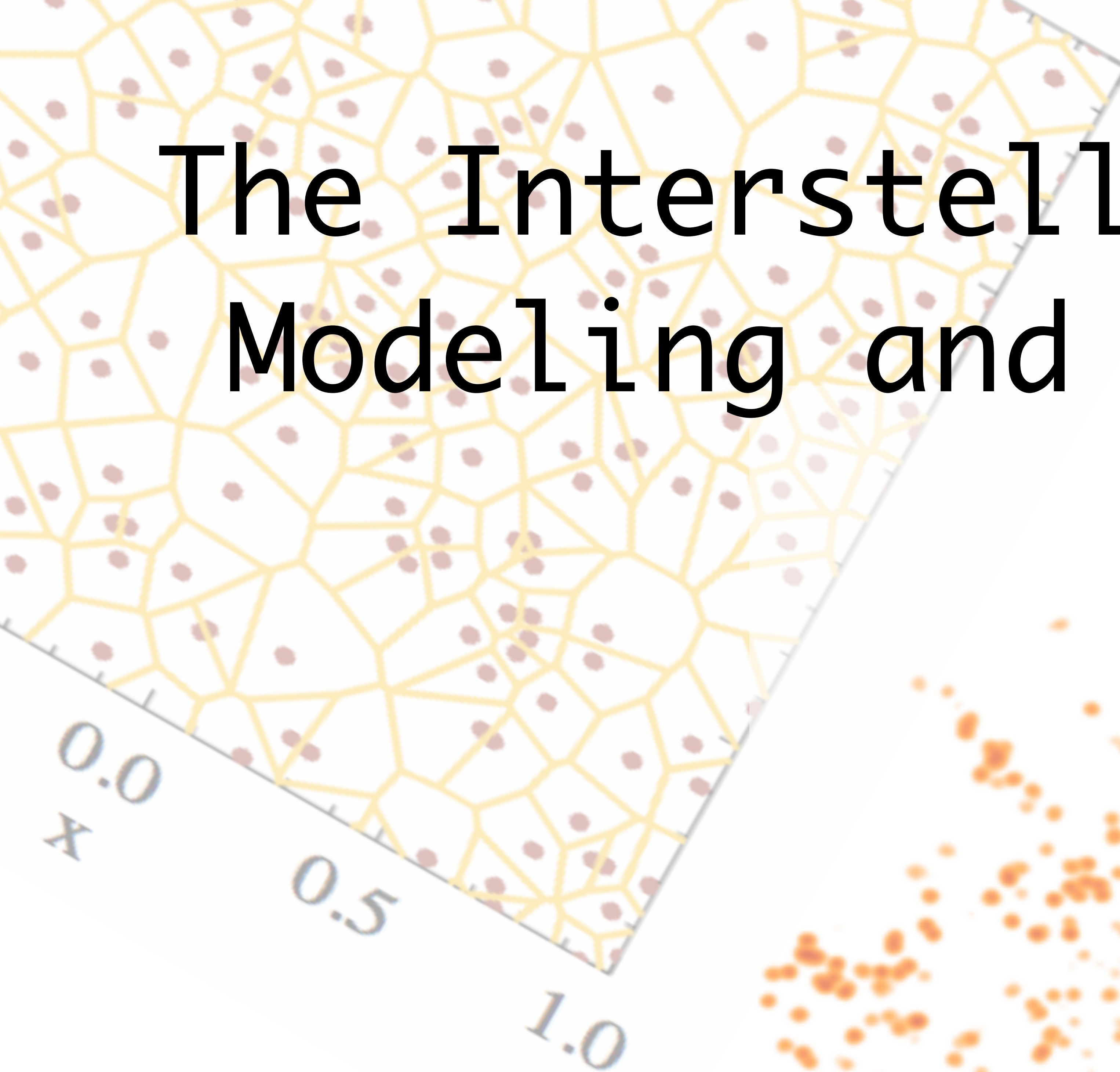
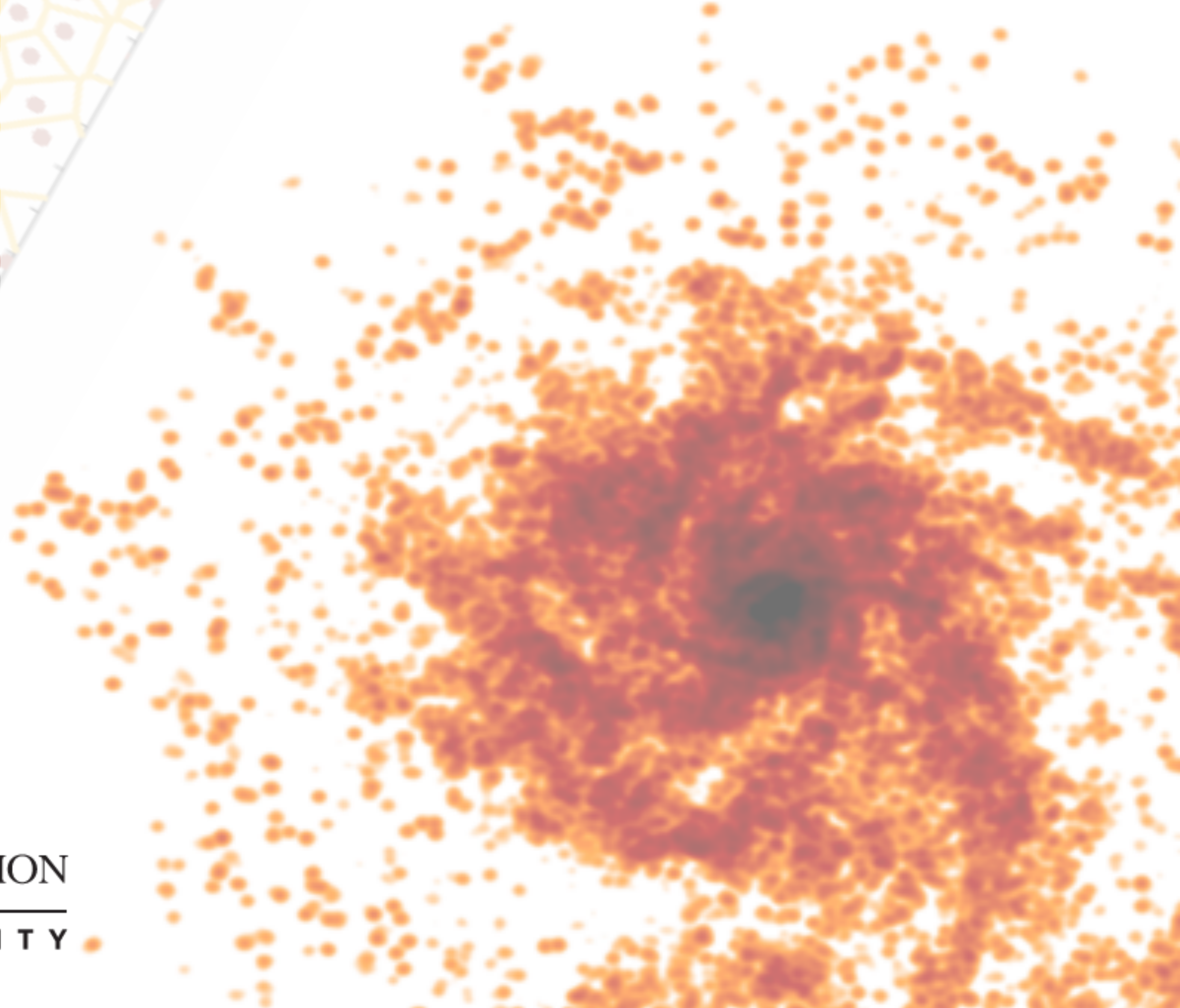
The Interstellar Medium: Modeling and Observing





Karen Pardos Olsen

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ARIZONA STATE UNIVERSITY

Dark Cosmology Centre

UNIVERSITY OF COPENHAGEN

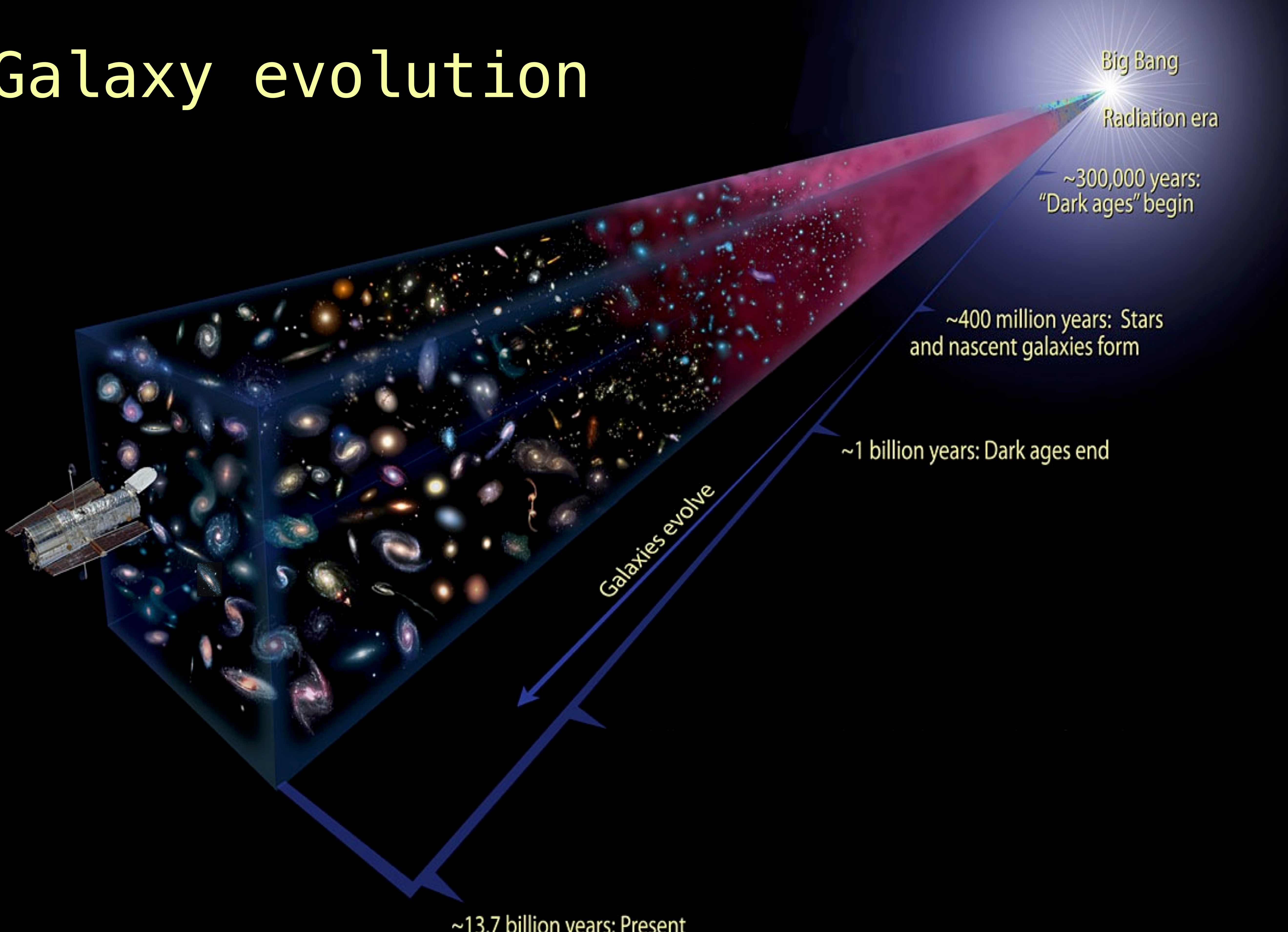
Ex-supervisors:

Sune Toft (DARK) and Thomas Greve (UCL)

Dark Cosmology Centre

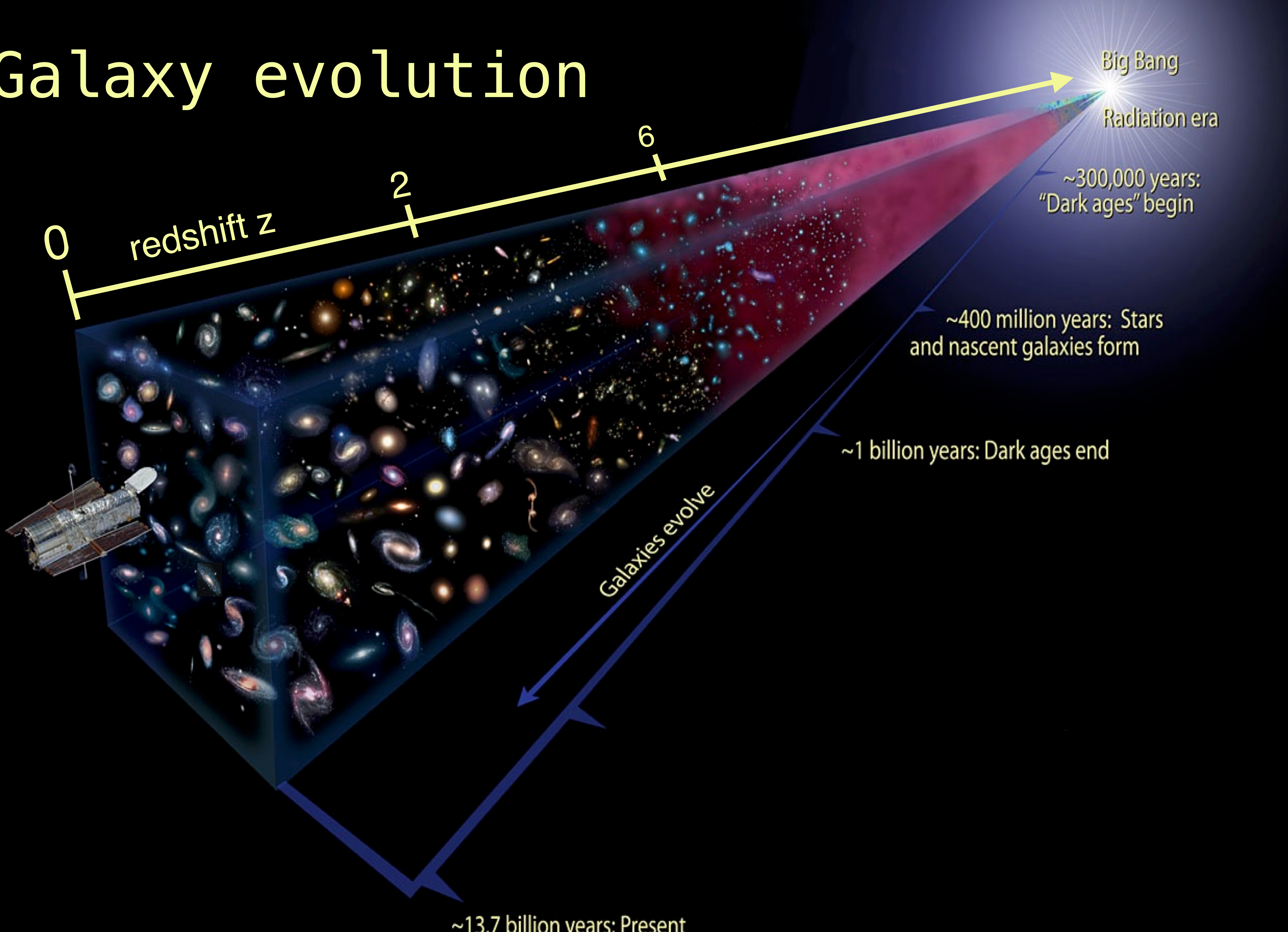
UNIVERSITY OF COPENHAGEN

Galaxy evolution



NASA, ESA, and A. Feild (STScI)

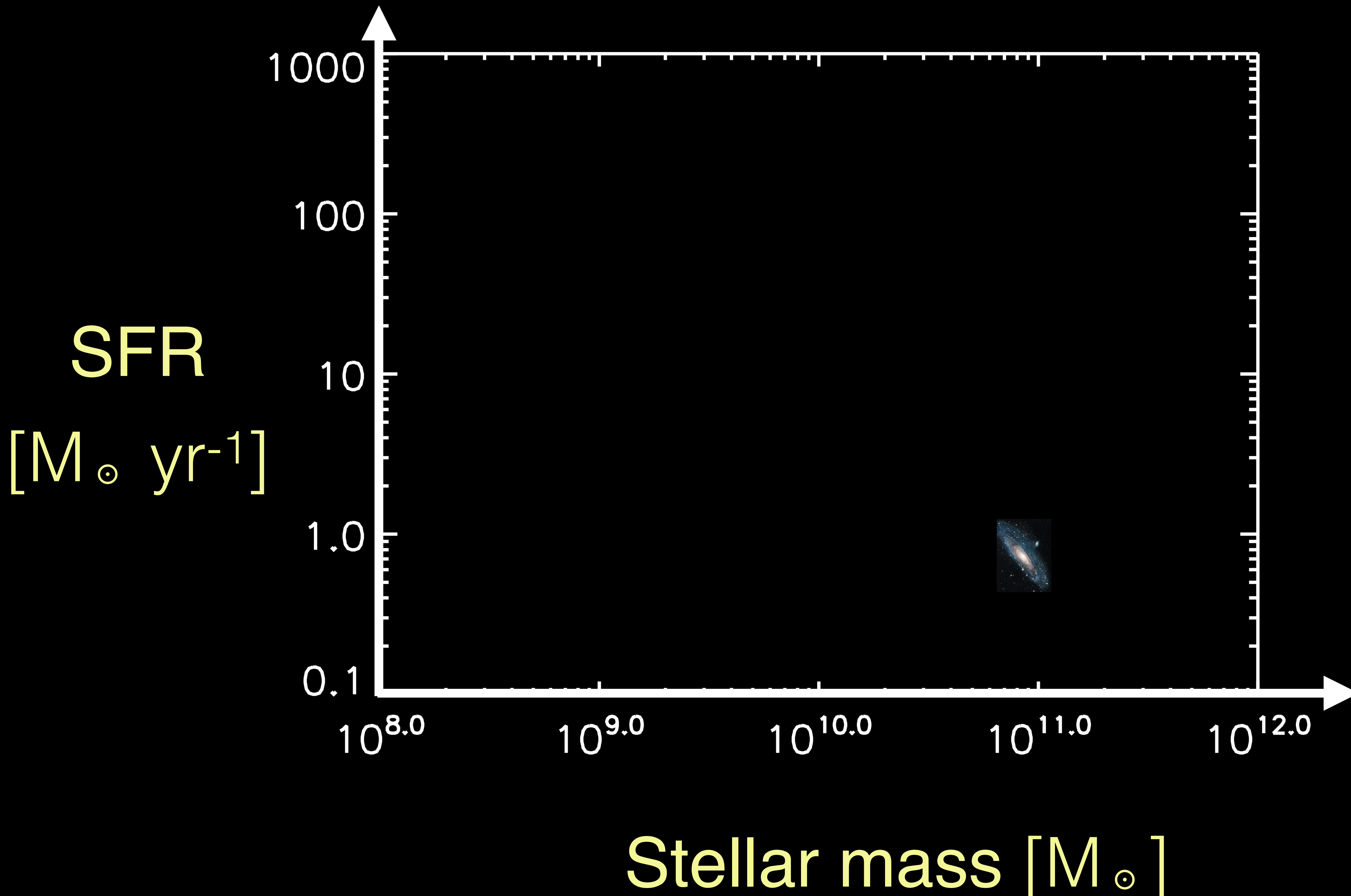
Galaxy evolution



NASA, ESA, and A. Feild (STScI)

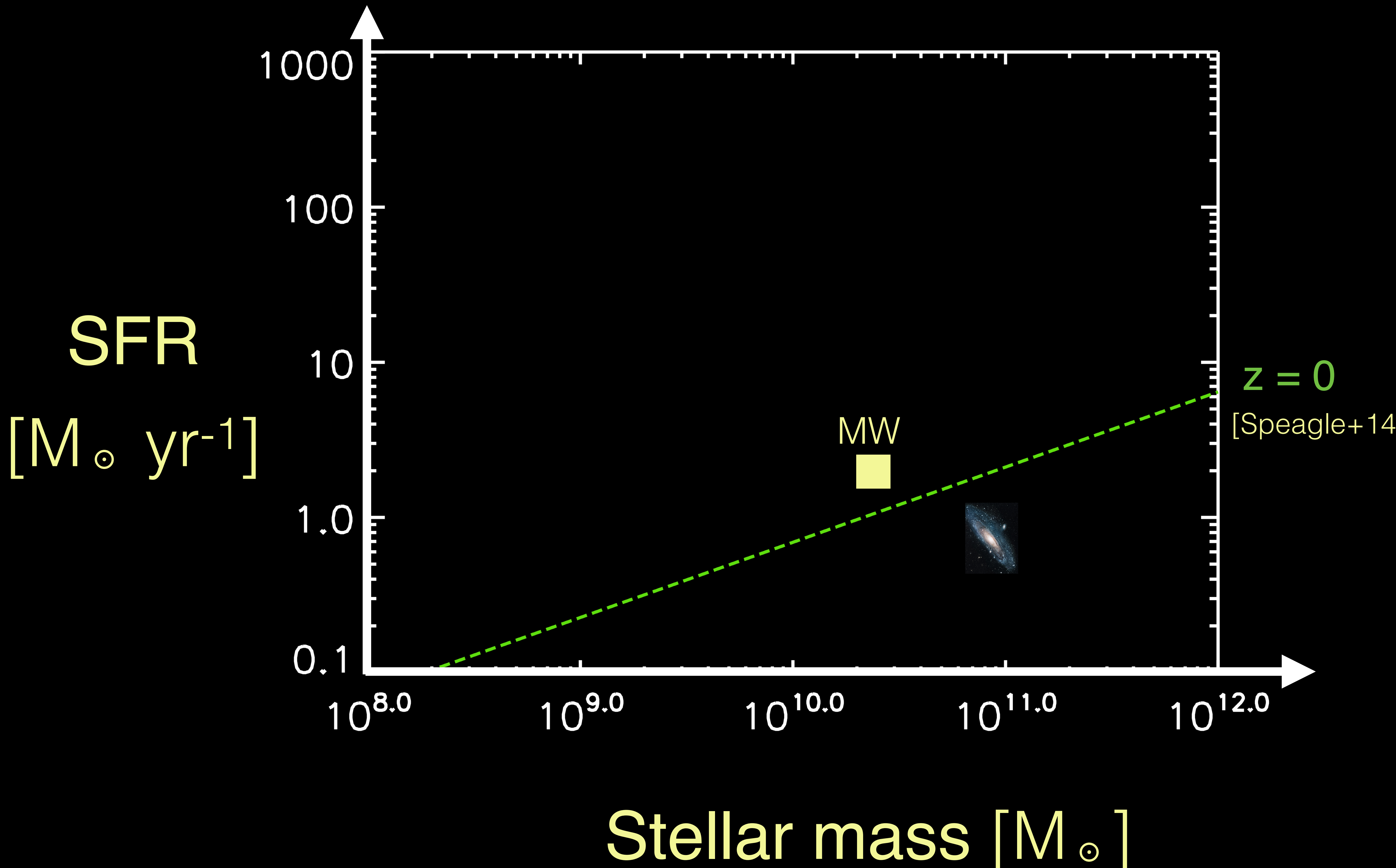
Andromeda (M31)
in optical

Credit: Robert Gendler



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

Main Sequence (MS)



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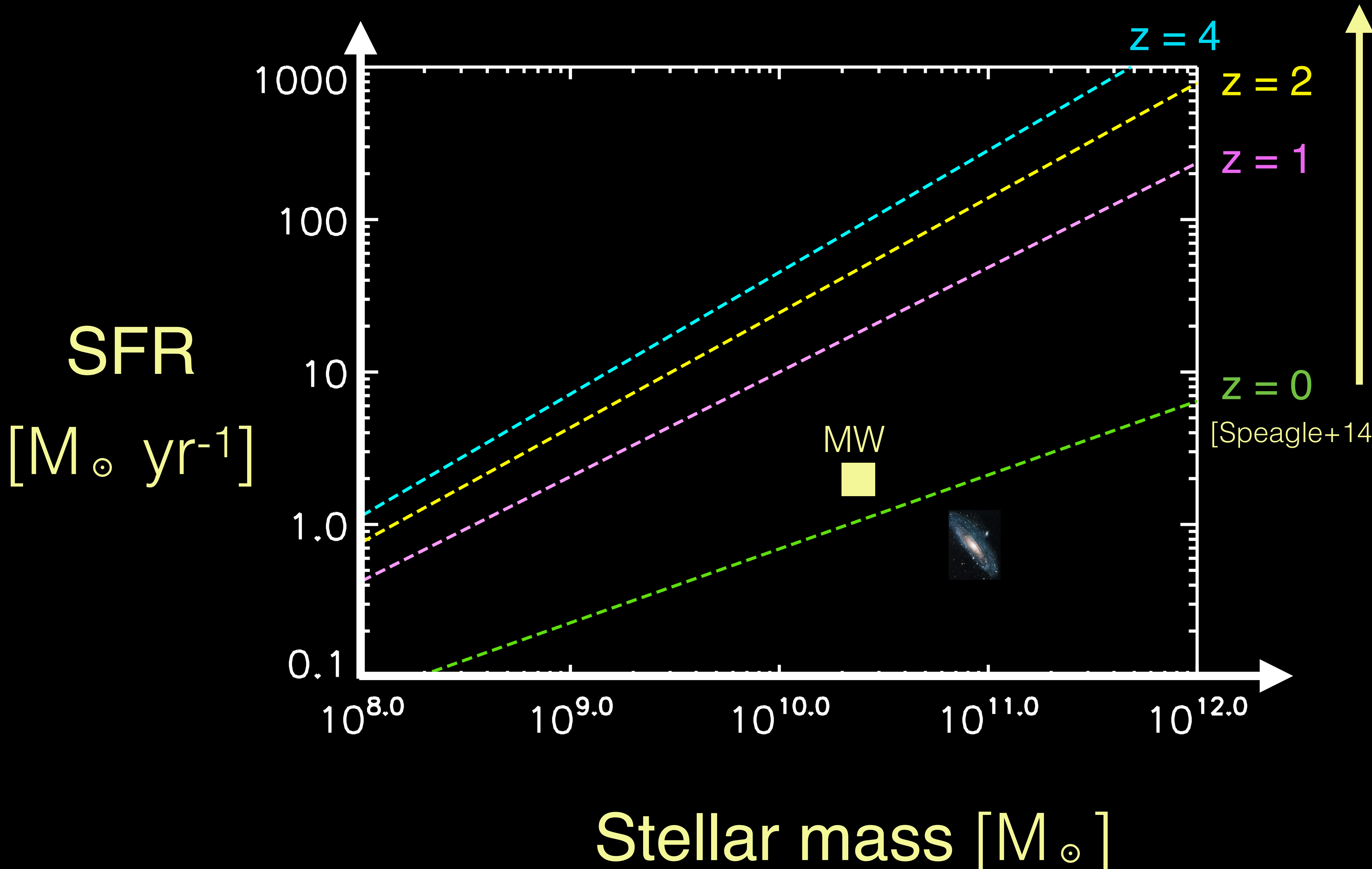

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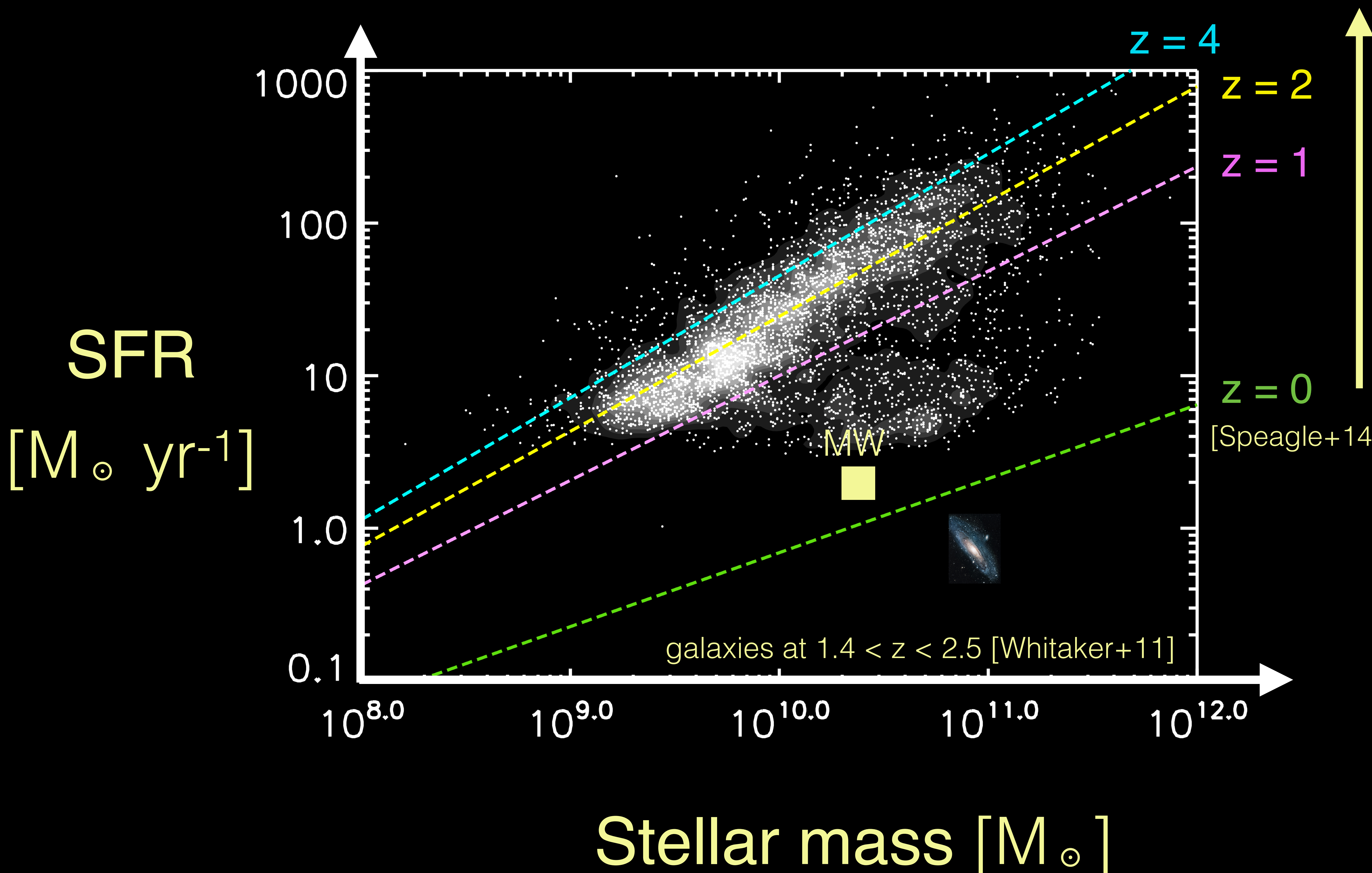

Andromeda (M31)
in optical

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How are stars formed?

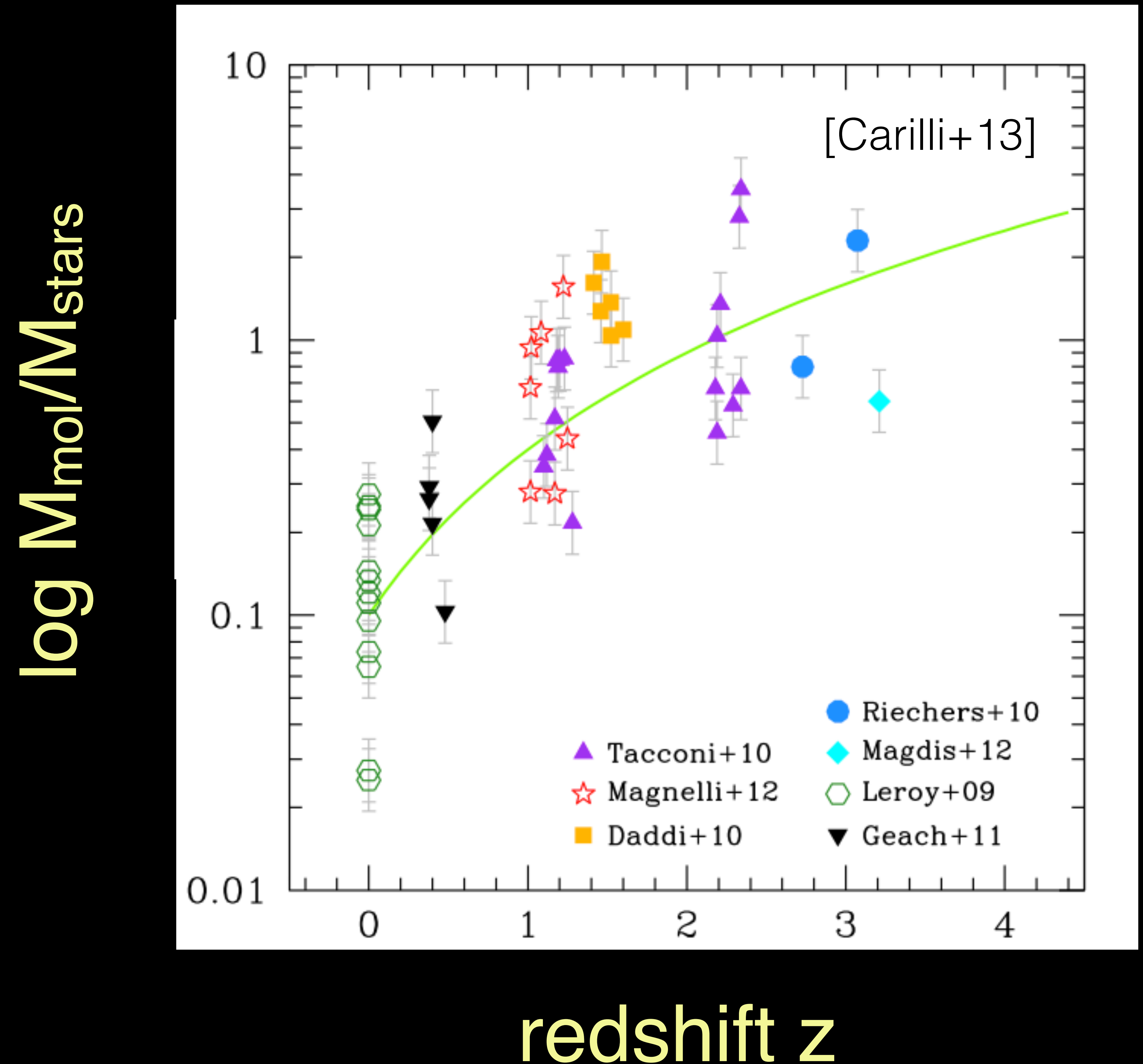
Andromeda (M31)
in optical

Credit: Robert Gendler

Out of dense, cold gas

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

Gas mass fraction



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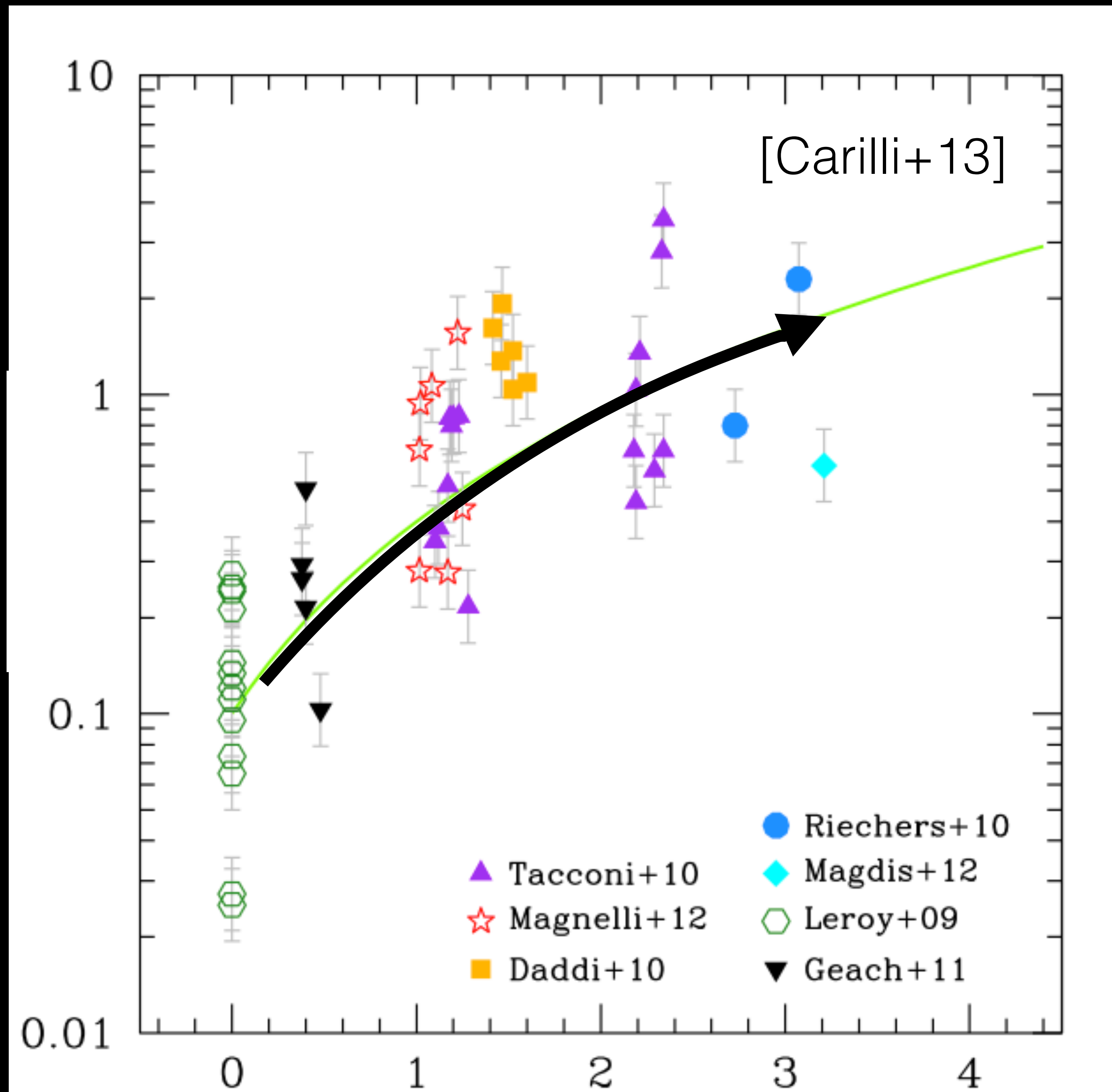


log M_{mol}/M_{stars}

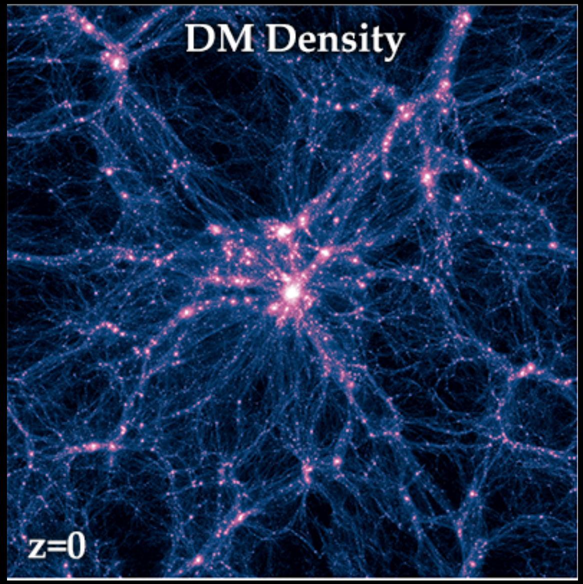
redshift z

Can higher gas fraction explain the redshift evolution of MS?

