Dwarf galaxies as laboratories for the interstellar medium at low metallicity

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Outline

☐ Chemistry in low-metallicity galaxies

☐ Dust evolution and its impact on ISM chemistry

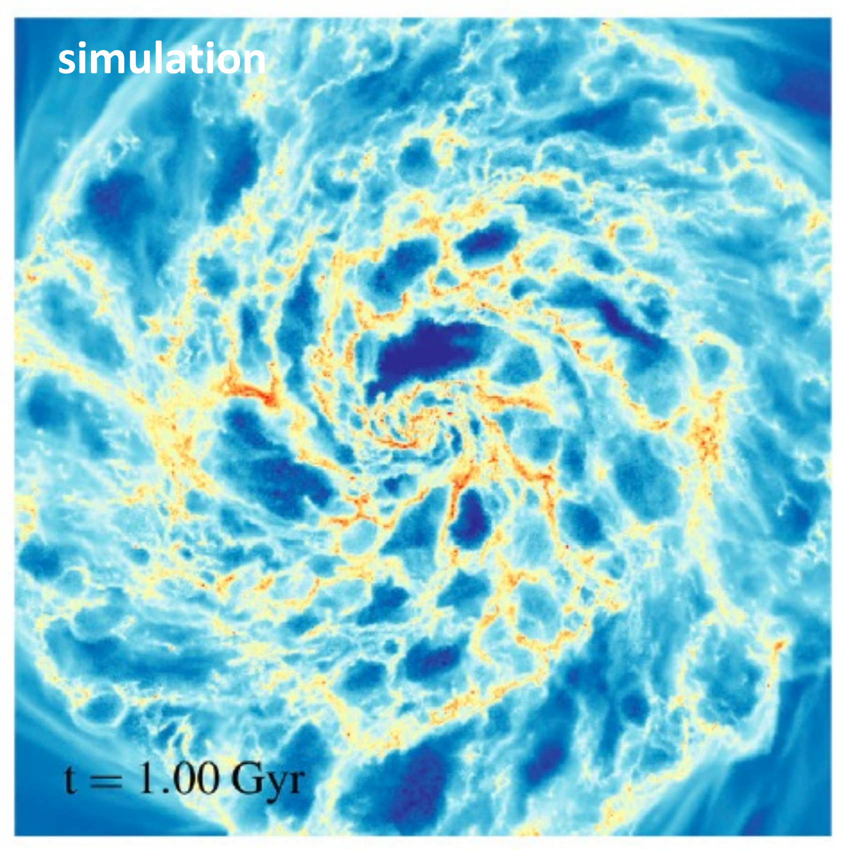
☐ Dust entrainment in galactic outflows

Chemistry in low-metallicity galaxies

Chemistry: connecting simulations & observations

Hydro simulations predict hydro properties (density, temperature...), which are NOT direct observables

- The ISM is multiphase, and different phases are traced by different chemical species.



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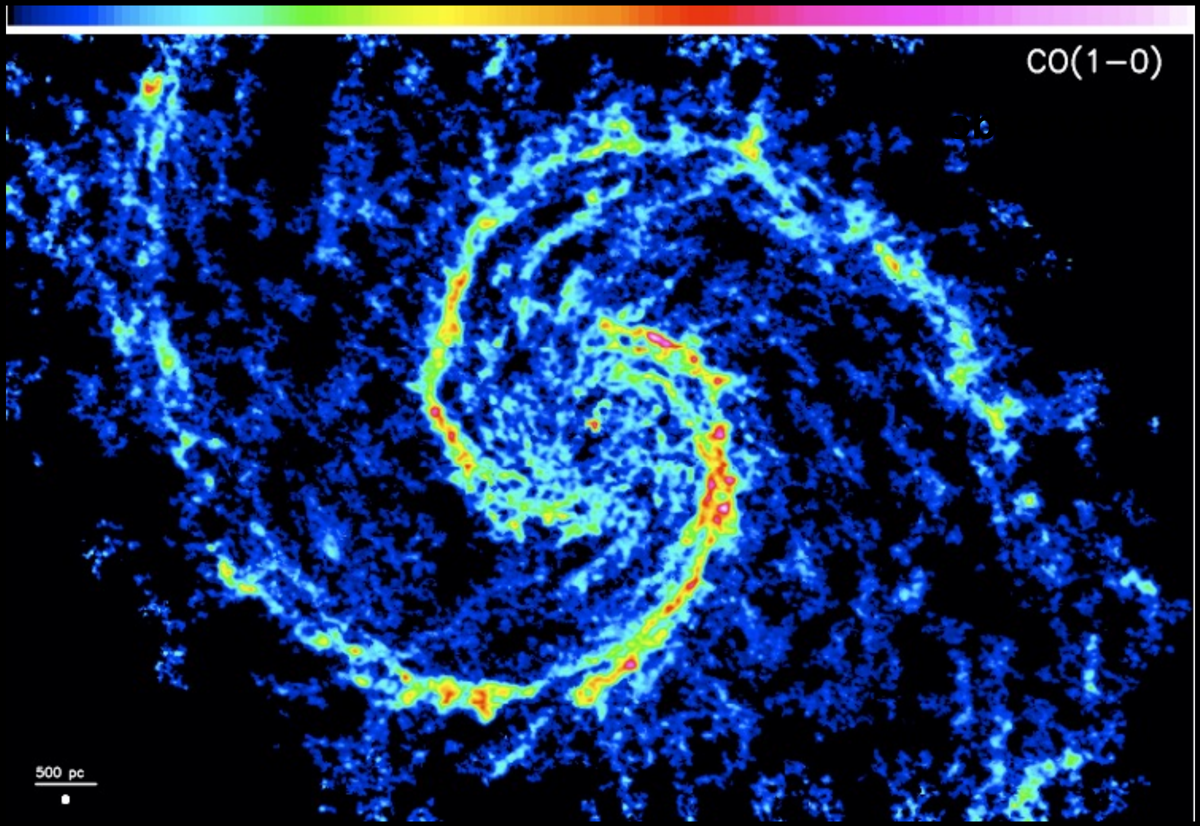
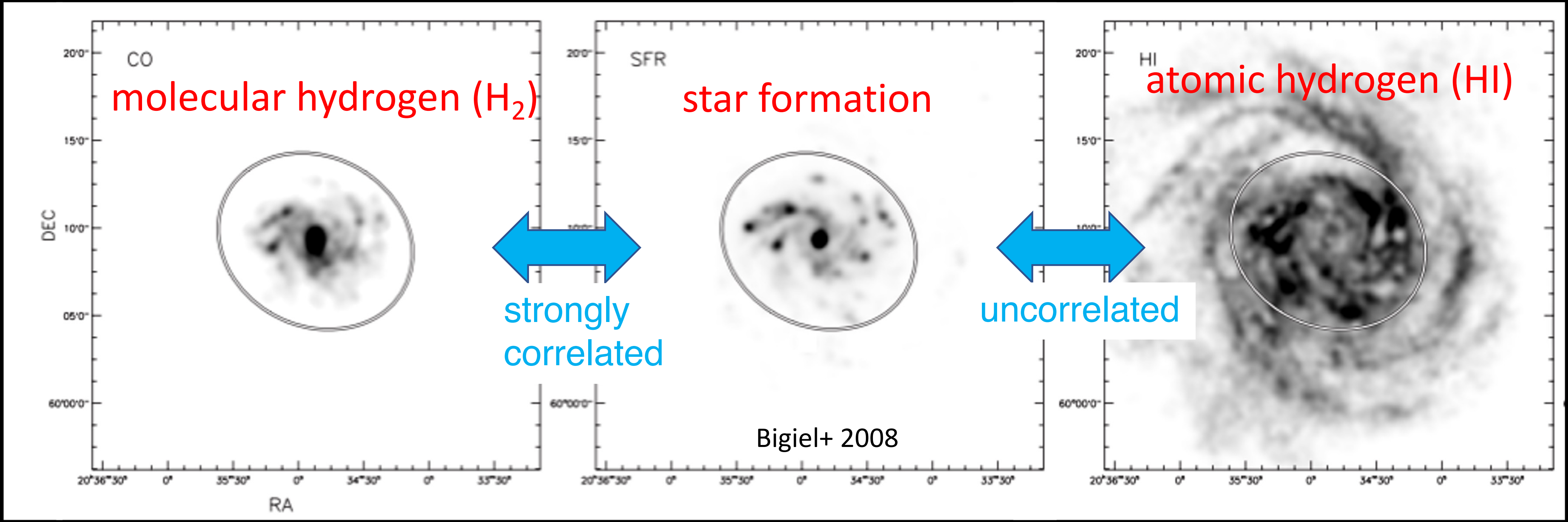


Star formation occurs in molecular gas

- Star formation occurs in molecular clouds where the dominant constituent is molecular hydrogen (H_2).



molecular hydrogen (H_2)

star formation

atomic hydrogen (HI)

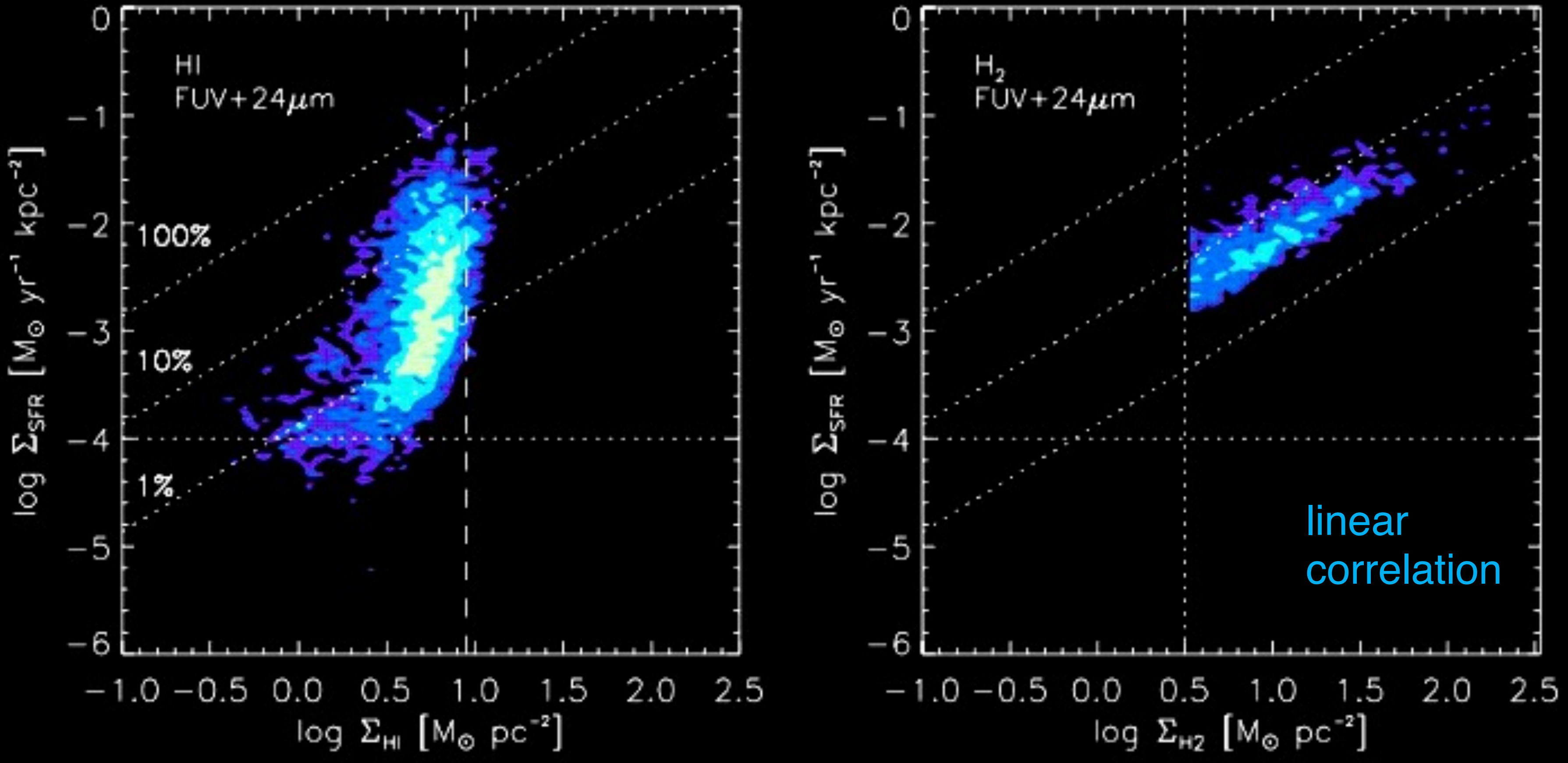
strongly correlated

uncorrelated

Bigiel+ 2008

The Kennicutt-Schmidt (KS) relation

Star formation rate



linear correlation

Gas depletion time:

$t_{dep} = M_{H2}$ / SFR

~ 2 Gyr

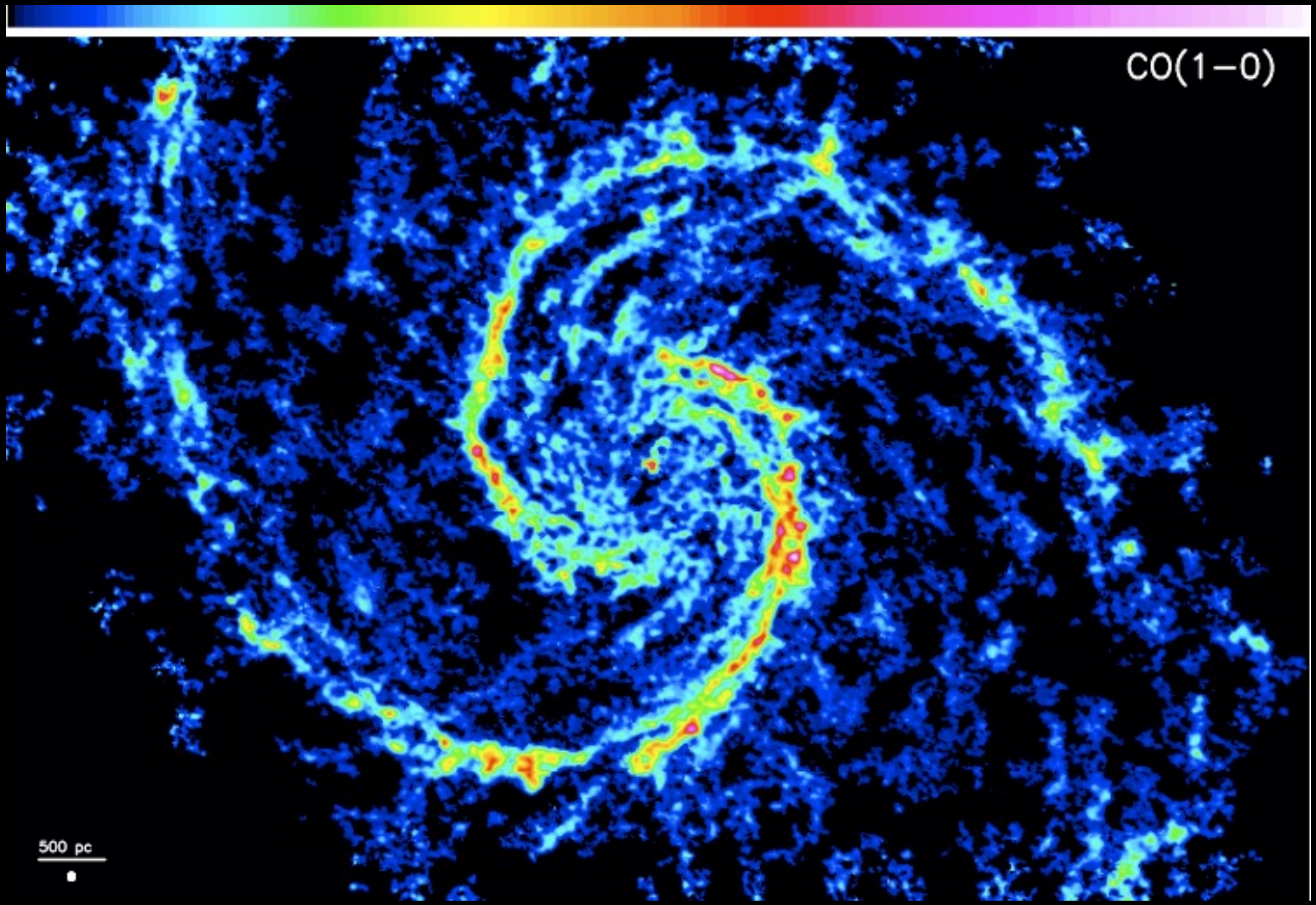
HI

Bigiel+ 2008

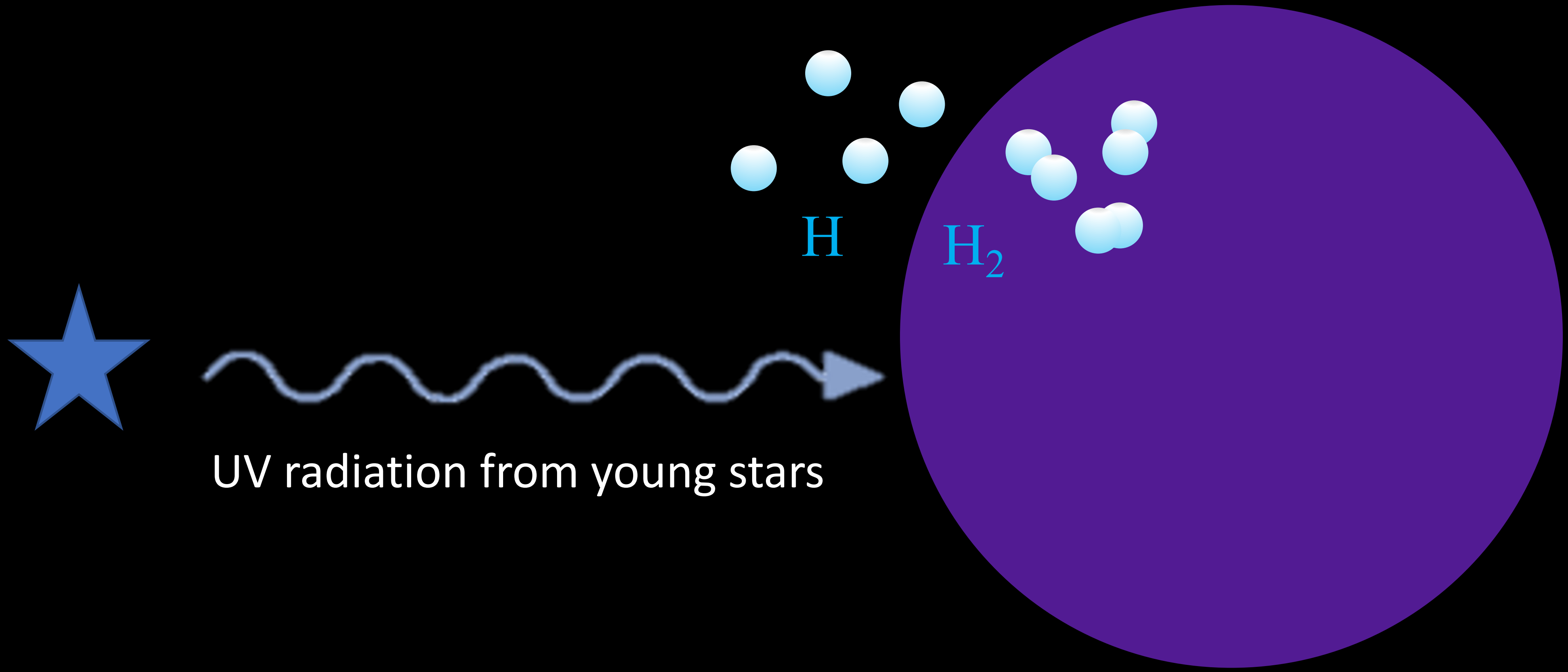
H_2

CO as an observational tracer for H_2

- H_2 does not emit efficiently in molecular clouds (too cold).
- Observationally, we need a tracer for H_2 to infer its existence.
- Carbon monoxide (CO) is the most widely used tracer for H_2.



