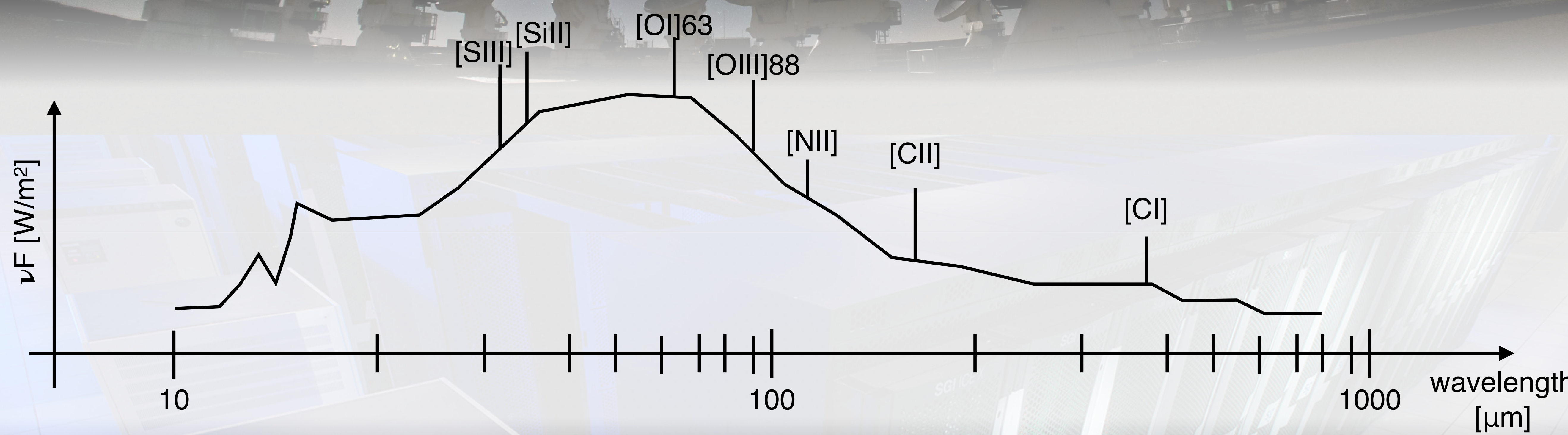
Simulations of FIR line emission from galaxies at high redshift

Karen Pardos Olsen



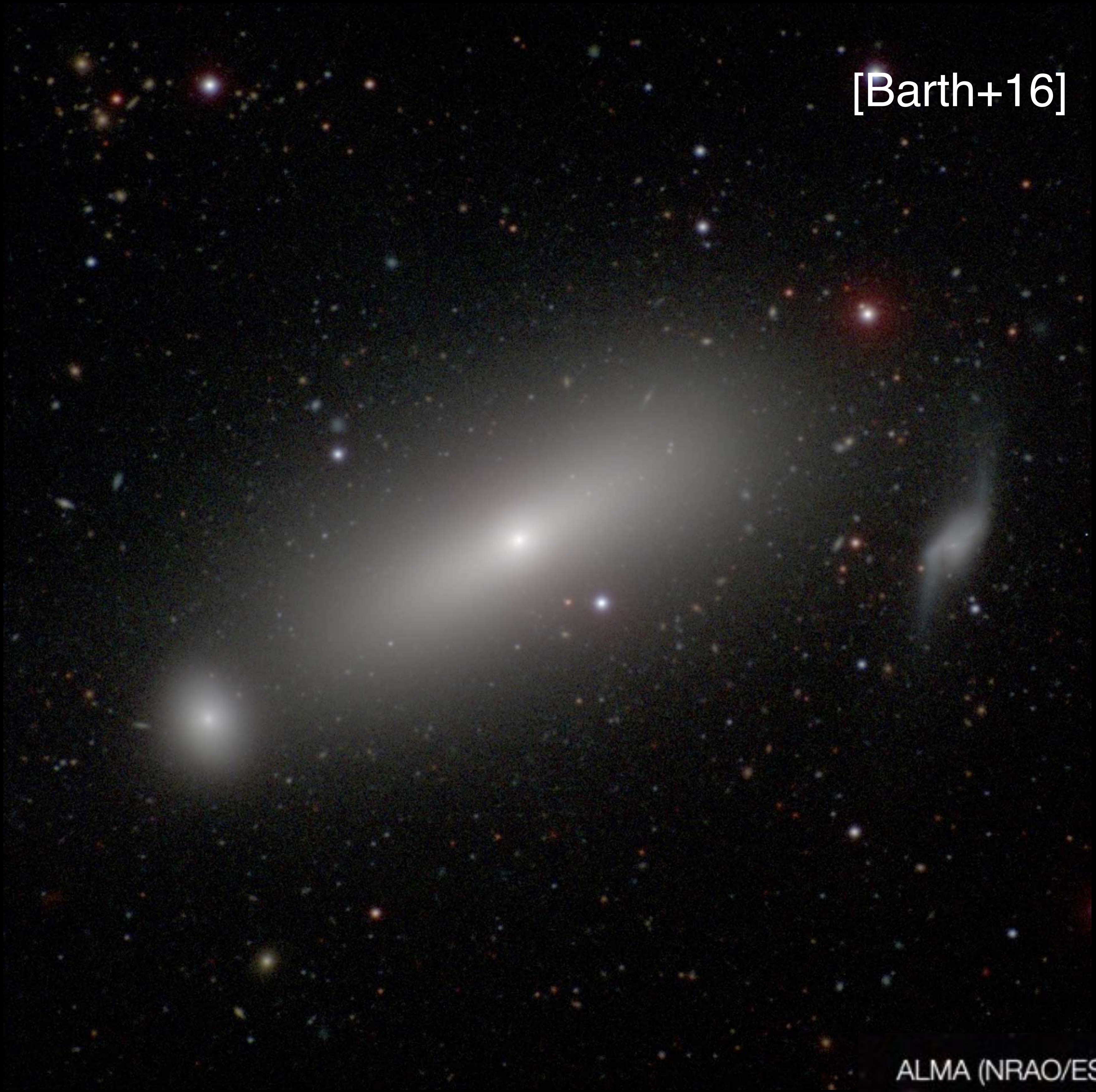
IRyA, UNAM, June 29 2017

SESE, ASU

Morelia

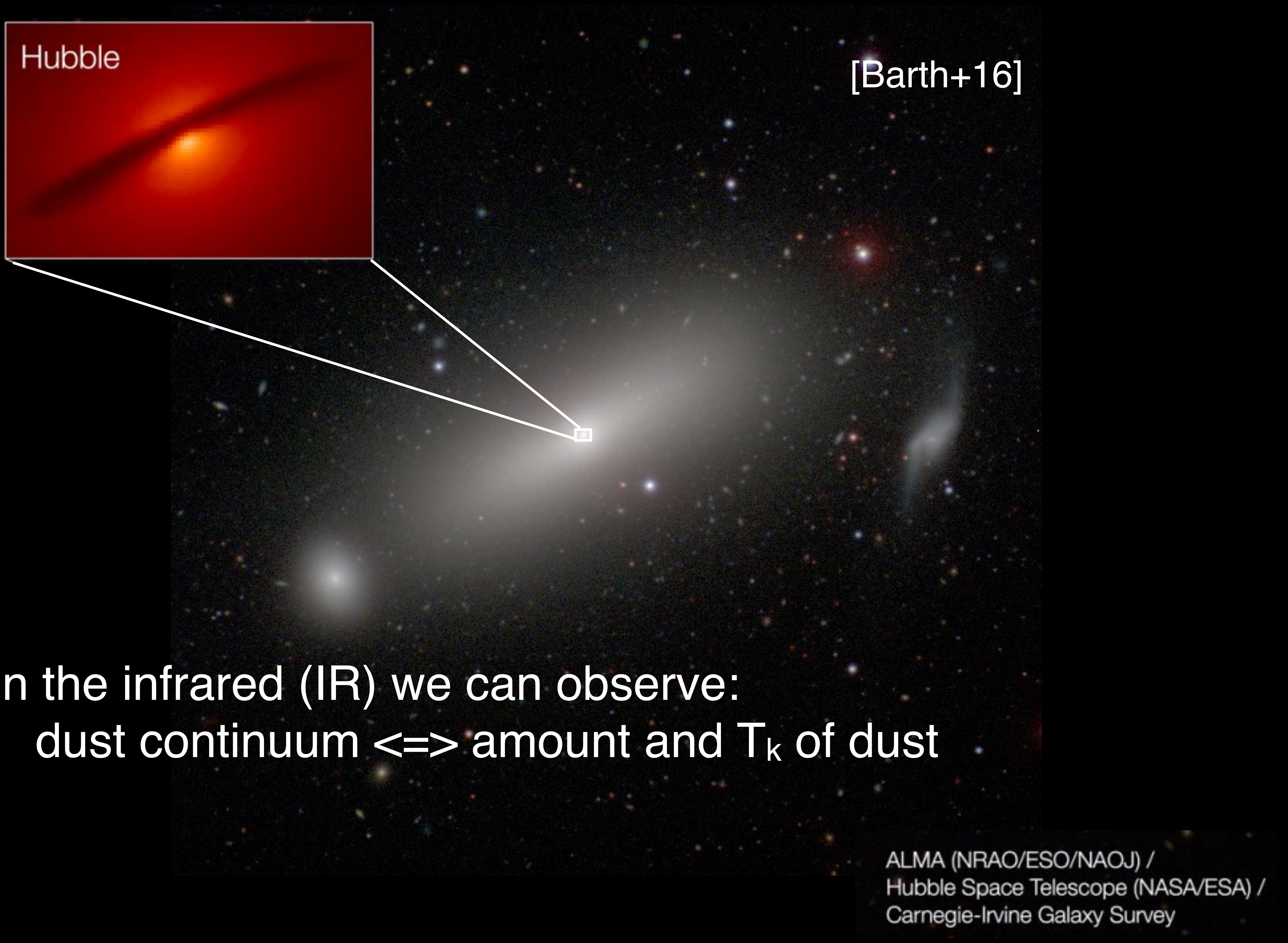
Copenhagen,
Denmark

NGC 1332



ALMA (NRAO/ESO/NAOJ) /
Hubble Space Telescope (NASA/ESA) /
Carnegie-Irvine Galaxy Survey

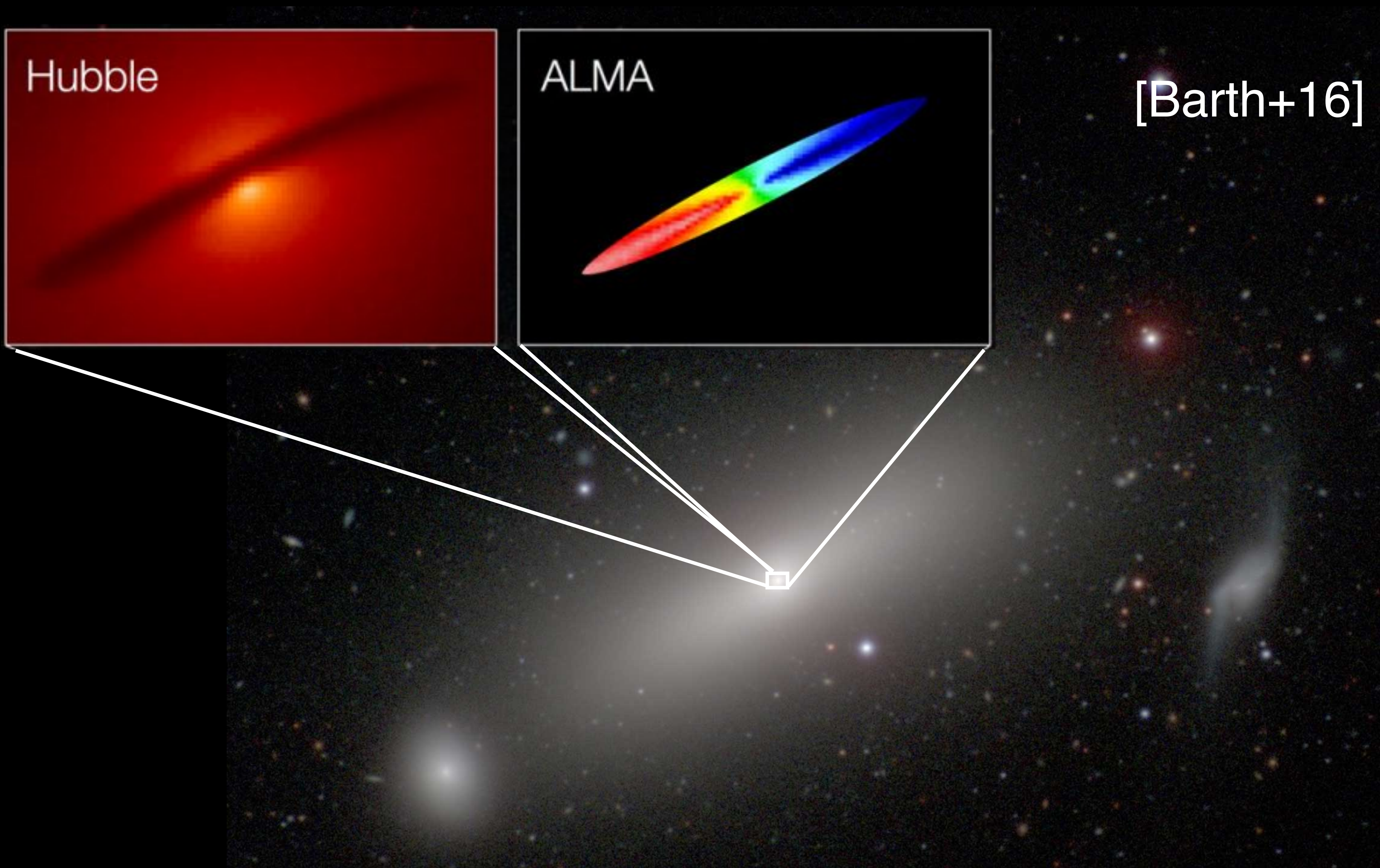
NGC 1332



In the infrared (IR) we can observe:

- dust continuum <=> amount and T_k of dust

NGC 1332



In the infrared (IR) we can observe:

- dust continuum <=> amount and T_k of dust
- line emission <=> amount, motion and state of gas

ALMA (NRAO/ESO/NAOJ) /
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Observing the gas at high redshift

Observing the gas at high redshift

Forbidden atomic emission lines from
the warm-phase interstellar medium (ISM)

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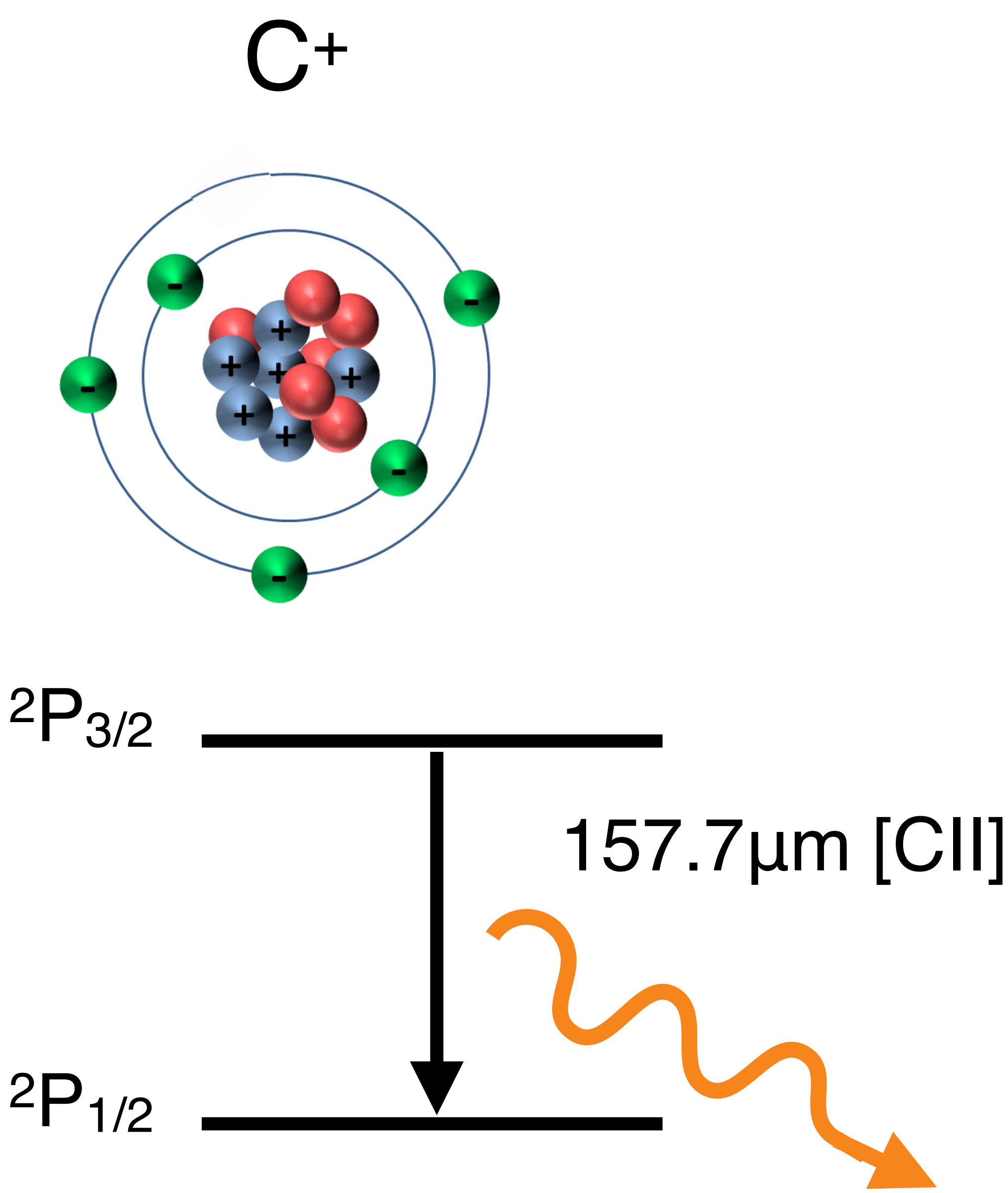
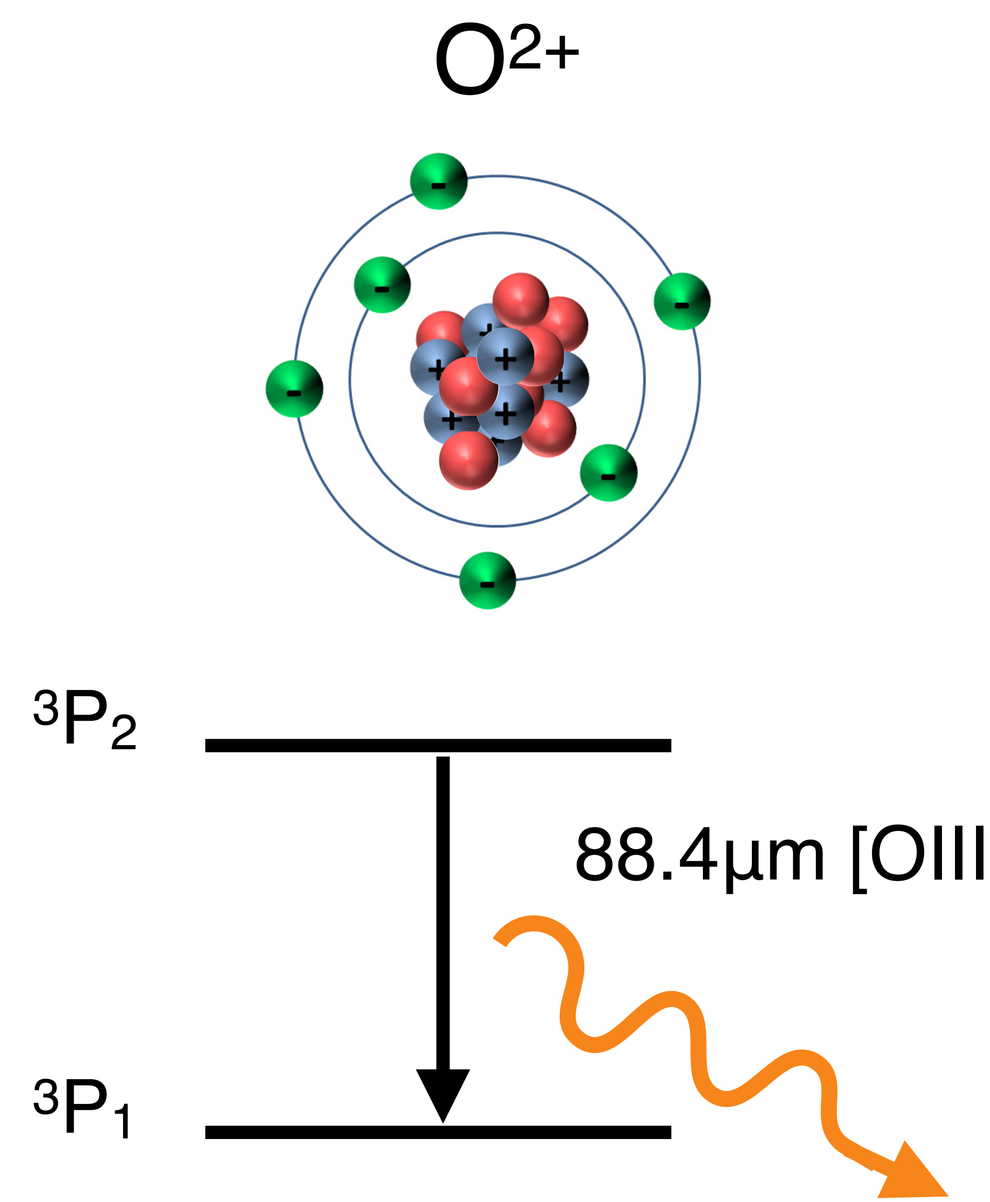
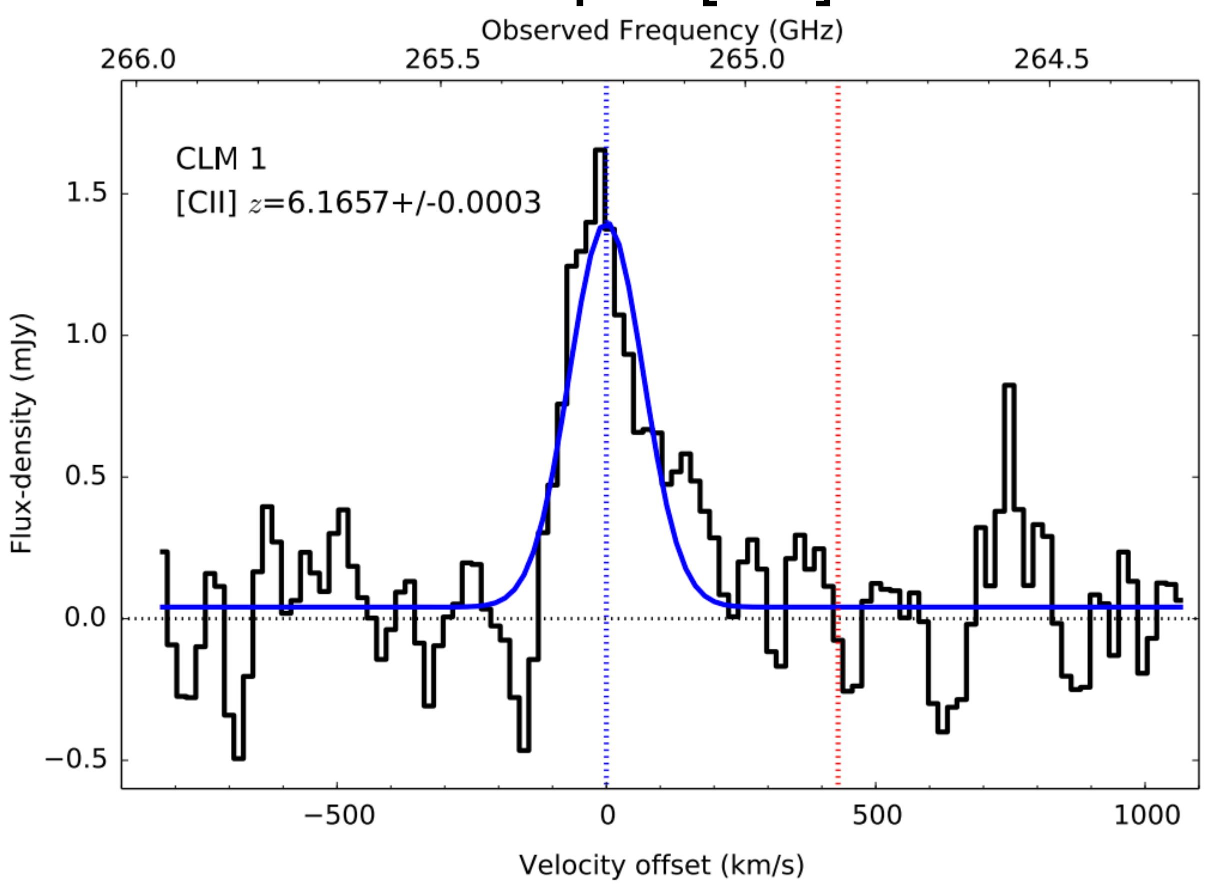




