The role of molecules in star formation

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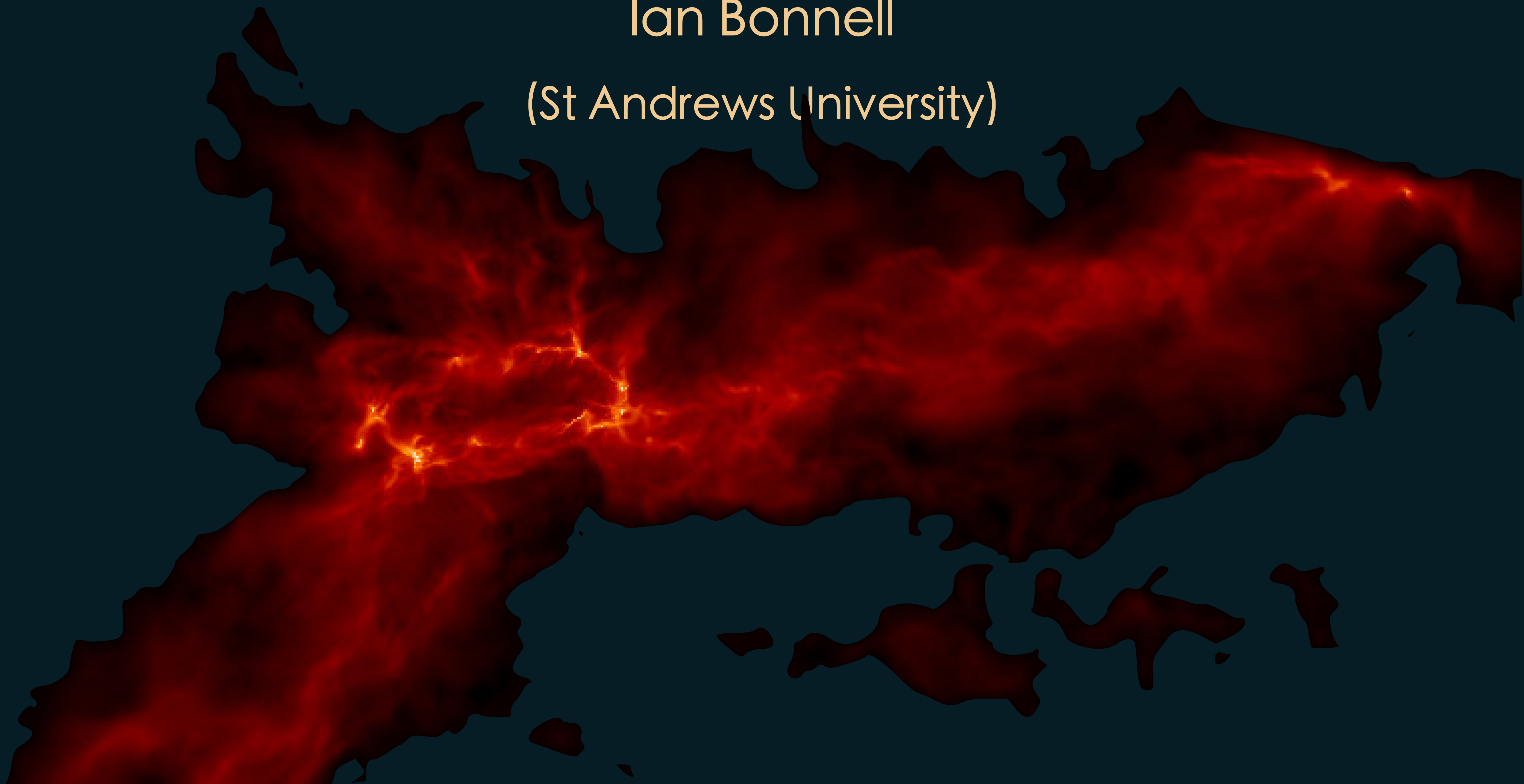
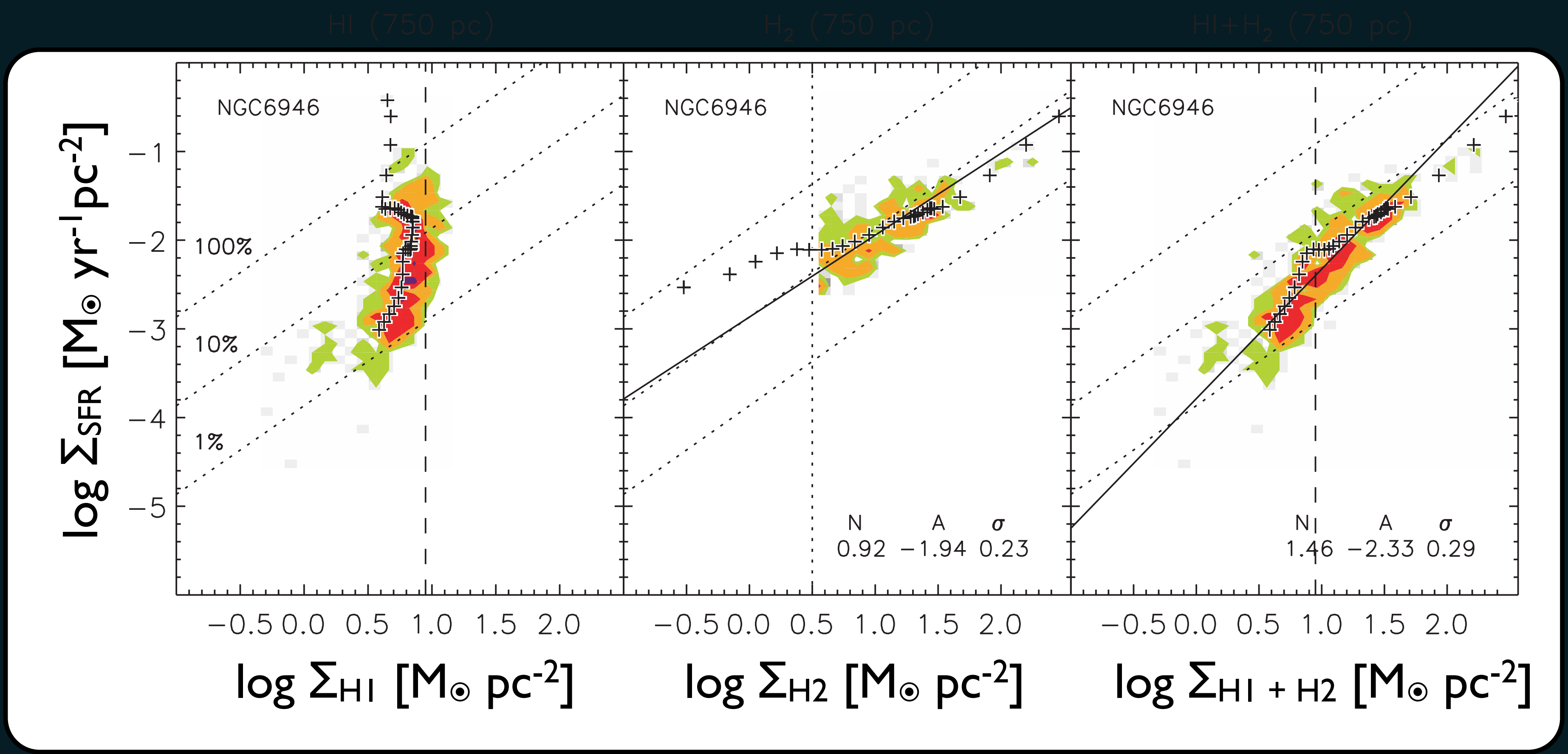


Correlation between molecular gas and the SFR

Bigiel et al. (2008)



