Environments, Muratov et al. 2015)

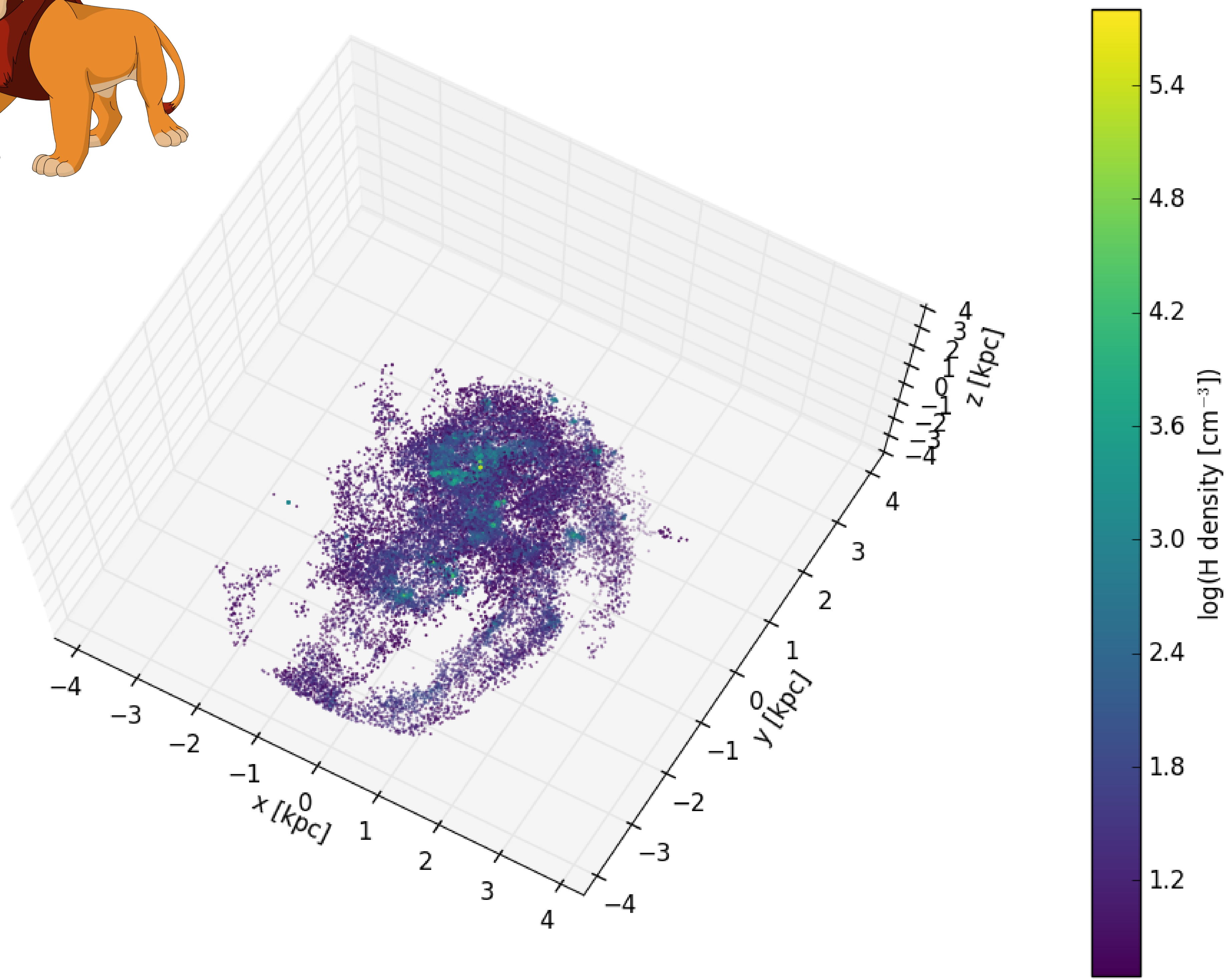
(1) Springel V., Hernquist L., 2003, MNRAS, 339, 312.

Key steps

1. Extract galaxies from simulation

Cosmological hydrodynamic simulations

(GIZMO simulations with MUFASA winds, see Davé+16 MNRAS 462)

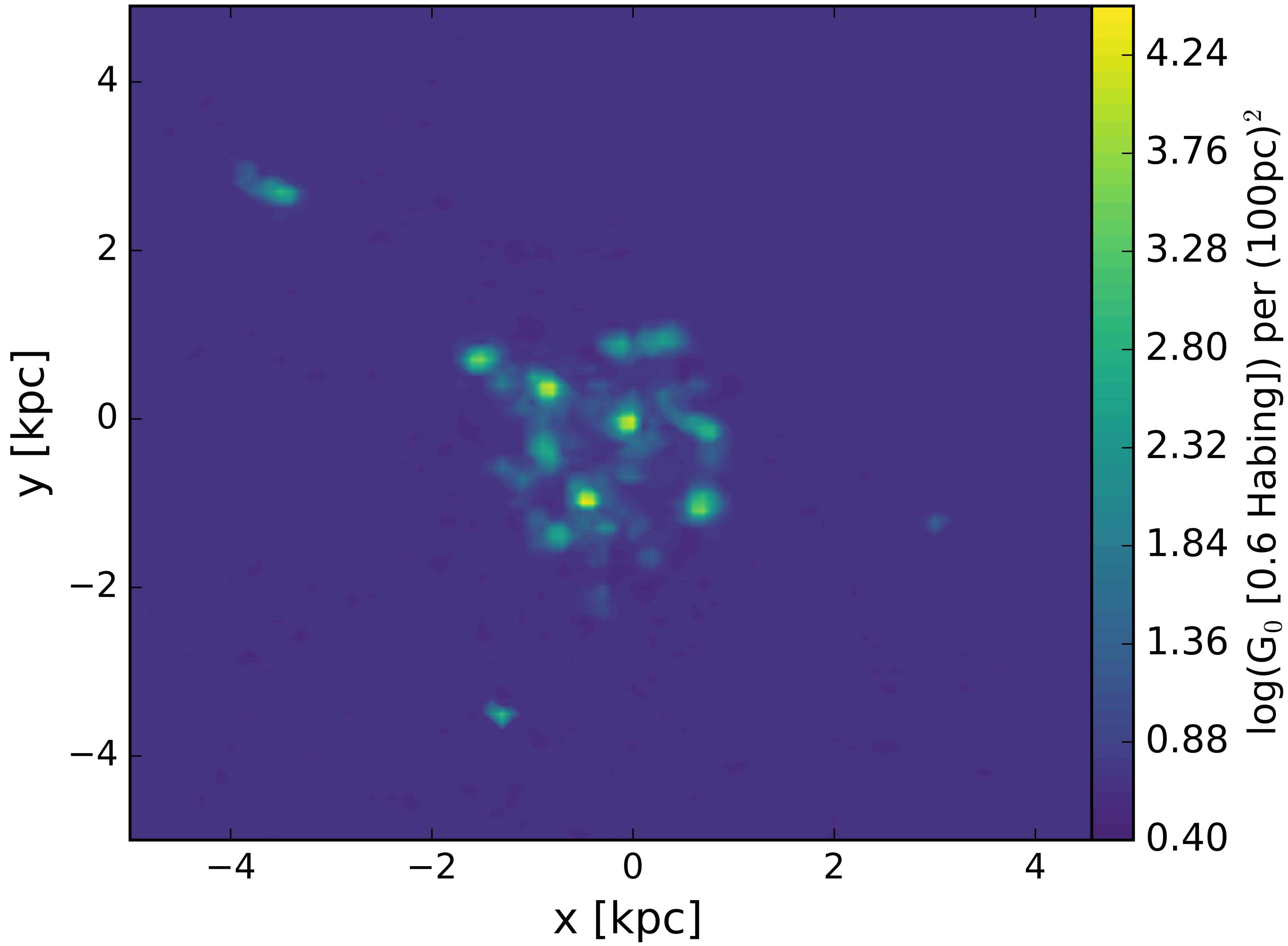


SÍGAME

Key steps

1. Extract galaxies from simulation

2. Derive large-scale ISM properties



FUV radiation (G_0) map made with starburst99

SÍGAME

Key steps

1. Extract galaxies from simulation
2. Derive large-scale ISM properties
3. Divide ISM into dense and diffuse gas

Depending upon the output from simulations and cloudy models, SÍGAME divides the gas mass into:

dense gas → **GMCs** (Giant Molecular Clouds): mostly molecular (but can contain partly ionized PDRs)

diffuse gas {

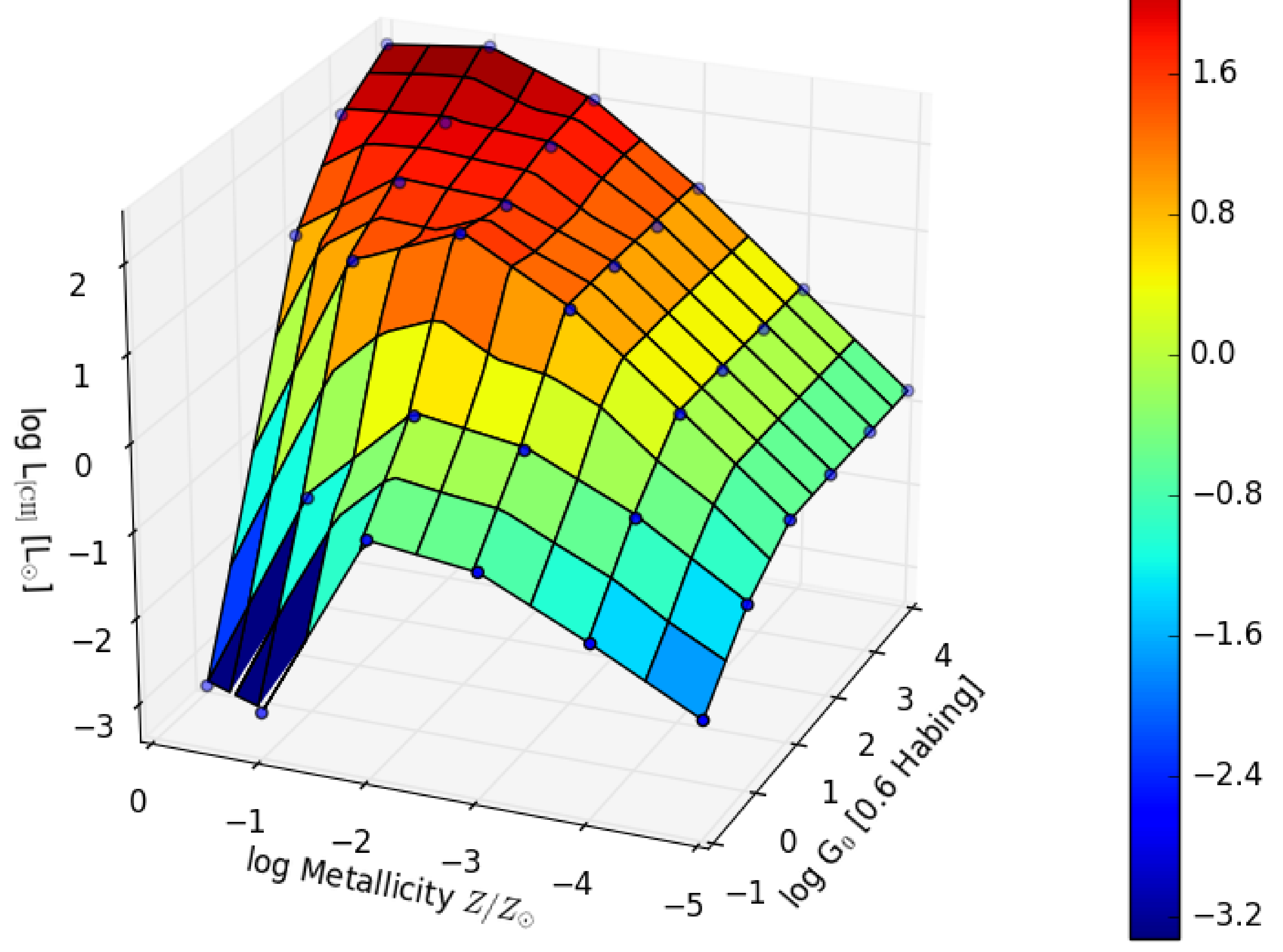
- **DNG** (Diffuse Neutral Gas): part of the diffuse gas clouds that is mostly neutral
- **DIG** (Diffuse Ionized Gas): part of the diffuse gas clouds that is mostly ionized

SÍGAME

Key steps

1. Extract galaxies from simulation
2. Derive large-scale ISM properties
3. Divide ISM into dense and diffuse gas
4. Interpolate in grids of Cloudy v17 models for line emission etc.

Example of grid of solutions with **Cloudy** (the photoionization code) for the [CII] line



Shameless self-promotion

Just made* a 2nd release of SIGAME, now in Python3

Check out the new website with code release and documentation:

https://kpolsen.github.io/SIGAME/index.html

*With **much** help from **Daisy Leung** (Cornell/Flatiron), Lily Whitler (ASU) and Satish Bhambri (CIDSE, Software Engineering ASU)

Modeling line ratios at z~0

- How can line ratios help in **diagnosing** the ISM?

Modeling line ratios at z~0

- How can line ratios help in **diagnosing** the ISM?

The [CII]158/[NII]205 ratio

Modeling line ratios at z~0

- How can line ratios help in **diagnosing** the ISM?

The [CII]158/[NII]205 ratio

If you know what that ratio is in fully ionized gas (R_{ionized}), you get how much of the [CII] comes from neutral gas:

$$f_{[\text{C II}],\text{Neutral}} = \frac{[\text{C II}] - R_{\text{ionized}} \times [\text{N II}]\ 205\ \mu\text{m}}{[\text{C II}]}$$

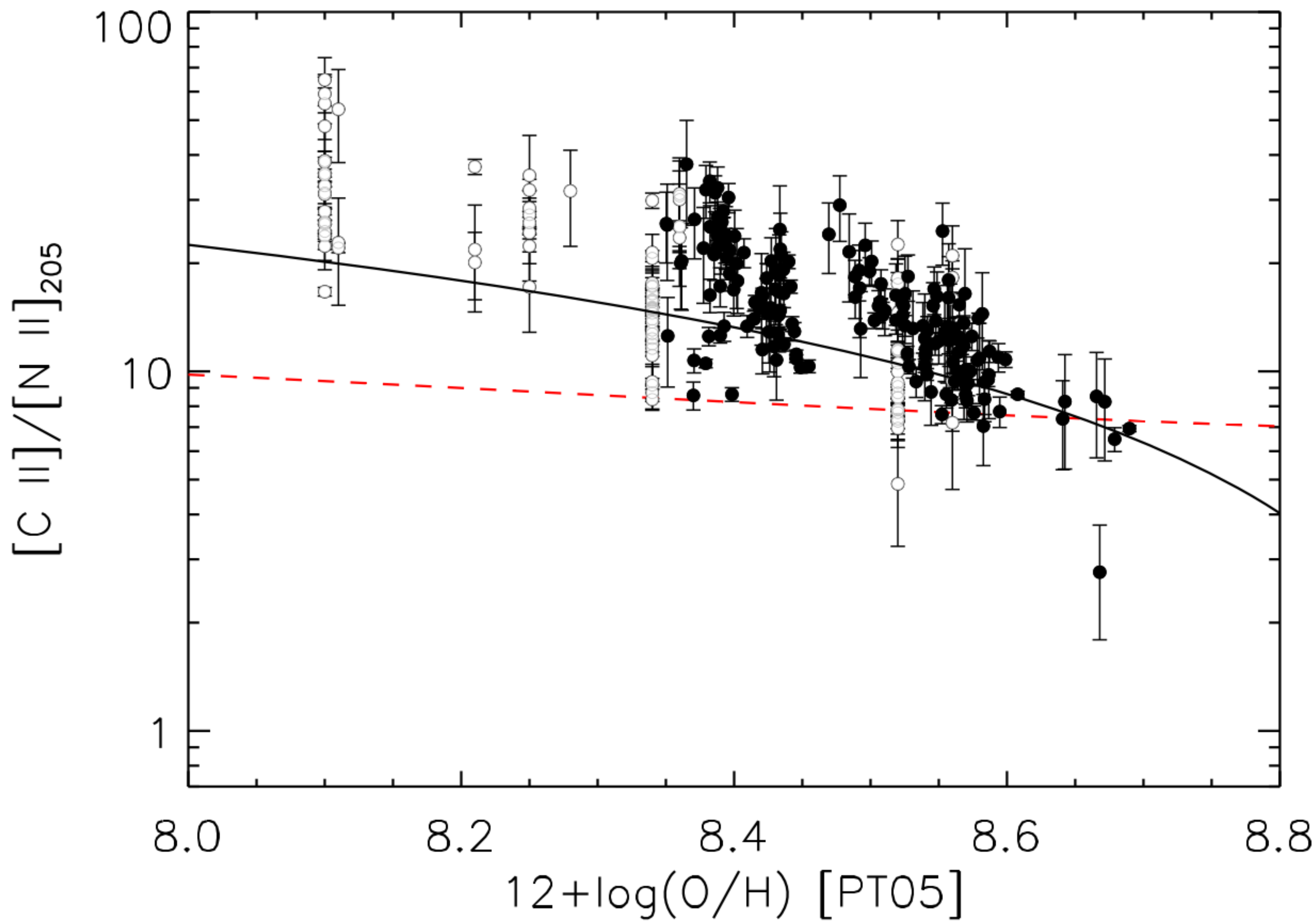
Can we use [CII]158/[NII]205 to estimate neutral/ionized gas mass ratio?

