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

Amiel Sternberg
Sackler School of Physics & Astronomy
Tel Aviv University
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Life Cycle of Gas in Galaxies
31 August 2015

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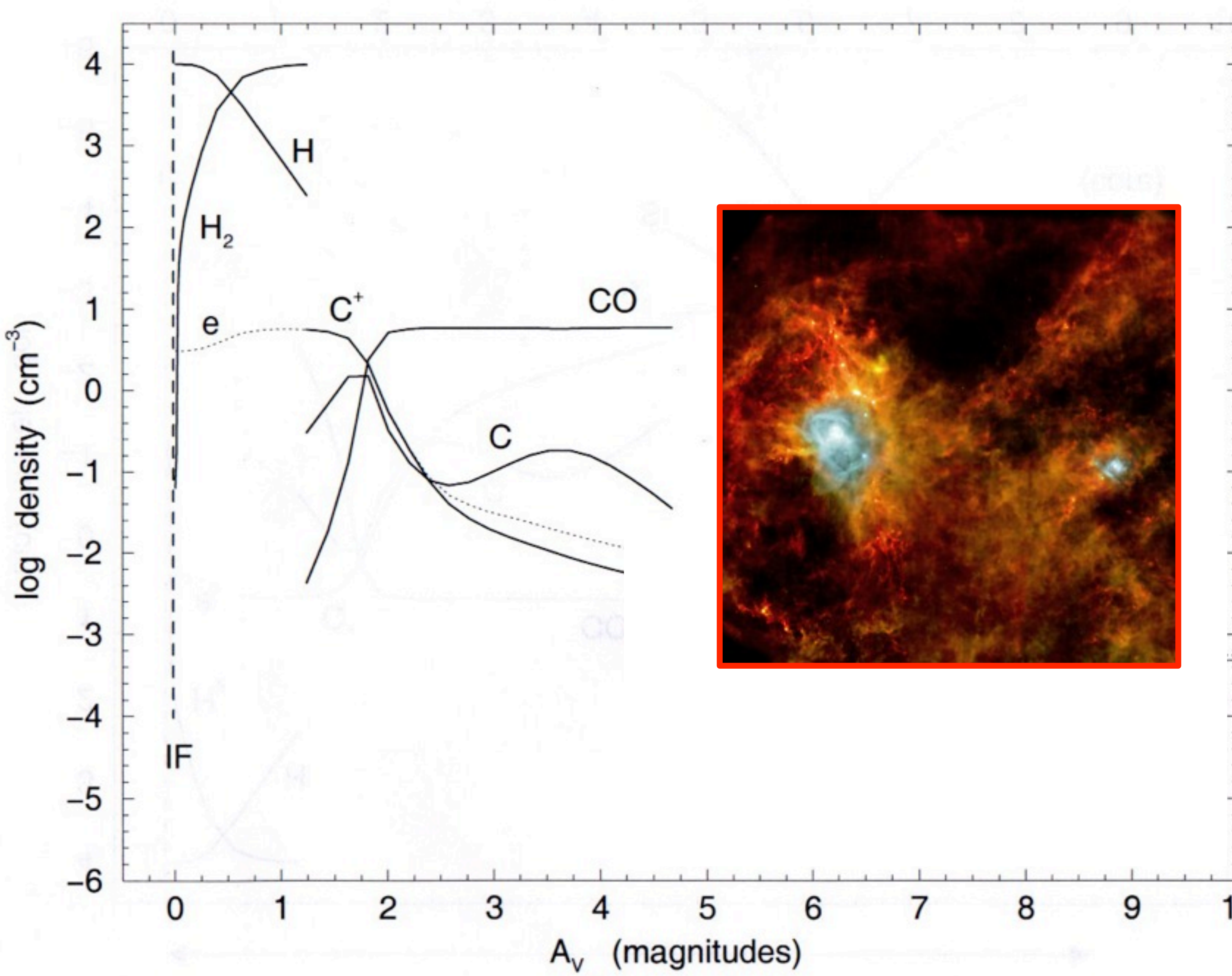

Life Cycle of Gas in Galaxies
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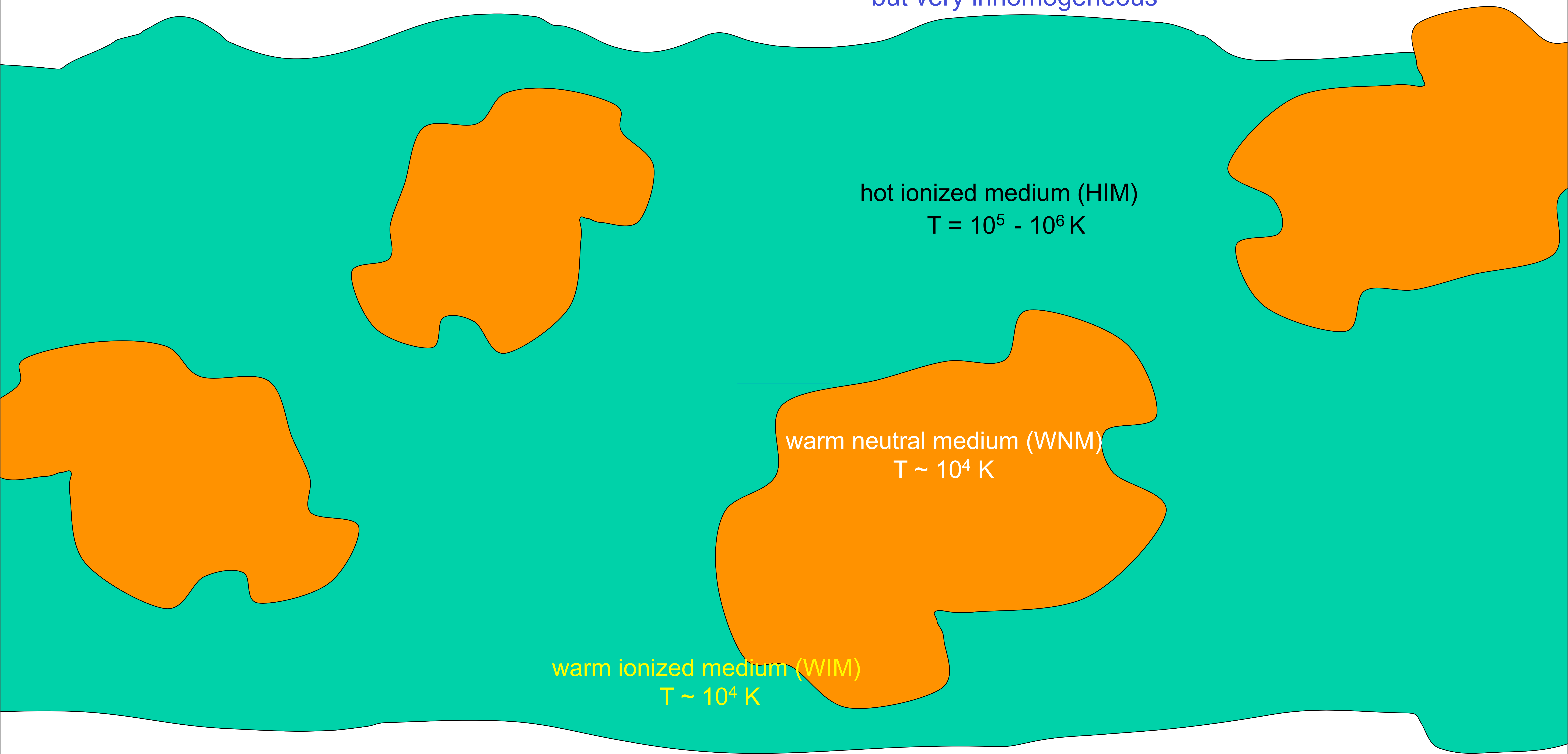
The Multi-Phased Interstellar Medium (ISM) and Star-Formation:

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



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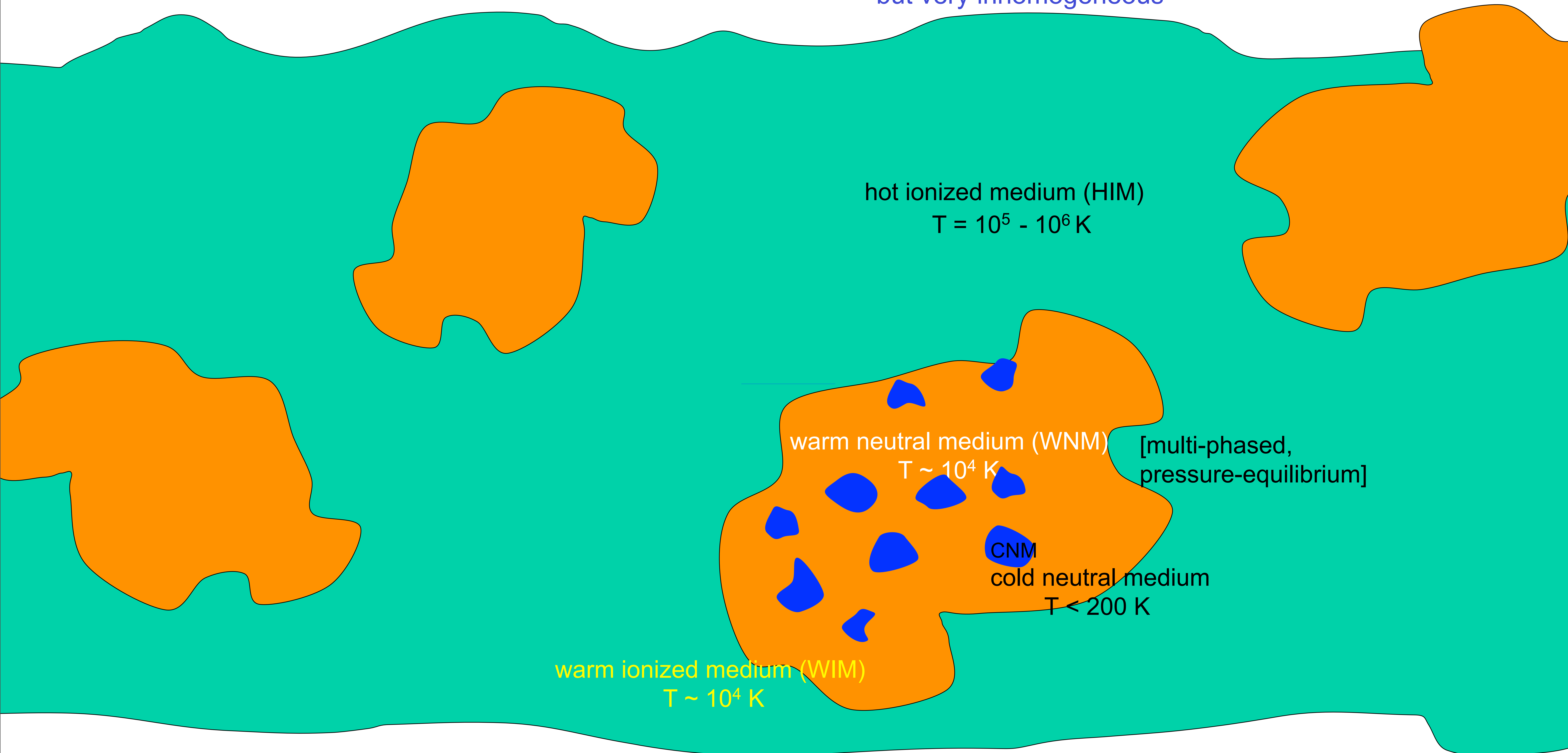


The Multi-Phased Interstellar Medium (ISM) and Star-Formation:

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

Interstellar gas exposed to

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

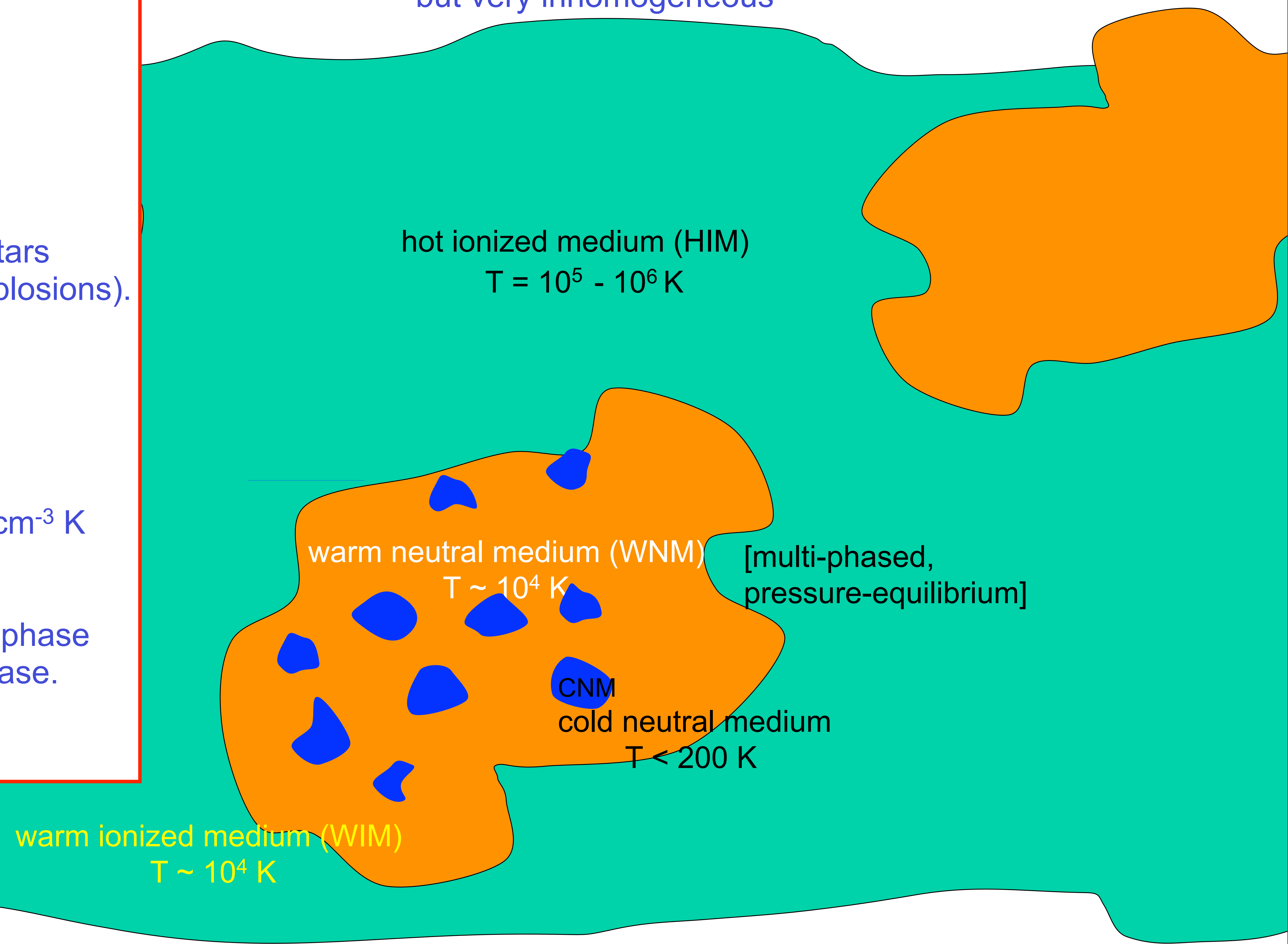
Global ISM heated and energized by stars (outflows, radiation, and supernova explosions).

Turbulent!

Total Galactic ISM mass = 5×10^{9} $M_{\odot}$

Mid-plane thermal pressure = 2.5×10^{3} cm^{-3} K (at Solar circle)

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



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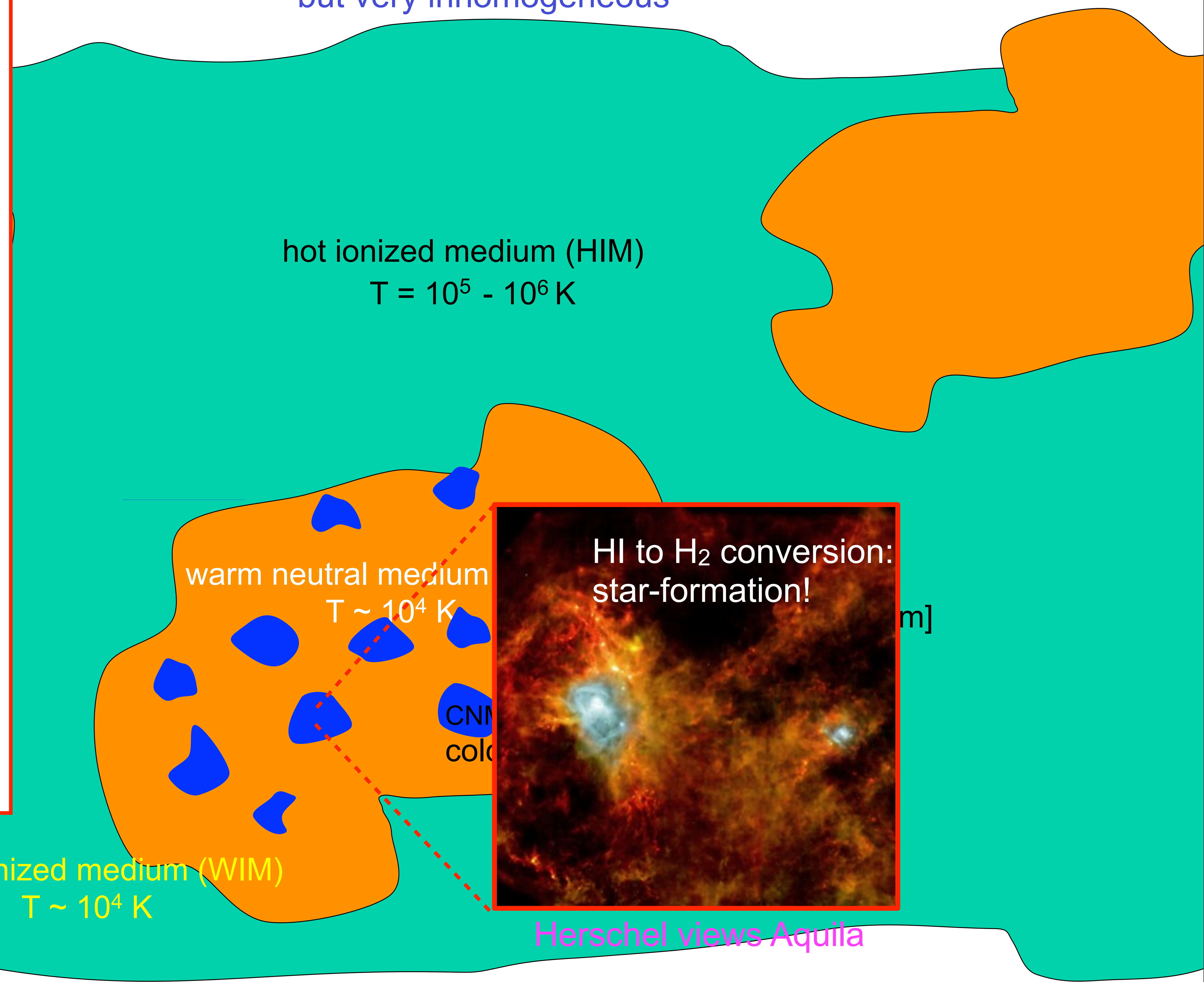
stars form in cold molecular (H_2) clouds:
Galactic star-formation rate ~3 $M_\odot$ yr^{-1}



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]

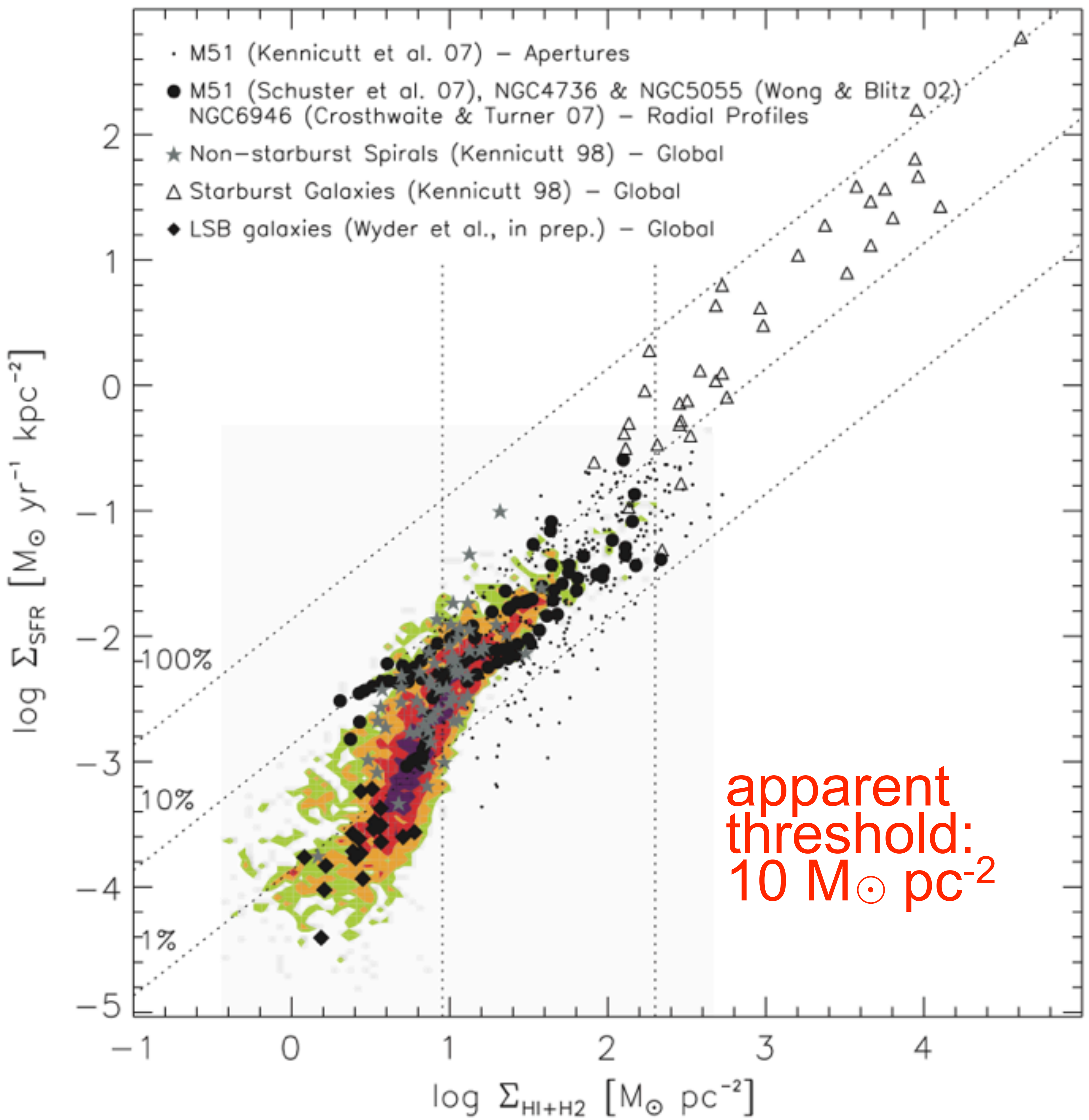
2014 ApJ 790 10

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]

