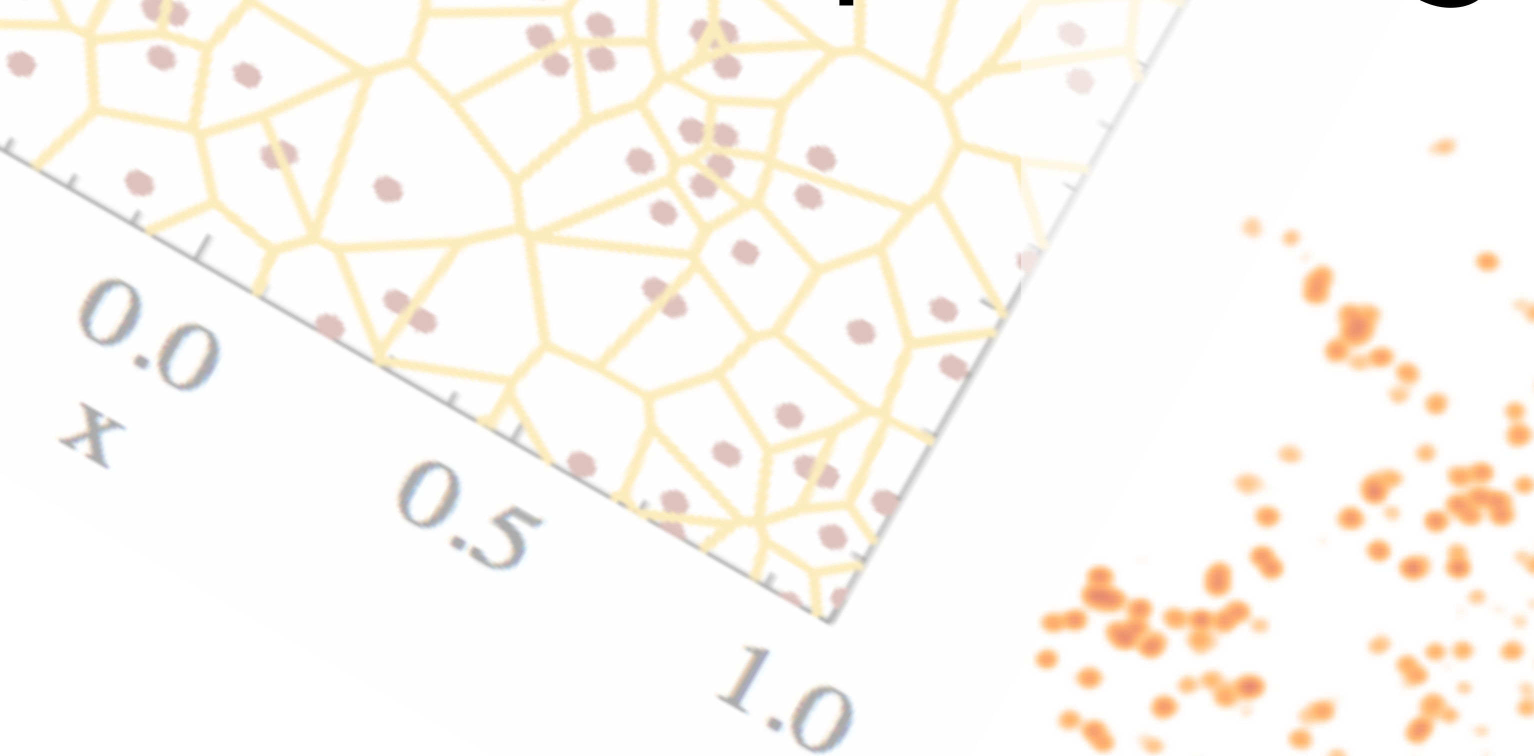
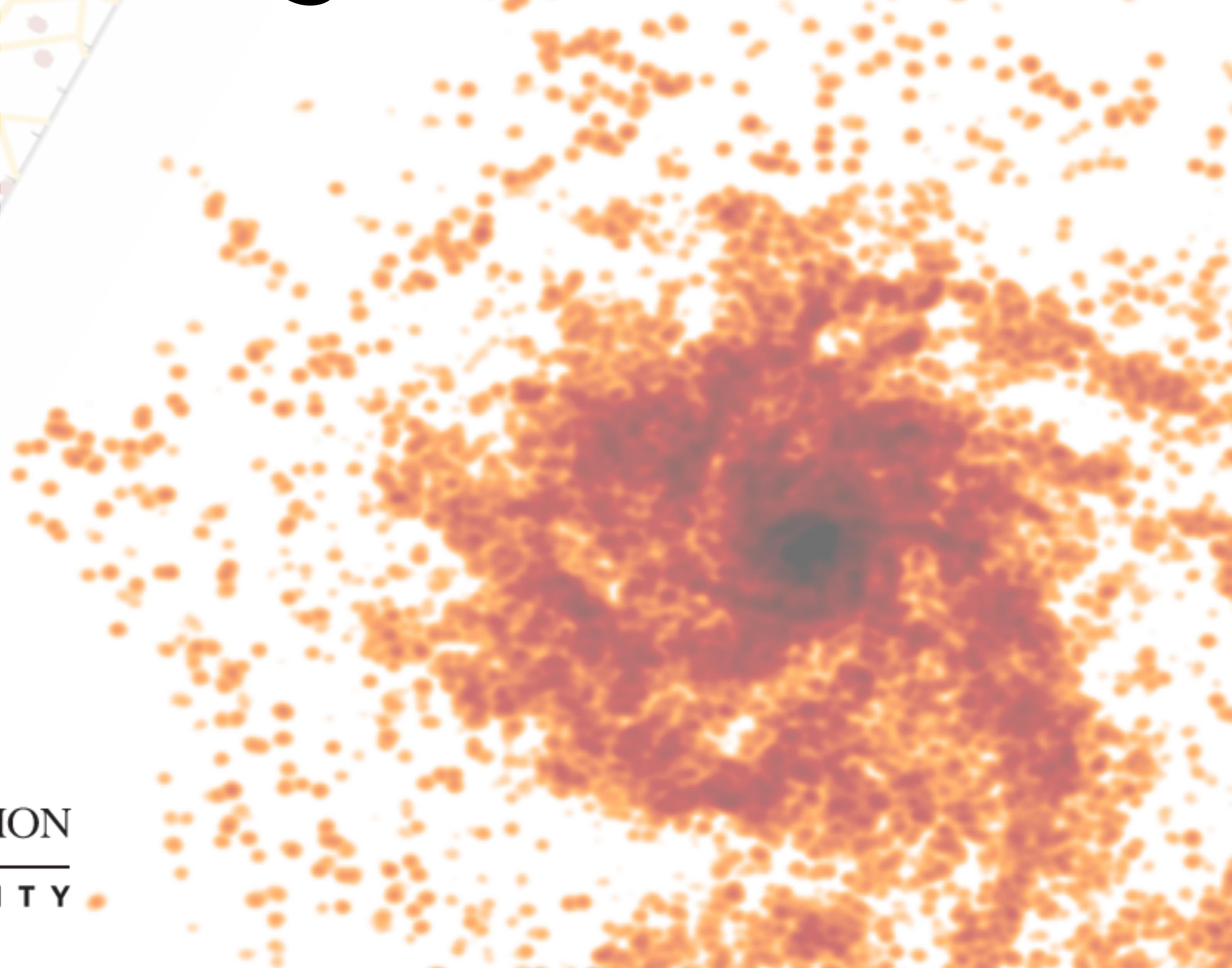
Simulating [CII] emission: Results for z=2 main sequence galaxies





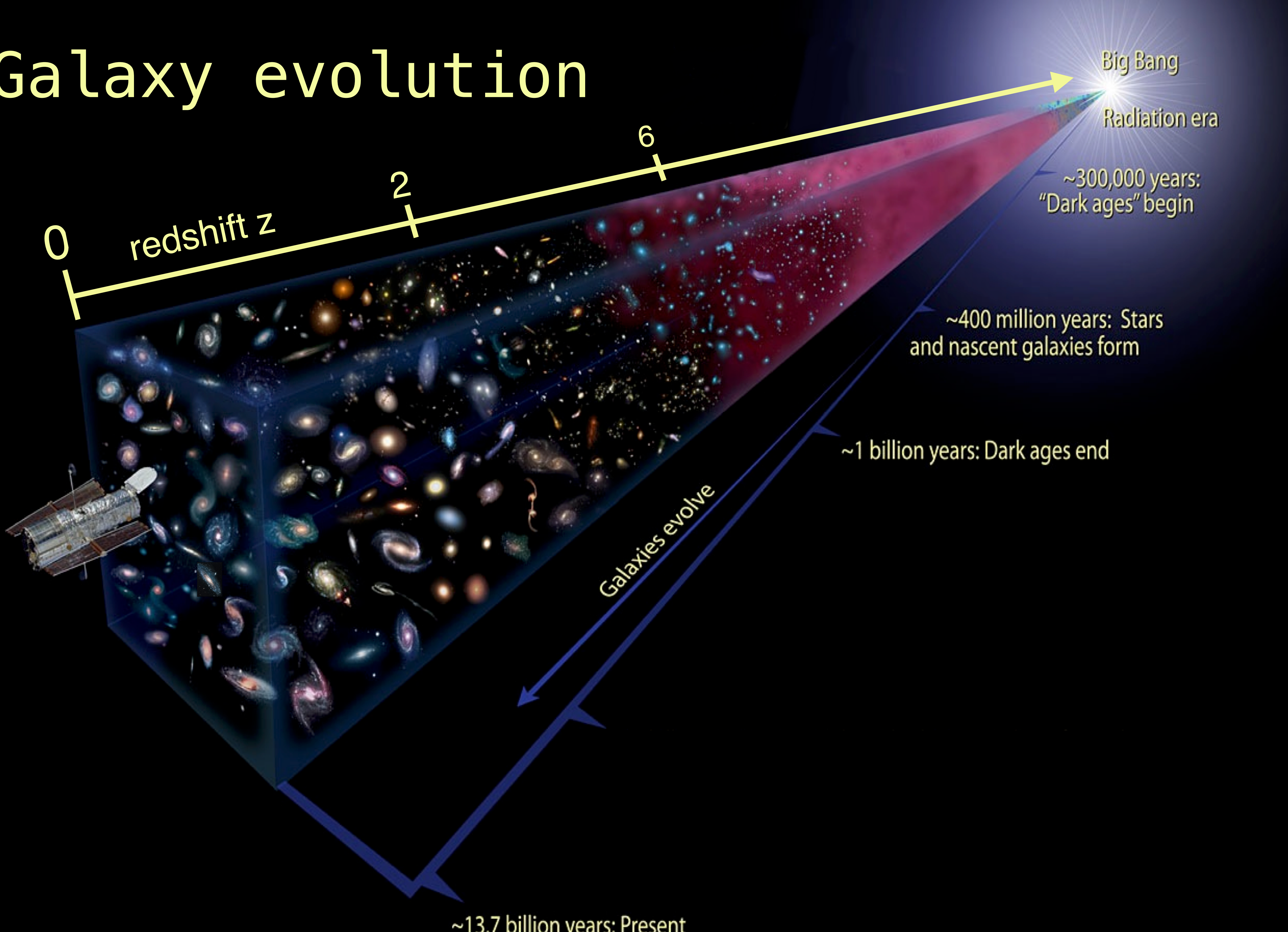
Karen Pardos Olsen

Exploration Fellow at

ASU School of Earth & Space Exploration

Arizona State University

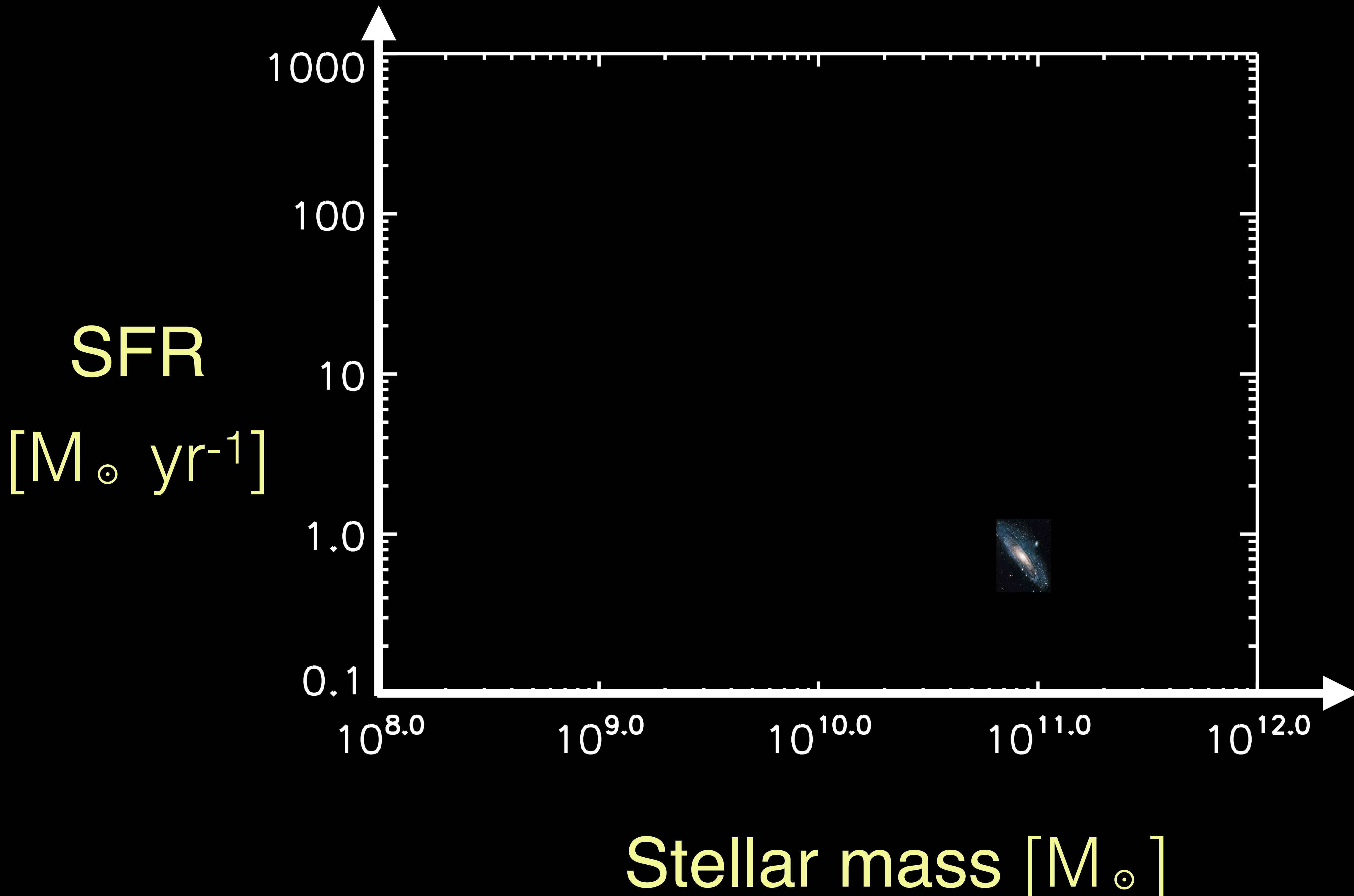
Galaxy evolution



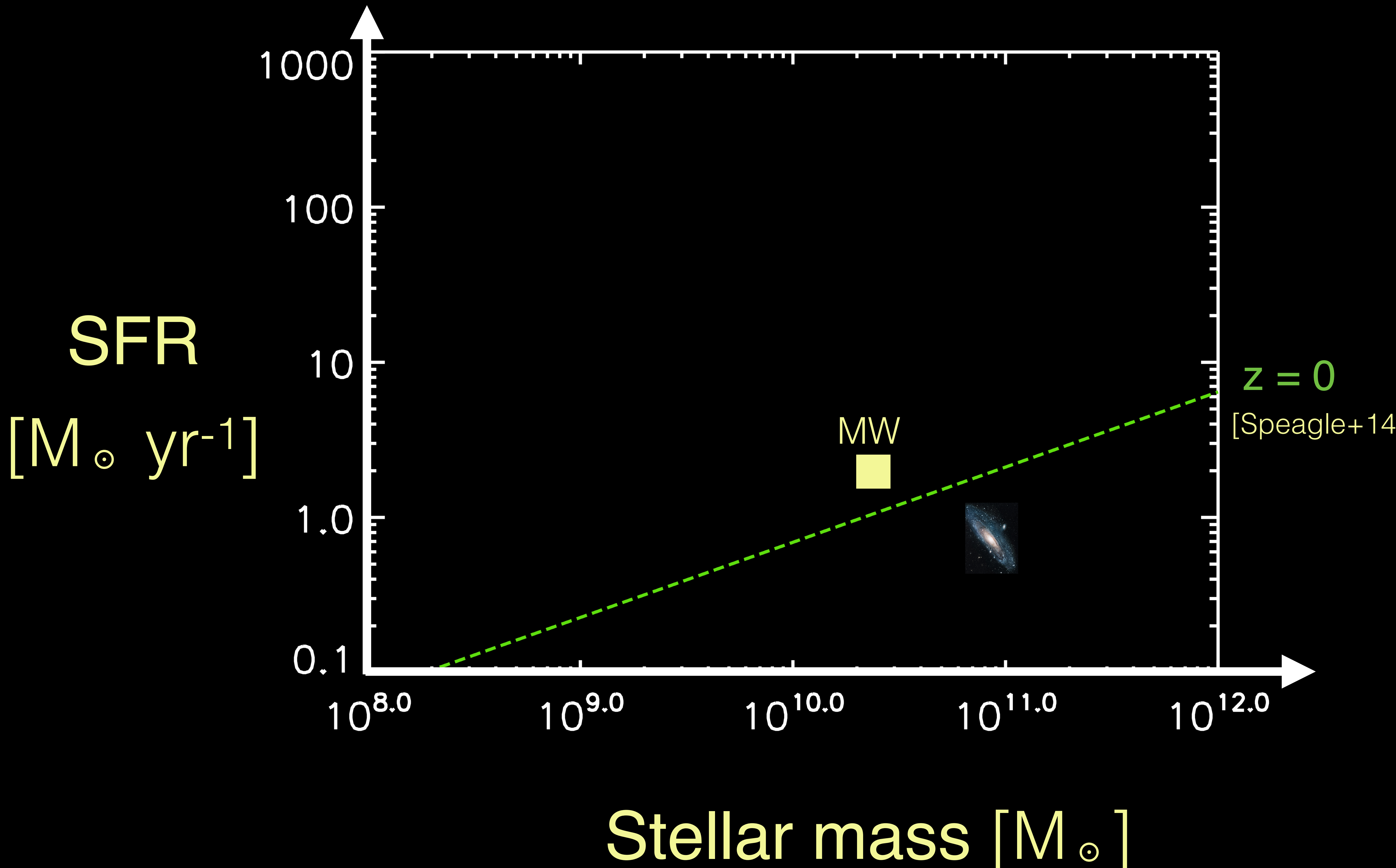
NASA, ESA, and A. Feild (STScI)

Andromeda (M31)
in optical

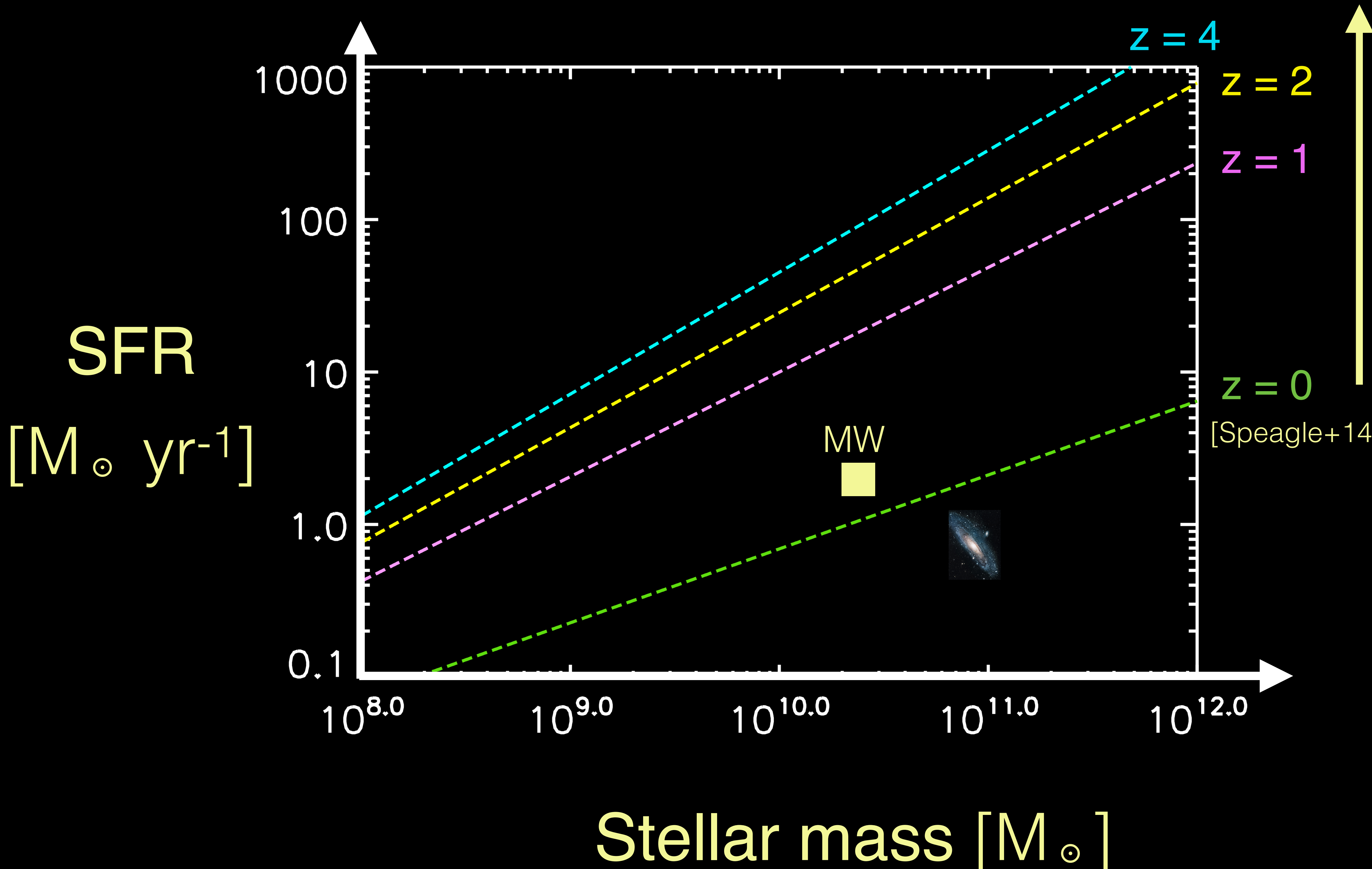
Credit: Robert Gendler


SFR
[M⊙ yr-1]
1000
100
10
1.0
0.1
10^8.0
10^9.0
10^10.0
10^11.0
10^12.0
Stellar mass [M⊙]

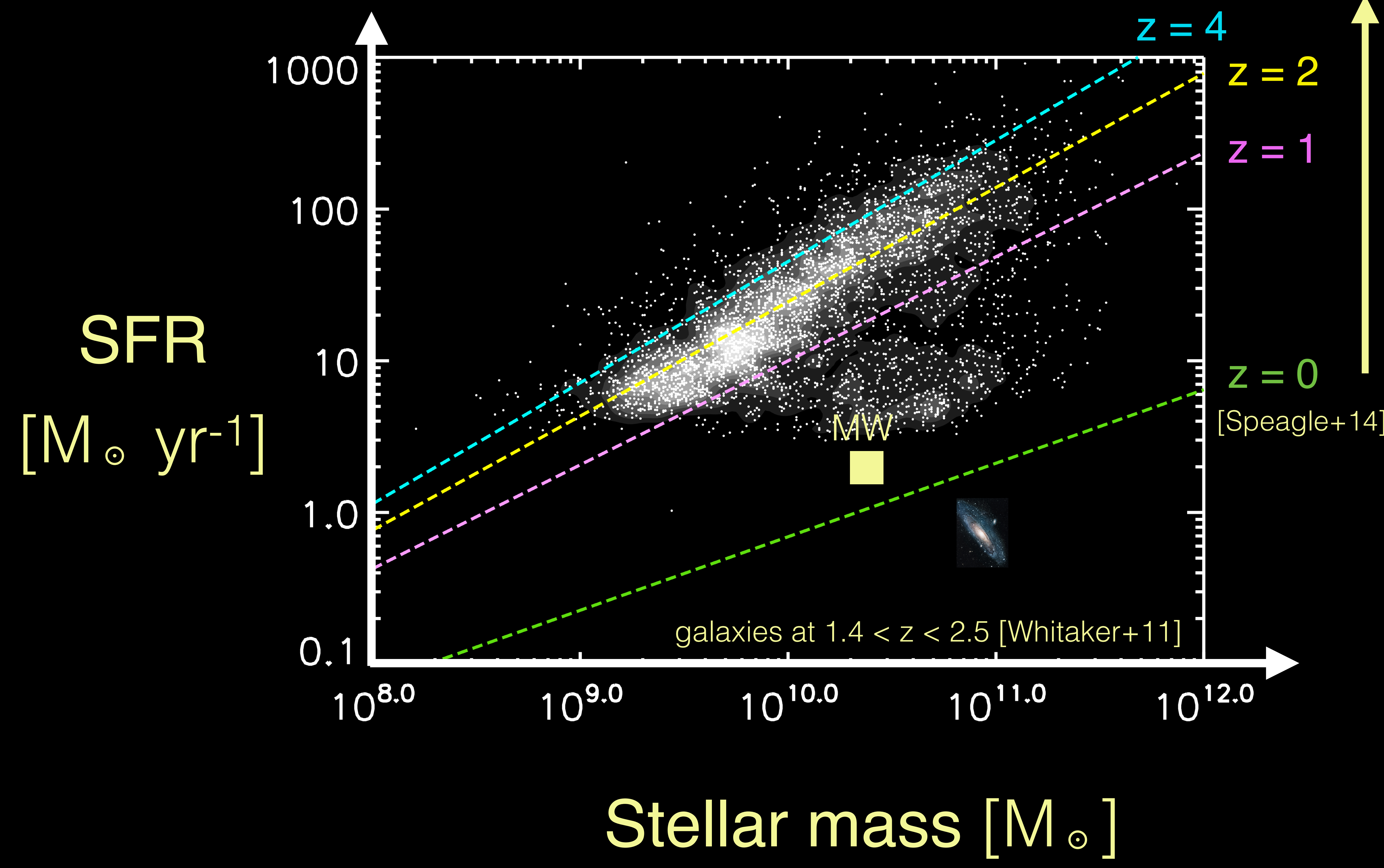
Main Sequence (MS)



Main Sequence (MS)



Main Sequence (MS)



How are stars formed?

Andromeda (M31)
in optical

Credit: Robert Gendler

How are stars formed?

