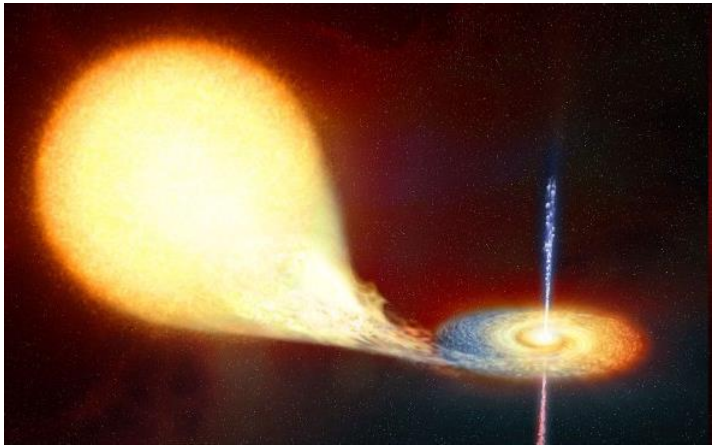
INTRODUCTION TO SPACE 25.3.2019

- The Galaxy II:
  - Stars:
    - Classification and evolution
    - Various types of stars
  - Interstellar matter: dust, gas
  - Dark matter



- ELEC-E4530 Radio astronomy: the Sun, pulsars, microquasars, masers, supernova remnants, radio Milky Way …

STARS: CLASSIFICATION

- Spectral classes based on (spectra and) temperature.

20 000 – 35 000 K

10 000 – 15 000

7 500 – 10 000

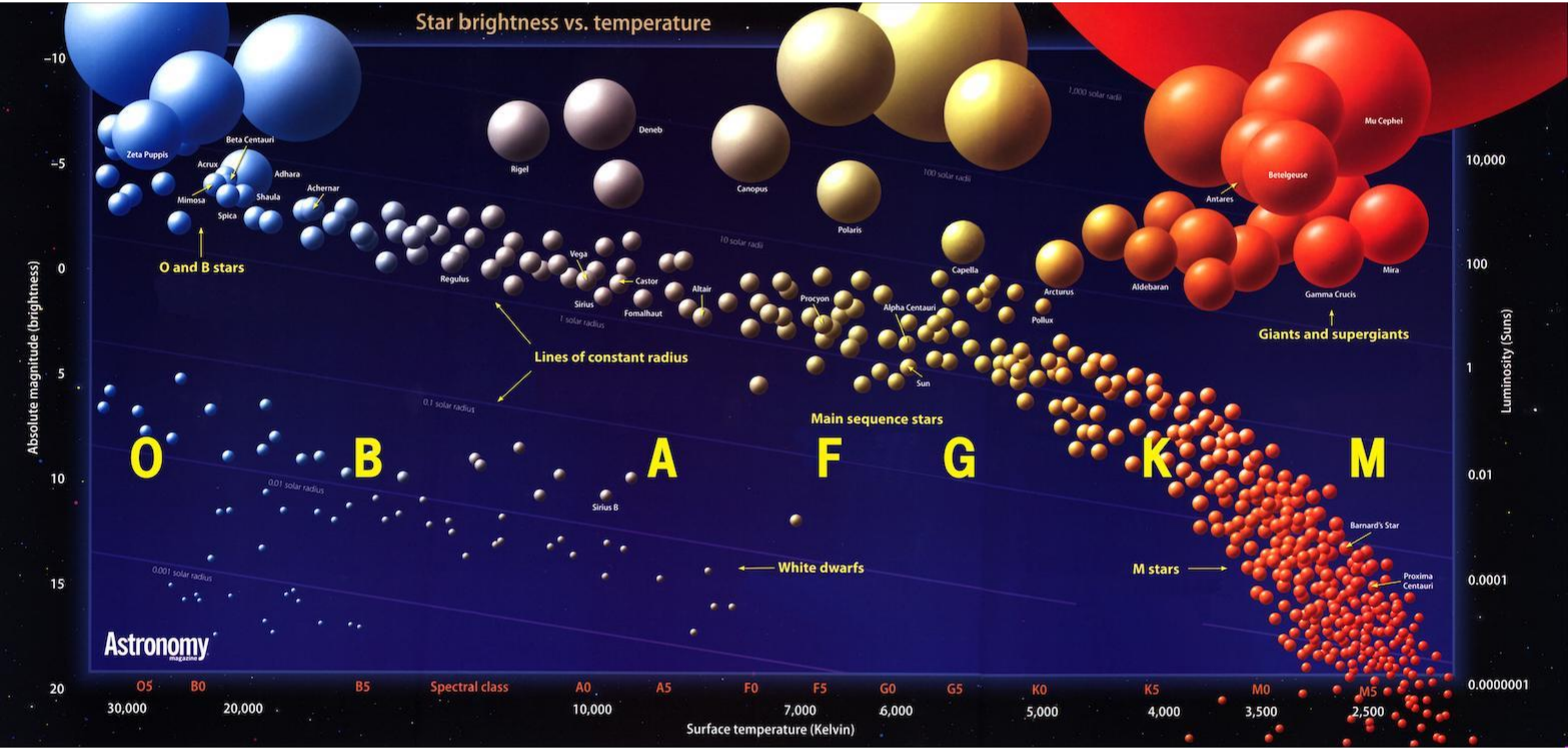
6 000 – 7 500

5 000 – 6 000

3 500 – 5 000

2 000 – 3 500

HERTZSPRUNG-RUSSELL DIAGRAM



STELLAR POPULATIONS

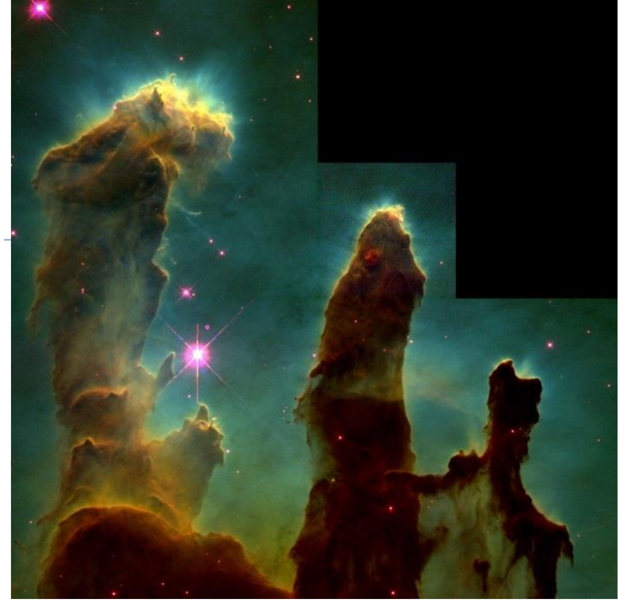
- **Population I**: young stars in the galactic plane, circular orbits, large amount of heavy elements (2 – 4%)
  - age: a few hundred million years
- **Population II**: old low-metallicity (~0.02%) stars, eccentric orbits (globular clusters, certain variable stars)
  - age: >6 billion years
- A sequence of intermediate populations, for example, the disc population (including the Sun).

STELLAR STATISTICS

- By systematically observing all stars in the solar neighbourhood ($r \leq 1$ kpc), one can find their distribution of absolute magnitudes (brightness i.e. luminosity function):
  - I. most of the nearby stars are faint.
  - II. most of the light in the solar neighbourhood is emitted by bright stars.
  - III. most of the mass in the solar neighbourhood is in faint stars.
- Only the brightest stars can be observed!
- Further away the stellar density can be calculated if one knows the luminosity function and the extinction.

luminosity function = relative number of stars with absolute magnitudes within a certain range

STELLAR EVOLUTION

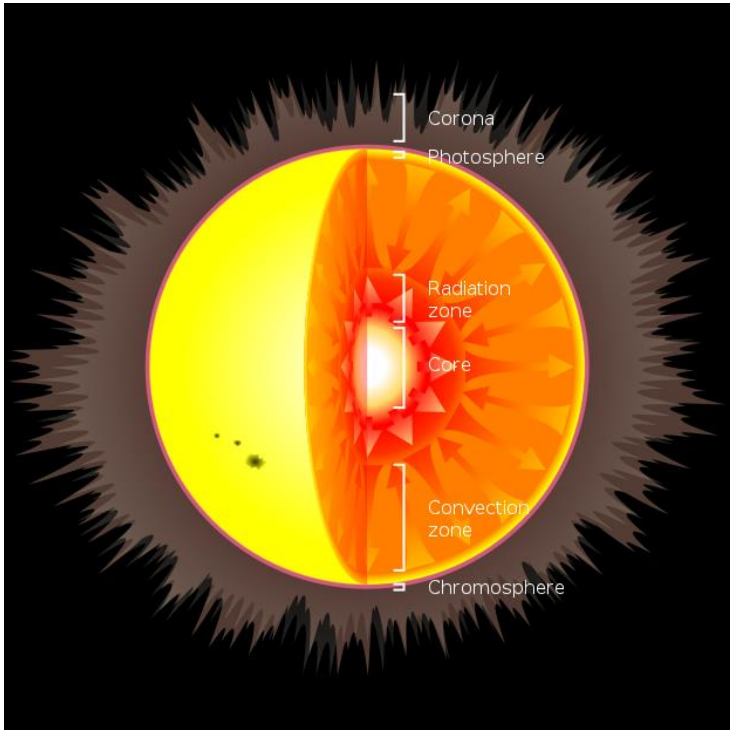


- Interstellar gas and dust clouds collapse and form protostars.
- Stars are powered by nuclear fusion of hydrogen (to helium) in the core.
  - Radiation pressure equals gravitational pressure: hydrostatic equilibrium.
- When equilibrium is achieved, the star settles in the main sequence.

- What happens next depends on the **mass** of the star.

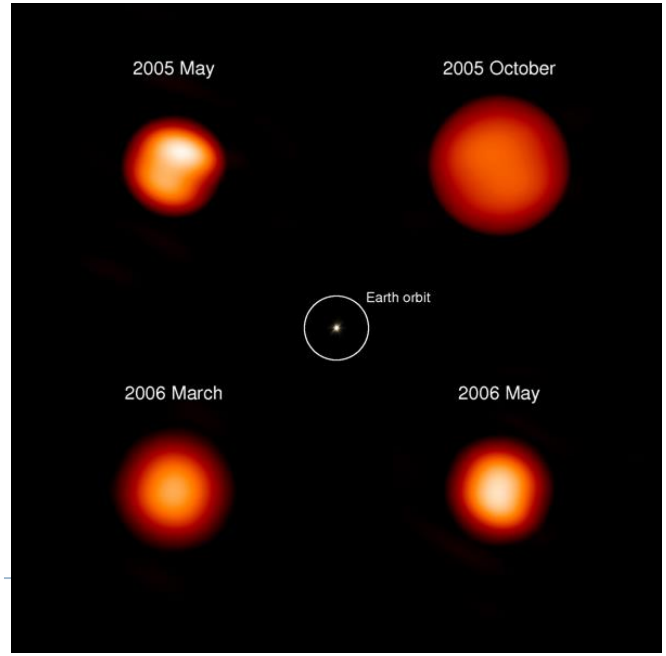
STELLAR EVOLUTION

- Very low-mass stars (< 0.26 $M_{\odot}$):
  - Fusion of hydrogen until almost the entire star is made of He.
  - Temperatures not high enough for He fusion, slow collapse.