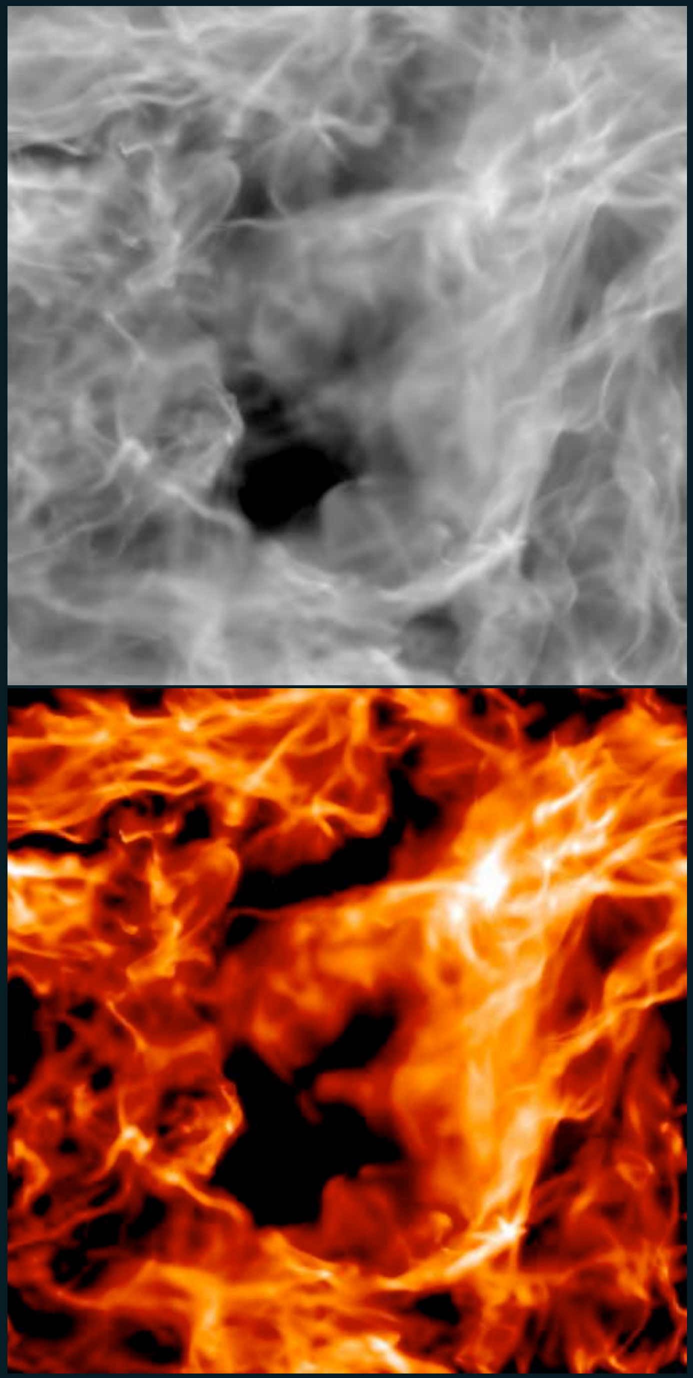
Has lead to assumption that molecular gas is needed for star formation:

- Schaye 2004
- Krumholz & McKee 2005
- Elmegreen 2007
- Krumholz et al. 2009

Can now test the effect of chemistry on gas thermodynamics

- Use time dependent chemical network to track H_2 + CO formation (see Glover & Clark 2012b).
- Implemented in Gadget2 (Springel 2005).
- Sink particle to model the star formation (Bate, Bonnell & Price 1995).
- ISRF attenuation treated by TreeCol (Clark, Glover & Klessen 2012a).
- Self-consistent gas and dust temperatures.

Simplified PDR code that runs alongside a fluid code



Glover et al. (2010)

Suite of models that test the role of chemistry

Glover & Clark (2012a)

- 10^4 $M_\odot$ clouds, with n ~300 cm^{-3}.
- Initially virialised turbulent velocity field, v_{RMS} ~2.5 km/s ($P(k) \propto k^{-4}$) .
- 'Black + Drain' ISRF ($1.7G_0$) + 3×10^{-17} s^{-1} CR-ionisation rate.
- Gas has 'solar' composition (C, Si, O, dust, etc).

Increase the complexity of the chemical model

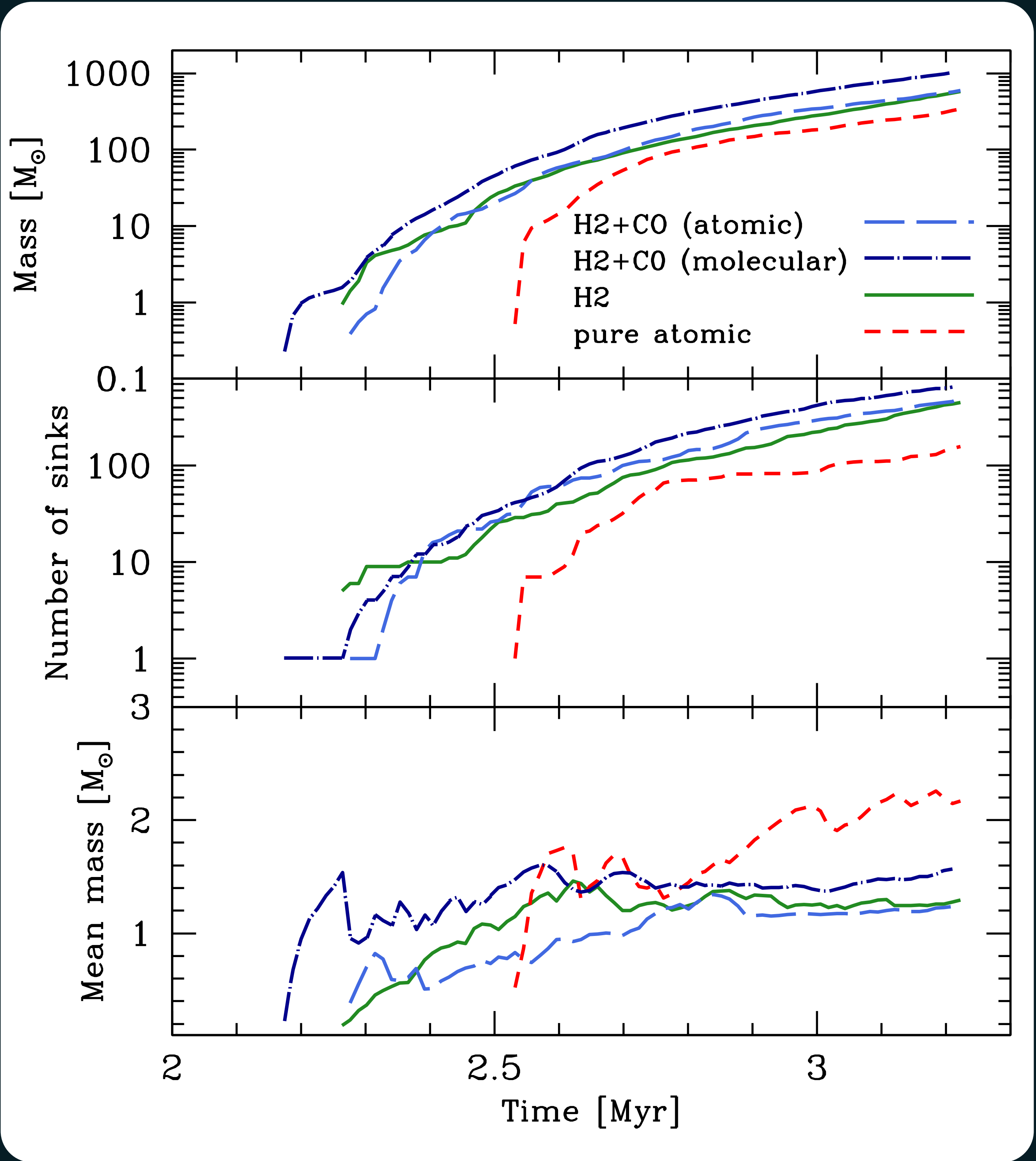
Atomic gas → H_2 formation → H_2+CO formation → No shielding

Shielding on →

Atomic ICs + Molecular ICs

Do the star formation rates differ?

Glover & Clark (2012a)



Clouds with shielding

- SFRs are the same!
- Atomic gas is *slightly* delayed:
  - Higher mean molecular weight
  - Slightly higher Jeans mass.

