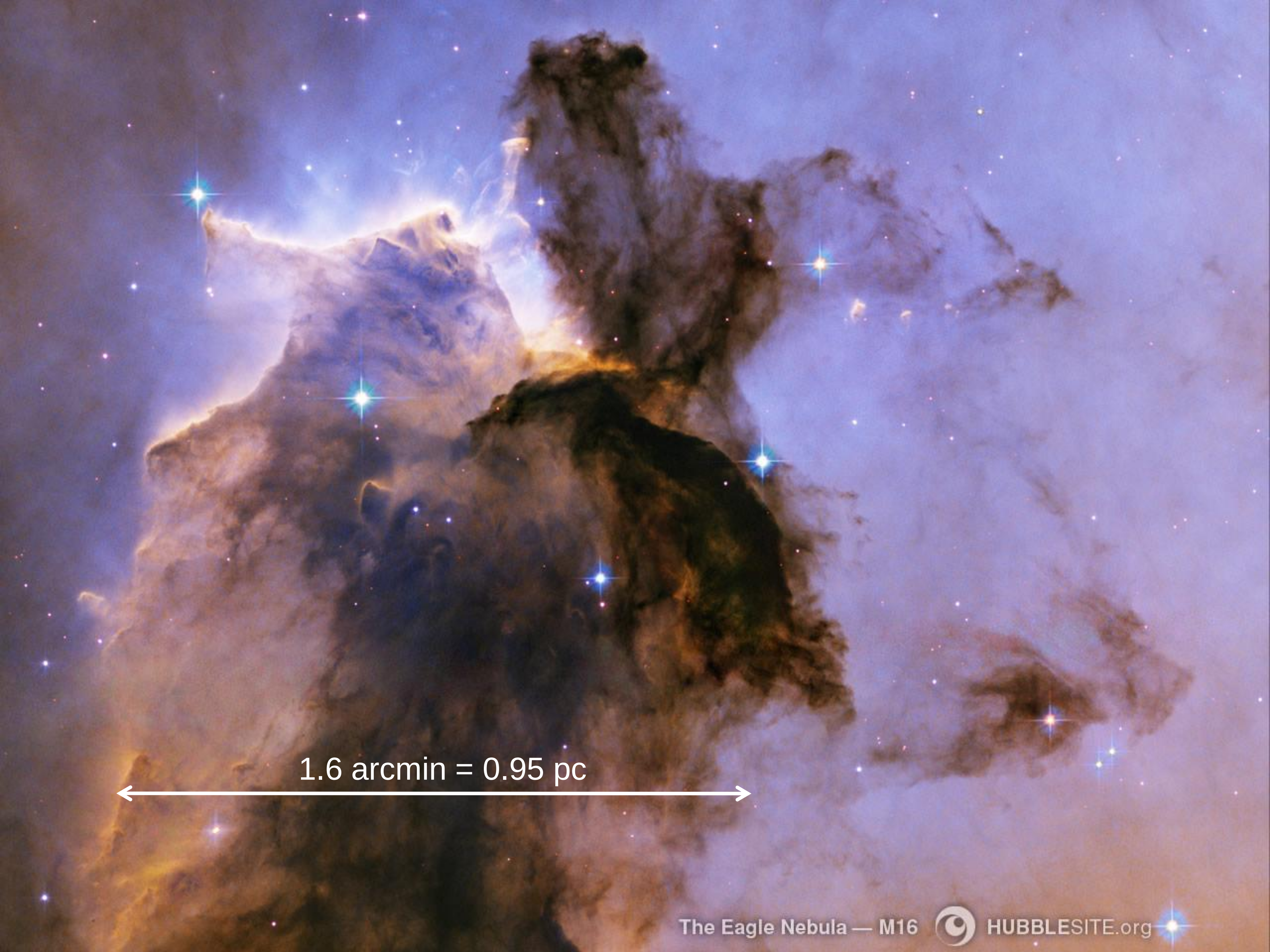
Today:

Cooler phases of ISM - non-ionised material

- What are the heating and cooling mechanisms here?

- What are the observational methods we use to probe these cool phases?
  - absorption line spectroscopy
  - abundance determination
- Why do we find some elements under-abundant compared to solar? -- something to do with pesky dust?

- More on dust
- Molecules & GMCs


1.6 arcmin = 0.95 pc
The Eagle Nebula — M16
HUBBLESITE.org

Temp regulation within Diffuse Clouds

Diffuse clouds: Similar composition to HII regions, but located far from any ionisation source. All ionising photons have been absorbed by other material.

But diffuse clouds do not have temp of 0 K – how are they heated?

All available photons have energies <13.6 eV
What atoms can we ionise with these low-energy photons?

Think of some commonly found atoms:
He I = 24 eV   (He II = 54 eV !!)
O I = 13.6 eV   N I = 14.4 eV   C I = 11.3 eV

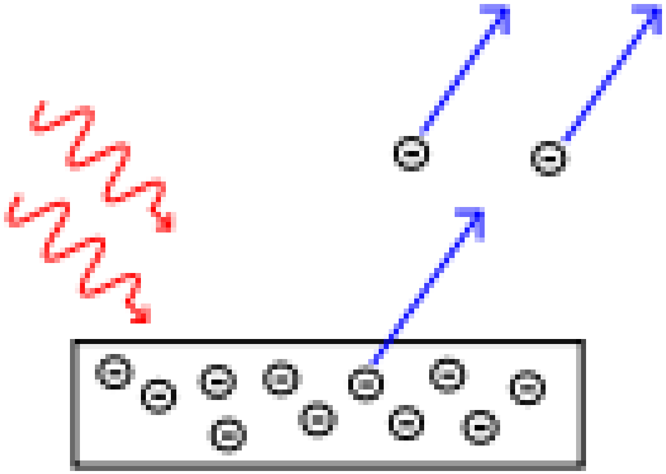
But photoionisation of C I not efficient as heating process because:

- C I not v. abundant
- small range of photon energies (11.3–13.6 eV = 912–1110 Å)
- max KE obtainable is 2.3 eV – quite low so not much heating

Remember **DUST**? (really smoke - small, sub-micron sized grains)

These dust grains give out (photo)electrons when struck by photons of sufficent energy

Because of the photoelectric effect



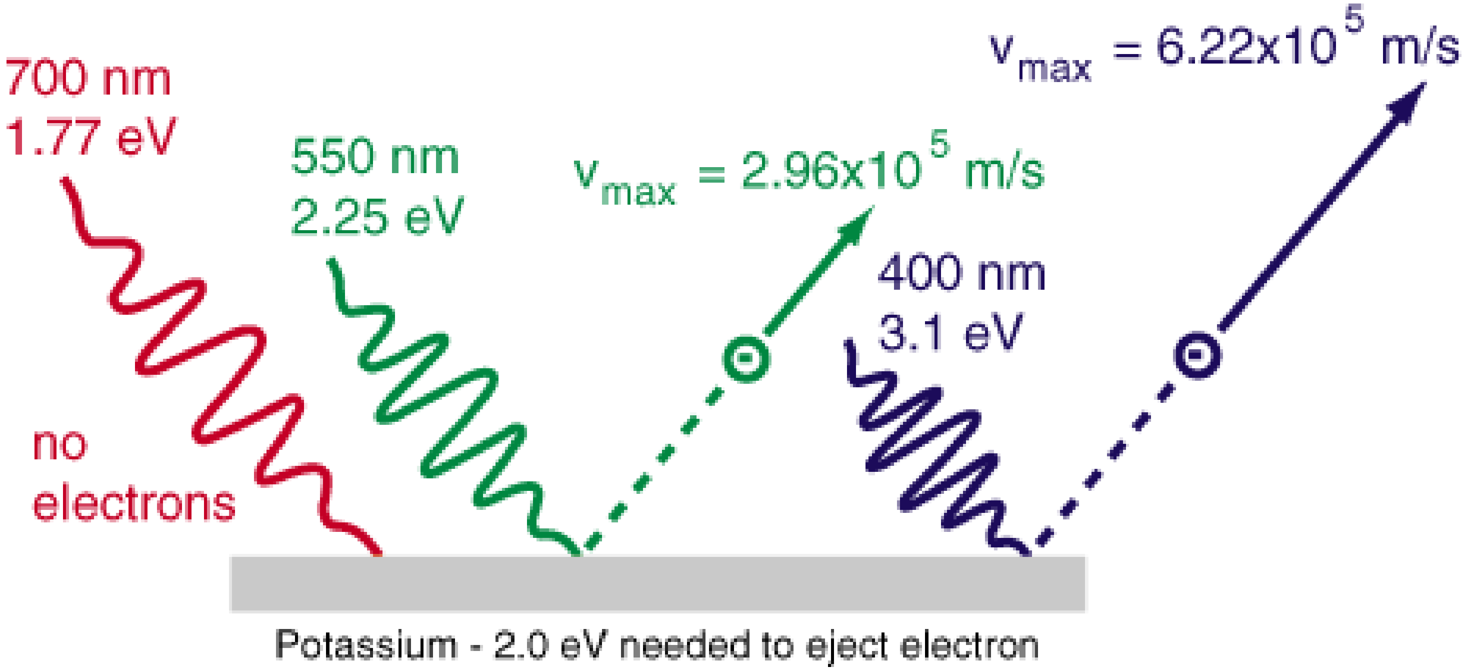
(Call them photoelectrons because they are produced by photons)

Einstein's explanation of the photoelectric effect won him the Nobel Prize (in Physics) of 1921.

Work function (analogous to *ionization potential* of atoms):

$$E(KE) = h\nu - W$$

E = energy of the ejected photoelectrons
***h*ν** = energy of photon (Planck constant, *h* × frequency, ν)
W = the “work function” of the grains. Small grains have *W* ~ 5 eV.



Work function (analogous to *ionization potential* of atoms):

$$E(KE) = h\nu - W$$

E = energy of the ejected photoelectrons
$h\nu$ = energy of photon (Planck constant, $h \times$ frequency, ν)
W = the “work function” of the grains. Small grains have $W \sim 5$ eV.

Take same photons as we were talking about with photon energies 11.3–13.6 eV
➔ resulting photoejected electrons have typical energies of ~6 eV.

This is much higher than can be achieved with photoionization.

This energy is shared with other gas particles via collisions

This is the major source of heating in a dark cloud

Cooling

The heated gas cools mainly by emitting forbidden-lines.

These come from low-lying (low energy) states of:
- neutral Oxygen – [O I] 146 μm
- singly ionized Carbon – [C II] 158 μm (far IR)

Thus *again* forbidden-line emission is a major cooling mechanism

Remember metallicity dependence

The heating rate is

$$G = 2 \times 10^{-32}\ \chi\, y_{pe}\ n_H \qquad\qquad [\mathrm{J\ m^{-3}\ s^{-1}}]$$

y_{pe} is the photoelectric efficiency of the grains (~0.1–1.0), χ the radiation field

The cooling rate (for e.g. CII) is

$$L_{\mathrm{CII}} = 2.5 \times 10^{-40}\ n_e n_{\mathrm{C+}}\ \ (\text{or } d_{\mathrm{C}} n_H) \qquad\qquad [\mathrm{J\ m^{-3}\ s^{-1}}]$$

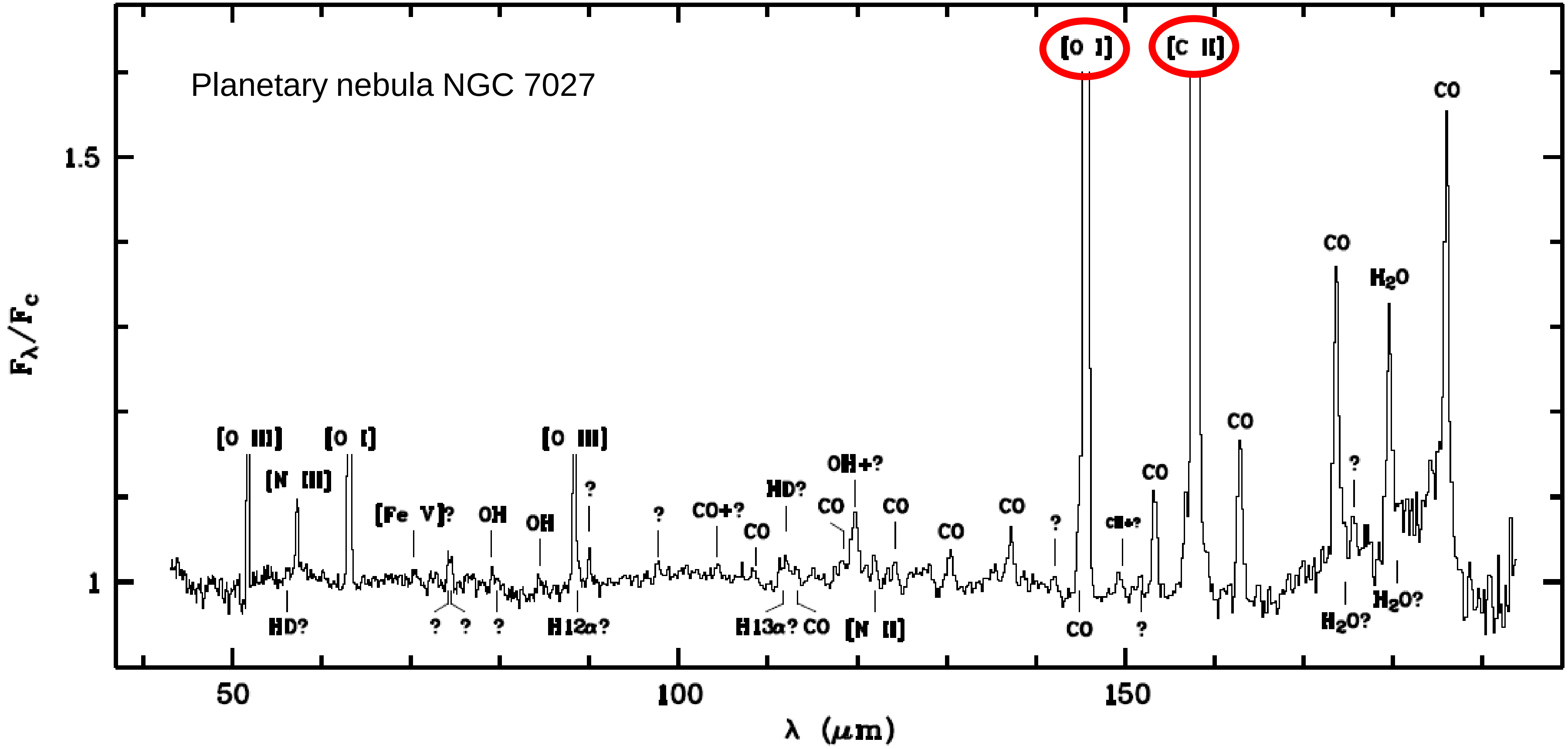
d_{C} = depletion factor: proportion of carbon atoms locked in dust grains.

Balance heating and cooling rates:
- assuming $n \sim 10^8$ m^{-3}

➔ calculate gas temperature

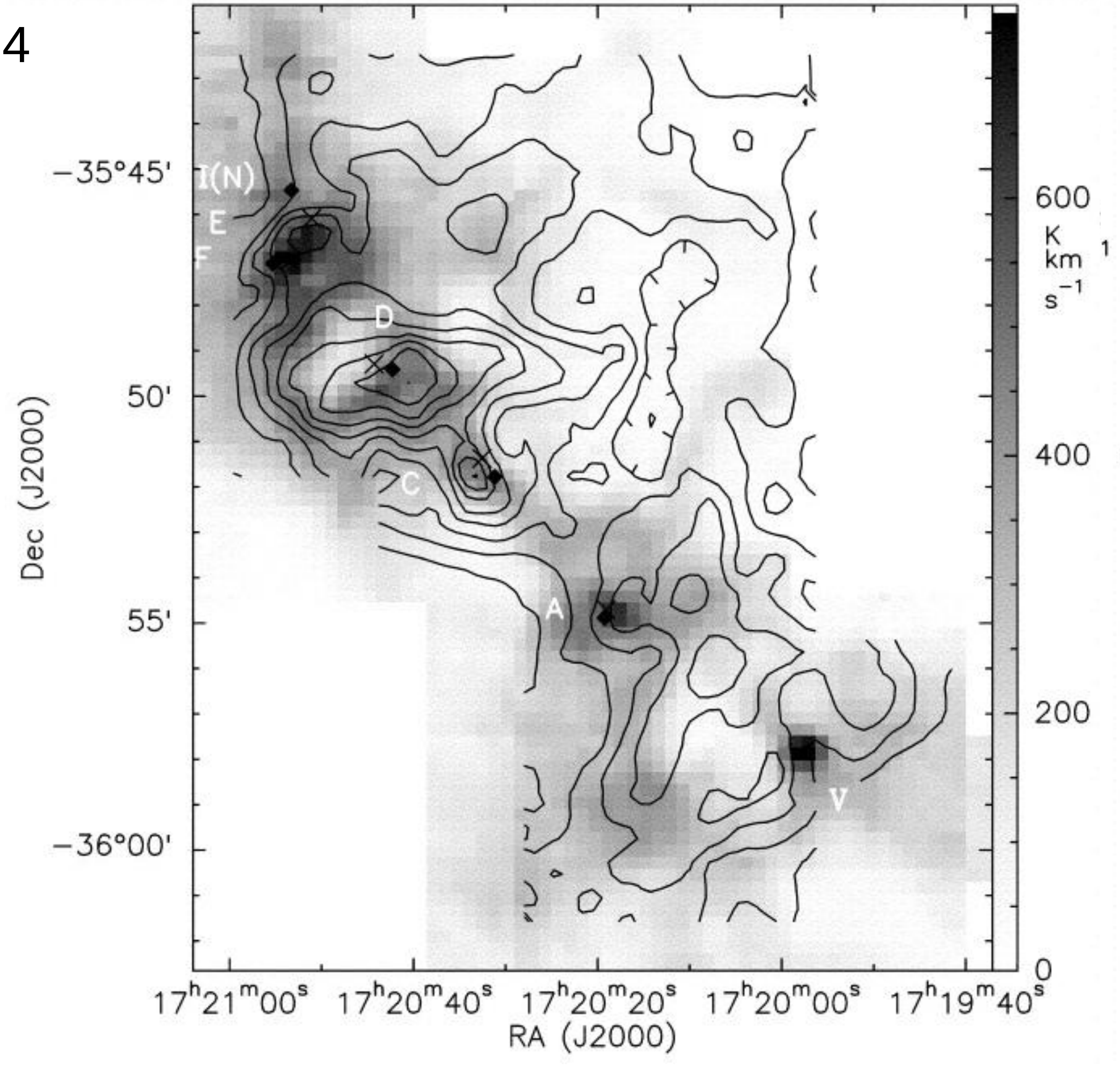
➔ in equilibrium $T \sim 70\text{–}100$ K

Liu et al., 1996, A&A, 315, L257


Planetary nebula NGC 7027

The [O I] and [C II] IR forbidden lines:
coolants in diffuse clouds, and at the edges of Planetary Nebulae and HII regions (called “photodissociation regions”)

NGC 6334



Far-Infrared Imaging Fabry-Pérot Interferometer (FIFI)

(Low temperature) Emission and absorption

Special case of emission: HI 21cm line

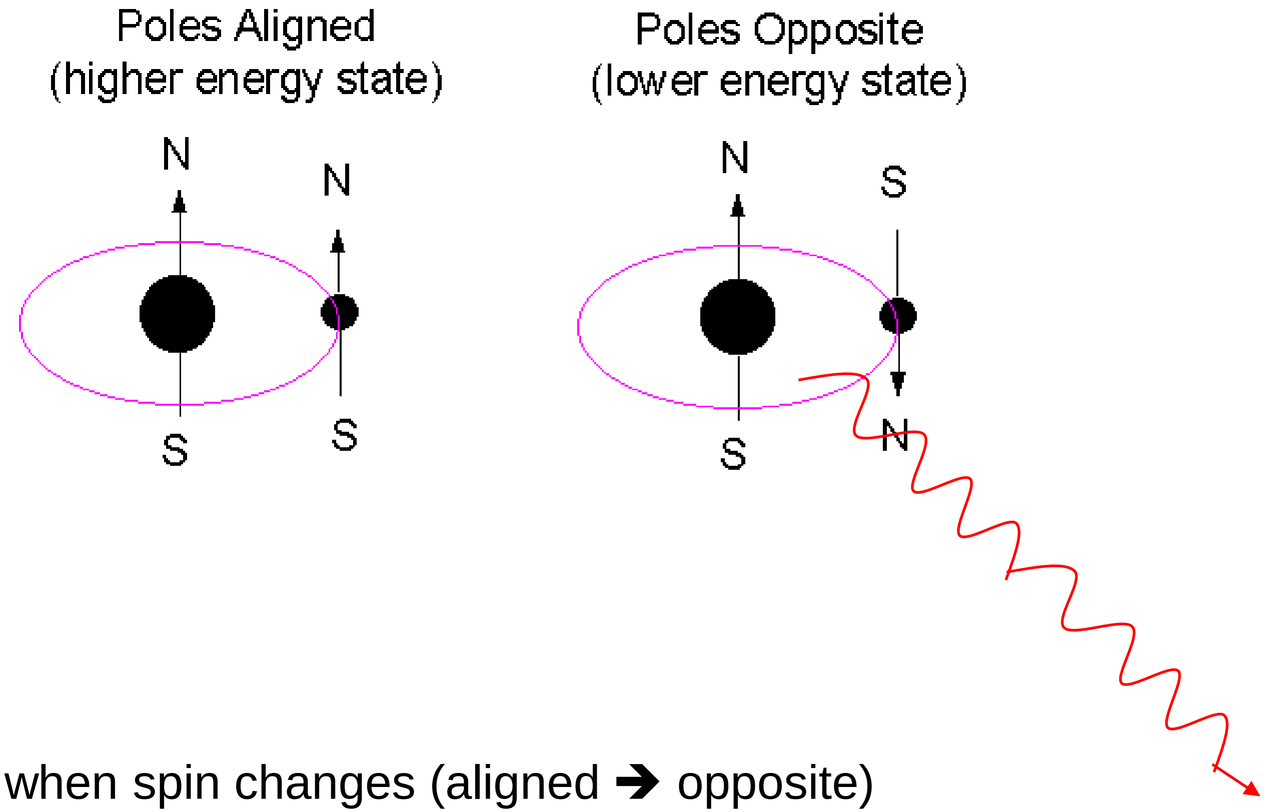
Absorption: resonance lines

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

HI (neutral *atomic* H) spin-flip

spin = magnetic orientation



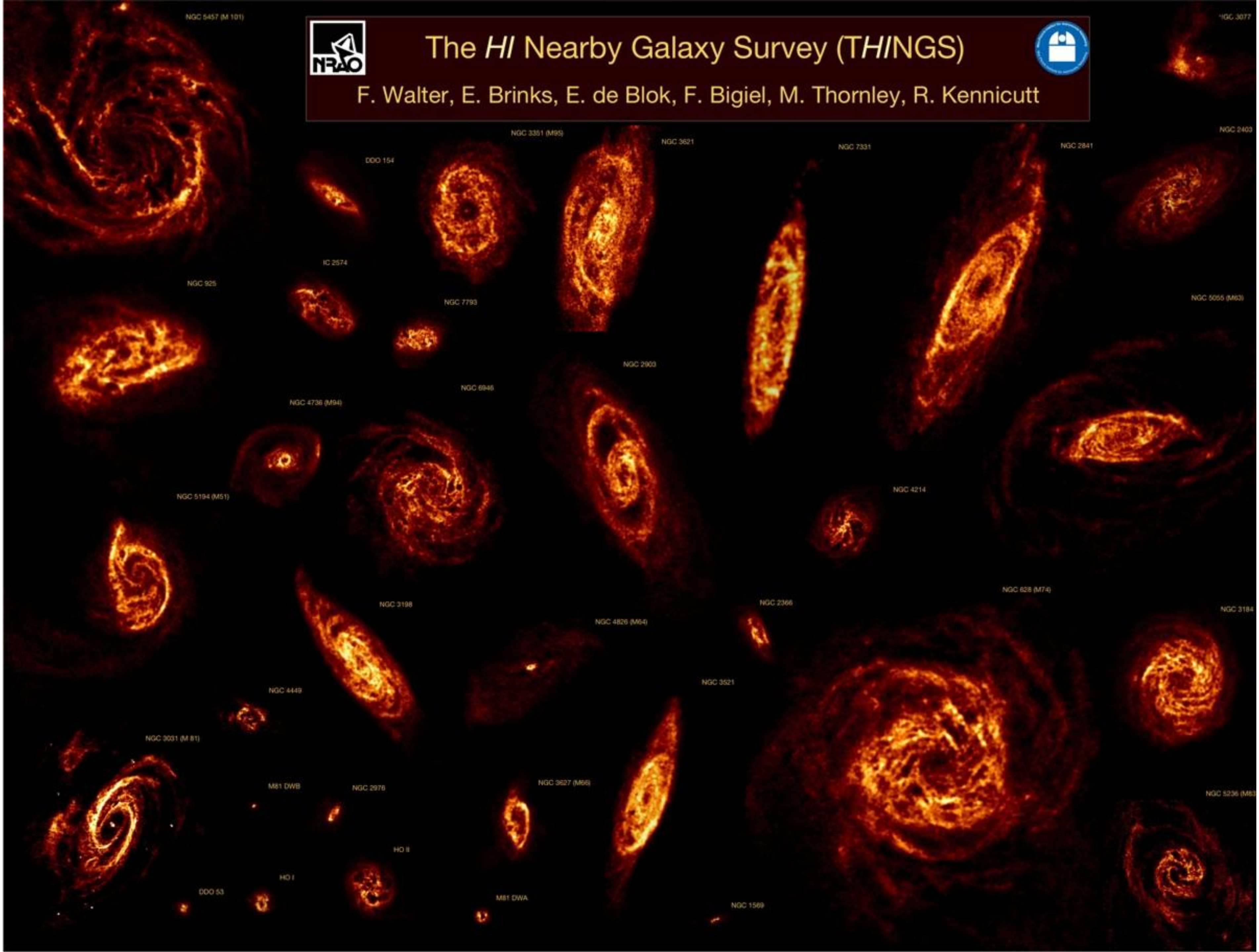
photon emitted when spin changes (aligned ➔ opposite)
wavelength = 21 cm (1.42 GHz)

prob of spontaneous flip = 1 in 10 million yrs, (highly forbidden)
but there is a lot of H!

