OAS Bologna, April 7th 2022, Joint Astrophysical Colloquium

The ISM across cosmic times

and how to disentangle its complexity

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Scuola Normale Superiore – Pisa

Key questions

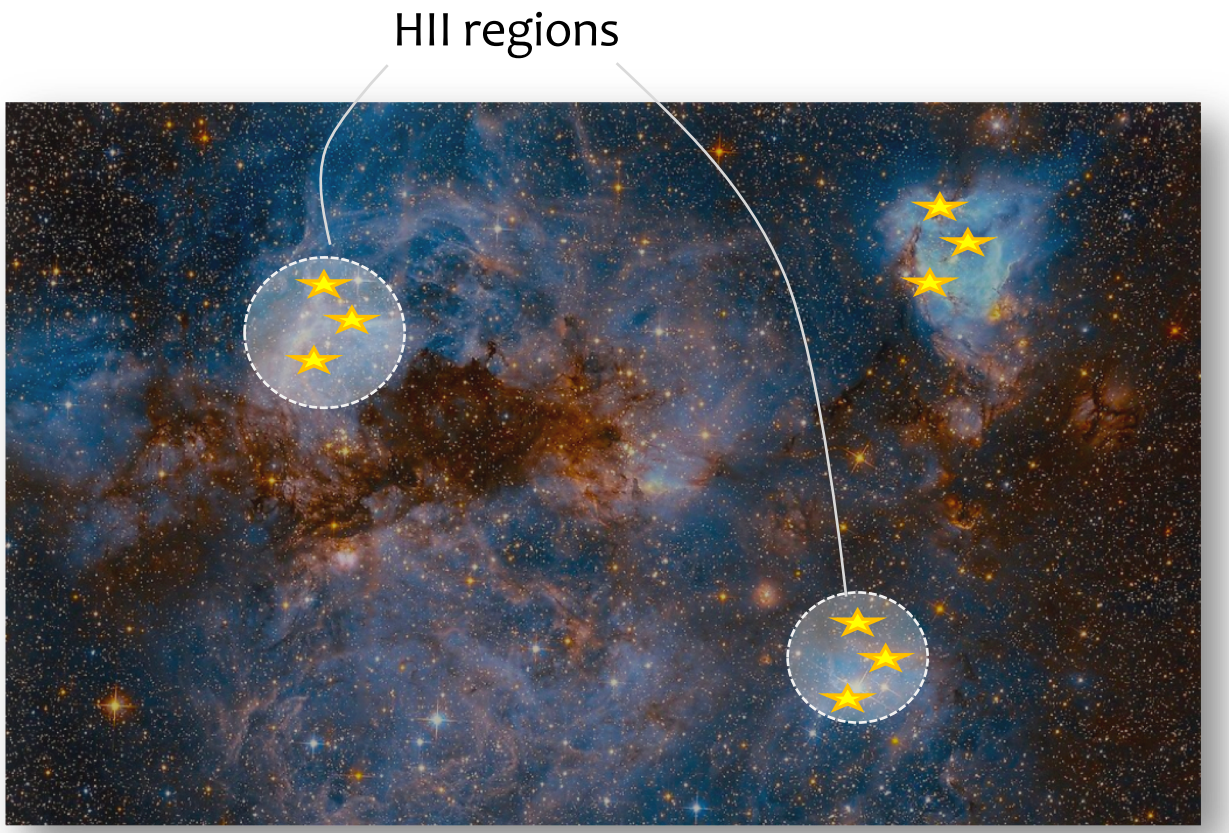
1. What are the differences between the ISM properties in local vs. high-z galaxies?
2. What are the implications for the star formation across cosmic times?
3. What is the effect of feedback (from AGN/star formation) on the ISM?

The ISM: a complex environment

The ISM: a complex environment

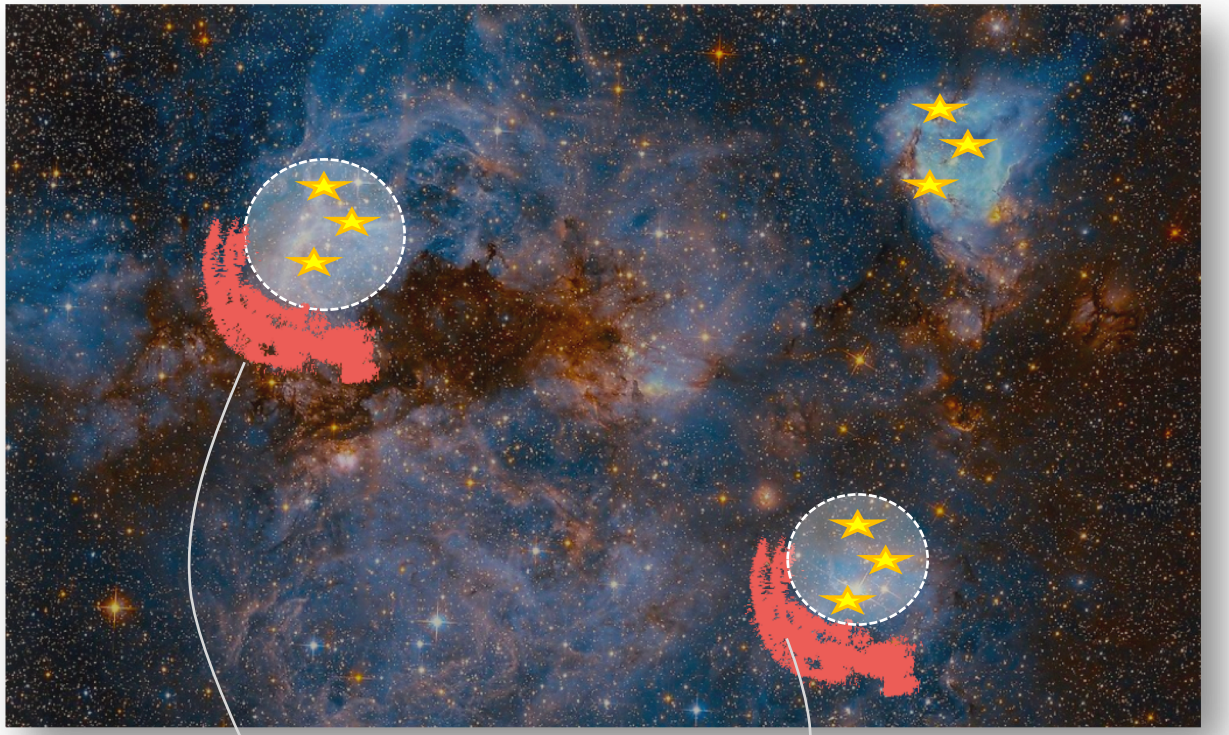
Star formation

The ISM: a complex environment



The ISM: a complex environment

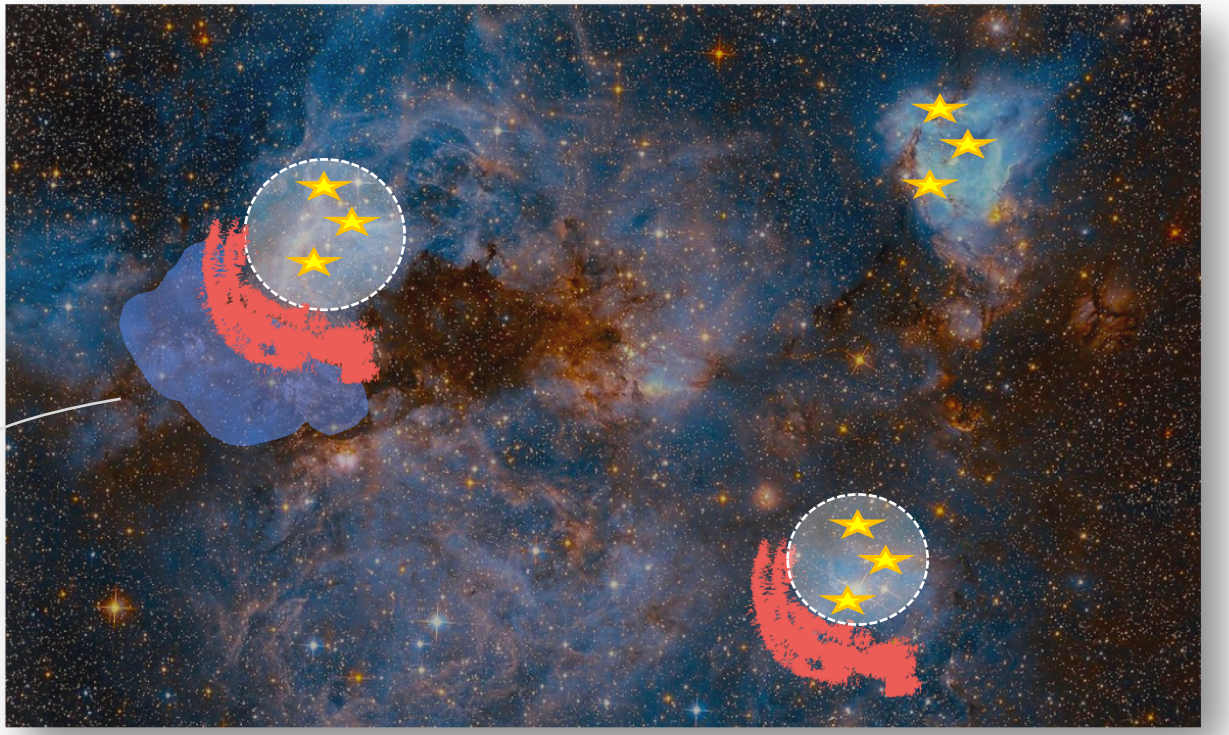
HII regions



Photodissociation regions

The ISM: a complex environment

HII regions

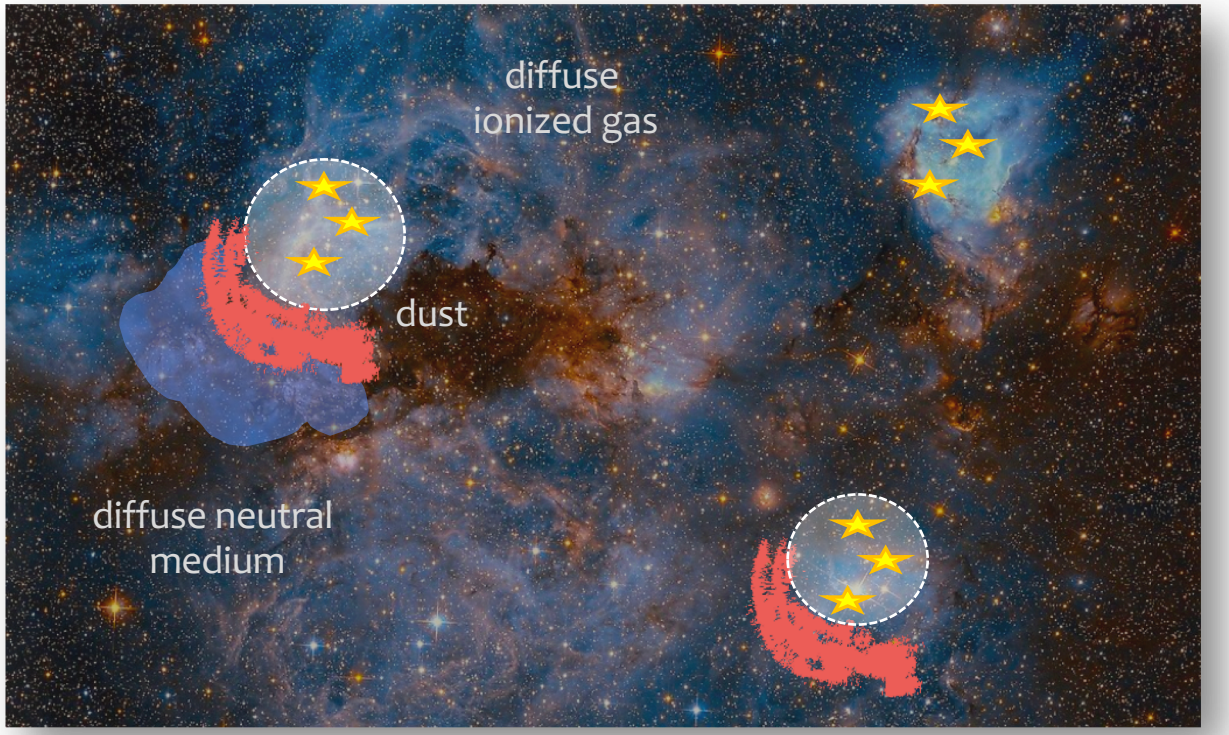


Giant Molecular Clouds

Photodissociation regions

The ISM: a complex environment

HII regions



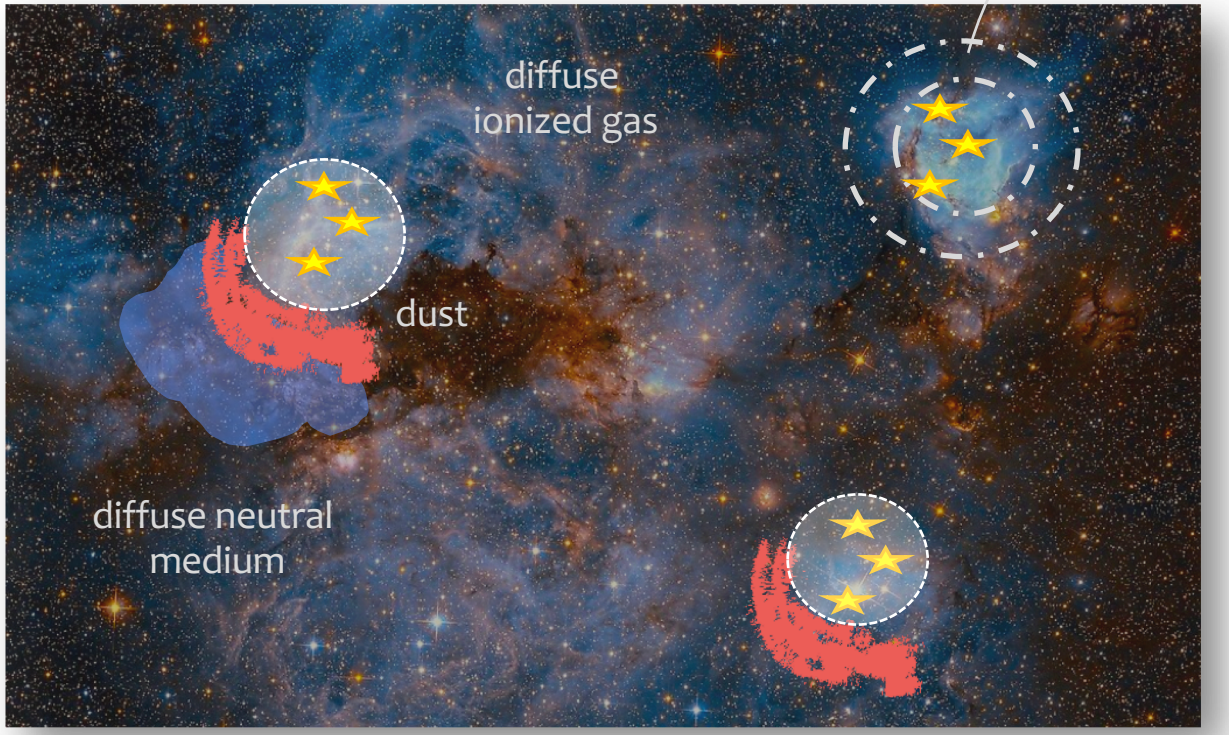
Giant Molecular Clouds

Photodissociation regions

The ISM: a complex environment

SN feedback
(turbulence/metal injection)

HII regions



Giant Molecular Clouds

Photodissociation regions

The ISM: a complex environment

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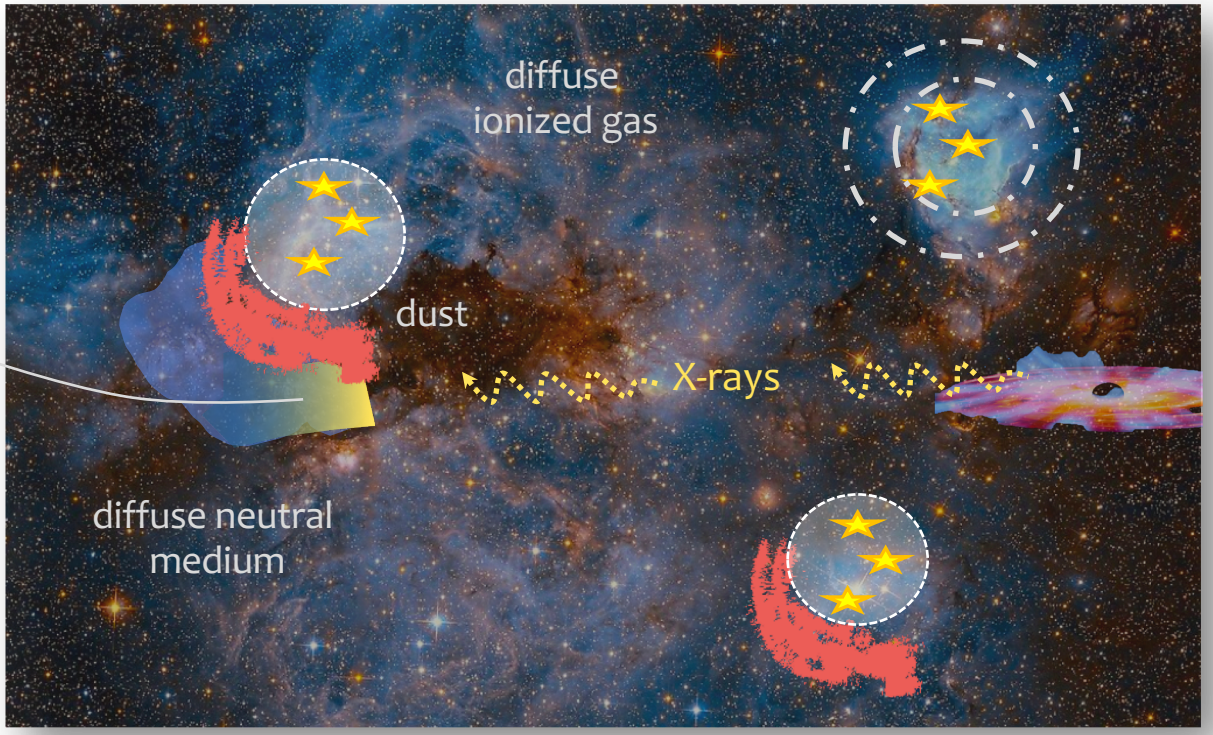


