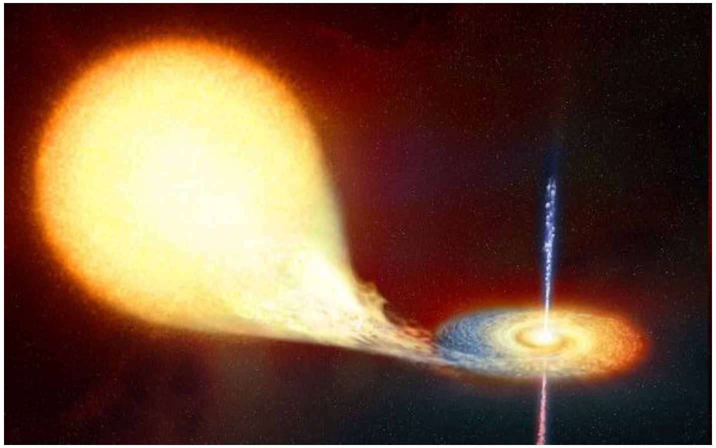
INTRODUCTION TO SPACE 23.11.2020

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



- Many topics will be discussed in more detail on the course ELEC-E4530 Radio Astronomy: the Sun, pulsars, microquasars, masers, supernova remnants, radio Milky Way …

STARS: CLASSIFICATION

- Spectral class of a star is based on (spectra and) temperature. It does not tell about the size of the star.

