Observational and Theoretical Review of the Multiphase ISM

Motte et al. 2010
Rosette

Observational and Theoretical Review of the Multiphase ISM

So, it works in Practice…but does it work in Theory?

So, it works in Theory….so What?

1)Galactic Diffuse Phases

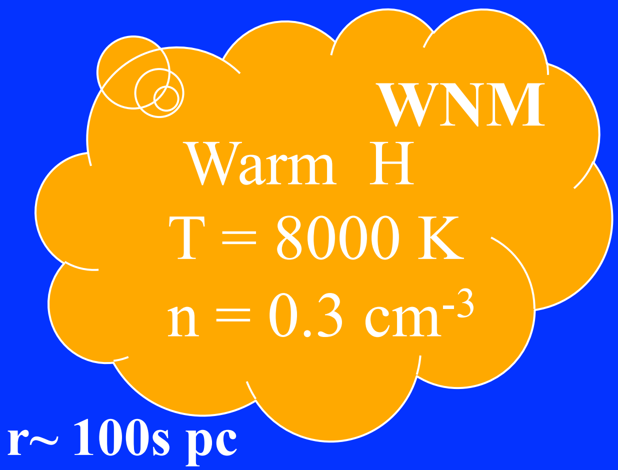
2)Extragalactic Diffuse Phases

3)Tracers of Dark Molecular Gas

4)OVI !!

Motte et al. 2010
Rosette

PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry



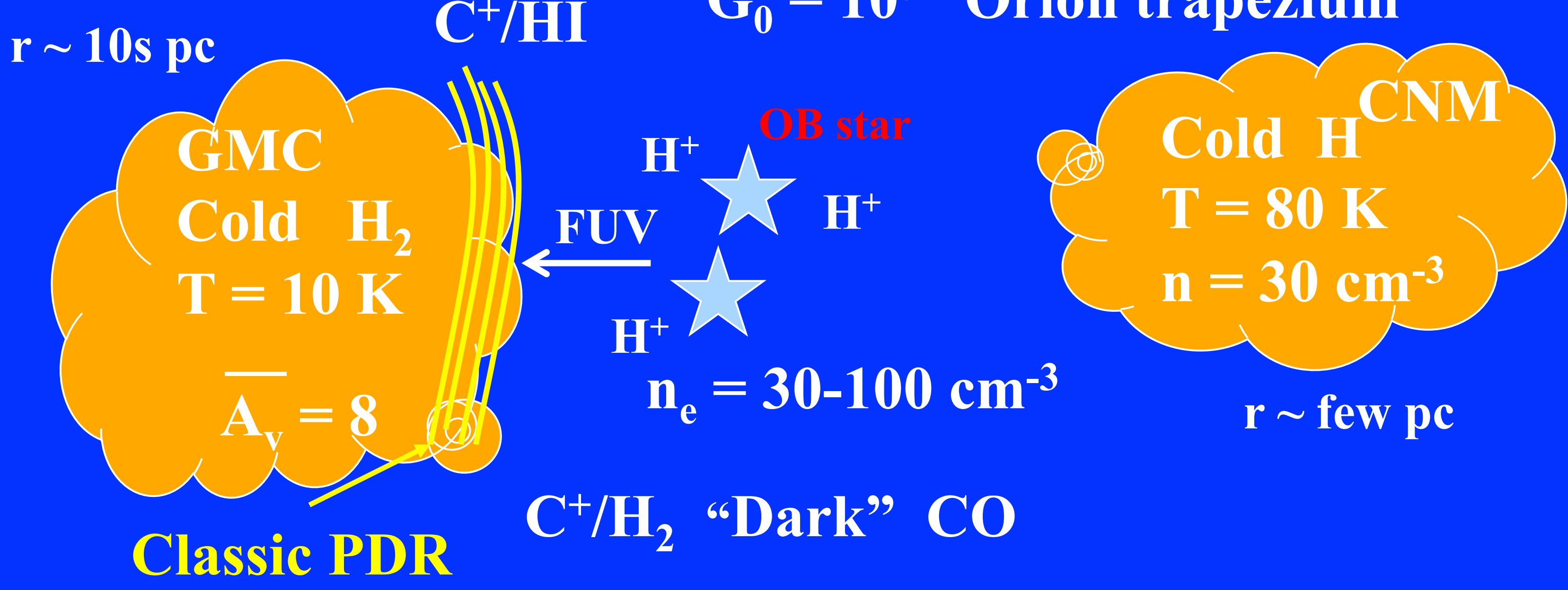
FUV: 6 eV – 13.6 eV

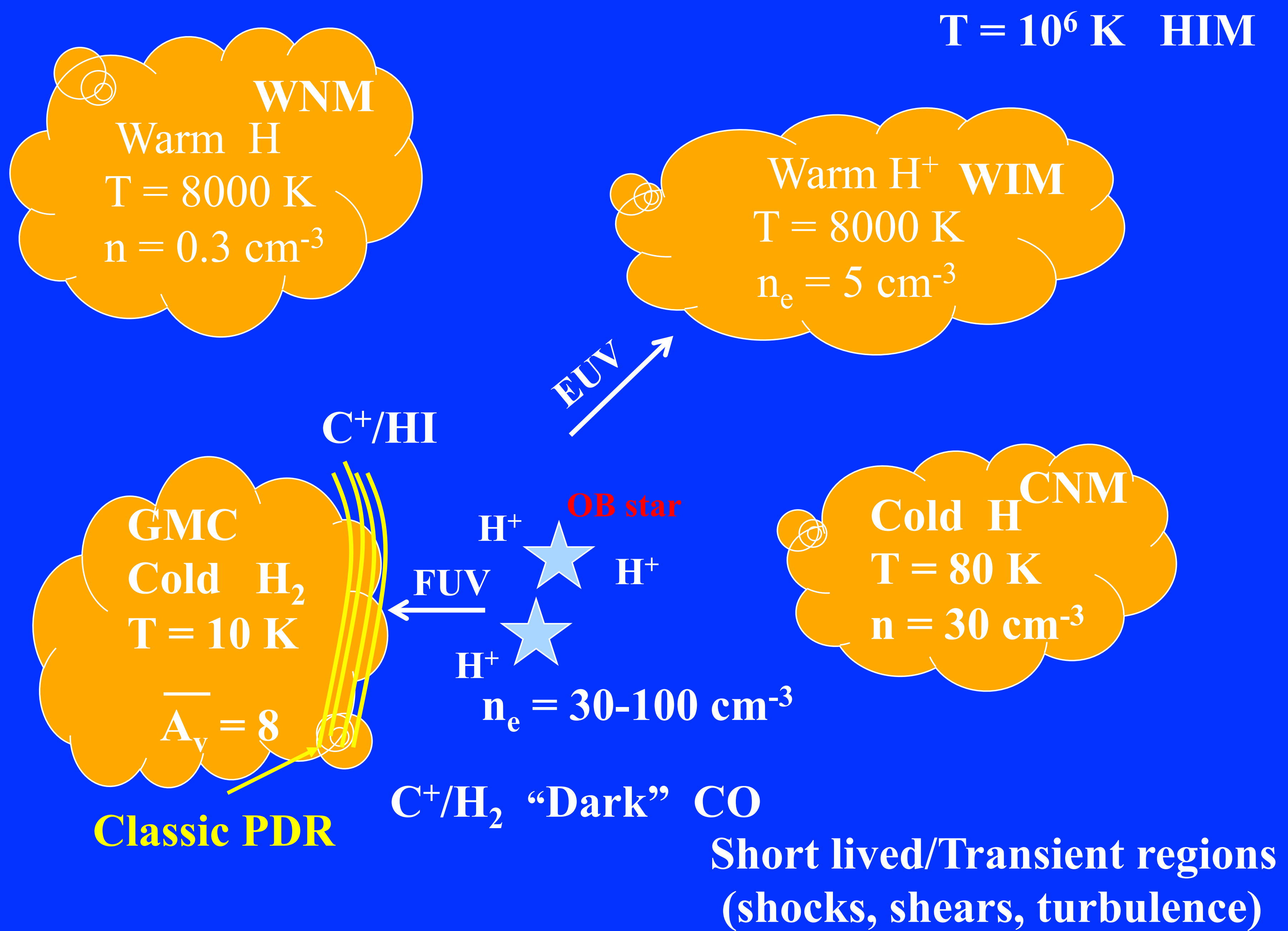
G_0 = 1 Interstellar field

G_0: Habing χ:Draine ~1.7 G_0

U: Mathis ~ 1.1G_0

$G_0 = 10^5$ Orion trapezium



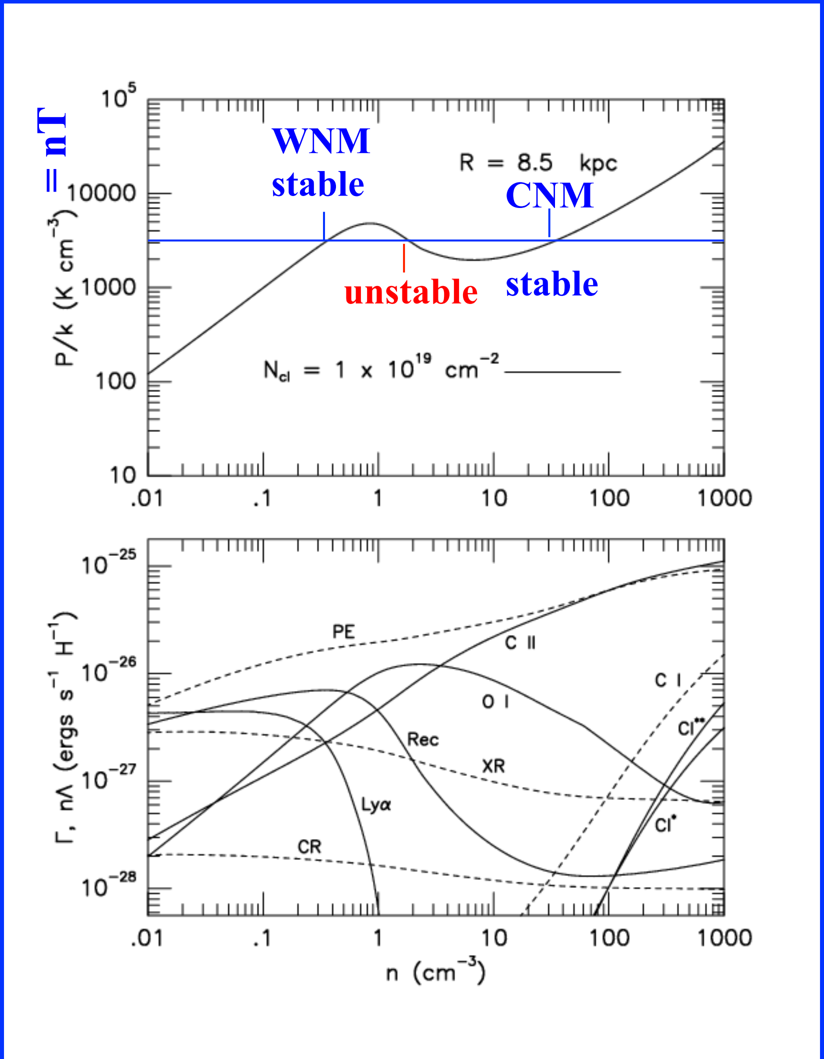


T = 10^6 K HIM
WNM
Warm H
T = 8000 K
n = 0.3 cm^-3
Warm H+ WIM
T = 8000 K
ne = 5 cm^-3
EUV
C+/HI
OB star
H+
H+
H+
FUV
GMC
Cold H2
T = 10 K
Av = 8
CNM
Cold H
T = 80 K
n = 30 cm^-3
ne = 30-100 cm^-3
C+/H2 “Dark” CO
Classic PDR
Short lived/Transient regions
(shocks, shears, turbulence)