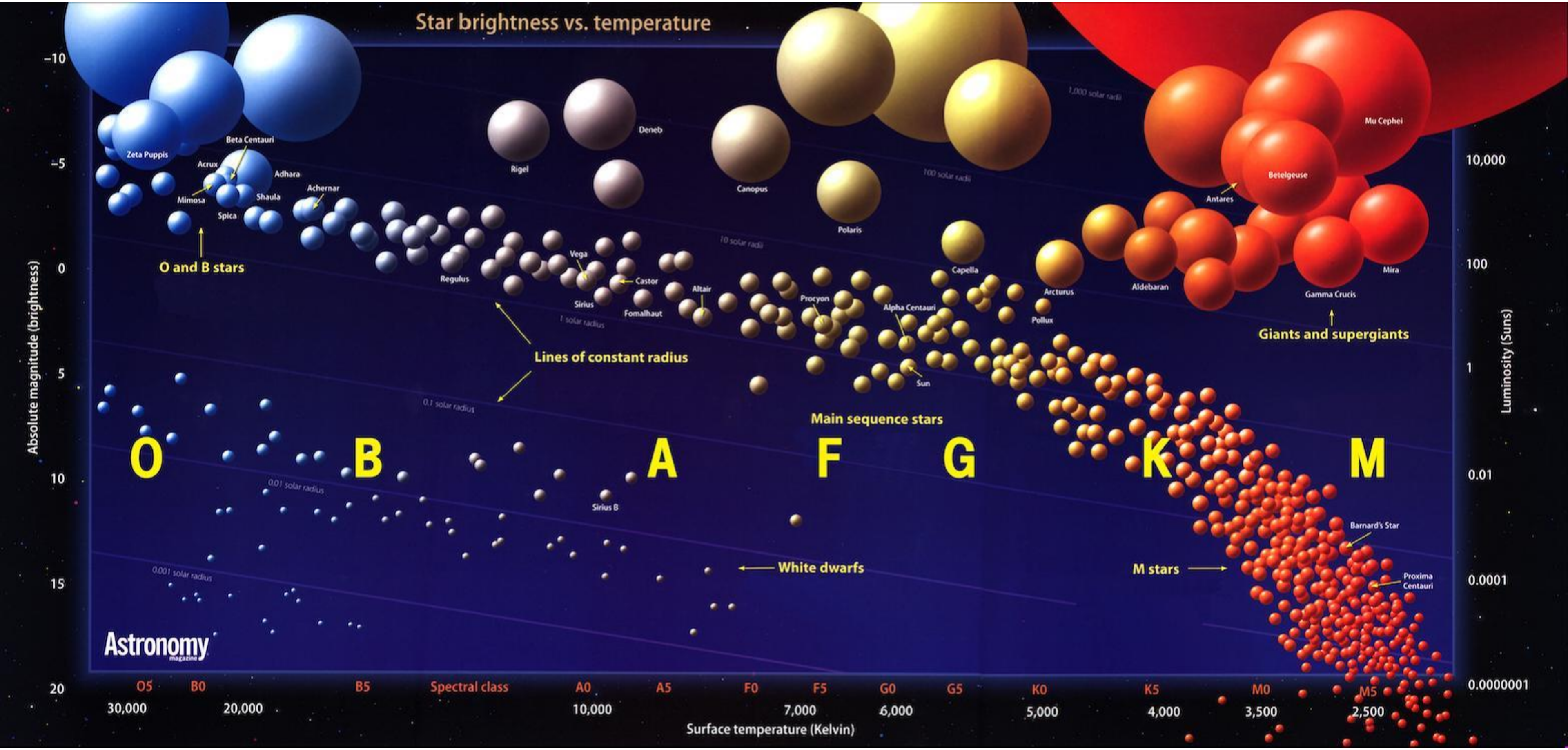
STELLAR EVOLUTION

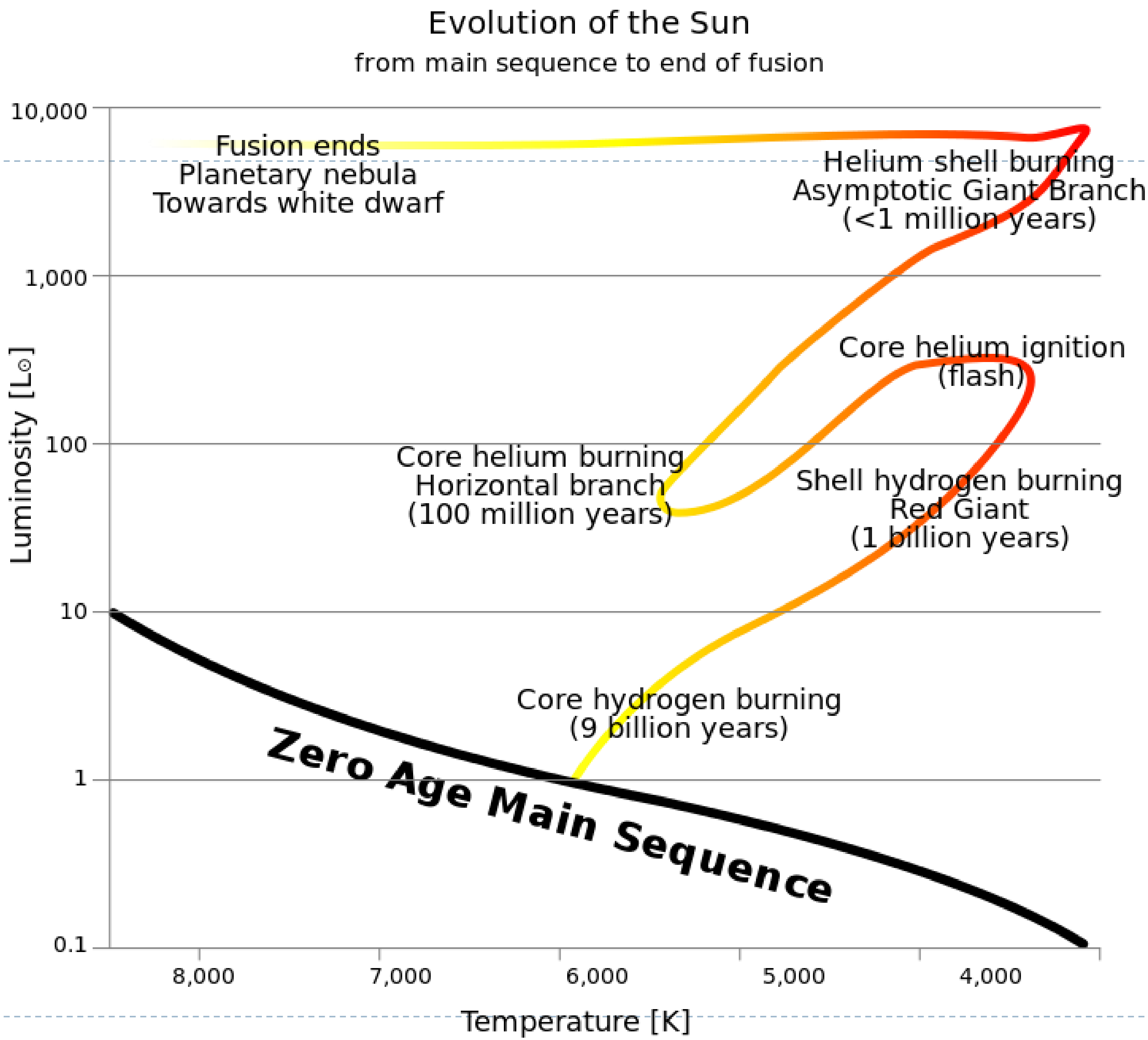
- Mid-mass stars (< 3 $M_{\odot}$) :
  - After hydrogen runs out in the core area, fusion continues in a shell around the core.
  - Radiation vs. gravitational pressure balance lost: core collapses and the star expands until new equilibrium is established (electron degeneracy vs. gravitational pressure) $\rightarrow$ red giant.
  - If hot enough, He fusion will start.
  - Shrinking & expanding, possibly pulsating, variable stars.



SAO/NASA

HERTZSPRUNG-RUSSELL DIAGRAM



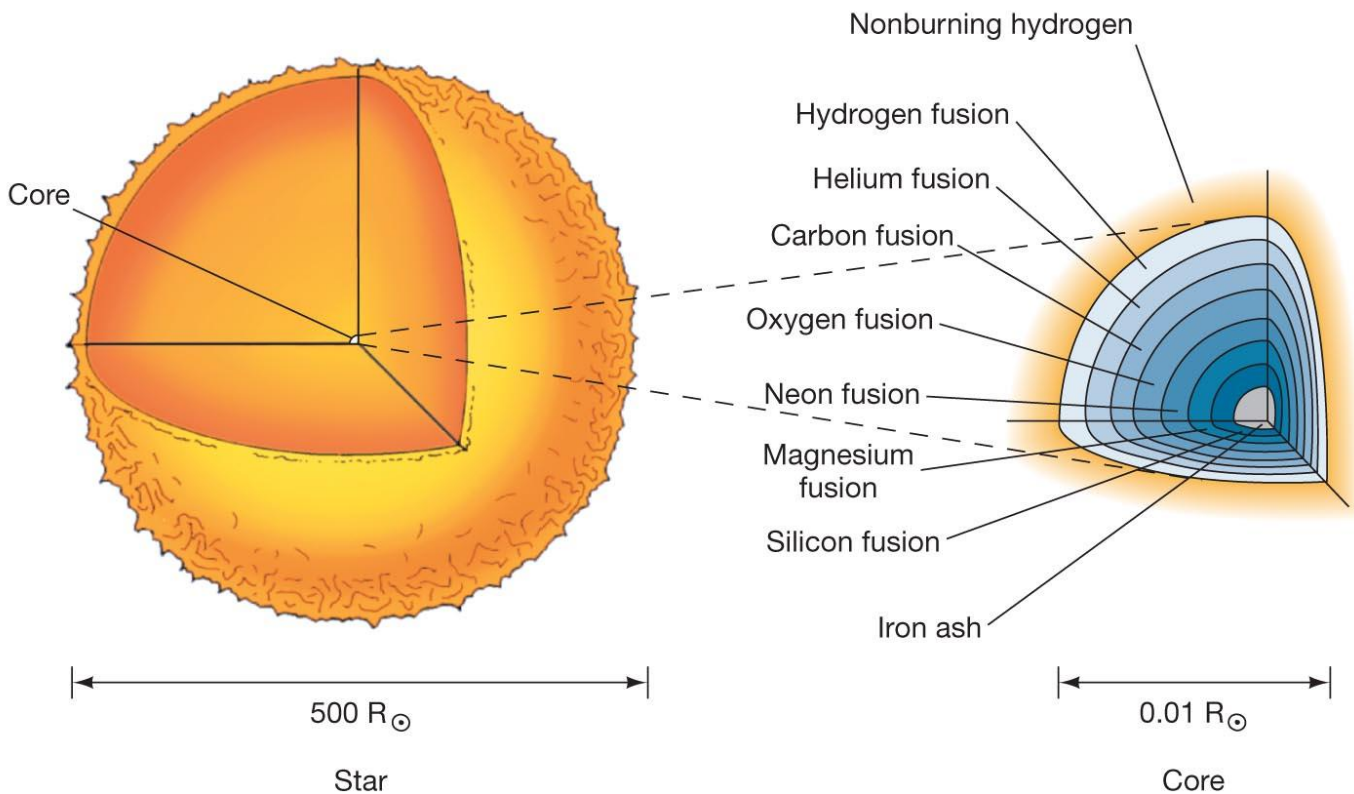


Evolution of the Sun
from main sequence to end of fusion
10,000
1,000
100
10
1
0.1
Luminosity [L☉]
8,000
7,000
6,000
5,000
4,000
Temperature [K]
Fusion ends
Planetary nebula
Towards white dwarf
Helium shell burning
Asymptotic Giant Branch
(<1 million years)
Core helium ignition
(flash)
Core helium burning
Horizontal branch
(100 million years)
Shell hydrogen burning
Red Giant
(1 billion years)
Core hydrogen burning
(9 billion years)
Zero Age Main Sequence

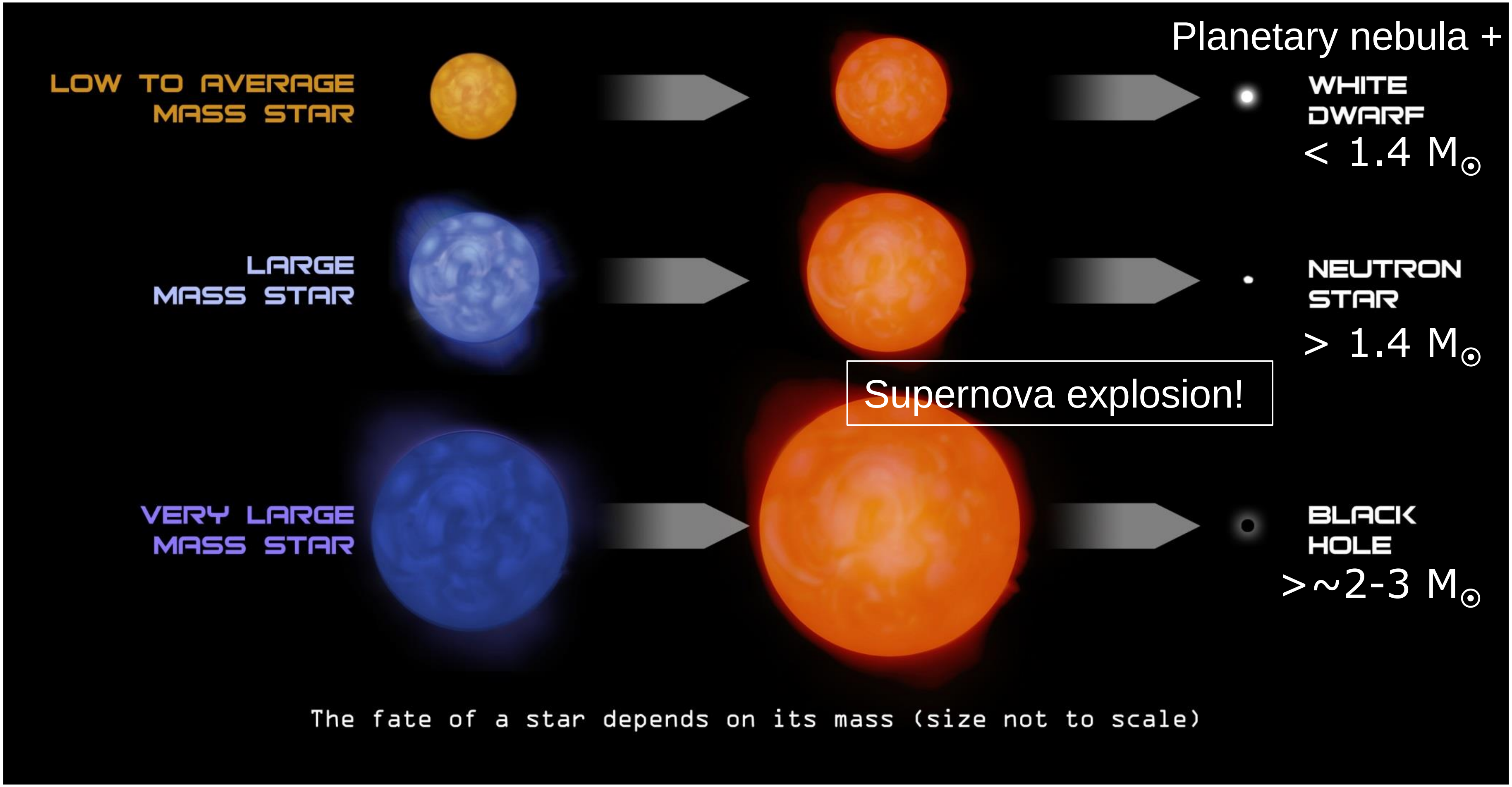
Szczureq

STELLAR EVOLUTION

- High-mass stars (> 3 $M_\odot$):
  - Continuous fusion of elements halt collapse.
  - Finally the core collapses: supernova explosion.



