Astrochemistry in Extreme Environments

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Molecules and planets in the outer Galaxy
Florence, 12-14 Nov, 2024

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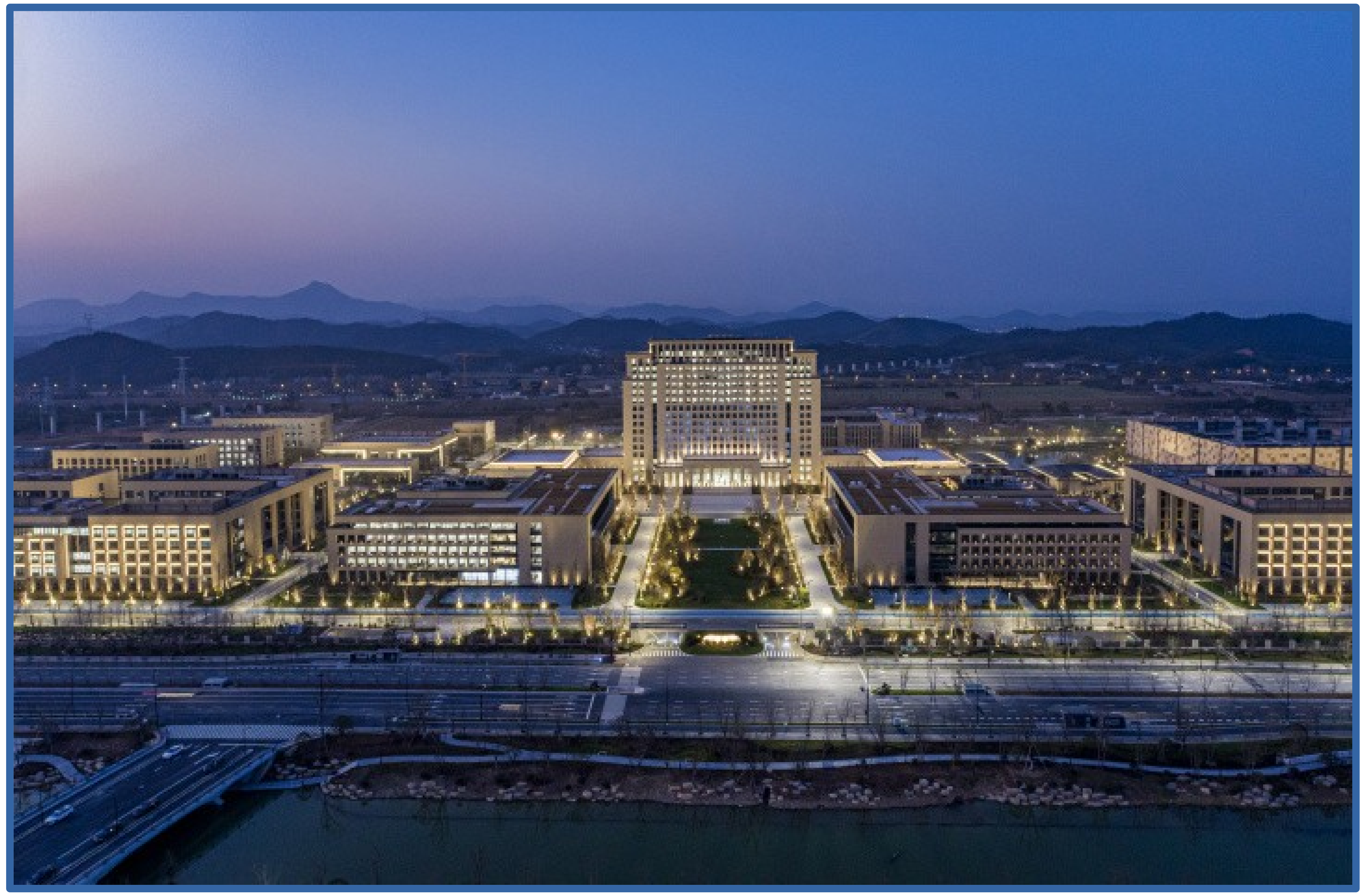


- Founded in September 2017, initiated by the Zhejiang Province
- Main focus: intelligent computing
- >3000 researchers

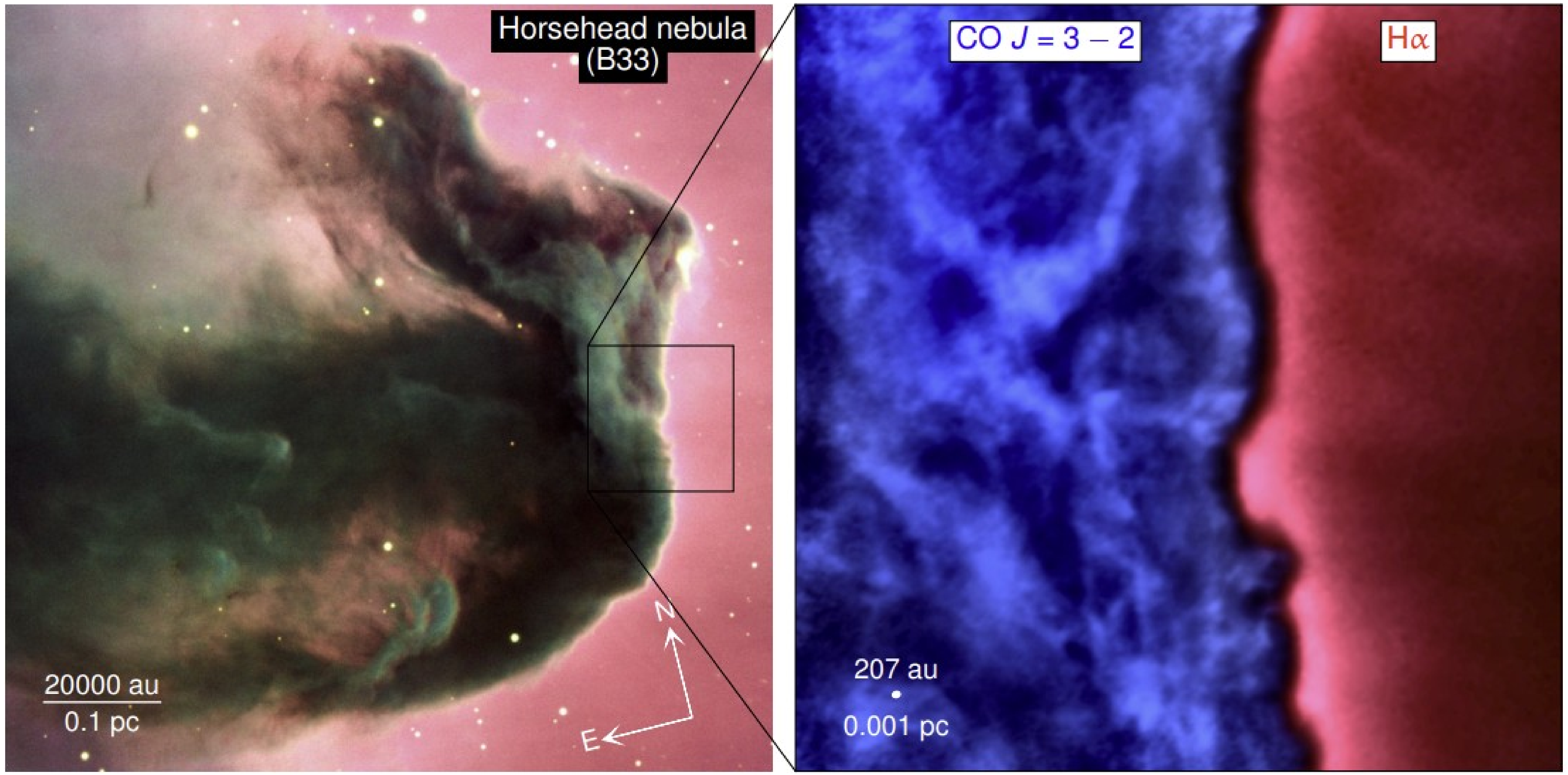
Photodissociation Regions (PDRs)

Neutral regions

Atomic-to-molecular (HI-to-H_2) transition

Radiation

JWST



Hernandez-Vera+ (2023)

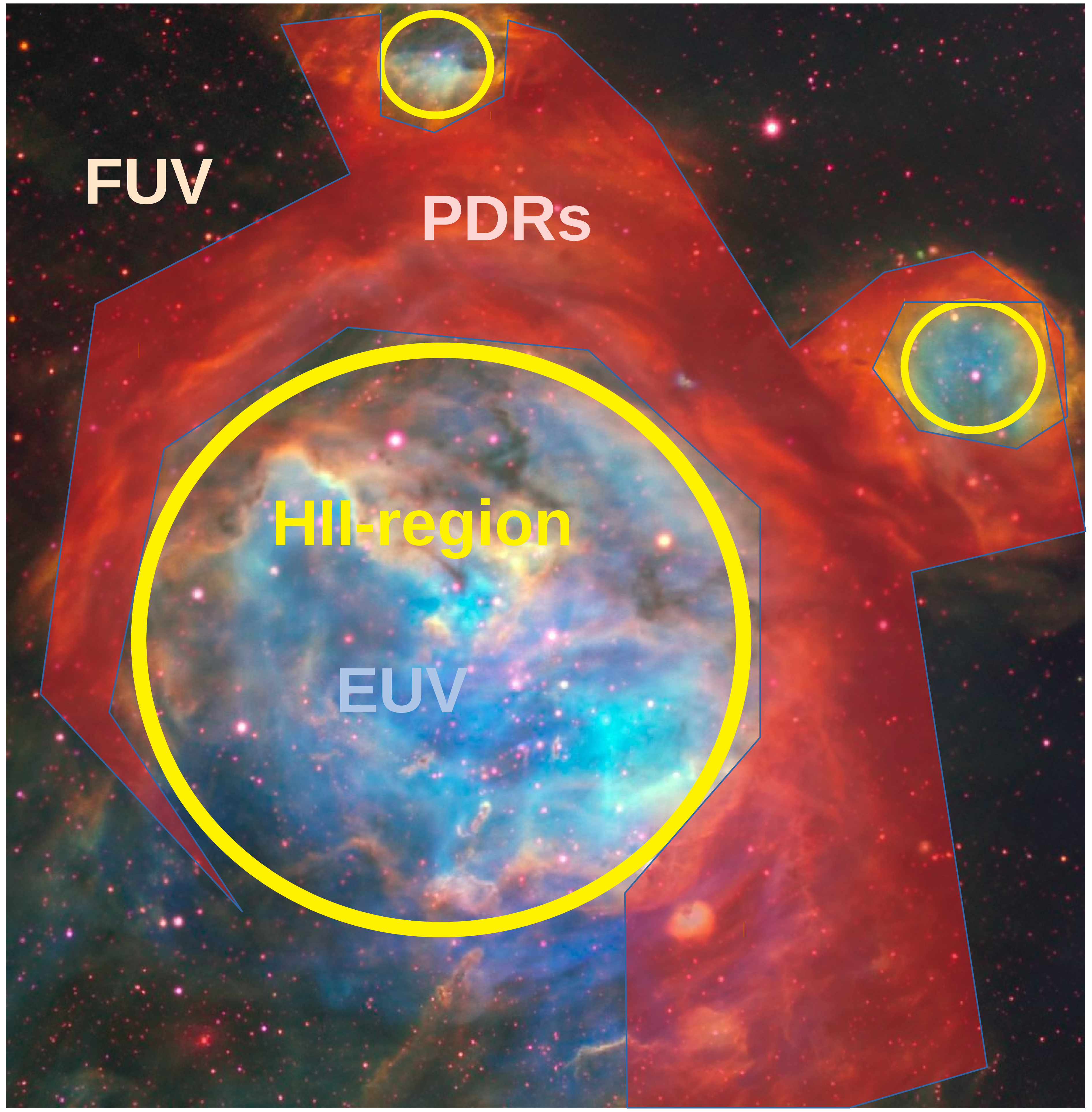
Interstellar Radiation Field (ISRF)

Extreme-ultraviolet (EUV): $h\nu \geq 13.6\,\mathrm{eV}$

Far-ultraviolet (FUV): $6 < h\nu < 13.6\,\mathrm{eV}$

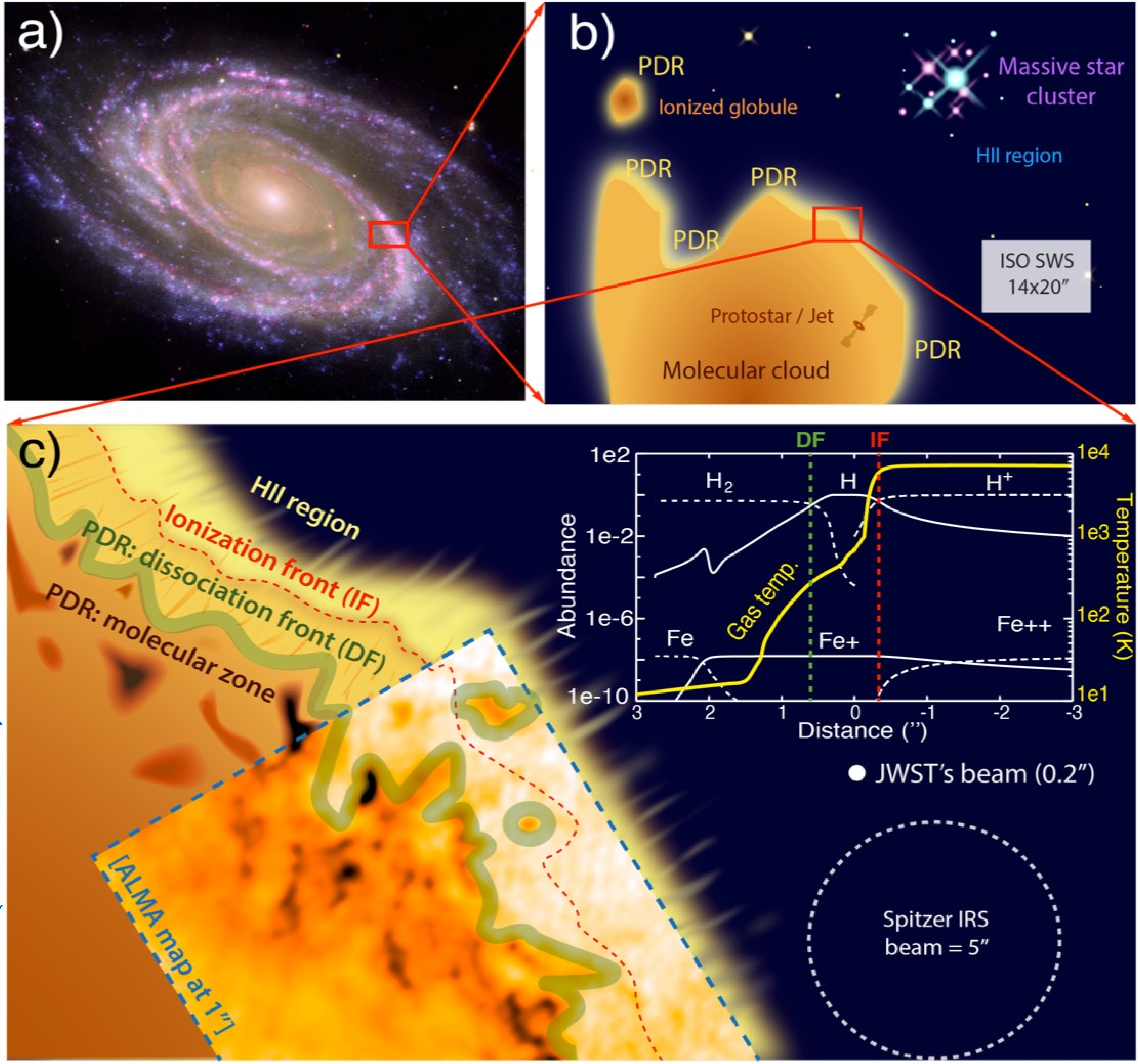
HII regions: regions around a bright source, rich in EUV photons

Photodissociation Regions (PDRs): regions rich in FUV photons. Important for controlling the ISM chemistry.



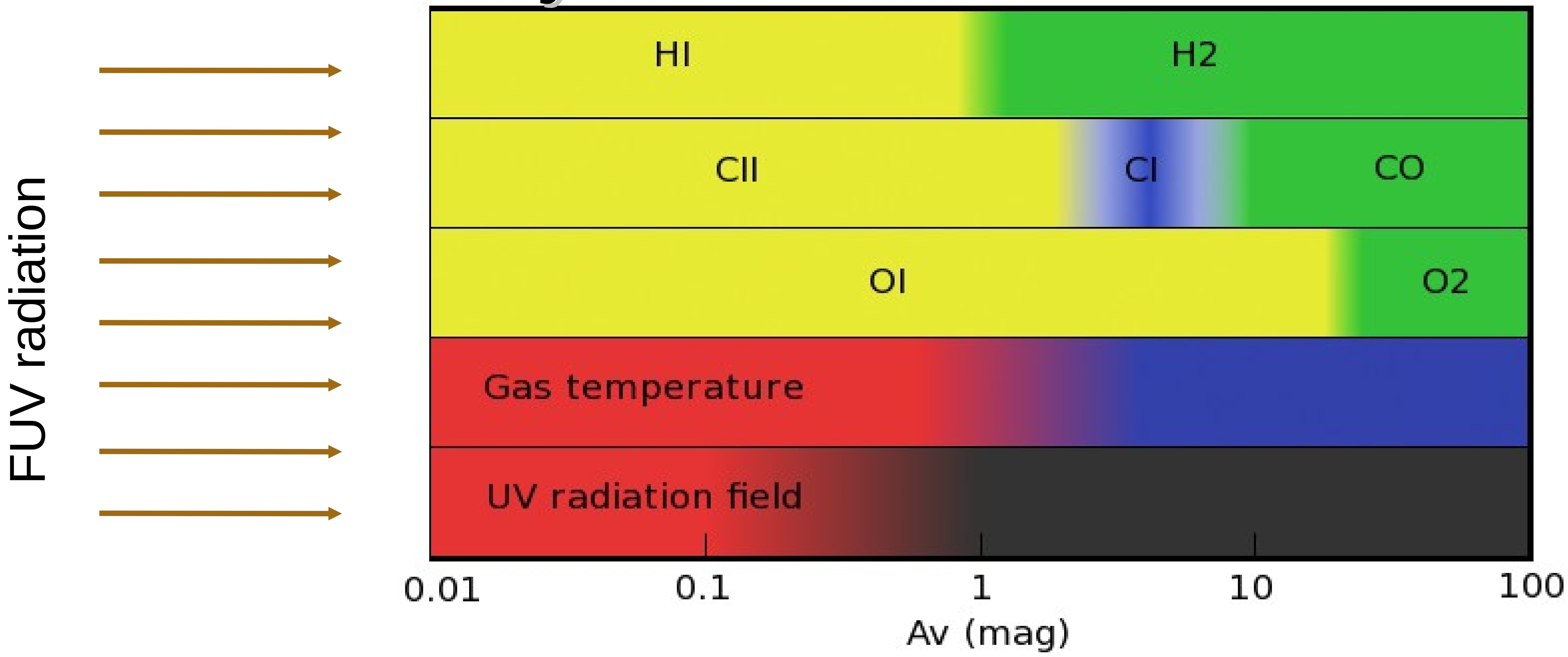
Photodissociation Regions

A large fraction of the ISM is associated with PDRs

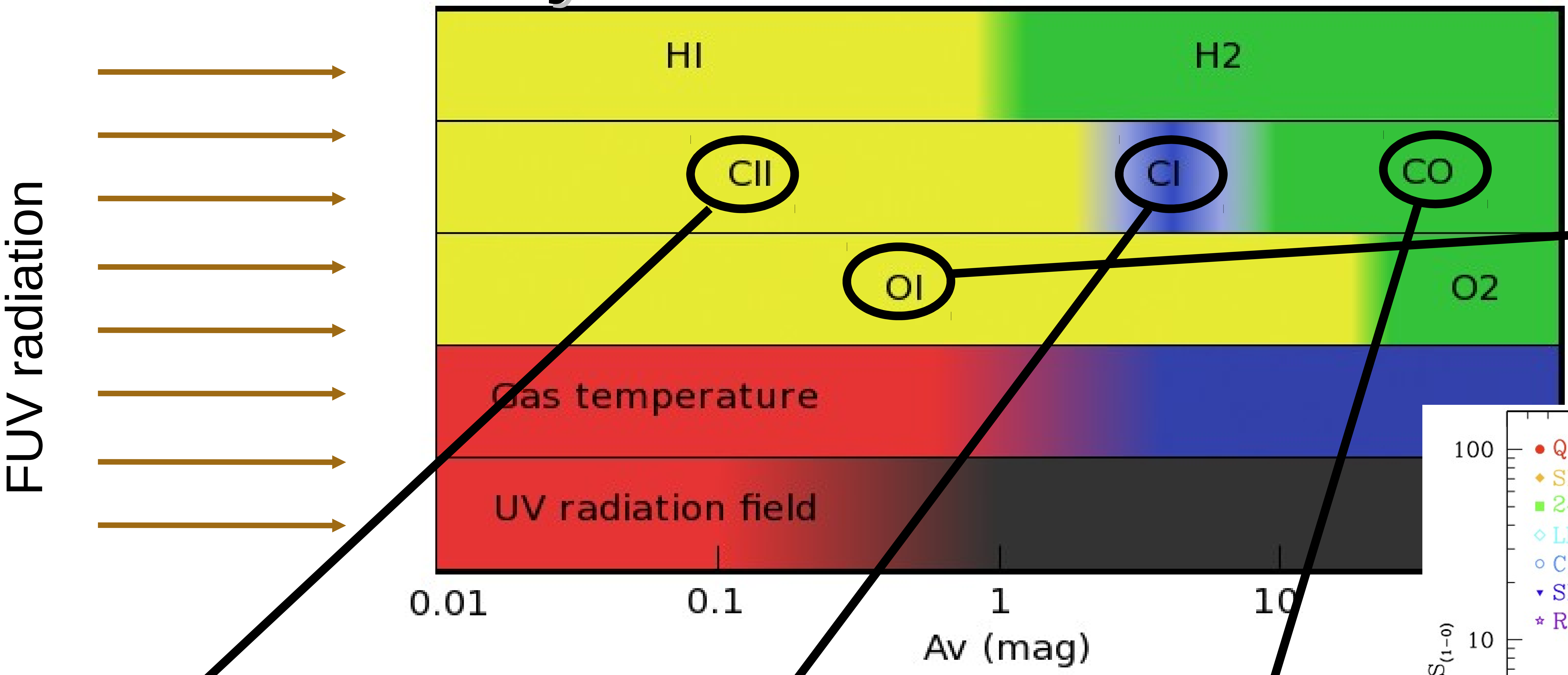


PDRs4all (Berne+ 2022)