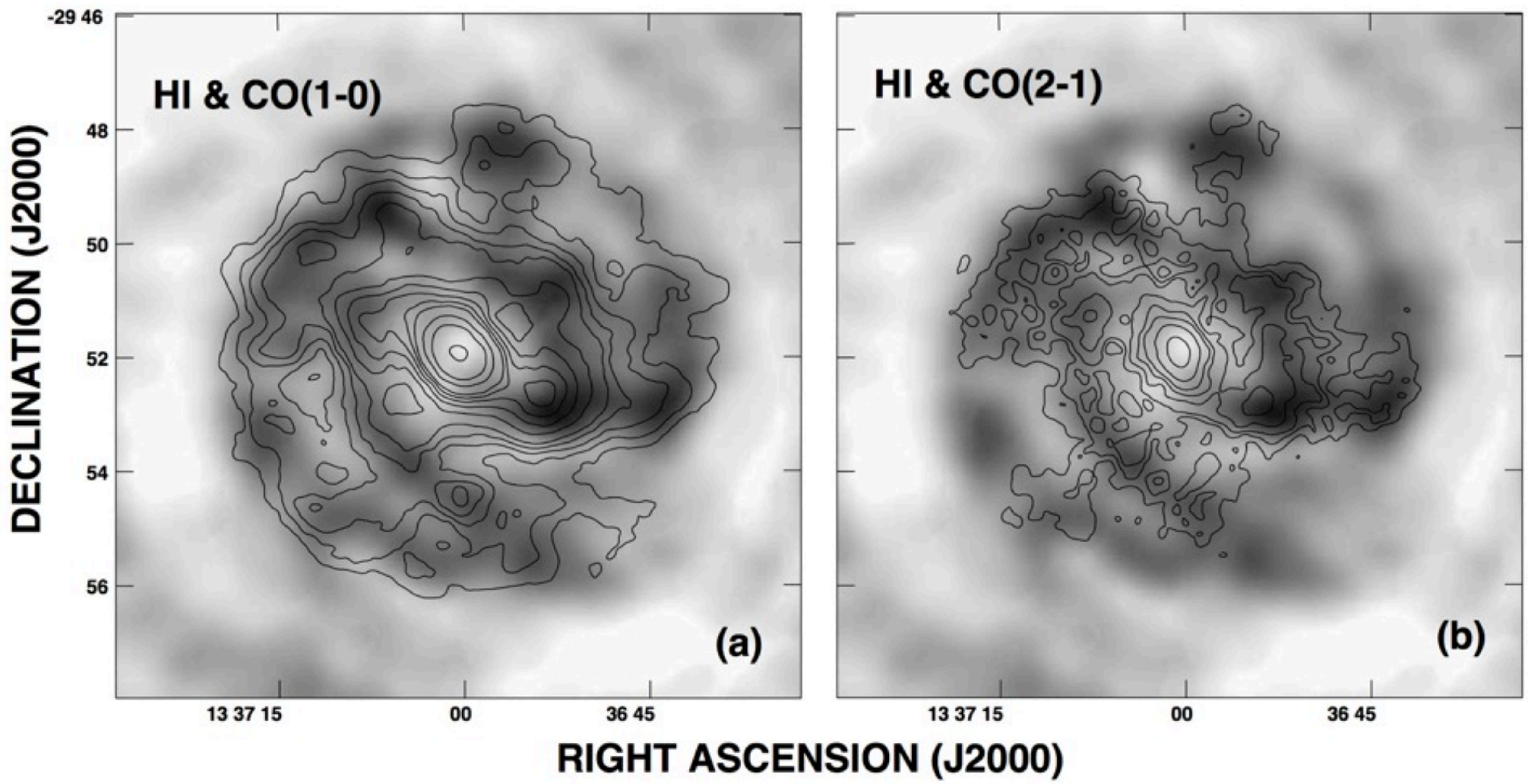
e.g., Bigiel+ 2008



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

HI as a Photodissociation Product in Molecular Spiral Arms:

M83 Crosthwaite+ 2002 ApJ 123 1892

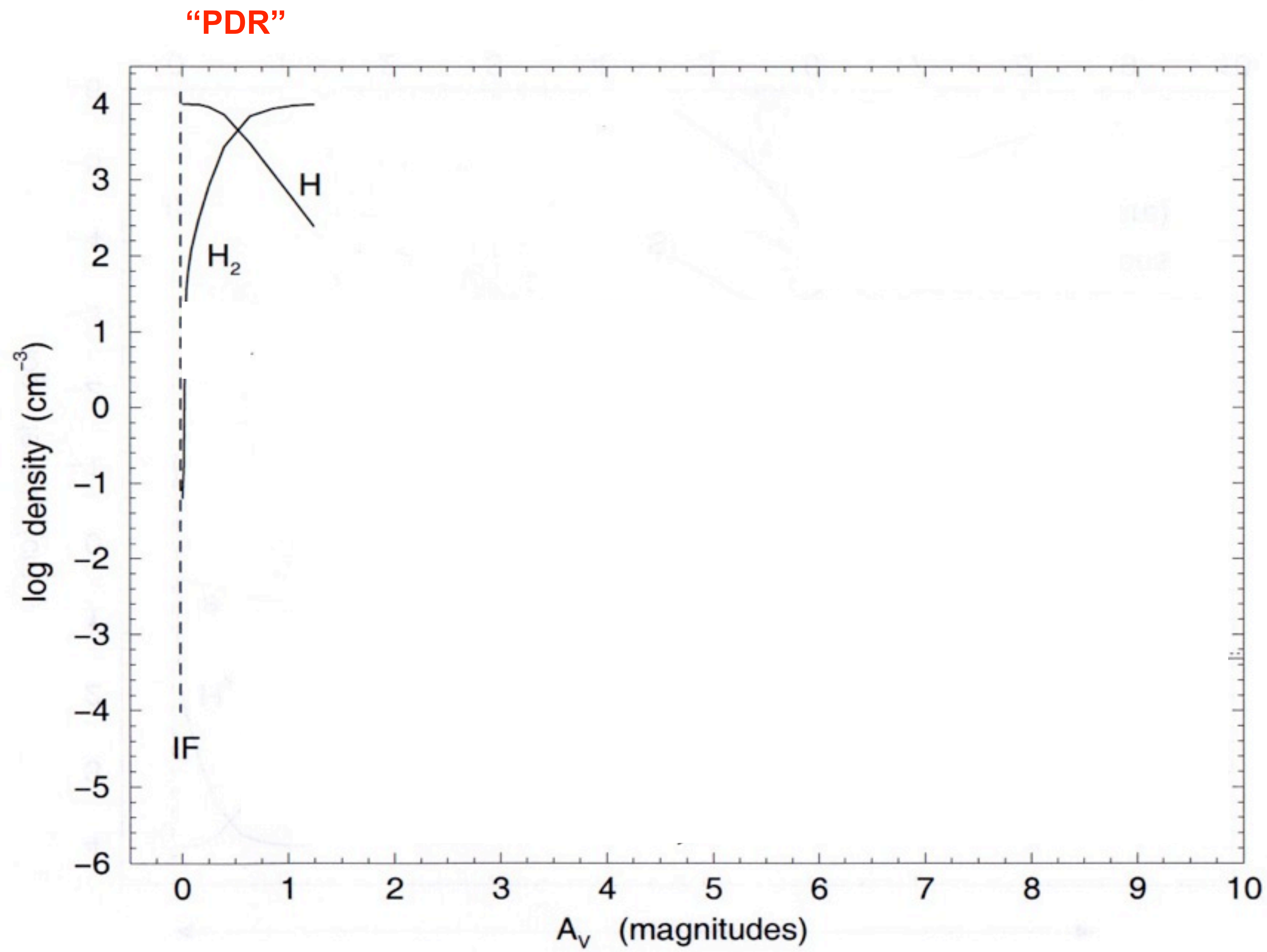


I am going to be juggling many parameters
- keep your eye on them!

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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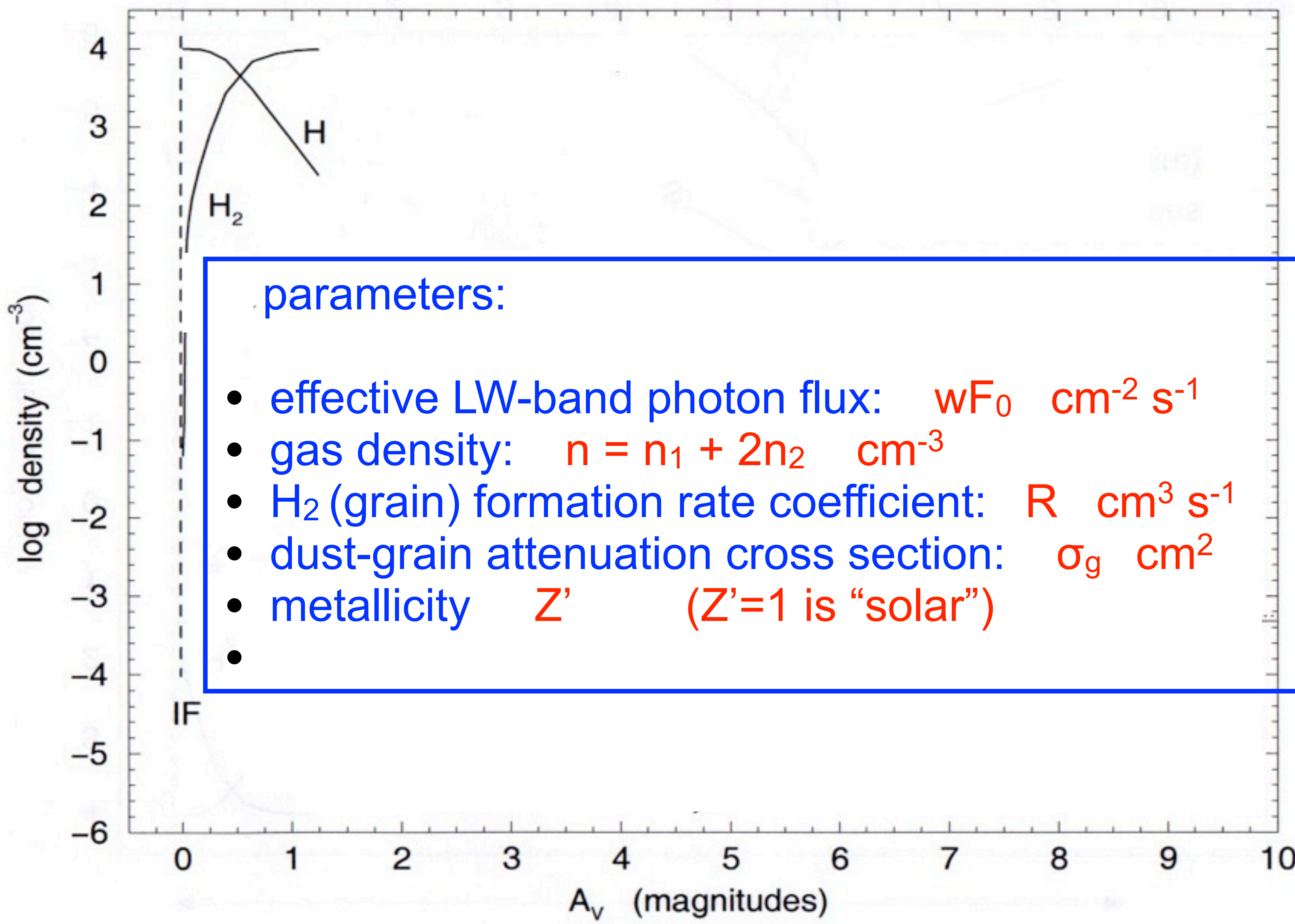
Shielding required.

“PDR”

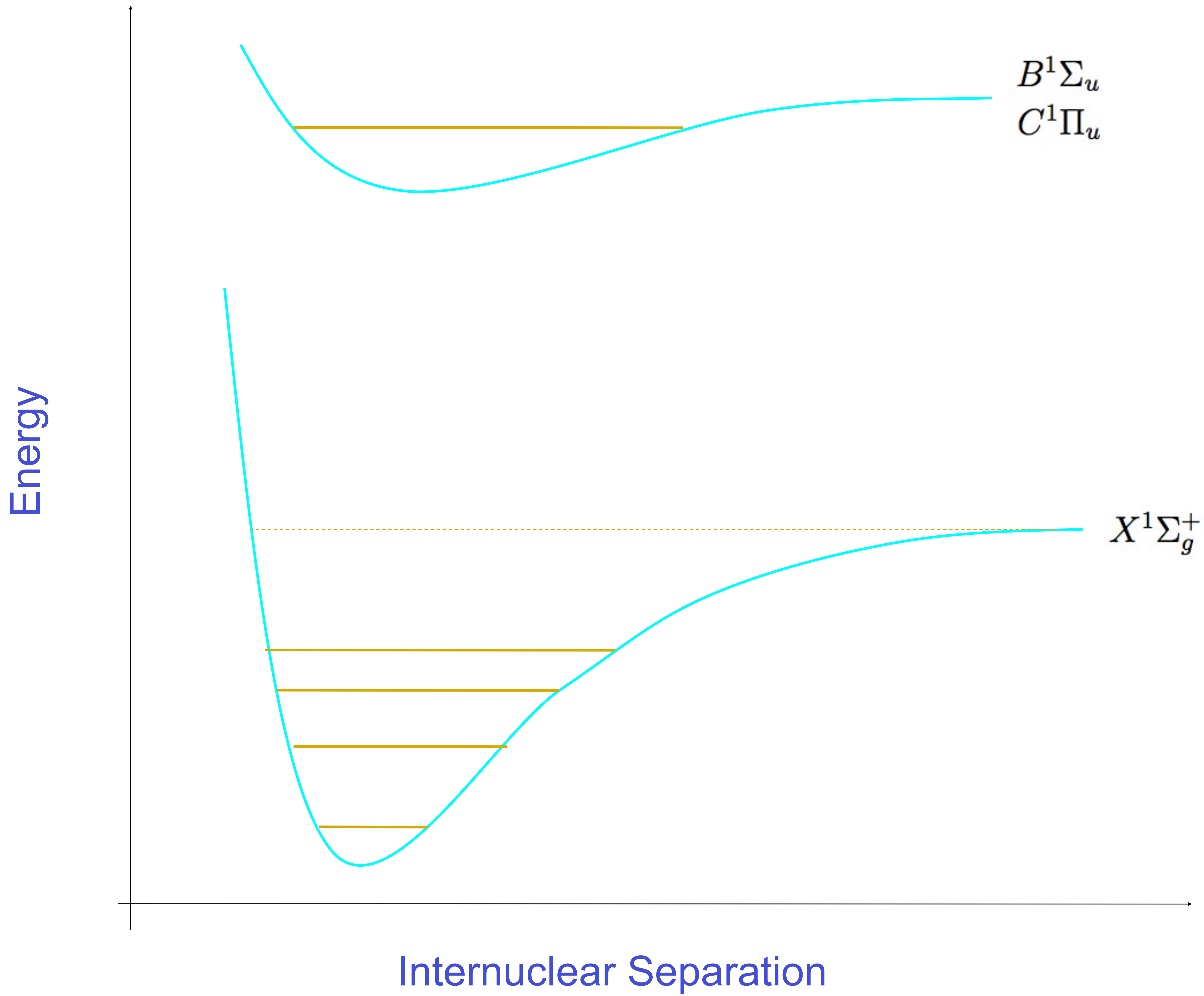


parameters:

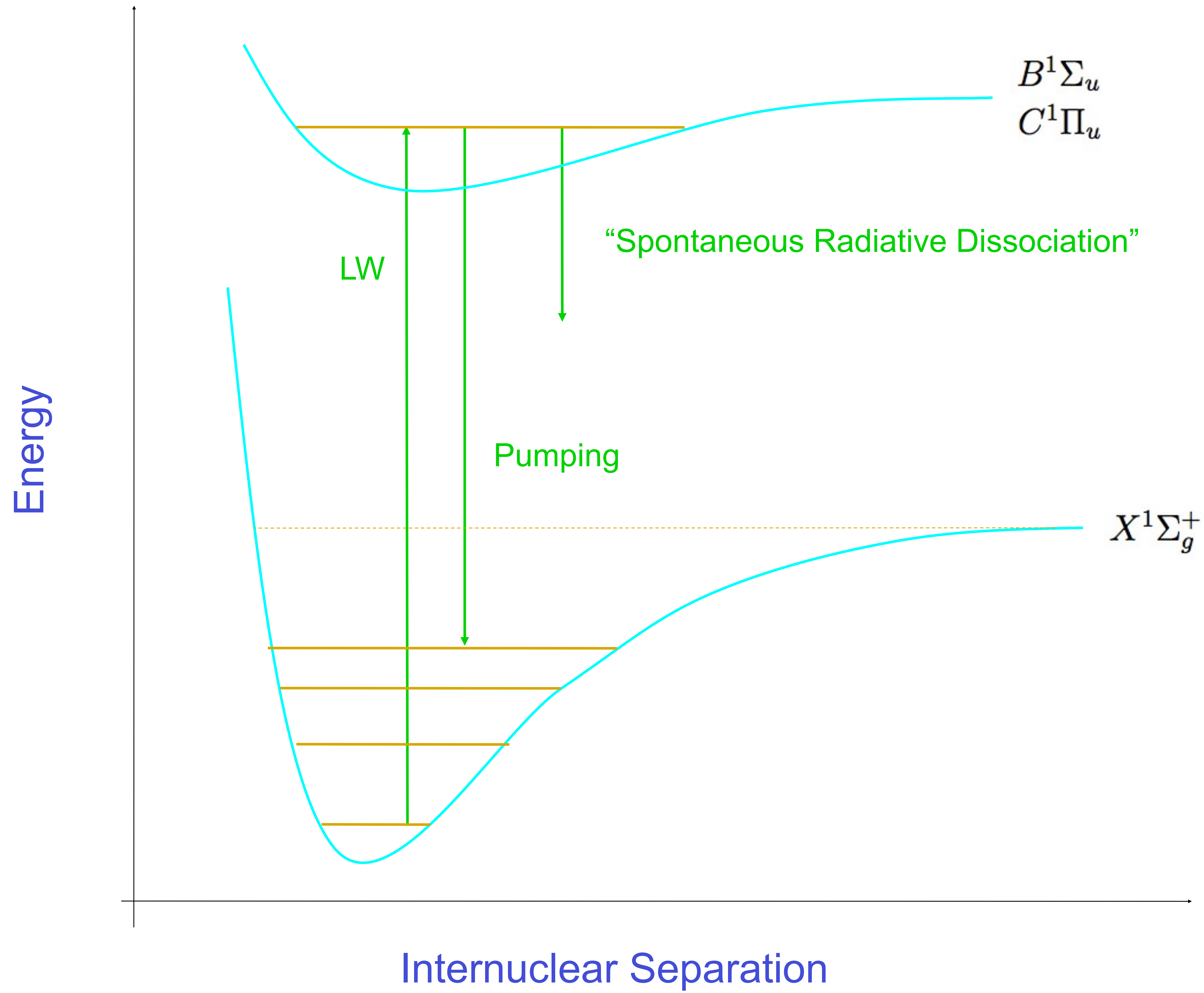
- effective LW-band photon flux: wF_0 $cm^{-2}\ s^{-1}$
- gas density: $n = n_1 + 2n_2$ cm^{-3}
- H_2 (grain) formation rate coefficient: R $cm^3\ s^{-1}$
- dust-grain attenuation cross section: σ_g cm^2
- metallicity Z' (Z'=1 is “solar”)
-

Stellar ultraviolet
“Lyman-Werner” radiation
11.2 - 13.6 eV

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



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



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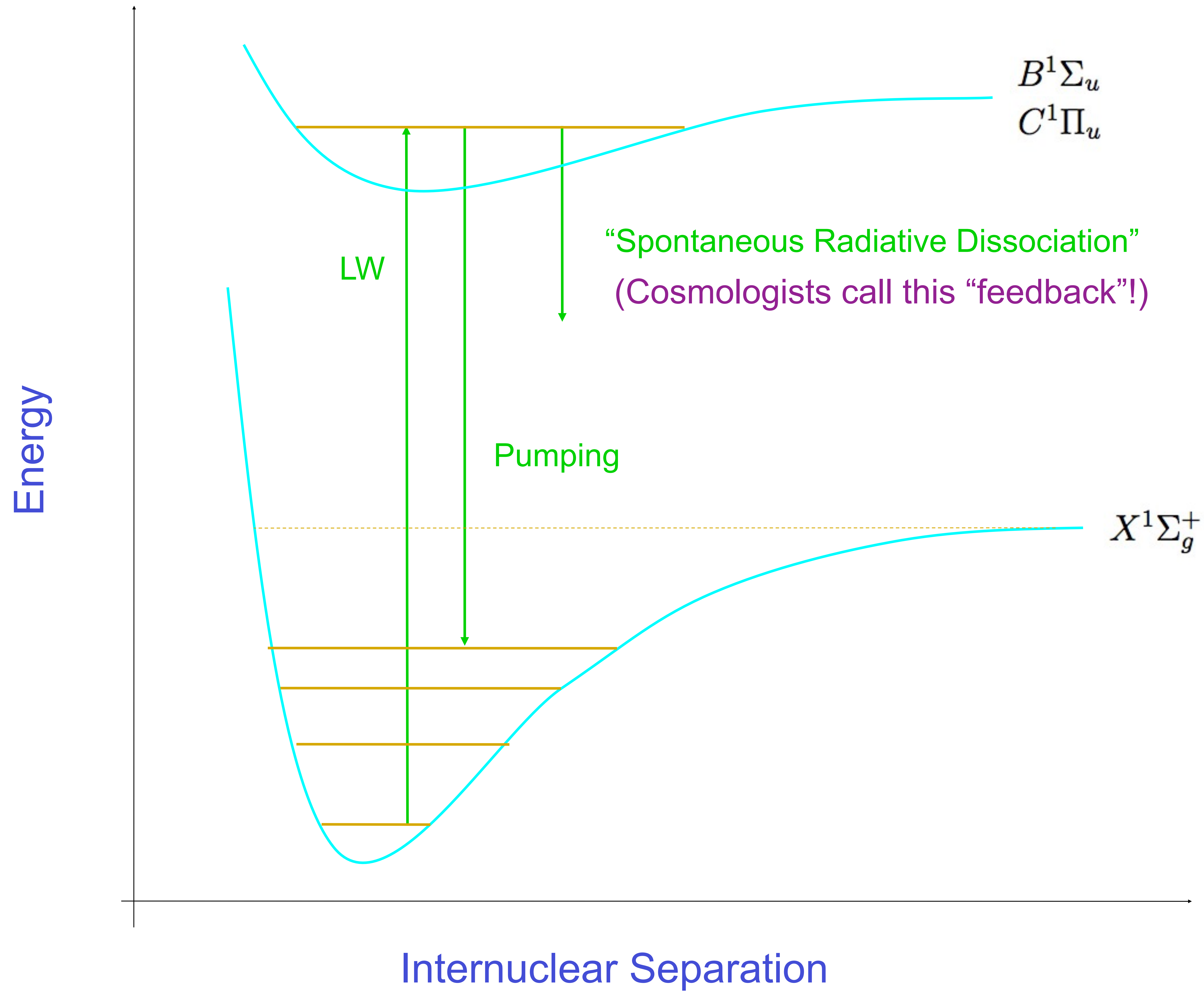

