The HI-to-H_2 Transition and HI columns in Galaxy Star-Forming Regions

Amiel Sternberg
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Star Formation Across Space and Time
14 November 2014

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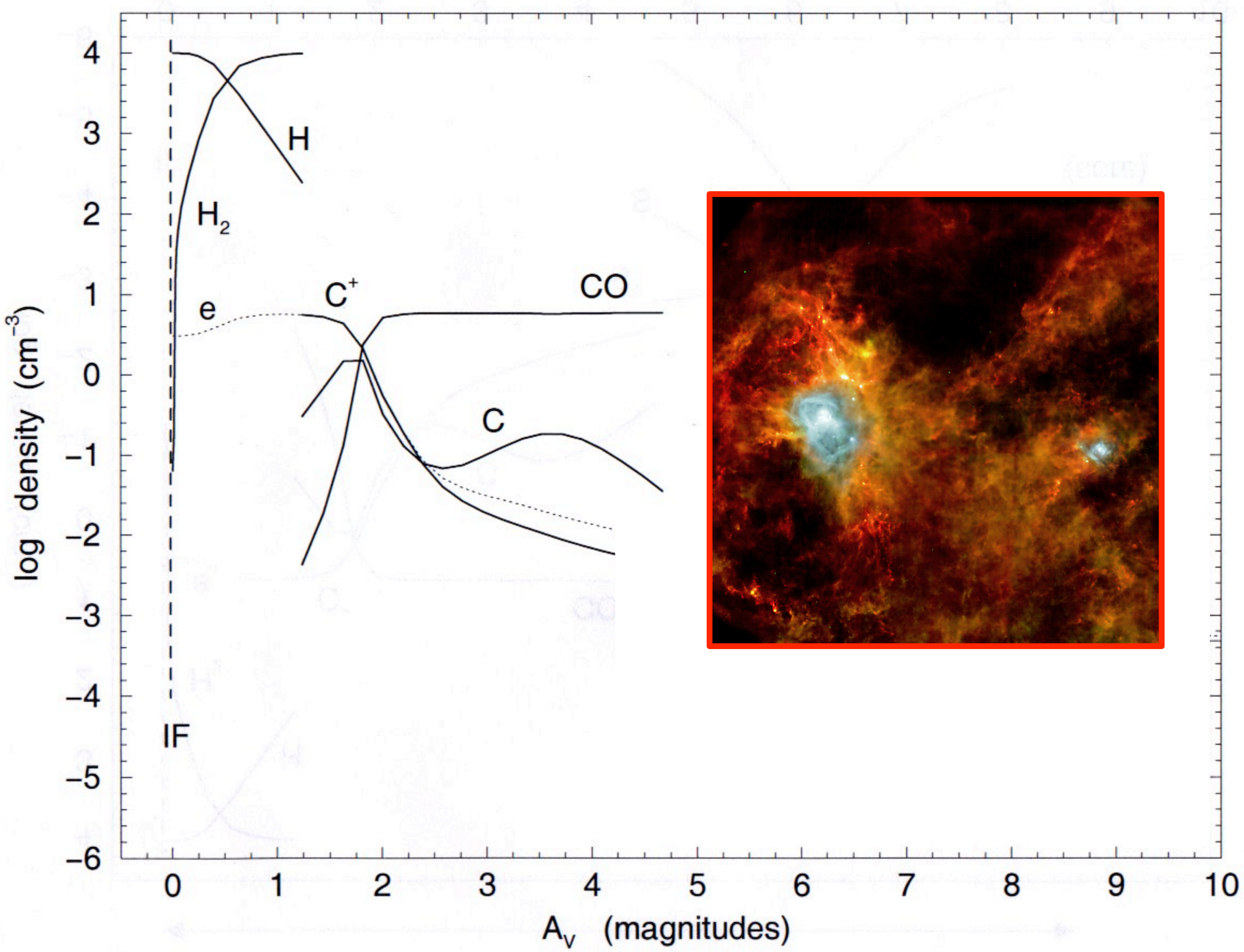

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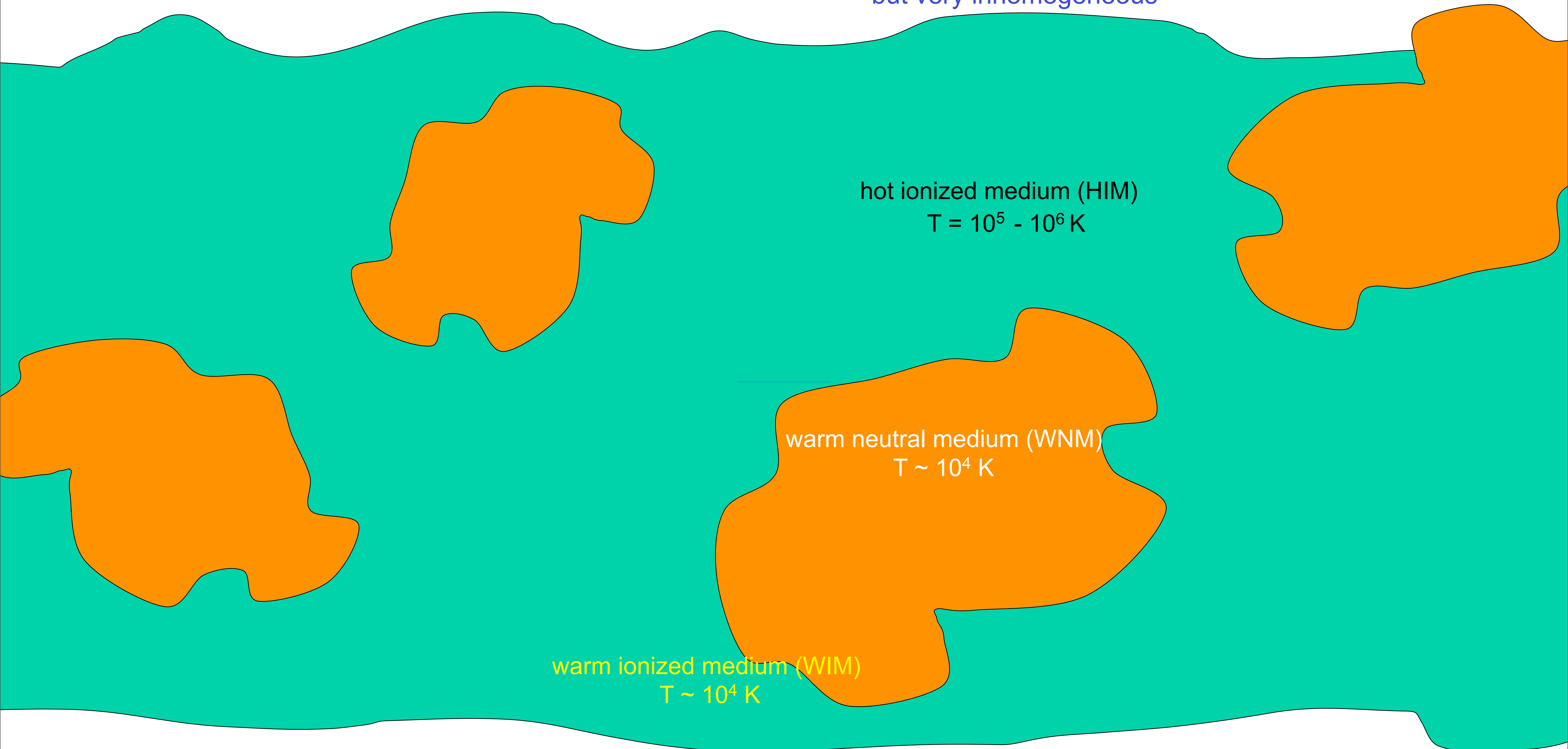
The Multi-Phased Interstellar Medium (ISM) and Star-Formation:

<density> = 1 cm^{-3}
but very inhomogeneous



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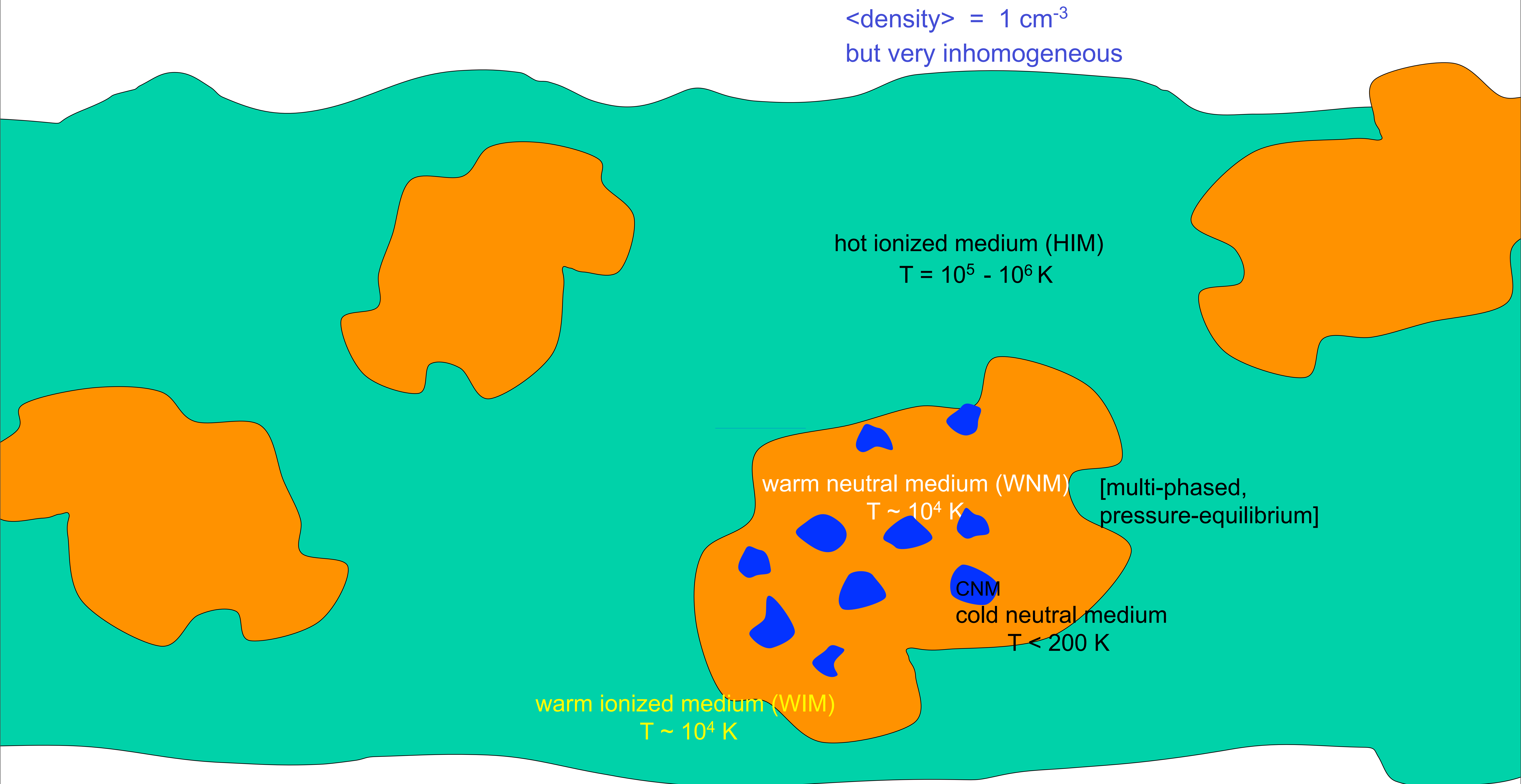

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<density> = 1 cm^{-3}
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Interstellar gas exposed to

starlight
shock waves
energetic particles (cosmic-rays)
magnetic fields

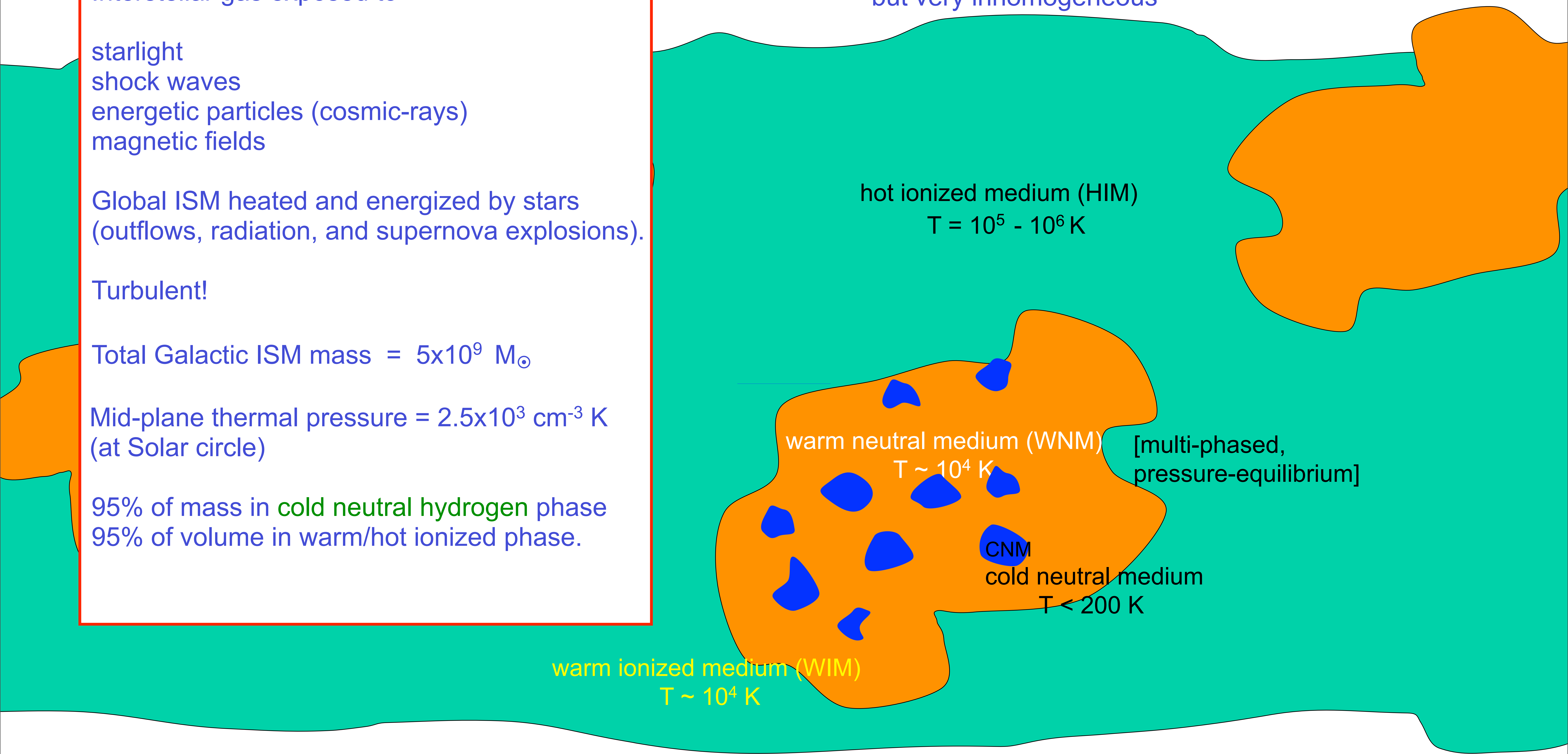
Global ISM heated and energized by stars (outflows, radiation, and supernova explosions).

Turbulent!

Total Galactic ISM mass = $5\times10^9\ M_\odot$

Mid-plane thermal pressure = $2.5\times10^3\ cm^{-3}\ K$ (at Solar circle)

95% of mass in cold neutral hydrogen phase
95% of volume in warm/hot ionized phase.



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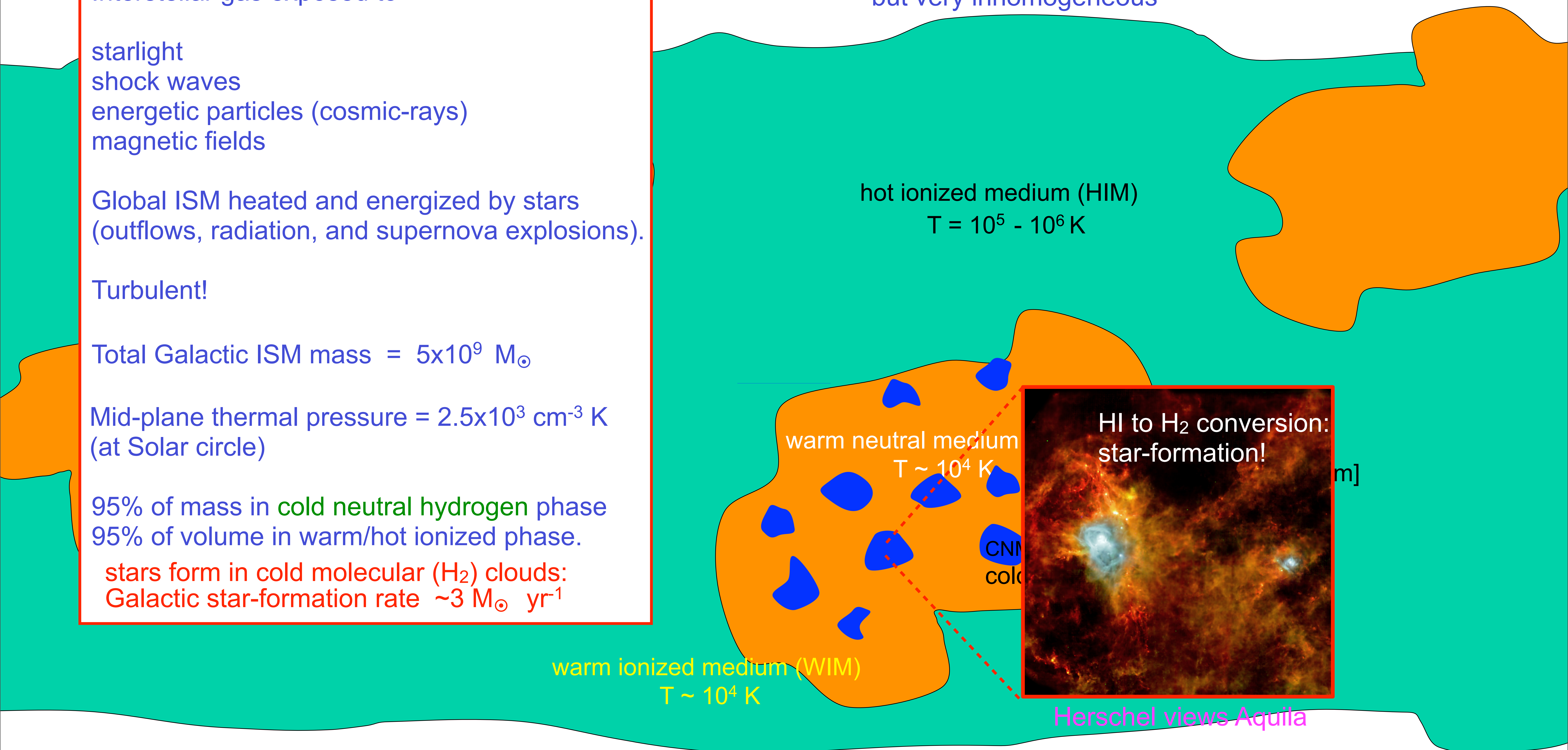
stars form in cold molecular (H_2) clouds:
Galactic star-formation rate ~3 $M_\odot\ yr^{-1}$



Herschel views Aquila

Talk Outline:

- motivation.
- HI-to-H_2 transition, some radiative transfer computations.
- analytic formula for the HI column density.
- self-regulated media.
- observations: from Perseus to galaxies.