Diffuse Gas Heating/Cooling

T = 7860 n = 0.35 cm^{-3} WNM

T = 85 n = 33 cm^{-3} CNM



Wolfire et al. (2003)

Diffuse Gas Heating/Cooling

T = 7860 n = 0.35 cm^{-3} WNM

T = 85   n = 33 cm^{-3} CNM

C II Cooling/H (CNM) >
20 CII Cooling/H (WNM)

** Note **

CNM in Thermal Balance:
[CII] measures the total energy dumped into the gas.

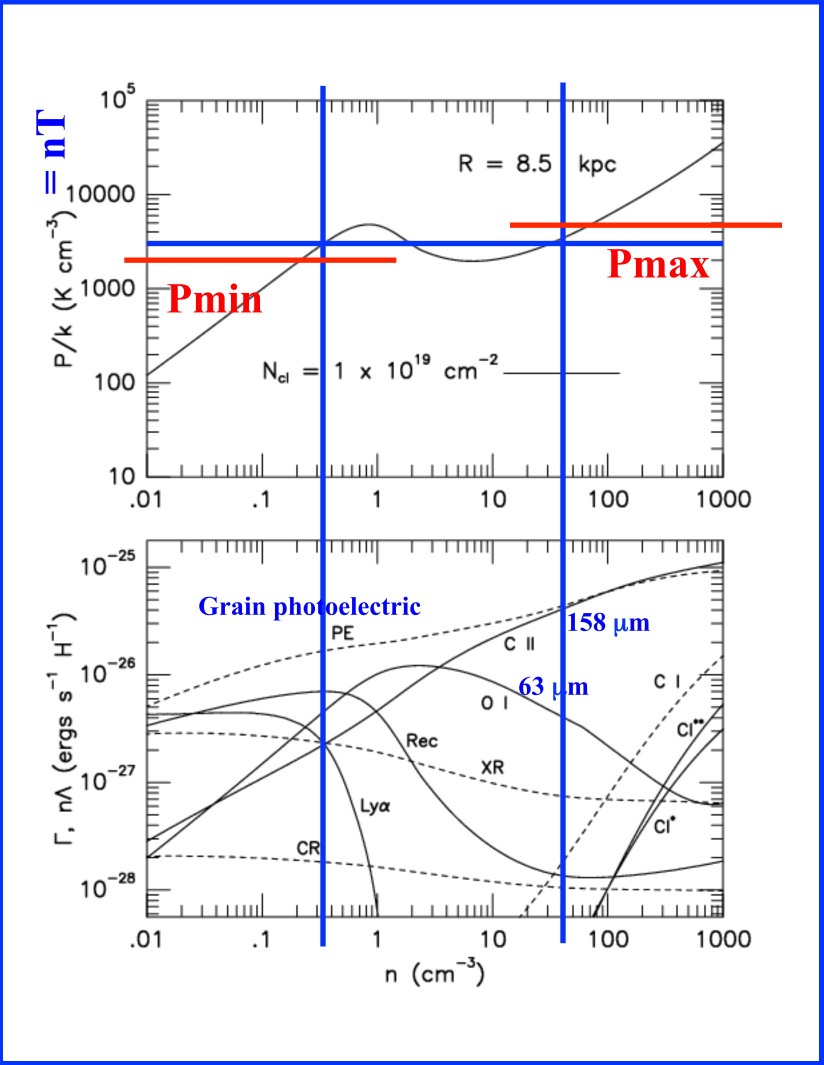
$I_{[CII]}$ prop to heating

Heating rate = const

n ↓   Z ↓

T ↑

$I_{[CII]}$ = const



Wolfire et al. (2003)

C.R. ionization x 10

Indriolo et al. 2012, 2015

H_3^+, OH^+, H_2O^+, H_3O^+

Thermal Pressure

Jenkins et al. 2011

C II Cooling/H (CNM) > 10 CII Cooling/H (WNM)

**** Note ****

CNM in Thermal Balance: [CII] measures the total energy dumped into the gas.

$I_{[CII]}$ prop to heating

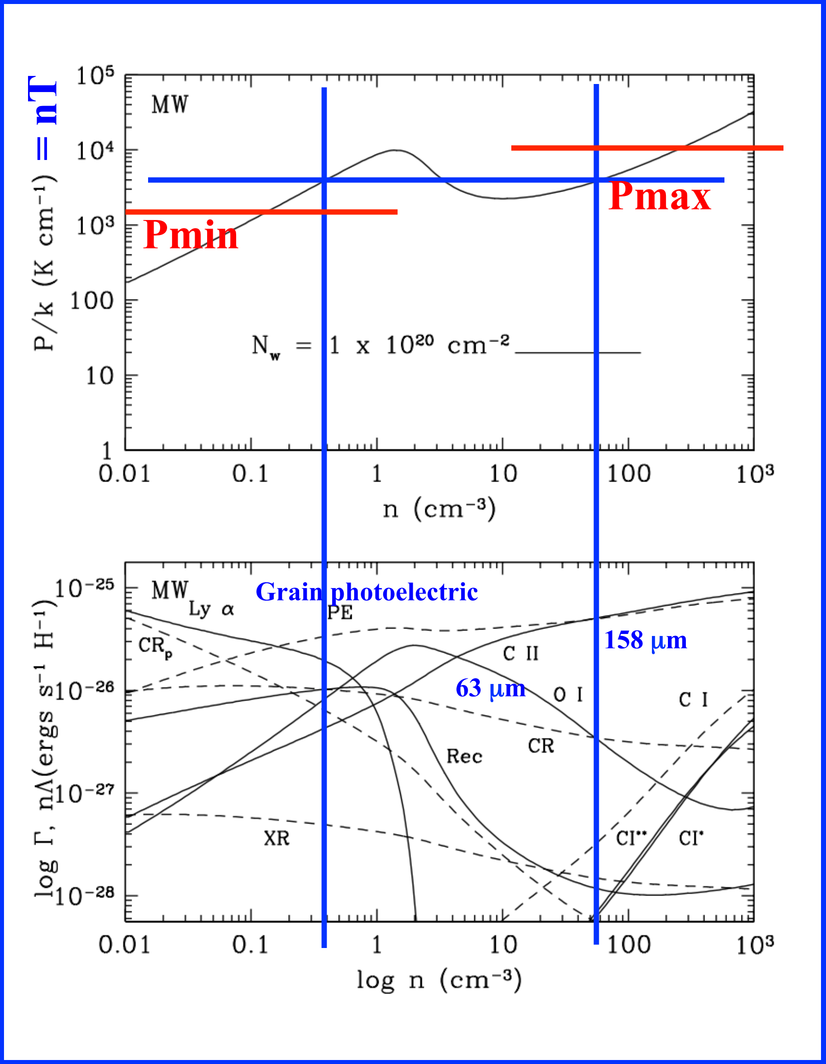
Heating rate = const

n ↓ Z ↓

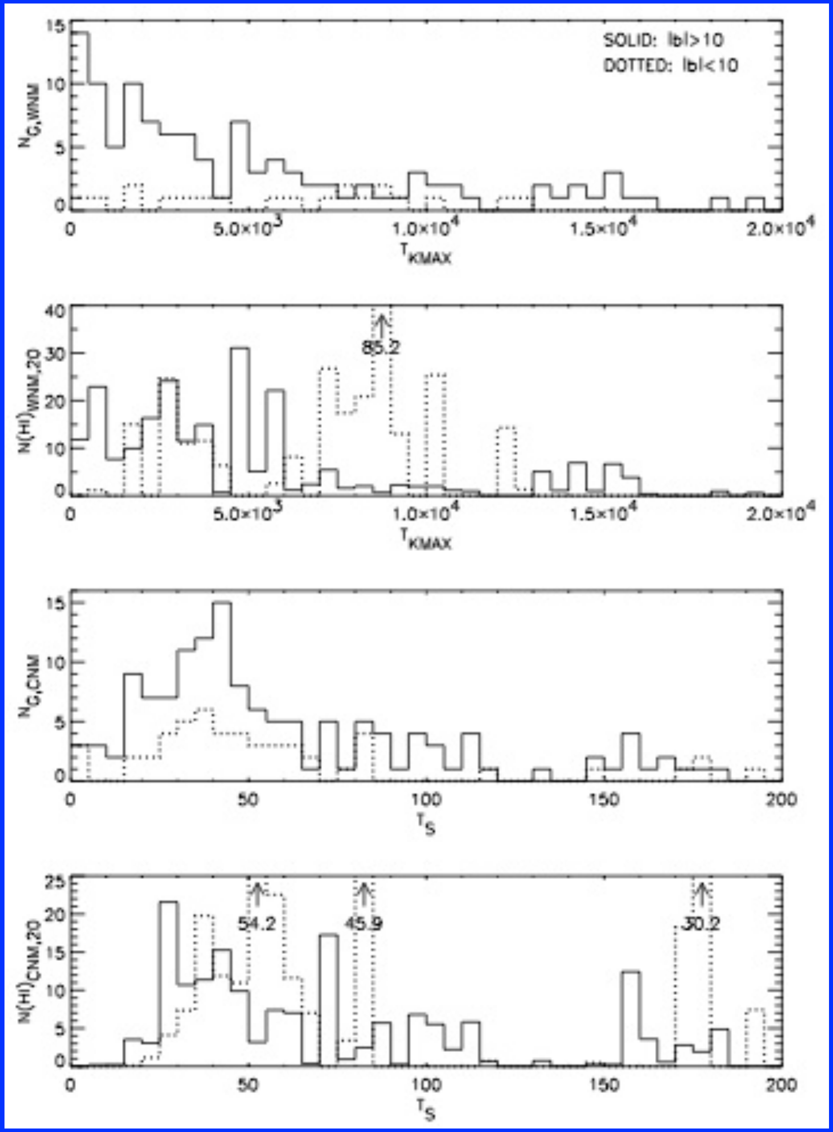
T ↑

$I_{[CII]}$ = const

Diffuse Gas Heating/Cooling



Wolfire et al. (2016)



Heiles & Troland 2003, ApJ, 586, 1067
Begum et al. 2010

WNM temperature distribution

50% of gas mass in unstable Ts ???