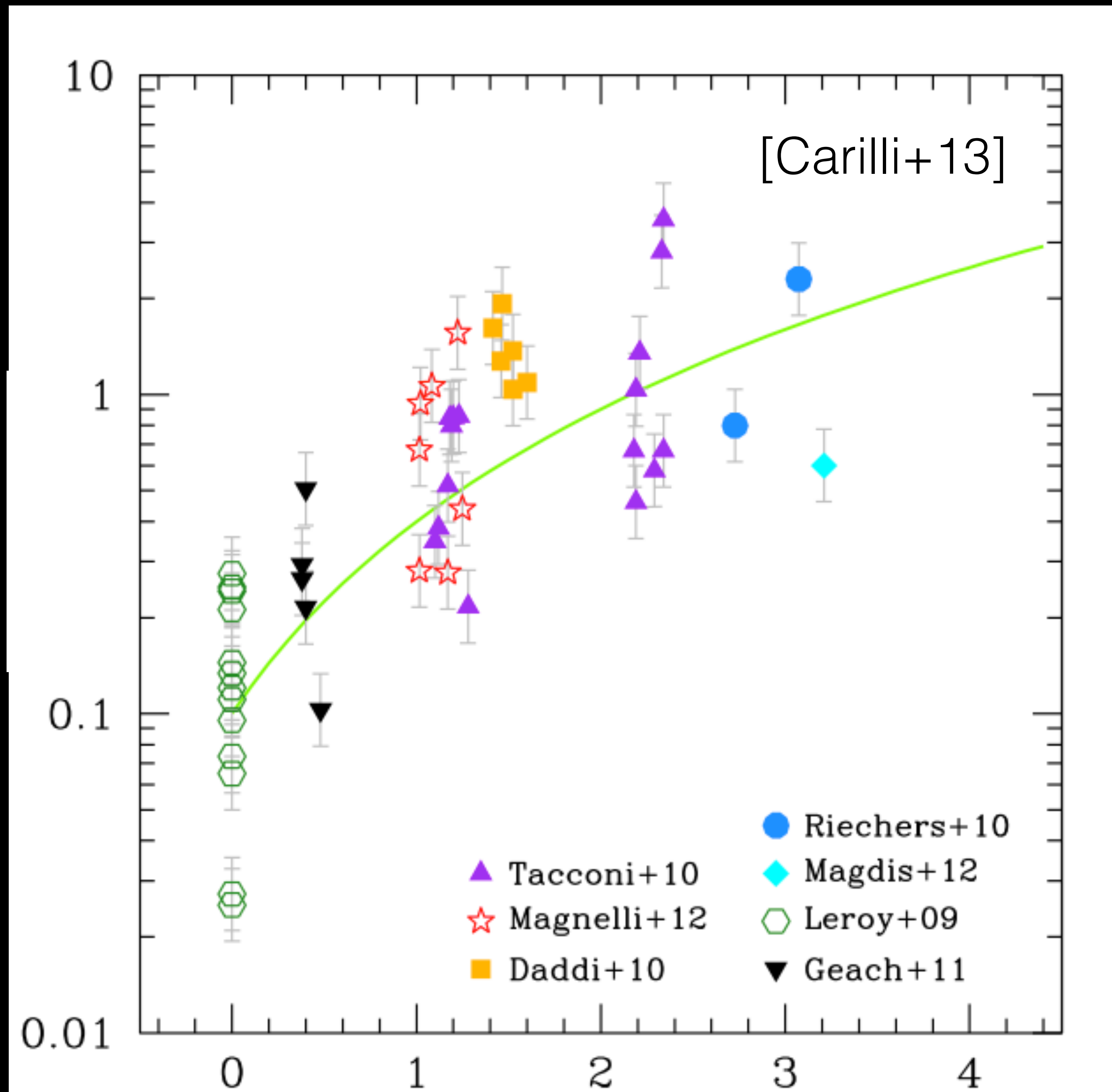
Andromeda (M31)
in optical

Credit: Robert Gendler

Out of dense, cold gas

Carina Nebula, credit: NASA, ESA and the Hubble SM4 ERO Team

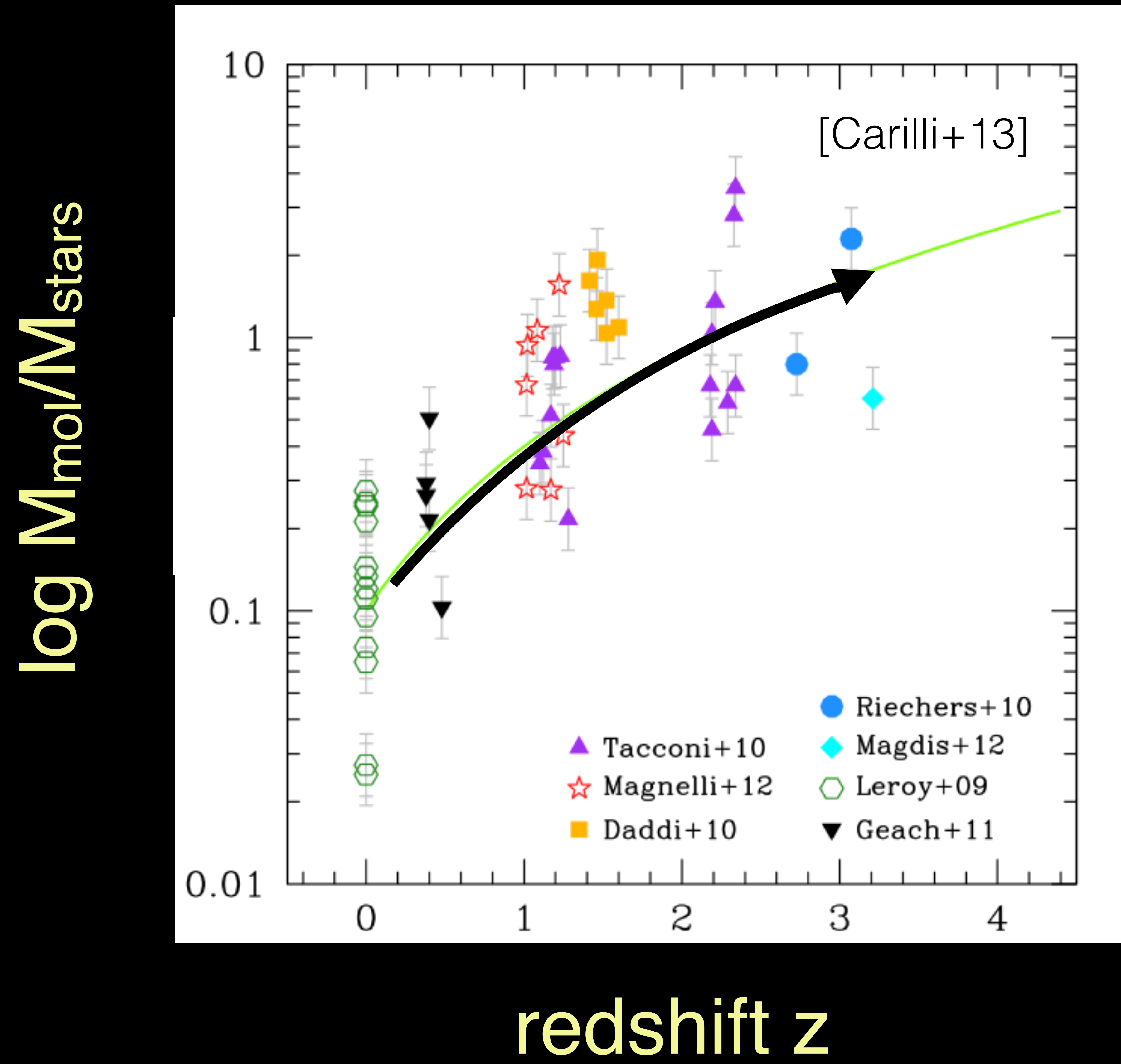
Gas mass fraction



log M_{mol}/M_{stars}

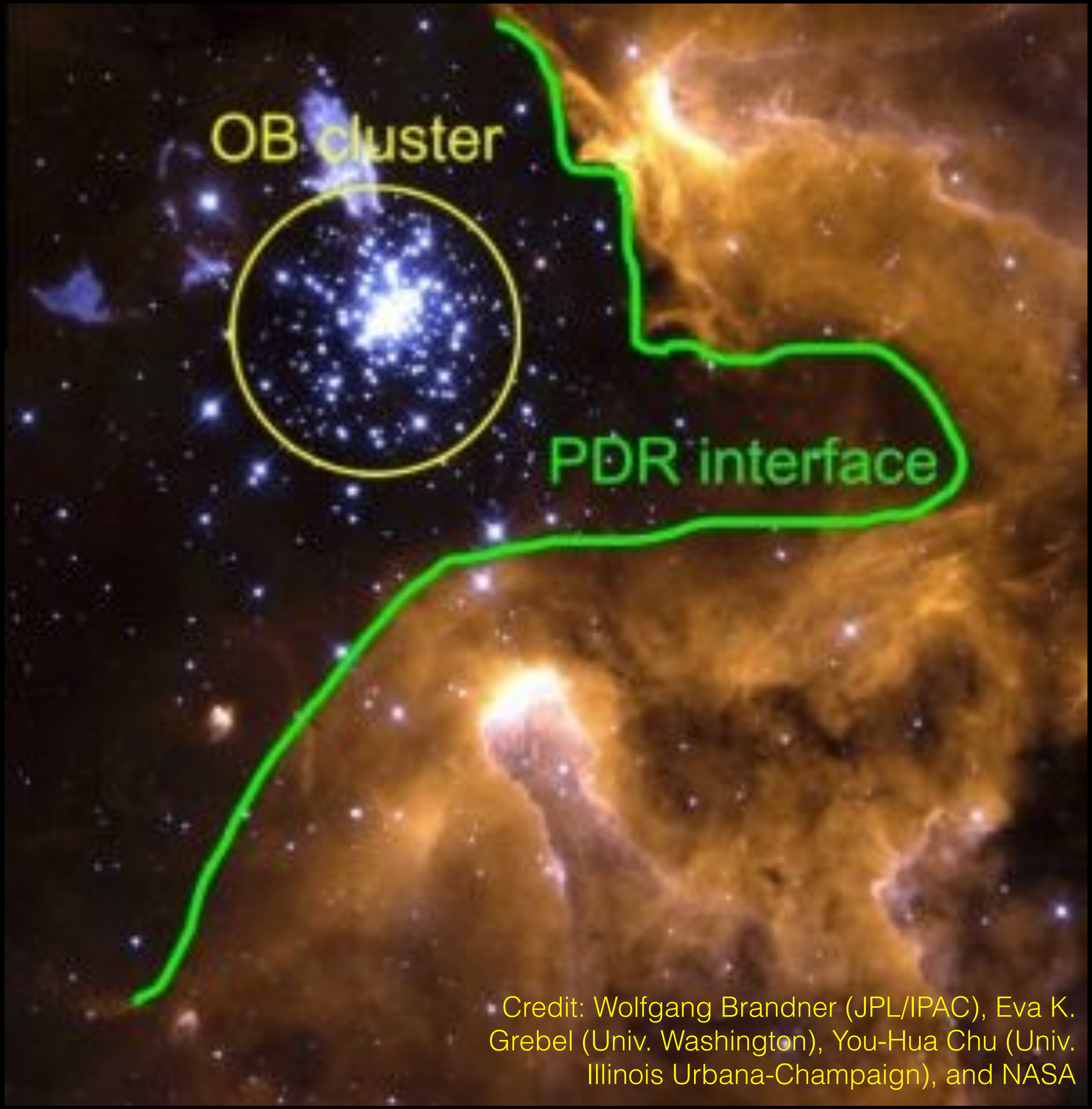
redshift z

Gas mass fraction

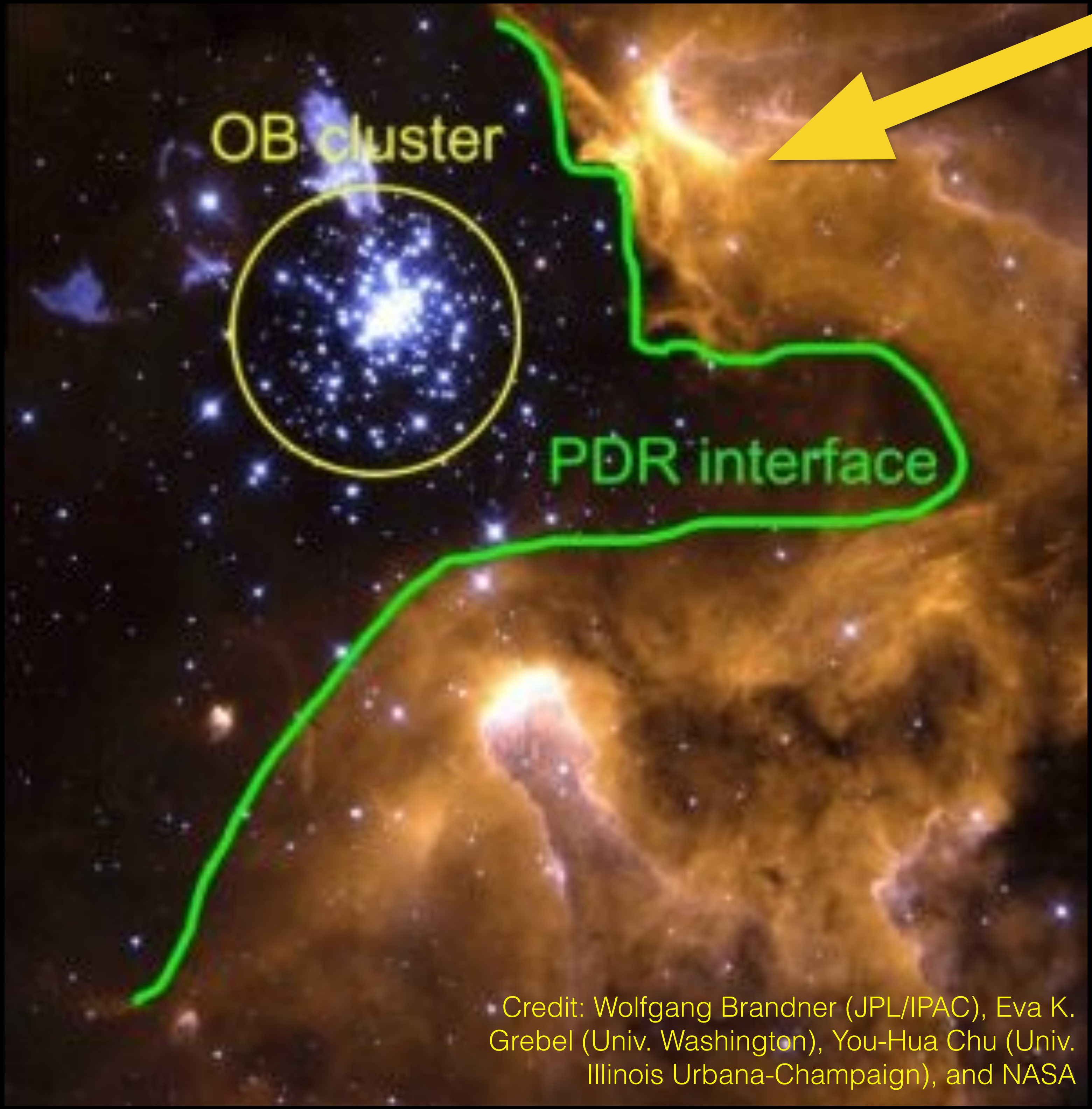


Can higher gas fraction explain the redshift evolution of MS?

How to probe gas in the ISM?

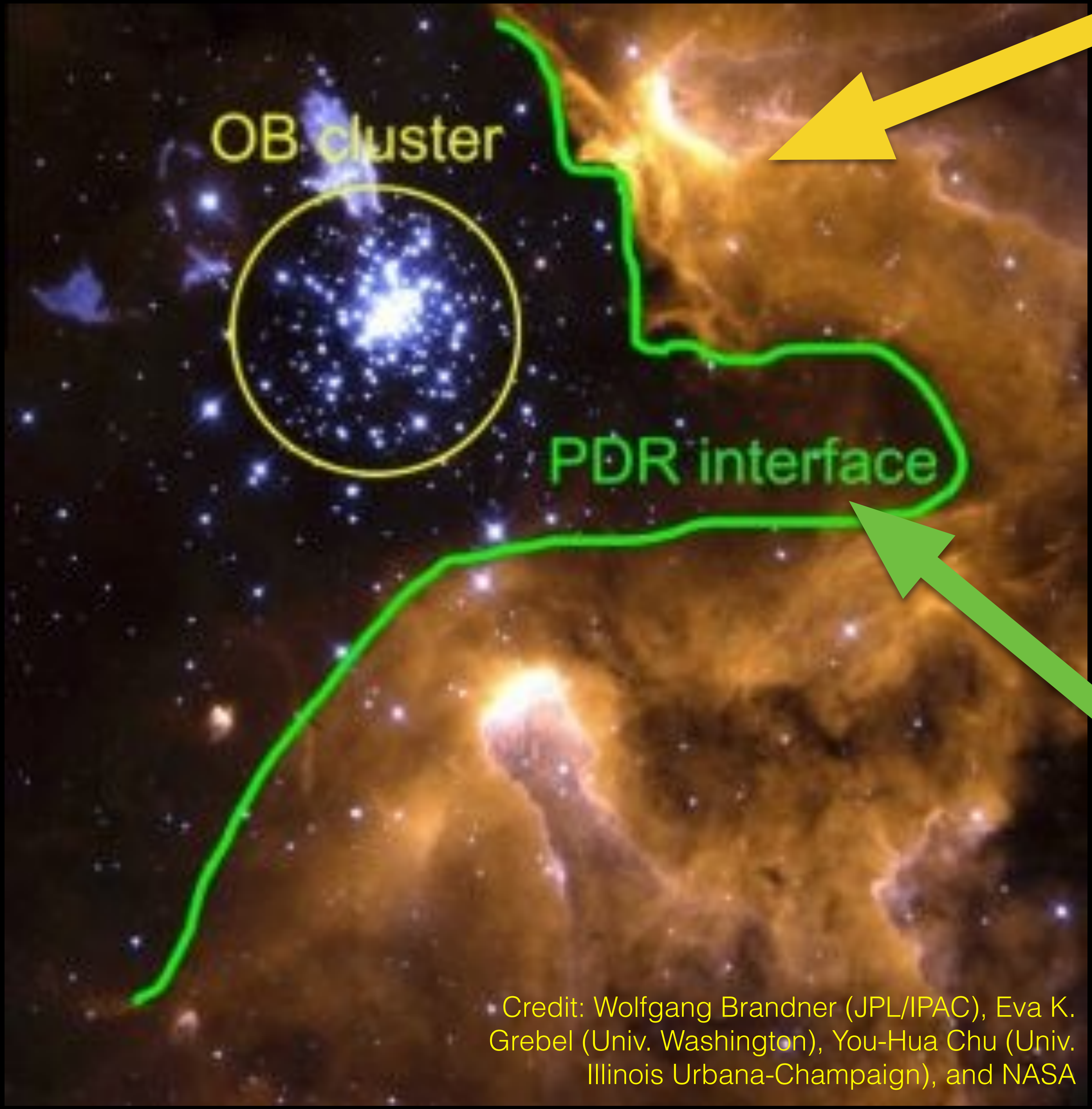


How to probe gas in the ISM?



CO rotational lines, HCN, HCO^+…

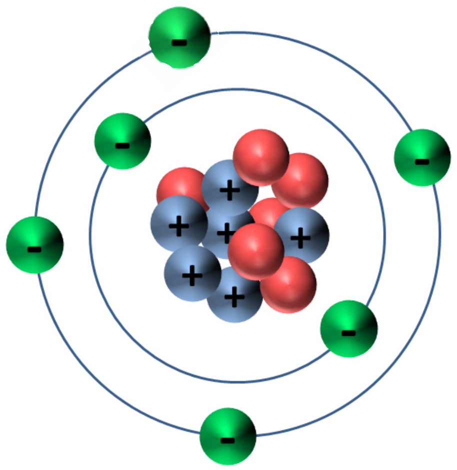
How to probe gas in the ISM?



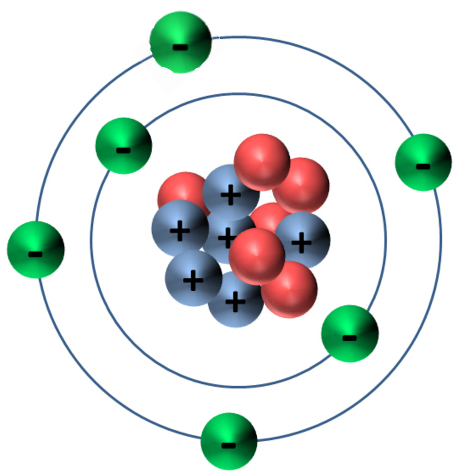
CO rotational lines, HCN, HCO^{+}…

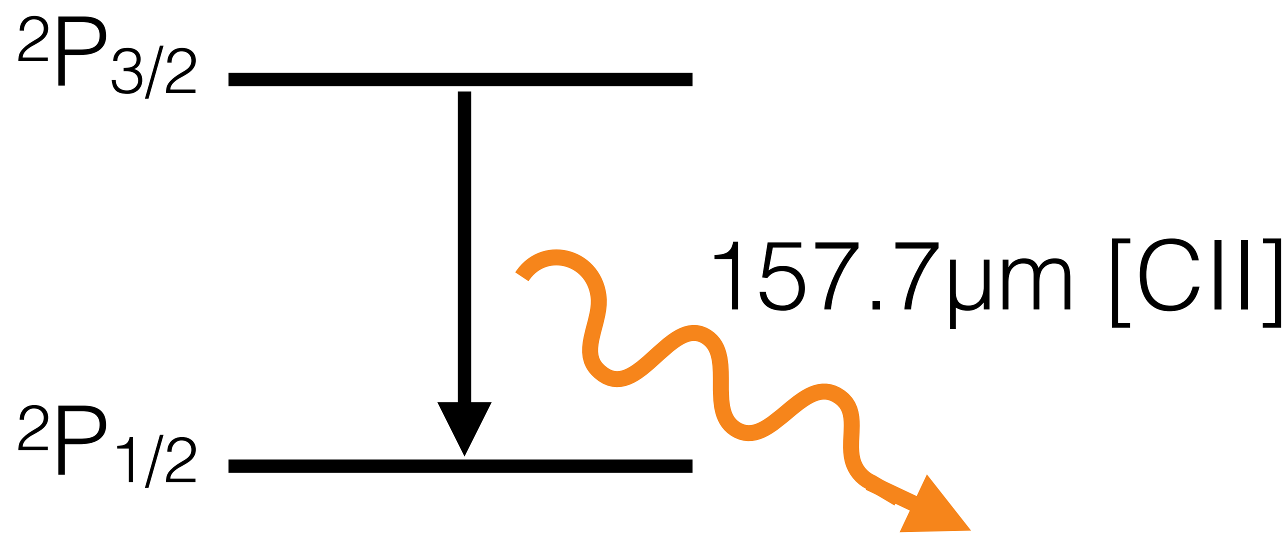
[CII] line emission

carbon



Singly ionized carbon





Excited by collisions with either electrons, atoms or molecules

⇒ can arise all over the ISM!

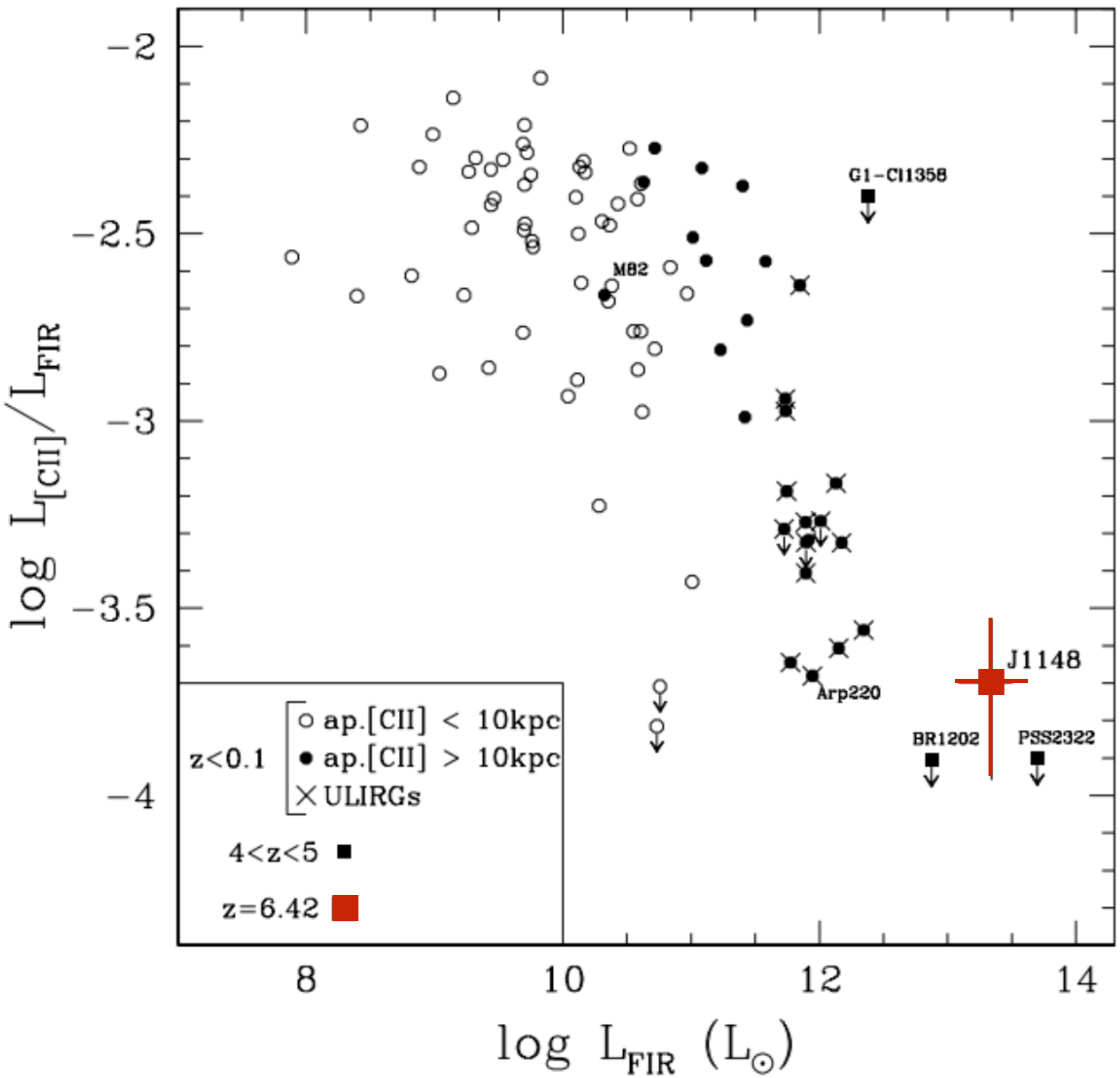
Observing [CII]
Option #1: Escaping Earths atmosphere

Kuiper Airborne Observatory
Crawford+86, Stacey+91

Herschel Space Observatory
Ivison+10, Valtchanov+11, George+11

Observing [CII]

