# The HI-H2 boundary: Importance of neutral hydrogen for molecule (and star) formation


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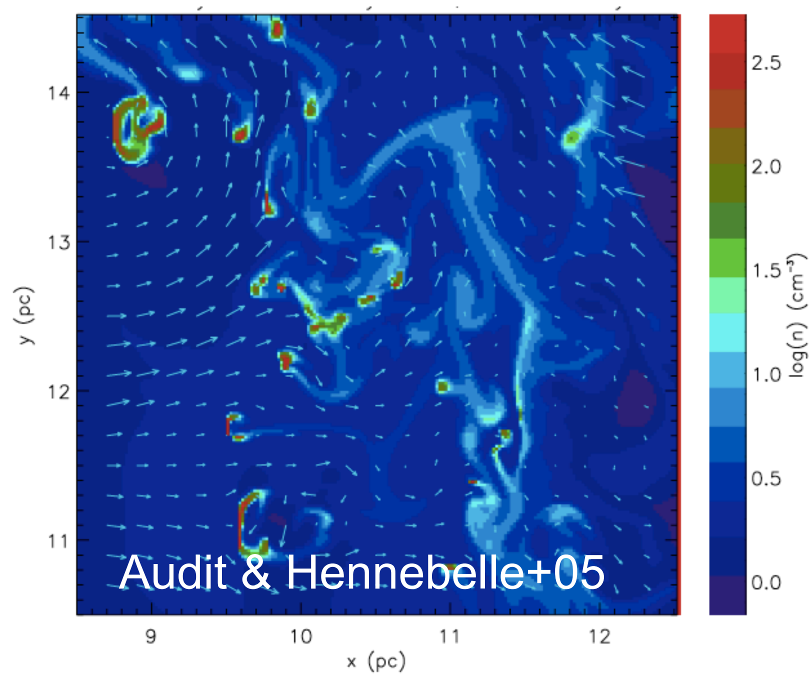
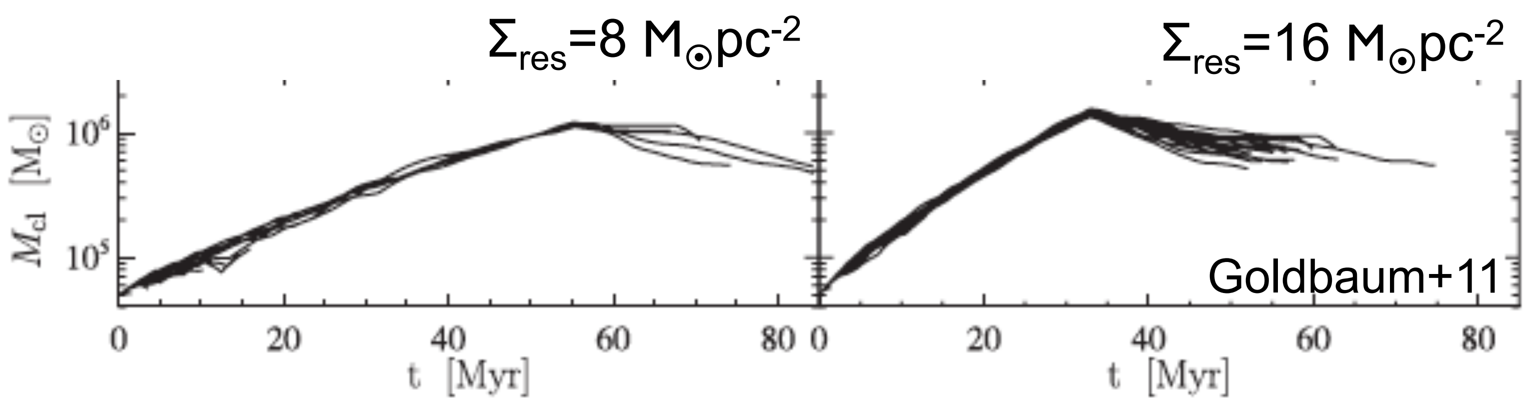
# What does HI do for molecular clouds?

- **Formation reservoir** (Shu73, Blitz07; Kim & Ostriker 06; Audit & Hennebelle05, Heitsch+05; Clark+12)
- **Source of turbulent energy via long-term accretion,** (Chieze & Pineau des Forest 89, Goldbaum+11)

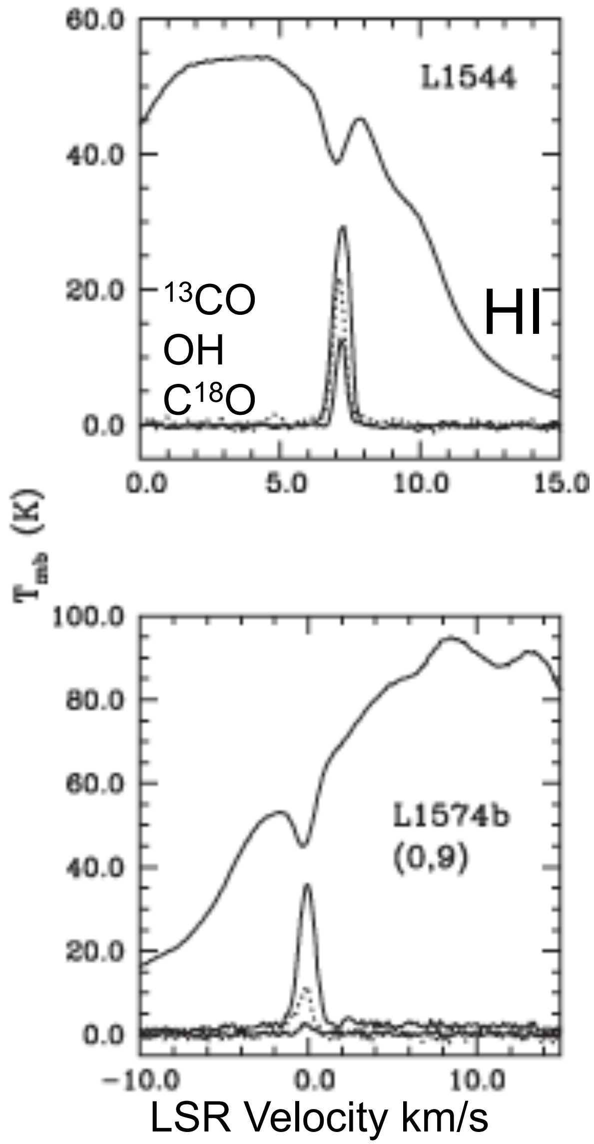
  → GMC mass and lifetime different wrt $\Sigma_{res}$: 8 vs 16 $M_\odot pc^{-2}$

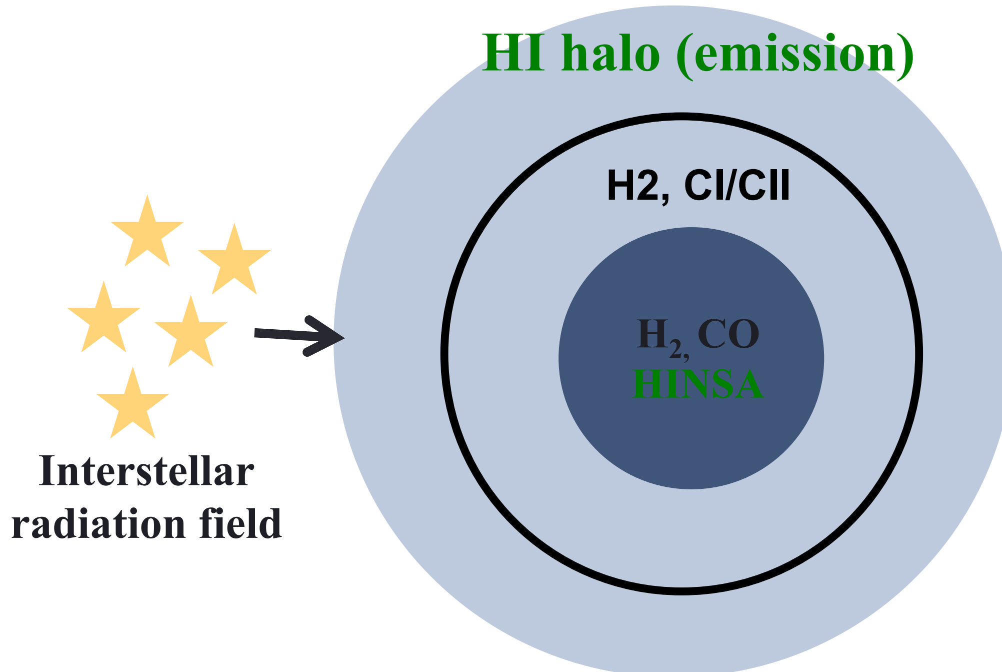



- **Helps chemistry via dust shielding and/or pressure support** (Spitzer78; Bensch06)



