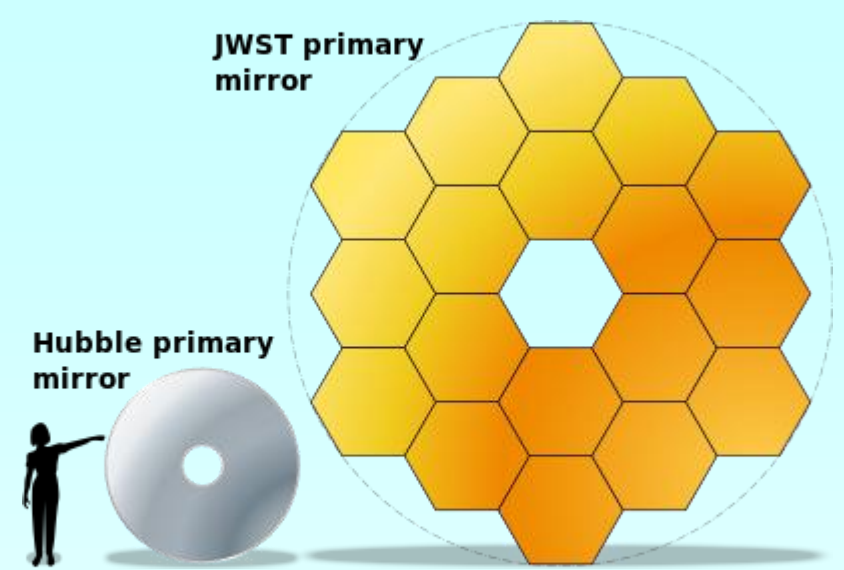
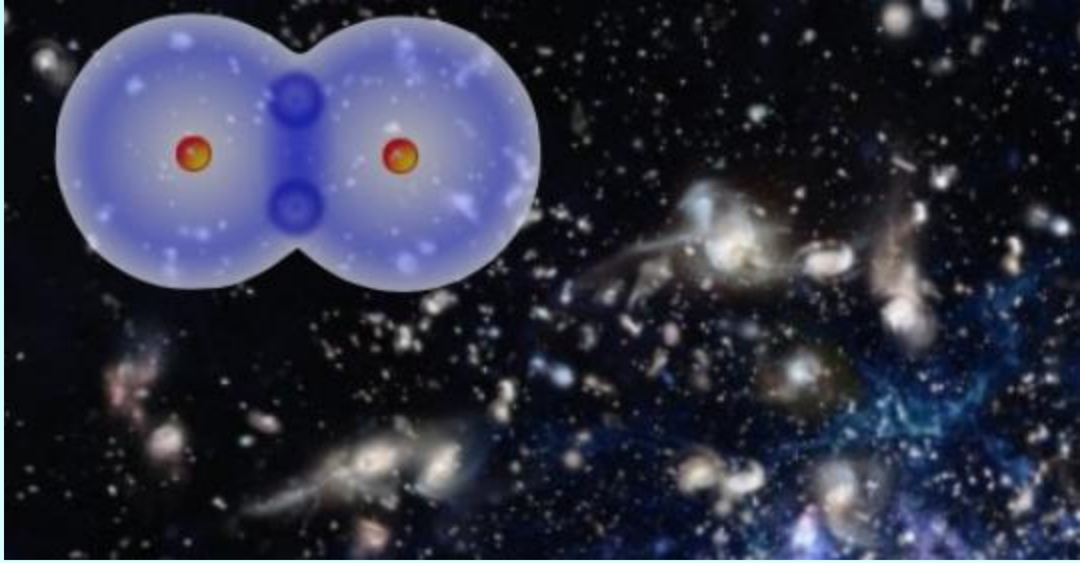


# Search for the molecular gas in the outer parts of galaxies

Françoise Combes, Observatoire de Paris

9 November 2016

COLLÈGE DE FRANCE 1530

l'Observatoire de Paris

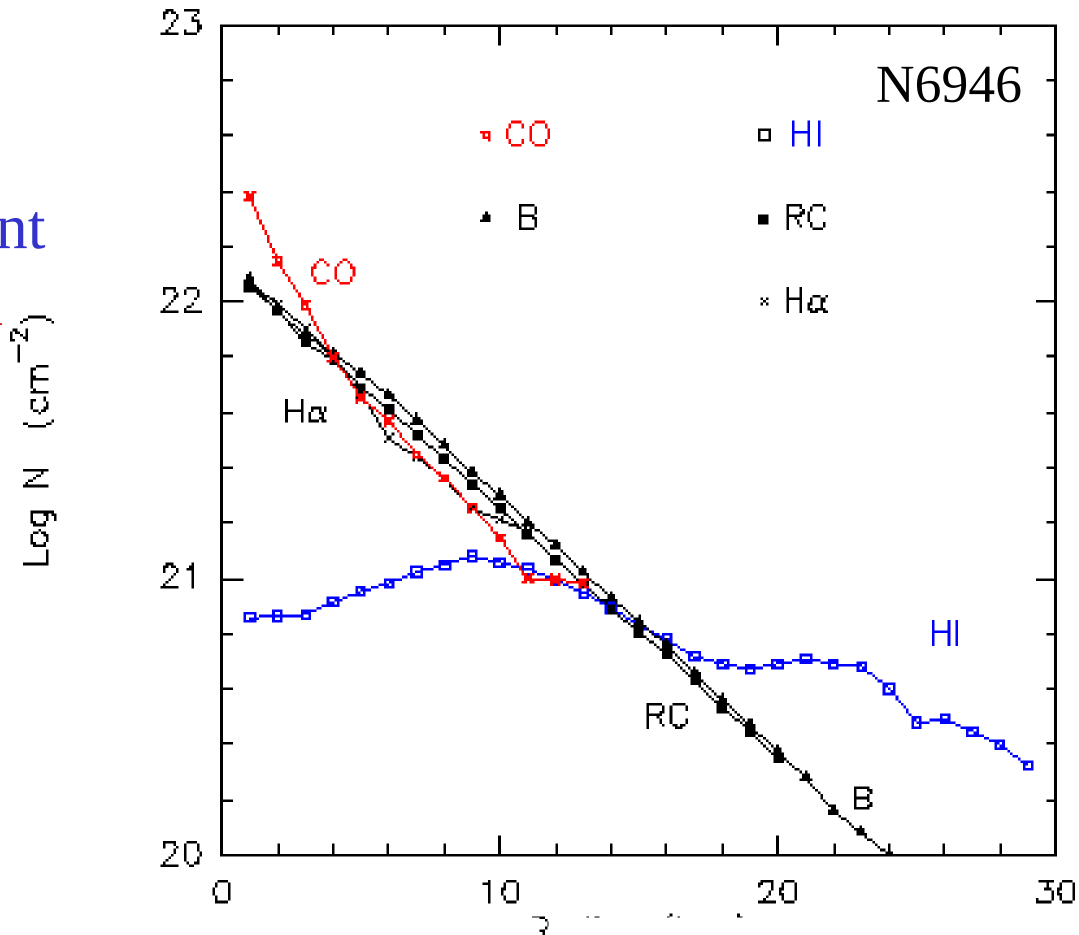
LERMA

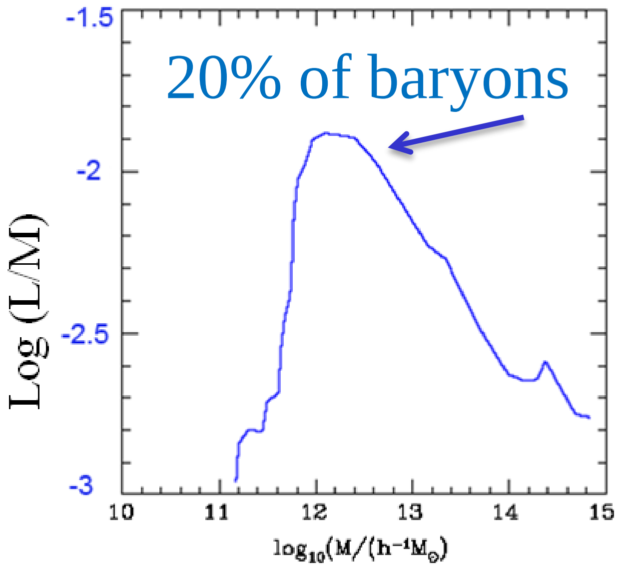
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

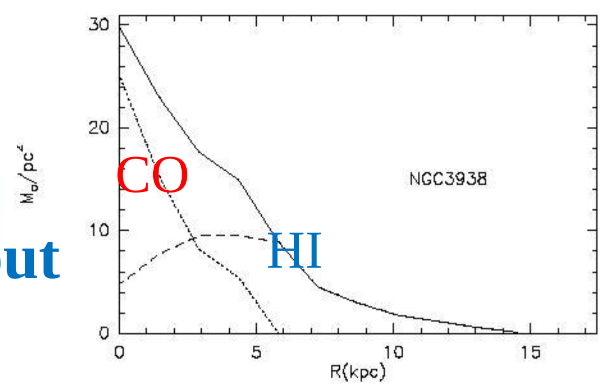
# Why outer parts of galaxies?

