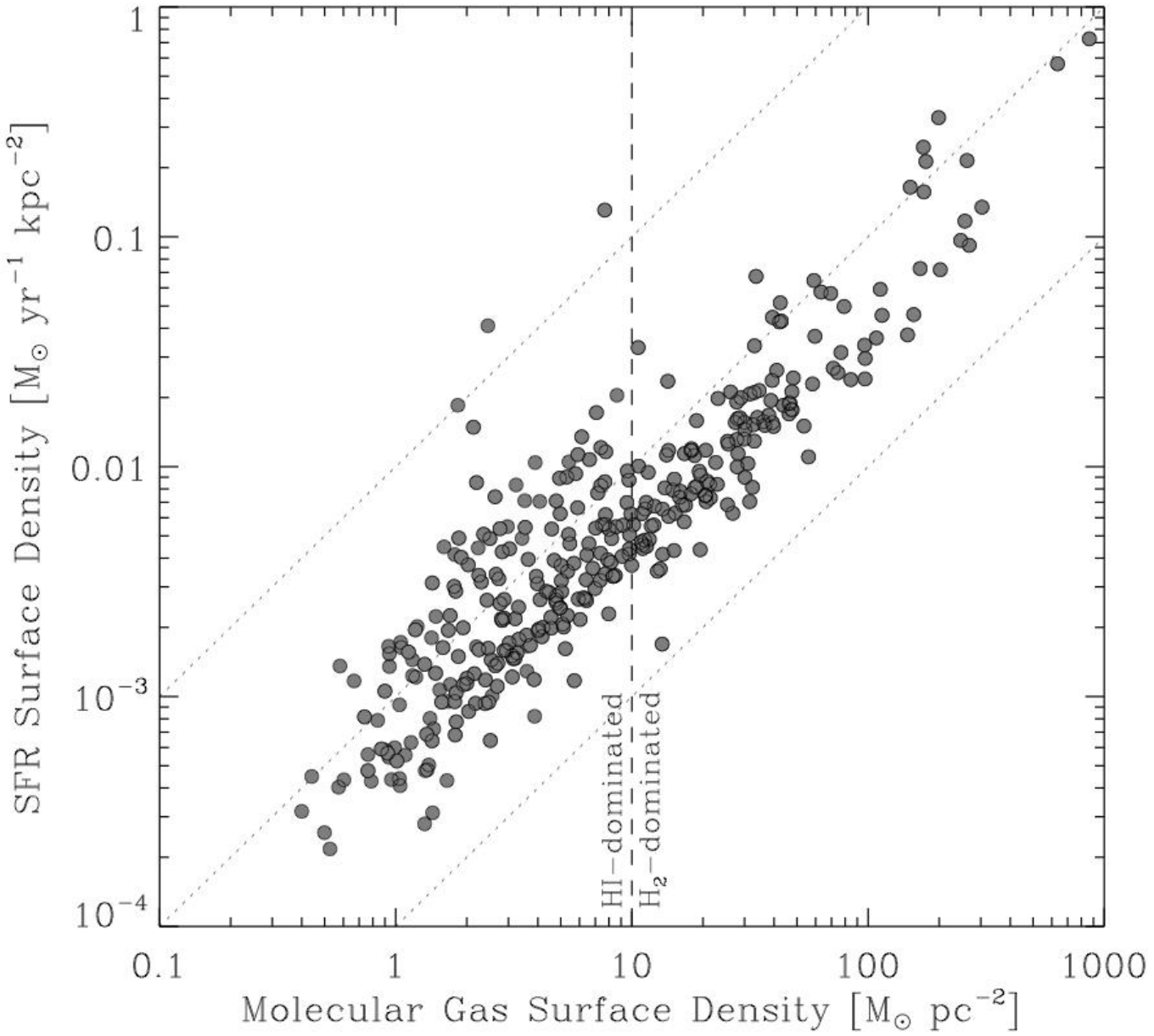
The role of molecular gas in star formation

Simon Glover & Paul Clark



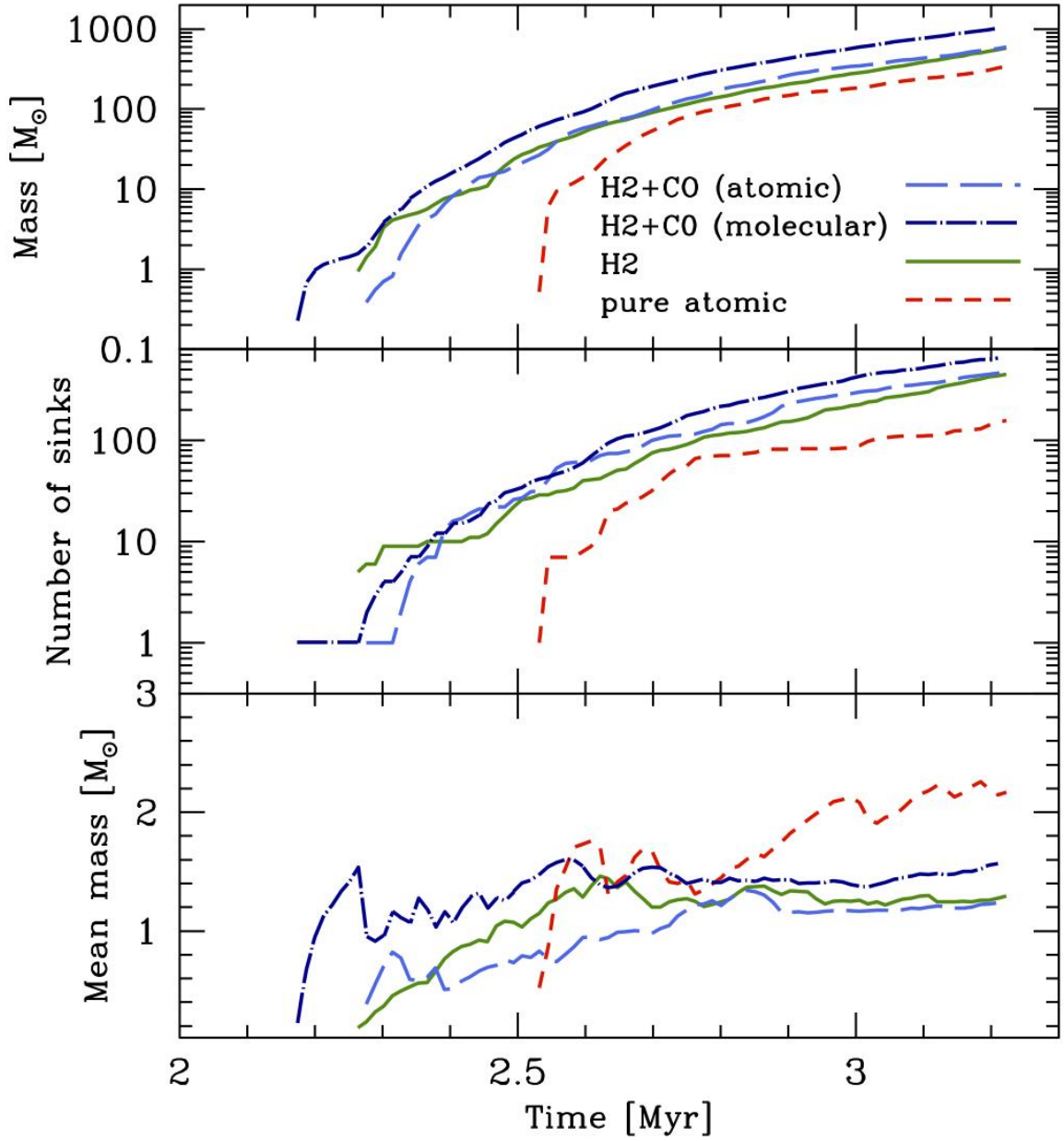
Schruba (2012)