Locally: 60% WNM, 40% CNM
(also Pineda et al. 2013)

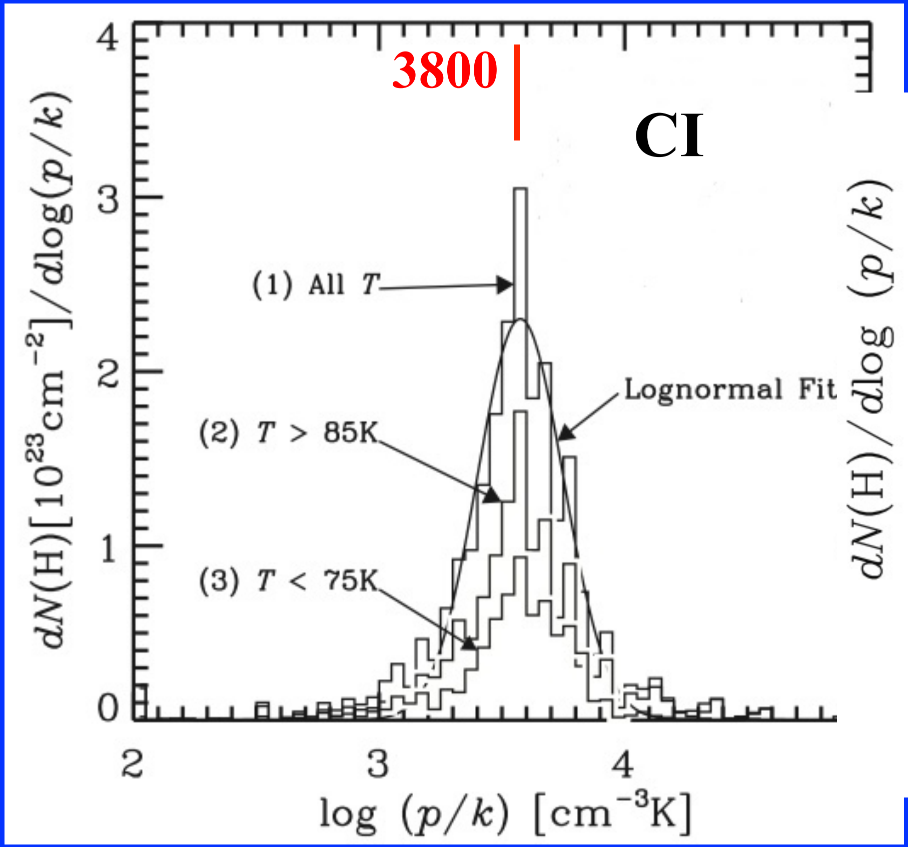
In plane 25% of WNM in unstable Ts
or 15% of total mass.

Out of plane dominated
by dynamical processes.

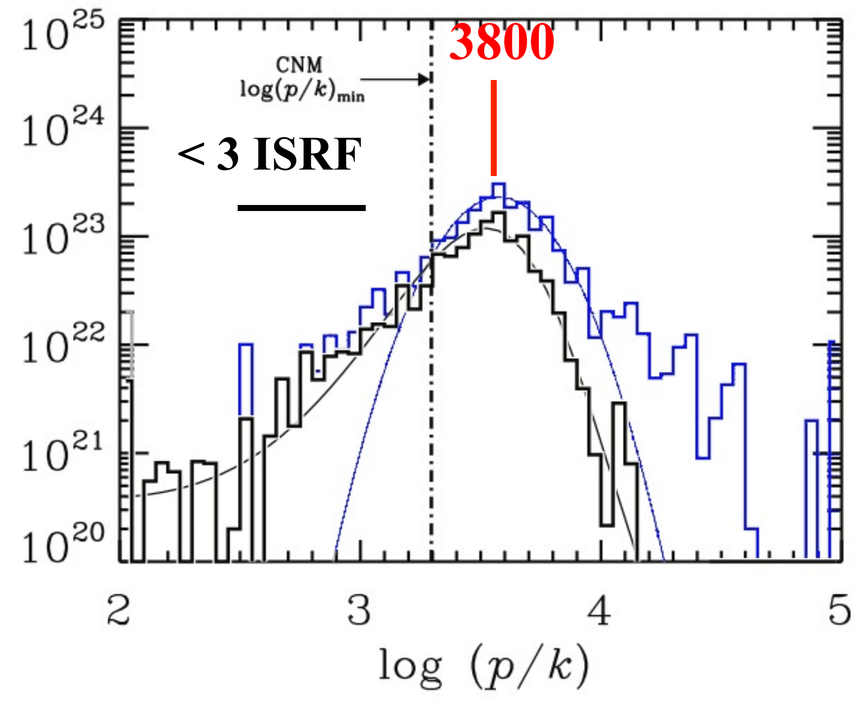
In plane uncertainties large, and
statistics poor: 8 in plane, 79 out

Murray, Stanimirovic et al. 2015
21-SPONGE Survey
Find only 20% (by number) thermally
unstable components !!