[Croxall+17]

Modeling line ratios at z~0

- How can line ratios help in **diagnosing** the ISM?
- Caveat: Line ratio also depends on gas metallicity

The [CII]158/[NII]205 ratio



CrossMark

The Origins of [C II] Emission in Local Star-forming Galaxies

K. V. Croxall[1,2,3], J. D. Smith[2,4], E. Pellegrini[4,5], B. Groves[6], A. Bolatto[7], R. Herrera-Camus[8], K. M. Sandstrom[9], B. Draine[10], M. G. Wolfire[7], L. Armus[11], M. Boquien[12], B. Brandl[13,14], D. Dale[15], M. Galametz[16,17], L. Hunt[18], R. Kennicutt, Jr.[19], K. Kreckel[2], D. Rigopoulou[20], P. van der Werf[13], and C. Wilson[21]

[Croxall+17]

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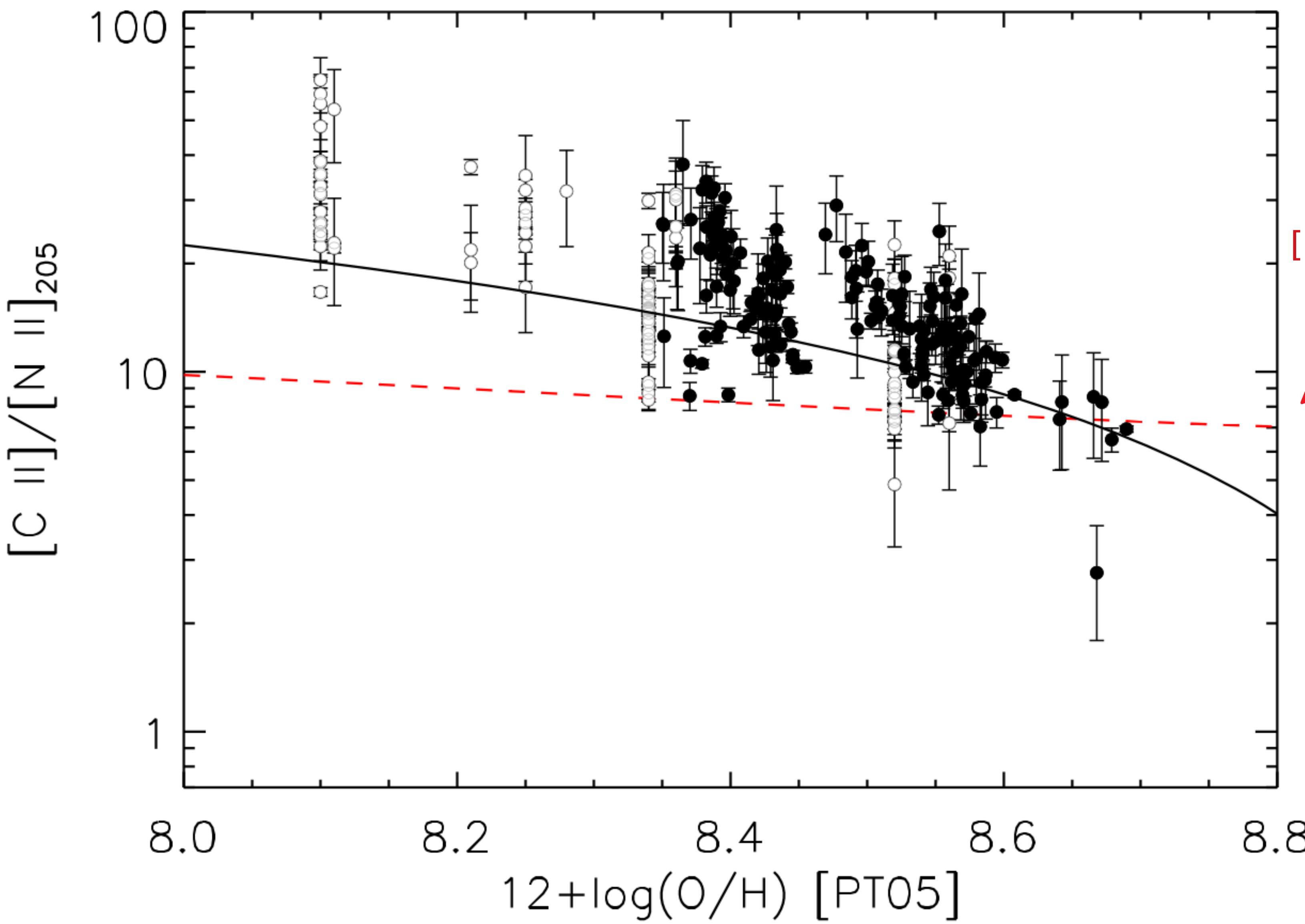
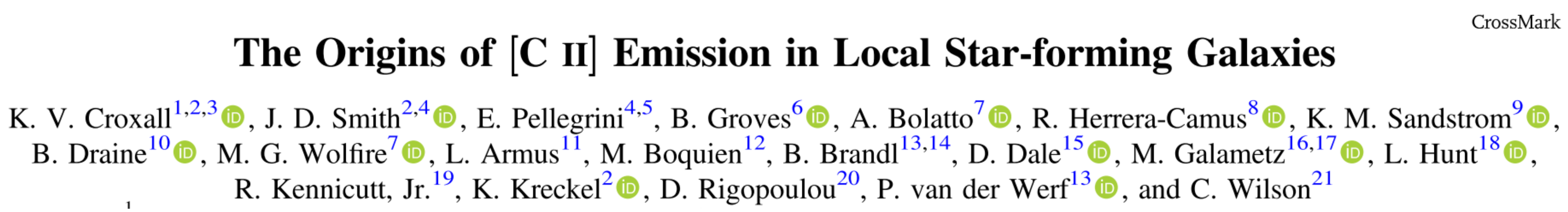


Partly due to increase of N/O and N/C with metallity [Nivea+Przybilla+12]

Cloudy modeling [Nagao+12]

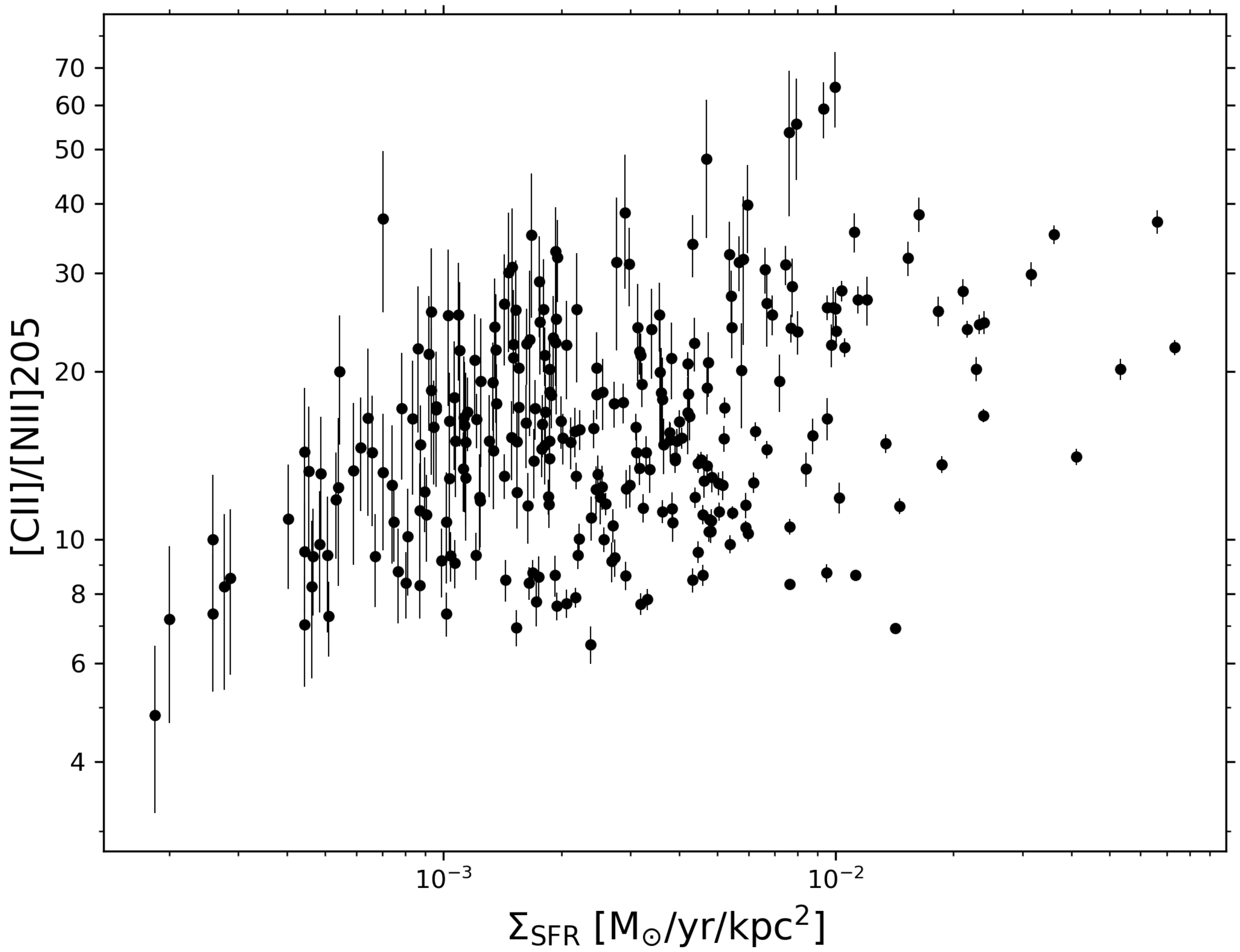


[Croxall+17]

Modeling line ratios at z~0

- How can line ratios help in **diagnosing** the ISM?
- Caveat: Line ratio also depends on gas metallicity and SFR surface density.

The [CII]158/[NII]205 ratio



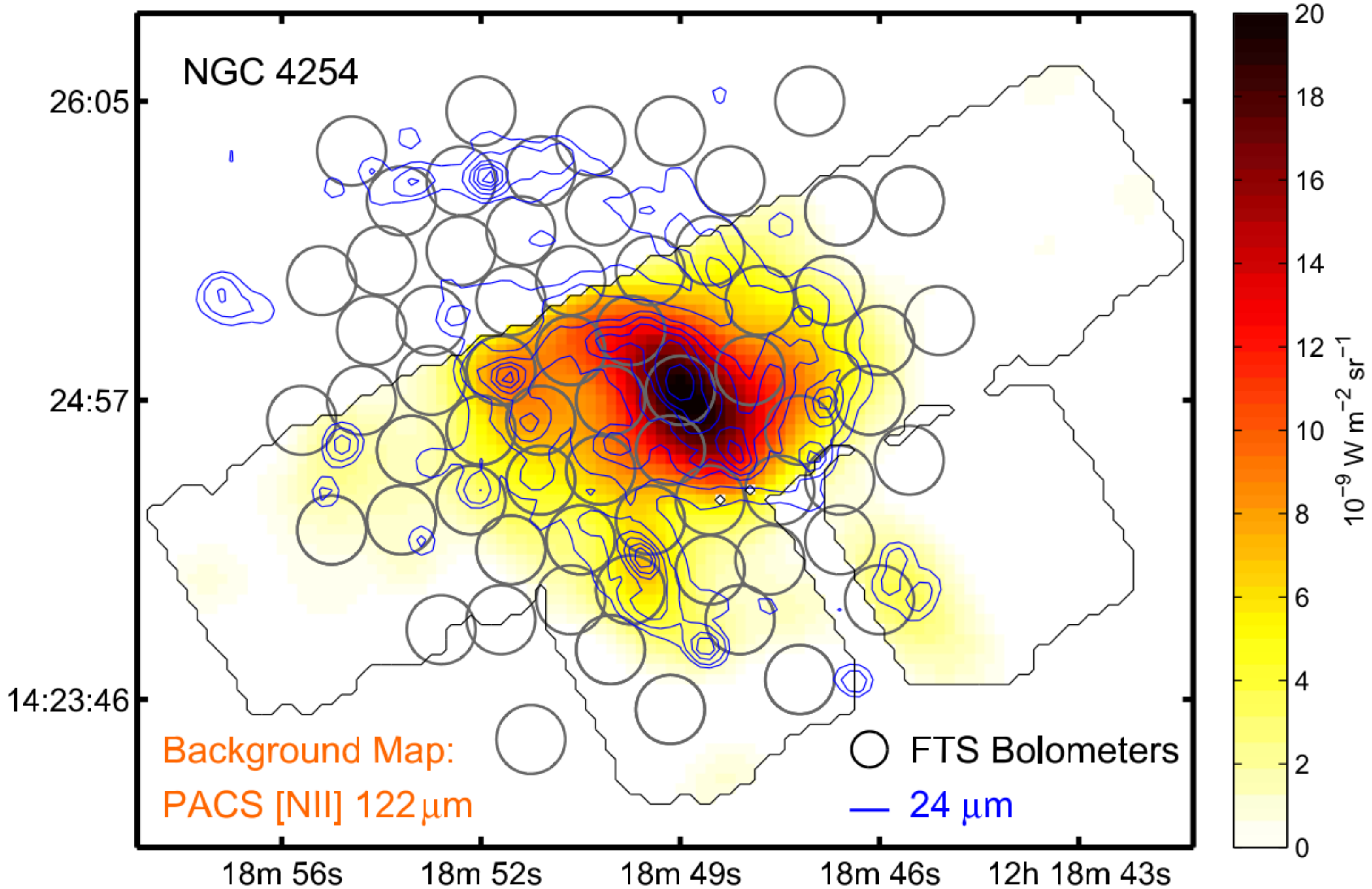
Is [CII] emission from neutral regions suppressed less by pressure?

[Croxall+17]

Modeling line ratios at z~0

- Goal: Simulating line ratios in resolved nearby galaxies to compare with resolved observations

Create synthetic observations similar to resolved *Herschel* observations:



Herrera-Camus+16

Modeling line ratios at z~0

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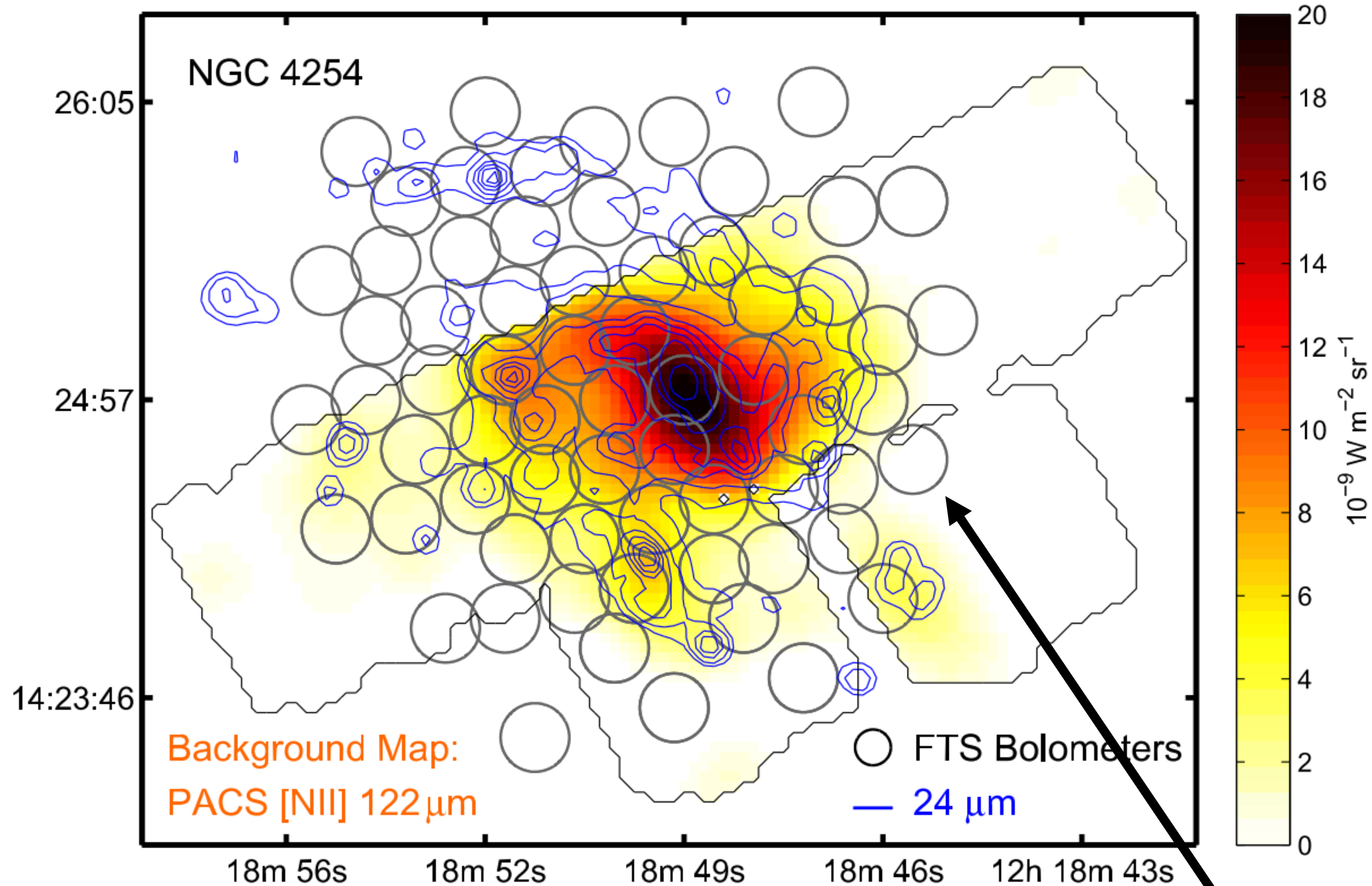
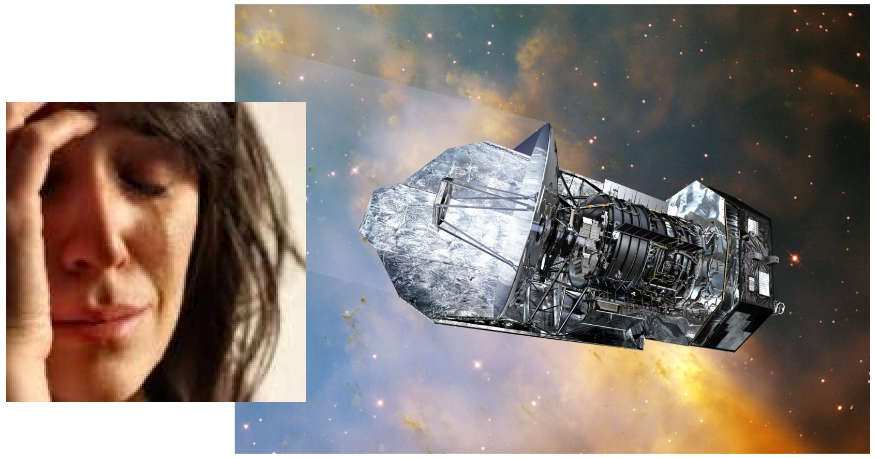


circles: 17″ SPIRE-FTS bolometers used to detect the [NII] 205 μm line.

