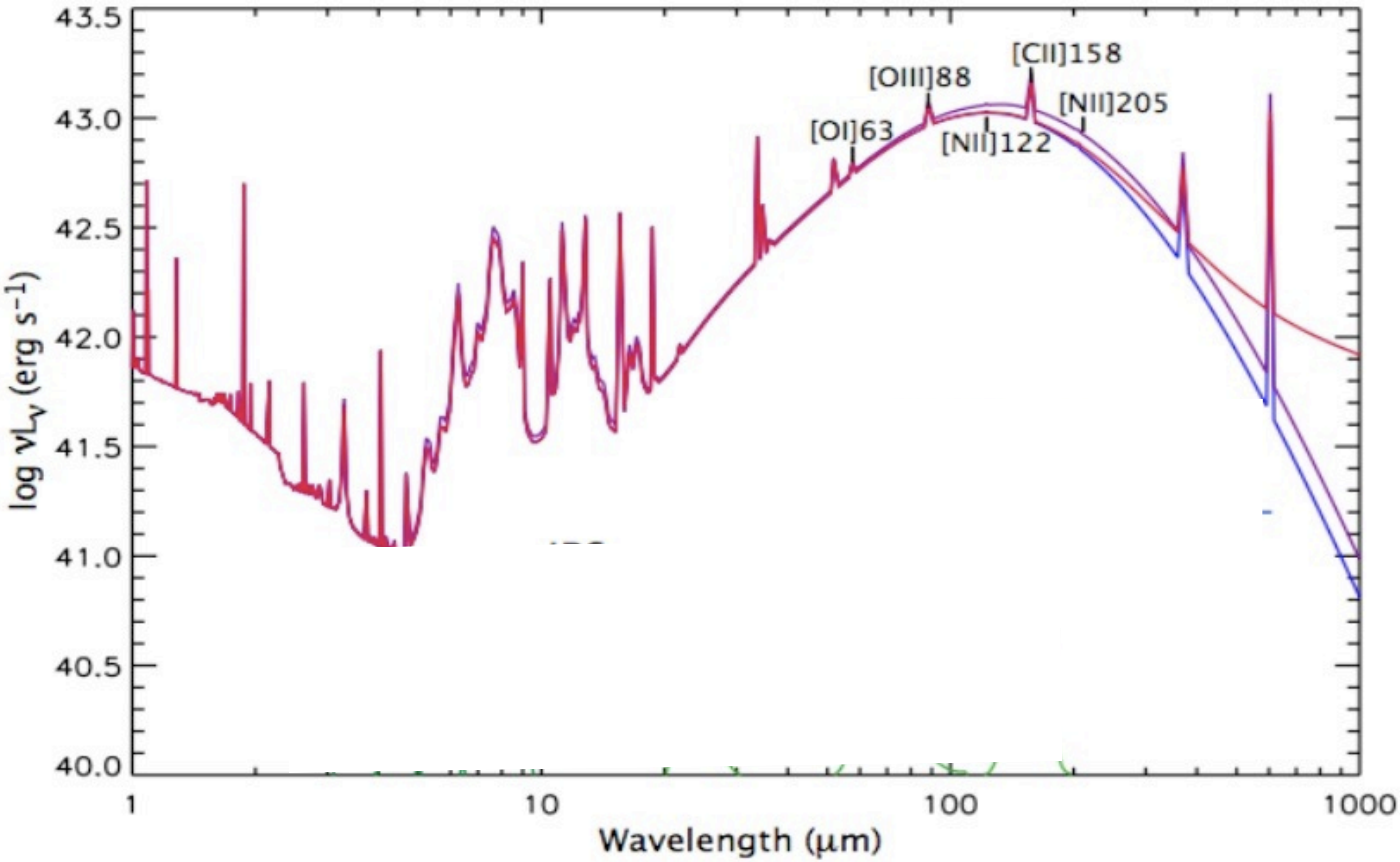
Observable Constituents:
Gas and Dust

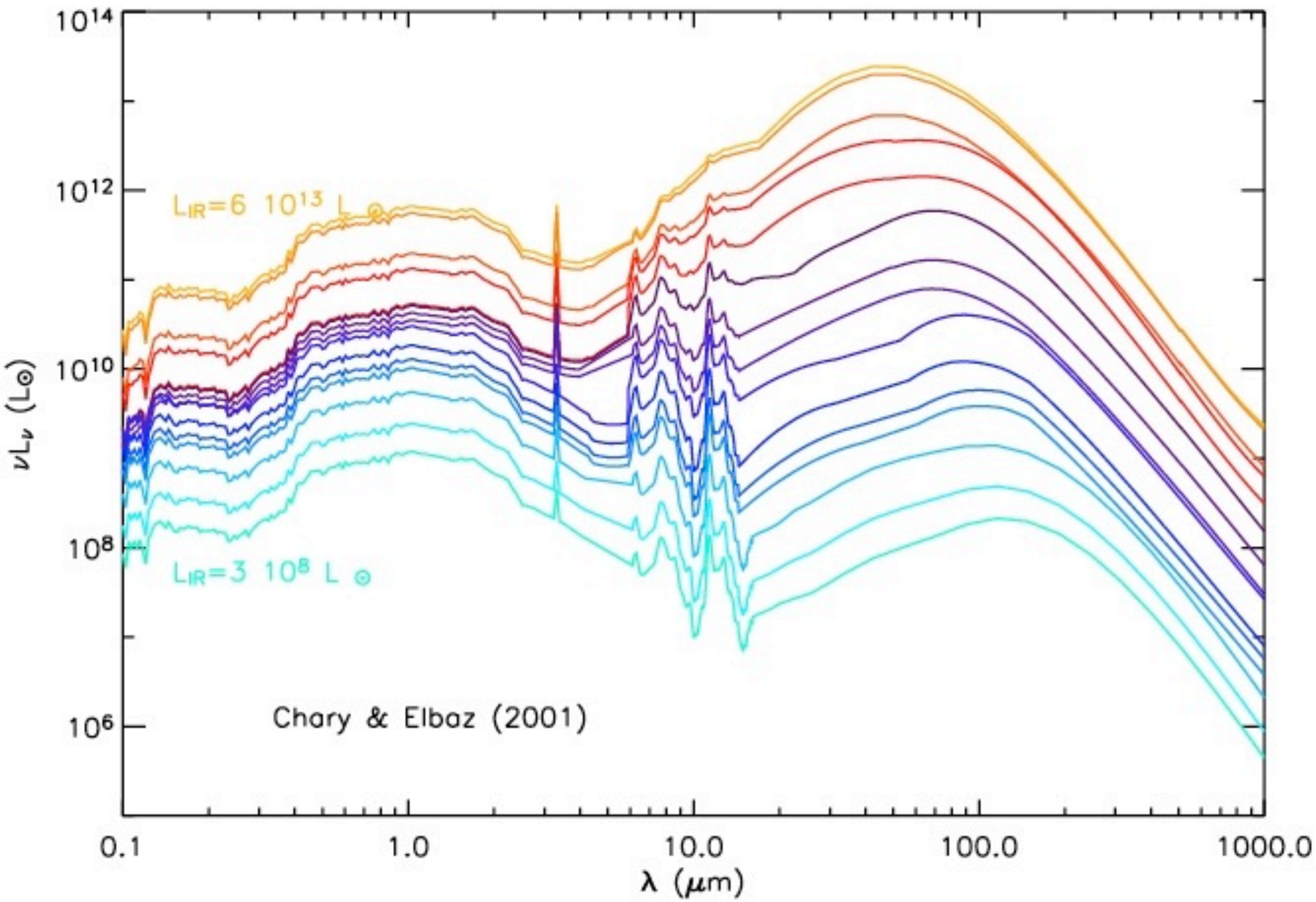
- Atomic gas: prerequisite for molecular gas
- Molecular gas: where stars form in the future
- Dust: reprocessing of 50% of all photons
- Both: repository of heavy elements

Spectral Energy Distribution of a Galaxy



...long wavelengths dominated by dust emission and spectral lines.

Spectral Energy Distribution of a Galaxy



...strong function of luminosity/metallicity/mass

There are 5 different phases of the ISM

Hot ionized medium (e.g. X-rays)

Warm ionized medium (e.g. H-alpha)

Warm neutral medium (e.g. HI)

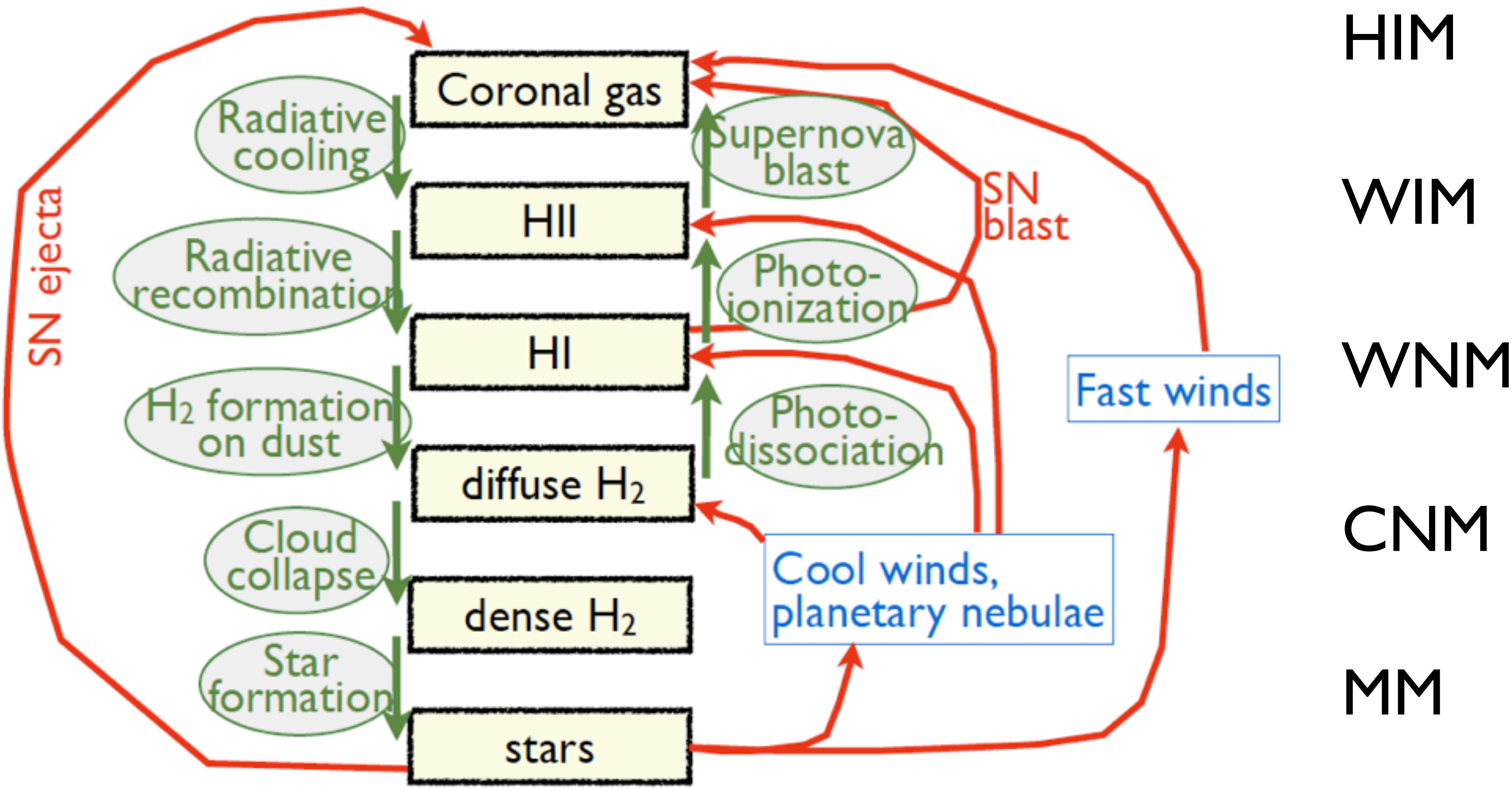
Cold neutral medium (e.g. HI)

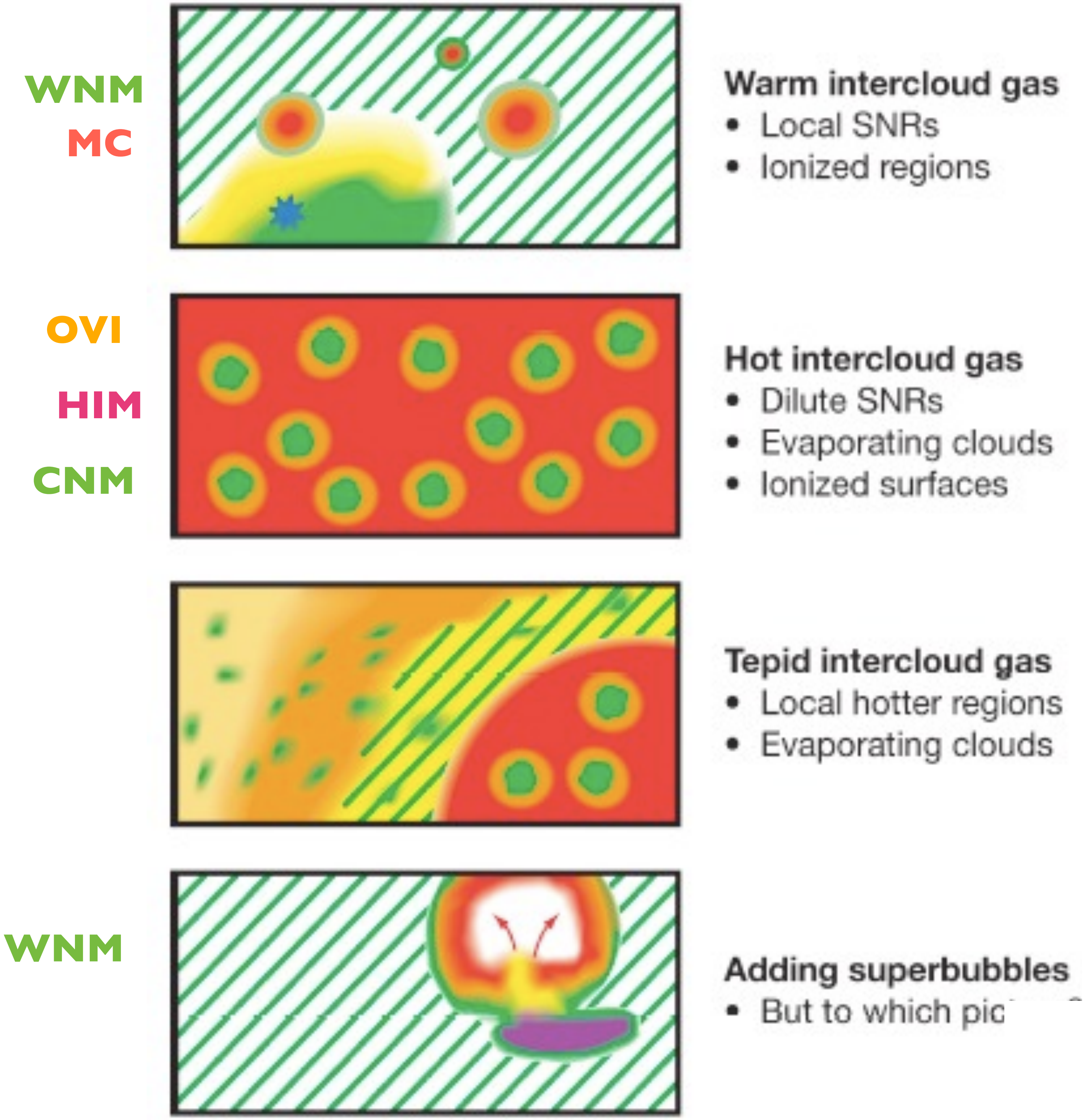
Molecular medium (e.g. CO)

	MM	CNM	WNM	WIM	HIM
n (cm^{-3})	$10^2 - 10^5$	4–80	0.1–0.6	$\approx$0.2 cm^{-3}	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	$\approx$ 8000	10^5–10^7
h (pc)	$\approx$ 70	$\approx$ 140	$\approx$ 400	$\approx$900	$\geq$1 kpc
f_{volume}	$< 1\%$	$\approx$2–4%	$\approx$30%	$\approx$20%	$\approx$50%
f_{mass}	$\approx$20%	$\approx$40%	$\approx$30%	$\approx$10%	$\approx$1%

...stars only form out of the molecular medium

Complex interaction between different phases





Purple= mol. clouds
Solid green= cold H I clouds
Hatched green= warm H I
Hatched green on yellow=
diffuse warm H II
Orange= Hotter gas with OVI
Red=Hot gas emitting X-rays
Blue= star

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The Three-Phase Interstellar Medium Revisited

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There are 5 different phases of the ISM

Hot ionized medium

Warm ionized medium

Warm neutral medium

Cold neutral medium

Molecular medium

TABLE 2.1— The different phases of the ISM.

	MM	CNM	WNM	WIM	HIM
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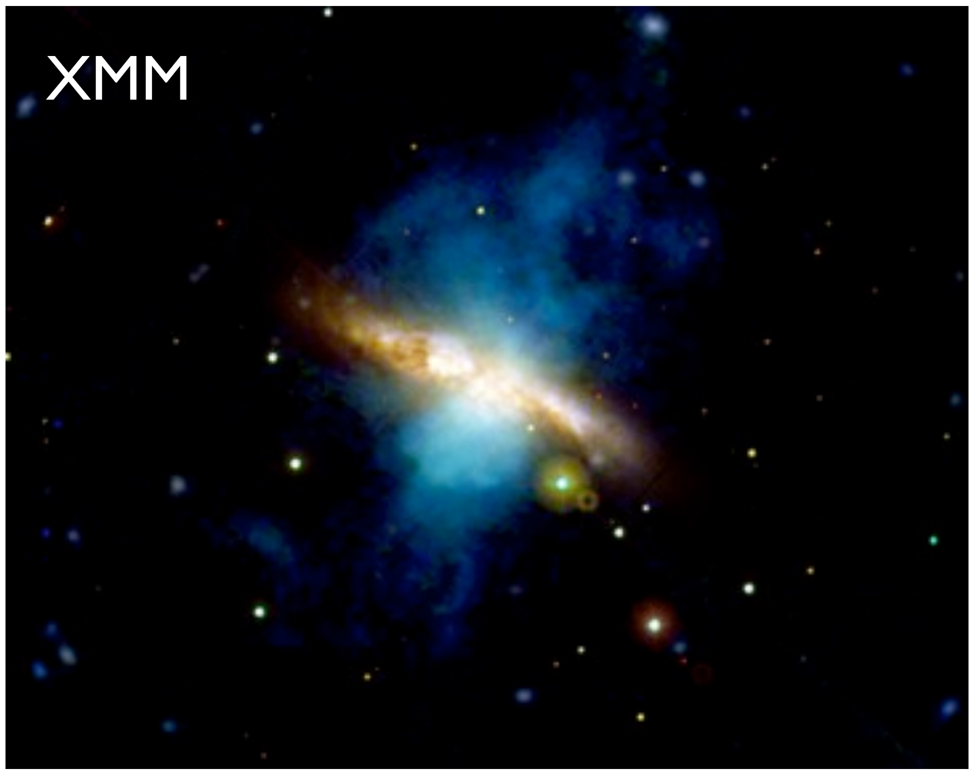
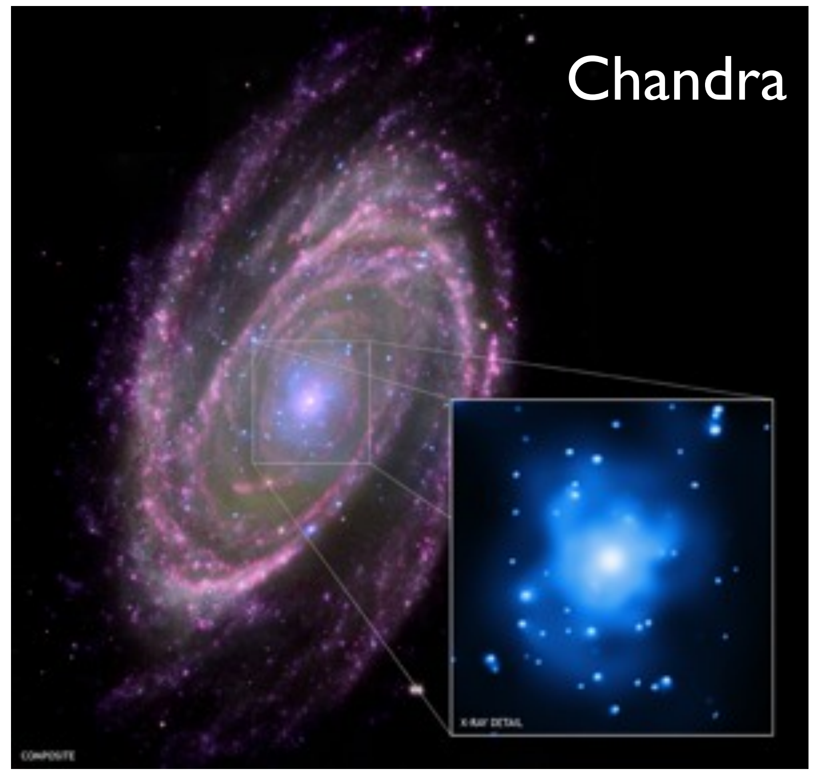
Note: the quoted numbers for each of the phases are only rough estimates. n is the particle density in cm^{-3}, T the temperature in K, h the scale height in pc, f_{volume} is the volume filling factors, and f_{mass} the mass fraction.

Hot Ionized Medium visible in X-rays





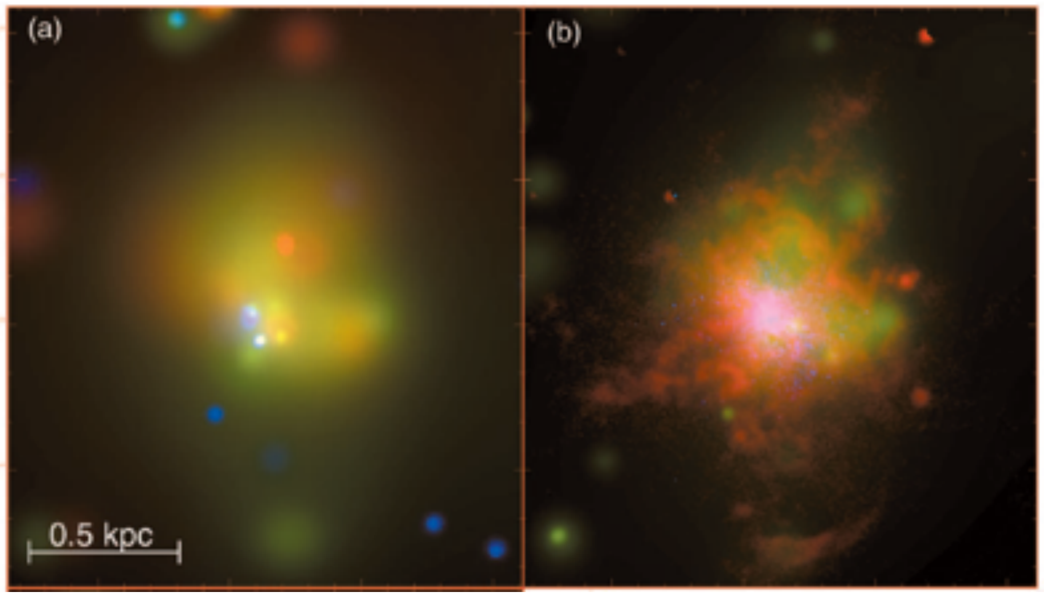
10^6 K gas -- X-ray emission

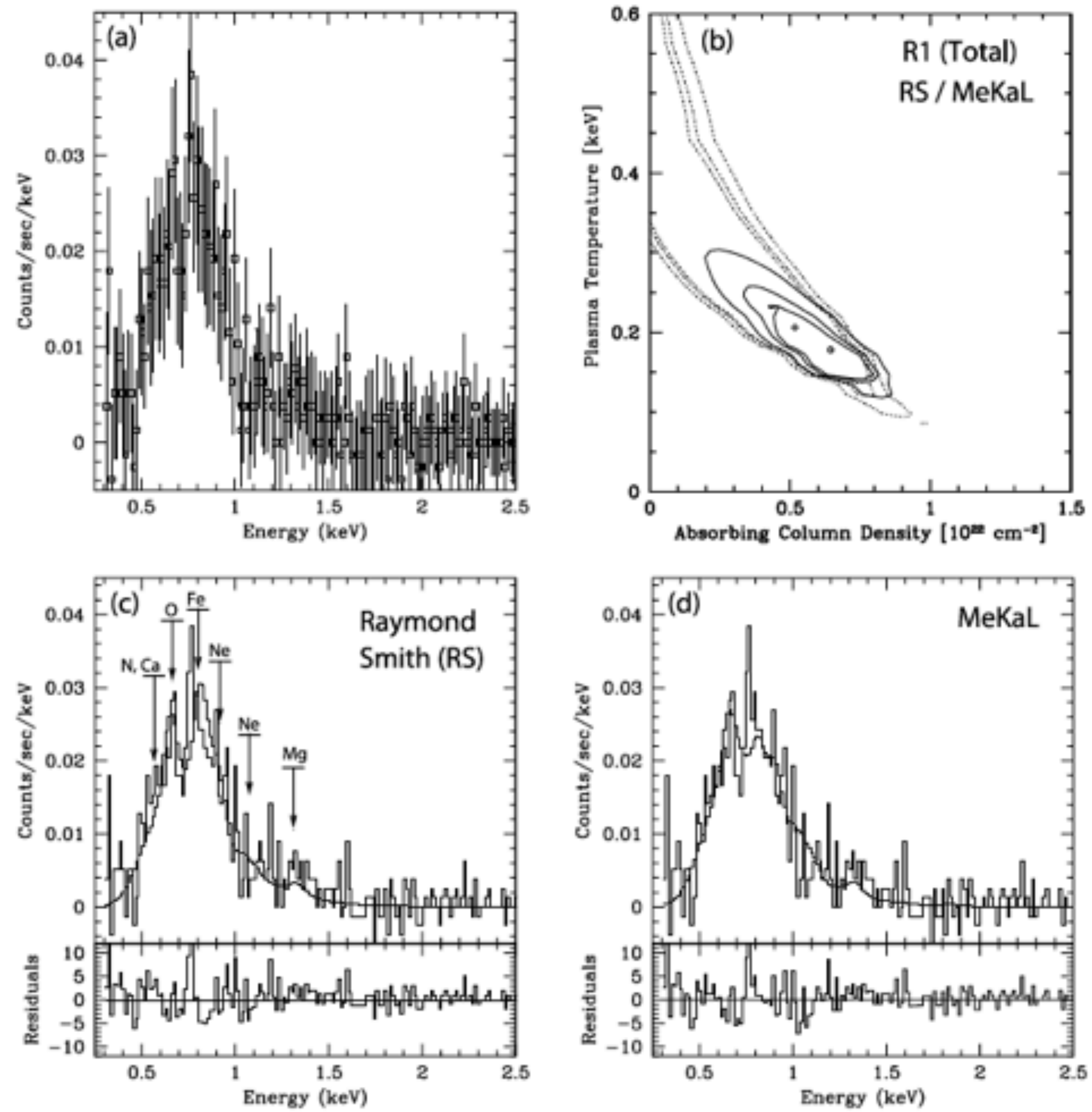
HIM difficult to detect in other galaxies given current facilities.