Observing the gas at high redshift

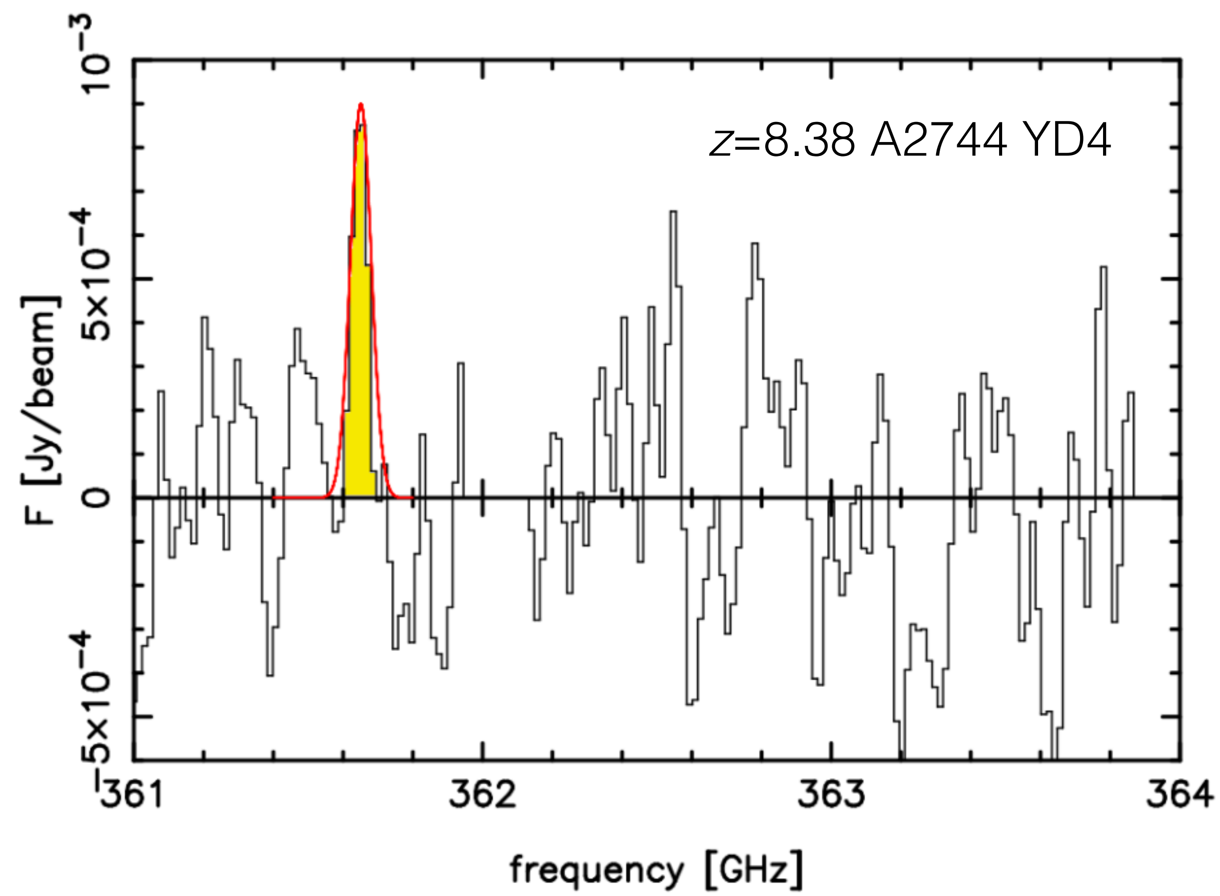
Examples

157.7µm [CII]



1.6hrs ALMA time (μ~1.13)
[Willott+15]

88.4µm [OIII]



2.5hrs ALMA time (μ~2)
[Laporte+17]

Observing the gas at high redshift

Examples

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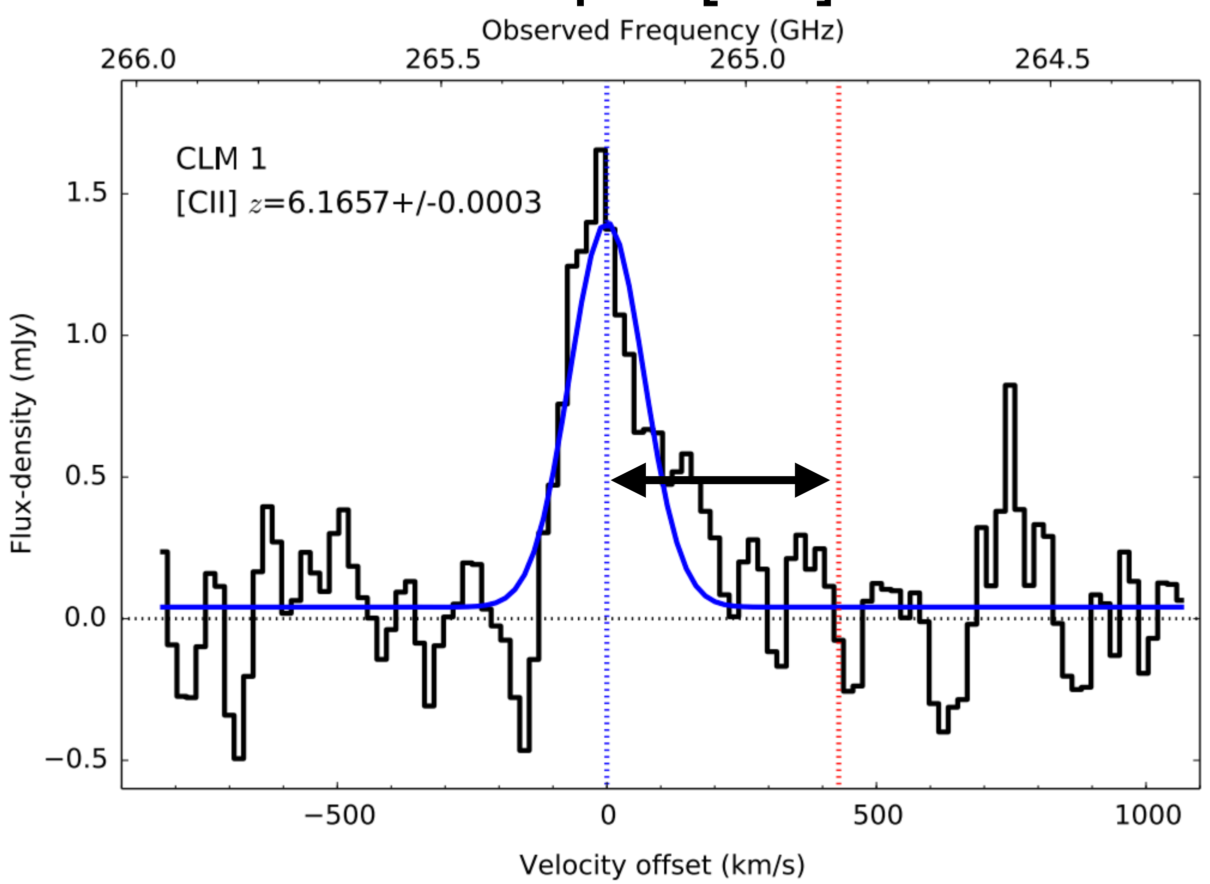

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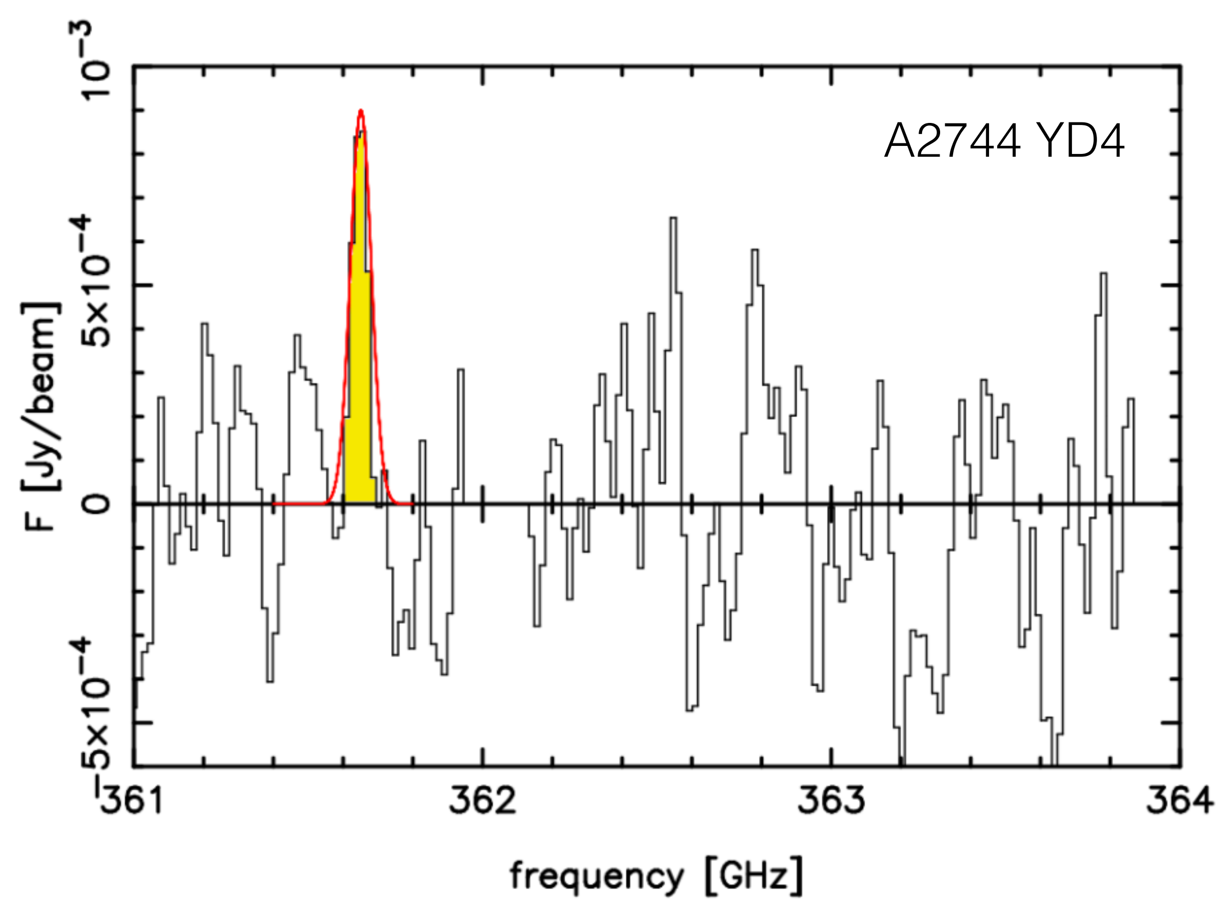


2.5hrs ALMA time (μ~2)
[Laporte+17]

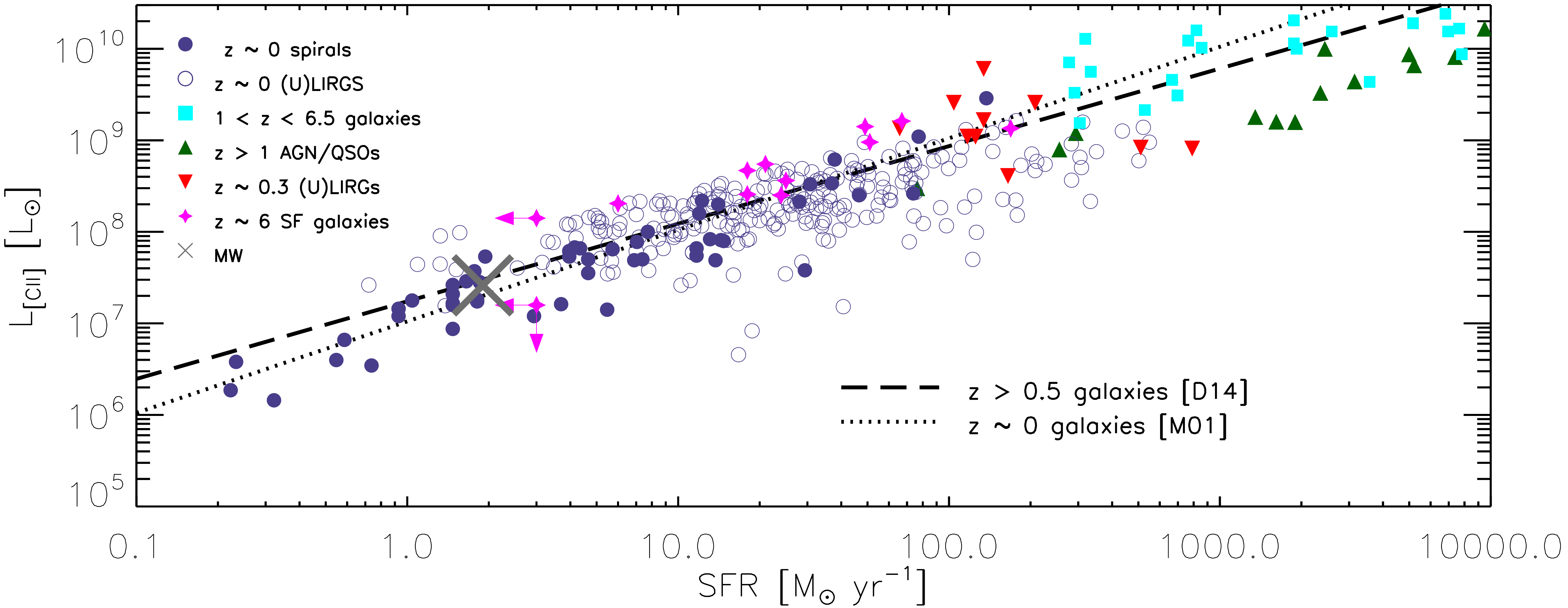
Improvement of intrinsic redshift, compared to when using Lyα!

[CII]-SFR relation

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

[CII]-SFR relation

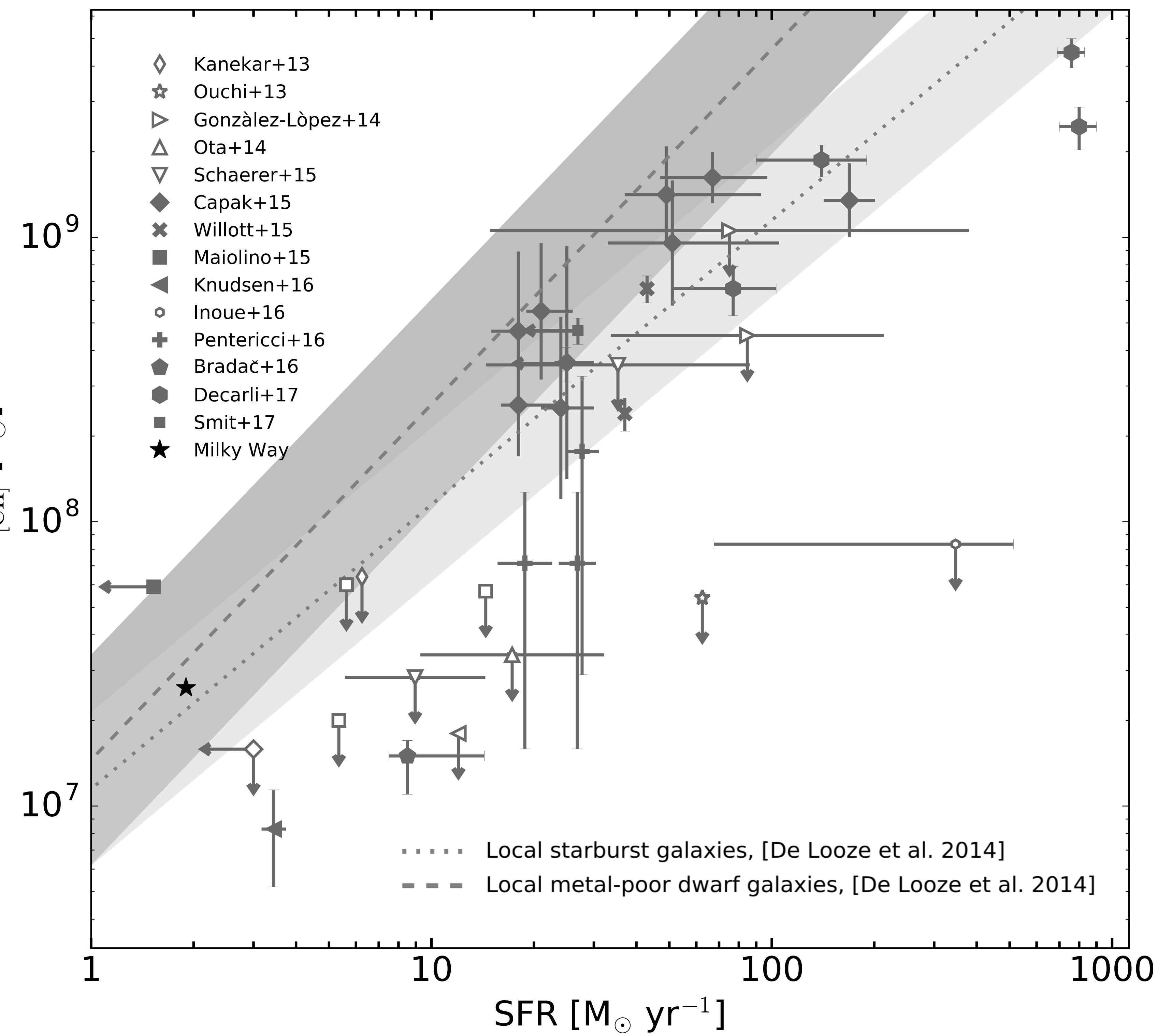
- [CII] emission higher from gas being heated by star formation



[Olsen et al. 2015]

[CII]-SFR relation

- at high redshift (?)



Both detections and non-detections!

[CII]-SFR relation

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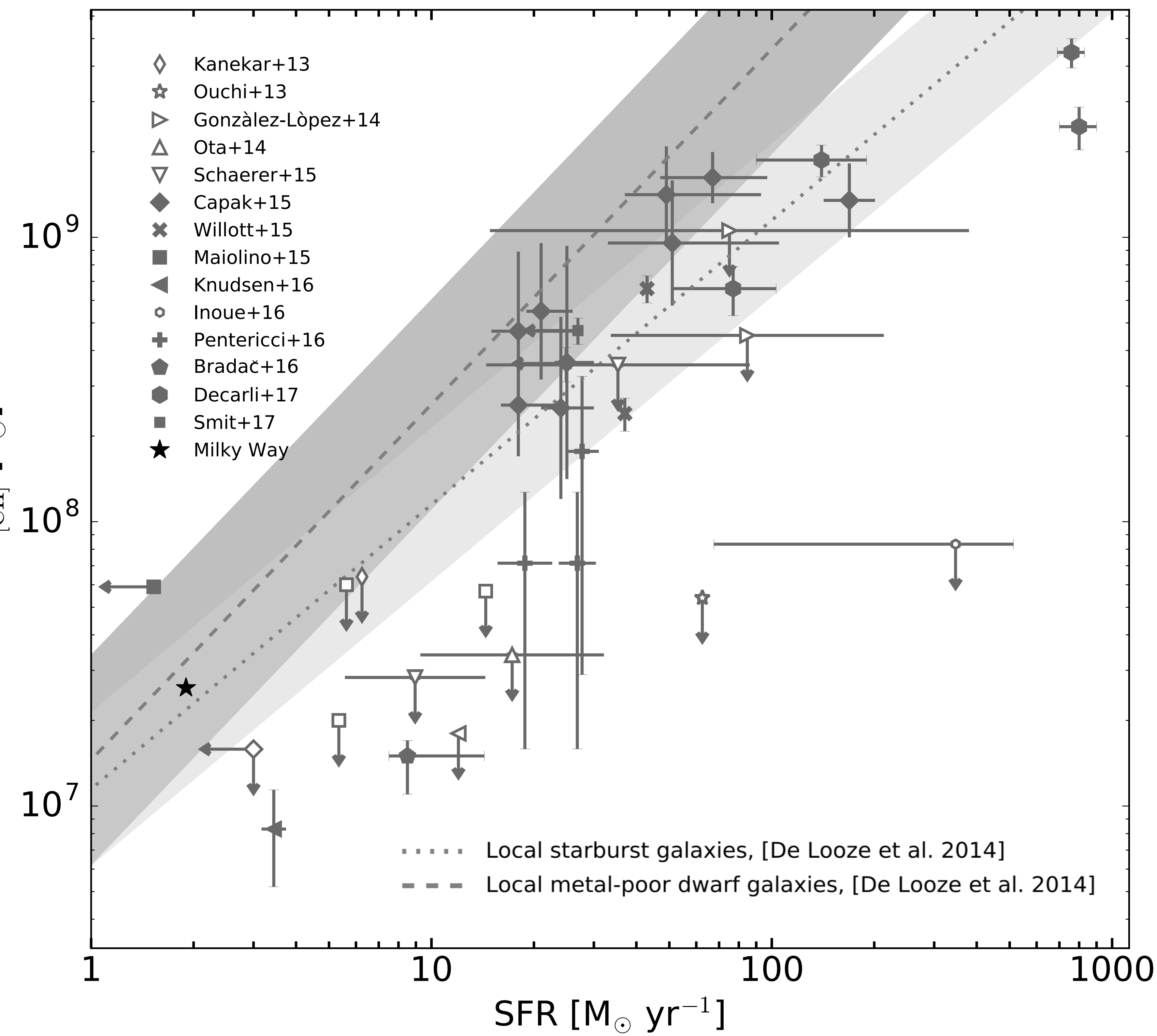


Both detections and non-detections!

- low metallicity (Z)?
- disrupted molecular clouds?
- high ionization parameter?

Observing the gas at high redshift

Questions that arise:

1. Why is there no strong [CII]-SFR relation?

2. How does *Z* affect [CII]?

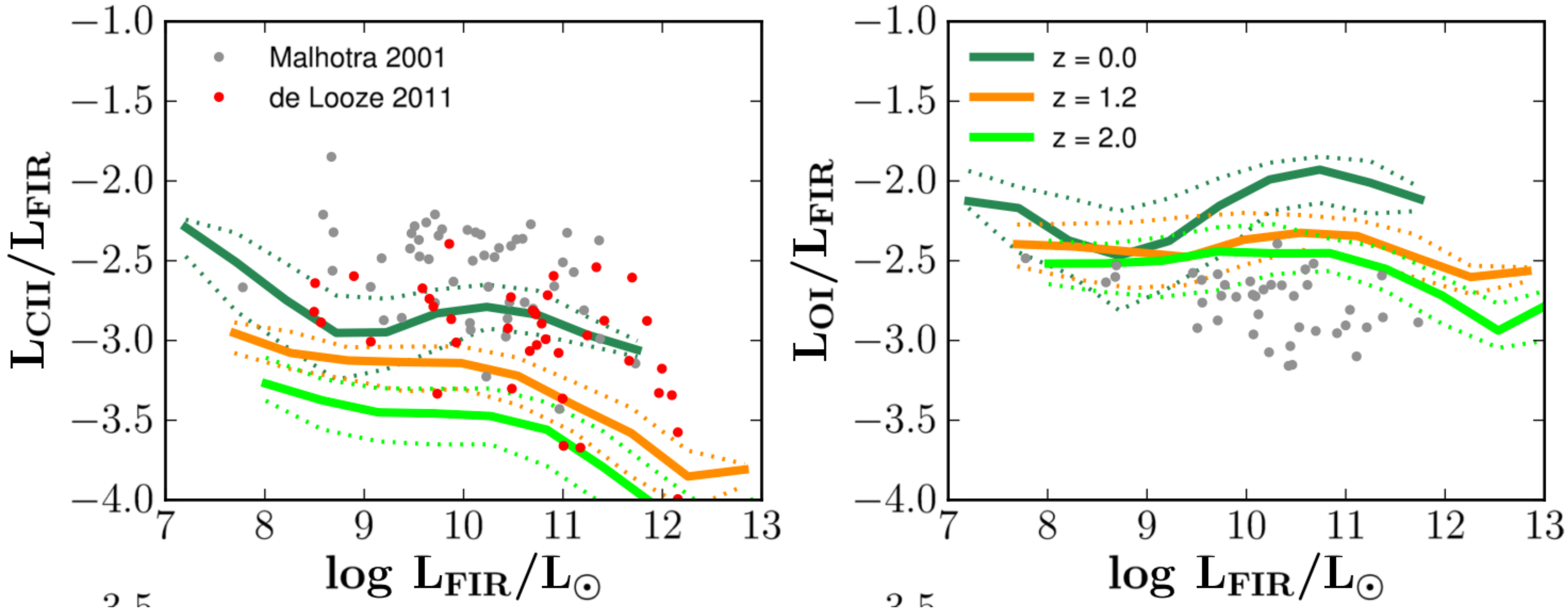
3. What is the origin of [CII]?

