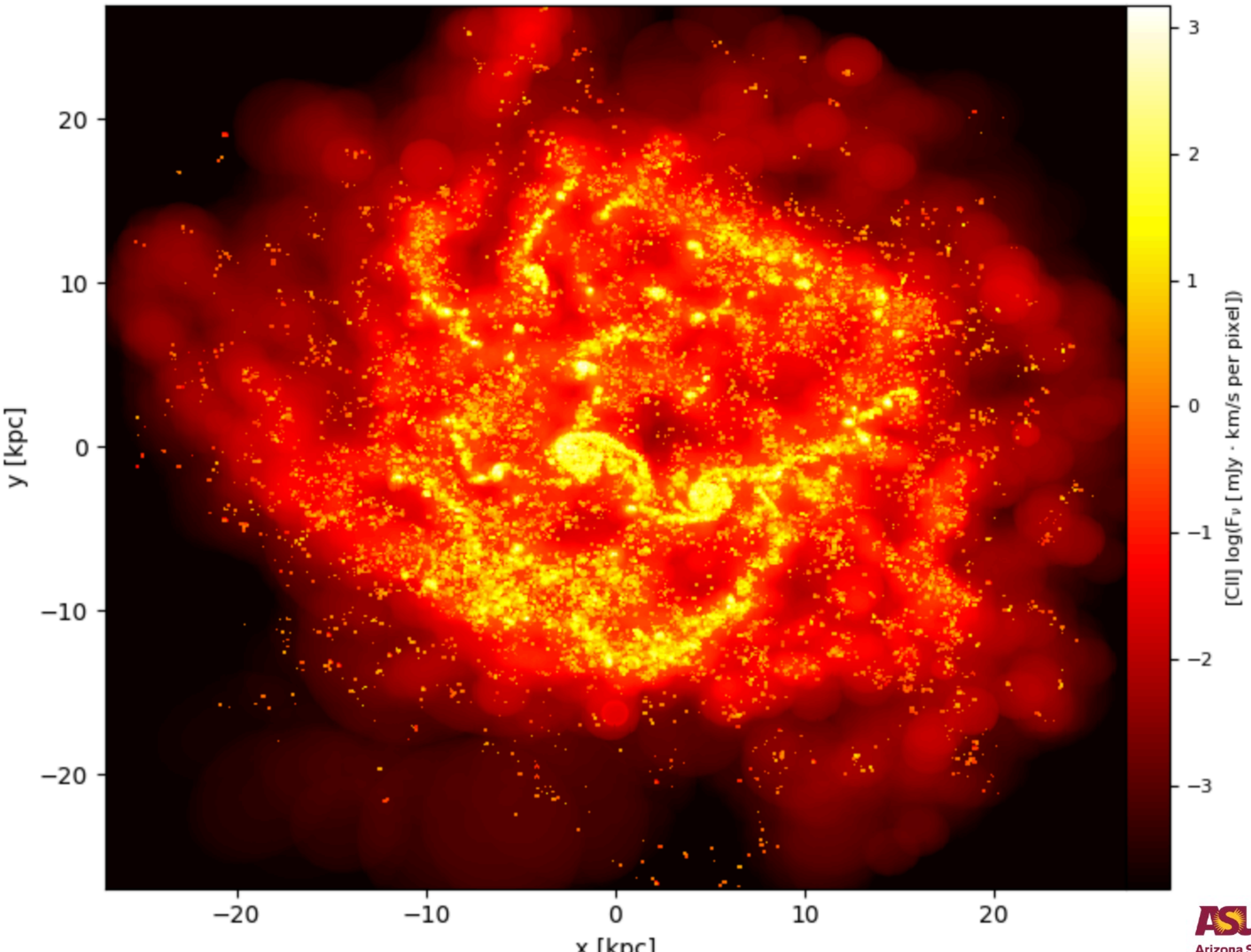
Making Sense of FIR Line Emission with Synthetic Observations

Karen Pardos Olsen



ASU School of Earth and Space Exploration
Arizona State University

Topics to cover

Background	- Far Infrared (FIR) line emission - Open Science questions
SÍGAME module	- Extractig galaxies from cosmological simulations - Subgrid procedures
Recent and preliminary results	- **NEW**: Line ratios as diagnostic tools - Collaboration and Project management on GitHub
	Future projects…

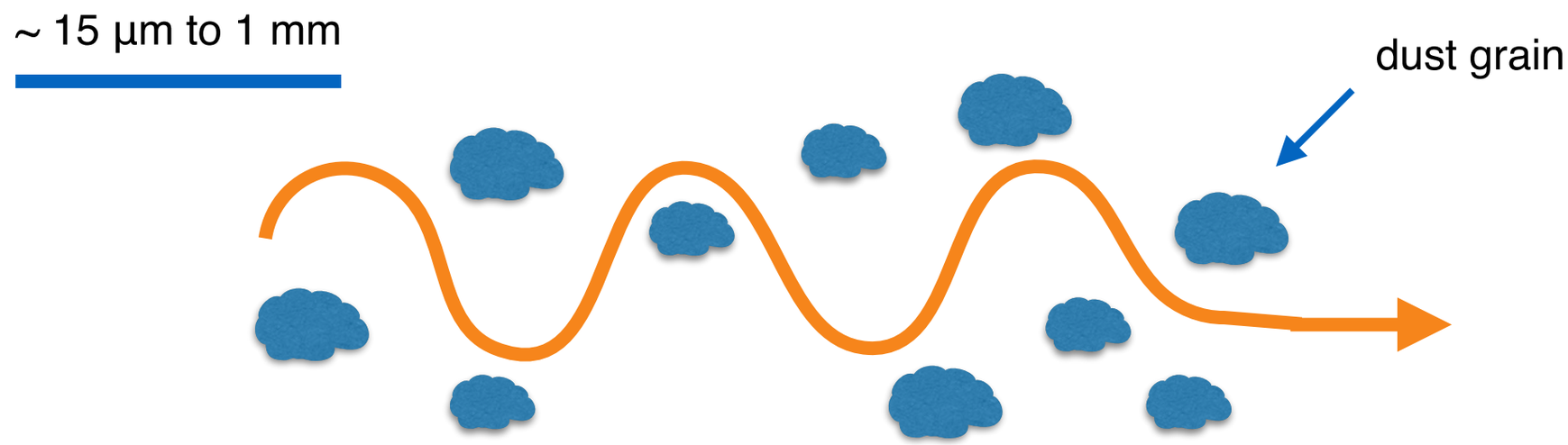
Why FIR?

Not all lines are equally accesible

Why FIR?

- **FIR lines** are often strongest because they avoid dust attenuation

Not all lines are equally accesible



Why FIR?

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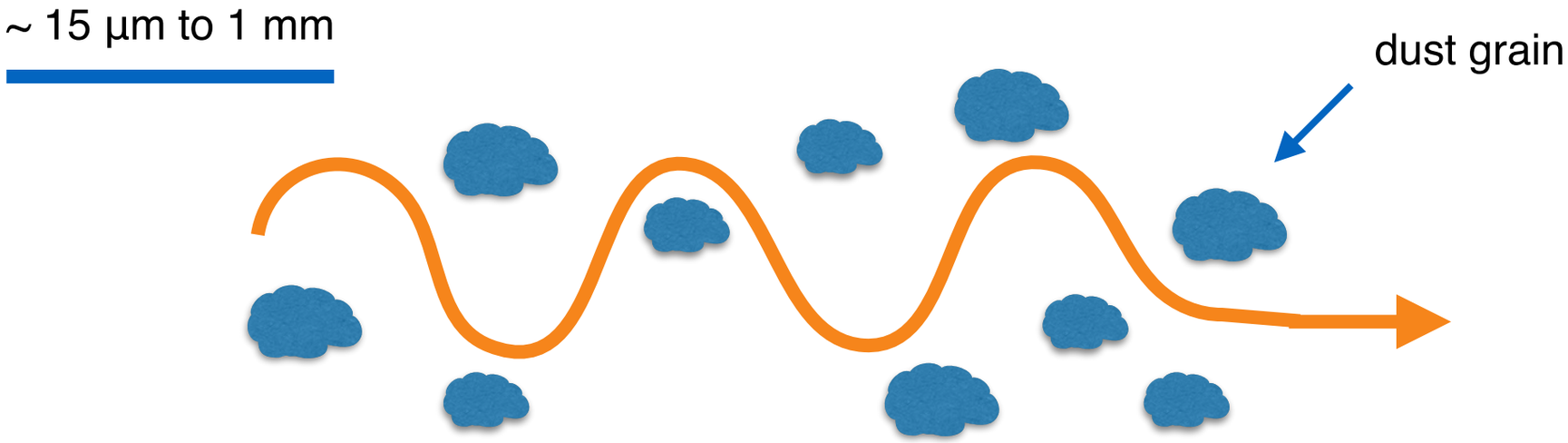
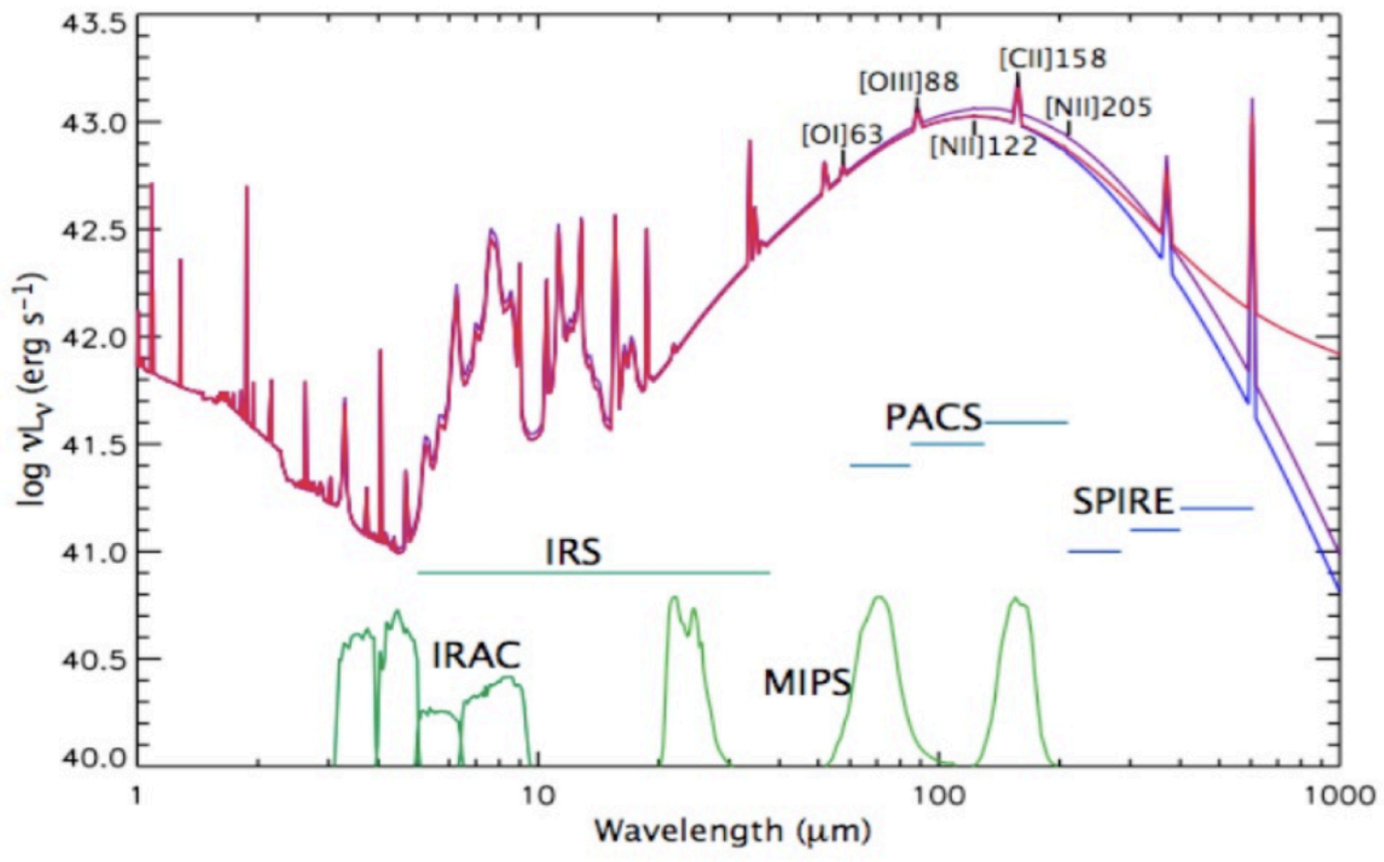
FIR lines are easier to model (and sometimes observe)





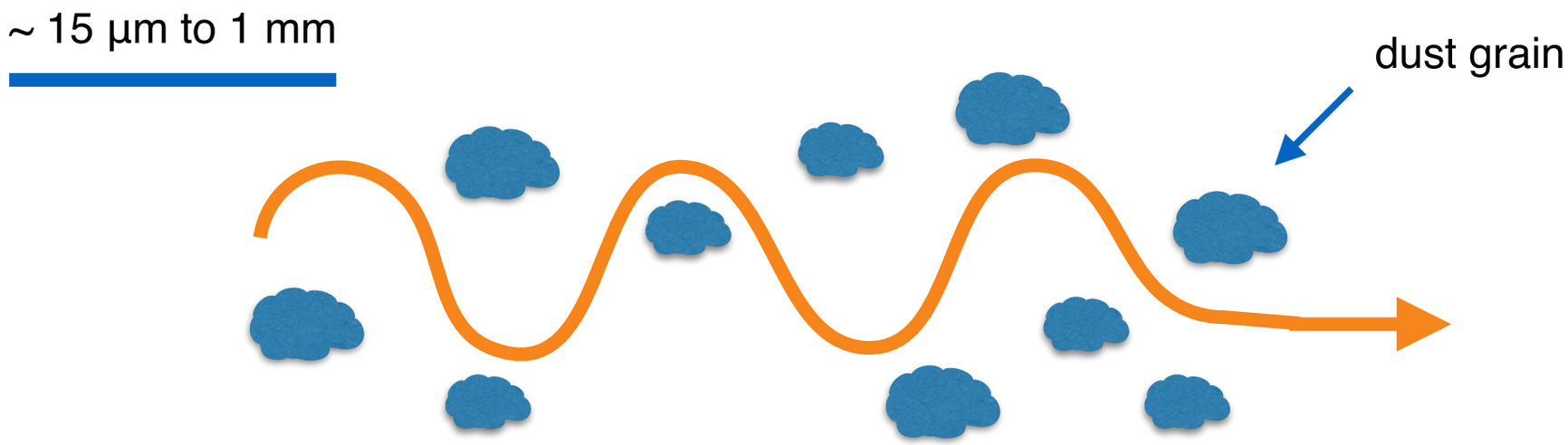
https://www.ast.cam.ac.uk/research/galaxies.and.active.galactic.nuclei/kingfish/science

Why FIR?