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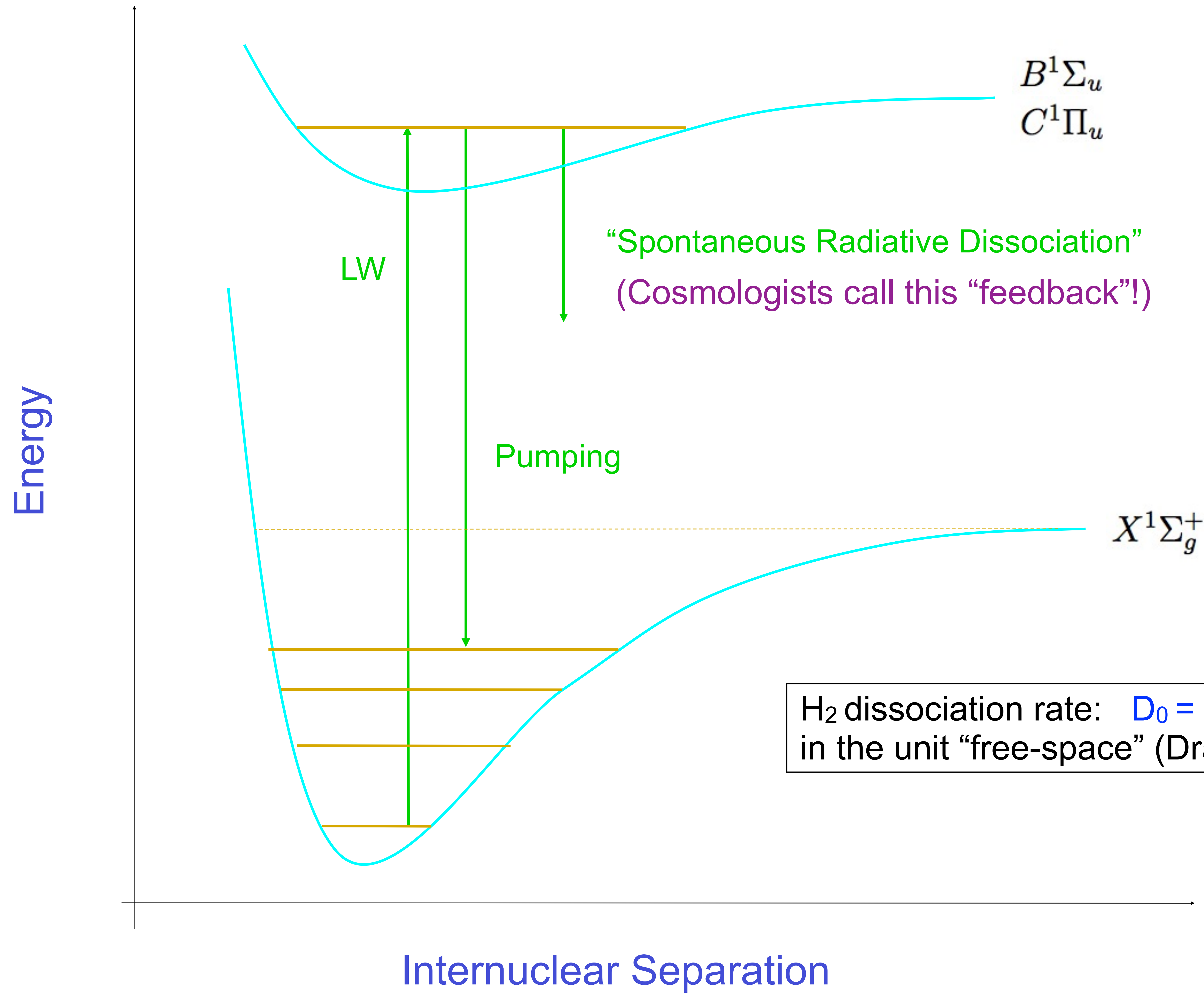
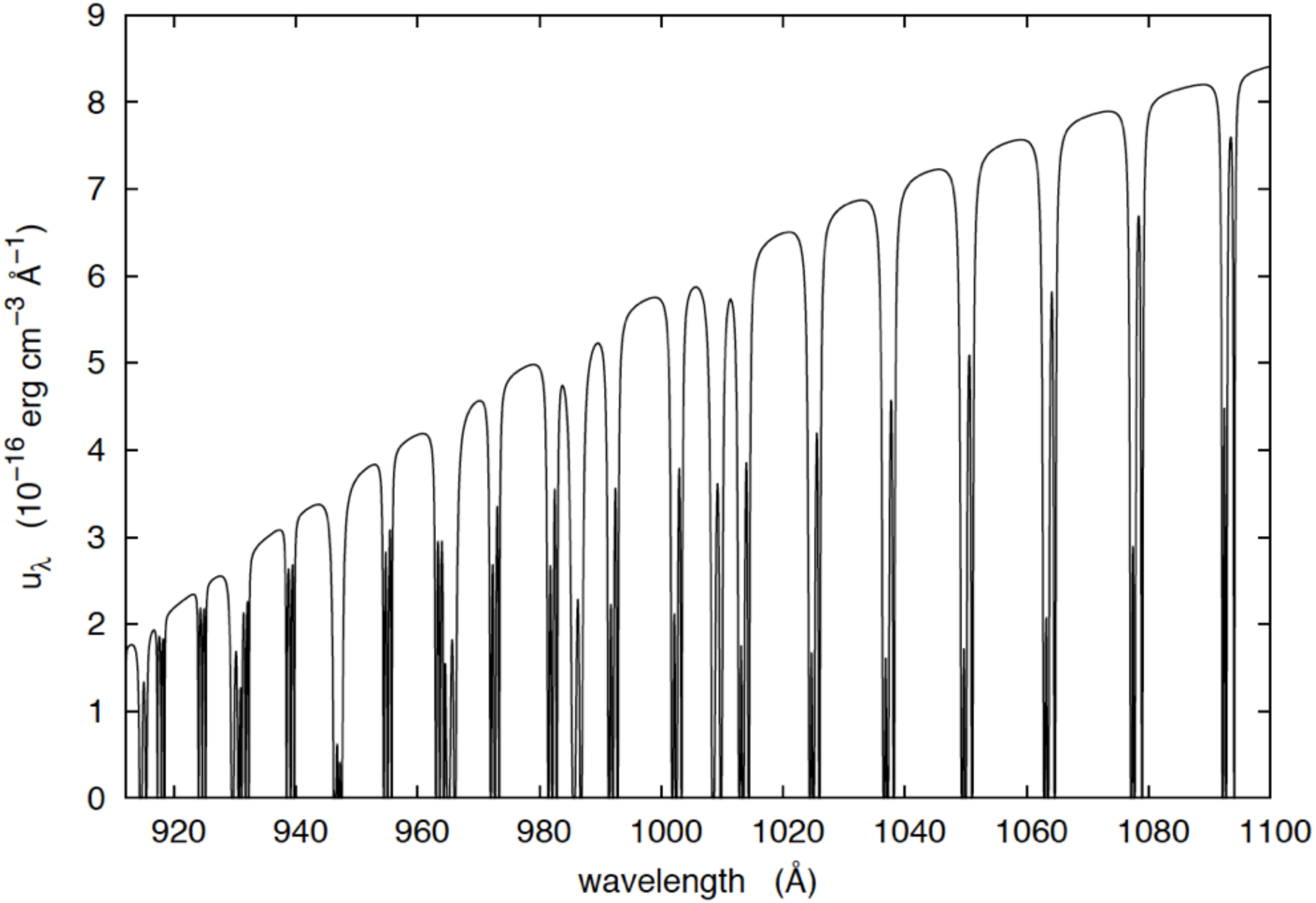


$\bar{f}_{\rm diss} = 0.12$

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”.

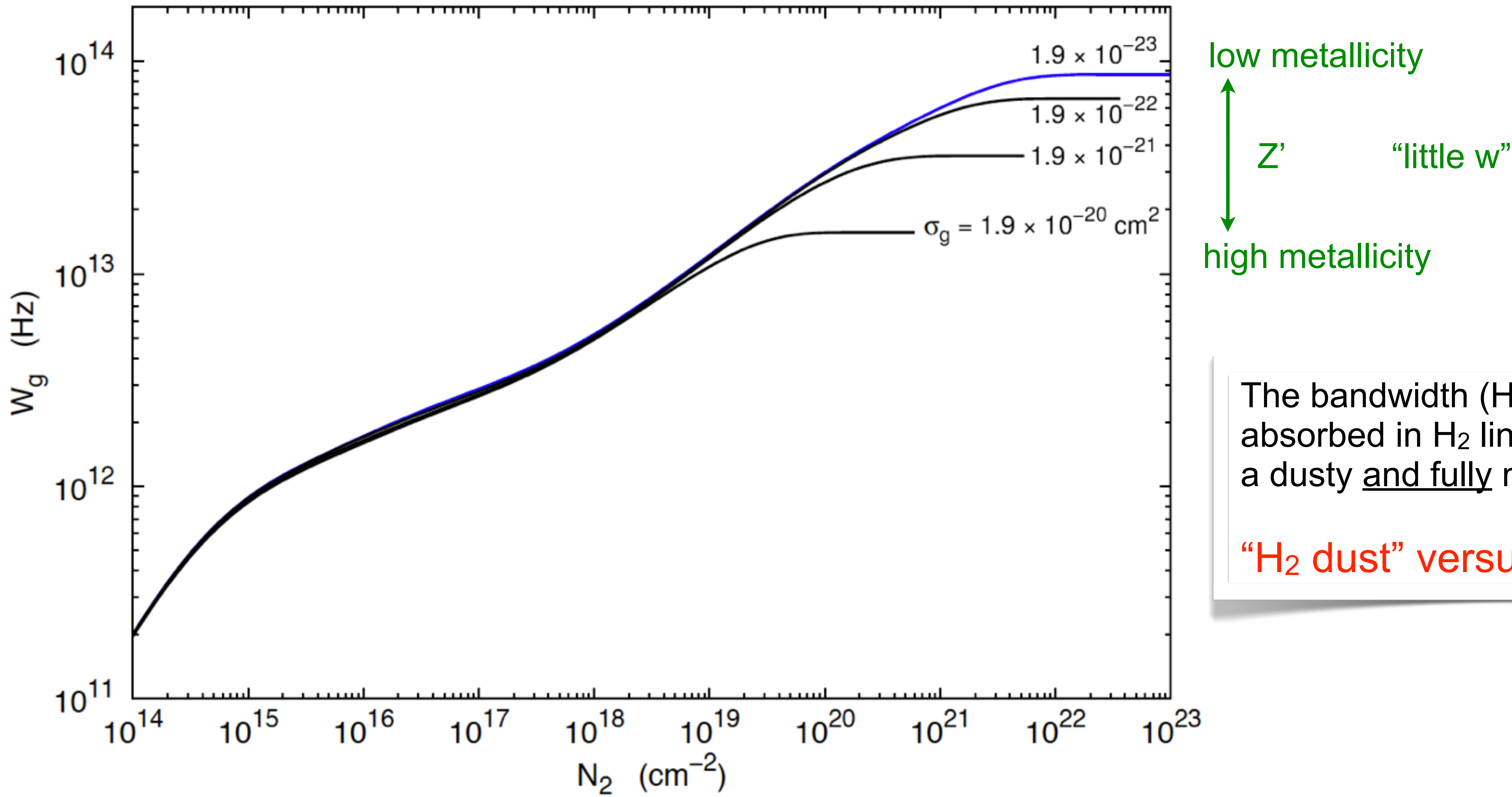
Dust absorption cross-section per hydrogen nucleus:

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

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"]



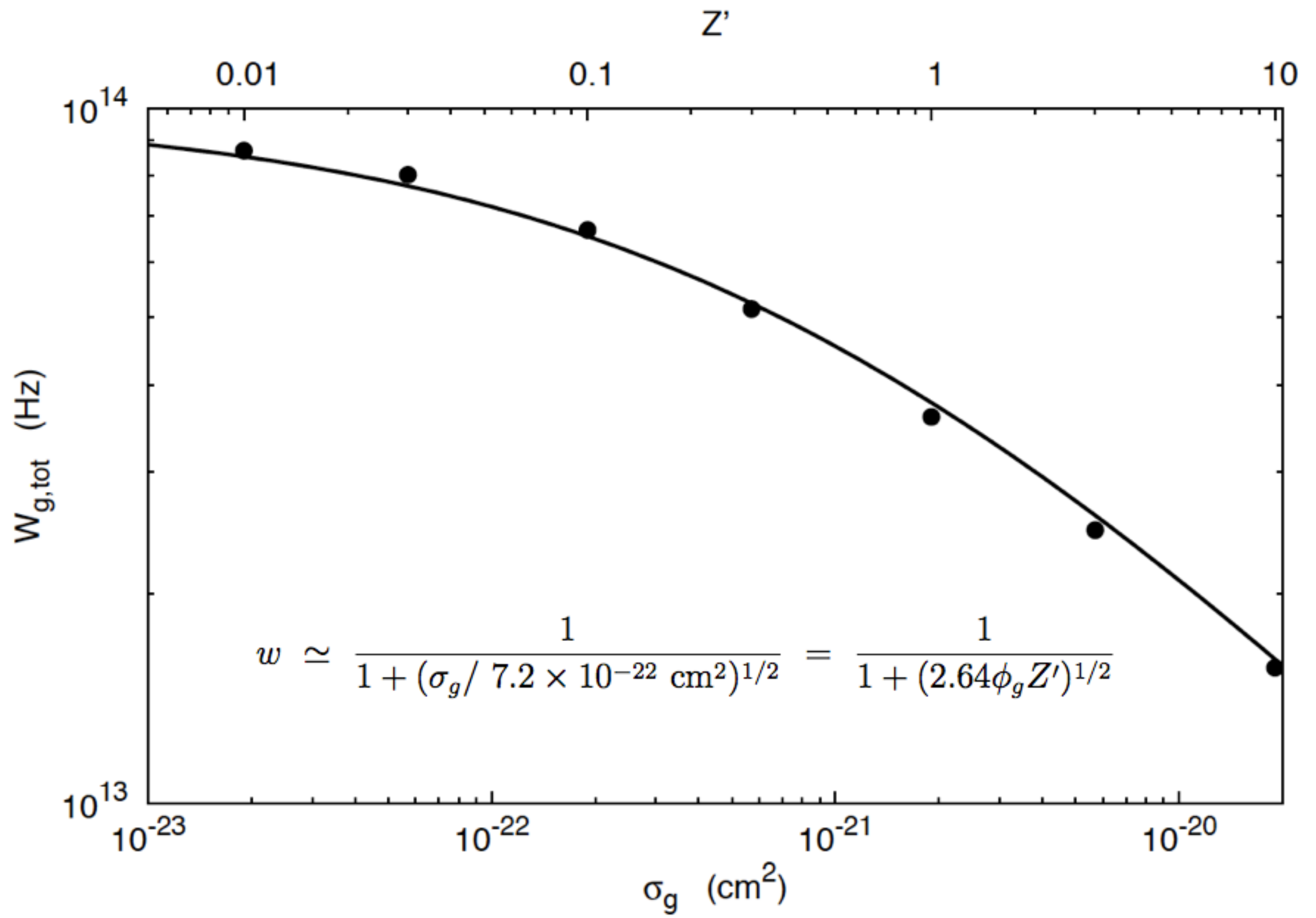
The bandwidth (Hz) of radiation absorbed in H_2 line dissociations in a dusty and fully molecular cloud.

"H_2 dust" versus "H_2 lines"

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

“Universal” Total H_2 Dust Limited Dissociation Bandwidth:

Sternberg+ 2014



low Z’ ⟵⟶ high Z’

solar

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

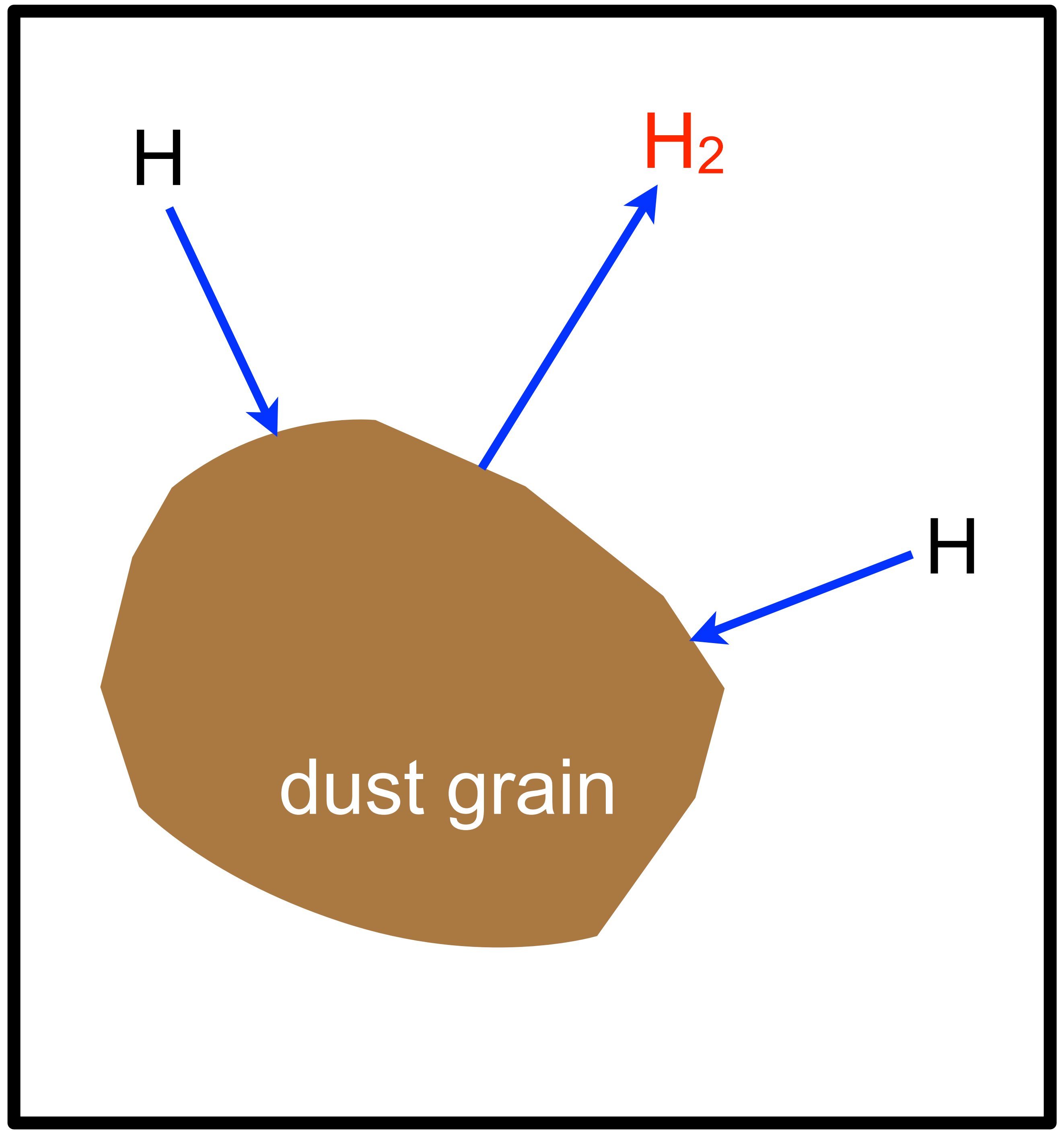
Total LW Flux:

$$F_0 \equiv \int_{\nu_1}^{\nu_2} F_\nu d\nu$$

“Effective Dissociation Flux”

$$\bar{f}_{\mathrm{diss}} \times w F_0$$

H_2 Formation:



In the absence of dust:

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

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

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

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

time scale for equilibrium

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:

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

Sternberg Parameter:

Sternberg 1988; McKee & Krumholz 2010; Sternberg+ 2014

$$\alpha G = \frac{D_0 G}{R n} = \bar{f}_{\rm diss} \frac{\sigma_g w F_0}{R n} = \bar{f}_{\rm diss} \frac{\sigma_g w F_0}{D_0} \frac{n_1}{n_2}\bigg|_{\rm freespace}$$

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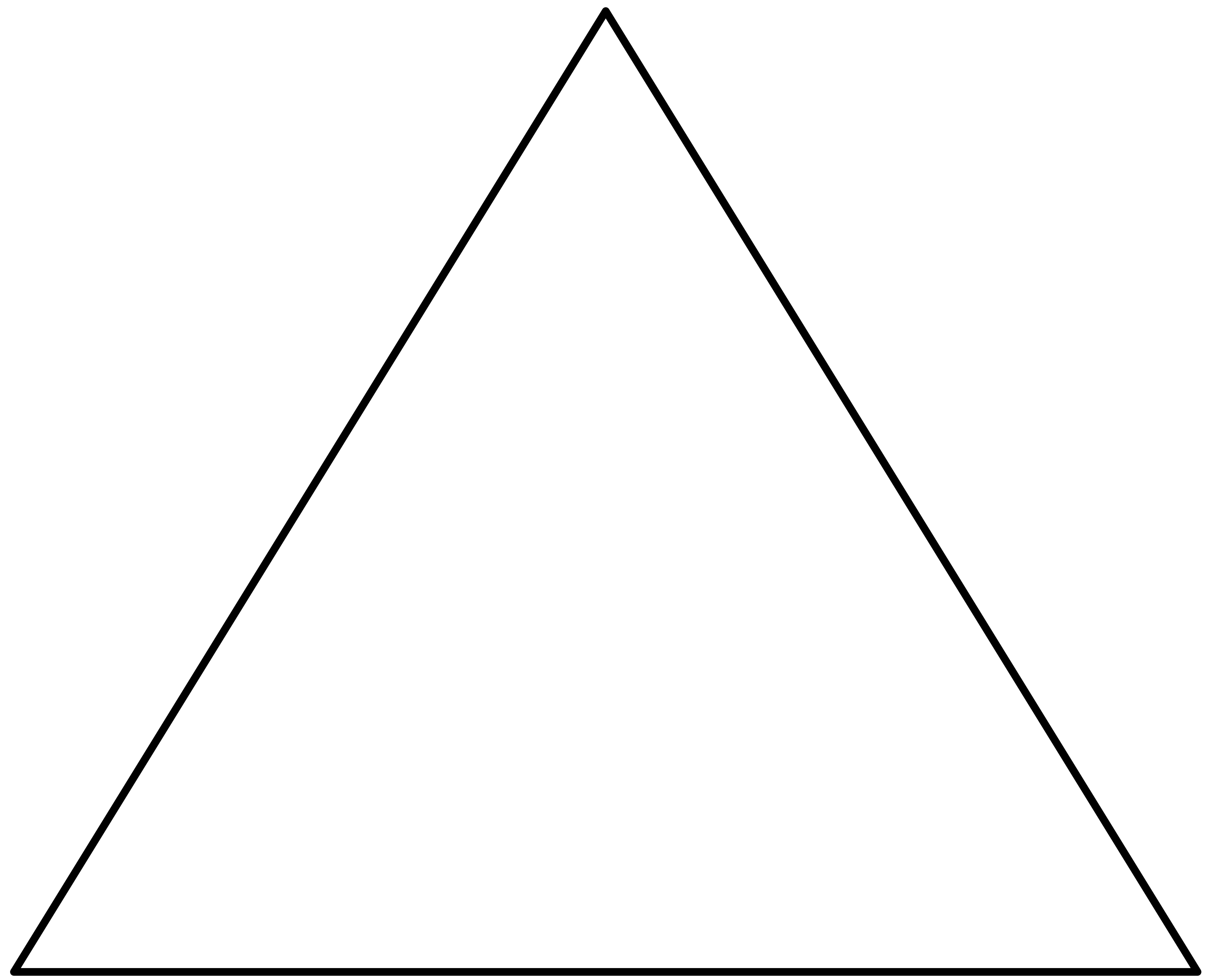
$$\alpha G = 1.54 \left(\frac{\sigma_g}{1.9 \times 10^{-21}\ {\rm cm}^2}\right)\left(\frac{F_0}{2.07 \times 10^7\ {\rm cm}^{-2}\ {\rm s}^{-1}}\right) \times \left(\frac{3 \times 10^{-17}\ {\rm cm}^3\ {\rm s}^{-1}}{R}\right)\left(\frac{100\ {\rm cm}^{-3}}{n}\right) \frac{1}{1 + (2.64 \phi_g Z')^{1/2}}$$