- Good evidence that molecular gas and star formation are correlated in local spirals
- Obvious hypothesis: need molecular gas in order to form stars (because of cooling?)
- But why? H_2 cooling ineffective at GMC temperatures, CO not much better than C^+

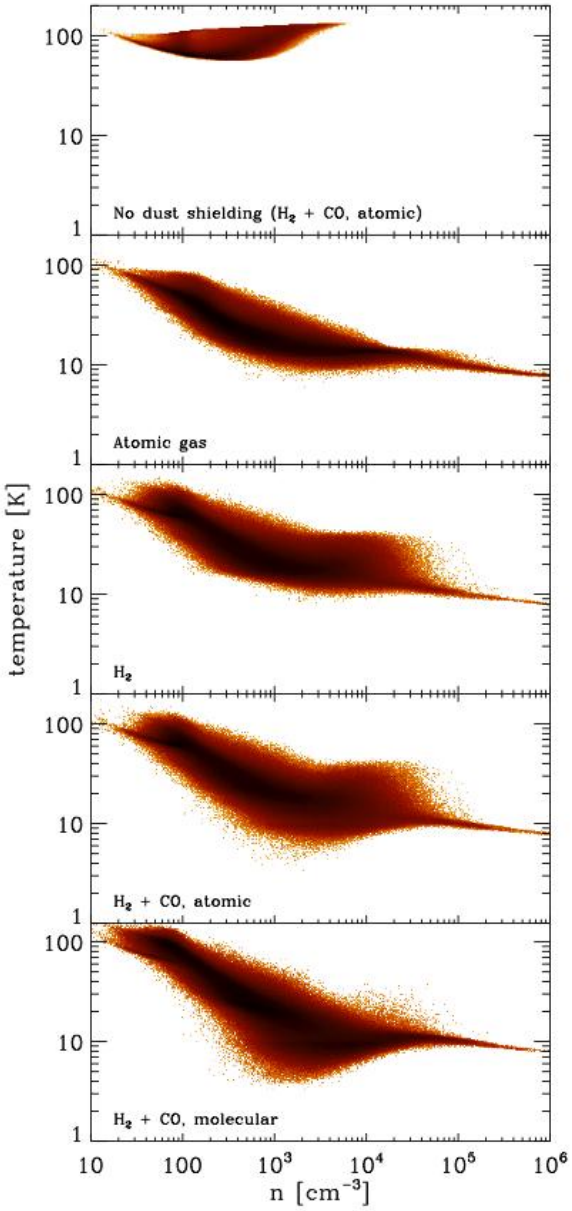
- In order to form stars, need low Jeans mass.
- Jeans mass is low in cold, dense gas.
- Cold dense gas clouds are also good place to form molecules
- Is star formation correlated with molecular gas simply because molecules and stars form in similar environments?

- We decided to investigate this using SPH simulations of isolated GMCs
- Cloud mass = 10000 solar masses
- Mean density = 300 cm^{-3}, radius = 6 pc
- 2 million SPH particles, so M_{res} = 0.5 M_{sun}

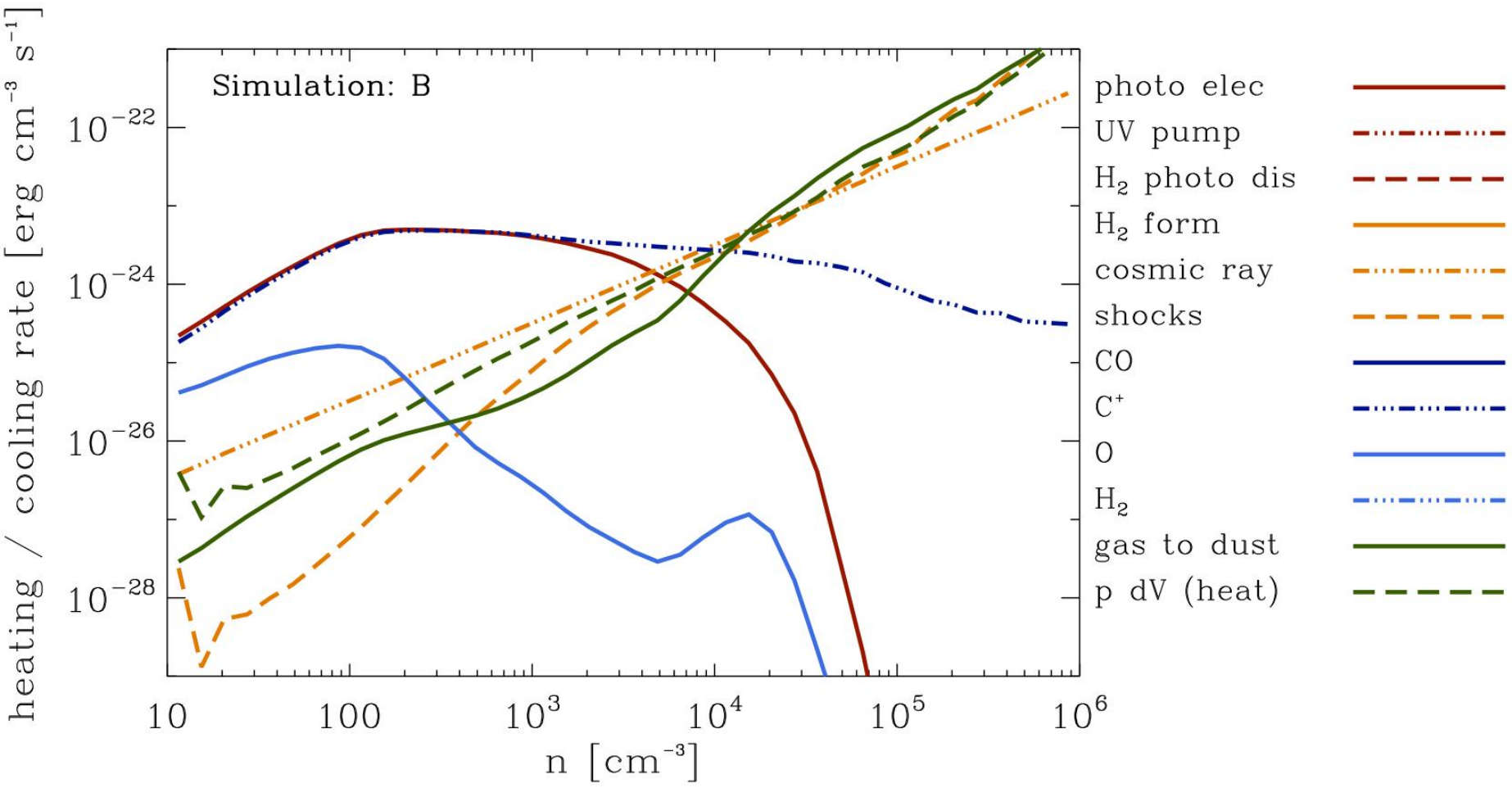
- Model A: detailed chemistry, cooling, but no shielding
- Model B: atomic cooling, no chemistry
- Model C: atomic, H_2 cooling; only hydrogen chemistry
- Models D1,D2: full chemistry & cooling