Towards a better understanding the Interstellar Medium (ISM)

Models of galaxy evolution have been focused on stellar and dark matter component

Illustris Simulation



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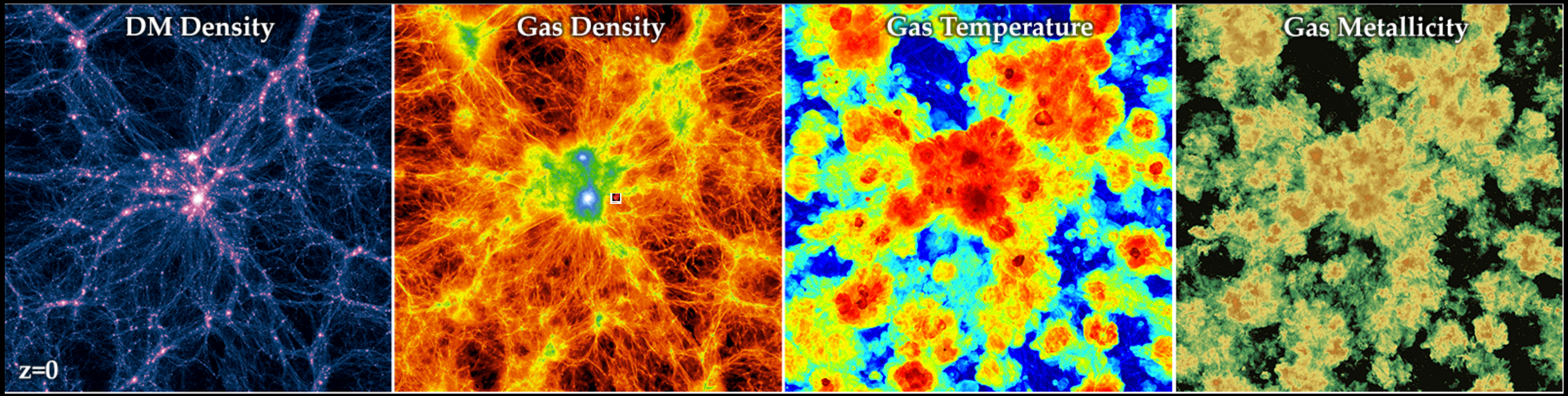

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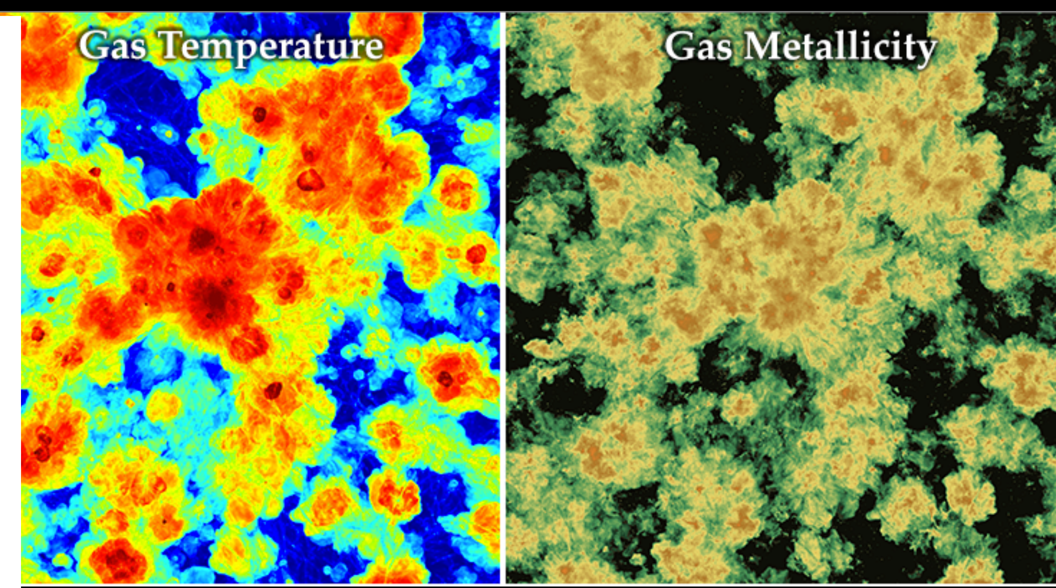
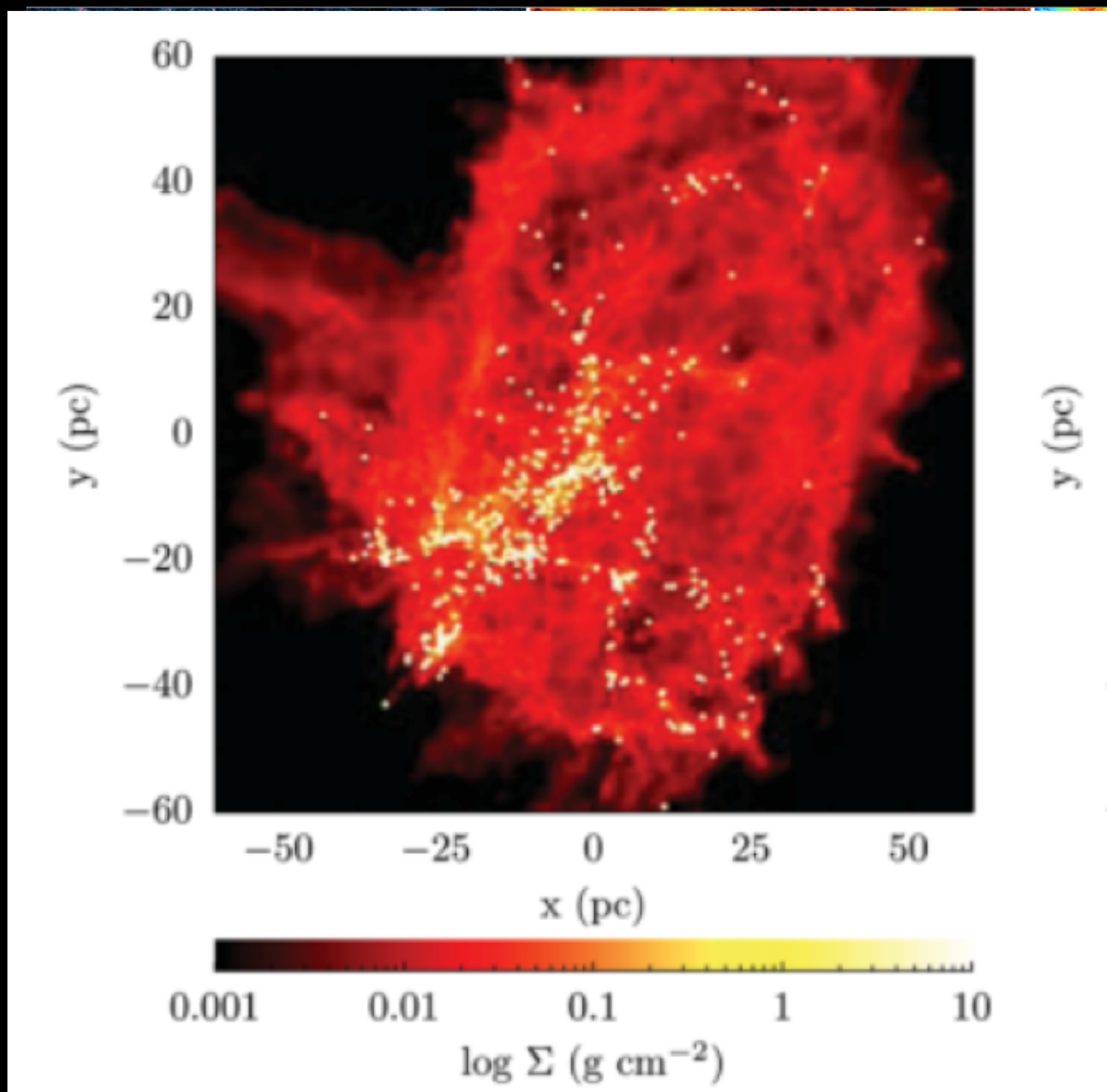
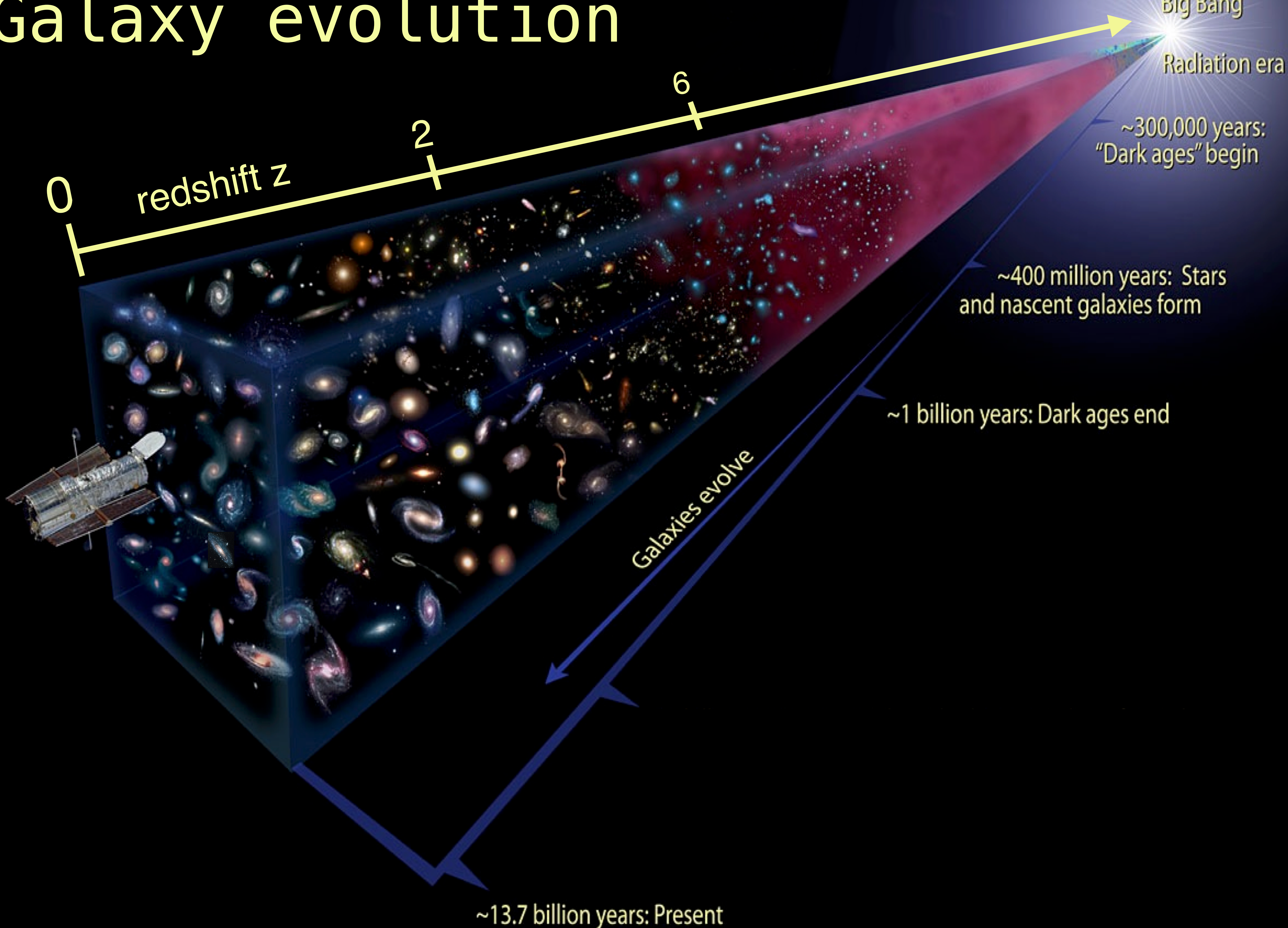




Simulations on smaller scale follow the actual star formation

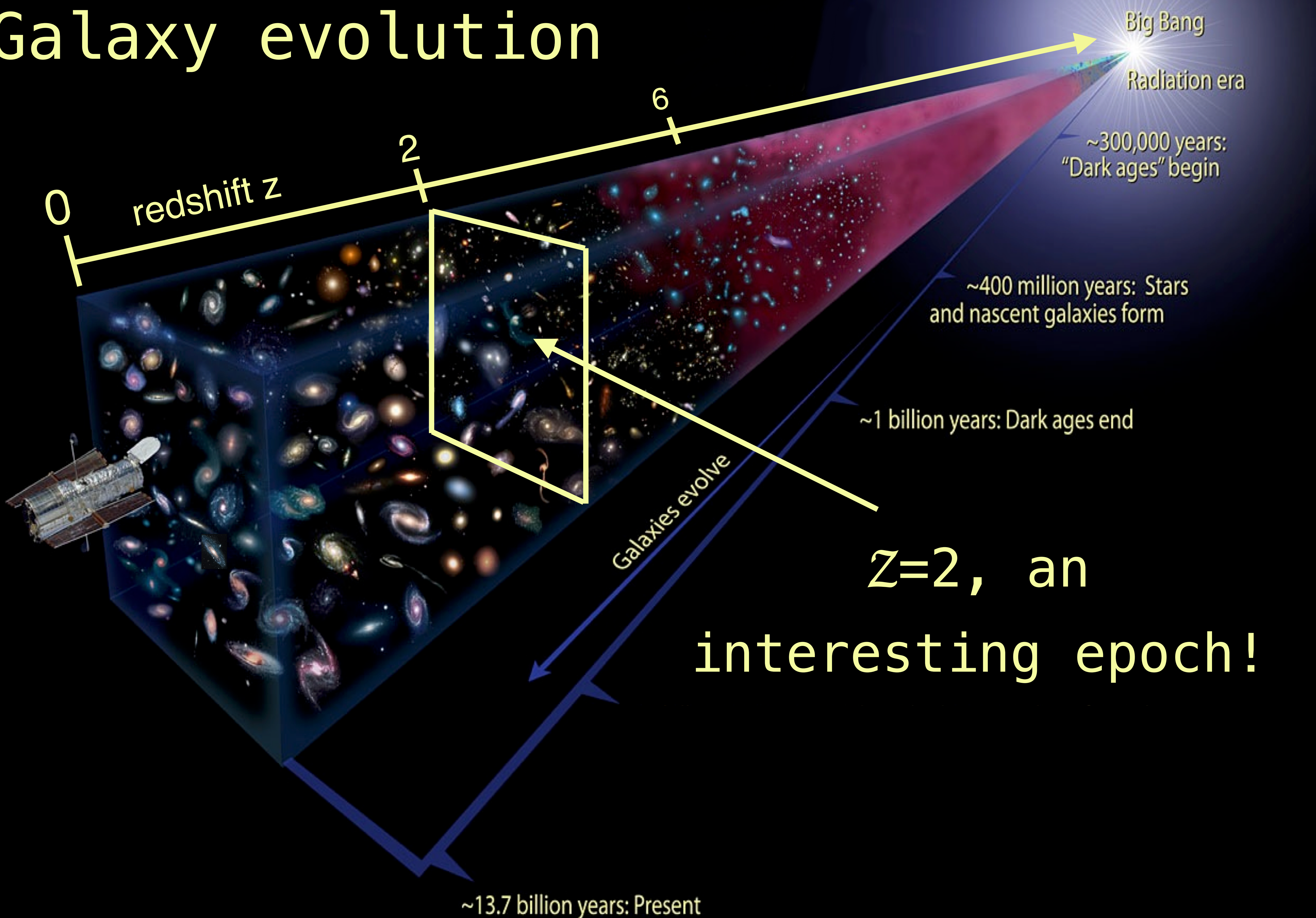
[Dale+12]

Galaxy evolution



NASA, ESA, and A. Feild (STScI)

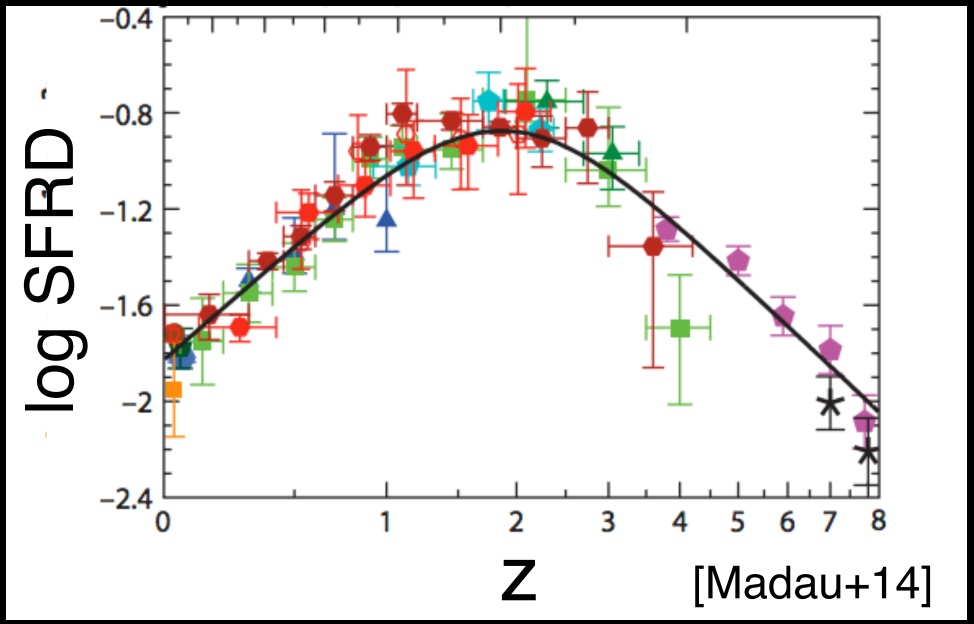
Galaxy evolution



NASA, ESA, and A. Feild (STScI)

$z \sim 2$: A phase change

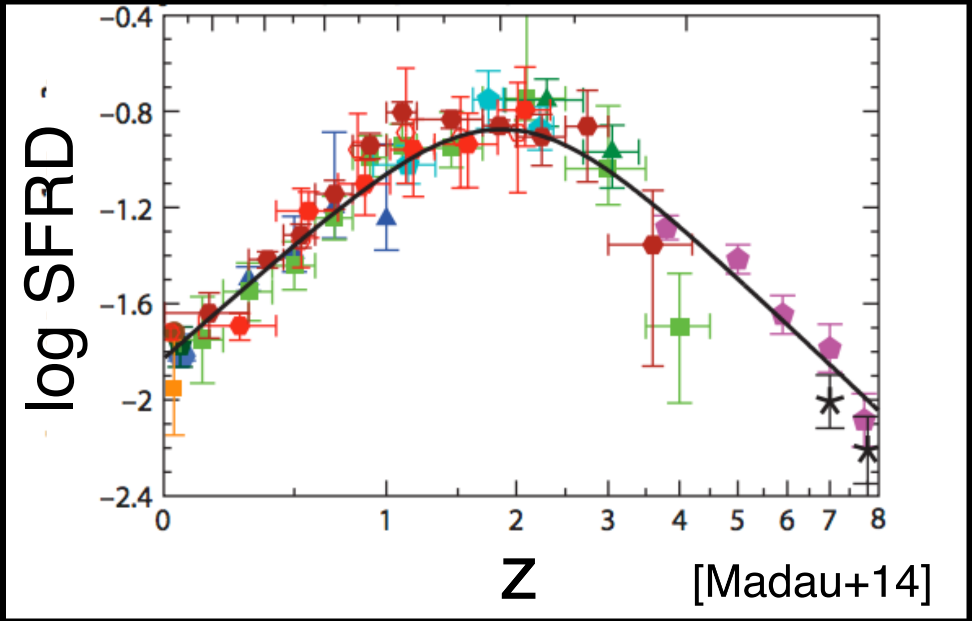
z ~ 2: A phase change



1. Peak of cosmic SFR density [e.g. Madau+14]

(the universe was more efficient at producing stars)

z ~ 2: A phase change



1. Peak of cosmic SFR density [e.g. Madau+14]
(the universe was more efficient at producing stars)

2. Peak of galactic nucleus activity [e.g. Bauer+10]
(SMBHs were consuming more gas)

3. Higher (major) merger rate than today [e.g. Man+14]
(galaxies were interacting more)

4. The ISM of z=2 galaxies can now be resolved!

Observing the ISM at z=2 and above

Observing the ISM at z=2 and above

Telescopes are being build for
observing gas at high redshift

Observing the ISM at z=2 and above

Telescopes are being build for
observing gas at high redshift

… models are lacking behind observations!

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Method for simulating ISM observations (SÍGAME)

1. Molecular gas (CO rotational lines)
2. Remaining ISM ([CII] fine structure line)

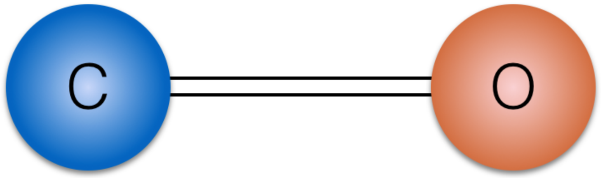
Summary+Outlook

Molecular gas

Molecular gas
– how to observe it?

Molecular gas
– how to observe it?

Carbonmonoxide
CO:



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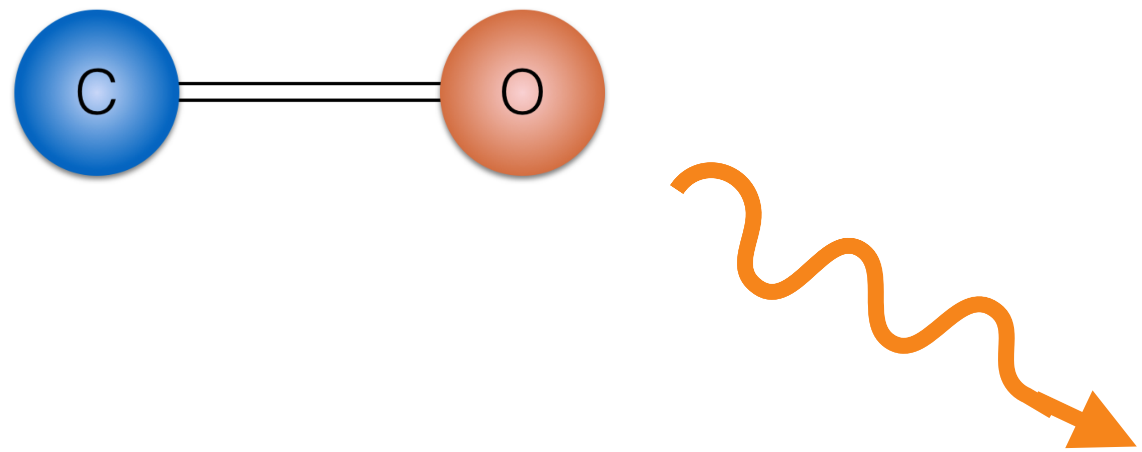
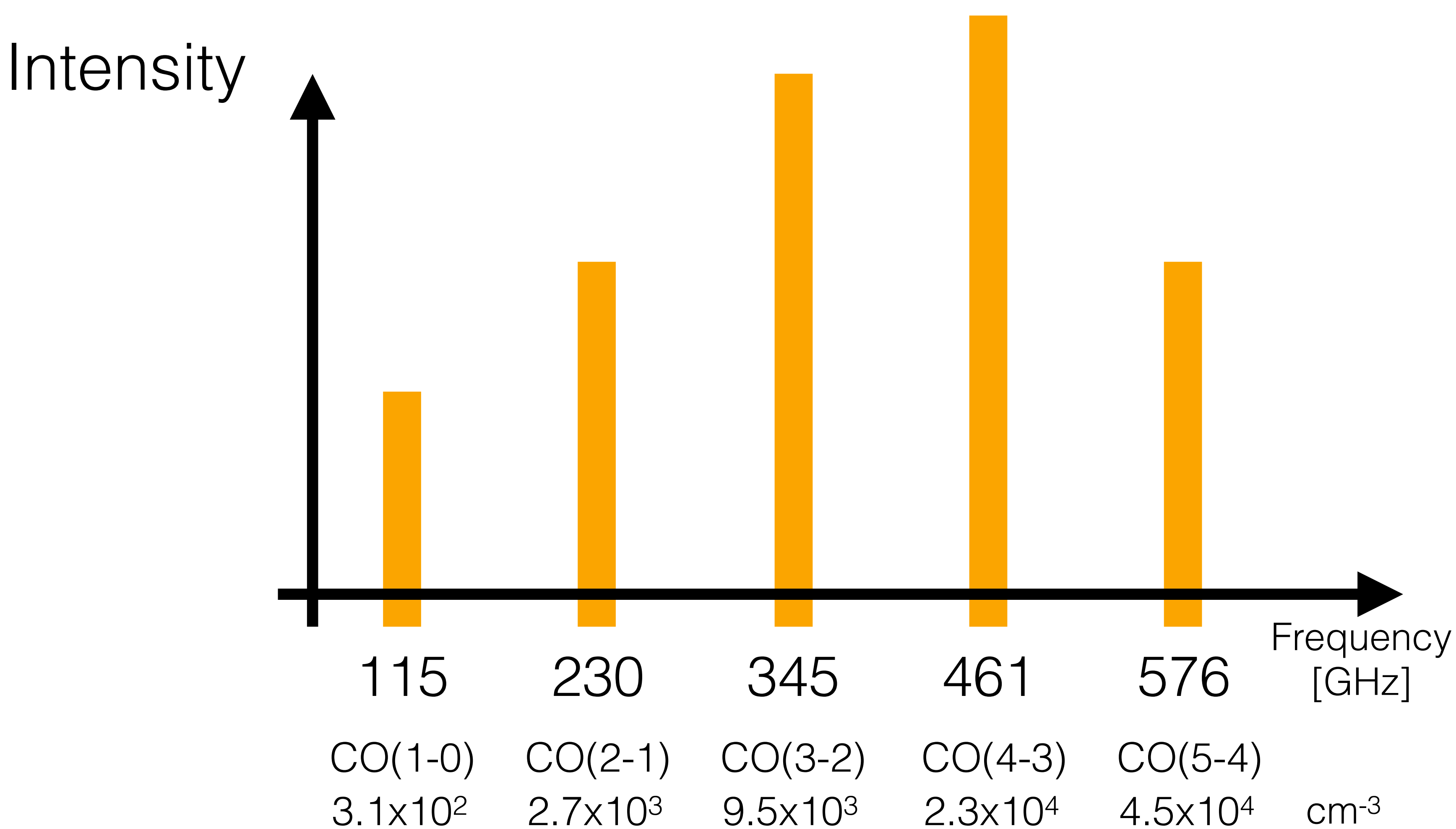




The CO–to–H2 conversion factor

$$M_{mol}\ [M_\odot] = \alpha_{CO} \times L_{CO(1\text{-}0)}\ [K\ km\ s^{-1}\ pc^2]$$

The CO-to-H2 conversion factor

$$M_{mol}\ [M_\odot] = \alpha_{CO} \times L_{CO(1\text{-}0)}\ [\mathrm{K\ km\ s^{-1}\ pc^2}]$$

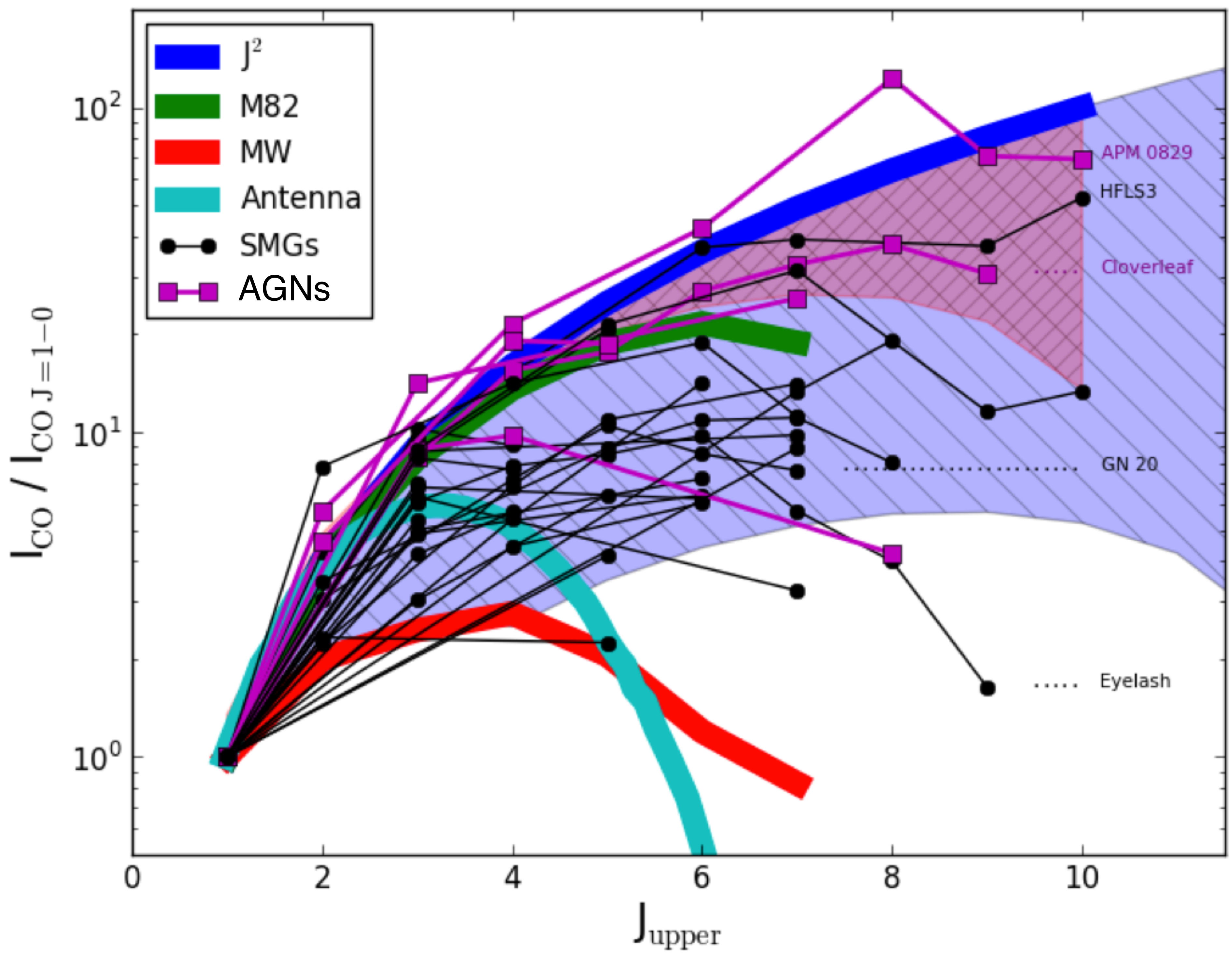
Or, the resolved version:

$$N(H_2)\ [\mathrm{cm^{-2}}] = X_{CO} \times W_{CO(1\text{-}0)}\ [\mathrm{K\ km\ s^{-1}}]$$

Two issues:

1. α_{CO} changes with galaxy type and redshift
2. Higher-J CO lines are easier to observe at high redshift

CO Spectral Line Energy Distribution (CO SLED)



[Casey+14]

