The formation of clumps and stars in GMCs

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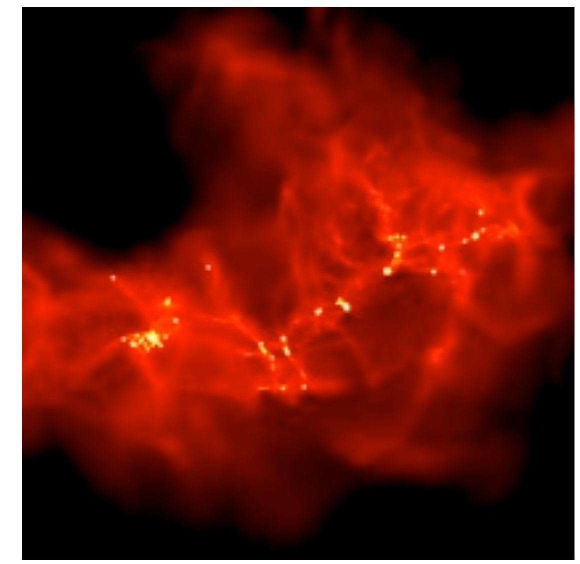
Exploring cluster formation through numerical experiments

You get out what you put in!:

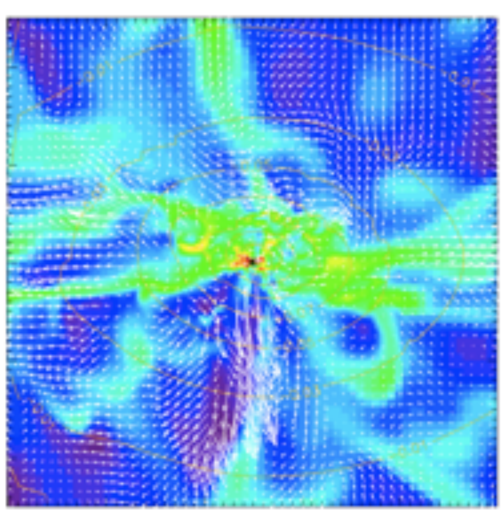
- Timescale for star formation = free-fall time of cloud
- Number of stars ~ number of Jeans masses
- Competitive accretion can function, given the right conditions
- Stellar density/SFE connected to energy state of cloud



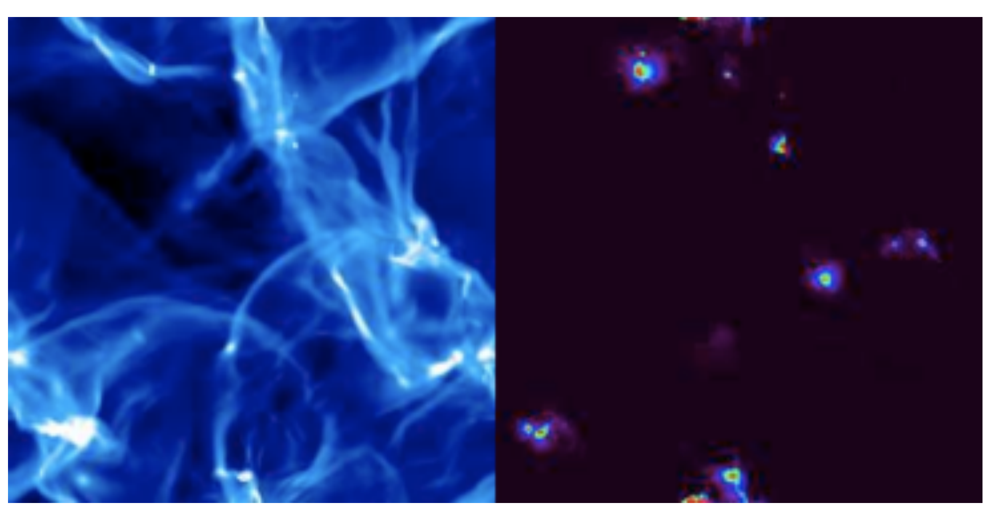
Clark, Bonnell & Klessen (2008)

Extra physics effects also play a role:

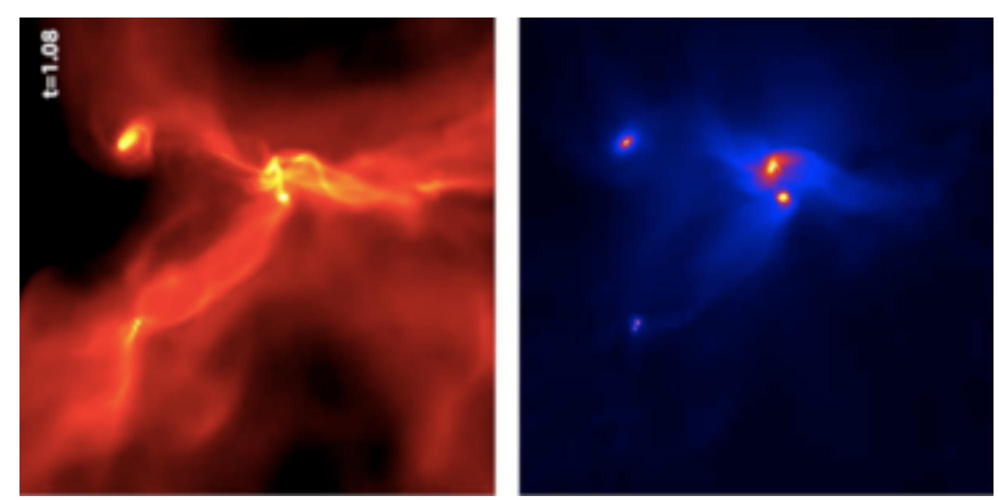
- Radiative feedback can suppress fragmentation, and alter the IMF
- Magnetic fields and/or outflows can reduce the SFE/SFR



Wang et al (2010)



Offner et al (2009)

