Following the Path of Metals From Galaxies to Habitable Planets

Alexandria – March 2006 – lecture 1

Metals in Galactic Ecology

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or … Journeys through the Galactic swamp

There are twists in the trail, dangerous bends, detours, misleading signposts, dead-ends, …

"The universe on a small scale is far from simple" *(*from the Chandra observatory outreach page.)

Galactic ecology

The precise way in which each level of structure – galaxies, stars, planets and life – is formed and evolves depends upon its elemental constituents.

And of course a lot more… → **ecosystem**

- supply of material, transport, sinks
- energy and momentum
- physical conditions
- feedback, interactions, inter-relationships

The role of metals? Effects of metallicity?

Metals

“Metals” is astronomy refers to virtually anything that is not H or He. By cosmic abundance standards, important ones are C, N, O and Si, Mg, Fe.

These metals are what make the interesting molecules and dust particles in interstellar space – and terrestrial planets, and us.

Dust is a major repository of the metals, so much so that if one looks in the gas phase, one notices a severe “depletion” of the elements (compared to some cosmic standard …).

Individual dust particles (grains) are 0.1 micron in size or smaller.

But do not forget Hydrogen

Most of the mass in the interstellar medium (ISM), and therefore in stars that form from the ISM material, is hydrogen. Metals in total are only about 1 %.

Hydrogen and Helium (10% by number) were formed during the first three minutes of the Big Bang. Metals were not. They formed by nucleosynthesis in stars and were ejected into the ISM.

The fact that there is still Hydrogen left in the ISM of our Milky Way Galaxy tells us that:

- Star formation is not 100% efficient
- Stars return Hydrogen to the ISM

Detecting various forms of H

ATOMIC

In the diffuse ISM, H is in atomic form and quite cold (80 K).

It is seen in emission in the radio-wave 21-cm line (1420 MHz) – flip of the spin orientation of the electron with respect to the proton produces this tiny energy difference.

It can also be seen in absorption via the electronic transitions from n=1, called the Lyman lines. Unlike the Balmer lines (n=2), these are in the ultraviolet. This method of detection is less general since it requires a background star, one which is hot enough to have an ultraviolet continuum. Plus an observatory in space.

Detecting various forms of H

MOLECULAR

In more dense regions of the interstellar medium, H is in molecular form, H_2. The molecules are thought to form by recombination of atoms on the surfaces of dust grains (which are formed of metals – we'll get back to them!).

1. Quadrupole transitions

In the ground electronic state, even the first rotational state is hard to excite: the excitation temperature is more than 100 K compared to the gas kinetic temperature of only 10 K in the molecular clouds. → Need to rely on tracer molecules like CO and OH.

Shock heated gas, and ultraviolet fluorescence (hot stars), provide special cases, in which the ro-vibrational emission is seen.

Orion nebula and OMC1

This is a "false colour" image, made from filtered infrared images (ESO).

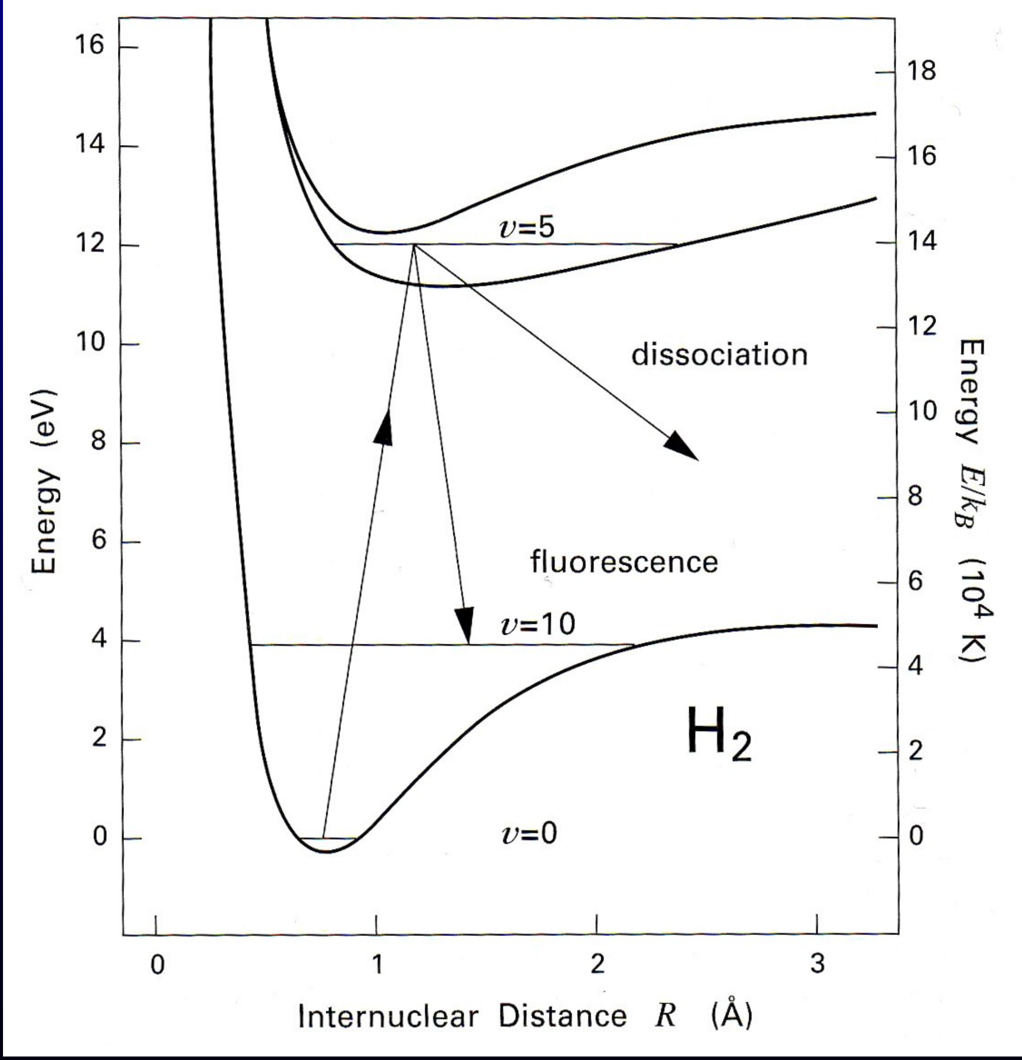
Red hue is from shock-excited H_2

Detecting various forms of H

MOLECULAR (continued)

2. H_2 can be detected by its electronic transitions in the ultraviolet, the Lyman and Werner bands (band structure owing to rotational and vibrational states). Need hot star in background.

Note that these transitions are what destroy and protect H_2.



Detecting various forms of H

IONIZED (H^+ or H II)
Where the gas is ionized (to which we shall return), there are two powerful ways to see the gas:

1. Free-free (or Bremstrahlung) radiation

This is continuum radiation produced as an electron is accelerated in a near collision with a proton. Because the kinetic temperature is quite hot (8000 K), this continues from the radio region of the spectrum right up to the optical.

In hotter shocked-heated plasma at nearly 10^6 K, soft X-ray emission is seen.

Detecting various forms of H

IONIZED (continued)

2. Recombination lines

When the electron actually recombines with the proton, it usually ends up in an excited electronic state. The subsequent cascade toward the ground state is effected by a series of line emissions.

The most famous for astronomers is H (n=3 to n=2), which is a red line at 6563 Å (656 nm) and so readily observed from ground-based observatories.

NGC 6888

WR shell

The red hue is from H

Phases of the ISM

All of these coexist, in near pressure equilibrium.

Table 2.2 Phases of the Interstellar Medium

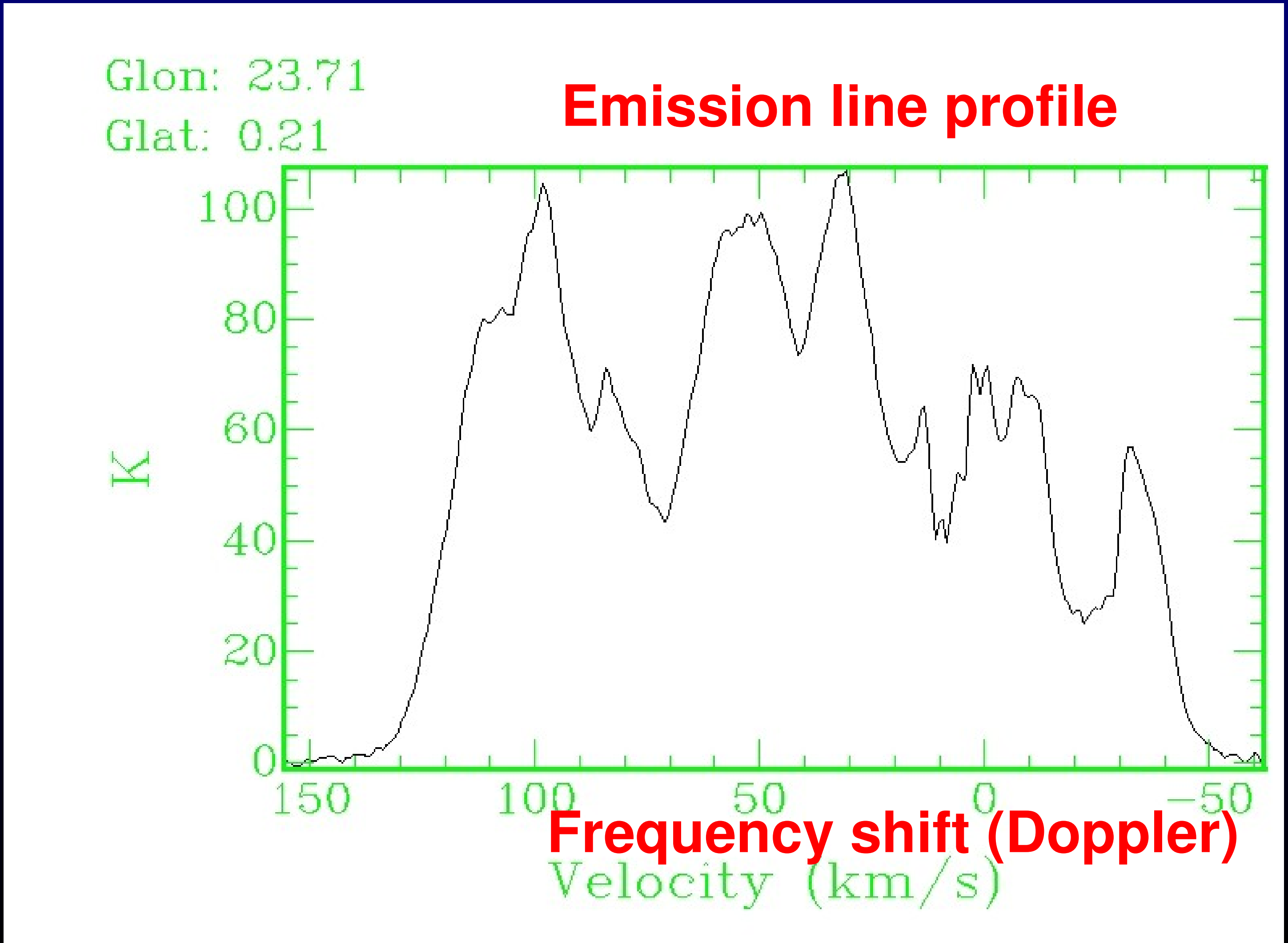
Phase	n_{tot} (cm^{-3})	T (K)	M ($10^9\ M_\odot$)	f
molecular	> 300	10	2.0	0.01
cold neutral	50	80	3.0	0.04
warm neutral	0.5	8×10^3	4.0	0.30
warm ionized	0.3	8×10^3	1.0	0.15
hot ionized	3×10^{-3}	5×10^5	–	0.50

f is the volume filling factor.

from Stahler and Palla

How is T measured?

One example, for cold atomic hydrogen (80 K).



How is T measured? (cont.)

Emissivity of the 21-cm line is independent of T, the kinetic temperature. The integral over the profile gives us N_H, the column density for that line of sight (also a route to n_H).

The profile tells us the radial velocity of the gas. Use the Doppler width from Brownian motion? No, much narrower than the peaks seen (usually).

The extra broadening comes from

- turbulent motions of order 10 km/s.
- differential Galactic rotation.

How is T measured? (cont.)

Emissivity of the 21-cm line is independent of T.

Kirchhoff's law tells us that absorptivity κ and are related by the Planck function, B_ν (T):

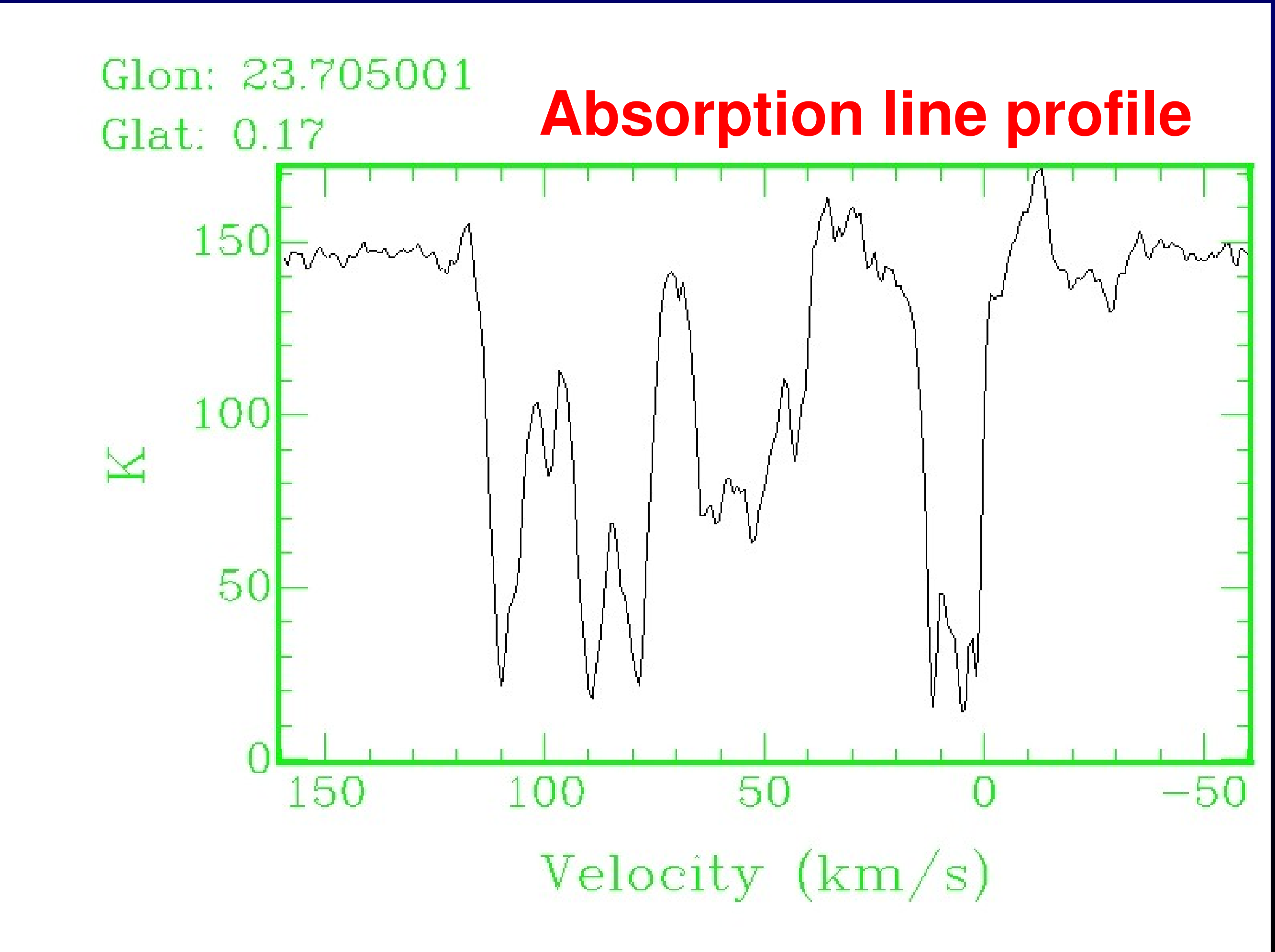
κ = /B(T) 1/T .

Cold gas absorbs much more strongly than warm gas, giving a way of measuring T if both emission and absorption profiles can be obtained.

Requires a strong radio continuum (point) source, against which the foreground H I absorbs, plus emission measured on adjacent patches of sky.

How is T measured?

H I which is detected in emission but does not absorb strongly indicates a warm (8000 K) phase too.



Star formation

Stars are self-gravitating objects, held up in equilibrium by their internal pressure which is maintained by nuclear fusion in (near) the core.

Most of the structures in the ISM are not self-gravitating; instead they are pressure confined and pressure supported.

But there must be a transition; if enough mass is packed into a small enough volume, then self-gravity will indeed be overwhelming.

We don’t fully understand how this packing occurs, but we can estimate the scale.

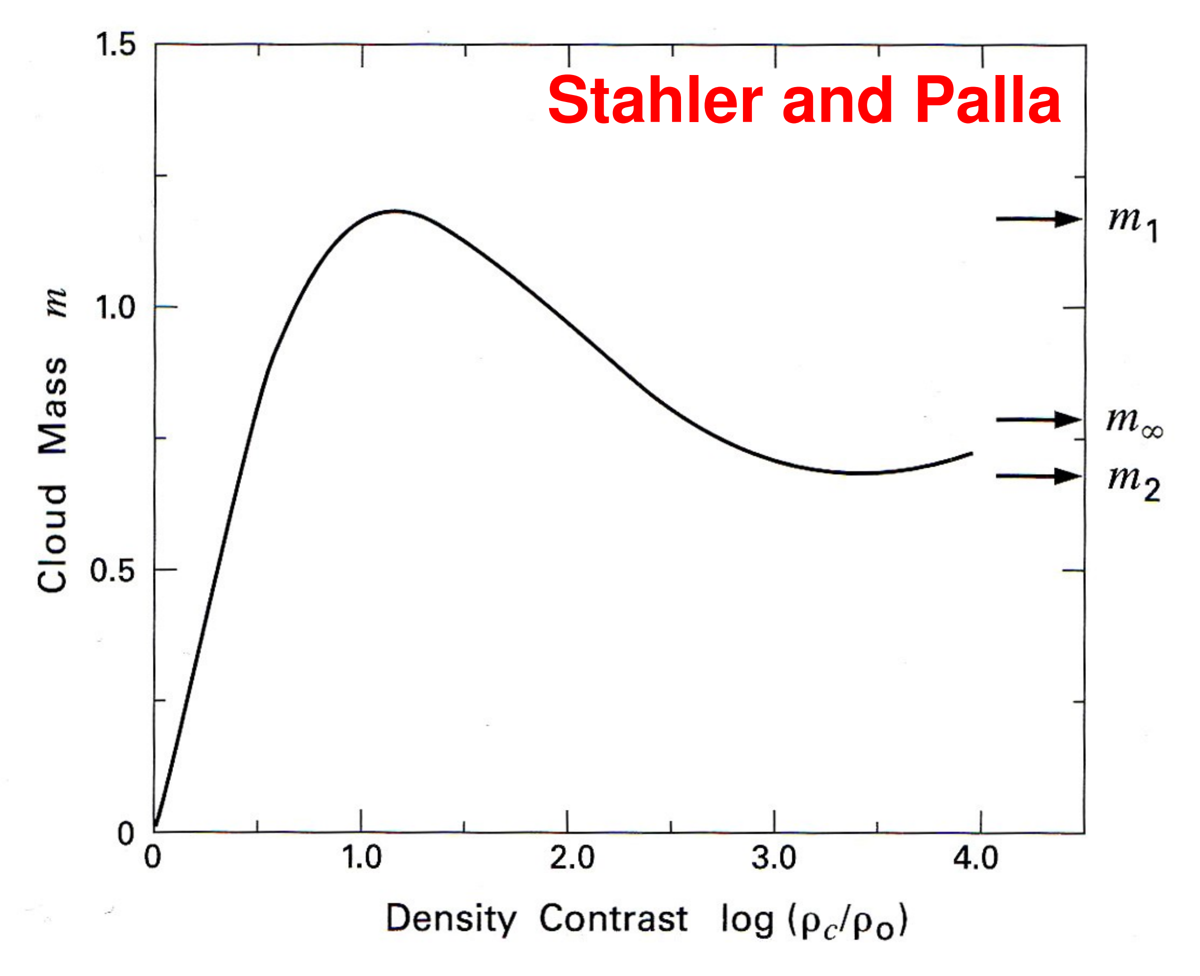
Gravitational instability

There are two theoretical approaches (in addition there is treatment of the instability of a disk, not presented here)

1. Bonner-Ebert spheres

Here one works out the hydrostatic equilibrium structure of a spherical cloud in a confining medium at the same temperature (isothermal approximation).

There is a family of solutions: the more massive the cloud (adding to the gravitational attraction), the higher the central density (adding to the internal pressure).



The low-mass clouds are stable, but beyond the peak (m_1=1.18), the clouds become dynamically unstable to the first or fundamental "breathing" mode and will collapse. This critical mass is the Bonner-Ebert mass.

Gravitational instability

2. Jean's analysis

Here, again for isothermal gas, of density ρ_0, one works out the "dispersion relation"

$$\omega^2 = k^2 a_T^2 - 4\pi G \rho_0 ,$$

where ω is the frequency of the travelling wave and k is the wavenumber. For large k (small spatial scales) this simply describes sound waves traveling at phase velocity ω/k equal to the isothermal sound speed a_T, where $a_T^2 = \mathcal{R} T/\mu$.

But above some critical size (small k where ω =0), the Jean's length λ_J, the disturbances are unstable to gravitational collapse.

Gravitational instability scales

λ_J = 76 pc $(T/80\ K)^{1/2}(n_H/1\ cm^{-3})^{-1/2}$. (~< scale height)

$M_J = M_{BE}$ = 3200 M_{Sun} $(T/80\ K)^{3/2}(n_H/1\ cm^{-3})^{-1/2}$.

Since average n_H is only 1 cm^{-3} in the ISM, only rather large structures, not star mass clouds, are unstable. Comparable to what are now molecular clouds.

Table 3.1 Physical Properties of Molecular Clouds

Cloud Type	A_V (mag)	n_{tot} (cm^{-3})	L (pc)	T (K)	M ($M_\odot$)	Examples
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Complexes	5	500	10	10	10^4	Taurus-Auriga
Individual	10	10^3	2	10	30	B1
Dense Cores/Bok Globules	10	10^4	0.1	10	10	TMC–1/B335

Stahler and Palla

Reality: added complexity

As the density increases, often accompanied by a decrease in T as the gas becomes molecular, both critical quantities decrease, meaning that smaller and smaller structures become unstable. This leads to the concept of fragmentation.

Given the measured strength of the interstellar magnetic field (a few μ Gauss or stronger), an important stabilizing influence is the magnetic pressure, which was not included in this simple estimate. The field couples to the neutral gas via a trace ionized fraction.

There is also turbulent pressure, cosmic ray pressure, and rotation… → a complex and dynamical situation requiring numerical modeling.

Temperature: roles of metals

One of the key factors above is the equilibrium T of the gas. This is a balance between heating and cooling. Both involve metals. Why is T = 80 K?

Heating comes from photoelectric emission by small dust particles (or large molecules). The energetic photoelectron shares its energy with the gas, through collisions.

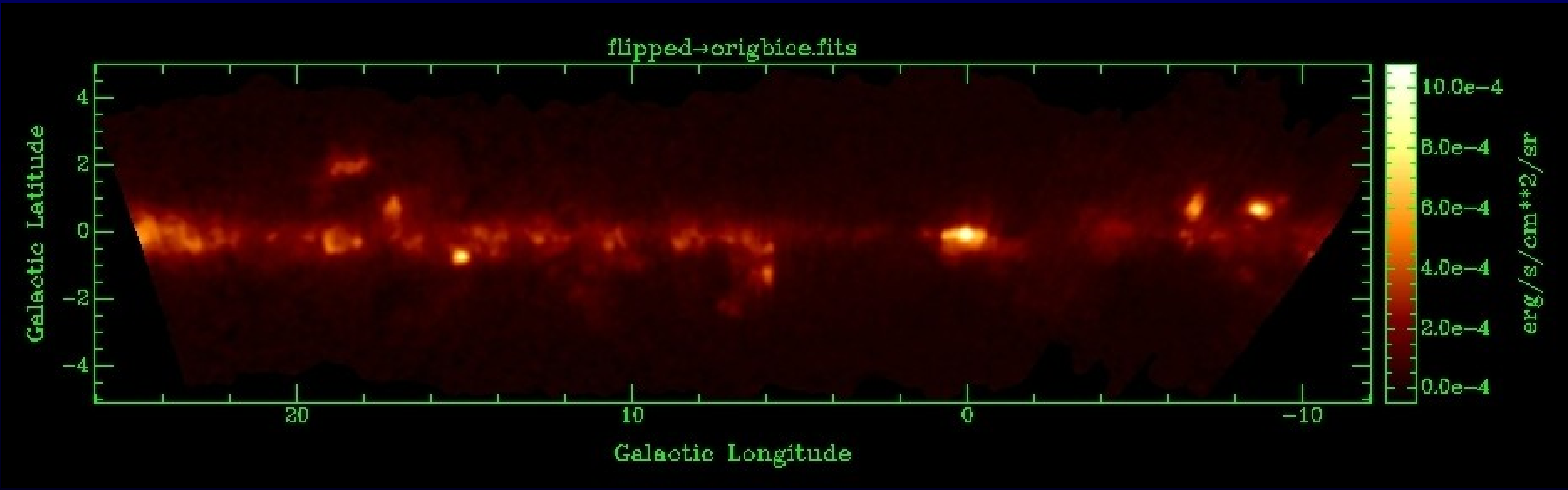
Cooling comes from collisional excitation of "metals" – atoms or ions. Energy is taken from kinetic energy into internal energy of the atom/ion, which subsequently radiates this away.