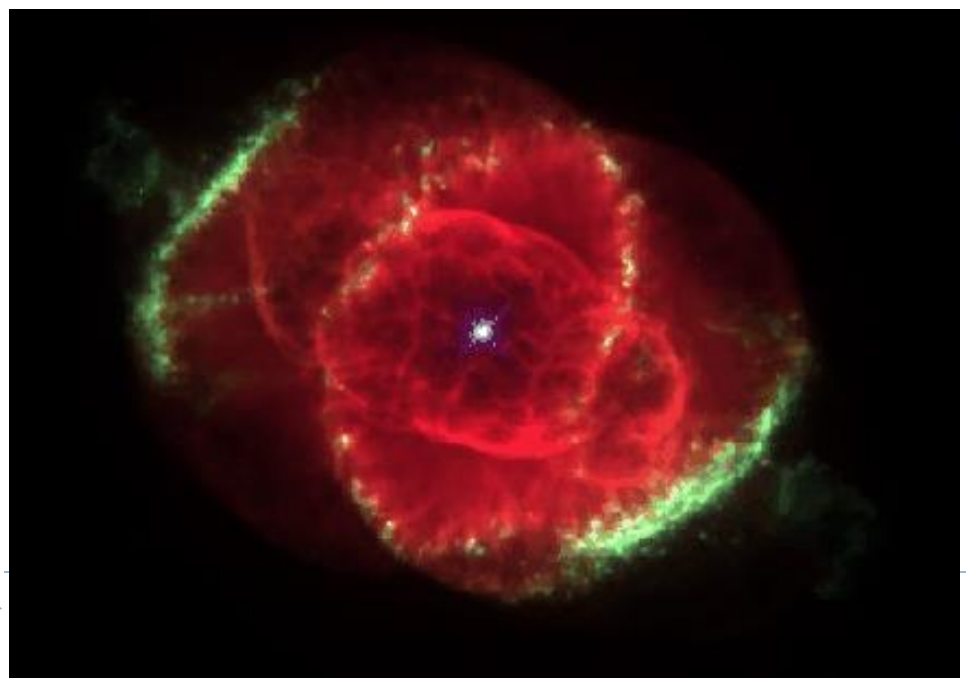
STELLAR EVOLUTION: THE END



NASA/CXC/M.Weiss

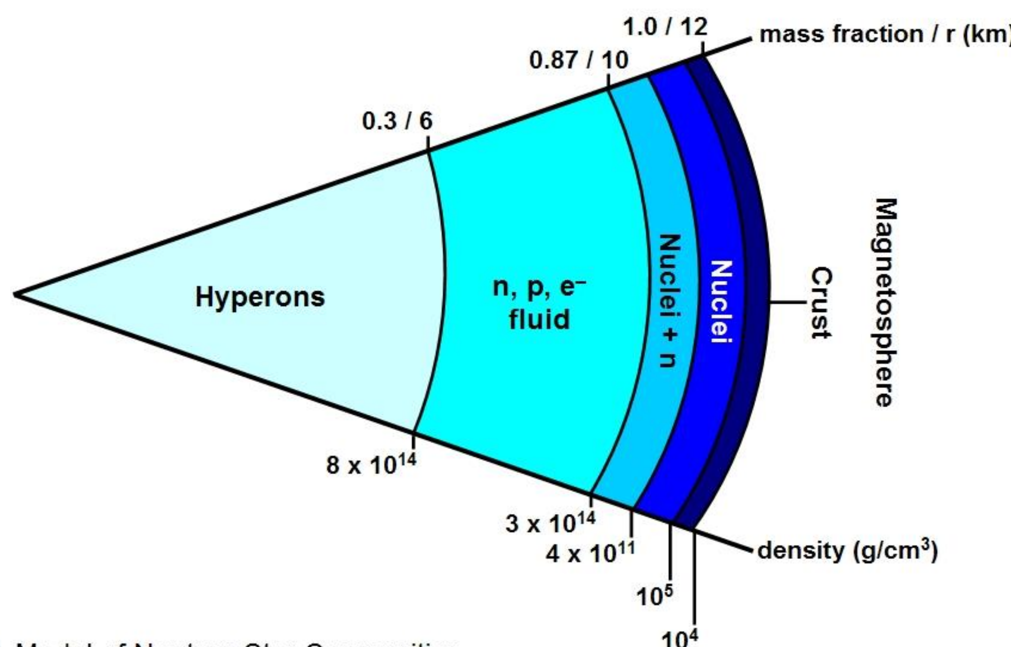
PLANETARY NEBULAE

- Expanding (~20 km/s) gas shells around old stars.
- The whole outer atmosphere of a star is ejected into space by stellar winds, ionized by UV emission.
- In a few ten thousand years the central star cools to become a white dwarf, and the planetary nebula disappears into the interstellar medium.



NEUTRON STARS

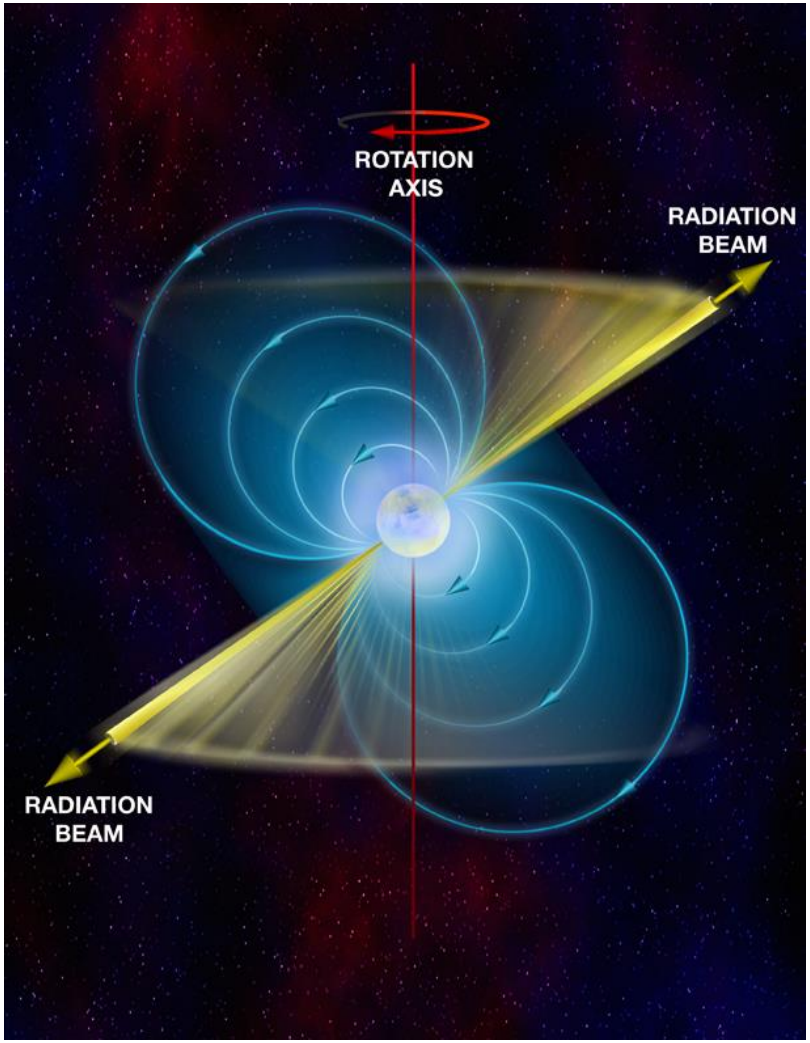
- If the mass of the collapsing star is larger than 1.4 $M_{\odot}$, a rapidly rotating neutron star is formed in a supernova explosion.
- Nuclei disappear, neutrons as suprafluid.
- Diameter typically 12 km, solid crust & surface.
- Very high rotation speeds.
- High magnetic field.



A Model of Neutron Star Composition

(Values from - Astrophysics I: Stars, Bowers & Deeming, 1984)

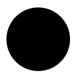
PULSARS (Radio astronomy)



Bill Saxton, NRAO/AUI/NSF

TWO MAIN TYPES OF BLACK HOLE

Stellar-mass

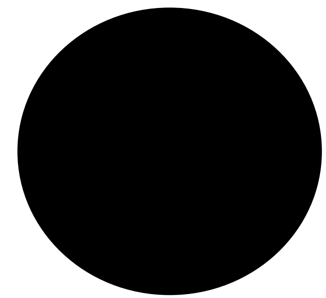


$>3\ M_\odot$ - $14\ M_\odot$

Observed in x-ray binary systems

Galactic

Supermassive



$10^6 - 10^9\ M_\odot$

Observed in the centres of galaxies

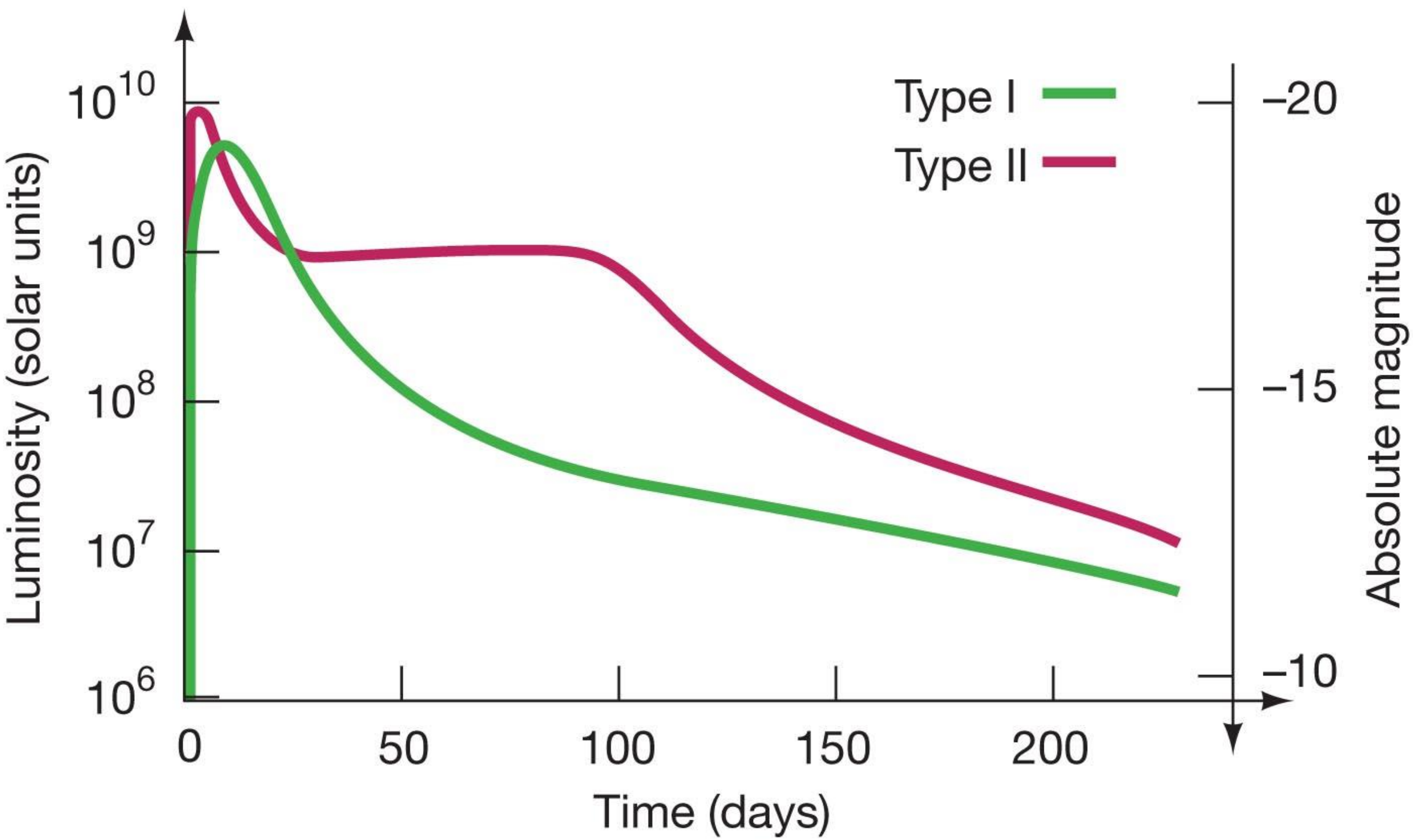
Extragalactic

SUPERNOVAE

- Star explodes: expanding (~10 000 km/s) gas shell, possibly also a neutron star or a black hole.