- **FIR lines** are often strongest because they avoid dust attenuation

- Large ground-based telescopes with bands in the radio, can detect **these lines at high z**

FIR lines are easier to model (and sometimes observe)



The Atacama Large Millimeter/submillimeter Array (**ALMA**)

Line Ratio observations

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

The [CII]158/[NII]205 ratio

Line Ratio observations

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Line Ratio observations

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

The [CII]158/[NII]205 ratio

Fine-structure lines that together give the fraction of [CII] coming from neutral gas:

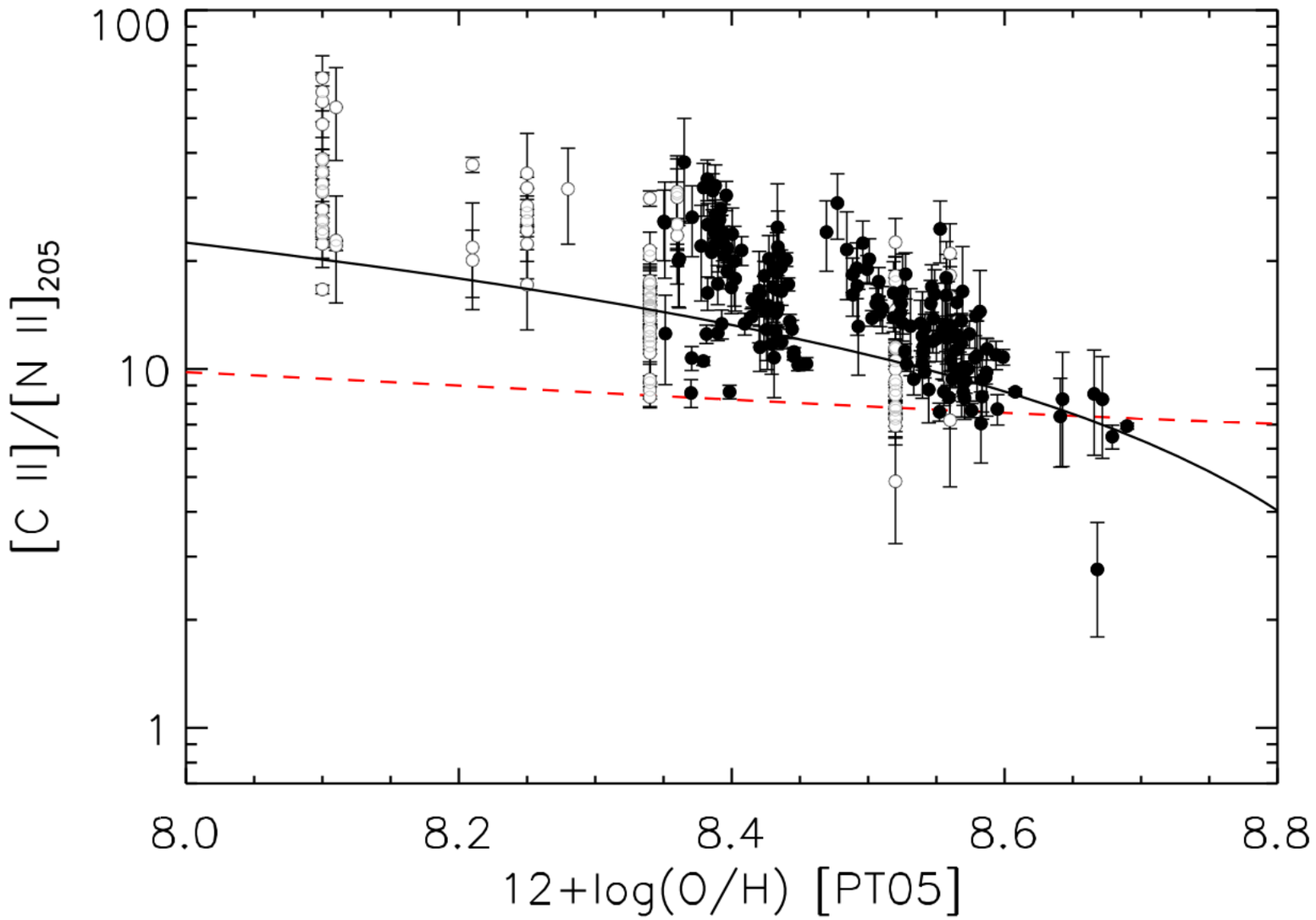
$$f_{[\mathrm{C\,II}],\mathrm{Neutral}} = \frac{[\mathrm{C\,II}] - R_{\mathrm{ionized}} \times [\mathrm{N\,II}]\,205\ \mu\mathrm{m}}{[\mathrm{C\,II}]}$$

[Croxall+17]

Line Ratio observations

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

Line Ratio observations

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

- Weak dependence on surface density of SFR

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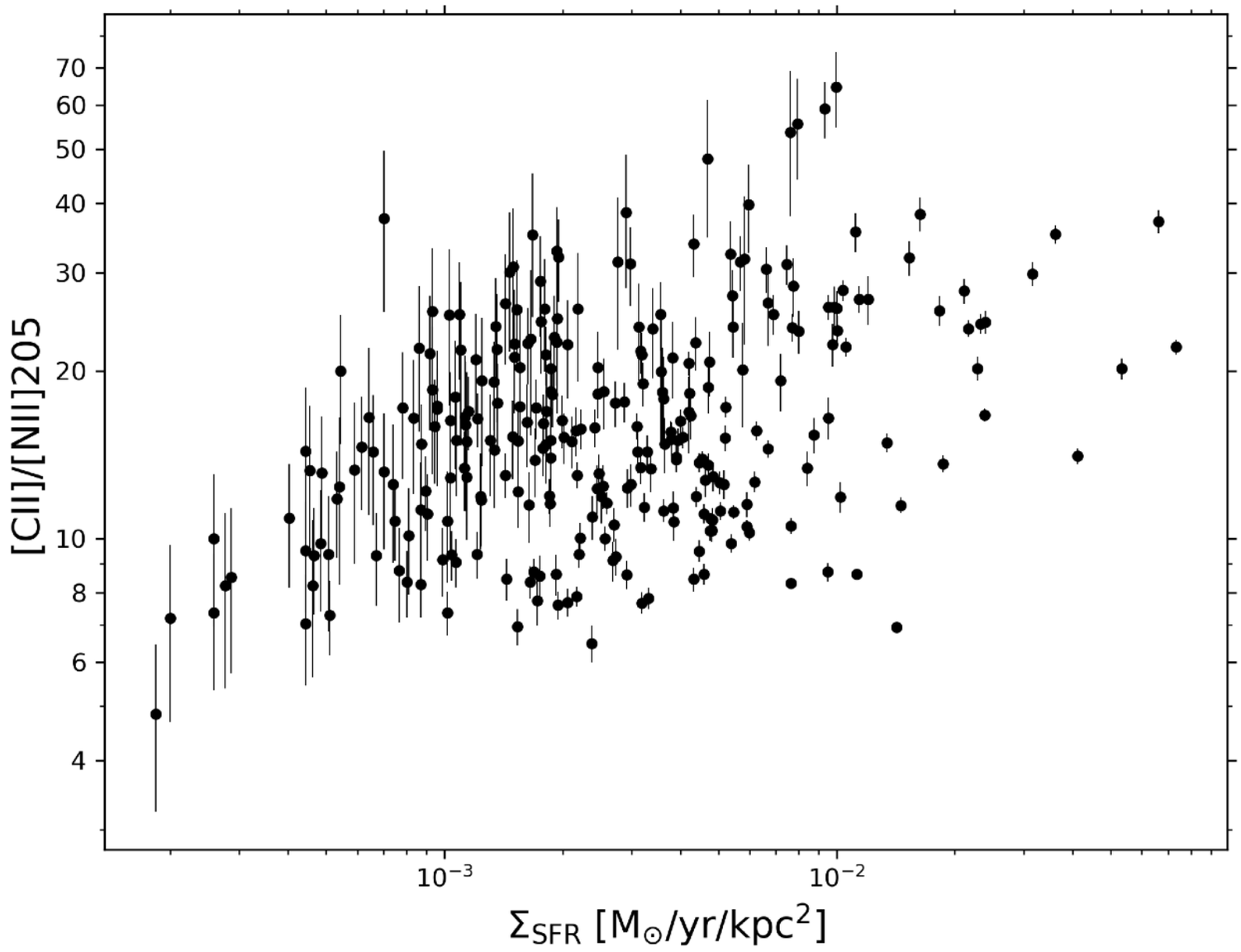

[Croxall+17]

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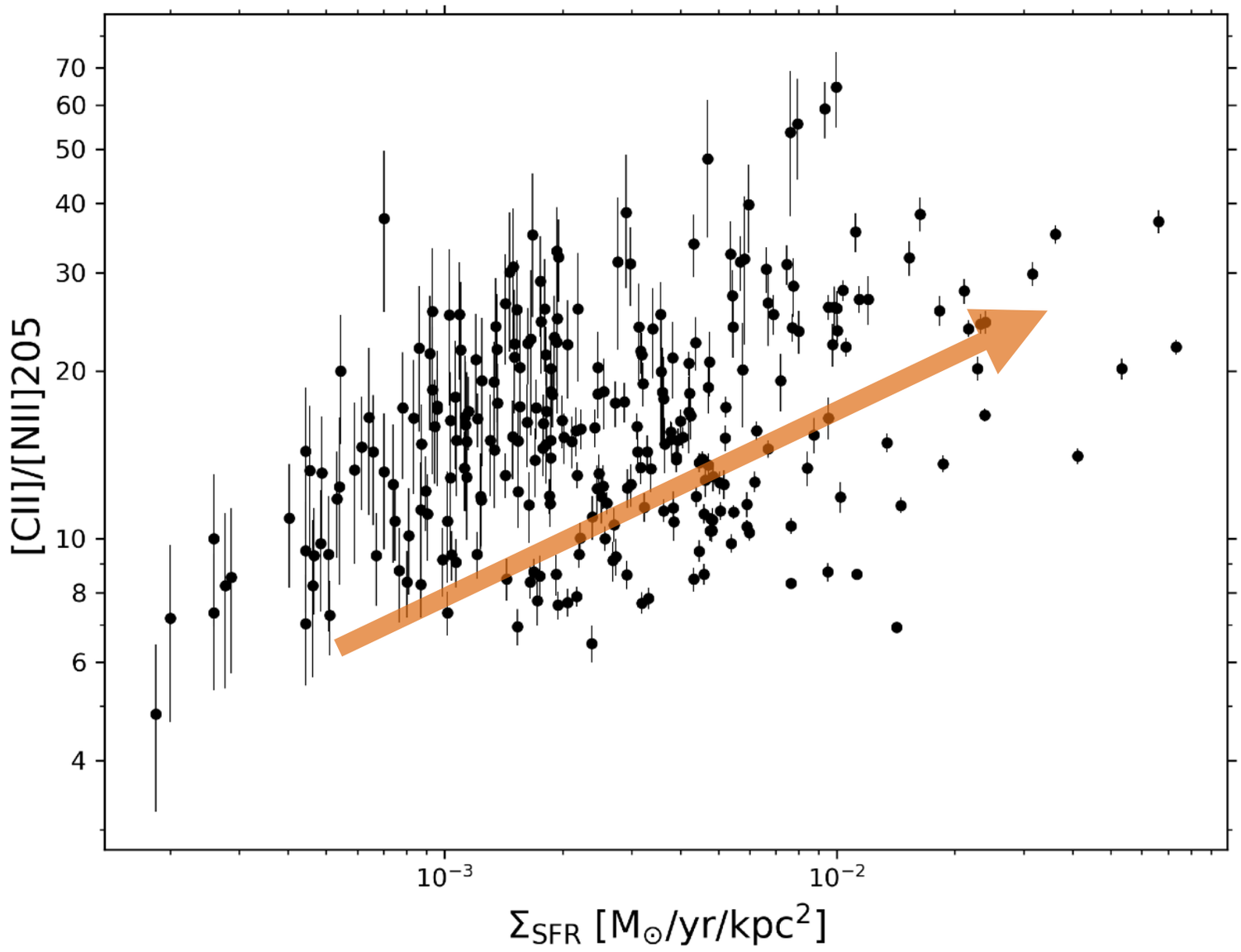


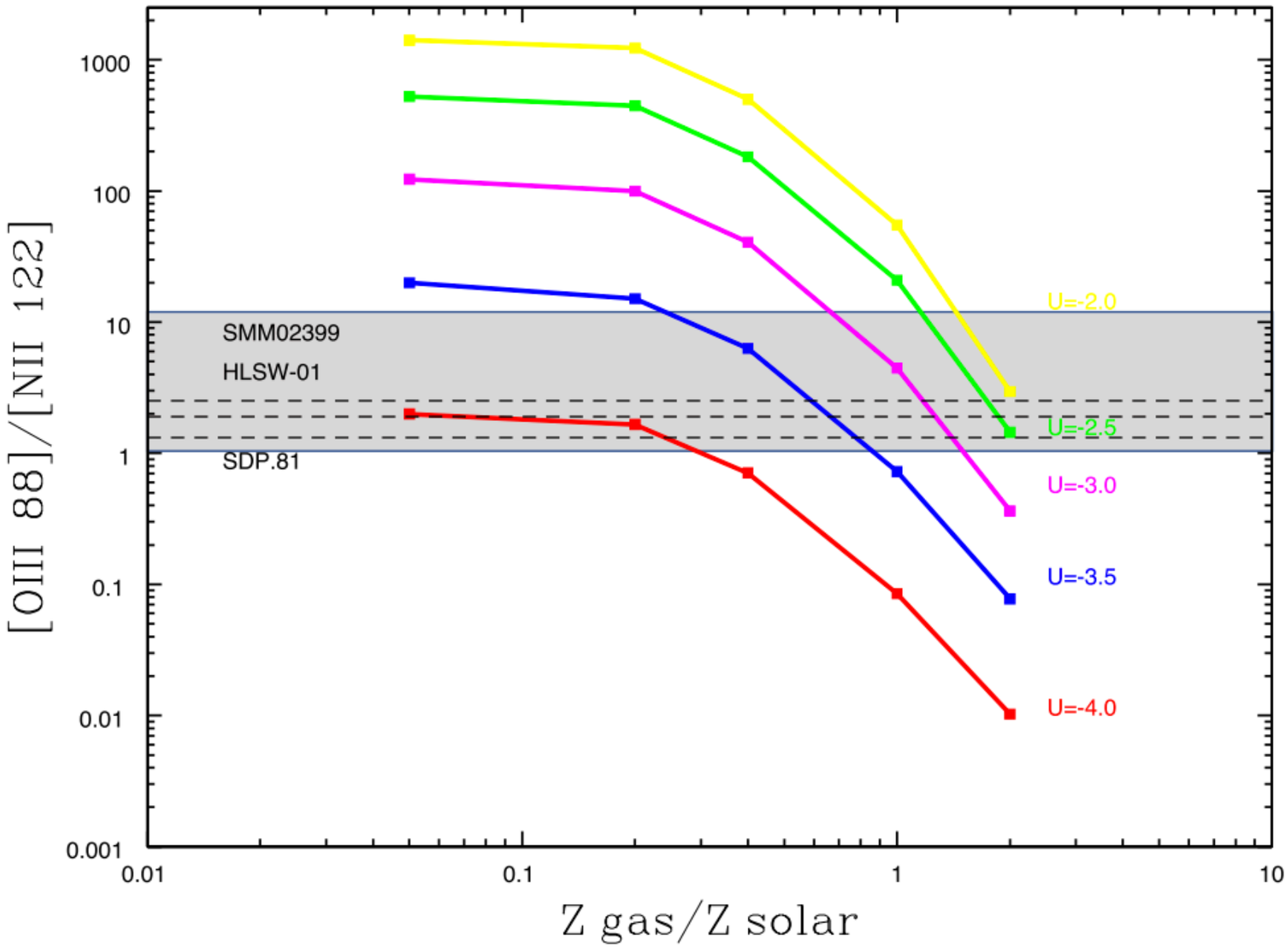
Increase towards central parts of galaxy with higher Σ_{SFR} (and more neutral gas)

[Croxall+17]

The [OIII] 88/[NII] 122 ratio

Line Ratio observations

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



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]