Cooling and heating of the neutral ISM: importance of C

Main coolant for 80 K neutral interstellar gas is C^+ 157 micron fine-structure line in the far infrared. Note that this has a low enough energy to be collisionally excited at low kinetic temperature, but it can't take the gas down to 10 K.

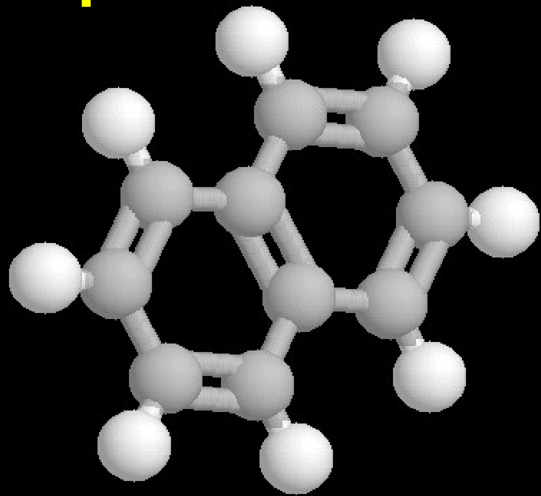
Watching the Milky Way cool

C+ emission was mapped by FIRAS but the best resolution so far in large area maps is this from BICE (15').

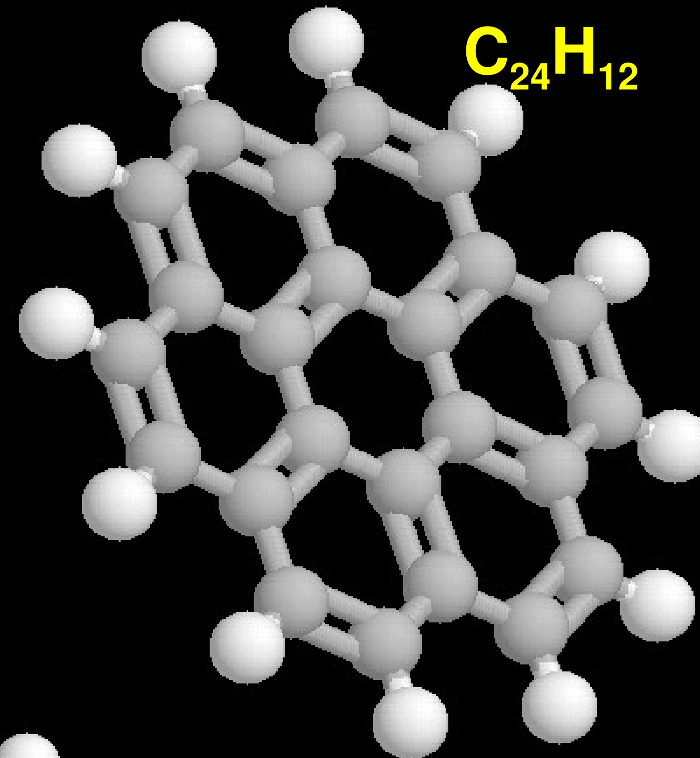


PAHs (simple ones)

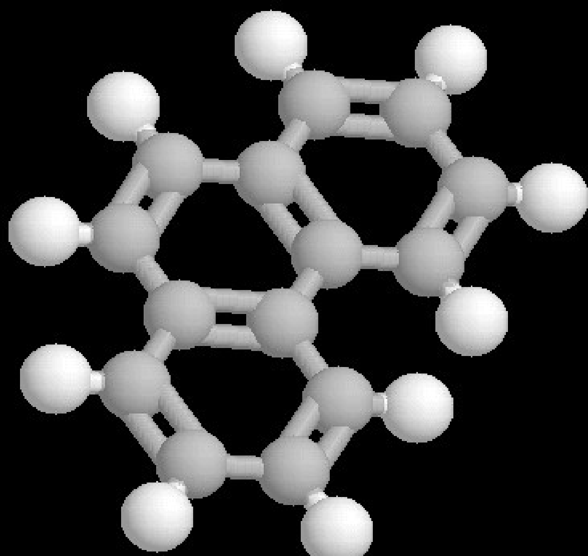
Naphthalene



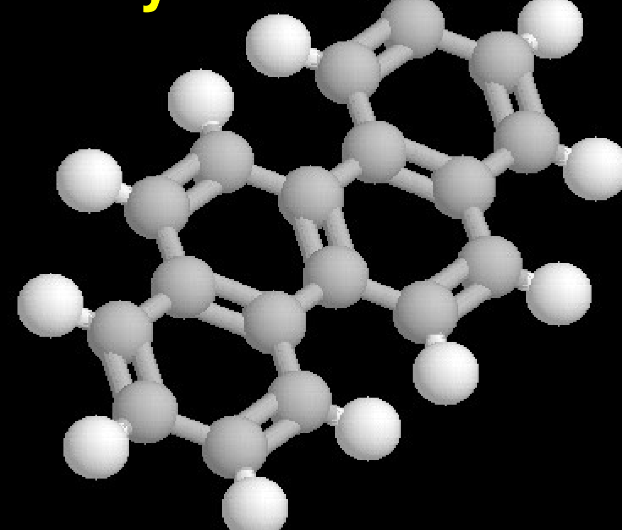
Coronene
$C_{24}H_{12}$



Phenanthrene

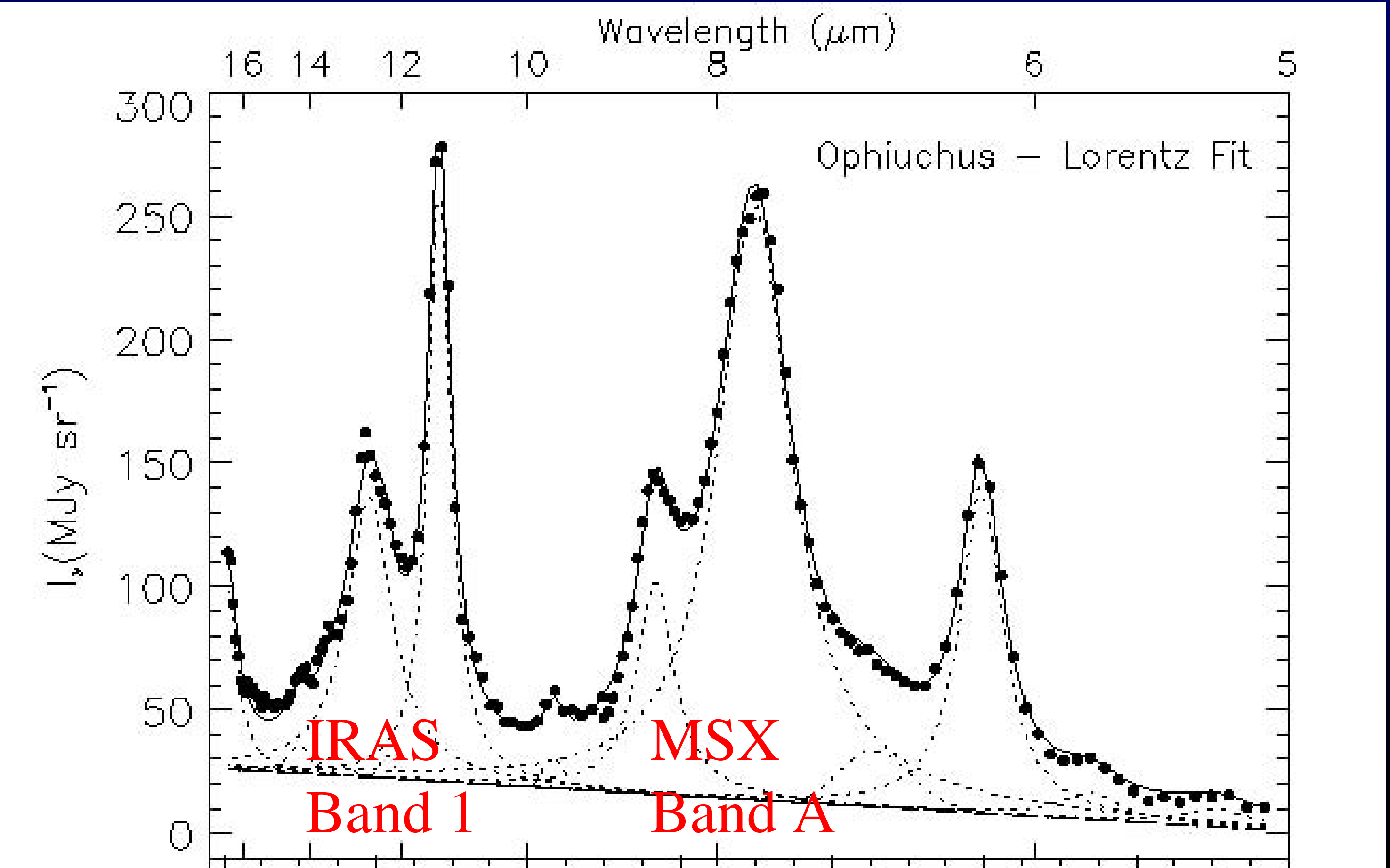


Chrysene



PAH mid-infrared spectrum

Common emission spectrum appears in many ISM environments, from diffuse cirrus to dense reflection nebulae (also a 3.3 micron emission feature).



PAH model

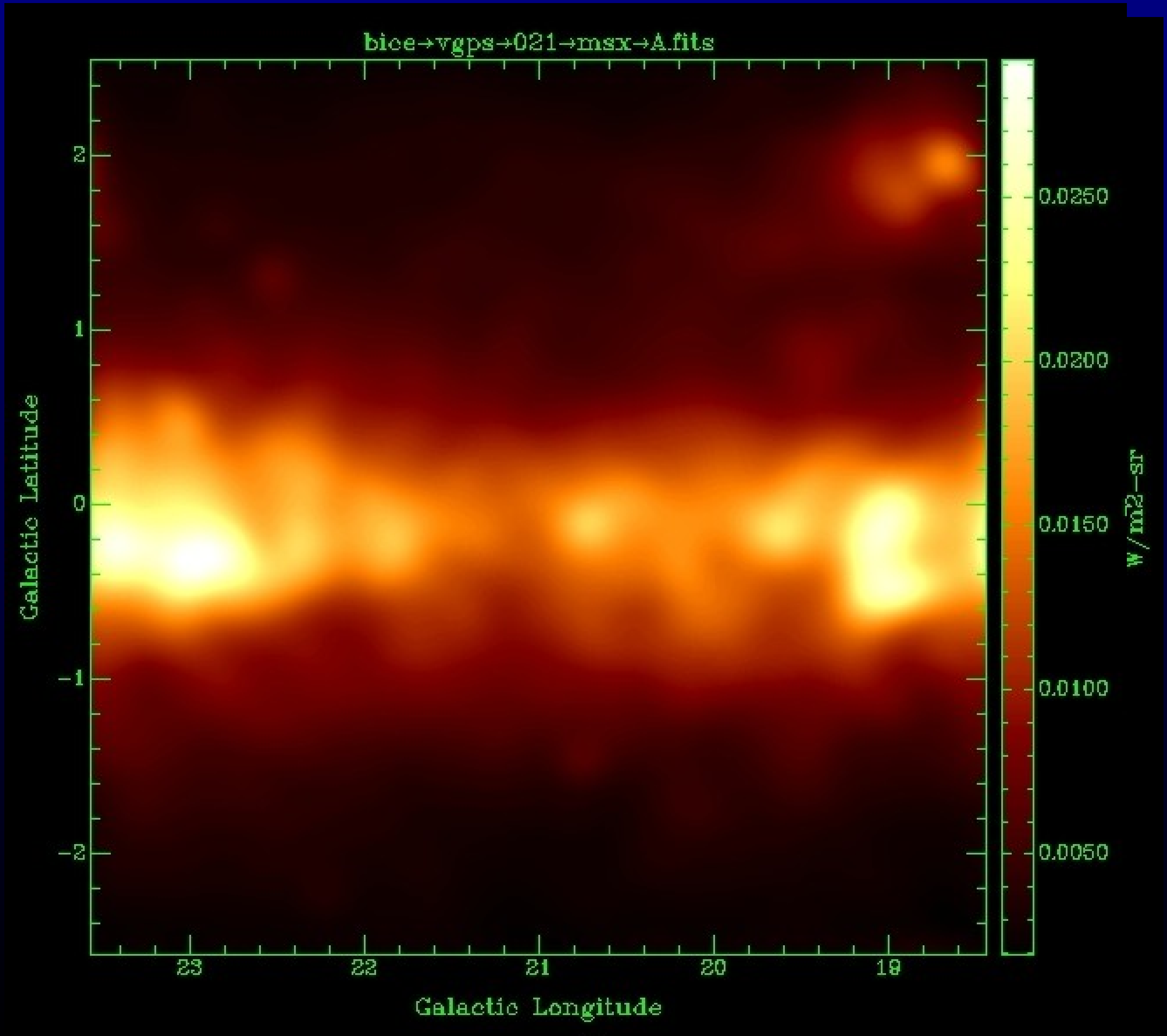
- emission features well fit by Lorentz profiles; pseudo-continuum from overlapping Lorentz profiles plus an underlying continuum.

- emission excited by single sub-ionizing UV photons. Narrow UV absorption signatures not seen (but there is a broad 2175 Å extinction feature).

- broad mid-IR features and continuum produced by particles/large molecules with a few 100 atoms, heated to several 100 K.

- 3.3 micron feature and continuum requires particles as small as 50 atoms (not much larger than coronene).

MSX band A at BICE resolution



Detects PAH

Traces heating

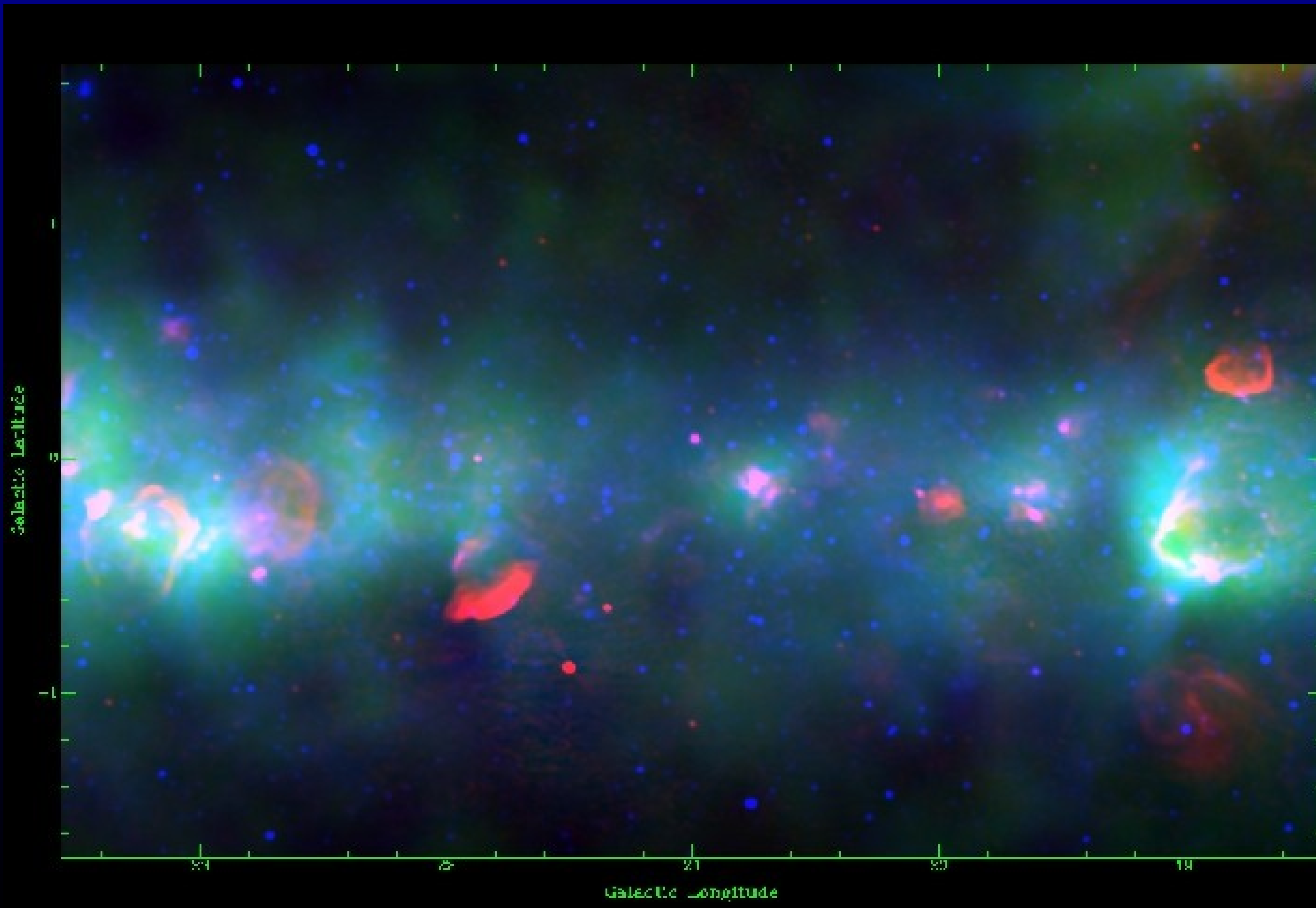
Cooling and heating of the neutral ISM: importance of C

UV photons (< 1 Ryd) cause photoelectric emission from grains. Photoemission from small particles, particularly PAHs, is favoured. → the same UV photons that excite PAH emission causes gas heating (most of energy goes into the PAH emission).

Both cooling and heating depend on C, in different forms.

Numerical models show that T near 80 K is reasonable.

Heating and cooling overlaid



Production and dispersion of metals

Seeing it happen…

Type Ia supernovae

Type II supernovae

Wolf-Rayet star winds

Massive stars and expanding HII regions

AGB stars and planetary nebulae

Supernovae type Ia

Thermonuclear explosion of a carbon-oxygen white dwarf that has accreted enough mass from a companion star to exceed the Chandrasekhar limit.

Source of Fe, about 0.6 M_sun per event
- "delayed" since low mass progenitors need to evolve

"Direct" evidence
- the observable light curve is powered by delayed energy input from the radioactive decay of ^{56}Ni and ^{56}Co (also type II)
- how much of this condenses into dust?

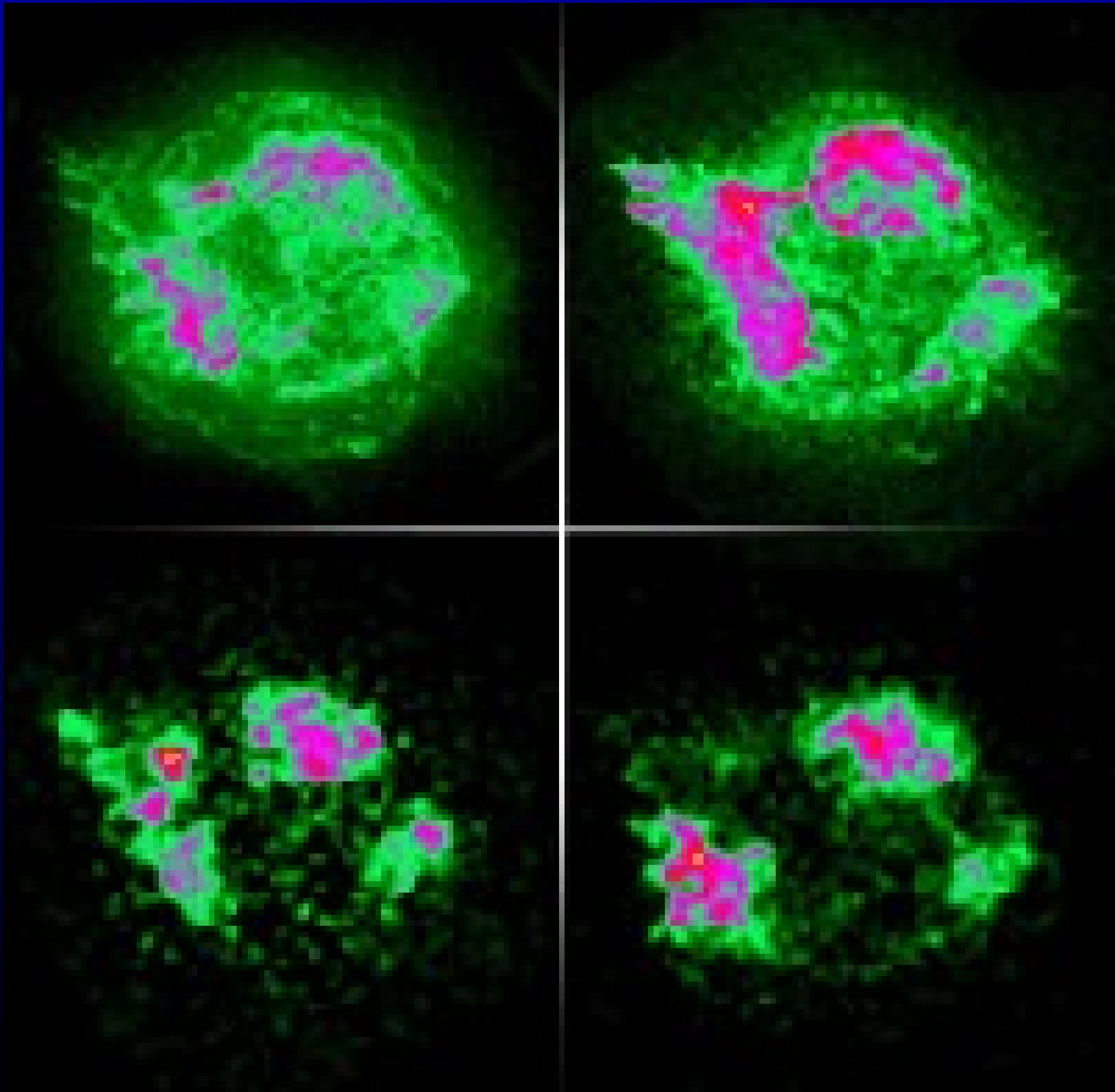
Cas A

Chandra
X-ray

BB Si
Ca Fe

Turnover
and mixing

What
fraction
condenses
into dust?