Contaminants: X-ray binaries (need spatial resolution, e.g. Chandra vs. XMM)

...and OVI, CIV absorption (UV lines)

Example for X-ray data: dwarf starburst NGC3077





hot X-ray gas can be fitted with different models

d_{eq} (pc)	1811
Mean line of sight (pc)	1207
$n_e\ [\times(\xi f_v)^{-0.5}]$ (cm^{-3})	0.05/0.03
EM $[\times(\xi f_v)^{-1}]$ (cm^{-6} pc)	3.0/1.1
$P/k\ [\times(\xi f_v)^{-0.5}]$ ($\times10^5$ K cm^{-3})	2.0/1.4
M_{hot} ($\times\xi^{-0.5}f_v^{0.5}$) ($\times10^4\ M_\odot$)	384.2/230.5
E_{th} ($\times\xi^{-0.5}f_v^{0.5}$) ($\times10^{52}$ ergs)	384.1/265.7
t_{cool} ($\times\xi^{-0.5}f_v^{0.5}$) (Myr)	27.0/55.9
$\dot{M}_{cool}$ ($M_\odot$ yr^{-1})	0.142/0.041
$\langle v_{hot}\rangle$ (km s^{-1})	300/380

Derived Parameters of the Hot Gas from the Best RS and MEKAL Fits

Ott et al. 2004

There are 5 different phases of the ISM

Hot ionized medium

Warm ionized medium

Warm neutral medium

Cold neutral medium

Molecular medium

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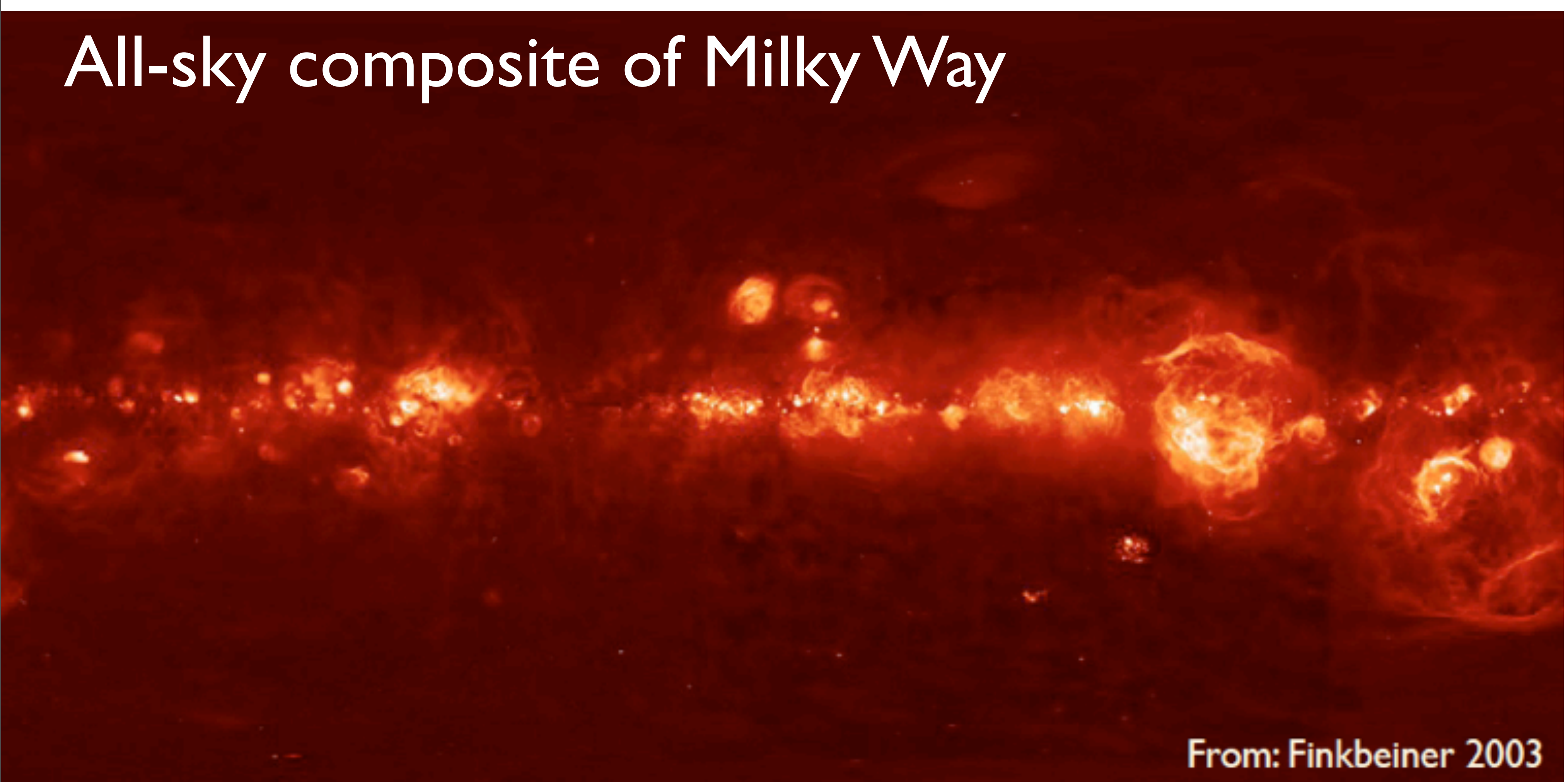
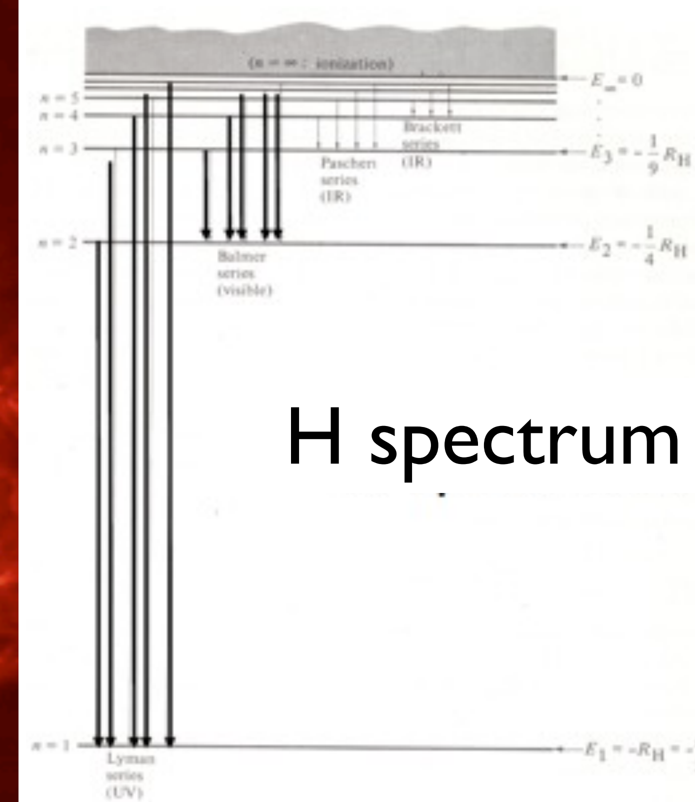
Warm Ionized Medium

- mainly traced by Hα
- most likely source: photoionization from OB stars
- scale height: 1kpc
- minimum energy rate: 3×10^5 kpc^{-2} s^{-1} (equiv. of 1 O4 star kpc^{-2})
- total energy requirement: 3×10^8 L_{sun}





There are 5 different phases of the ISM

- Hot ionized medium
- Warm ionized medium
- **Warm neutral medium**
- **Cold neutral medium**
- Molecular medium

TABLE 2.1— The different phases of the ISM.

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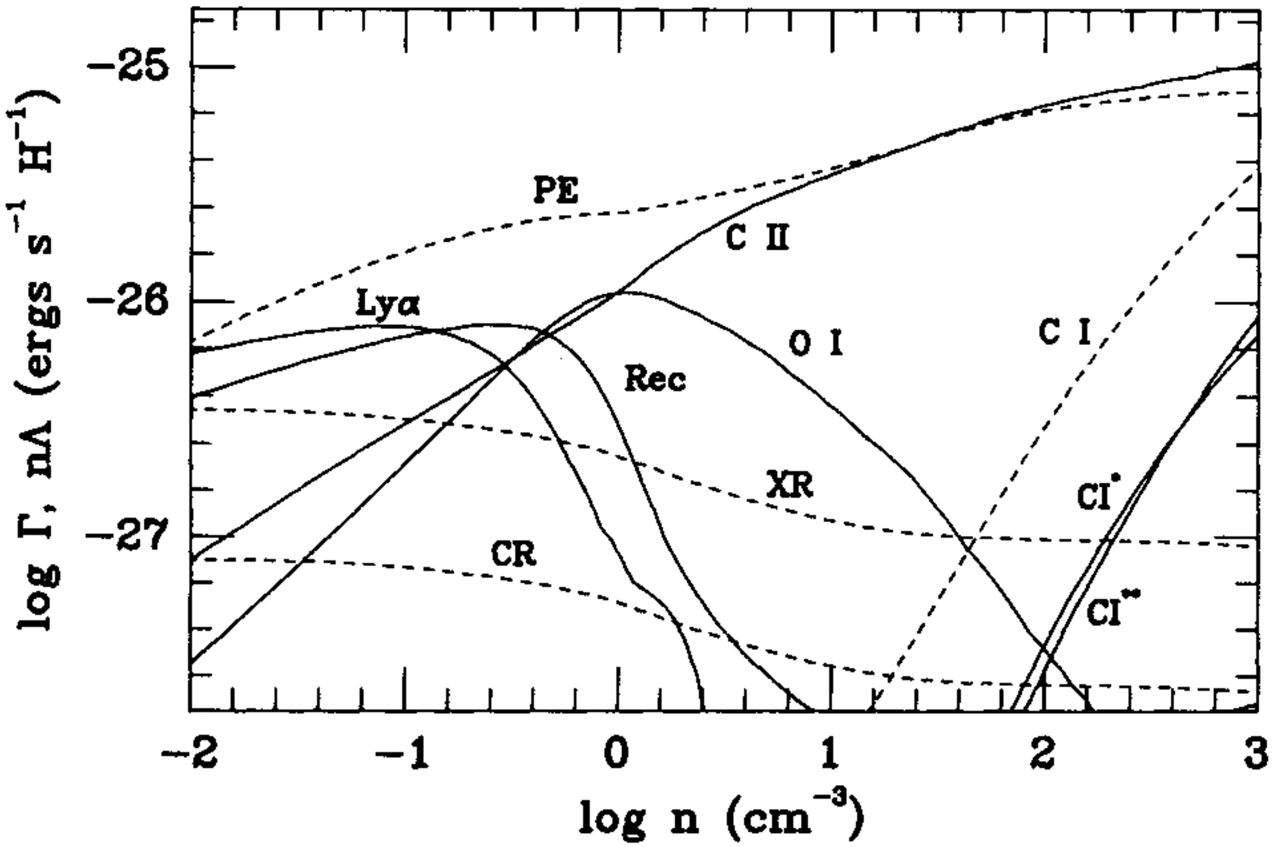
heating/cooling:



dashed lines: heating rates

PE: photoelectric heating from grains and PAHs

CR: cosmic ray heating

XR: soft X-ray heating

CI: heating by photoionization of CI

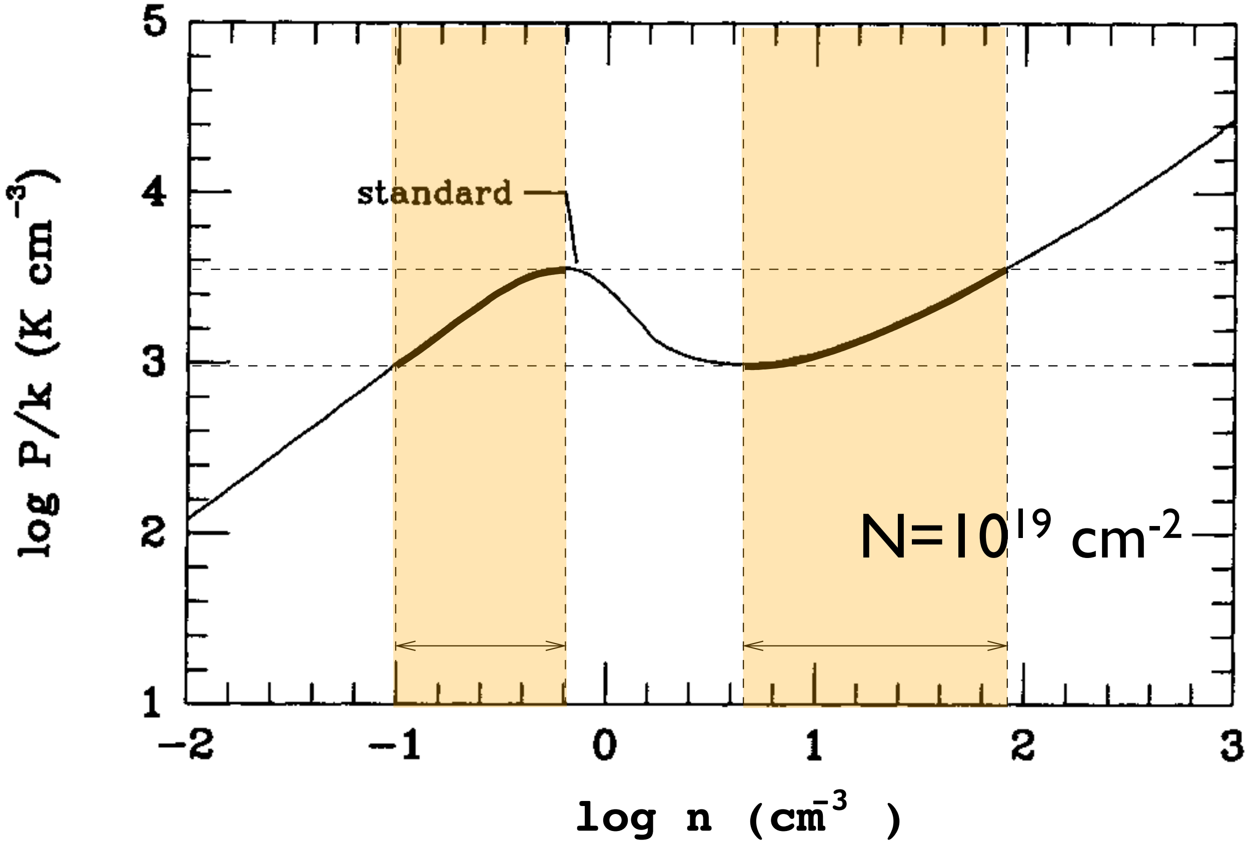
full lines: colling rates

fine structure lines

electron recombination lines

resonance and metastable lines (e.g. Ly alpha)

resulting pressure:



pressure vs. density:

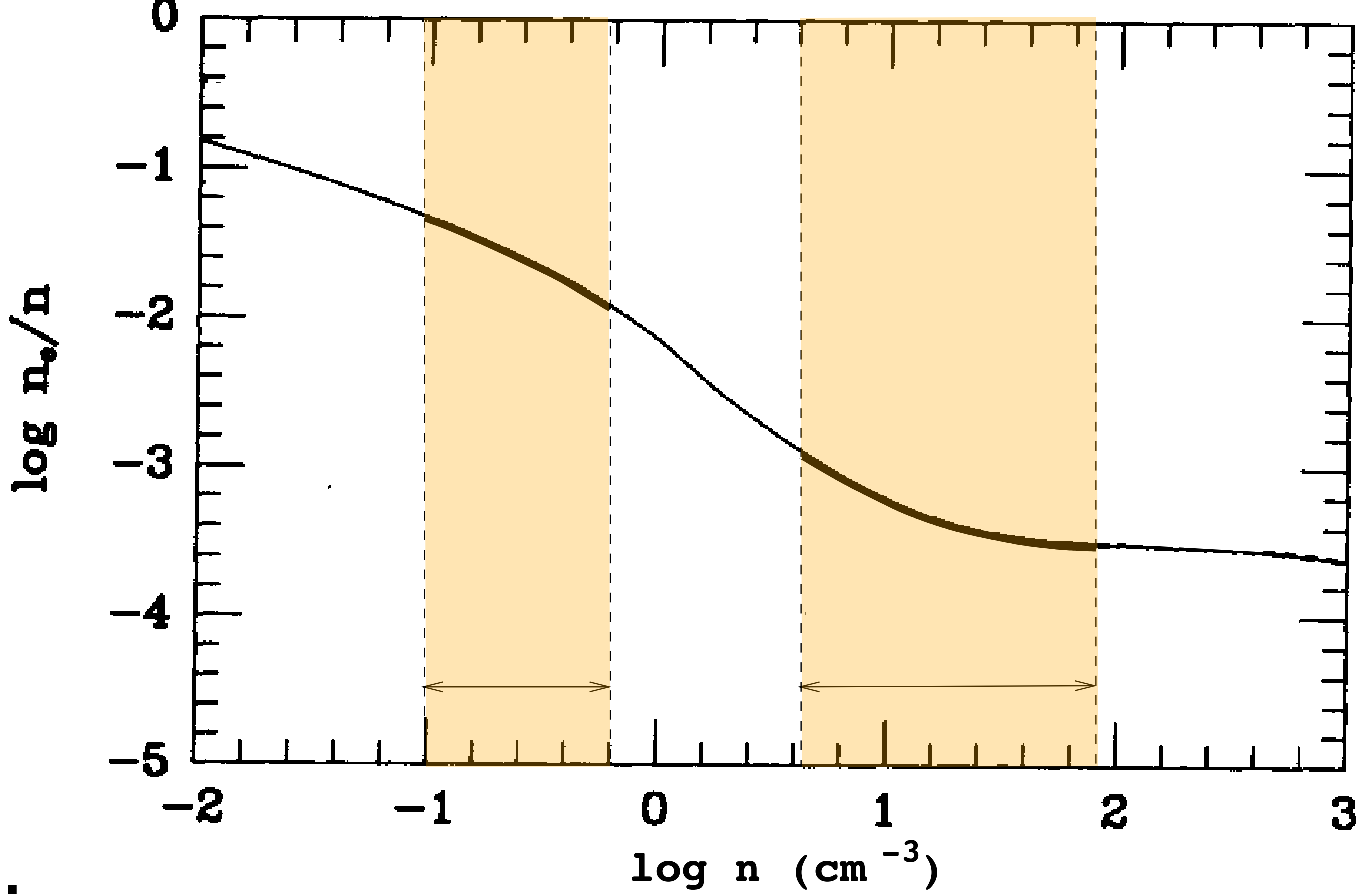
- only regions with d(log P)/d(log n) are stable
- assuming pressure equilibrium: 2 stable phases.

CNM: n=[4.2 80] cm^{-3}

WNM: n=[0.1, 0.59] cm^{-3}

Wolfire et al. 1996

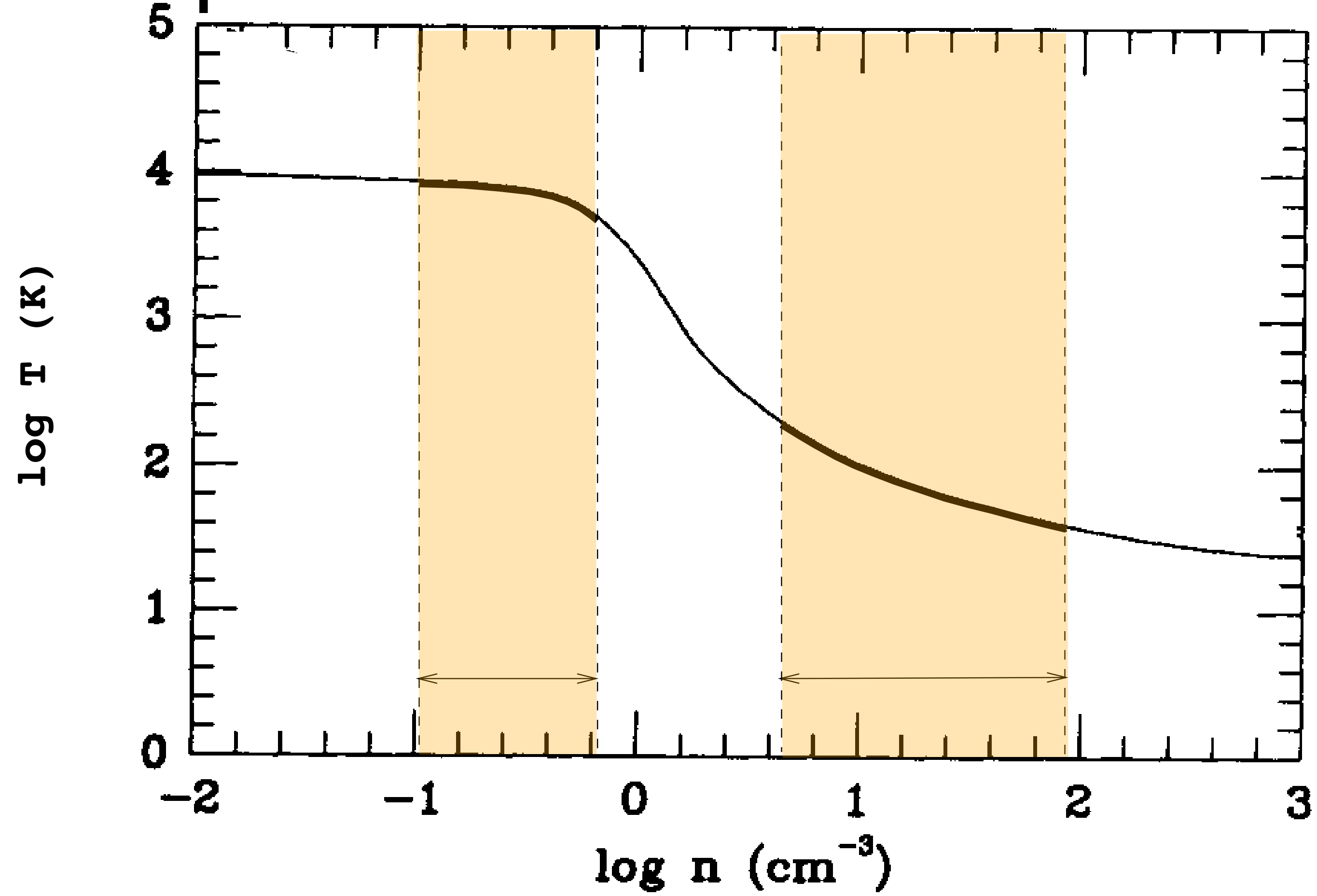
resulting density:



electron fraction vs. density:

CNM: n=[1.3 10^{-3}, 3.2 10^{-4}]
WNM: n=[4.6 10^{-2}, 1.3 10^{-2}]

...and temperature



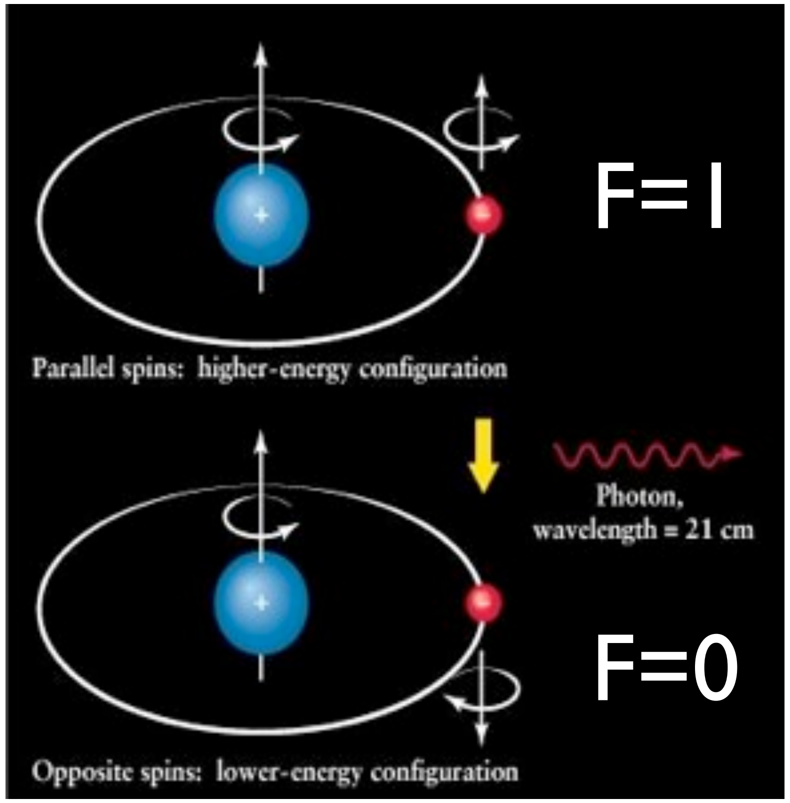
temperature vs. density:

CNM: n=[41 210] K
WNM: n=[5500 8700] K

these are the two phases of the ISM

Wolfire et al. 1996

Most important tracer for warm/cold neutral medium: HI 21cm line



- H atom consists of 1 proton + 1 electron
  - Electron: spin S=1/2
  - Proton: nuclear spin I=1/2
  - Total spin: $F = S + I = 0, 1$
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $g_u = 2F+1 = 3$ $E = 5.87\times10^{-6}$ eV
  - $F = 0$ $g_l = 2F+1 = 1$ $E = 0$ eV

- Transition between $F = 0$ and $F = 1$:
  - $\nu = 1420$ MHz, $\lambda = 21.11$ cm
  - $\Delta E / k = 0.0682$ K
  - $A_{ul} = 2.869\times10^{-15}$ s^{-1} = $1/(1.1\times10^{7}$ yr$)$ (very small!)