HI-to-H_2 Transitions and HI Column Densities in Galaxy Star-Forming Regions

Amiel Sternberg[1], Franck Le Petit[2], Evelyne Roueff,[2] and Jacques Le Bourlot[2]

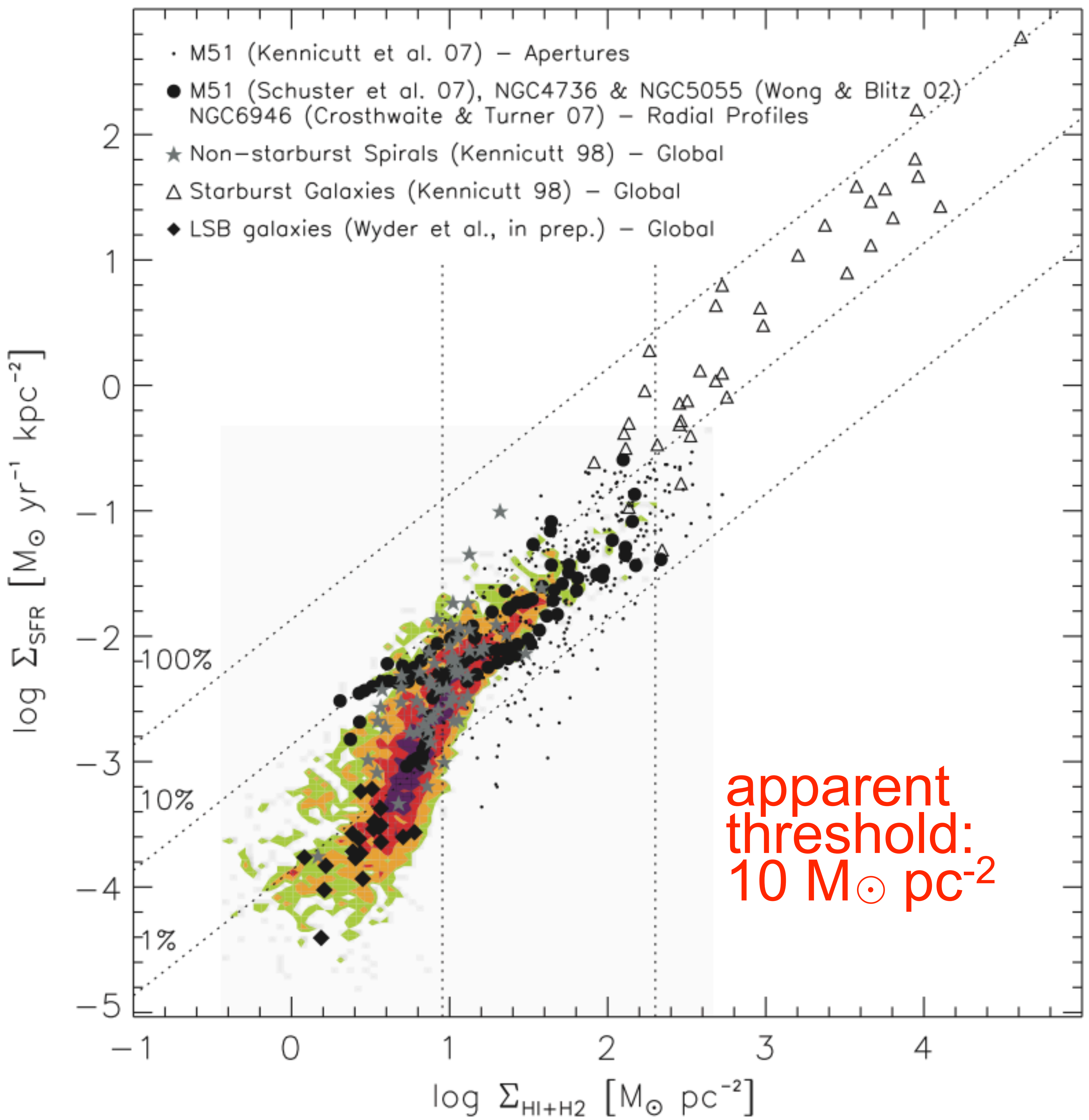
2014 ApJ 790 10

l'Observatoire de Paris

Kennicutt-Schmidt Relation:

Schmidt 1959 ApJ 129 253
Kennicutt 1998 ApJ498 541
Genzel et al. 2010 MNRAS 407 2091 [“SINS(VLT)/IRAM” projects]

e.g., Bigiel+ 2008



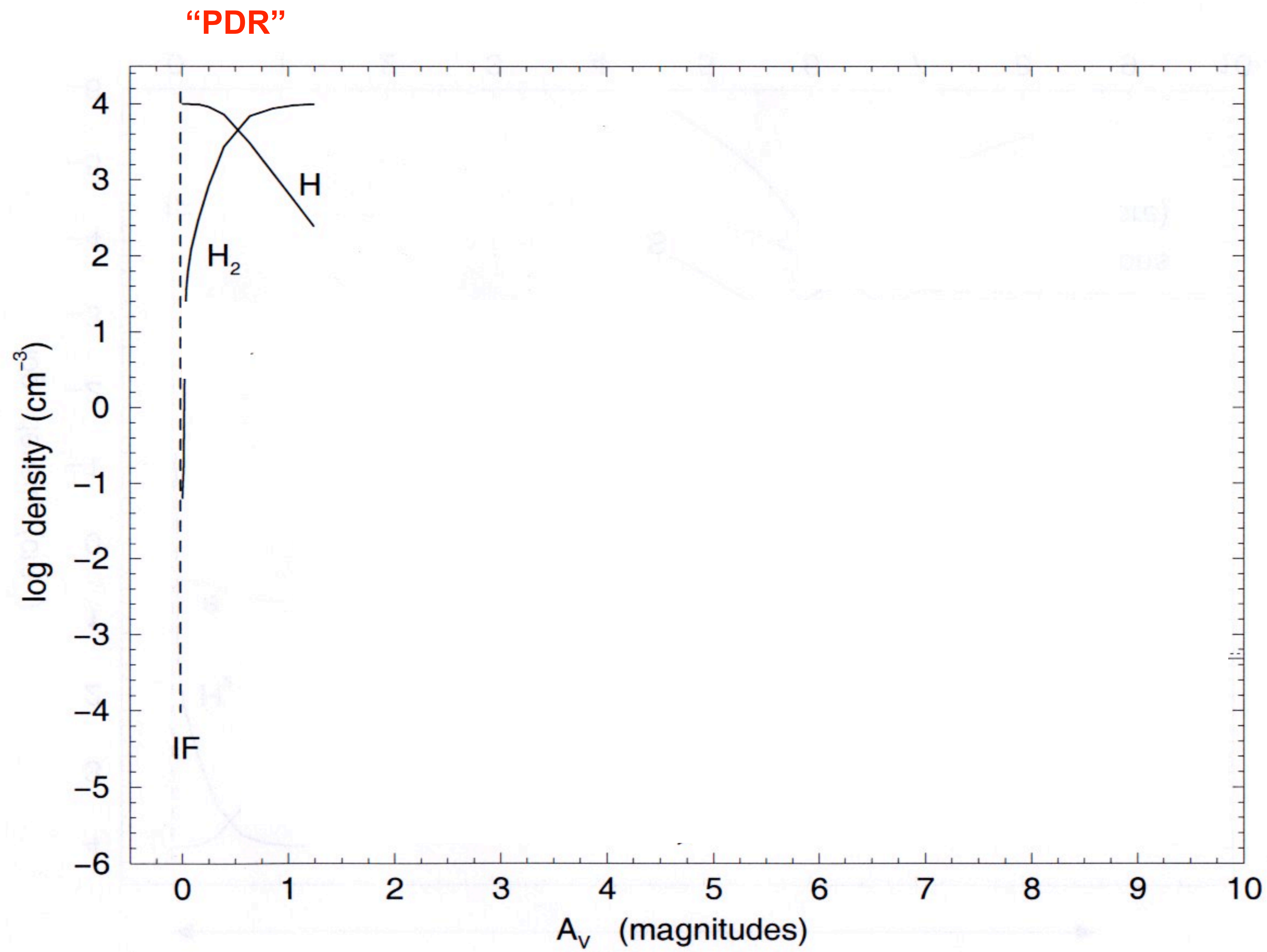
$$\Sigma_{\rm SFR} = \epsilon \, \frac{f_{\rm H_2} \, \Sigma_{\rm gas}}{\tau_d}$$

I am going to be juggling many parameters
- keep your eye on them!

HI to H_2 Transition in Dense Star-Forming Molecular Clouds:

H_2 formation (by grain catalysis) versus far-UV photodissociation.

Shielding required.



Stellar ultraviolet
"Lyman-Werner" radiation
11.2 - 13.6 eV

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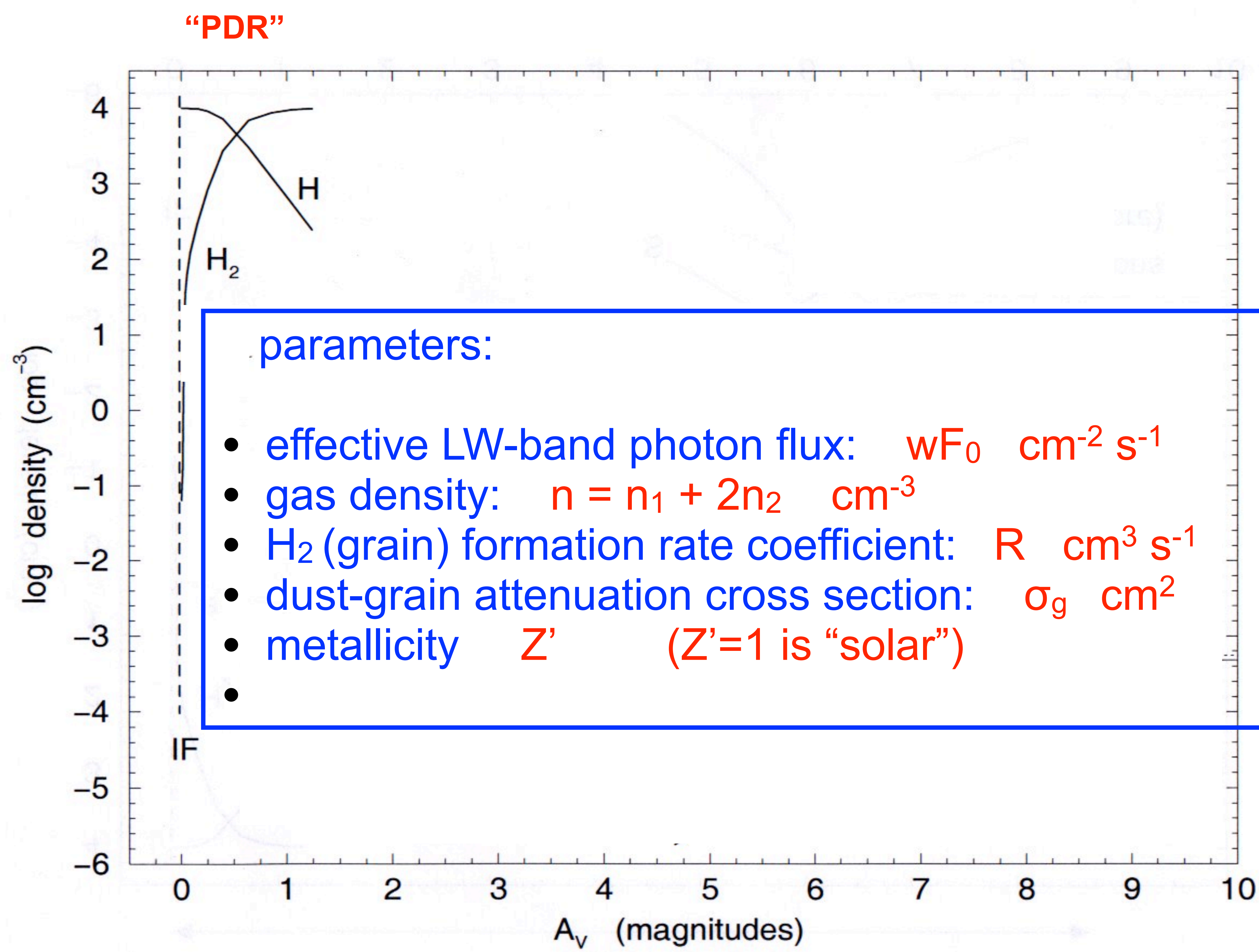
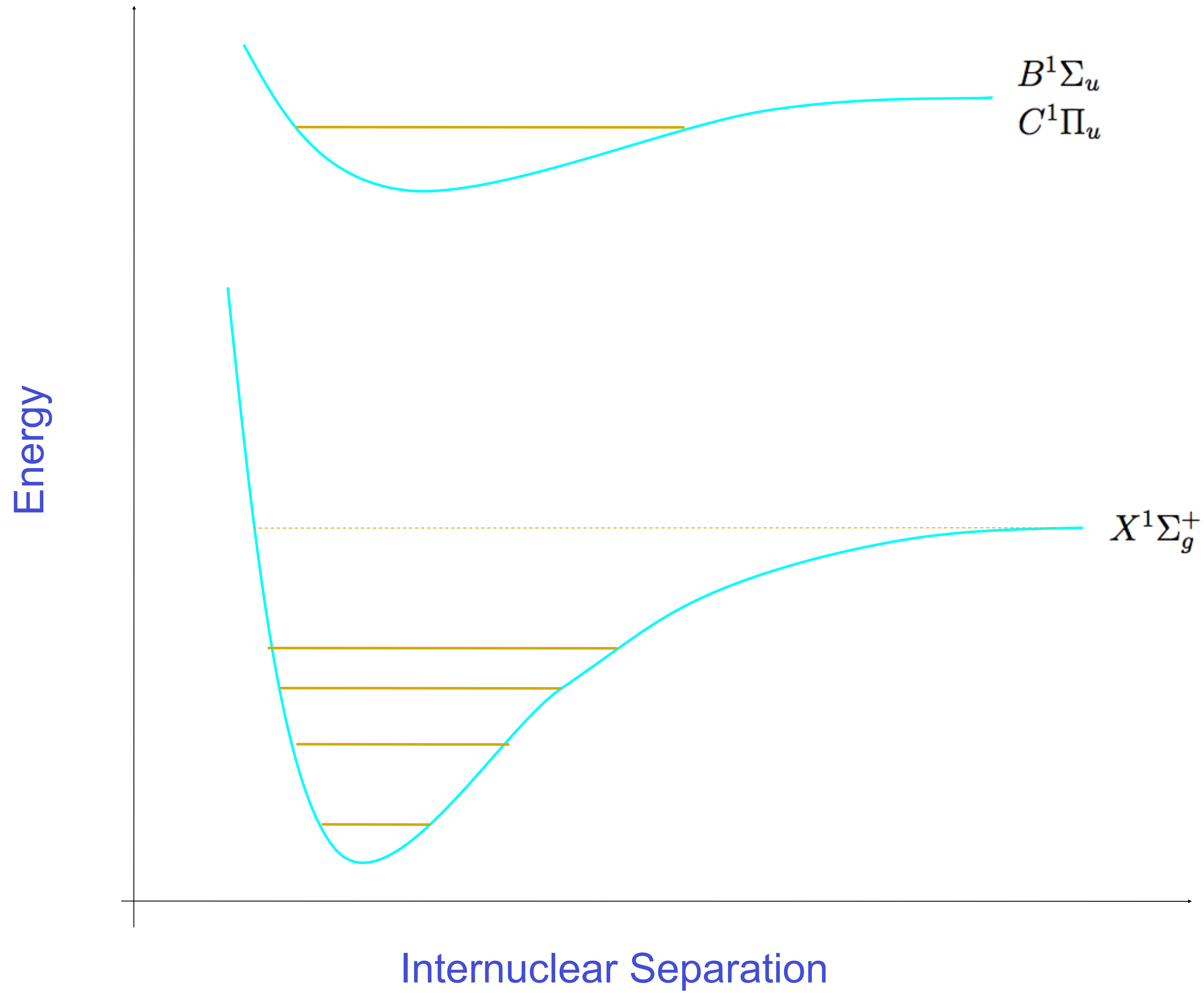


parameters:

- effective LW-band photon flux: wF_0 $cm^{-2}\ s^{-1}$
- gas density: $n = n_1 + 2n_2$ cm^{-3}
- H_2 (grain) formation rate coefficient: R $cm^3\ s^{-1}$
- dust-grain attenuation cross section: σ_g cm^2
- metallicity Z' ($Z'=1$ is "solar")
-

Stellar ultraviolet
"Lyman-Werner" radiation
11.2 - 13.6 eV

H_2 Photodissociation in the Lyman-Werner bands (912-1108 Å):



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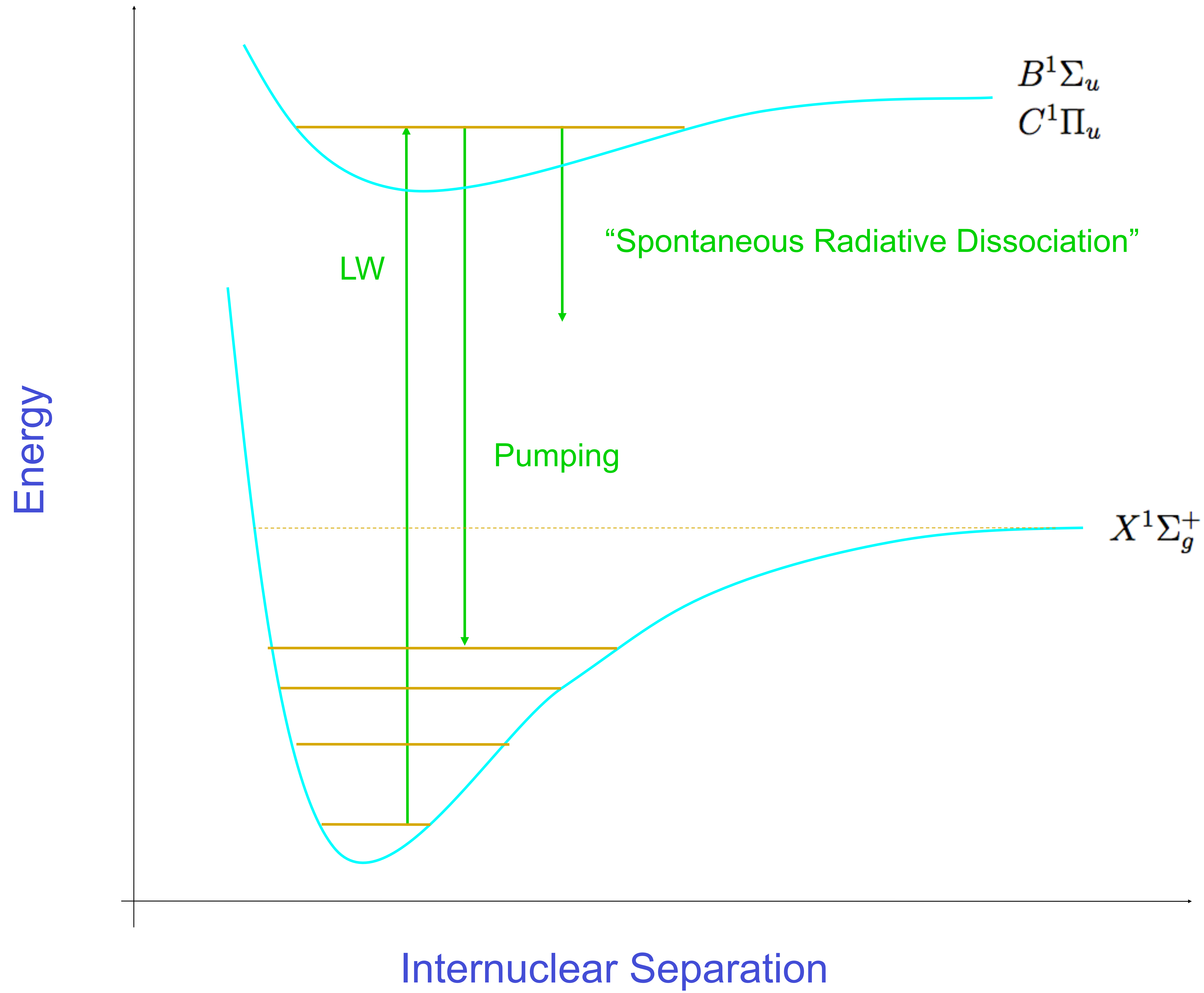

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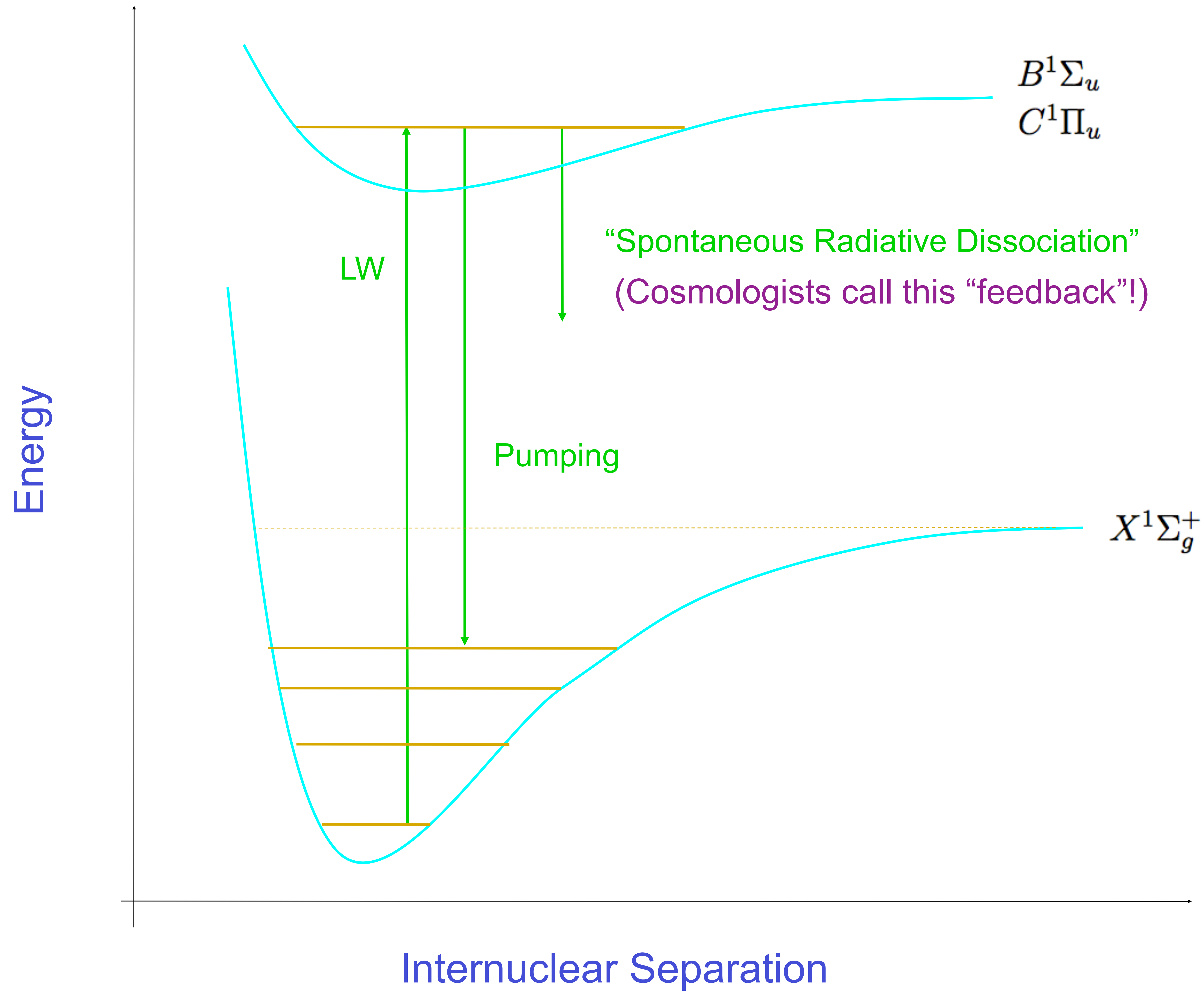