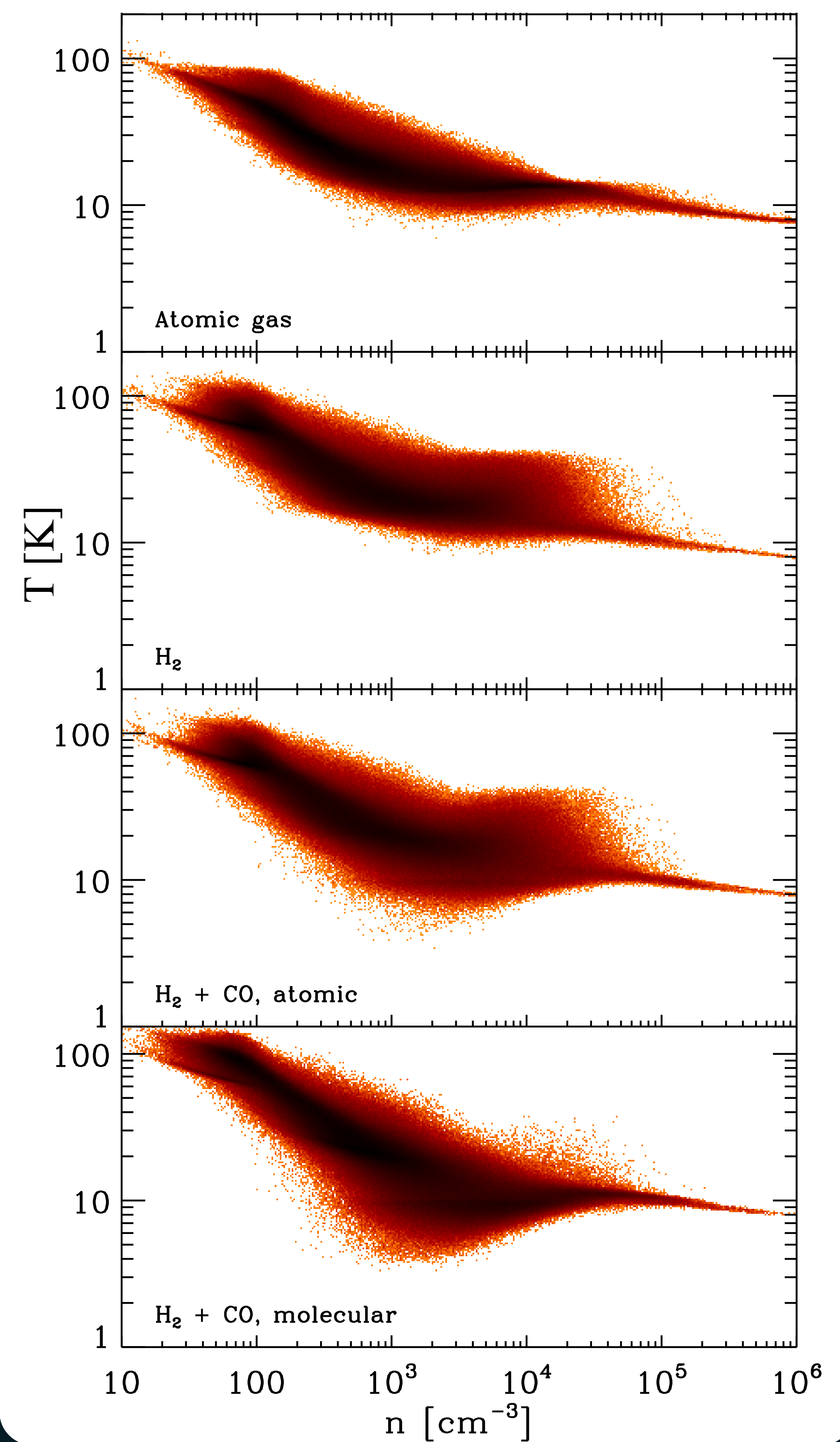
Clouds without shielding

- Eventually forms a massive star at about 9 Myr.
- Looks almost like Pop III star formation.

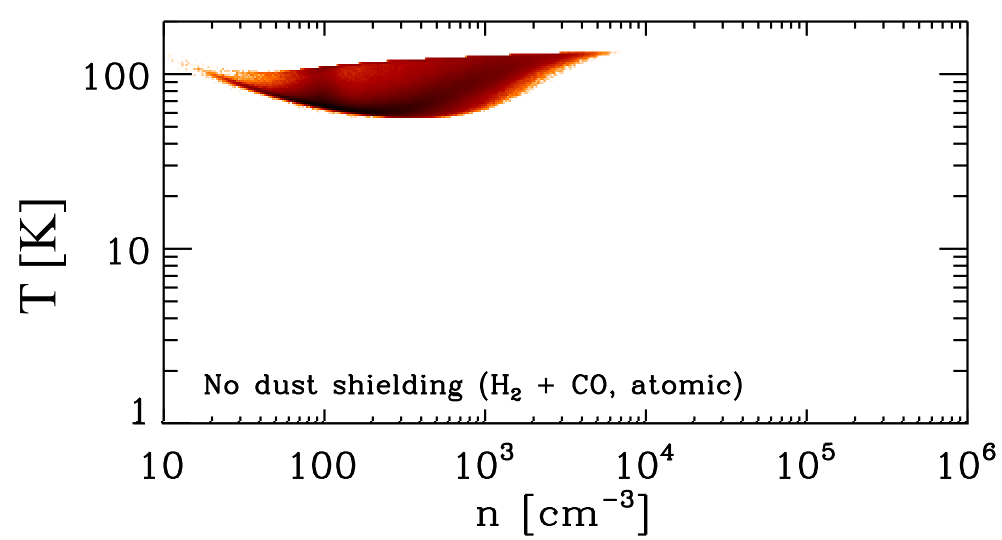
Temperature distribution

Glover & Clark (2012a)

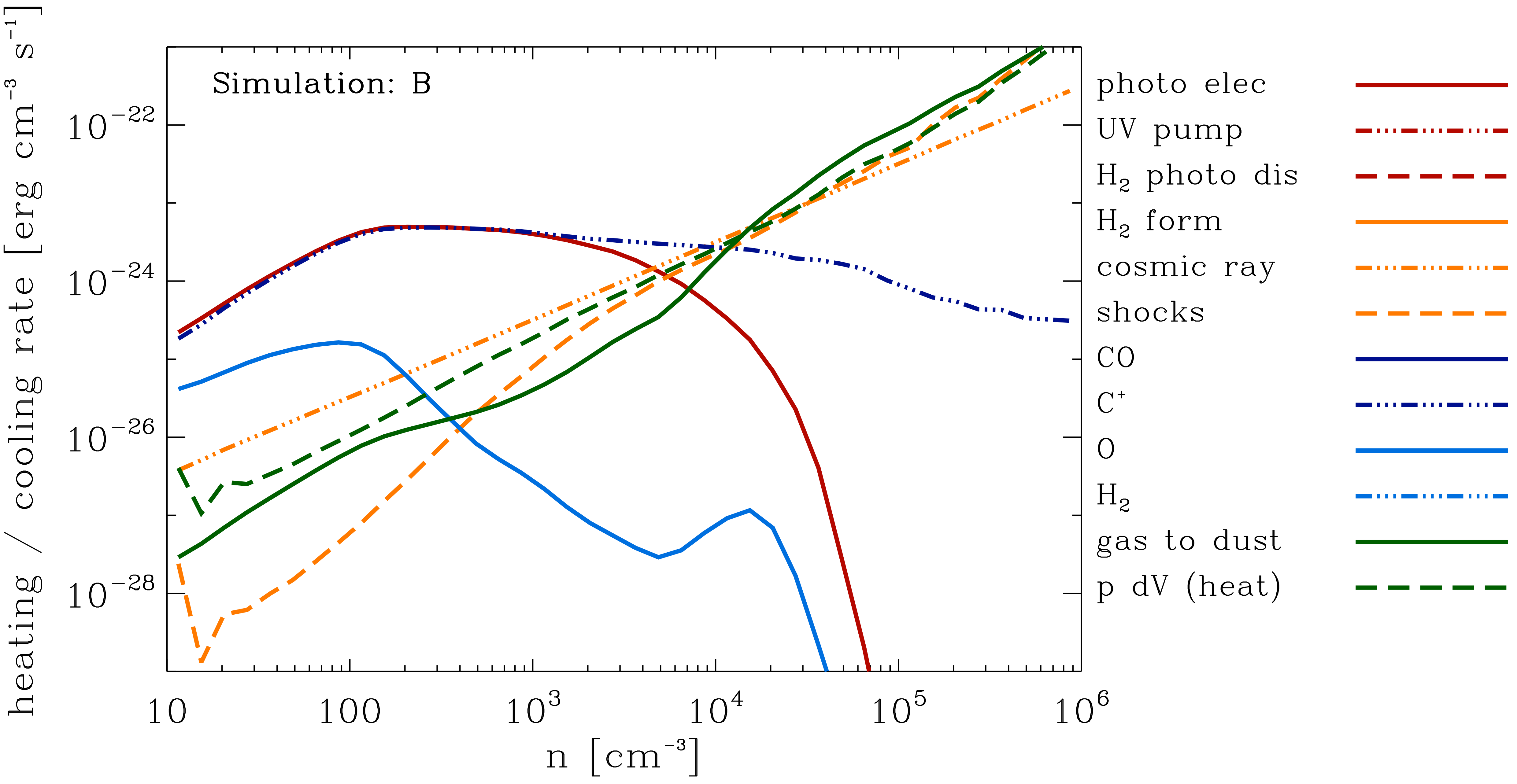
- Temperature distribution largely insensitive to the gas chemistry.
- Formation of H_2 heats gas.
- CO allows gas to cool down to CMB.
- Dust-gas coupling at $n > 10^5$ cm^{-3} regulates temperature.
- Dust temperature set by ISRF + CR-ionisation