The [OIII] 88/[NII] 122 ratio

Line Ratio observations

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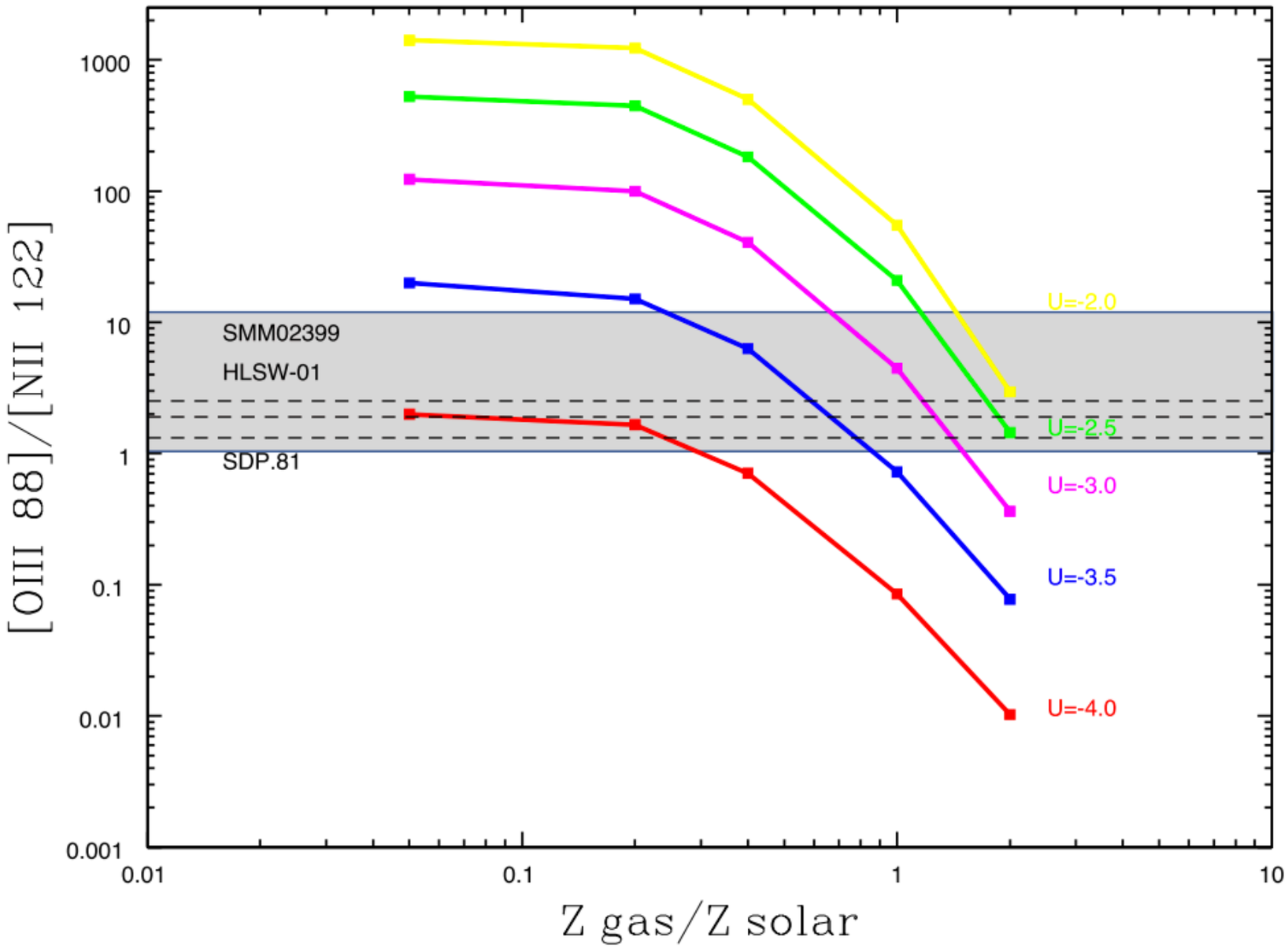

Can be used as a rough metallicity indicator, if you also now ionization parameter *U* ?

[Rigopoulou+17]

State of the art…

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

[Croxall+17]

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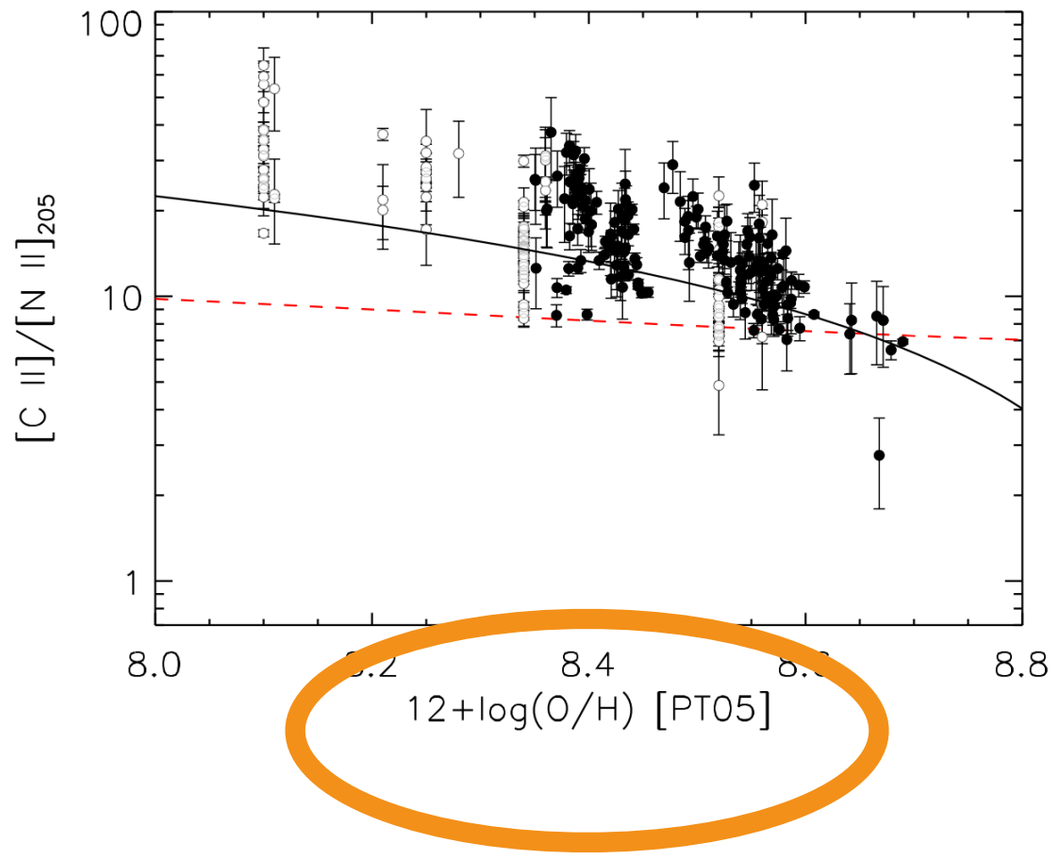

Not the actual Z, but **a proxy for Z** using optical emission lines and indirect/direct methods (see Moustakas+10)

[Croxall+17]

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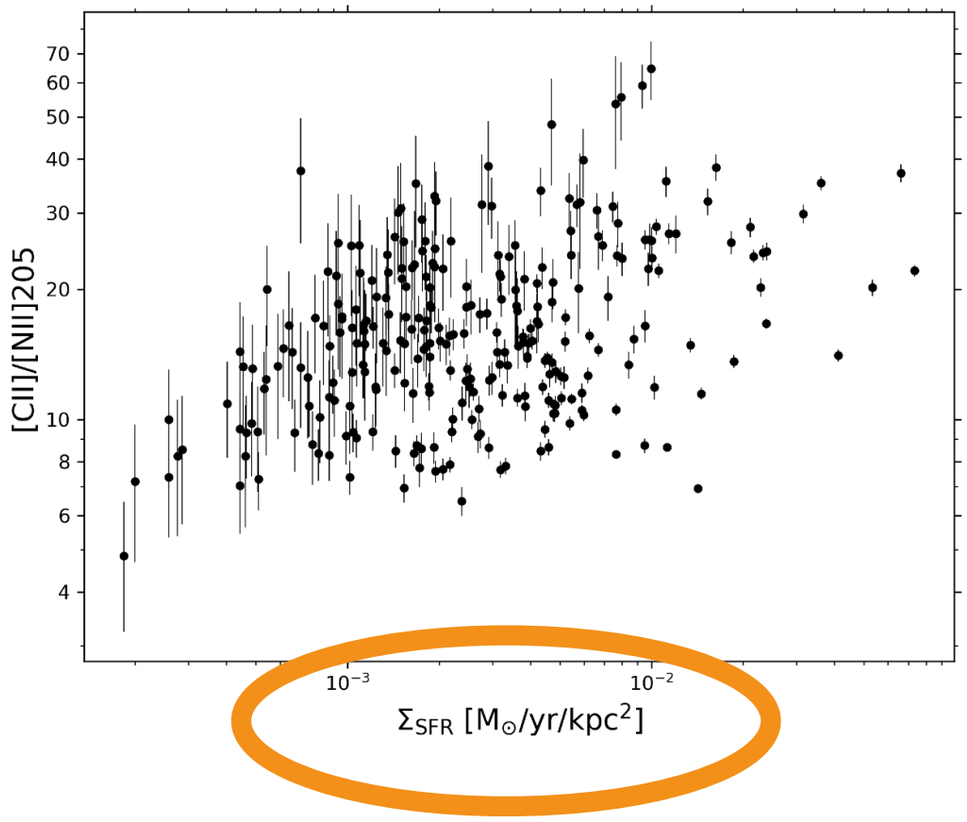
- **Problems** associated with the observations of ISM properties

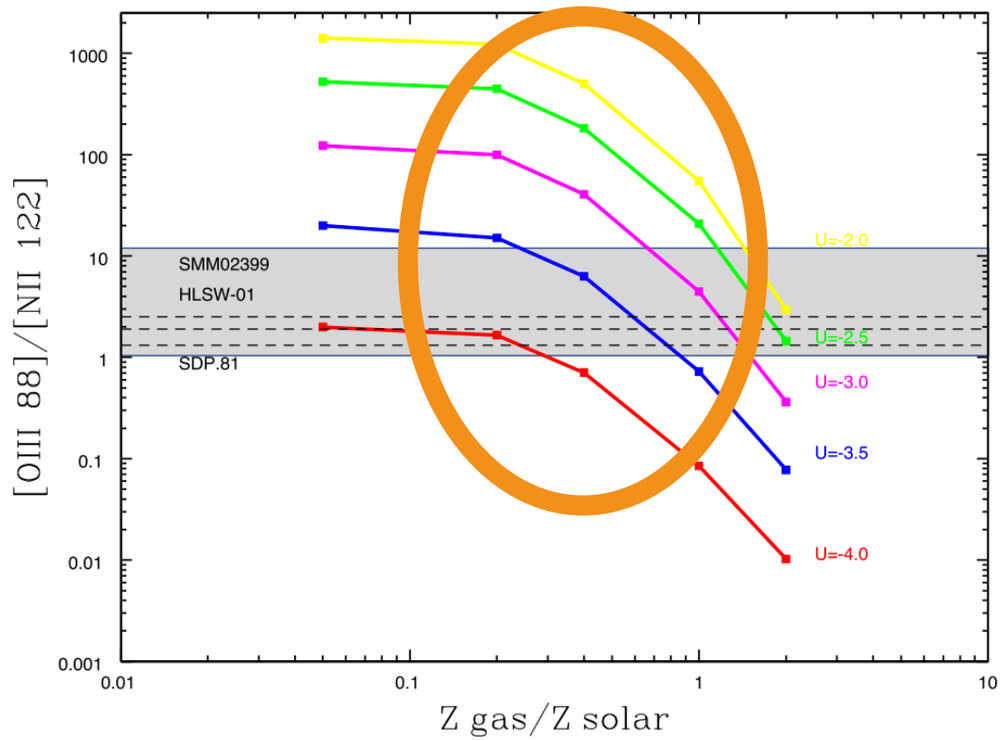


$$\Sigma_{\rm SFR}(M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}) = 3.823\times10^{-47} \times(\Sigma_{\rm [C\,II]}({\rm erg\,s}^{-1}\,{\rm kpc}^{-2})\times\Psi)^{1.130}$$

[Croxall+17]

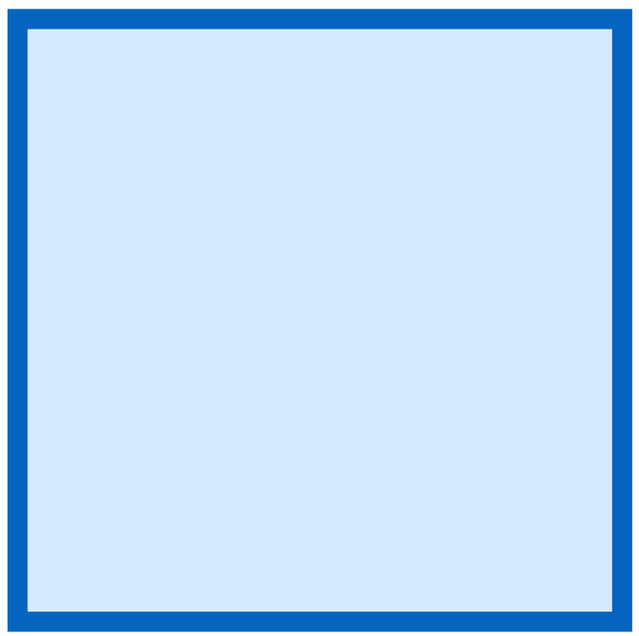
State of the art…

- **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…

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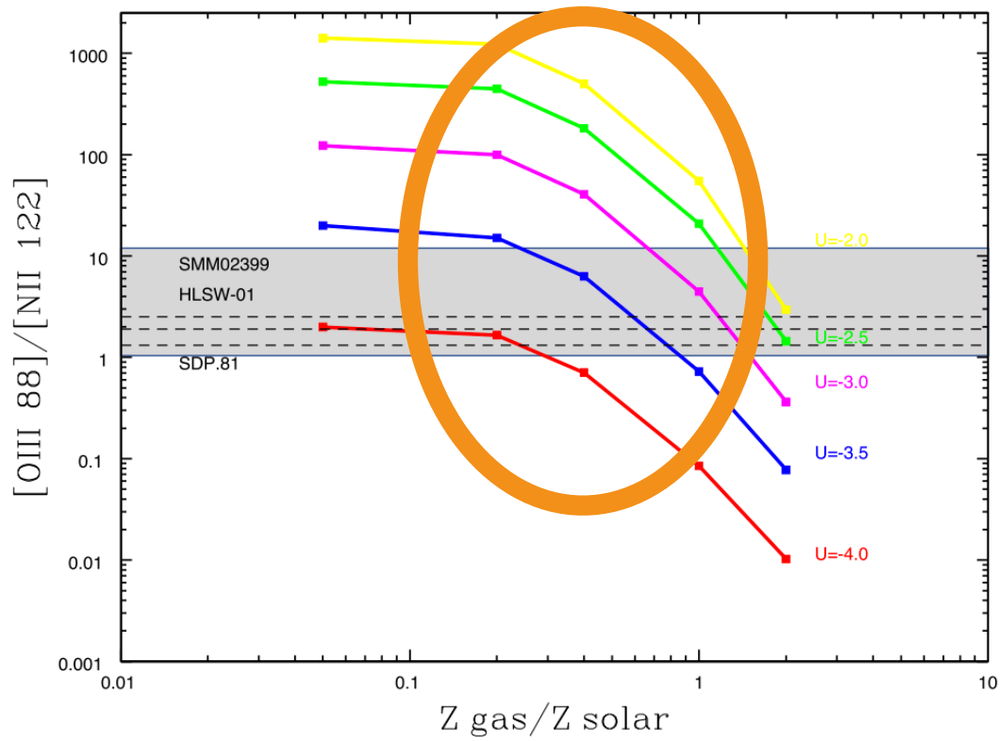
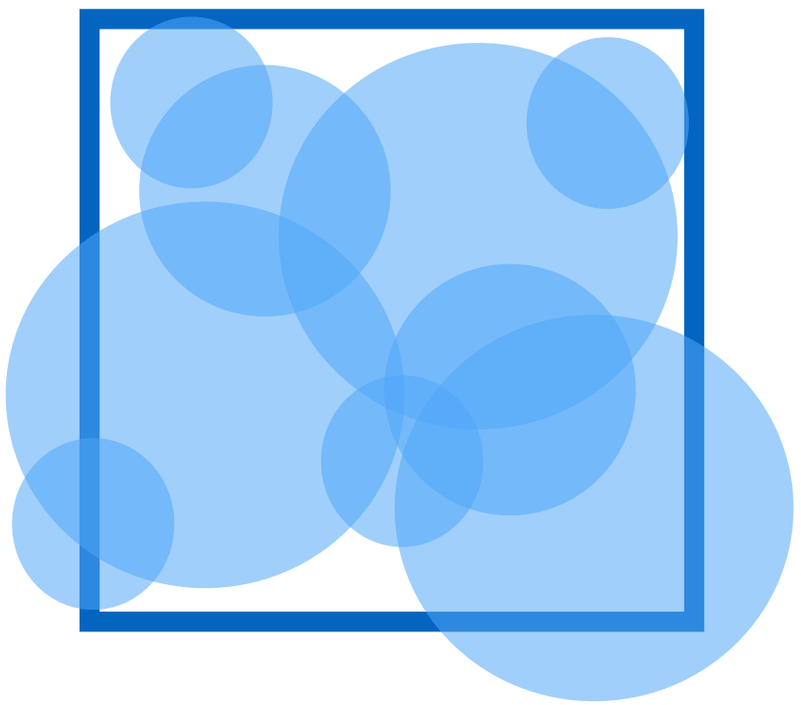


When really, looking at resolved observations of a region in a galaxy, you see **many clouds superimposed**

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



[Rigopoulou+17]

State of the art…

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

- **Open questions** that can be better answered via modeling

Can resolved observations of [CII]/[NII]205 be used:

1) to estimate actual ionized gas mass fraction?
2) to estimate gas metallicity?
3) and how does that callibration depend on Σ_{SFR} (or other ISM properties)?