...so can be small "weak-field"
or large "strong-field"

Three-Way Competition for the FUV Absorption:

$\alpha G >> 1$ “strong-field”

HI dust



H_2 lines + H_2 dust

H_2 lines

$\alpha G << 1$ “weak-field”
$Z' \gtrsim 1$ “high-metallicity”

$\alpha G << 1$ “weak-field”
$Z' \lesssim 1$ “low-metallicity”

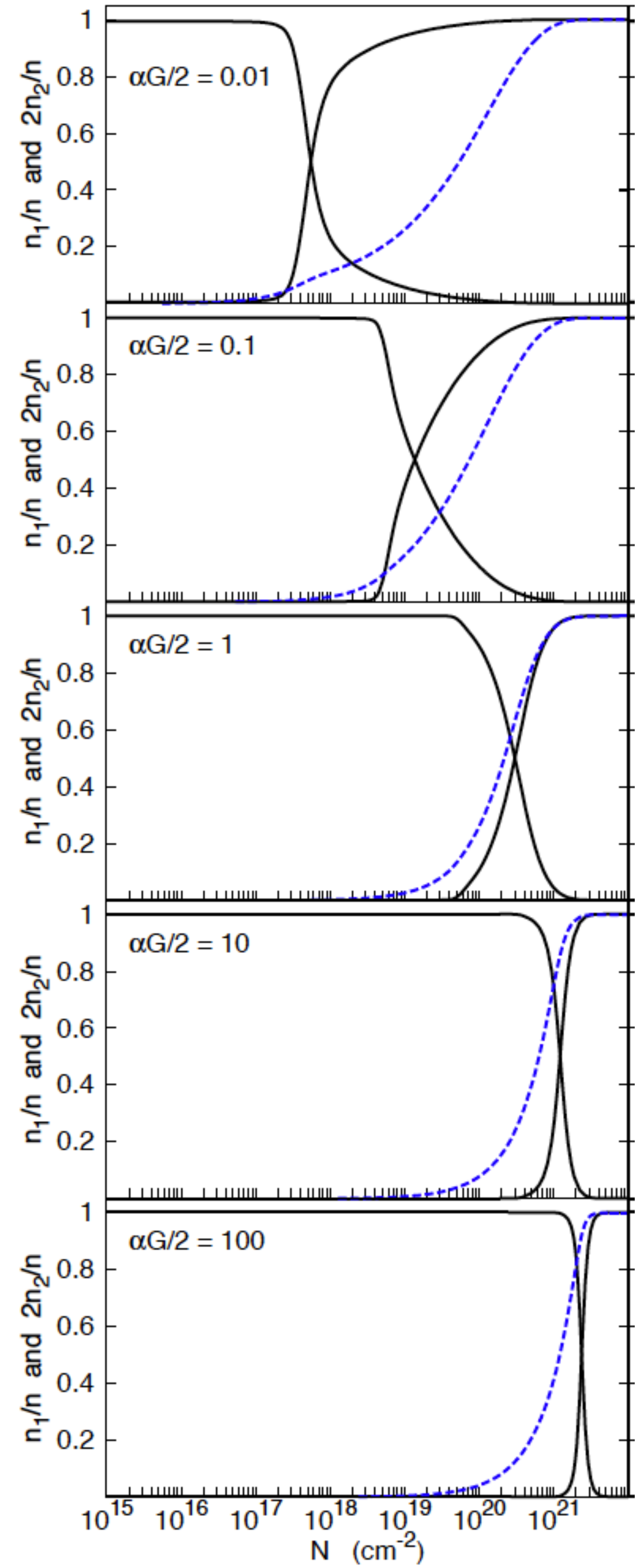
HI-to-H_2 Transition Profiles: Z'=1 (solar metallicity)

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)

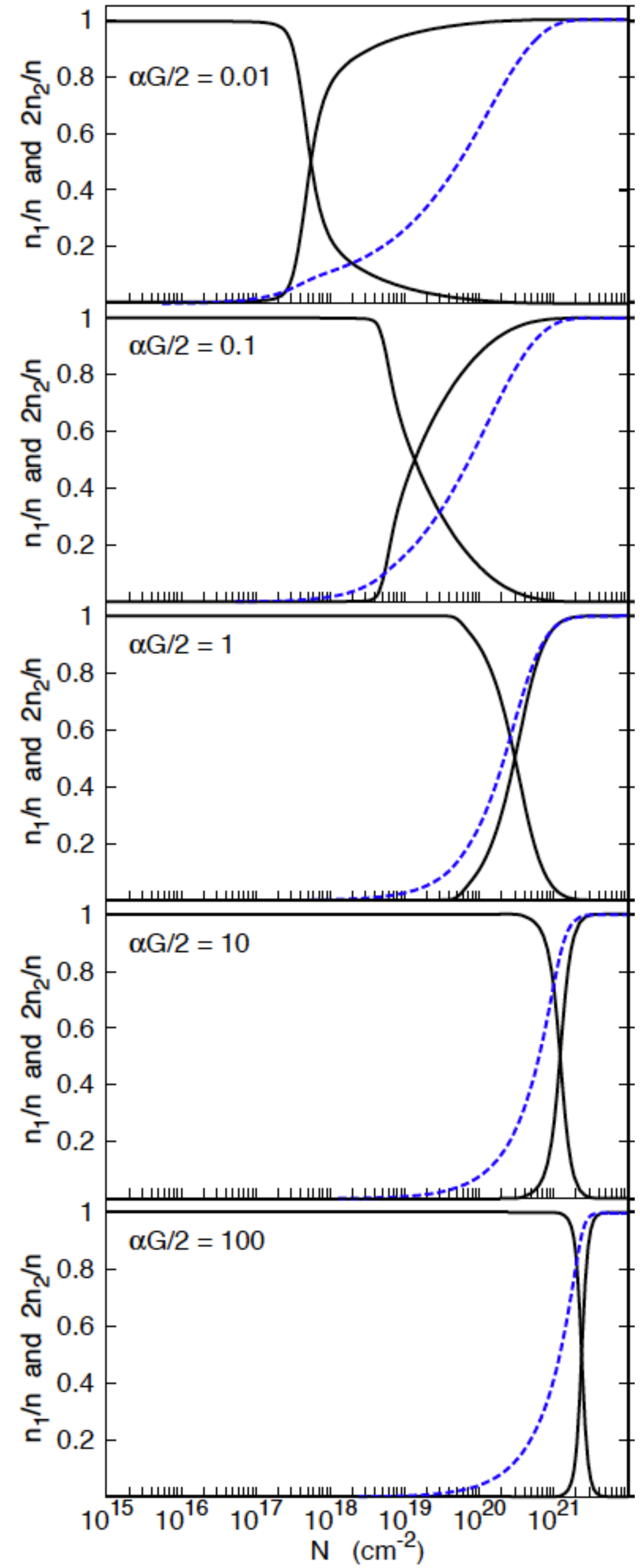
weak-field: most of the HI built up inside the H_2 zone, "gradual profiles"

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"

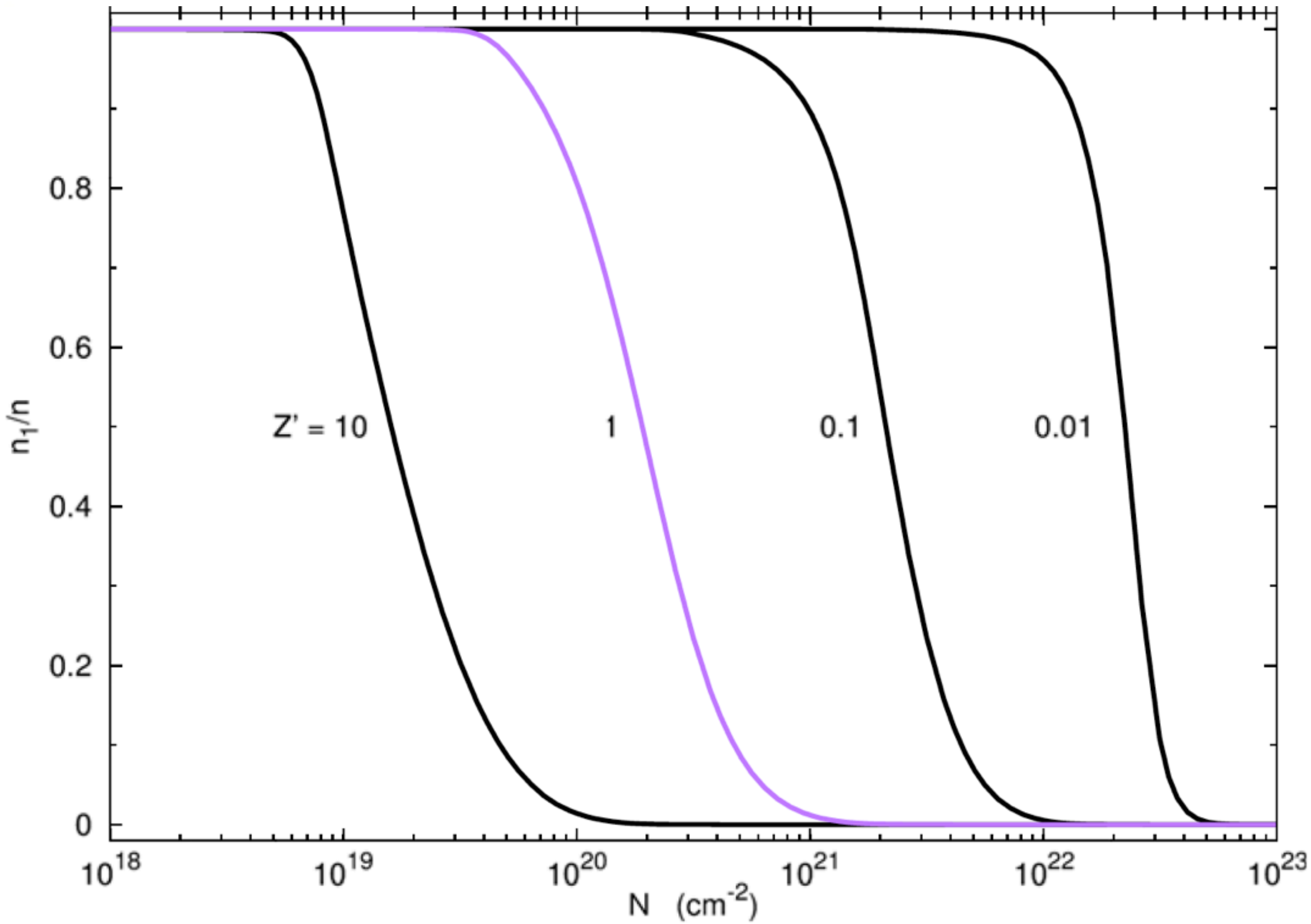


For a given αG the profile "scale lengths" are determined by Z'.

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

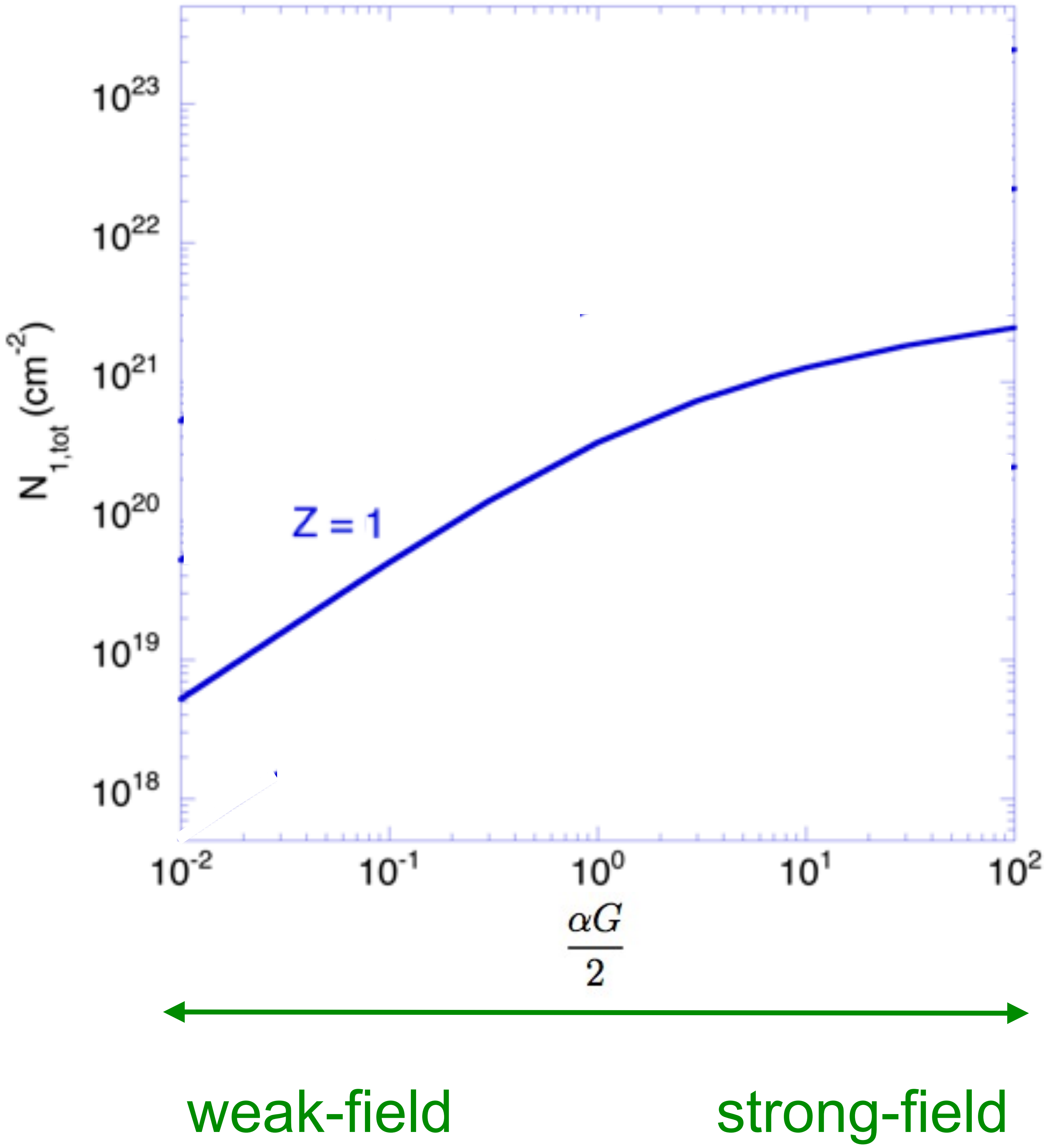
$$R = 3 \times 10^{-17} \left(\frac{T}{100\ \mathrm{K}}\right)^{1/2} Z' \quad \mathrm{cm}^3\ \mathrm{s}^{-1}$$

E.g., HI profiles for $\alpha G/2 \approx 1$



General Purpose Analytic Formula for the Total HI Column Density:

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

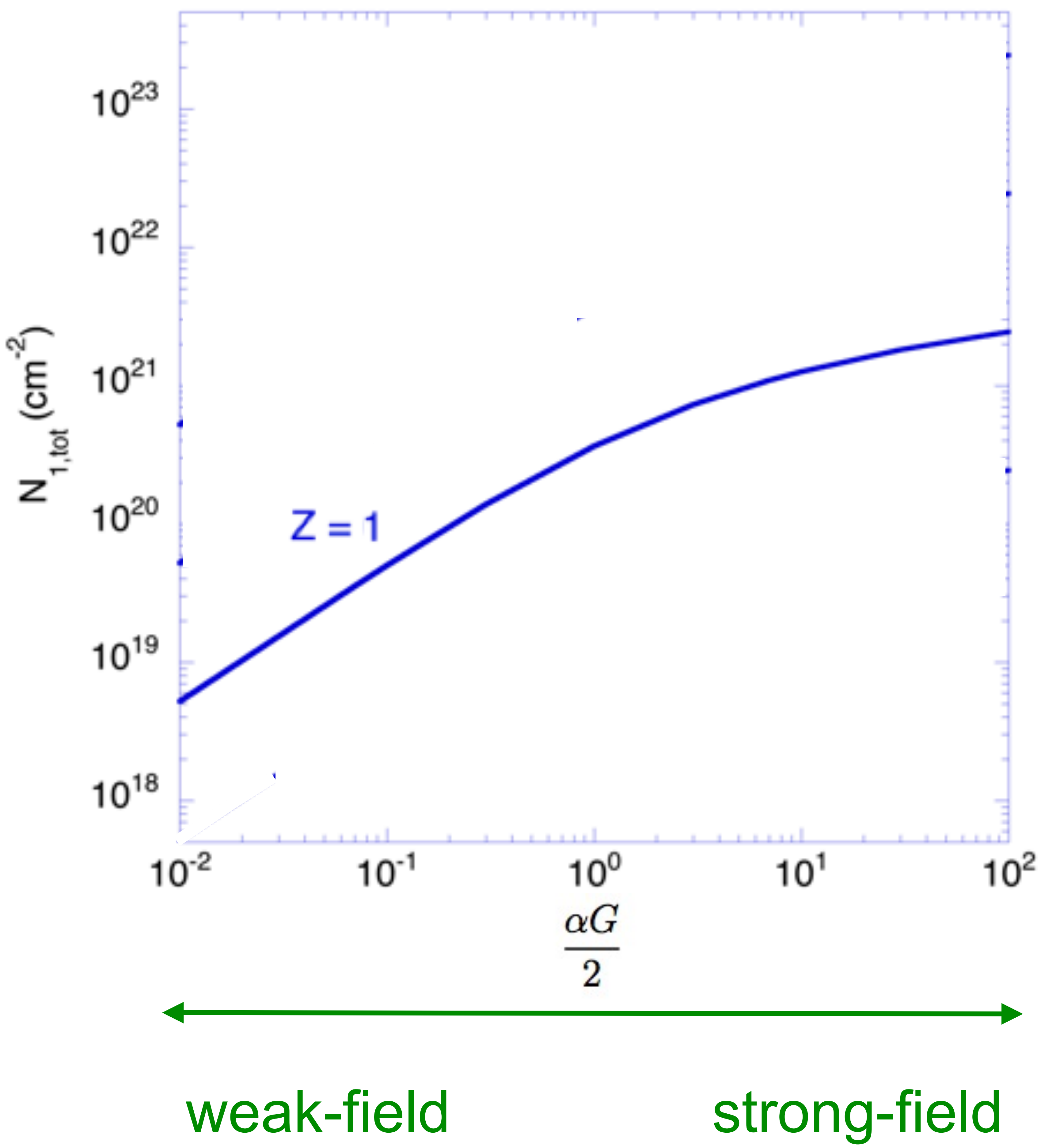


Valid for all regimes:

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

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

Weak-Field Limit:



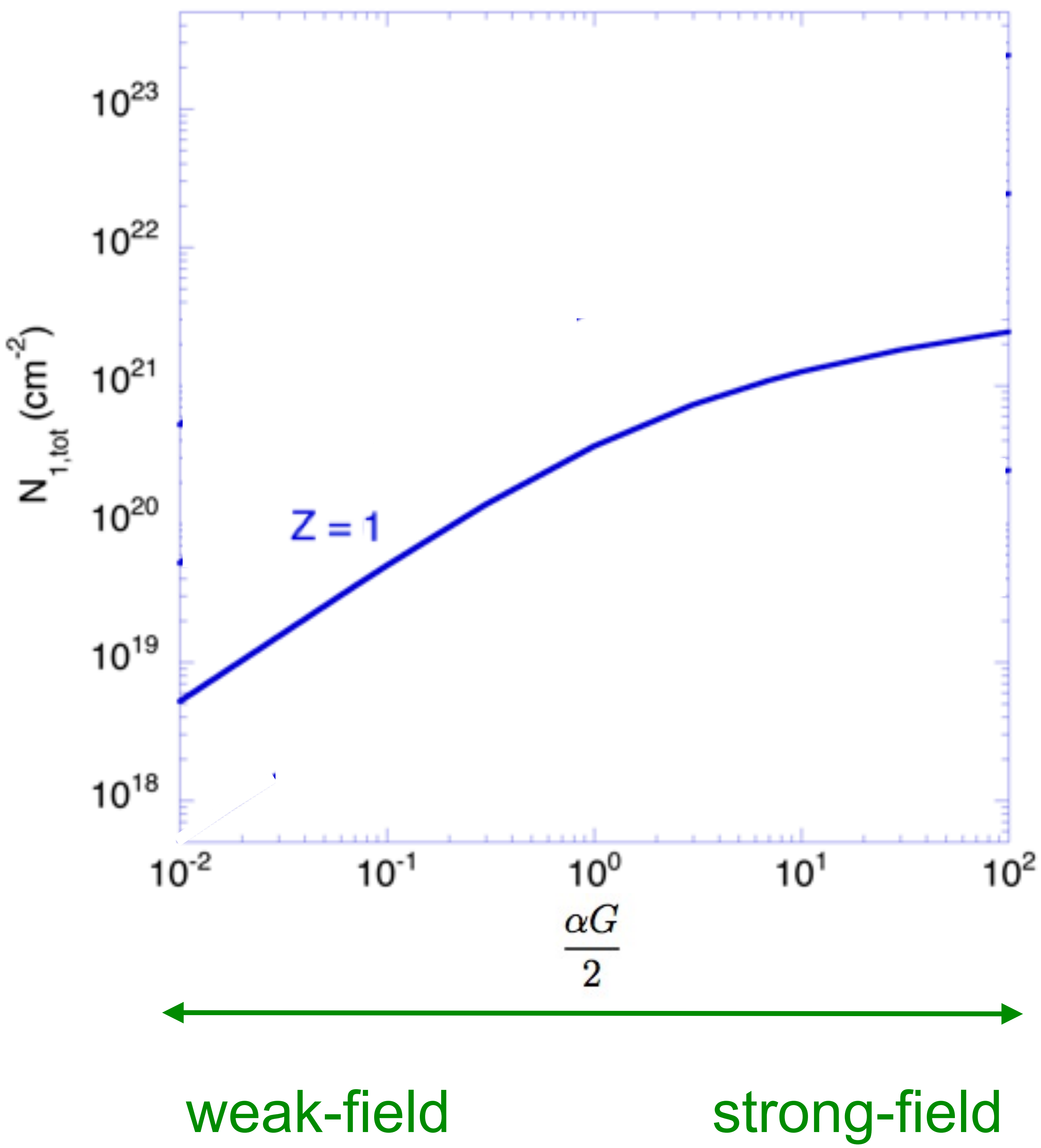
$$\boxed{N_{1,\mathrm{tot}} = \frac{1}{4}\frac{\bar{f}_{\mathrm{diss}} w F_0}{Rn}}$$