Run with no shielding

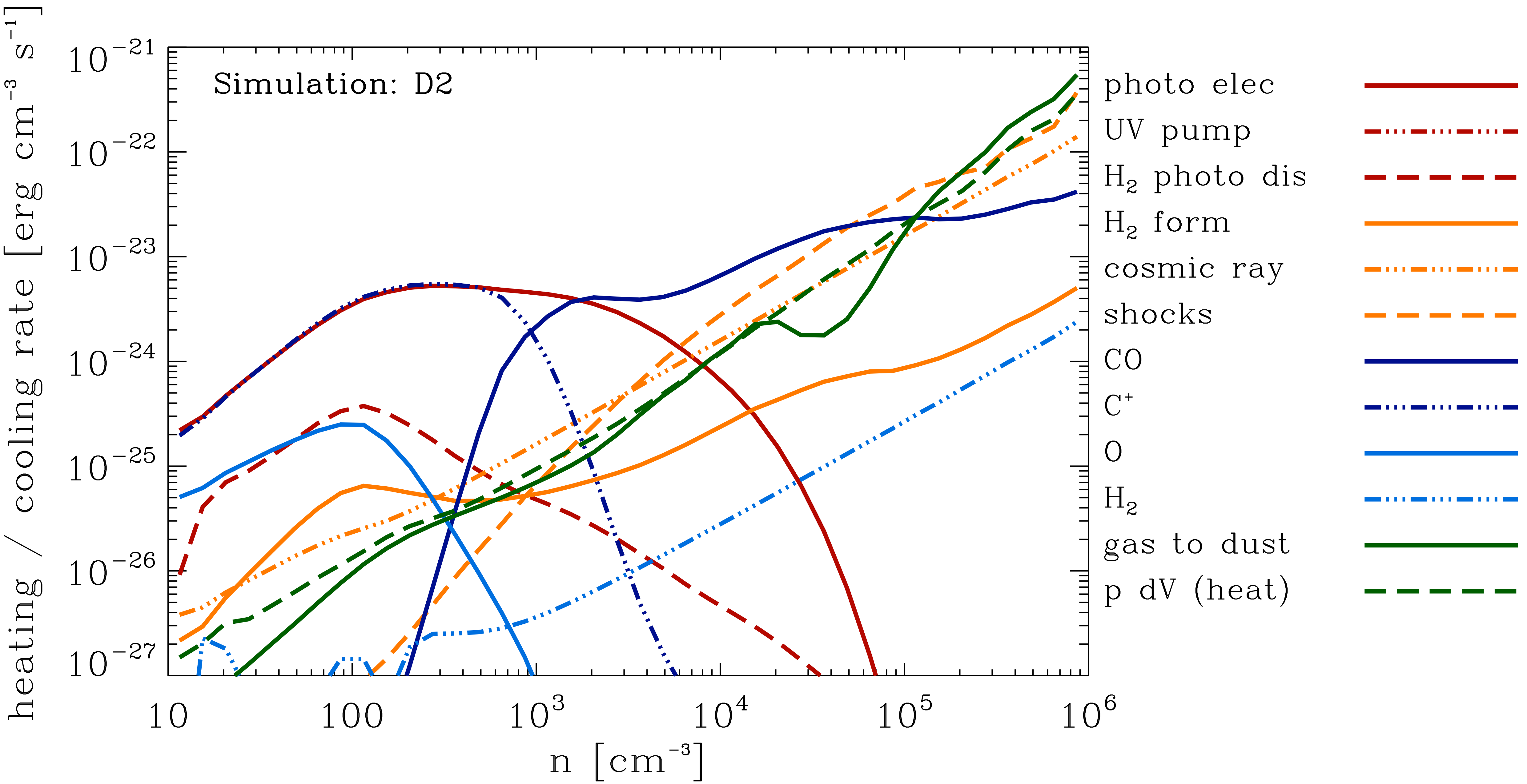


Heating/cooling processes (no CO)



Glover & Clark (2012a)

Heating/cooling processes (with CO)



Glover & Clark (2012a)

Summary so far:

- Molecule formation has very little effect on the rate at which stars form.
- Molecular gas and star formation are correlated because they both require well-shielded gas.

Glover & Clark (2012a)

So why do we care?

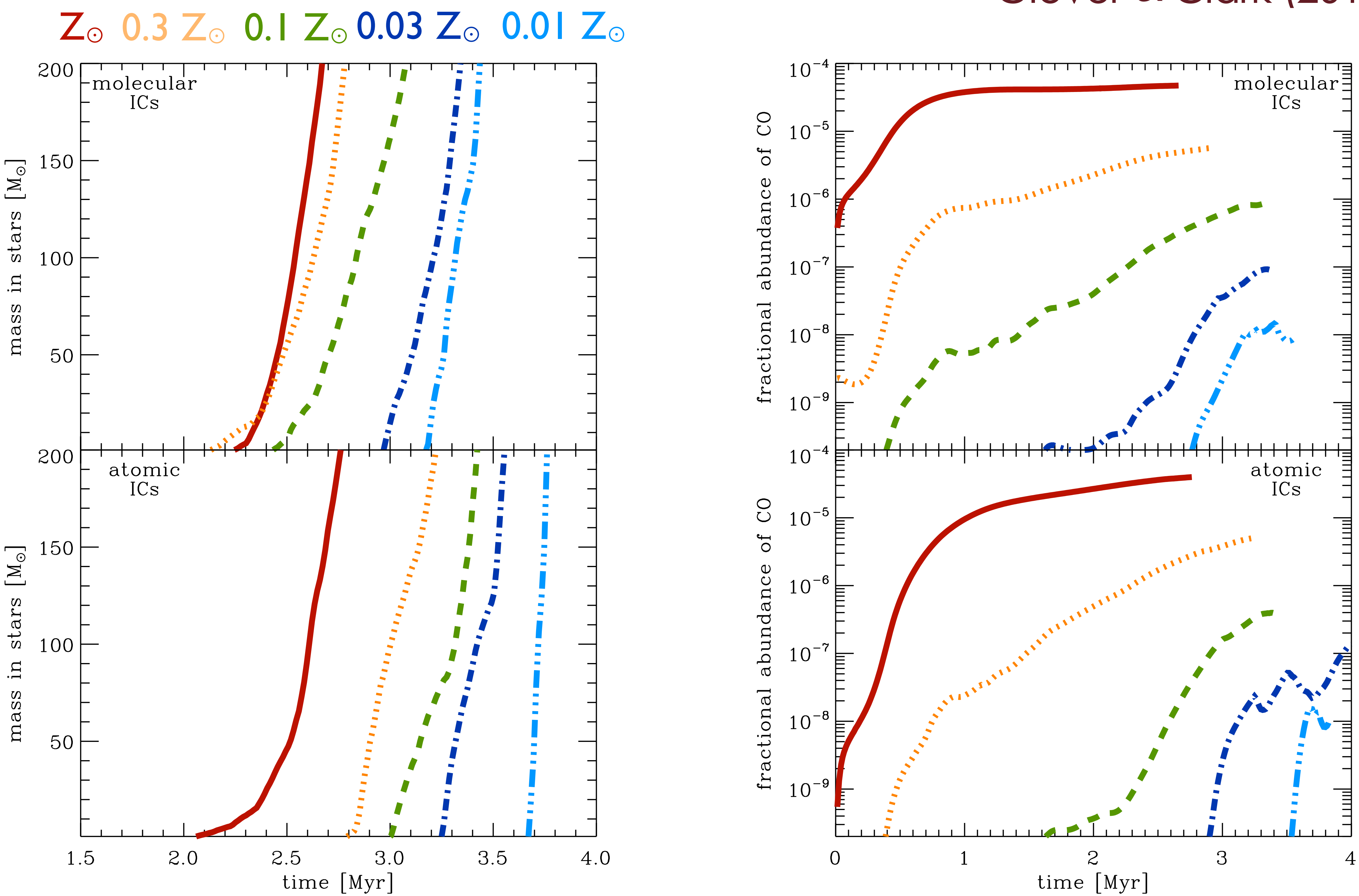
Low metallicity star formation:

- Observed SFE to CO luminosity ratio (SFE/W_{CO}) is systematically higher as we look at progressively more metal-poor galaxies.
    - Taylor, Kobulnicky & Skillman (1998); Leroy et al. (2007); Schruba et al. (2011).

