HI-to-H_2 Transitions in Galaxy Star-Forming Regions

Amiel Sternberg
Sackler School of Physics & Astronomy
Tel Aviv University
ISRAEL

Molecules and Dust as Fuel for Star Formation
Kavli Institute for Theoretical Physics
June 2016

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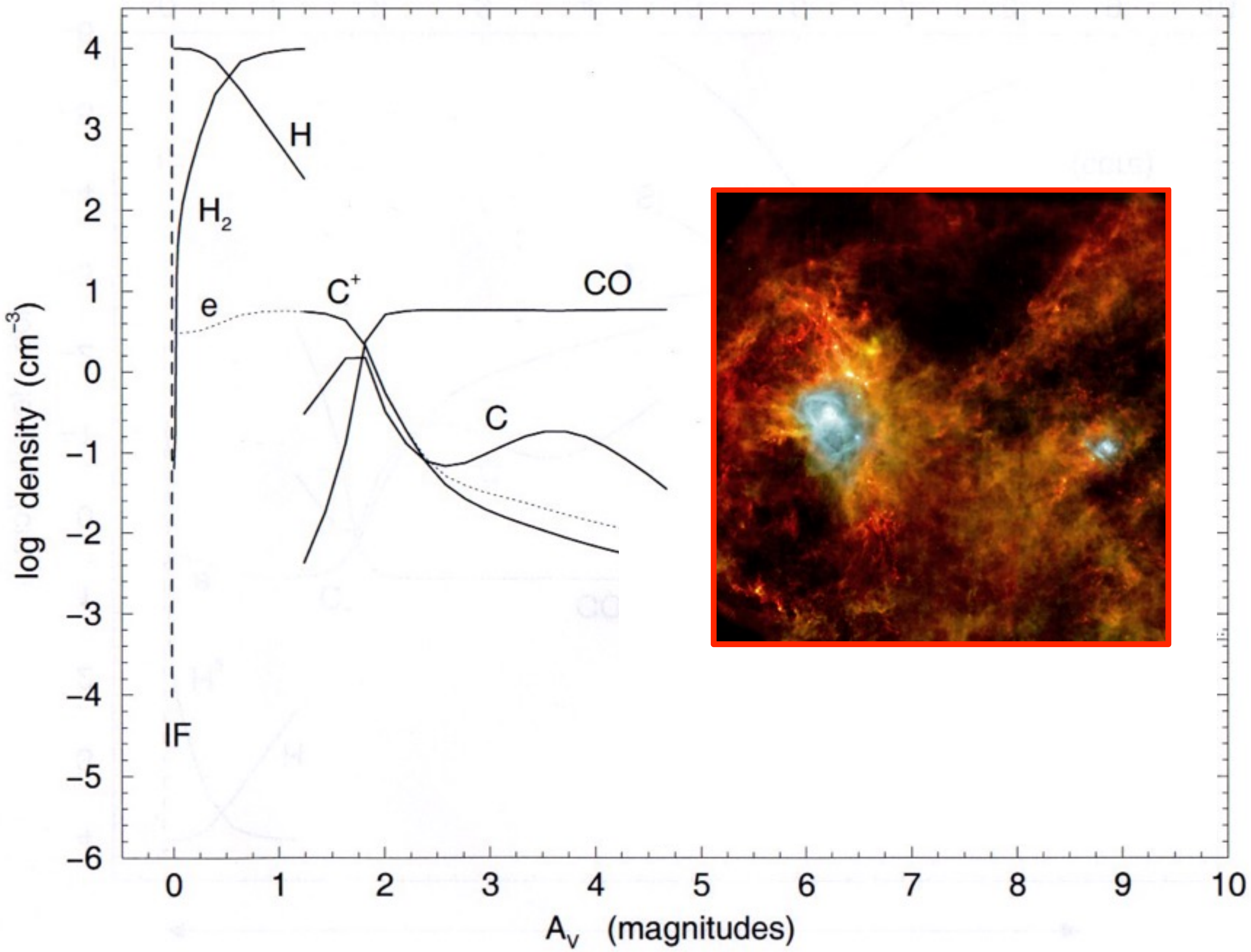

Molecules and Dust as Fuel for Star Formation
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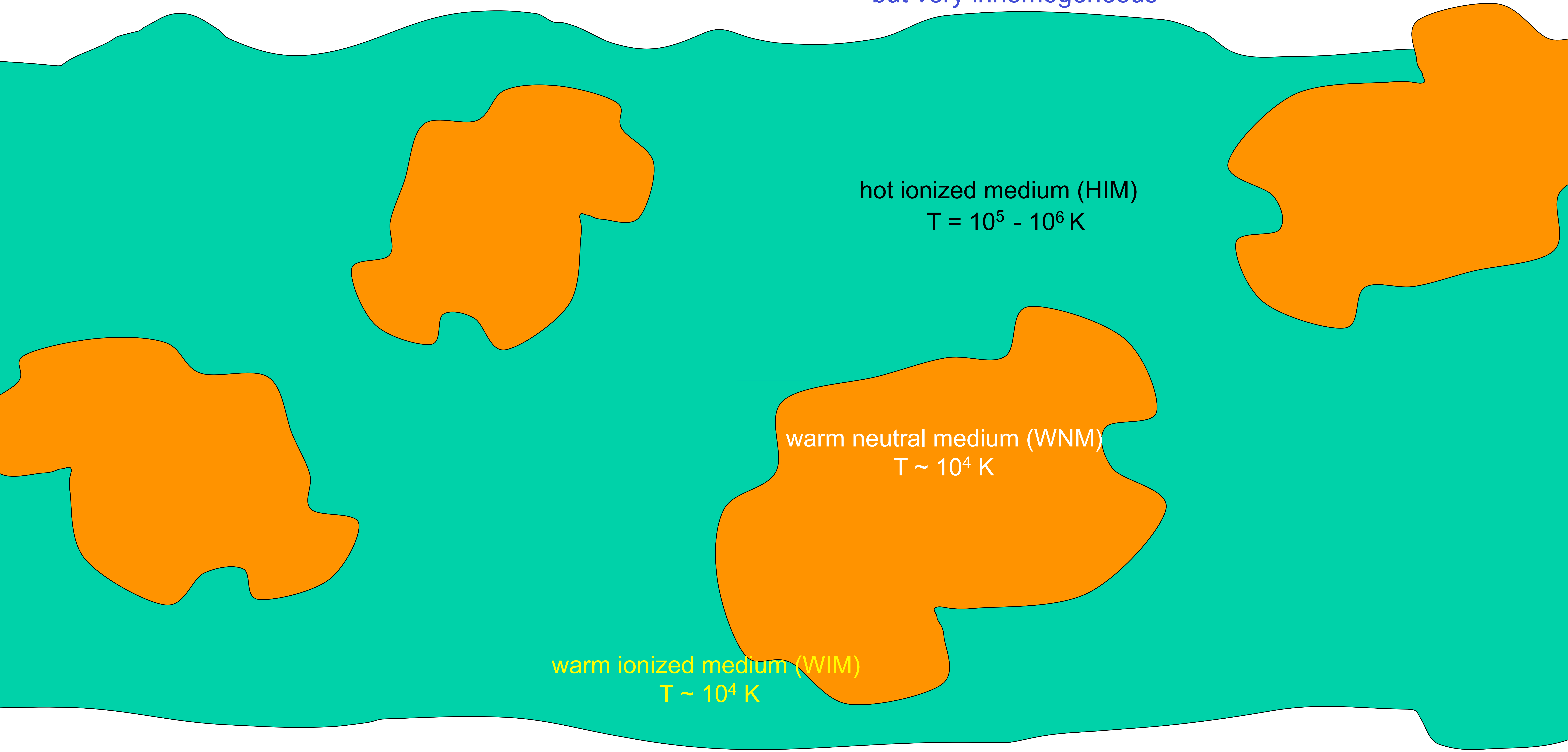
The Multi-Phased Interstellar Medium (ISM) and Star-Formation:

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



hot ionized medium (HIM)
$T = 10^5 - 10^6$ K

warm neutral medium (WNM)
T ~ 10^4 K

warm ionized medium (WIM)
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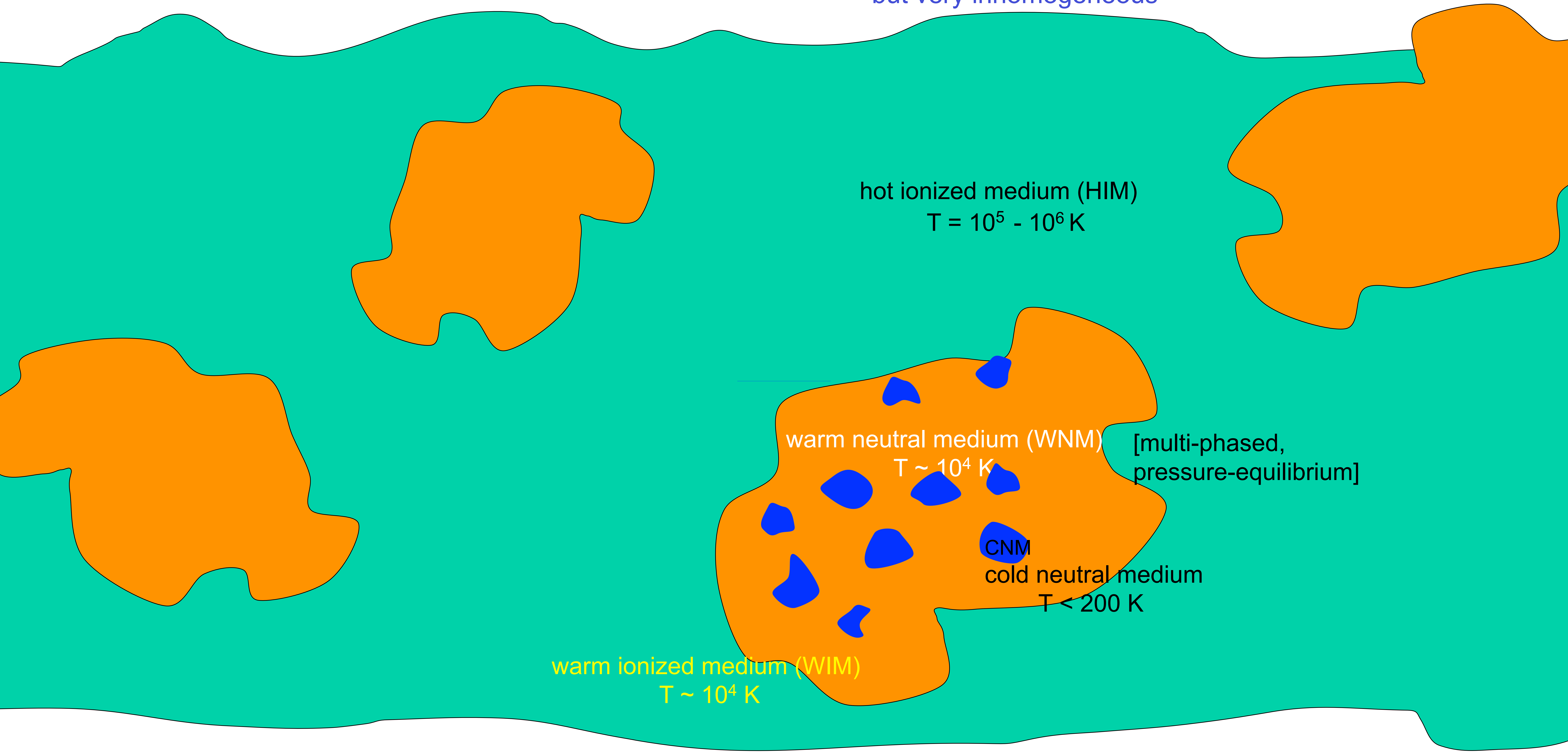

hot ionized medium (HIM)
T = 10^5 - 10^6 K

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T ~ 10^4 K

[multi-phased,
pressure-equilibrium]

CNM
cold neutral medium
T < 200 K

warm ionized medium (WIM)
T ~ 10^4 K

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

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).

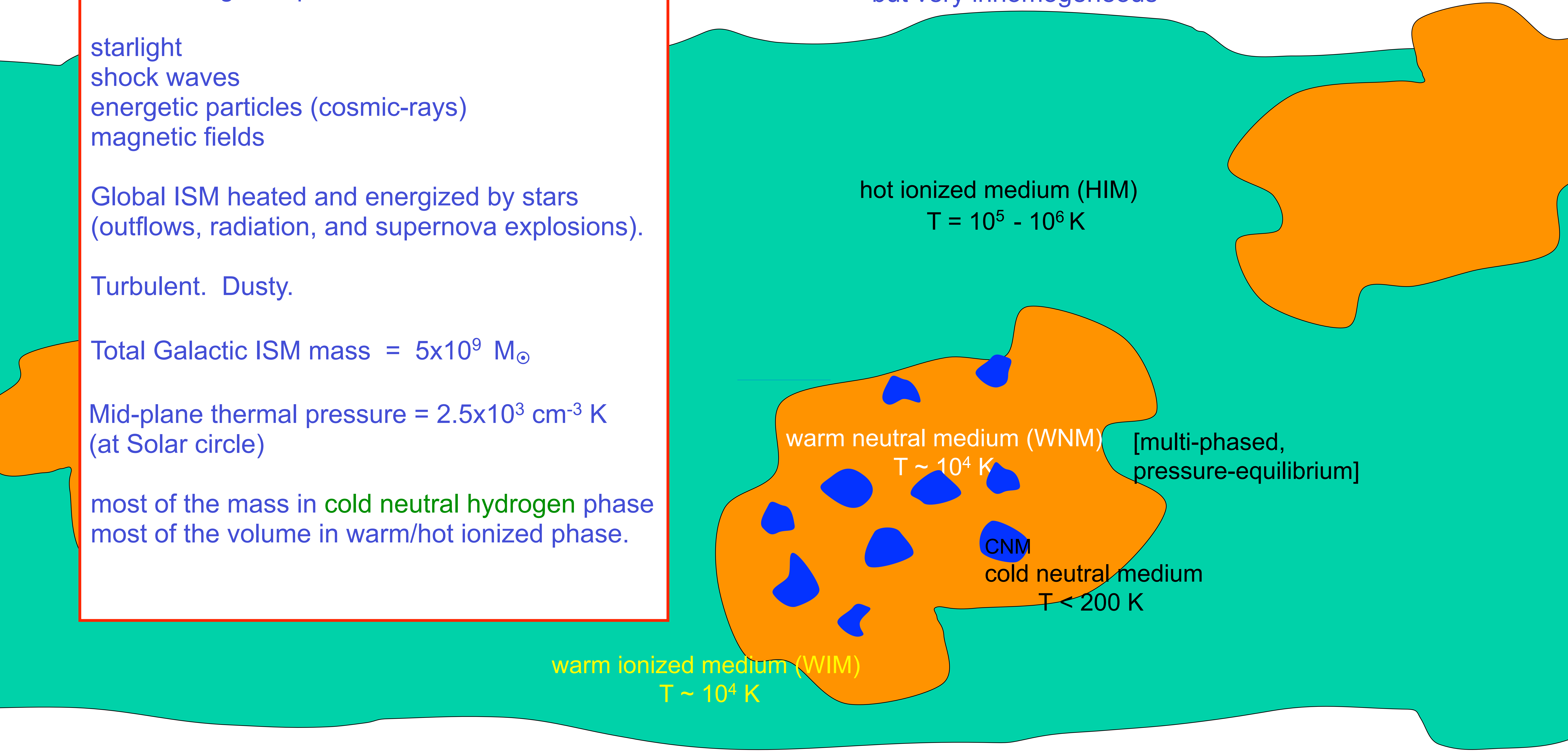
Turbulent. Dusty.

Total Galactic ISM mass = $5 \times 10^9\ M_\odot$

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

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

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



hot ionized medium (HIM)
$T = 10^5 - 10^6$ K

warm neutral medium (WNM)
$T \sim 10^4$ K

[multi-phased,
pressure-equilibrium]

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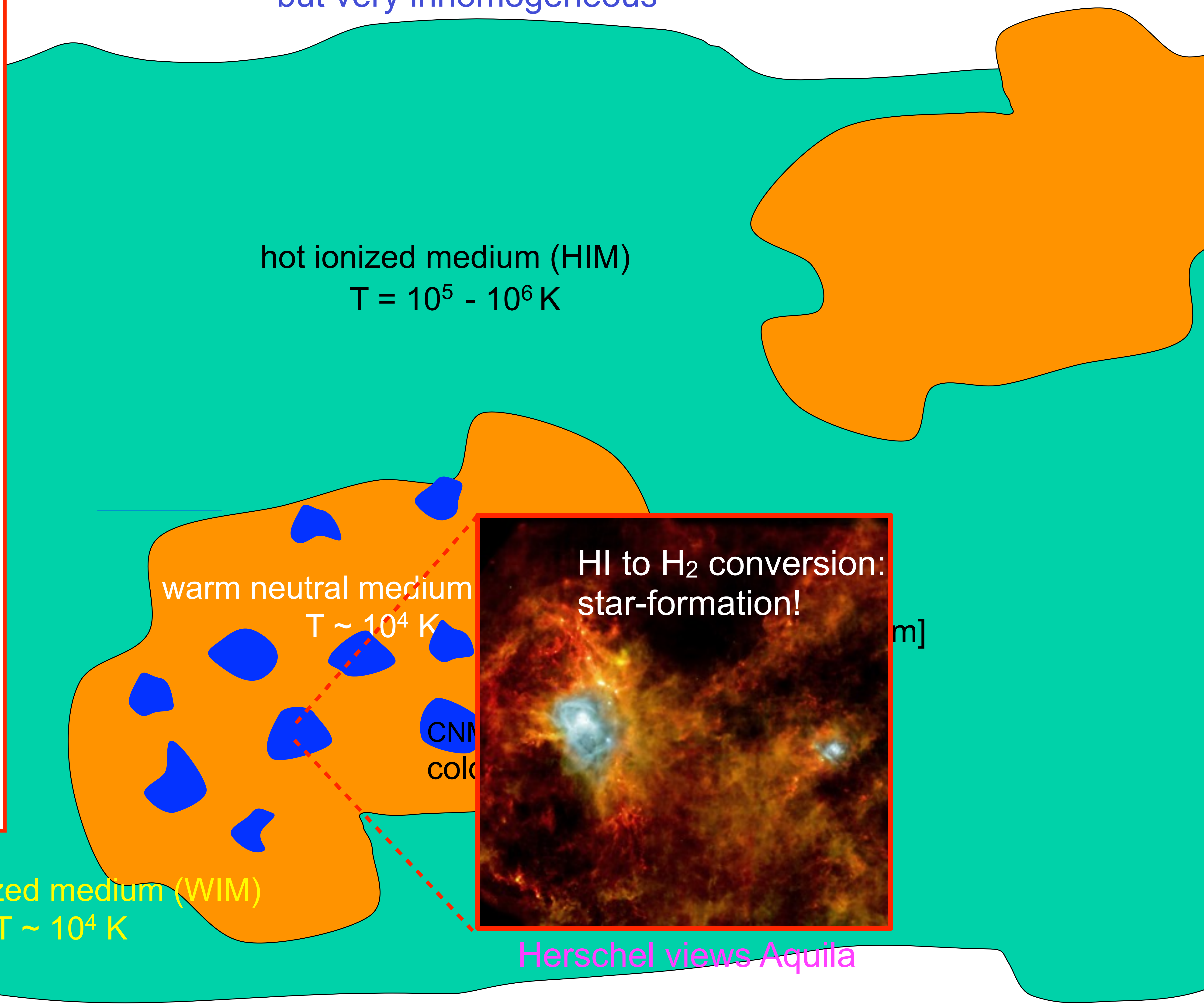
most of the mass in cold neutral hydrogen phase
most of the volume in warm/hot ionized phase.

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



Herschel views Aquila

Talk Outline:

- brief history and 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"
  Sternberg, Le Petit, Roueff, & Le Bourlot, 2014 ApJ 790 10

- "HI-to-H_2 Transitions in the Perseus Molecular Cloud"
  Bialy, Sternberg, Min-Young, Le Petit, & Roueff, 2015 ApJ 809 122

- "Analytic HI-to-H_2 Photodissociation Transition Profiles"
  Bialy & Sternberg, 2016 ApJ 822 83

see also "C^+/H_2 Gas in Star-Forming Clouds and Galaxies"
Nordon & Sternberg arXiv:1603.02300

1948 ApJ 107 6

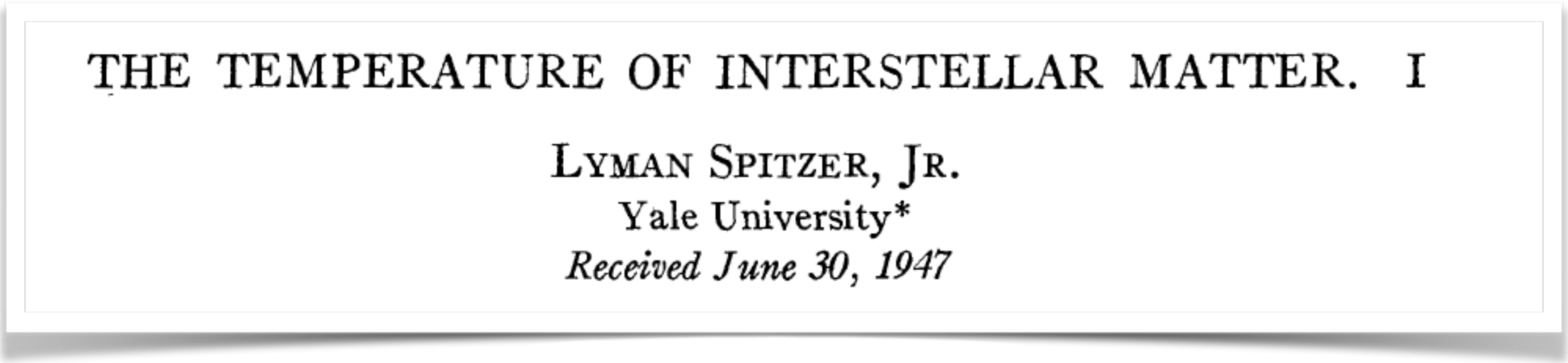
THE TEMPERATURE OF INTERSTELLAR MATTER. I

LYMAN SPITZER, JR.
Yale University*

Received June 30, 1947

Molecular hydrogen may possibly be much more abundant in *H* I regions of interstellar space than are the observed molecules *CH* and *CN*. However, the ionization

1948 ApJ 107 6



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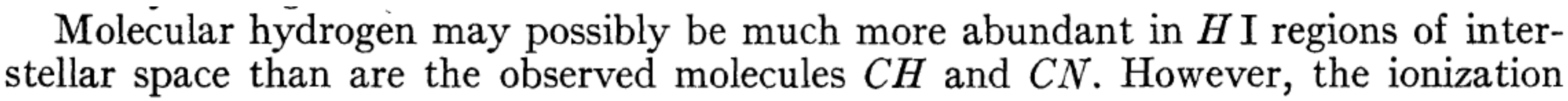

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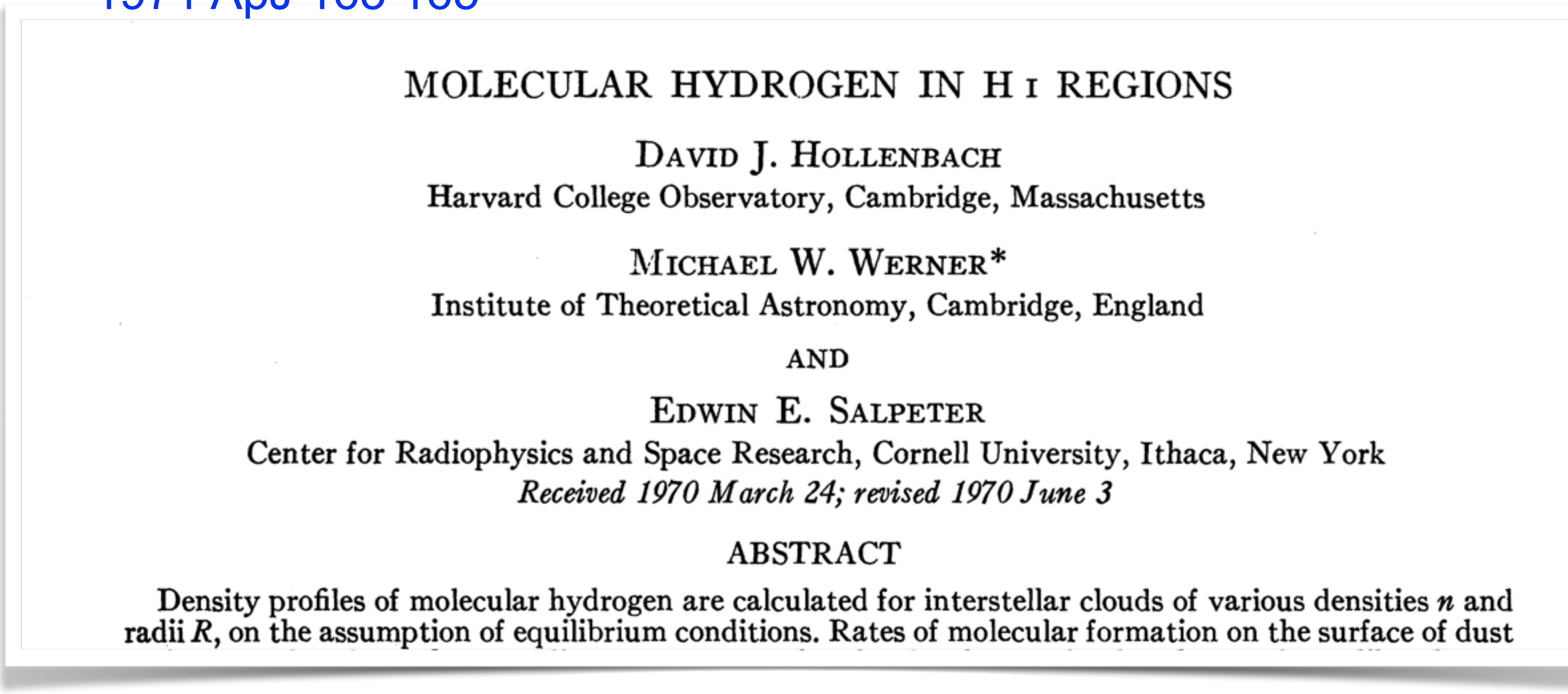
1971 ApJ 163 165



MOLECULAR HYDROGEN IN H I REGIONS

DAVID J. HOLLENBACH
Harvard College Observatory, Cambridge, Massachusetts

MICHAEL W. WERNER*
Institute of Theoretical Astronomy, Cambridge, England

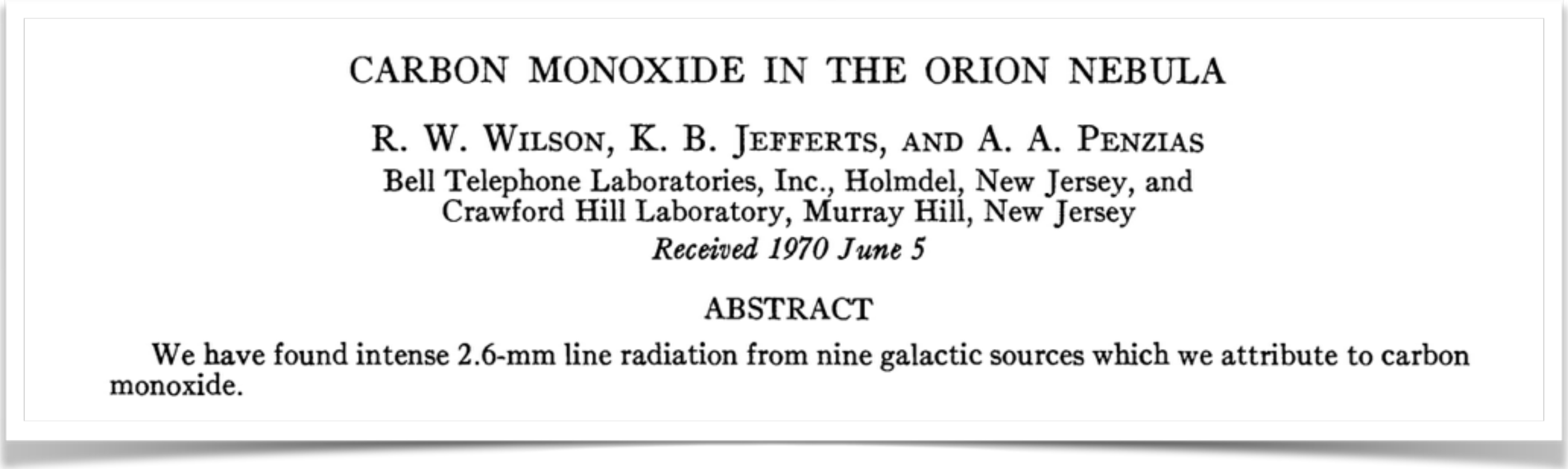
AND

EDWIN E. SALPETER
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York
Received 1970 March 24; revised 1970 June 3

ABSTRACT

Density profiles of molecular hydrogen are calculated for interstellar clouds of various densities n and radii R, on the assumption of equilibrium conditions. Rates of molecular formation on the surface of dust

1970 ApJ 161 L43



CARBON MONOXIDE IN THE ORION NEBULA

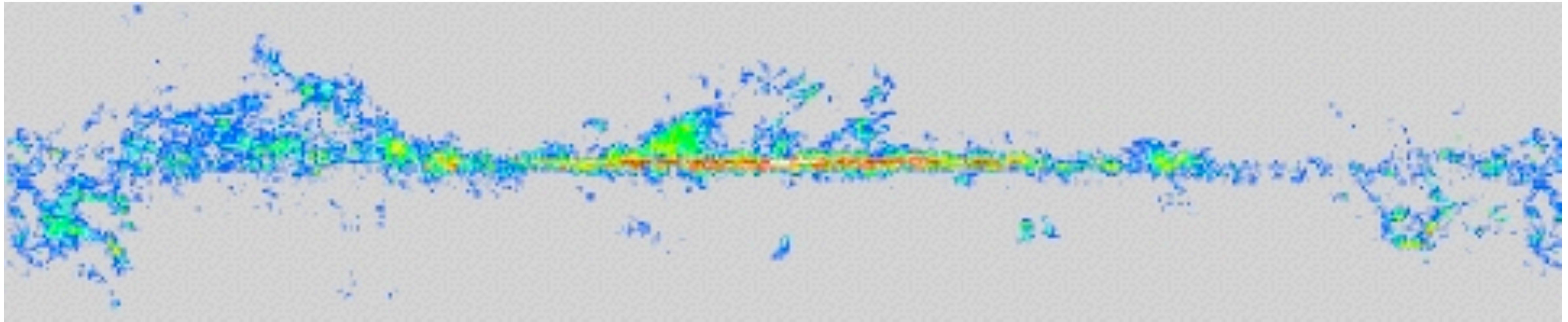
R. W. Wilson, K. B. Jefferts, and A. A. Penzias
Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey

Received 1970 June 5

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

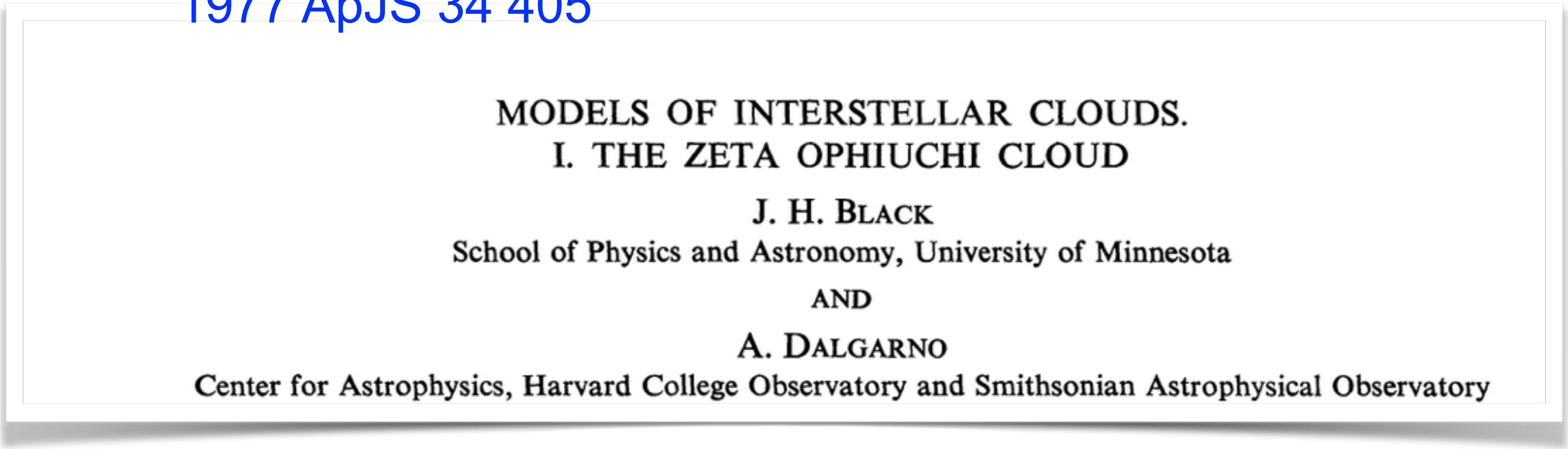
Milky-Way in CO 1-0



Dame, Hartmann & Thaddeus 2001 ApJ 546 792

H_2 usually difficult to observe directly.
CO is the tracer molecule.