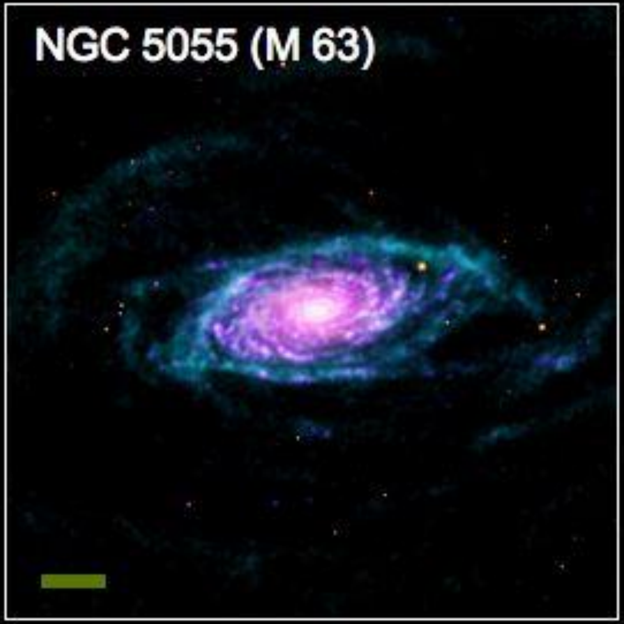
Dennis di Cicco/Sean Walker

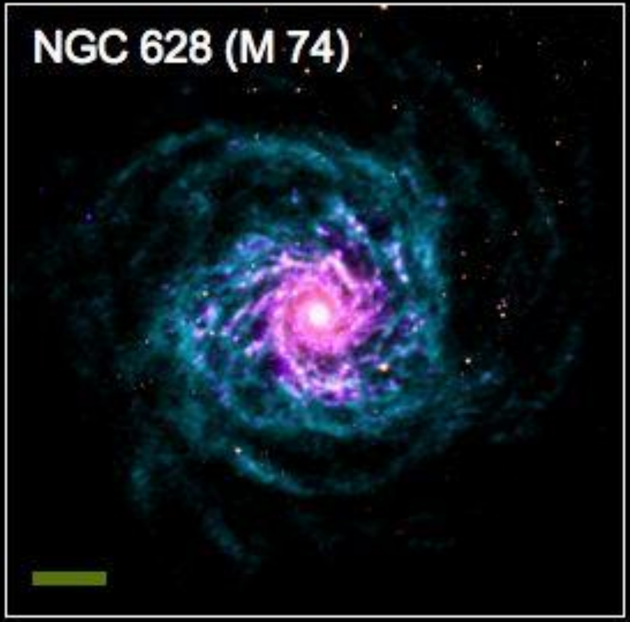
The *HI* Nearby Galaxy Survey (T*HI*NGS)

F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt



Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey


NGC 5055 (M 63)


NGC 628 (M 74)


NGC 3031 (M 81)


NGC 5194 (M 51)

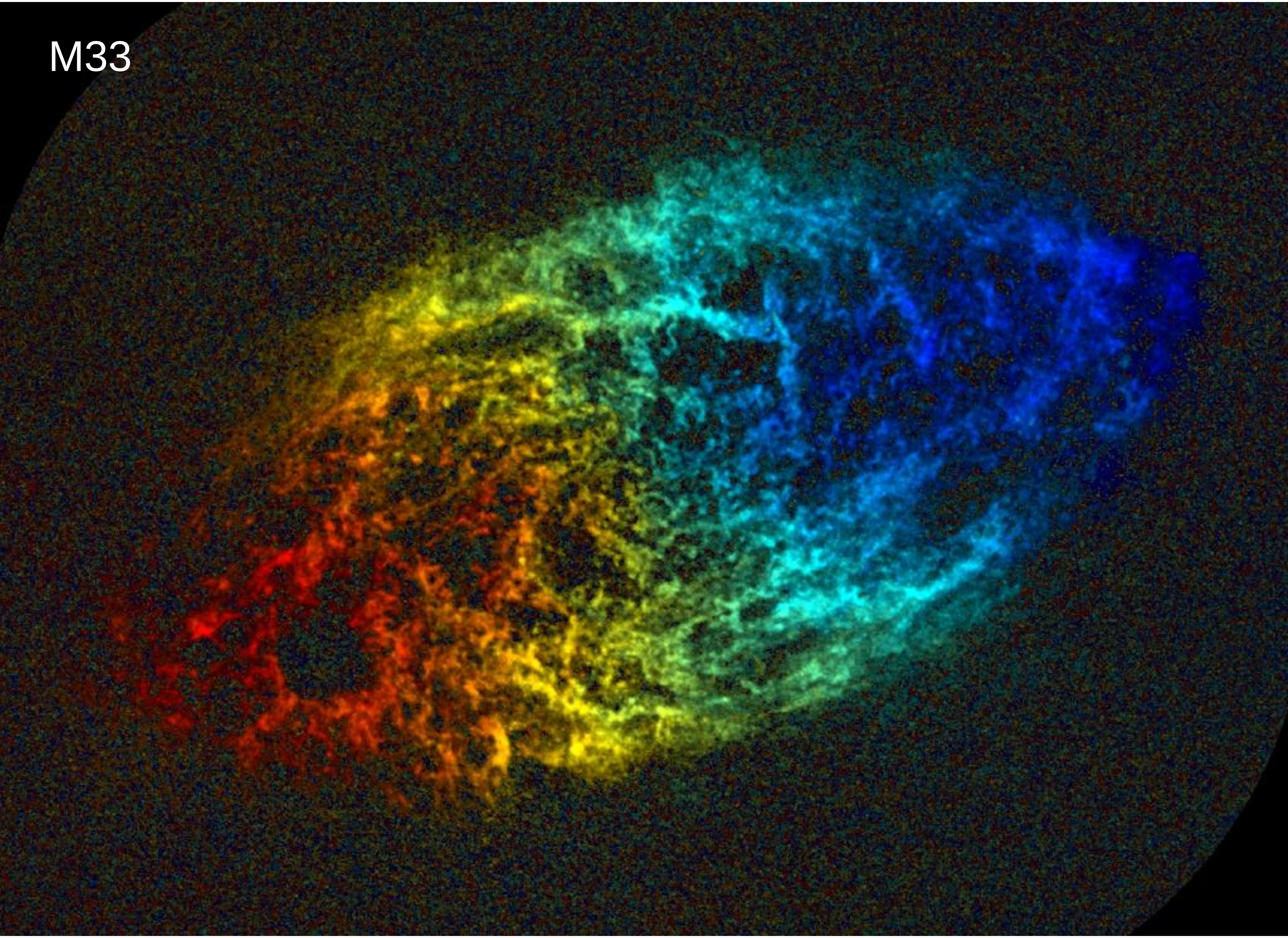
THINGS

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


M33

Q: How can we understand the gas if we can’t see it?

A: use a bright background source in order to see foreground ISM in ‘silhouette’

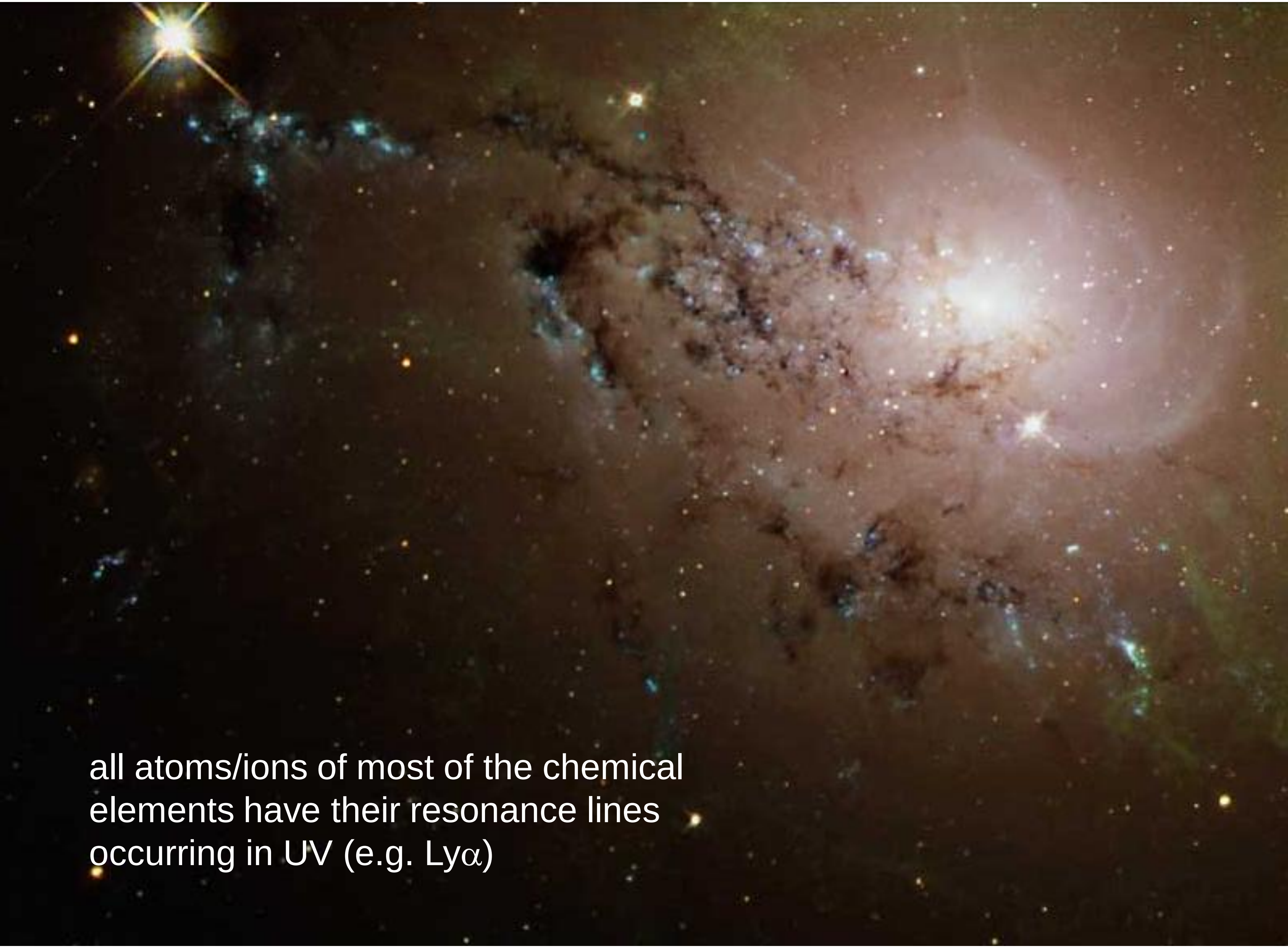
NASA/ESA and The Hubble Heritage Team (STScI/AURA)

can be complicated: observed spectrum includes

- intrinsic source spectrum
- contrib from dust → scattering and absorption
  (reddening extinction)
- contrib from gas → absorption lines

Rewards of careful study:

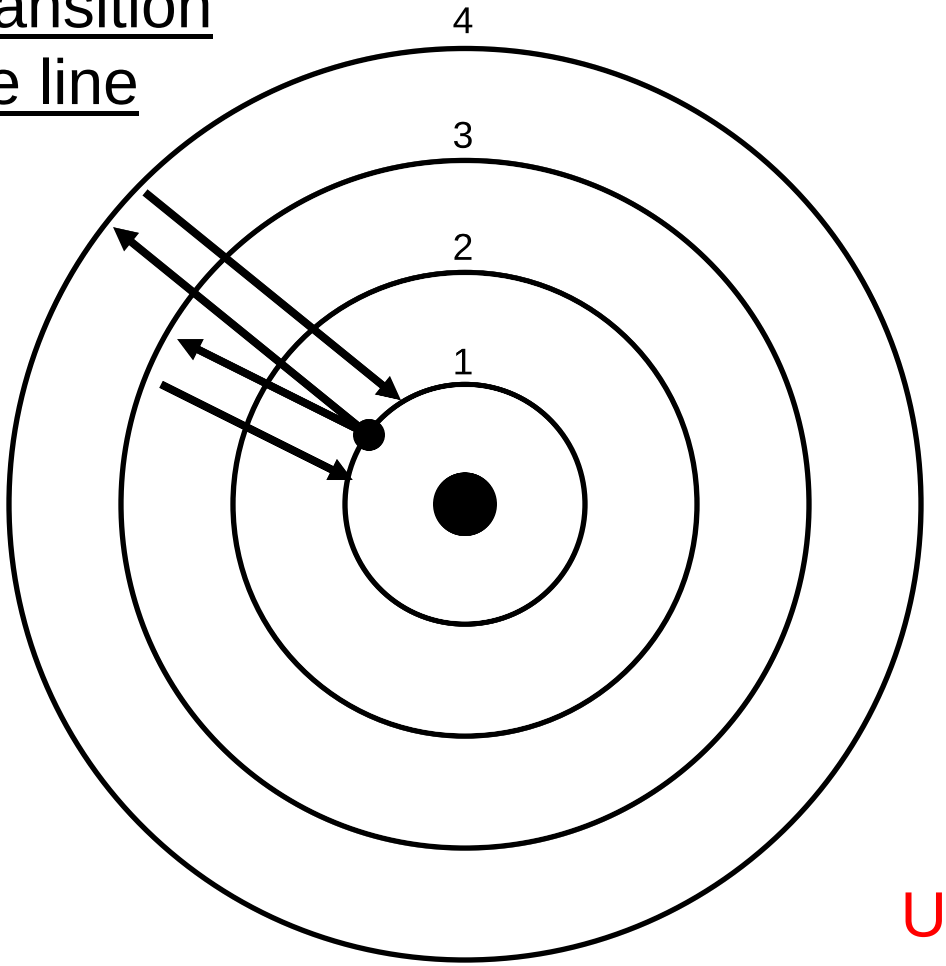
- temperature
- density
- line-of-sight motions
- chemical composition of the ISM material



all atoms/ions of most of the chemical elements have their resonance lines occurring in UV (e.g. Lyα)