20 000 – 35 000 K

10 000 – 15 000

7 500 – 10 000

6 000 – 7 500

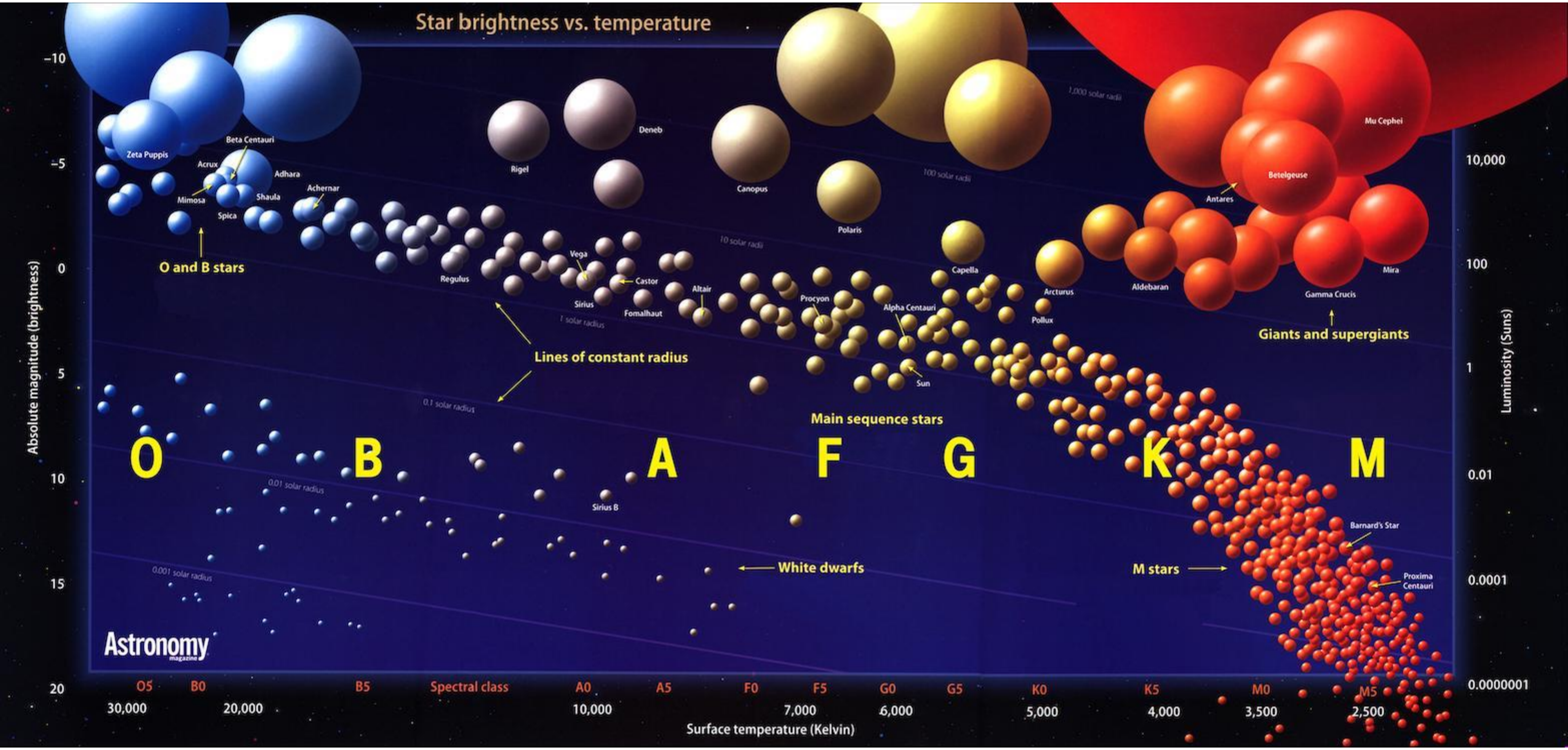
5 000 – 6 000

3 500 – 5 000

2 000 – 3 500

Sun: G2
T = 5 800 K

HERTZSPRUNG-RUSSELL DIAGRAM



- Links to stellar classification and HR diagram that explain the previous two slides.
  - https://en.wikipedia.org/wiki/Stellar_classification (contains lots of additional information)
  - https://en.wikipedia.org/wiki/Hertzsprung%E2%80%93Russell_diagram

  - See also links about stellar evolution later

STELLAR POPULATIONS

- **Population I**: young stars in the galactic plane, move in circular orbits, contain a large amount of heavy elements (2 – 4%)
  - age: a few hundred million years

- **Population II**: old low-metallicity (~0.02%) stars, on eccentric orbits (globular clusters, certain variable stars)
  - age: >6 billion years

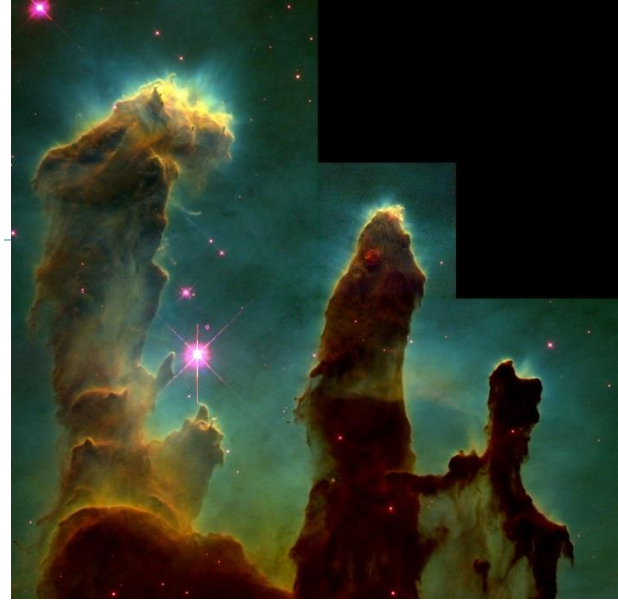
- A sequence of intermediate populations, for example, the disc population (including the Sun).

STELLAR STATISTICS

- By systematically observing all stars in the solar neighbourhood ($r \leq 1$ kpc), one can find their distribution of absolute magnitudes (that is, brightness or 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