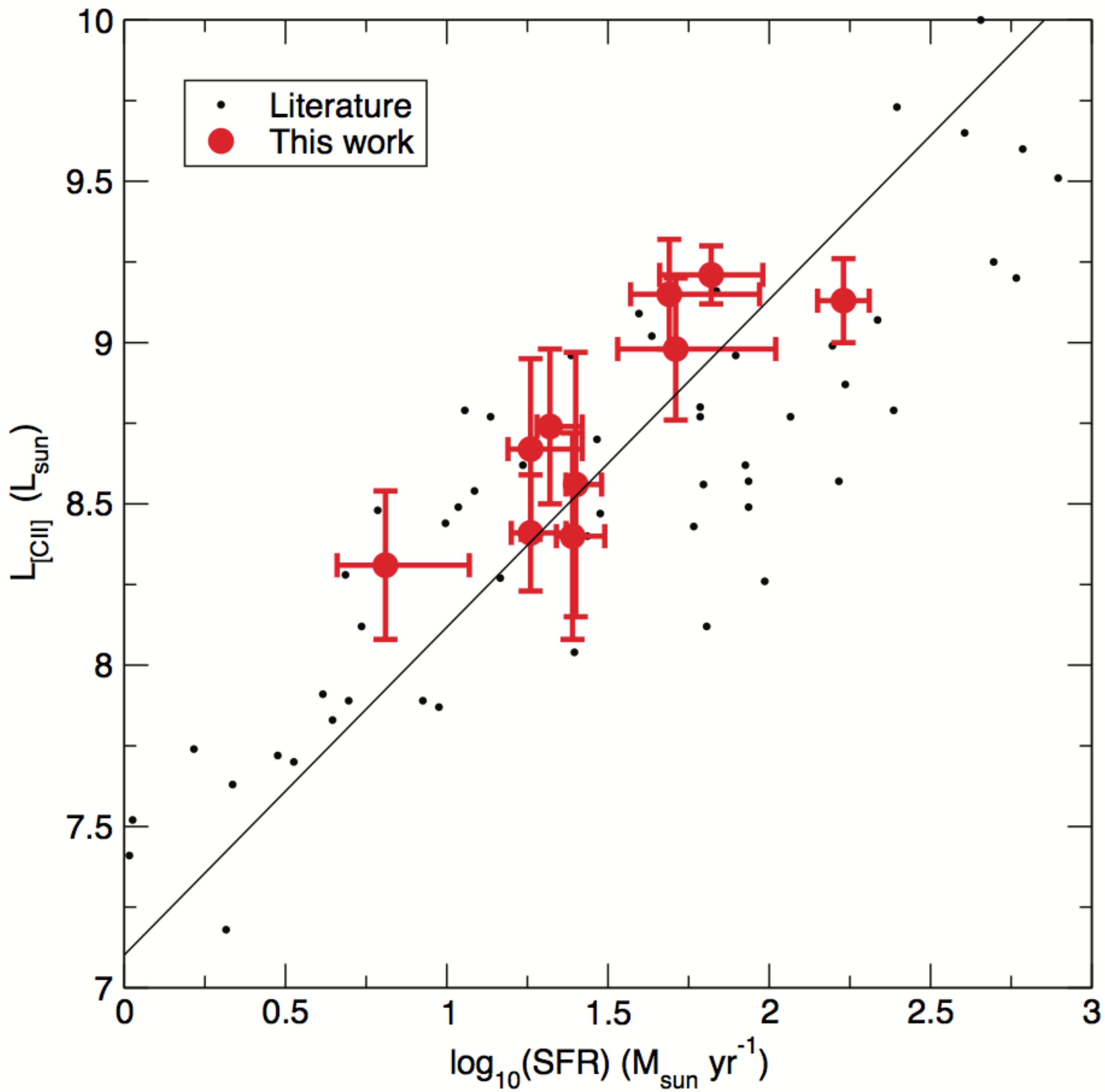
Option #2: Going to high redshift

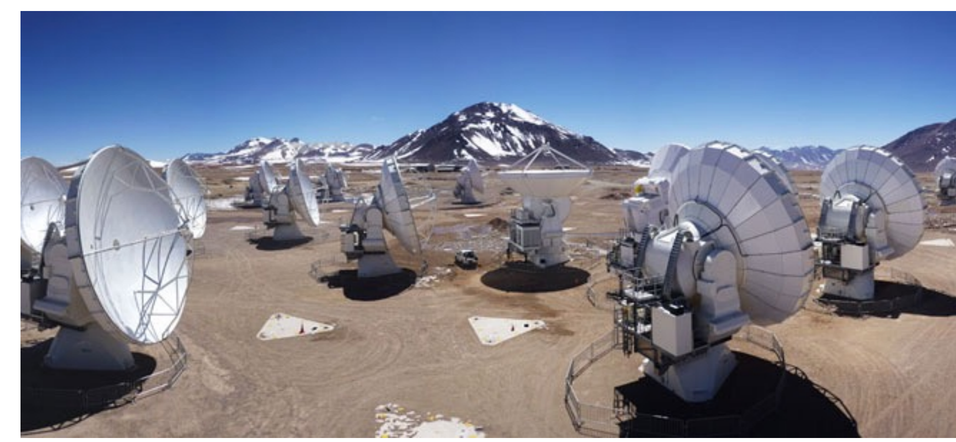


z = 6.42 quasar with IRAM 30-m [Maiolino+05]

Observing [CII]

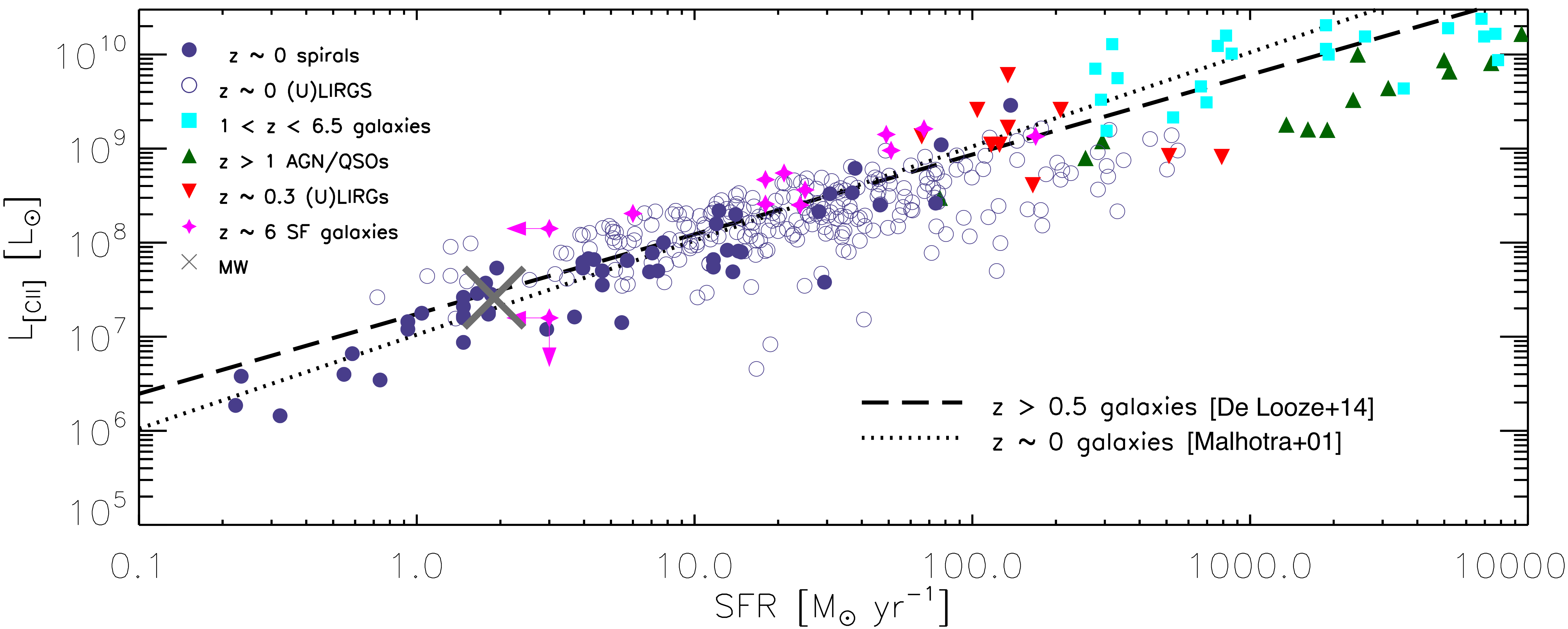
Option #2: Going to high redshift



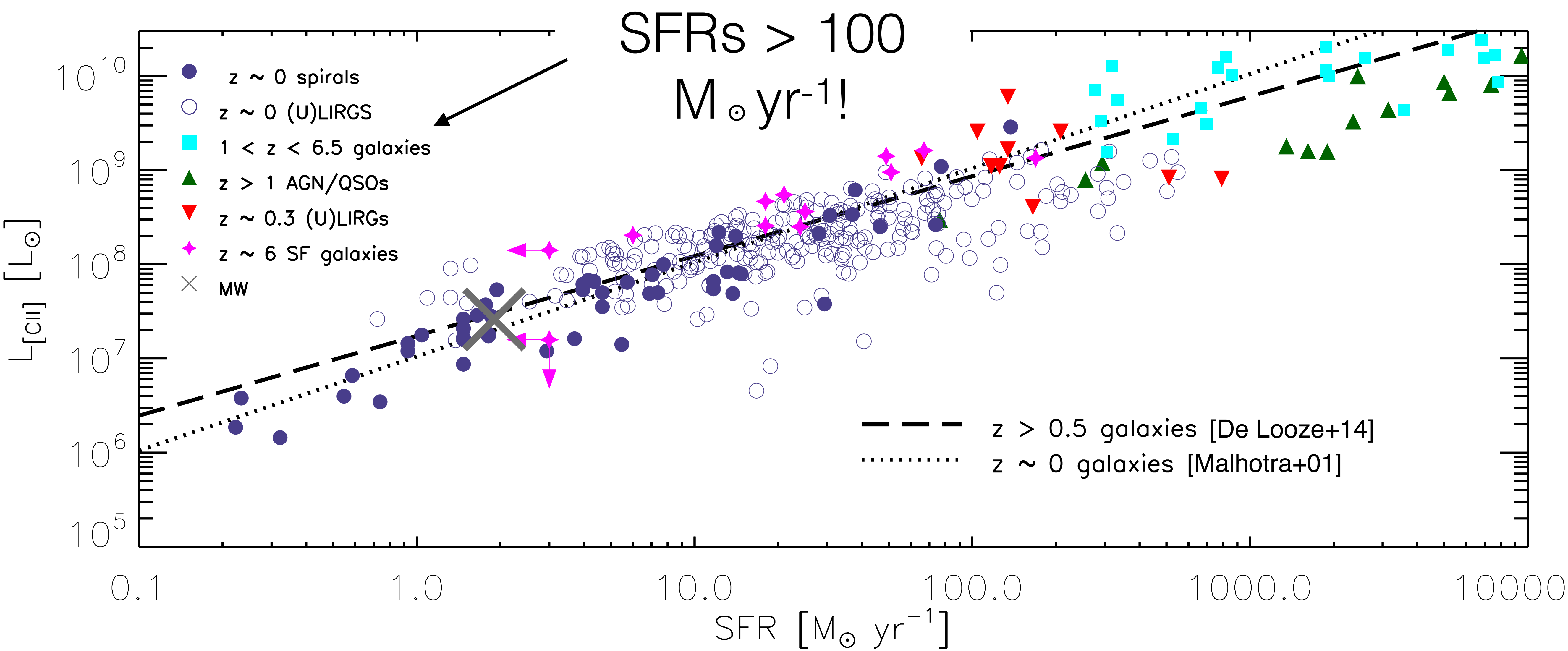


z ~ 5-6 with ALMA [Capak+15]

The SFR-$L_{[CII]}$ relation

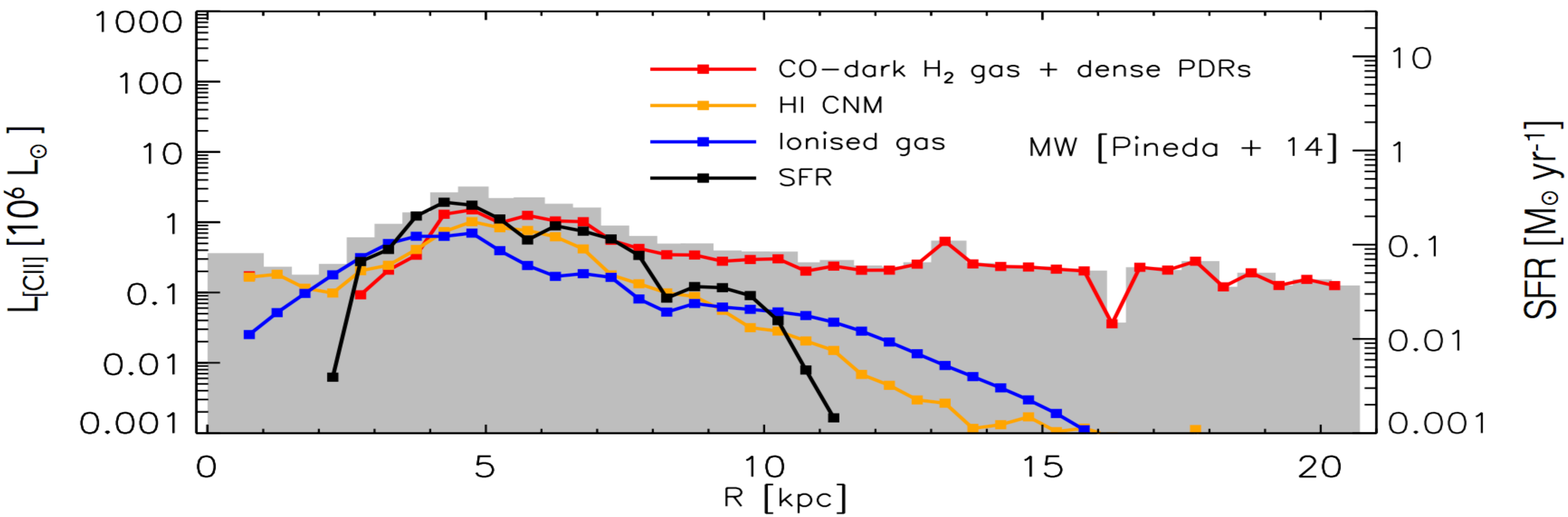


The SFR-$L_{[CII]}$ relation



1. How does [CII]-SFR relation look for normal galaxies at intermediate z?

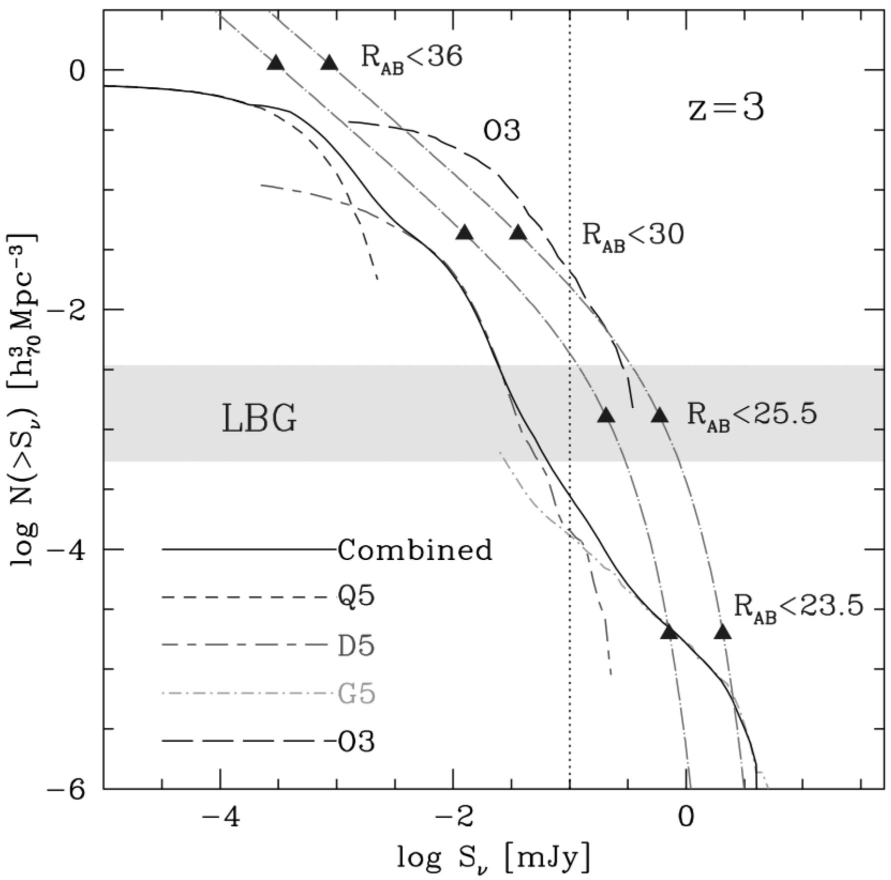
The origin of [CII] emission



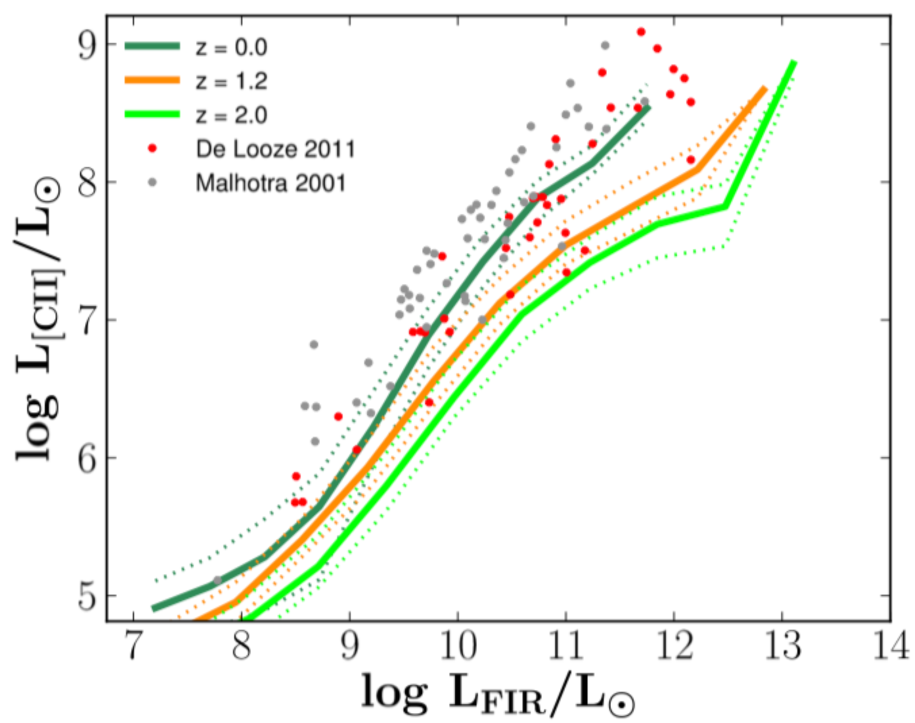
1. How does [CII]-SFR relation look for normal galaxies at intermediate z?
2. What is the origin of [CII] in the ISM?

Previous simulations of [CII] emission

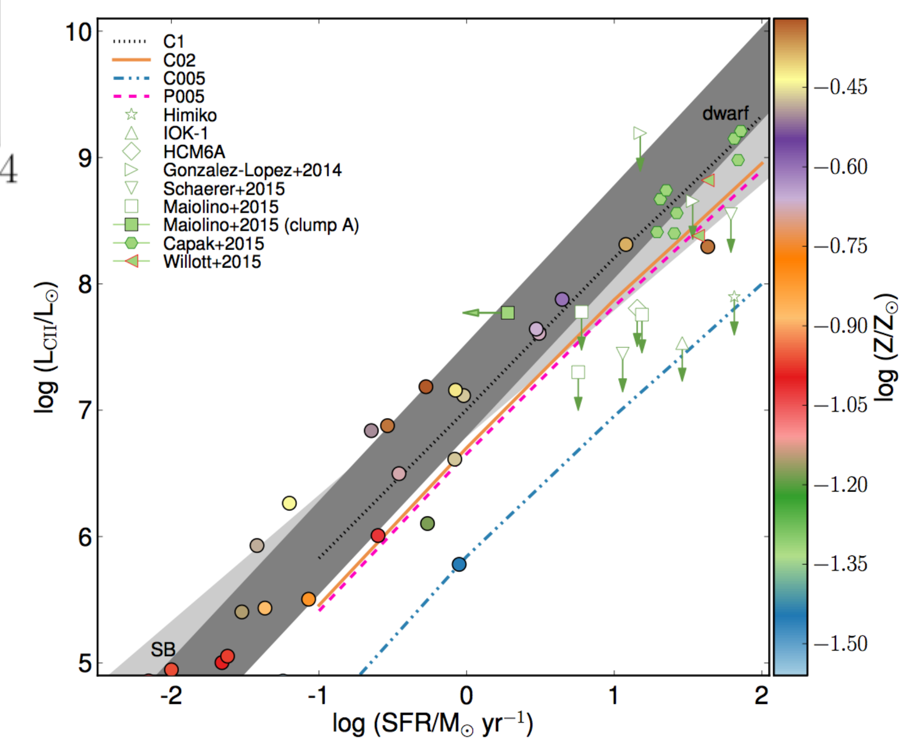
[Nagamine+06]



[Popping+14]

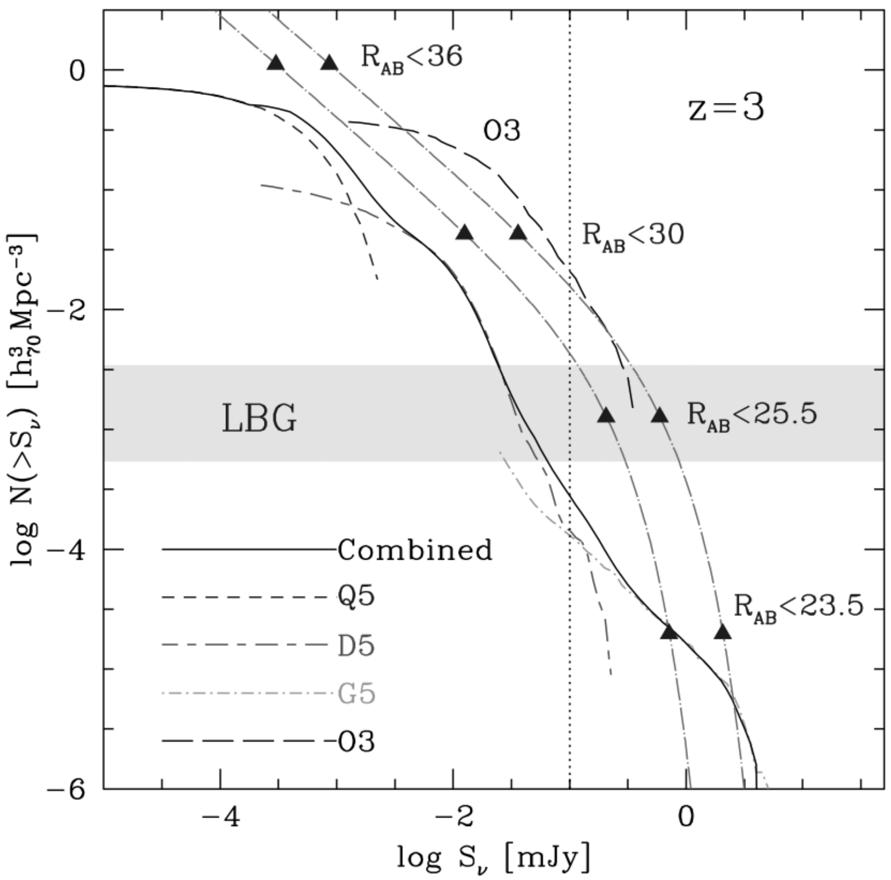


[Vallini+13+15]

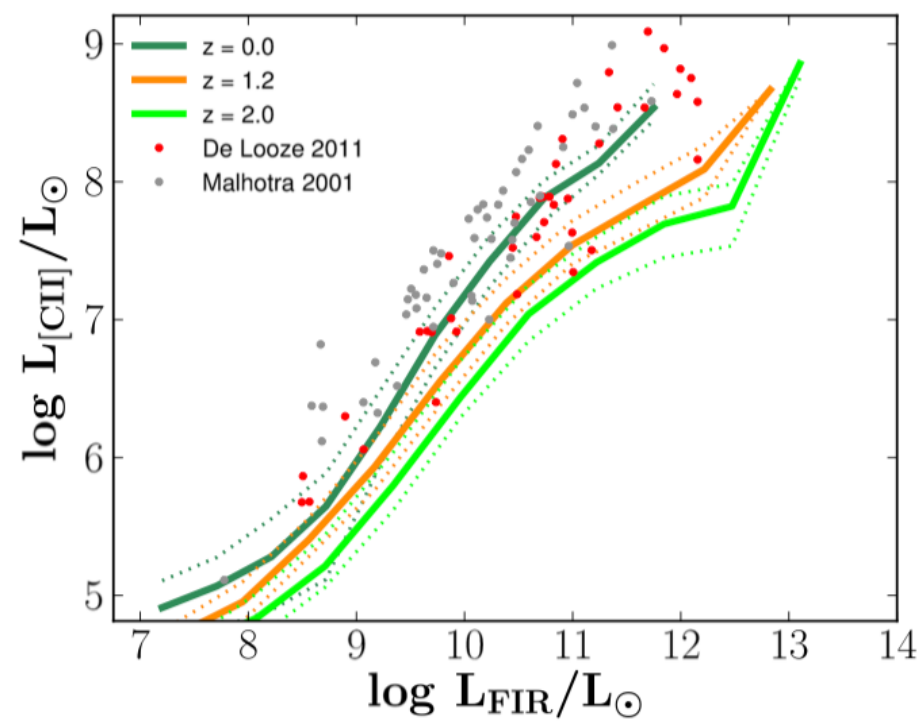


Previous simulations of [CII] emission

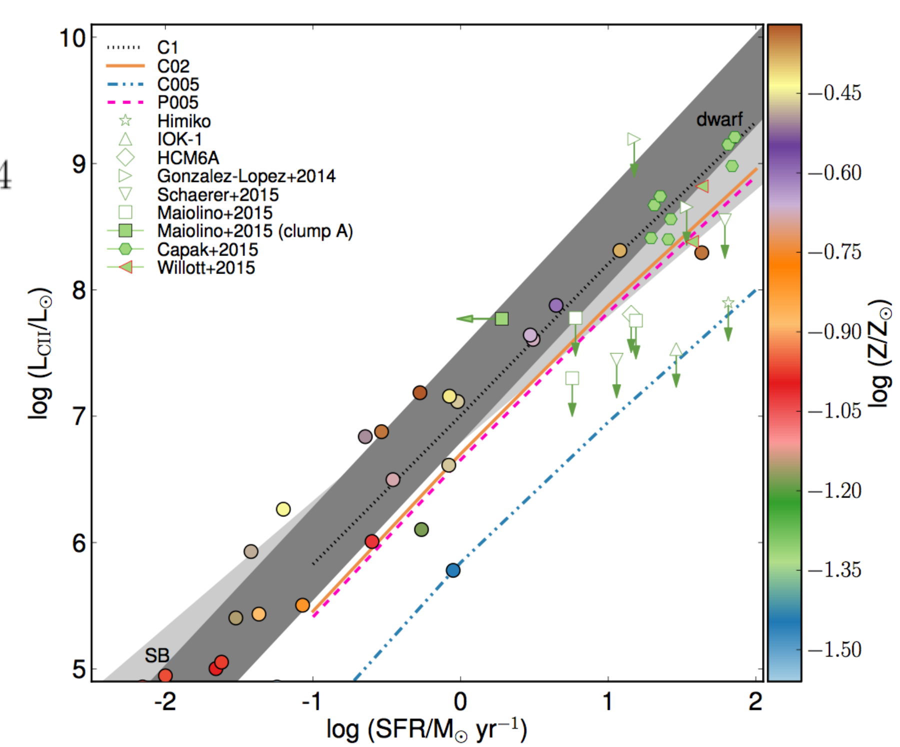
[Nagamine+06]



[Popping+14]



[Vallini+13+15]



We wanted:

- Full advantage of a cosmological sim (metallicity, gas distribution)
- More complete heating/cooling (cosmic rays)
- [CII] from all phases (not just WNM)

SÍGAME

SImulator of GAlaxy Millimeter/submillimeter Emission

Collaborators: Thomas R Greve[2], Desika Narayanan[3], Robert Thompson[4], Christian Brinch[5,6], Jesper Sommer-Larsen[1,7,8], Jesper Rasmussen[1,9], Sune Toft[1] and Andrew Zirm[1]