X-ray dominated regions

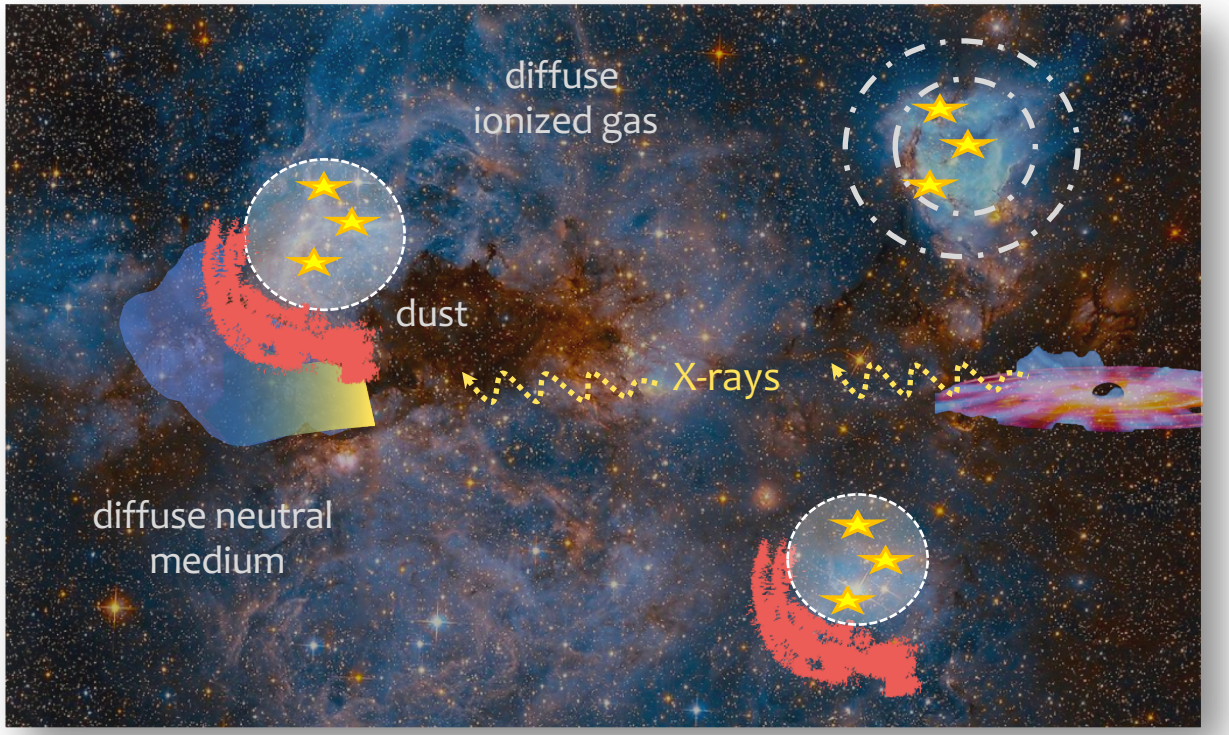
AGN feedback

Giant Molecular Clouds

Photodissociation regions

The ISM: a complex environment

HII regions



X-ray dominated regions

Giant Molecular Clouds

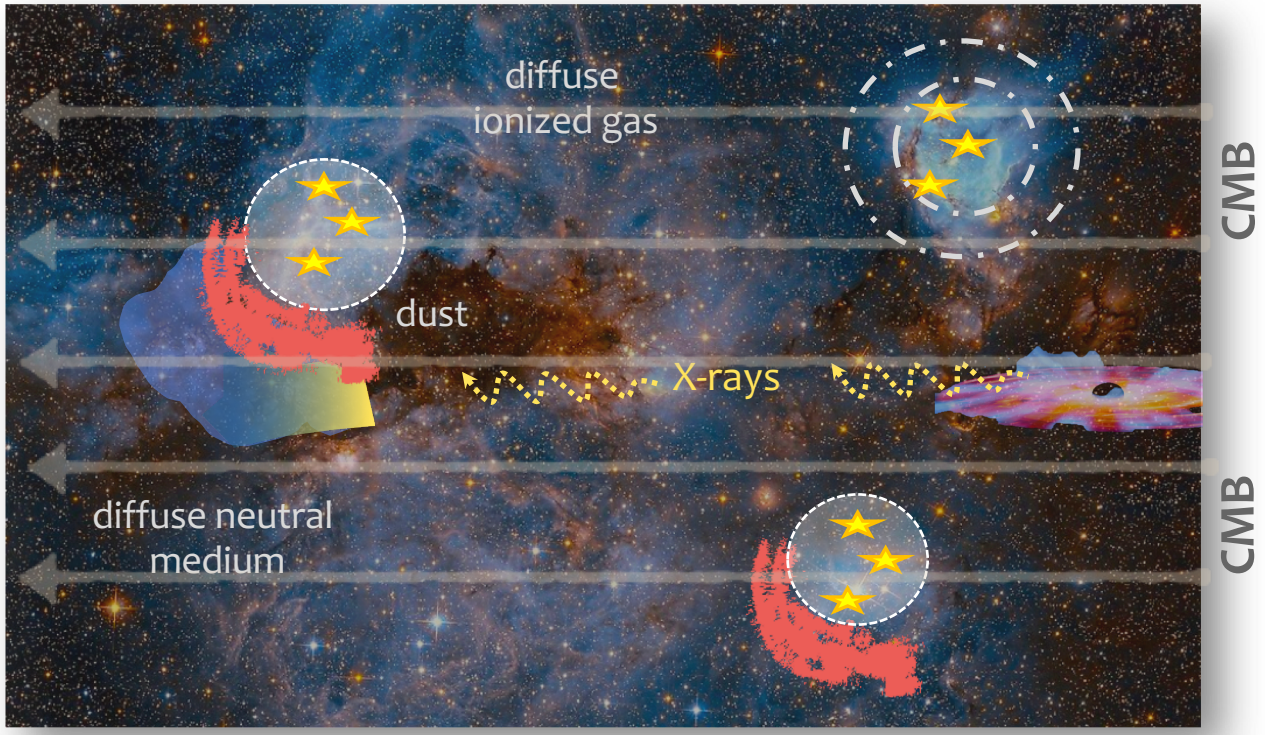
Photodissociation regions

For a recent review:
Wolfire, Vallini, Chevance, ARAA, Vol 60, 2022

The ISM: a complex environment

HII regions

X-ray dominated regions



Giant Molecular Clouds

Photodissociation regions

The ISM: a complex environment as traced by ALMA and JWST

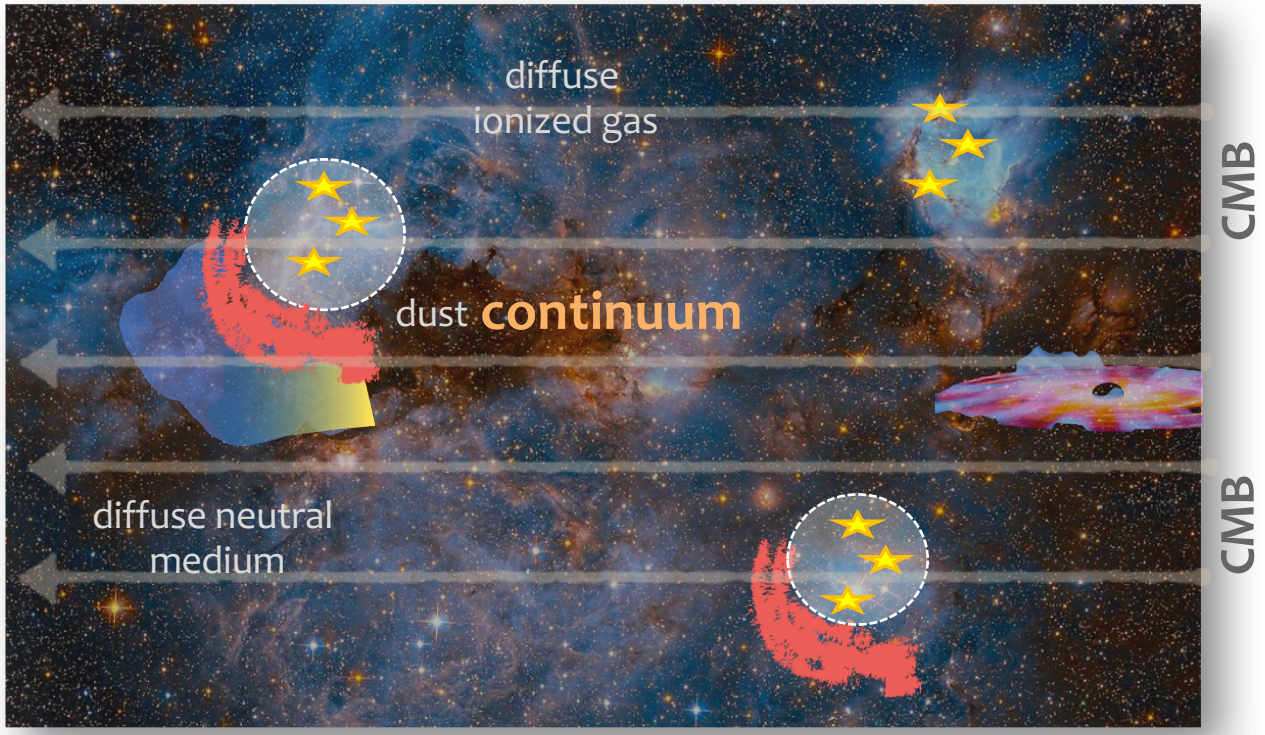
[OIII] 88μm, CIII]1909 Å

HII regions

X-ray dominated regions

CO lines

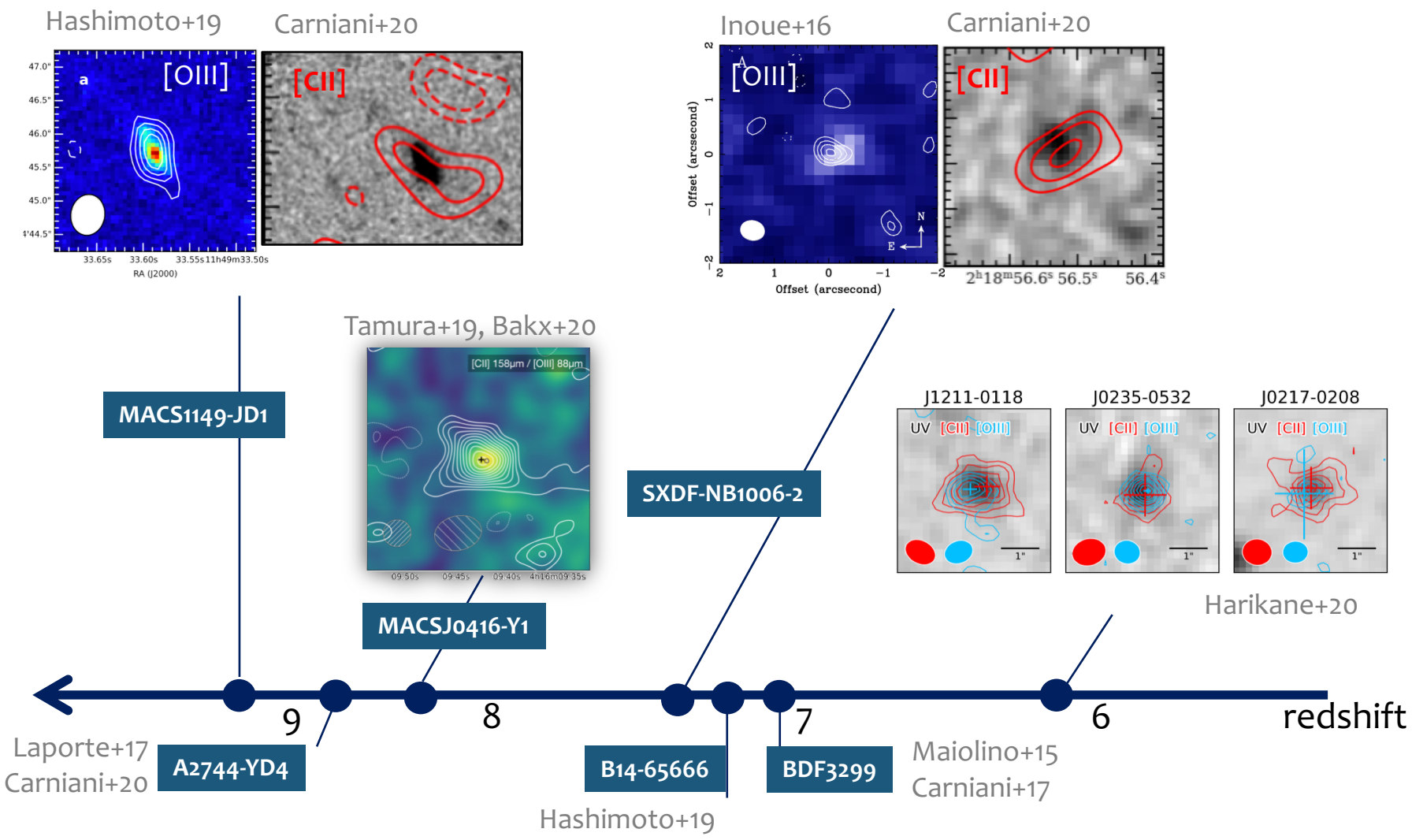
Giant Molecular Clouds



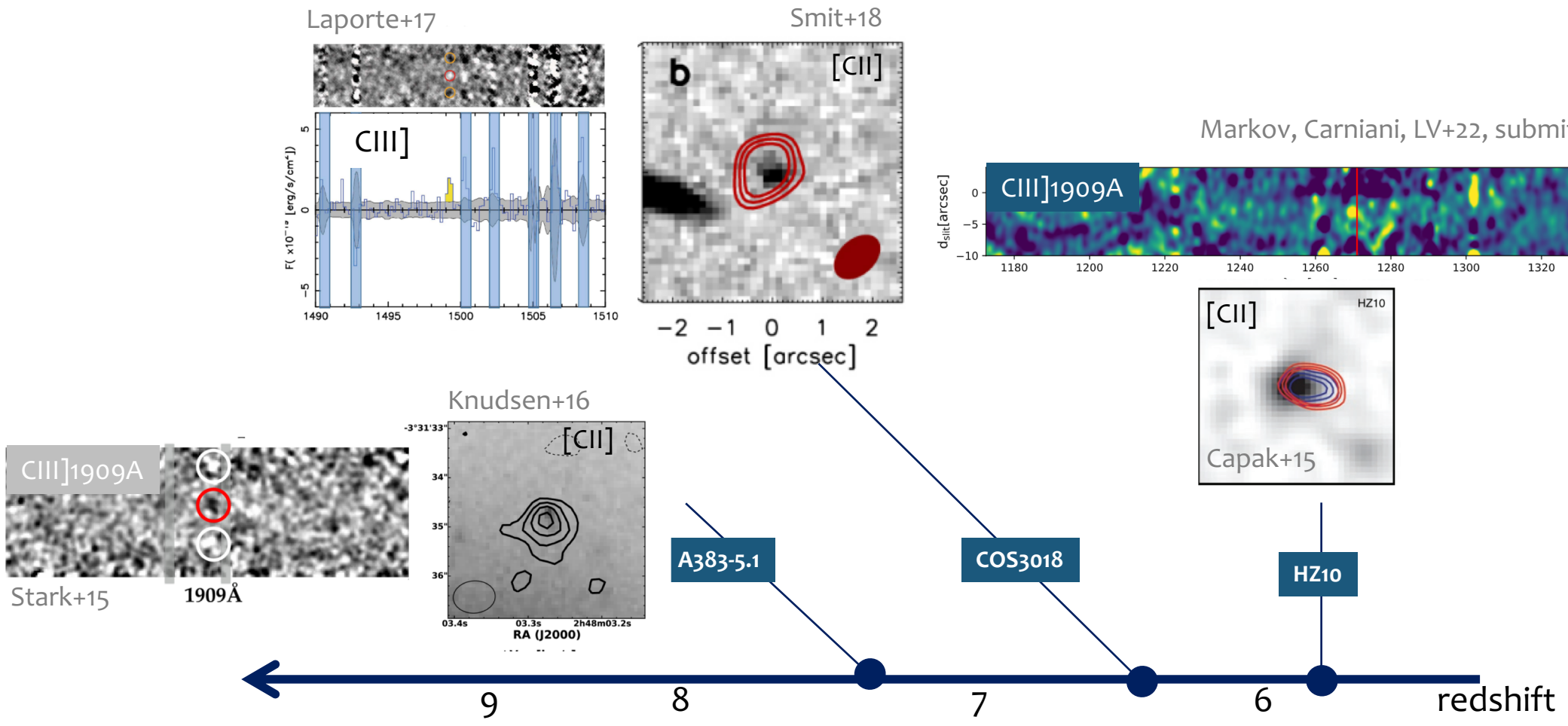
[CII] 158μm

Photodissociation regions

Joint [OIII]-[CII] detections towards the Epoch of Reionization



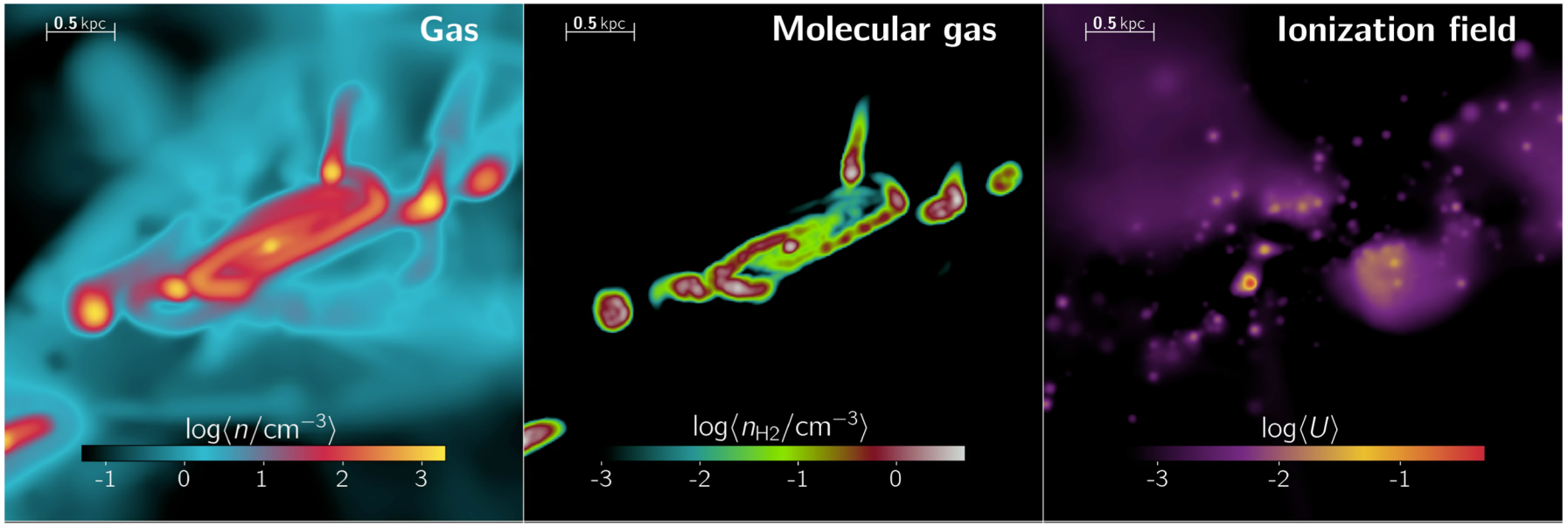
Joint CIII]-[CII] detections towards the Epoch of Reionization



Zooming in on the ISM of the first galaxies

Zoom-in cosmological simulations

Pallottini+17,19,22



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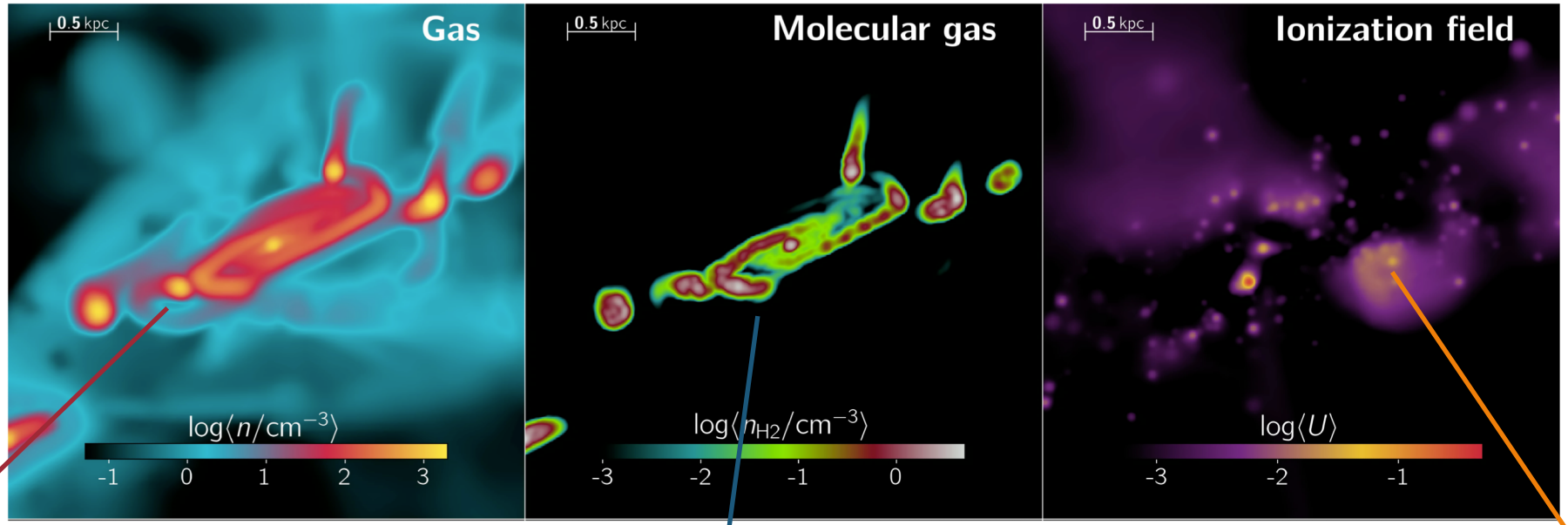


subgrid models including PDR processes

[CII] emission

Vallini+13,15,17

subgrid models for the internal structure of GMCs

CO emission

Vallini+18,19

RT and inclusion of nebular emission

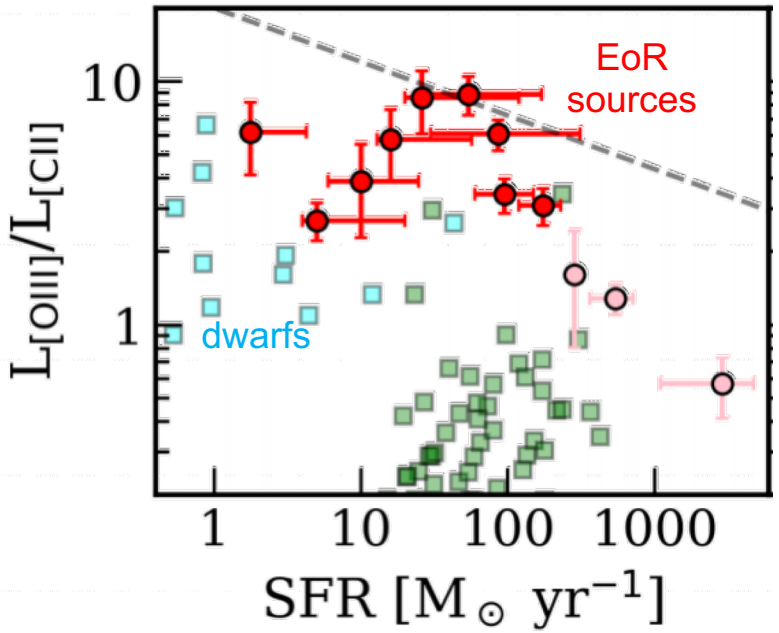