Thermal Pressure in CNM

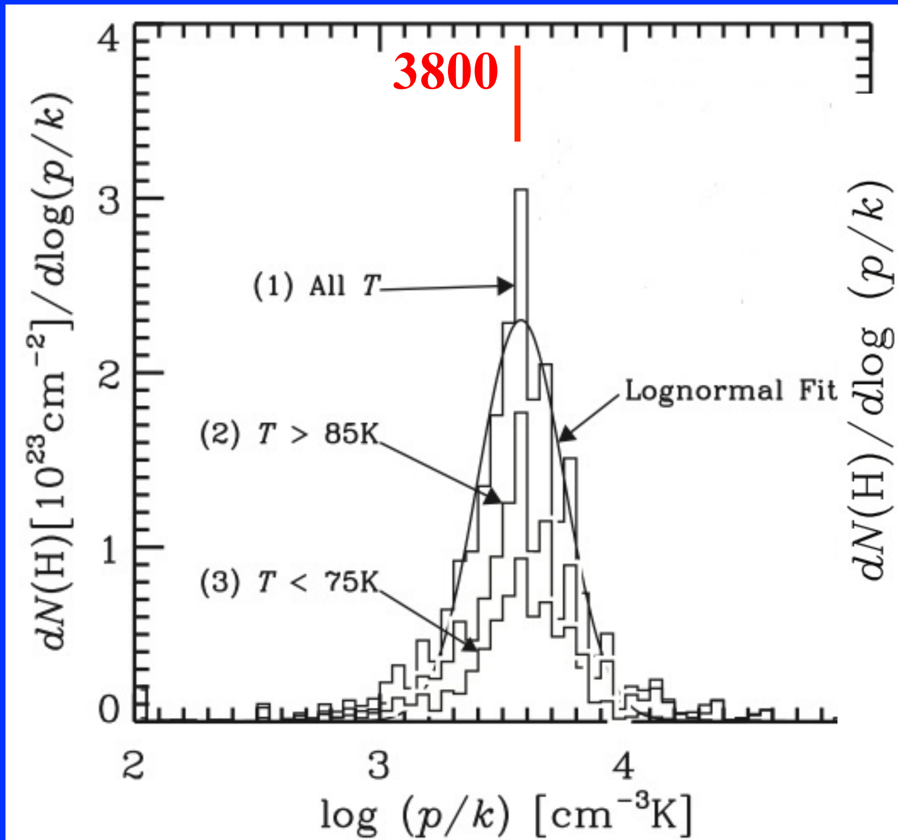


Jenkins & Tripp 2011

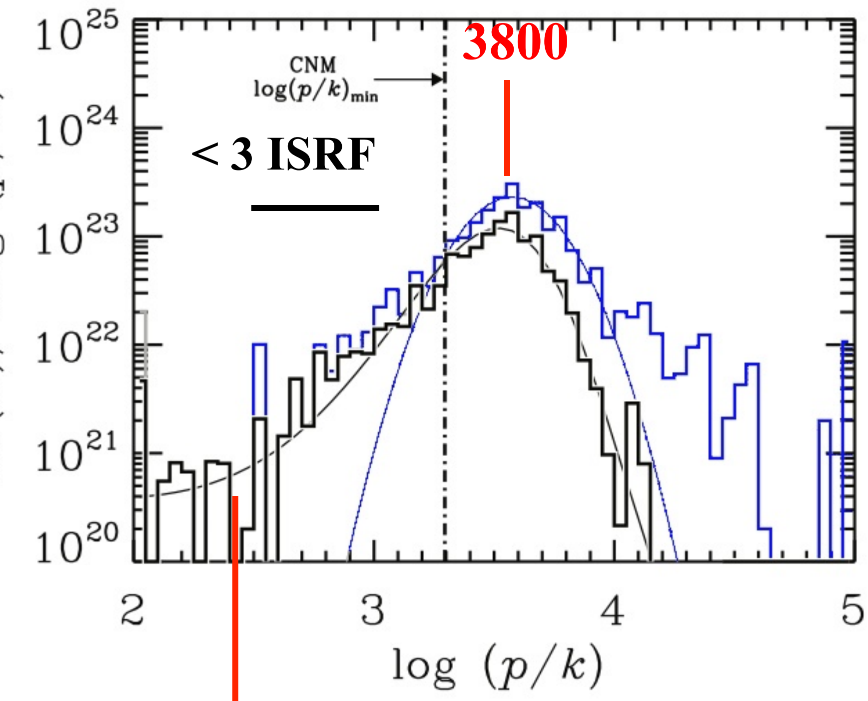


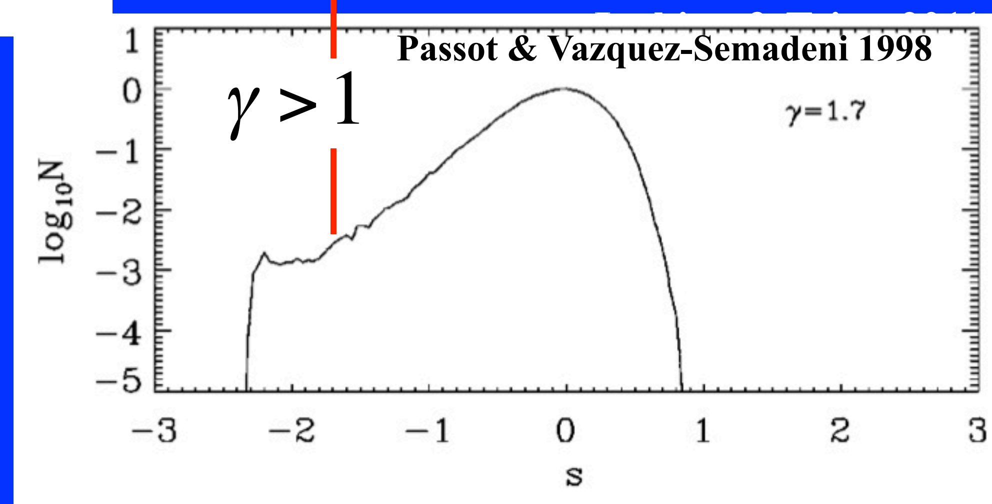
Jenkins & Tripp 2011

Thermal Pressure in CNM



Jenkins & Tripp 2011



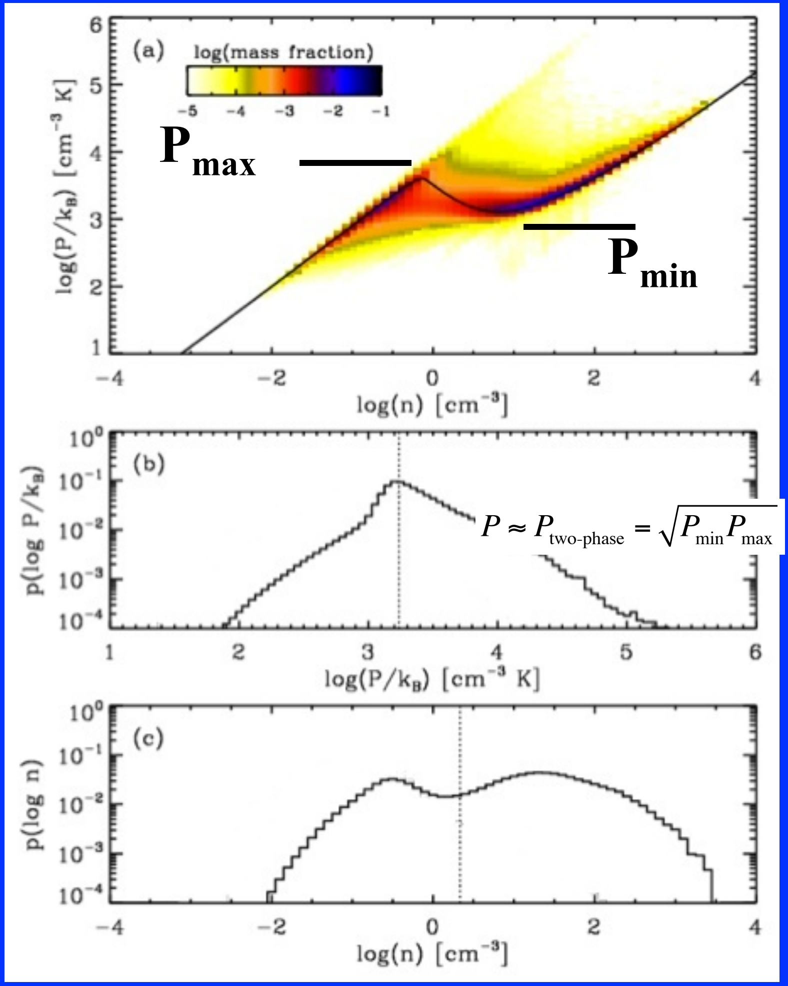


$\Delta t = r / \Delta \mathrm{v}$

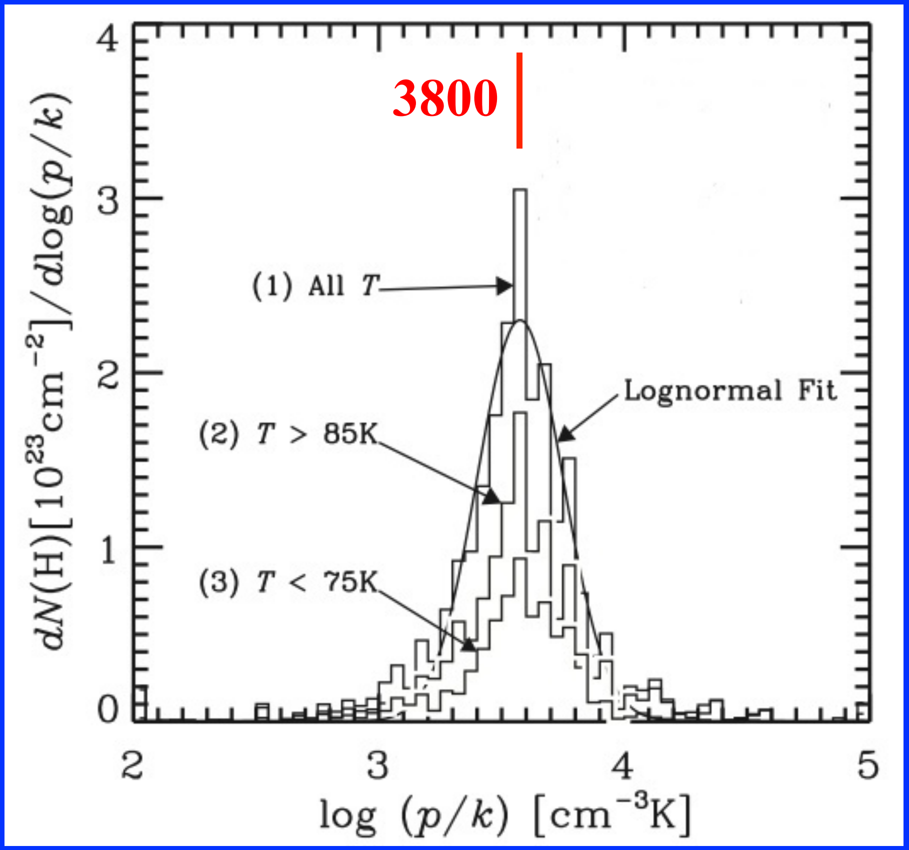
r < 1000 AU

$\Delta t < t_{cool} \quad \gamma > 1$

Multiphase Galactic Disks



Thermal Pressure in CNM



Jenkins & Tripp 2011

Kim, Kim, & Ostriker 2011; Kim, Ostriker, & Kim 2013

Kim, Chang-Goo, & Ostriker 2015; Walch et al. 2015

Regulation of Thermal Pressure

$$P_{\text{tot}} \propto \Sigma^2_{(\text{WNM})\ \text{gas}}$$

$$P_{\text{th}} = \alpha P_{\text{tot}}$$

$$\alpha \approx 10\% - 20\%$$

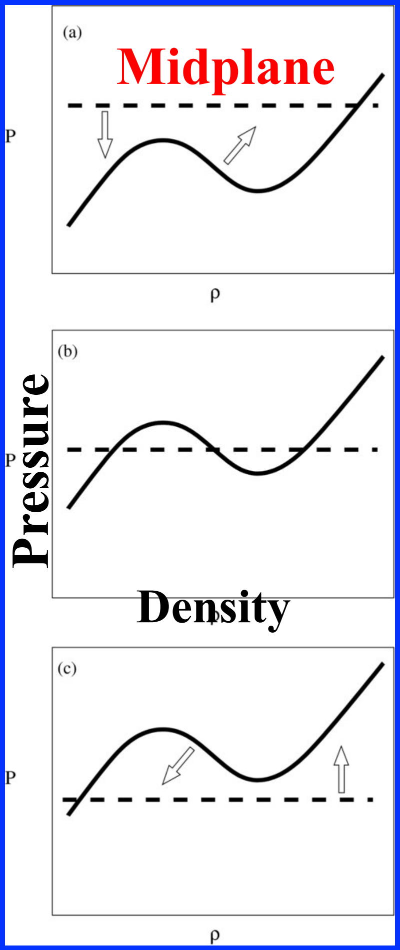
CNM / WNM are PDRs (heated by FUV)

More CNM leads to more star formation (FUV)