[Croxall+17]

My current work!

- Started during PhD at Dark Cosmology Centre in Copenhagen

SÍGAME

(='follow me' in Spanish)

SImulator of GAlaxy Millimeter/submillimeter Emission

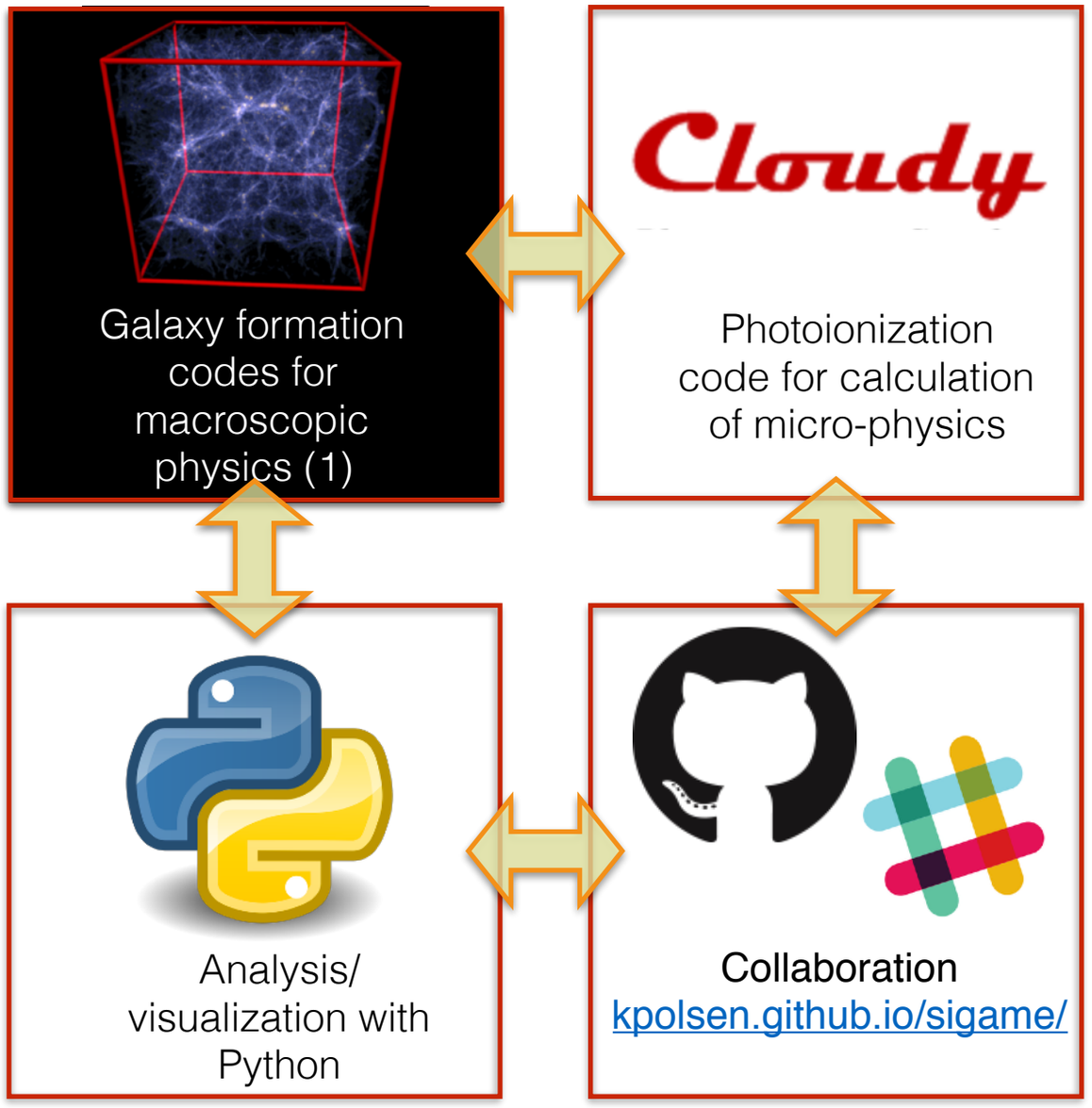
My current work!

- Started during PhD at Dark Cosmology Centre in Copenhagen
- Now a project that combines…

SÍGAME

(='follow me' in Spanish)

SImulator of GAlaxy Millimeter/submillimeter Emission



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

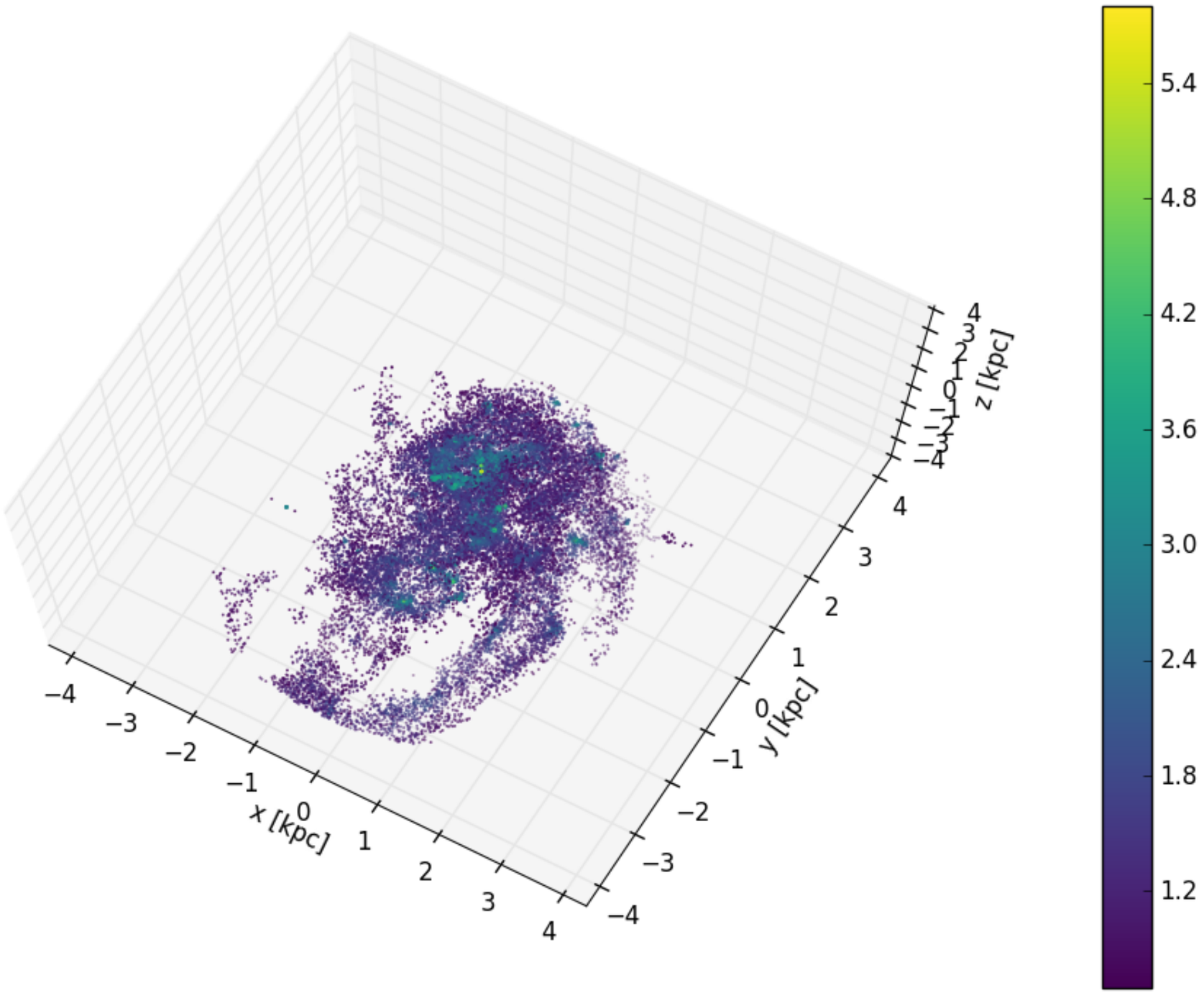
SÍGAME

Key steps

1. Extract galaxies from simulation

Cosmological hydrodynamic simulations

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



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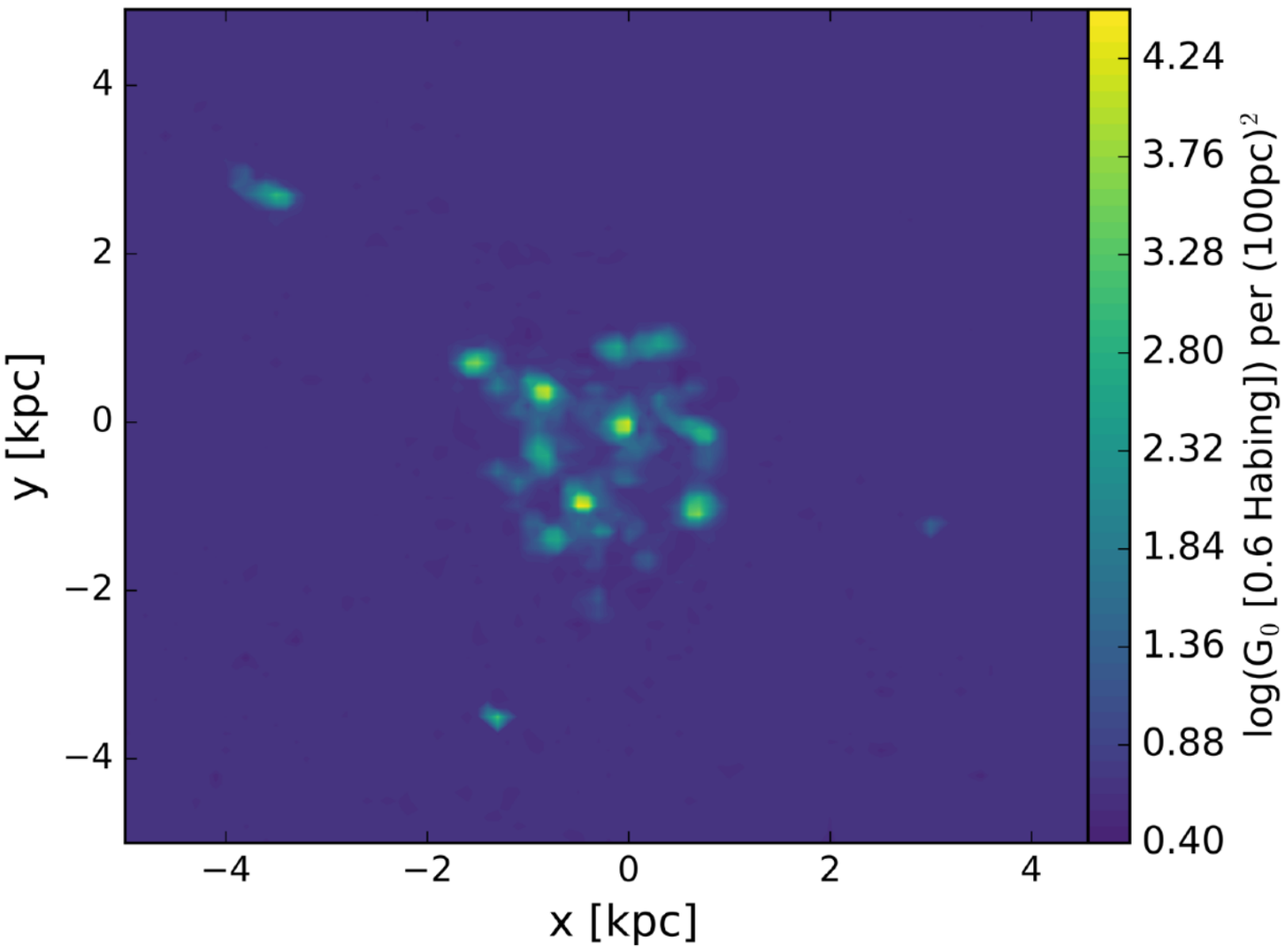
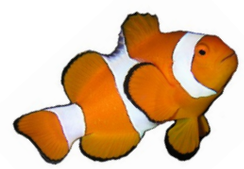
Key steps