Recap on ISM chemistry: H/H_2 transition



UV radiation from young stars

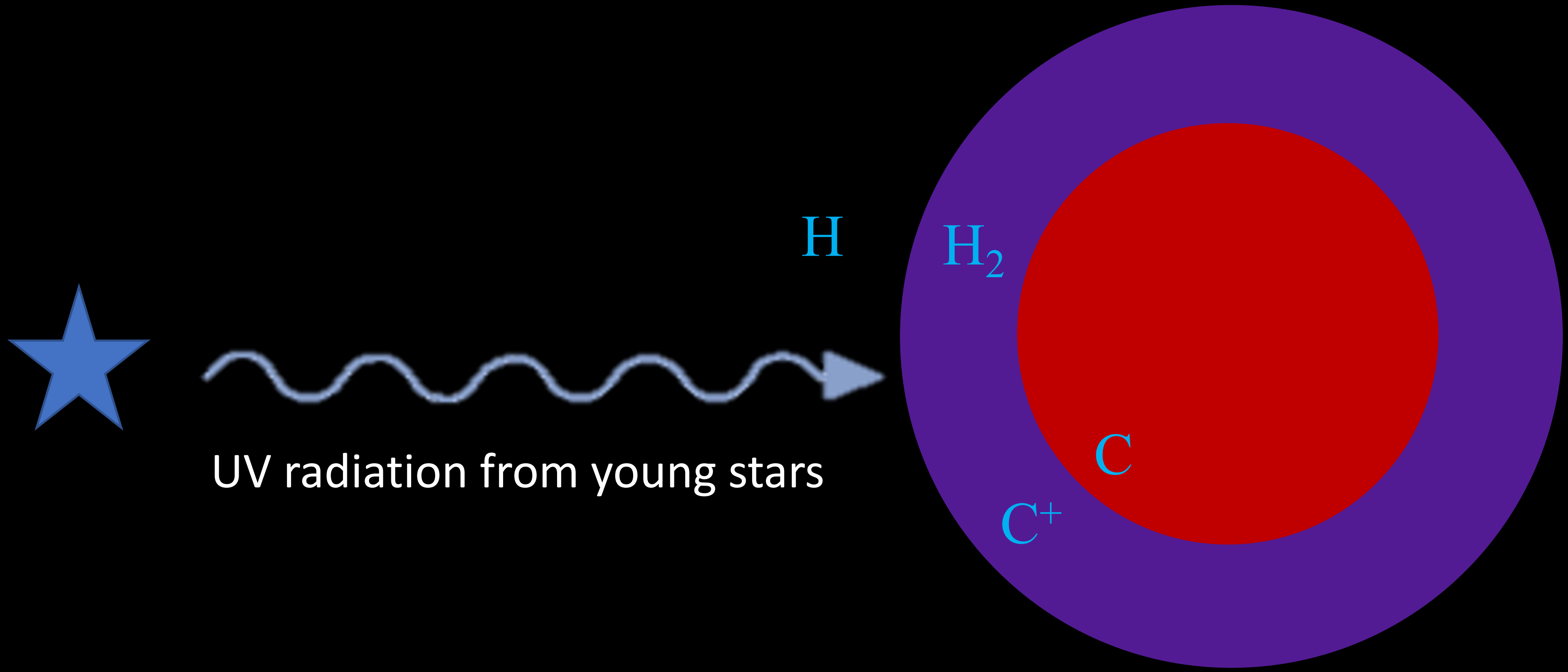
H_2 destruction: photodissociation

$$H_2 + h\nu \rightarrow H + H$$

H_2 formation: on surfaces of dust grains

$$H + H:\mathrm{dust} \rightarrow H_2$$

Recap on ISM chemistry: C^+/C transition



UV radiation from young stars

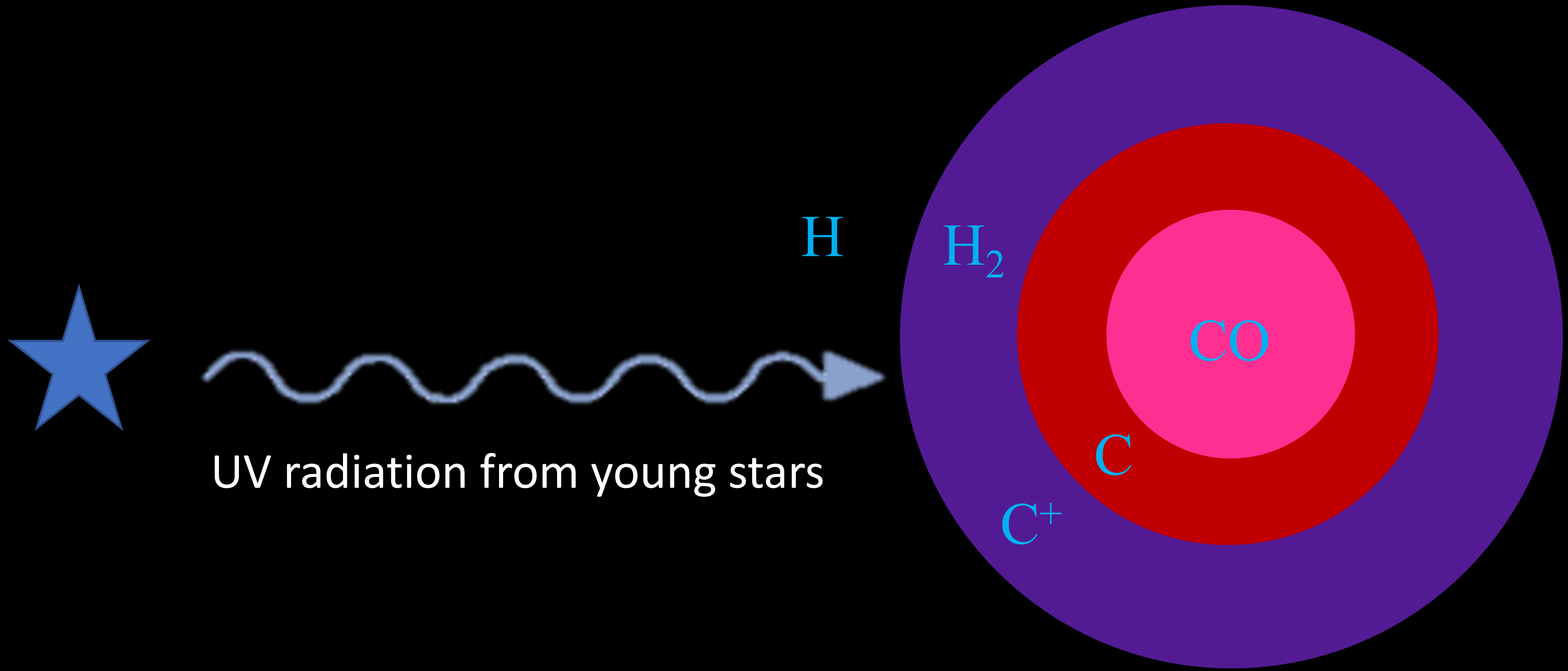
C destruction: photoionization

$$C + \gamma \rightarrow C^+ + e^-$$

C formation: recombination

$$C^+ + e^- \rightarrow C + \gamma$$

Recap on ISM chemistry: C/CO transition



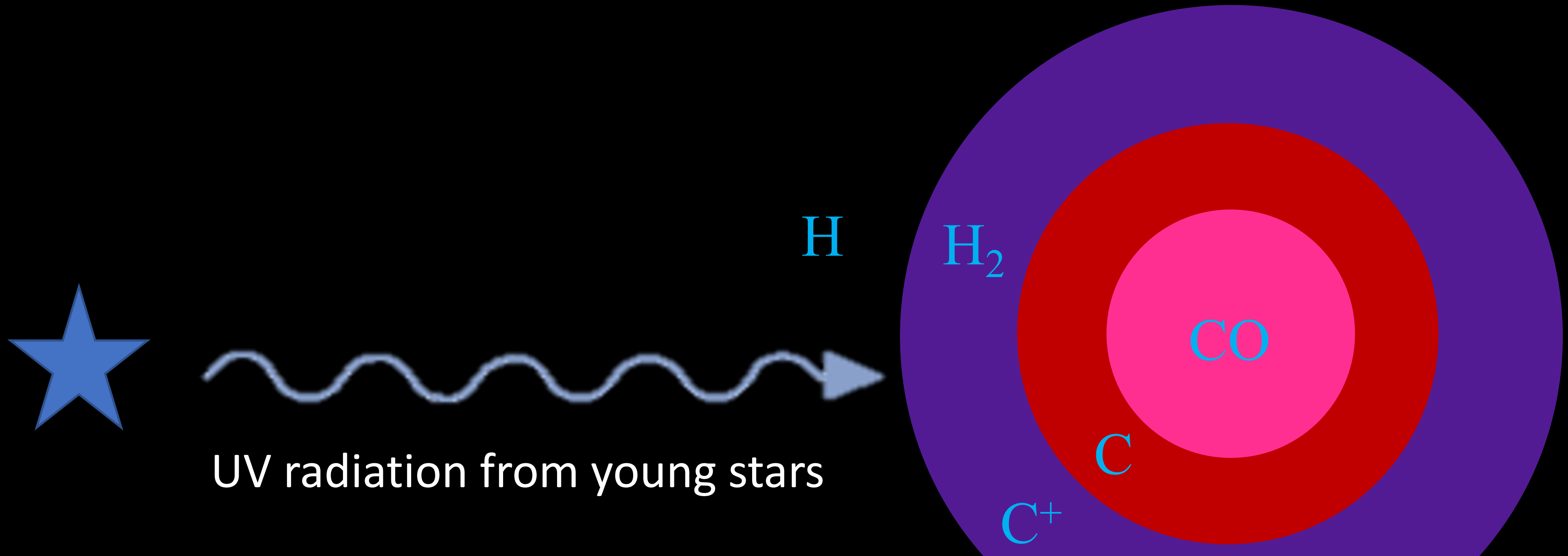
CO destruction: photodissociation

$$\mathrm{CO} + h\nu \rightarrow \mathrm{C} + \mathrm{O}$$

CO formation:
requires H_2!

$$\begin{cases} \mathrm{C}^+ + \mathrm{H}_2 \rightarrow \mathrm{CH}_2^+ + h\nu \\ \mathrm{CH}_2^+ + e^- \rightarrow \begin{cases} \mathrm{CH} + \mathrm{H} & (25\%) \\ \mathrm{C} + \mathrm{H}_2 & (12\%) \\ \mathrm{C{+}H{+}H} & (63\%) \end{cases} \\ \mathrm{CH} + \mathrm{O} \rightarrow \mathrm{CO} + \mathrm{H} \end{cases}$$

Recap on ISM chemistry: C/CO transition



UV radiation from young stars

CO is expected to trace H_2!

CO destruction: photodissociation

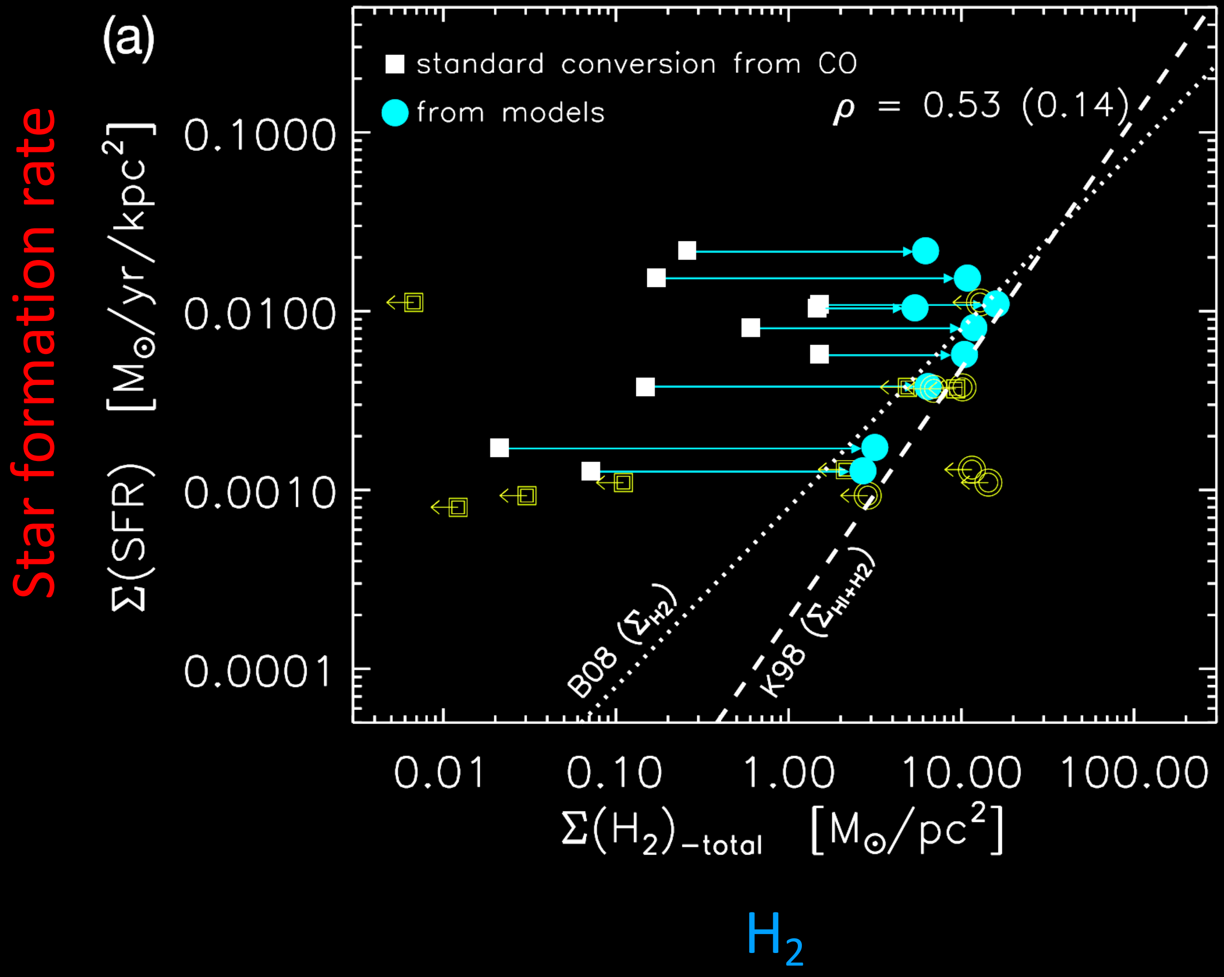
$$\mathrm{CO} + h\nu \rightarrow \mathrm{C} + \mathrm{O}$$

CO formation:
requires H_2!

$$\left\{\begin{array}{l} \mathrm{C}^+ + \mathrm{H}_2 \rightarrow \mathrm{CH}_2^+ + h\nu \\ \mathrm{CH}_2^+ + e^- \rightarrow \begin{cases} \mathrm{CH} + \mathrm{H} & (25\%) \\ \mathrm{C} + \mathrm{H}_2 & (12\%) \\ \mathrm{C} + \mathrm{H} + \mathrm{H} & (63\%) \end{cases} \\ \mathrm{CH} + \mathrm{O} \rightarrow \mathrm{CO} + \mathrm{H} \end{array}\right.$$

Dwarf galaxies have much higher SFR/L_{CO} ratio

Madden+ 2020

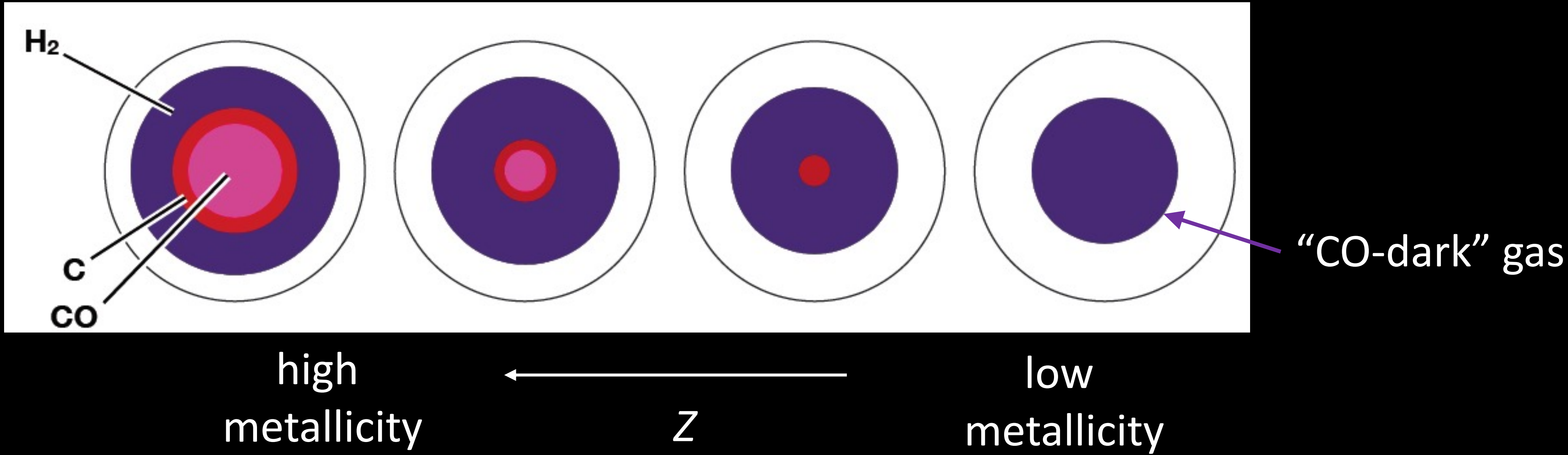


- Naïve explanation: they form stars much more efficiently.

- However, dwarf galaxies tend to have low metallicity, which leads to very different chemistry properties.

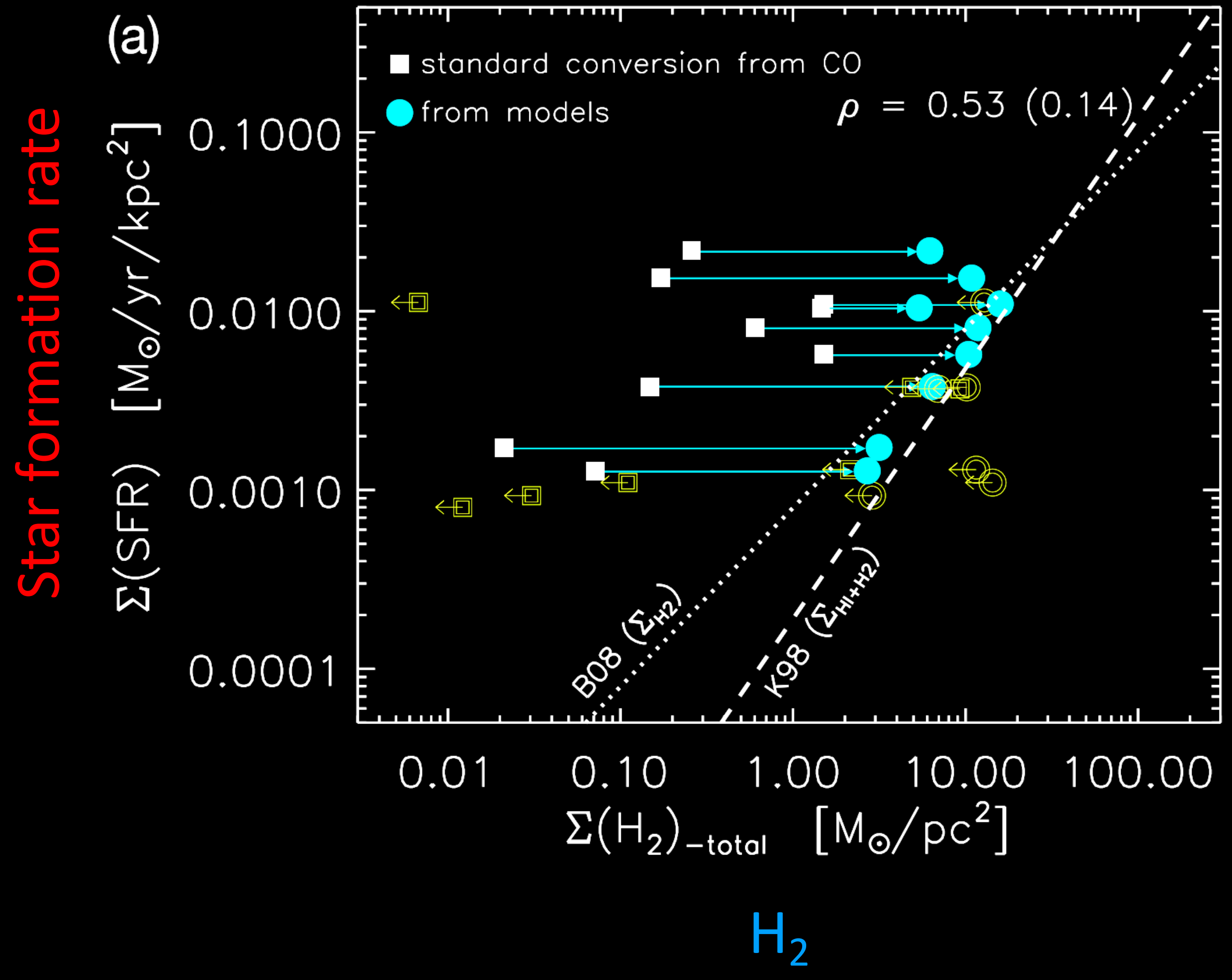
ISM chemistry changes significantly with metallicity

- low metallicity => low dust abundance => less shielding by dust => FUV radiation penetrates deeper into clouds
- C^+/C & C/CO boundaries contract significantly.
- H/H_2 boundary contracts too, but not as much (self-shielding).



Putting dwarf galaxies back to the KS relation

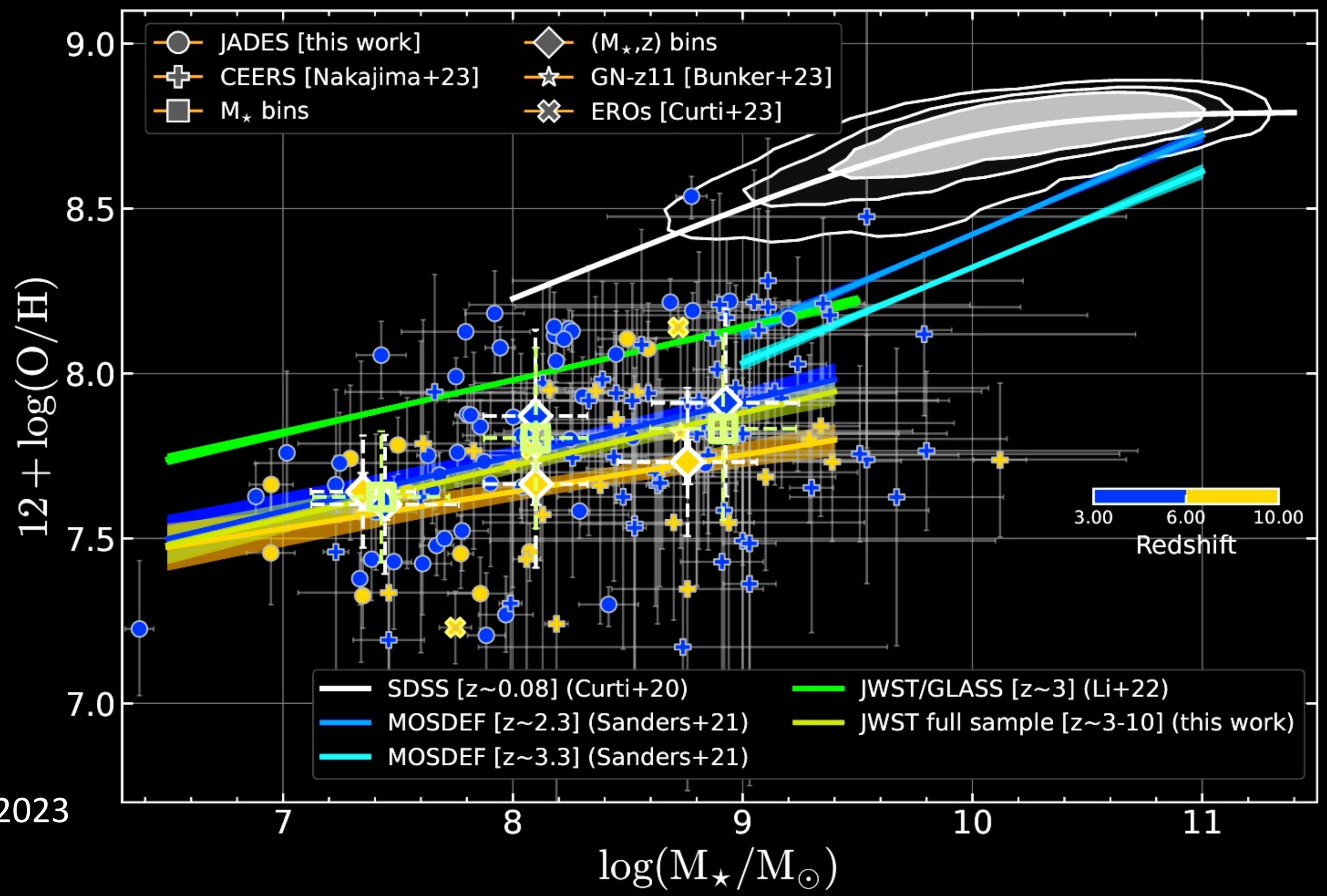
Madden+ 2020



- By accounting for the CO-dark molecular gas (adopting high X_{CO}), dwarf galaxies follow the KS relation similar to spiral galaxies.
- But is there really a large reservoir of CO-dark molecular gas?