[OIII], CIII] emission

Vallini+20,21

Open questions: why such a high [OIII]/[CII] ratios?

The [OIII]/[CII] ratios are higher than the average value reported for local star forming galaxies

Harikane+20, Arata+20



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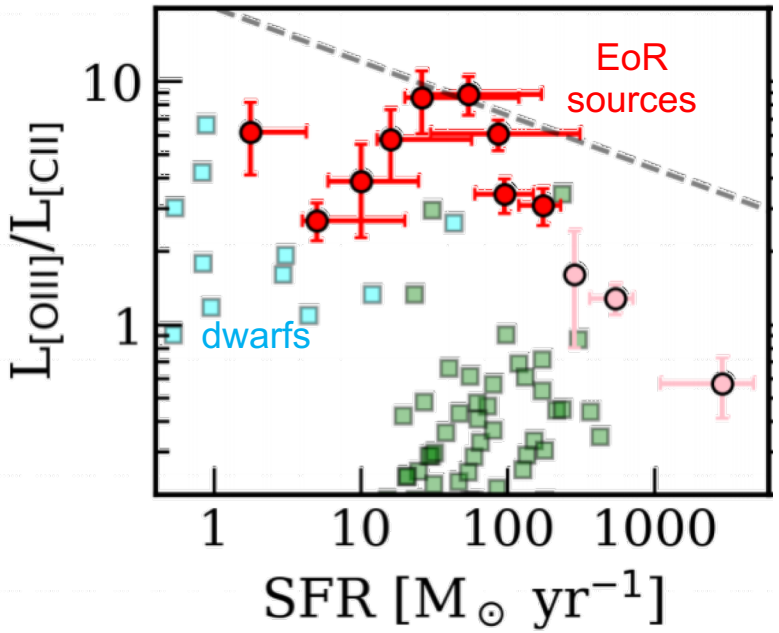
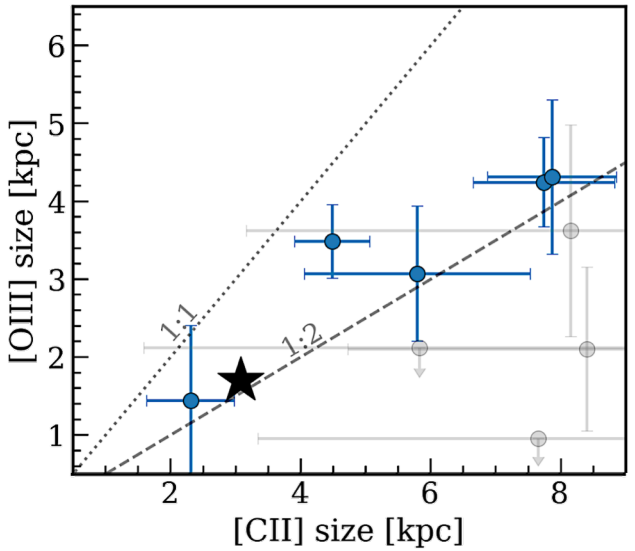


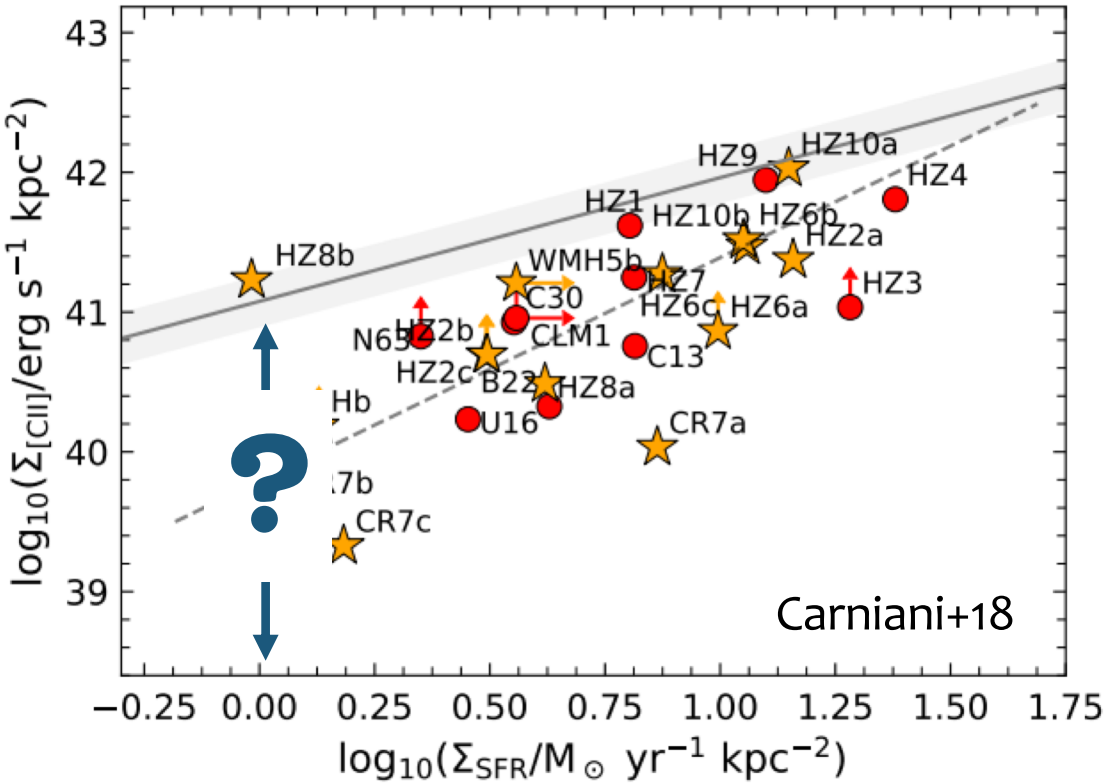
Carniani+20



The [CII] size is overall 2-3 times larger than the [OIII] one,
this might influence the $L_{[OIII]}/L_{[CII]}$ ratio if we miss the [CII] extended component

Open questions: why such a low [CII] surface brightness?

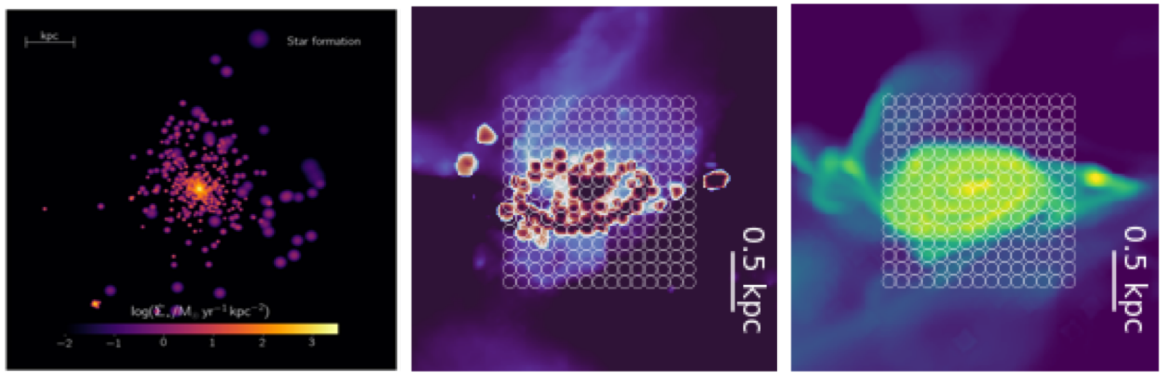
The **surface brightness of [CII] in high-z galaxies is systematically lower than** what is observed in **local galaxies** with comparable SFR surface brightness



[OIII] vs [CII] a spatially resolved view from simulations

- For $\Sigma_{[OIII]}/\Sigma_{[CII]}$ different extension of the emitting regions are explicitly accounted for
- $\Sigma_{[OIII]}/\Sigma_{[CII]}$ ratios, and the Σ_{SFR}, are more closely related to the local ISM conditions

Pallottini+19, Vallini+21



UV map [OIII] map [CII] map

Resolution of the simulation ~10 pc

[OIII] vs [CII] a spatially resolved view from simulations

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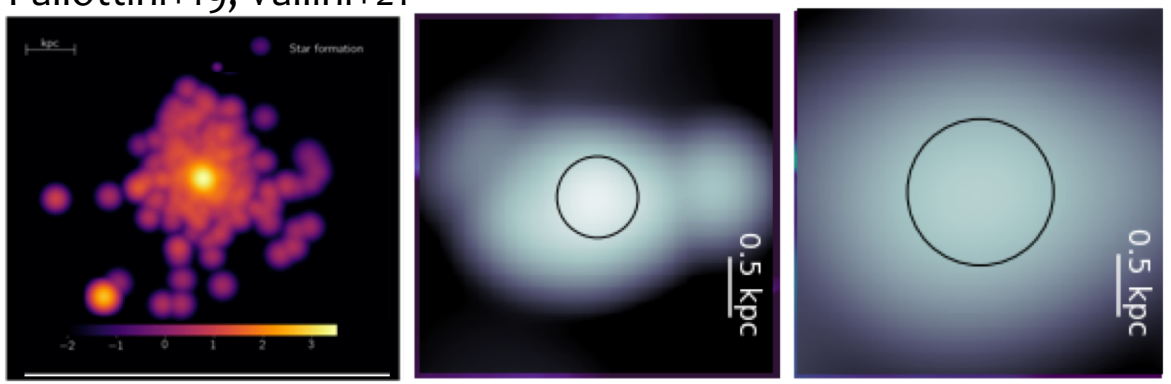
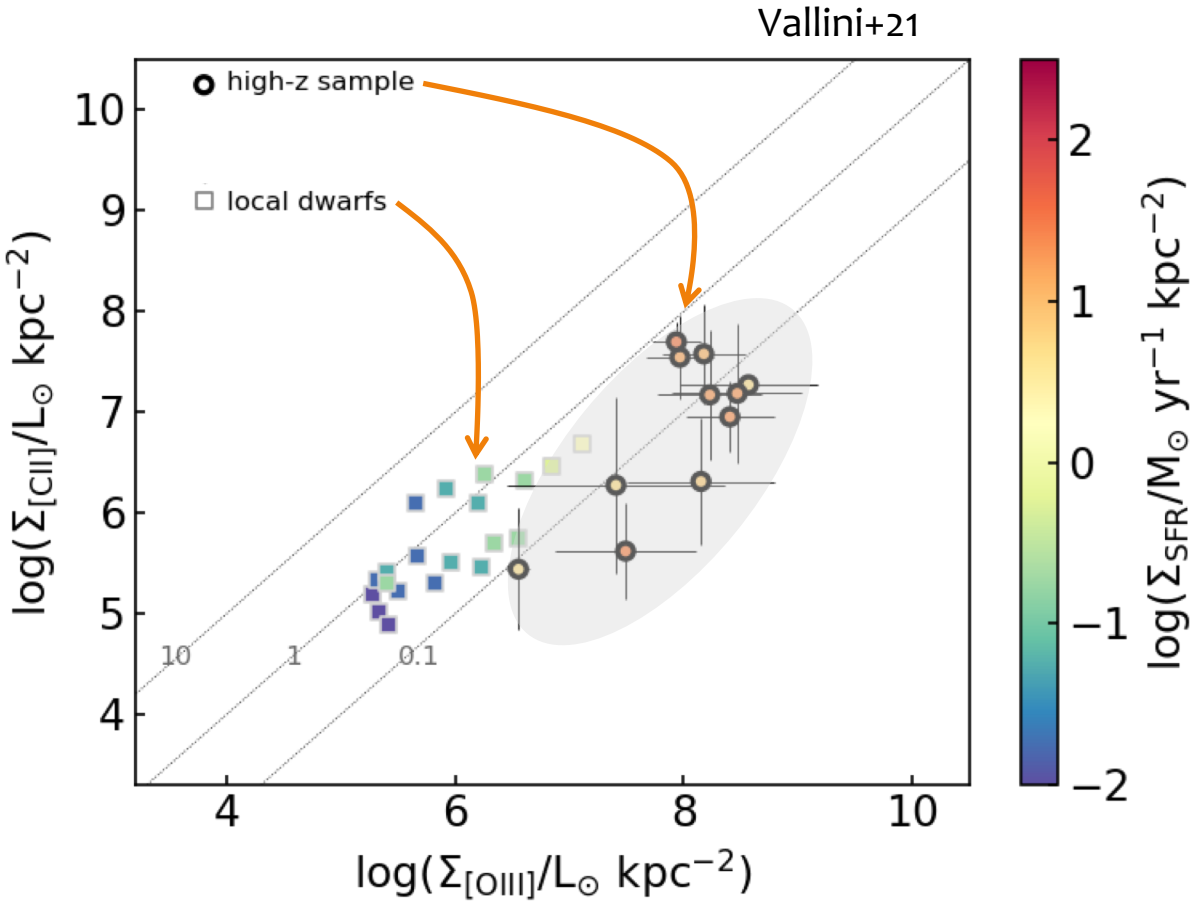