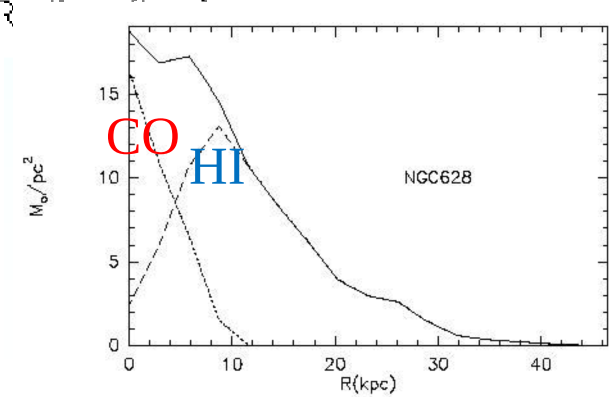
CO in exponential disks similar to optical

The HI is the only component not following star formation



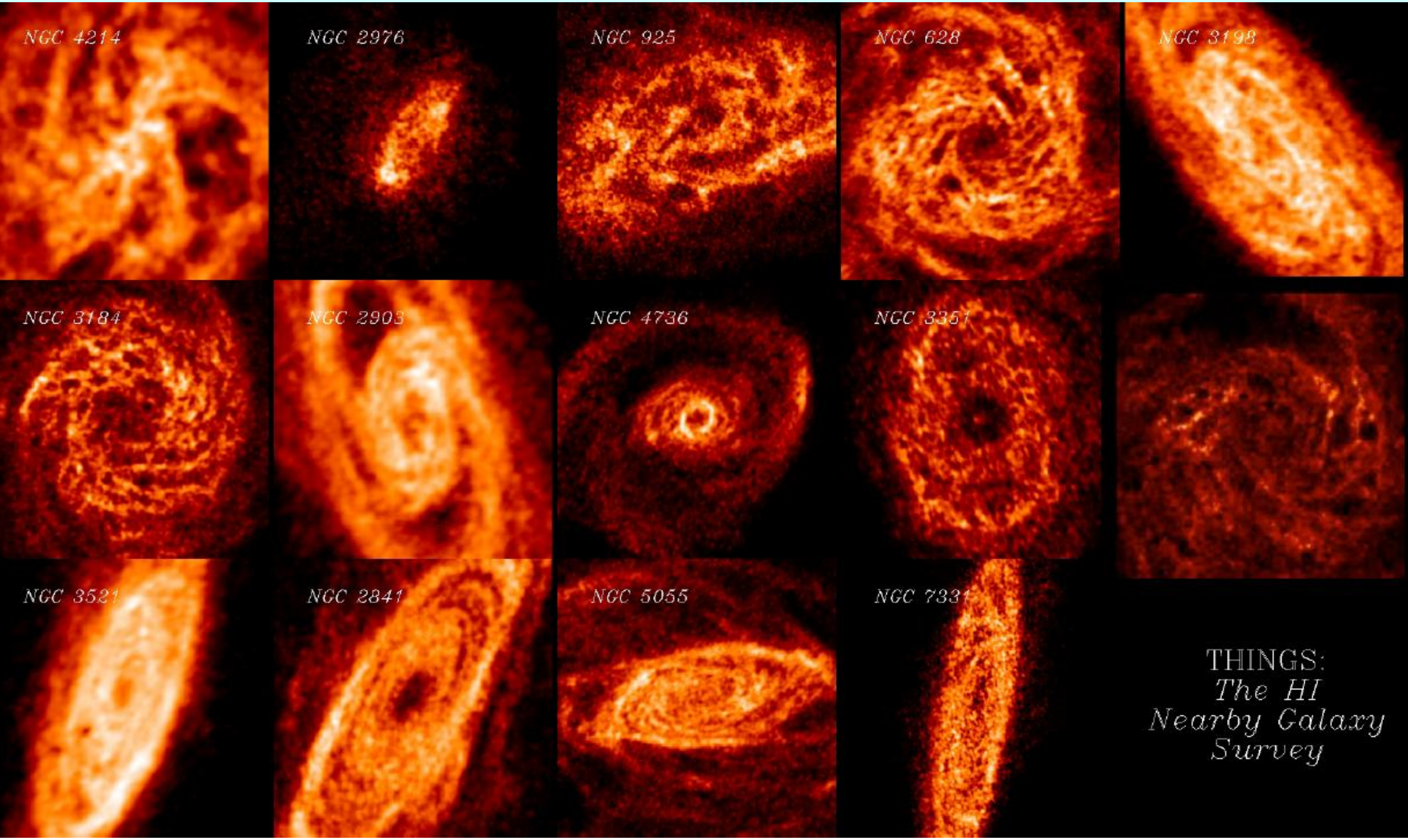



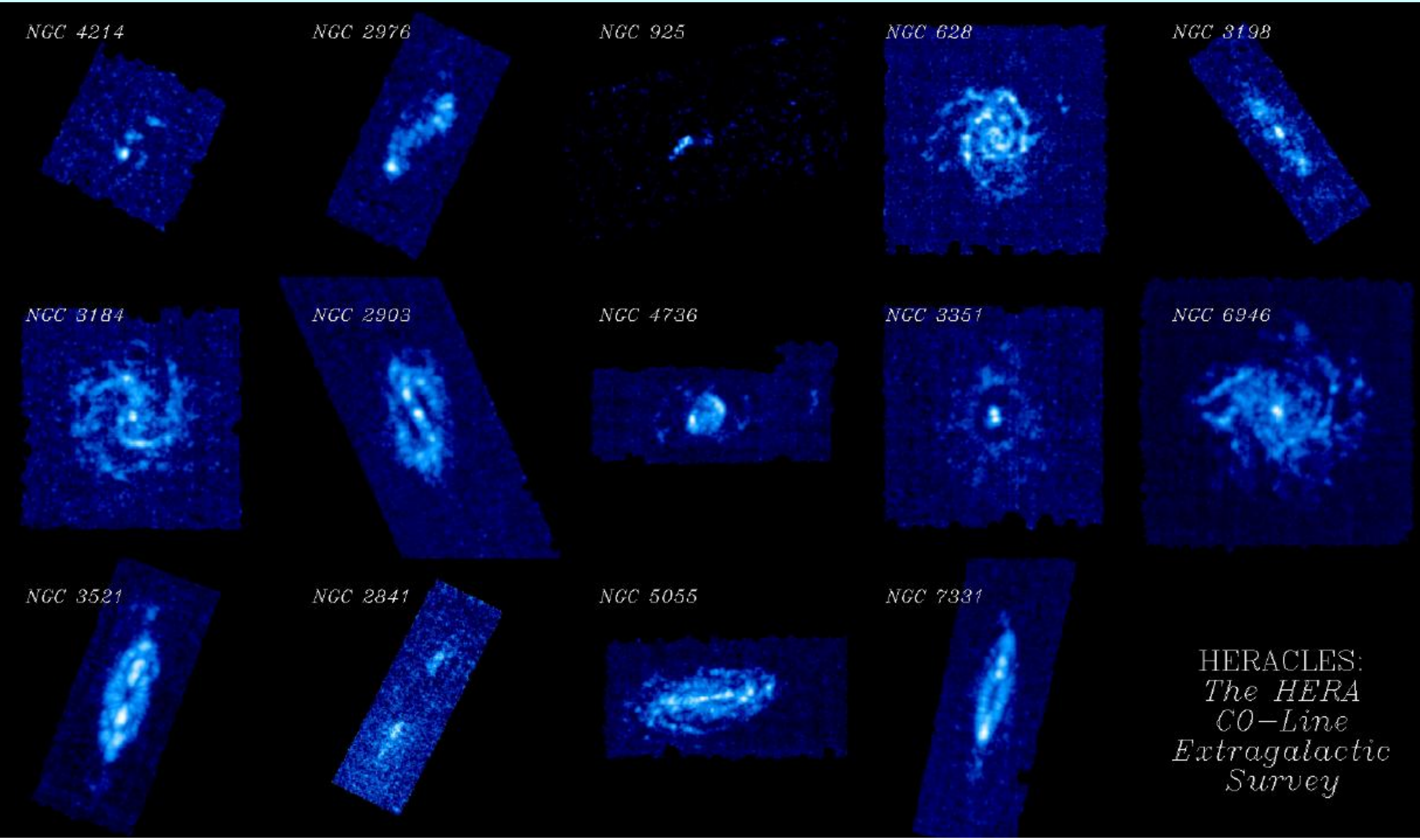




**>80% of baryons are out of galaxies**

# Atomic hydrogen HI-21cm

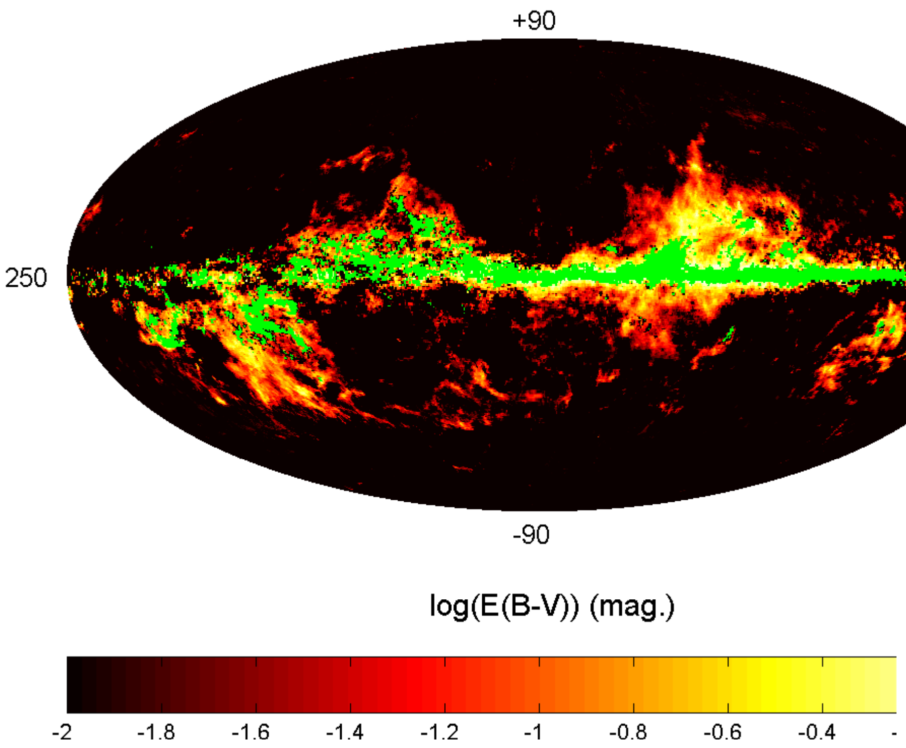


# Molecular gas from CO(2-1)



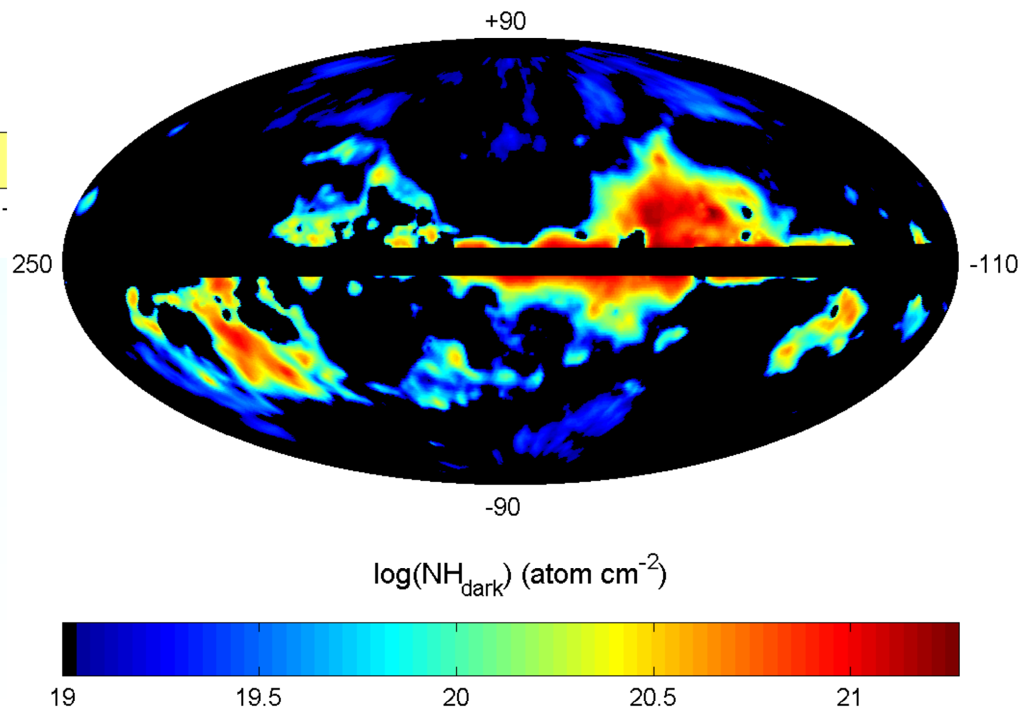

Leroy et al 2013

# Dark gas in the solar neighborhood




Dust detected in B-V