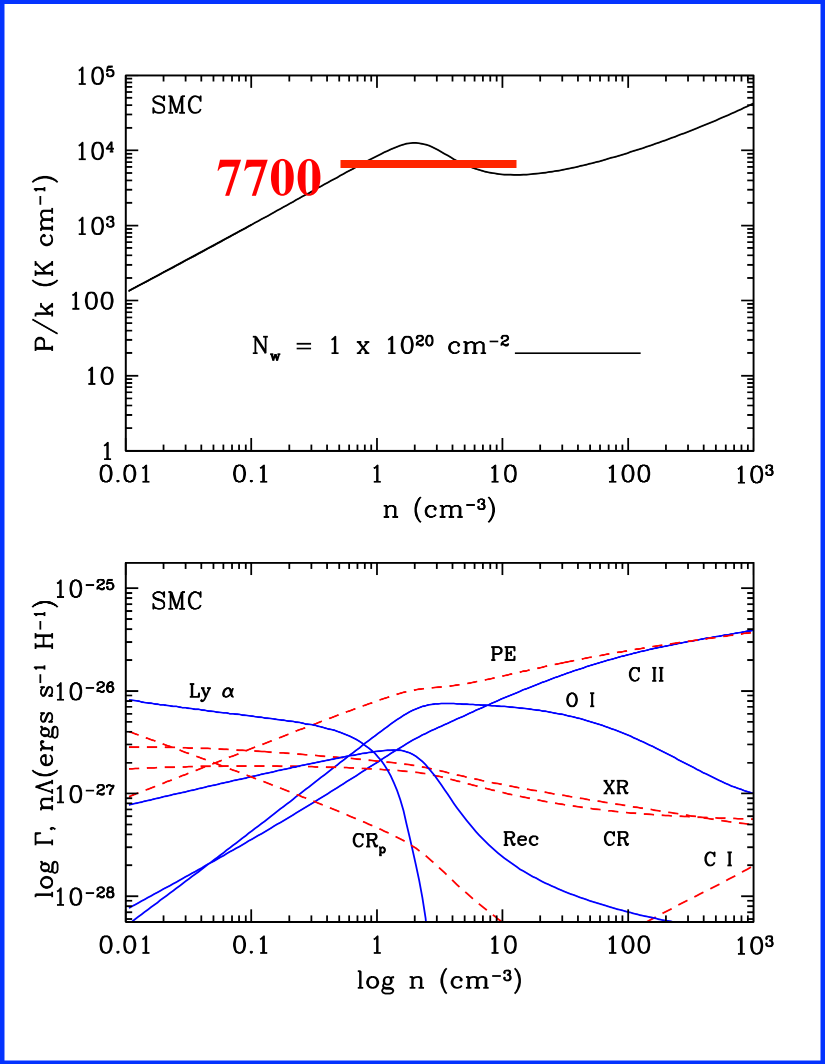
Too Warm

Just Right

Too Cold



Ostriker, McKee, & Leroy 2010



Wolfire, McKee, Bolatto, Ostriker 2016

SMC Bar Parameters

C/n : 1/5 MW

Dufour (1984),Welty (2016)

PAH/n: 1/7.7 MW

Sandstrom et al. 2010

G_0: 5 MW

Sandstrom et al. 2010

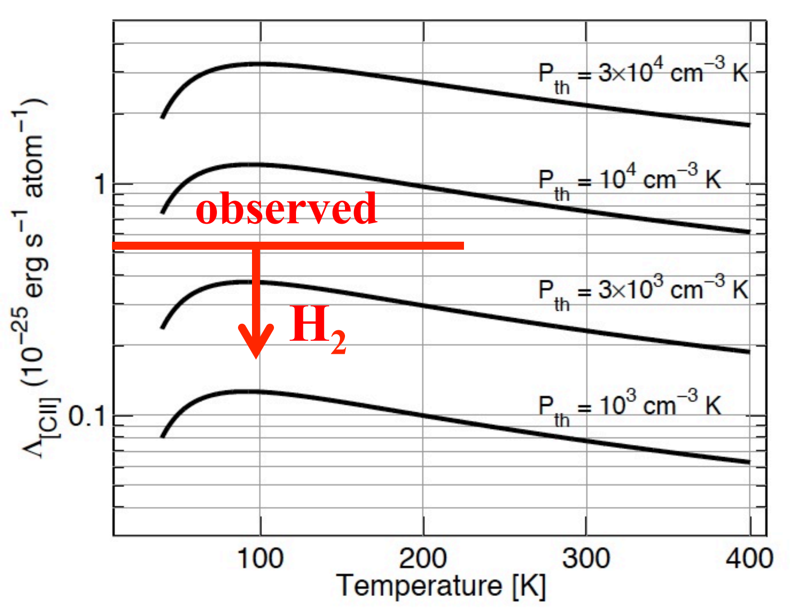
CR: 15% MW

Abdo et al. 2010

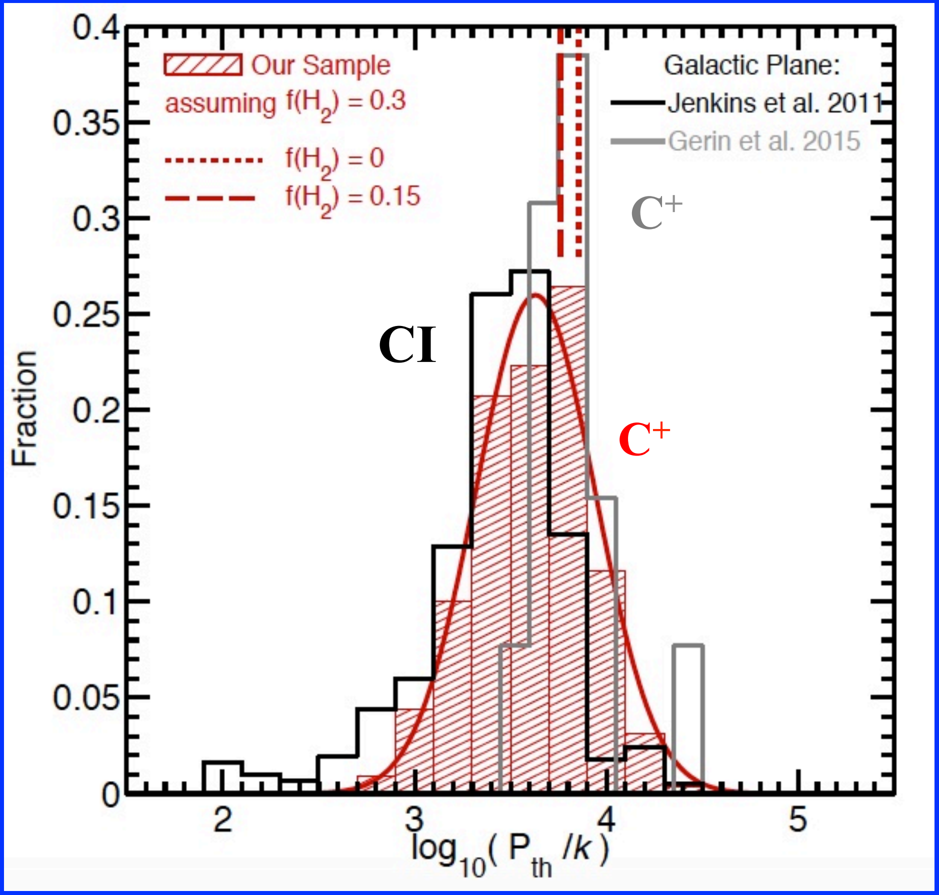
$P_{th}/k < 2$ x Local Galactic

KINGFISH Regions

$\Sigma(H_2)/\Sigma(HI) < 1$ $U < 3$



Heiles 1985

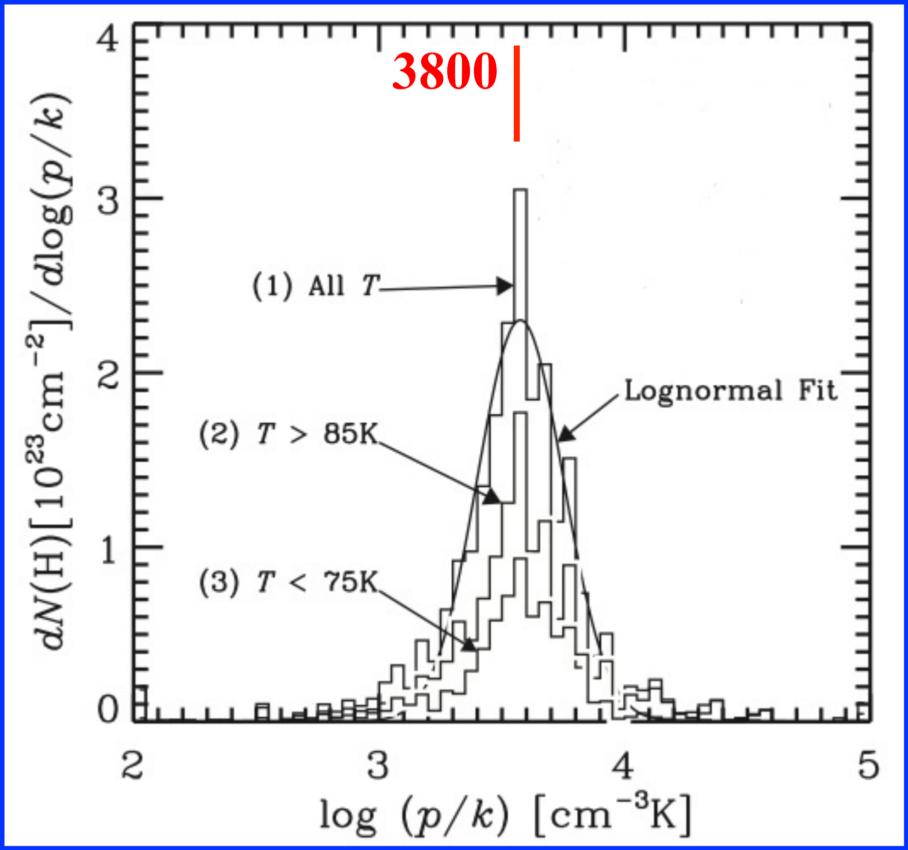


Herrera-Camus, Bolatto, Wolfire et al. 2016

P(CII) about same as P(CI)

P(CII) regions like local Galactic

P(CII) as expected from OML 2010



Jenkins & Tripp 2011

Small Scale Structure Turbulent Dissipation in CNM

1)Warm diffuse cloud chemistry: CH^+, HCO^+, CO, SH
Godard et al. 2014, Falgarone et al. 2010
Myers et al. 2015, Neufeld et al. 2015

