The Atomic to Molecular Transition

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Transition from H to H_2

H_2 formation

- H_2 forms on dust grains at a rate:

$$R_{form} = 3 \times 10^{-17} f(T,T_d) (Z/Z_\odot)\, n\, n_H \ \mathrm{cm^{-3}\ s^{-1}}$$

- For typical CNM conditions, $f(T,T_d) \sim 1$

- H_2 formation timescale:

$$t_{form} \sim 10^9\, n^{-1} (Z/Z_\odot)^{-1}\ \mathrm{yr}$$

H_2 photodissociation

- In optically thin gas, H_2 photodissociated by UV photons at a rate:

$$R_{dis} = 3.3 \times 10^{-11} G_0 \ s^{-1}$$

- For standard UV field, this corresponds to a photodissociation timescale:

$$t_{dis} \sim 1000 \ G_0^{-1} \ yr$$

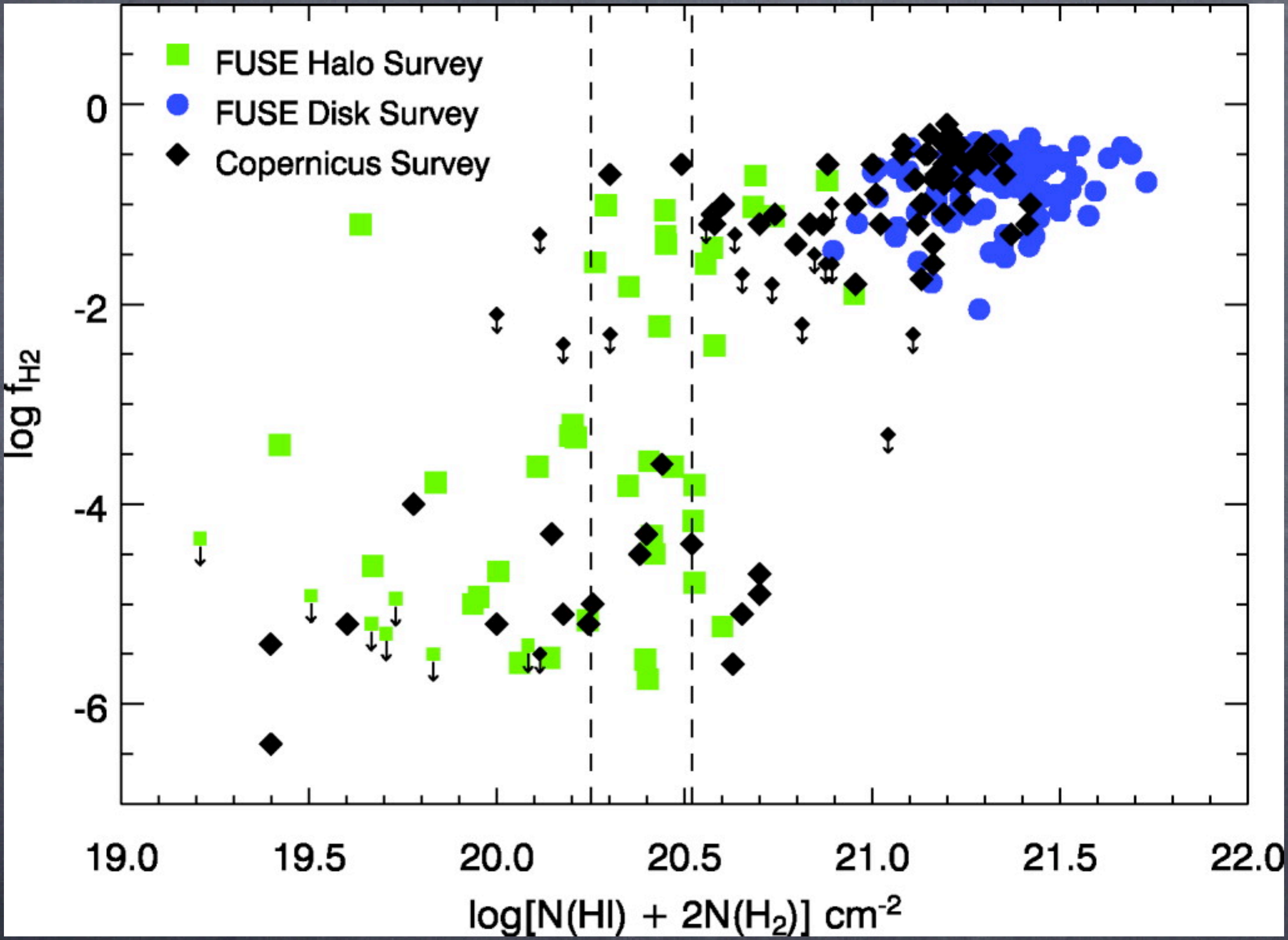
- In optically thin gas, H_2 fraction always small

- Two main effects protect H_2 against photodissociation: self-shielding and dust
- Self-shielding: unimportant for $\log N_{H2} < 14$
For higher column densities, we have:

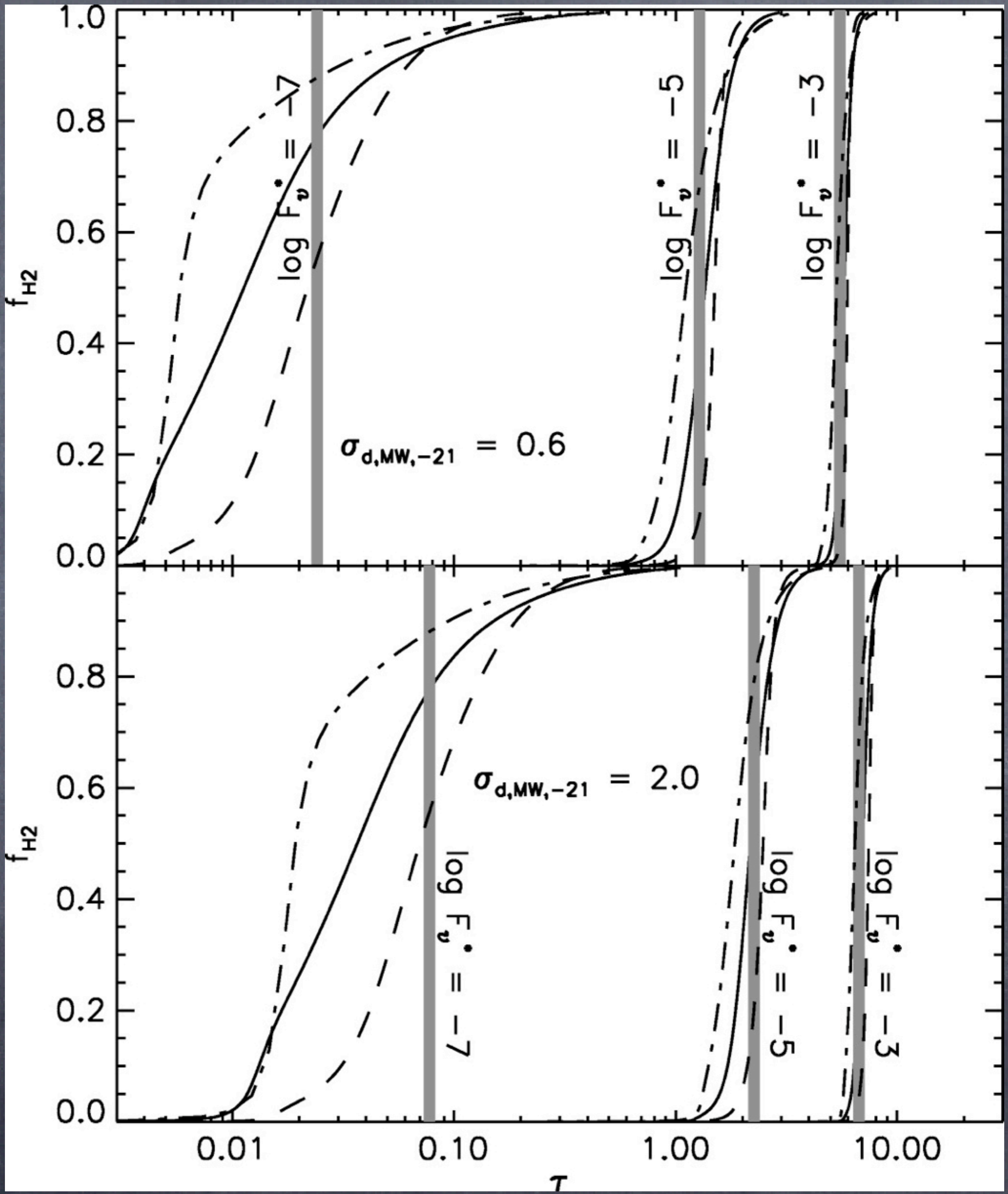
$$R_{dis,\ thick} = R_{dis,\ thin} \times (N_{H2} / 10^{14}\ cm^{-2})^{-0.75}$$

- Dust reduces photodissociation rate by a factor:

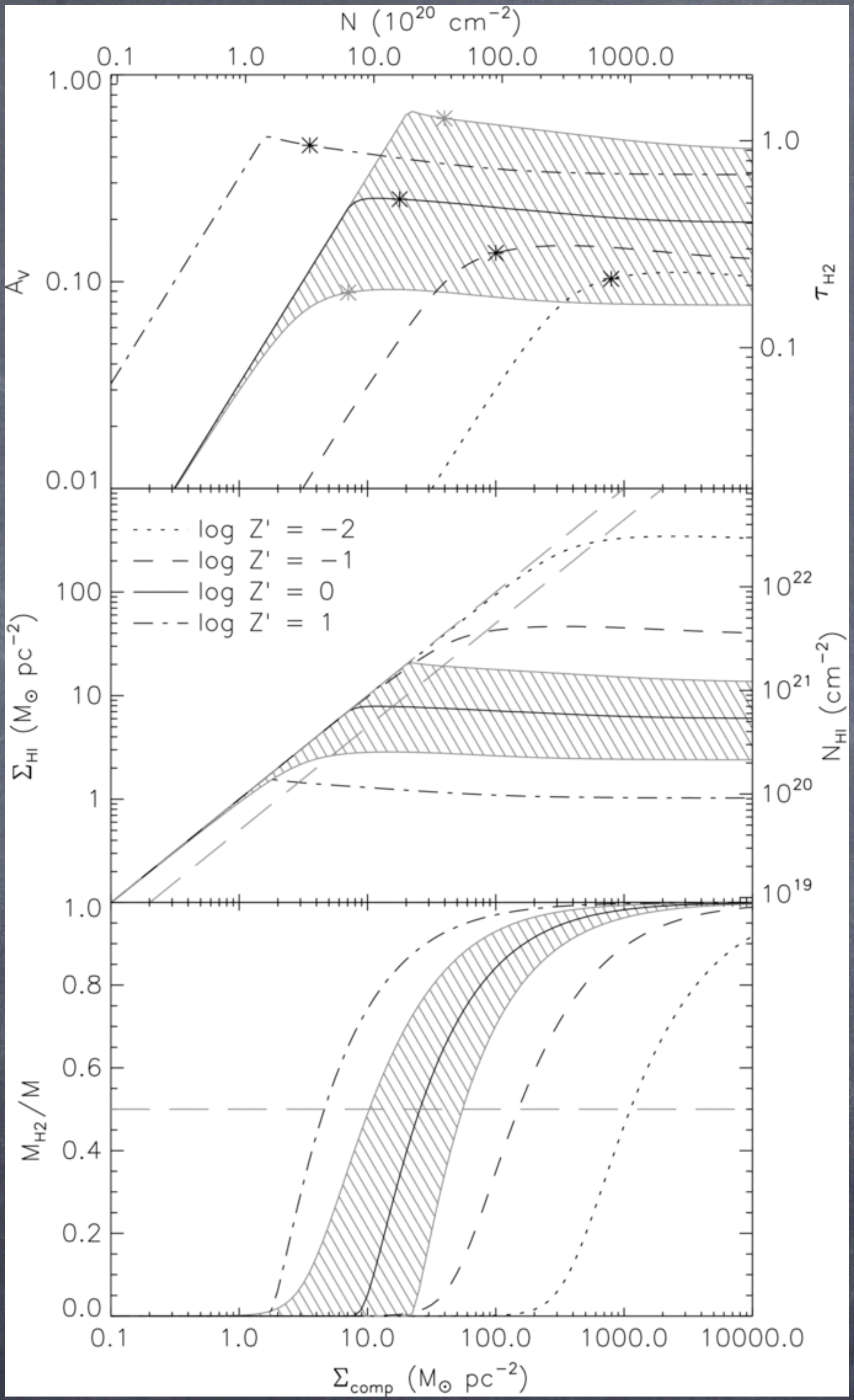
$$R_{dis,\ thick} = R_{dis,\ thin} \times \exp(-3.7\ A_V)$$



Gillmon et al. (2006)