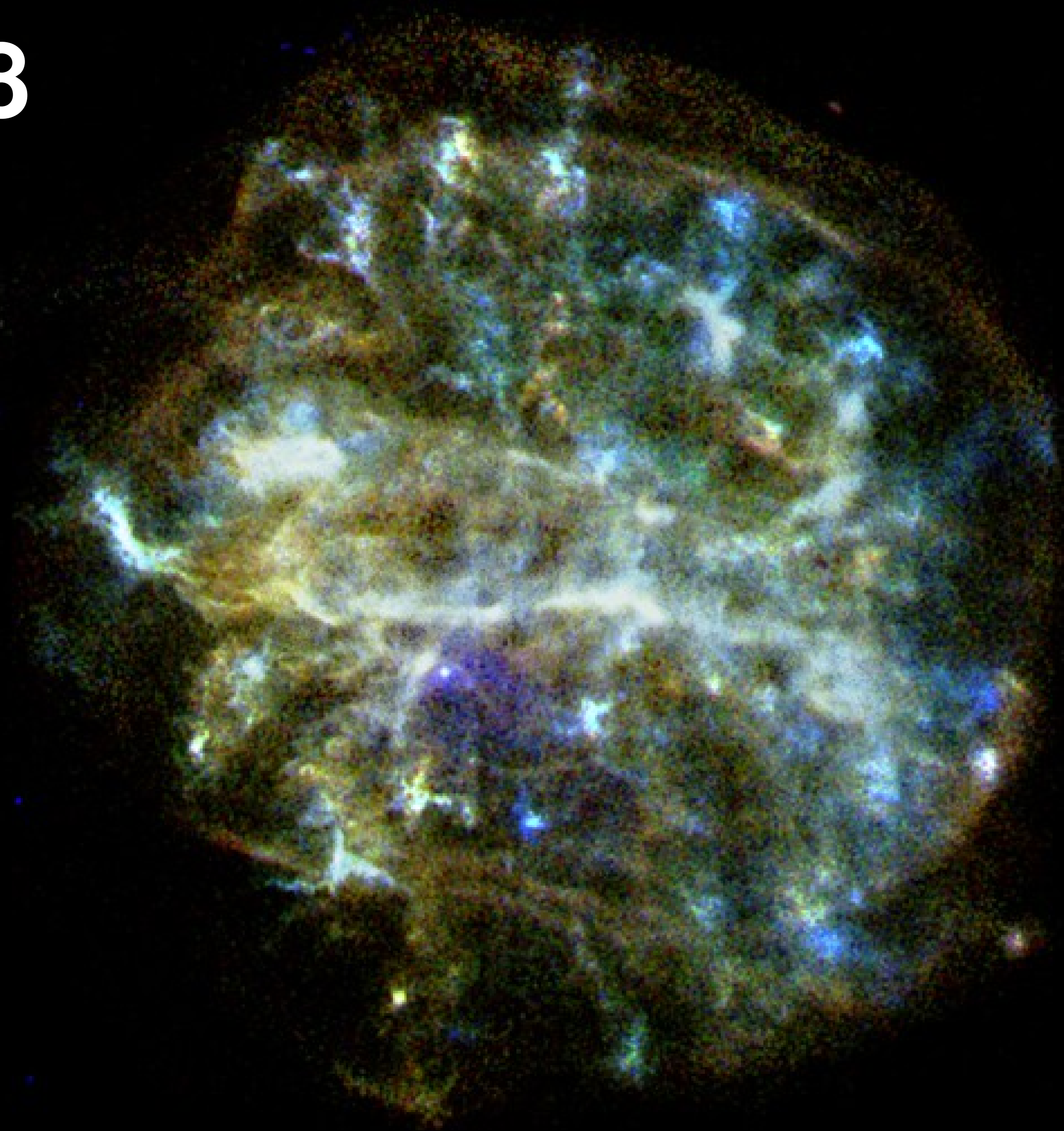


G292+1.8

O, Mg, Ne-rich knots (blue)

SN from massive star

Neutron star remnant



Massive stars

Conditioning of interstellar medium, pre supernova

Stellar winds inject momentum (rate depends on radiation pressure on metals) and chemically-enriched material (especially evident in the case of WR stars)

Hot bubbles from shocked winds

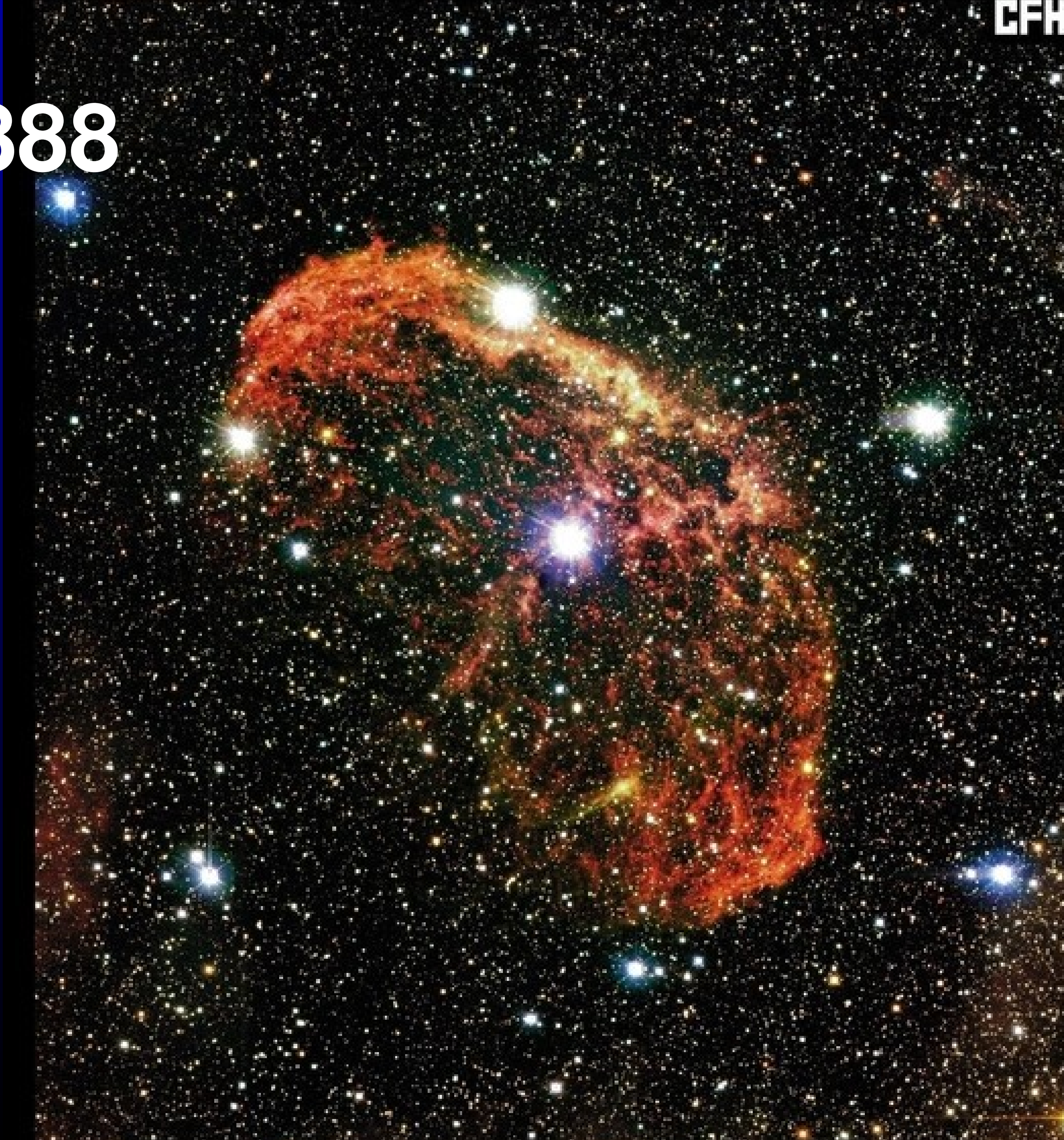
Expanding H II regions and blisters (e.g., Orion)

Chimneys: channels to the Galactic halo

NGC 6888

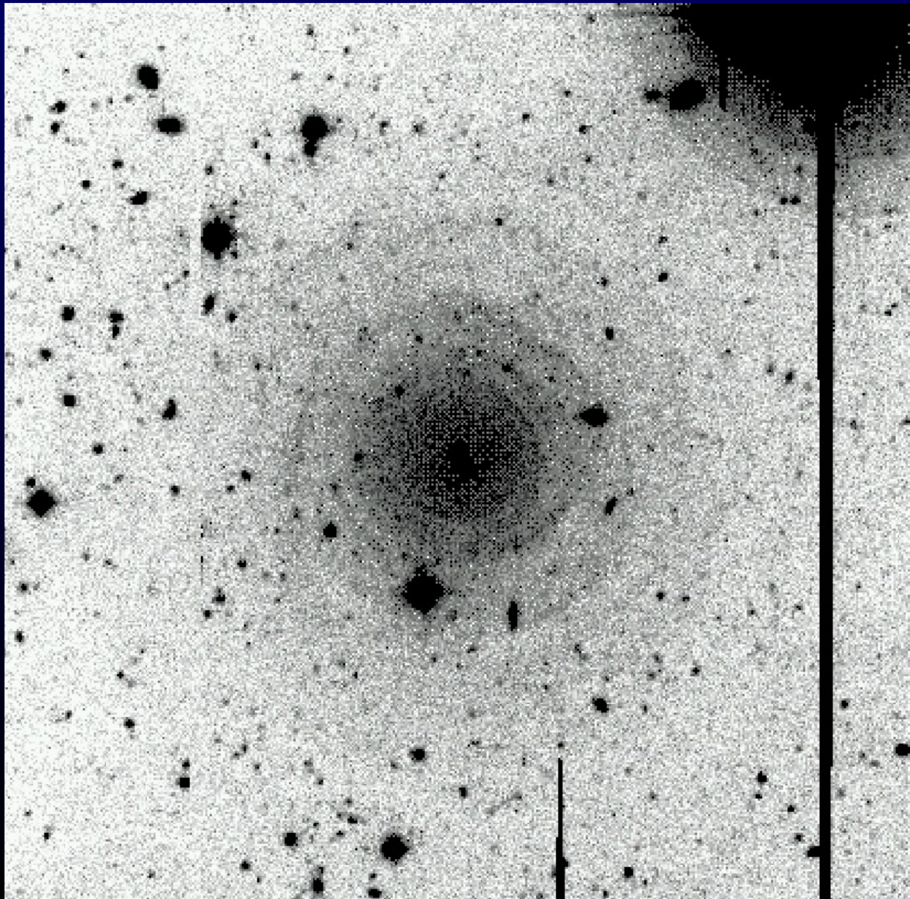
WR shell

Wind driven by radiation pressure through metal absorption lines



AGB stars

Carbon stars are injecting freshly synthesized material as molecules and carbon-rich dust. Slow wind (15 km/s) driven by radiation pressure on dust. Amorphous C and SiC dust.



8000 y history of mass loss by CW Leo (IRC+10216) as illuminated in the V band by the interstellar radiation field.

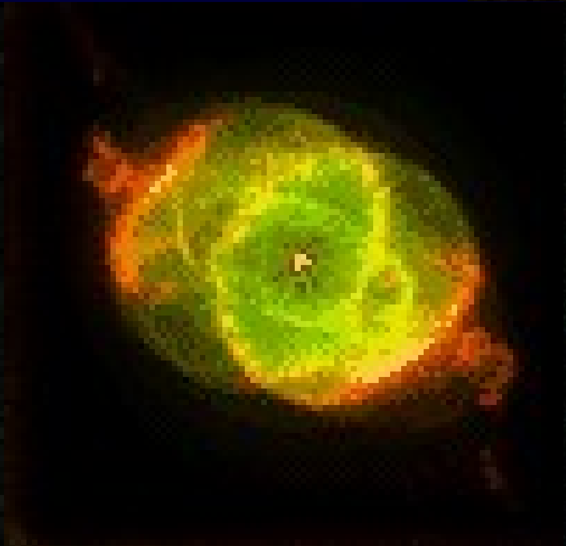
Shells from non-steady mass loss, drifting dust.

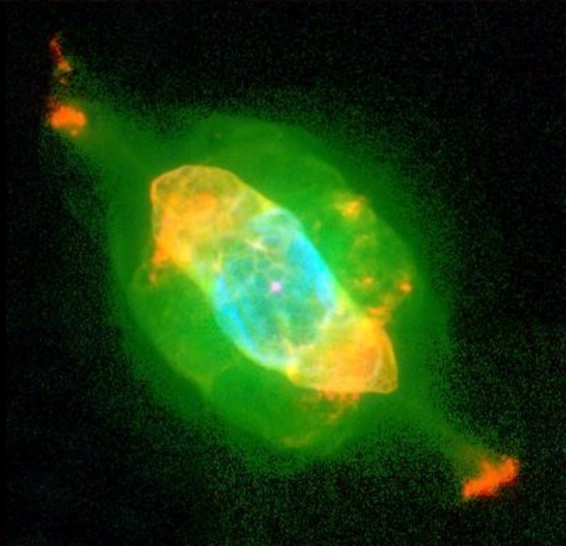
Planetary nebulae

Ionization of ejecta by hot central star. Interaction of fast wind with AGB star wind. Not spherical.

"PAH" emission

- only in carbon-rich case
- pumped by UV
- not in ionized regions



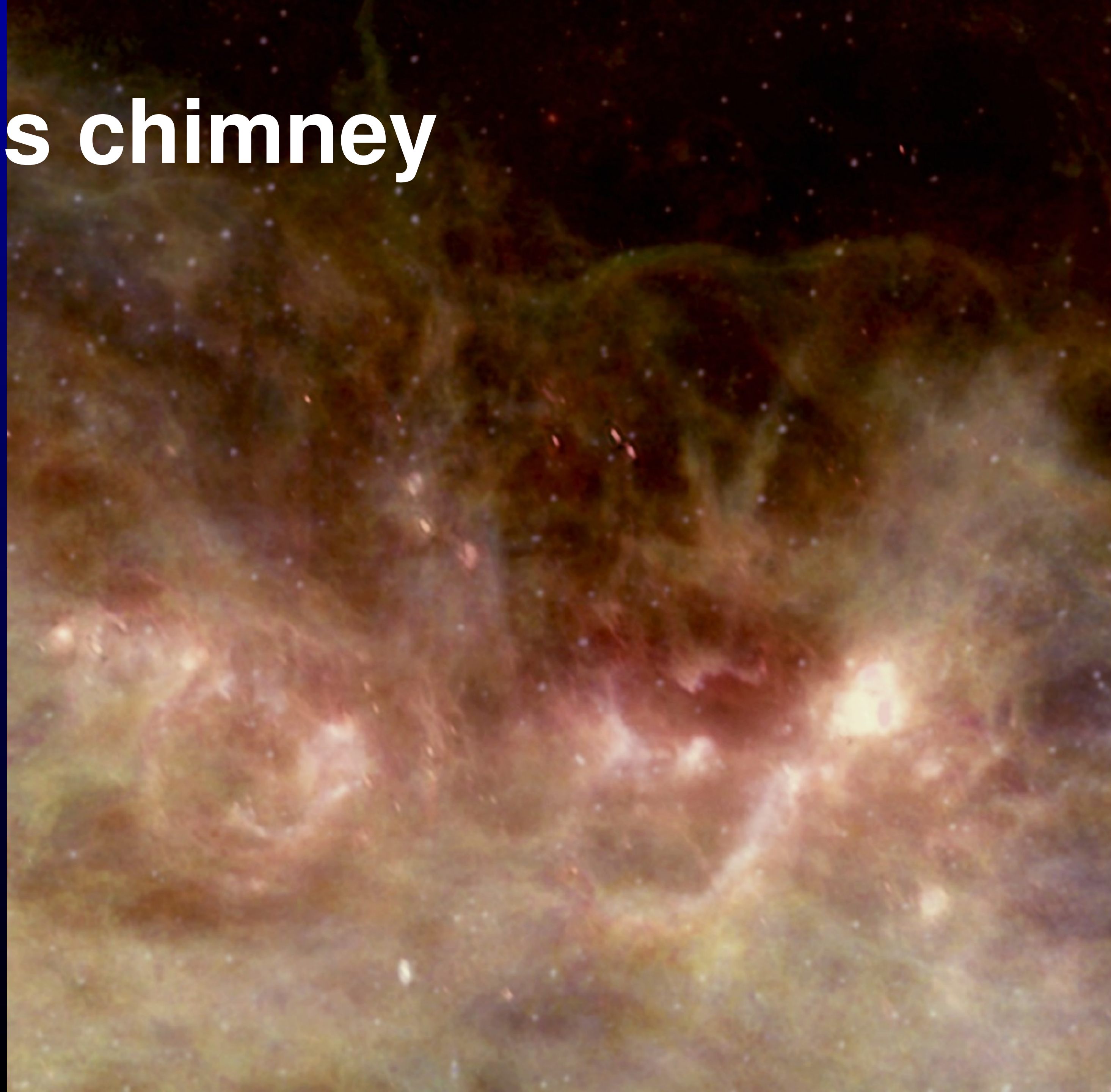


Dispersion, stirring up

There are many large scale mass motions in the ISM, some already seen, causing mixing of the elements.

This does not make the entire Galaxy have the same metallicity. Closer in to the Galactic centre than the Sun, the ISM mass and higher star formation rate have resulted in a somewhat higher metallicity.

Perseus chimney



W5, W4, W3

Passage to halo, especially ionizing radiation

Shapes environment prior to SN explosions

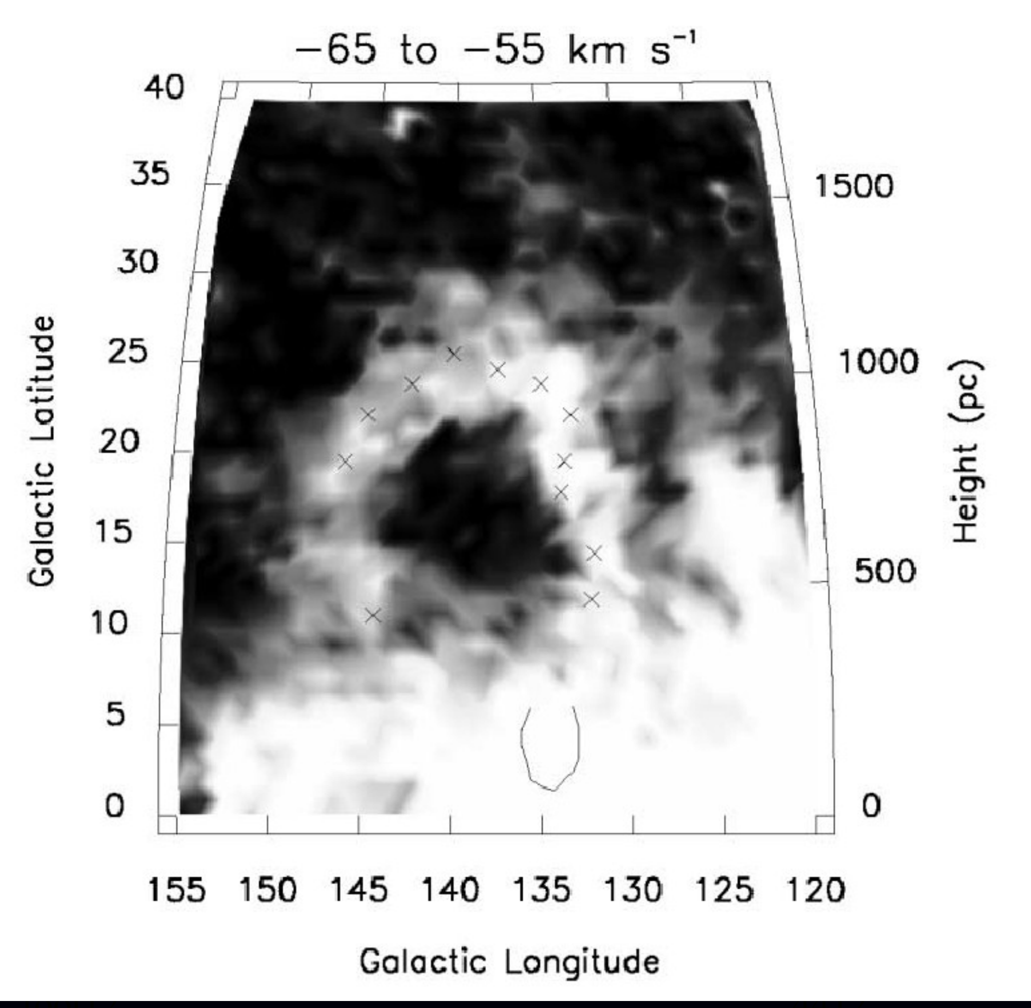
Cas OB6 arc

A 10^5 M_{sun} ionized gas "arc" is seen in H   in the WHAM survey, more or less above the Perseus chimney ("U").

Origin? Superbubble blowout into the halo?

Mass into halo.

Ionizing radiation into halo.



Halo and IGM

Intermediate velocity clouds
- normal metals, dust
- part of Galactic fountain

High velocity clouds
- low metals: FUSE and WHAM; possibly some dust
- dilute the ISM (not a closed box)

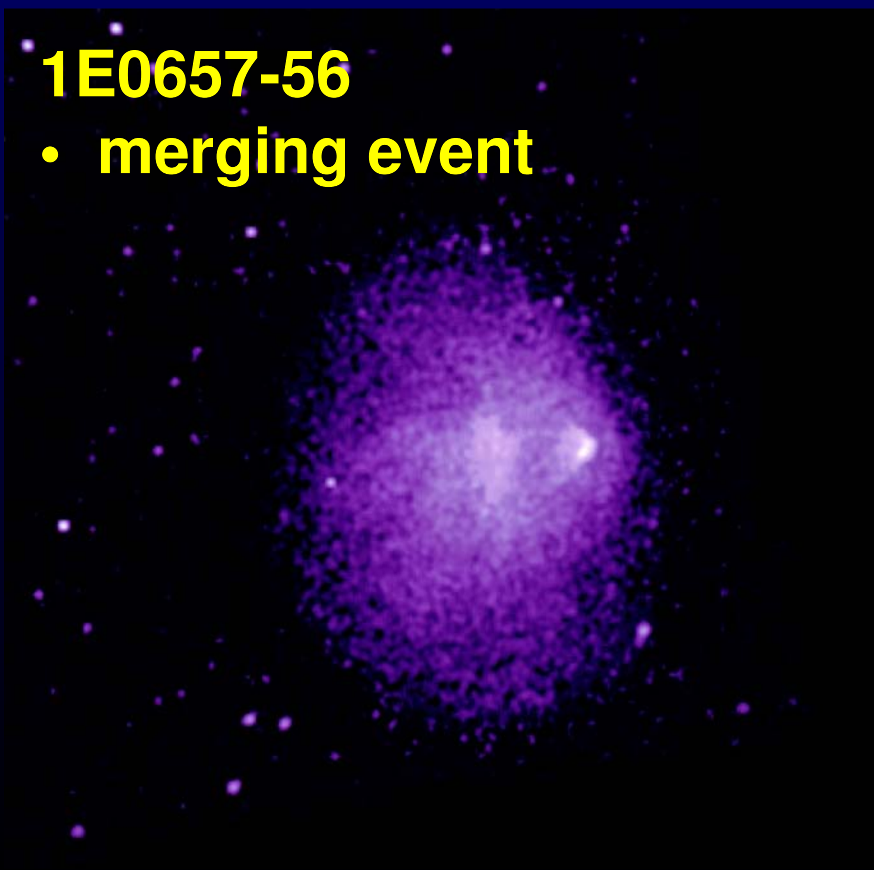
Starburst galaxies have superwinds driven by SNe
- mass outflow rate comparable to star formation rate
- precursors to ellipticals and spheroids
- dust to gas ratio in wind like Milky Way (1%)
- pollute local IGM to 0.1 to 0.3 solar (like HVCs)

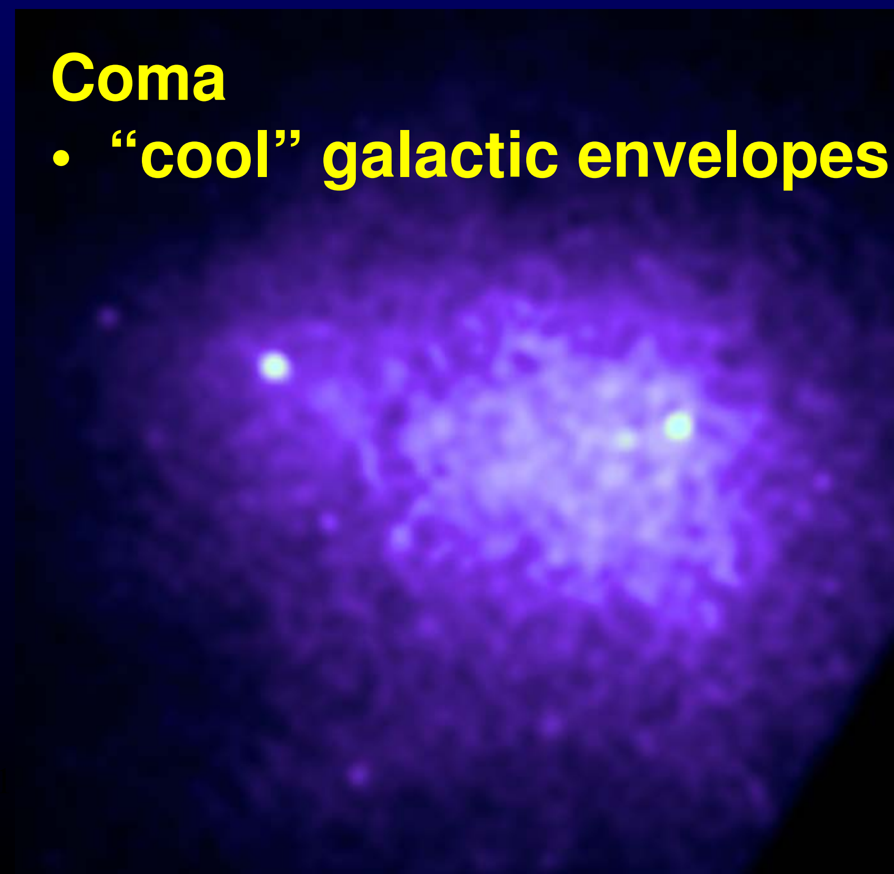
ICM

Clusters of galaxies (seen here in X-rays by Chandra)

- > 10 times mass in intracluster gas as in galaxies
- significant metallicity > 0.1 solar

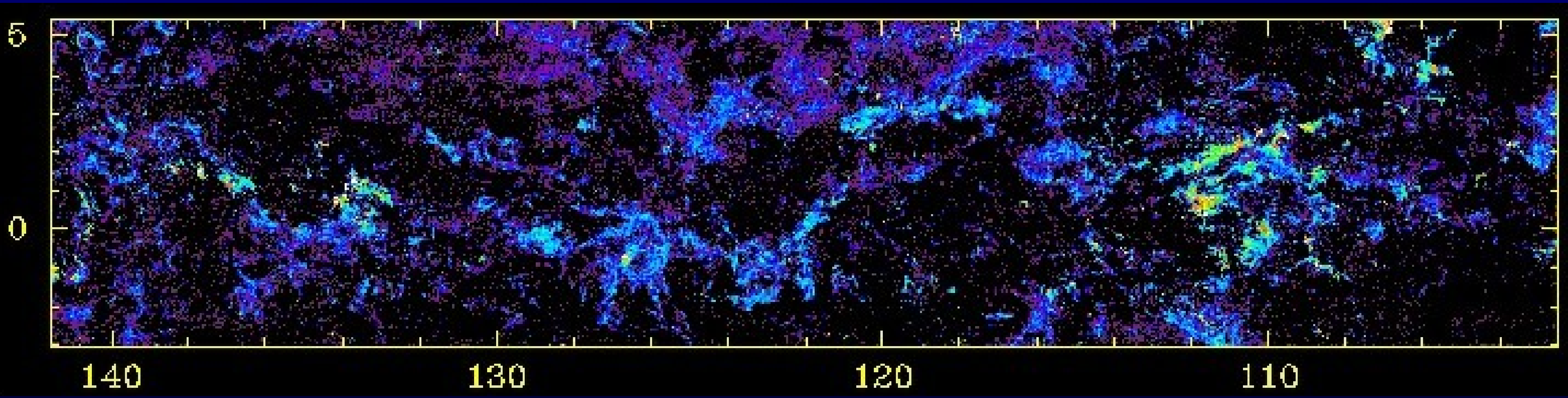
  → most metals are in the ICM





Molecular clouds

Integrated CO (1-0 emission line) from FCRAO Outer Galaxy Survey.