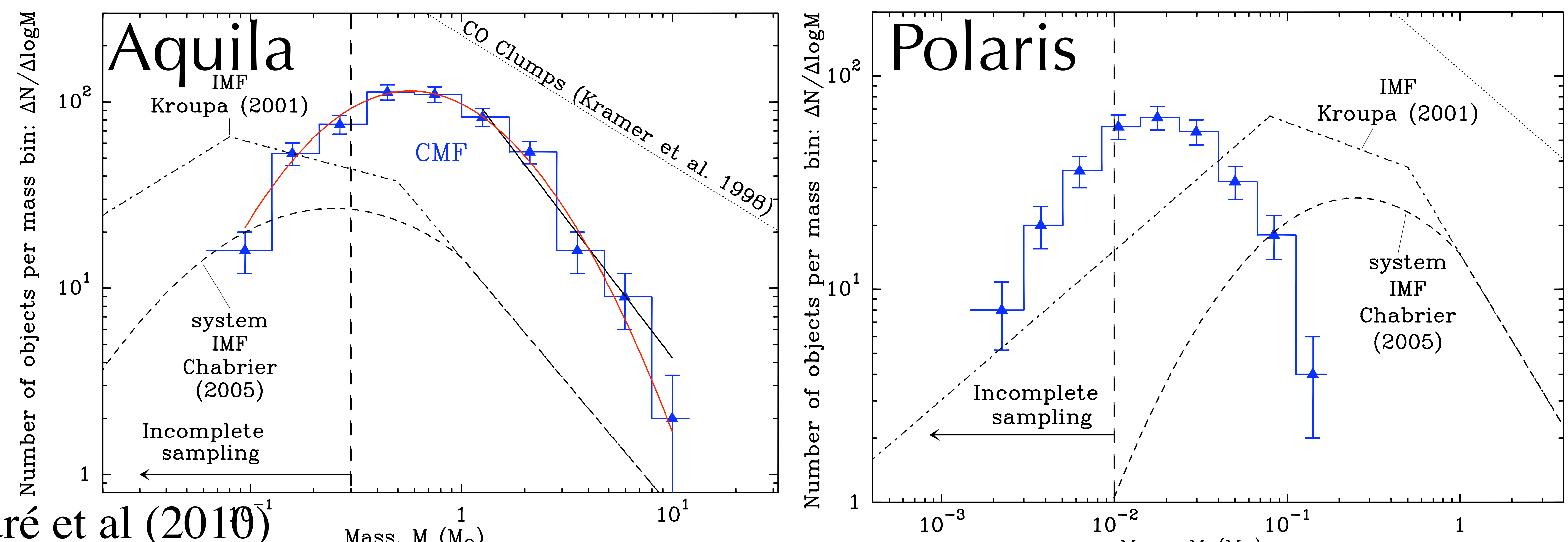


Bate (2008)

Unanswered questions...

So far, we've really only looked at what dust-gas coupled regimes might do once they have formed

- How do these dust-coupled regimes appear?
- How fast?
- Clump mass - IMF connection? (Motte et al 1997; Padoan & Nordlund 2002)
- Environmental influence? Is the IMF/CMF universal? (Nutter & Ward Thompson 2007; André et al 2010; Elmegreen et al 2008)
- How would we see all this? --> Need for chemical tracers



André et al (2010)

Different Physics - Heating and cooling balance...

Heating

photoelectric emission
(Bakes & Tielens 1994; Wolfire et al 2003)

Heating by H2 formation on dust grains
(Duley & Williams 1993; Glover 2009)

Excitation and photodissociation of H2
(Black & Dalgarno 1977; Draine & Bertoldi 1996)

Cosmic ray ionisation
(Goldsmith & Langer 1978)

Heating of the dust by the interstellar radiation field
(Mathis et al 1983; Black 1994; Ossenkopf & Henning 1994).

Heating by H2 formation on dust grains (Duley & Williams 1993; Glover 2009).

Shock heating

Cooling

Molecular line cooling from H2 (Le Bourlot et al 1999), CO and H_2O
(Neufeld & Kaufmann 1993; Neufeld, Lepp & Melnick 1995; Glover & Clark *in prep*).

Fine-structure atomic line cooling from CI, CII, OI, SiI, SiI I
(Glover & Mac Low 2007a).

Both

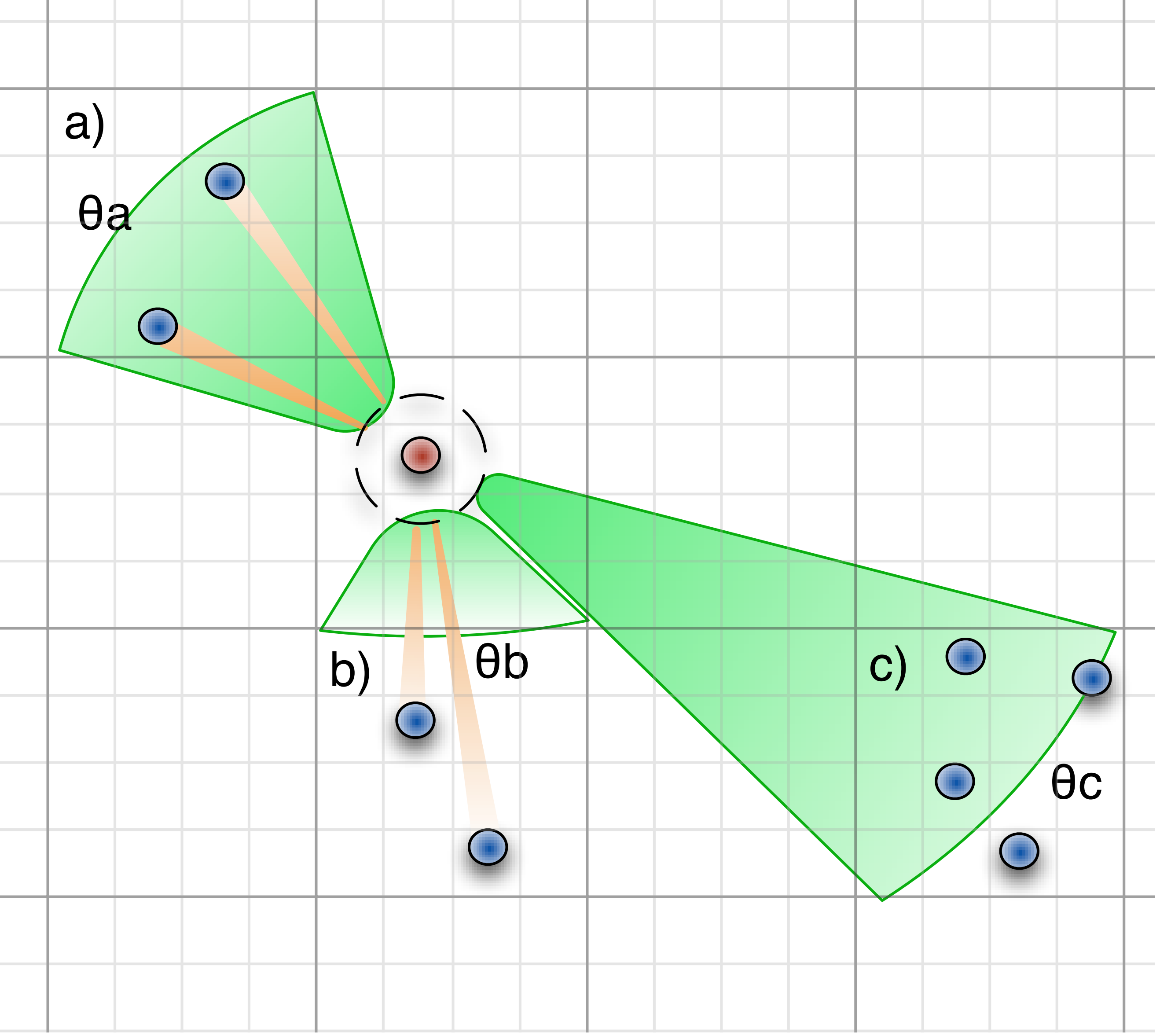
pdV from gas dynamics.