(by extinction)
and in emission at 3mm

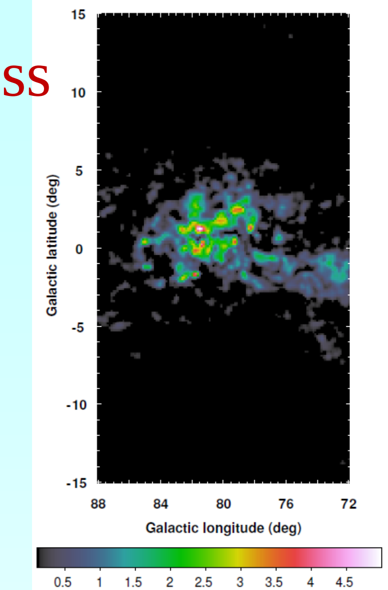
Emission Gamma associated
To the dark gas



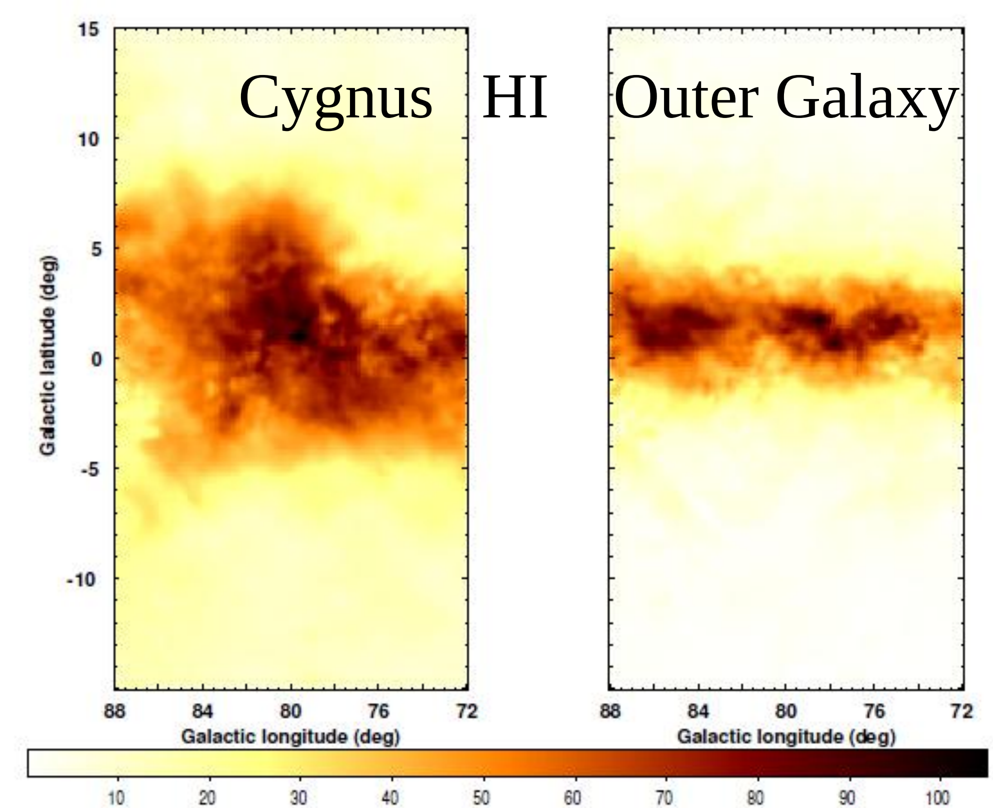

By a factor 2 (or more)
*Grenier et al (2005)*

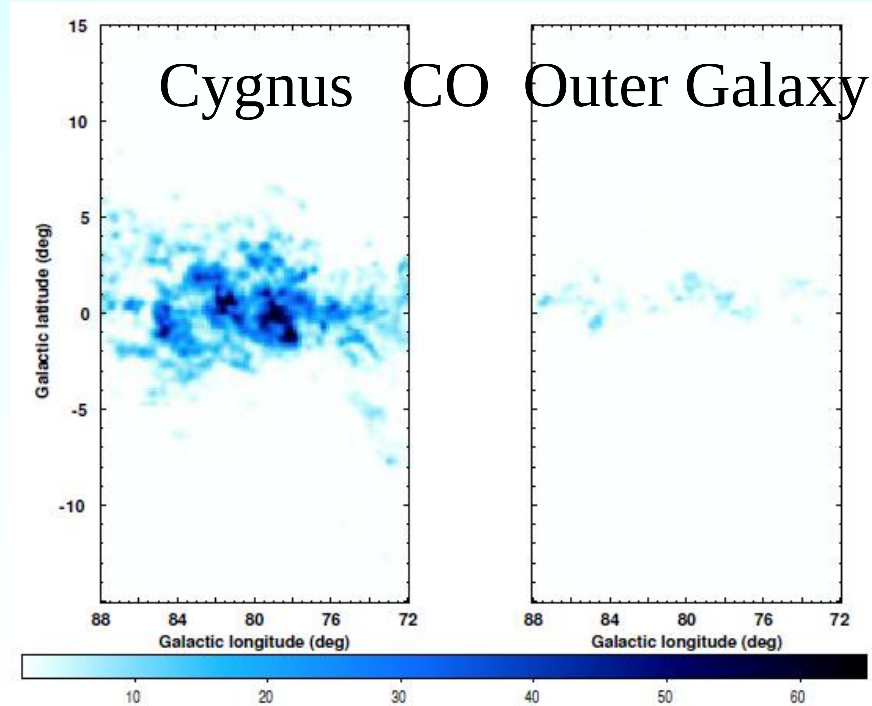
# Fermi-LAT in Cygnus

Av excess map



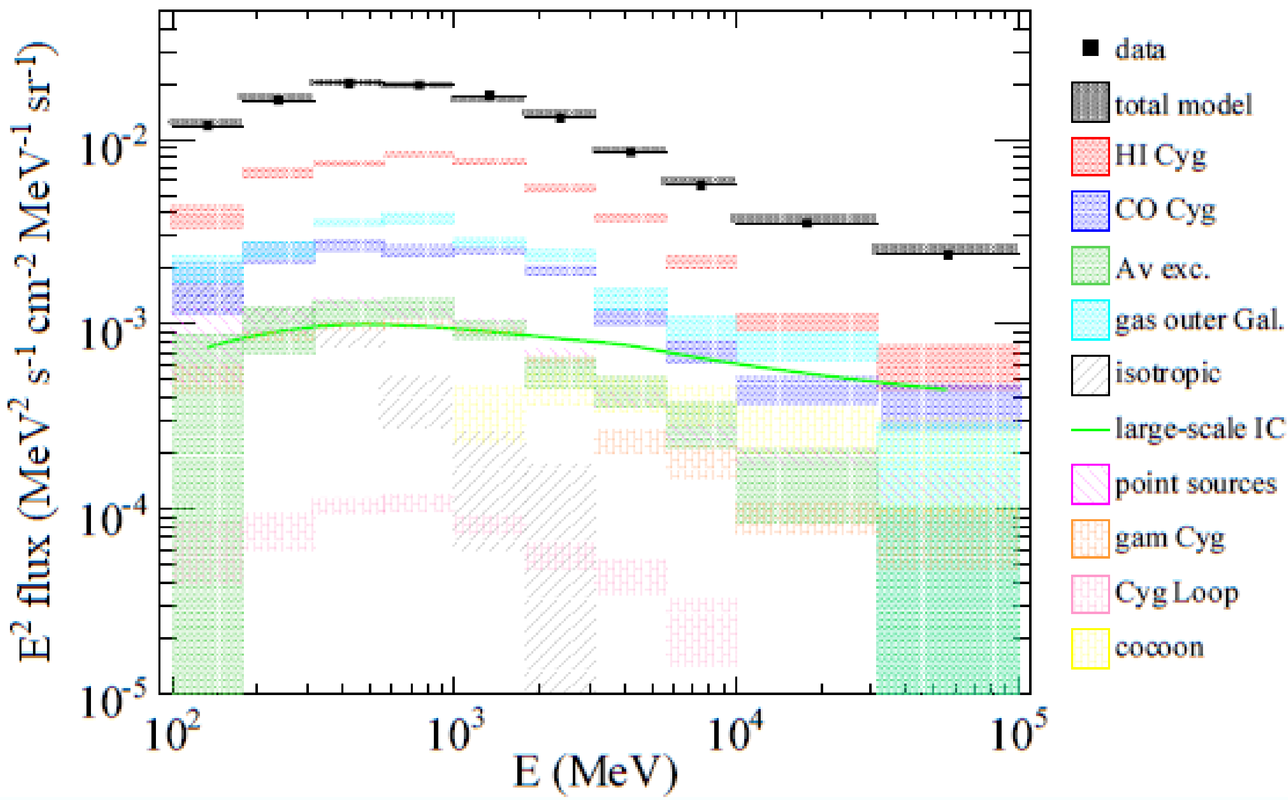

Significant γ-ray emission from dark neutral gas for a mass corresponding to ~ 40% of what is traced by CO
Even though Cygnus is an actively star forming region