...but there is a lot of hydrogen out there!

HI 21cm line

energy distribution, asuming Boltzmann: $$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu/kT_{\rm ex}}$$

HI atom: g_1=1 and g_0=3 (statistical weights given degeneracy of levels)

hv/k = 0.07 K, i.e. hv/k << T

A_{10}: spontaneous emission, *B_{10}, B_{01}*: absorption and stimulated emission (Einstein coefficients)

emission and absorption coefficient of any 2-level system:

$$\begin{aligned} j_\nu &= \frac{h\nu}{4\pi} A_{10} n_1 \Phi(\nu), \\ \kappa_\nu &= \frac{h\nu}{c}[n_1 B_{10} - n_0 B_{01}]\Phi(\nu) \end{aligned}$$

recall that:

$$g_0 B_{01} = g_I B_{10},$$
$$A_{10} = \frac{8\pi h \nu_o^3}{c^3} B_{01}$$

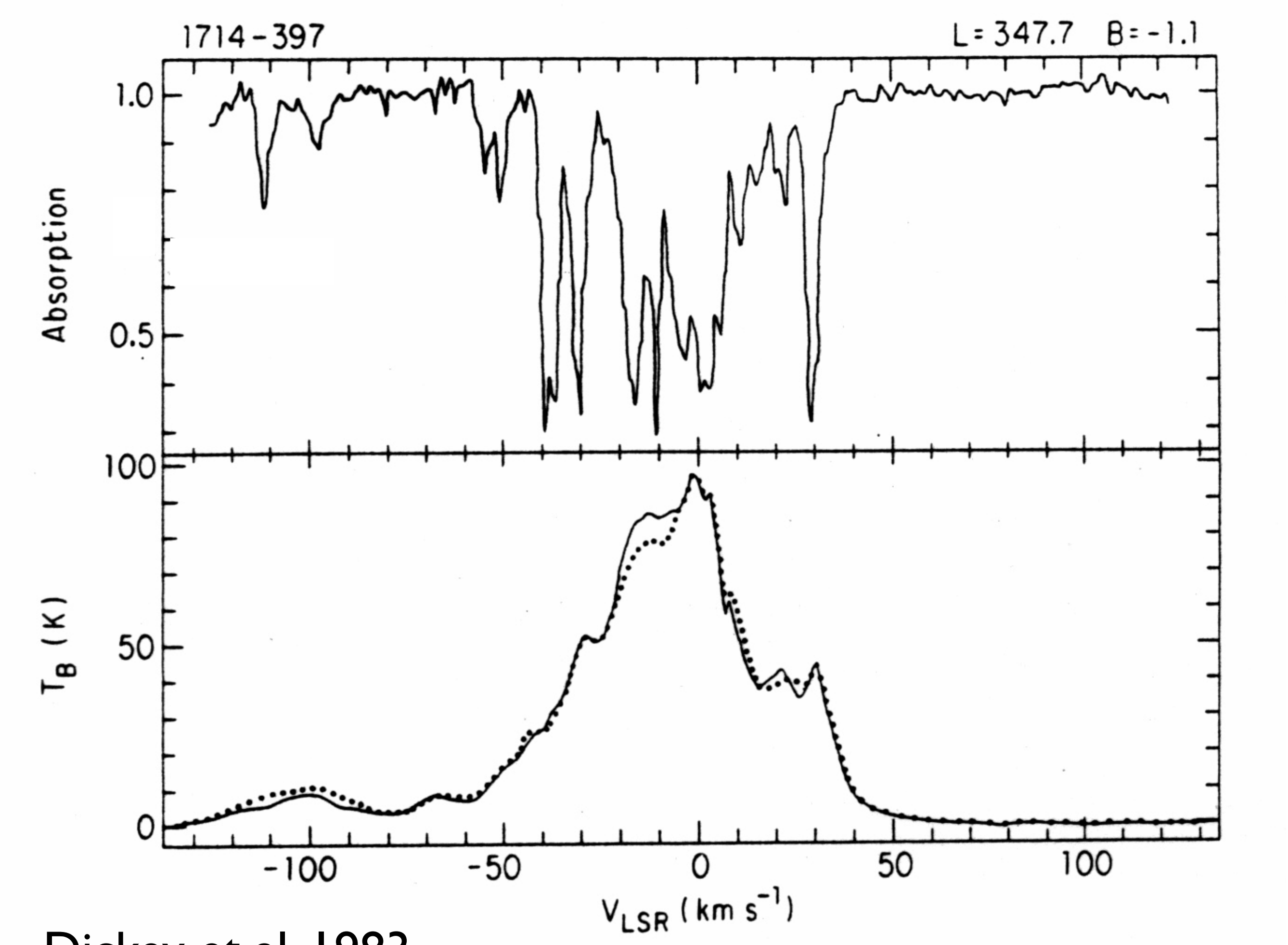
so that:

$$\begin{aligned} j_\nu &= \frac{h\nu}{4\pi}\frac{3n_H}{4} A_{10}\Phi(\nu), \\ \kappa_\nu &= \frac{(h\nu)^2}{c}\frac{n_H B_{01}}{4kT_{\rm ex}}\Phi(\nu) \end{aligned}$$

note: both coefficients are f(*n_H*) --- *j_v* not f(T_{ex}), but *k_v* is (recall T for CNM and WNM)

natural line width is 10^{-16} km s^{-1}, CNM (100K): 0.9 kms^{-1}, WNM (8000K): 8.3 kms^{-1}

HI emission vs. absorption



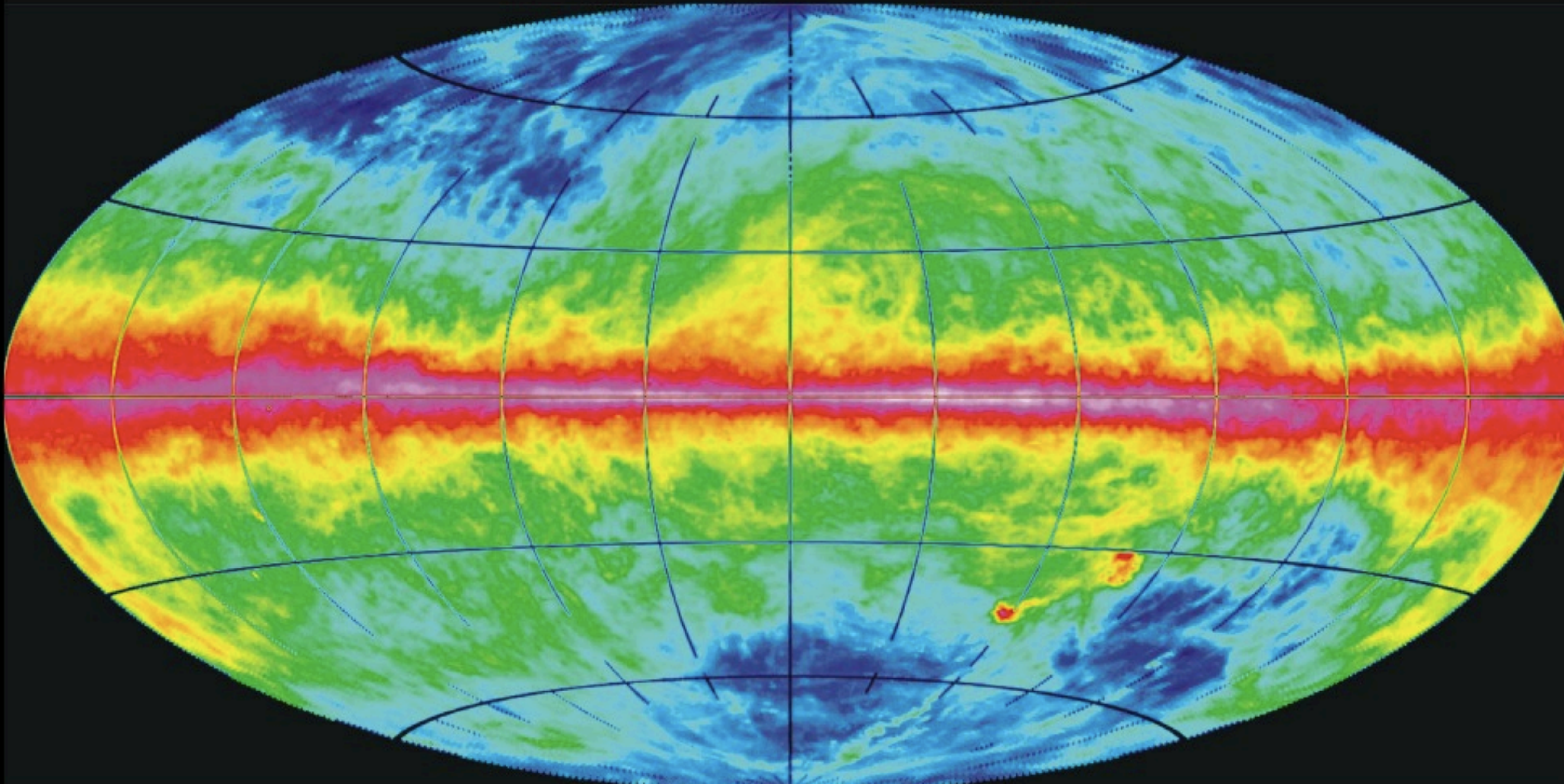
Dickey et al. 1983

$$
\begin{aligned}
j_\nu &= \frac{h\nu}{4\pi}\frac{3n_H}{4}A_{10}\Phi(\nu), \\
\kappa_\nu &= \frac{(h\nu)^2}{c}\frac{n_H B_{01}}{4kT_{\rm ex}}\Phi(\nu)
\end{aligned}
$$

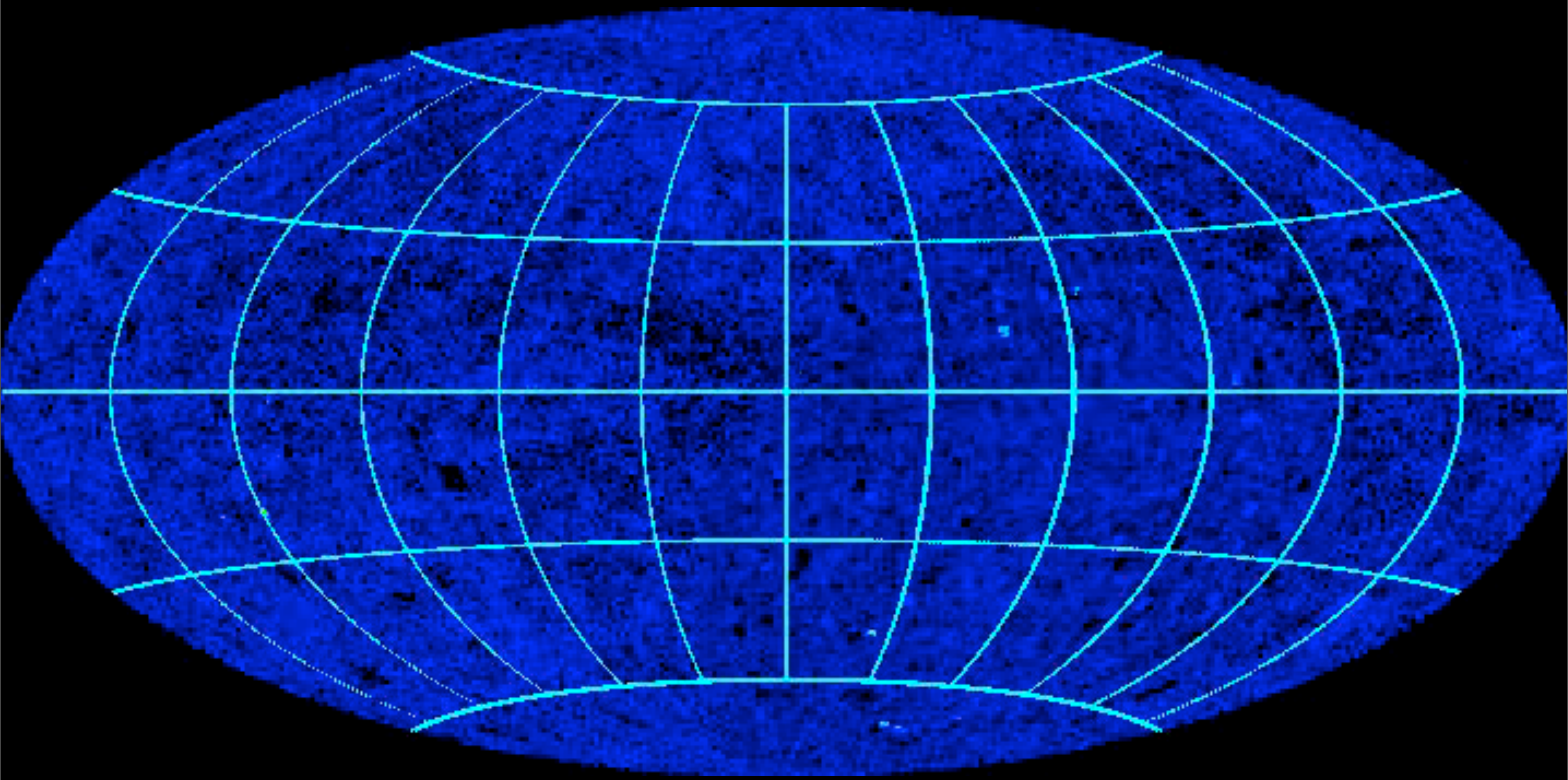
Spectra taken towards same direction within our galaxy
This first suggested that the neutral ISM consists of 2 phases

Neutral hydrogen

All-Sky Survey in the HI line (Leiden/Argentina/Bonn)

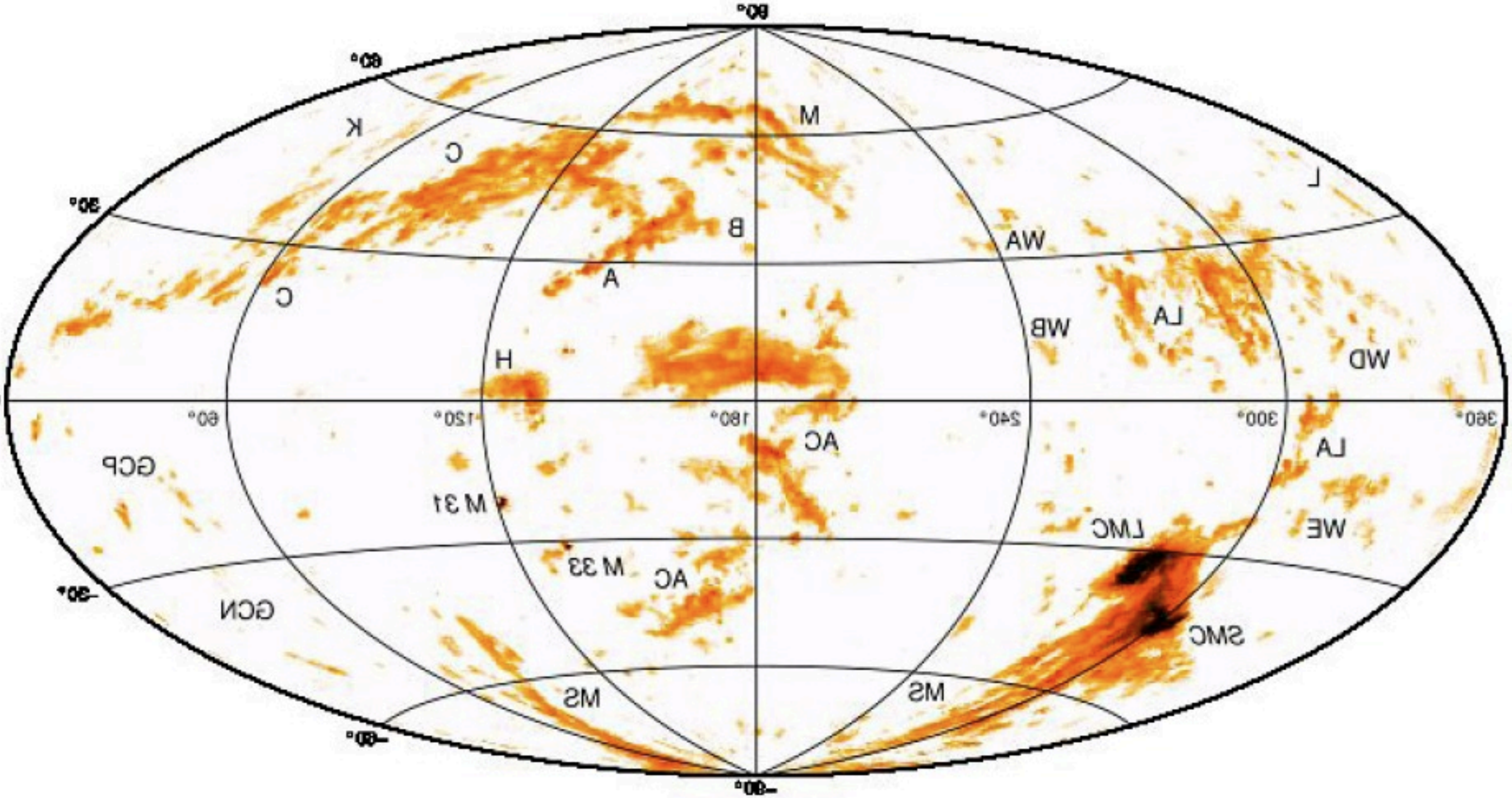


see http://www.astro.uni-bonn.de/~webrai/german/tools_labsurvey.php

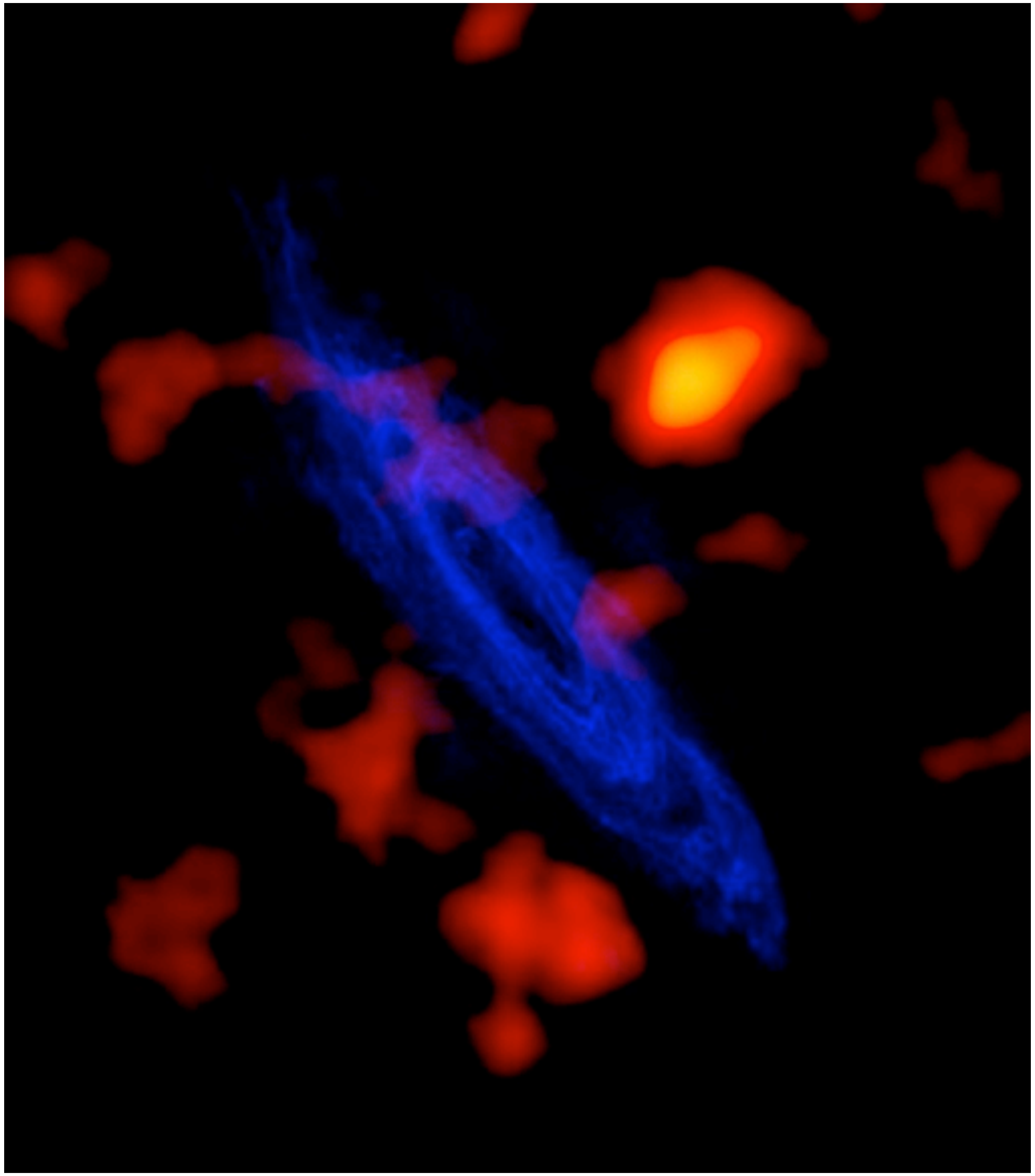


Leiden-Argentine-Bonn 21cm Survey
-400 km/s → +400 km/s

‘High-velocity’ gas in our galaxy



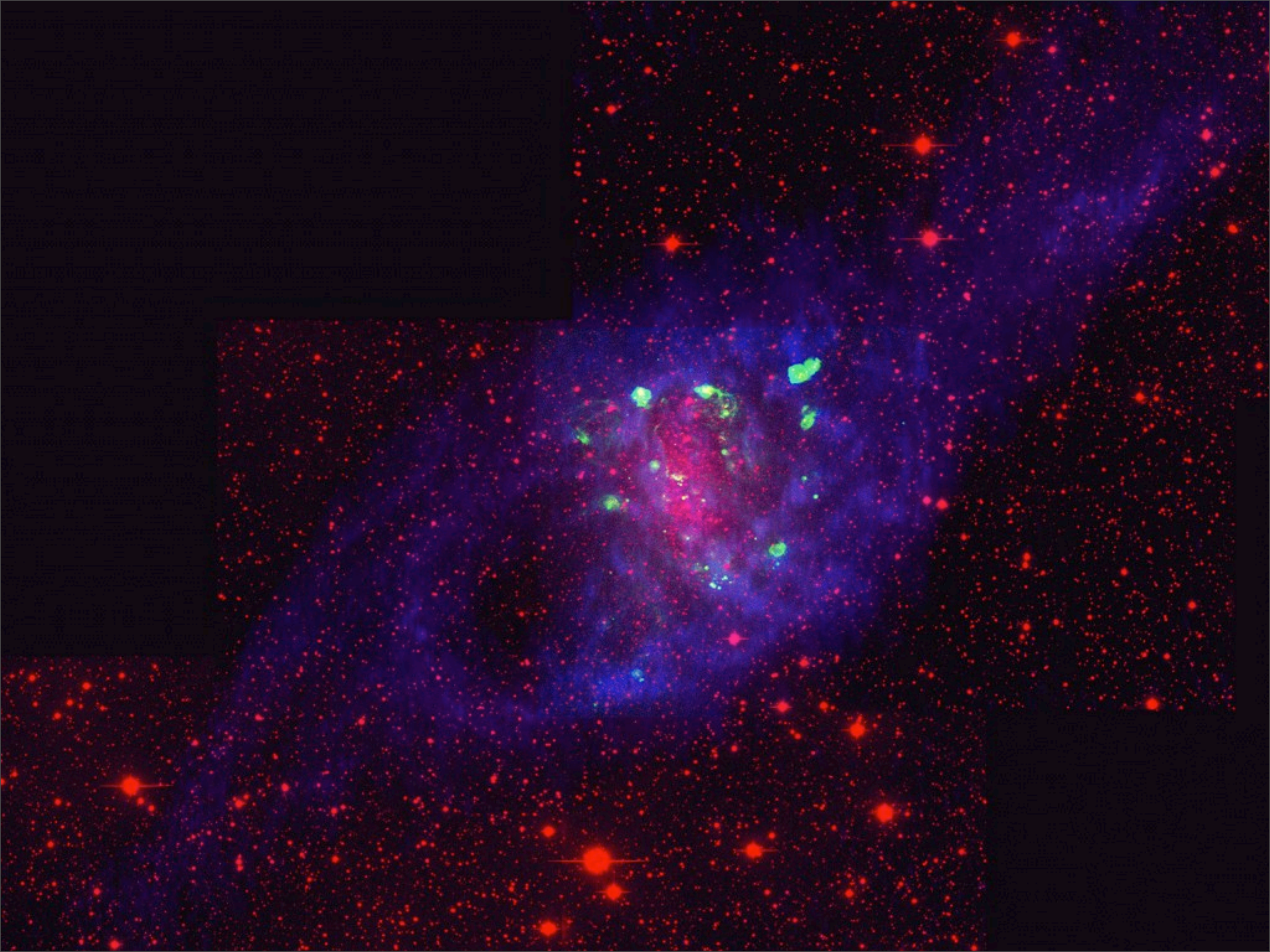
'High-velocity' gas around M31 (Andromeda)



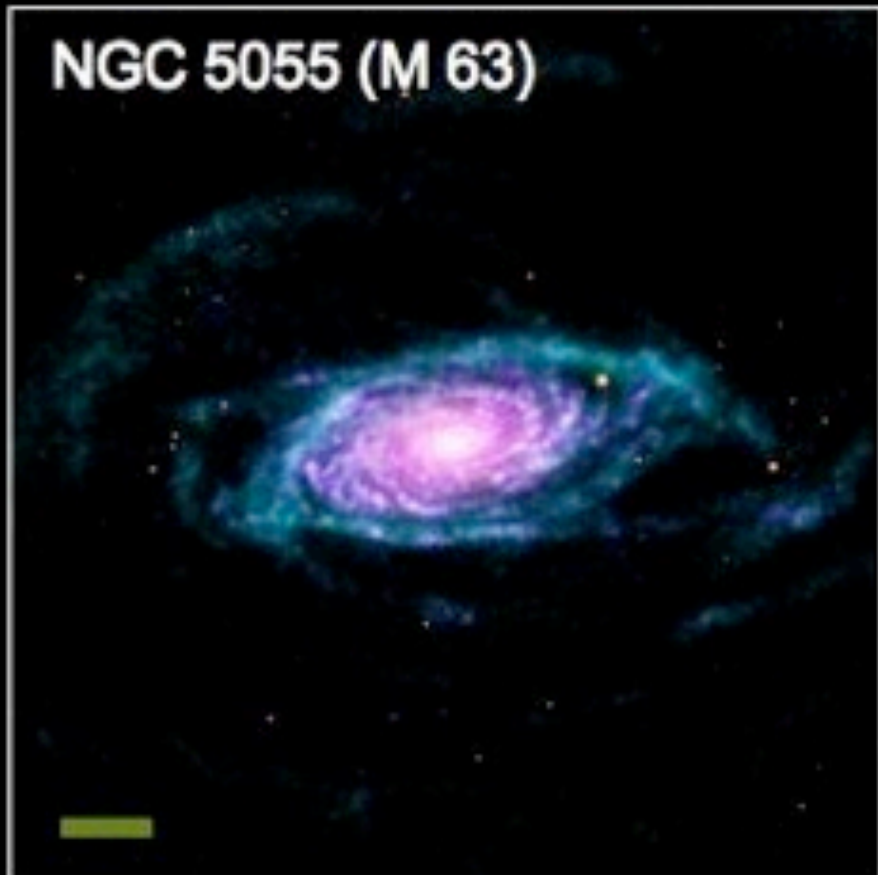
red: HI (single dish)
blue: HI (interferometer)

connection to cosmic web?

can these structures supply fuel for future star formation?



Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey



color coding:

THINGS Atomic Hydrogen
(Very Large Array)

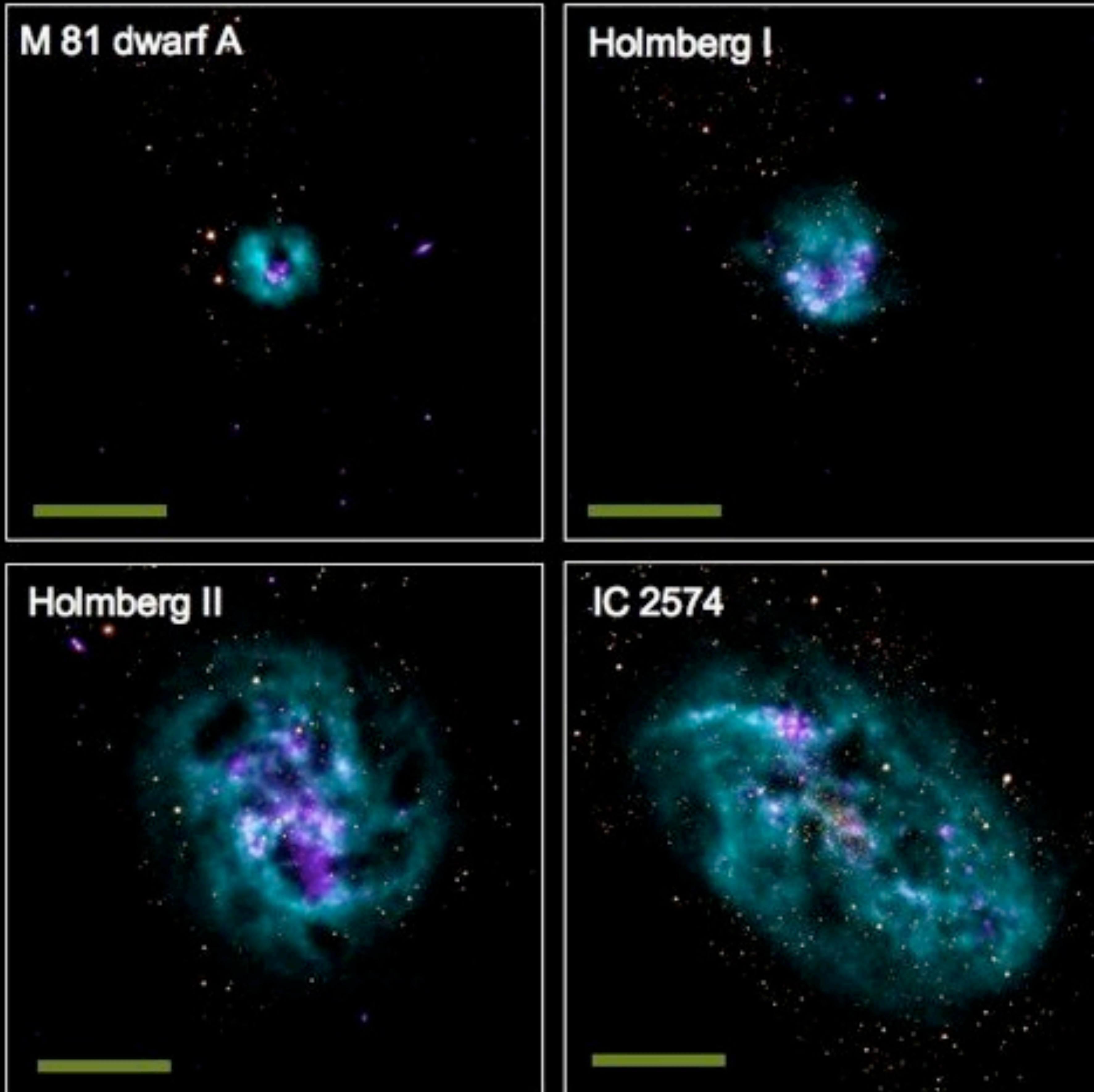
Old stars
(Spitzer Space Telescope)

Star Formation
(GALEX & Spitzer)

scale: 15,000 light years

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07

Dwarf Galaxies in THINGS — The HI Nearby Galaxy Survey



THINGS

The HI Nearby Galaxy Survey

color coding:

THINGS Atomic Hydrogen
(Very Large Array)

Old stars
(Spitzer Space Telescope)

Star Formation
(GALEX & Spitzer)

scale:

15,000 light years

Image credits:
VLA THINGS: Walter et al. 08
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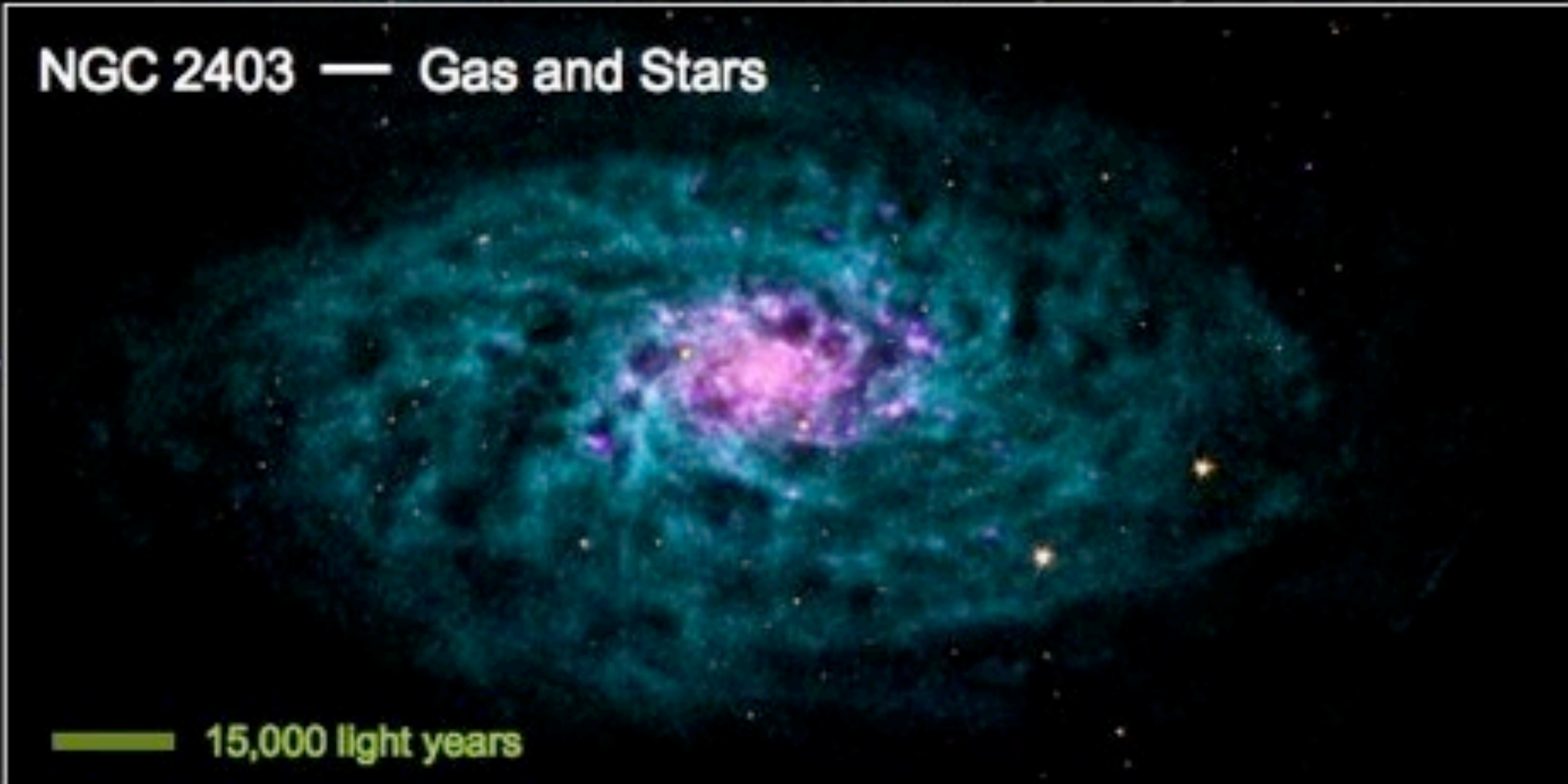
Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey

THINGS

The HI Nearby Galaxy Survey



Color Coding:

THINGS Atomic Hydrogen
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Old stars
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Star Formation
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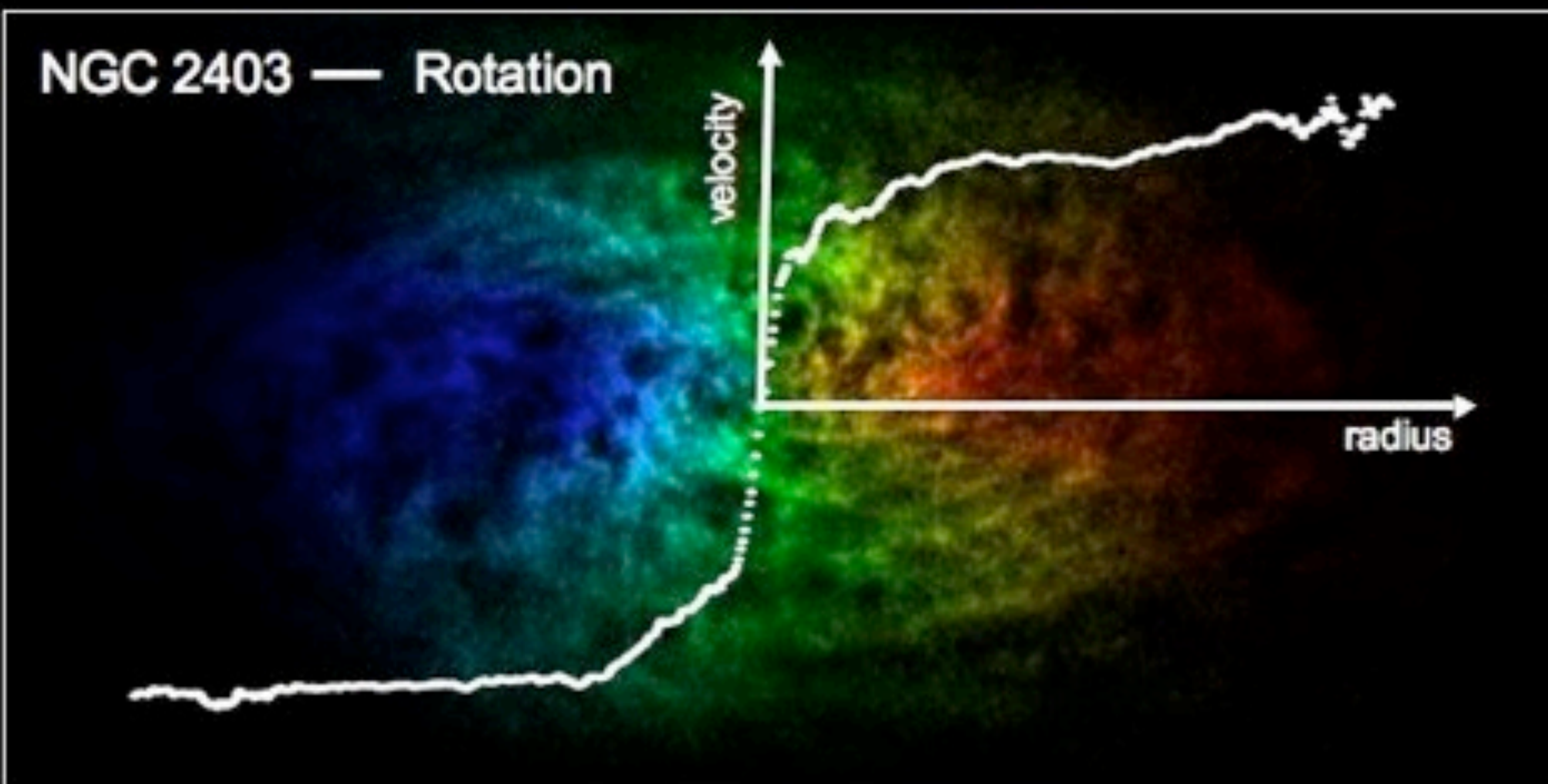


Color coding:
THINGS HI distribution:

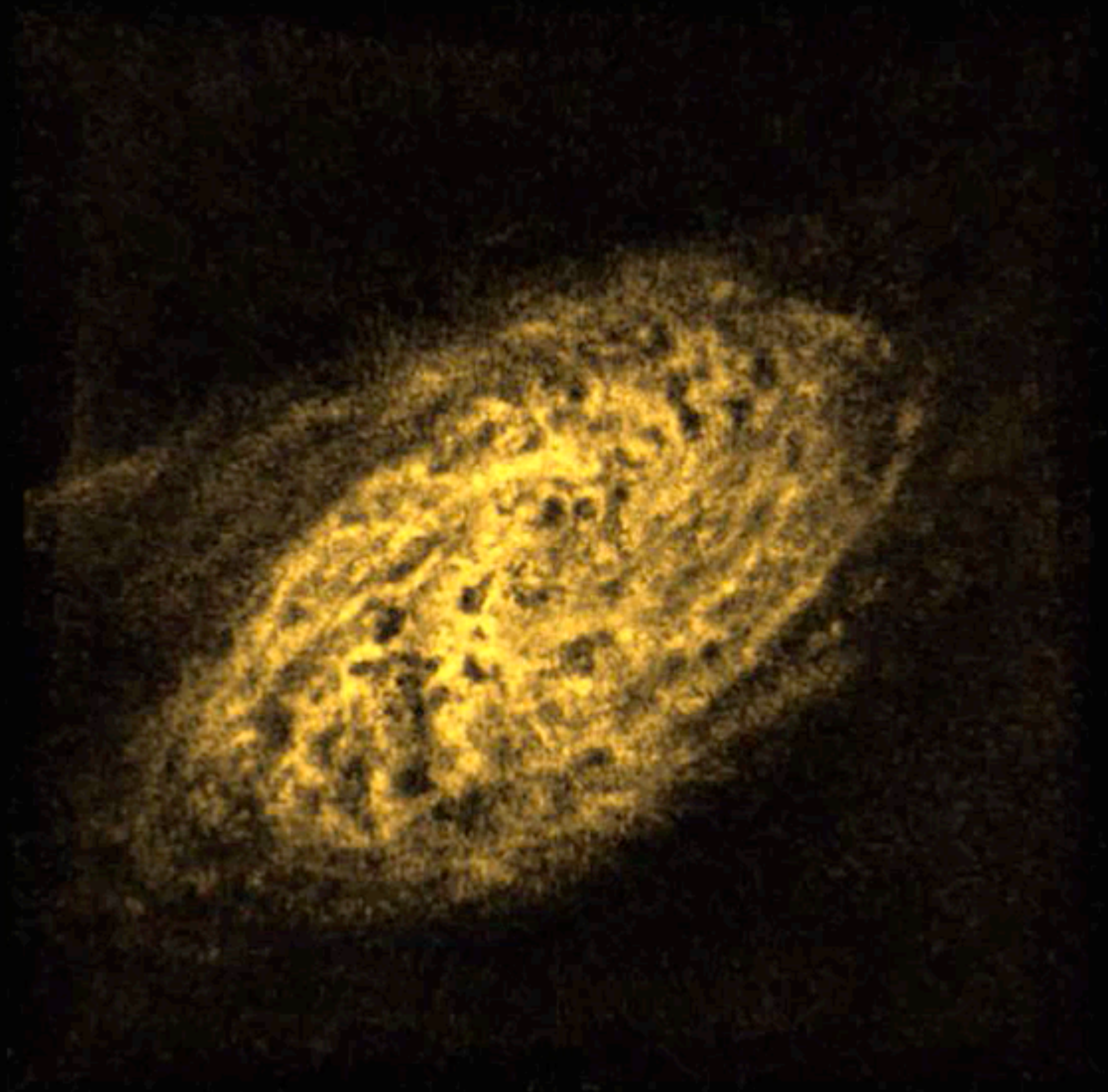
Red-shifted (receding)

Blue-shifted (approaching)

Rotation Curve

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

WL: 152 WW: 206



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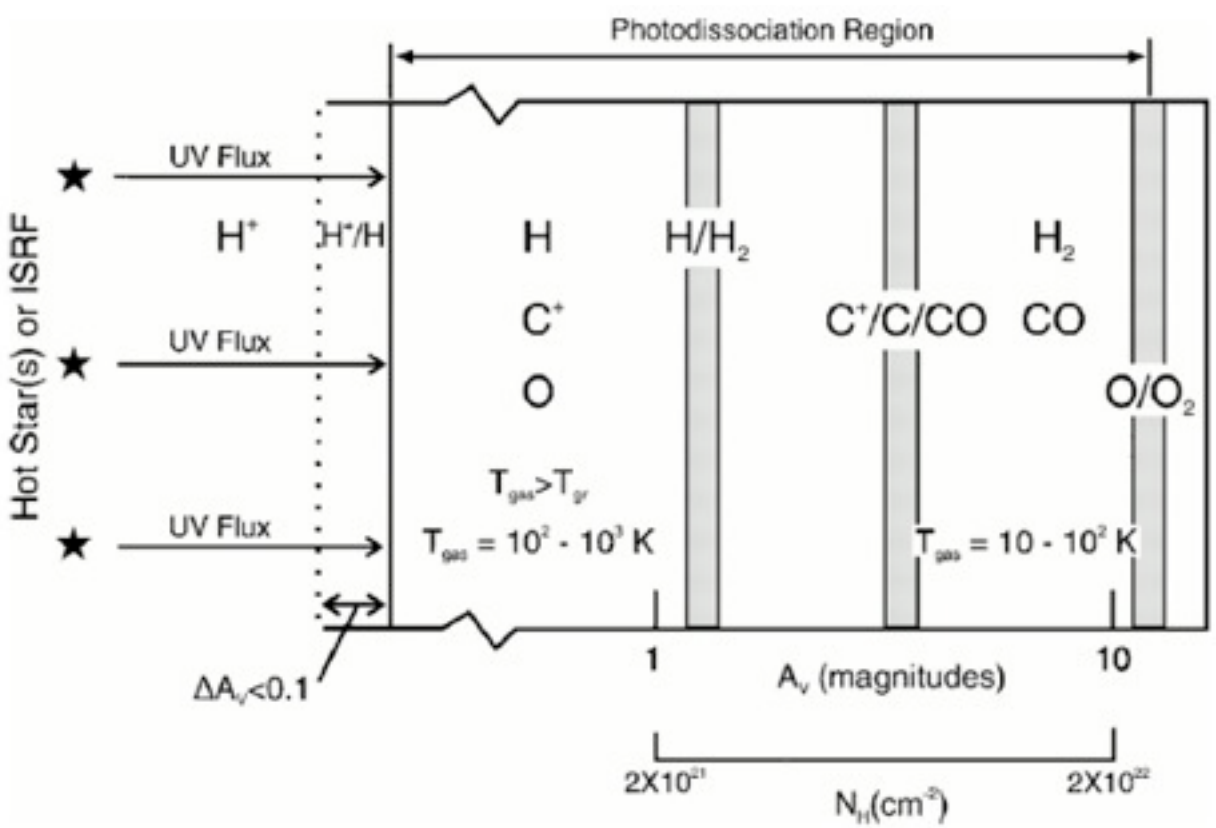
A molecular can make a transition from one state to another described by an electronic, vibrational or rotational quantum number

At radio/submillimeter wavelengths: rotational transitions

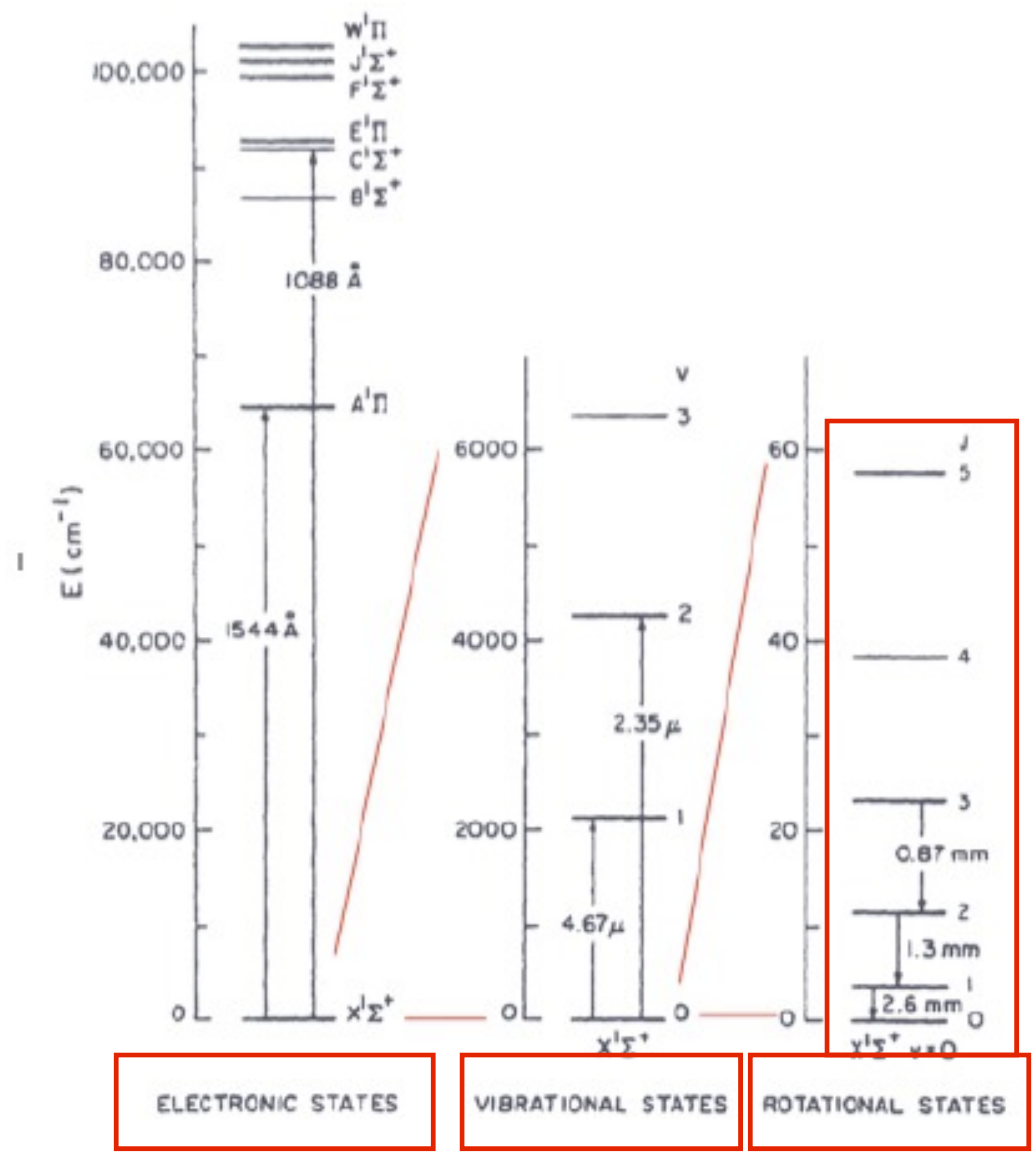
Allowed transition depends on selection rules