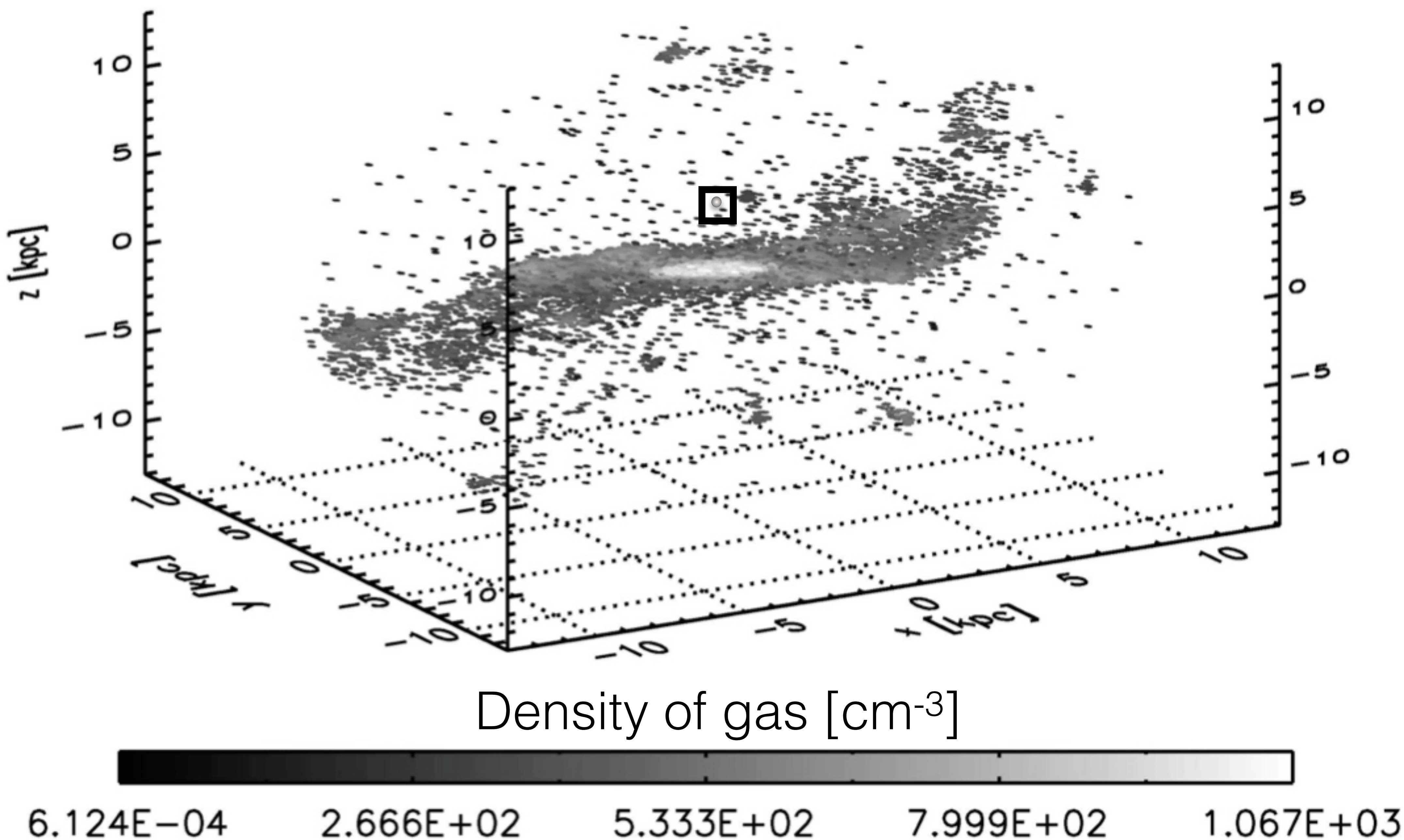
[1] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Denmark
[2] Dept of Physics and Astronomy, University College London
[3] Haverford College, PA, US
[4] Centre for Extragalactic Theory, University of West Cape, South Africa
[5] Centre for Star and Planet formation (Starplan) and Niels Bohr Institute, Denmark
[6] DeIC, Technical University of Denmark
[7] Excellence Cluster Universe, Garching, Germany
[8] Marie Kruses Skole, Farum, Denmark
[9] Department of Physics, Technical University of Denmark

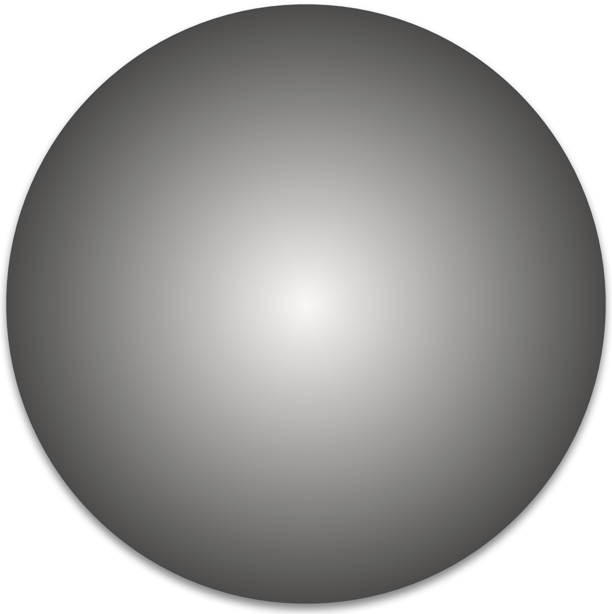
(='follow me' in Spanish)

Galaxy simulations

Cosmological Smoothed Particle Hydrodynamics (SPH) simulations

(Jesper Sommer-Larsen, see 2005 paper)

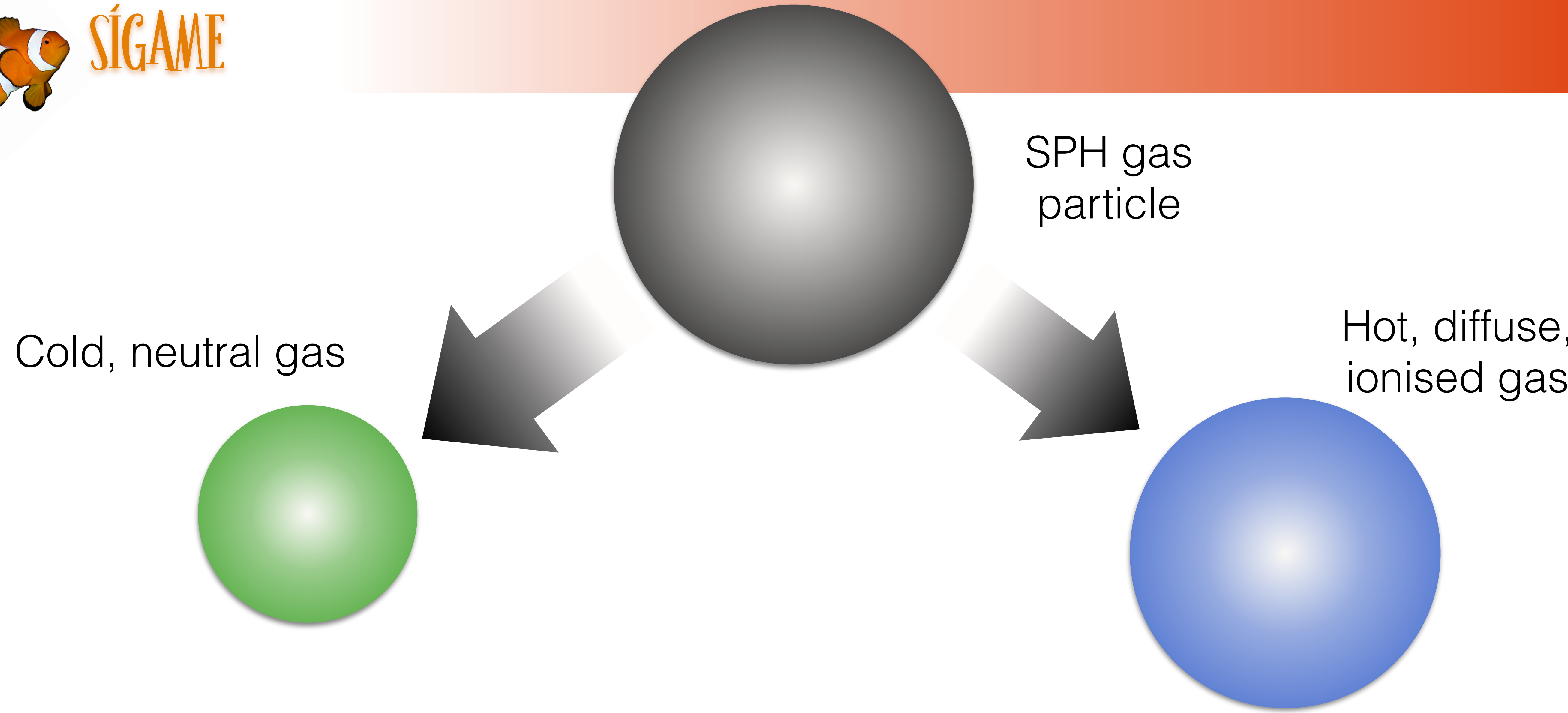


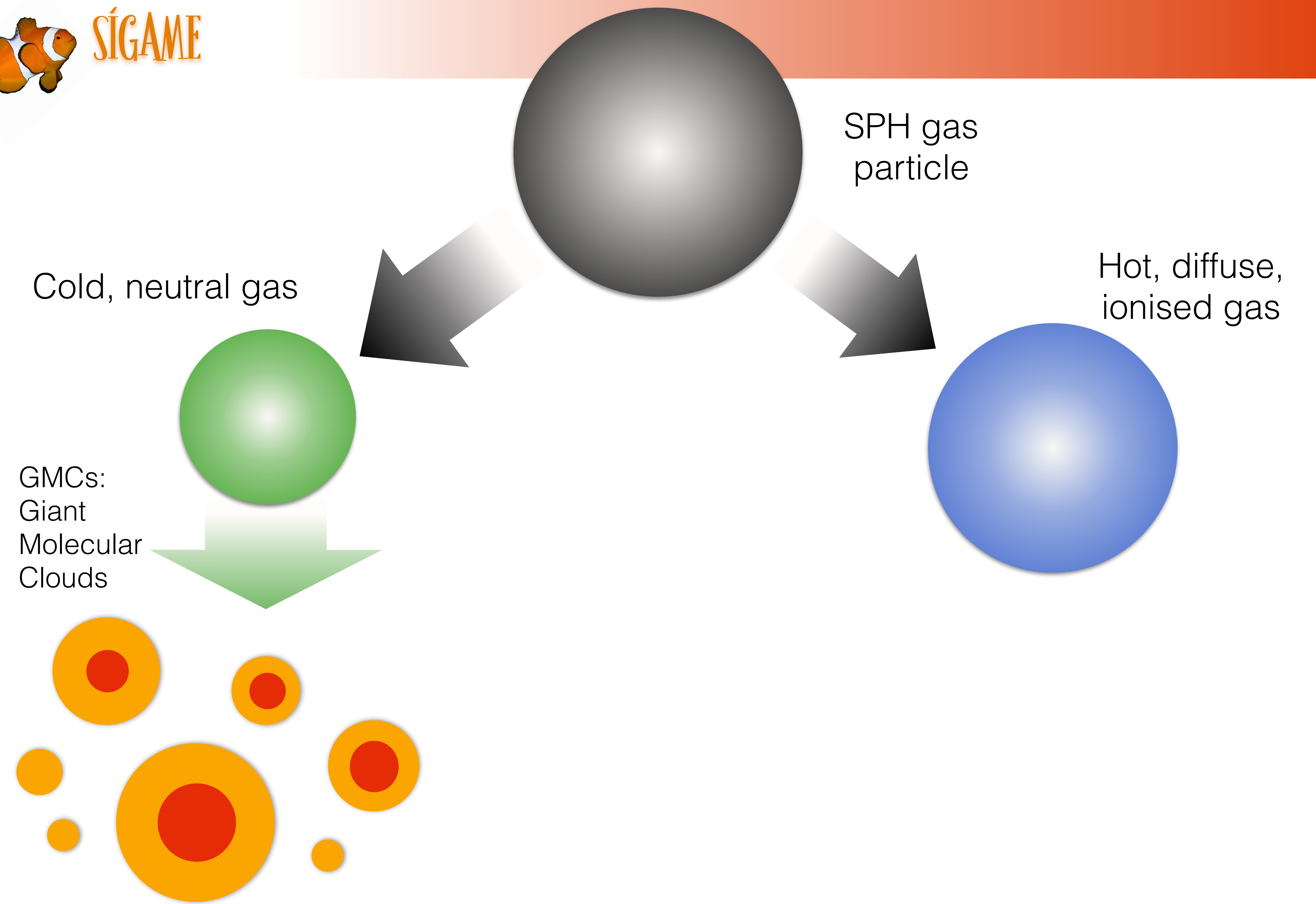


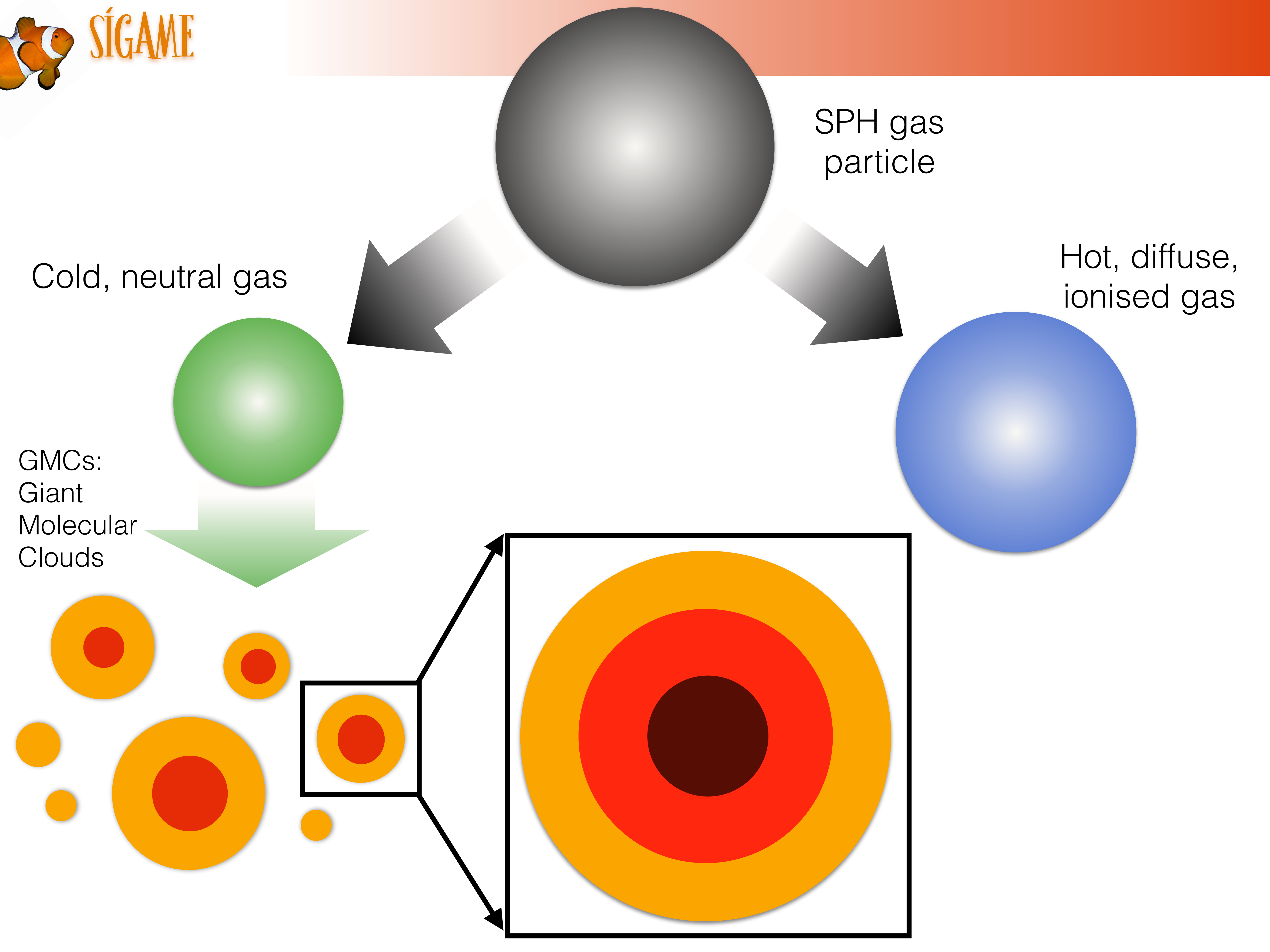
SPH gas particle

$(m_{SPH}, n_{SPH}, T_{SPH}, Z, x_e)$

$(\mathbf{r}_{SPH}, \mathbf{v}_{SPH})$


SPH gas particle
Cold, neutral gas
Hot, diffuse, ionised gas


SÍGAME
SPH gas
particle
Cold, neutral gas
Hot, diffuse,
ionised gas
GMCs:
Giant
Molecular
Clouds


SÍGAME
SPH gas particle
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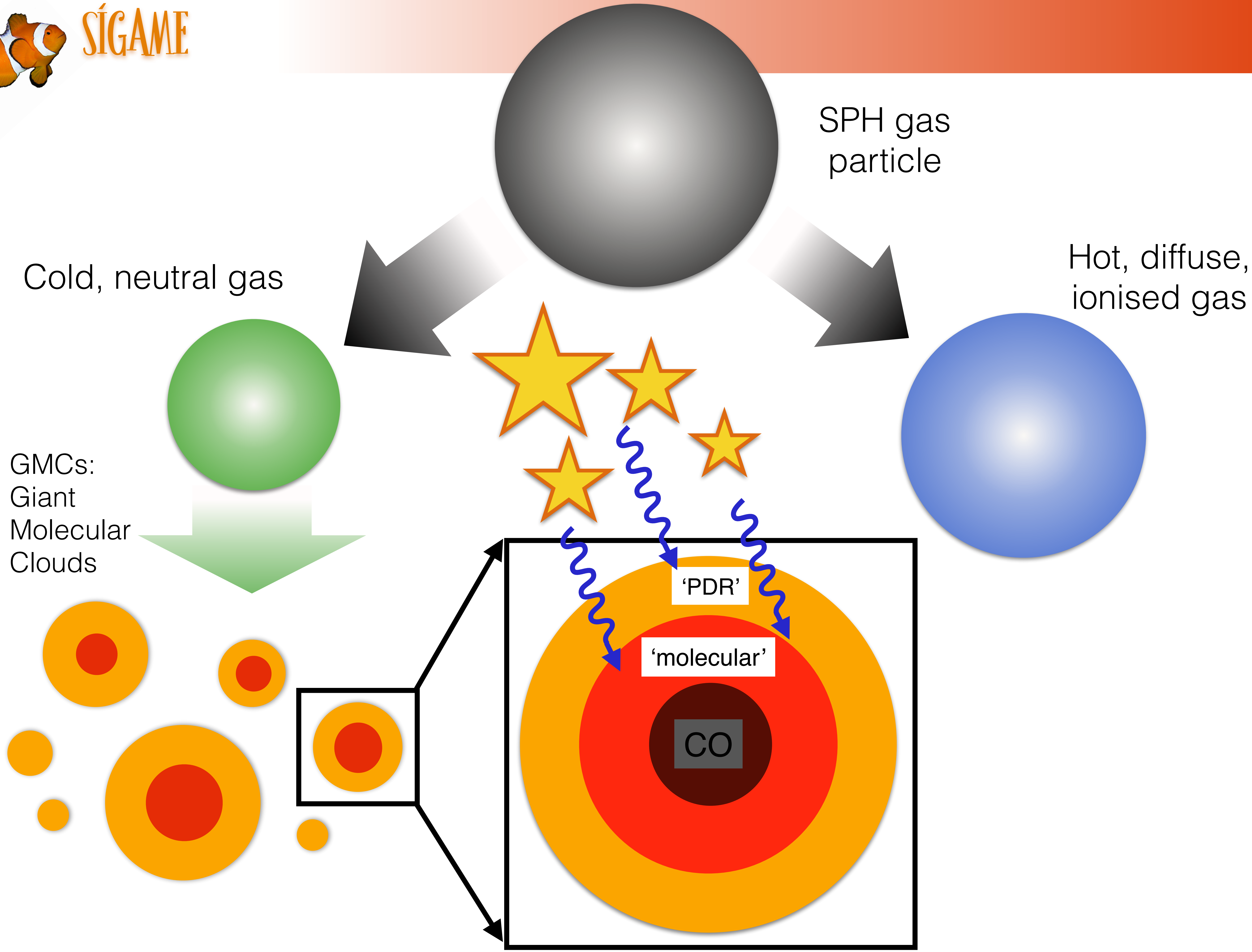
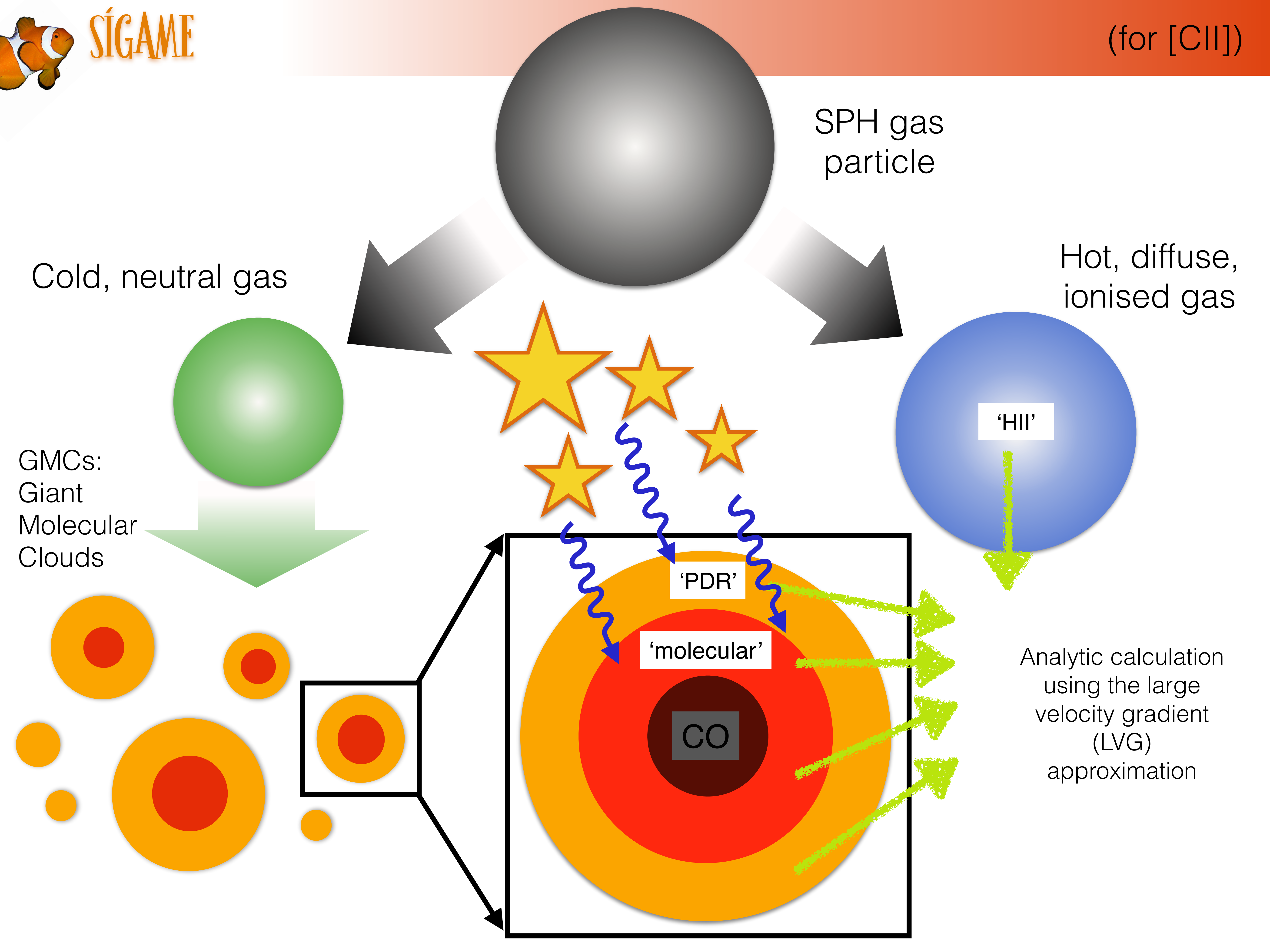
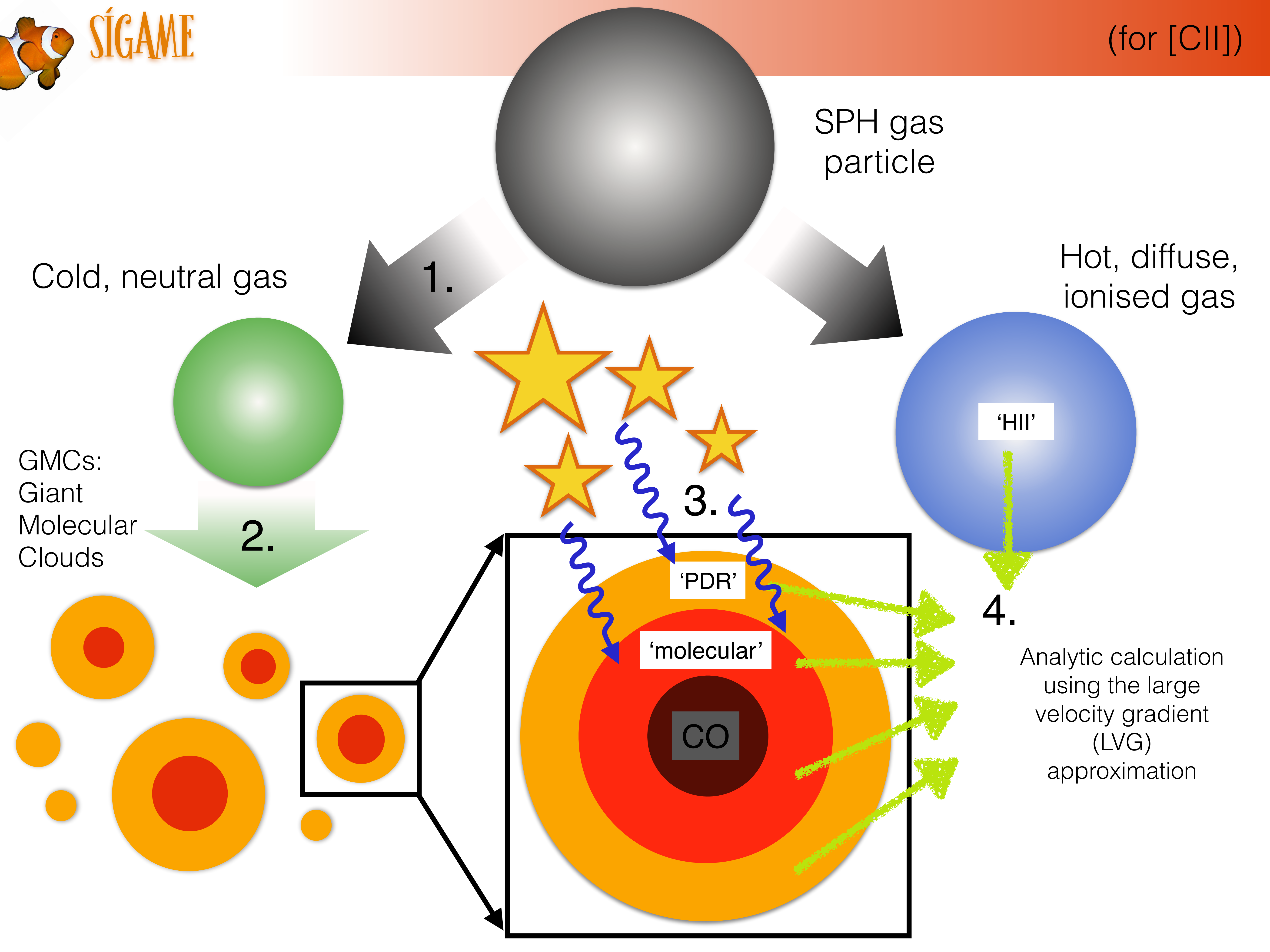
GMCs: Giant Molecular Clouds

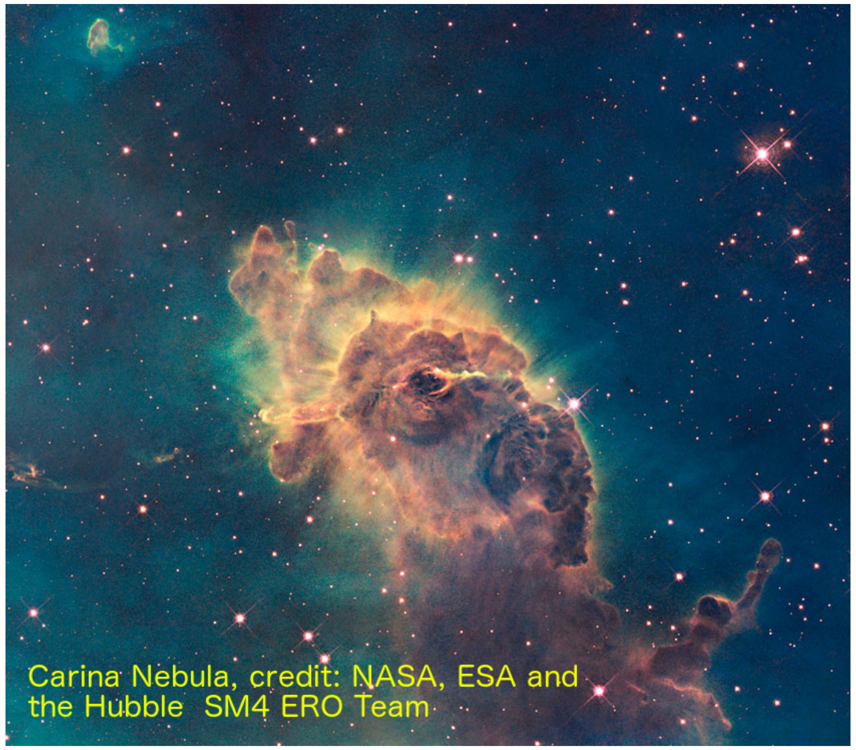
SÍGAME


SPH gas particle
Cold, neutral gas
Hot, diffuse, ionised gas
GMCs: Giant Molecular Clouds
'PDR'
'molecular'
CO