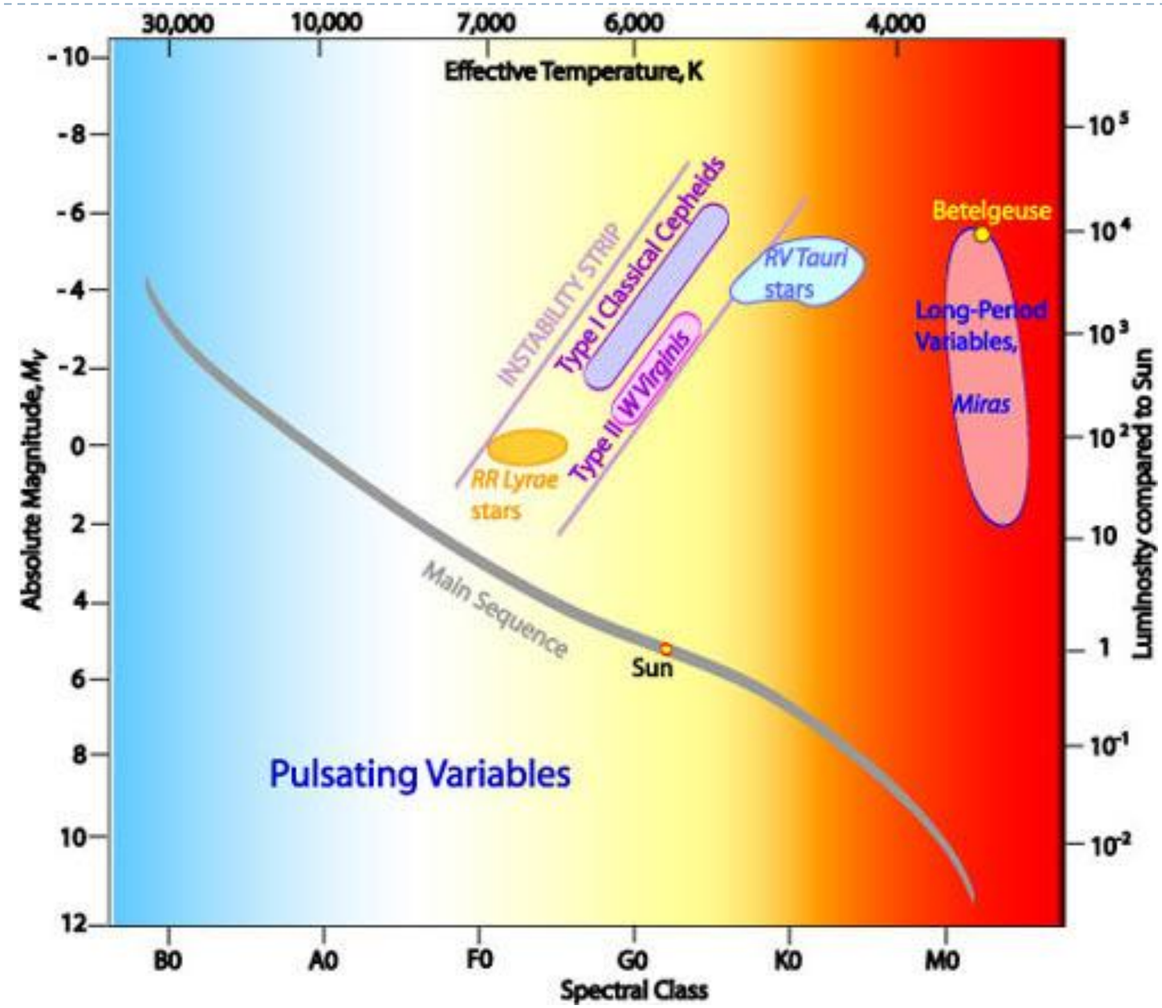
- **Type I**: fades away in a regular manner (almost exponentially), produced by old low-mass stars (white dwarfs in x-ray binary systems turned into novae by accretion).
- **Type II**: declines less regularly, maximum luminosity smaller, produced by young massive stars.

- At least 6 supernovae observed in the Galaxy, e.g. the Crab Nebula in 1054.
- Also in other galaxies (e.g., SN1987A in the Large Magellanic Cloud).


Type I
Type II
10^{10}
10^9
10^8
10^7
10^6
Luminosity (solar units)
0
50
100
150
200
Time (days)
–20
–15
–10
Absolute magnitude

VARIABLE STARS

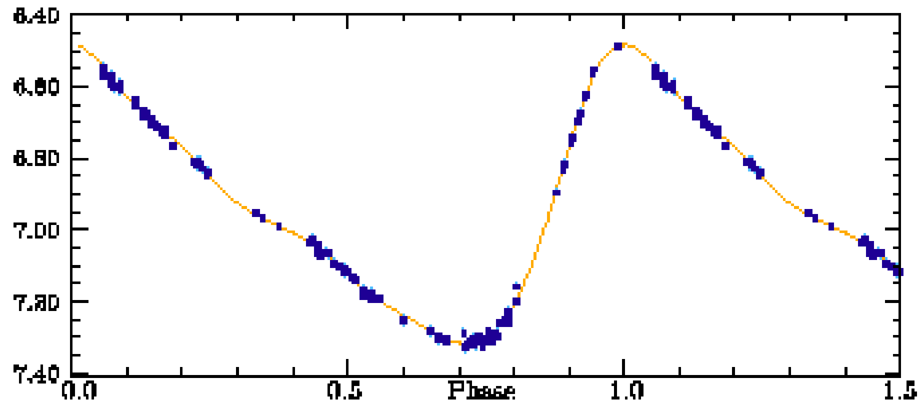
- **Pulsating stars** expand and shrink because of their evolution (giants)
  - Mira variables: 100 – 500 days, approx. 6 mag
  - Cepheids: 1 – 50 days, approx 2.5 mag
    - Two types: classical (Population I) and W Virginis (Population II in, for example, globular clusters)
  - RR Lyrae stars: <1 day, <1 mag
    - Population II in globular clusters
- **Erupting stars**
  - Flare stars (UV Ceti, T Tauri)
  - Novae (binary and multiple stars can exchange mass)
  - Supernovae
- **Eclipsing stars** (binary/multiple stars, extrasolar planets)


30,000
10,000
7,000
6,000
4,000
Effective Temperature, K
Absolute Magnitude, M_V
Luminosity compared to Sun
INSTABILITY STRIP
Type I Classical Cepheids
Type II W Virginis
RV Tauri stars
Betelgeuse
Long-Period Variables,
Miras
RR Lyrae stars
Main Sequence
Sun
Pulsating Variables
B0
A0
F0
G0
K0
M0
Spectral Class

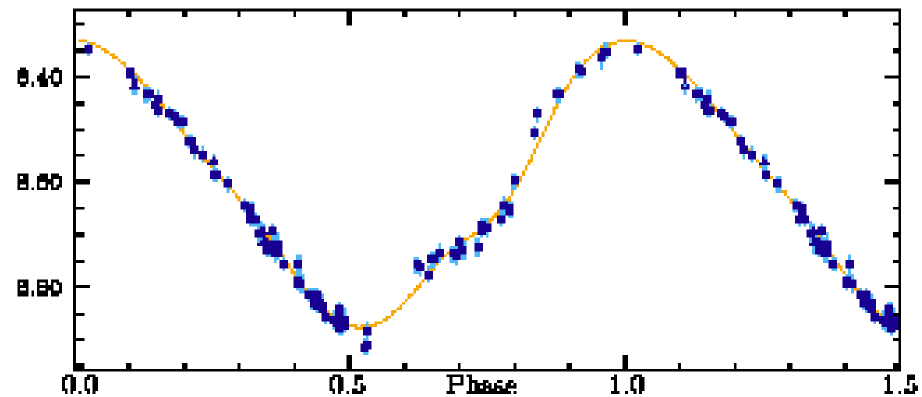
ATNF/CSIRO

CEPHEID PERIOD-LUMINOSITY RELATION

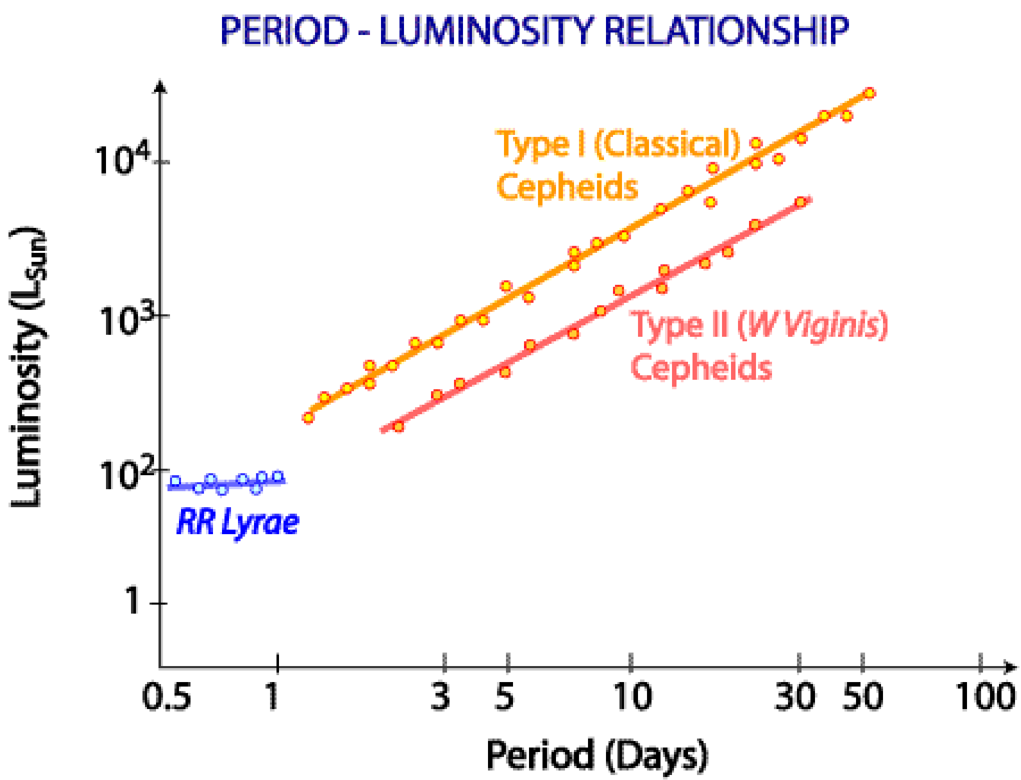
- Classical
- W Virginis



- Period depends on the density of the star, so do the size (and temperature) and therefore luminosity.



M_V=-1.6 - 2.6 lg(P/1d)



ATNF/CSIRO

- **Cepheids**: variation period is related to the luminosity i.e. M
- **RR Lyrae** stars all have the same M
- Supernova Type I (decay rate vs. brightness i.e. M)

MEASURING COSMIC DISTANCES

The cosmic distance ladder

- Parallax: up to a few hundred light years
- Variable stars
- Cosmological redshift
- Gravitational waves
- …

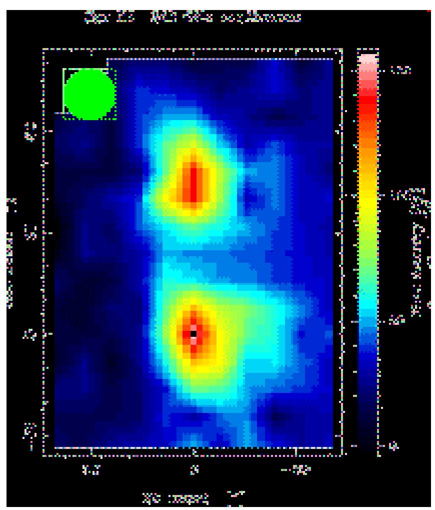
Redshift and Hubble's constant discussed next week!