Very clumpy structure in velocity and space → clouds.

This is a mm-wave transition, and so its collisional excitation by H_2 can cool the gas down to 10 K, conditions more conducive to collapse and fragmentation.

A range of cloud properties

The mass spectrum continues to large mass, and in fact most mass (and star formation) is in the giant clouds (GMCs), not the small local clouds like Taurus which form only lower mass stars. Local clouds are well-studied to take advantage of the small spatial scales that can be probed in nearby clouds, but this is not necessarily representative of all star formation.

Table 3.1 Physical Properties of Molecular Clouds

Cloud Type	A_V (mag)	$n_{\rm tot}$ (cm^{-3})	L (pc)	T (K)	M ($M_\odot$)	Examples
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Dense Cores/Bok Globules	10	10^4	0.1	10	10	TMC–1/B335

Stahler and Palla

A range of cloud properties

The mass spectrum of stars also covers a range in mass. But unlike the molecular clouds, the stellar mass function has most mass in low mass objects; high mass stars are quite rare.

Thus a likely reason that high mass stars are not found in local low mass star-forming molecular clouds is that there simply is not enough mass in them, statistically, to produce even one high mass star.

Statistically, the Sun would have been born in a GMC. But this is not necessarily the best place for a proto-solar system disk to survive long enough to form planets.

Following the Path of Metals From Galaxies to Habitable Planets

Alexandria – March 2006 – lecture 2

Orion nebula and OMC1 – blister

Metals: cooling – sets pressure

Depletion evident

Trapezium exposed

Buried cluster

Bar

A hostile place for the build-up of planets?

Interstellar dust – extinction

Major repository of metals in the ISM.

First detected by dark silhouettes of clouds against bright background of stars. This is caused by:

extinction = absorption + scattering .

Stars seen through foreground dust are redder than their intrinsic colours, which implies that there is more extinction at blue wavelengths (higher frequencies).

What colour is the Sun at noon? At sunset?
What colour is the sky? Why?

Reflection nebulae.

Reflection nebulae

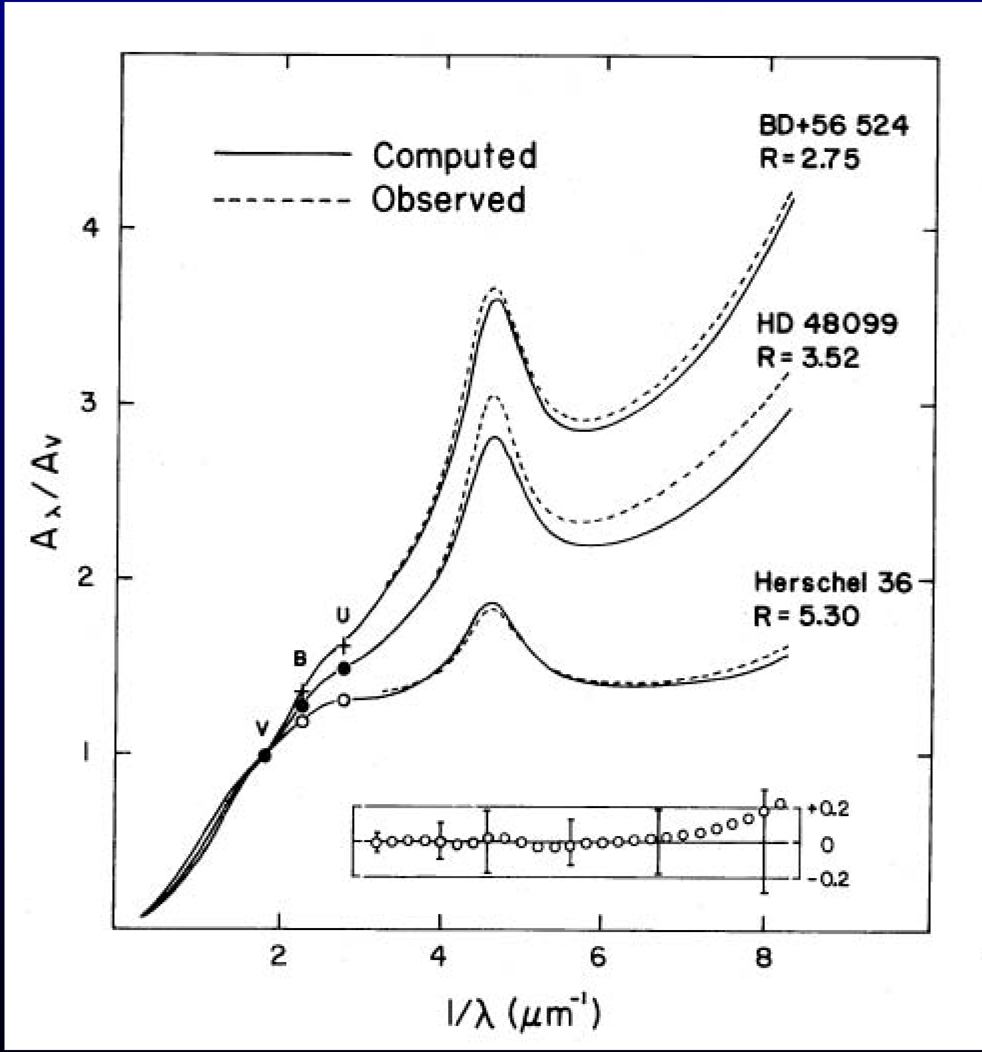
These are bluer than the light from the illuminating star, because the dust scattering cross section is higher at shorter wavelengths. Those pictured are in the Pleiades.

Extinction curve

The dependence of extinction on frequency.

At optical frequencies, A ~ λ^{-1} which indicates that the particles causing the extinction there are about the same size as the wavelength, a ~ 0.1 micron.

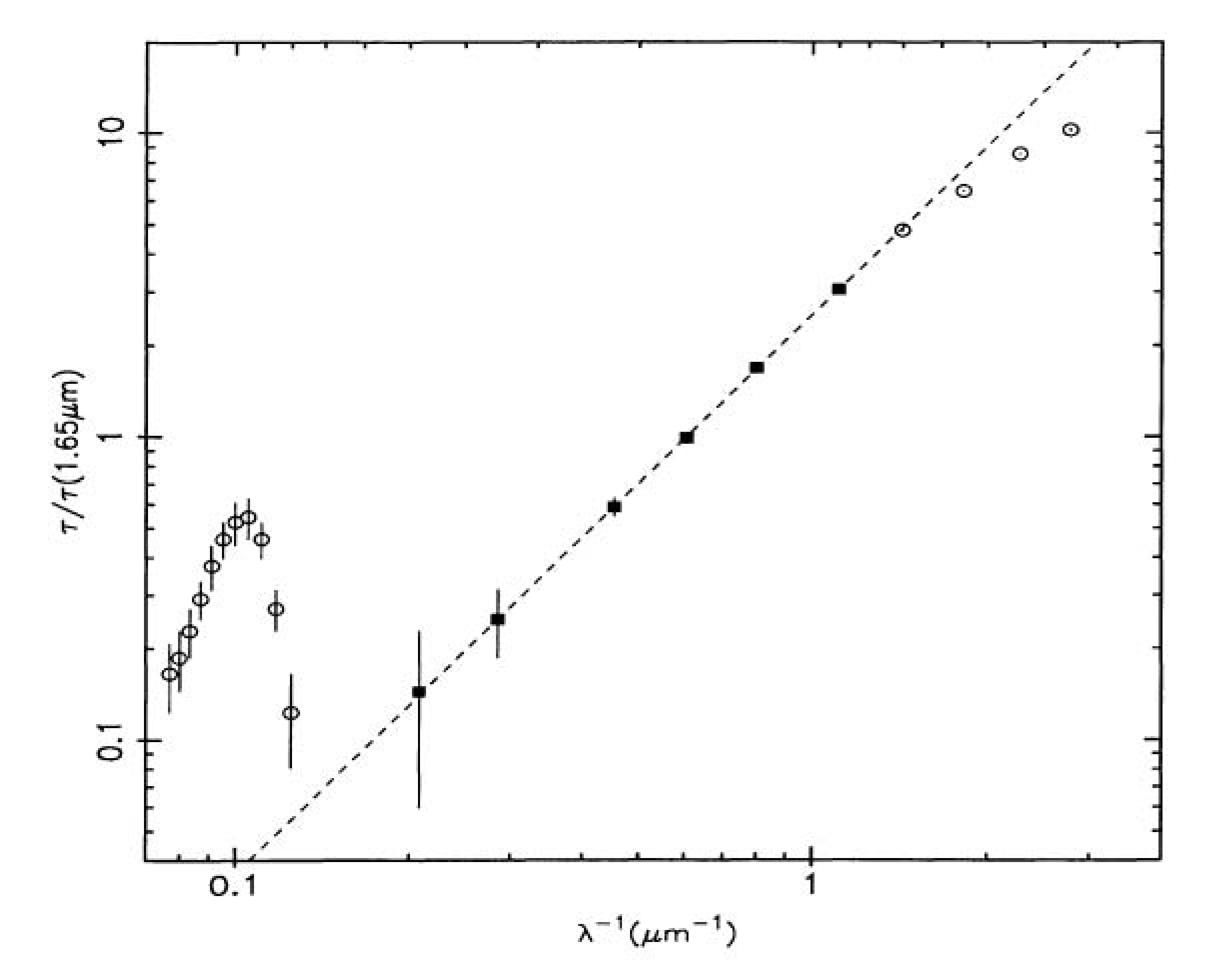
For most stars, R ~ 3.



Extinction curve – IR

Falls off in near IR as $\lambda^{-1.8}$.

Interesting spectral feature at 10 microns (seen in emission near protostars too, and around O-rich AGB stars).



The extinction dies away, so that the ISM and star forming regions are much more transparent.

Extinction – UV

The continued rise in extinction into the vacuum ultraviolet indicates there are much smaller particles too, down to the size of PAHs.

What happens at FUV and X-ray energies?

Range of sizes

The size distribution is such that most of the surface area (relevant to molecule formation) is on smaller particles, whereas most of the mass is in the larger particles.

The amount of extinction compared to the amount of Hydrogen along the same path indicates that most of the metals are locked up in dust particles (consistent with “depletion” of atoms/ions in the gas phase).

There is some C left over in the gas, which provides the main coolant C^+ and in molecular clouds, CO.

Interstellar dust – composition

A good way to chemically identify a substance is through its unique spectral fingerprint. There are very few clues in the extinction curve.

- 2175 Å bump: related to carbon, like small graphite particles, PAHs. Not yet firmly reproduced in the laboratory.

- 10 micron feature: stretching of SiO bond in silicates.

- 3.1 micron feature in molecular clouds: water ice (frost formed on the surfaces of dust particles).

Grain lifetime in the ISM

Grains form in material injected into ISM; e.g., AGB stars: silicates, amorphous carbon, PAHs – grains <u>cause</u> the outflow. SN ejecta too? Called "stardust."

Does not mean that stardust == interstellar dust!

For that, grain lifetime in ISM must be longer than the enrichment and/or injection timescale.
- Shock destruction is so efficient that this is not the case – an order of magnitude discrepancy (possibly mitigated by grain shattering?)
- PAHs are destroyed where the gas is photoionized.

→ Grains are regenerated in regions of star formation. Evidence: Accretion/depletion. Ices. Agglomeration.

Transport into solar system

Some grains have survived a journey through the ISM and incorporation in solar system bodies (comets and asteroids). Identified by isotopic anomalies. <u>Not necessarily representative of interstellar grains in either composition or size</u>

Presolar grains isolated from meteorites.

- **Nanodiamonds. SiC. Graphite.**

IDPs (from comets)

- **Fluffy agglomerates of silicate.**
- **GEMS are backbone of anhydrous IDPs.**

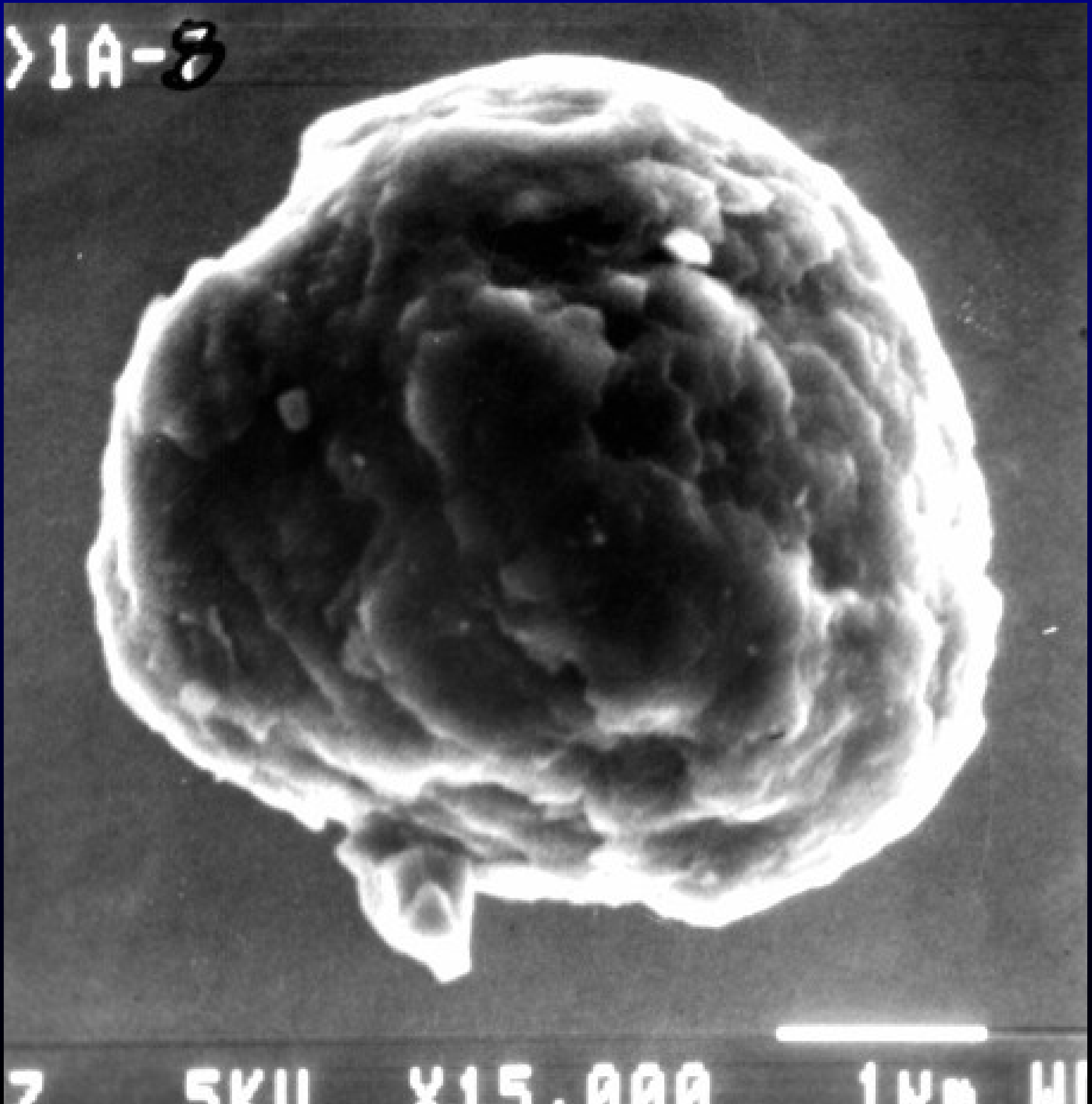
Micrometeorites.

Graphite

Layered

Much larger than interstellar grains

Supernova?

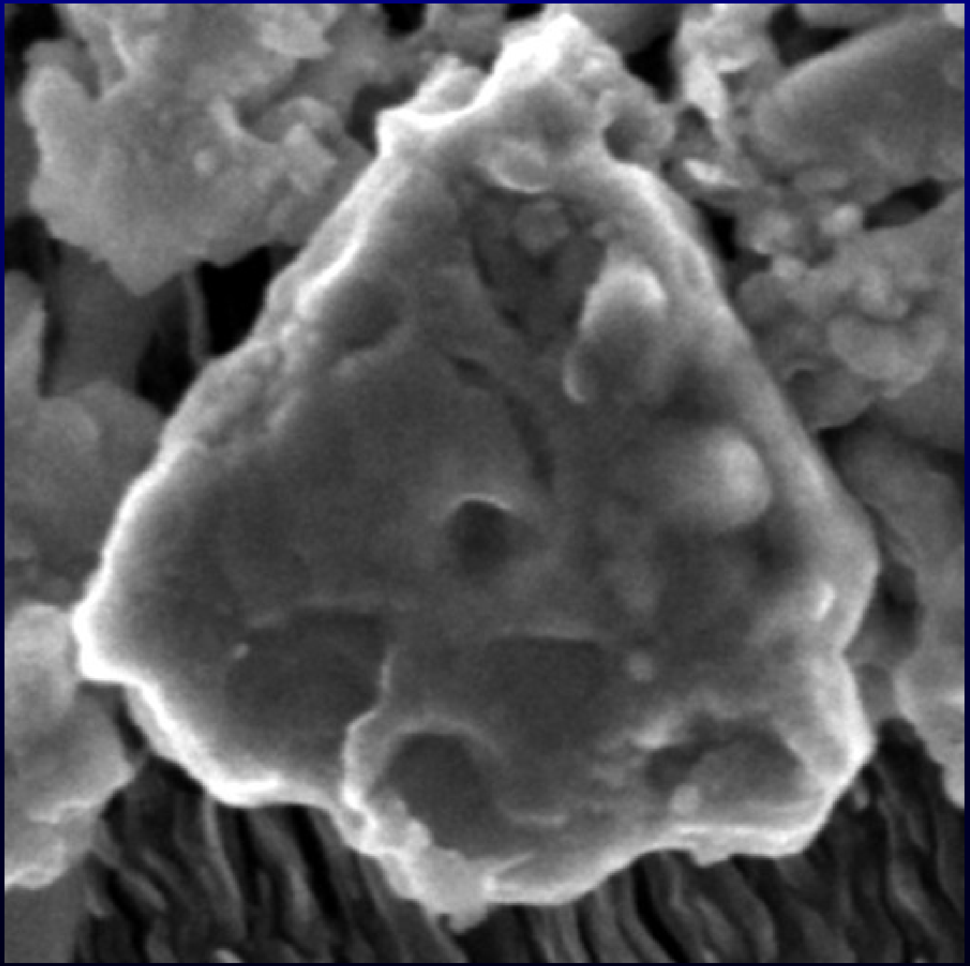


SiC

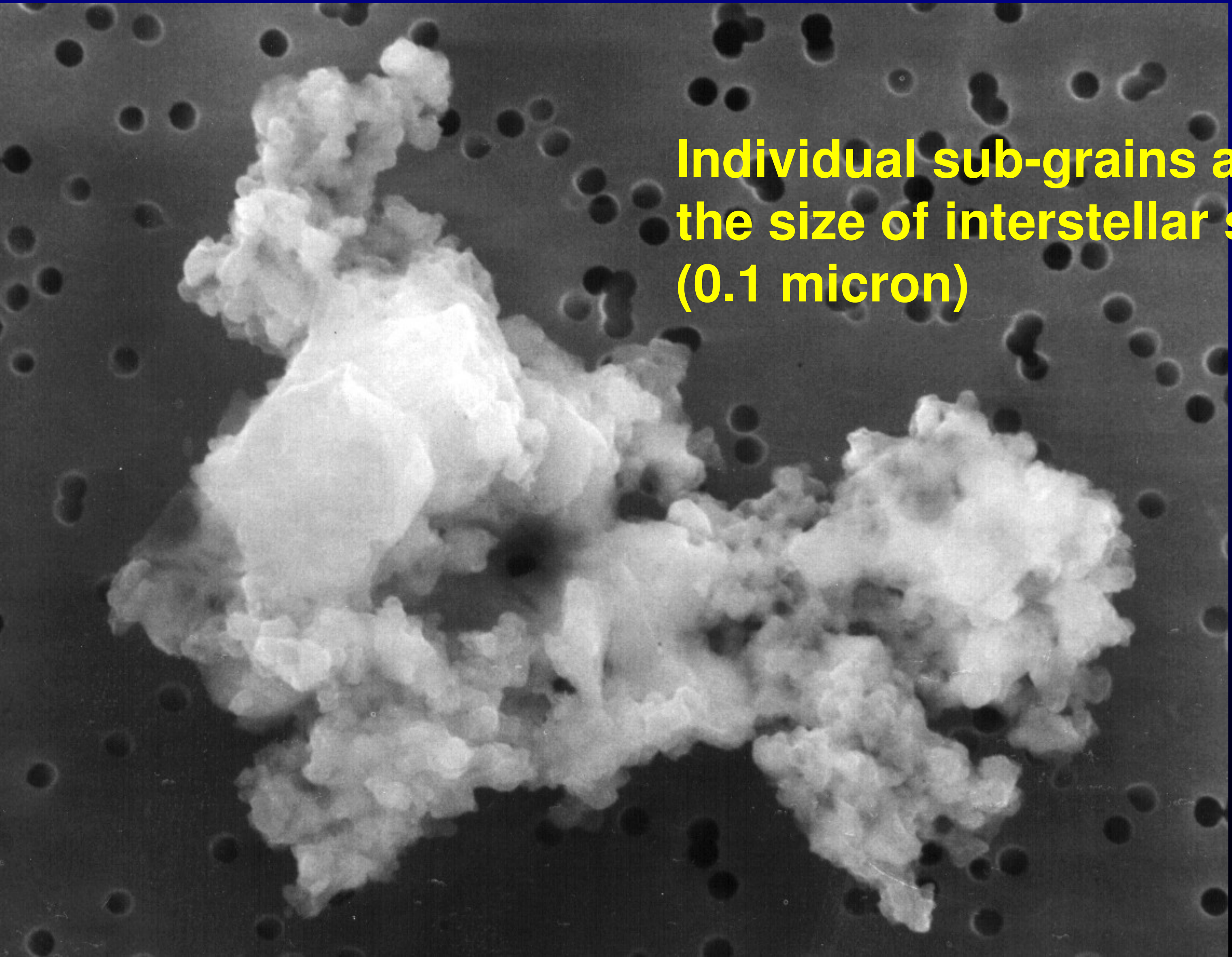
Typically larger than interstellar grains

Little of Si is in the form of SiC in the interstellar medium in any case

C-rich AGB star

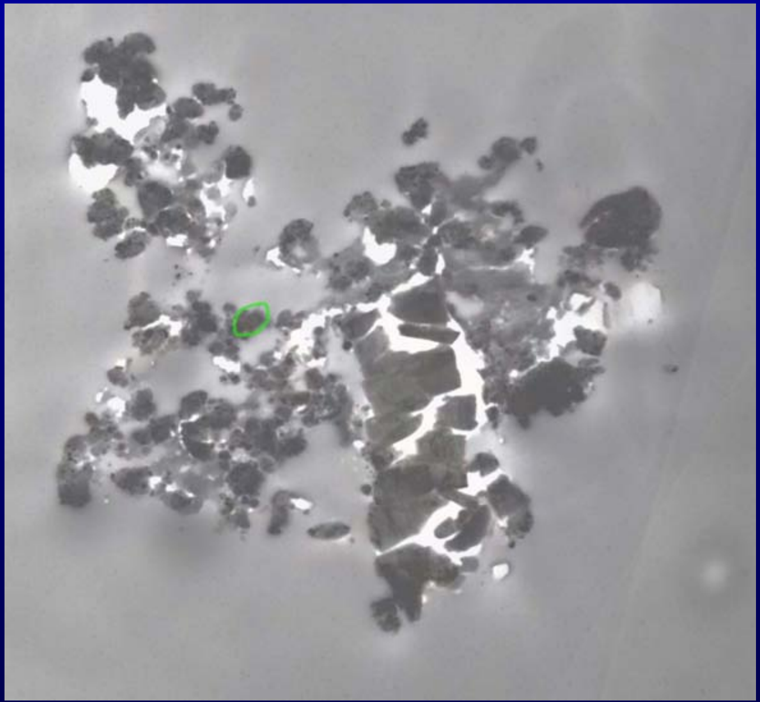


Fluffy silicate agglomerate IDP



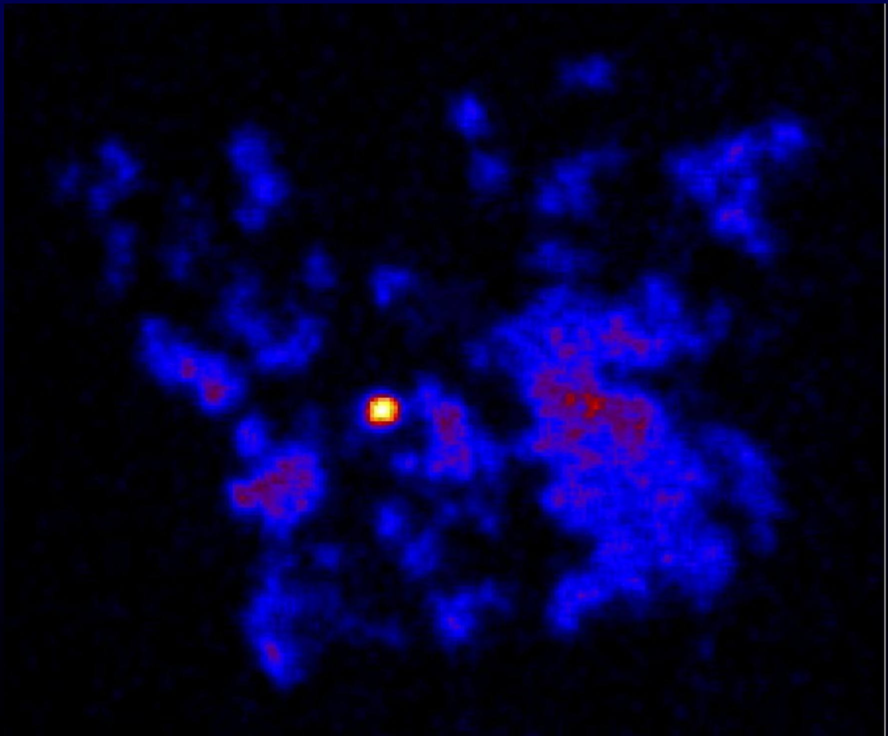
Individual sub-grains are about the size of interstellar silicates (0.1 micron)