# HI inside vs outside molecular clouds



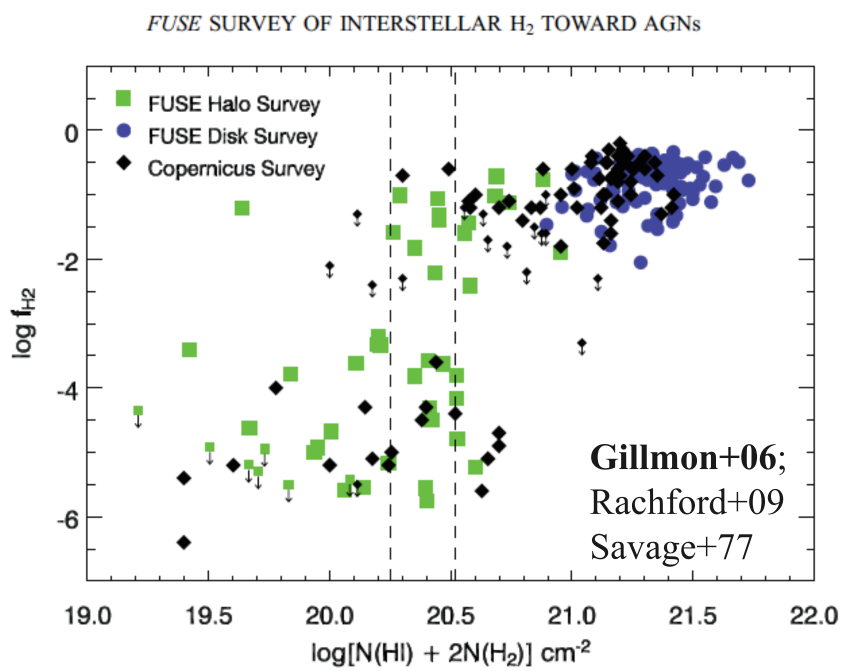

- HINSA = HI narrow self-absorption
- FWHM(HI)<FWHM(CO)
- good correlation with OH/CO
- detection rate ~80%
- T<40K, n(HI)~a few $cm^{-3}$
- N(cold HI)/N($H_2$) = 0.0016

→ Cloud age ~3-30 Myrs

Knapp74; Goodman & Heiles94; Li & Goldsmith 03; Wannier+83,91, Fukui+09

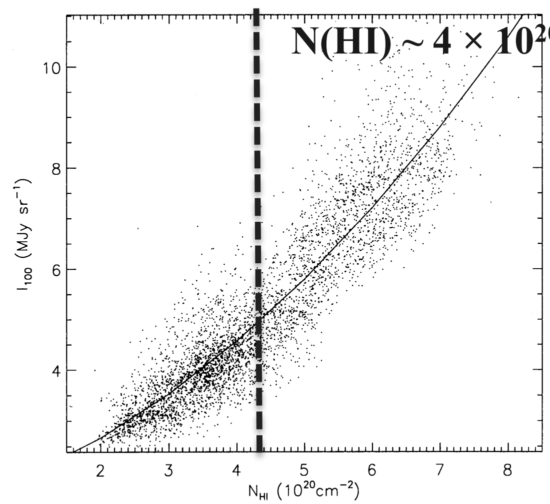
# HI-to-$H_2$ Transition: Observations

## (1) Direct: UV absorption lines




**N(HI) ~ 5 × $10^{20}$ $cm^{-2}$** ~5 $M_\odot pc^{-2}$

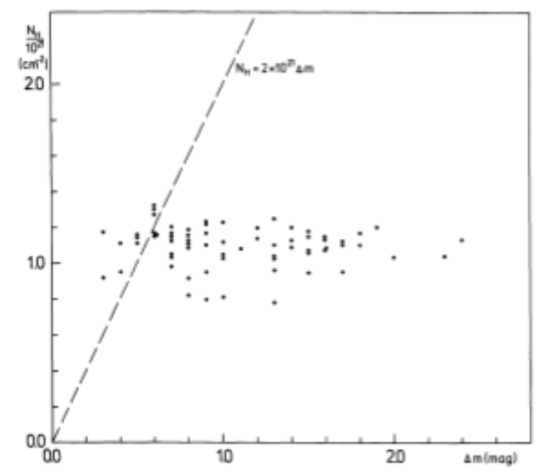
## (2) Indirect: other gas tracers




**"IR excess"**

e.g. Reach+94

**"HI saturation"**




Sancisi+74; Wong & Blitz02; Blitz & Rosolowsky04; Schruba+11; Bigiel+08

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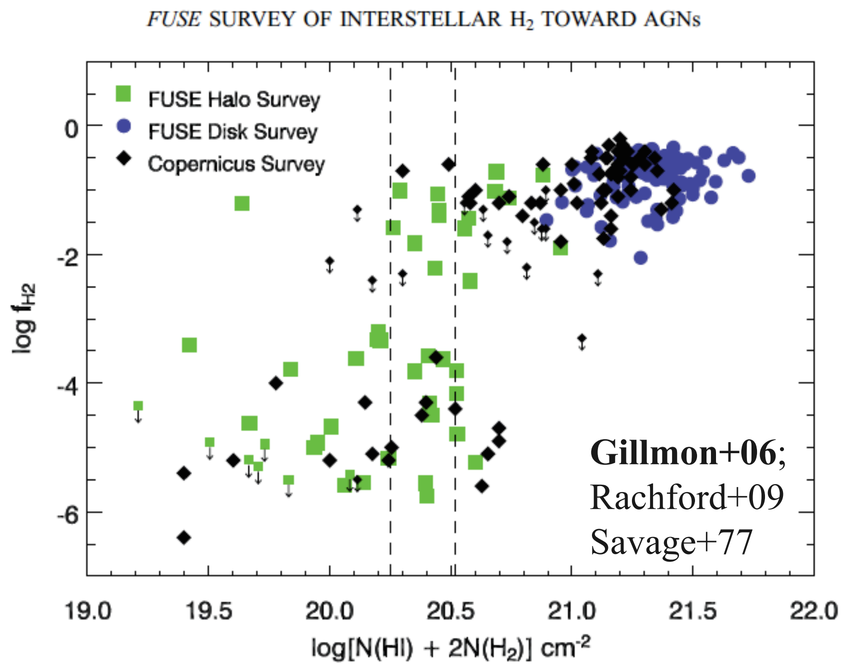


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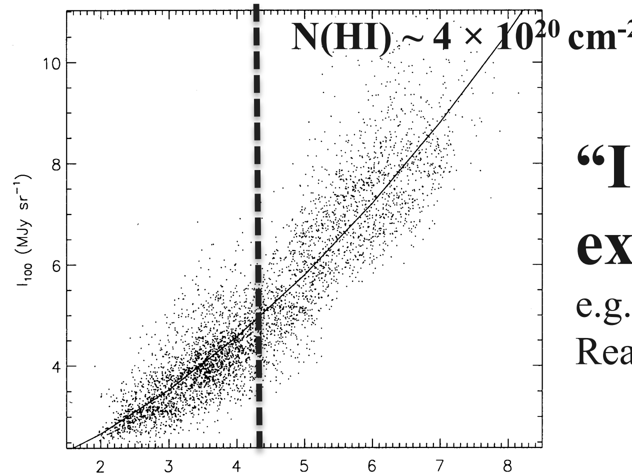


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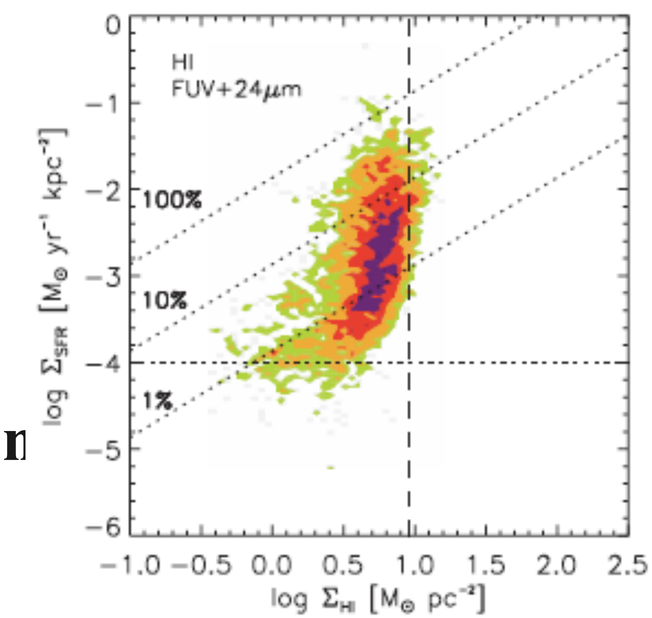


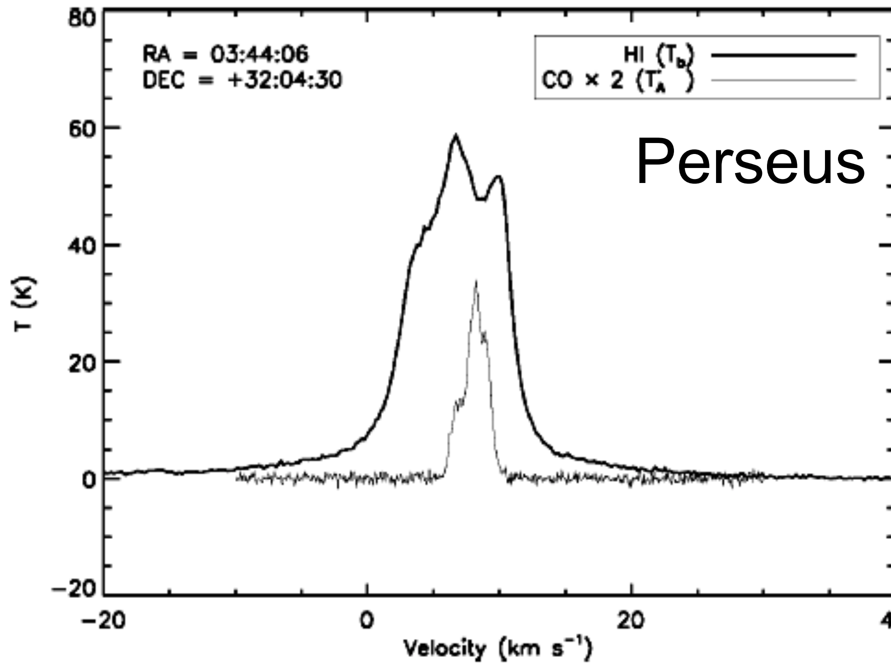

Sancisi+74; Wong & Blitz02; Blitz & Rosolowsky04; Schruba+11; Bigiel+08

# HI halos: Observational difficulties

- **Self-absorption**: temperature fluctuations vs self-absorption?

