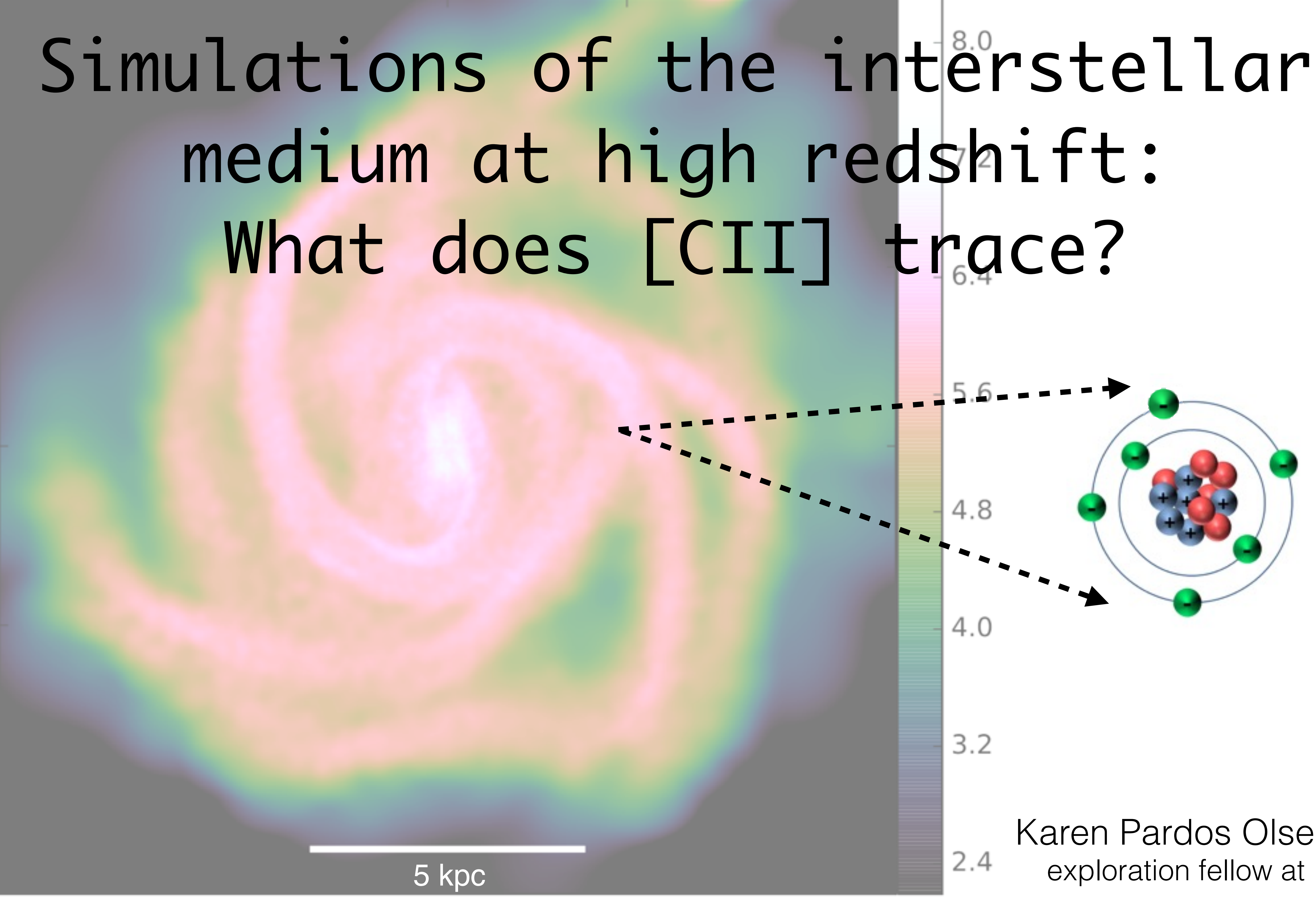
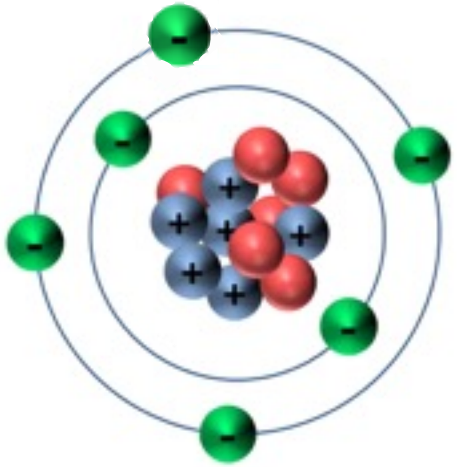
Simulations of the interstellar medium at high redshift: What does [CII] trace?



Karen Pardos Olsen
exploration fellow at

School of Earth and Space Exploration
Arizona State University

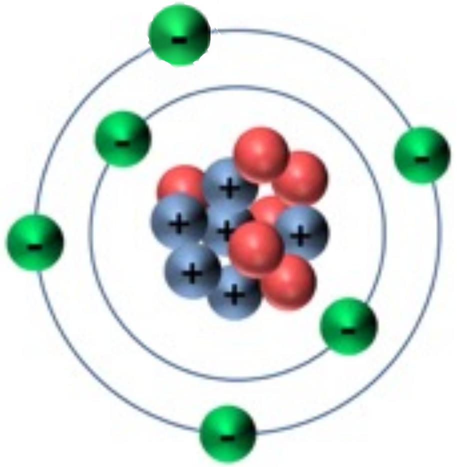
NMSU, Nov 18 2016



Carbon is all over the ISM (CO, HCN, CH_3CCH…)

“carbon is my favorite element - it’s like the slut of the periodic table.”

Jon Stewart quoted by Neil deGrasse Tyson



Singly ionized carbon, CII

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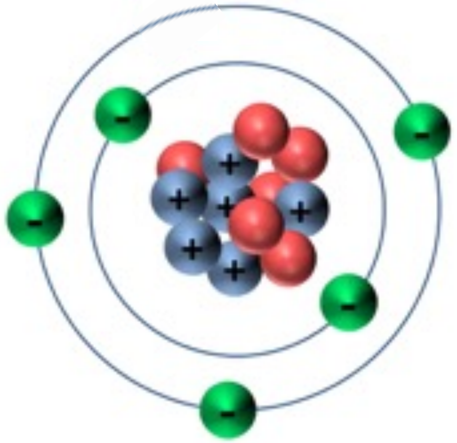
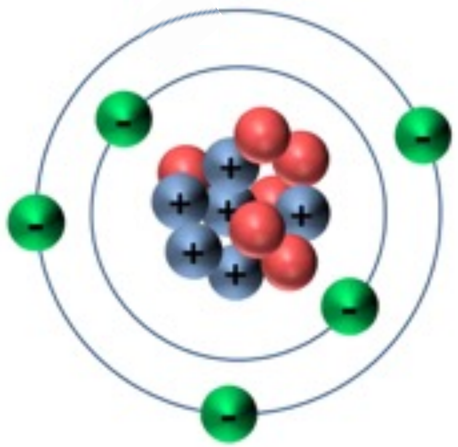


Singly ionized carbon, CII

producing the fine-structure line [CII]



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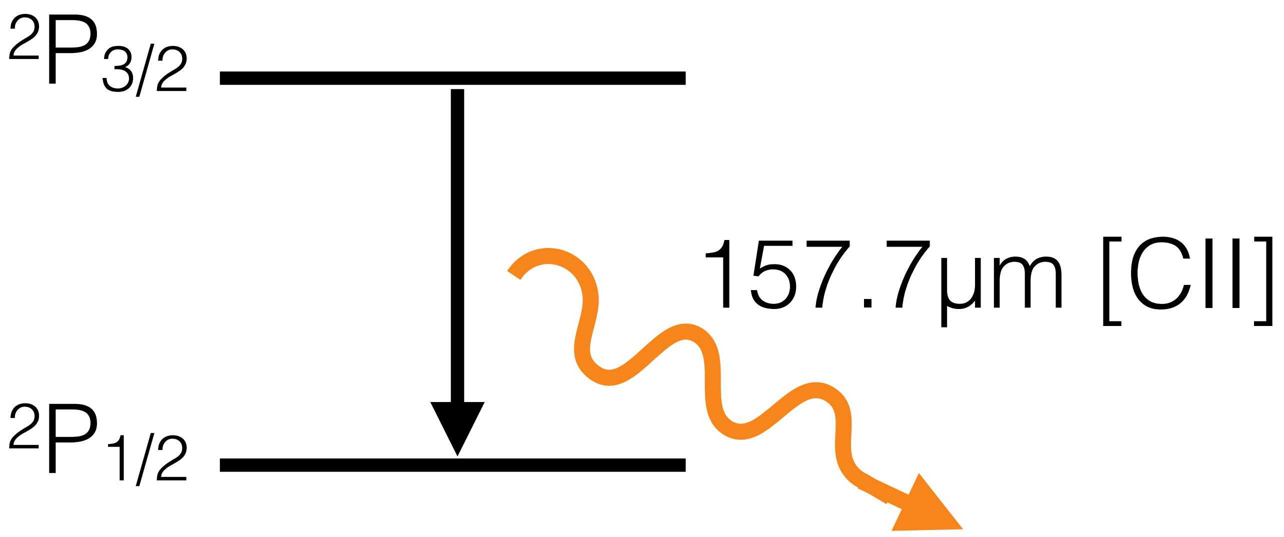
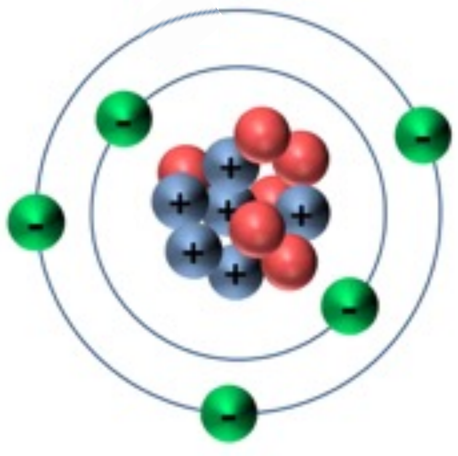


- Excited by collisions with either electrons, atoms or molecules
- Ionization potential (11.3eV) below that of hydrogen (13.6eV)

⇒ can arise all over the ISM!



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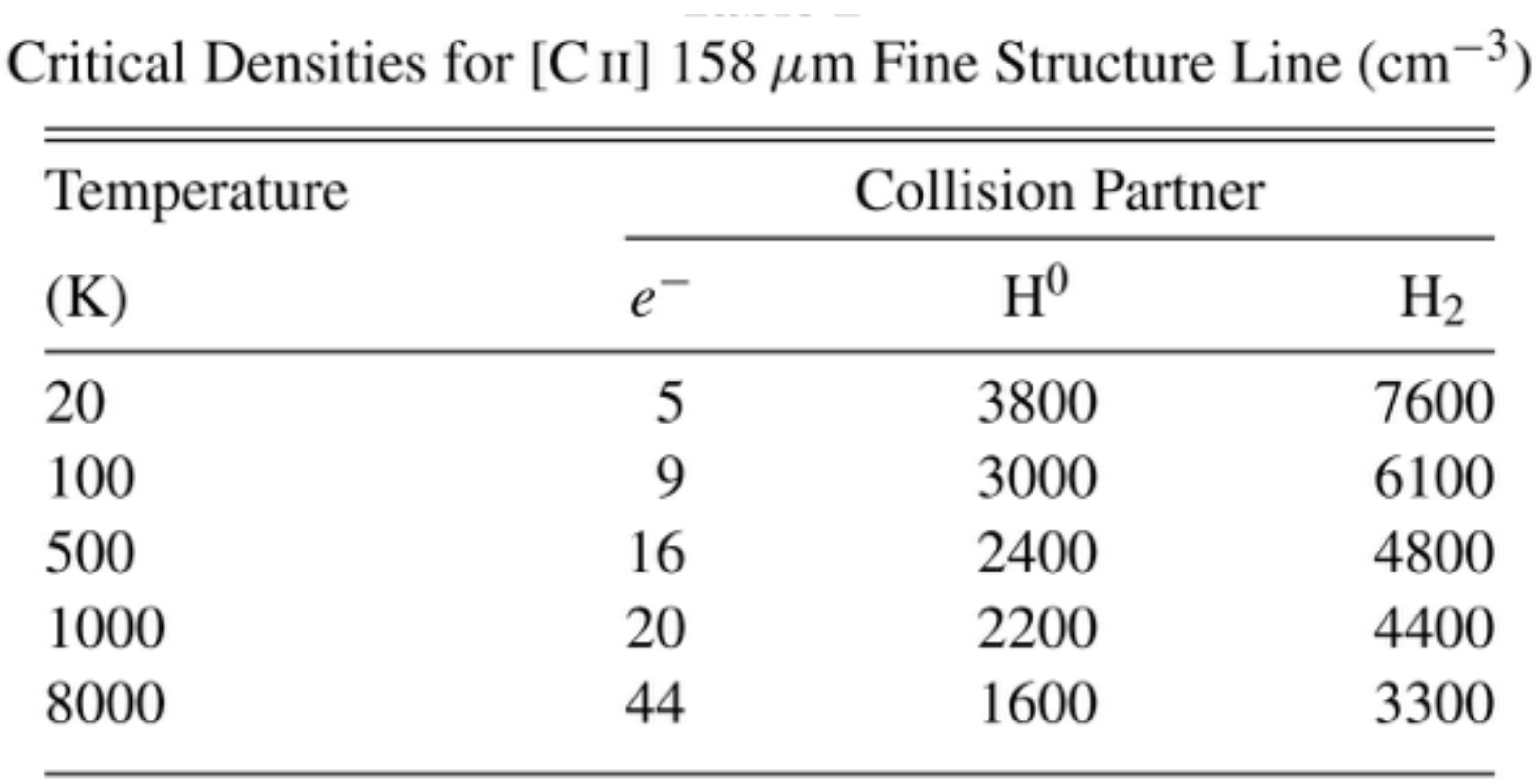

Critical Densities for [C II] 158 μm Fine Structure Line (cm^{-3})

Temperature (K)	Collision Partner e^-	H^0	H_2
20	5	3800	7600
100	9	3000	6100
500	16	2400	4800
1000	20	2200	4400
8000	44	1600	3300

[Goldsmith+12]

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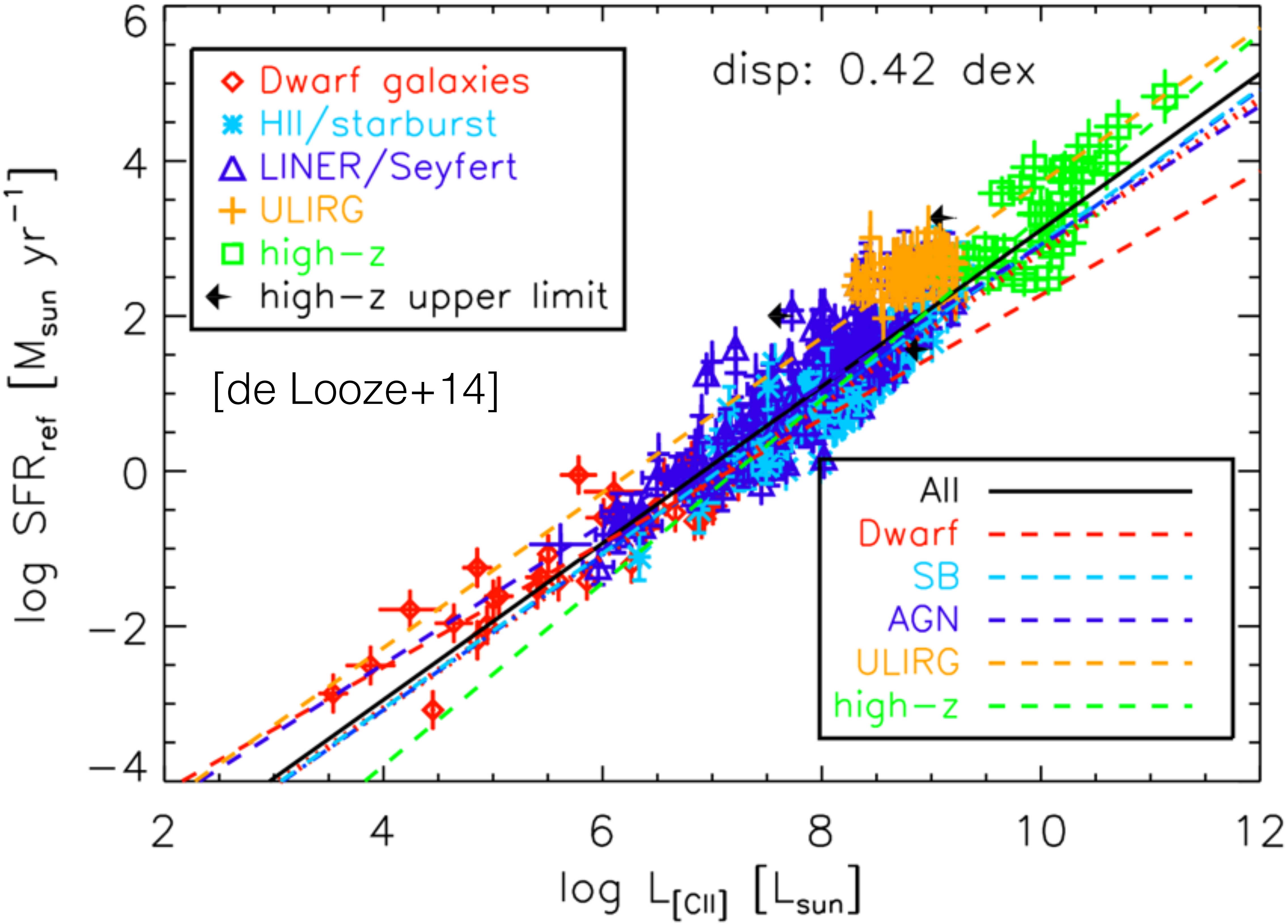
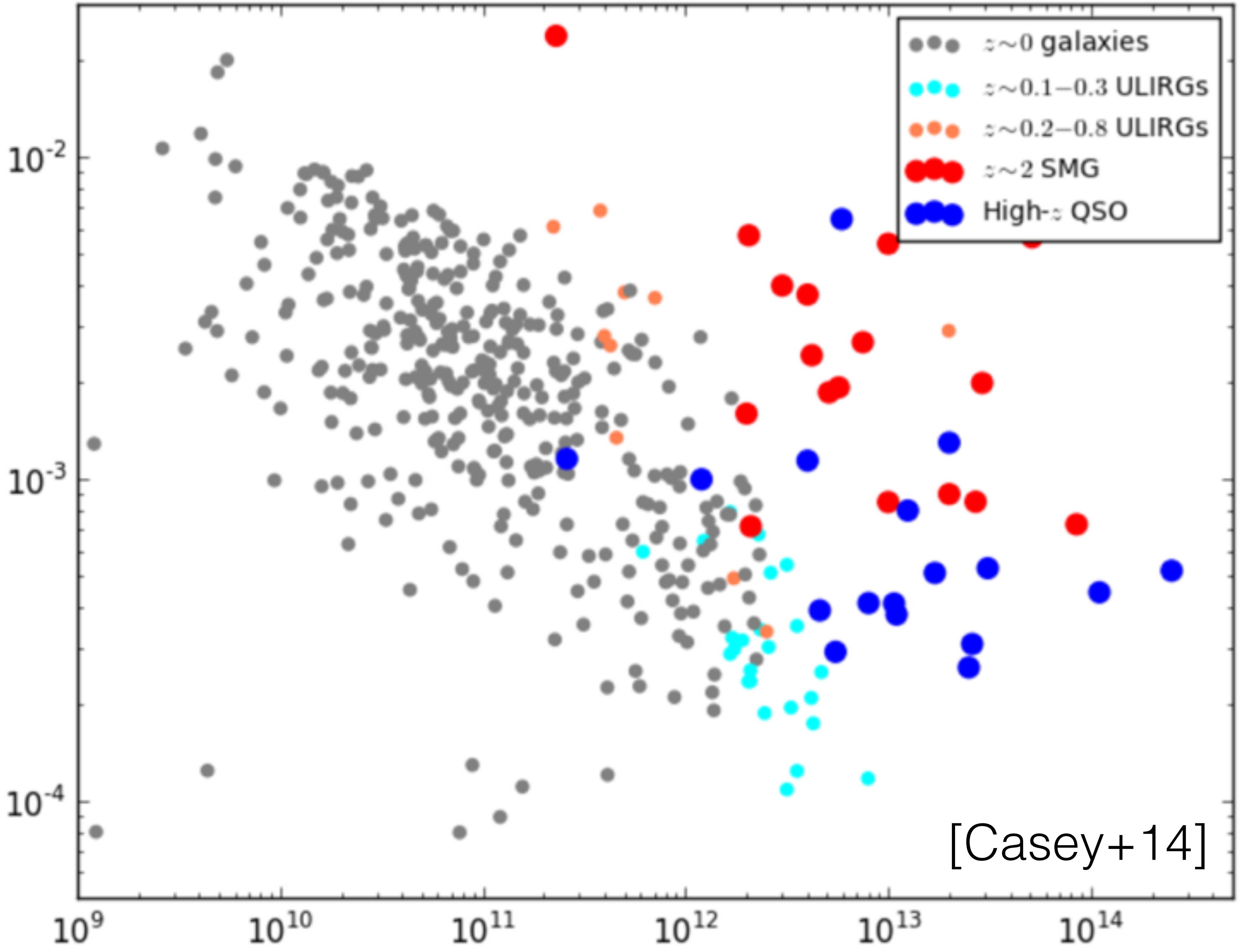
The correlation with SFR



[de Looze+14]