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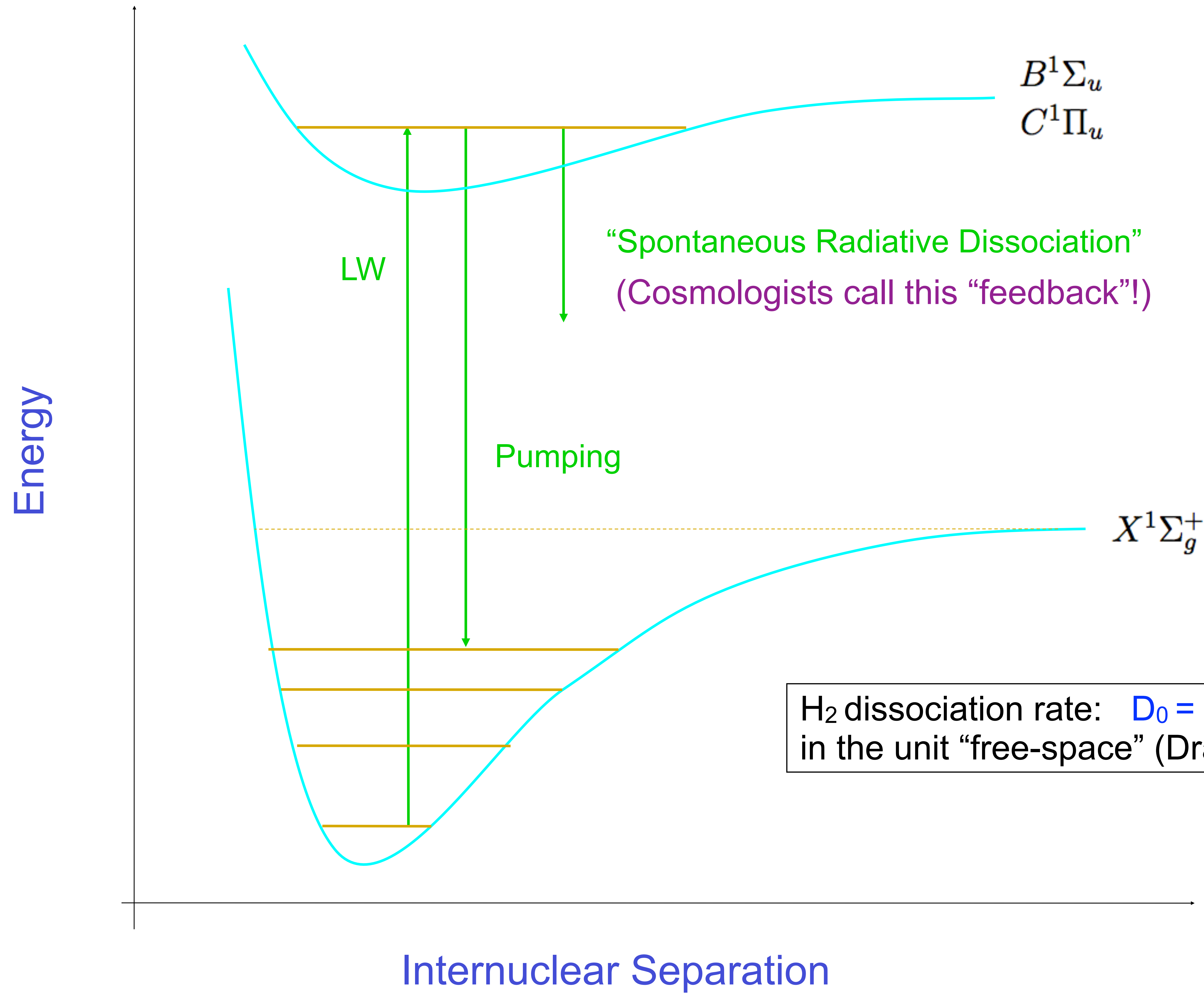
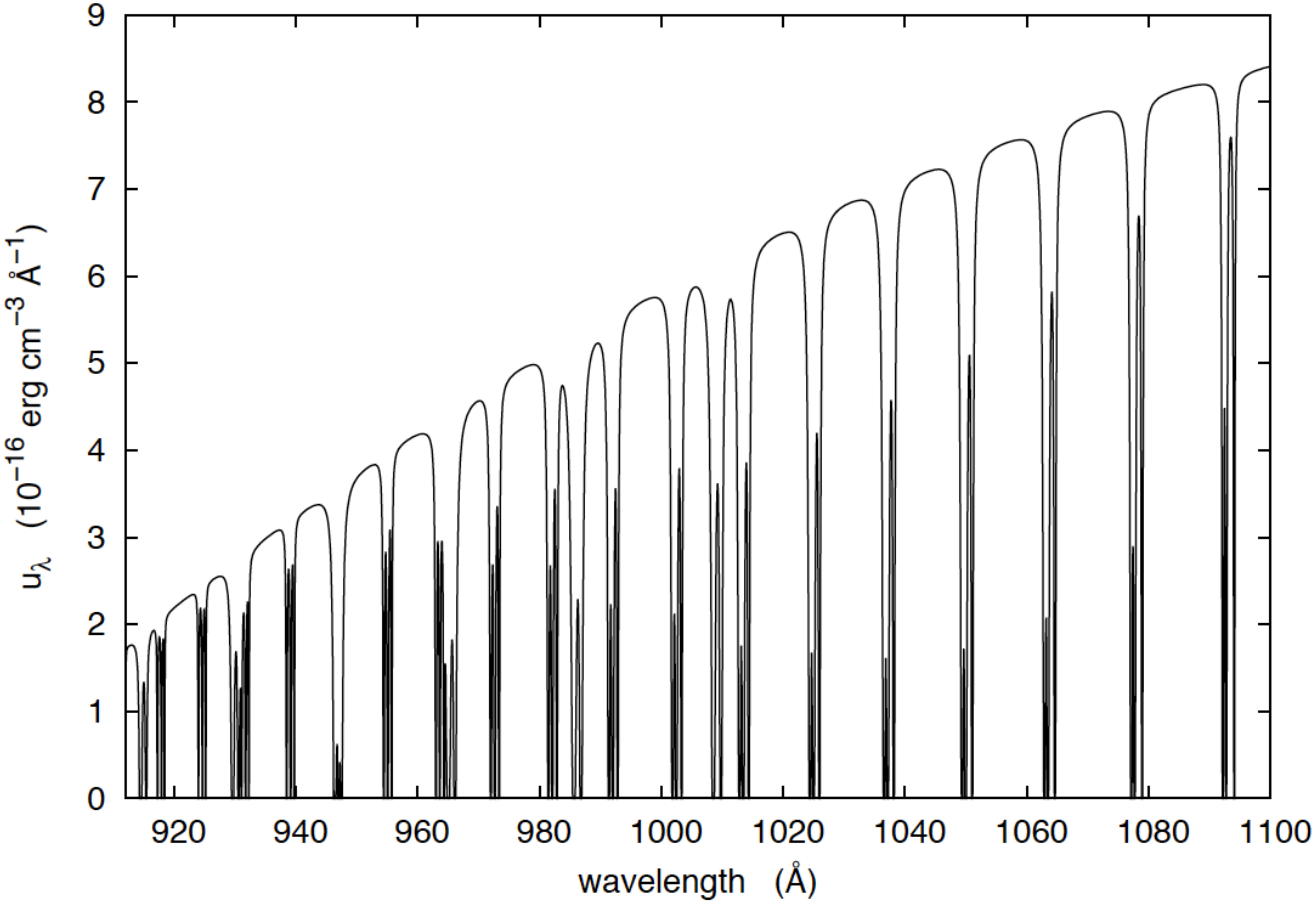


$\bar{f}_{\rm diss} = 0.12$

H_2 dissociation rate: $D_0 = 5.8 \times 10^{-11}\ s^{-1}$
in the unit "free-space" (Draine) interstellar field.

Lyman-Werner Radiative Transfer:

S+ 2014 ["Meudon PDR code"]



Characteristic multi-line H_2 absorption spectrum, and "self-shielding".

Dust absorption cross-section per hydrogen nucleus:

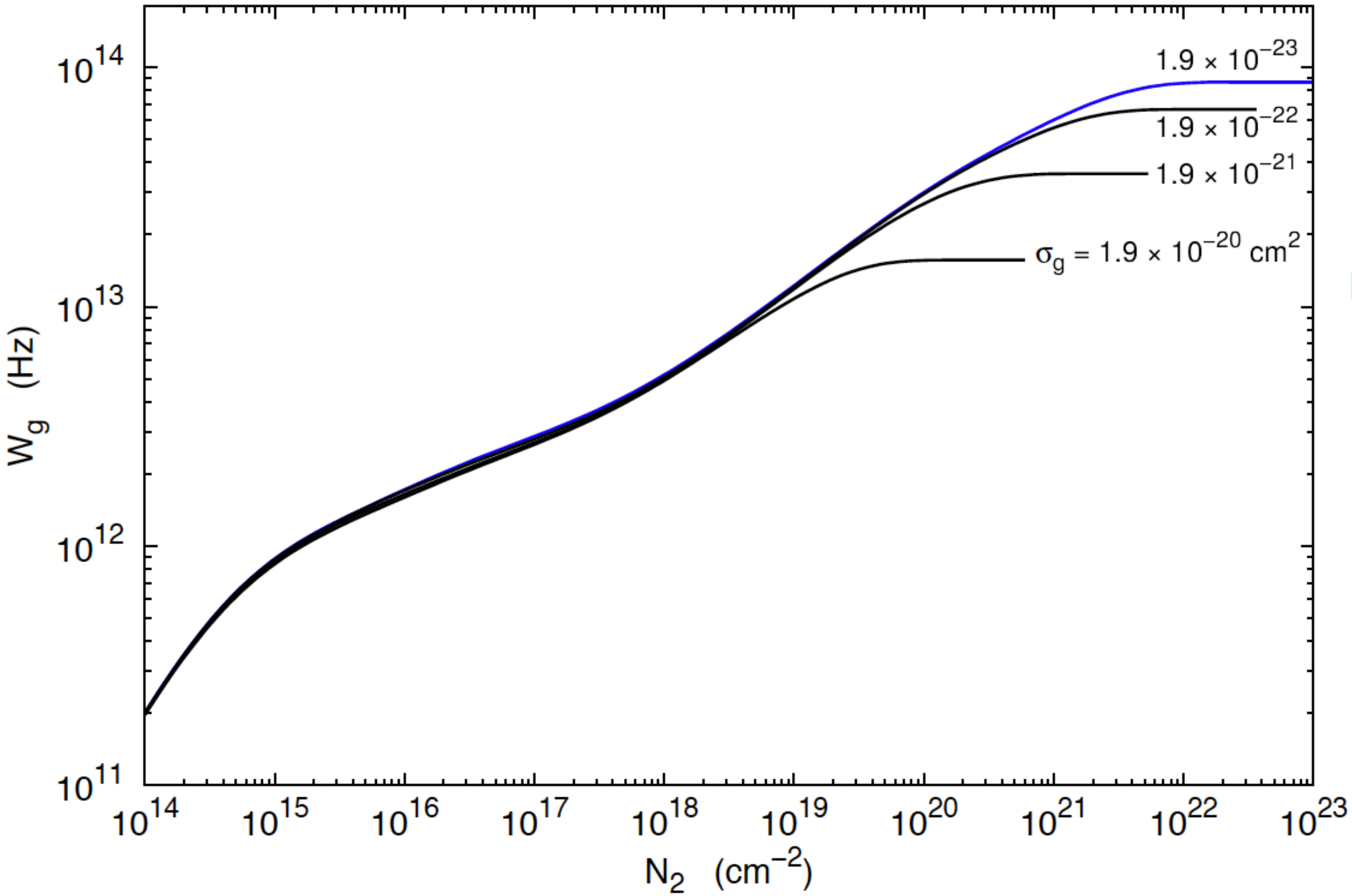
$$\sigma_g = 1.9 \times 10^{-21} \phi_g \; Z' \quad \mathrm{cm}^2$$

Numerical radiative transfer on a fine frequency grid with a spectral resolution ~ 10^5.

Curve-of-Growth for the "H_2 Dust-Limited Dissociation Bandwidth":

[integrated over all LW lines]

Sternberg+ 2014 ["Meudon PDR code"]



low metallicity

Z' "little w"

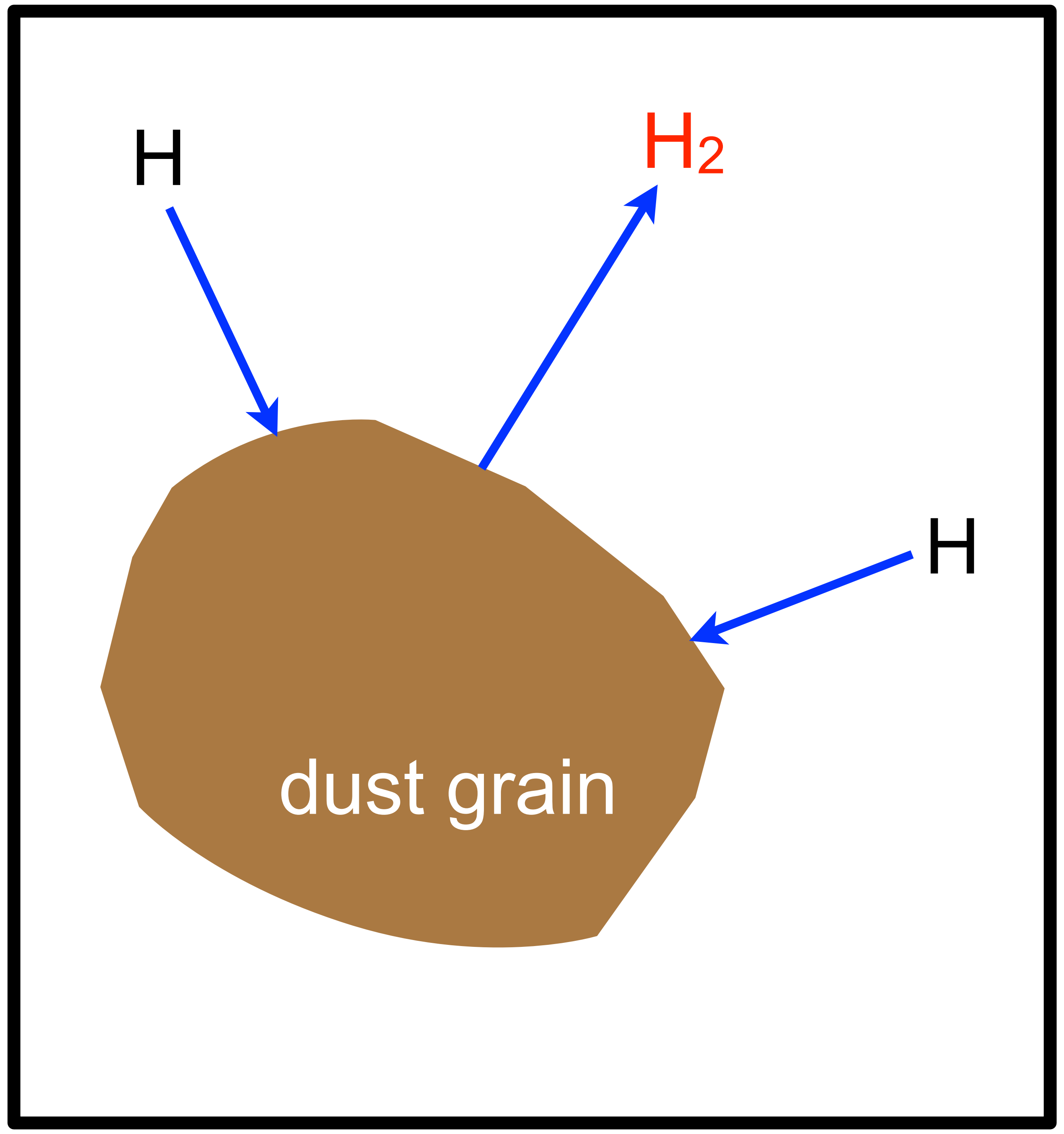
high metallicity

The bandwidth (Hz) of radiation absorbed in H_2 line dissociations in a dusty and fully molecular cloud.

"H_2 dust" versus "H_2 lines"

Universal: independent of radiation field intensity, or cloud gas density, etc.

H_2 Formation:



$$R = 3 \times 10^{-17} \left(\frac{T}{100\ \mathrm{K}}\right)^{1/2} Z' \quad \mathrm{cm^3\ s^{-1}}$$

$$t_{\rm eq} = \frac{1}{Rn} = \frac{10^9}{Z'n}\ \mathrm{yr}$$

time scale for equilibrium

In the absence of dust:

$H + e \rightarrow H^- + \text{photon}$

$H^- + H \rightarrow H_2 + e$

Basic Theory Question:

What is the total HI column density (cm^{-2})
or HI mass surface density ($M_\odot$ pc^{-2})
in far-UV irradiated systems?

Dimensionless Parameter:

Sternberg 1988; McKee & Krumholz 2010; Sternberg+ 2014

$$\alpha G \equiv \bar{f}_{\rm diss} \frac{\sigma_g w F_0}{R n}$$

Physical Meaning:

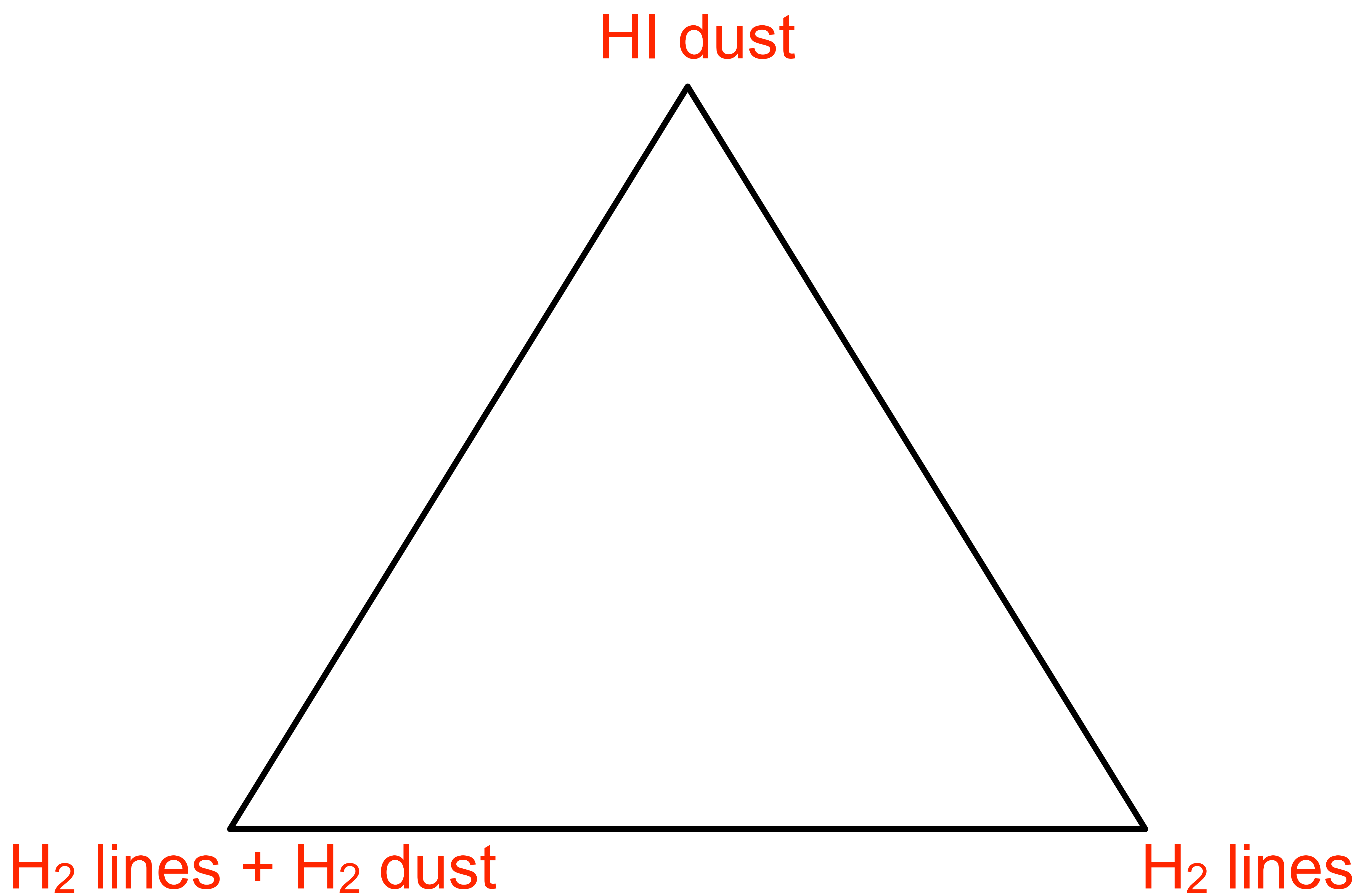
$$\frac{\text{self-shielded } H_2 \text{ dissociation rate}}{H_2 \text{ rate formation rate}}$$

or:

$$\frac{\text{HI-dust absorption rate of the effective dissociation flux}}{\text{free space } H_2 \text{ photodissociation rate}}$$

Three-Way Competition for the FUV Absorption:

αG >> 1 “strong-field”



αG << 1 “weak-field”
Z’ ≳ 1 “high-metallicity”

αG << 1 “weak-field”
Z’ ≲ 1 “low-metallicity”

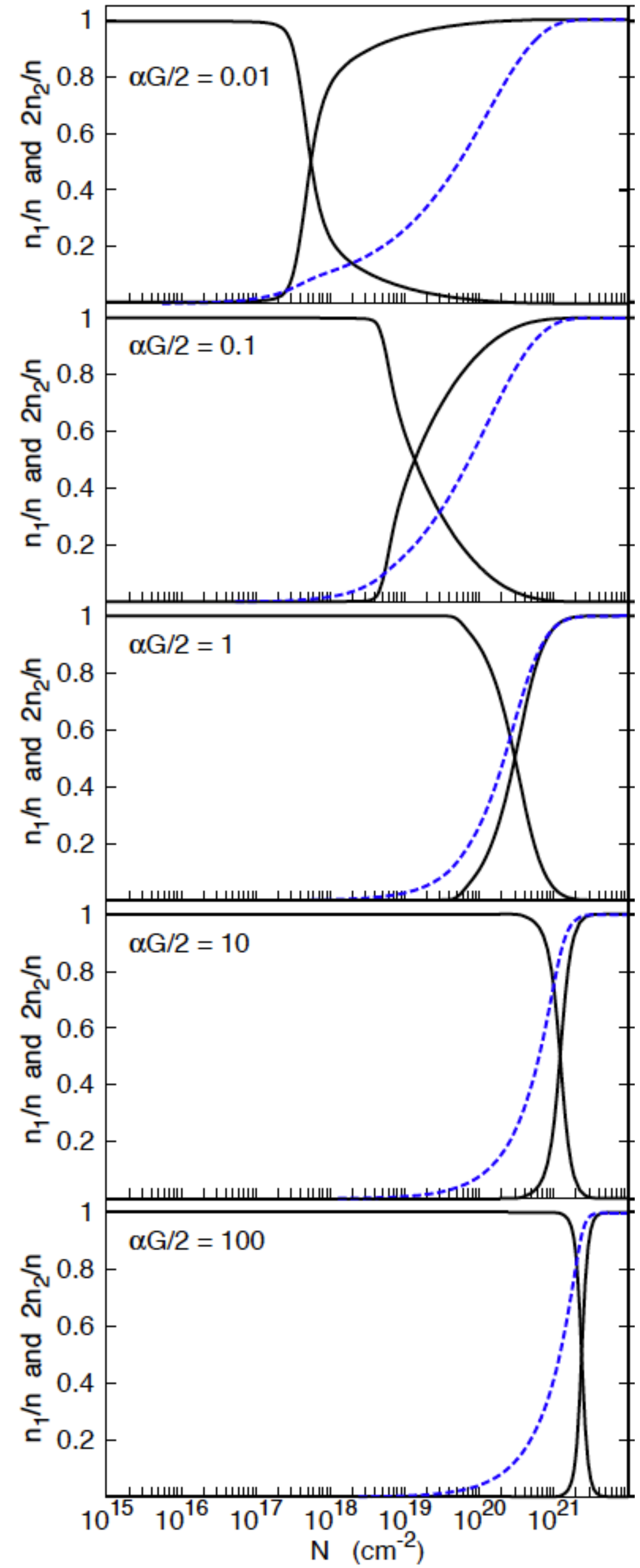
HI-to-H_2 Transition Profiles: Z'=1 (solar metallicity)

weak-field: most of the HI built up inside the H_2 zone, "gradual profiles"

