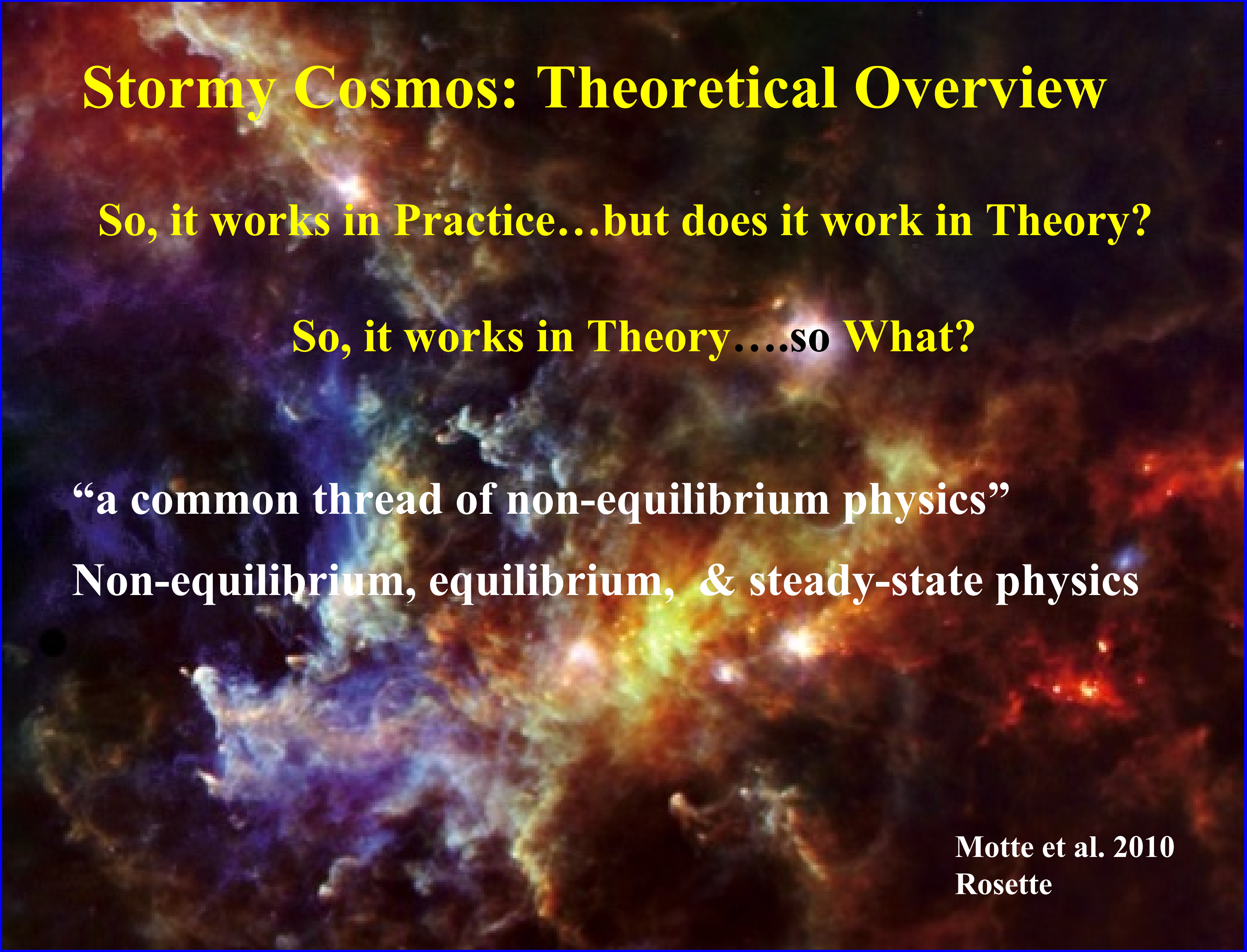
Stormy Cosmos: Theoretical Overview



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

So, it works in Theory….so What?

“a common thread of non-equilibrium physics”

Non-equilibrium, equilibrium, & steady-state physics

Motte et al. 2010
Rosette

- **Astrochemistry of Shocks and Other Dynamic Interstellar Processes** - **shocks, PDRs, XDRs, diffuse ISM**

- **Thermodynamics and Mechanics of the ISM** - **jets, winds, cosmic-rays, SN**

- **Coupling of Radiation, Gas and Dust** - **dust emission, PAHs, grain chemistry, polarimetry, SFR**

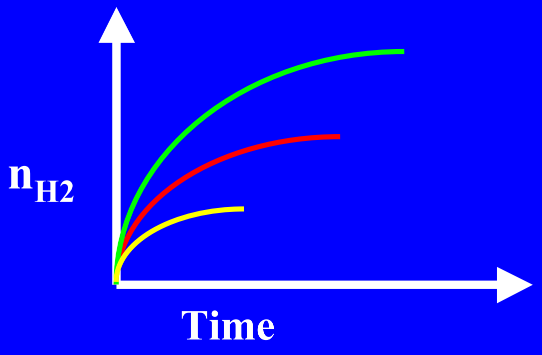
- **Secular Evolution of ISM Properties over Galactic and Cosmic Timescales** - **starburst galaxies, evolved stars, dwarf galaxies, SFR, molecules at high z**

Astrochemistry of Shocks and Other Dynamic Interstellar Processes

Time for H_2 equilibrium abundance?

$$\frac{dn_{H2}}{dt} = \underbrace{Rnn_{HI}}_{\text{Formation}} - \underbrace{G_0 In_{H2}\beta(N_{H2})e^{-\sigma N}}_{\text{Destruction}}$$

Formation **Destruction**



Liszt 2007

$$t_{eq} = \frac{f(H_2)_{eq}}{\underbrace{2R}_{3 \text{ x } 10^{-17} \text{ s}^{-1}}n} \approx \frac{5\text{x}10^8}{\text{n}}\ \text{yr}$$

$3 \text{ x } 10^{-17} \text{ s}^{-1}$

Fast or Slow?

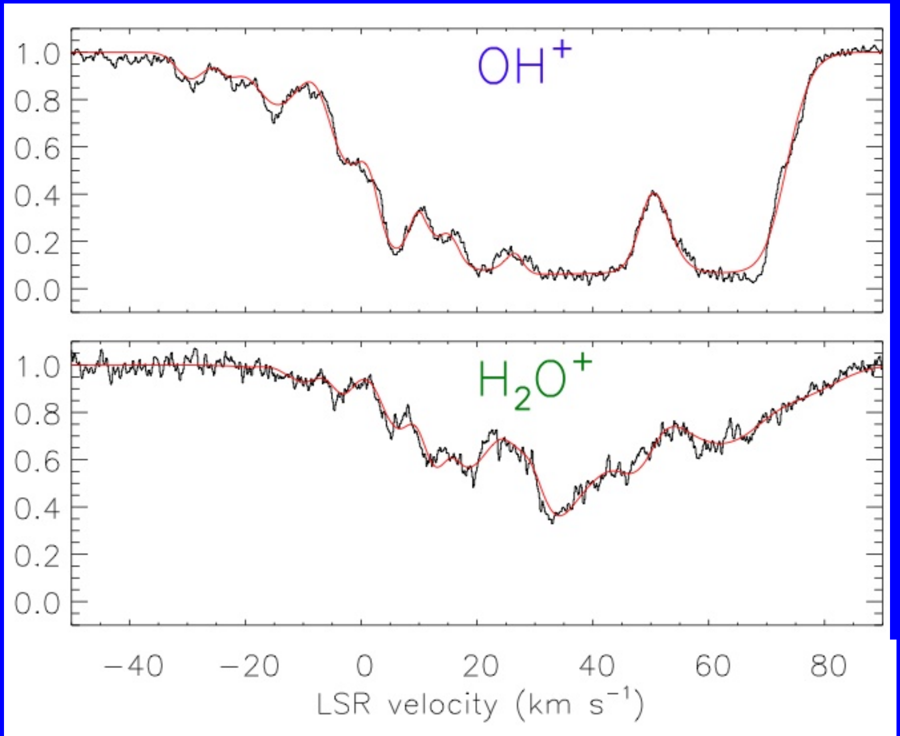
Ion-Neutral Reactions
$OH^+ + H_2 \longrightarrow H_2O^+ + H$
t = 70/n yr
SLOW!

GMC Life Time
t > 3 Myr
FAST!

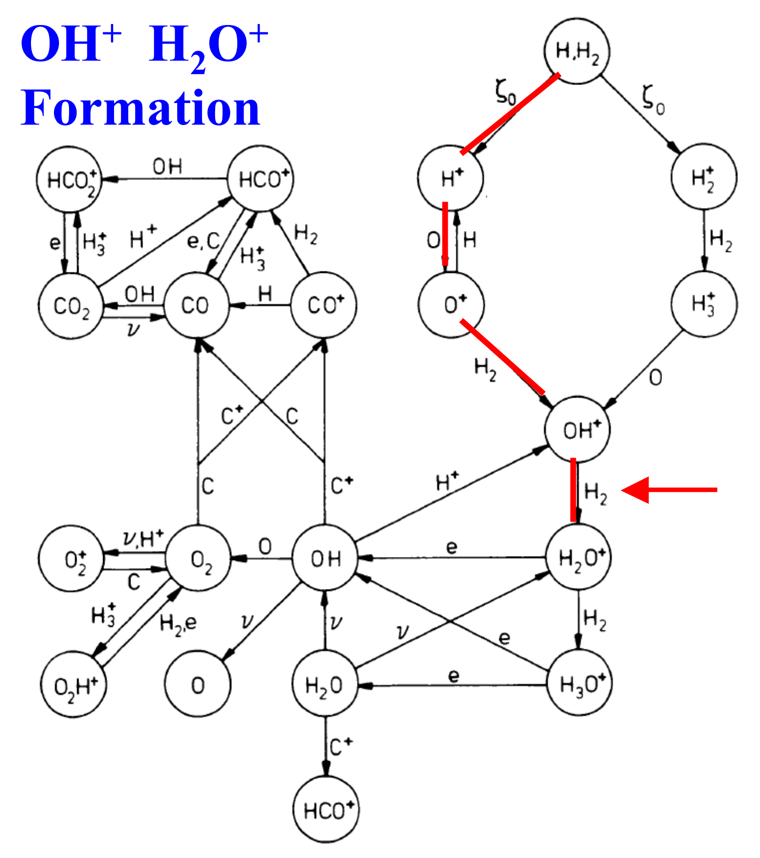
Dynamical Time

Slow! Or FAST!

W49N



Neufeld et al 2010 Gerin et al. 2010



OH^+ H_2O^+ Formation

van Dishoeck & Black 1986

$OH^+/H_2O^+ \sim 3\text{-}15$

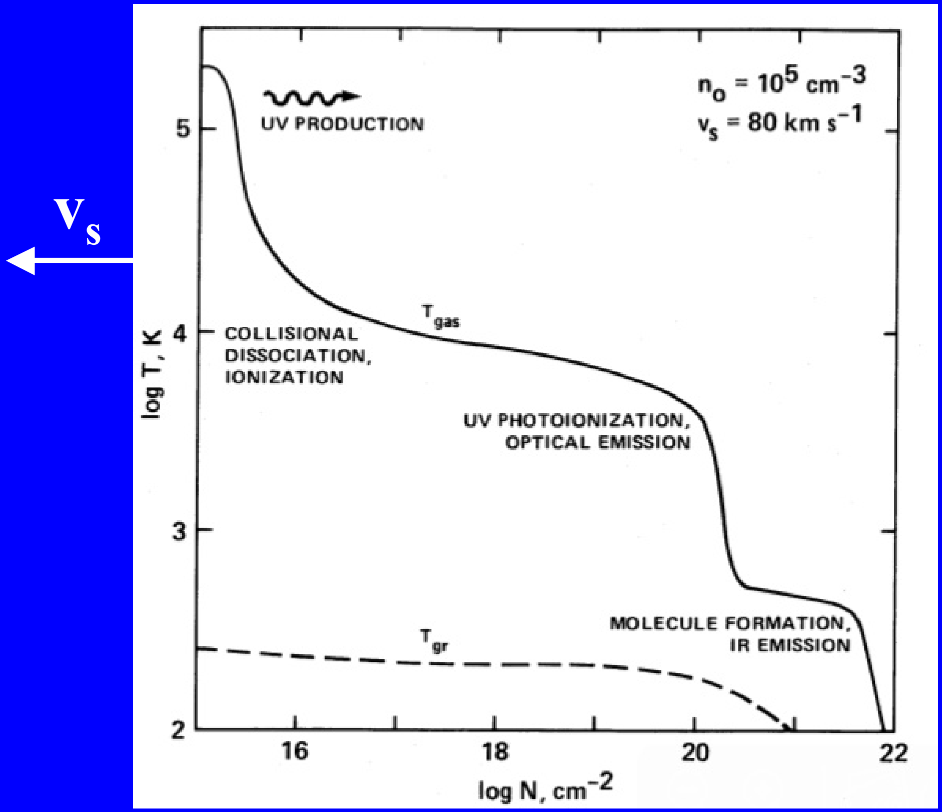
$n(H_2)/n \sim 2\text{-}8\%$ Non-equilibrium H_2 abundance!

$A_V \sim 3$

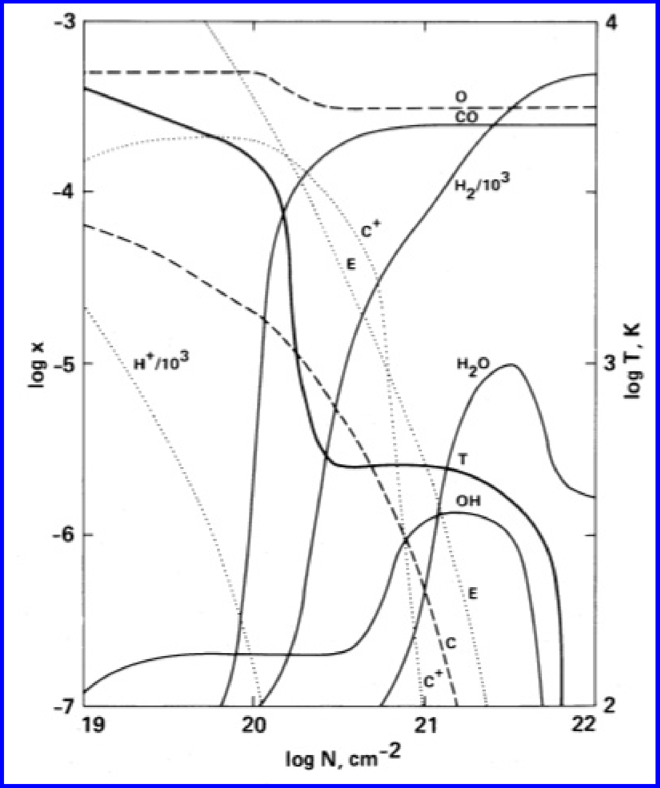
Also get ζ_{cr} van Disoeck & Black 1986

J - Shocks

Hollenbach & McKee 1989



Hollenbach & McKee 1989



$$z_{1/2} = 5.2x10^{14} b^2 \left(\frac{10^5 \mathrm{cm}^{-3}}{n}\right)\left(\frac{100\ \mathrm{km\ s}^{-1}}{v_s}\right) \mathrm{cm}$$