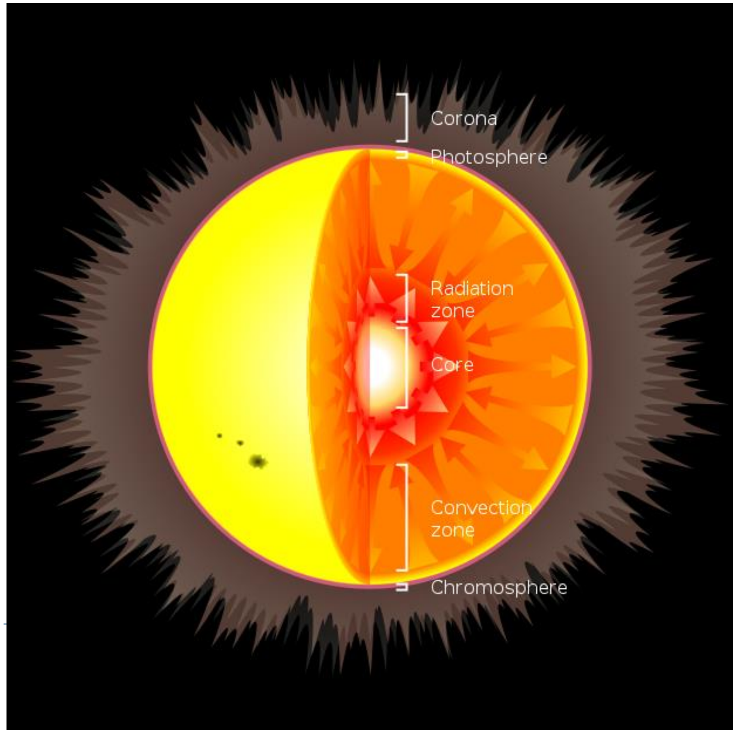


- Interstellar gas and dust clouds collapse and form protostars.
- Stars are powered by nuclear fusion of hydrogen (to helium) in the core.
  - Radiation pressure equals gravitational pressure: hydrostatic equilibrium.
  - Requires a mass > 0.08 $M_\odot$
- When equilibrium is achieved, the star settles in the main sequence.

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

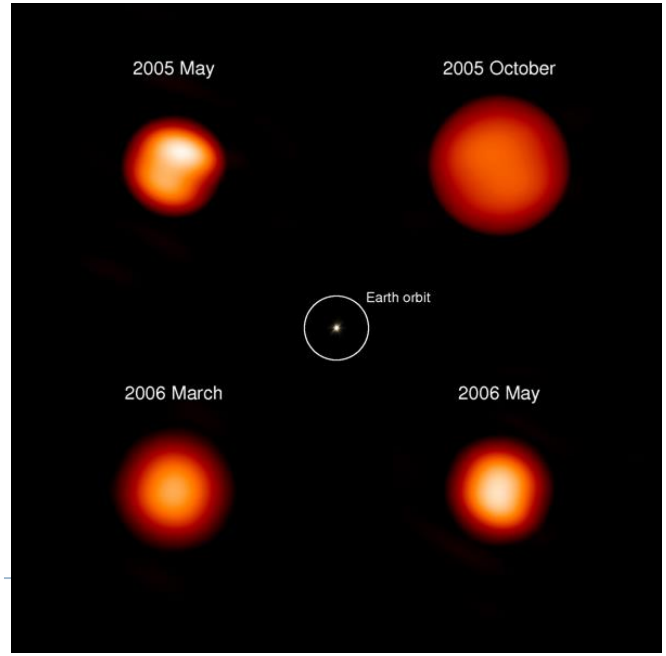
STELLAR EVOLUTION

- Very low-mass stars ($< 0.26\ M_{\odot}$):
  - Fusion of hydrogen until almost the entire star is made of helium.
  - Temperatures are not high enough for helium fusion, and a slow collapse follows.
  - The lifetimes of very low-mass stars can be longer than the age of the universe.



STELLAR EVOLUTION

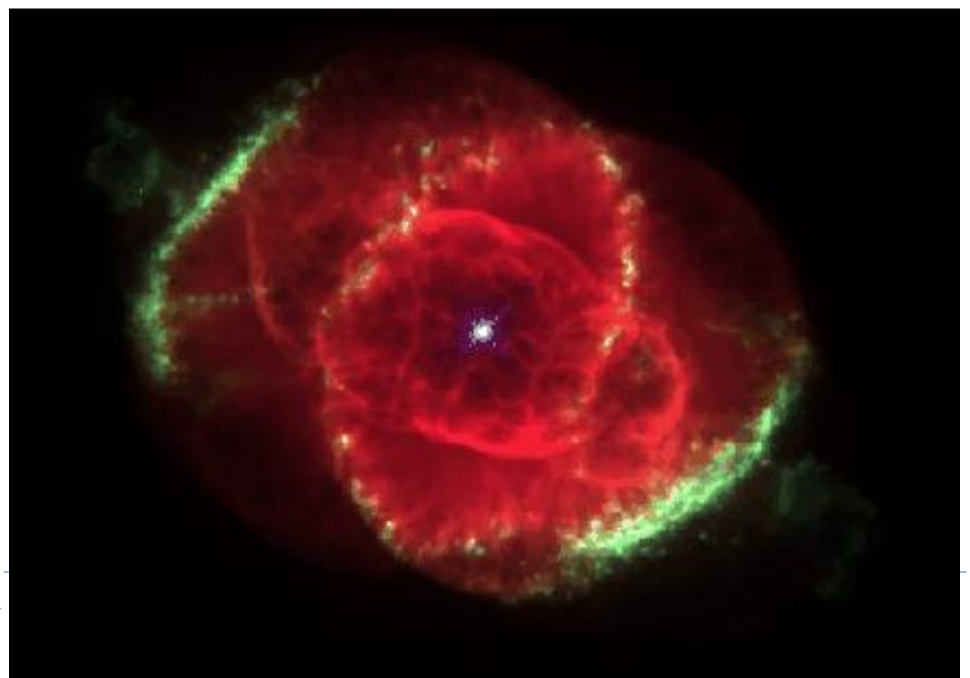
- Mid-mass stars (core $< 3\ M_{\odot}$) :
  - After hydrogen runs out in the core area, fusion continues in a shell around the core.
  - Radiation vs. gravitational pressure balance is lost: the core collapses and the star expands until new equilibrium is established (electron degeneracy vs. gravitational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