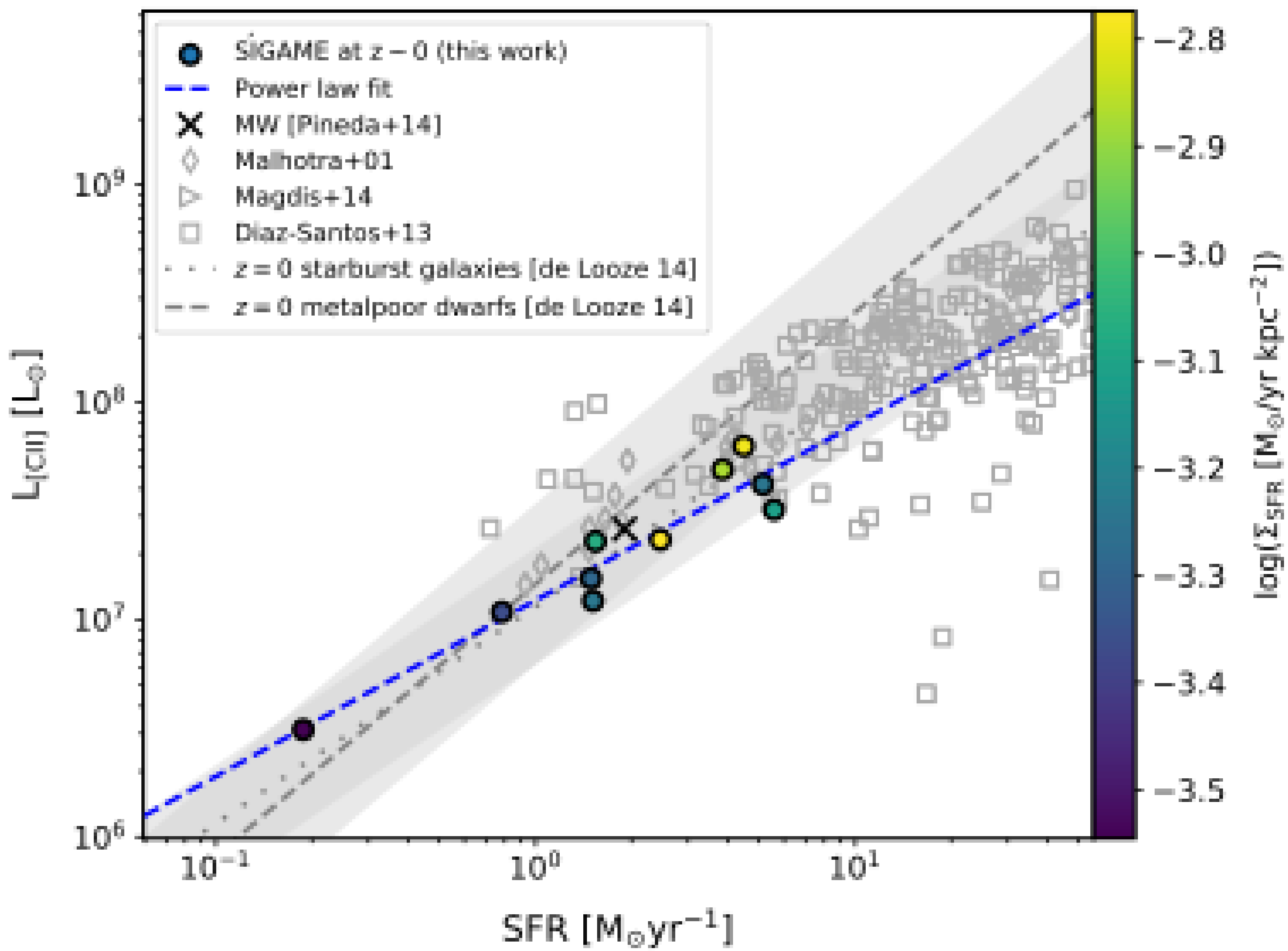


Herrera-Camus+16

Modeling line ratios at z~0

- Check #1: that we reproduce the [CII]-SFR relation at z~0

Applying SÍGAME to 10 z~0 galaxies from zoom simulations

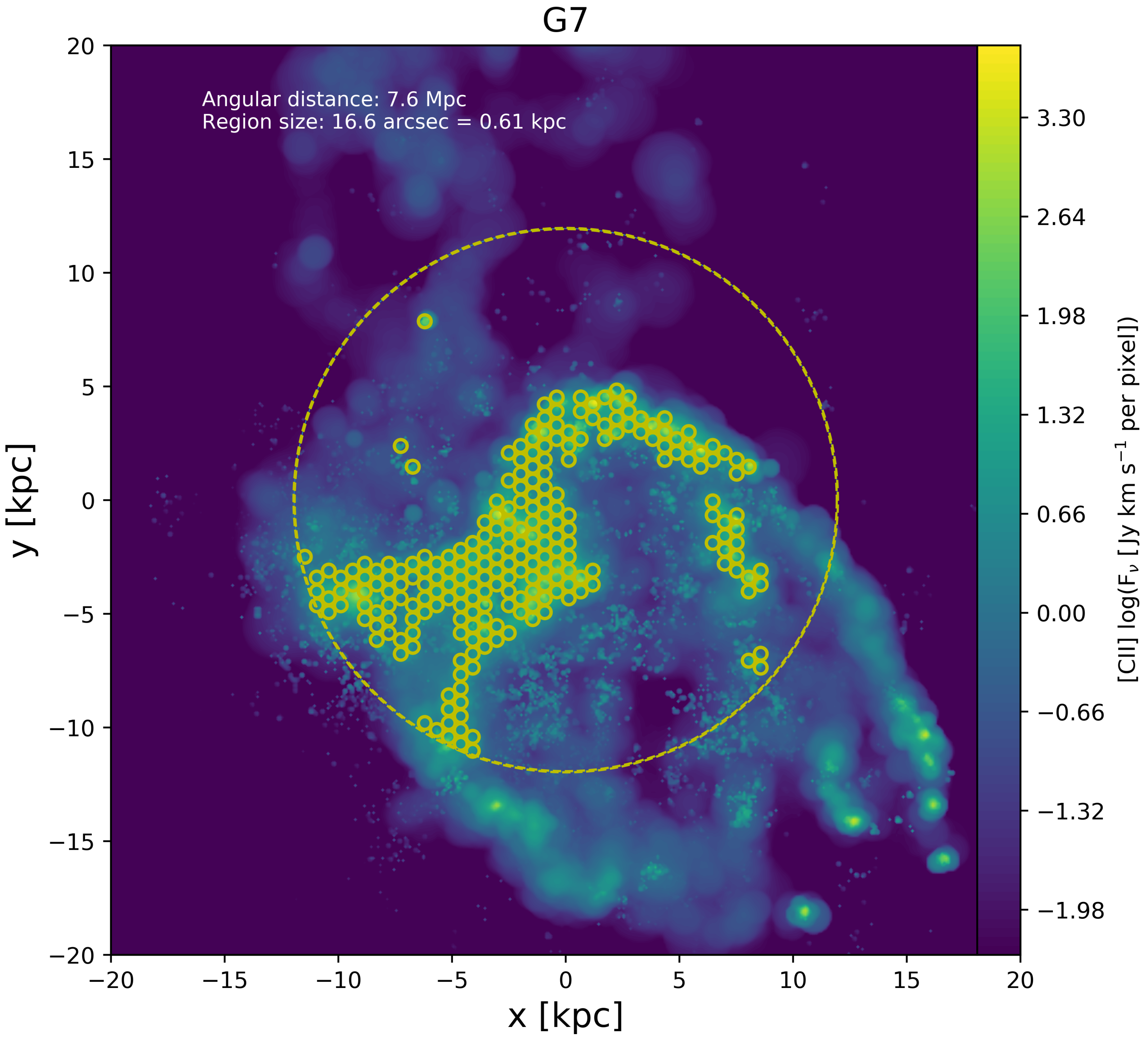


MUFASA simulations by Desika Narayanan @ UF

Modeling line ratios at z~0

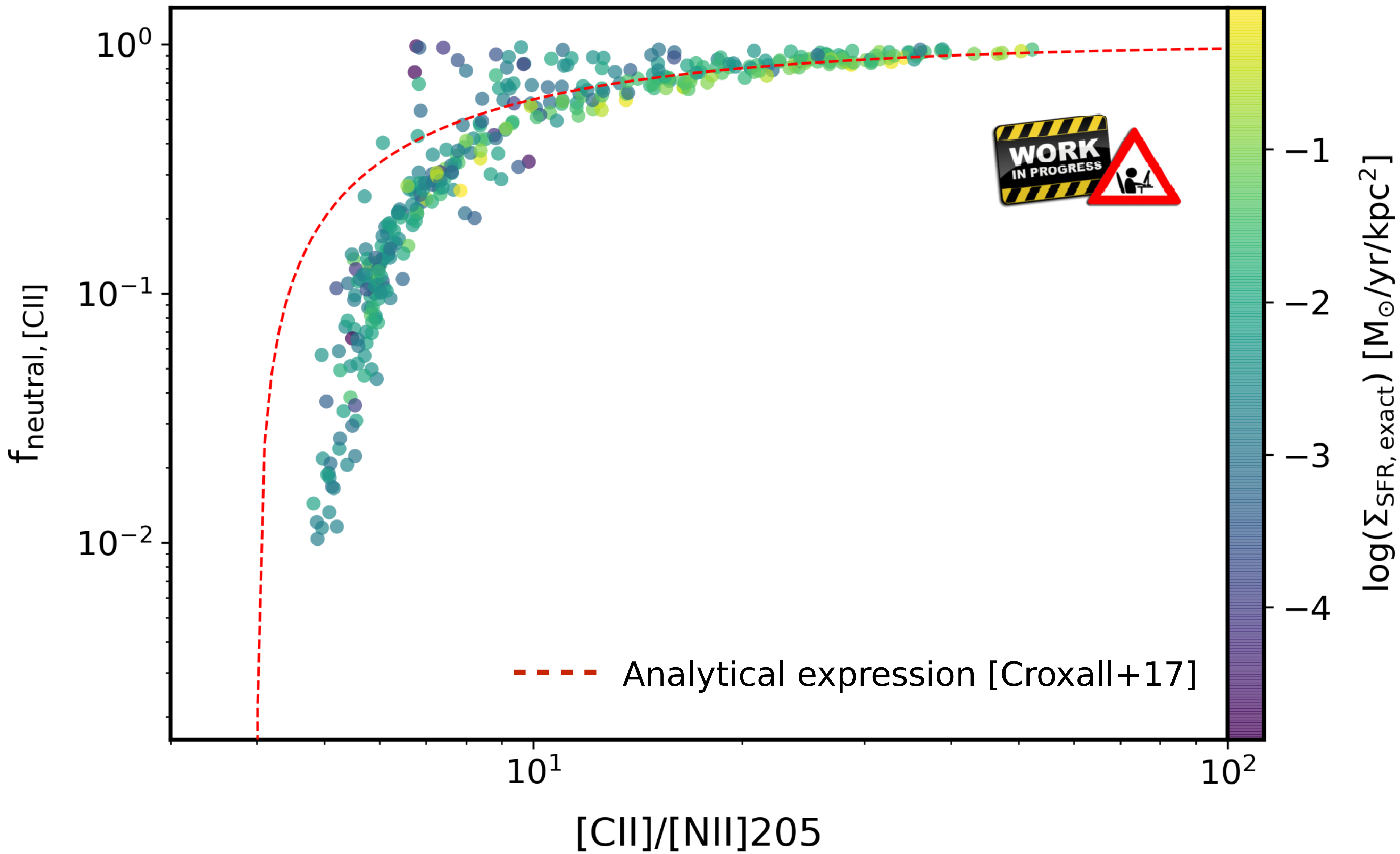
- Check #1: that we reproduce the [CII]-SFR relation at z~0
- Smooth the resulting line emission maps by Herschel beam and select regions

Applying SÍGAME to 10 z~0 galaxies from zoom simulations



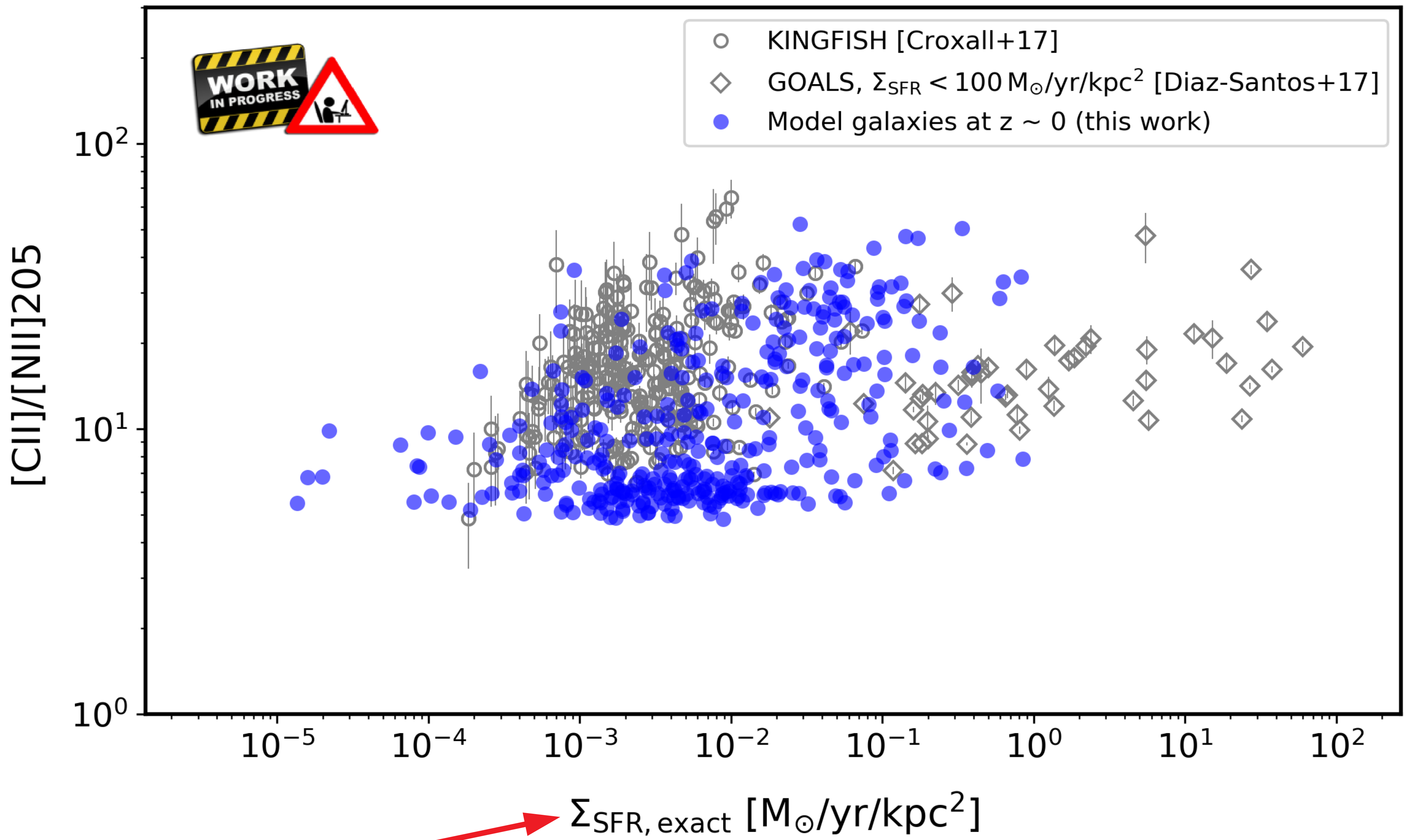
Modeling line ratios at z~0

Correlate line ratios with ISM properties - such as neutral [CII] fraction



Modeling line ratios at z~0

Correlate line ratios with ISM properties - such as Σ_{SFR}

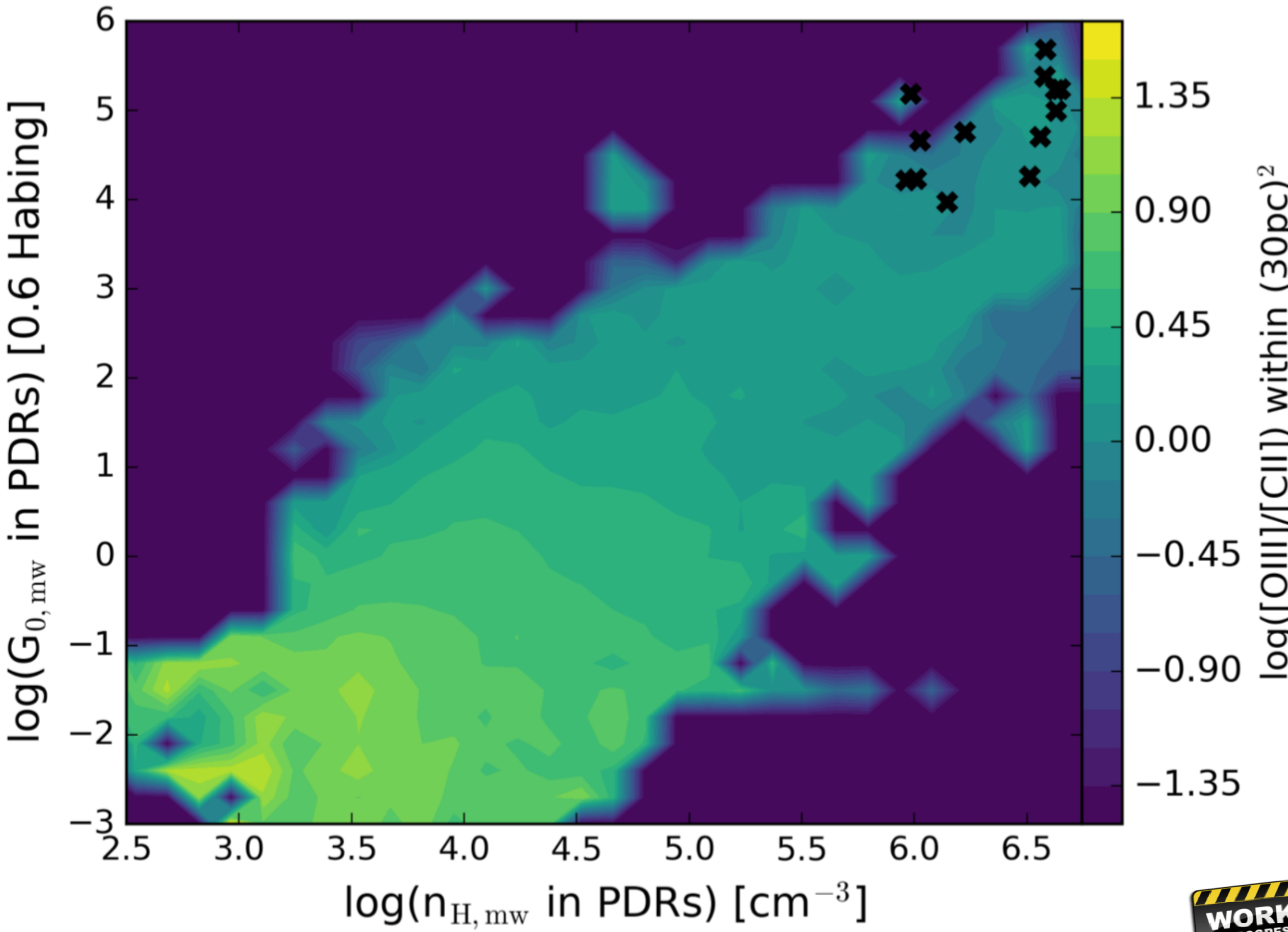


Herrera-Camus+15 method: Combination of 24m, H, TIR, FUV or those available.
Here: We use instantaneous SFR inherent in gas particles.