1977 ApJS 34 405



MODELS OF INTERSTELLAR CLOUDS.
I. THE ZETA OPHIUCHI CLOUD

J. H. BLACK
School of Physics and Astronomy, University of Minnesota

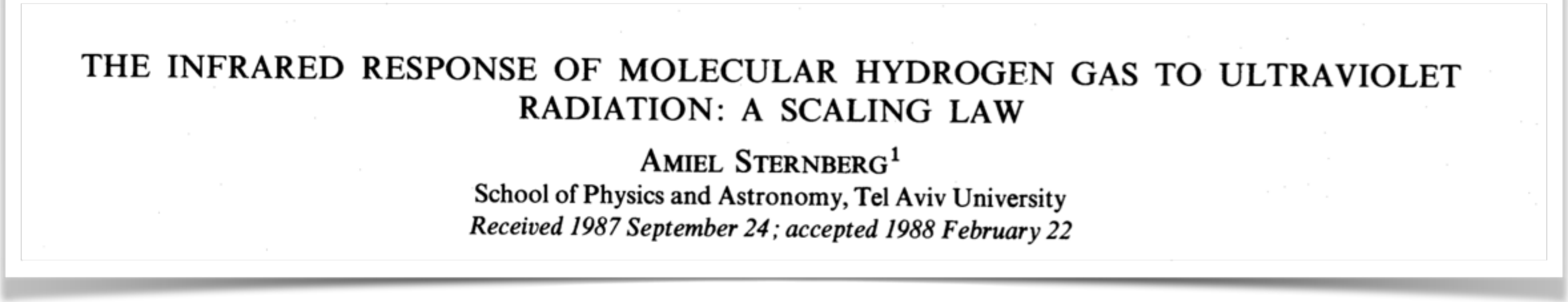
AND

A. DALGARNO
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory

...HI-to-H_2 initiates chemistry...

Improved H_2 line transfer:

1988 ApJ 332 400

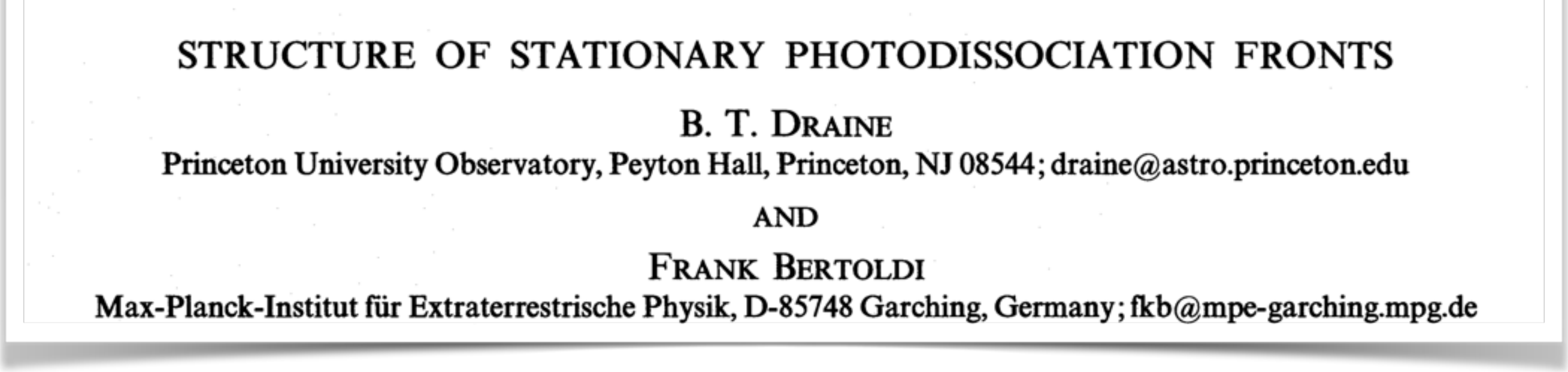


THE INFRARED RESPONSE OF MOLECULAR HYDROGEN GAS TO ULTRAVIOLET RADIATION: A SCALING LAW

AMIEL STERNBERG[1]
School of Physics and Astronomy, Tel Aviv University

Received 1987 September 24; accepted 1988 February 22

1996 ApJ 468 269

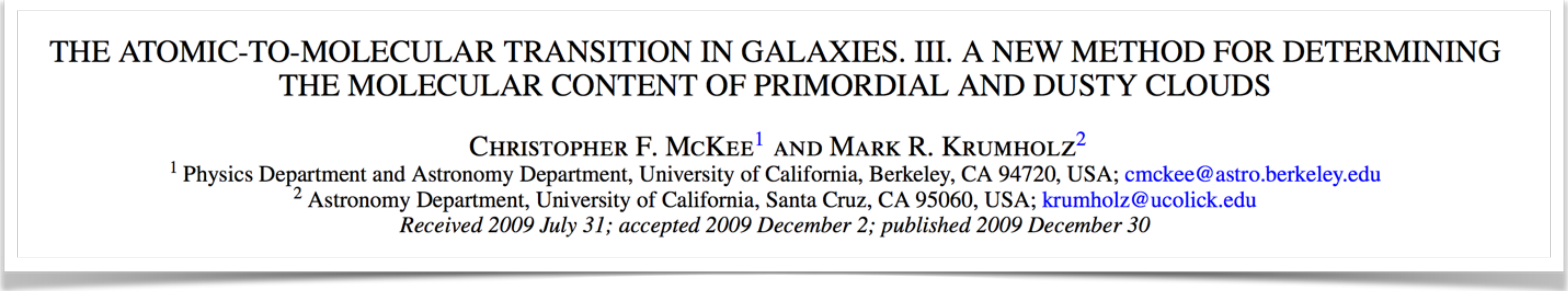


STRUCTURE OF STATIONARY PHOTODISSOCIATION FRONTS

B. T. DRAINE
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544; draine@astro.princeton.edu
AND
FRANK BERTOLDI
Max-Planck-Institut für Extraterrestrische Physik, D-85748 Garching, Germany; fkb@mpe-garching.mpg.de

Global Galaxy Properties:

2010 ApJ 709 308

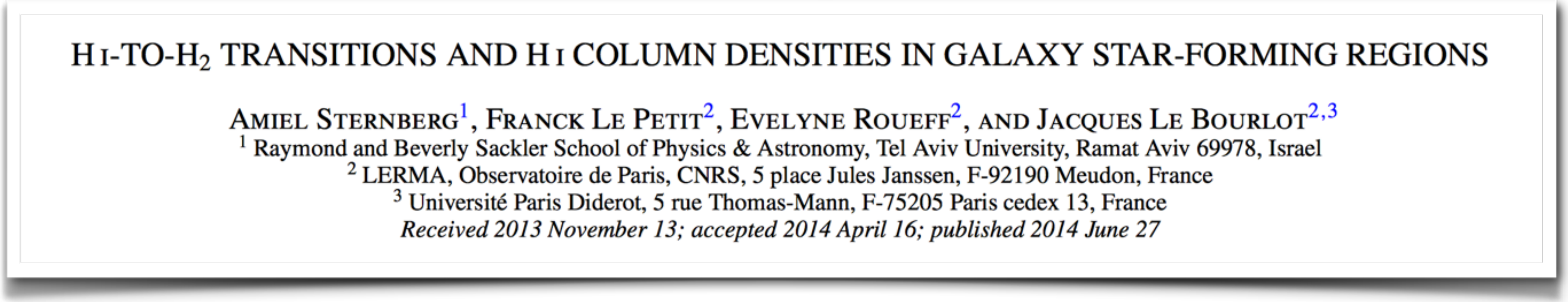


THE ATOMIC-TO-MOLECULAR TRANSITION IN GALAXIES. III. A NEW METHOD FOR DETERMINING THE MOLECULAR CONTENT OF PRIMORDIAL AND DUSTY CLOUDS

CHRISTOPHER F. MCKEE[1] AND MARK R. KRUMHOLZ[2]
[1] Physics Department and Astronomy Department, University of California, Berkeley, CA 94720, USA; cmckee@astro.berkeley.edu
[2] Astronomy Department, University of California, Santa Cruz, CA 95060, USA; krumholz@ucolick.edu

Received 2009 July 31; accepted 2009 December 2; published 2009 December 30

2014 ApJ 790 10



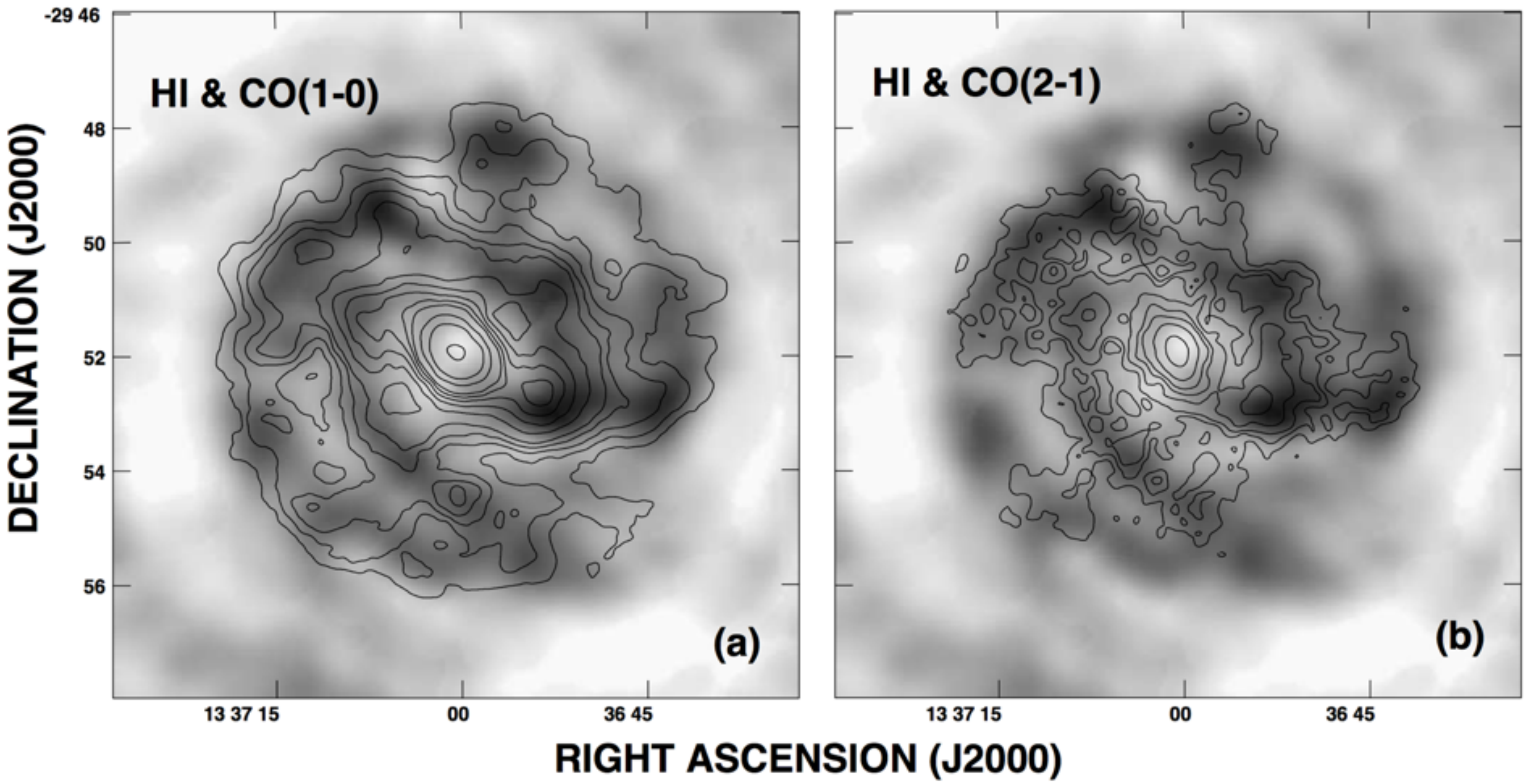
H I-TO-H_2 TRANSITIONS AND H I COLUMN DENSITIES IN GALAXY STAR-FORMING REGIONS

AMIEL STERNBERG[1], FRANCK LE PETIT[2], EVELYNE ROUEFF[2], AND JACQUES LE BOURLOT[2,3]
[1] Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Ramat Aviv 69978, Israel
[2] LERMA, Observatoire de Paris, CNRS, 5 place Jules Janssen, F-92190 Meudon, France
[3] Université Paris Diderot, 5 rue Thomas-Mann, F-75205 Paris cedex 13, France

Received 2013 November 13; accepted 2014 April 16; published 2014 June 27

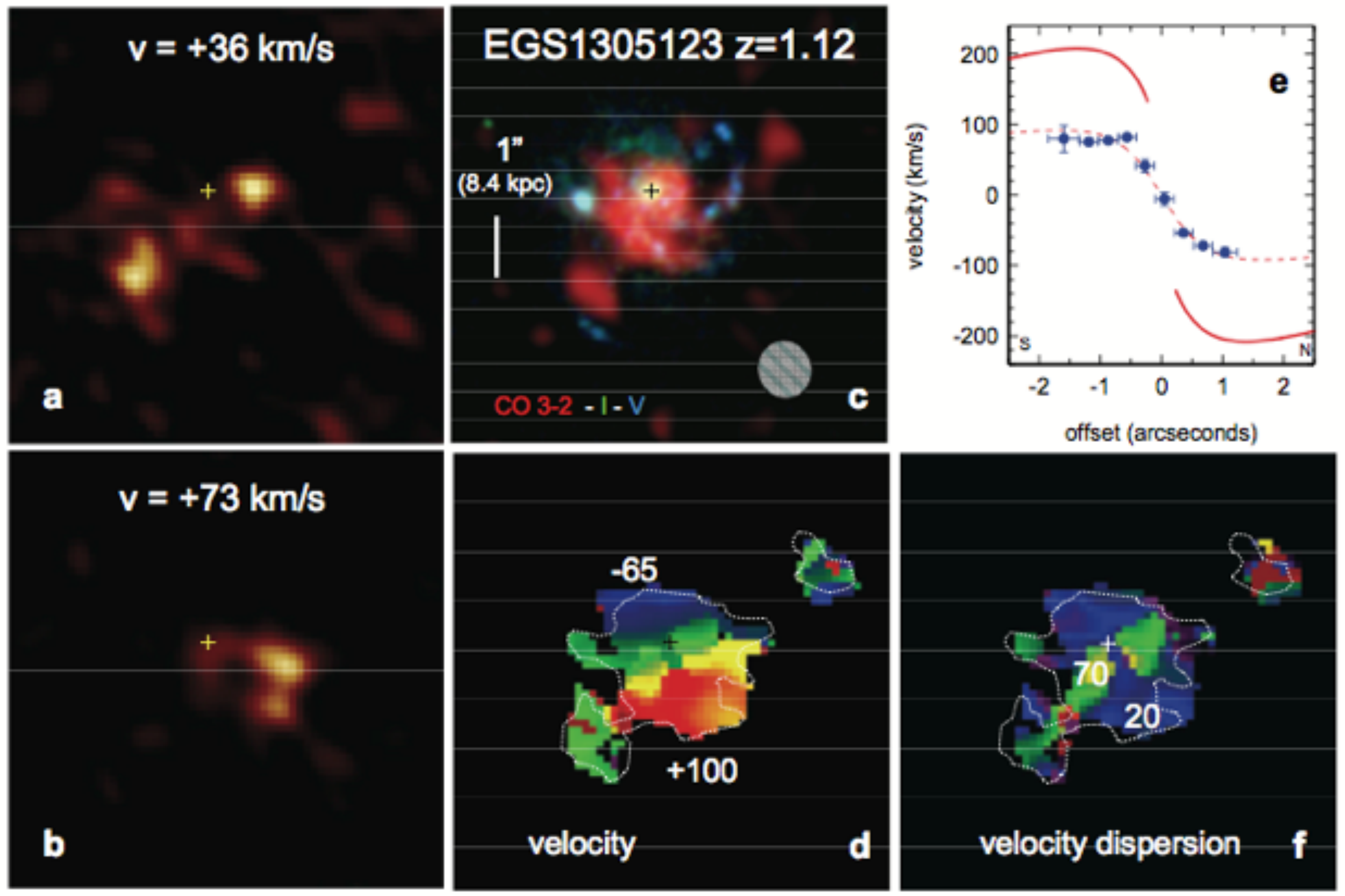
HI as a *Photodissociation Product* in Molecular Spiral Arms:

M83 Crosthwaite+ 2002 ApJ 123 1892

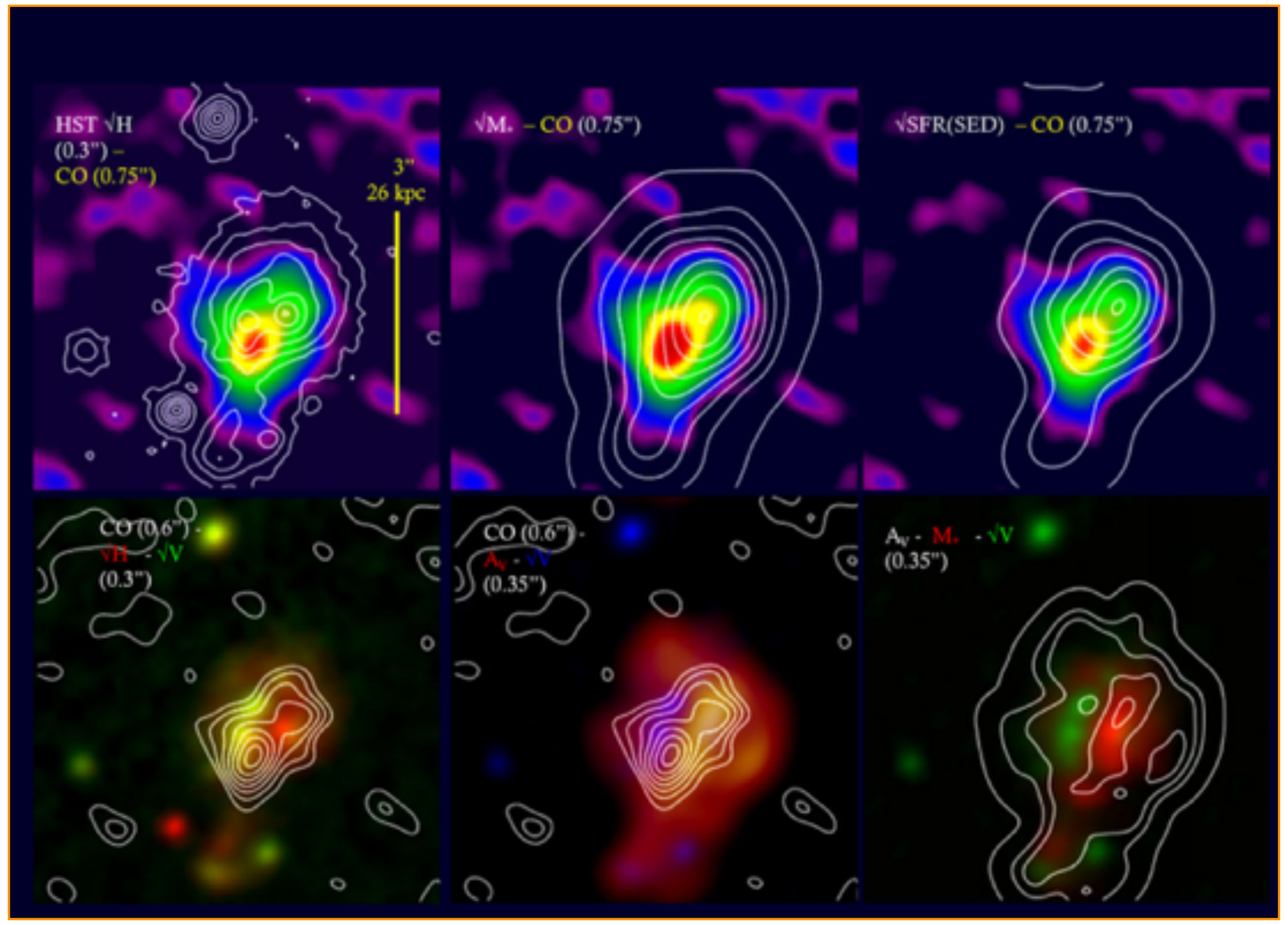


Conversion to molecular gas in high redshift galaxies:

Tacconi et al. 2010 Nature 463 781



Genzel+ 2013 EGS13011166 z=1.5



PdBI NOEMA

PHIBSS2

MOLECULAR GAS AT THE PEAK EPOCH OF GALAXY FORMATION

HOME SCIENCE TEAM DATA RELEASE PAPERS TEAM LOGIN

Team

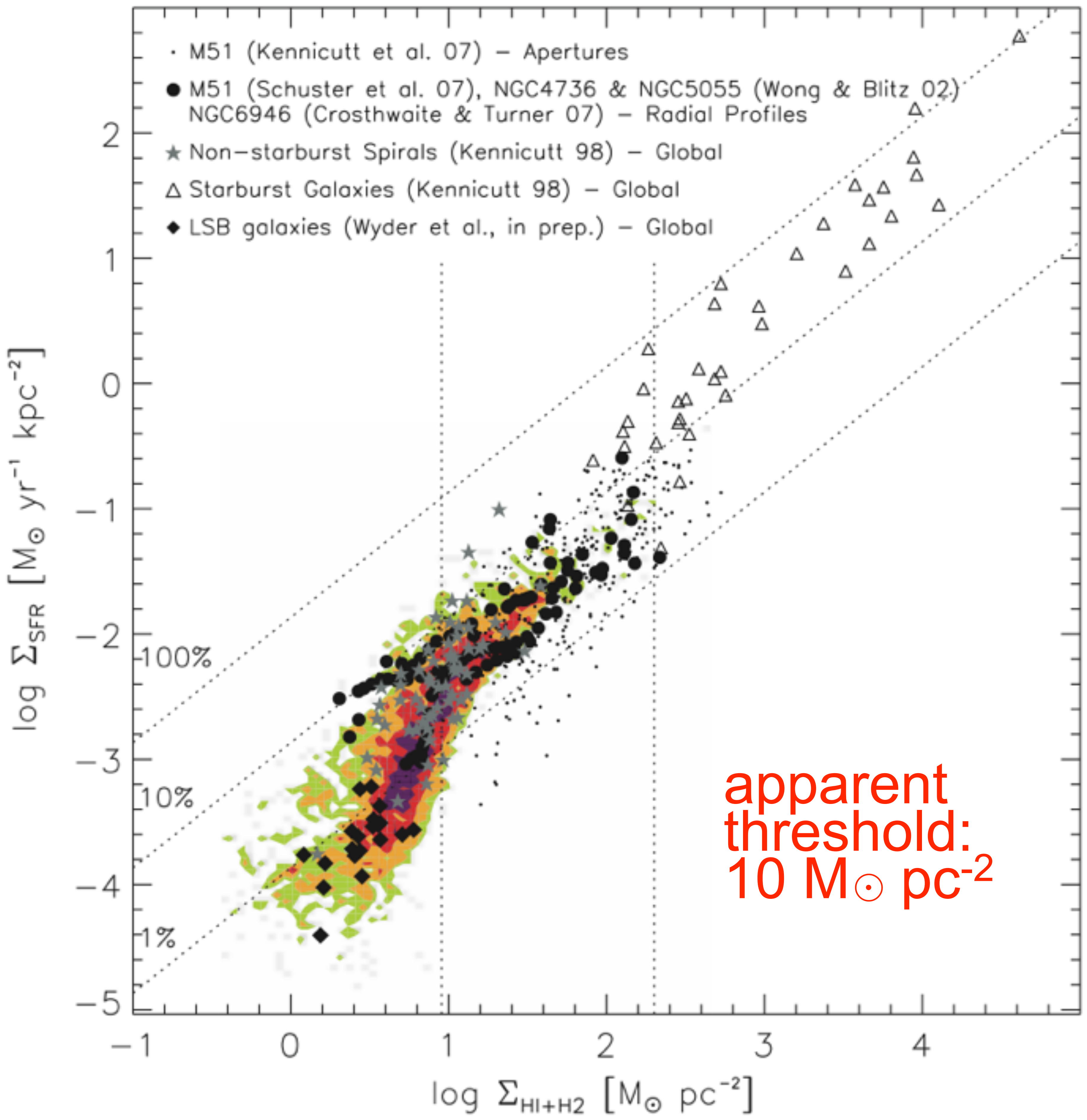
PHIBSS2 is an international and IRAM-wide effort, involves collaborators from a broad variety of backgrounds, and builds upon and enhances previous IRAM PdBI studies of molecular gas in high-redshift galaxies.