Ideally want to measure H_2 in cold phase but no accessible transitions

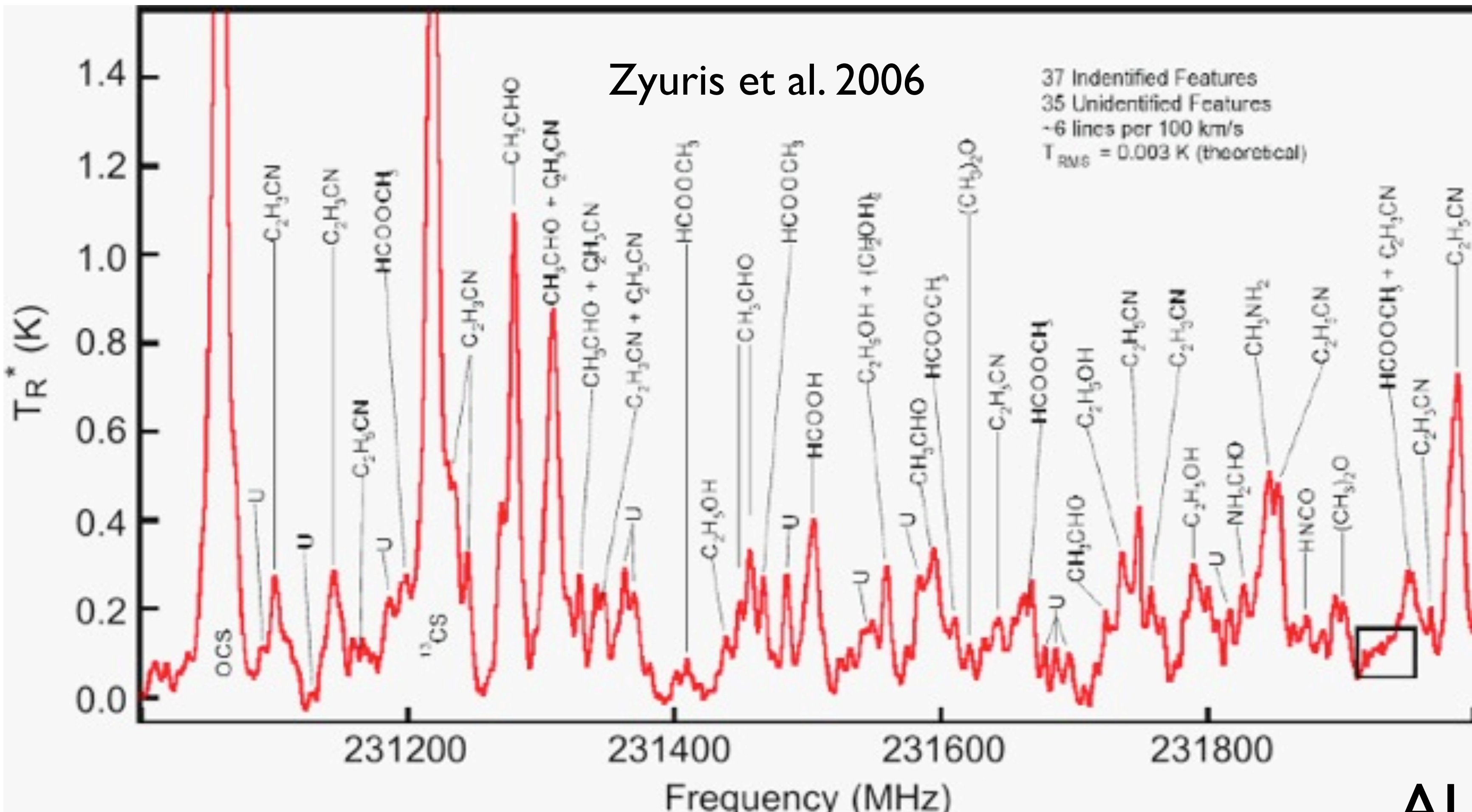
CO is most abundant molecule after H_2. To first order reasonable tracer of H_2.



example: CO



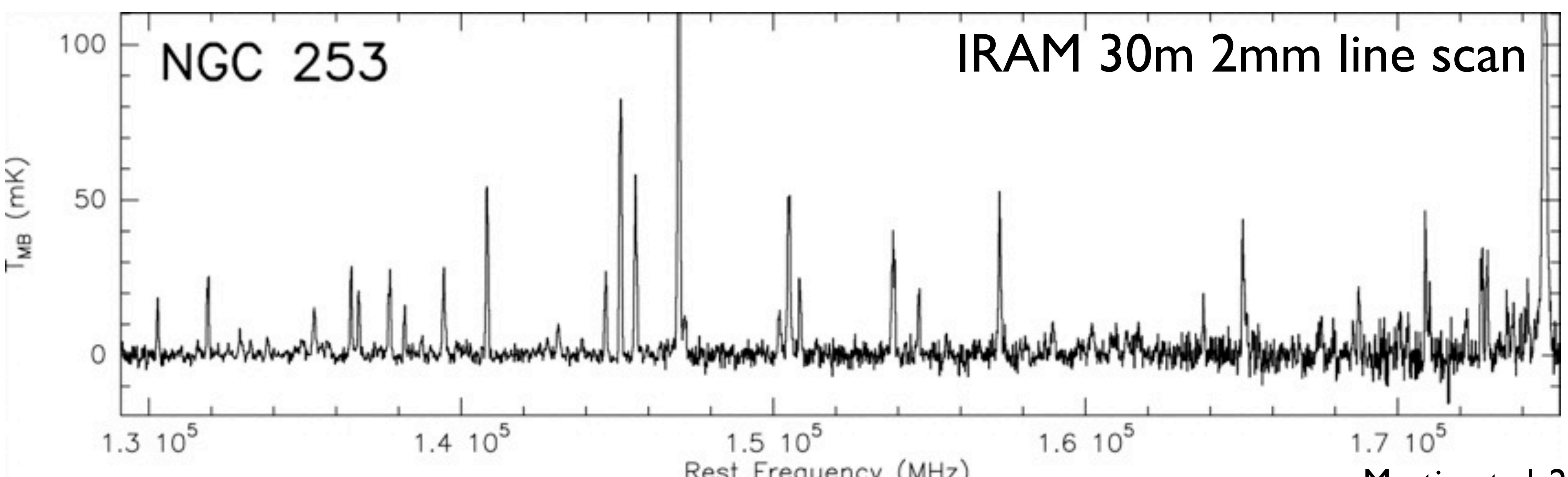
Molecular Lines



1.3 mm spectrum of SgrB2(N) near the Galactic Center

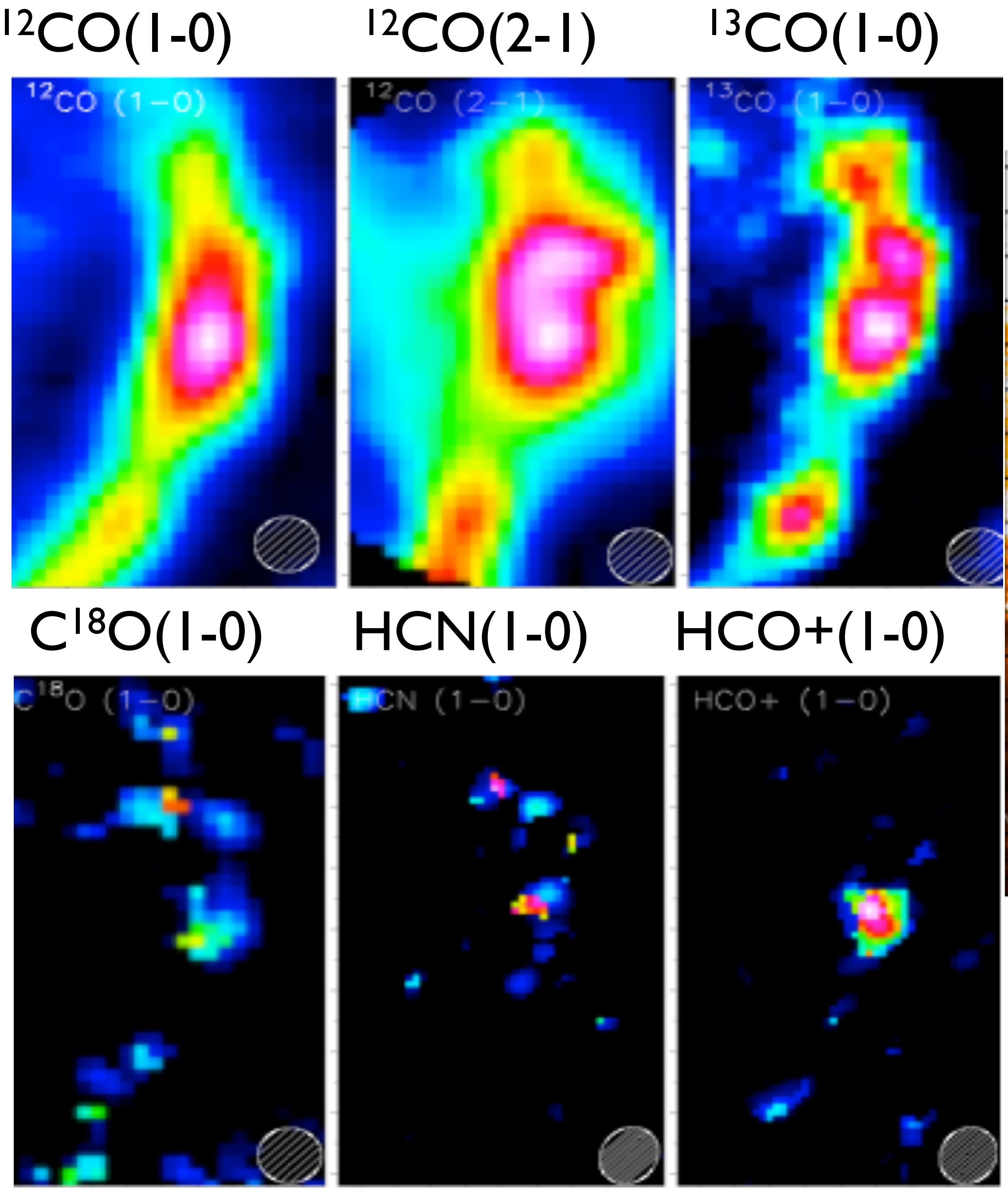
(note: numerous unidentified features)

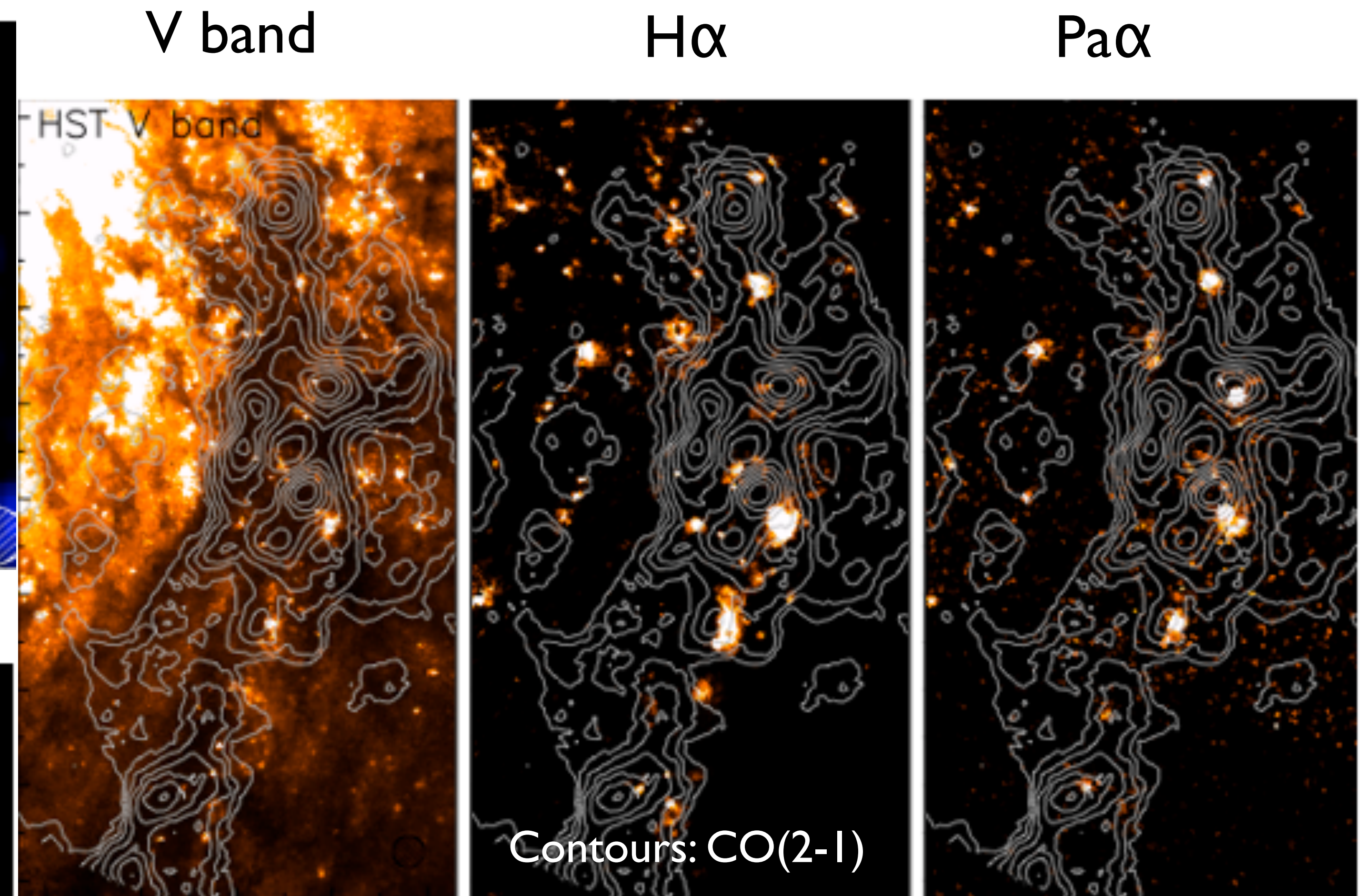
ALMA: 'involuntary line surveys



Martin et al. 2006

Molecular Gas Tracers





example: spiral arm in M51 -- Schinnerer et al. 2010

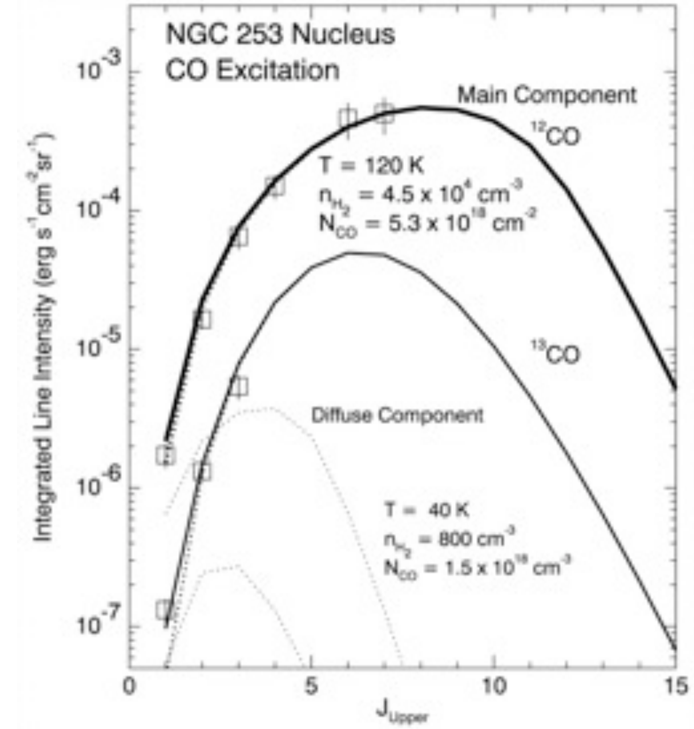
critical density of CO: few 100 cm^{-3}

but star formation only sets in at >1000 cm^{-3}

need dense gas tracers: HCN, HCO$^+$, ... (typically <10 fainter than CO)

Characterizing molecular gas conditions: CO SEDs

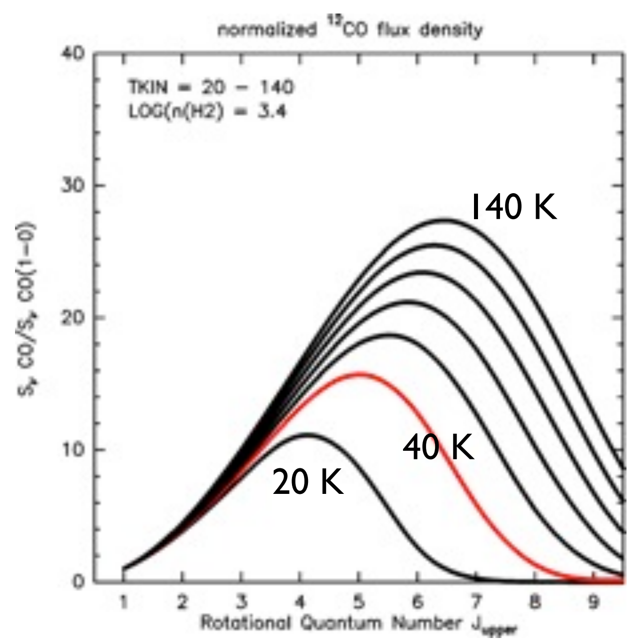
study temperature and density of the gas by observing multiple transitions, so called CO line SEDs



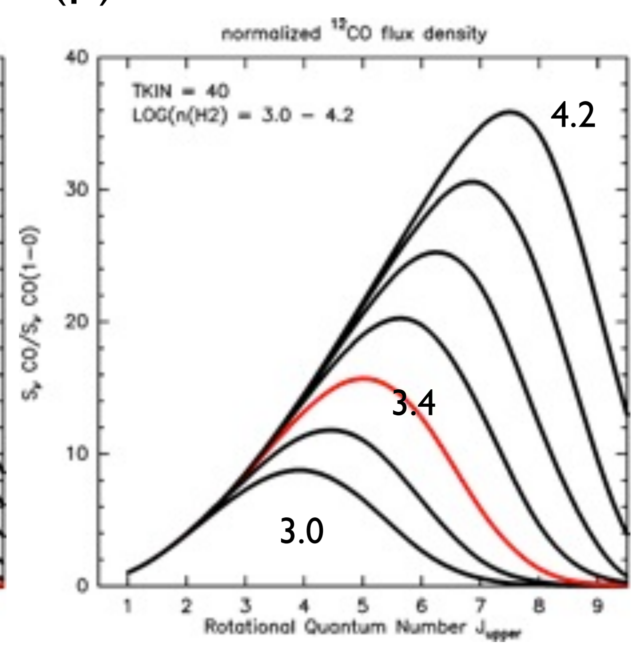
difficult from the ground at z~0 -- easier done at high z(!)

Large Velocity Gradient (LVG) modelling:

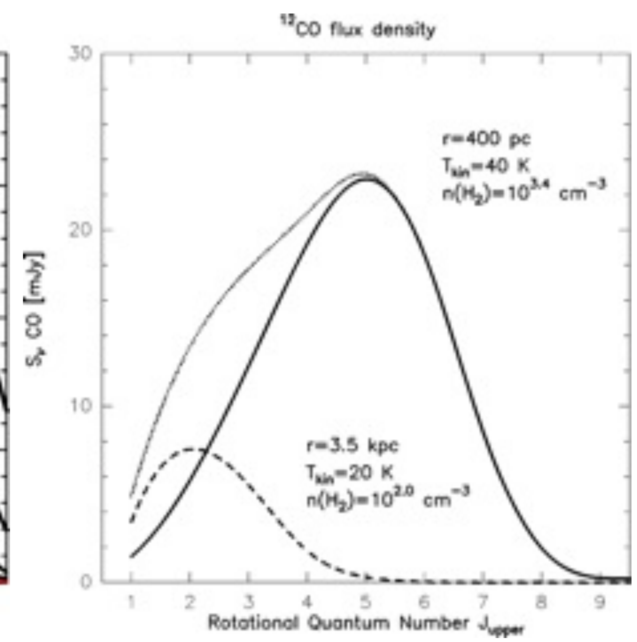
f(T)



f(ρ)



Multiple components

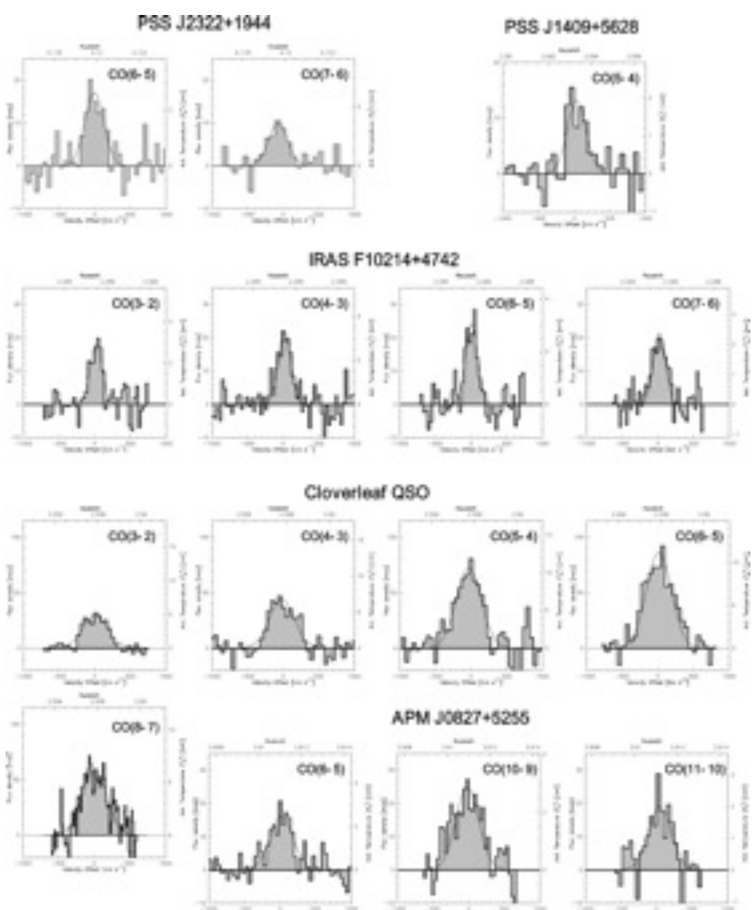


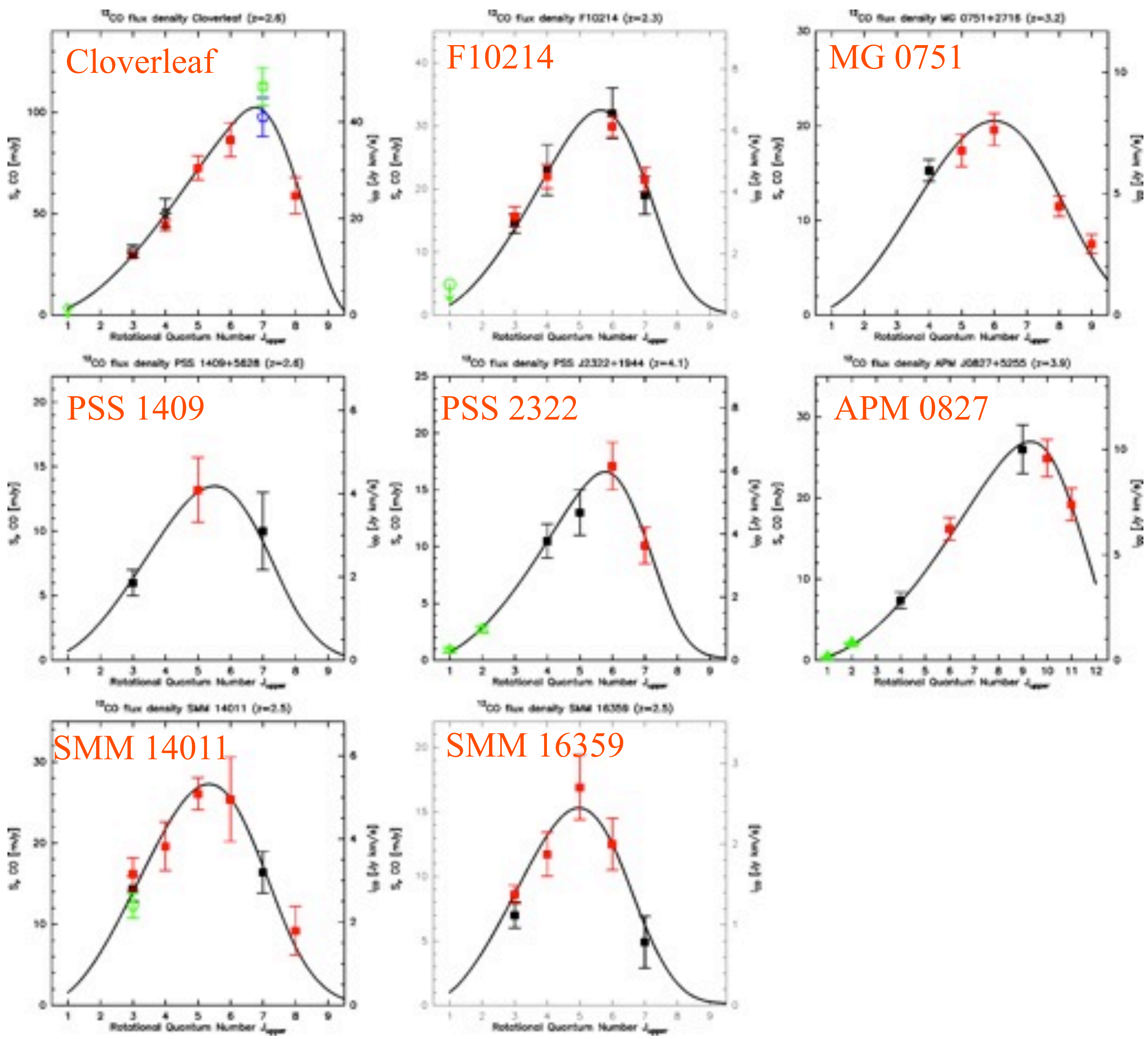
turnover: measure of the CO excitation
shape is temperature/density dependent
shape: search for extended CO