Work with student Lily Whitler @ ASU

Modeling line ratios at z~0

Create diagnostic line ratio plots



Modeling line ratios at z~0

Can we use FIR FS line ratios to:

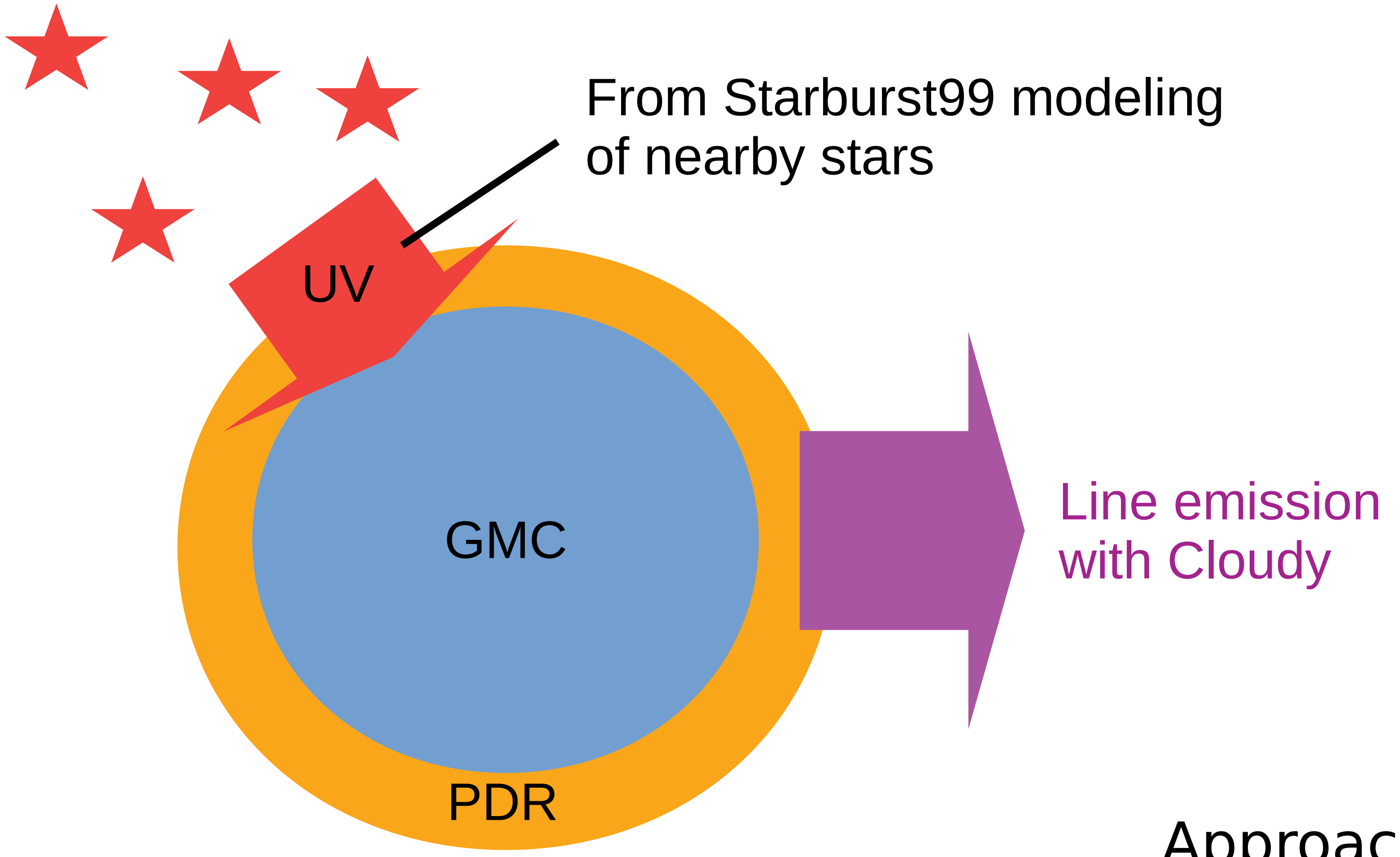
1) to estimate actual ionized gas mass fraction?

2) to estimate gas metallicity (mass-weighted)?

3) and how do such callibrations depend on Σ_{SFR}?

Modeling line ratios at z~0

... and another question for the modelers: how do we “subgrid” the ISRF?



Approach in Olsen+17

Modeling line ratios at z~0

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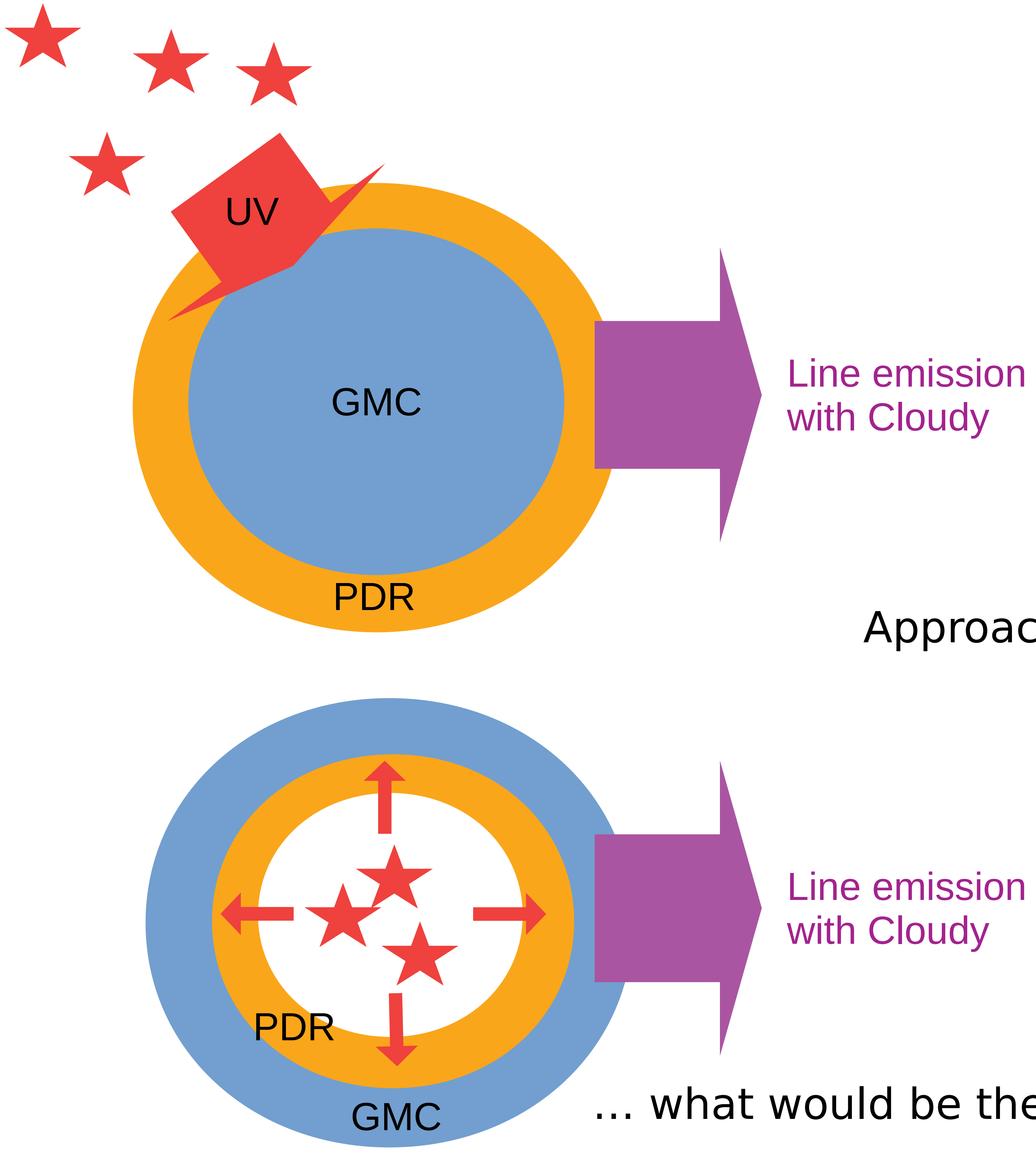
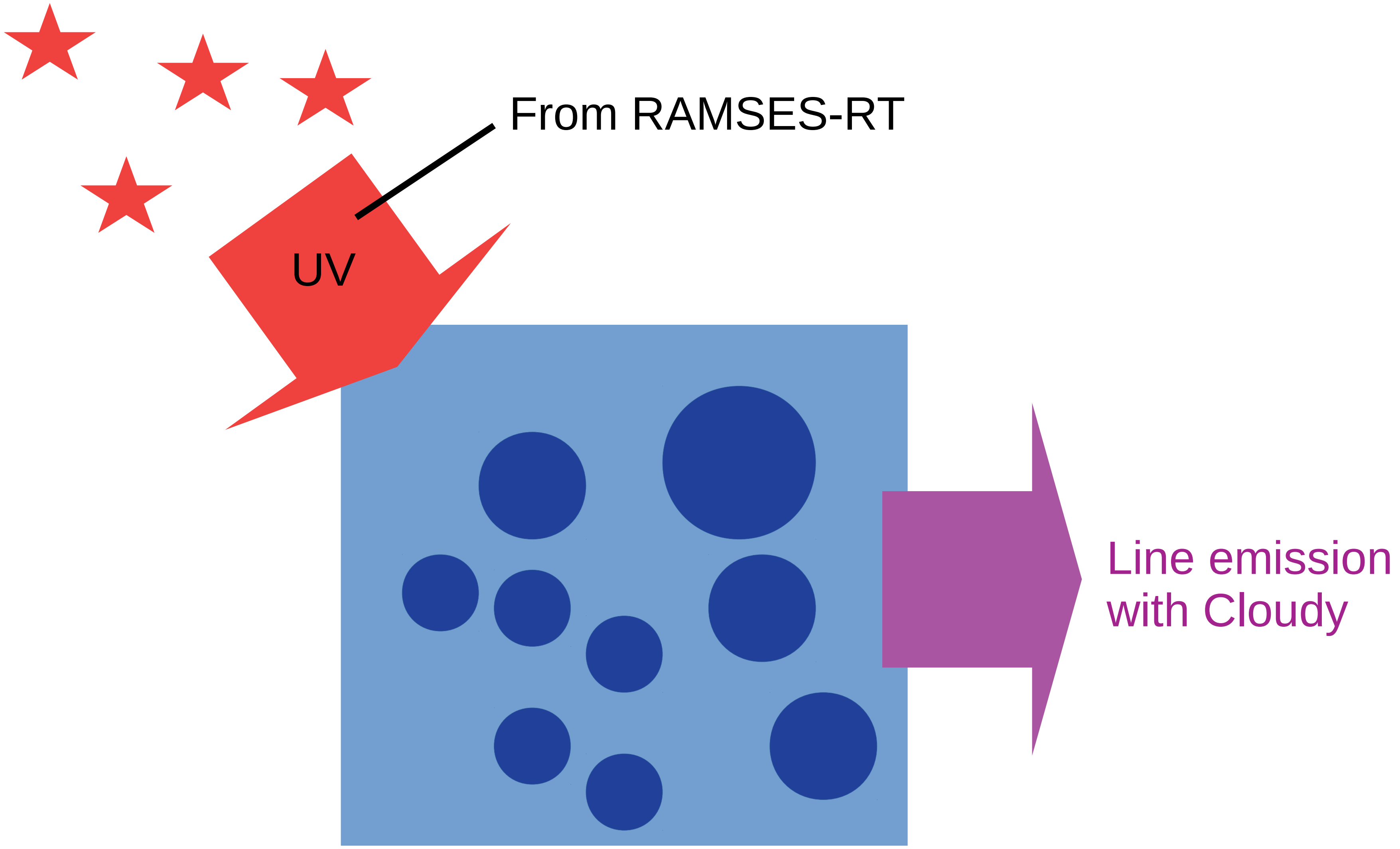


Approach in Olsen+17

... what would be the consequence?

Modeling line ratios at z~0

... and another question for the modelers: how do we "subgrid" the ISRF?



Approach in Pallottini+19

Modeling line ratios at z~0

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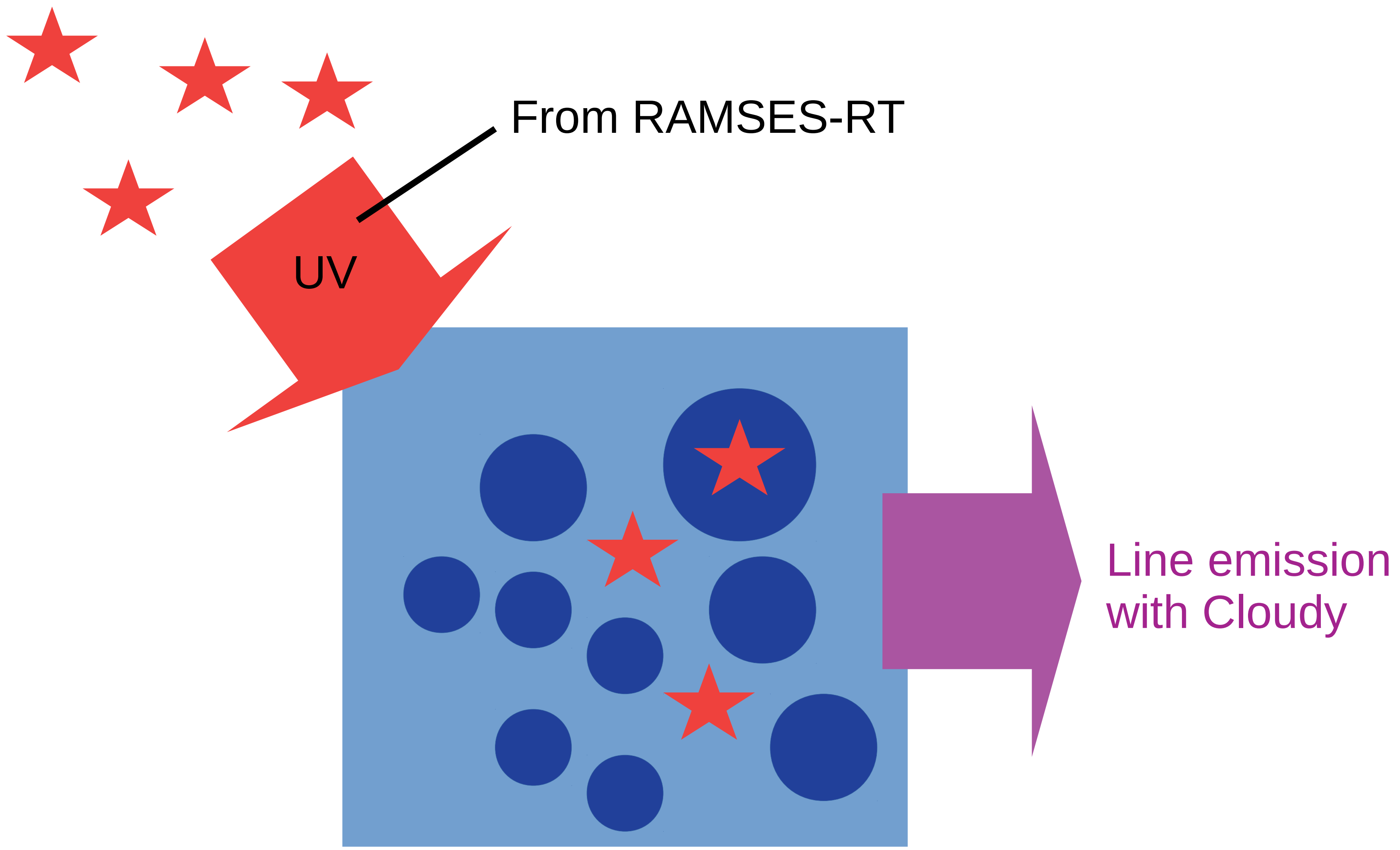


... if there are stars inside the cell,

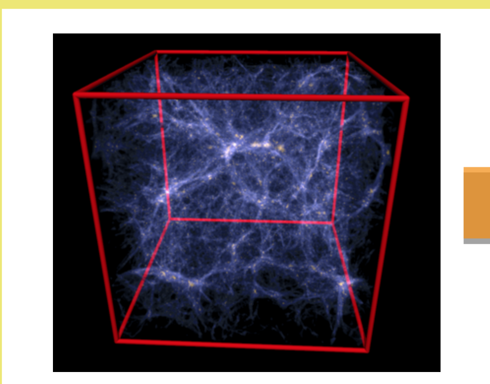
would it make sense to further stratify the UV?

Approach in Pallottini+19

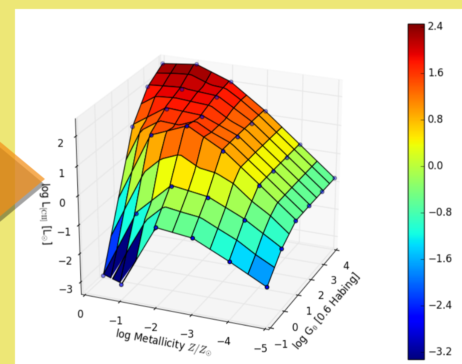
Summary

Synthetic observations are important for understanding/predicting real observations.

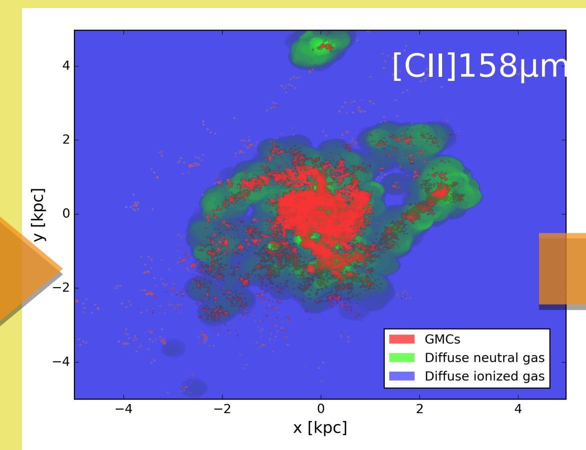
(1)
Galaxy formation codes for large-scale physics



(2)
Extract knowledge, like FUV field and pressure, and apply look-up tables of photoionization models



(3)
Make datacubes of different lines



SÍGAME

Create synthetic observations!

Questions for discussion session!!!

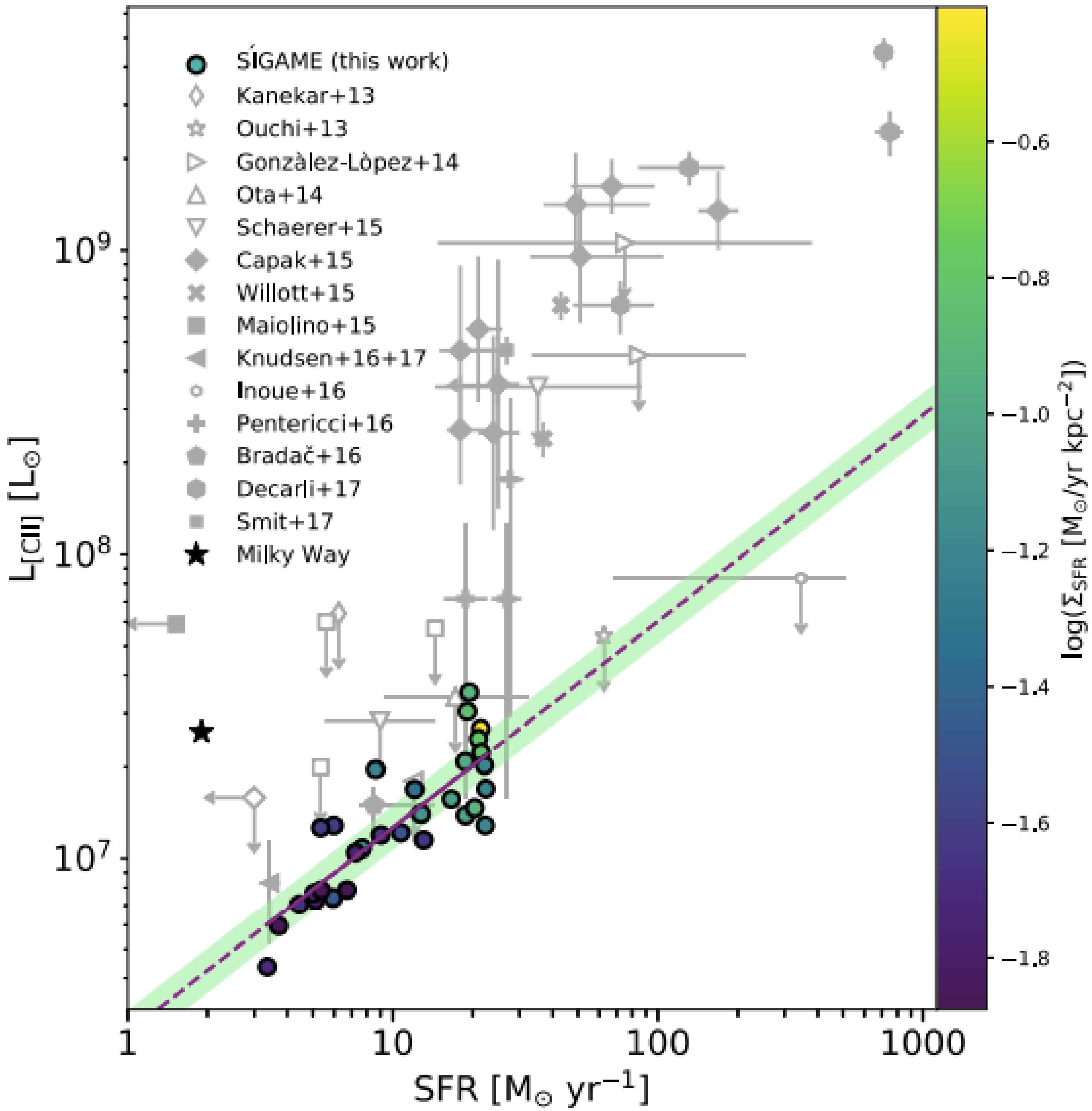
1. How can we motivate observers to go for more lines?
2. How do we make sure that the FUV radiation is distributed consistently?
3. Should we start an effort to benchmark our codes?