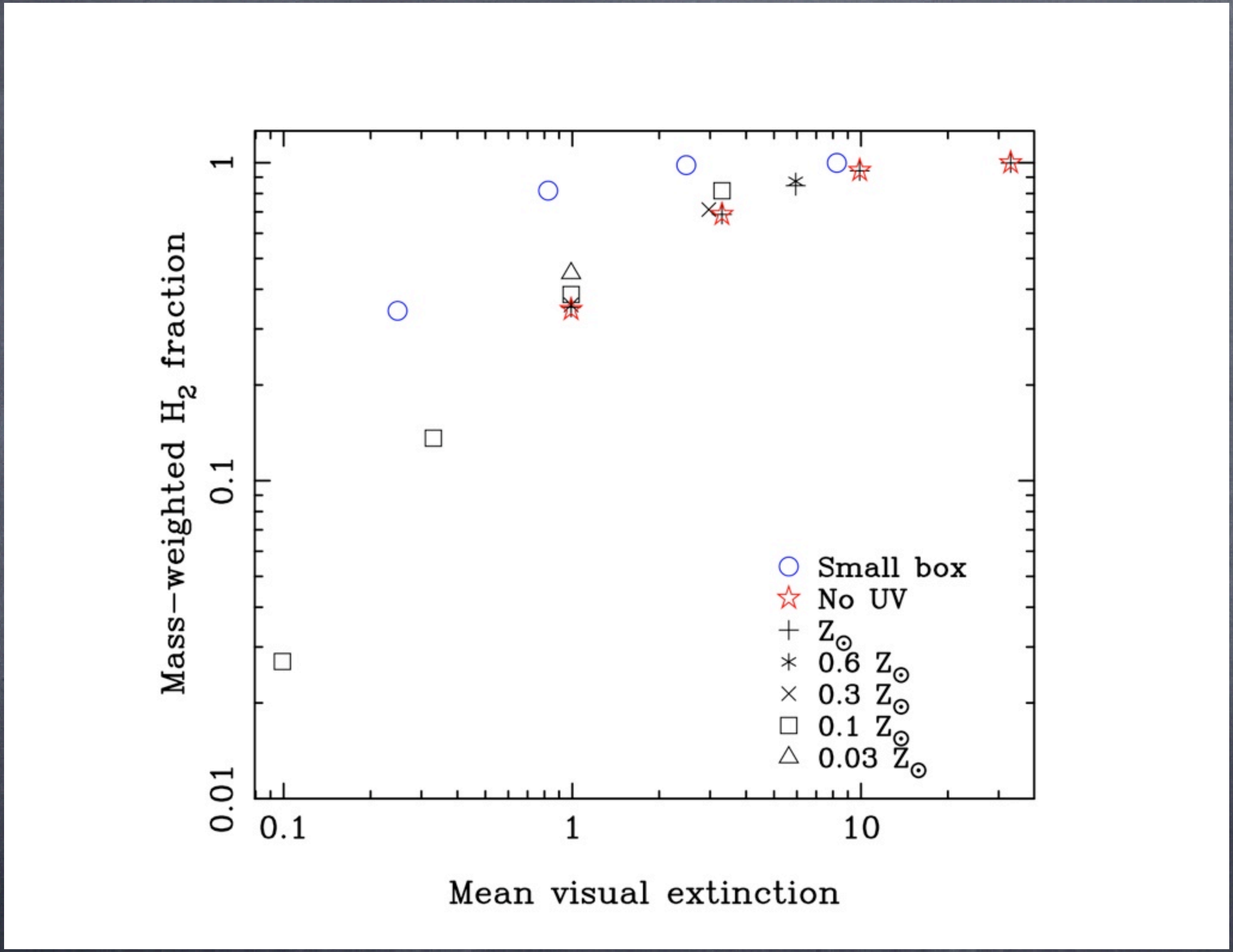


Krumholz et al (2008)



Krumholz et al (2009)

- Krumholz et al. model assumes chemical equilibrium
- Probably valid in a global sense, but may not hold so well on scale of individual clouds