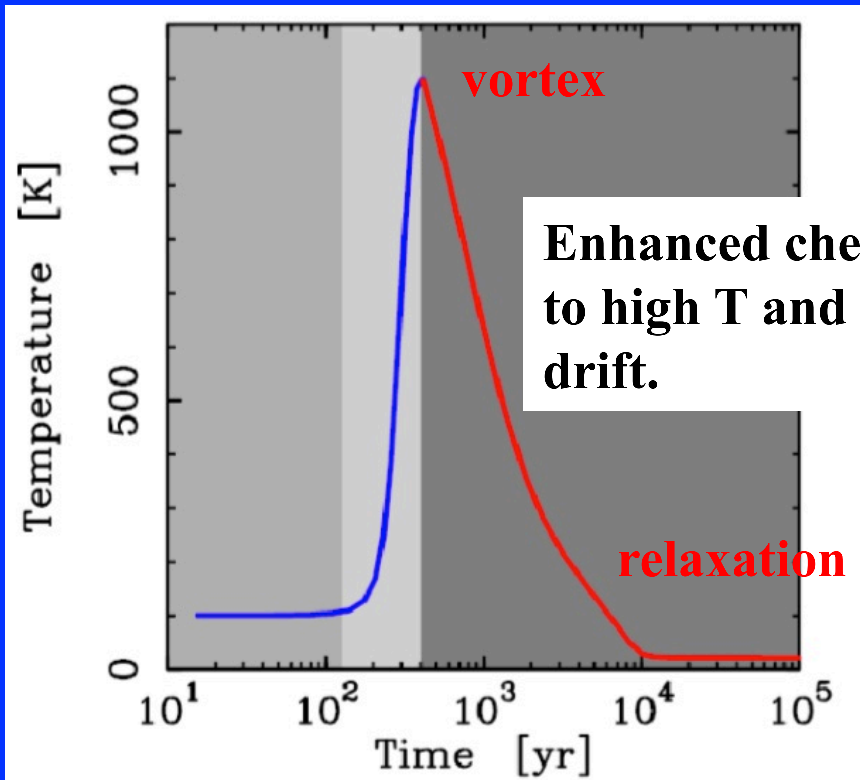
2)Tiny-Scale Atomic Structure (TSAS): HI absorption 10s AU
Heiles 1997, Stanimirovic et al. 2010
(TSIS), (TSMS)

3)Warm diffuse H_2 seen in emission
Falgarone et al. 2005, Habart et al. 2011, Valdivia et al. 2016, Le Petit et al. 2016

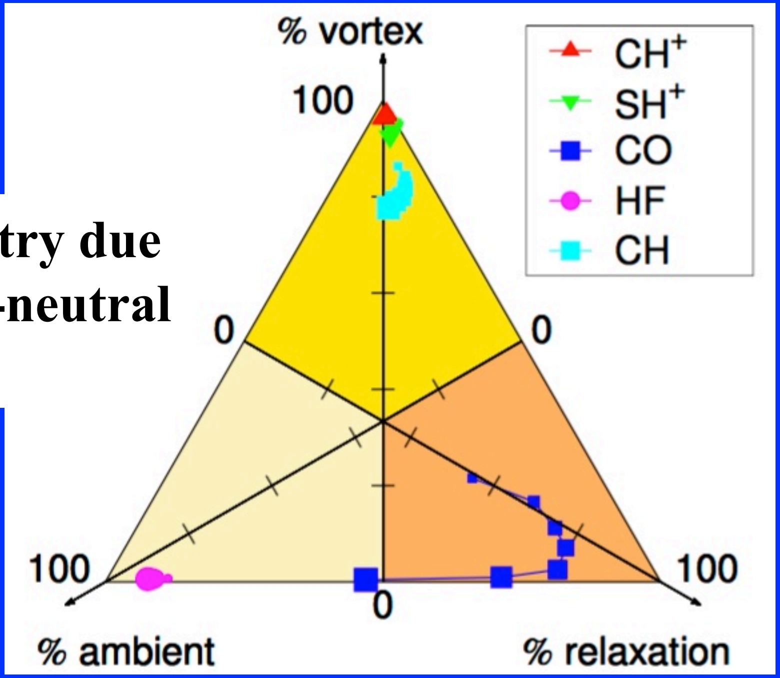
Log normal fit + 0.05% $3x10^5$ K cm^{-3}

Small Scale Structure (Continued)
Turbulent Dissipation in CNM

100 AU TDRs



Enhanced chemistry due to high T and ion-neutral drift.



Godard et al. 2015, Myers et al. 2015

MHD shocks: Pineau des Forêts et al 1986
Shears: Joulain et al. 1998

Diffuse Cloud Chemistry
Dark Gas Tracers
HF, H_2O

Formation:

$$F + H_2 \rightarrow HF + H$$

Destruction:

$$HF + h\nu \rightarrow H + F$$

$$HF + C^+ \rightarrow CF^+ + H$$

$$HF + He^+ \rightarrow H + F^+ + He$$

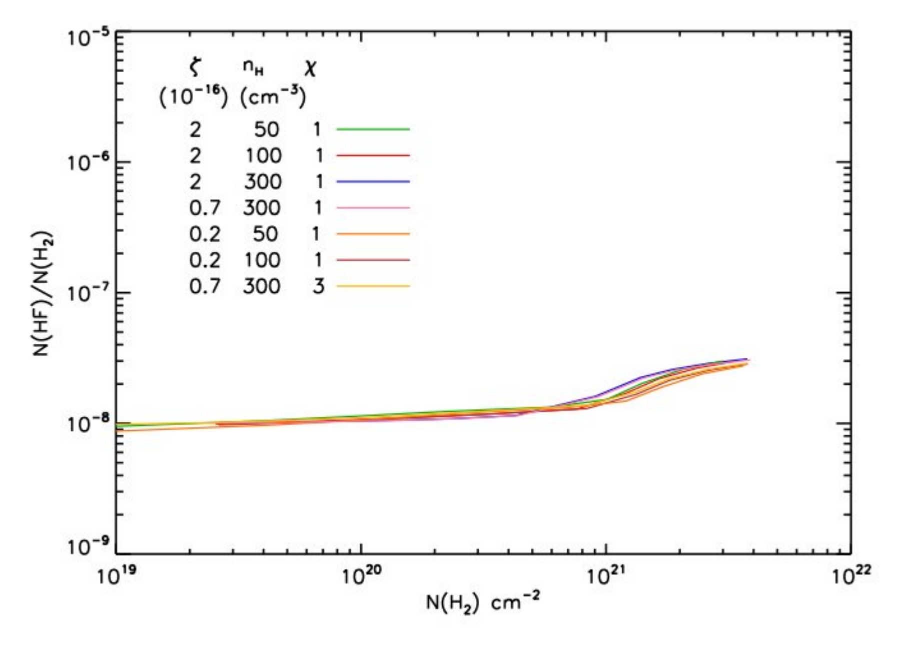
$$HF + Si^+ \rightarrow SiF^+ + H$$

Neufeld, Wolfire & Schilke 2005

Neufeld & Wolfire 2009

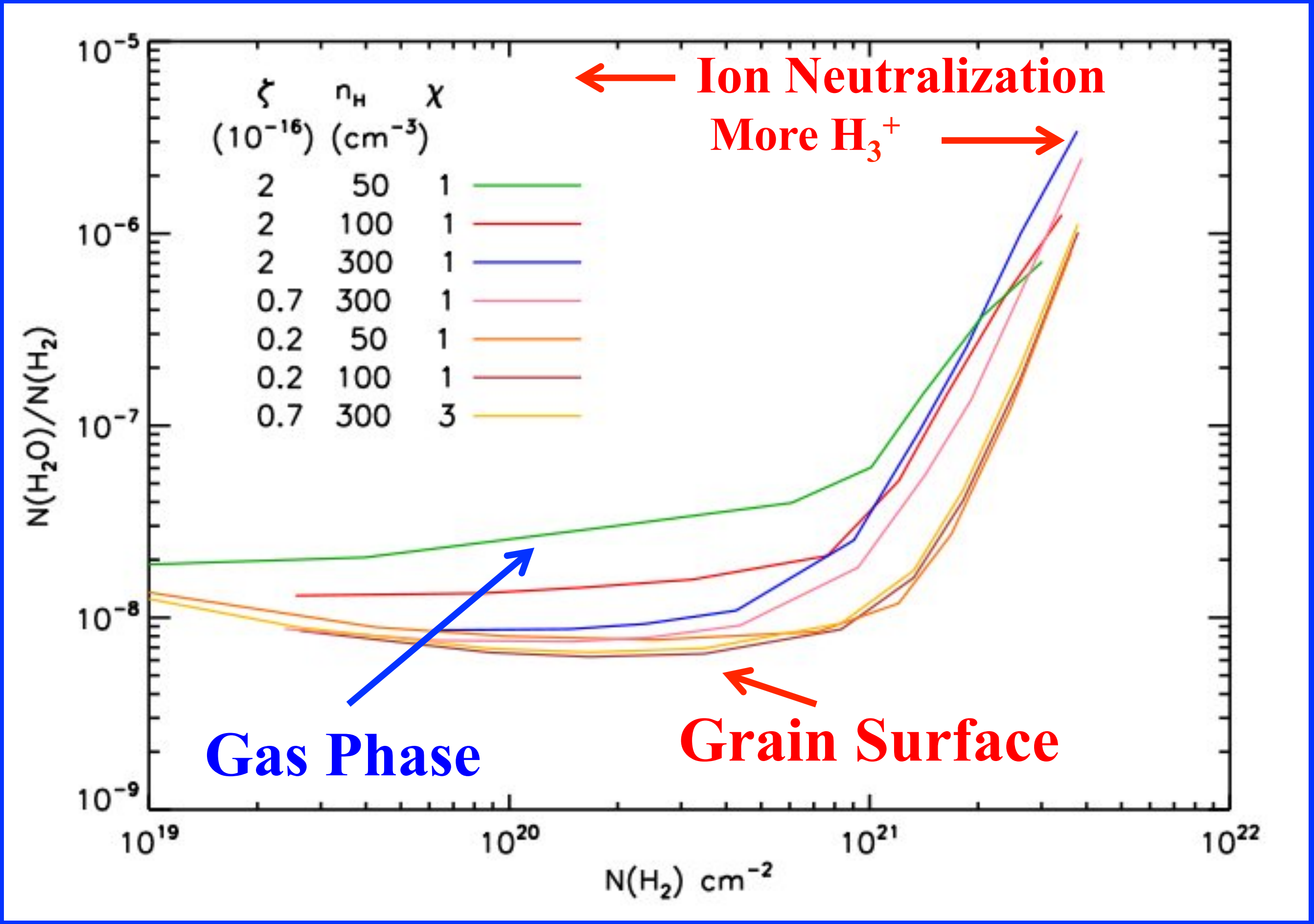
2- Sided PDR model

Variable total column density A_v



Sonnentrucker, Wolfire et al. 2015

2- Sided PDR model
Variable total column density A_v



Sonnentrucker , Wolfire, et al. 2015
Hollenbach et al. 2012

Argonium - ArH^+

Observed by PRISMAS and HEXOS but unidentified – Muller et al. 2013

Observed in emission in Crab Nebula identified as $^{36}ArH^+$ - Barlow et al. 2013