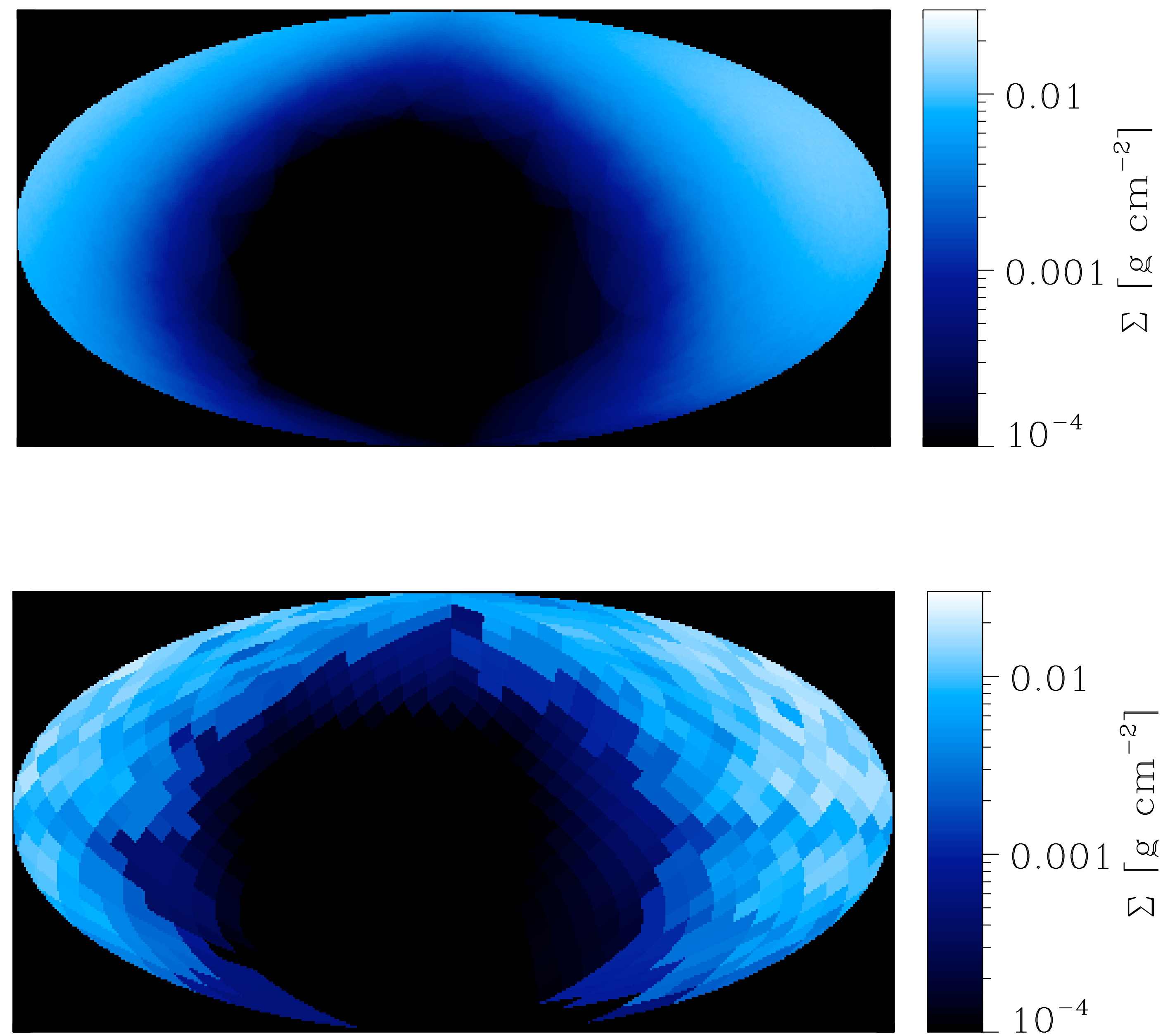
Accurate treatment of the adiabatic index
(Boley et al 2007).

Energy transfer between the gas and dust (Hollenbach & McKee 1979)

TreeCol

Get column densities while walking the tree during the gravity calculation





Cloud model

- Chemistry and cooling module incorporated into Gadget-2, publicly available SPH code (Springel 2005)
- Conditions in cloud:

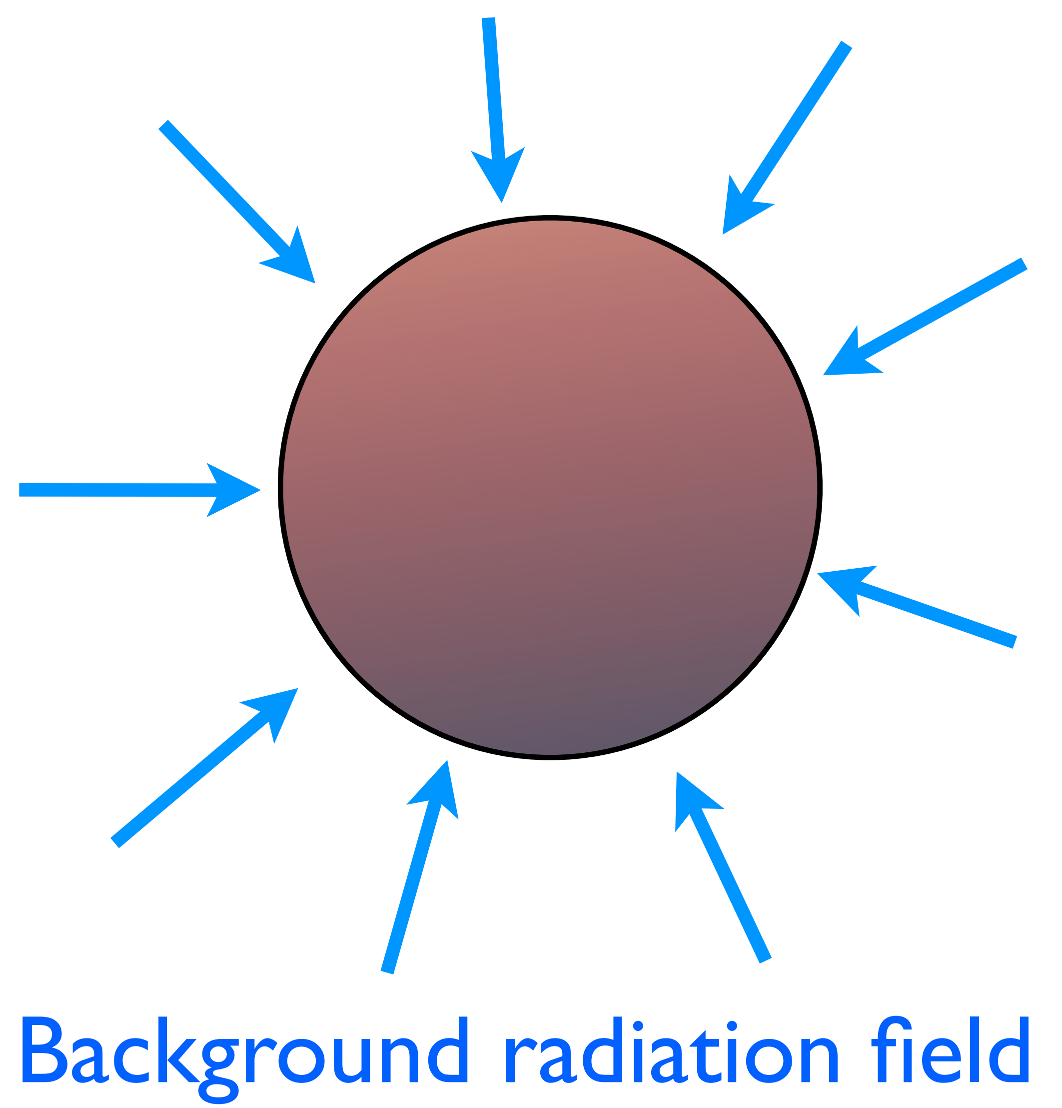
  $10^4\ M_\odot$ 8.7 pc $n = 300\ cm^{-3}$

  2,000,000 SPH particles $m_{res} \sim 0.5\ M_\odot$

  $v_{turb,3D} \sim 8\ km\ s^{-1}$ ($P(k) = P_0\ k^{-4}$)
- Initial chemistry: H, C, O fully atomic.
- Look at 2 different values for the background radiation field:

  1.7 G_0 (Habing 1968) ~ solar neighbourhood

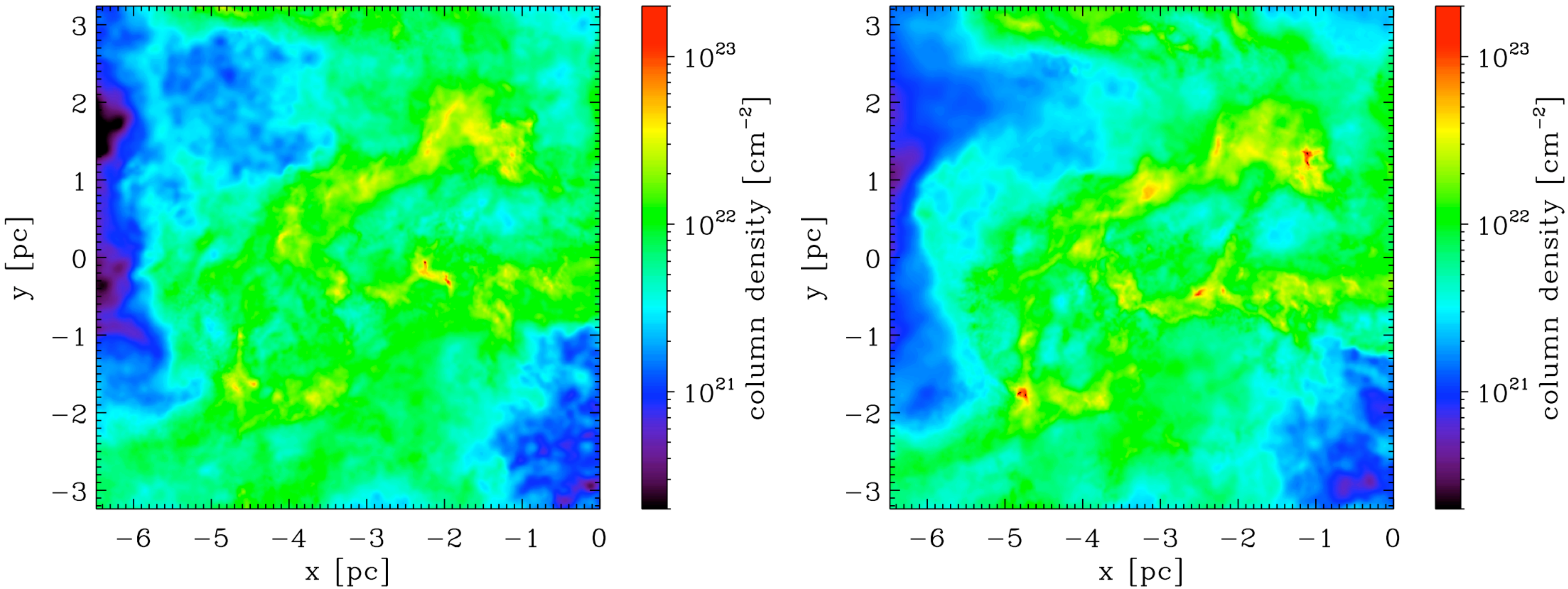
  17 G_0
- + one simulation with low metallicity $Z = 0.1\ Z_\odot$



Different environments?

More high density gas at onset of star formation

UV = 1.7 G_0 UV = 17 G_0

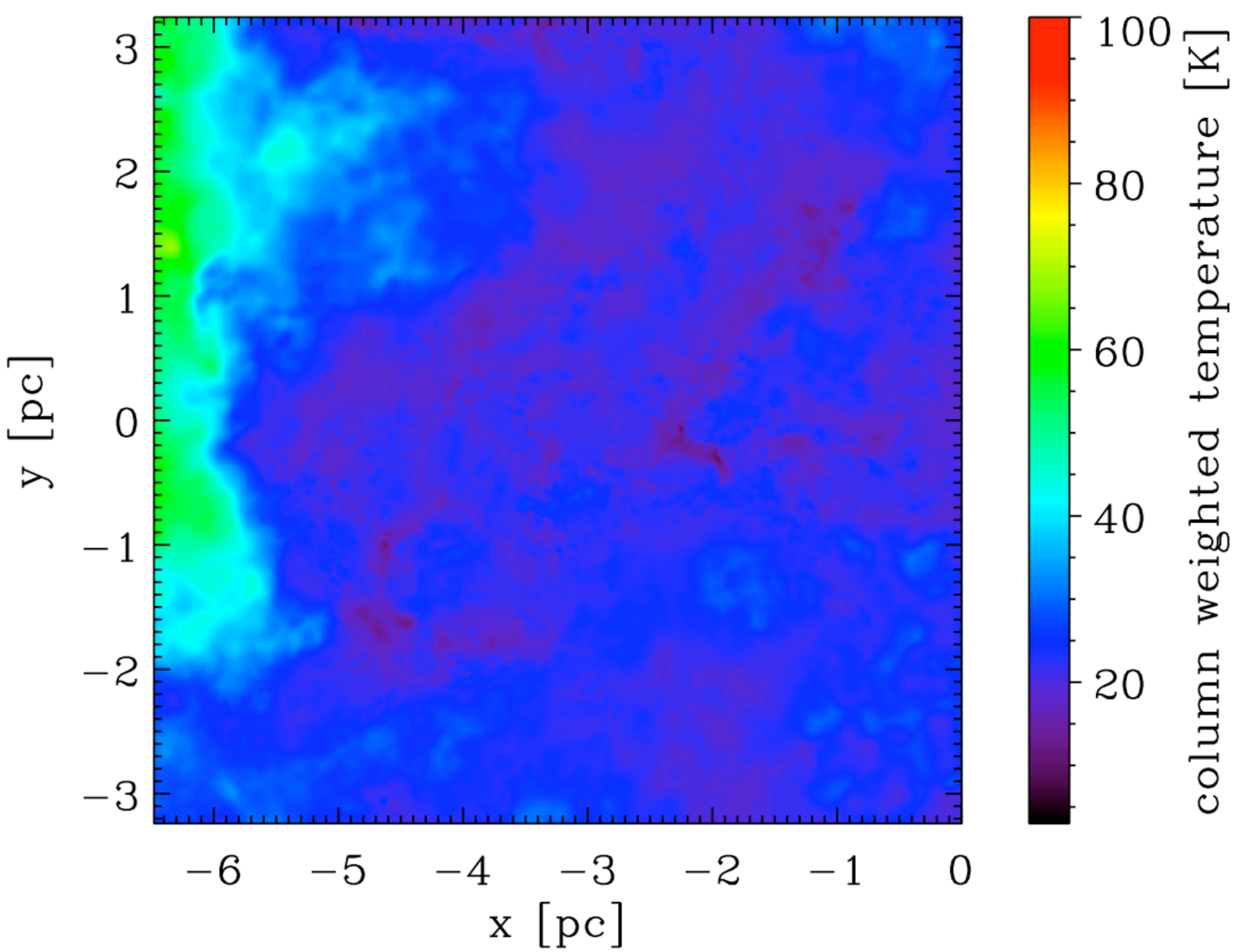


1) Takes slightly longer to form stars in the higher background UV simulation.
2) Higher pressure in the low-density gas