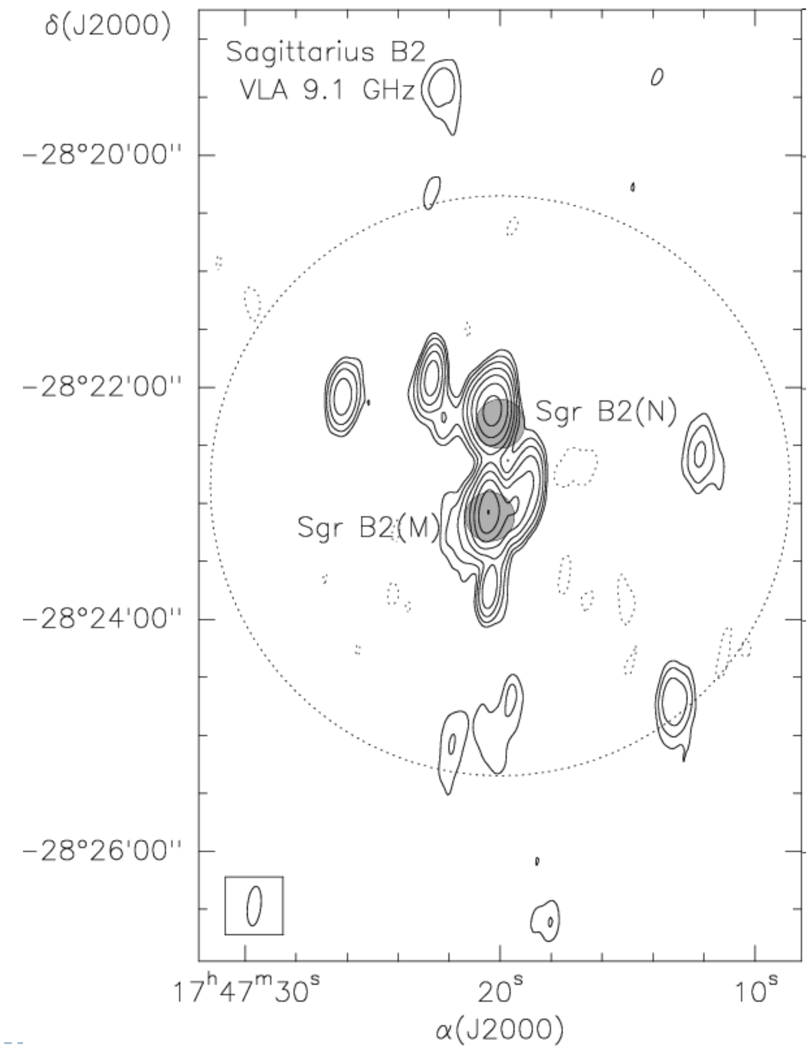
INTERSTELLAR MEDIUM, ISM

- Most of the mass is in stars.
- In the space between the stars in the Galaxy there is, in clouds and as a diffuse medium:
  - gas: 1 atom / cm^3
  - dust: 1 particle / 100 000 cm^3
  - molecules: 1 molecule / 10^{14} cm^3
- Concentrated in the galactic plane:
  - 100 pc layer of dust
  - 200 pc layer of gas.

EXAMPLE: INTERSTELLAR MEDIUM

For 10 grams of alcohol we need a molecular cloud with a size of 1.3×10^{38} cm^3.
In the cloud Sgr B2 there are 10^{28} bottles of booze.

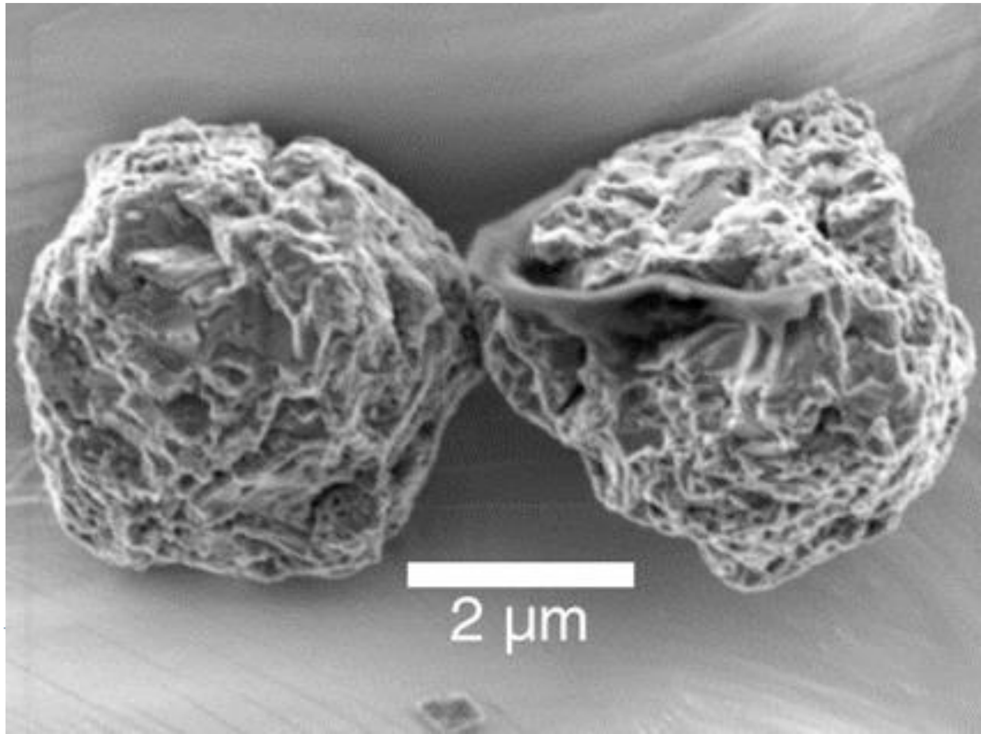




DUST

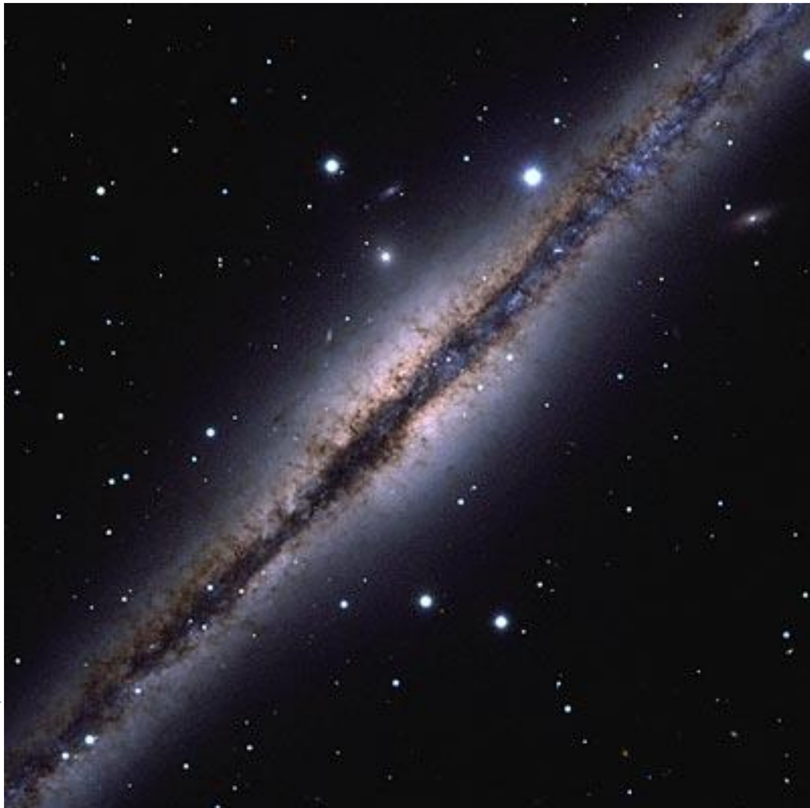
- The amount of dust is 1 % of the amount of gas.
- At the inner edges of spiral arms, also in individual clouds.
- Composition: at least water ice, silicates, graphite.
- Particle size usually < 1 µm.

Stardust grains extracted from a meteorite.



DUST

- Formed in the atmospheres of stars, in connection with star formation, and possibly also directly from atoms and molecules in interstellar clouds.
- Induces extinction and reddening.
  - Strongest scattering due to grains of about 0.3 μm.
- IR observations!



DUST

- Dark nebulae (cold, 10 - 20 K)
  - star-poor regions
- Reflection nebulae (warm, 100 - 600 K)
  - Dust cloud scatters the light of a nearby bright star.
  - The colour depends on the colour of the star.
  - The size depends on the brightness of the star.
  - (Don’t confuse with emission nebulae that are HII regions.)

- Diffuse galactic light constitutes 20 - 30 % of the total brightness of the Galaxy.




INTERSTELLAR GAS

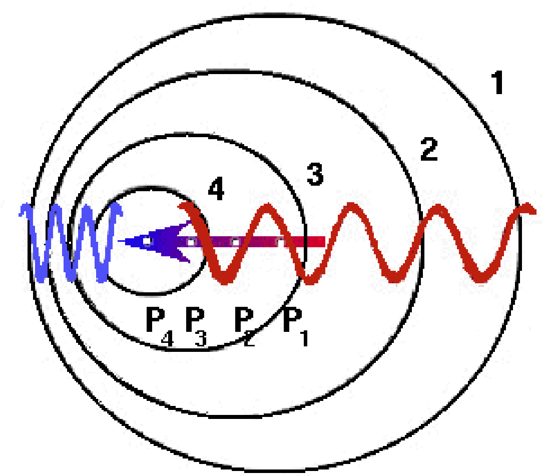
- The amount of gas is 10 % of the total mass of the Galaxy.
- Does not induce extinction, yet difficult to observe optically (only a few spectral lines).
- Most elements are ionized (UV emission from stars, cosmic rays).
- 30 elements, ~90 % H, ~10 % He. There are less of the heavier elements than in the Sun or in stars $\Rightarrow$ incorporated into dust grains, do not produce absorption lines.

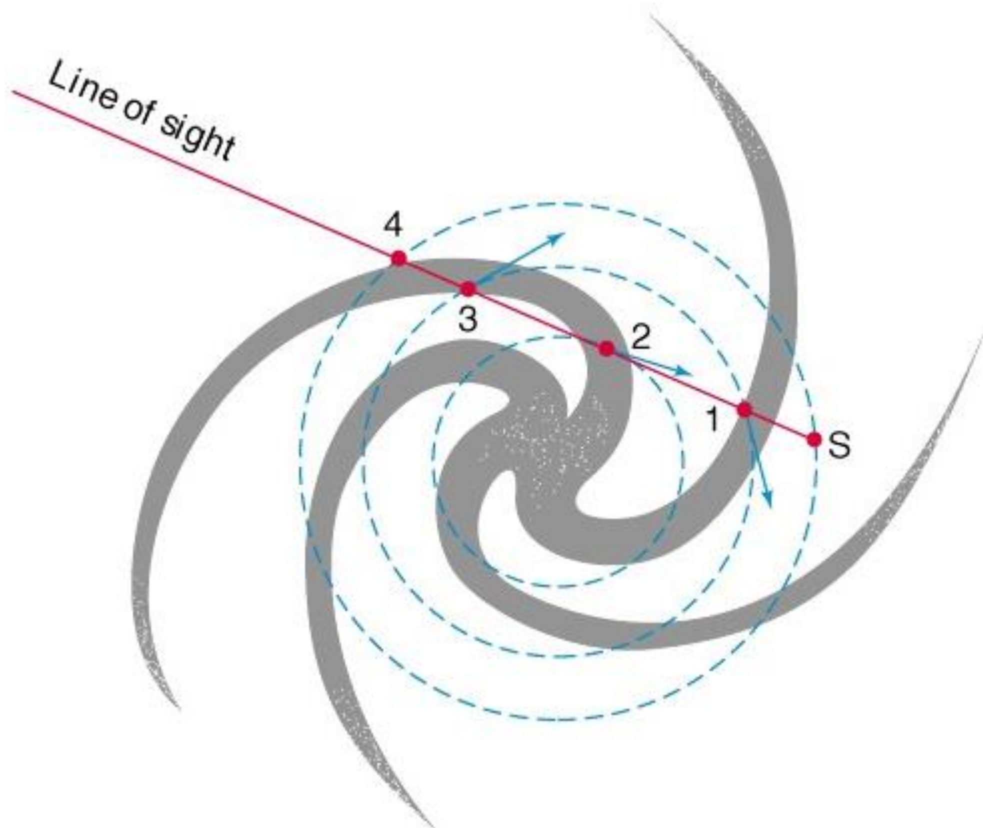
DISTRIBUTION OF INTERSTELLAR MATTER

- Determine the distance and the number of objects.