UV map [OIII] map [CII] map

Considering the beam smearing

[OIII] vs [CII] a spatially resolved view from simulations



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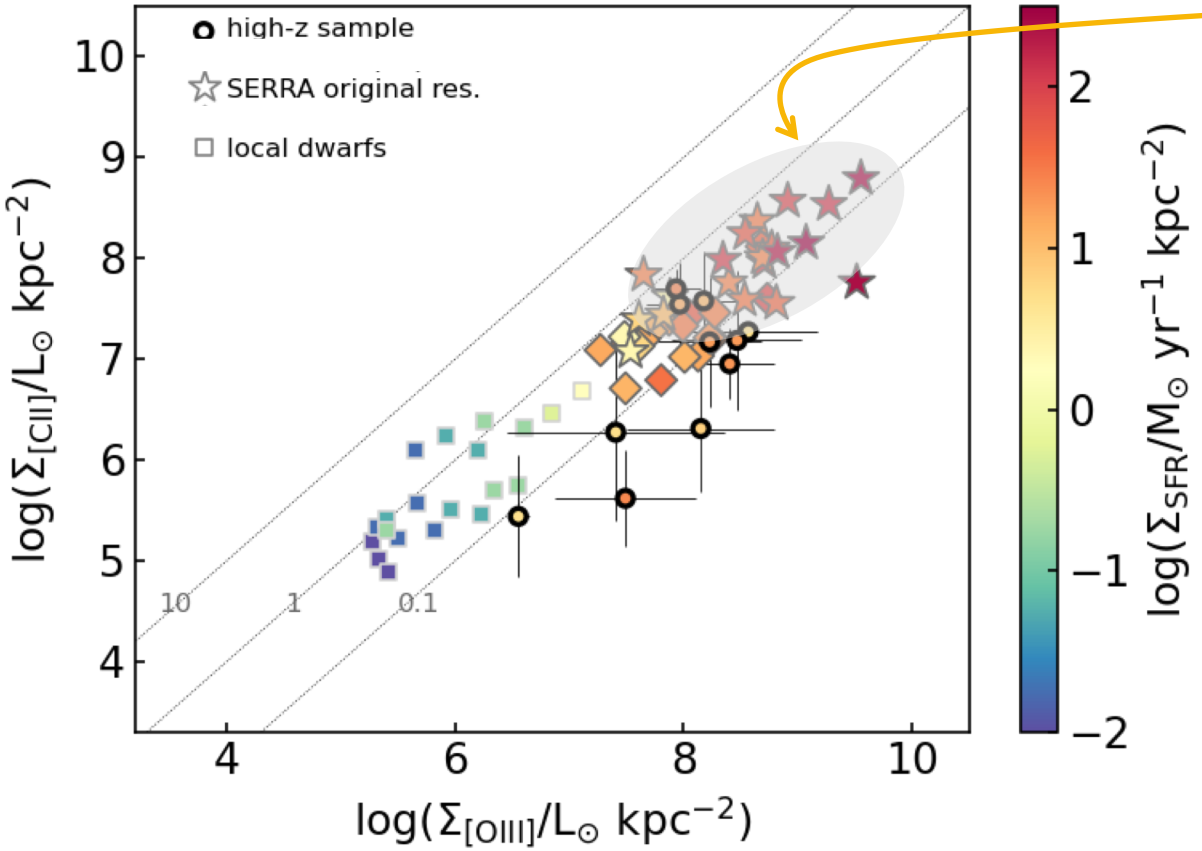
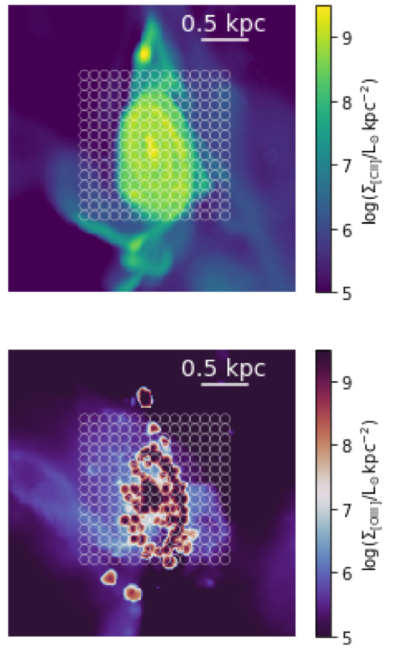
Vallini+21





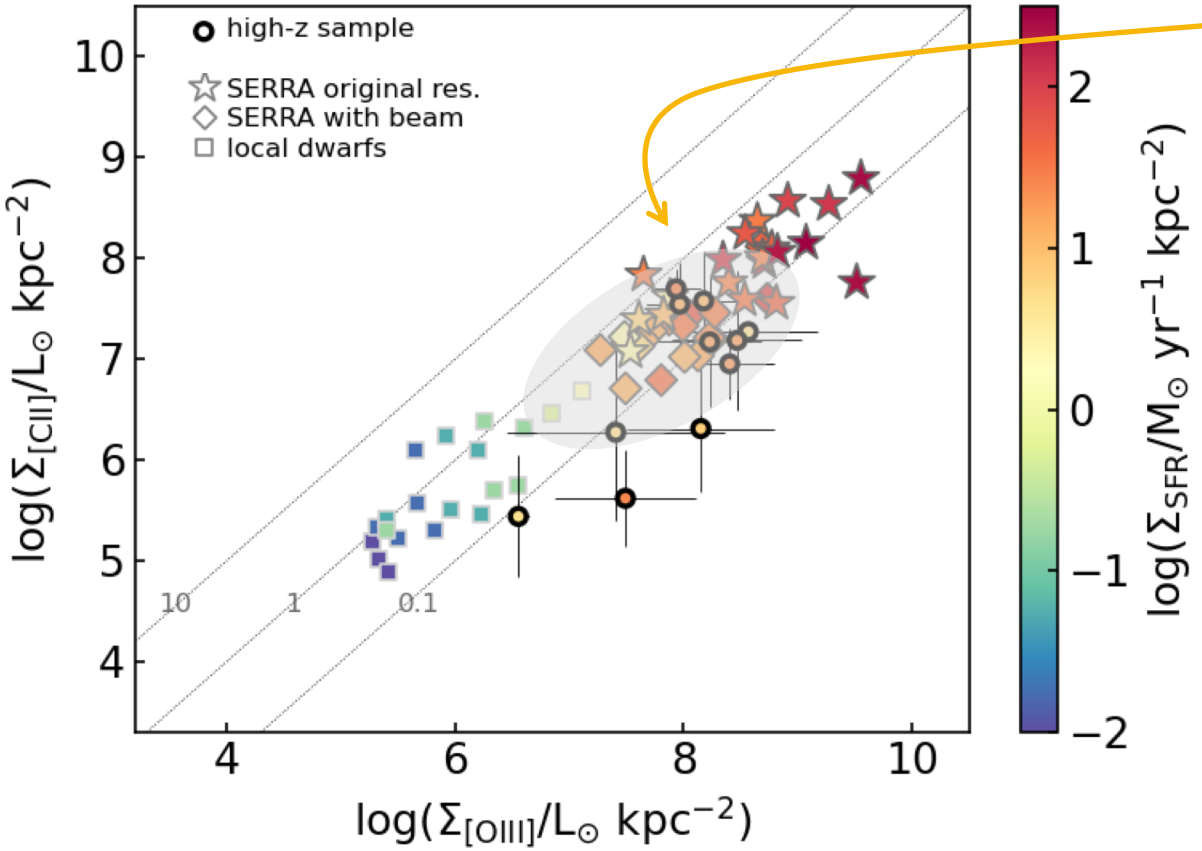
SERRA Simulation at z=7.7

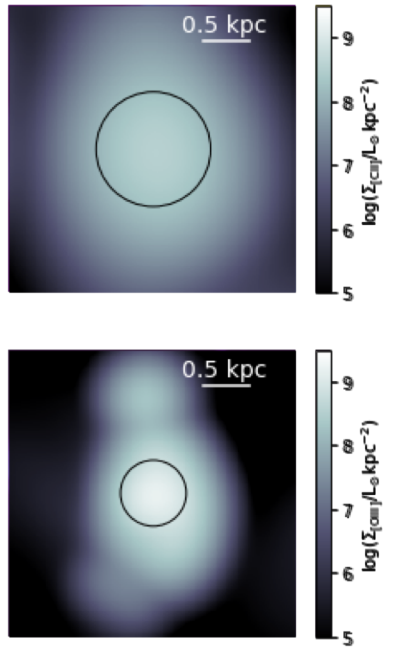
Pallottini+22

Pallottini+17,19

[OIII] vs [CII] a spatially resolved view from simulations

Vallini+21





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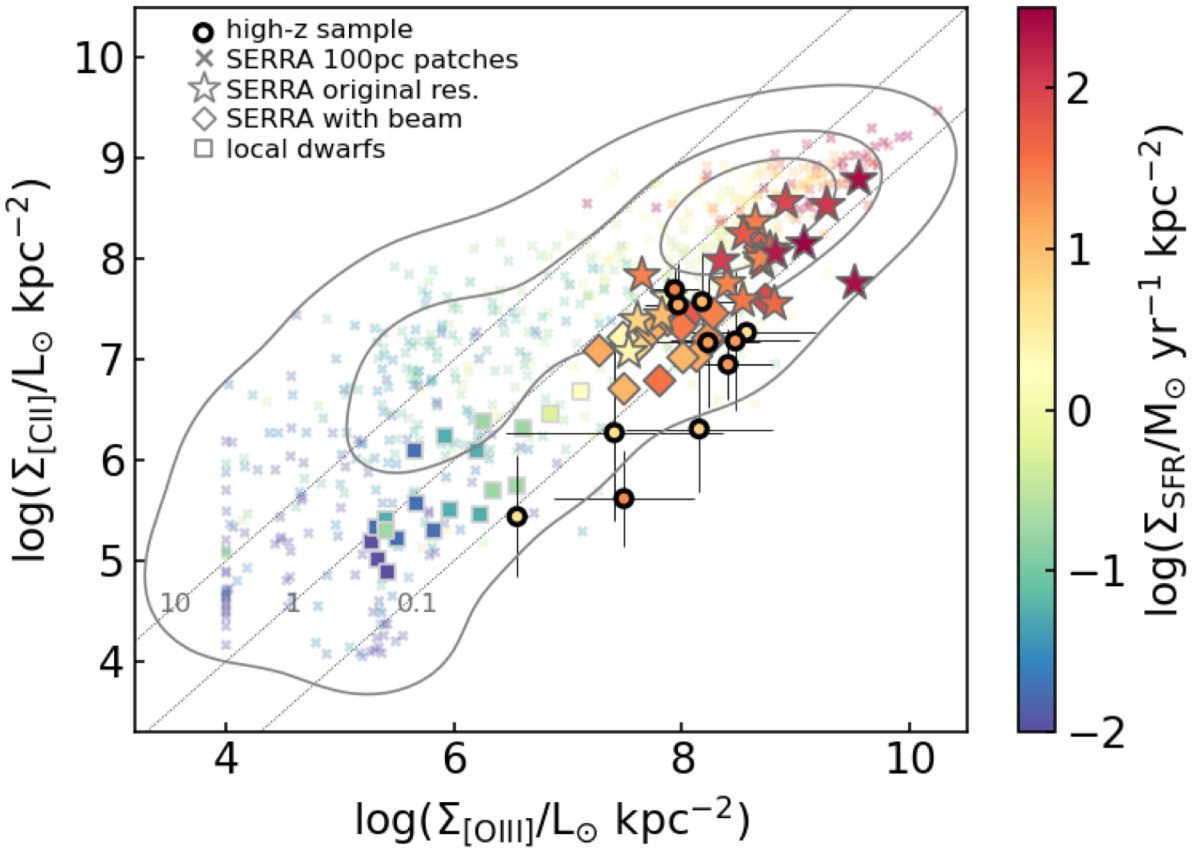

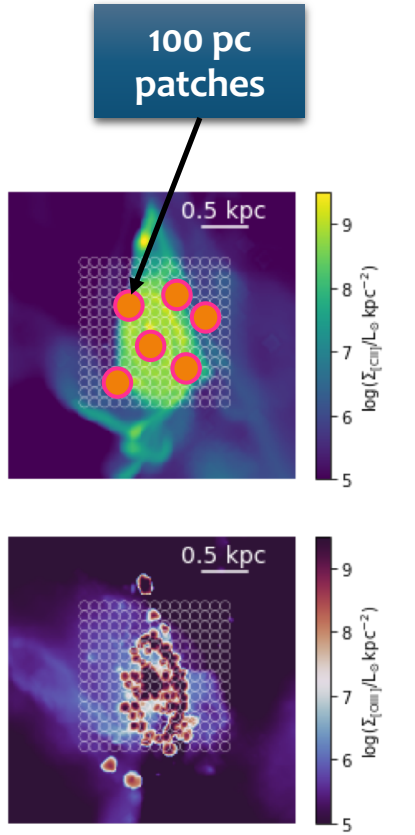

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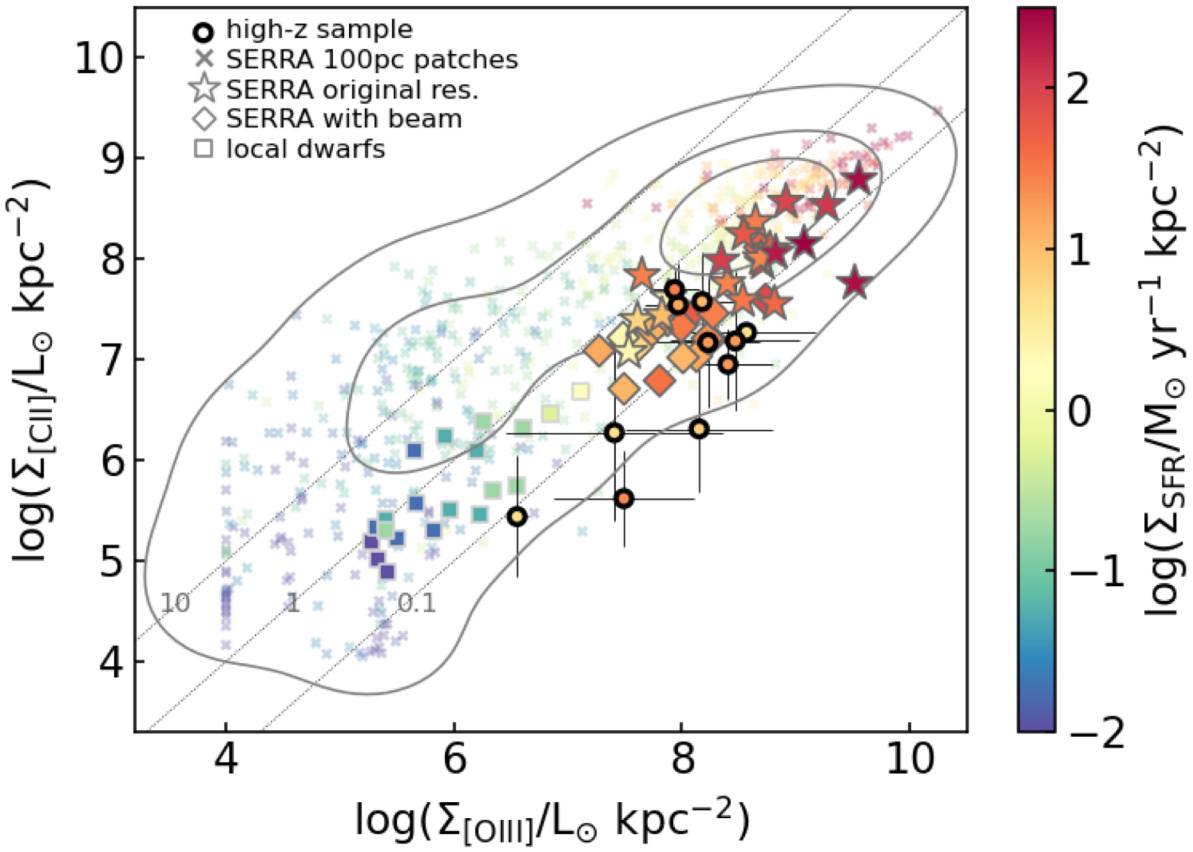