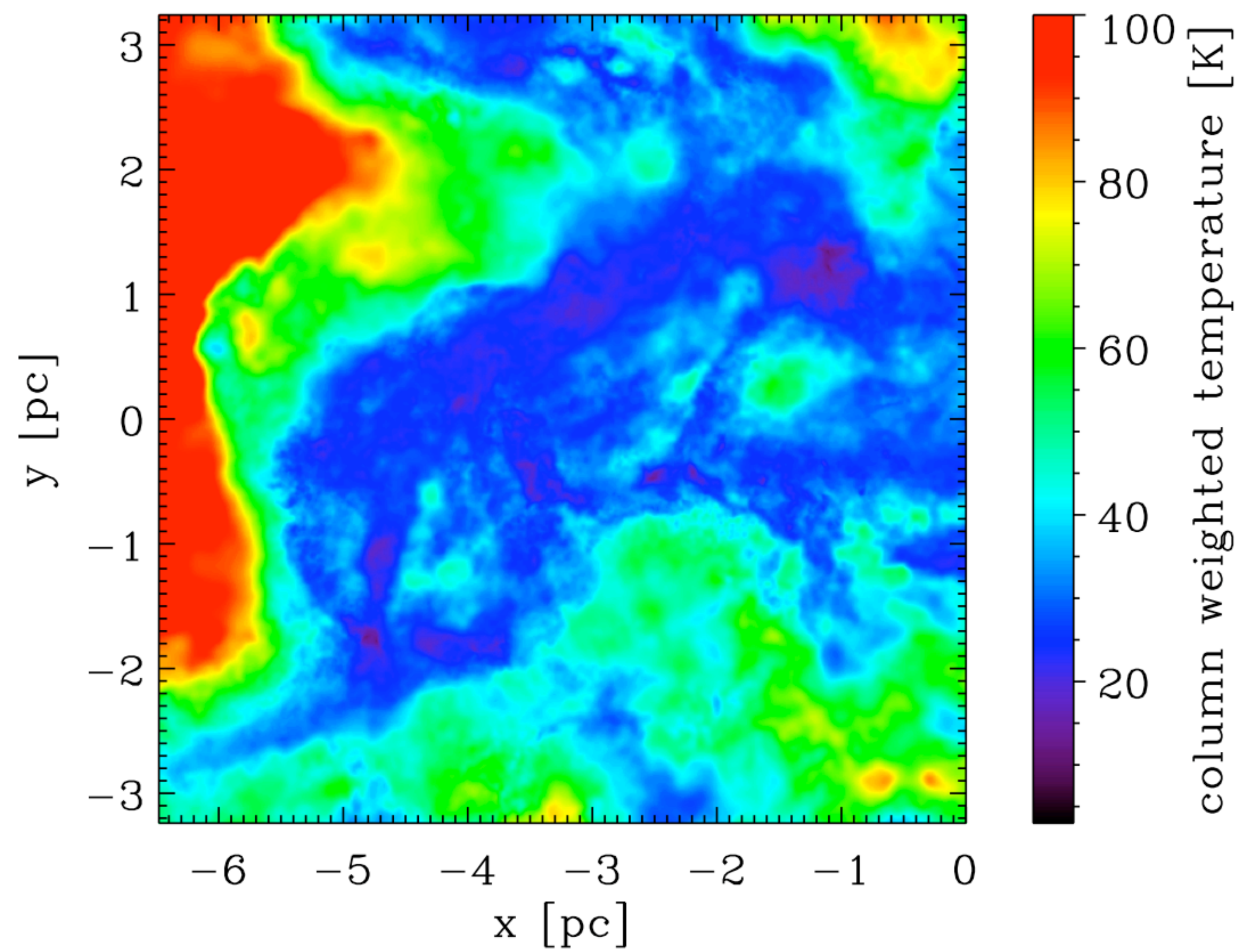
Different environments?