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

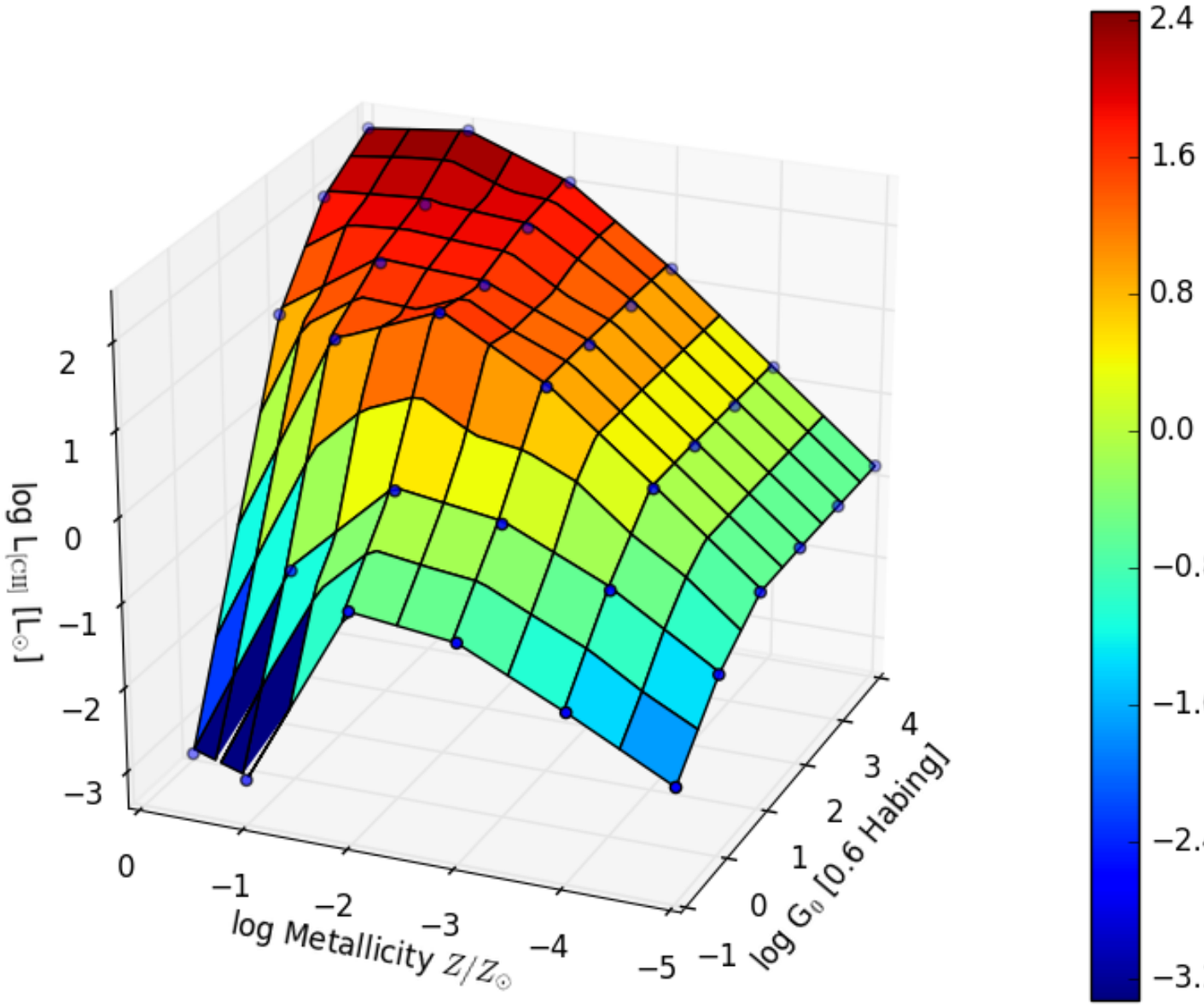
DIG (Diffuse Ionized Gas) — part of the diffuse gas clouds that is mostly ionized

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” 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

SÍGAME

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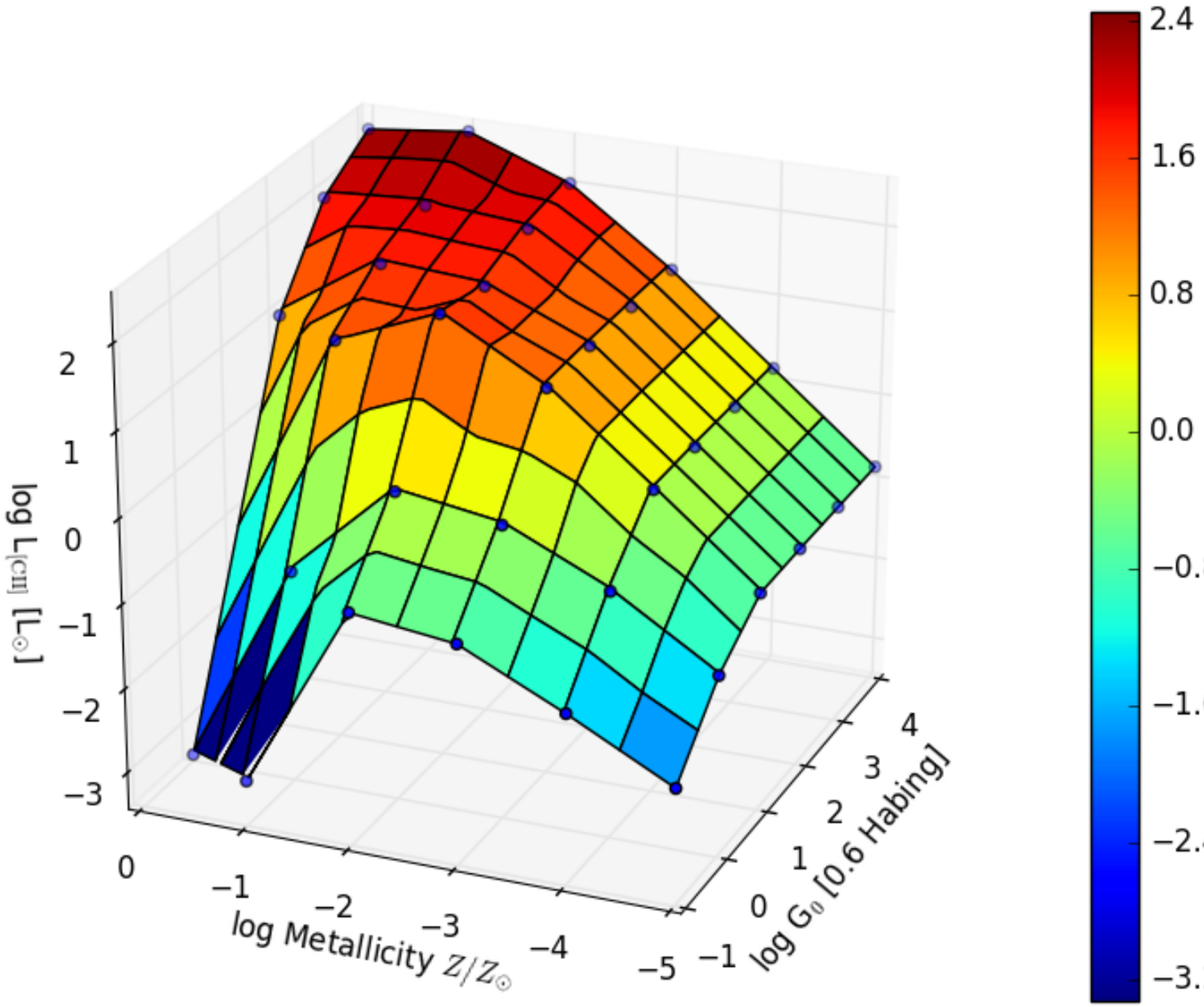


running models on Pleiades Supercomputer @ NASA with multiprocessing.Pool()

Work with student Luis R. Niebla

SÍGAME

Key steps

1. Extract galaxies from simulation

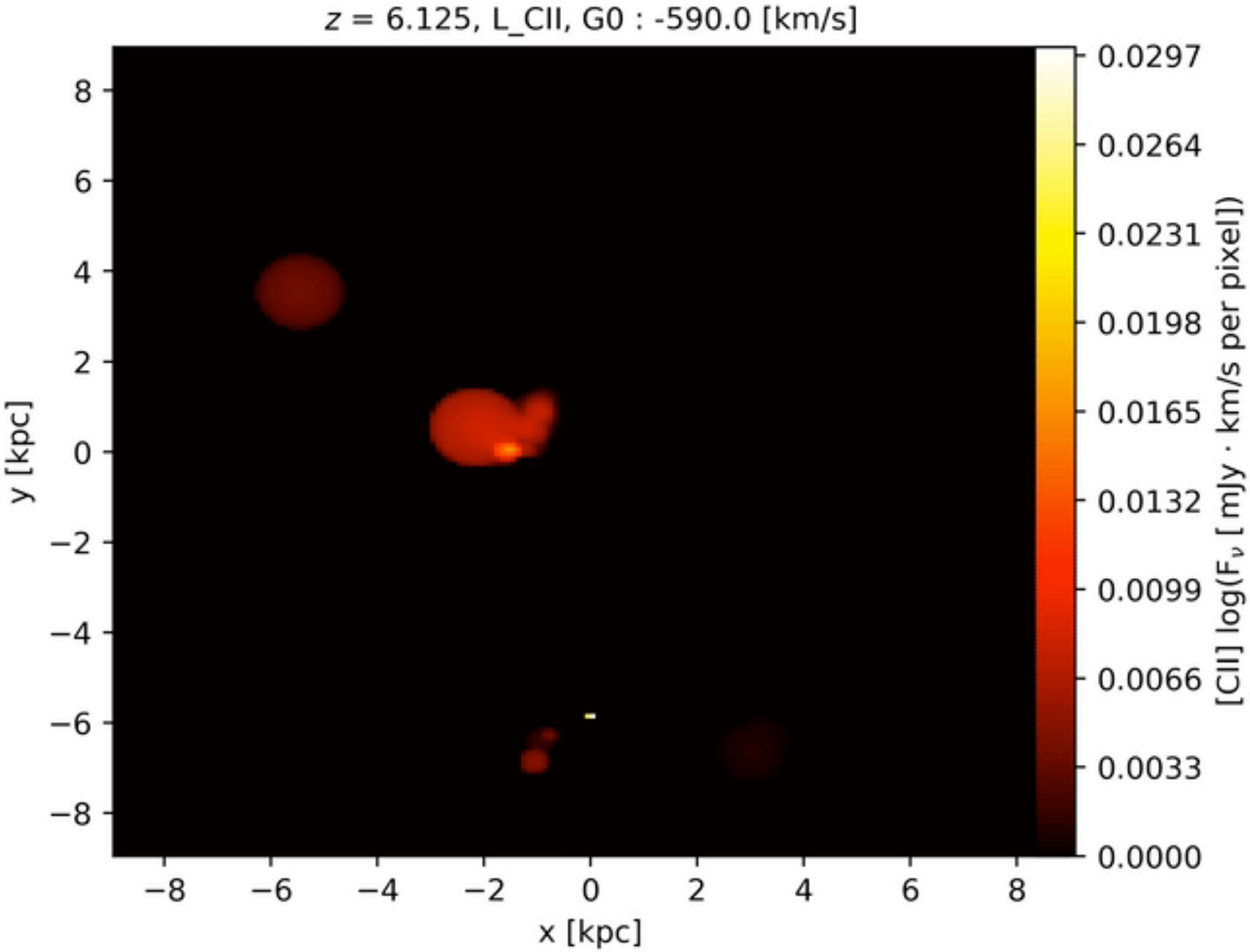
2. Derive large-scale ISM properties

3. Divide ISM into dense and diffuse gas

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

5. Create and analyze **datacubes**!

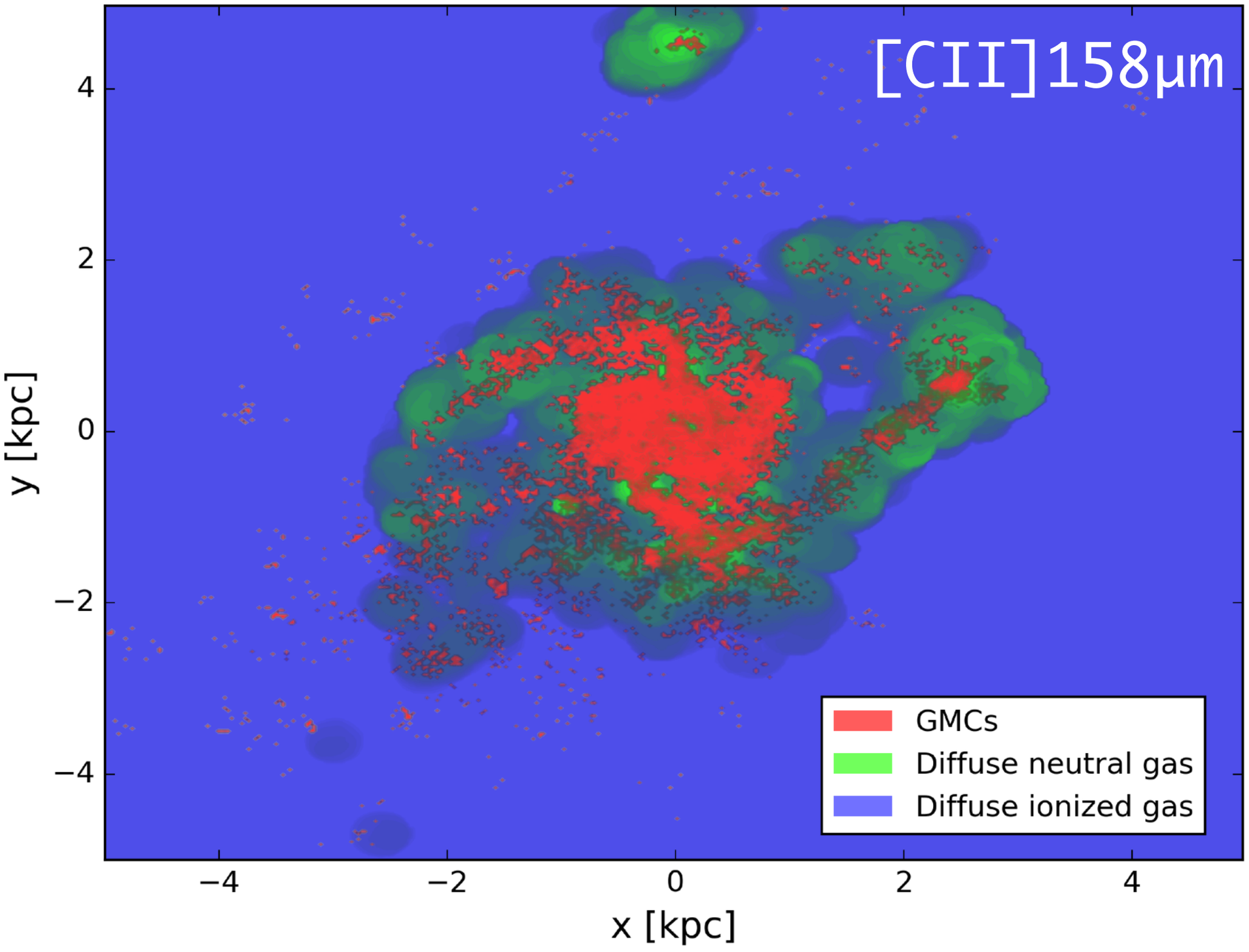
Video from datacube in space and velocity:



Work with student Jacob Cluff

Recent results

- With SÍGAME we can look at the FIR line emission coming from different ISM phases

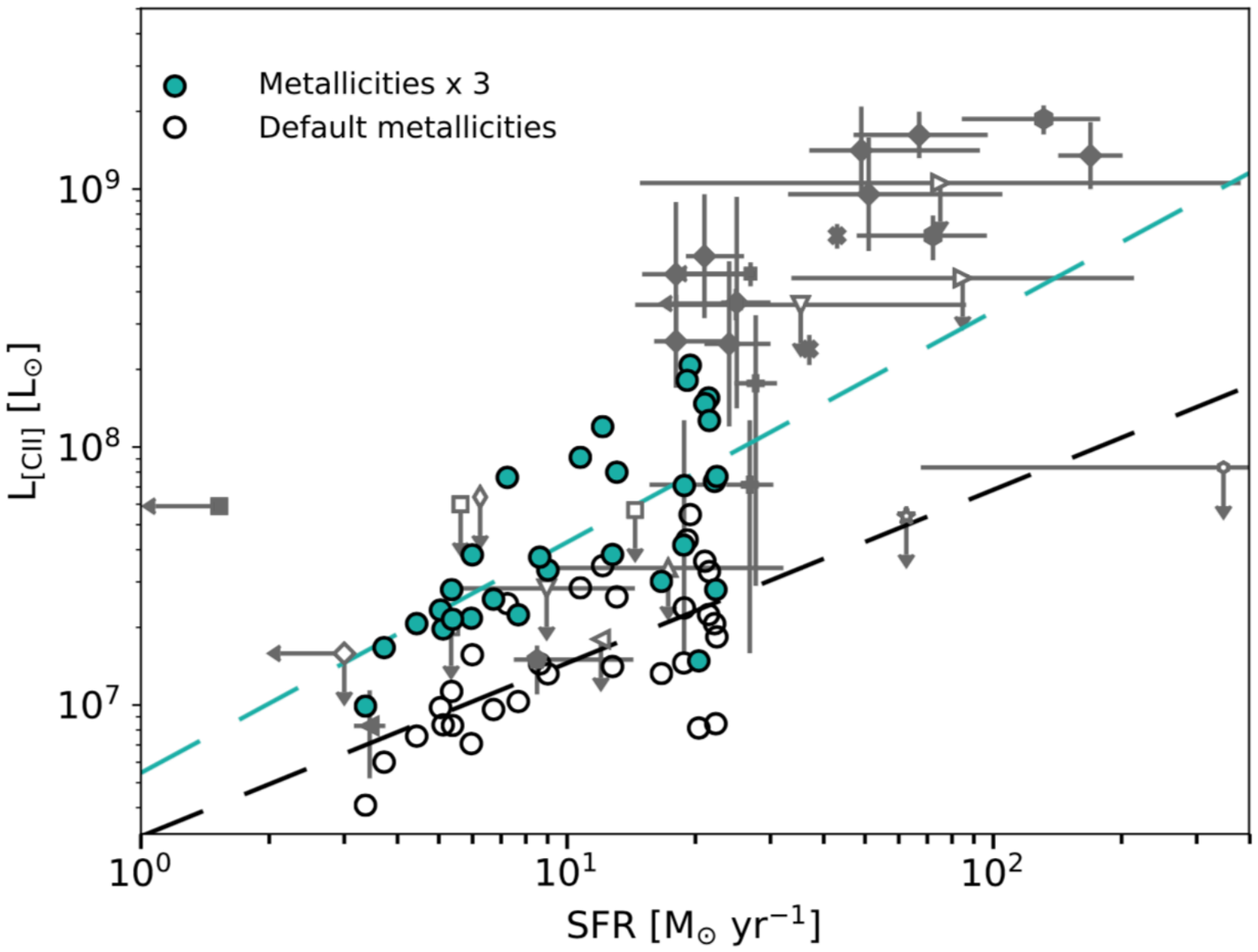


SÍGAME

Recent results

Non-detections of [CII] at high redshift is a signature of **low metallicity** combined with low molecular gas masses