- Gas clouds at different distances have different velocities, therefore give rise to emission lines with different Doppler shifts (the emitted wavelength changes when the emitter moves relative to the observer).
  - Redshift (λ increases)
  - Blueshift (λ decreases)

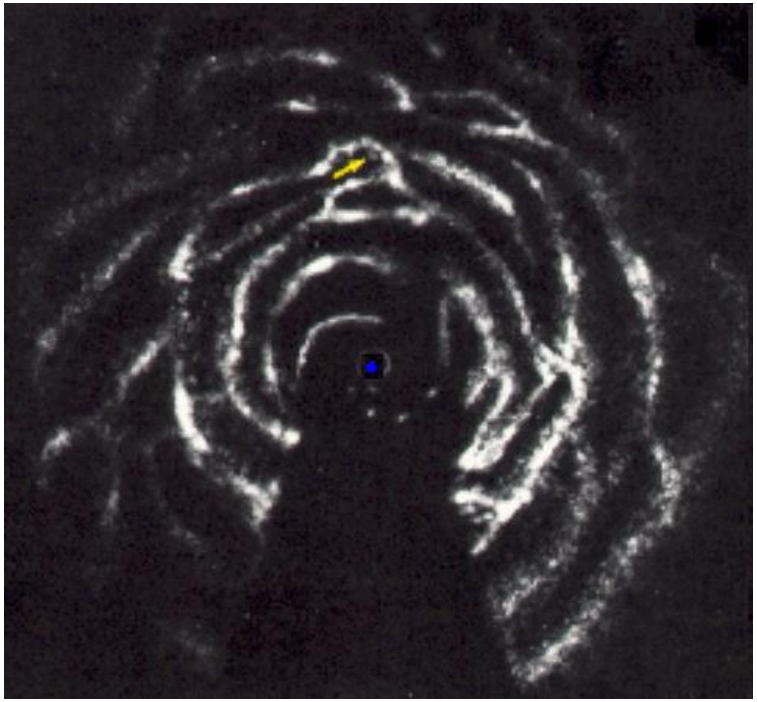
$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$




Line of sight
4
3
2
1
S

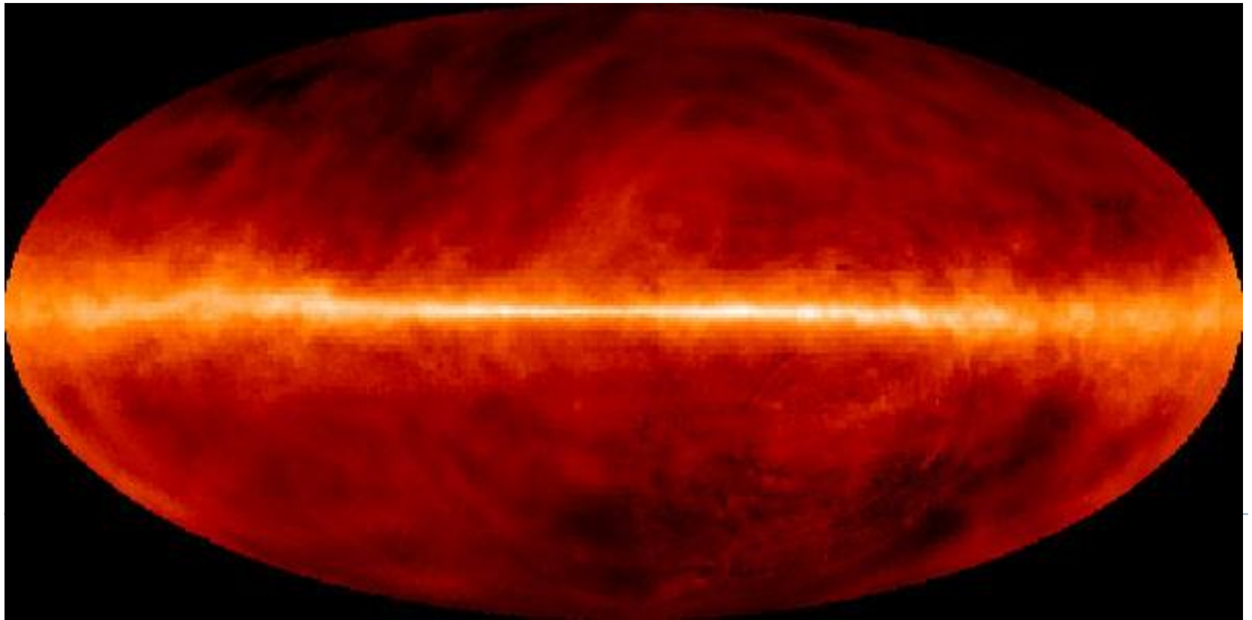
H I (neutral i.e. atomic hydrogen)

- Abundant, suits very well for studying the ISM and the Galaxy .
- Mapping of HI reveals:
  - The Galaxy is a spiral galaxy, HI concentrated in the spiral arms.
  - Density and distribution.
  - Temperature.
  - Rotation.



GALACTIC H I

- Mass ~3 – 5 x 10^9 $M_\odot$
- Mostly in the galactic plane, but not smoothly distributed → clumps, cirrus clouds, filaments…
  - Density ~0.7 atoms / cm^3 within 1 kpc radius of the Sun
  - In the solar neighbourhood (~10 pc), 0.02 - 0.1 atoms / cm^3
- Temperature in warm component ~8000 K, in cold clouds 40 – 140 K

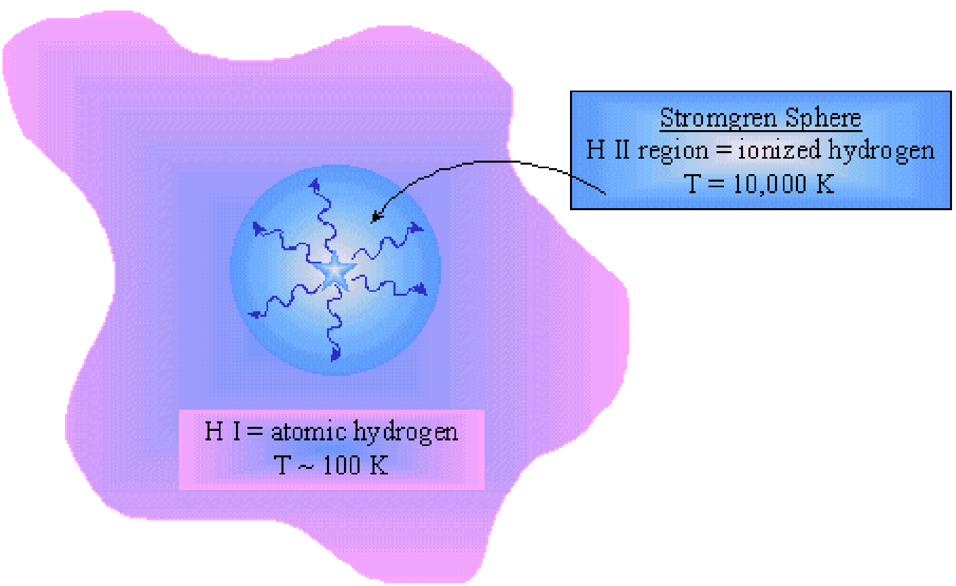


H II (ionized hydrogen)

- HII regions, emission nebulae,.
- Typically around hot O type stars.
- H ionized by UV radiation, temperature 8000 – 10 000 K.
  - H atom remains ionized for hundreds of years, neutral for only a few months.

H II

- Boundary between HII and HI regions is sharp, because HI absorbs UV radiation efficiently.
  - Strömgren sphere (1 - 50 pc)

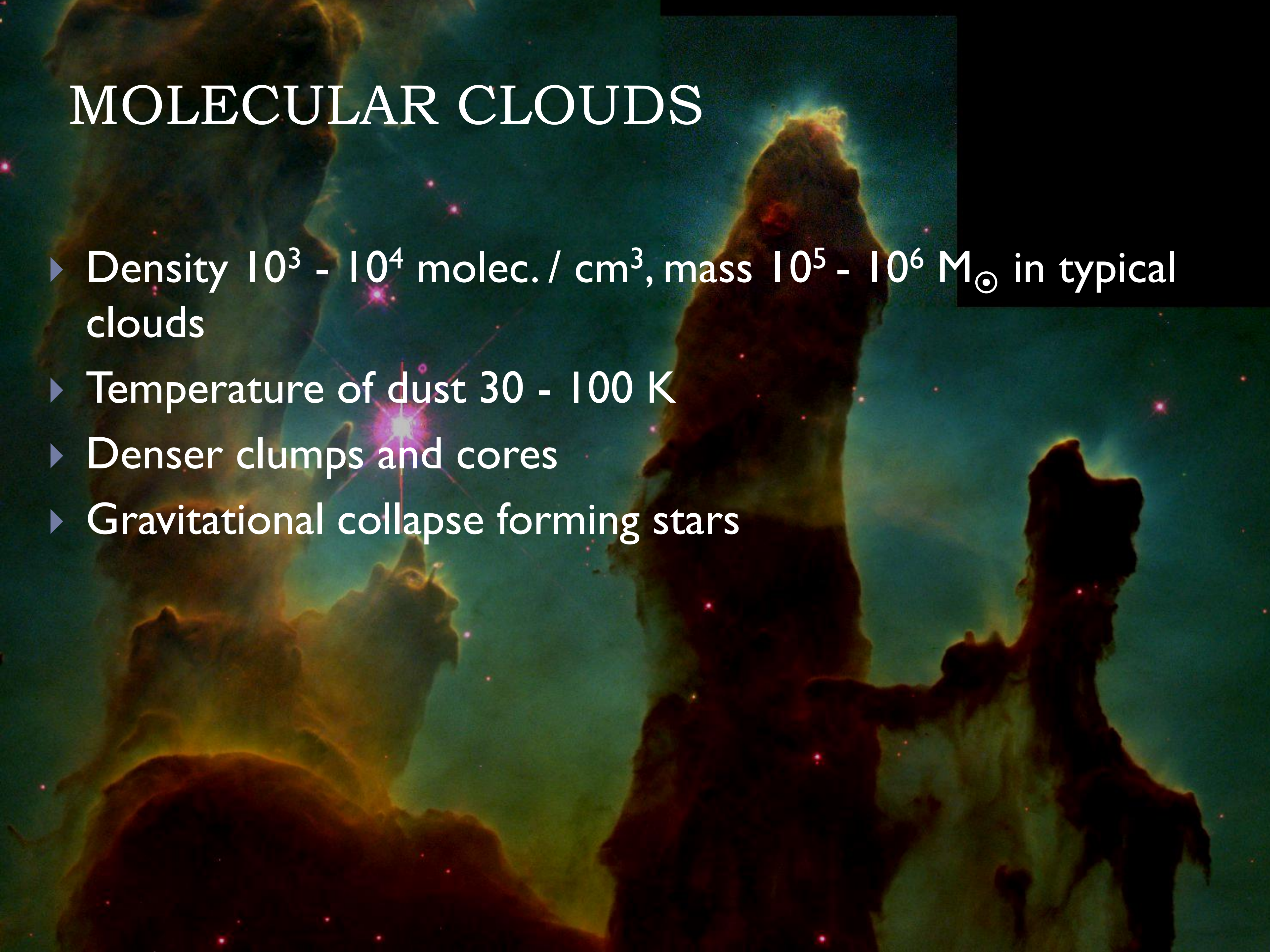


INTERSTELLAR MOLECULES

- Discovered at optical and UV frequencies, examples:
  - methylidyne CH (1937)
  - cyanogen CN (1938)
  - hydrogen molecule H_2 (1970)
- Discovered at radio frequencies, examples:
  - hydroxyl radical OH (1963)
  - carbon monoxide CO (1970)
  - silicon monoxide SiO (1971)
  - water H_20 (1969)
  - hydrogen cyanide HCN (1970)
  - ammonia NH_3 (1968)
  - ethanol C_2H_5OH (1975)

INTERSTELLAR MOLECULES

- Approx. 200 molecules found so far.
- Formation and preservation require dense clouds.
- Form through collisions or on the surface of dust grains (or in gas clouds).
- Dark nebulae or dense molecular clouds in the vicinity of HII regions the most favourable environment.