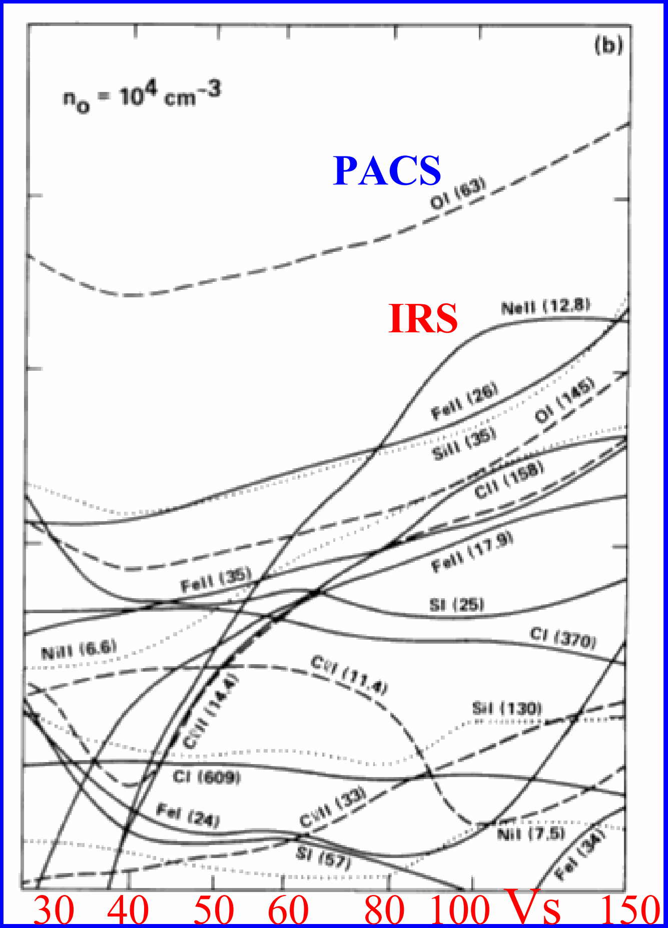
$O + H_2 \longrightarrow OH + H$

$OH + H_2 \longrightarrow H_2O + H$

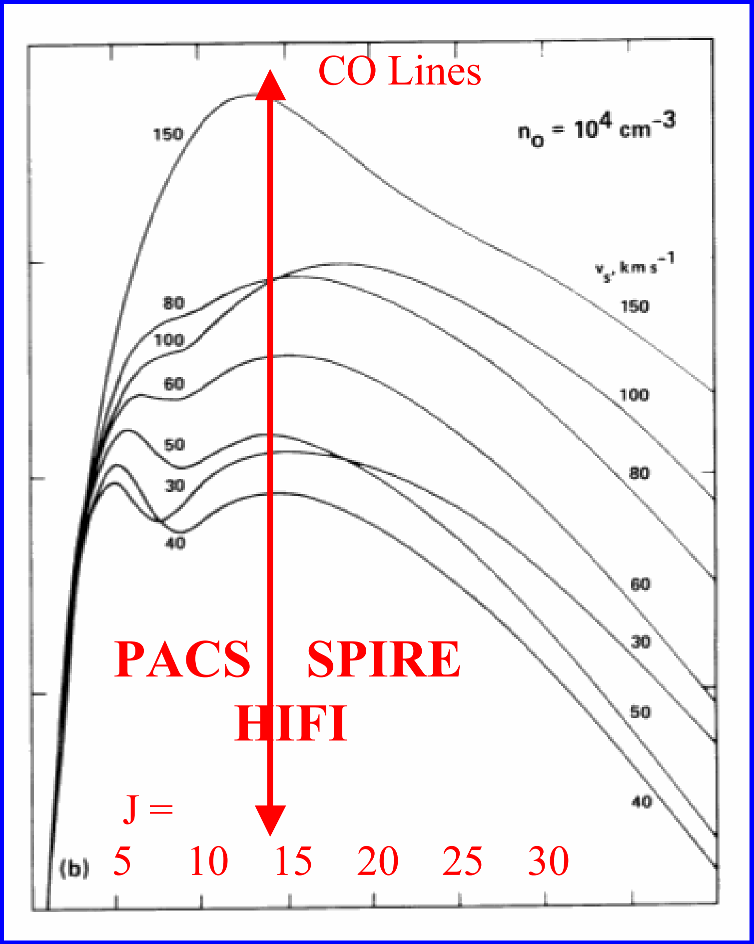
$T > 400$ K

J - Shocks

Hollenbach & McKee 1989



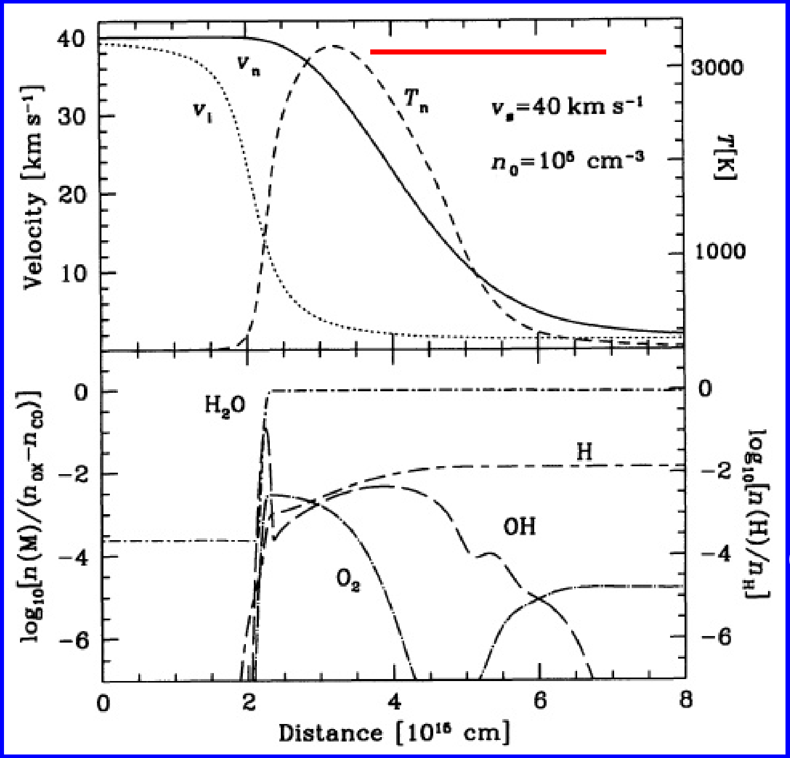
Hollenbach & McKee 1989



Also
OH
H_2O
H_2
$n>10^{4-5}$
cm^{-3}

High [OI]/[CII] [SiII], [FeII]
High Line/Continuum
High J CO lines

C-Shocks



Kaufman & Neufeld 1996

T ~ 3000 K

Large Line/L$_{FIR}$

No [CII]

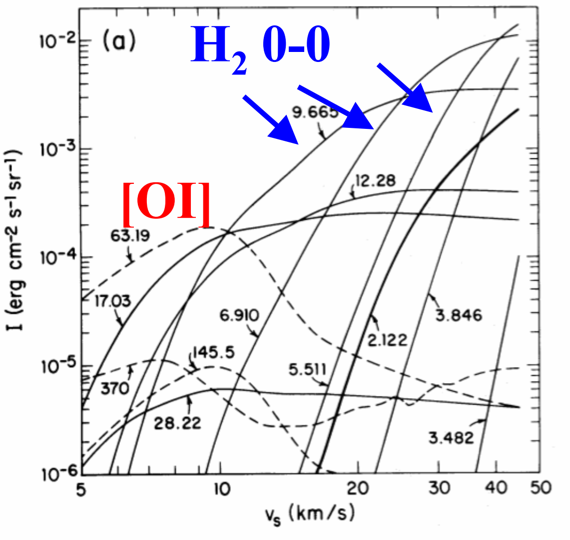
v_s ~ 40 km/s

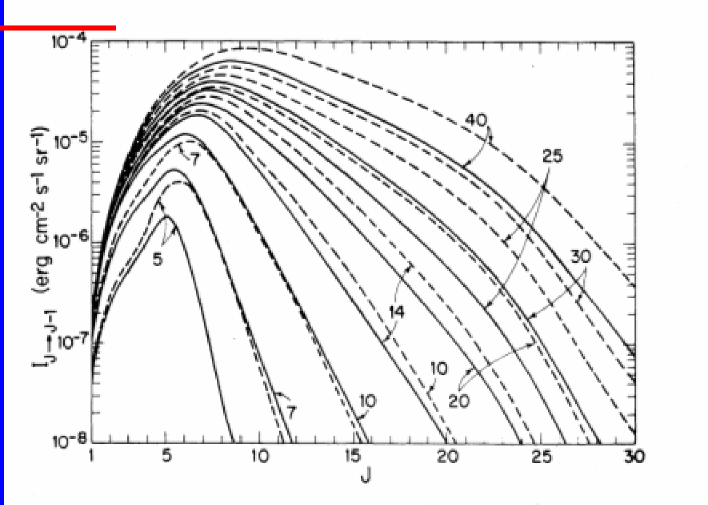
H_2O

CO peak J~ 5-10

Z ~ 10^{16} cm

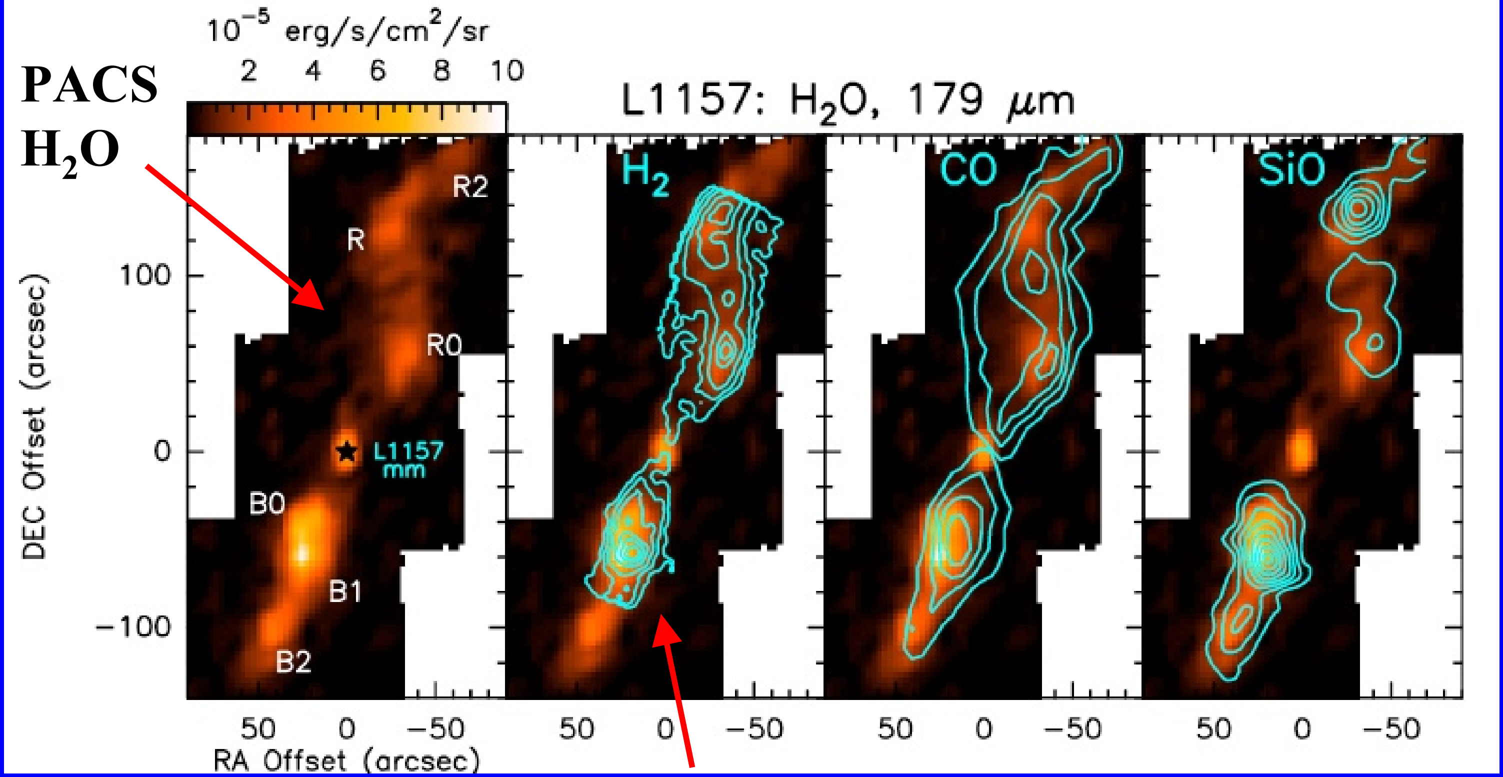
Draine, Roberge, Dalgarno 1983





Draine & Roberge 1984

Dynamics, Cooling, and Chemistry of Protostellar Outflows



PACS H_2O

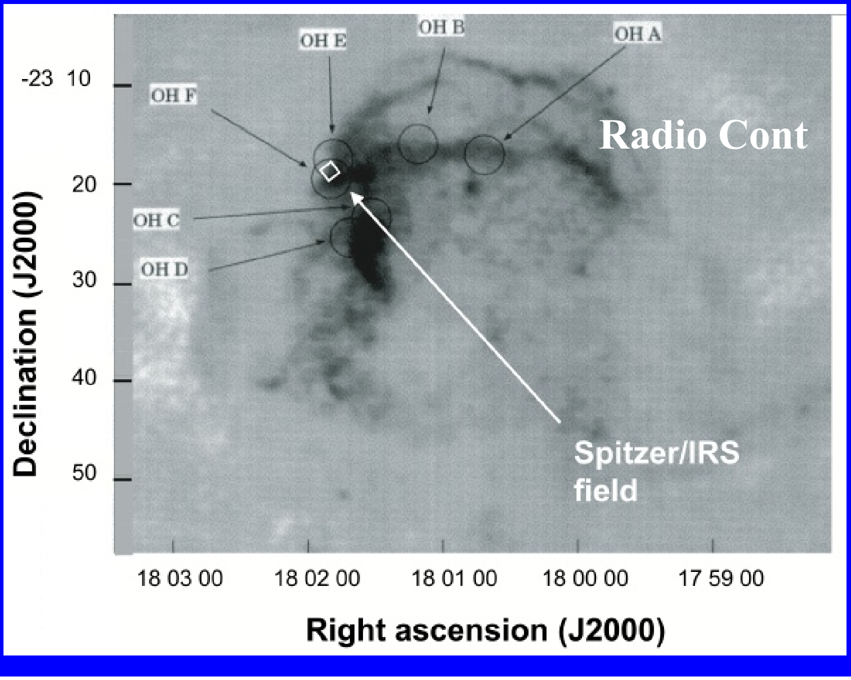
Nisini et al. 2010 (WISH)

Spitzer IRS H_2 0-0 S(1)

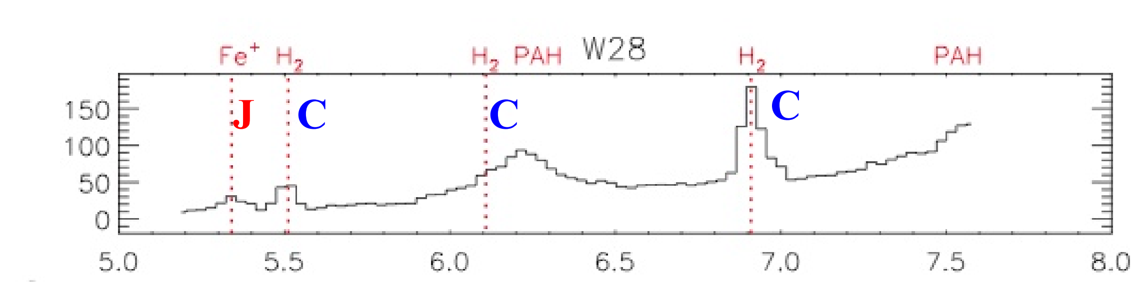
H_2O Cooling ~ 25% of shock energy!