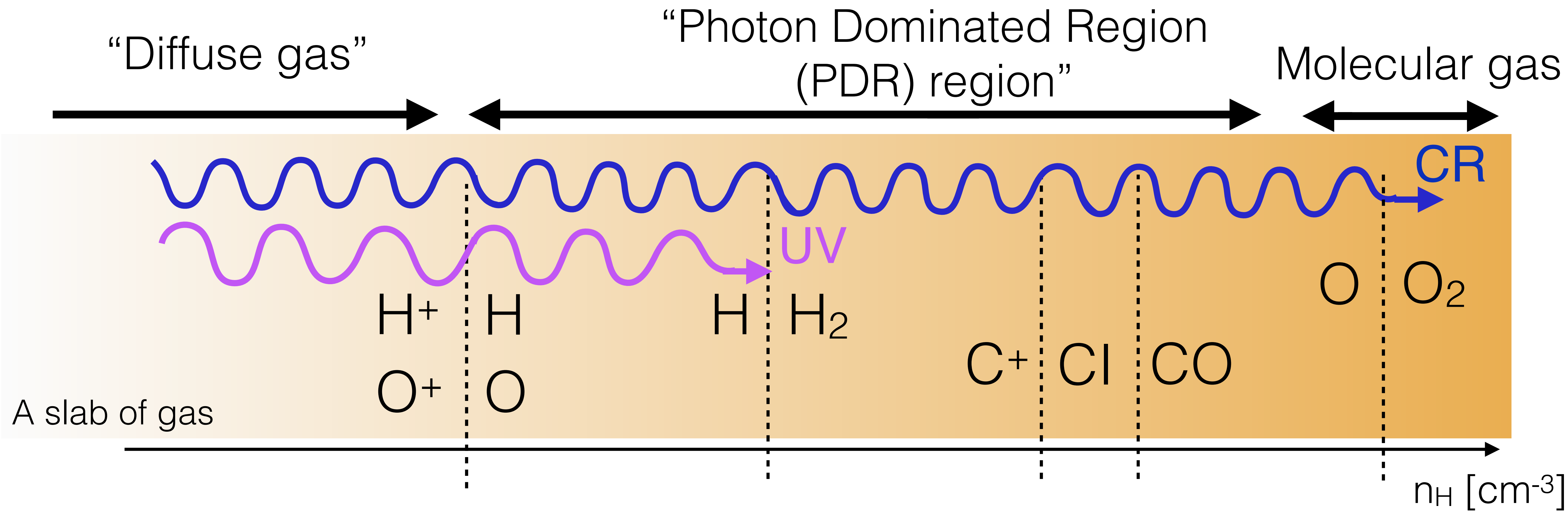

SÍGAME
(for [CII])
SPH gas particle
Cold, neutral gas
Hot, diffuse, ionised gas
GMCs: Giant Molecular Clouds
'HII'
'PDR'
'molecular'
CO
Analytic calculation using the large velocity gradient (LVG) approximation


SÍGAME
(for [CII])
SPH gas
particle
Cold, neutral gas
1.
Hot, diffuse,
ionised gas
'HII'
GMCs:
Giant
Molecular
Clouds
2.
3.
'PDR'
'molecular'
CO
4.
Analytic calculation
using the large
velocity gradient
(LVG)
approximation

Gas physics and terminology

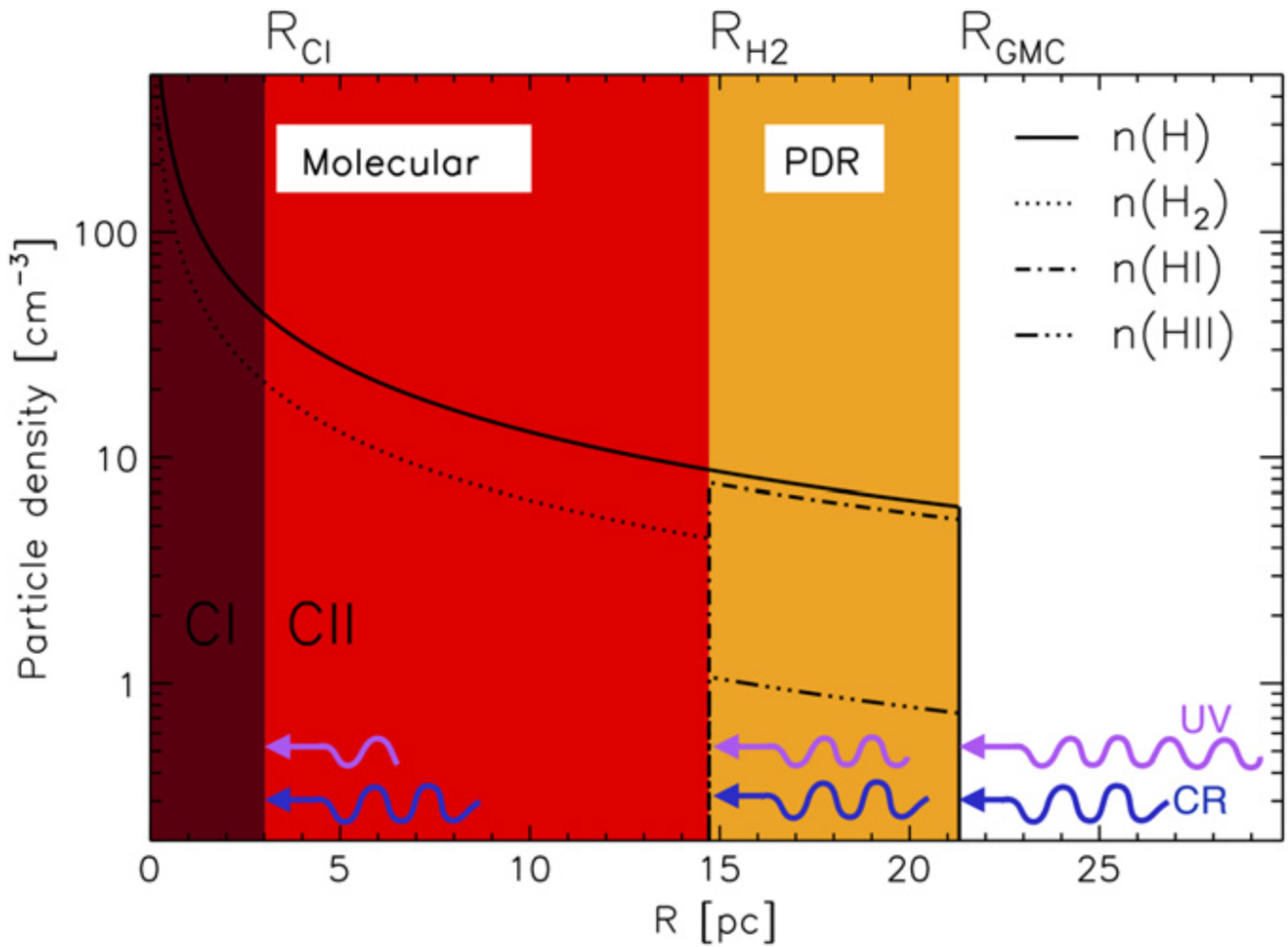


Molecular gas is organized in Giant Molecular Clouds (GMCs)



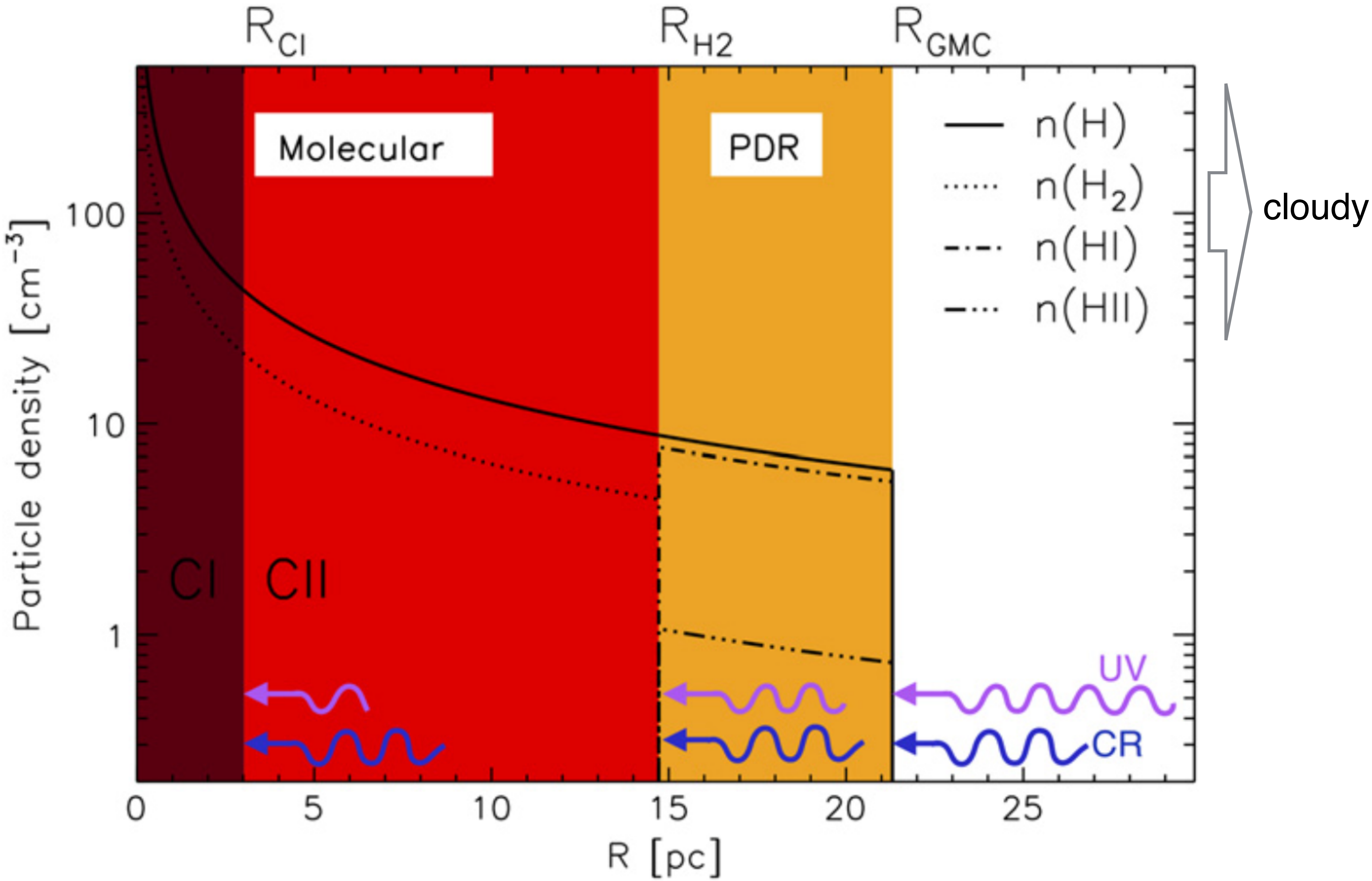
Thermal state of GMCs

Definition of some radii for logotropic density profile: $$n_{\rm H}(R) = n_{\rm H,ext}\left(\frac{R_{\rm GMC}}{R}\right)$$



Thermal state of GMCs

Definition of some radii for logotropic density profile: $$n_{\rm H}(R) = n_{\rm H,ext}\left(\frac{R_{\rm GMC}}{R}\right)$$

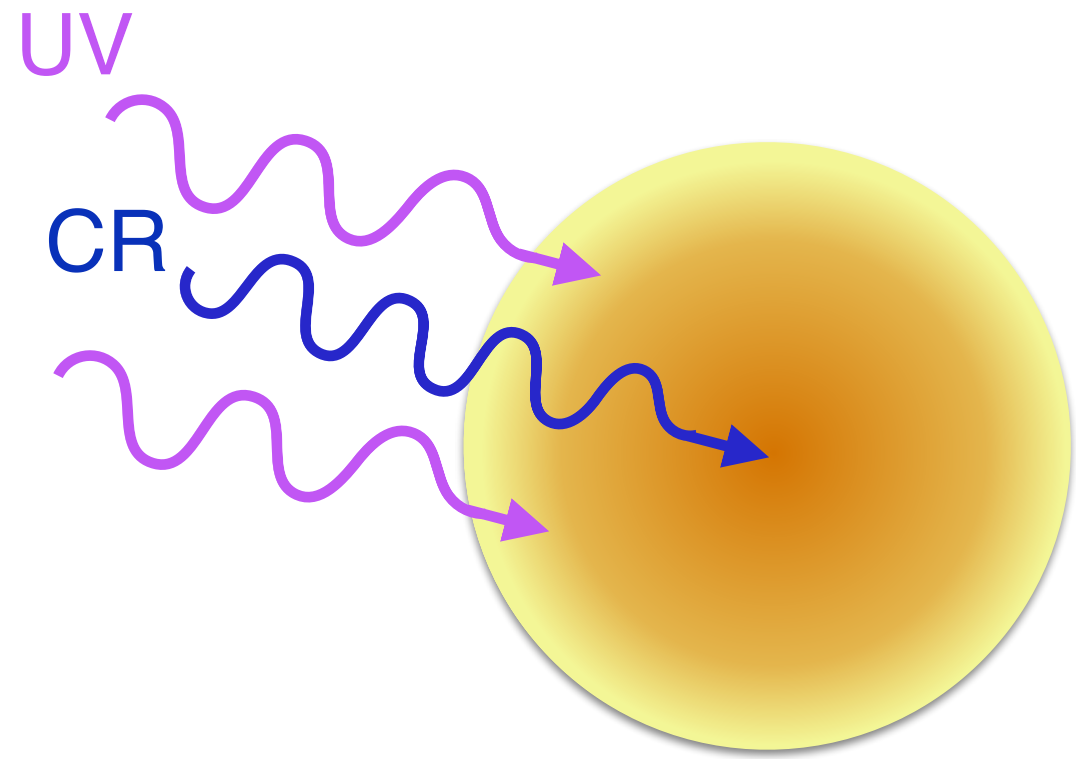


Thermal state of GMCs

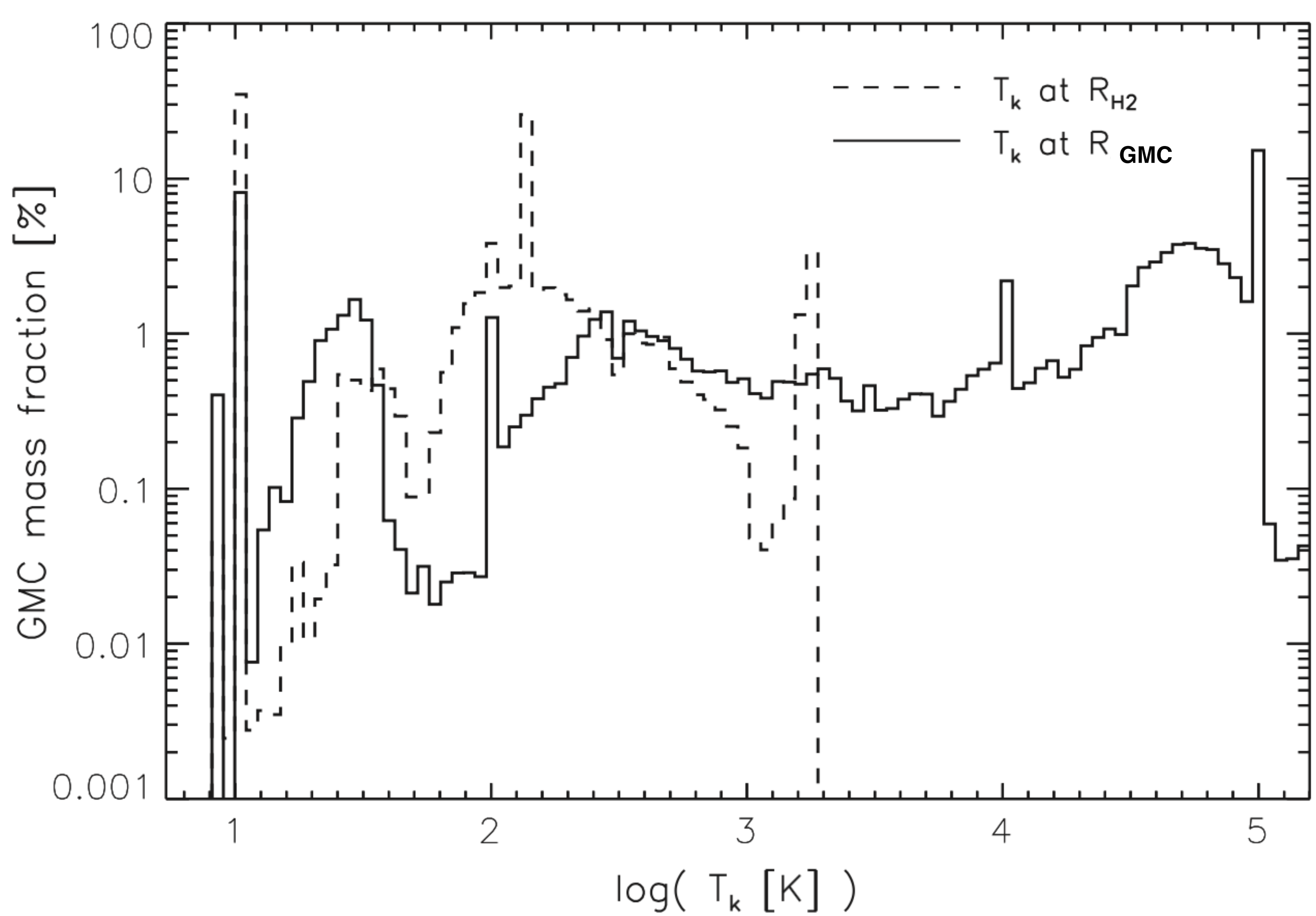
Iterate for the temperature at two radii:

R_{H2}: $\Gamma_{PE}+\Gamma_{CR,H2} = \Lambda_{H2} + \Lambda_{CII} + \Lambda_{OI}$

R_{GMC}: $\Gamma_{PE}+\Gamma_{CR,HI} = \Lambda_{CII} + \Lambda_{OI}$



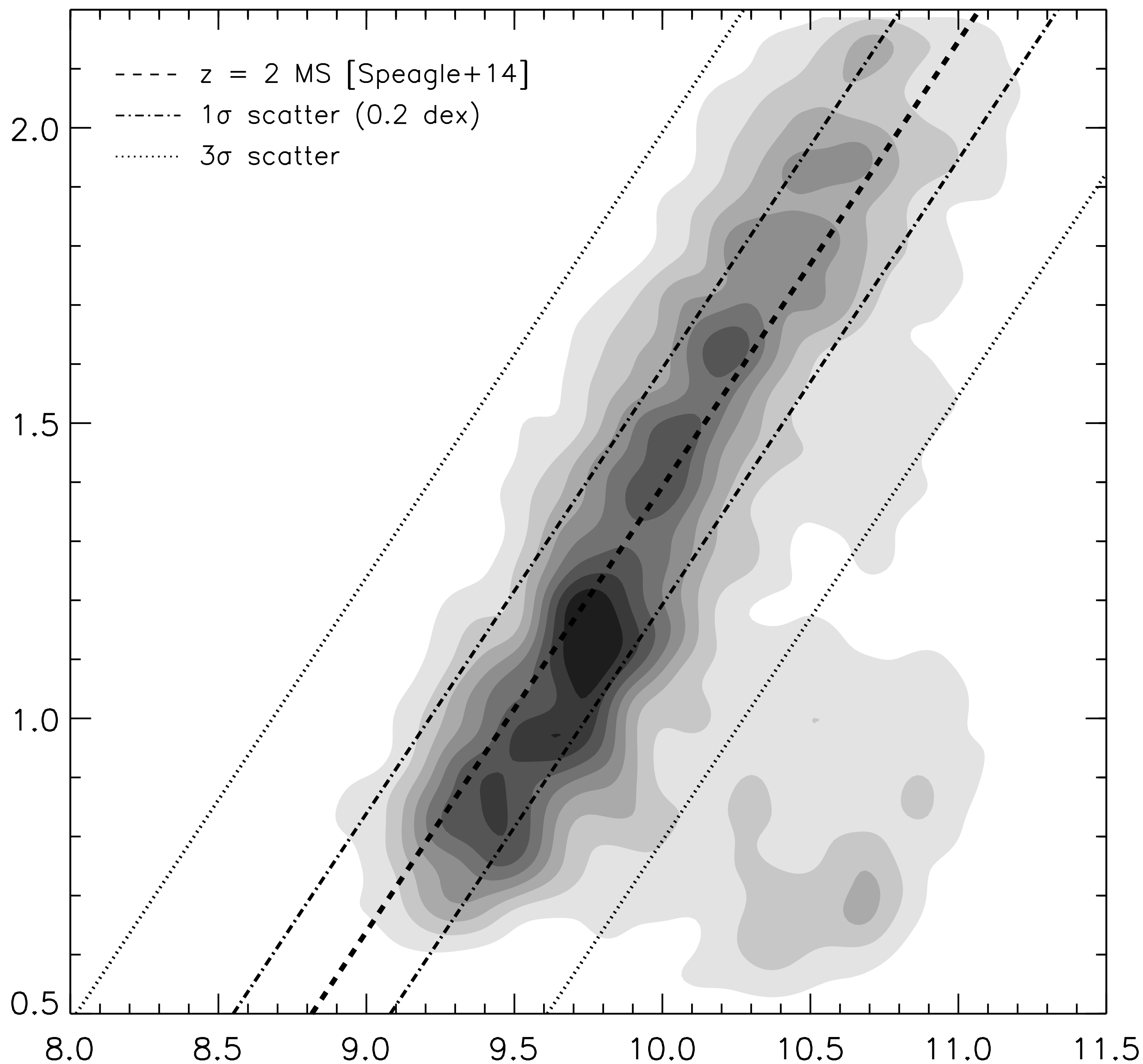
Temperatures in G1 (one of 7 model galaxies):



7 z~2 star-forming galaxies

Cosmological simulations (Gadget-3) at z=2 by [Thompson+14]

SFRs ~ 5-60 $M_\odot$ yr^{-1}



log SFR [$M_\odot$ yr^{-1}]

log stellar mass [$M_\odot$]

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Cosmological simulations (Gadget-3) at z=2 by [Thompson+14]

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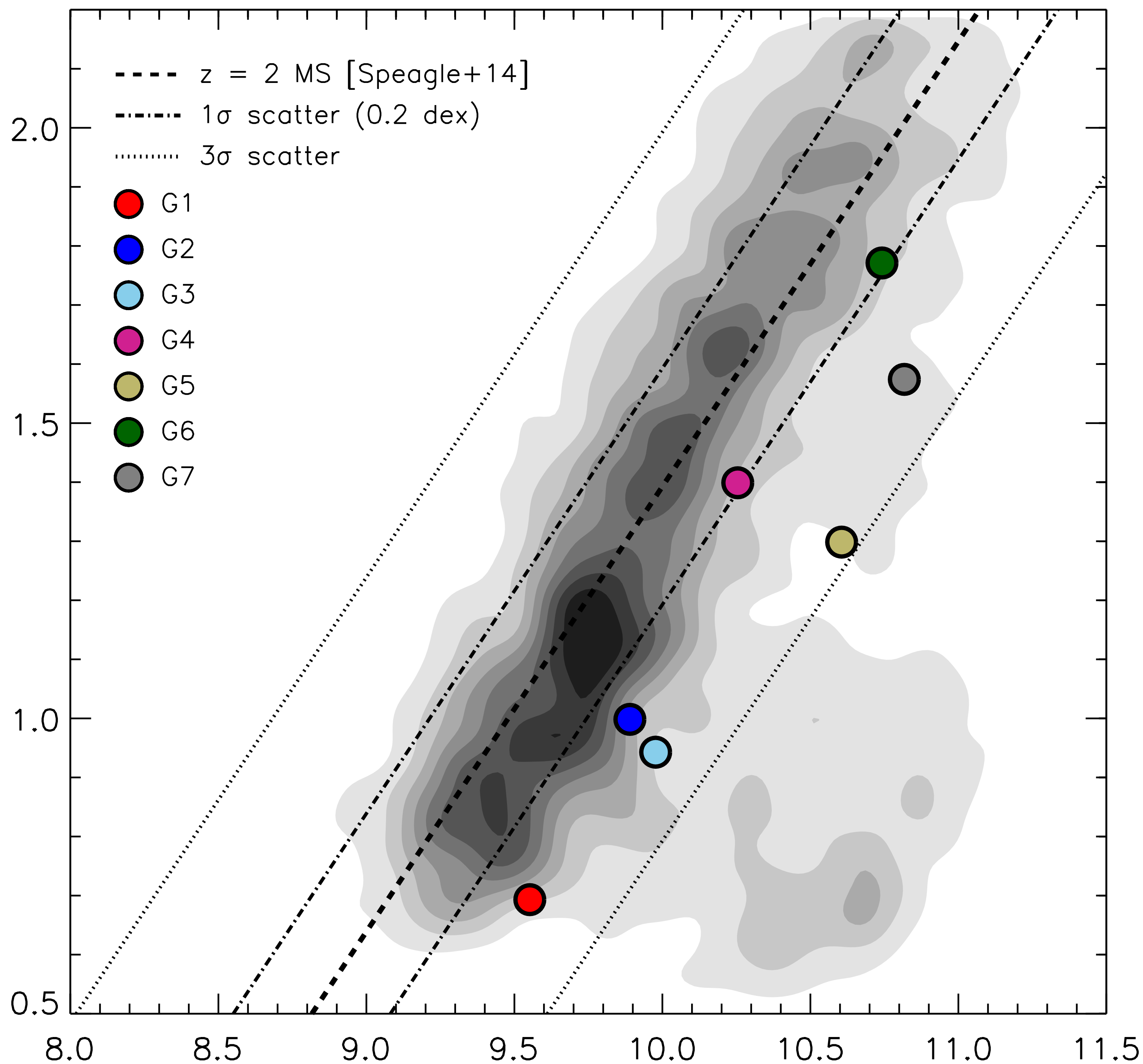
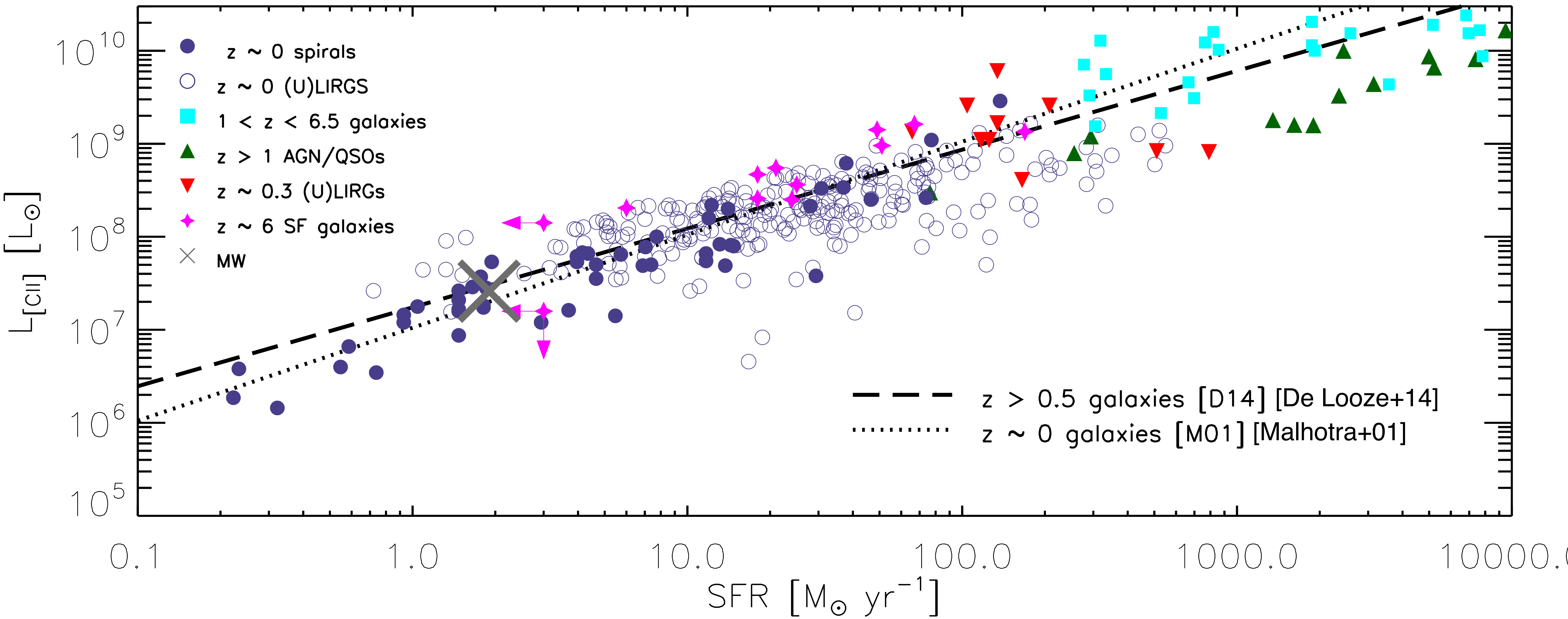


log SFR [$M_\odot$ yr^{-1}]

log stellar mass [$M_\odot$]