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

formation rate per unit area = effective dissociation flux

(a "Strömgren Relation")

Strong-Field Limit:



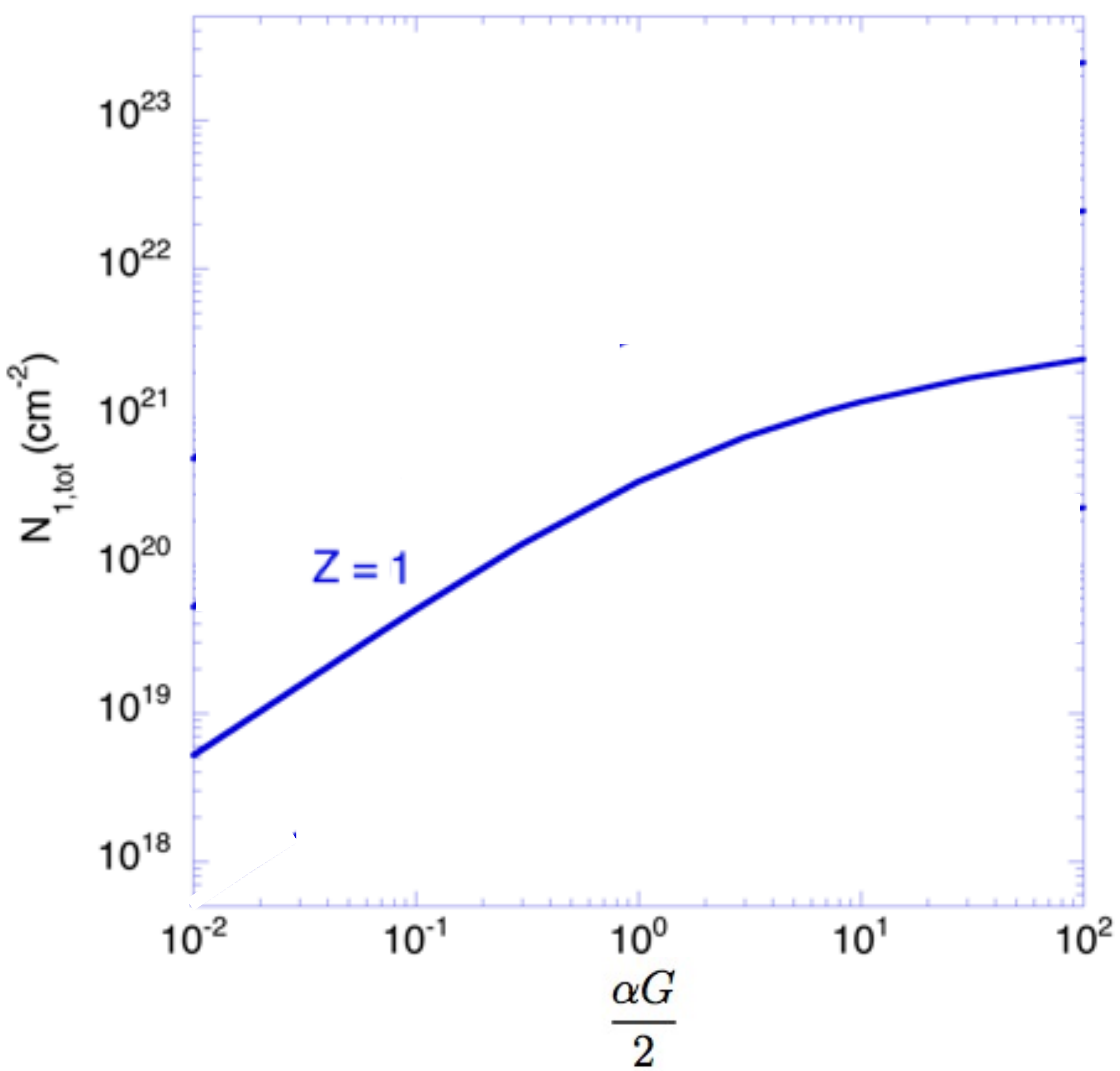
$$\boxed{N_{1,\mathrm{tot}} \approx \frac{1}{\sigma_g}}$$

(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.

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

weak-field

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

strong-field

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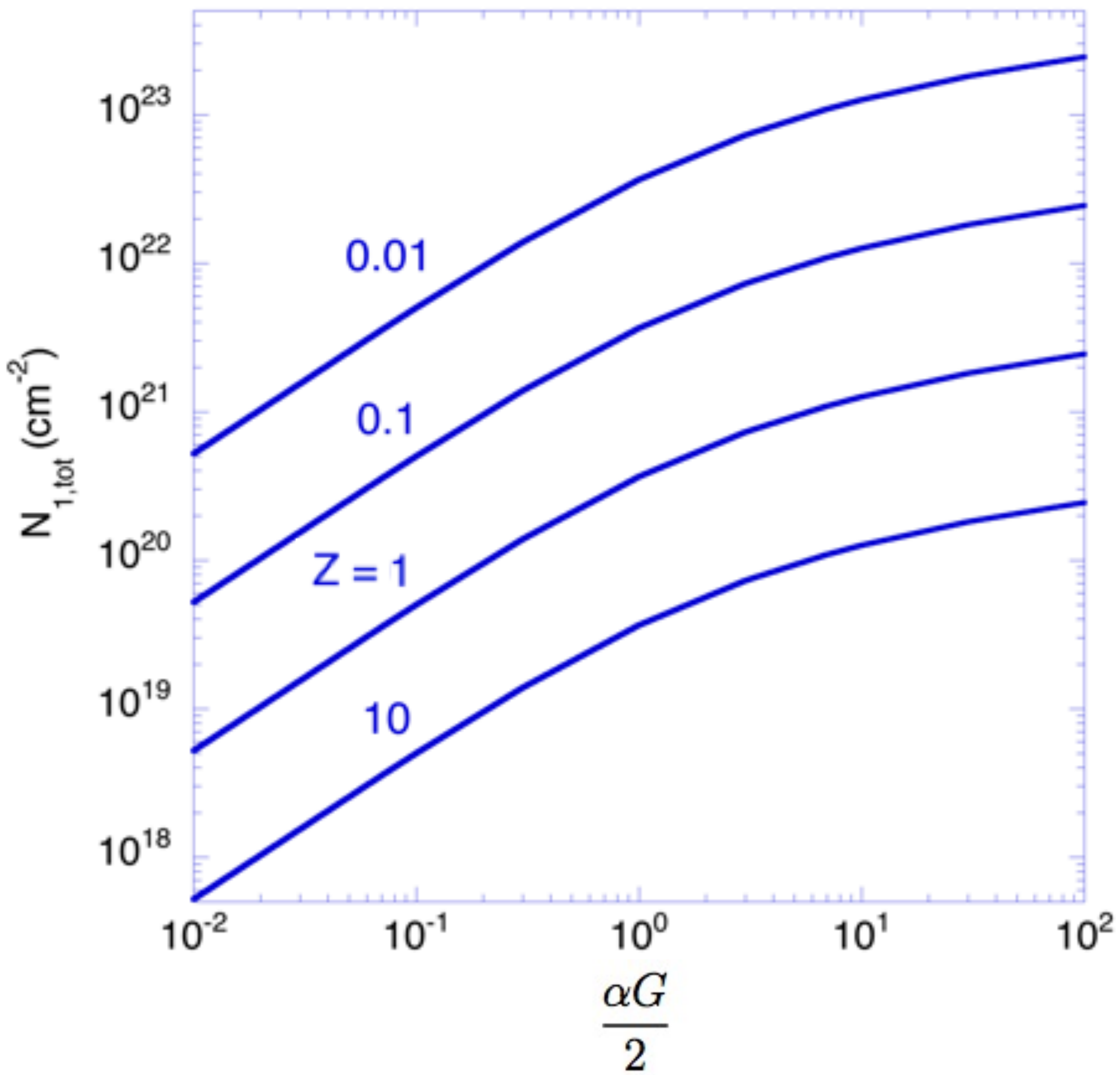

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$$\boxed{N_{1,\mathrm{tot}} \approx \frac{1}{\sigma_g} \propto \frac{1}{Z'}}$$

strong-field

General Purpose Analytic Formula for the Total HI Column Density: S+ 2014

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

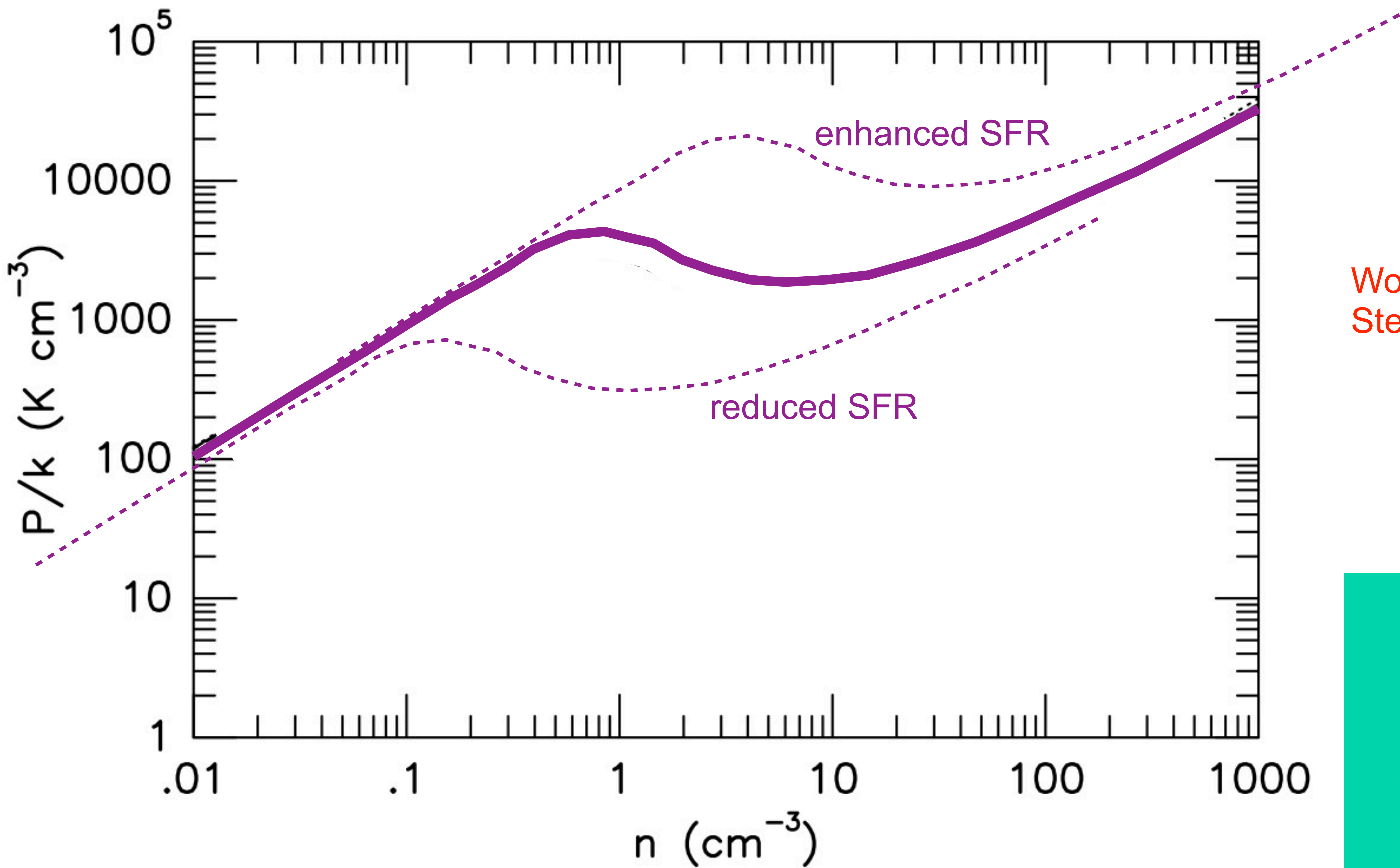
- useful for interpreting 21cm observations
- incorporation into hydrodynamics simulations
- application to “self-regulated” media

HI Thermal Phases in Self-Regulated Media:

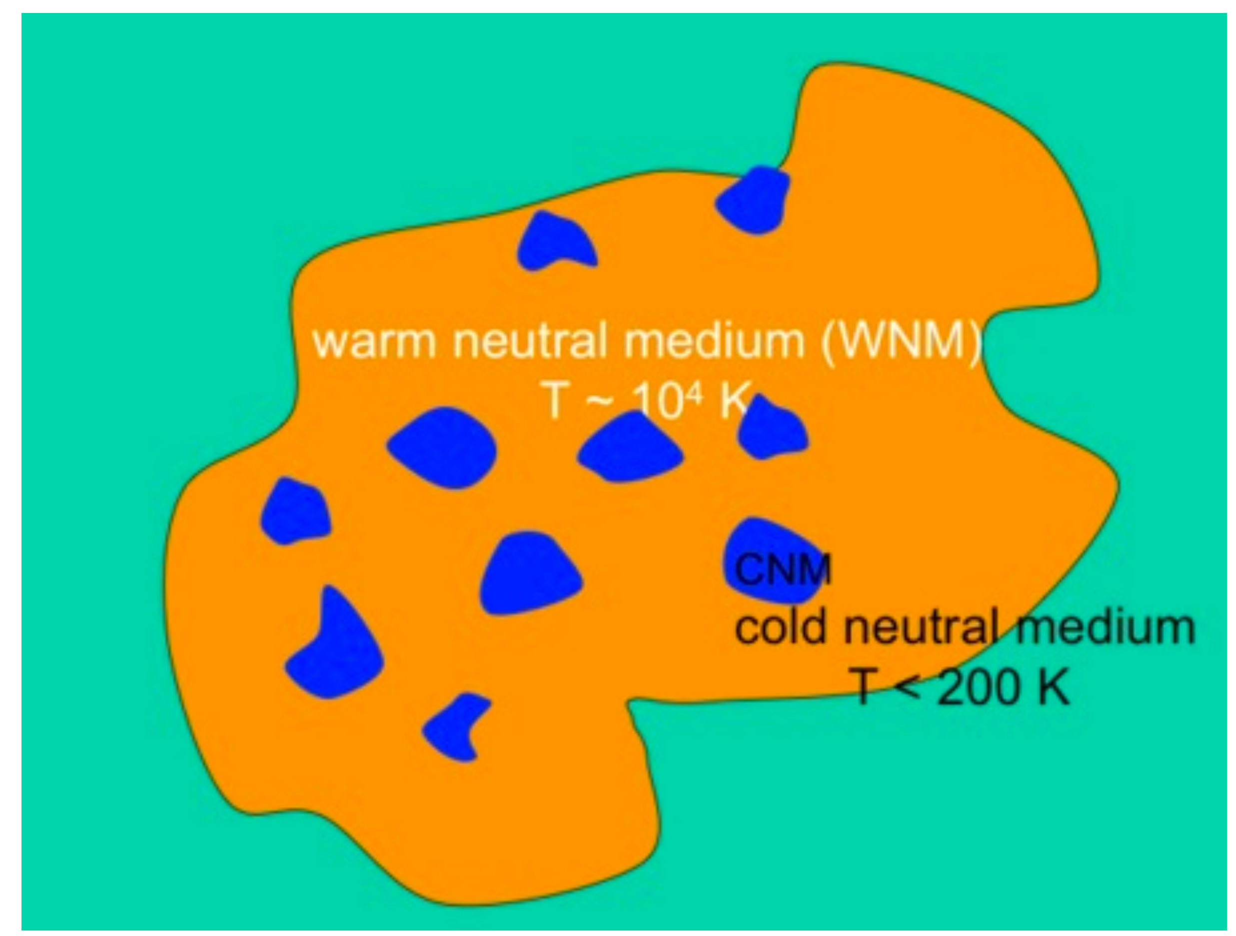
Ansatz:
Krumholz, McKee & Tumlinson 2009

P/k = nT

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



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



Field, Goldsmith & Habing 1969 ApJ 155 149

HI Thermal Phases in Self-Regulated Media:

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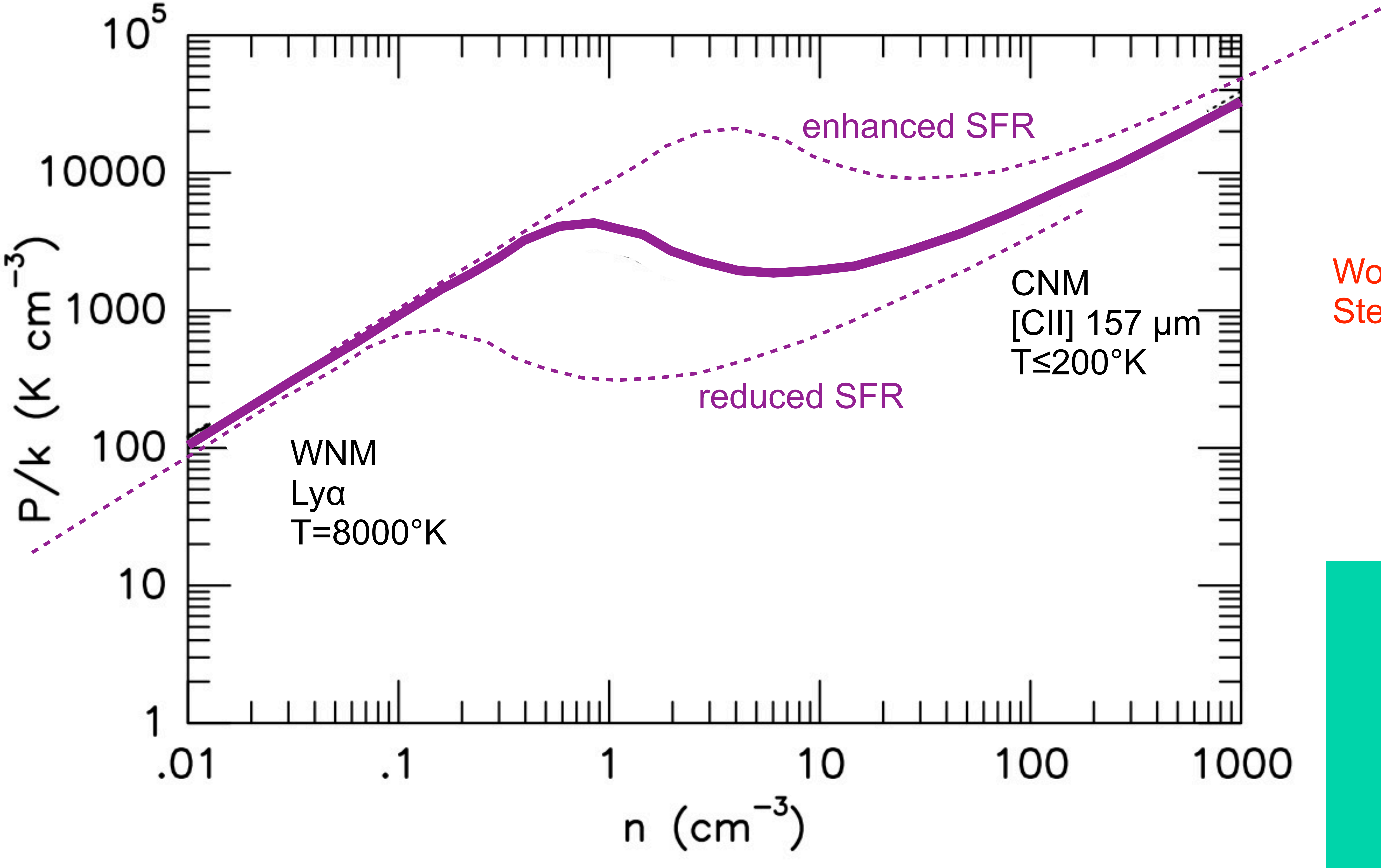

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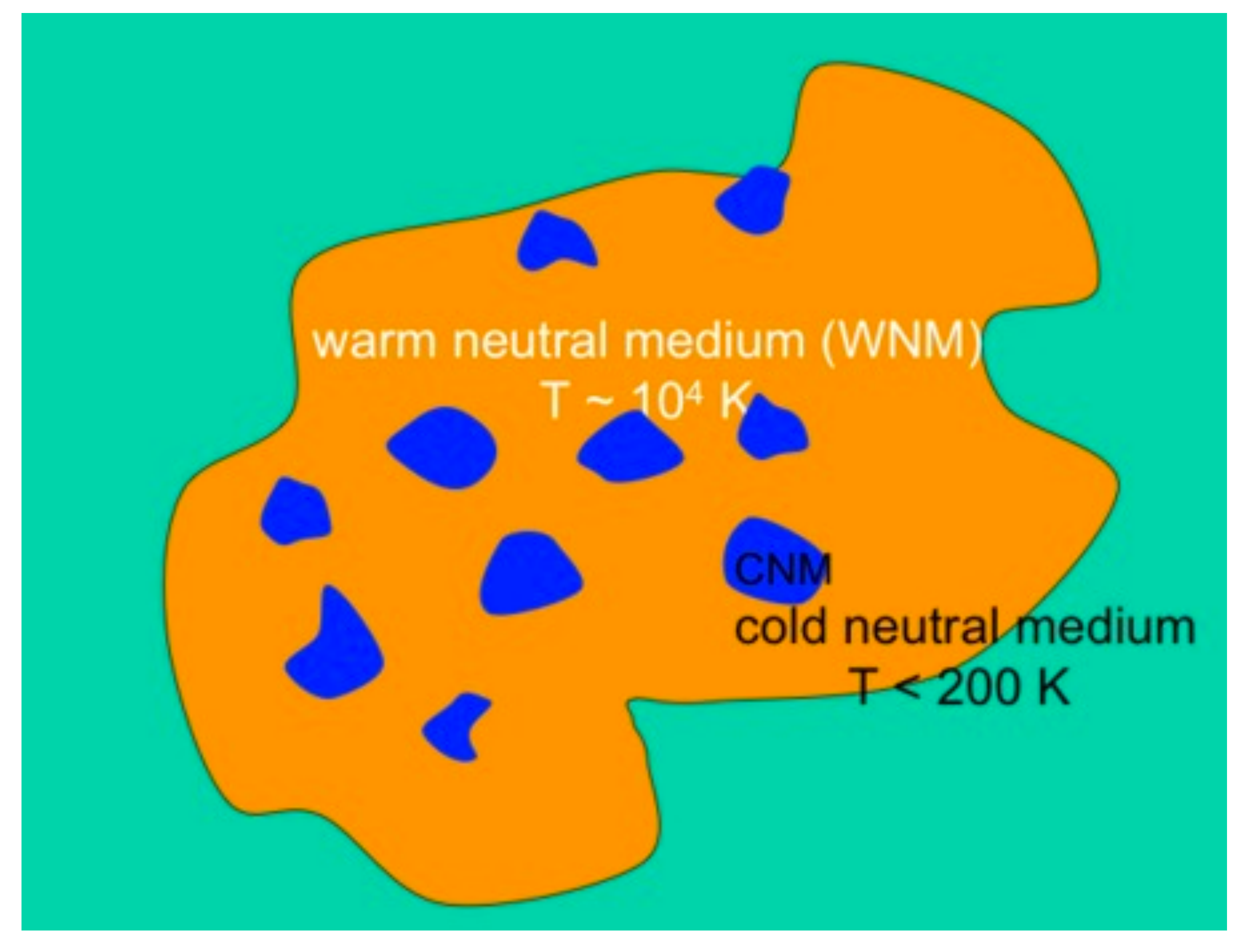