Large scale cloud temperature morphology is very different

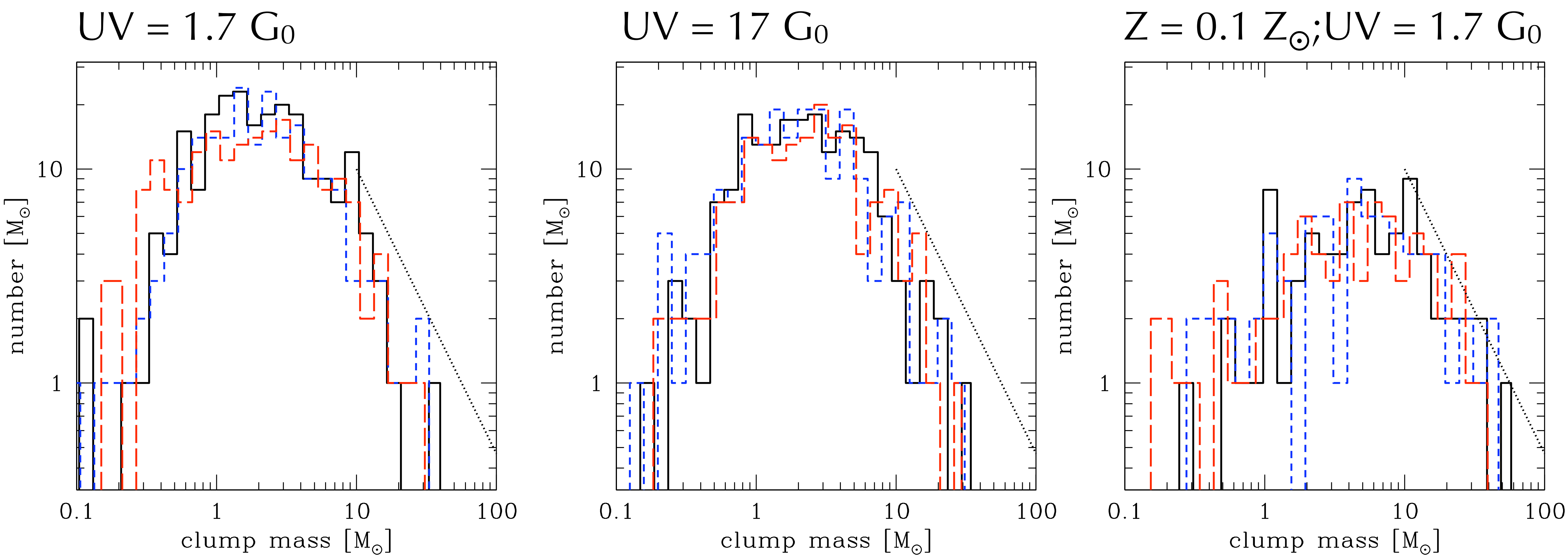
UV = 1.7 G_0



UV = 17 G_0

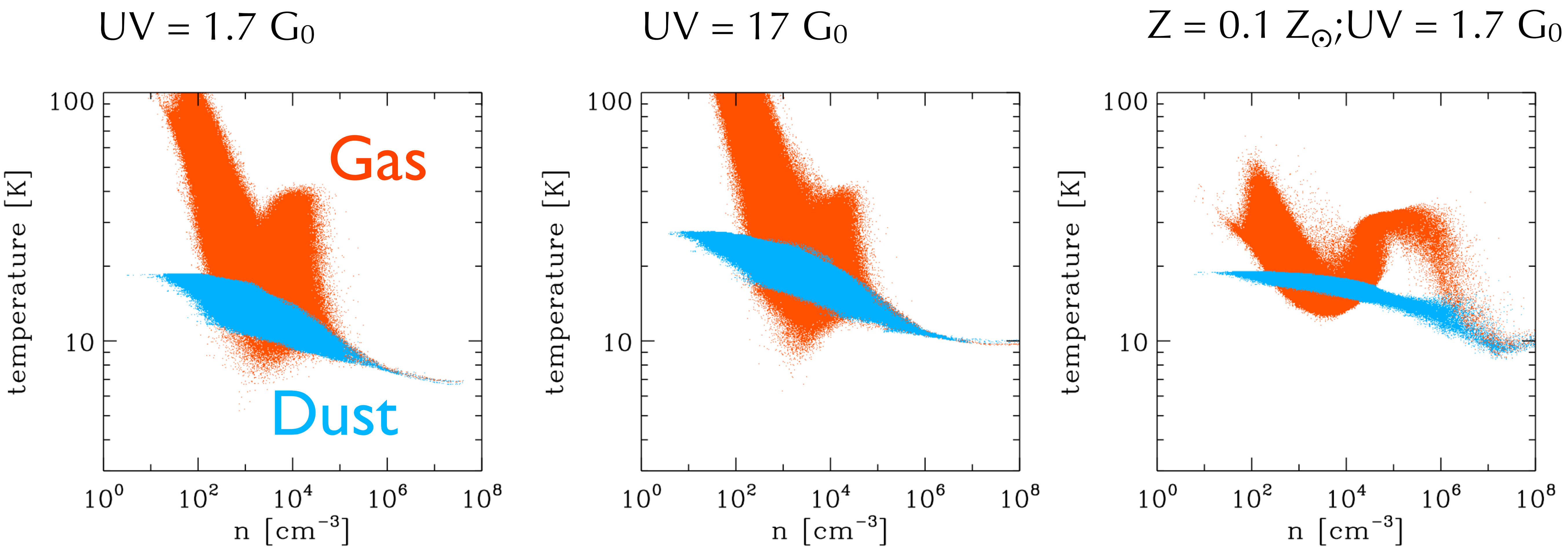


Clump (prestellar core?) IMFs



- Don't see the very low-mass clumps that André et al (2010) find in the Polaris region.
- But do see a shift to higher masses with decreasing metallacity.
- Background radiation field doesn't appear to significantly affect the fragmentation of the gas.

Temperature density relation



- Clouds are FAR from isothermal: low column is hot, high column is cold.
- H_2 formation heating produces a warm 'bump' at n ~ 10^3 -10^4 cm^{-3}
- But dust remains largely unaffected -- > important for fragmentation.
- Elmegreen, Klessen & Wilson (2008) prediction seems to hold.

Stellar system IMFs

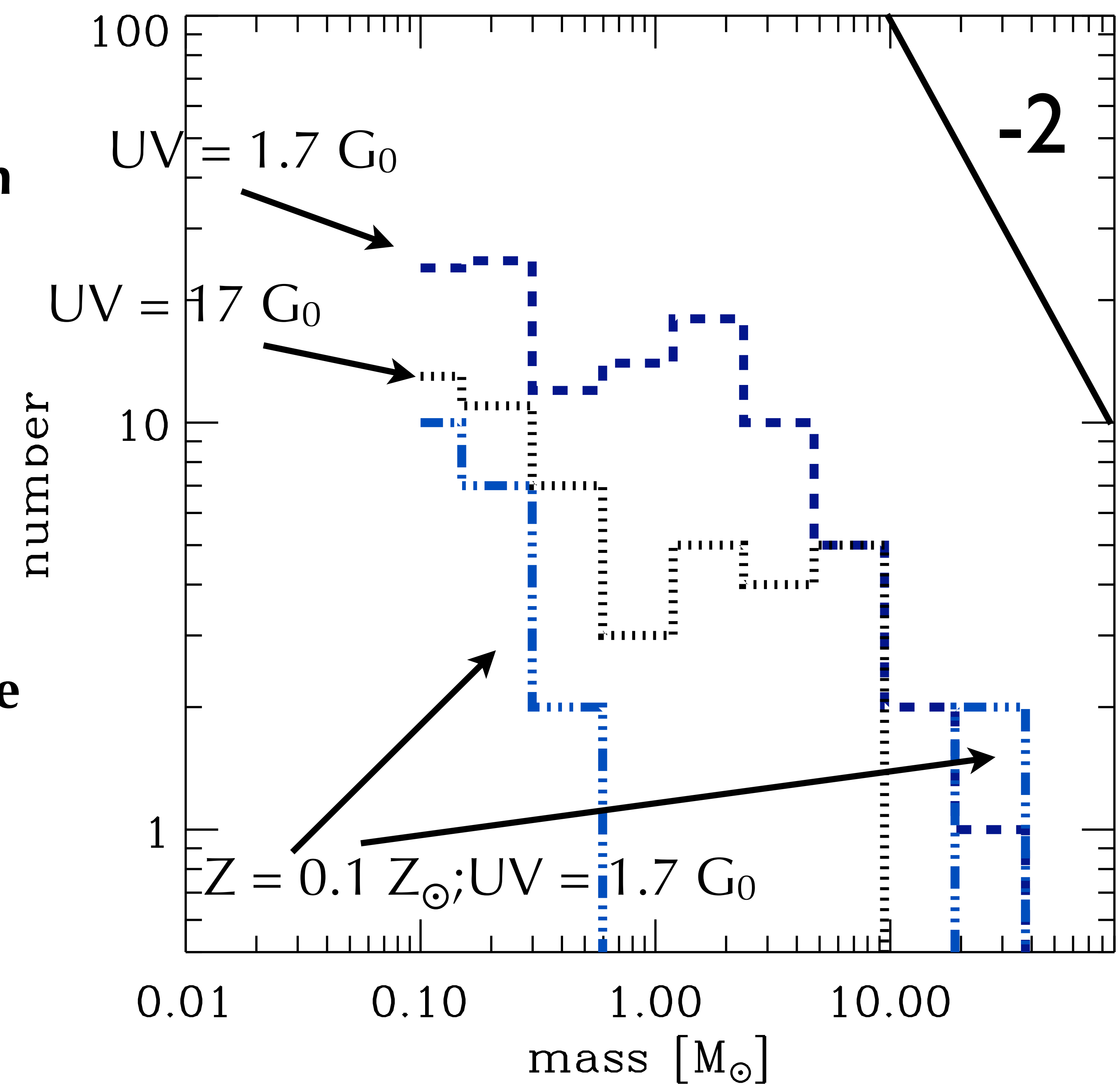
- Sinks are very large (r_{acc} ~ 200 au)

- Solar neighbourhood UV looks similar to previous calculations (such as Bonnell, Vine & Bate 2004)

- The $17G_0$ ISRF calculation looks bad, but the 1.7G0 looked the same at that point in the calculation… should recover

- Low metallicity calculation is more worrying… One 'system' enjoys run-away un-competitive accretion.