LVG input: $n(H_2)$, T_{kin}, $[CO]/[H_2]/dv/dr$ (fixed to 810^{-5} pc $(km/s)^{-1}$)

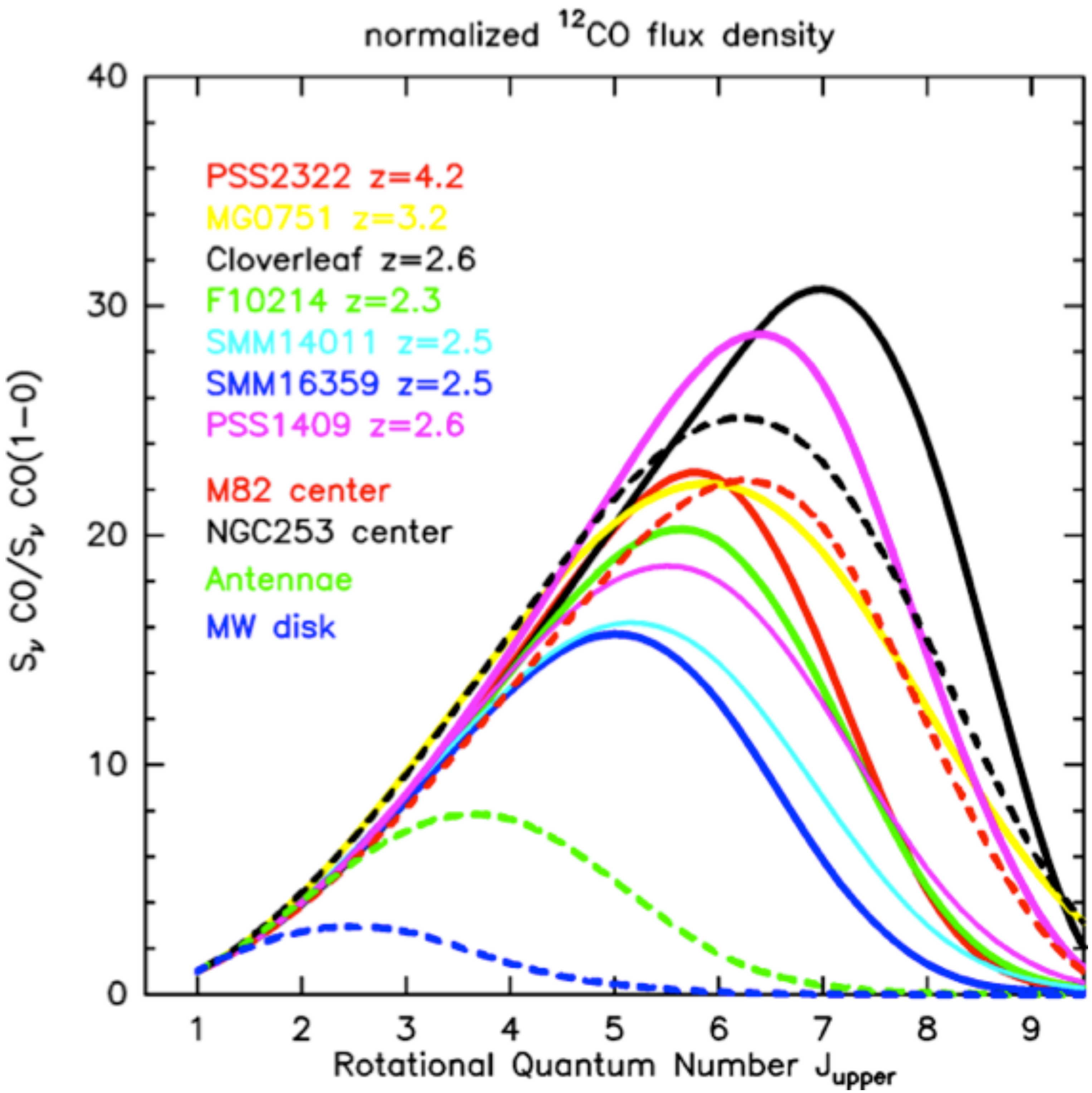
observe individual targets in many CO lines to get CO excitation.

only the brightest sources can be studied at high redshift.





(Weiss, Walter, Downes, Henkel)



full lines: high redshift

dashed lines: low redshift

single gas component

QSO turnover: J>6-5

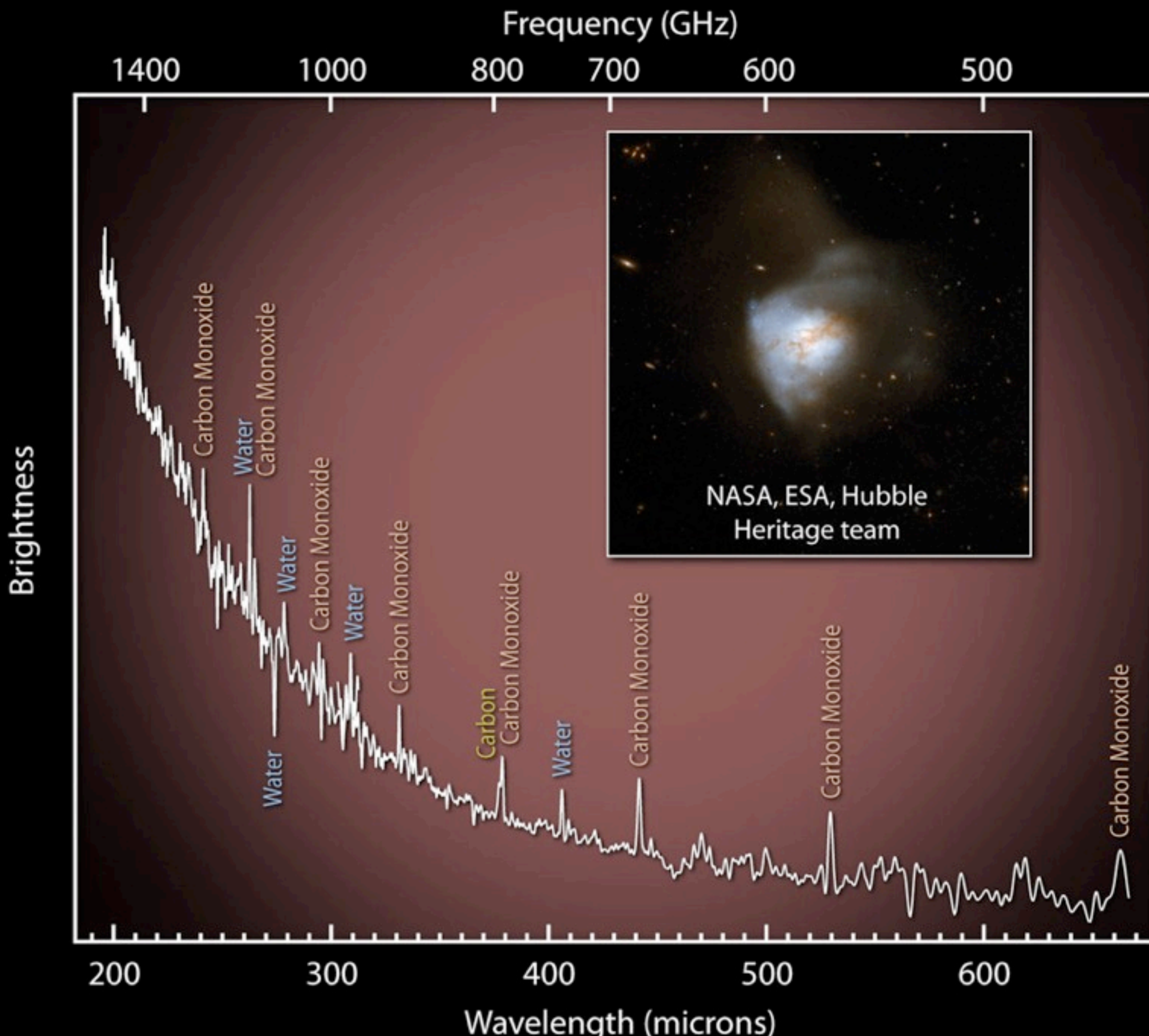
SMM turnover: J~5-4

compact (<1.5kpc)

no indication for extended comp.

gas typically much more excited than in Milky Way disk
(but see BzK galaxies)

Weiss et al. 2007



Arp 220

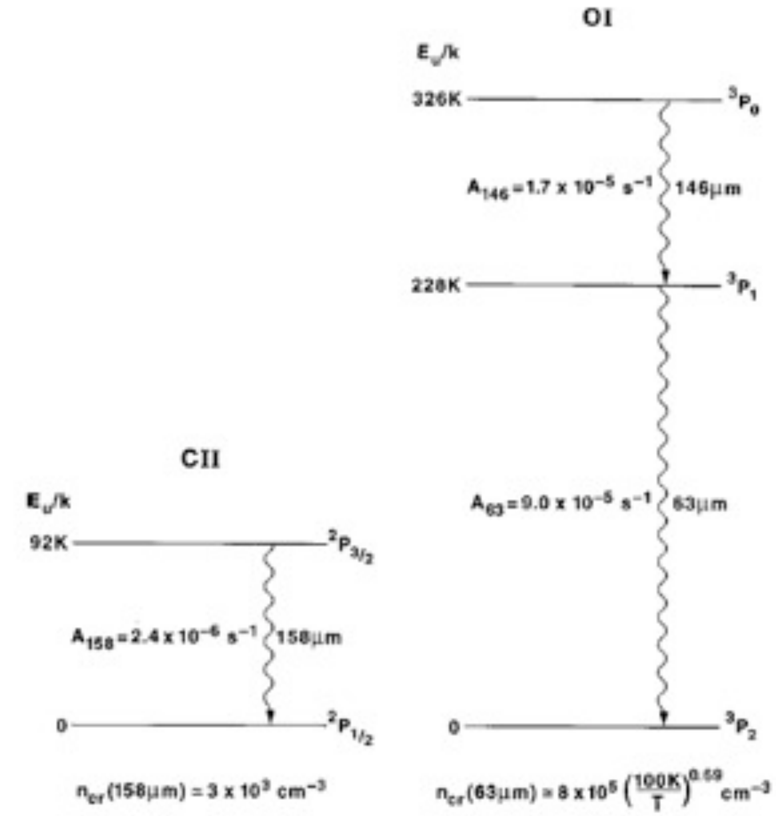
© ESA and the SPIRE consortium

X-Factor

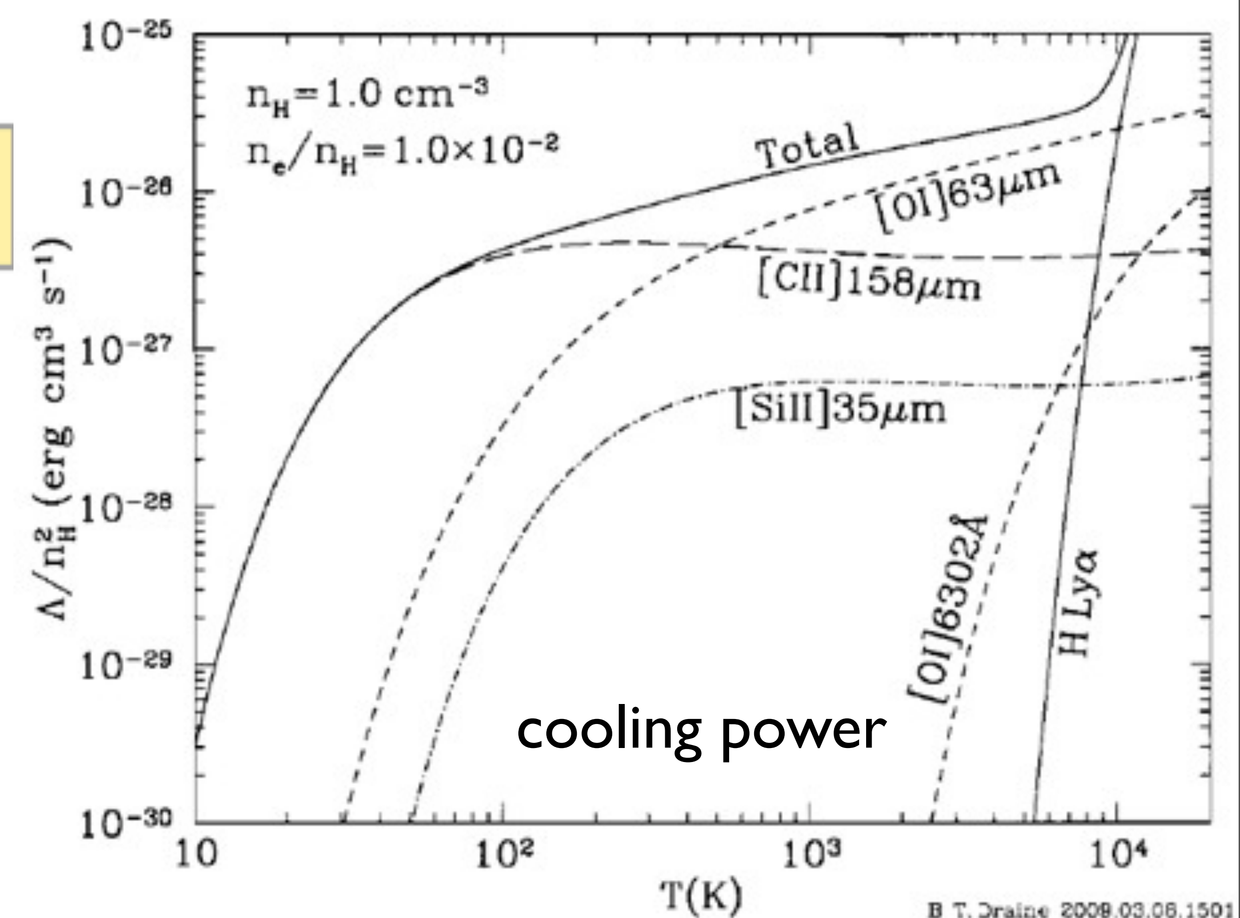
- problem: want H_2 mass but can only observe CO
- $M(H_2)=\alpha_{CO}\ L(CO)$, ($\alpha_{CO}$ used for masses, X_{CO} for column densities)
- approaches:
  - virial masses: assume resolved cloud is bound
  - dust: infer H_2 from dust mass assuming dust/gas ratio
  - Gamma-ray (measure for H_2 column)
  - dynamical arguments ($M(H_2)$ not to exceed M_{dyn})
- there is general consensus that $X_{CO} \sim 2\ 10^{20}\ cm^{-2}\ (K\ kms^{-1})$ for normal galactic environments

Atomic Fine Structure Lines

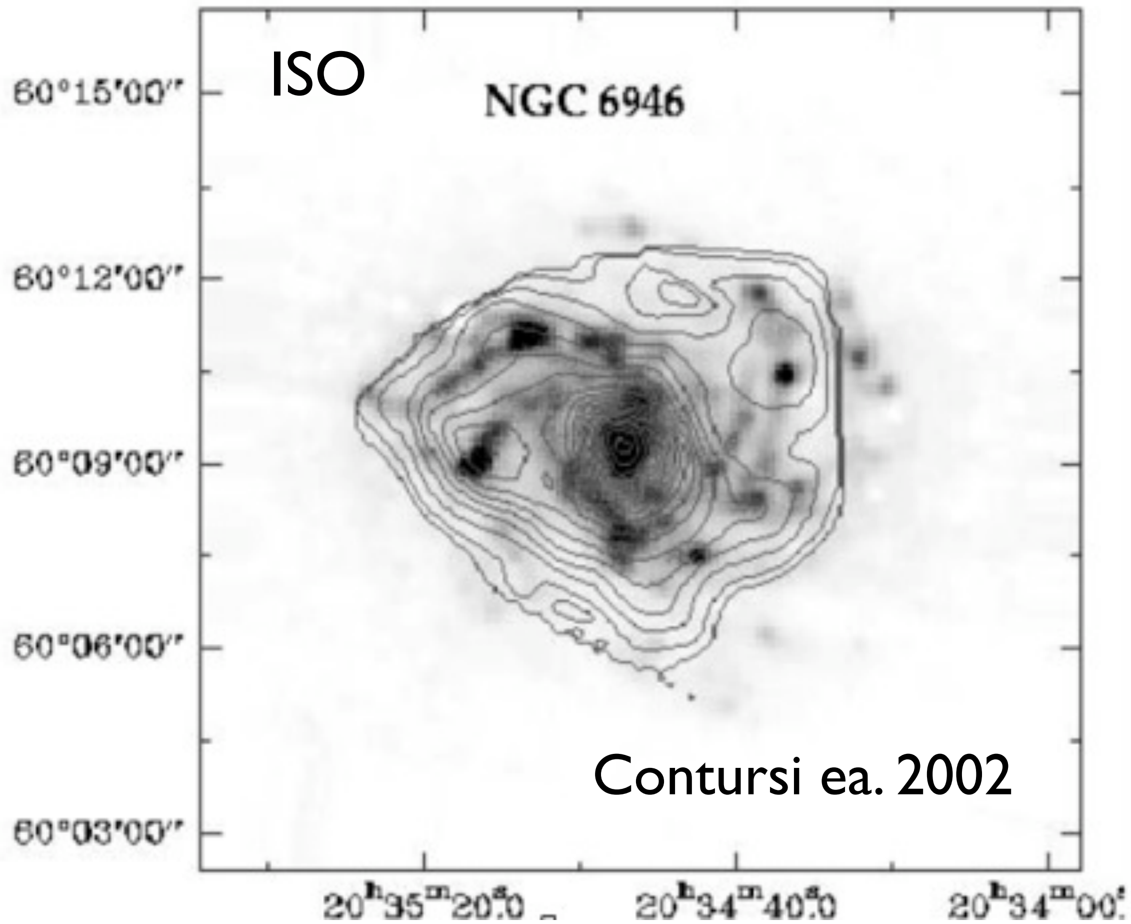
...splitting of spectral lines due to relativistic corrections



- Transitions between fine structure levels are magnetic dipole transitions ($\Delta J = \pm 1, \Delta L = 0, \Delta S = 0$)
- Transition probabilities are a factor α_{fs}^2 weaker than those of (electric dipole) permitted transitions
- Fine structure lines are therefore normally optically thin and easily excited collisionally
- Fine-structure lines are in the far-infrared regime (10μm-300μm):
  - Example OI: $^3P_1$ - $^3P_2$ 63μm, $^3P_0$ - $^3P_1$ 145μm
- Fine-structure lines are important coolants of interstellar gas:
  - Example: C^+ $^3P_{3/2}$ - $^3P_{1/2}$ 158μm



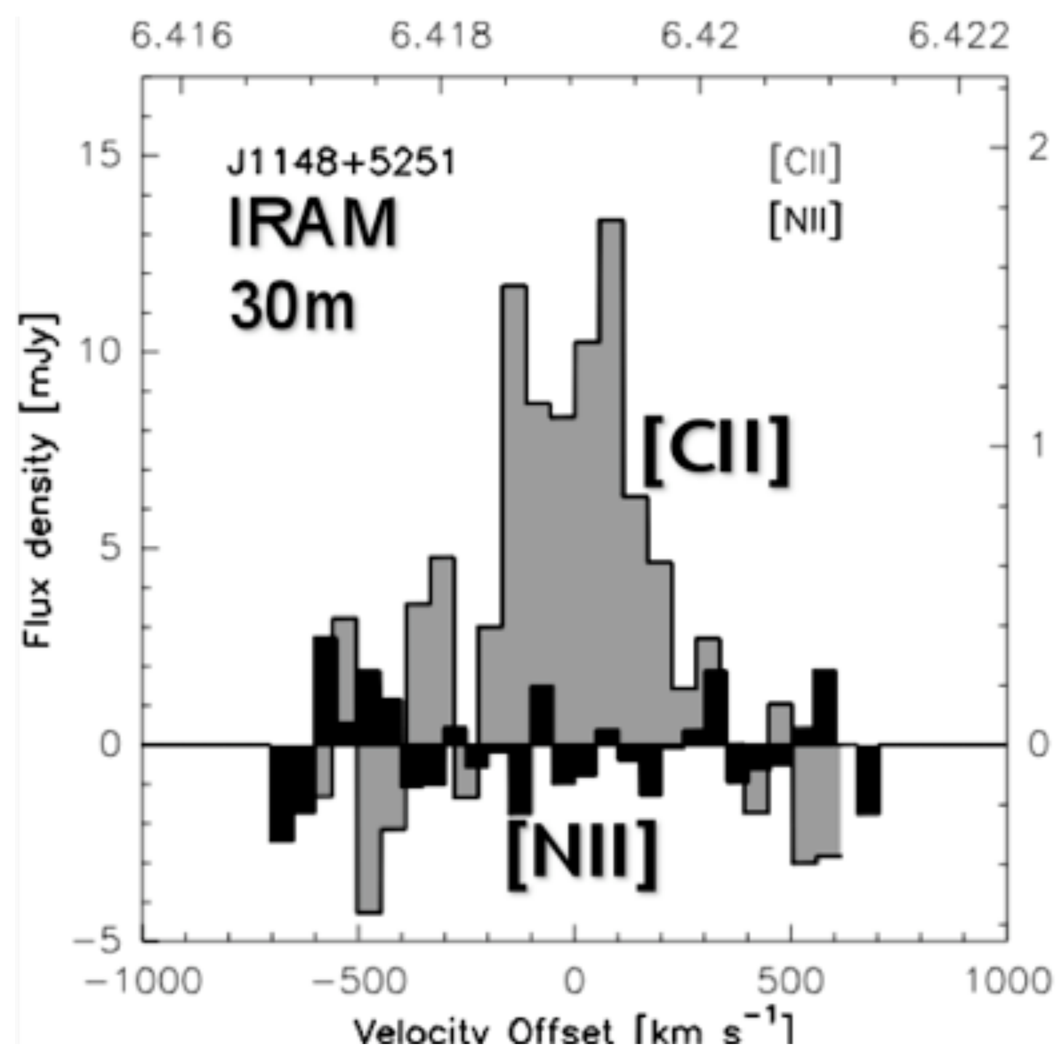
[CII] (ionized carbon): major cooling line of the ISM



ISO obs.: [CII] carries high fraction of L_{FIR}, much brighter than CO (z~0)

J1148+5251 (z=6.42)

- $L_{[CII]} = 4\times10^9 L_o$ ($L_{[NII]} < 0.1 L_{[CII]}$)
- SFR ~ 6.5e-6 $L_{[CII]}$ ~ 3000 M_o/yr

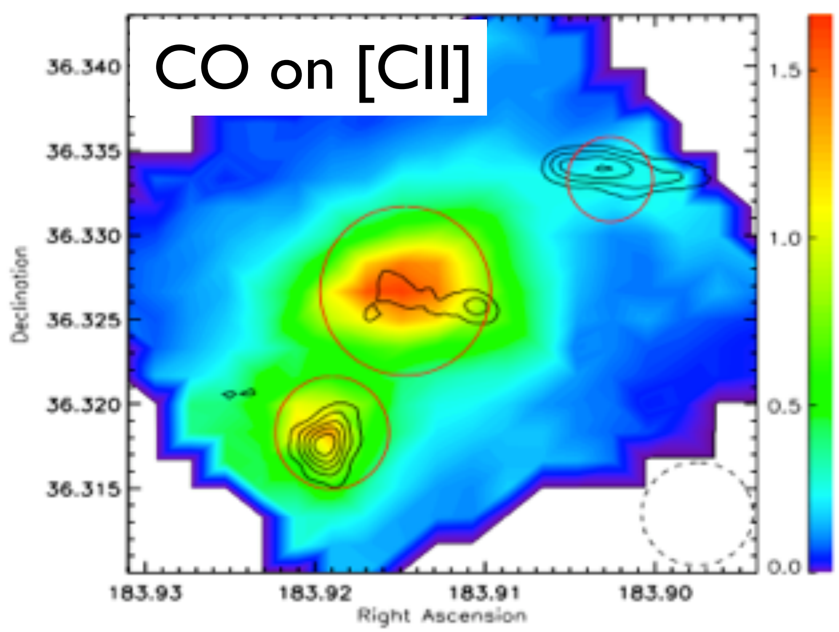


Maiolino ea. 2005

Walter, ea. 2009

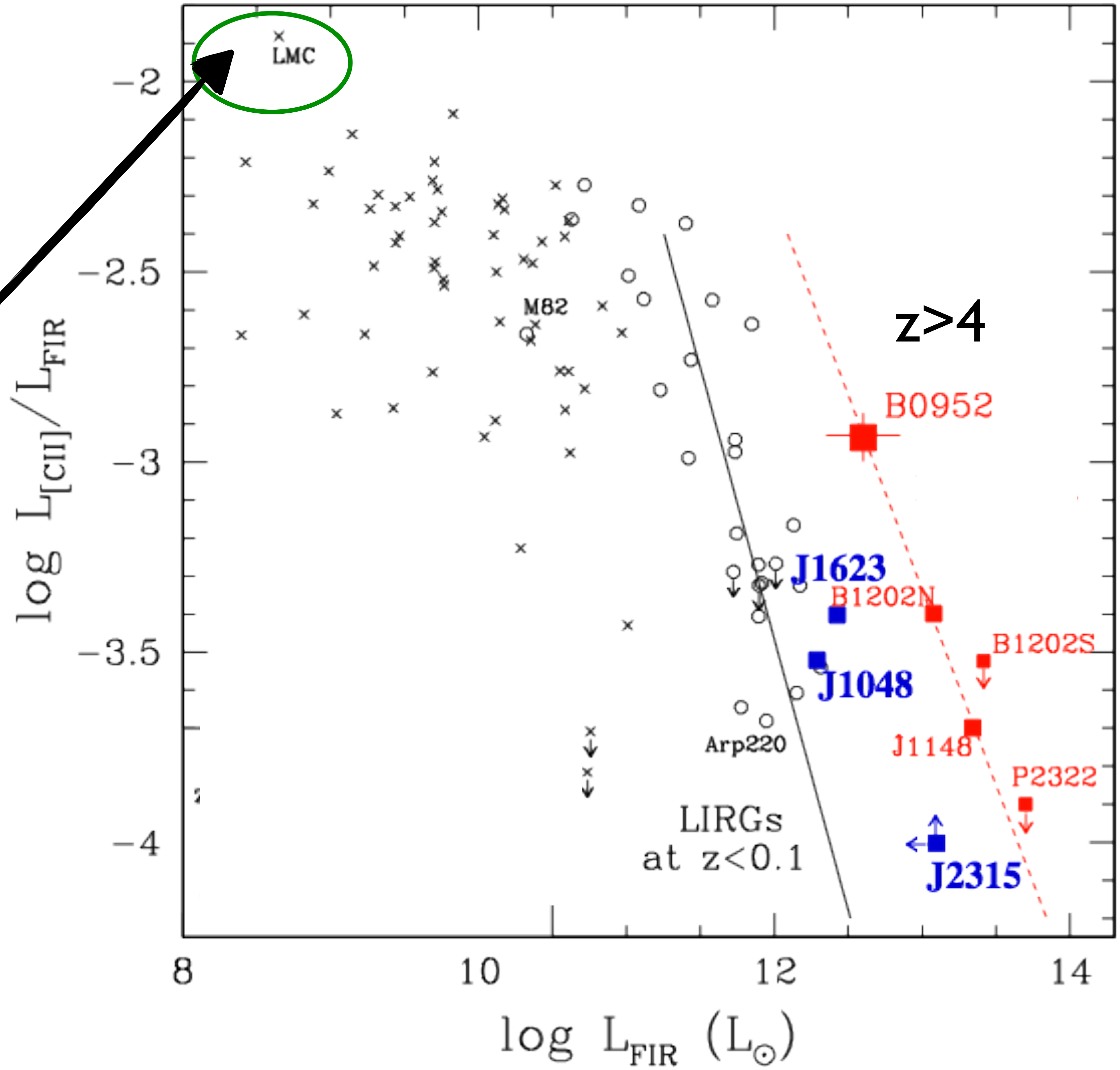
[CII] - FIR relation

may be easier to detect fainter, low metallicity sources?