$n = 1 \rightarrow n'$

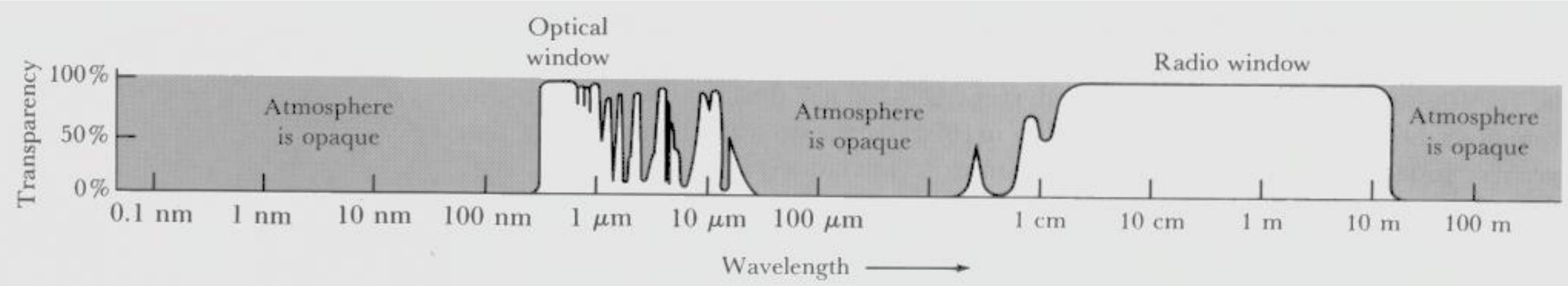
resonance transition
➔ resonance line

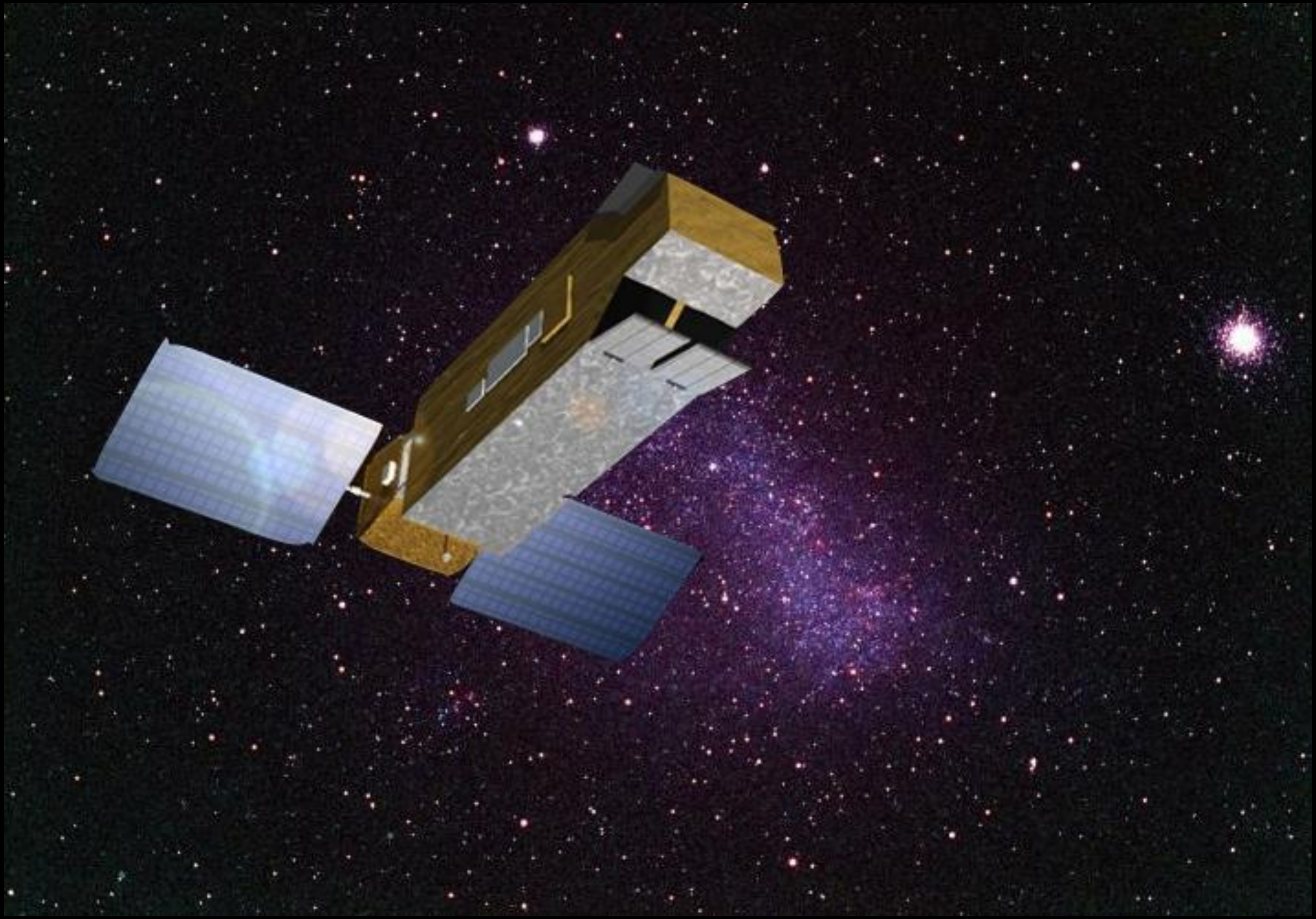


UV: 1200-3300 Å
FUV: 912-1200 Å
EUV: 100-912 Å

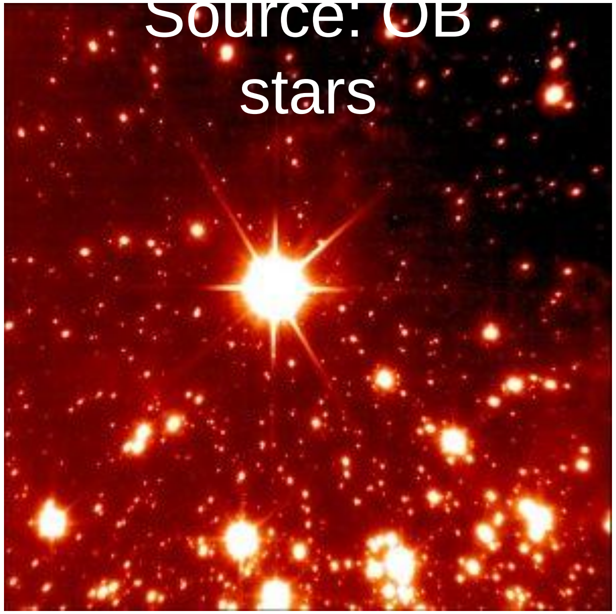
Atmospheric transmission

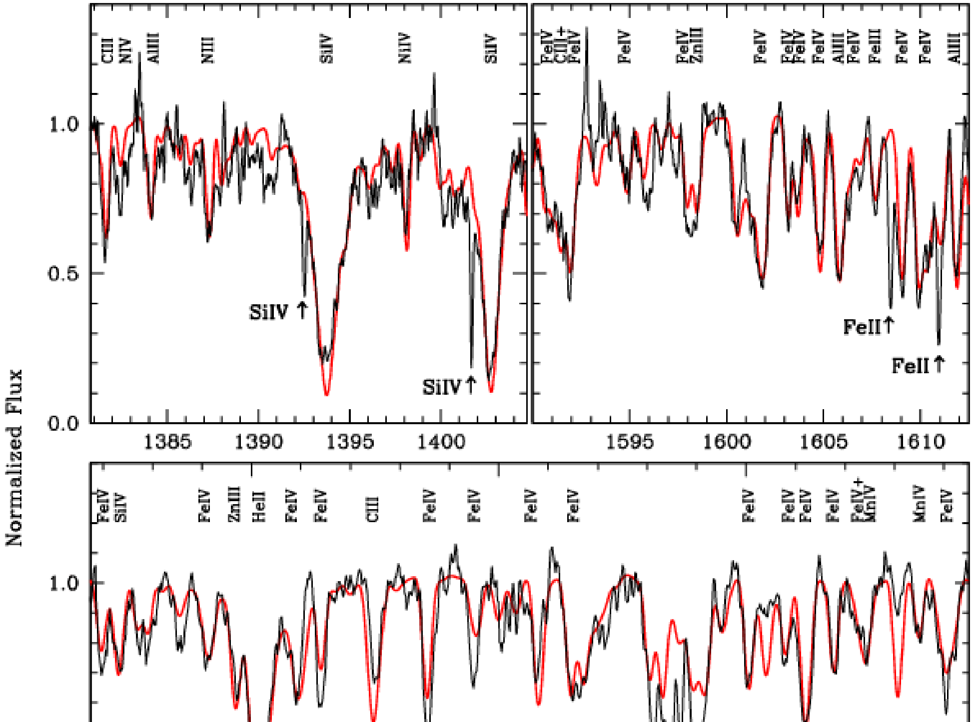
UV

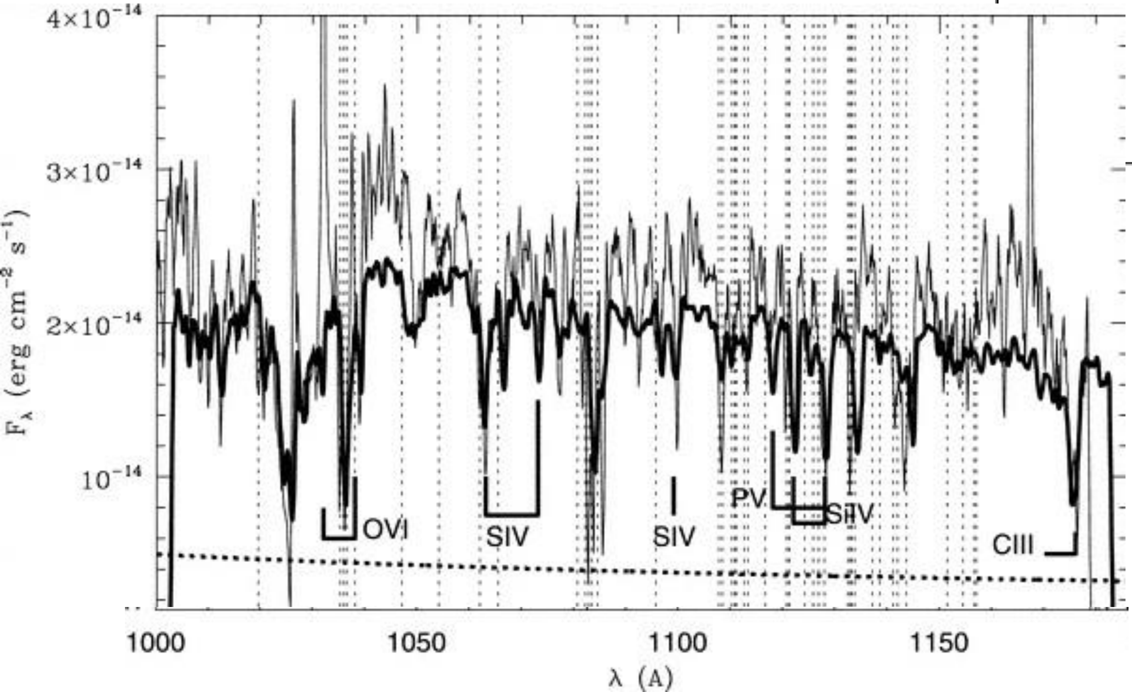




Source: OB stars





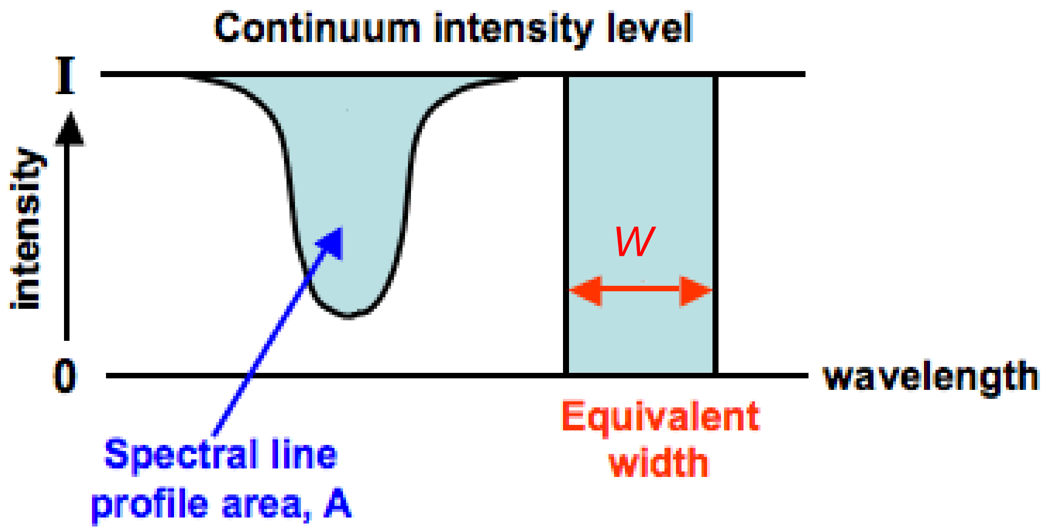


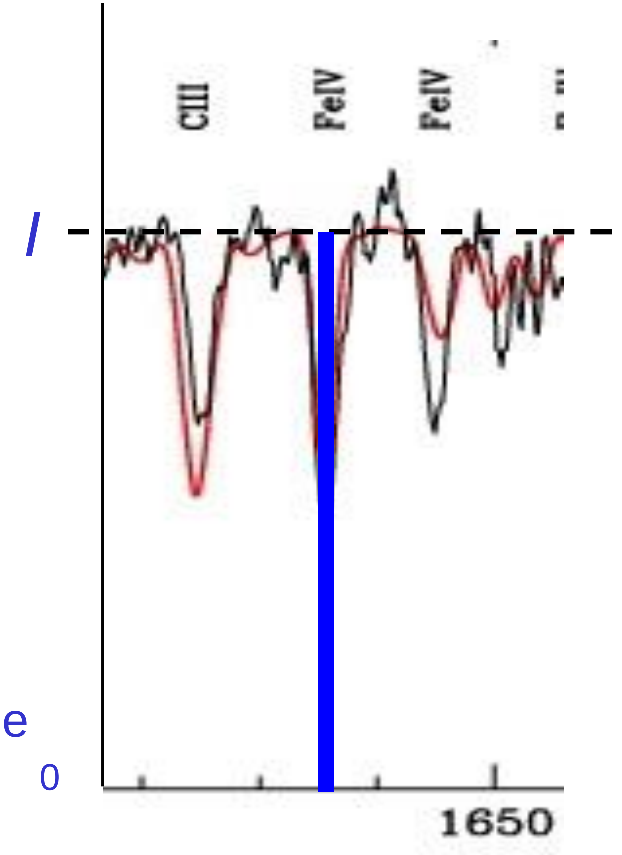
dashed lines = theoretical IS absn

Aim:
determine the abundance of chemical elements in the neutral ISM (CNM, WNM), where T is <100 K

Method: use absorption line spectroscopy

but how do we get abundances using *absorption lines*?





What is the equivalent width of a **rectangular** line profile with area = the real line profile

$$A = I \times W$$

I = intensity level of the continuum
W = equivalent width of the absorption line -- units of *length* (Å).

(identical for emission lines as well)

How do Equivalent Widths relate to abundances?

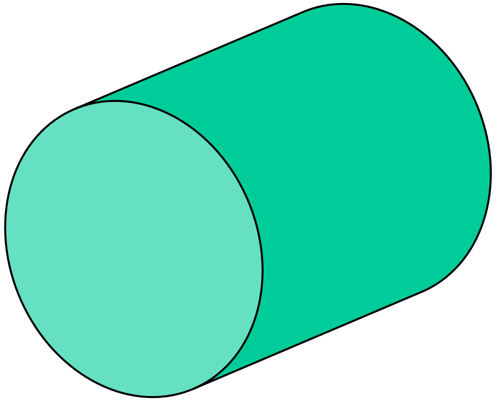
The EW of an absorption line grows as the number of absorbers along a particular sight line increases.

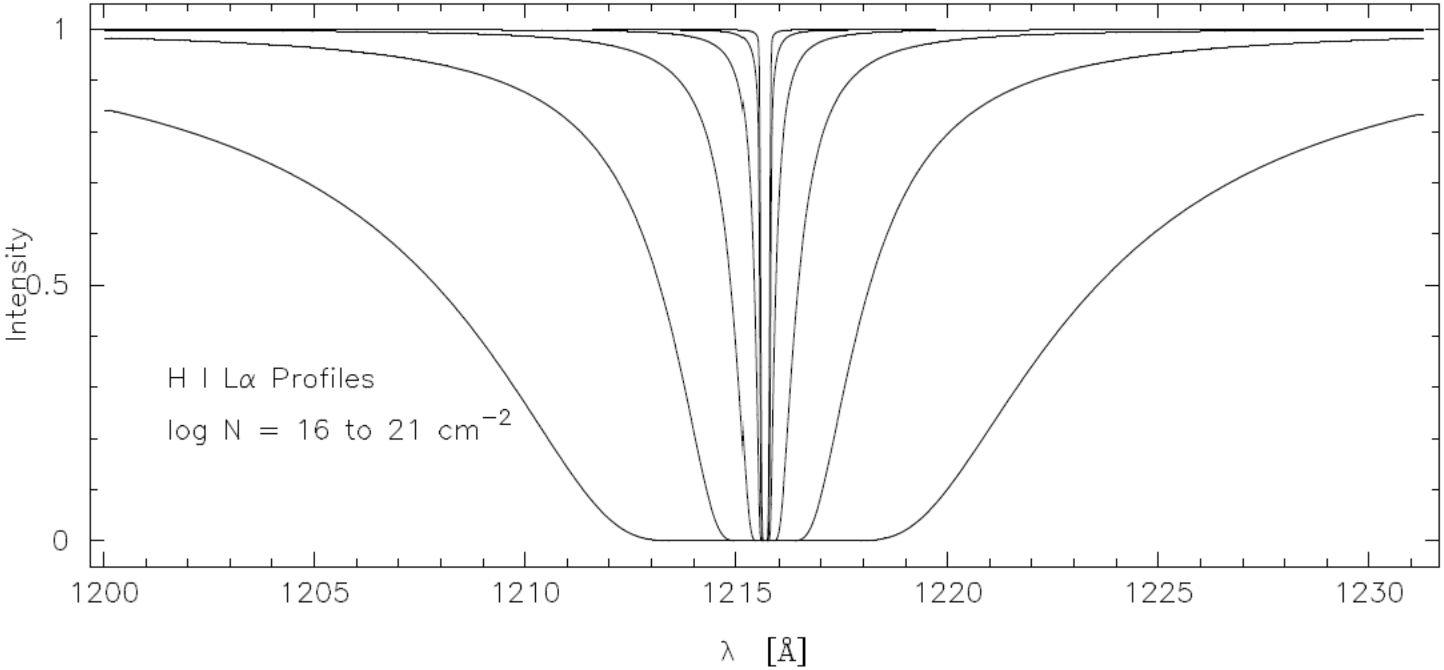
➔ EW is proportional to the abundance of the species **and** the probability of absorption.

Abundance can be defined in terms of the **column density, N** of the species:

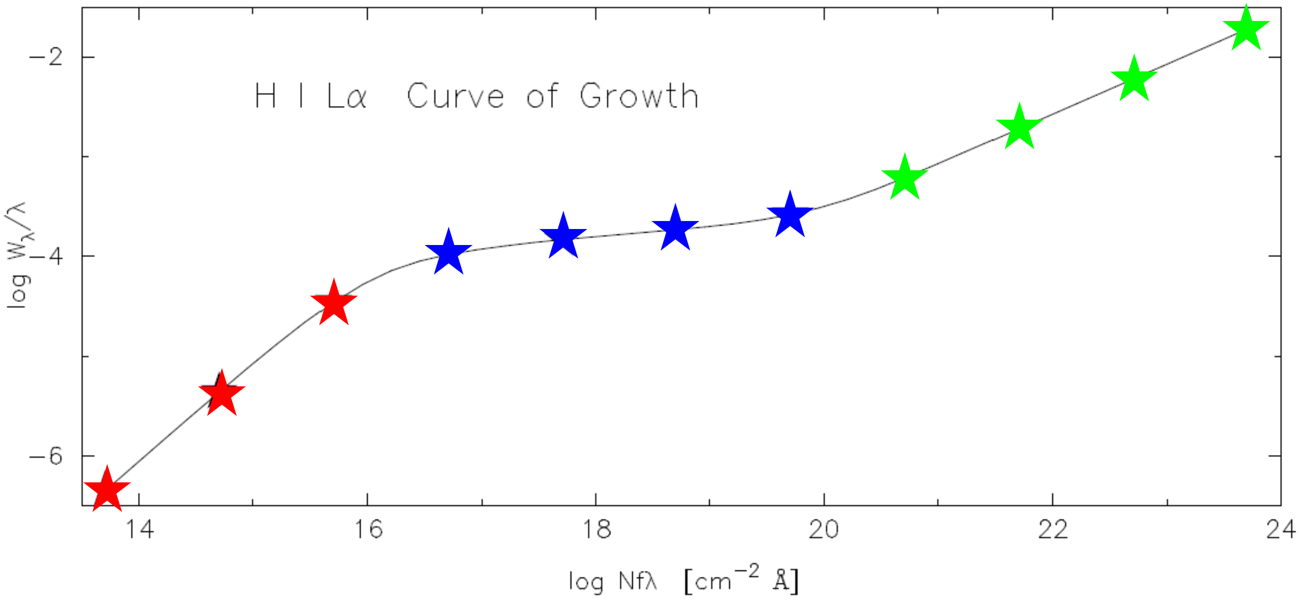
$$N(\text{absorber}) = n(\text{absorber}) \times l$$

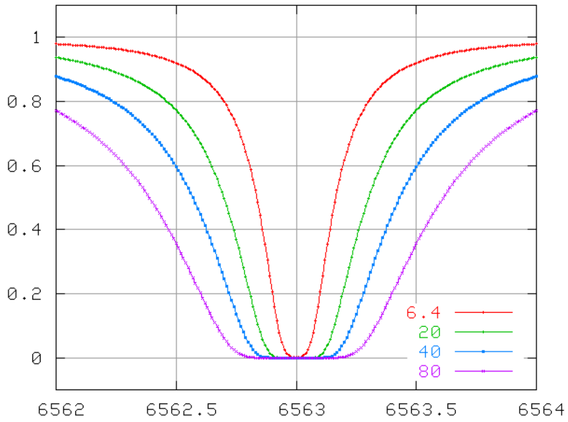
n(absorber) = number density of absorbing species (m^{-3})
l = length of ISM sight line (distance to cloud)





Intensity
1
0.5
0
H I Lα Profiles
log N = 16 to 21 cm^{-2}
1200
1205
1210
1215
1220
1225
1230
λ [Å]





Linear part: behaviour of EW for very weak lines. EW grows directly (linearly) proportional to the column density, N.

Flat part: EW grows only slowly with increasing column density.
Most of background radiation has been absorbed by the line core which reaches zero intensity (becomes *saturated*). Only absorption in the line wings contributes to EW growth. Absorption there is weaker than in core so curve flattens out.

Damping part: At very large column densities the absorption in the line wings dominates EW growth and curve rises faster again (proportional to $\sqrt{N}$).

Abundance determination: the method

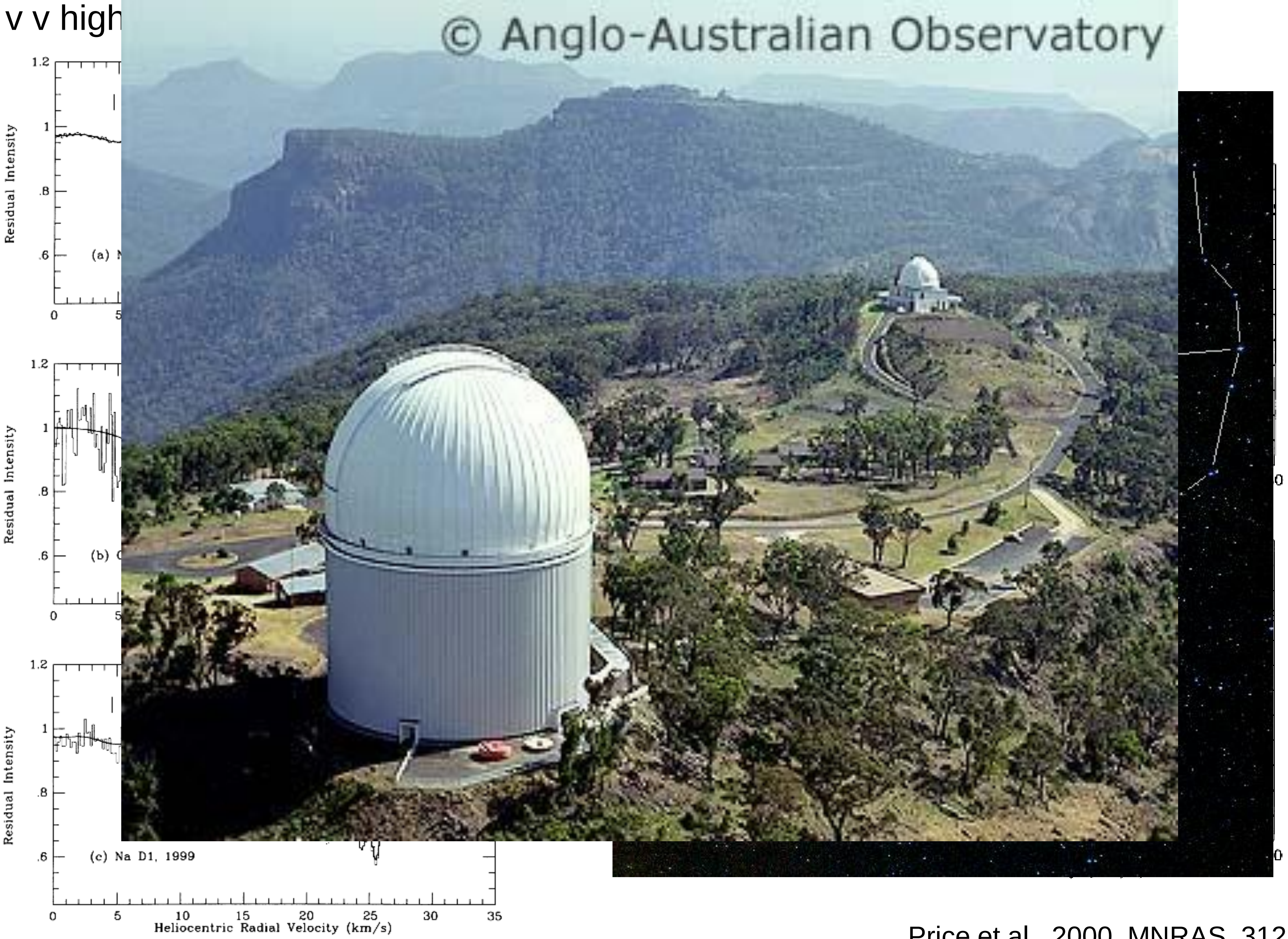
1. observe high-resolution spectrum of a suitable bright source
   use a space telescope (e.g. IUE, HST, FUSE).
2. Identify set of resonance lines of elements/ions from comparison with a theoretical line list.
3. Measure the EW of the lines.
4. Use curve of growth to get the column density of each species.
5. Determine column density of Hydrogen (using same technique - use Lyman resonance lines) → get abundances of species relative to Hydrogen.

AAT (Anglo-Australian Telescope)

Ultra-high resolution facility (UHRF) ← Built at UCL!

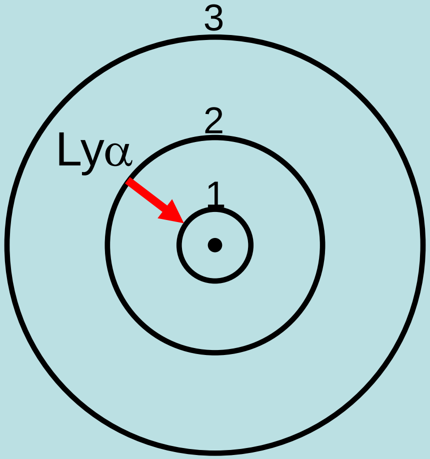
v v high

star: Δ Ori A (HD 36486) - O9.5II



Price et al., 2000, MNRAS, 312, L43

Lyα

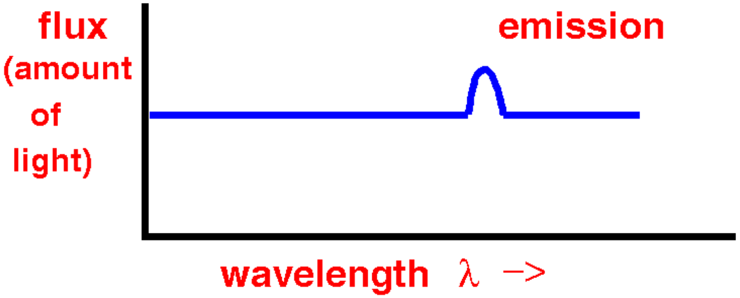


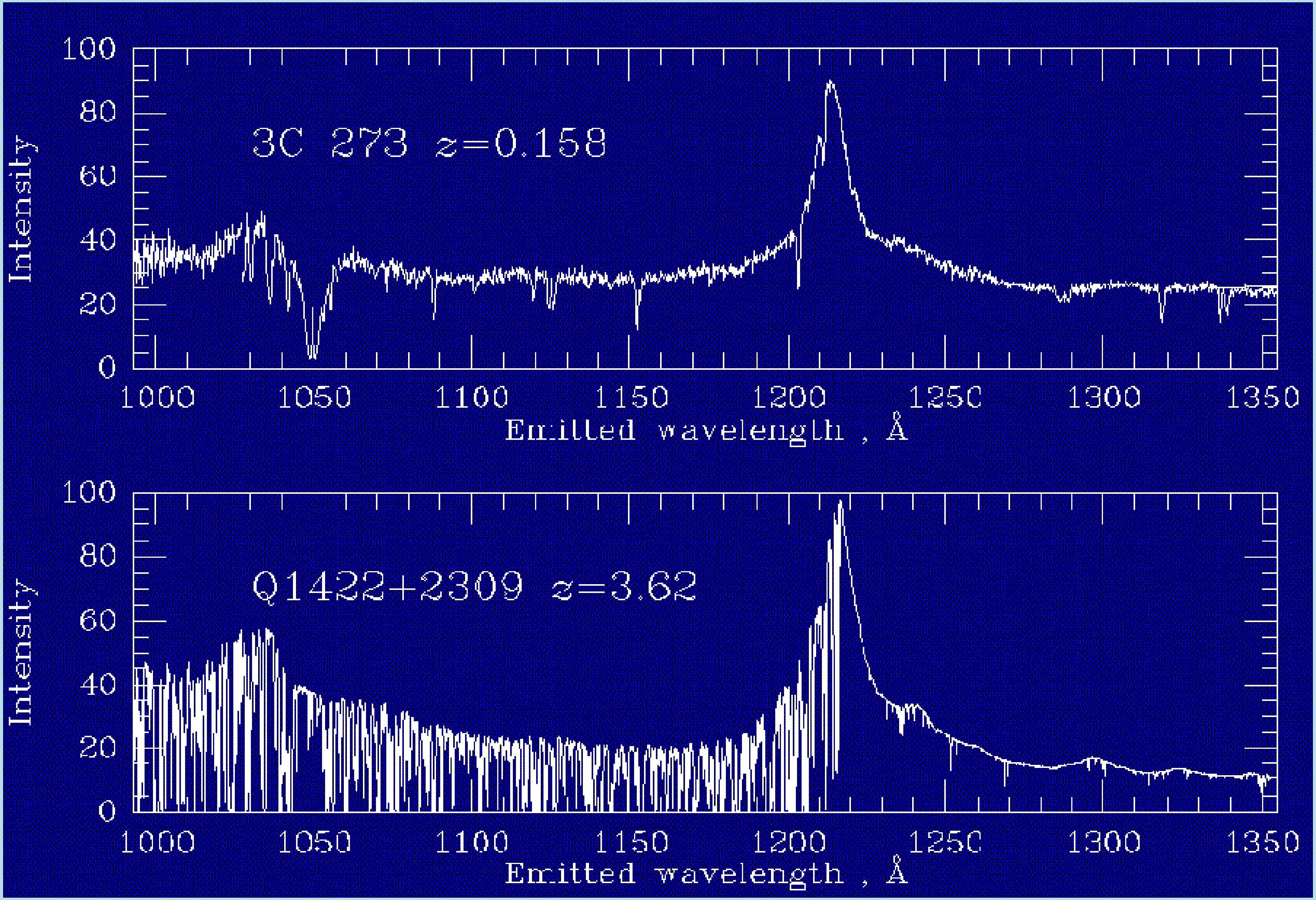
Lyα = 1216 Å (10.2 eV)
very useful transition in cosmology
- although in rest-frame UV, it is shifted into optical for high-z systems