Low-metallicity galaxies are common at high redshift

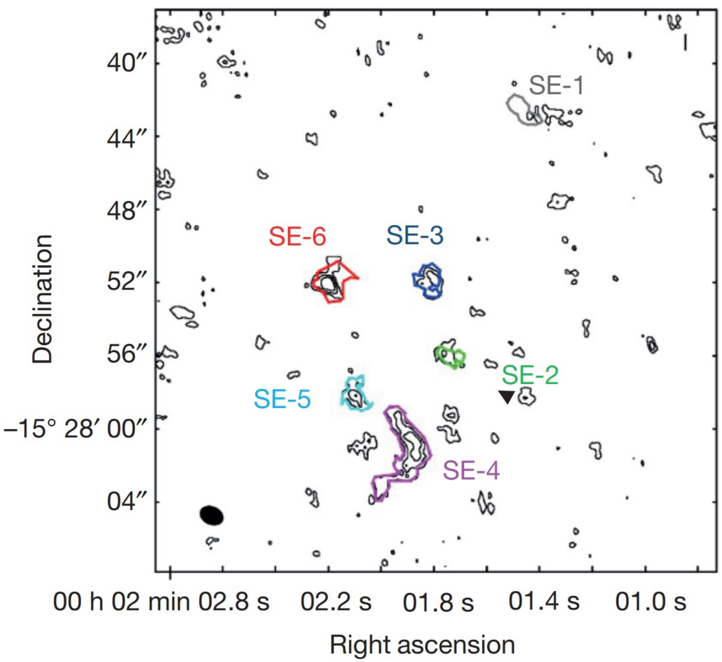
- Dwarf galaxies provide high-resolution information on low-metallicity ISM.
- This helps us understand high-redshift galaxies where resolution is limited.

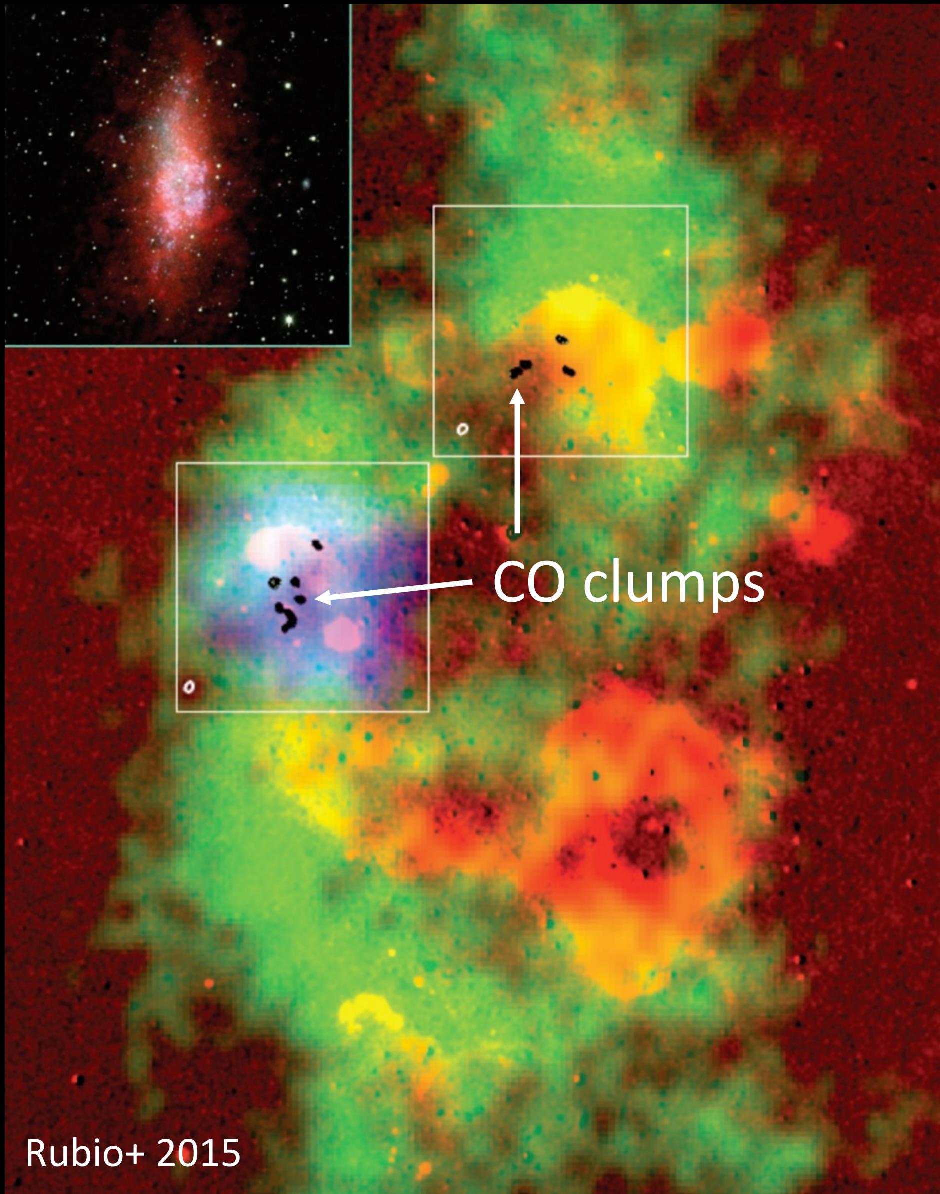


Curti+ 2023

Observed CO emission at low metallicity

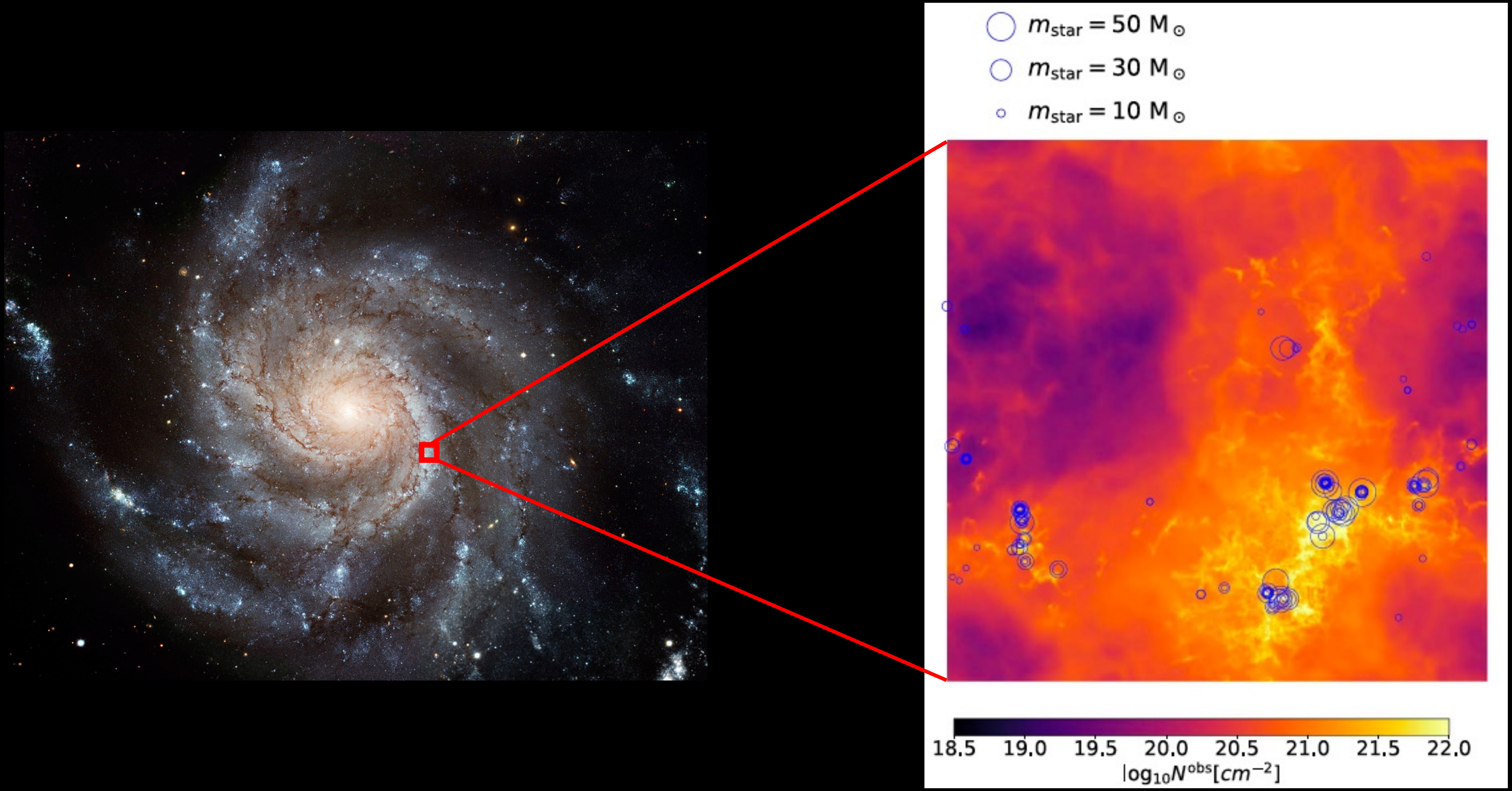
- The WLM dwarf galaxy: lowest metallicity (~0.1 $Z_\odot$) with CO detection (by ALMA)
- CO at low metallicity exists in compact, pc-scale clumps.
- Need high-resolution (sub-pc) simulations to resolve them!





Rubio+ 2015

Hydrodynamical simulations coupled with hydrogen chemistry

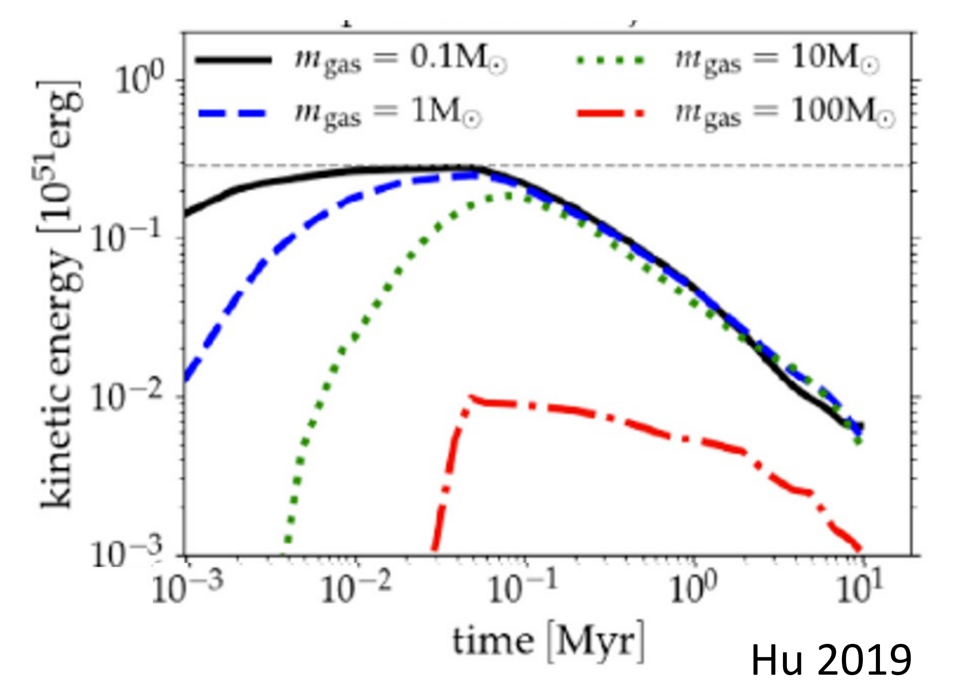


Hu+ 2021

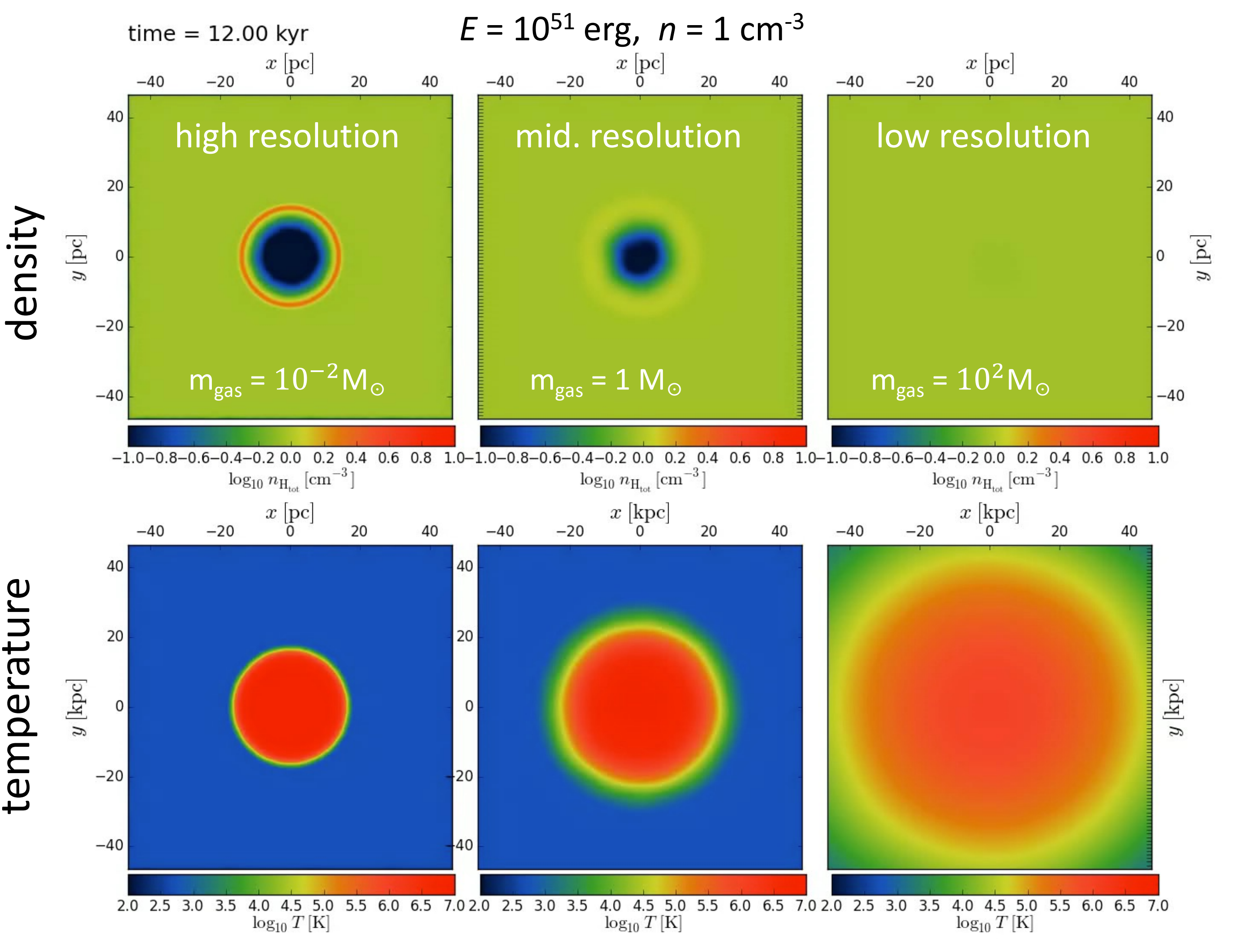
Resolving supervona (SN) feedback

- To capture the dynamical impact of SN feedback, the cooling radius has to be resolved:

$$r_{\rm sf} = 22.6\ {\rm pc}\ E_{51}^{0.29} n_0^{-0.42}$$



Hu 2019



Simulation Details

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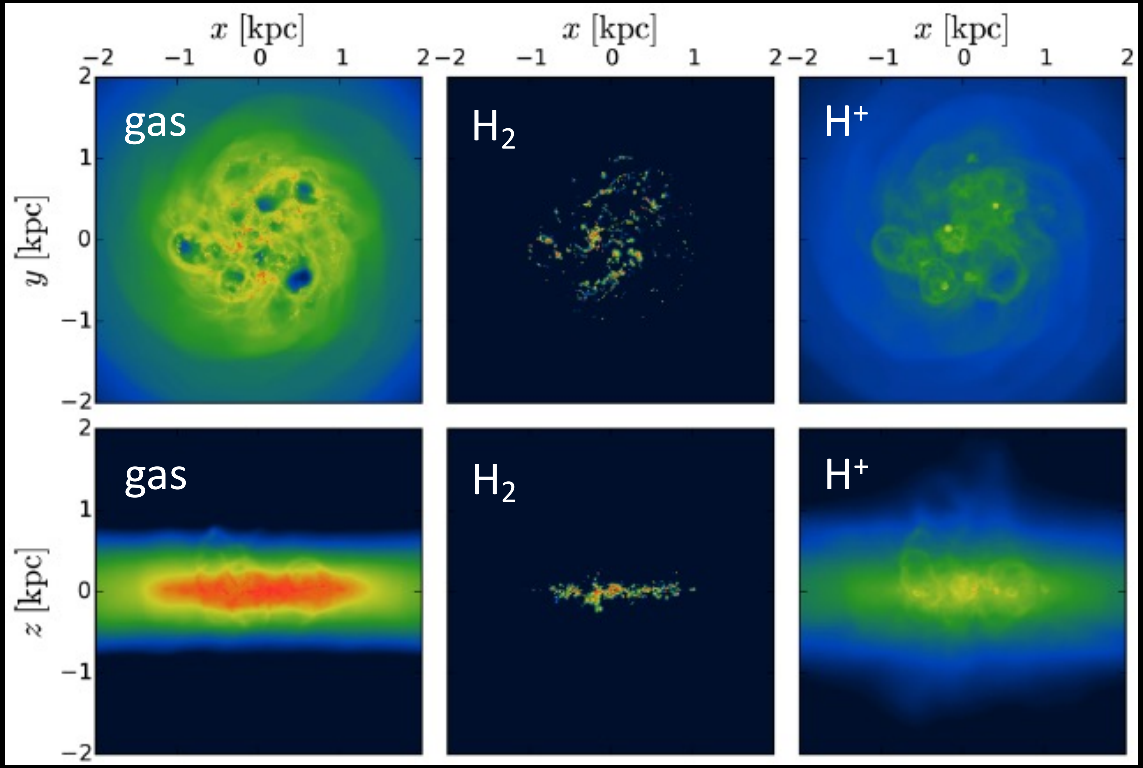

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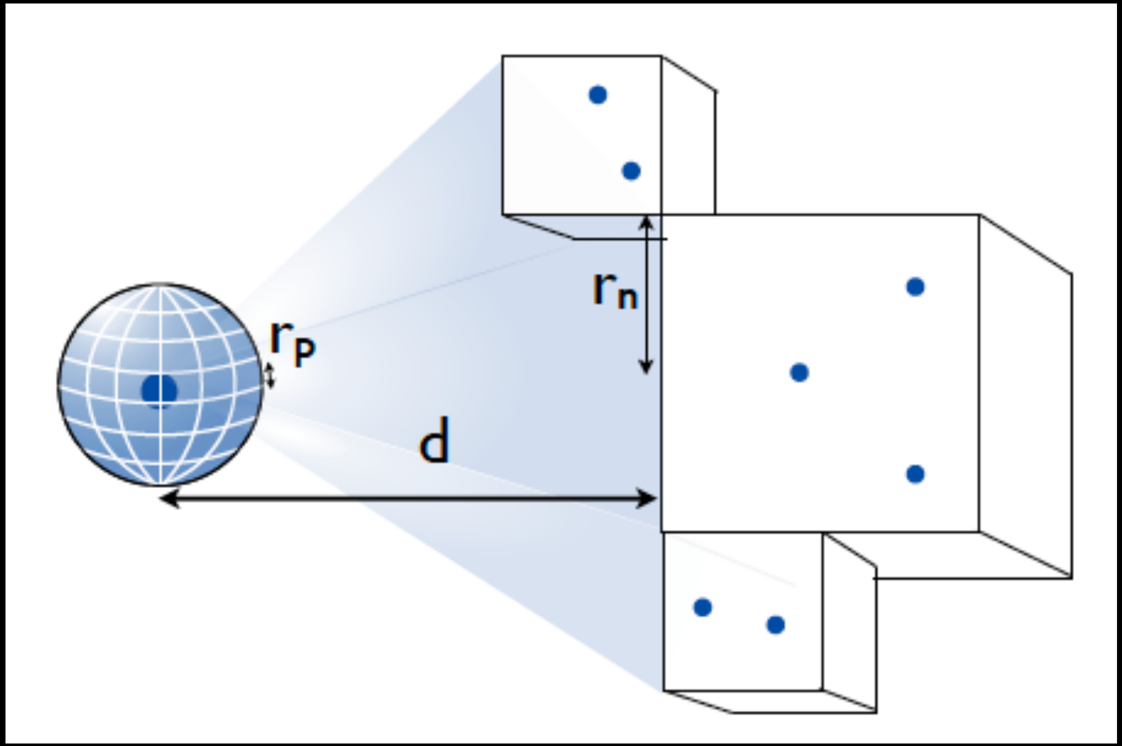