The carbon cycle and the HI-to-H2 transition



The carbon cycle and the HI-to-H2 transition

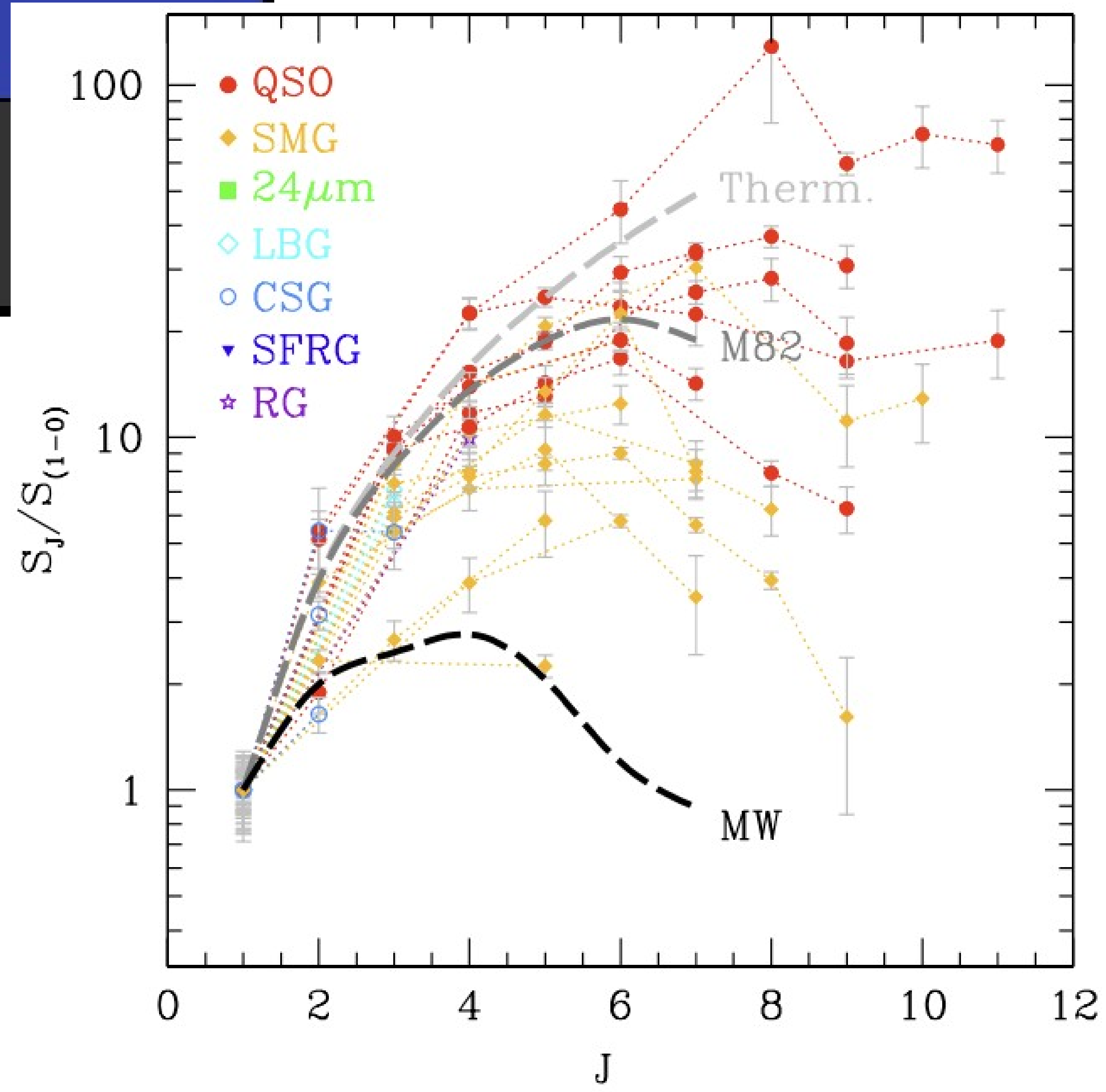


[OI] 63 µm
[OI] 146 µm

[CII] 158 µm

[CI](1-0) 609 µm
[CI](2-1) 370 µm

CO J=1-0
CO J=2-1
CO J=3-2 …



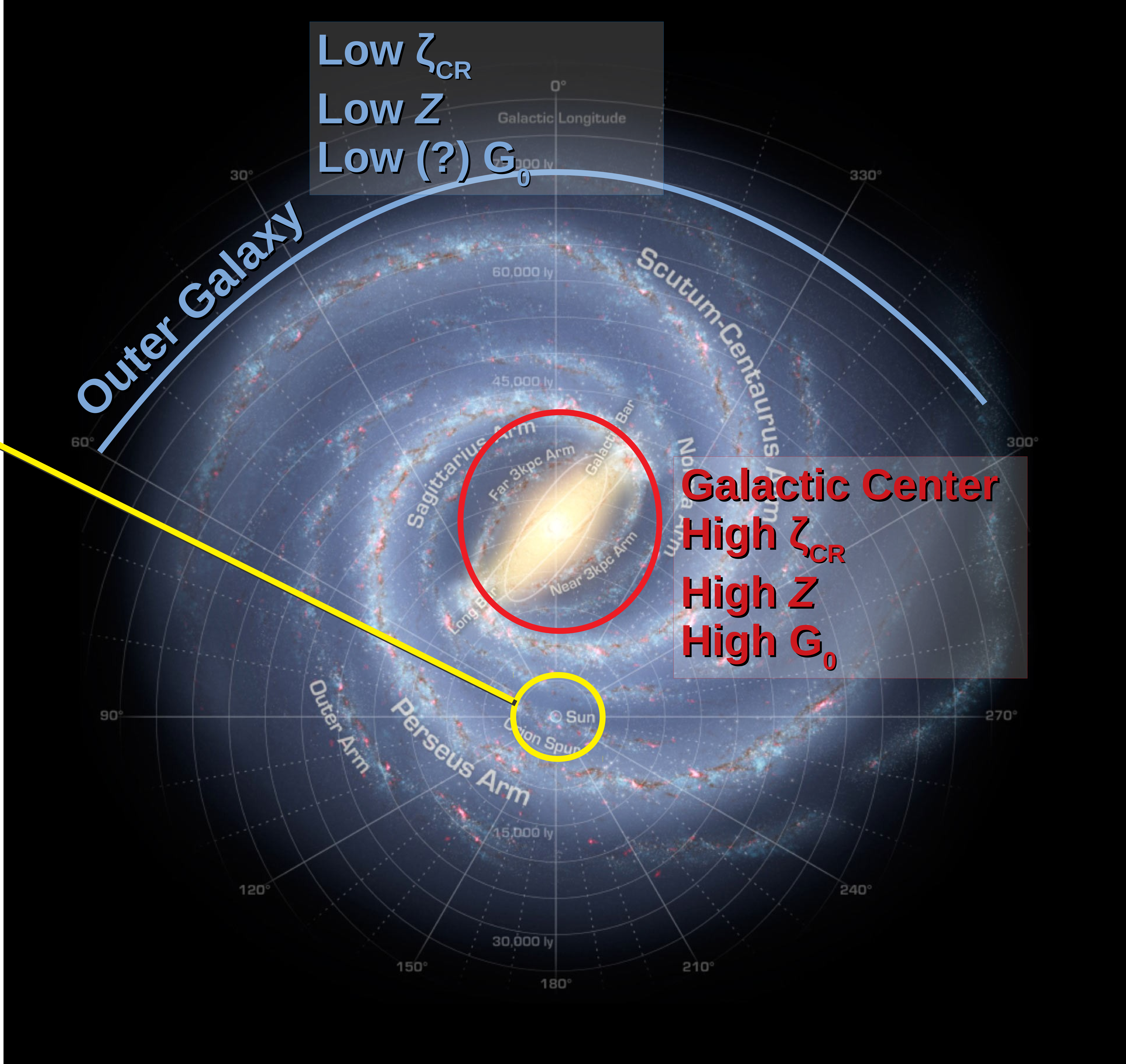
Carilli & Walter (2013)

The higher the transition, the denser the ISM it traces.

What are "extreme" conditions?

"*Extreme*" defined in contrast to the more "*typical*" ISM environments

- ✓Radiation Field
- ✓Gas temperature
- ✓Density
- ✓Pressure
- ✓Cosmic-ray flux
- ✓X-ray flux
- ✓Metallicity
- ...etc



In the extragalactic context

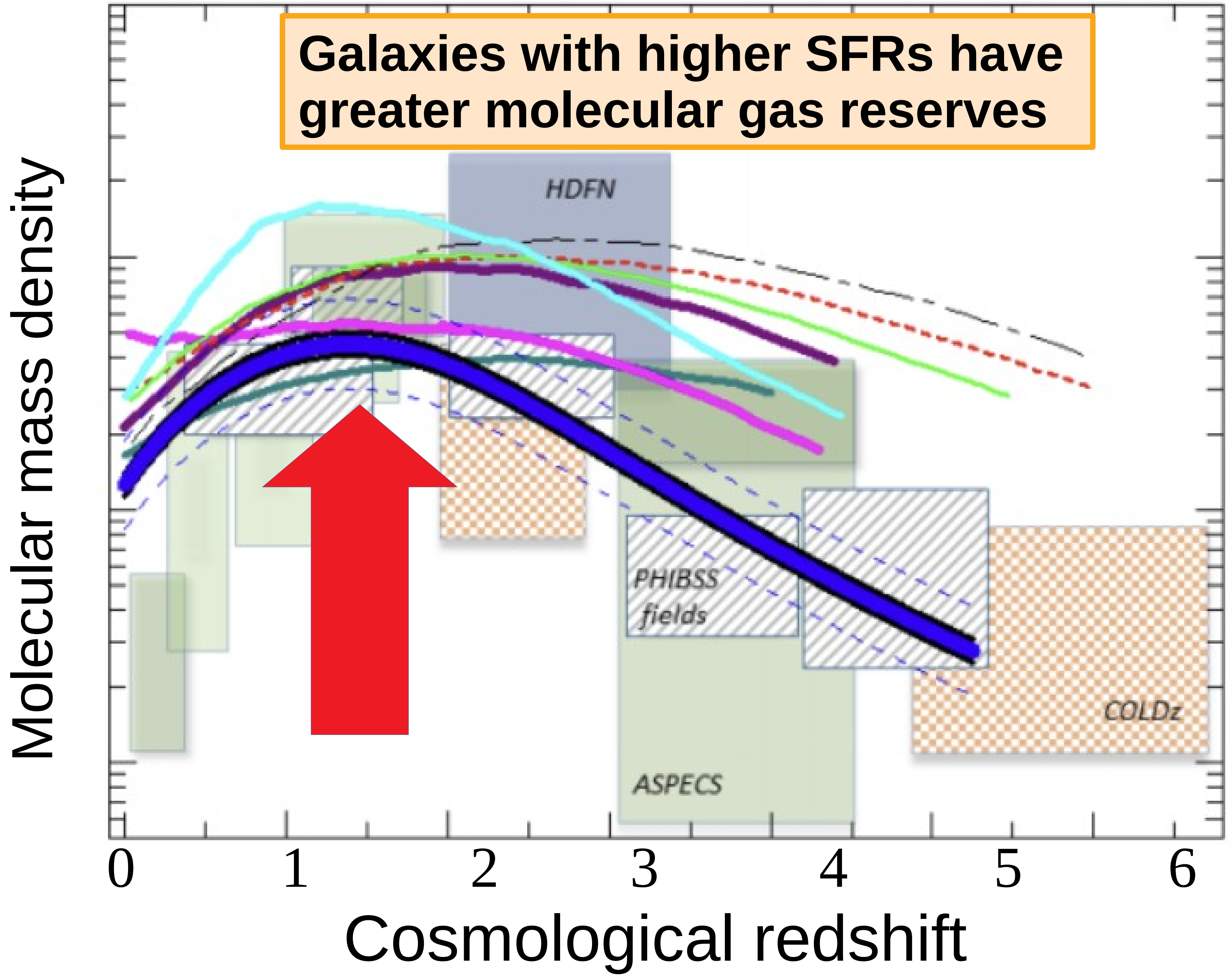
Star Formation Rate

Cosmic-ray ionization rate

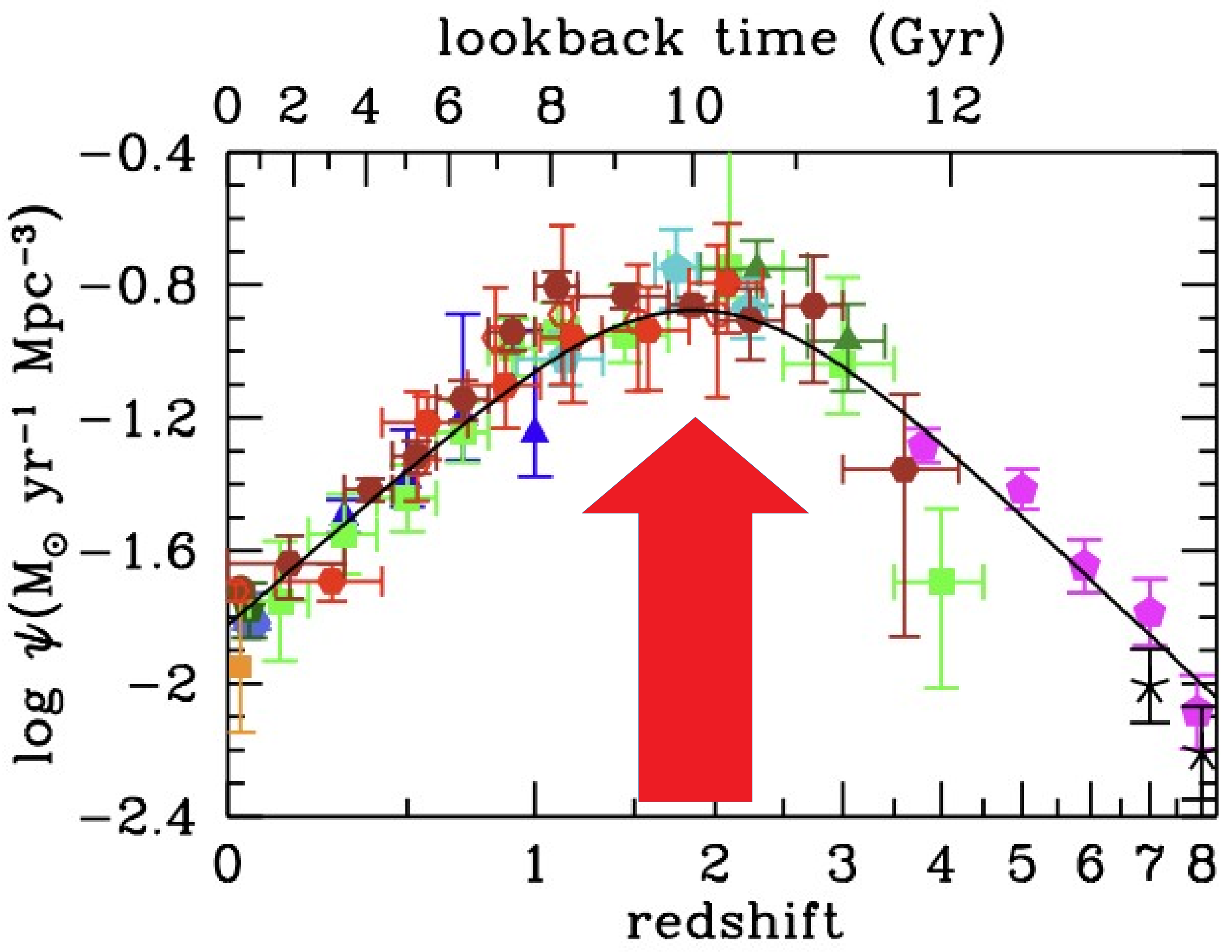
FUV intensity

Metallicity

- Higher SFR increases ζ_{CR} and FUV intensities
- High FUV intensities reflect star formation activity
- Metallicity modulates the amount of cooling