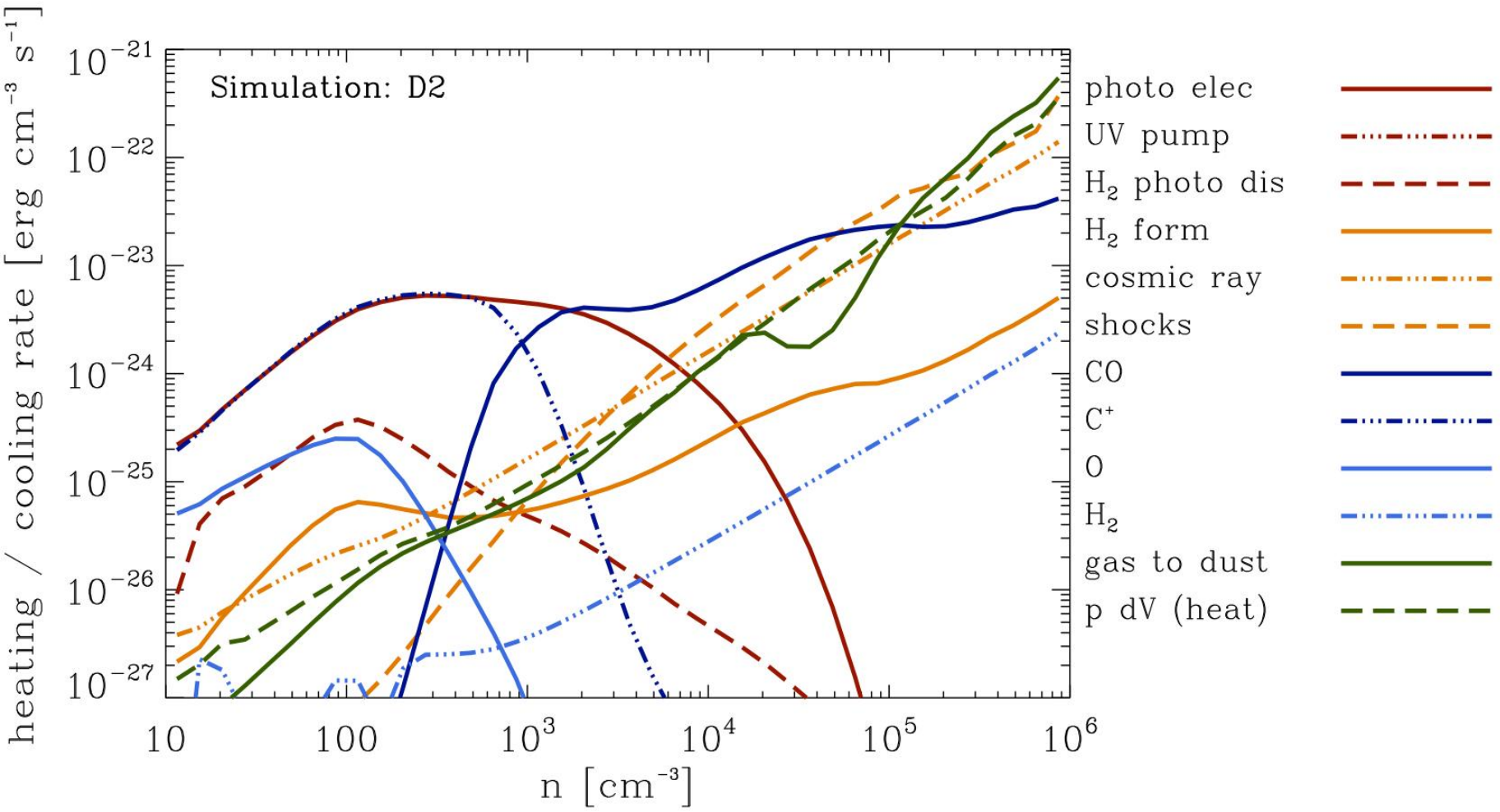
Glover & Clark (2012a, MNRAS, 421, 9)



Glover & Clark (2012a)



Glover & Clark (2012a)



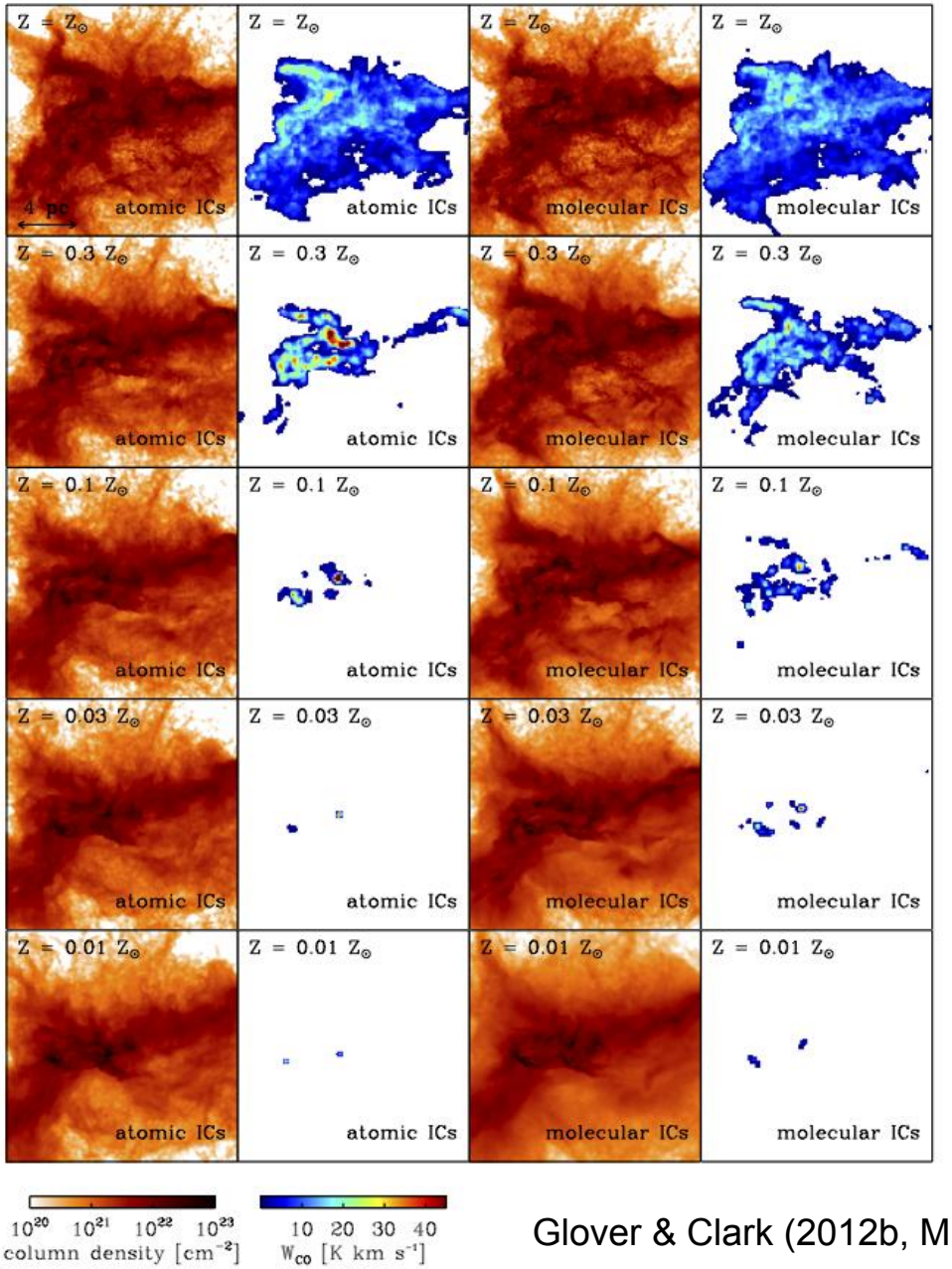
Glover & Clark (2012a)