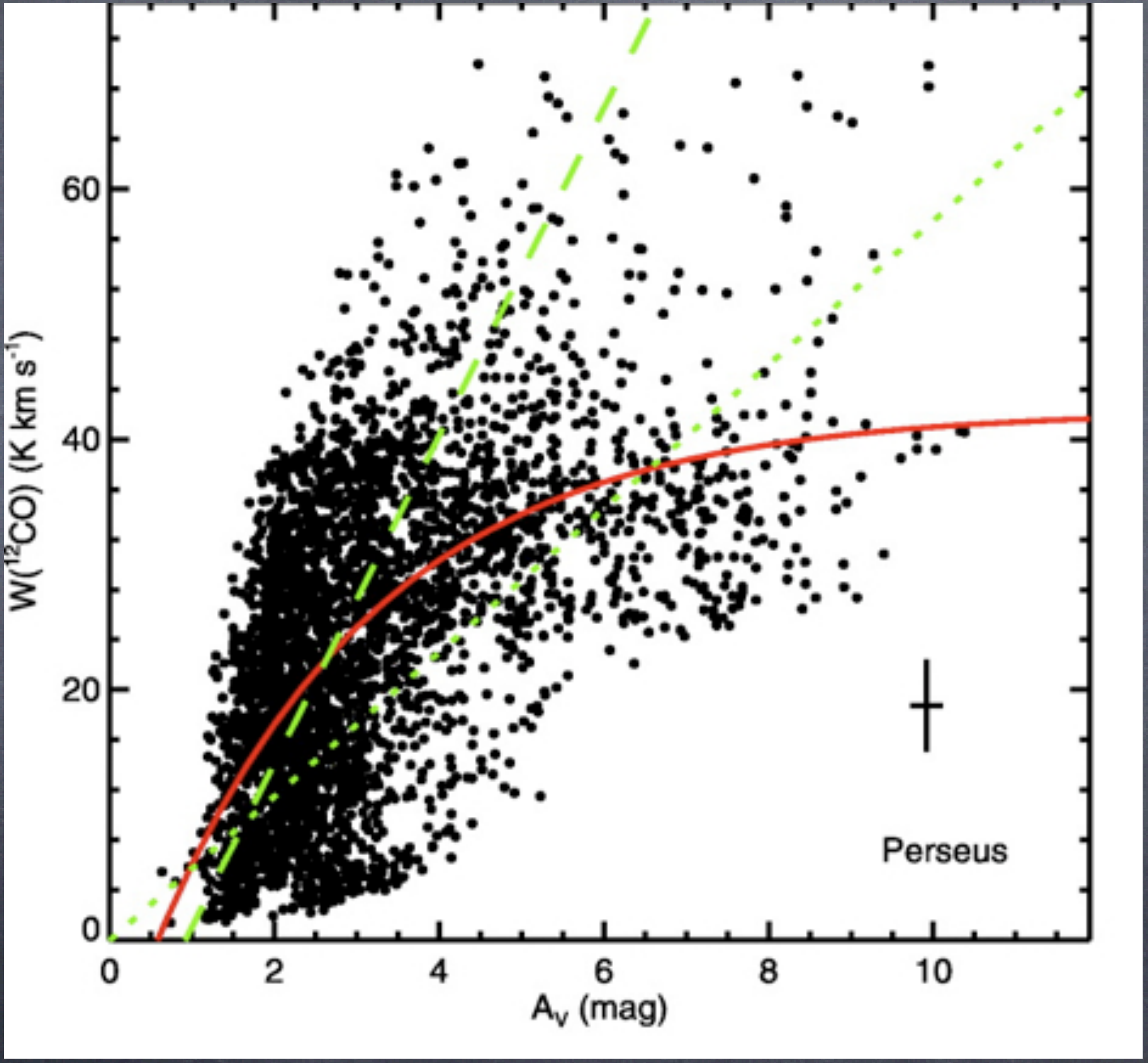
Glover & Mac Low 2011

Transition from C^+ to CO

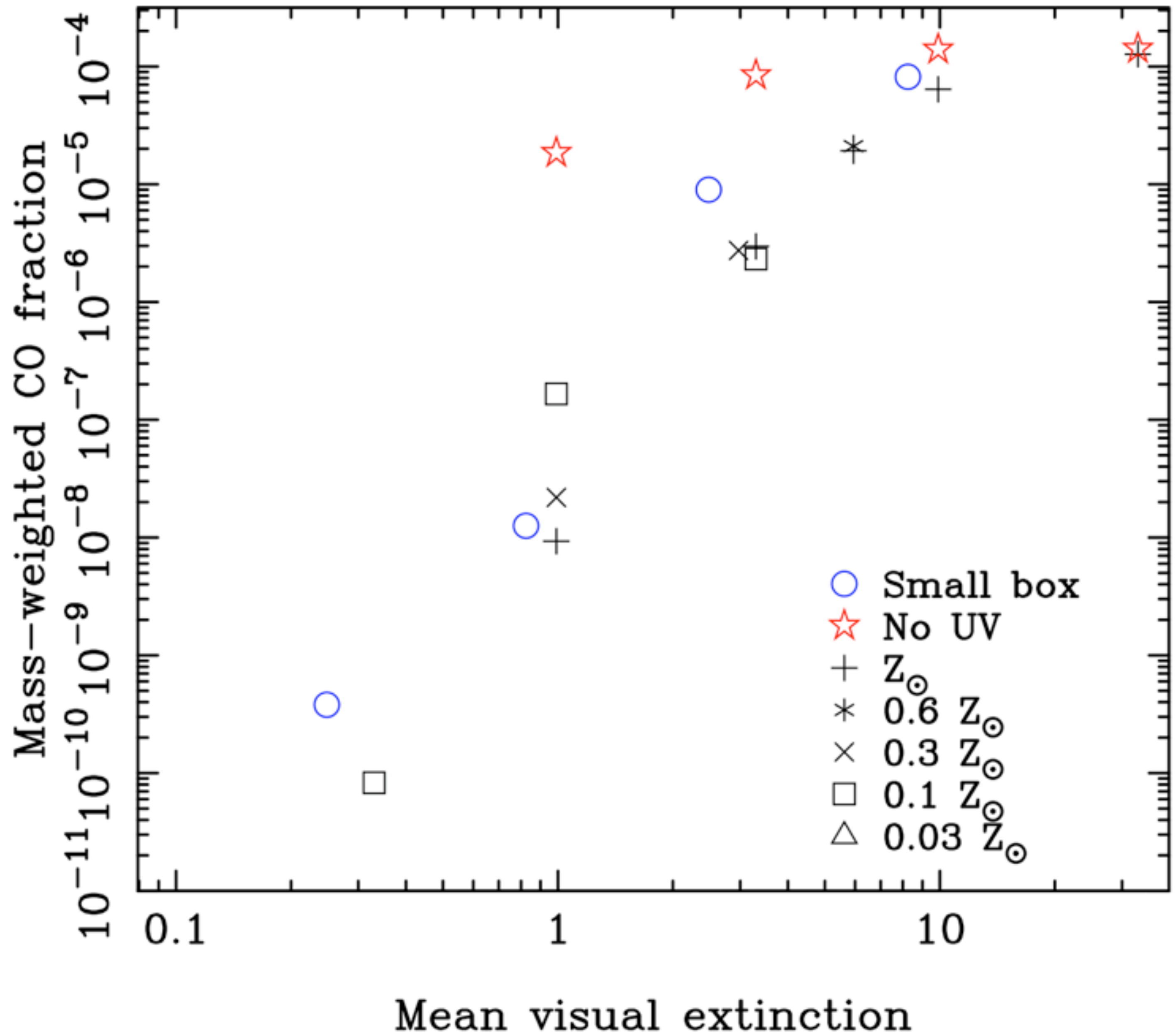
Carbon chemistry

- Far more complex than hydrogen chemistry; multiple routes to form CO
- Most routes to CO require H_2
- CO destroyed primarily by photodissociation