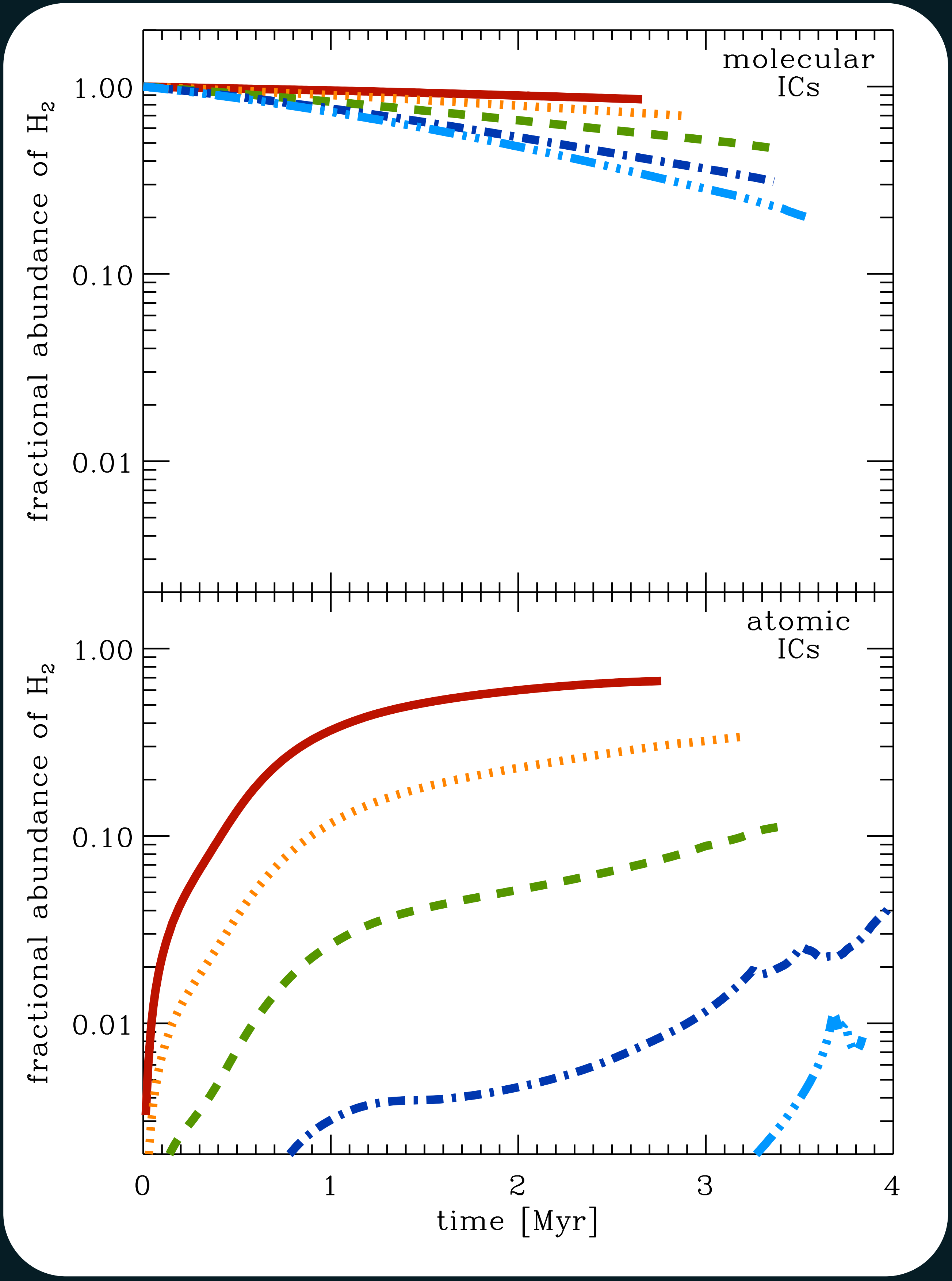
- So either:
    - metal-poor gas forms stars more efficiently than metal-rich gas (unlikely).
    - Xco (N_{H2}/W_{CO}) is much higher than Milky Way value.

SFR + CO formation with decreasing metallicity

Glover & Clark (2012c)



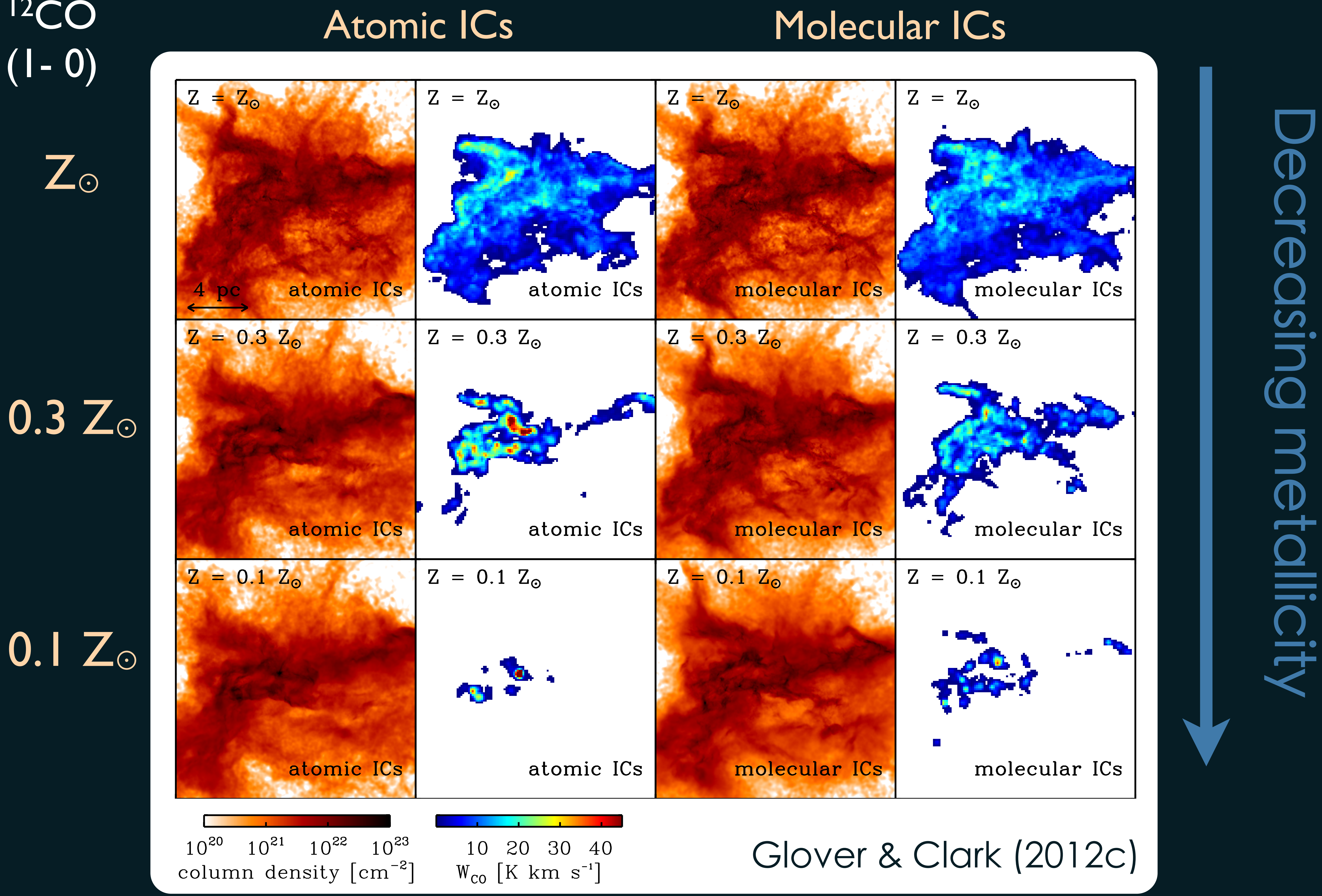
H_2 formation with Z



Glover & Clark (2012c)

Observed SFR/W_{CO} strongly depends on Z!

^{12}CO (1- 0)



Glover & Clark (2012c)