[CII], [OI] and [OIII] lines in z~6 galaxies



Olsen et al. 2017, ApJ 846

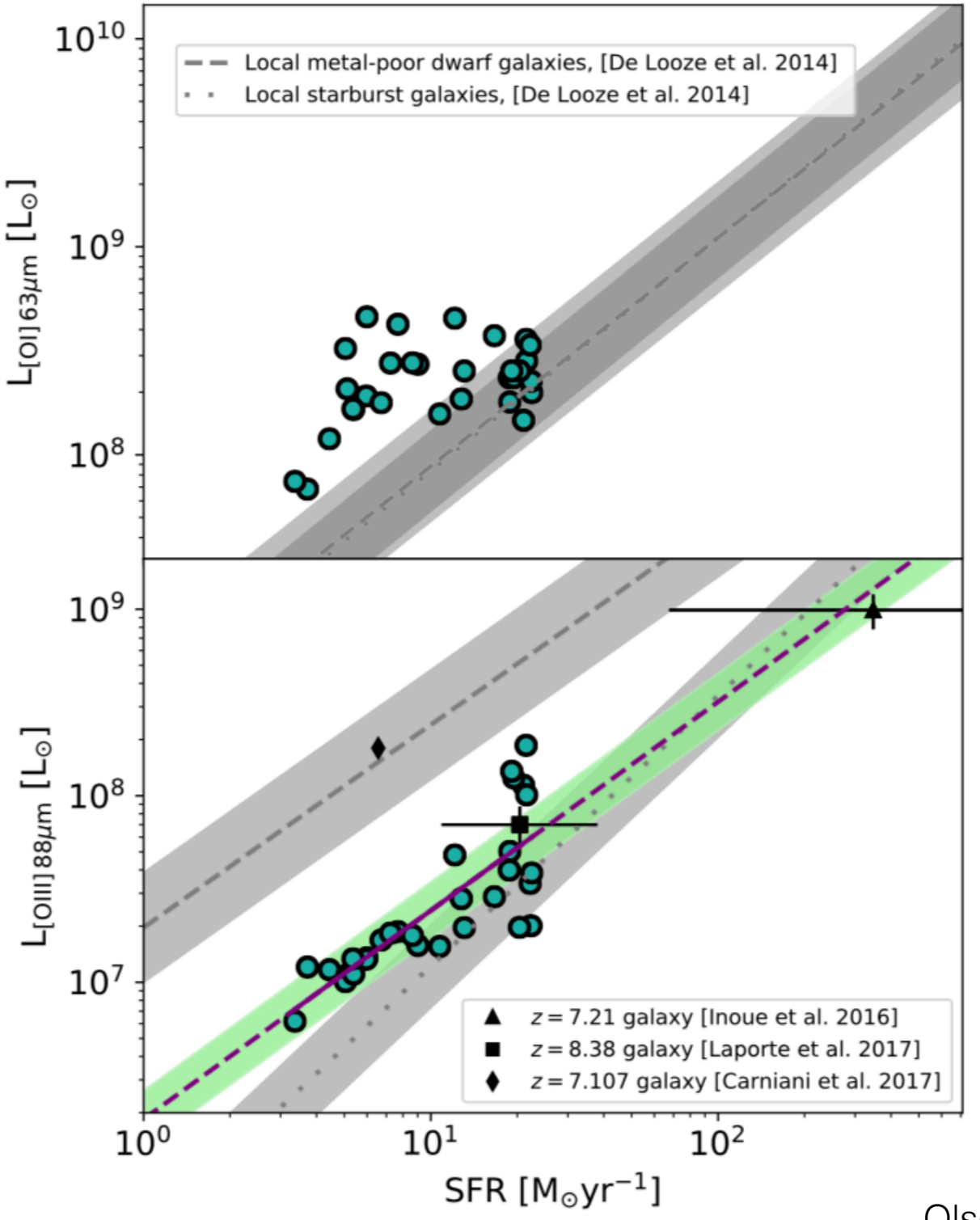
SÍGAME

Recent results

Non-detections of [CII] at high redshift is a signature of **low metallicity** combined with low molecular gas masses

At the same time, the **[OIII]-SFR relation** matched that at low z and two of three high-z galaxies detected so far.

[CII], [OI] and [OIII] lines in z~6 galaxies



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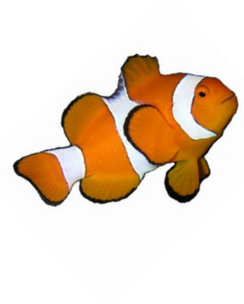

SÍGAME

Preliminary results

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

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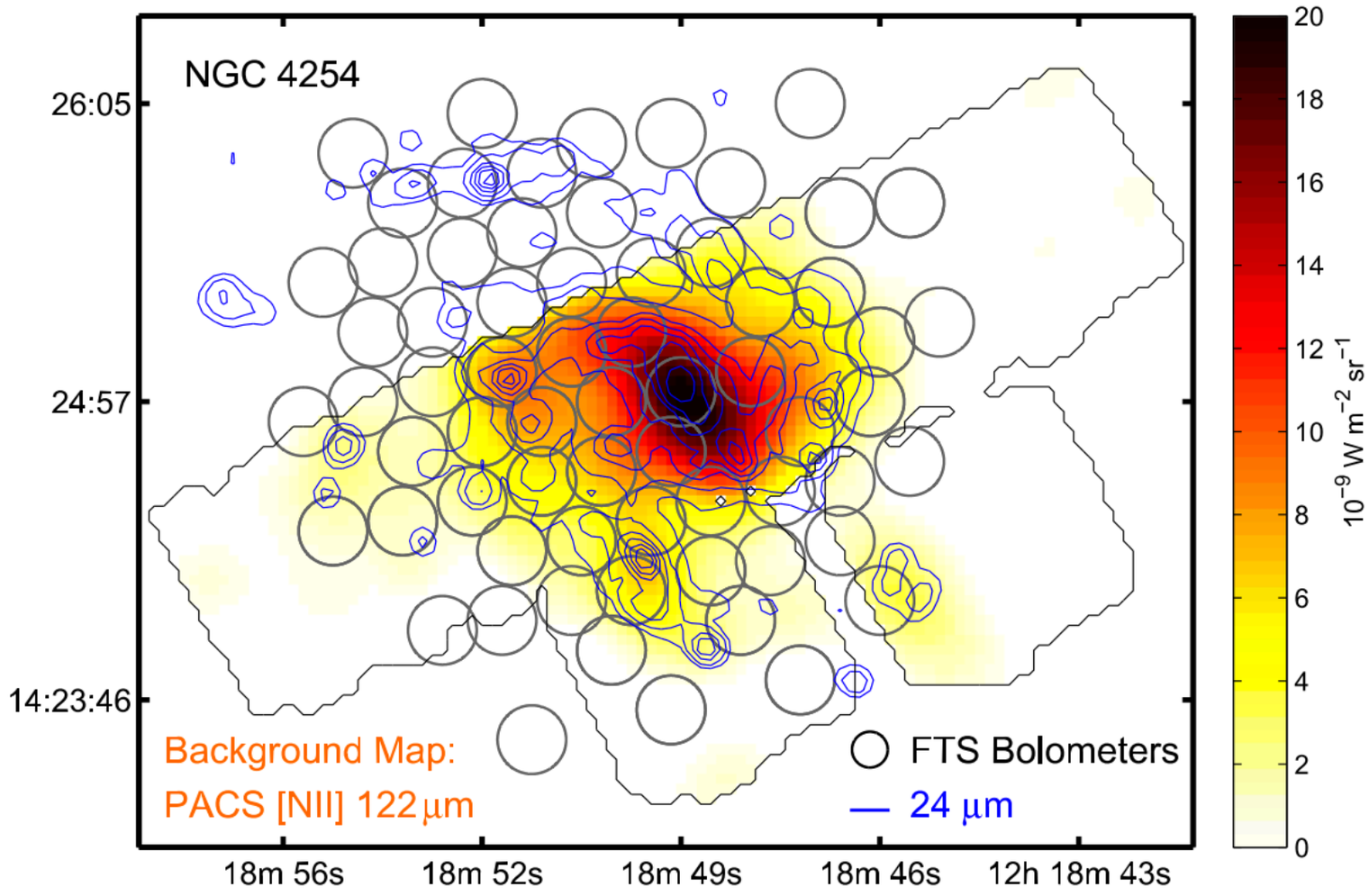
Create synthetic observations similar to resolved *Herschel* observations:



Herrera-Camus+16

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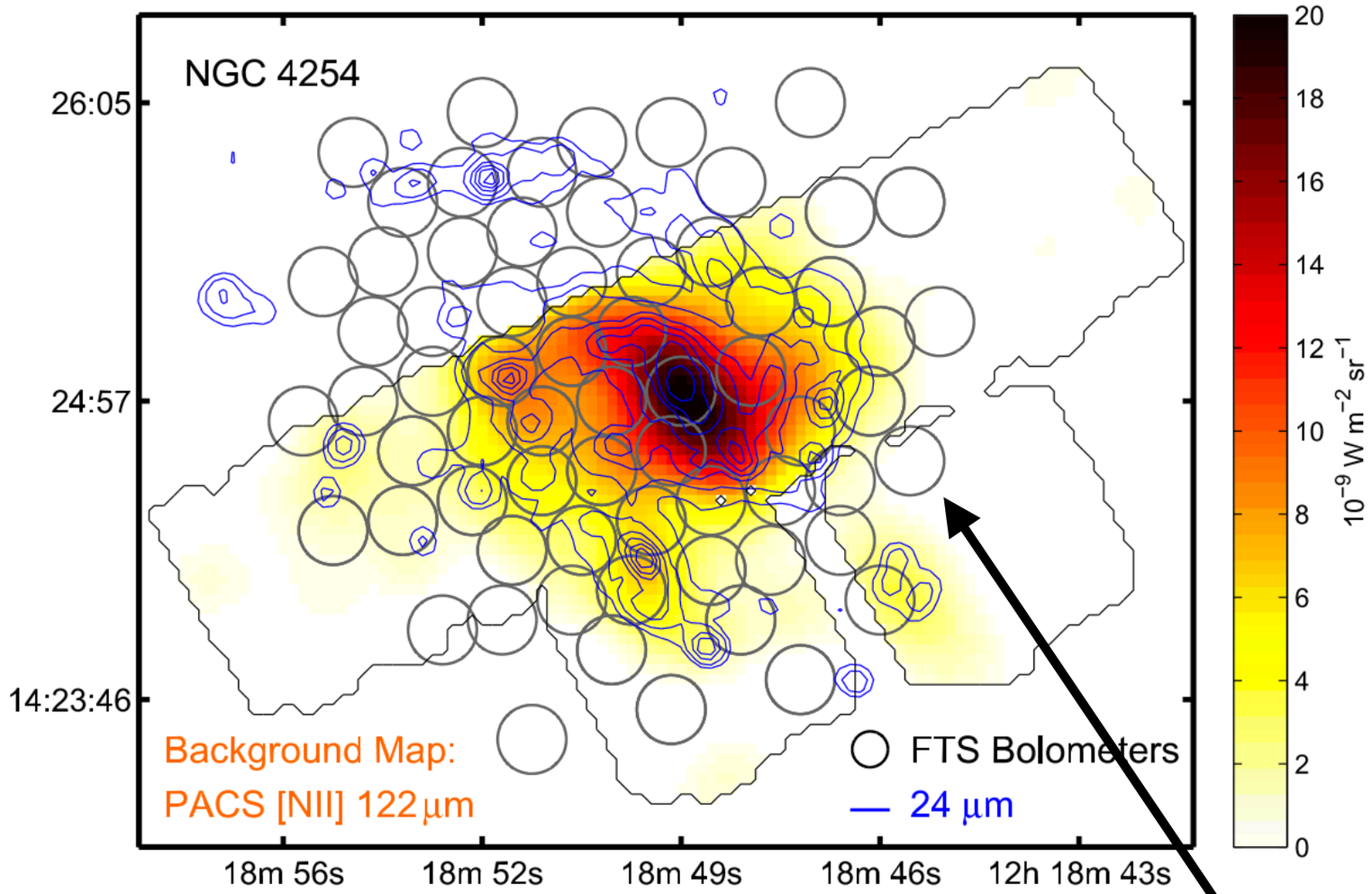
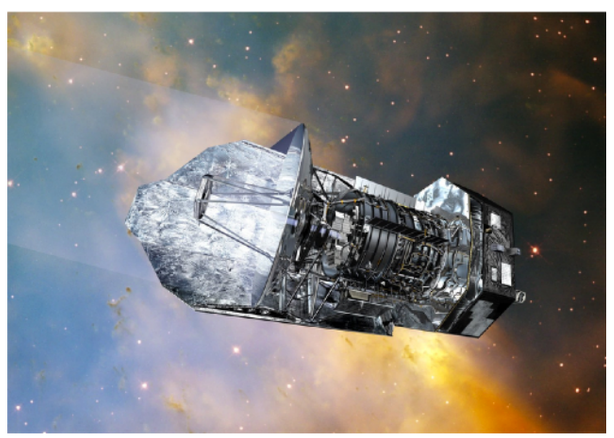




circles: 17″ SPIRE-FTS bolometers used to detect the [N II] 205 μm line.