[CII] deficit locally

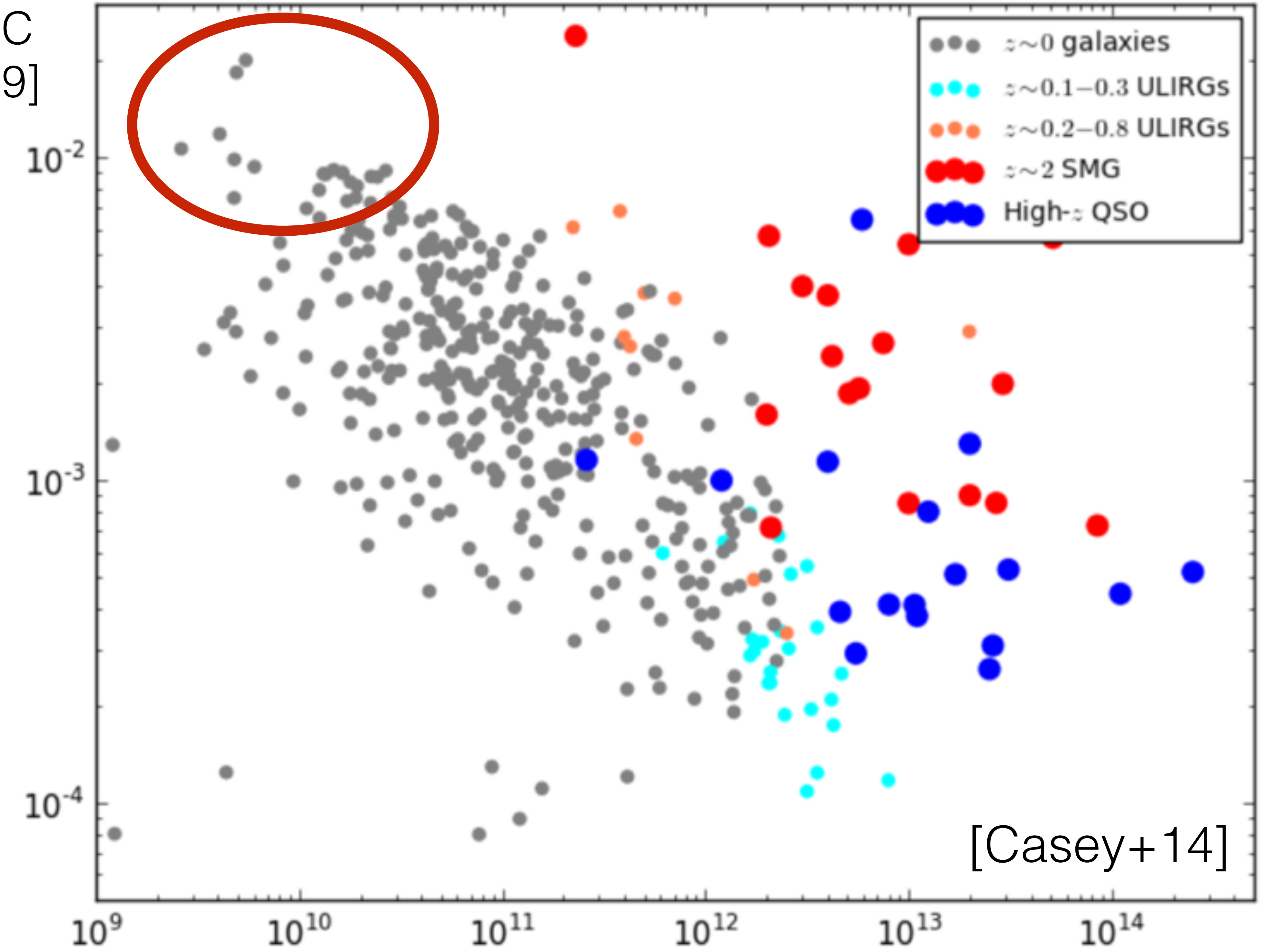


$L_{[CII]}$ / $L_{[FIR]}$

$L_{[FIR]} \sim$ SFR

[CII] deficit locally

LMC/SMC
[Israel+09]



[Casey+14]

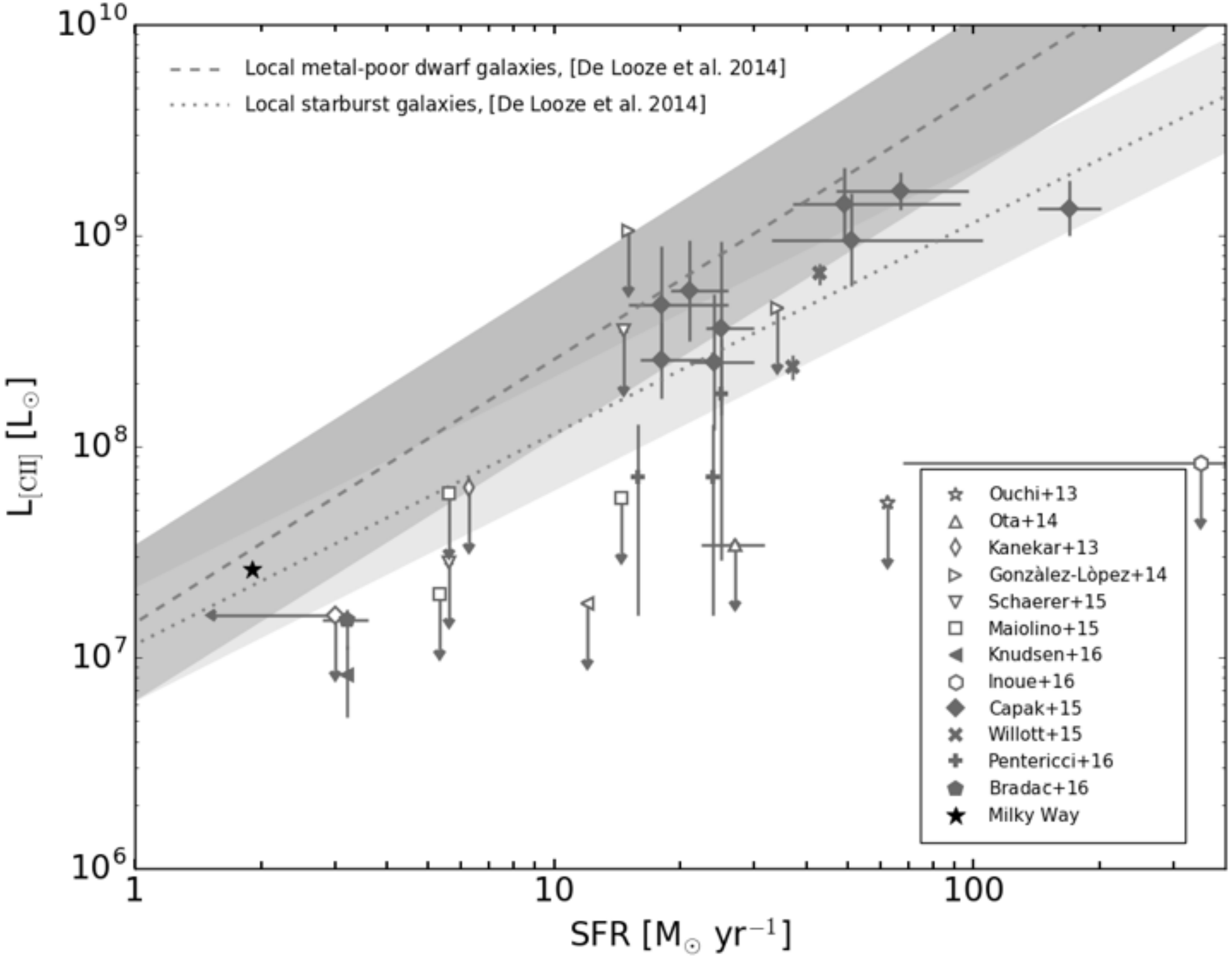
$L_{[CII]}$ / $L_{[FIR]}$

$L_{[FIR]}$ ~ SFR

High [CII] luminosity in LMC/SMC indicate: low metallicities allow FUV radiation to penetrate deeper, creating **larger C^+ regions** [Madden+01]

[CII] at high redshifts

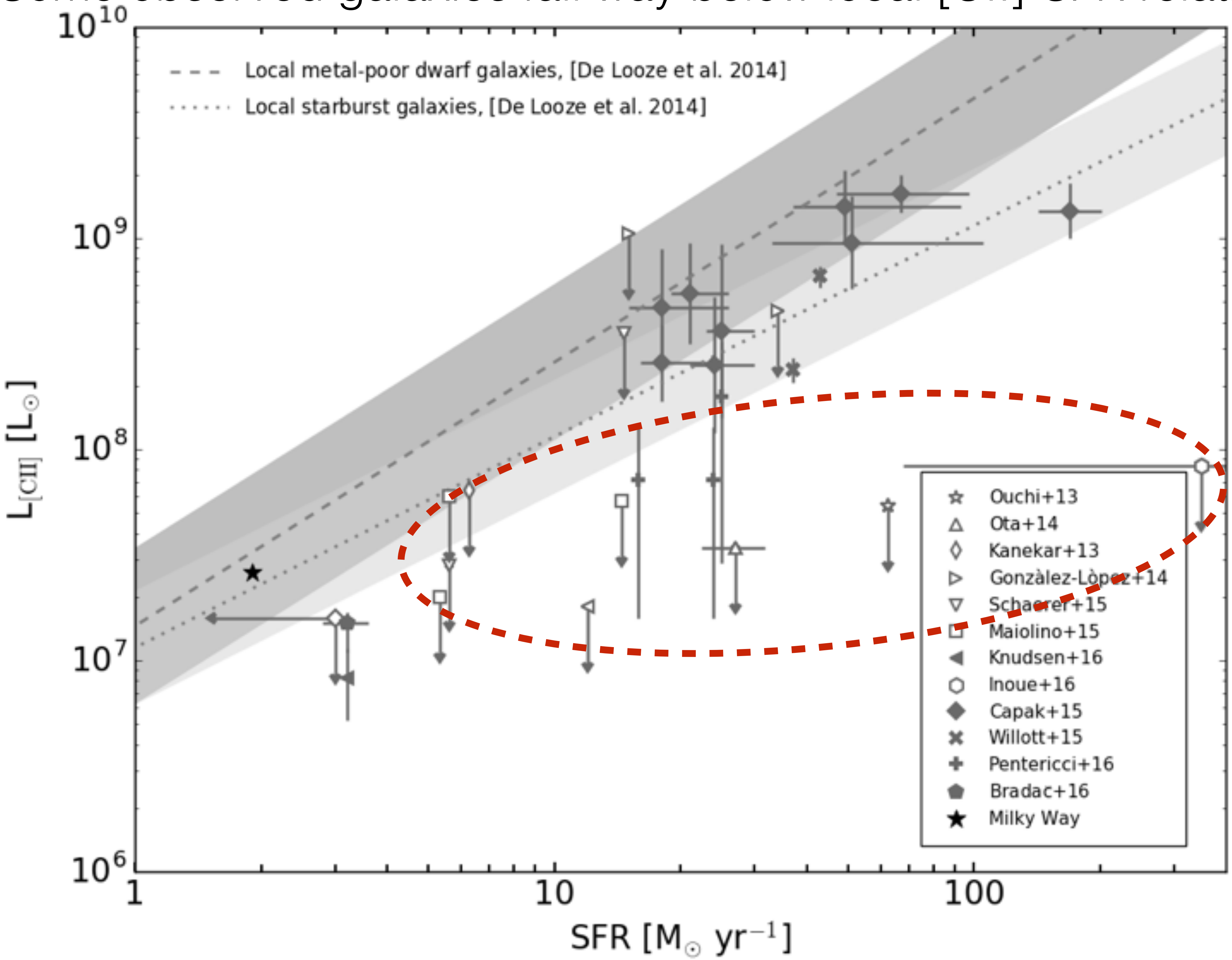
[CII] at high redshifts



[Olsen+16: in prep]

[CII] at high redshifts

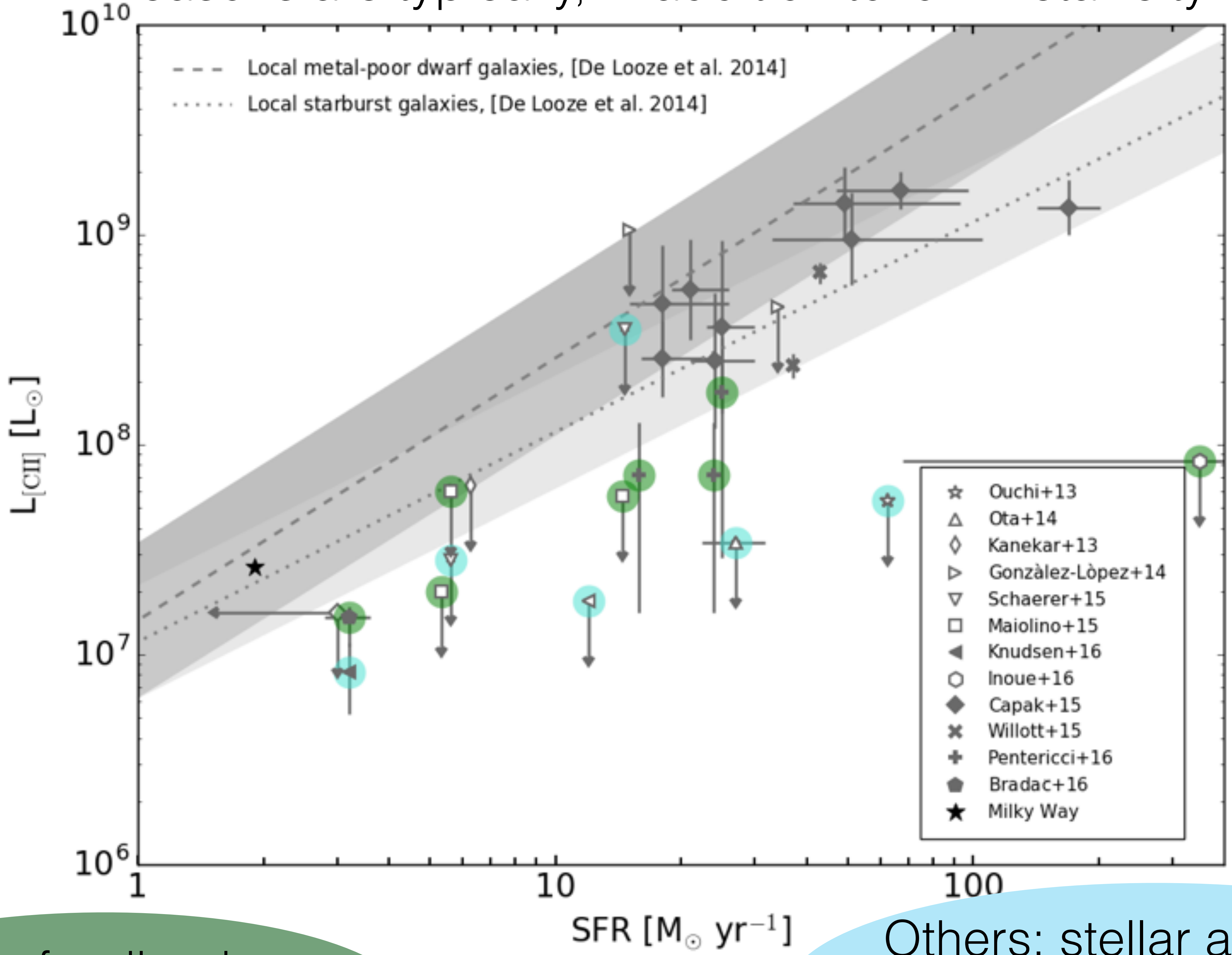
Some observed galaxies fall way below local [CII]-SFR relations!



[Olsen+16: in prep]

[CII] at high redshifts

Reasons are typically, in addition to low metallicity:



Stellar feedback => little neutral gas mass

Others: stellar age effects, higher ionization parameter, PDR structure

[Olsen+16: in prep]

Simulations of [CII] emission

Simulations of [CII] emission

- Low metallicity, Z
- Disrupted molecular clouds/PDRs
- Strong radiation field:
  - positive grain charge, less heating
  - dust emits in FIR
- High density and temperature:
  - Other lines can take over!
  - de-excitation of [CII] [Goldsmith+12]
- Other?

Simulations of [CII] emission

[Vallini+15]

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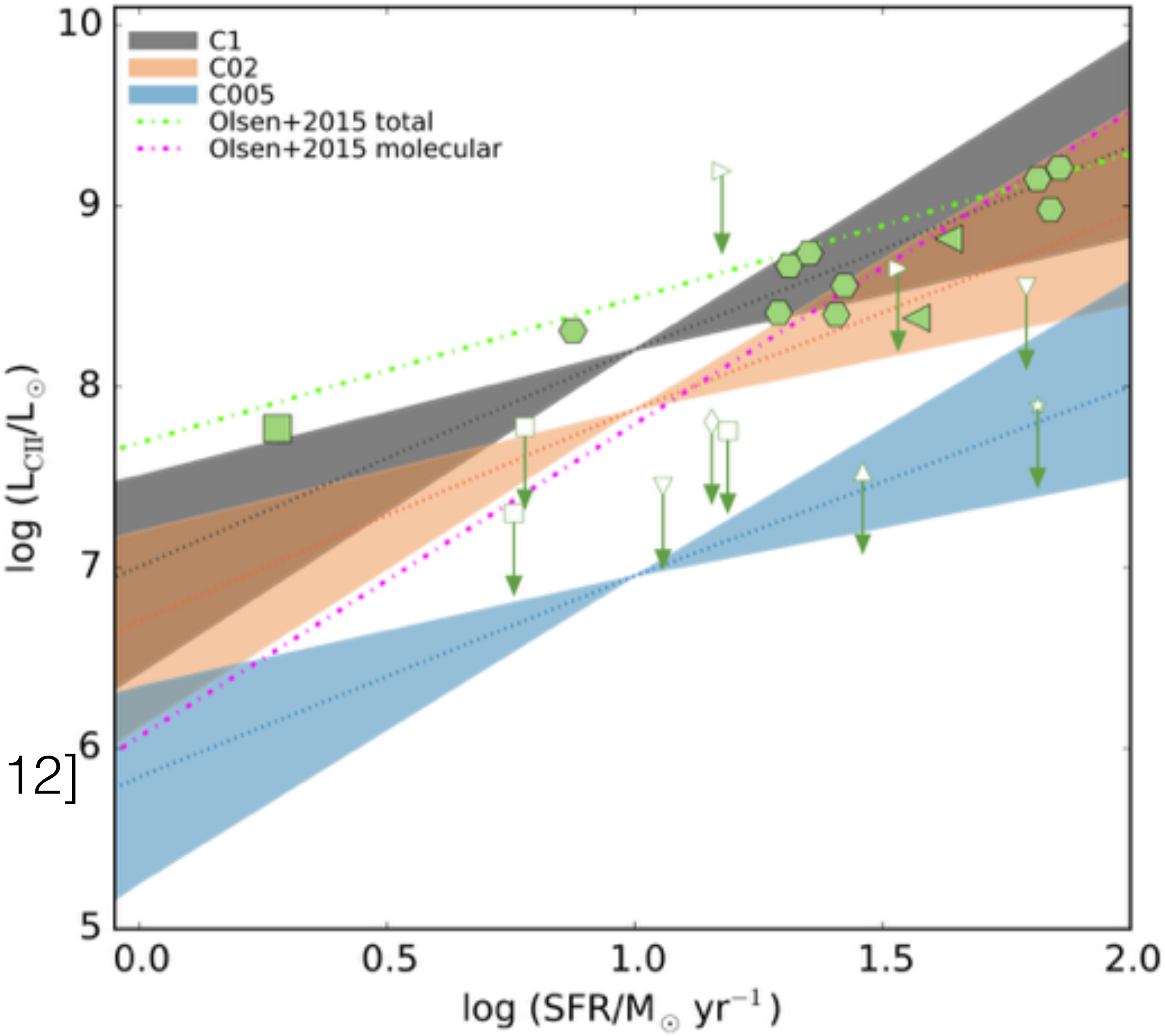

Simulations of [CII] emission

[Vallini+13] (in [Maiolino+15])

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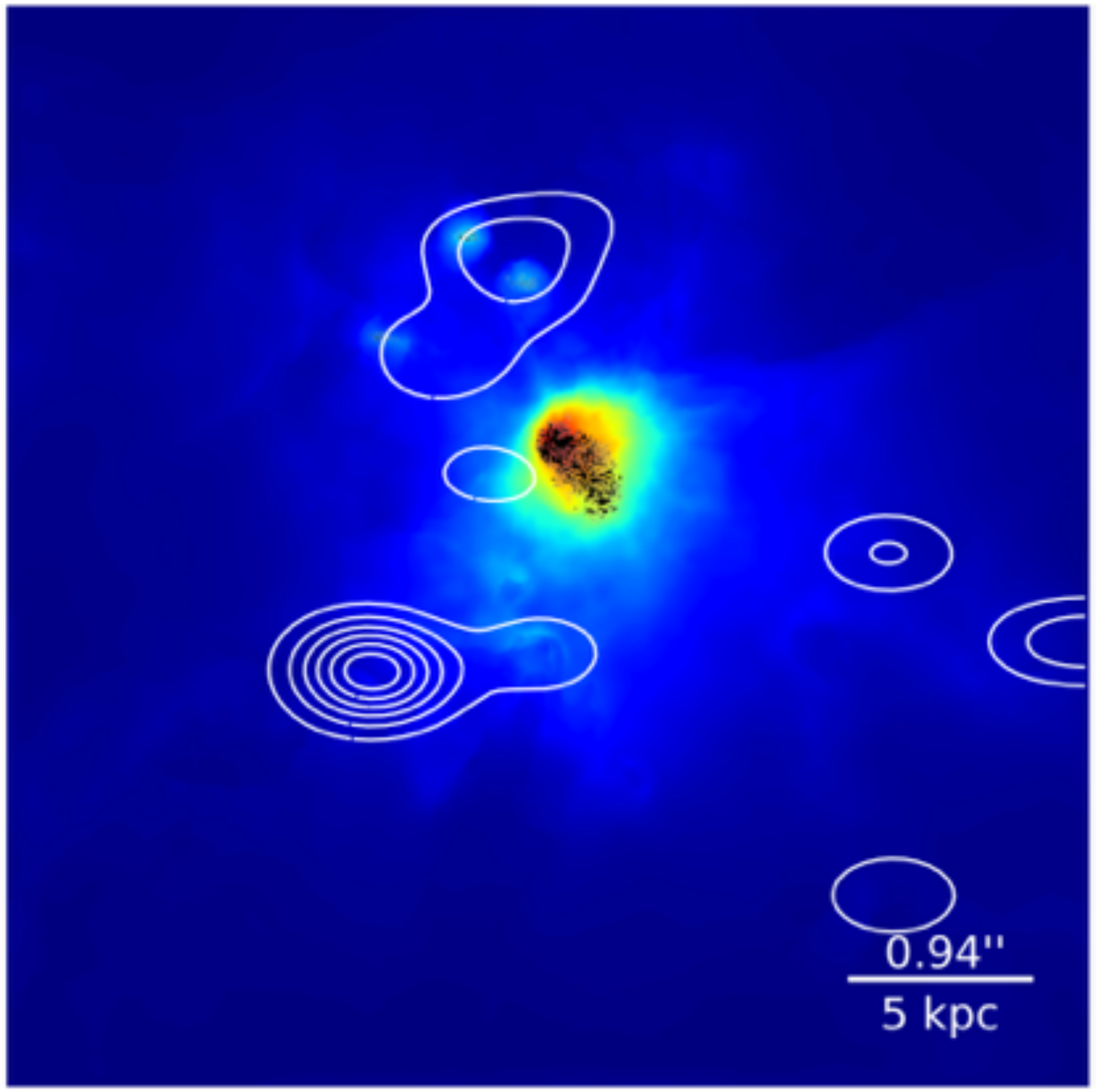