The SFR-$L_{[CII]}$ relation

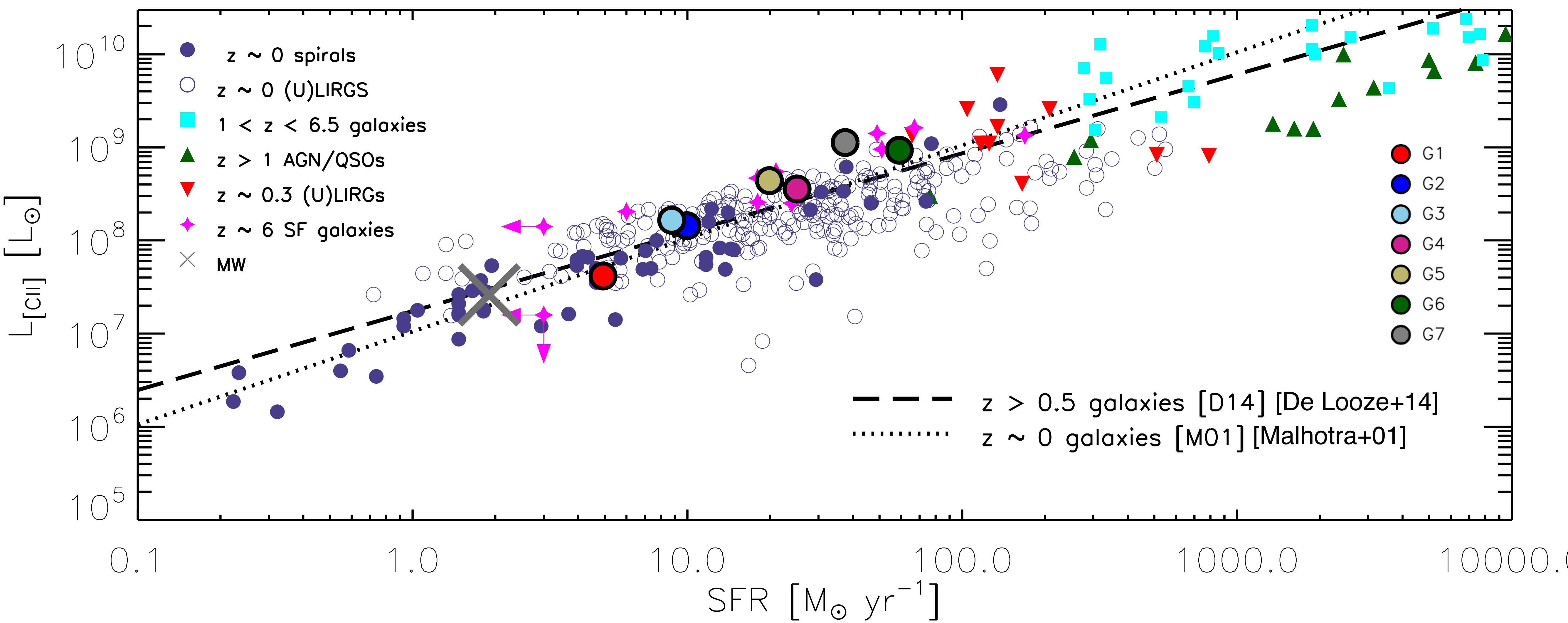
On the [CII]-SFR relation as observed from z=0 to z~6.5:



[Olsen+15: ApJ, 814, 76]

The SFR-$L_{[CII]}$ relation

On the [CII]-SFR relation as observed from z=0 to z~6.5:



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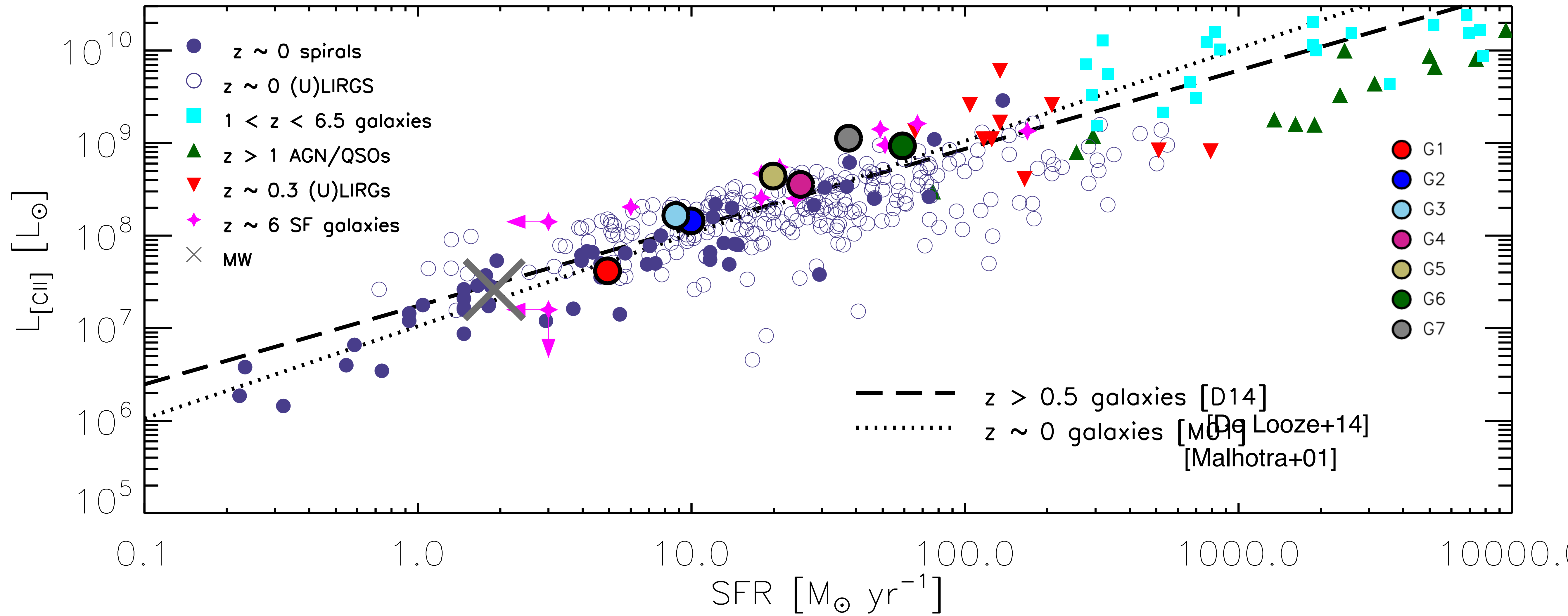
The SFR-$L_{[CII]}$ relation

On the [CII]-SFR relation as observed from z=0 to z~6.5:

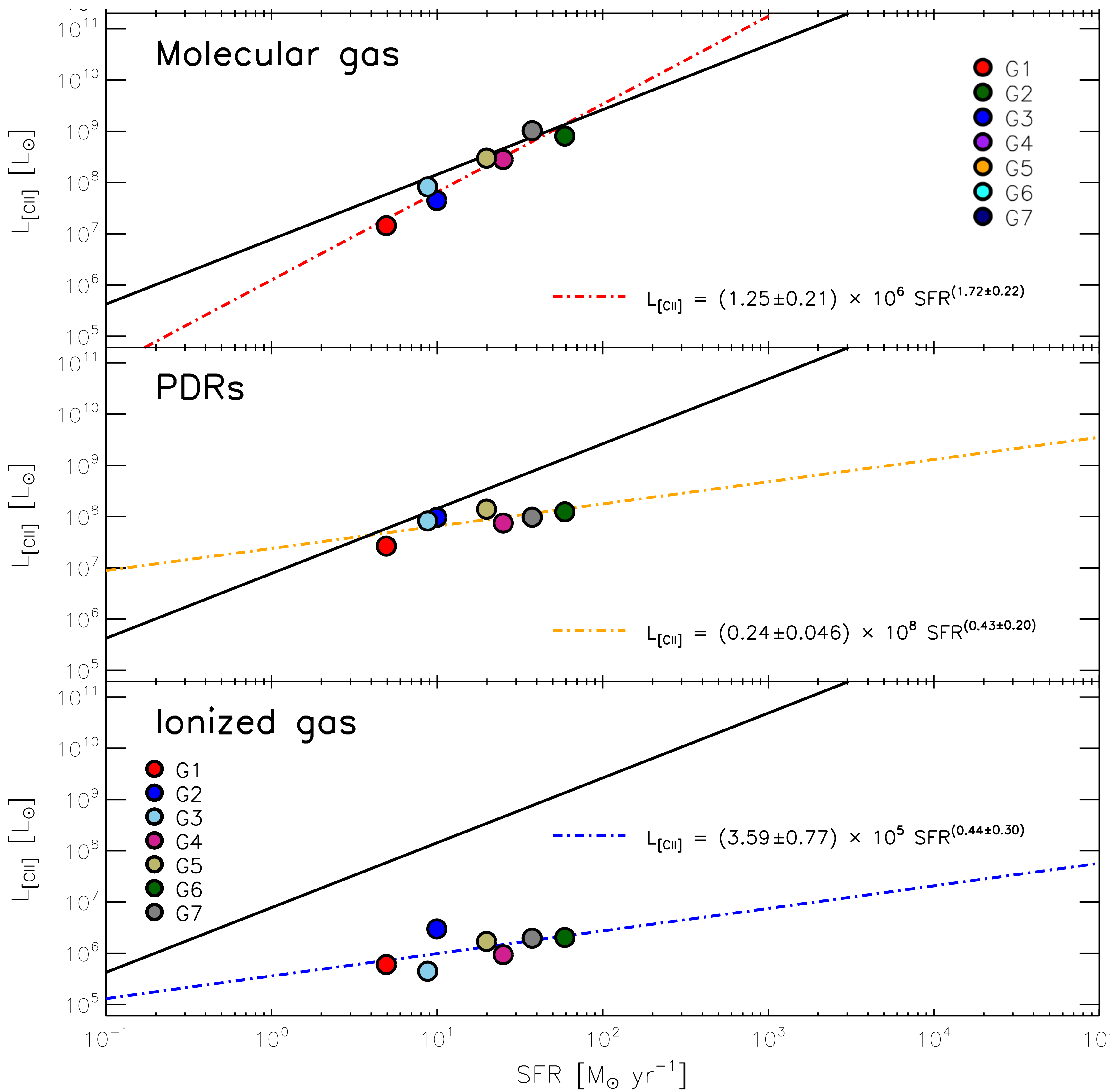


- Slope: 1.27±0.17 significantly (σ>1) steeper than that of z~0 galaxy samples (spirals and (U)LIRGs)
- Crossing local galaxies at about 10 $M_\odot$ yr^{-1}

[Olsen+15: ApJ, 814, 76]

The SFR-$L_{[CII]}$ relation

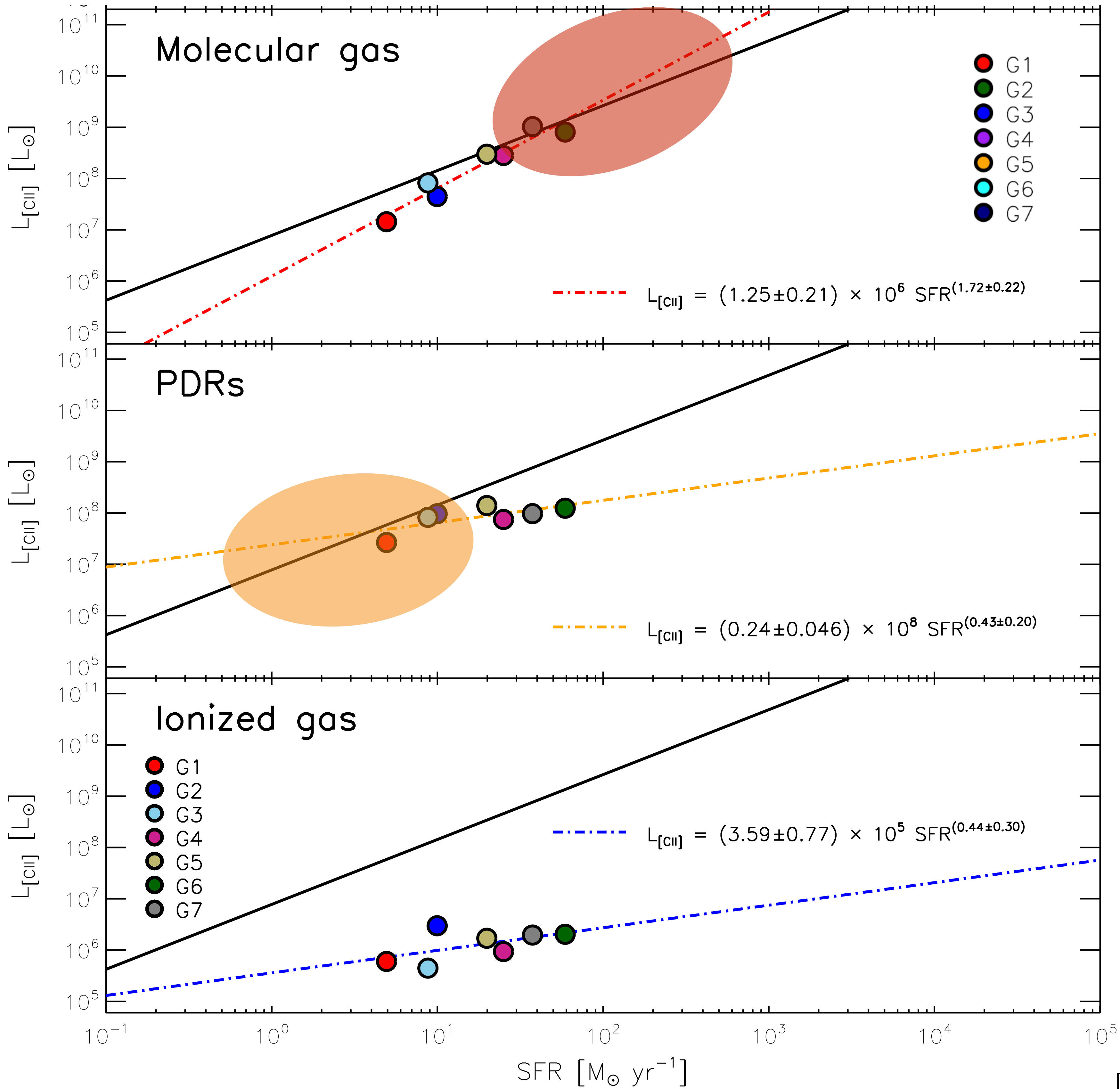
From different ISM phases:



[Olsen+15: ApJ, 814, 76]

The SFR-$L_{[CII]}$ relation

From different ISM phases:



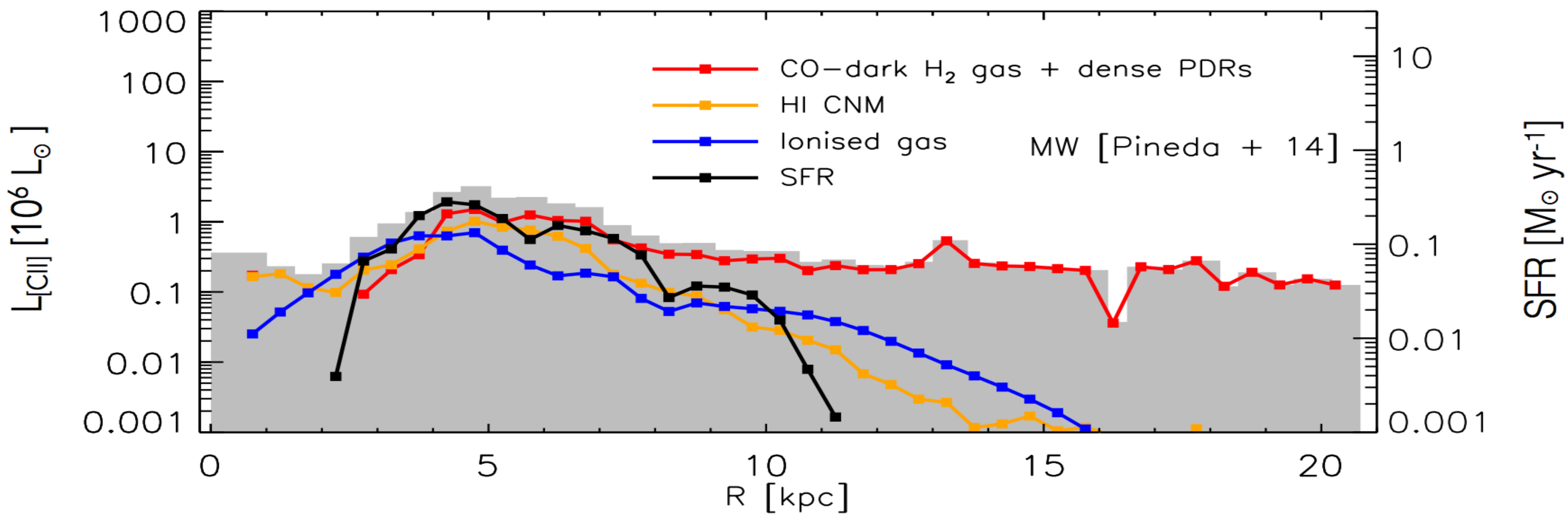
High SFR: molecular gas dominates [CII] luminosity

Low SFR: PDRs dominate [CII] luminosity

[Olsen+15: ApJ, 814, 76]

The origin of [CII] emission

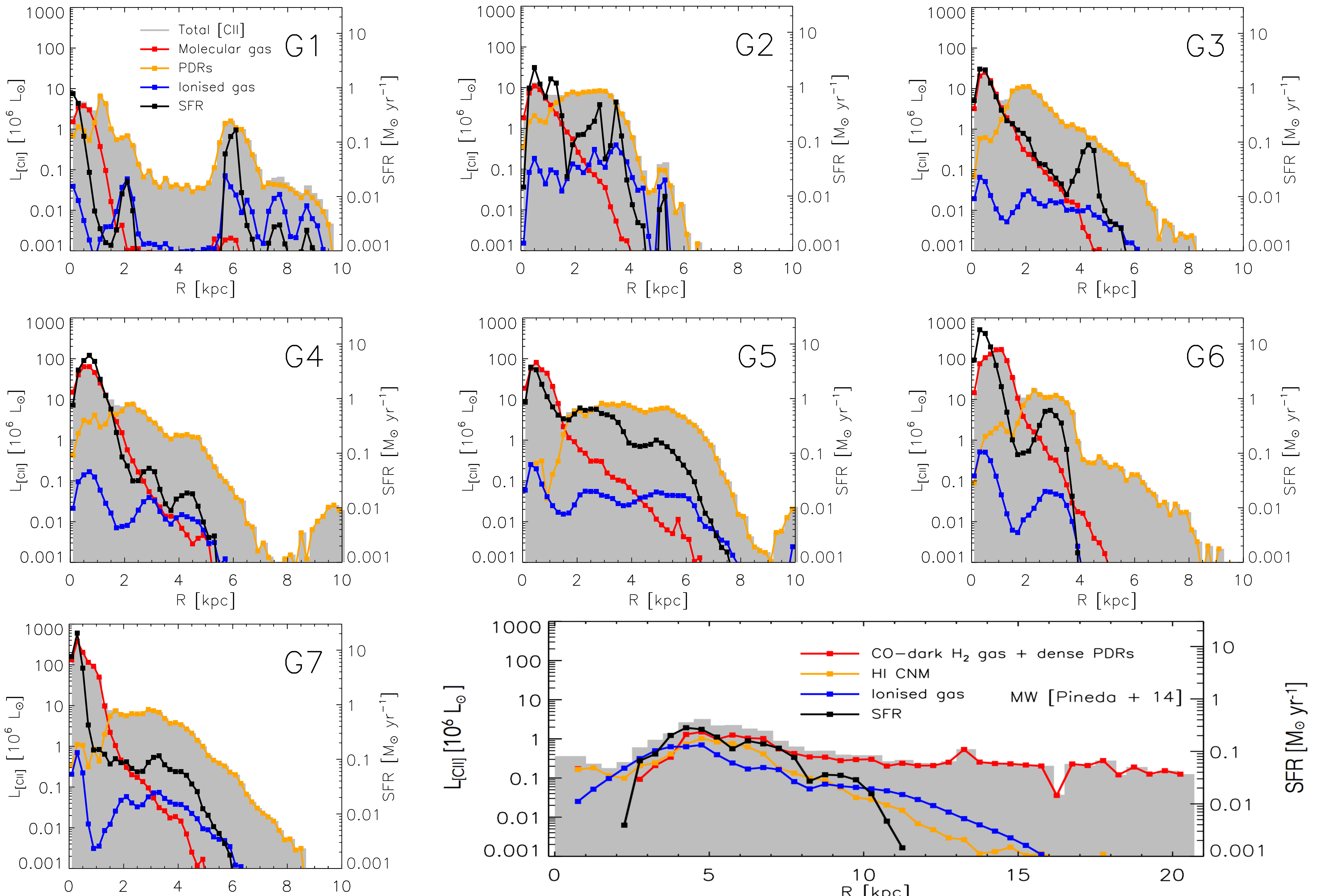
The origin of [CII] emission



[Olsen+15: ApJ, 814, 76]

SÍGAME

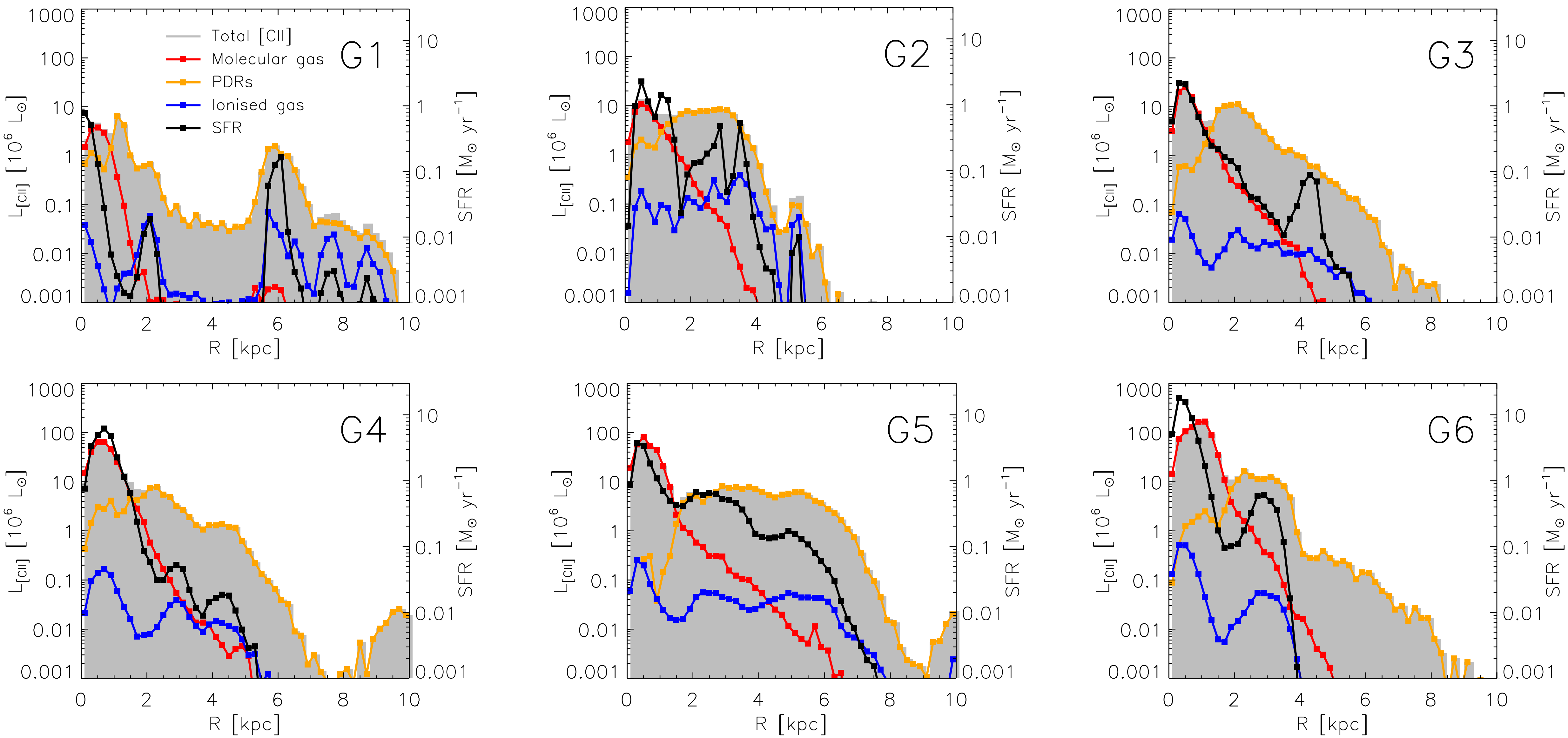
The origin of [CII] emission

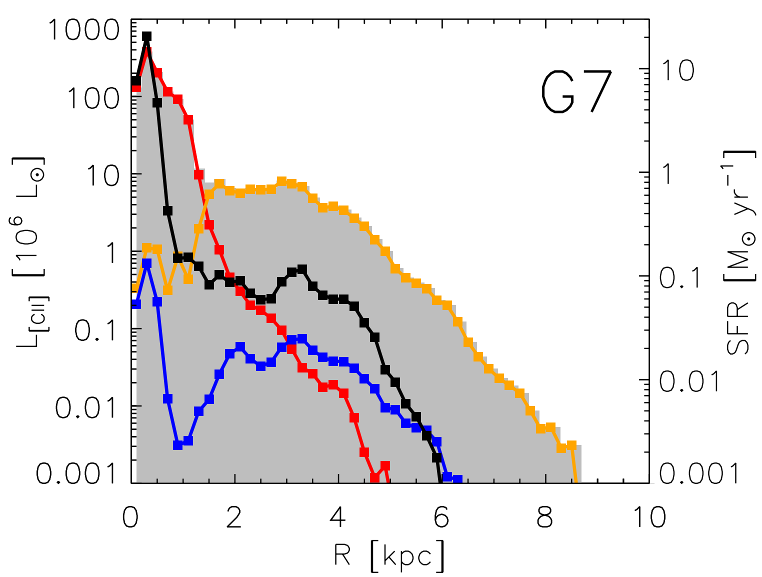


[Olsen+15: ApJ, 814, 76]