Herrera-Camus+16

Preliminary results

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

SÍGAME

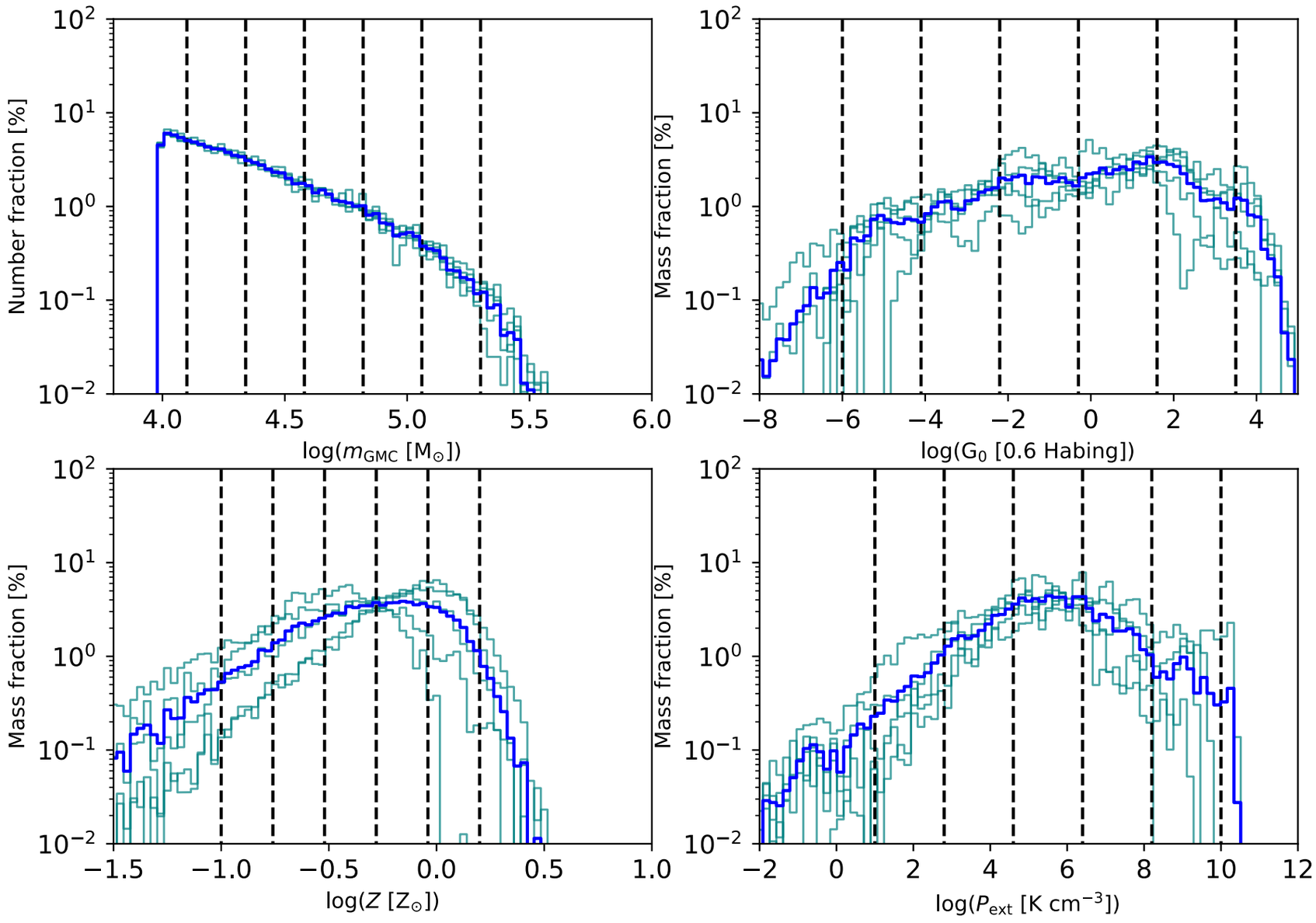
Step 1/5: Extract z=0 galaxies from zoom simulations

	M_{star}	M_{gas}	M_{mol}/M_{gas}	SFR	D_L
G1	7.10E+08	2.57E+09	9%	0.1876	12.77
G2	4.95E+09	4.87E+09	15%	0.7855	9.99
G3	6.43E+09	8.41E+09	9%	1.5130	13.57
G4	9.58E+09	9.09E+09	13%	1.5406	8.79
G5	3.16E+10	3.21E+10	8%	5.58	7.46

Preliminary results

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

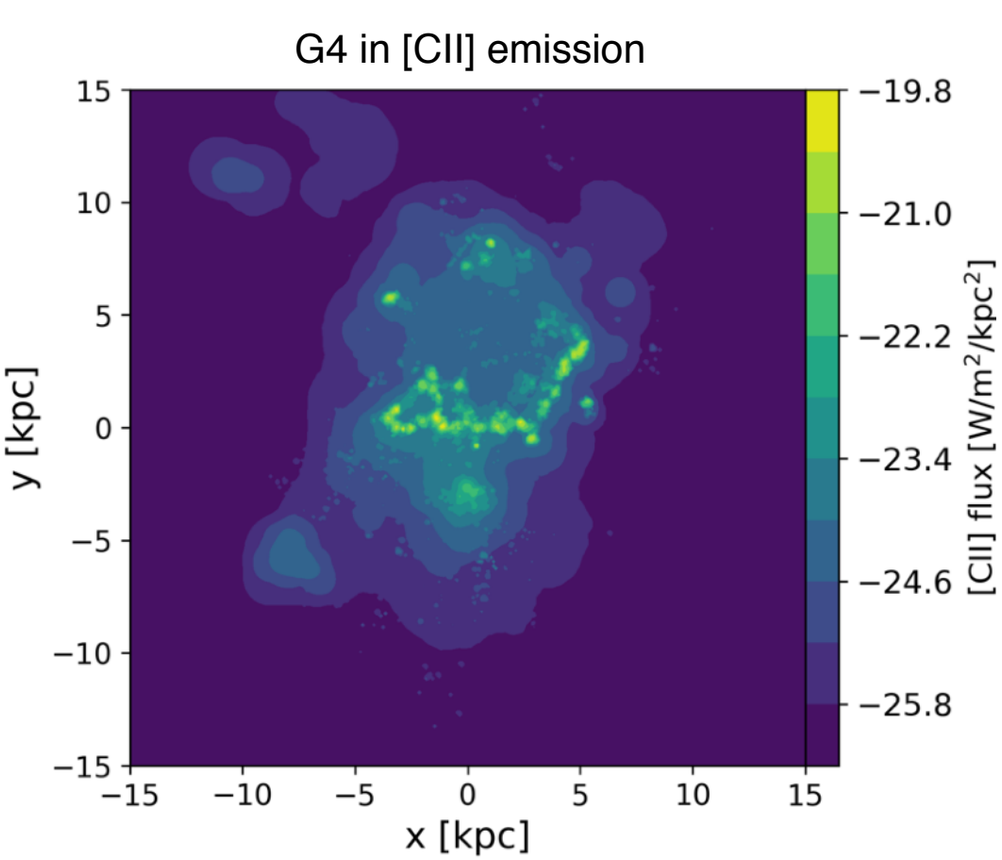
Step 2/5: Subgrid to get ISM properties

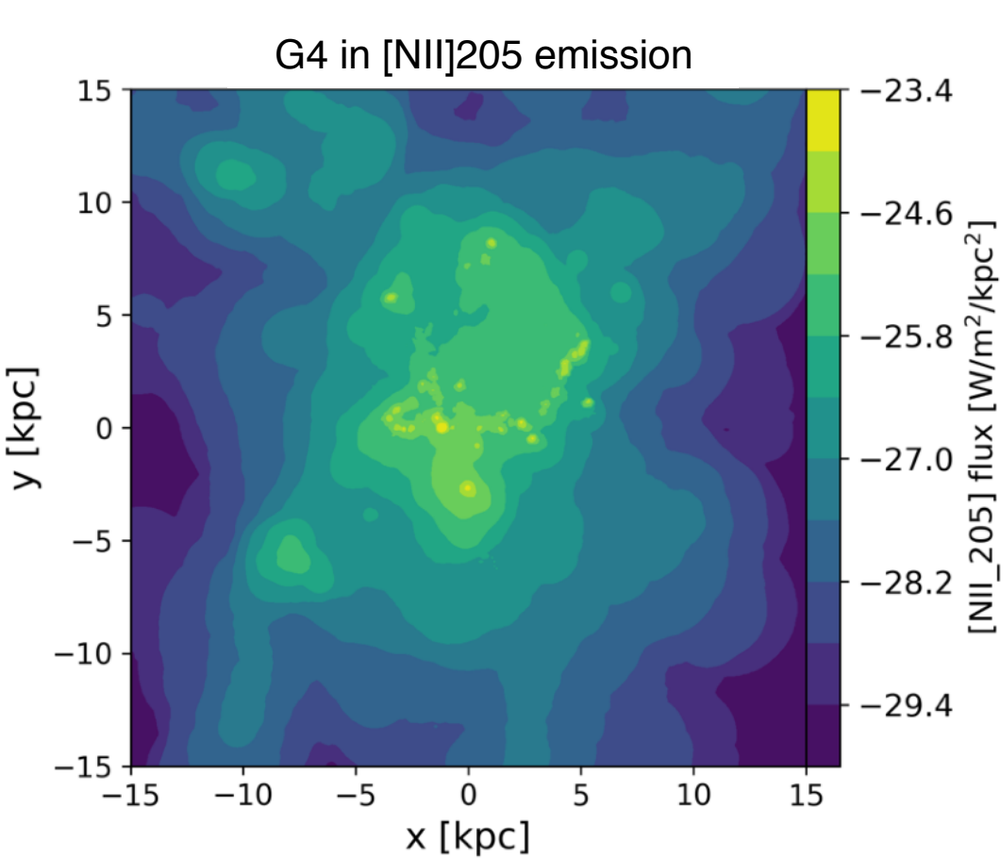


Step 3/5: Create datacubes of emission

Preliminary results

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



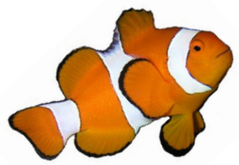


… and divide to get a line ratio map

Preliminary results

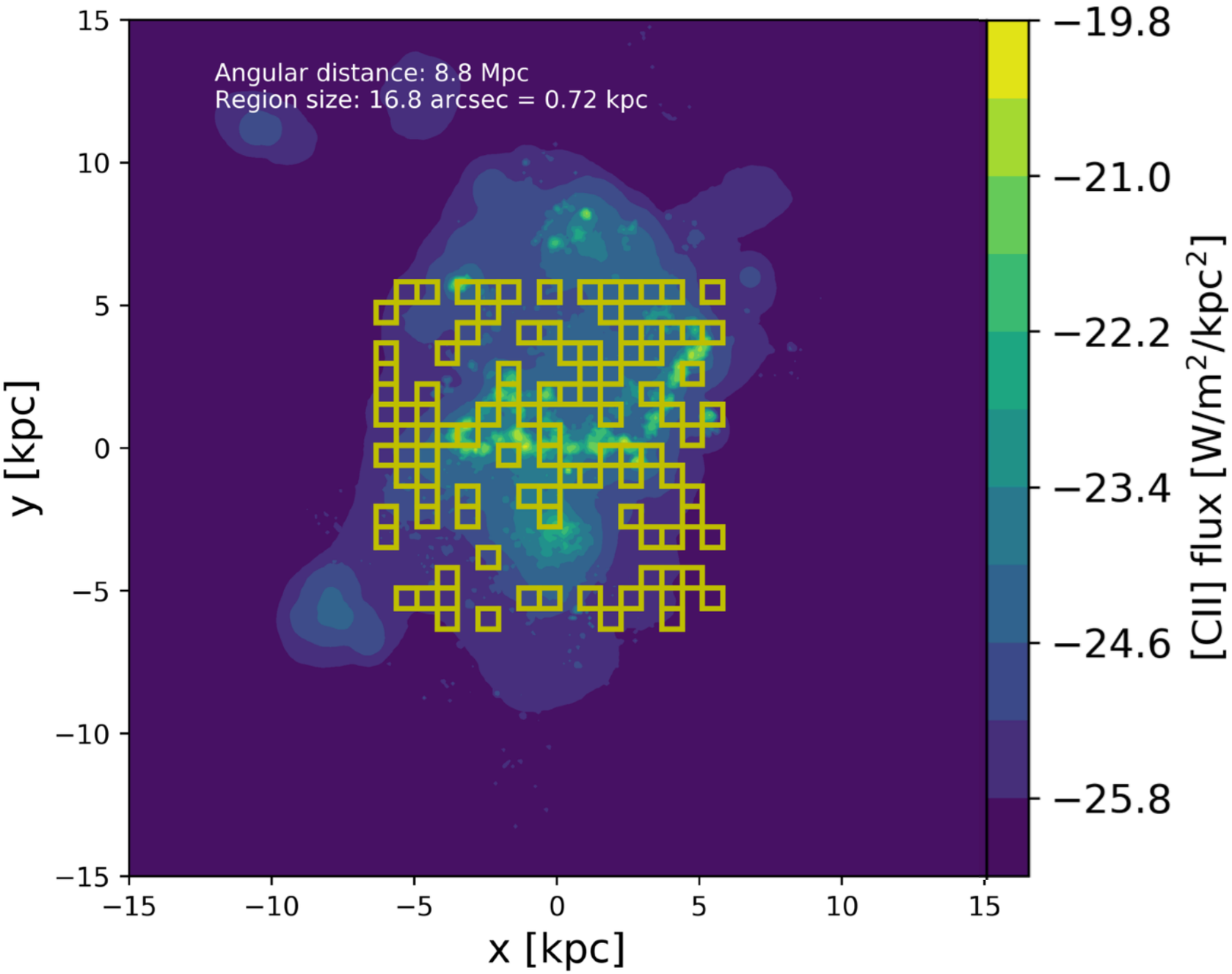
- Goal: Simulating line ratios in resolved nearby galaxies to compare with resolved observations