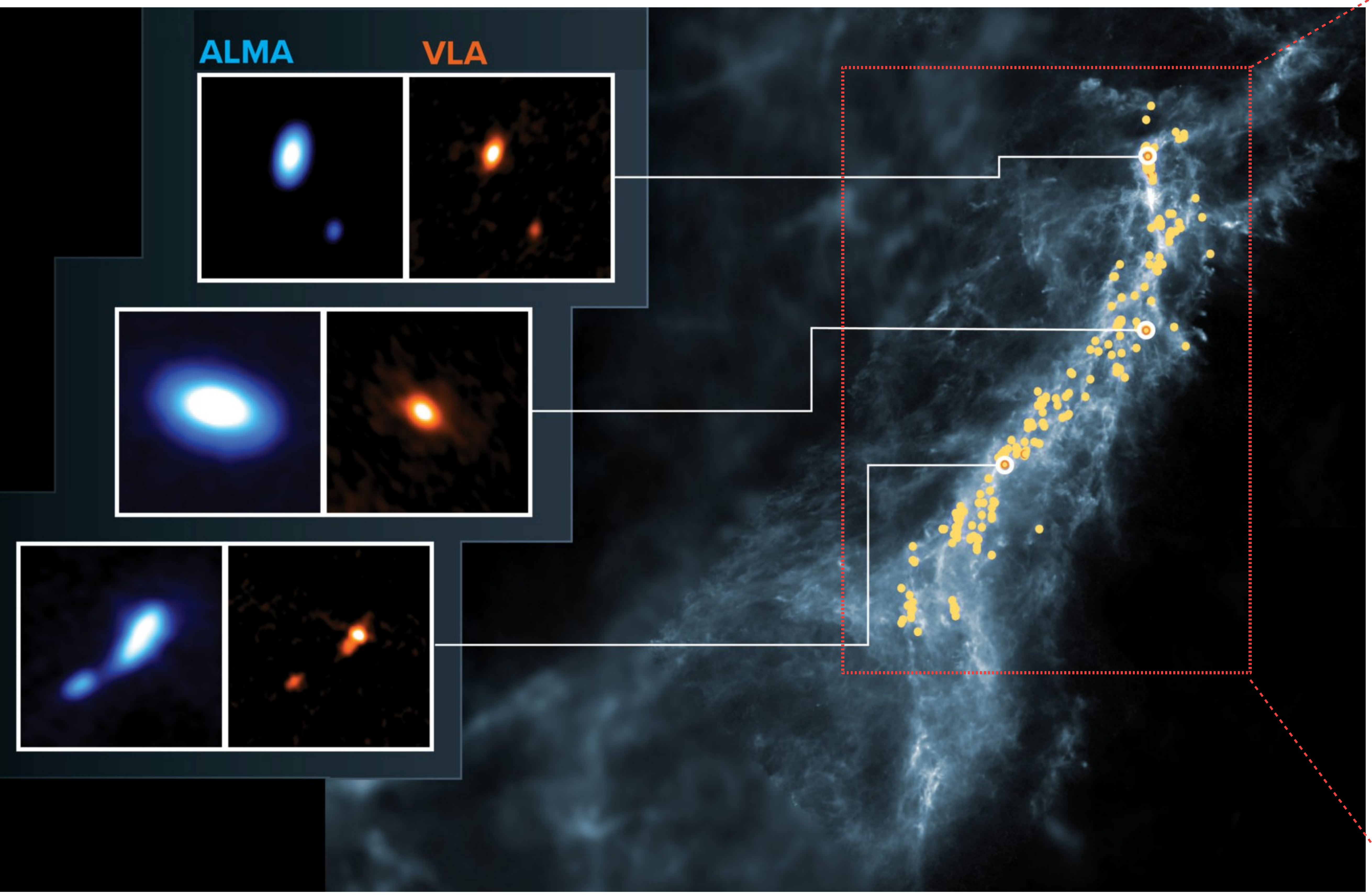


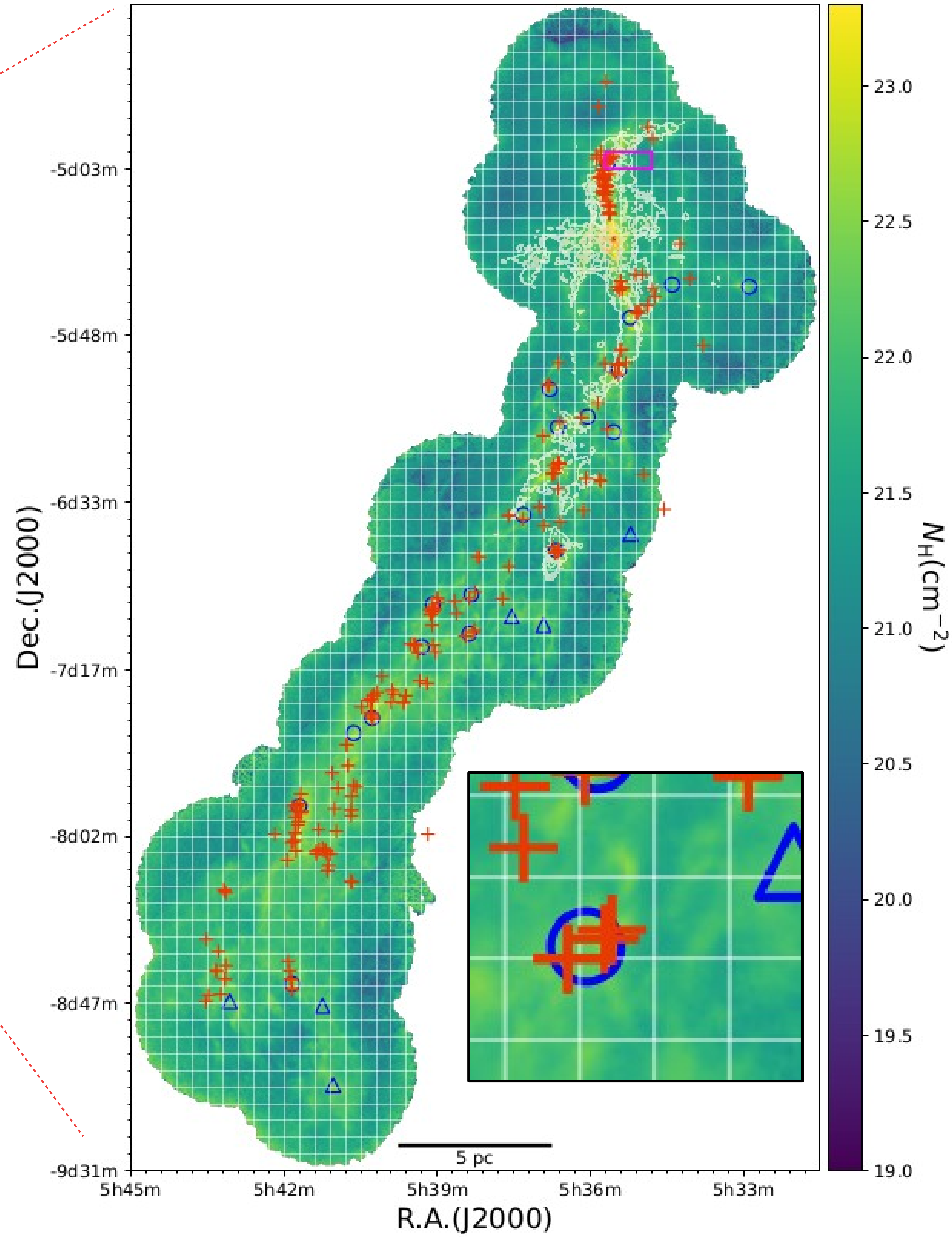
Tacconi+20



Madau & Dickinson 14

Example: Orion A molecular cloud





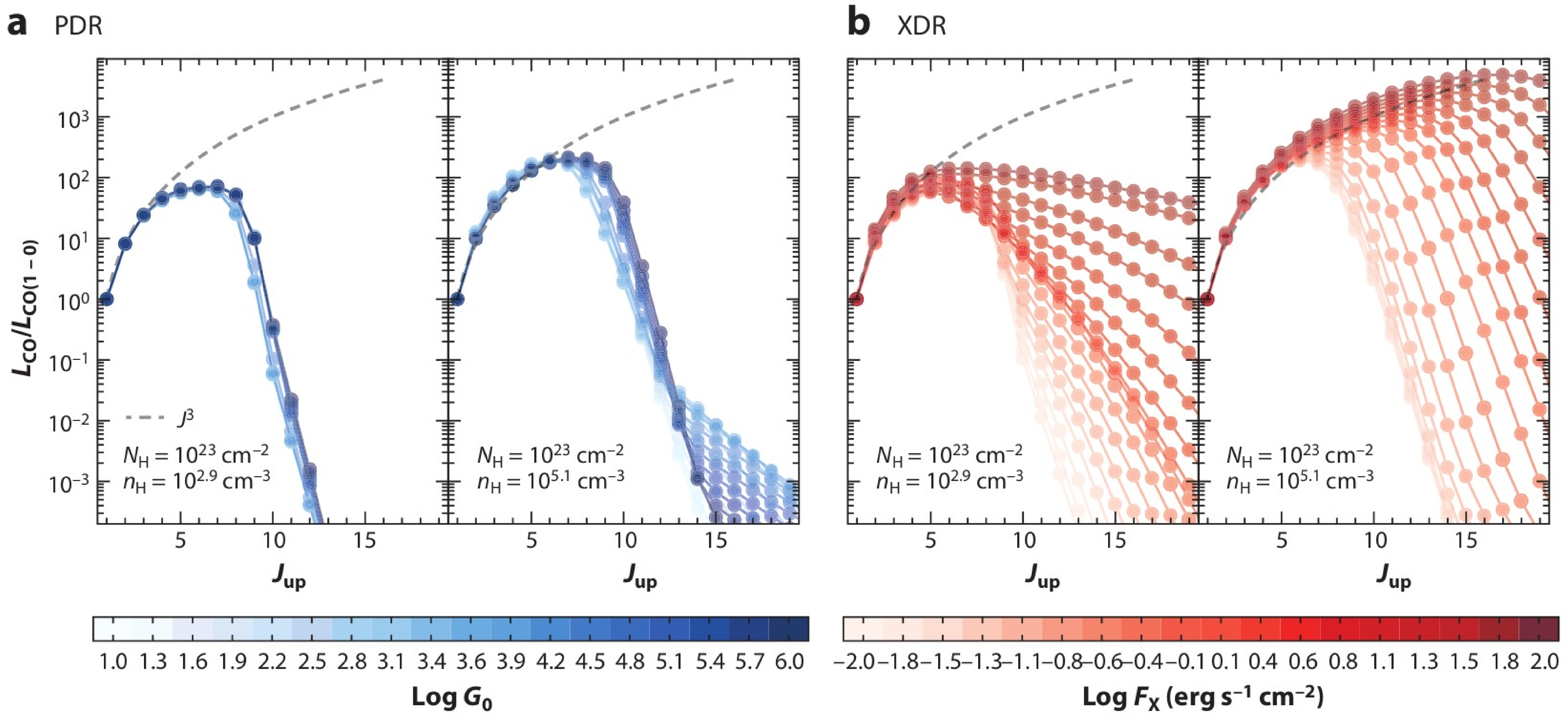
PDFchem

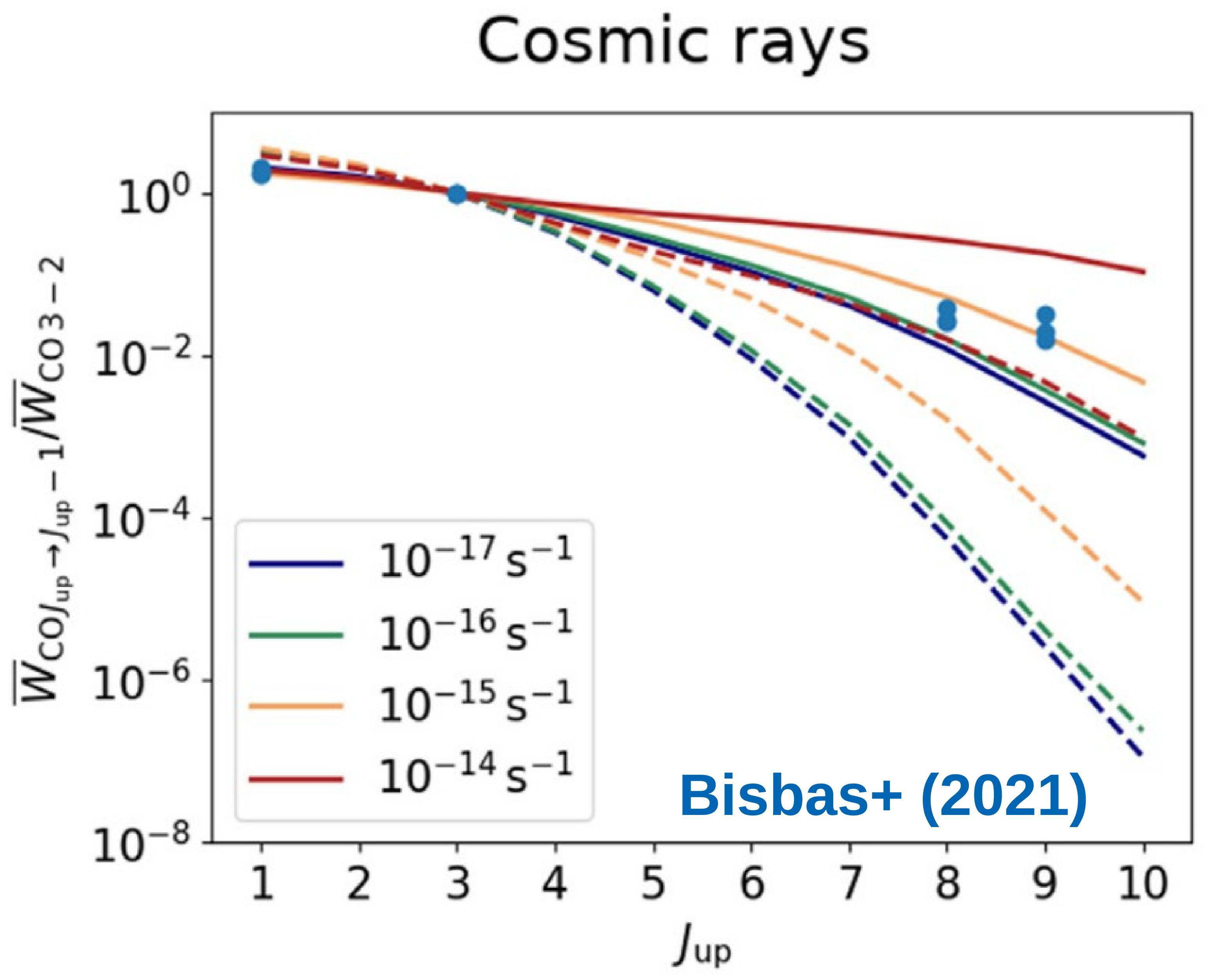
Bisbas et al. (2023)
Jiang, Bisbas et al. *submitted*

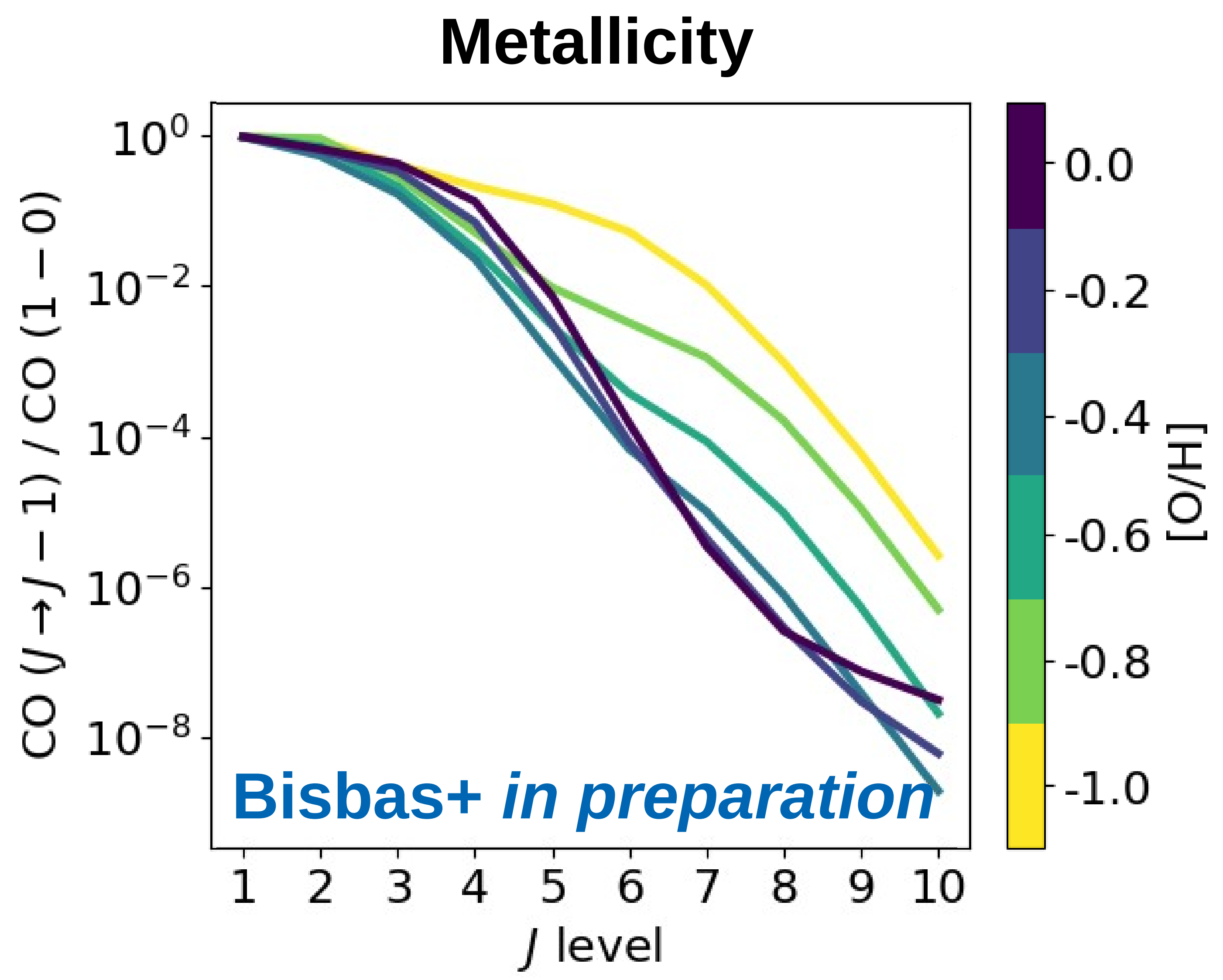
Fast computations!

Results: synthetic maps of ① FUV, ② ζ_{CR} and ③ carbon cycle

CO Spectral Line Energy Distributions (SLEDs)







Pensabene+ (2021)
See also review by **Wolfire+ (2023)**

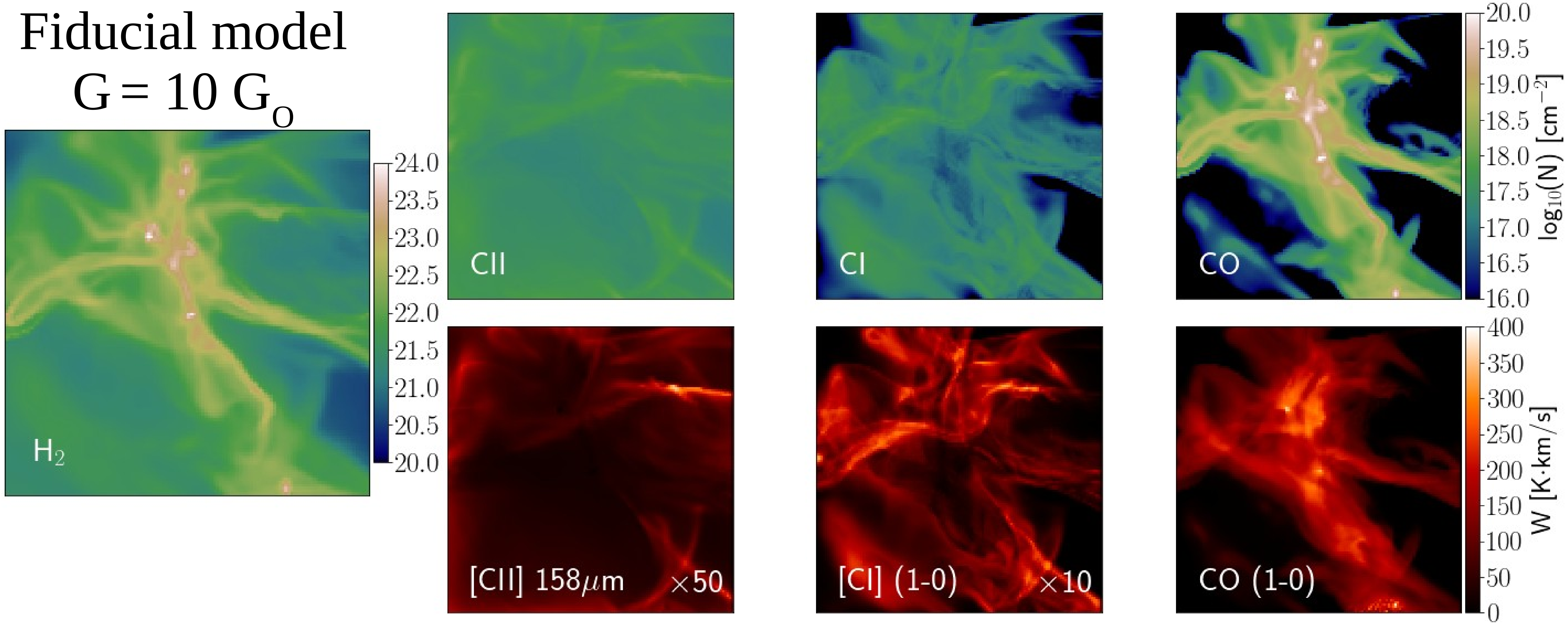
> Elevated high-*J* CO SLEDs indicate the presence of a heating source at high column densities

Effect of FUV intensity

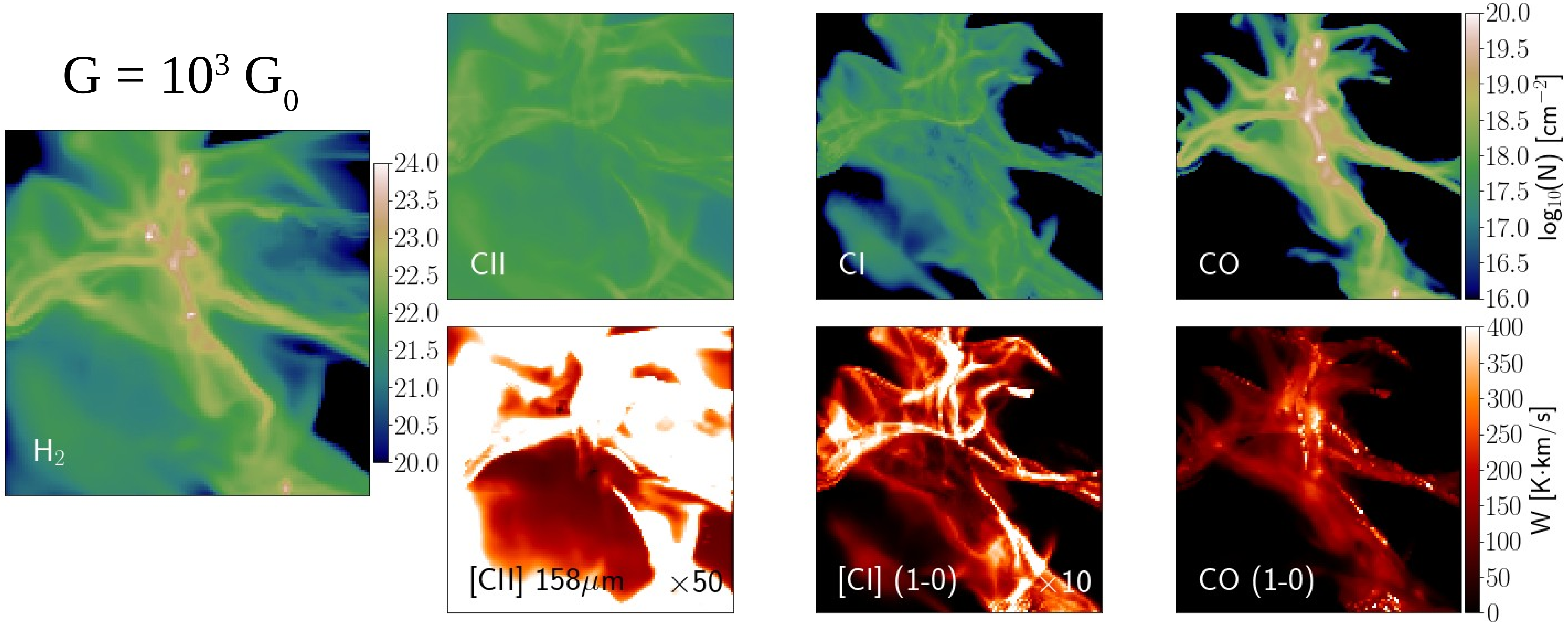
Bisbas et al. (2021)

- $N(H_2)$ is affected in the outer parts
- $N(CII)$ is increased
- $W(CII)$ is highly increased in the outer parts.
  → [CII] deficit?