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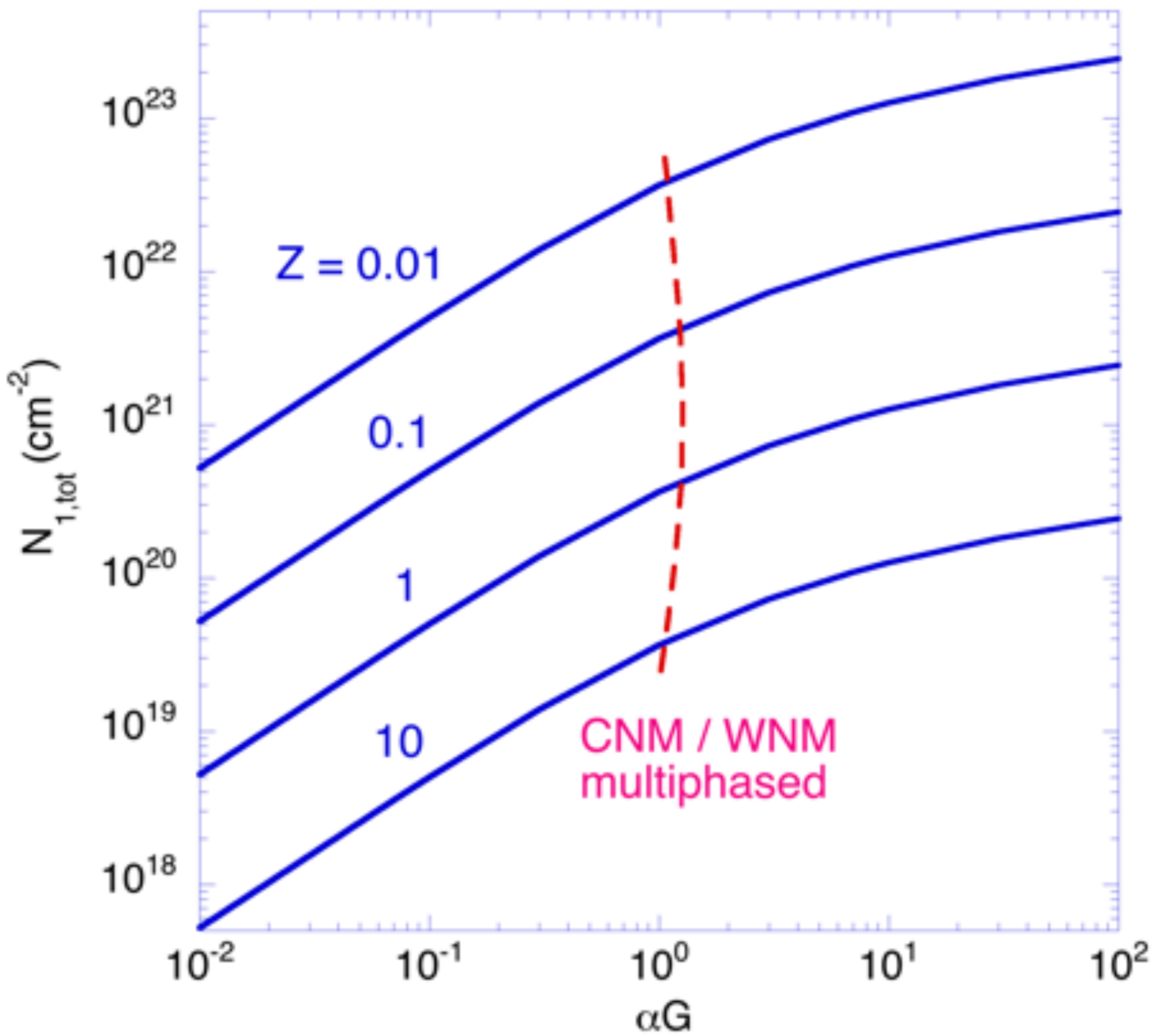
HI Column Density for Self-Regulated Media:

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

remarkable!



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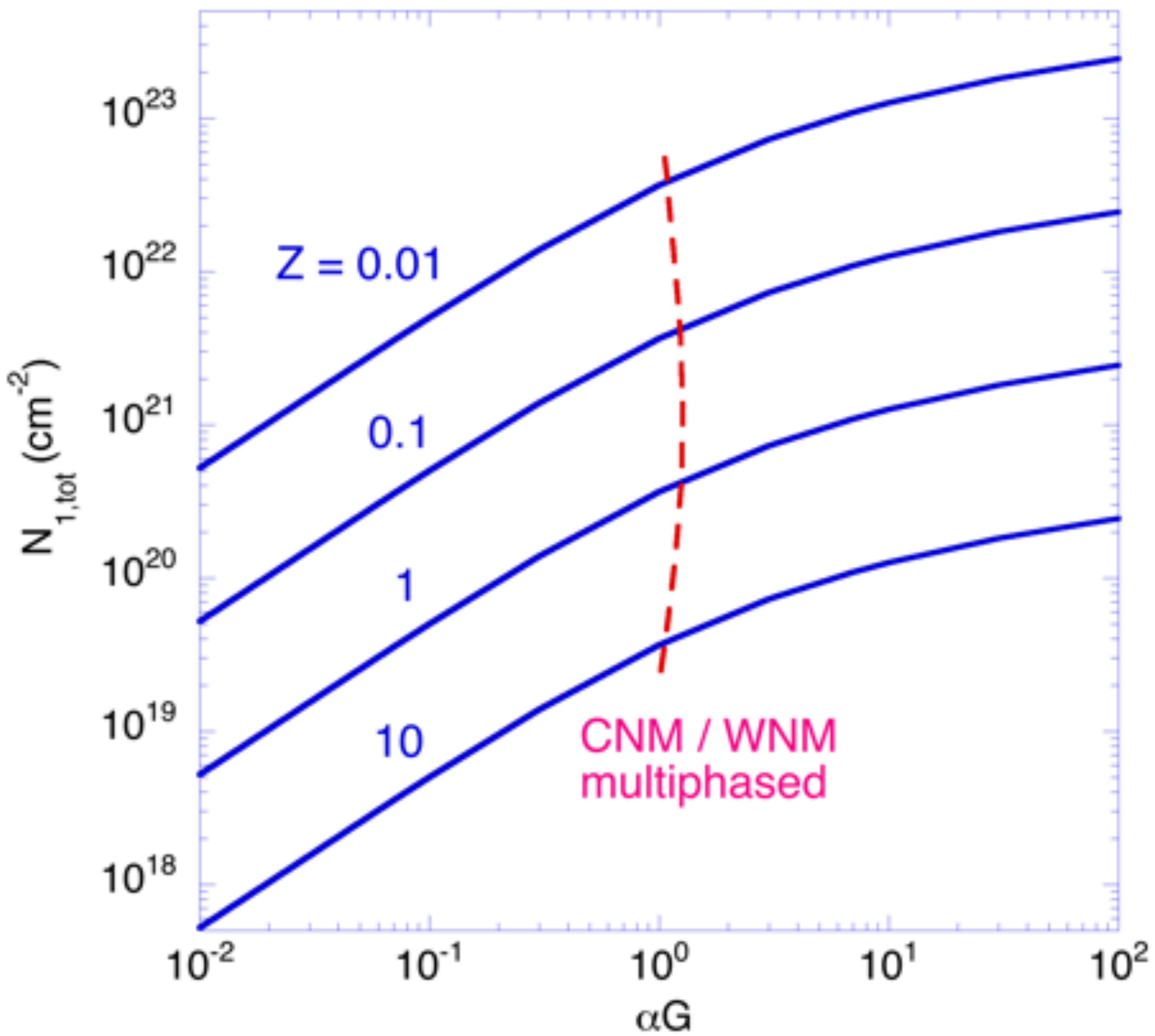


$$\Sigma_{\rm HI} \approx \frac{6}{\phi_g Z'} \quad {\rm M_\odot\ pc^{-2}}$$

characteristic HI photodissociation mass surface density in self-regulated systems

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

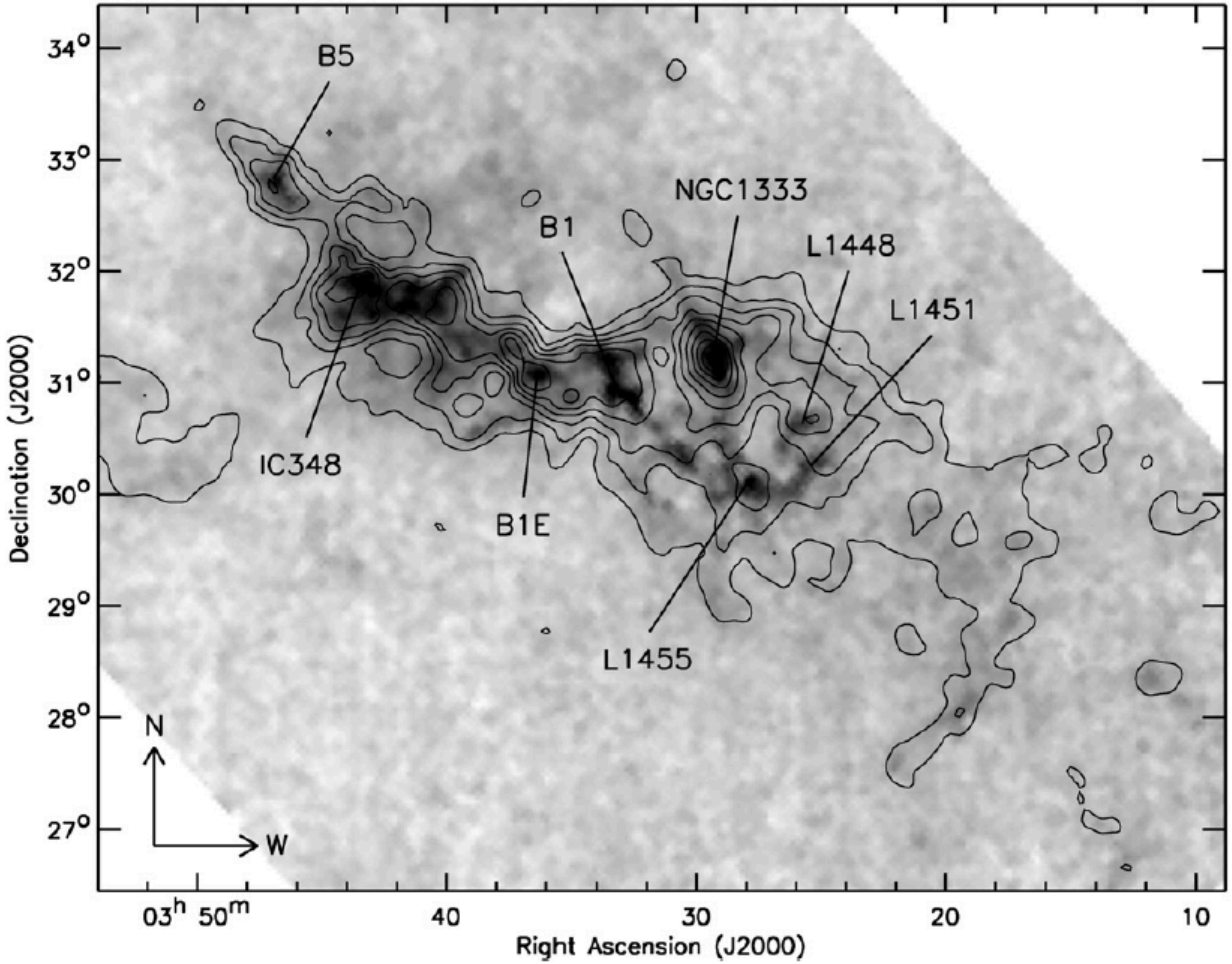
“transition” total gas mass surface density... star-formation threshold...galaxies.

independent of radiation field intensity and/or gas density.

HI-to-H_2 in Perseus:

Lee et al. 2012; 2015

Perseus Cloud   distance 300 pc



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

Dame+ 2001 Ridge+ 2006

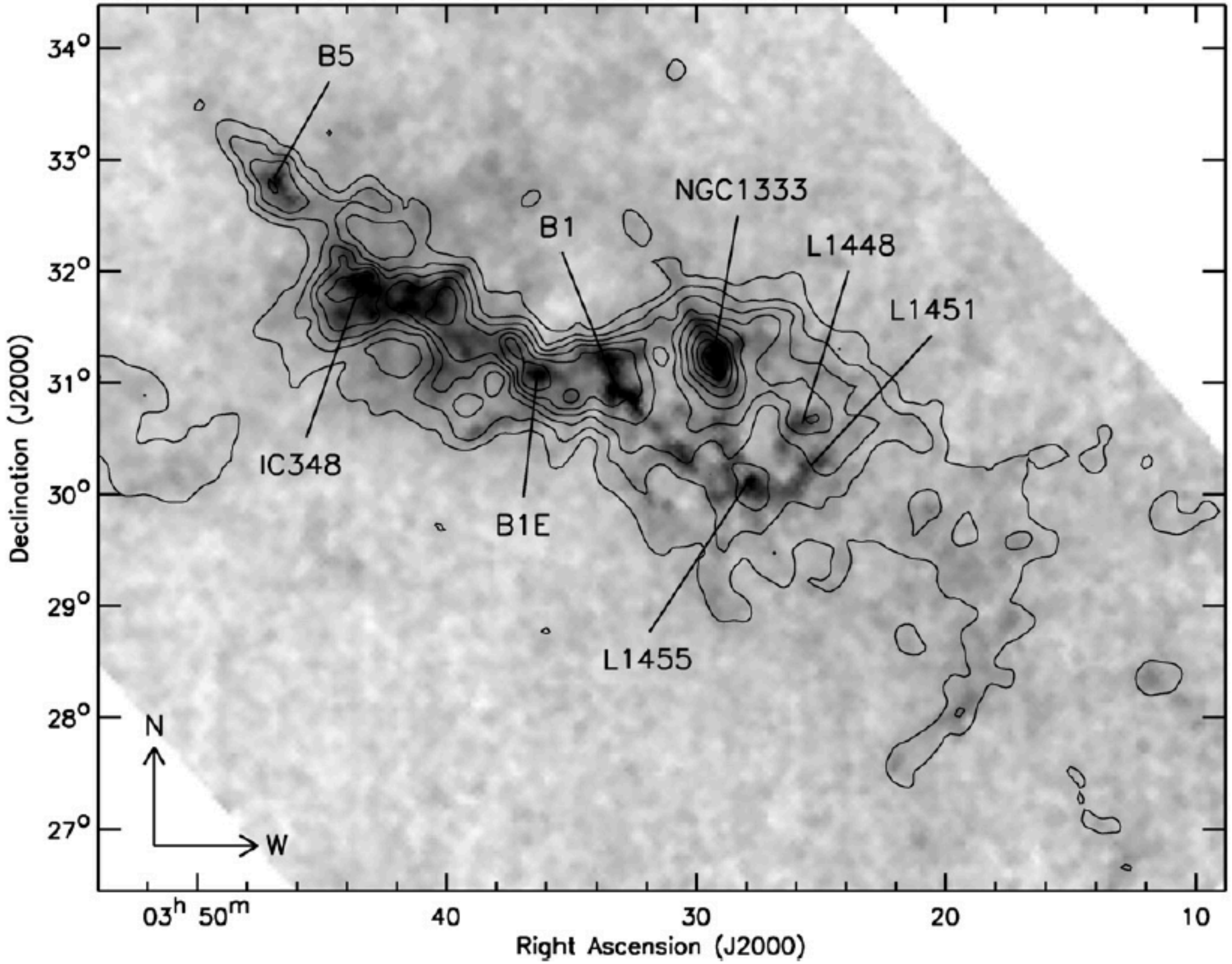
HI-to-H_2 in Perseus:

Lee et al. 2012; 2015

dark clouds &
low-mass star-forming regions:

B1
B1E
B5
NGC1333
IC348

Perseus Cloud distance 300 pc



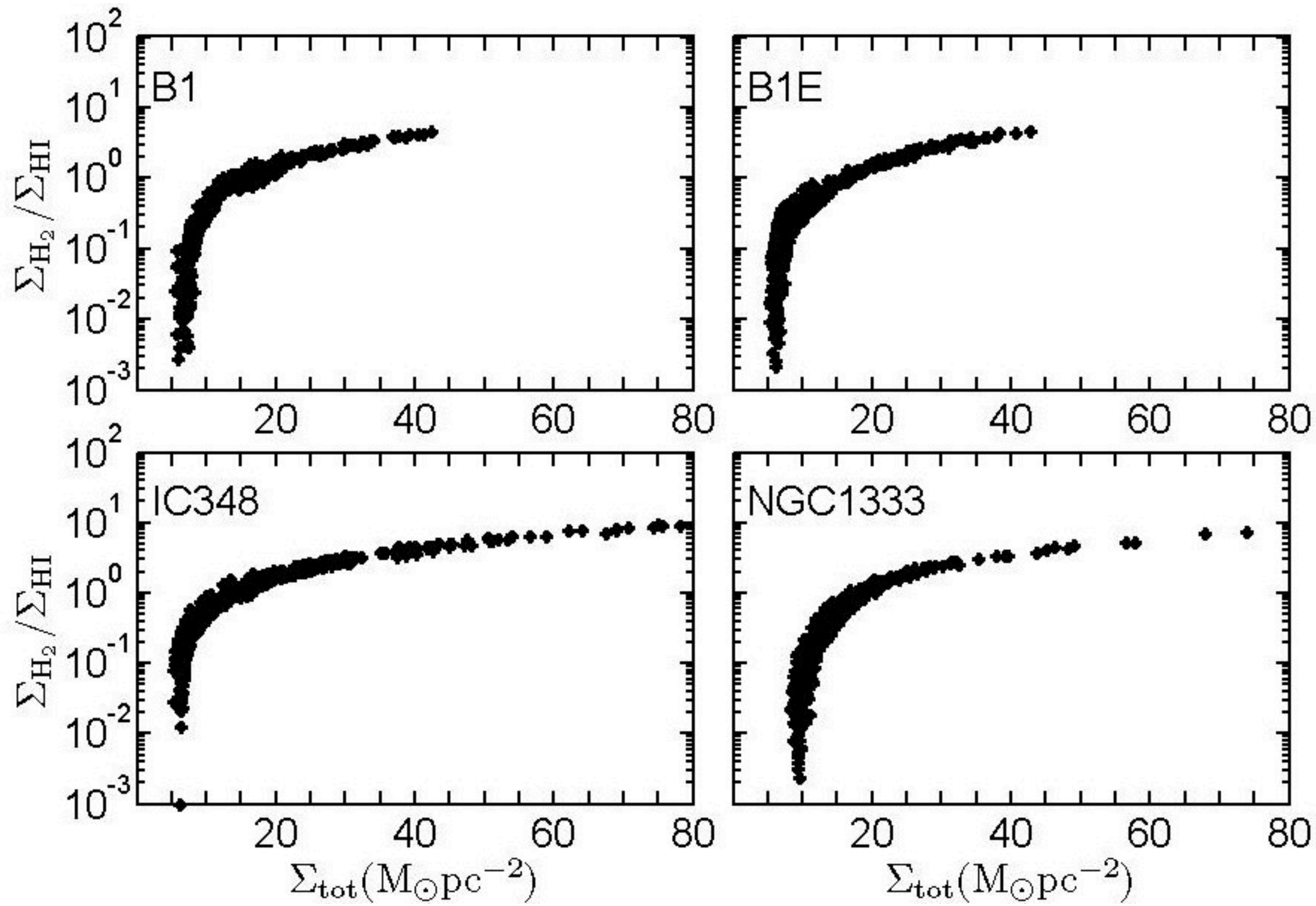
2MASS A_V and I_{CO} CfA & COMPLETE surveys