4. [OIII] or [OI] better SFR-tracers?

Simulating line emission

Simulating line emission

Previous work:



[Popping+14]

Simulating line emission

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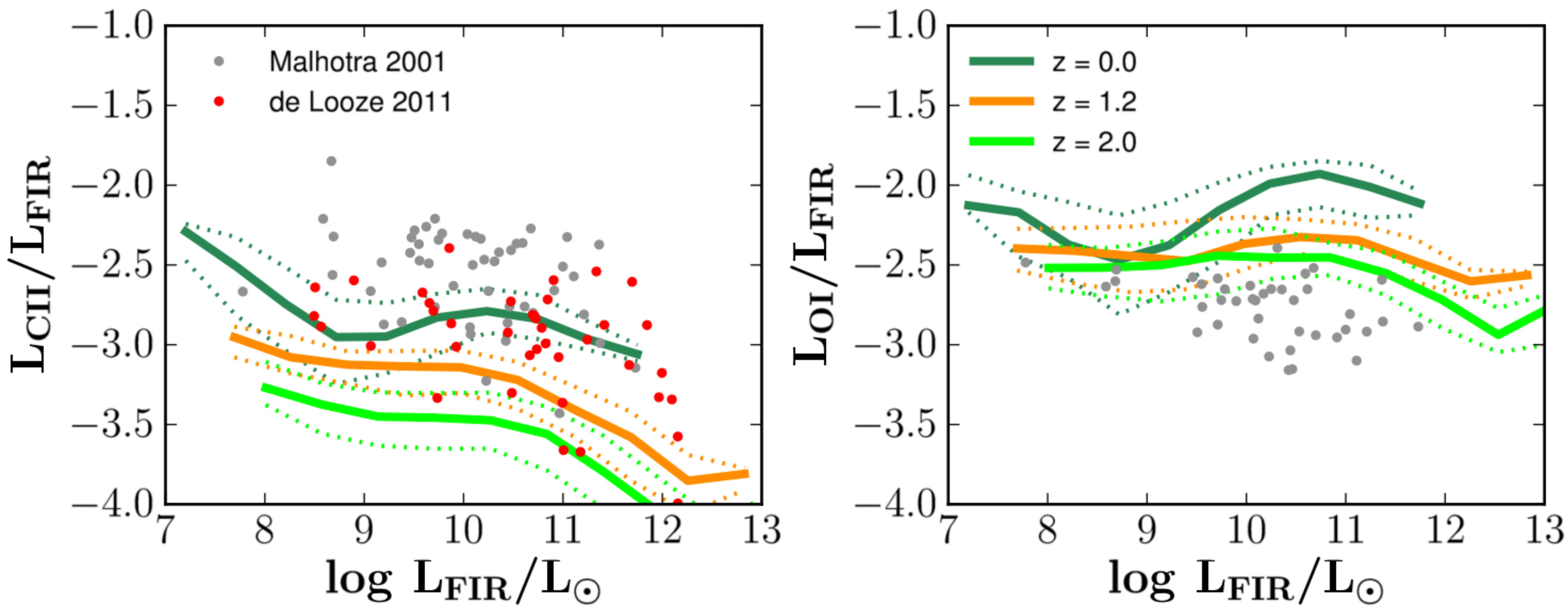

at higher z, $L_{[CII]}$ goes down, but $L_{[OI]}$ stays almost constant

[Popping+14]

Simulating line emission

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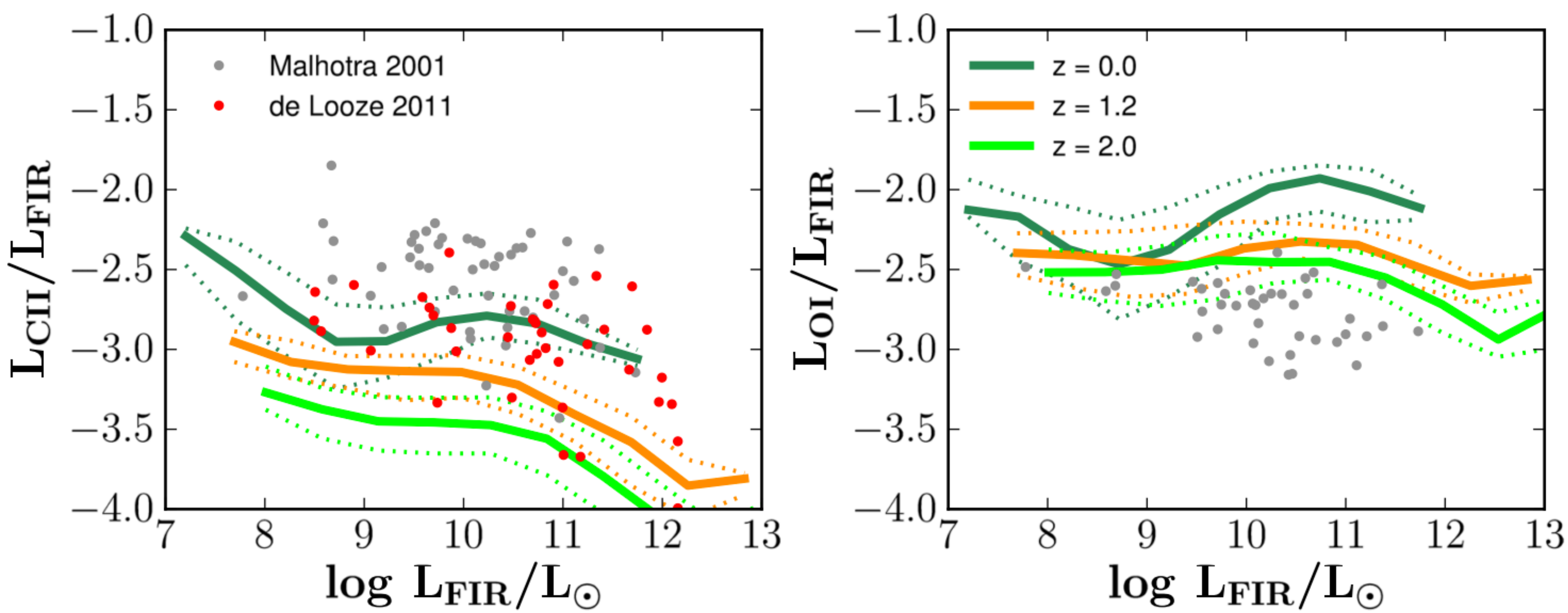


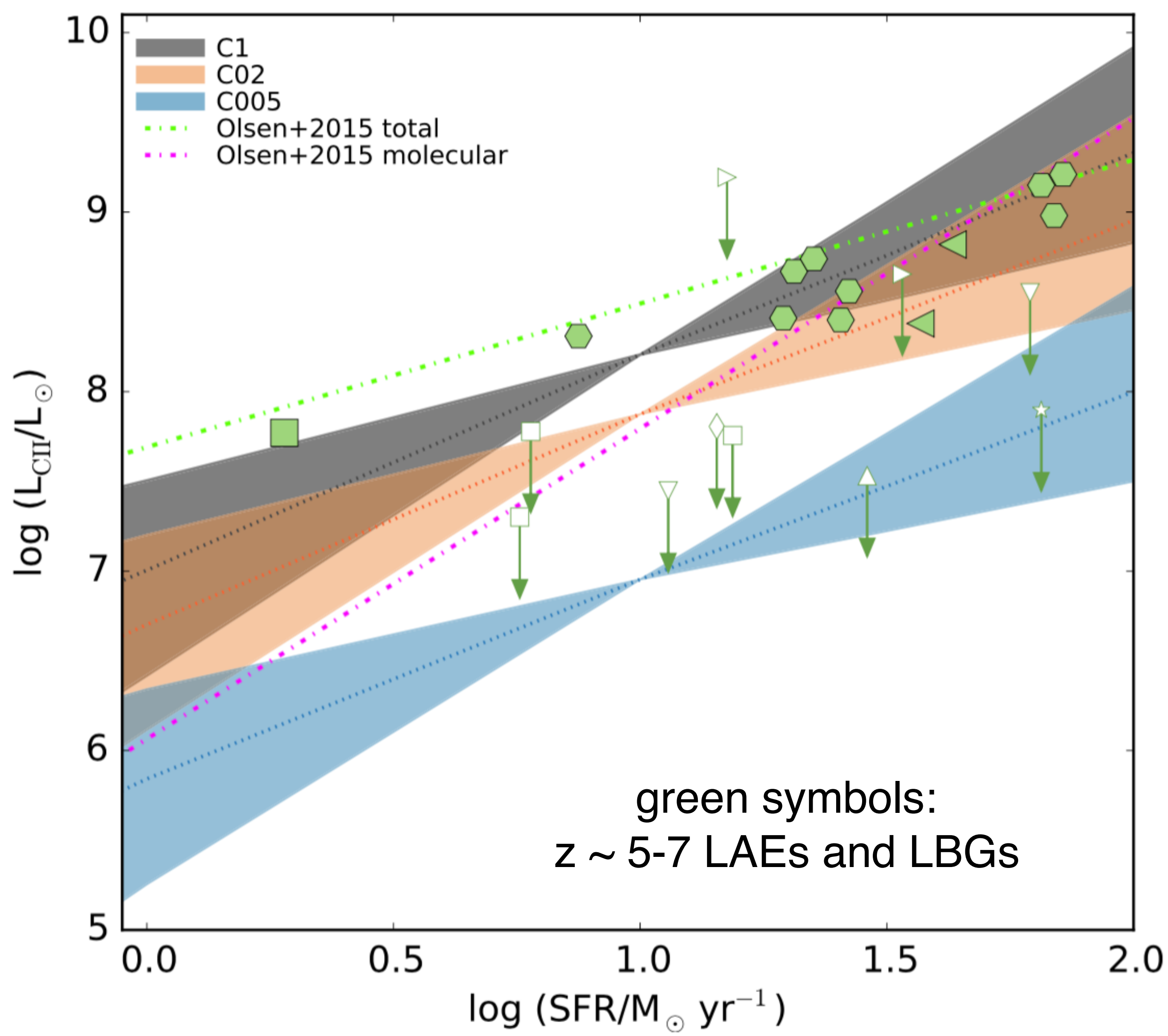
at higher z, $L_{[CII]}$ goes down, but $L_{[OI]}$ stays almost constant

- cold gas is distributed in exponential disks
- C^+ abundance set to scale with carbon abundance
- local FUV background field only
- no CRs nor turbulence

[Popping+14]

Simulating line emission

Previous work:

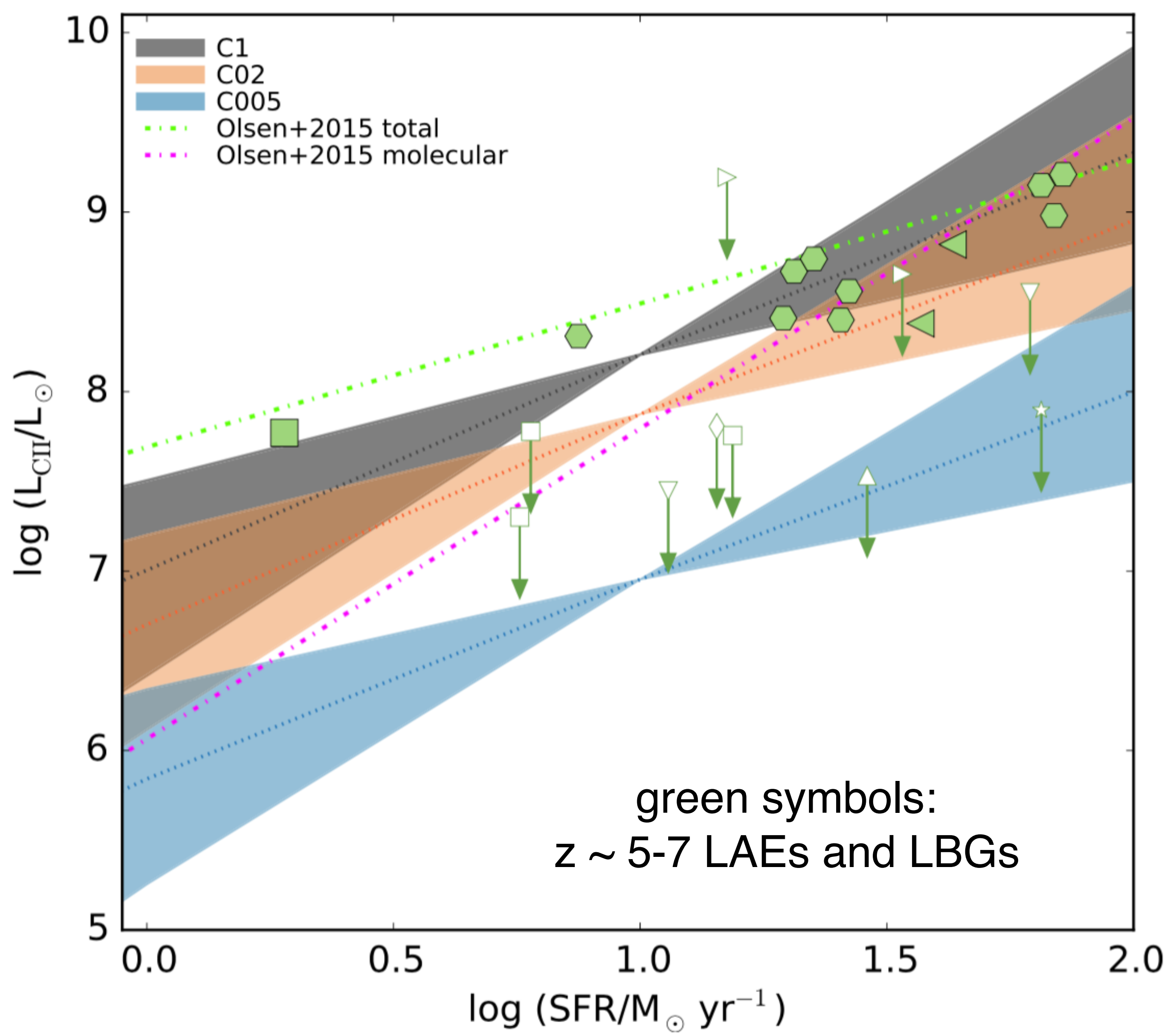


z ~ 7 galaxy: Strong increase in $L_{[CII]}$ with metallicity Z

[Vallini+15]

Simulating line emission

Previous work:



z ~ 7 galaxy: Strong increase in $L_{[CII]}$ with metallicity Z

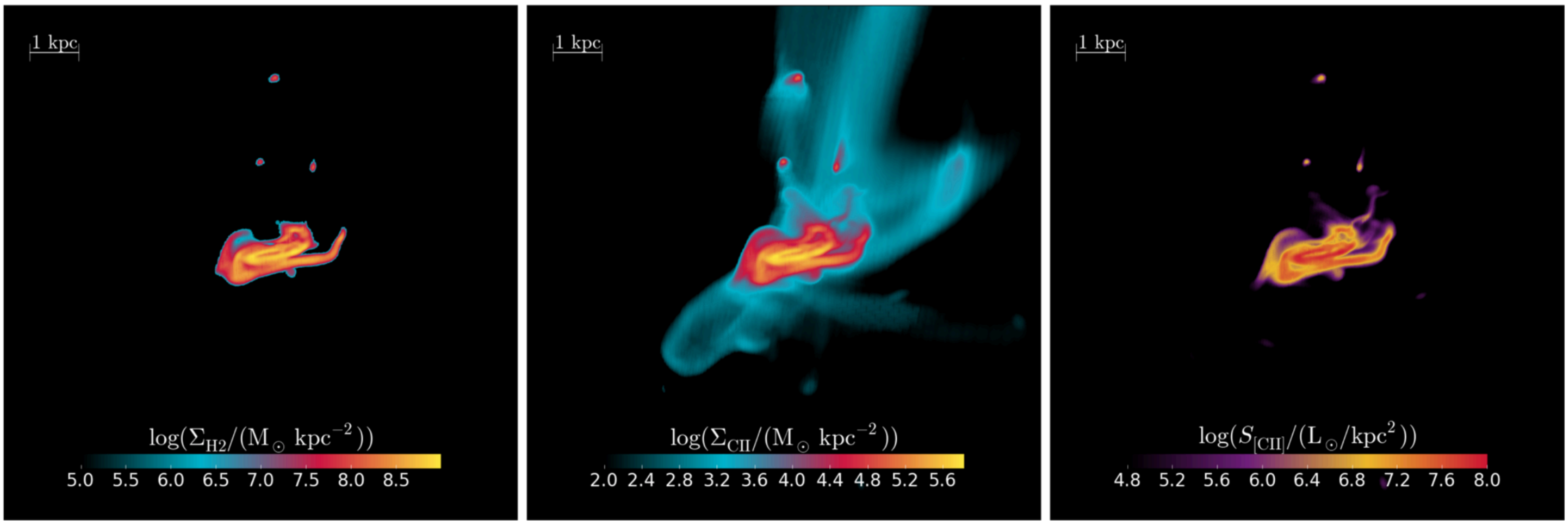
- metallicity is kept constant across the entire galaxy
- local UV radiation field scales with local SFR
- cosmological simulation, but no stellar feedback on gas

[Vallini+15]

Simulating line emission

Previous work:

[Pallottini+17]: an update to the Vallini+15 method, now with stellar feedback



z ~ 6 LBG: Much C^+ is transported out of the H_2 disk, but it does not radiate in [CII]

[Pallottini+17]

Simulating line emission

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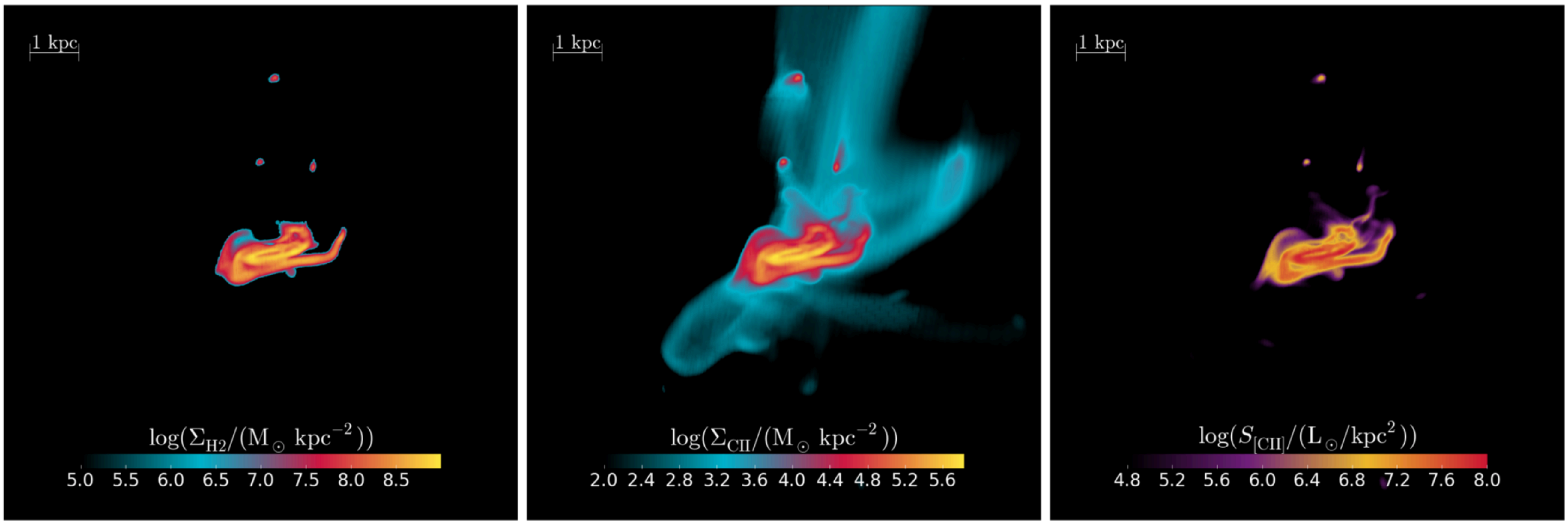
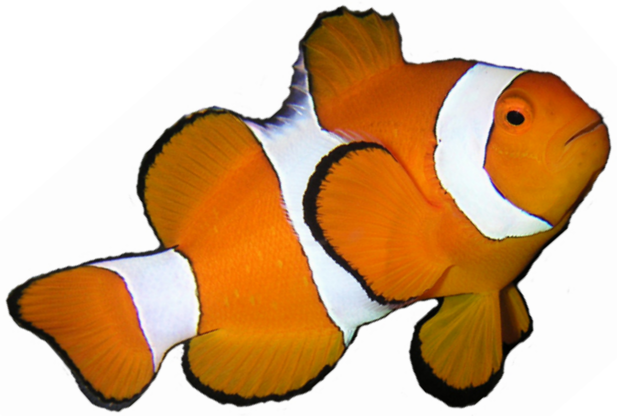


Much C^+ is transported out of the H_2 disk, but it does not radiate in [CII]

- variable metallicity, but still uniform UV background

[Pallottini+17]

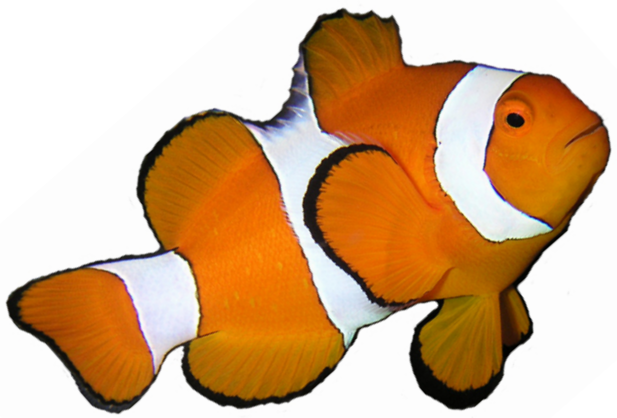


SÍGAME

(='follow me' in Spanish)

SImulator of GAlaxy Millimeter/submillimeter Emission

http://kpolsen.github.io/sigame/



SÍGAME

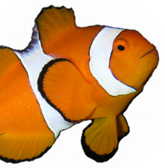
(='follow me' in Spanish)

SImulator of GAlaxy Millimeter/submillimeter Emission

Aim:

- derive line emission from all ISM phases simultaneously
- cosmological simulations with self-consistent Z
- reliable local pressure and radiation field strength
- full chemistry
- control over the dust!

http://kpolsen.github.io/sigame/



SImulator of GAlaxy Millimeter/submillimeter Emission

Current team:

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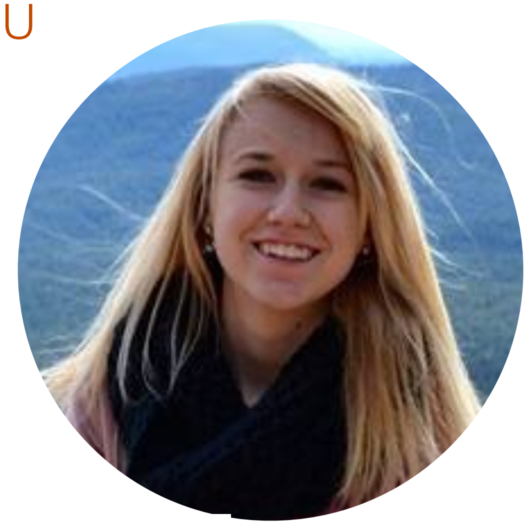
Dept of Physics and Astronomy, UCL, UK