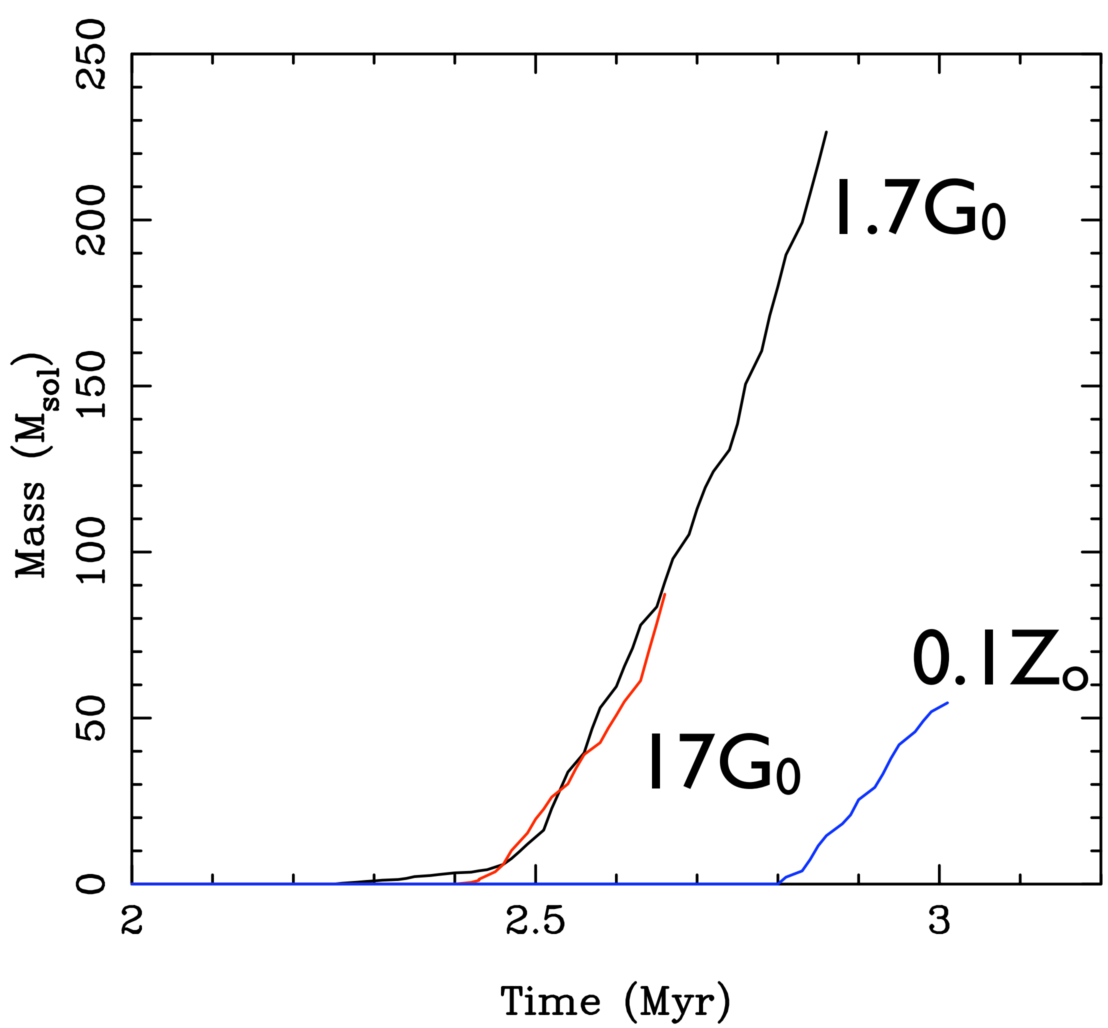
- BUT none look like their clump-mass distribution.

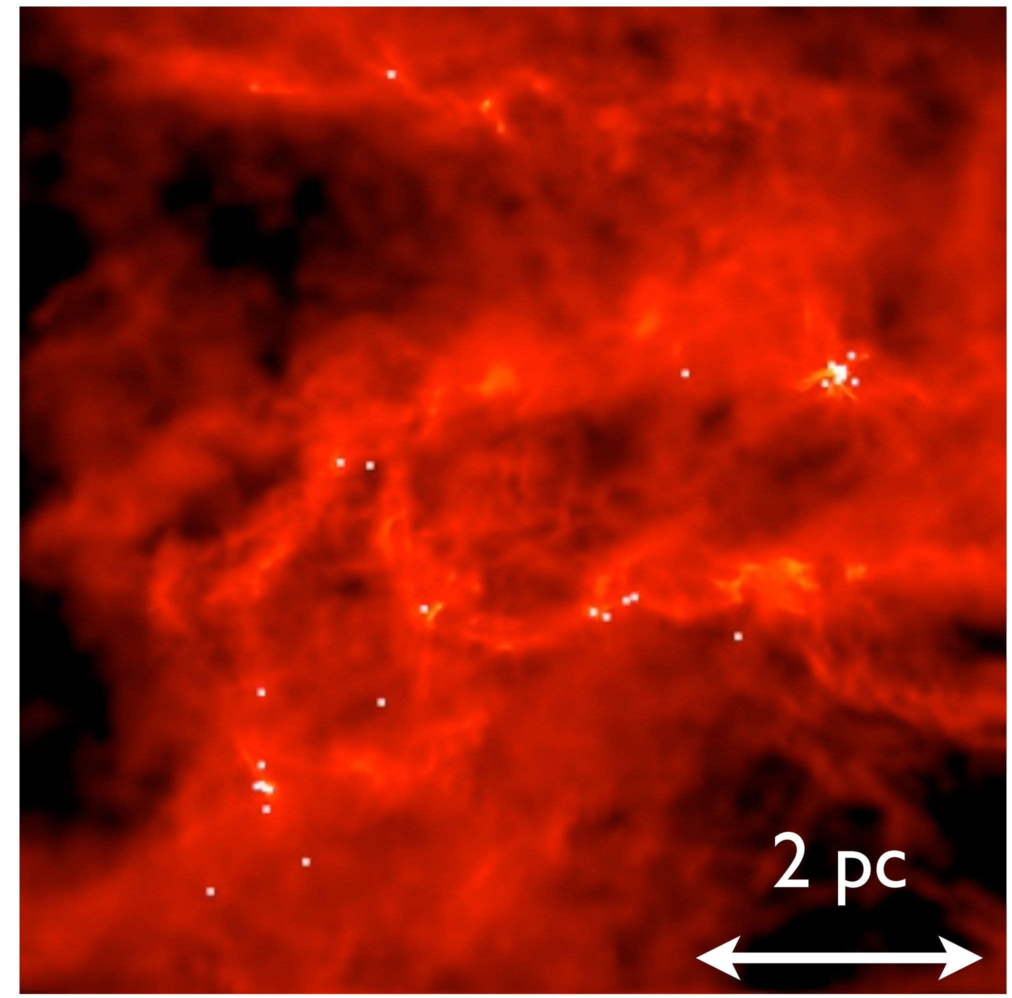


Spatial/temporal distribution of stars?

After roughly 400,000 yr:

- Roughly 100 stellar systems are distributed throughout a region of about 6 pc on a side.
- Contain only a few hundred $M_\odot$ of gas (total cloud is 10,000 $M_\odot$).