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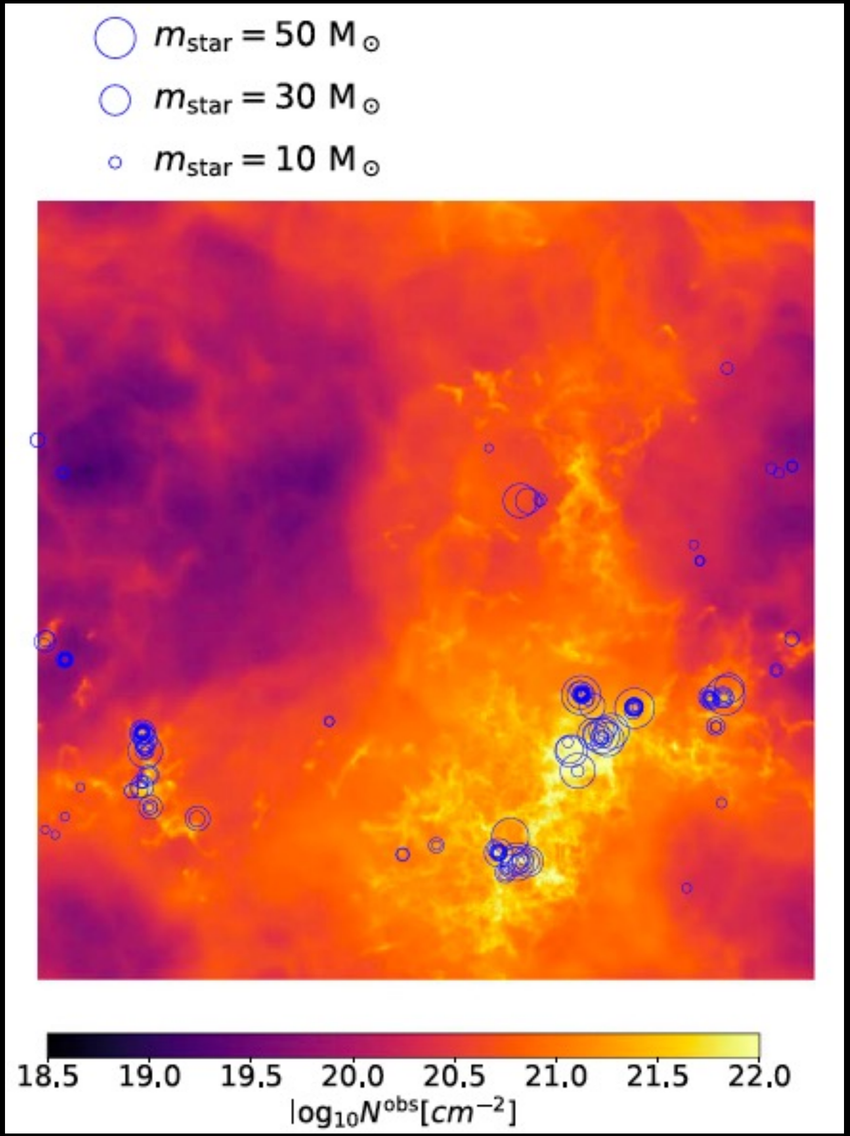

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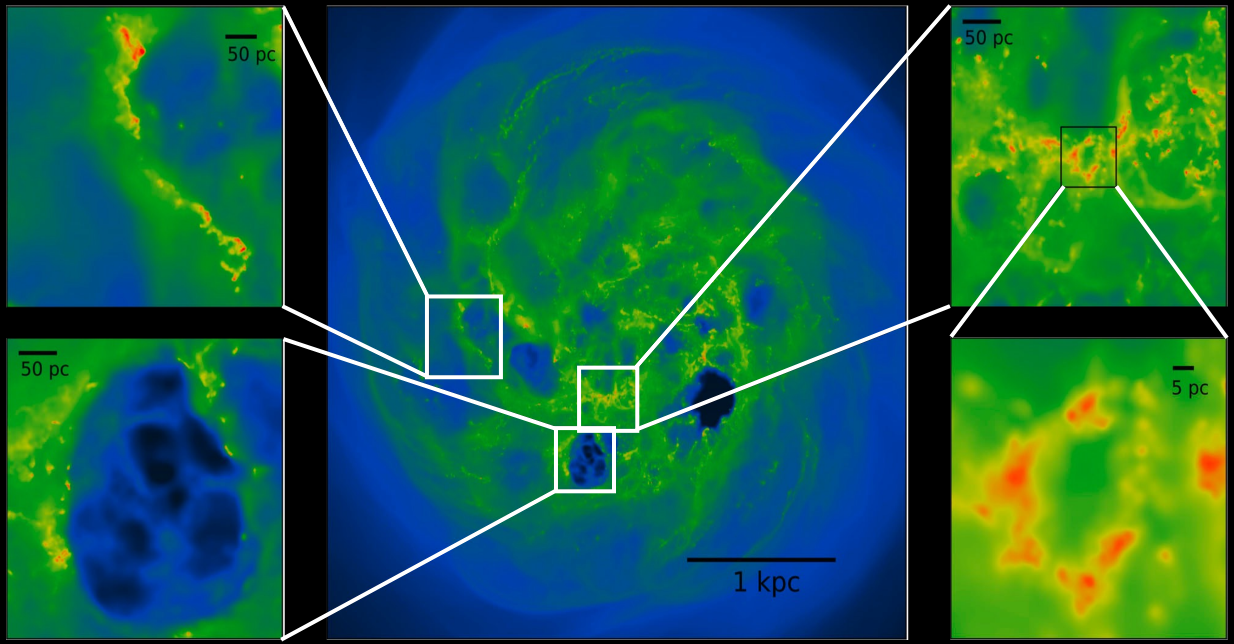


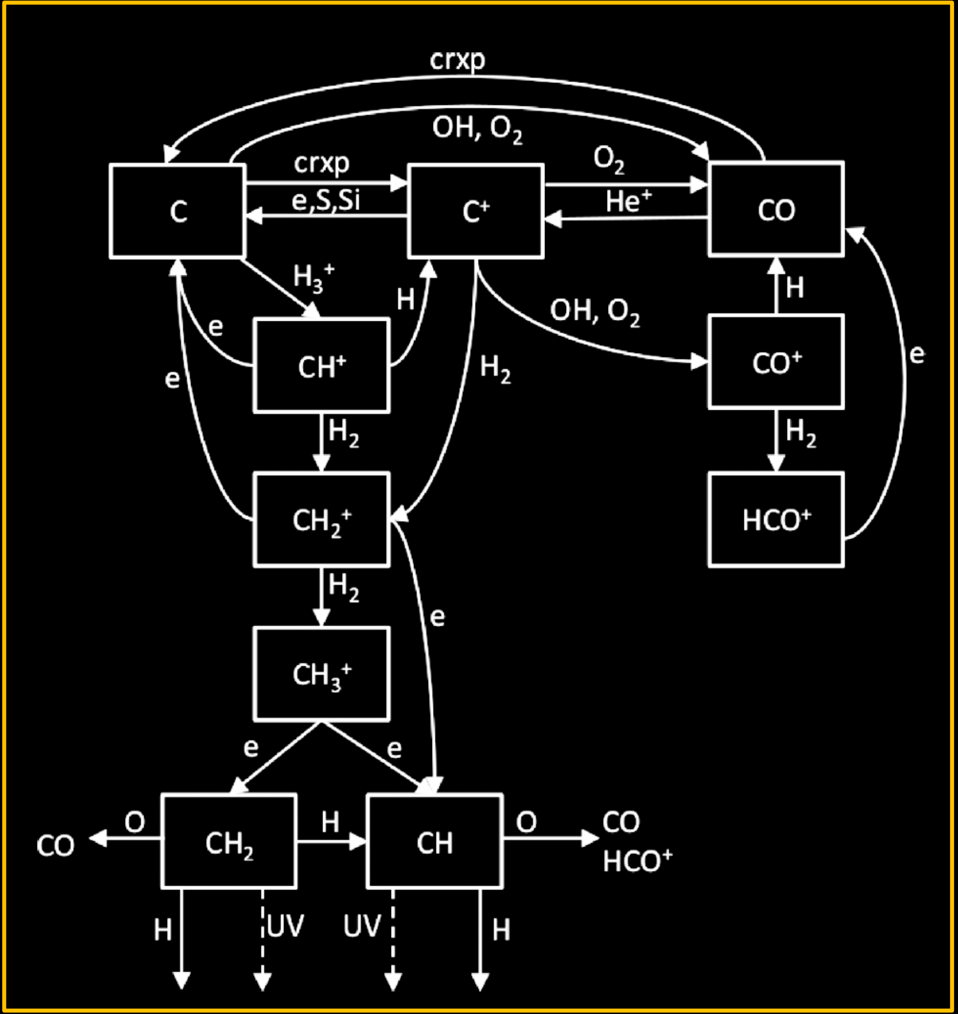
Challenges for modeling carbon chemistry in simulations

1) Need high resolution to resolve the compact CO clumps (pc scales).

2) Carbon chemistry is complicated and expensive to solve.

Previous simulations:

- adopt a simplified CO network (e.g. SILCC, Cloud Factory)
  - pros: fast
  - cons: low accuracy, tend to over-produce CO
- post-processing (e.g. TIGRESS)
  - pros: more accurate network
  - cons: need to assume chemical equilibrium

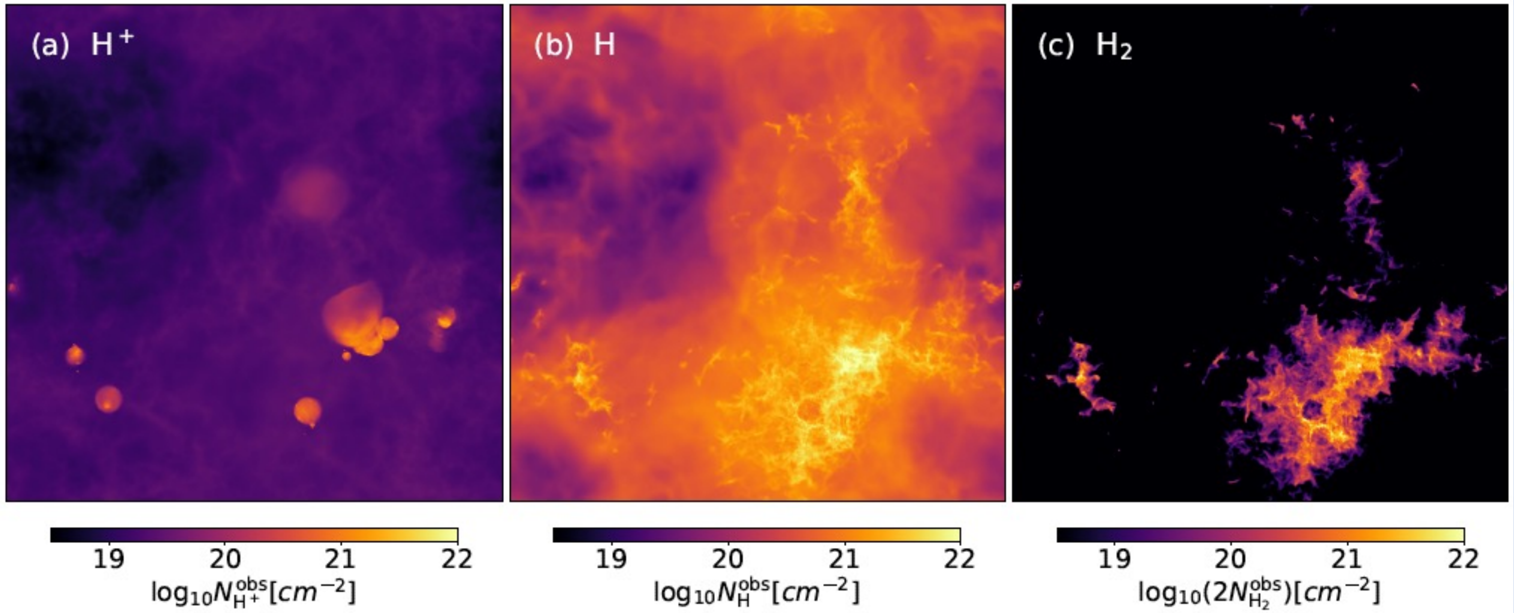


A hybrid approach

Hu+ 2021

Hydro simulation with a non-equilibrium H_2 chemistry network

simulation



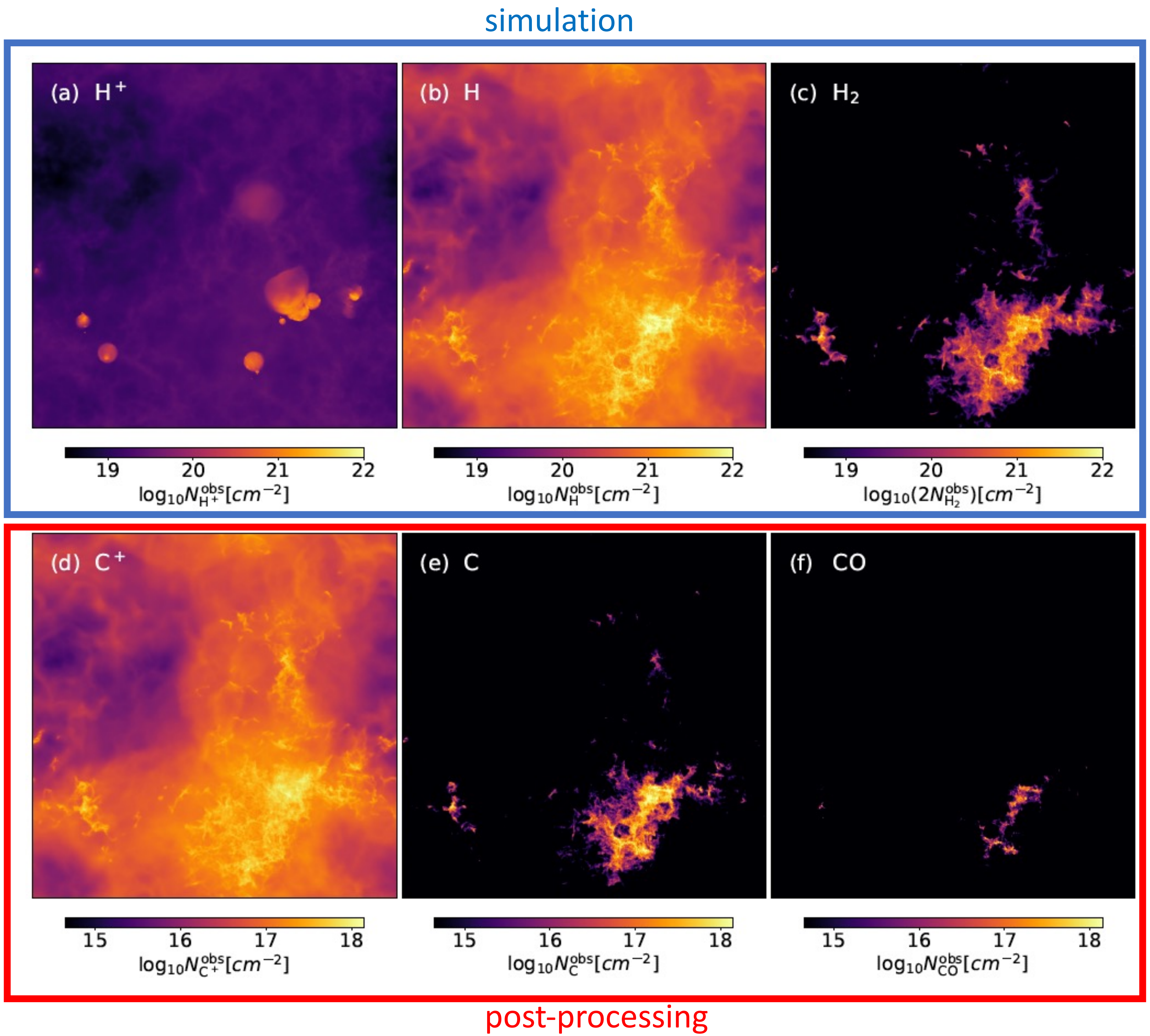
A hybrid approach

Hu+ 2021

Hydro simulation with a non-equilibrium H_2 chemistry network

Post-processing chemistry network, but using the non-equilibrium H_2 from simulations (31 species, 286 reactions)

H, H^-, H_2, H^+, H_2^+, H_3^+, e^-, He, He^+, HeH^+, C, C^+, CO, HCO^+, O, O^+, OH, OH^+, H_2O^+, H_3O^+, H_2O, O_2, CO^+, O_2^+, CH_2, CH_2^+, CH, CH^+, CH_3^+, Si^+ and Si.



H_2 has no time to reach equilibrium (steady state)

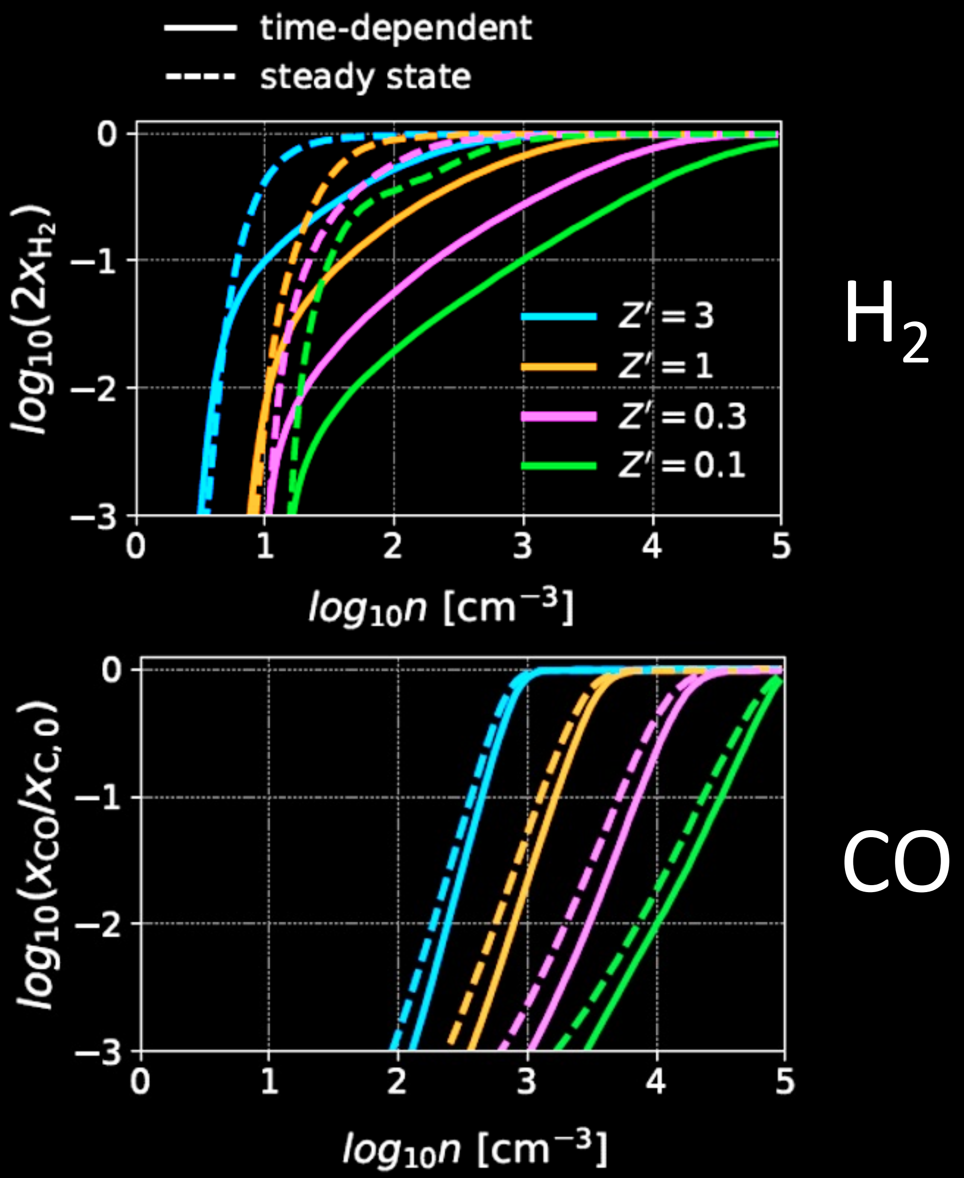
$$t_{\mathrm{form,H2}} = \frac{1\ \mathrm{Gyr}}{n\ Z'}$$

gas number density (cm^{-3})

normalized metallicity ($Z' = 1$ for solar)