- **HI emission**: Velocity crowding and blending of components, broad line width
- Ubiquity of HI, variations of HI intensity over a range of scales

- No systematic study in the MW.
- New: high-resolution wide area HI observations comparable to IR data (IRAS, Spitzer, Herschel) → explore spatial correlations + undertake detailed comparisons with models




GALFA HI

Peek+11

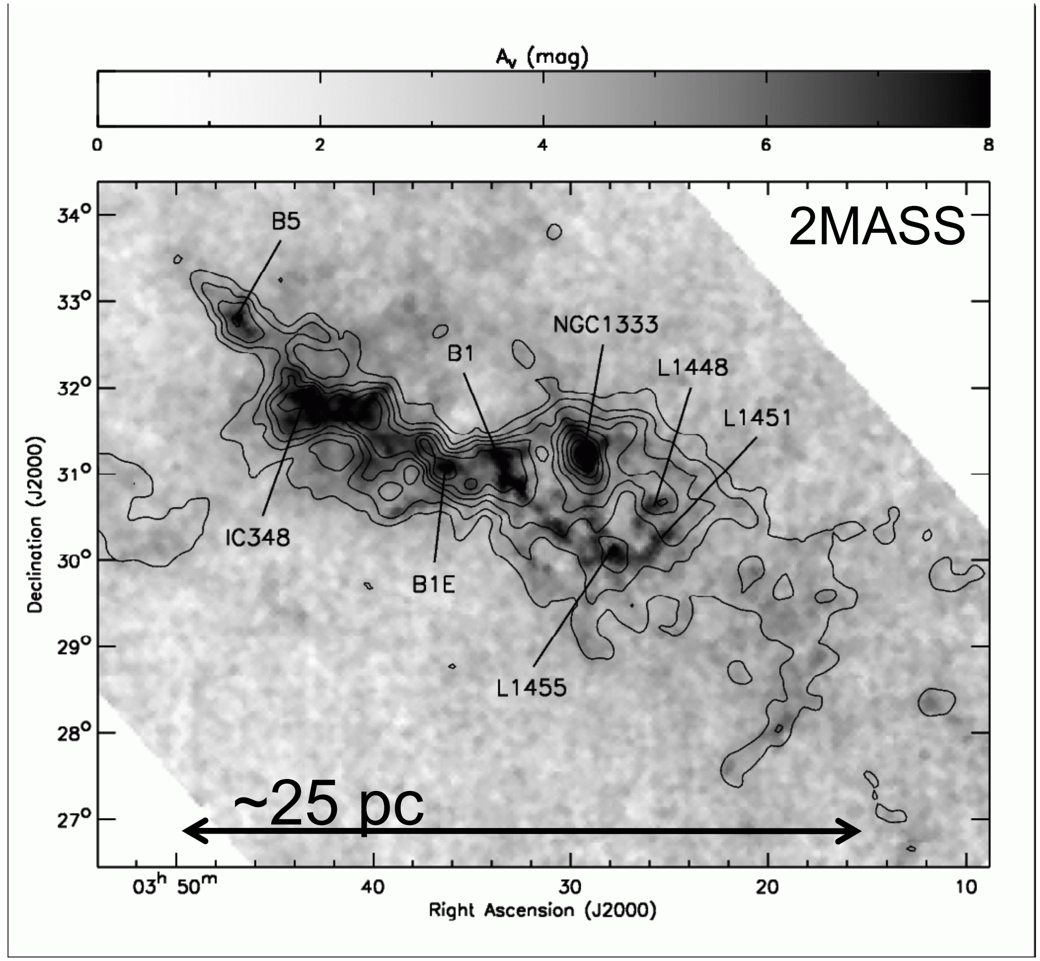
# Zoom-in on the HI halo in Perseus

1. Does HI saturation persist on sub-pc scales?

2. Properties of the HI/$H_2$ transition?

3. Alternative: High optical depth HI?

4. Is HI important for $H_2$ and CO formation?




D = 200 – 350 pc

M ~$10^4$ $M_\odot$;

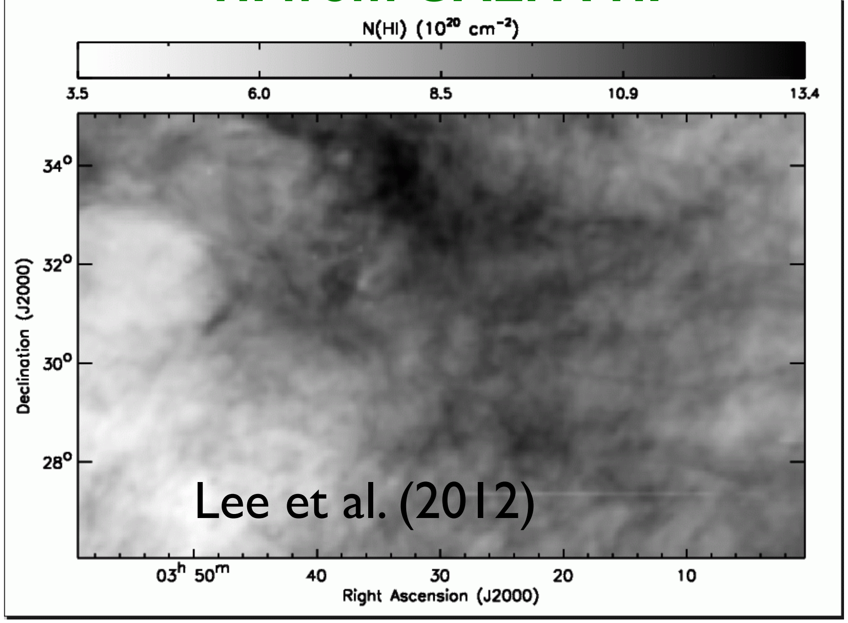
Intermediate SFR

Age~10 Myrs → evolved

# Perseus molecular cloud: deriving $H_2$

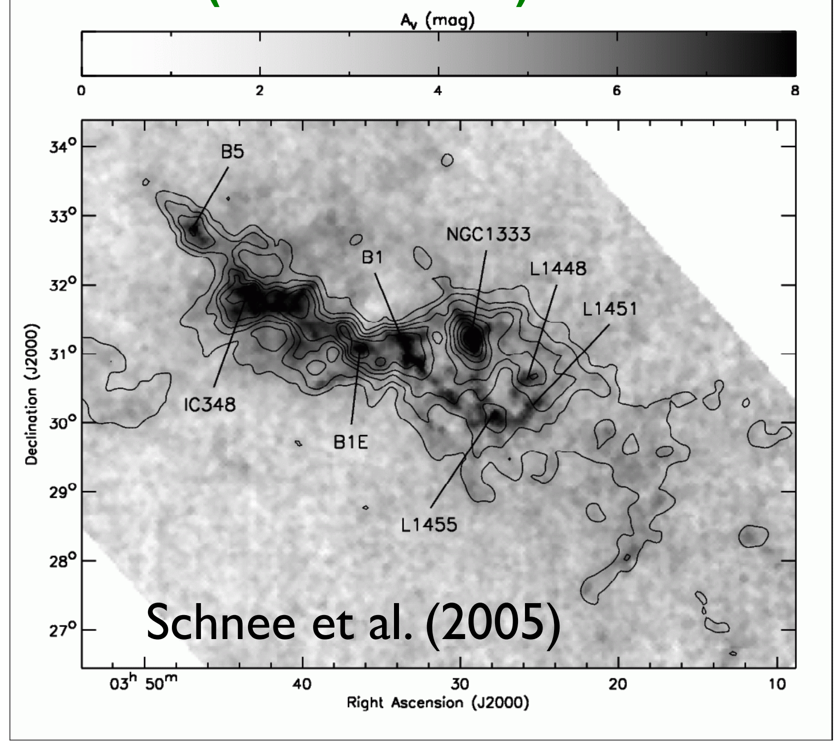
(D = 200 – 350 pc → $\Delta x$ = 0.4 pc)

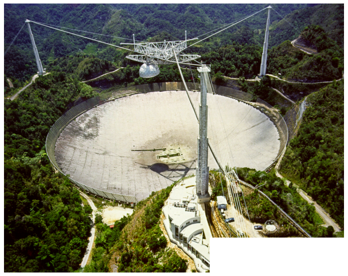
## HI from GALFA-HI




[agrees with Sancisi+74; Imara & Blitz11]