Dynamics and Chemistry of SN Remnants

W28 Supernova Remnant

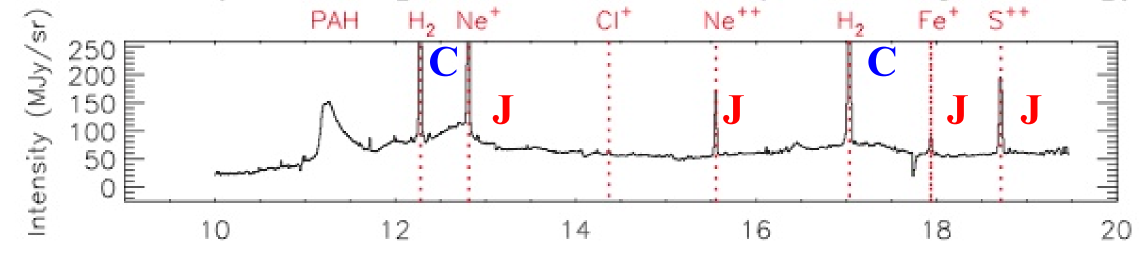


Neufeld et al. 2007



C - Shock H_2 lines

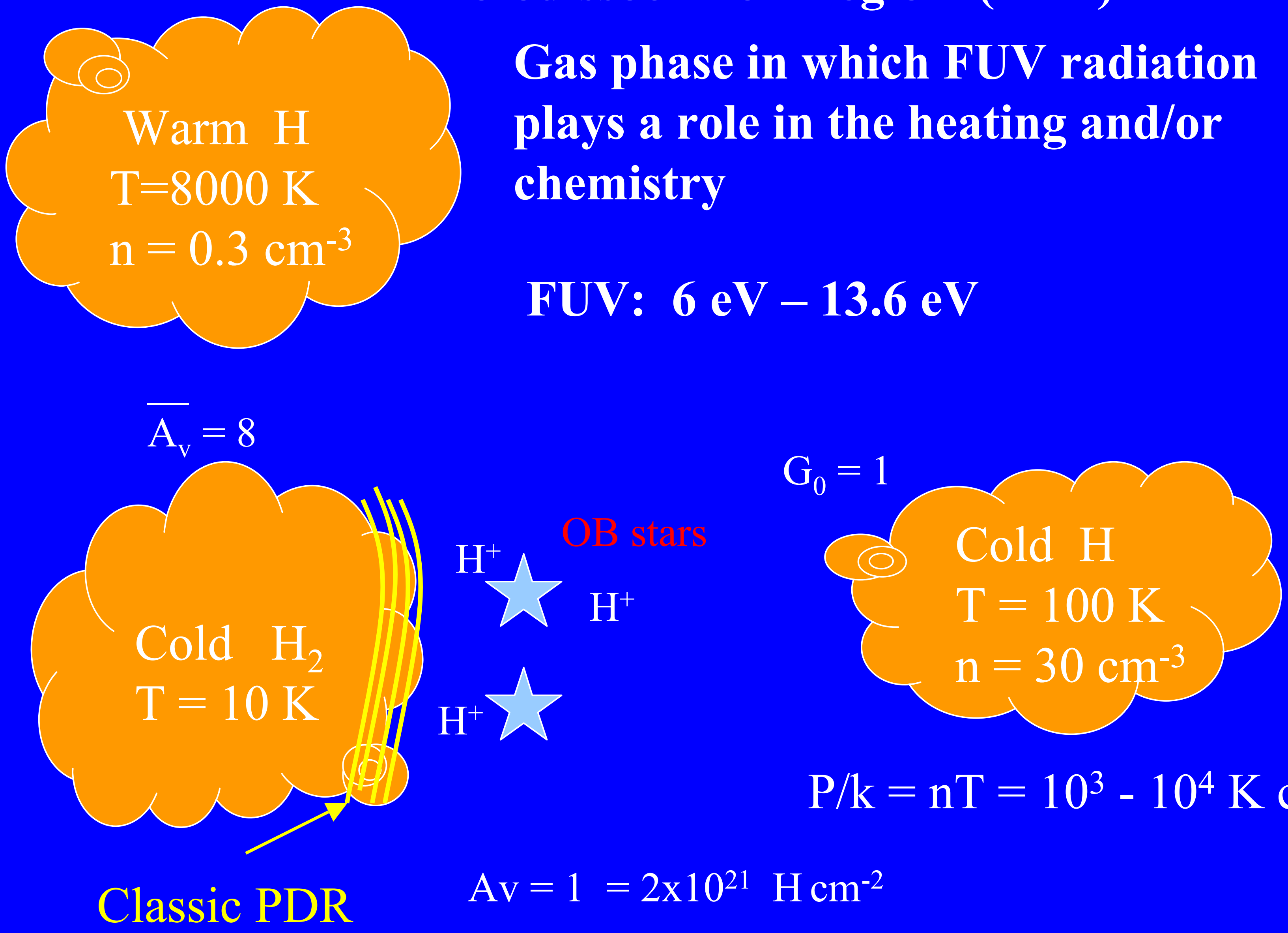
J - Shock Ionized lines



Photodissociation Region (PDR)

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

FUV: 6 eV – 13.6 eV



Warm H
T=8000 K
$n = 0.3\ \mathrm{cm}^{-3}$

$\overline{A_v} = 8$

Cold H_2
T = 10 K

Classic PDR

H^+

OB stars

H^+

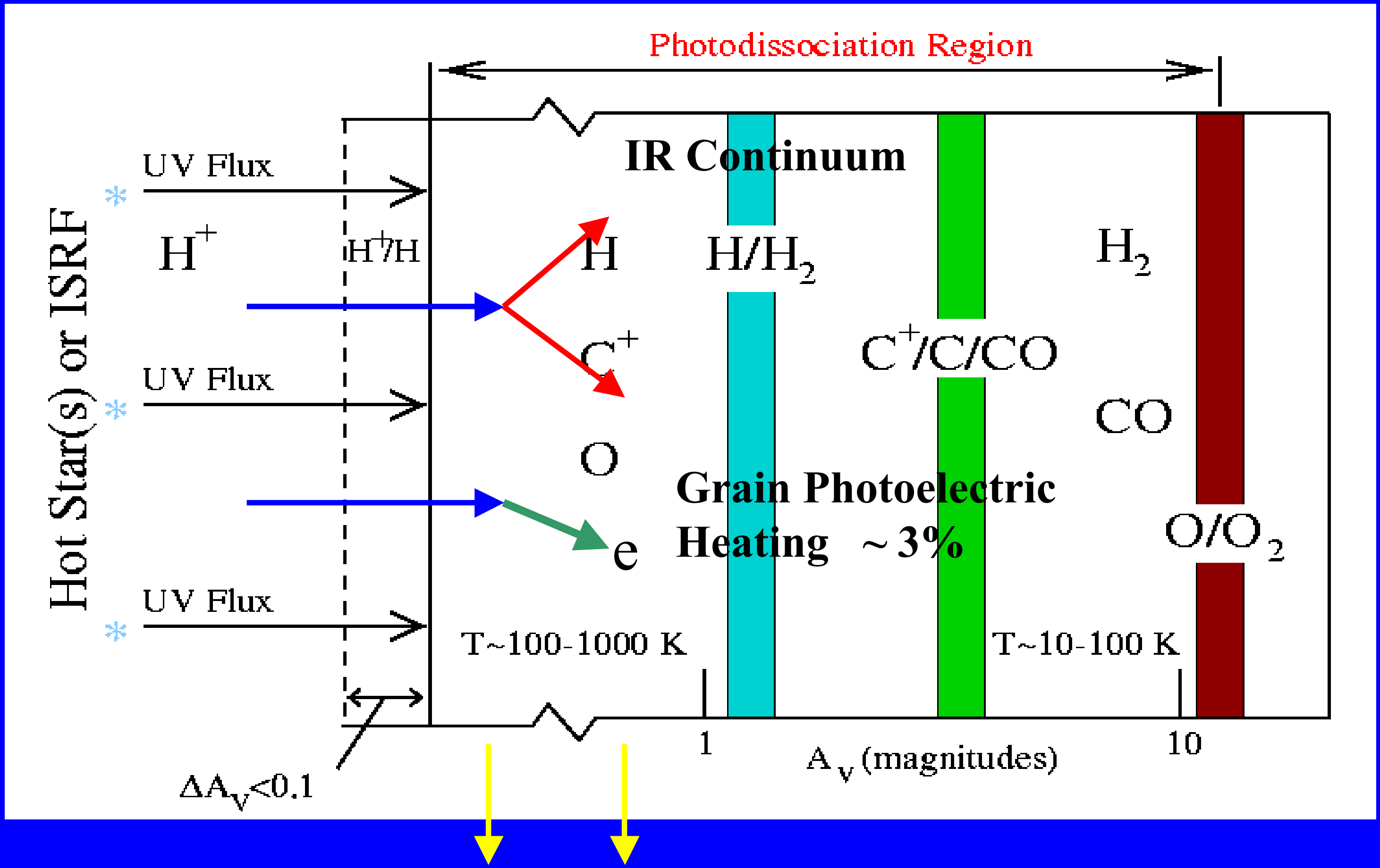
H^+

$G_0 = 1$

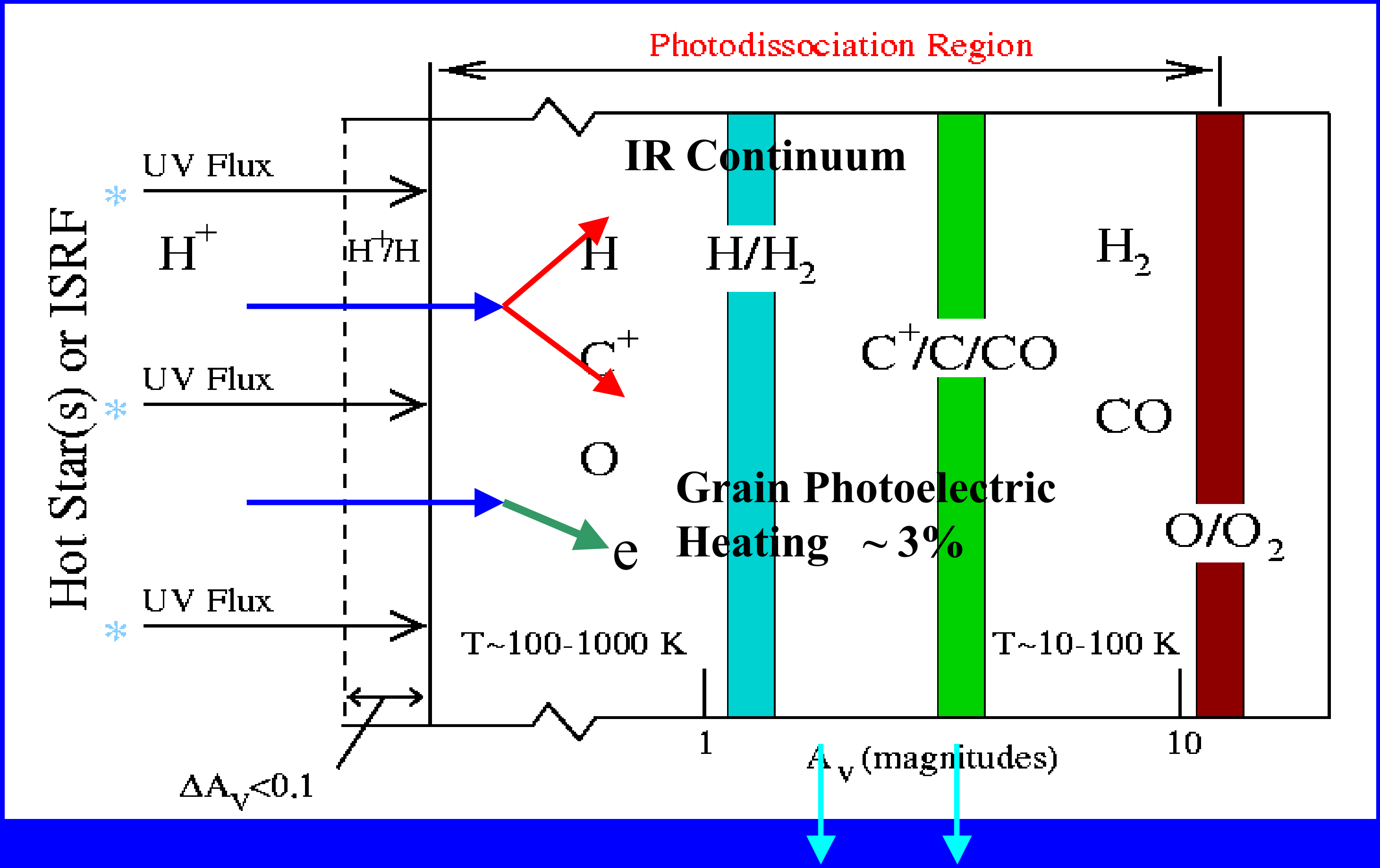
Cold H
T = 100 K
$n = 30\ \mathrm{cm}^{-3}$

$P/k = nT = 10^3 - 10^4\ \mathrm{K\ cm}^{-3}$

$Av = 1 = 2\mathrm{x}10^{21}\ \mathrm{H\ cm}^{-2}$



Diagnostics:	**C^+ 158 μm**	**Herschel**
	O 63 μm, 145 μm	**Herschel**
	Si^+ 35 μm, Fe^+ 26 μm	**Spitzer**
	Dust Continuum	**H, S**
	PAH 3.3, 6.2, 7.7, 8.6	**Spitzer**
	11.2 μm	**Spitzer**



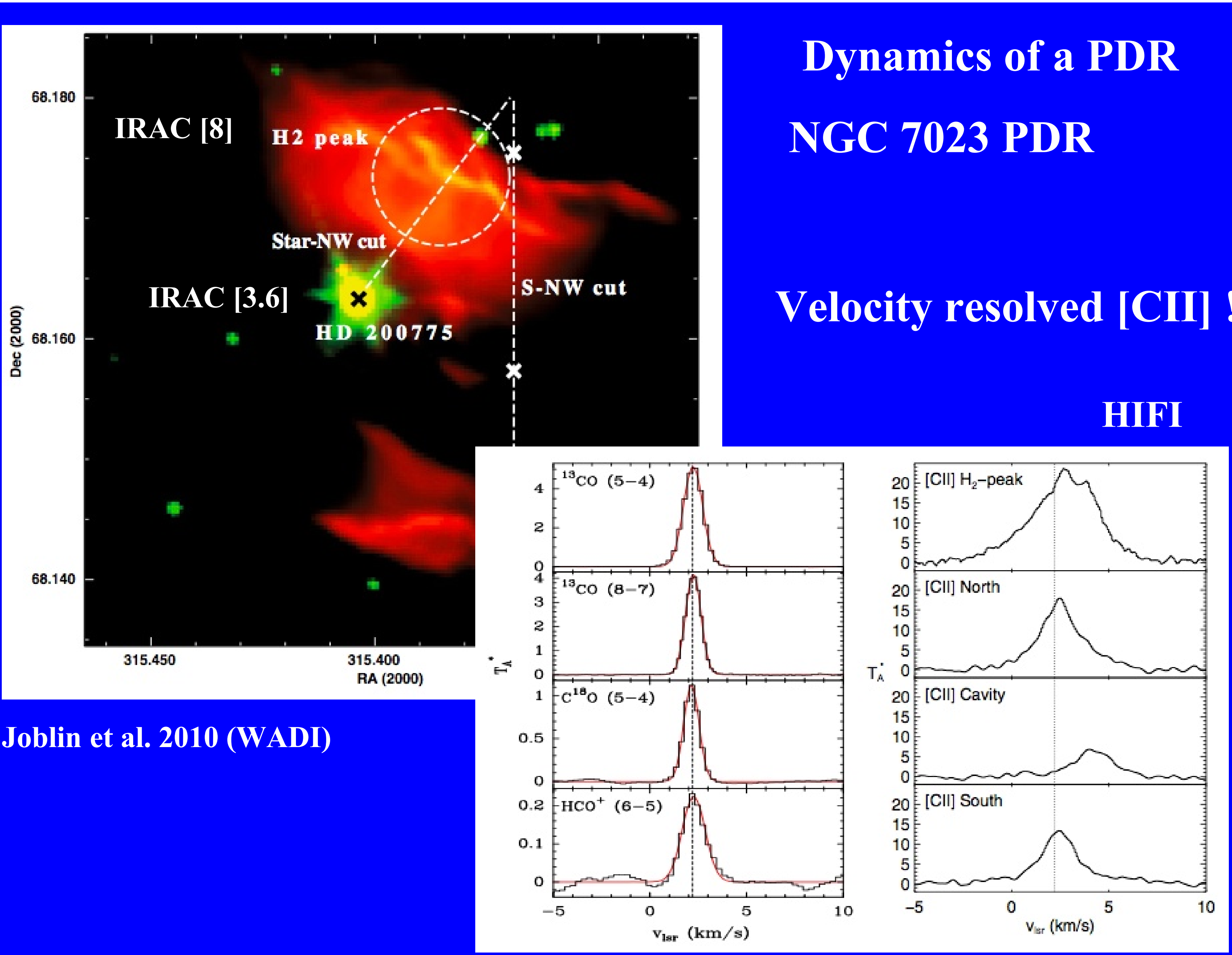
Diagnostics:	C^+ 158 μm	H
	C 609 μm, 370 μm	H
	H_2 0-0 S(2) 12.3 μm	S
	High-J CO	H

Dynamics of a PDR

NGC 7023 PDR

Velocity resolved [CII] !