Co-PI: Francoise Combes (Obs. Paris -- France)
Co-PI: Santiago Garcia-Burillo (OAN -- Spain)
Co-PI: Roberto Neri (IRAM -- France)
Co-PI: Linda Tacconi (MPE -- Germany)
R. Genzel (MPE – Germany)
T. Contini (IRAP – France)
A. Bolatto (UMd – USA)
S. Lilly (ETH – Switzerland)
F. Boone (IRAP – France)
N. Bouche (IRAP – France)
F. Bournaud (CEA – France)
A. Burkert (USM – Germany)
M. Carollo (ETH – Switzerland)
L. Colina (CSIC – Spain)
M. Cooper (UCI – US)
P. Cox (IRAM – France)
C. Feruglio (IRAM – France)
J. Freundlich (Obs.Paris – France)
N. Förster Schreiber (MPE – Germany)
S. Juneau (CEA – France)
K. Kovac (ETH – Switzerland)
M. Lippa (MPE – Germany)
D. Lutz (MPE – Germany)
T. Naab (MPA – Germany)
A. Omont (IAP – France)
A. Renzini (Univ.Padova – Italy)
A. Saintonge (MPE – Germany)
P. Salomé (Obs.Paris – France)
A. Sternberg (Univ.Tel Aviv – Israel)
F. Walter (MPIA – Germany)
B. Weiner (Steward Obs.Arizona – US)
A. Weiß (MPIfR – Germany)
S. Wuyts (MPE – Germany)

Kennicutt-Schmidt Relation:

Schmidt 1959 ApJ 129 253
Kennicutt 1998 ApJ 498 541
Genzel, Tacconi, Sternberg, et al. 2010 MNRAS 407 2091 [SINS/KMOS(VLT) IRAM projects]

e.g., Bigiel+ 2008



apparent threshold: 10 $M_\odot$ pc^{-2}

$$\Sigma_{\mathrm{SFR}} = \epsilon \frac{f_{\mathrm{H}_2}\,\Sigma_{\mathrm{gas}}}{\tau_d}$$

see also Semenov et al. poster

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

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

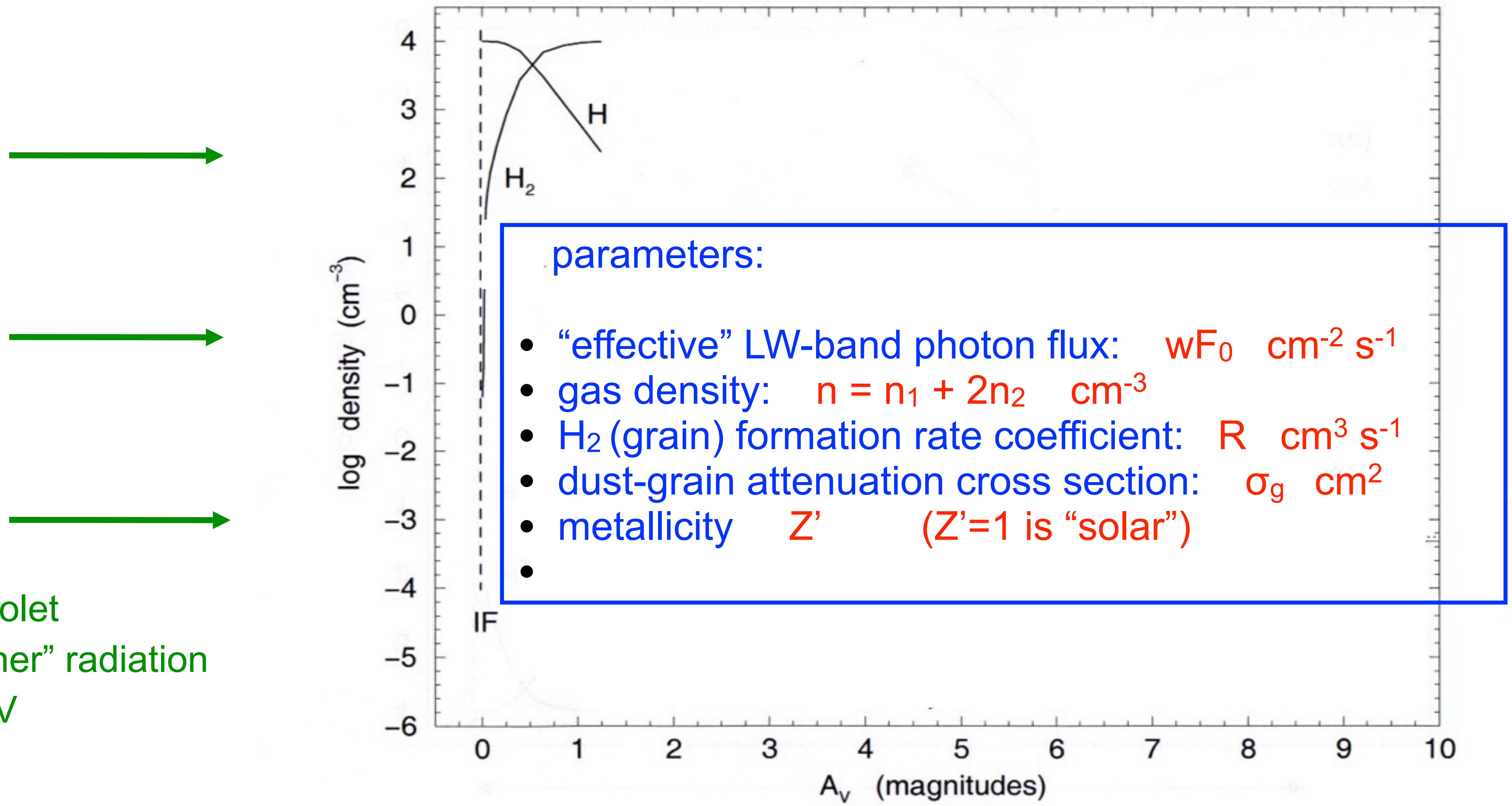
"...A perspicuous representation produces just that understanding which consists of 'seeing connections'. Hence the importance of finding and inventing *intermediate cases*. The concept of a perspicuous representation is of fundamental significance for us. It earmarks the form of account we give, the way we look at things..."

Part I, paragraph122
Philosophical Investigations
Ludwig Wittgenstein

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

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

Shielding required.

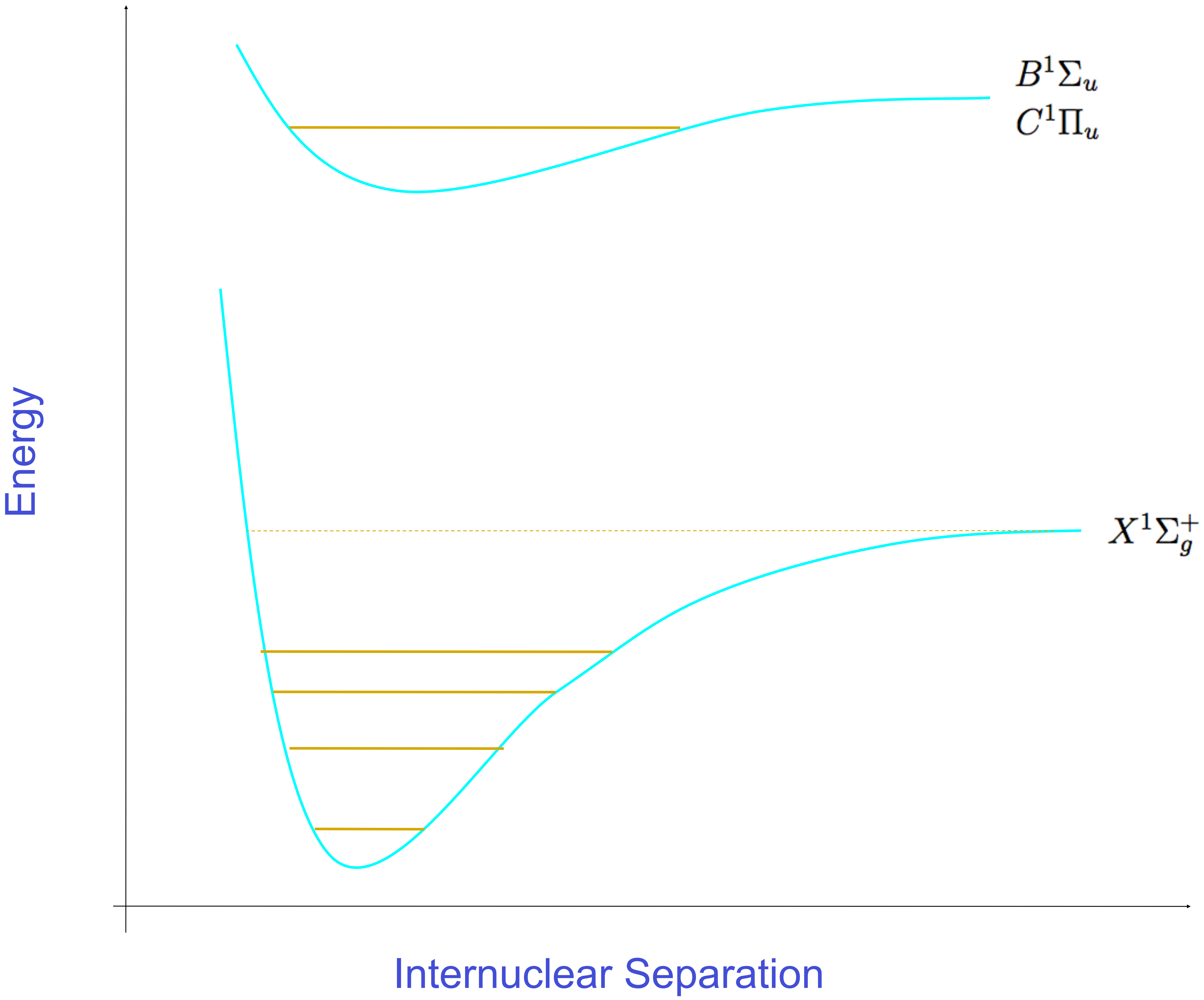


Stellar ultraviolet
“Lyman-Werner” radiation
11.2 - 13.6 eV

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”)
-

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



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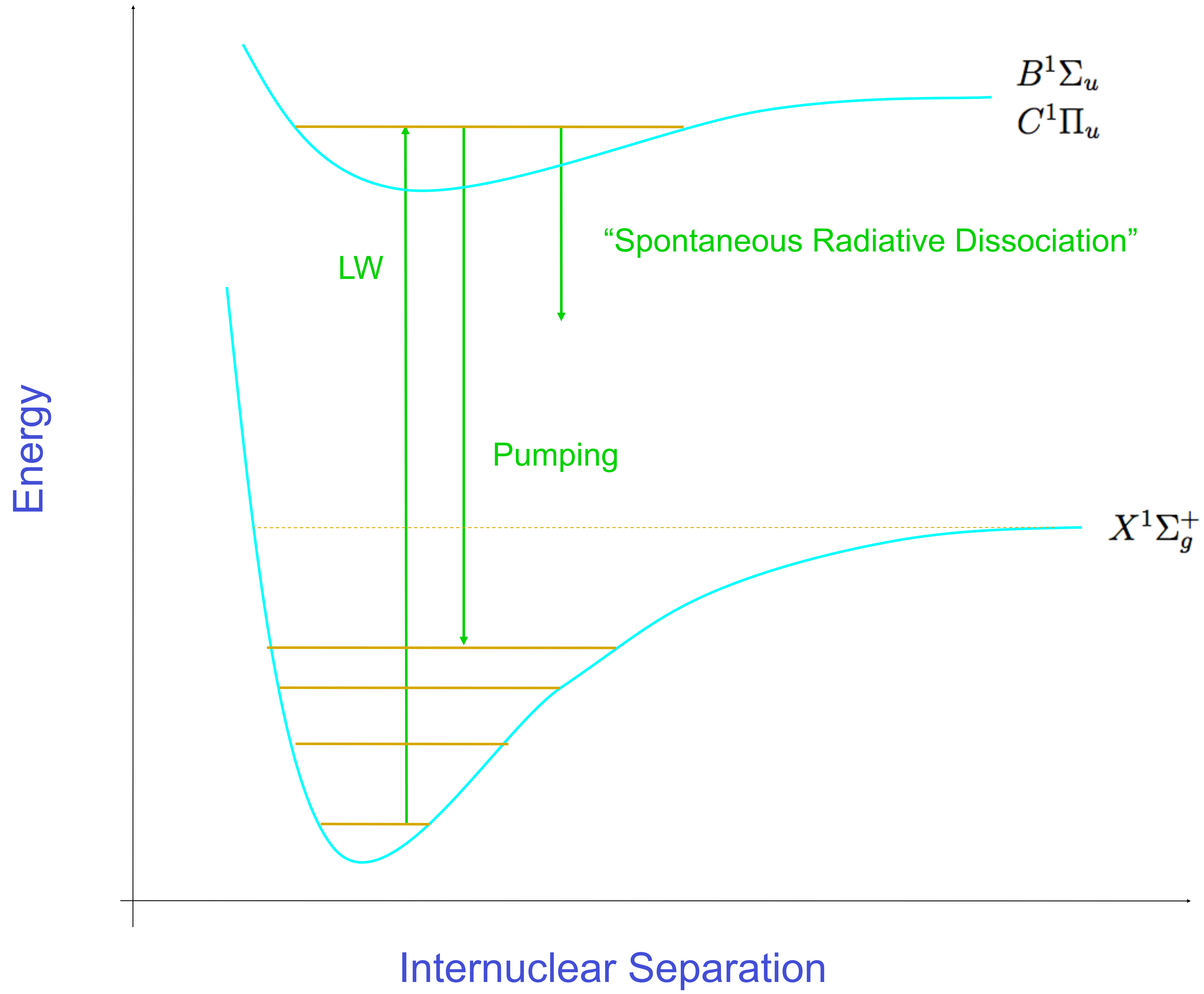

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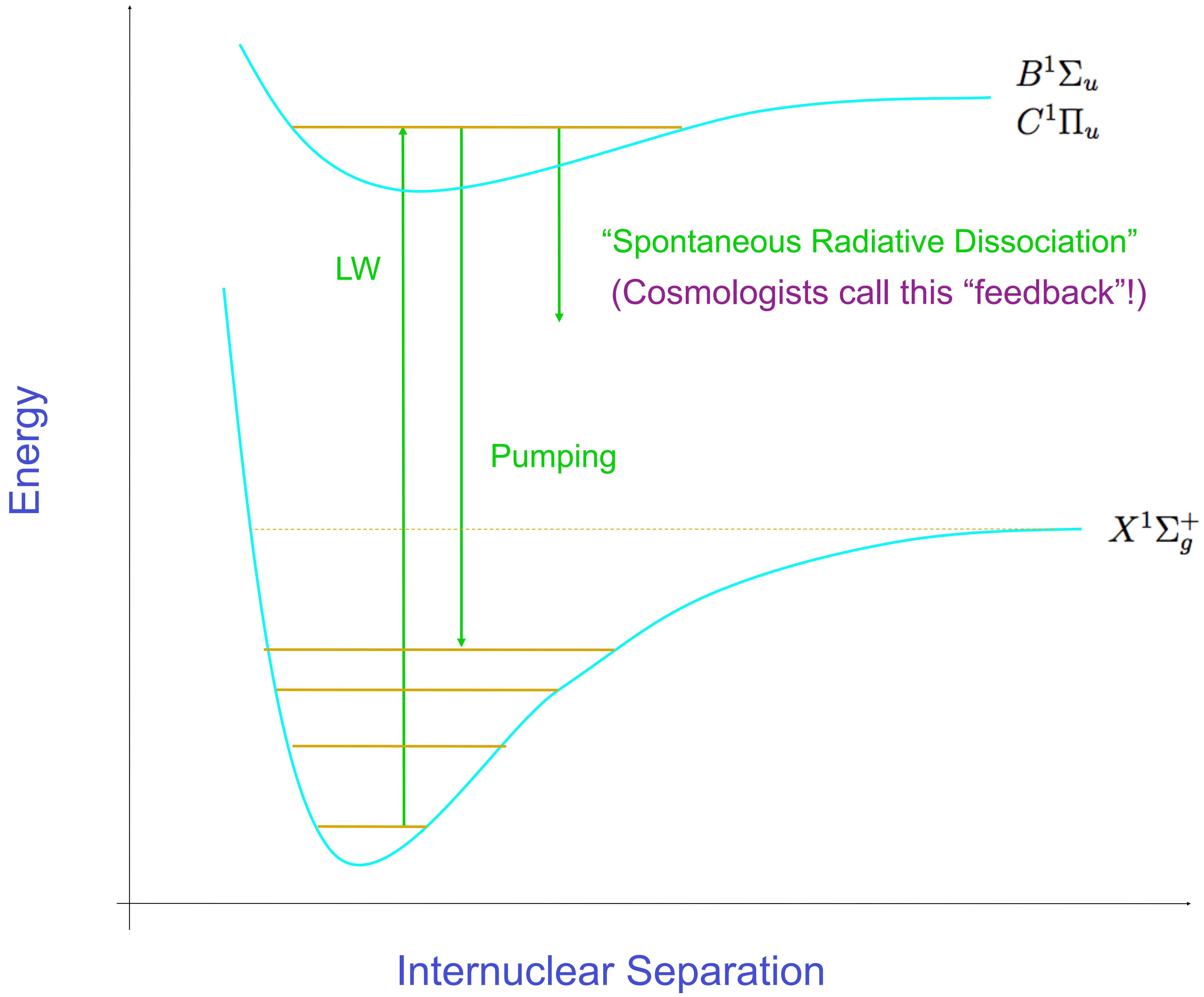

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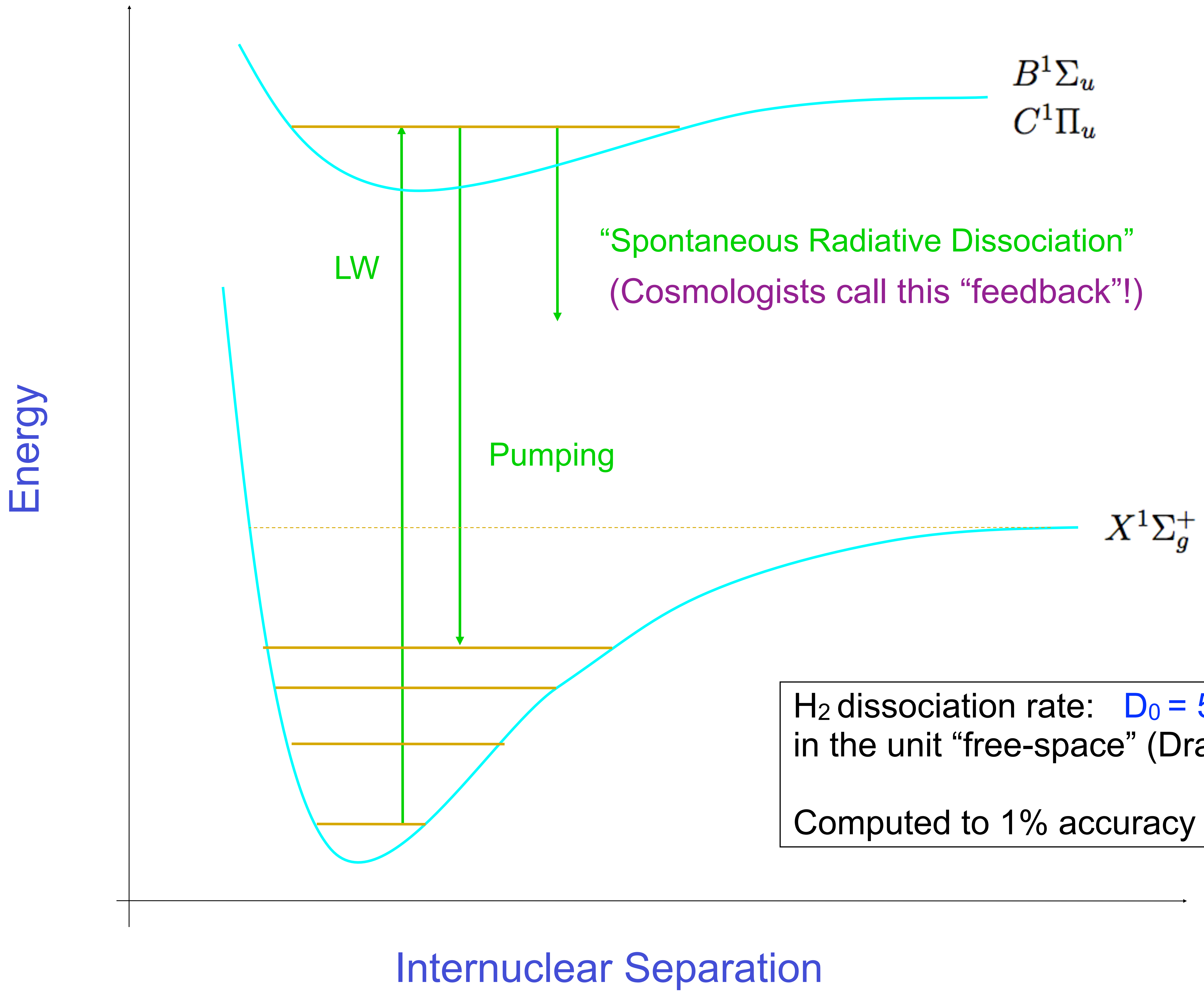


$B^1\Sigma_u$

$C^1\Pi_u$

LW

“Spontaneous Radiative Dissociation”

(Cosmologists call this “feedback”!)

Pumping

$X^1\Sigma_g^+$

Energy

Internuclear Separation

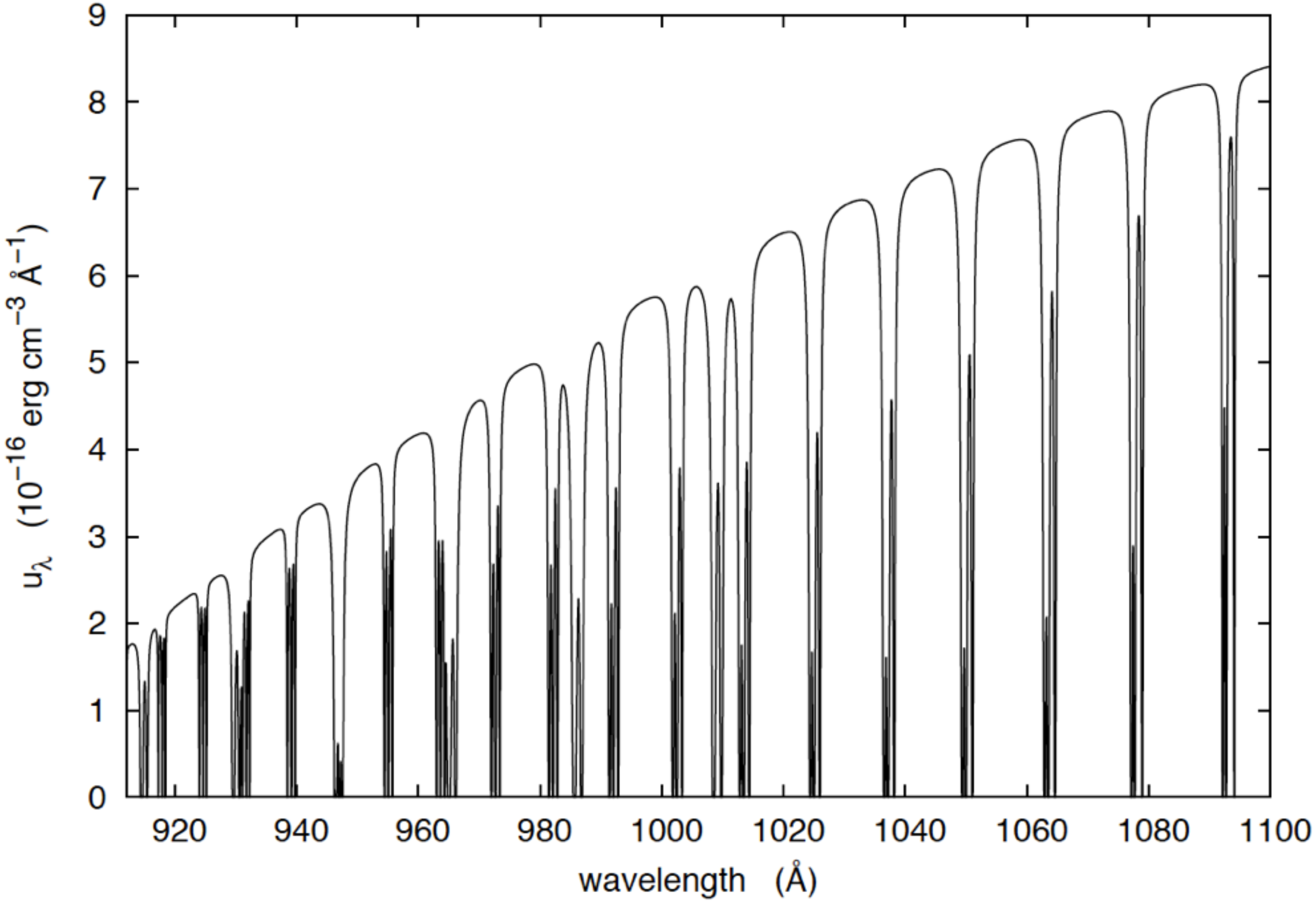
$\bar{f}_{\rm diss} = 0.12$

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

Computed to 1% accuracy in S+ 14

Lyman-Werner Radiative Transfer:

S+ 2014 [“Meudon PDR code”]



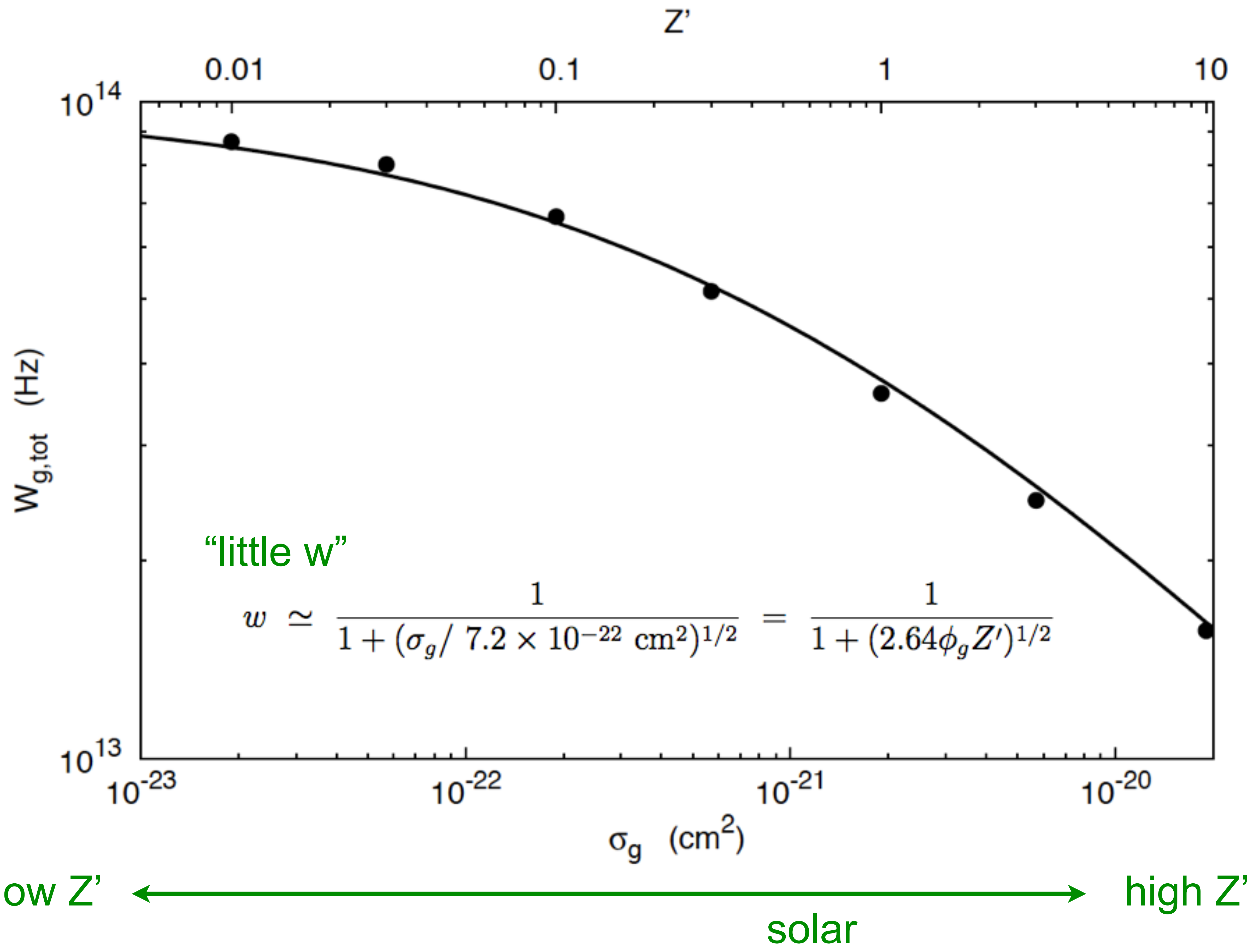
Characteristic multi-line H_2 absorption spectrum, and “self-shielding”.

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.