FUV attenuation dominated by H_2 lines plus "H_2 dust"

strong-field: most of the HI built up in an outer layer, "sharp profiles"

FUV attenuation dominated by "HI-dust"



HI-to-H_2 Transition Profiles: Z'=1 (solar metallicity)

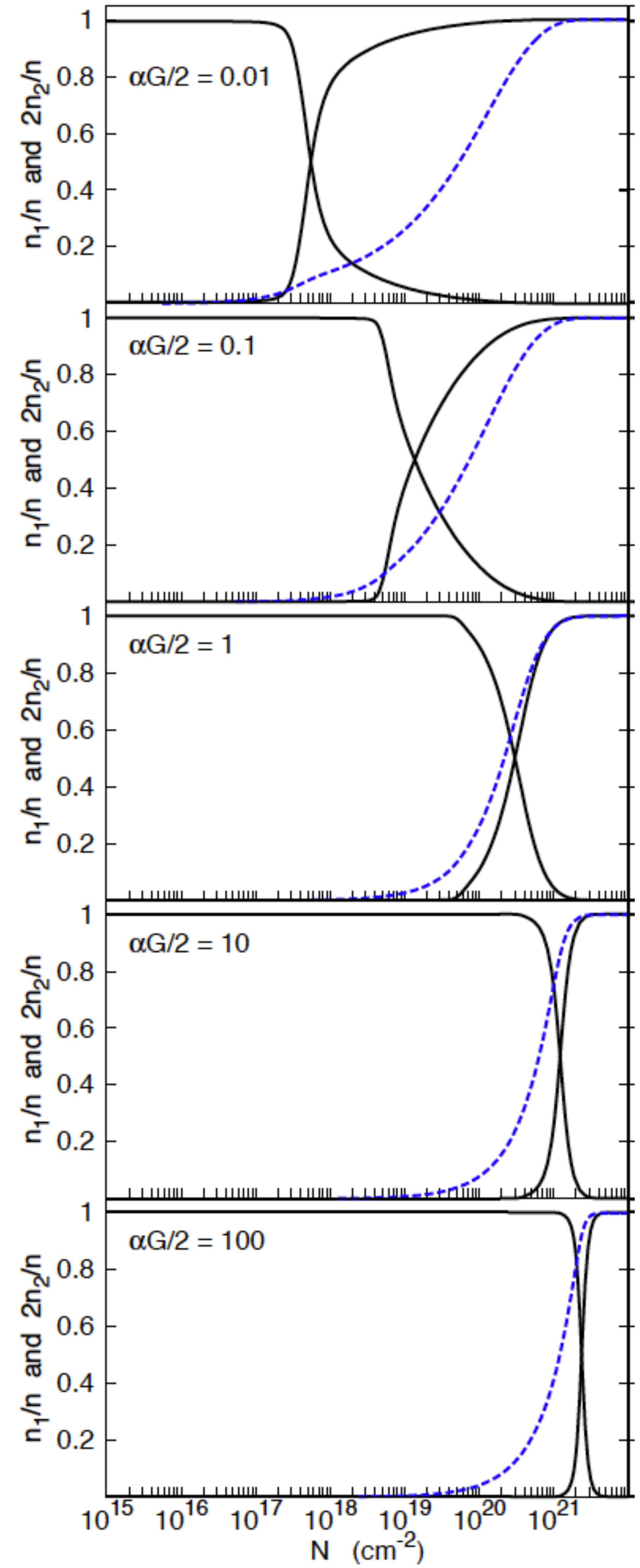
weak-field: most of the HI built up inside the H_2 zone, "gradual profiles"

FUV attenuation dominated by H_2 lines plus "H_2 dust"

For a given Z', the profile shapes depend on the dimensionless parameter αG.

strong-field: most of the HI built up in an outer layer, "sharp profiles"

FUV attenuation dominated by "HI-dust"

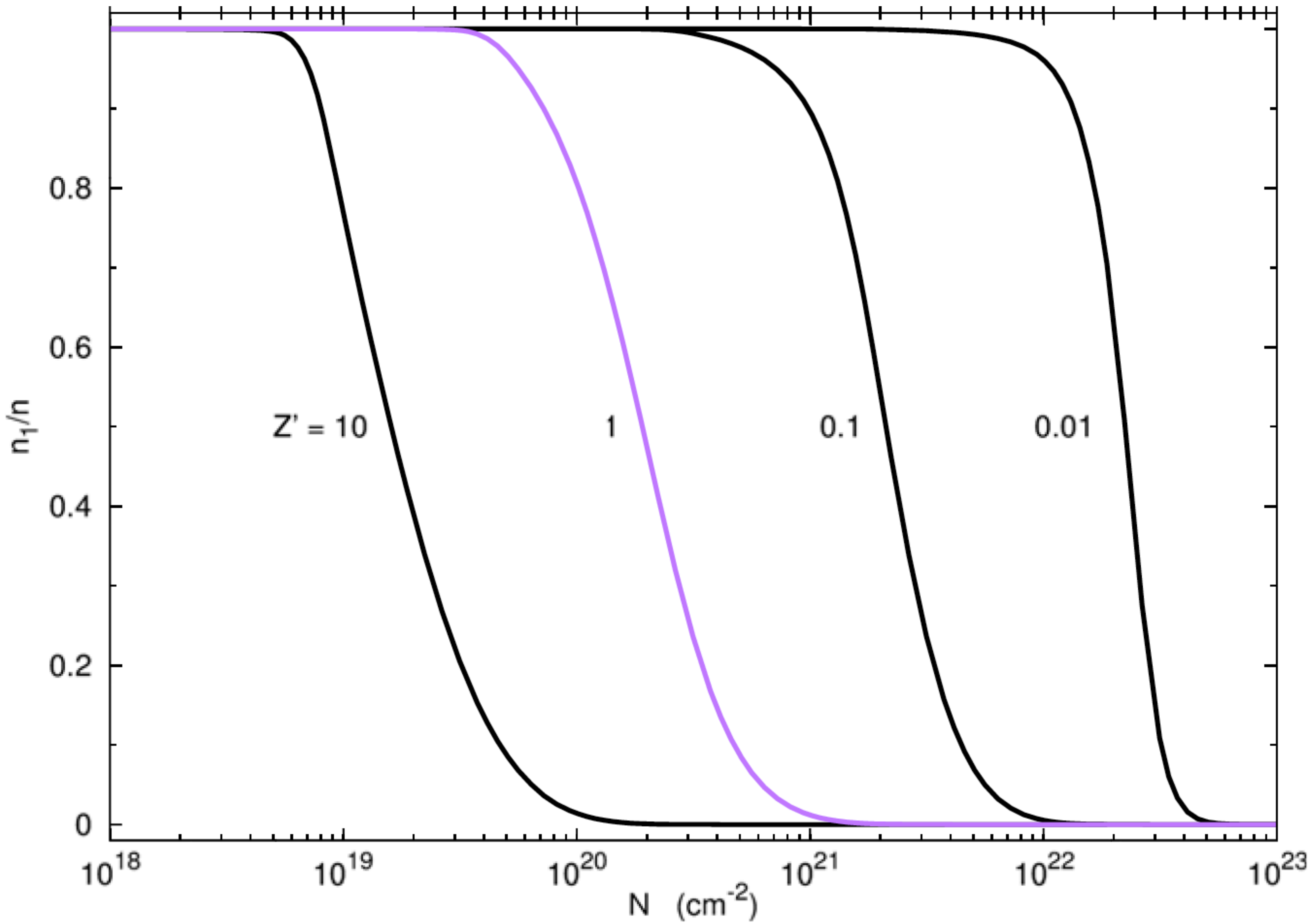


For a given αG the profile “scale lengths” are determined by Z’.

$$\sigma_g = 1.9 \times 10^{-21} \phi_g \ Z' \quad \mathrm{cm}^2$$

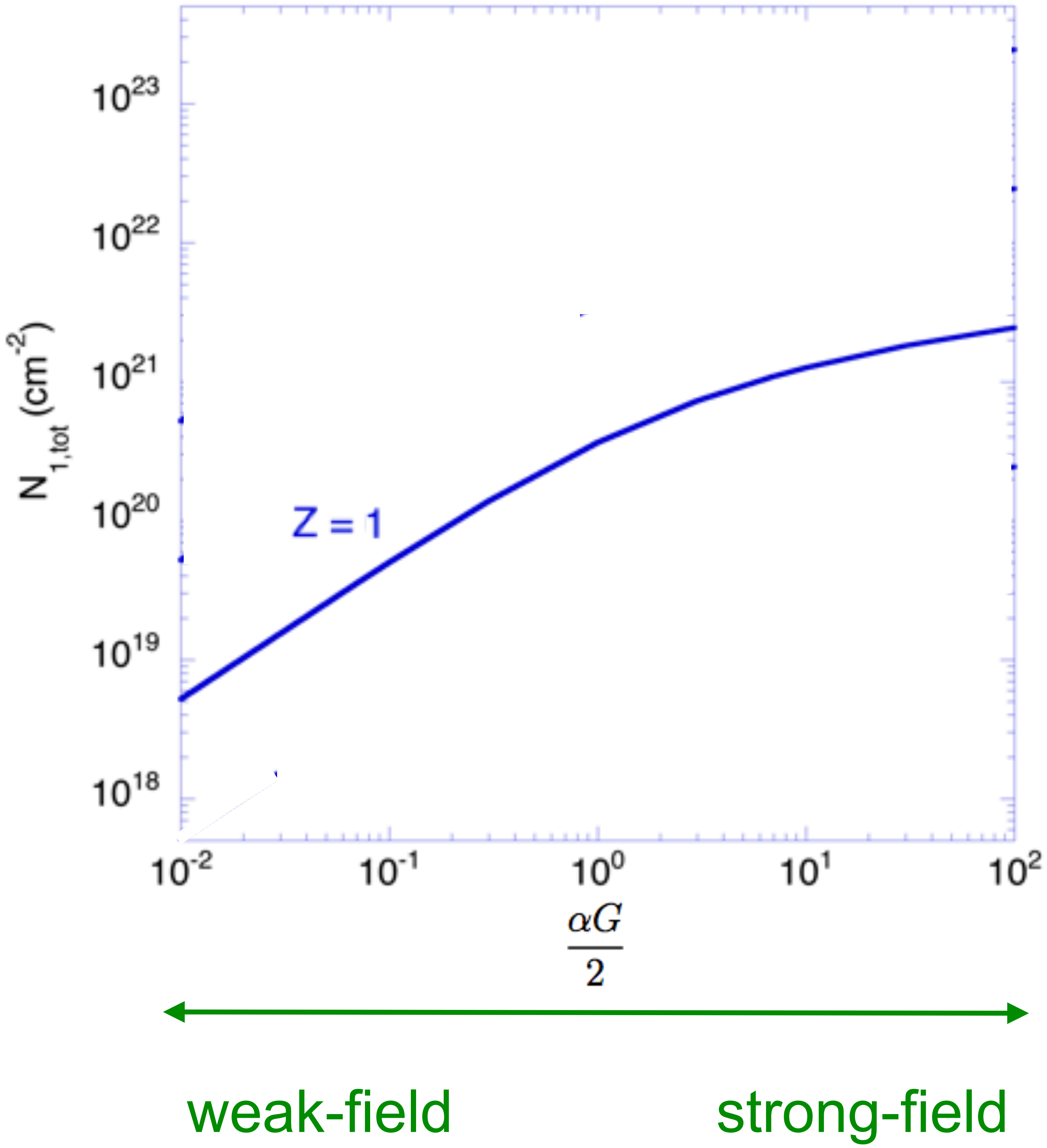
$$R = 3 \times 10^{-17} \left(\frac{T}{100\ \mathrm{K}}\right)^{1/2} Z' \quad \mathrm{cm}^3\ \mathrm{s}^{-1}$$

E.g., HI profiles for αG/2 ≈ 1



General Purpose Analytic Formula for the Total HI Column Density:

$$N_{1,\rm tot} = \frac{1}{\sigma_g} \ln[\frac{\alpha G}{4} + 1] = \frac{1}{\sigma_g} \ln[\frac{1}{4}\frac{\bar{f}_{\rm diss}\sigma_g w F_0}{Rn} + 1]$$

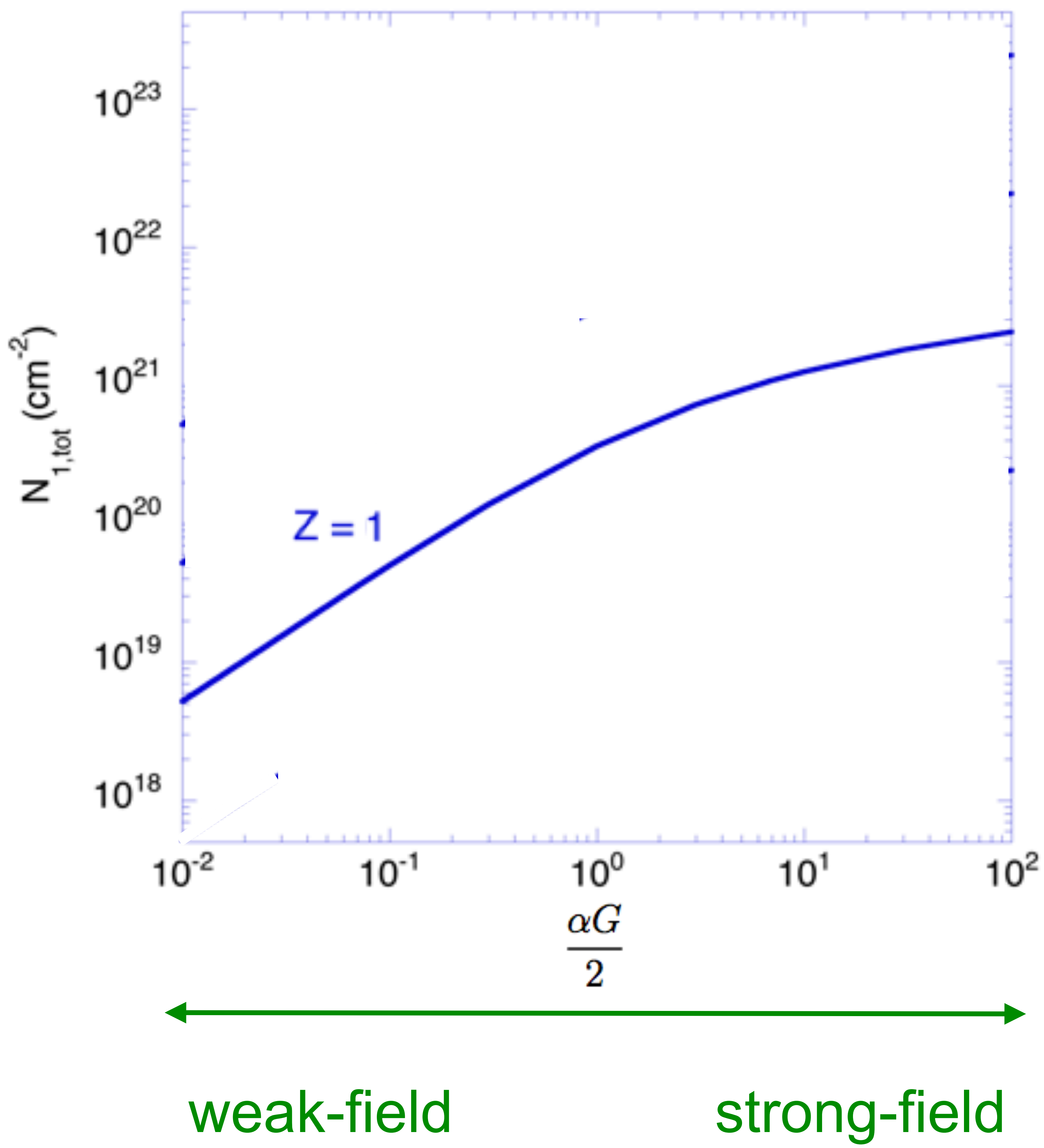


Valid for all regimes:

- weak and strong fields
- gradual to sharp transitions
- arbitrary metallicity

[note: no reference to the H_2 line photodissociation cross sections!]

Weak-Field Limit:



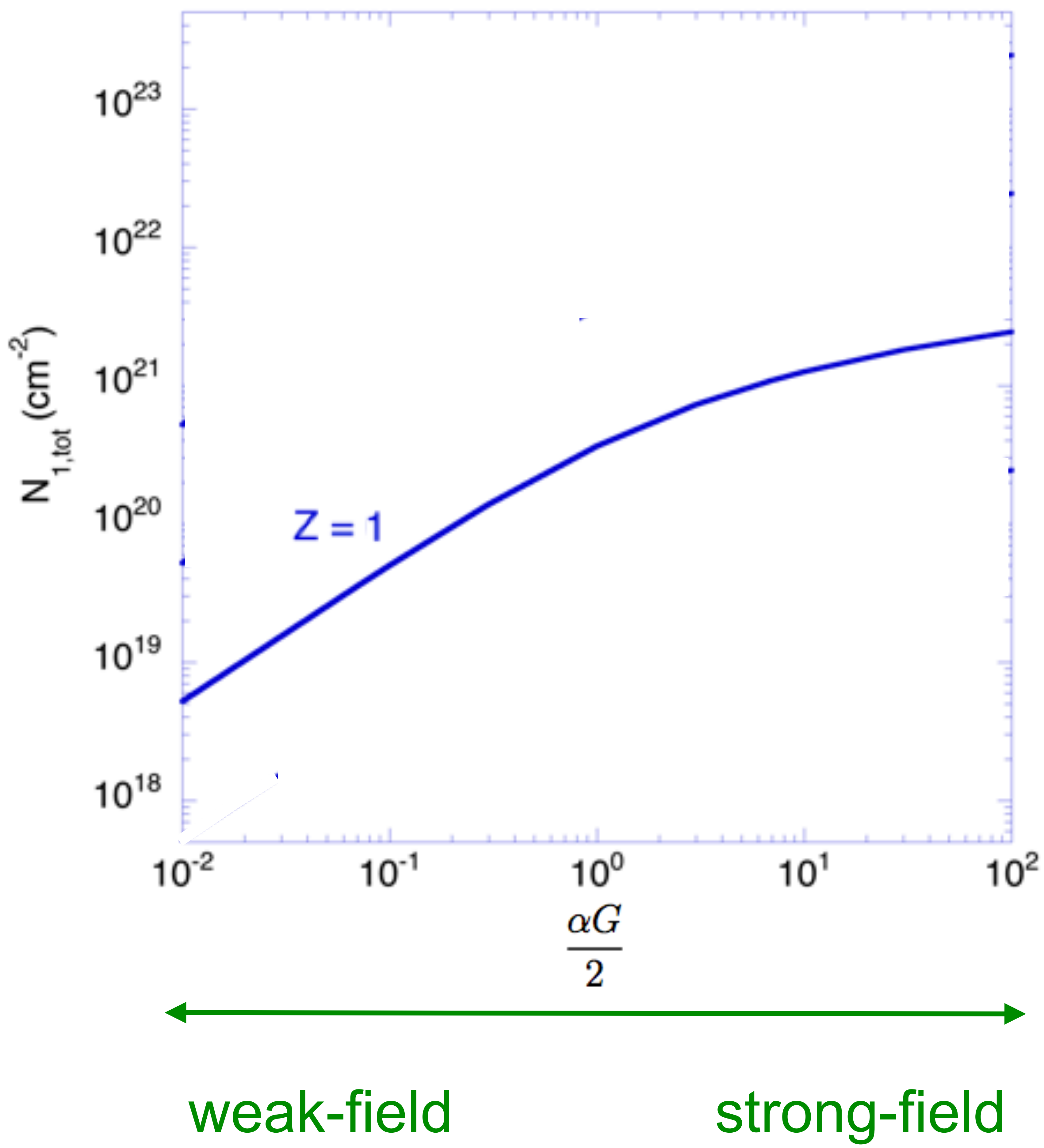
$$N_{1,\mathrm{tot}} = \frac{1}{4}\frac{\bar{f}_{\mathrm{diss}} w F_0}{Rn}$$

$$Rn\ N_{1,\mathrm{tot}} = \frac{1}{4}\bar{f}_{\mathrm{diss}} w F_0$$

formation rate per unit area = effective dissociation flux

(a “Strömgren Relation”)

<u>Strong-Field Limit:</u>



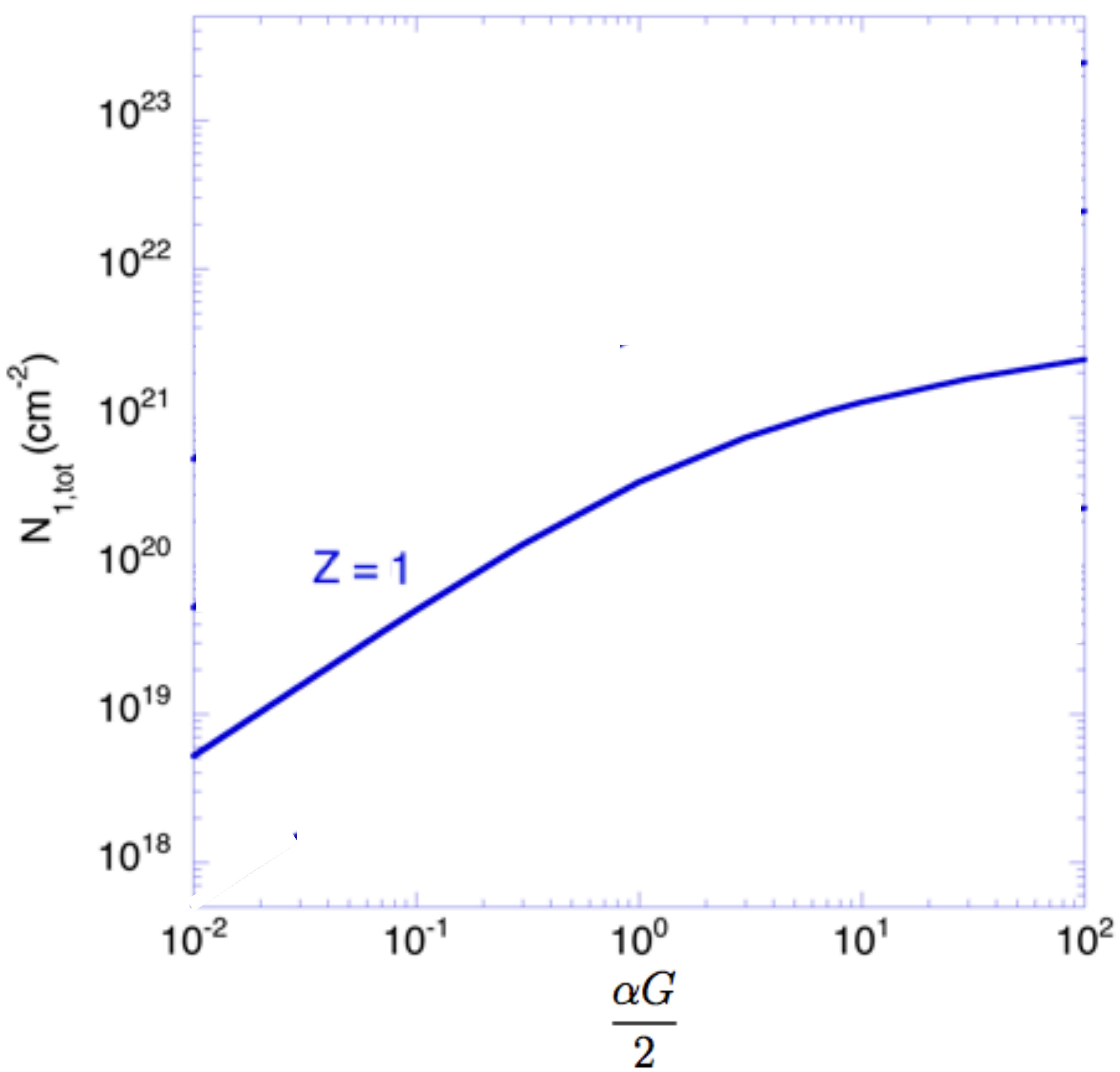
$$N_{1,\mathrm{tot}} \approx \frac{1}{\sigma_g}$$