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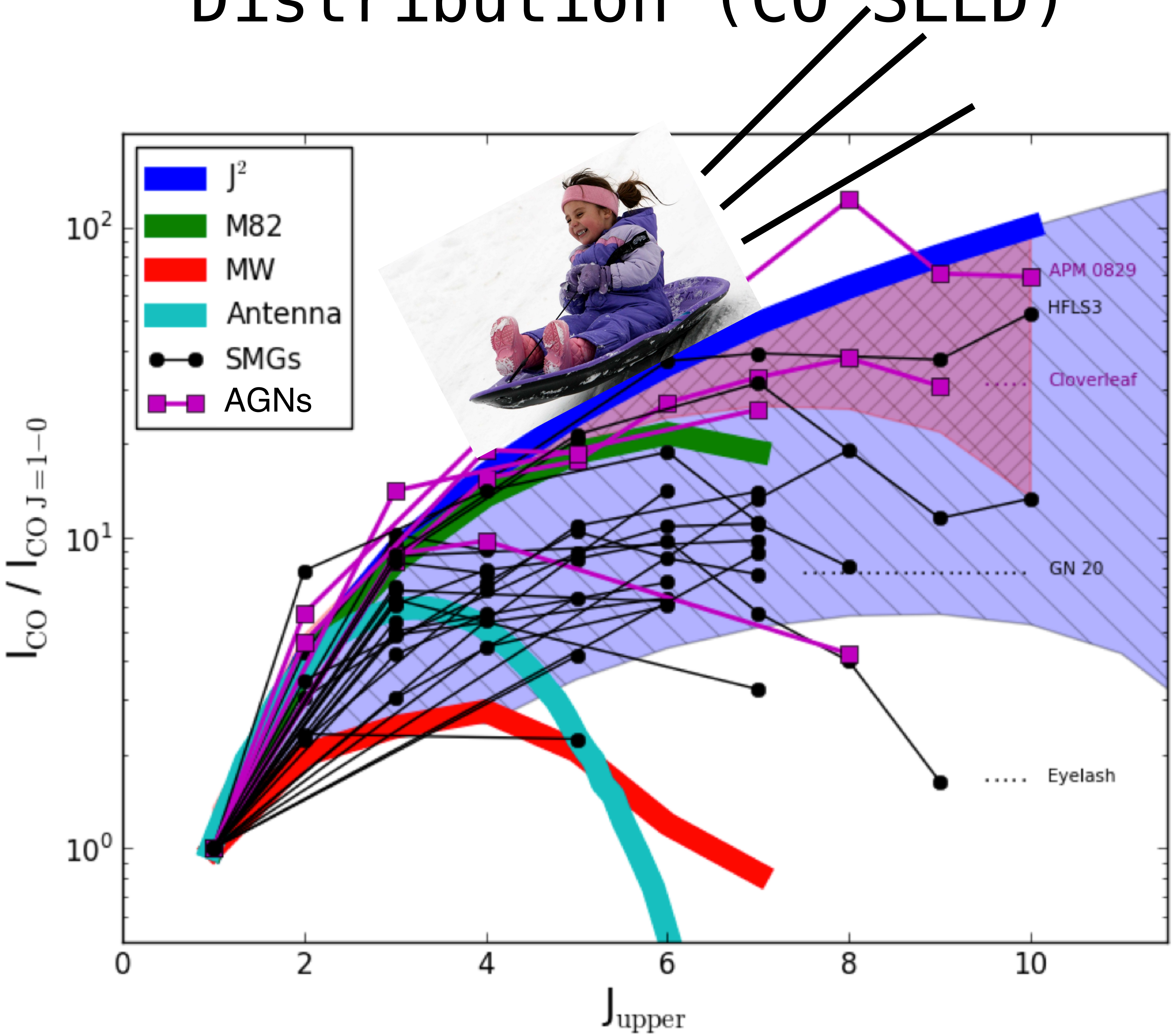
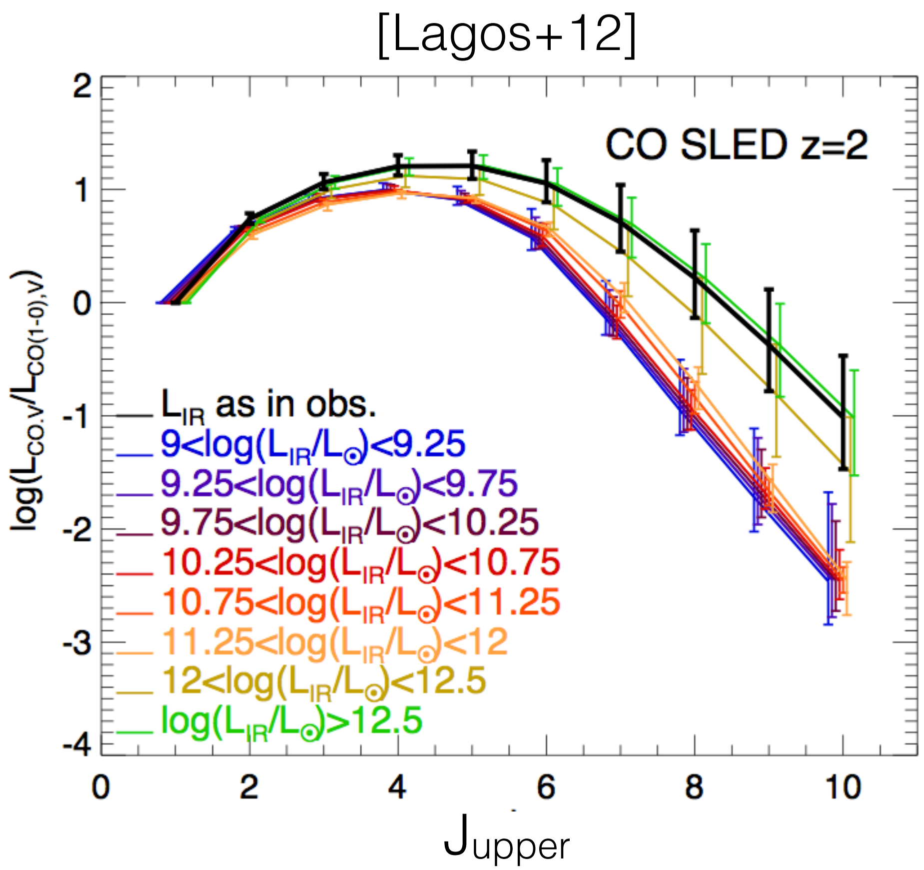
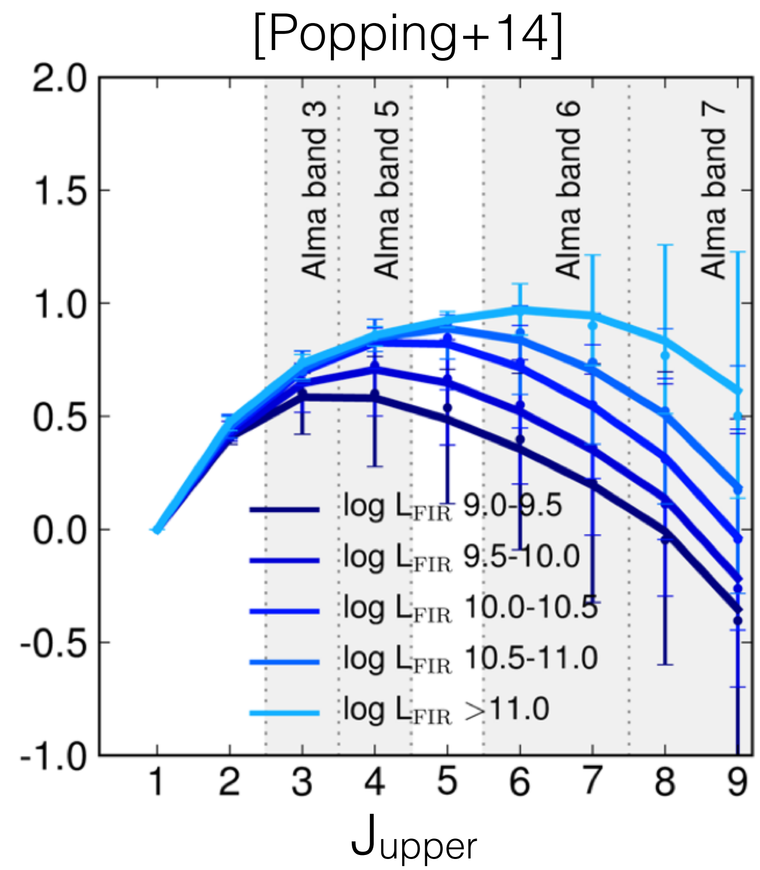
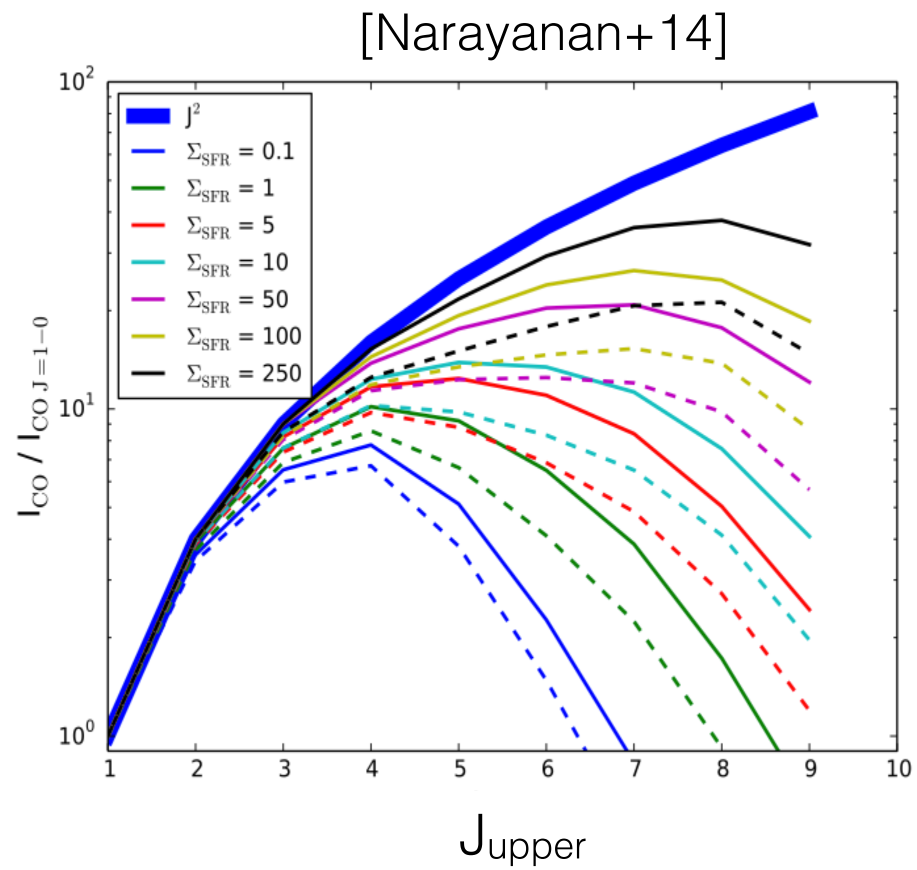


[Casey+14]

Modeling of the CO SLED







Shape parametrized according to:

L_{IR} ~ SFR L_{FIR} ~ SFR Σ_{SFR}

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]

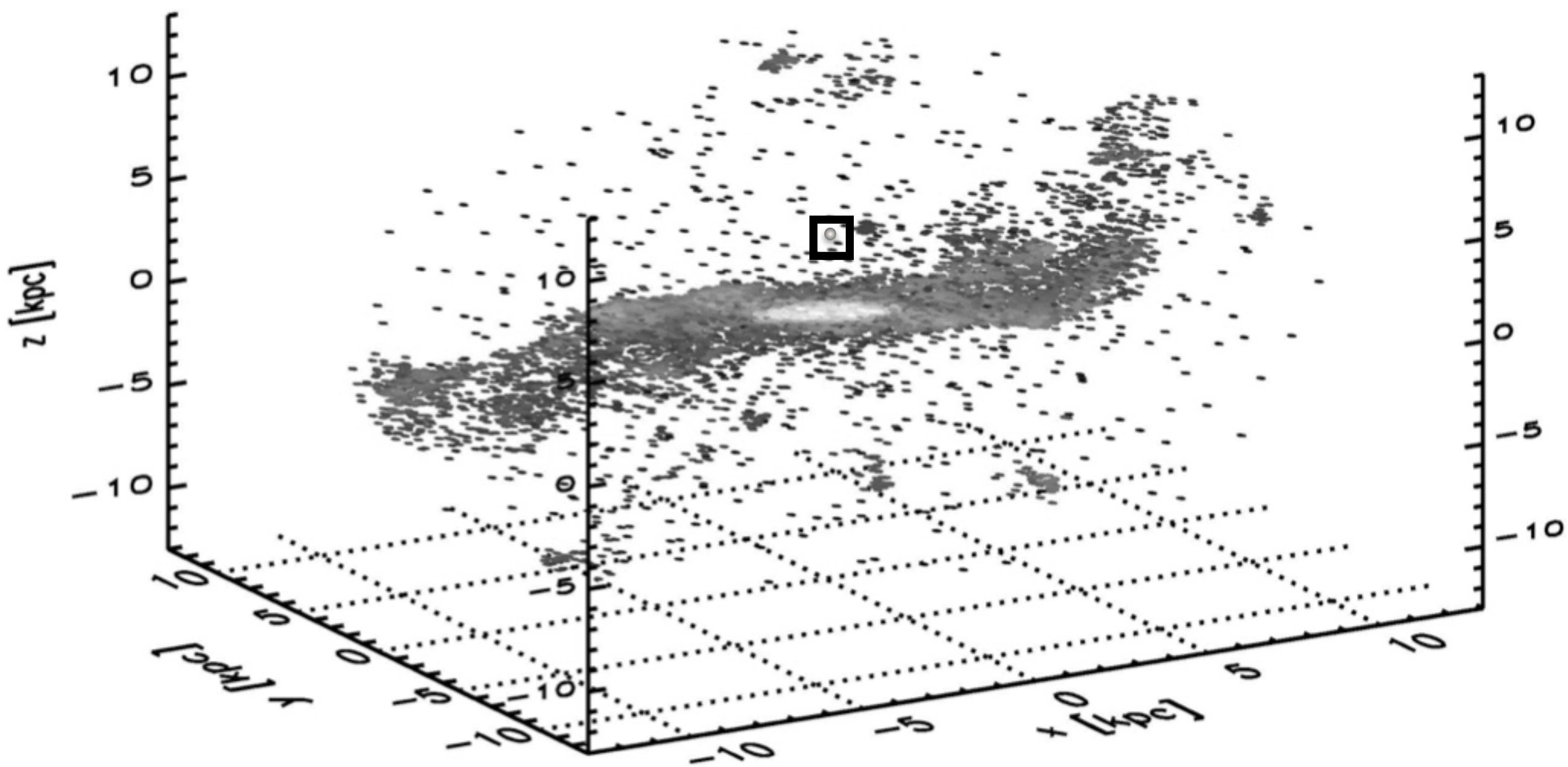
[1] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Denmark
[2] Dept of Physics and Astronomy, University College London
[3] Haverford College, PA, US
[4] Centre for Extragalactic Theory, University of West Cape, South Africa
[5] Centre for Star and Planet formation (Starplan) 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)

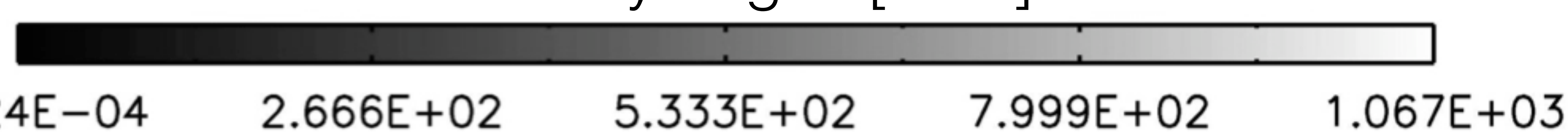
Galaxy simulations

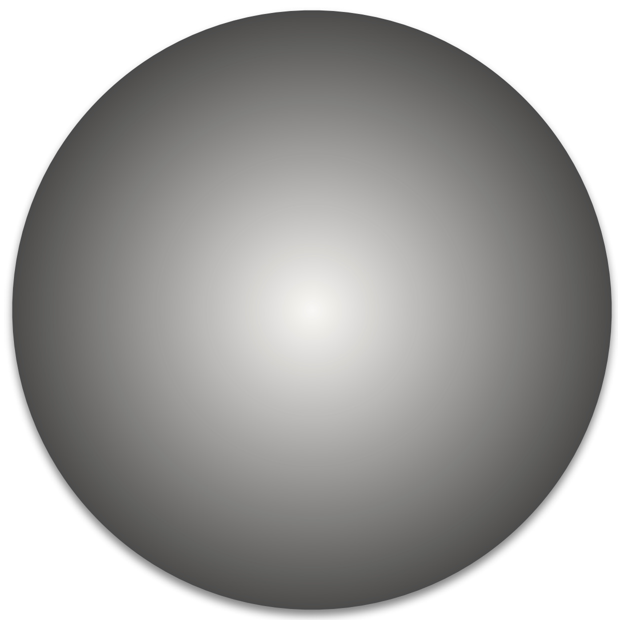
Cosmological Smoothed Particle Hydrodynamics (SPH) simulations

(Jesper Sommer-Larsen, see 2005 paper)



Density of gas [cm^{-3}]

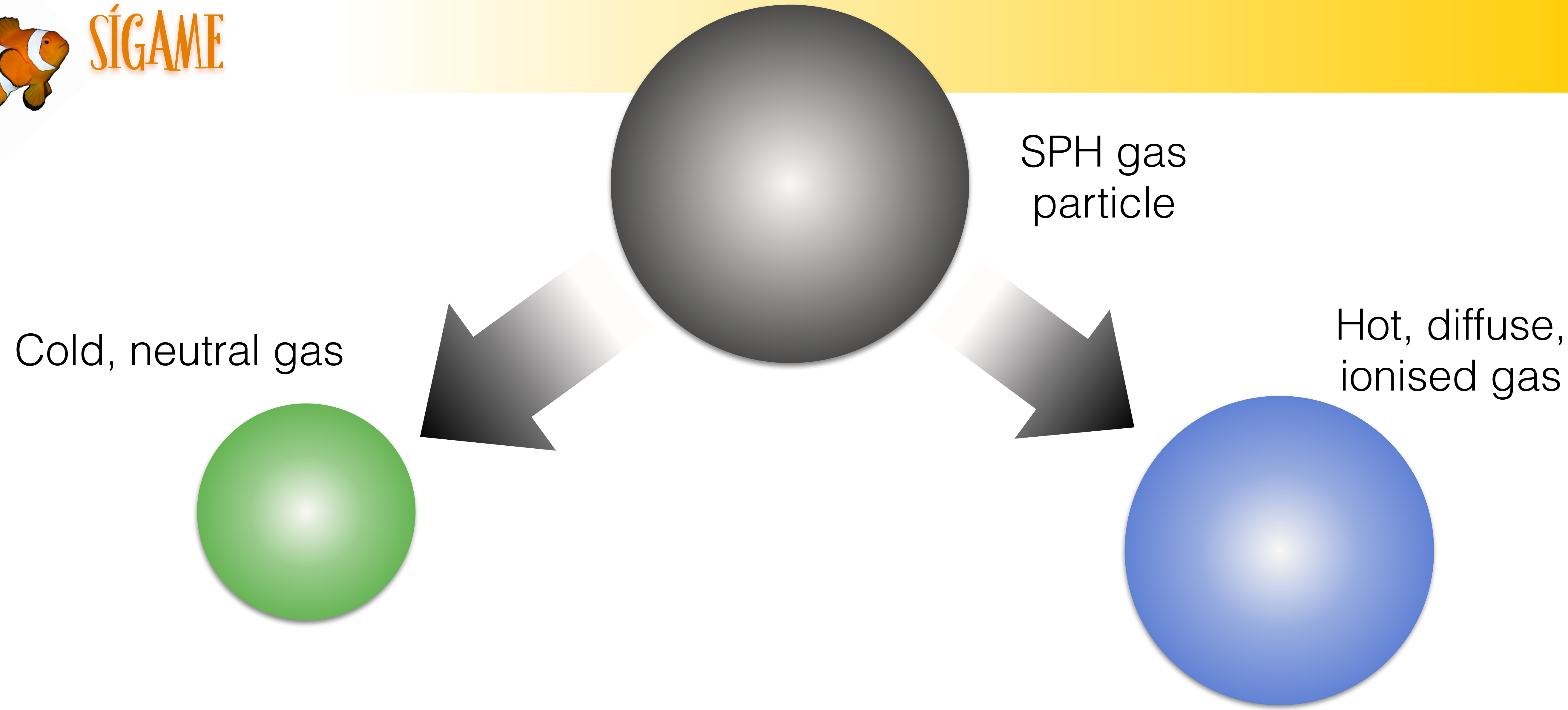


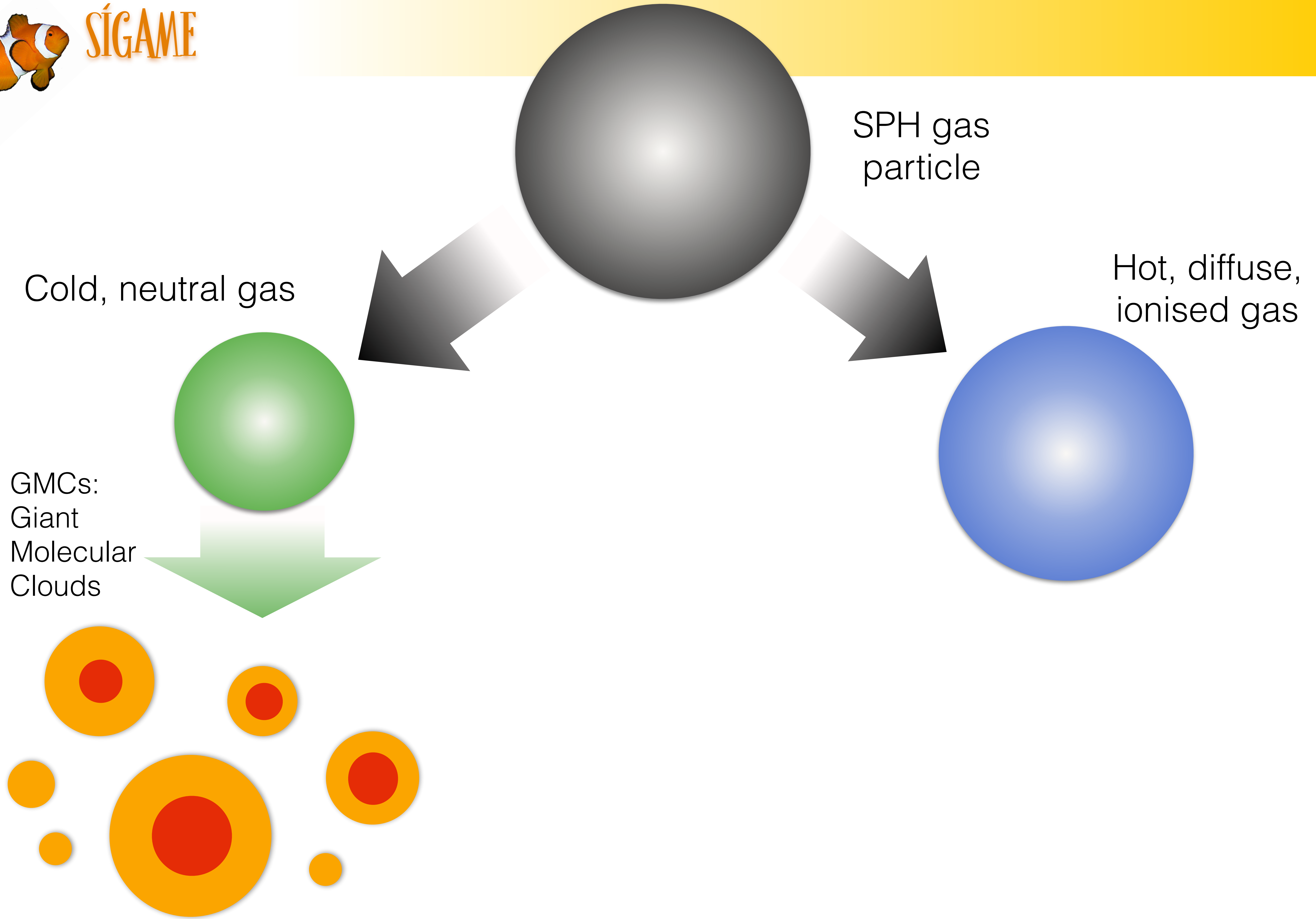


SPH gas particle

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

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


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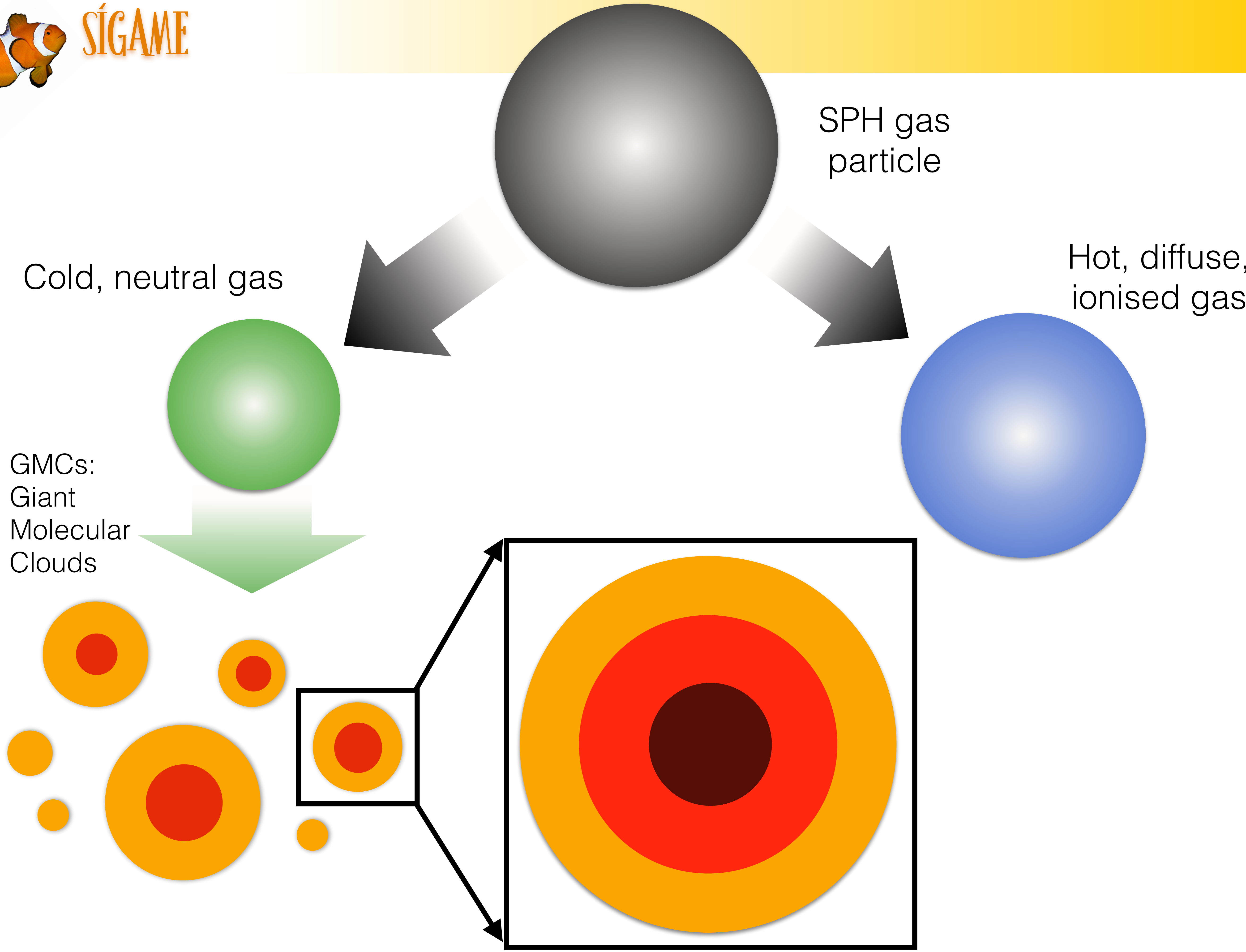
GMCs: Giant Molecular Clouds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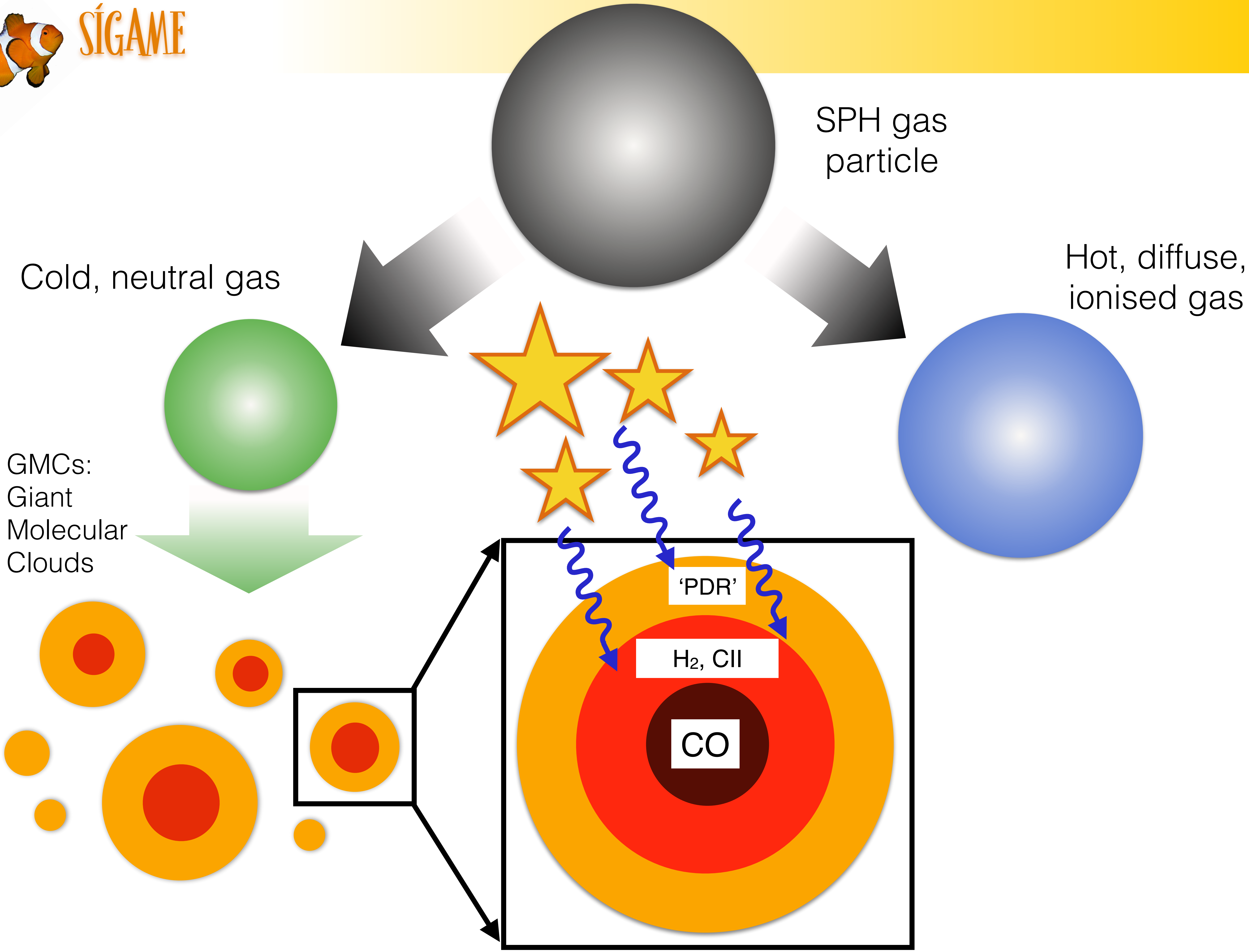
SÍGAME



SPH gas
particle
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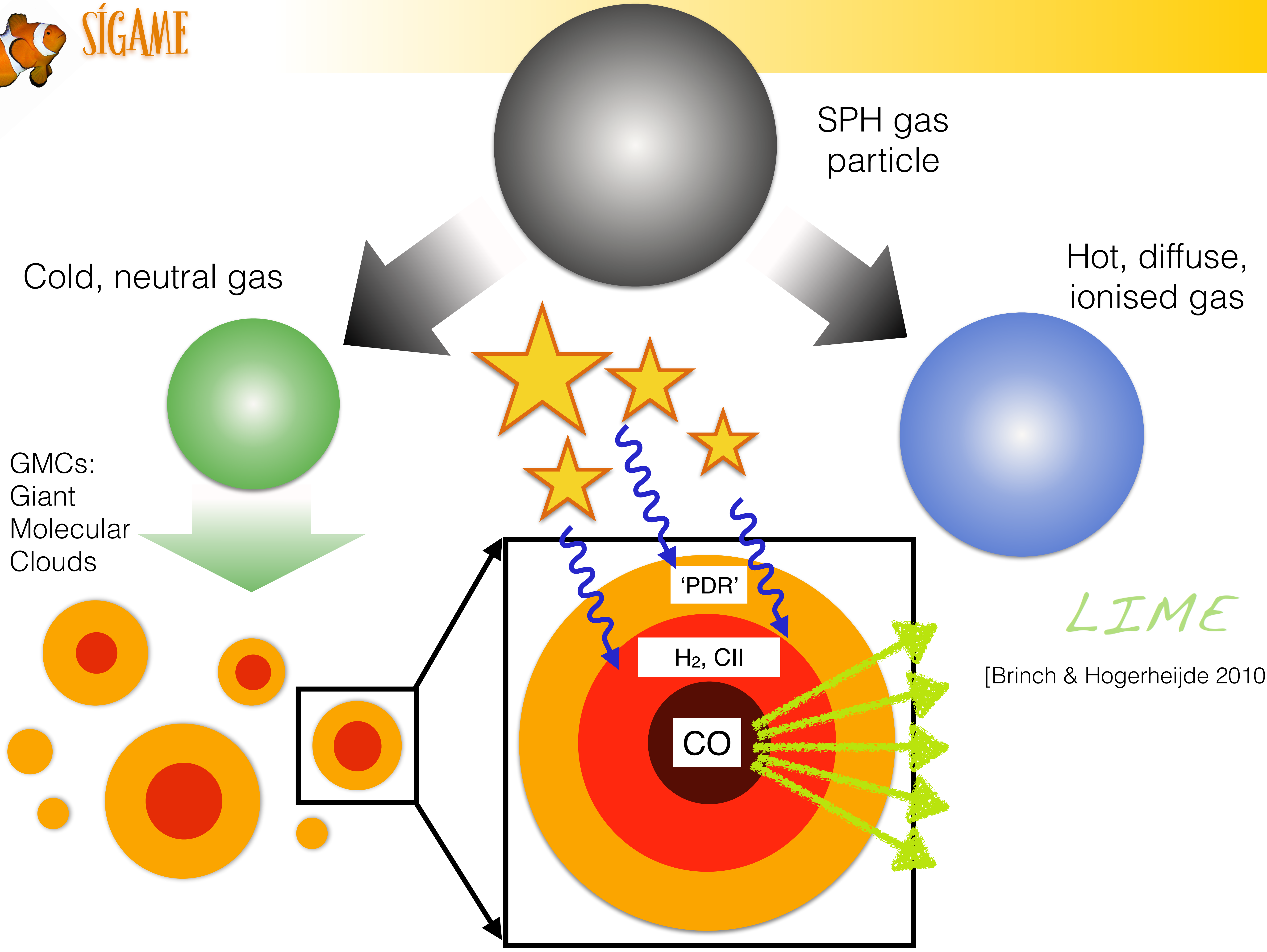
GMCs:
Giant
Molecular
Clouds
'PDR'
H_2, CII
CO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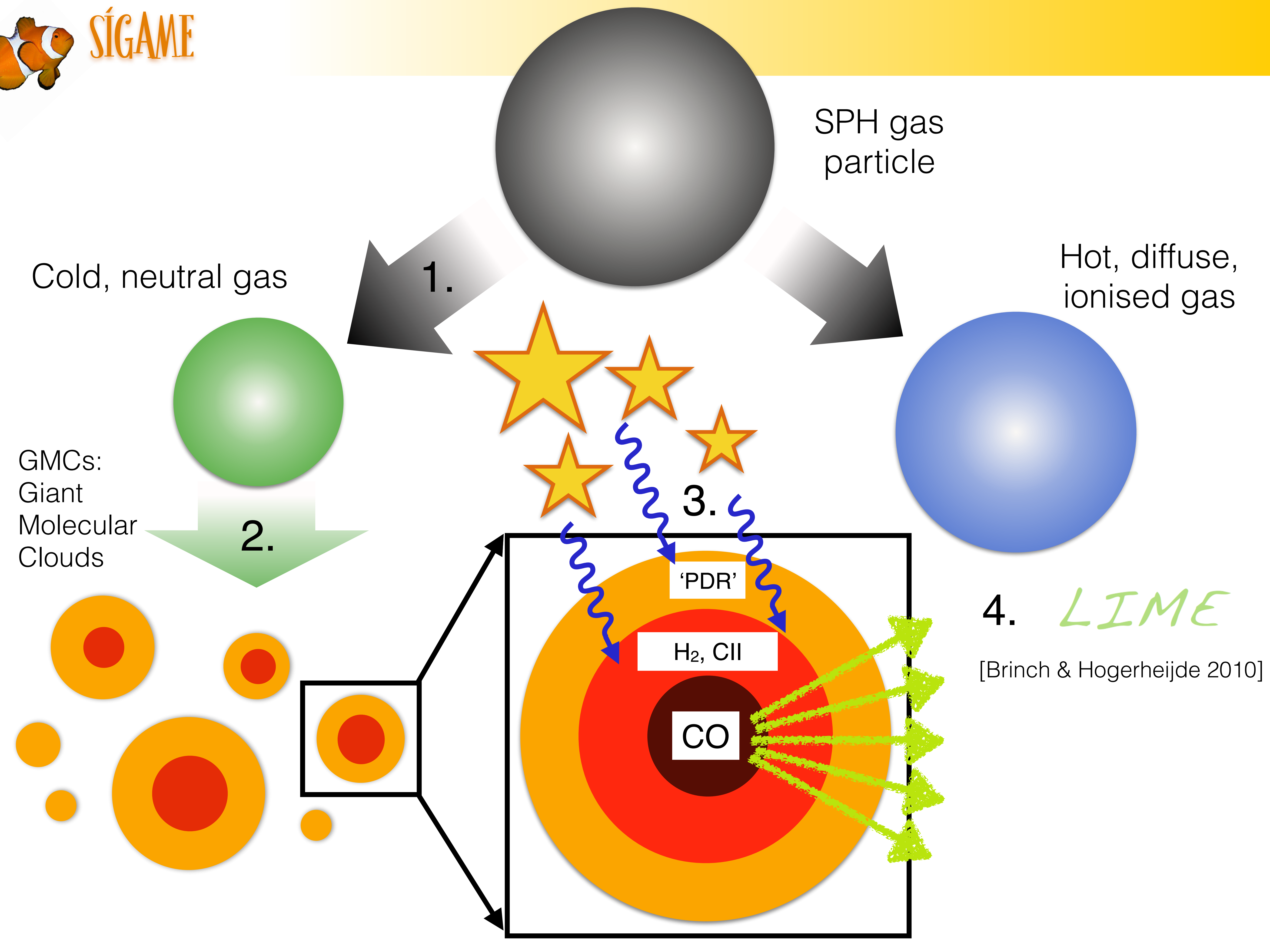
LIME
[Brinch & Hogerheijde 2010]


SÍGAME
SPH gas particle
Cold, neutral gas
1.
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2.
3.
'PDR'
H2, CII
CO
4. LIME
[Brinch & Hogerheijde 2010]

Assumed ISM models

SÍGAME

Assumed ISM models

Radiation fields

Relevant for the ionisation and chemistry of GMCs:

- Far-ultraviolet (FUV) field, G_0
- Cosmic ray field, ζ_{CR}
- Scaled by local SFRD within 5 kpc

SÍGAME

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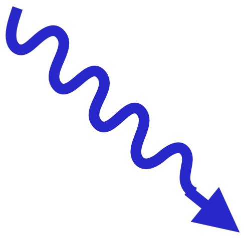
GMC mass spectrum

From observations of MW and local galaxies: $\mathrm{d}N/\mathrm{d}m_{\mathrm{GMC}}$ α $m_{\mathrm{GMC}}^{-\beta}$

Assumed ISM models



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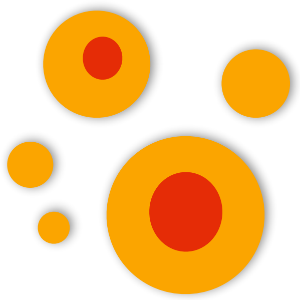
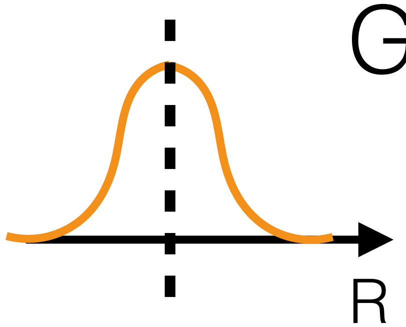


GMC mass spectrum

From observations of MW and local galaxies: $dN/dm_{GMC} \propto m_{GMC}^{-\beta}$

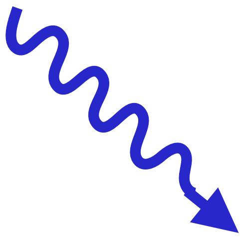


GMC radial density profile

Plummer radial profile

- Drops as R^{-1} in outskirts, finite central value

Assumed ISM models



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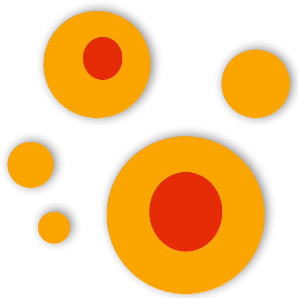

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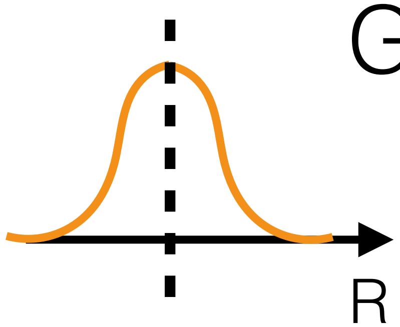

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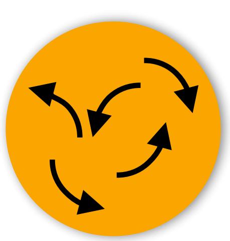

Size and velocity dispersion of each GMC

Pressure-normalised scaling relations for virialized clouds

Assumed ISM models

Experimented with!