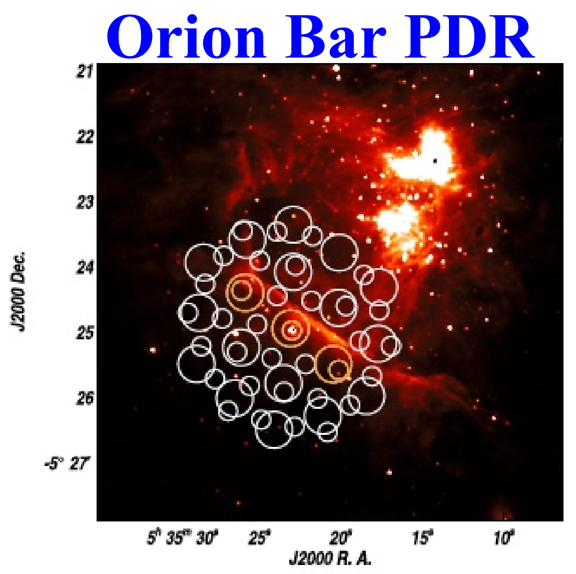
HIFI

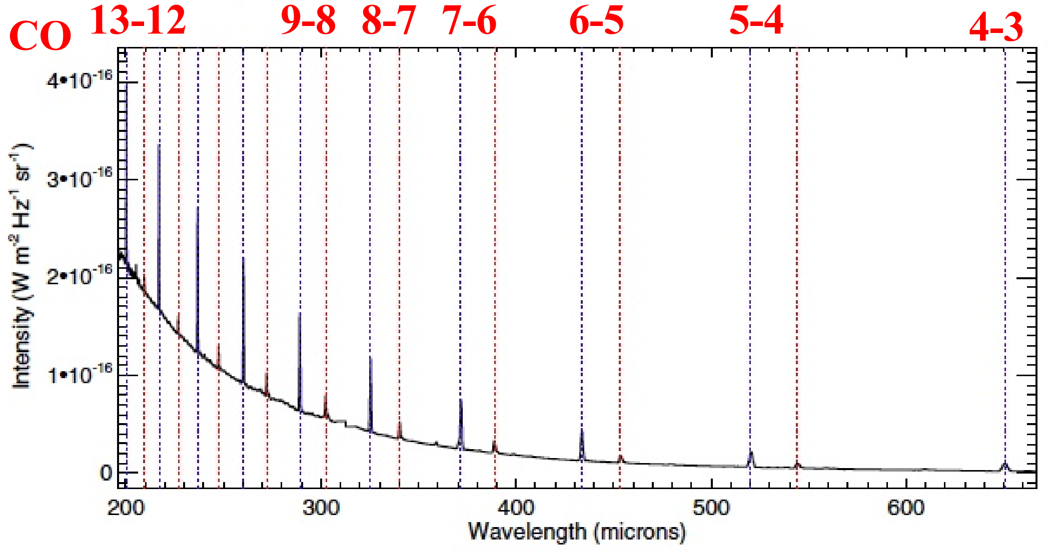


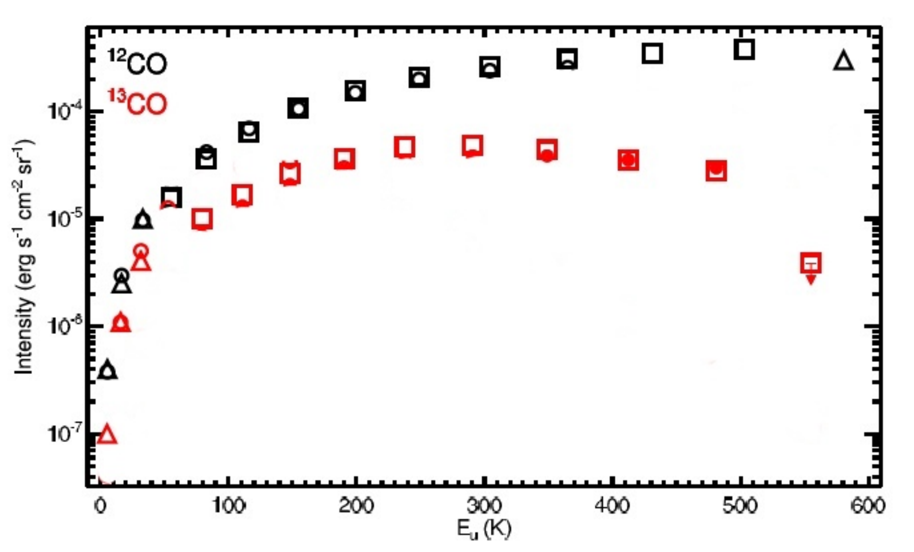
Joblin et al. 2010 (WADI)

Physical Conditions in Star Forming Regions

Habart et al. 2010







High J CO Problem

1)Dense Clumps

2)Additional Heating

(Shocks or turbulence)

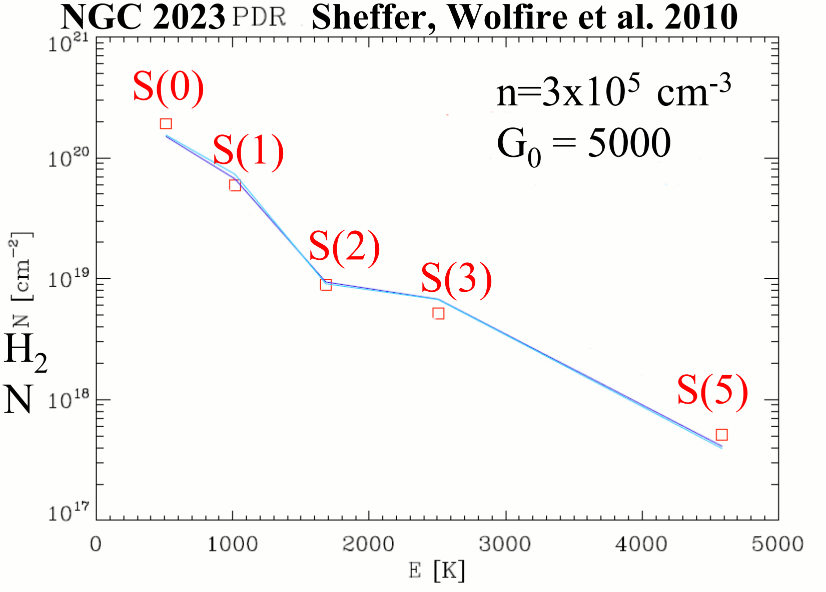
3)Non-equilibrium advection

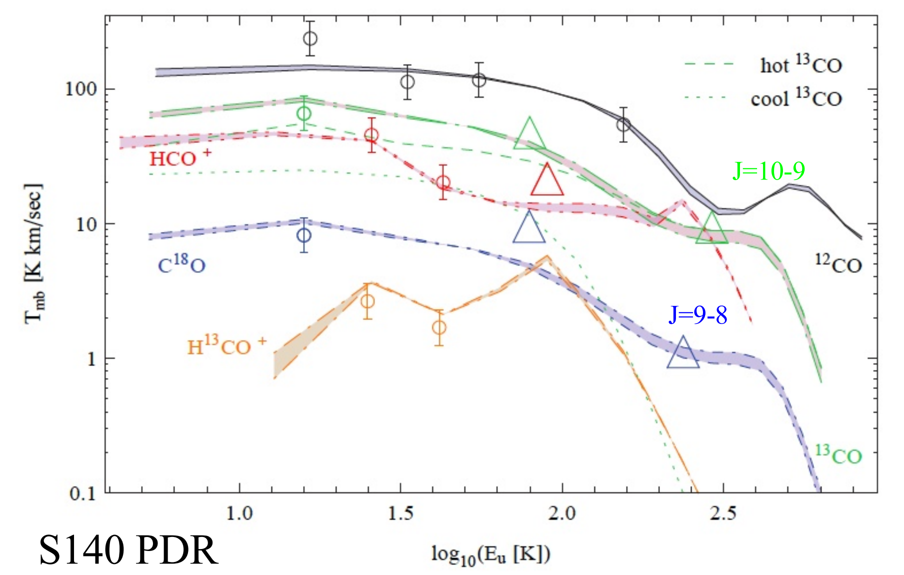
Observations of H_2 and CO: Too warm?

1)CO(J=7-6) and CO(14-13) in PDRs M17 (Harris et al. 1987; KAO)

2)H_2 0-0 S(1), S(2), S(4) Orion Bar (Allers et al. 2005; IRTF)

3)H_2 0-0 S(0), S(1), S(2), S(3) Taurus Cloud (Goldsmith et al. 2010 Spitzer)


NGC 2023 PDR **Sheffer, Wolfire et al. 2010**


S140 PDR

Dedes et al. 2010 using KOSMA-tau

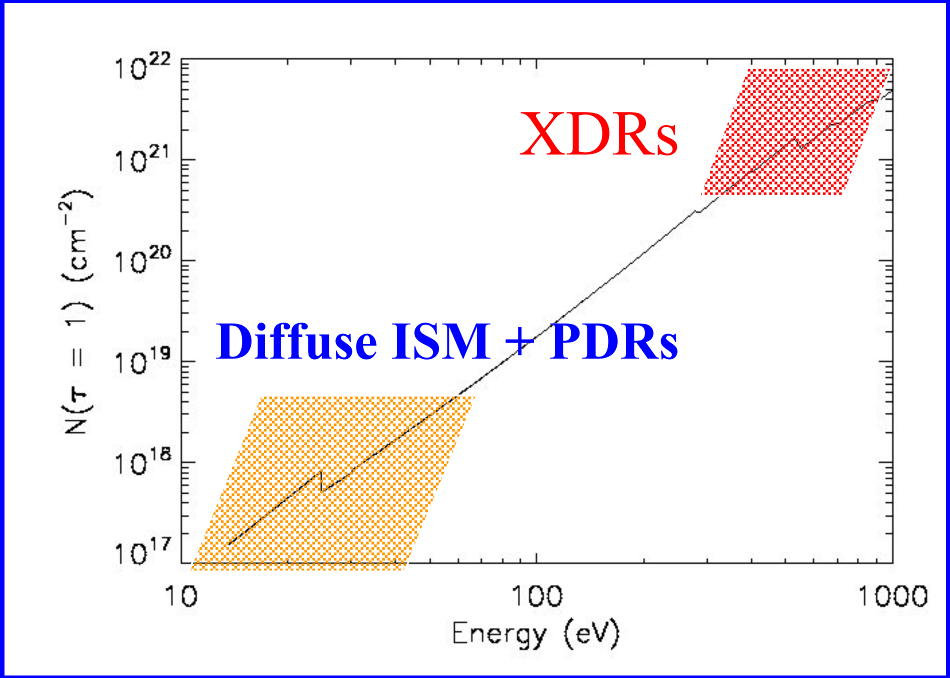
Herschel Observations → [OI], [CII], [CI]

total cooling → total heating

H_2, high J CO, H_2O, OH

XDRs

X-rays dominate the Heating and Ionization



$\sigma \sim 1/\nu^3$ atomic photoionization cross section

Energy dumped into molecular gas

Photoionized electron energy goes into Coulomb heating

AGNs:

Maloney et al. 1996
Meijerink et al. 2007
Spaans & Meijerink 2008

Protoplanetary Disks:

Meijerink et al. 2008a
Meijerink et al. 2008b

Shocks:

Maloney et al. 1996

Probing AGNs

XDR: OH^+, H_2O^+ emission

ion-neutral reactions

$$H^+ + O \rightarrow O^+ + H$$

$$O^+ + H_2 \rightarrow OH^+ + H$$

$$H^+ + OH \rightarrow OH^+ + H$$

$$OH^+ + H_2 \rightarrow H_2O^+ + H$$

Maloney et al. 1996

van der Werf et al. 2010

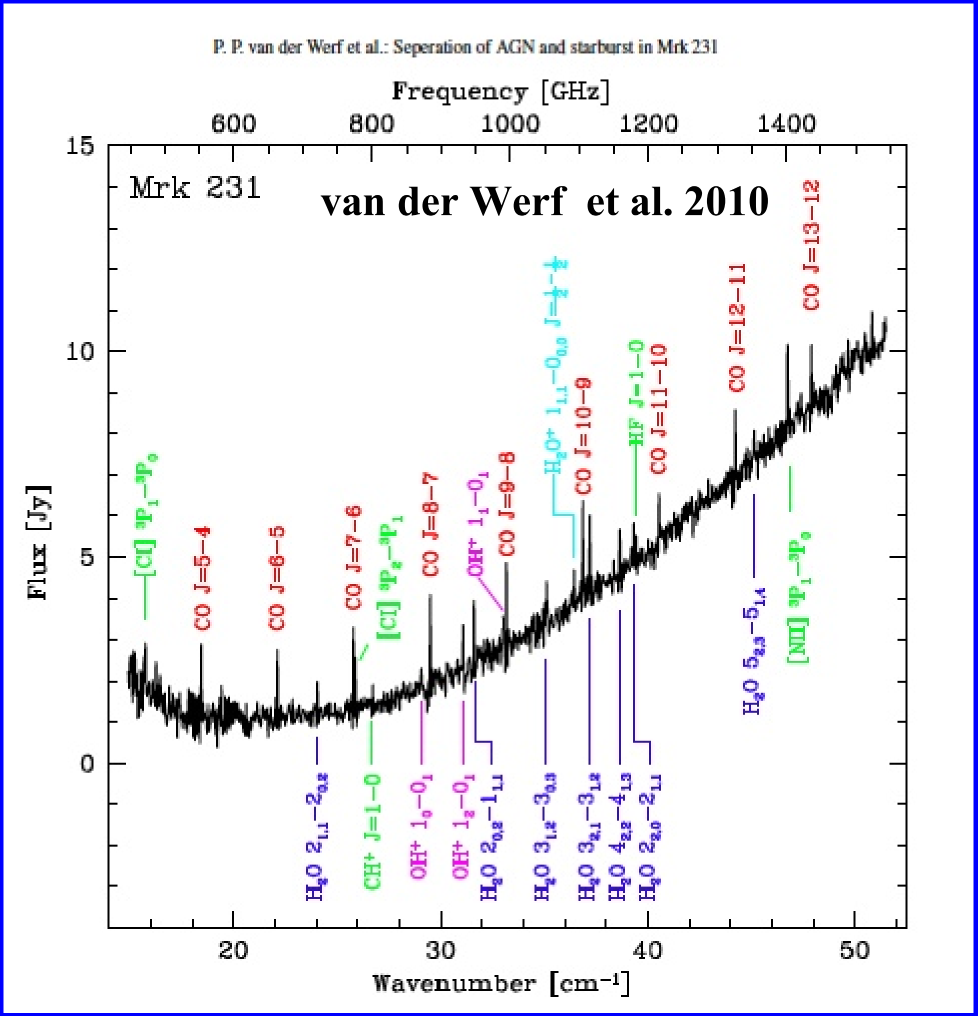
OH, H_2O emission

neutral-neutral reactions

$$O + H_2 \longrightarrow OH + H$$

$$OH + H_2 \longrightarrow H_2O + H$$

high J (13-12) CO lines



Thermodynamics and Mechanics of the ISM

What is the cooling time and the dynamical time?