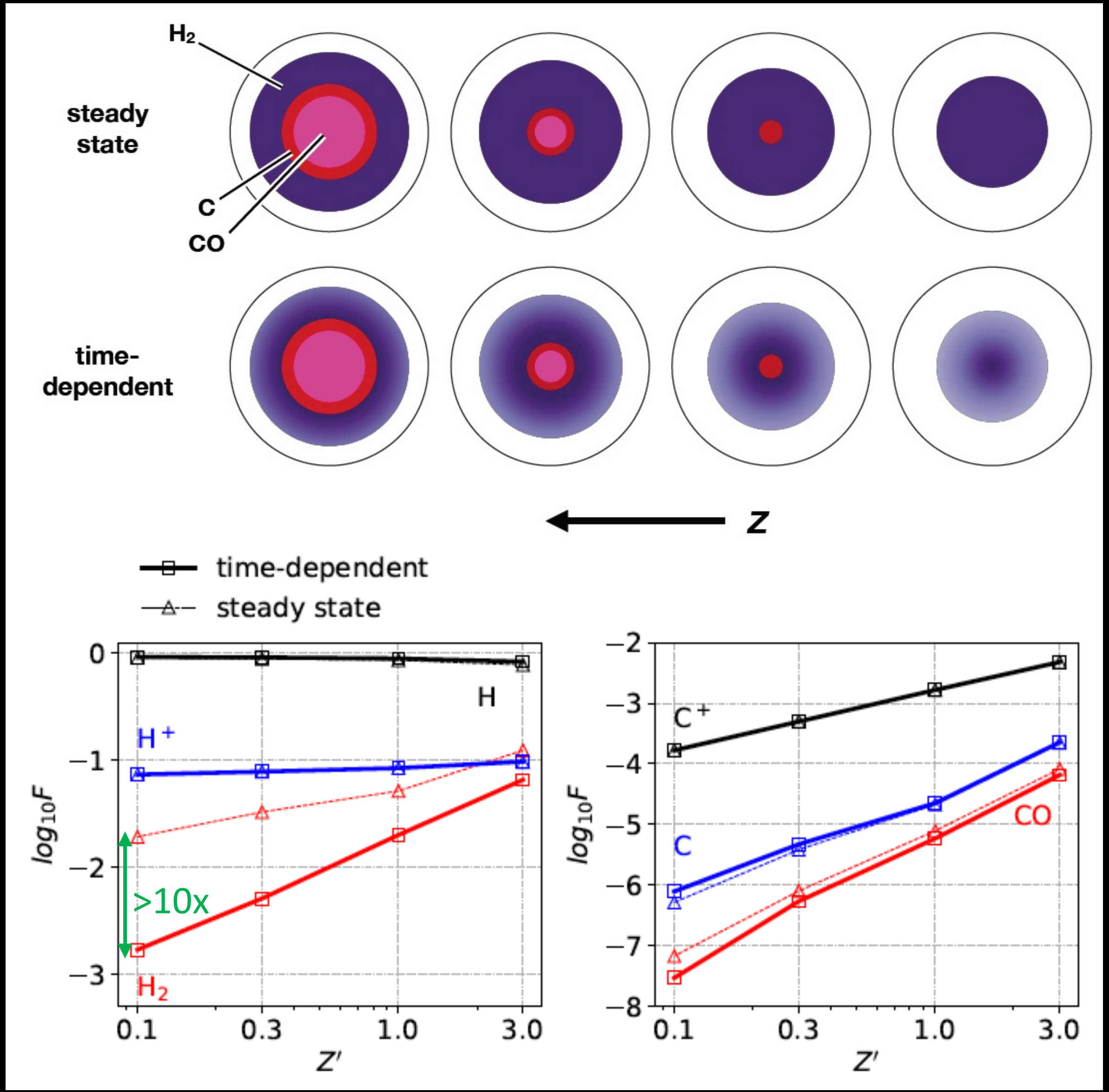
$t_{\mathrm{form,H2}} \gg t_{\mathrm{dyn}}$, especially at *low metallicity* (Z')

- H_2 has no time to reach steady state before getting destroyed by feedback!
- The dense, star-forming gas ($n > 100\ \mathrm{cm}^{-3}$) at low metallicity is dominated by atomic hydrogen.



The time-dependent (non-equilibrium) effect

At low Z, the time-dependent effect significantly suppresses H_2 formation, while C+/C/CO is almost unaffected.

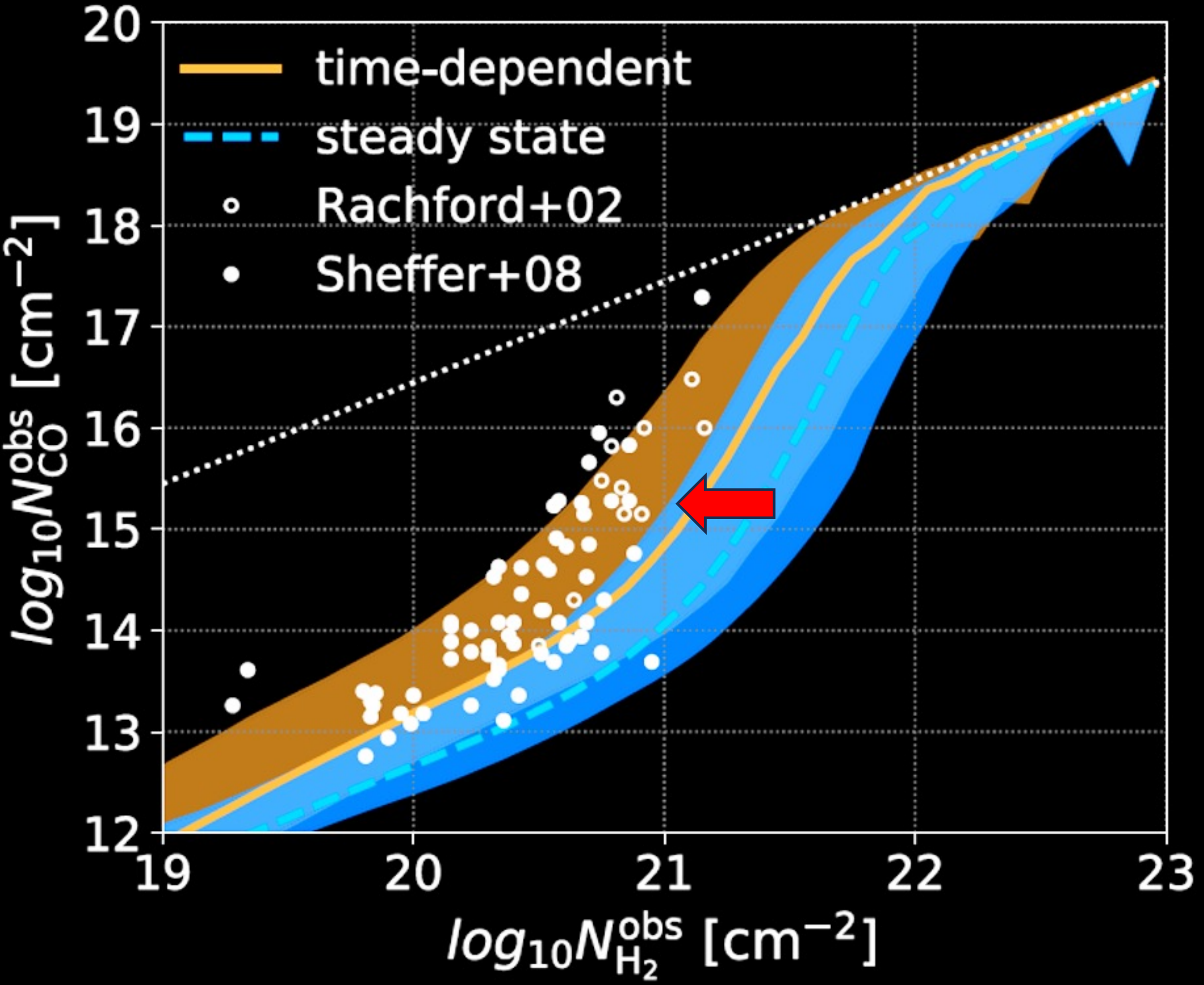


The time-dependent (non-equilibrium) effect

At low Z, the time-dependent effect significantly suppresses H_2 formation, while C+/C/CO is almost unaffected.

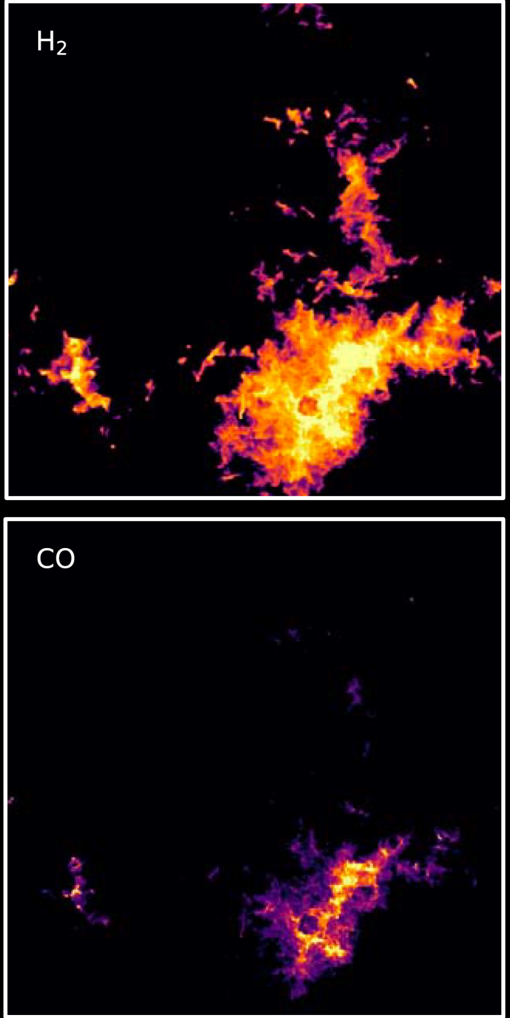
Steady-state model *overproduces* H_2!

Hu+ 2021



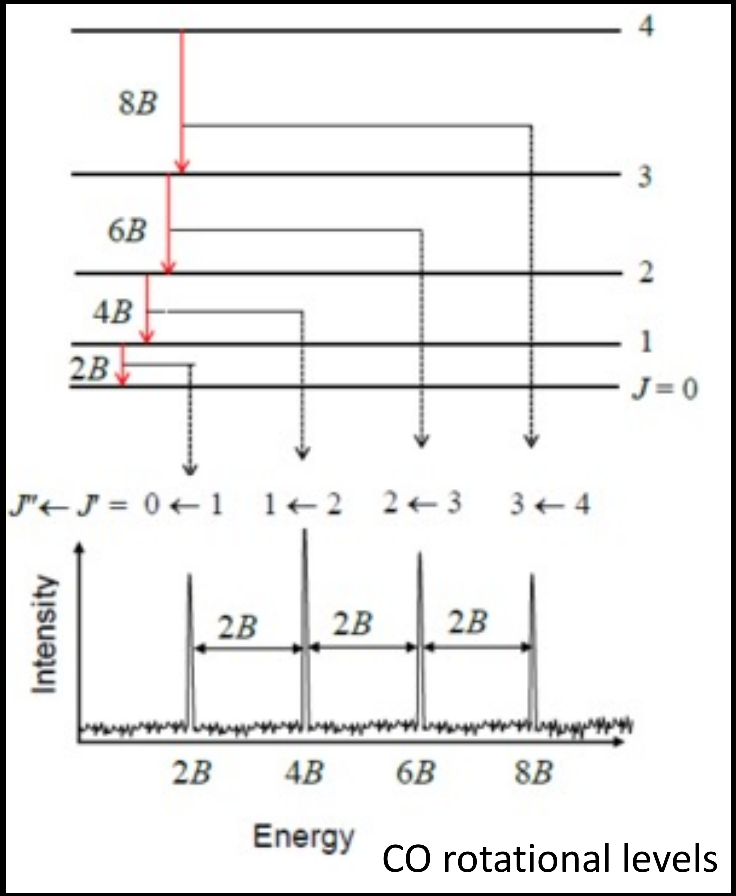
Modeling emission lines via radiative transfer

Hu+ 2022



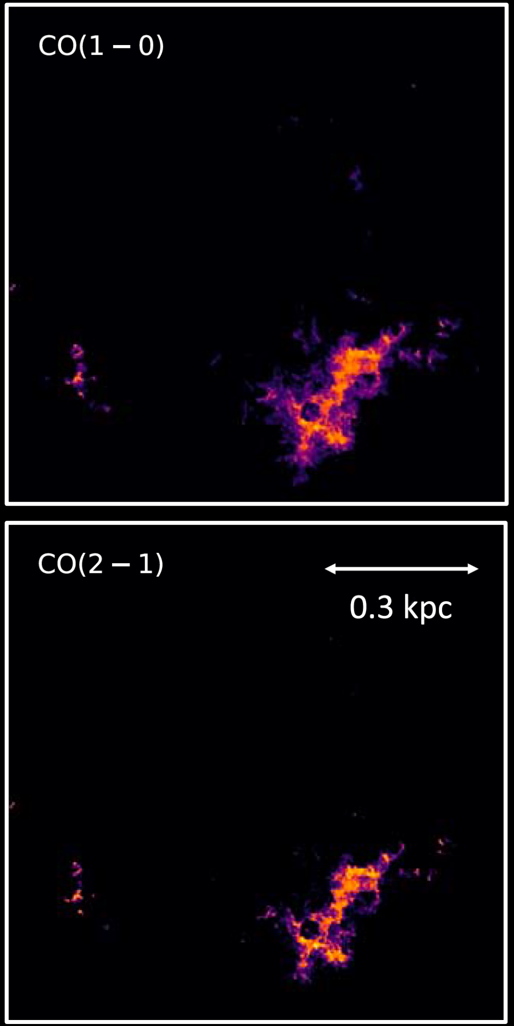
simulation

+



CO rotational levels

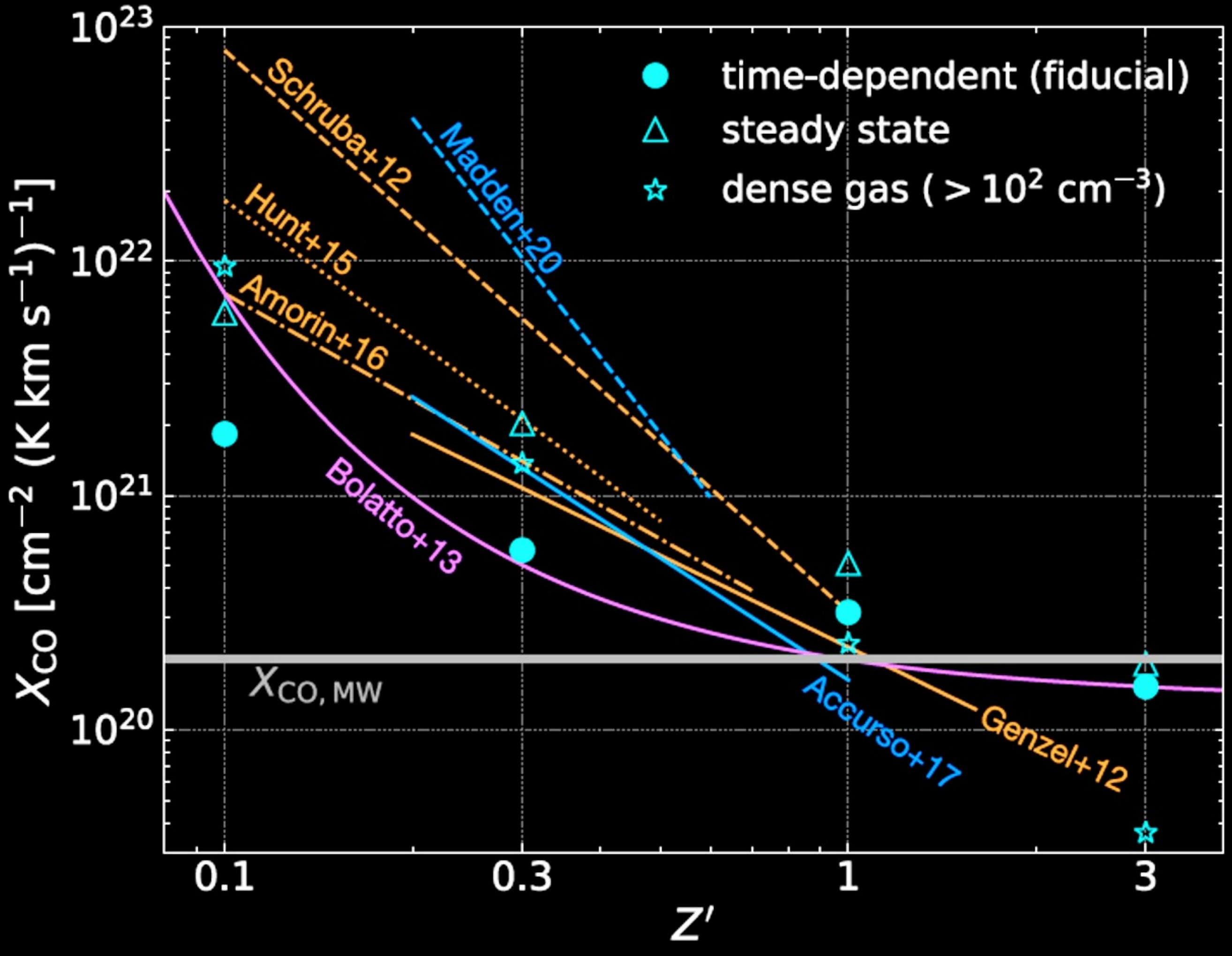
non-LTE calculation w/ LVG
using RADMC-3D



mock observation

Metallicity dependence of the CO-to-H_2 conversion factor (X_{CO})

Hu+ 2022



$$X_{CO} \equiv \frac{N_{H2}}{W_{10}}$$

H_2 column density

CO(1-0) line intensity

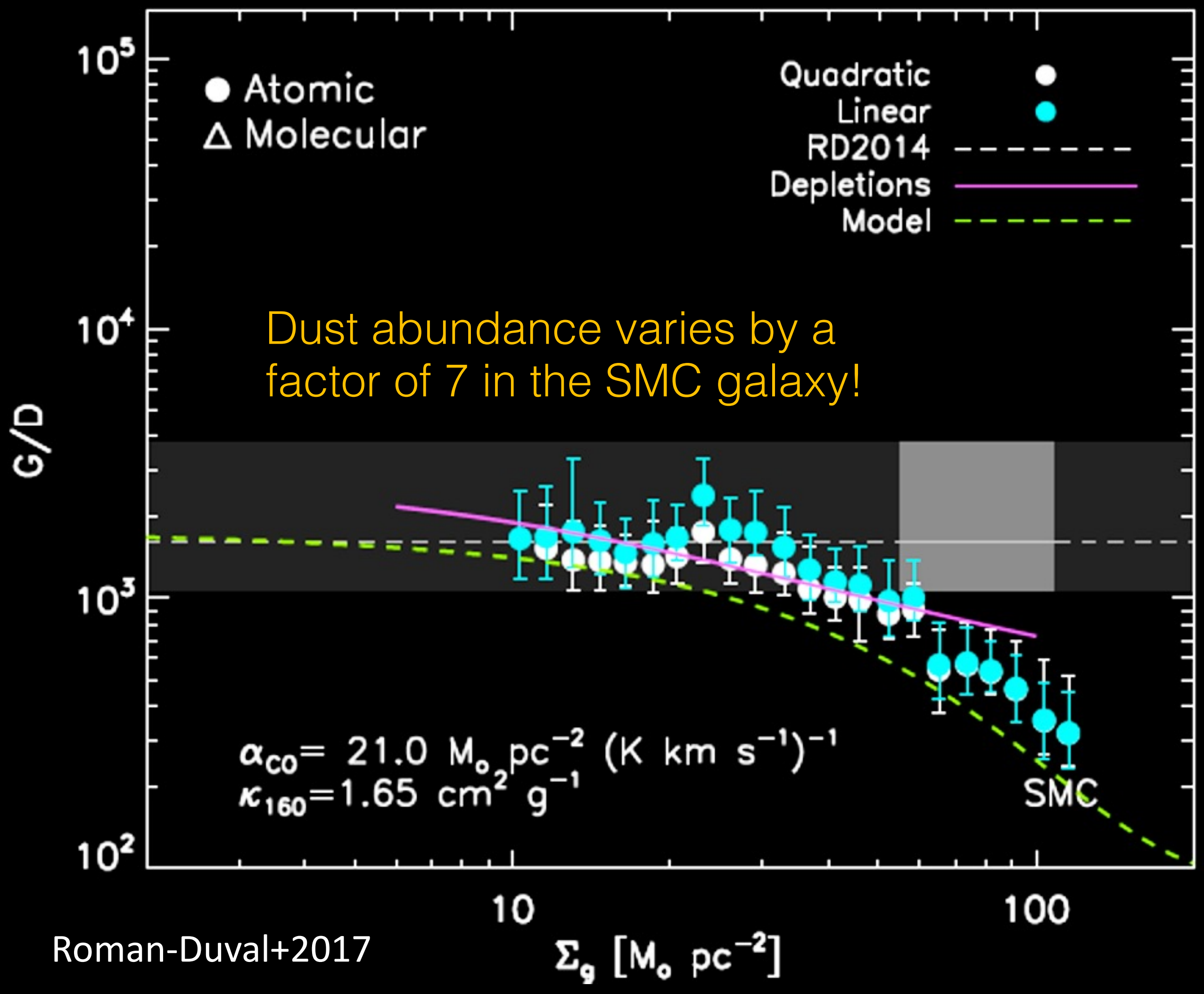
Observations overestimated X_{CO} (especially at low metallicity) because:

(1) Assuming steady-state chemistry (PDR modeling)

(2) Assuming star formation only in molecular gas (inverse Kennicutt-Schmidt law, M_{H2} = SFR / t_{dep})

Dust evolution and its impact on ISM chemistry

Spatial variation of dust abundance in the ISM



Dust abundance varies by a factor of 7 in the SMC galaxy!

Roman-Duval+2017

- Dust abundance varies from place to place as dust grows in the ISM and gets destroyed by SN shocks.
- However, most simulations assume a constant dust abundance.