- CO self-shielding not very effective, dust shielding generally dominates

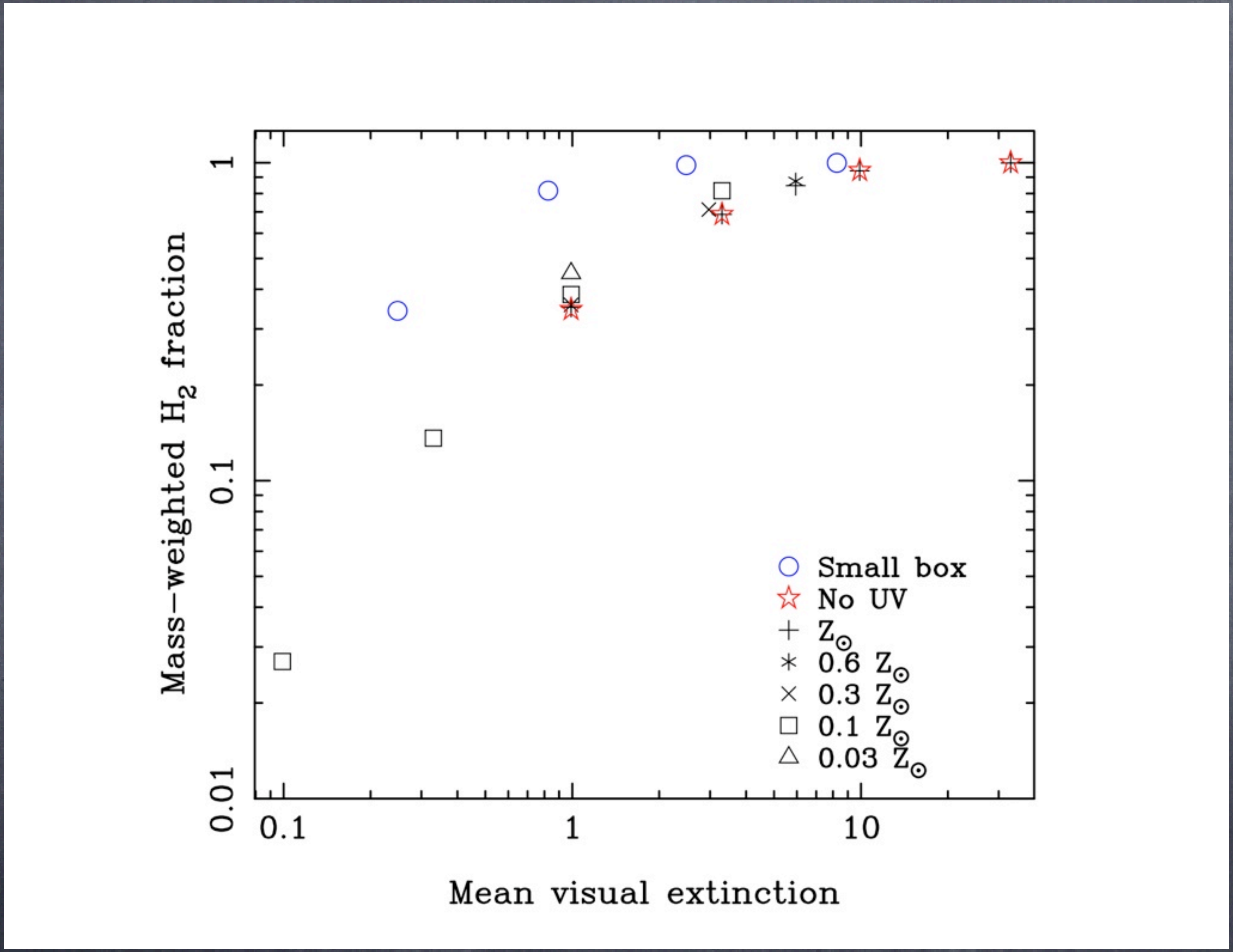
- Numerical modelling helps us deal with complexity
- Now possible in realistic 3D models (see e.g. Glover et al, 2010)
- Main findings: CO needs $A_V > 1$, but forms rapidly when we have H_2