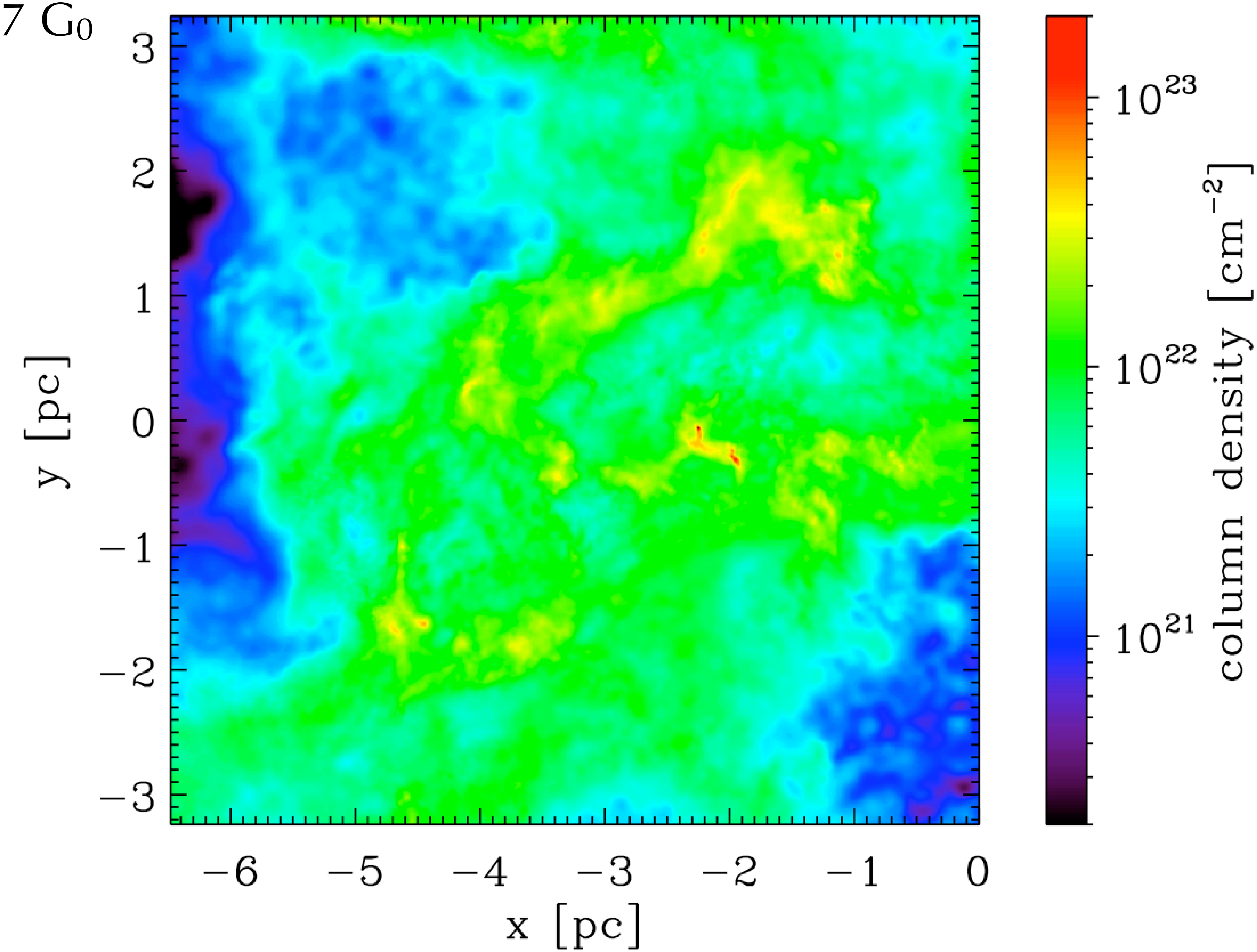


Slow/fast debate?
Takes at least **1 -2 Myr** to assemble something like the ONC.

Onset of star formation...

UV = 1.7 G_0

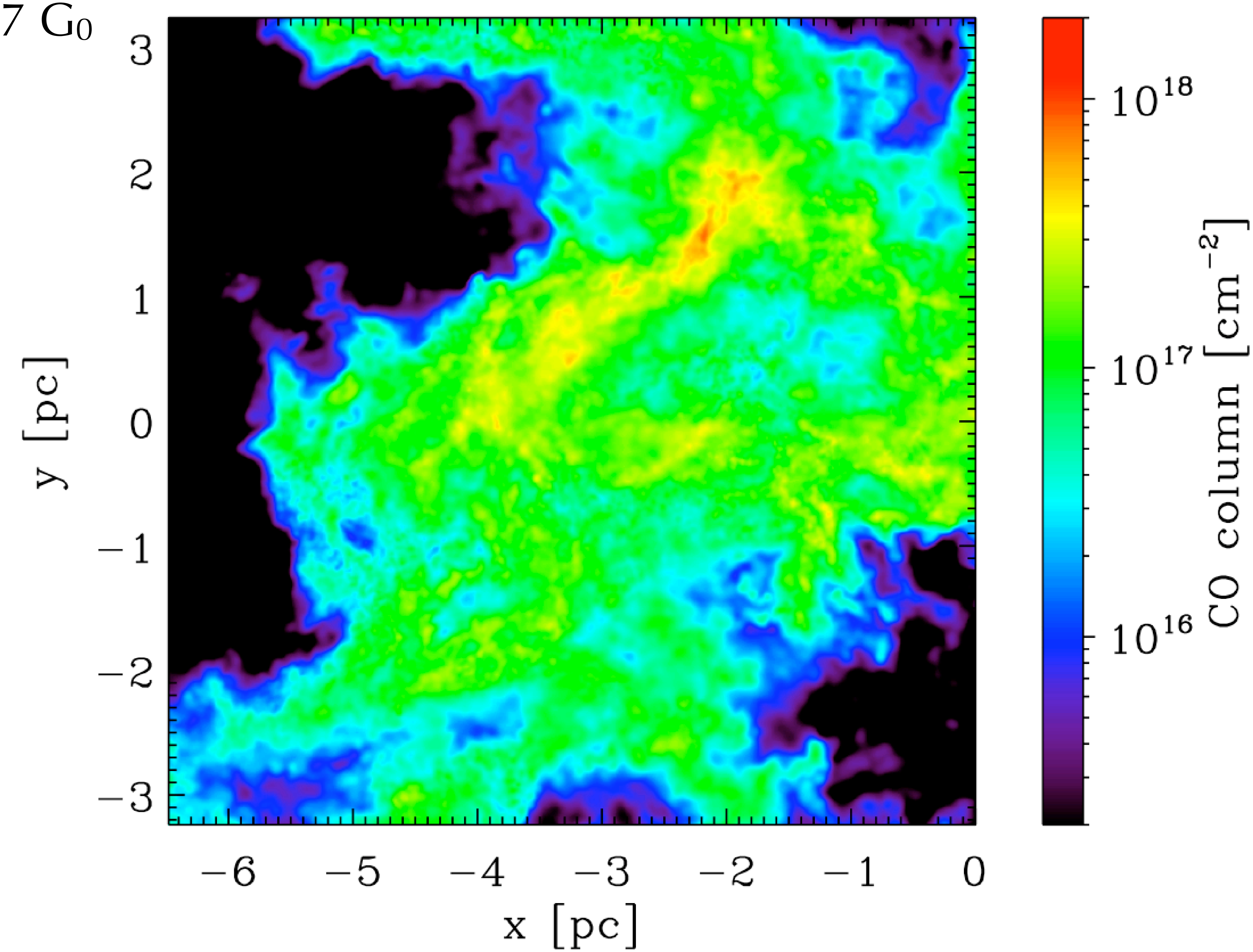
gas column density



Onset of star formation...

UV = 1.7 G_0

CO column density



Summary

- New simulations are able to model the low-density environment in GMCs.
- Catches the line-cooling to dust-cooling transition (1st-order PDR-type code).
- Follows non-equilibrium species such as, C^+, CO, HCO^+, H_2O.
- Can now compare models (via line RT) to the observations (e.g. recent analysis of Kirk, Pineda, André).

- Most of the volume of the GMC sits at higher temperatures than normally assumed
- Temperature in this volume depends strongly on cloud properties and environment)
- Gas isn't isothermal (temperature depends strongly on column)
- Density and temperature are poorly correlated at $n < 10^4$ cm^{-3}
- But well correlated at higher densities
- Clump properties are largely independent of radiative environment
- But do depend on metallicity