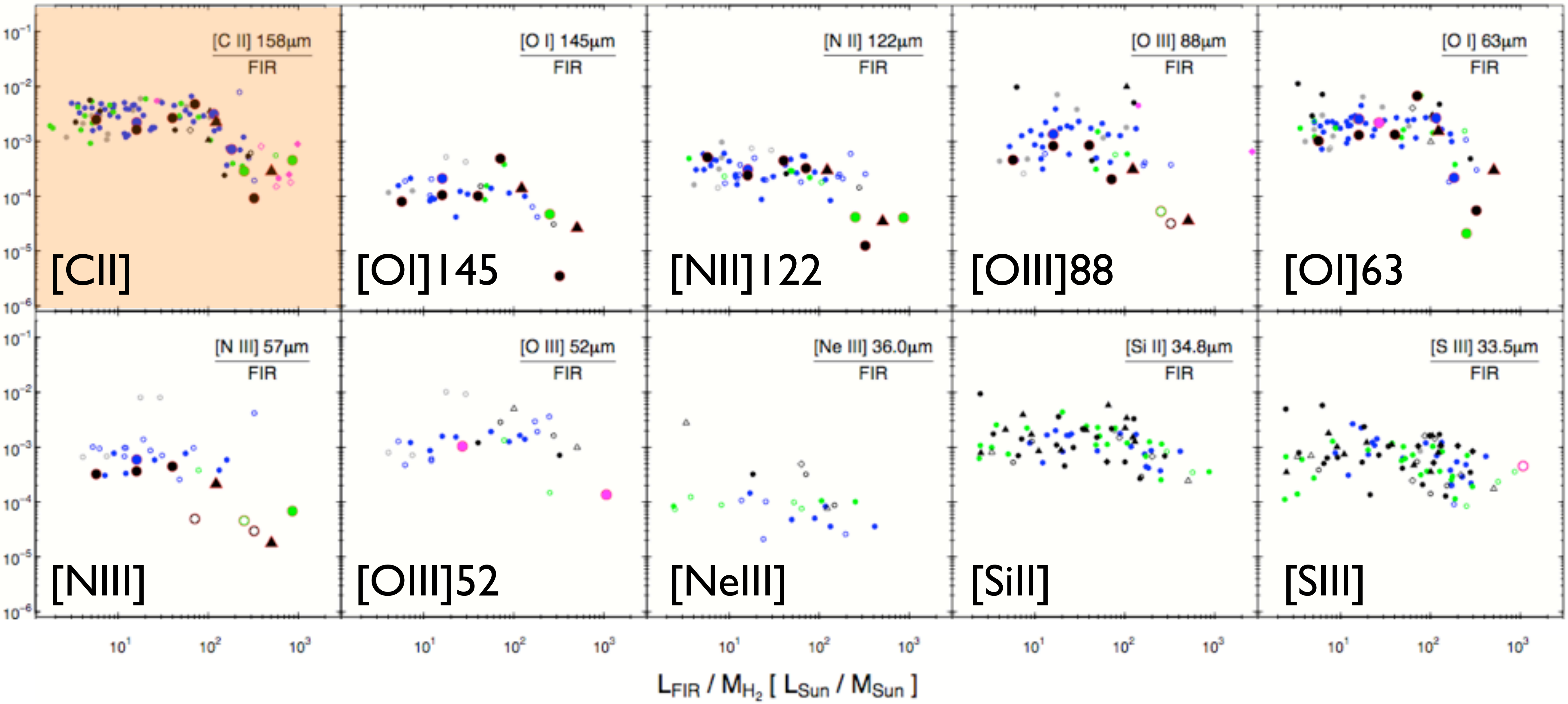
[CII] Herschel-PACS image of NGC 4214 ($Z \sim 0.3 Z_{sun}$)

[CII]/FIR ~ 0.01
[CII]/CO ~ 50000 !



Maiolino+09, Bertoldi+??

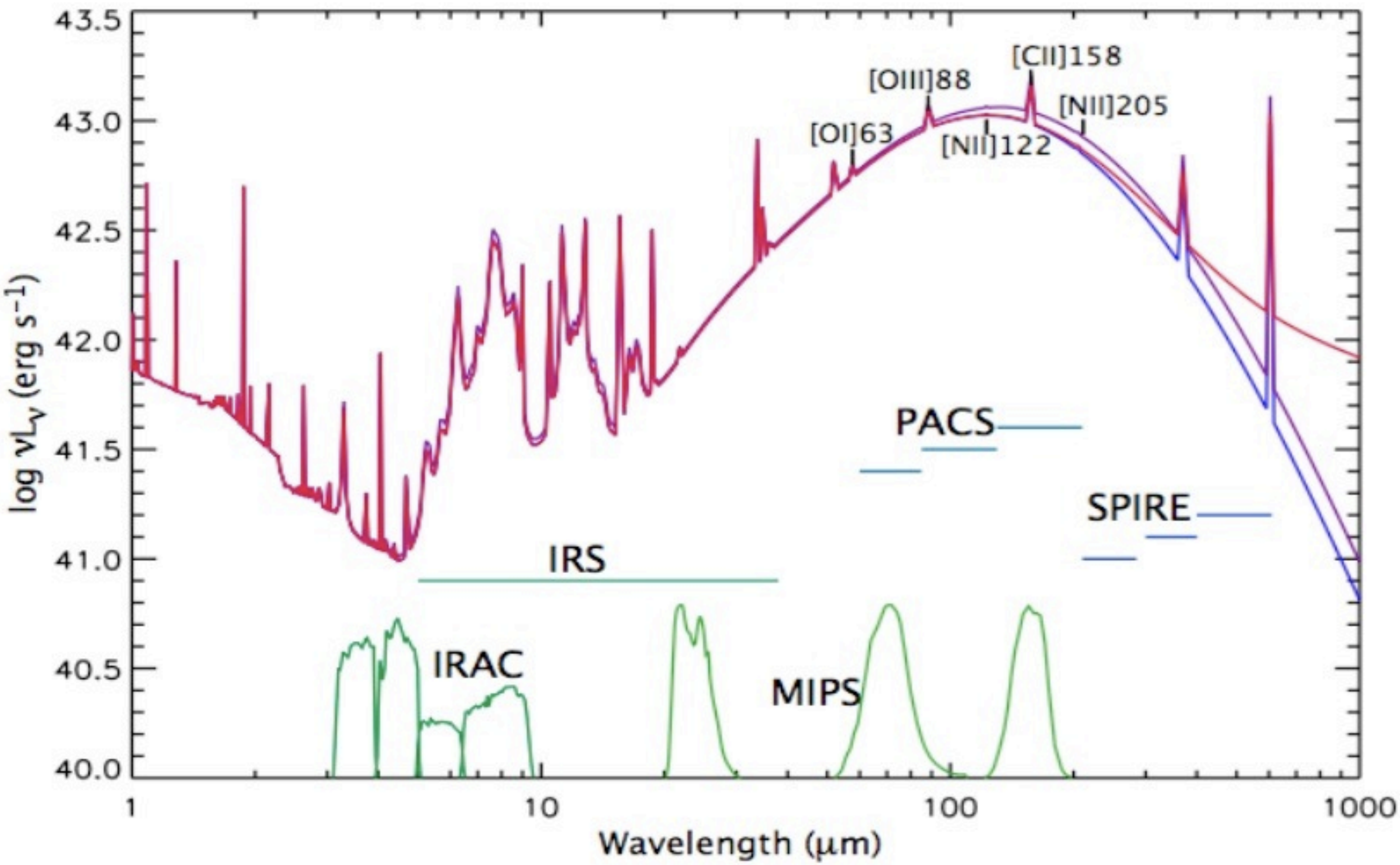
Herschel will provide key measurements of FS lines in local universe



high-redshift: ALMA

Gracia-Carpio et SHINING 2011

Dust



log νL_ν (erg s^{-1})
43.5
43.0
42.5
42.0
41.5
41.0
40.5
40.0
1
10
100
1000
Wavelength (μm)
[CII]158
[OIII]88
[NII]205
[OI]63
[NII]122
PACS
SPIRE
IRS
IRAC
MIPS

Dust Facts

Dust mass insignificant (~1% of total HI gas mass)

Dust is formed from stellar ejecta and/or formation in ISM

Dust grains come in different sizes

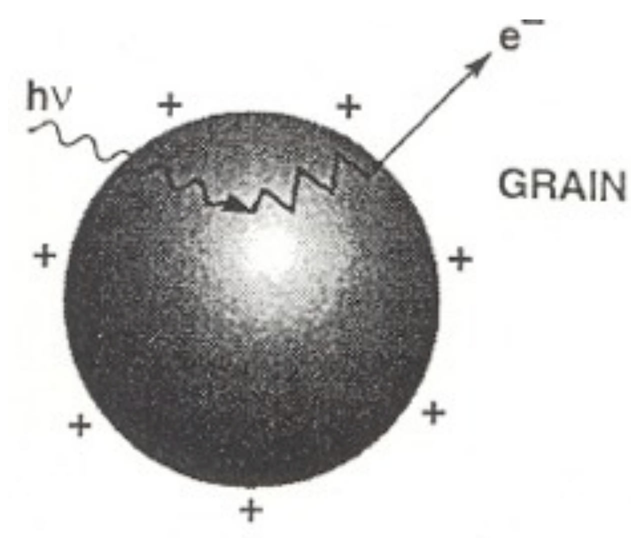
Dust grains are mainly: silicates (Mg/Fe-rich) or graphites (C)

Grains provide surface for complex astrochemistry (and H_2 formation)

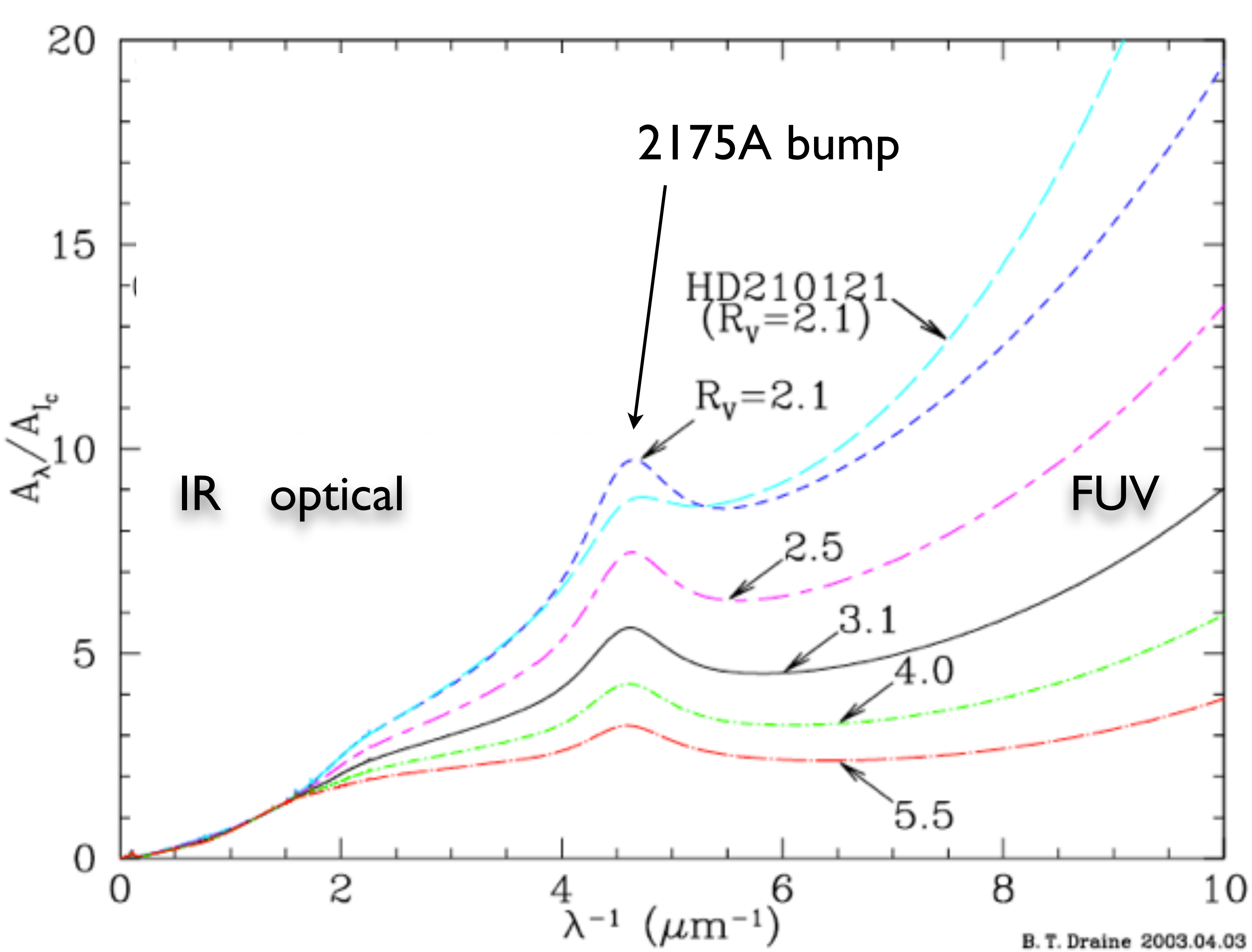
Dust is the main heating mechanism of the ISM (through photo-electric effect)

Photoeffect (Hertz 1887): photon liberates e^- from solid (e.g. dust).

This process is the main heating source of the molecular gas in galaxies!
Mostly working on PAHs and small dust grains.
FUV photons with $h\nu$>6eV heat the gas via photoelectrons, with typical efficiency of 0.1-1%



Extinction Curves



$R_V=A_V/(A_B-A_V)$ -- measure of slope of extinction curve

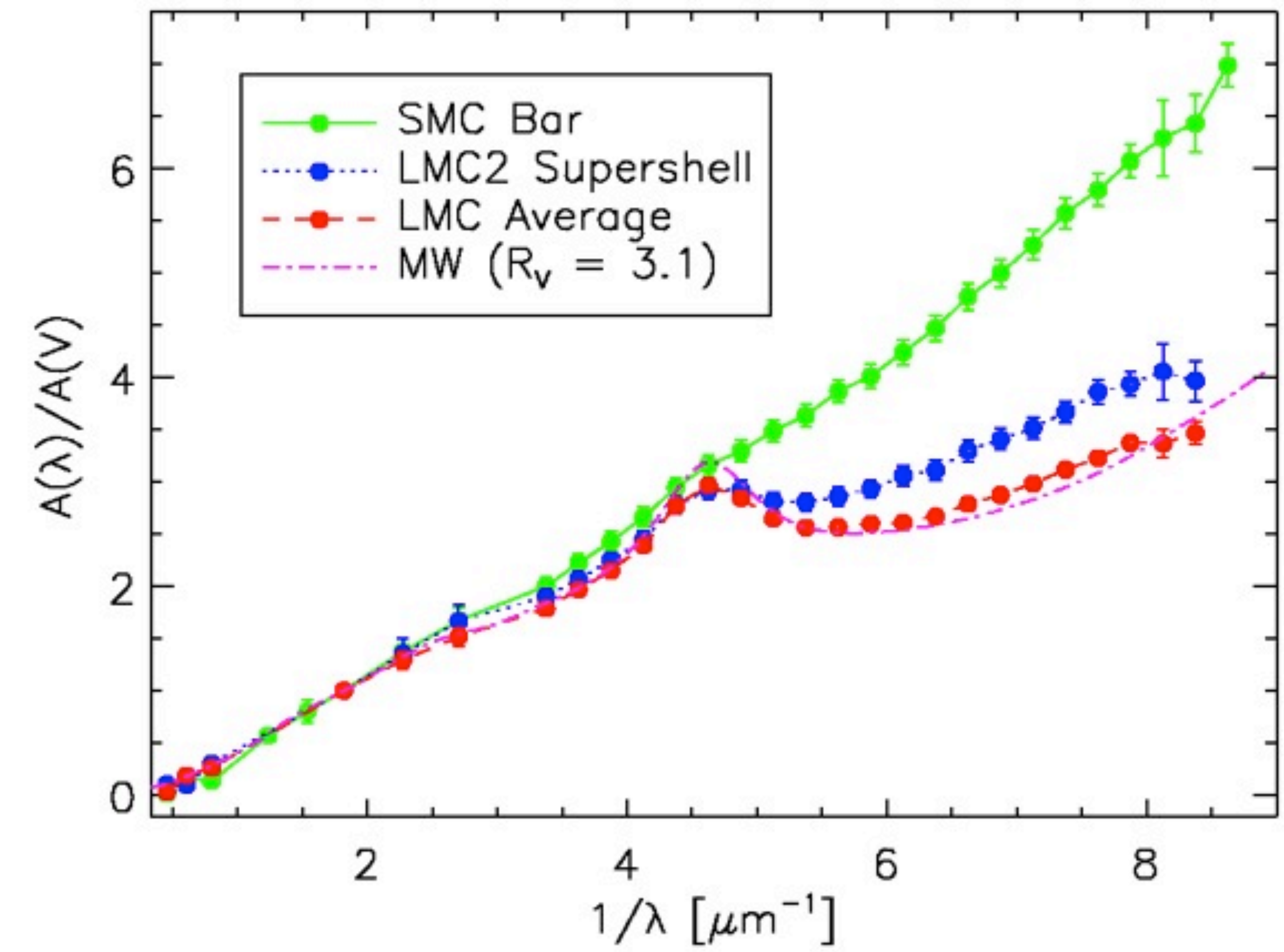
R_V=3.1: standard diffuse ISM value

R_V increases (ie extinction becomes "grayer") in denser ISM material, probably from coagulation of grains.

2175A feature likely mixture of graphite grains and PAHs

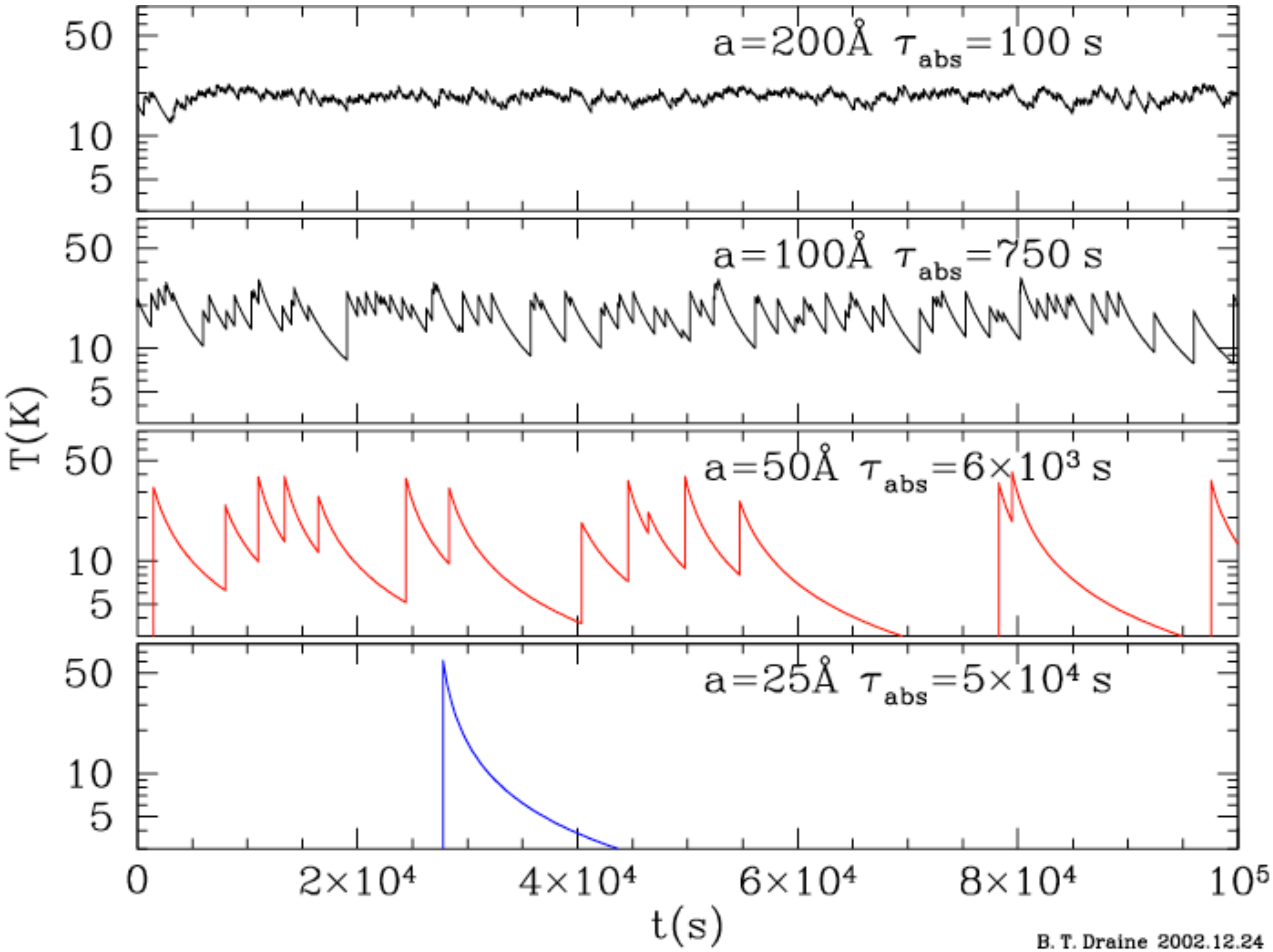
This effect is also called 'reddening': blue emission more extinct than red, resulting in redder color

Extinction Curves



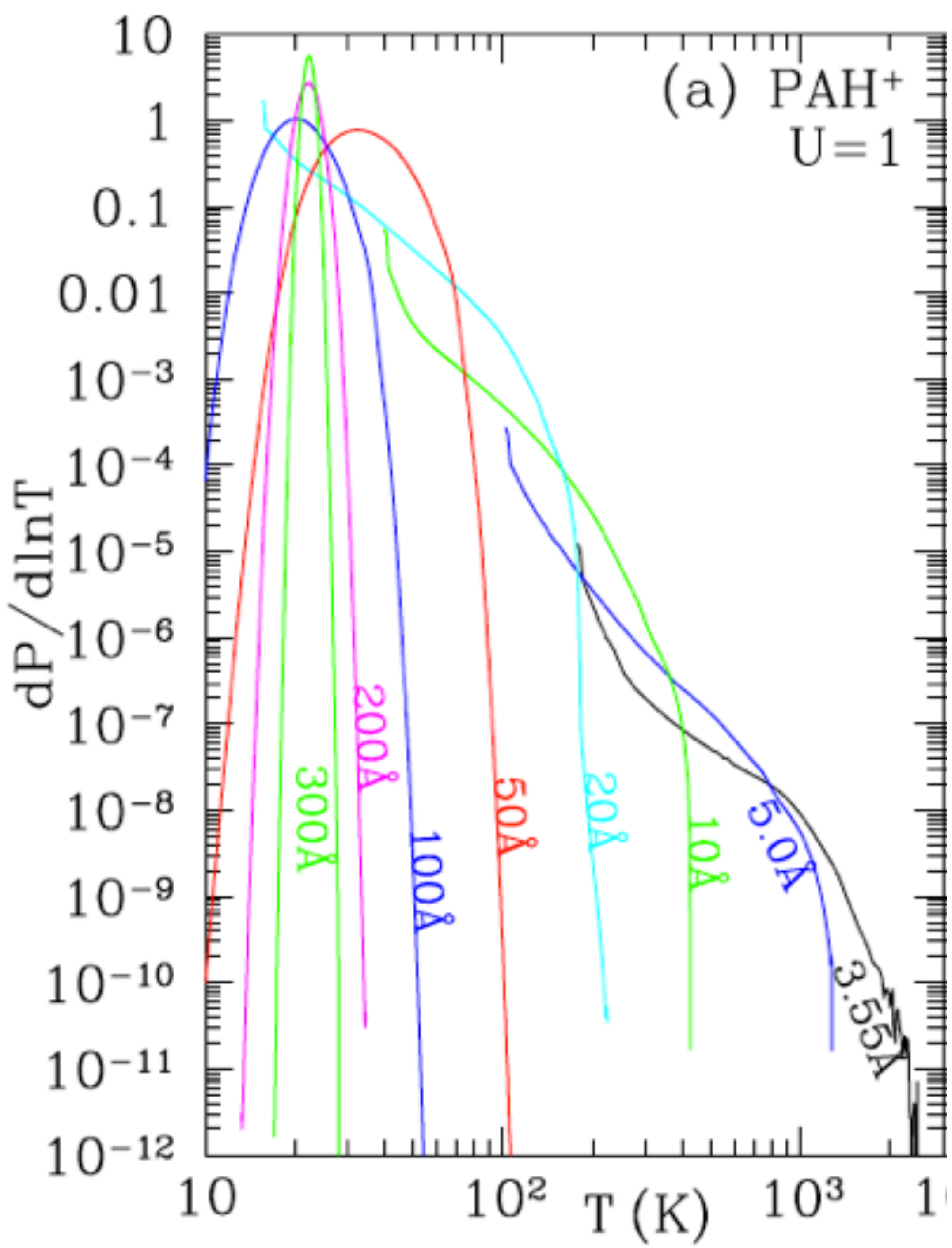
SMC extinction curve is significantly different -- metallicity effect?