HI gas cooling:

$$t_{\text{cooling}} = 6\text{x}10^{6}\ \ \text{yr}\ \ \ (\text{T}\ =\ 8000\ \text{K})$$

$$t_{\text{cooling}} = 3\text{x}10^{4}\ \ \text{yr}\ \ \ (\text{T} = 100\text{K})$$

HI Turbulence:

$$\text{v} = \text{v}_0 l^{q}$$

Line-width size relation

For large l $\ P_{\text{turb}} > P_{\text{th}}$

Take l for $\text{P}_{\text{th}} > \text{P}_{\text{turb}}$

$$\Psi = \frac{t_{\text{cooling}}}{t_{\text{shock}}} < 1 \Rightarrow \text{Two Phase ISM}$$

$$\Psi \approx 0.1\ \ (\text{T}\ =\ 100\ \text{K})$$

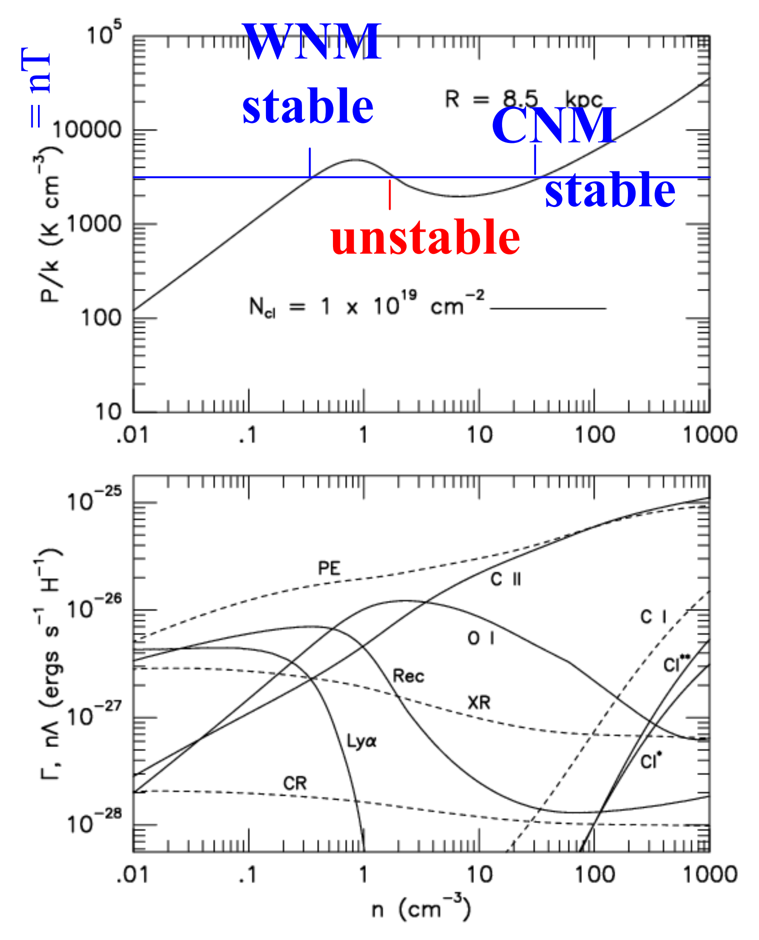
$$\Psi \approx 0.3\ \ (\text{T}\ =\ 8000\ \text{K})$$

Wolfire et al. 2003

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

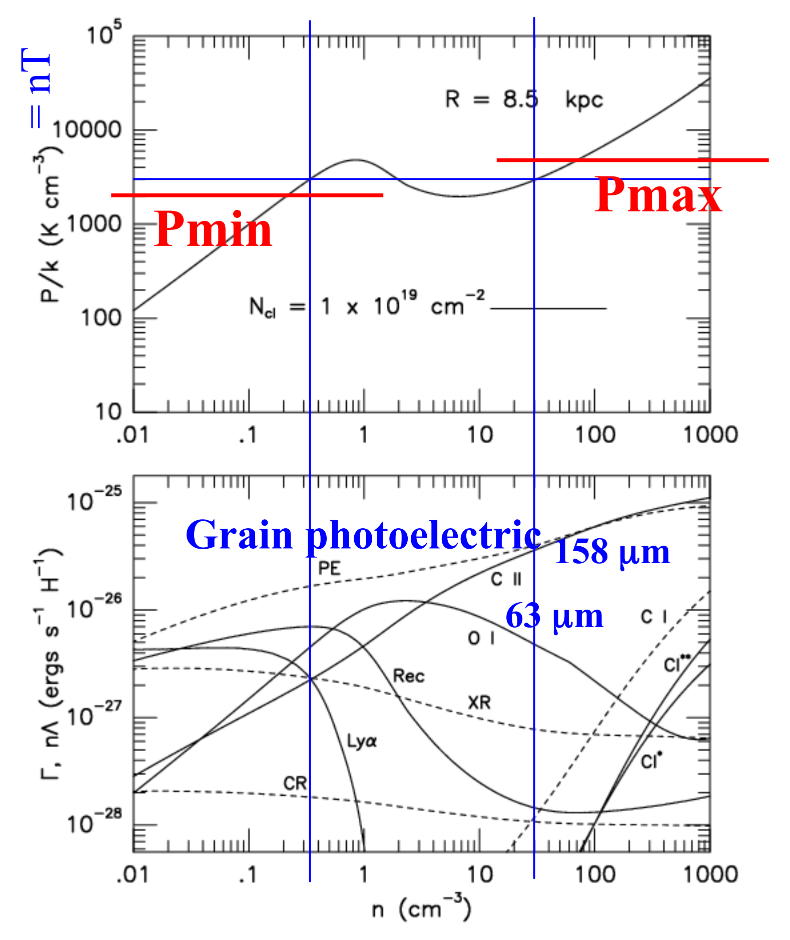
$T = 85$
$n = 33\ \mathrm{cm}^{-3}$
CNM

Wolfire, McKee, Hollenbach, & Tielens (2003)



Langer et al. 2010

GOT C+



Wolfire, McKee, Hollenbach, & Tielens (2003)

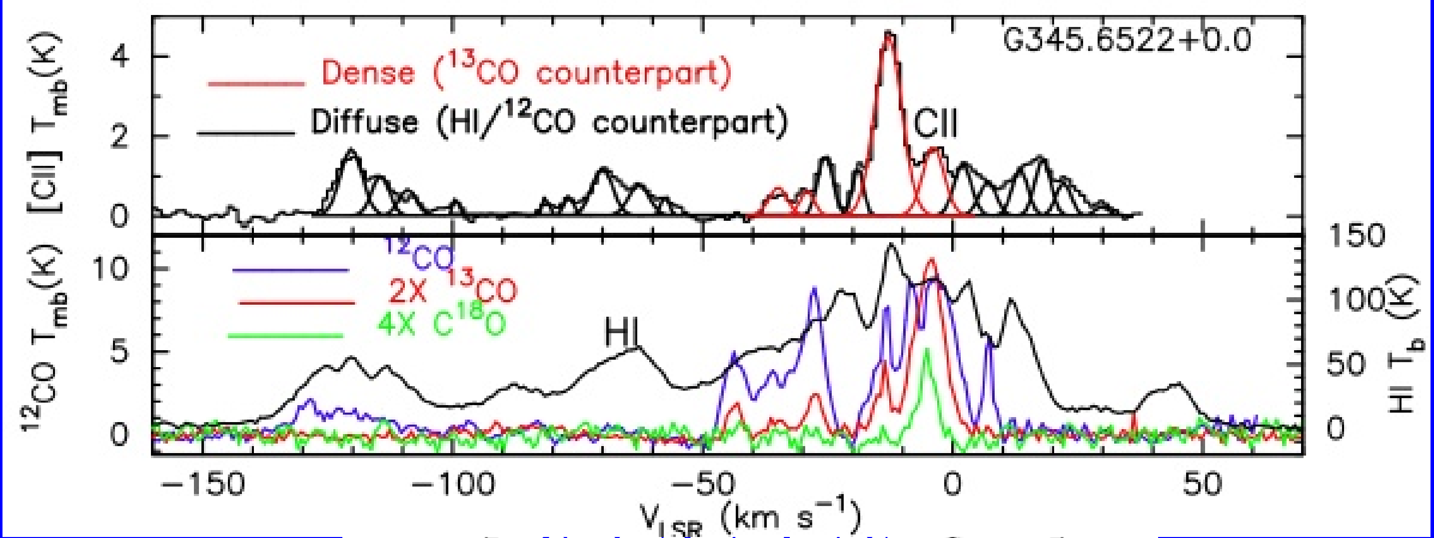
C II Cooling/H (CNM) > 10 CII Cooling/H (WNM)

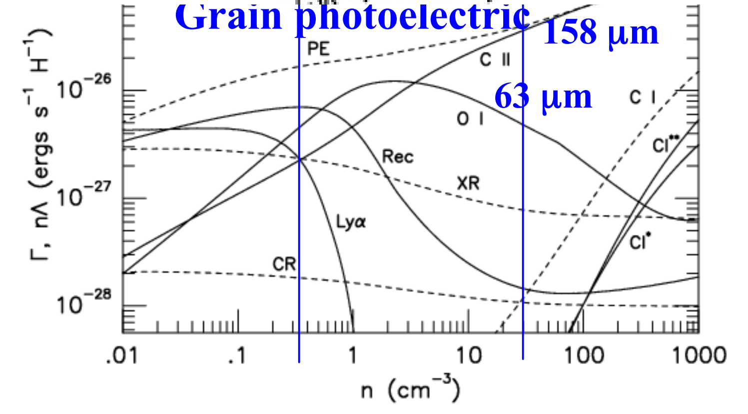
C II emission isolates the CNM clouds. Previously seen only in absorption.

Langer et al. 2010

Wolfire, McKee, Hollenbach, & Tielens (2003)

GOT C+





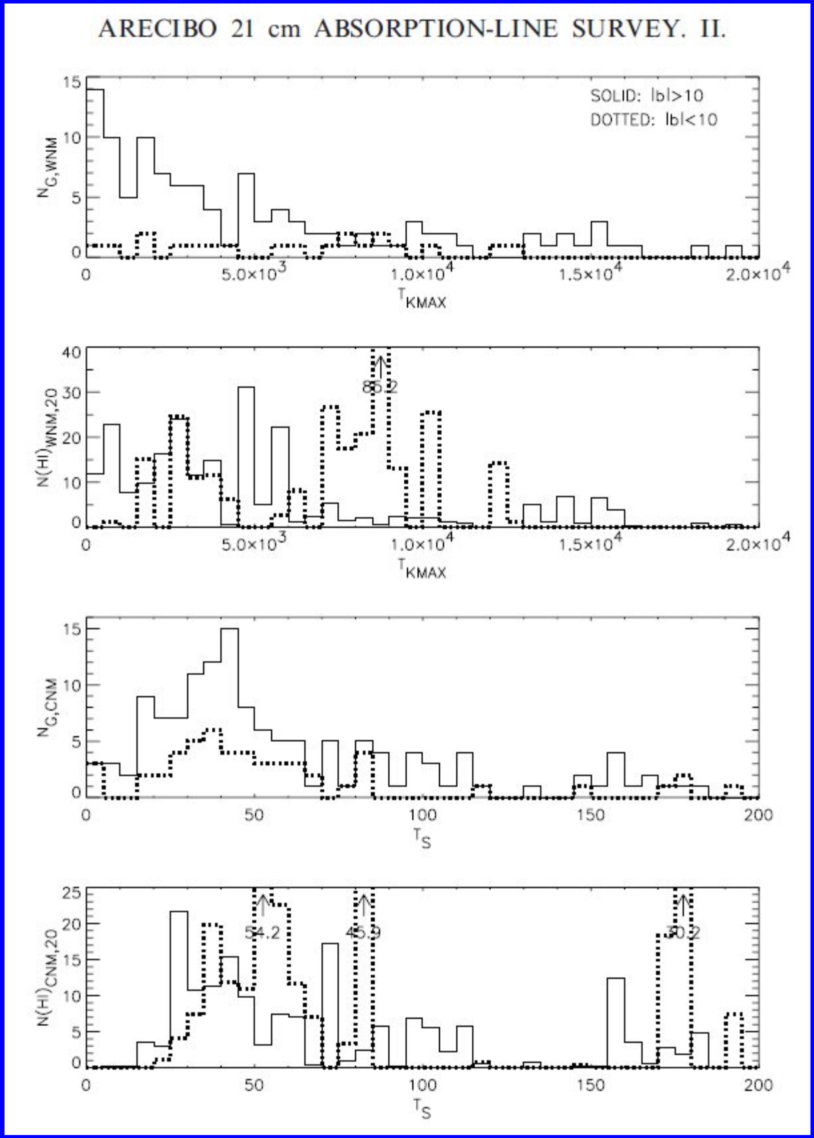
Grain photoelectric

158 µm

63 µm

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

C II emission isolates the CNM clouds. Previously seen only in absorption.



Heiles & Troland 2003, ApJ, 586, 1067

Are There Phases in the ISM?
Vaquez-Semadeni 2009

50% of gas mass in unstable
Temp ?

Really 25% of WNM in unstable
Temp or 15% of total mass.

In plane dominated by TI.
Out of plane by dynamical
processes.

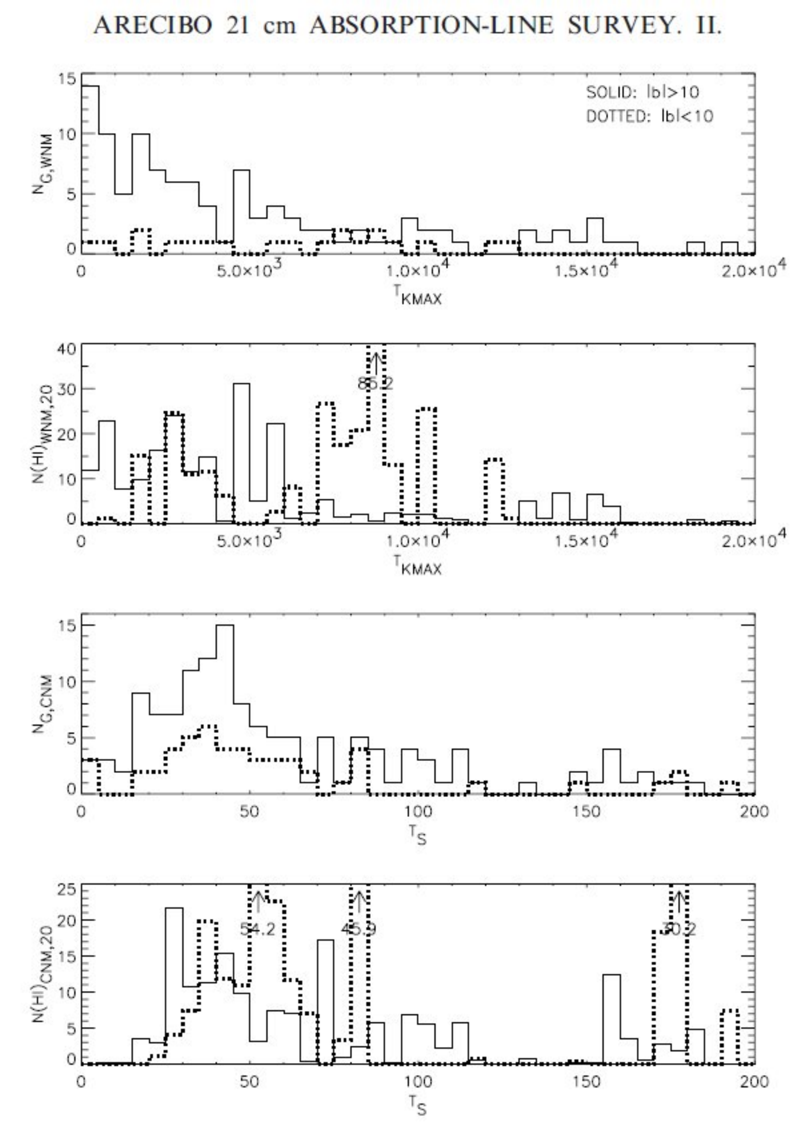
Numerical Simulations

No or weak TI:

Vazquez-Semadini et al. 2000, Gazol et, al. 2001, Gazol 2005

Significant TI:

Piontek & Ostriker 2005, Hennebelle & Audit 2007, Koyama & Ostriker 2009



Heiles & Troland 2003, ApJ, 586, 1067

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Herschel
SOFIA HELP!
STO

Numerical Simulations
No or weak TI:
Vazquez-Semadini et al. 2000, Gazol et, al. 2001, Gazol 2005

Significant TI:
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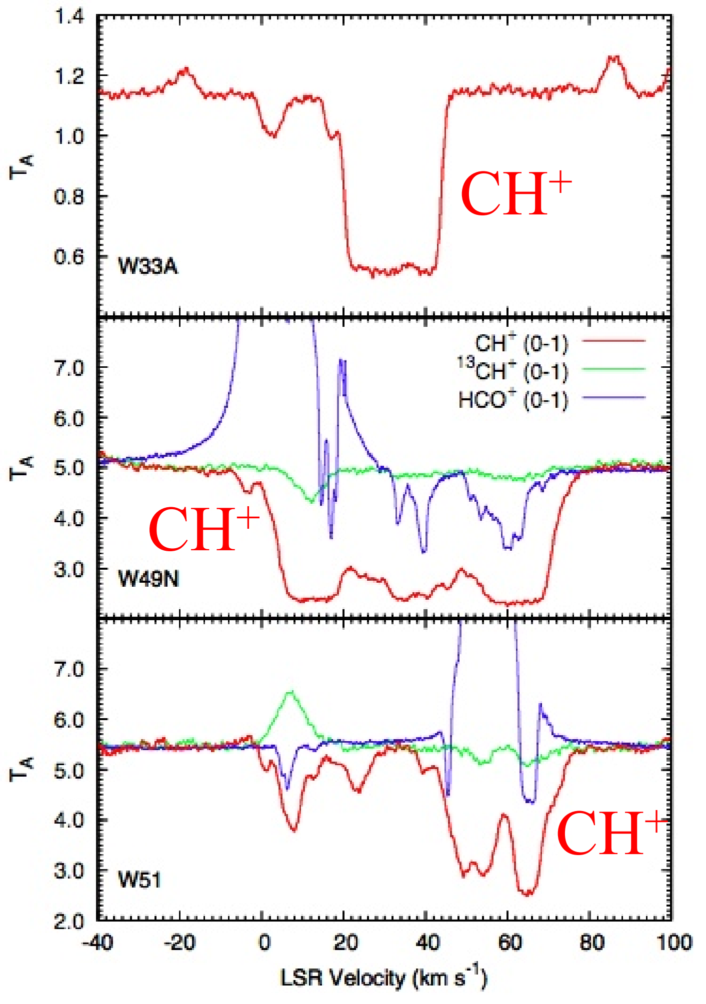
Turbulence/Shocks in Diffuse Gas

HIFI



Falgarone et al. 2010

CH$^+$ Problem

$$C^+ + H_2 \longrightarrow CH^+ + H$$
$$\Delta E/k = 4640\ K$$

Shocks ?