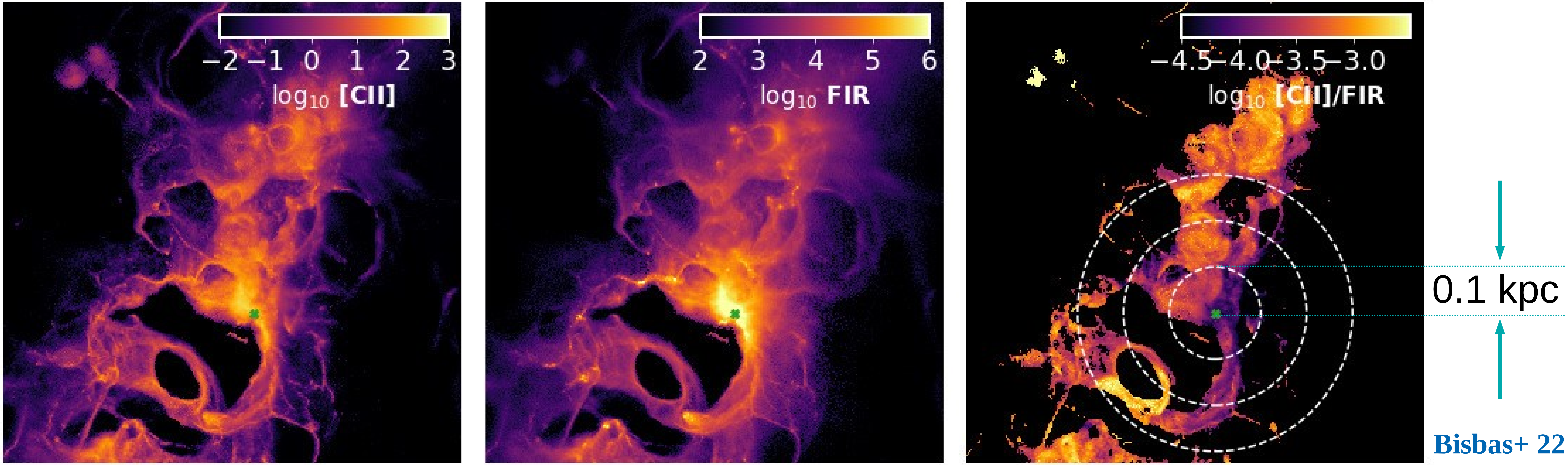
Fiducial model
$G = 10\ G_O$



$G = 10^3\ G_0$

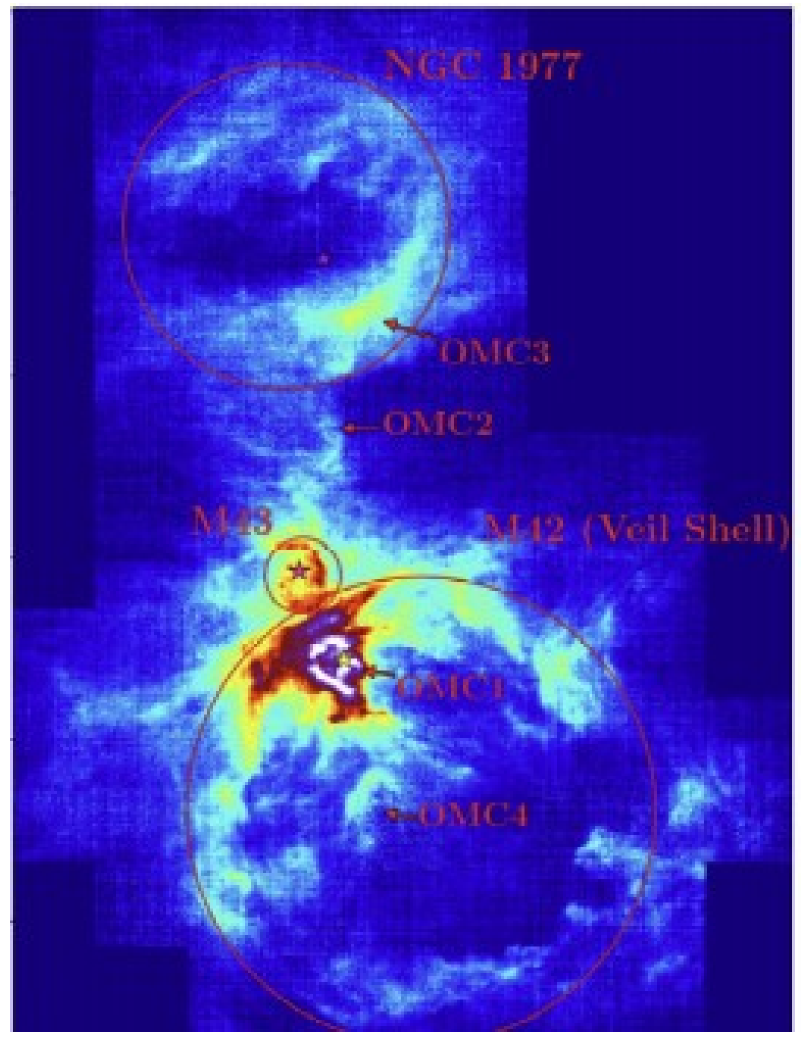


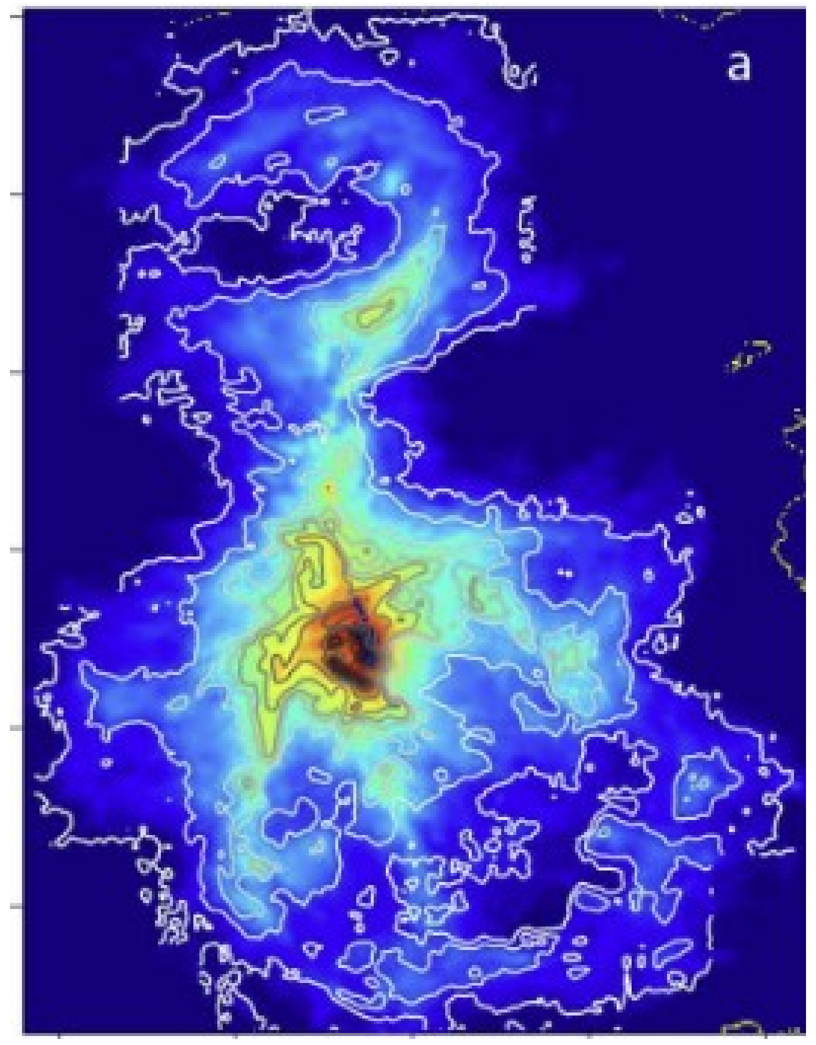
Exploring the origin of [CII]-deficit: thermal saturation of [CII]