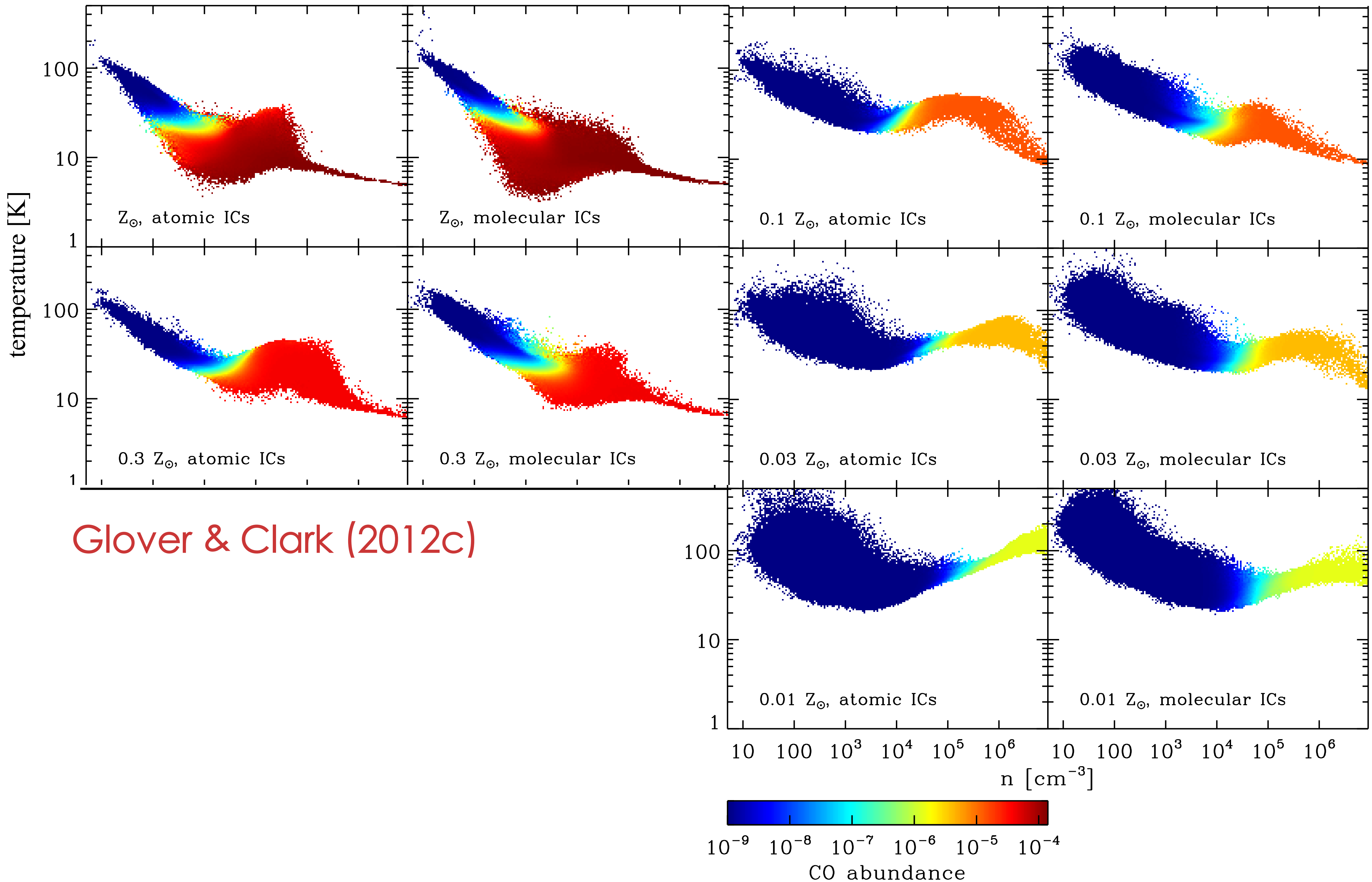
X-factor with metallicity

Run	$W_{CO,max}$	$W_{CO,mean}$	X_{CO} / $X_{CO,gal}$
Z1-M	25.7	3.46	2.06
Z1-A	29.9	3.23	1.53
Z03-M	37.0	1.34	4.76
Z03-A	53.5	1.27	1.97
Z01-M	37.7	0.217	22.6
Z01-A	98.2	0.144	4.99
Z003-M	38.7	0.045	66.3
Z003-A	32.8	0.016	10.0
Z001-M	8.16	0.0068	306.7
Z001-A	25.6	0.0106	8.27

Decreasing metallicity

Glover & Clark (2012b)

Temperature - density distribution



Glover & Clark (2012c)

Summary so far:

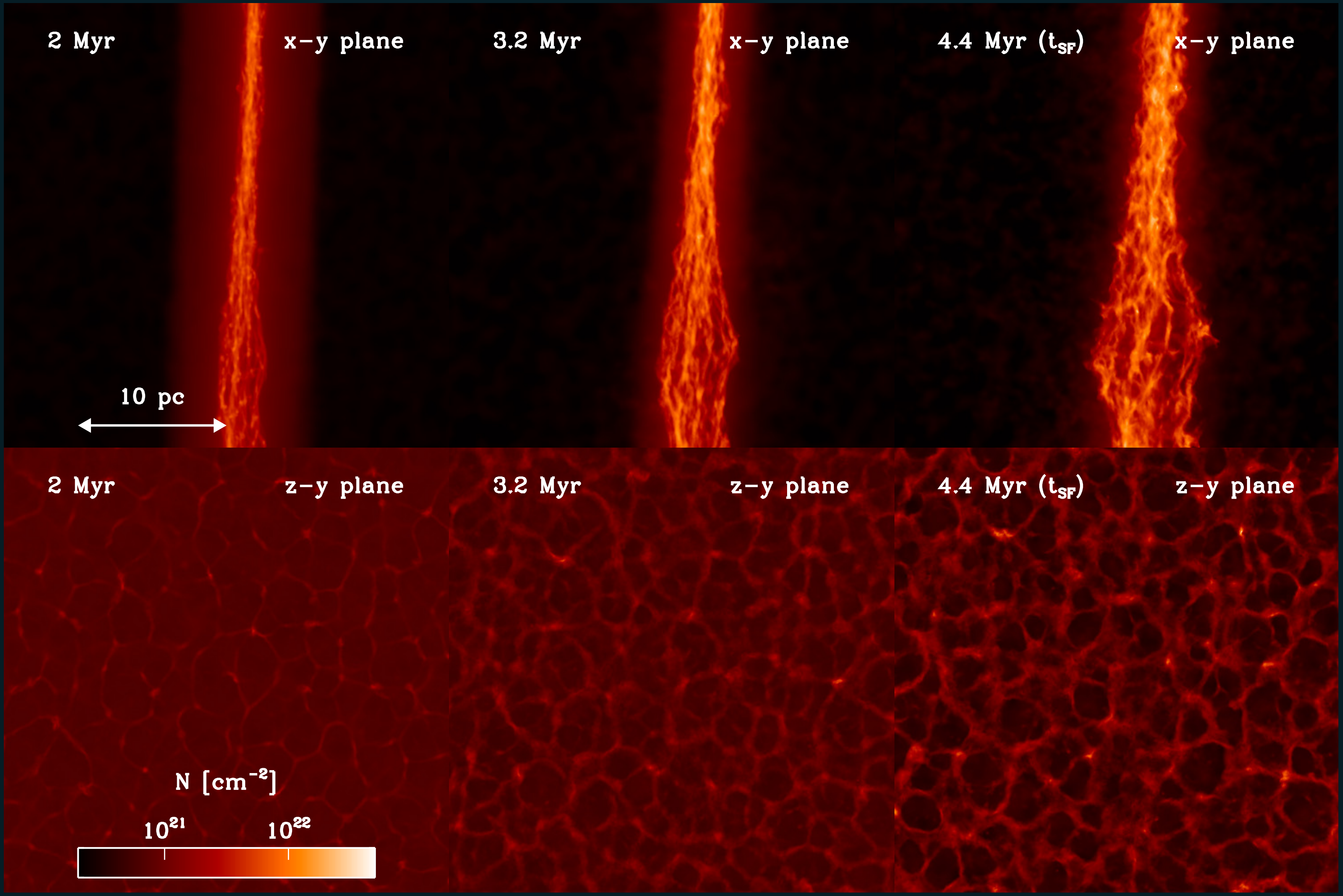
- At low metallicities, where molecular formation becomes difficult, star formation proceeds in largely atomic gas.
- Star formation rate is insensitive to the metallicity of the gas.
- 'X-factor' is strongly metallicity-dependent (and likely time-dependent).

Glover & Clark (2012b)

But those clouds were pre-assembled...

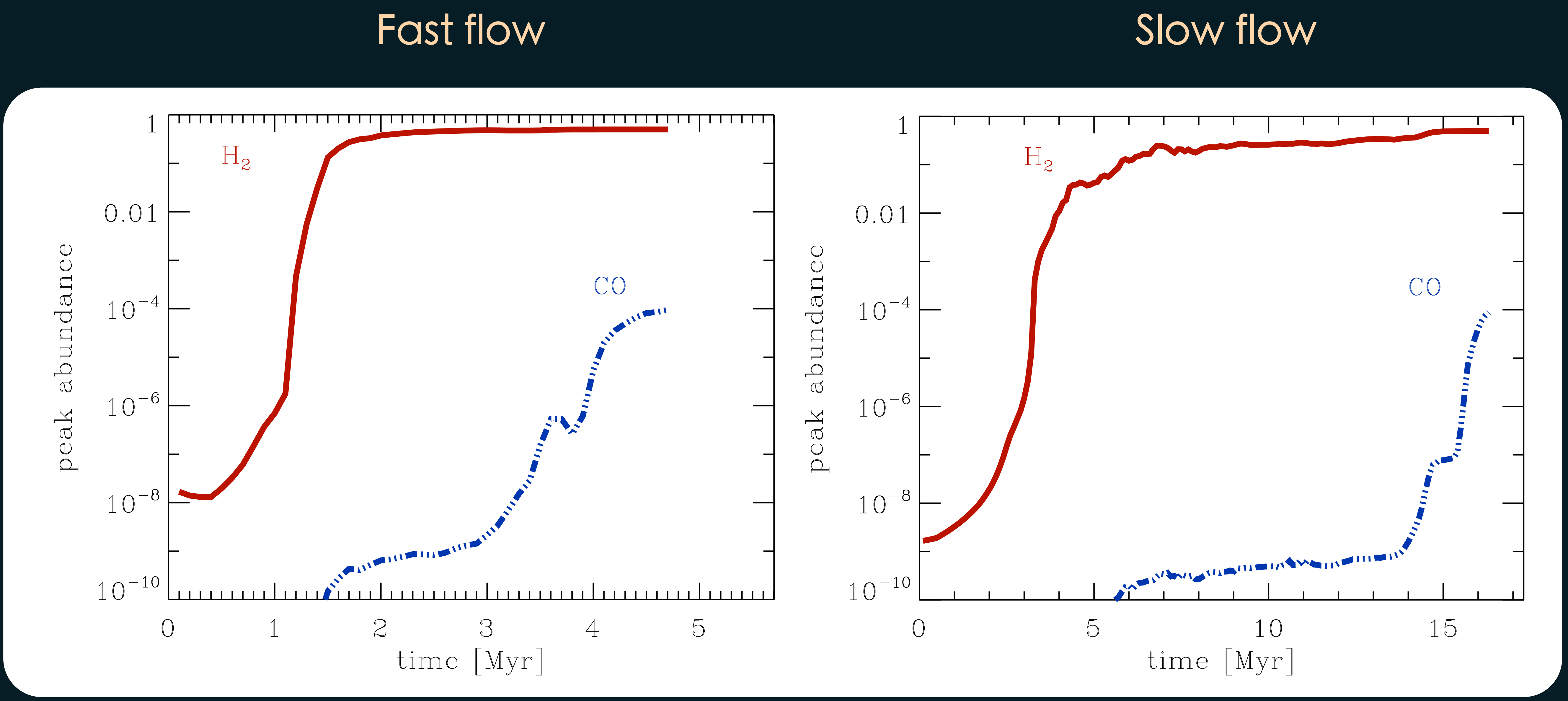
... what happens when we try to form them?