Dame+ 2001 Ridge+ 2006

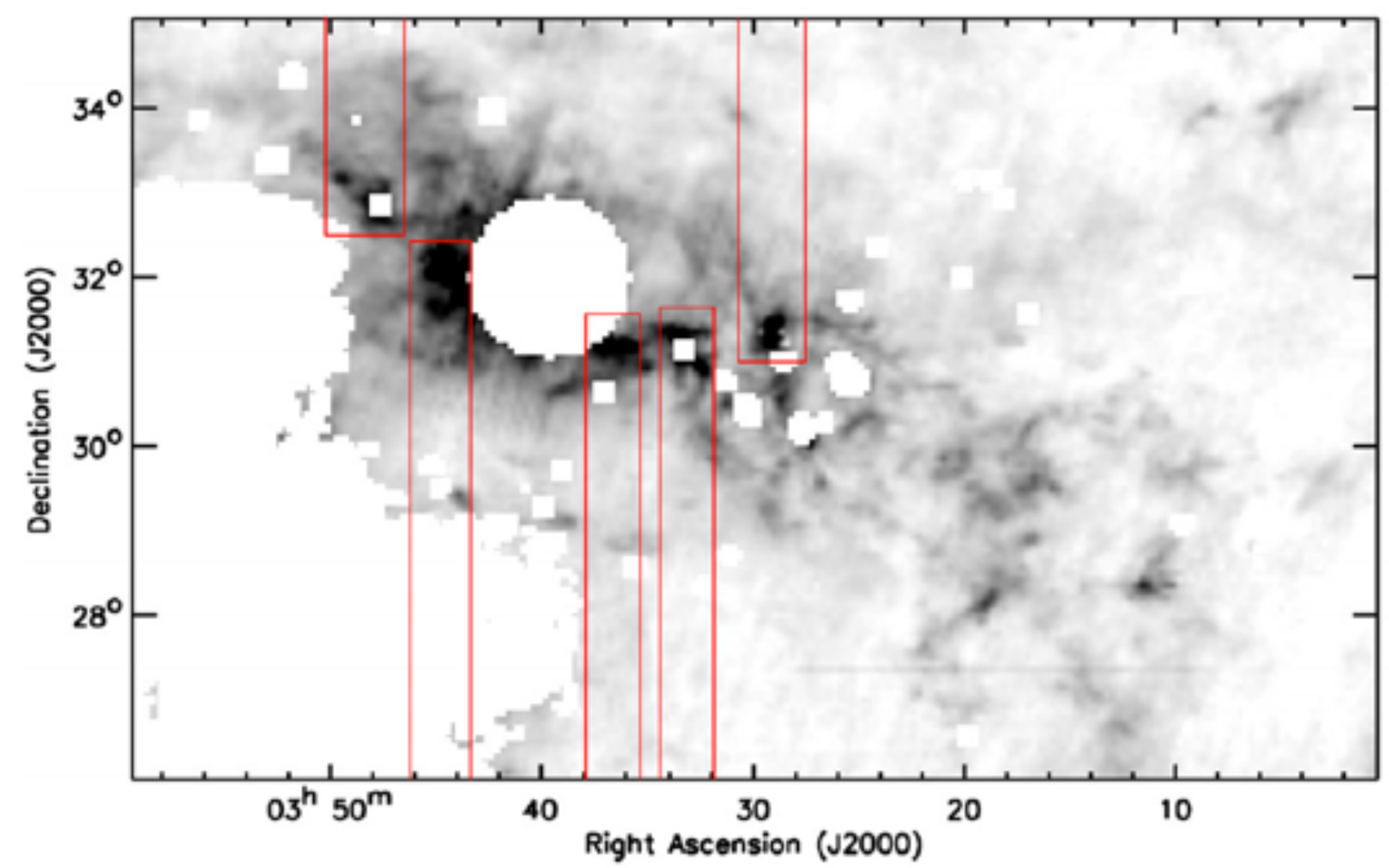
HI-to-H_2 in Perseus:

Lee+ 2012, 2015 Peek+ 2011 GALFA HI Survey (Arecibo 4arcmin)

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



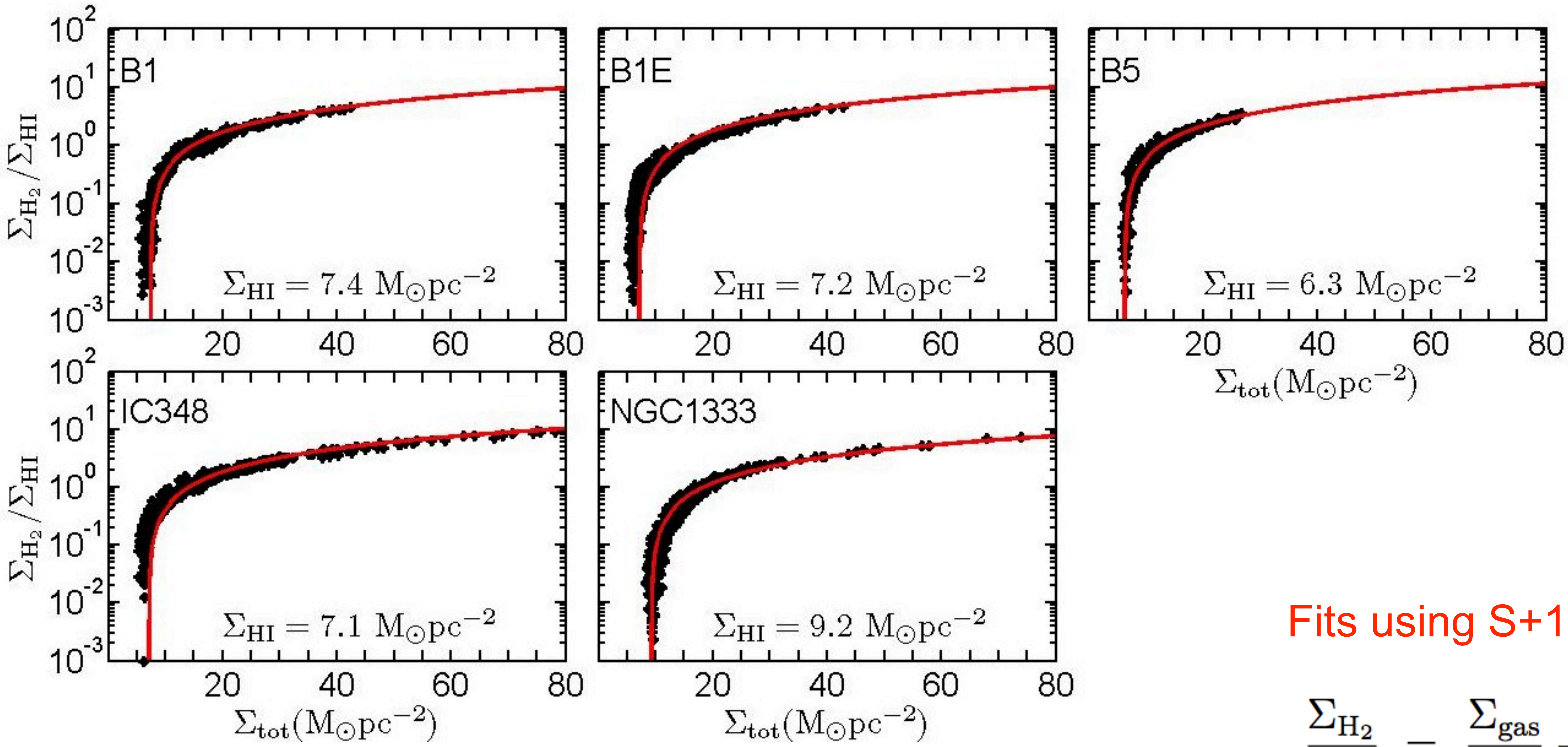
Σ_{H_2}/Σ_{HI}



HI-to-H_2 in Perseus:

Bialy, Sternberg, Lee, Le Petit & Roueff 2015 ApJ 809 122

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

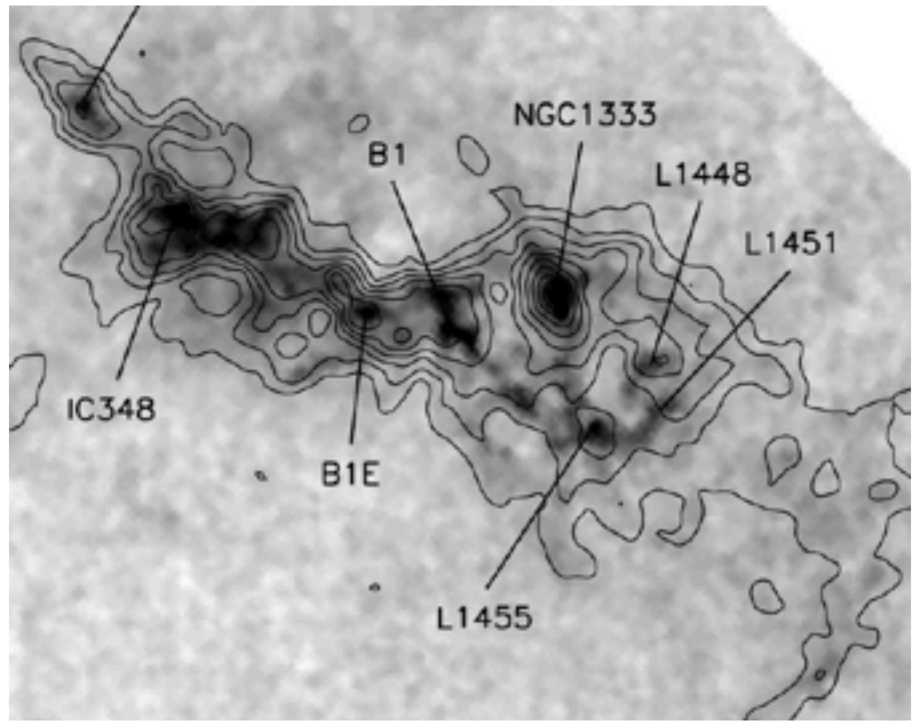


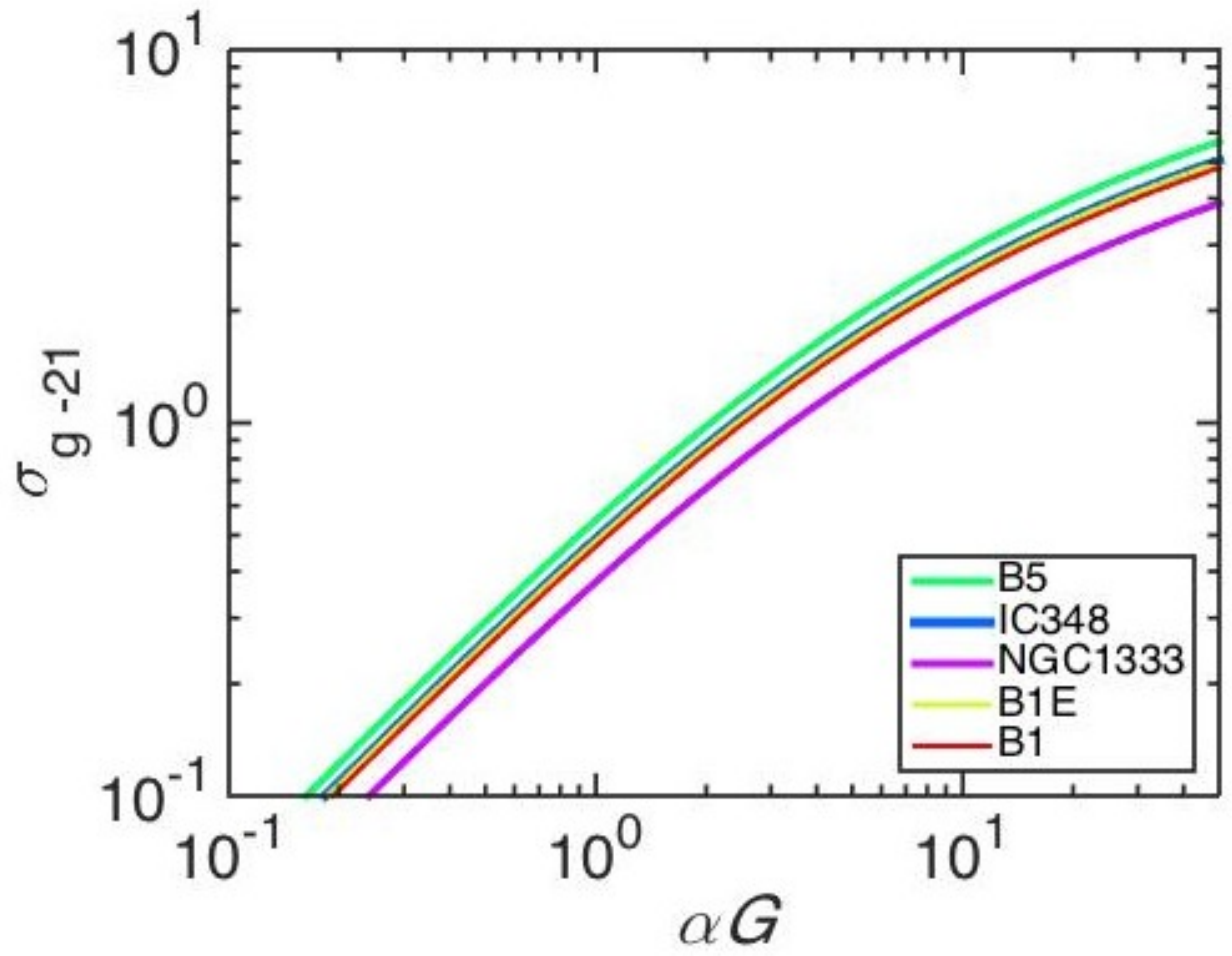
Fits using S+14:

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

HI-to-H_2 in Perseus: Bialy+ 2015

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





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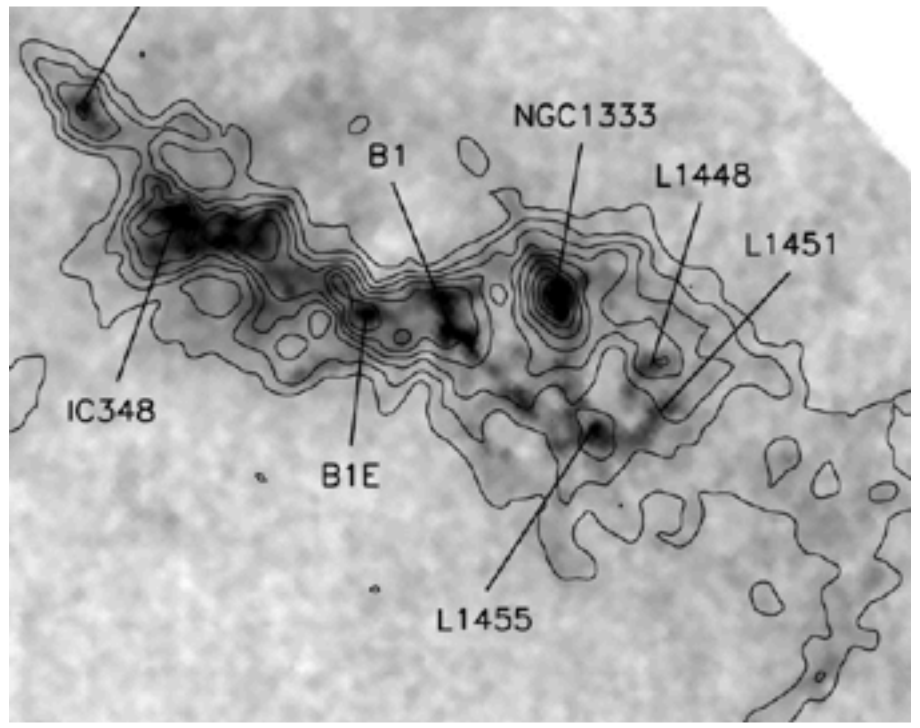

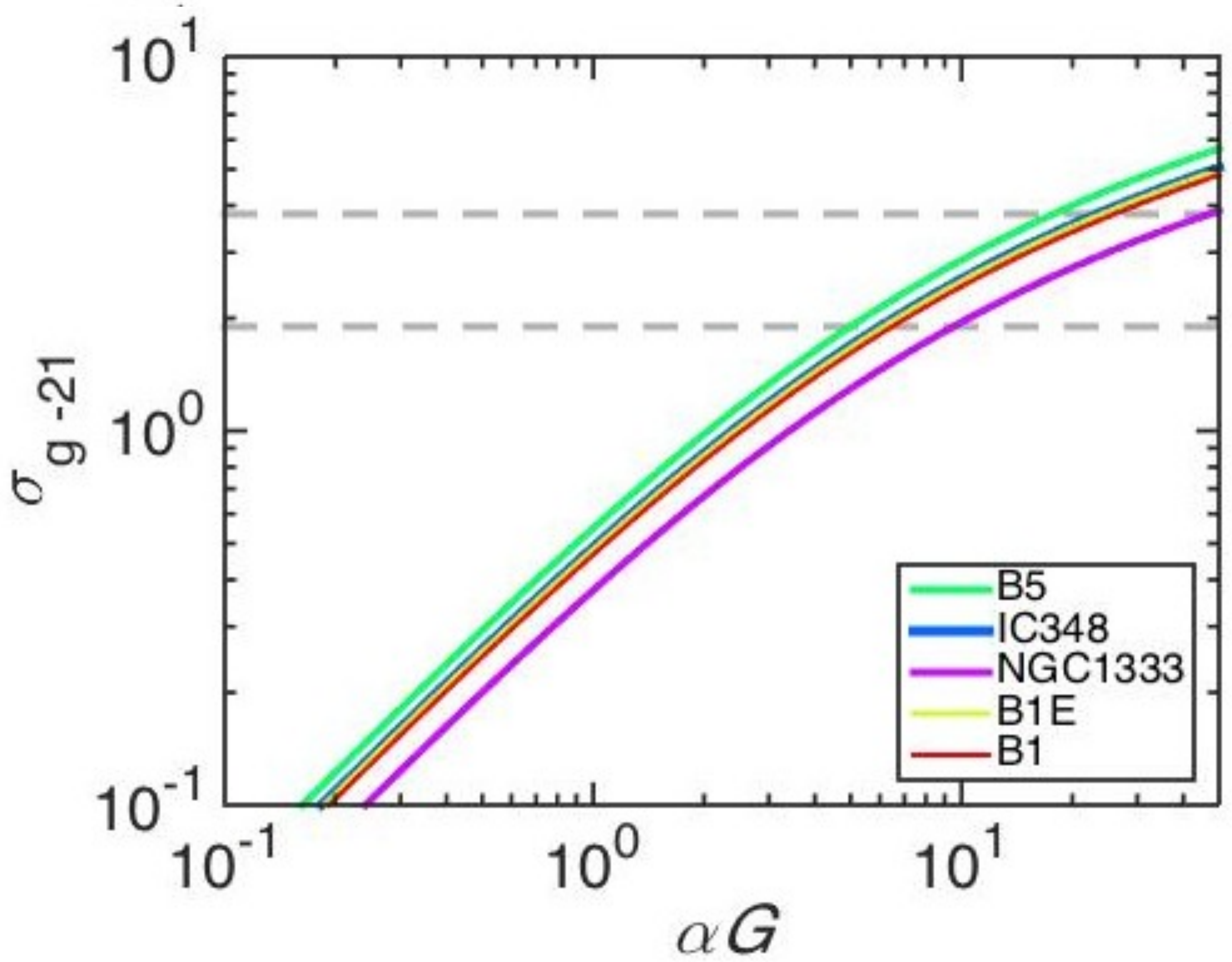

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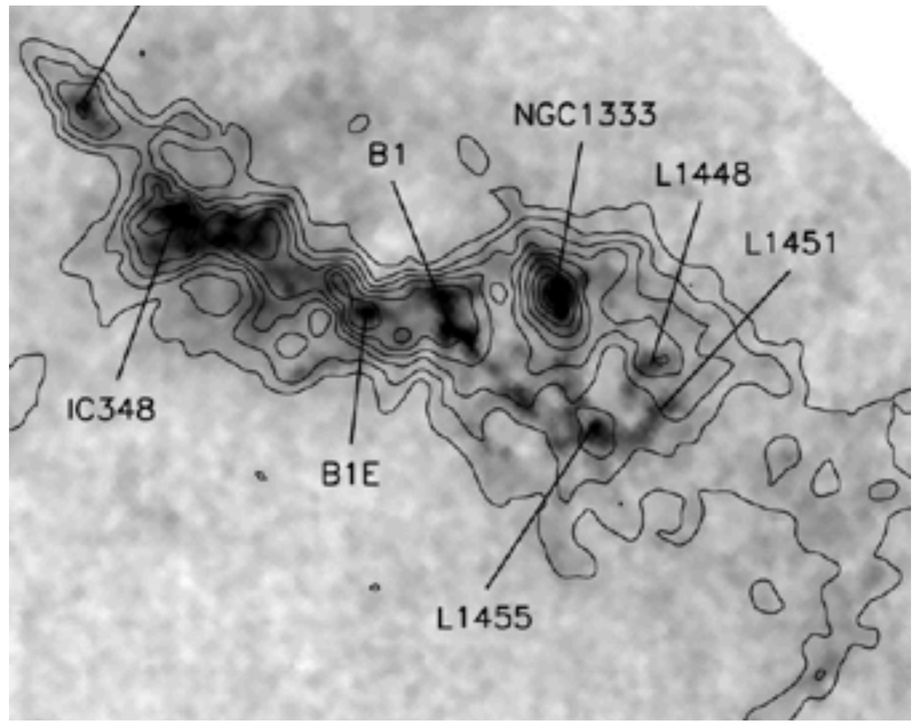