Extra slides

[CII], [OI], [OIII] results at z~6

- **Low [CII] luminosity** comes out naturally for the normal star-forming galaxies selected.

[CII]-SFR relation at z~6



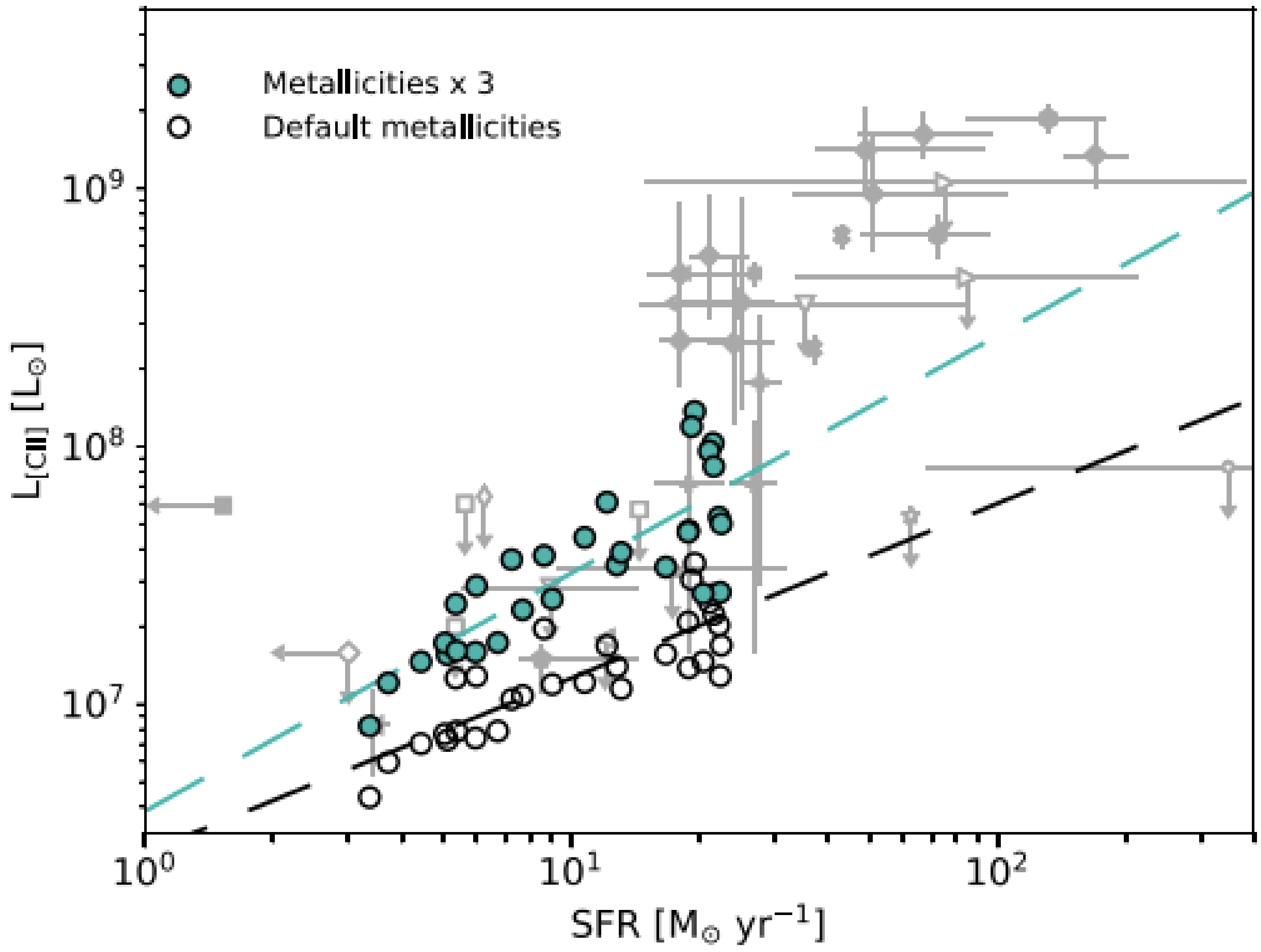
Olsen et al. 2018

[CII], [OI], [OIII] results at z~6

- **Low [CII] luminosity** comes out naturally for the normal star-forming galaxies selected.

- **Higher [CII] luminosity** is an affect of higher metallicity than expected and/or higher molecular gas mass fraction.

[CII]-SFR relation at z~6

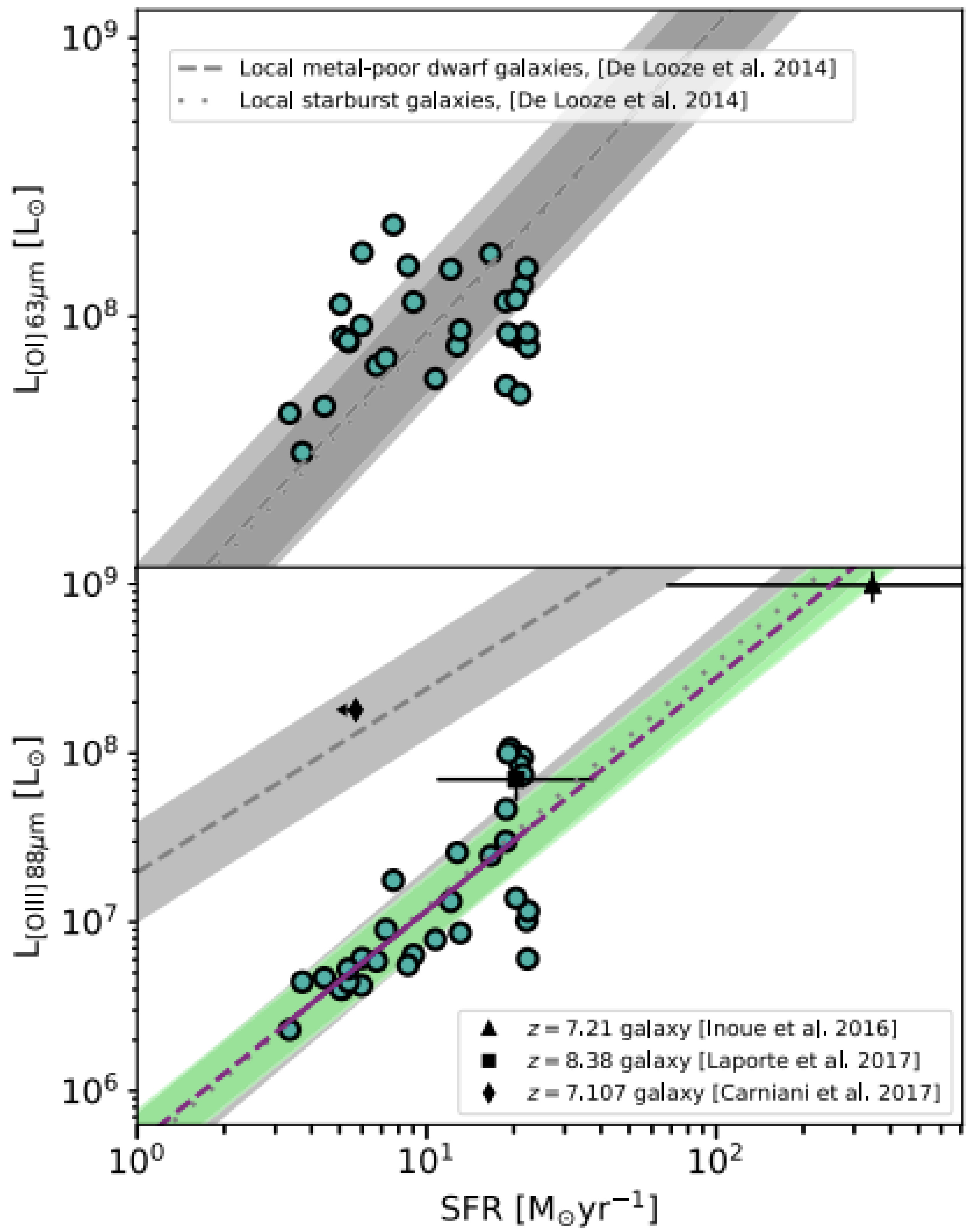


Olsen et al. 2018

[CII], [OI], [OIII] results at z~6

- **[OI]** does not show a strong correlation with SFR.

[OI] and [OIII] as SFR tracers at z~6

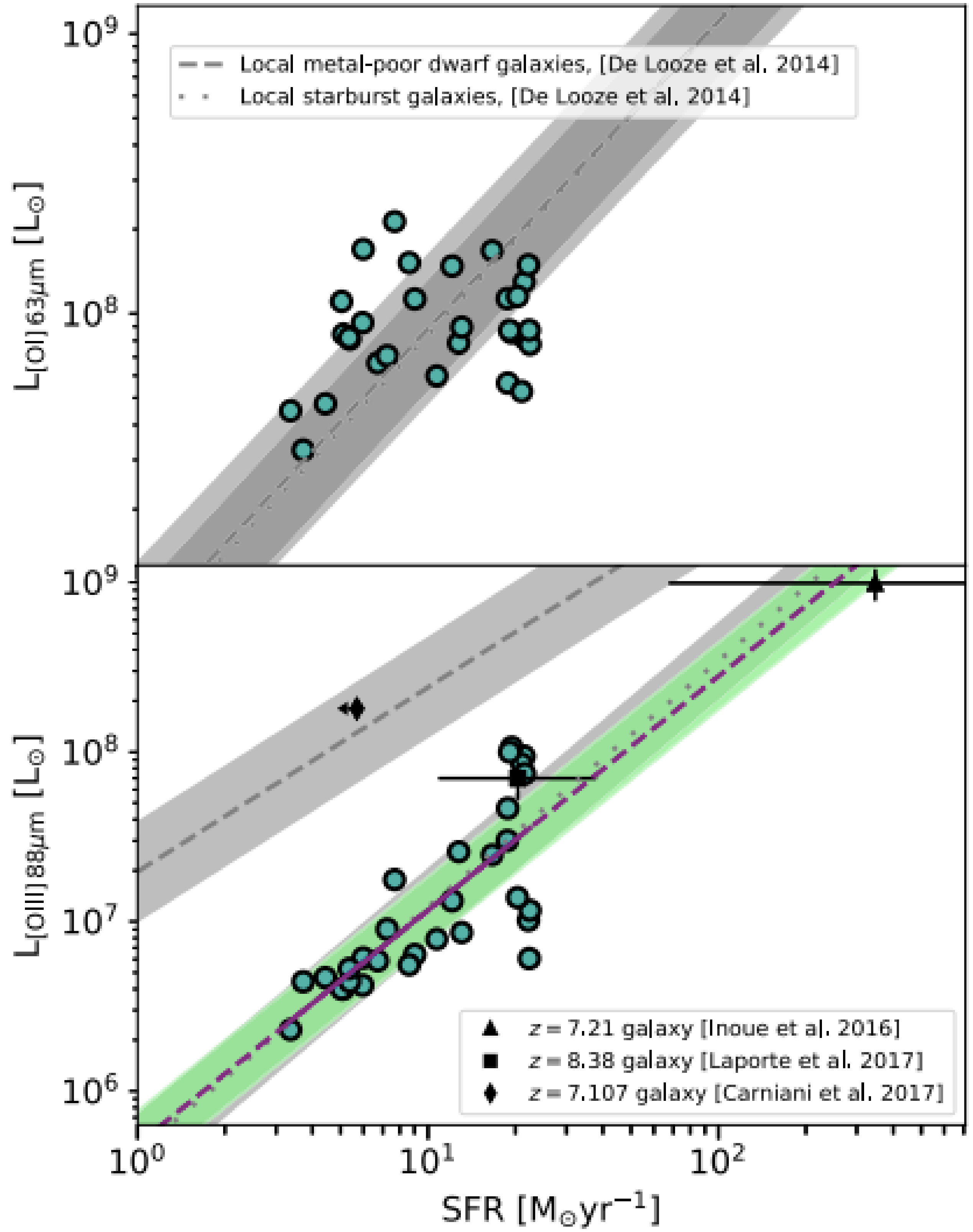


Olsen et al. 2018

[CII], [OI], [OIII] results at z~6

- **[OI]** does not show a strong correlation with SFR.
- **[OIII]** however correlates with SFR and matches that at low z and two of three high-z galaxies detected so far.

[OI] and [OIII] as SFR tracers at z~6



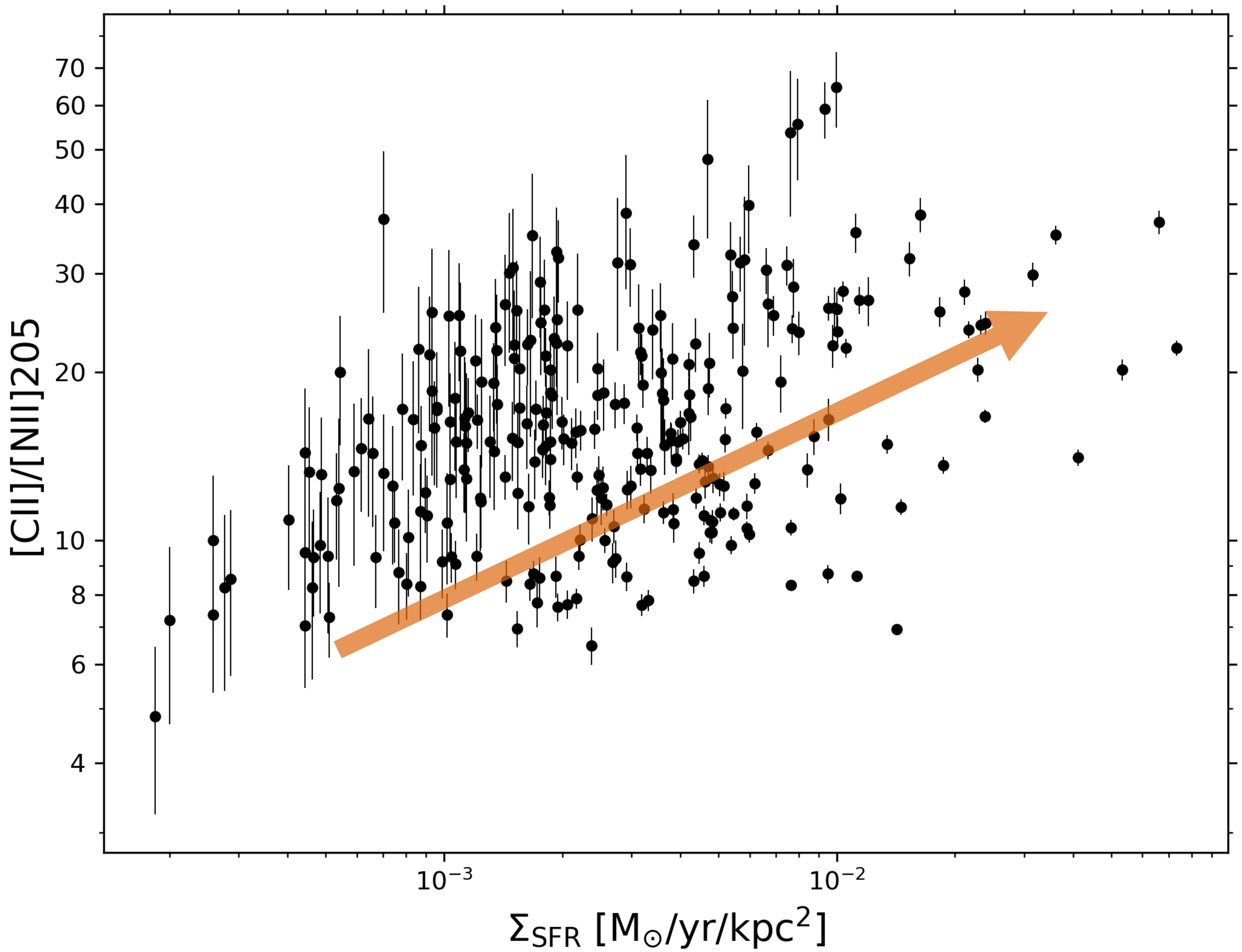
Olsen et al. 2018

Line ratios

Line Ratio observations

- How can line ratios help in **diagnosing** the ISM?
- Weak dependence on surface density of SFR