Cloud formation in colliding flows:



Clark et al. (2012b)

Delay between CO formation and star formation?

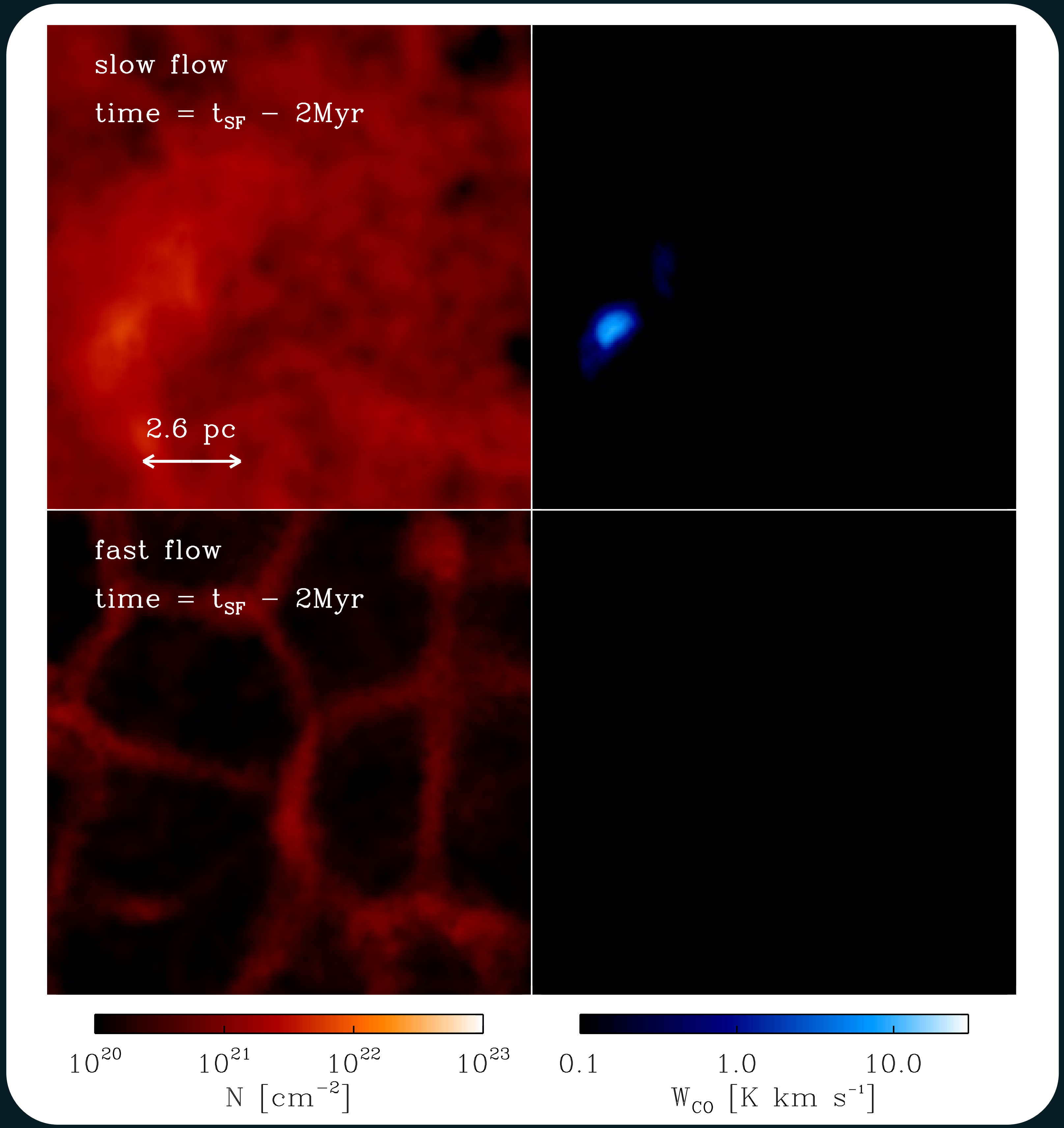


Clark et al. (2012b)

- CO appears 2 Myr before star formation in both flows.
- H_2 can appear much earlier (depending on flow).

Observational time-sequence

^{12}CO
(1- 0)

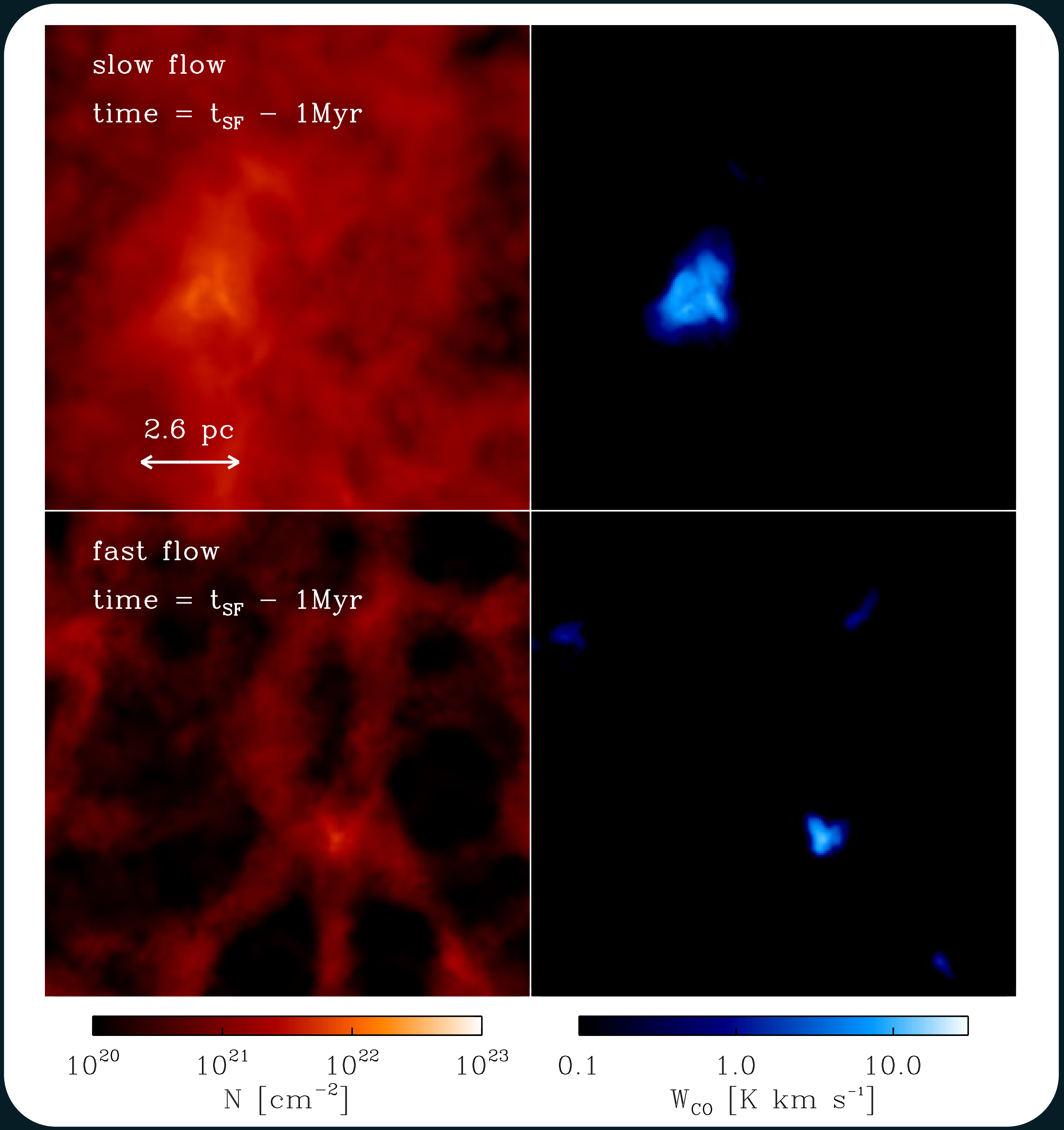


Clark et al. (2012b)