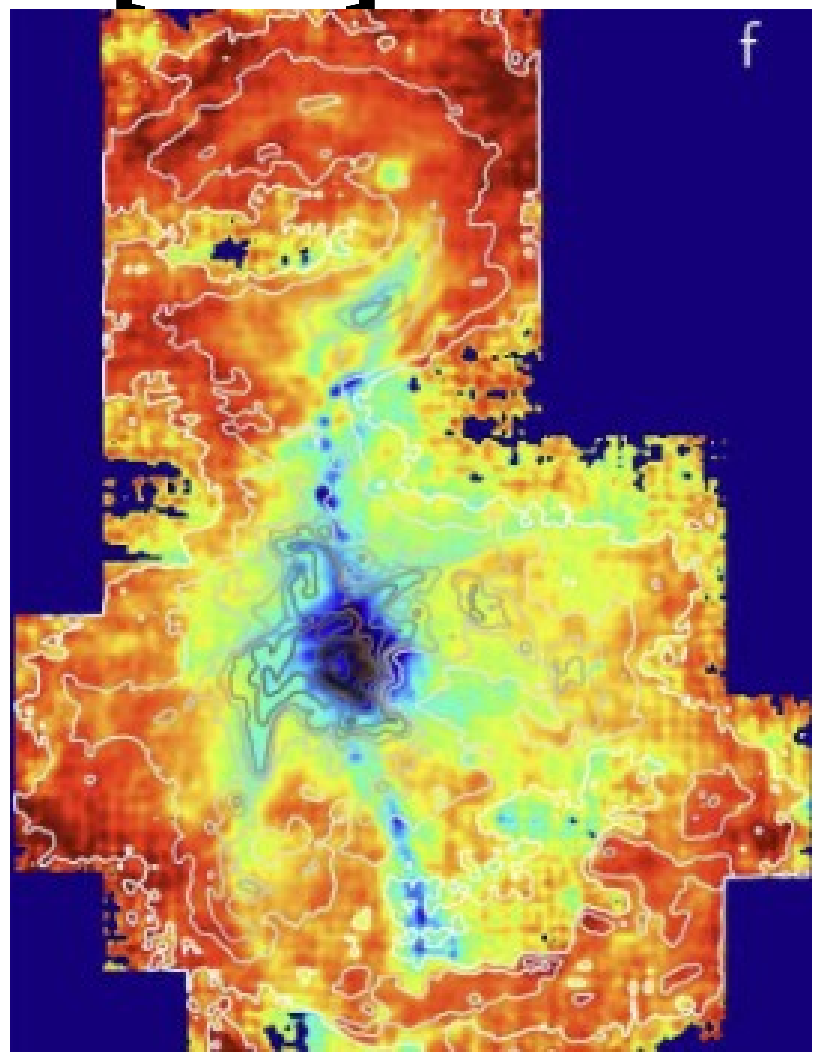


Bisbas+ 22
Ebagezio+ 24

CII emission **FIR emission** **[CII]/FIR**

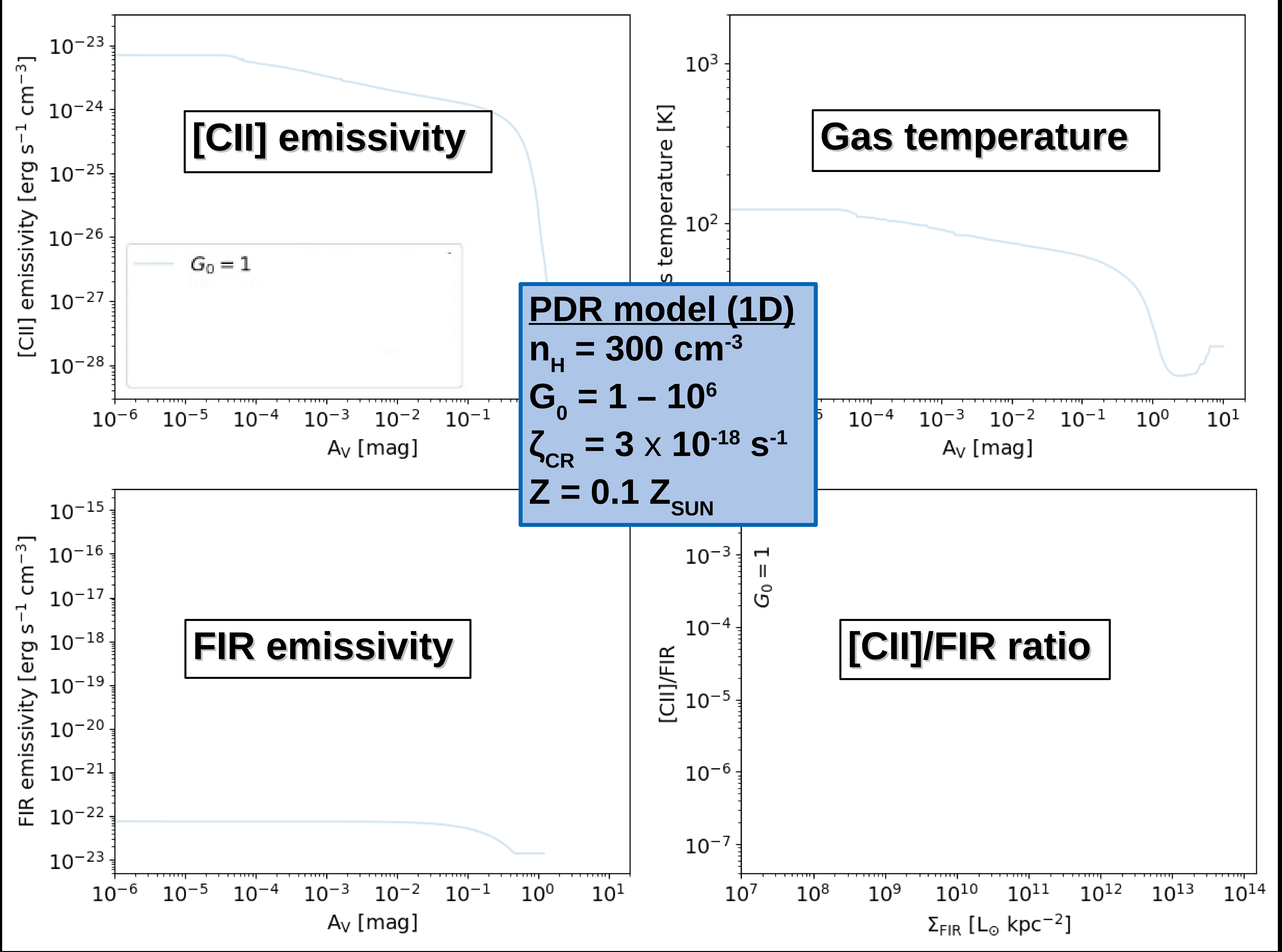


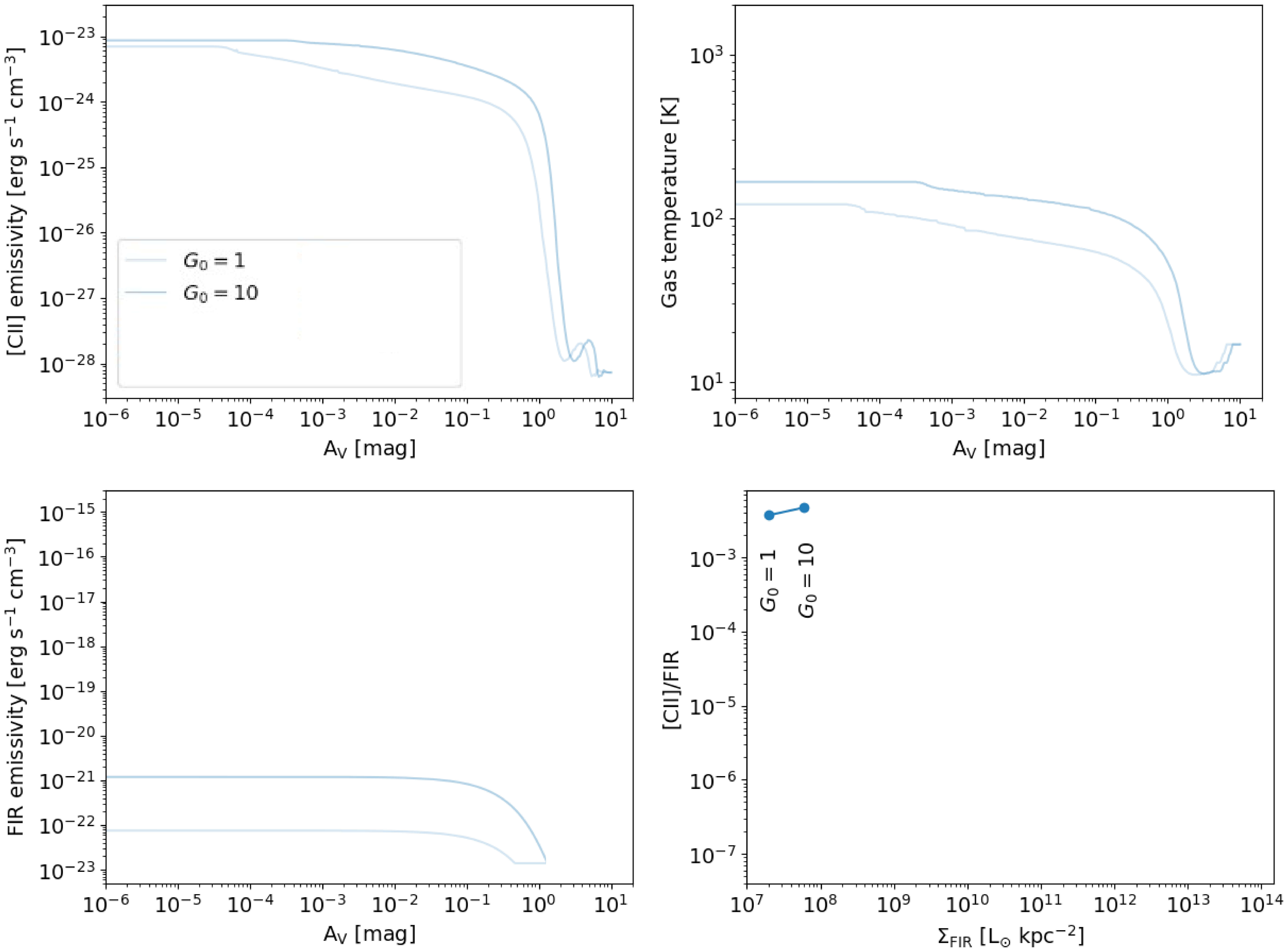




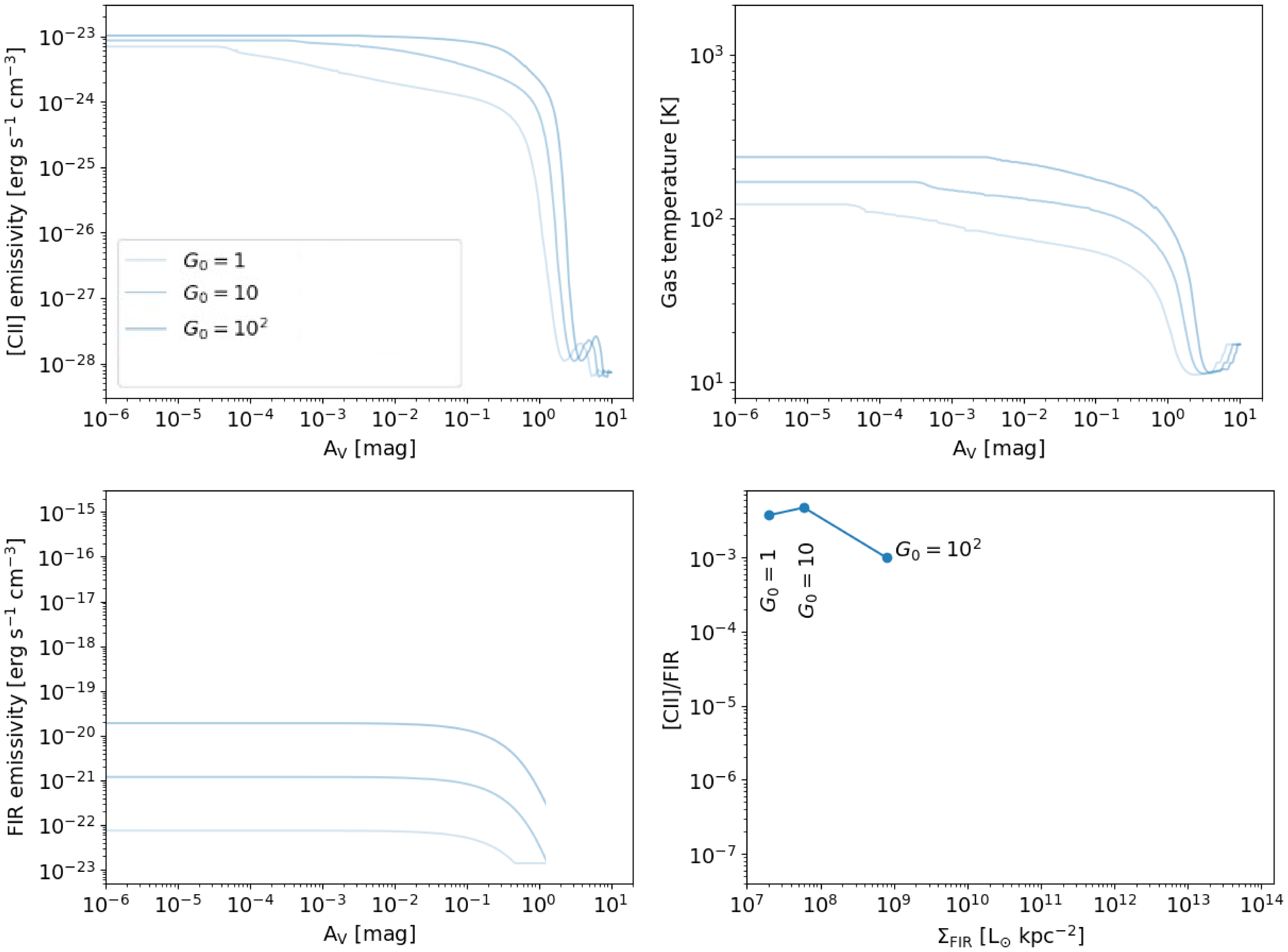
CII-deficit in the Trapezium

Pabst+ 21
Goicoechea+ 15

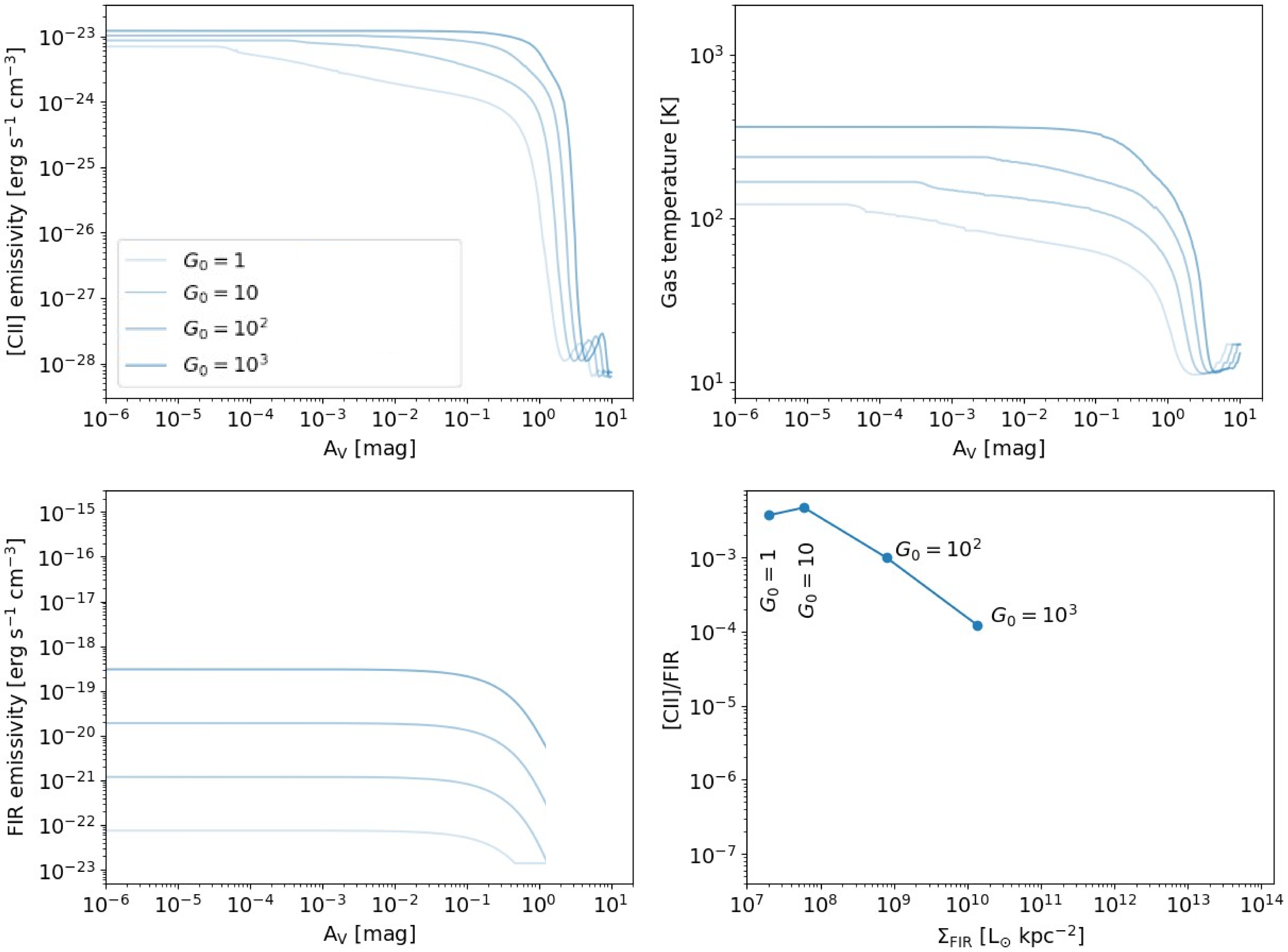

[CII] emissivity
[CII] emissivity [erg s^{-1} cm^{-3}]
$G_0 = 1$
A_V [mag]
Gas temperature
Gas temperature [K]
FIR emissivity
FIR emissivity [erg s^{-1} cm^{-3}]
[CII]/FIR ratio
[CII]/FIR
Σ_{FIR} [$L_\odot$ kpc^{-2}]
PDR model (1D)
n_H = 300 cm^{-3}
G_0 = 1 – 10^6
ζ_{CR} = 3 x 10^{-18} s^{-1}
Z = 0.1 Z_{SUN}



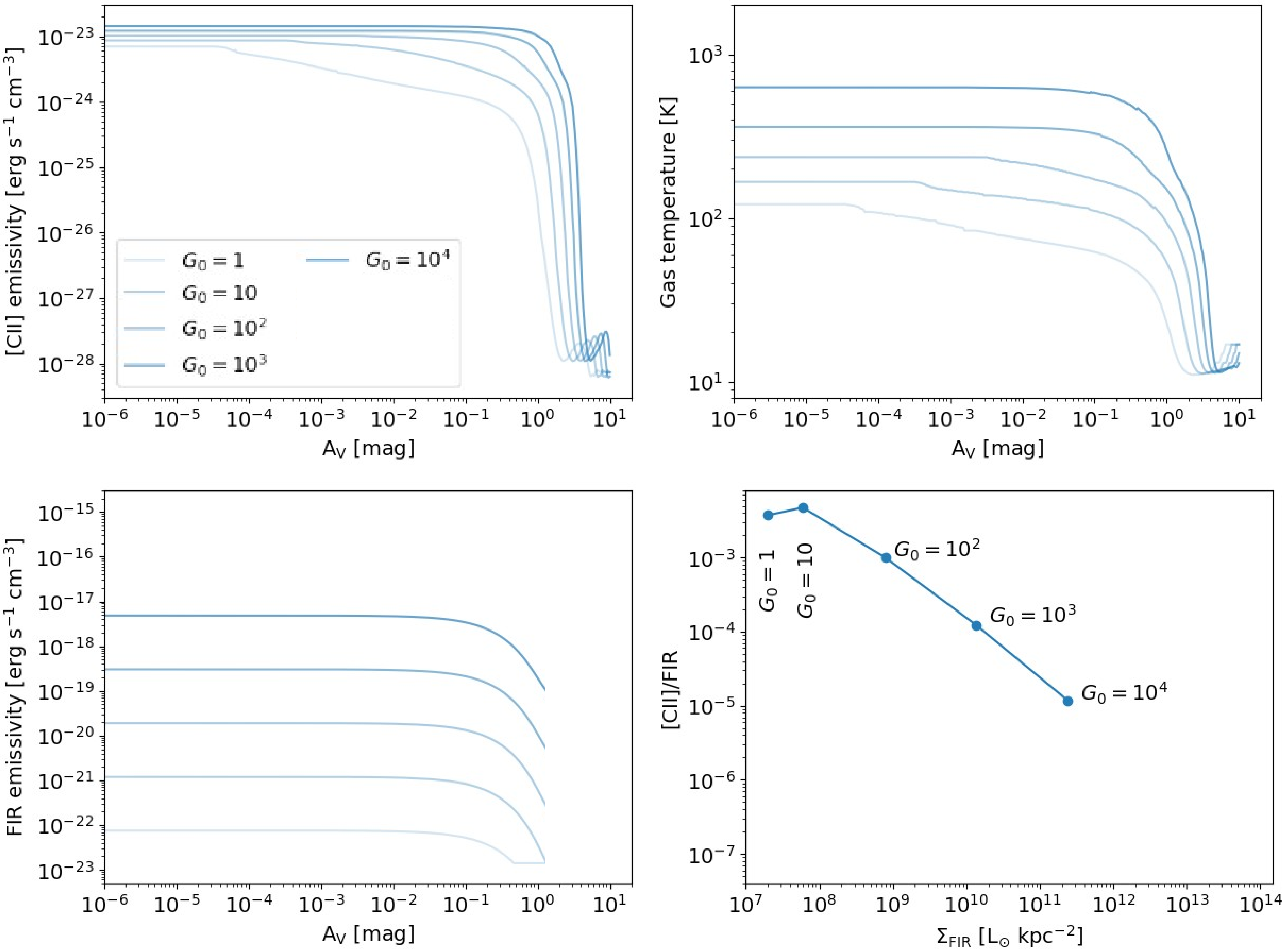
[CII] emissivity [erg s^{-1} cm^{-3}]
$G_0 = 1$
$G_0 = 10$
A$_V$ [mag]
Gas temperature [K]
A$_V$ [mag]
FIR emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
[CII]/FIR
$G_0 = 1$
$G_0 = 10$
Σ_{FIR} [L$_\odot$ kpc^{-2}]



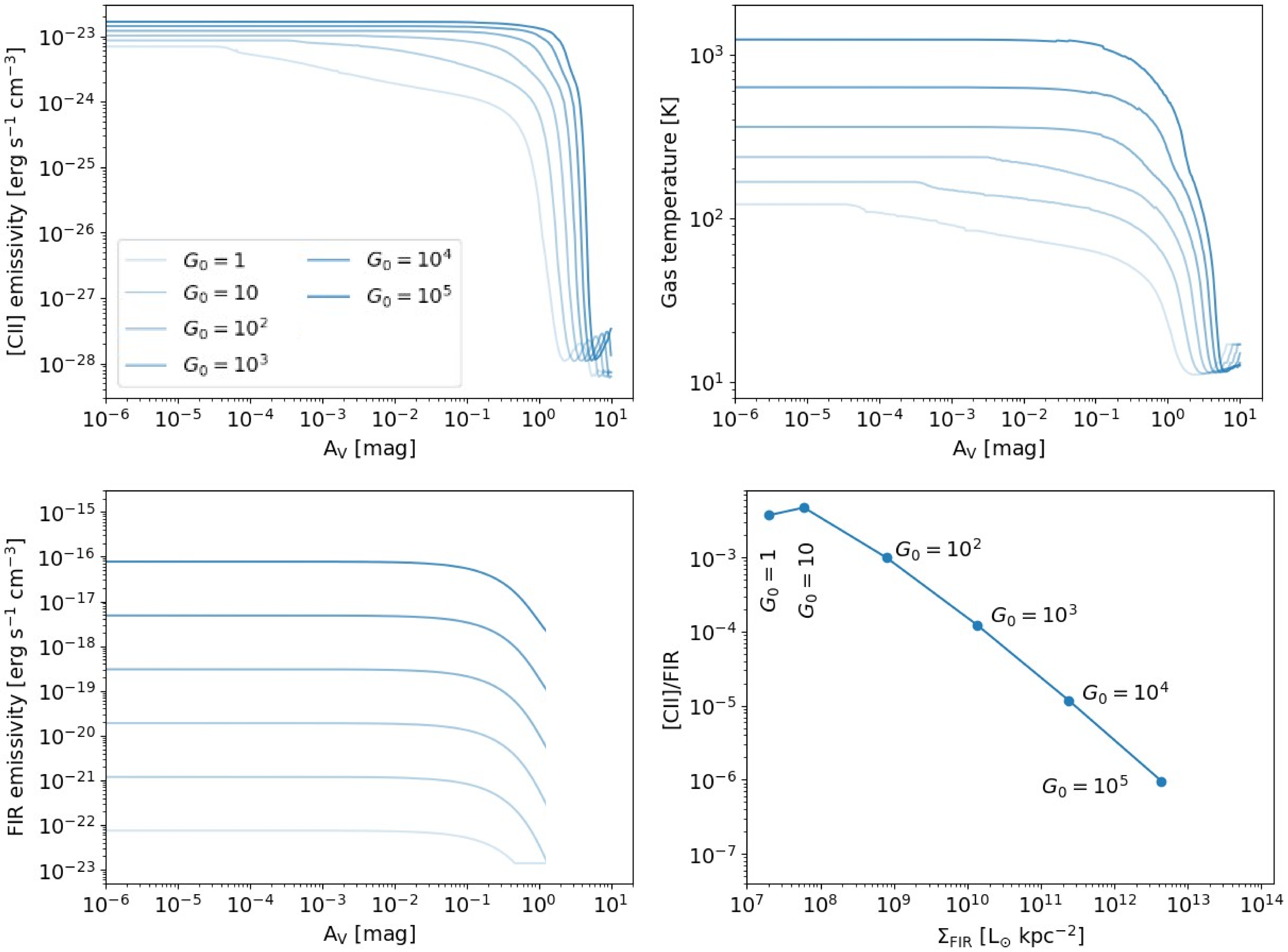
[CII] emissivity [erg s^{-1} cm^{-3}]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
A$_V$ [mag]
Gas temperature [K]
A$_V$ [mag]
FIR emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
[CII]/FIR
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
Σ_{FIR} [L$_\odot$ kpc^{-2}]



[CII] emissivity [erg s^{-1} cm^{-3}]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
A_V [mag]
Gas temperature [K]
A_V [mag]
FIR emissivity [erg s^{-1} cm^{-3}]
A_V [mag]
[CII]/FIR
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
Σ_{FIR} [$L_\odot$ kpc^{-2}]



[CII] emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
$G_0 = 10^4$
Gas temperature [K]
A$_V$ [mag]
FIR emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
[CII]/FIR
Σ_{FIR} [L$_\odot$ kpc^{-2}]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
$G_0 = 10^4$


[CII] emissivity [erg s^{-1} cm^{-3}]
$G_0 = 1$
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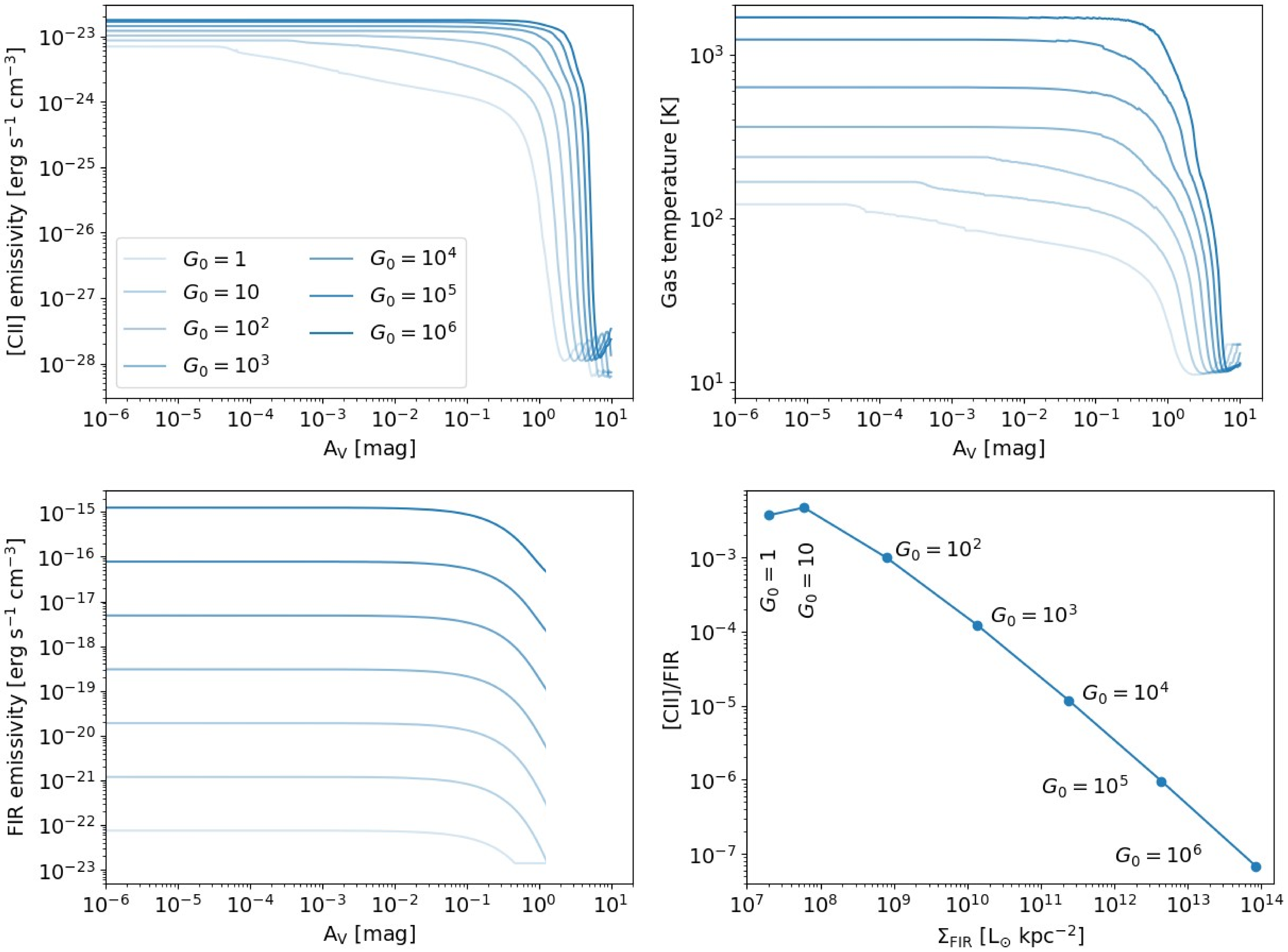
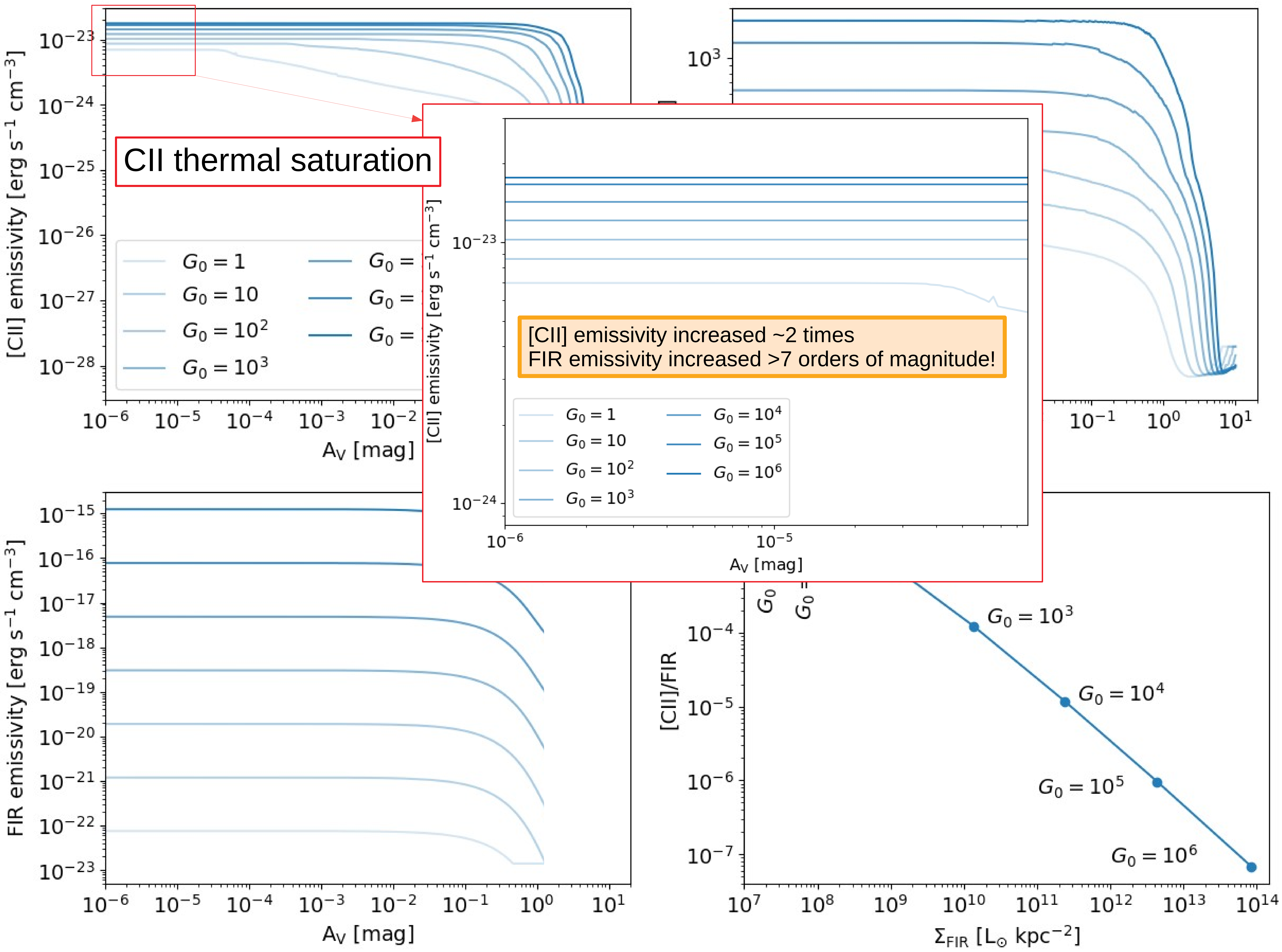
$G_0 = 10^2$
$G_0 = 10^3$
$G_0 = 10^4$
$G_0 = 10^5$
A_V [mag]
Gas temperature [K]
FIR emissivity [erg s^{-1} cm^{-3}]
[CII]/FIR
Σ_{FIR} [$L_\odot$ kpc^{-2}]