Radiation fields

Relevant for the ionisation and chemistry of GMCs:

- Far-ultraviolet (FUV) field, G_0
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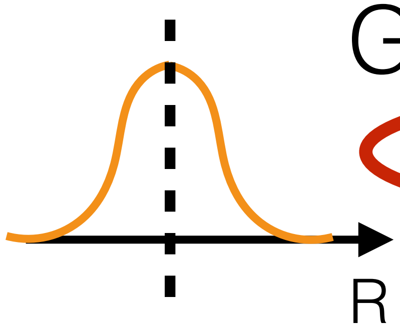


Plummer radial profile

- Drops as R^{-1} in outskirts, finite central value

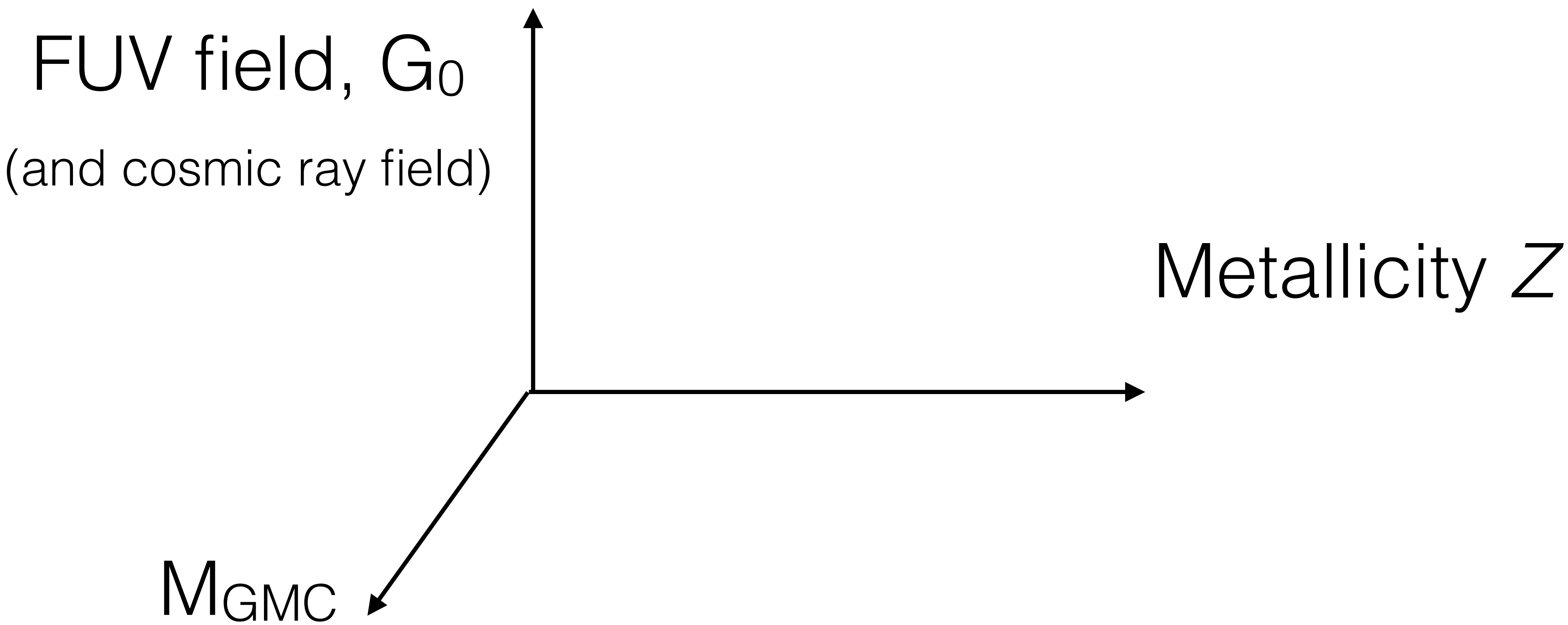
Size and velocity dispersion of each GMC

Pressure-normalised scaling relations for virialized clouds

A grid of GMC models

A grid of GMC models

CO emission determined by 3 parameters:



A grid of GMC models

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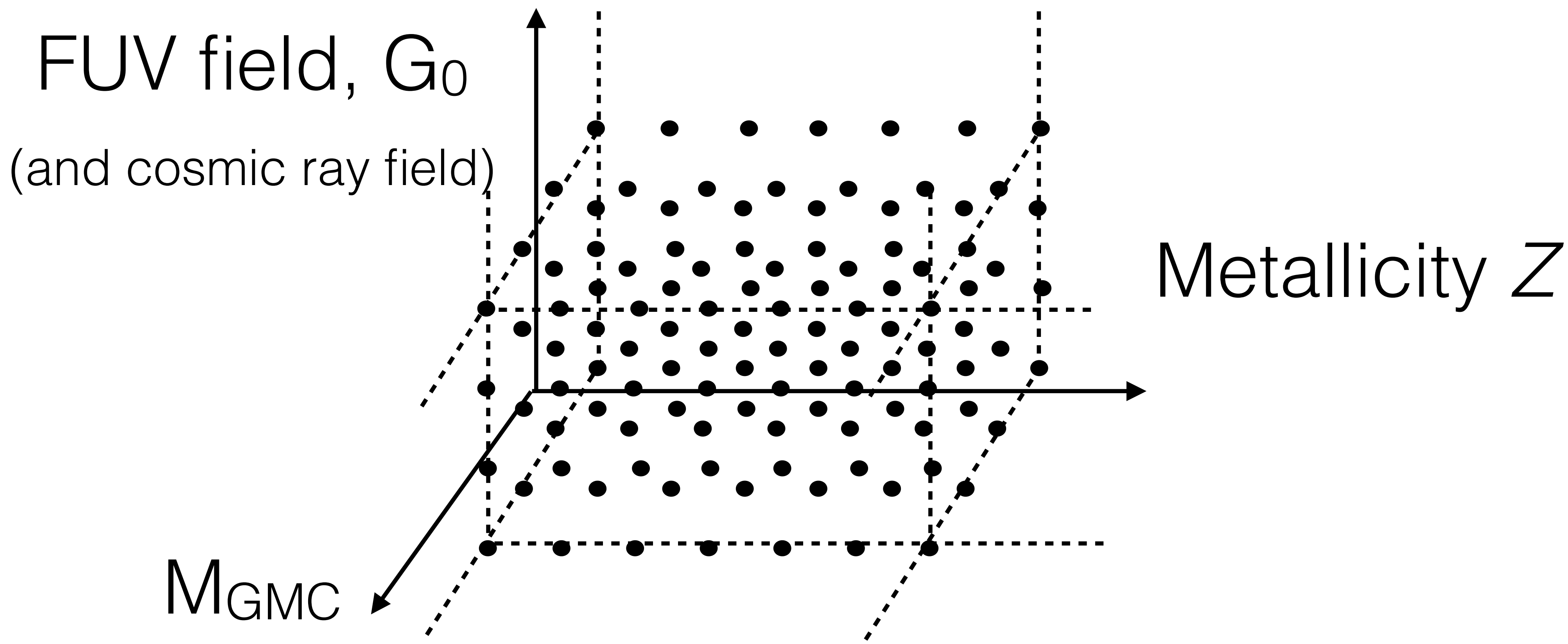

A grid of GMC models

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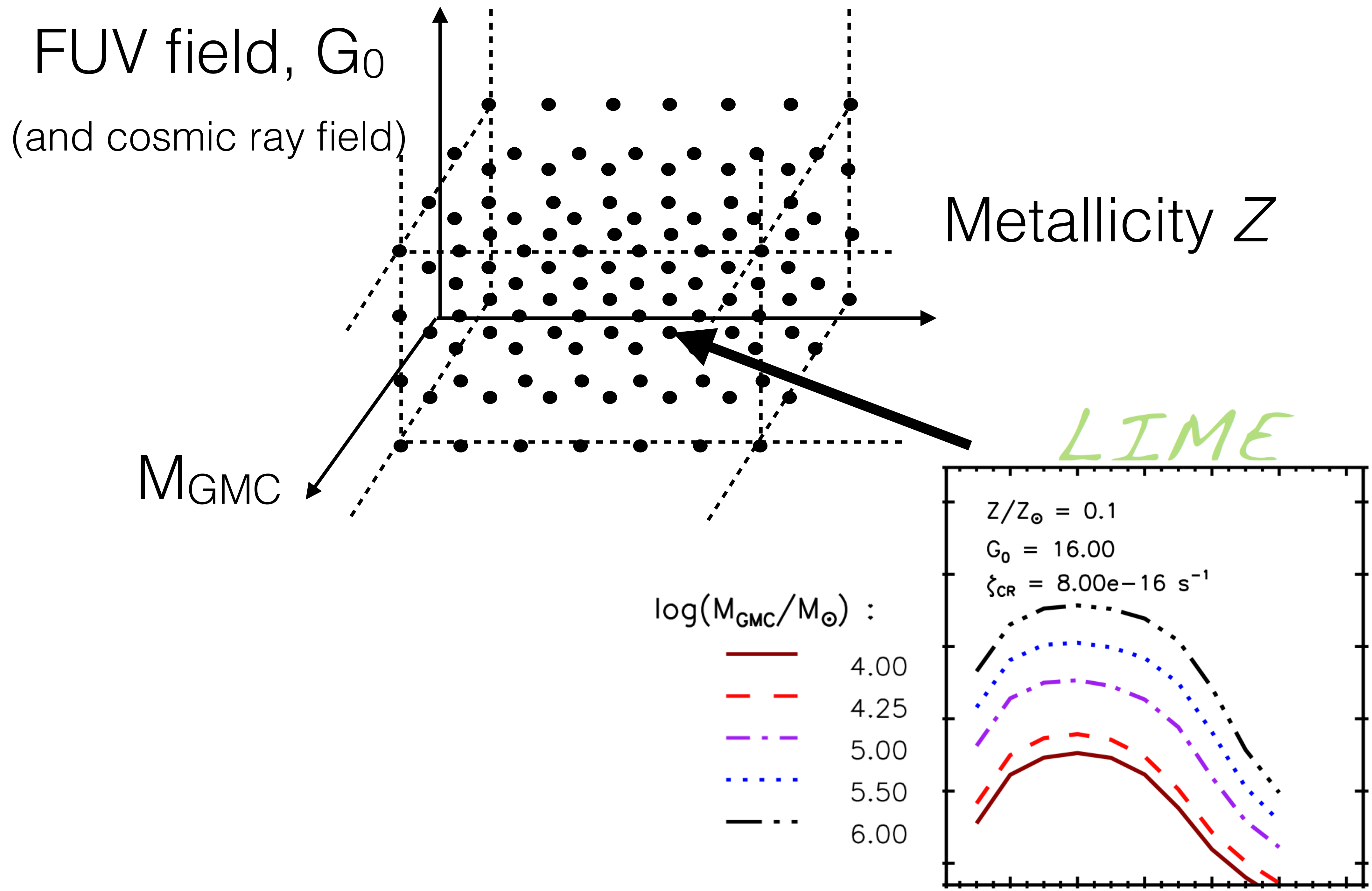


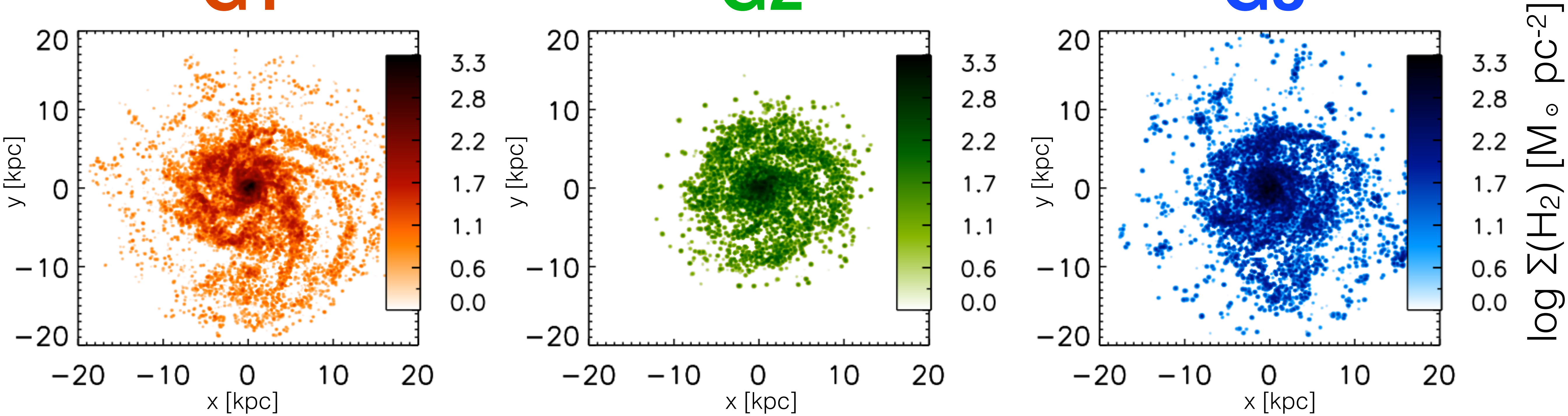
[Olsen+15: arXiv:1507.00012]

SÍGAME

The model galaxies, H_2 maps

3 normal star-forming galaxies at z=2

G1 **G2** **G3**

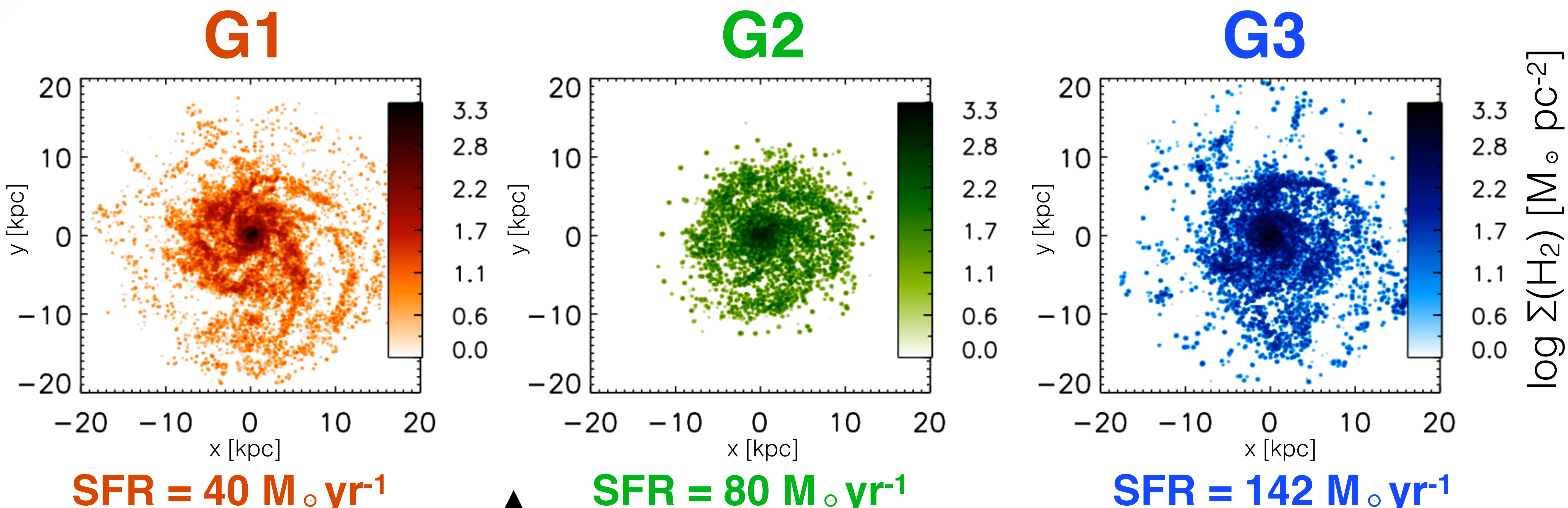


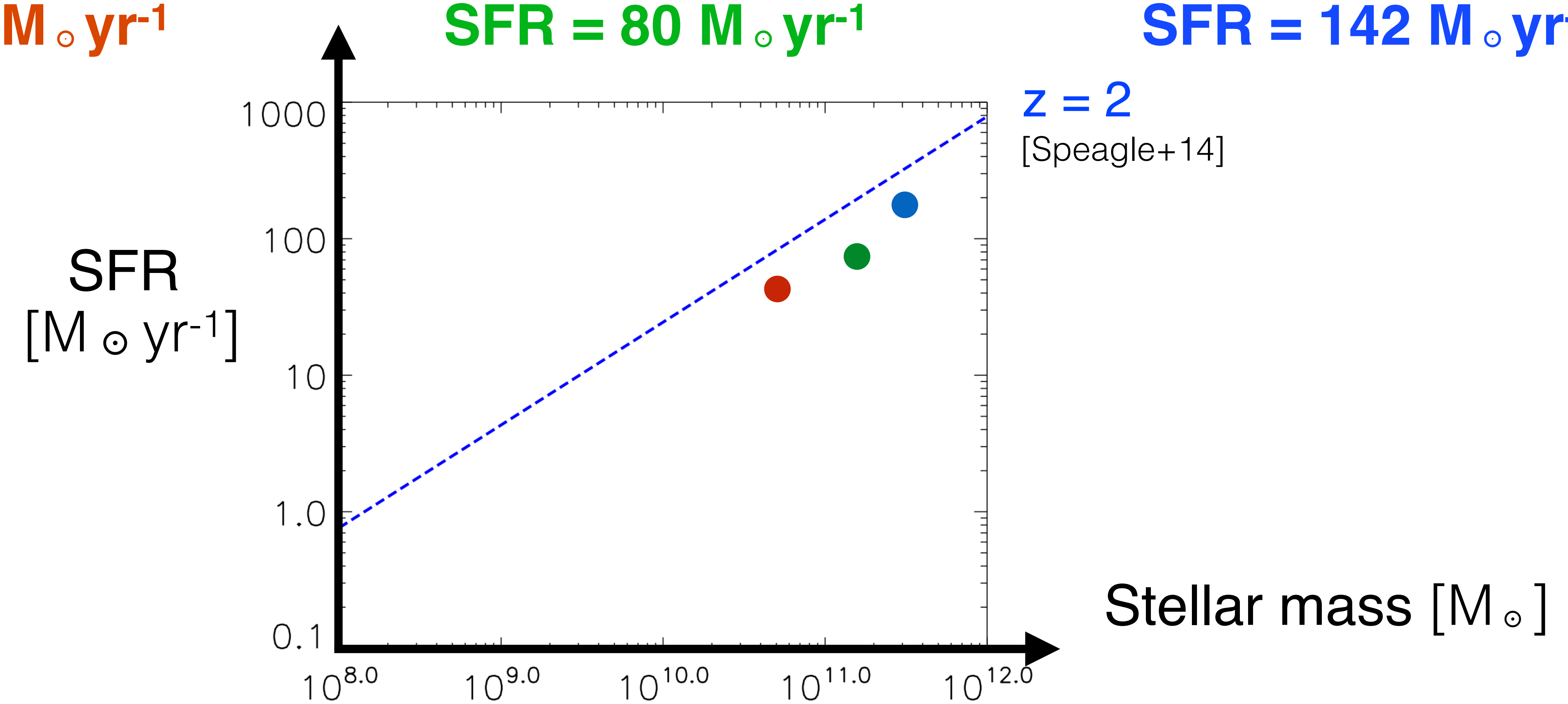
SFR = 40 $M_\odot\,yr^{-1}$ **SFR = 80 $M_\odot\,yr^{-1}$** **SFR = 142 $M_\odot\,yr^{-1}$**

[Olsen+15: arXiv:1507.00012]

The model galaxies, H_2 maps

3 normal star-forming galaxies at z=2





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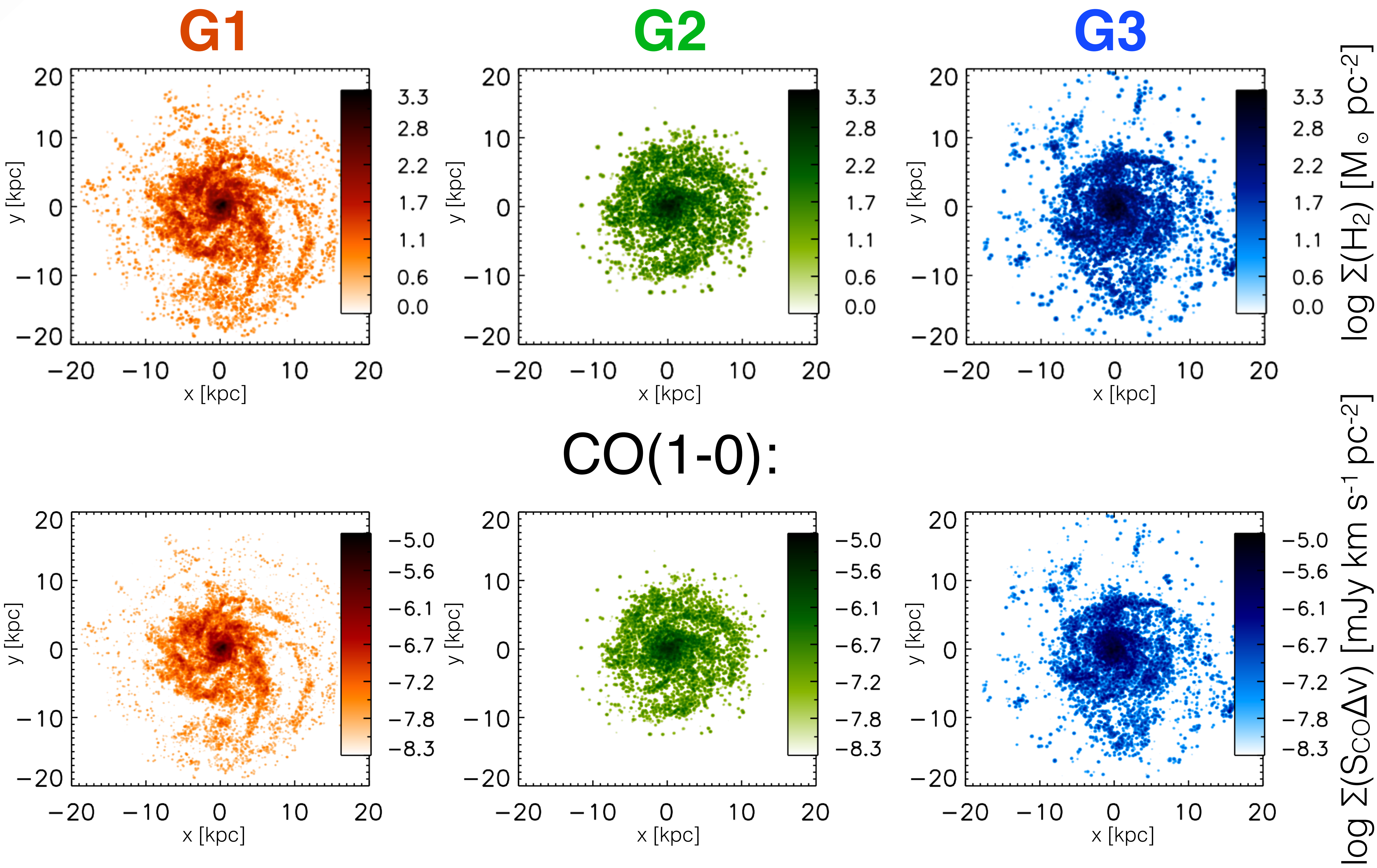
SÍGAME

In CO emission

3 normal star-forming galaxies at z=2



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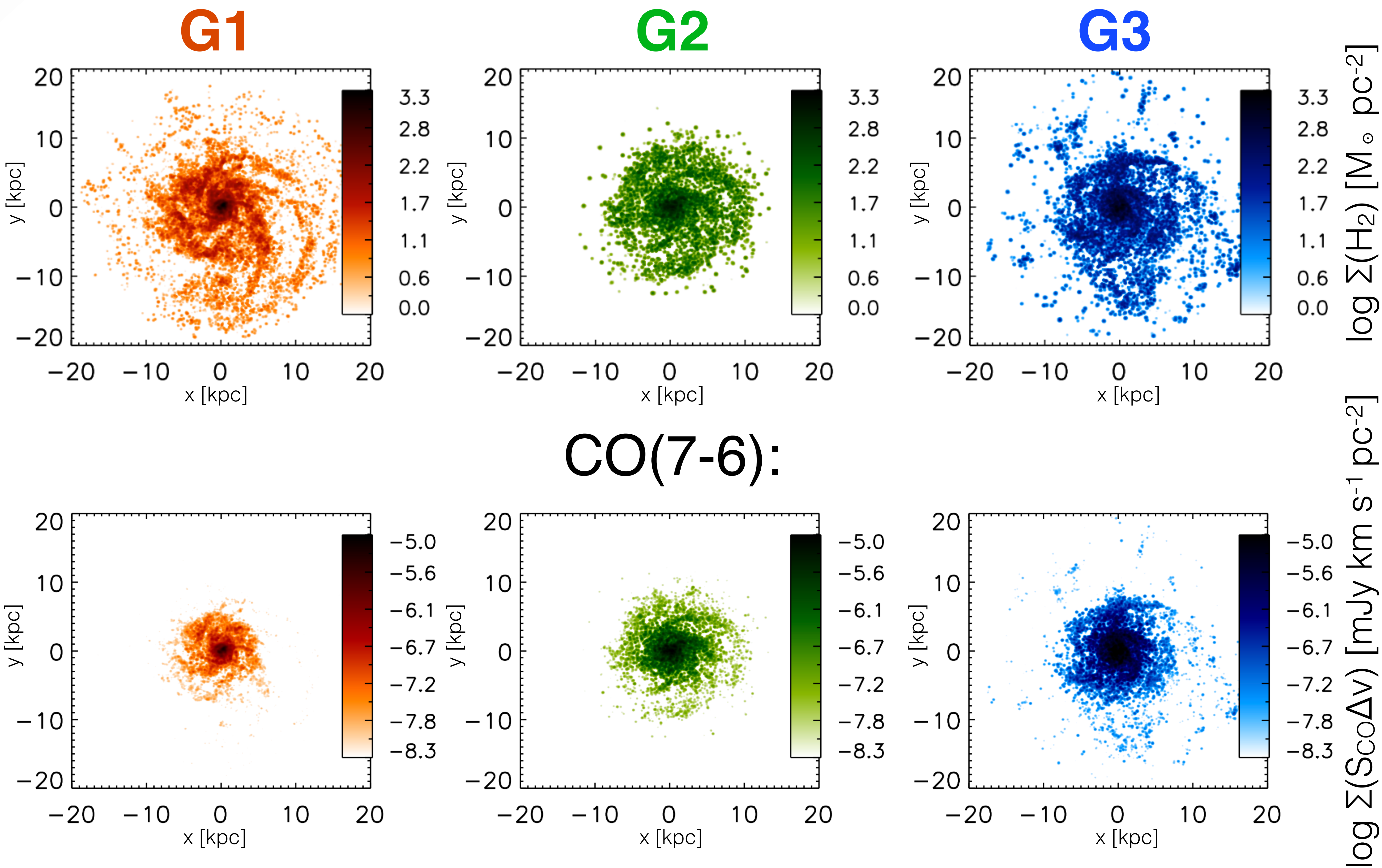
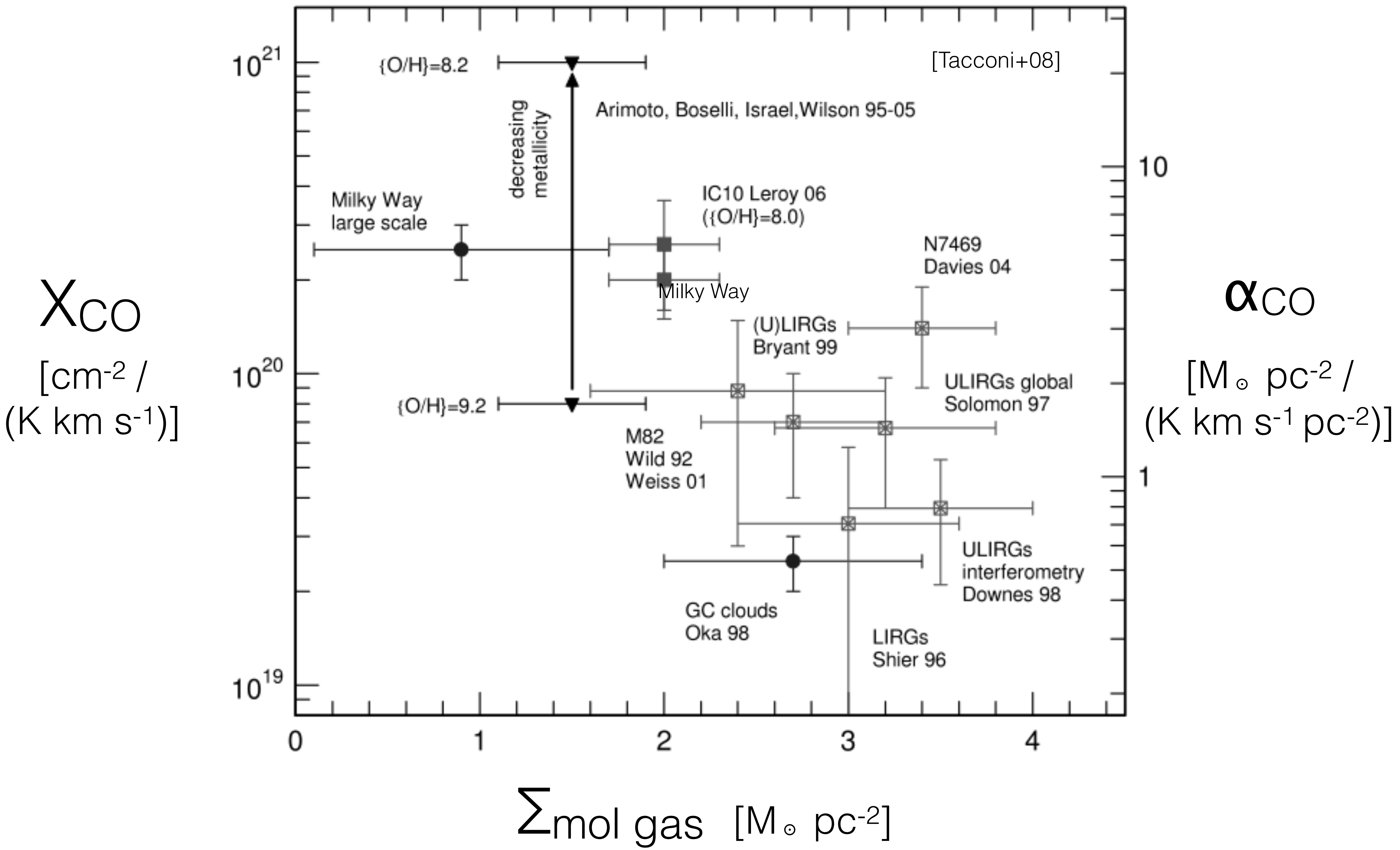


[Olsen+15: arXiv:1507.00012]

Global α_{CO} (CO-to-H_2) factors

Observed α_{CO} factors depend on galaxy type:



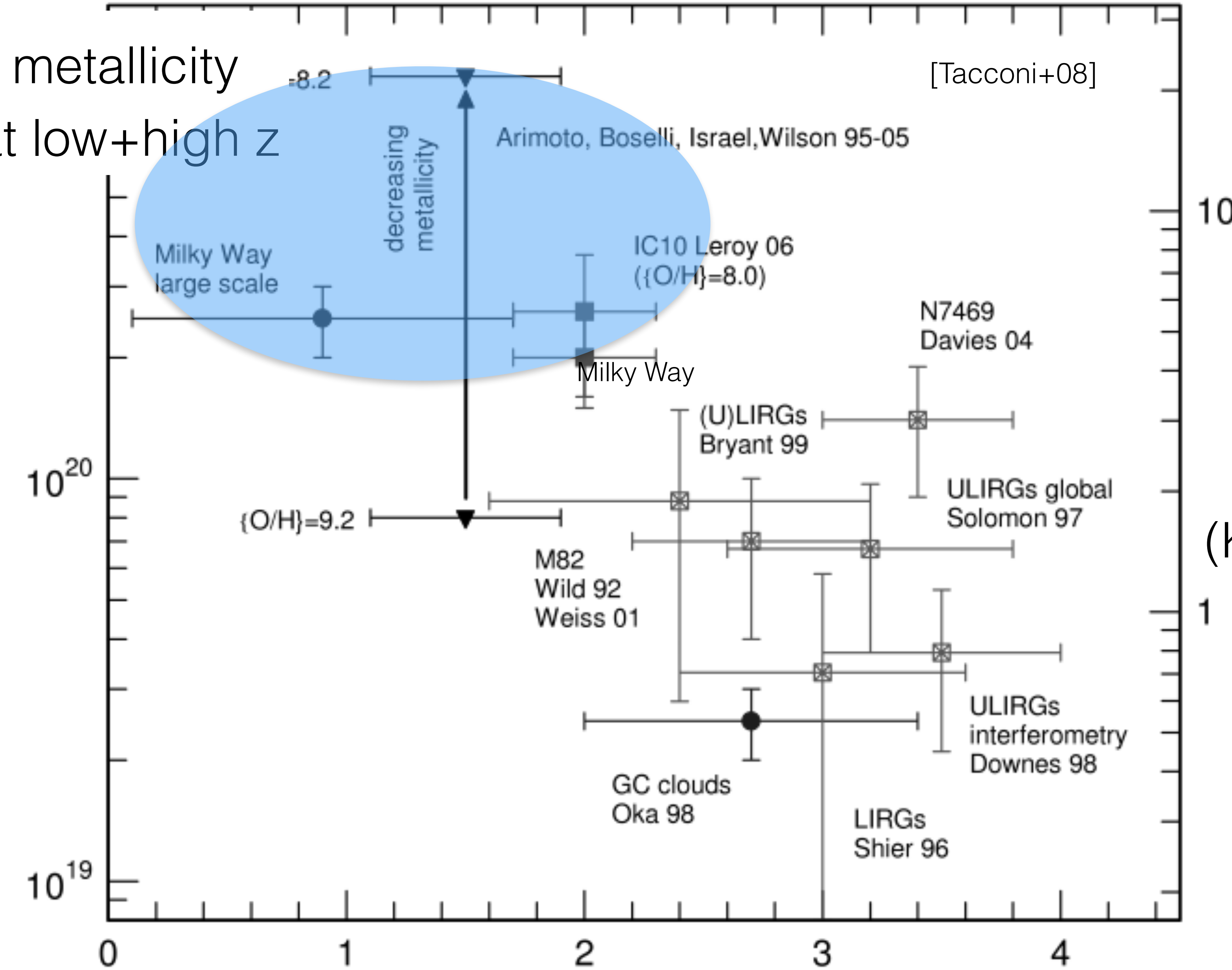
SÍGAME

Global α_{CO} (CO-to-H_2) factors

Observed α_{CO} factors depend on galaxy type:

Higher in lower metallicity environments at low+high z

X_{CO} [cm^{-2} / (K km s^{-1})]



α_{CO} [$M_\odot$ pc^{-2} / (K km s^{-1} pc^{-2})]

$\Sigma_{mol\ gas}$ [$M_\odot$ pc^{-2}]

Global α_{CO} (CO-to-H_2) factors

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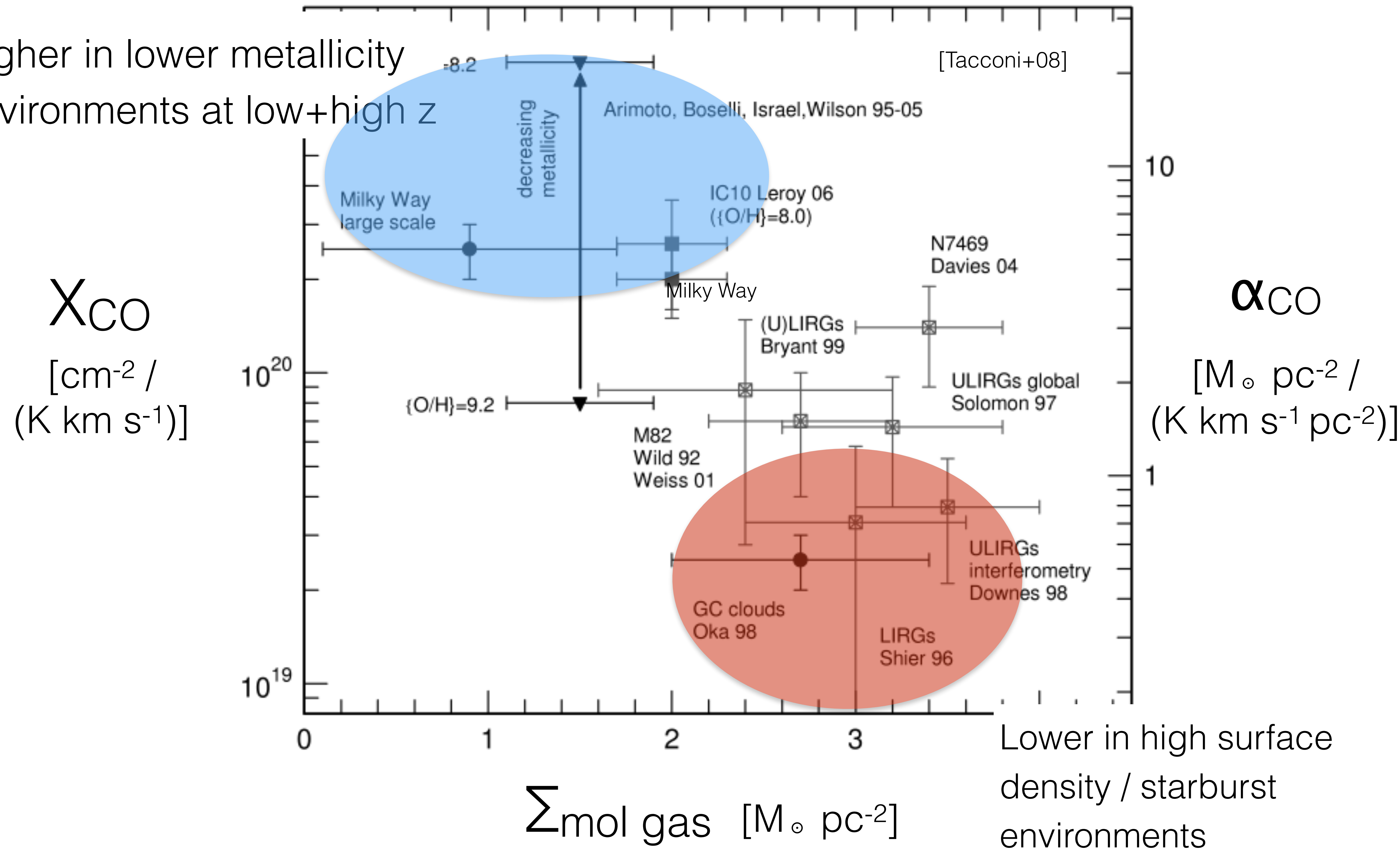

Lower in high surface density / starburst environments

SÍGAME

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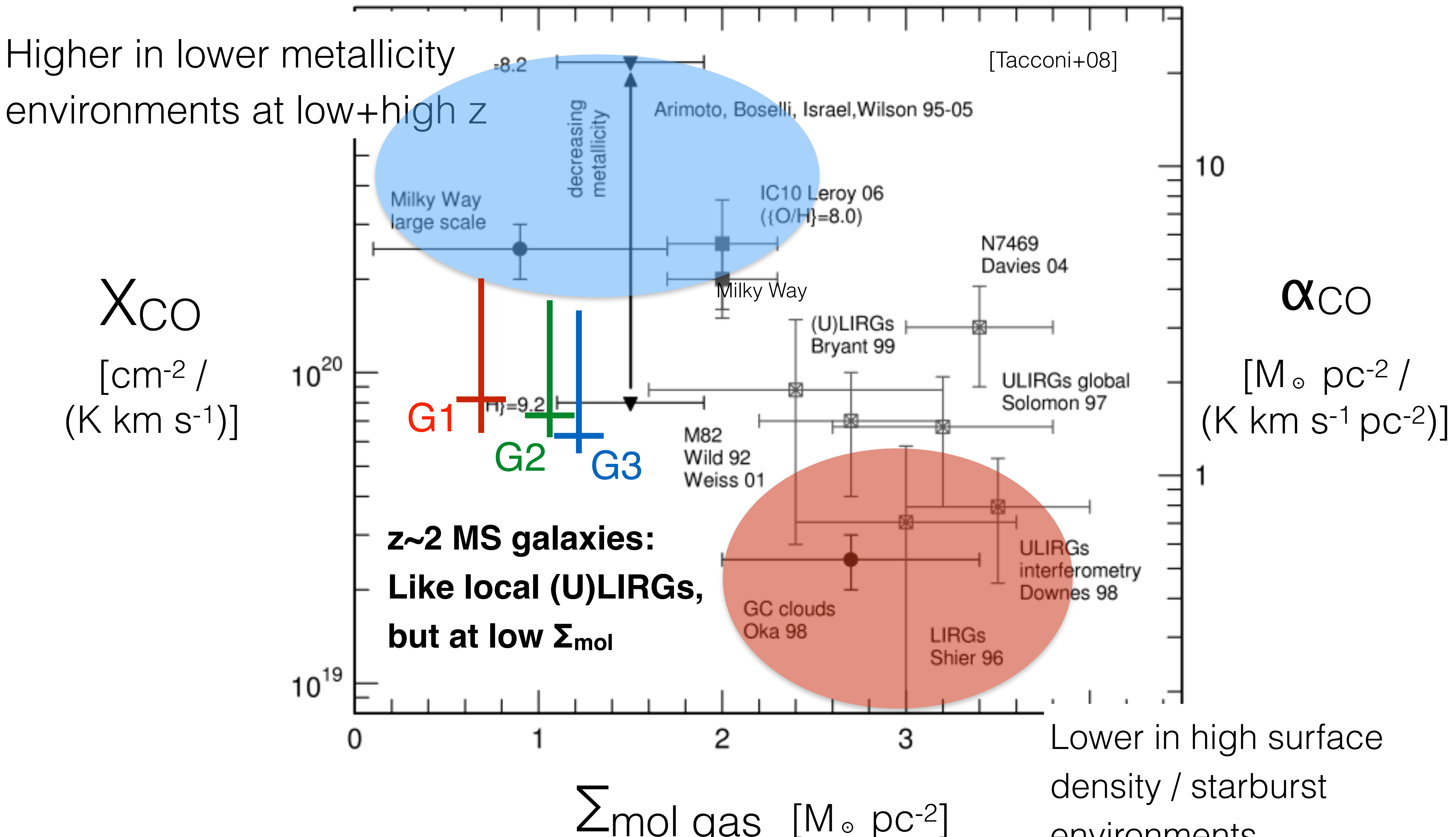
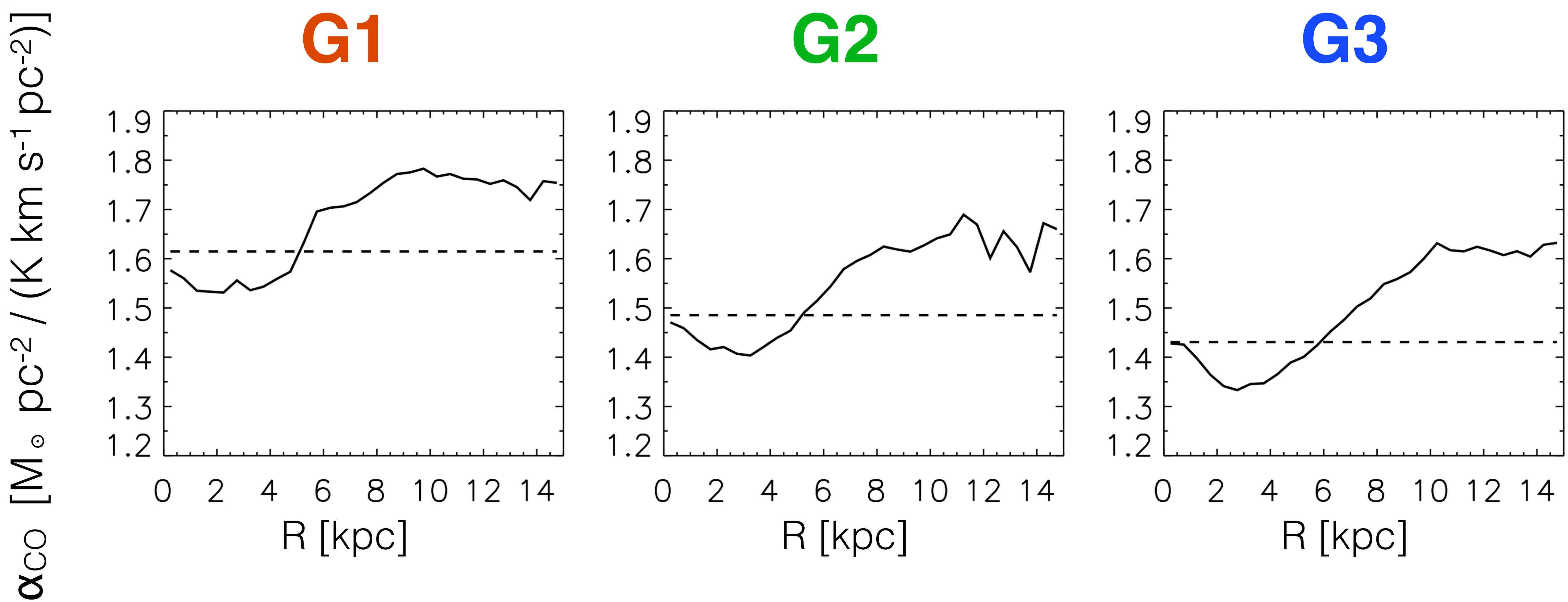


Lower in high surface density / starburst environments

The α_{CO} factor on resolved scales



[Olsen+15: arXiv:1507.00012]

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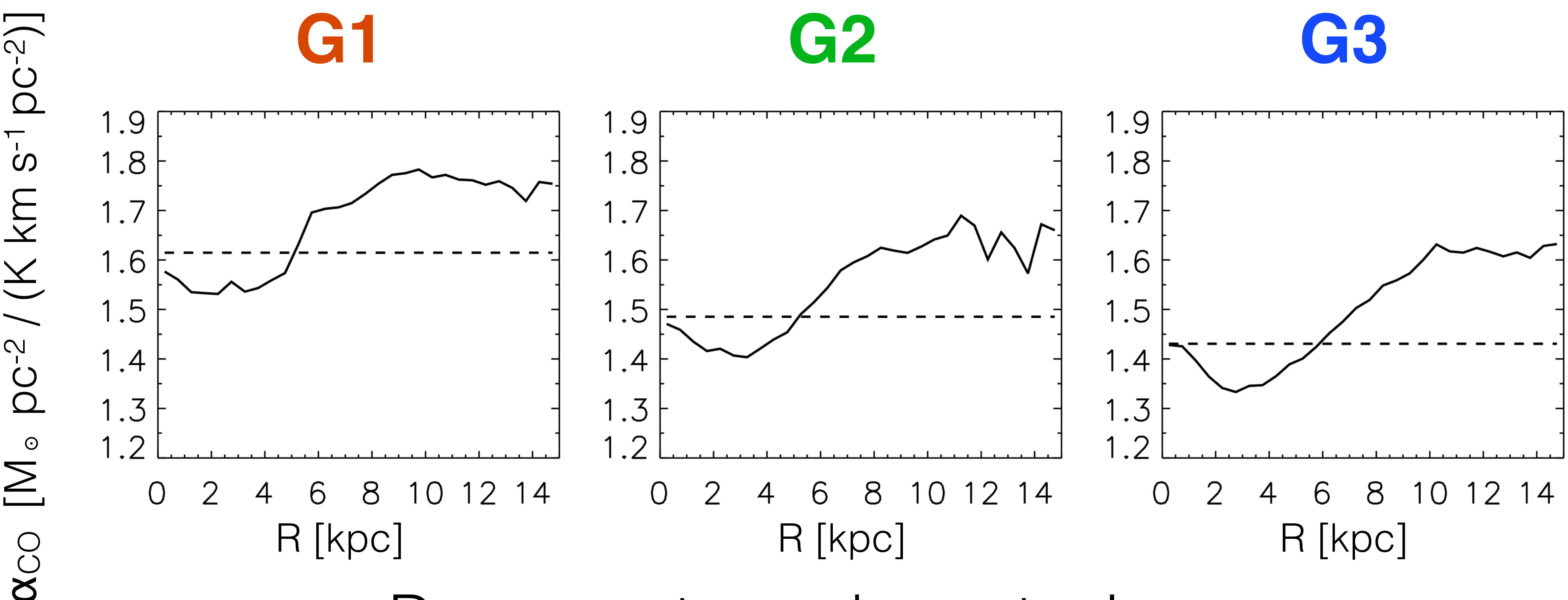

Decrease towards centre in α_{CO}

[Olsen+15: arXiv:1507.00012]

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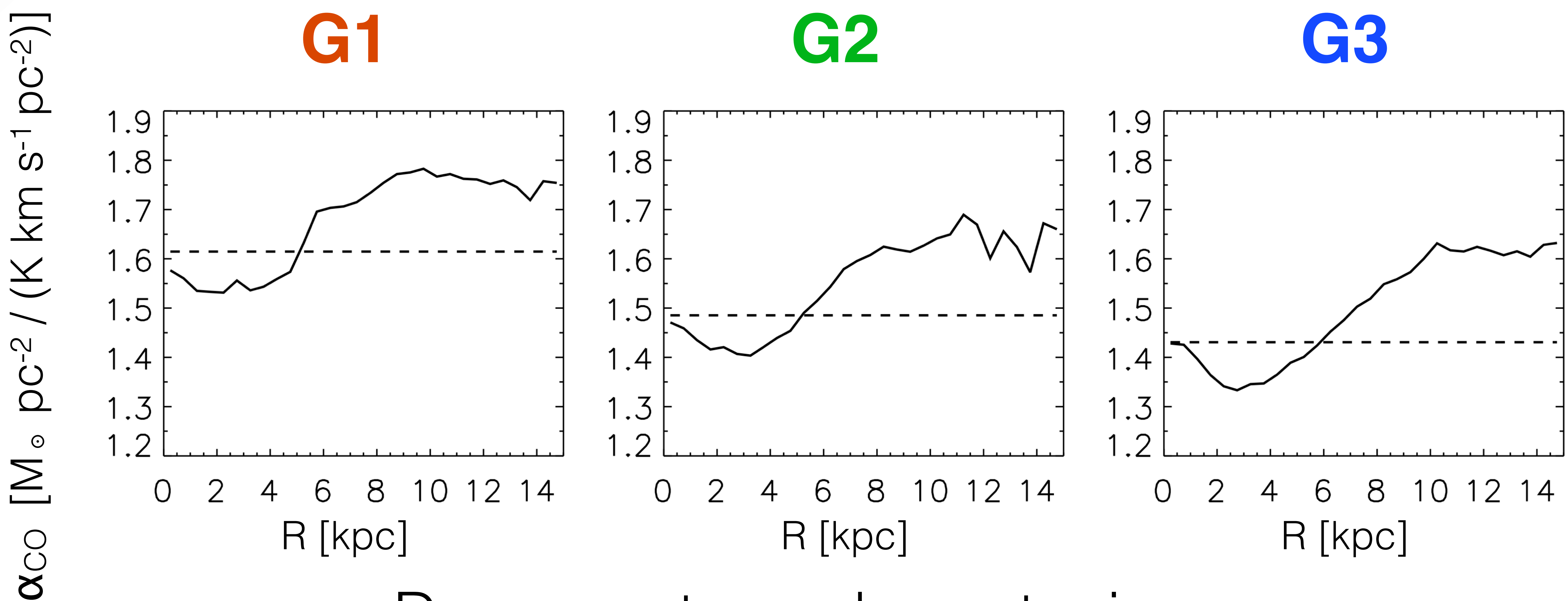


Decrease towards centre in α_{CO}

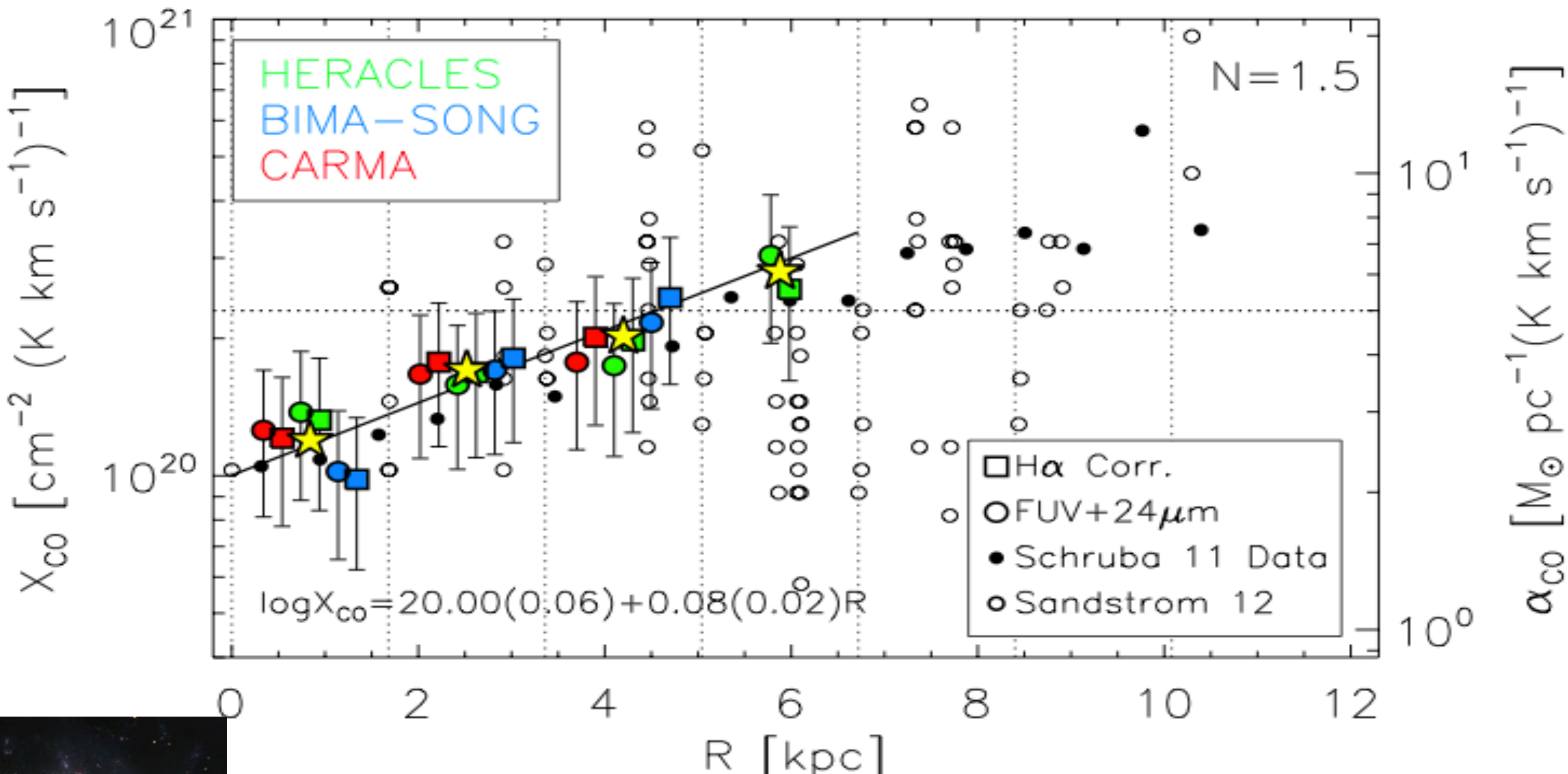
as observed in nearby spiral galaxies [Blanc+13, Sandstrom+13]

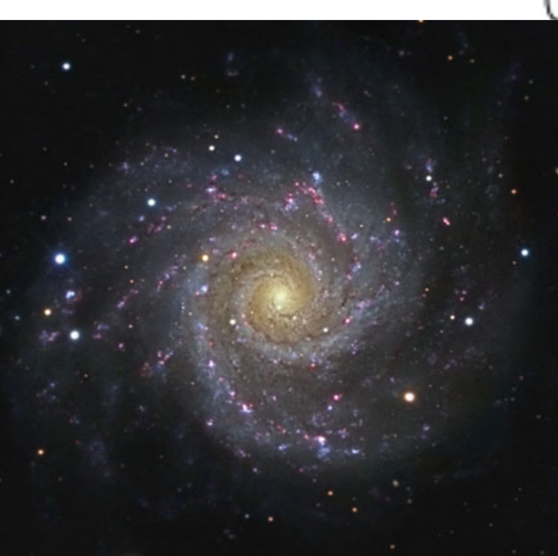
[Olsen+15: arXiv:1507.00012]

The α_{CO} factor on resolved scales

α_{CO} [$M_\odot$ pc^{-2} / (K km s^{-1} pc^{-2})]

G1 G2 G3



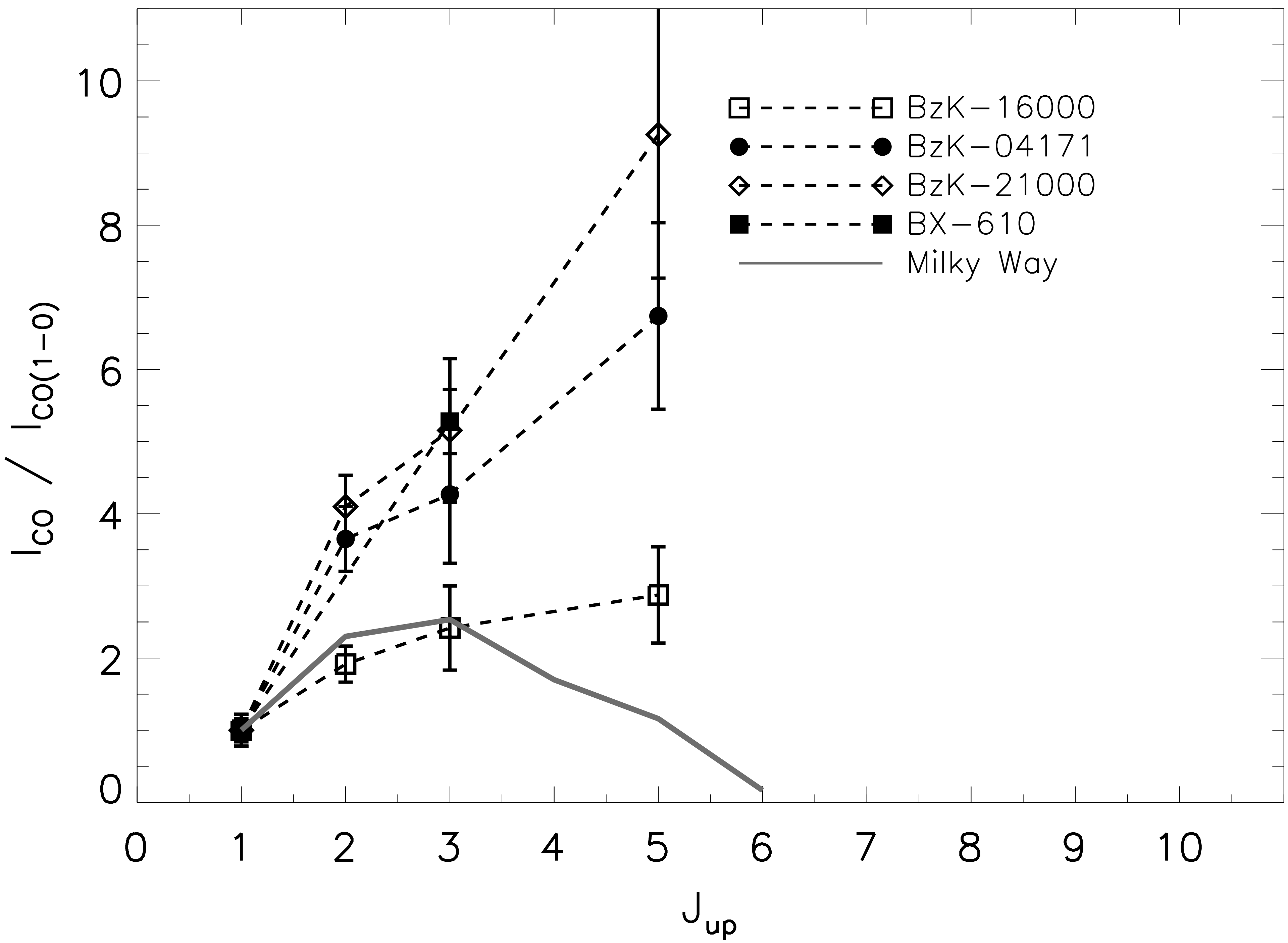


Nearby spiral NGC 628 [Blanc+13]

[Olsen+15: arXiv:1507.00012]

The CO SLED

In z ~ 1.5 normal star-forming galaxies



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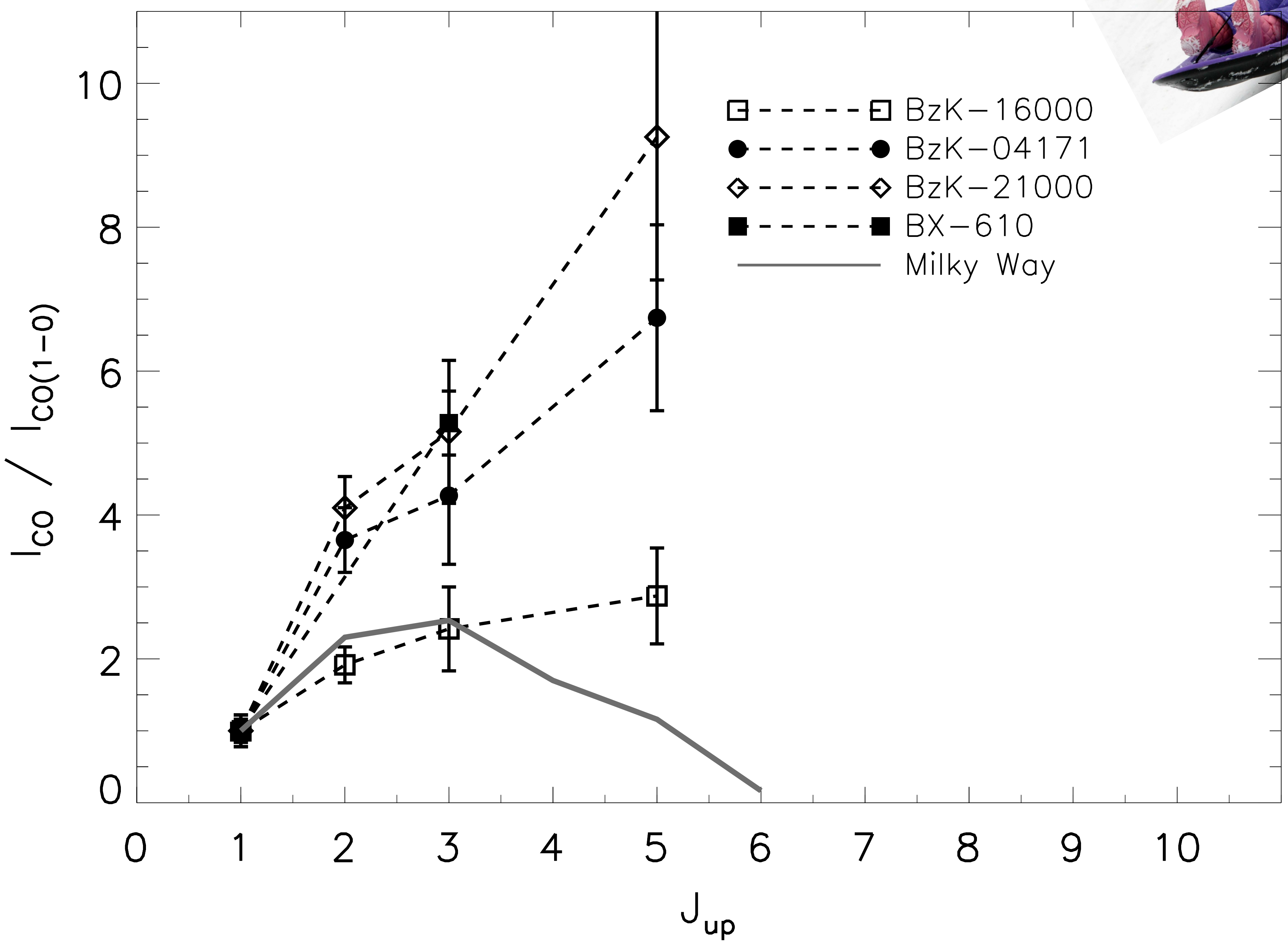

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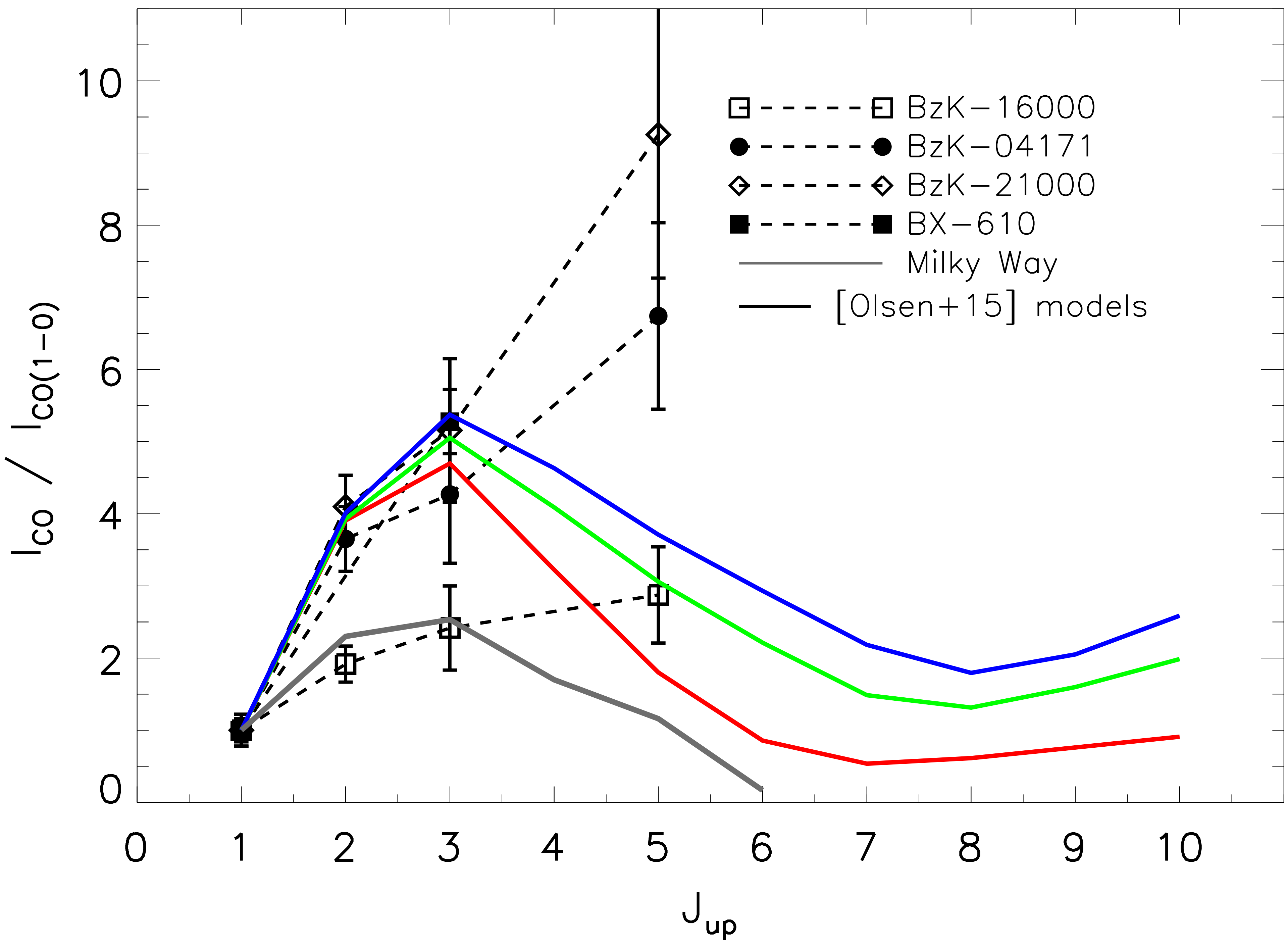