The [CII]158/[NII]205 ratio



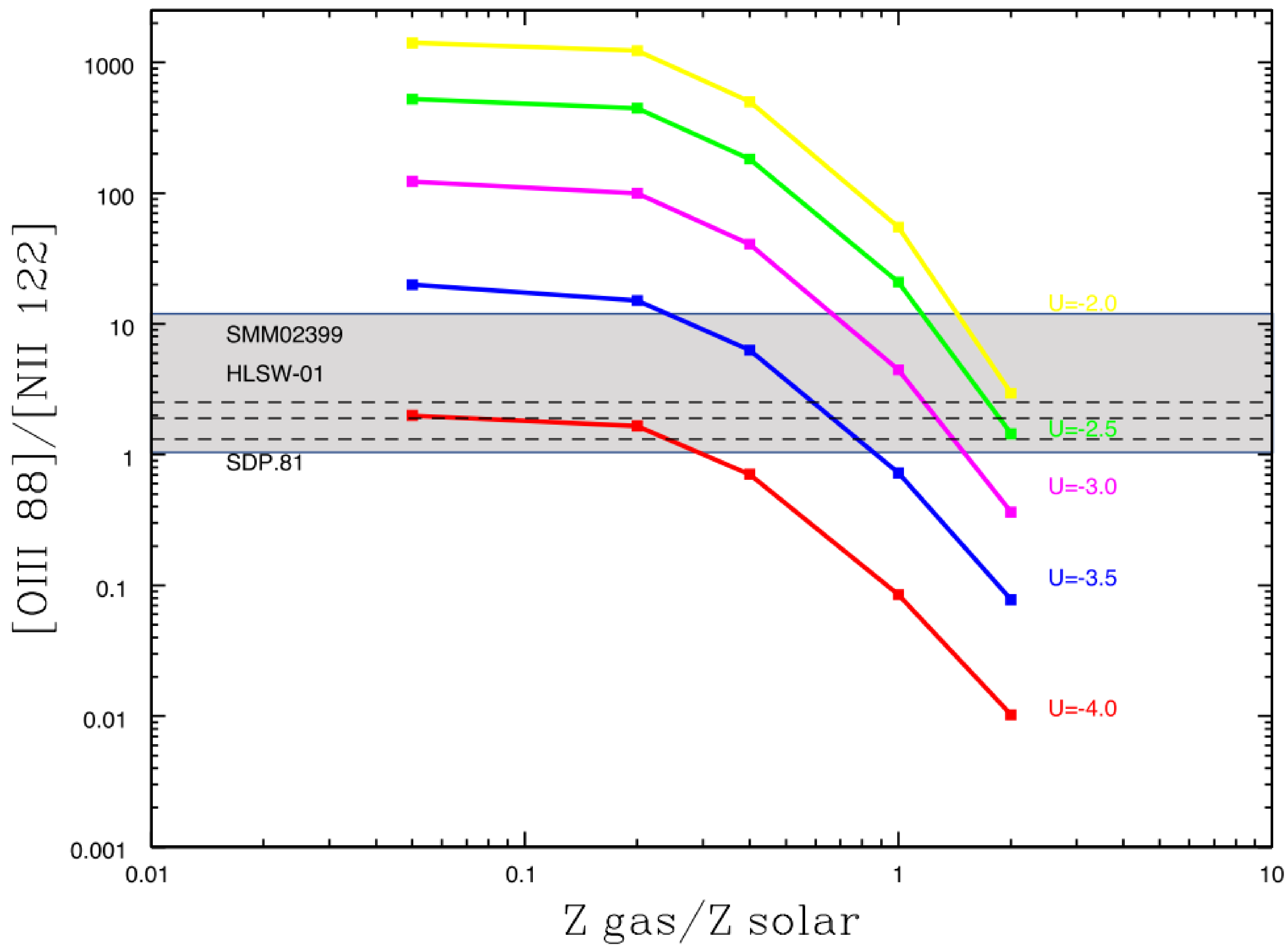
Increase towards central parts of galaxy with higher Σ_{SFR} (and more neutral gas)

[Croxall+17]

Line Ratio observations

- How can line ratios help in **diagnosing** the ISM?
- Other **FIR line ratios** have been used to estimate metallicity *Z*

The [OIII] 88/[NII] 122 ratio



On the far-infrared metallicity diagnostics: applications to high-redshift galaxies

D. Rigopoulou,[1★] M. Pereira-Santaella[1], G.E. Magdis[2], A. Cooray[3], D. Farrah[4], R. Marques-Chaves[5,6], I. Perez-Fournon[5,6], D. Riechers[7]

[Rigopoulou+17]

Line Ratio observations

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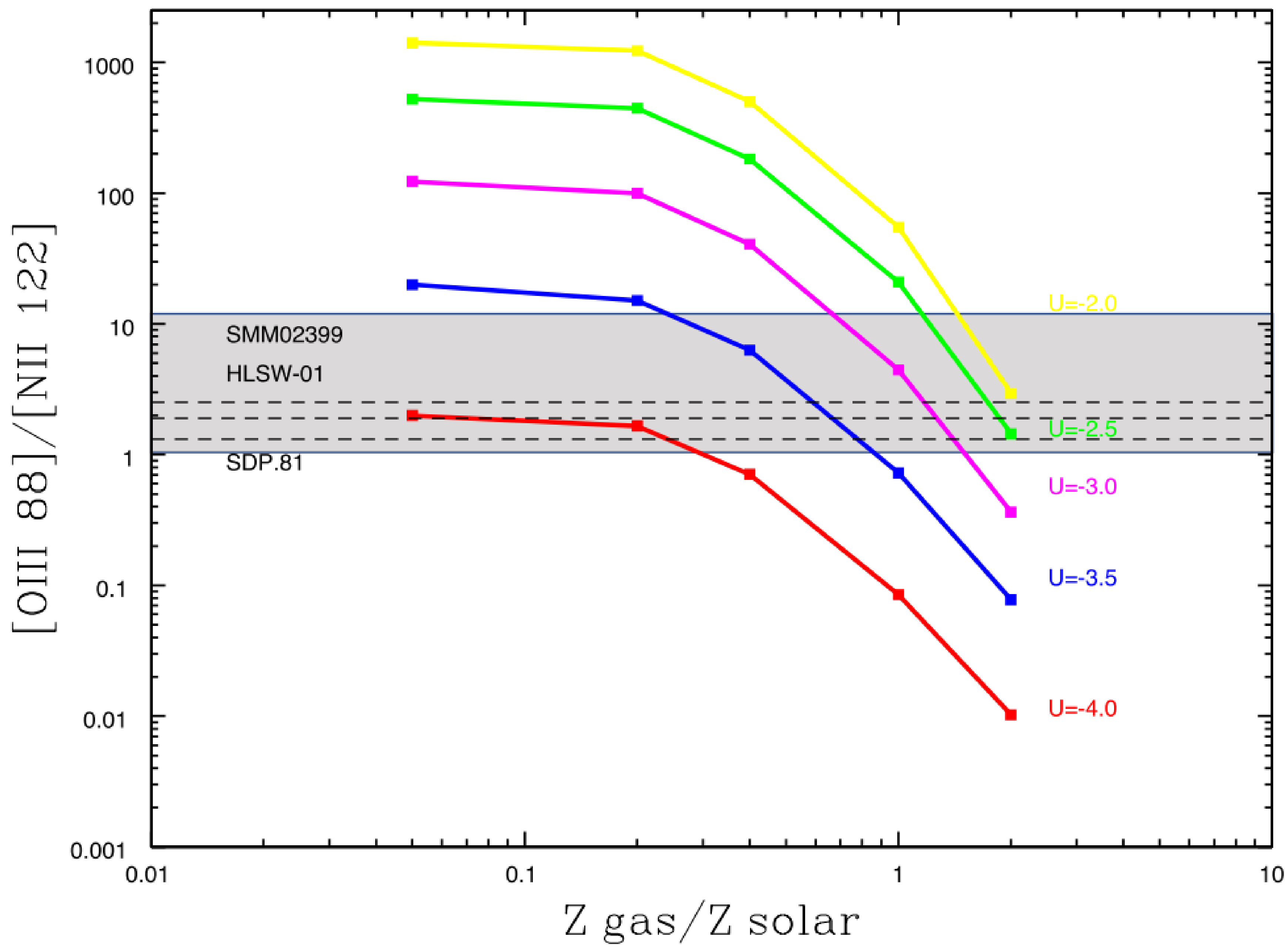
The [OIII] 88/[NII] 122 ratio



Can be used as a rough metallicity indicator, if you also now ionization parameter *U* ?

[Rigopoulou+17]

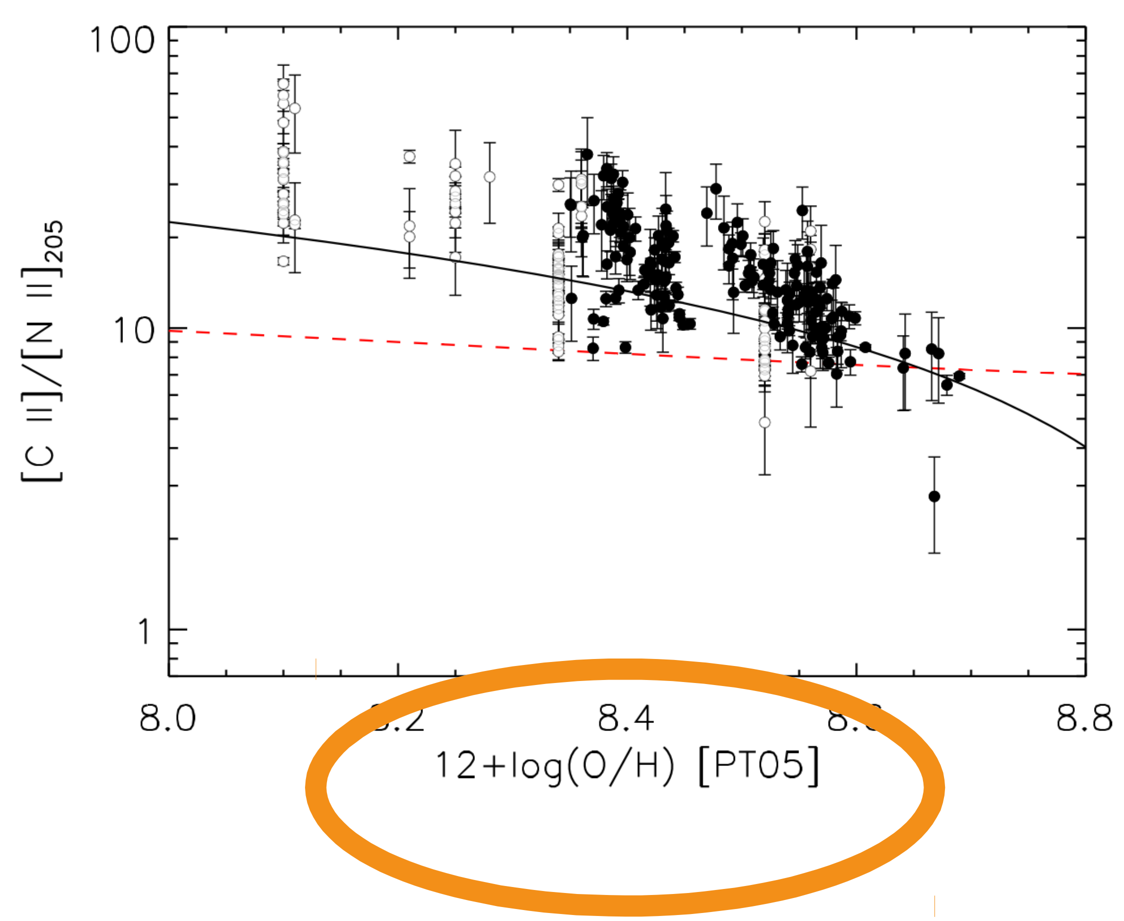
State of the art…

- **Problems** associated with the observations of ISM properties

[Croxall+17]

State of the art…

- **Problems** associated with the observations of ISM properties

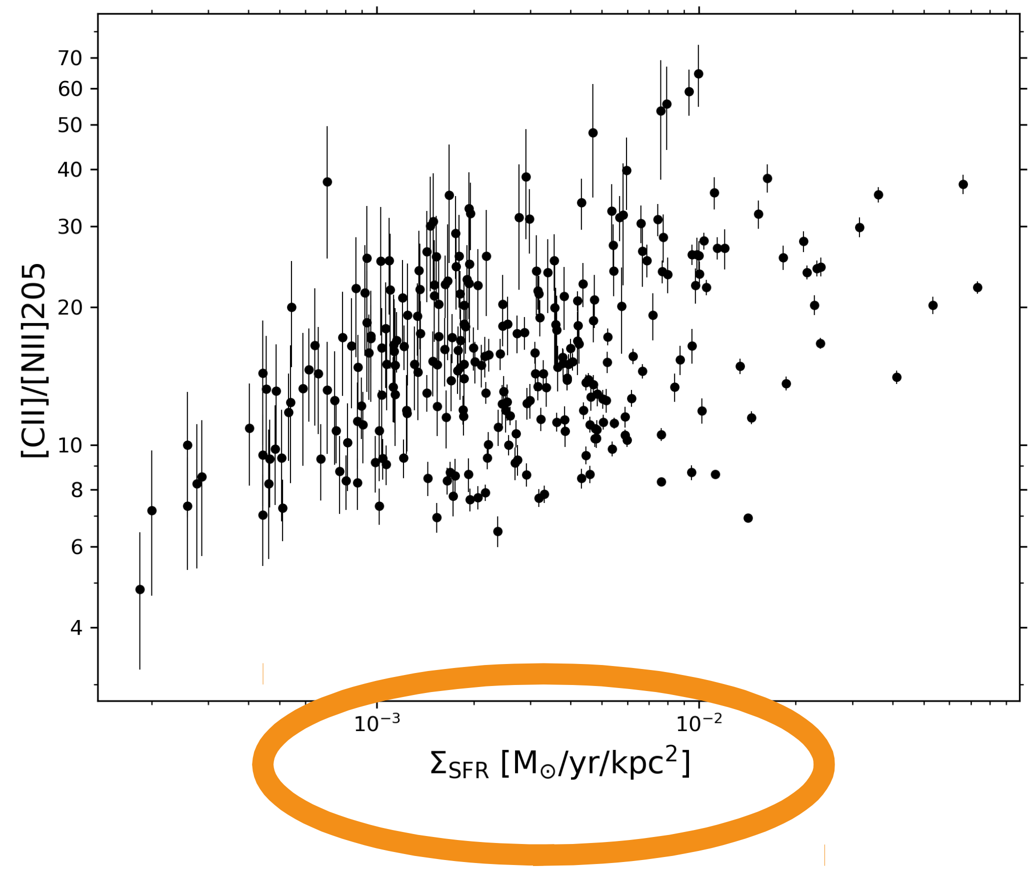


Not the actual Z, but **a proxy for Z** using optical emission lines and indirect/direct methods (see Moustakas+10)

[Croxall+17]

State of the art...

- **Problems** associated with the observations of ISM properties

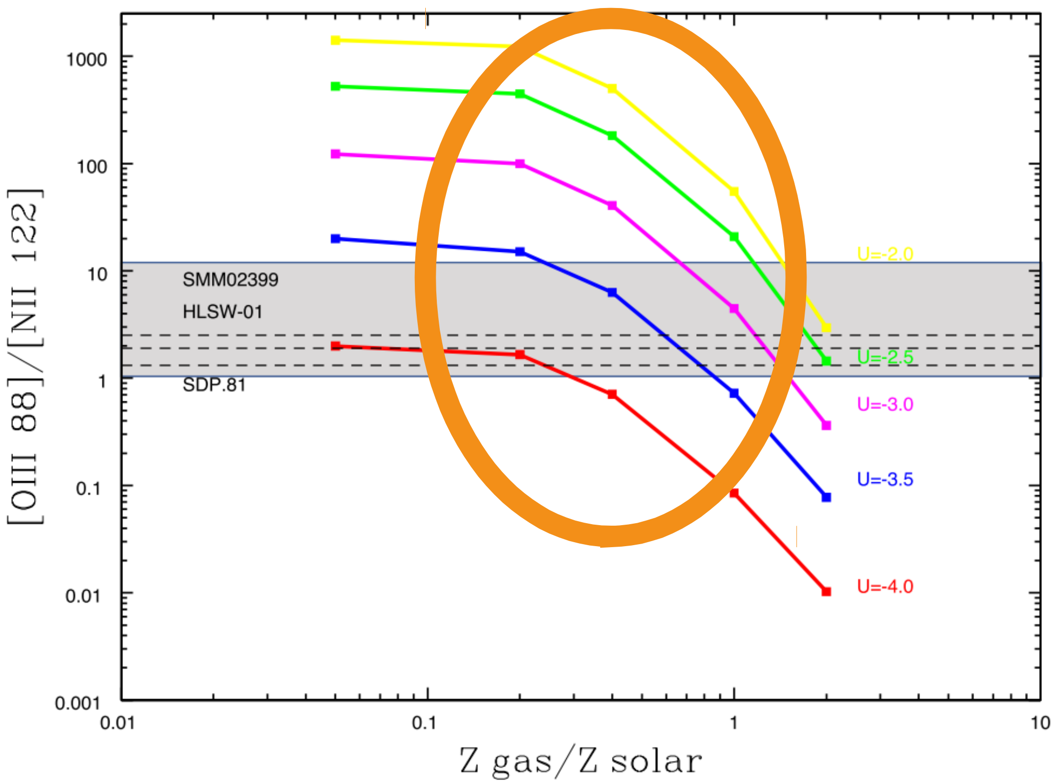


$$\Sigma_{\rm SFR}(M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}) = 3.823 \times 10^{-47} \times (\Sigma_{\rm [C\,II]}({\rm erg\,s}^{-1}\,{\rm kpc}^{-2}) \times \Psi)^{1.130}$$

[Croxall+17]

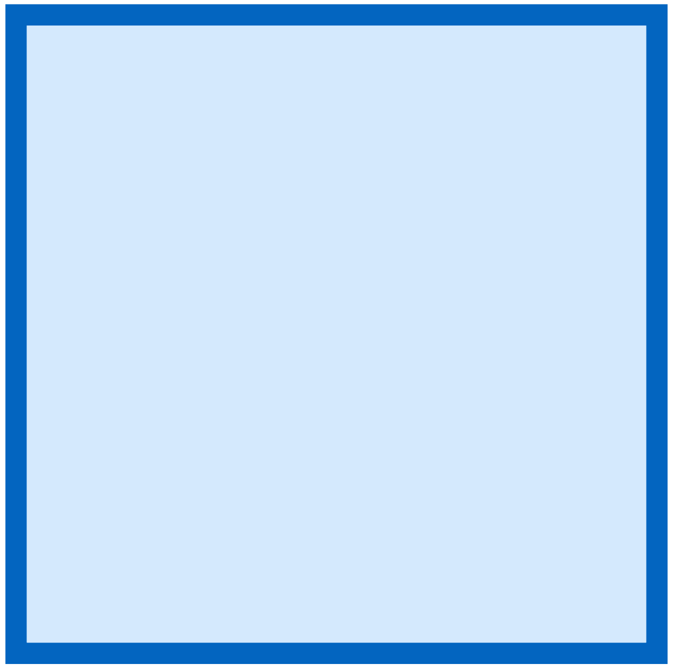
State of the art…

- **Problems** associated with the observations of ISM properties



Models made with **single-value cells**

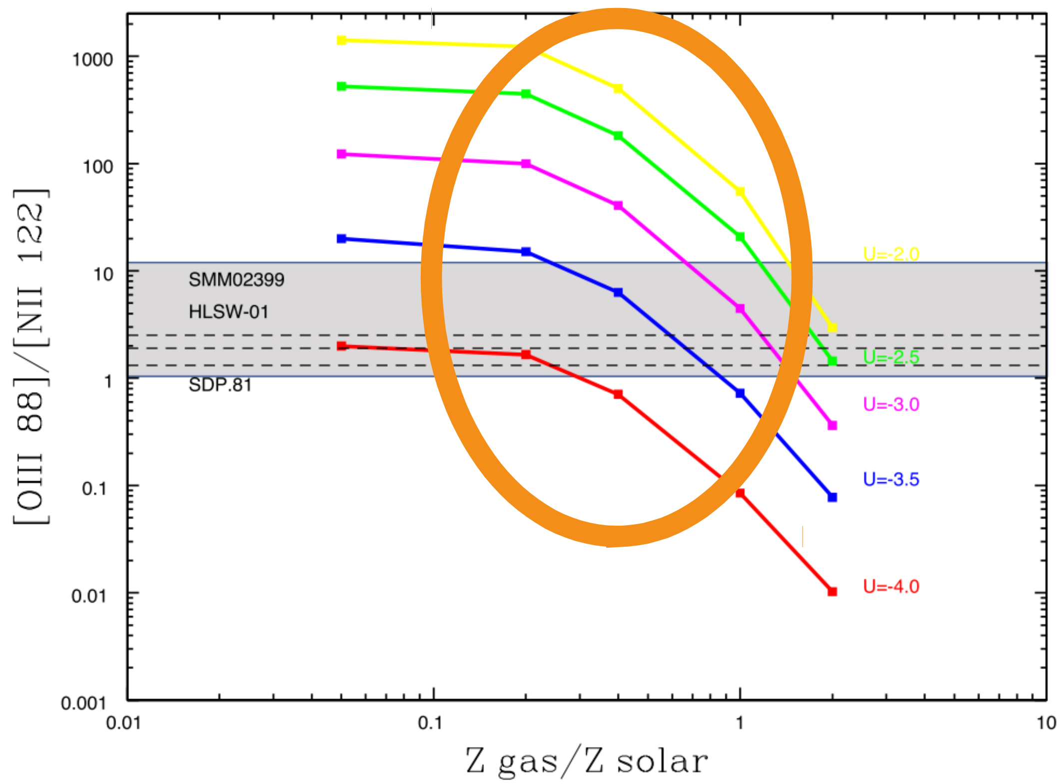
log(n_H) [cm-3]	log(U)
1	-2
2	-2.5
3	-3
4	-3.5
5	-4