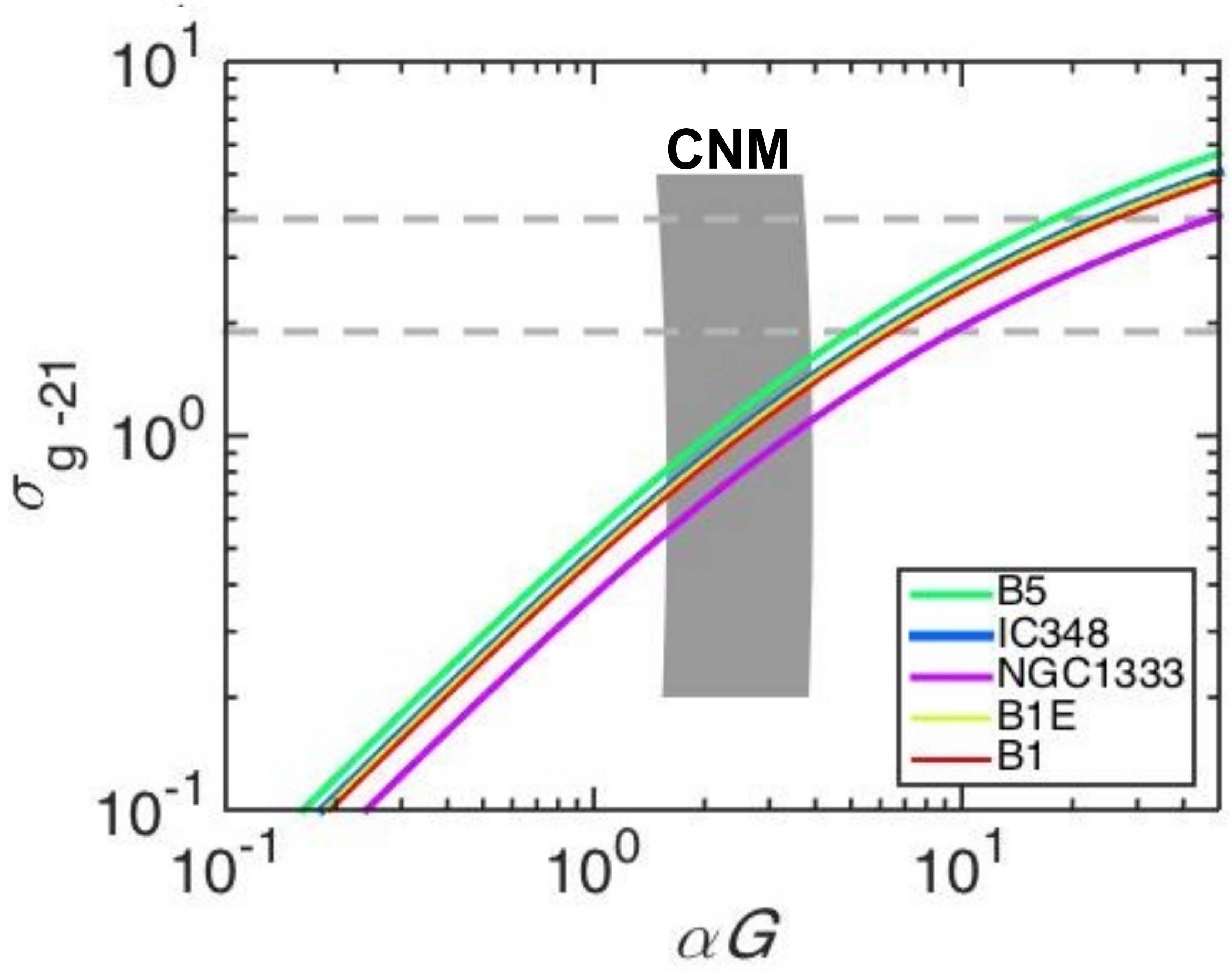

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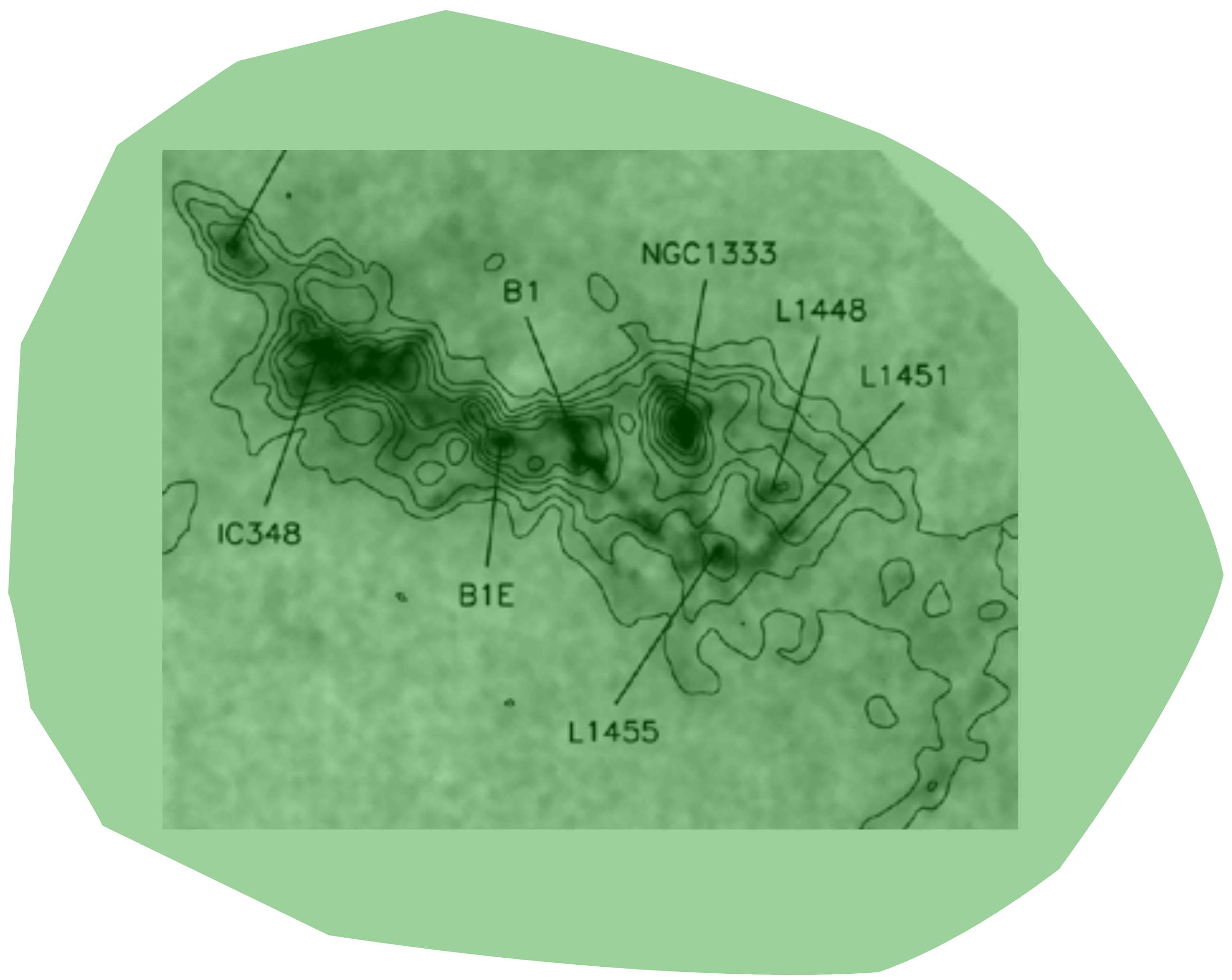
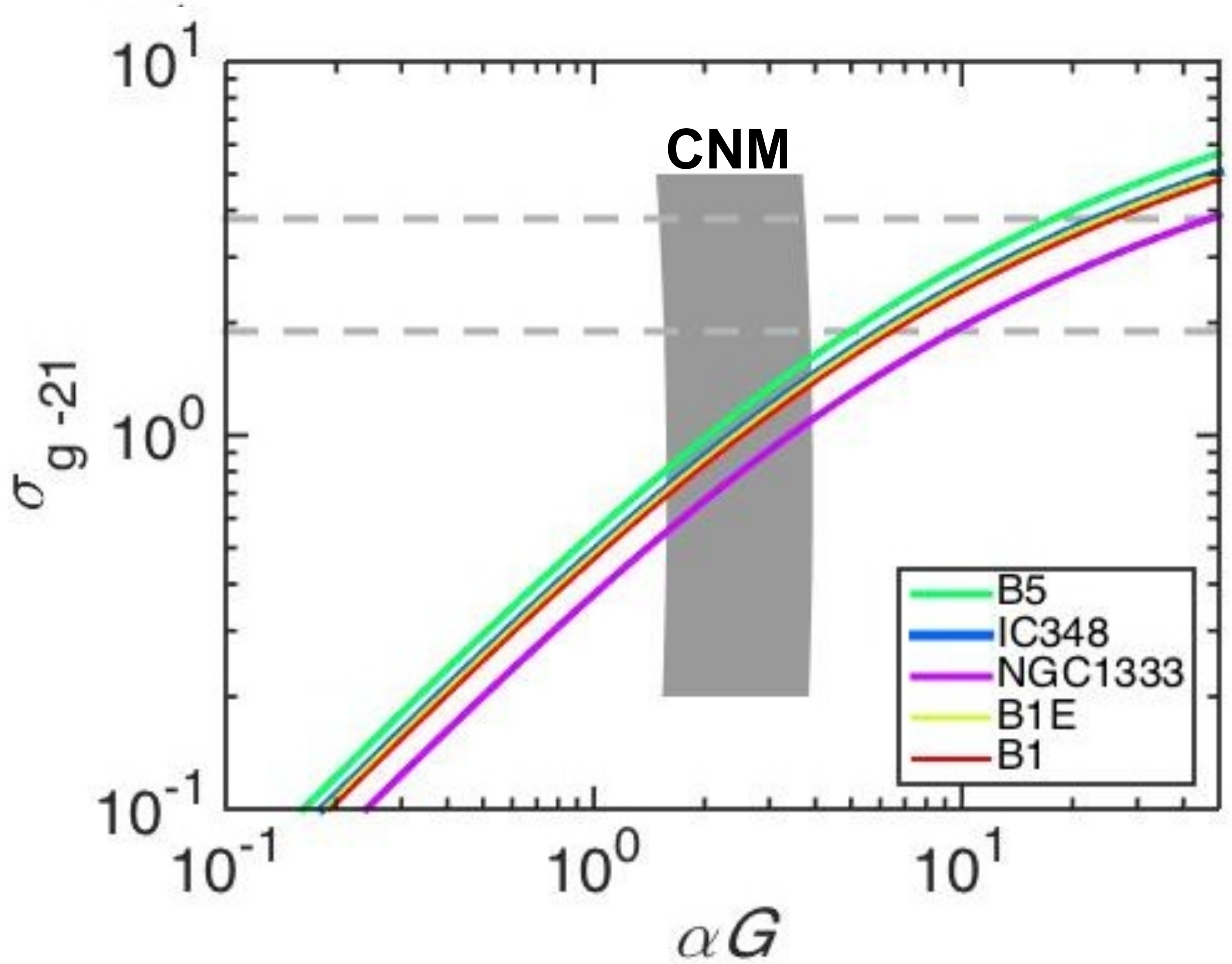


Galactic interstellar LW radiation field:
$F_0 \approx 2 \times 10^7$ photons cm^{-2} s^{-1}

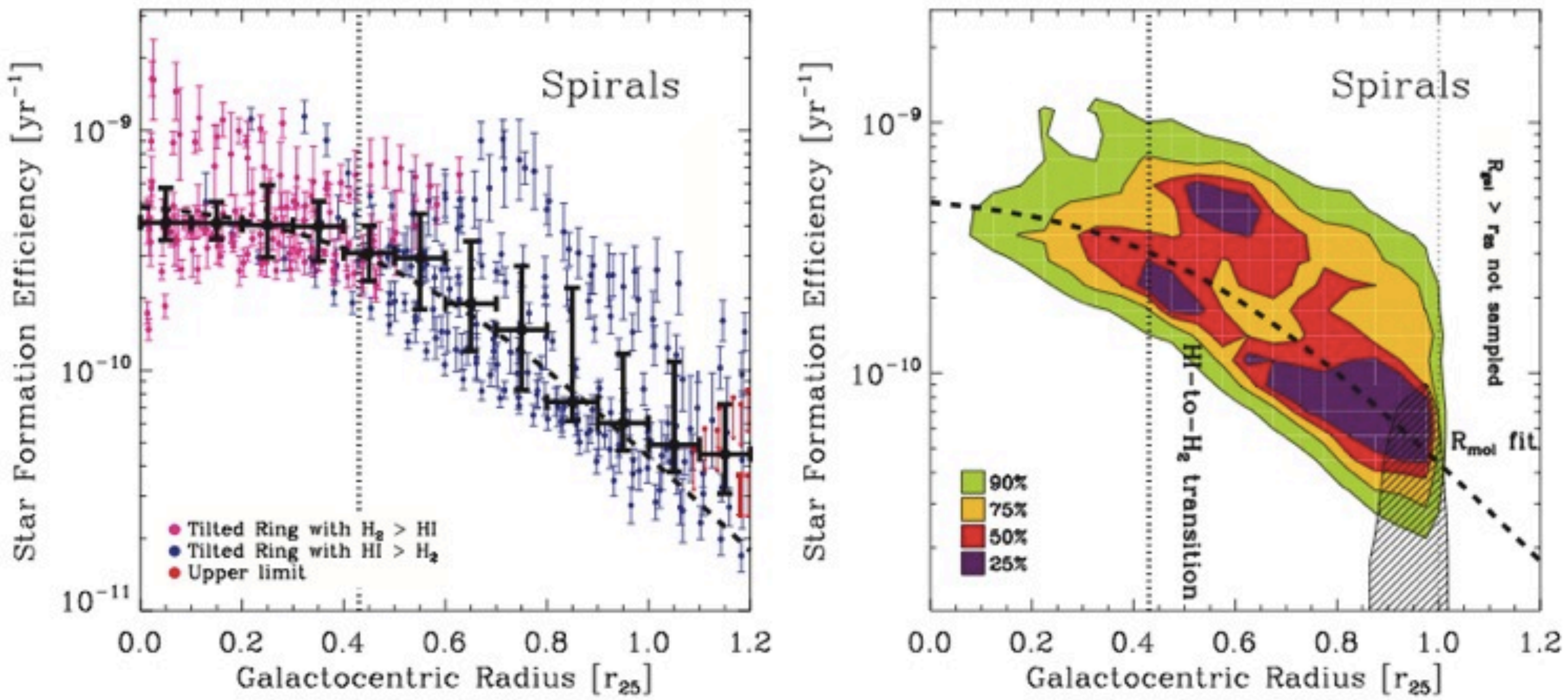


Conclusions: $\alpha G \approx 5$ to 50

- FUV absorption dominated by HI-dust
- $n_{HI} \approx 10$ to 2 cm^{-3}
- probably a UNM/CNM multiphase

Galaxies:

e.g. Bigiel+ 08



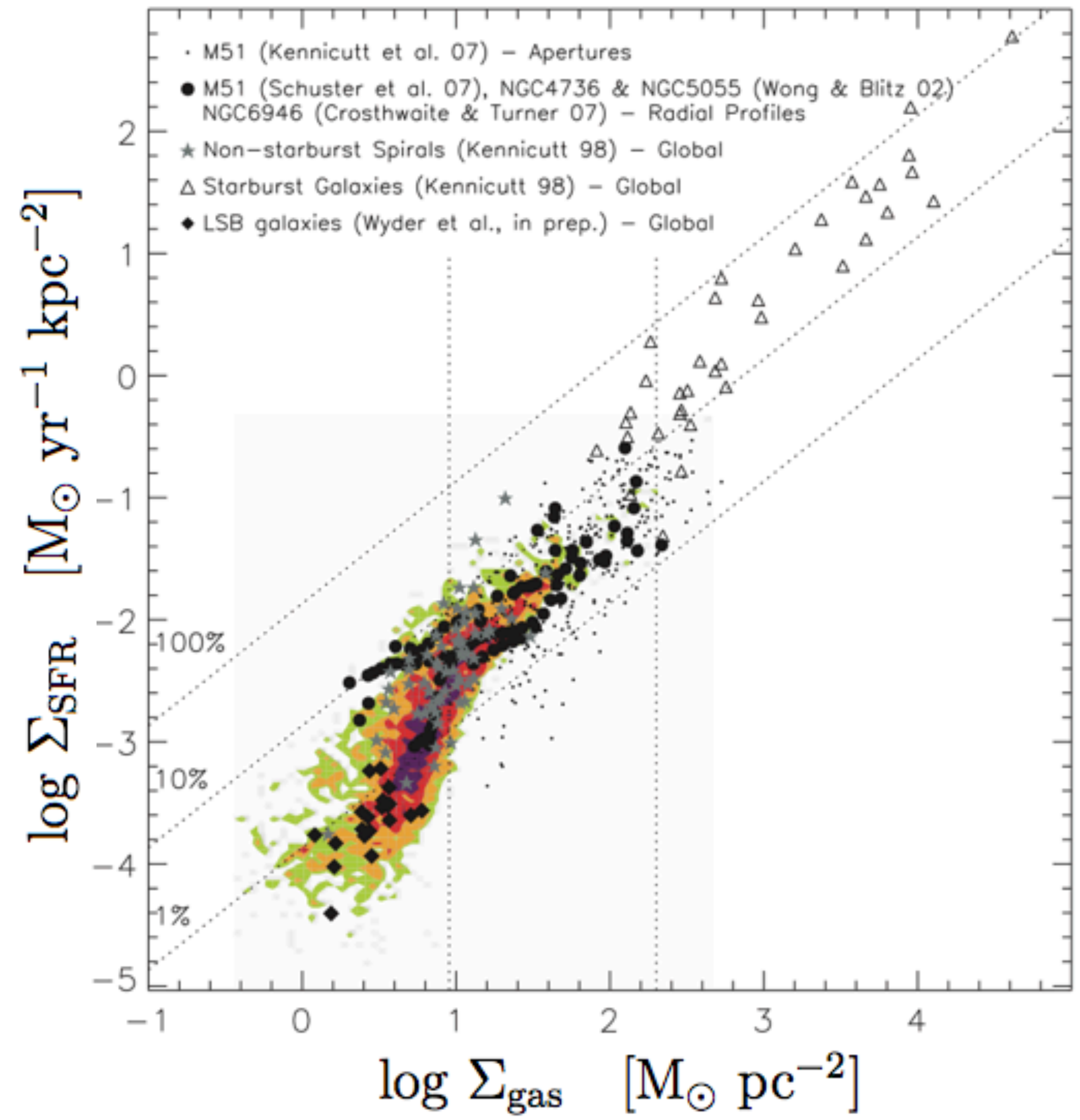


Table 5
Conditions at the H I-to-H_2 Transition

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

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

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

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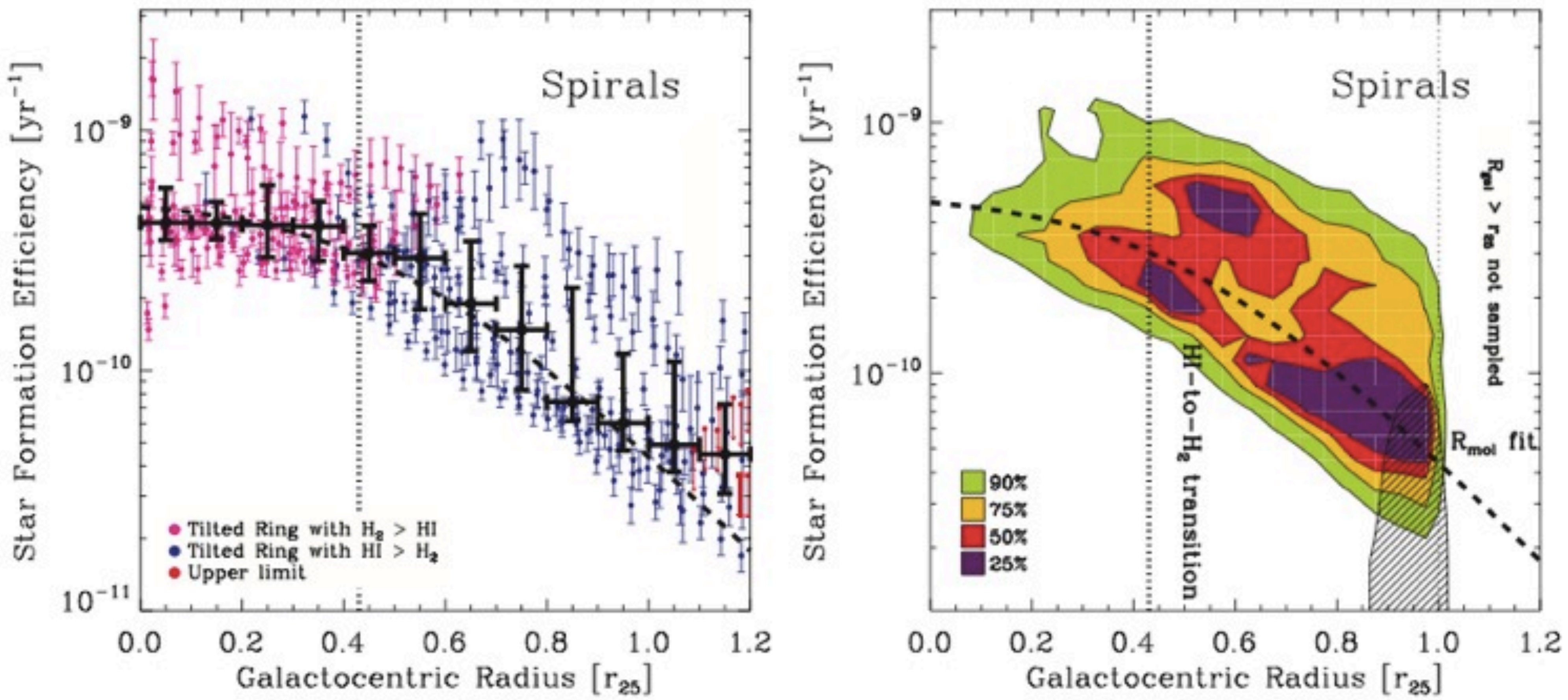

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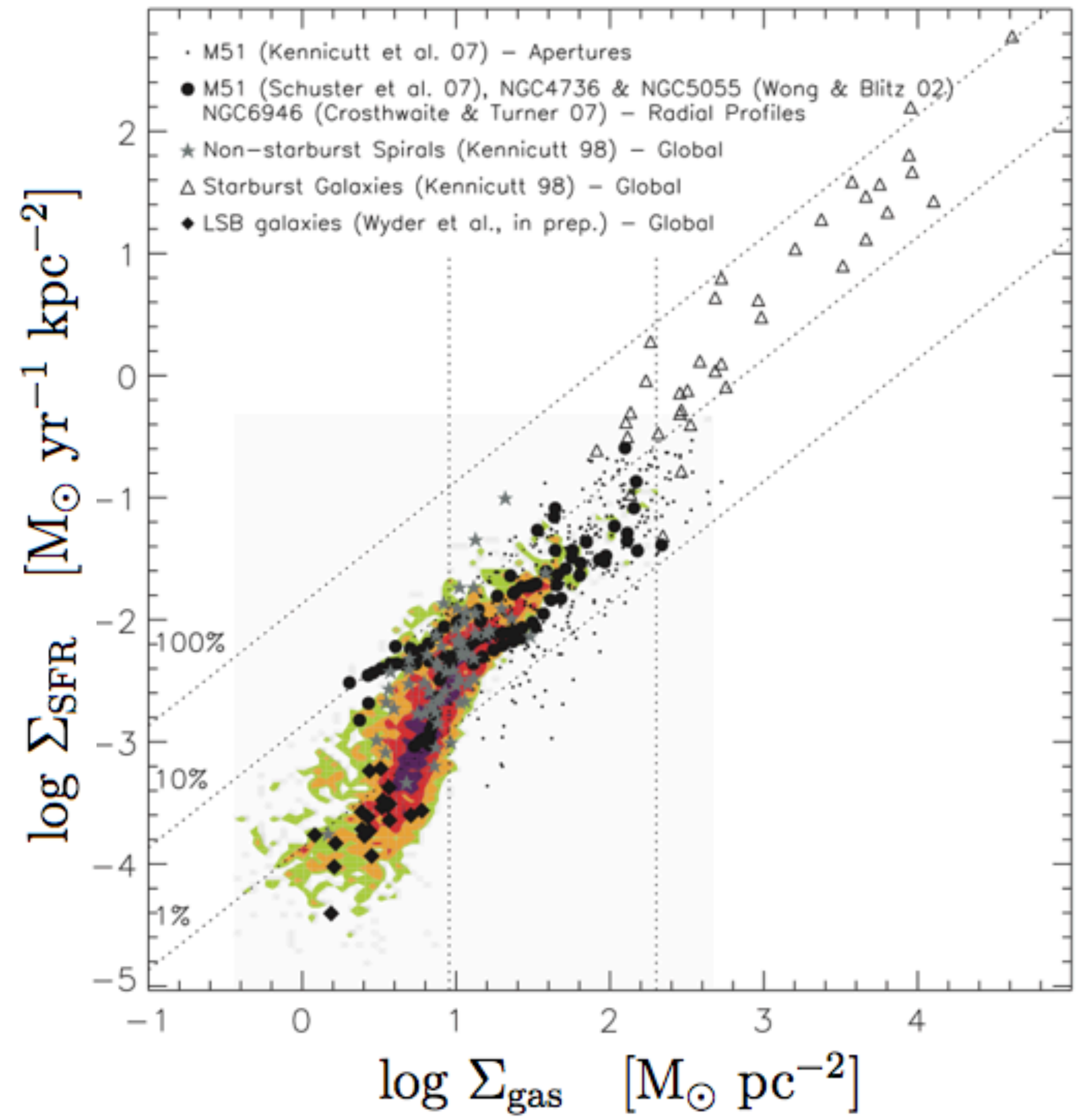

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Caveat: This interpretation requires typically "one" primary cloud per line-of-sight.

To Conclude:

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

HI-to-H$_2$ Transitions and HI Column Densities in Galaxy Star-Forming Regions

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

2014 ApJ 790 10 arXiv:1404.5042