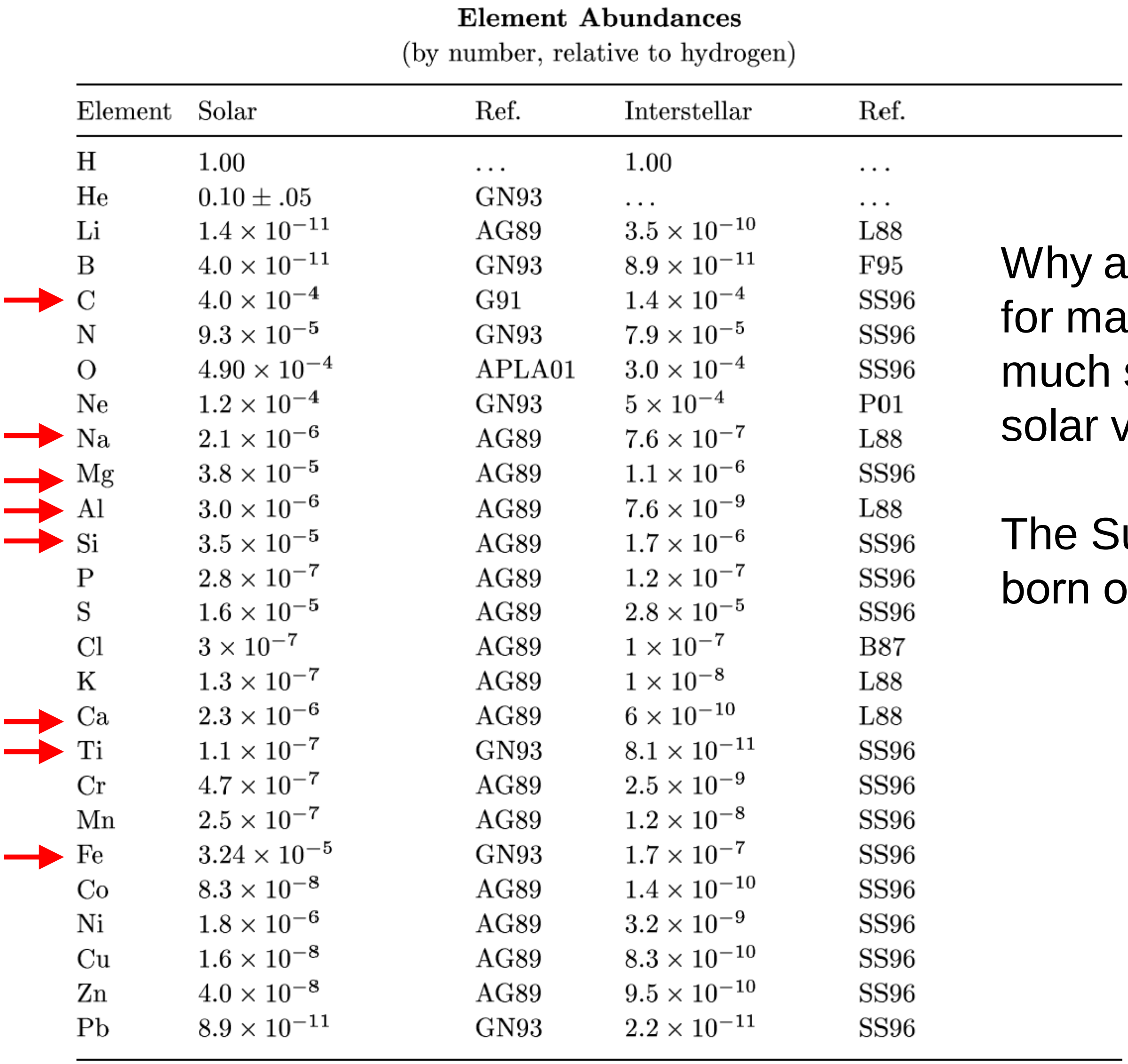
neutral atomic hydrogen (HI) is very hard to observe - very few transitions, very little emission (we will see main mechanism later)

however, Lyα photons are <u>absorbed</u> by neutral hydrogen in line-of-sight

No absorbing clouds




3C 273 z=0.158
Intensity
0
20
40
60
80
100
1000
1050
1100
1150
1200
1250
1300
1350
Emitted wavelength , Å
Q1422+2309 z=3.62
Intensity
0
20
40
60
80
100
1000
1050
1100
1150
1200
1250
1300
1350
Emitted wavelength , Å



Element Abundances
(by number, relative to hydrogen)

	Element	Solar	Ref.	Interstellar	Ref.
	H	1.00	...	1.00	...
	He	$0.10 \pm .05$	GN93	...	...
	Li	1.4×10^{-11}	AG89	3.5×10^{-10}	L88
	B	4.0×10^{-11}	GN93	8.9×10^{-11}	F95
→	C	4.0×10^{-4}	G91	1.4×10^{-4}	SS96
	N	9.3×10^{-5}	GN93	7.9×10^{-5}	SS96
	O	4.90×10^{-4}	APLA01	3.0×10^{-4}	SS96
	Ne	1.2×10^{-4}	GN93	5×10^{-4}	P01
→	Na	2.1×10^{-6}	AG89	7.6×10^{-7}	L88
→	Mg	3.8×10^{-5}	AG89	1.1×10^{-6}	SS96
→	Al	3.0×10^{-6}	AG89	7.6×10^{-9}	L88
→	Si	3.5×10^{-5}	AG89	1.7×10^{-6}	SS96
	P	2.8×10^{-7}	AG89	1.2×10^{-7}	SS96
	S	1.6×10^{-5}	AG89	2.8×10^{-5}	SS96
	Cl	3×10^{-7}	AG89	1×10^{-7}	B87
	K	1.3×10^{-7}	AG89	1×10^{-8}	L88
→	Ca	2.3×10^{-6}	AG89	6×10^{-10}	L88
→	Ti	1.1×10^{-7}	GN93	8.1×10^{-11}	SS96
	Cr	4.7×10^{-7}	AG89	2.5×10^{-9}	SS96
	Mn	2.5×10^{-7}	AG89	1.2×10^{-8}	SS96
→	Fe	3.24×10^{-5}	GN93	1.7×10^{-7}	SS96
	Co	8.3×10^{-8}	AG89	1.4×10^{-10}	SS96
	Ni	1.8×10^{-6}	AG89	3.2×10^{-9}	SS96
	Cu	1.6×10^{-8}	AG89	8.3×10^{-10}	SS96
	Zn	4.0×10^{-8}	AG89	9.5×10^{-10}	SS96
	Pb	8.9×10^{-11}	GN93	2.2×10^{-11}	SS96

Why are ISM abundances for many elements so much smaller than their solar values?

The Sun is a normal star born out of the ISM…

Depletion onto dust

Certain elements can **convert** from GAS to SOLID
Result: matter is removed (depleted) from GAS phase
matter is added to SOLID phase = DUST

The level of depletion of each element tells us something about the **composition of the dust**.
Depleted elements = *refractory* elements (high-melting point, non-volatile)
e.g. O, Fe, Mg, Si, Al

➔ ISM abundance studies:

- composition of the gaseous ISM
- composition of ISM dust

remember: Dust = only 1% by mass of the ISM but very important

Dust

Dust in the ISM

Dust particles are extremely small (~0.1–10 microns)

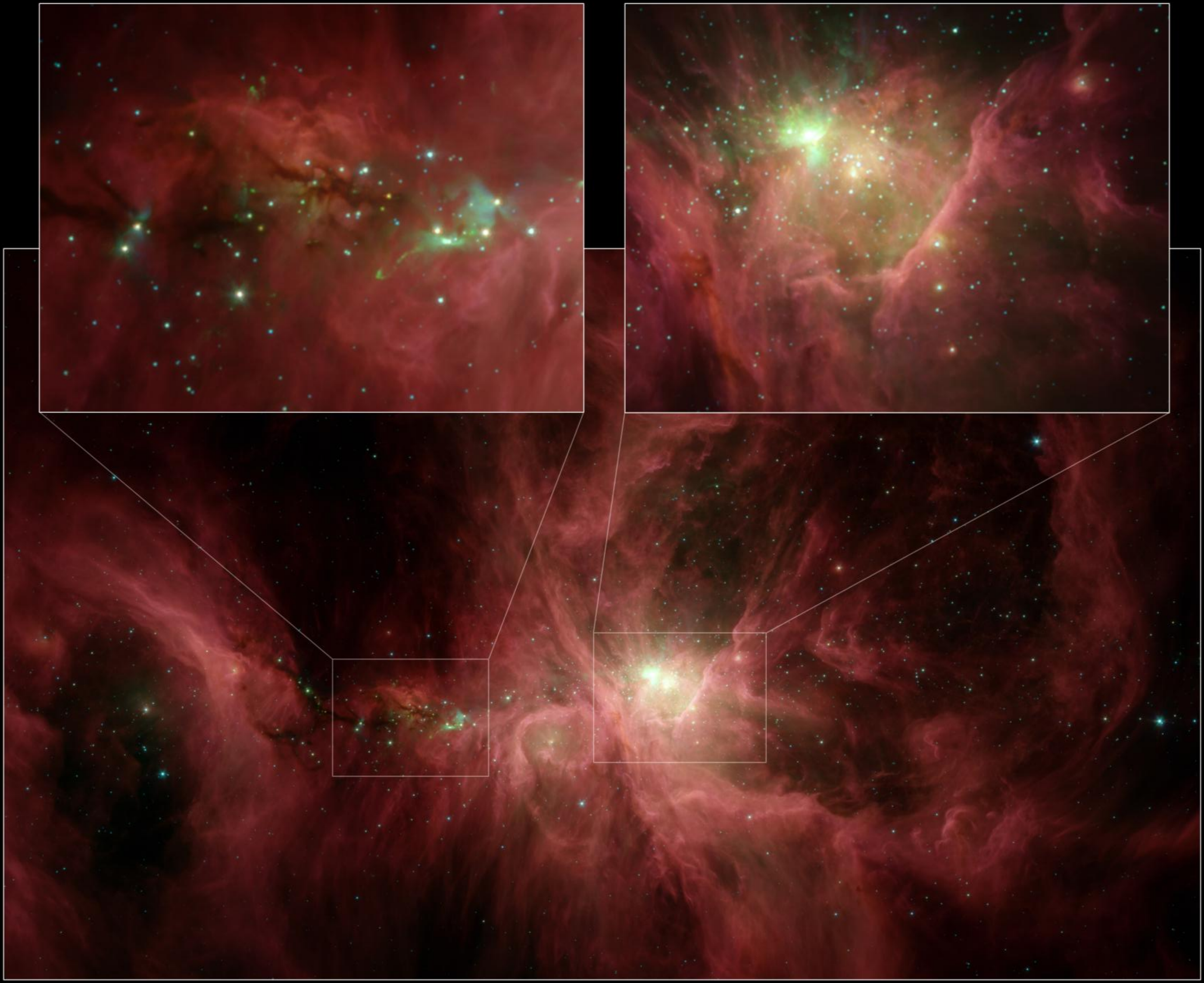
Particles are irregularly shaped
Composed of *silicates*, *carbon*, *ices* (water, methane, ammonia etc) and/or *iron* compounds.

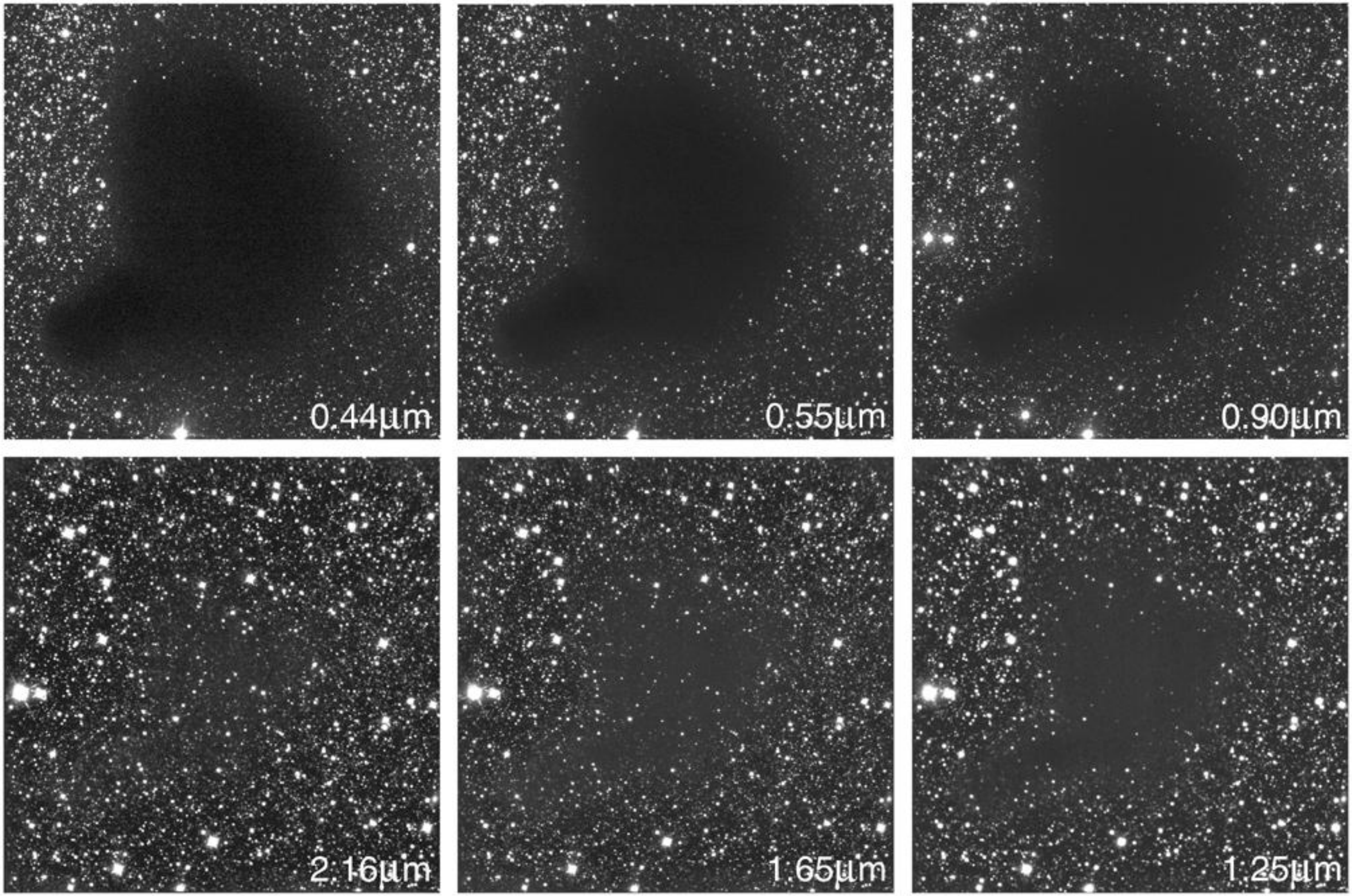
Effects of the Dust:

- On Elemental Abundances: We saw how elements are depleted from the GAS phase of the ISM sticking on to dust grains thus lowering the gas phase abundances of certain (mostly refractory) elements.

- On E/M radiation: dust grains absorb or scatter blue light more than red light removing it from the line of sight to the observer. Distant objects thus appear *reddened.*

Visible





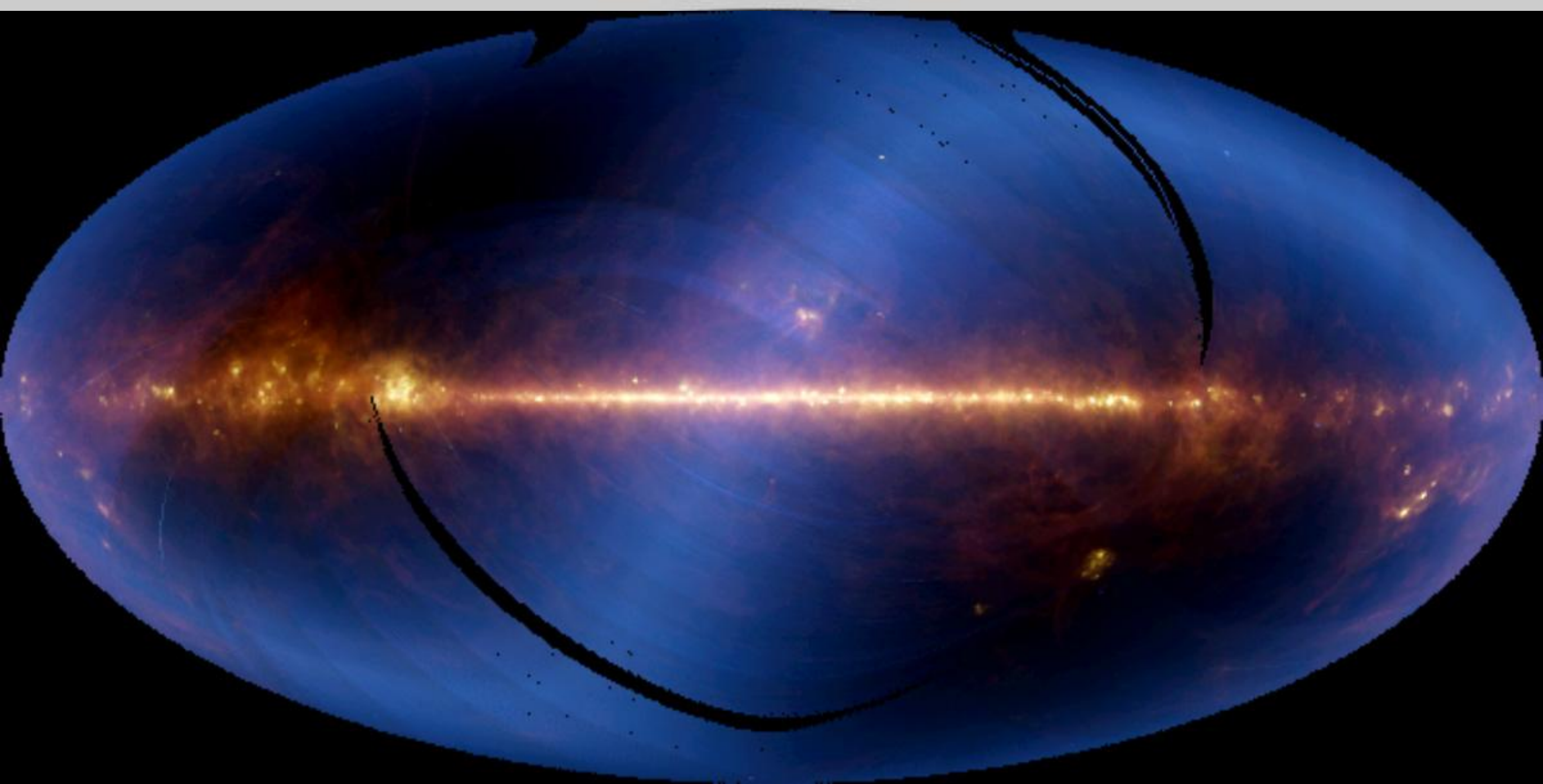
The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

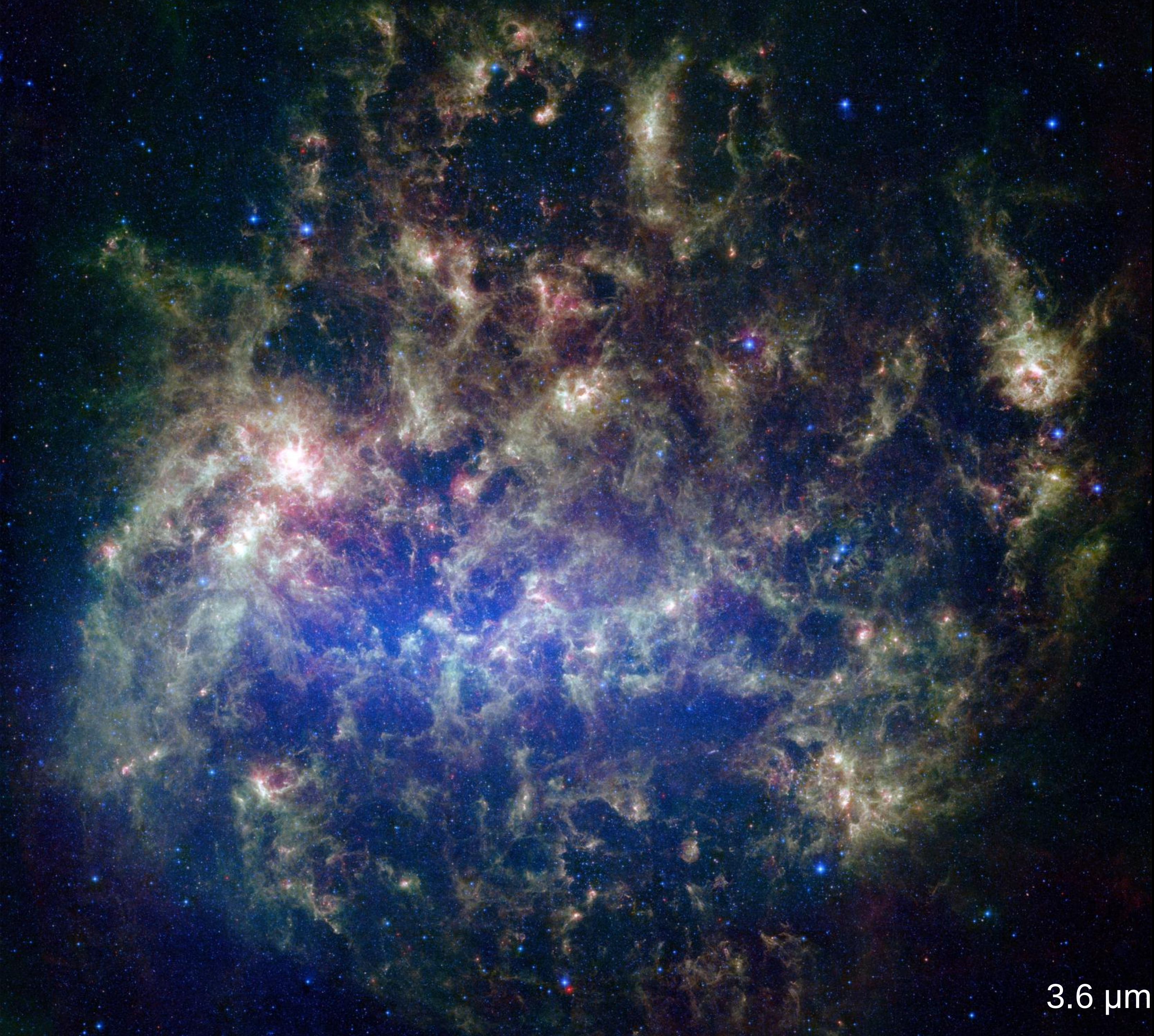
ESO PR Photo 29b/99 (2 July 1999)