Heating of dust grains of various sizes



"A day in the life of dust grains" (Draine 2003) of different sizes. τ_{abs} is mean time between photon absorption

Temperature dependence on grain sizes



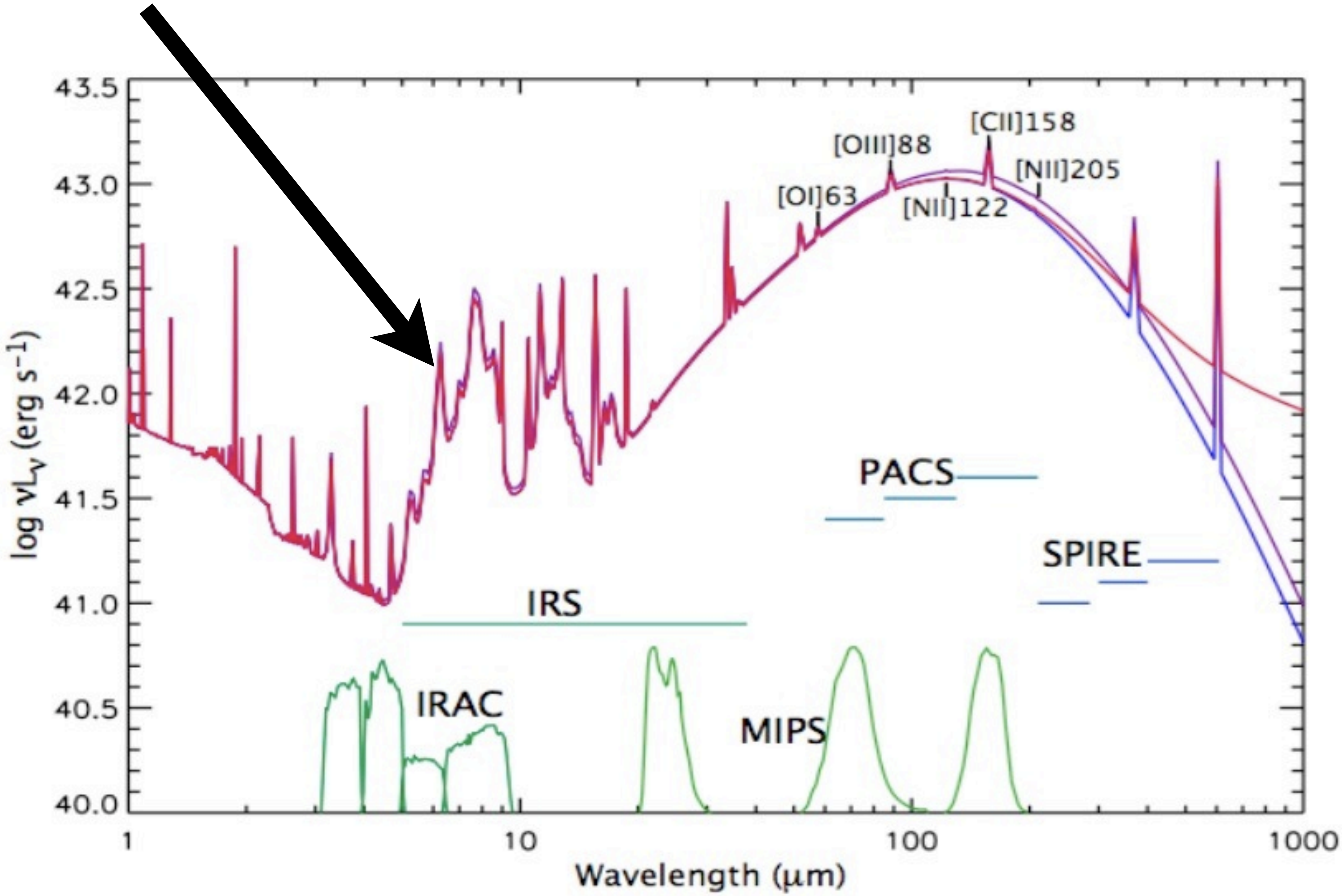
Temperature probability distribution of selected grains heated by starlight.

Large grains: low temperatures and more narrow distribution

sum of all these curves will determine shape of the FIR SED

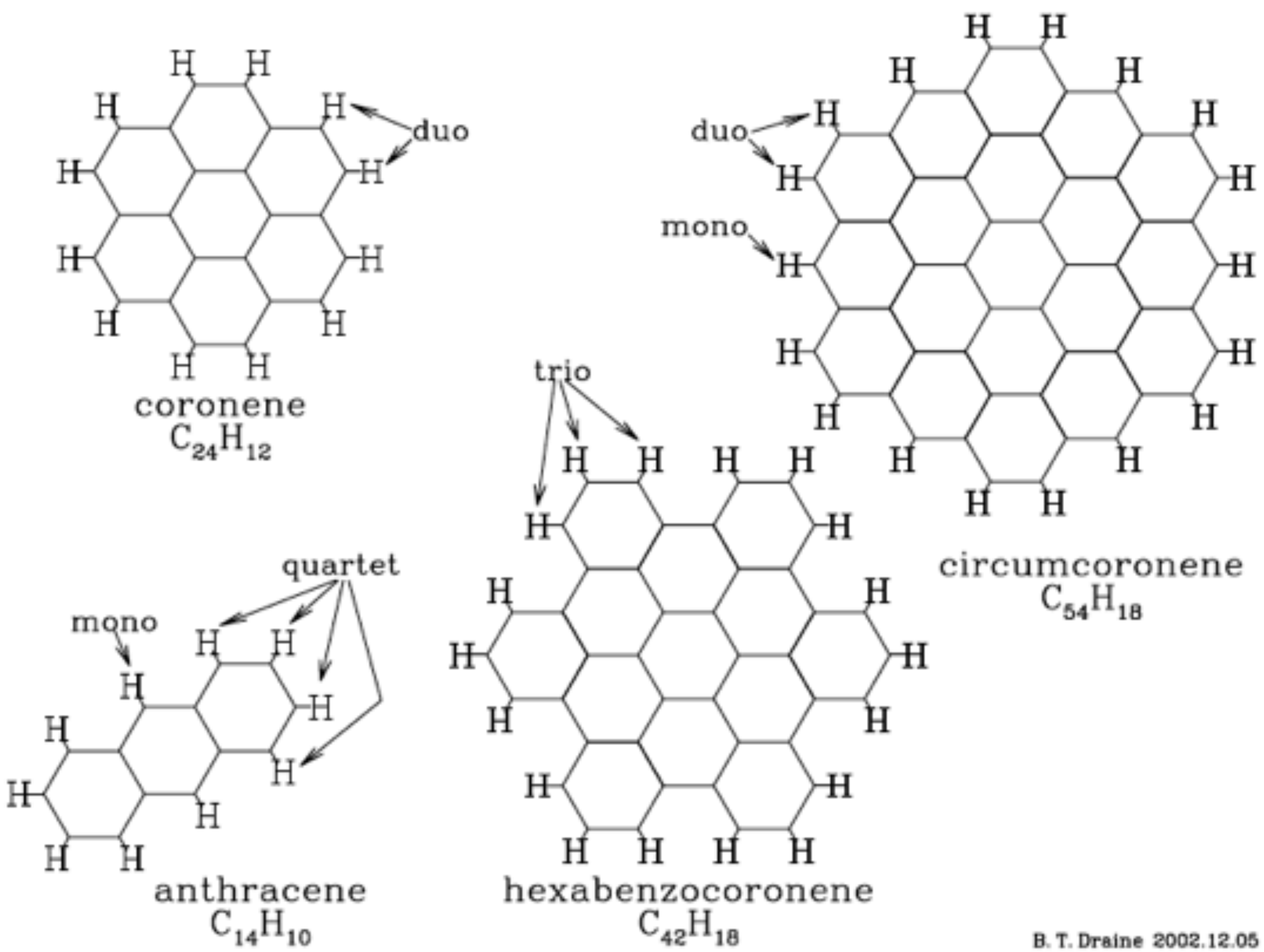
Draine 2003

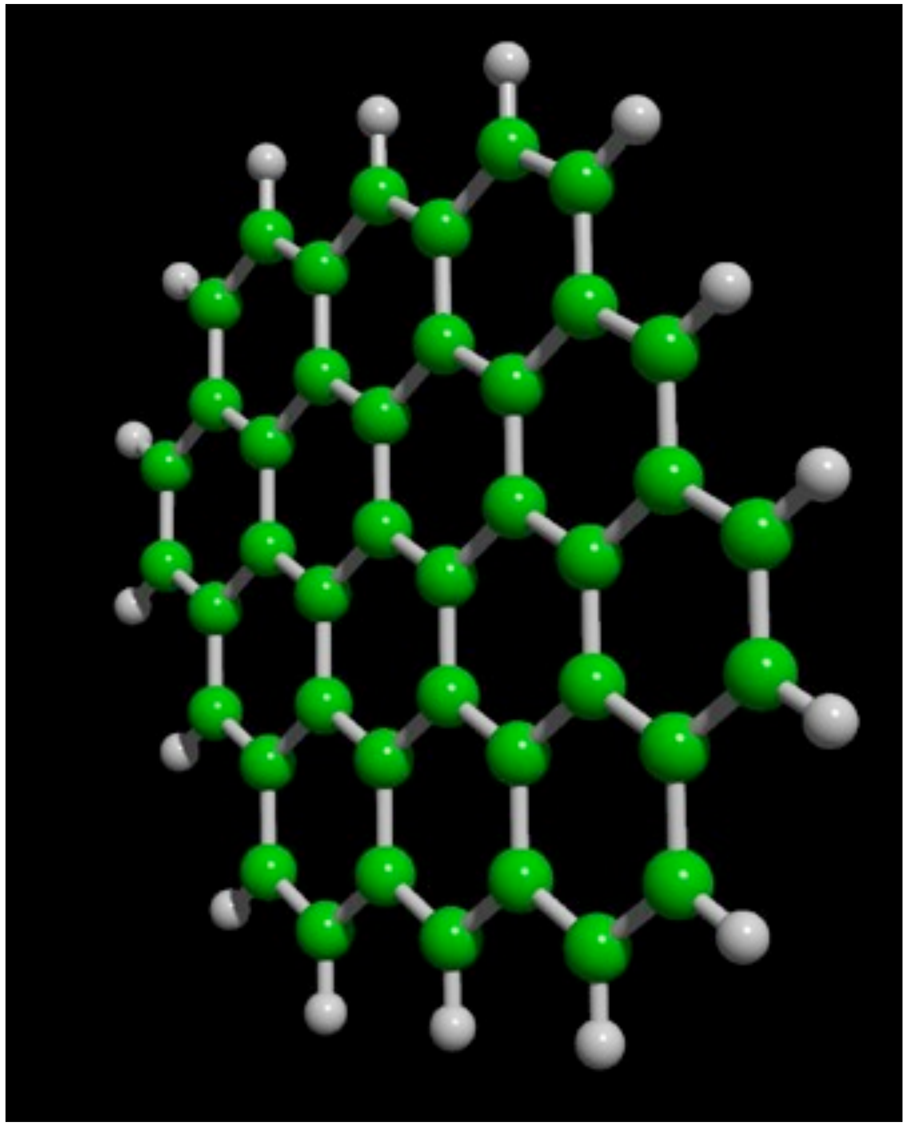
PAH's: Polycyclic Aromatic Hydrocarbons



...are responsible for ~50% of the heating of the molecular gas (through photo-effect)

PAH Examples





ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

POLYCYCLIC AROMATIC HYDROCARBONS (PAHs)

Agency for Toxic Substances and Disease Registry ToxFAQs **September 1996**

This fact sheet answers the most frequently asked health questions (FAQs) about polycyclic aromatic hydrocarbons (PAHs). For more information, call the ATSDR Information Center at 1-888-422-8737. This fact sheet is one in a series of summaries about hazardous substances and their health effects. This information is important because this substance may harm you. The effects of exposure to any hazardous substance depend on the dose, the duration, how you are exposed, personal traits and habits, and whether other chemicals are present.

SUMMARY: Exposure to polycyclic aromatic hydrocarbons usually occurs by breathing air contaminated by wild fires or coal tar, or by eating foods that have been grilled. PAHs have been found in at least 600 of the 1,430 National Priorities List sites identified by the Environmental Protection Agency (EPA).

What are polycyclic aromatic hydrocarbons?

(Pronounced pŏl′ĭ-sī′klĭk ăr′ə-măt′ĭk hī′drə-kar′bənz)

Polycyclic aromatic hydrocarbons (PAHs) are a group of over 100 different chemicals that are formed during the incomplete burning of coal, oil and gas, garbage, or other organic substances like tobacco or charbroiled meat. PAHs are usually found as a mixture containing two or more of these compounds, such as soot.

Some PAHs are manufactured. These pure PAHs usually exist as colorless, white, or pale yellow-green solids. PAHs are found in coal tar, crude oil, creosote, and roofing tar, but a few are used in medicines or to make dyes, plastics, and pesticides.

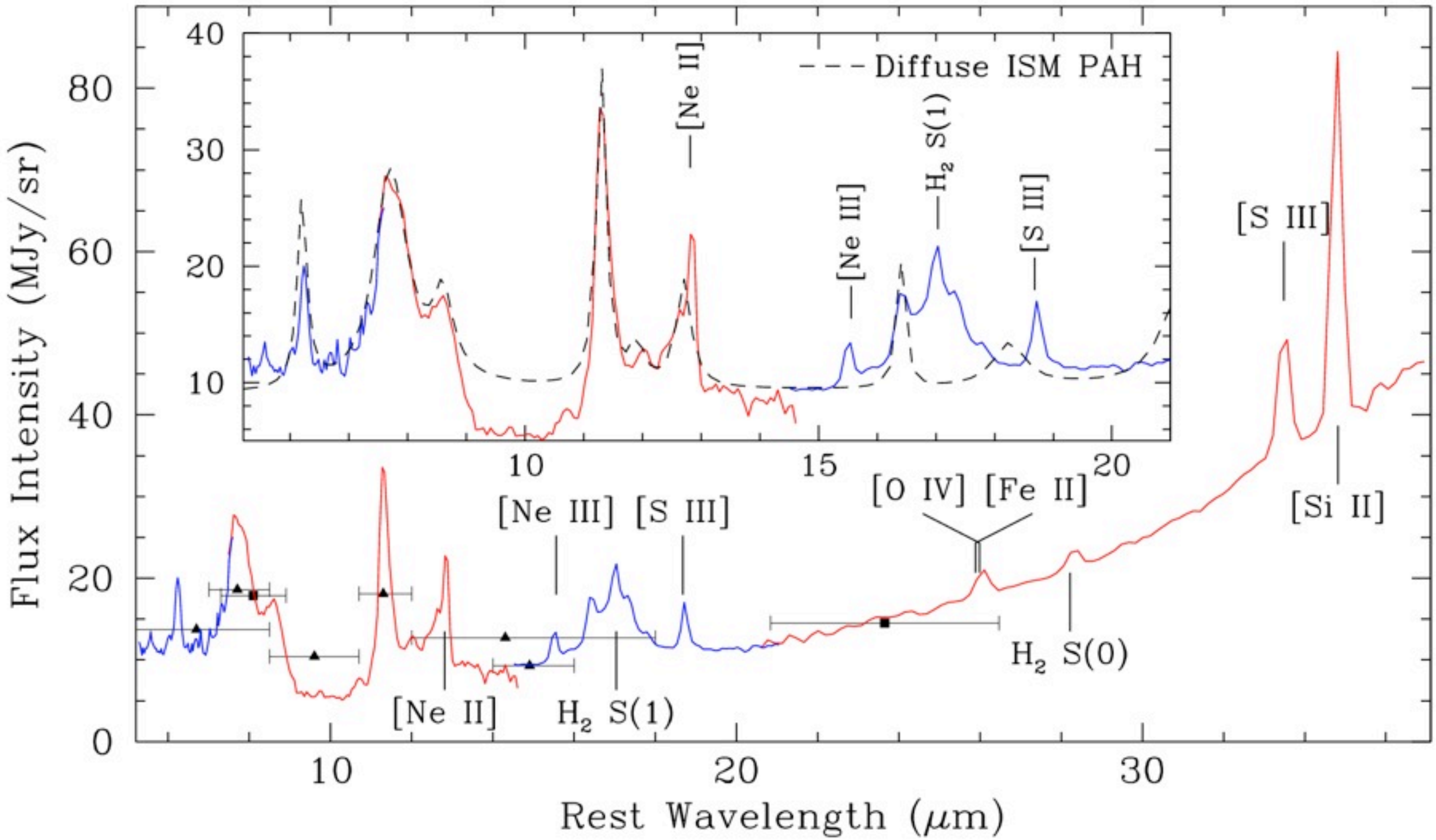
- PAHs enter water through discharges from industrial and wastewater treatment plants.
- Most PAHs do not dissolve easily in water. They stick to solid particles and settle to the bottoms of lakes or rivers.
- Microorganisms can break down PAHs in soil or water after a period of weeks to months.
- In soils, PAHs are most likely to stick tightly to particles; certain PAHs move through soil to contaminate underground water.
- PAH contents of plants and animals may be much higher than PAH contents of soil or water in which they live.

How might I be exposed to PAHs?

- Breathing air containing PAHs in the workplace of coking, coal-tar, and asphalt production plants; smokehouses; and municipal trash incineration facilities.
- Breathing air containing PAHs from cigarette smoke,

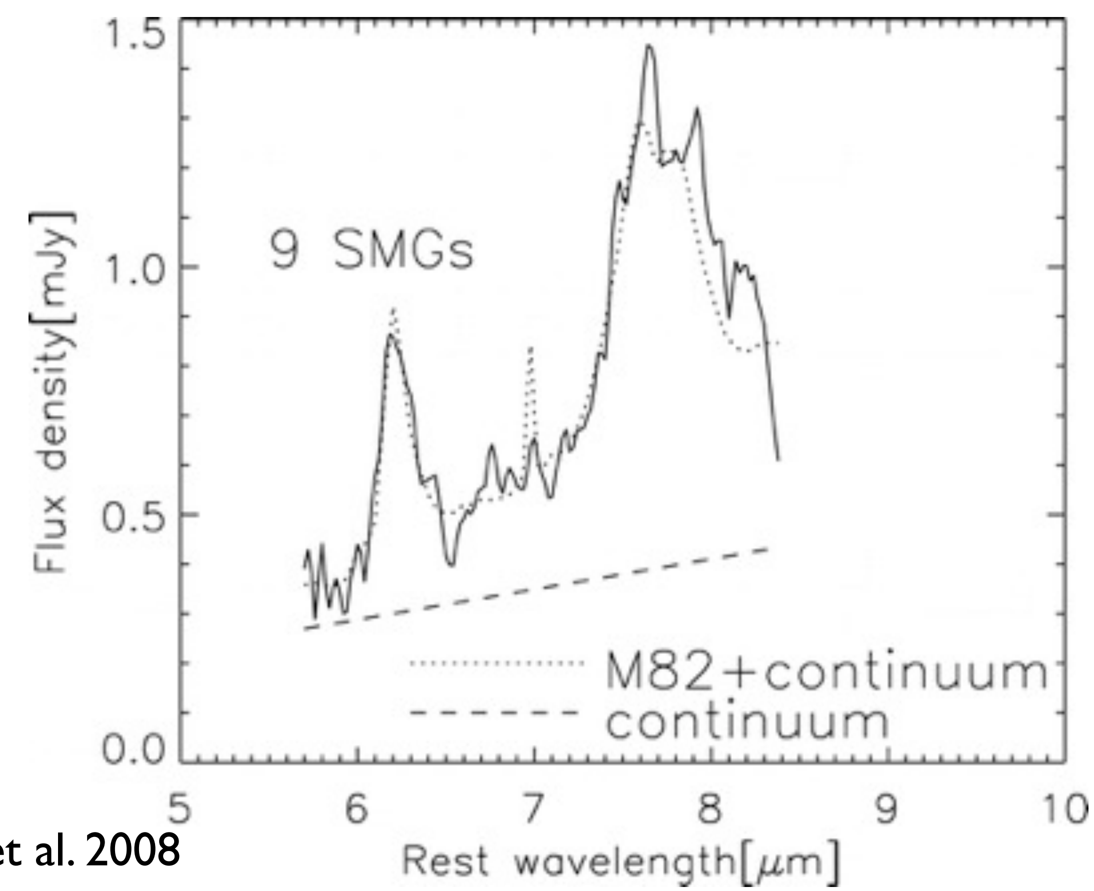
PAH emission: example: NGC 7331

PAH emission: example: NGC 7331



Smith et. al. 2004

PAHs at high redshift

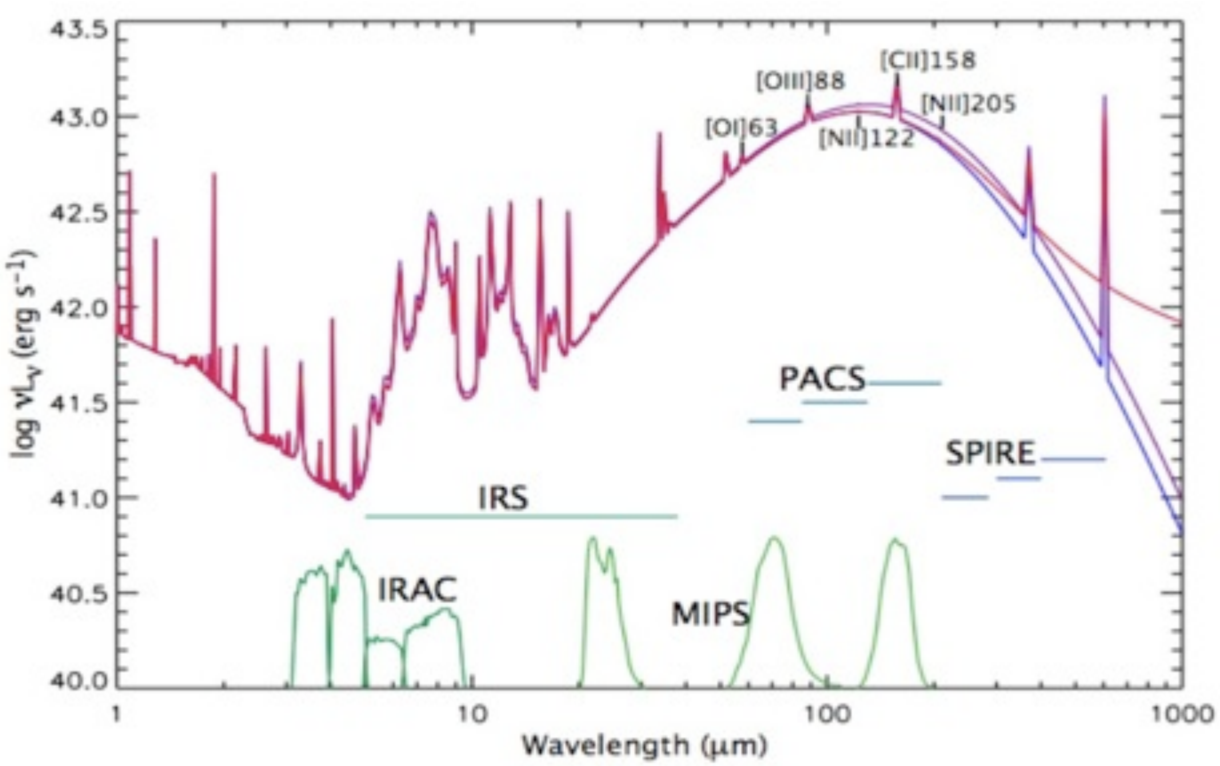


Valiante et al. 2008

stacked PAH spectrum of 9 z~2.5 SMGs (QSOs are also detected at similar redshift)

- Up to 30% IR luminosity in PAH features alone.
- Strongest PAH features in Spitzer's 24μm band at z=0.5-3.
- will affect: photo-z's and star formation rates

The end



HI - fundamental diagnotic line
there is a multi-phase ISM
molecules: more difficult, use CO
atomic fine structure lines, in particular [CII]
dust key for reprocessing UV photons and heating
importance of PAH's