- Presence of molecular gas has only small influence on star formation rate
- H_2 cooling never important in dense cloud conditions
- CO important if present; but C^+ good substitute when CO absent

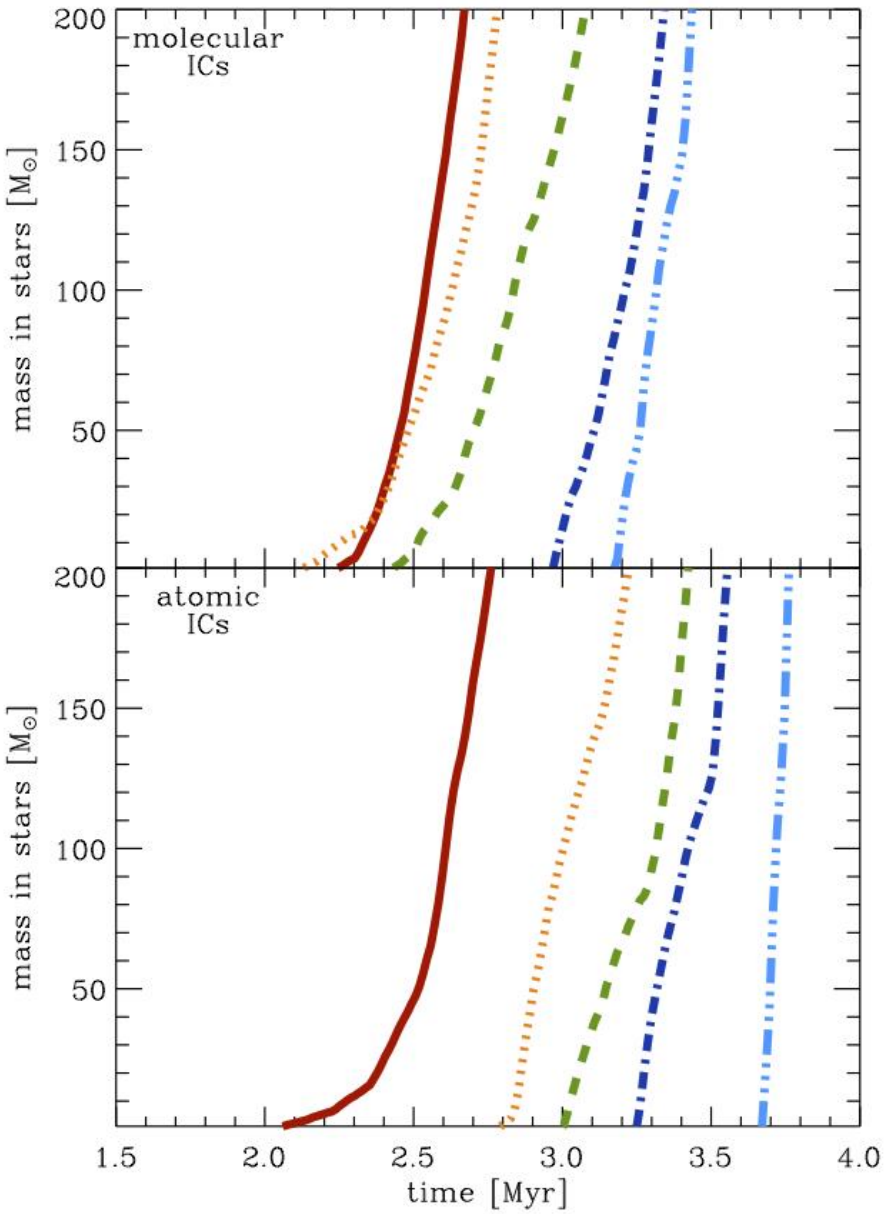
- This study was somewhat artificial, since we just switched off bits of the chemistry.

- Are there real systems where we might expect star formation without (much) molecular gas?

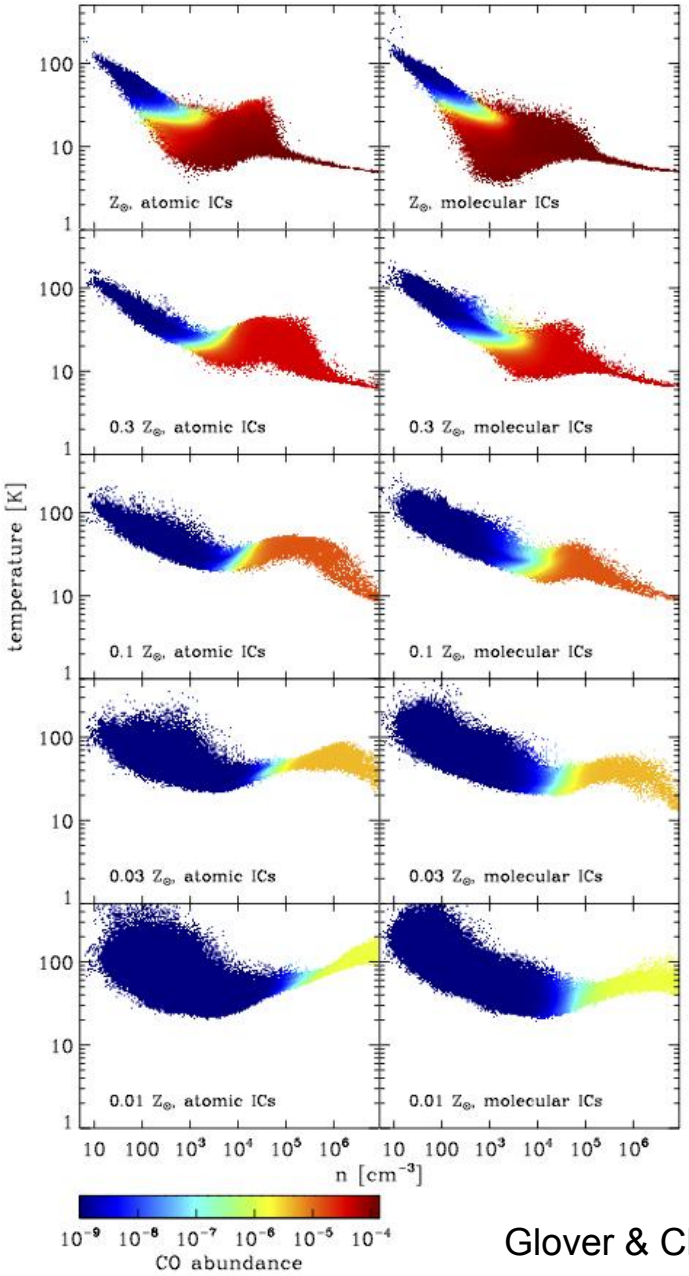
- Yes! We just need to look at low metallicity...