Pineau des Forêts et al. 1986

Turbulent Dissipation ?

Godard et al. 2009

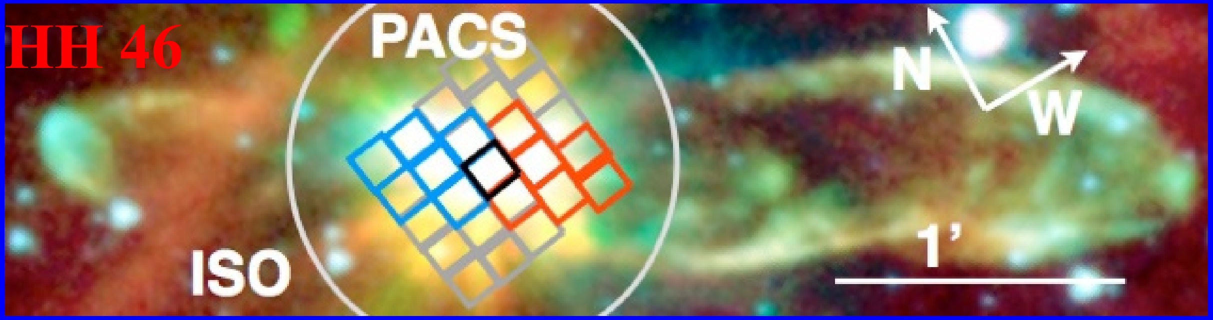
HCO$^+$ Problem

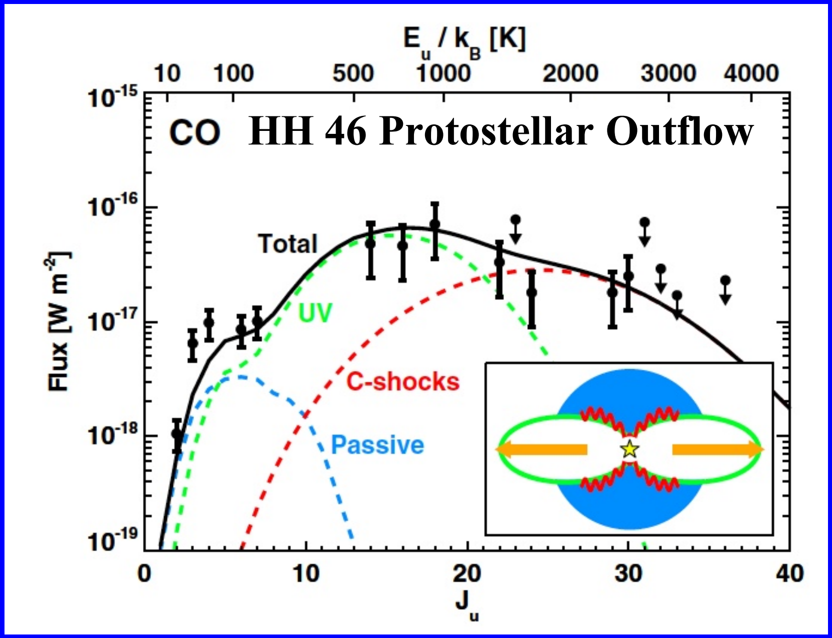
Godard et al. 2010

CO Problem

Liszt 2007

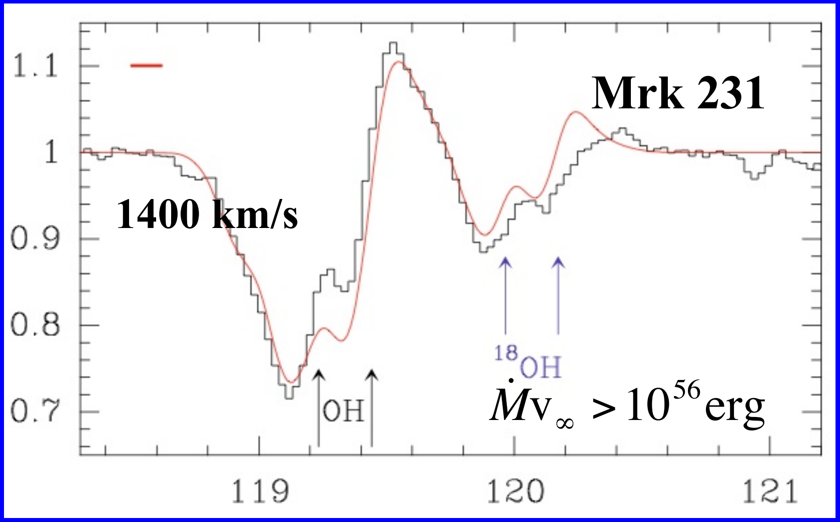
Mechanical Energy Input to the ISM





van Kempen et al. 2010 (WISH)

Fischer et al. 2010 (SHINING)

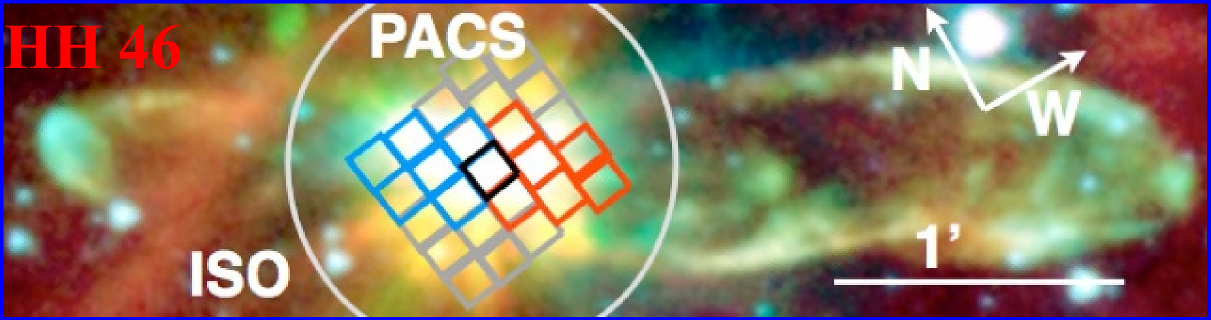


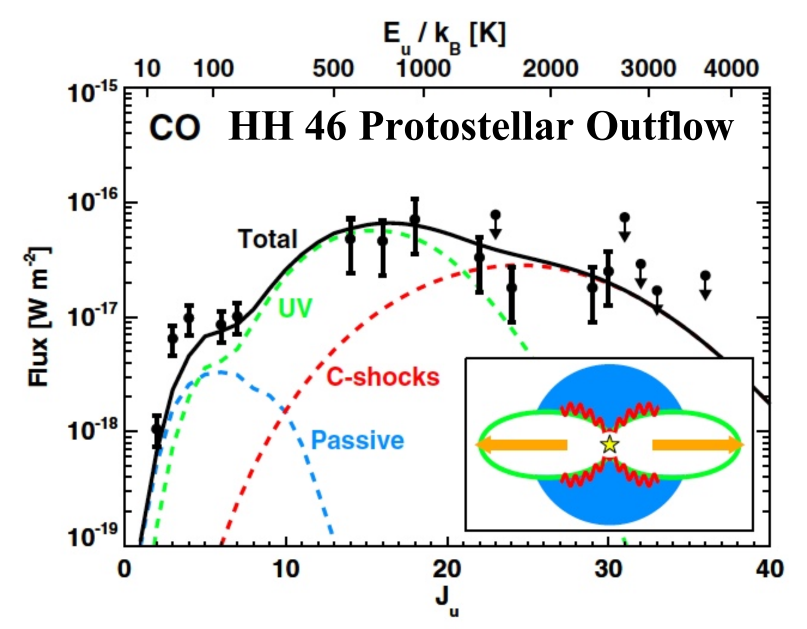
OH Superwind!

May halt star formation

Mechanical Energy Input to the I~~S~~M

IGM





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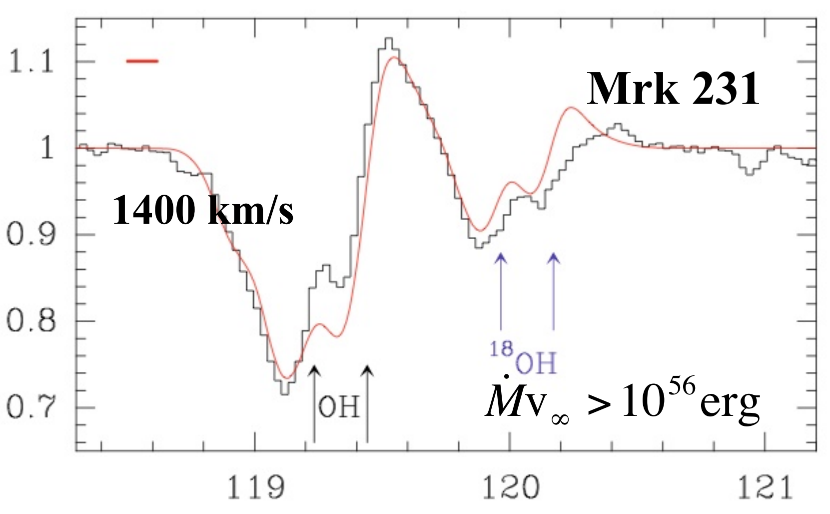


OH Superwind!

May halt star formation

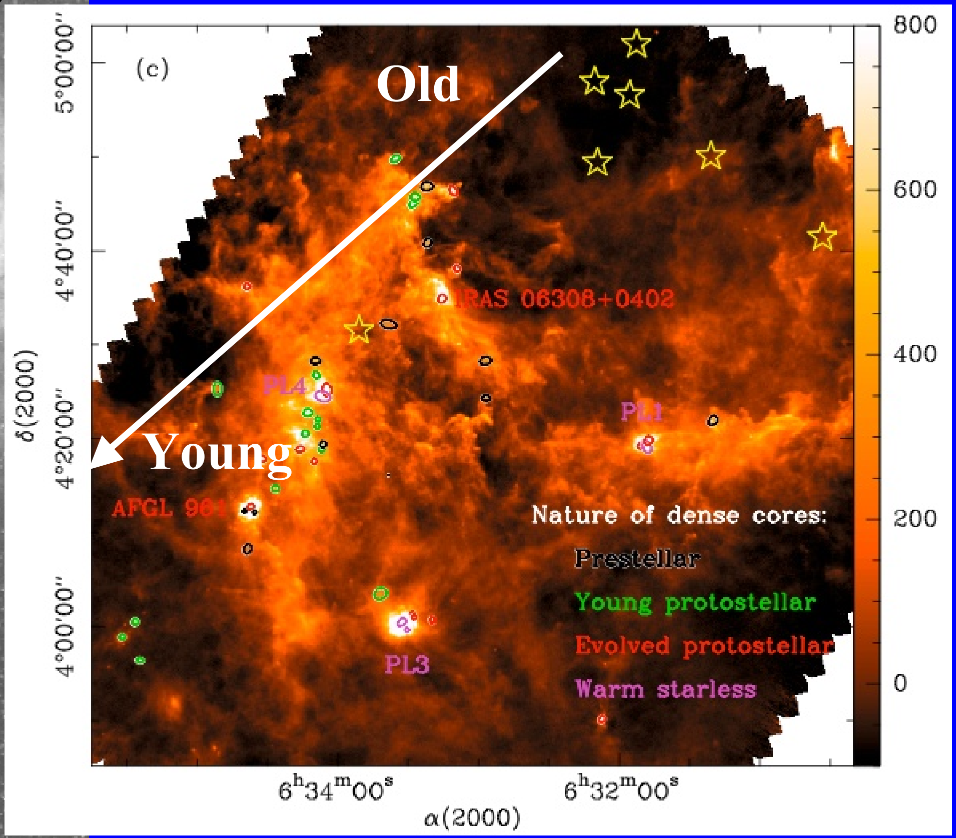
Coupling of Radiation, Gas and Dust

Cluster interaction, OB protostar evolution, triggering.

Radiation Pressure
Photodissociation
Photoevaporation
Turbulence
Stellar Winds

Schnieder et al. 2010 (HOBYS)

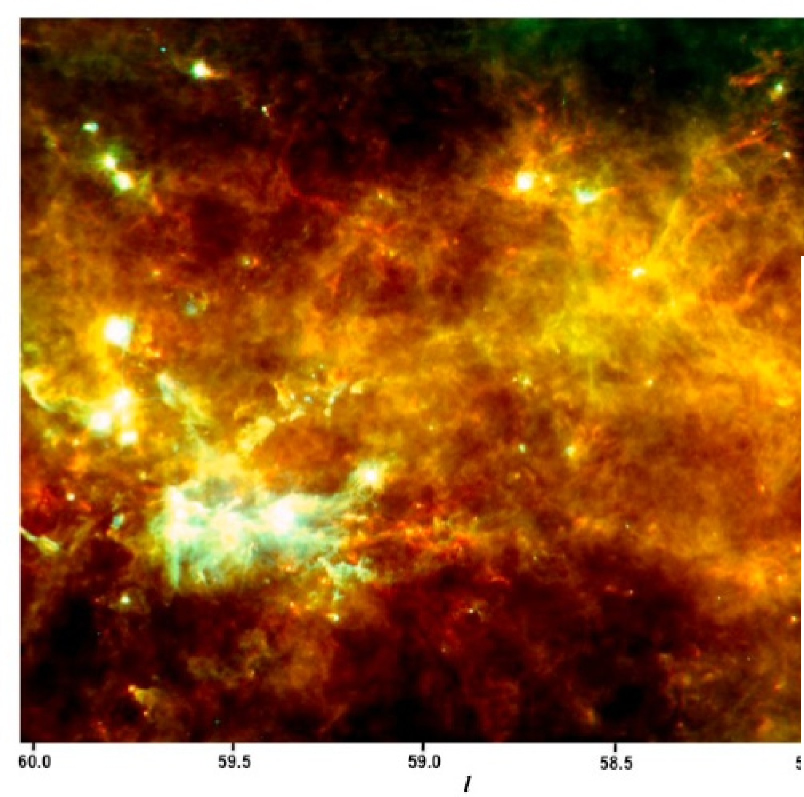
Unbiased OB protstar survey



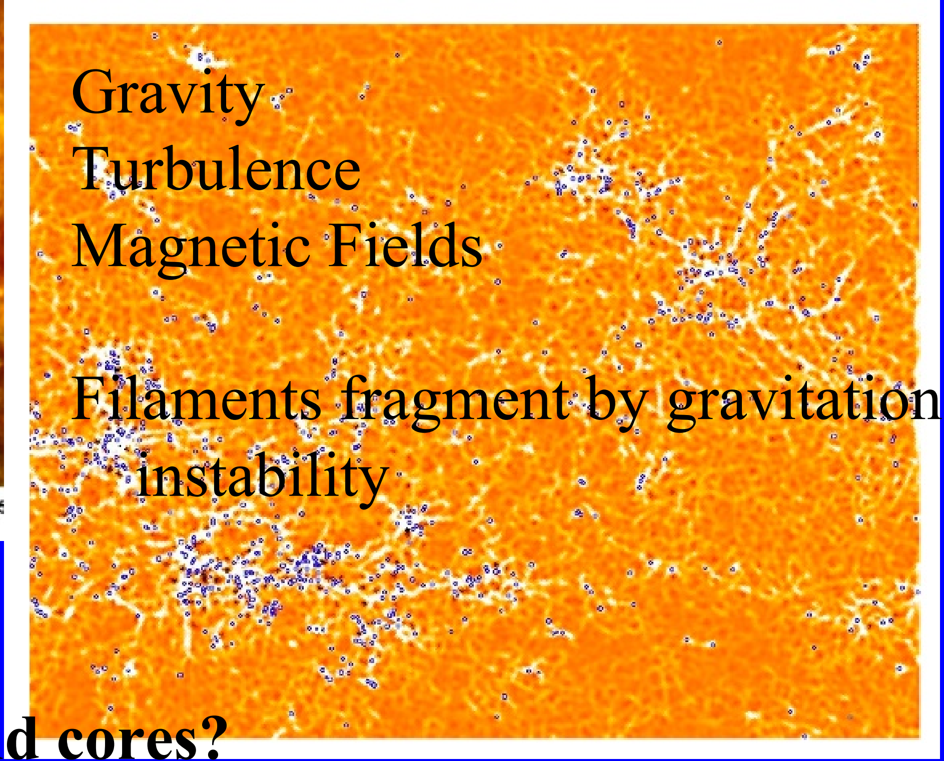
Motte et al. 2010 (HOBYS)