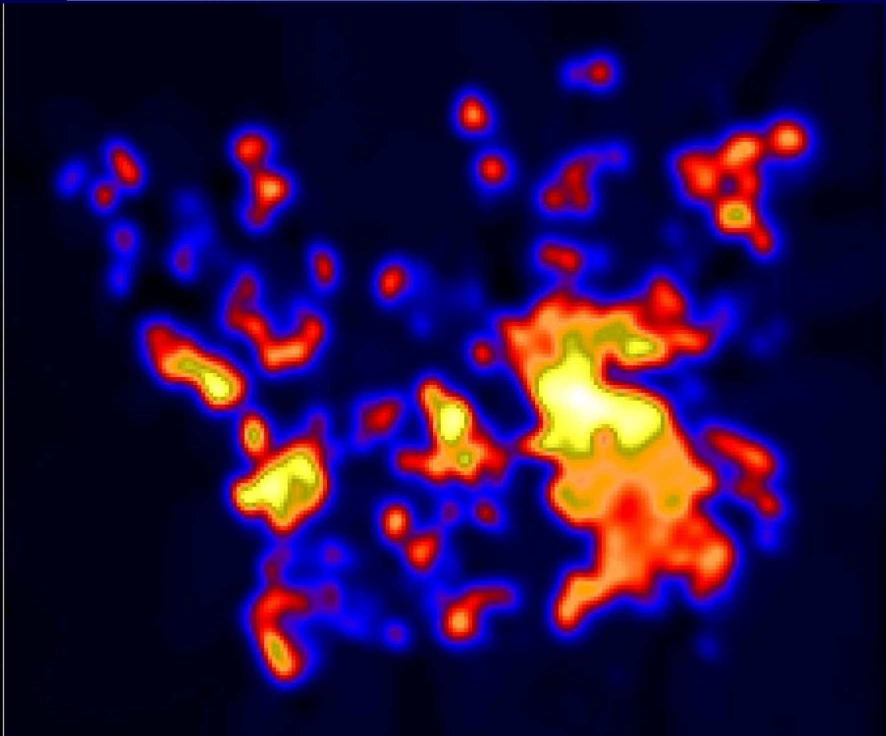
^{17}O anomaly



A sub-grain enriched in ^{17}O.

Supernova condensate or massive star?



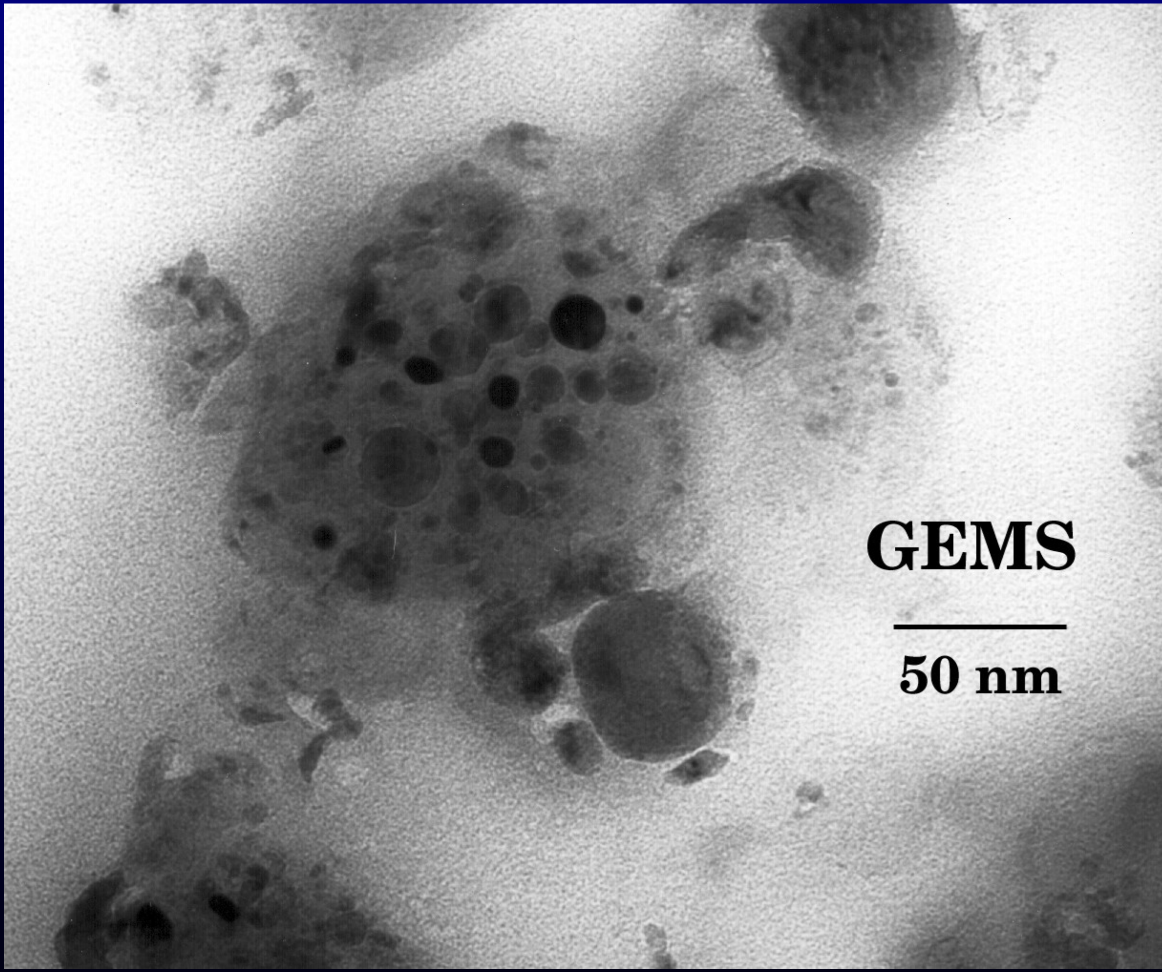


GEMS

Glass with embedded metals and sulfides.

Mg-rich silicate. Mid-IR spectrum like comets.

Fe and FeS inclusions. Lack of S depletion in gas a problem if GEMS interstellar?



“Stardust” sample return

Dust particles from a comet have been captured and returned to earth for laboratory analysis. Studies of their structure and isotope ratios should be revolutionary to our understanding of conditions in the early solar system and the buildup of rocky (terrestrial planets).

In addition the mission has brought back interstellar grains which have recently penetrated the solar system.

Dust emission

Dust absorbs starlight. This warms the dust. Warm dust emits far-infrared and sub-mm radiation according to

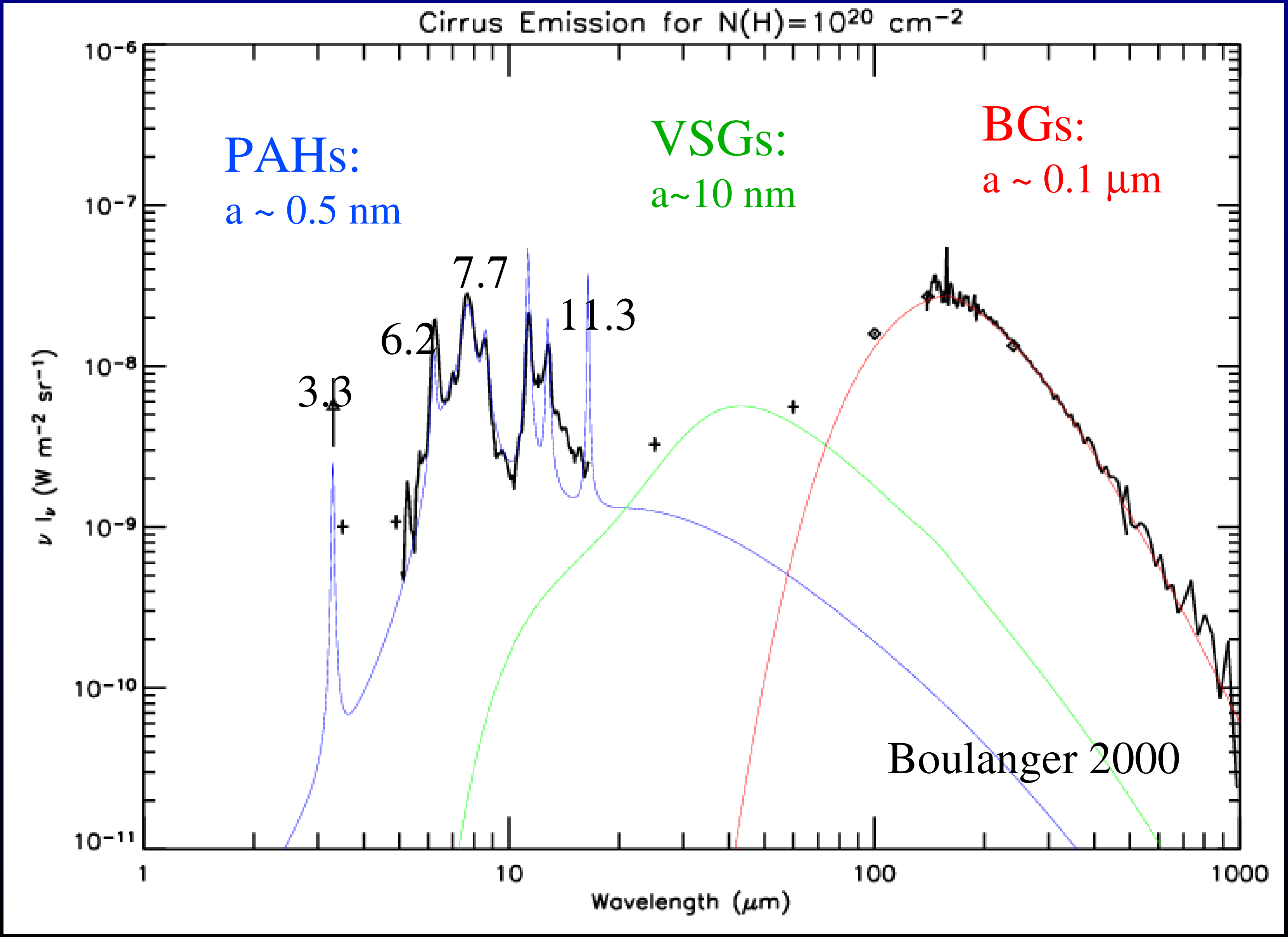
$$\text{emissivity} = \text{absorptivity } B_\nu(T_d)$$

At these frequencies, absorptivity $\sim \nu^2$.

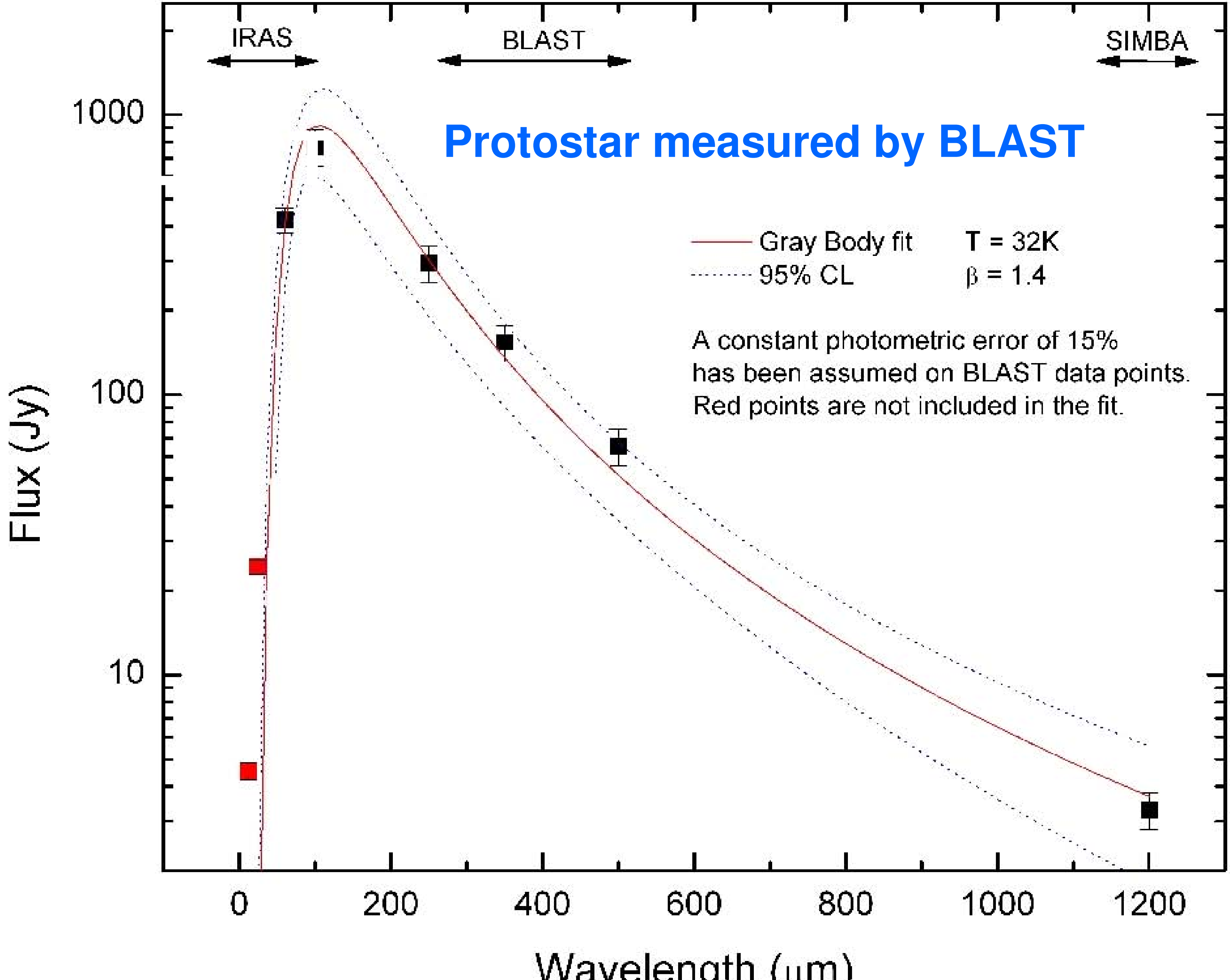
Quantitatively, for the average interstellar radiation field and submicron grain sizes, $T_d \sim 17$ K.

Near a luminous star, including dust clouds with embedded protostars, the dust can be somewhat warmer.

Interstellar dust emission components



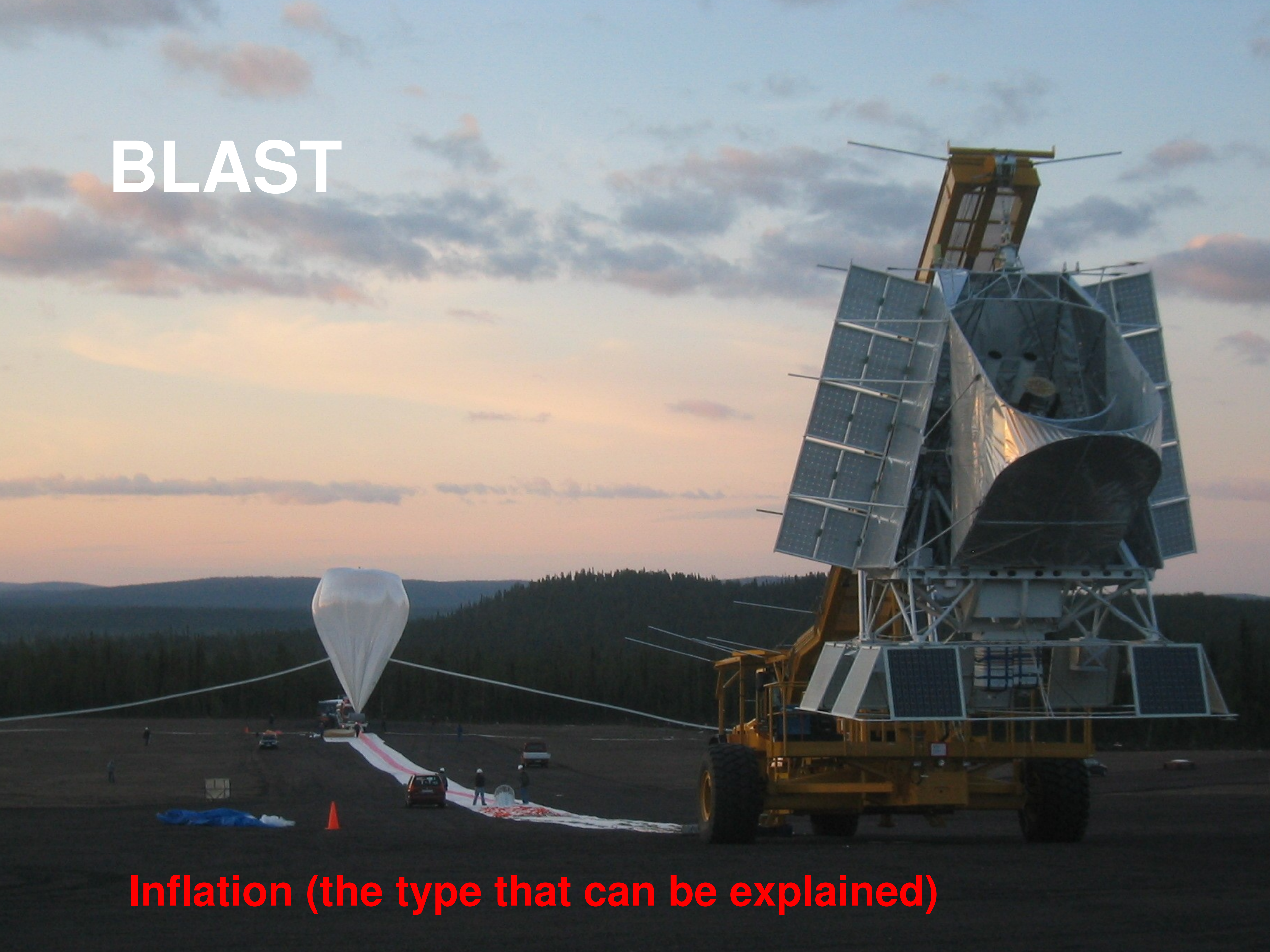
Protostar measured by BLAST

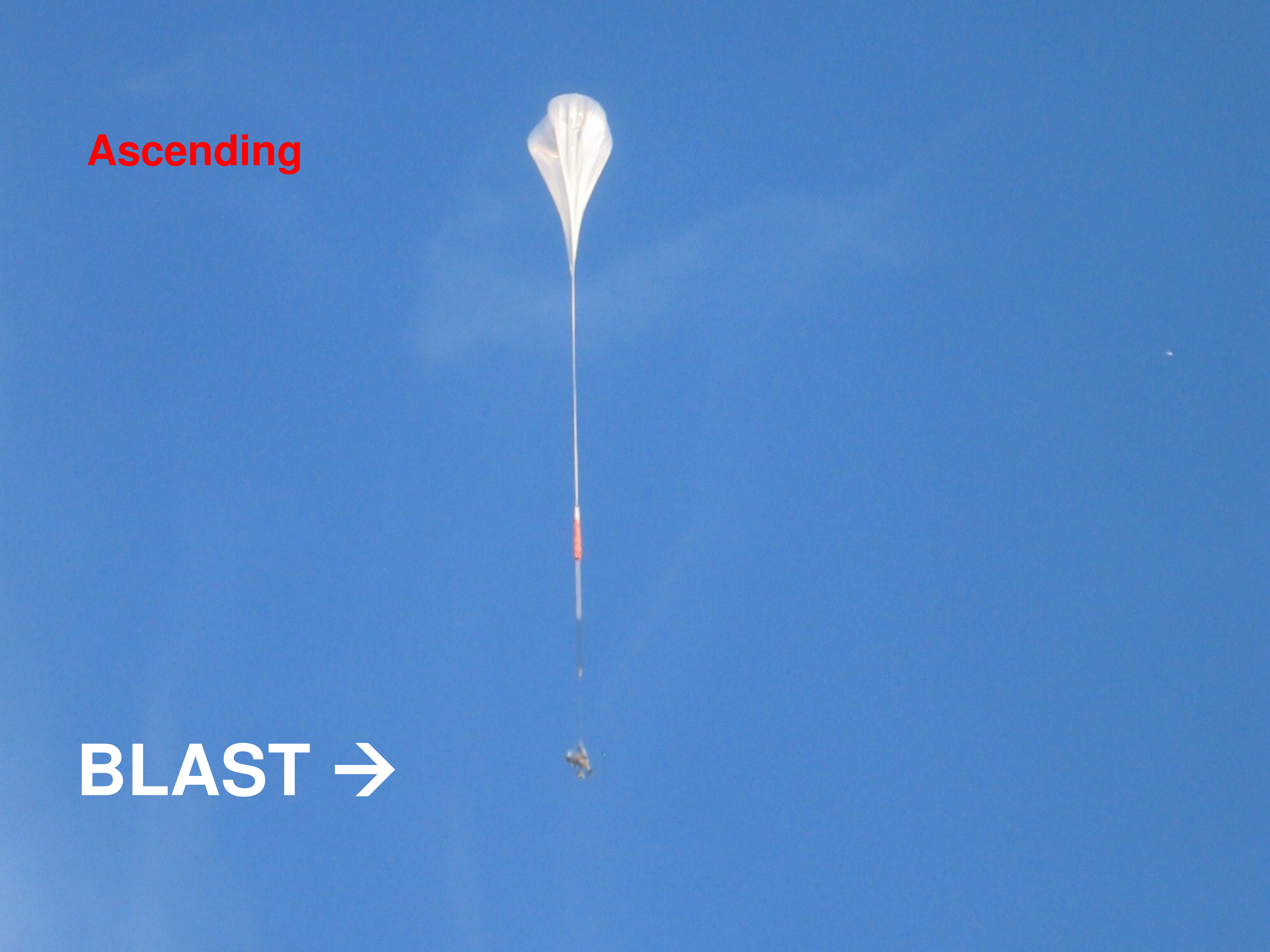



BLAST
Star cameras

BLAST

With baffling, solar panels, telemetry…


BLAST
Inflation (the type that can be explained)


Ascending
BLAST →

BLAST

At float, 40 km

Imaging dust emission

Requires observations from space, since atmosphere is opaque.

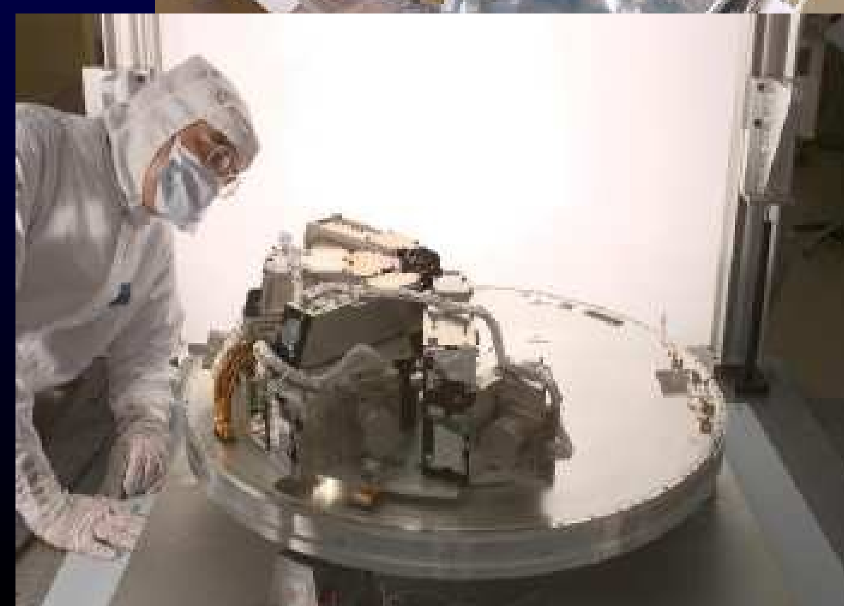
All sky map at 12, 25, 60 and 100 microns by IRAS.