"Universal" Total H_2 Dust Limited Dissociation Bandwidth: S+ 2014



"little w"

$$w \simeq \frac{1}{1+(\sigma_g/\ 7.2\times10^{-22}\ \mathrm{cm}^2)^{1/2}} = \frac{1}{1+(2.64\phi_g Z')^{1/2}}$$

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

Total LW Flux:

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

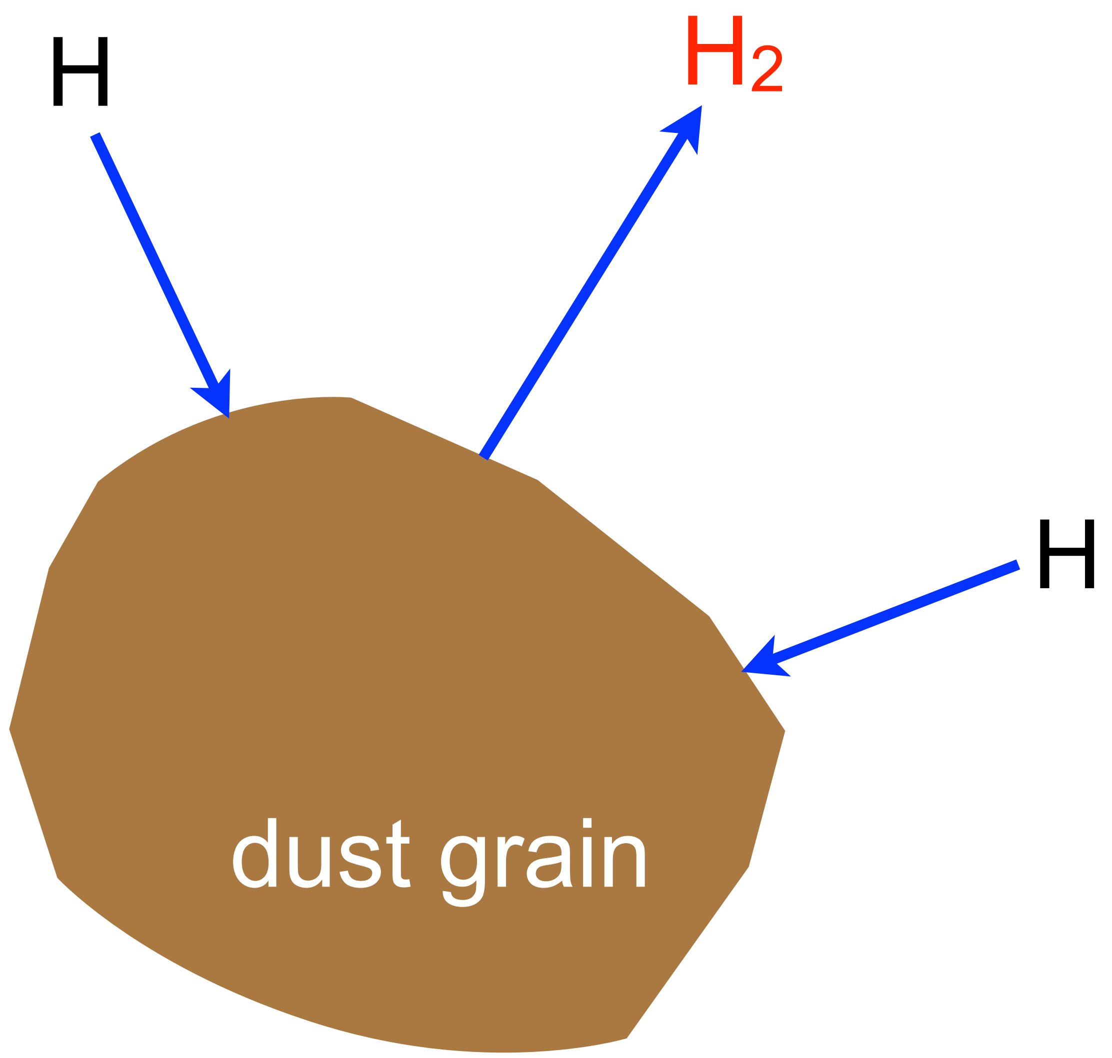
"Effective Dissociation Flux"

$$\bar{f}_{\rm diss} \times wF_0$$

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"

H_2 Formation:



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

Z' is the "metallicity" (Z'=1 is solar)

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

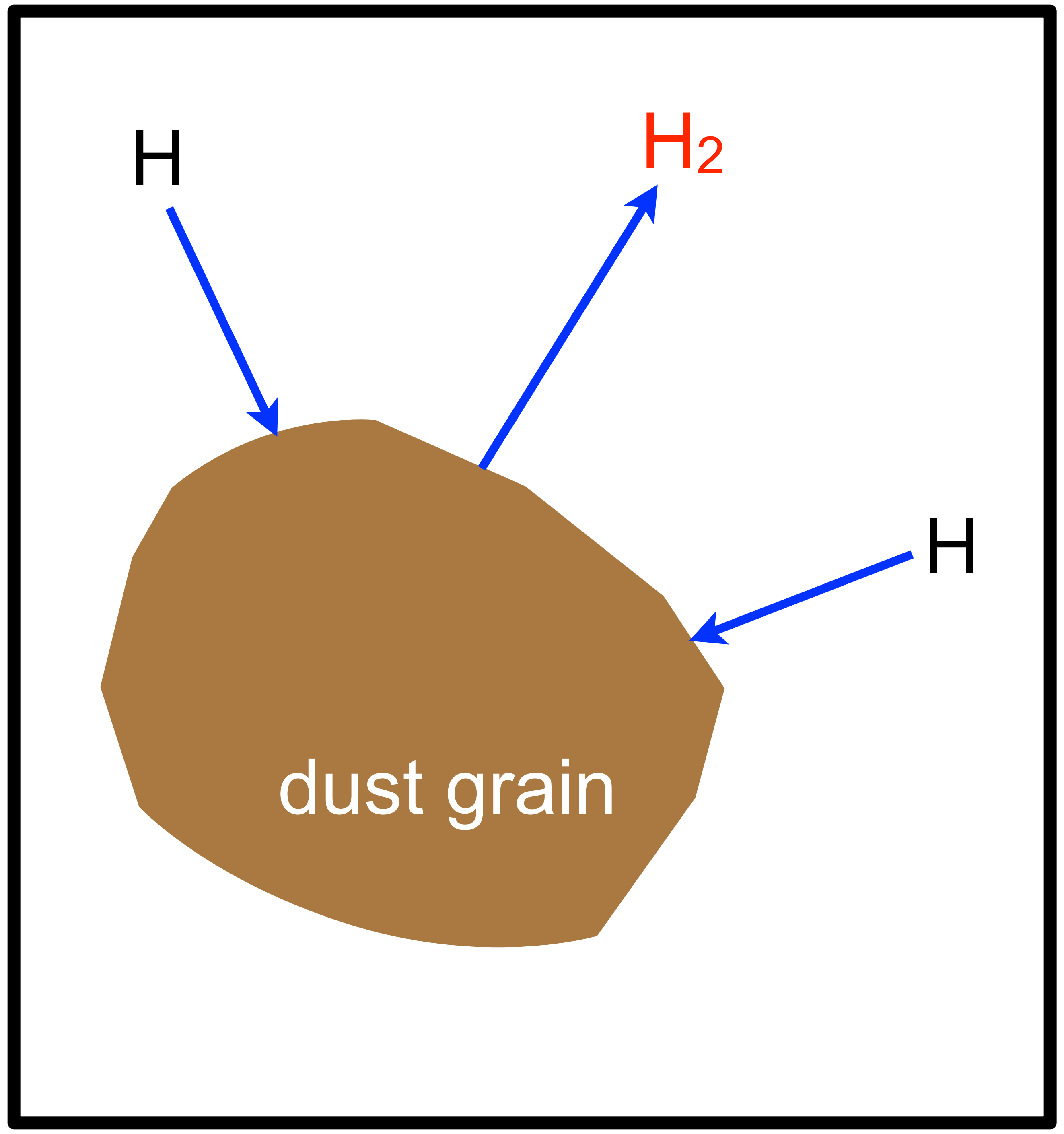
time scale for equilibrium

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

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

H_2 Formation:

a black box...
and another talk!



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

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

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

time scale for equilibrium

Z' is the “metallicity” (Z'=1 is solar)

Basic Theory Questions:

- What do the depth-dependent HI-to-H_2 transition profiles look like for far-UV irradiated systems?

- What is the resulting total HI column densities (cm^{-2}) or HI mass surface densities ($M_\odot\ pc^{-2}$) ?

Dimensionless Parameter:

$$\alpha G \equiv \frac{D_0 G}{R n}$$

Physical Meaning:

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

Dimensionless Parameter:

Sternberg 1988; McKee & Krumholz 2010; Sternberg+ 2014

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

Physical Meaning:

$$\frac{\text{HI-dust absorption rate of the effective dissociation flux}}{\text{free space H}_2\text{ photodissociation rate}}$$

Dimensionless Parameter:

Sternberg 1988; McKee & Krumholz 2010; Sternberg+ 2014

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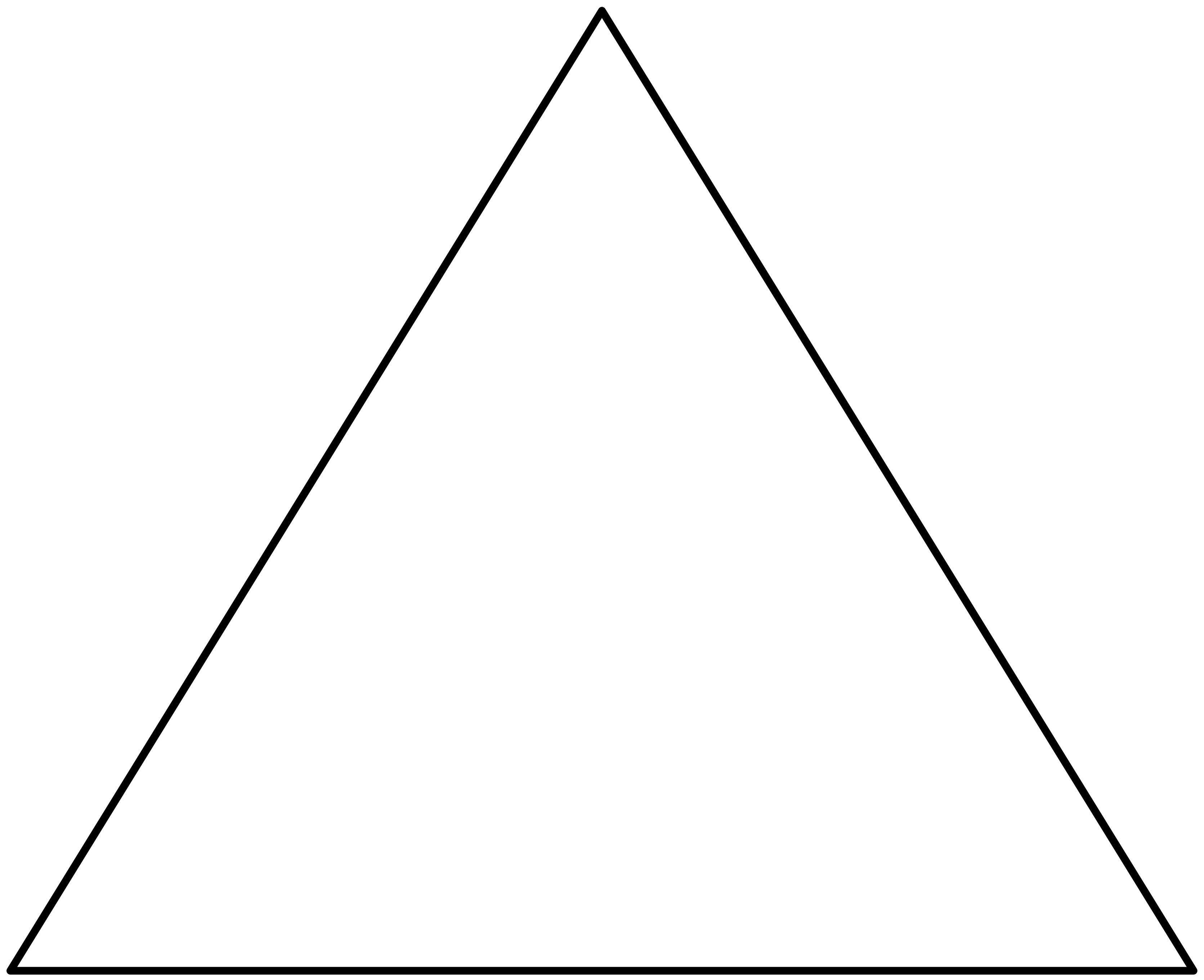
Physical Meaning:

$$\frac{\text{HI-dust absorption rate of the effective dissociation flux}}{\text{free space H}_2\text{ photodissociation rate}}$$

$$\alpha G = 1.54\left(\frac{\sigma_g}{1.9\times10^{-21}\ {\rm cm}^2}\right)\left(\frac{F_0}{2.07\times10^{7}\ {\rm cm}^{-2}\ {\rm s}^{-1}}\right) \times\left(\frac{3\times10^{-17}\ {\rm cm}^3\ {\rm s}^{-1}}{R}\right)\left(\frac{100\ {\rm cm}^{-3}}{n}\right)\frac{1}{1+(2.64\phi_g Z')^{1/2}}$$

...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: S+14   Bialy & Sternberg 2016 arXiv:1601.02608

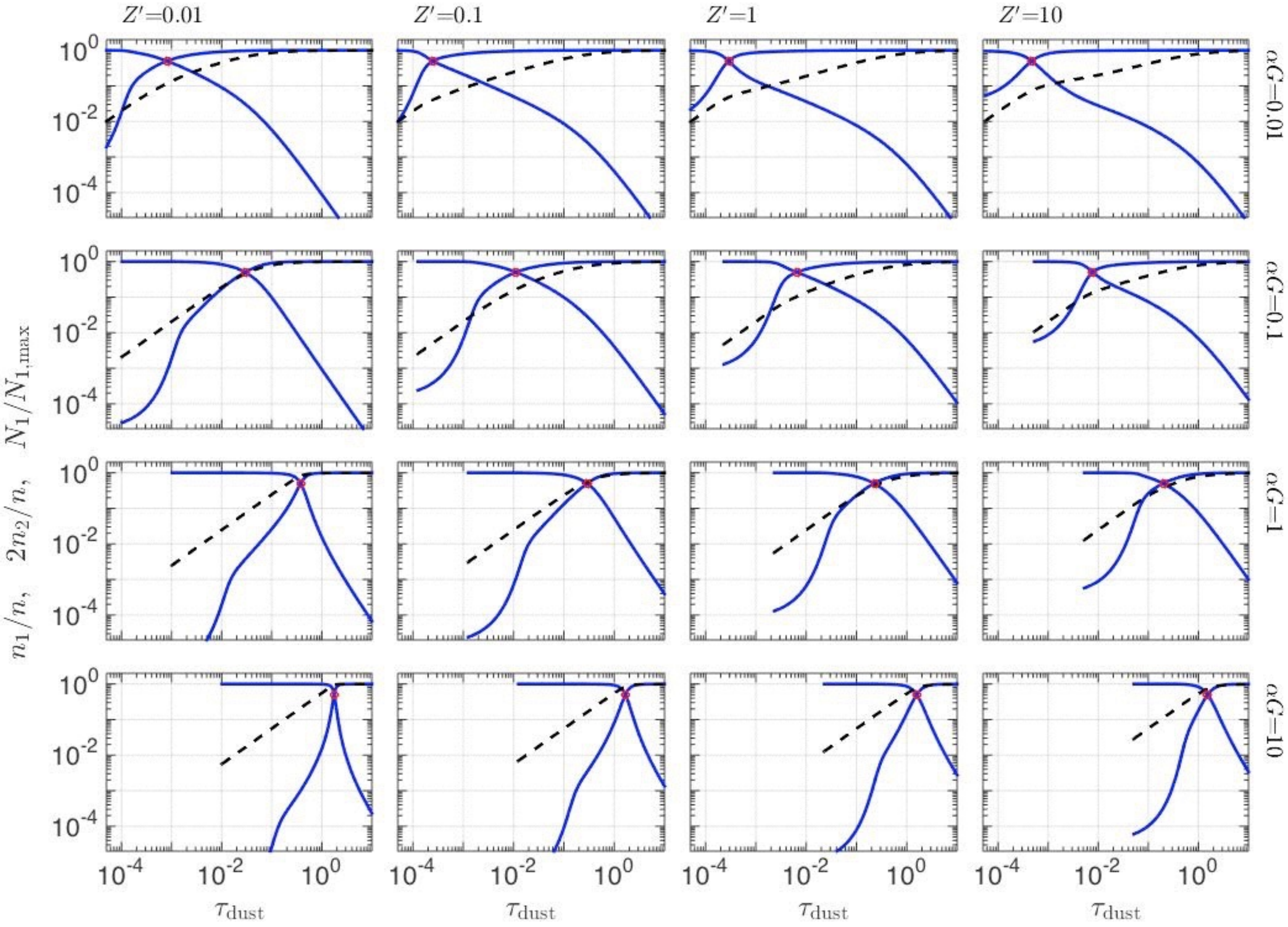
The profile shapes depend primarily on the dimensionless parameter αG.

HI-to-H_2 Transition Profiles: S+14 Bialy & Sternberg 2016 ApJ 822 83

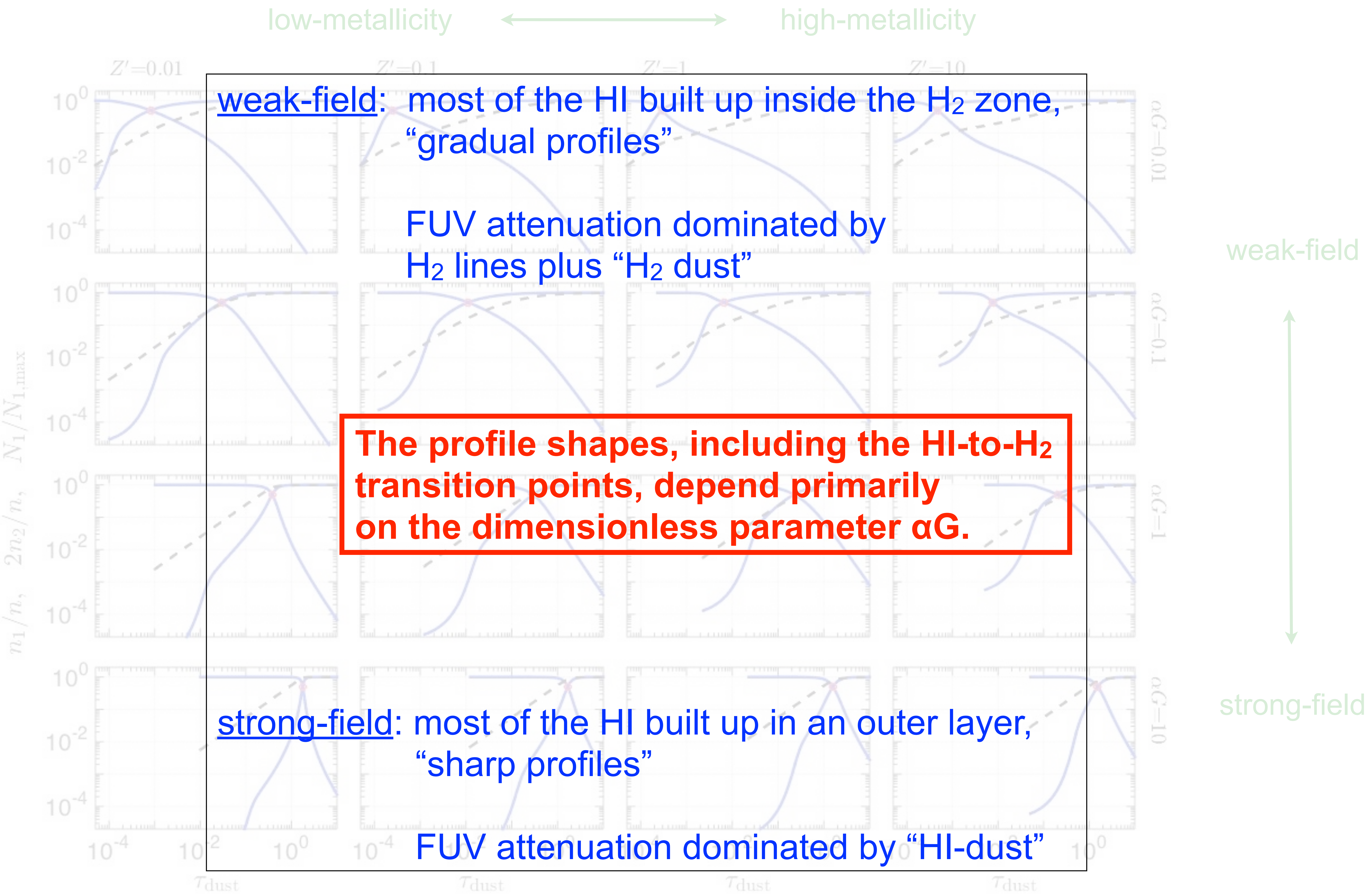
low-metallicity ⟷ high-metallicity

weak-field

strong-field



HI-to-H_2 Transition Profiles: S+14 Bialy & Sternberg 2016 arXiv:1601.02608



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"

The profile shapes, including the HI-to-H_2 transition points, depend primarily on the dimensionless parameter αG.

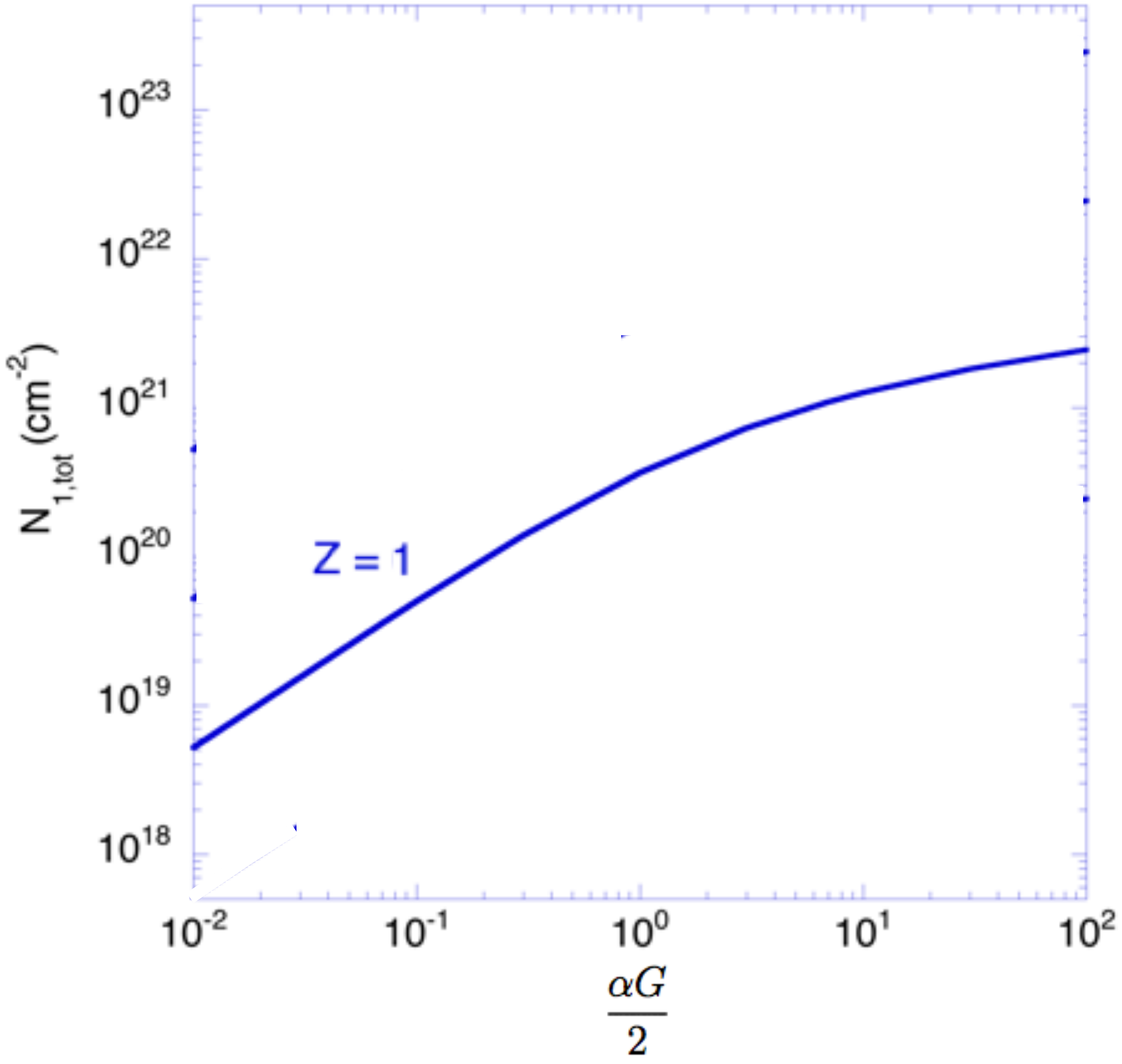
strong-field: most of the HI built up in an outer layer,
"sharp profiles"

FUV attenuation dominated by "HI-dust"

General Purpose Analytic Formula for the Total HI Column Density:

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

[derived in two ways in S+14]



weak-field

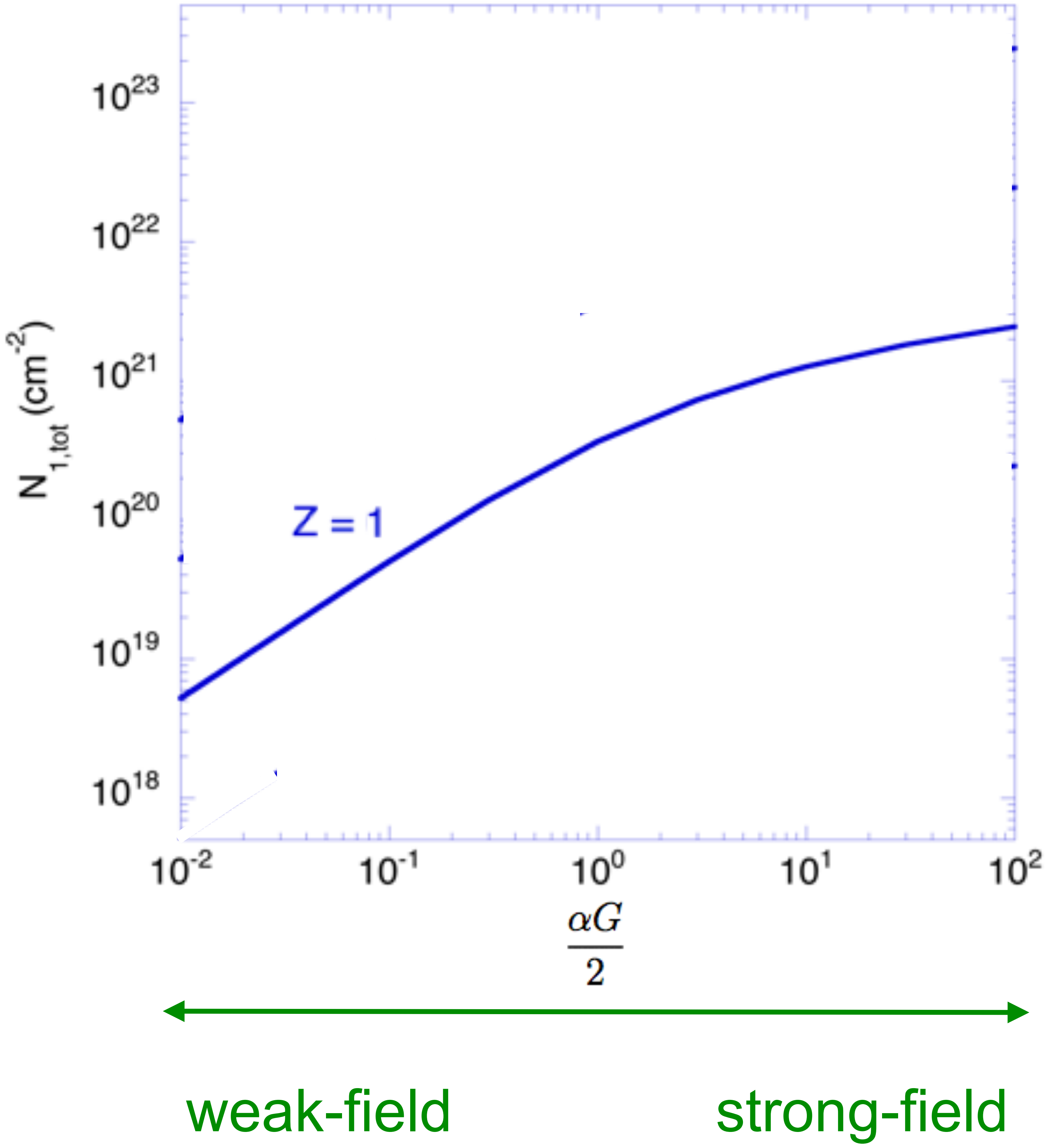
strong-field

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:



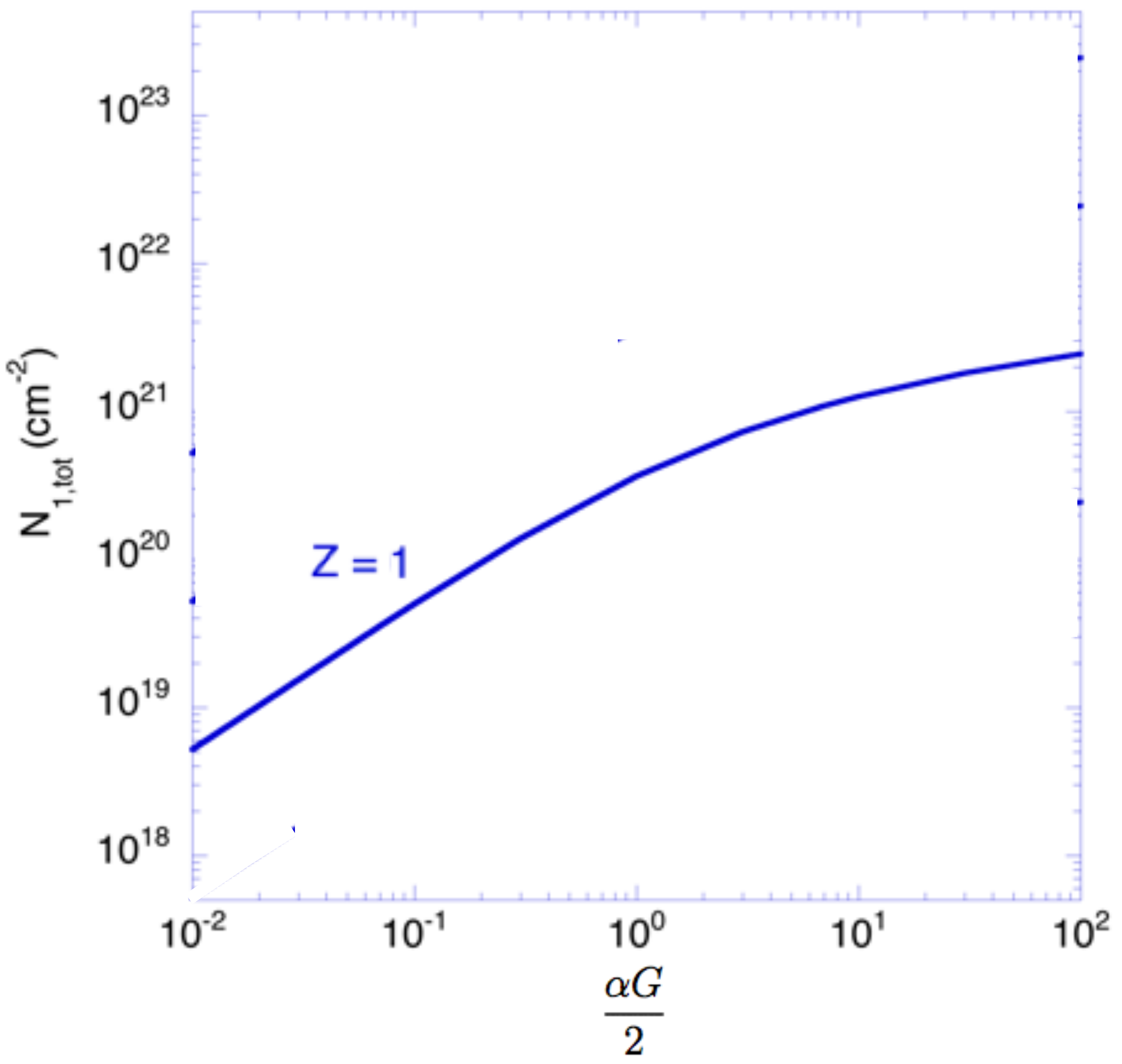
$$\boxed{N_{1,\mathrm{tot}} = \frac{1}{4}\frac{\bar{f}_{\mathrm{diss}} w F_0}{R n}}$$