[Rigopoulou+17]

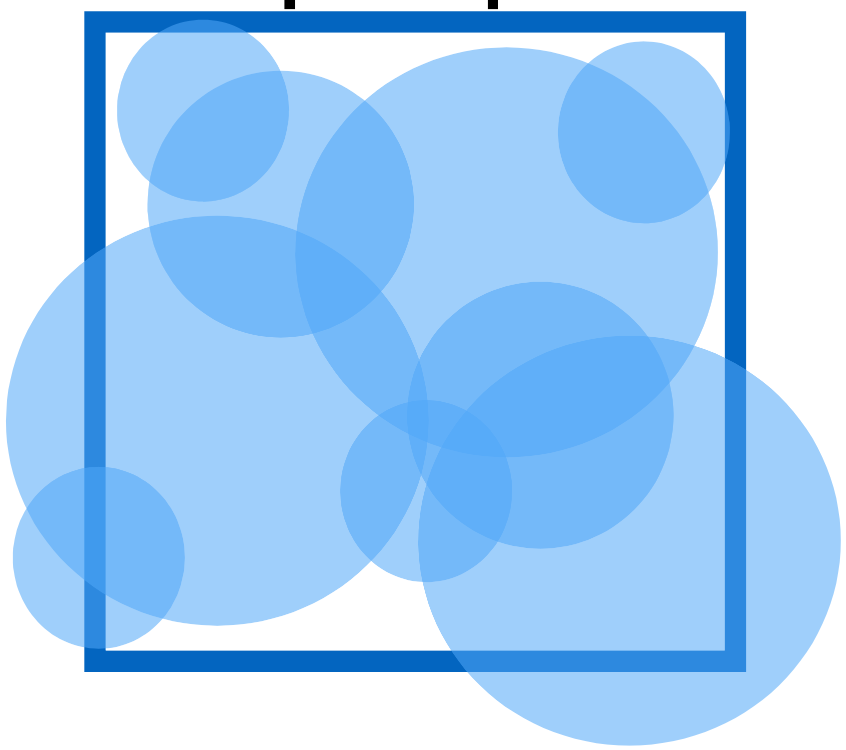
State of the art…

- **Problems** associated with the observations of ISM properties

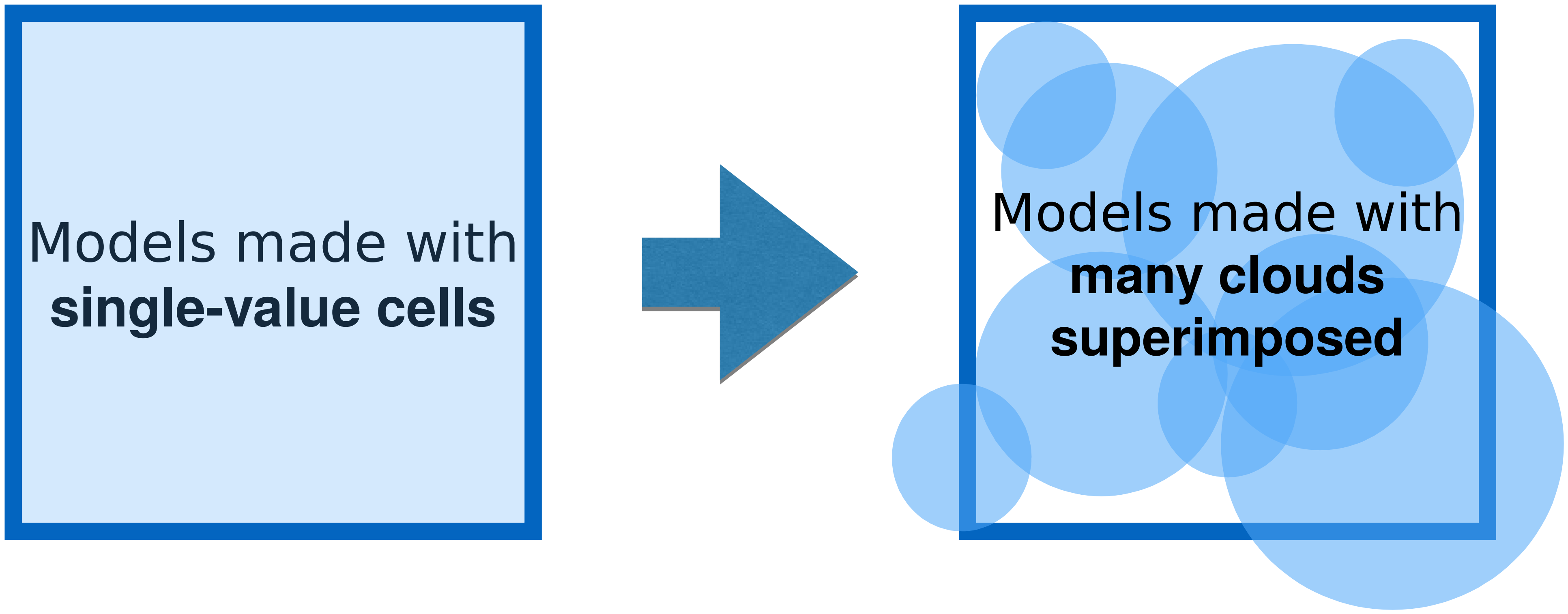


When really, looking at resolved observations of a region in a galaxy, you see **many clouds superimposed**

Each with a different set of [n_H, U, Z, T_k…]



[Rigopoulou+17]



[Rigopoulou+17]

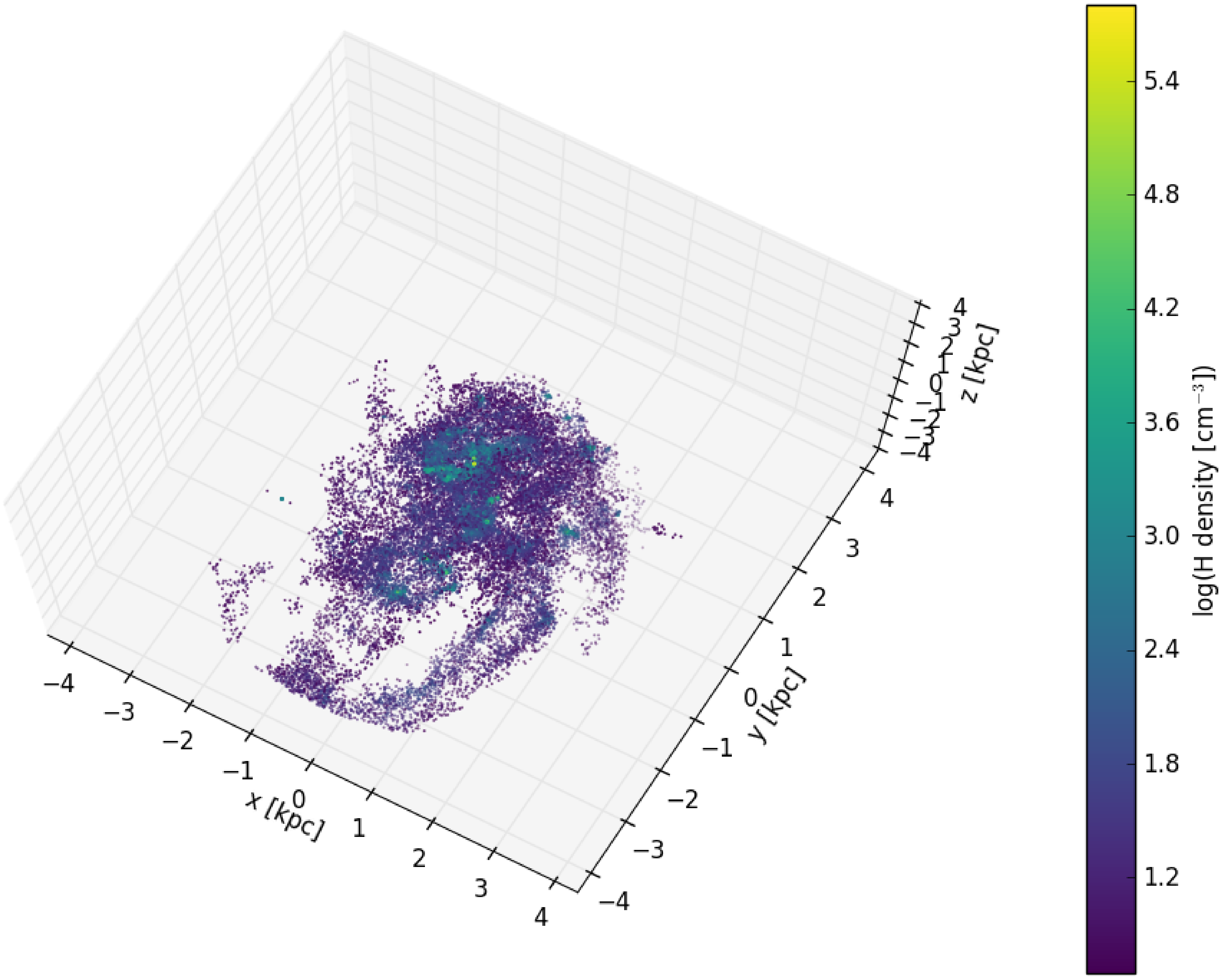
SÍGAME

Key steps

1. Extract galaxies from simulation

Cosmological hydrodynamic simulations

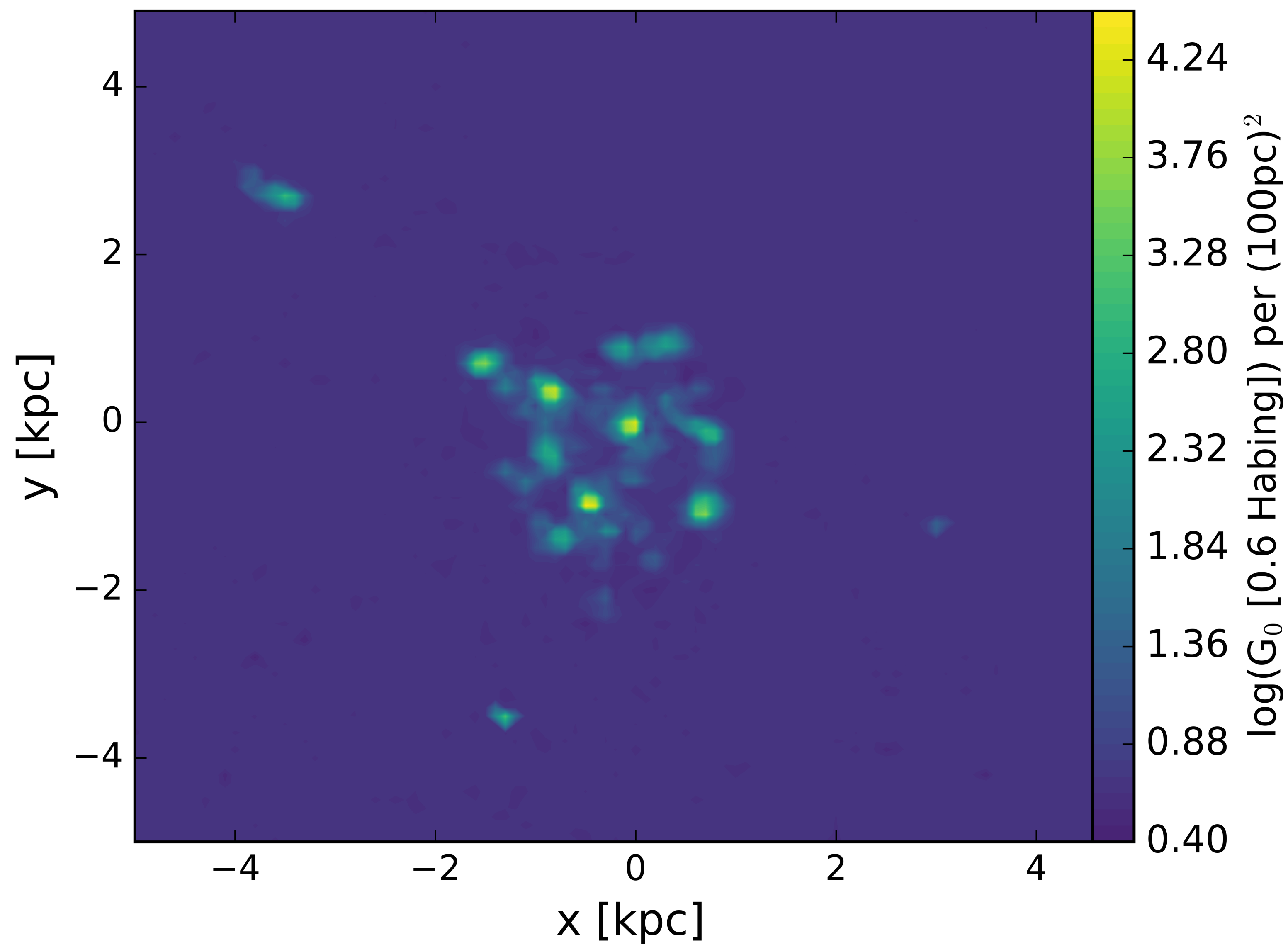
(GIZMO simulations with MUFASA winds, see Davé+16 MNRAS 462)



Key steps

1. Extract galaxies from simulation

2. Derive large-scale ISM properties



FUV radiation (G_0) map made with starburst99

Key steps

1. Extract galaxies from simulation

2. Derive large-scale ISM properties

3. Divide ISM into dense and diffuse gas

Depending upon the output from simulations and cloudy models, SÍGAME divides the gas mass into:

dense gas → **GMCs** (Giant Molecular Clouds): mostly molecular (but can contain partly ionized PDRs)

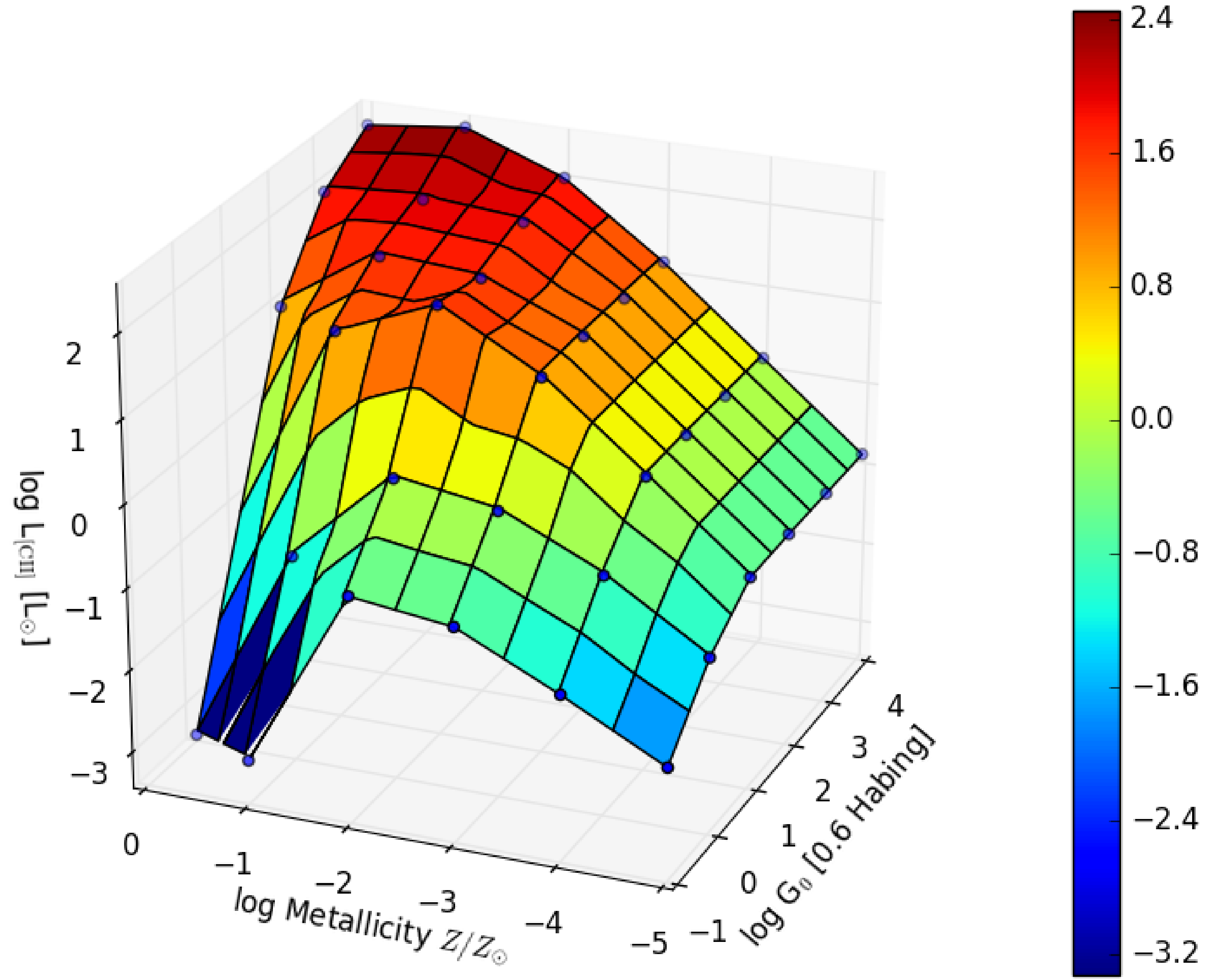
diffuse gas:

- **DNG** (Diffuse Neutral Gas): part of the diffuse gas clouds that is mostly neutral
- **DIG** (Diffuse Ionized Gas): part of the diffuse gas clouds that is mostly ionized

Key steps

1. Extract galaxies from simulation
2. Derive large-scale ISM properties
3. Divide ISM into dense and diffuse gas
4. Interpolate in grids of "Cloudy" models for line emission etc.