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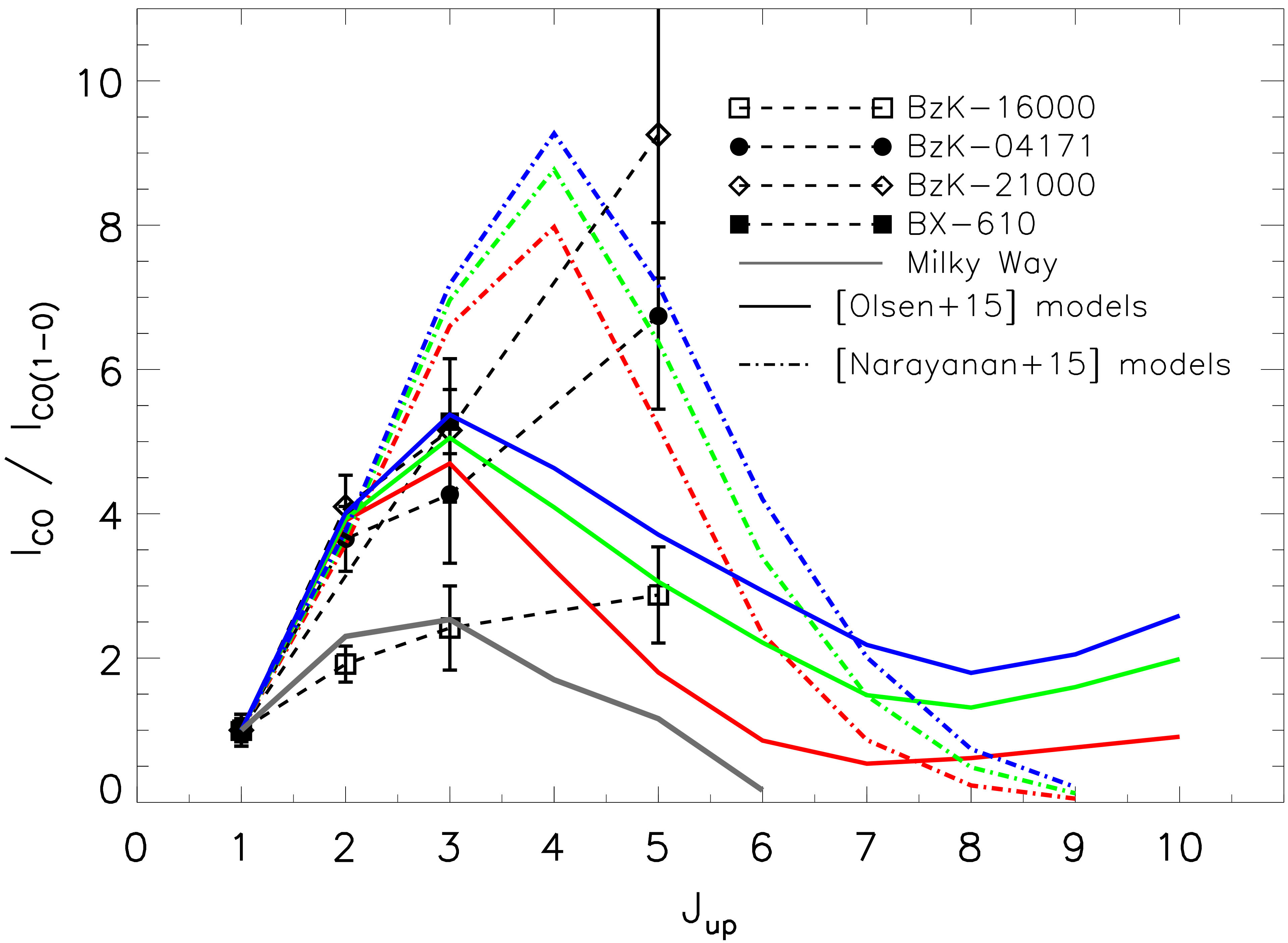
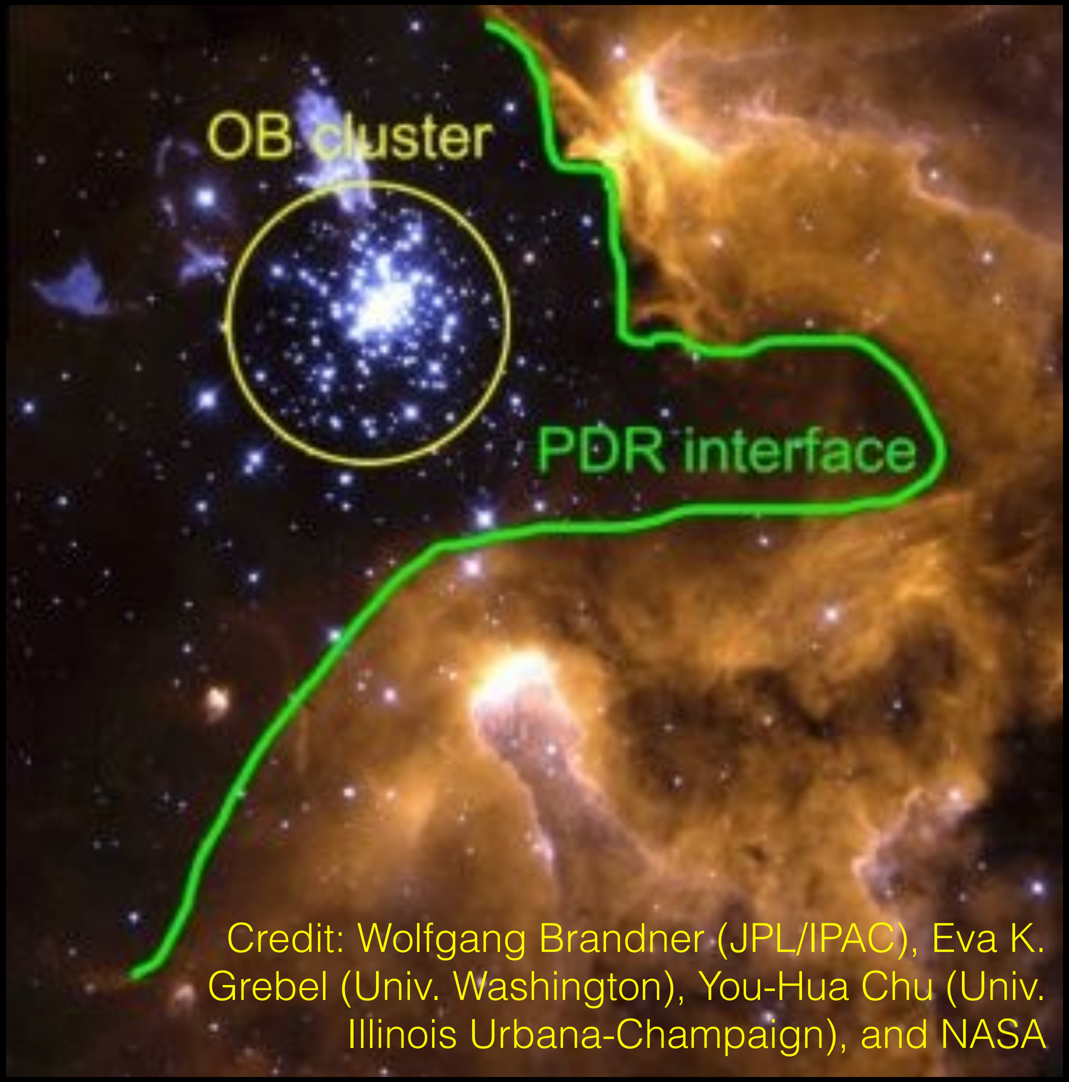


Dense gas component in z ~1.5 galaxies?
- more observations and modelling will tell

[Olsen+15: arXiv:1507.00012]

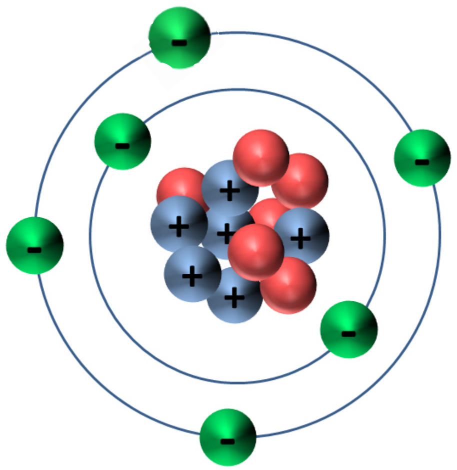
That's fine but….

What about regions where the radiation field is too high for CO to survive?

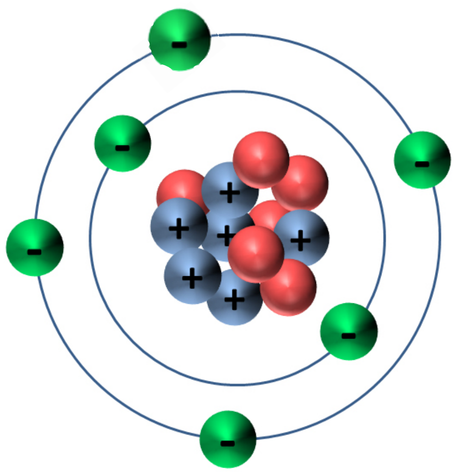


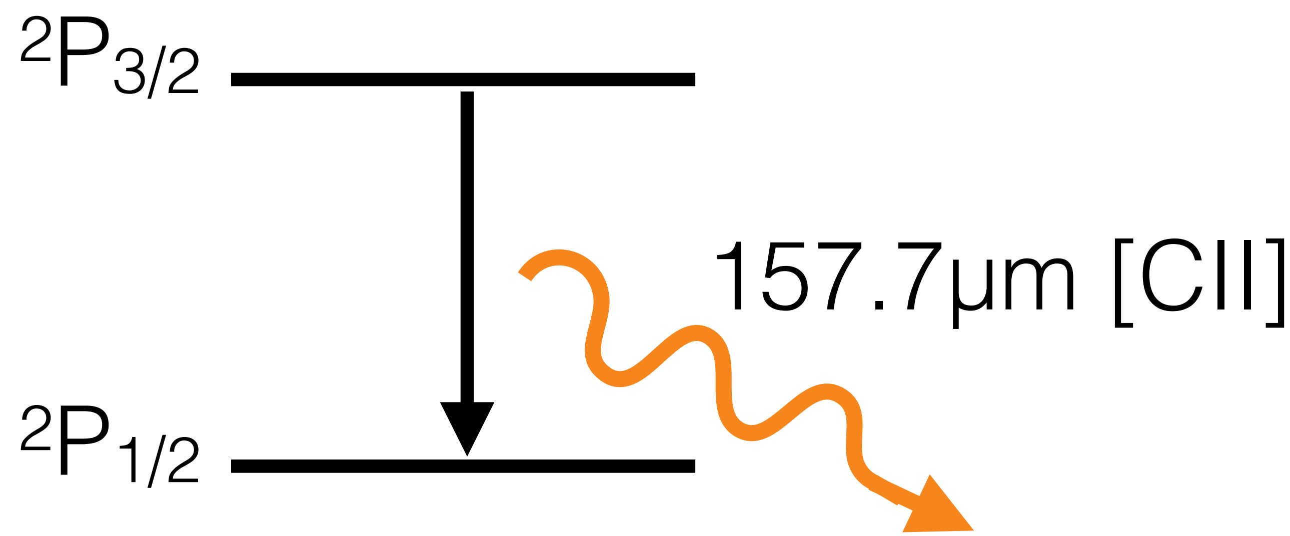
i.e. Photo-dissociation Regions (PDRs)

carbon



Singly ionized carbon

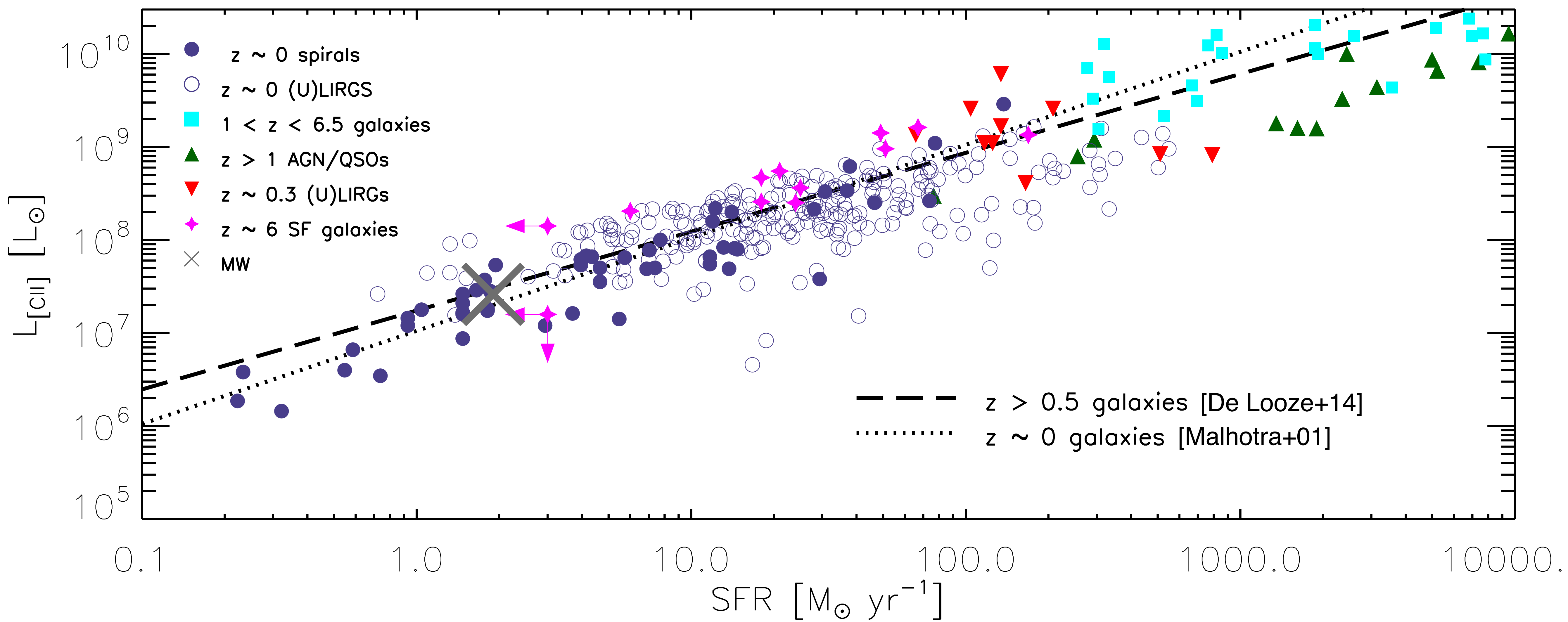




Excited by collisions with either electrons, atoms or molecules

⇒ can arise all over the ISM!

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



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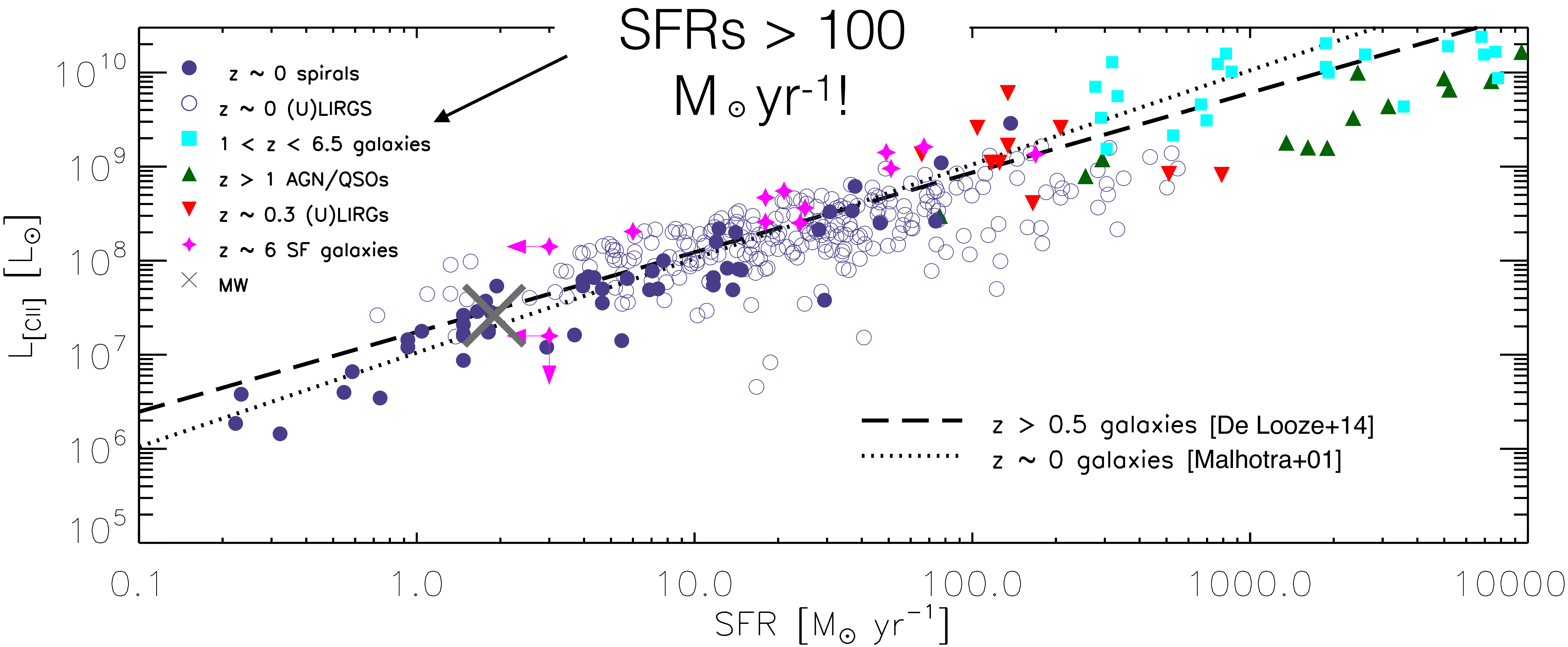
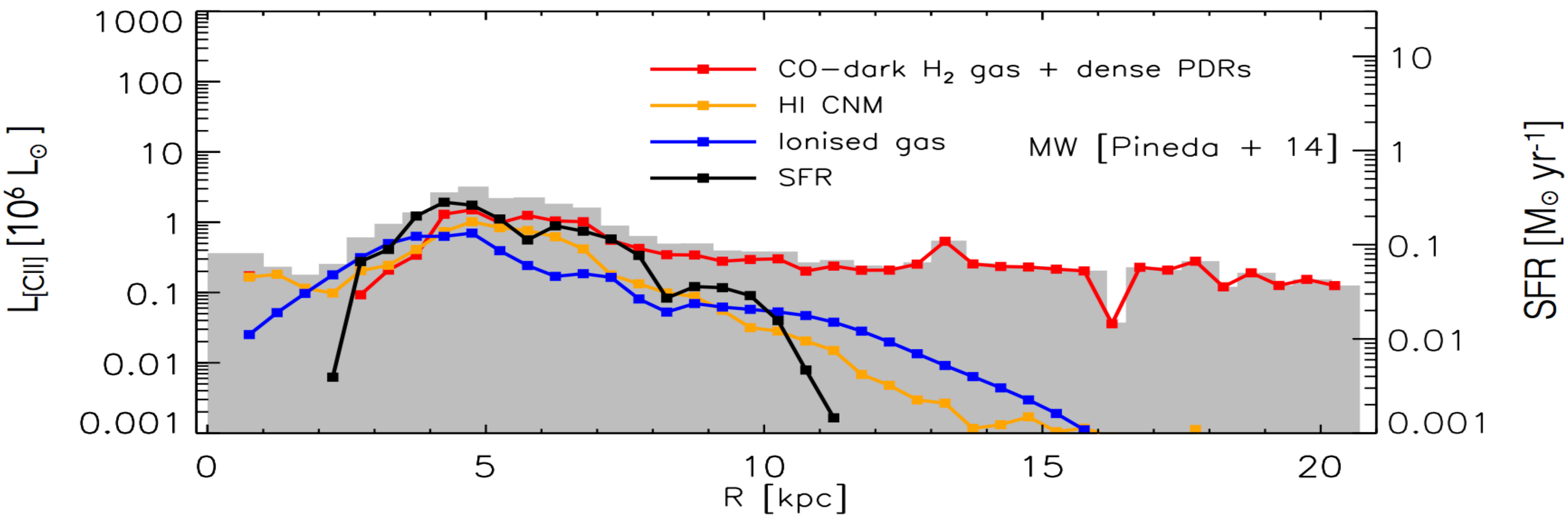


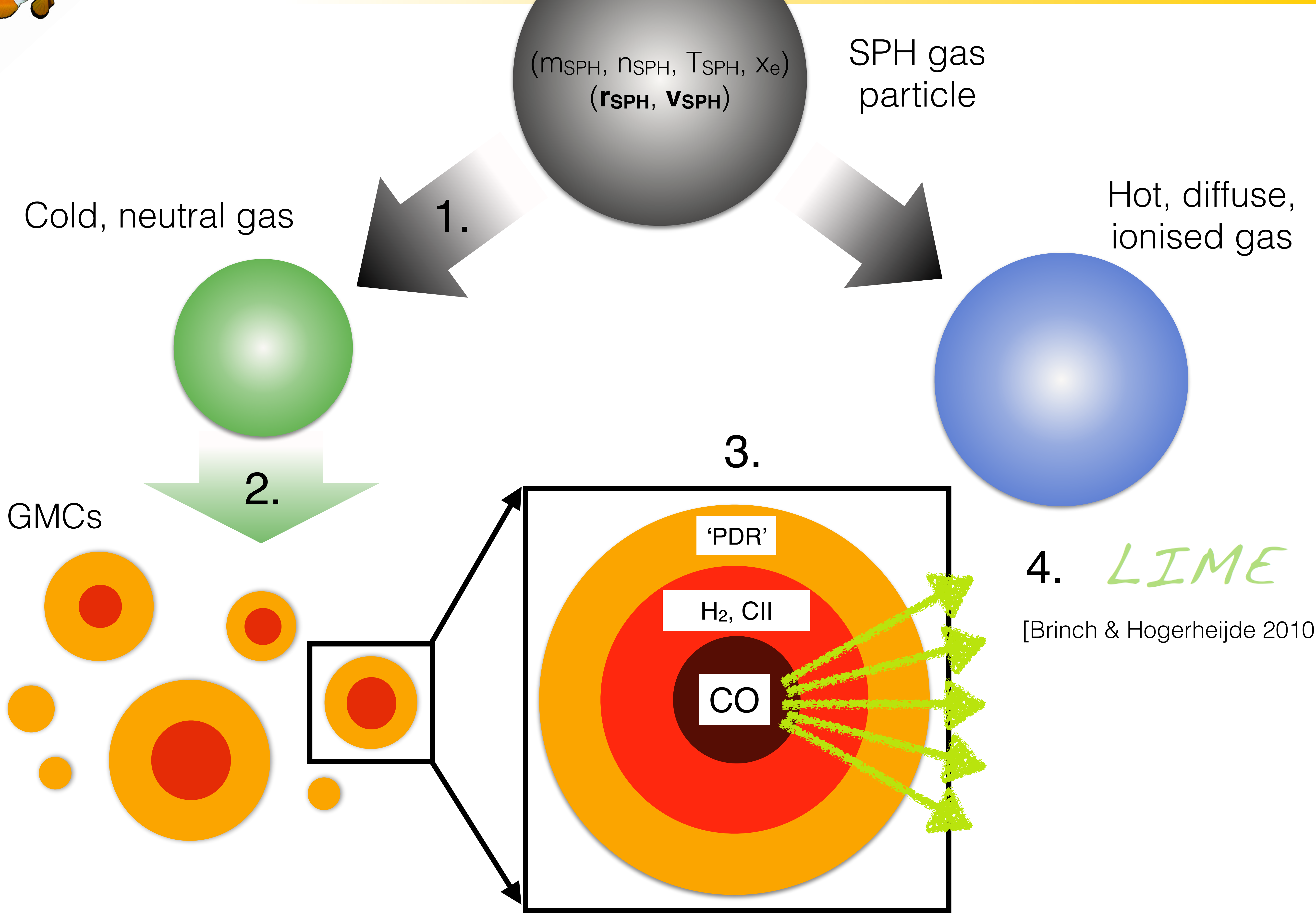
1. How does [CII]-SFR relation look for normal galaxies at high-z?

The origin of [CII] emission

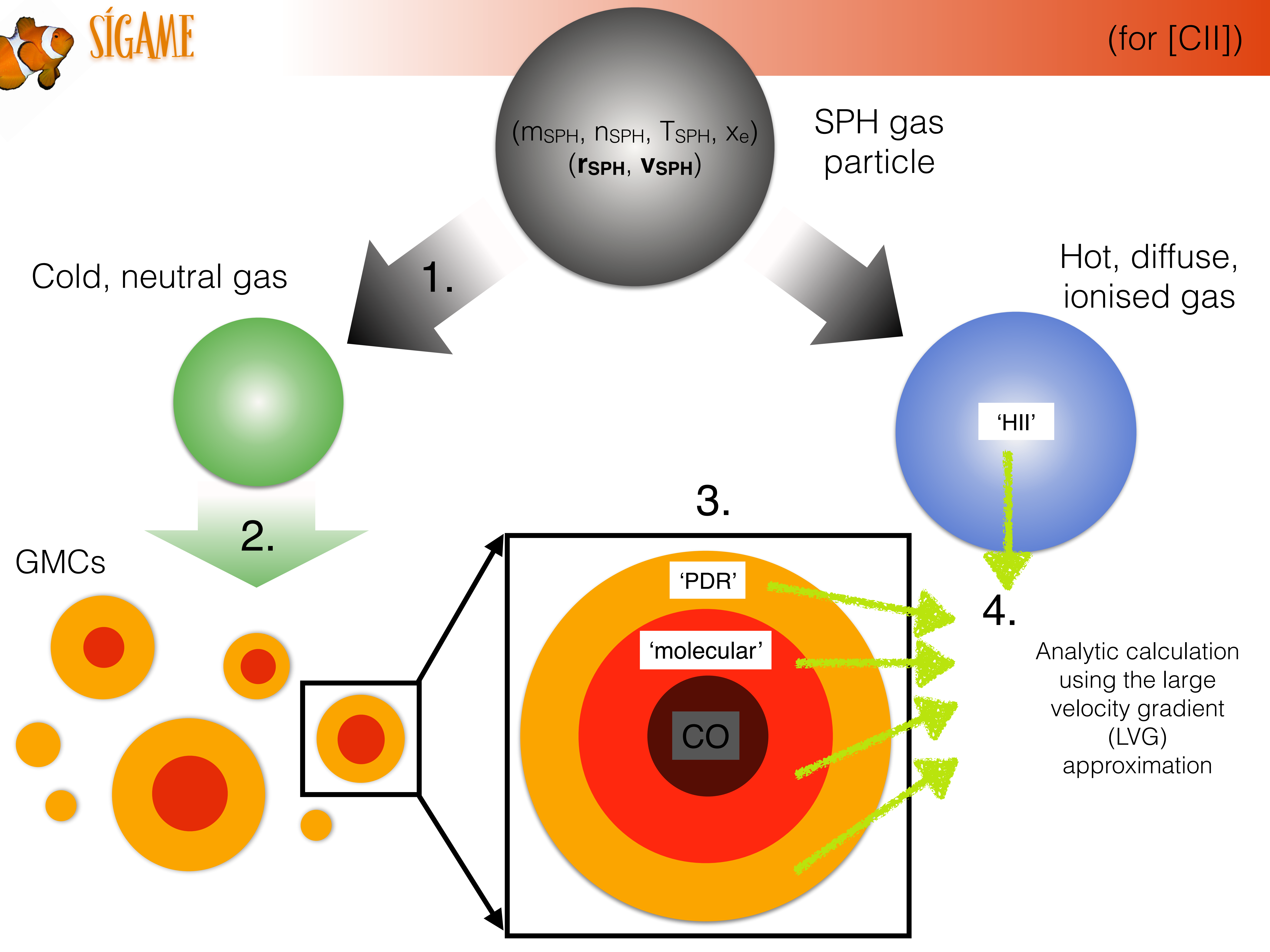


1. How does [CII]-SFR relation look for normal galaxies at high-z?
2. What is the origin of [CII] in the ISM?

(for CO)



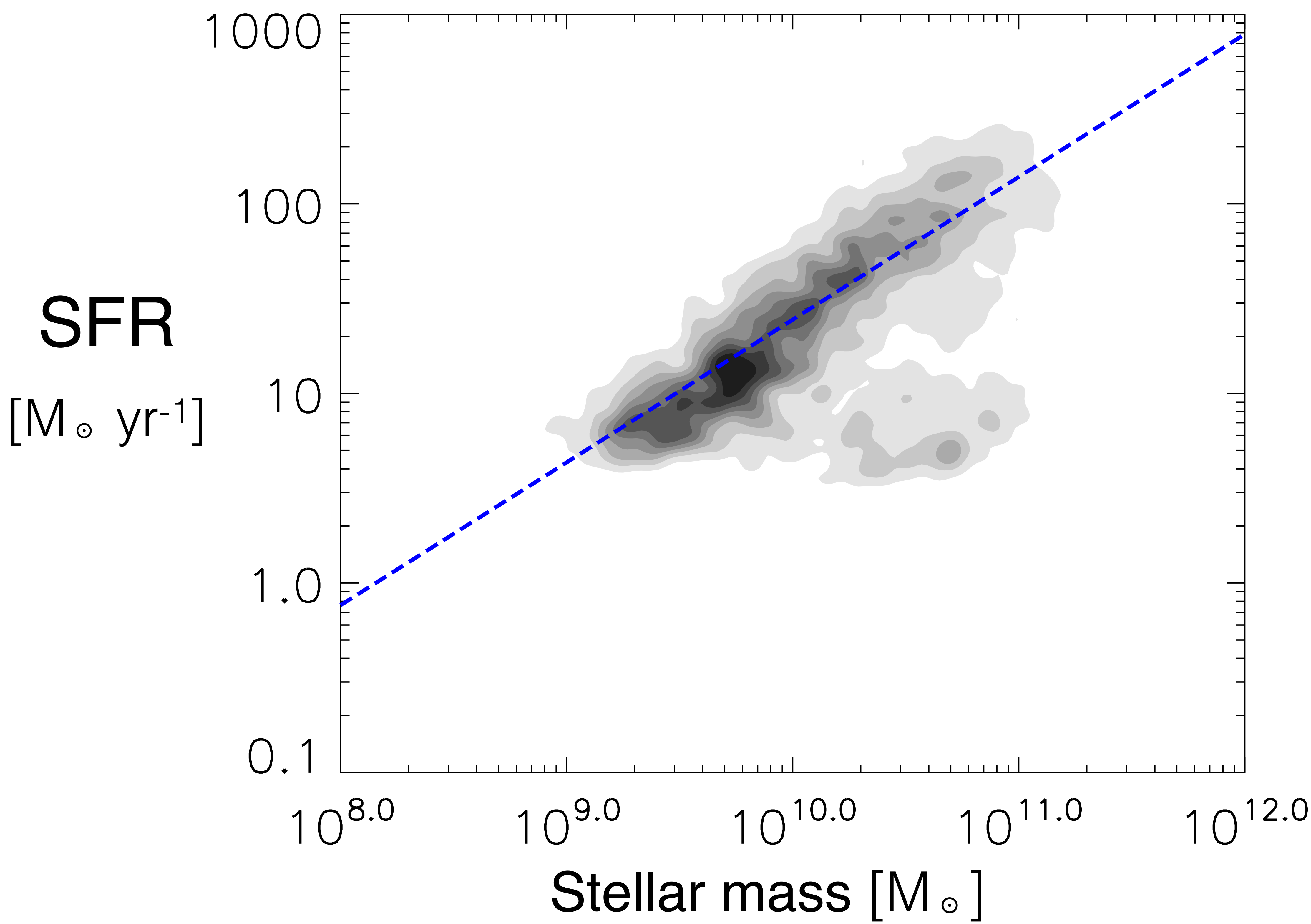
(mSPH, nSPH, TSPH, xe)
(rSPH, vSPH)
SPH gas particle
1.
Cold, neutral gas
Hot, diffuse, ionised gas
2.
GMCs
3.
'PDR'
H2, CII
CO
4. LIME
[Brinch & Hogerheijde 2010]



SÍGAME
(for [CII])
(m_{SPH}, n_{SPH}, T_{SPH}, x_e)
($\mathbf{r}_{SPH}$, $\mathbf{v}_{SPH}$)
SPH gas particle
1.
Cold, neutral gas
Hot, diffuse, ionised gas
'HII'
2.
GMCs
3.
'PDR'
'molecular'
CO
4.
Analytic calculation using the large velocity gradient (LVG) approximation

7 z~2 star-forming galaxies

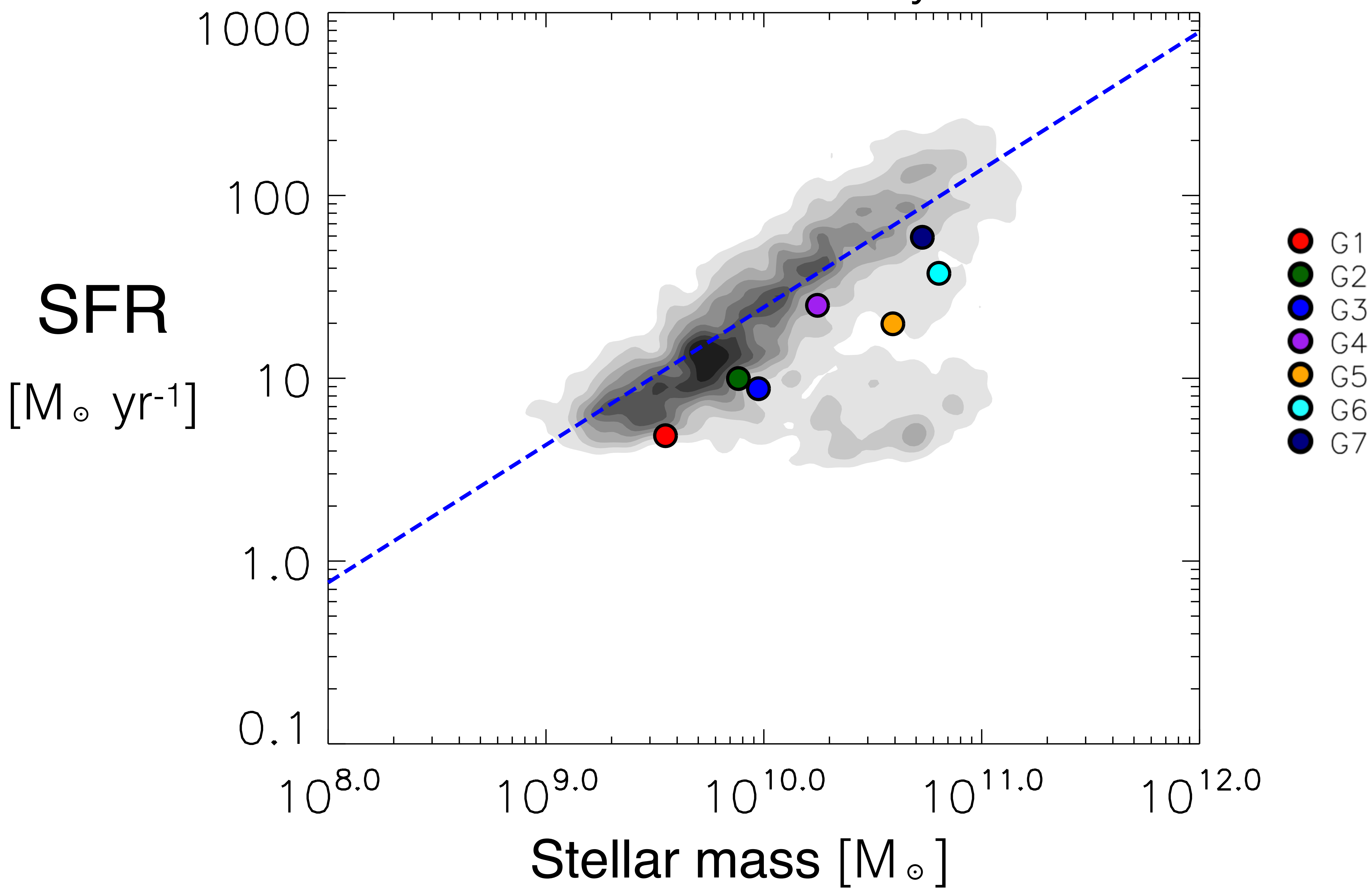
Cosmological simulations (Gadget-3) at z=2 by [Thompson+14]