Stephanie Stawinski
SESE, ASU



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SESE, ASU

Lily Whitler
SESE, ASU

Robert Thompson
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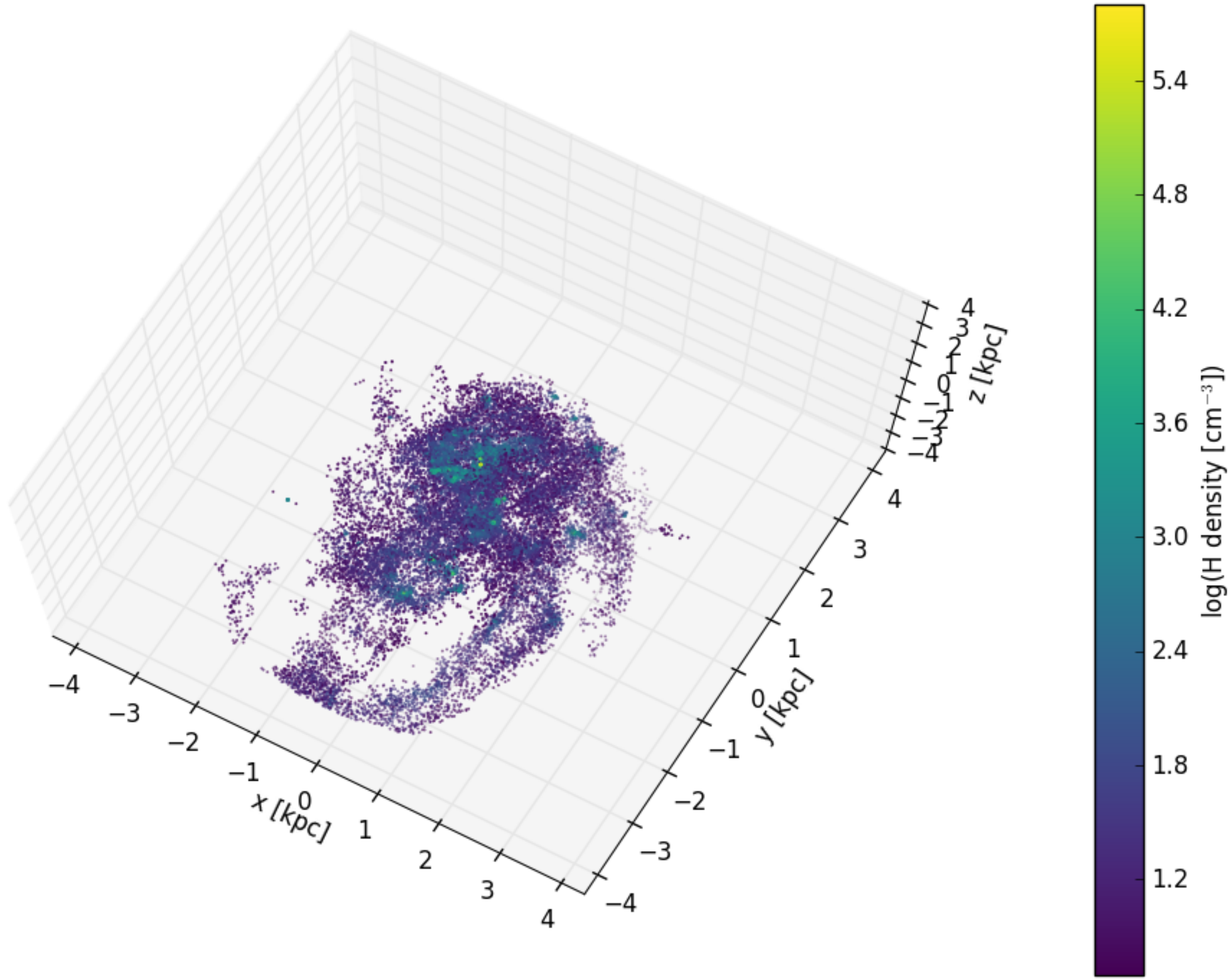
Desika Narayanan
Haverford College, PA, US

Romeel Davé
University of Western Cape, South Africa

Previous team members: Christian Brinch, Jesper Rasmussen, Jesper Sommer-Larsen, Sune Toft, Andrew Zirm

Key steps

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



Key steps

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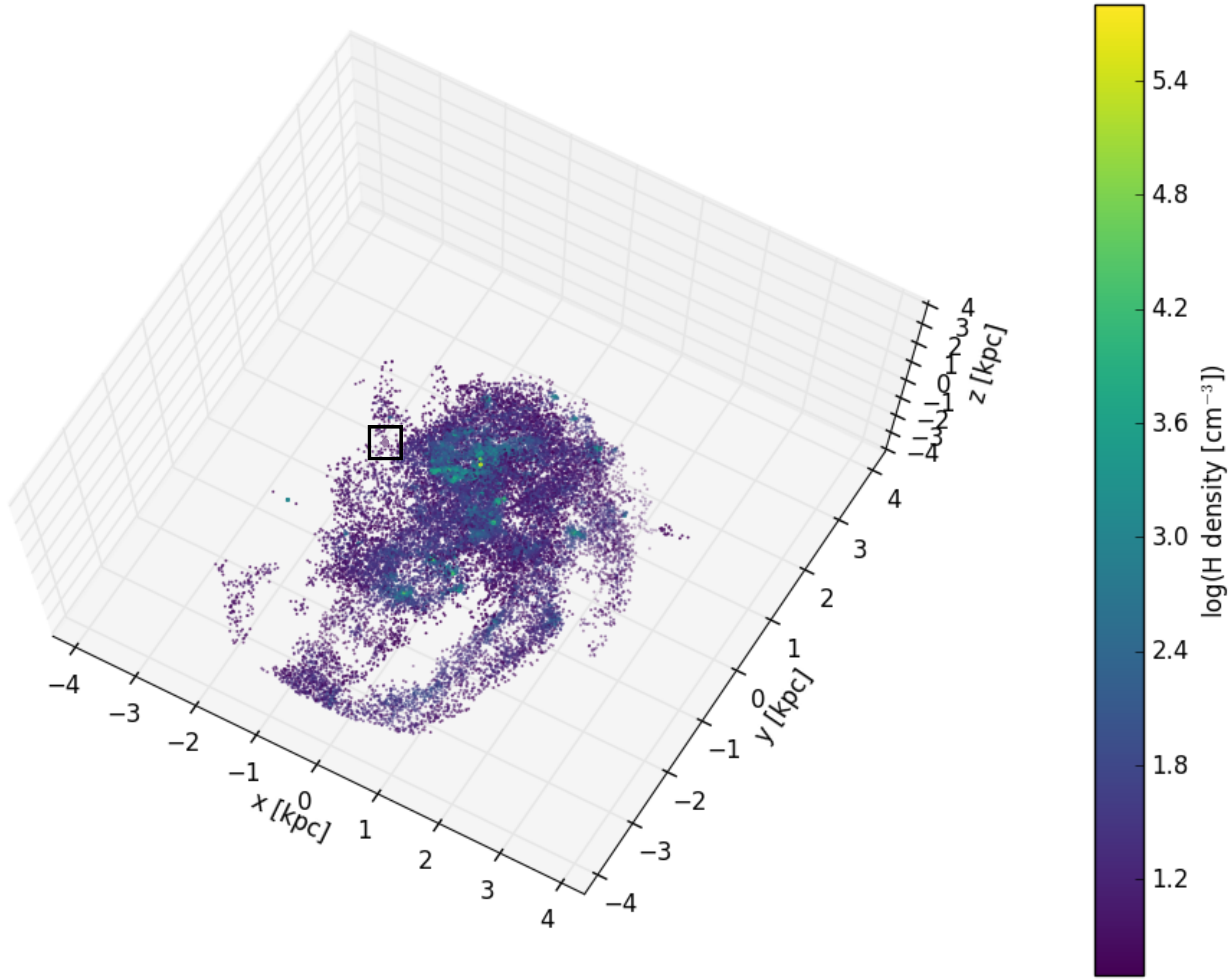

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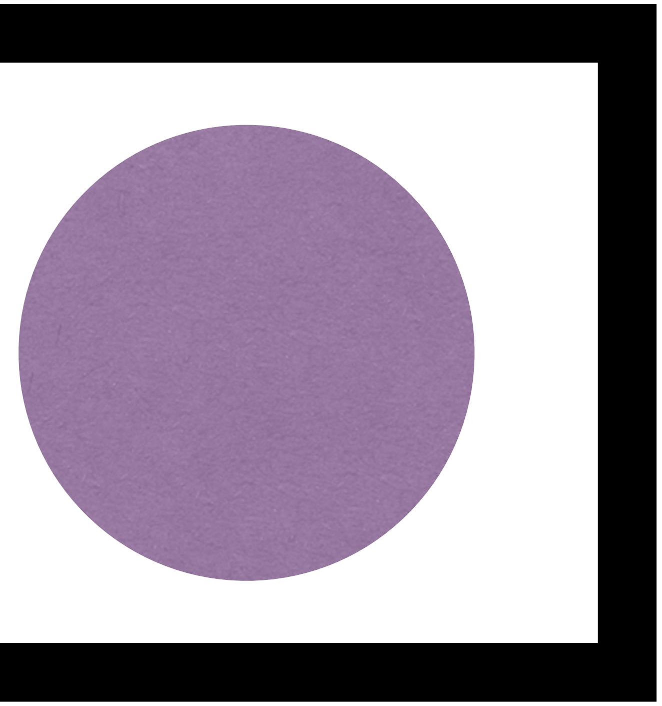

Key steps

Step 1:
Derive "large-scale" properties

Fluid element (FE):
[r, v, m_{FE}, T_{FE}, Z_{FE}, h, f_{H2}]

Derived properties:
[G_0, P_{ext}]

Key steps

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$m_{diffuse} = (1-f_{H2})m_{FE}$
$R_{diffuse} = h$
$n_{diffuse} = m_{diffuse}/(4/3\pi h^3)$
$T_{diffuse} = T_{FE}$

$m_{dense} = f_{H2}m_{FE}$
$R_{GMC} \propto (m_{GMC})^{1/2}(P_{ext})^{-1/4}$
$\sigma_{v,GMC} \propto (m_{GMC})^{1/2}(P_{ext})^{1/4}$
$n_{GMC}(R) \propto R^{-1}$

Step 2:
Divide into dense and diffuse gas

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Key steps

Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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cloudy model output

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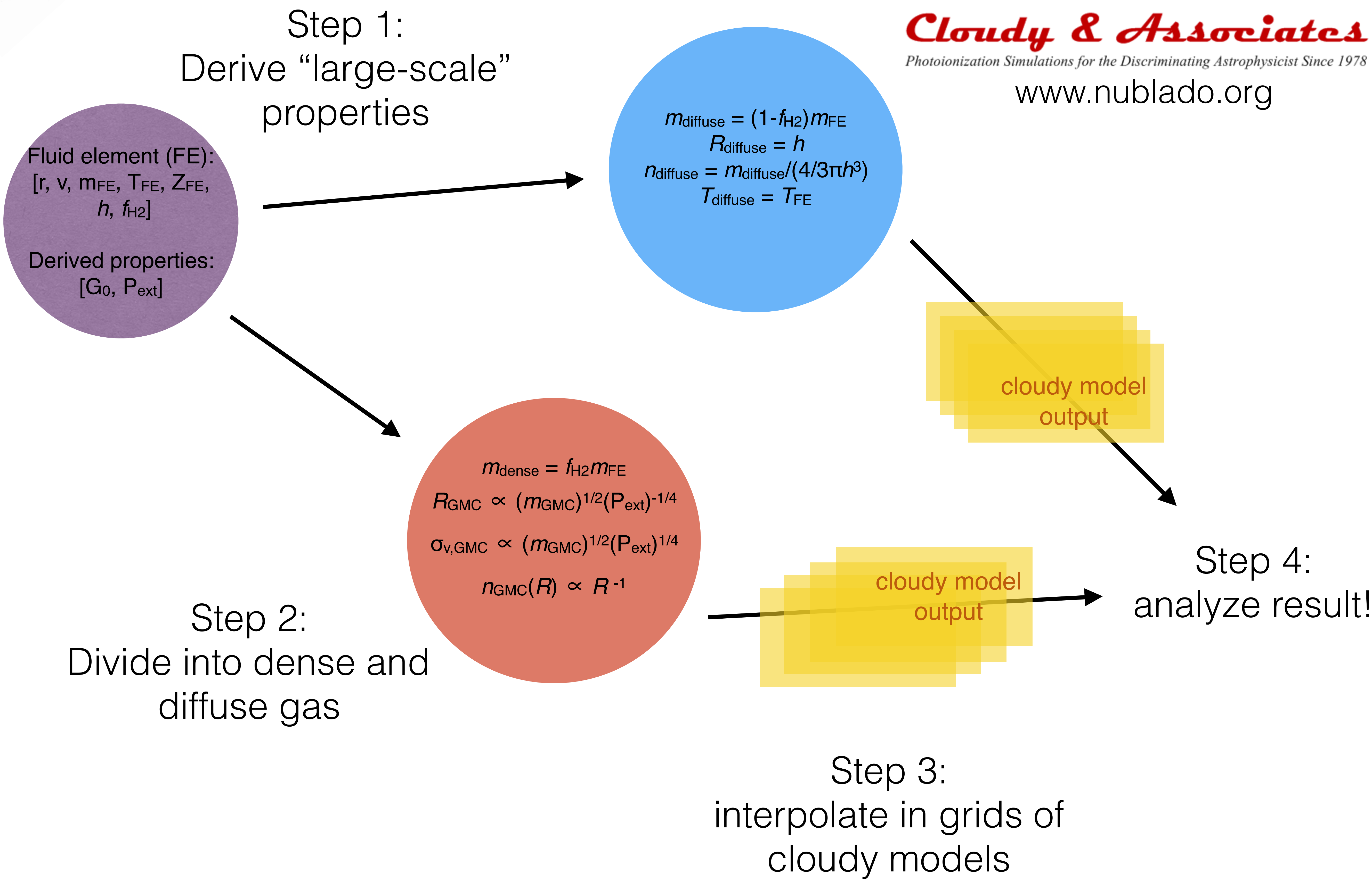
cloudy model output

Step 2:
Divide into dense and diffuse gas

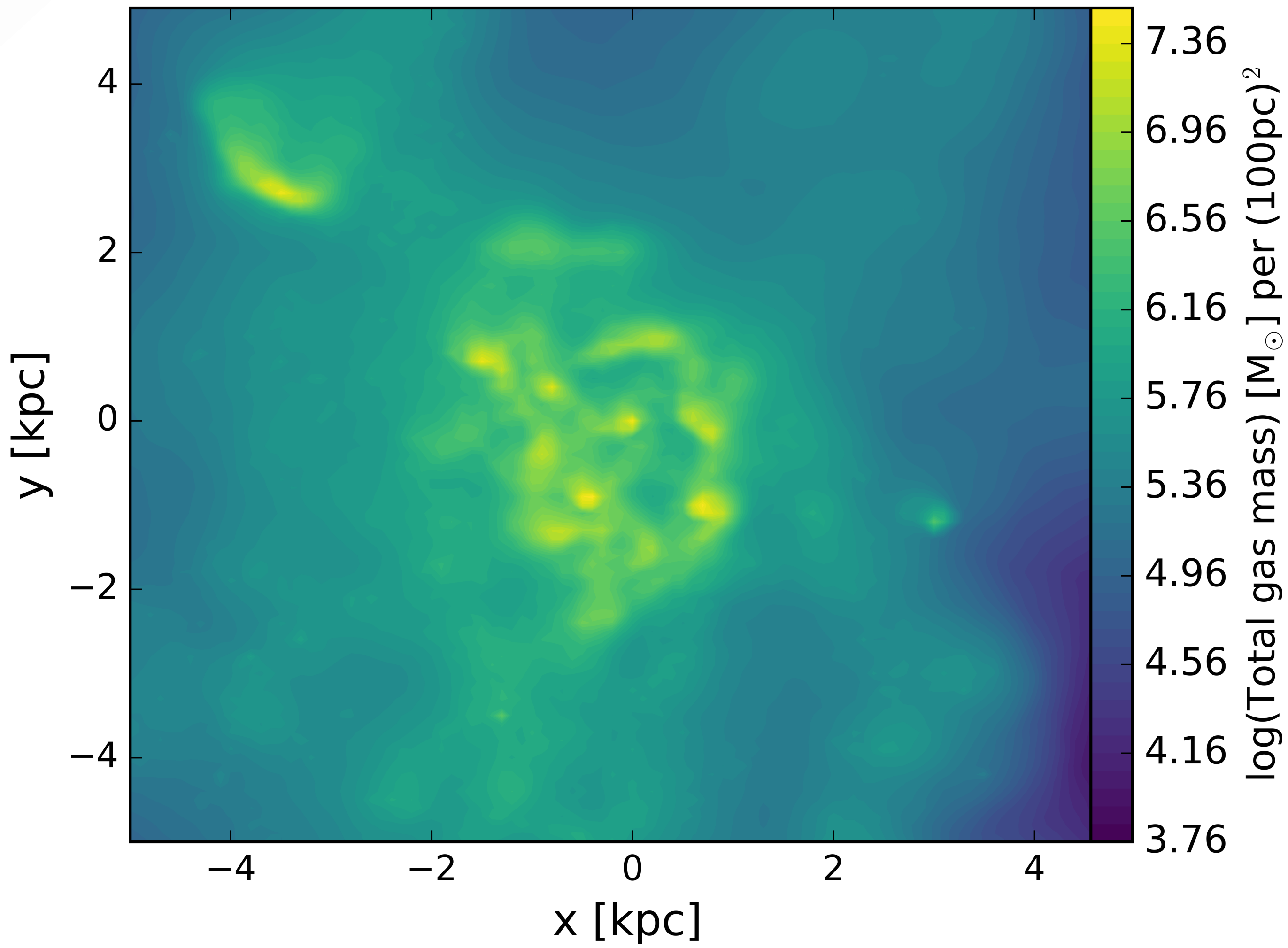
Step 3:
interpolate in grids of cloudy models

Key steps

SÍGAME



Deriving local gas properties



Gas map

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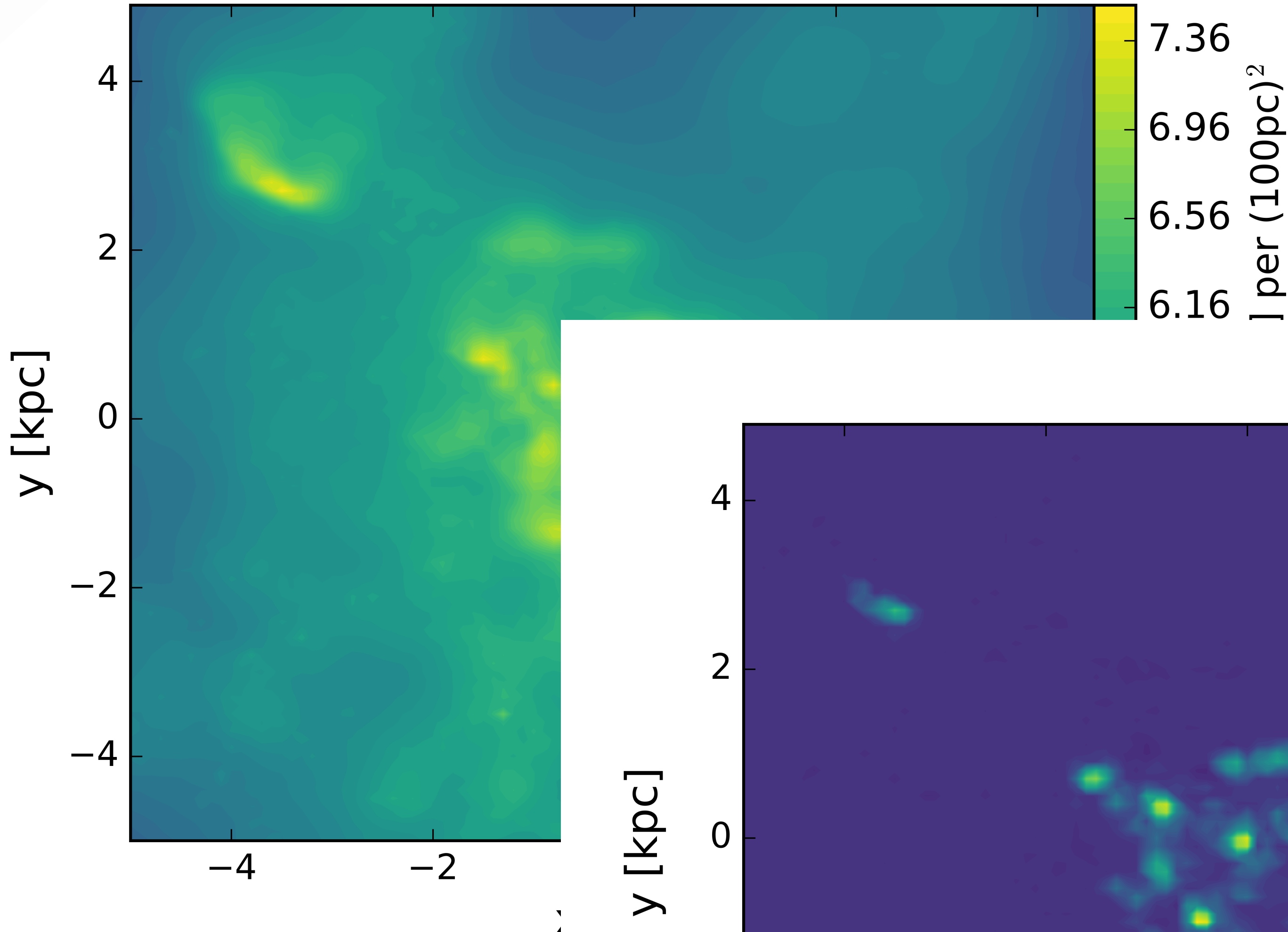
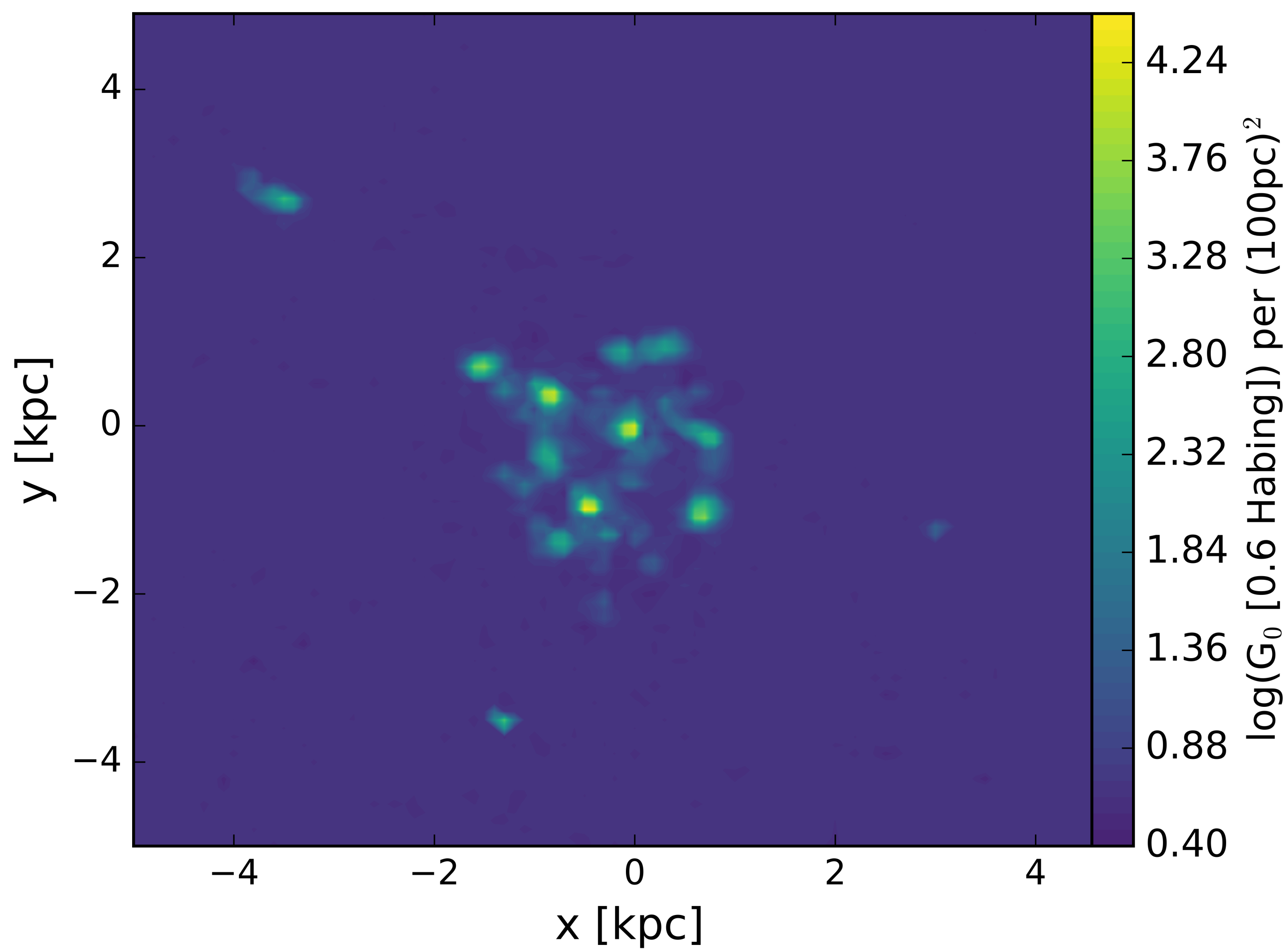
Deriving local gas properties