Example of grid of solutions with **Cloudy** (the photoionization code) for the [CII] line



Work with student Luis R. Niebla

Key steps

1. Extract galaxies from simulation
2. Derive large-scale ISM properties
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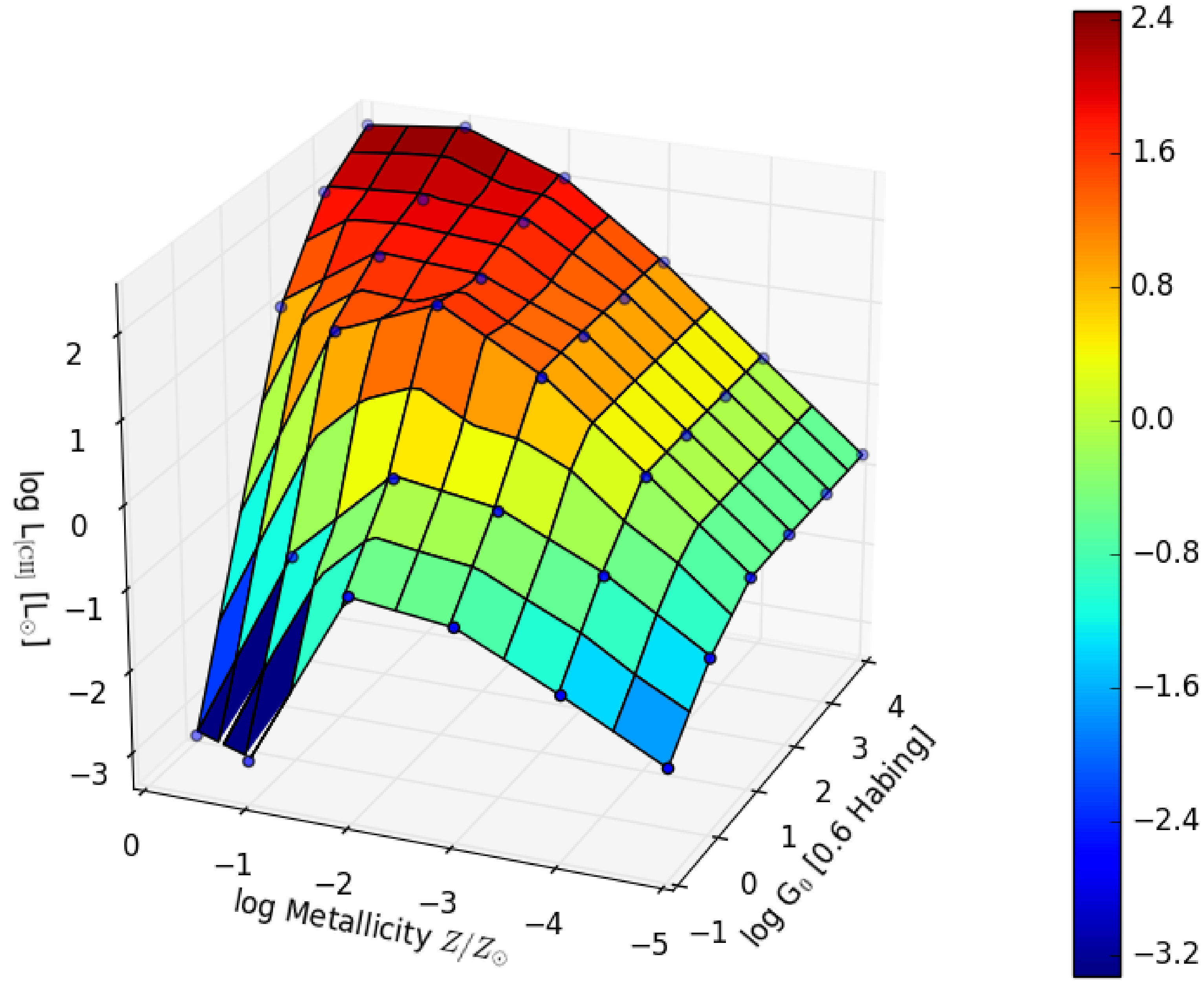
Example of grid of solutions with **Cloudy** (the photoionization code) for the [CII] line



running models on Pleiades Supercomputer @ NASA with multiprocessing.Pool()

Work with student Luis R. Niebla

Key steps

1. Extract galaxies from simulation

2. Derive large-scale ISM properties

3. Divide ISM into dense and diffuse gas

4. Interpolate in grids of cloudy models for line emission etc.

5. Create and analyze **datacubes**!

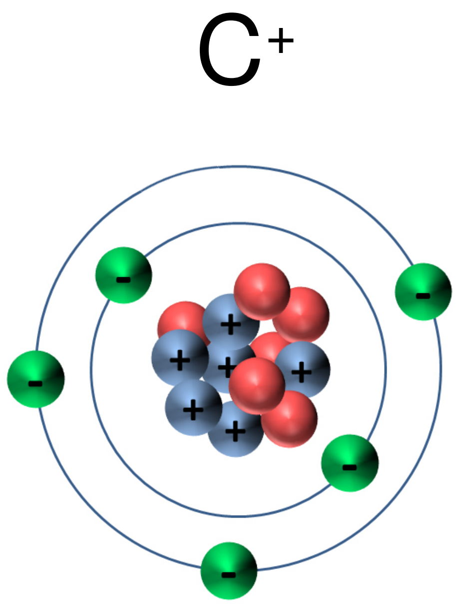
Video from datacube in space and velocity:

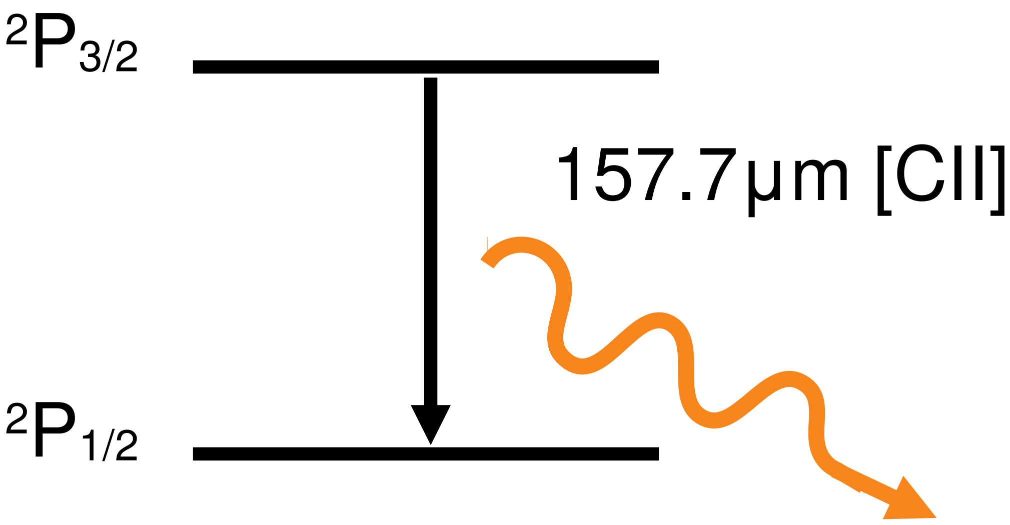
Work with student Jacob Cluf

A reminder…

Background

- [CII] as a SFR indicator (cf. talks by O. Le Fevre and A. Faisst)





Can arise from all ISM phases

- Ionization potential (11.3eV) below that of hydrogen (13.6eV)
- Excited by collisions with either electrons, atoms or molecules

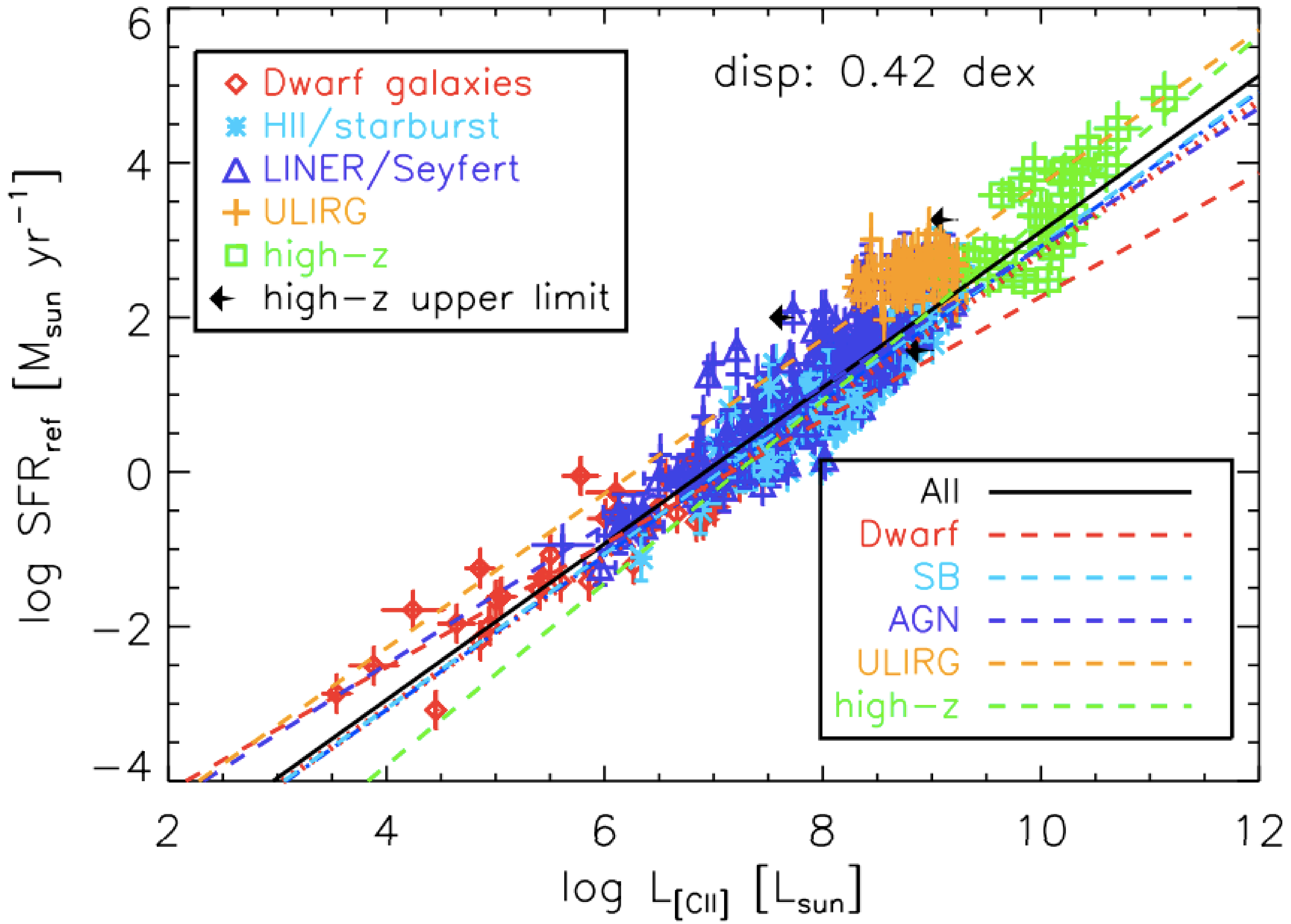
Intensity depends mainly on density and temperature of gas

- ISM heated by young stars emit more [CII]

Background

- [CII] as a SFR indicator (cf. talks by O. Le Fevre and A. Faisst)

At low redshift

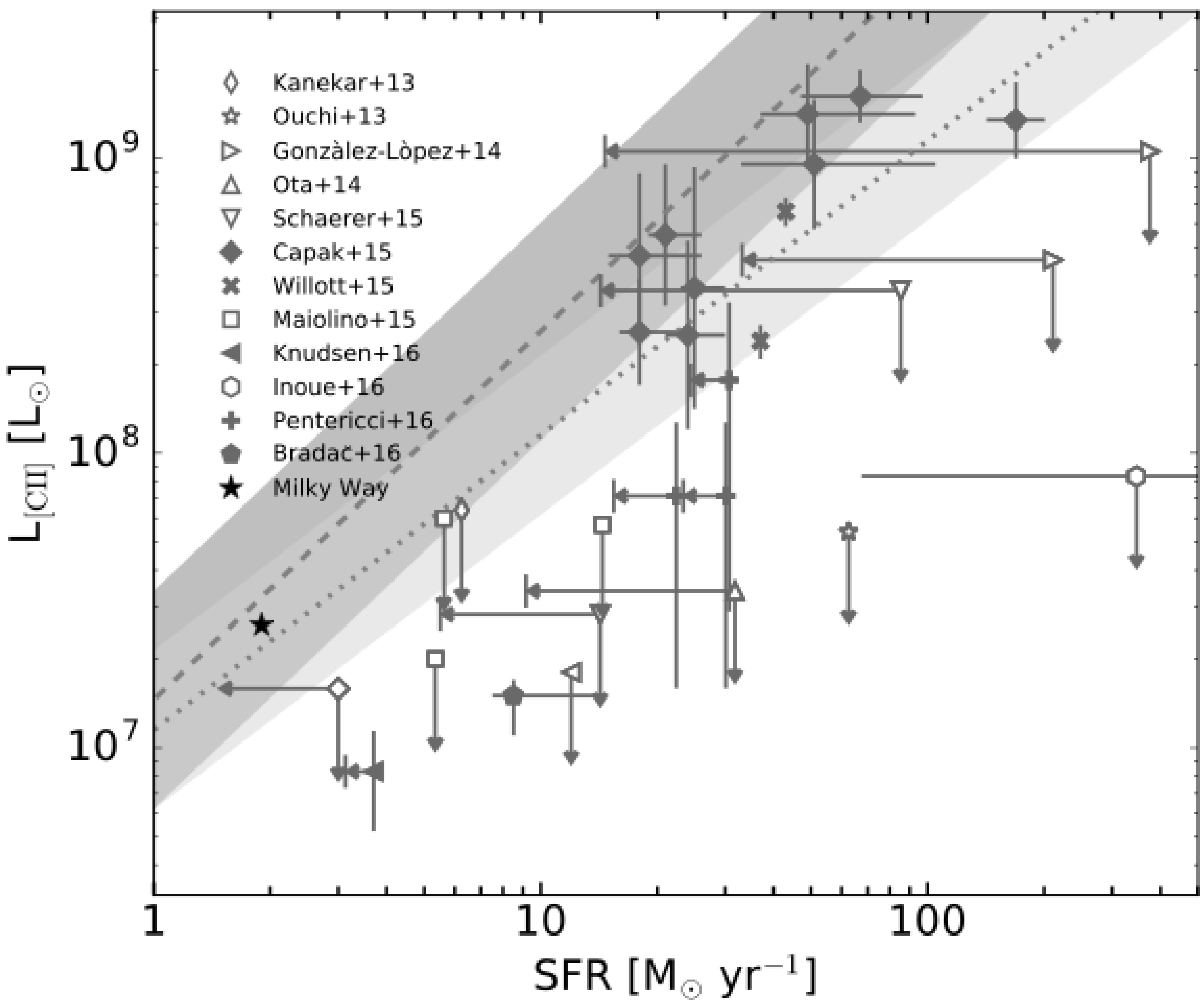


de Looze at al. 2014

Background

- [CII] as a SFR indicator (cf. talks by O. Le Fevre and A. Faisst)

At high z (< 5)… ?

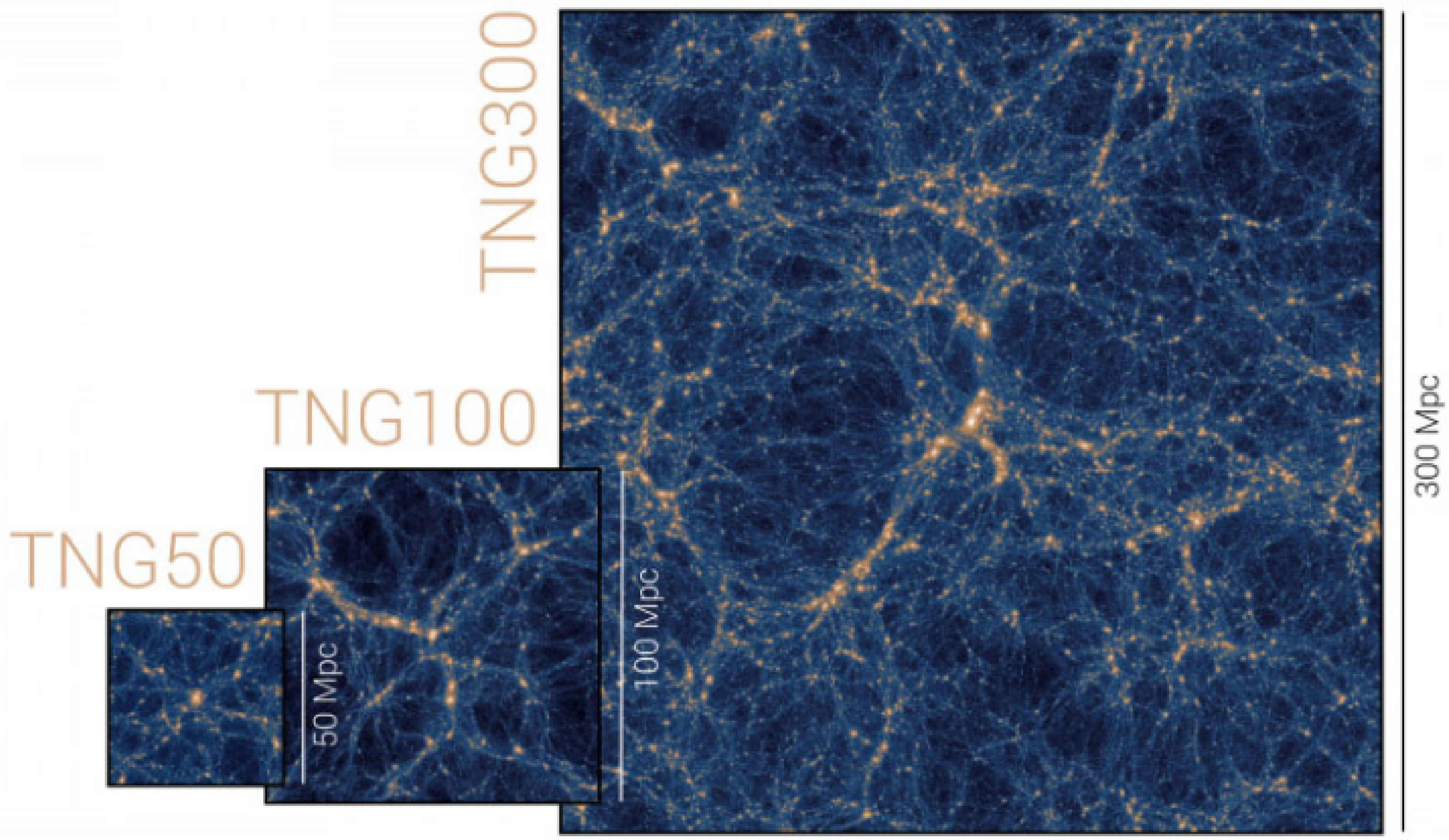


Future projects

Apply SÍGAME to IllustrisTNG

... uncovering any dependency on simulation type.

(cf. talks by M. Sparre)



http://www.tng-project.org/