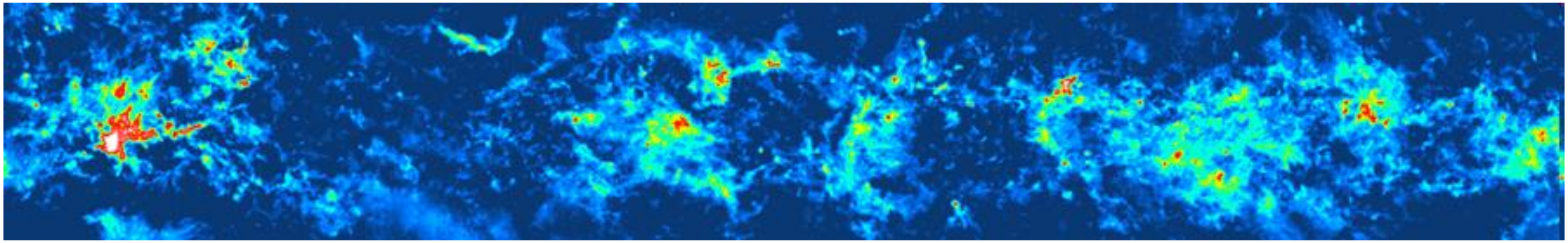
MOLECULAR CLOUDS

- Density 10^3 - 10^4 molec. / cm^3, mass 10^5 - 10^6 $M_{\odot}$ in typical clouds
- Temperature of dust 30 - 100 K
- Denser clumps and cores
- Gravitational collapse forming stars

MOLECULAR CLOUDS

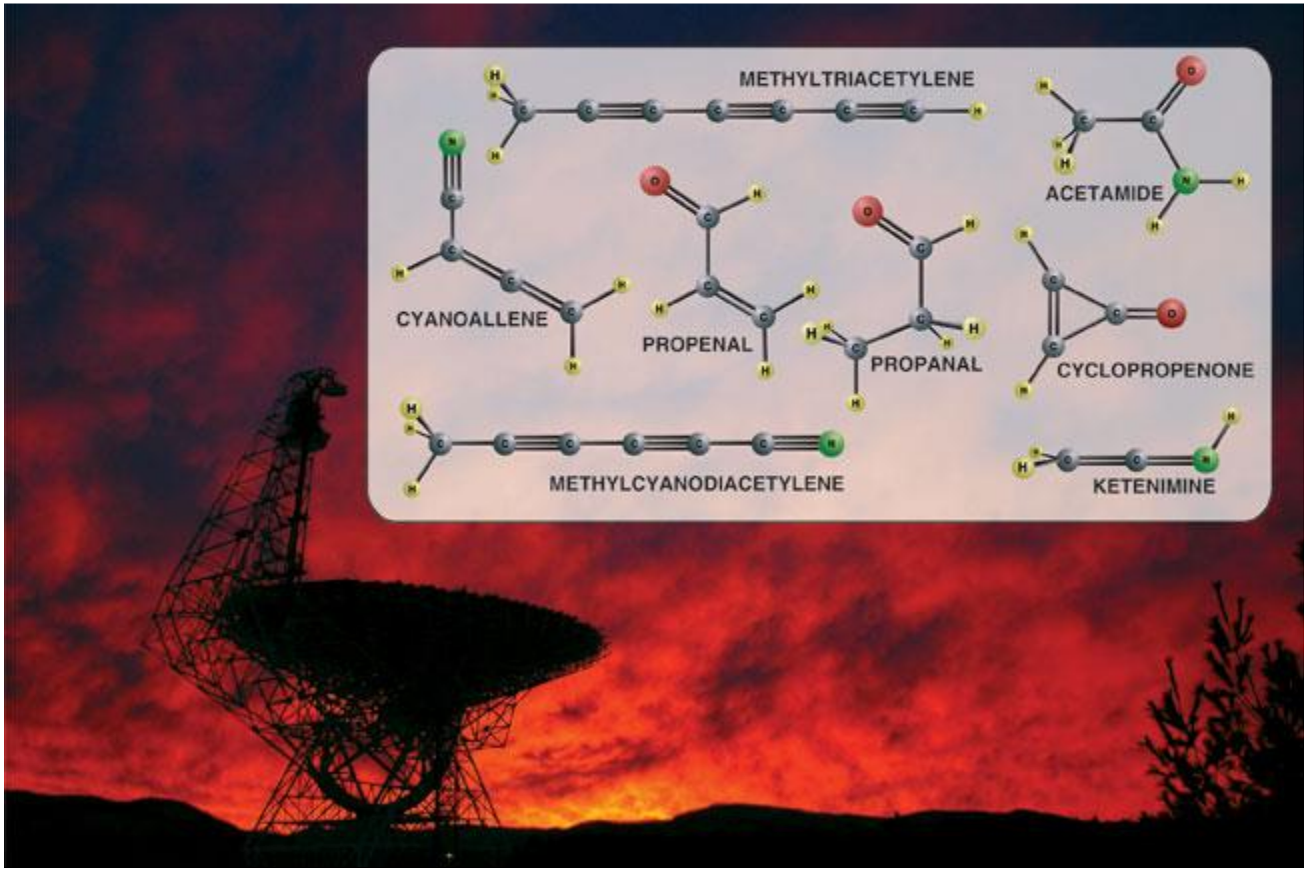
- Most abundant H_2, second CO.
- Significant fraction of all hydrogen is molecular, H_2.
- Fraction of H_2 increases strongly with density and extinction.
  - Formed on the surface of interstellar dust grains.
  - Enables studies of the relation between gas and dust.

- *For example, Sgr B2 contains almost all interstellar molecules found. Some molecules are found *only* in Sgr B2!*



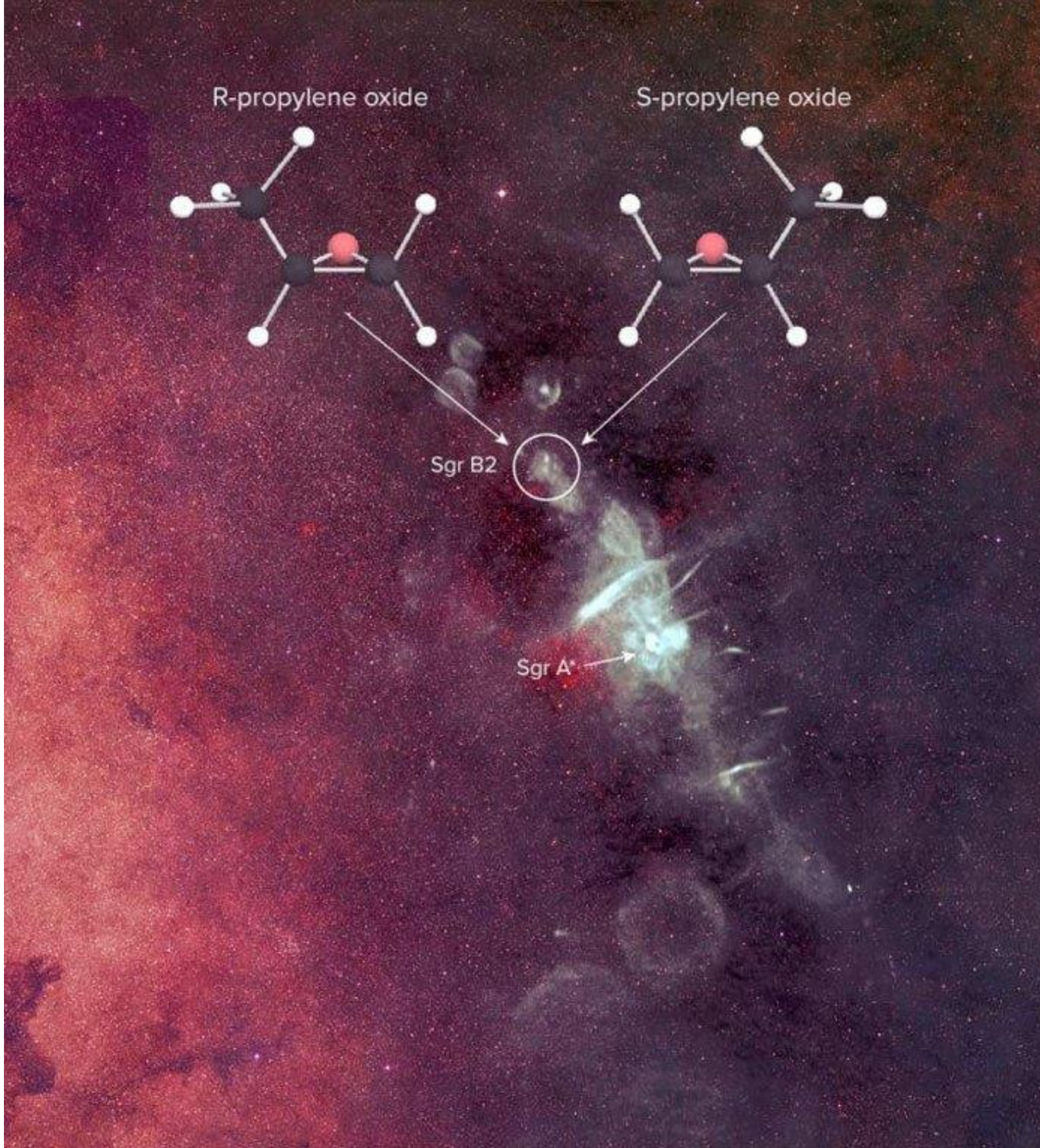
Galactic ring of CO at 110 GHz

ORGANIC MOLECULES



NRAO

- June 2016



B. Saxton, NRAO/AUI/NSF

FORMS OF GAS IN THE ISM

- Gas in equilibrium is either hot and diffuse, or cold and dense.

1. Hot ionized gas

- 10^5 - 10^6 K, density 10^{-3} atoms / cm^3, mass fraction < 0.1 %
- shells of supernova remnants (UV, x-rays)

2. Warm ionized gas

- 8000 - 10 000 K, density >0.3, mass fraction ~1%
- HII (bremsstrahlung, recombination lines)

FORMS OF ISM GAS

3. Warm neutral gas

- 1000 - 8000 K, density 0.05 - 0.3, mass fraction ~20%
- gas between HI clouds (21 cm line)

4. Cool neutral gas

- 100 K, density 20, mass fraction ~25%
- HI (21 cm) and molecular hydrogen H_2

5. Cold neutral gas

- 20 K, density $\geq 10^3$, mass fraction ~45%
- H_2, other molecules (molecular lines)

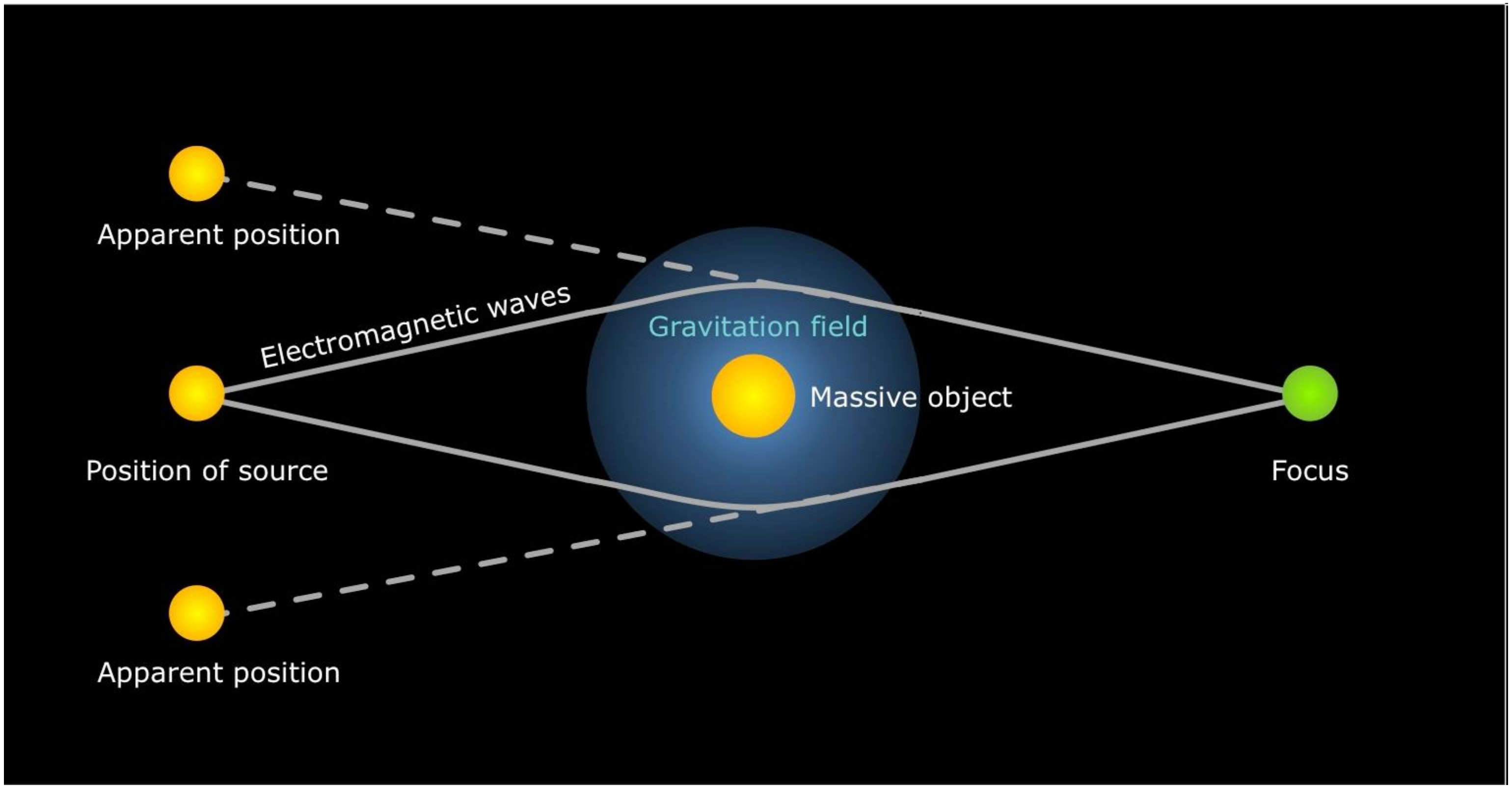
DARK MATTER?