Billet et al. 2010 (MIPSGAL
+GLIMPSE)

Spitzer: GLIMPSE + MIPSGAL 3.6 µm - 70 µm
Herschel: Hi-GAL 70 µm - 500 µm



Star formation occurs along filaments.
c2d + Gould's Belt



Gravity
Turbulence
Magnetic Fields

Filaments fragment by gravitational instability

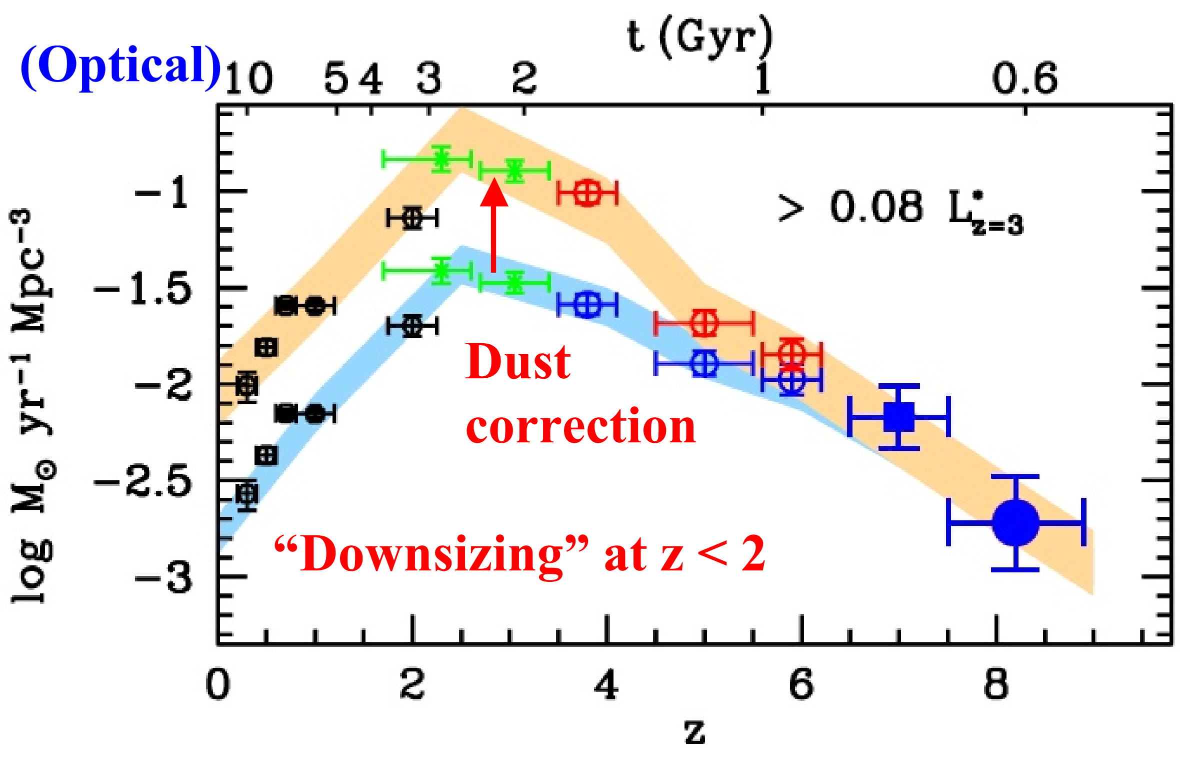
Motte et al. 2010 (Hi-GAL)

What forms the filaments and cores?

ISM Properties over Galactic and Cosmic Time

Galaxy Formation and Evolution

(Optical)



Dust correction

“Downsizing” at z < 2

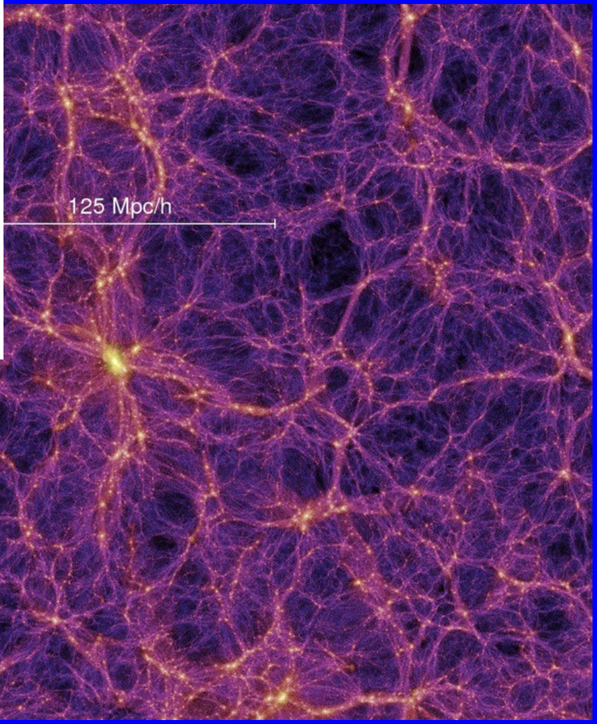
Bouwens et al. 2010

Galaxy Building

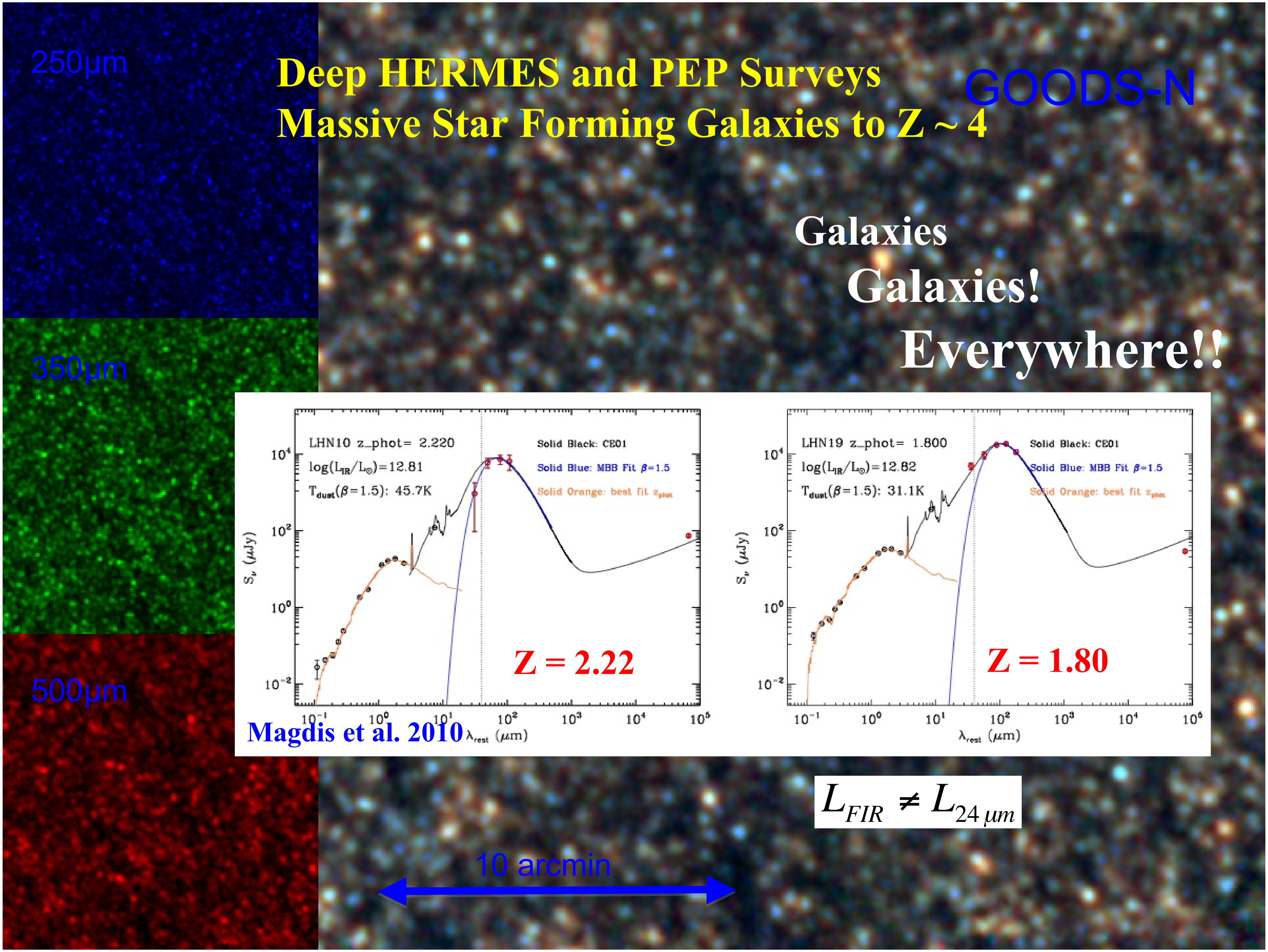
Feedback

Star Formation

Millennium Simulation



Deep HERMES and PEP Surveys
Massive Star Forming Galaxies to Z ~ 4



Galaxies

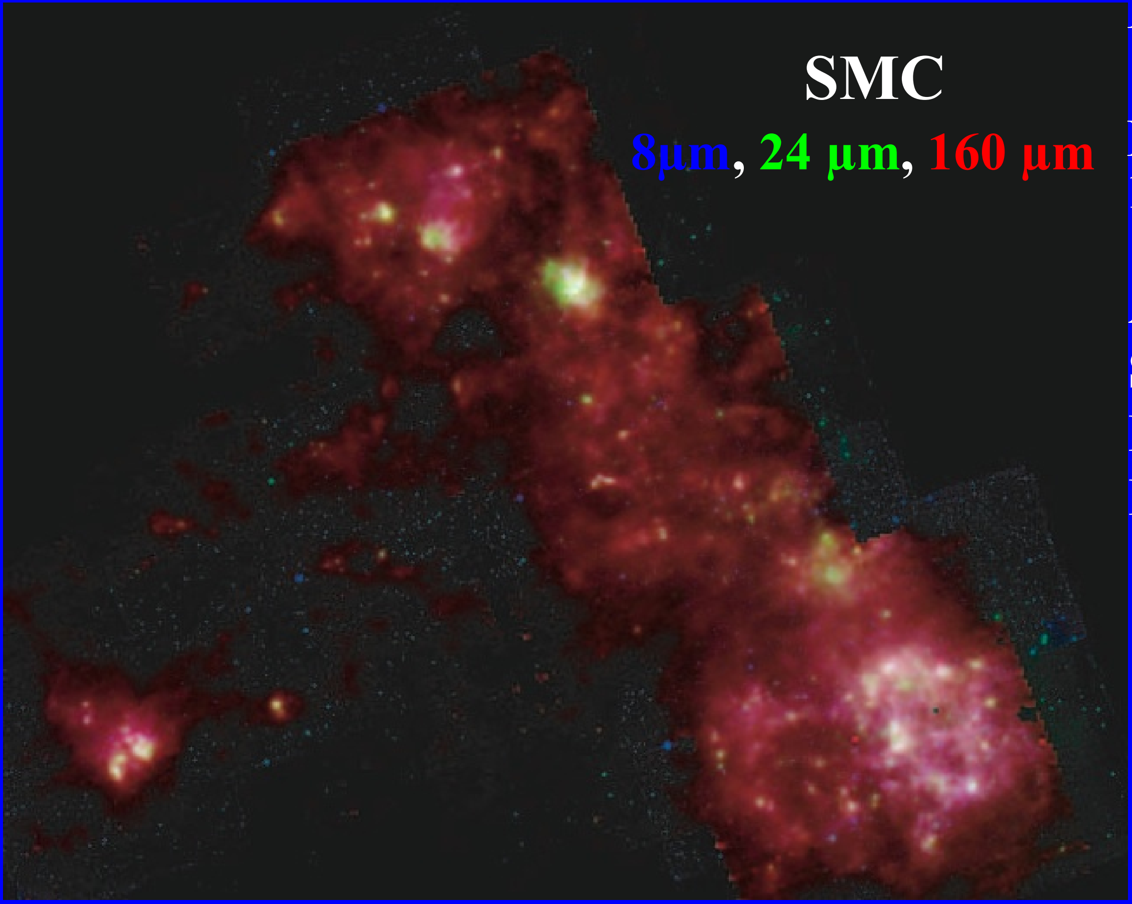
Galaxies!

Everywhere!!

Magdis et al. 2010

$$L_{FIR} \neq L_{24\,\mu m}$$

Effects of Metallicity



Leroy et al. 2007

LMC, SMC:
HERITAGE (Meixner)
Dwarf Galaxy Survey:
1/50 < Z < 1/20 (Madden)

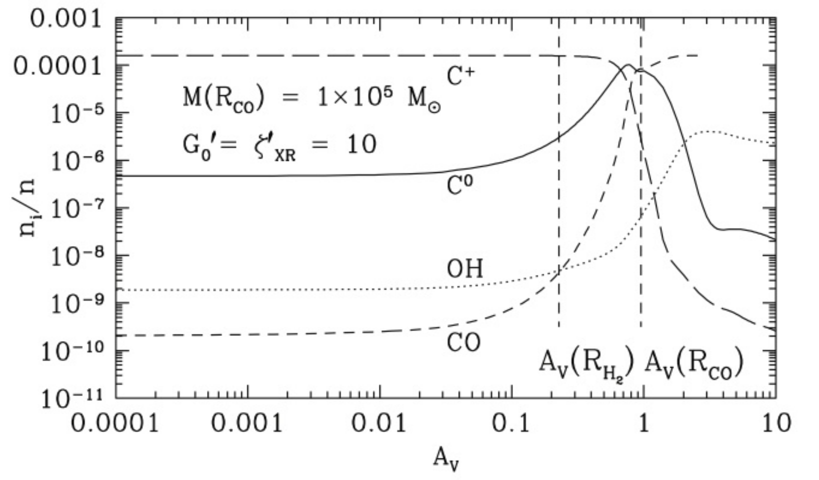
Also
SHINING (Sturm)
HER33ES (Kramer)
KINGFISH (Kennicutt)

$$\text{Heating} \propto Z_{\text{dust}}$$
$$\text{Cooling} \propto Z_{\text{gas}}$$
$$\text{ISRF} \propto 1/Z_{\text{dust}}$$

$$\text{Shielding Column for } H_2,\text{CO} \propto 1/Z_{\text{dust}}$$

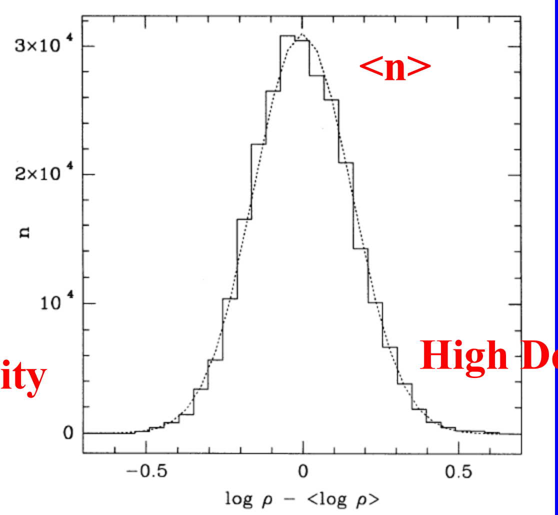
Dark Molecular Gas

1)Add turbulent density distribution
2)Applied global GMC properties
3)Calculated cloud masses



Wolfire, Hollenbach, & McKee 2010
Tielens & Hollenbach 1985
van Dishoeck & Black 1988
Smith & Madden 1997