7 z~2 star-forming galaxies

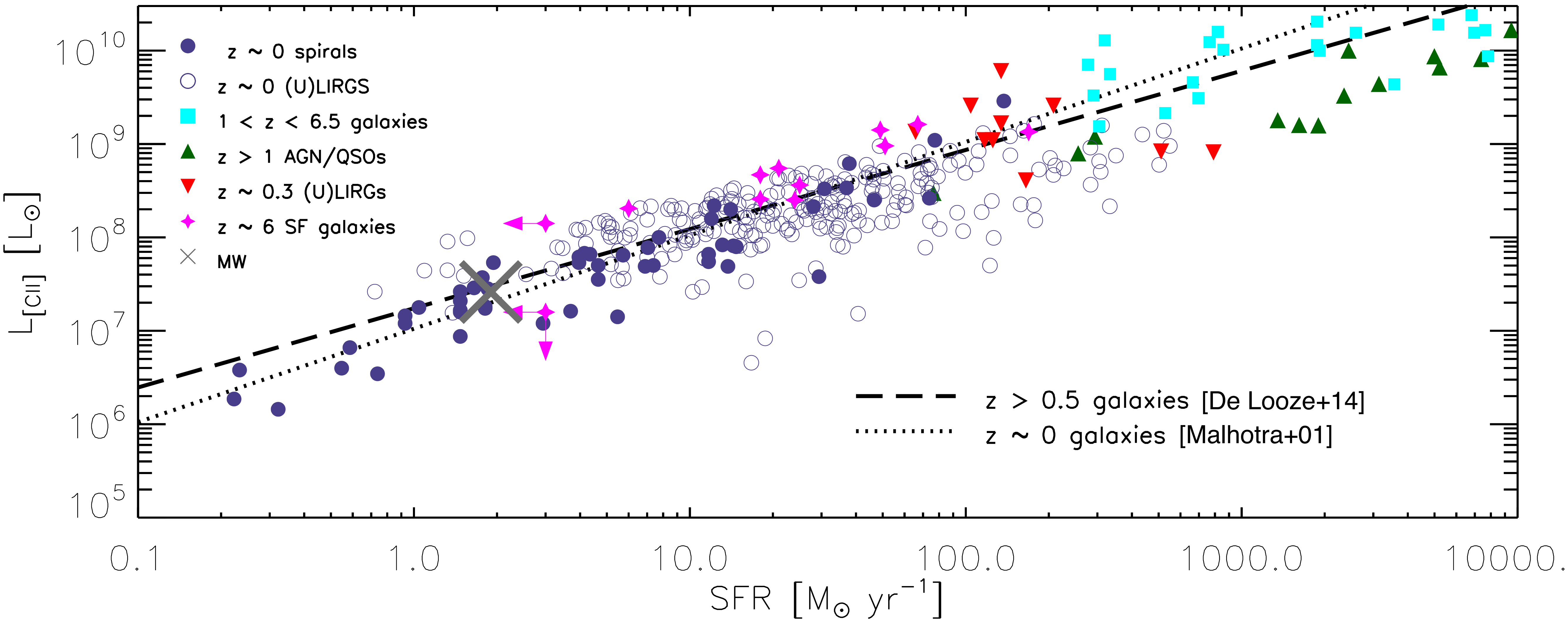
Cosmological simulations (Gadget-3) at z=2 by [Thompson+14]

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



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

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



[Olsen+15: arXiv:1507.00362]

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

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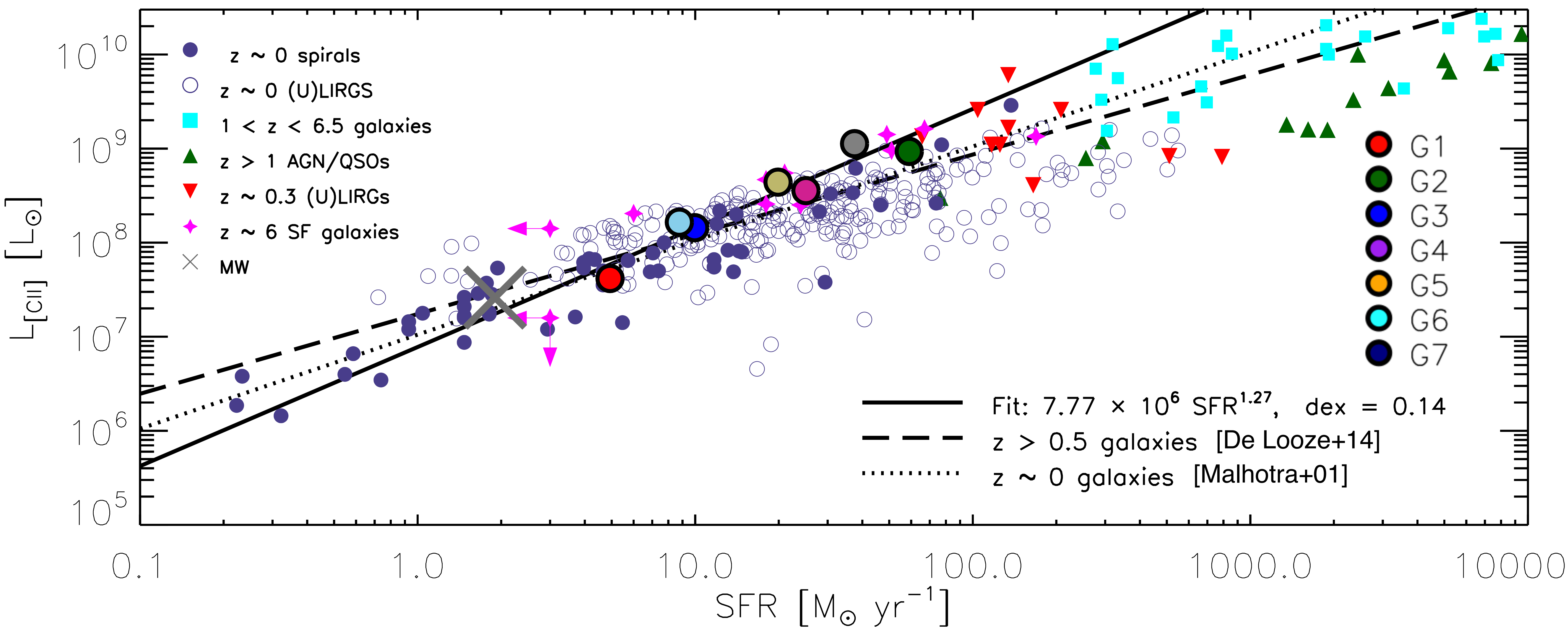

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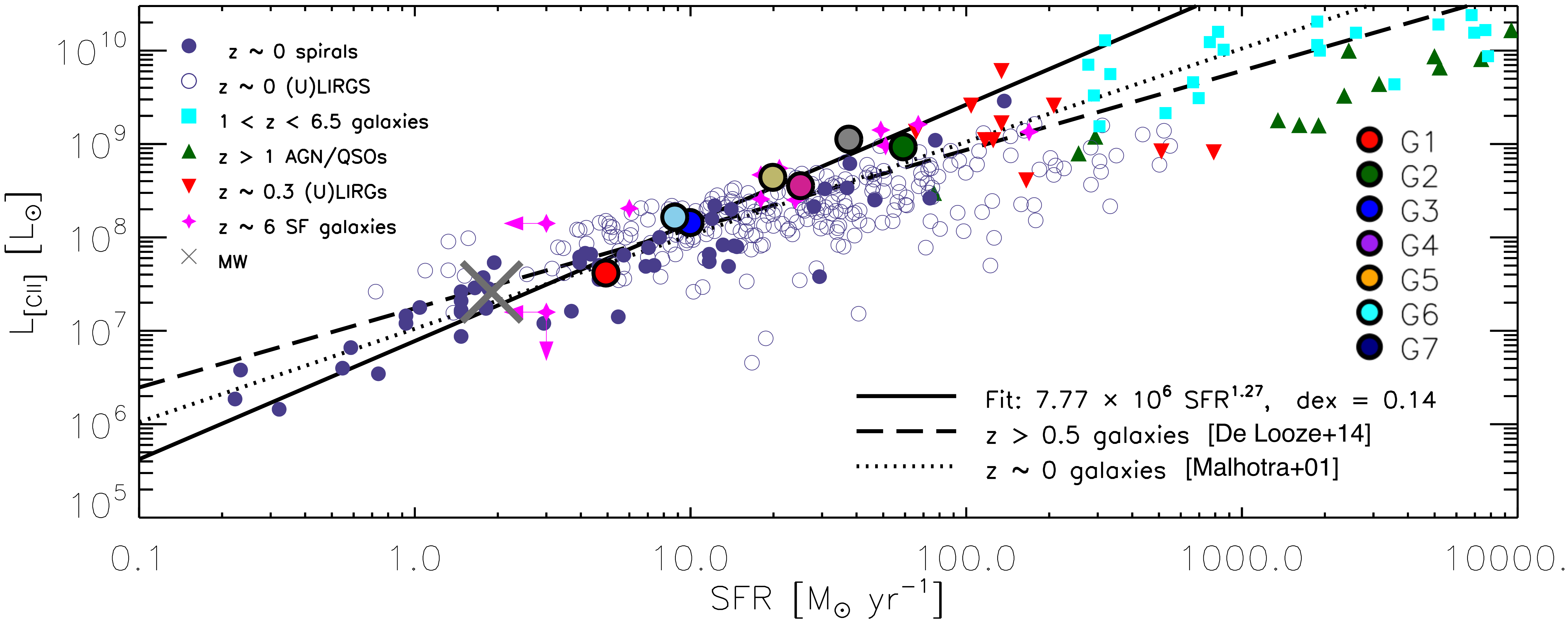
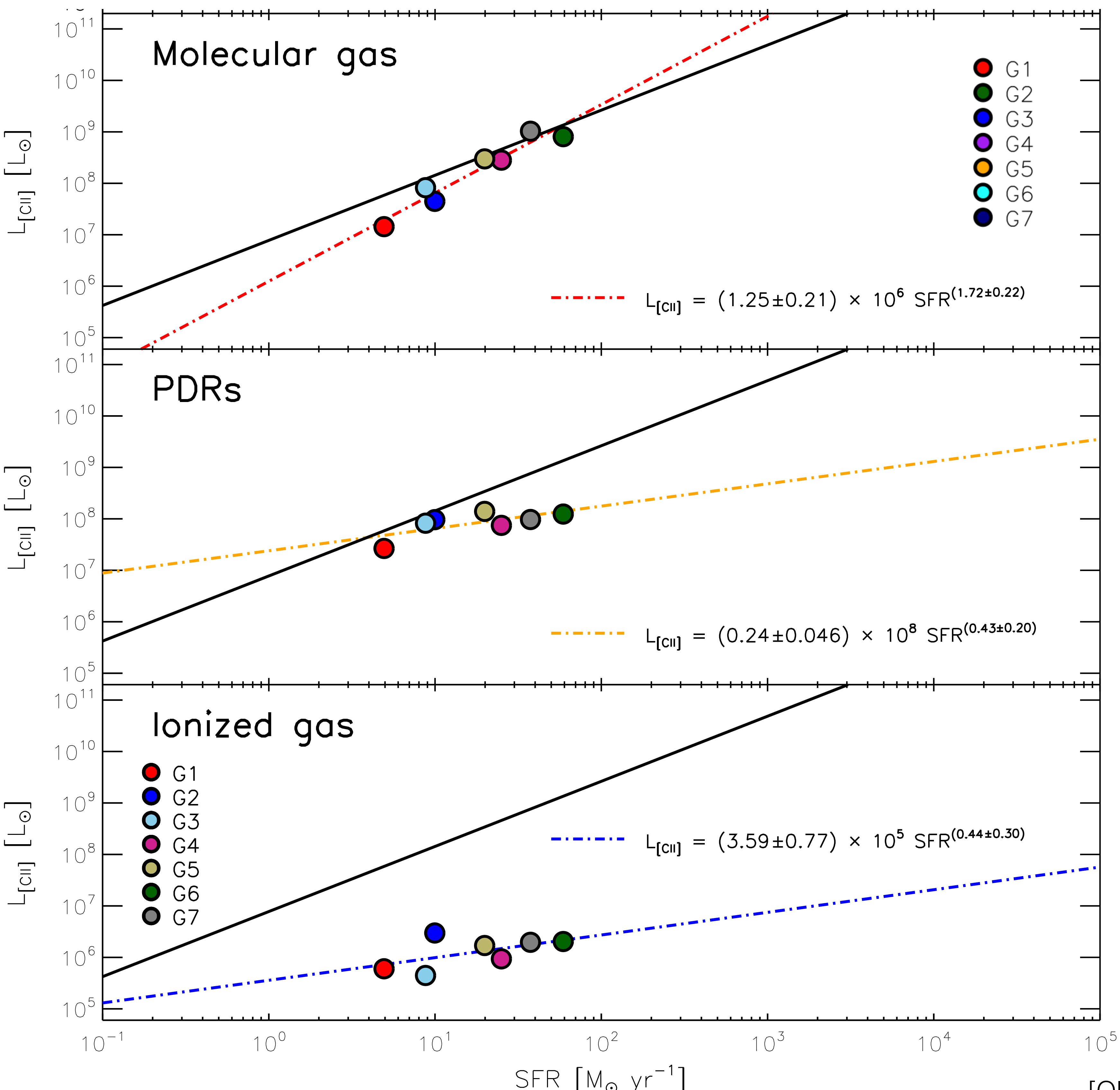


- Slope: 1.27±0.17 significantly (σ>1) steeper than that of z~0 galaxy samples (spirals and (U)LIRGs)
- Crossing local galaxies at about 10 $M_\odot\ yr^{-1}$

[Olsen+15: arXiv:1507.00362]

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

From different ISM phases:



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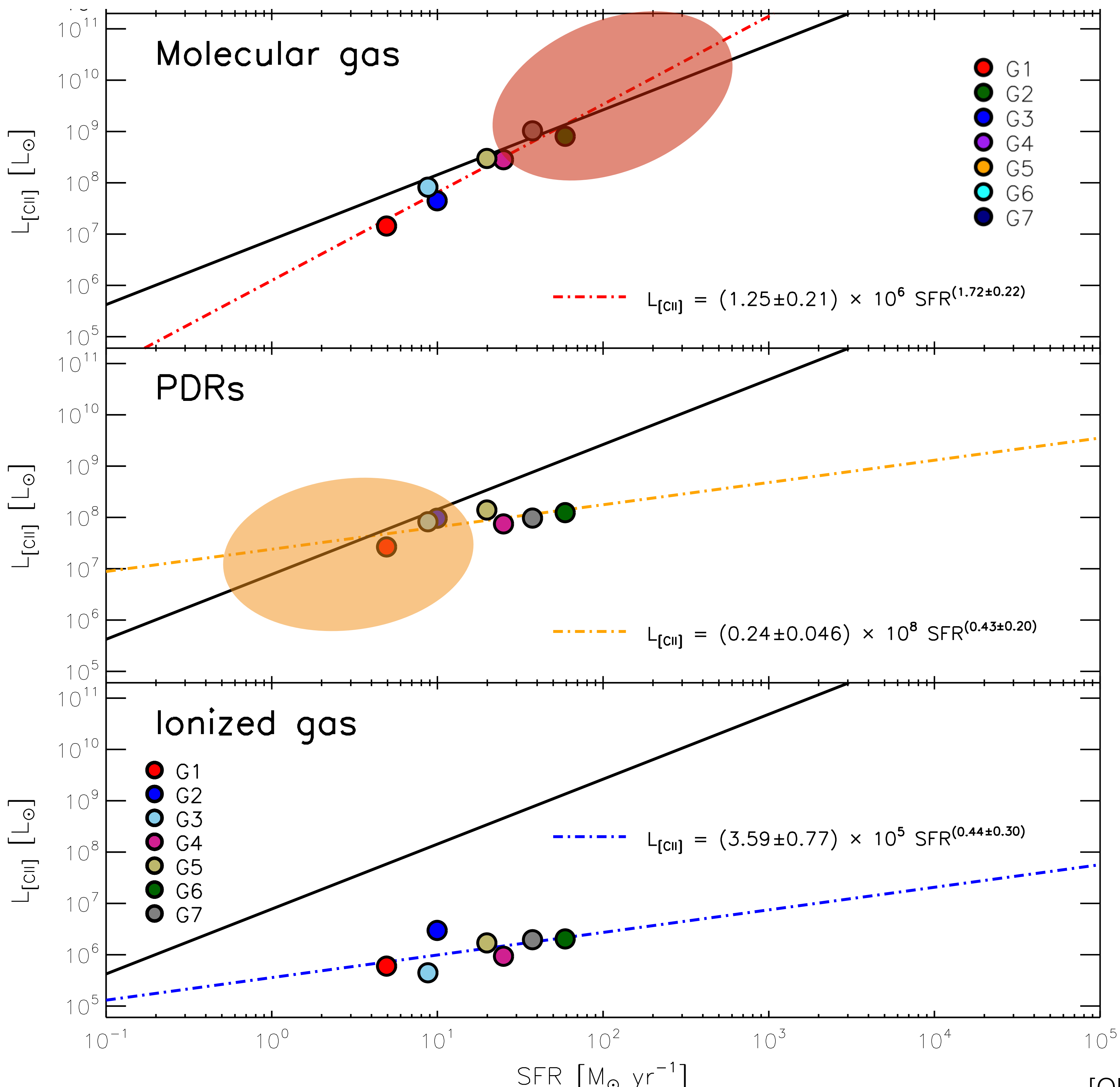
From different ISM phases:



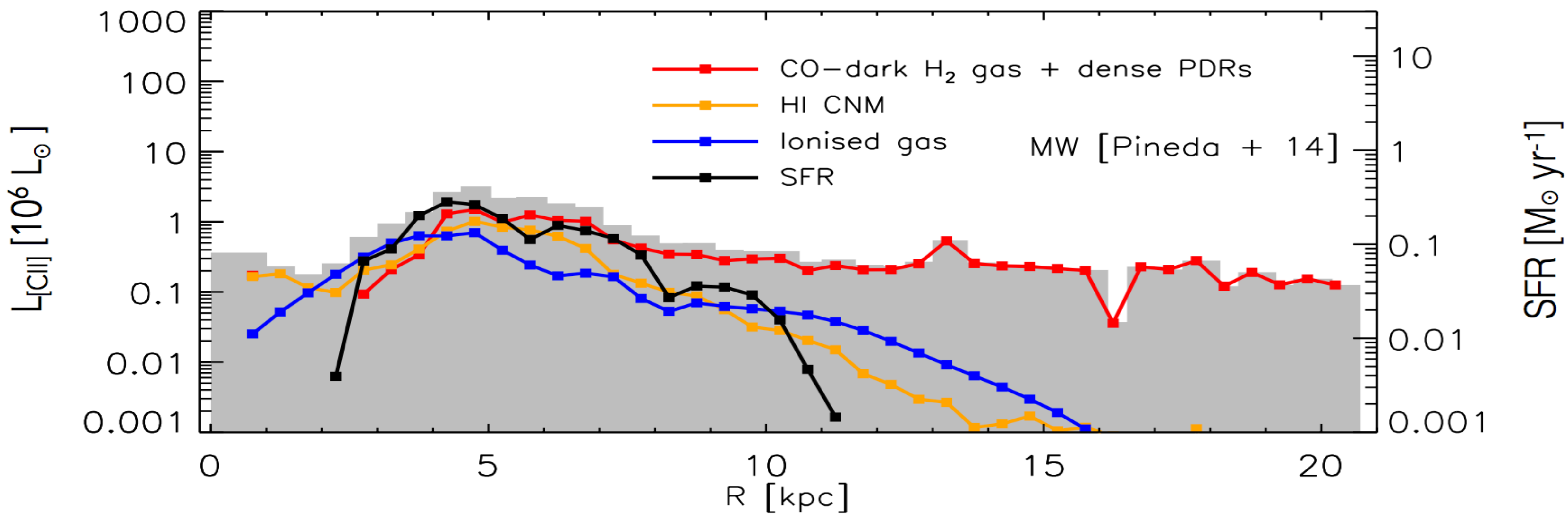
High SFR:
molecular gas
dominates [CII]
luminosity

Low SFR:
PDRs dominate [CII]
luminosity

[Olsen+15: arXiv:1507.00362]

The origin of [CII] emission

The origin of [CII] emission



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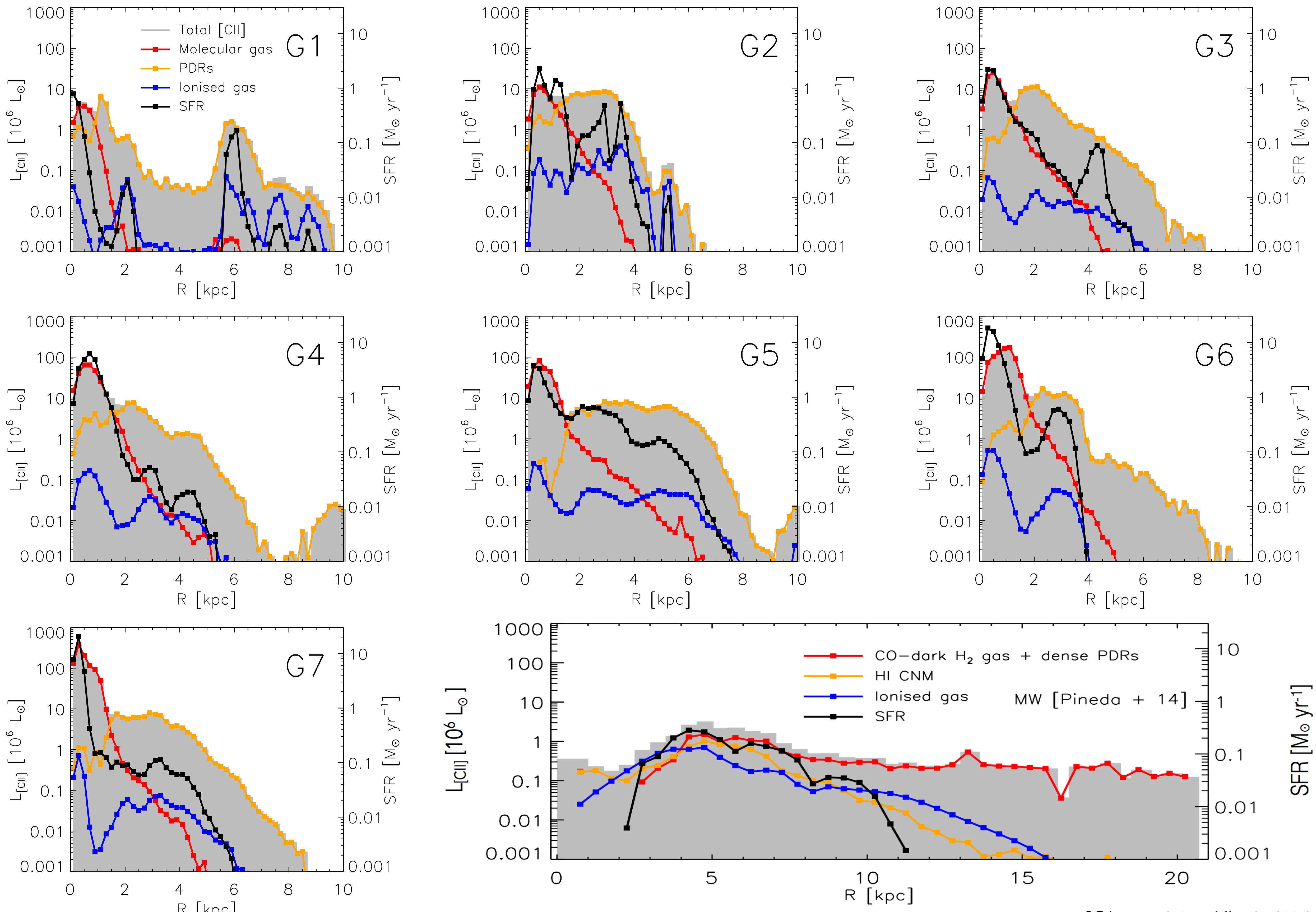

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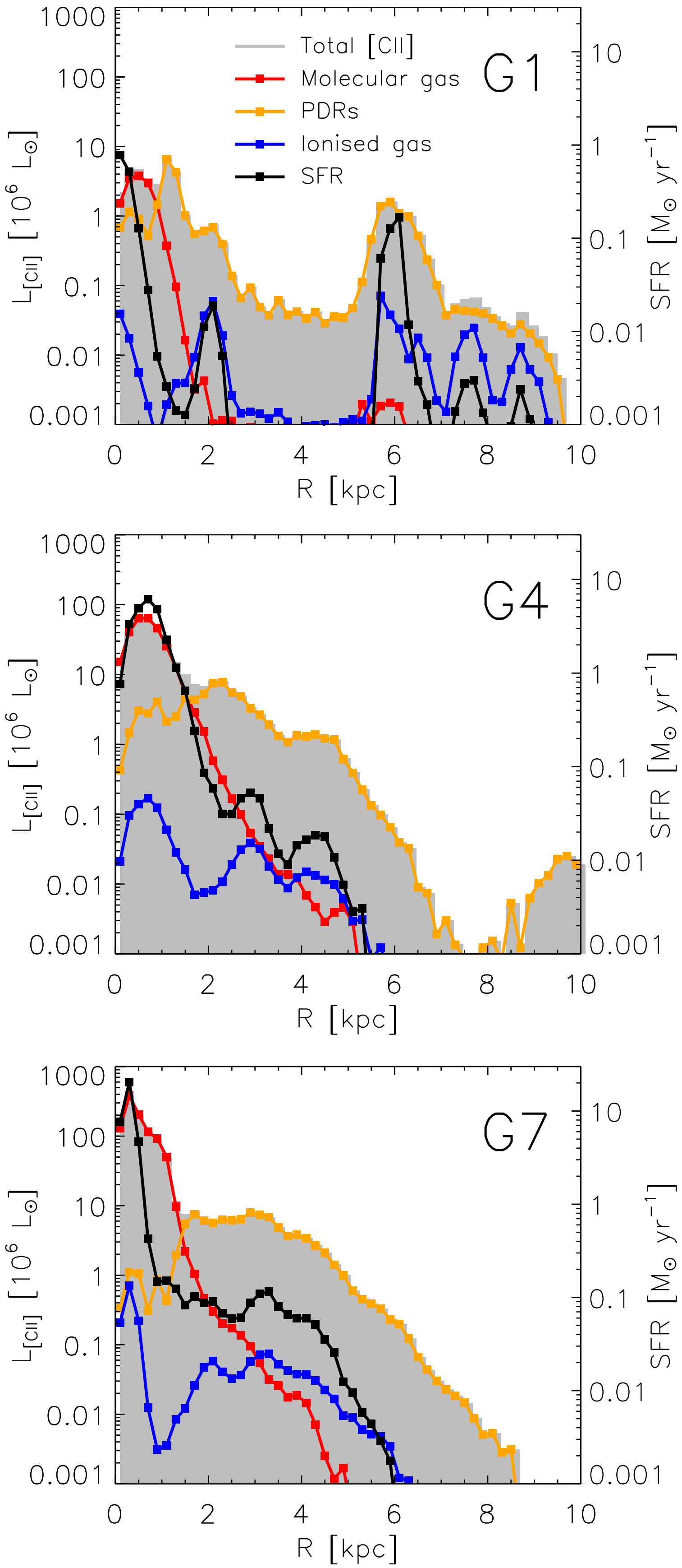
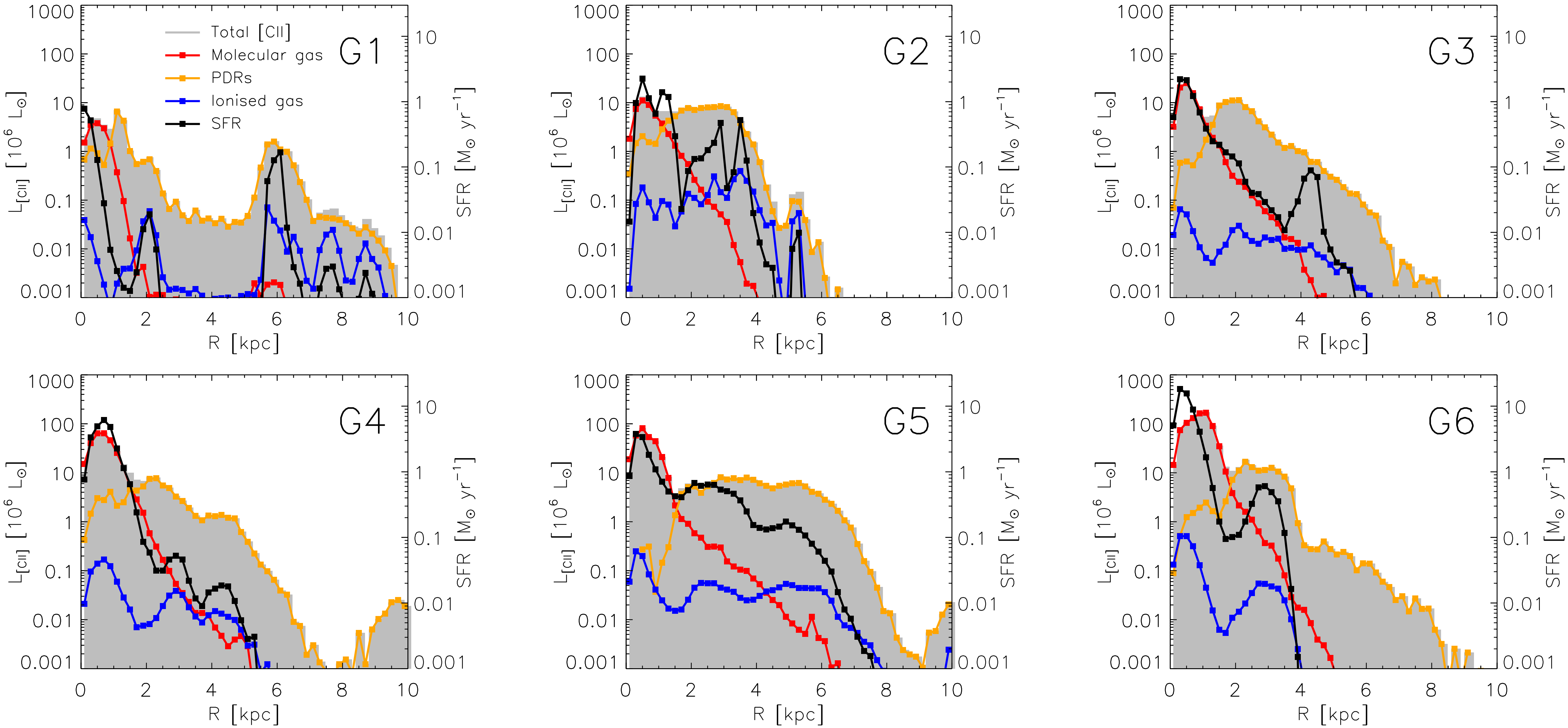


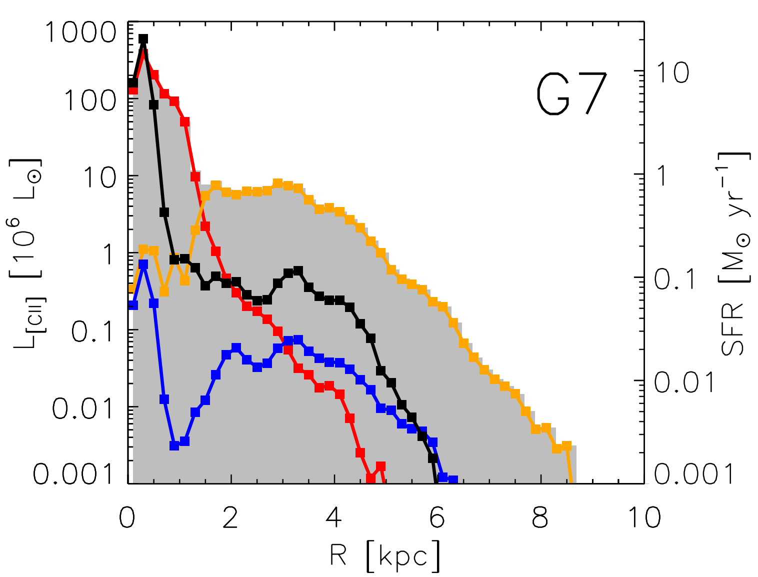
- [CII] from molecular gas dominates at low radii, PDRs at higher radii

[Olsen+15: arXiv:1507.00362]

SÍGAME

The origin of [CII] emission



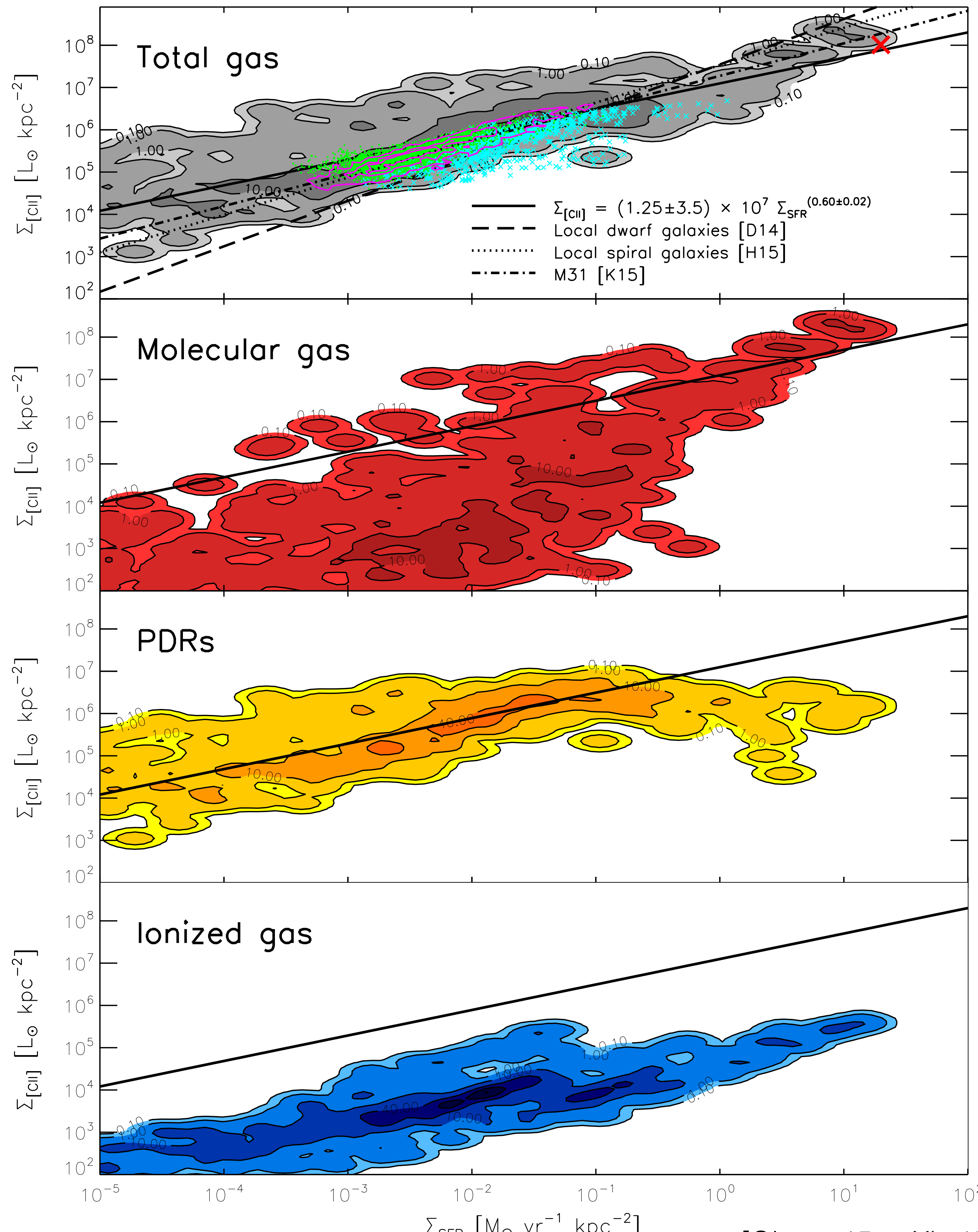


- [CII] from molecular gas dominates at low radii, PDRs at higher radii
- Total [CII] (grey) does not always follow SFR profile

[Olsen+15: arXiv:1507.00362]

The origin of [CII] emission

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



[Olsen+15: arXiv:1507.00362]