## $H_2$: IR (IRAS) T-corrected+ Av (COMPLETE)





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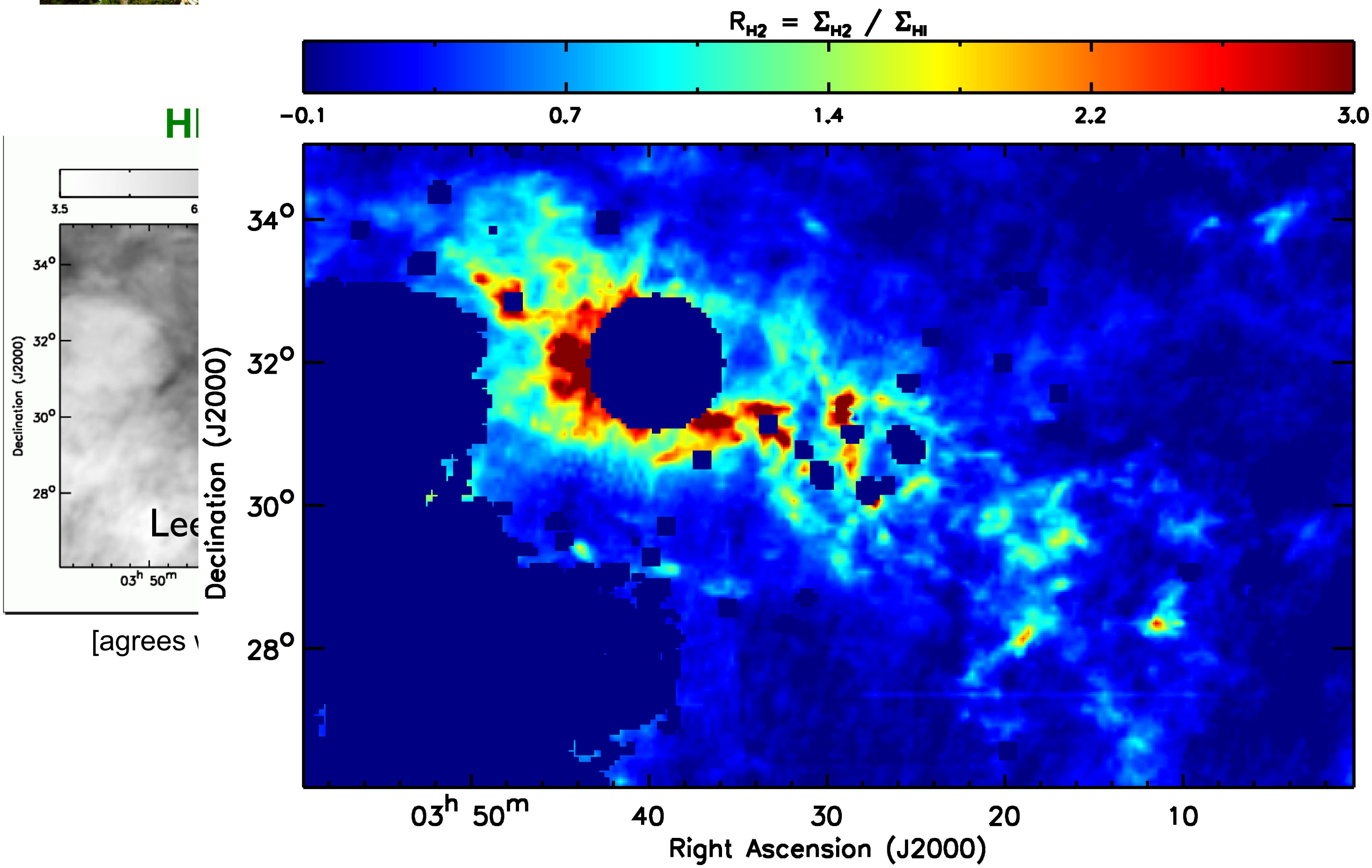
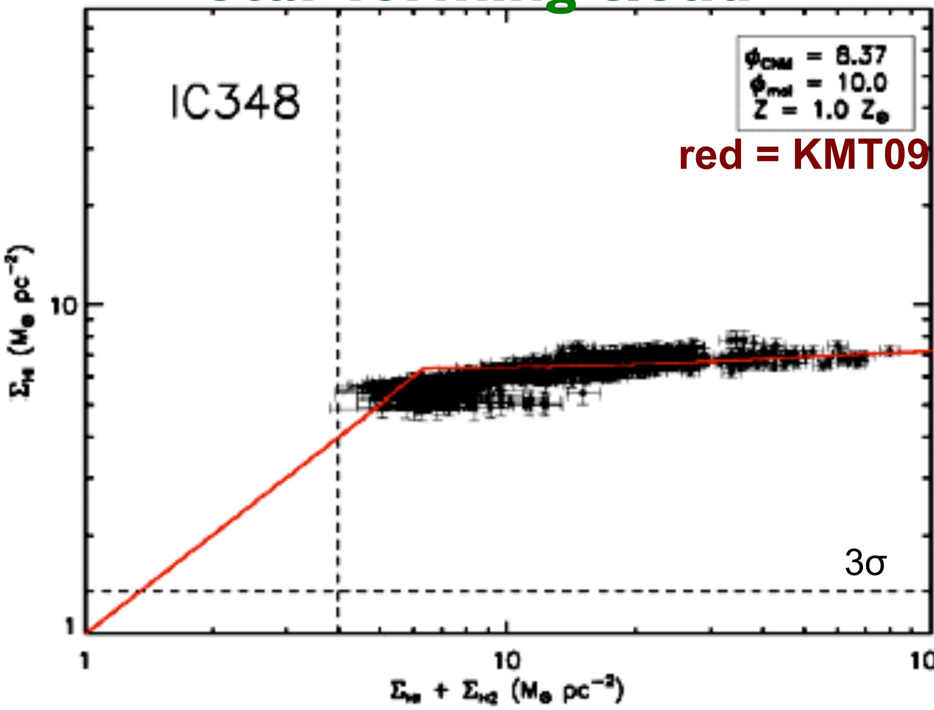


Star forming cloud

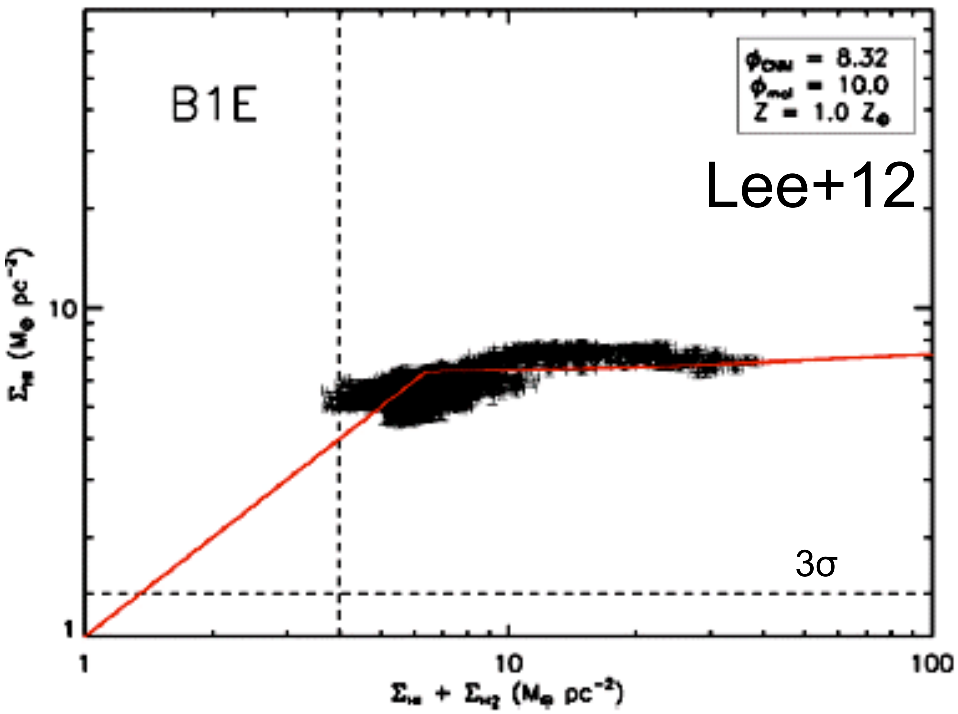



# 1. $\Sigma_{HI}$ vs. $\Sigma_{HI + H2}$

HI saturates at 6-8 $M_{\odot}pc^{-2}$ @0.4pc for both star-forming and dark clouds.