Simulation Details

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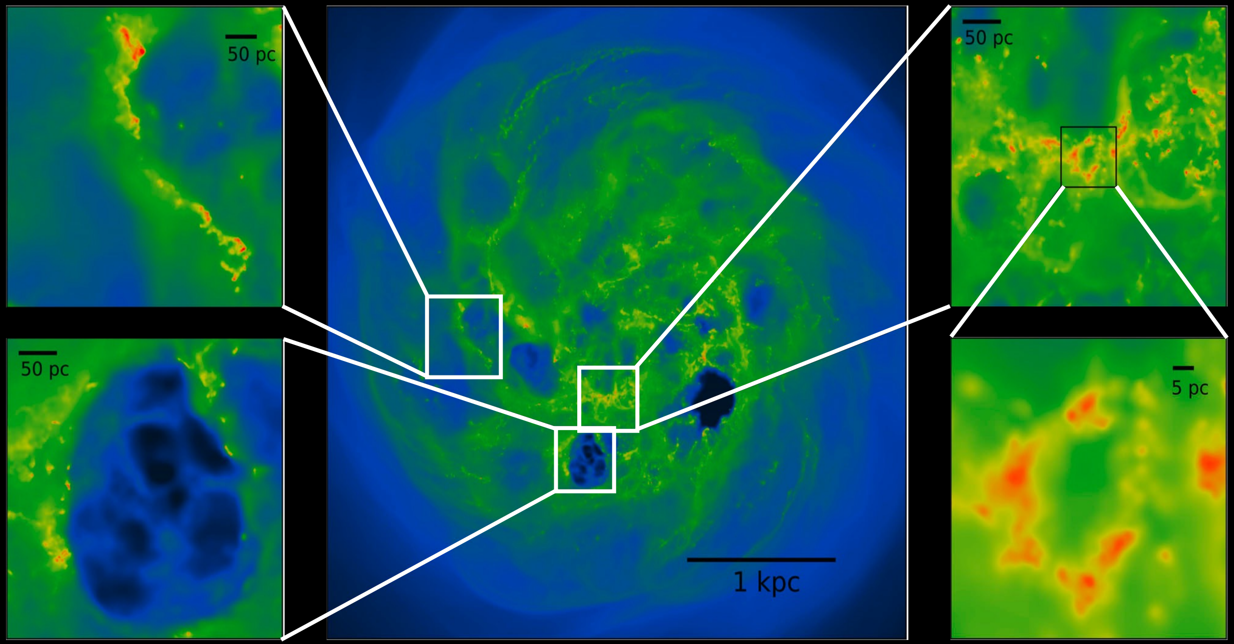
- ☐ Star formation w/ individual stars (Hu+2017, 2021)
- ☐ Feedback: supernova & photoionization (Hu+2017)
- ☐ Dust evolution: sputtering & dust growth (Hu+2023)



Dust destruction: sputtering

- Sputtering: collision between gas and dust
  - return dust material into gas phase

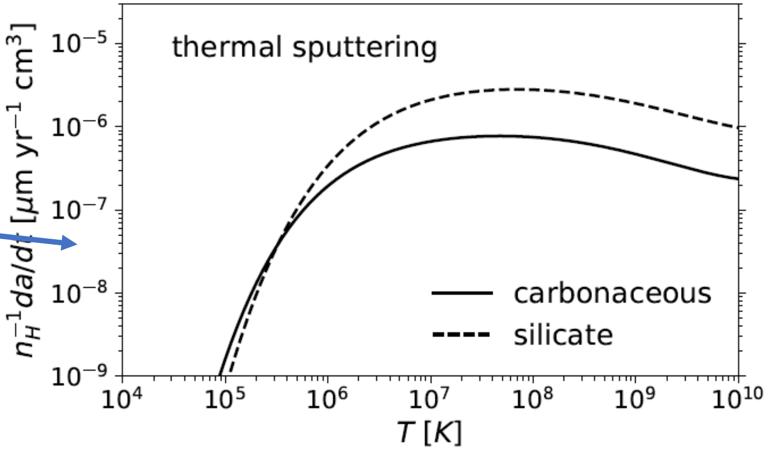
$$\frac{\mathrm{d}m_{\rm dust}}{\mathrm{d}t} = \frac{3 n_{\rm H} m_{\rm dust}}{a} \boxed{Y_{\rm tot}}$$

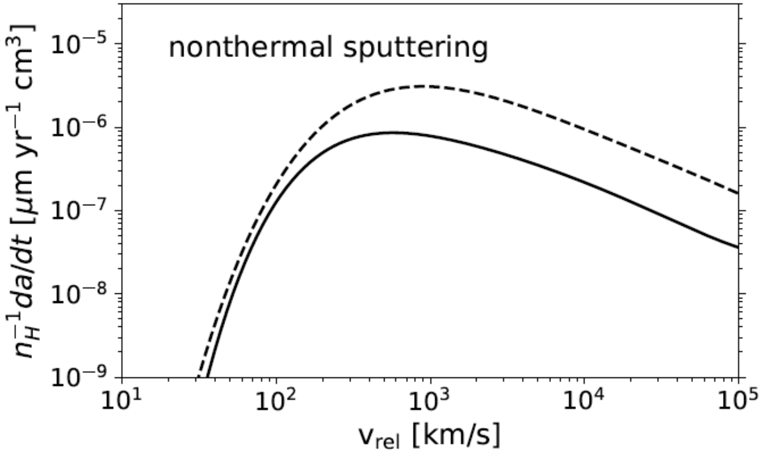
- One-fluid approach:
  dust is spatially coupled with gas
  (Larmor radius is small)

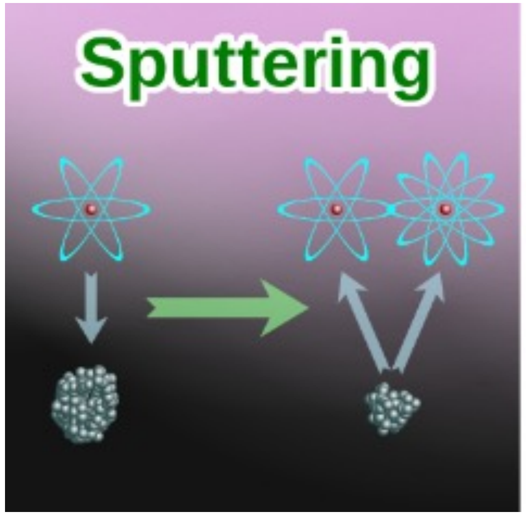
- The dust-gas relative velocity ($v_{\rm rel}$) leads to nonthermal sputtering

$$\frac{\mathrm{d}\mathbf{v}_{\rm rel}}{\mathrm{d}t} = \mathbf{a}_{\rm drag} + \mathbf{a}_{\rm beta} - \mathbf{a}_{\rm hydro}$$

Stiff! Need sub-cycling





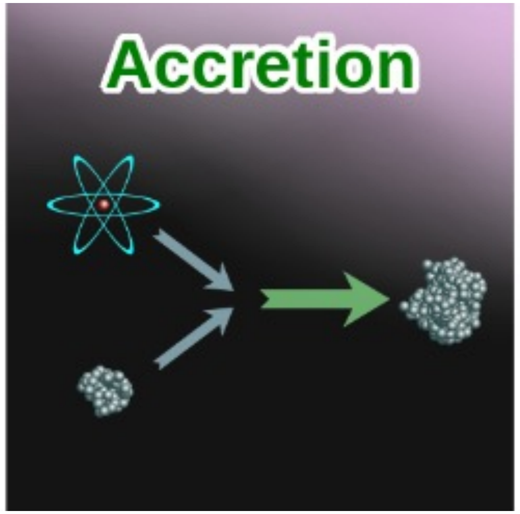


Dust formation: dust growth in the cold ISM

- Dust growth: collision between gas-phase metals and dust
  -> metals stick onto the surfaces of dust grains

- Growth timescale:

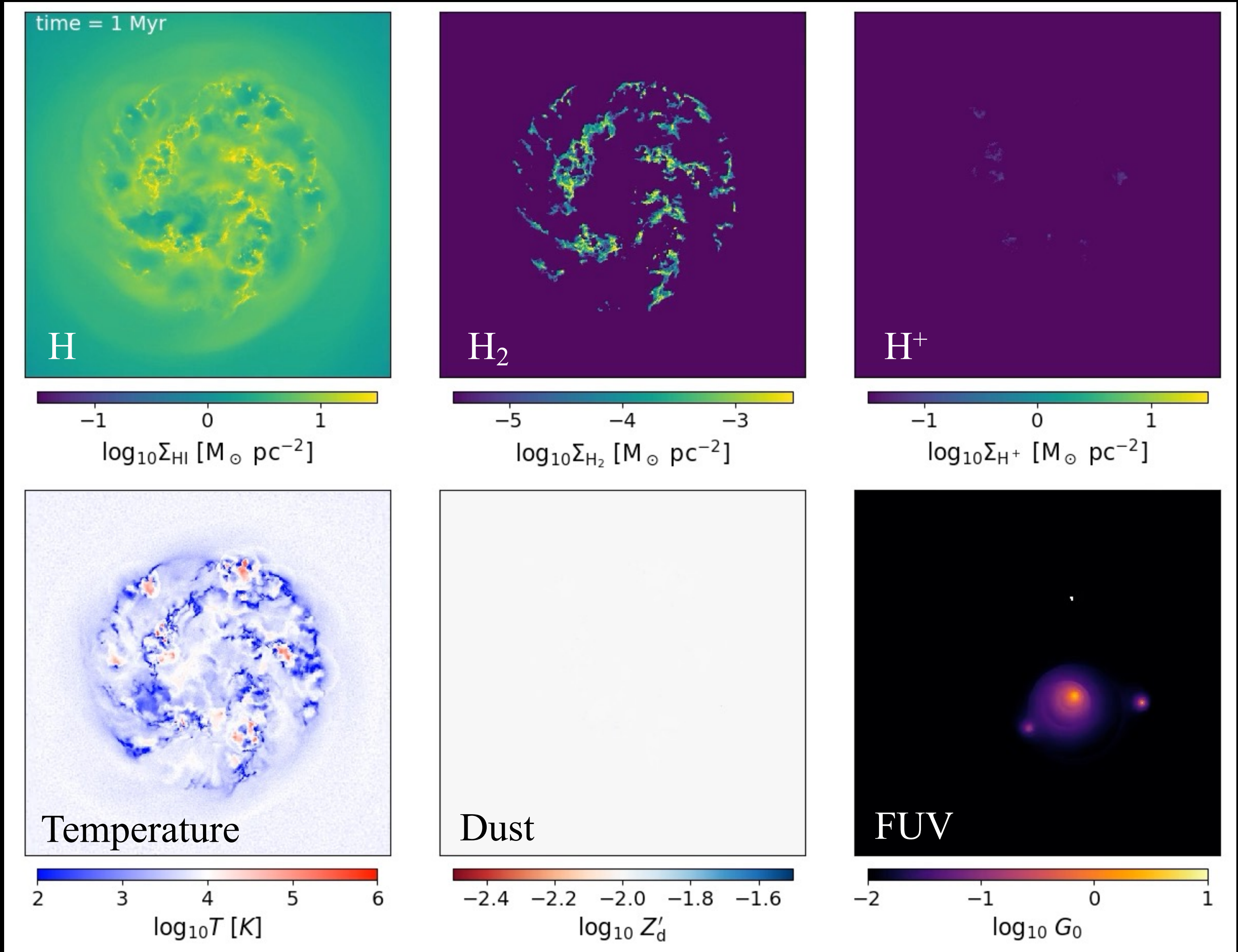
$$\tau = \frac{4 a s_d}{3 \alpha_s v_{\rm th} \rho_{\rm g} Z} = 1.4\ {\rm Myr} \left(\underset{\text{density}}{\boxed{\frac{n}{10^3 {\rm cm}^{-3}}}}\right)^{-1} \left(\underset{\text{temperature}}{\boxed{\frac{T}{100{\rm K}}}}\right)^{-0.5} \left(\underset{\text{metallicity}}{\boxed{\frac{Z}{Z_\odot}}}\right)^{-1} \left(\underset{\text{grain size}}{\boxed{\frac{a}{0.03 \mu{\rm m}}}}\right) \left(\underset{\text{sticking coefficient}}{\boxed{\frac{\alpha_s}{1.0}}}\right)$$



The effect of dust evolution on ISM chemistry

Hu+ 2023

- Dust destruction in SN shocks (Hu+2019)
- Dust growth in dense ISM **(Hu+2023)**
- Fully coupled with ISM chemistry!



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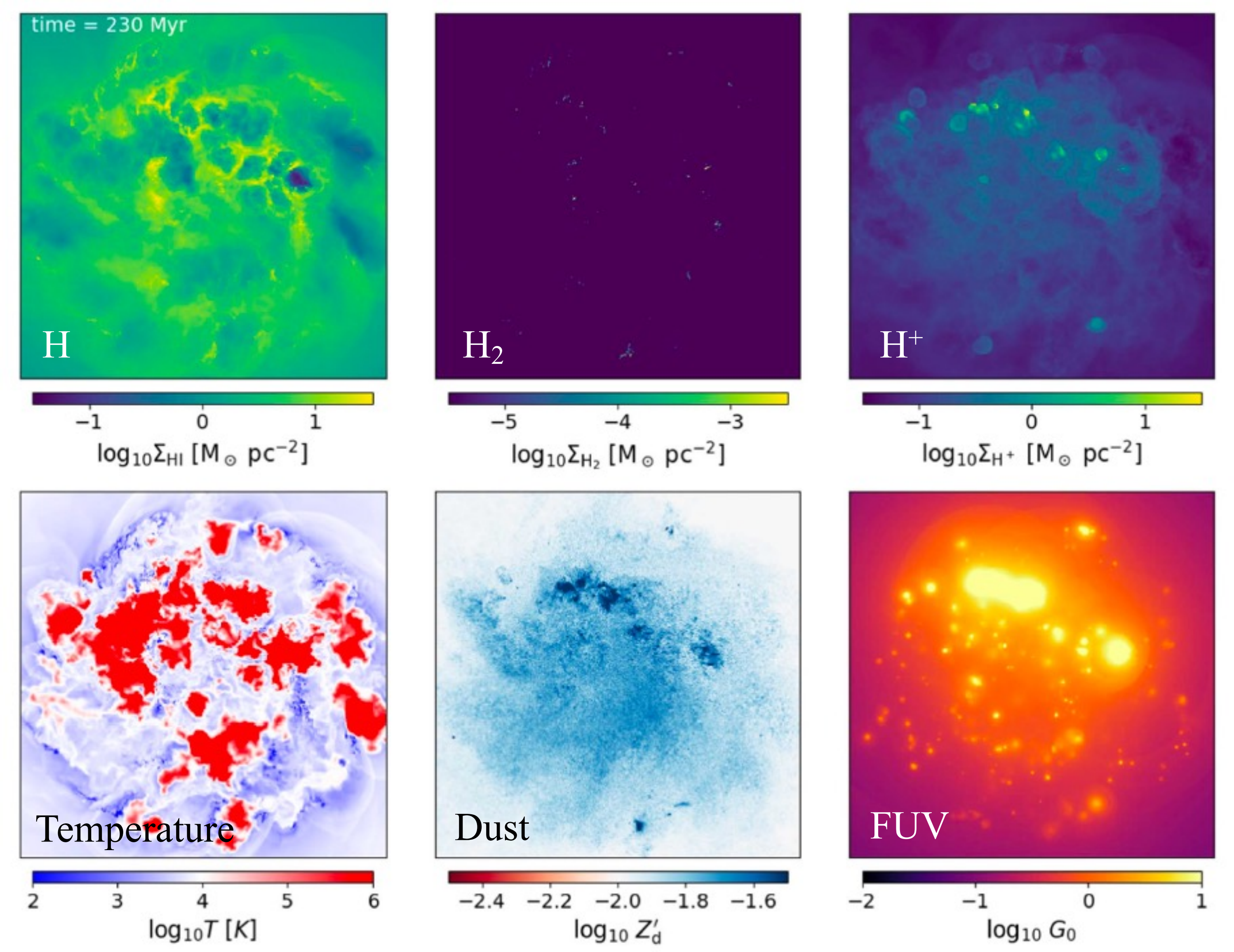
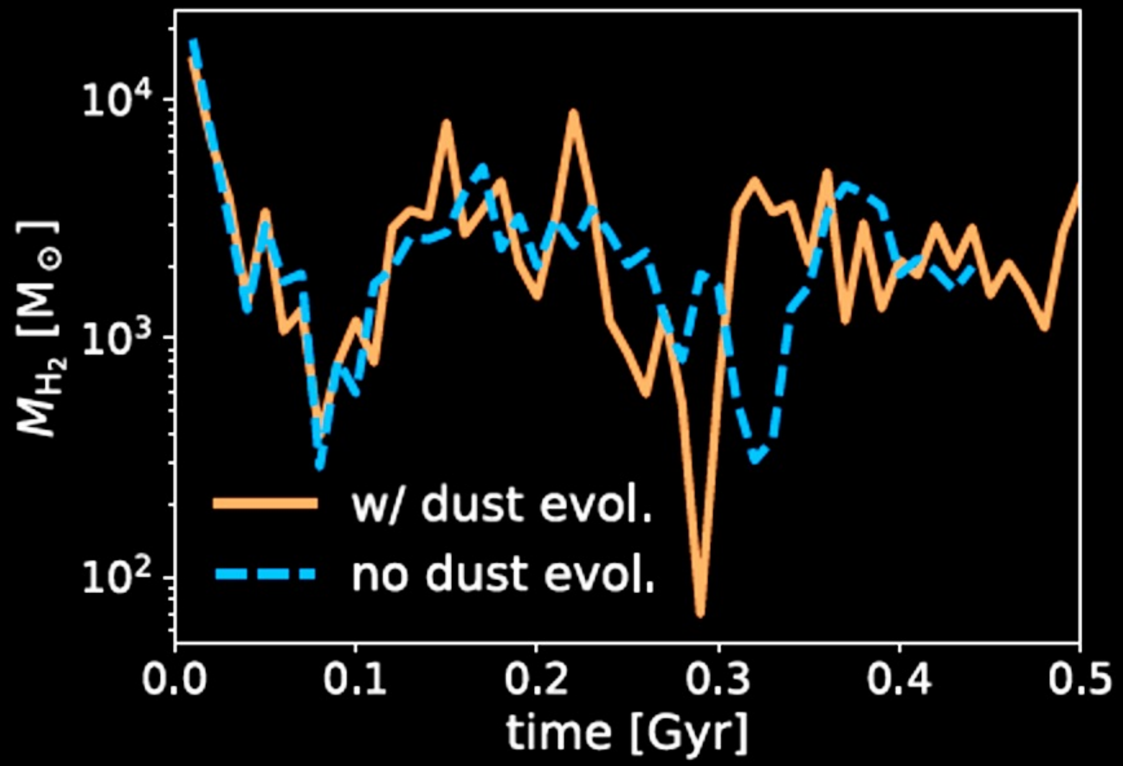
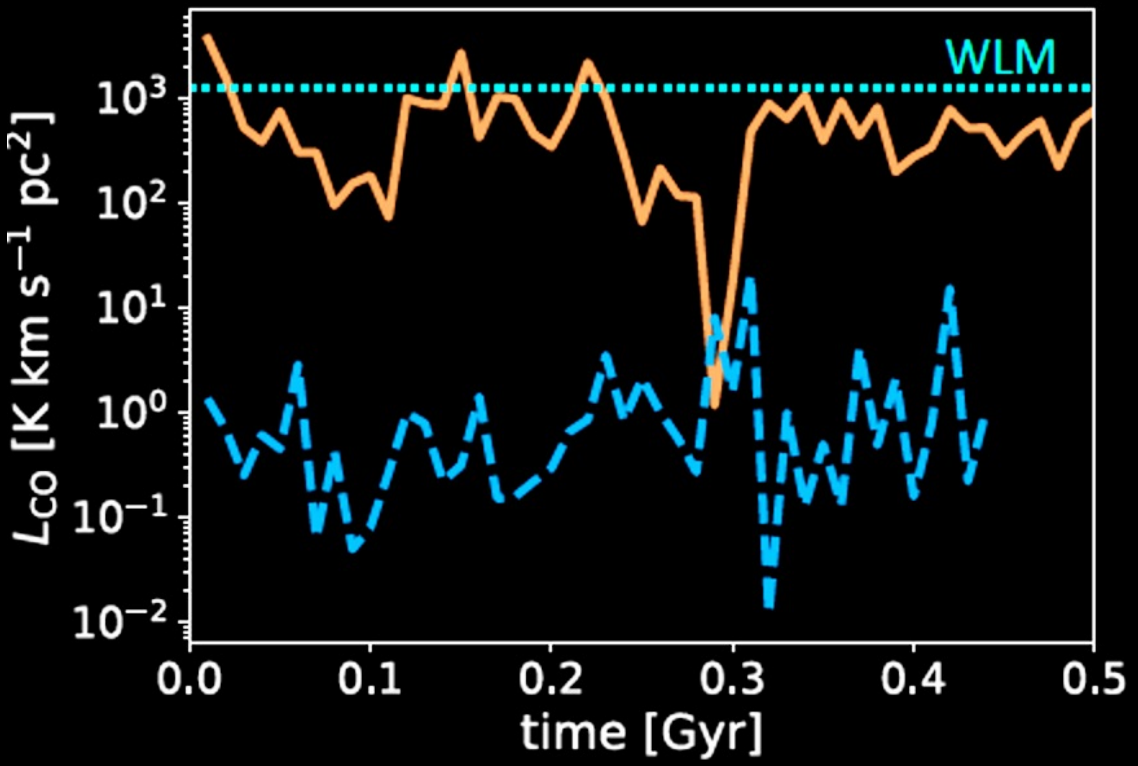


Dust evolution has a strong effect on CO



Very little H_2 w/wo dust evolution ($F_{H2} \sim 10^{-4}$)