(neglecting the logarithmic term)

makes sense: When HI-dust dominates the attenuation of the far-UV field, the HI-column is "self-limited" and

$$\tau_{\mathrm{HIdust}} = \sigma_g N_{1,\mathrm{tot}} \approx 1$$

Heavy-Element Abundances "Metallicity": Z'



$$R \propto Z' \qquad \sigma_g \propto Z'$$

H_2 formation rate coefficient
and dust absorption cross-section
both proportional to metallicity.

$$N_{1,\mathrm{tot}} = \frac{1}{4}\frac{\bar{f}_{\mathrm{diss}} w F_0}{Rn} \propto \frac{1}{Z'}$$

weak-field

$$N_{1,\mathrm{tot}} \approx \frac{1}{\sigma_g} \propto \frac{1}{Z'}$$

strong-field

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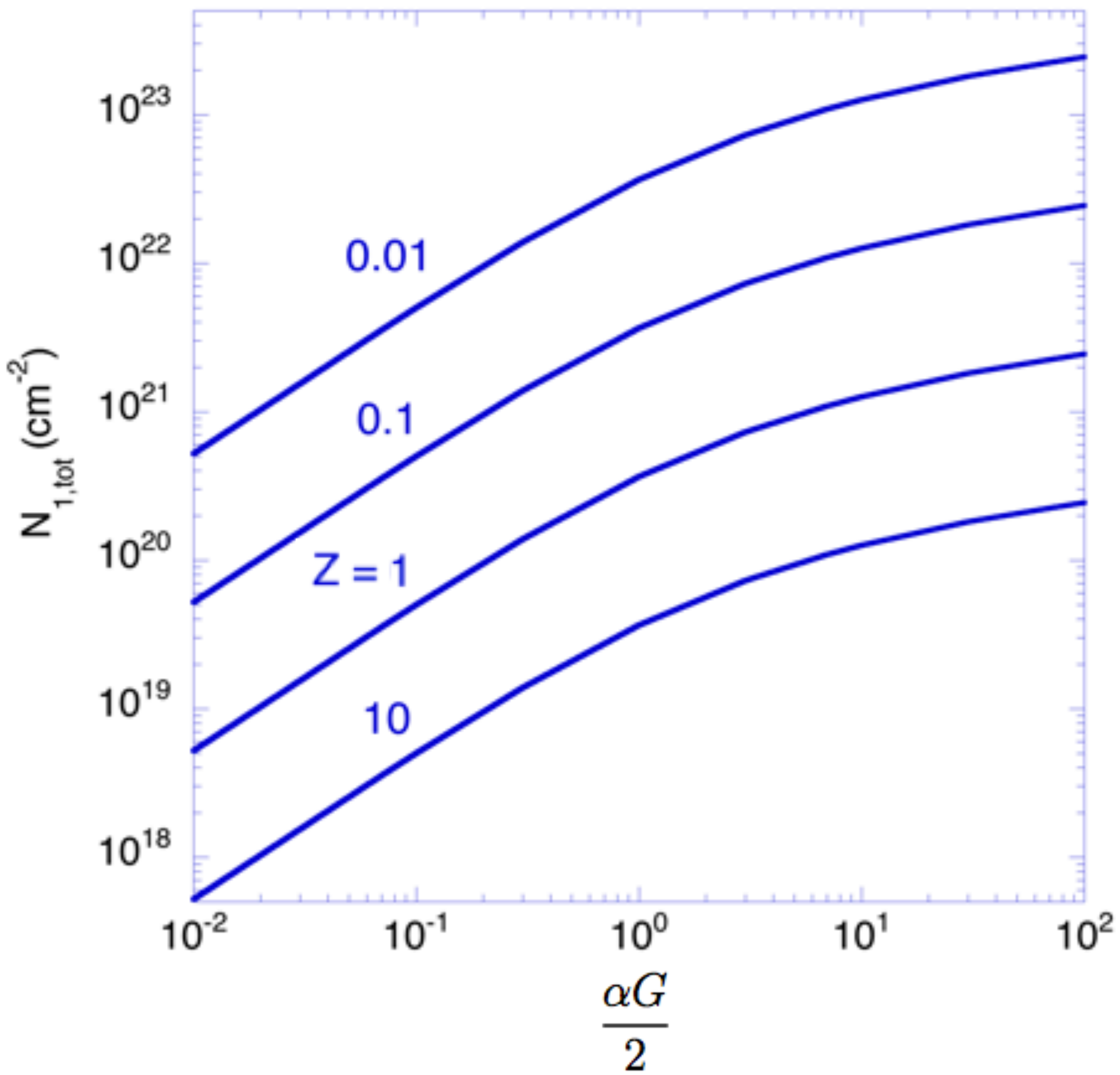

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S+ 2014

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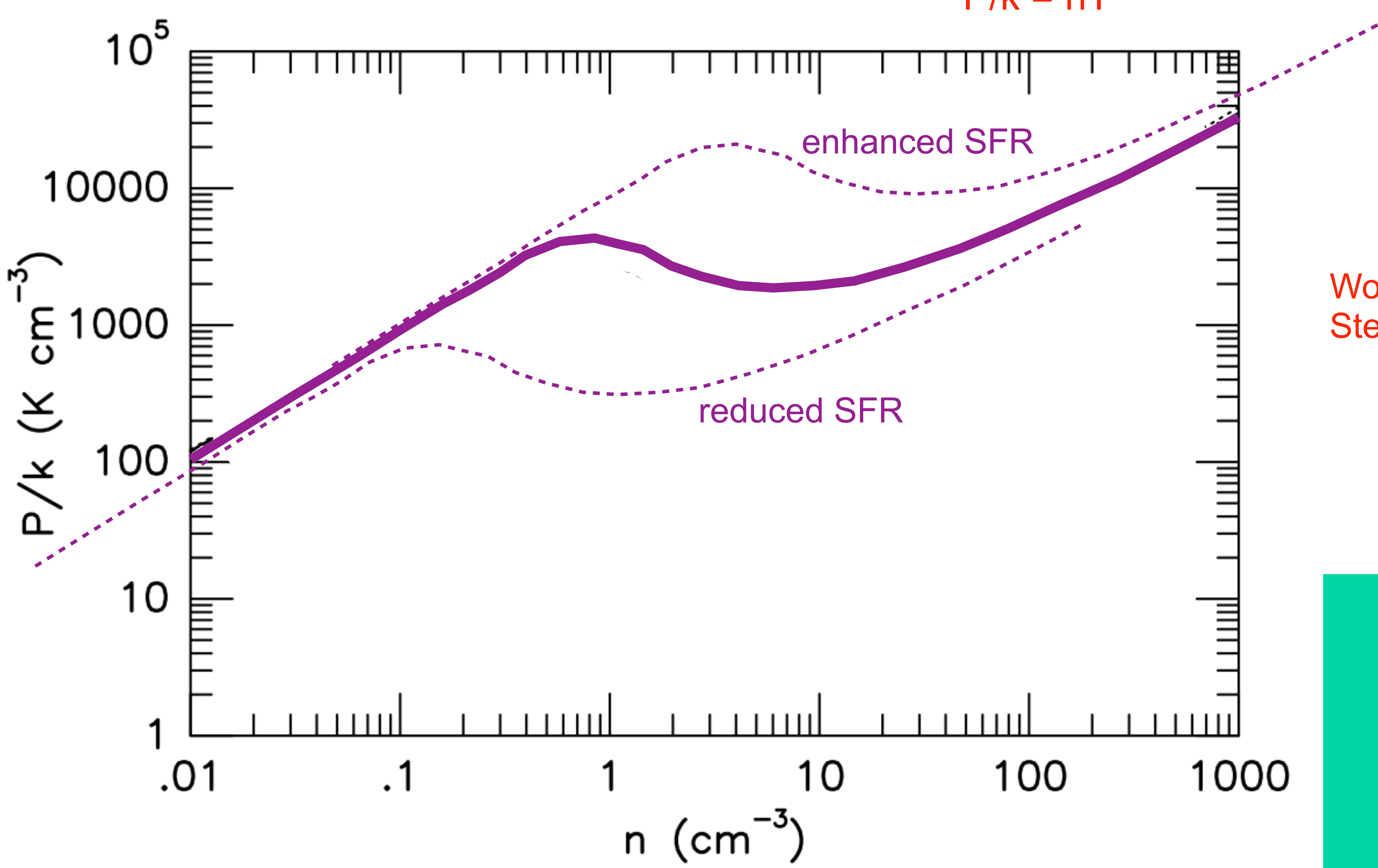
- useful for interpreting 21cm observations
- incorporation into hydrodynamics simulations
- application to "self-regulated" media

HI Thermal Phases in Self-Regulated Media:

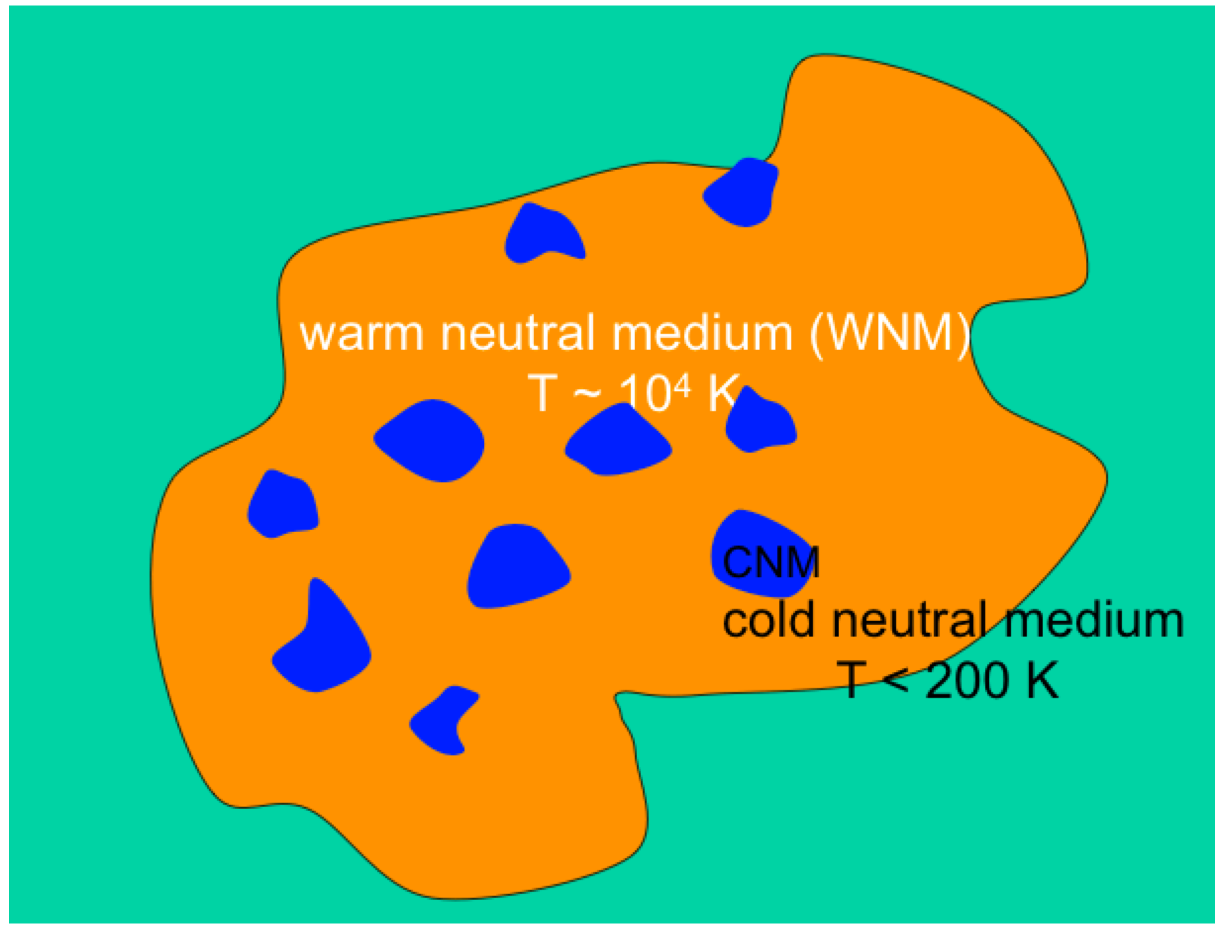
Ansatz:
Krumholz, McKee & Tumlinson 2009

P/k = nT

$$n_{\mathrm{CNM}} \propto F_0$$



Wolfire, McKee & Hollenbach 2003
Sternberg, McKee & Wolfire 2002



Field, Goldsmith & Habing 1969 ApJ 155 149

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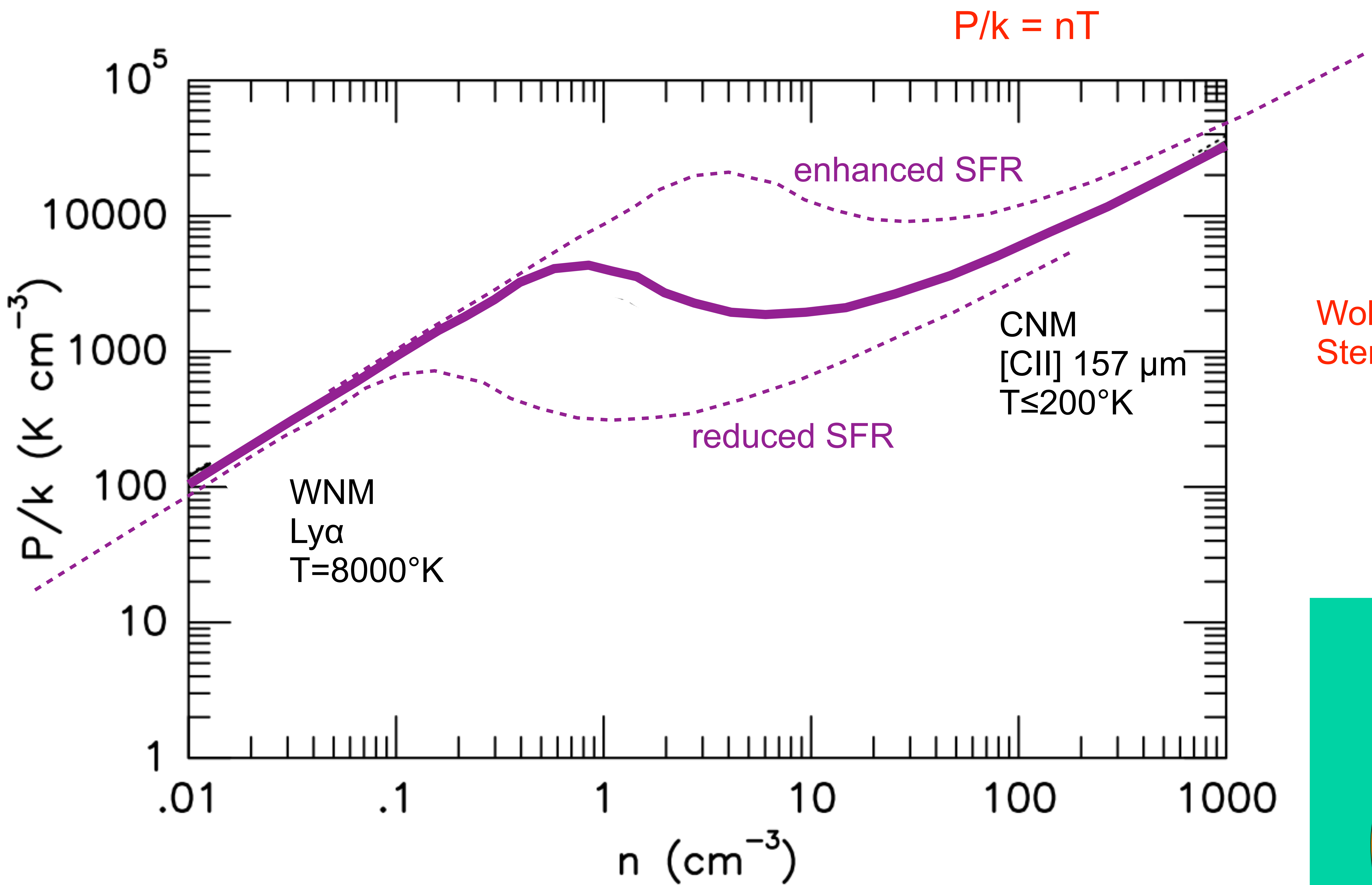

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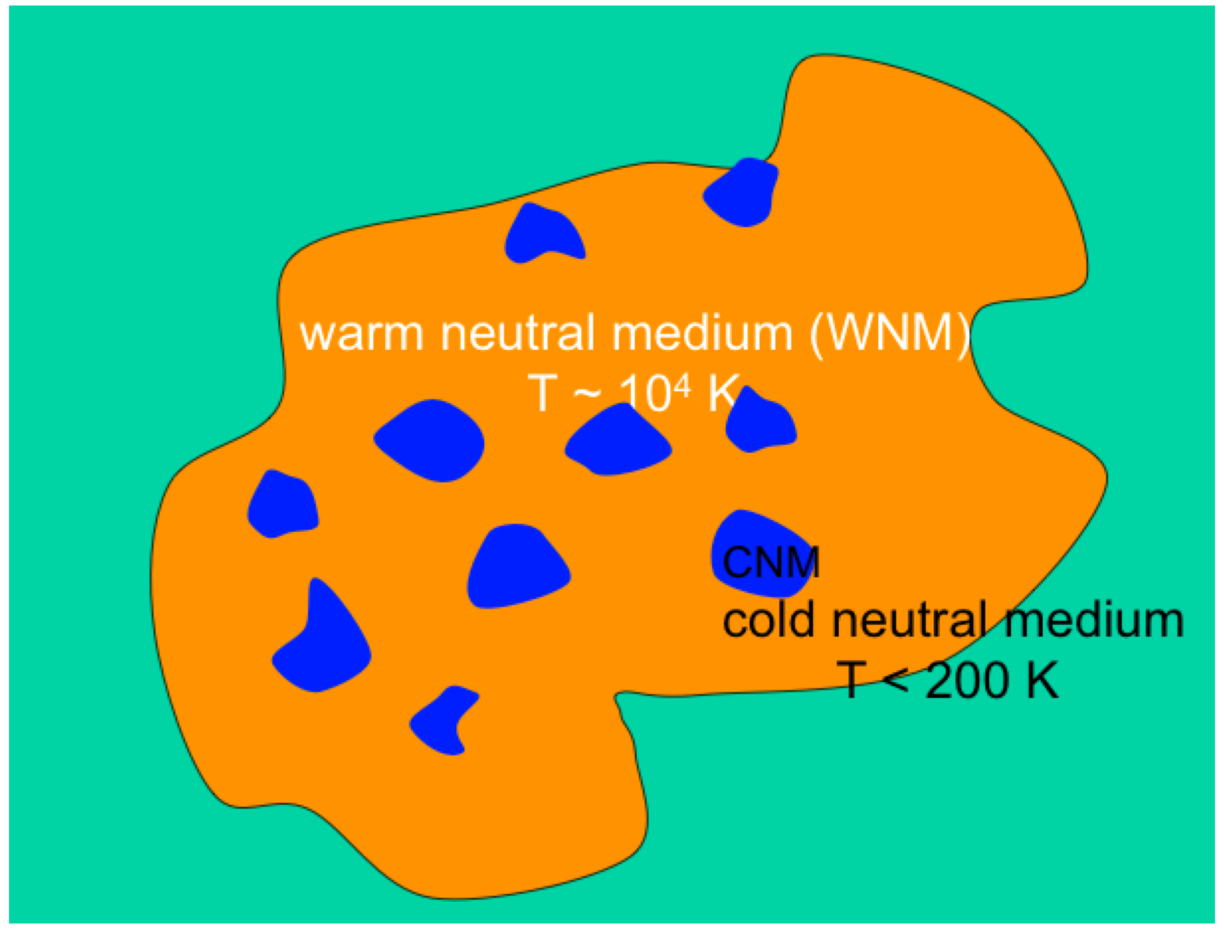

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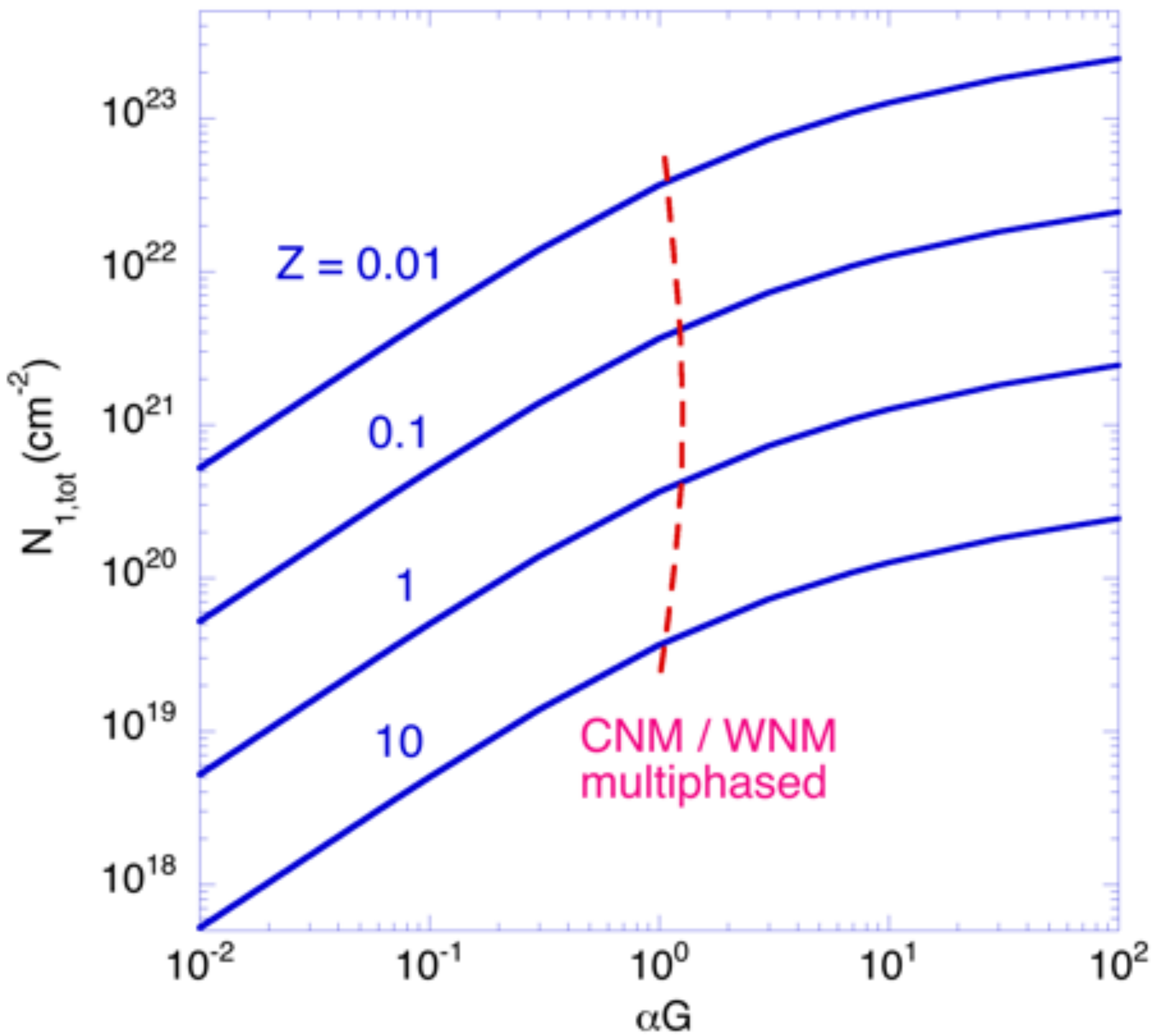
HI Column Density for Self-Regulated Media:

$$\frac{(\alpha G)_{\rm CNM}}{2} \approx 1$$

remarkable!