Gas map

G_0 (FUV radiation) map with starburst99

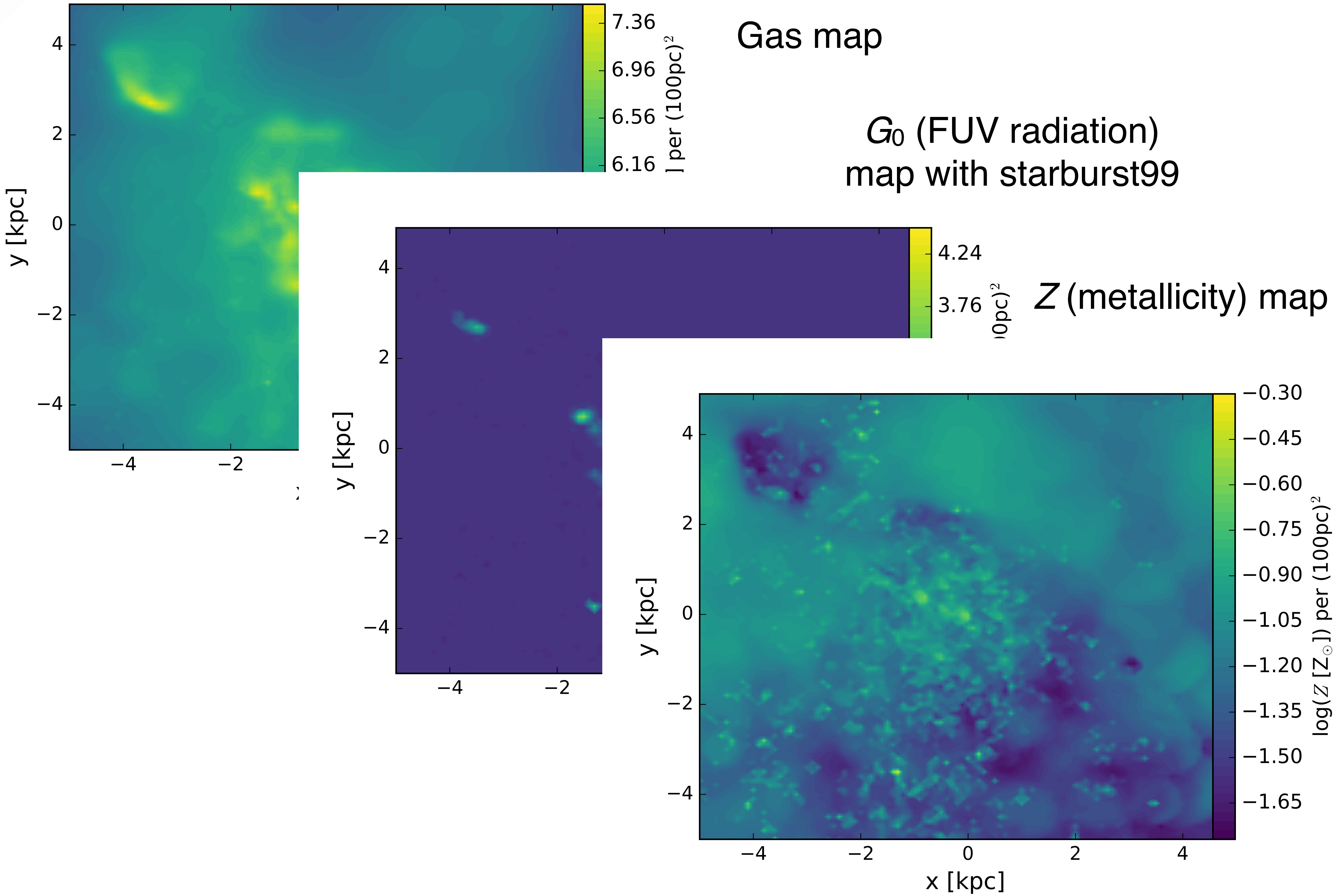


Deriving local gas properties

Gas map

G_0 (FUV radiation) map with starburst99

Z (metallicity) map



SÍGAME

Definition of ISM phases

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

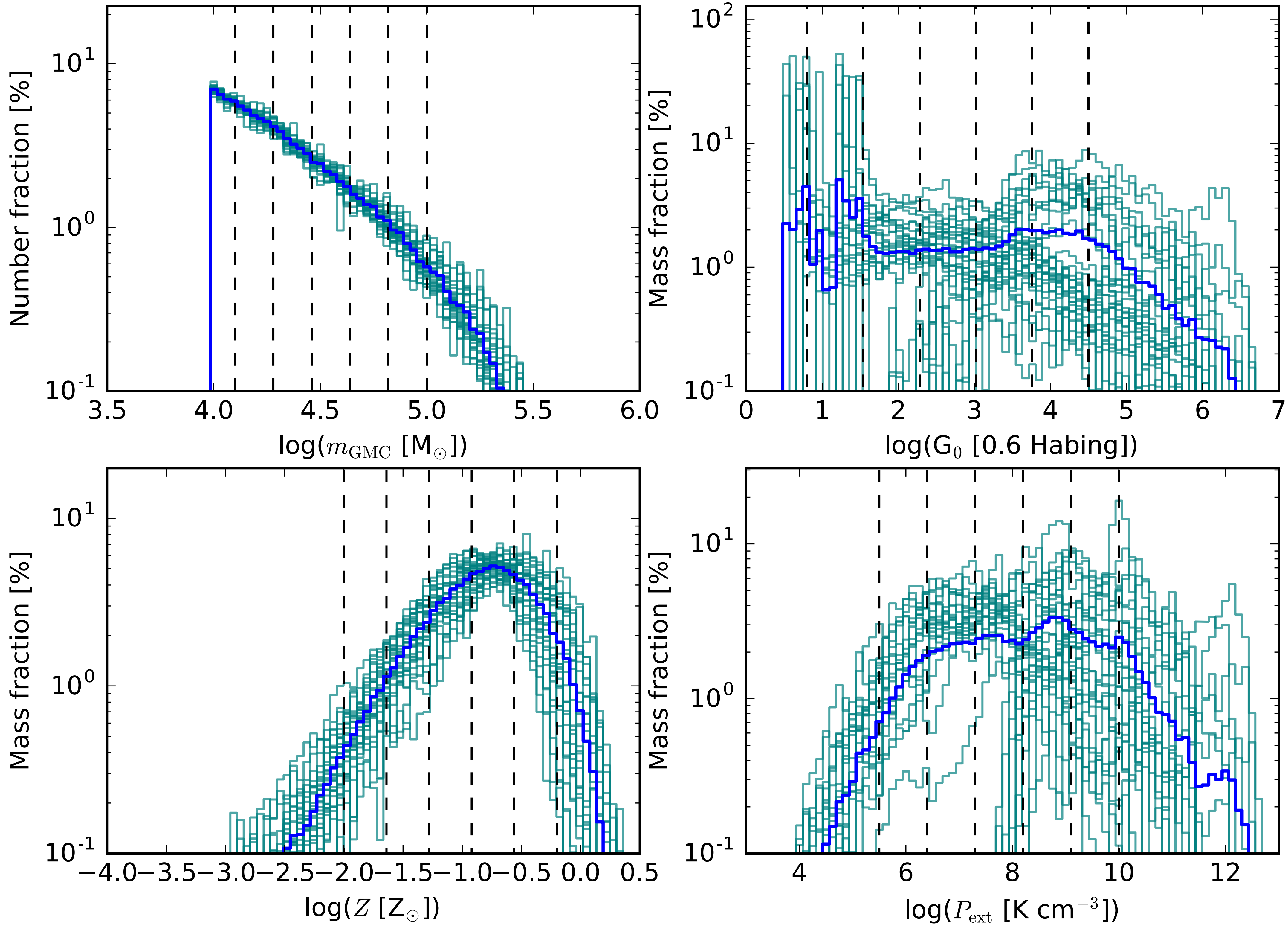
dense gas → **GMCs** (Giant Molecular Clouds): mostly molecular (but can contain partly ionized PDRs)

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

Cloudy models

Illustrating the GMC model grid



SÍGAME

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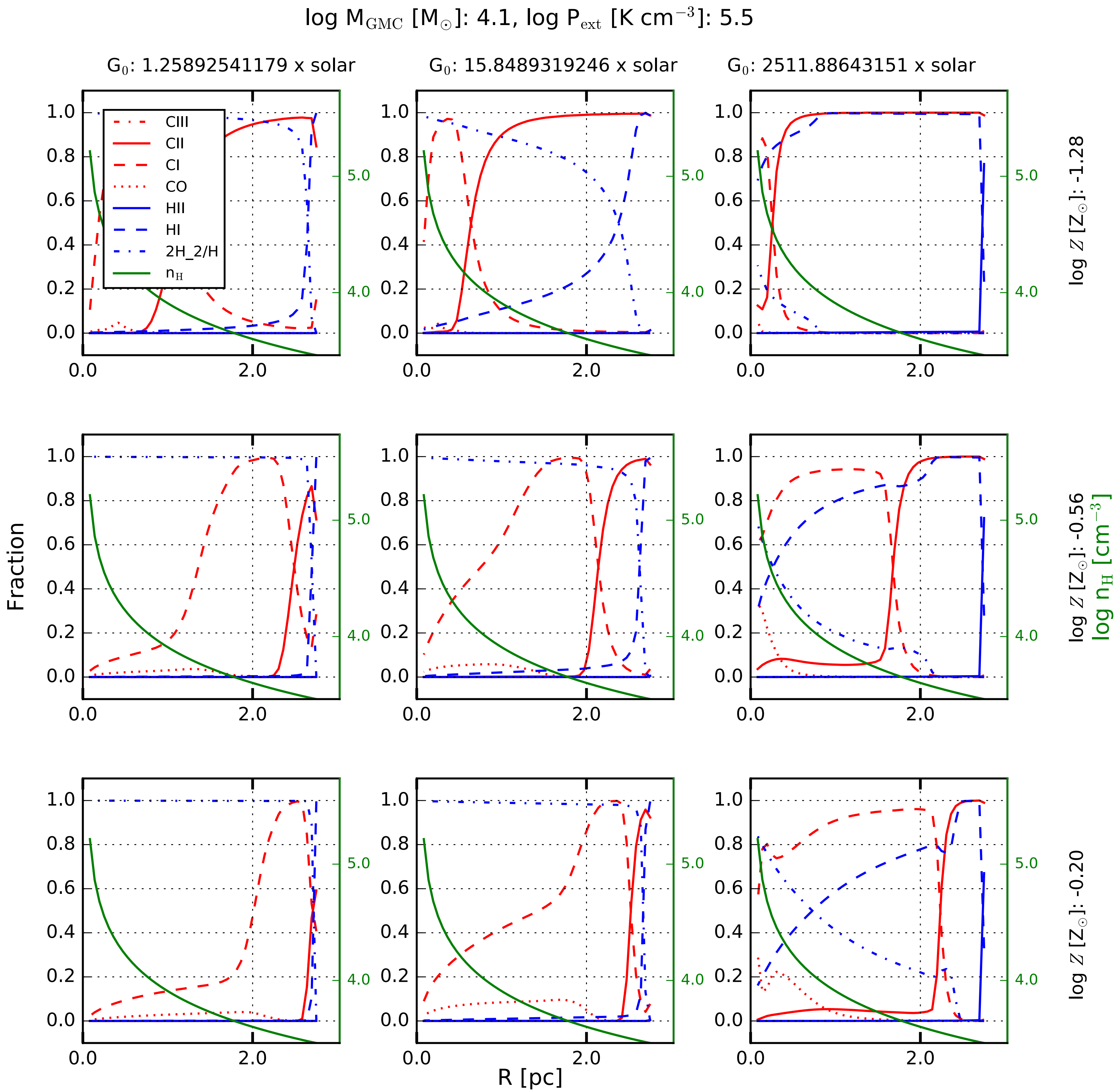
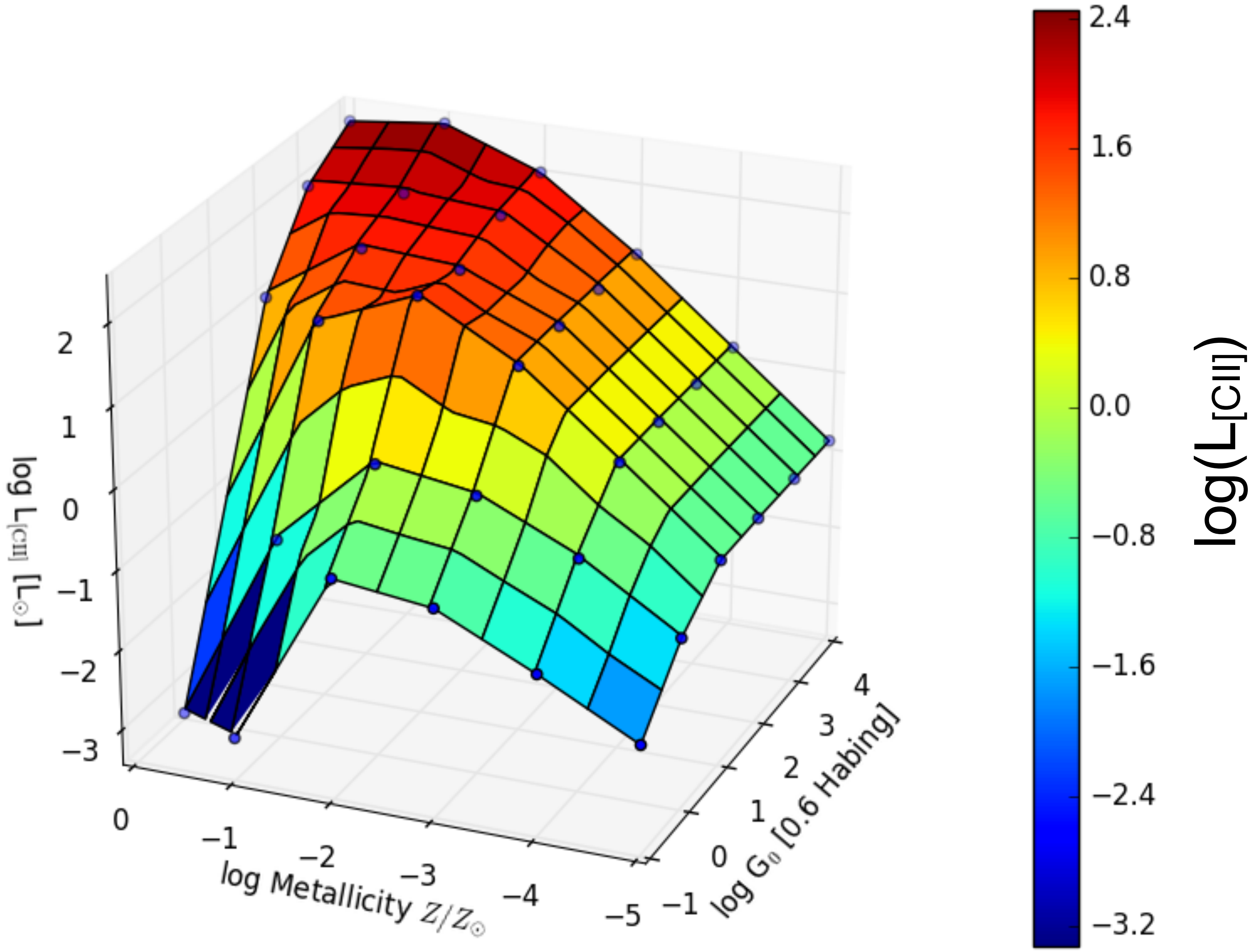


Cloudy models

Illustrating the GMC model grid



Work by Luis N Rios

Observing the gas at high redshift

Questions that arise:

1. Why is there no strong [CII]-SFR relation?

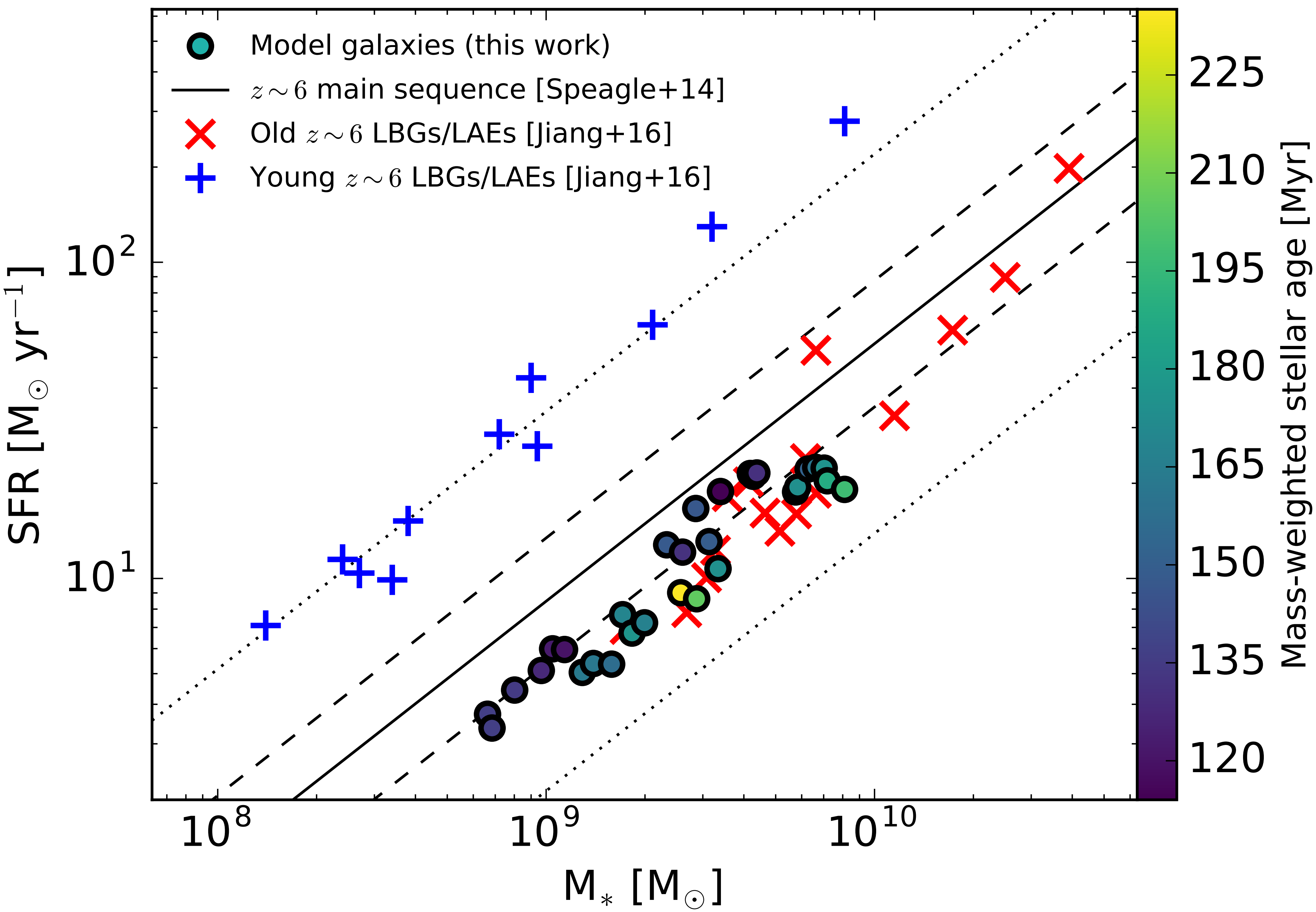
2. What is the origin of [CII]?

3. How does metallicity, Z, affect [CII]?

4. [OIII] or [OI] better SFR-tracers?

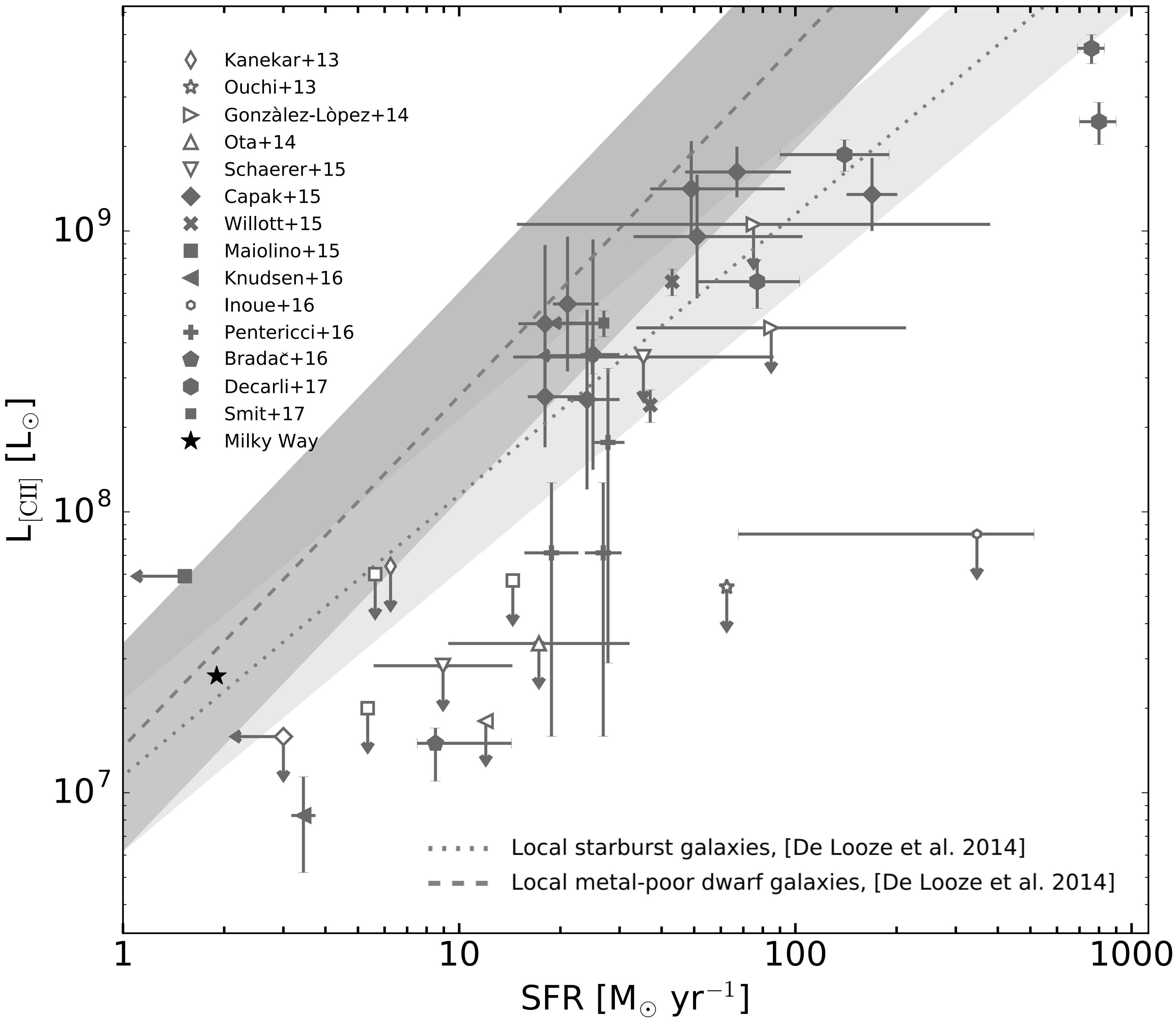
Model galaxy sample

30 star-forming galaxies at 5.75 < z < 6.25 from GIZMO/MUFASA suite



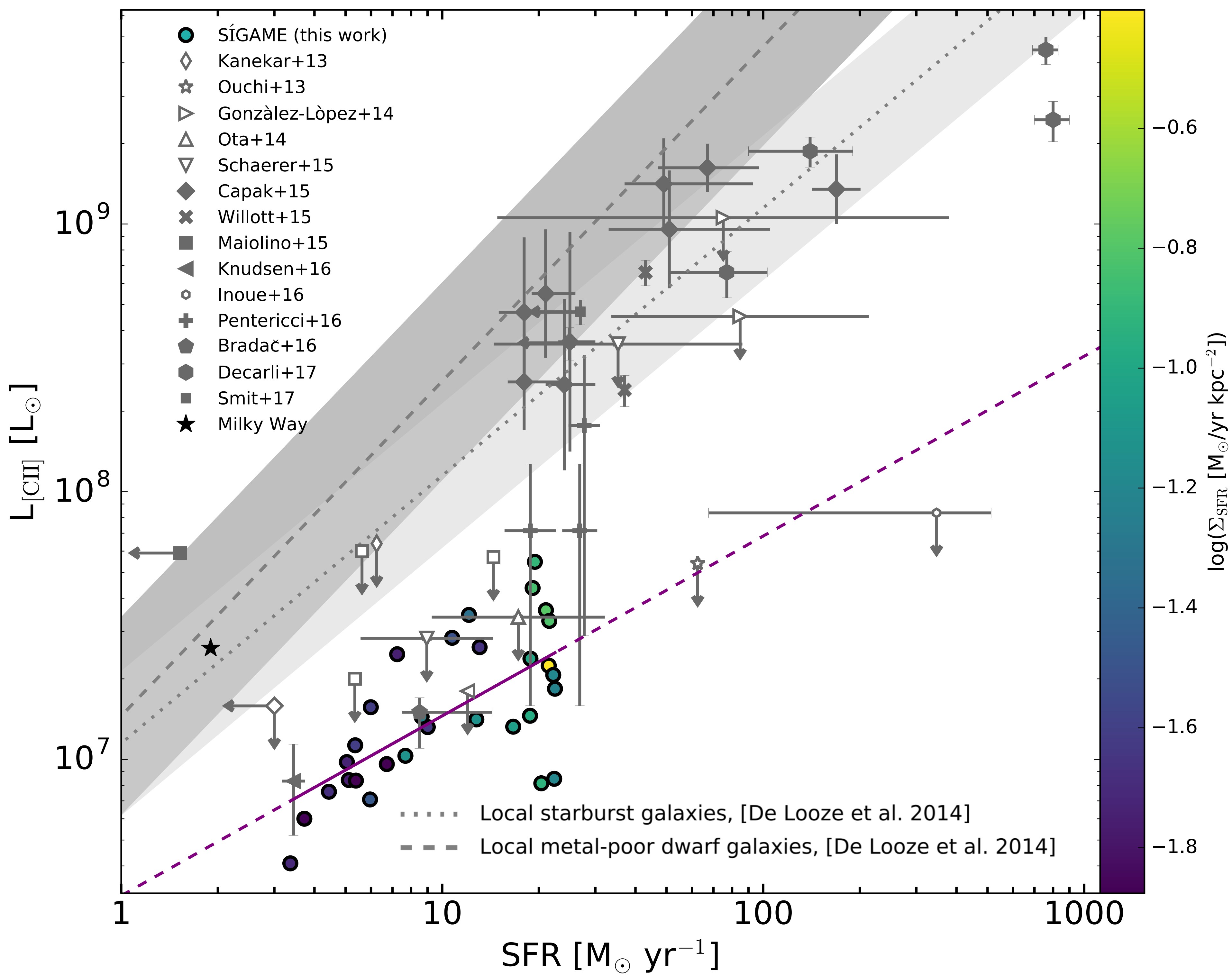
1: The [CII]-SFR relation

Observed galaxies, detected and non-detected:



1: The [CII]-SFR relation

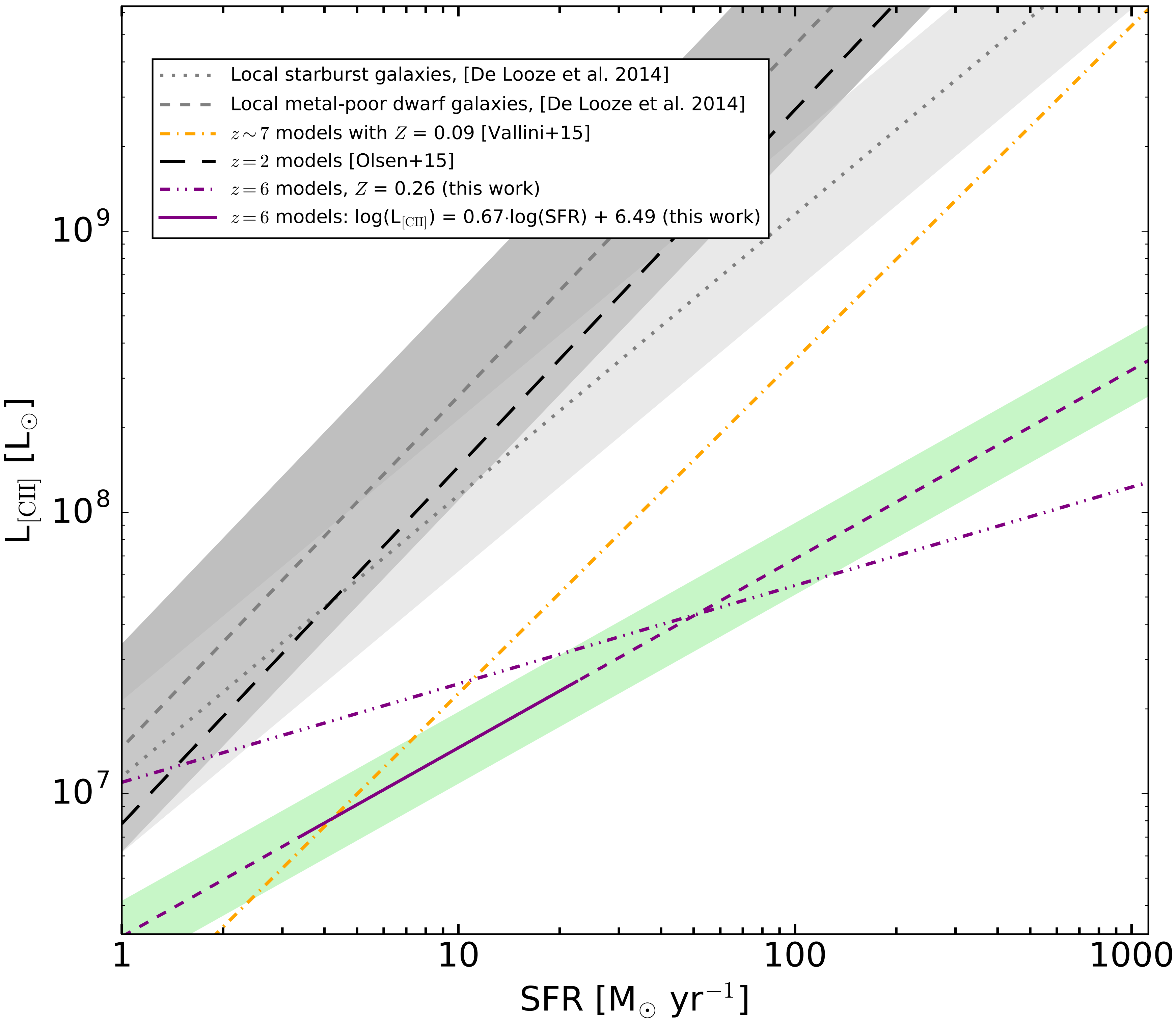
Observed galaxies + model results:



[Olsen+17 submitted]

1: The [CII]-SFR relation

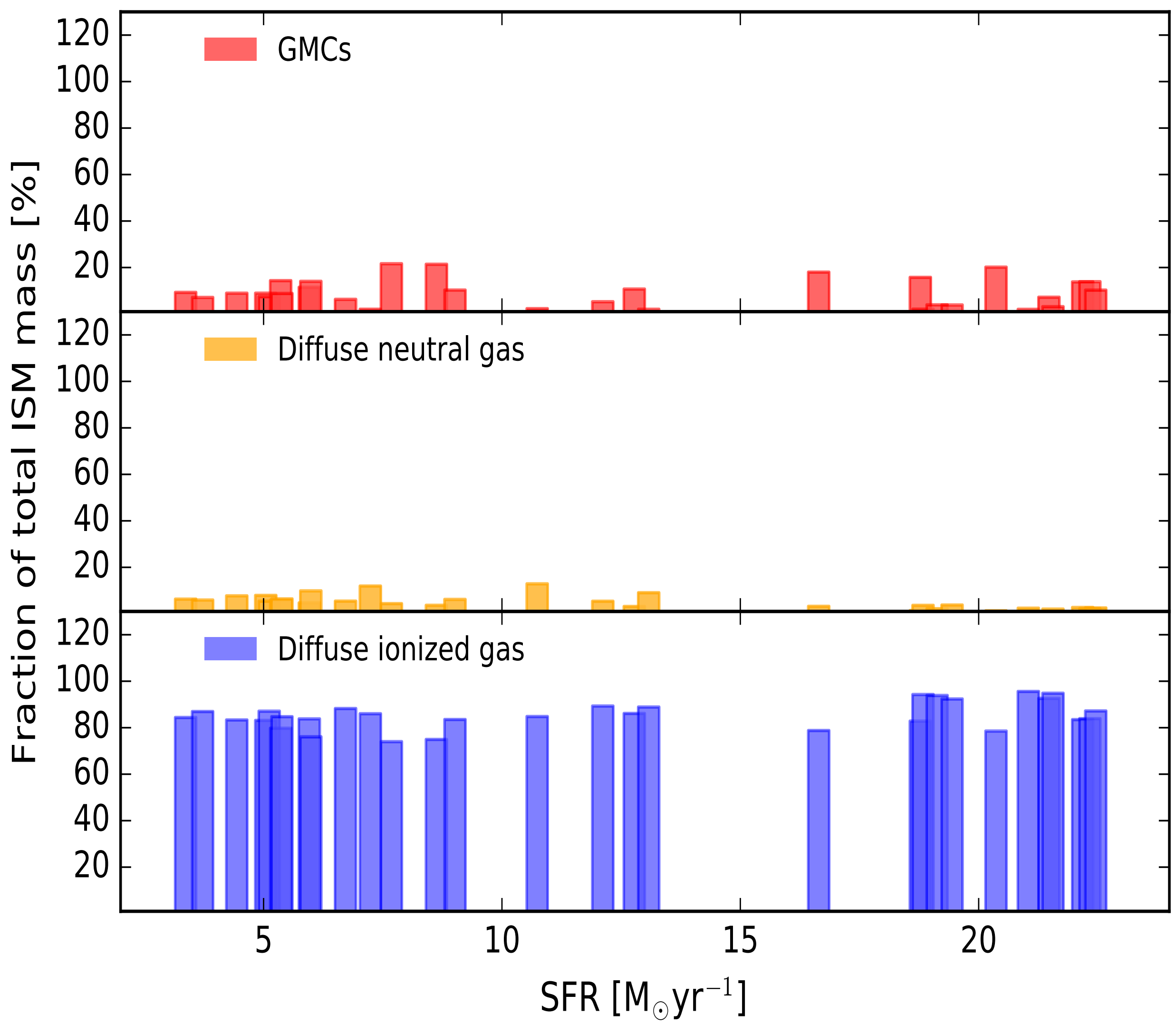
Comparing models:

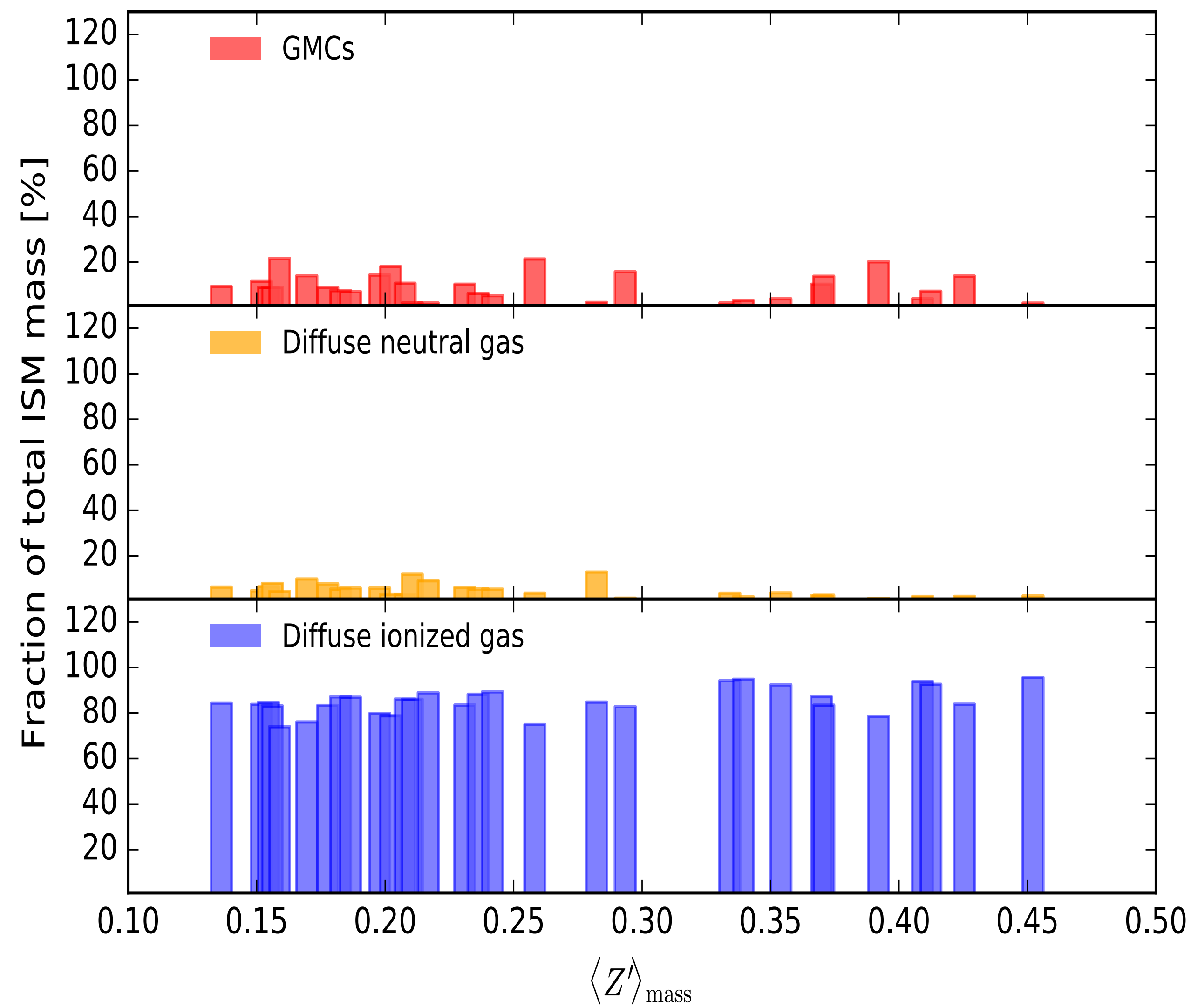


[Olsen+17 submitted]

2: Origin of [CII]

First, what does the ISM consist of at z ~ 6?

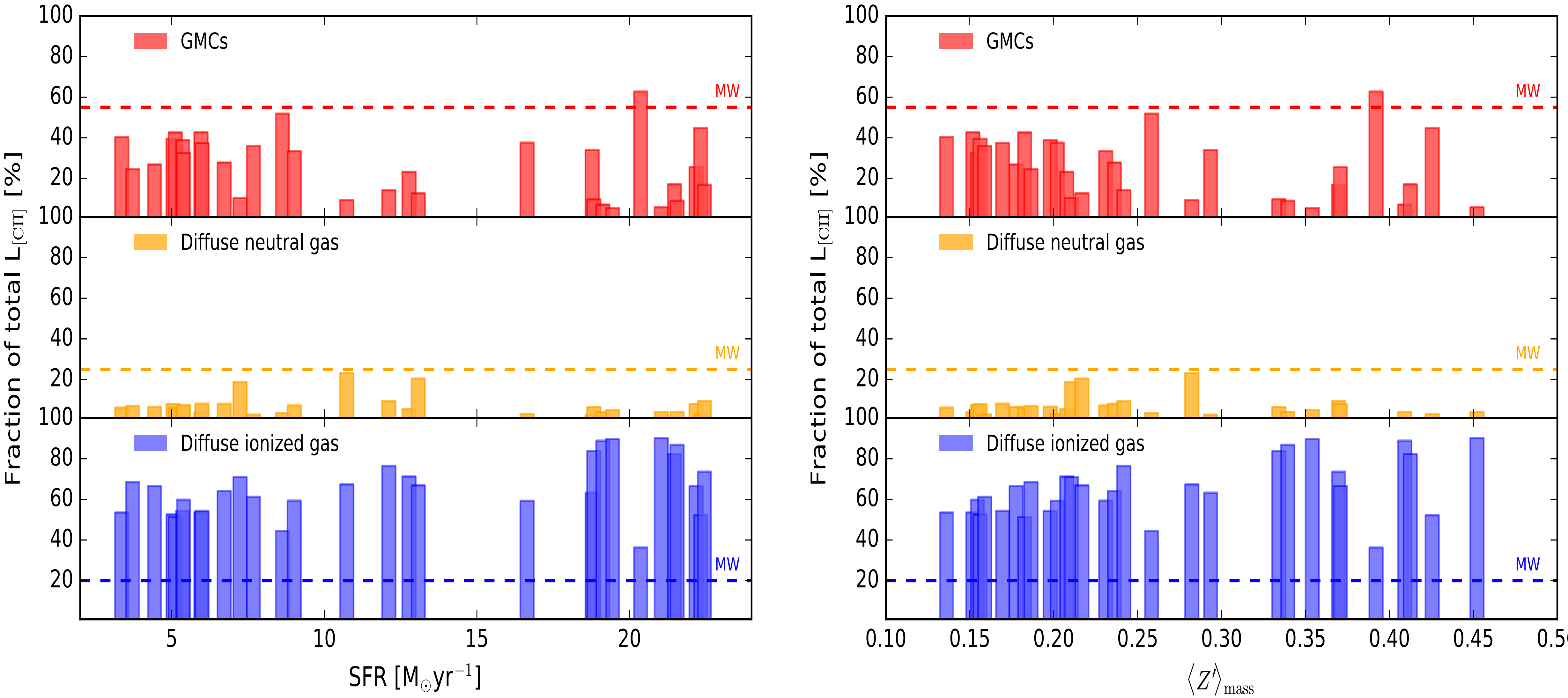




[Olsen+17 submitted]

2: Origin of [CII]

Second, where does the [CII] come from?

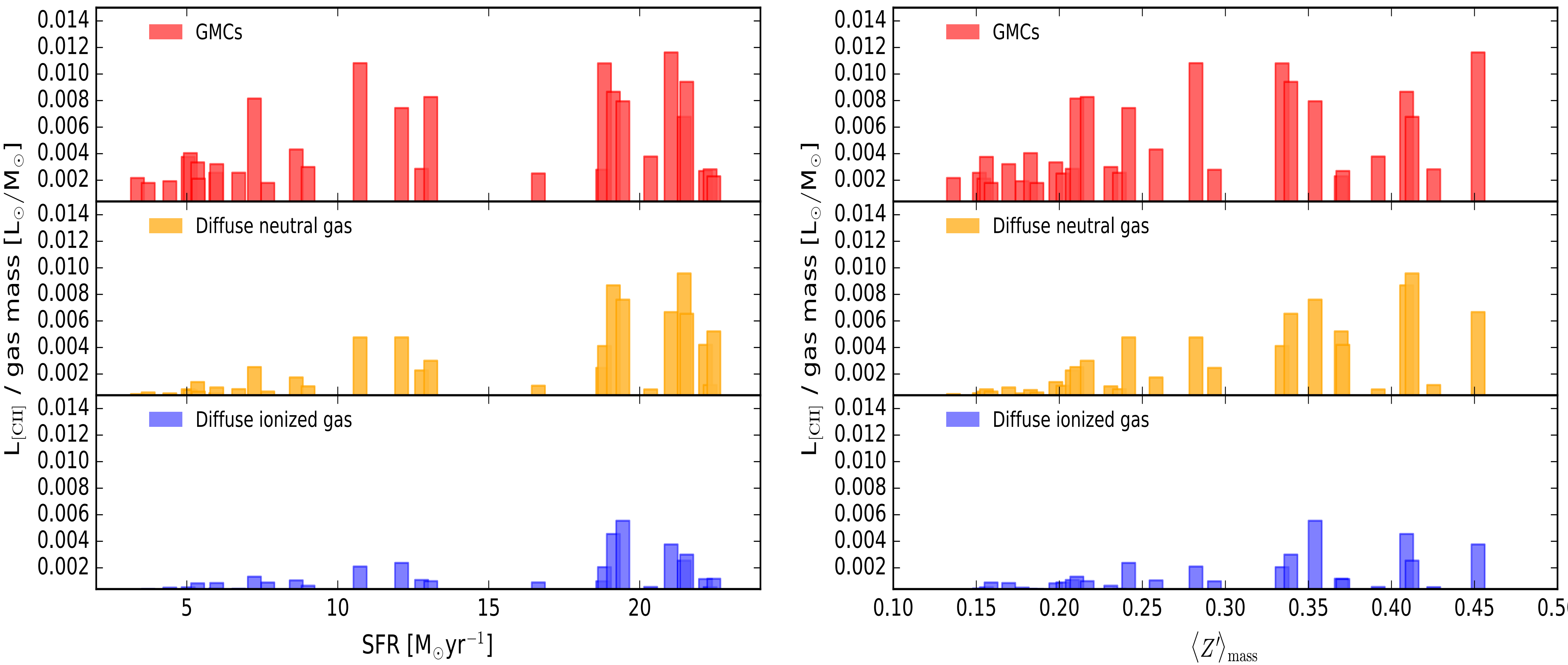


mass fraction are similar, but [CII] contributions from each ISM phase is not!

[Olsen+17 submitted]

2: Origin of [CII]

What is the [CII] efficiency? (luminosity/mass)



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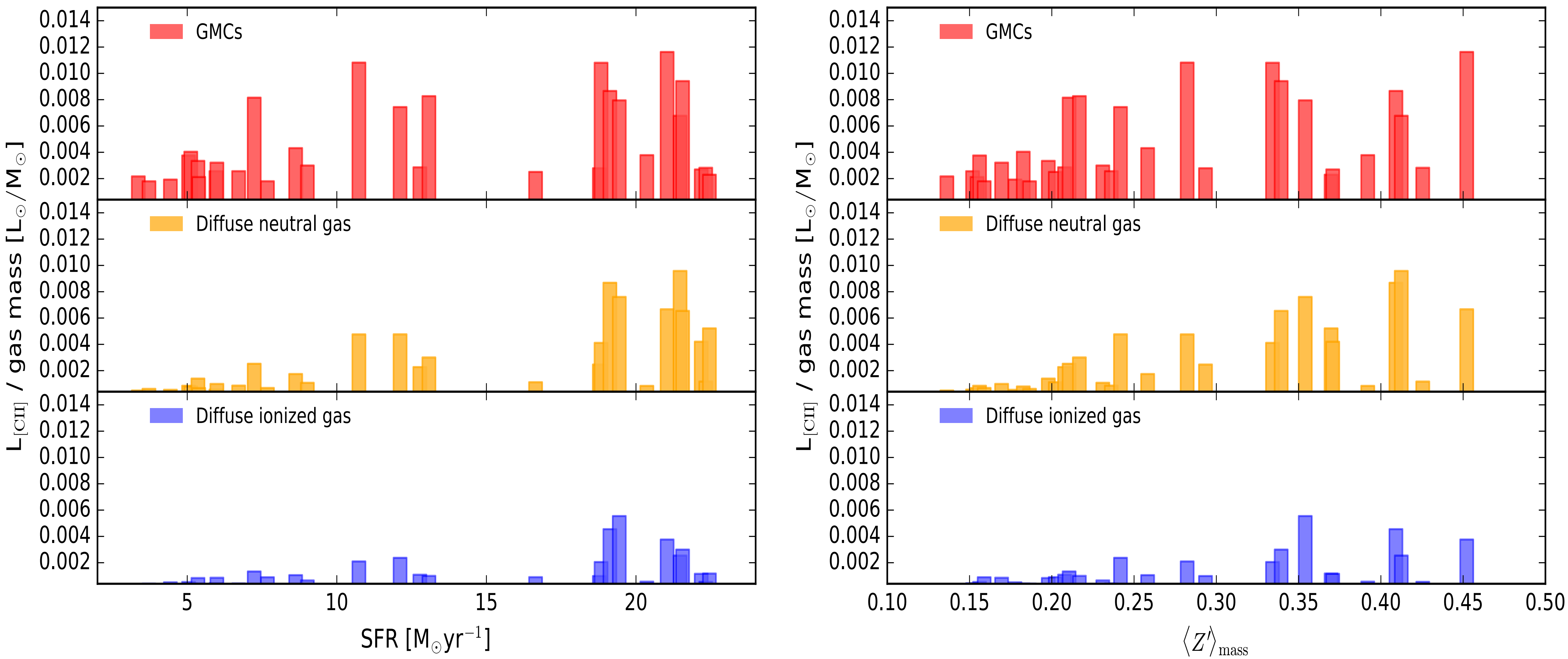
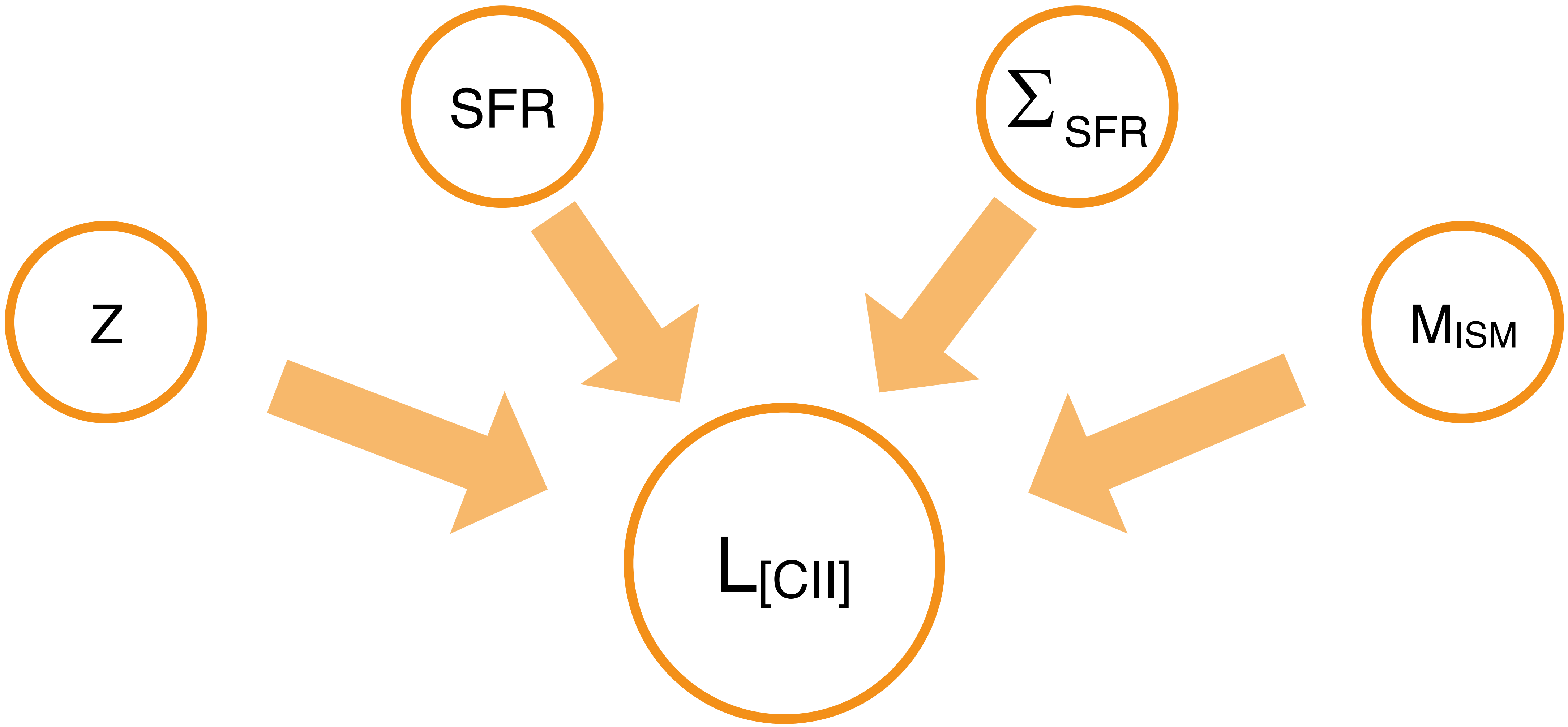