Disruption of GMCs+PDRs

Simulations of [CII] emission

[Narayanan+16]

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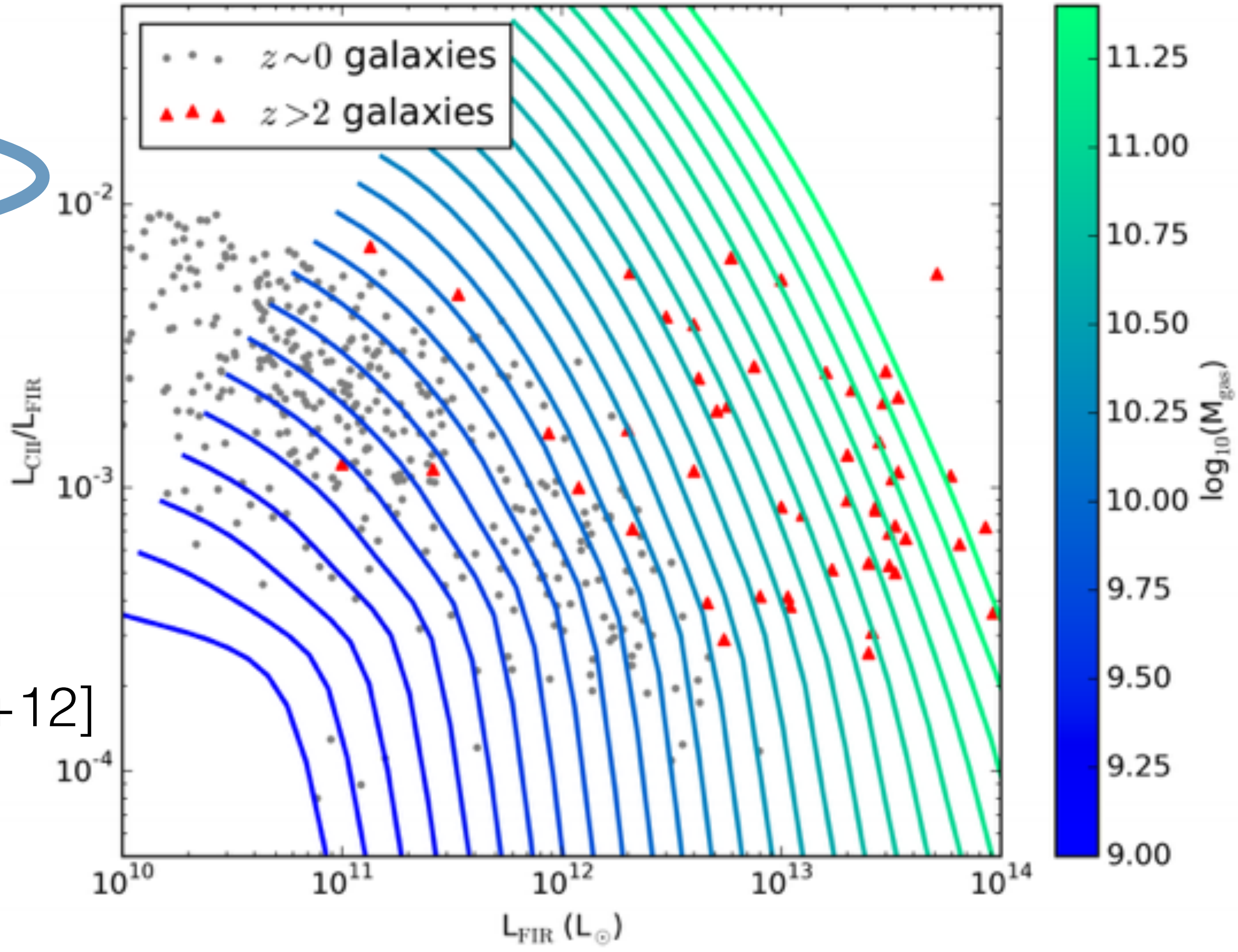

larger gas mass fraction -> more carbon in CO

Simulations of [CII] emission

[Graciá-Carpio+11]

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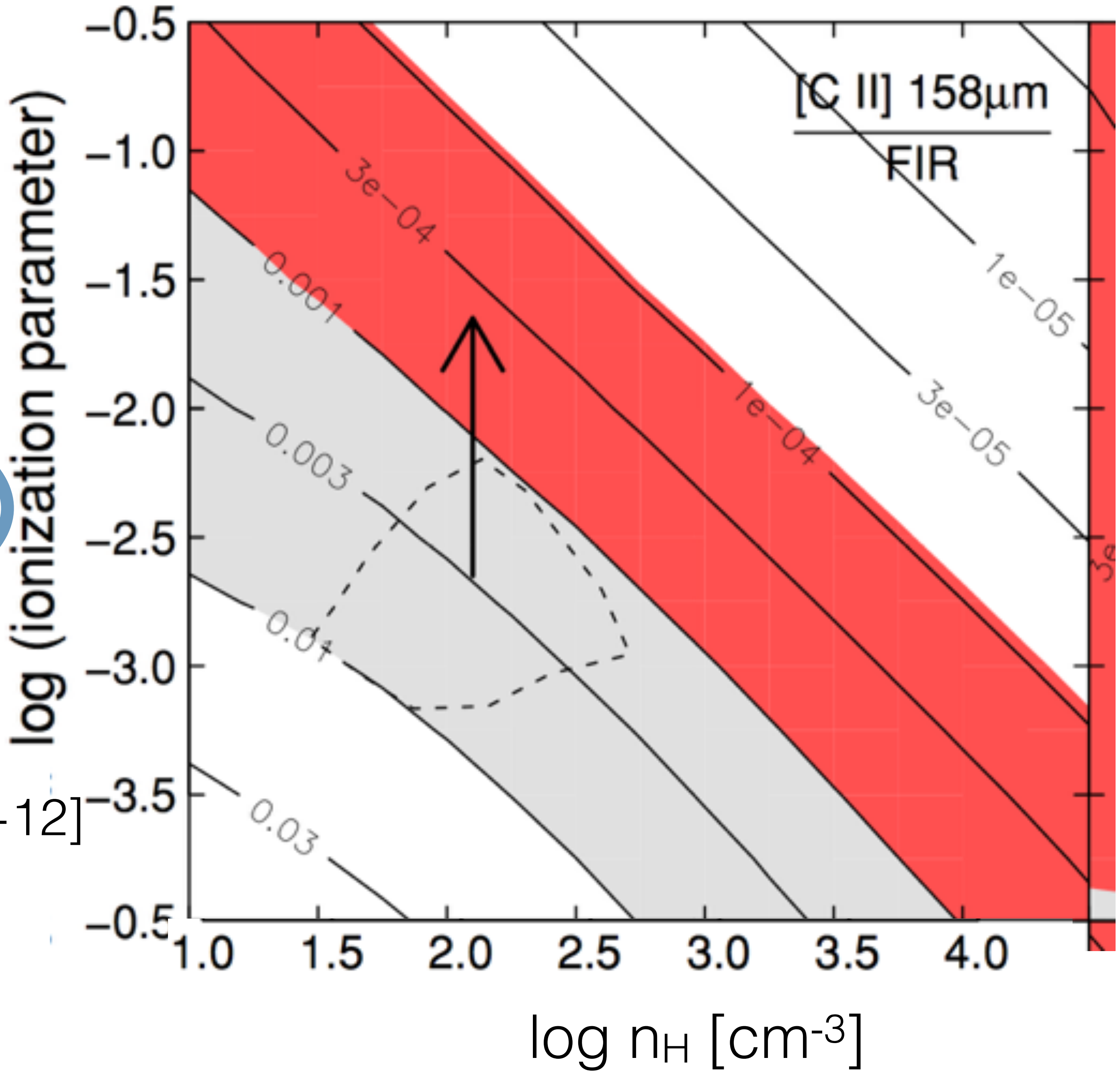

increasing the number of ionizing photons per H

Simulations of [CII] emission

[Popping+14]

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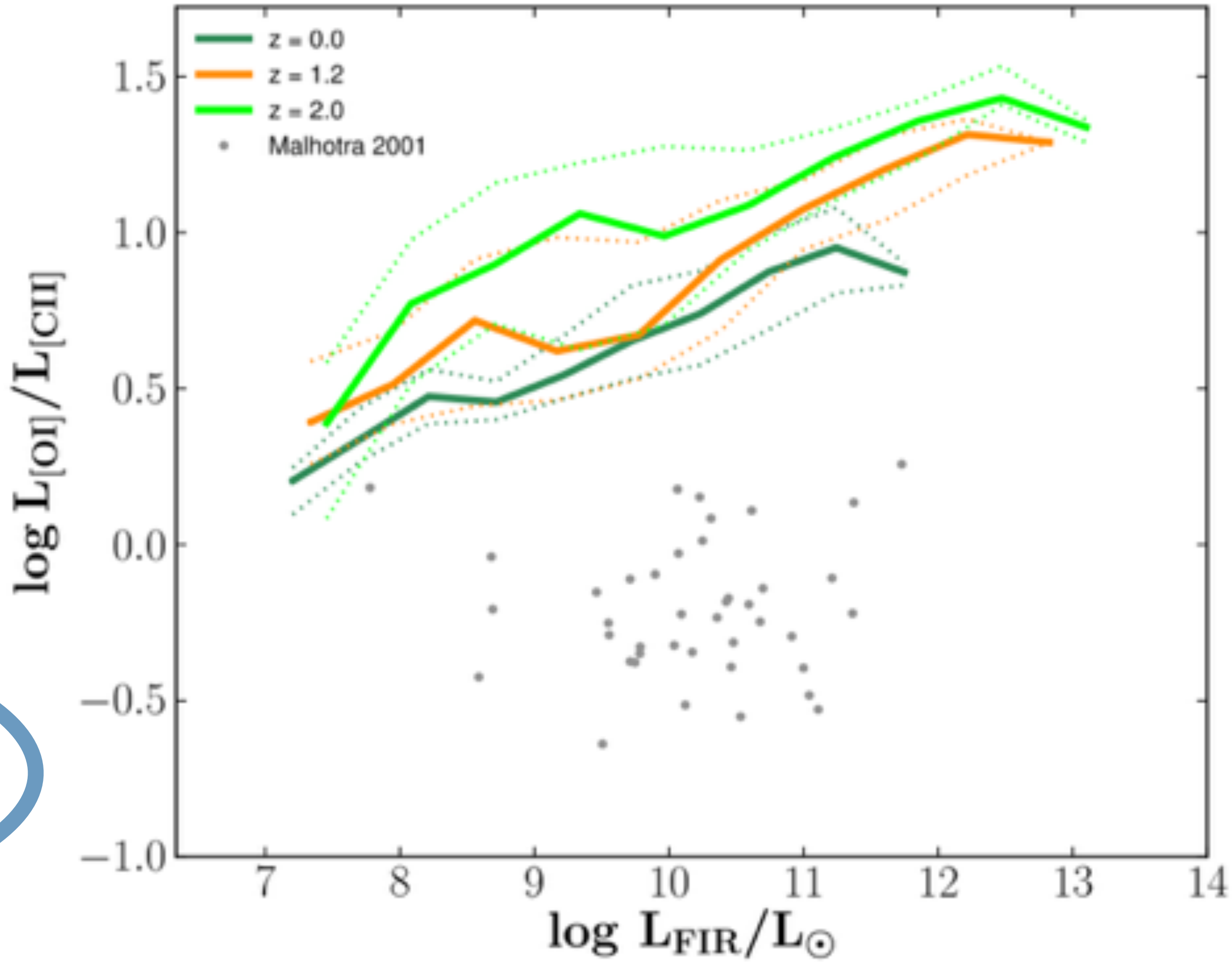
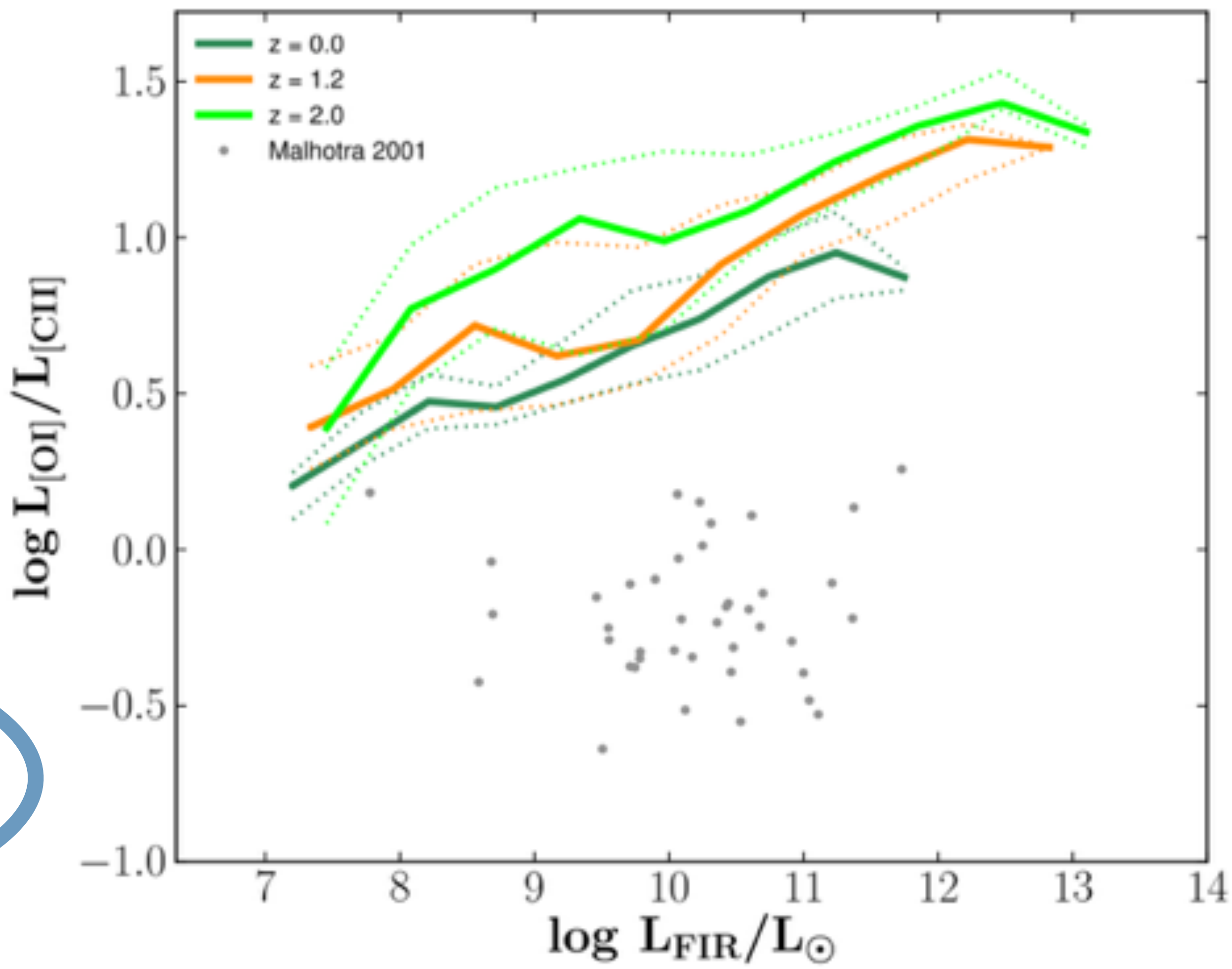


Simulations of [CII] emission

[Popping+14]



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- Other?

Finding the dominant mechanism depends on where [CII] comes from!

SÍGAME

SImulator of GAlaxy Millimeter/submillimeter Emission

SÍGAME

(='follow me' in Spanish)

SImulator of GAlaxy Millimeter/submillimeter Emission

Our aim:

- [CII] 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/

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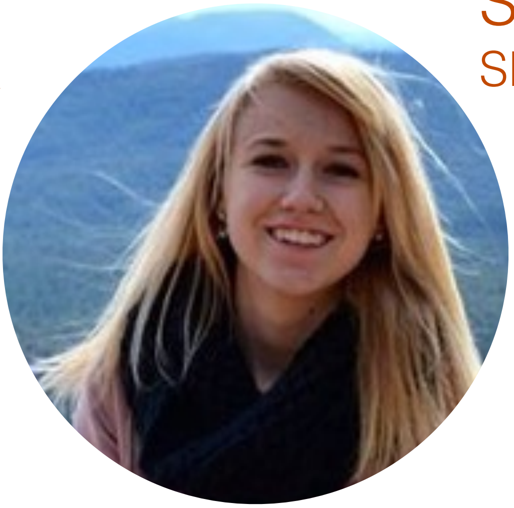
SImulator of GAlaxy Millimeter/submillimeter Emission

Current team:

Thomas R Greve
Dept of Physics and
Astronomy, UCL, UK



Stephanie Stawinski
SESE, ASU

Luis Niebla Rios
SESE, ASU

Robert Thompson
National Center for
Supercomputing Applications,
Urbana, IL, USA

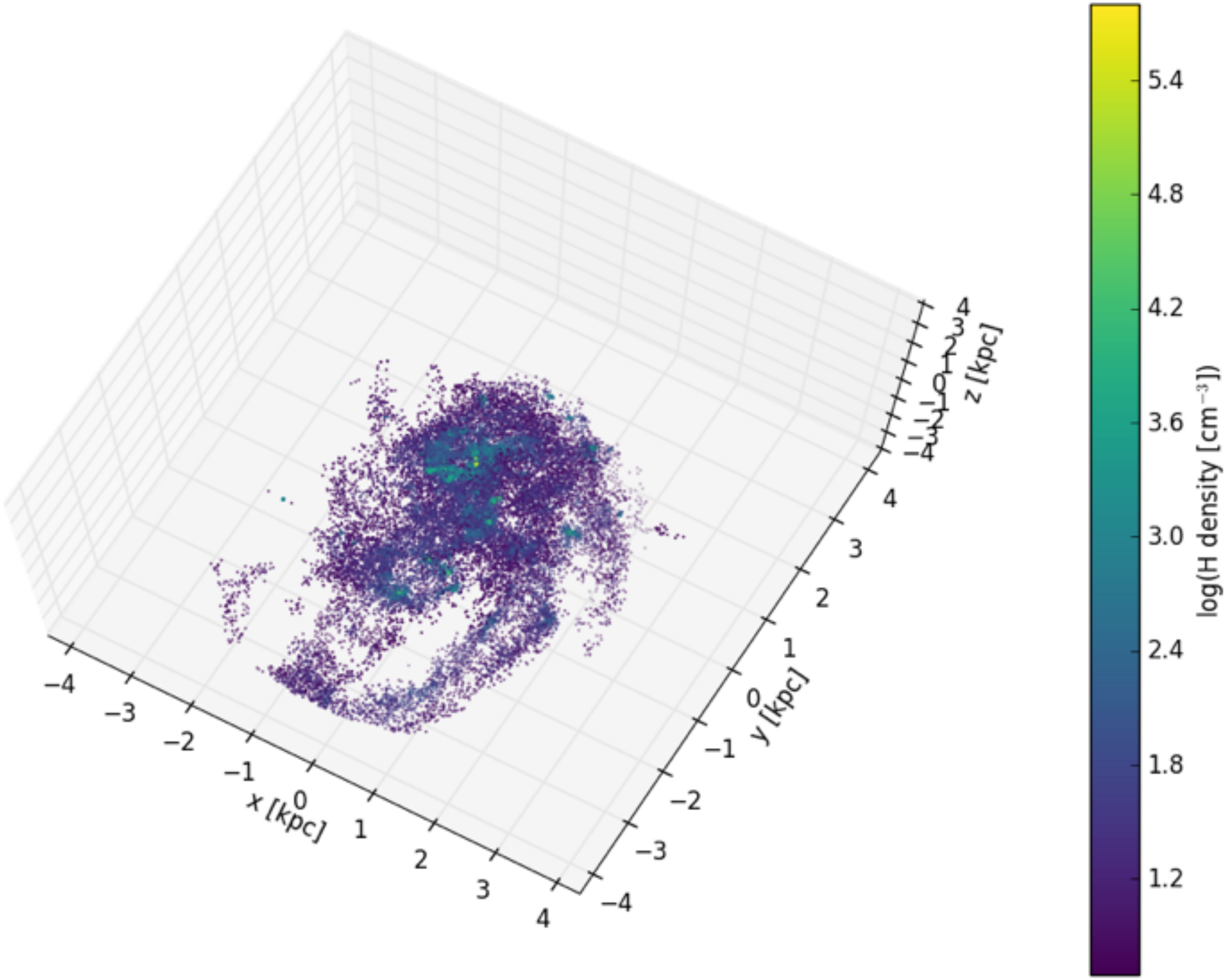
Desika Narayanan
Haverford College, PA, US