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

formation rate per unit area = effective dissociation flux

(a “Strömgren Relation”)

Strong-Field Limit:



$$\longleftrightarrow$$

weak-field strong-field

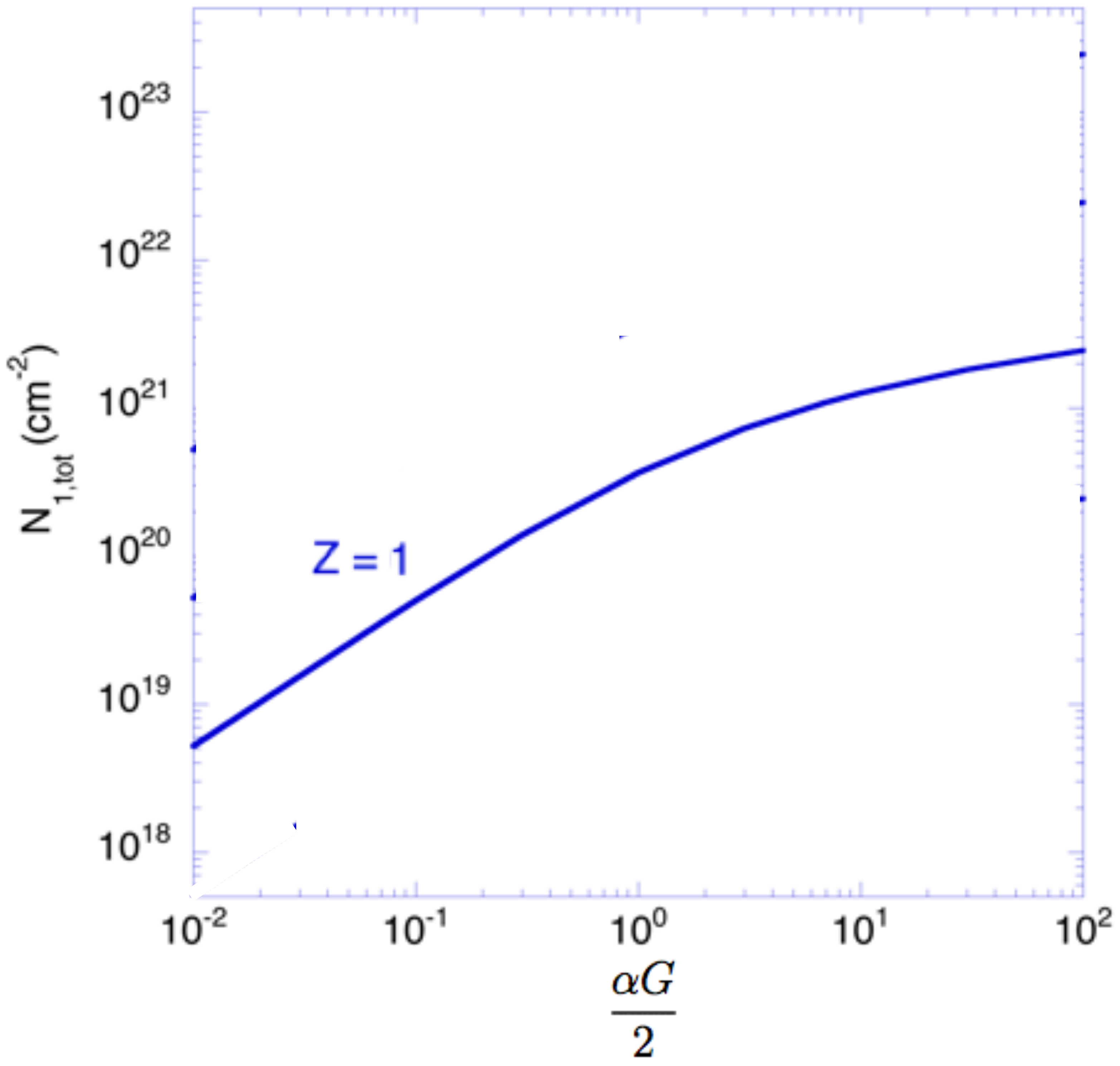
$$\boxed{N_{1,\rm tot} \approx \frac{1}{\sigma_g}}$$

(neglecting the logarithmic term)

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

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

Heavy-Element Abundances "Metallicity":



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

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

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

weak-field

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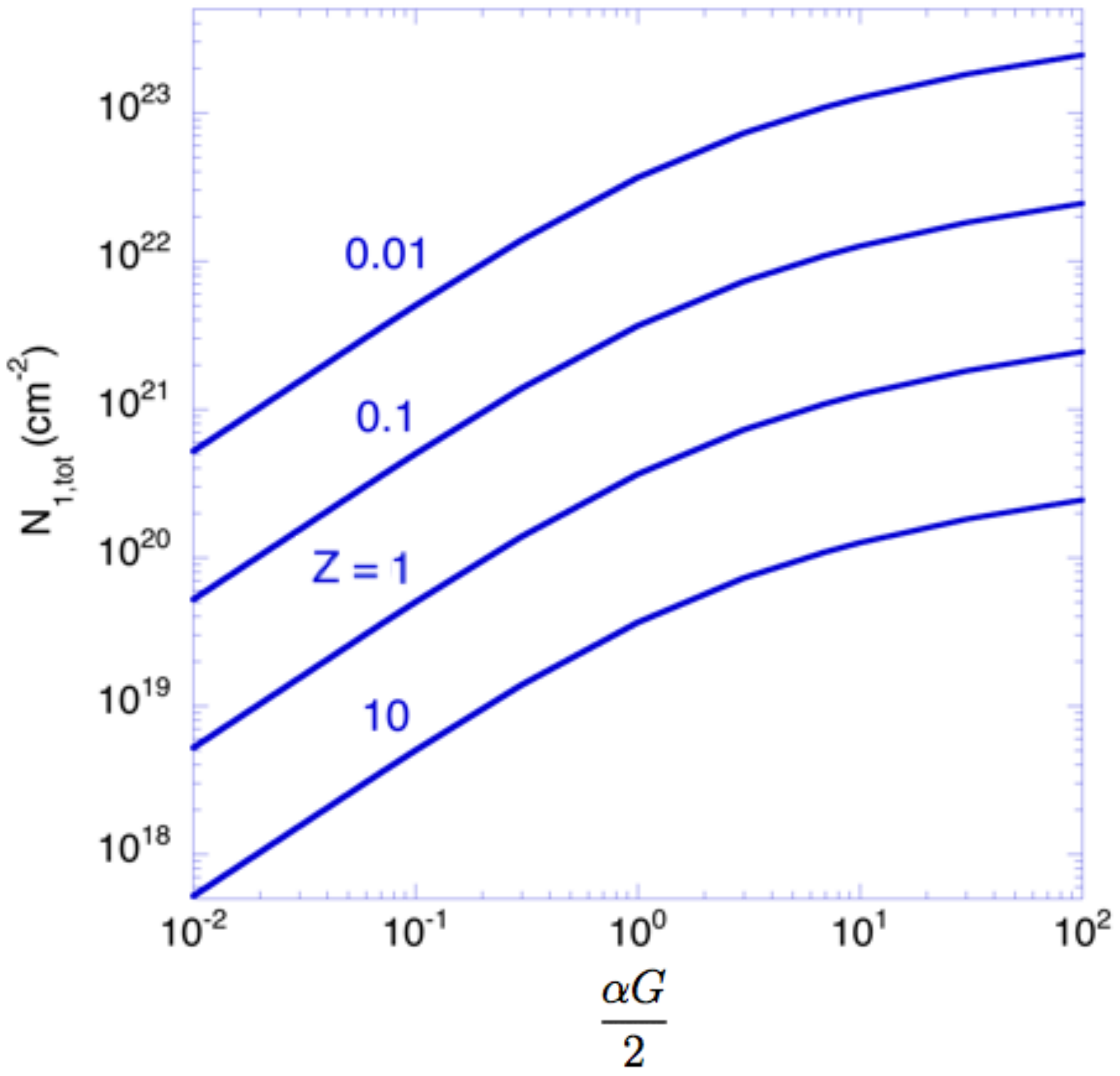

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General Purpose Analytic Formula for the Total HI Column Density: S+14

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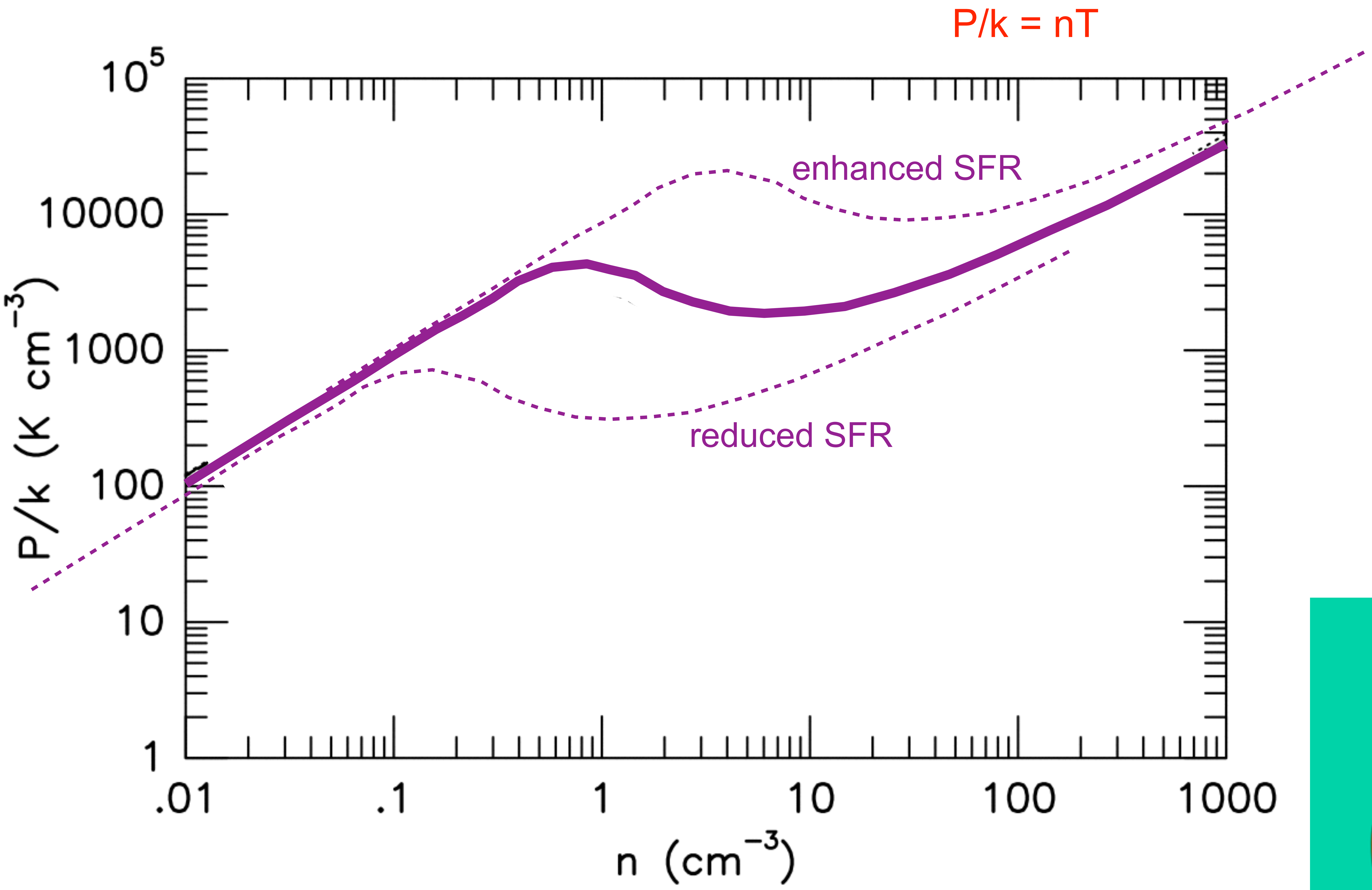
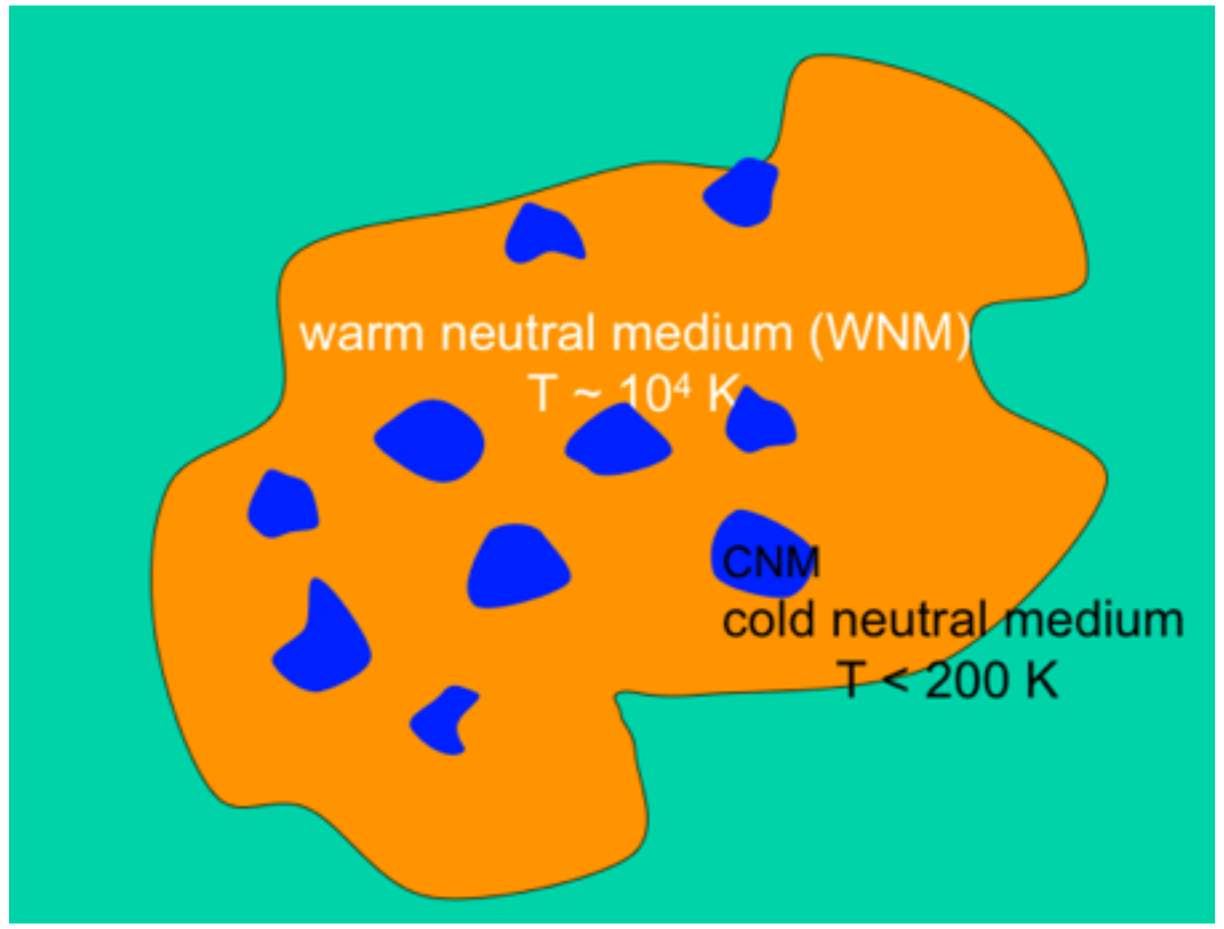
- useful for interpreting 21cm observations
- incorporation into hydrodynamics simulations
- application to “self-regulated” media

HI Thermal Phases in Self-Regulated Media:



Field, Goldsmith & Habing 1969 ApJ 155 149



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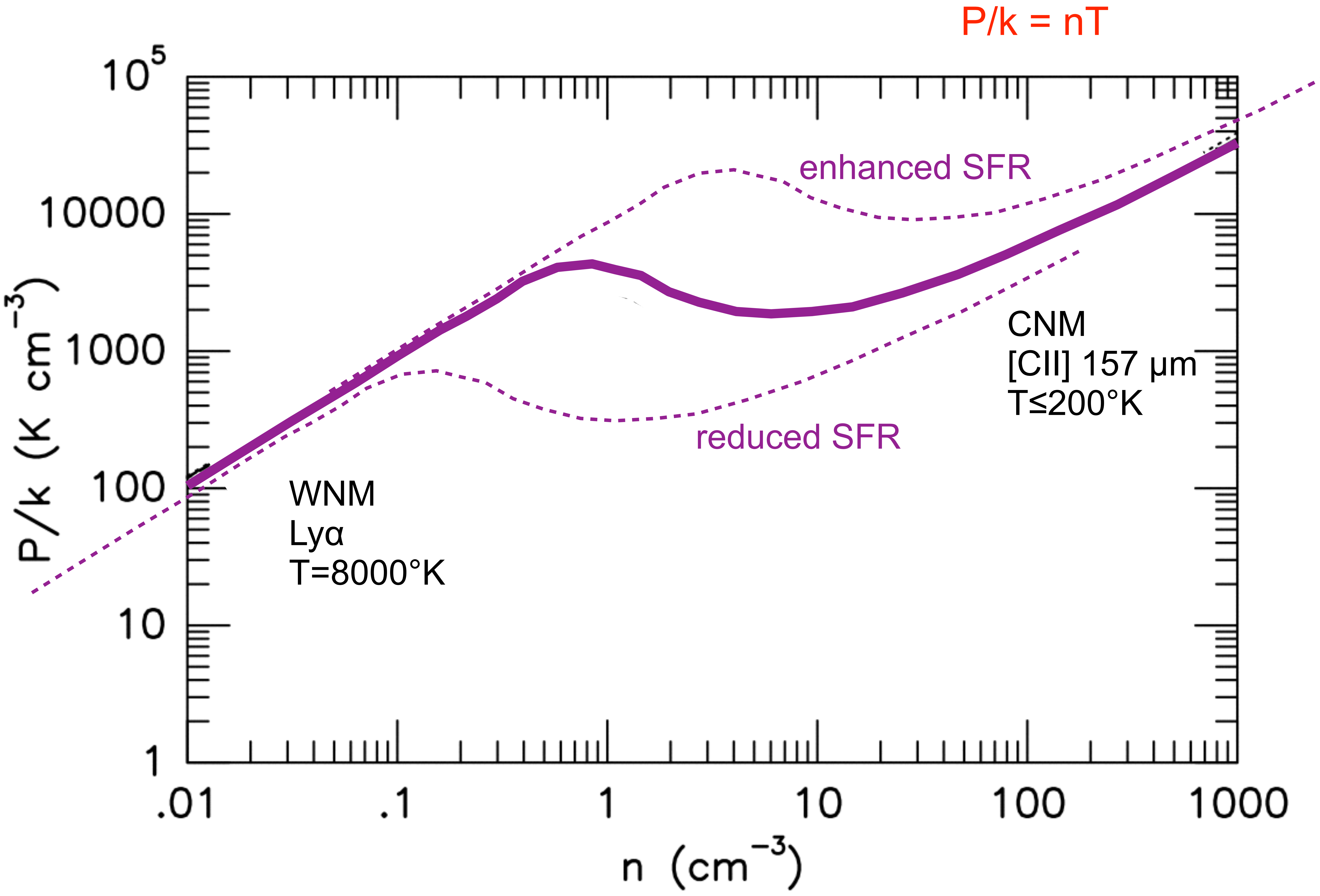

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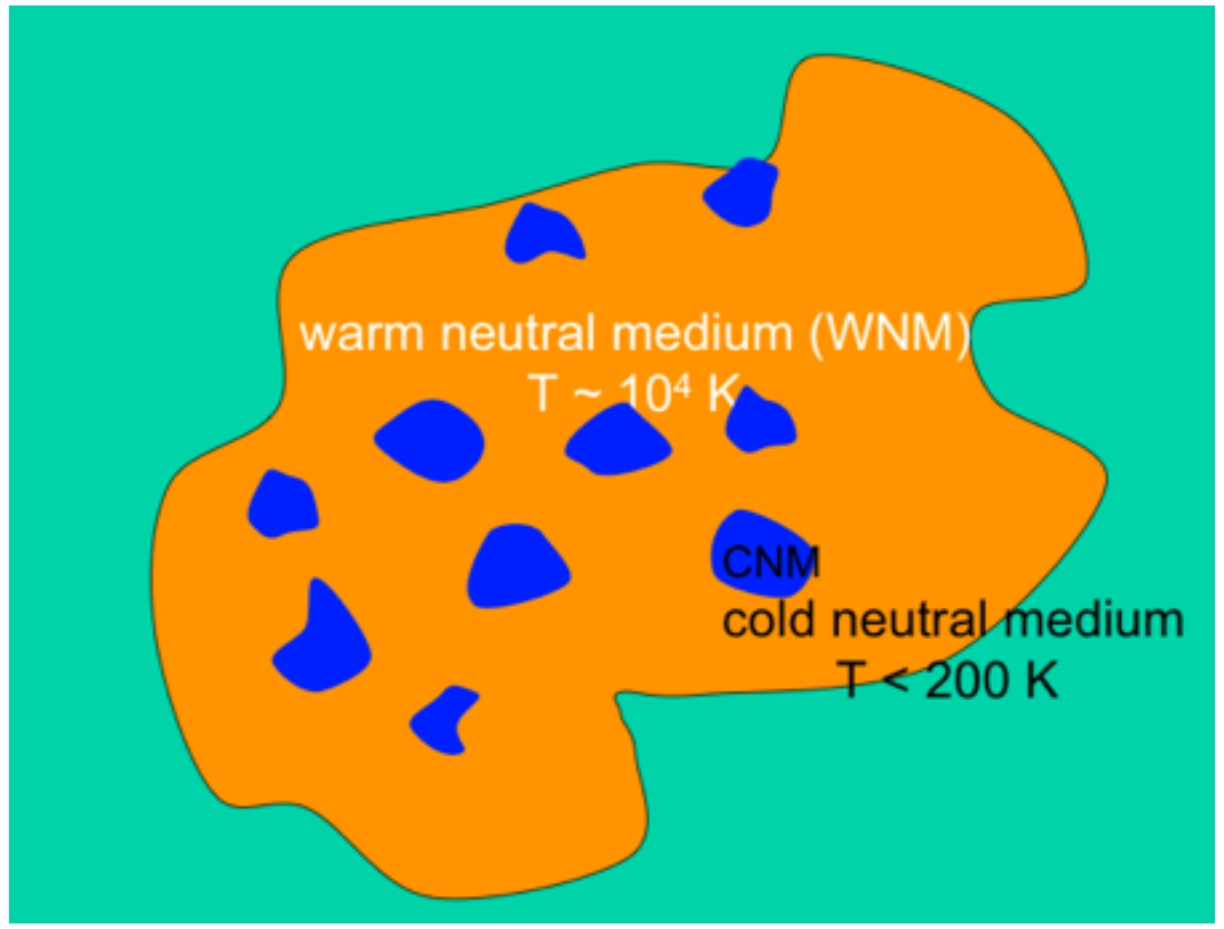
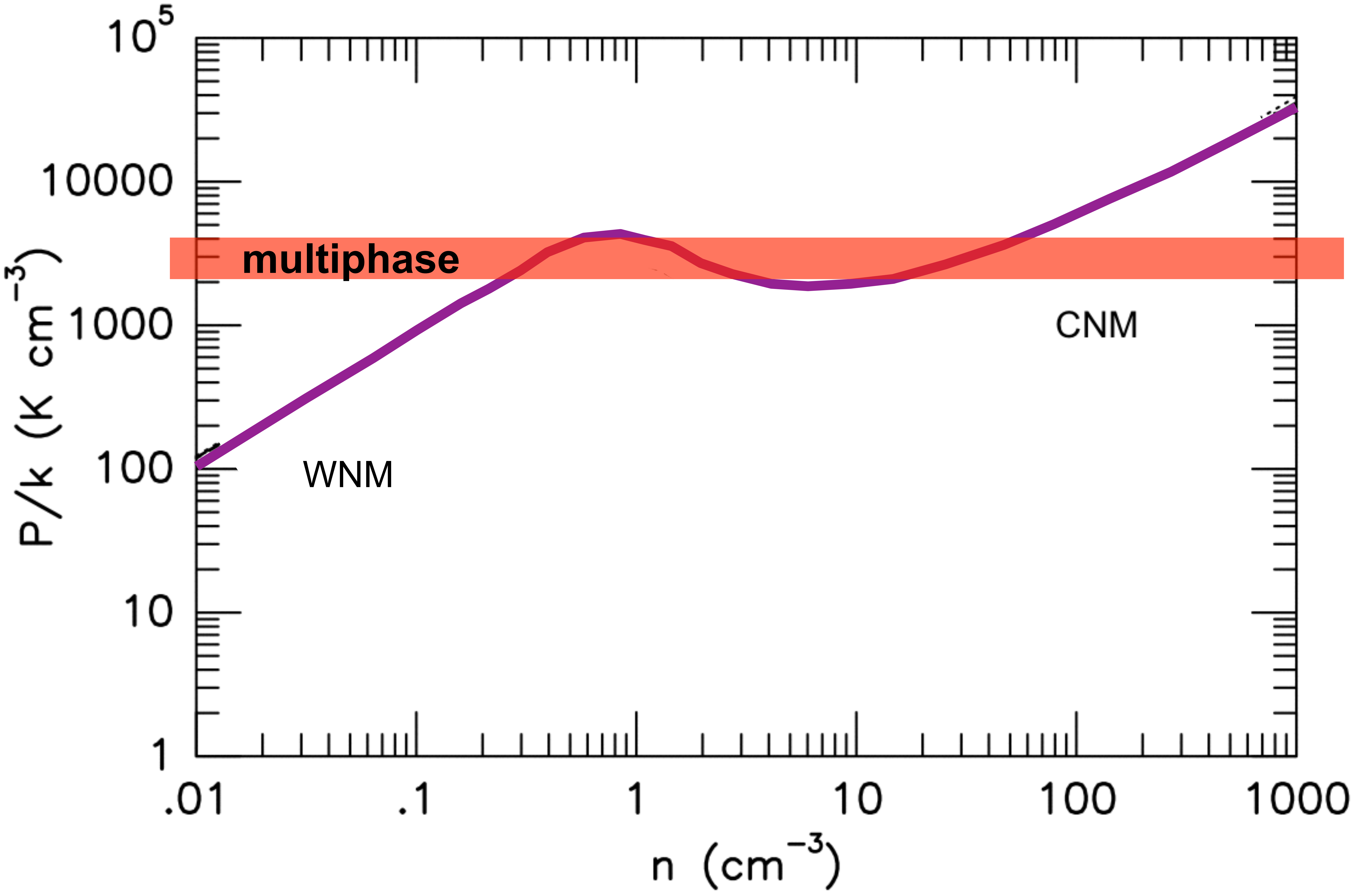


HI Thermal Phases in Self-Regulated Media:

Ansatz:
Krumholz McKee & Tumlinson 2009

P/k = nT



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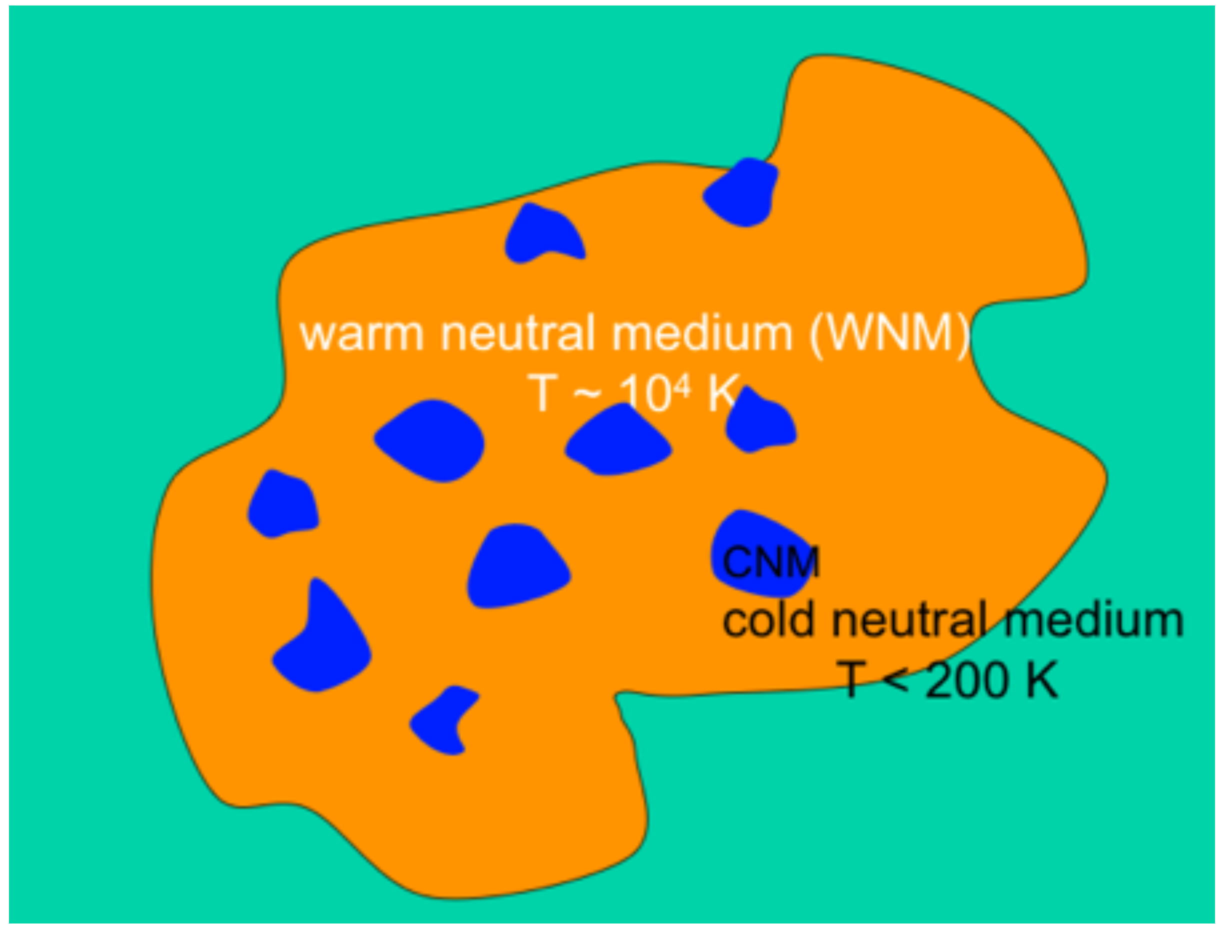
field strength

$$n_{\rm CNM} \approx \frac{93}{1 + 3.1 Z'^{0.365}} F'_0 \quad {\rm cm}^{-3}$$

metallicity

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



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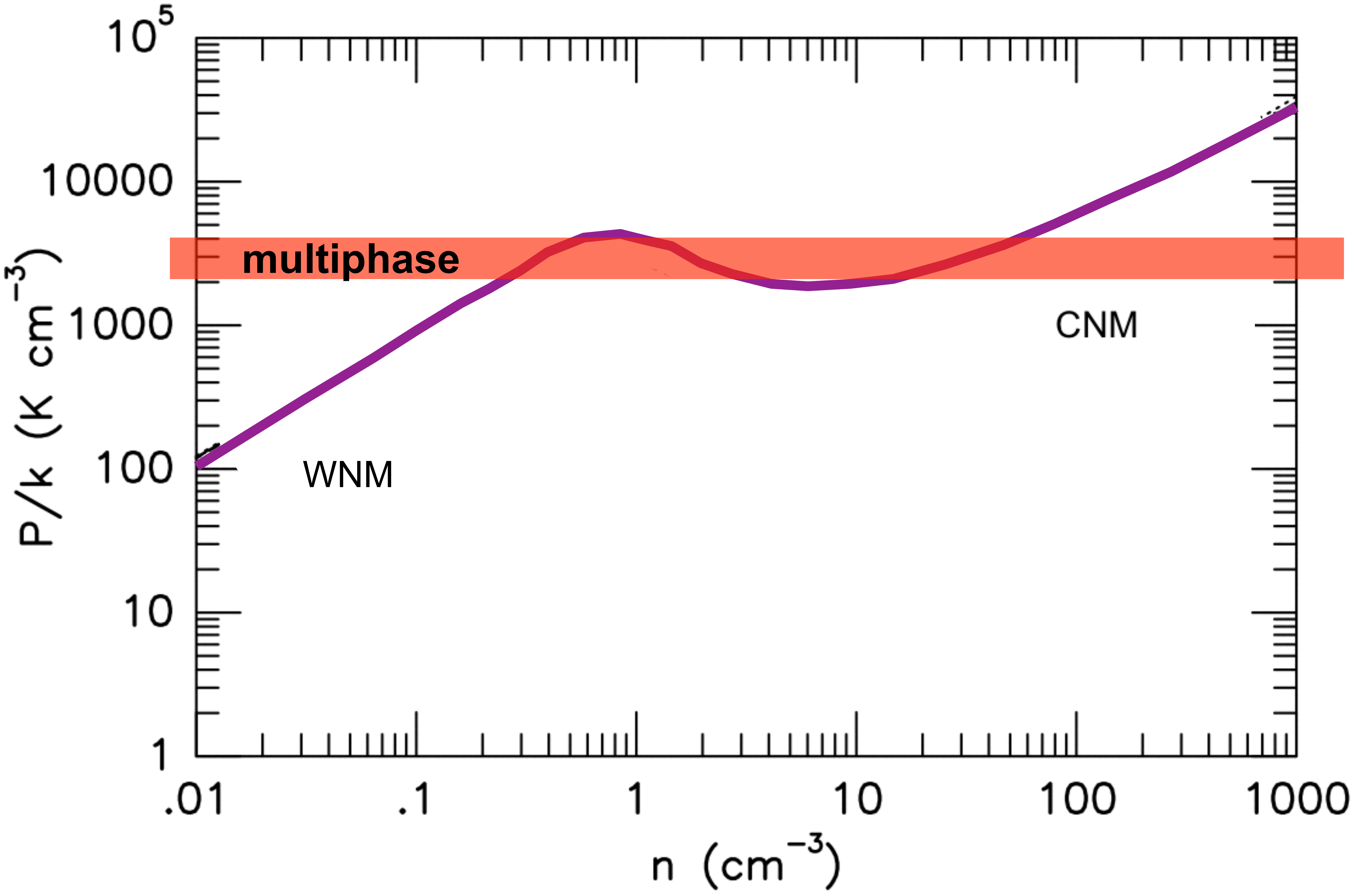

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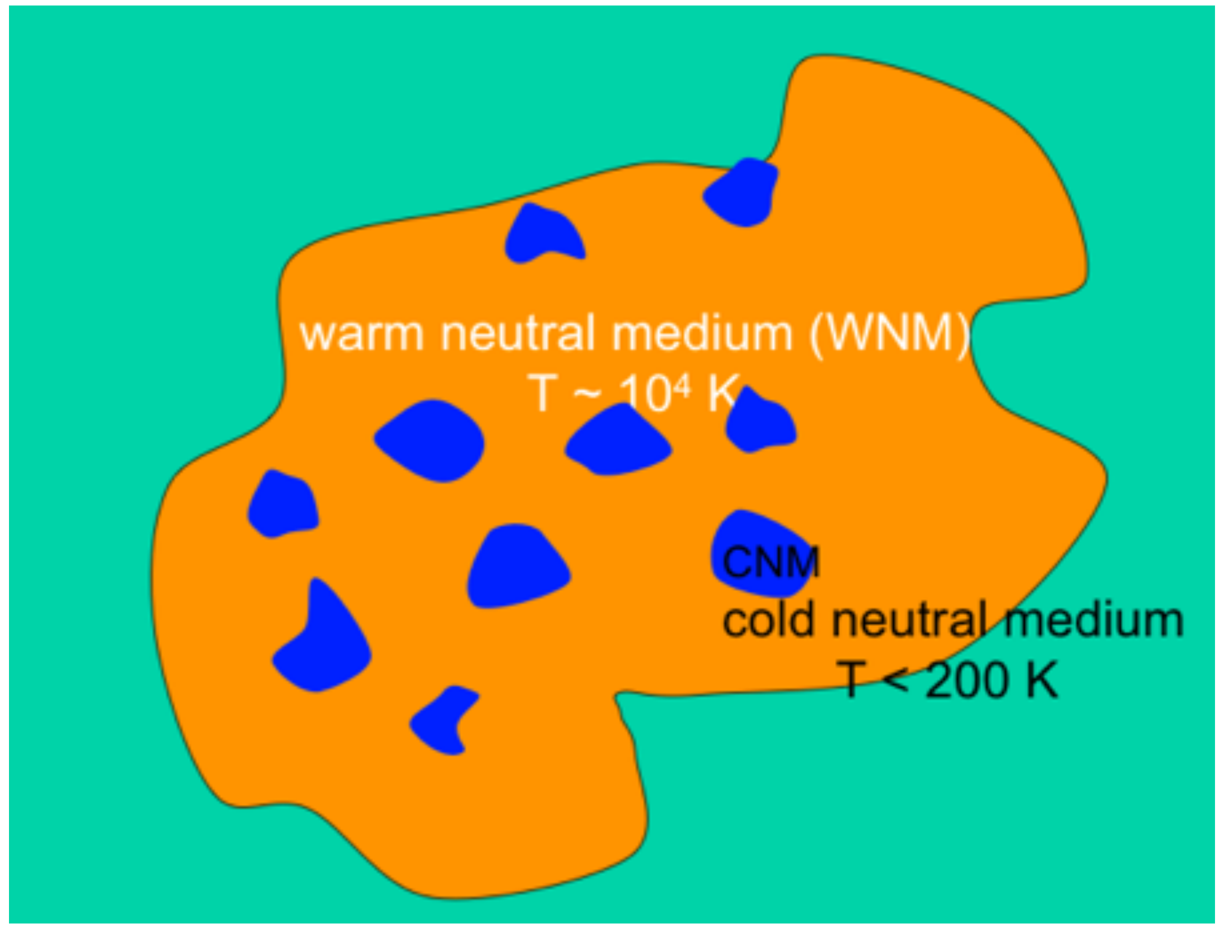
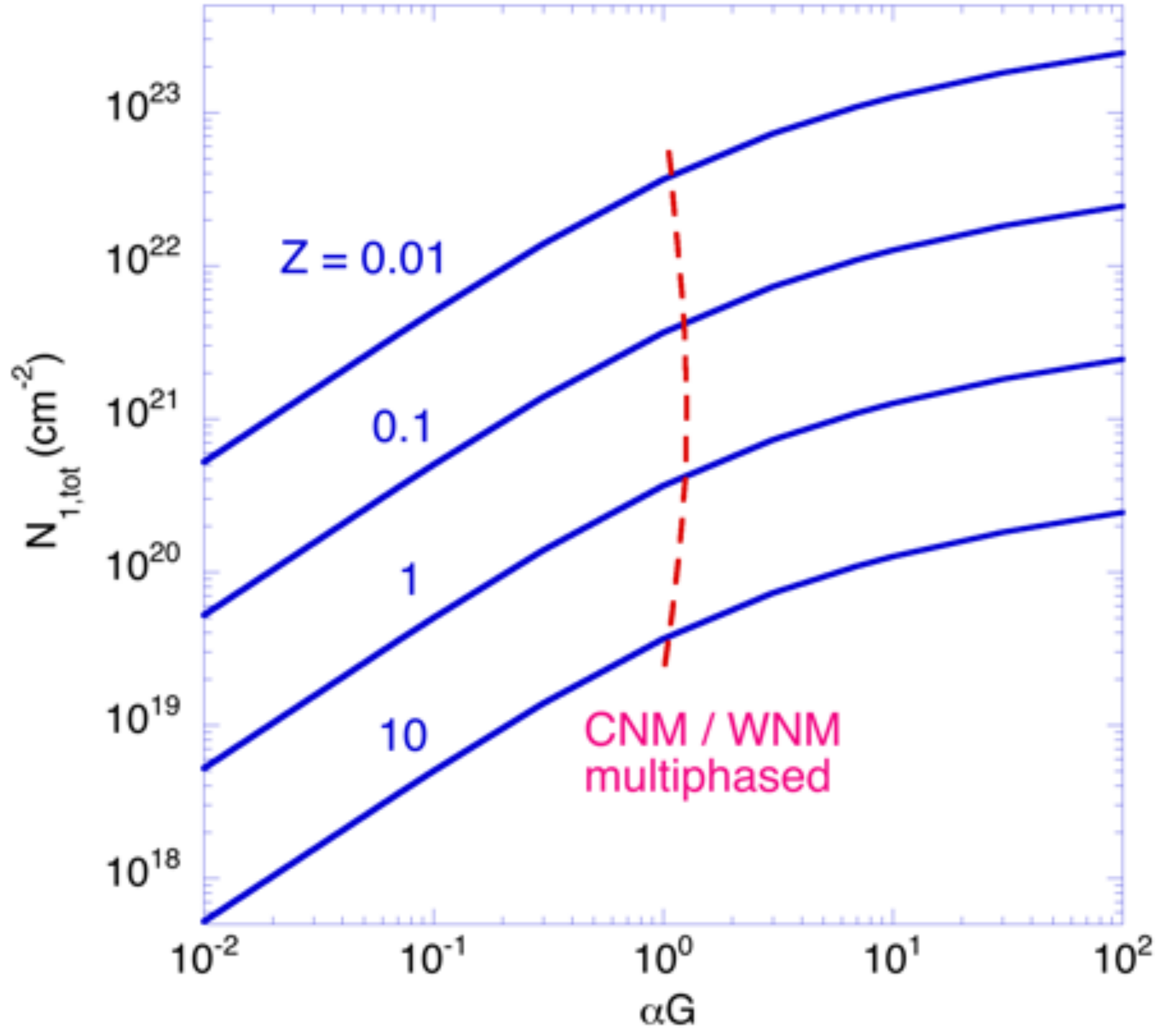


HI Column Density for Self-Regulated Media:

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

remarkable!



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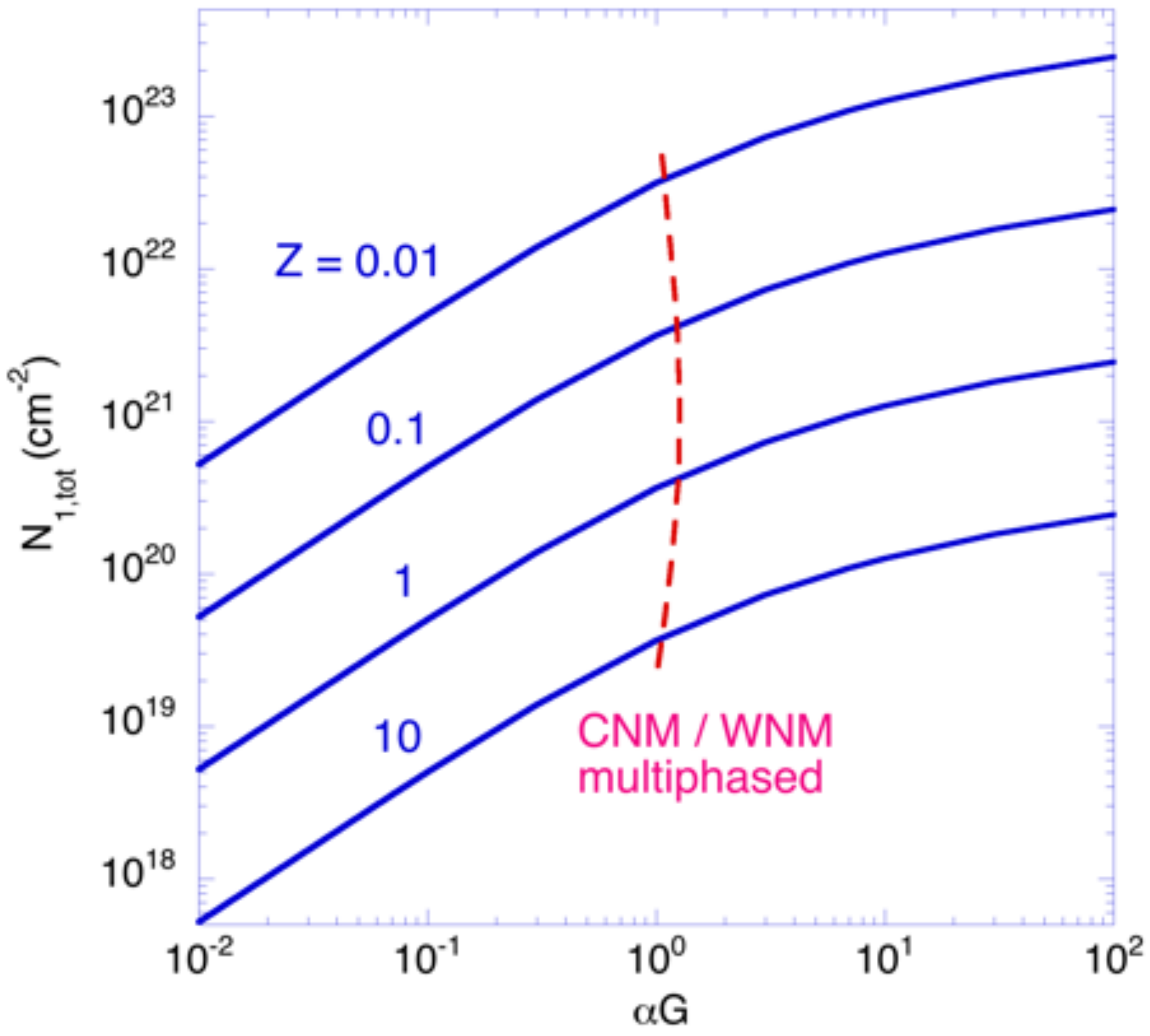


$$\boxed{\Sigma_{\rm HI} \approx \frac{6}{\phi_g Z'} \quad {\rm M}_\odot\ {\rm pc}^{-2}}$$

characteristic HI photodissociation mass surface density in self-regulated systems

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

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

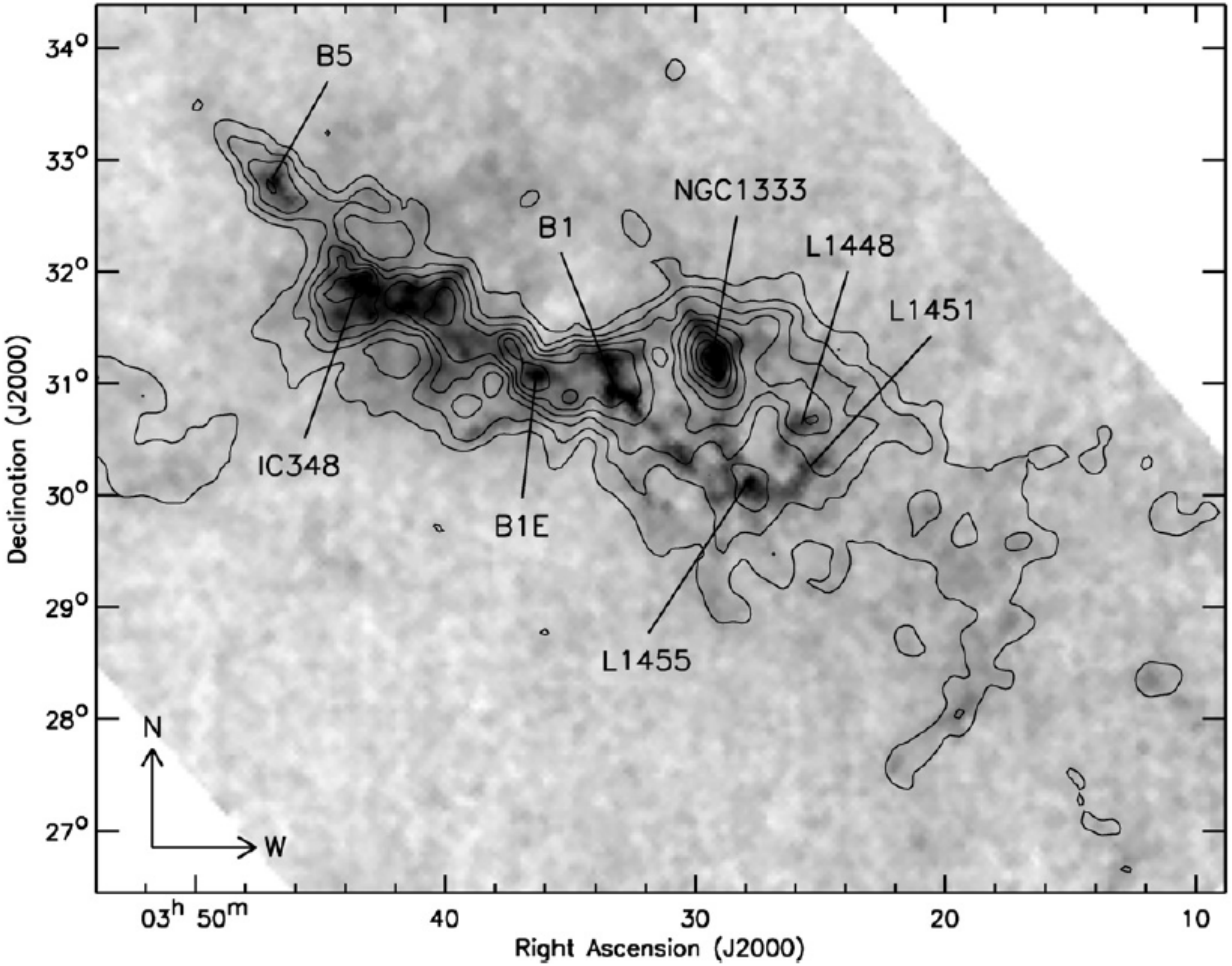
independent of radiation field intensity and/or gas density.

HI-to-H_2 in the Perseus Molecular Cloud:

Giovanni Antonio Vanosino’s celestial globe 1567   Vatican Museum

HI-to-H_2 in Perseus:

Perseus Cloud distance 300 pc



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

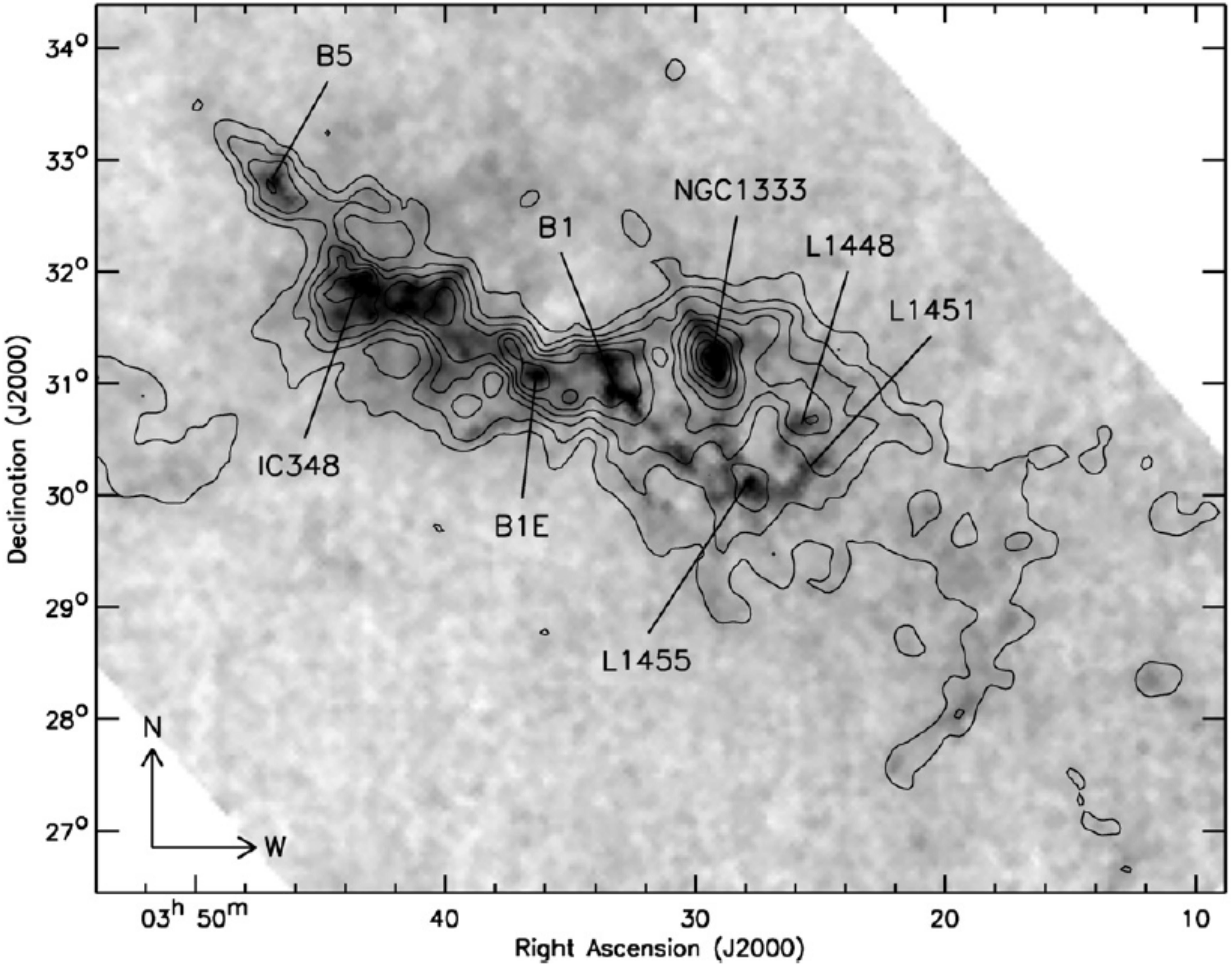
Dame+ 2001 Ridge+ 2006

HI-to-H_2 in Perseus:

dark clouds &
low-mass star-forming regions:

B1
B1E
B5
NGC1333
IC348

Perseus Cloud distance 300 pc



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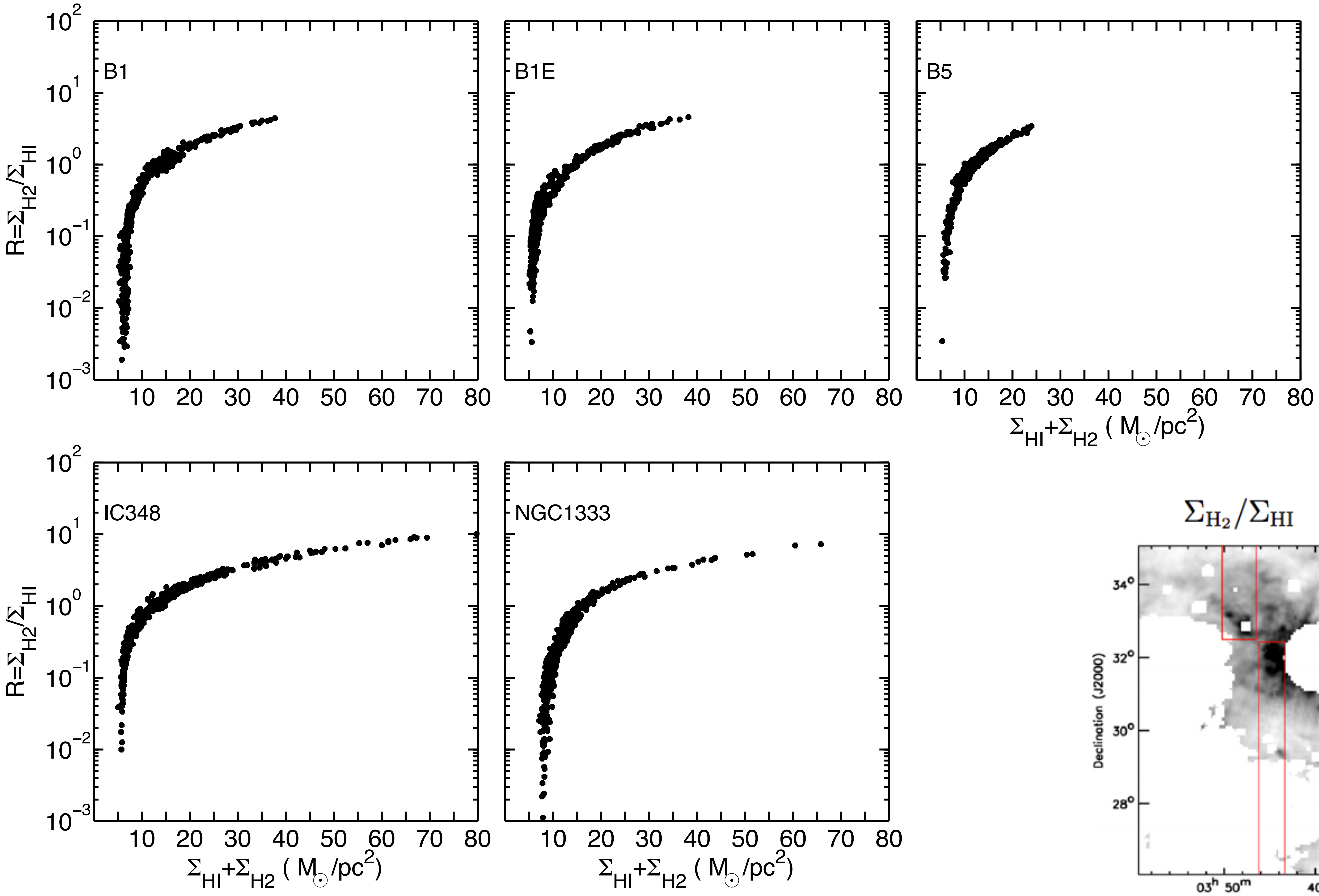
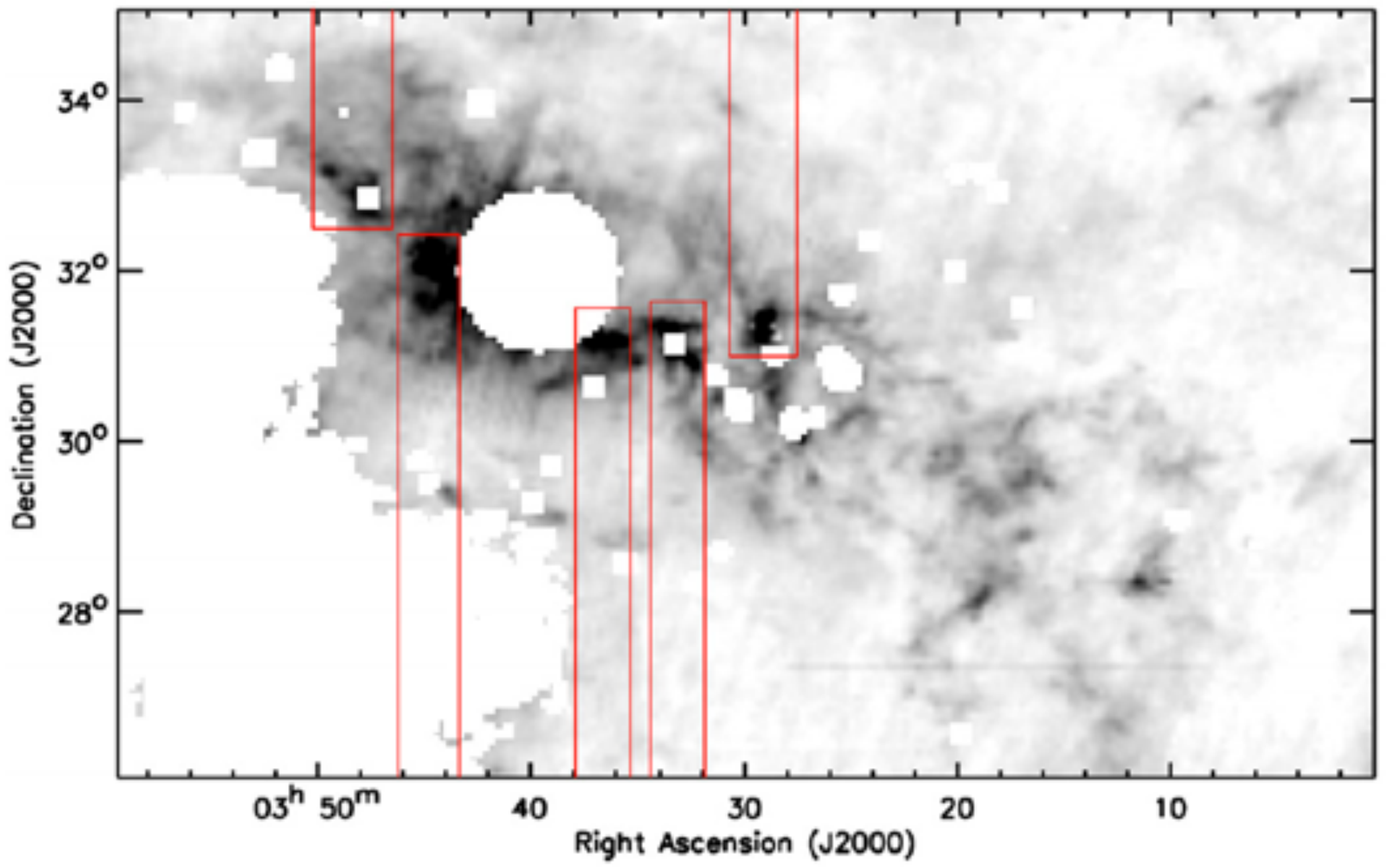
HI-to-H$_2$ in Perseus:

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

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



$\Sigma_{\mathrm{H_2}}/\Sigma_{\mathrm{HI}}$ Lee+ 2012



HI-to-H_2 in Perseus: Bialy, Sternberg, Lee, Le Petit, & Roueff 2015 ApJ 809, 122

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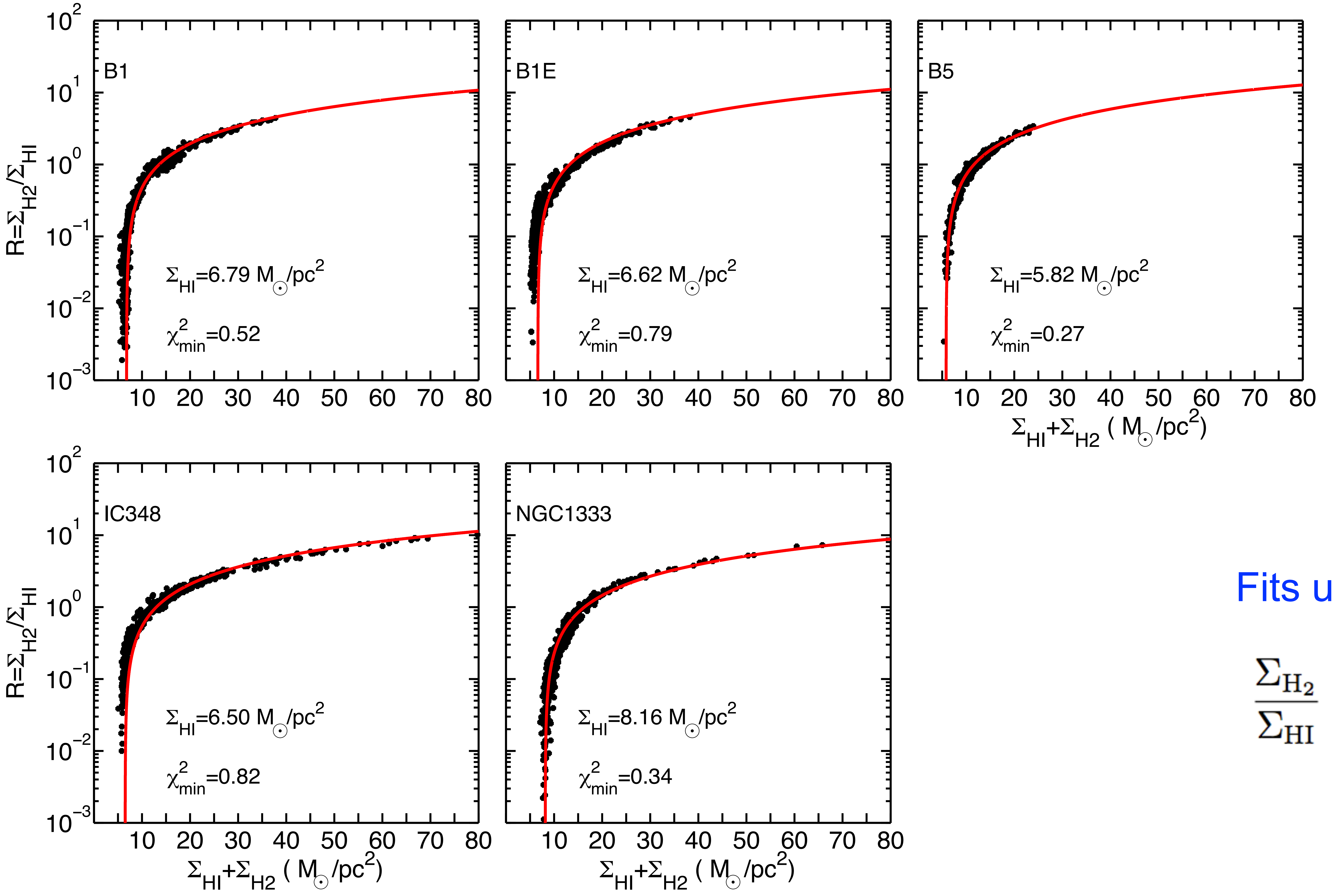
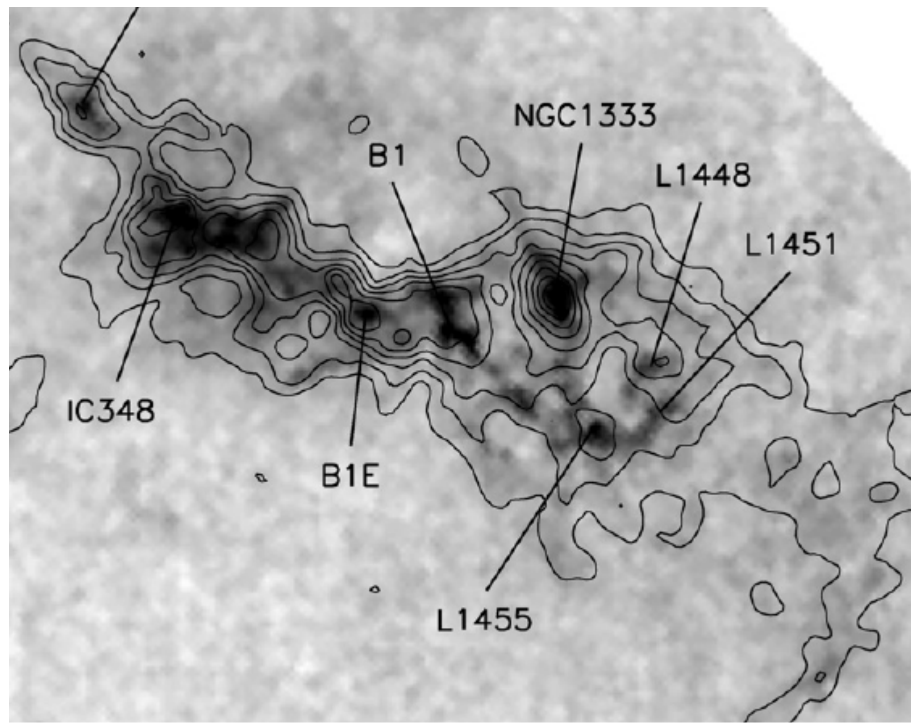


Fits using S+14:

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

HI-to-H_2 in Perseus: Bialy+ 2015



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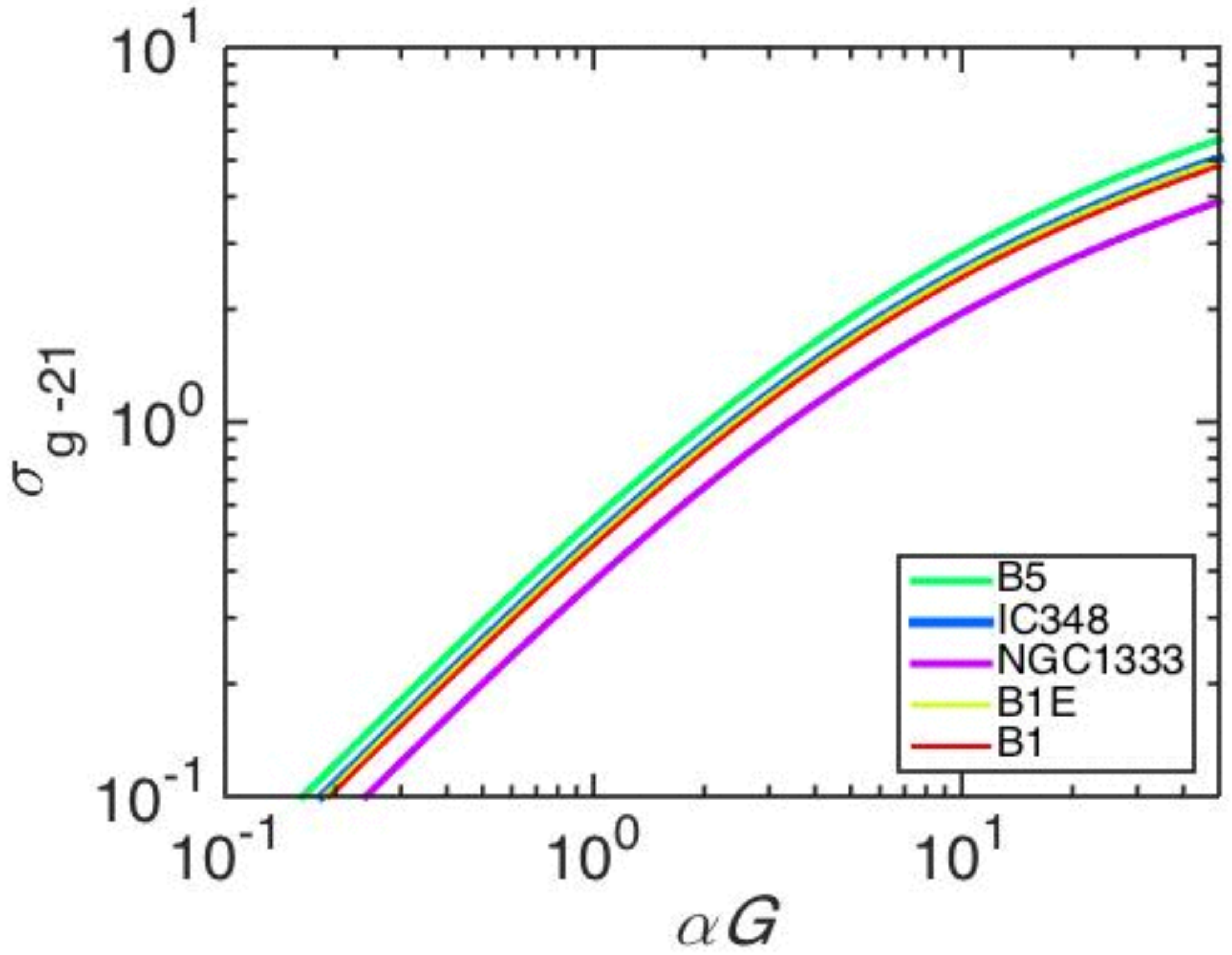

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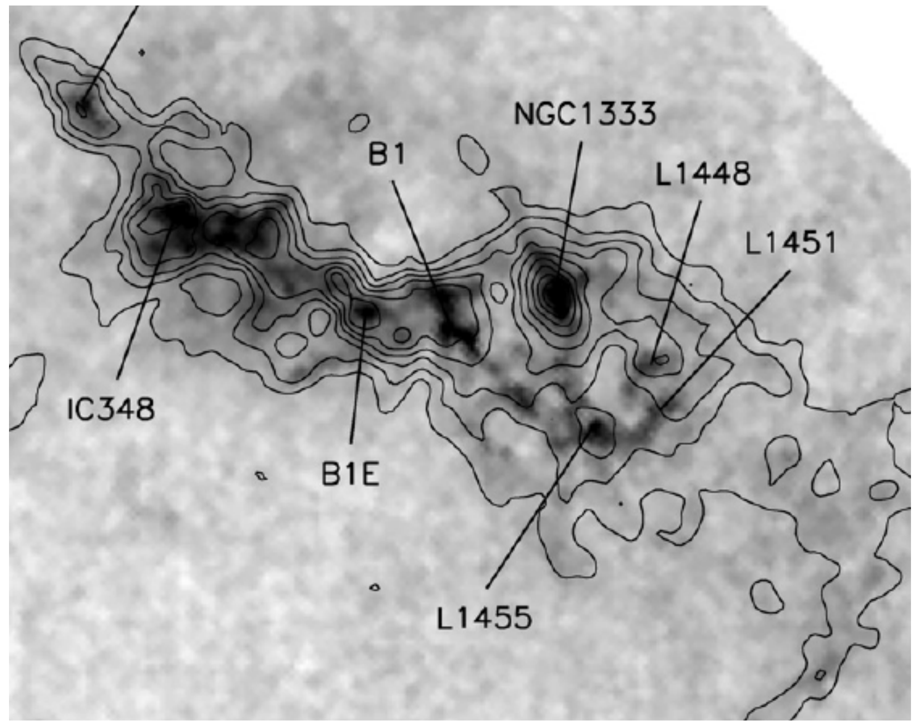

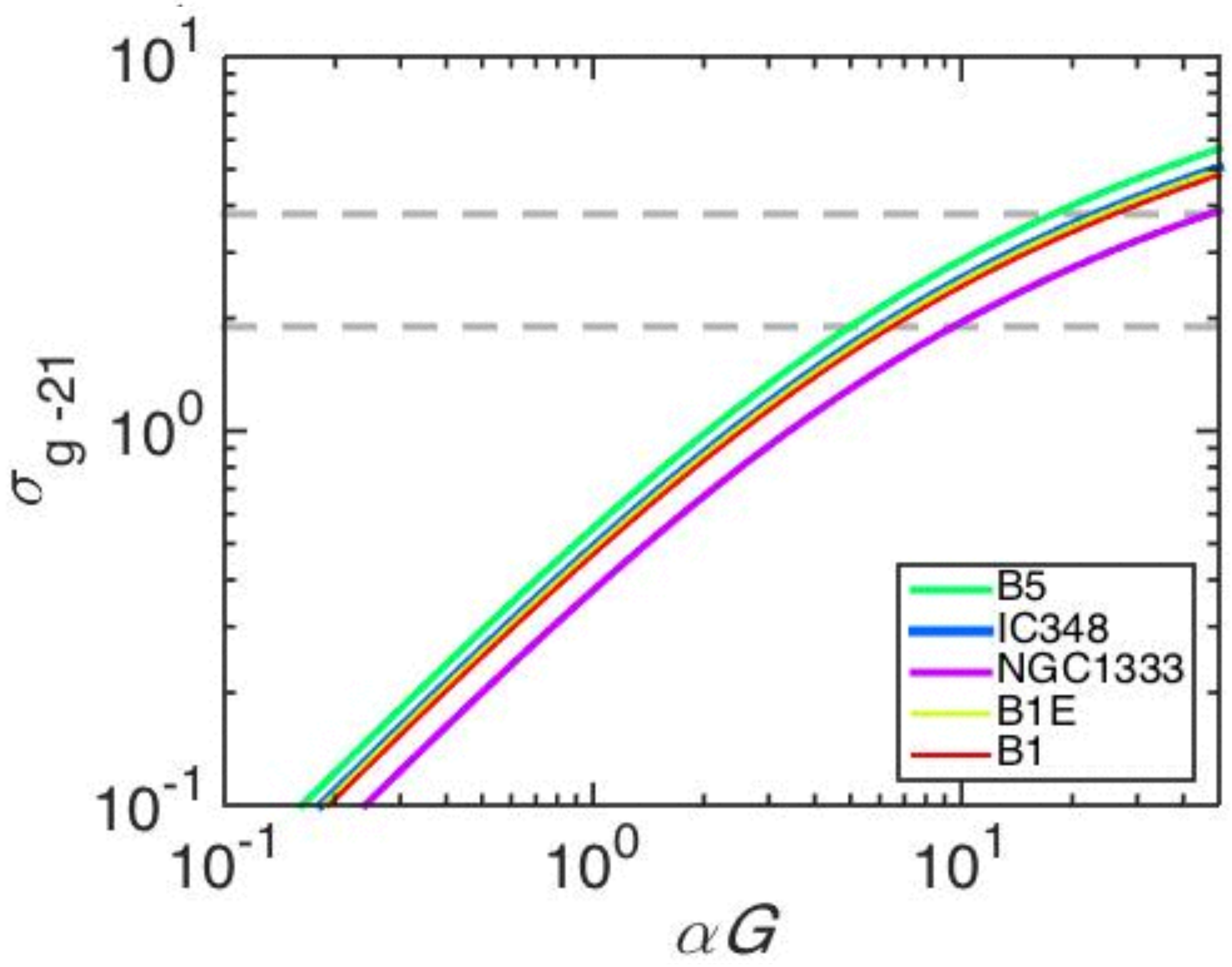

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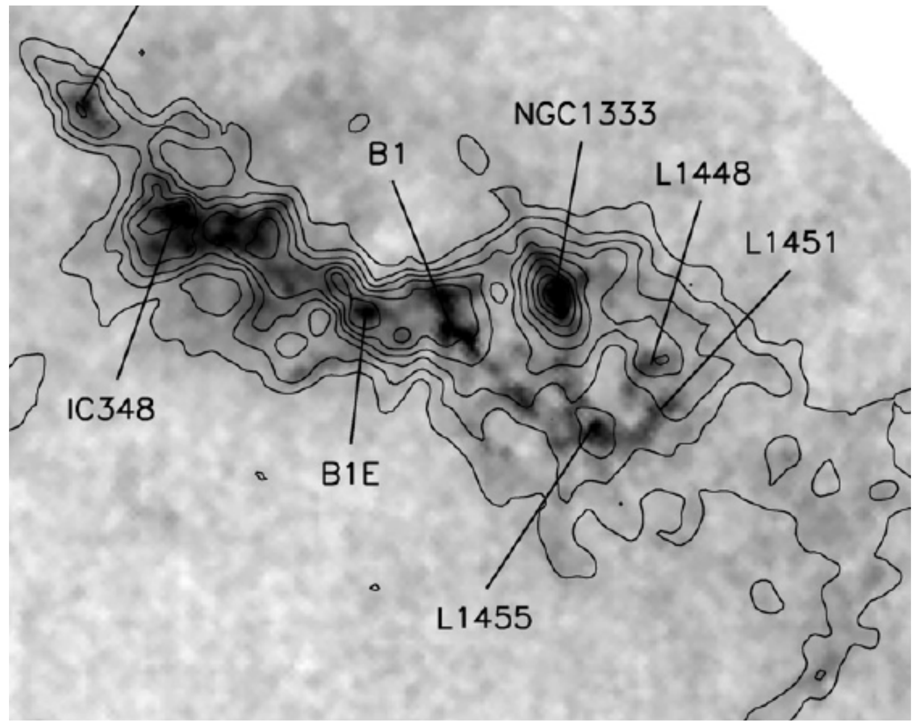

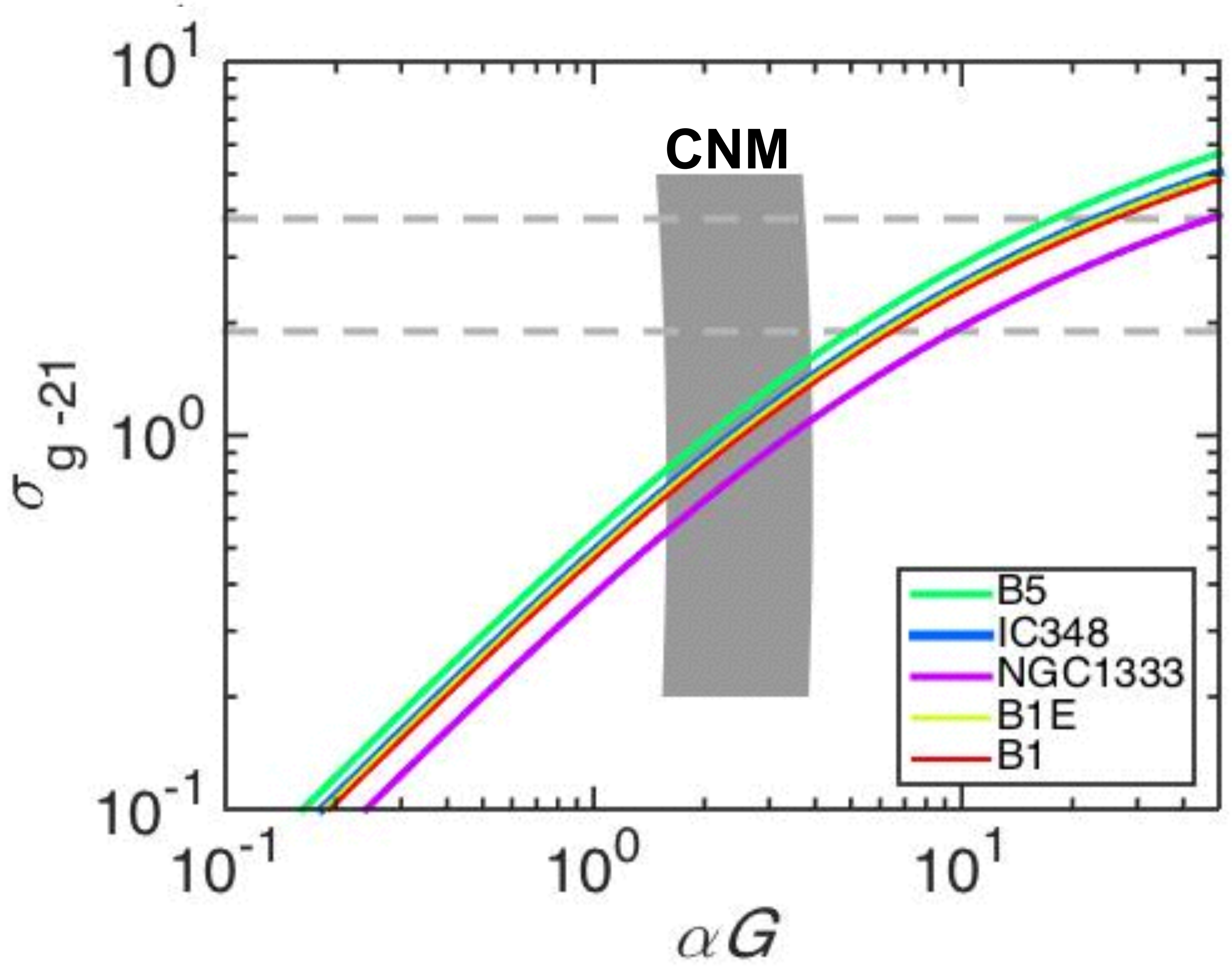

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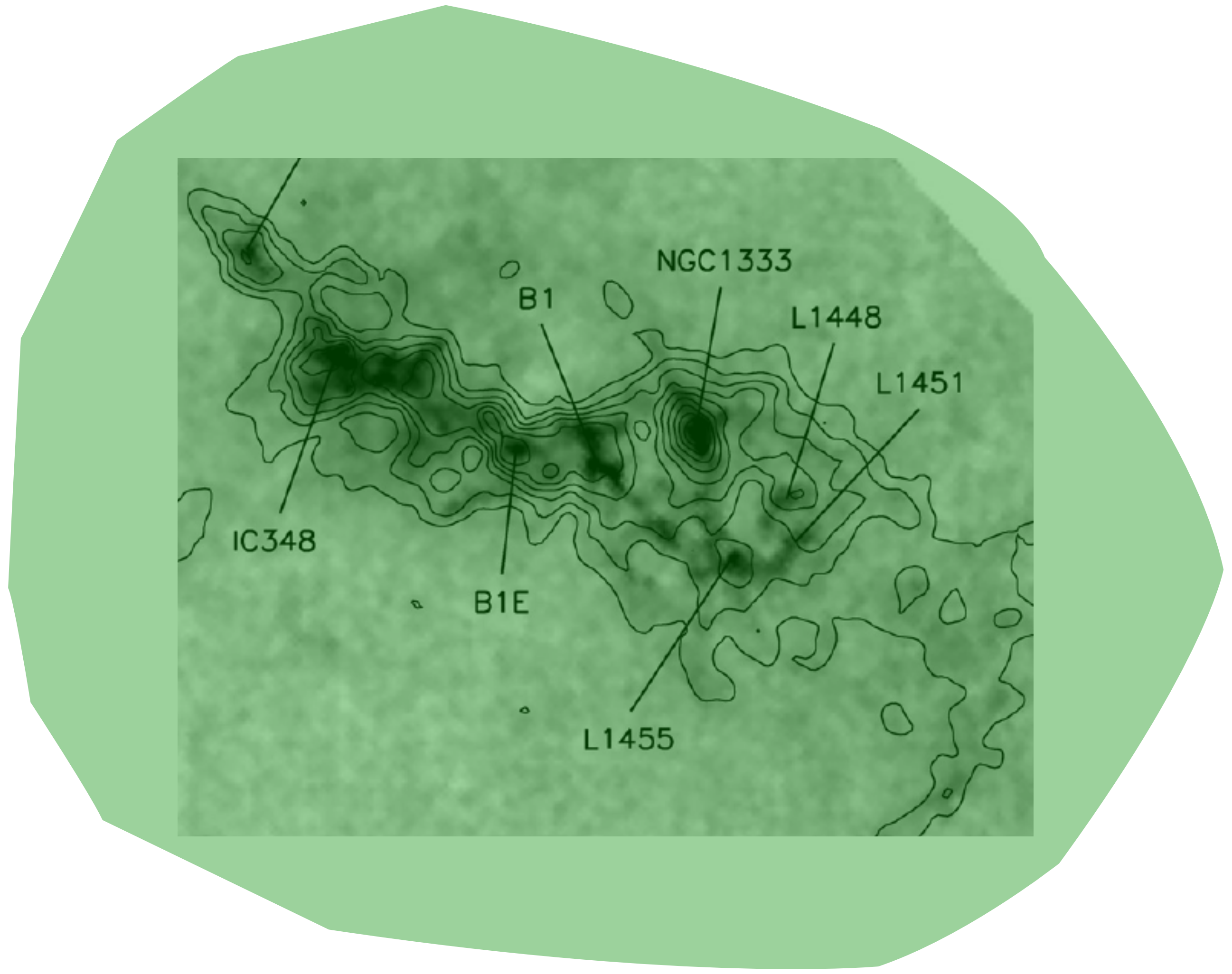
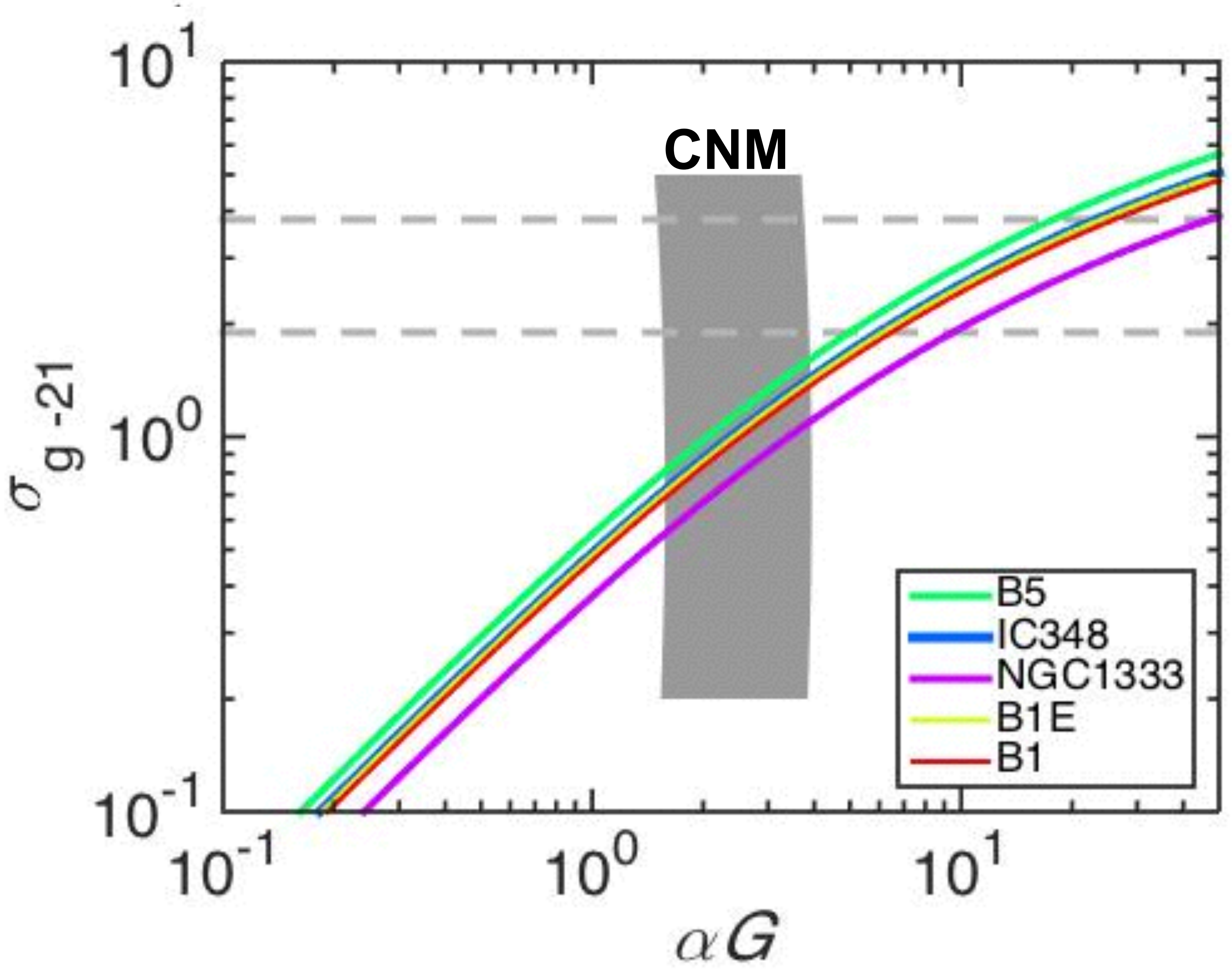