Slight increase in [CII] efficiency with SFR and Z

[Olsen+17 submitted]

3: Importance of metallicity

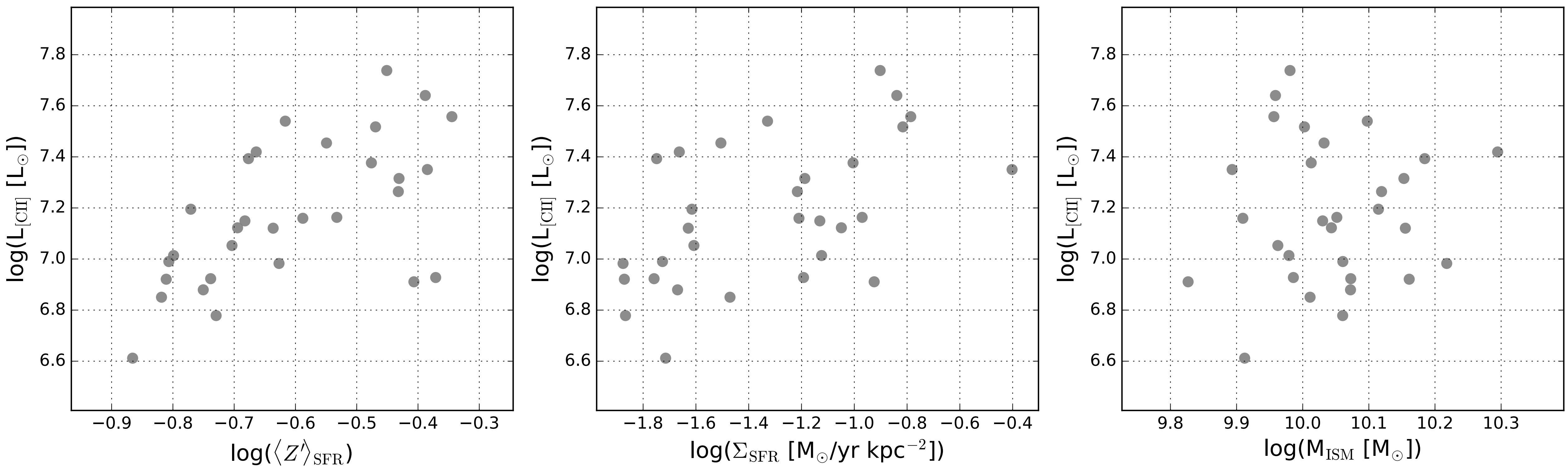
We did a principle component regression (PCR) analysis on $L_{[CII]}$ to study the effect of different parameters on $L_{[CII]}$:



[Olsen+17 submitted]

3: Importance of metallicity

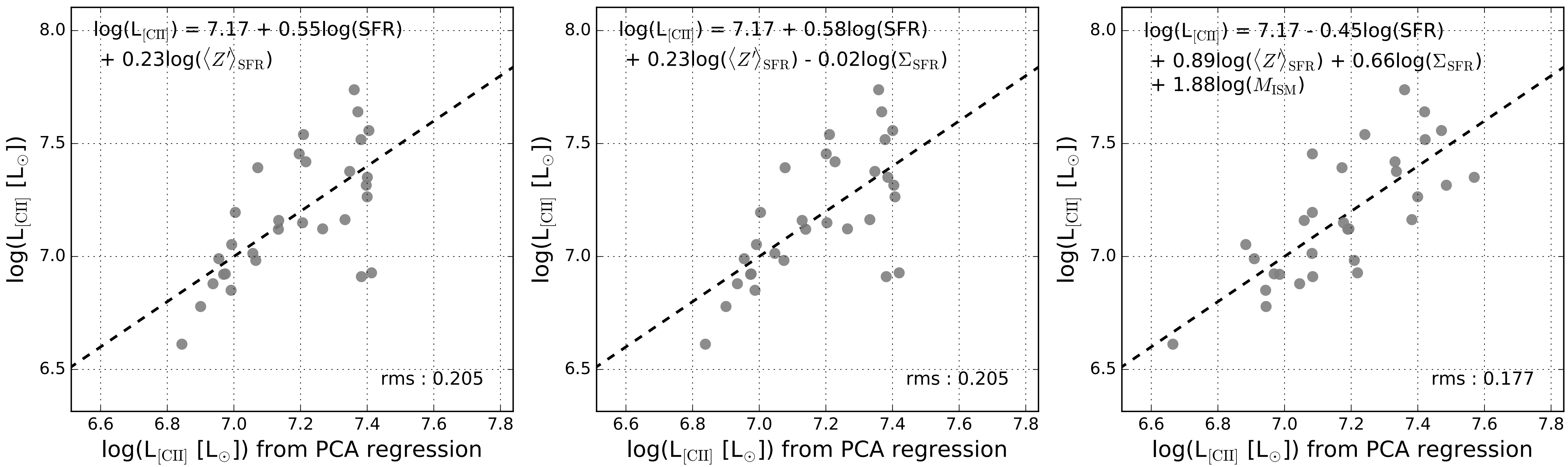
Each parameter on their own, do not determine $L_{[CII]}$ very well:



[Olsen+17 submitted]

3: Importance of metallicity

But combined, we can estimate $L_{[CII]}$ better:



-> Metallicity (Z) is more important than Σ_{SFR} and combined with M_{ISM}, $L_{[CII]}$ can be determined better

[Olsen+17 submitted]

3: Importance of metallicity

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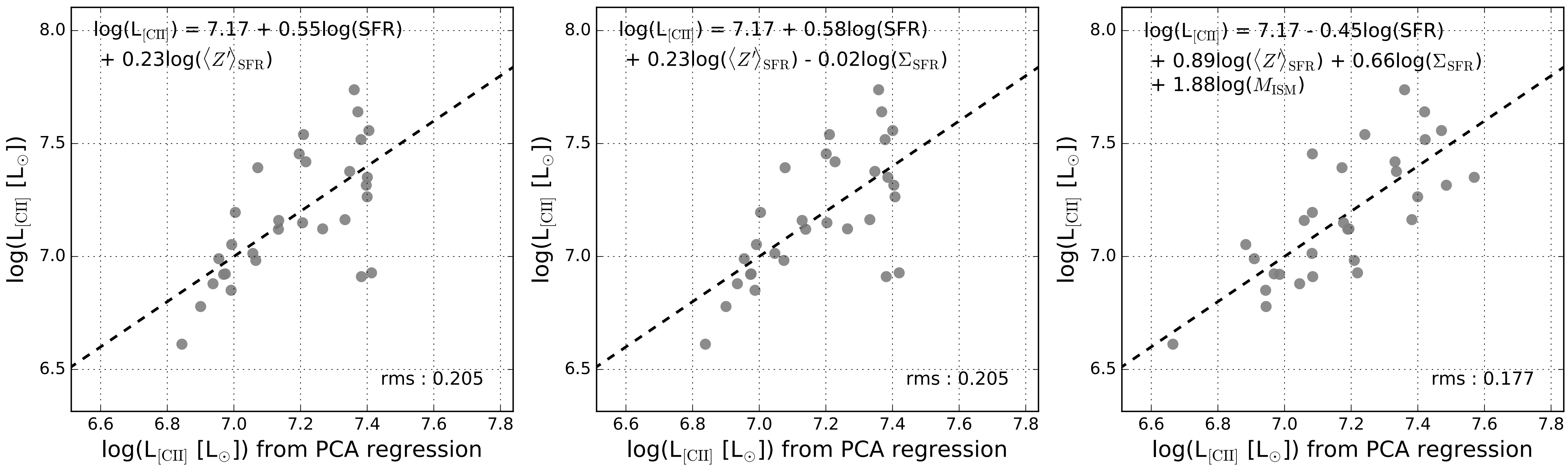


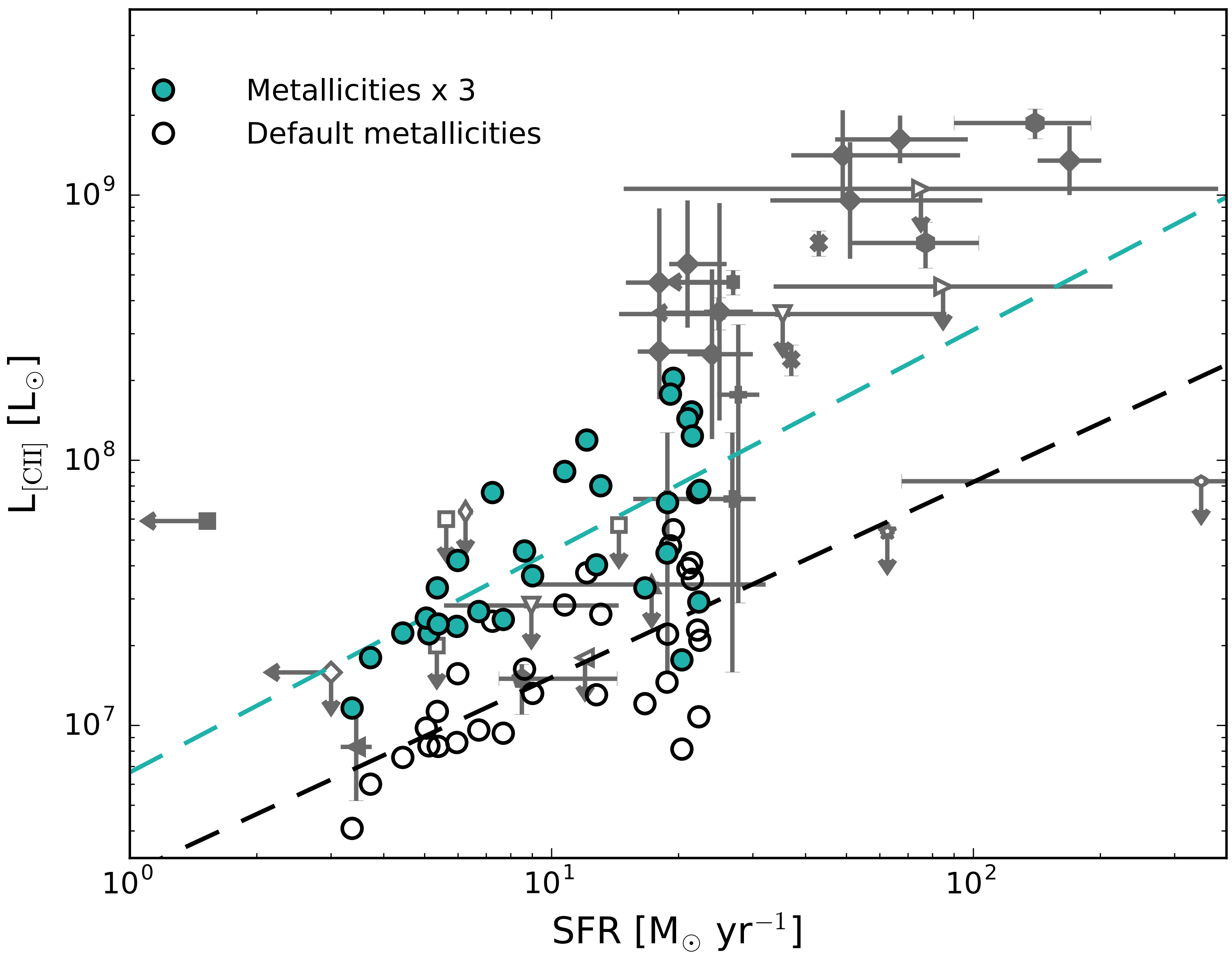
-> Metallicity (Z) is more important than Σ_{SFR} and combined with M_{ISM}, $L_{[CII]}$ can be determined better

However, we are limited by a very small range in Z

[Olsen+17 submitted]

3: Importance of metallicity

Experiment: Scale the metallicity up artificially:

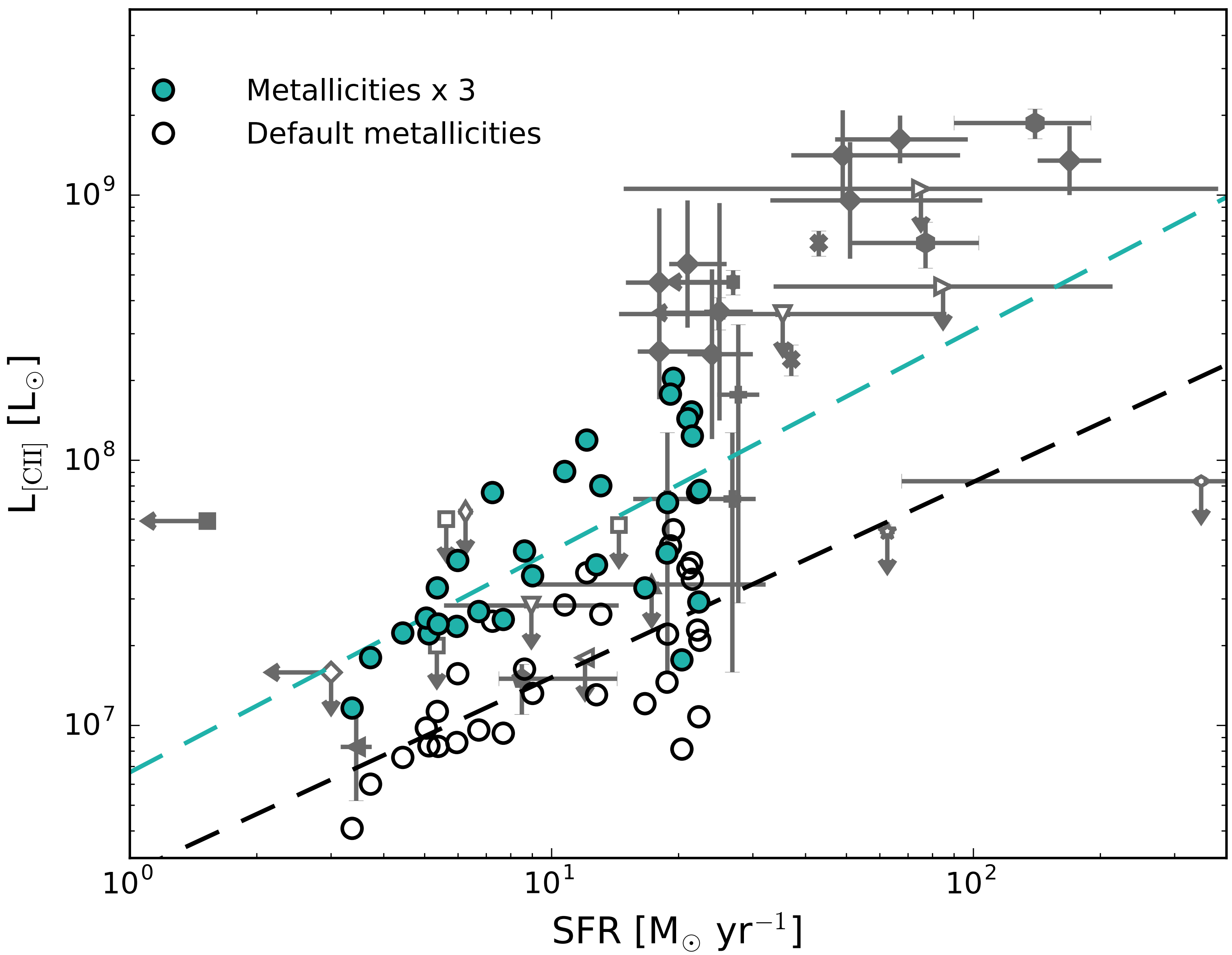


-> scaling *Z* by factor of 3: big impact (see also [Vallini+15])

[Olsen+17 submitted]

3: Importance of metallicity

Experiment: Scale the metallicity up artificially:



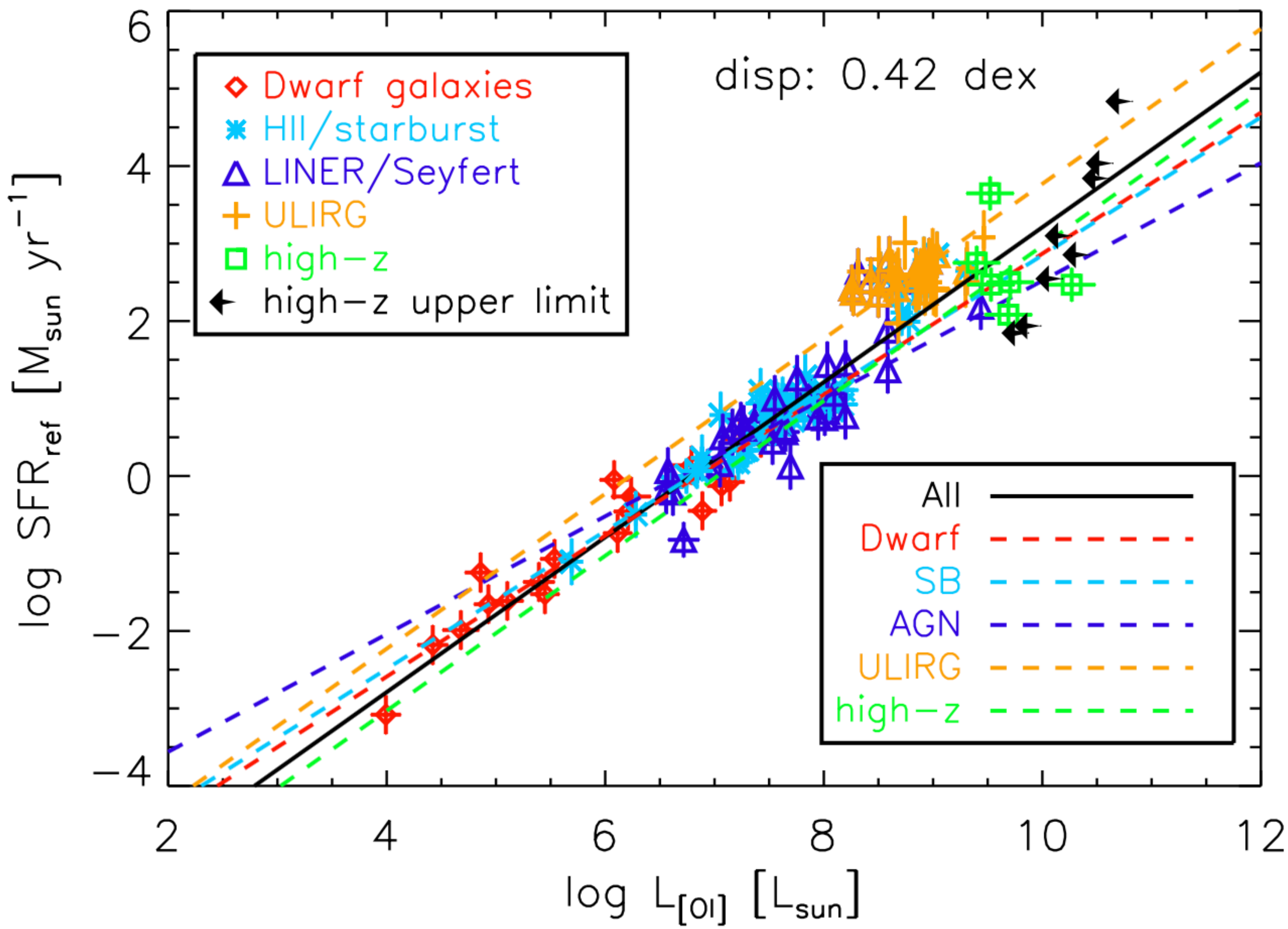
-> scaling *Z* by factor of 3: big impact (see also [Vallini+15])

-> In addition, observed SFRs could be very understimated [Capak+15]

[Olsen+17 submitted]

3: [OI] and [OIII]

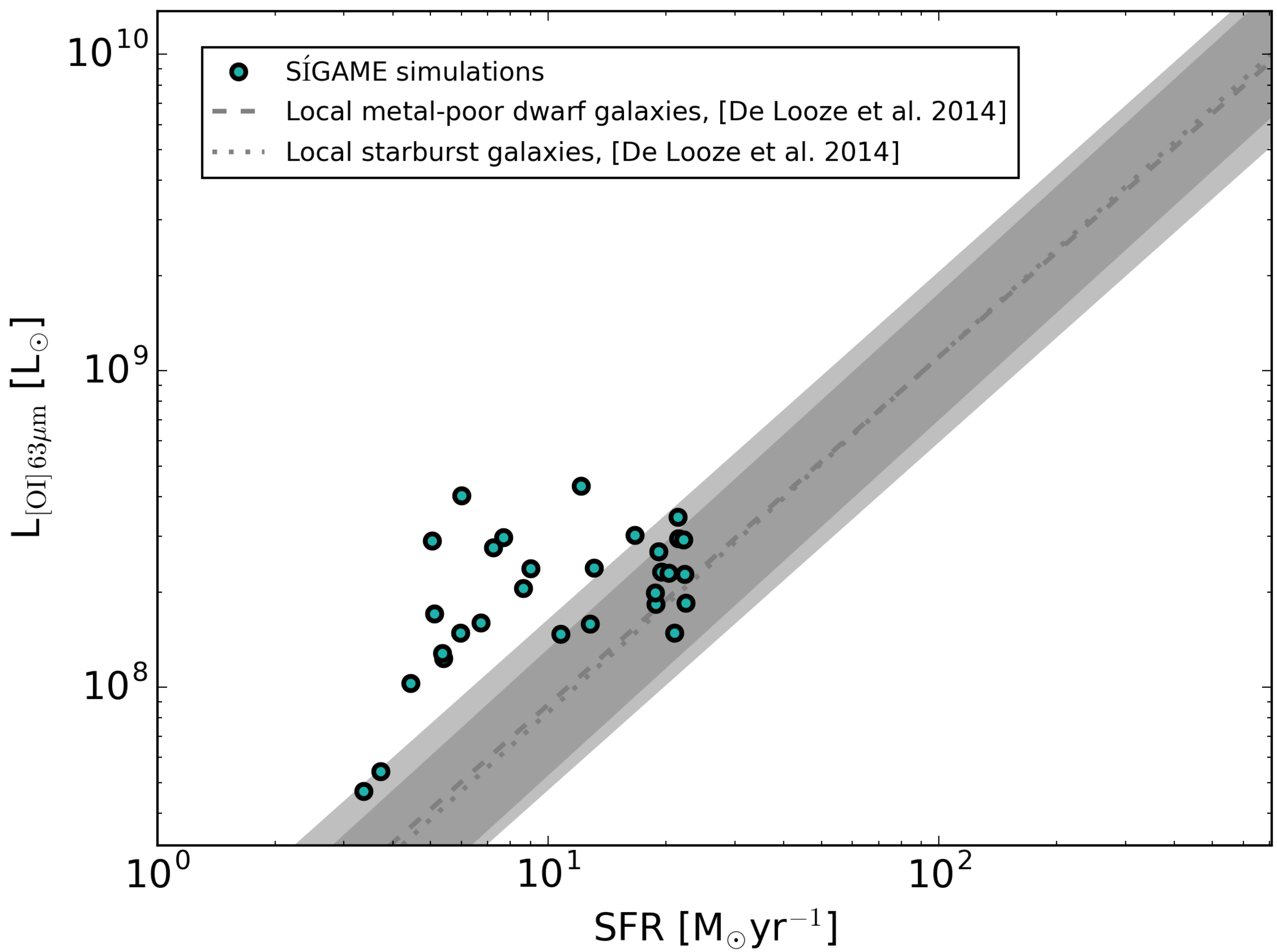
Locally, [OI] is a better SFR tracer than [OIII] and [CII]!