Glover & Clark (2012b, MNRAS, 426, 377)

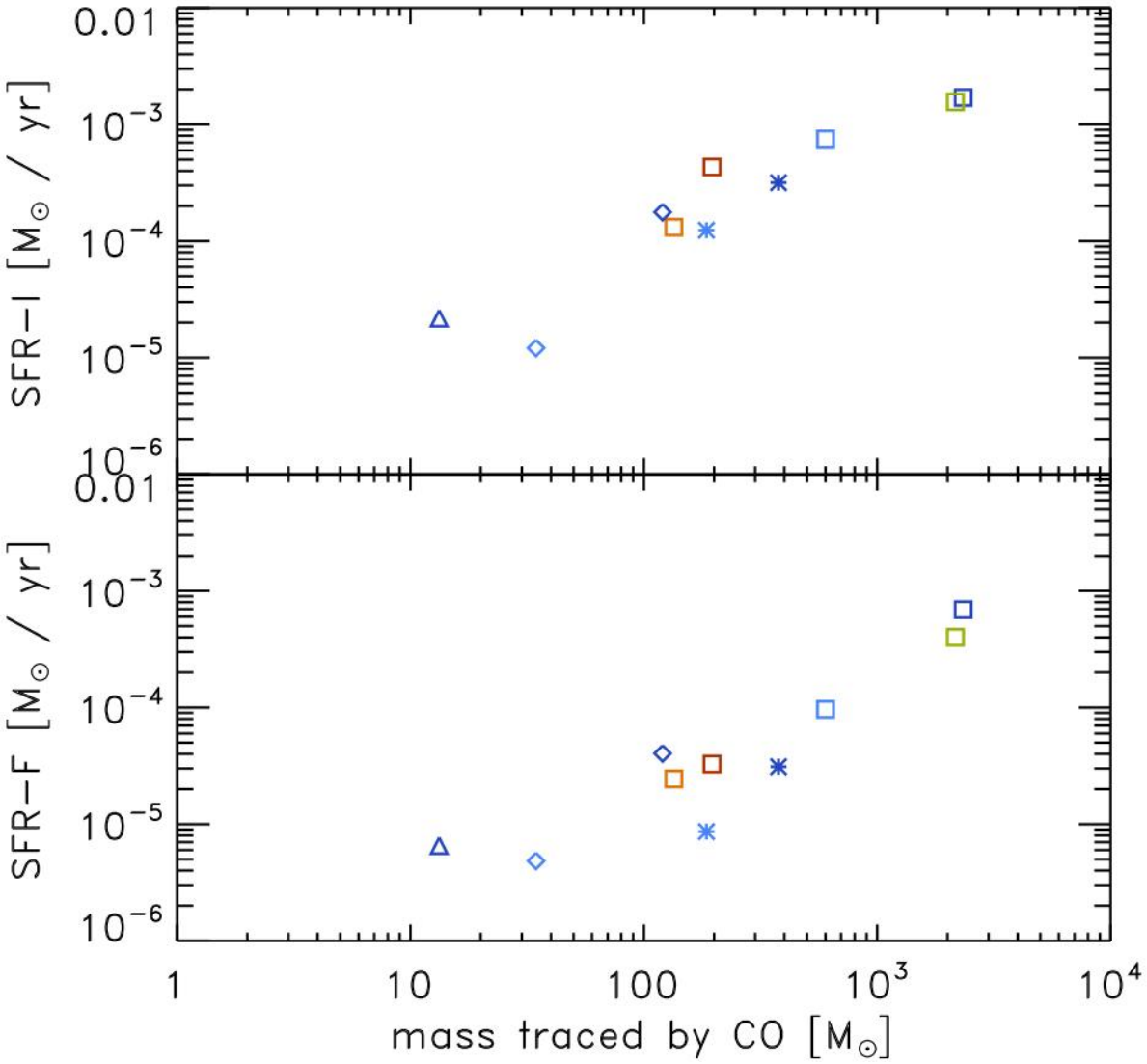


Glover & Clark (2012b)

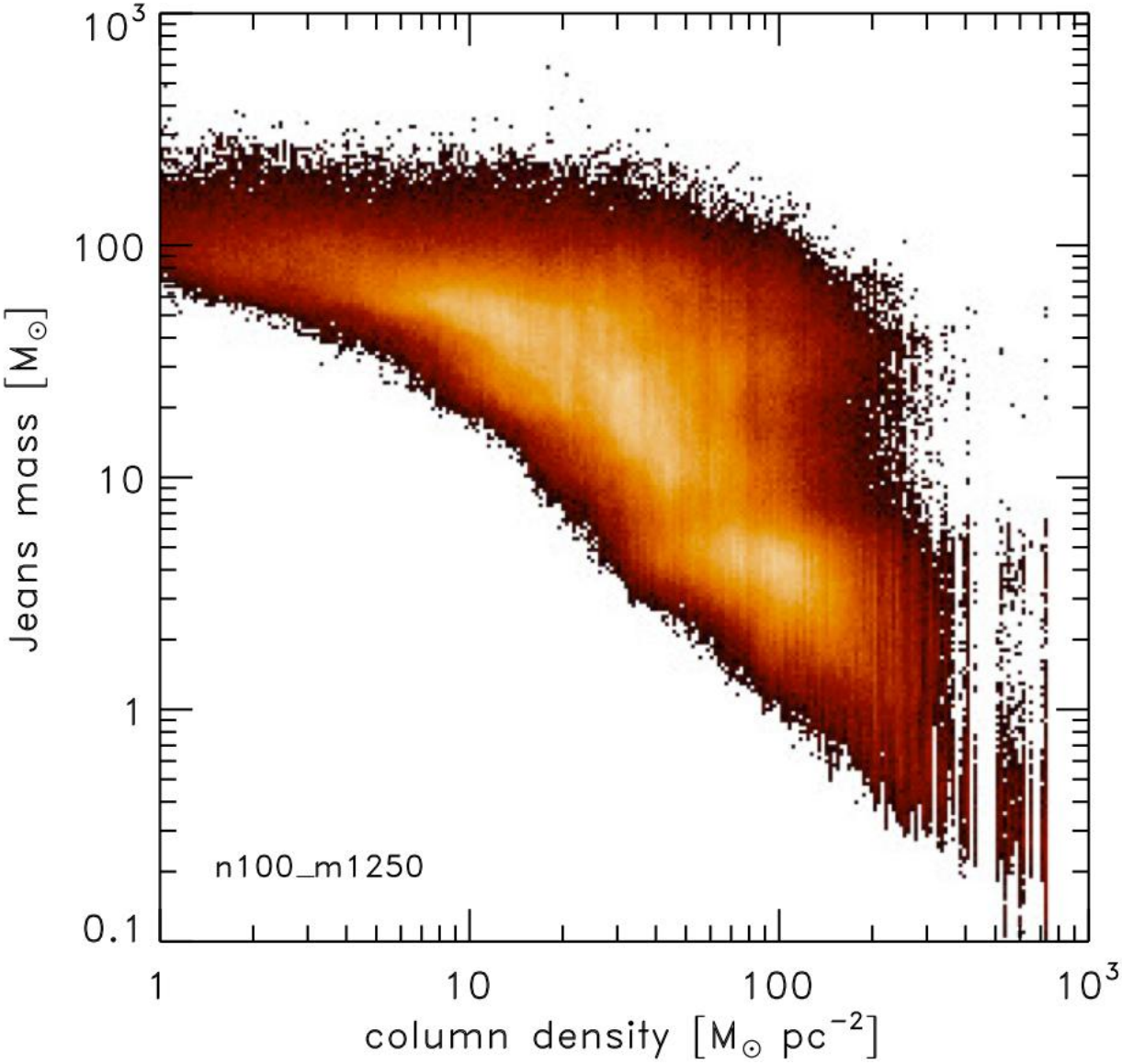


Glover & Clark (2012b)