Pineda et al. (2008)

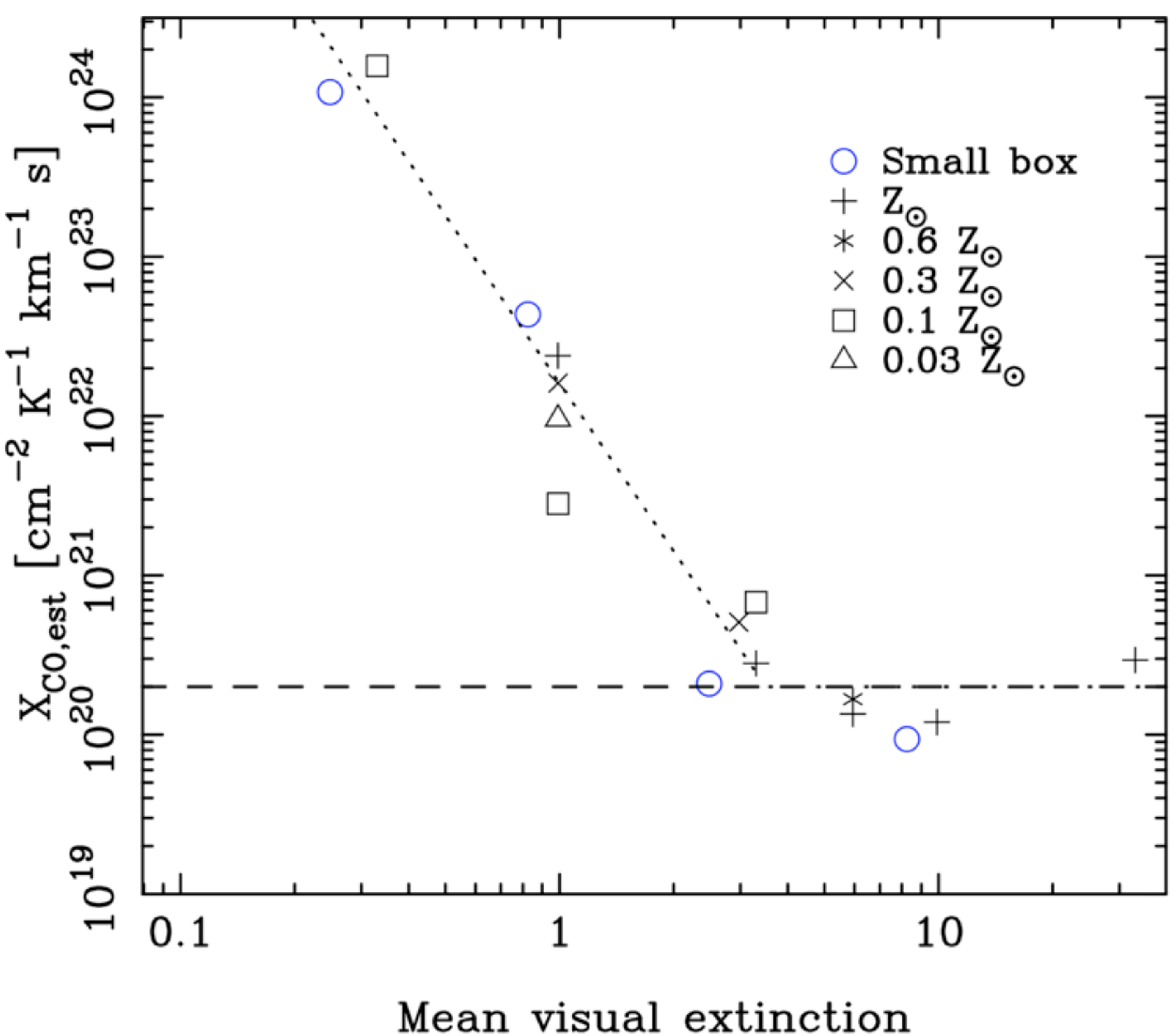


Glover & Mac Low 2011

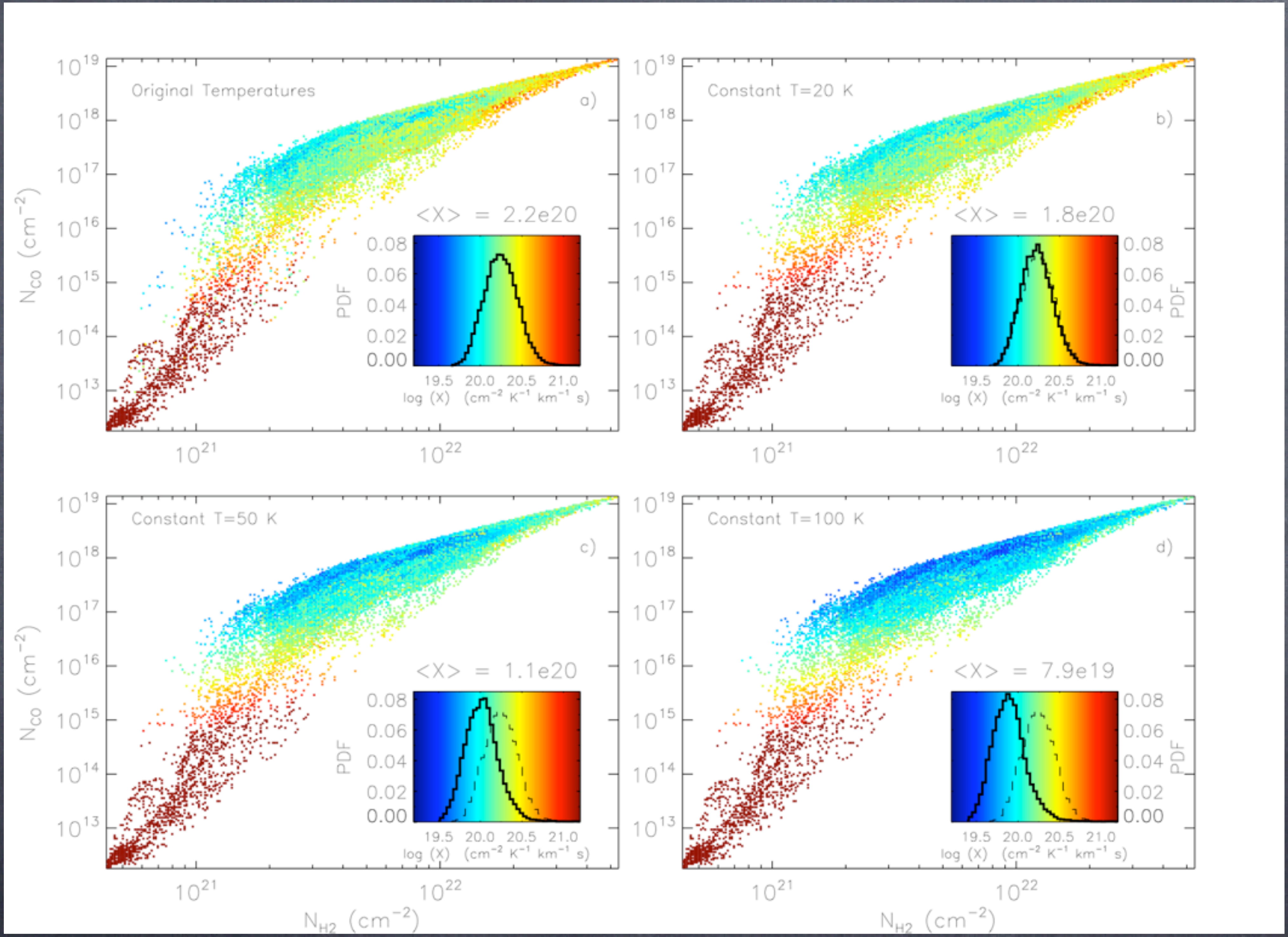


Glover & Mac Low 2011

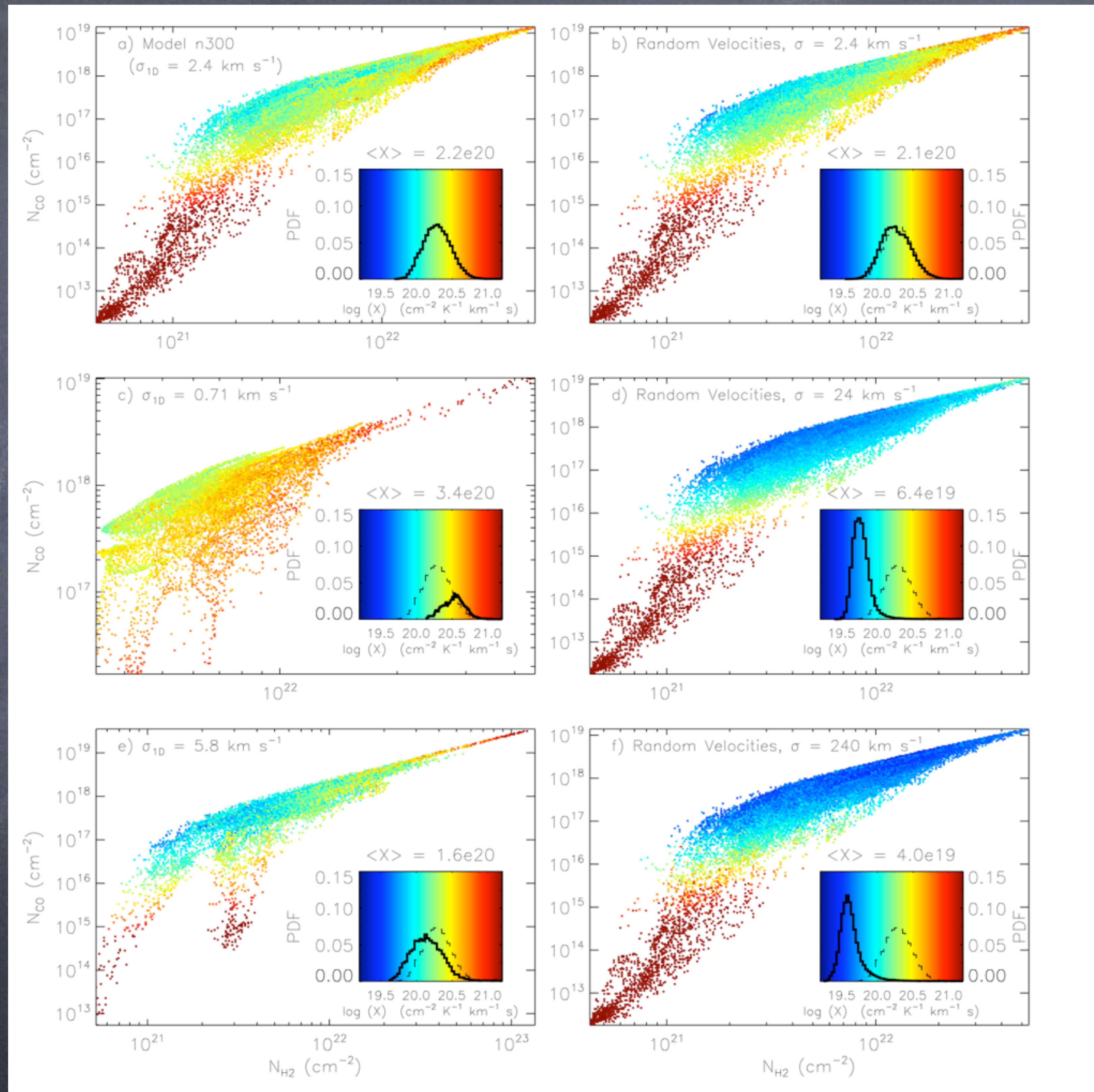
- Need less dust to get high H_2 fractions than to get high CO fractions
- Molecular clouds permeated by gas that is H_2-rich but CO-poor
- Small molecular clouds may be completely invisible in CO
- Implication: X factor very sensitive to mean dust extinction