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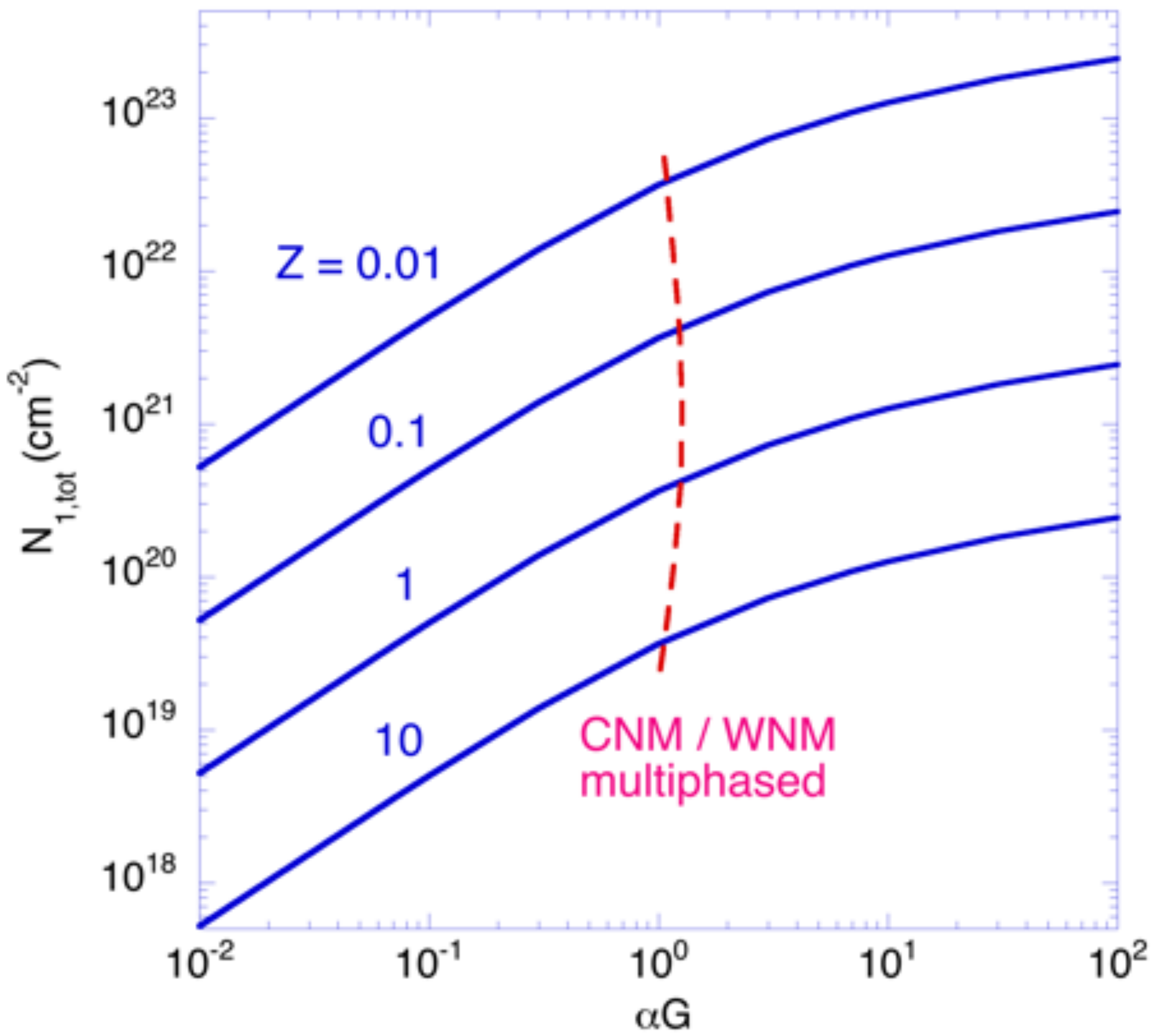


$$\Sigma_{\rm HI} \approx \frac{6}{\phi_g Z'} \quad {\rm M}_\odot\ {\rm pc}^{-2}$$

characteristic HI photodissociation mass surface density in self-regulated systems

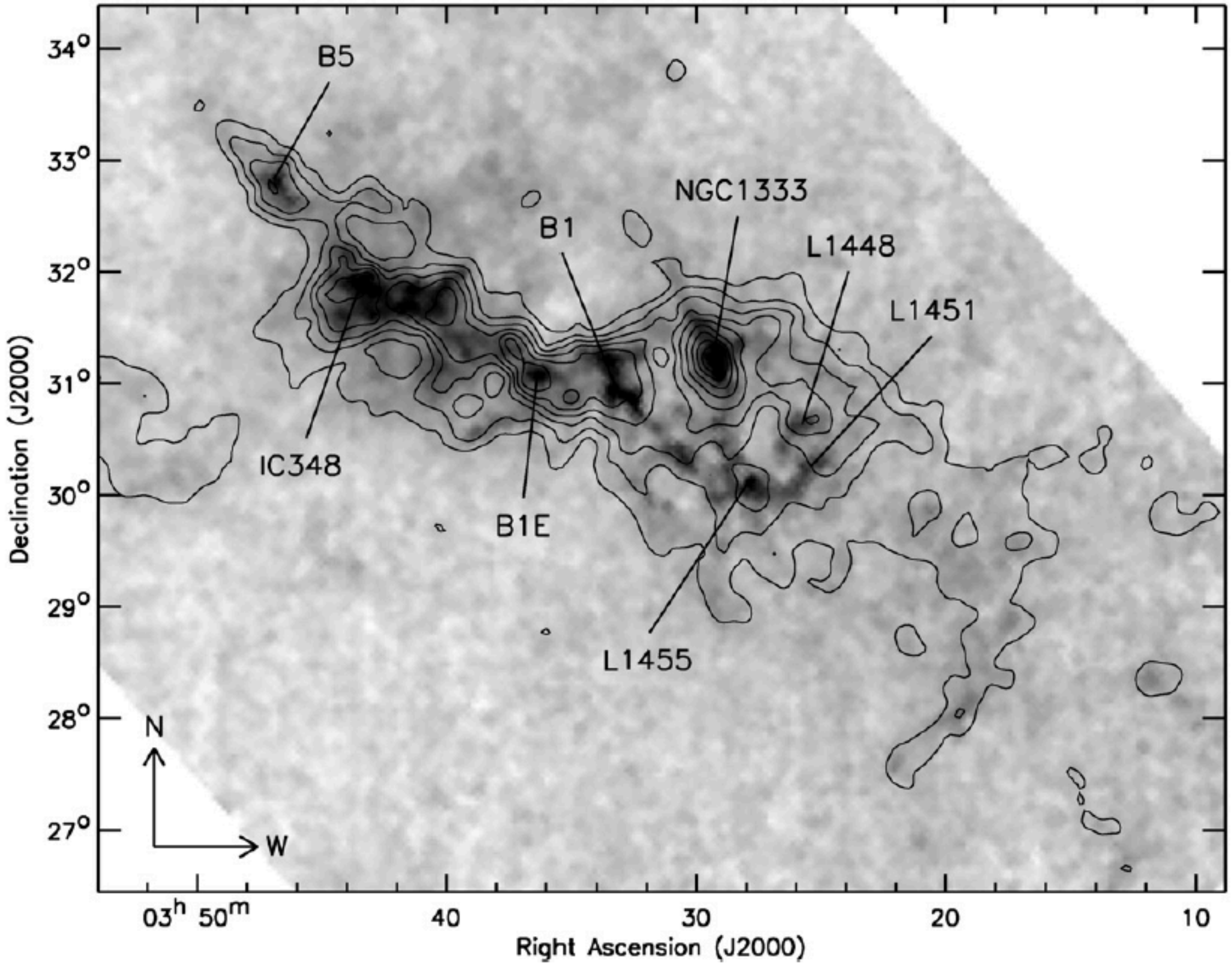
$$\Sigma_{\rm gas,*}(Z') \equiv 2 \times \Sigma_{\rm HI} \approx \frac{12}{\phi_g Z'} \quad {\rm M}_\odot\ {\rm pc}^{-2}$$

“transition” total gas mass surface density... star-formation threshold...galaxies.

independent of radiation field intensity and/or gas density.

HI-to-H_2 in Perseus:

Perseus Cloud   distance 300 pc



2MASS A_V and I_{CO} CfA & COMPLETE surveys

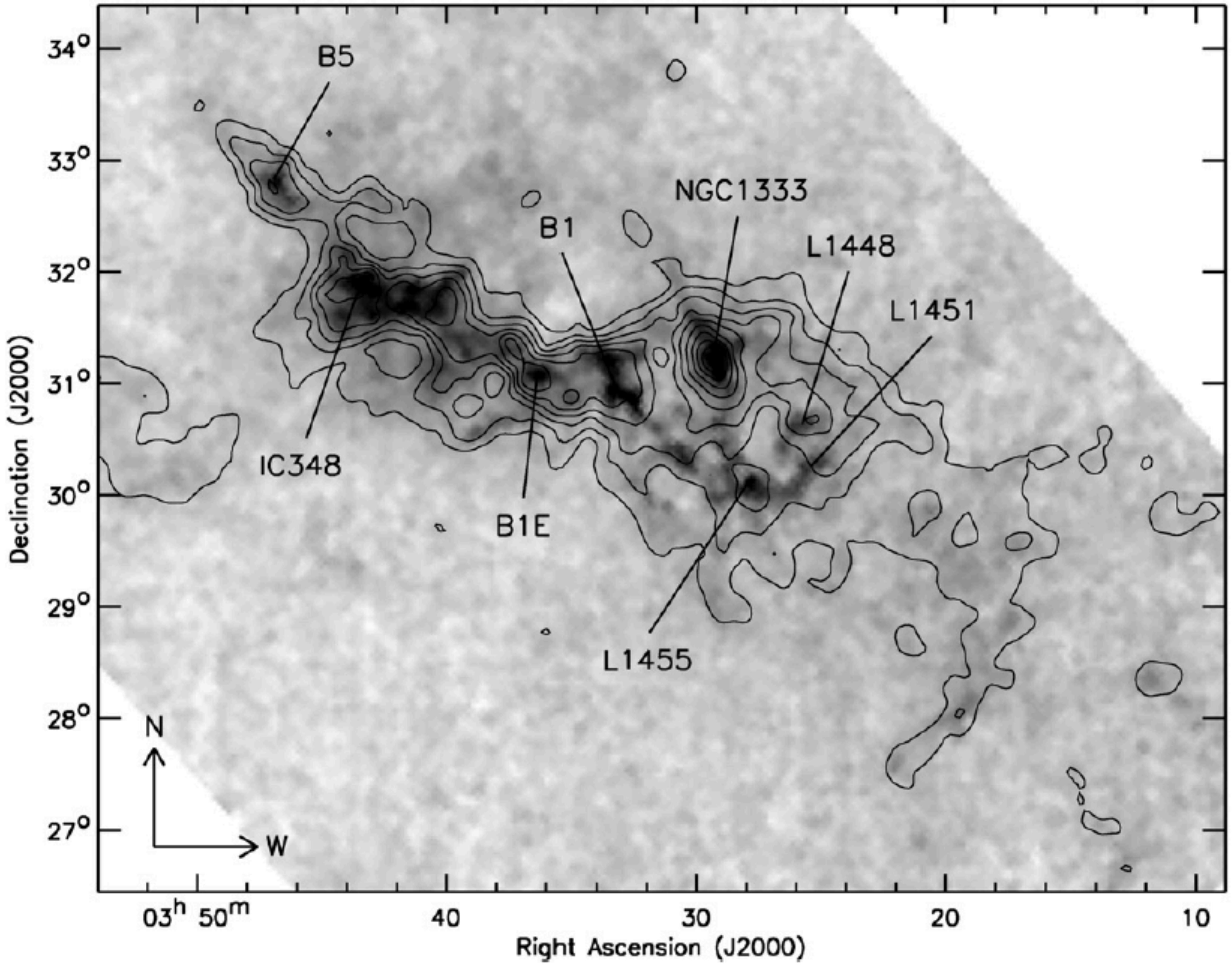
Dame+ 2001 Ridge+ 2006

HI-to-H_2 in Perseus:

dark clouds &
low-mass star-forming regions:

B1
B1E
B5
NGC1333
IC348

Perseus Cloud   distance 300 pc



2MASS A_V and I_{CO} CfA & COMPLETE surveys

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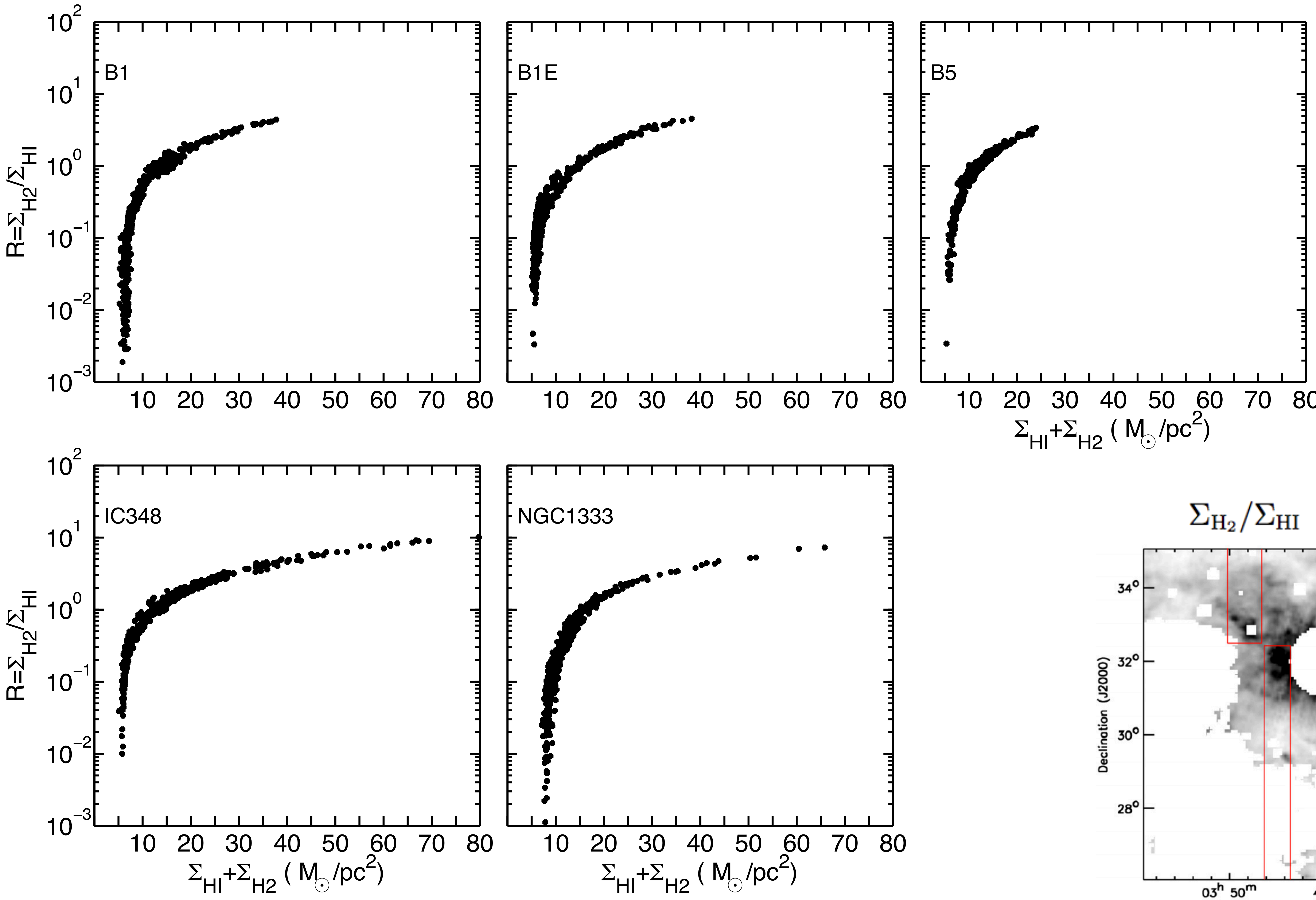
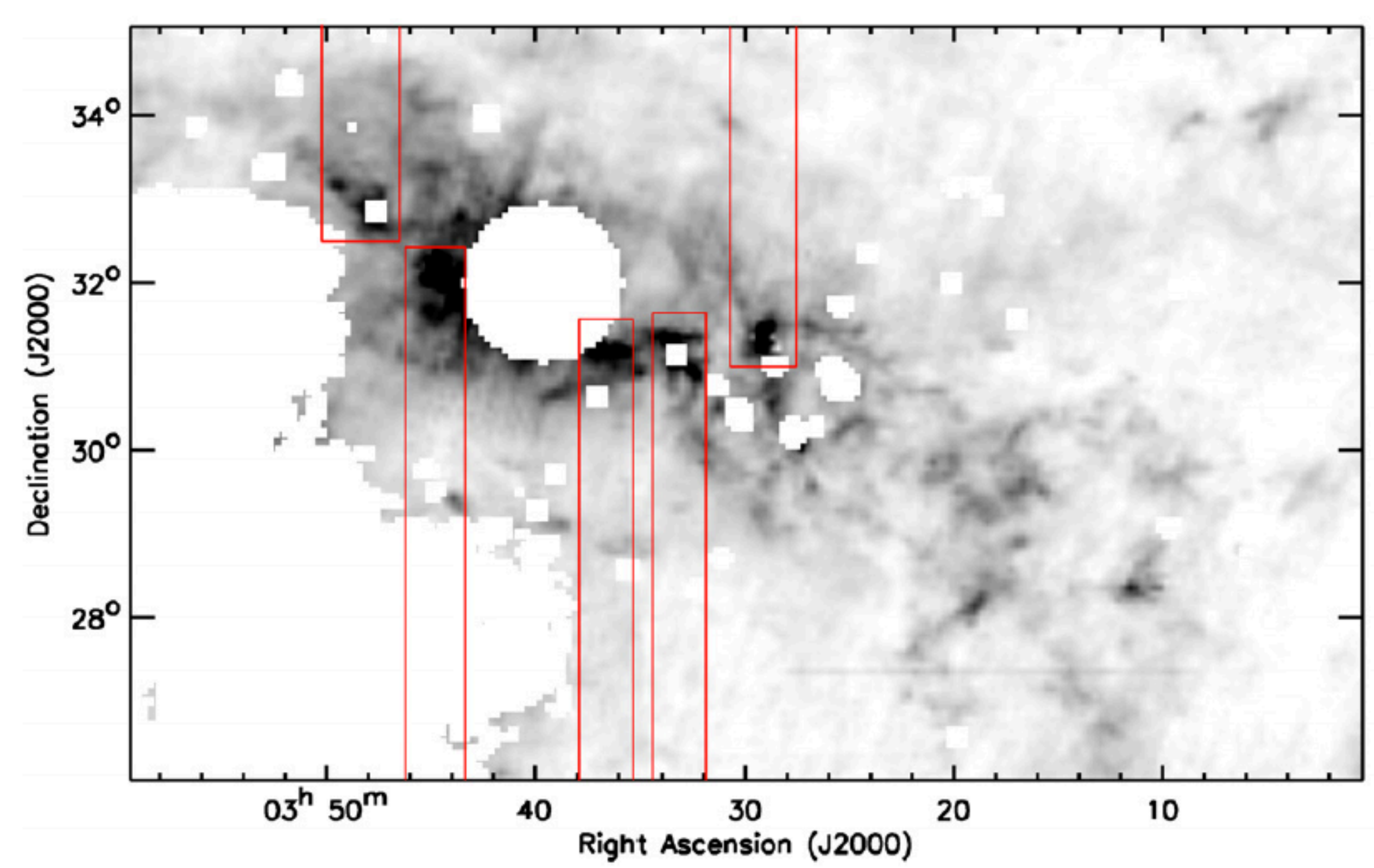
HI-to-H_2 in Perseus:

Lee+ 2012   Peek+ 2011   GALFA HI Survey (Arecibo 4arcmin)

$$\frac{\Sigma_{H_2}}{\Sigma_{HI}} \quad \text{versus} \quad \Sigma_{gas} \equiv \Sigma_{HI} + \Sigma_{H_2}$$