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

Key steps

Cosmological Smoothed Particle Hydrodynamics (SPH) simulations

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



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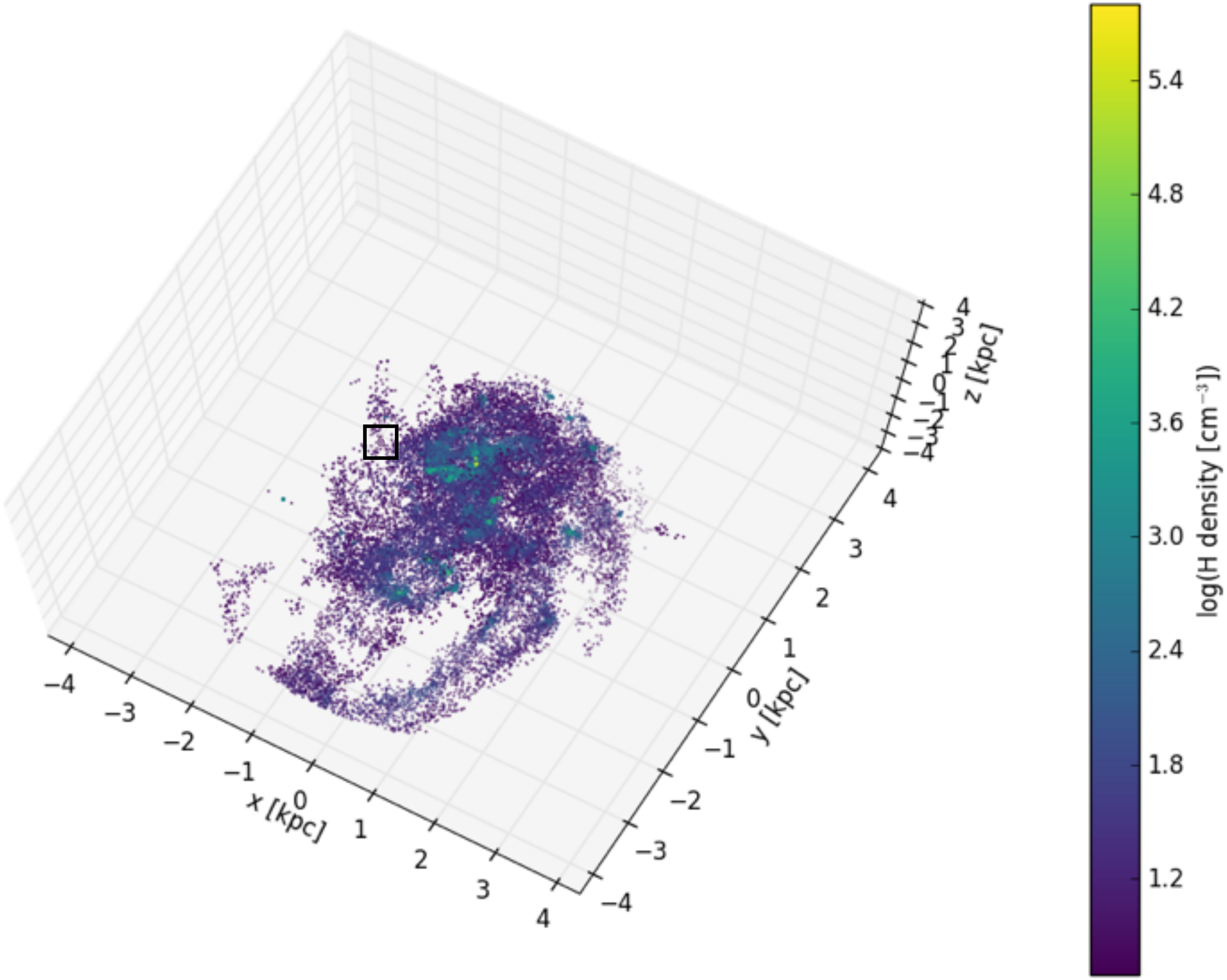
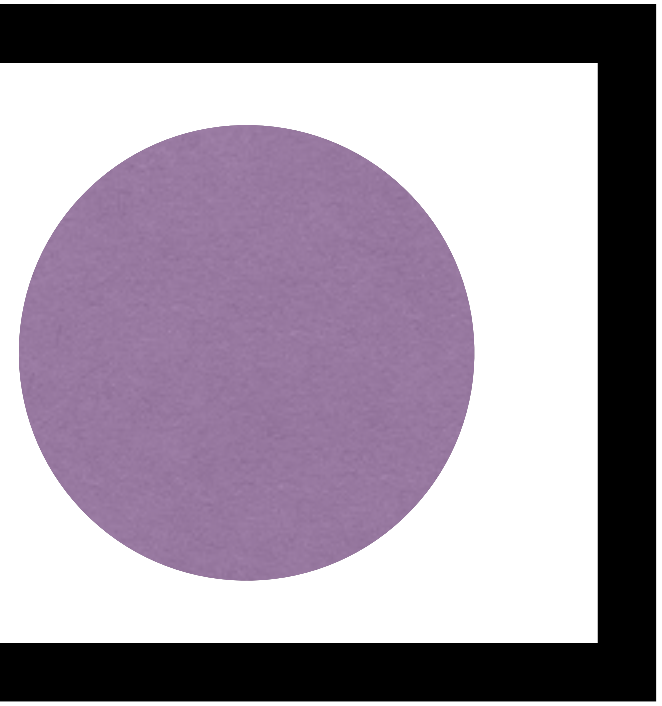


Key steps



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Key steps

Step 1: Derive “large-scale” properties

SPH particle:
[m_{SPH}, T_k, Z, h, x_e, f_{H2}]

Derived properties:
[G_0, P_{ext}]

SÍGAME

Key steps

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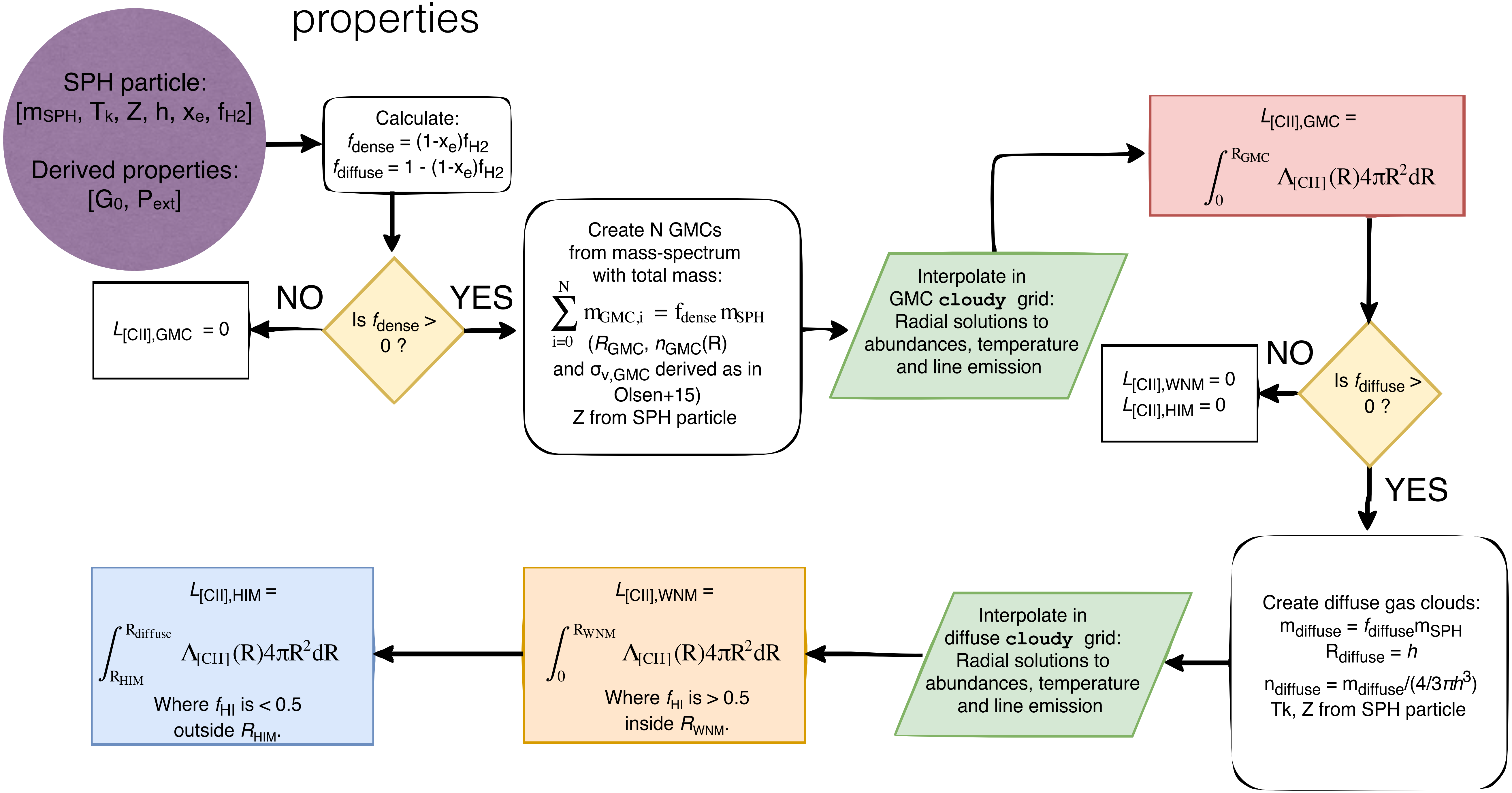


SPH particle: $[m_{SPH}, T_k, Z, h, x_e, f_{H2}]$

Derived properties: $[G_0, P_{ext}]$

Calculate:
$f_{dense} = (1-x_e)f_{H2}$
$f_{diffuse} = 1 - (1-x_e)f_{H2}$

Is $f_{dense} > 0$?

NO

$L_{[CII],GMC} = 0$

YES

Create N GMCs from mass-spectrum with total mass:

$$\sum_{i=0}^{N} m_{GMC,i} = f_{dense}\, m_{SPH}$$

$(R_{GMC}, n_{GMC}(R)$ and $\sigma_{v,GMC}$ derived as in Olsen+15)
Z from SPH particle

Interpolate in GMC `cloudy` grid: Radial solutions to abundances, temperature and line emission

$$L_{[CII],GMC} = \int_0^{R_{GMC}} \Lambda_{[CII]}(R) 4\pi R^2 dR$$

Is $f_{diffuse} > 0$?

NO

$L_{[CII],WNM} = 0$
$L_{[CII],HIM} = 0$

YES

Create diffuse gas clouds:
$m_{diffuse} = f_{diffuse} m_{SPH}$
$R_{diffuse} = h$
$n_{diffuse} = m_{diffuse}/(4/3\pi h^3)$
Tk, Z from SPH particle

Interpolate in diffuse `cloudy` grid: Radial solutions to abundances, temperature and line emission

$$L_{[CII],WNM} = \int_0^{R_{WNM}} \Lambda_{[CII]}(R) 4\pi R^2 dR$$

Where f_{HI} is > 0.5 inside R_{WNM}.

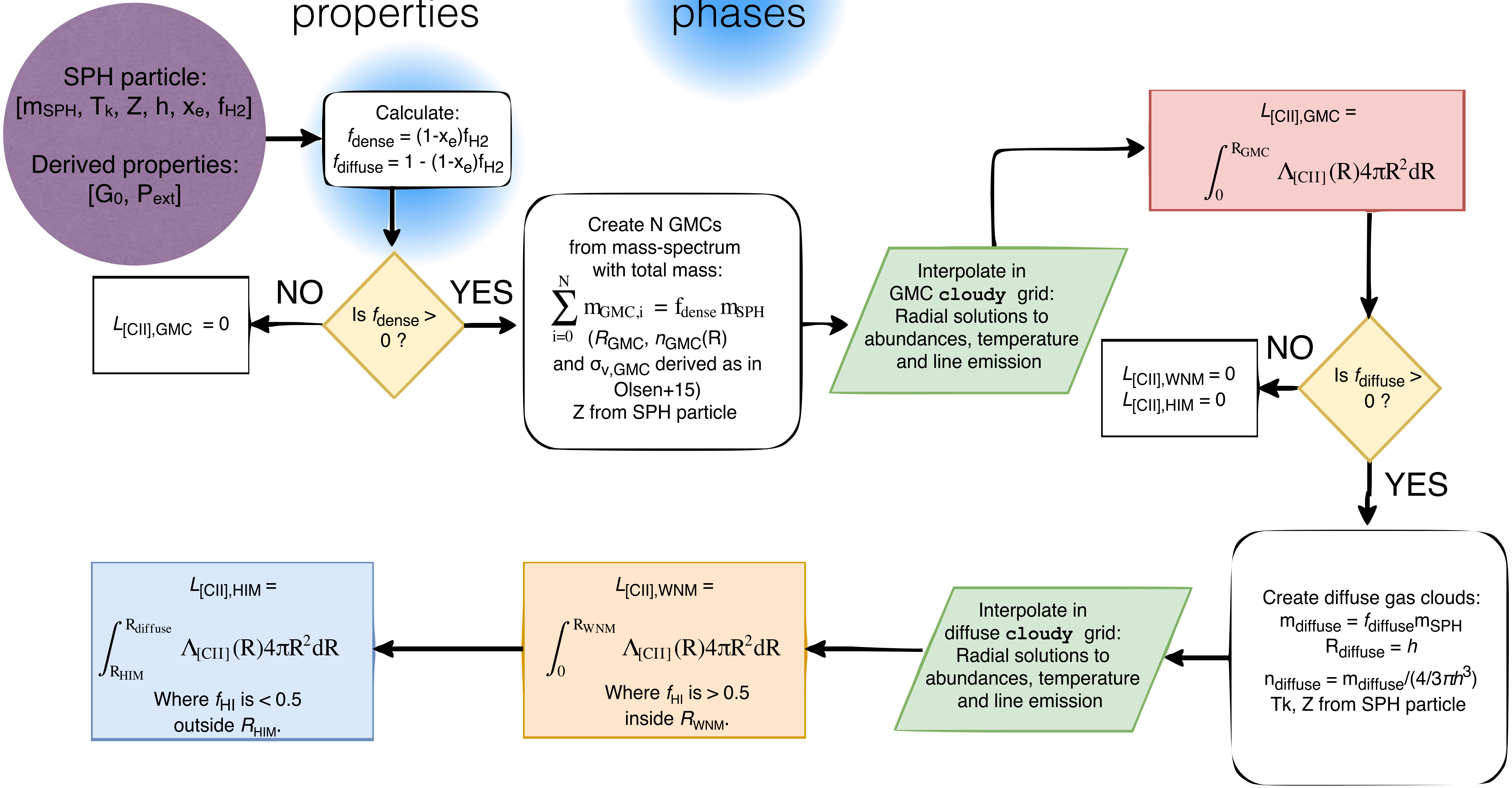
$$L_{[CII],HIM} = \int_{R_{HIM}}^{R_{diffuse}} \Lambda_{[CII]}(R) 4\pi R^2 dR$$

Where f_{HI} is < 0.5 outside R_{HIM}.

Key steps

Step 1:
Derive “large-scale” properties

Step 2:
Divide into two phases



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Radial solutions to
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Create diffuse gas clouds:
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Tk, Z from SPH particle

Interpolate in
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Where f_{HI} is > 0.5
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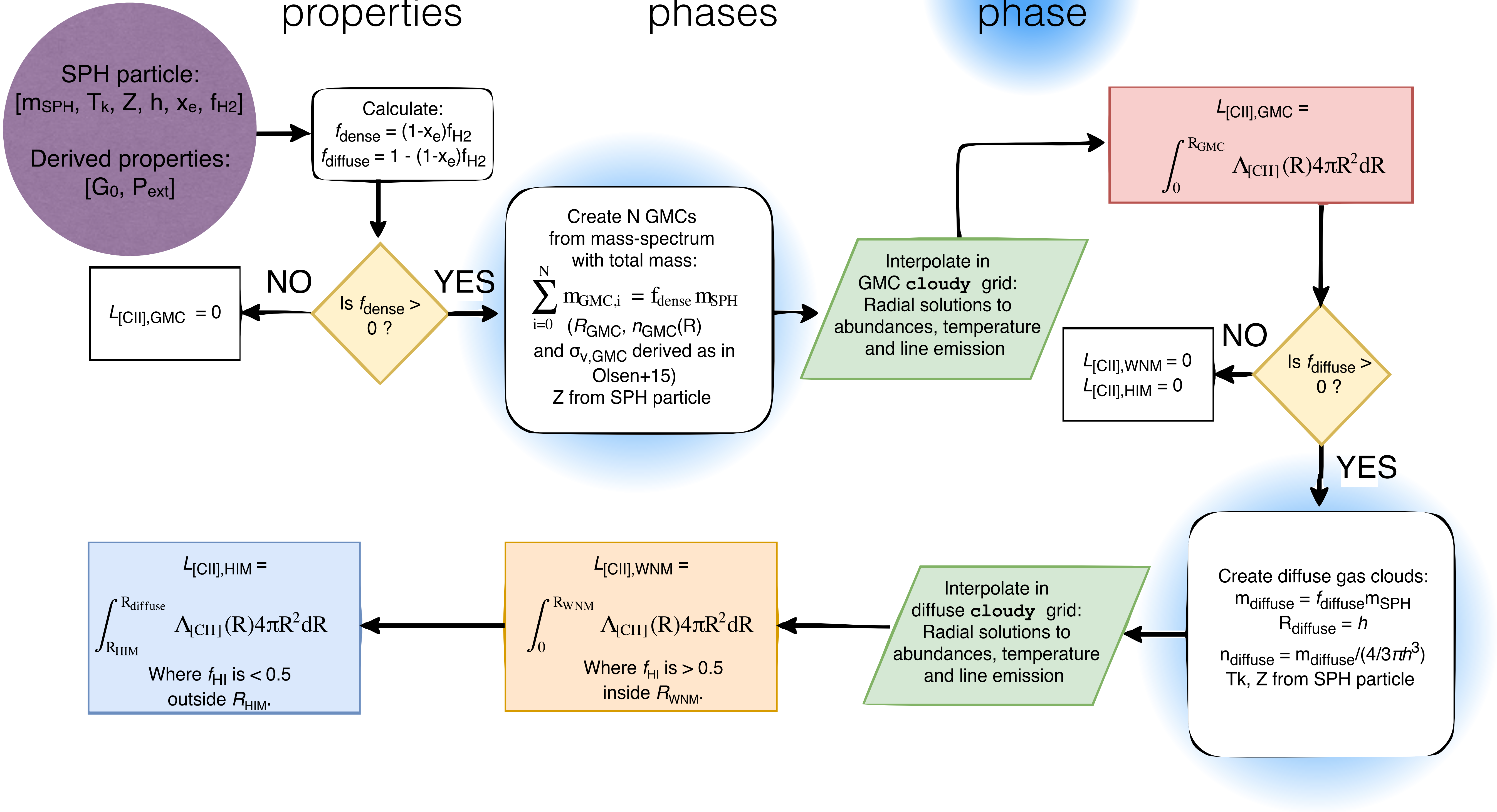
Key steps

Step 1: Derive “large-scale” properties

Step 2: Divide into two phases

Step 3: Subgrid each phase



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Key steps

Step 1:
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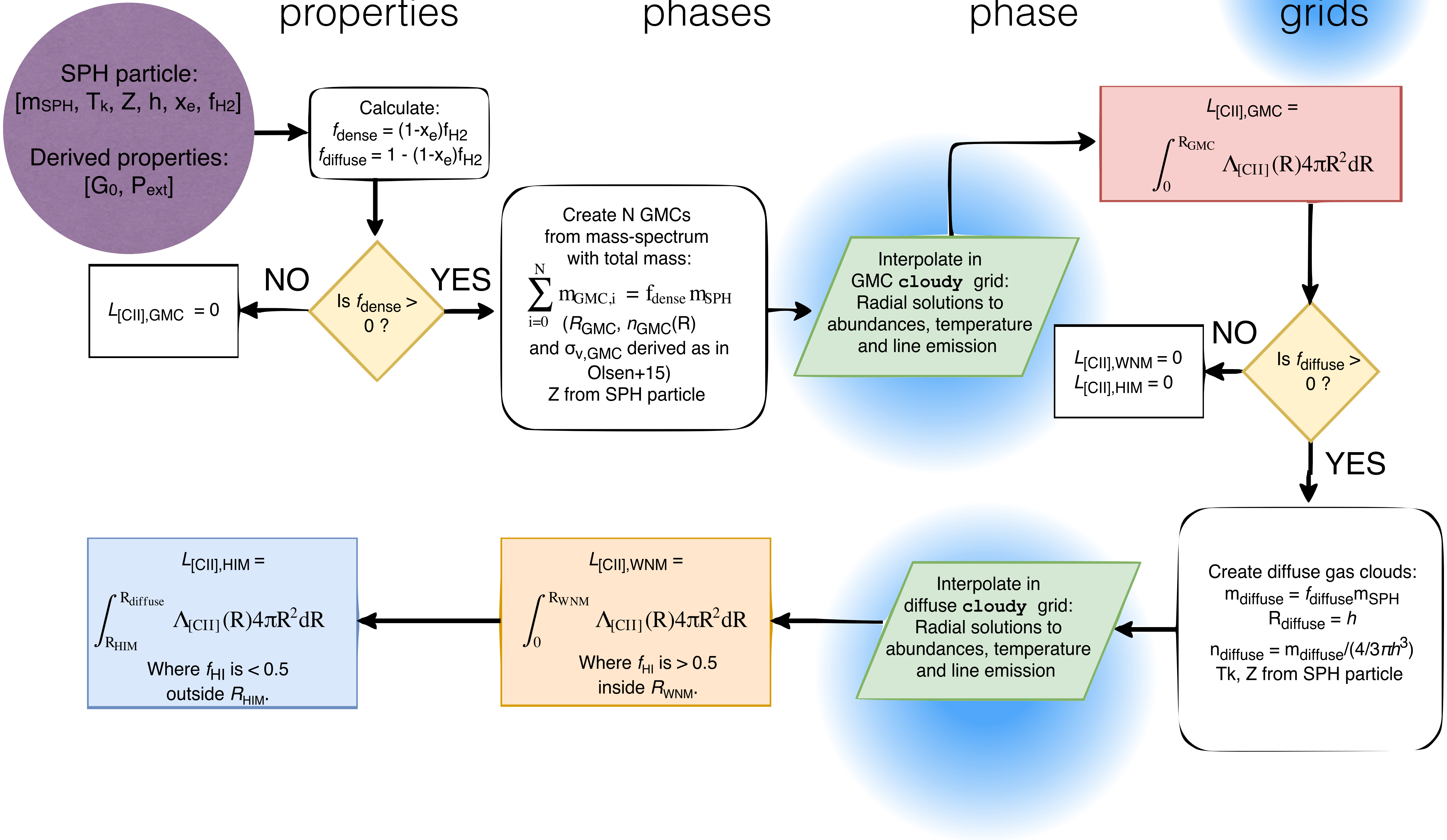
Step 2:
Divide into two phases

Step 3:
Subgrid each phase

Step 4:
Interpolate in grids



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Where f_{HI} is < 0.5 outside R_{HIM}.