IR observations of dust

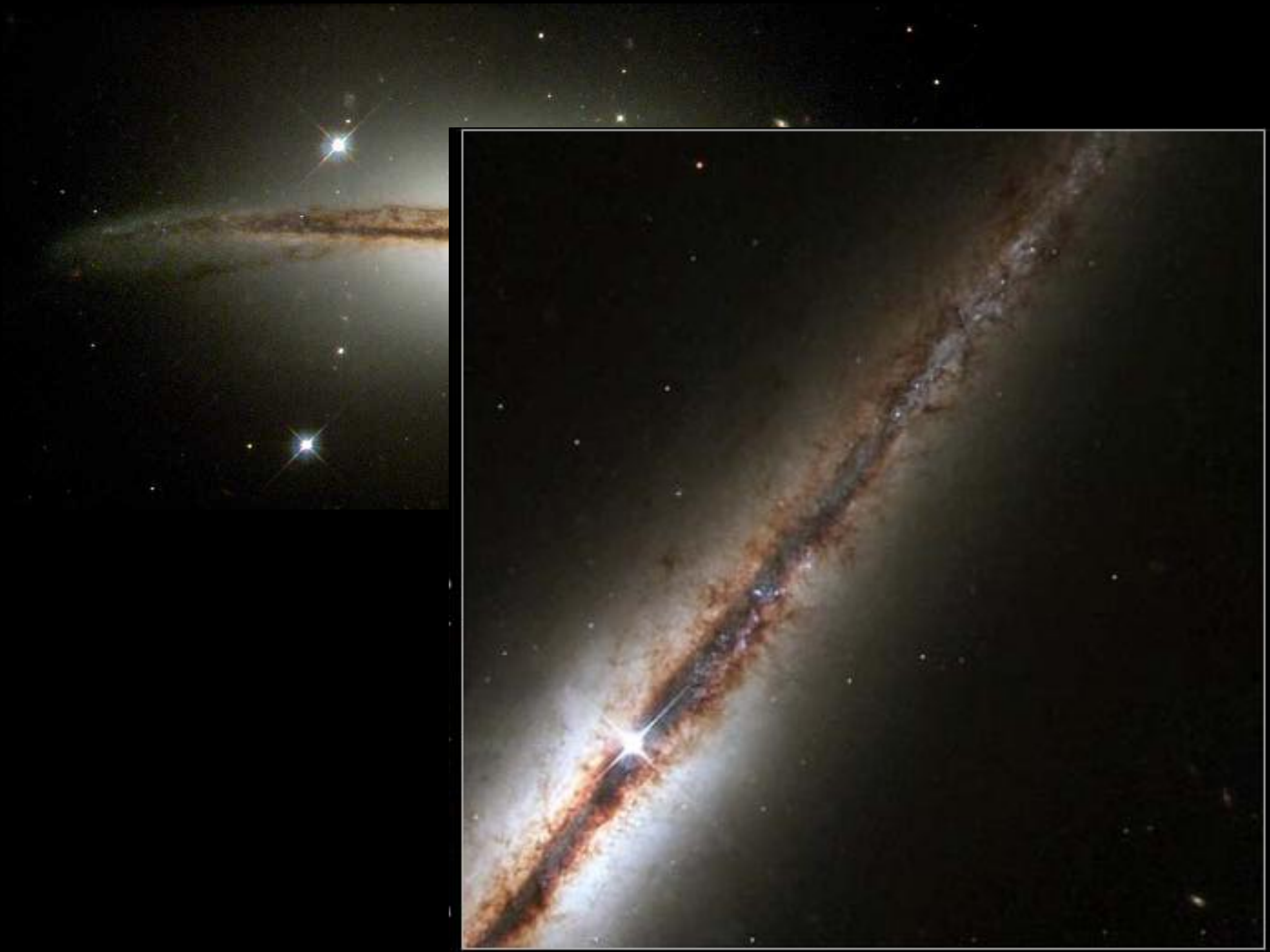
1. Image taken at 2 μm by 2MASS survey
2. Composite image at 12 μm, 60 μm, 100 μm by *IRAS* satellite

Dust warmed by far-UV starlight re-radiates light in the IR
"Wien's law": λ (re-emitted light) ~ 1/T (dust)





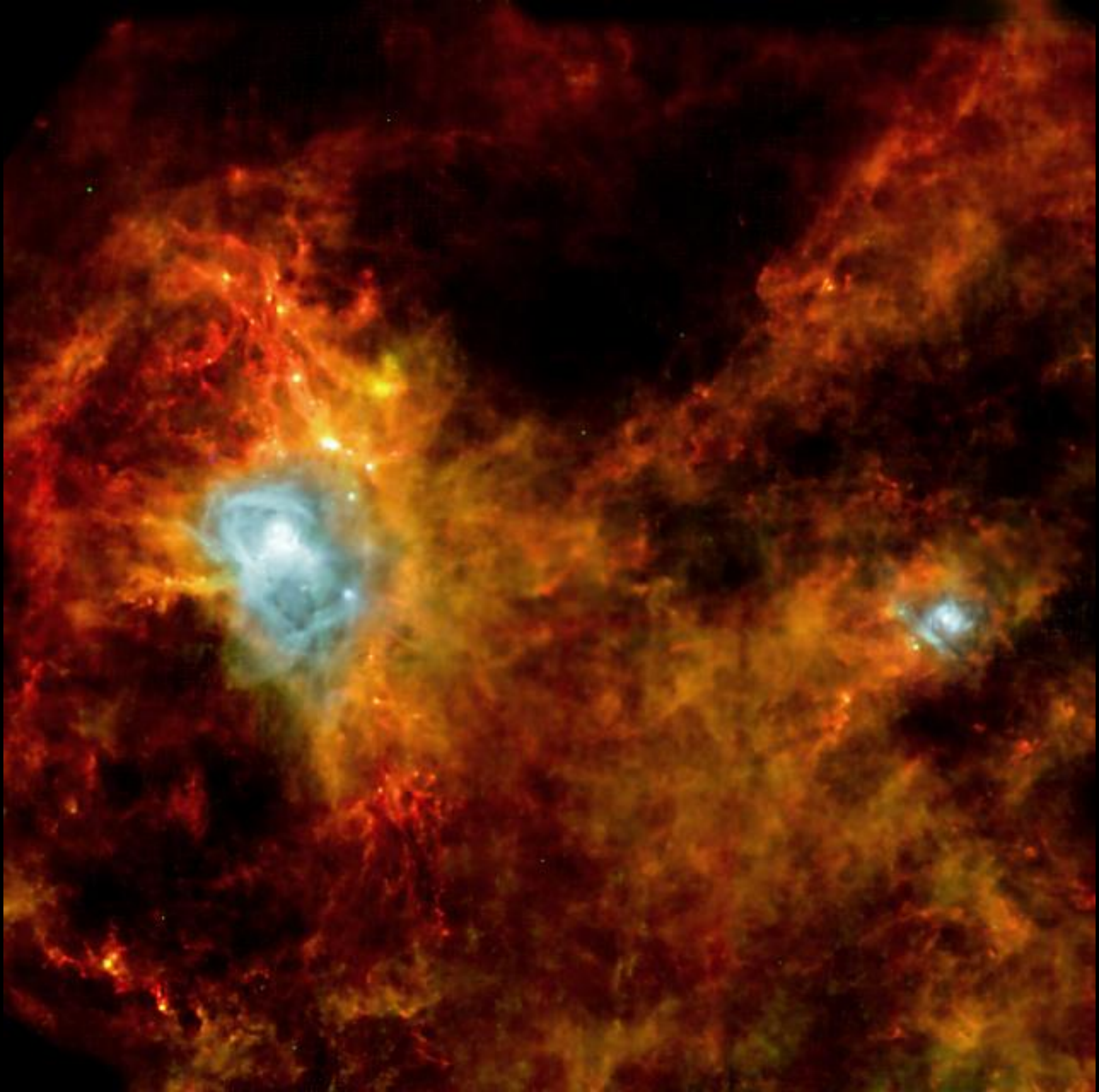
3.6 µm, 8 µm, 24 µm



Herschel

©ESA and the SPIRE & PACS consortia

70 µm, 160 µm, 250/350/500 µm

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Cl	3×10^{-7}	AG89	1×10^{-7}	B87
K	1.3×10^{-7}	AG89	1×10^{-8}	L88
→ Ca	2.3×10^{-6}	AG89	6×10^{-10}	L88
→ Ti	1.1×10^{-7}	GN93	8.1×10^{-11}	SS96
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Cu	1.6×10^{-8}	AG89	8.3×10^{-10}	SS96
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The Sun is a normal star born out of the ISM…

Evidence for dust:

1) Absorption/Scattering of E/M radiation (extinction/reddening)

   (a) Reflection nebulae

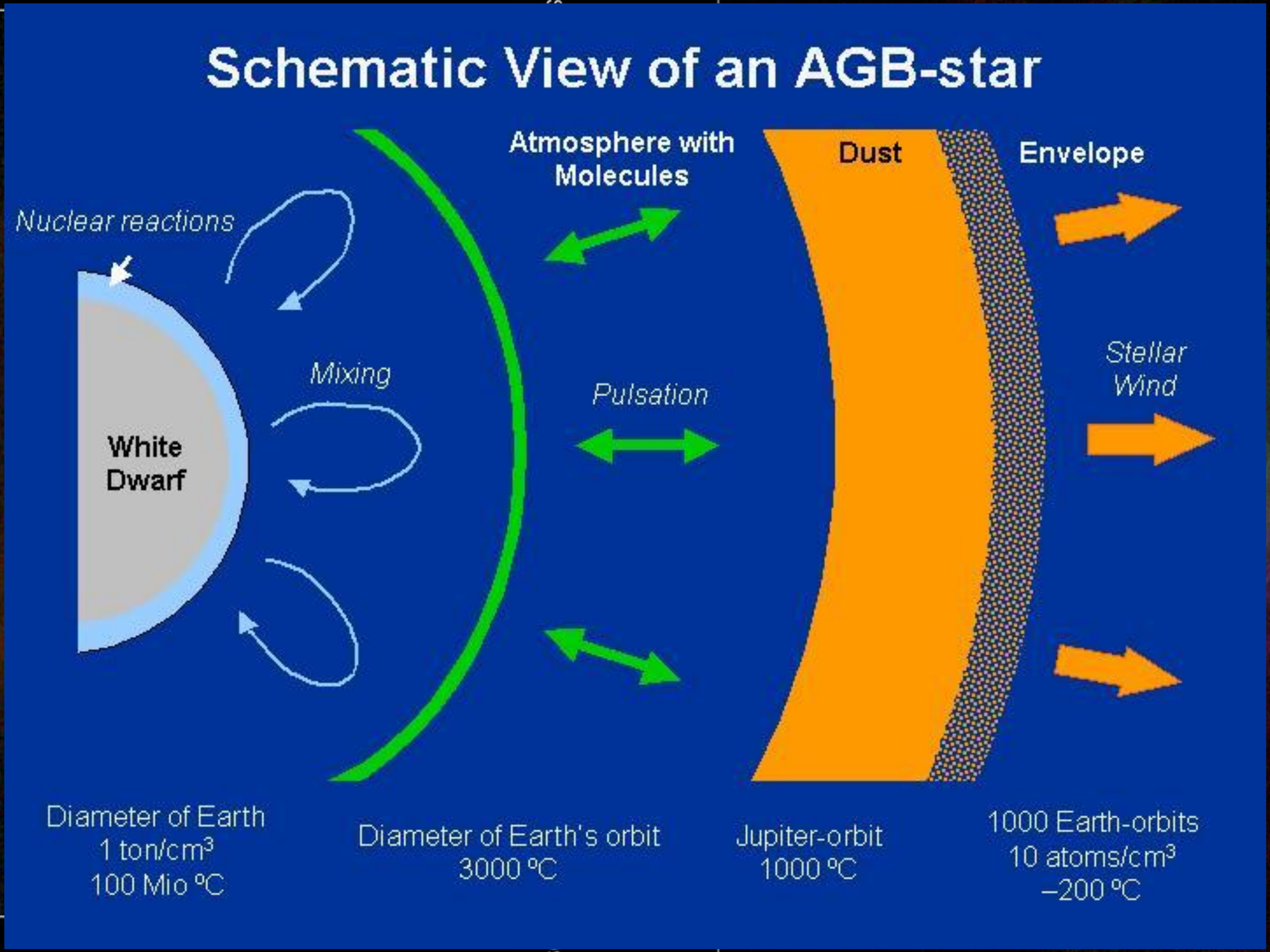
   (b) Dark nebulae/clouds

2) Depletion of abundances compared to solar

3) Dust emission in thermal IR – see it directly

Dust: where is it made? - AGB

Hourglass Nebula



Schematic View of an AGB-star

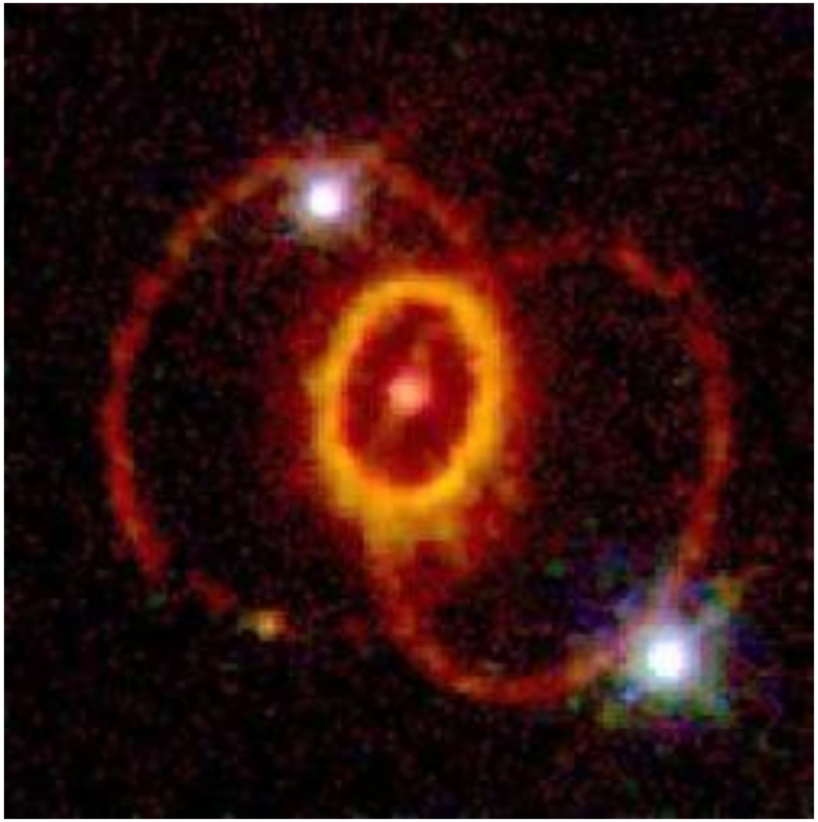
Diameter of Earth
1 ton/cm^3
100 Mio °C

Diameter of Earth's orbit
3000 °C

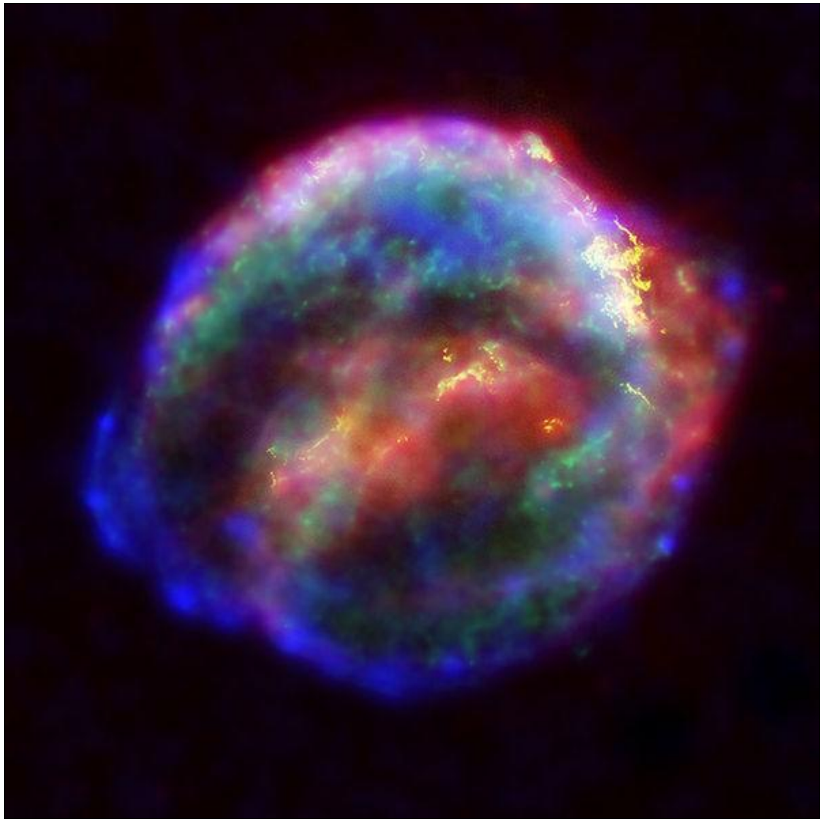
Jupiter-orbit
1000 °C

1000 Earth-orbits
10 atoms/cm^3
–200 °C

Dust: where is it made? - SNe

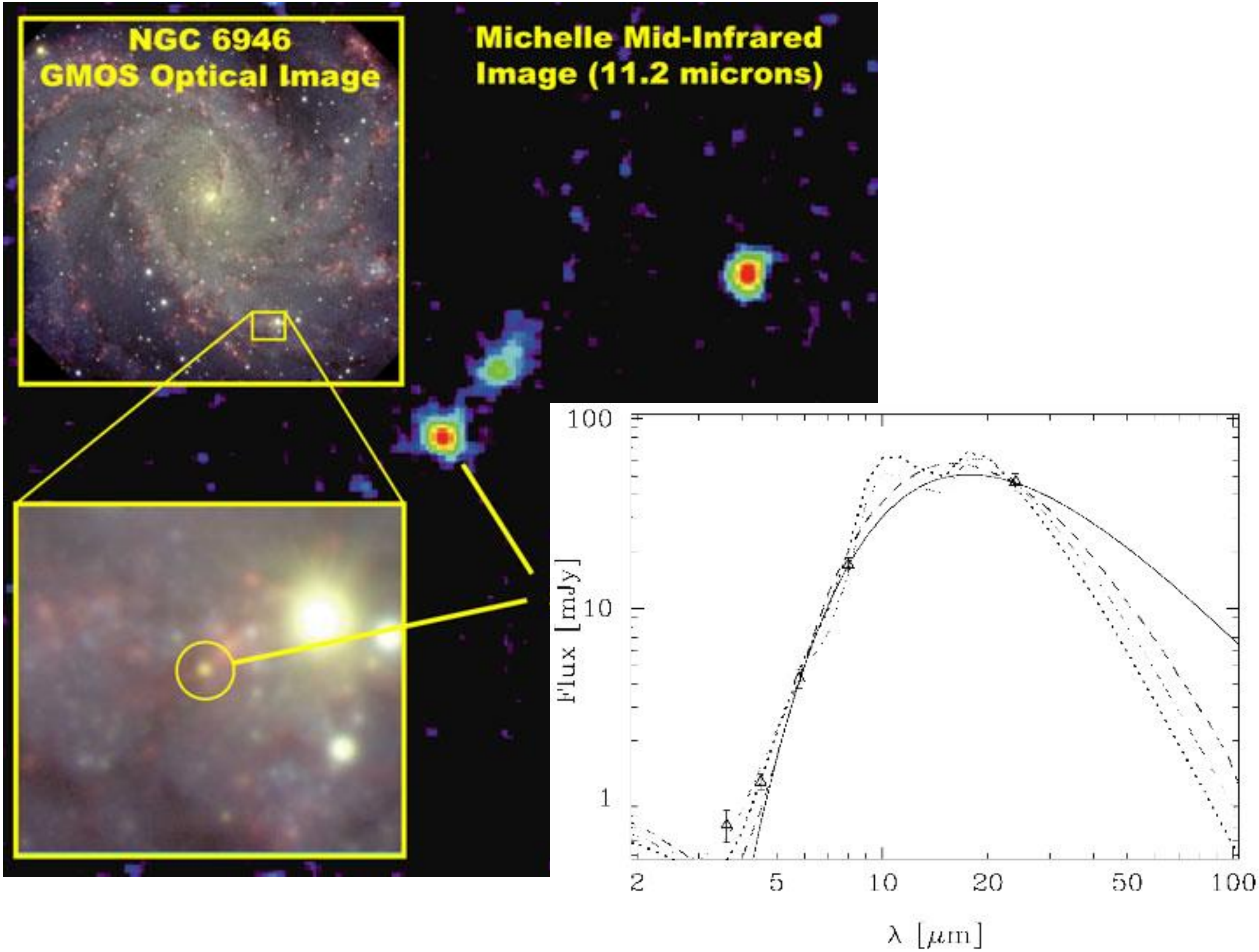


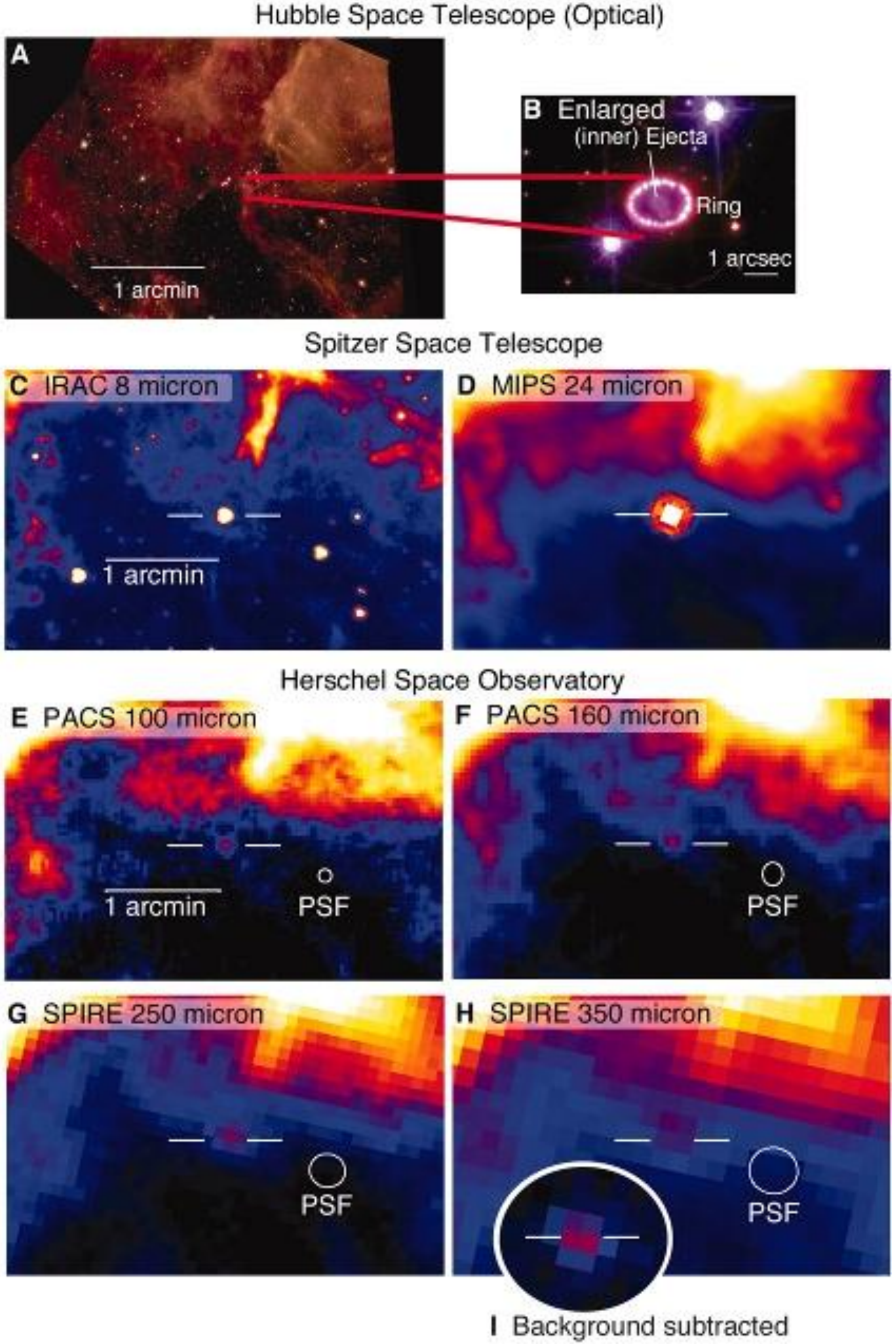
SN1987A
(HST)



SN1604 (Kepler’s SNR)
(Spitzer + HST + Chandra)

aftermath of supernova explosions as the expanding remnant slowly cools


NGC 6946
GMOS Optical Image
Michelle Mid-Infrared
Image (11.2 microns)
100
10
1
Flux [mJy]
2
5
10
20
50
100
λ [μm]



SNR1987A

(Matsuura et al. 2011)

0.5 M_sol of dust

1000x more than before

Could be a major source of dust in galaxies, particularly at high redshift.