ISRF of IC348 = ~2 ISRF of B1E
($ISRF \sim T_{dust}^{6}$)

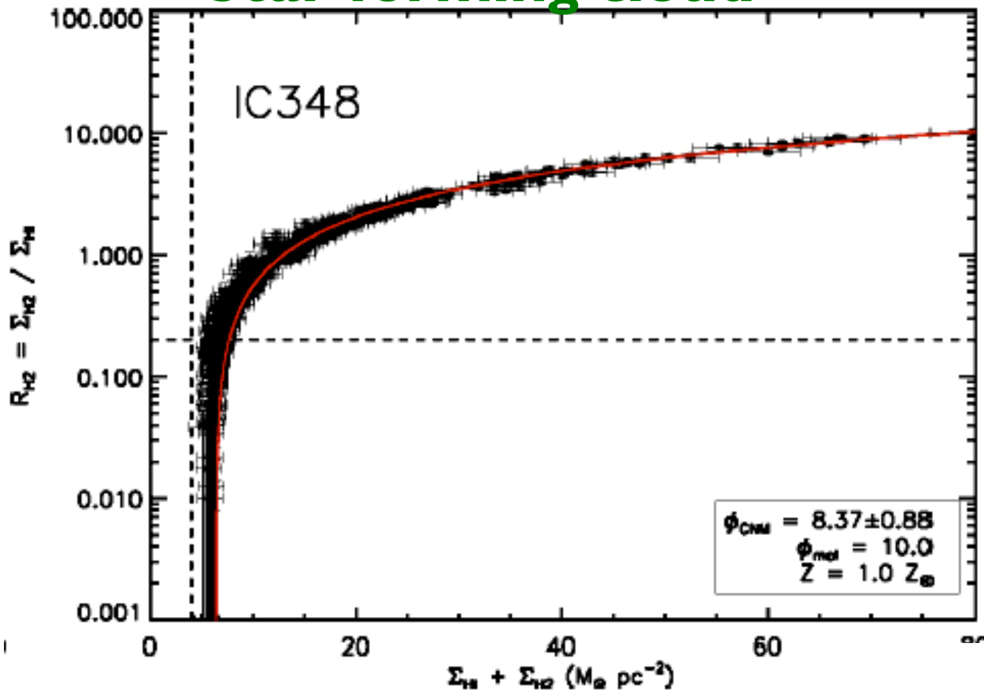
Dark cloud




$\Sigma_{HI}$ has very narrow distribution with only small region-to-region variations.

*HI saturation persists at sub-pc resolution.*

**Star forming cloud**



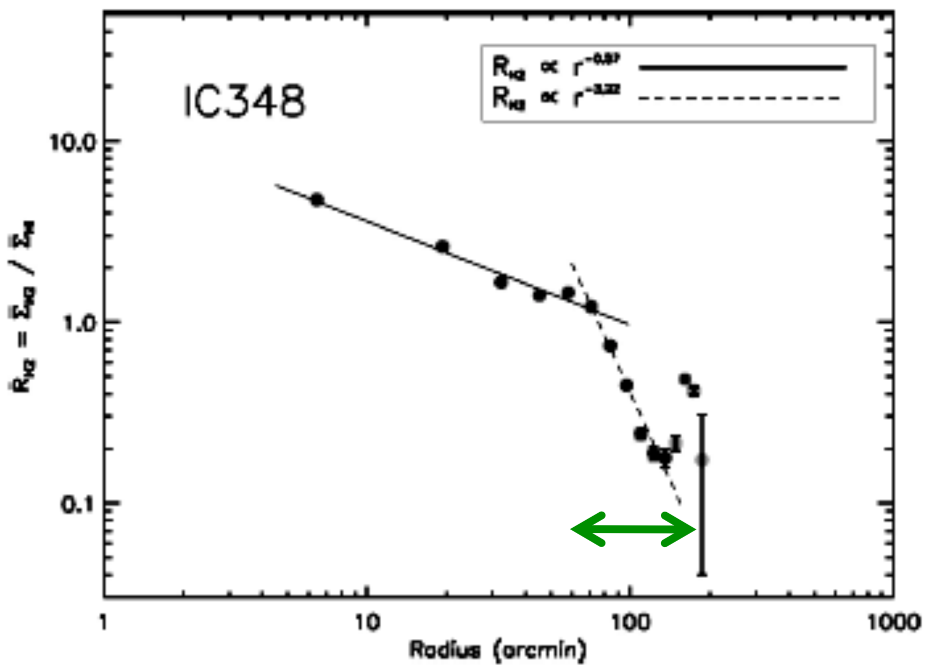

# 2. $\Sigma_{H2}/\Sigma_{HI}$ vs. $\Sigma_{HI + H2}$

Assumed: Z = 1.0 $Z_\odot$
Fitted: $\phi_{CNM}$ = 7.0 ~ 8.0 or $T_{CNM}$ = 60-75K

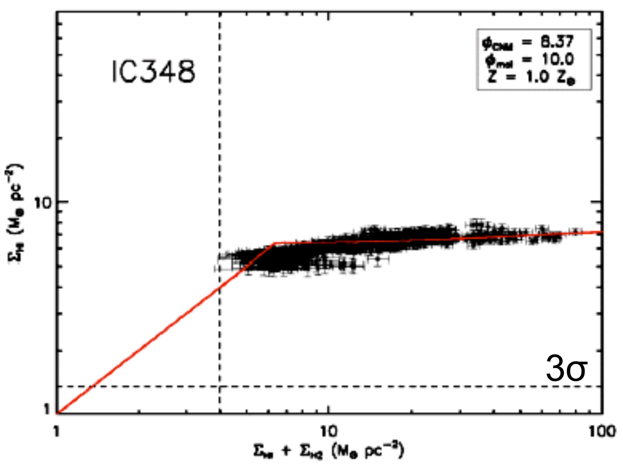
- Once shielding achieved, $H_2$ abundance sharply increases

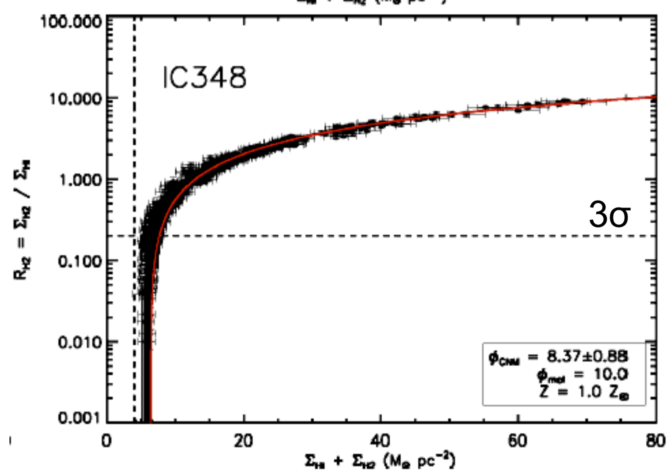
- $H_2$ extends up to 20 pc from the CO peaks. → Pure HI to >20pc.

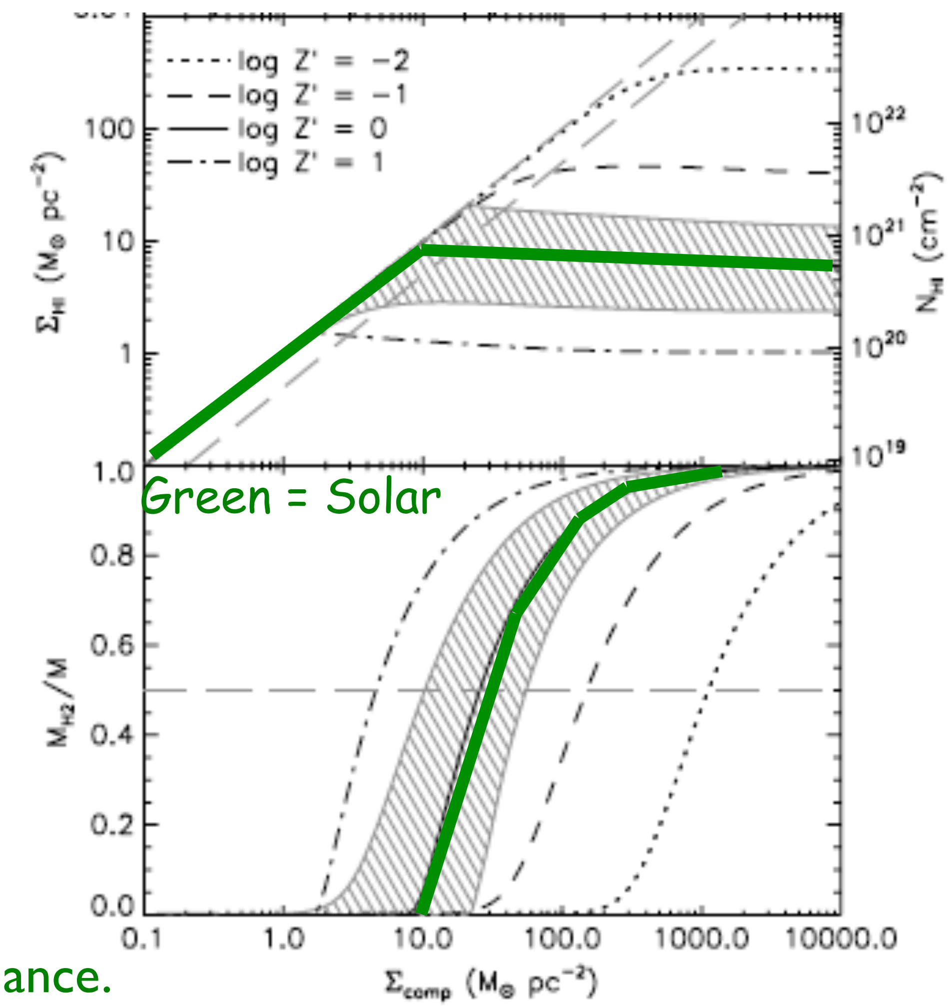
- Transition thickness ($H_2$ fraction from 0.1 to 0.25): 3-5 pc.