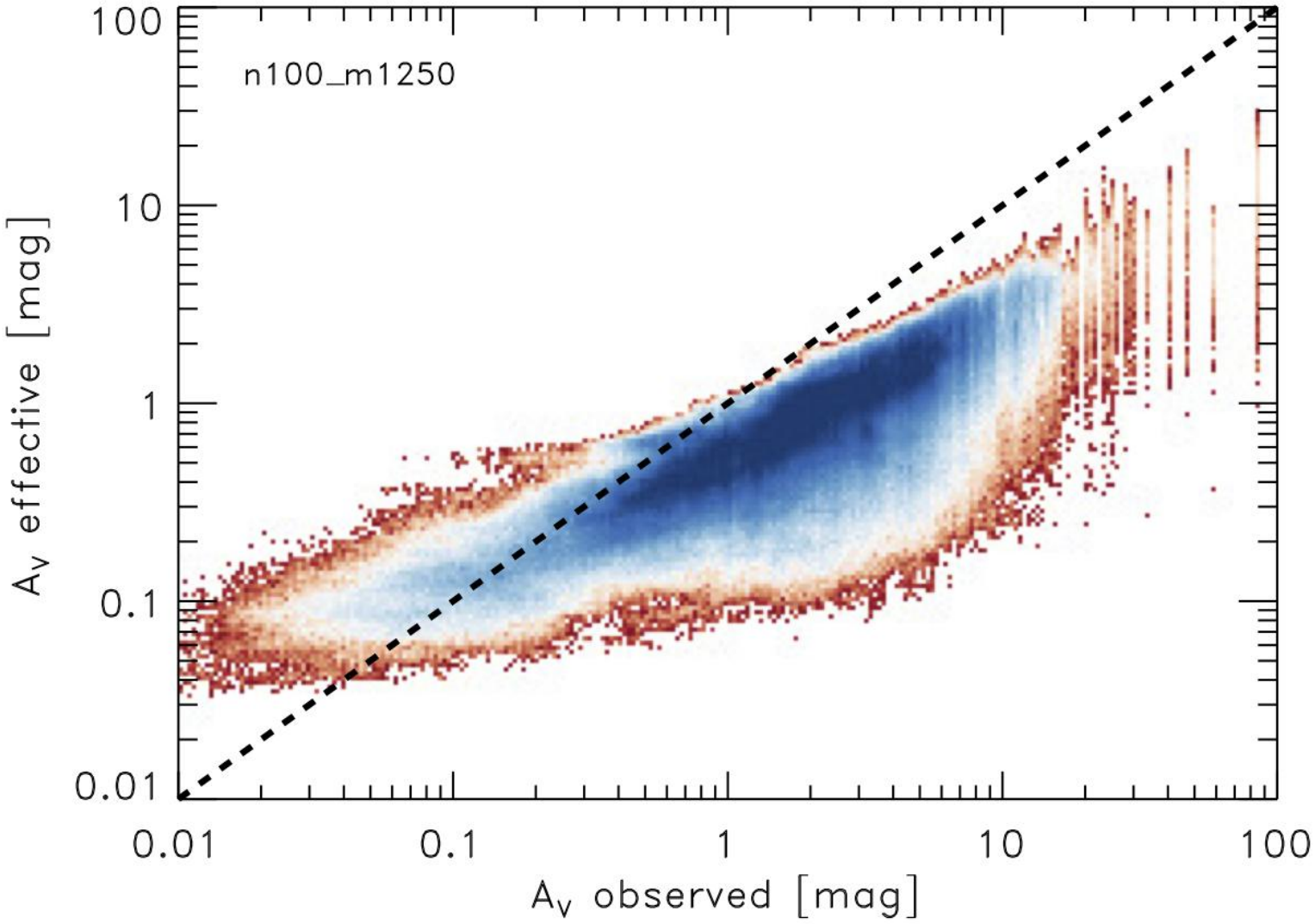
- Star-forming gas eventually becomes molecular
- At low Z, this happens after runaway collapse has already begun
- Supports idea that molecular gas often traces star formation, but isn't necessary



Clark & Glover (2013, arXiv: 1306.5714)



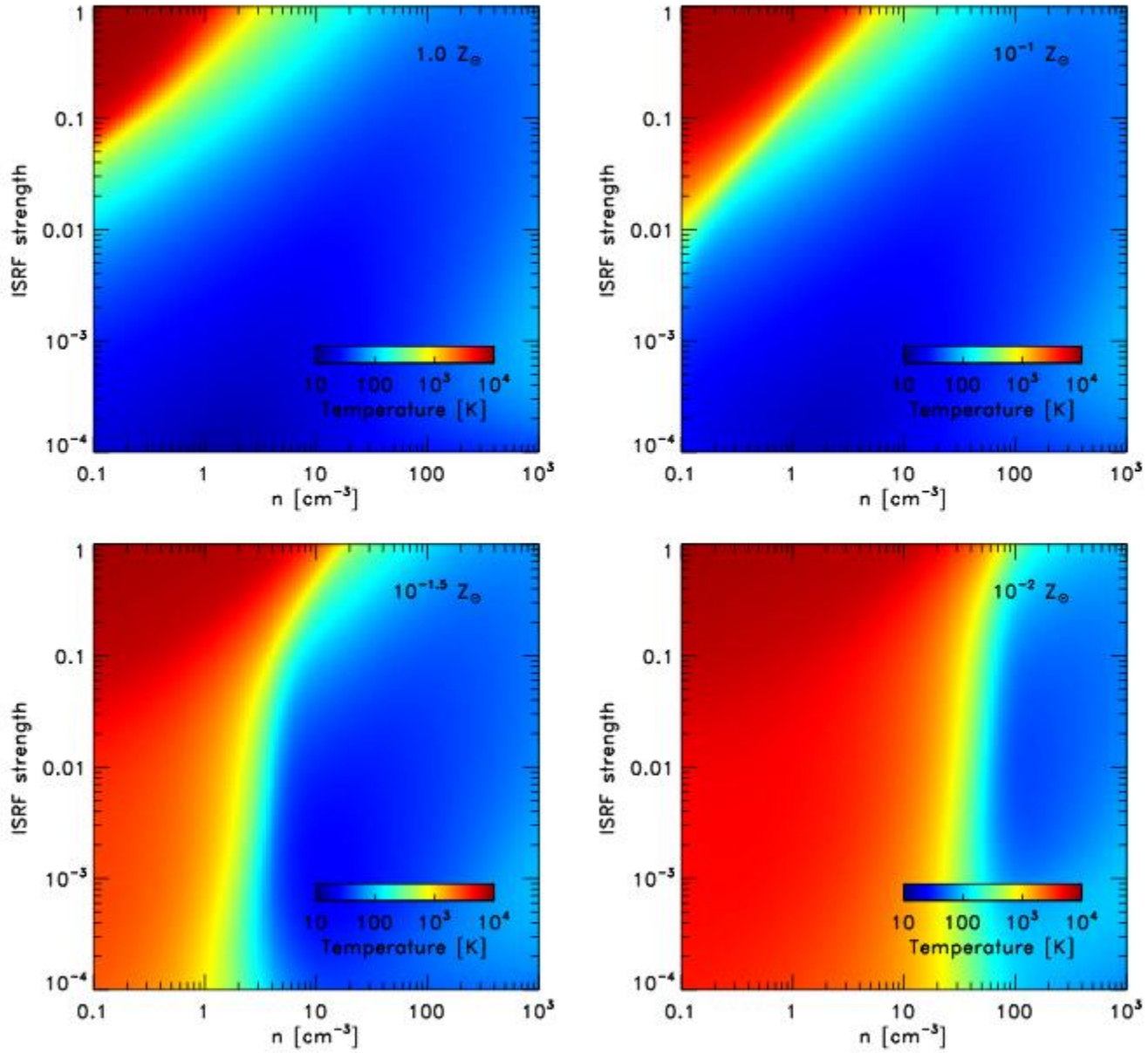
Clark & Glover (2013)