Definition of ISM phases

SÍGAME divides the entire SPH gas mass into:

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

diffuse gas:

- **WNM** Warm Neutral Medium — part of the diffuse gas clouds that is mostly neutral
- **HIM** Hot Ionized Medium — part of the diffuse gas clouds that is mostly ionized

SÍGAME Preliminary results at z~6 with SÍGAME

Science Questions:

1. Do our models predict a $L_{[CII]}$-SFR relation?

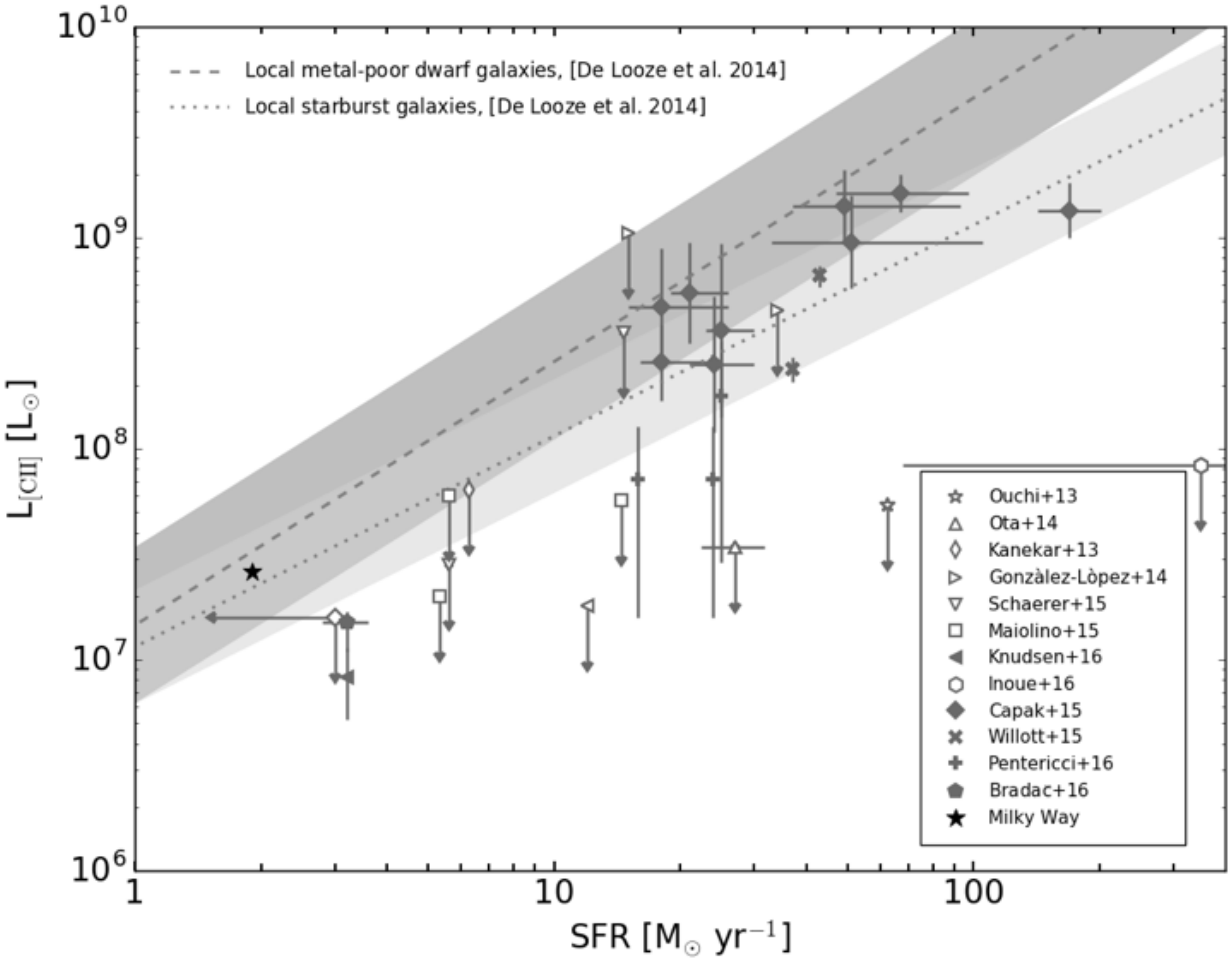
2. Where does the [CII] emission come from?

2.1. What controls the contribution from star-forming gas?

3. If not SFR, what does [CII] trace?

The [CII]-SFR relation at z~6

[CII] and SFR measurements at z~5-7.5:

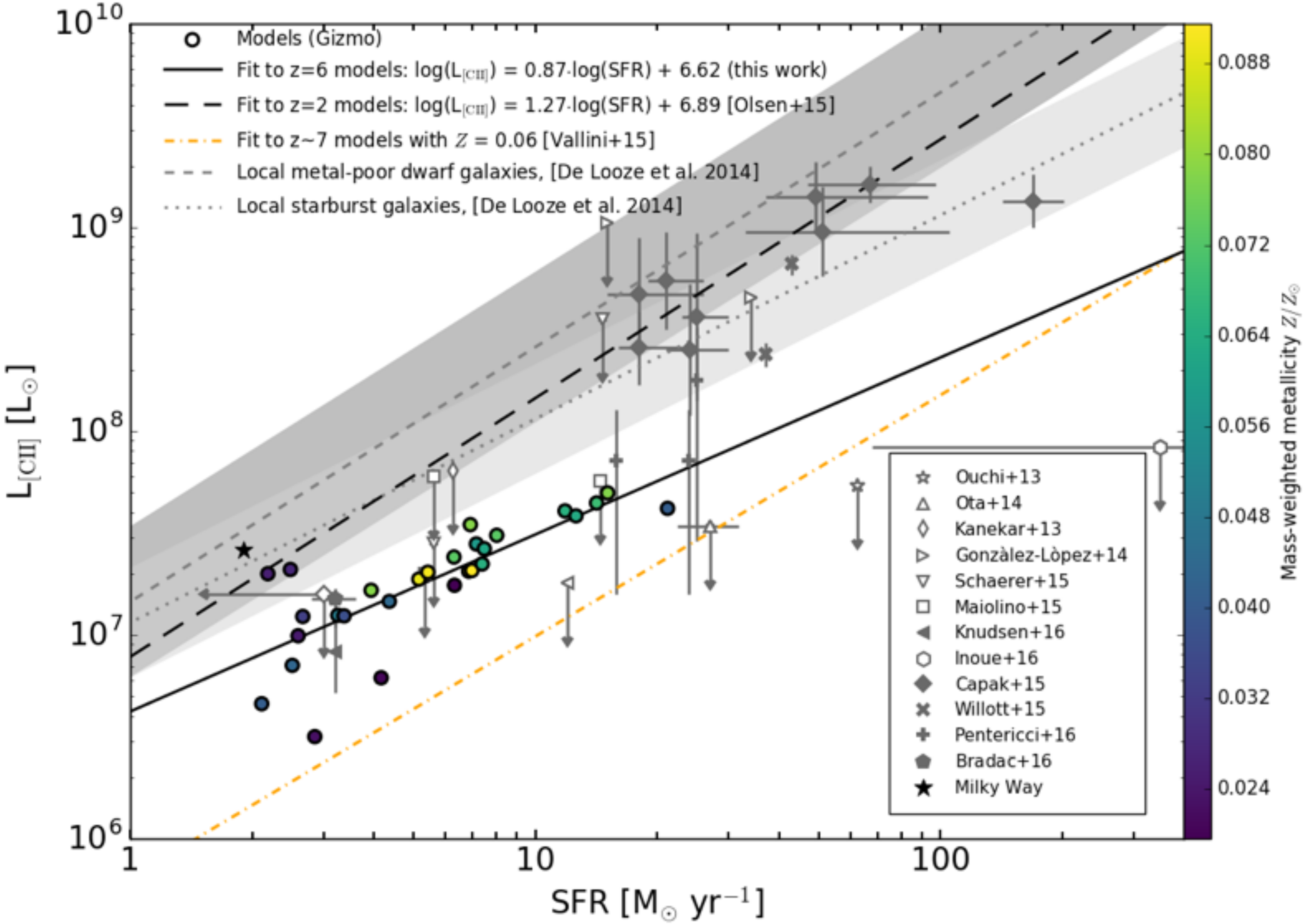


NMSU, Nov 18 2016

[Olsen+16: in prep]

The [CII]-SFR relation at z~6

[CII] and SFR measurements at z~5-7.5,
with our model galaxies at z~5.875-6.125:



[Olsen+16: in prep]

SÍGAME

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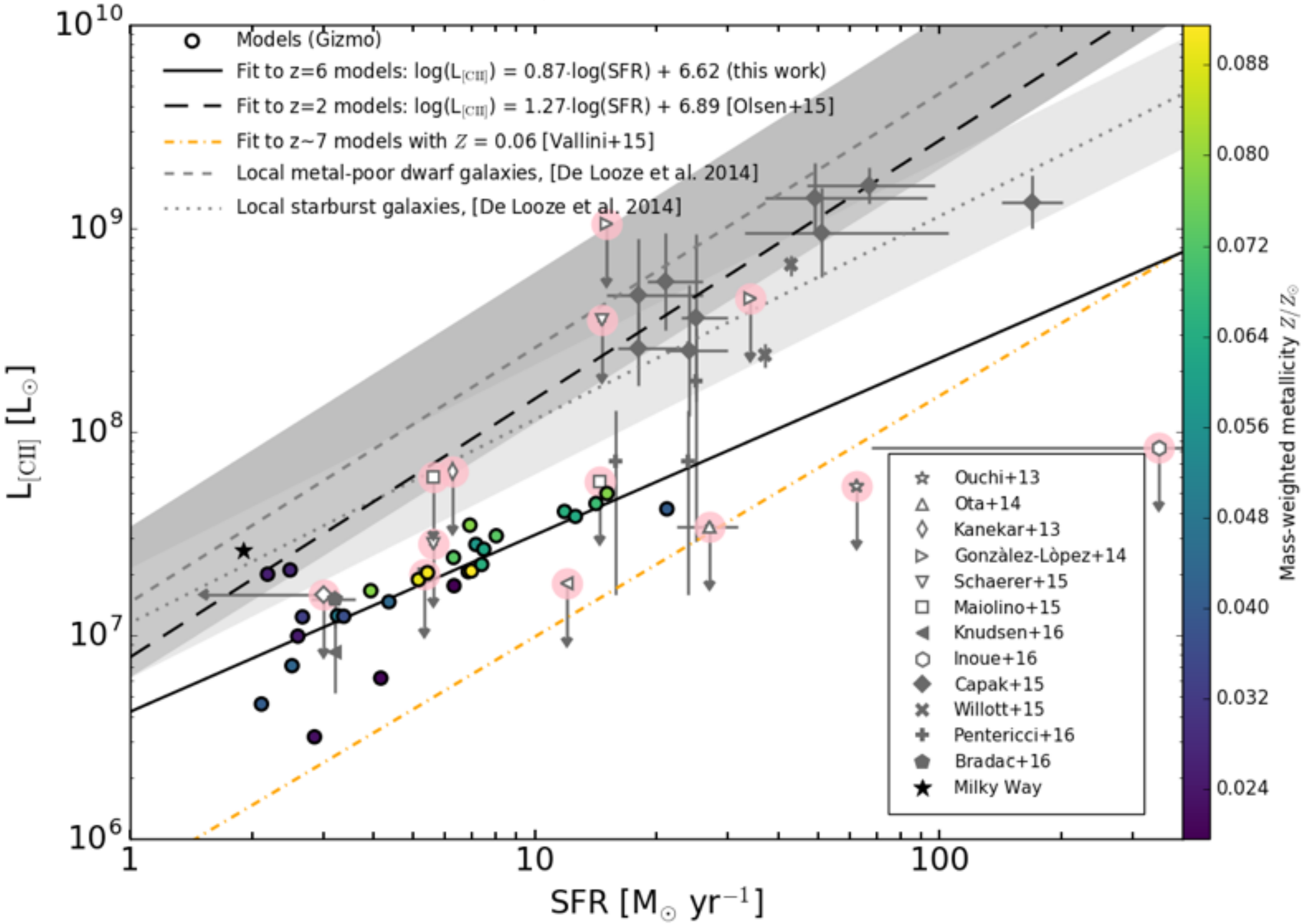

1. Models are in agreement with most (10/14) upper limits

[Olsen+16: in prep]

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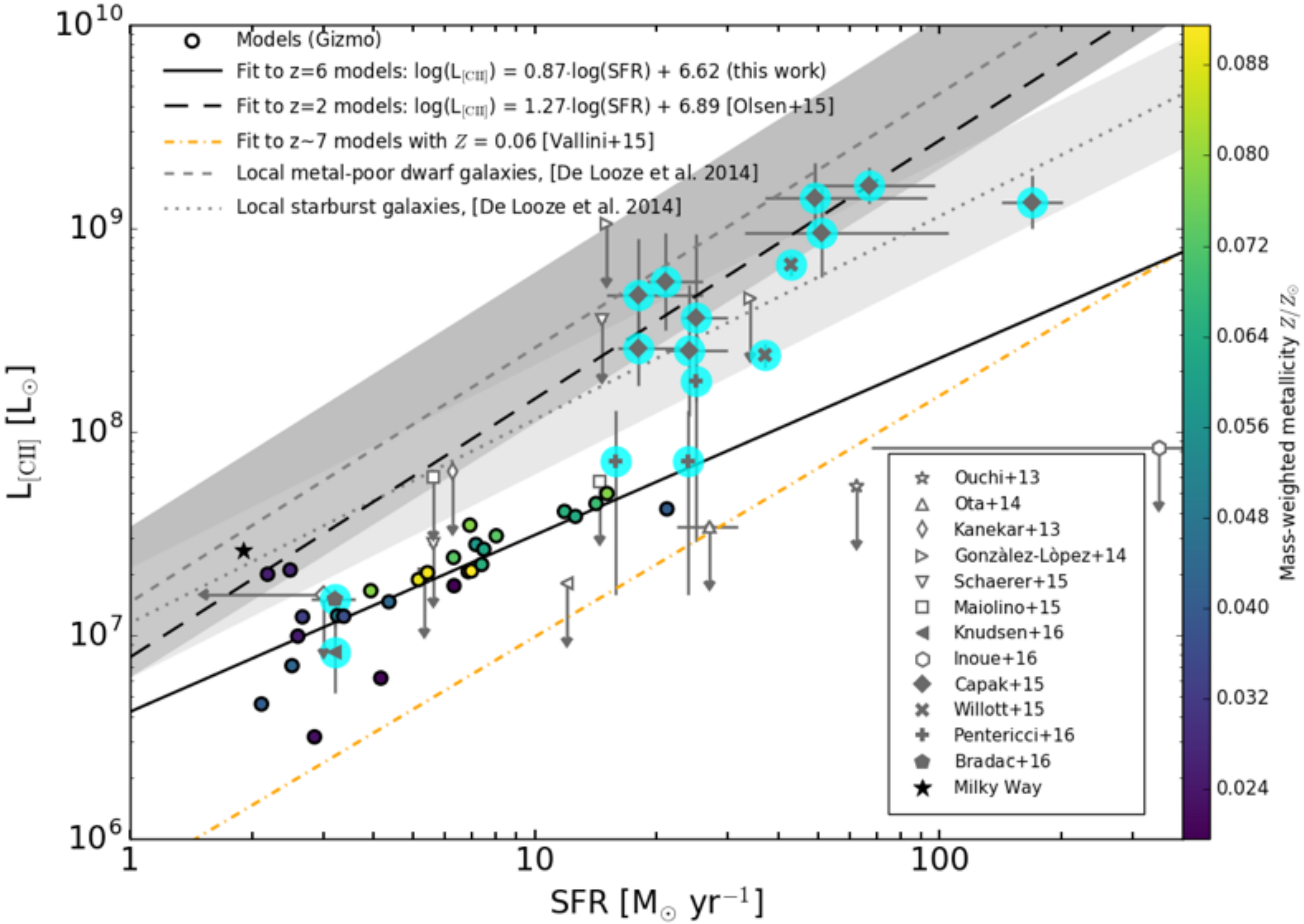

2. below most (11/16) detections

[Olsen+16: in prep]

Where does the [CII] emission come from?

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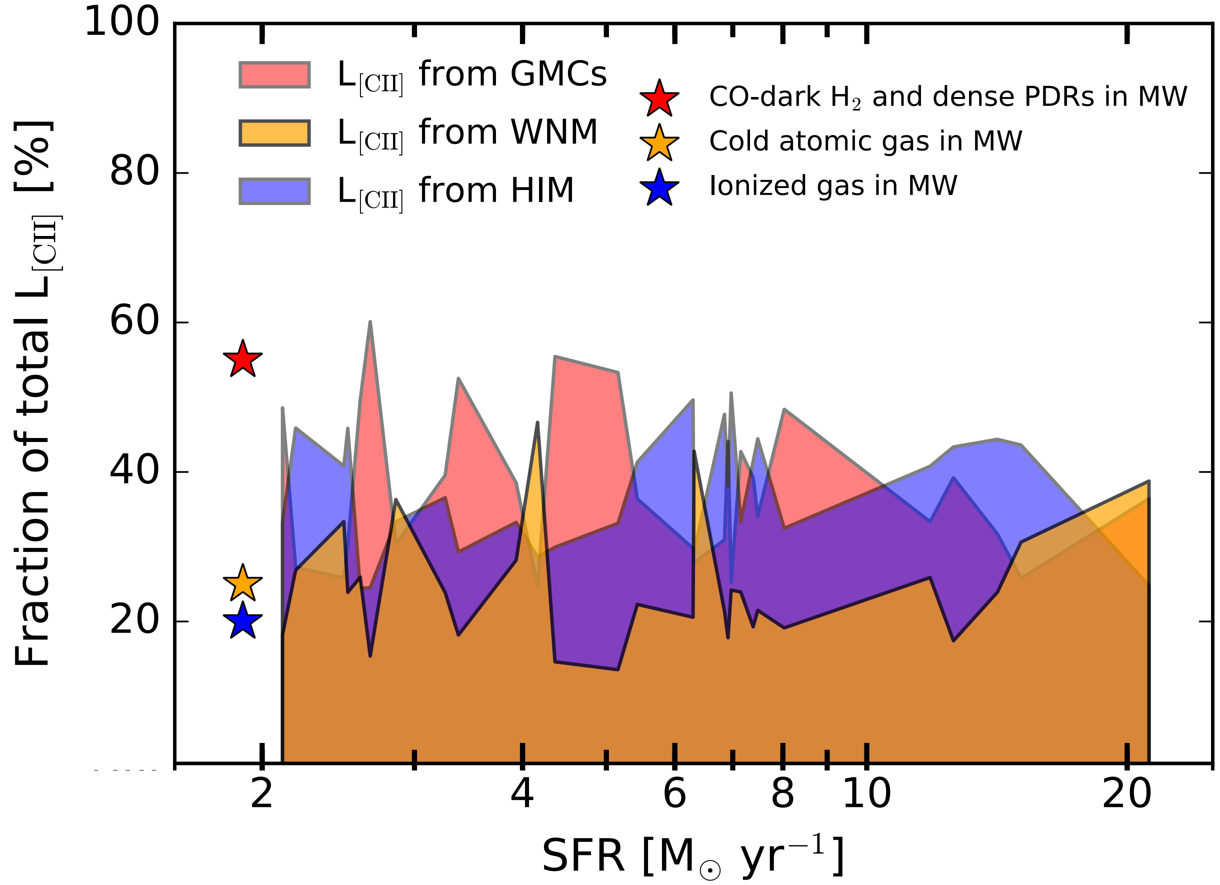

[Olsen+16: in prep]

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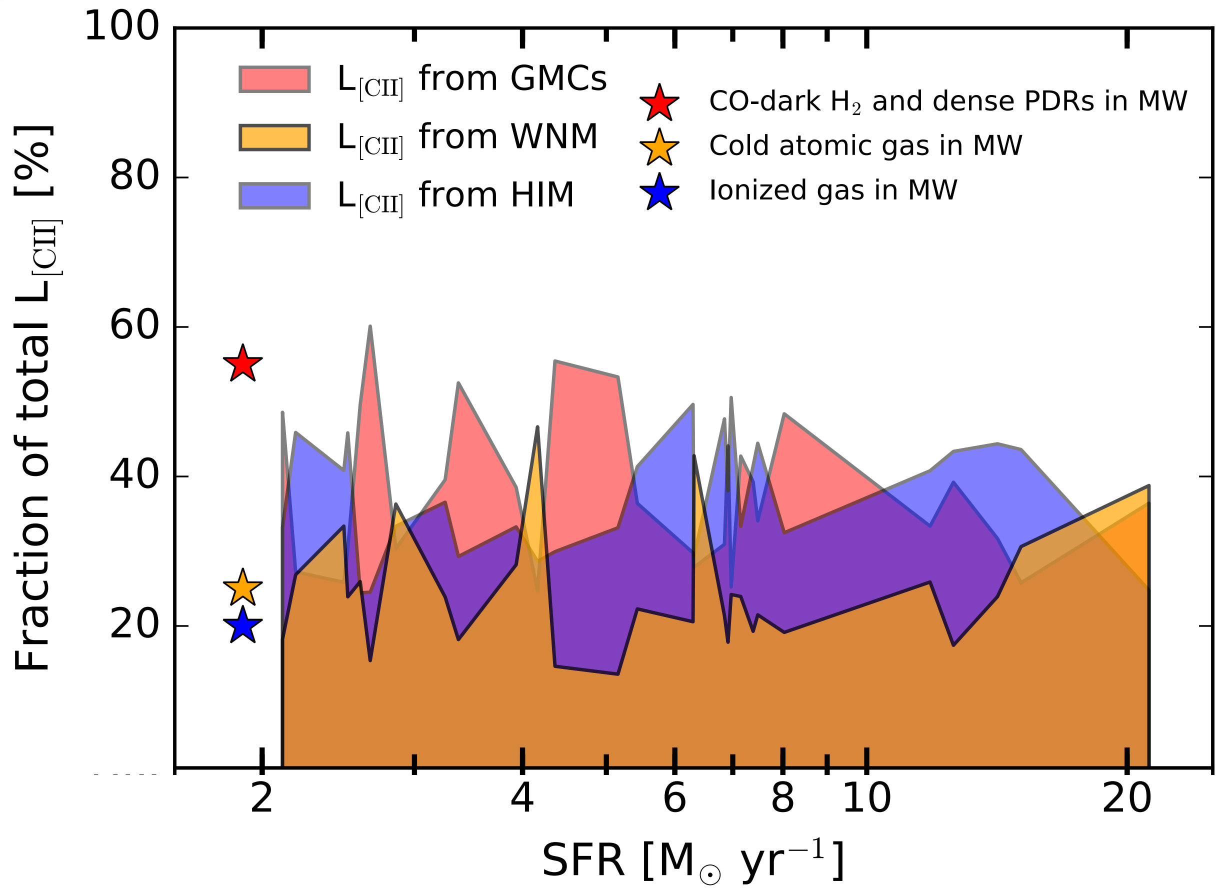