Observational time-sequence

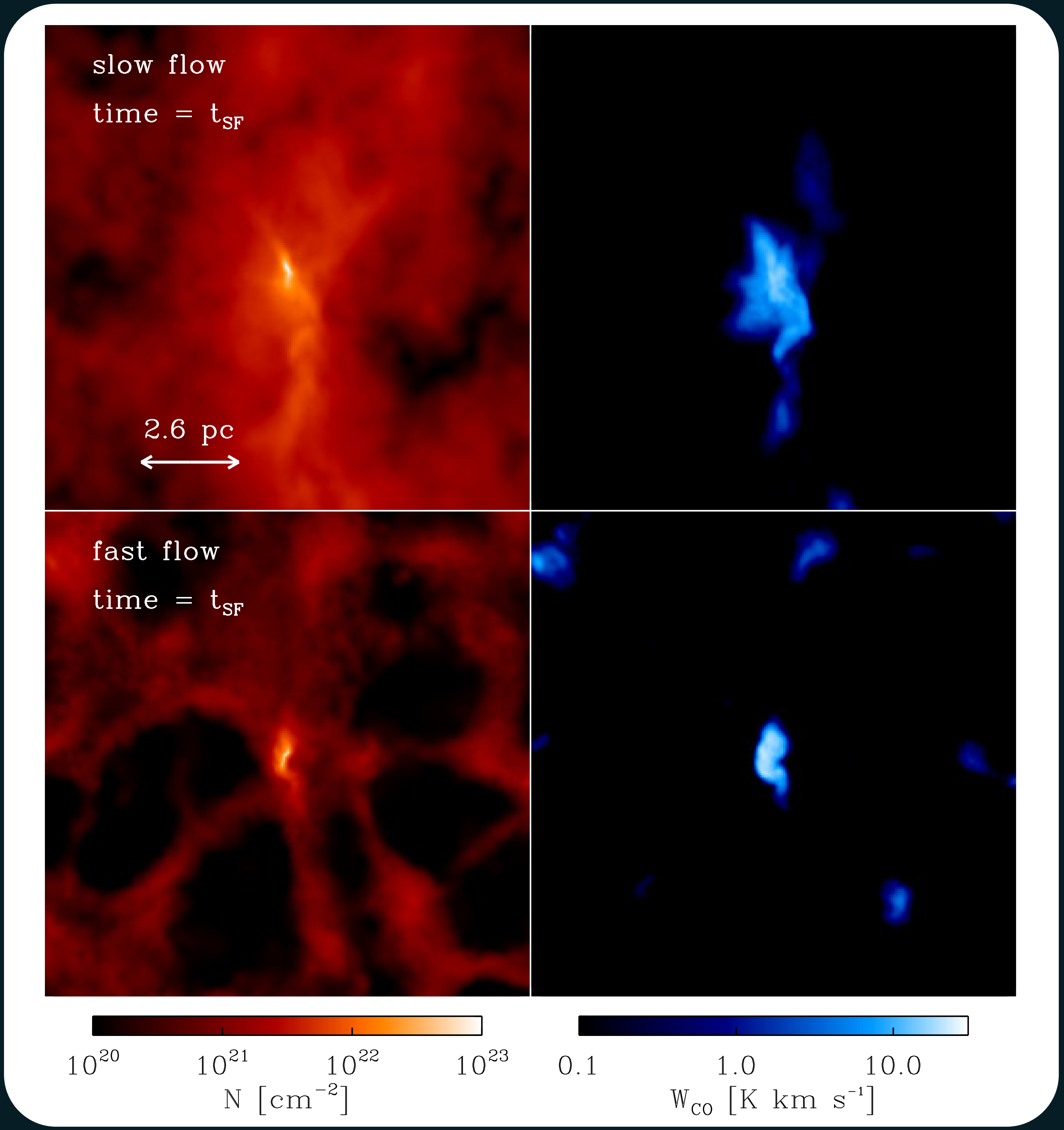
^{12}CO (1- 0)

Clark et al. (2012b)



Observational time-sequence

^{12}CO (1- 0)

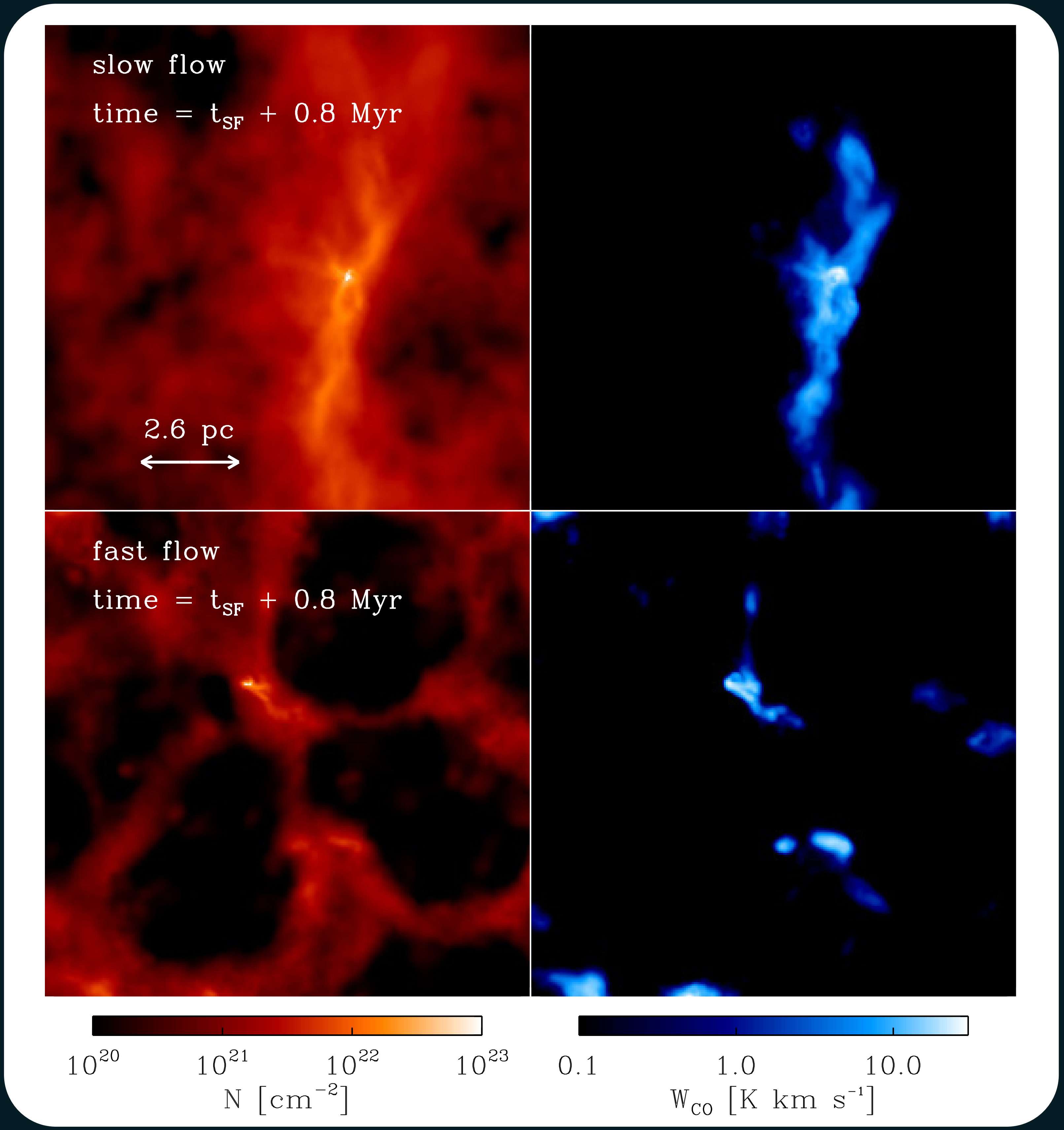


Clark et al. (2012b)

Observational time-sequence

^{12}CO (1- 0)

Clark et al. (2012b)



Summary:

- CO is tracer of star-forming gas, but is **not** needed for stars to form.
- At lower metallicities, CO is confined to denser, hotter cores.
- X_{CO} varies dramatically as we go to lower metallicities.
- CO seems to preceed star formation by about 2 Myr under local galactic conditions.