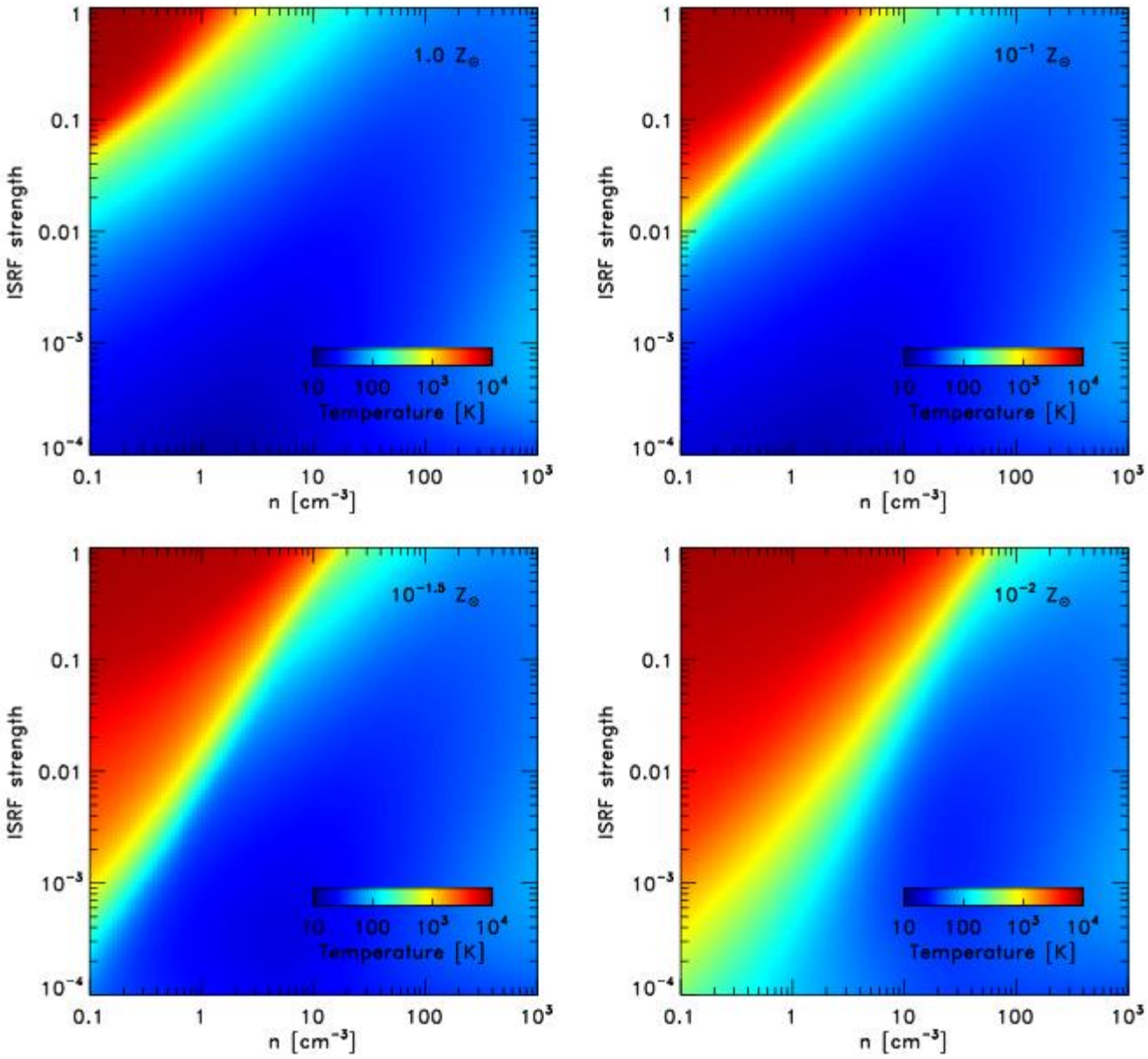


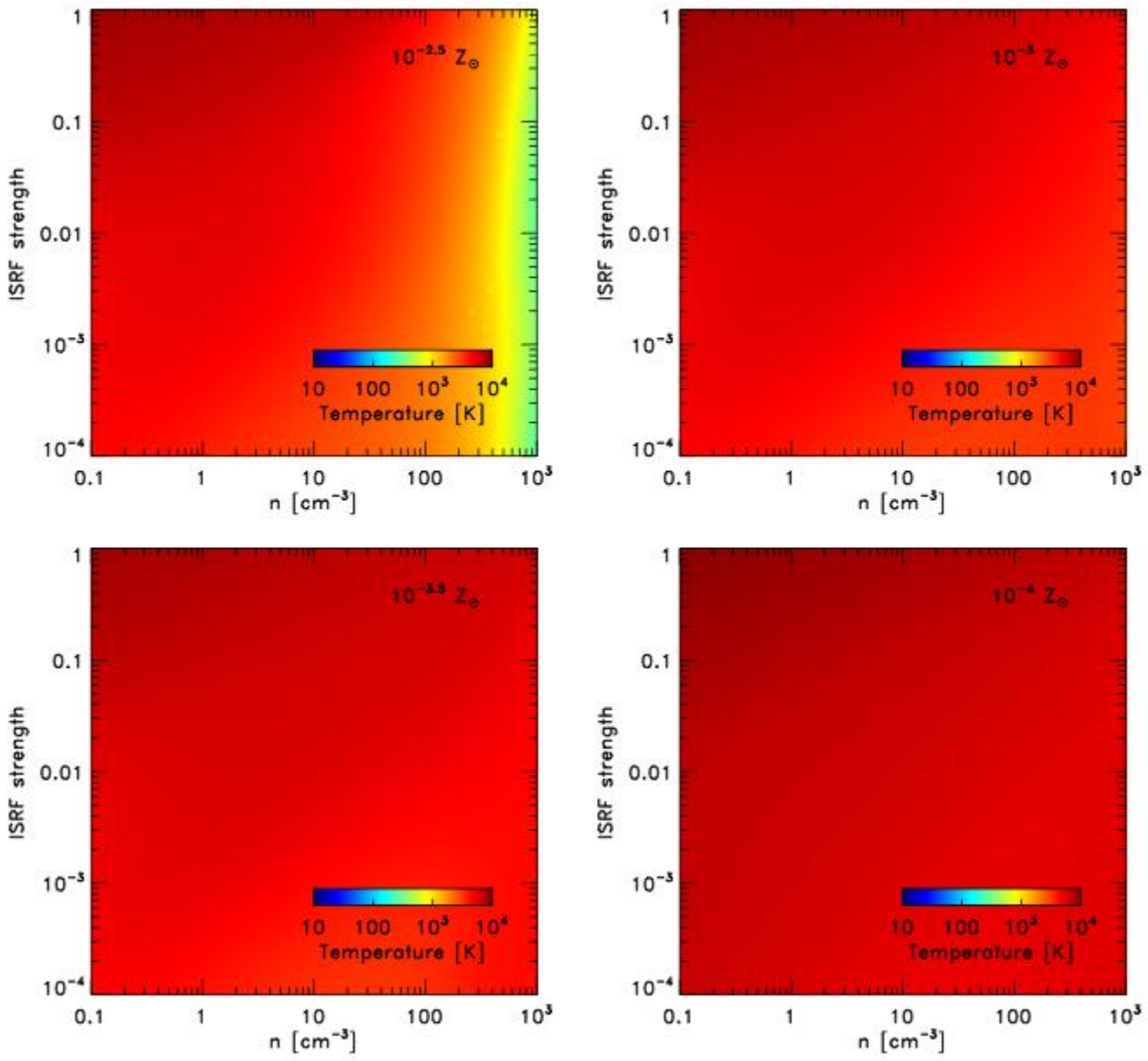
Clark & Glover (2013)