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25% from WNM

38% from HIM

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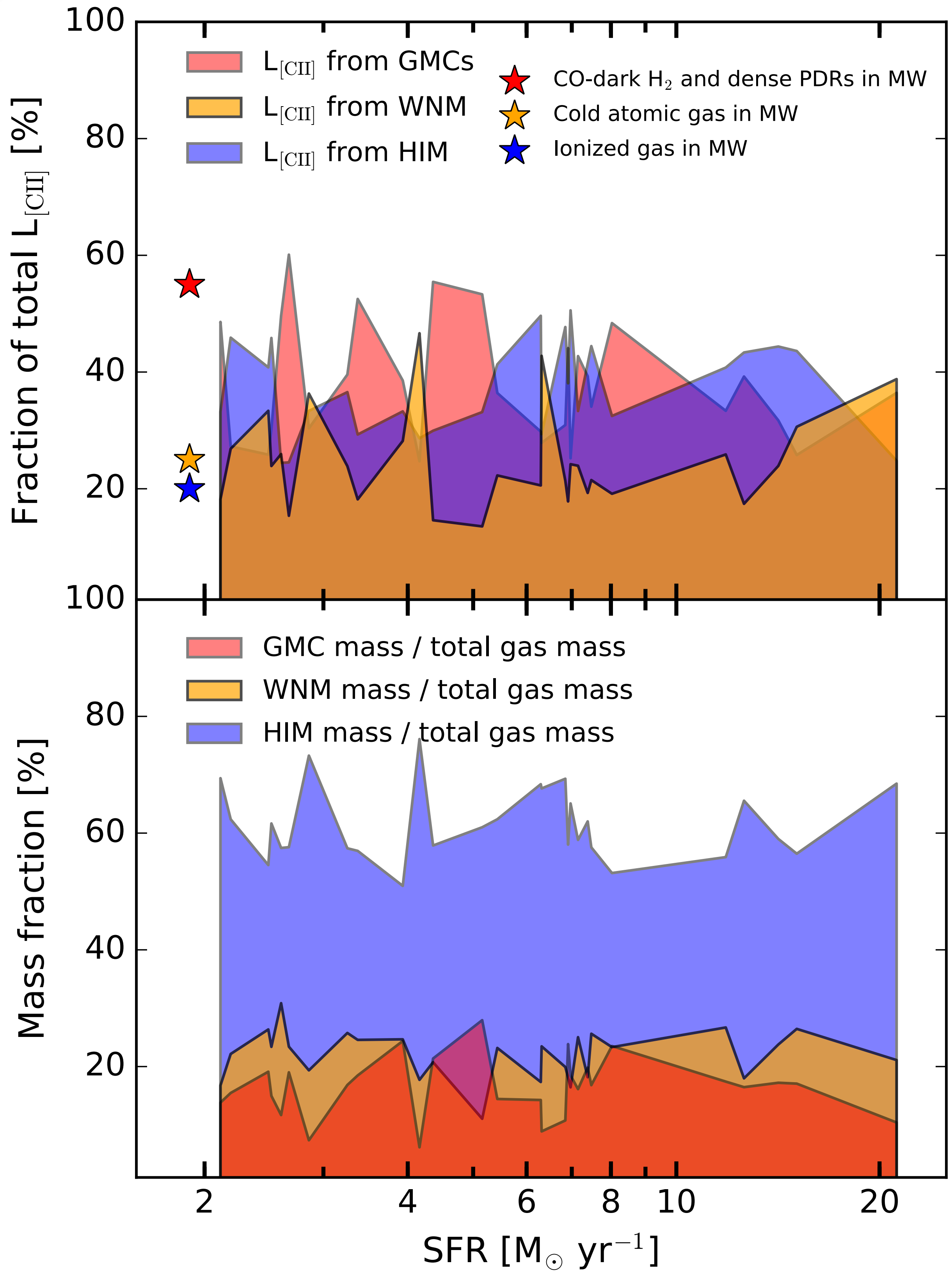

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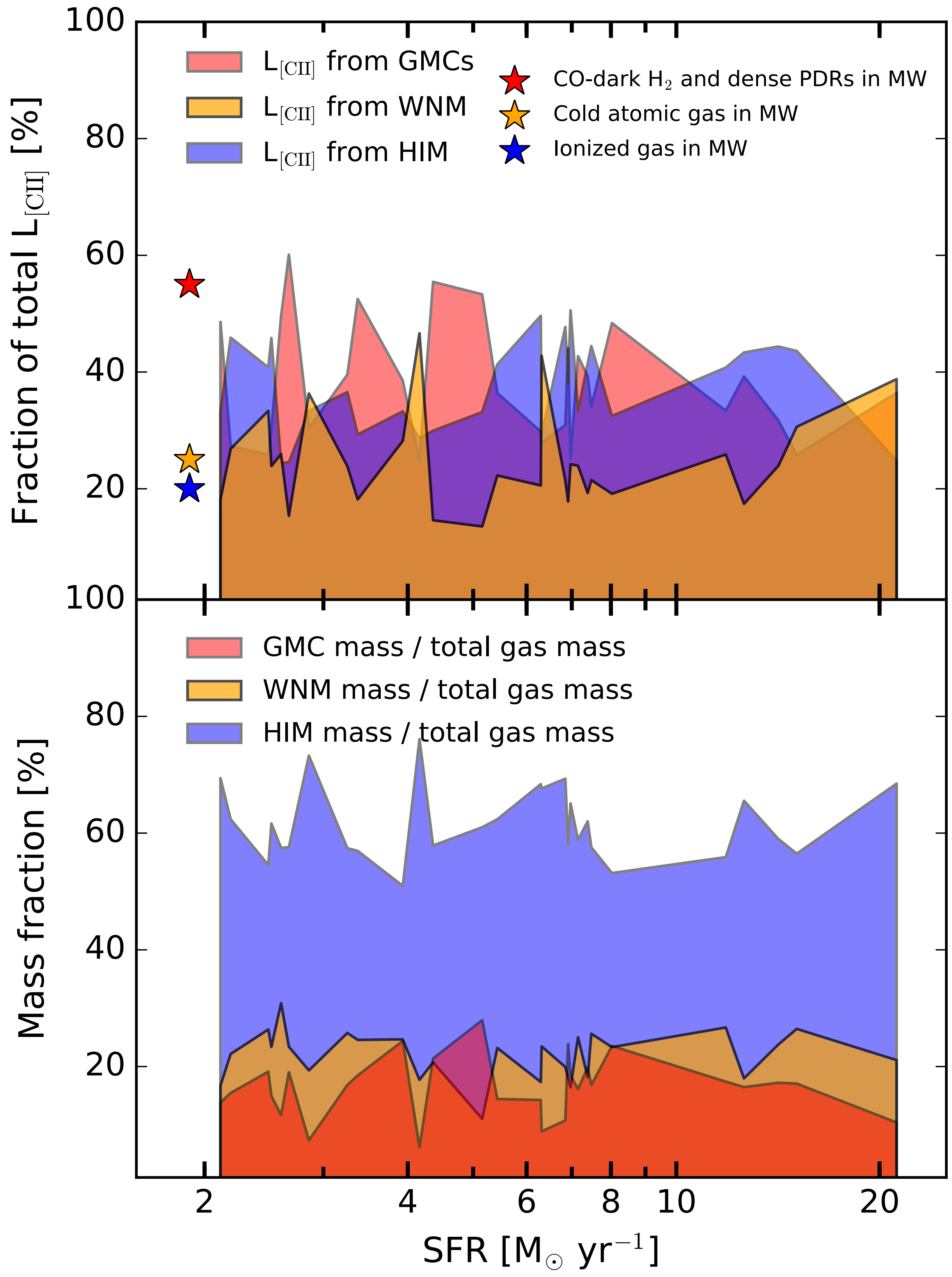

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On average, the ISM mass is composed of:
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22% from WNM
62% from HIM

[Olsen+16: in prep]

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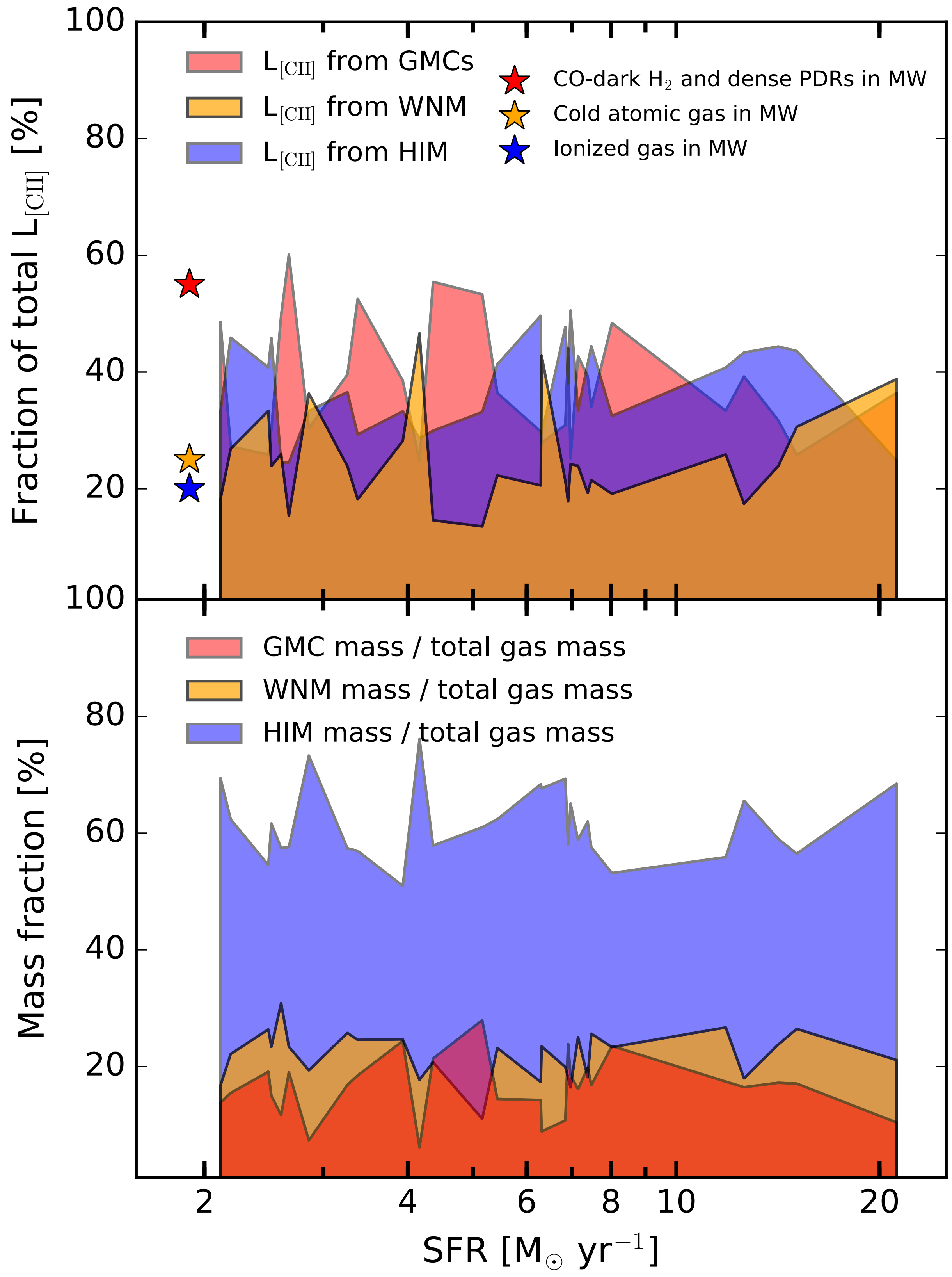

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=> GMCs are more efficient [CII] emitters!

NMSU, Nov 18 2016

[Olsen+16: in prep]

What controls the fraction of $L_{[CII]}$ coming from GMCs?

(See also [Accurso+16])

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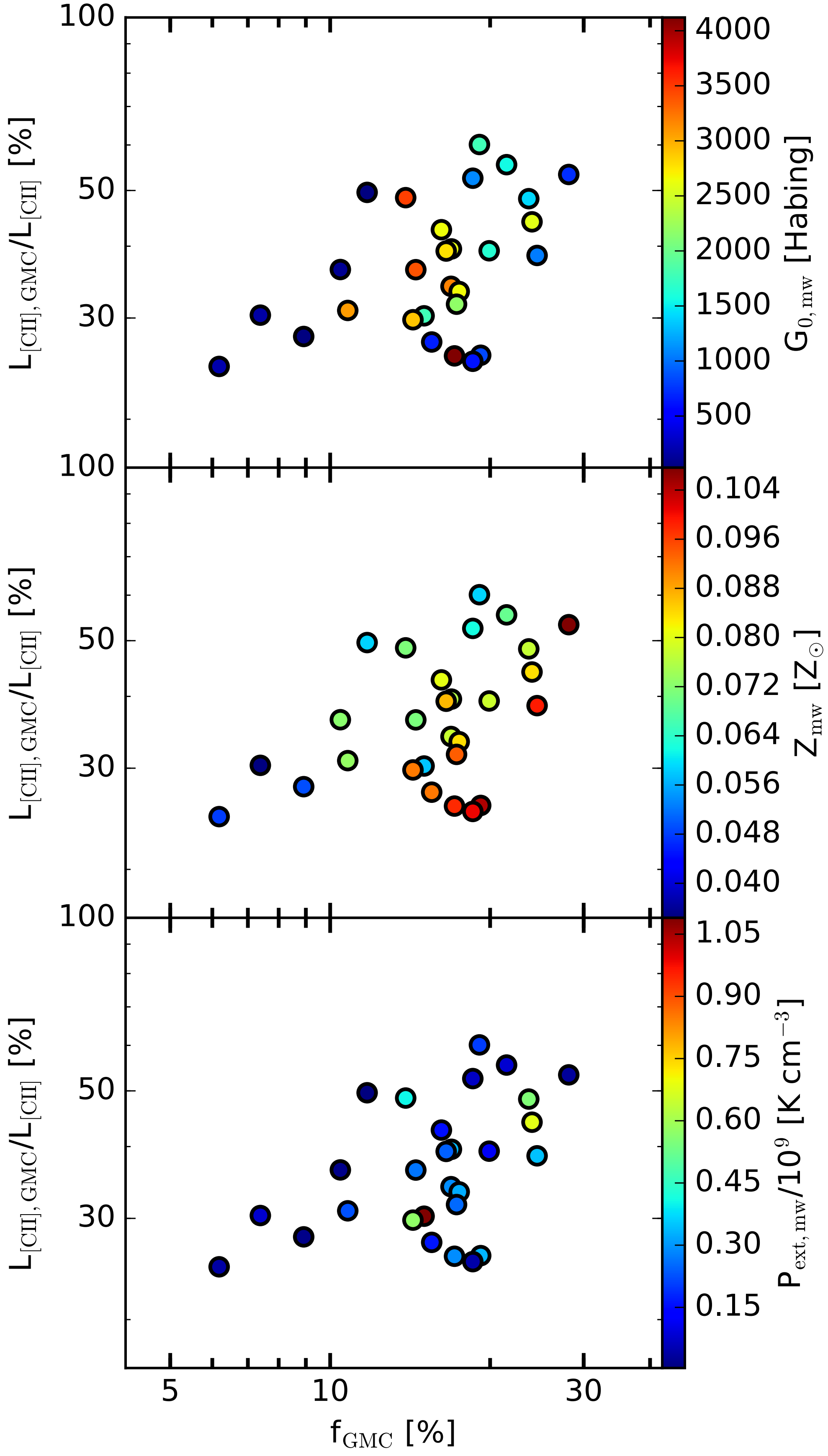

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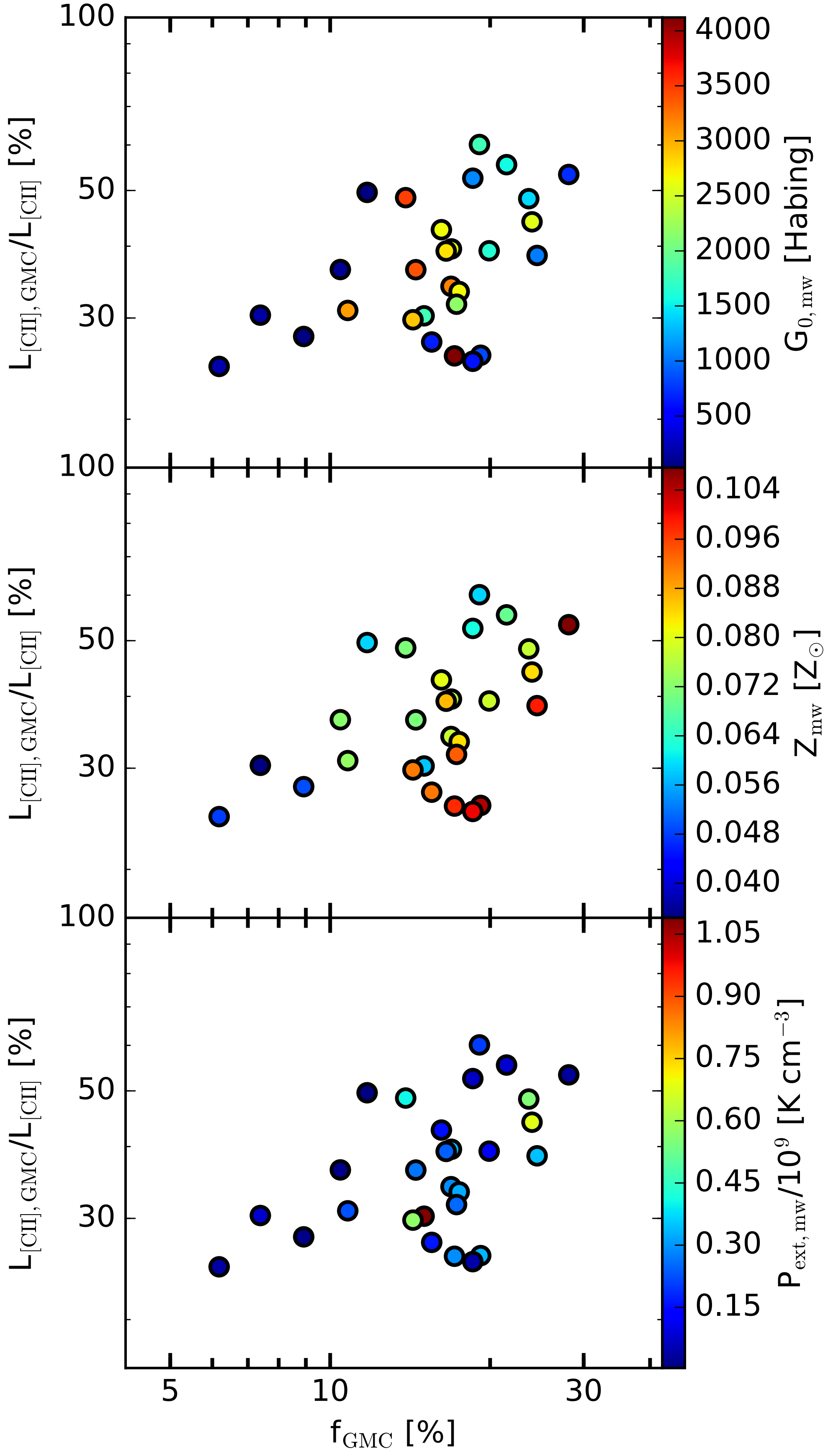

For higher mass-weighted metallicity, a smaller fraction of $L_{[CII]}$ comes from GMCs