Dust in the ISM: What is it made of?

Tiny sub-micron sized grains whose composition can be either:

- mostly SILICATES (compounds containing Si – silicon and O – oxygen) forming in the outflows of Oxygen-rich stars as they evolve towards the PN phase and Supernova remnants

- mostly CARBON-based compounds (*especially polycyclic aromatic hydrocarbons* - PAHs – like *benzene* and more complex stuff), forming in the outflows of Carbon-rich stars

When these are ejected deep into the ISM and find themselves in very cold conditions they can acquire a mantle (a shell) of “ices” (water, ammonia, methane etc.)

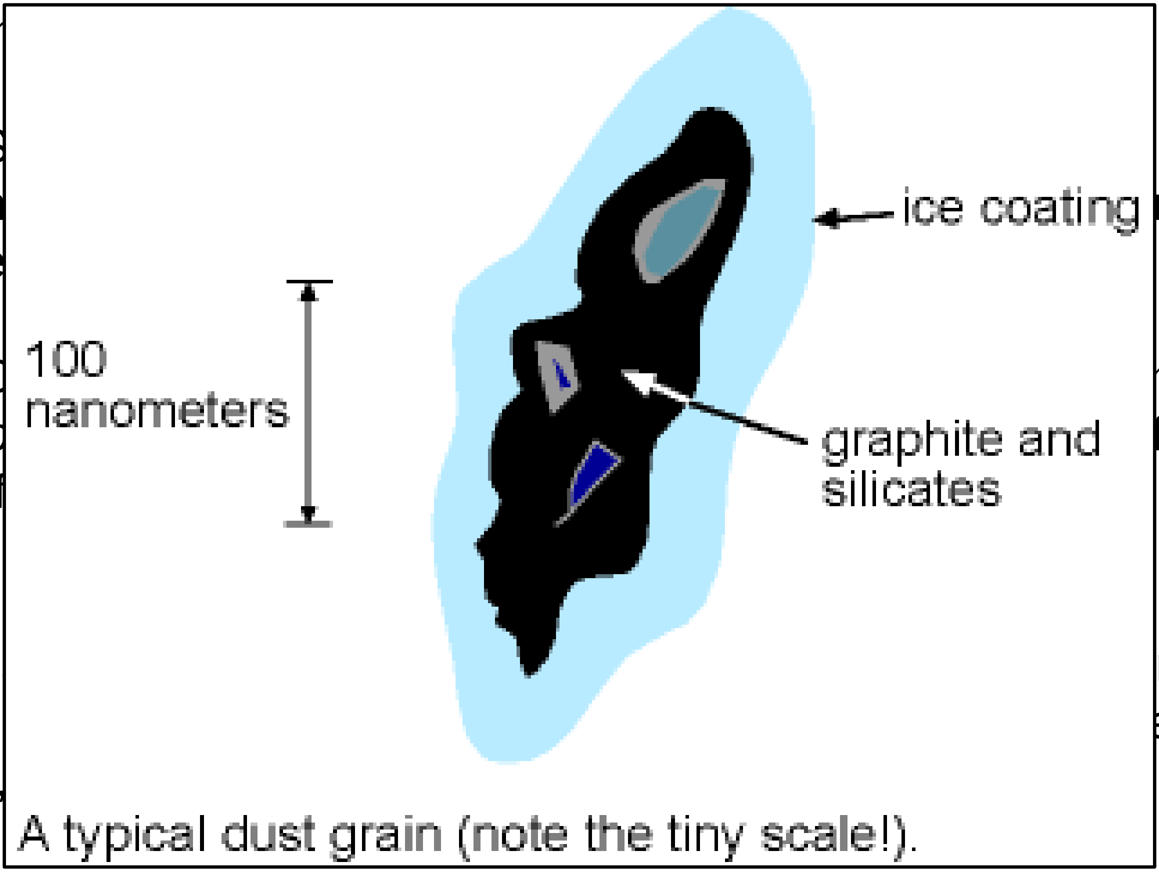
Dust in the ISM: What is it made of?

Tiny sub-r

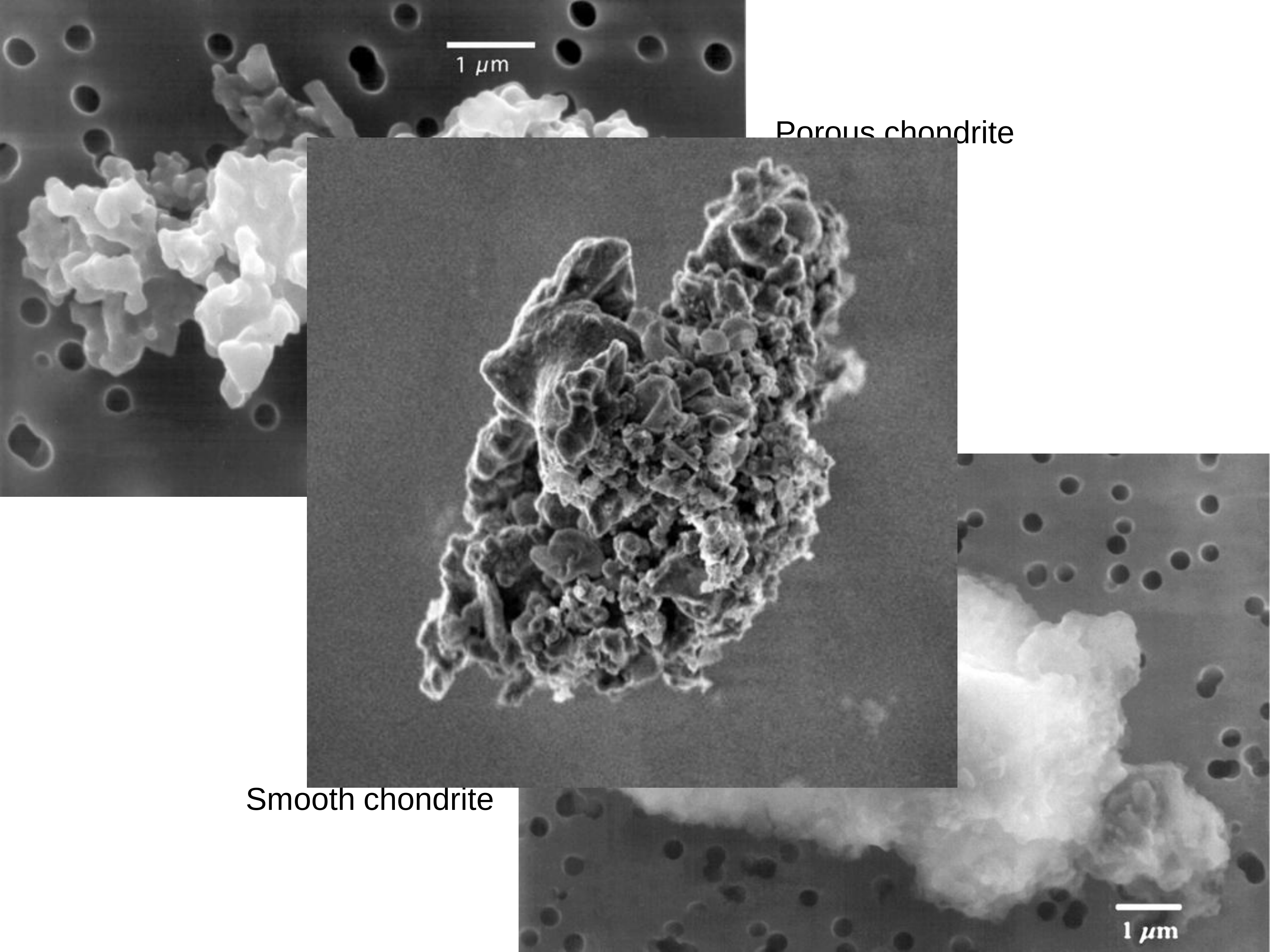
• mostly S oxygen) forming in rds the PN phase

• mostly C *natic hydrocarb* forming in the outf

When the n very cold cond er, ammonia,

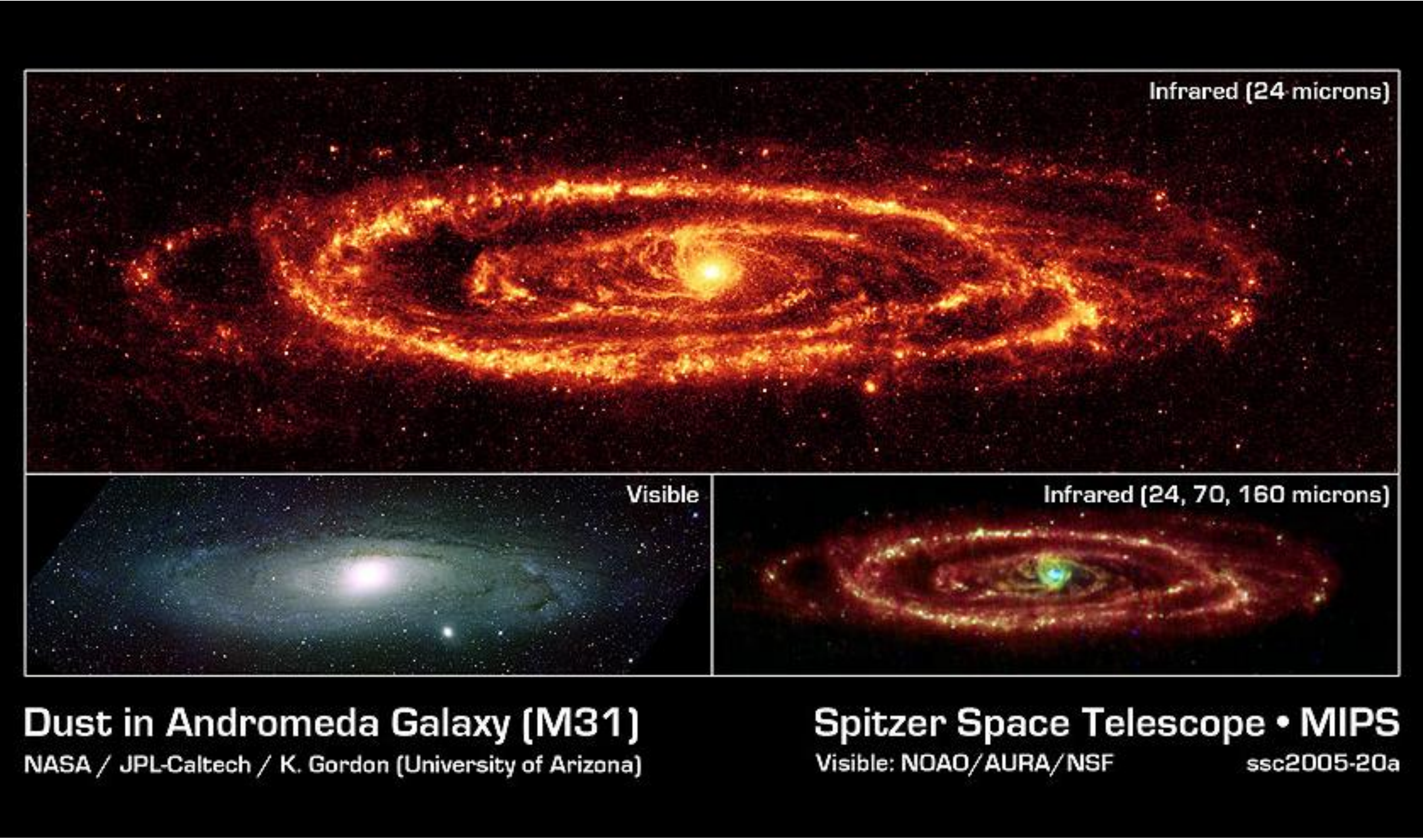


A typical dust grain (note the tiny scale!).

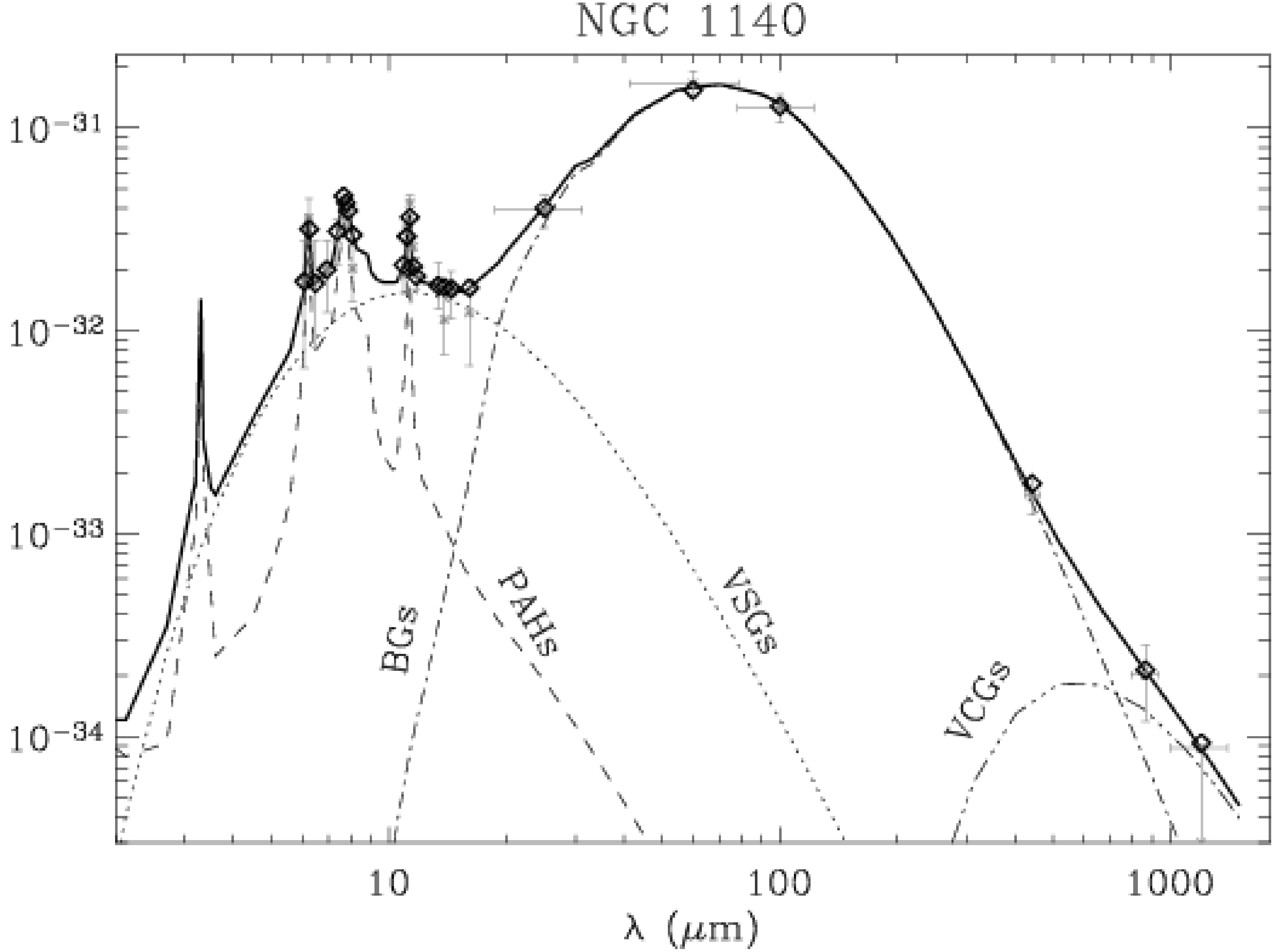


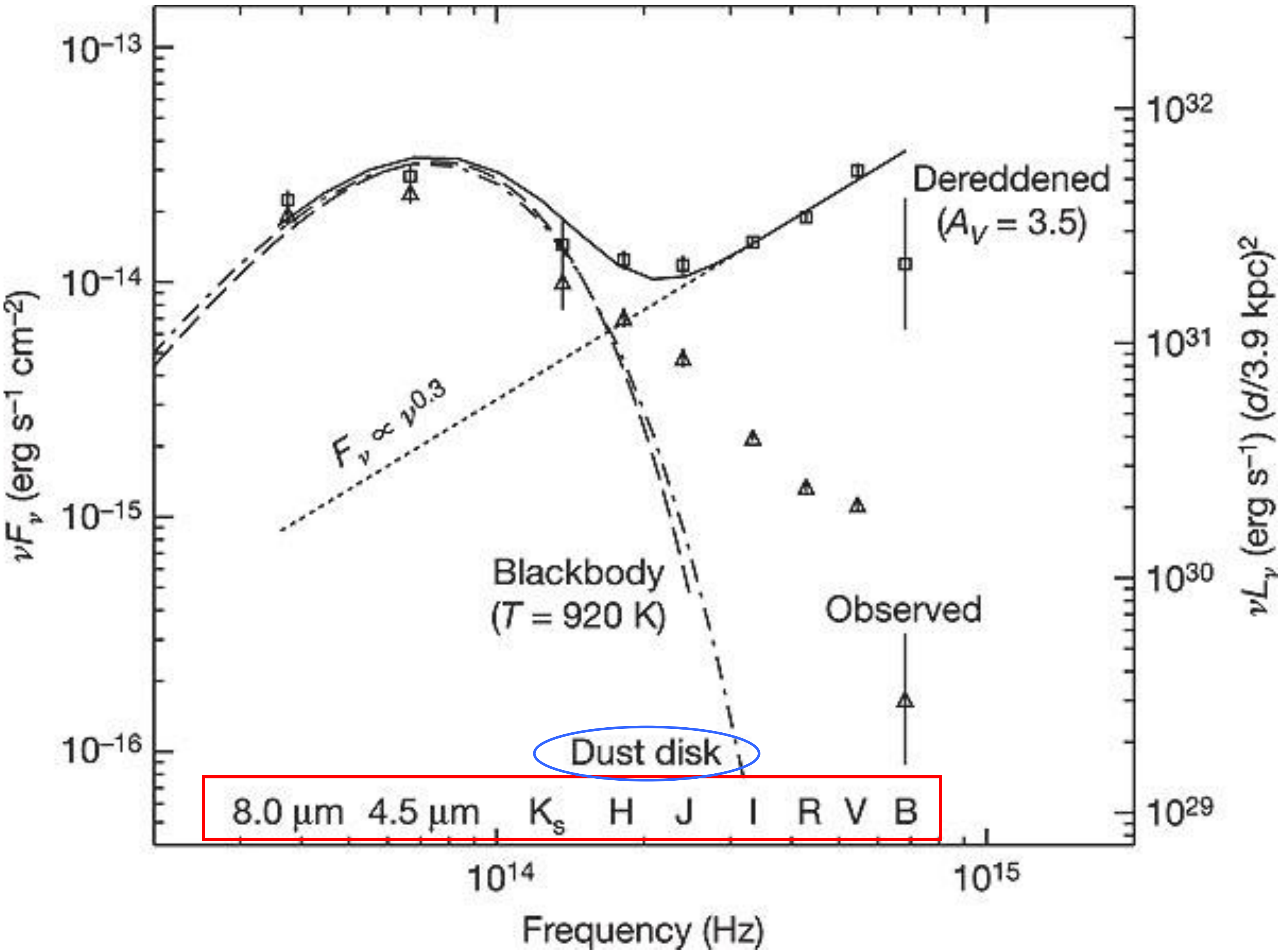
Porous chondrite

Smooth chondrite



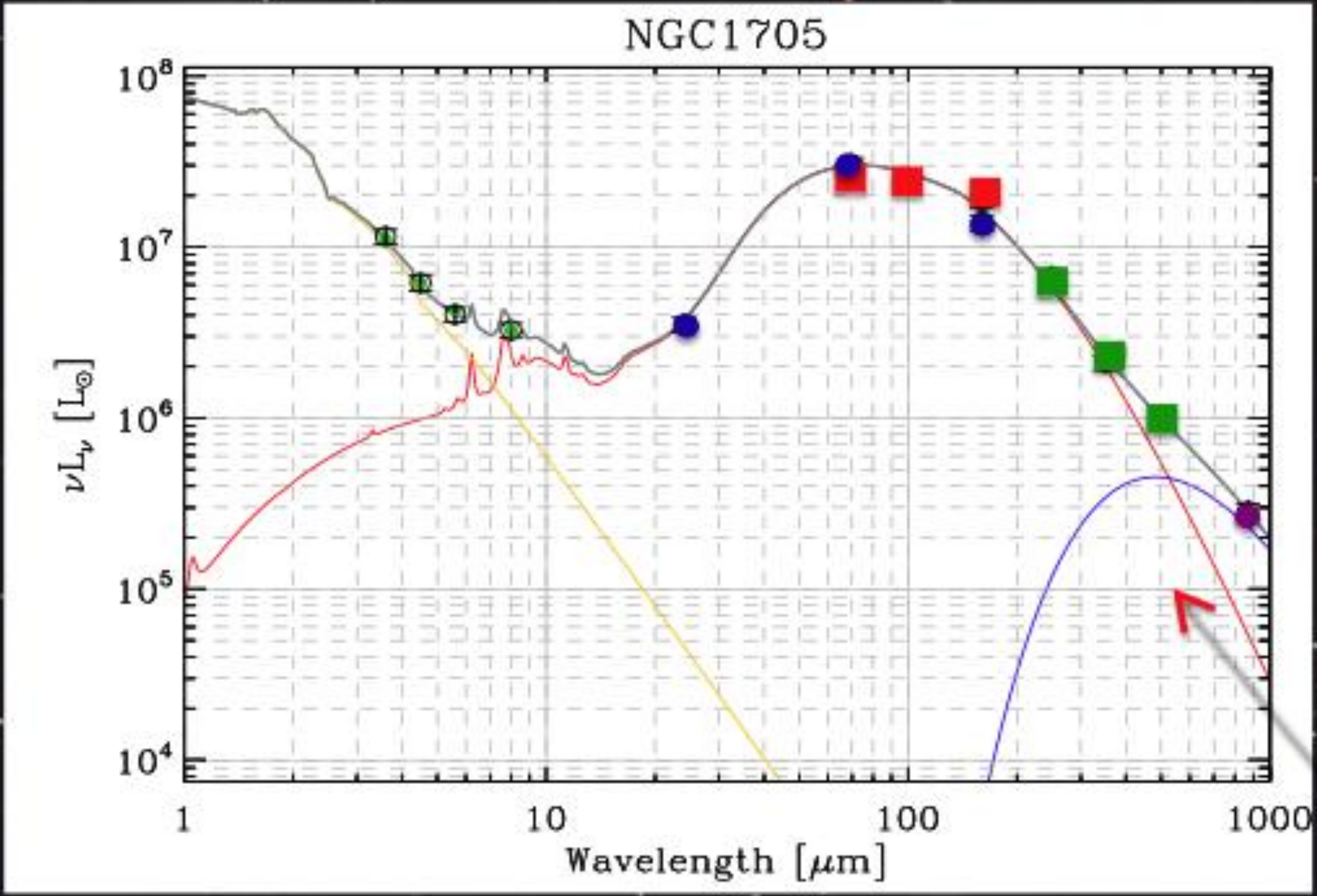
blue (24 μm), green (70 μm), red (160 μm)