Glover & Mac Low (2011)



Shetty et al. (2011); arXiv:1104.3695



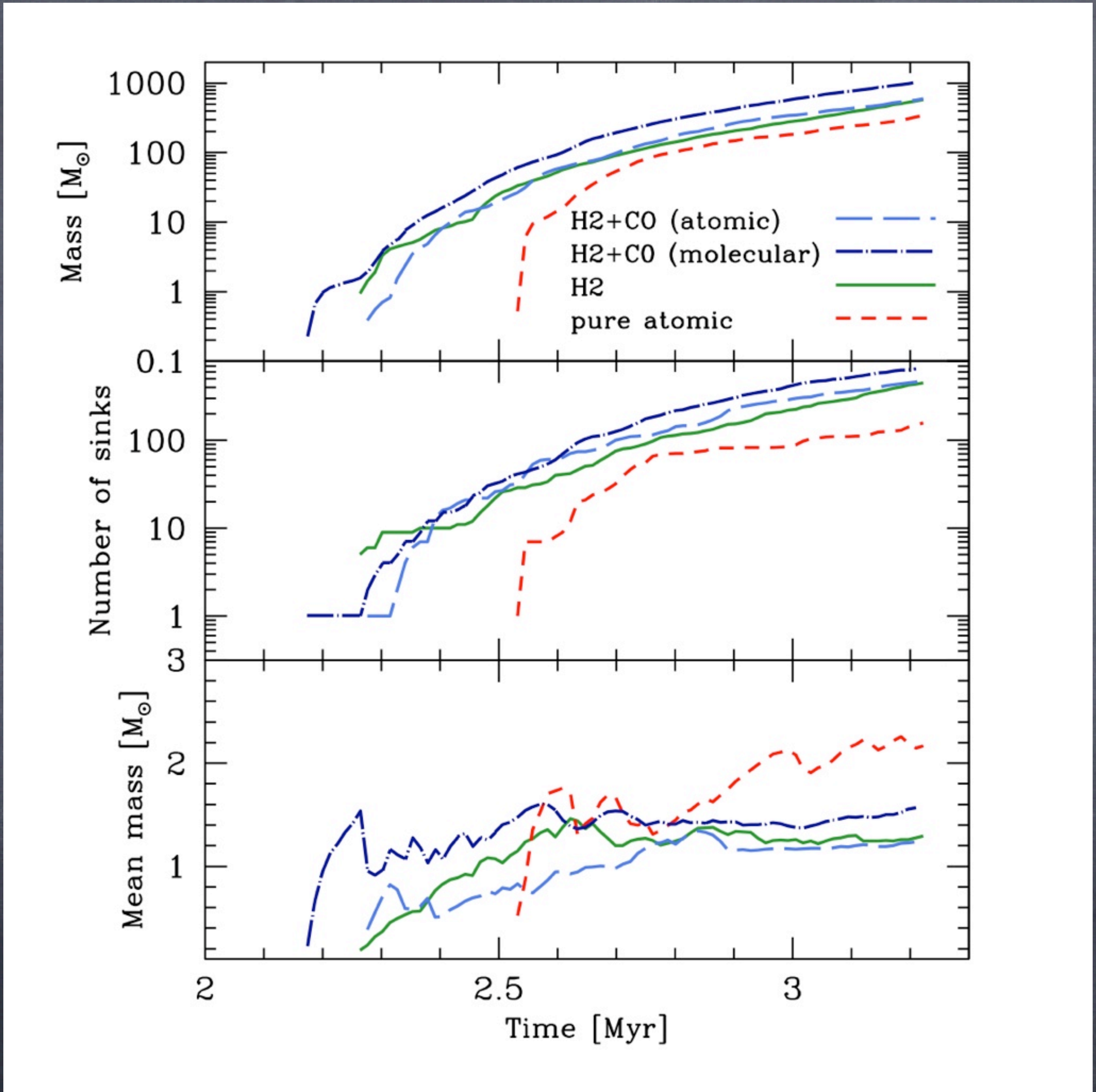
Shetty et al. (2011); arXiv:1104.3695

- Increased velocity dispersion and/or mean temperature at fixed N_{H2} ⇒ smaller X_{CO}
- Higher temperatures at fixed column are a natural consequence of a higher ISRF
- Expect increased velocity dispersion in regions with higher stellar feedback. If clouds aren't virialized, then N_{H2} need not be larger
- See also Narayanan et al. (arXiv: 1104.4118), who come to similar conclusions

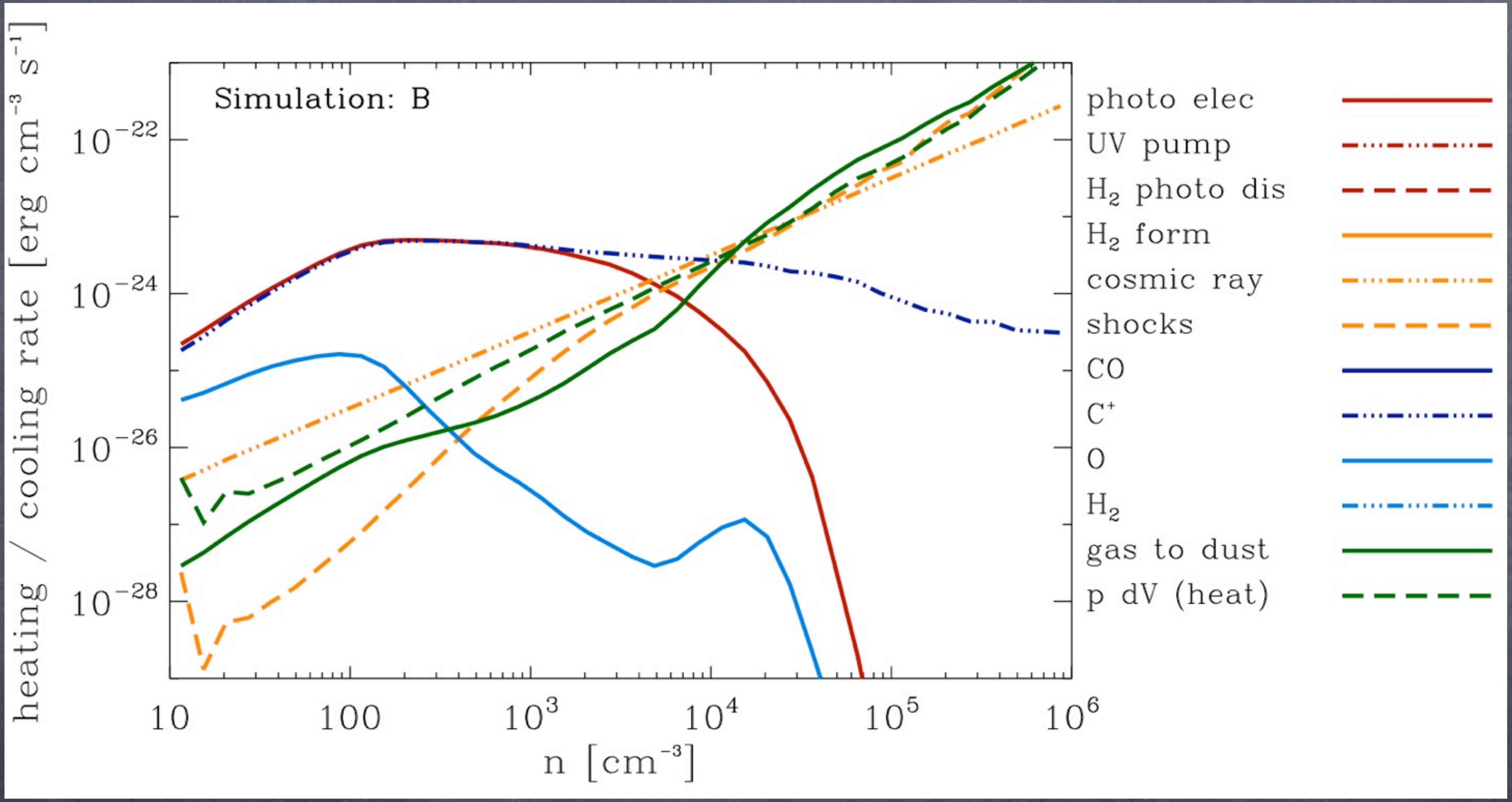
Do we actually need th molecules?