Galactic interstellar LW radiation field:
$F_0 \approx 2 \times 10^7$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



Conclusions: αG ≈ 5 to 50

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

HI-to-H_2 in Perseus: Bialy+ 2015

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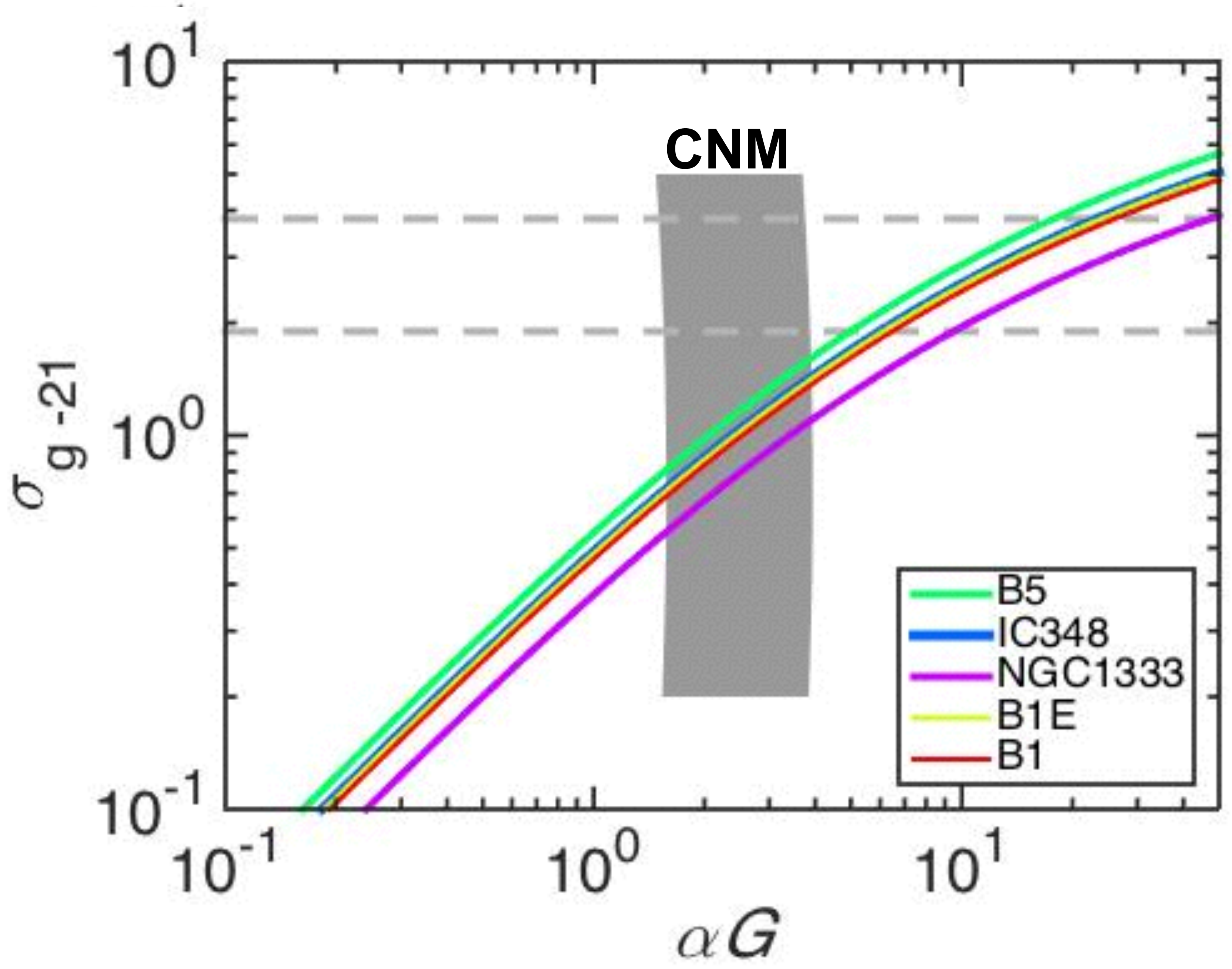

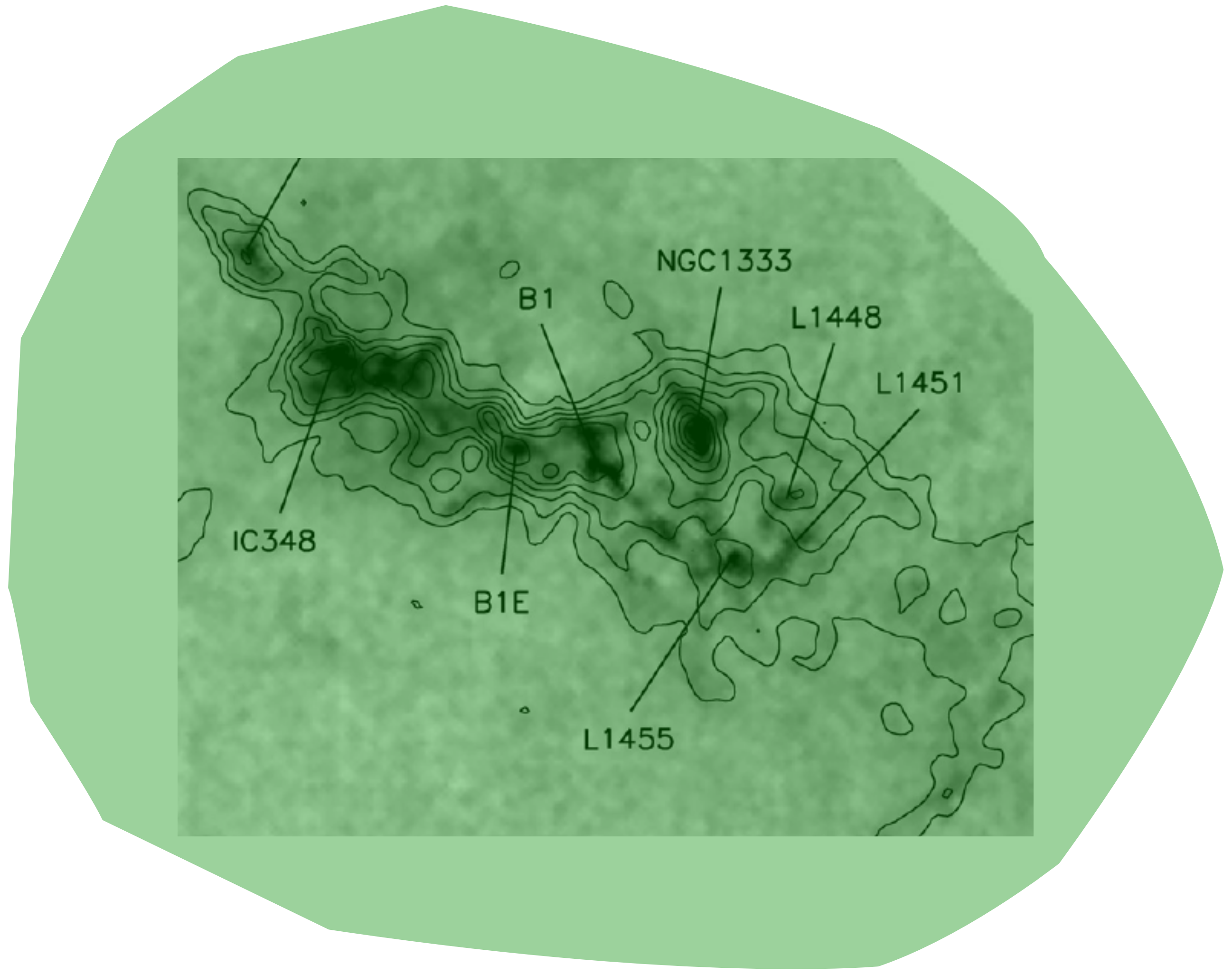

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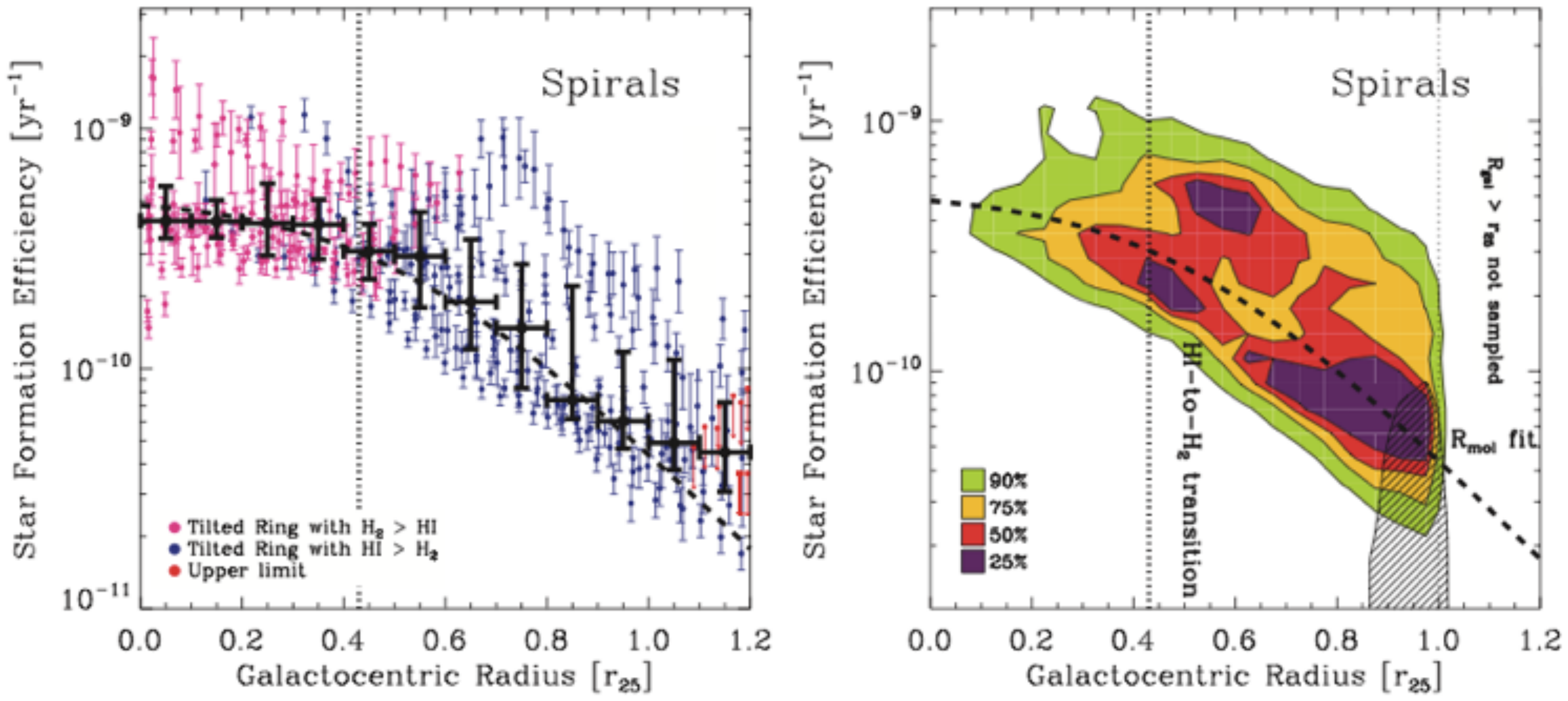
consistent with spin-temperatures
Stanimirovic et al. 2015

Galaxies:

e.g. Bigiel+ 08



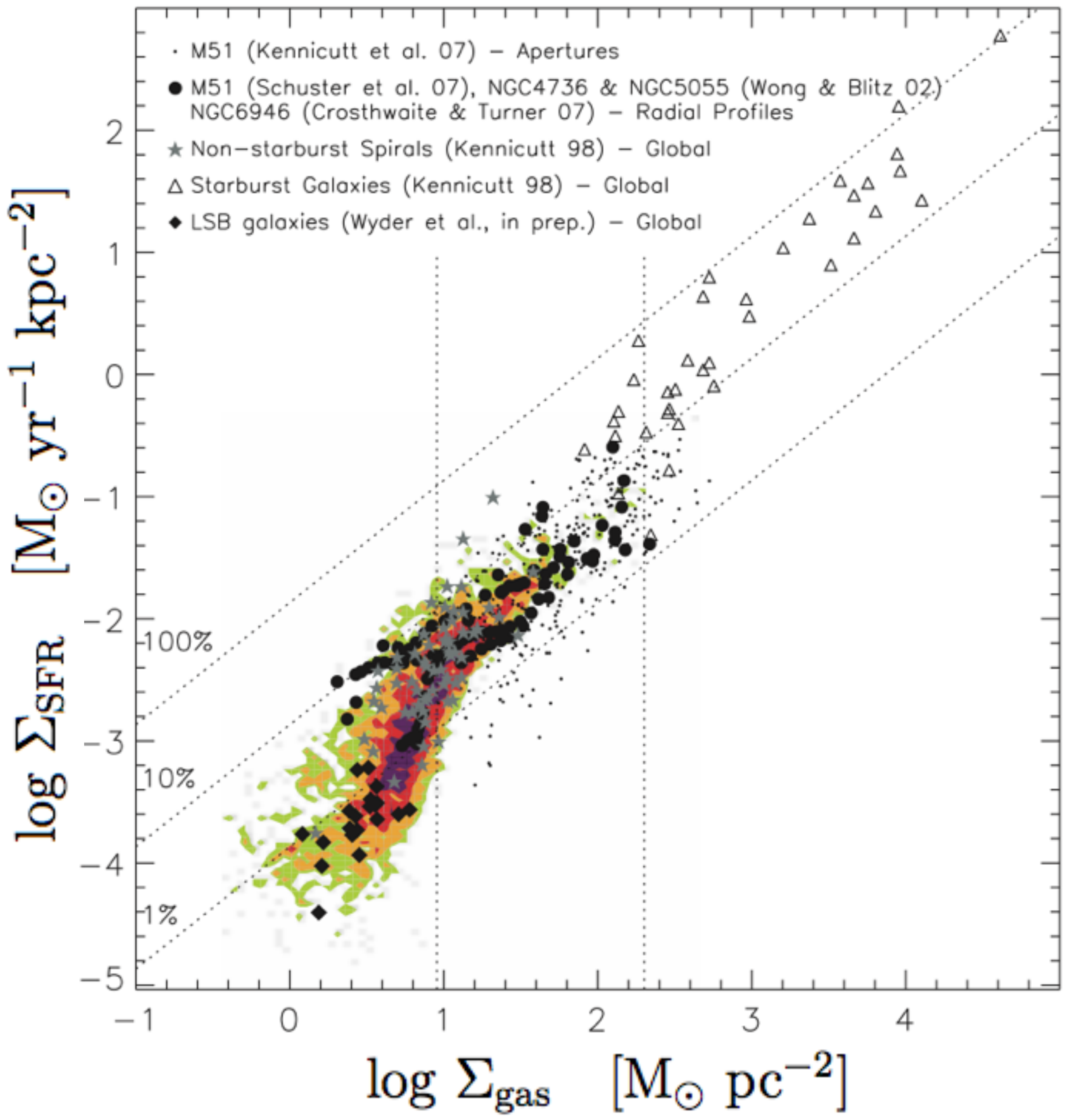


Table 5
Conditions at the H I-to-H_2 Transition

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

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

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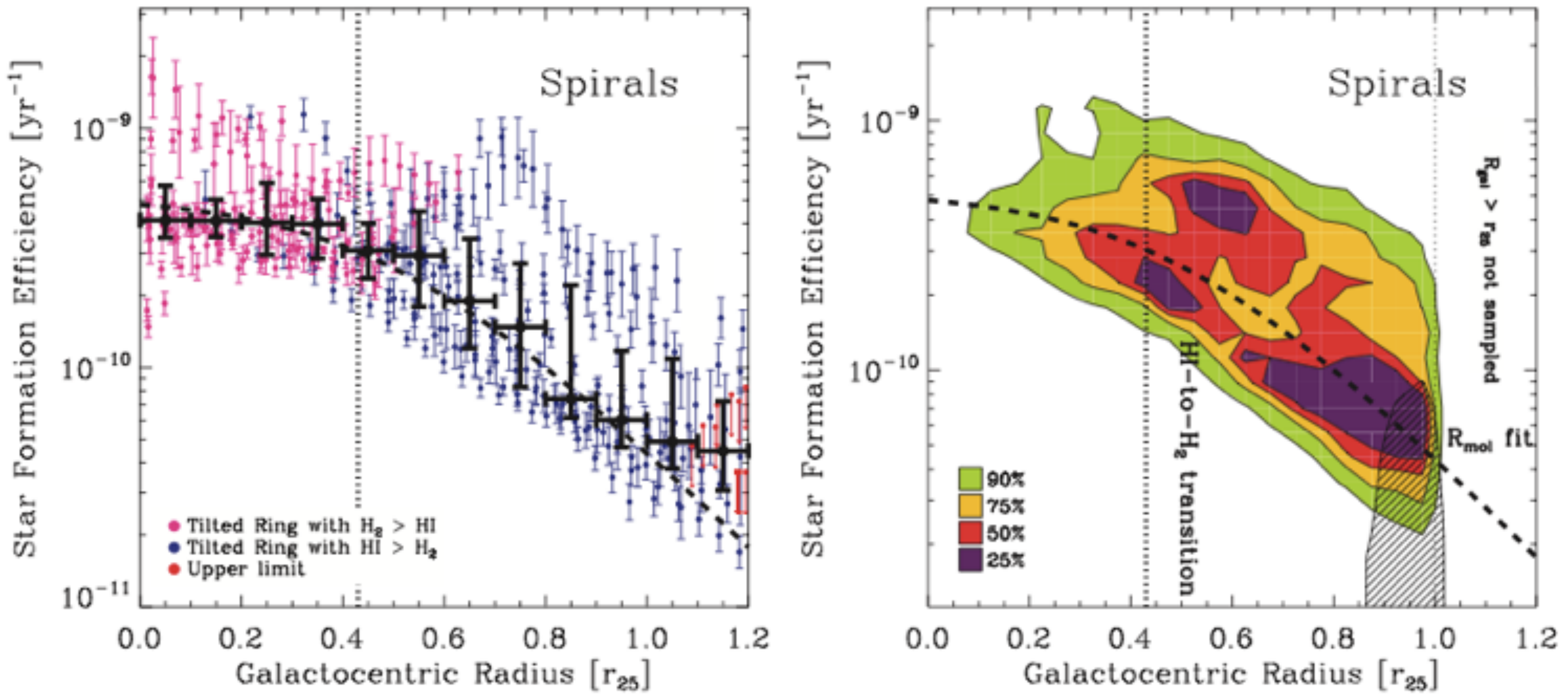

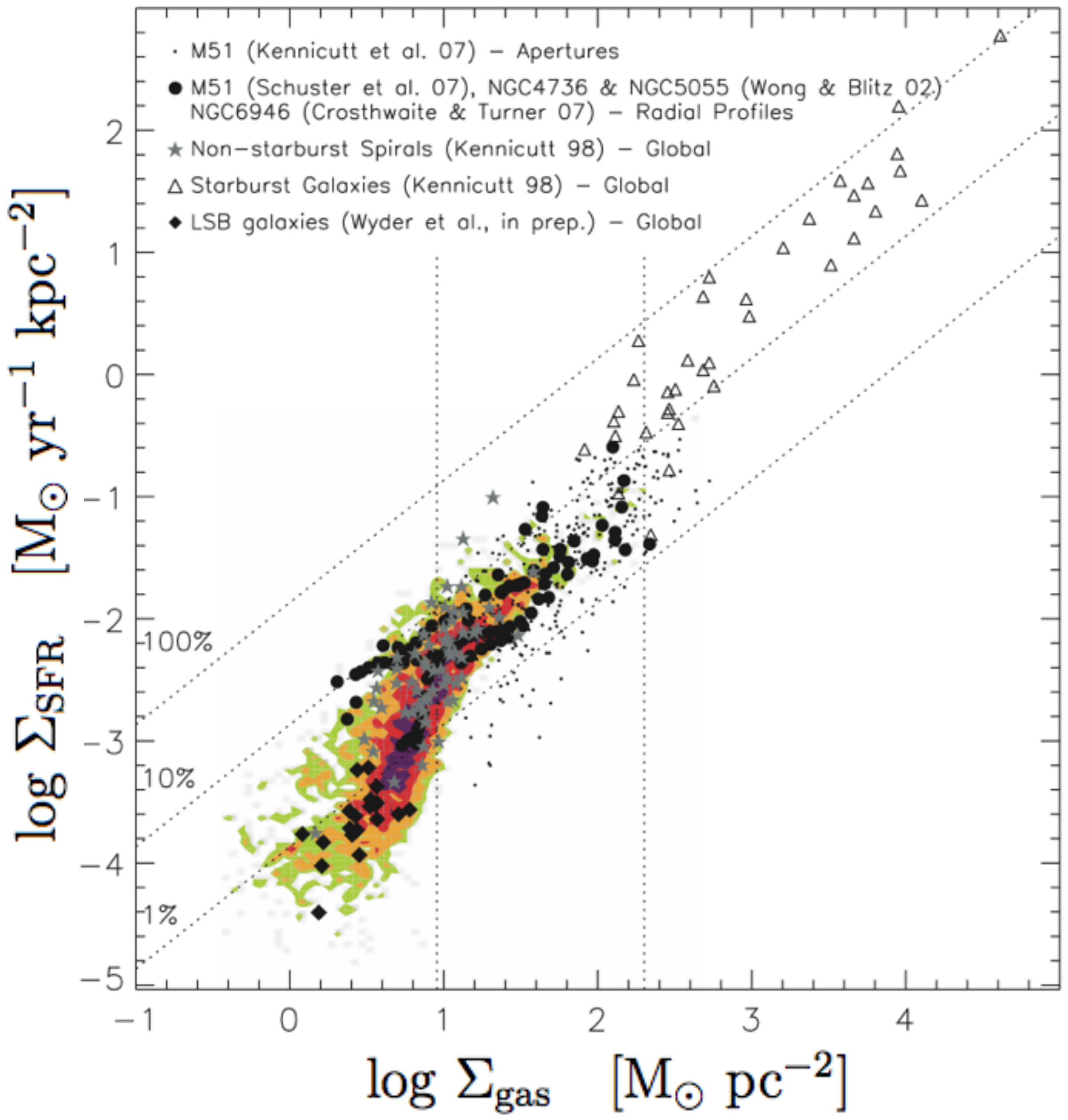

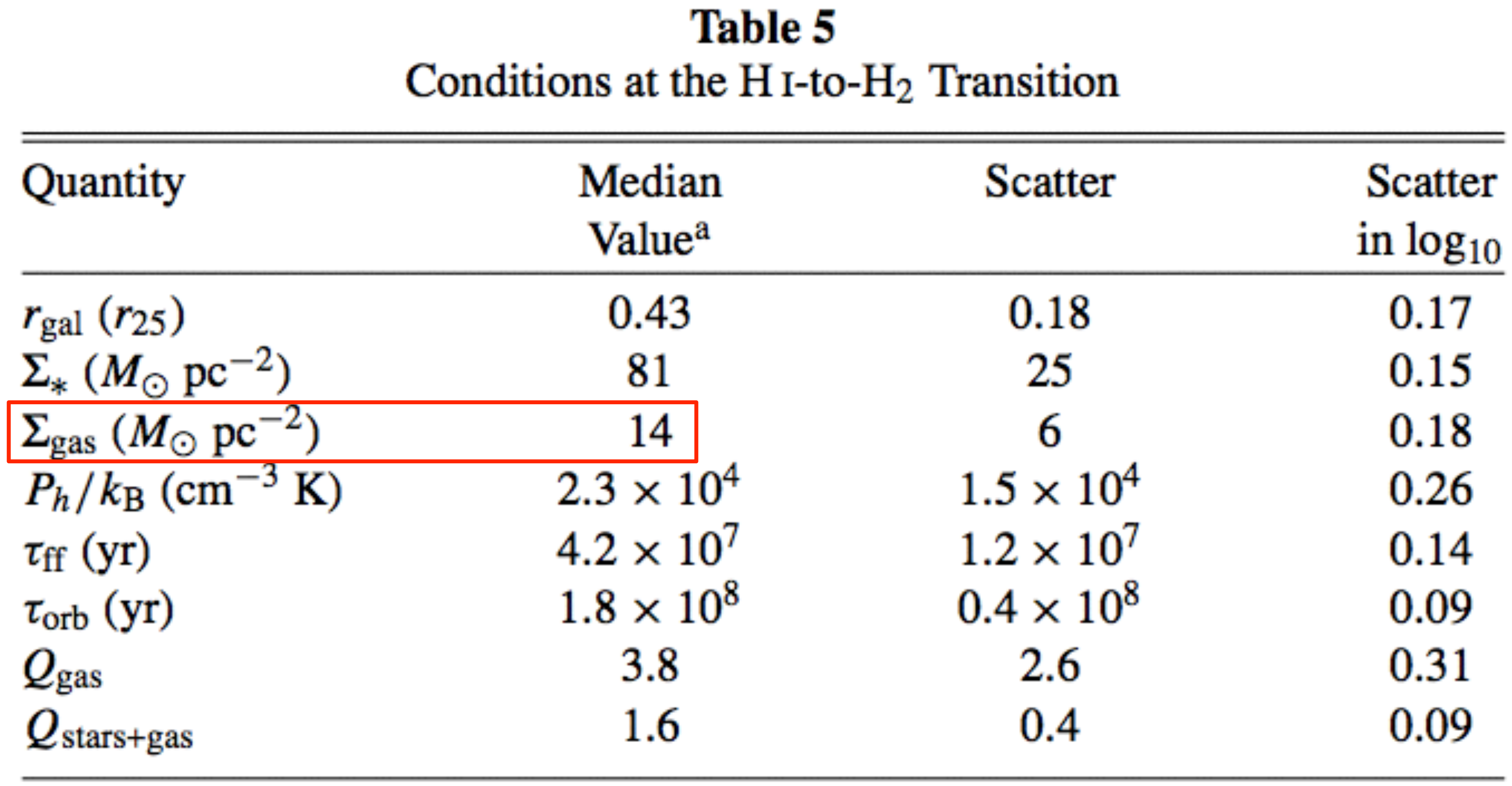

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Caveat: This interpretation requires typically "one" primary cloud per line-of-sight.

To Conclude:

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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