NGC 1140
νL_ν (W.H^{-1})
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10
100
1000
λ (μm)
BGs
PAHs
VSGs
VCGs


10^{-13}
10^{-14}
10^{-15}
10^{-16}
νF_ν (erg s^{-1} cm^{-2})
10^{32}
10^{31}
10^{30}
10^{29}
νL_ν (erg s^{-1}) (d/3.9 kpc)^2
Dereddened
(A_V = 3.5)
$F_\nu \propto \nu^{0.3}$
Blackbody
(T = 920 K)
Observed
Dust disk
8.0 μm
4.5 μm
K_s
H
J
I
R
V
B
10^{14}
10^{15}
Frequency (Hz)

NGC 1705 – *preliminary* global SED

IRAC + MIPS + PACS + SPIRE + Laboca 870 mu

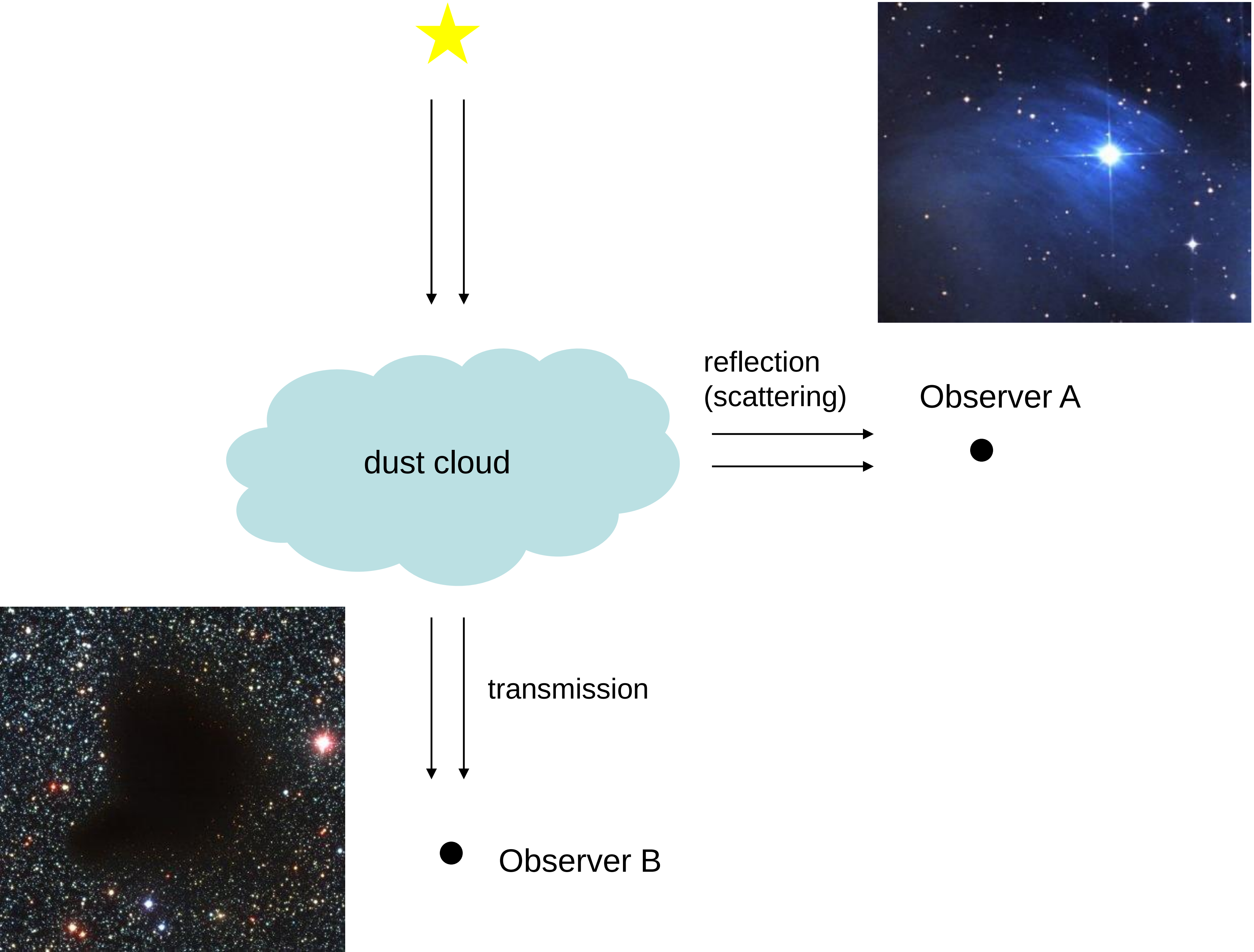


- ● MIPS
- 🟥 PACS
- 🟩 SPIRE
- ● LABOCA

Very cold dust component:

T dust ~ 6 K
β = 1.0

SED model based on Galliano et al 2008 & Galametz et al 2009



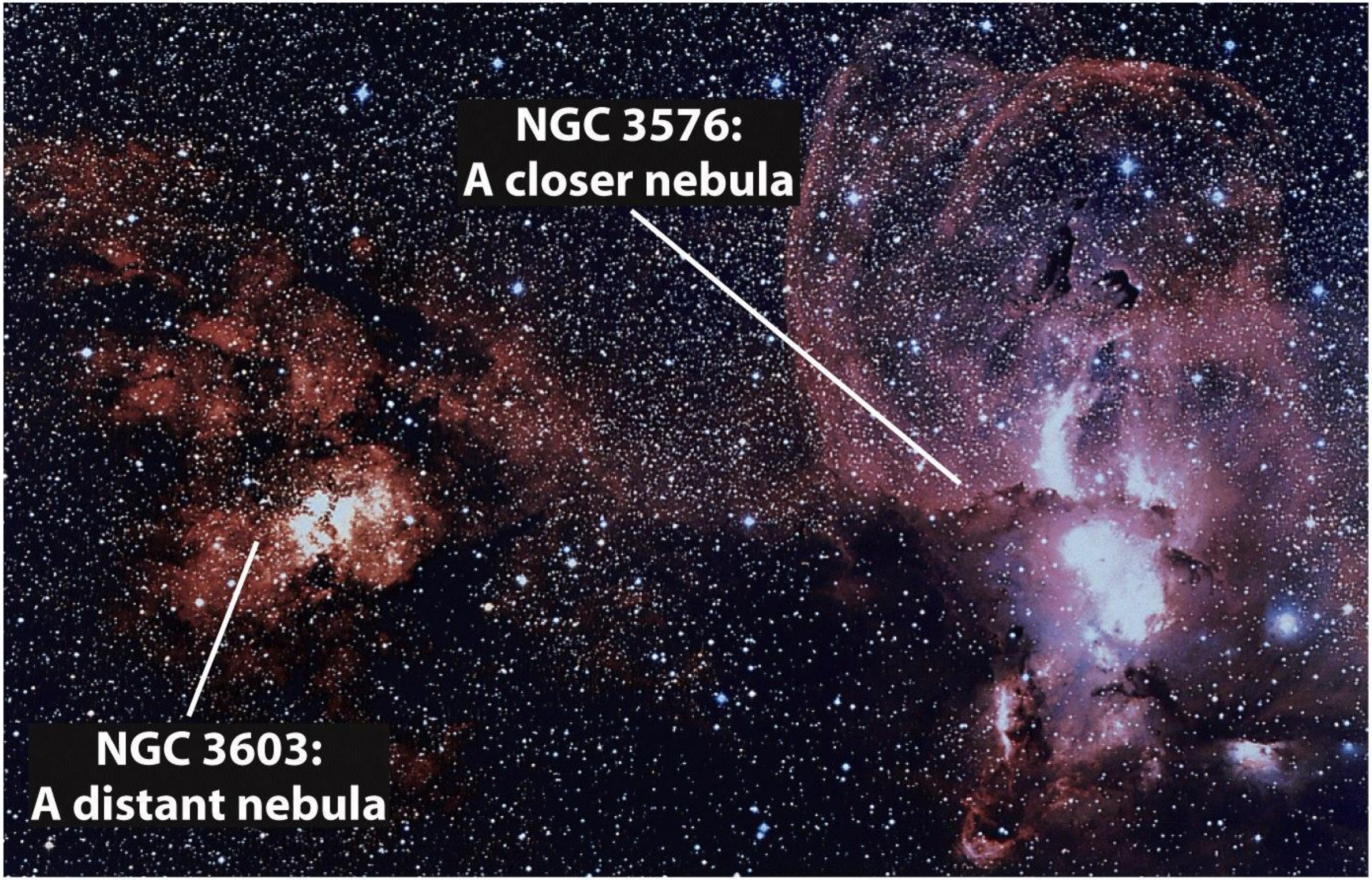
reflection (scattering)

Observer A

dust cloud

transmission

Observer B

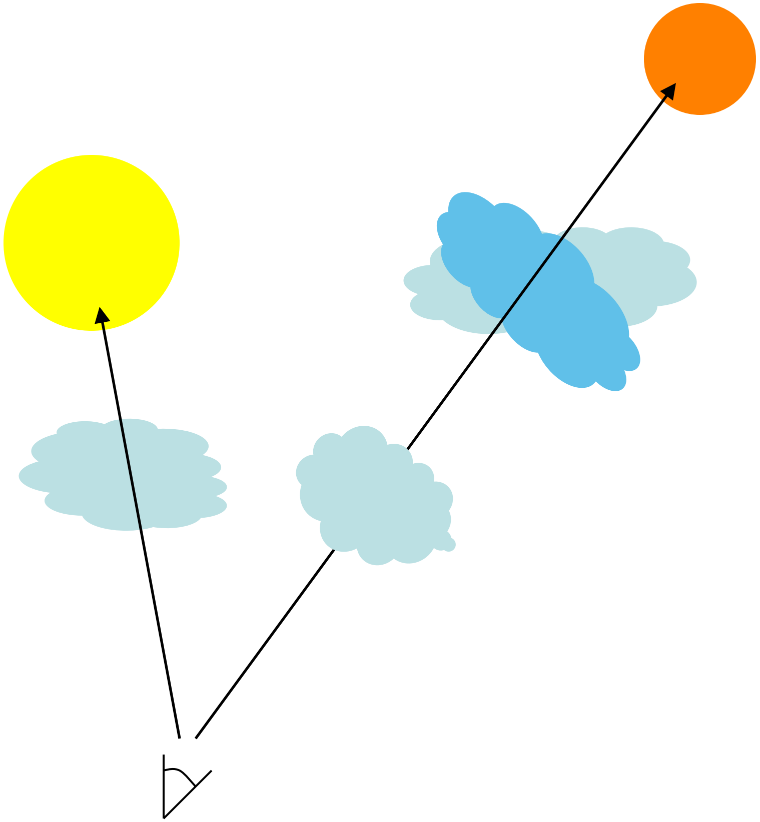


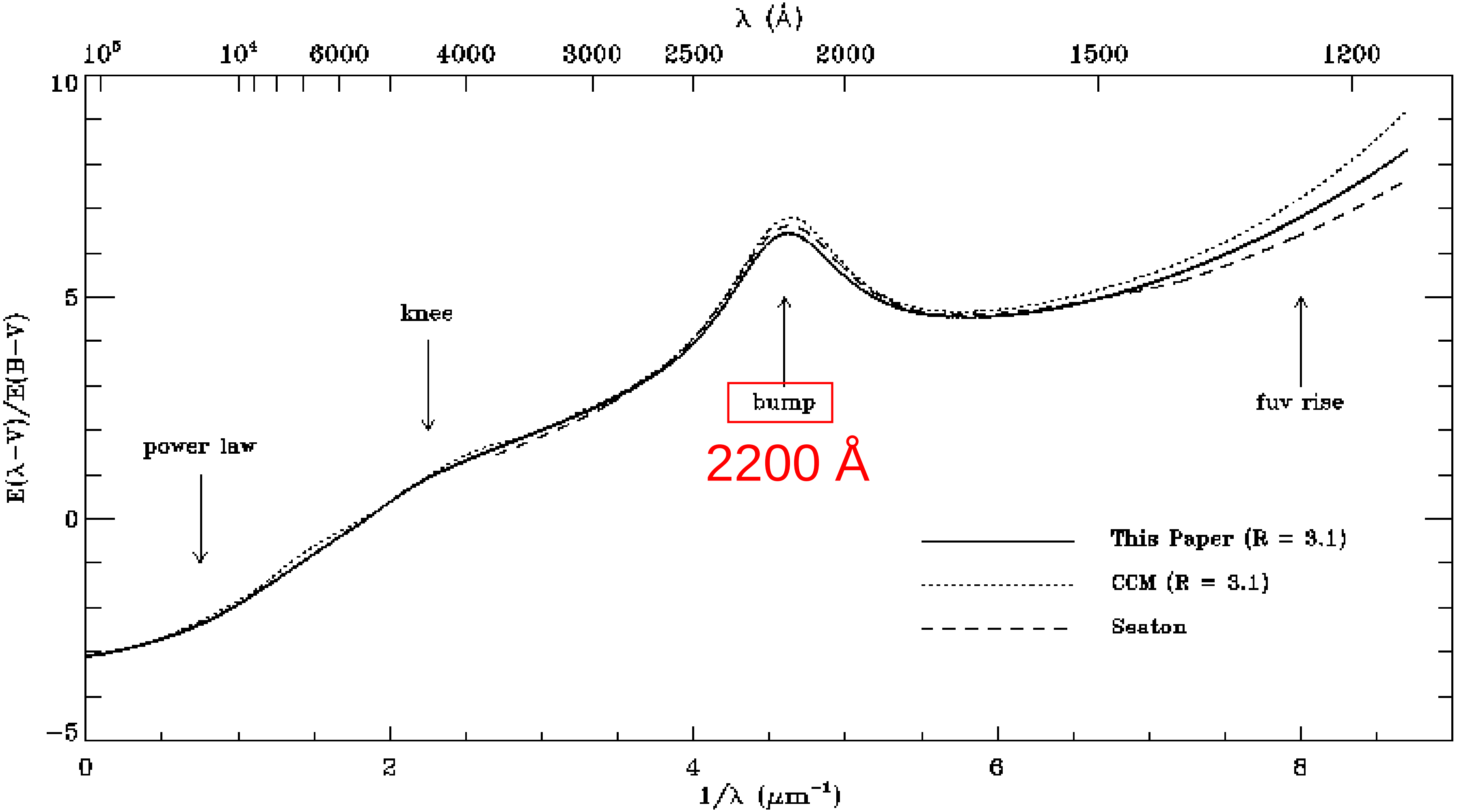
Reddening depends on distance

Figure 18-6b
Universe, Eighth Edition

Method: Observe spectra from intrinsically identical stars, but at different distances (and thus different amounts of dust extinction) -- and compare

Result: Determine the detailed scattering/absorption properties of the dust *as a function of wavelength*





bump: very broad (~400 Å), still unidentified!
(possibly absorption from Graphite grains)

A_V = level of extinction at $\lambda = V$
$(B-V)$ = observed colour
$(B-V)_0$ = intrinsic colour of object (e.g. star)

define $E(B-V) = (B-V) - (B-V)_0$

in the V-band, $A_V \sim 3.2\ E(B-V)$

Can we relate all these magnitudes to the actual physics of the absorbing dust?
The intensity of light propagating through ISM **dust** is reduced according to the equation

$$I_\lambda = I_{\lambda 0} e^{-\tau_\lambda}$$

I_λ = the light collected at the telescope
$I_{\lambda 0}$ = the intensity of the light that would have been collected in the absence of dust
τ_λ = the optical depth (**physical meaning!**) at the wavelength of the observation - can relate to extinction coefficient which can be measured in lab

τ_λ = the optical depth at the wavelength of the observation - can relate to extinction coefficient which can be measured in lab
(can also be a function of frequency)

$$\tau_\nu = \int \kappa_\nu \, \mathrm{d}l$$

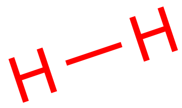
It is also related to the equivalent width (W), in the case where τ is small (<1; optically thin case – line is not saturated)

$$W = \int (1 - e^{-\tau_\nu}) \, \mathrm{d}\nu$$

Back to gases…
we’ve looked at ionised hydrogen
(HII regions)

and neutral hydrogen, HI
(diffuse clouds)

But what if we want to observe
molecular hydrogen?



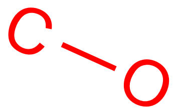
Molecules, found in cold regions, typically emit *cm* or *mm-wave* radiation
→ observable with radio-telescopes (large antennas).

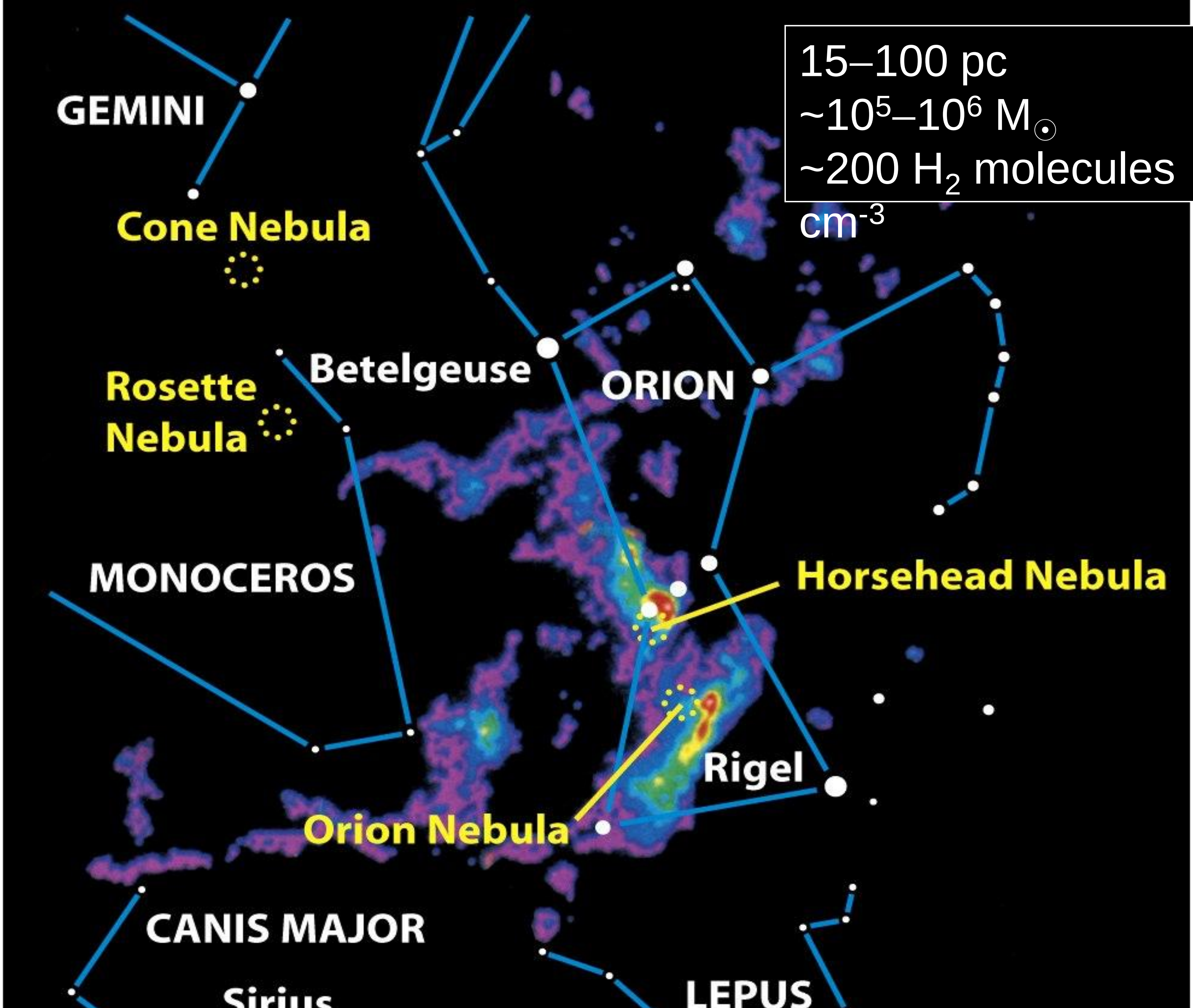
The most abundant molecule, H_2, has very few transitions - in fact v. difficult to observe at any wavelength!

On the other hand, CO has a strong line at 2.6 mm – v. convenient!

The CO/H_2 ratio in the Galaxy is about 10^{-4} (1:10000) and remains ~constant.

CO observations can therefore be used to trace molecular hydrogen.