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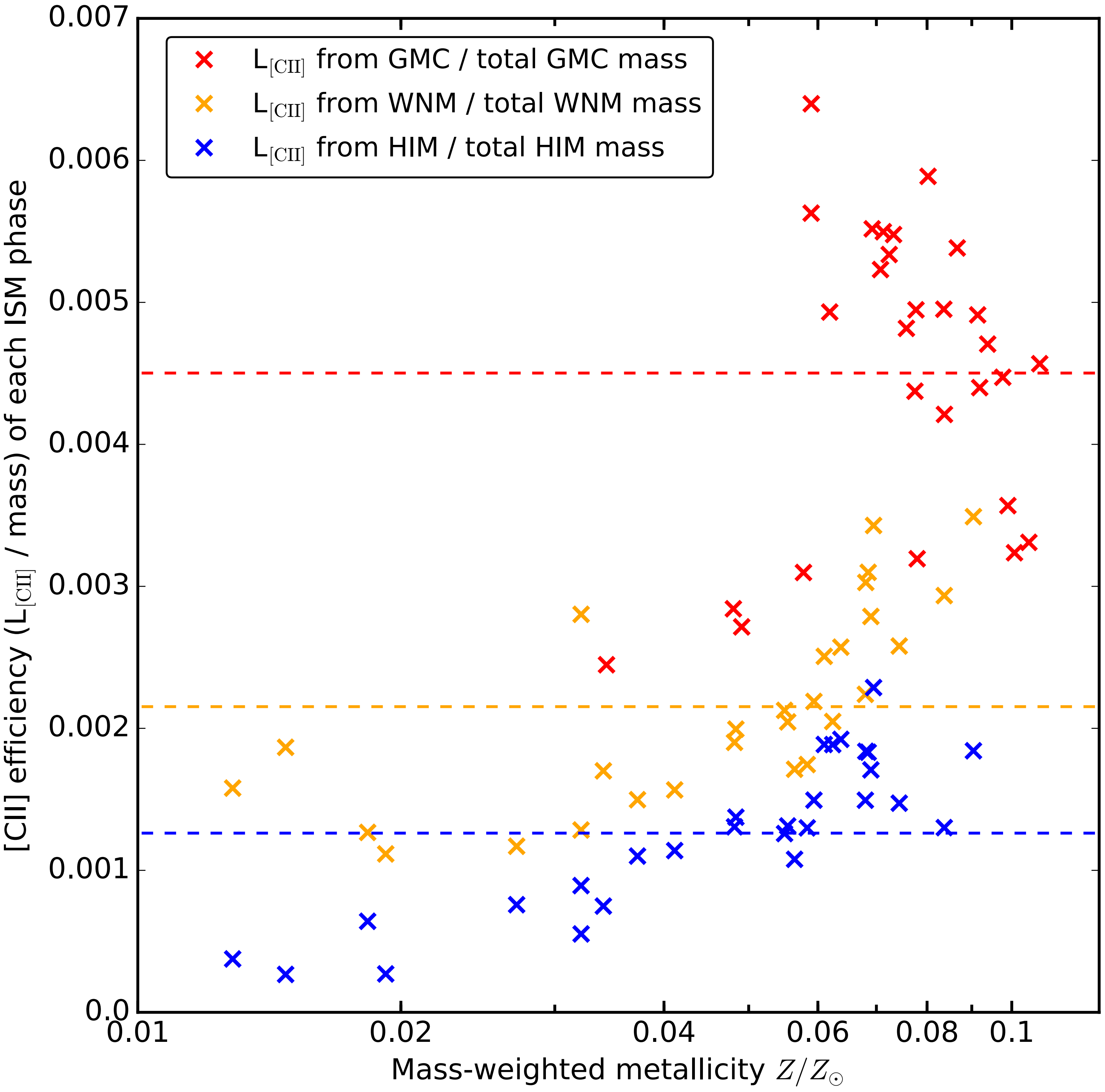
[Olsen+16: in prep]

[CII] efficiency of each ISM phase



[Olsen+16: in prep]

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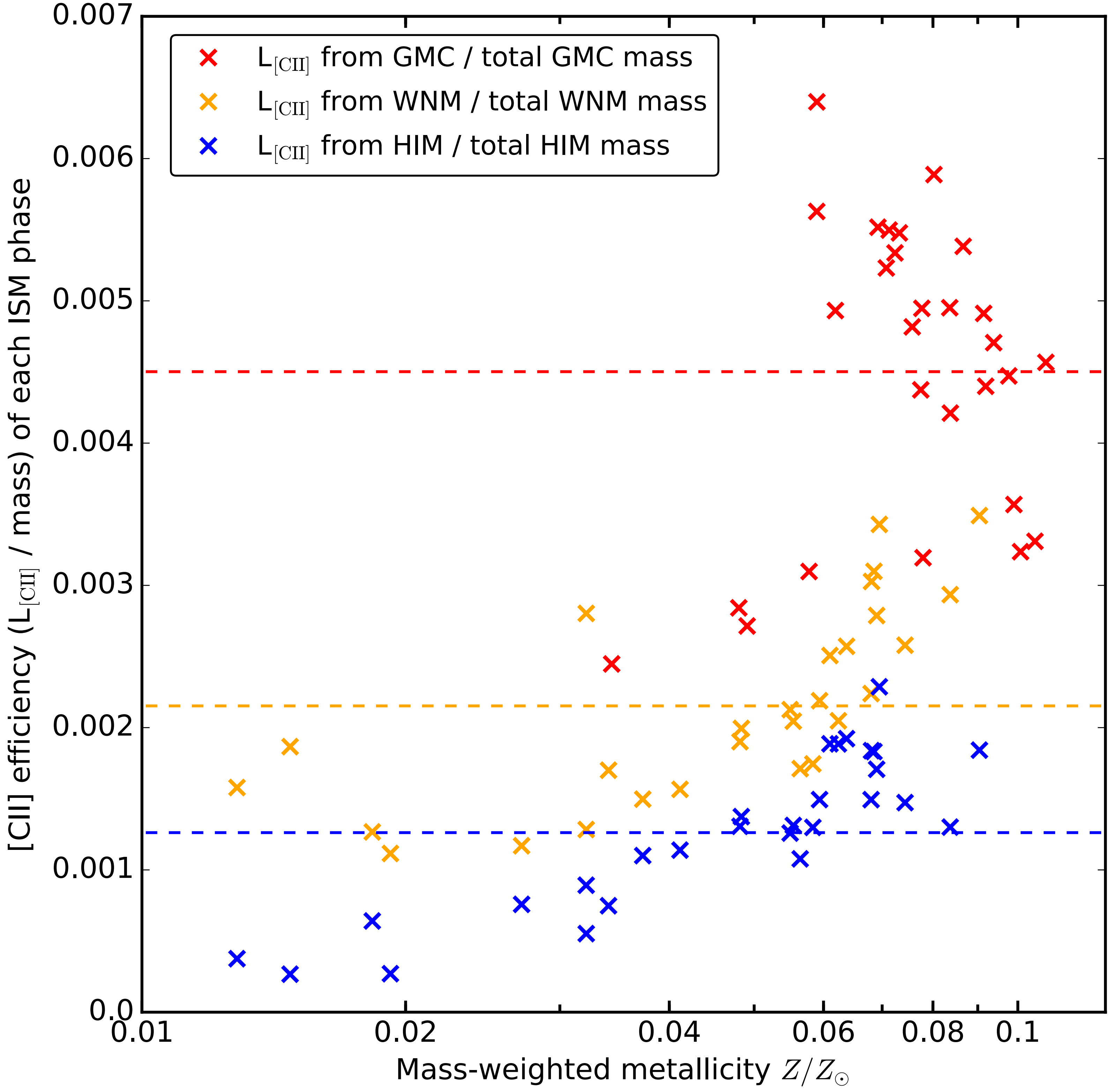

A factor 5
above HIM

1. GMCs are more efficient [CII] emitters!

[Olsen+16: in prep]

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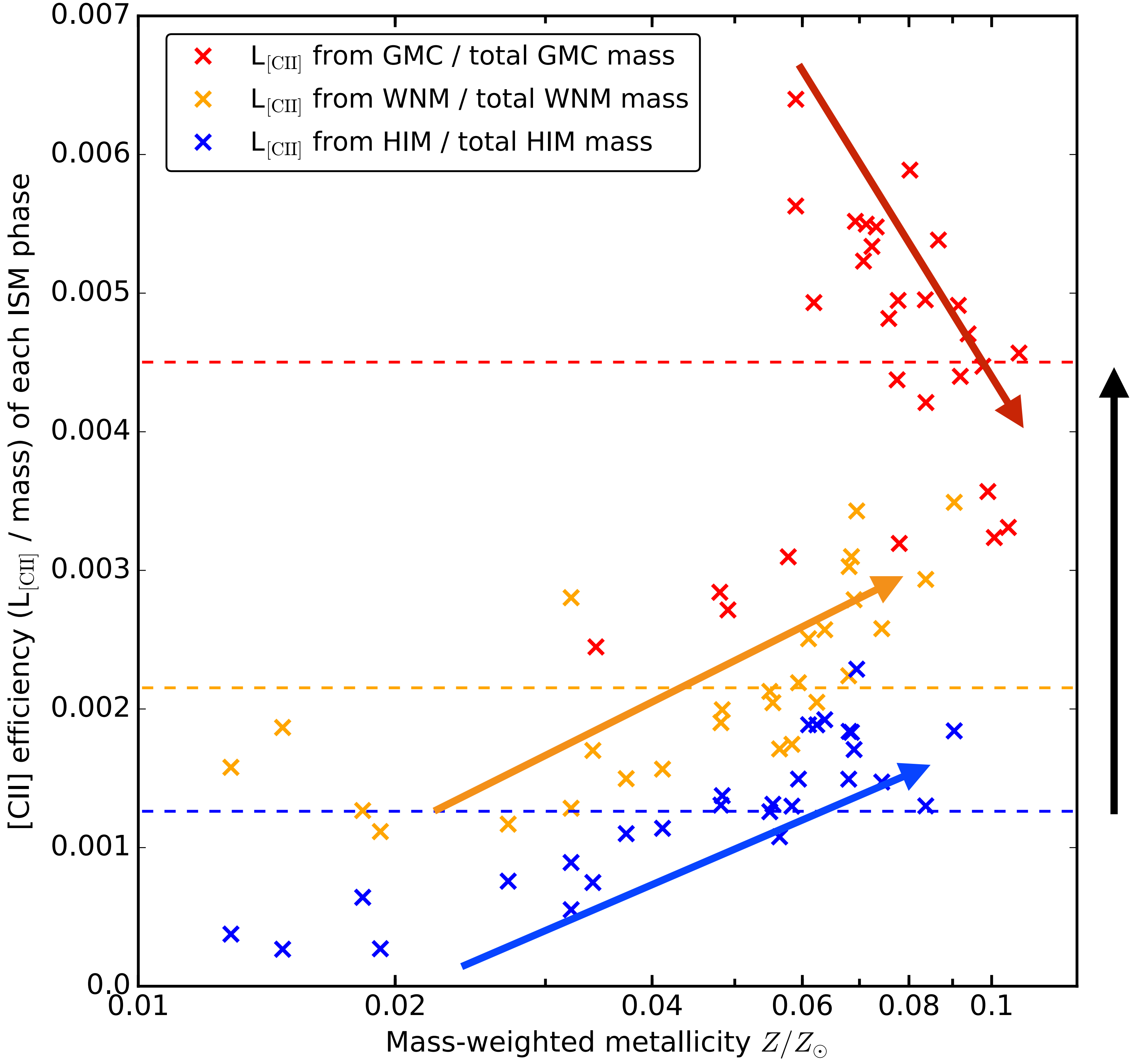

A factor 5 above HIM

1. GMCs are more efficient [CII] emitters!
2. At higher Z, HIM+WNM regions increase their [CII] efficiency

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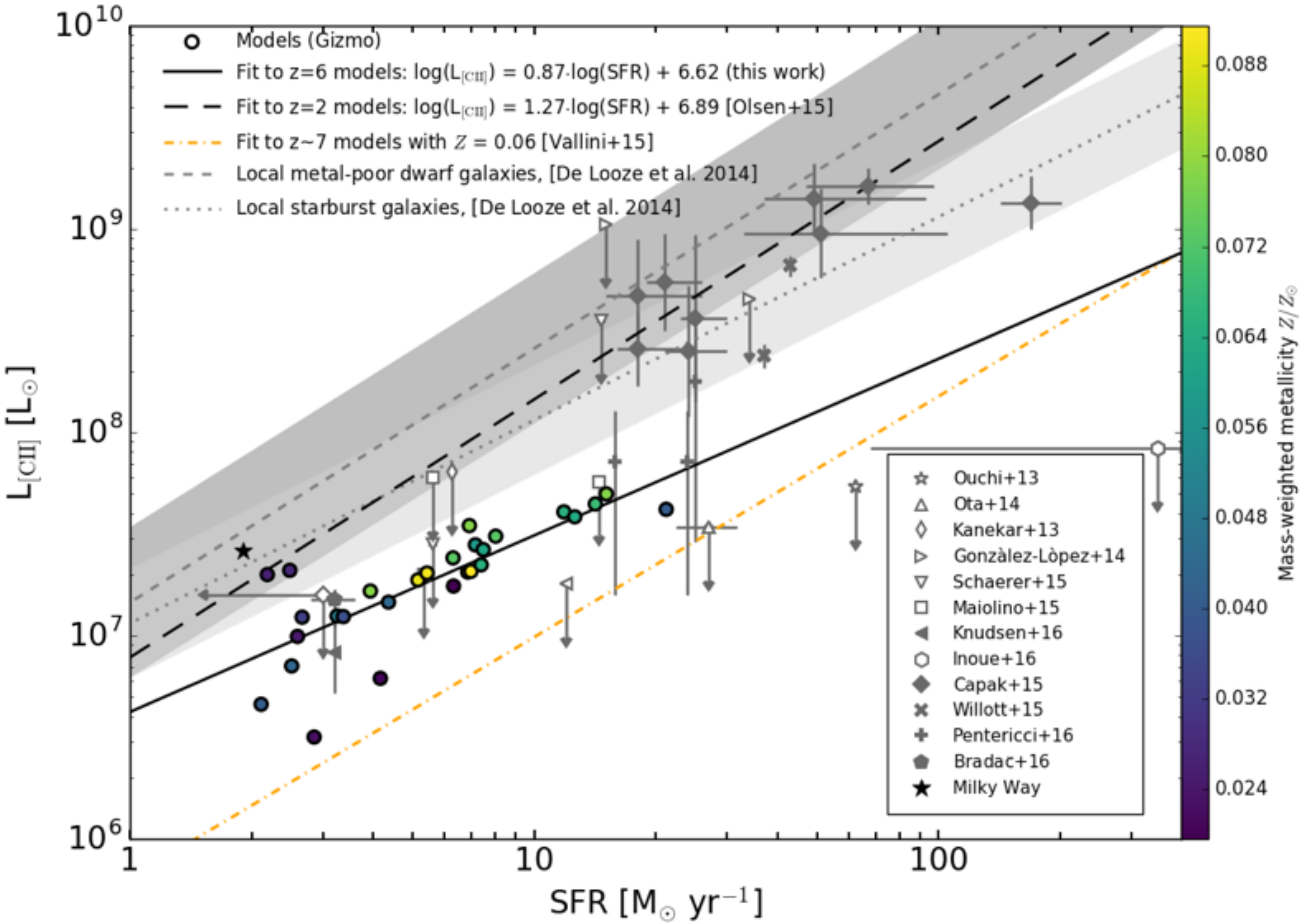
[Olsen+16: in prep]

[CII] a tracer of what?

If [CII] is not the best tracer of SFR, what can it reveal in stead?



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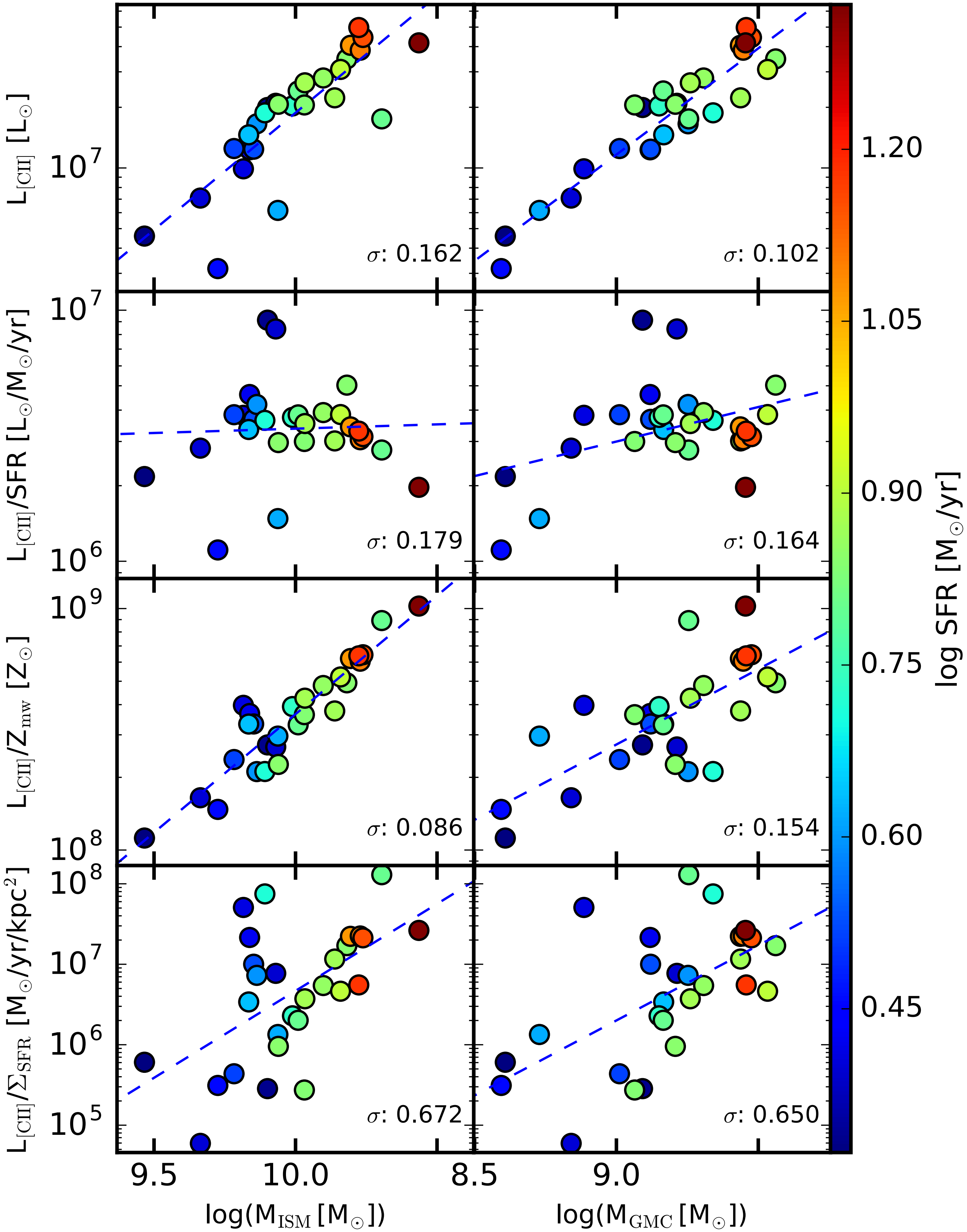

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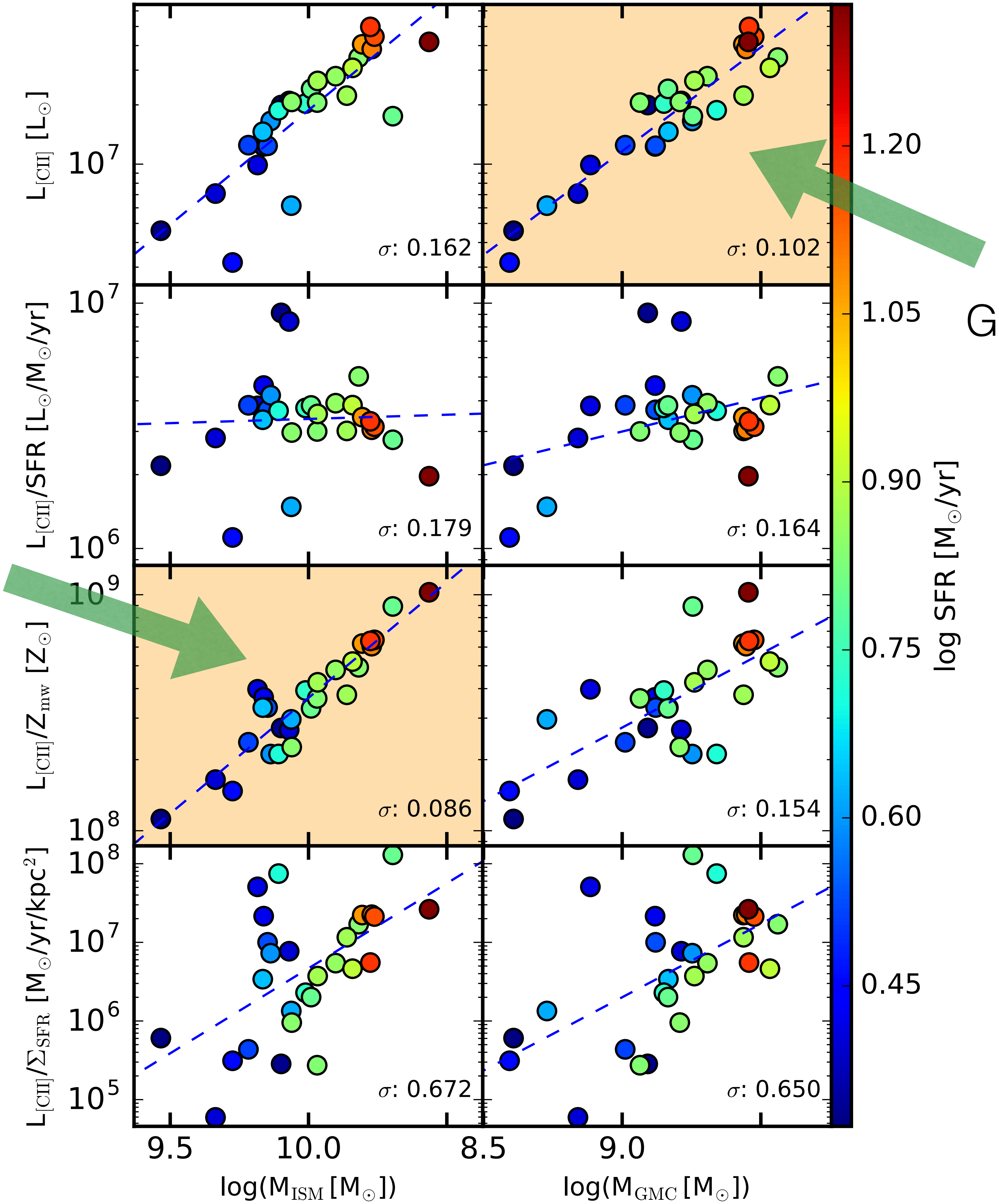

$L_{[CII]}$ scales with GMC mass (or, ISM mass ready for star-formation)