SÍGAME

The origin of [CII] emission



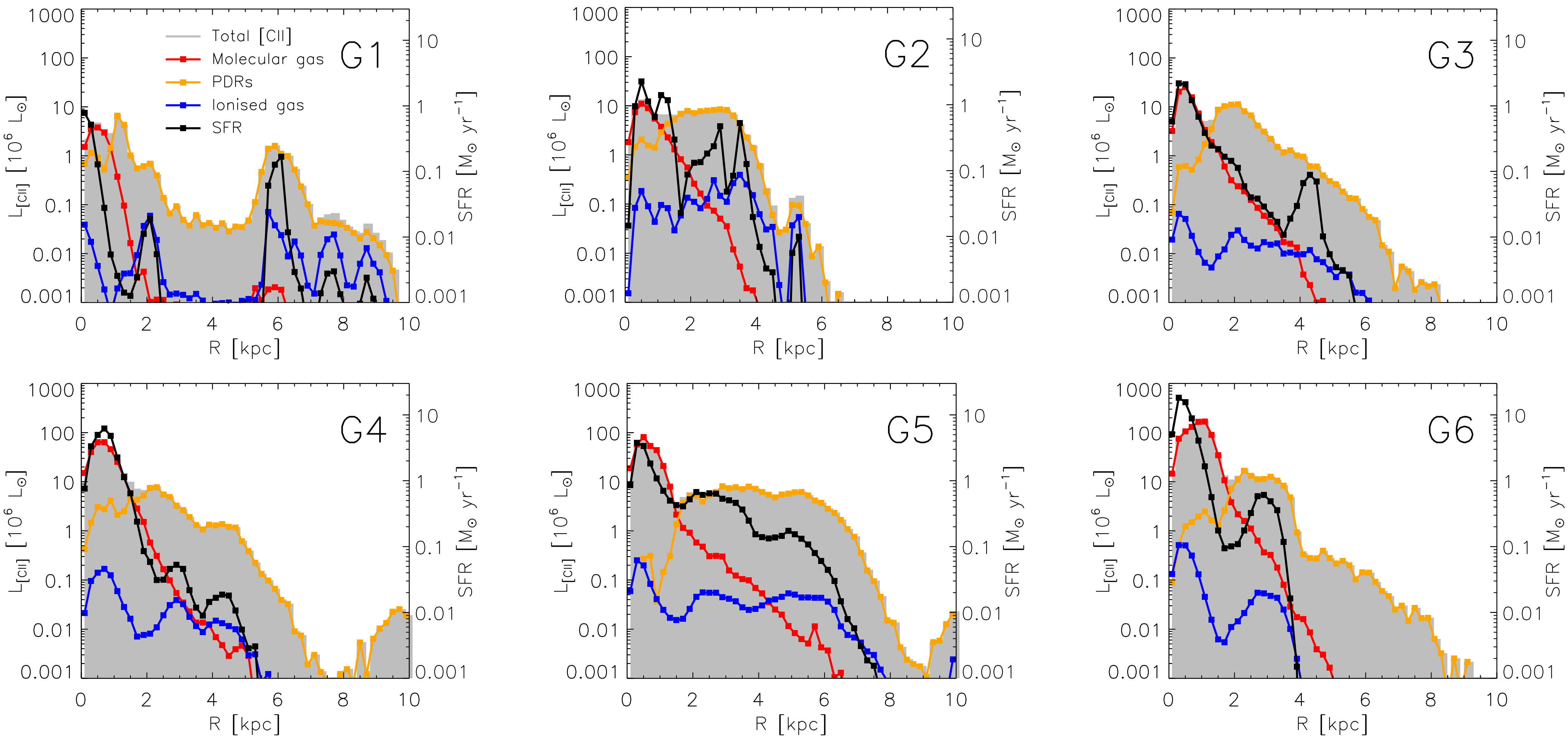


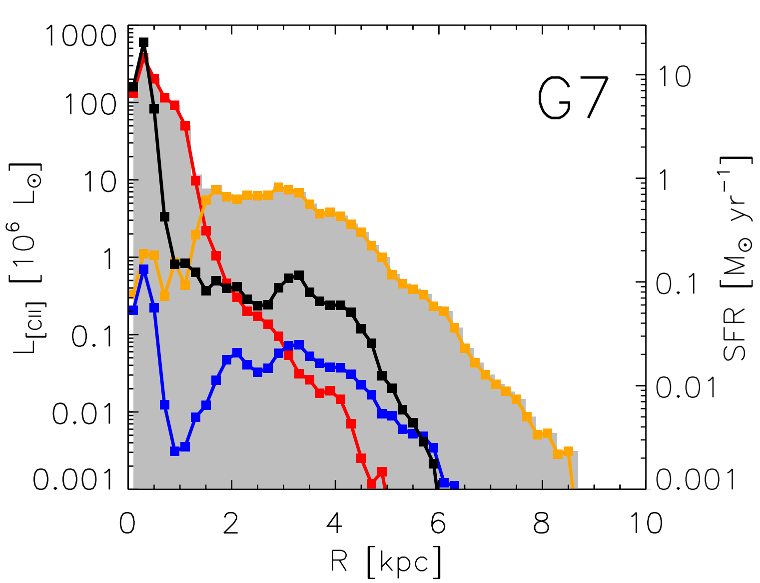
- [CII] from molecular gas dominates at low radii, PDRs at higher radii

[Olsen+15: ApJ, 814, 76]

SÍGAME

The origin of [CII] emission



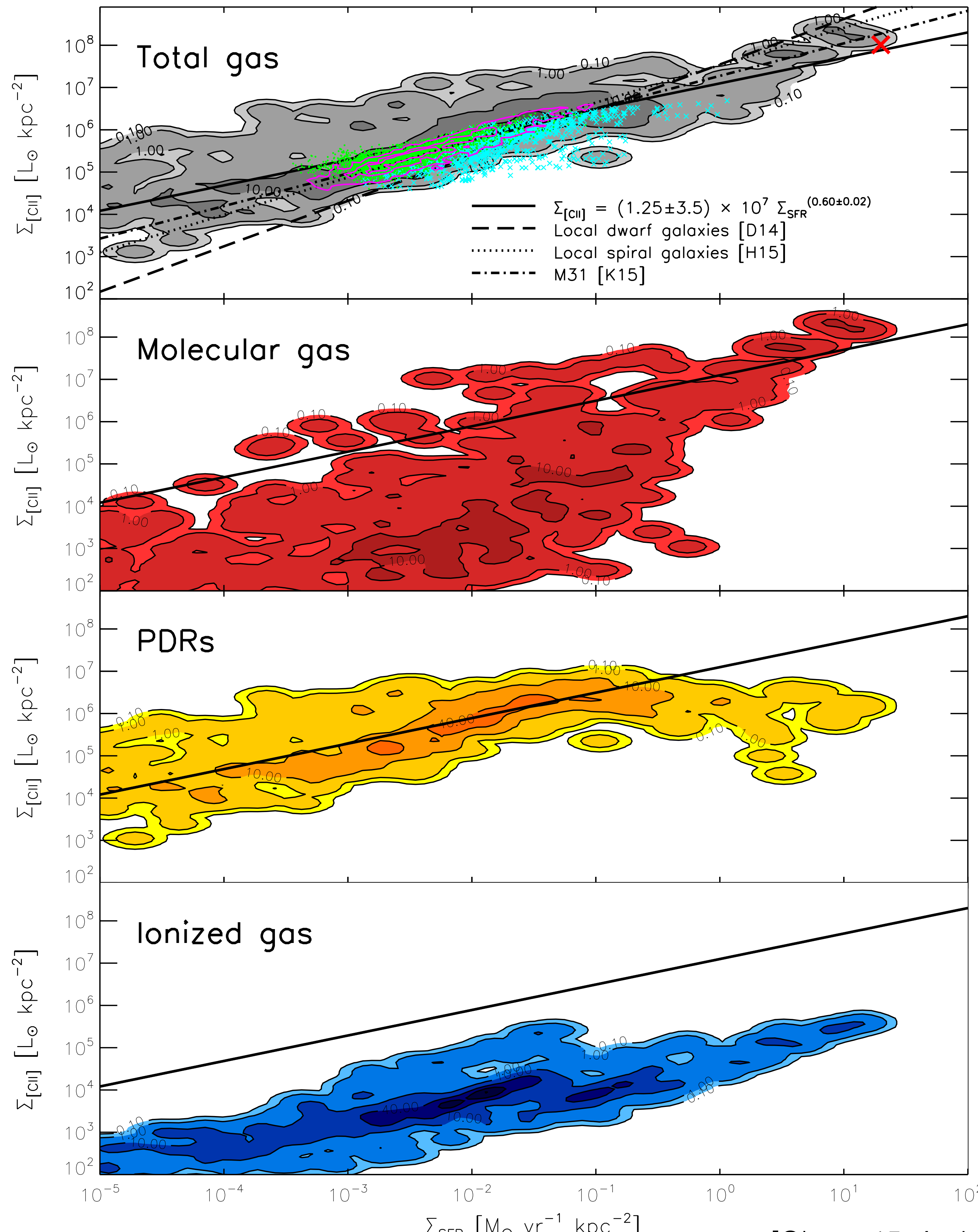


- [CII] from molecular gas dominates at low radii, PDRs at higher radii
- Total [CII] (grey) does not always follow SFR profile

[Olsen+15: ApJ, 814, 76]

The origin of [CII] emission

Resolved $\Sigma_{[CII]}$-Σ_{SFR} relation:

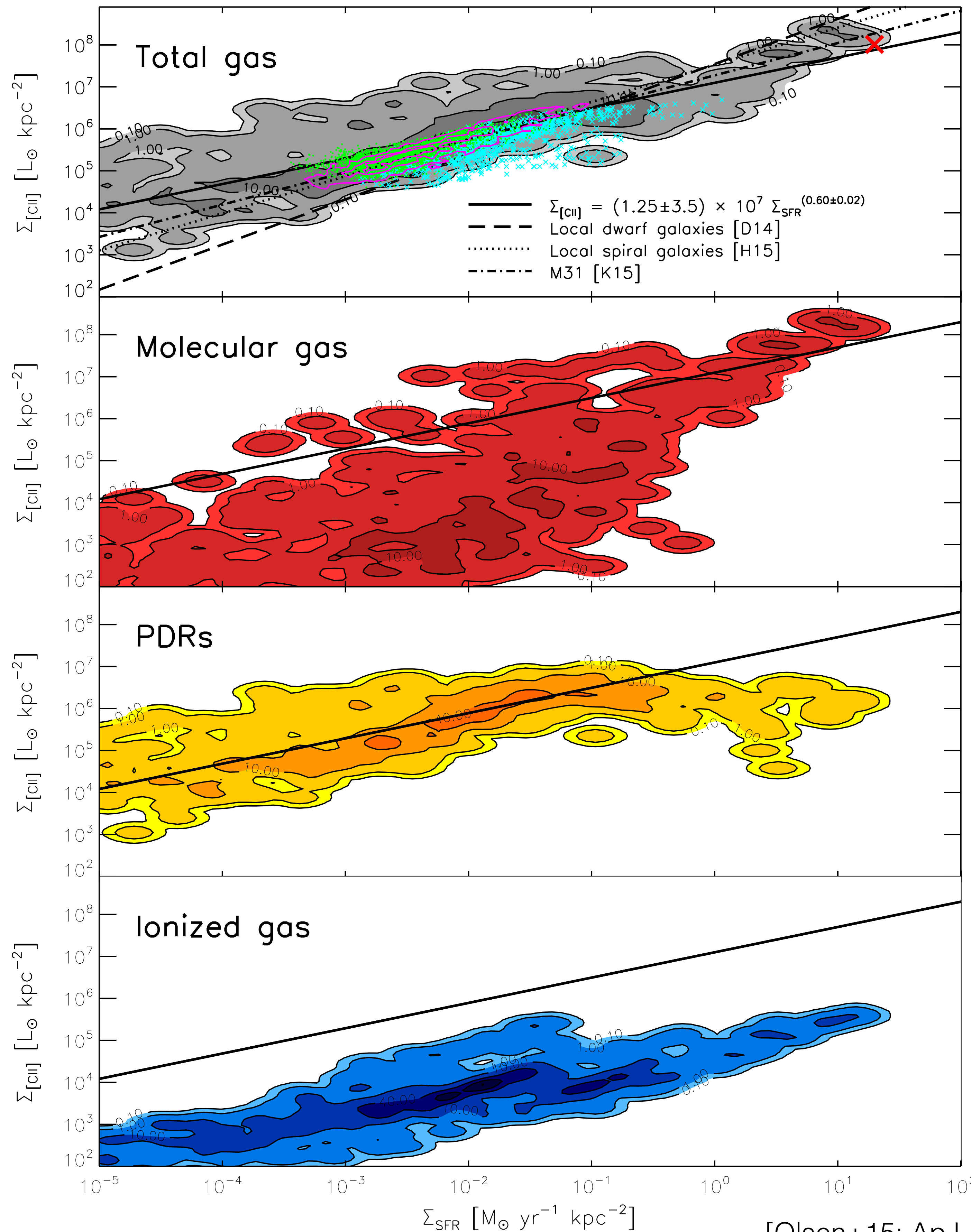


[Olsen+15: ApJ, 814, 76]

The origin of [CII] emission

Resolved $\Sigma_{[CII]}$-Σ_{SFR} relation:

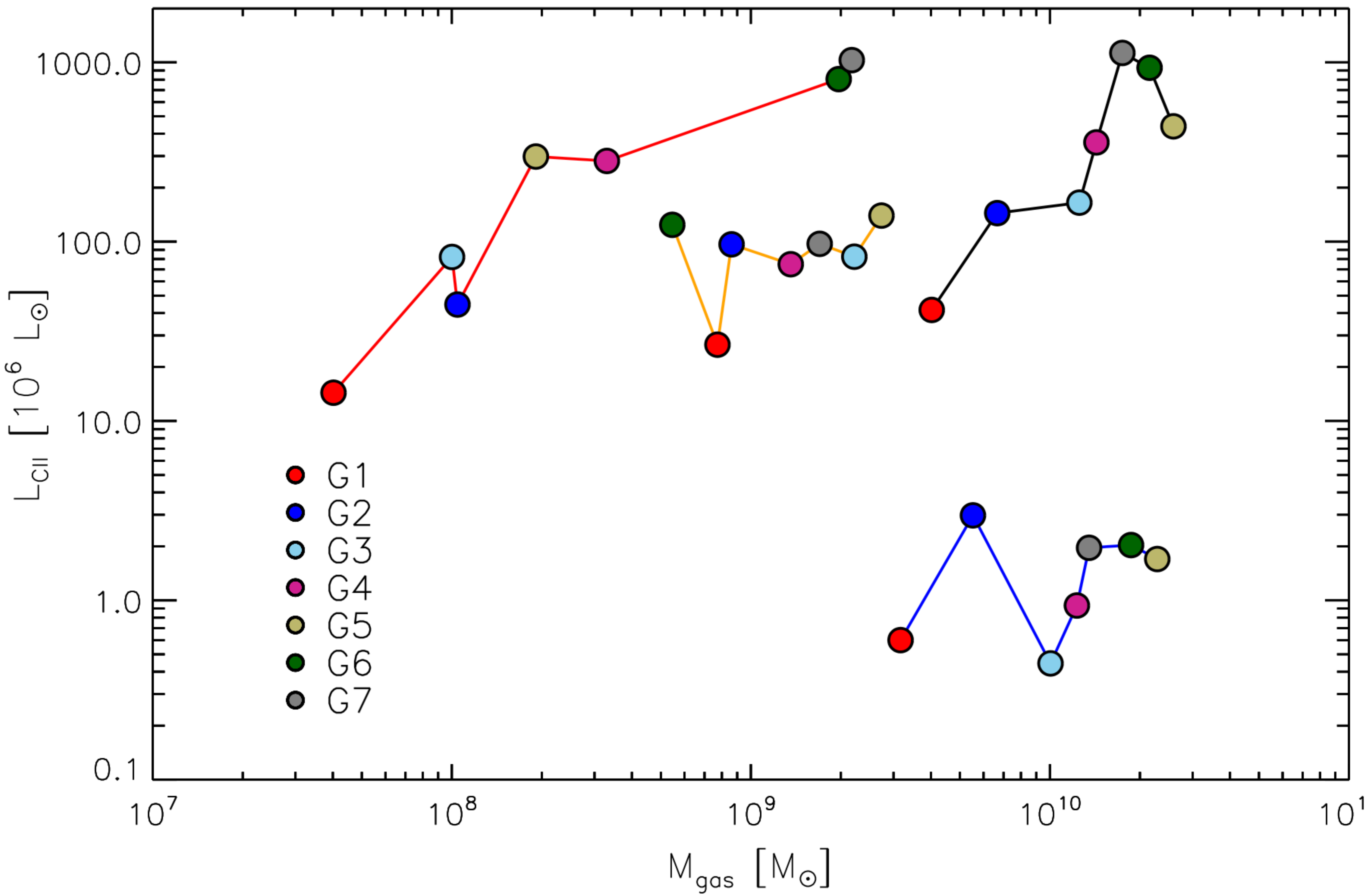
- Agreement with observations
  - De Looze+14
  - Herrera-Camus+15
  - Kapala+15
  - De Breuck +14, z=4.76 SMG
- Again: Molecular gas only dominating at high Σ_{SFR}



[Olsen+15: ApJ, 814, 76]

SÍGAME

‘[CII] efficiency’



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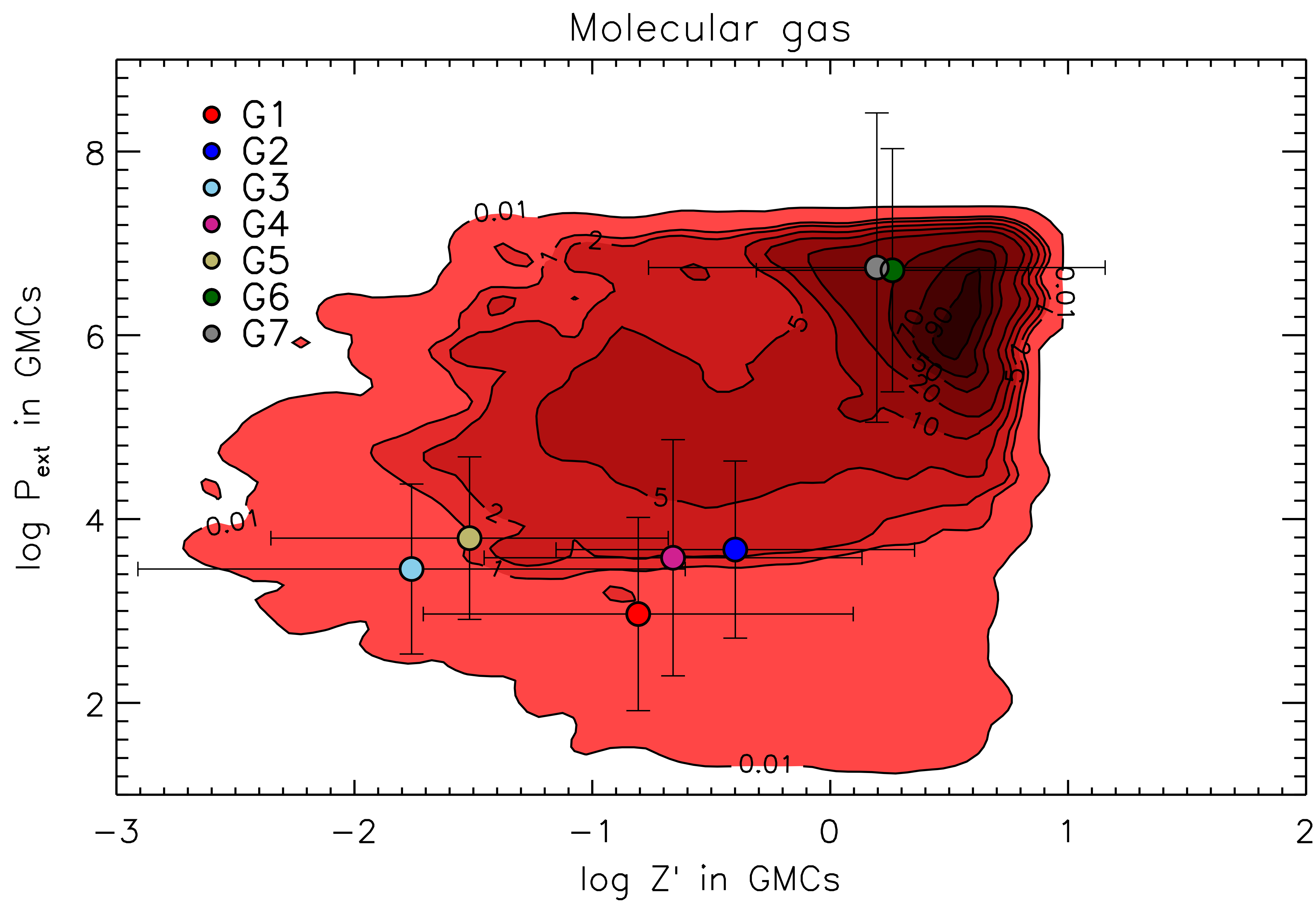

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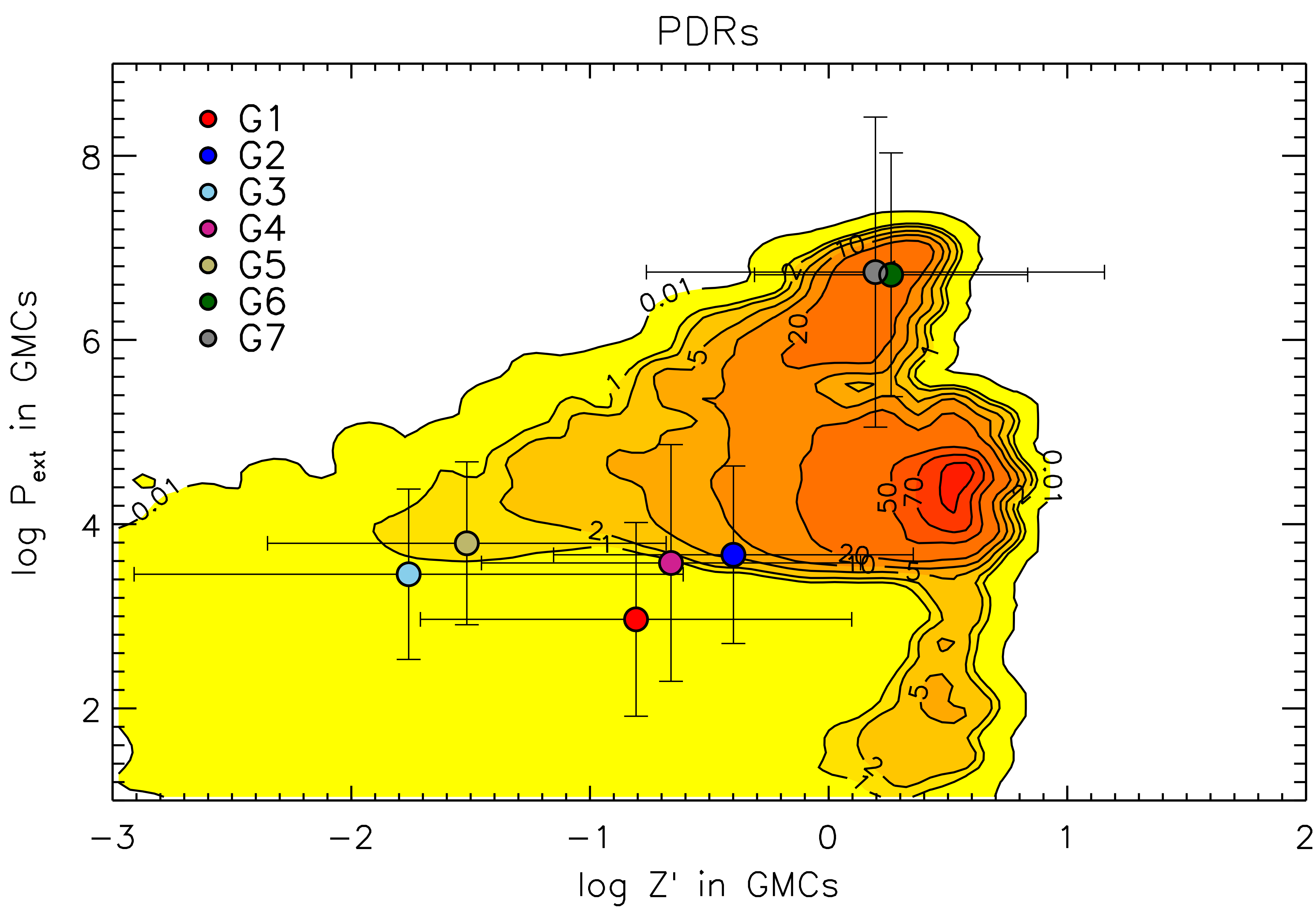

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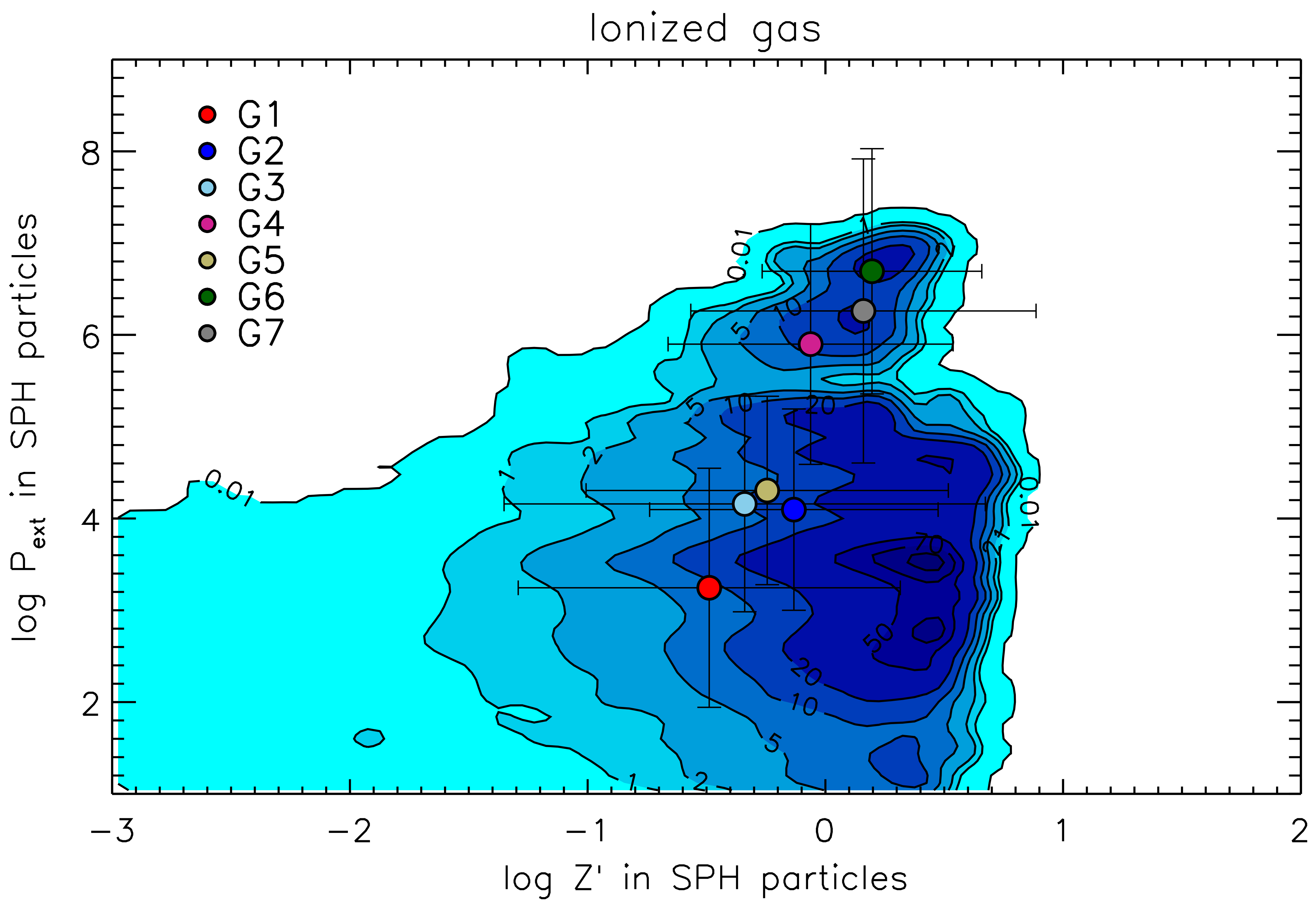