# Dark gas in Cygnus -- 2011

➔ Siginficant fraction of dark neutral gas

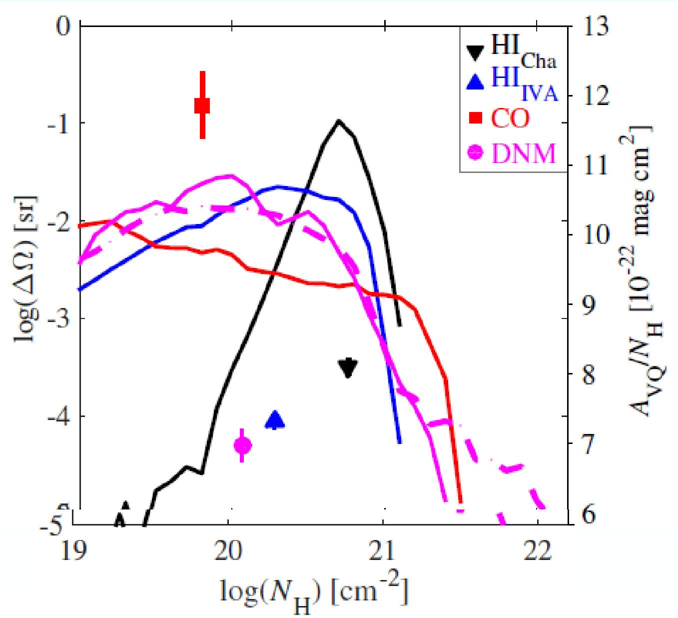


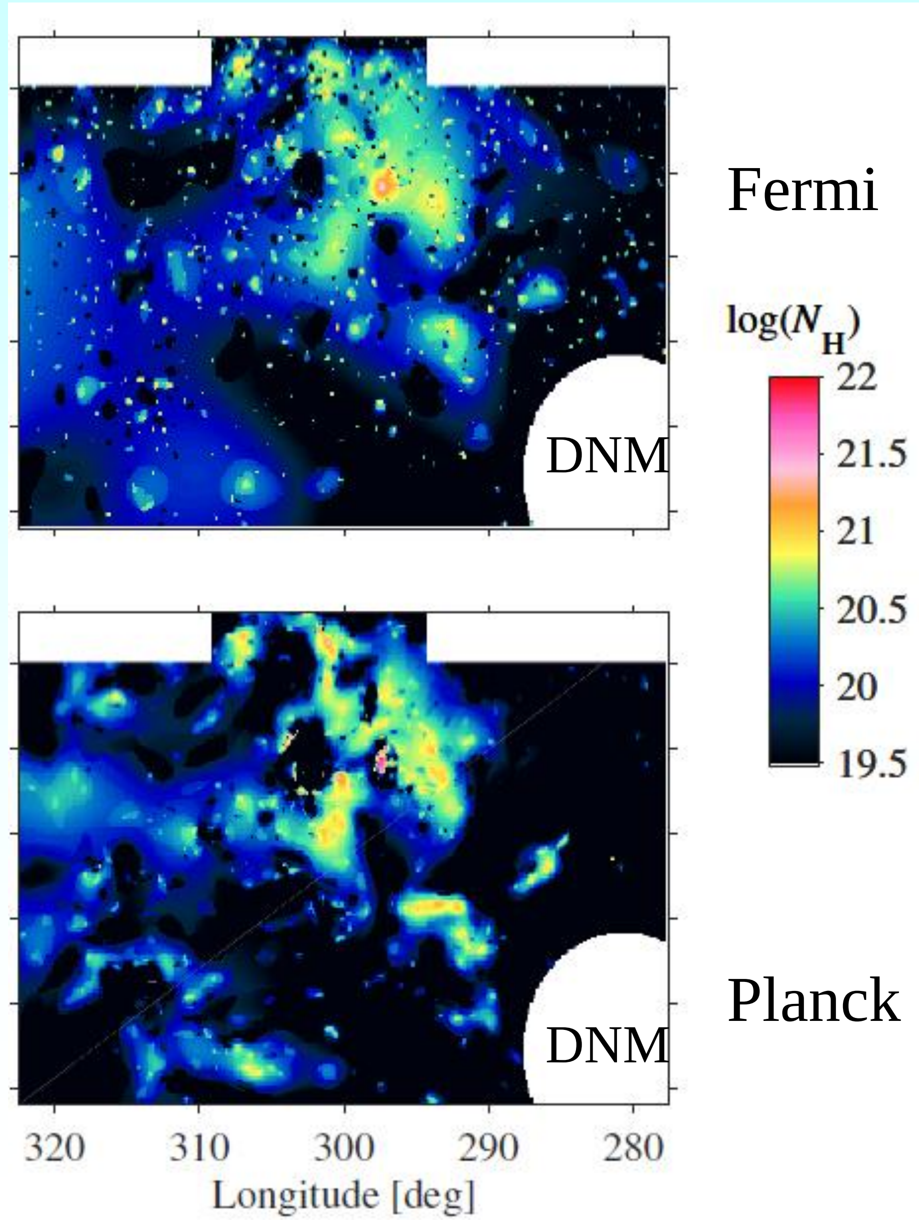

No difference in emissivities
CR couple equally to the dense clouds
No action of B
Magnetic field

Fermi 100 Mev- 100Gev
XCO = 1.7 $10^{20}$ cm-2 /(Kkm/s), as in the Local arm
Total mass 8 $10^6$Mo, at D=1.4kpc

# DNM in Chamaeleon: Planck + Fermi (2015)

Dust seen by Planck at 353 GHz,
γ-rays by Fermi
XCO varies by factors 2 or more
There is a significant fraction of
Dark Neutral Medium (DNM)
Either CO-dark $H_2$ or HI-dark atomic
$A_V$, or τ353, all agree



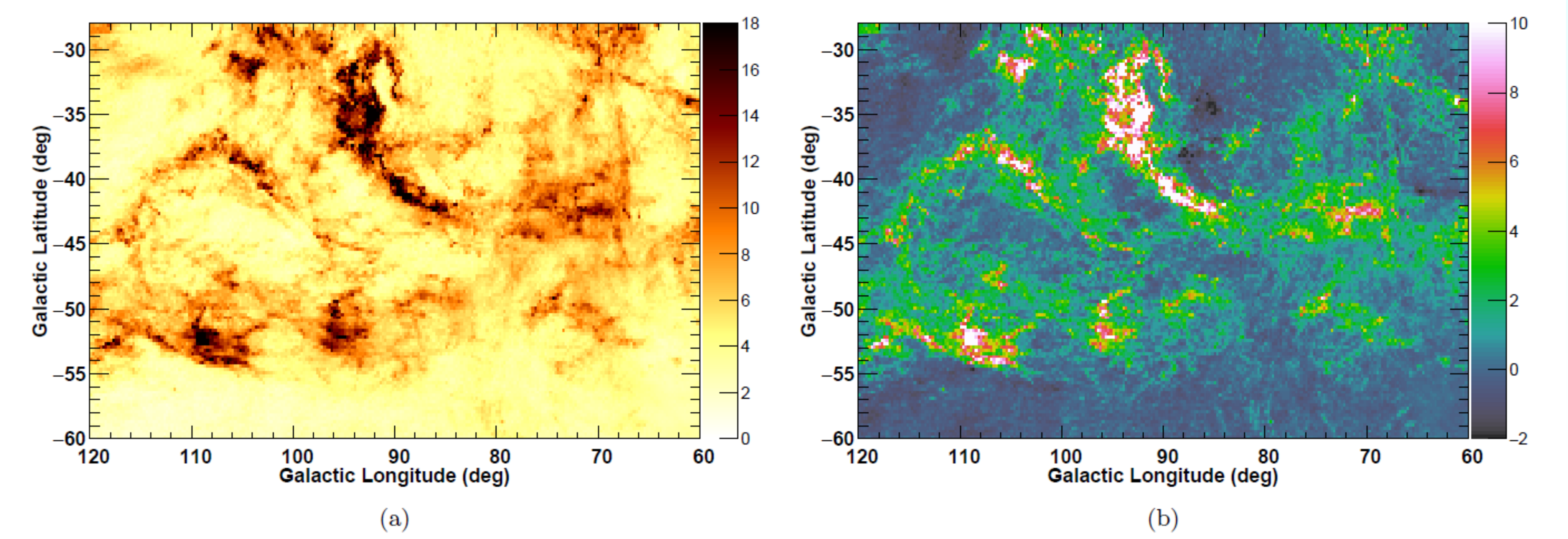



# DNM in high-latitude clouds MBM

The dark gas amounts to 5 times the CO-bright $H_2$, 25% HI
*Mizuno et al 2016*

γ-rays +CR, Av, dust opacity at 353 GHz, Dust Radiance

Total H DNM



# DNM seen from Planck dust emission

DNM = 118% of the CO emitting gas in the solar neighbourhood

XCO = 2.5 $10^{20}$ $cm^{-2}$ /(Kkm/s)

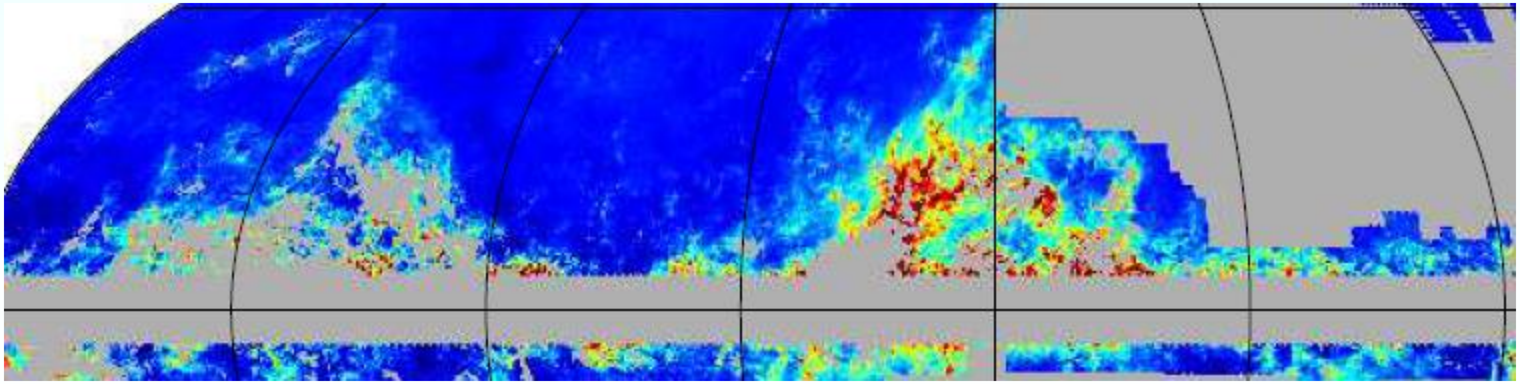
The DNM appears as a phase transition between HI and CO-bright H2