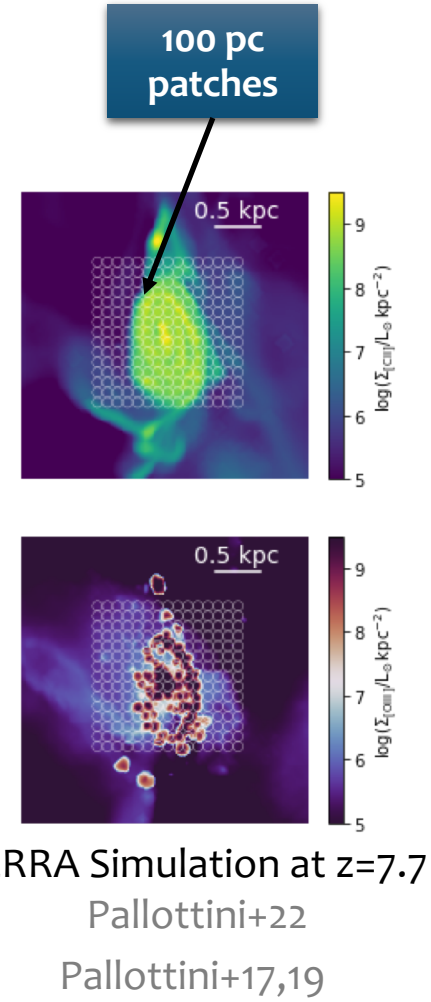

SERRA Simulation at z=7.7

Pallottini+22

Pallottini+17,19

High $\Sigma_{[OIII]}/\Sigma_{[CII]}$ ratios are not due to observational biases rather they reflect the conditions of the most extreme (and bright) ISM regions

Linking line emission to the ISM properties

$\Sigma_{[CII]}(\mathbf{k_s, n, Z})$ Ferrara, LV+19

$\Sigma_{CIII]1909A}(k_s, n, Z)$ Vallini+20

$\Sigma_{[OIII]}(k_s, n, Z)$ Vallini+21

Linking line emission to the ISM properties

$\Sigma_{[CII]}(\mathbf{k_s}, \mathbf{n}, \mathbf{Z})$ Ferrara, LV+19

$\mathbf{k_s}$ = ”burstiness” parameter describing the deviation from the Kennicutt-Schimidt law

$\Sigma_{CIII]1909A}(k_s, n, Z)$ Vallini+20

$\Sigma_{[OIII]}(k_s, n, Z)$ Vallini+21

Linking line emission to the ISM properties

$\Sigma_{[CII]}(k_s, n, Z)$ Ferrara, LV+19 **n** = gas density

$\Sigma_{CIII]1909A}(k_s, n, Z)$ Vallini+20

$\Sigma_{[OIII]}(k_s, n, Z)$ Vallini+21

Linking line emission to the ISM properties

$\Sigma_{[CII]}(k_s, n, Z)$ Ferrara, LV+19 **Z** = gas metallicity

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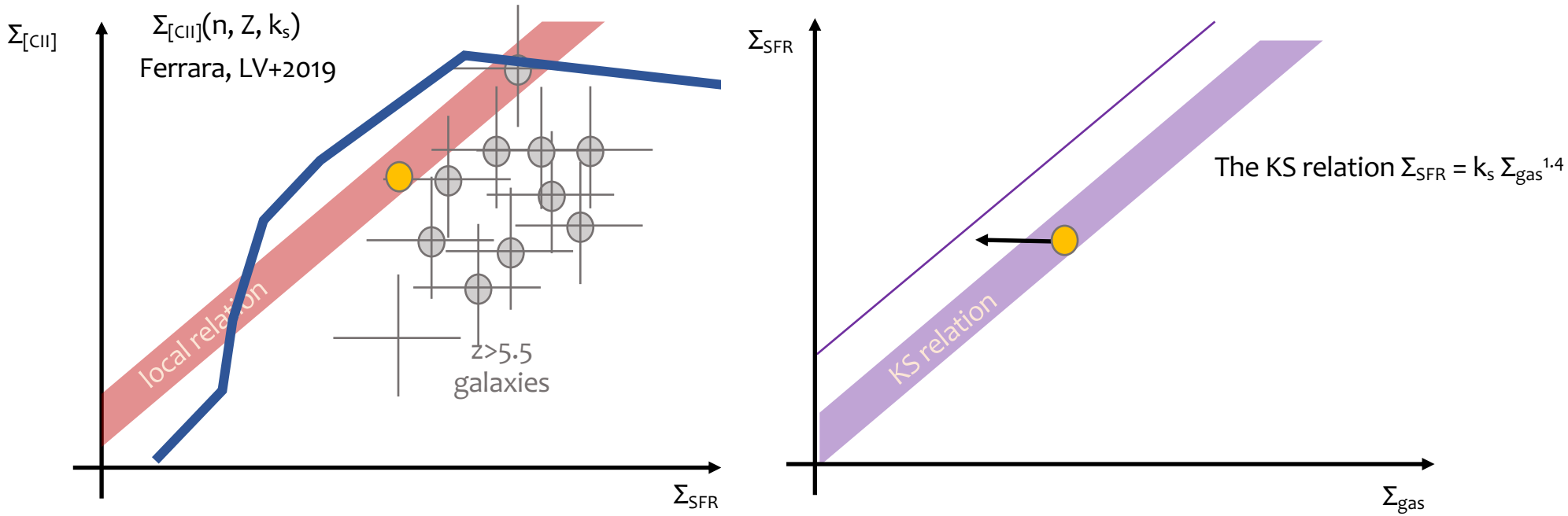
$\Sigma_{[OIII]}(k_s, n, Z)$ Vallini+21

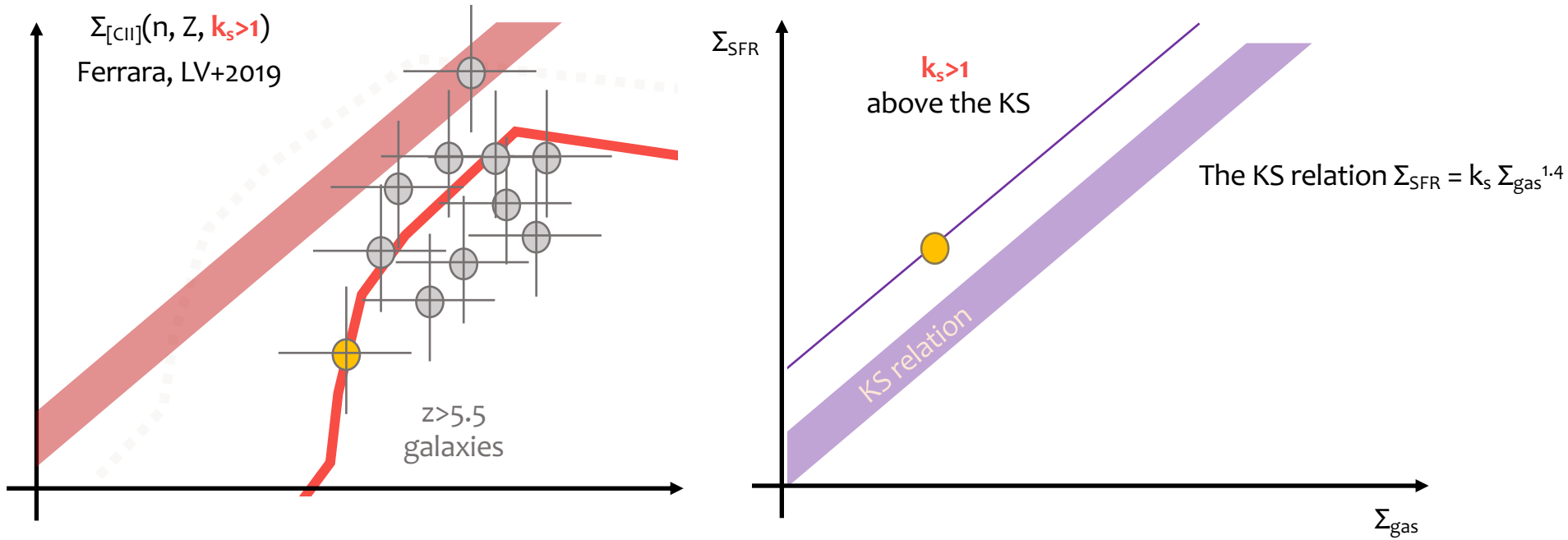
Linking line emission to the ISM properties



For local relation $\Sigma_{[CII]}$-Σ_{SFR}: De Looze+2014, Herrera-Camus+15

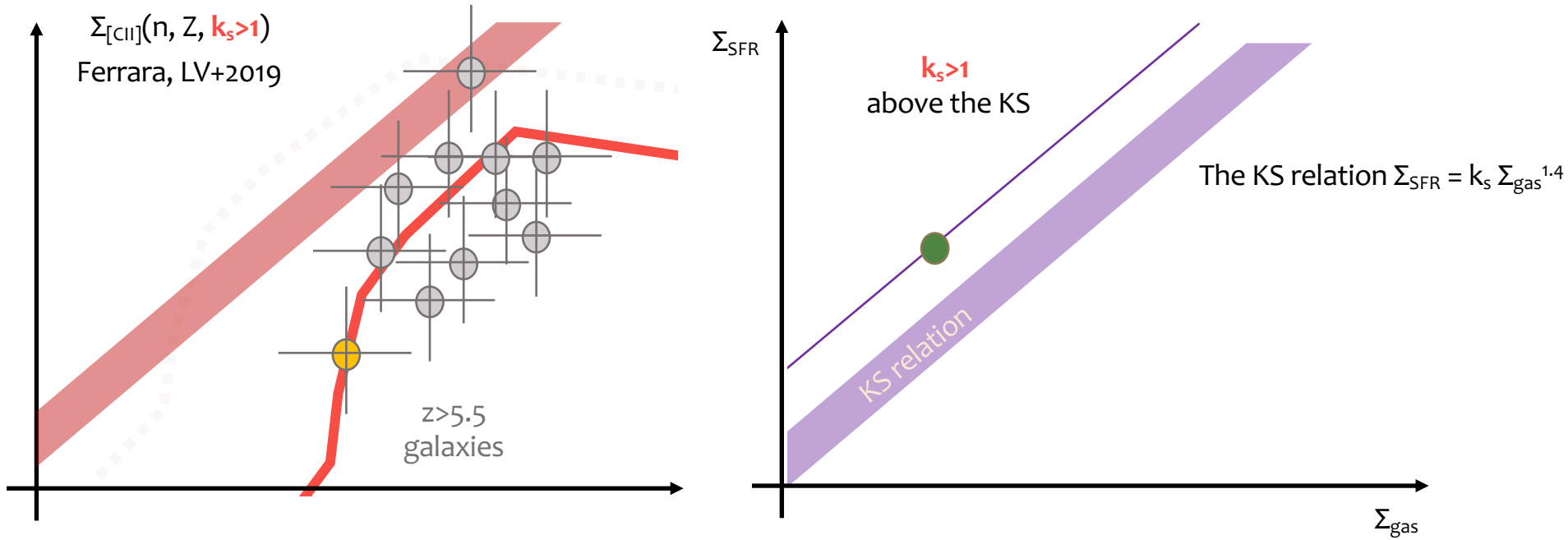
For details on the model see: Ferrara+19, Vallini+20

The effect of deviations from the Kennicutt-Schmidt relation



Starburst → larger U → higher **ionized gas column density** & **low PDR column density** → Decrease $\Sigma_{[CII]}$

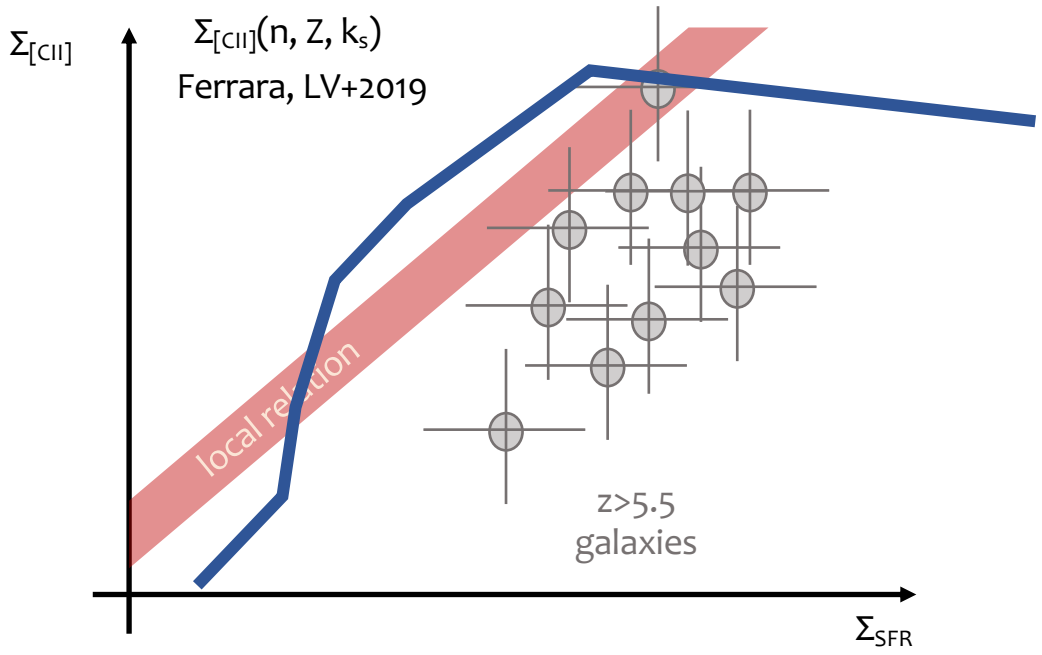
The effect of deviations from the Kennicutt-Schmidt relation



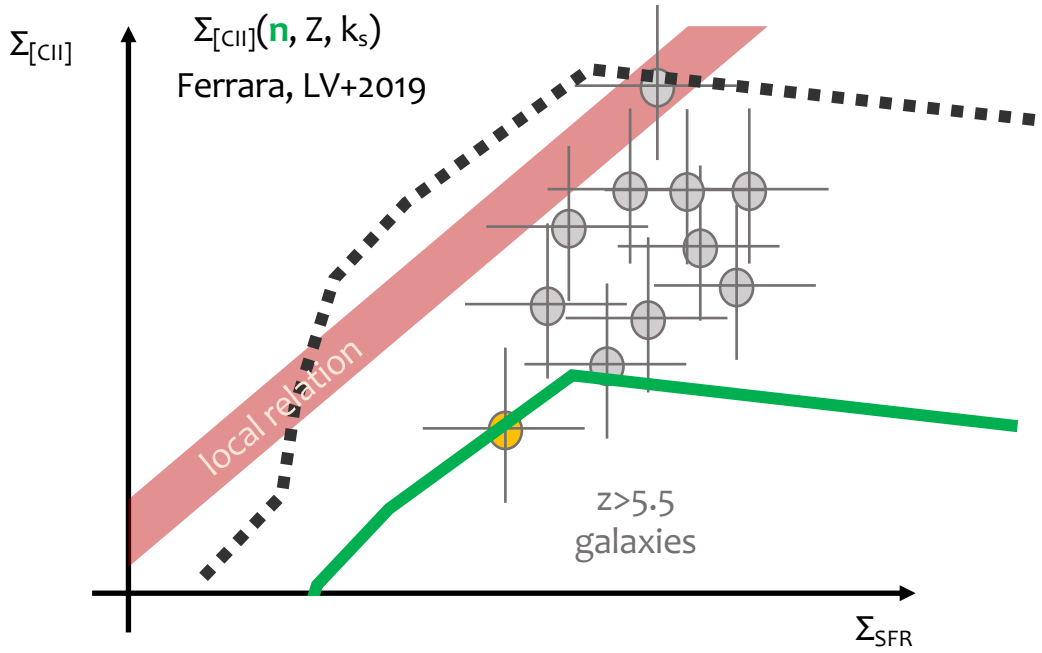
Starburst → larger U → higher **ionized gas column density** & **low PDR column density** → Decrease $\Sigma_{[CII]}$

Starburst → larger U → higher **ionized gas column density** & **low PDR column density** → Increase $\Sigma_{[OIII]}$