Presently, Spitzer Space Telescope, at similar and shorter wavelengths, and higher sensitivity and angular resolution.

Recent launch of ASTRO-F (Japanese), mapping at 160 microns.

BLAST, precursor to Herschel Space Observatory.

Spitzer



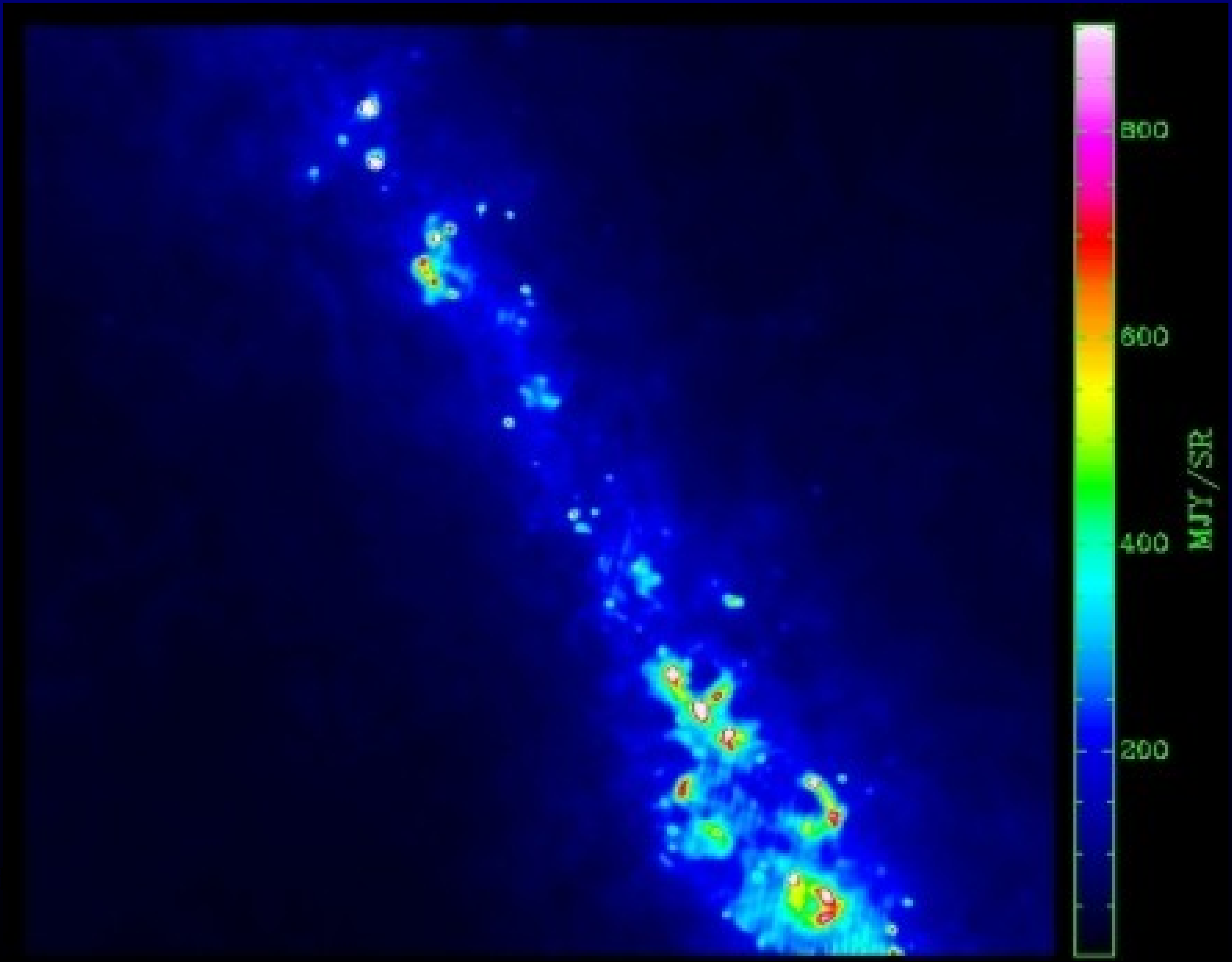
Launch in Feb. 2008

Herschel

Planck

Infrared cirrus

Dust is everywhere, well mixed with interstellar gas.



Where there's dust, there's gas…

Given infrared emission, which reveals the presence of dust, can we characterize the gas and the environment in which this dust resides?

Problem:
Infrared images show the accumulated effect of emission from all the dust along the line of sight.

Potential solution:
Tomography based on gas spectra.

Tomography (Human)

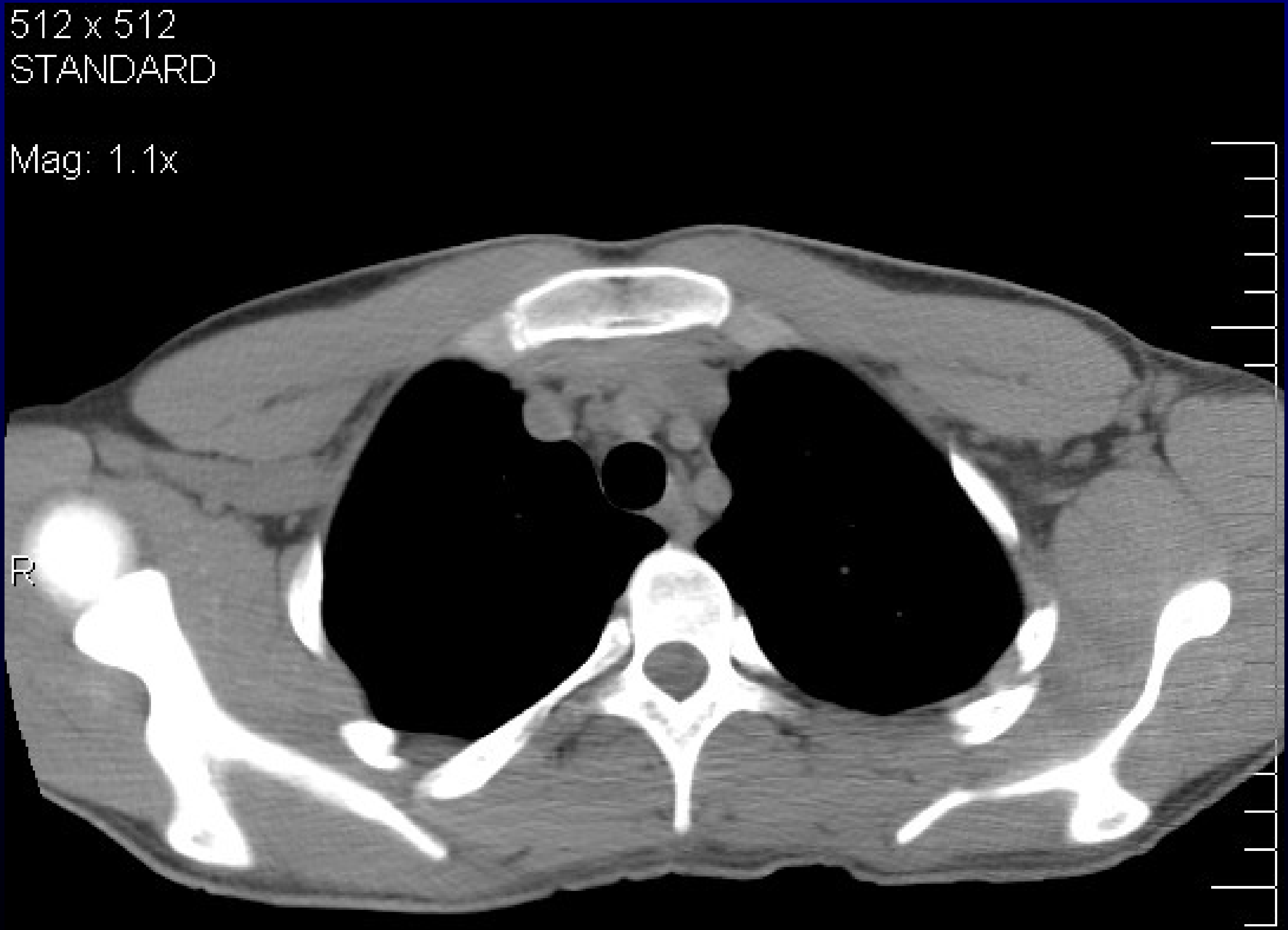
Image the body in thin slices perpendicular to the spine.

Tomography

Shoulders. Areas of higher density.

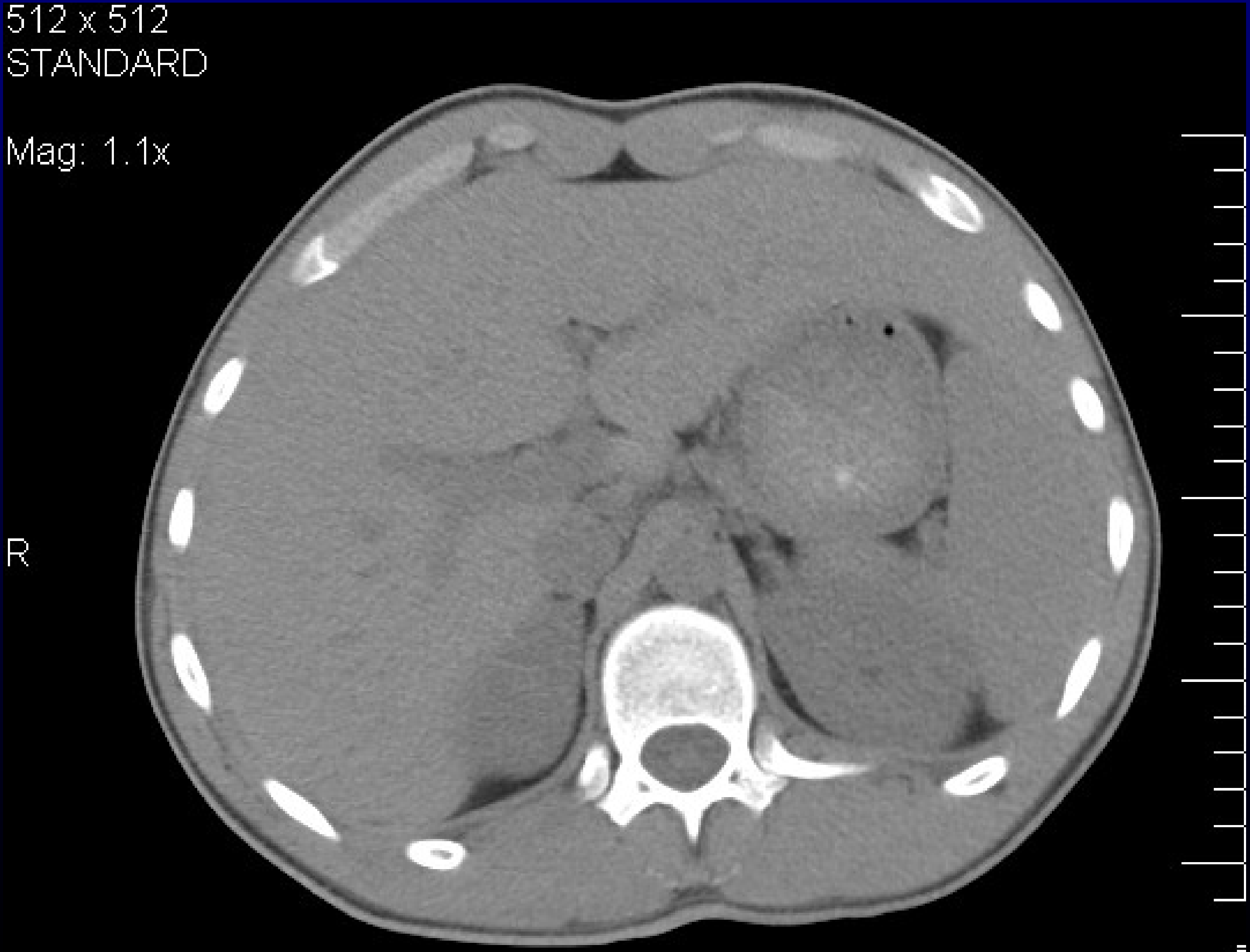
Tomography

Lungs (voids)



Tomography

And below…



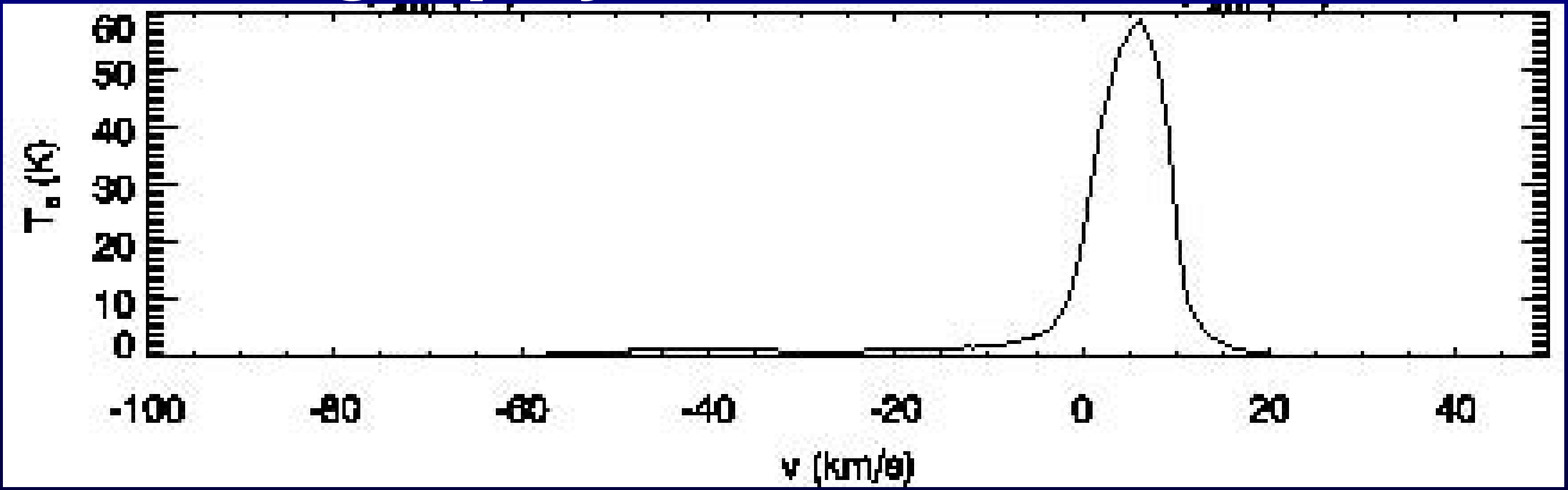
Tomography (Human)

Image the body in thin slices perpendicular to the spine.

Arrange images slice after slice → a cube data structure.

Replay image after image → movie, moving along spine.

H I (atomic hydrogen) Tomography



- For every position, measure how bright H I is as a function of velocity.
- Make a map (image) of this brightness at each velocity.
- Arrange in a cube → movie along velocity axis ~ movie along distance*.

(*Because of differential Galactic rotation, each velocity corresponds to a different (known) distance.)

Gas-phase tomography of dust

Velocity differences along the line of sight arise from

- differential Galactic rotation
- streaming motions
- peculiar motions, e.g., infalling gas (HVC) and Galactic fountain (IVC, circulation into the halo)

To some approximation, each velocity corresponds to a different assemblage of gas.

If morphological features (e.g., ridge, shell, void) in a dust emission image are also found in an image of gas emission at a particular velocity, then that is the gas associated with the dust.

Can use others species too, e.g., CO

Angular (and linear) resolution

This is important in defining morphology.

At a distance r, the linear scale s probed at angle θ is

$$s = r\ \theta$$

where θ is in radians (there are 206265 arc sec in a radian).

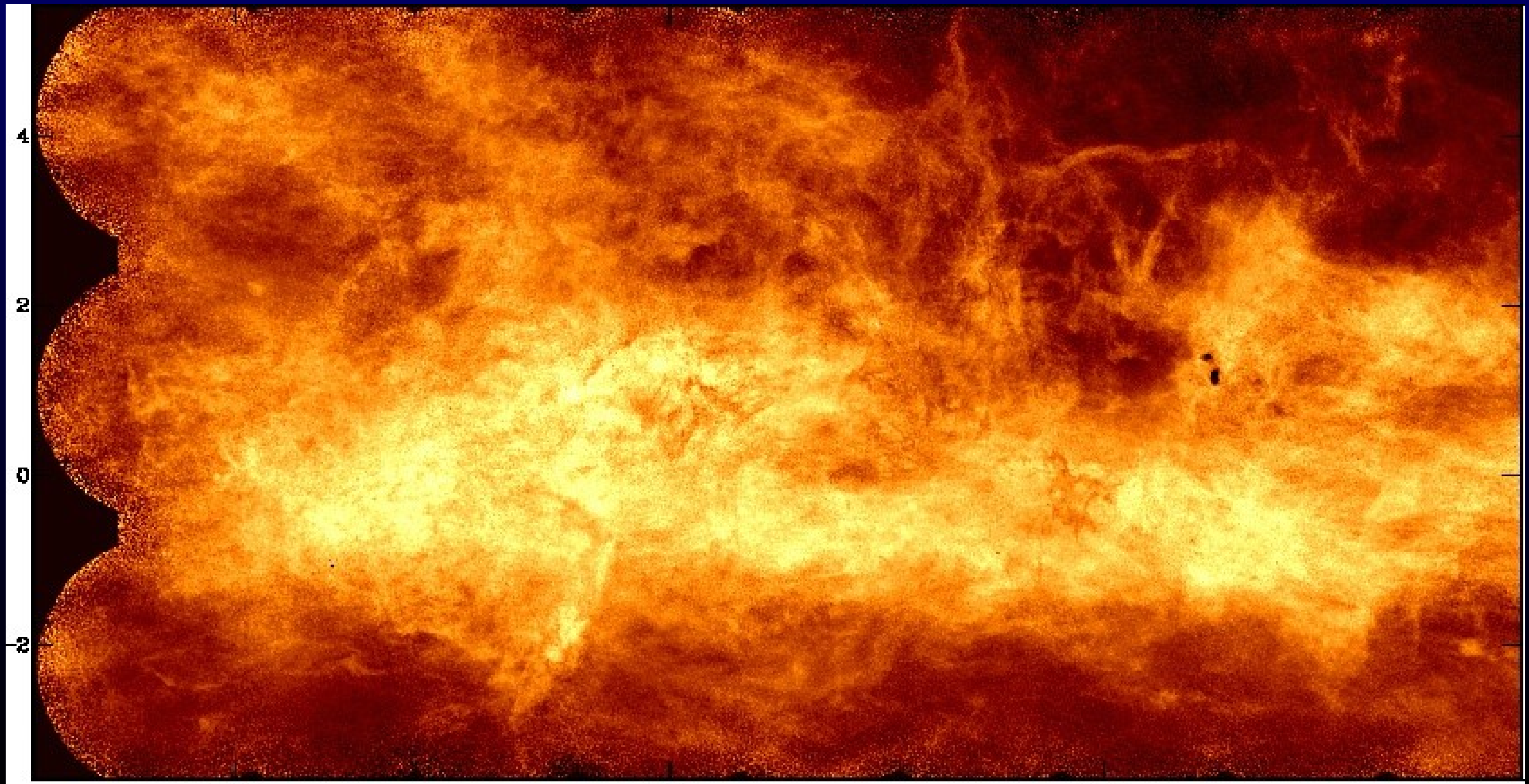
A telescope of size d observing at wavelength λ, has resolution

$$\theta = 1.2\ \lambda\ /\ d\ .$$

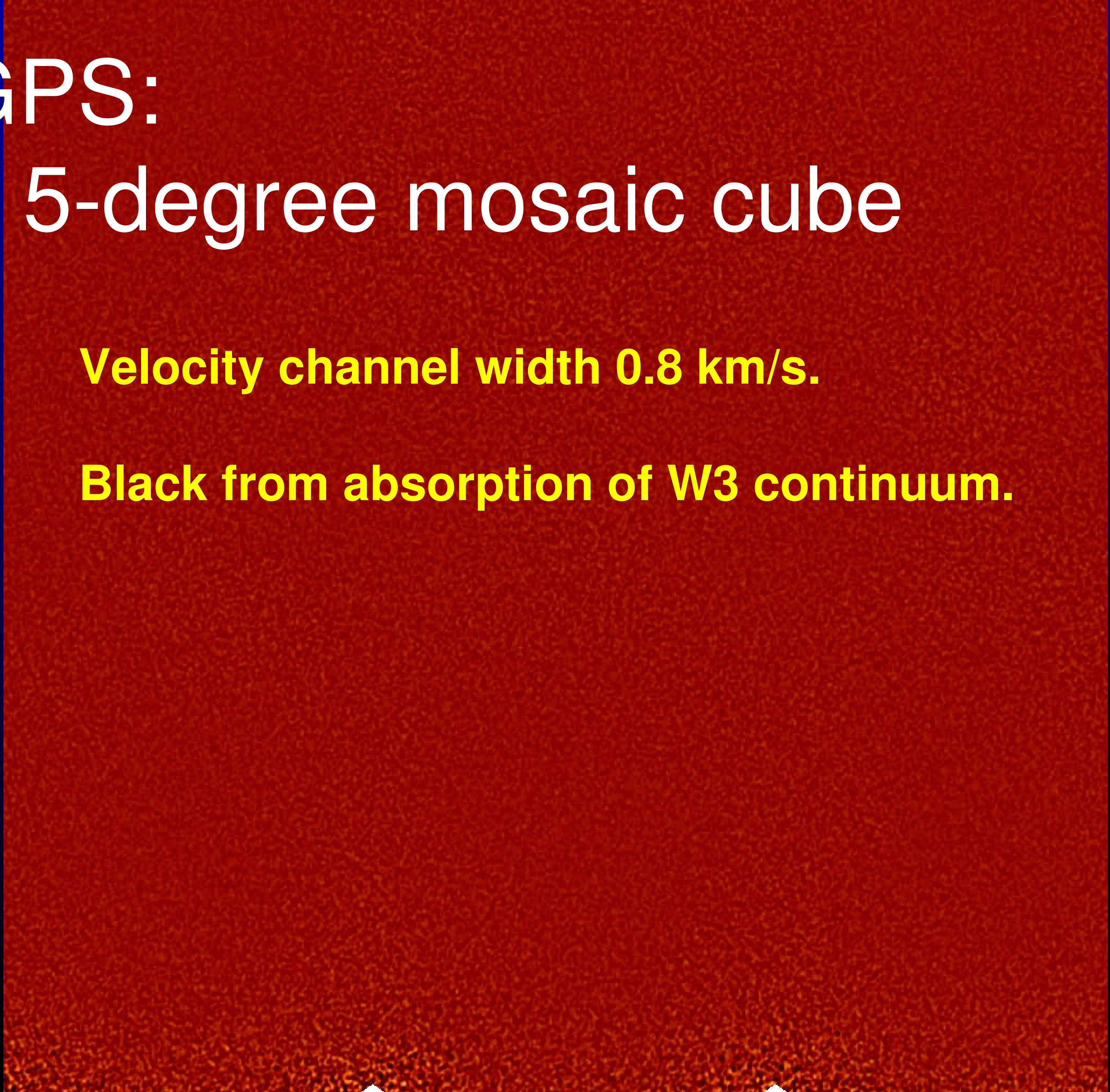
DRAO Synthesis Telescope

CGPS: Resolution matters

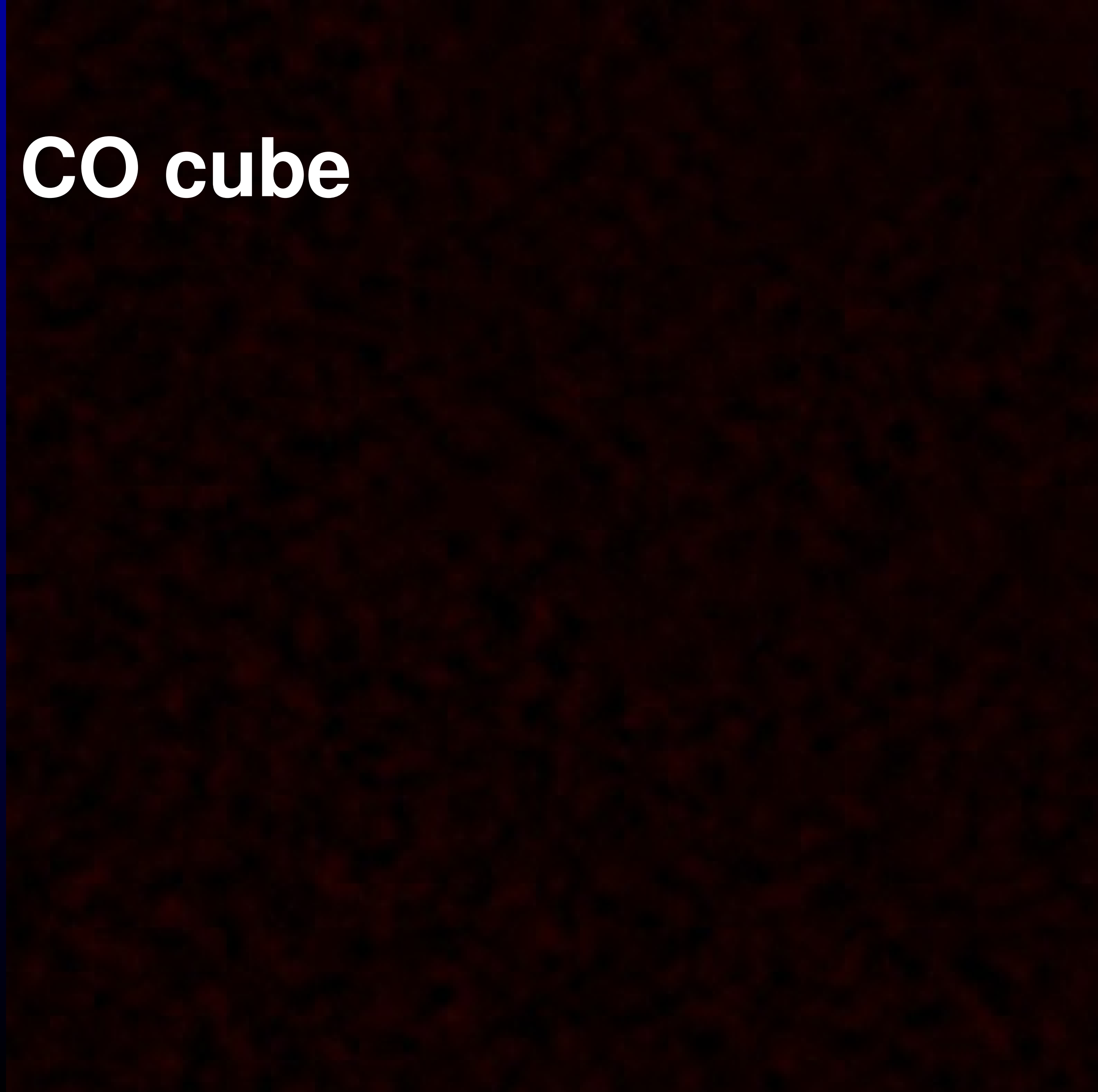
All data ~1 arc minute (H I shown here, vs. LDS)