Av~0.4, could be traced by CI or CII?

$$f_{\rm DARK} = \frac{2N(\rm H_2^{dark})}{2N(\rm H_2) + N(\rm HI)} = f(\rm H_2) f_{DG}$$

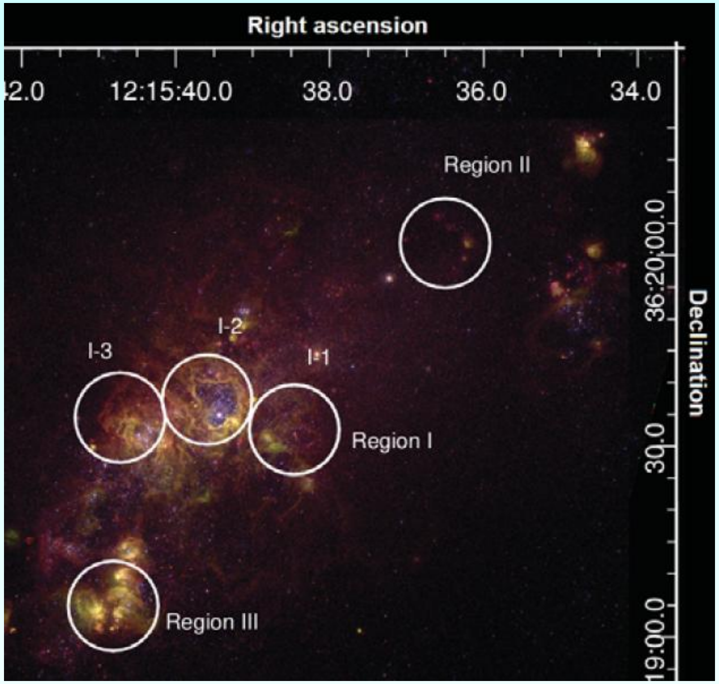
$f_{DG}$ =1.06-1.22

Some DNM could also be thick HI



*Planck Collaboration 2011*

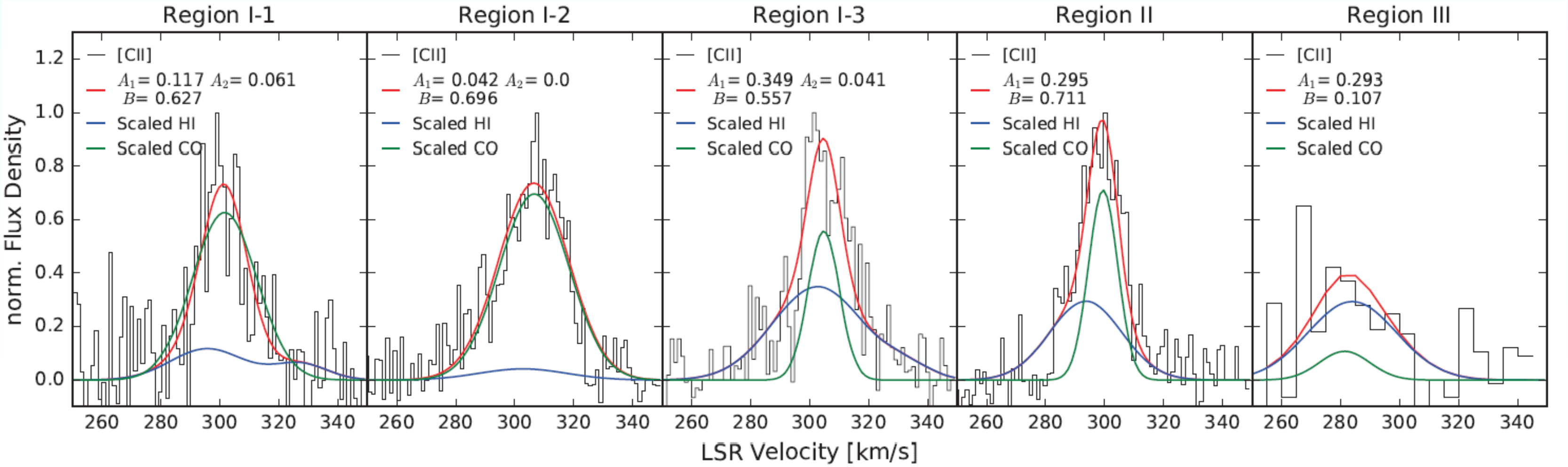
# CO-dark $H_2$ traced by CII




NGC4214
CII associated to PDR

79% of the total molecular gas is CO-dark

*Fahrion et al 2016*



# The CO-$H_2$ conversion factor

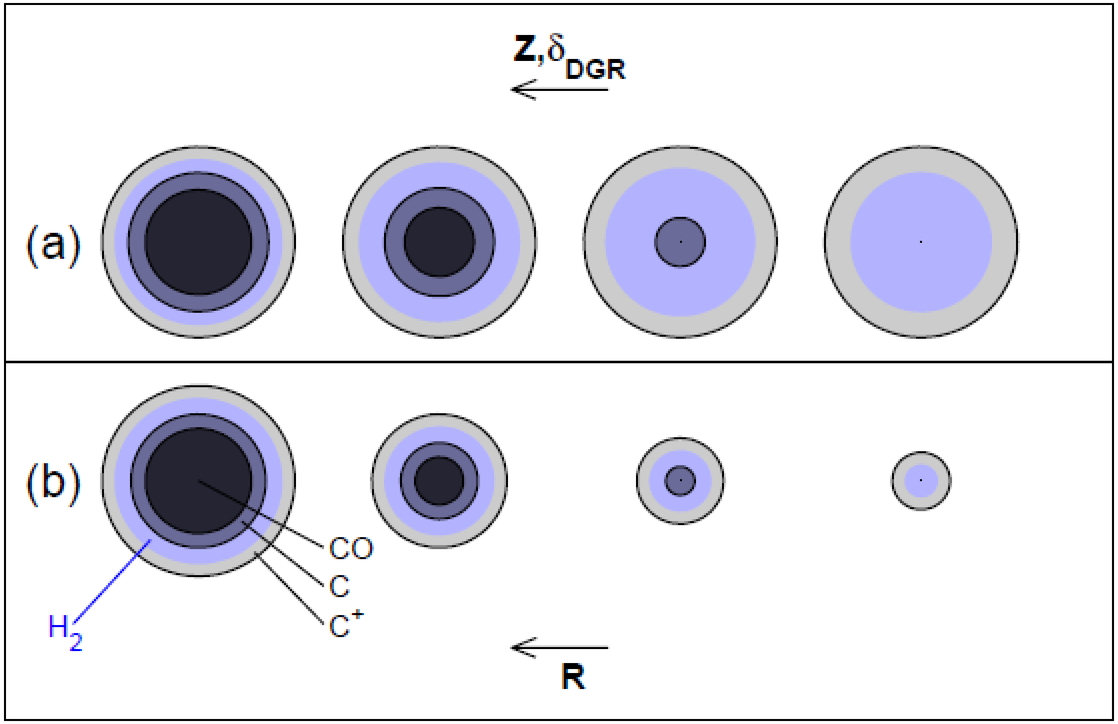
Virial assumption: $\alpha_{CO} \propto \frac{\rho^{0.5}}{T_B}$

$N(H_2) = 2\ 10^{20}$ ICO $cm^{-2}$ /(Kkm/s)

$\boldsymbol{\alpha_{CO}}$ **= 4.36** (with x1.36 for He)

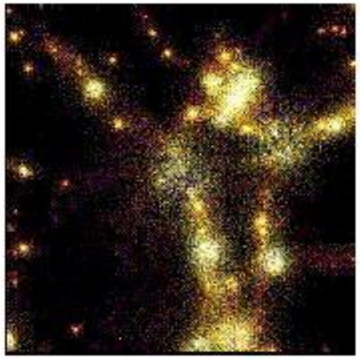
In ULIRGs, $\boldsymbol{\alpha_{CO}}$ **= 0.8**
But, not sure at high z

At low metallicity
CO photodissociated,
Less dust more UV,
$H_2$ self-shielded
$\boldsymbol{\alpha_{CO}}$ **in $1/Z^2$?**