$L_{[CII]}$ combined with metallicity can give a good estimate of the total ISM mass

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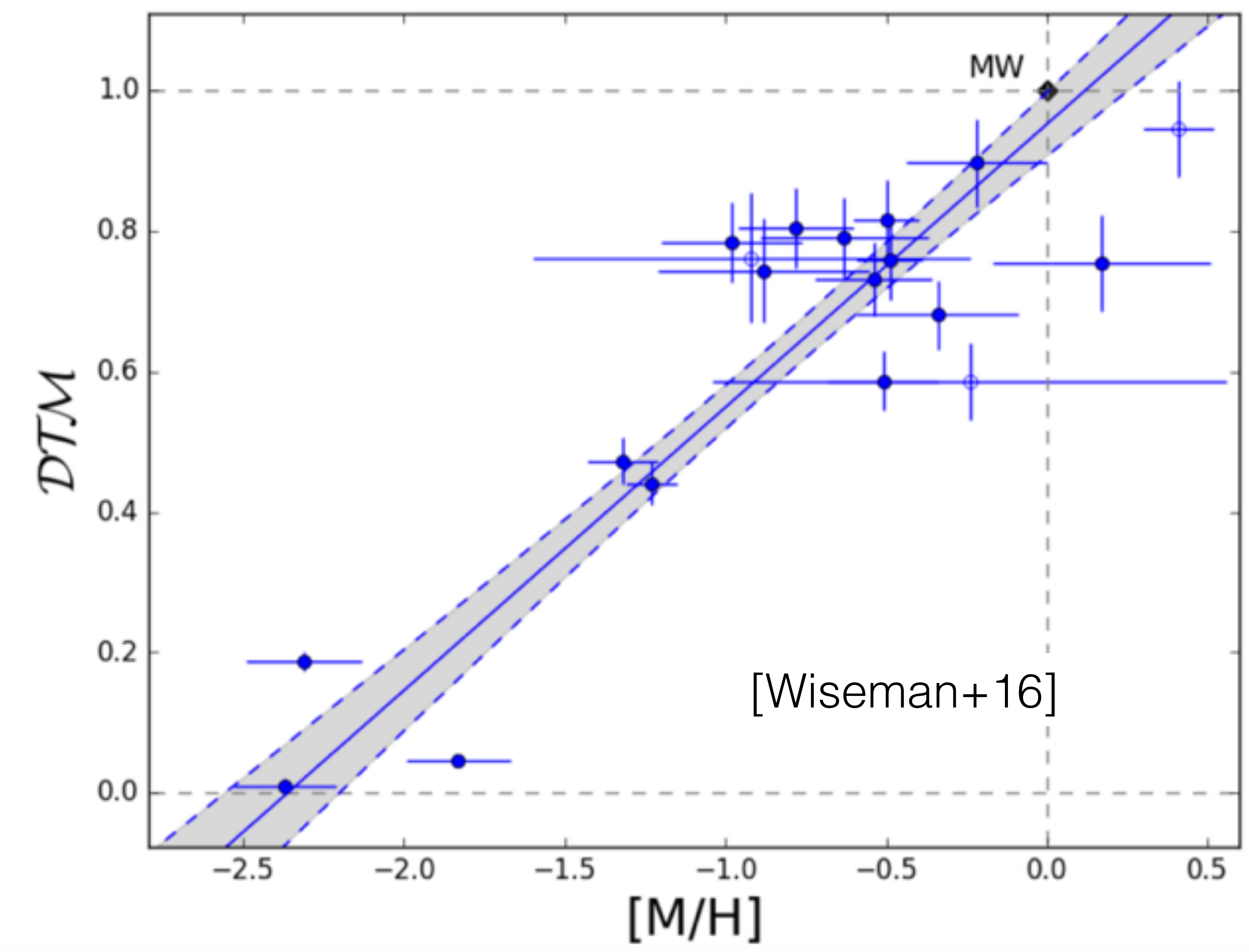
[Olsen+16: in prep]

Effect of alternative DTM ratio

Dust depletion studies of GRB-DLAs have shown a much lower dust-to-metals (DTM) ratio at low metallicity and redshifts out to 5 [De Cia+13, Wiseman+16]: (but see also [Zafar+13] for a constant DTM with redshift and Z)



[Wiseman+16]

What happens if we lower the DTM ratio by 50%?

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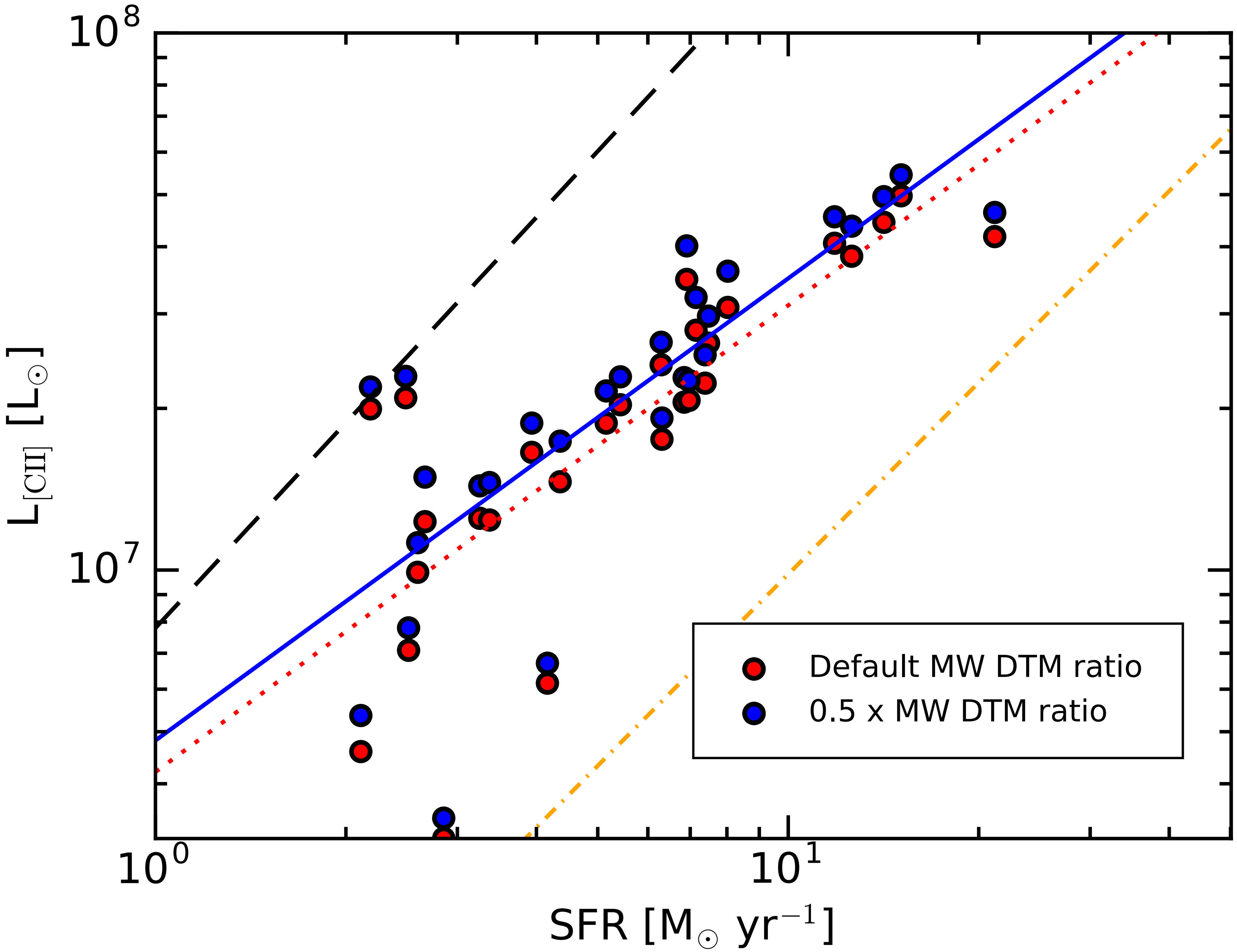
Effect of alternative DTM ratio

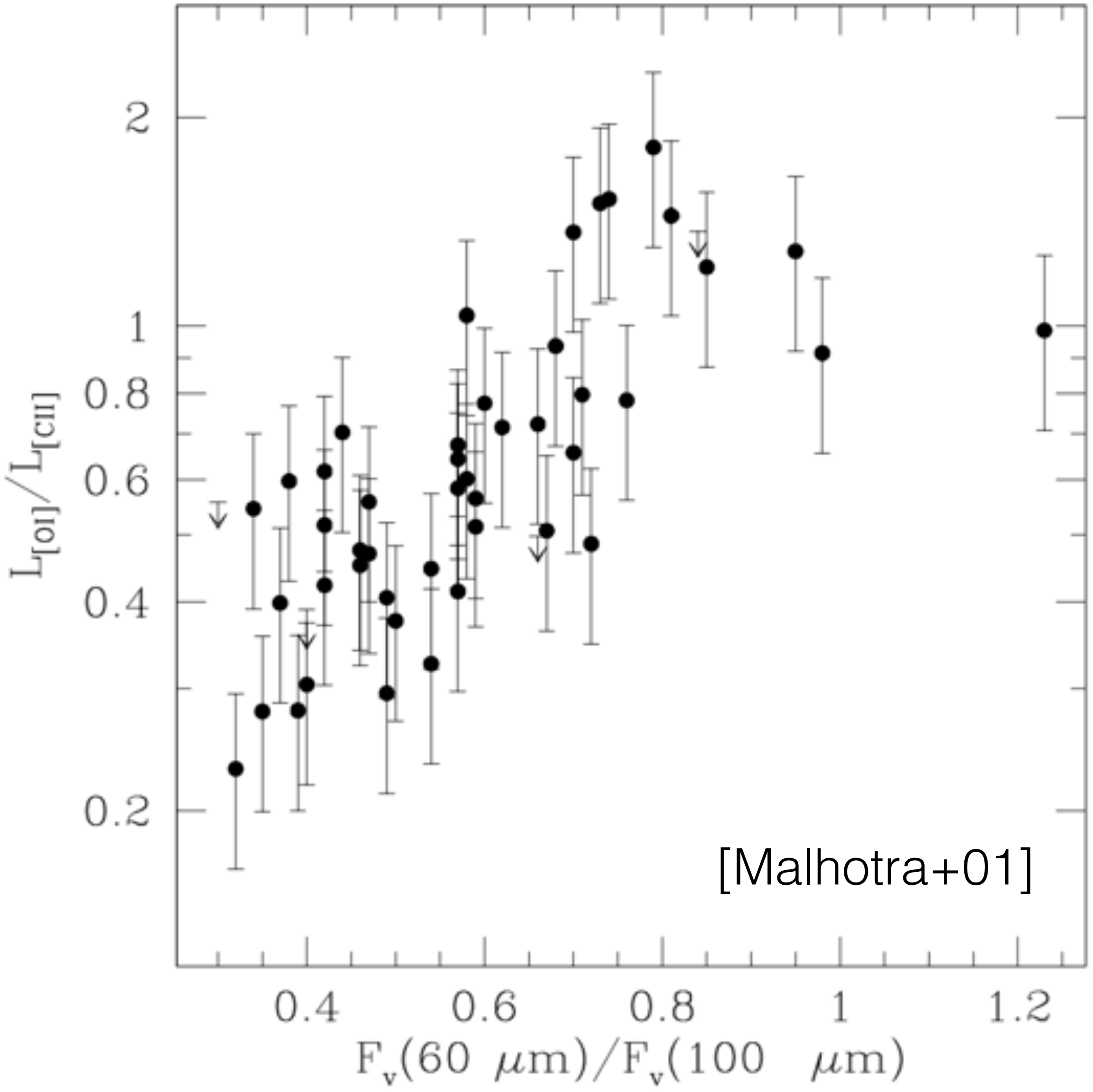


Only about 0.05 dex increase!
(mostly caused by larger C+ regions inside GMCs)

What happens if we lower the DTM ratio by 50%?

[Olsen+16: in prep]

Meanwhile: What is [OI] doing?



In 60 local star-forming galaxies; OI/CII luminosity ratio increasess with dust temperature

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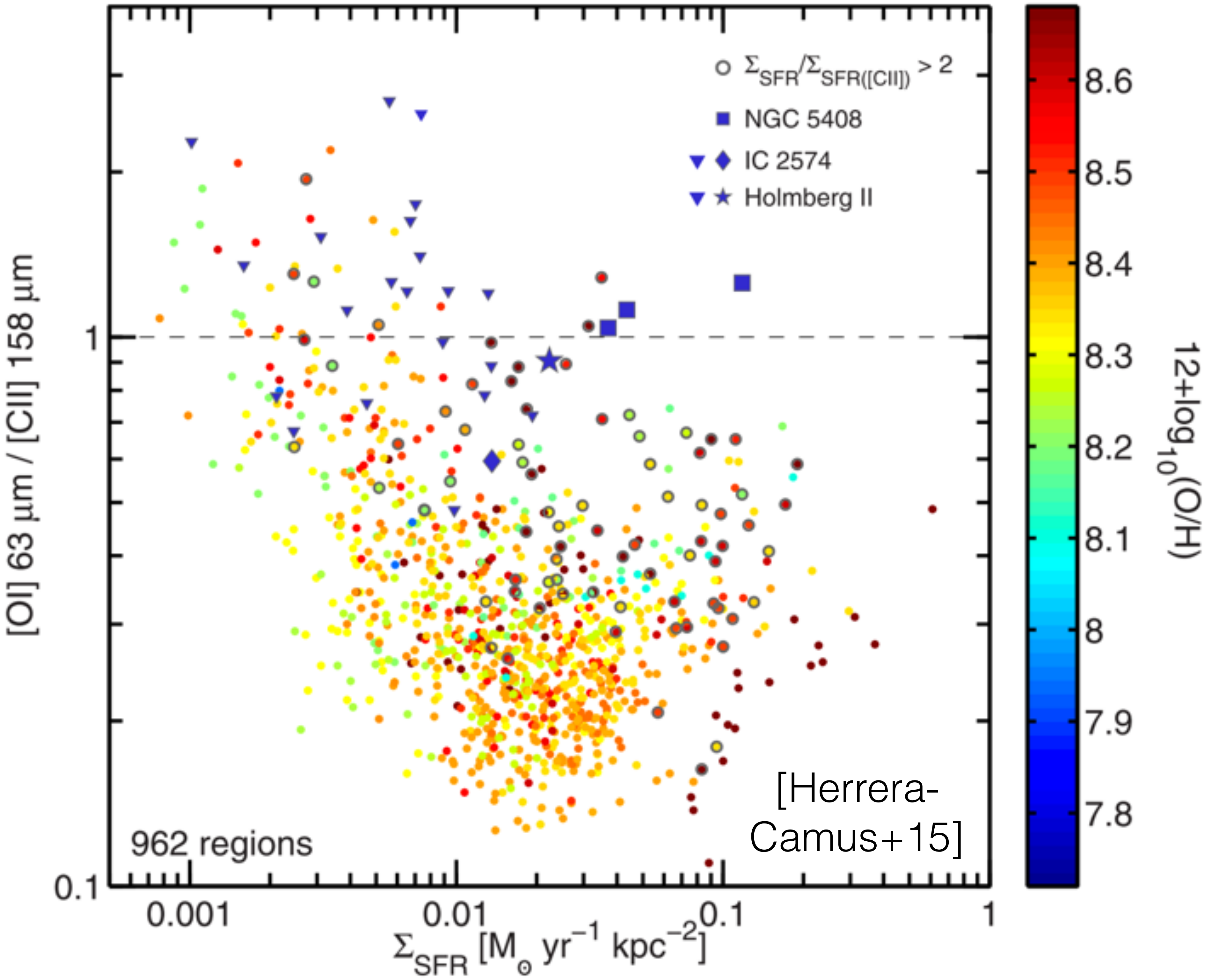

[Herrera-Camus+15]

In 46 local star-forming galaxies; [OI] not dominating and [OI]/[CII] luminosity ratio higher for galaxies with low [CII]-predicted Σ_{SFR}.

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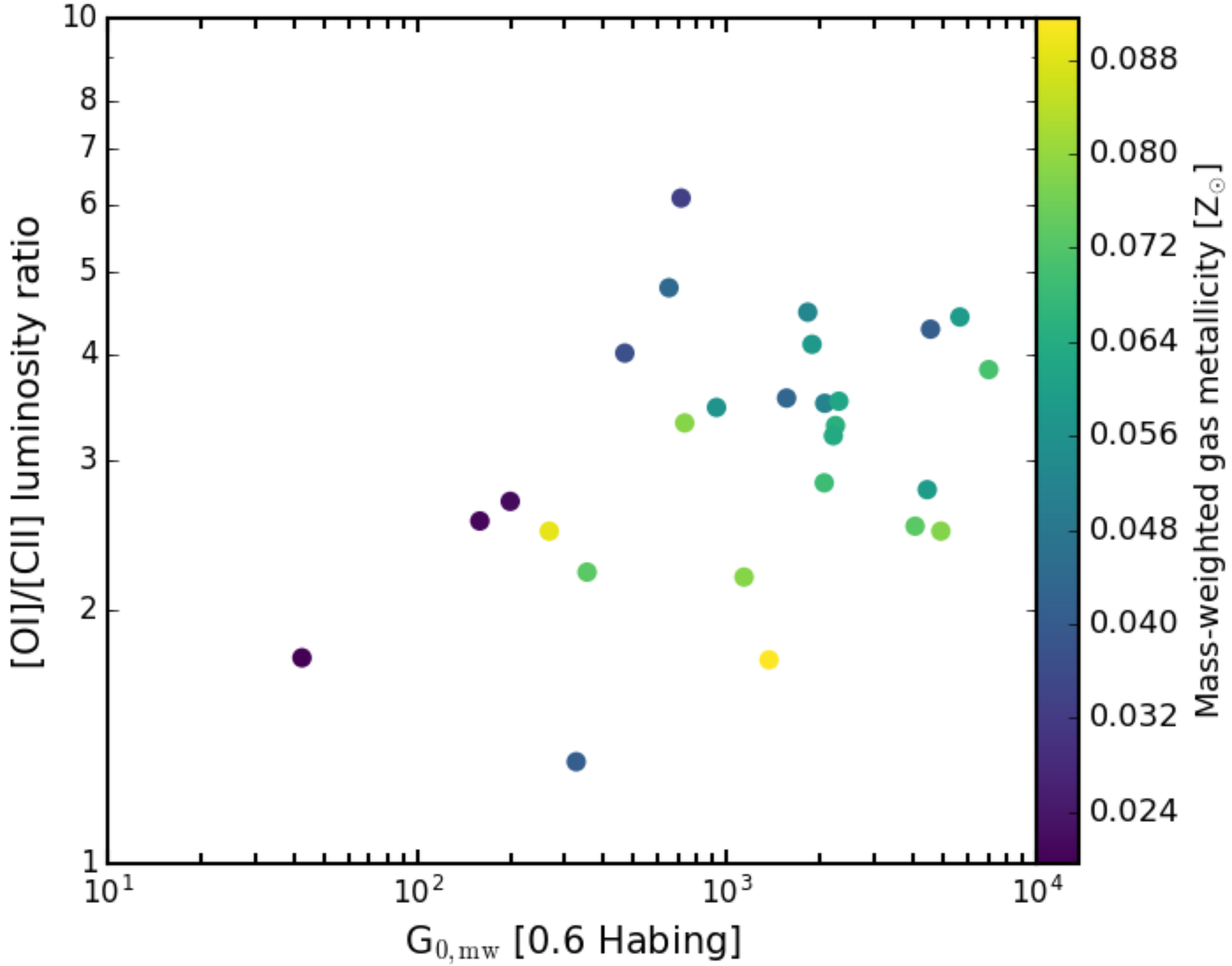
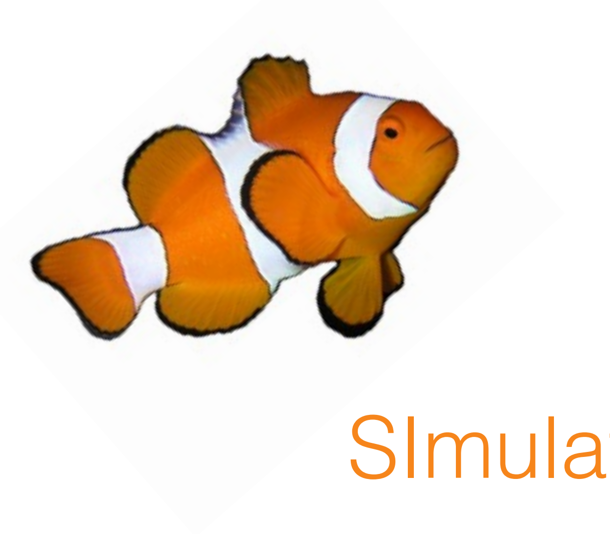
Meanwhile: What is [OI] doing?



At z~6, we find that [OI] is typically dominating, and [OI]/[CII] increases with mass-weighted FUV field.

[Olsen+16: in prep]



SÍGAME

SImulator of GAlaxy Millimeter/submillimeter Emission

A novel method that simultaneously considers:

- all ISM phases simultaneously
- cosmological simulations
- effects of pressure on molecular clouds
- full chemistry
- reliable local FUV estimates
- control over the dust!

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SImulator of GAlaxy Millimeter/submillimeter Emission

Still to be done:

- run cloudy models for a grid of higher resolution
- apply to our z=2 model galaxies
- extract FIR luminosity to derive CII/FIR deficit
- extract 60µm/100µm flux ratio to look at [CII] deficit and [OI]/[CII] ratio as a function of T_{dust}
- make a public version on github

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SImulator of GAlaxy Millimeter/submillimeter Emission

Conclusions at z~6:

- We predict a [CII]-SFR relation, though weak
- [CII] might be better suited for estimates of M_{ISM} and M_{GMC}
- Most of the [CII] emission arises in GMCs and HIM regions, with 1/4th from WNM
- GMCs emit most [CII] per mass of gas
- Decreasing the dust-to-metals ratio increases $L_{[CII]}$ slightly
- We predict very high [OI]/[CII] luminosity ratios, increasing with average radiation field of a galaxy

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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!:

- 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)

Thank you!