CGPS:
H I 5-degree mosaic cube



CGPS: CO cube



Pre-biotic molecules

Issues

- formation of complex pre-biotic molecules in the cold interstellar medium (without aqueous solution)
- transport into the solar system and incorporation
- transport to earth

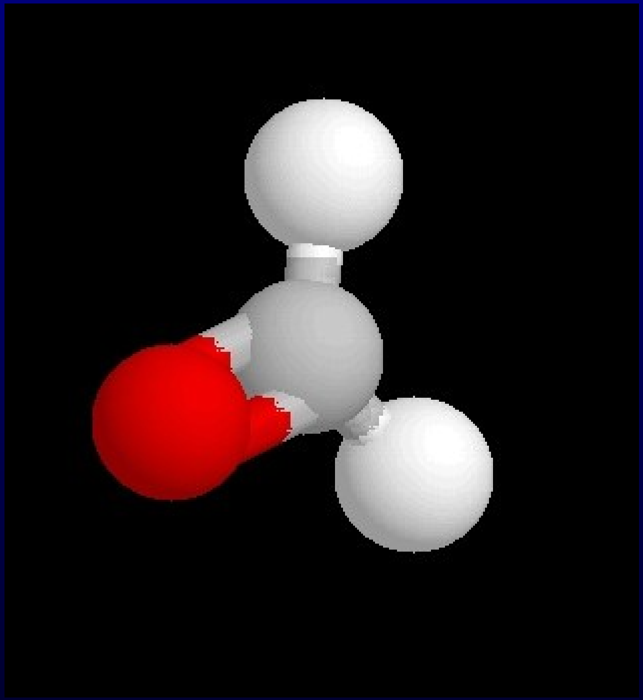
Formaldehyde

Formaldehyde is common.

H_2CO

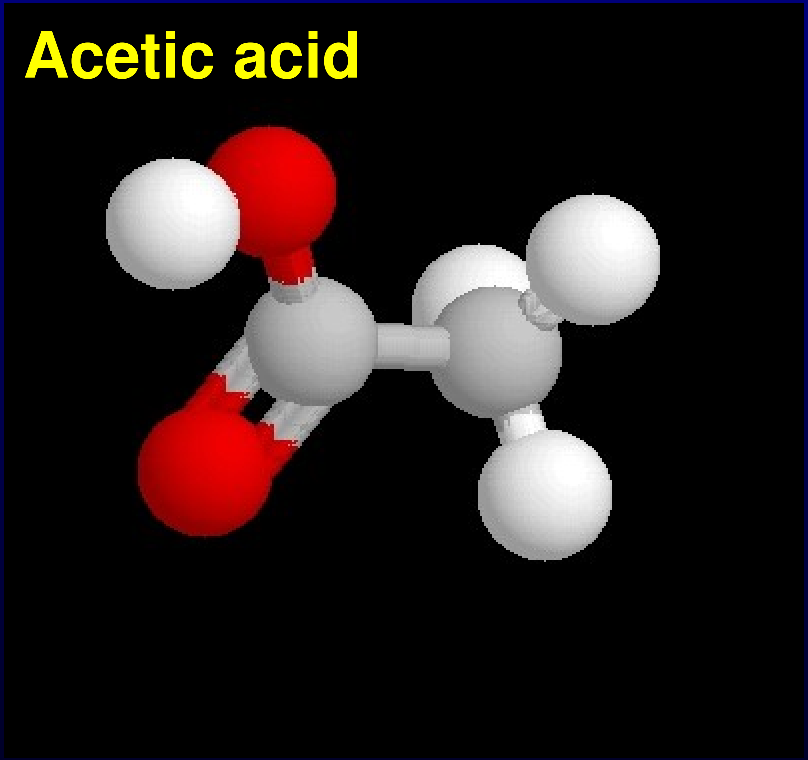
or

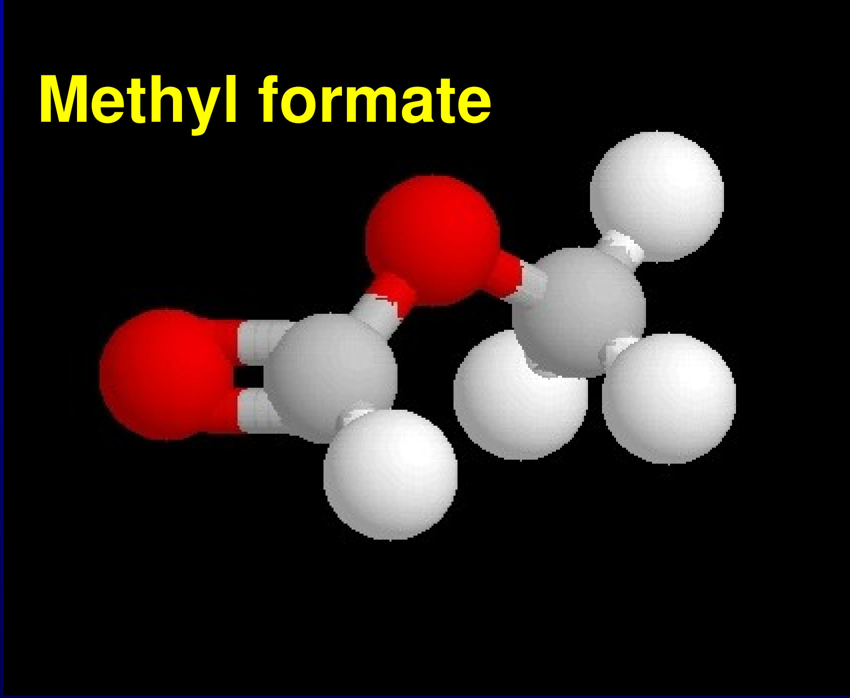
$(CH_2O)_n$ with n=1

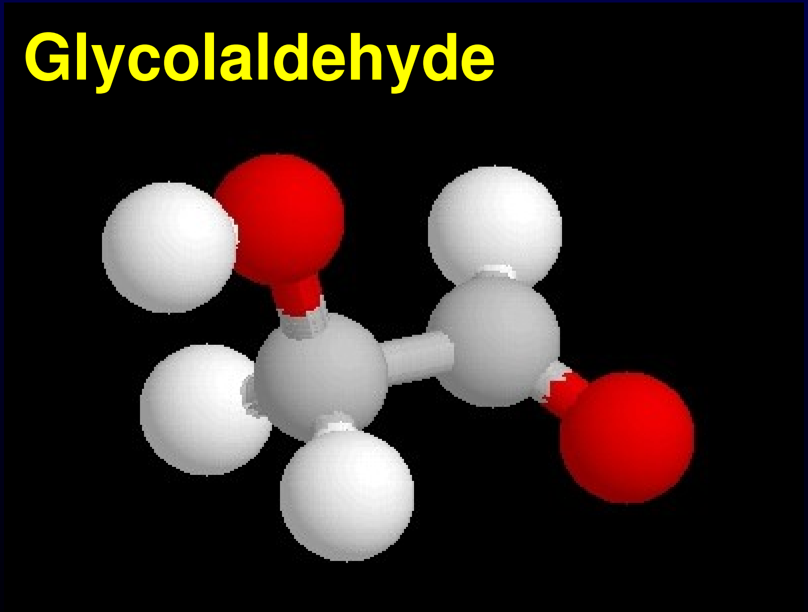


Colour code: H, C, N, O

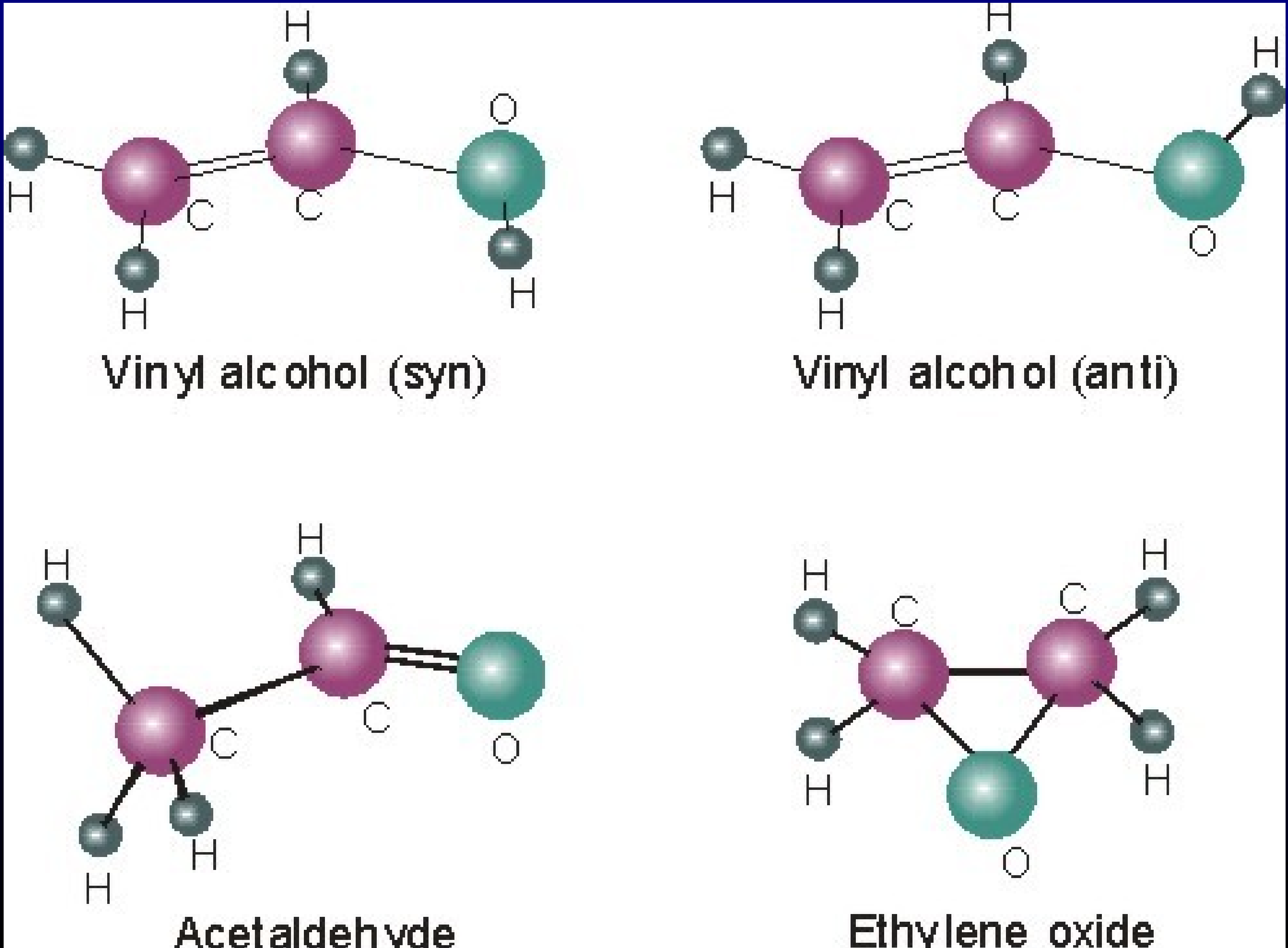
Isomers with n=2







Isomers of H4C2O



Formation in the ISM

Ingredients

- cold grain surfaces
- ices, including CO, ammonia, ethanol
- UV radiation (thermal spikes, bond-breaking)

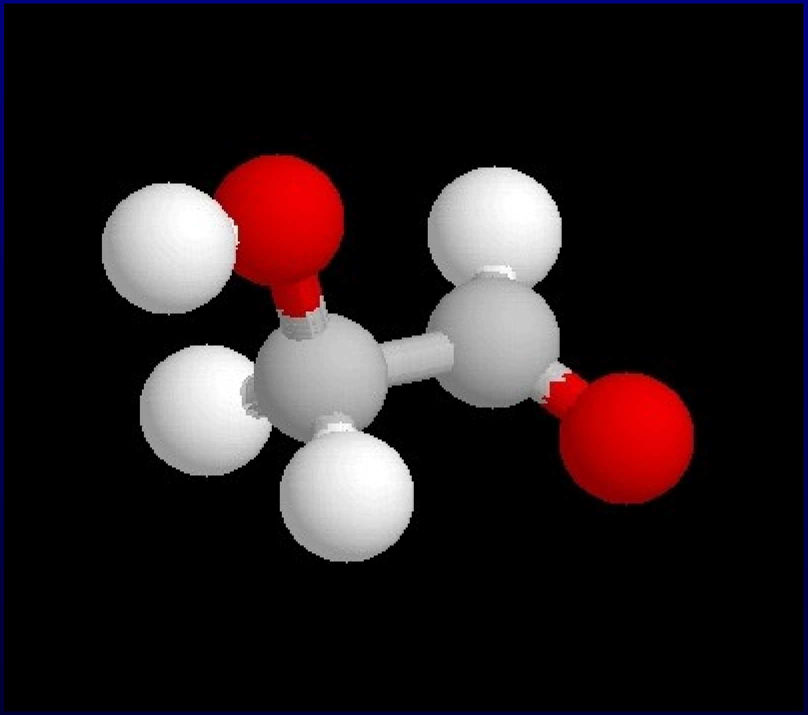
Cosmic "musical chairs"?

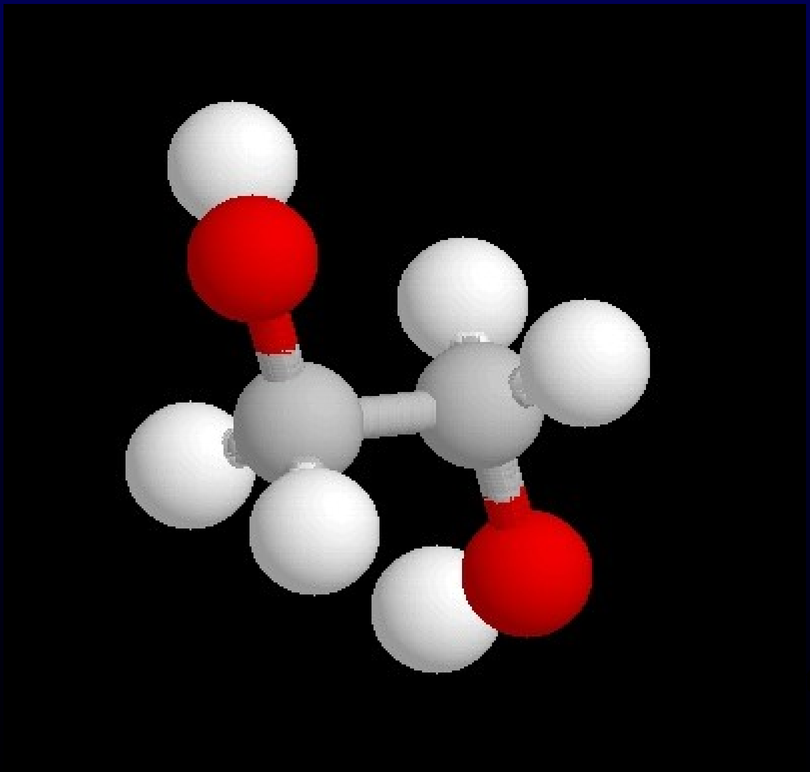
In the melee are there common chemical precursors which join together by chance to account for the observed high degree of isomerism?

What about substitutions?

Glycolaldehyde (n=2) and Glycol

Glycolaldehyde, the very simplest monosaccharide, is the first interstellar sugar detected (Sgr B2 N).





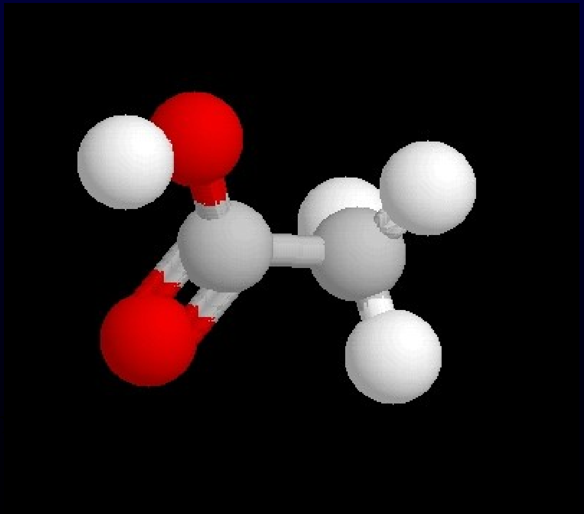
The alcohol sugar of this, ethylene glycol, has also been detected (more symmetrical).

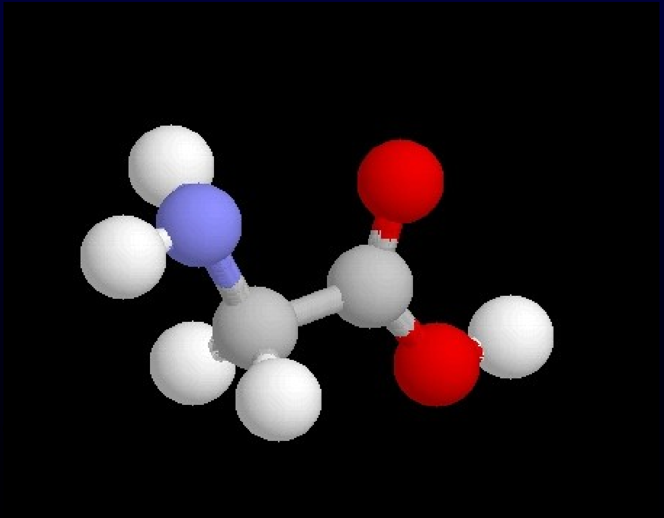
Musical Chair Outcomes

Above: glycolaldehyde and glycol (whose ends are symmetrical – seems reasonable to have the double-ended version, since having one is OK)

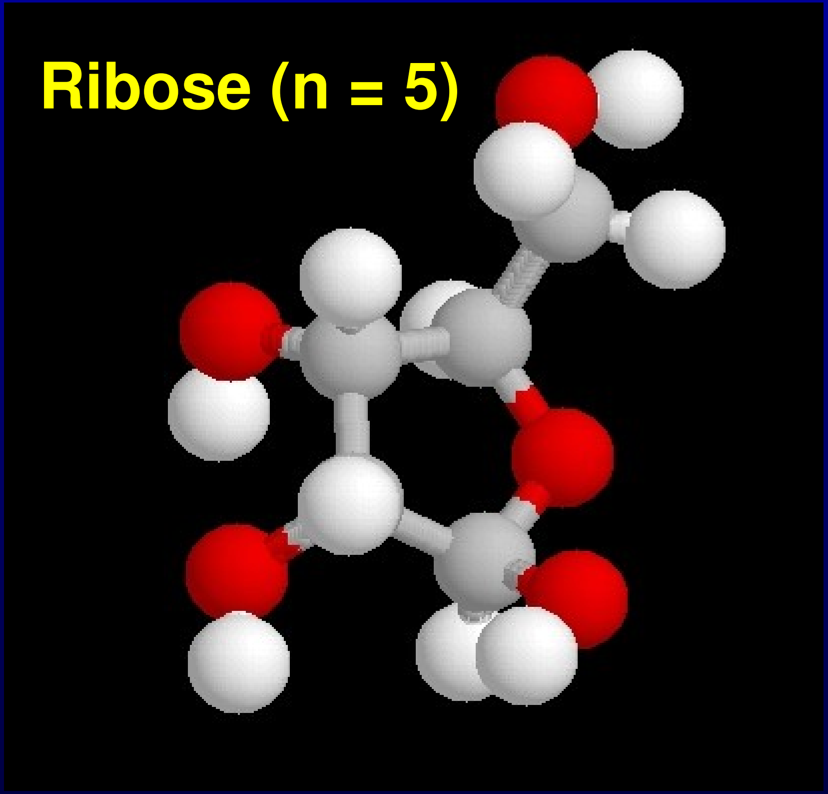
Acetaldehyde to hydroxyacetaldehyde (glycolaldehyde), by substituting H with OH (not shown)

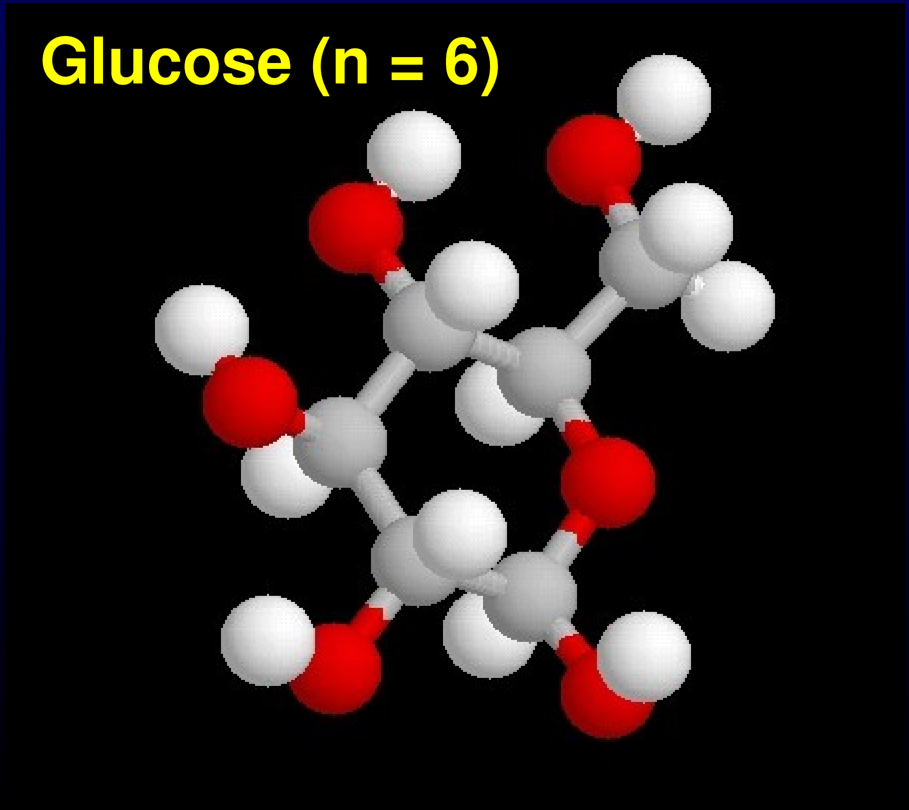
Acetic acid to glycine, by changing H to NH_2.