# Perseus HI halo vs equilibrium-$H_2$ formation model



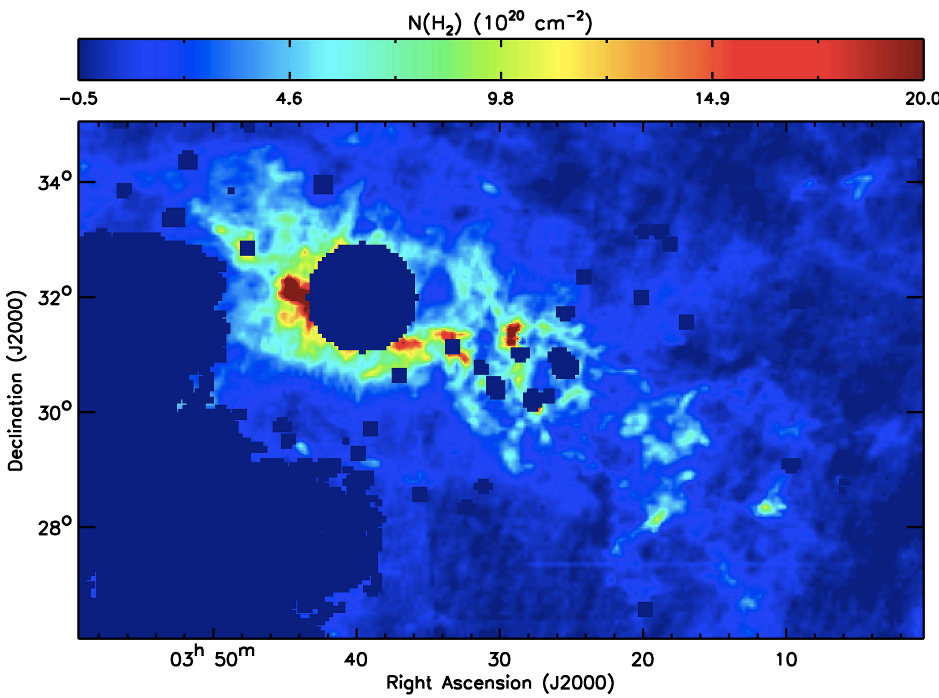




Shielding HI column → predict $H_2$ abundance.

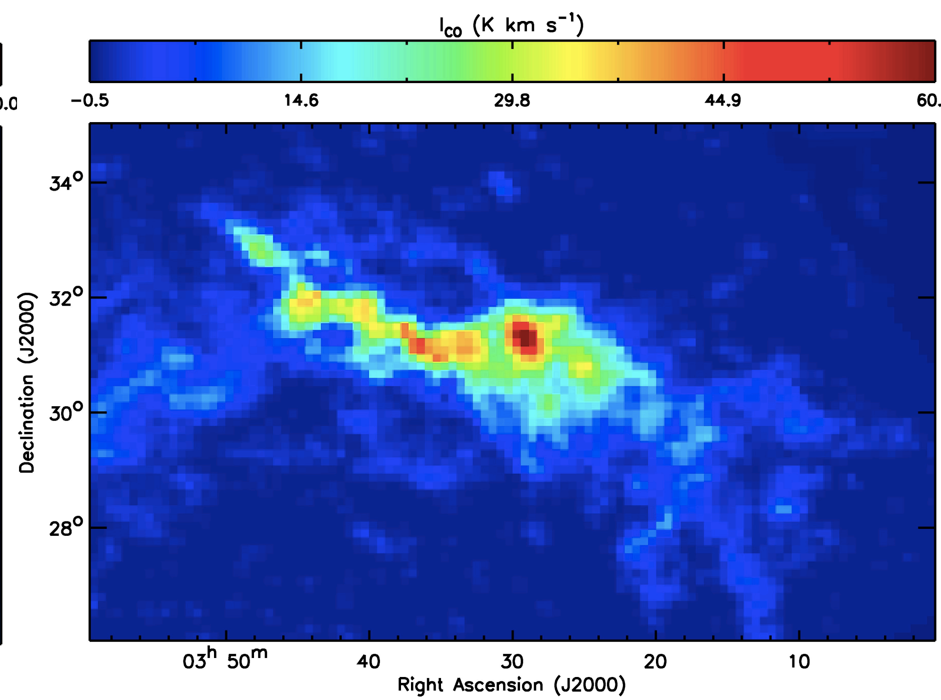
Krumholz et al. (2008, 2009)
Spitzer & Jenkins 75; Ostriker+10

Dust shielding and $H_2$ self-shielding equally important.

# 4. $X_{CO} = N(H_2) / I_{CO}$ in Perseus @ 0.4 pc resolution




$N(H_2)$ image at 4.3’ resolution (Lee et al. 2012)

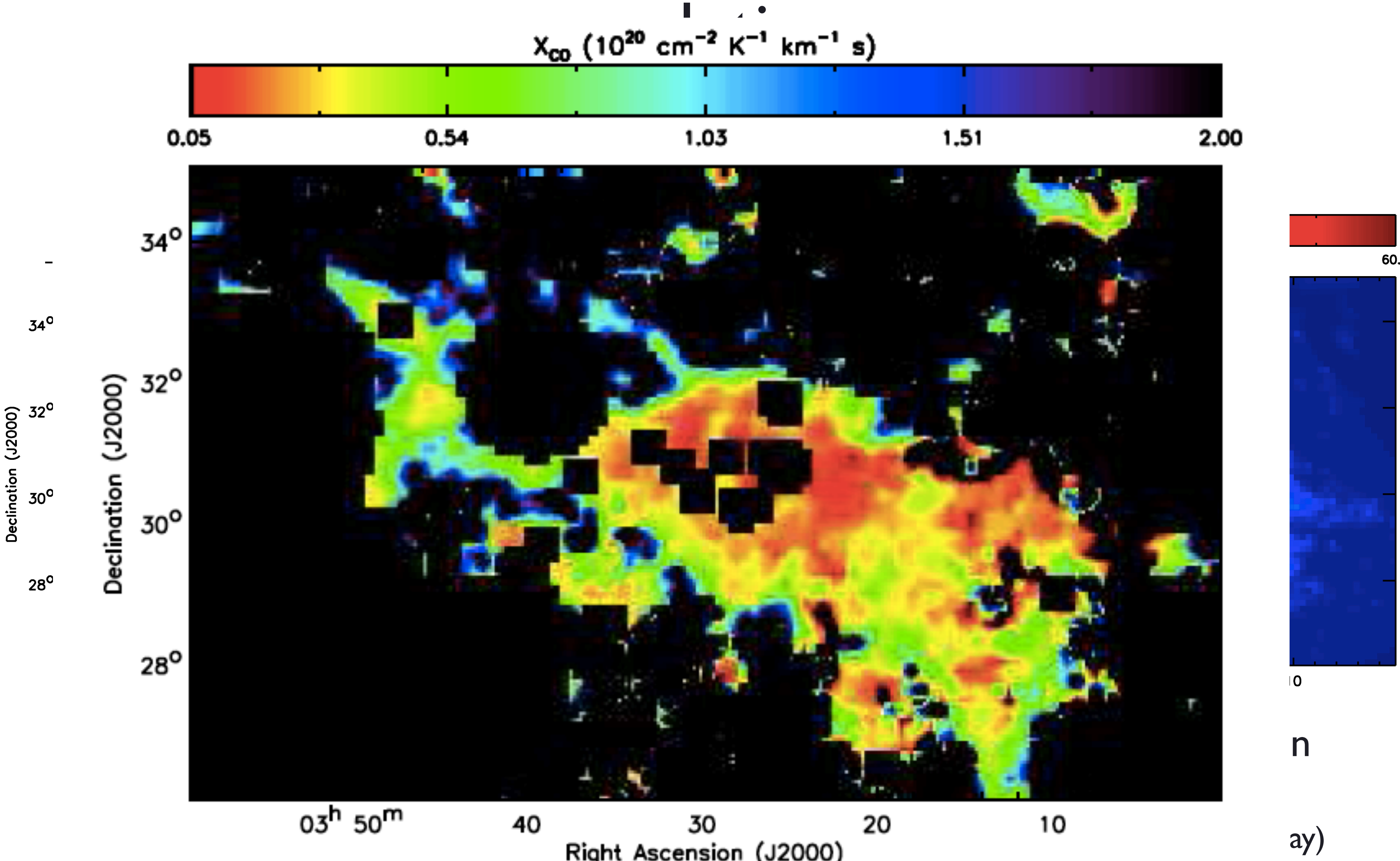



$I_{CO}$ image at 46” resolution (COMPLETE)

Here $I_{CO}$ image from CfA (for display)

Lee, SS+13

# 4. $X_{CO} = N(H_2) / I_{CO}$ in Perseus @ 0.4 pc




Lee, SS+13

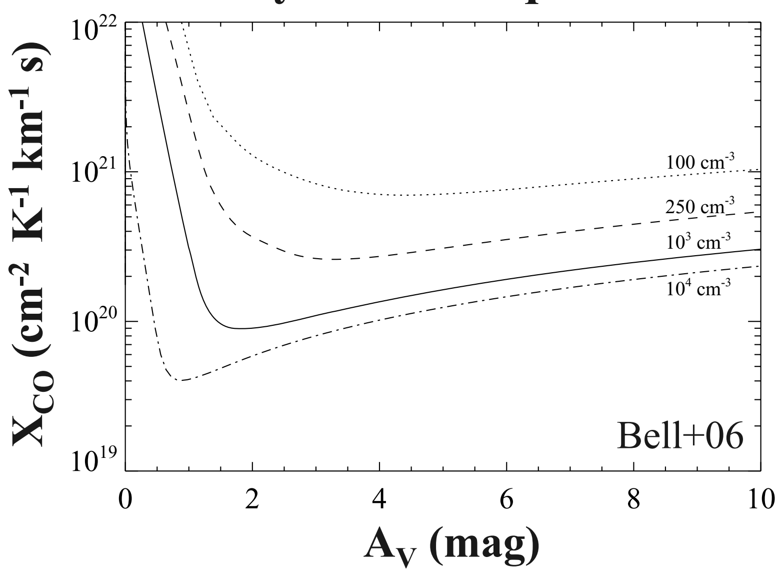
**Median $X_{CO} = 3 \times 10^{19} \sim \Sigma\, N(H_2) / \Sigma\, I_{CO}$**