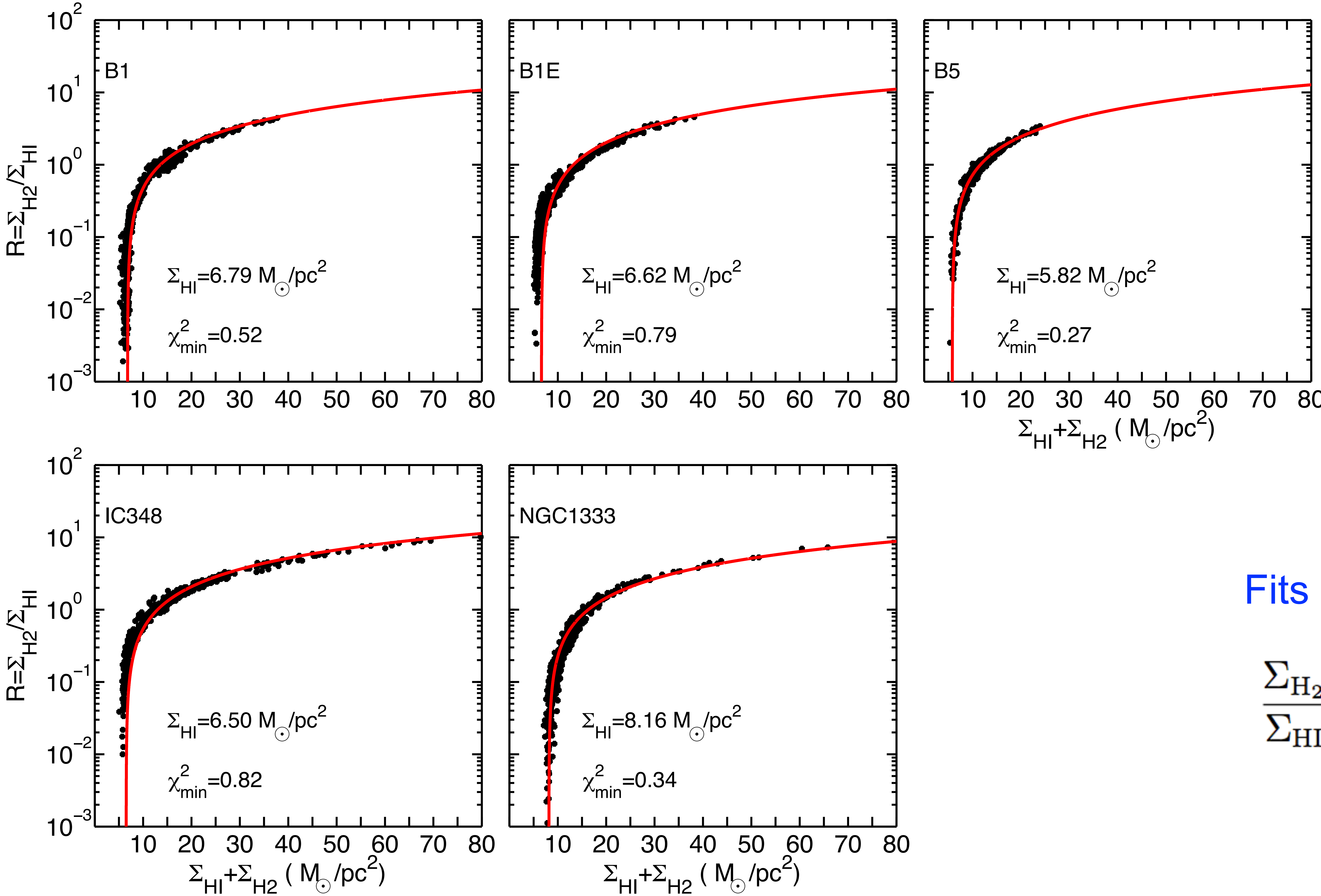


Σ_{H_2}/Σ_{HI} Lee+ 2012



HI-to-H_2 in Perseus:

$$\frac{\Sigma_{H_2}}{\Sigma_{HI}} \quad \text{versus} \quad \Sigma \equiv \Sigma_{HI} + \Sigma_{H_2}$$

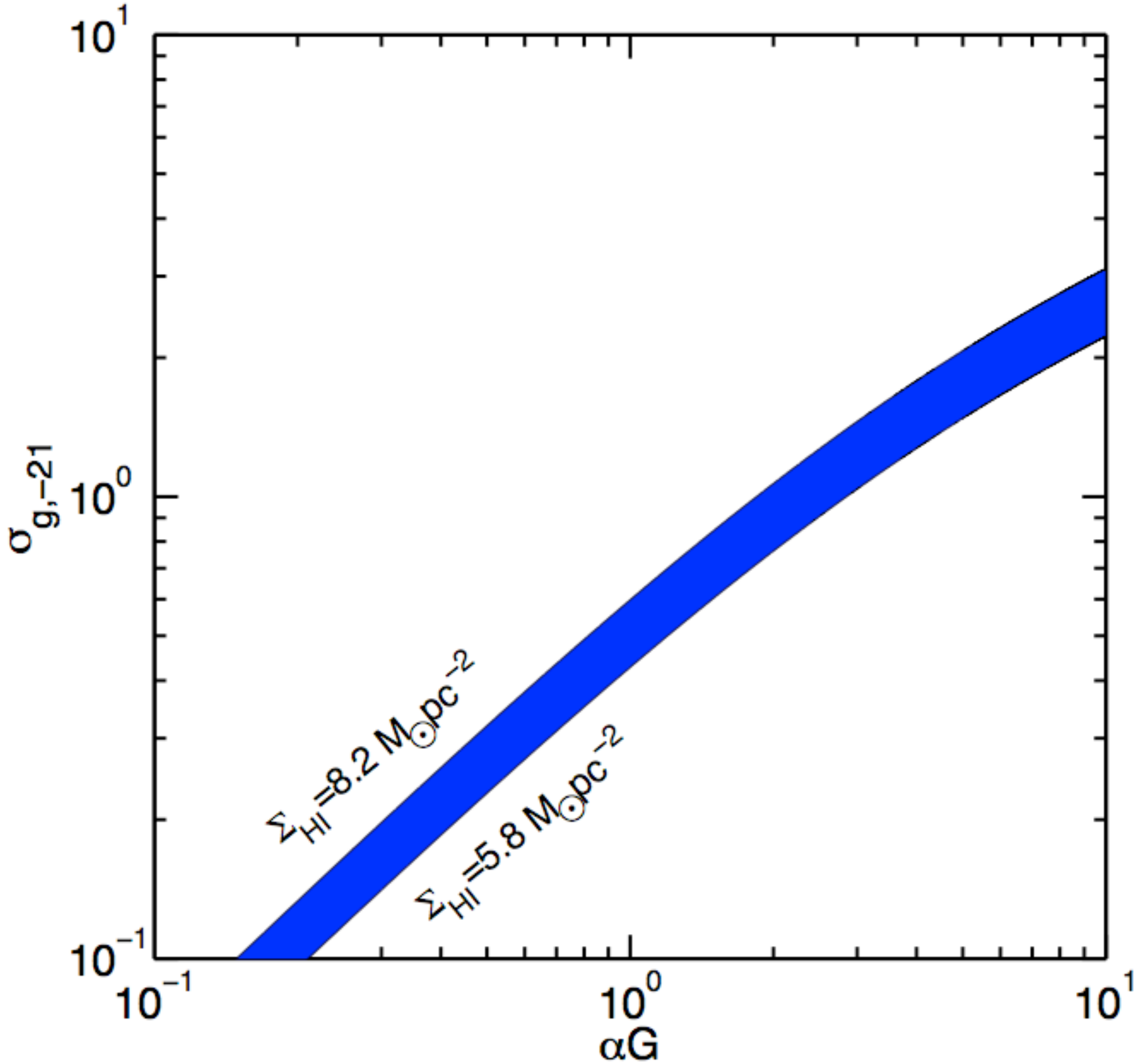


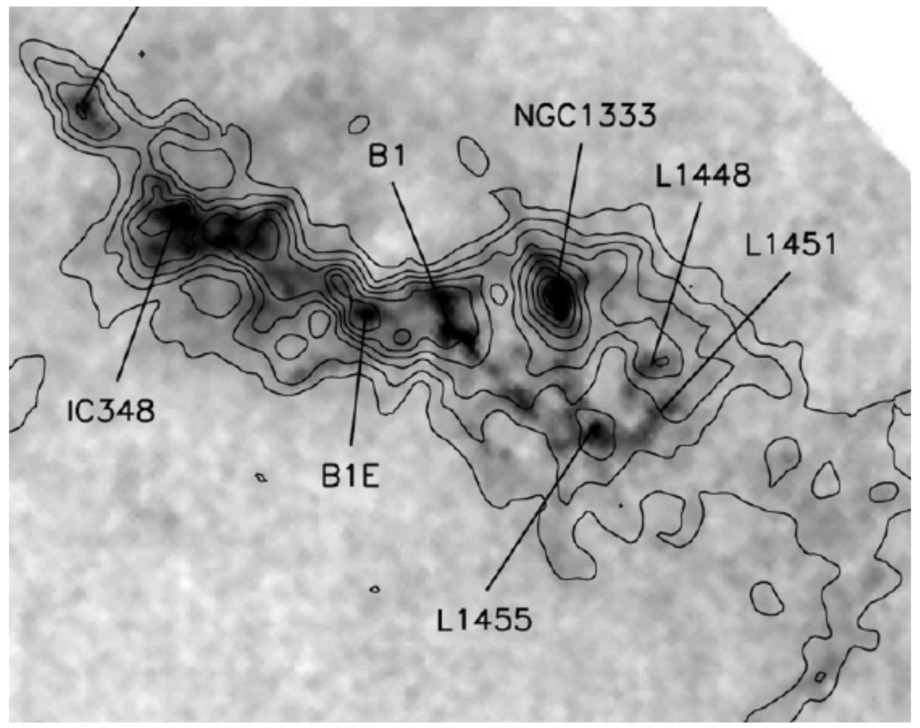
Fits using S+14:

$$\frac{\Sigma_{H_2}}{\Sigma_{HI}} = \frac{\Sigma_{gas}}{\Sigma_{HI}} - 1$$

HI-to-H_2 in Perseus: Analysis

$$N_{1,\mathrm{tot}} = \frac{1}{\sigma_g} \ln\left[\frac{\alpha G}{4} + 1\right]$$





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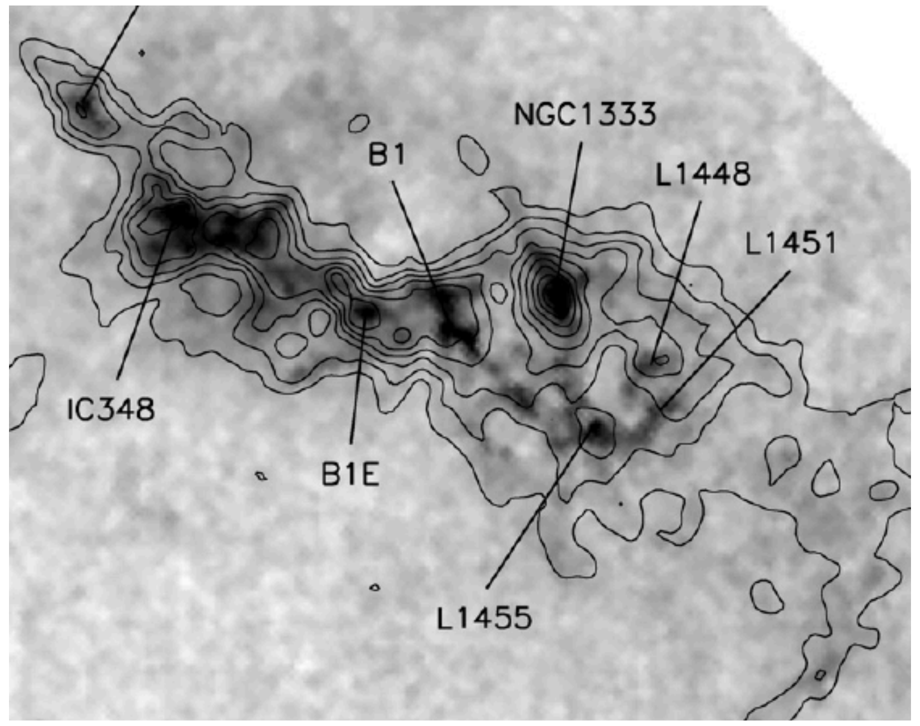

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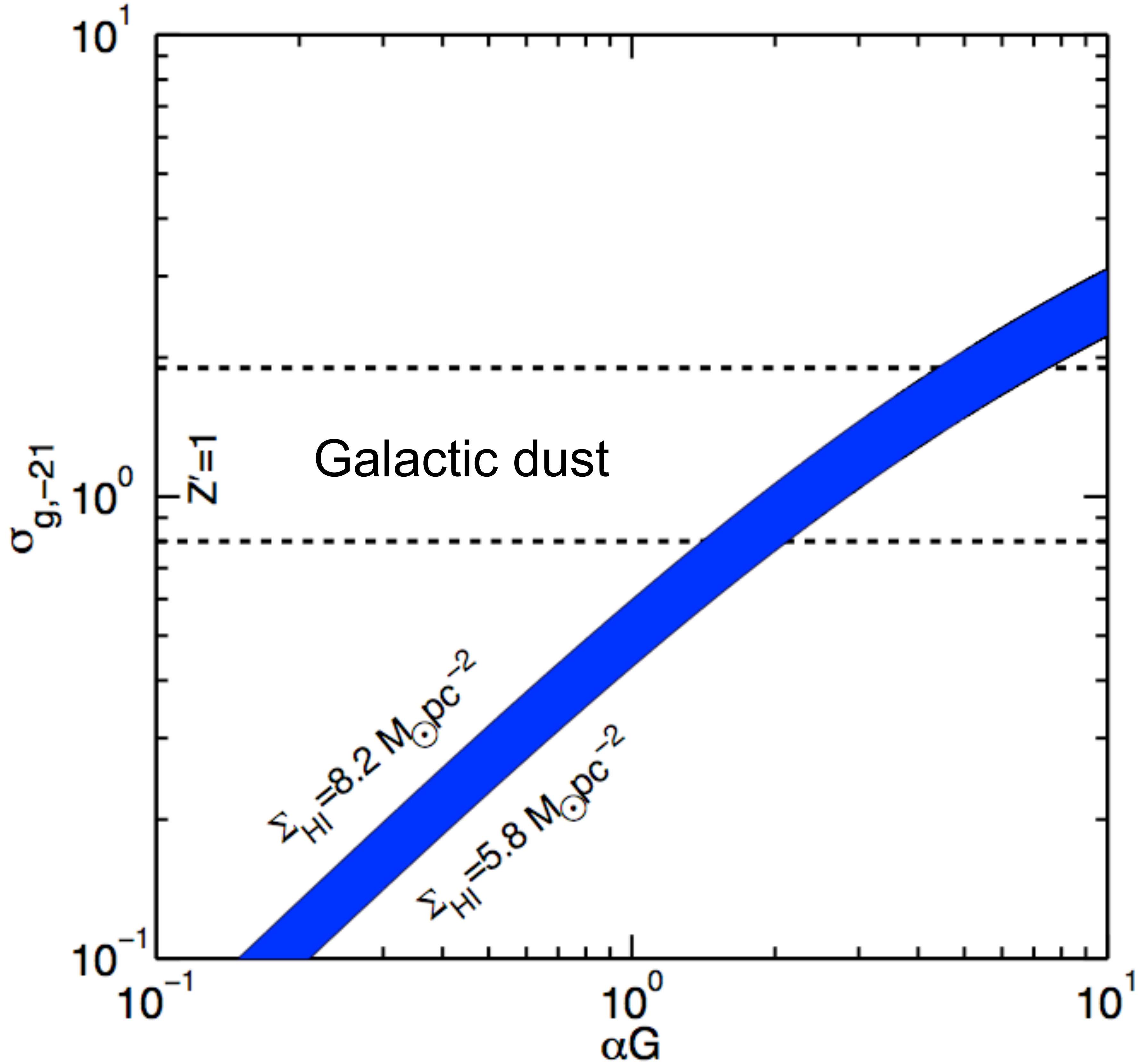

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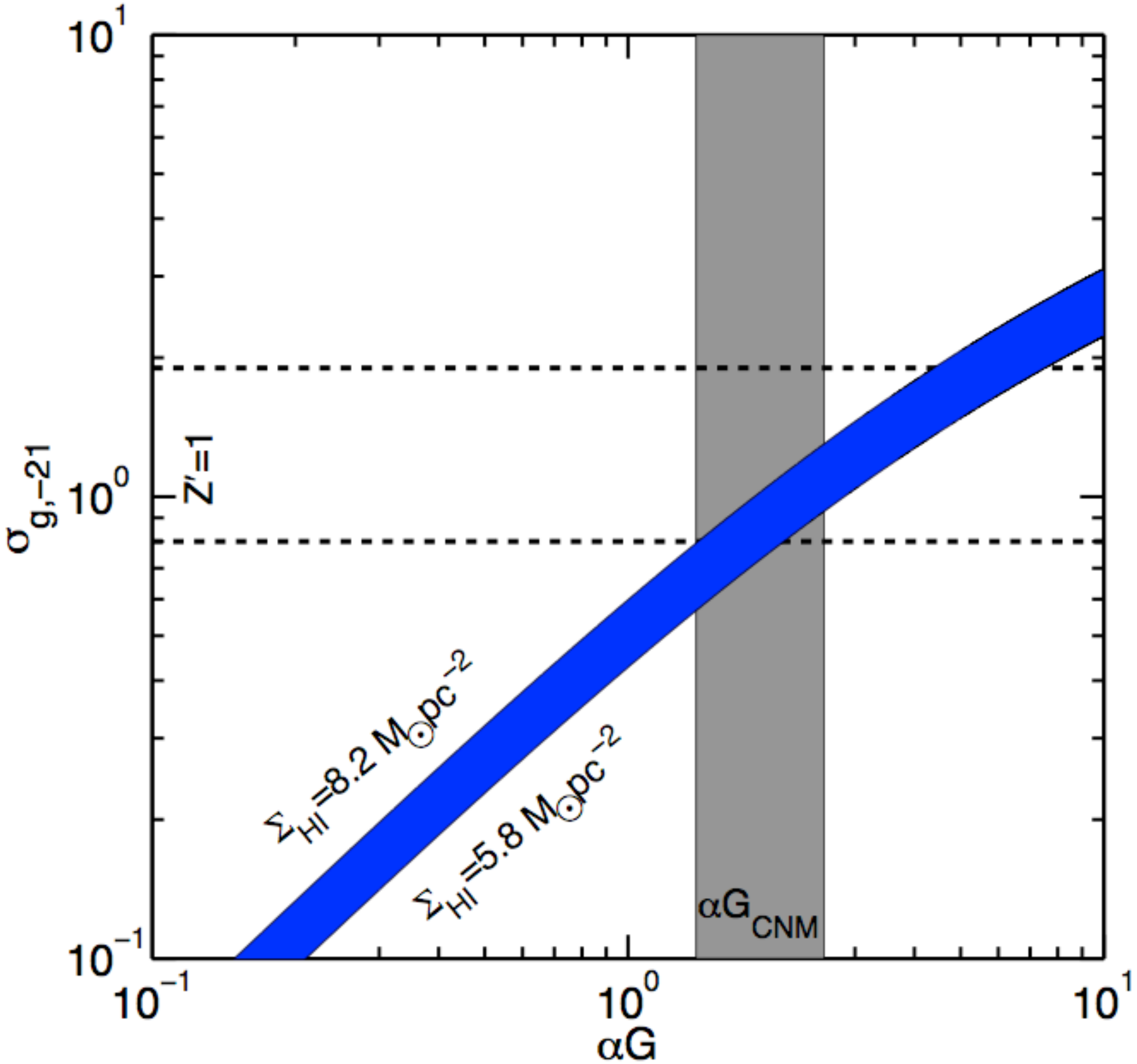
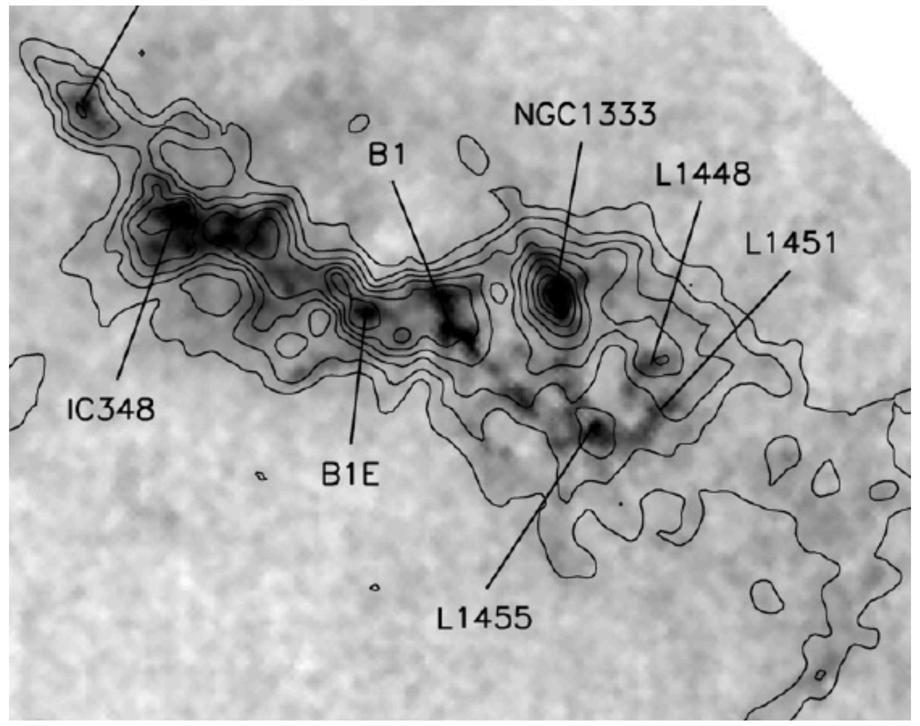
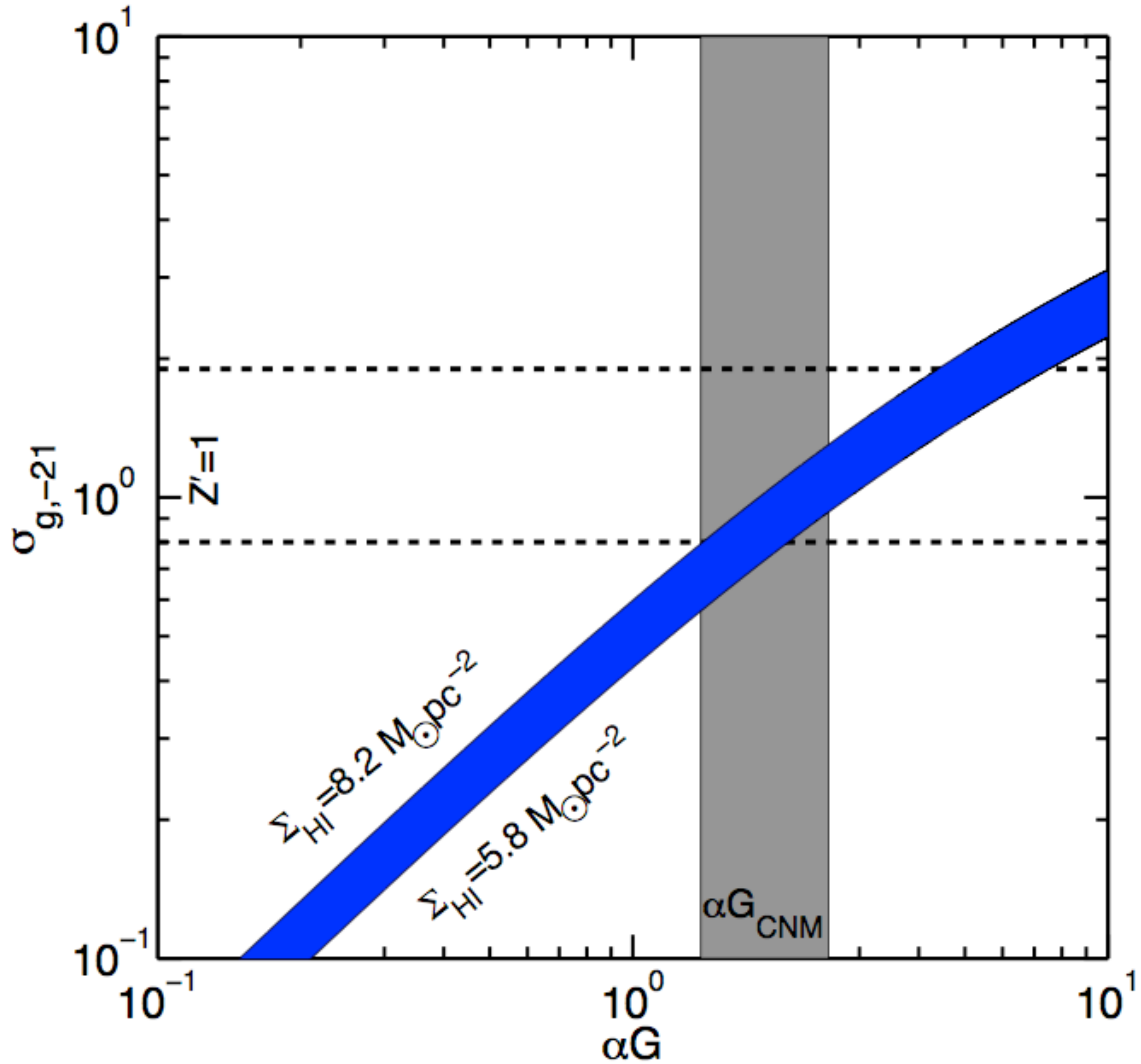
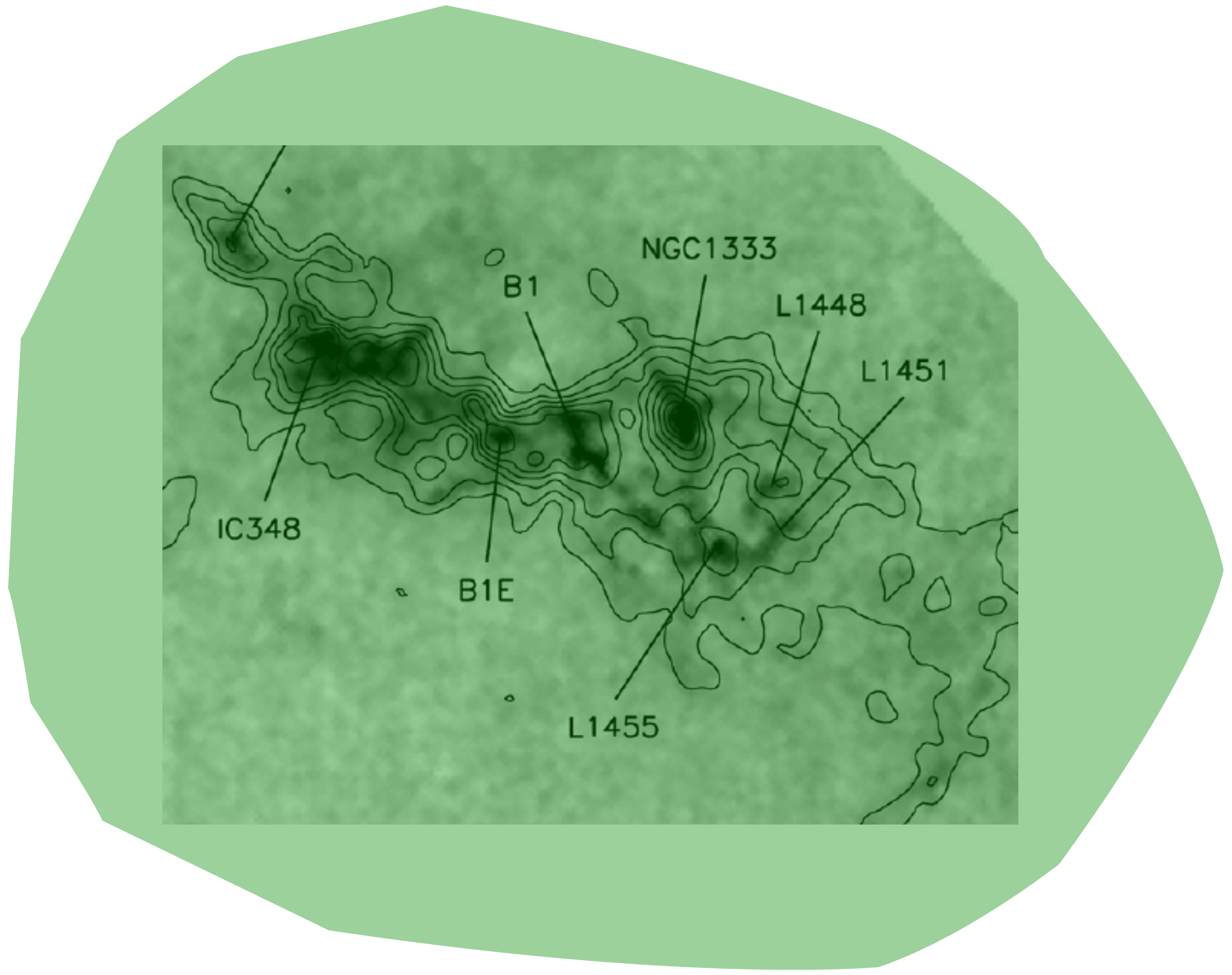