[CII] emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
$G_0 = 10^4$
$G_0 = 10^5$
$G_0 = 10^6$
Gas temperature [K]
FIR emissivity [erg s^{-1} cm^{-3}]
[CII]/FIR
Σ_{FIR} [L$_\odot$ kpc^{-2}]


CII thermal saturation
[CII] emissivity increased ~2 times
FIR emissivity increased >7 orders of magnitude!
[CII] emissivity [erg s^{-1} cm^{-3}]
FIR emissivity [erg s^{-1} cm^{-3}]
A$_V$ [mag]
$G_0 = 1$
$G_0 = 10$
$G_0 = 10^2$
$G_0 = 10^3$
$G_0 = 10^4$
$G_0 = 10^5$
$G_0 = 10^6$
[CII]/FIR
Σ_{FIR} [L$_\odot$ kpc^{-2}]

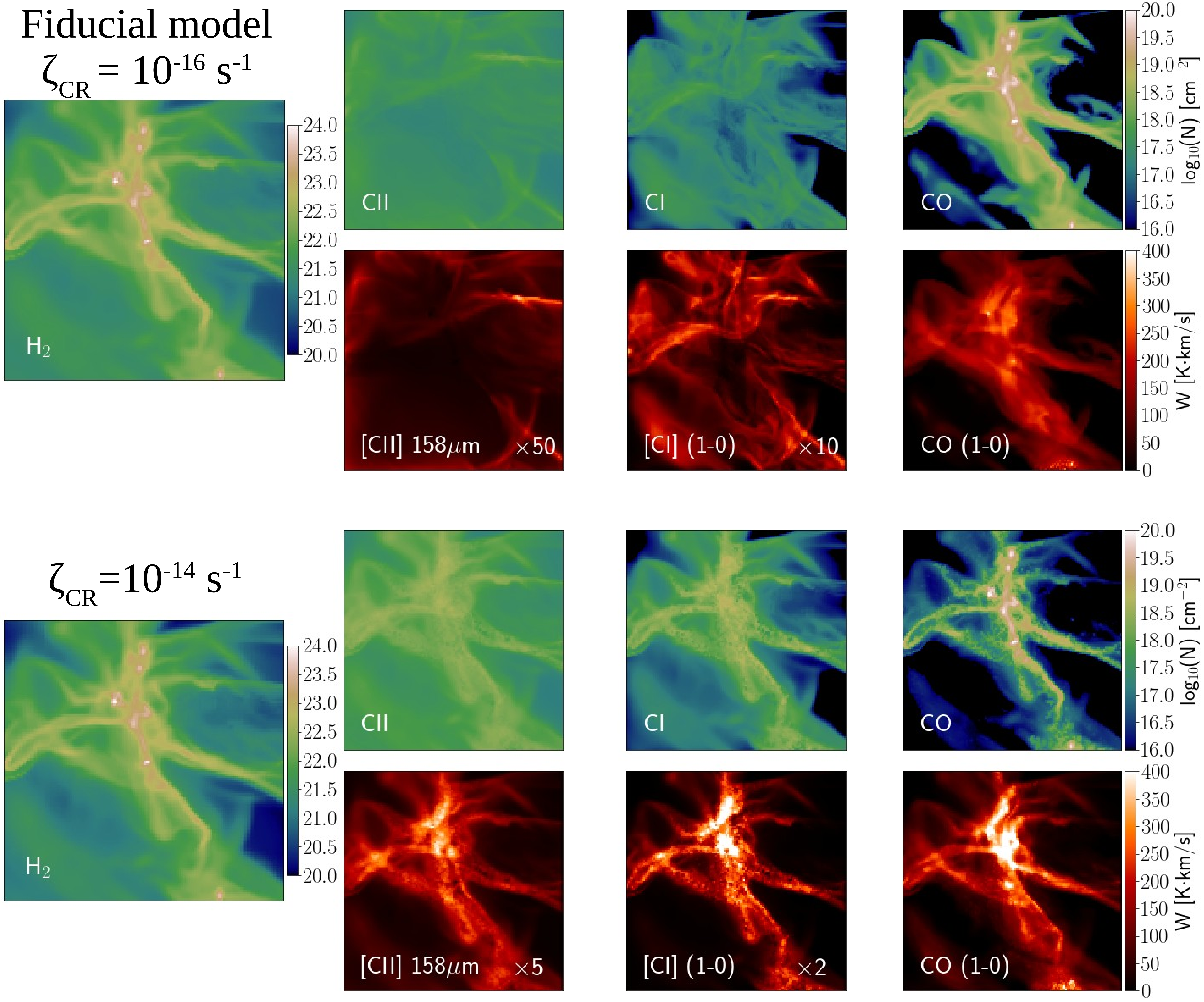
Effect of cosmic-rays

Bisbas et al. (2015a, 2017b, 2021)

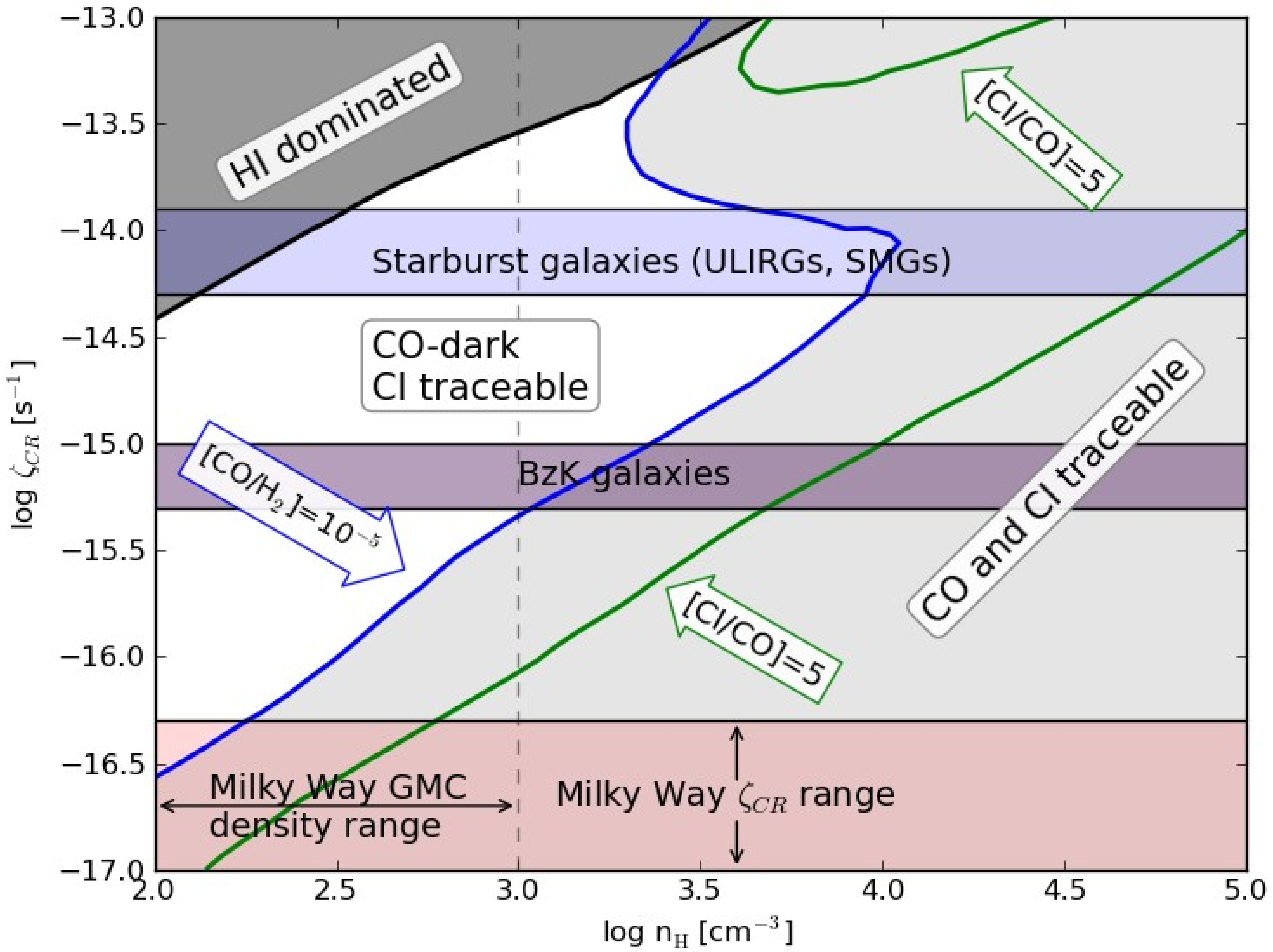
- $N(H_2)$ remains nearly unchanged
- N(CII), N(CI) and W(CII) and W(CI), are increased due to destruction of CO by cosmic-rays (**Bisbas et al., 2015a, 2017b**)

R1: $He + CR \rightarrow He^+ + e^-$
R2: $He^+ + CO \rightarrow He + O + C^+$
R3: $C^+ + e^- \rightarrow C + h\nu$

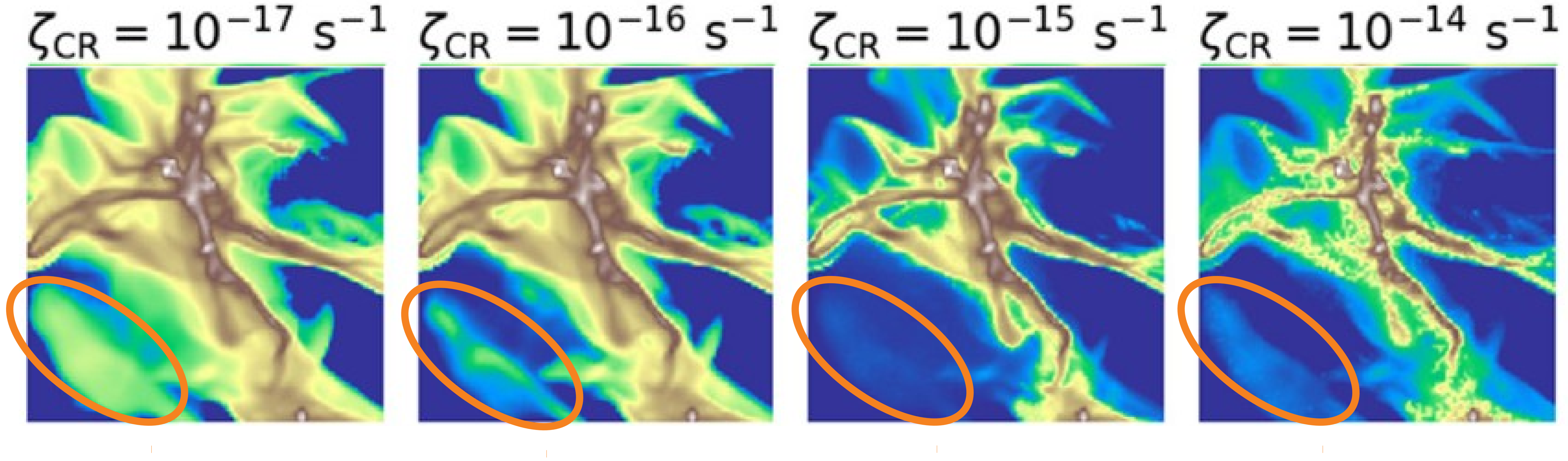
- W(CO) decreases in the outer parts but increases at high column densities



Destruction of CO by CRs:
not a linear correlation!



Bisbas et al., 2015



Bisbas et al., 2021

CO can ‘re-form’ in high cosmic-ray ionization rates

The crucial role of OH

OH formation is initiated by:

➔ **Proton transfer reaction**

$$O + H_3^+ \rightarrow OH^+ + H_2$$

➔ **Charge transfer reaction**

$$O + H^+ \rightarrow O^+ + H$$

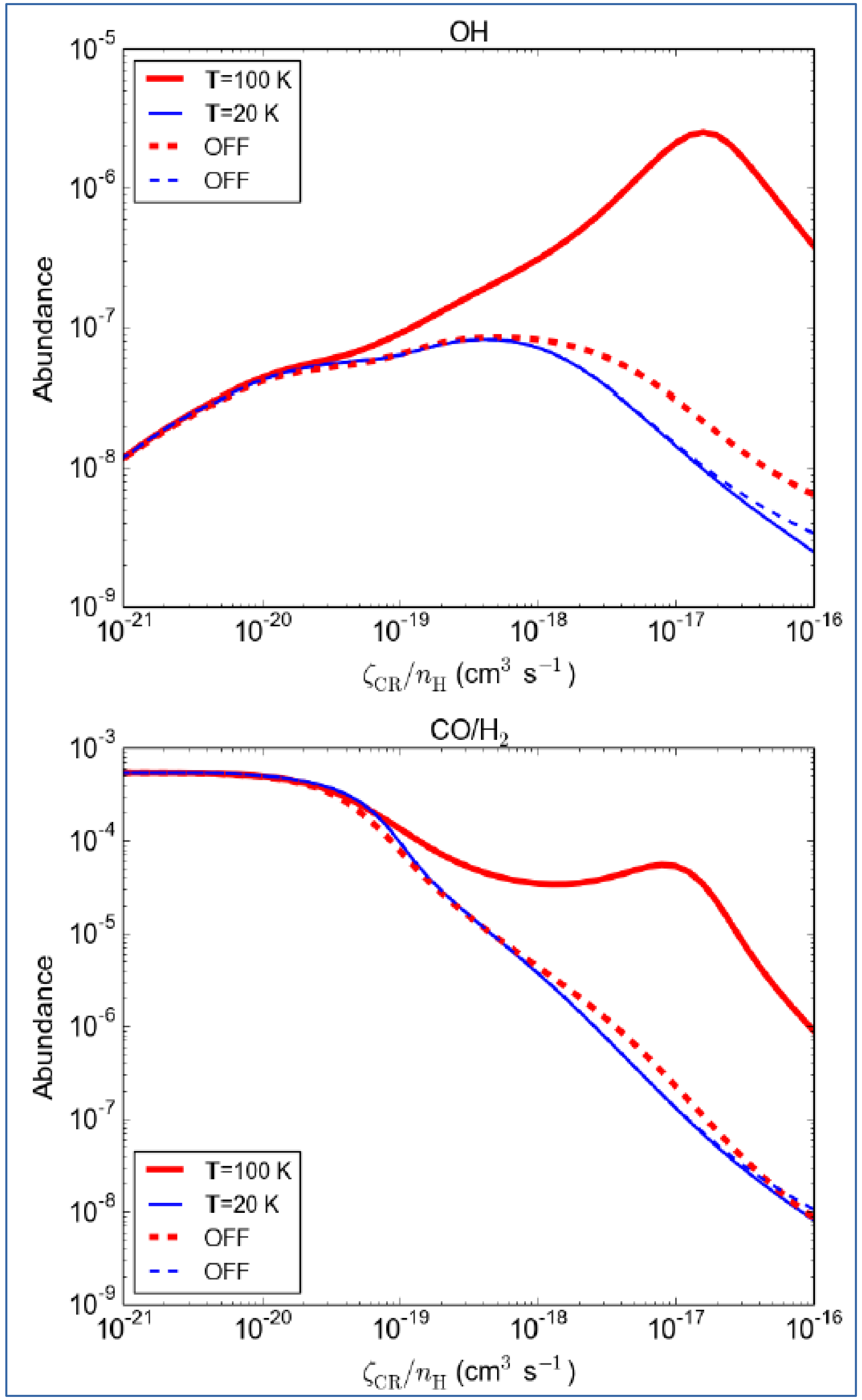
ON: Solid line
OFF: Dashed line

At moderate-to-high CRIR and in low-Z gas, CO formation depends on the OH intermediary:

$$C + OH \rightarrow CO + H$$

$$C^+ + OH \rightarrow CO^+ + H$$

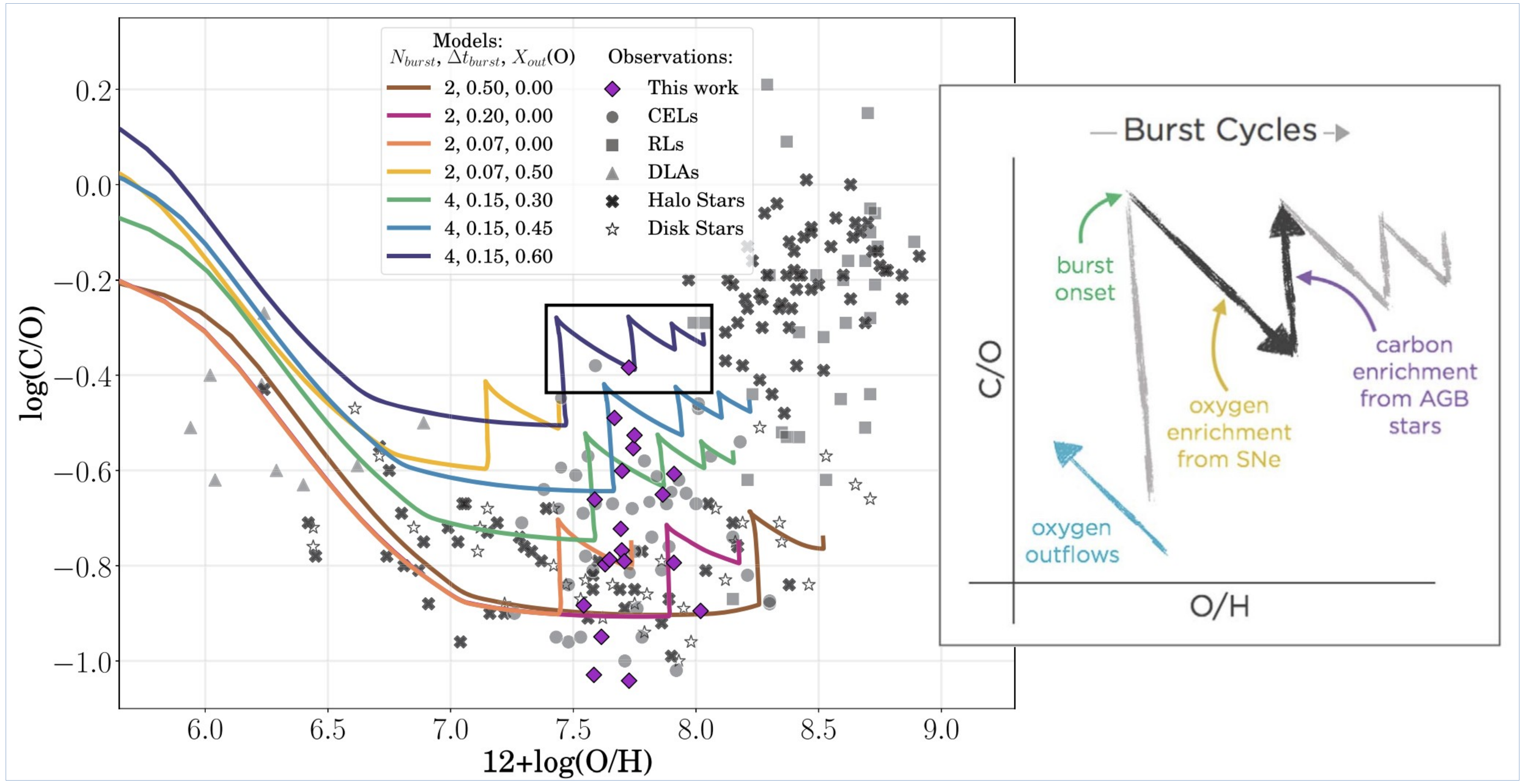
Bisbas et al., 2017, ApJ, 839, 90

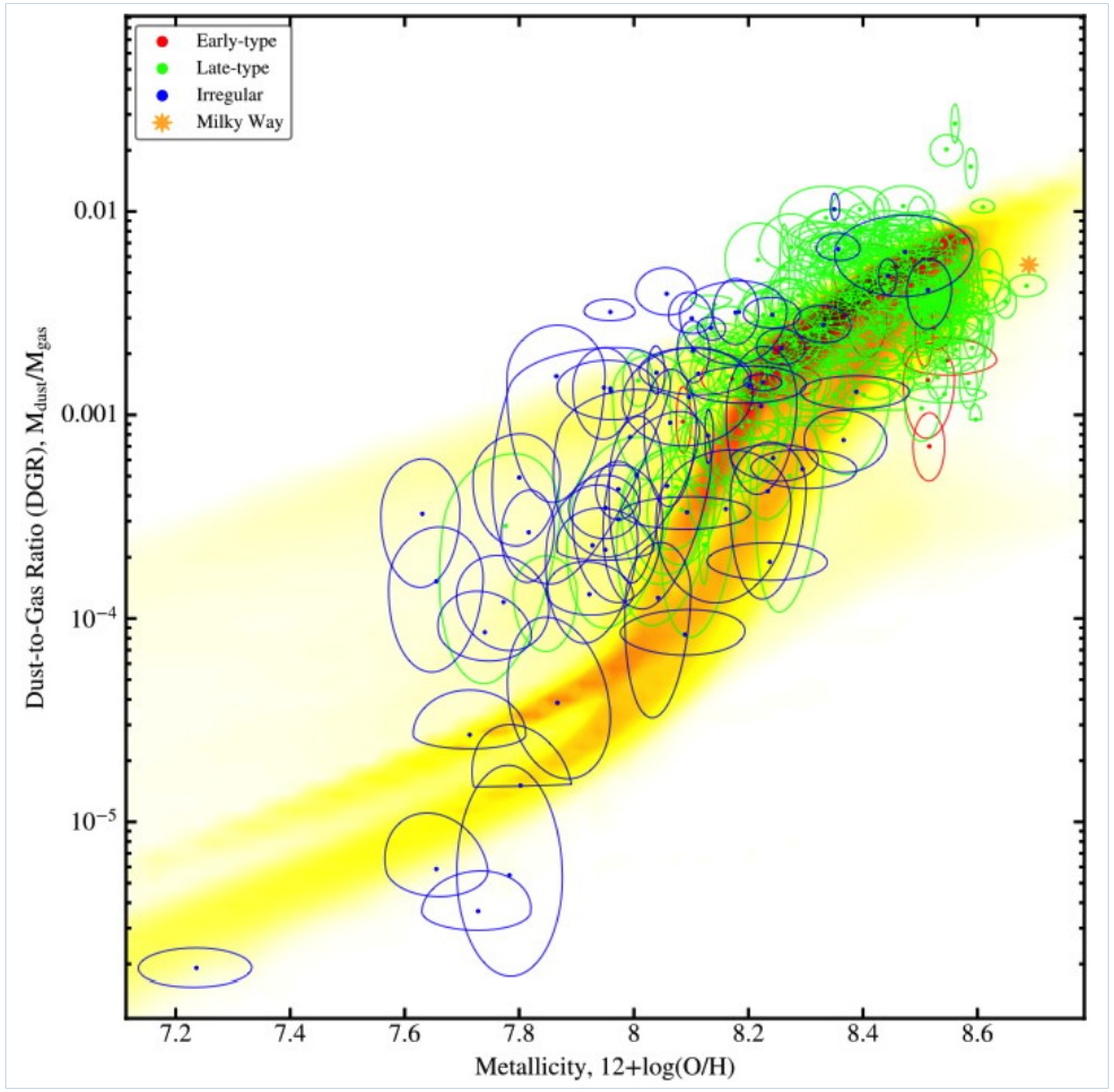


Effect of metallicity

Dust-to-gas ratio

Abundance of carbon

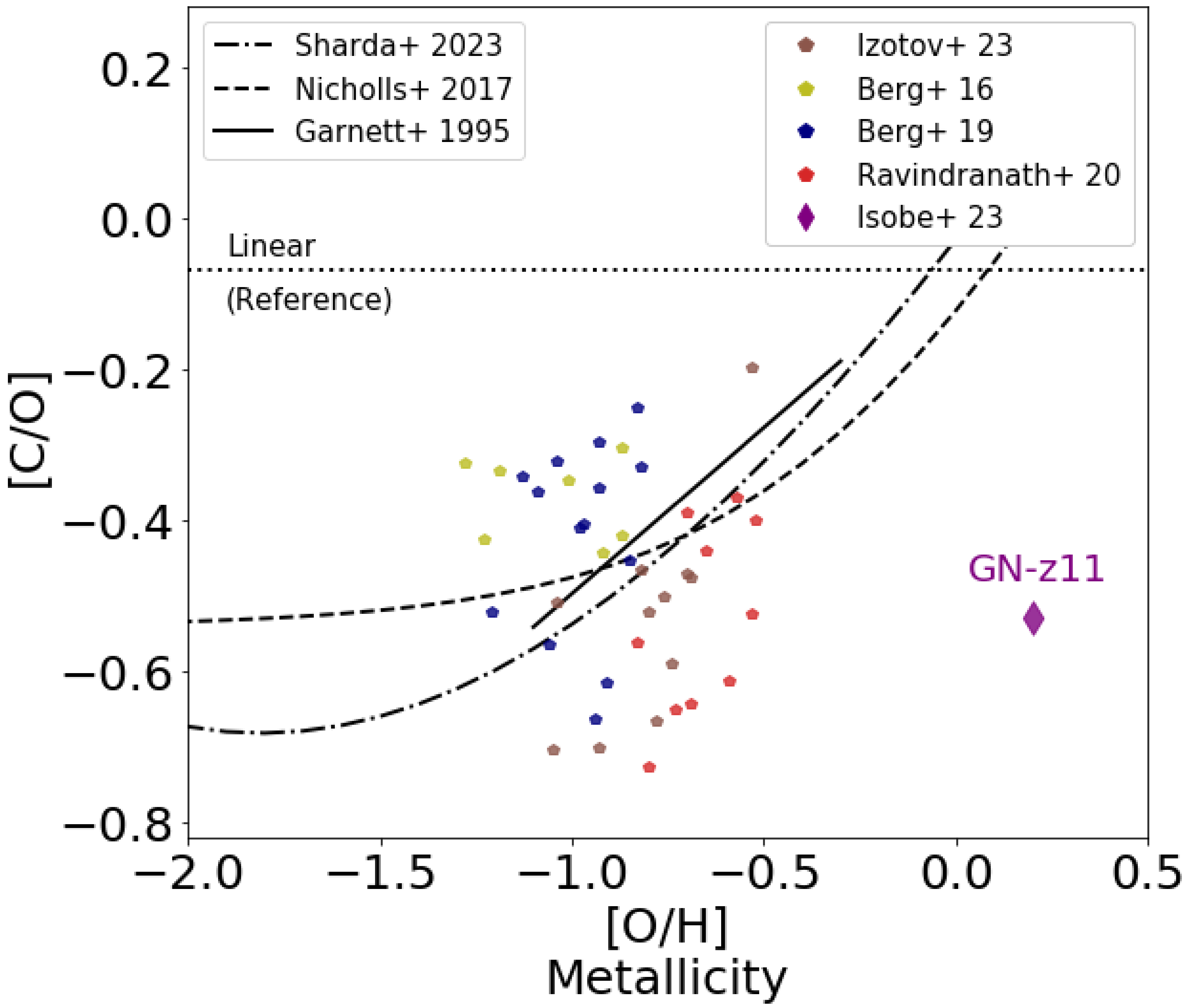


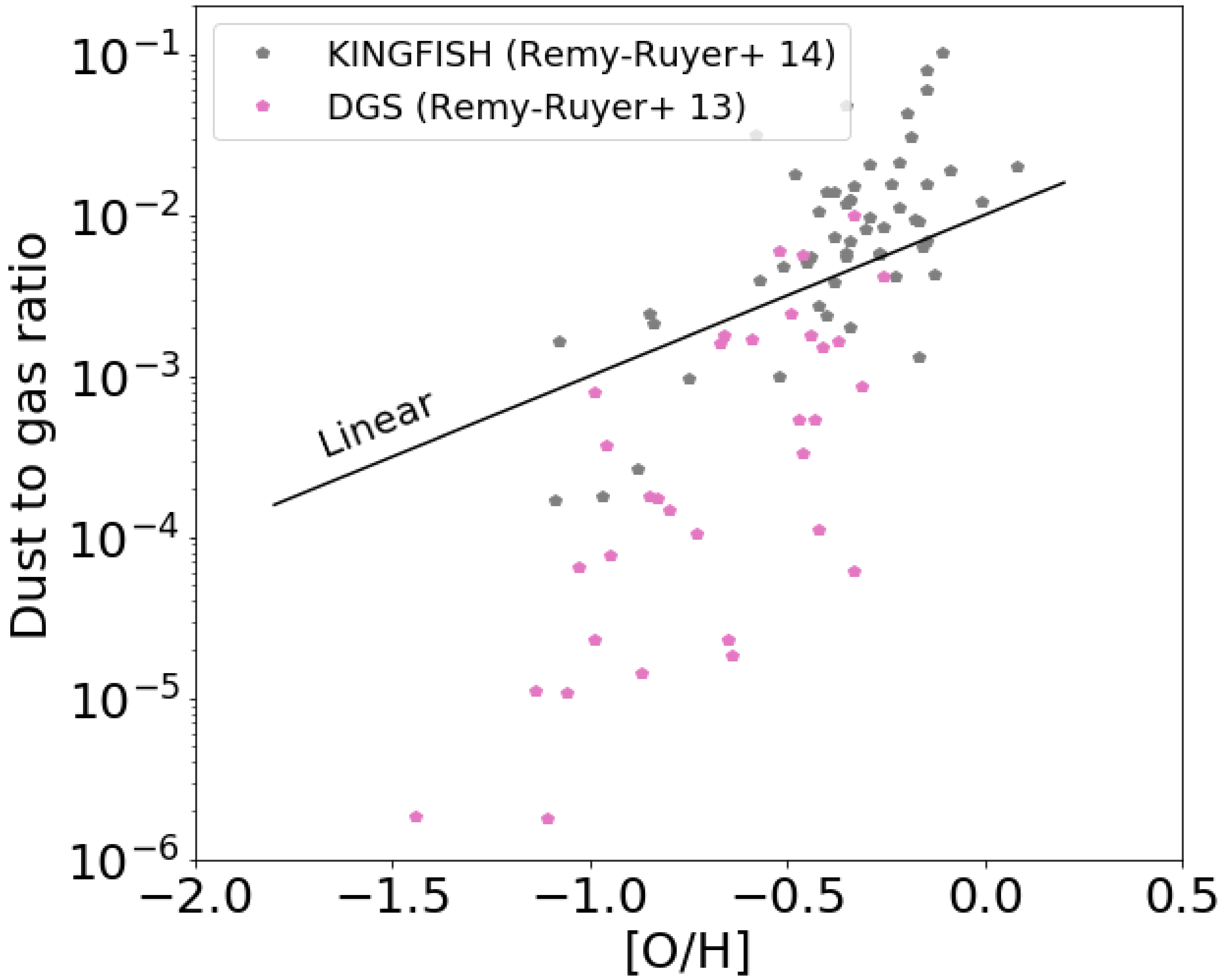


See **Berg+ 2019** (ApJ, 874, 93) for detailed discussion

Galliano+ 2021 (A&A, 649, 18)