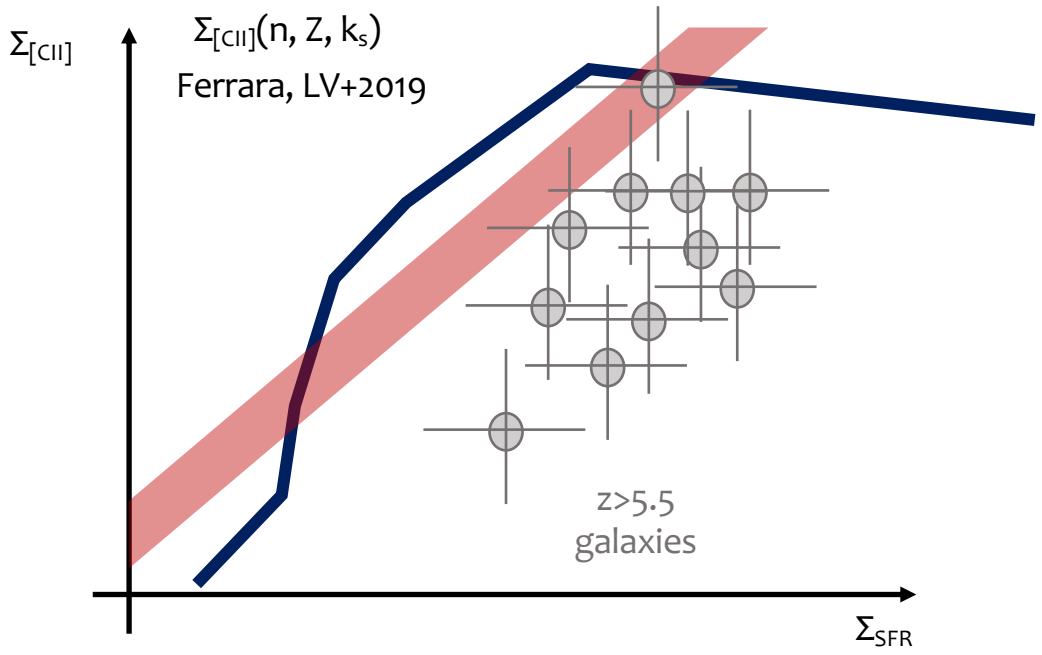
The effect of gas density



The effect of gas density



The effect of gas metallicity



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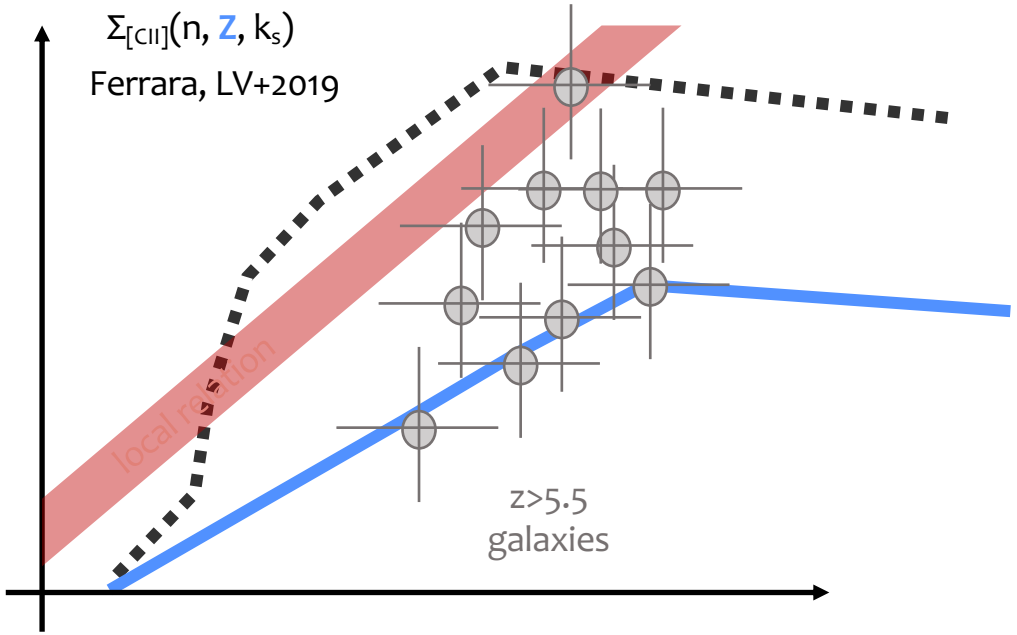
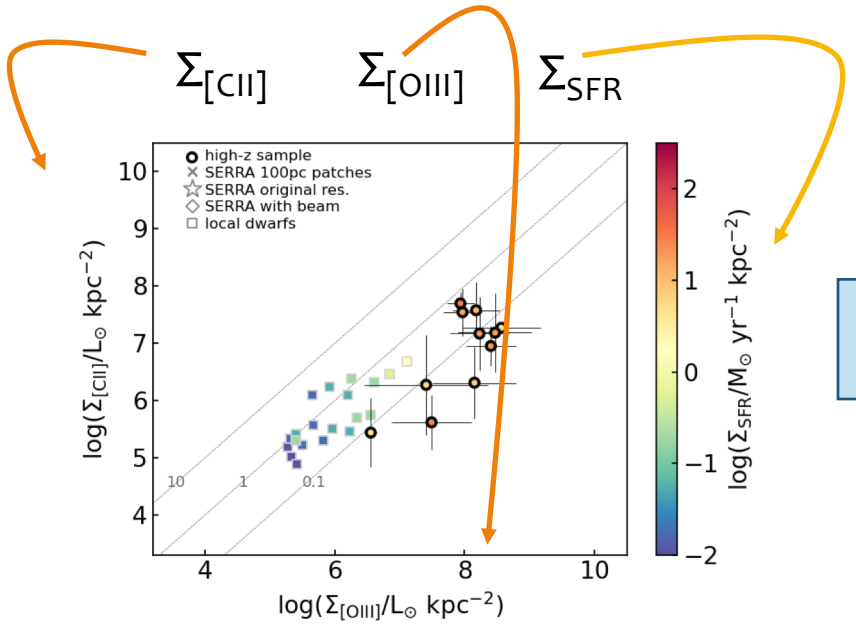


Disentangling the ISM complexity

Three observables



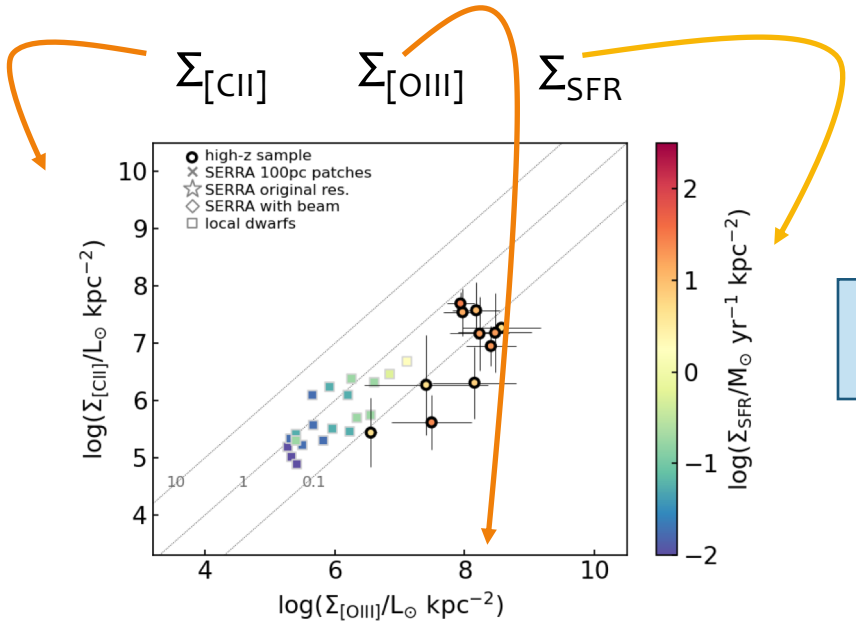
MCMC algorithm

Three parameters

- Gas density n
- Deviation from Kennicutt-Schmidt
- Gas metallicity Z

Disentangling the ISM complexity

Three observables



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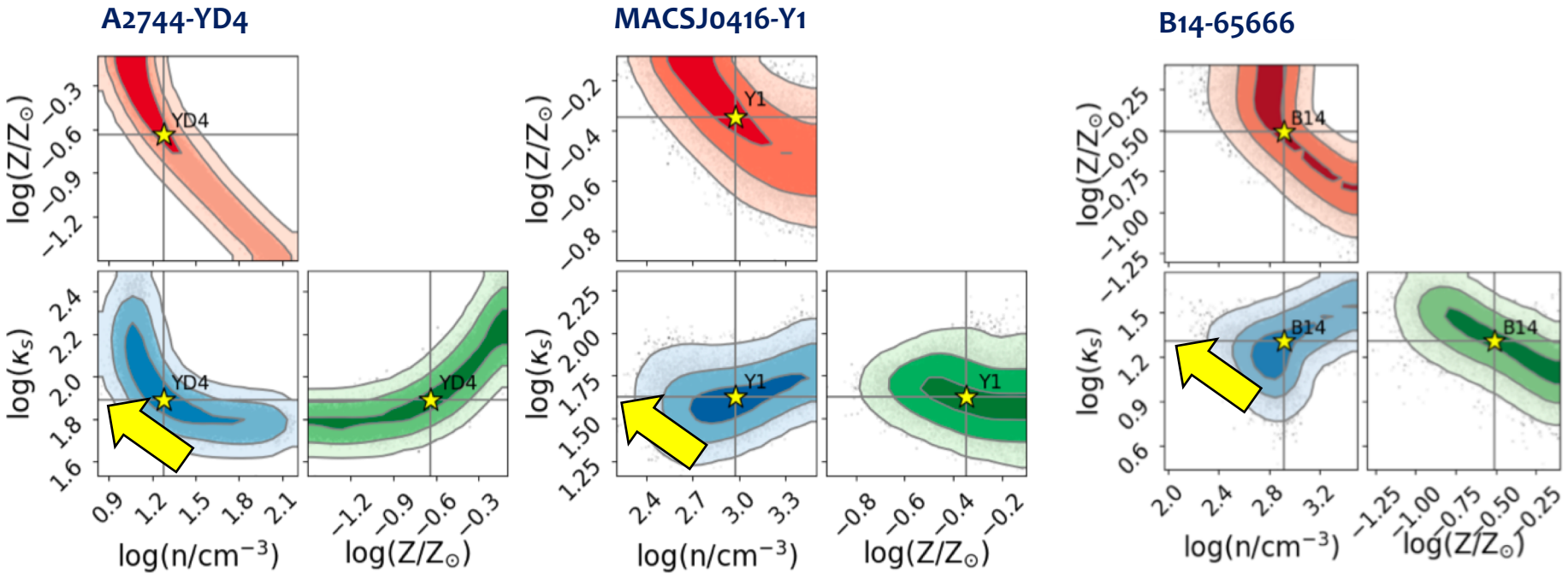
The code (GLAM! Galaxy Line Analyzer with MCMC) and Jupyter notebooks for running on any galaxy of interest is released at: https://lvallini.github.io/MCMC_galaxyline_analyzer/

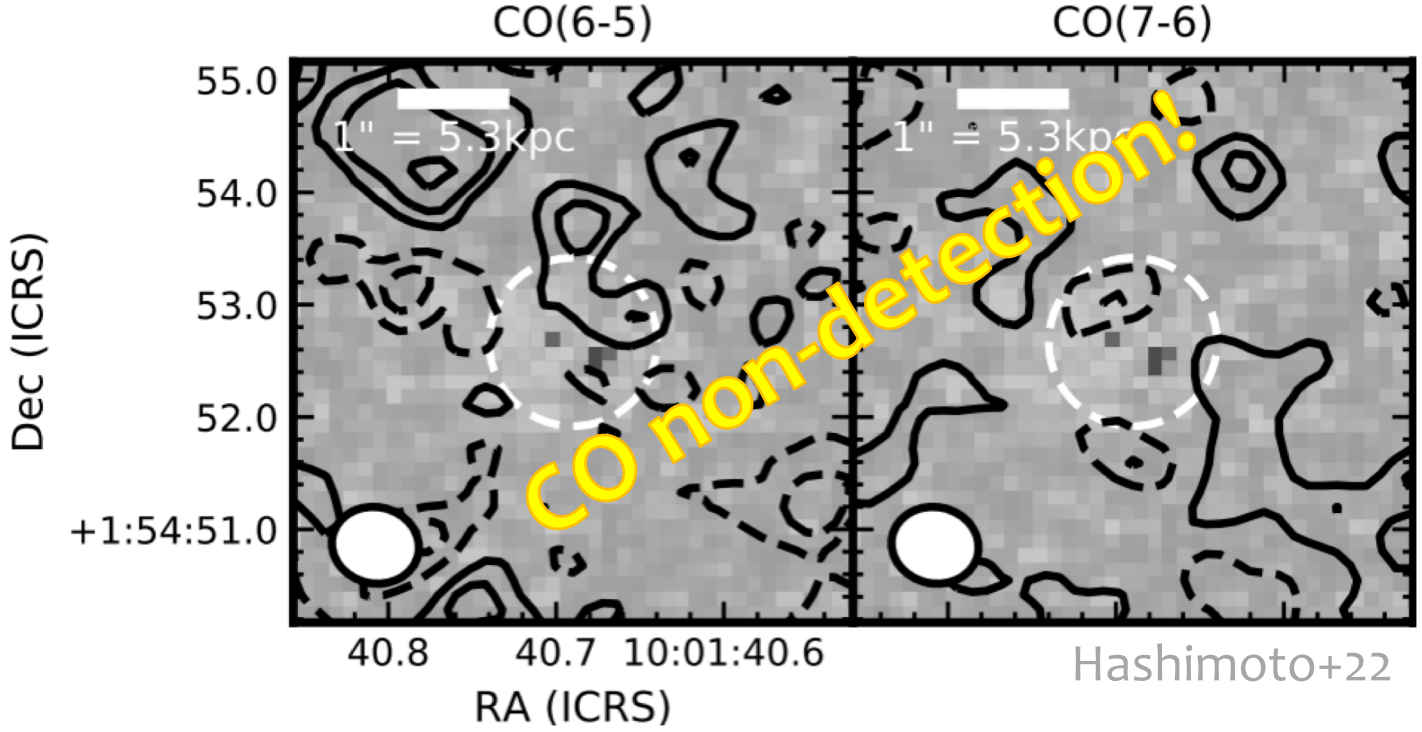
Disentangling the ISM complexity

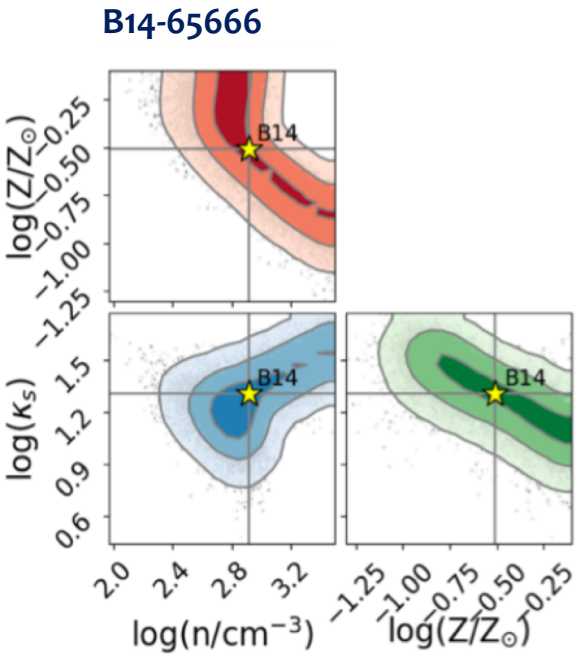


We find k_s ~10-100: [OIII]-[CII] emitters in the EoR are **starburst galaxies with upwards deviation from the KS**

This corresponds to **short depletion times**: $t_{dep} = 6 - 49\ Myr$

Direct measure of the KS relation at high-z



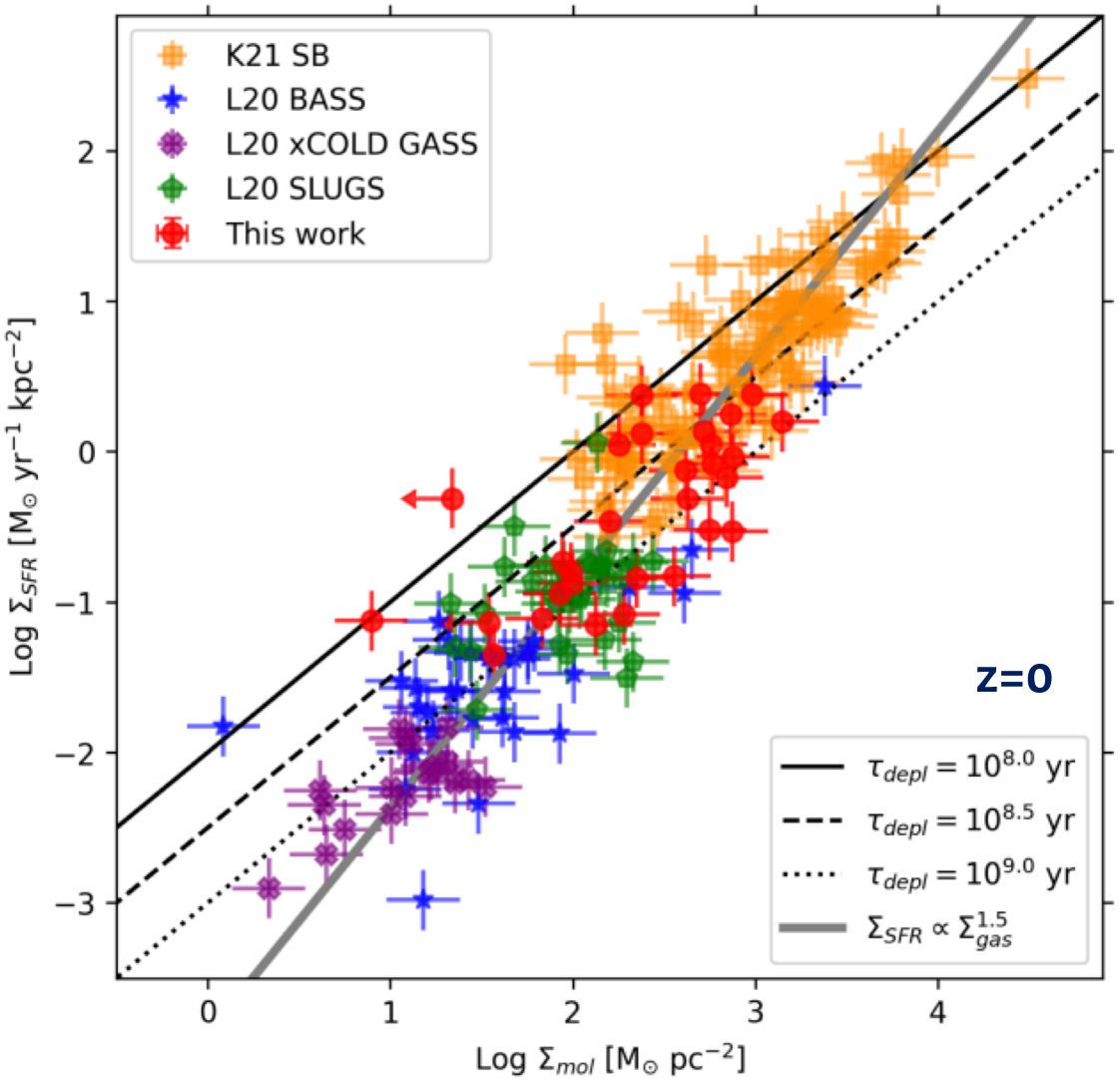


The depletion time can be directly measured if we derive Σ_{gas} from the CO emission: t_{dep}<2.5-550 Myr

This corresponds to **short depletion times**: $t_{dep} = 6 - 49$ *Myr*

Does the Kennicutt-Schmidt relation evolve?