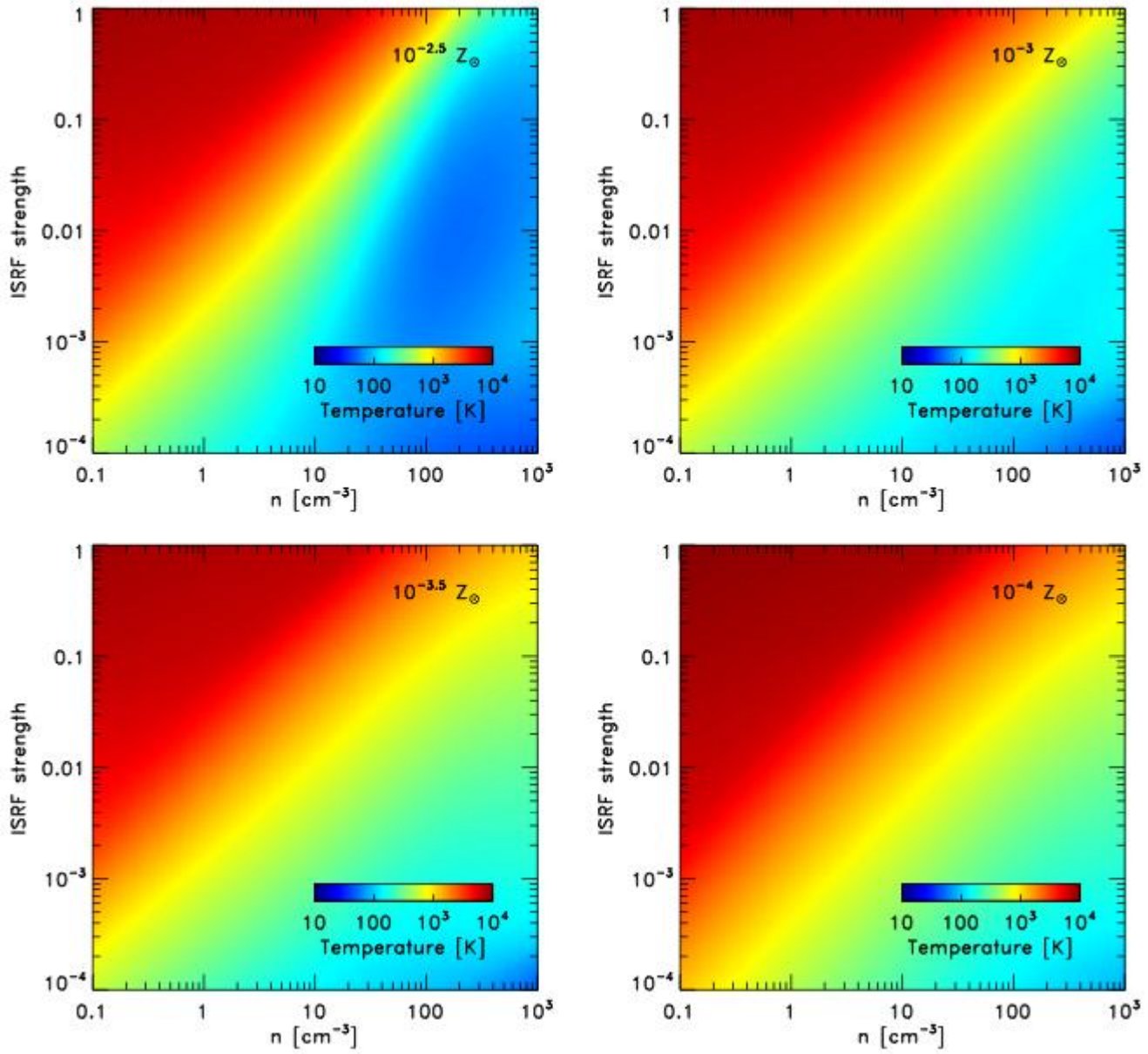
- Does this mean molecular gas is never important for star formation?
- Clearly not, since we know of some situations in which it is essential
- Simplest example is formation of Pop. III stars - no metals, so no metal cooling
- Similarly, when forming very low metallicity Pop. II stars, need H_2 cooling to get to the densities at which dust takes over

- What about diffuse gas?
- H_2 cooling unimportant in GMCs, as the gas is too cold
- In the warm, diffuse ISM, temperatures are much higher: can H_2 cooling become important there?


1.0 Z⊙
10^{-1} Z⊙
$10^{-1.5}$ Z⊙
10^{-2} Z⊙
ISRF strength
n [cm^{-3}]
Temperature [K]
10 100 10^3 10^4
1
0.1
0.01
10^{-3}
10^{-4}
0.1 1 10 100 10^3


1.0 Z⊙
10^{-1} Z⊙
$10^{-1.5}$ Z⊙
10^{-2} Z⊙
ISRF strength
n [cm^{-3}]
Temperature [K]
10
100
10^3
10^4
0.1
1
10
100
10^3
10^{-4}
10^{-3}
0.01
0.1
1


$10^{-2.5}$ $Z_\odot$
10^{-3} $Z_\odot$
$10^{-3.5}$ $Z_\odot$
10^{-4} $Z_\odot$
ISRF strength
n [cm^{-3}]
Temperature [K]
10 100 10^3 10^4
0.1 1 10 100 10^3
1 0.1 0.01 10^{-3} 10^{-4}


$10^{-2.5}$ $Z_\odot$
10^{-3} $Z_\odot$
$10^{-3.5}$ $Z_\odot$
10^{-4} $Z_\odot$
ISRF strength
n [cm^{-3}]
Temperature [K]
10 100 10^3 10^4
1 0.1 0.01 10^{-3} 10^{-4}
0.1 1 10 100 10^3

- At $Z > 0.1\ Z_{sol}$, H_2 cooling unimportant, regardless of density or ISRF strength
- At lower metallicity, H_2 cooling important when G_0/n small
- H_2 therefore plays important role in enabling formation of GMCs when Z, G_0 both small
- For more details, see arXiv:1305.7365

Conclusions

- CO traces star formation well at metallicities near solar, but not at lower metallicity.
  - CO and star formation both trace dense, cold gas

- H_2 cooling unimportant at solar metallicity, grows more important as we decrease Z
  - BUT: primary importance is as a trace coolant in diffuse <u>atomic</u> gas! By the time gas is fully molecular, generally too cold to cool via H_2

- Cooling (and hence fragmentation) require increasingly high densities as we move to lower Z
  - Implies that star formation will become more clustered at low Z than at high Z

- Is molecular gas necessary for star formation?
  - Yes and no: the answer depends on metallicity, environment