HI-to-H_2 in Perseus: Analysis

$$N_{1,\mathrm{tot}} = \frac{1}{\sigma_g} \ln[\frac{\alpha G}{4} + 1]$$





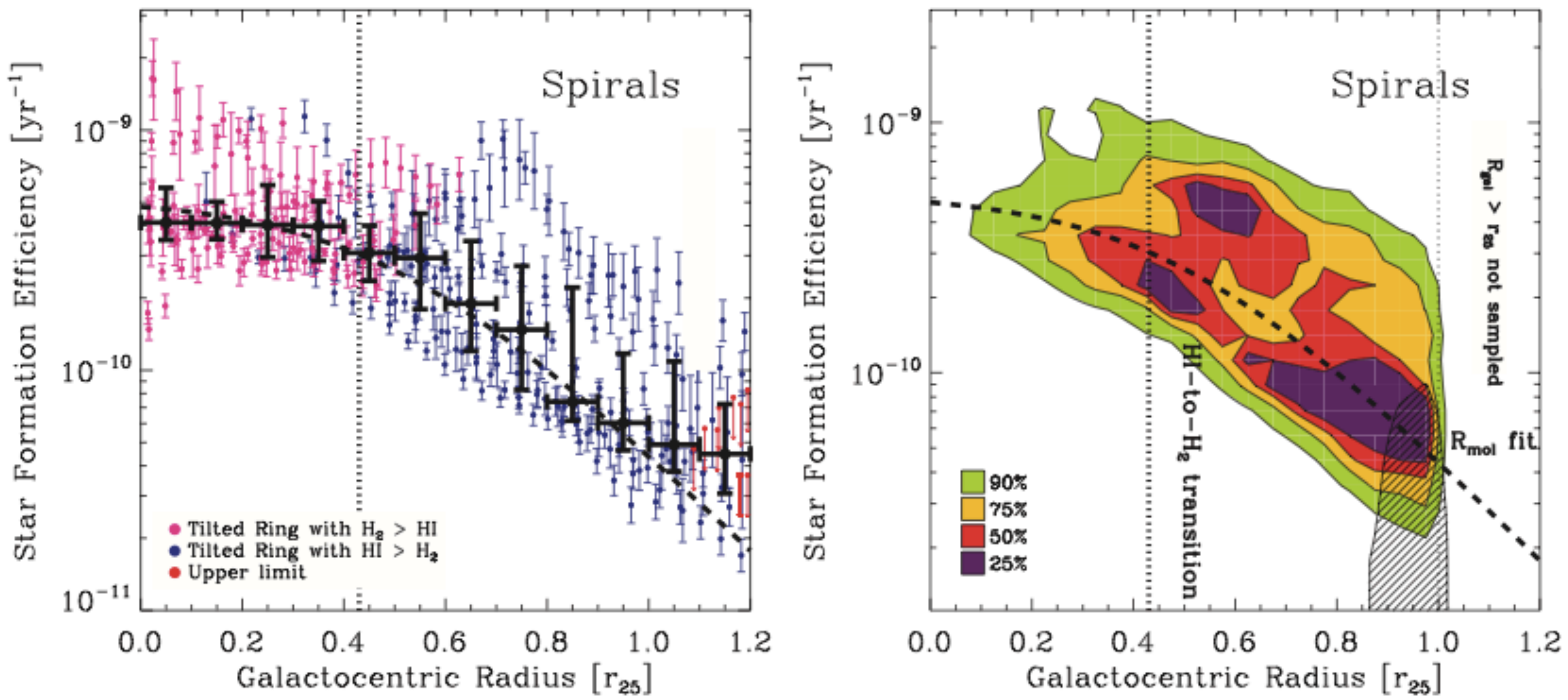
Galactic interstellar LW radiation field:
$F_0 \approx 2 \times 10^7$ photons cm^{-2} s^{-1}

Conclusions: $\alpha G \approx 2$ to 6

- FUV absorption dominated by HI-dust
- $n_{HI} \approx 20$ to 3 cm^{-3}
- consistent with CNM/WNM mixture

Galaxies:

e.g. Bigiel+ 08



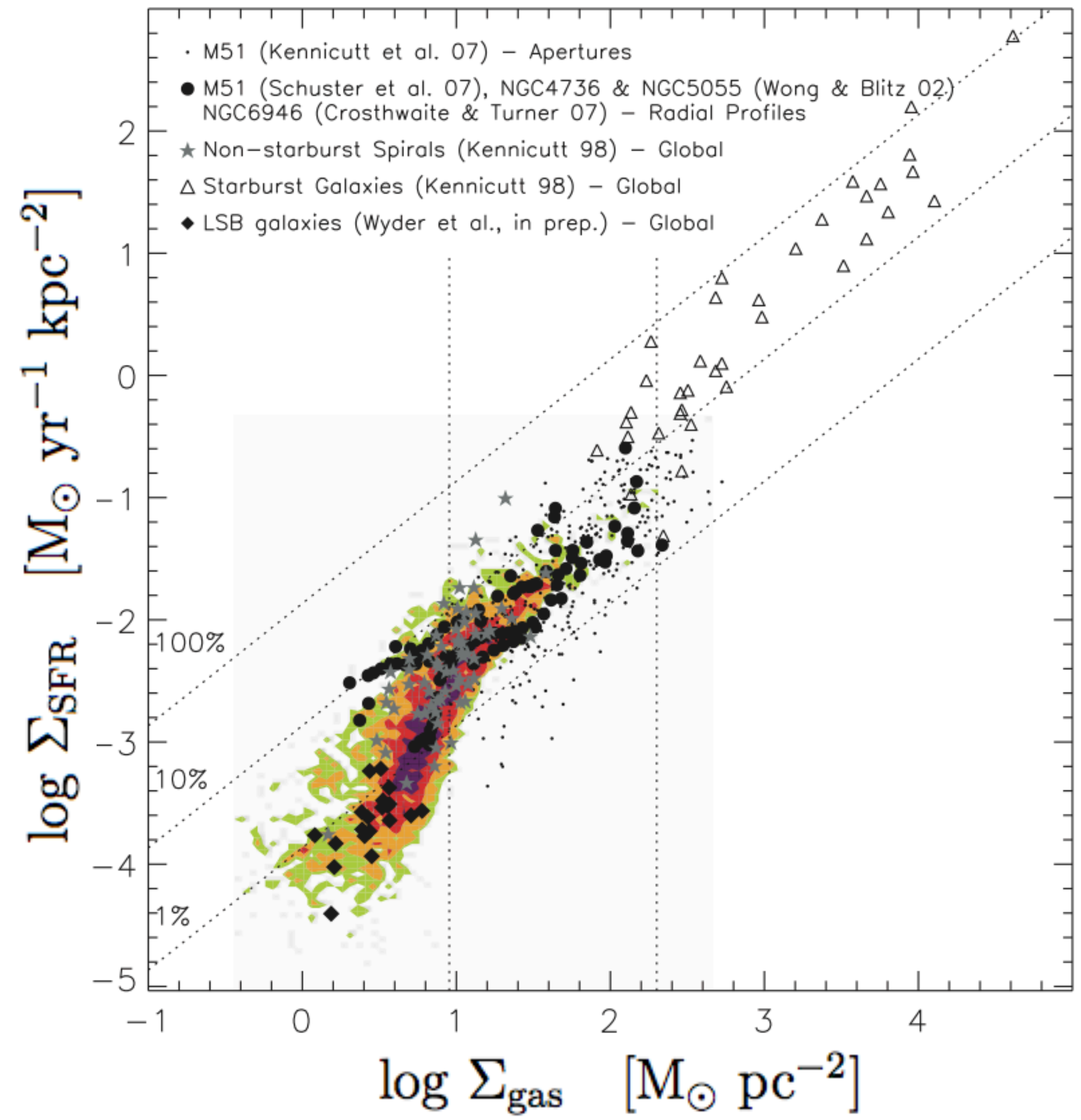


Table 5
Conditions at the H I-to-H$_2$ Transition

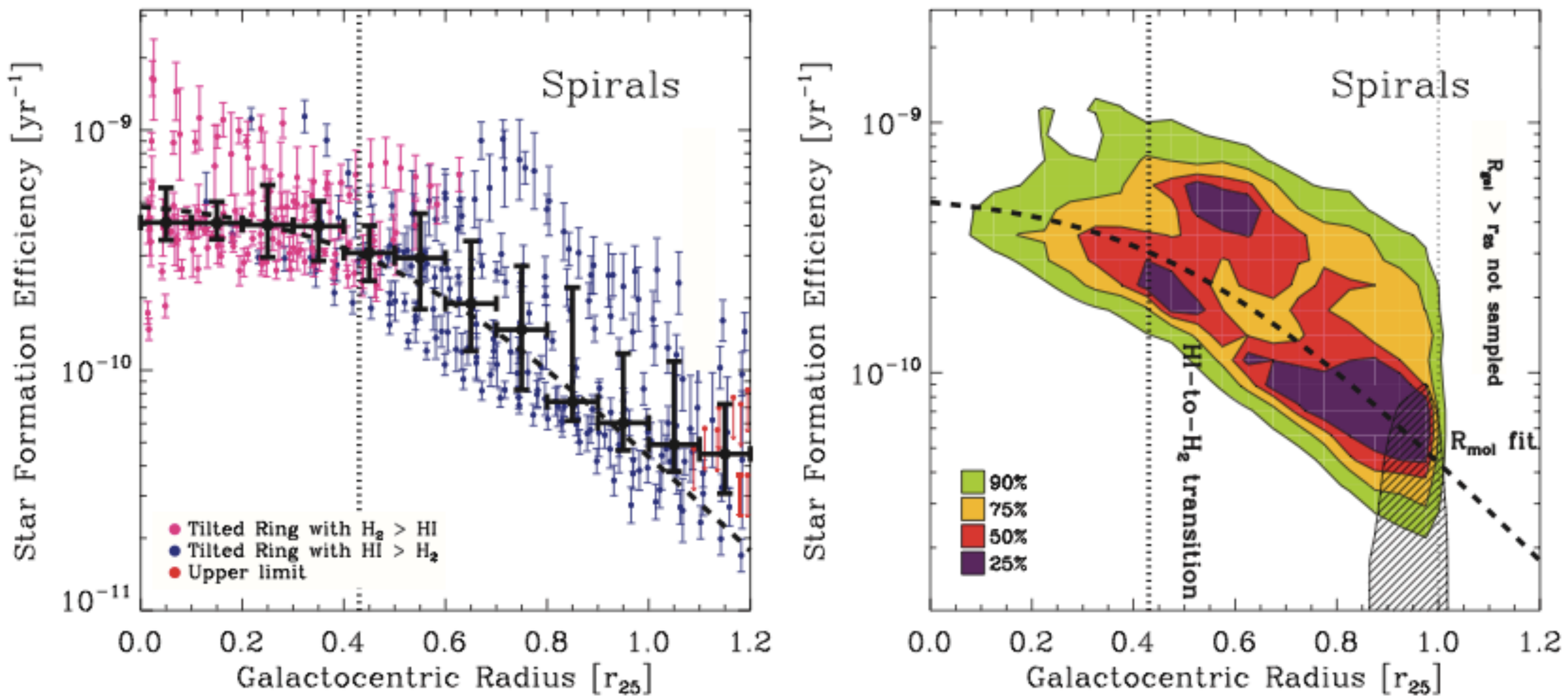
Quantity	Median Value[a]	Scatter	Scatter in log$_{10}$
r_{gal} (r_{25})	0.43	0.18	0.17
Σ_* ($M_\odot$ pc^{-2})	81	25	0.15
Σ_{gas} ($M_\odot$ pc^{-2})	14	6	0.18
P_h/k_B (cm^{-3} K)	2.3×10^4	1.5×10^4	0.26
τ_{ff} (yr)	4.2×10^7	1.2×10^7	0.14
τ_{orb} (yr)	1.8×10^8	0.4×10^8	0.09
Q_{gas}	3.8	2.6	0.31
$Q_{stars+gas}$	1.6	0.4	0.09

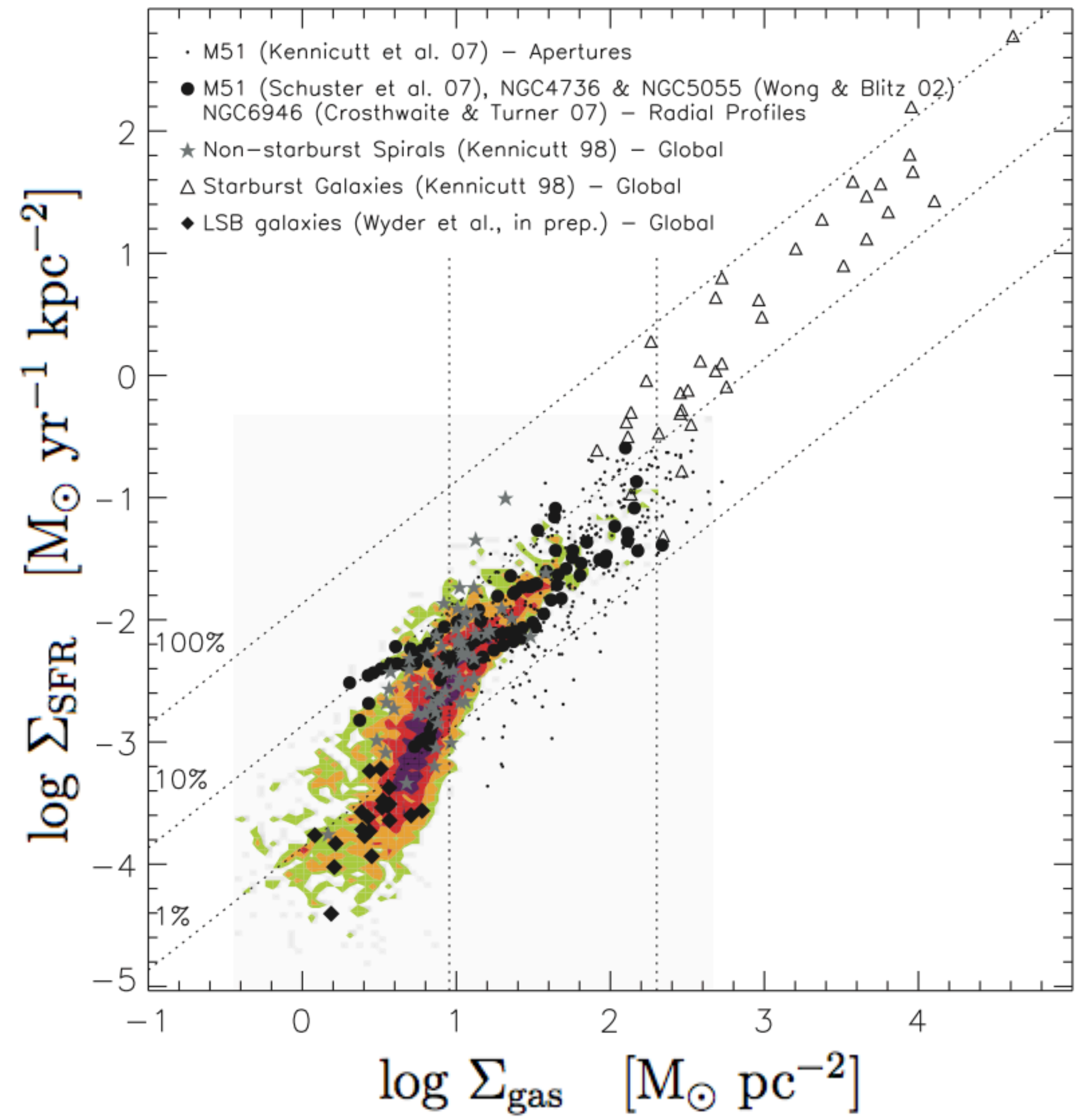
Assuming $\alpha G = (\alpha G)_{CNM}$

$$\Sigma_{gas,*} \approx \frac{12}{\phi_g Z'} \quad M_\odot\ pc^{-2}$$

Galaxies:

e.g. Bigiel+ 08





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Assuming $\alpha G = (\alpha G)_{\rm CNM}$

$$\Sigma_{{\rm gas},*} \approx \frac{12}{\phi_g Z'} \ {\rm M_\odot\ pc^{-2}}$$

Caveat: This interpretation requires typically "one" primary cloud per line-of-sight.

To Conclude:

$$N_{1,\mathrm{tot}} = \frac{1}{\sigma_g} \ln[\frac{\alpha G}{4} + 1] = \frac{1}{\sigma_g} \ln[\frac{1}{4} \frac{\bar{f}_{\mathrm{diss}} \sigma_g w F_0}{Rn} + 1]$$

HI-to-H_2 Transitions and HI Column Densities in Galaxy Star-Forming Regions

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