Step 4/5: Extract regions from those line ratio maps



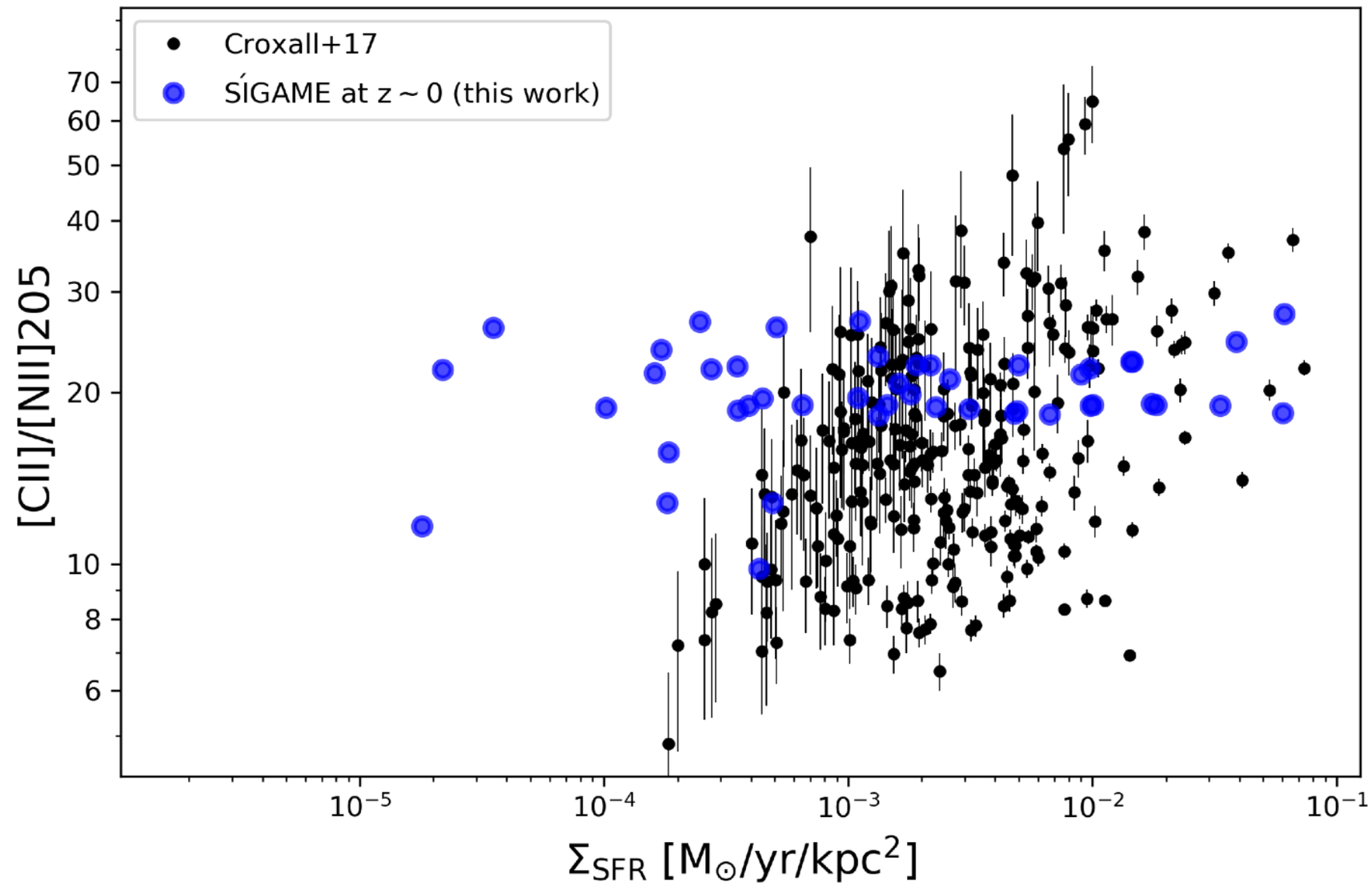
SÍGAME

G4



Preliminary results

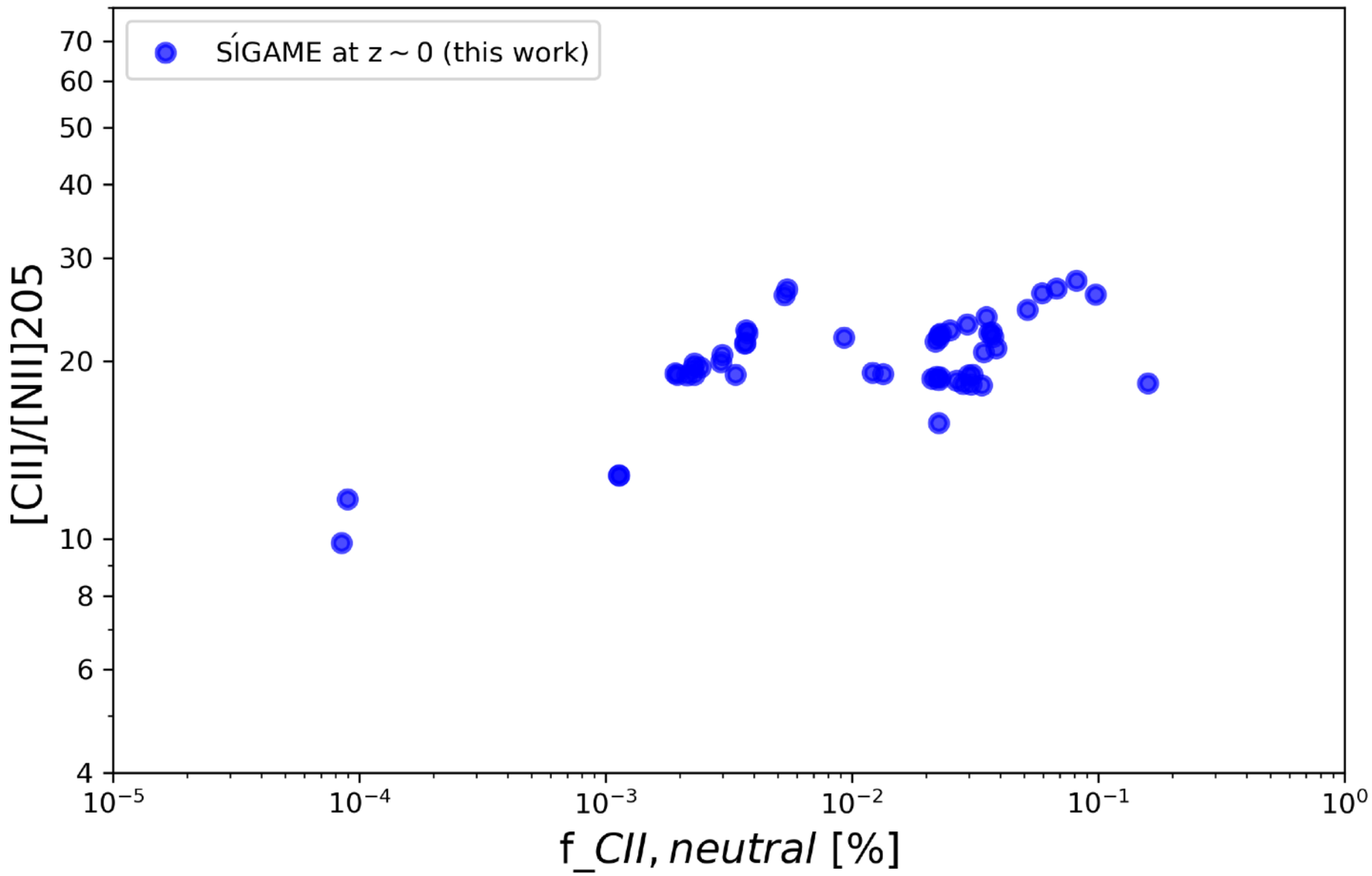
Step 5/5: Correlate with ISM properties - such as Σ_{SFR}



Work with student Lily Whitler

Preliminary results

Step 5/5: Correlate with ISM properties - or neutral fraction of [CII]



Future projects

Answer these questions:

1) to estimate actual ionized gas mass fraction?
2) to estimate gas metallicity?
3) and how does that callibration depend on Σ_{SFR}?

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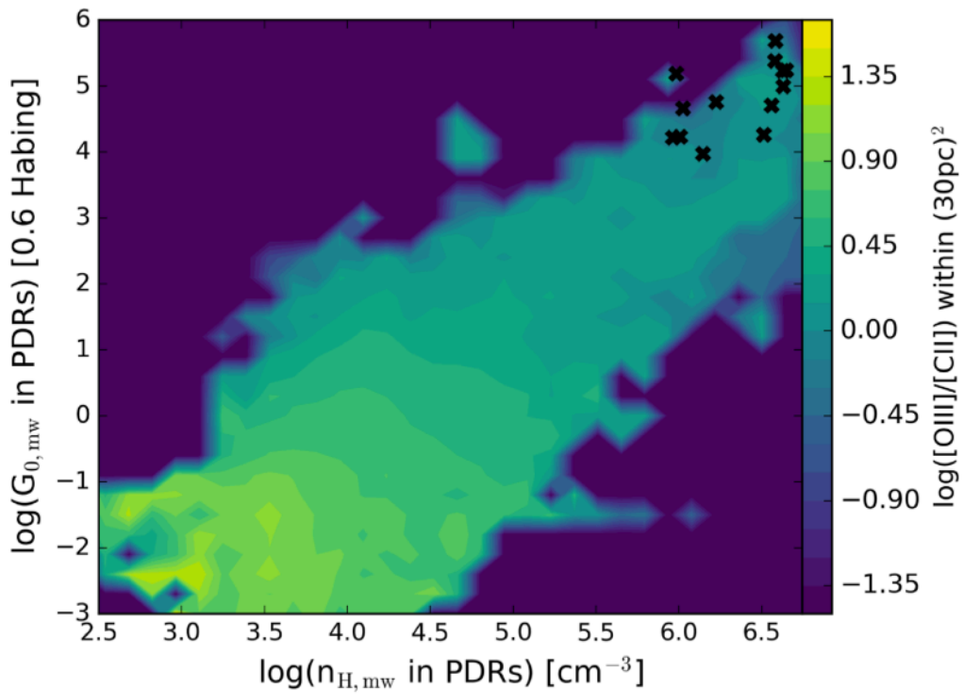
… expand analysis to more line ratios and larger galaxy sample, in preparation for NASA ADAP:

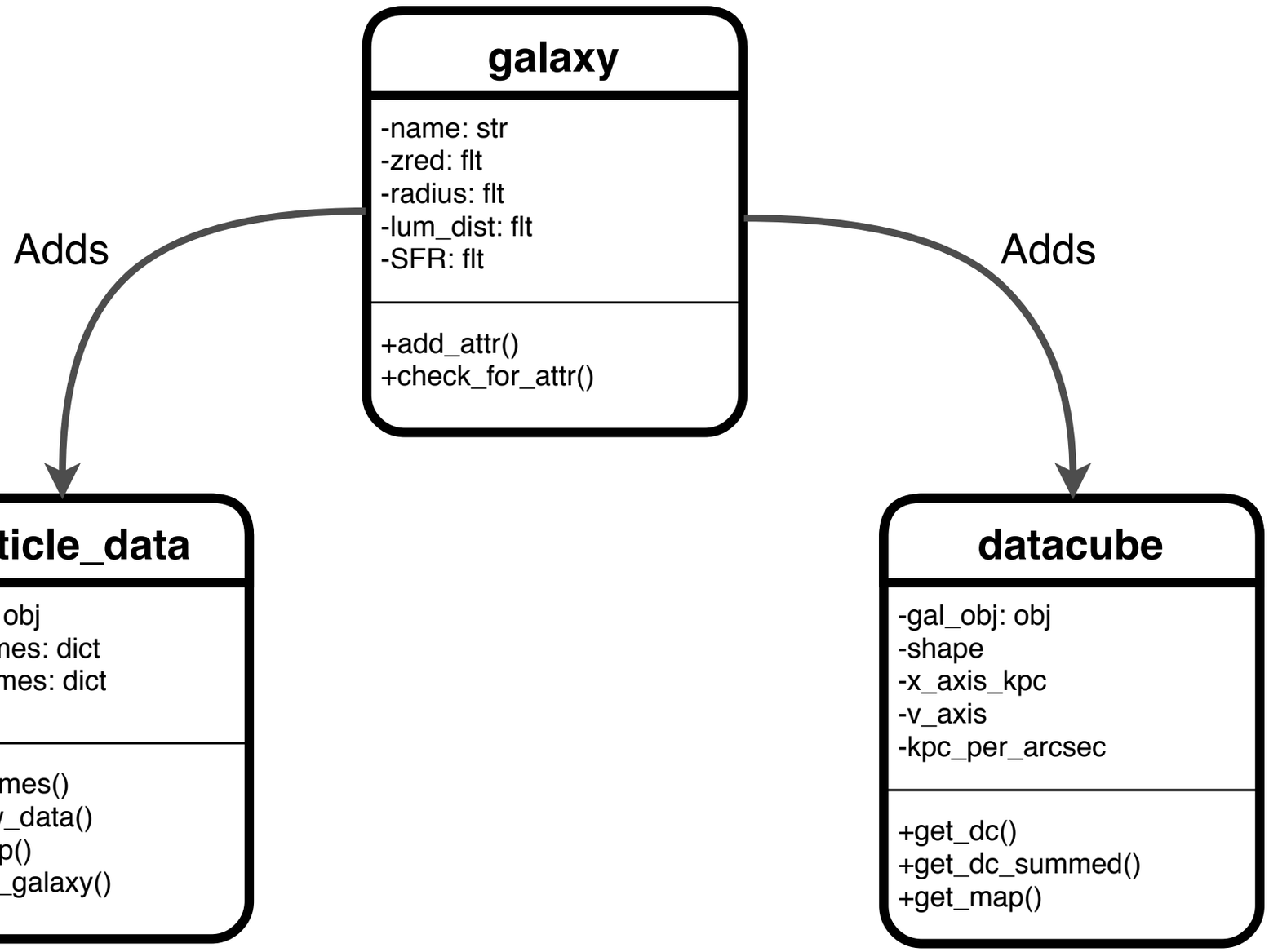


Archival Herschel spectroscopy of star-forming galaxies in the light of multi-phase ISM galaxy simulations

Karen Olsen, Huan Yang, Desika Narayanan, Julia Kamenetzky, Sangeeta Malhotra, Naseem Rangwala, Romeel Davé and Thomas Greve

Future projects

Improving work flow and readability in programming

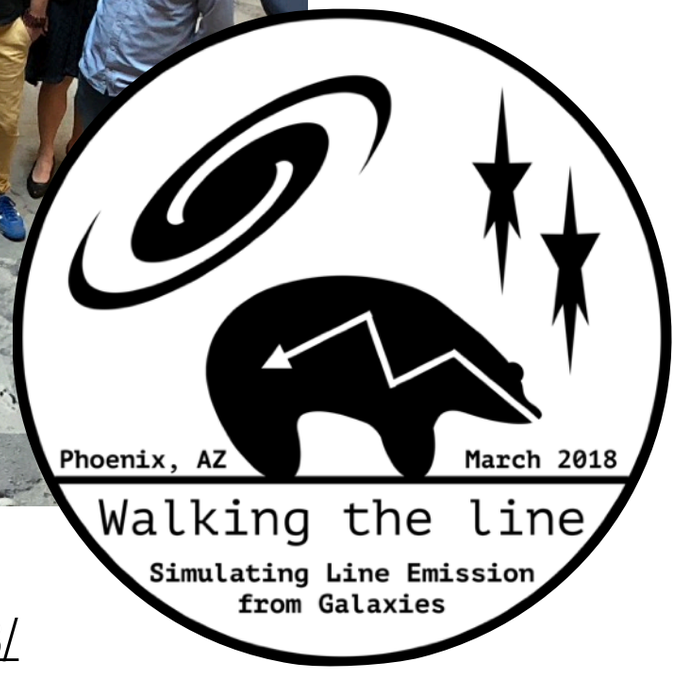


Satish Bhambri, CIDSE, Software Engineering

Future projects

Helping out with a workshop next year in Sweden

… as follow-up of my workshop in March:

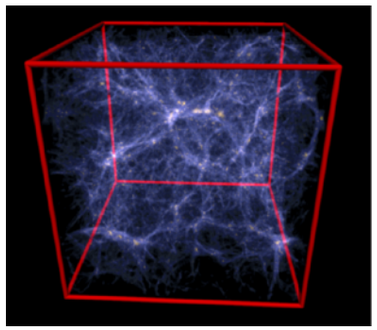


https://walk2018.weebly.com/
https://zenodo.org/communities/walk2018/

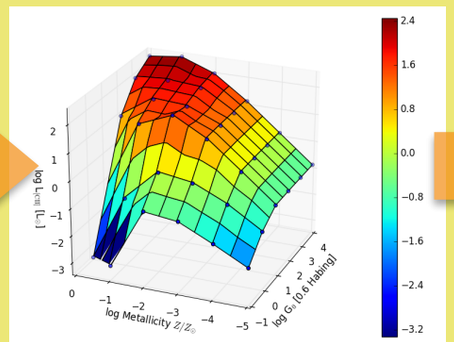
Summary

Synthetic observations are important for understanding/predicting real observations.

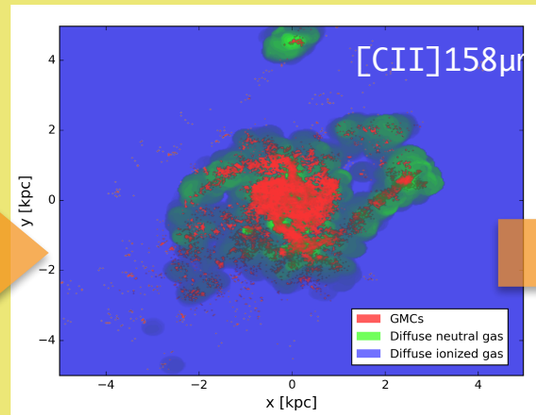
(1)
Galaxy formation codes for large-scale physics



(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!

Future

1. Study **line ratios like [CII]/[NII]205** and compare with resolved observations of nearby galaxies
   - Run more galaxies, do a Principle Component of Bayesian analysis of ISM parameter space
2. Use SÍGAME to analyze **[CII], [NII], [OI], [OIII]** from ~230 nearby galaxies (NASA ADAP)
3. **Improve work flow** of code for future users.
4. Help **organize a 4-week workshop** in Sweden next year on line simulations.