Observed CO luminosity is reproduced only if dust evolution is included

Hu+ 2023

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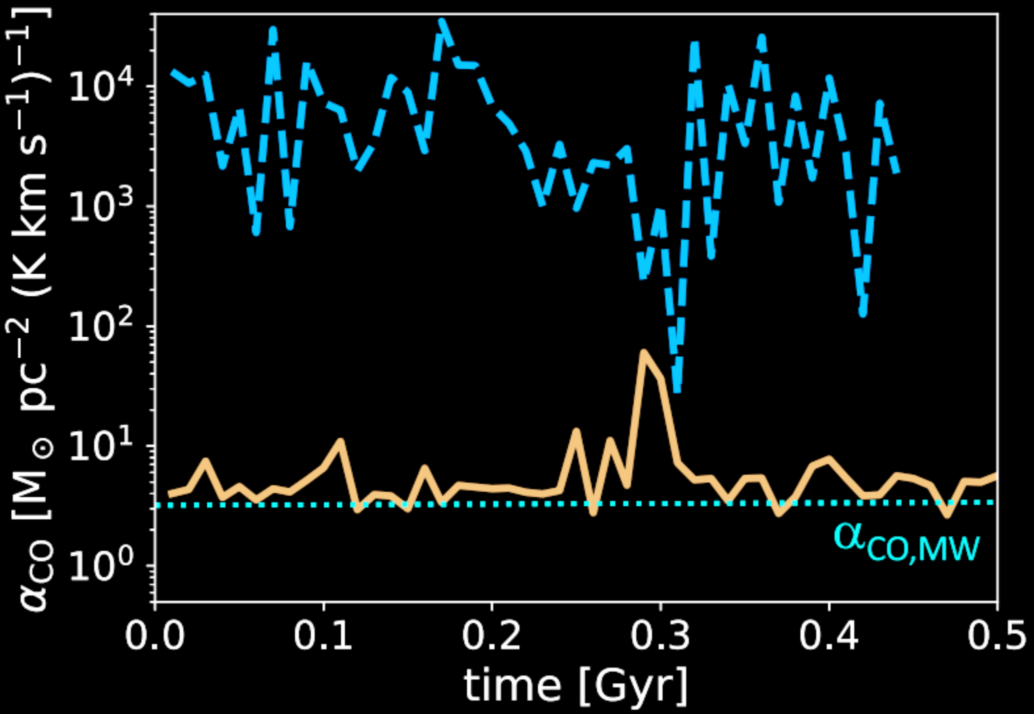
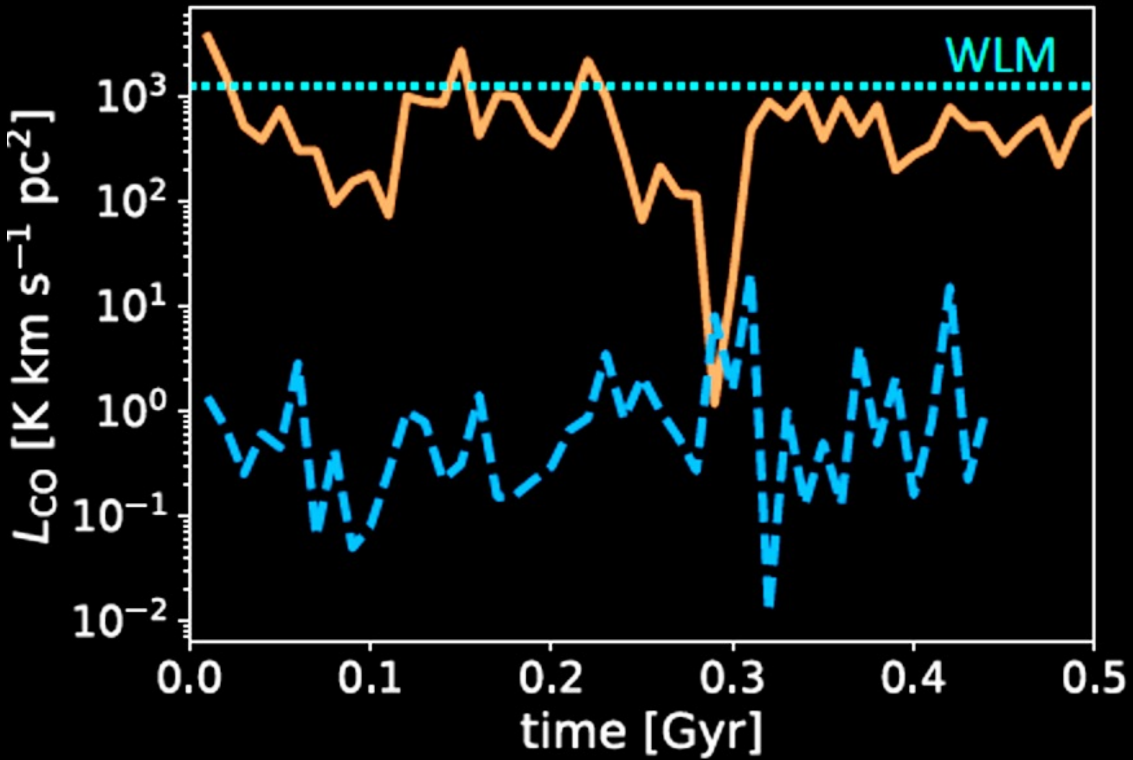


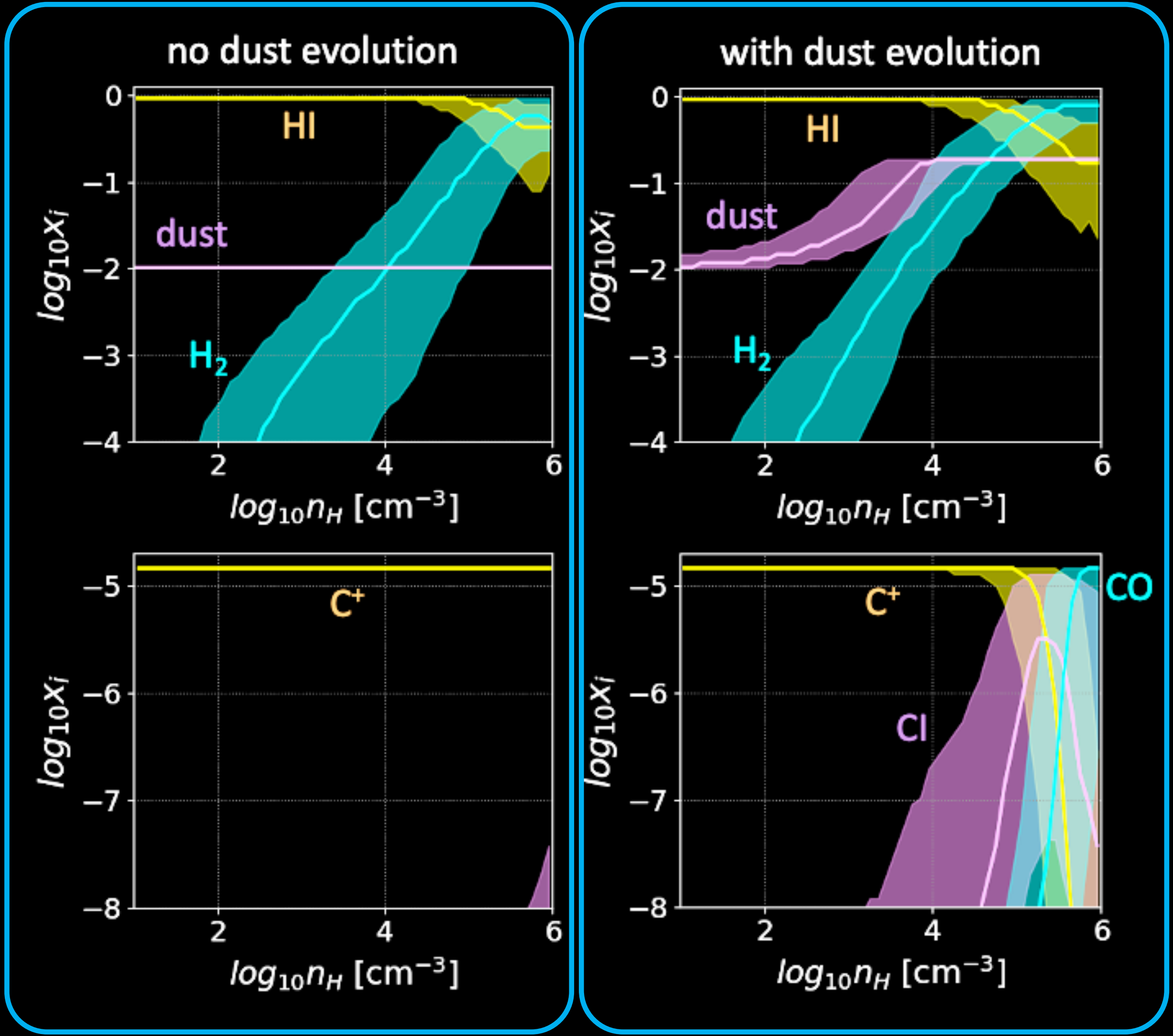


X_{CO} only slightly higher than the standard Milky Way value!

Observed CO luminosity is reproduced only if dust evolution is included

Hu+ 2023

Dust evolution has a strong effect on CO, but has little effect on H_2



HI/H_2 : insensitive to dust evolution

Dust growth is only efficient in very dense gas

H_2 can self-shield against FUV radiation

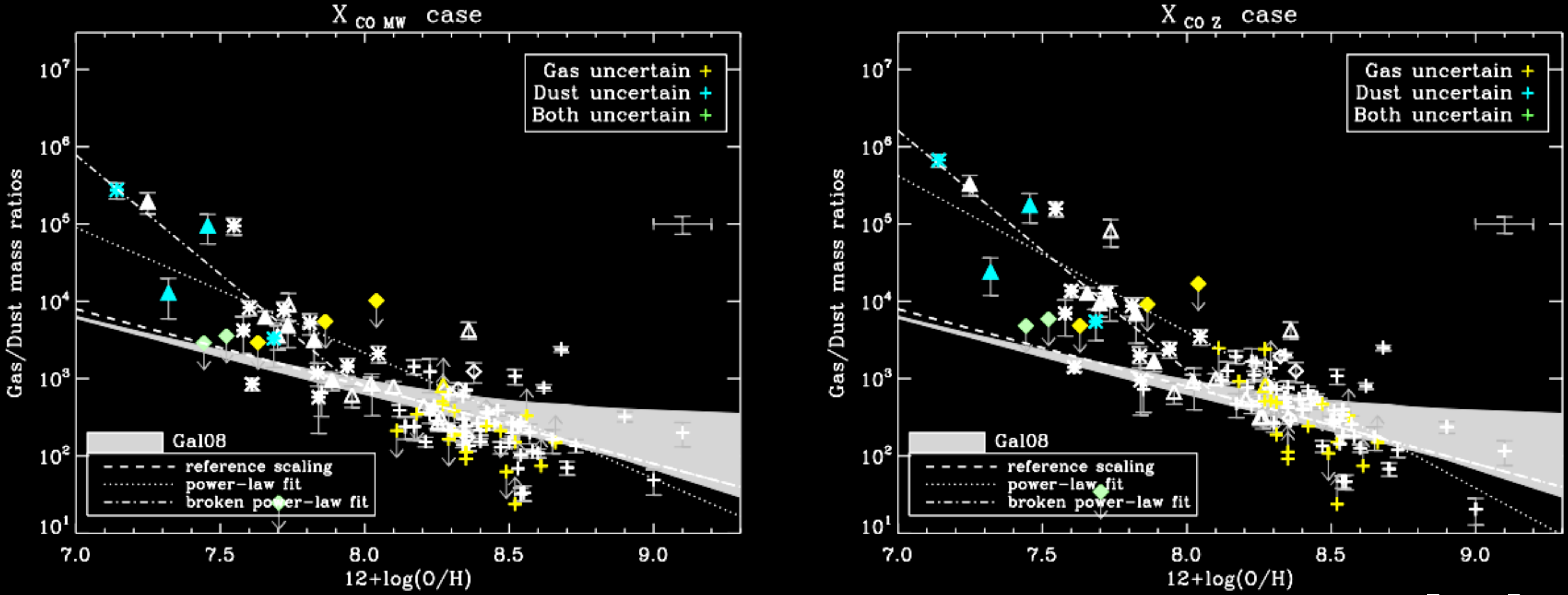
C^+/CI/CO: very sensitive to dust evolution

Dust shielding controls the C^+/CI/CO transitions (self-shielding is inefficient)

Hu+ 2023

D/G is underestimated if adopting too high X_{CO}

$$Z_{\mathrm{d}} = \frac{M_{\mathrm{d}}}{\boxed{M_{\mathrm{H_2}}} + M_{\mathrm{H\,I}}} = \frac{M_{\mathrm{d}}}{\boxed{L_{\mathrm{CO}}\alpha_{\mathrm{CO}}} + M_{\mathrm{H\,I}}}$$

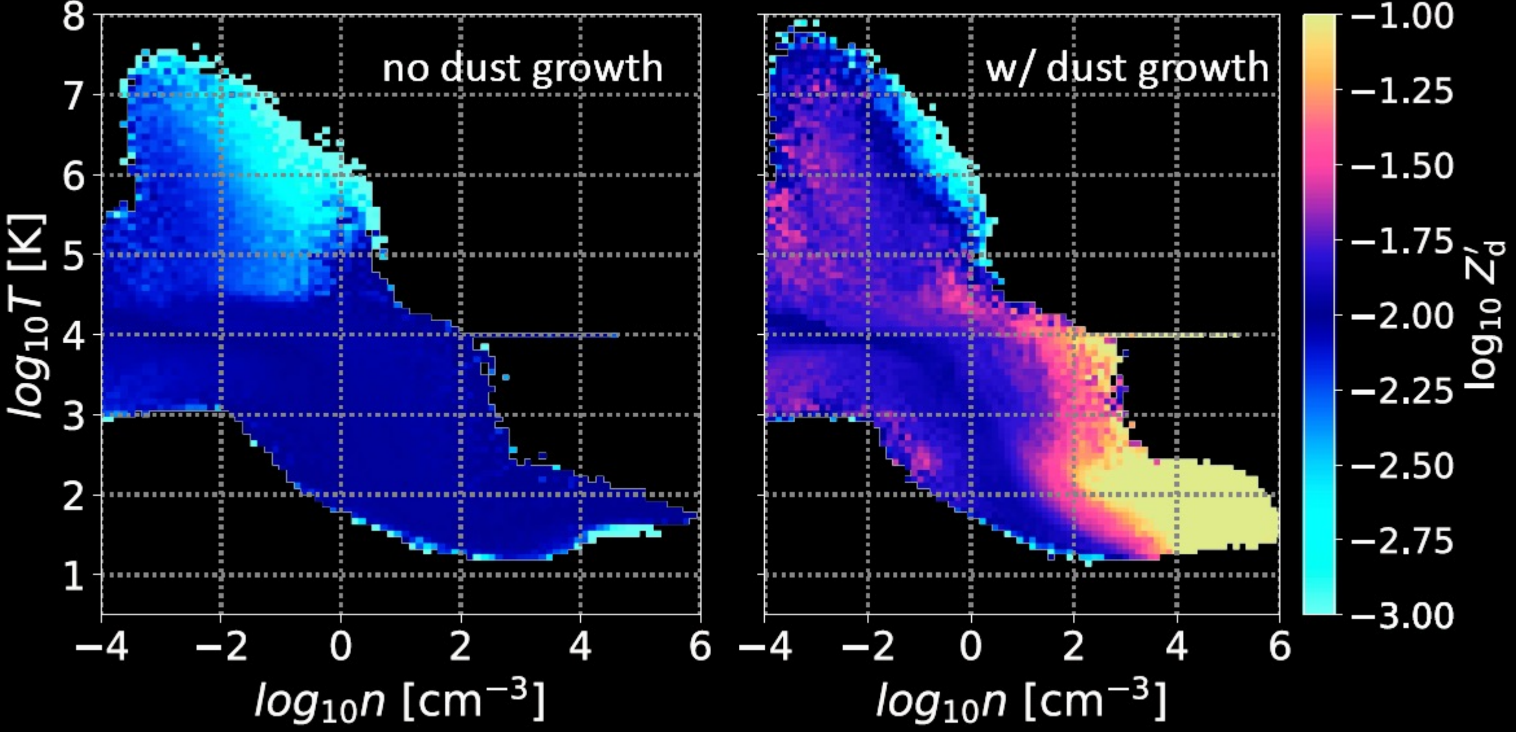


Remy-Ruyer+14

Su+ in prep.

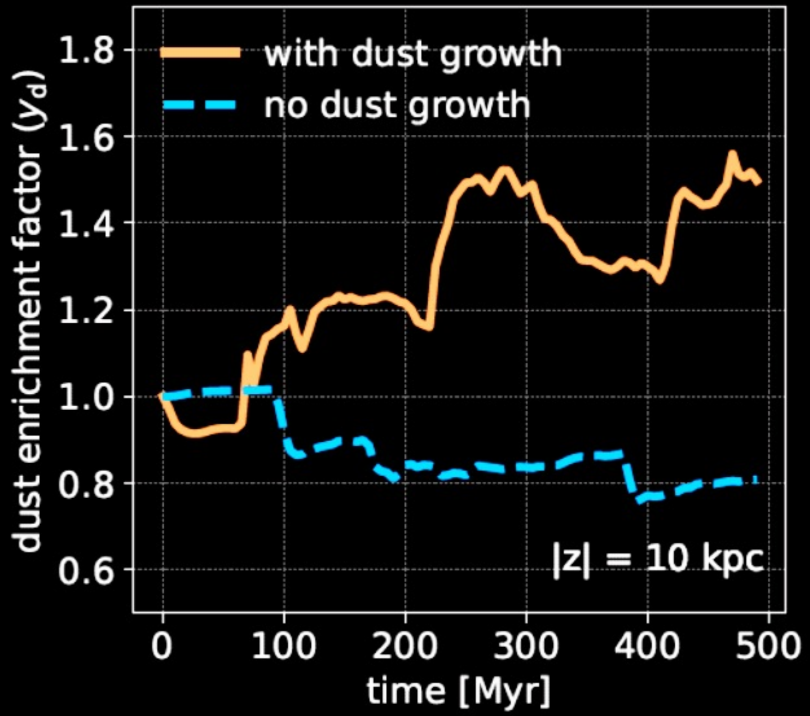
Dust entrainment in galactic outflows

Dust abundance is significantly enhanced in dense gas due to dust growth.



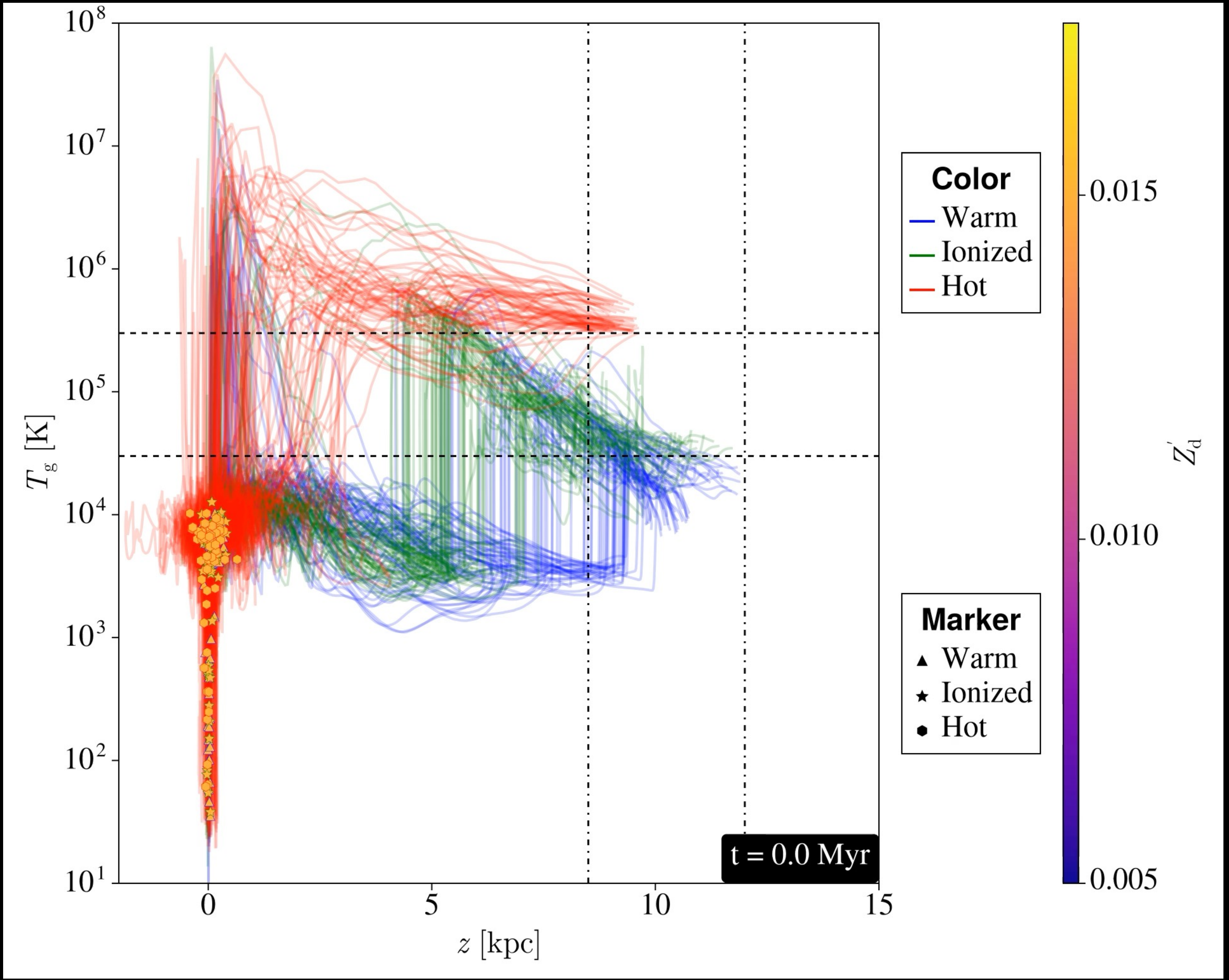
Dust is more abundant in outflows than in the ISM.