Esposito, LV+22



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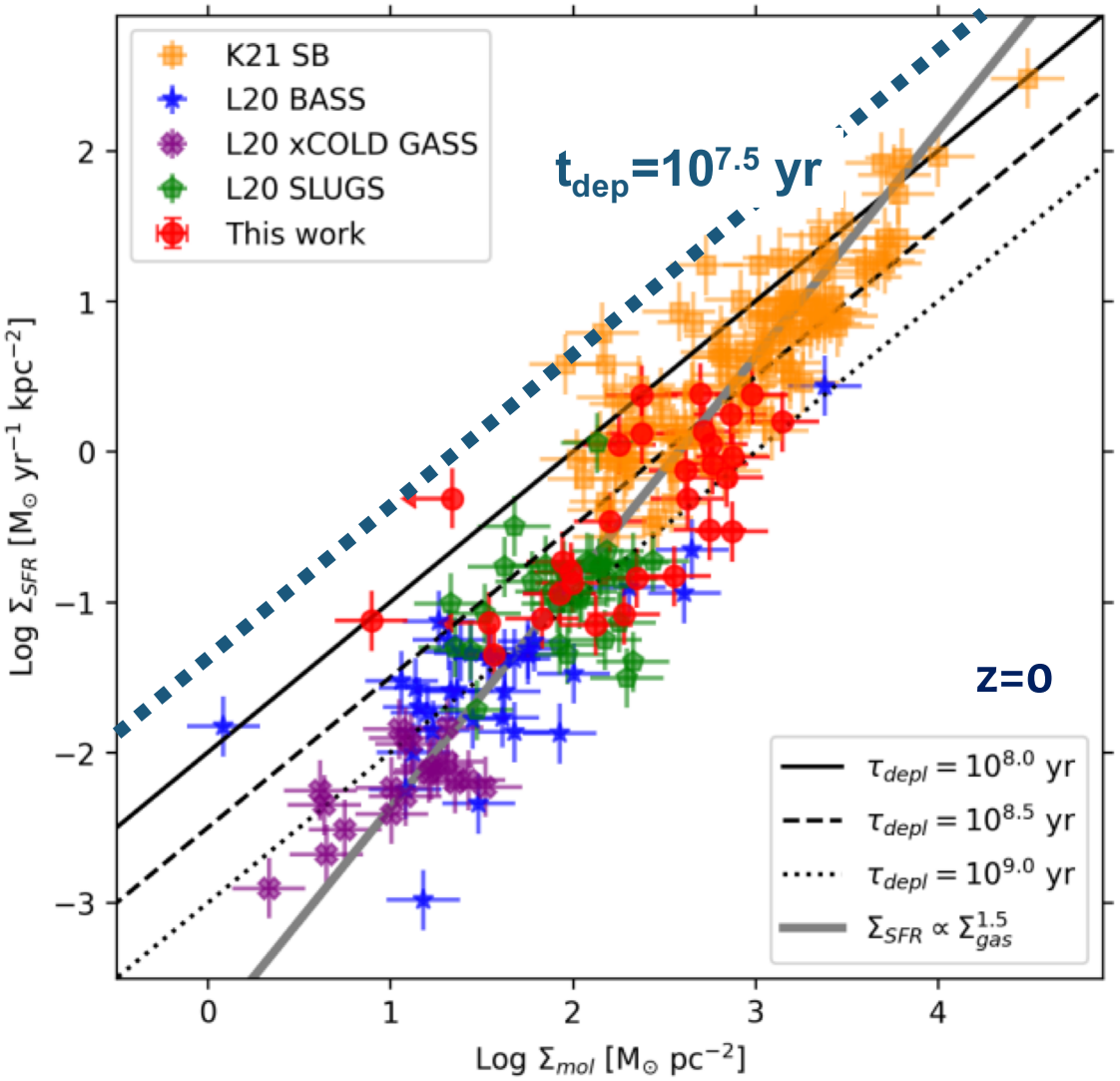

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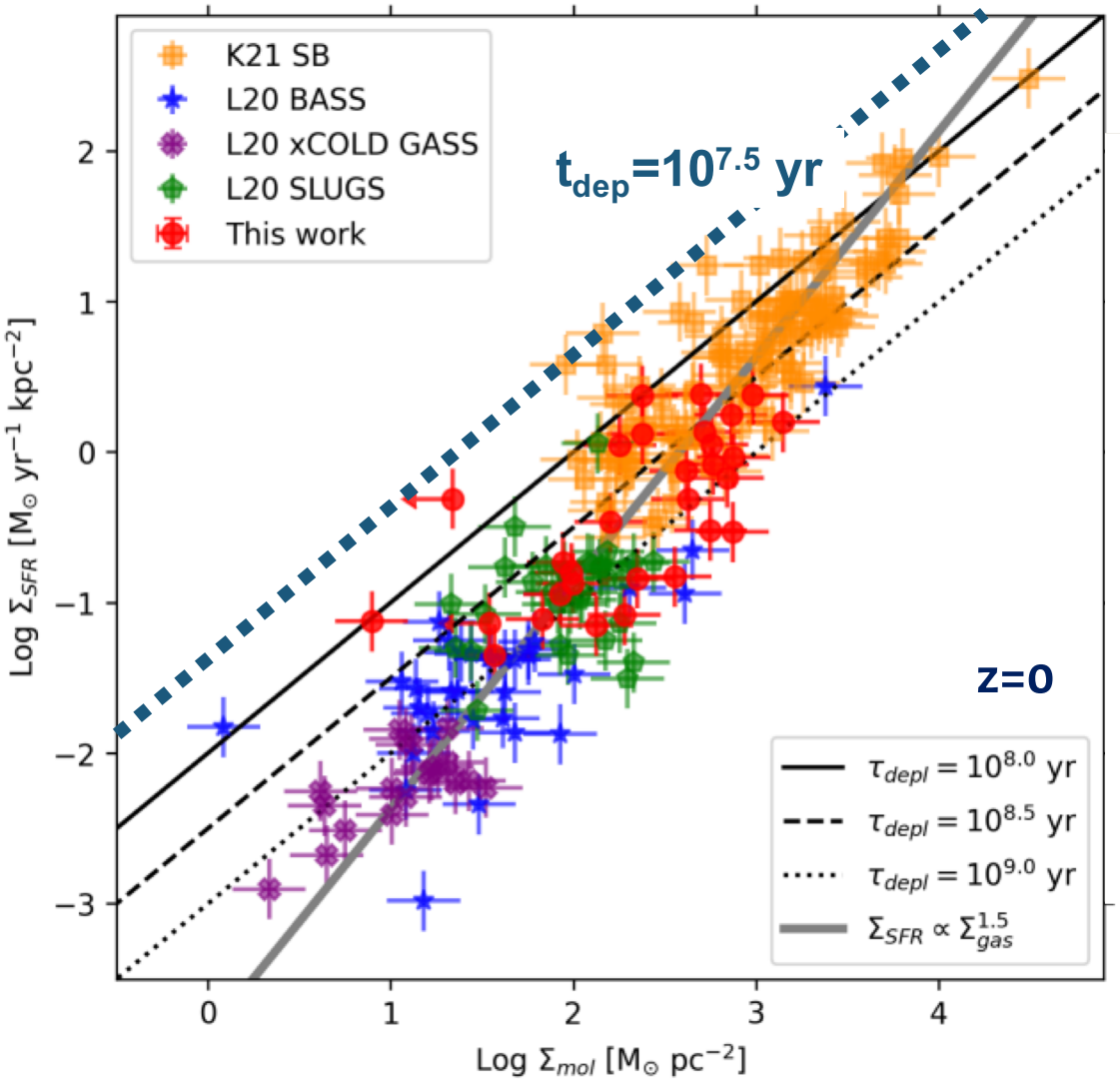
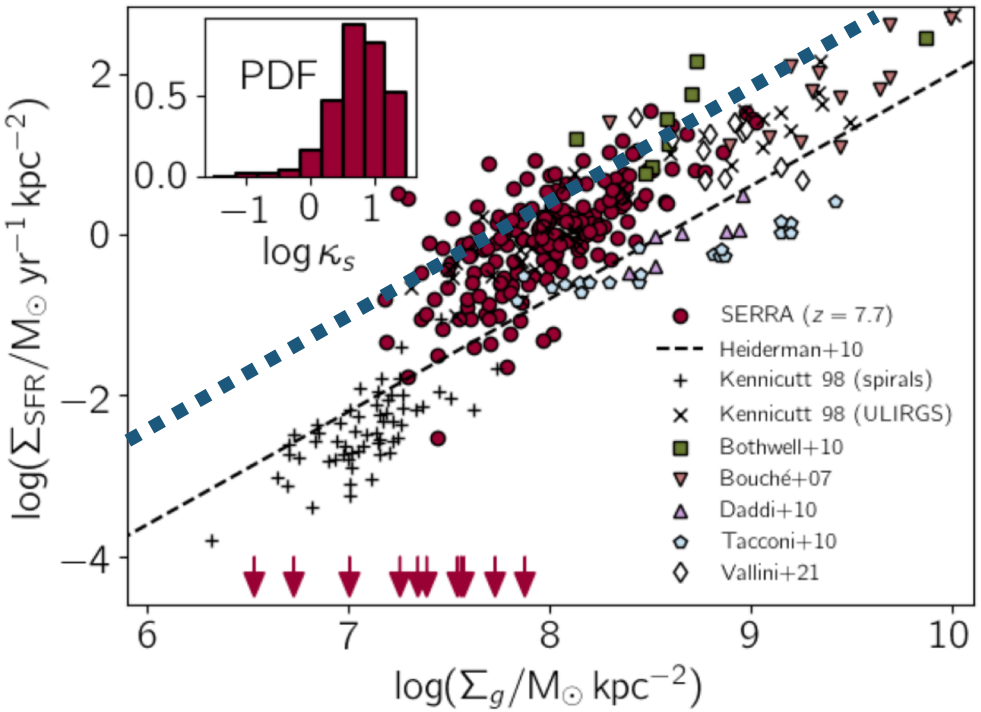
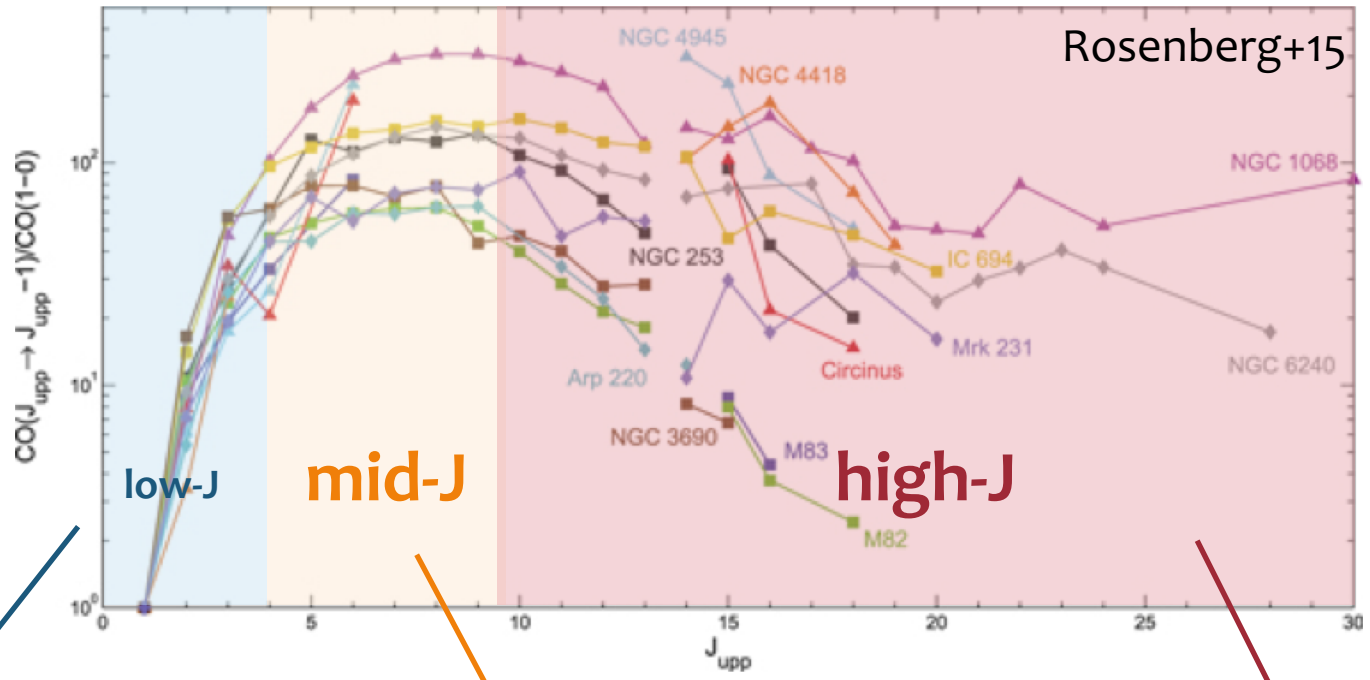


Pallottini+22 z=6-7 SIMULATED GALAXIES



Modelling the CO excitation

CO spectral line energy distribution



see also:
Pozzi+17
Mingozzi+18
Vallini+19
Pensabene+21

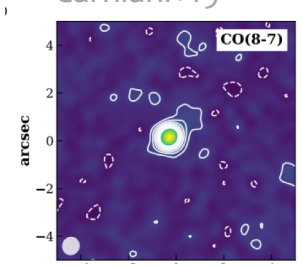
Cold diffuse molecular gas

Warm dense molecular gas

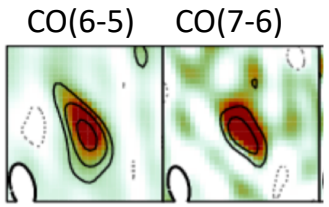
Shocks/X-ray presence

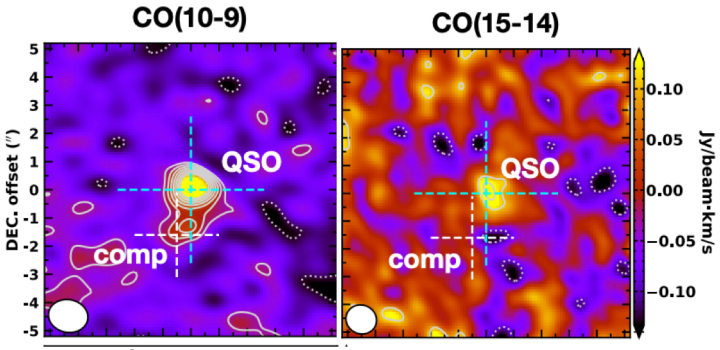
CO detections towards the Epoch of Reionization

Carniani+19



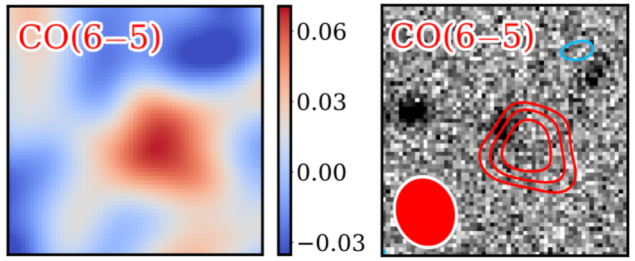
Decarli+22



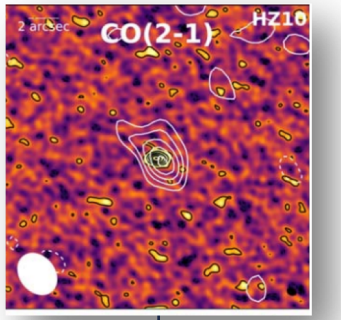


Pensabene+21

Ono, … , LV+22, subm.