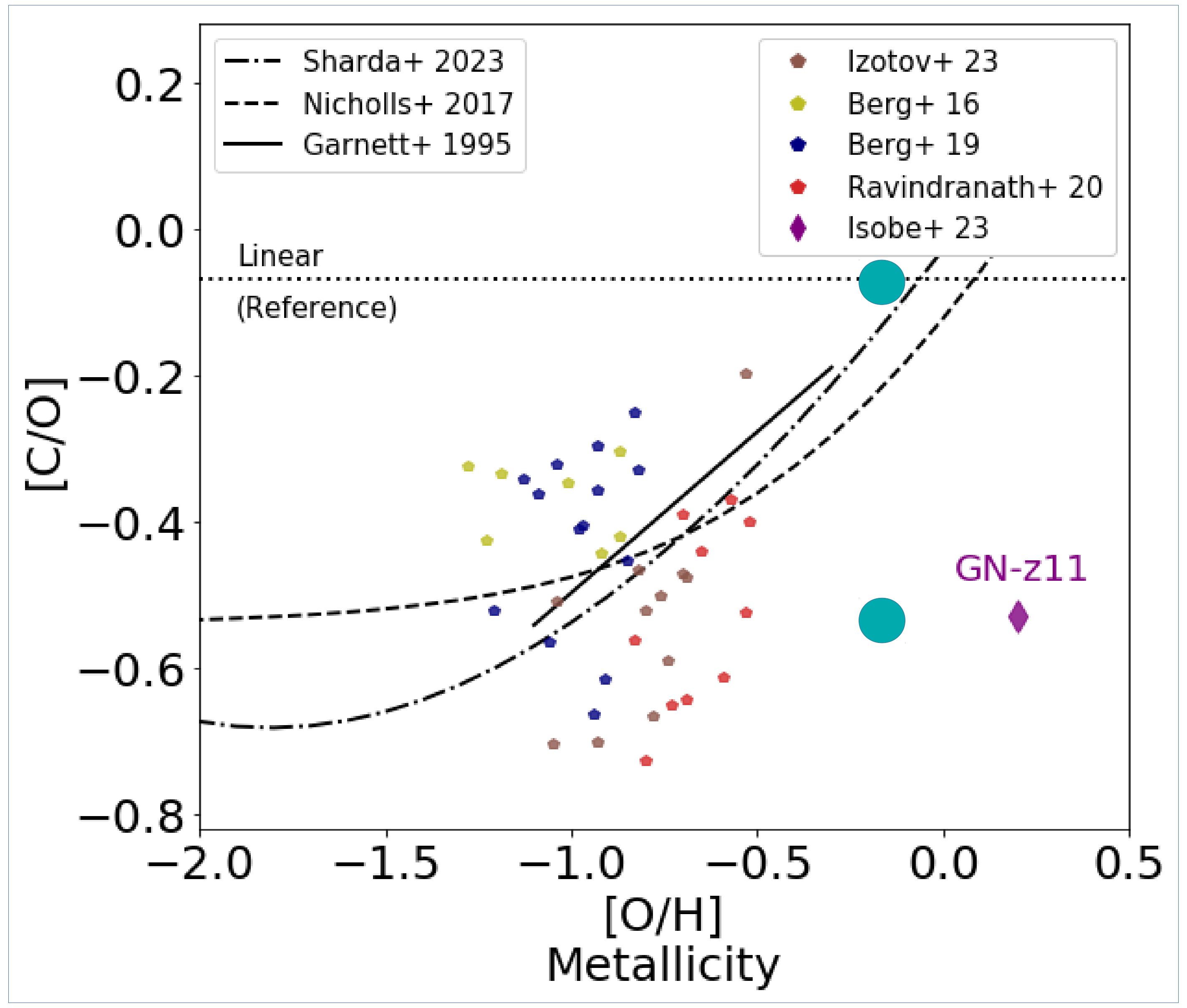
Effect of metallicity

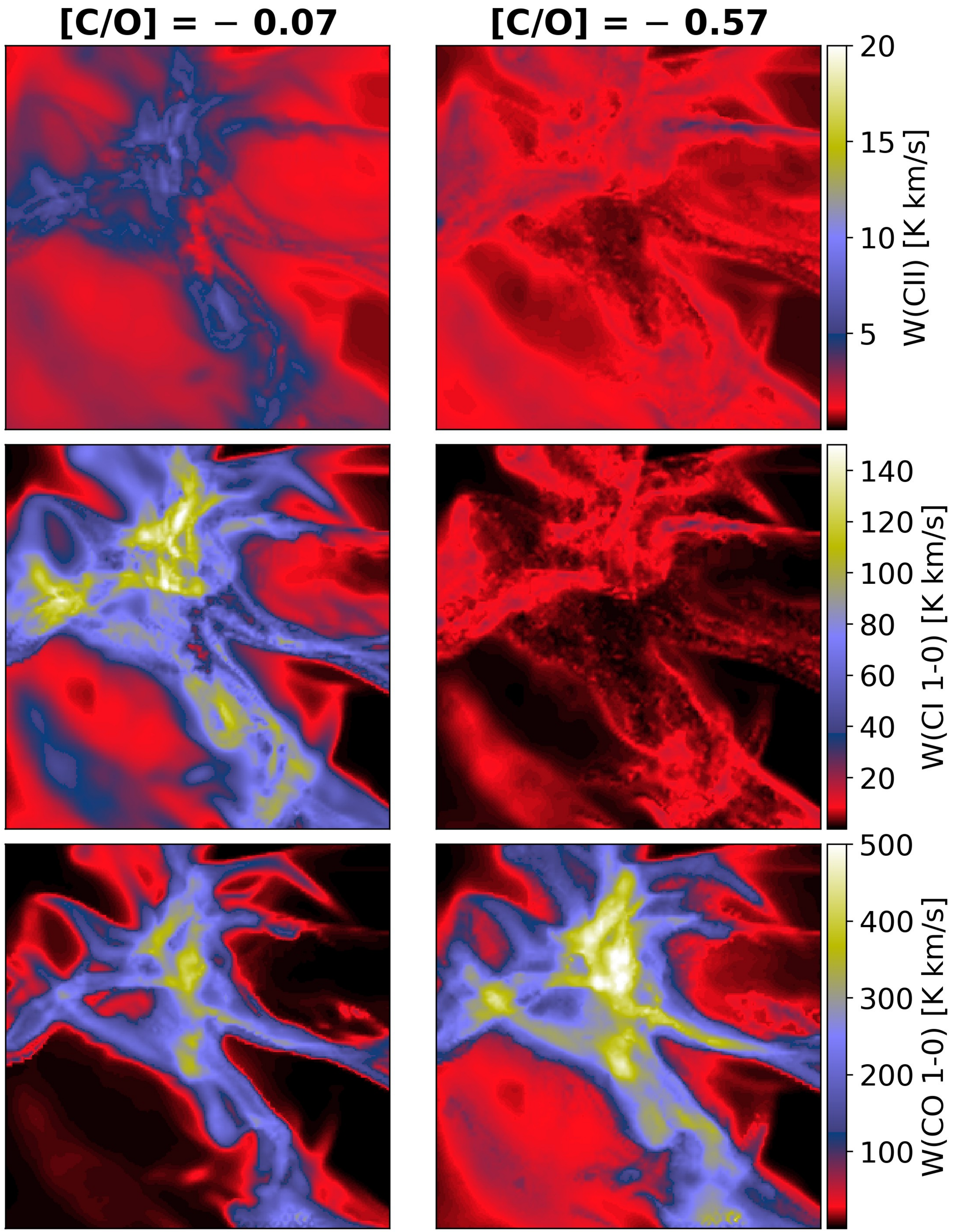




Effect of metallicity

Effect of metallicity





$\zeta_{CR} = 10^{-15}$ s^{-1}

[CII] decreases

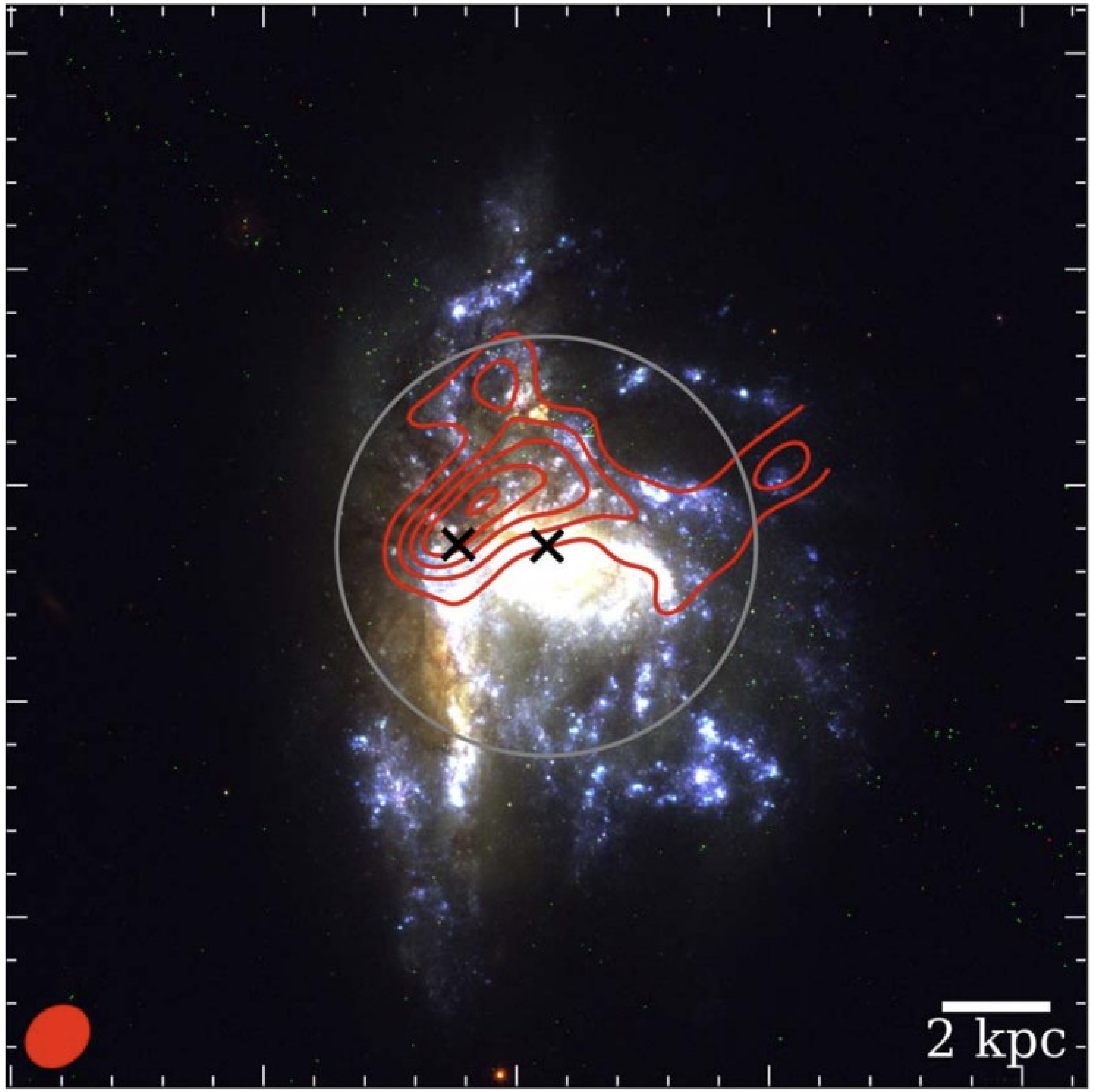
[CI] decreases

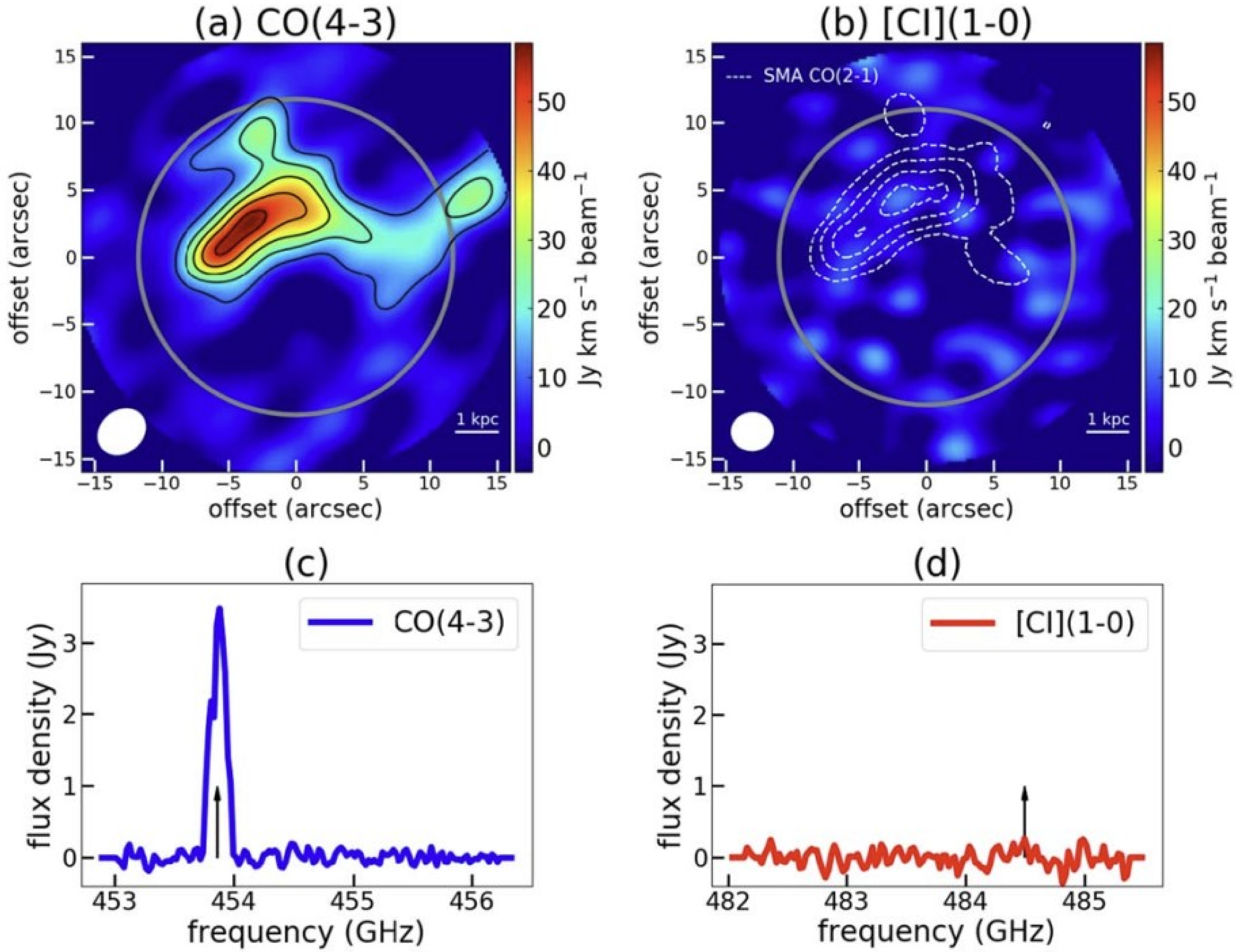
CO increases (!)

Bisbas et al. (2024)

[CI]-dark galaxies

NGC 6052



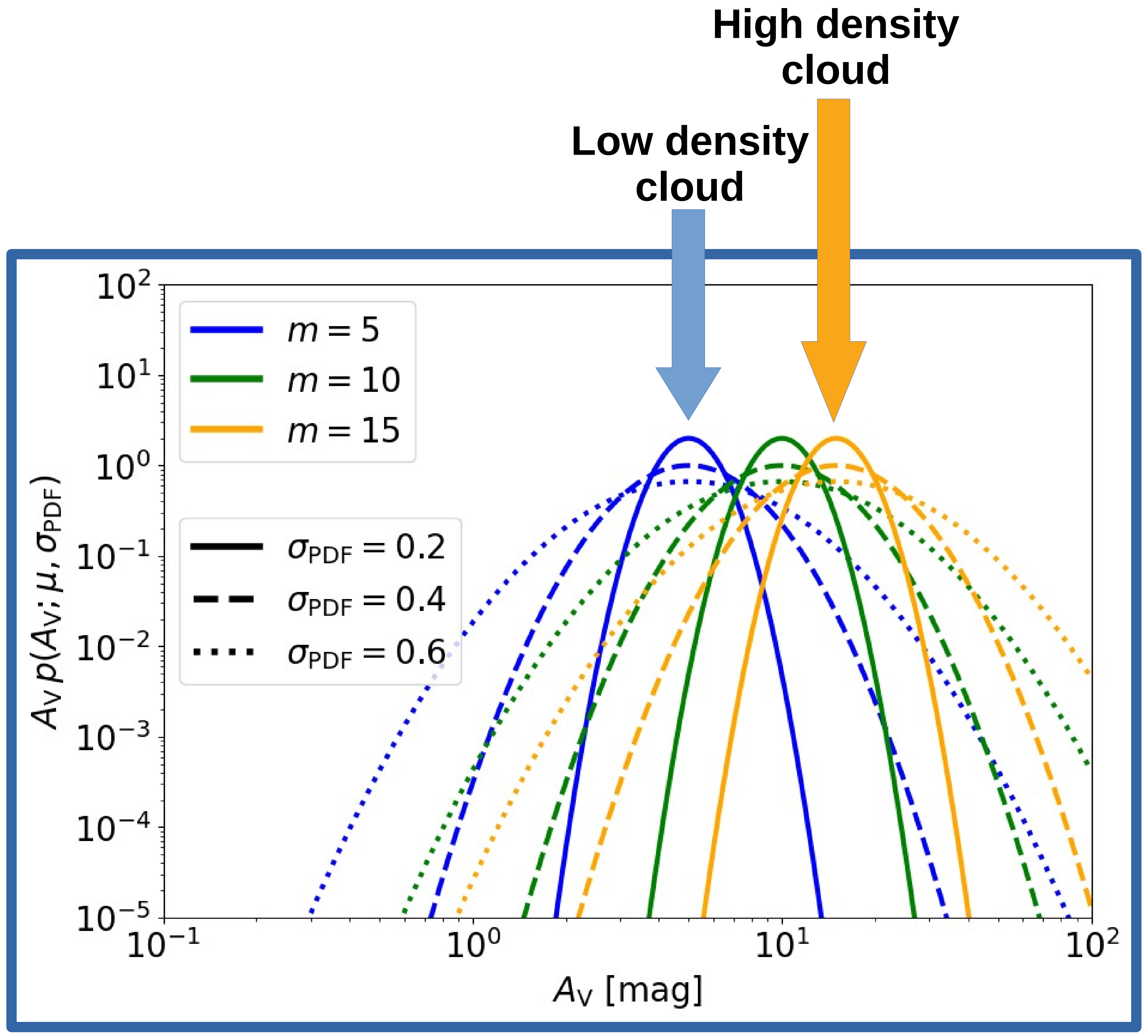


SFR ~ 18 M_O / yr
Colliding galaxies

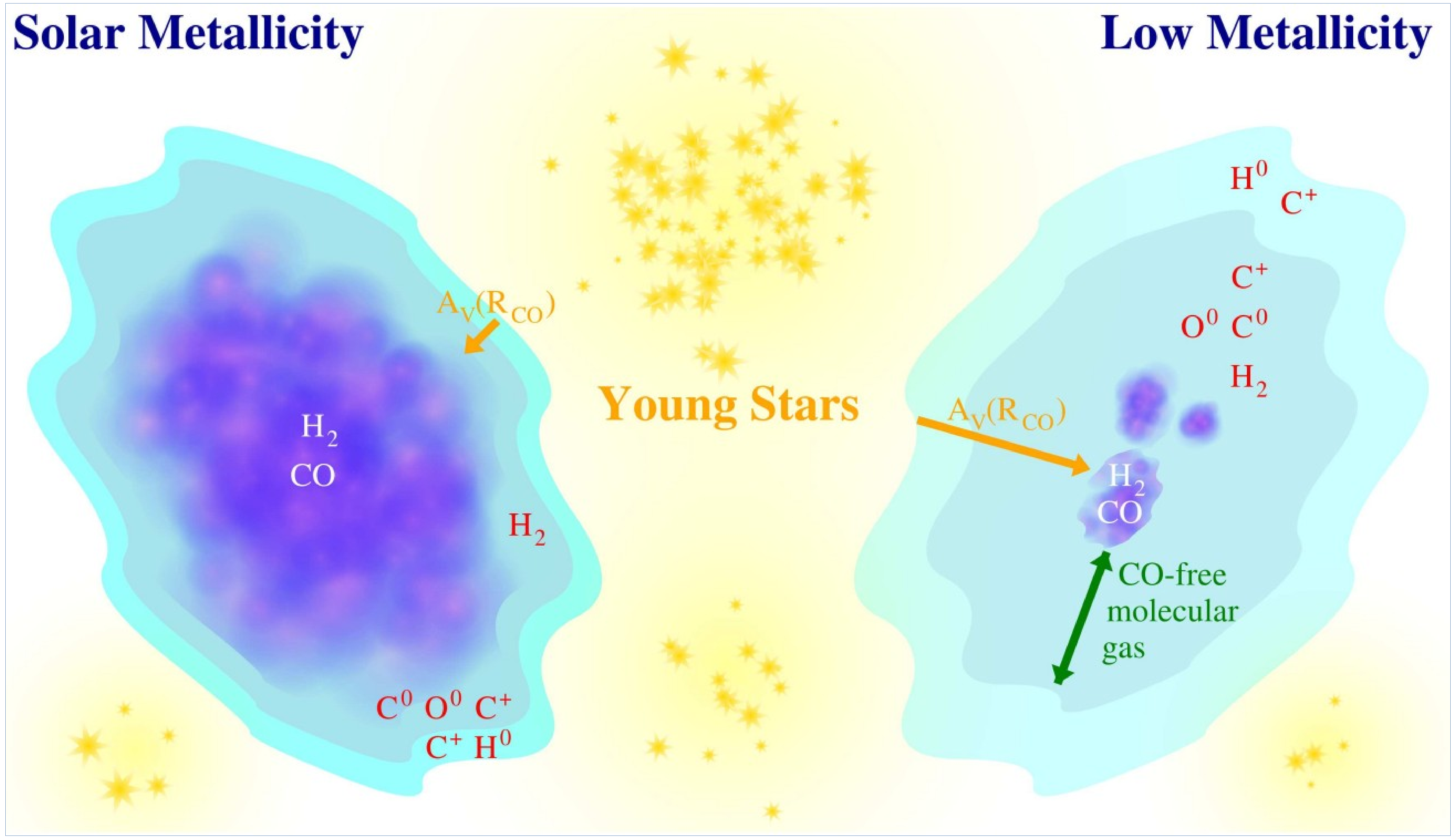
Michiyama et al. (2020)

Conversion factors

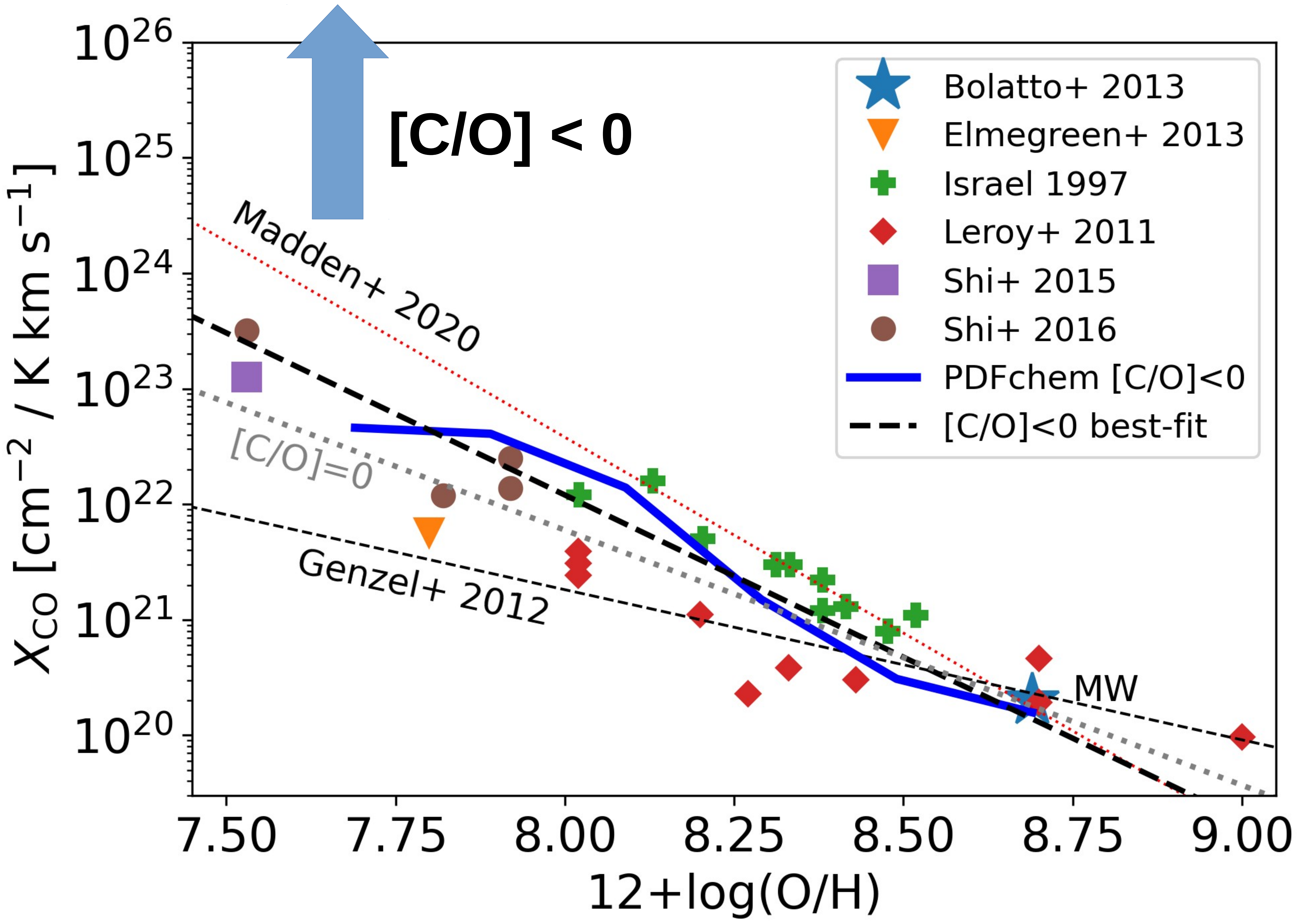
PDFchem
Bisbas+ 2019, 2023
Jiang+ *submitted*



Madden+ 2020



Conversion factors



Best-fit CO-to-H2 conversion factor

$$\log_{10} X_{\rm CO} = -2.611Z + 42.919$$

Lower C/O tend to increase the CO-to-H2 factor as metallicity decreases

Conclusions and remarks

- The carbon cycle (C+/C/CO) is a non-linear function of the ISM parameters (cosmic-rays, FUV intensities, metallicity)
- [CII]-deficit can result from strong FUV radiation fields
- C/O is very important! 4th basic parameter?
- Low C/O may explain [CI]-dark galaxies
- The CO-to-H2 factor depends on the C/O ratio

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