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Observing the ISM at z=2 and above

Telescopes can now observe [CII]
in normal galaxies at high redshift

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Neutral+ionized gas ([CII] fine structure line)

Olsen, K., Greve, T., Brinch, C., Sommer-Larsen, J., Rasmussen, J., Toft, S., Zirm, A 2015, ApJ, 814, 76

Molecular gas (CO rotational lines)

Olsen, K., Greve, T., Narayanan, D., Thompson, R., Toft, S., Brinch, C. 2015, arXiv: 1507.00012

Summary

SÍGAME - a novel method by simultaneously including

- local UV and cosmic ray fields
- cosmological simulations
- several ISM phases
- radiative transfer code

Applied at z=2 for simulating:

[CII] fine structure line:

- reproduced [CII] luminosities of normal star-forming galaxies at **z**~0
- good tracer of SFR with a steeper slope than at low z
- boost of [CII] for: high molecular gas mass, metallicity and pressure

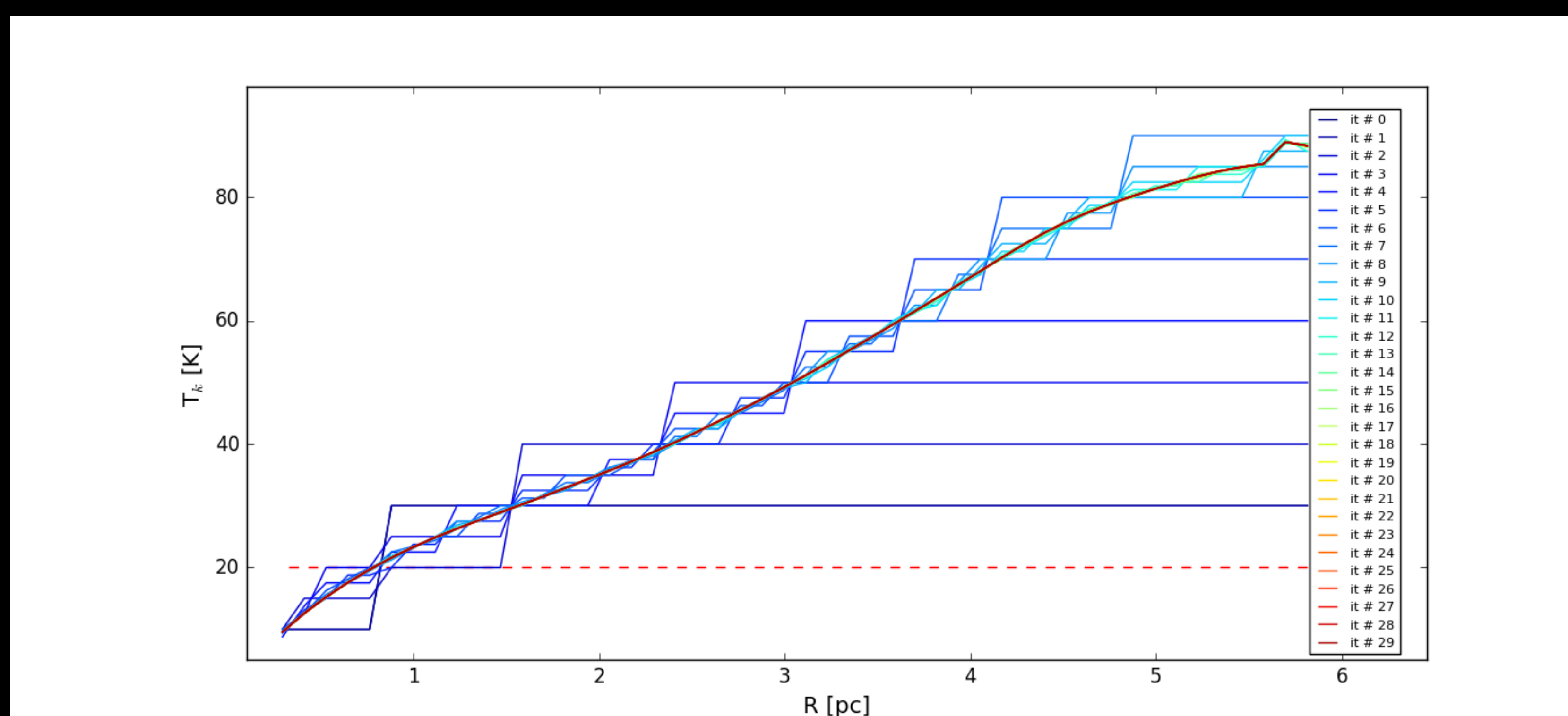
CO rotational transitions:

- reproduced CO luminosities of normal star-forming galaxies at z~2
- good tracer of molecular gas with α_{CO} factors about 1/3 x the MW
- decreasing α_{CO} towards center

Outlook

SÍGAME - focusing on [CII] at higher redshift!

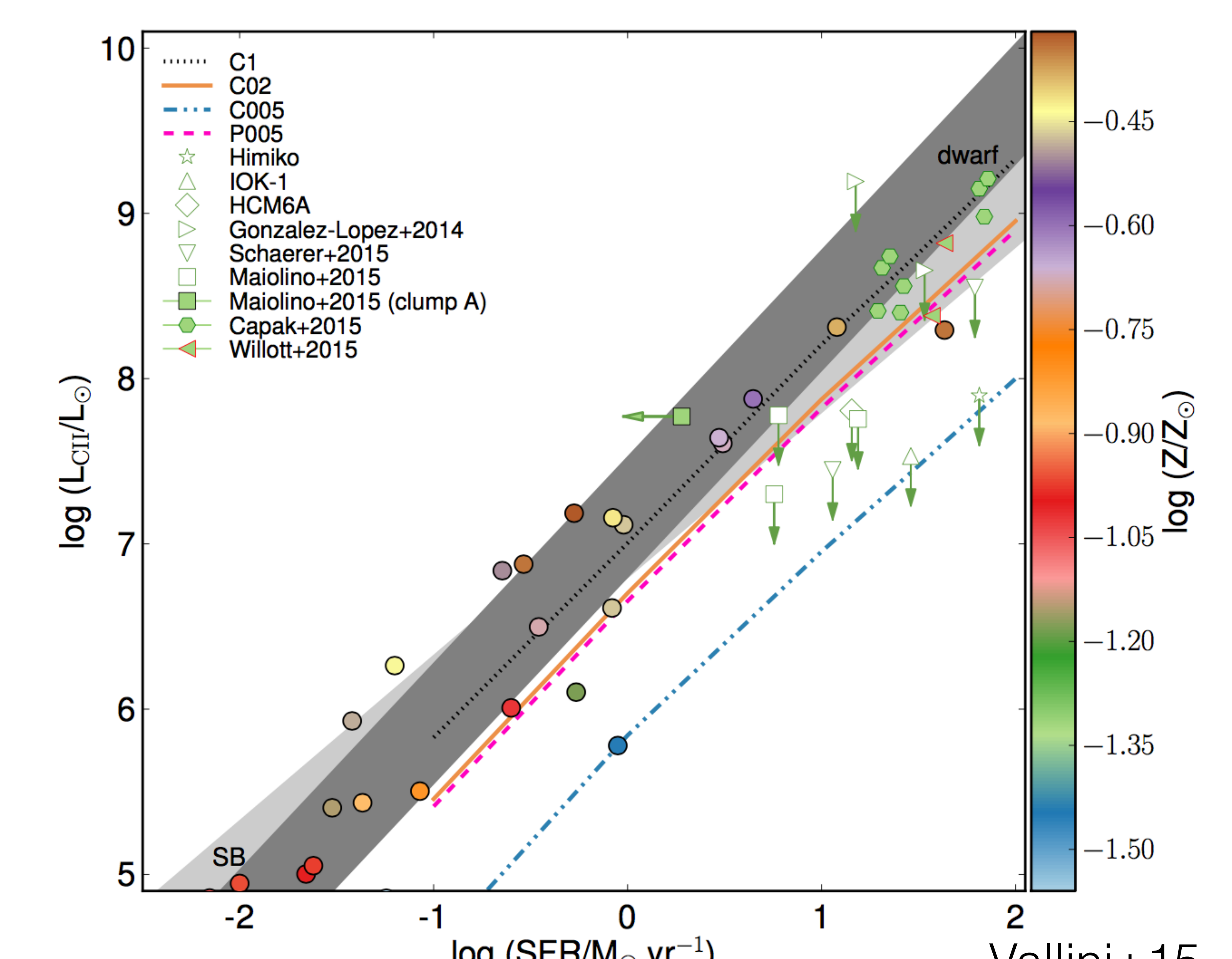
1. Improve on method
   - more continous interior of GMCs, better incorporation of CNM
   - dust radiative transfer incorporated (Powderday; D. Narayanan)
   - larger variation in galaxy sample (Z, SFR etc.)



Outlook

SÍGAME - focusing on [CII] at higher redshift!

2. Make predictions for z~6 galaxies



Vallini+15

Outlook

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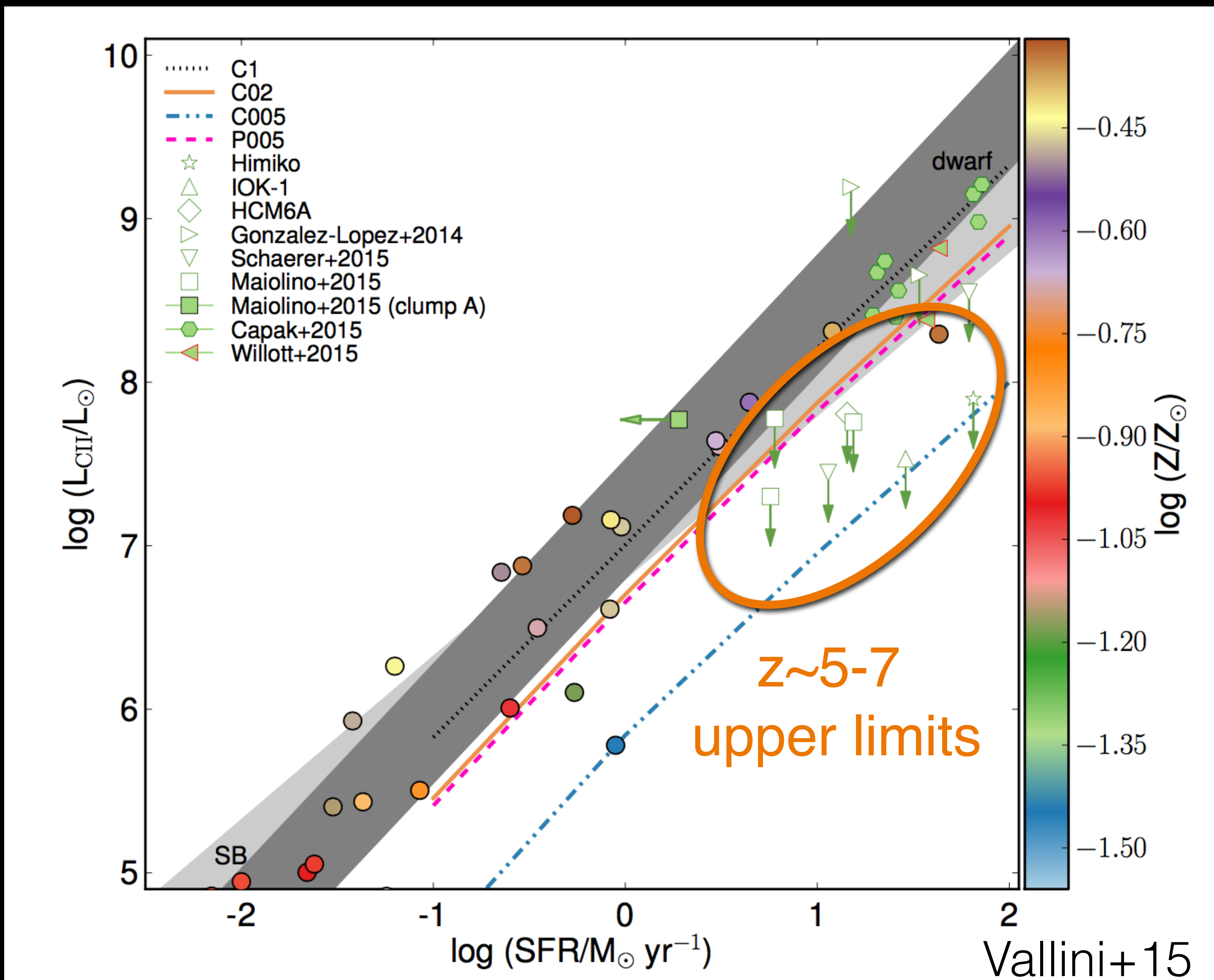

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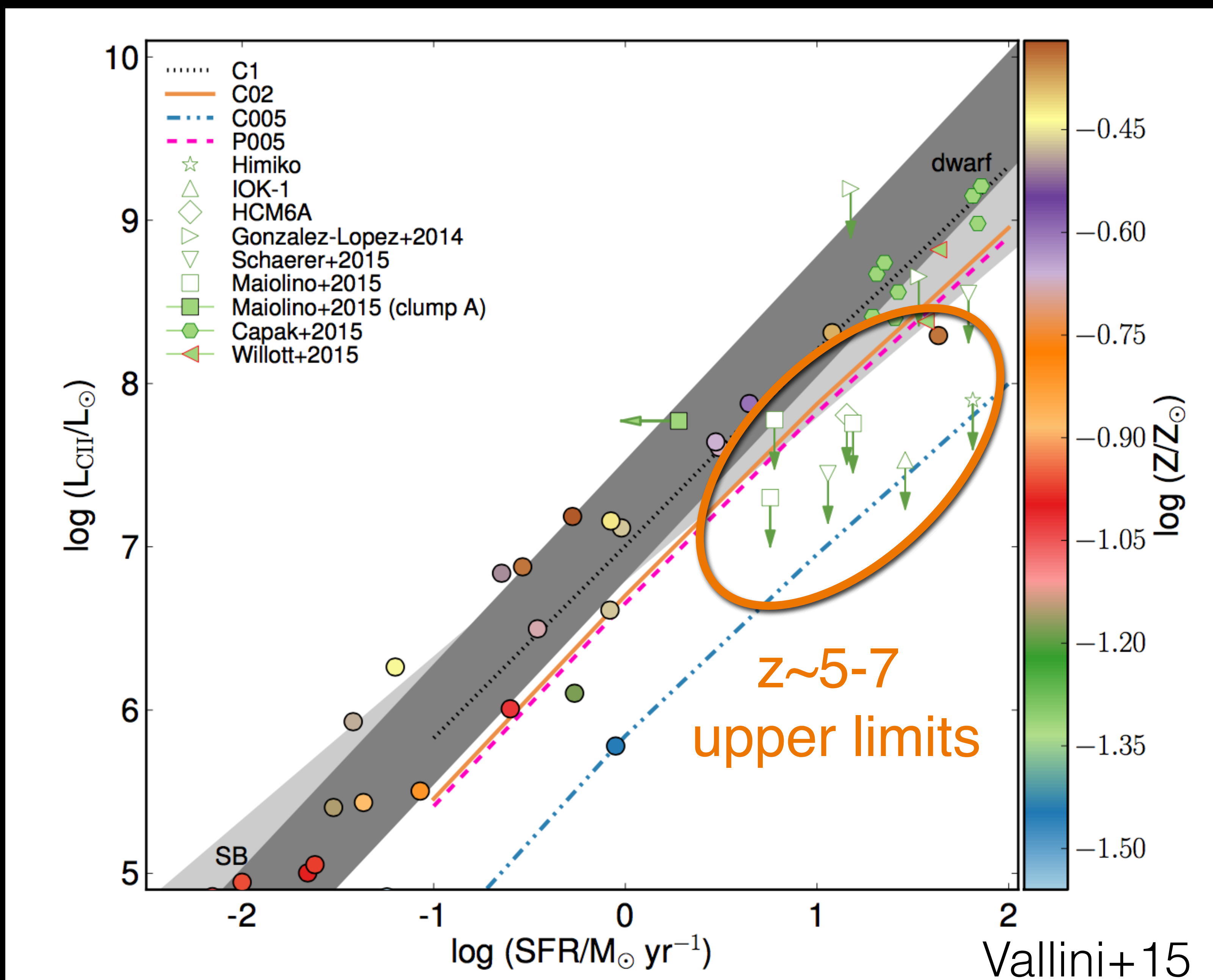

- low metallicity?

- disruption of molecular clouds by star formation?

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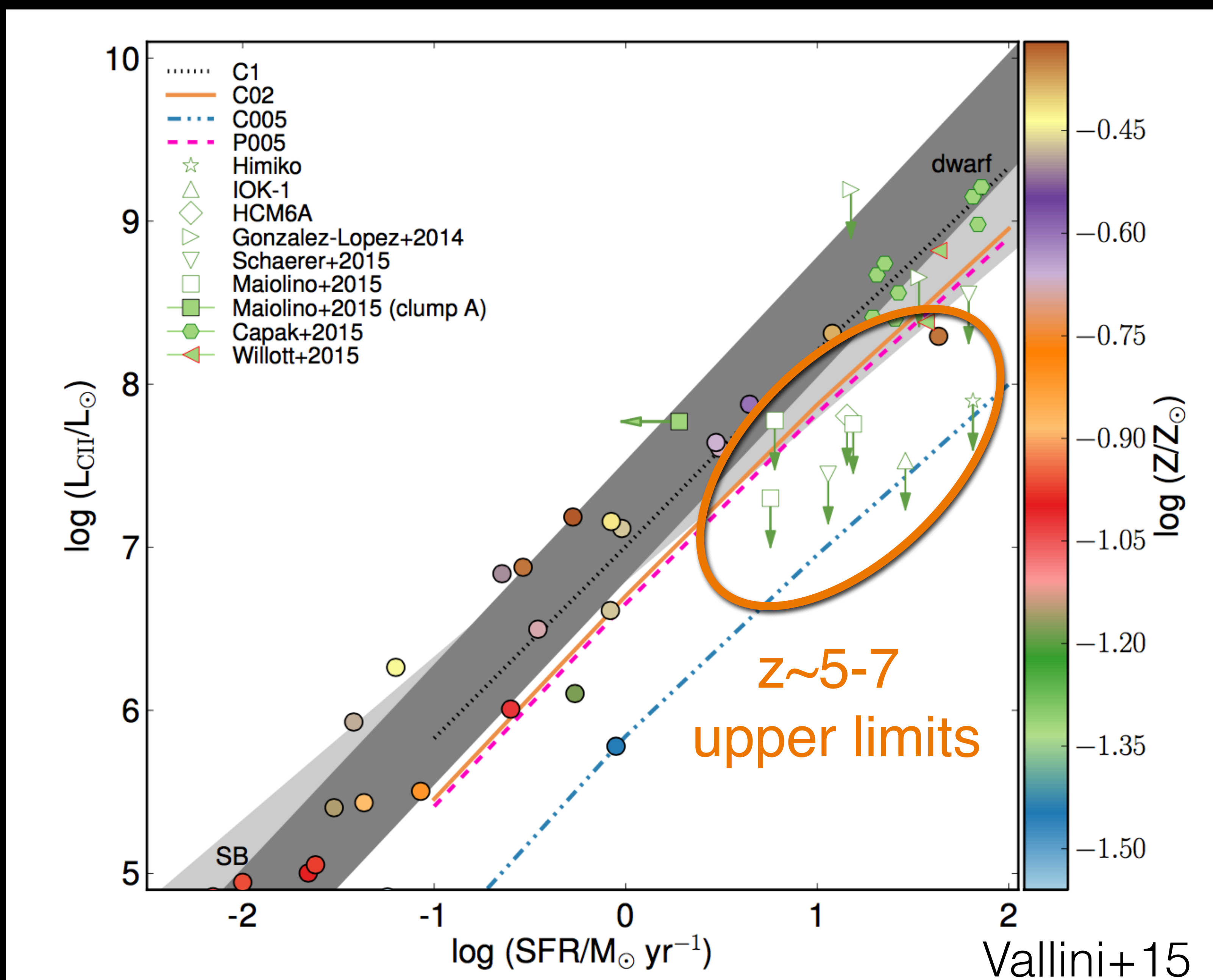


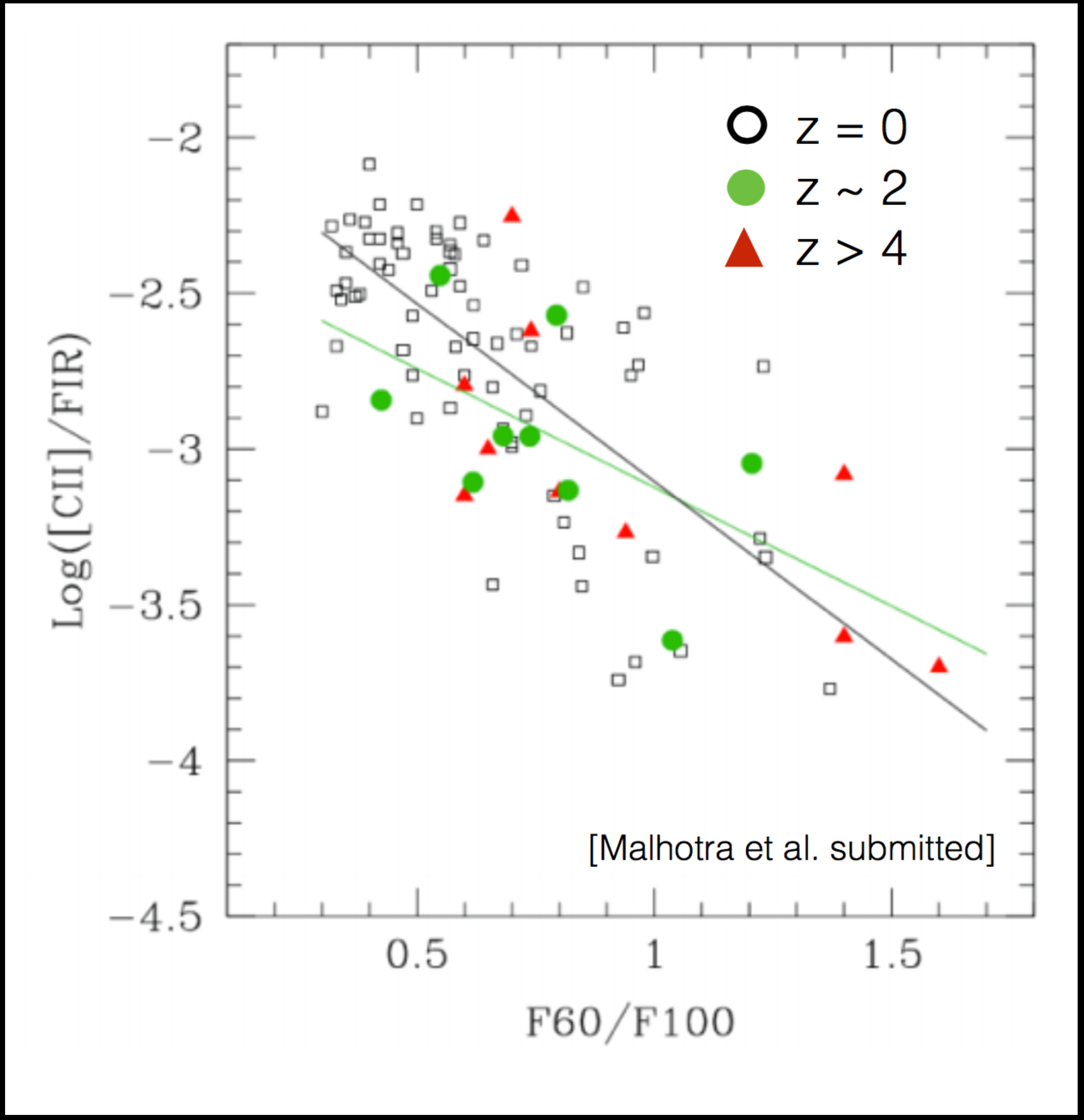
- low metallicity?
- disruption of molecular clouds by star formation?
- no physically consistent star formation and metallicity in their models…

Outlook

SÍGAME - focusing on [CII] at higher redshift!

3. Bridging the gap…
   - direct comparison with observations of normal star-forming galaxies at z~2 with [CII] AND CO detections

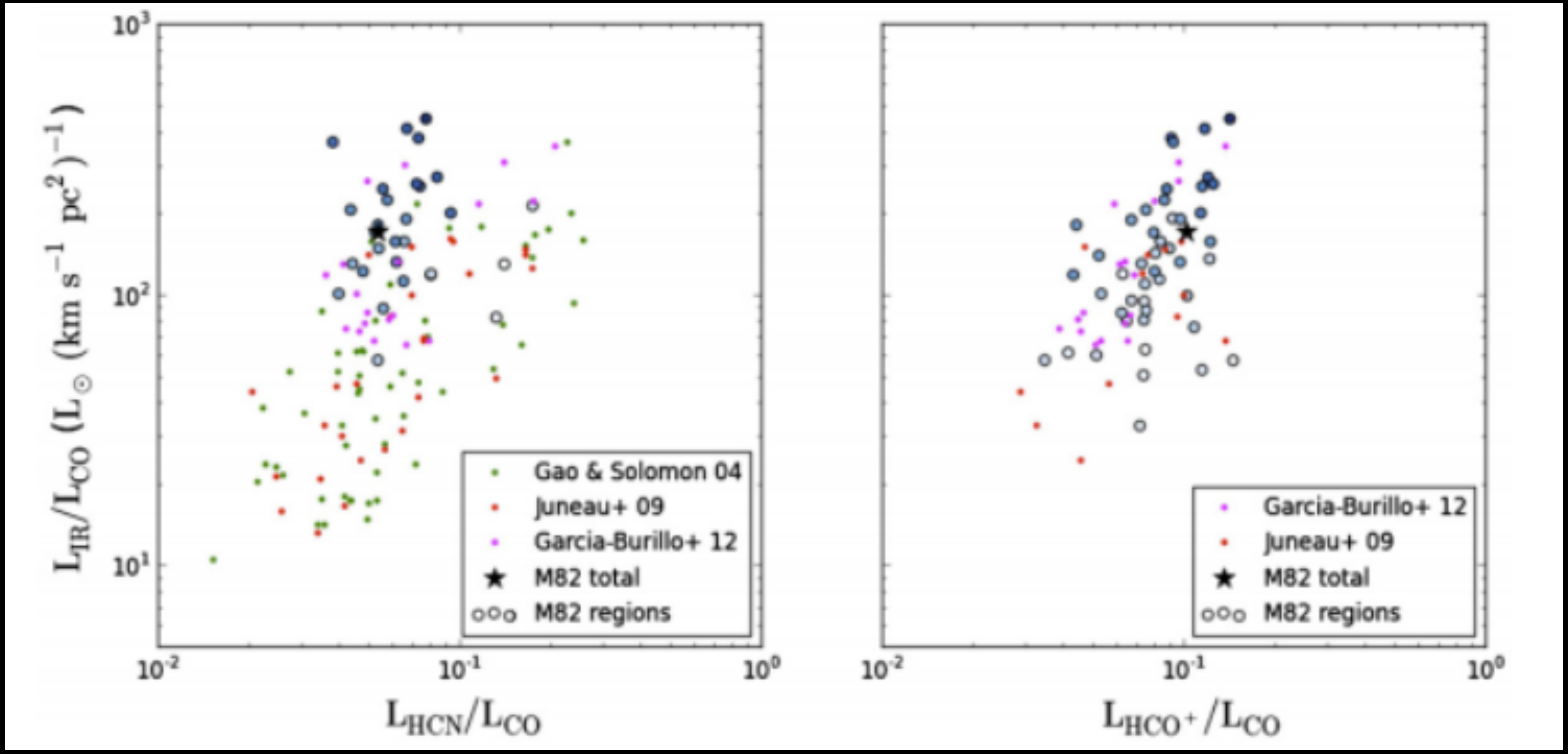
HELLO galaxy sample



Outlook

SÍGAME - looking at high density tracers

4. HCN, HCO+: Revealing the dense gas mass fraction, more directly related to star formation



[Kepley+14]

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