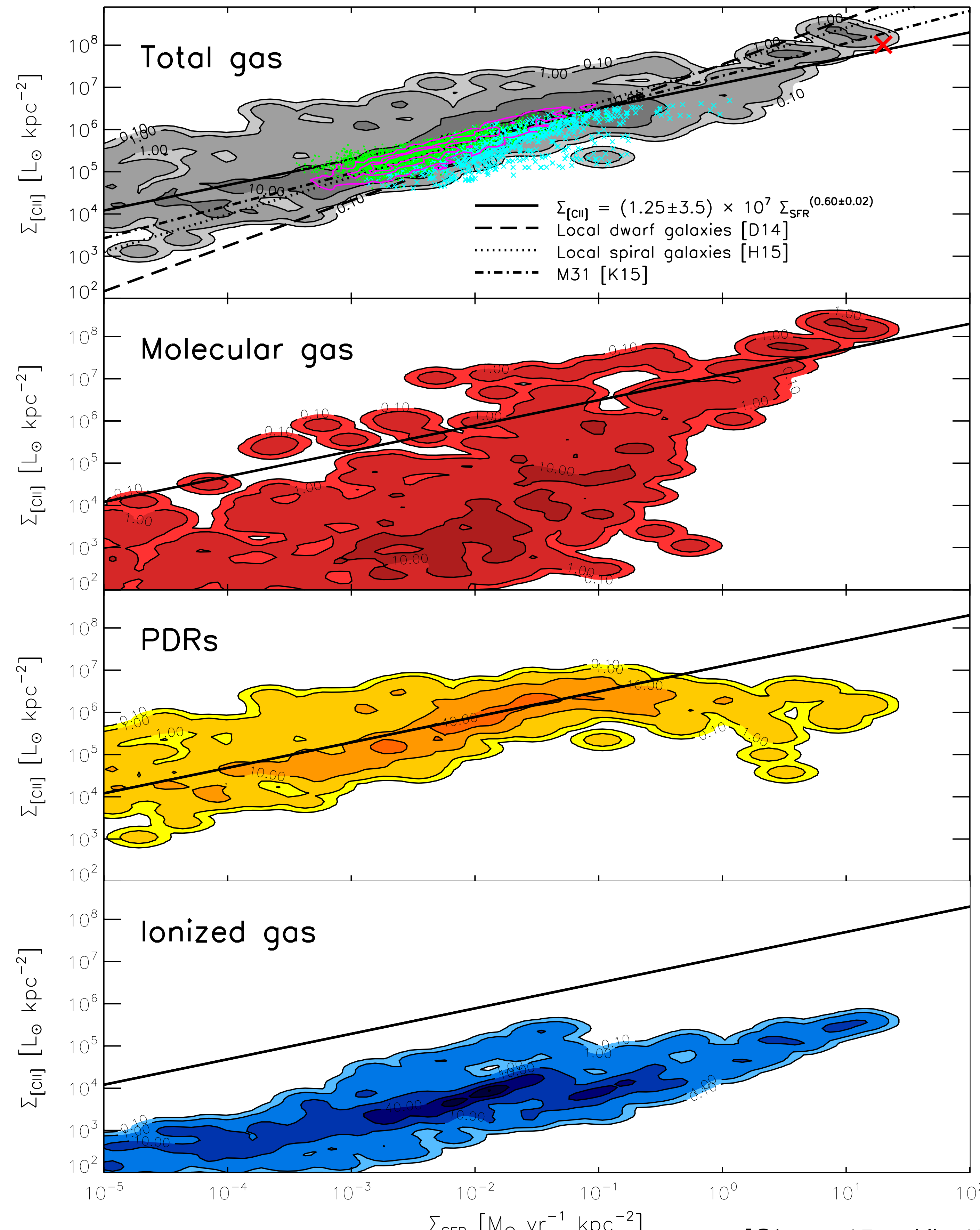
The origin of [CII] emission

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

- Agreement with observations

  De Looze+14
  Herrera-Camus+15
  Kapala+15

- Again: Molecular gas only dominating at high Σ_{SFR}



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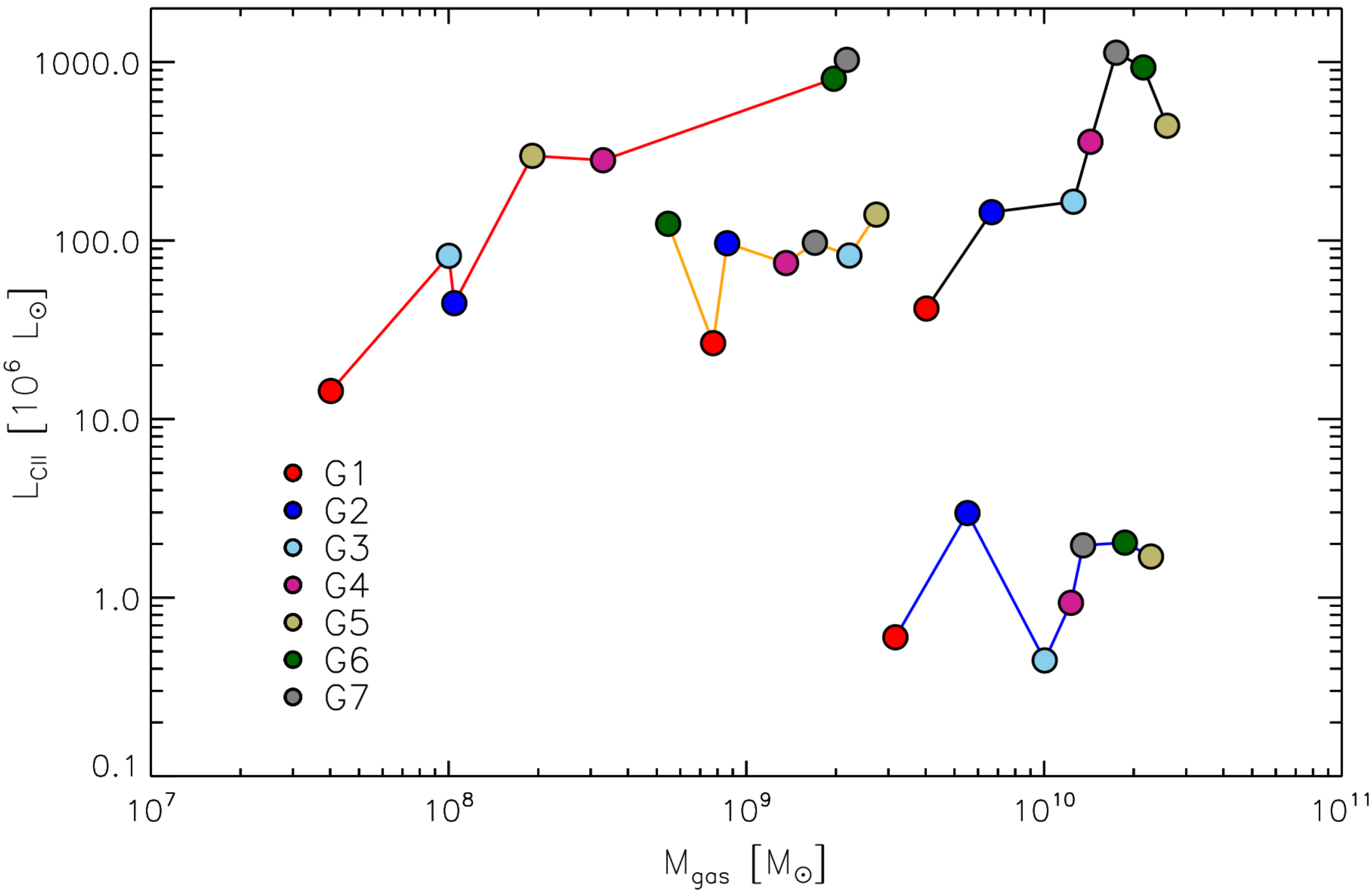
SÍGAME

'[CII] efficiency'



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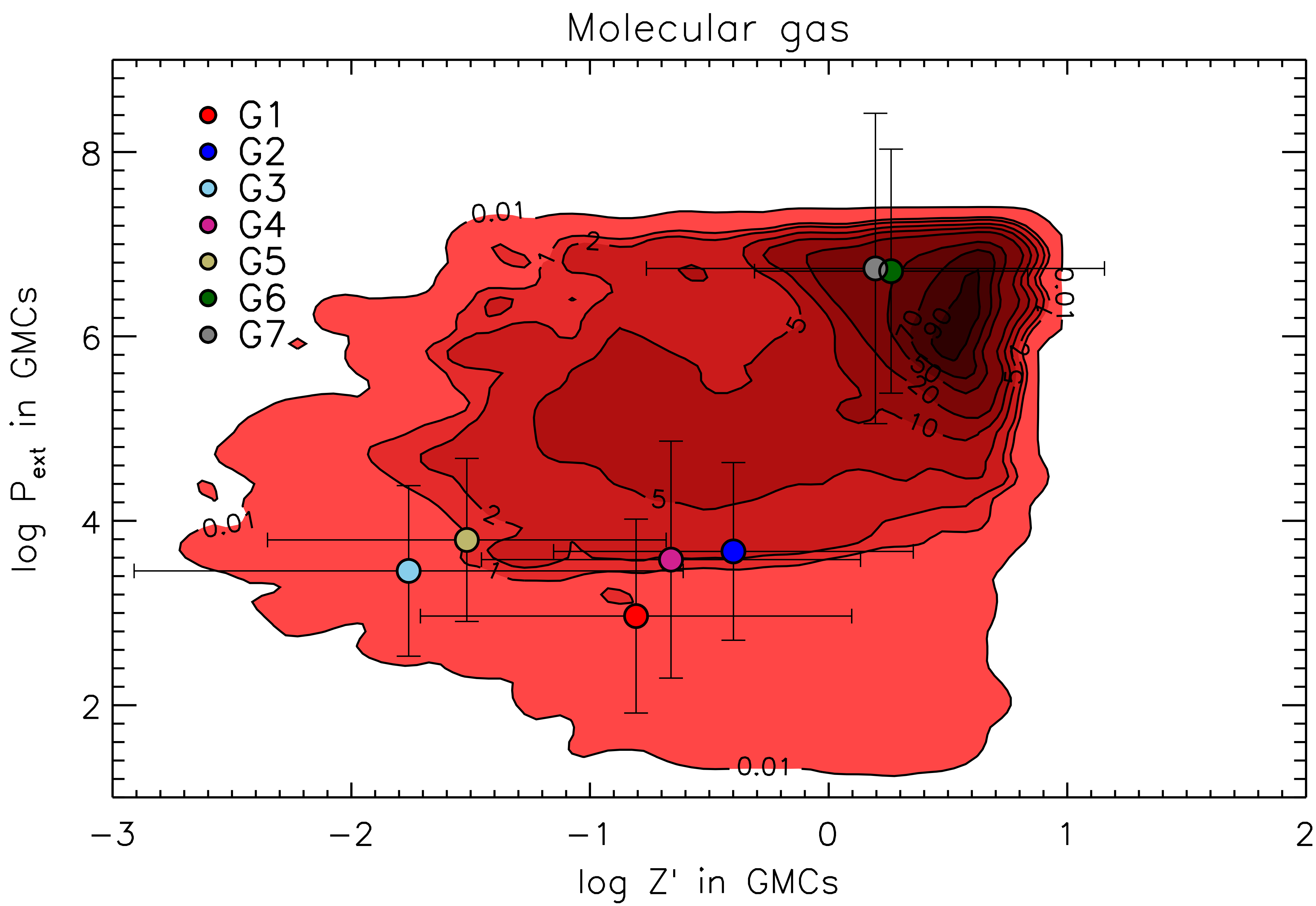

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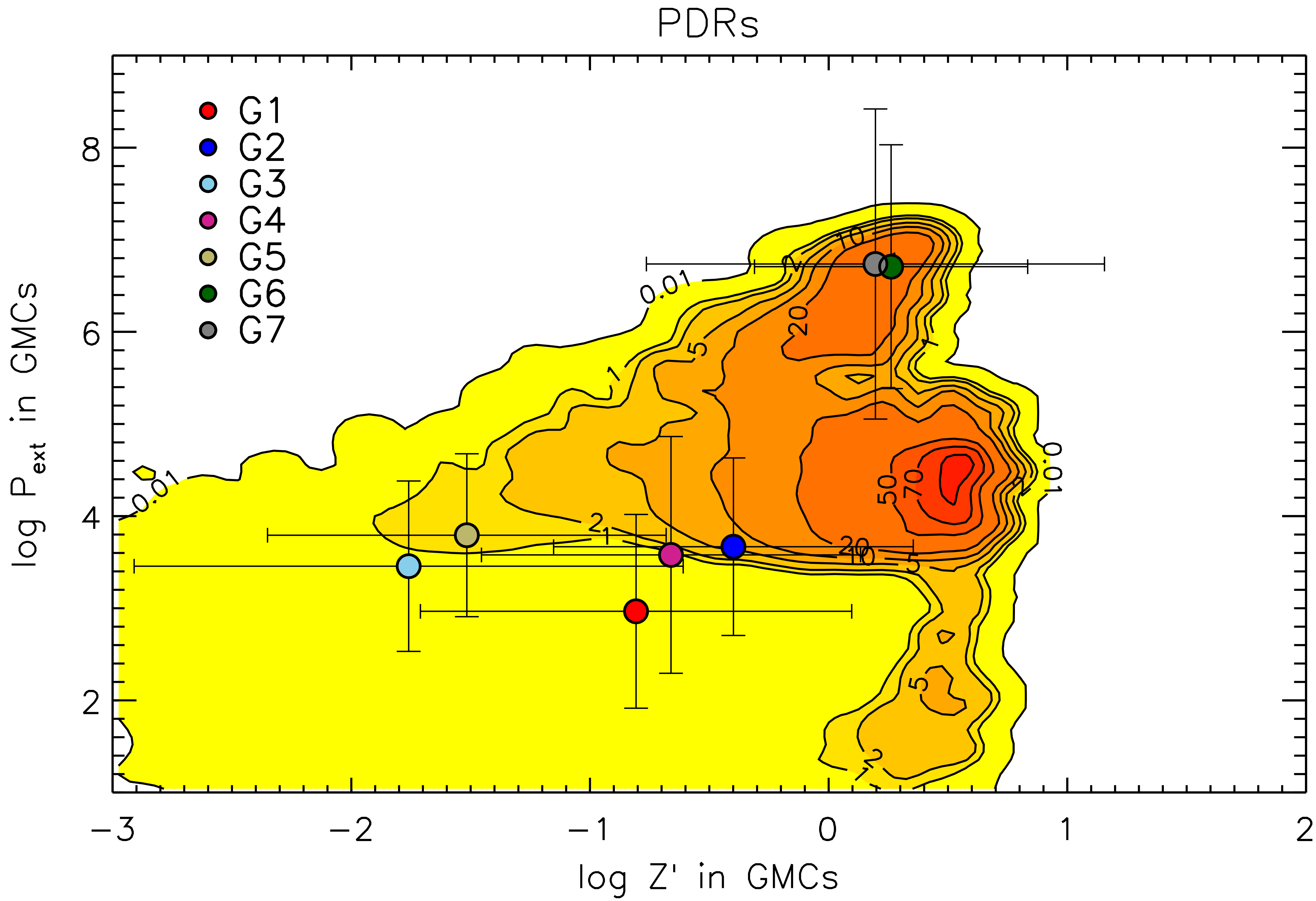

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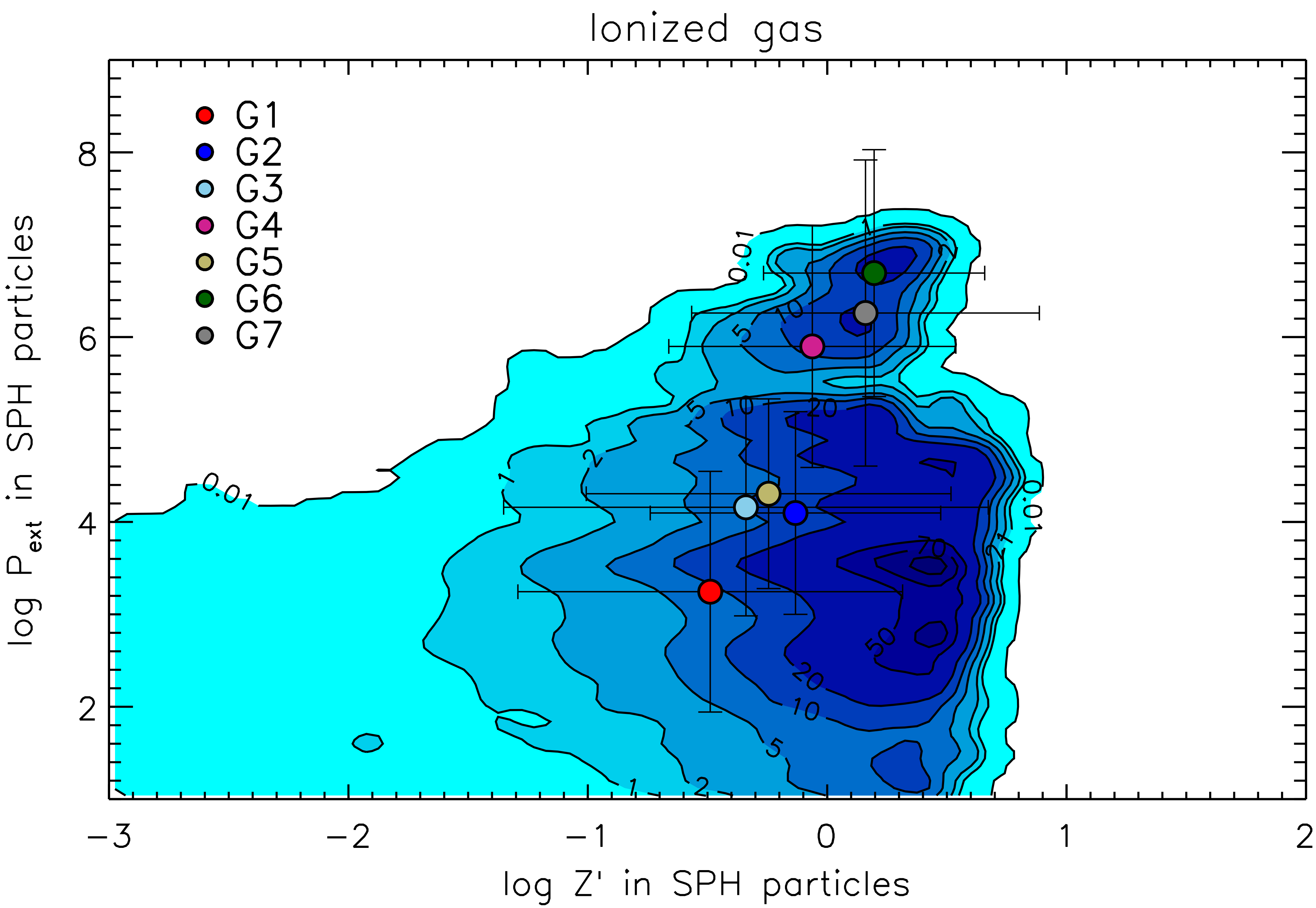

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Summary

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:

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

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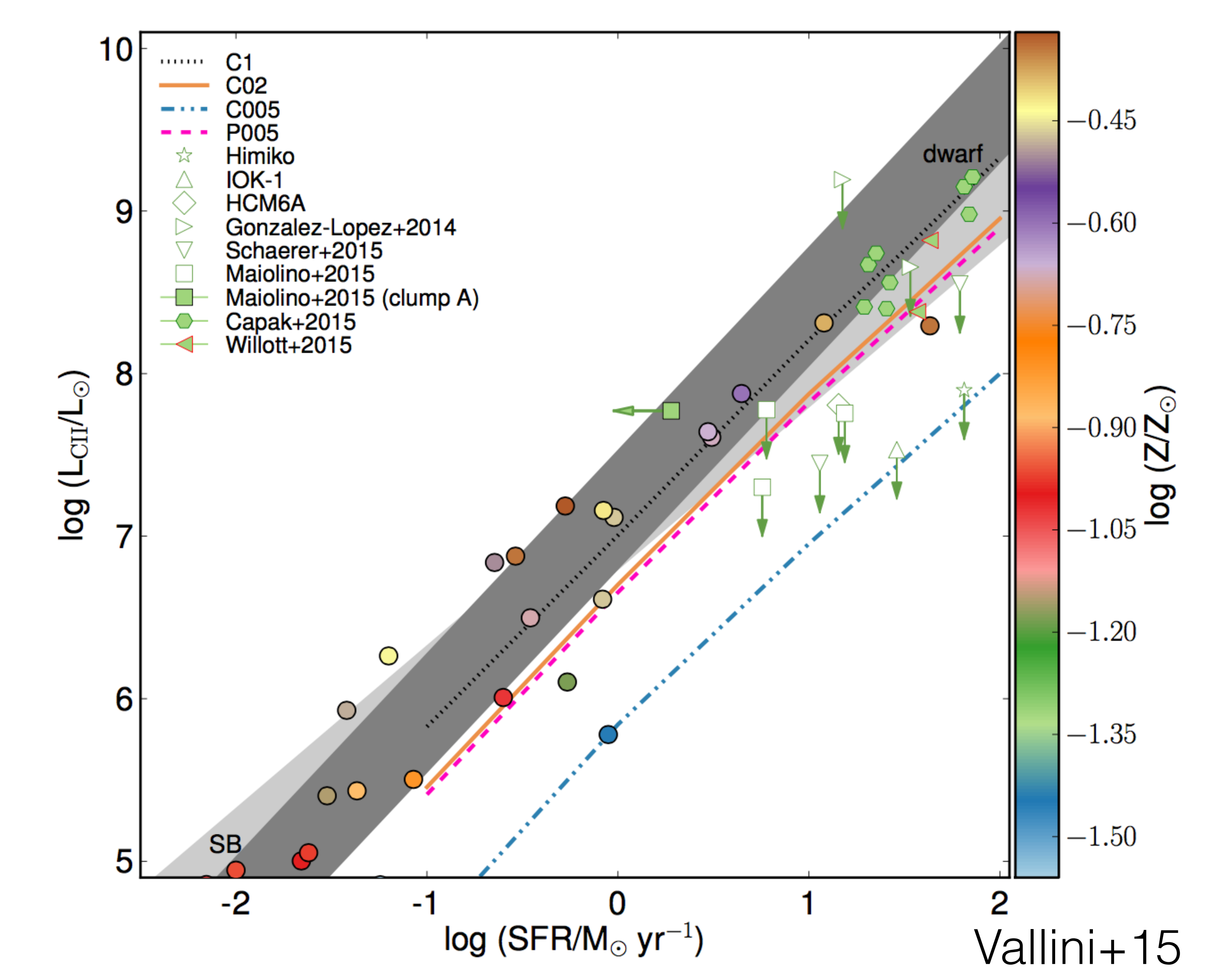
Outlook

SÍGAME - focusing on [CII] at higher redshift!

1. Make predictions for z~6 galaxies



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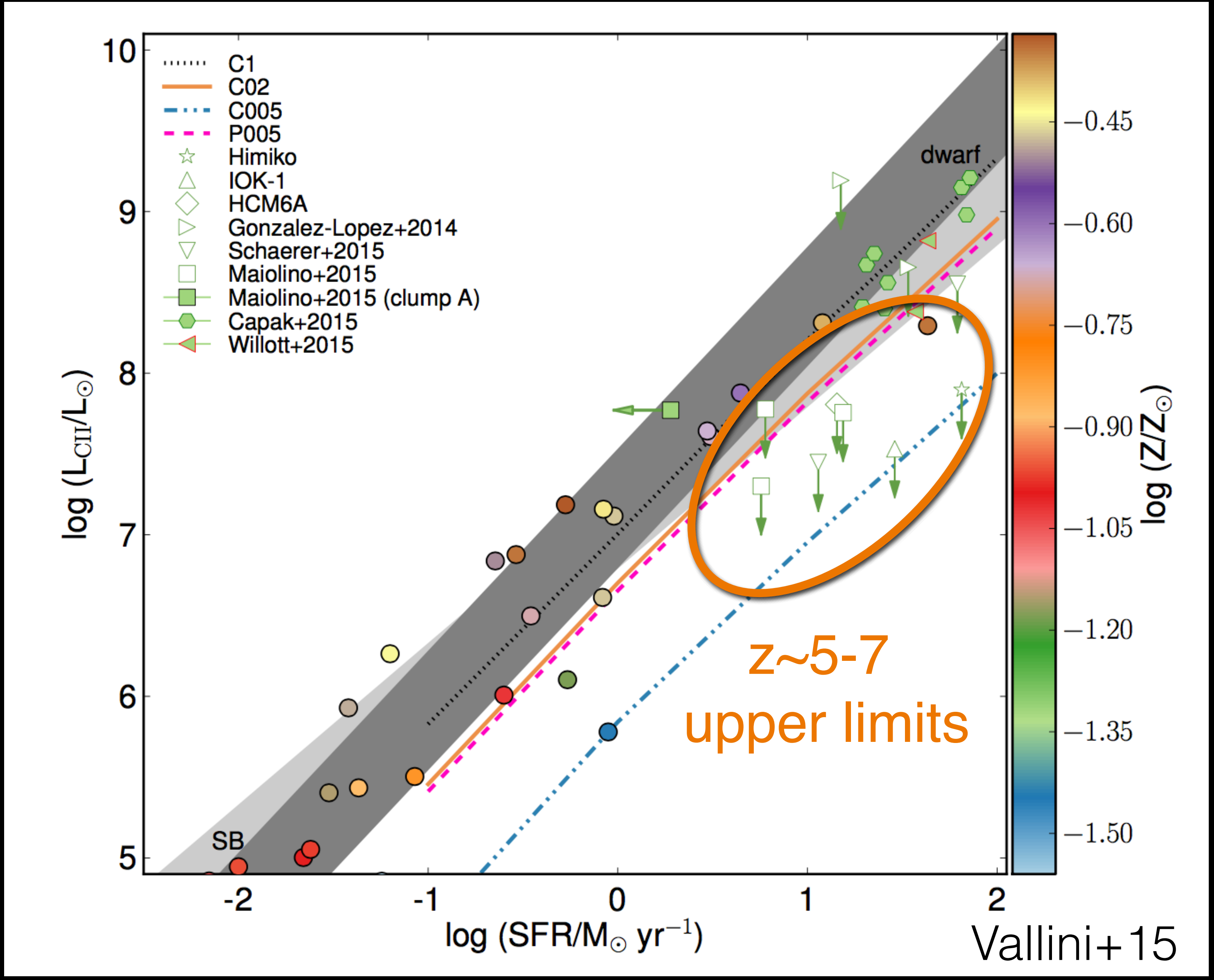

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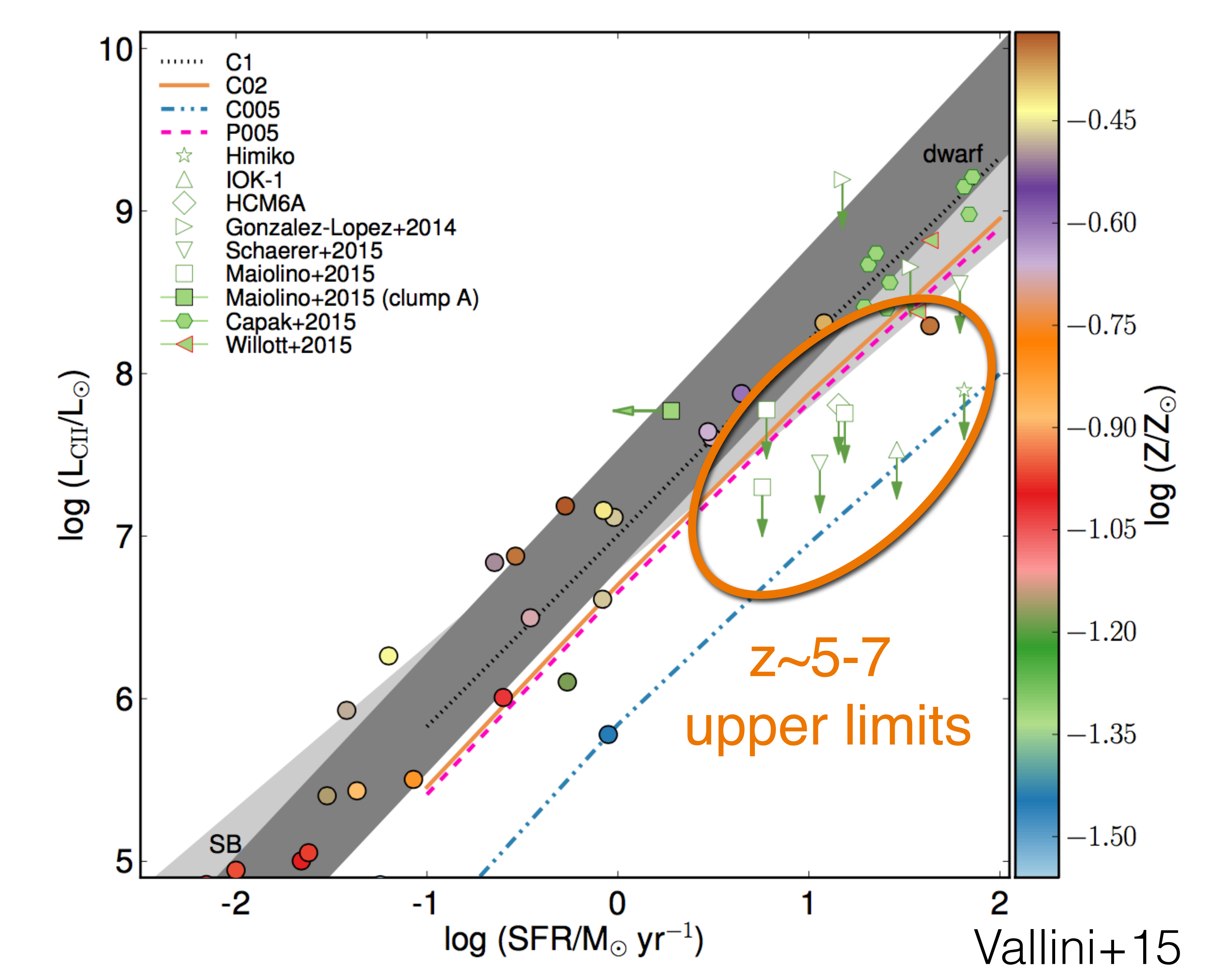

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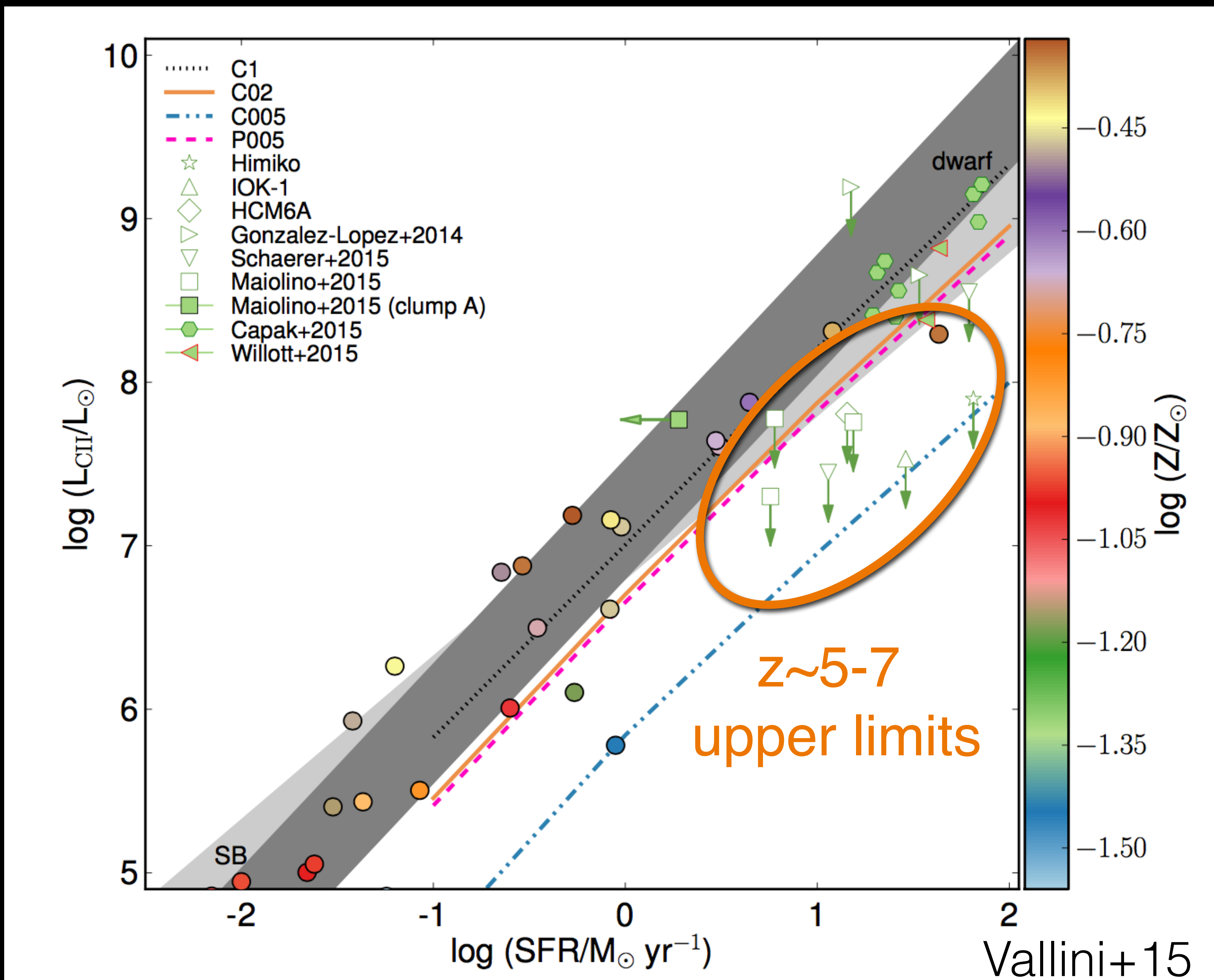


- low metallicity?
- disruption of molecular clouds by star formation?
- no star formation, no metallicity in their models…

Outlook

SÍGAME - focusing on [CII] at higher redshift!

2. Improve on method

- dust radiative transfer incorporated (Powderday; D. Narayanan)
- cosmological simulations with more complex chemistry (RAMSES +KROME; E. Scannapieco and others)
- larger variation in galaxy sample (Z, SFR etc.)

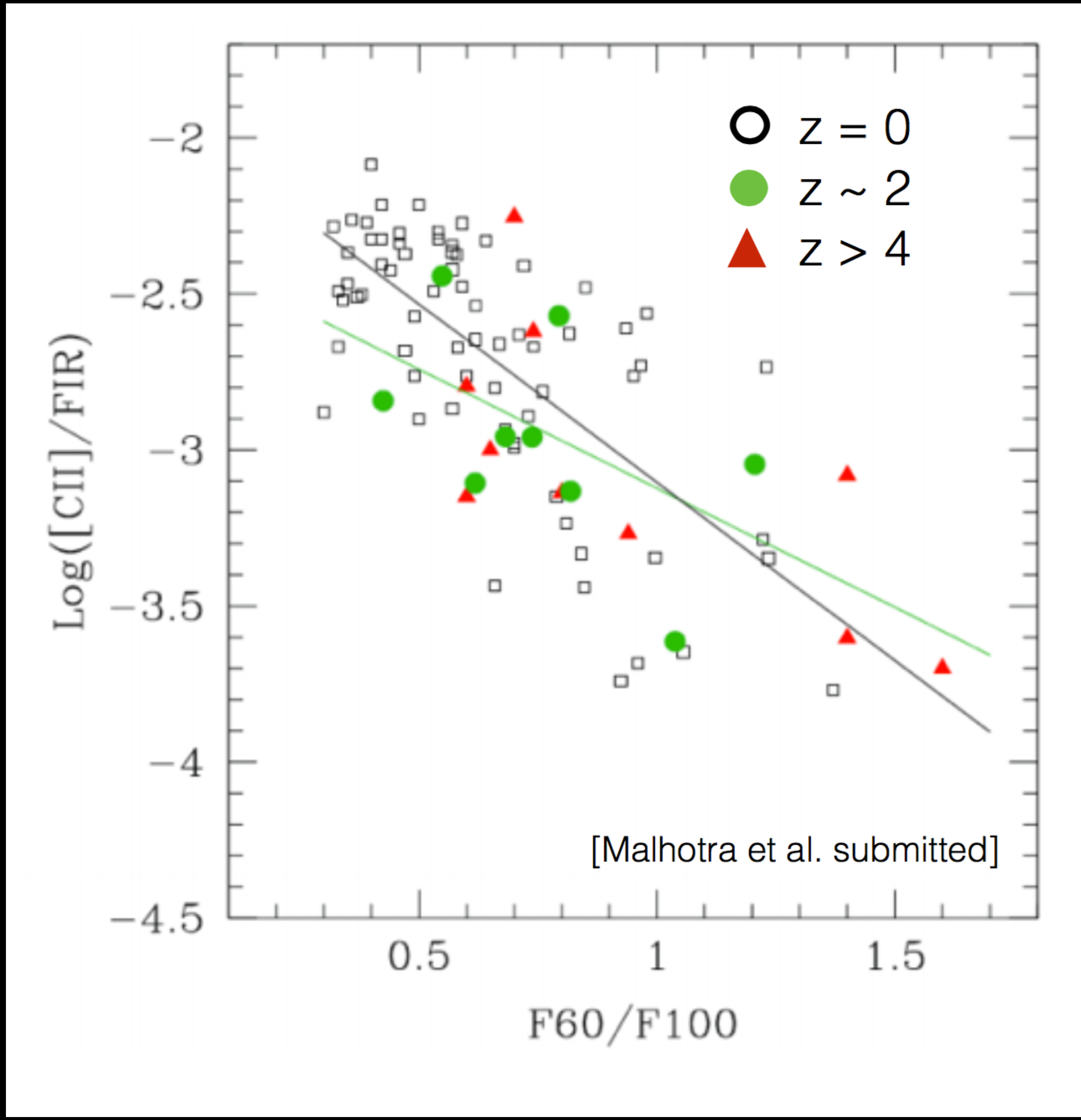
Outlook

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



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