Origin of intergalactic dust?

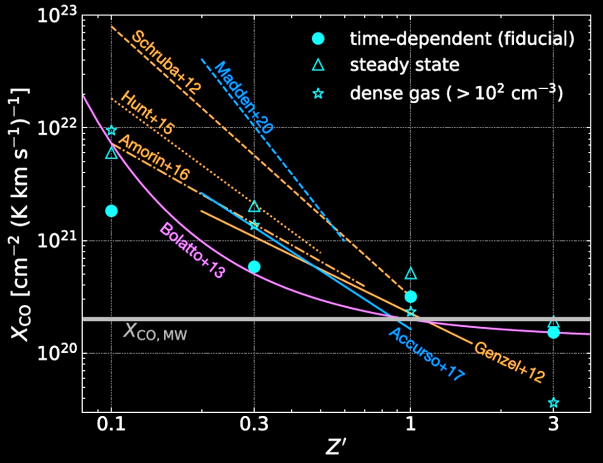


Su+ in prep.

- Dust in the warm/ionized phase ($T < 3\text{x}10^5$ K) has never heated up to high enough temperature to get sputtered
- Dust in the hot phase ($T > 3\text{x}10^5$ K) only stays hot for a very short amount of time, mostly near the disk.
- Sputtering is very inefficient!



Summary



There is not much CO-dark H_2 reservoir at low metallicity

- H_2 has not time to form
- Steady-state chemistry significantly overestimates X_{CO}
- The cold ISM is dominated by HI instead of H_2

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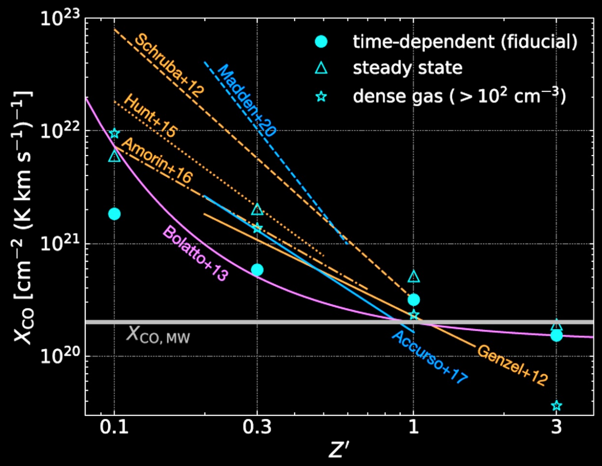
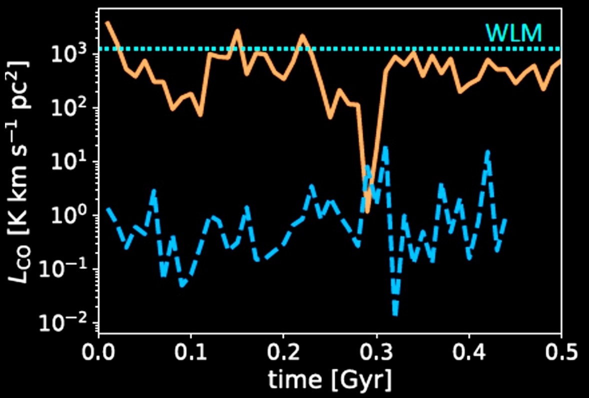
Dust evolution helps explain the observed CO luminosity in the WLM galaxy

- Dust growth enhances radiation shielding and facilitates CO formation.
- The resulting X_{CO} is only slightly higher than the Milky Way value.





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Dust evolution helps explain the observed CO luminosity in the WLM galaxy

- Dust growth enhances radiation shielding and facilitates CO formation.
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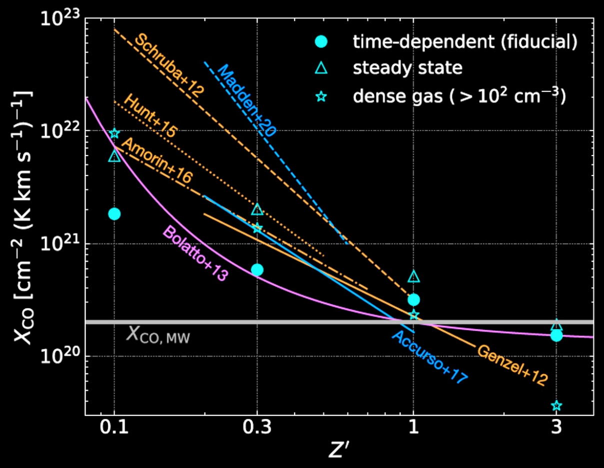
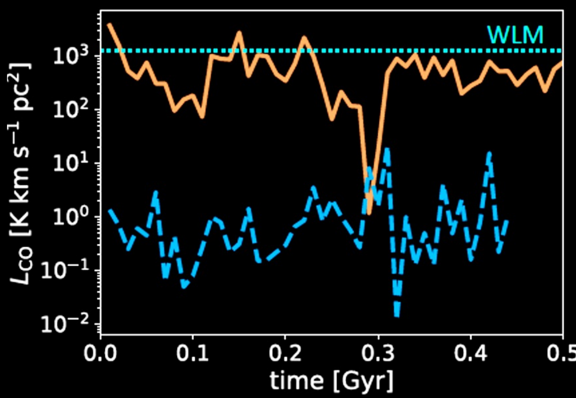
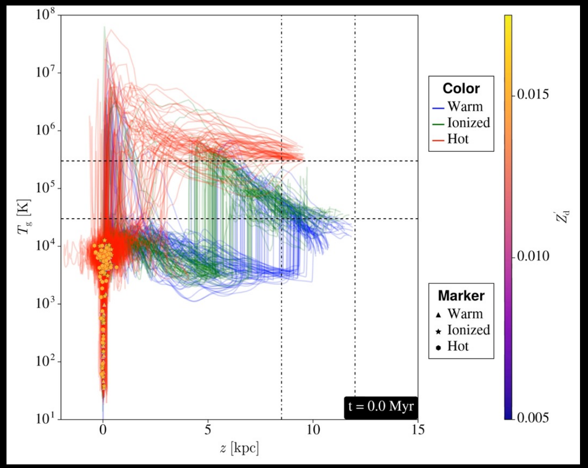
Dust can be entrained in galactic outflows

- Most dust never enters the hot phase for long enough time to be sputtered.
- Dust growth can further enhance the abundance.

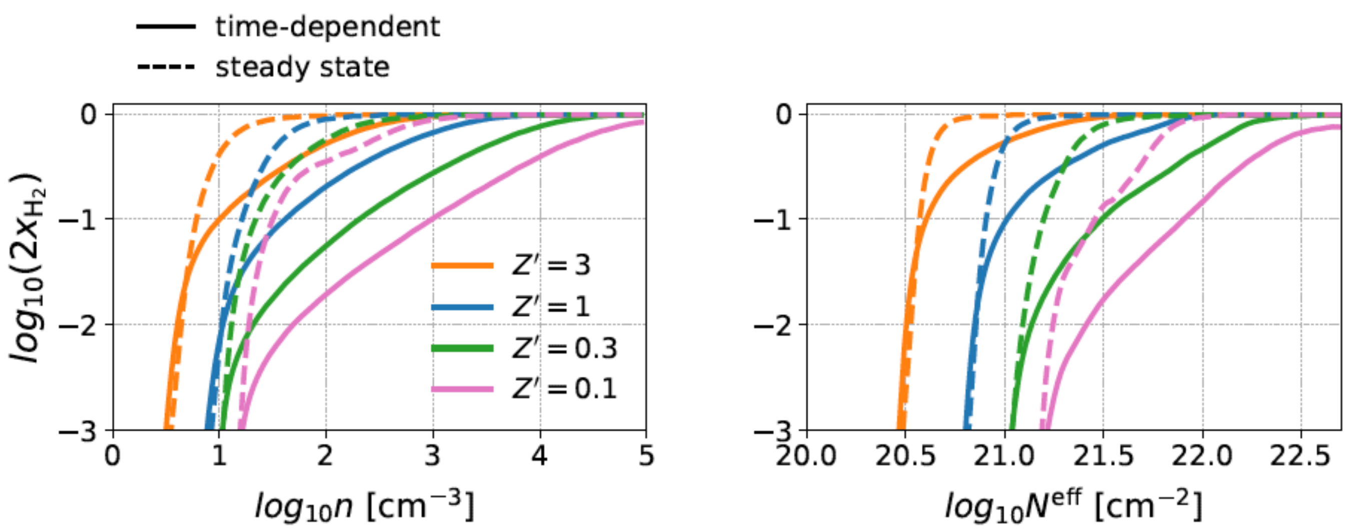






Backup slides

Chemical transitions



Timescale comparison:

$t_{form,H2} \gg t_{dyn}$, especially at low Z

~1 Gyr /(nZ')

~3 Myr

H_2 has no time to reach steady state before getting destroyed by feedback.

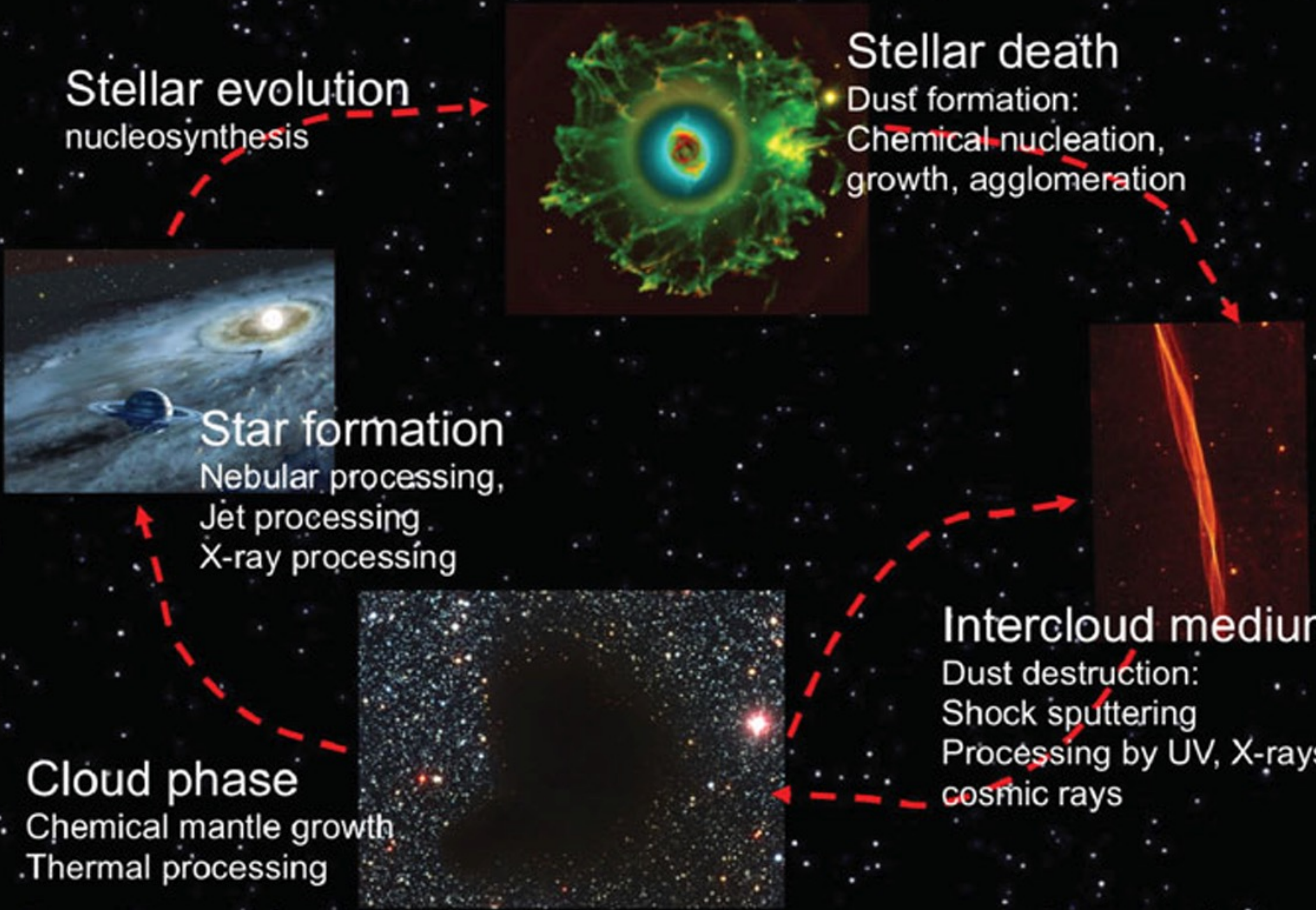
Time-dependent model: integrate the equation of chemical reaction:

$$\frac{dn_X}{dt} = \frac{dn_X}{dt}(\text{formation}) + \frac{dn_X}{dt}(\text{destruction})$$

If X reaches a steady state, $\frac{dn_X}{dt} = 0$

X can be far from steady state if the reaction time is long.

Cosmic Journey of Interstellar Dust



Stellar evolution
nucleosynthesis

Stellar death
Dust formation:
Chemical nucleation,
growth, agglomeration

Intercloud medium
Dust destruction:
Shock sputtering
Processing by UV, X-rays, &
cosmic rays

Cloud phase
Chemical mantle growth
Thermal processing

Star formation
Nebular processing,
Jet processing
X-ray processing

The multi-variate line ratio of CO(2–1) to CO(1–0)

- The line ratio is a multi-variate function of metallicity, line intensity, and telescope beam size.
- Can use higher-level lines to infer the ground-level line CO(1-0).

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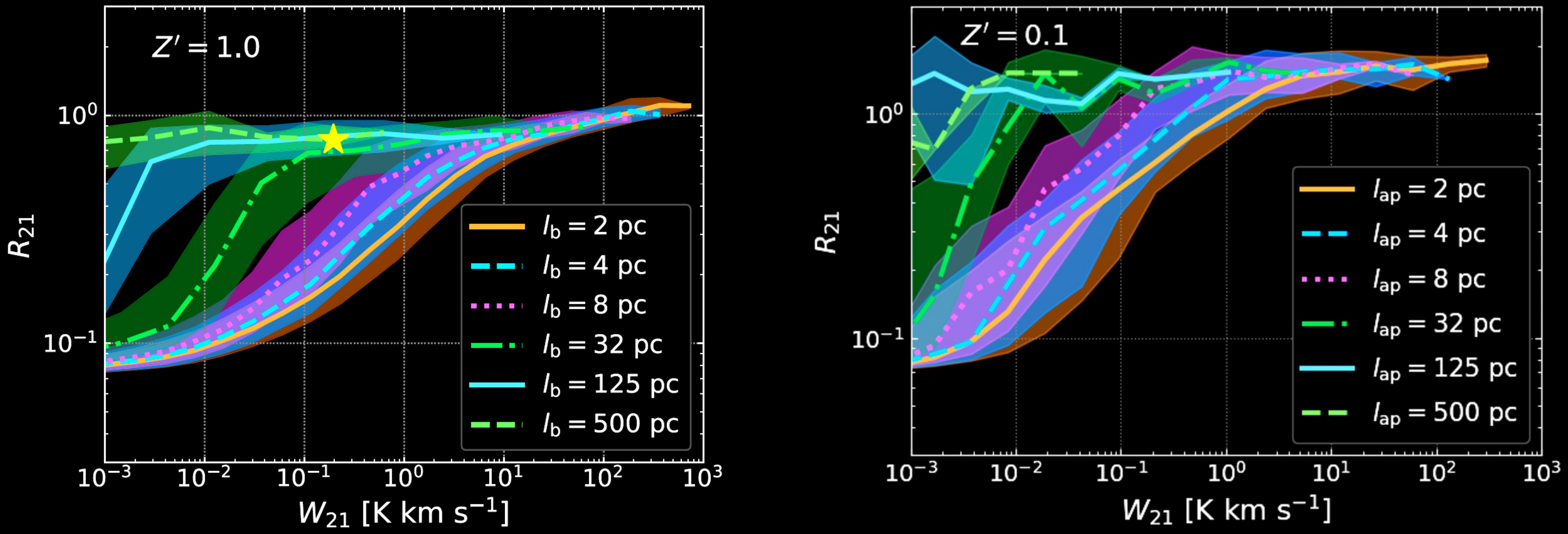


Star formation occurs in molecular gas

- In local spiral galaxies, the SFR shows a strong correlation with H_2 while little correlation with HI.

- The strong correlation between SFR and H_2 results in a widely used sub-grid model for star formation:

$$SFR = \epsilon \frac{\rho(H_2)}{t_{ff}}$$

H_2 density

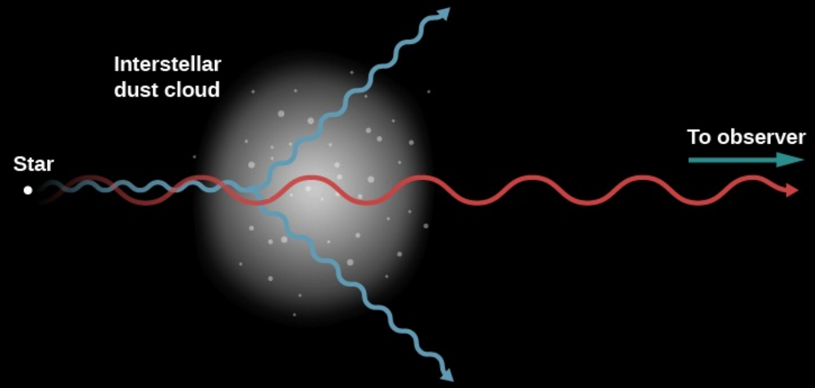
efficiency

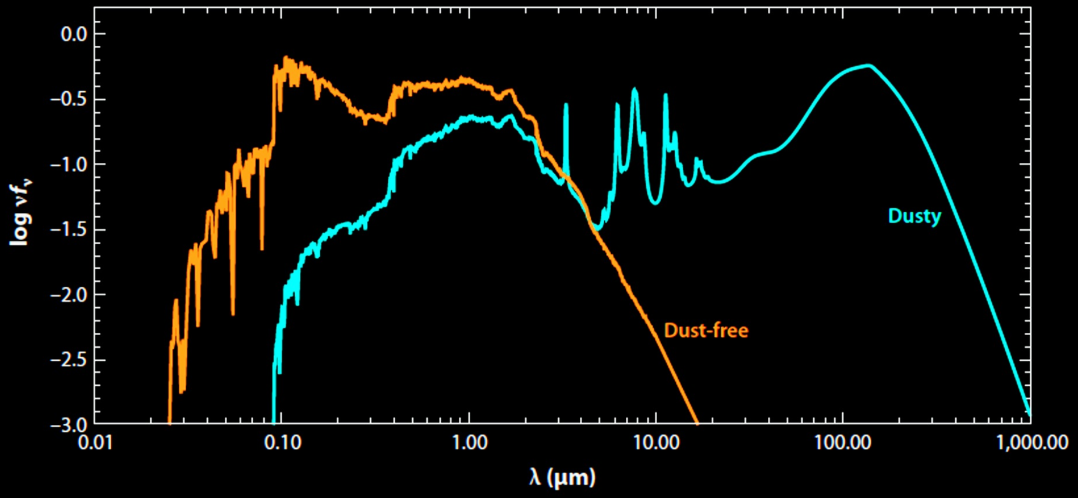
free-fall time

- However, this correlation has not been tested in low-metallicity conditions.

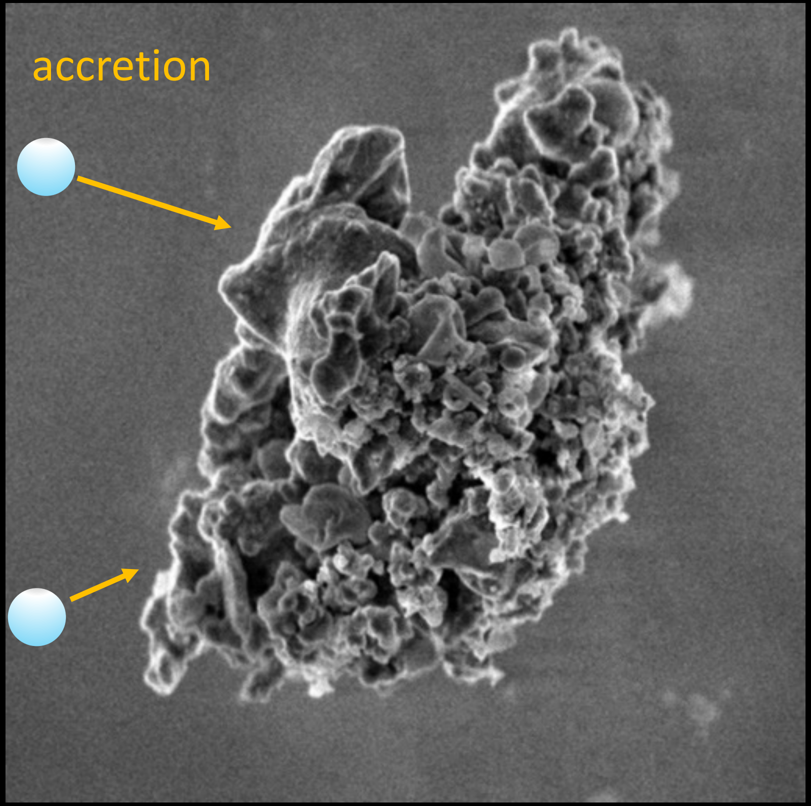
The effect of dust on ISM chemistry

shielding against stellar radiation





catalyst of chemical reactions (e.g. H_2)



Dwarf galaxies as laboratories for the interstellar medium at low metallicity

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