Formation:

$$Ar + CR \rightarrow Ar^+ + e$$

$$Ar^+ + H_2 \rightarrow ArH^+ + H$$

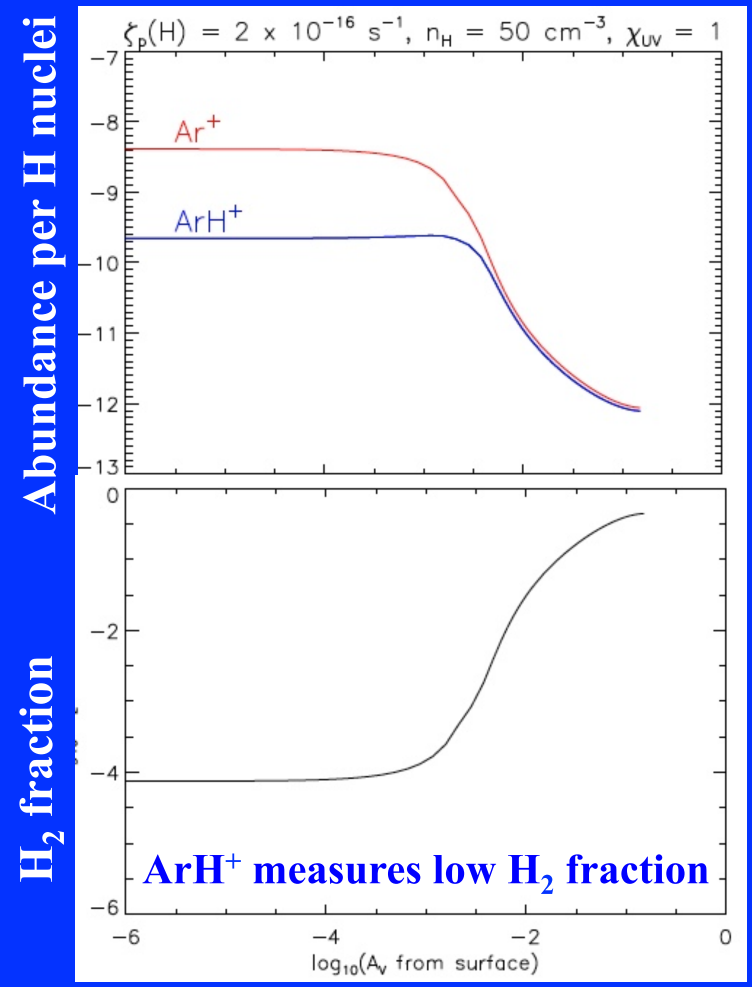
Destruction:

$$ArH^+ + O \rightarrow Ar + OH^+$$

$$ArH^+ + H_2 \rightarrow Ar + H_3^+$$

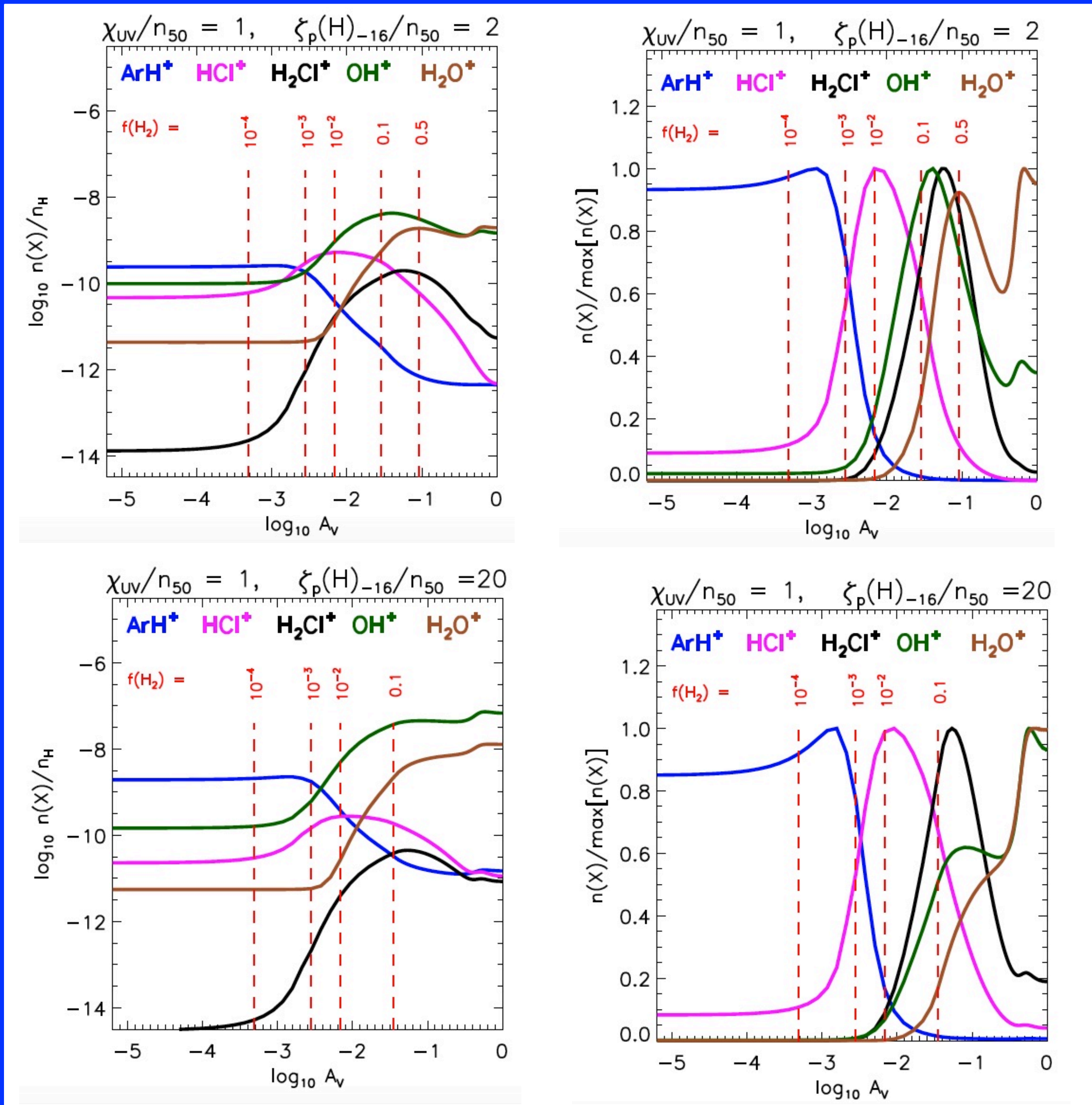
	ArH^+	OH^+/H_2O^+	HF
$f(H_2)$:	< 0.01	0.1	1

2- Sided PDR model
$A_v = 0.3$



Schilke et al. 2014

ArH^+, HCl^+, H_2Cl^+, OH^+, H_2O^+ Neufeld & Wolfire 2016



H_2O^+

H_2Cl^+

OH^+

HCl^+

ArH^+

$f(H_2)$

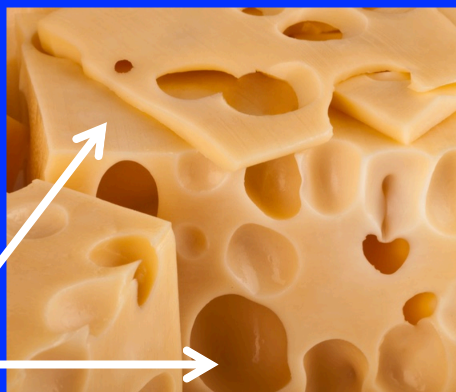
Increasing C.R. ionization rate

Phase Distribution Constraints from OVI

ISM Topology ?

WNM

HIM



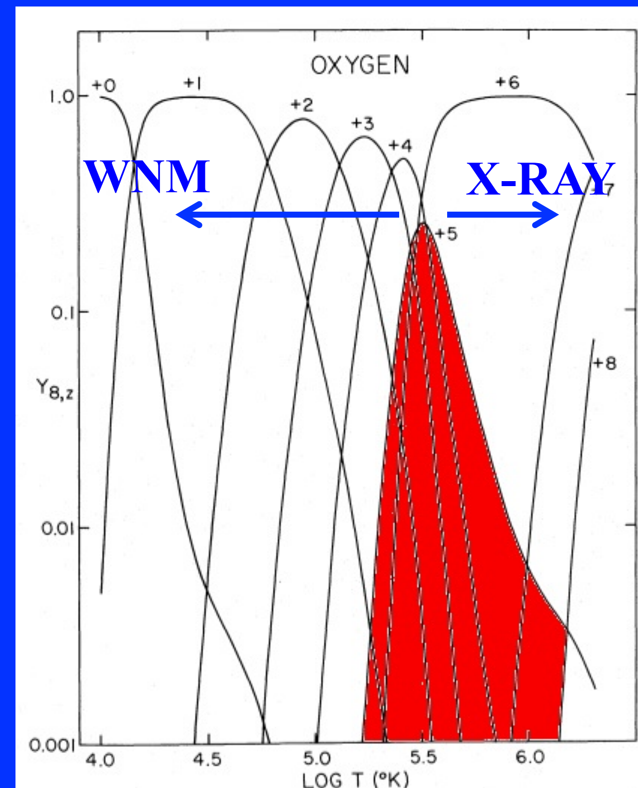
Cox

WNM

HIM

MO

N(OVI) from FUV absorption line of OVI



Conductive interfaces

Turbulent mixing layers

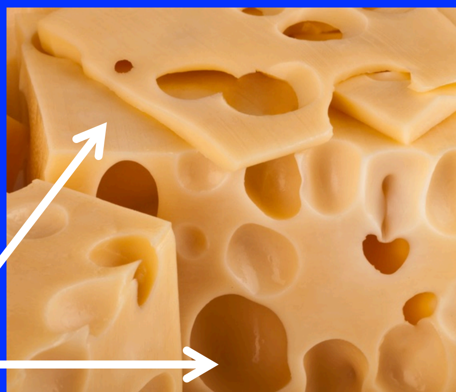
de Avillez & Breitschwerdt 2005

Phase Distribution Constraints from OVI

ISM Topology ?