Pineda+08: factor of 2-3 variation across regions

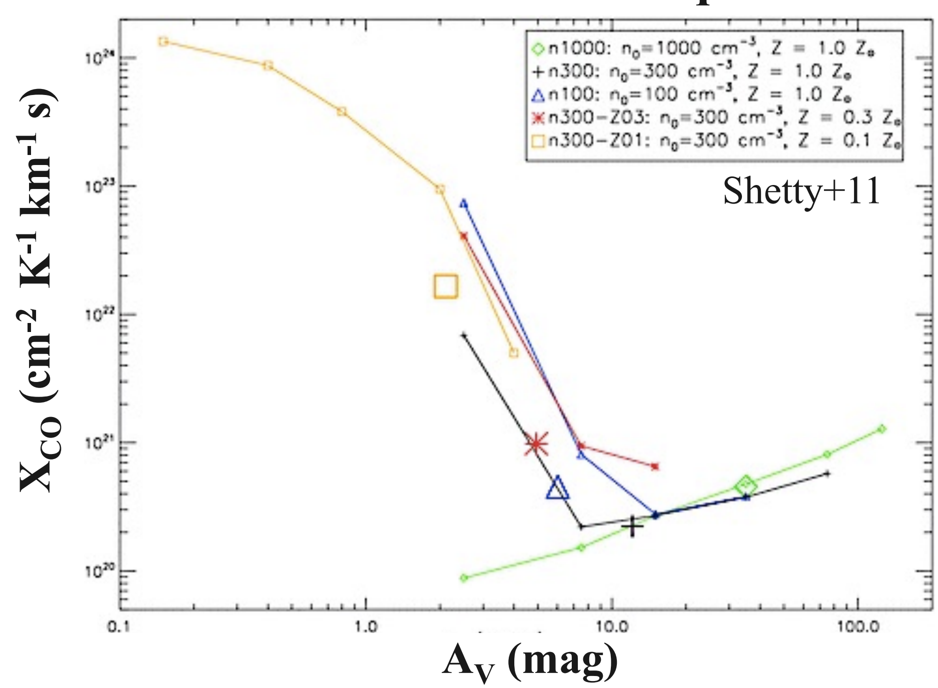
# What does the CO-to-$H_2$ Conversion Factor tells us about HI halos?

- Theory $Xco = F\,(n, G, Z, \xi\,, \sigma_{CO}, \text{cloud age})$
- Large degeneracy BUT Characteristic dependence on $A_V$

**PDR model**
**“Steady state & Equilibrium”**



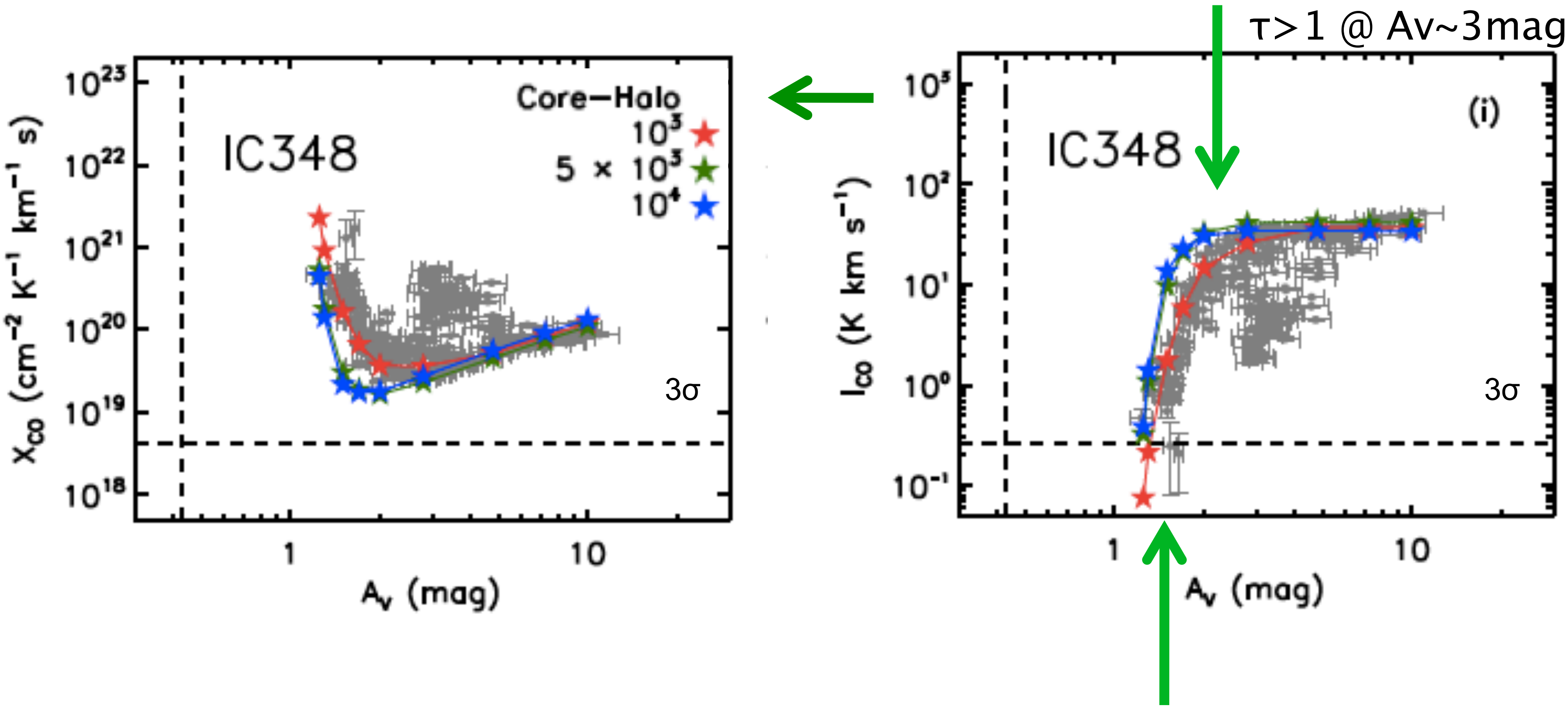

**MHD model**
**“Macroturbulent & Non-equilibrium”**

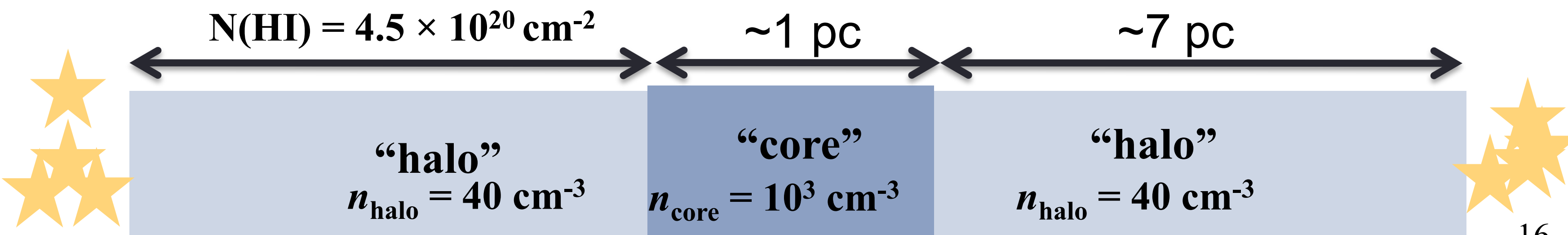



*For a chemically evolved Perseus (age ~10 Myrs), model results should converge.*