[De Looze 2014]

3: [OI] and [OIII]

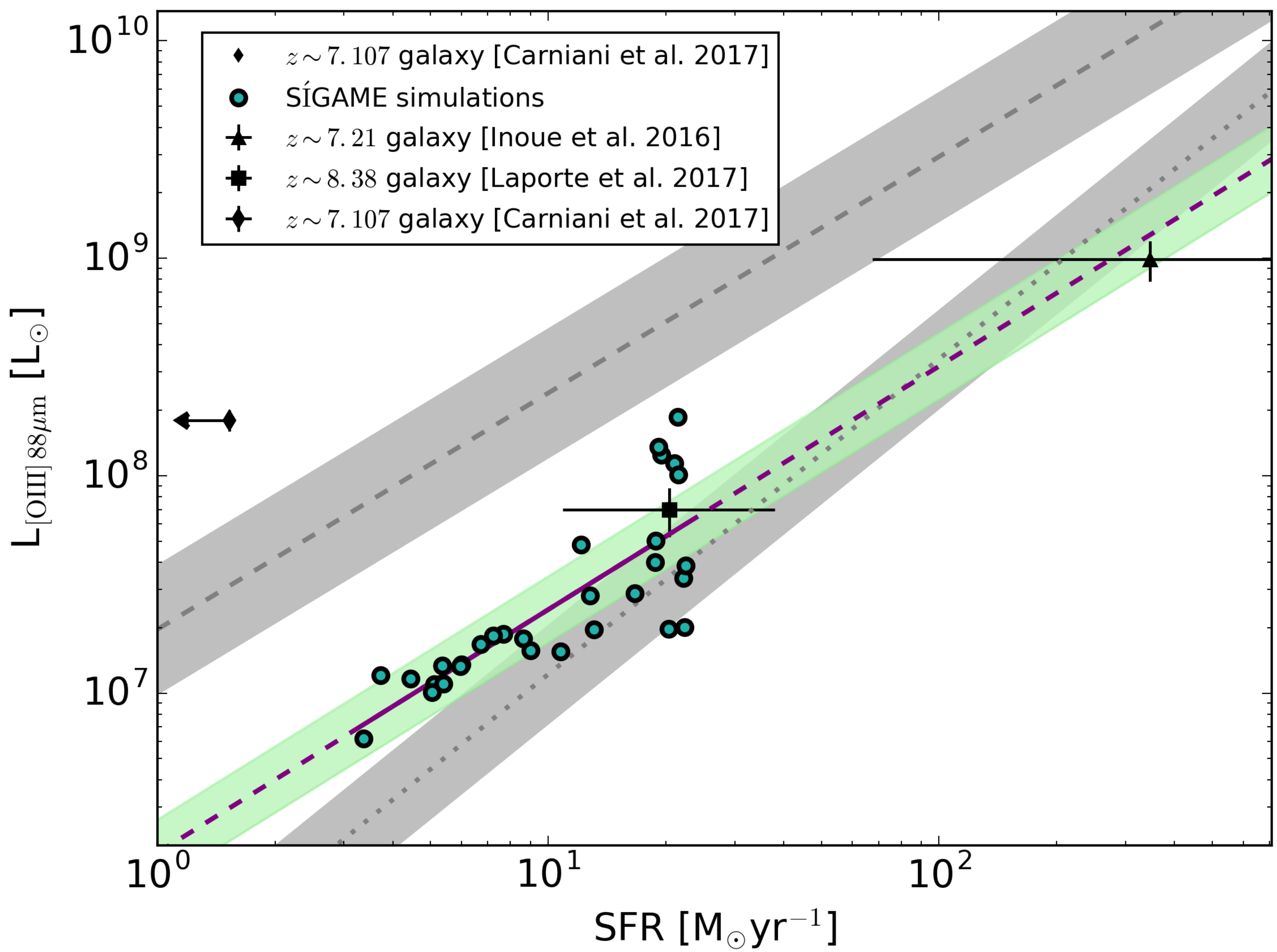
No high-z detections so far of [OI] so we compare with local relations:



[Olsen+17 submitted]

3: [OI] and [OIII]

[OIII] has been detected at $z > 6$ in three cases



[Olsen+17 submitted]

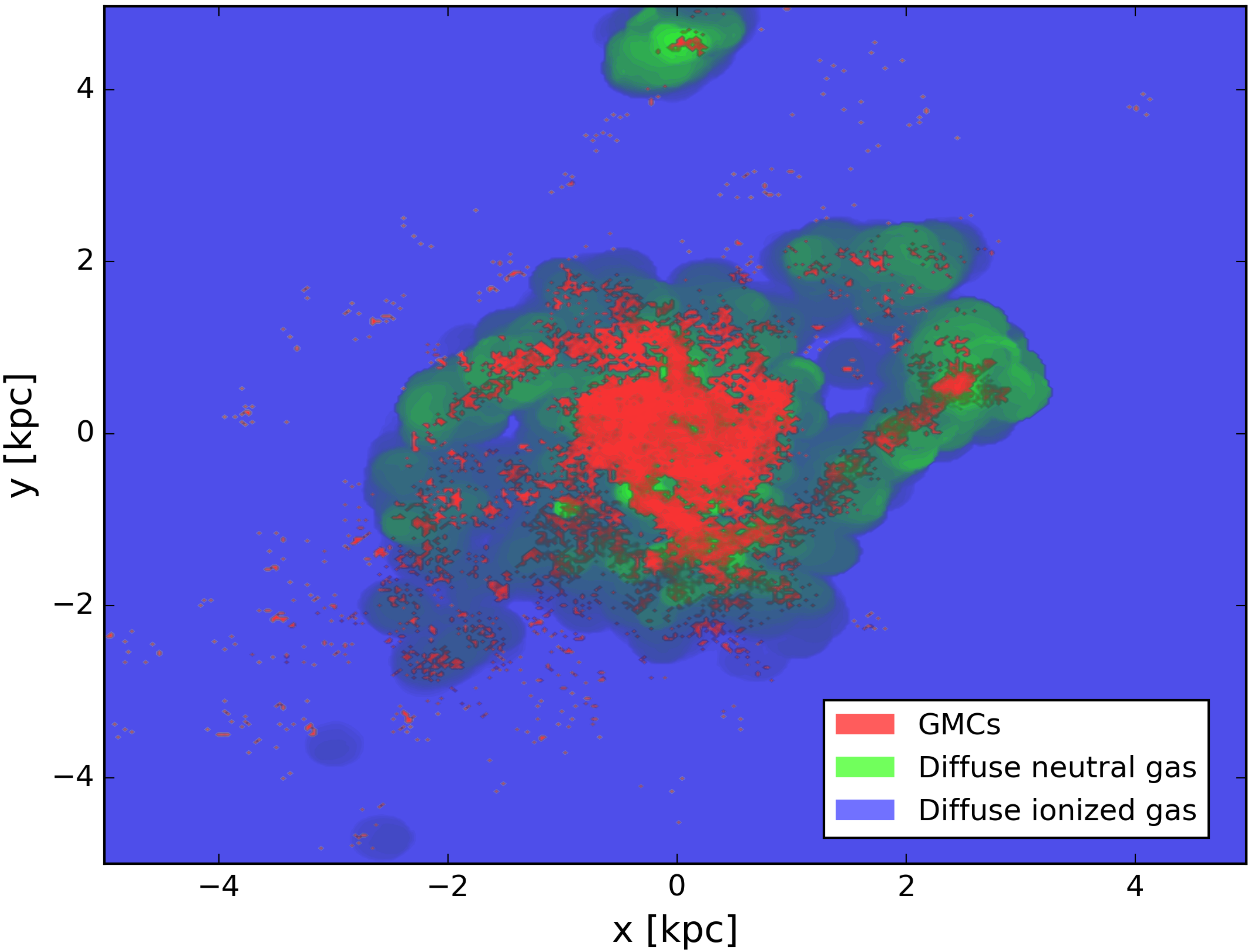
Future!

Where to go next with SÍGAME…

- Make the code public!
- Try on different set of galaxies, with wider dynamic range in parameters
- Go to lower redshifts to compare with resolved observations…
- Improve on subgrid method

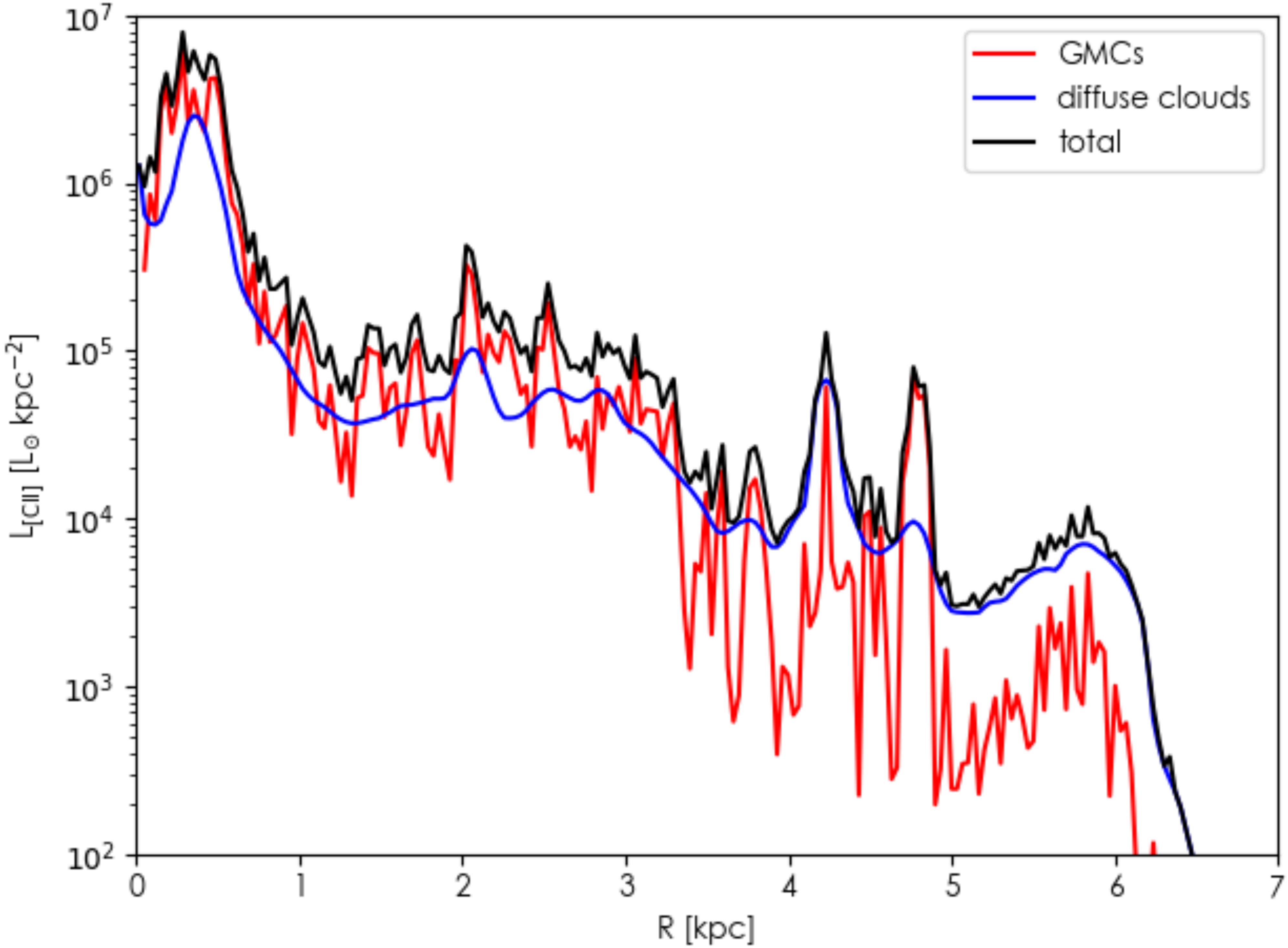
[Olsen+17 in prep.]

Maps of line emission



Radial profiles

Work by Lily Whitler

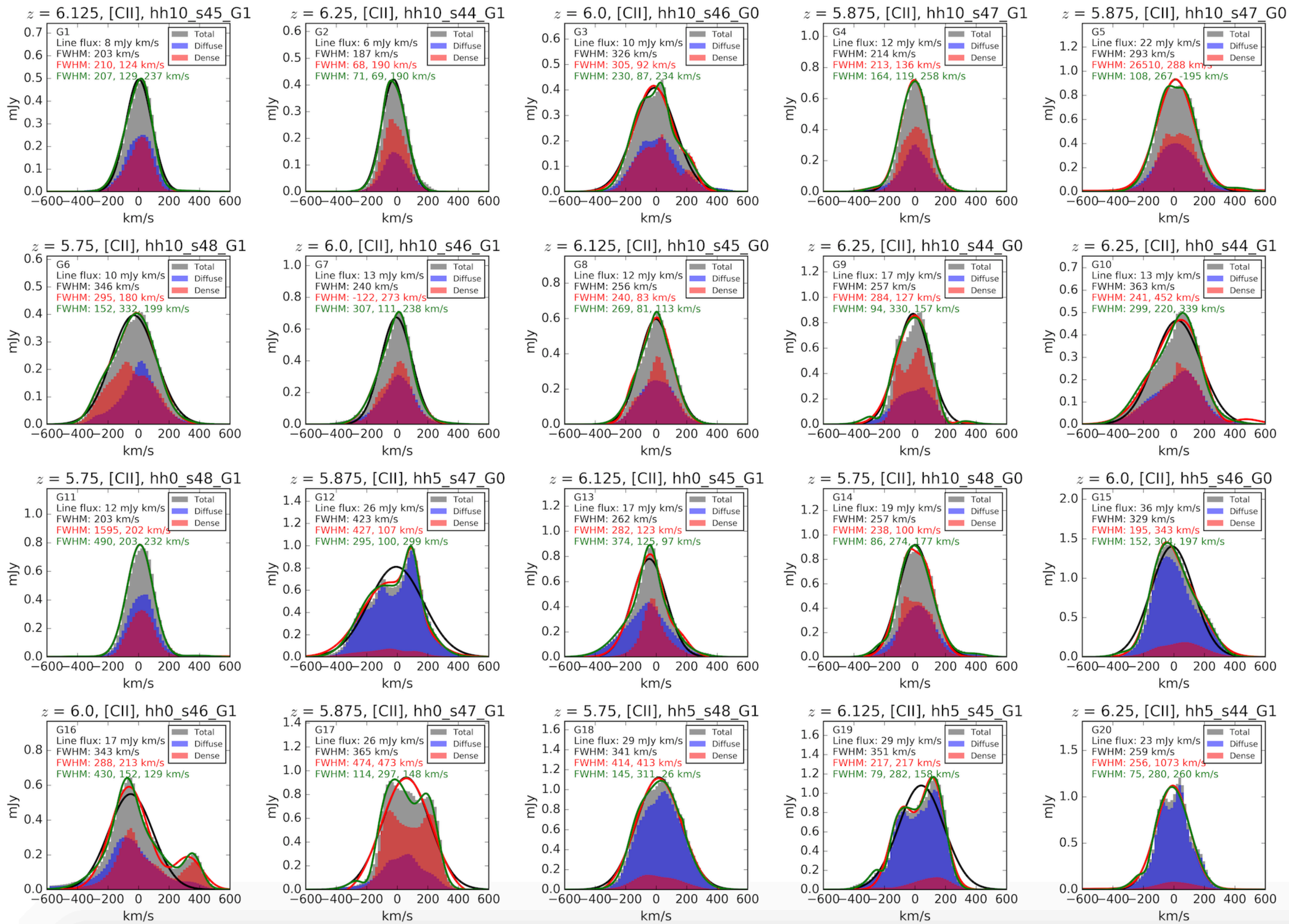


$L_{[CII],GMC} = 7.45 \times 10^6 \, L_\odot$

$L_{[CII],dif} = 3.01 \times 10^6 \, L_\odot$

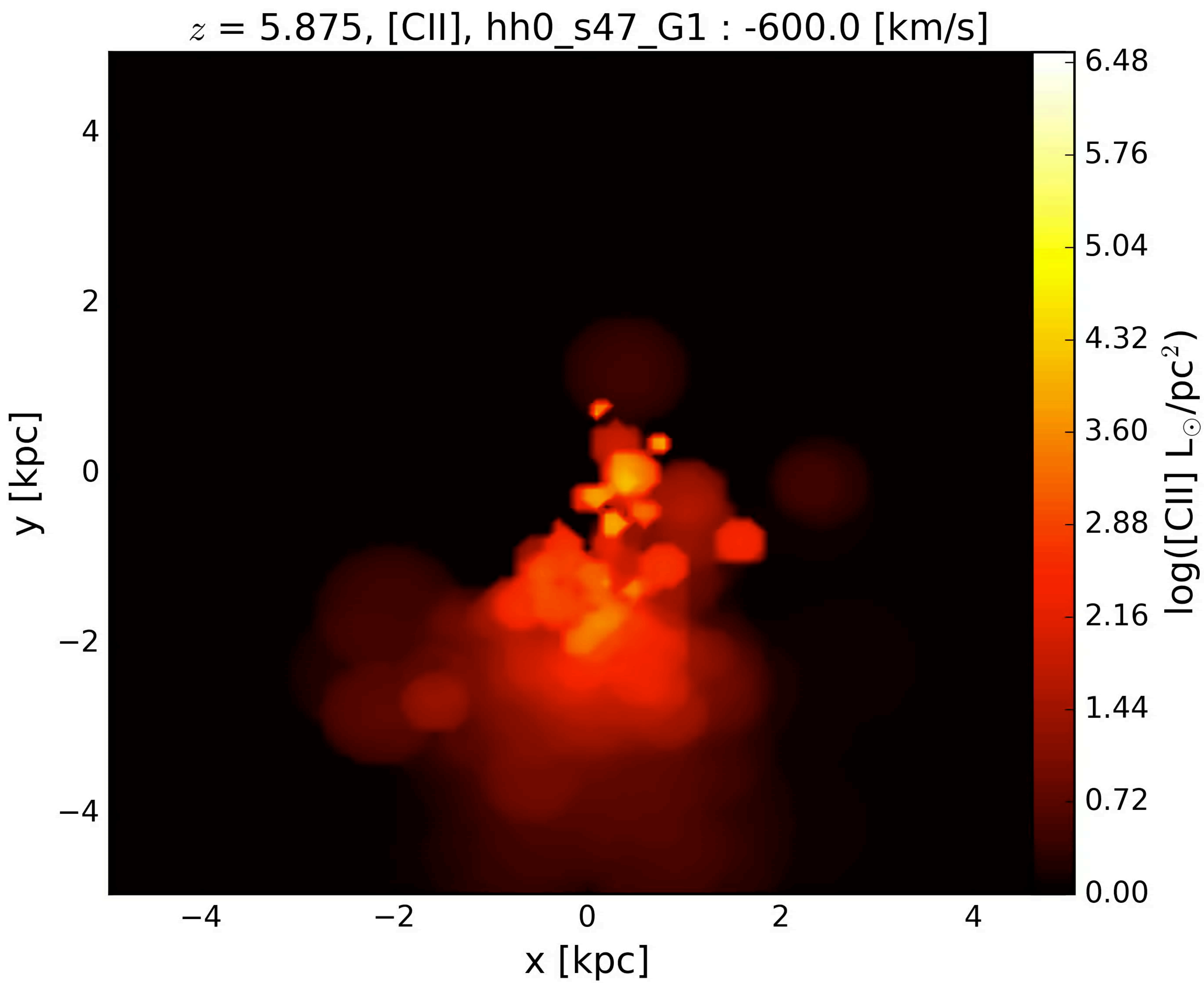
Line profiles

Work by Jacob Cluff



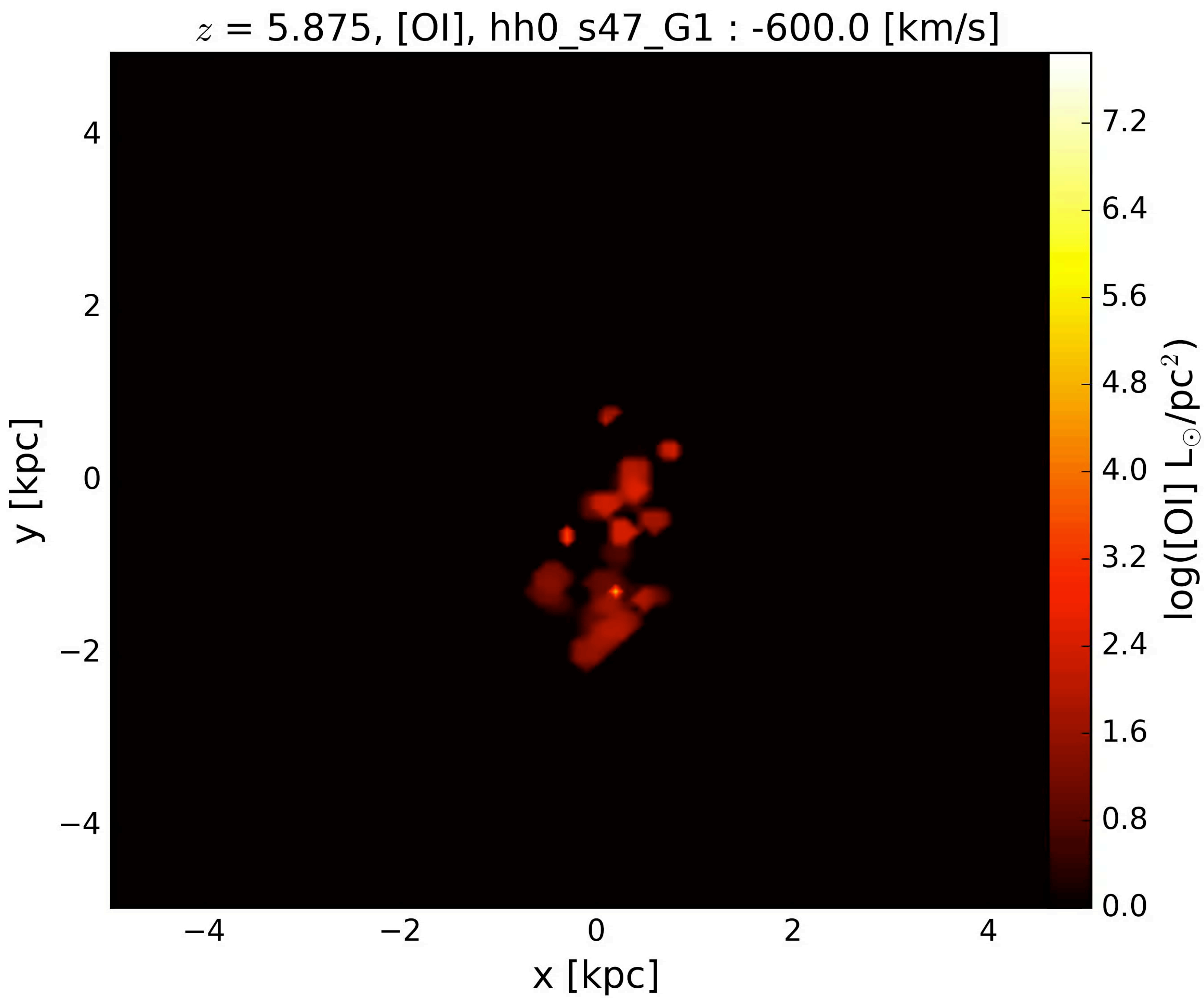
Velocity cubes

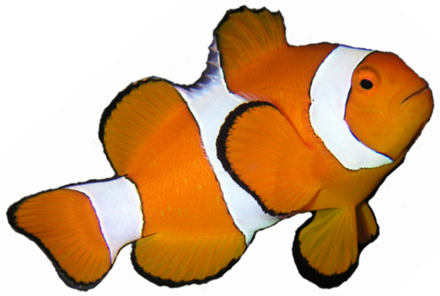
Work by Jacob Cluff



Velocity cubes

Work by Jacob Cluff



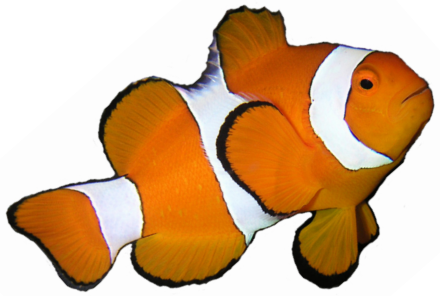


SÍGAME

SImulator of GAlaxy Millimeter/submillimeter Emission

Conclusions at z~6:

- We predict a [CII]-SFR relation, though weak
- Within our range in Z, [CII] does not depend strongly on Z
- Most of the [CII] emission arises in diffuse gas
- GMCs less important [CII] emitters at high SFR
- $L_{[OIII]}$ - SFR in agreement with observations
- Radial and line profiles on the way…



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[CII] with SÍGAME at z = 2:
Olsen+15, ApJ 814 76

CO line emission with SÍGAME at z = 2:
Olsen+16, MNRAS 457 3

Plea to observers/theorists!:

- extragalactic mass-size (and velocity dispersion) relations for molecular gas
- cosmic ray intensity in different environments

Stay tuned: http://kpolsen.github.io/sigame/ !!

(See also: http://www.digame.online/ - DIrectory for Galaxy Millimeter/submillimeter Emission)