WNM

HIM



Cox

WNM

HIM

MO

N(OVI) from FUV absorption line of OVI

n(OVI) only few 10^{-8} cm^{-3}
D. Cox numerous

WNM X-RAY

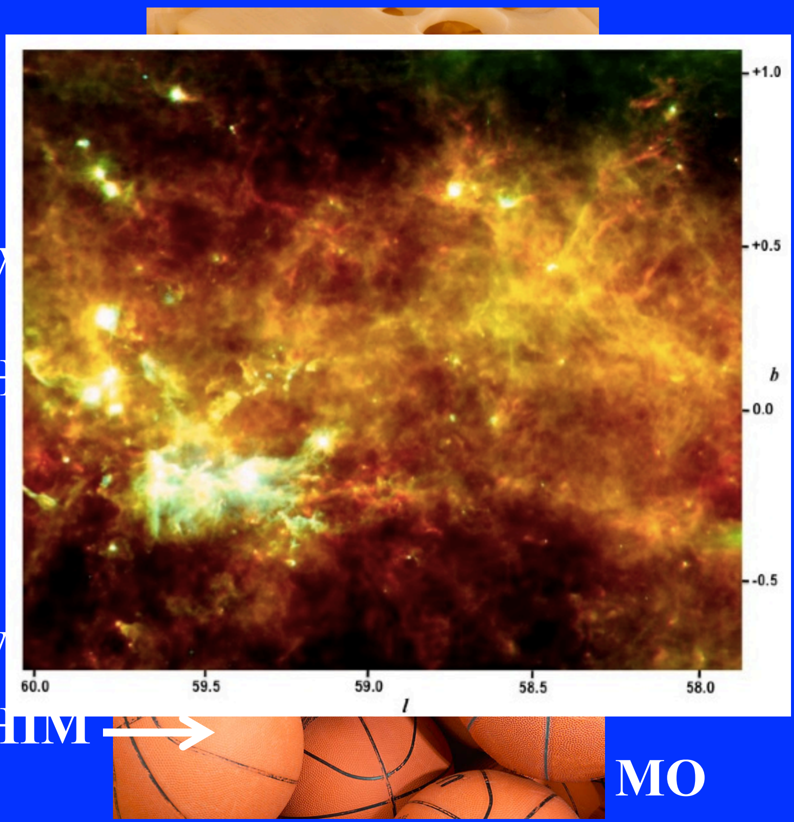
MO too much OVI
Slavin & Cox clouds in WNM reduces OVI

Phase Distribution Constraints from OVI

ISM Topology ?

W

H



W

HIM →

MO

N(OVI) from FUV absorption line of OVI

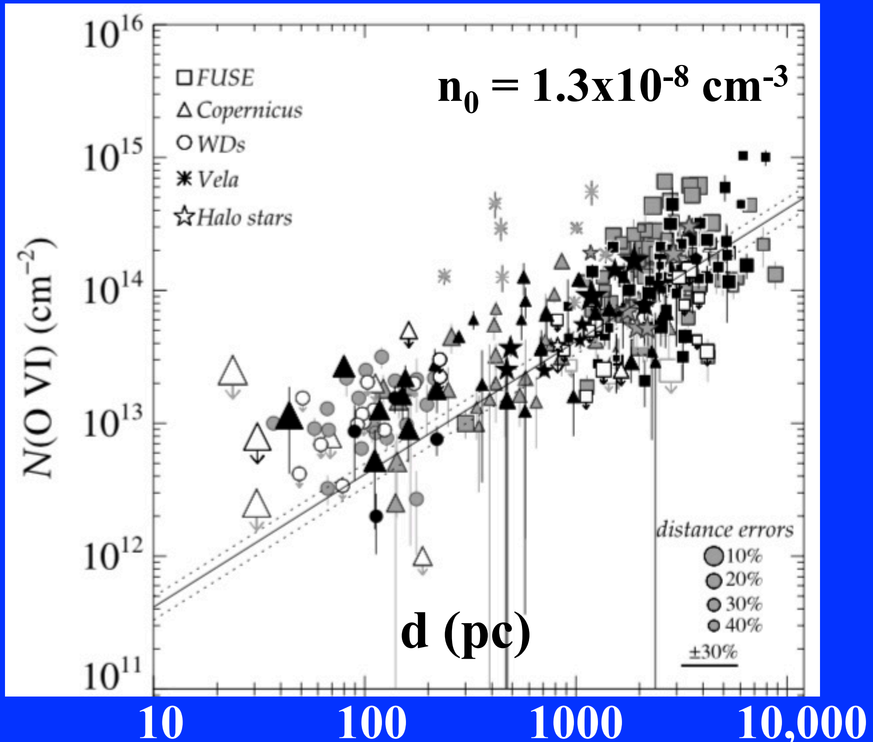
n(OVI) only few 10^{-8} cm^{-3}

D. Cox numerous

WNM X-RAY

MO too much OVI

Slavin & Cox clouds in WNM reduces OVI

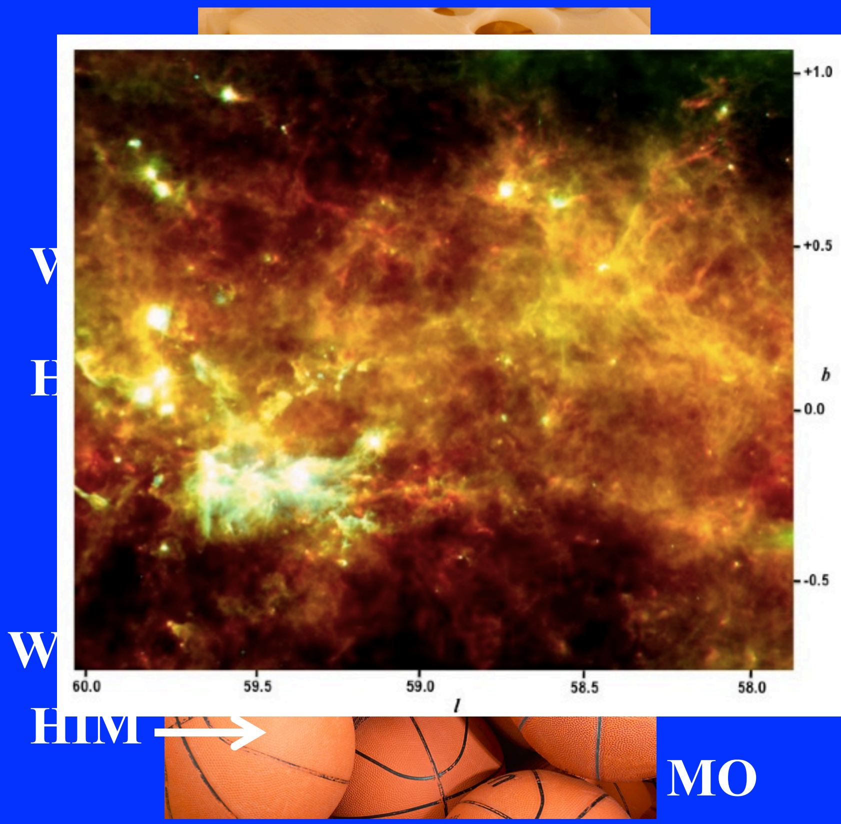


Bowen et al. 2008; Wakker et al. 2003

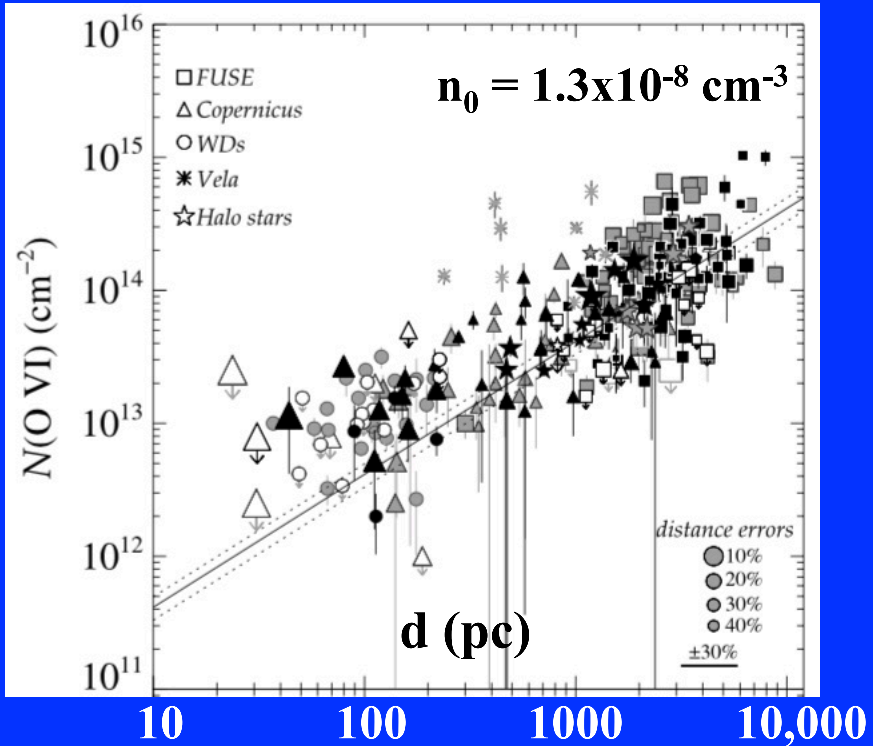
Phase Distribution Constraints from OVI

OVI constrains the topology of the ISM
and the interaction of SN with ISM

ISM Topology ?



de Avillez & Breitschwerdt 2005
Miao, et al. 2015



Bowen et al. 2008; Wakker et al. 2003

Conclusions

1.) CNM pressure distribution width set by turbulence but median set by two-phase pressure.

2.) Observed two-phase pressure is matched by models including grain photoelectric heating and fine-structure line cooling

3.) Local fraction of thermally unstable gas is not large

4.) Self-regulating cycle (pressure, star formation, phase transitions) maintains the two-phase pressure in the midplane

5.) Ample evidence from pressure/chemistry observations for small scale high pressure regions (shocks, TDRs)

6.) Various molecules can be used as probes of molecular fraction, HF, H_2O, ArH^+, and the C.R. ionization rate OH^+, H_2O^+

7.) OVI can provide model constraints on the topology of the ISM and SN interaction with the ISM