Glover & Mac Low11; Feldmann+12

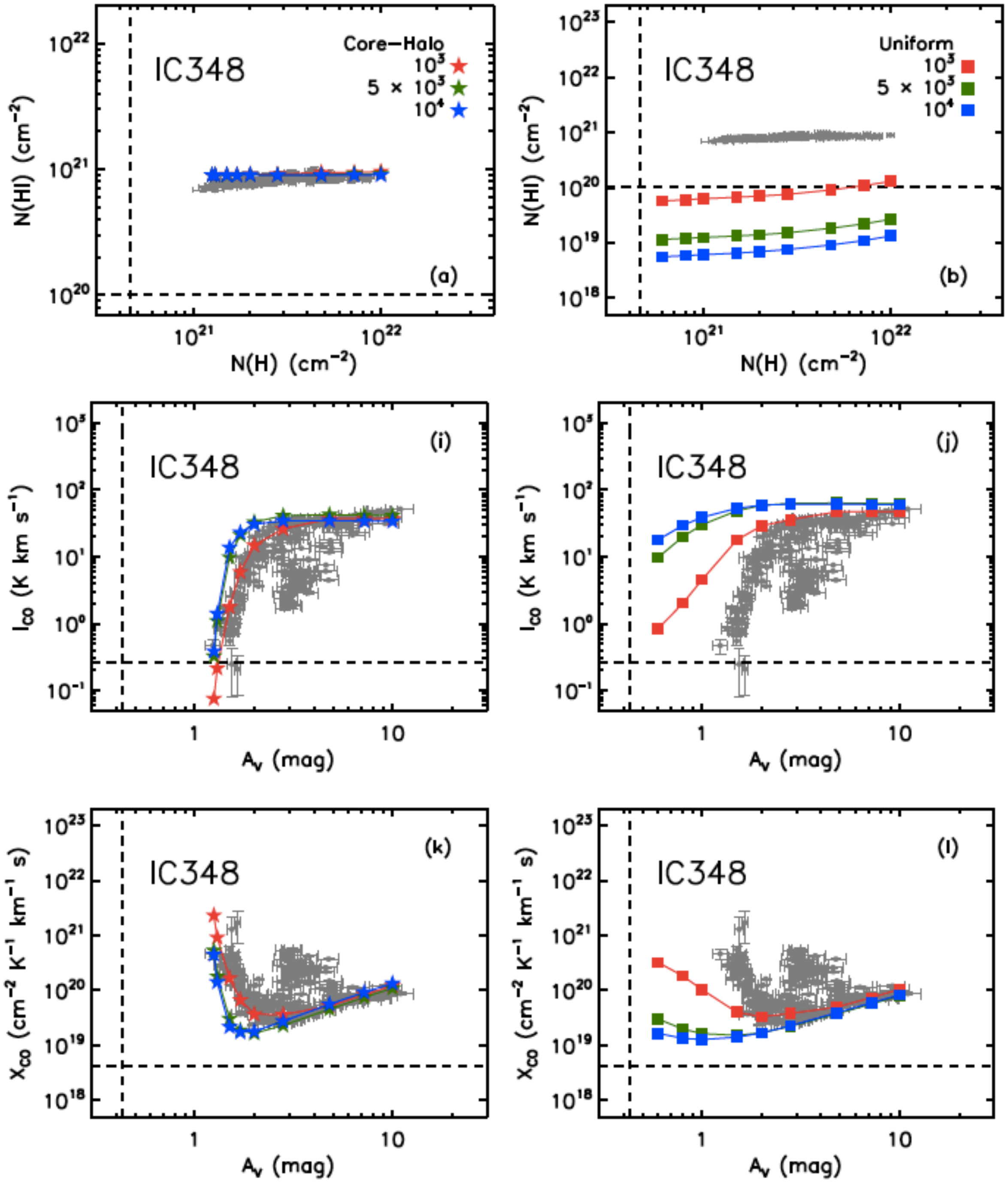
# $X_{CO}$ variations: a factor of ~80 over ~7pc




PDR model by Wolfire et al. (2010)

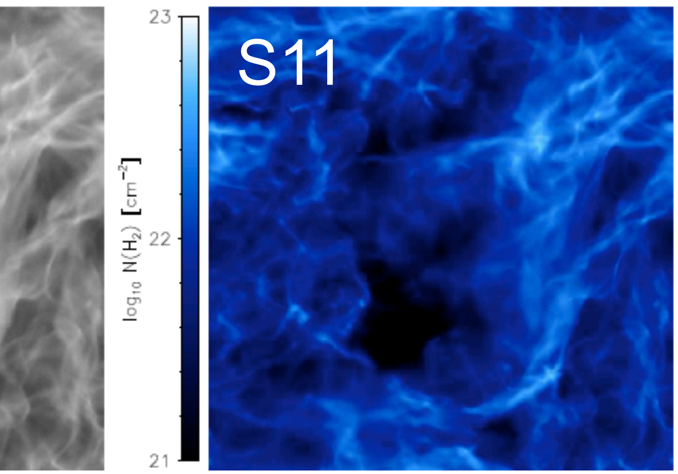
Core-halo model

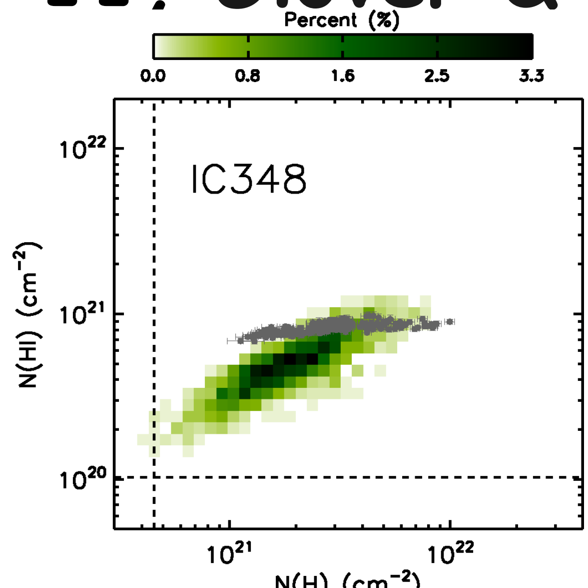



Uniform (just core) density model

**Dust shielding in <u>extended</u> HI envelopes of molecular clouds, essential to explain: N(HI), $I_{CO}$, and $X_{CO}$.**

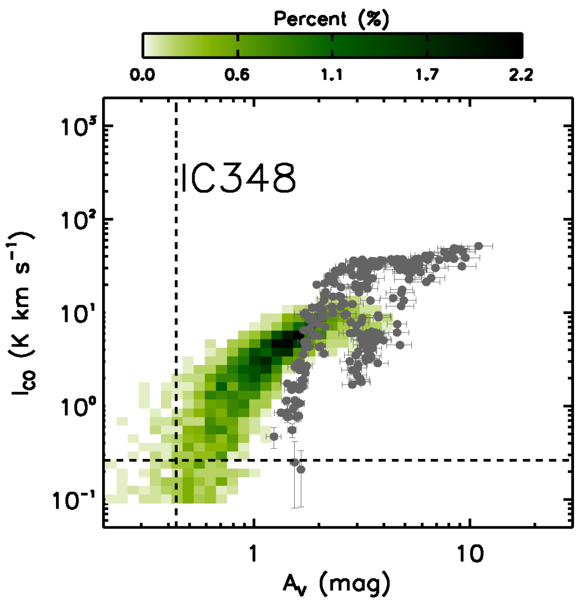
# Comparison with the MHD model (Shetty+11, Glover & Mac Low11)

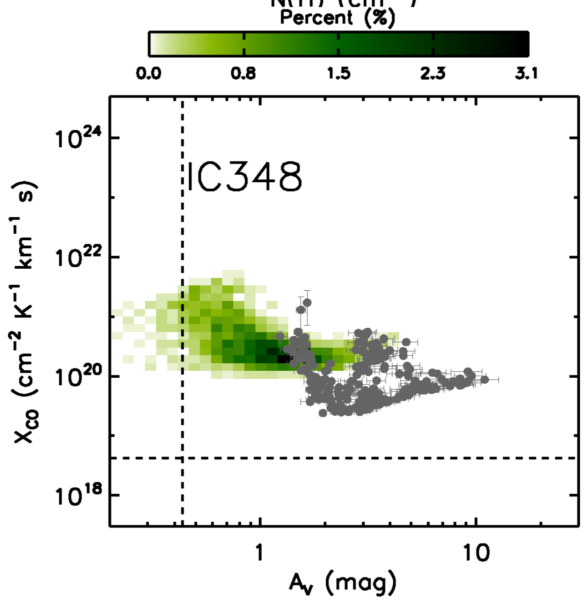



Generally good qualitative agreement – good!

Discrepancies:
- N(HI) – turbulent mixing?
- Shallow increase of $I_{CO}$
- Larger scatter
- Smaller Δv (CO)



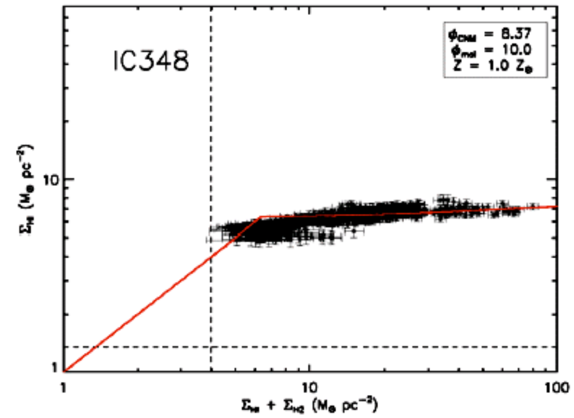




Difficulties in comparison:
- Scaling of simulation data?

*Note very different HI-$H_2$-CO geometry relative to PDR*
*→ geometry not very important, just shielding?*

# Summary:

1. **HI surface density** saturates ~10 $M_\odot$ $pc^{-2}$ on sub-pc scales "Spitzer shield".




**2. Properties of the HI/$H_2$ transition:**
3-5pc thickness, >20pc from CO centers
Absorbing HI: Ts~40-70 K, CNM to WNM: ~50-50%

**3. High optical depth HI?**
High-τ HI can be significant but can not fully explain the saturation.

**4. HI & dust are important for $H_2$ and CO?**
Dust shielding from extended HI envelopes essential to explain: sharp HI-$H_2$ transition, CI/CII → CO transition, and the characteristic dependence of $X_{CO}$ on $A_v$.

**Future work:**
- Probe more extreme interstellar environments.
- Map out temperature distribution in halos and cloud centers.

*More high-res HI observations on the horizon!*