Vazquez-Semadeni 1994



<n>

Low Density

High Density

Probability Density Function

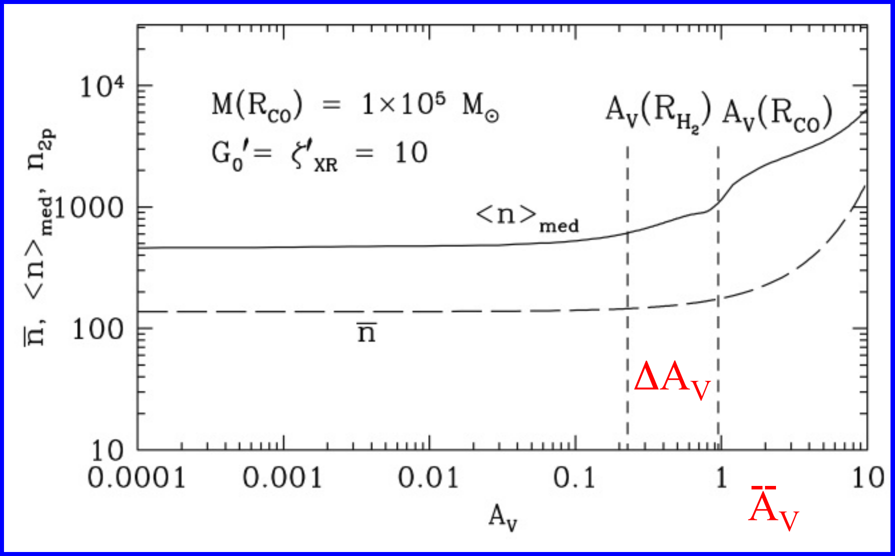
$$\langle n\rangle = \bar{n}\exp(\mu)$$

$$\mu = 0.5\ln(1 + 0.25\,M^2)$$

→ T

→ Vturb α $r^{1/2}$

Volume averaged density α $1/r$



ΔA$_V$

Ā$_V$

Wolfire, Hollenbach, & McKee 2010

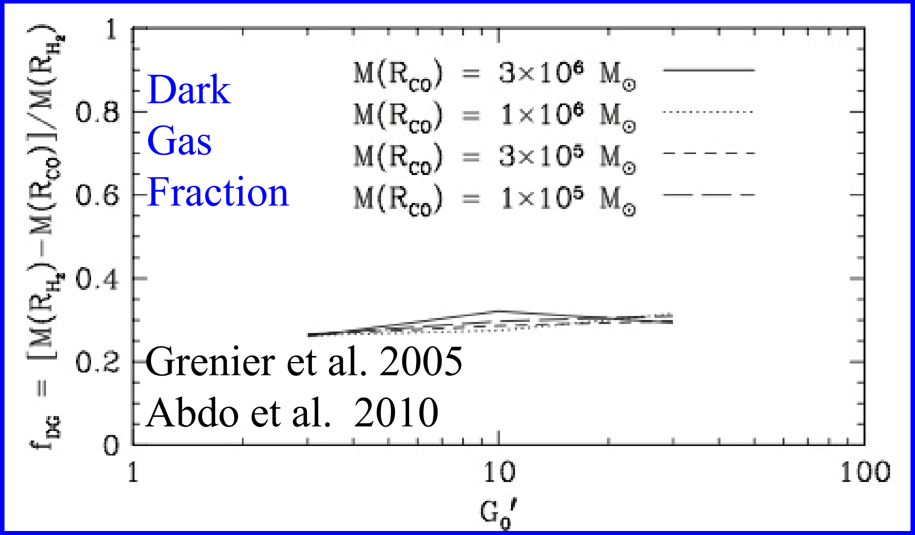
$$A_V(R_{\rm CO}) \simeq 0.102 \ln\left[3.3\times10^7\left(\frac{G_0'}{Z'n_c}\right)^2+1\right]$$

$$A_V(R_{\rm H_2}) \simeq 0.142 \ln\left[5.2\times10^3 Z'\left(\frac{G_0'}{Z'n_c}\right)^{1.75}+1\right]$$

$$\Delta A_{V,\,\rm DG} = 0.53 - 0.045\ln\left(\frac{G_0'}{n_c}\right) - 0.097\ln(Z')$$

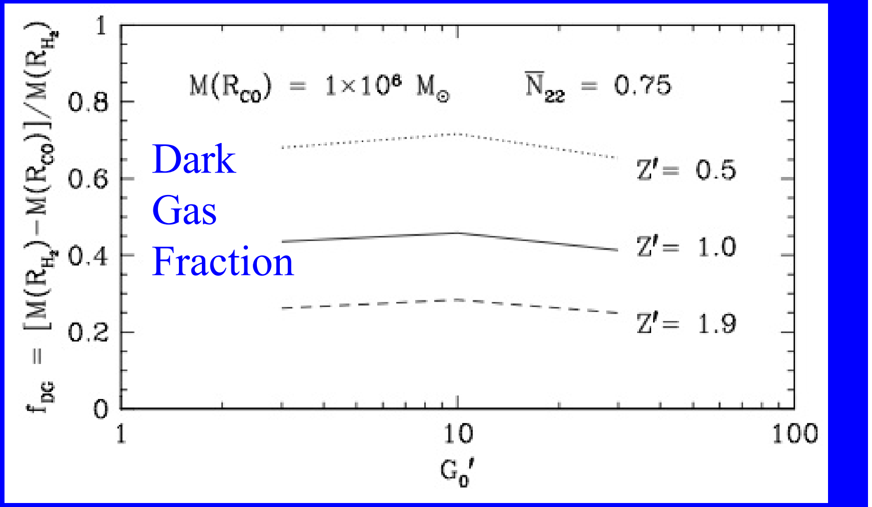
$$f_{\rm DG} = 1 - \exp\left(\frac{-4.0\Delta A_{V,\,\rm DG}}{\bar{A}_V}\right)$$

$$\bar{A}_V \equiv 5.26 Z'\bar{N}_{22}$$



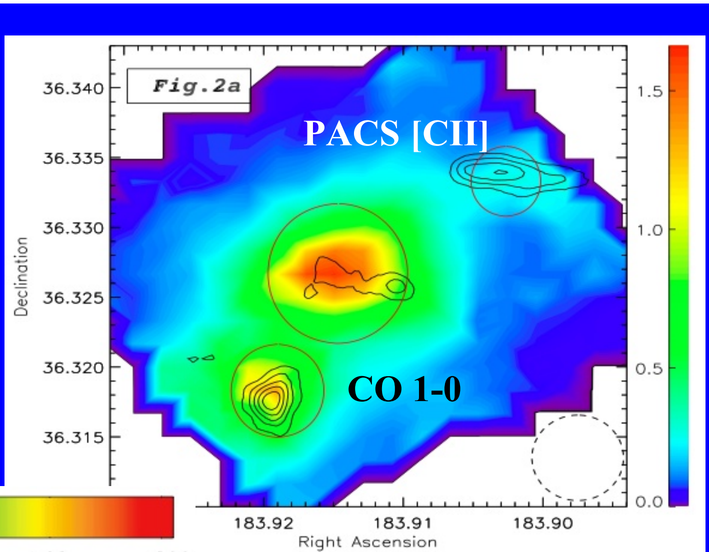
Dark
Gas
Fraction

Grenier et al. 2005
Abdo et al. 2010



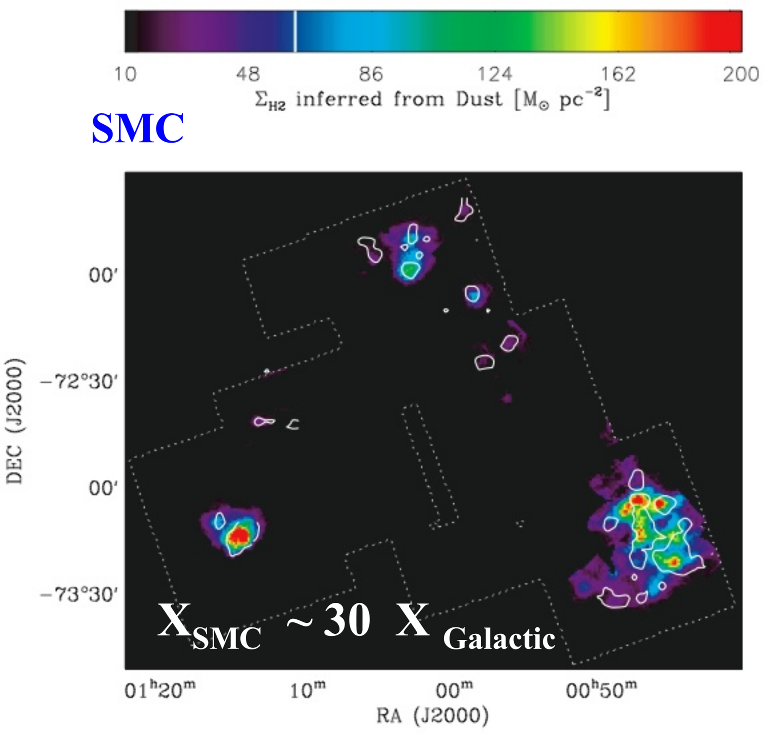
Dark
Gas
Fraction

The real X factor?



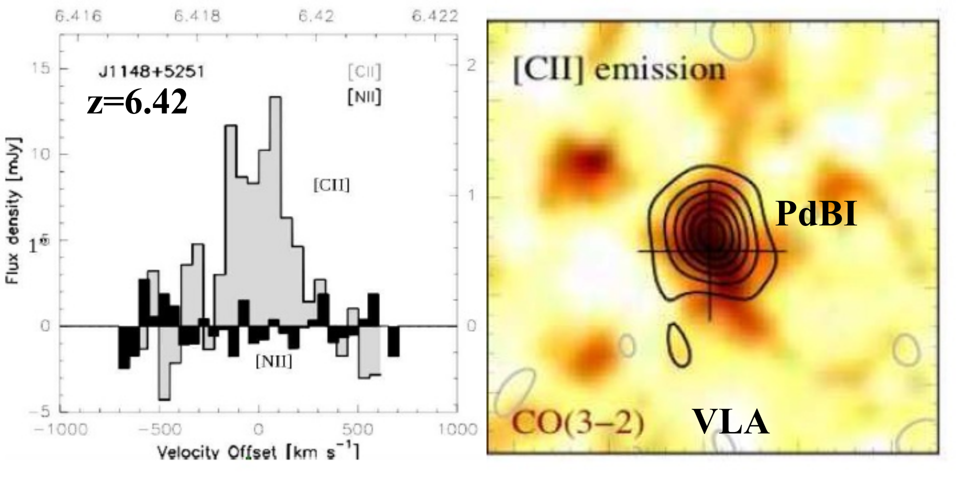
Cormier et al. 2010
(SHINING)

NGC 4214
O/H ~ 1.6 x10^{-4}
[CII]/CO ~ 20,000 - 70,000

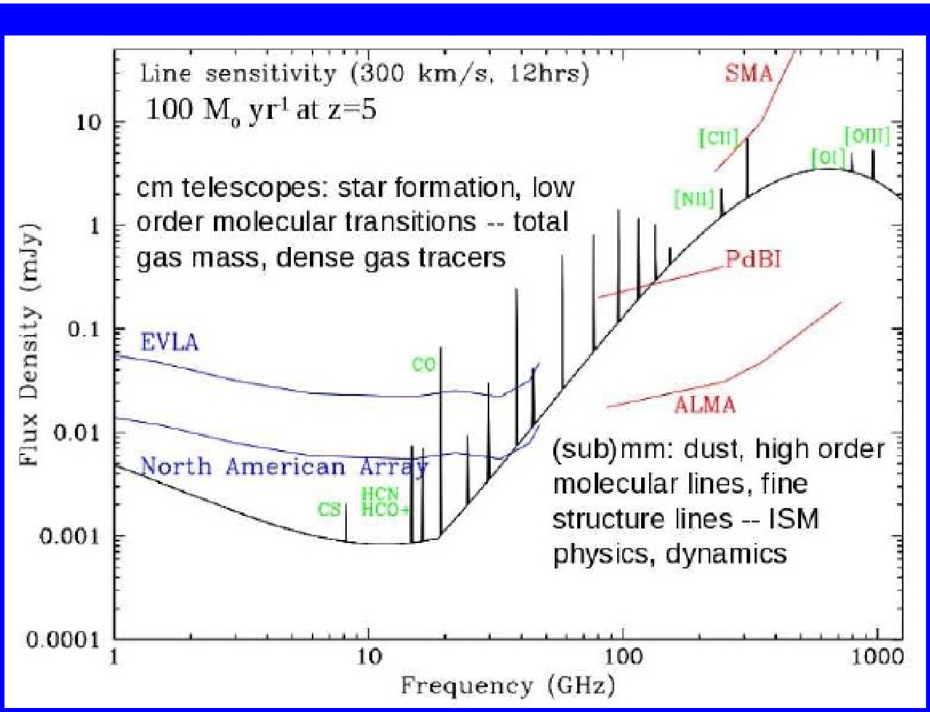


X_{SMC} ~ 30 $X_{Galactic}$

Leroy et al. 2007



Carilli et al. 2010



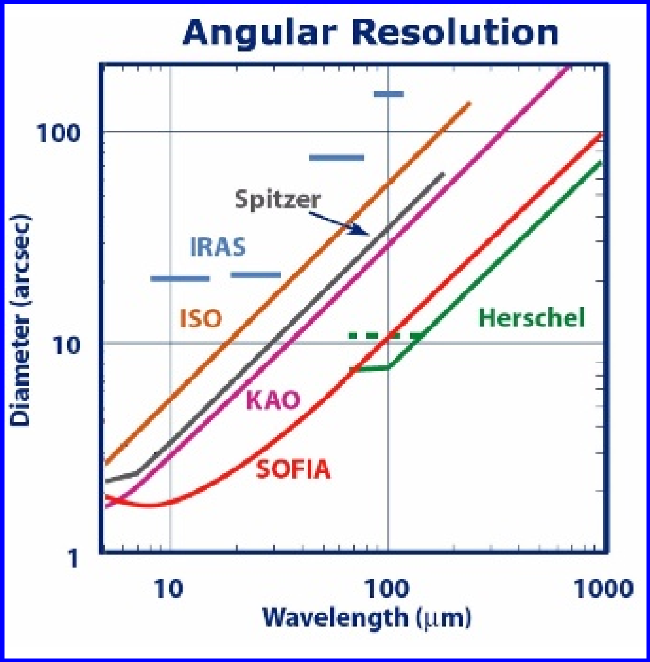
ALMA

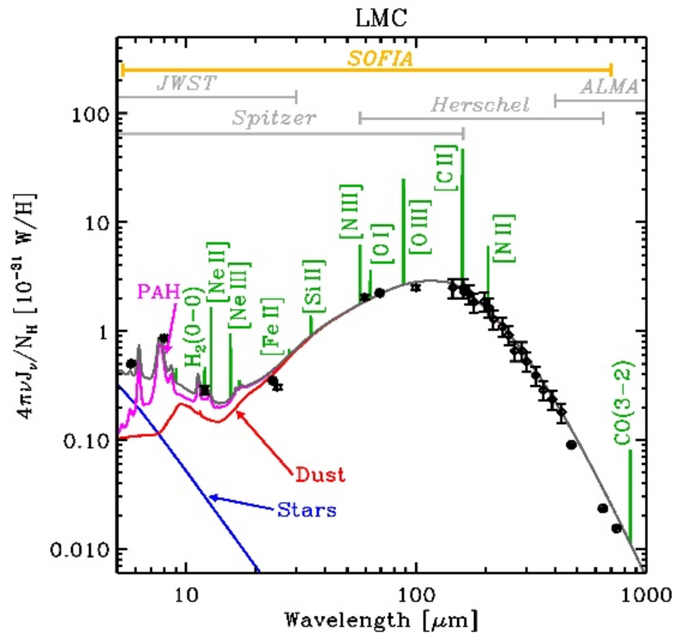
Detect [CII] to z ~ 6-10

SOFIA

Stratospheric Observatory for Infrared Astronomy

Carilli, Walter et al. 2010





▪Astrochemistry of Shocks and Other Dynamic Interstellar Processes

Models provide emission/absorption line diagnostics to obtain gas physical conditions. (T, n, FUV, cosmic ray, X-ray fields).

Line emission/absorption provides gas abundances and gas dynamics (turbulence, shocks).

Provides an understanding of how molecules form under a variety of conditions (including gas and grain reactions).

Provides probes of star formation and outflow processes.

▪Thermodynamics and Mechanics of the ISM

Provides for an understanding of the cycle of the ISM
warm → cold → molecular → stars

Provides for an understanding of the geometry of the diffuse and dense ISM (clumpy, smooth, sheets, filaments, swiss cheese or billiard balls?)

Provides an understanding of feedback from stars, SN, protostars, disks, and AGN to the ISM (IGM).

- **Coupling of Radiation, Gas and Dust**

Dust traces the radiation field and gas mass

Provides opacity for molecule formation

Probes the magnetic field

- **Secular Evolution of ISM Properties over Galactic and Cosmic Timescales**

Provides an understanding of galaxy formation and evolution

Provides an understanding of star formation history of the Universe

END