- SPH simulations of isolated, gravitationally bound molecular clouds
- Cloud mass = 10000 solar masses
- Mean density = 300 cm^{-3}
- Use 2 million SPH particles, for a mass resolution of 0.5 solar masses

- 5 different simulations:
  - no shielding
  - no chemistry, gas remains atomic
  - H_2 chemistry, but no CO
  - H_2 and CO chemistry, hydrogen initially atomic



Glover & Clark (2011)



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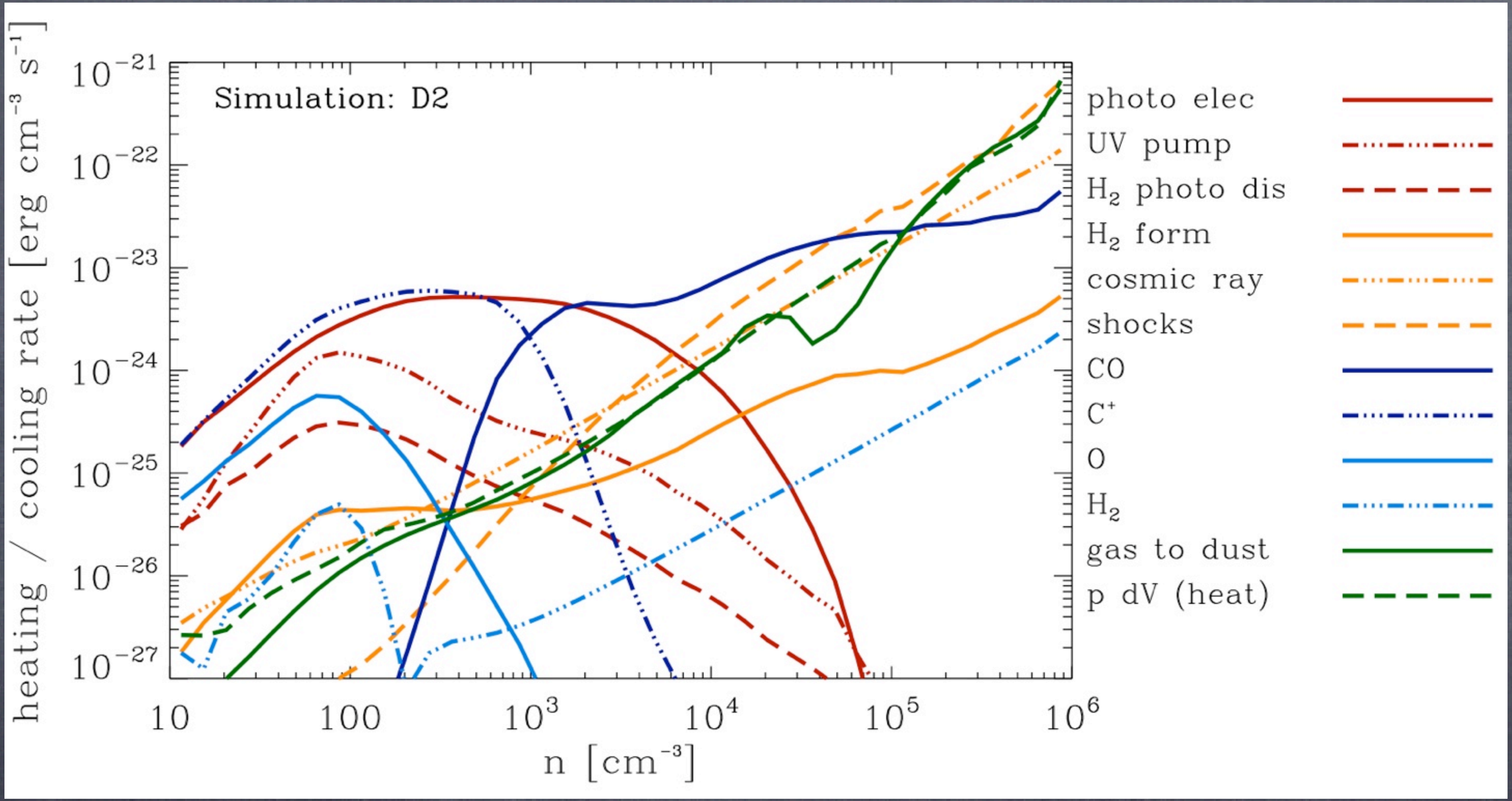

Glover & Clark (2011)

Summary

- In equilibrium, sharp transition from HI-dominated regime to H_2-dominated regime; explains upper limit on typical HI column densities (see also Schaye 2001)
- May take a long time to reach equilibrium, particularly at low n and/or low Z
- Abundant CO requires higher A_V than abundant H_2 $\Rightarrow$ expect "dark" molecular gas

Summary (II)

- X factor for a given cloud depends on mean extinction, velocity dispersion, temperature
- To understand X factor on larger scales, need to average over appropriate cloud distribution
- Molecular gas not necessary for star formation; simply traces regions where gas is cold