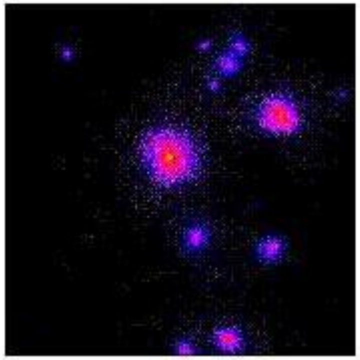



*Bolatto et al 2013*

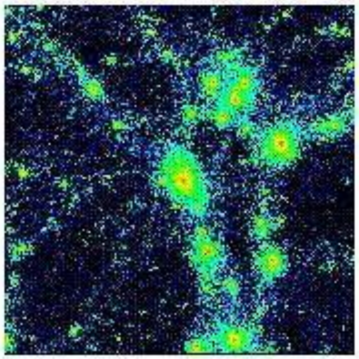
# Hot Gas in filaments



WHIM

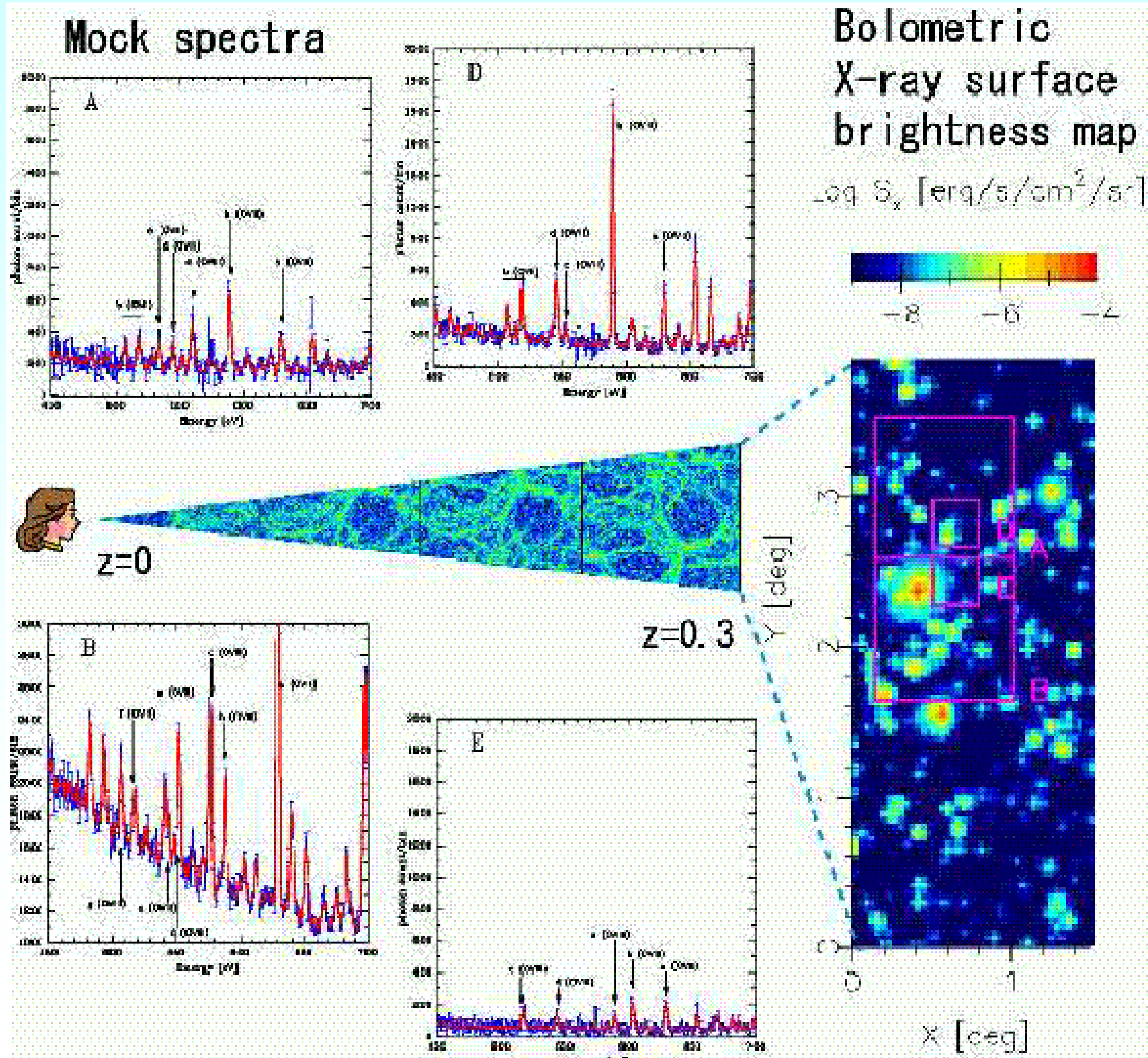


ICM



DM

Detection of OVI in X-ray?



# MUSE discovery of « cold » atomic gas illuminated by quasars

Blind survey for giant Ly-α nebulae around **17 bright RQQ** at 3<z<4

All QSO have 100-320kpc Ly-α nebulae

*Borisova et al 2016*

➔Ubiquitous, like the Slug nebula,

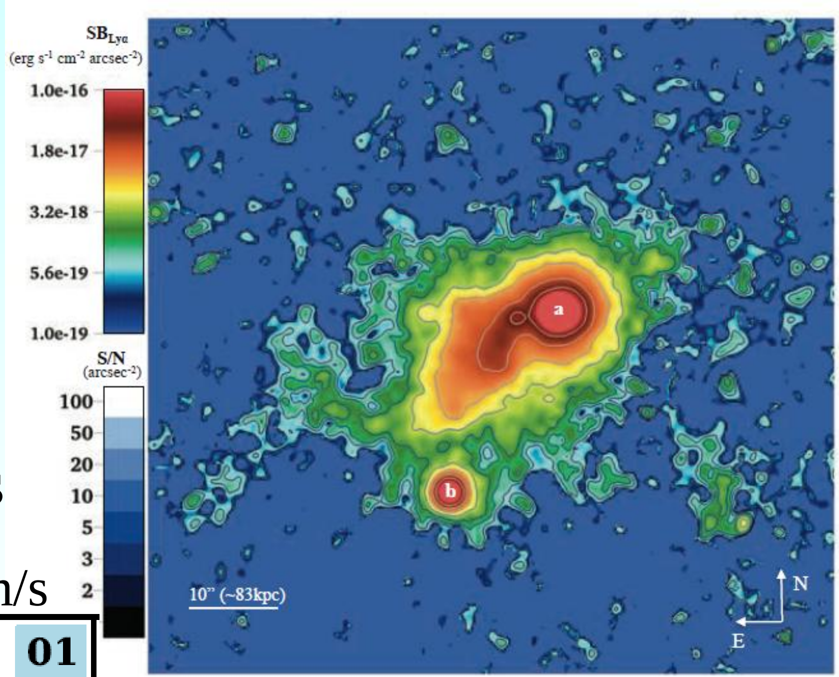
Fluorescence of gas up to 500kpc

at z=2, $10^{12}$Mo filament

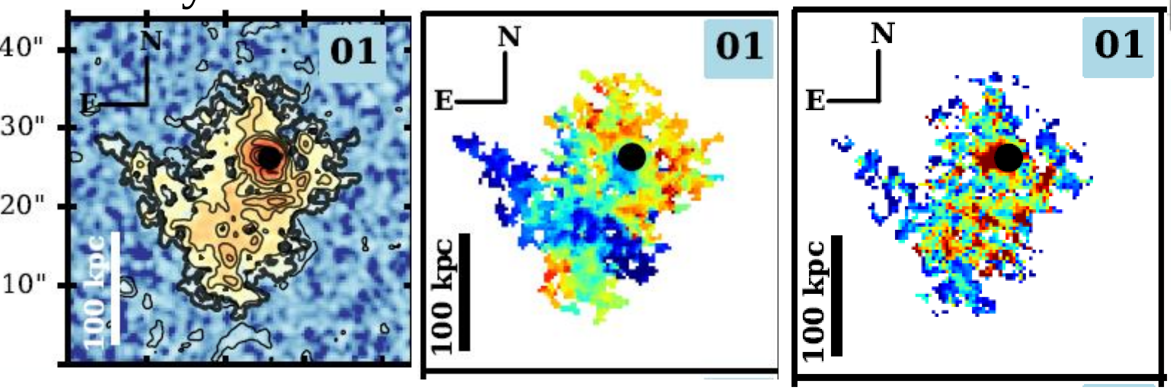
*Cantalupo et al 2014*

Also absorption lines in front of he QSO

➔ 60% filling factor of "cold" dense gas



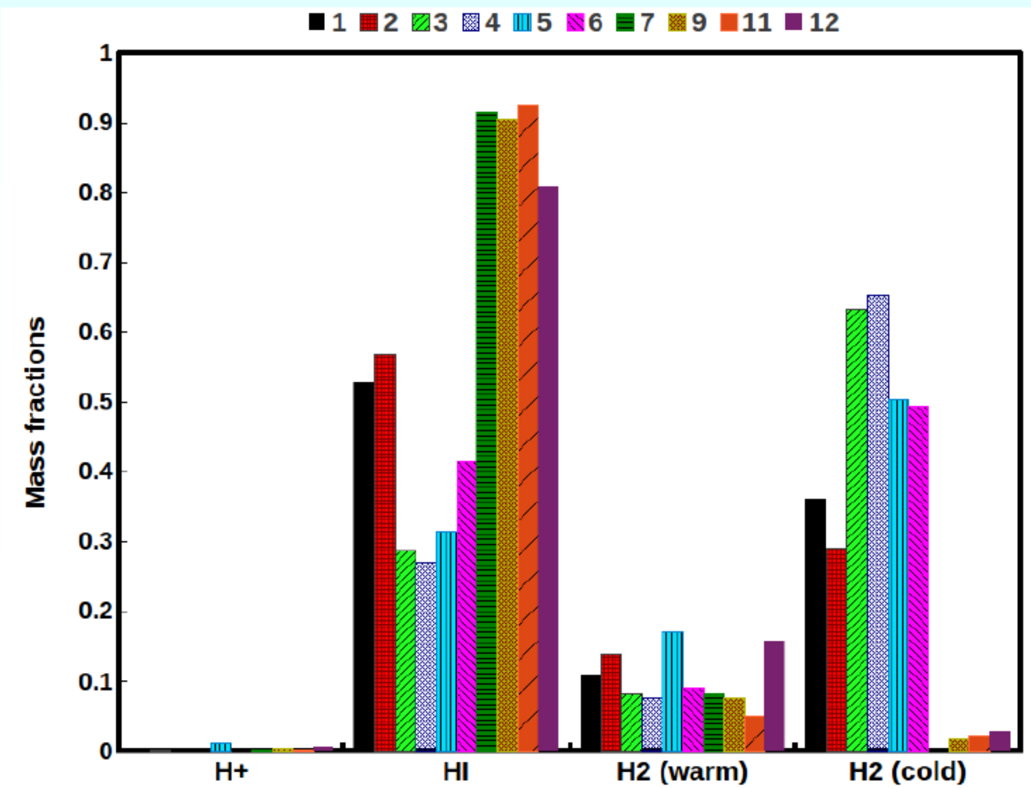

Density -400<V<400km/s DV ~600km/s

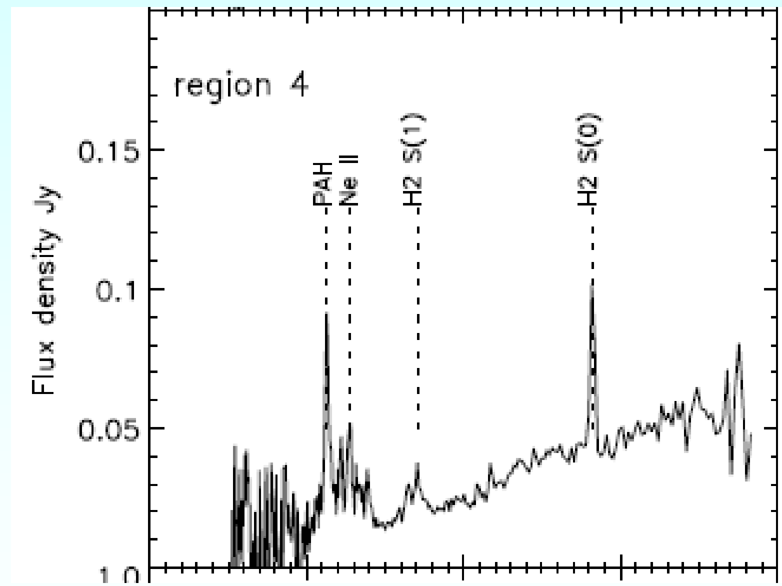



*Borisova et al 2016*

# LMC $H_2$ rotational lines, IRS Spitzer

10 regions in 28 and 17 μm, 3 regions in 12 and  9μu
Tex= 86-137 K
The excited $H_2$ gas is 5-17% of the total
Correlation with PAH and FIR emission