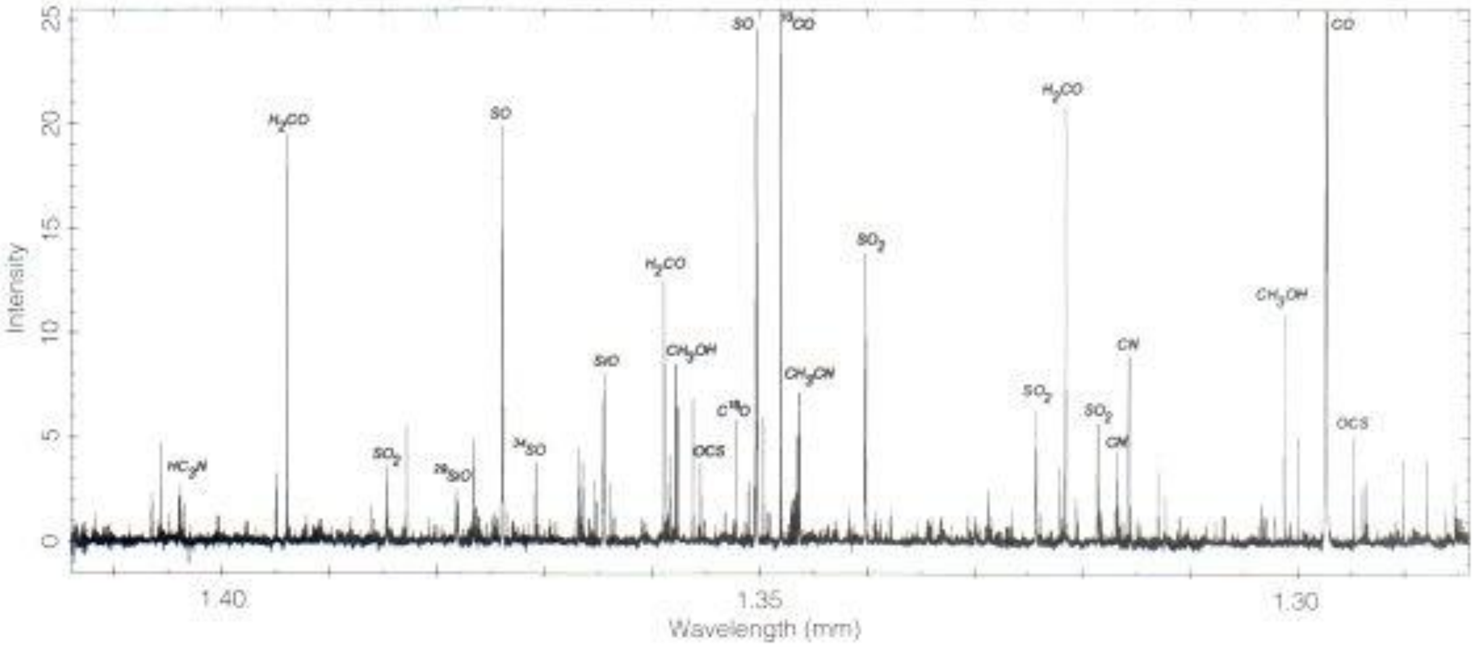


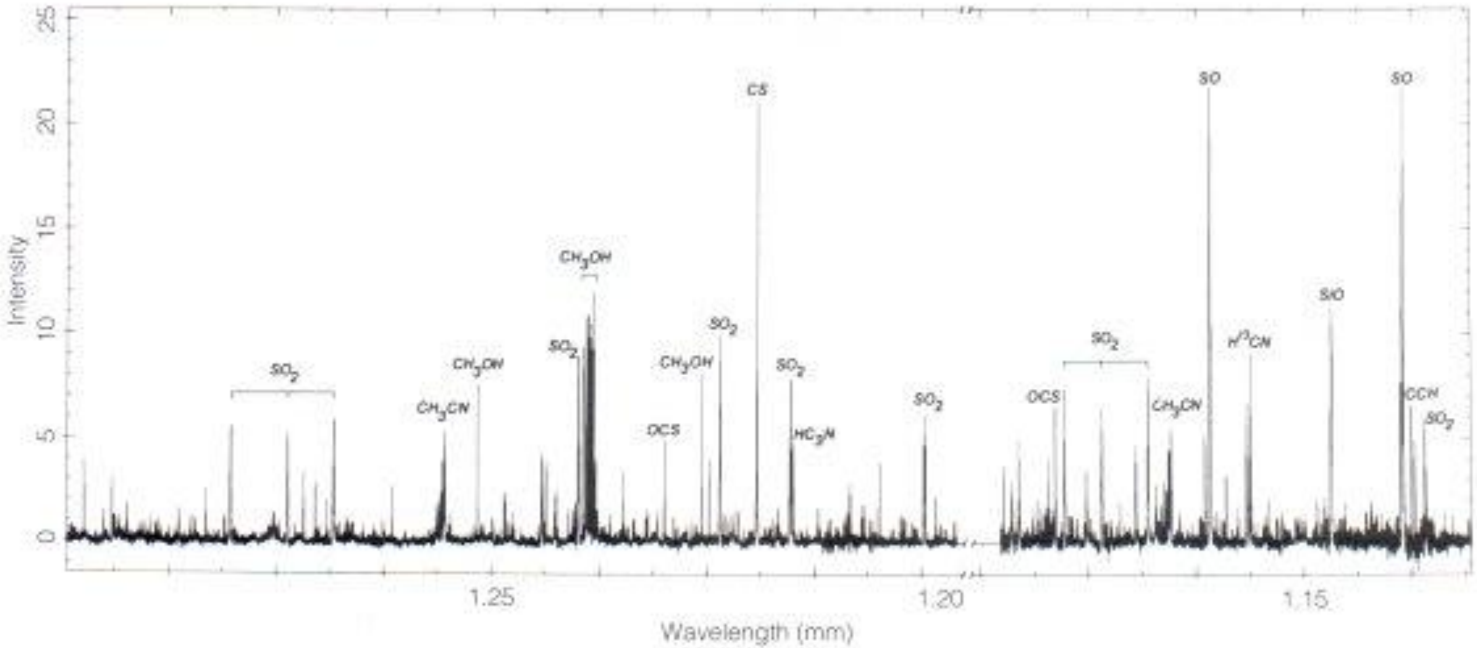
15–100 pc

~10^5–10^6 $M_\odot$

~200 H_2 molecules cm^{-3}

Complexity	**Inorganic**		**Organic**	
Diatomic	H_2	**hydrogen**	CH	methylidyne radical
	OH	hydroxyl radical	CN	cyanogen radical
	SiO	silicon monoxide	CO	**carbon monoxide**
	SO	sulphur monixide	C_2	carbon
	NO	nitric oxide	CS	carbon monosulphide
Triatomic	H_2O	**water**	CCH	ethynyl radical
	H_2S	hydrogen sulphide	HCN	hydrogen **cyanide**
	SO_2	sulphur dioxide	HCO	formyl radical
4-atomic	NH_3	**ammonia**	H_2CO	**formaldehyde**
			$HNCO$	hydrocyanic acid
			H_2CS	thioformaldehyde
5-atomic			CH_4	**methane**
			$HCOOH$	**formic acid**
…			…	…
13-atomic			$HC_{11}N$	cyanopentaacetylene


25
20
15
10
5
0
Intensity
HC3N
H2CO
SO2
29SiO
SO
34SO
SiO
H2CO
CH3OH
OCS
C18O
SO
13CO
CH3CN
SO2
SO2
H2CO
SO2
CN
CN
CH3OH
CO
OCS
1.40
1.35
1.30
Wavelength (mm)

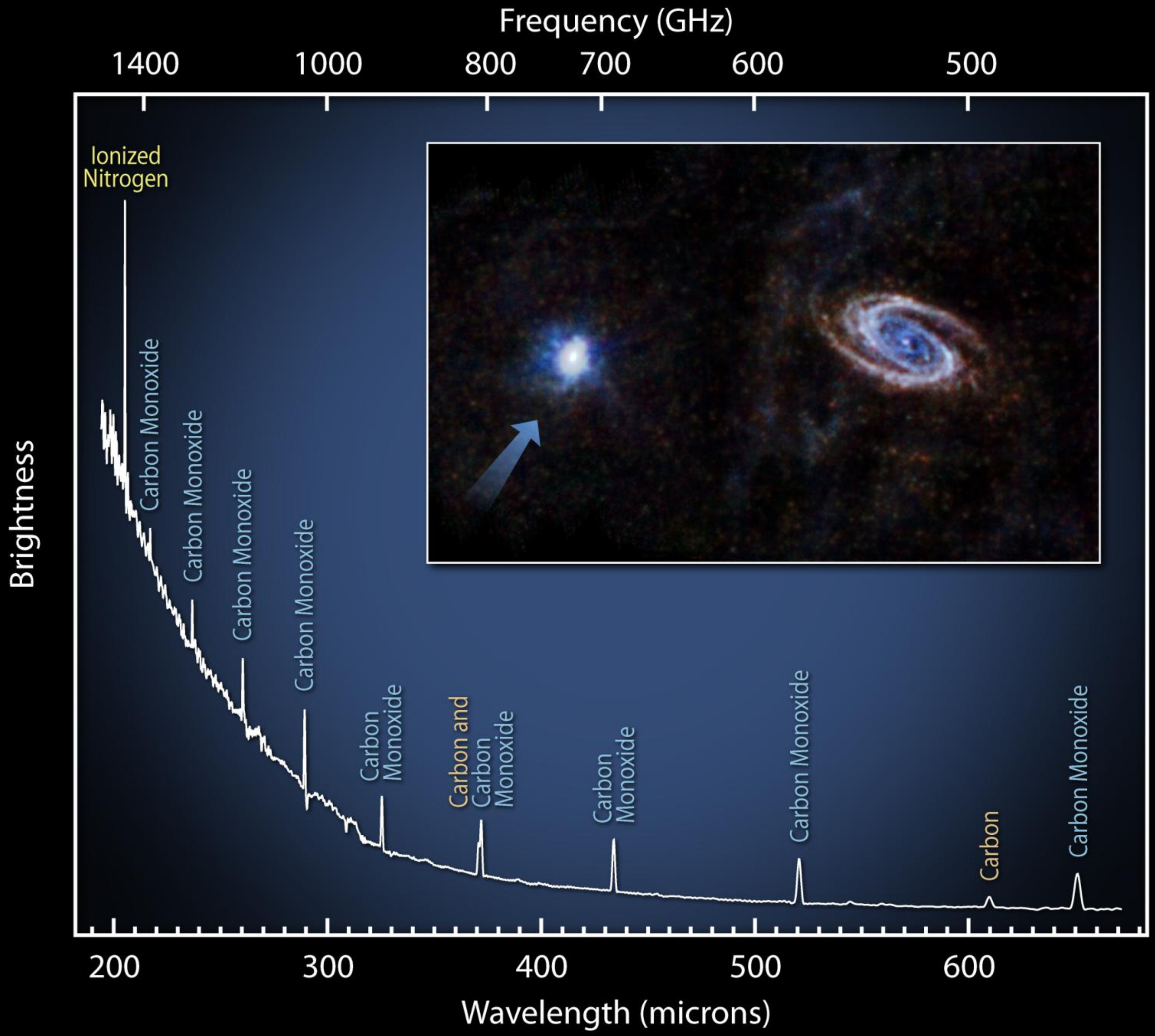

25
20
15
10
5
0
Intensity
SO2
CH3CN
CH3OH
SO2
CH3OH
OCS
CH3OH
SO2
CS
SO2
HC3N
SO2
OCS
SO2
CH3CN
SO
H13CN
SiO
SO
CCH
SO2
1.25
1.20
1.15
Wavelength (mm)

The Galaxy contains ~5000 GMCs

GMCs are mostly found within the spiral arms of the Galaxy, and are spaced out along a given arm by ~1000pc.

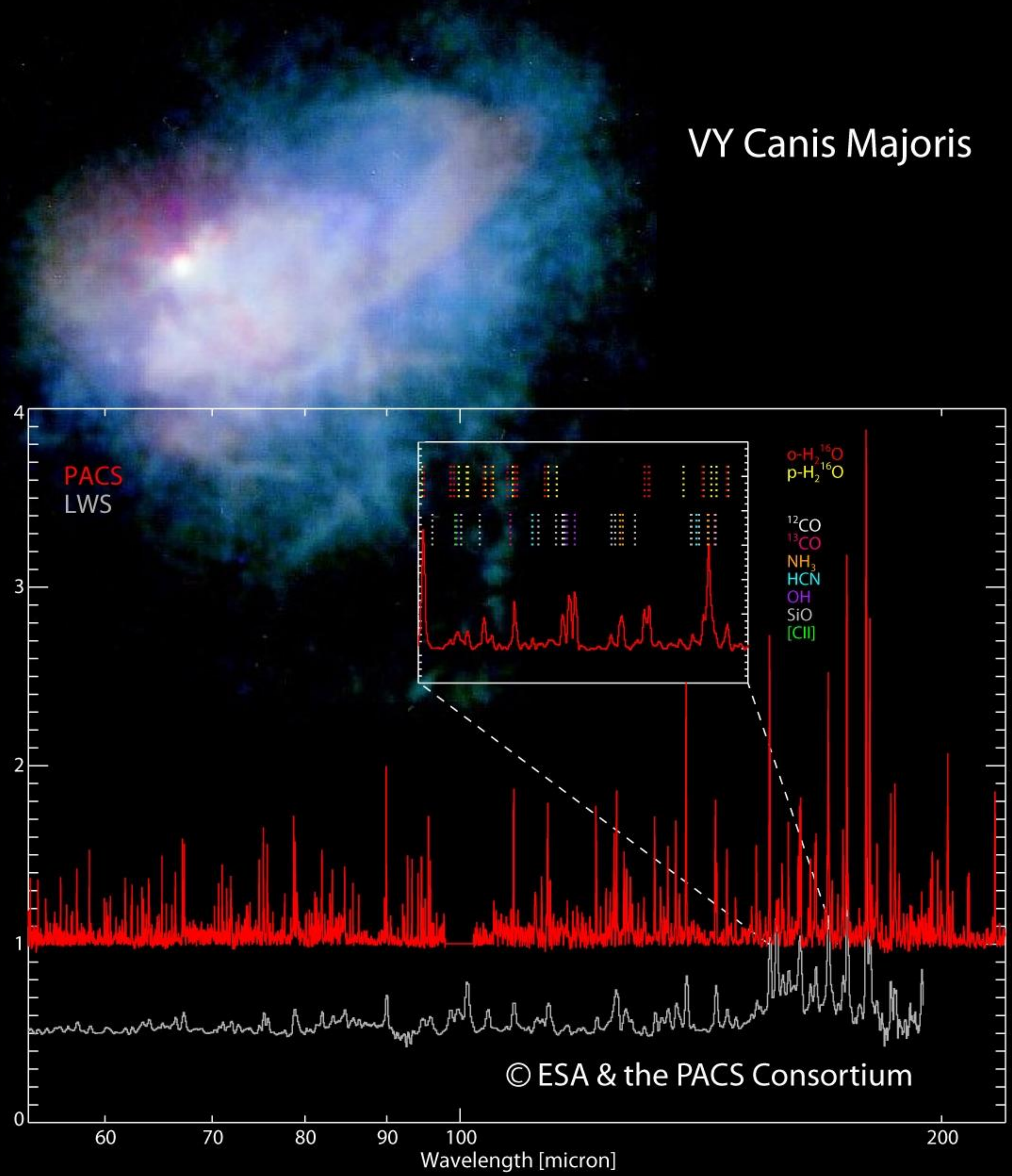
This resembles the distribution of HII Regions in external face-on spiral galaxies

GMCs are therefore clearly associated with Star Formation (since HII Regions are where young stars are found)


Frequency (GHz)
1400
1000
800
700
600
500
Ionized Nitrogen
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon and Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon
Carbon Monoxide
Brightness
200
300
400
500
600
Wavelength (microns)

Messier 82

VY Canis Majoris



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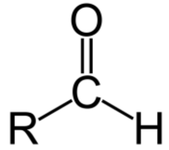
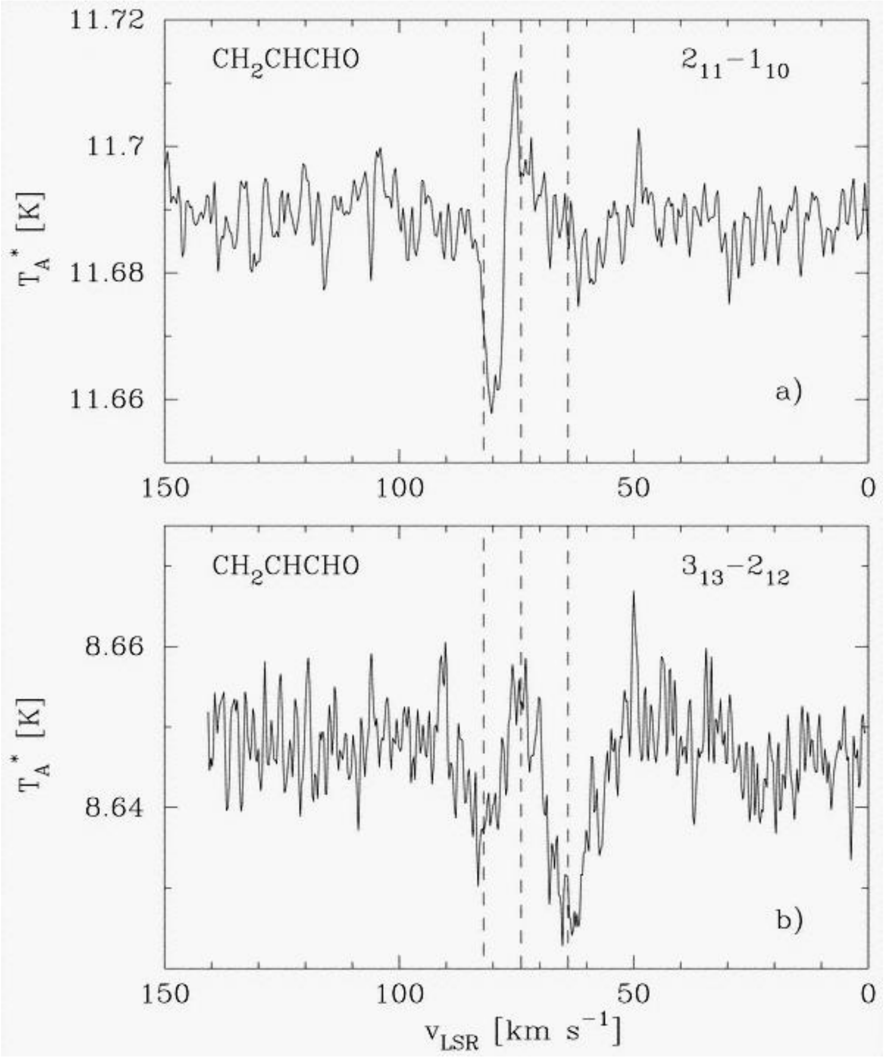
Complex Molecules

NaCl	salt
$CH_3 CH_2OH$	alcohol
$HOCH_2CH_2OH$	anti-freeze
CH_2OHCHO	simple sugars
$(CH_3)_2CO$	acetone
NH_2CH_2COOH	glycine (not confirmed)
	amino acids??

Aminoacids are the building blocks of *proteins*: life in interstellar space??

Glycolaldehyde (in absorption!)



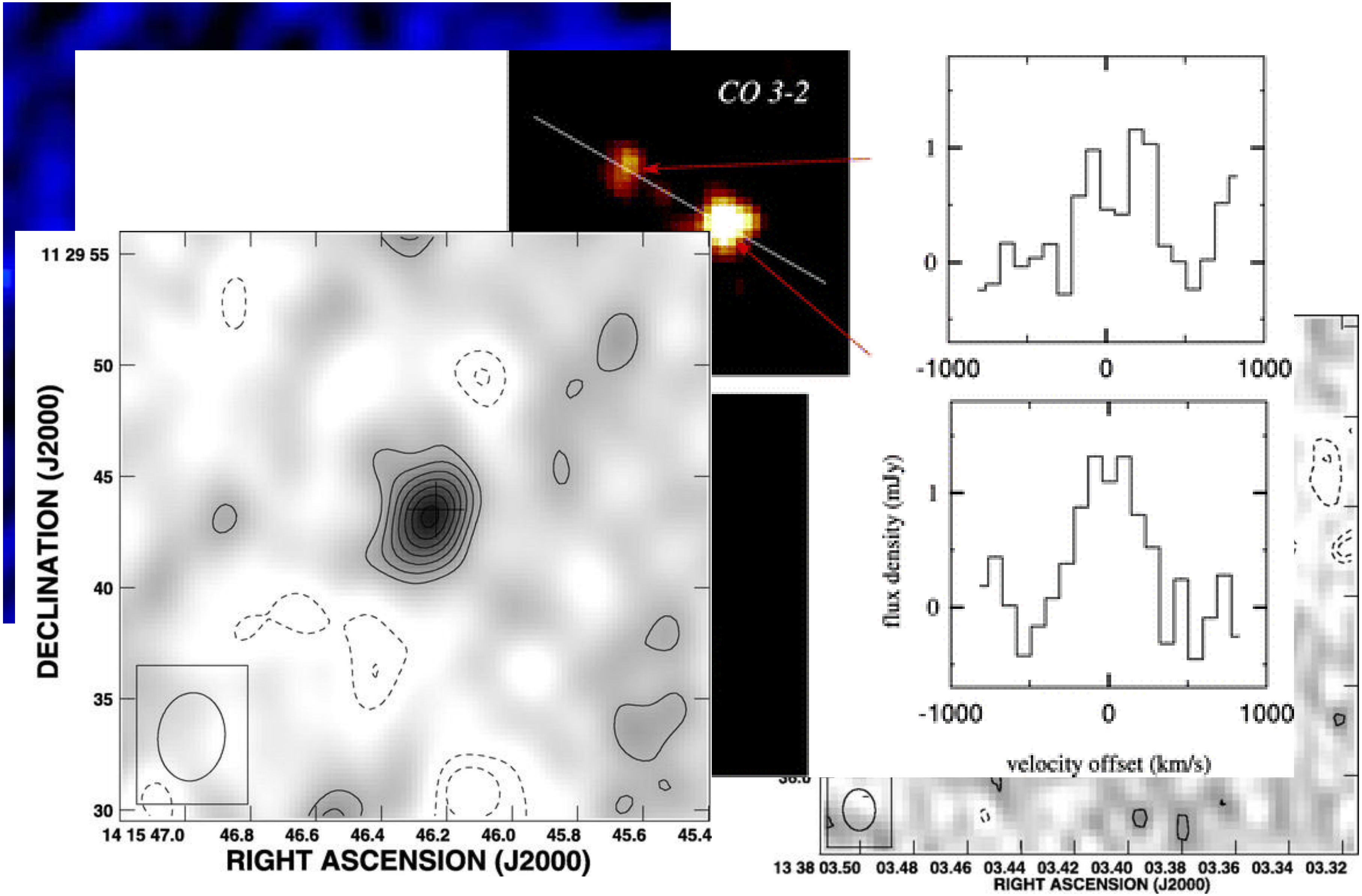


Aldehydes (e.g., *propenal & propanal*): absorption lines in the star-forming region Sgr B2 ("hot core" source):

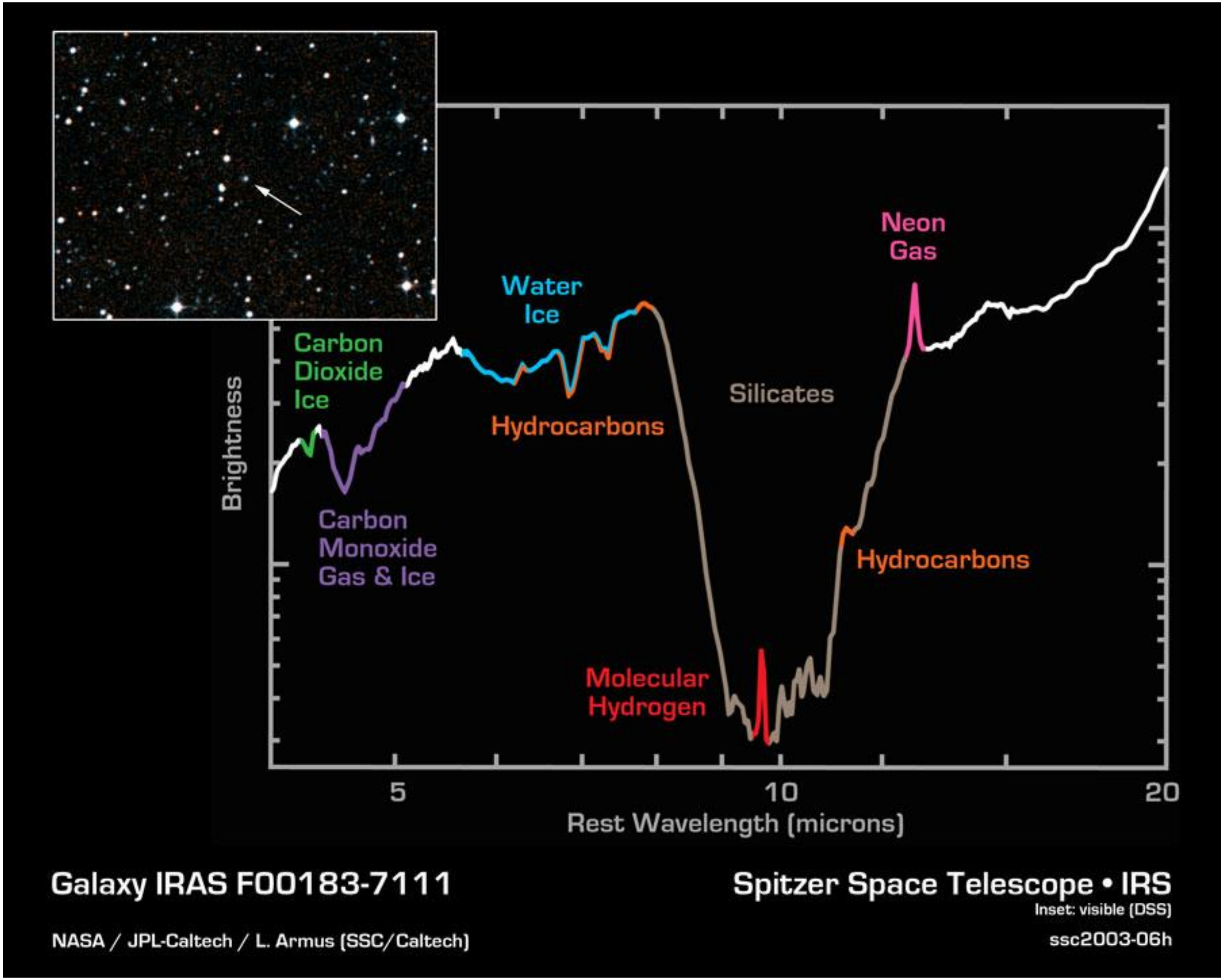
Complex chemistry can take place on dust grain surface
Protostar ➔ irradiation (heating) of dust grains ➔ chemicals evaporating off into gas phase

cm-wave obs with a 100m antenna (GBT)
(Hollis et al., 2004, ApJ 610, L21-L24)

Molecules at high-*z*



AGN: IRAS F00183-7111



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Phil Plait -- @badastronomer on Twitter