DARK MATTER

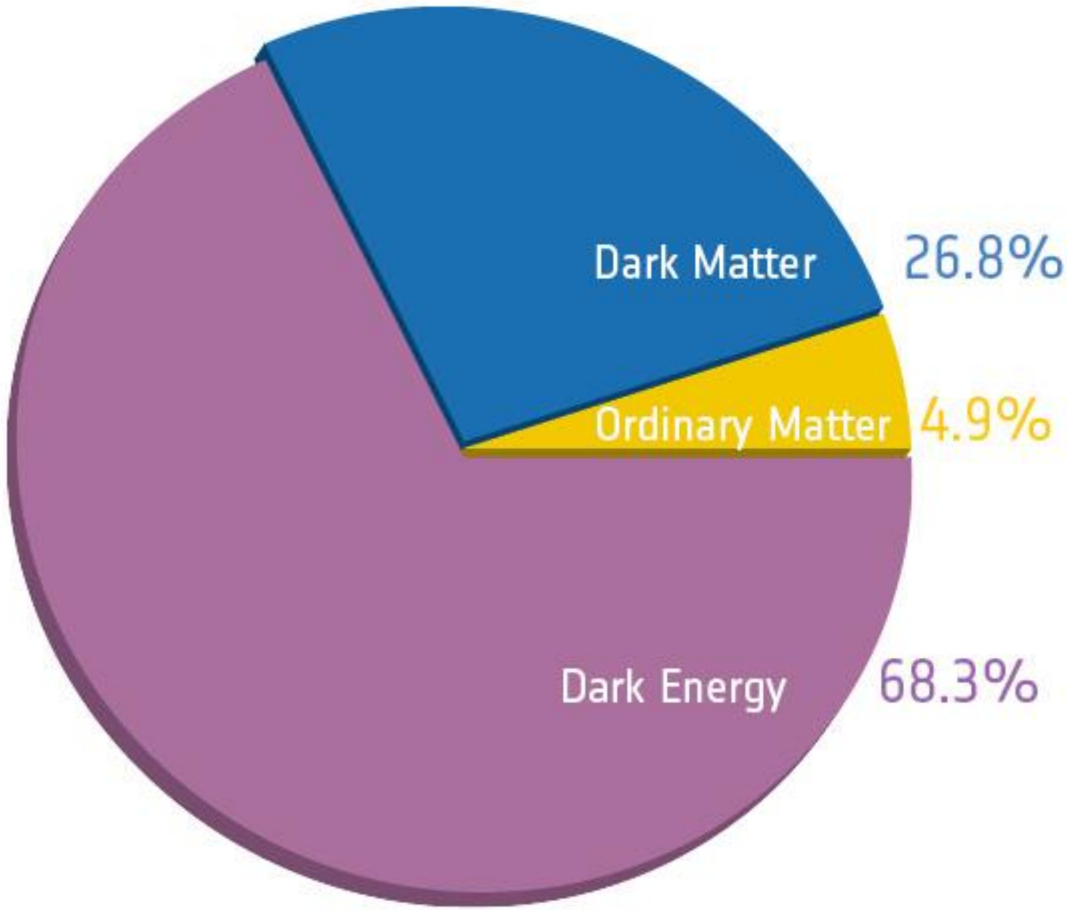
1. The outer part of the Galaxy is rotating "too fast".
2. Observed masses of galaxies and galaxy clusters are not large enough to keep them together.
3. Plenty of dark matter is needed for the formation of stars and galaxies.
4. Gravitational lenses must be larger than they appear to be able to cause the observed effect.

$\Rightarrow$ At least 80% of the mass of the universe is made of some kind of obscure, dark matter.

GRAVITATIONAL LENSING

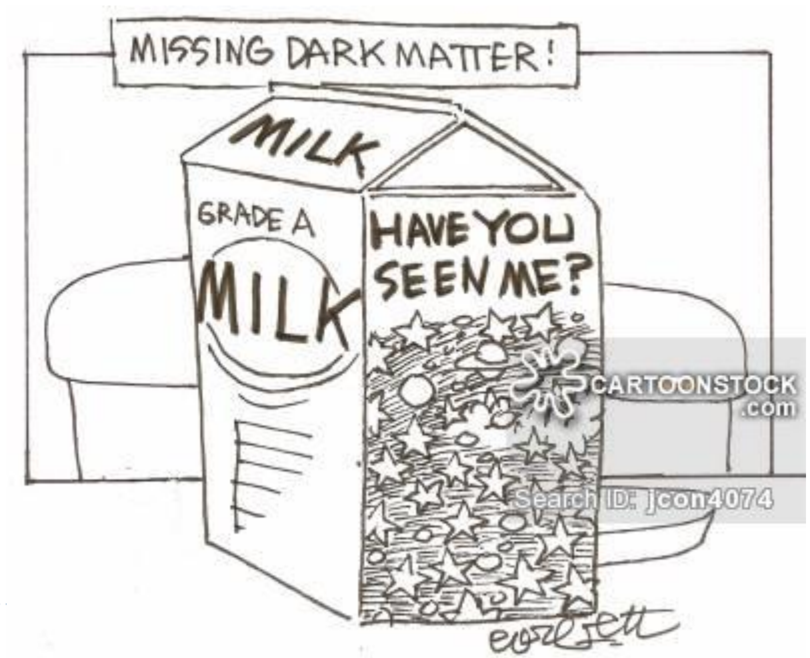


CONTENTS OF THE UNIVERSE

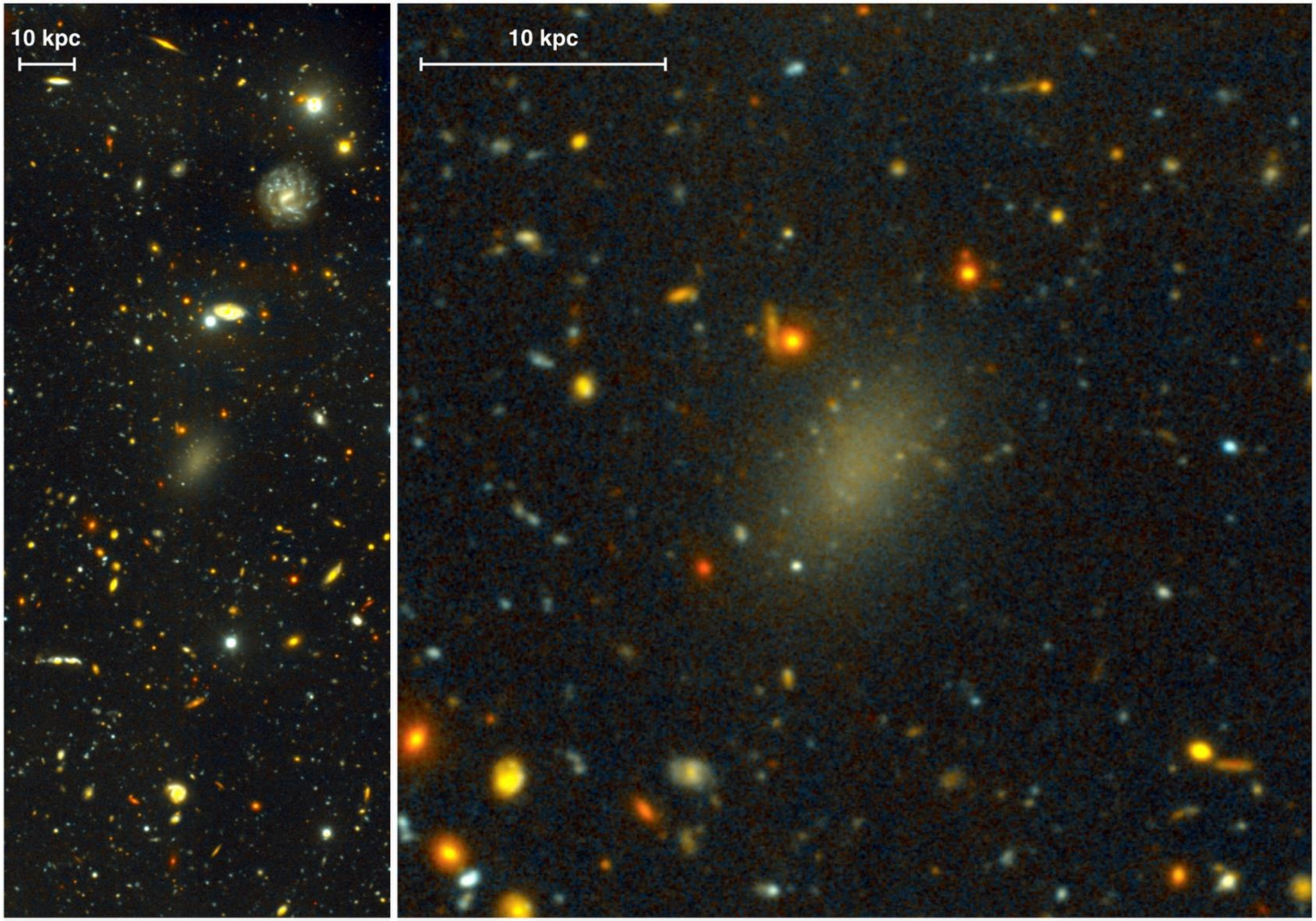


DARK MATTER

- Dark matter is being searched for, for example, in the halo of the Galaxy (MACHOs via microlensing) and in other galaxies.
- Gas, dust, faint stars, neutron stars, black holes, giant planets…
- …or something more exotic such as WIMPs
- Baryonic vs. non-baryonic ???



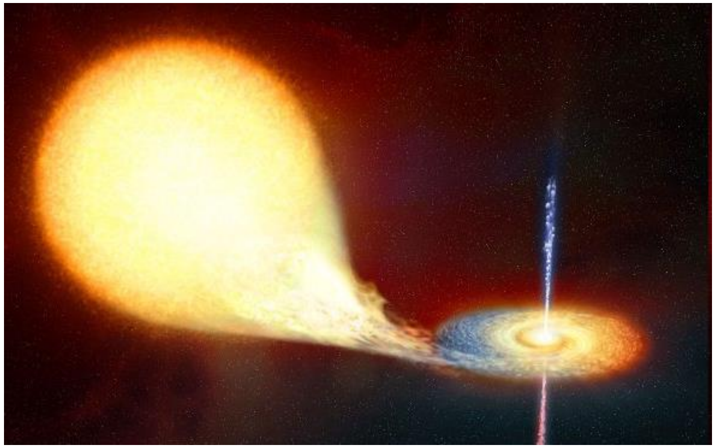
A DARK MATTER GALAXY: DRAGONFLY 44



Pieter van Dokkum, Roberto Abraham, Gemini Observatory/AURA

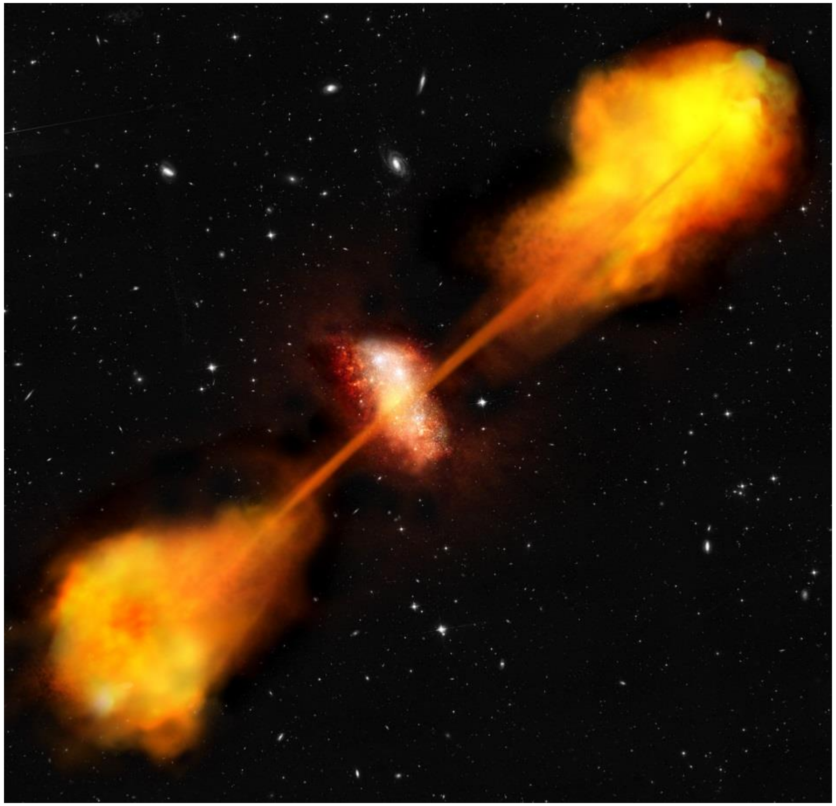
TODAY

- The Galaxy II:
  - Stars:
    - Classification and evolution
    - Various types of stars
  - Interstellar matter: dust, gas
  - Dark matter



NEXT WEEK 1.4.2019

- Extragalactic astronomy
- Cosmology



- Reminder:
  Exam on 12.4.2019!
  Check MyCourses for details.