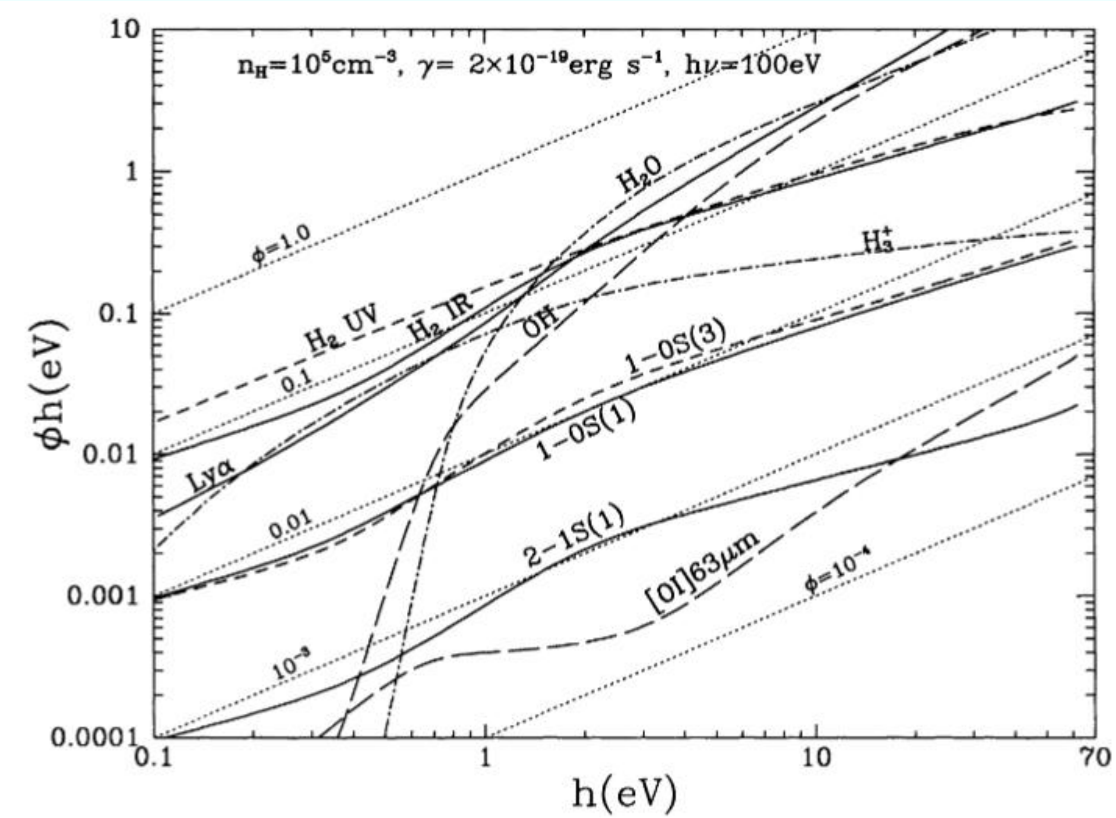

*Naslim et al 2015*

Line of 50 mJy

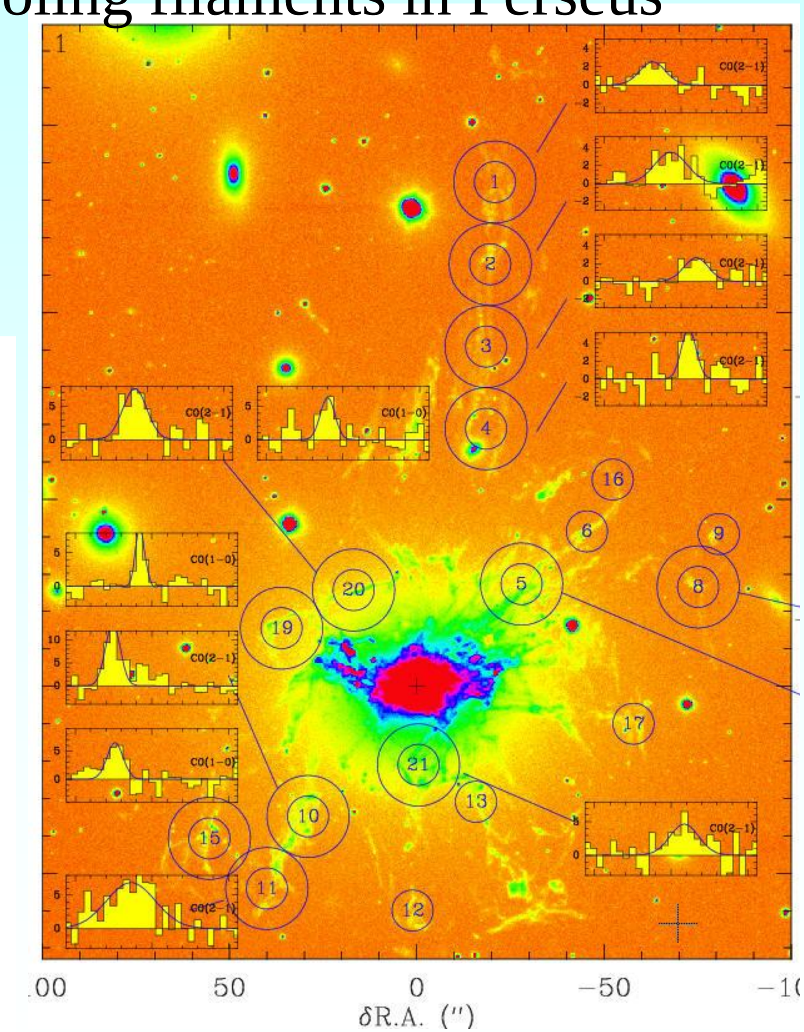
# $H_2$ found in shocked regions

NGC 6240

*Draine & Woods 1990*



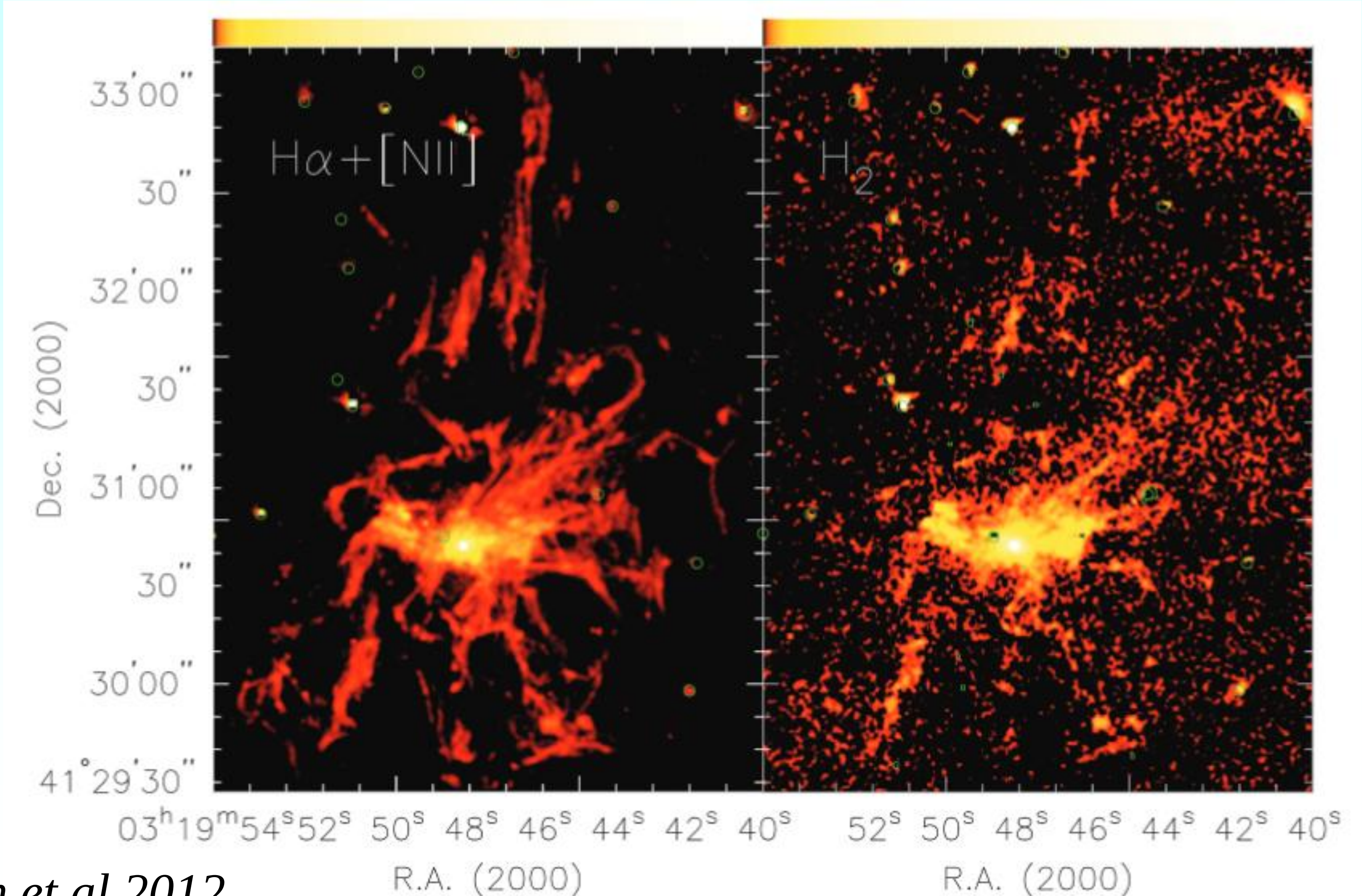

Cooling filaments in Perseus




*Salome et al 2006, 2008*

# $H_2$ mapping in cooling filaments

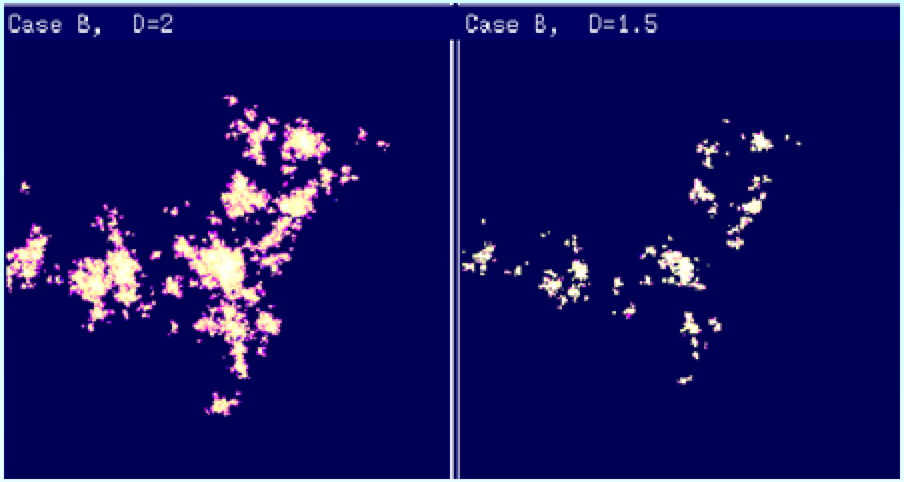
1-0 S(1) ro-vibrational transition, in the NIR