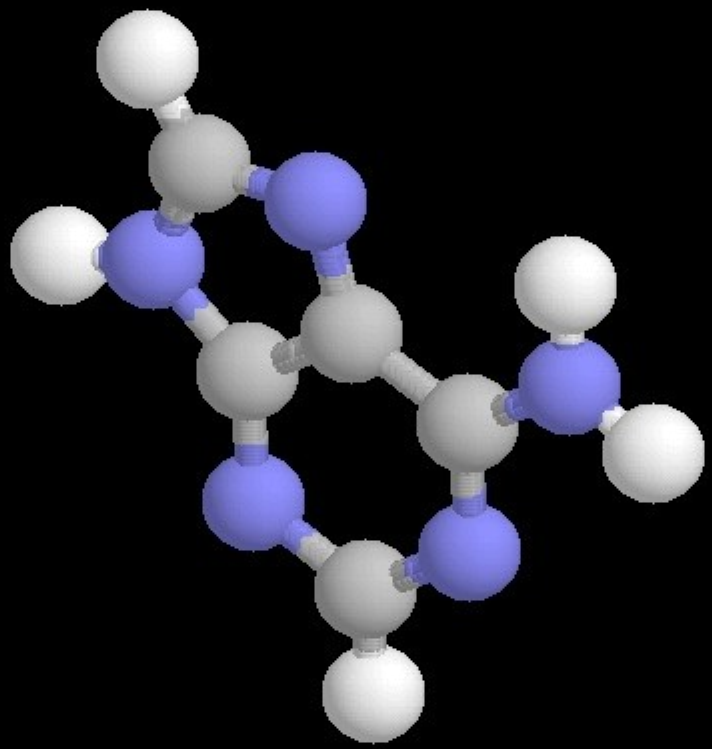


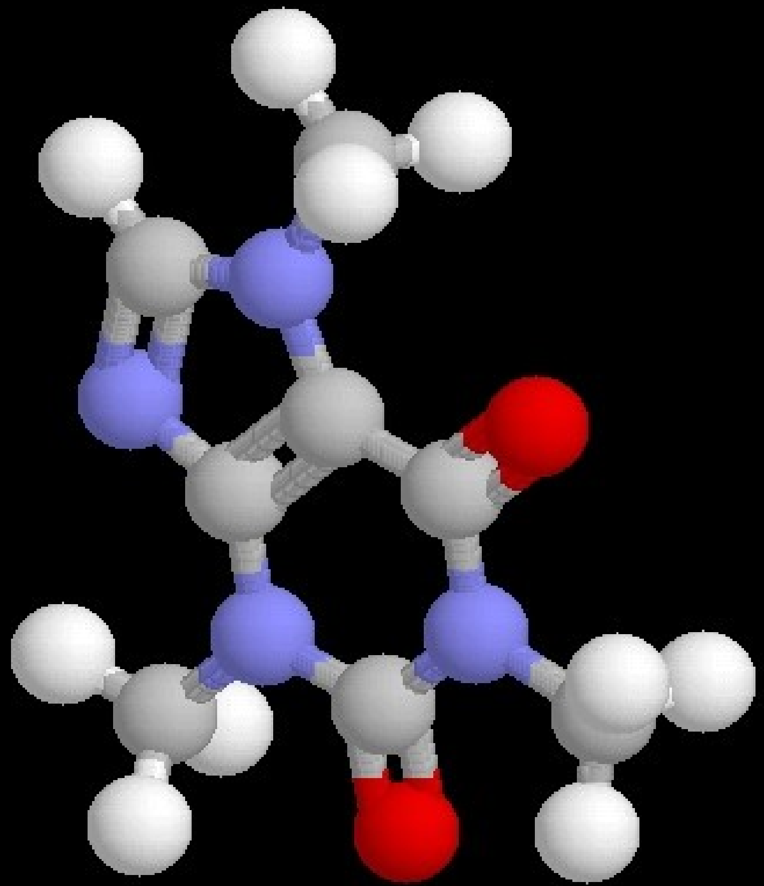
Why stop there?



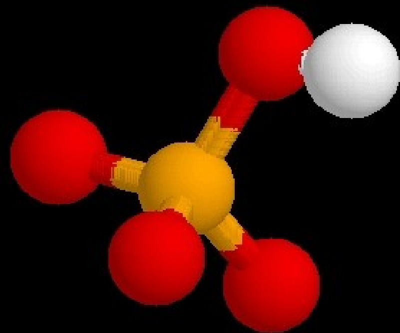


Adenine and C…?



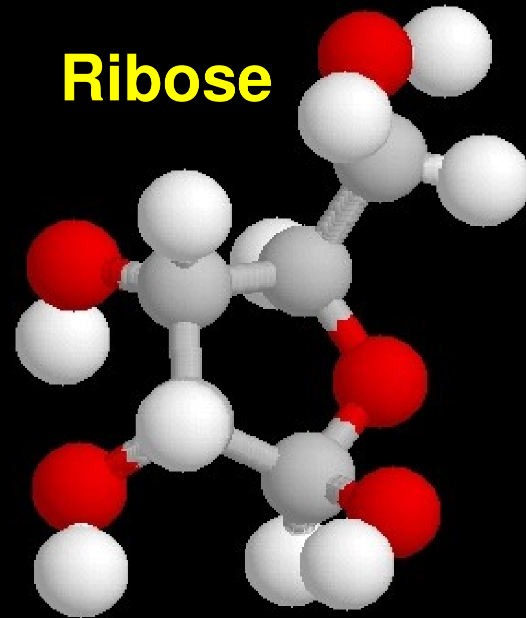


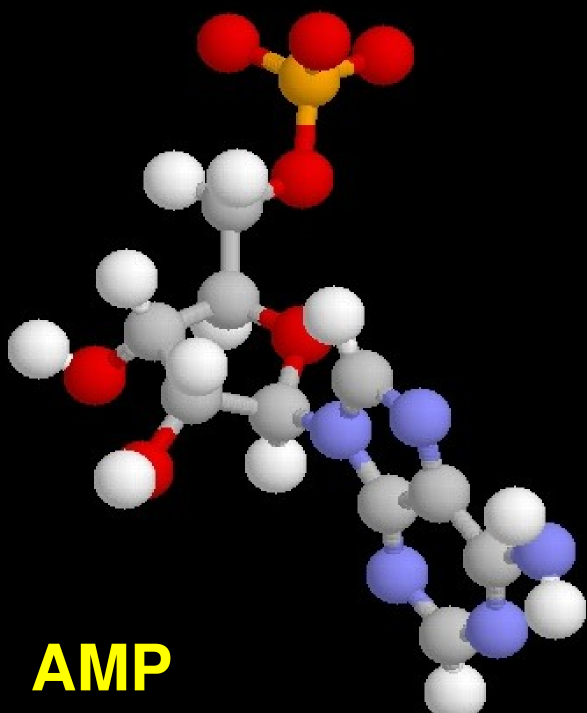
Nucleotides?



Phosphate

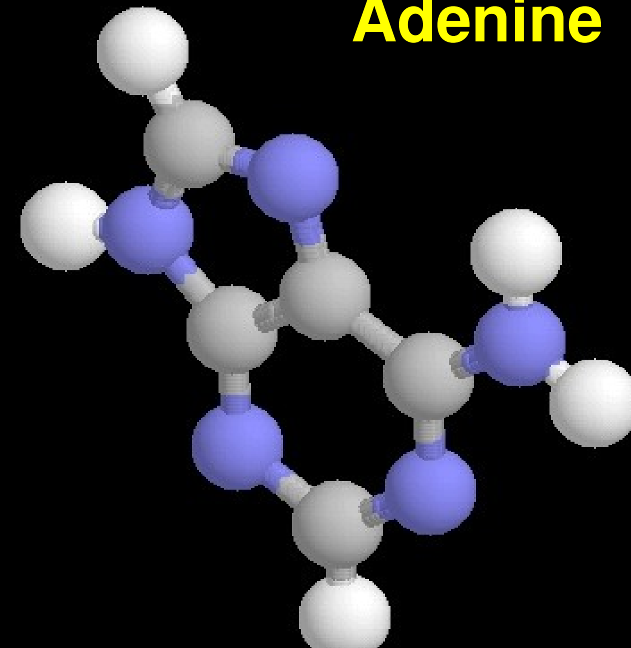
Ribose



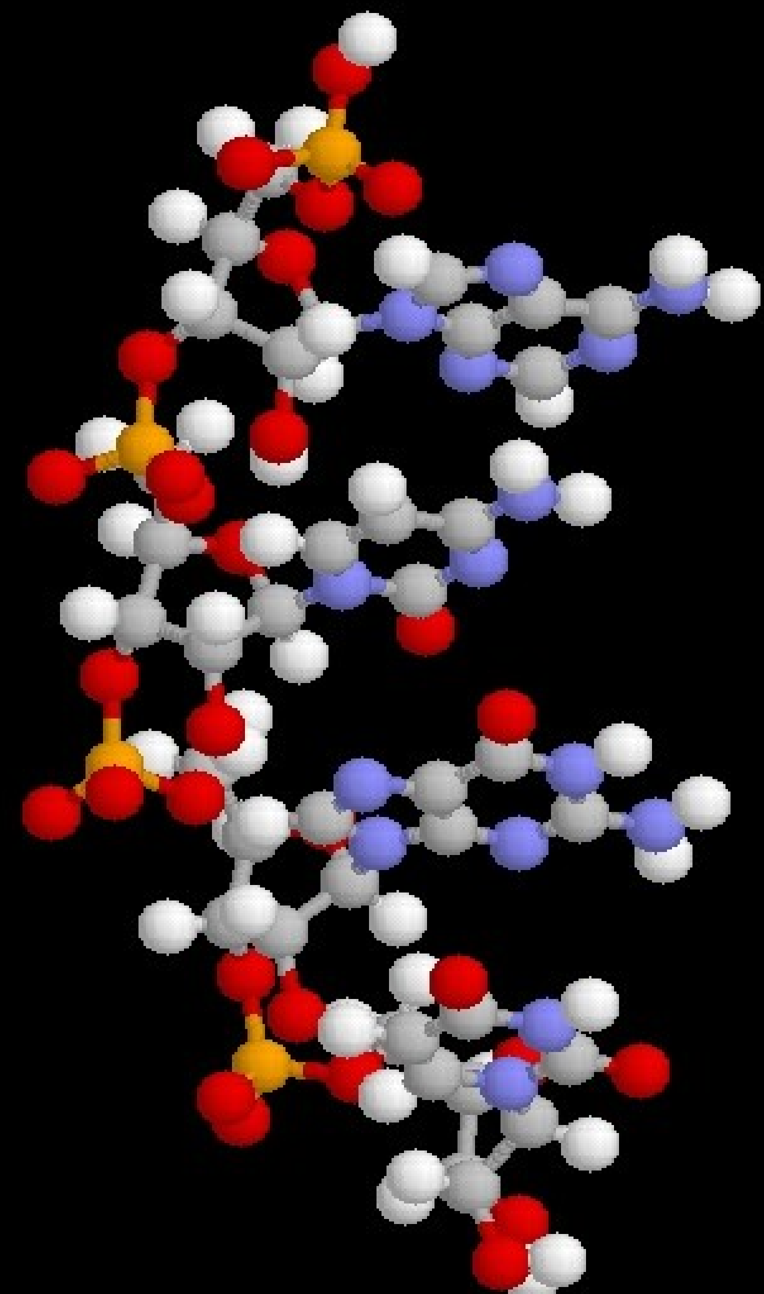


AMP

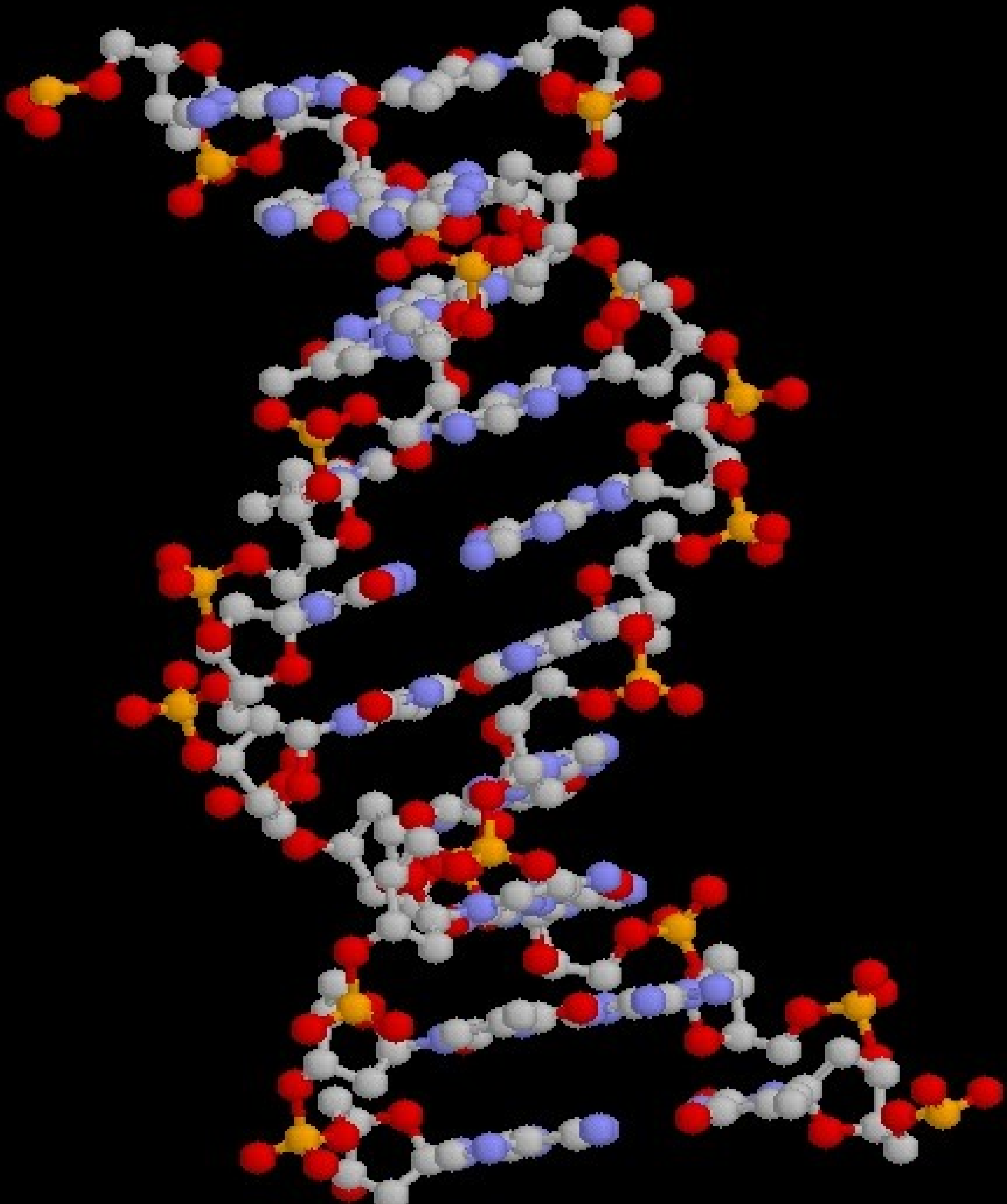
Adenine



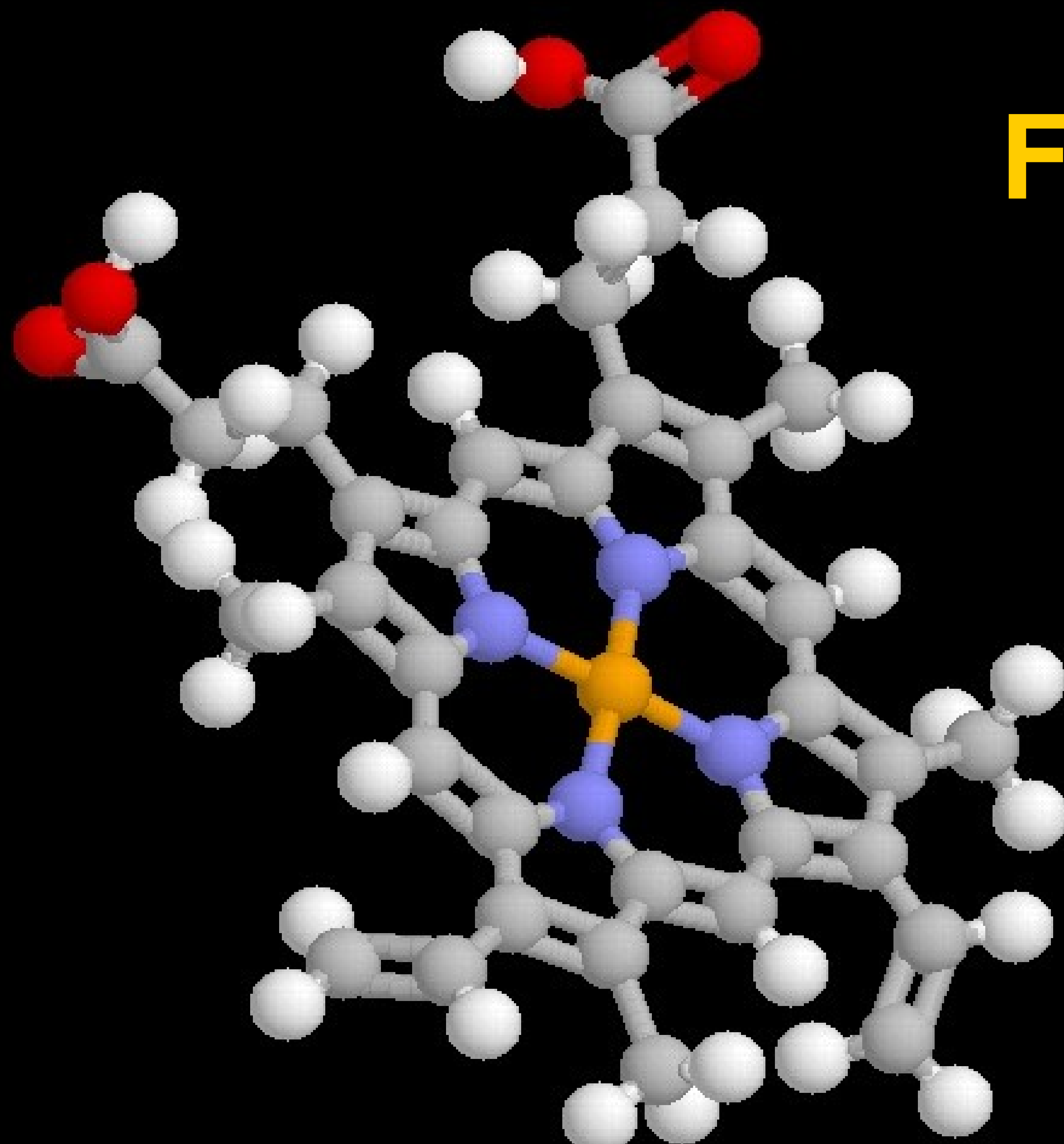
RNA?



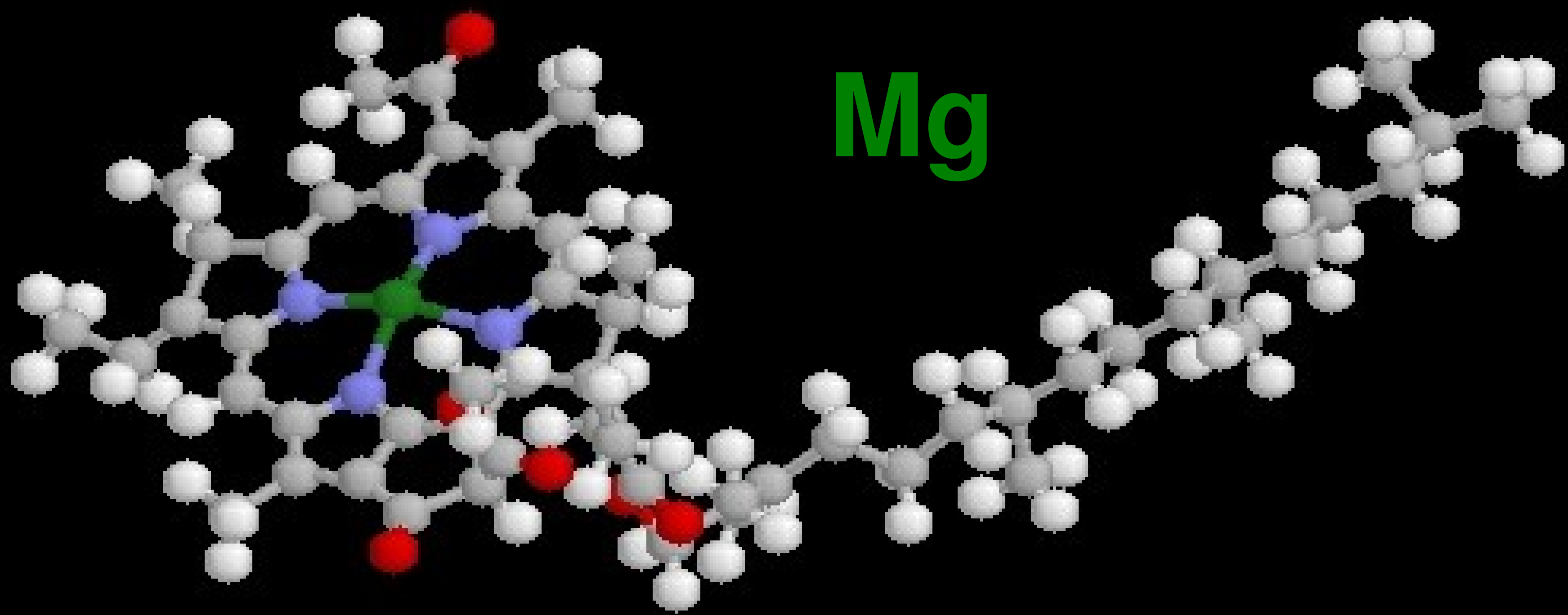
DNA?



H...?



C...?



Experiments on interstellar ice analogs – "deep space ice"

Ices spiked with ammonia and ethanol. UV irradiation.

Complex organic molecules produced including:
- the amino acids glycine, alanine, serine
- urea, aldehydes, carboxylic acids
- a class of compounds called amphiphiles that can self-organize to form membranes
- a class of compounds called quinones, aromatic ketones that play important roles in metabolism

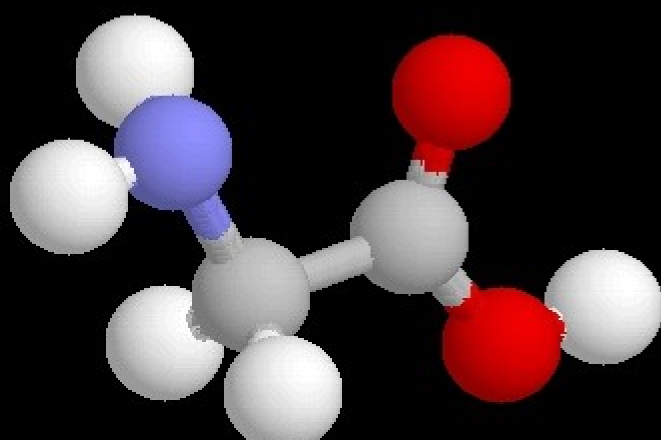
Is processing on PAH surfaces relevant? Or in mixtures involving condensed PAHs?

Amino Acids

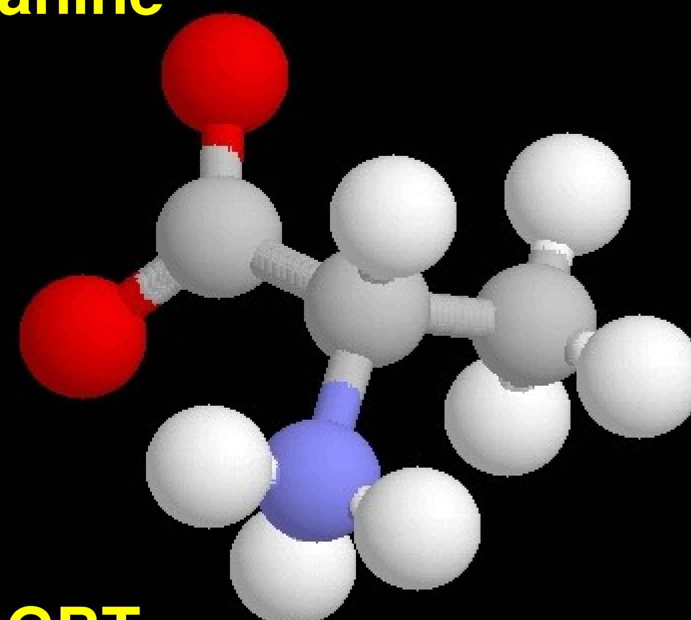
Found in carbonaceous chondrite meteorites like Murray and Murchison (along with sugar-related compounds like dihydroxyacetone).

Slight preference (7 to 9 % bias) for left-handed (as on earth).

Glycine



Alanine



Tentative – new searches with GBT

Chirality

How did the bias for l-amino acids (and d-sugars) used in life on earth arise?

Seeded by meteoritic material? How did the bias in meteorites arise?

If in interstellar/protosolar space, then one more ingredient would seem to be required: circular polarization of the ultraviolet light implicated in the molecule formation (destruction).   Amenable to experimental study with interstellar ice analogs.

Check cometary material (Stardust; Rosetta)?

Check sub-surface Mars.

Following the Path of Metals From Galaxies to Habitable Planets…

Even in the Galaxy it is a long and tortuous journey, but nevertheless it is a real trip!

It is nice that a habitable world happened at least once…

…without prejudging whether life is common in the universe and/or if we are at all special!

The End.

Really.

www.cita.utoronto.ca/~pgmartin/

Alexandria/pgmartin_lectures1_2.pdf

(does not include the animation of the cubes)