Pavesi+16



several QSOs

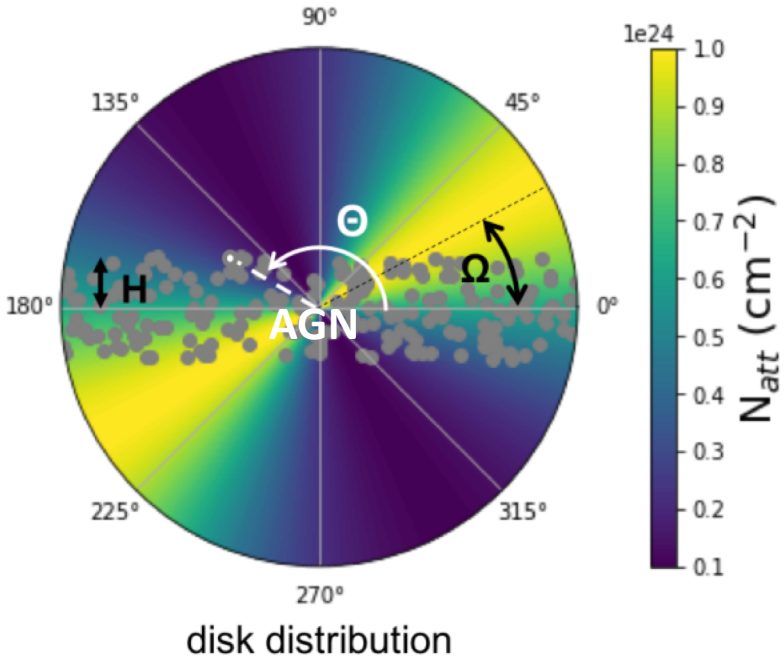
J0235

HZ10

9 8 7 6 redshift

Modelling the CO excitation

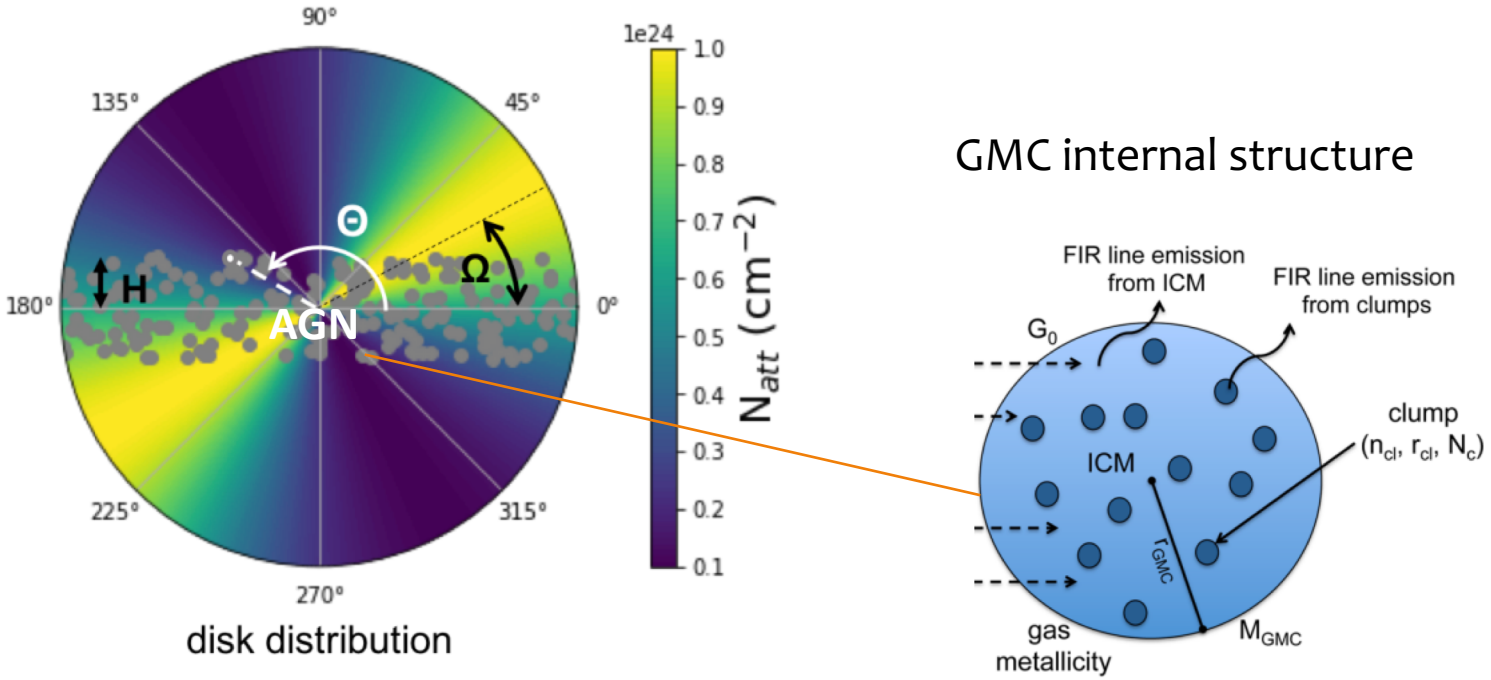
GMC distribution



disk distribution

Modelling the CO excitation

GMC distribution

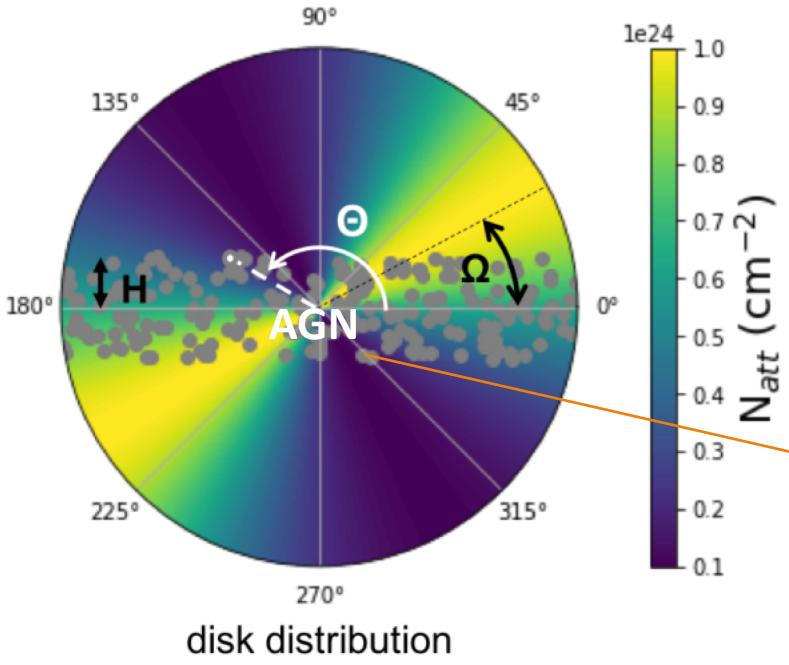


disk distribution

GMC internal structure

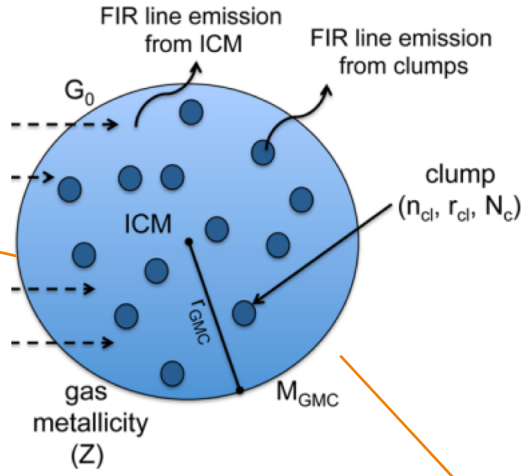
Modelling the CO excitation

GMC distribution

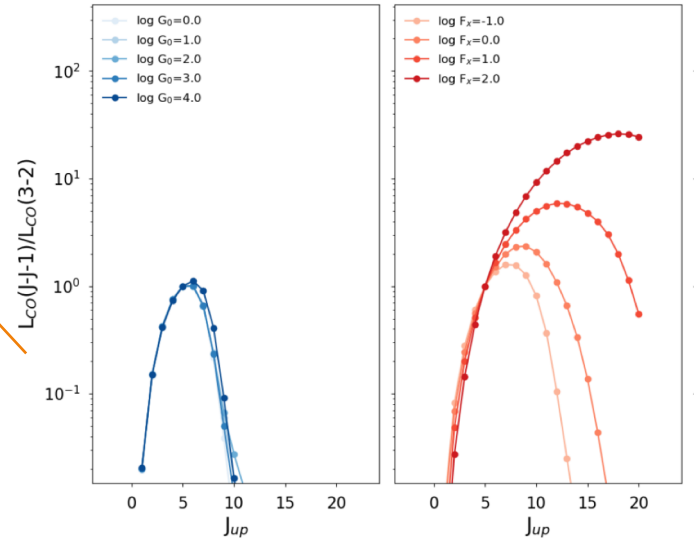


disk distribution

GMC internal structure

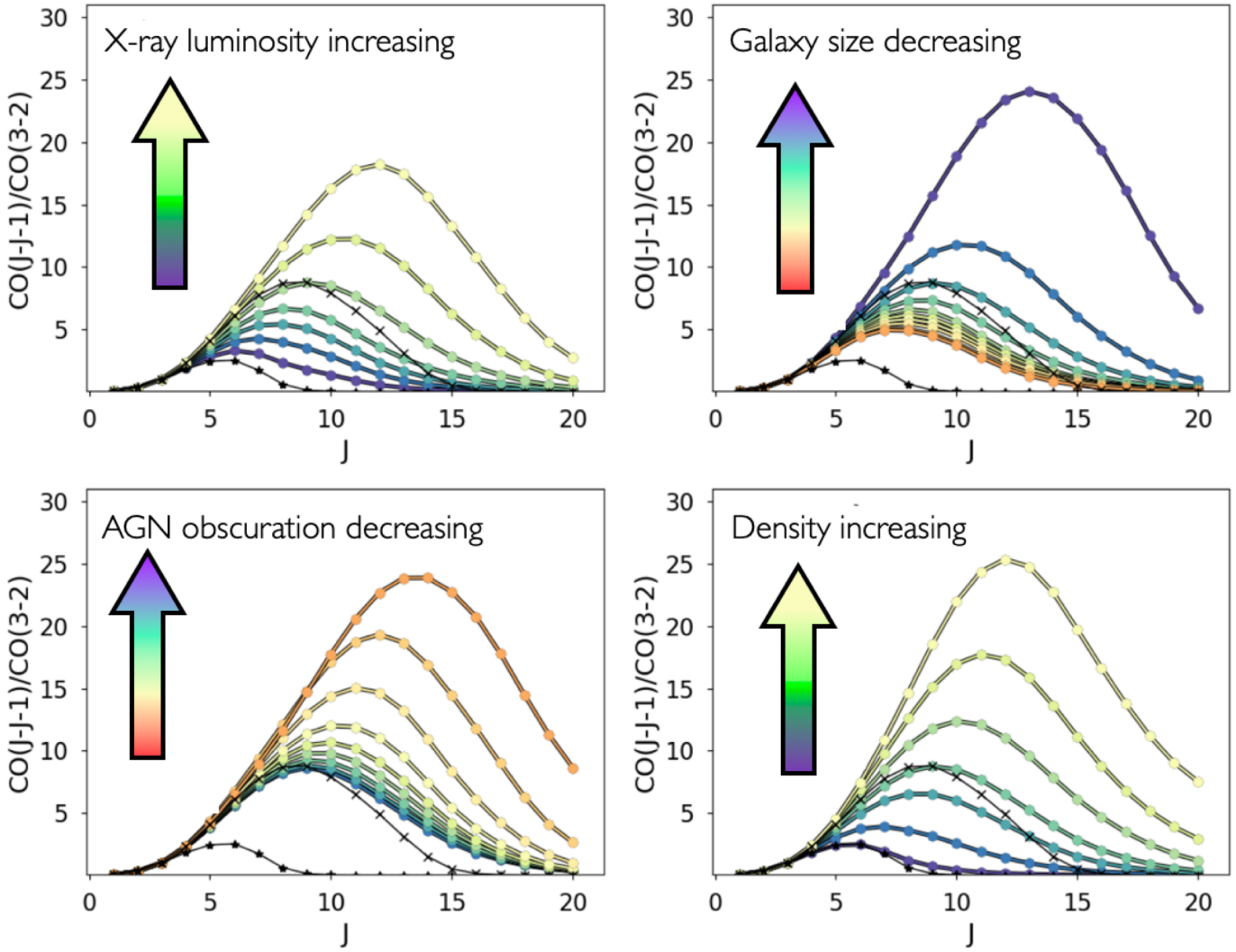


CO emission



Modelling the CO excitation

Vallini+19



Key questions

1. What are the differences between the ISM properties in local vs. high-z galaxies?
2. What are the implications for the star formation across cosmic times?
3. What is the effect of feedback (from AGN/star formation) on the ISM?

A few answers

1. What are the differences between the ISM properties in local vs. high-z galaxies?

High-z galaxies are overall denser, more turbulent, and compact.
This affects the line emission, especially [CII] and CO from molecular clouds

A few answers

1. What are the differences between the ISM properties in local vs. high-z galaxies?
2. What are the implications for the star formation across cosmic times?

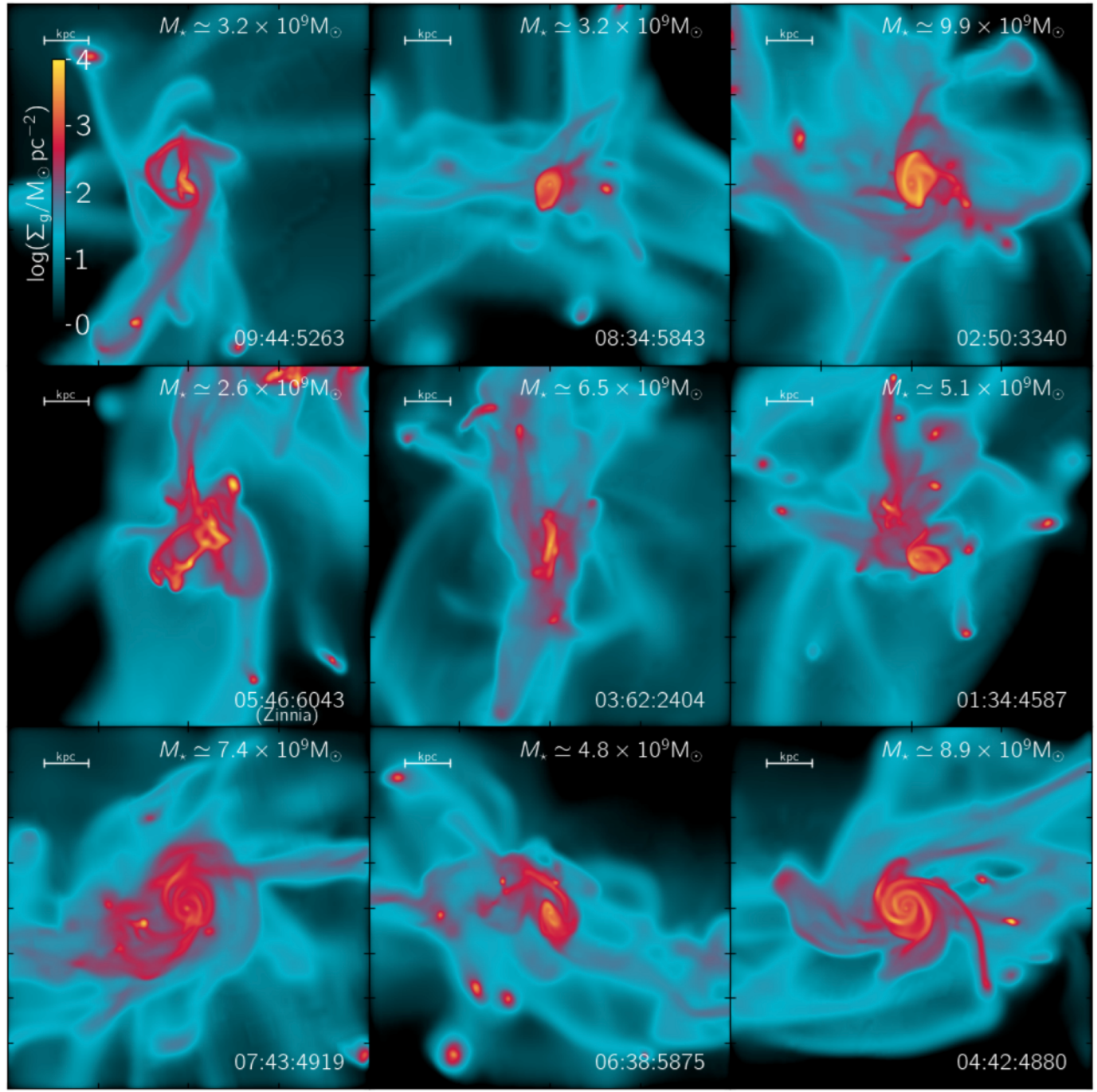
Some hints of a possible evolution of the Kennicutt-Schmidt relation.
Galaxies are overall more bursty, thus [OIII]/[CII] ratios are higher

A few answers

1. What are the differences between the ISM properties in local vs. high-z galaxies?
2. What are the implications for the star formation across cosmic times?
3. What is the effect of feedback (from AGN/star formation) on the ISM?

Possible effect of AGN in the excitation of CO needs to be further addressed
if we want to trace directly the KS relation from the mid-J CO line emission


Thank you


kpc
$M_\star \simeq 3.2 \times 10^9 M_\odot$
$\log(\Sigma_g / M_\odot\,pc^{-2})$
4
3
2
1
0
09:44:5263
$M_\star \simeq 3.2 \times 10^9 M_\odot$
08:34:5843
$M_\star \simeq 9.9 \times 10^9 M_\odot$
02:50:3340
$M_\star \simeq 2.6 \times 10^9 M_\odot$
05:46:6043
(Zinnia)
$M_\star \simeq 6.5 \times 10^9 M_\odot$
03:62:2404
$M_\star \simeq 5.1 \times 10^9 M_\odot$
01:34:4587
$M_\star \simeq 7.4 \times 10^9 M_\odot$
07:43:4919
$M_\star \simeq 4.8 \times 10^9 M_\odot$
06:38:5875
$M_\star \simeq 8.9 \times 10^9 M_\odot$
04:42:4880