*Lim et al 2012*

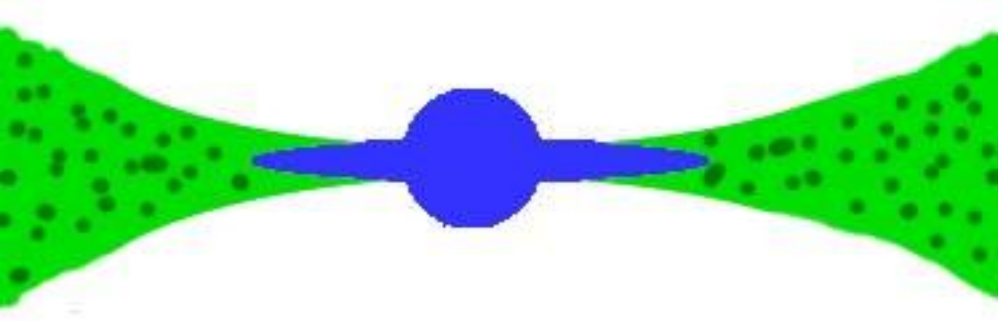
# Some baryonic dark matter?

## Cold $H_2$ Clouds




Filling factor < 1% for D=1.7

The stability of cold $H_2$ gas is due to its fractal structure



Mass ~ $10^{-3}$ Mo
density ~$10^{10}$ $cm^{-3}$

size ~ 20 AU

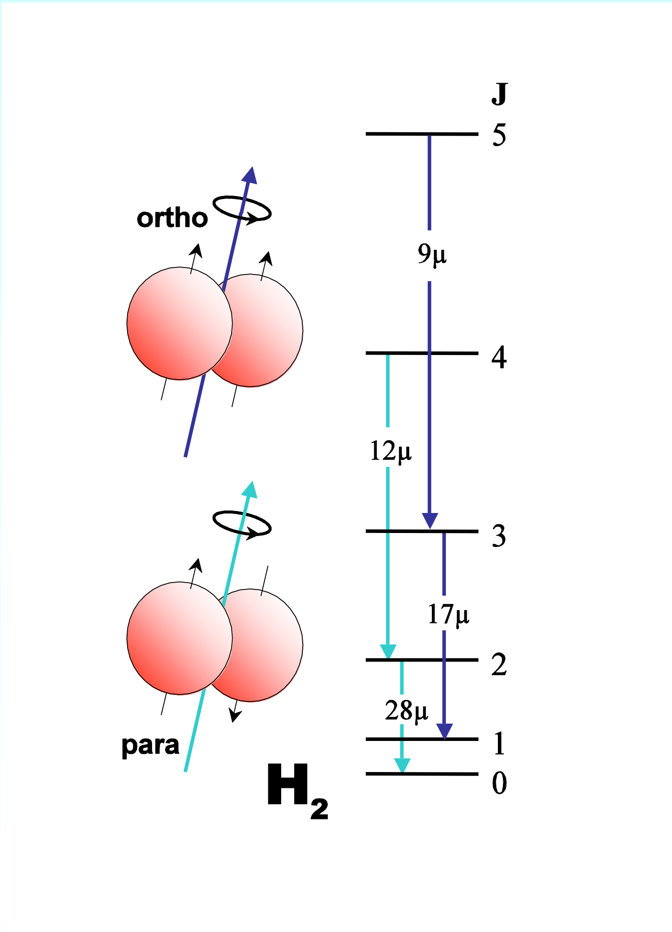
$N(H_2)$ ~ $10^{25}$ $cm^{-2}$

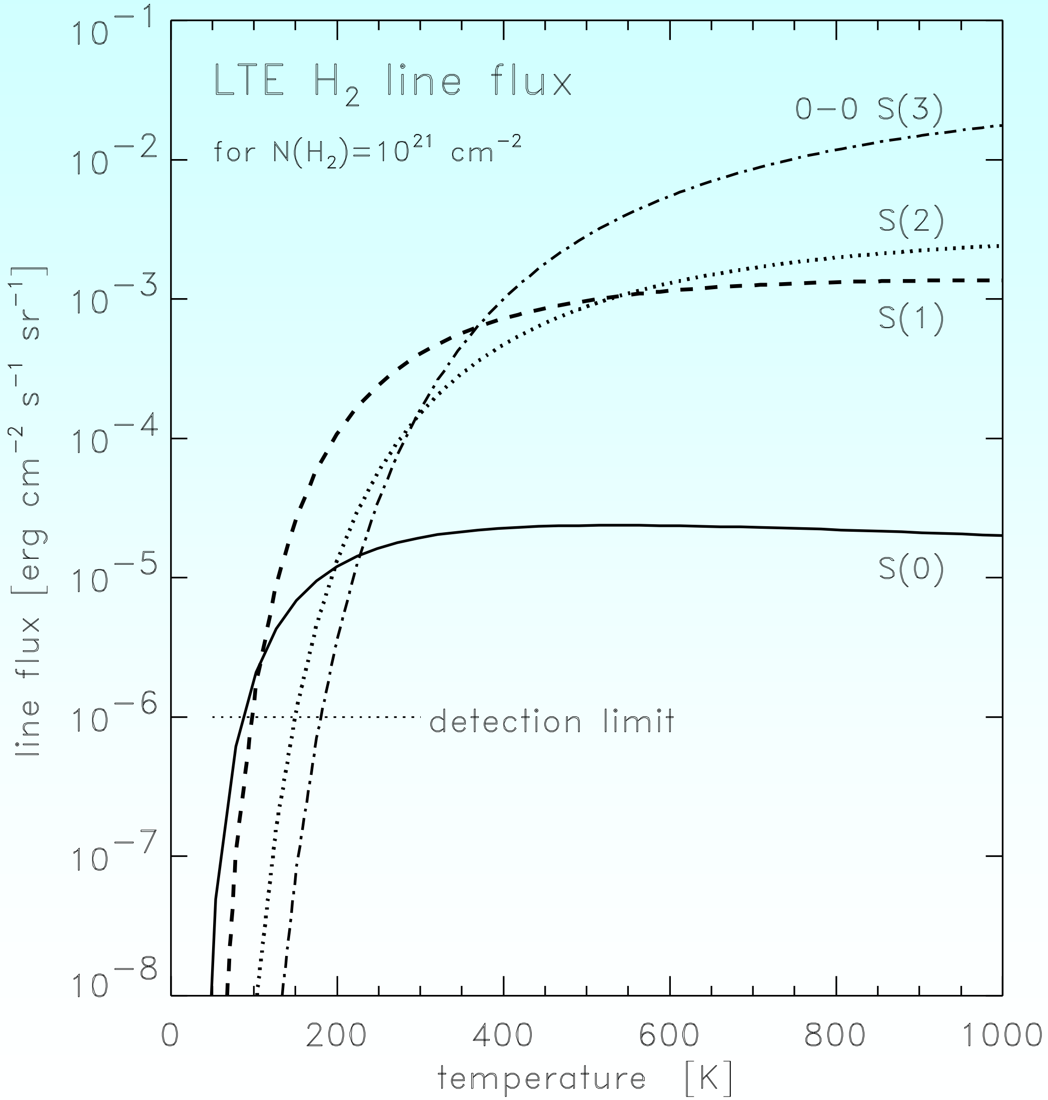
$t_{ff}$ ~ 1000 yr

Adiabatic regime:
much longer life-time

**Fractal:** collisions lead to coalescence, heating, and to a statistical equilibrium
(Pfenniger & Combes 94)

# $H_2$ pure rotational lines



# JWST MIRI sensitivity

Point source, 10$\sigma$, 3h

**Medium resolution spectroscopy (5-28 microns)**

| Lamda (Microns) | Line Flux (W/m^2) |
|---|---|
| 6.4 | 7.00E-21 |
| 9.2 | 1.00E-20 |
| 14.5 | 1.20E-20 |
| 22.5 | 6.00E-20 |

erg/s/cm2

| | |
|---|---|
| 7E-18 | 0.3” |
| 1E-17 | 0.4” |
| 1.2E-17 | 0.6” |
| 6E-17 | 1” |

**MIRI Camera**

| Lambda (Microns) | microJansky |
|---|---|
| 5.6 | 0.2 |
| 7.7 | 0.28 |
| 10 | 0.7 |
| 11.3 | 1.7 |
| 12.8 | 1.4 |
| 15 | 1.8 |
| 18 | 4.3 |
| 21 | 8.6 |
| 25.5 | 28 |

$\Delta\upsilon = 10^9 - 10^{10}$ Hz     $\Delta\Omega = 2$ e-11 sr

## H2EXplorer

| Survey | integration [sec] | 5$\sigma$ limit [erg $s^{-1}$ $cm^{-2}$ $sr^{-1}$] | total area [degrees] |
|---|---|---|---|
| Milky Way | 100 | 10-6 | 110 |
| ISM SF | 100 | 10-6 | 55 |
| Nearby Galaxies | 200 | 7 10-7 | 55 |
| Deep Extra-Galactic | 1000 | 3 10-7 | 5 |

# Summary

**The physics of the baryonic gas is a crucial clue to the formation of galaxies**

There could be more baryons in the form of cold neutral gas around galaxy disks, as reservoirs for star formation

Cold gas might exist in cosmic filaments, providing cold gas accretion

**Where are the baryons?**
**How much cold gas in filaments?**