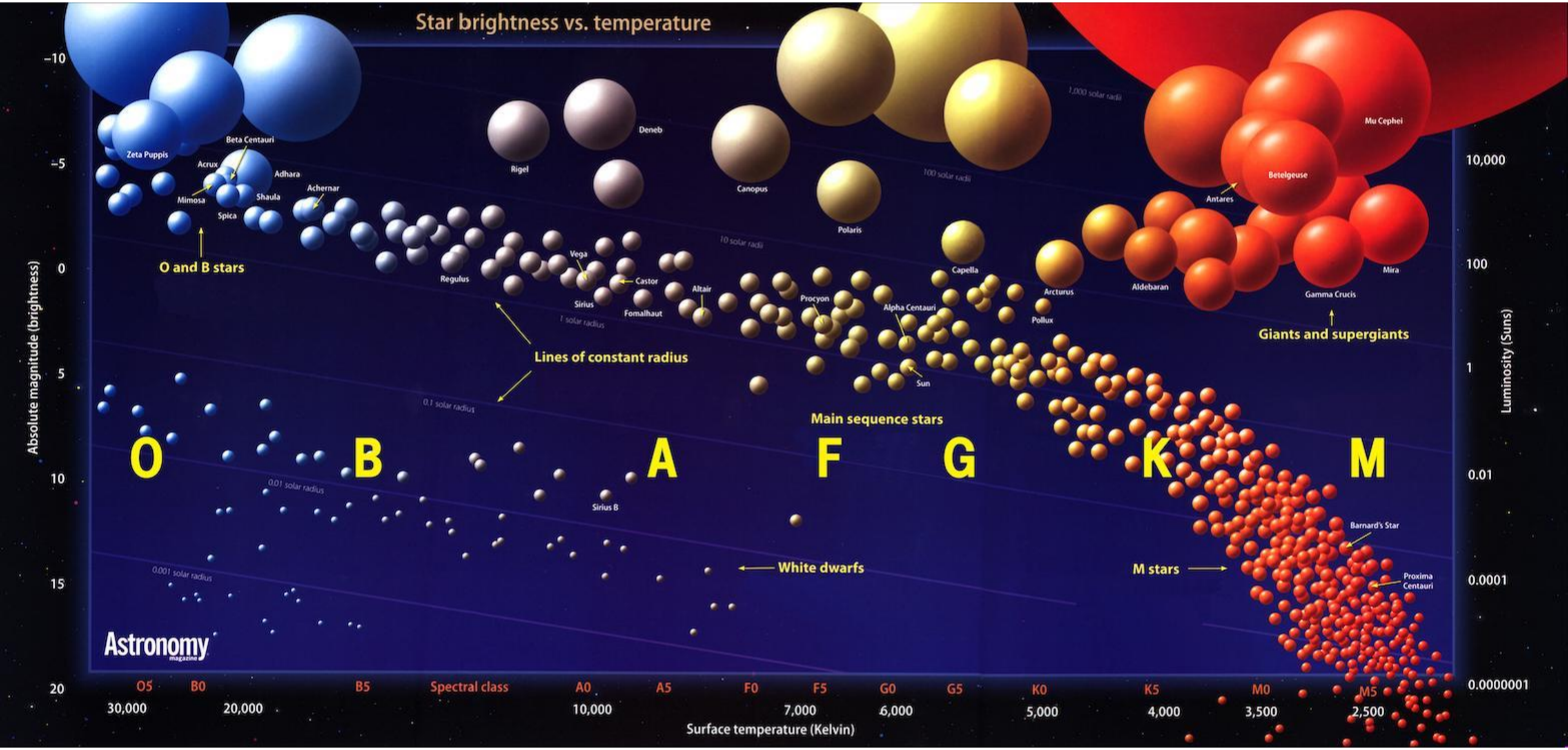
SAO/NASA

PLANETARY NEBULAE

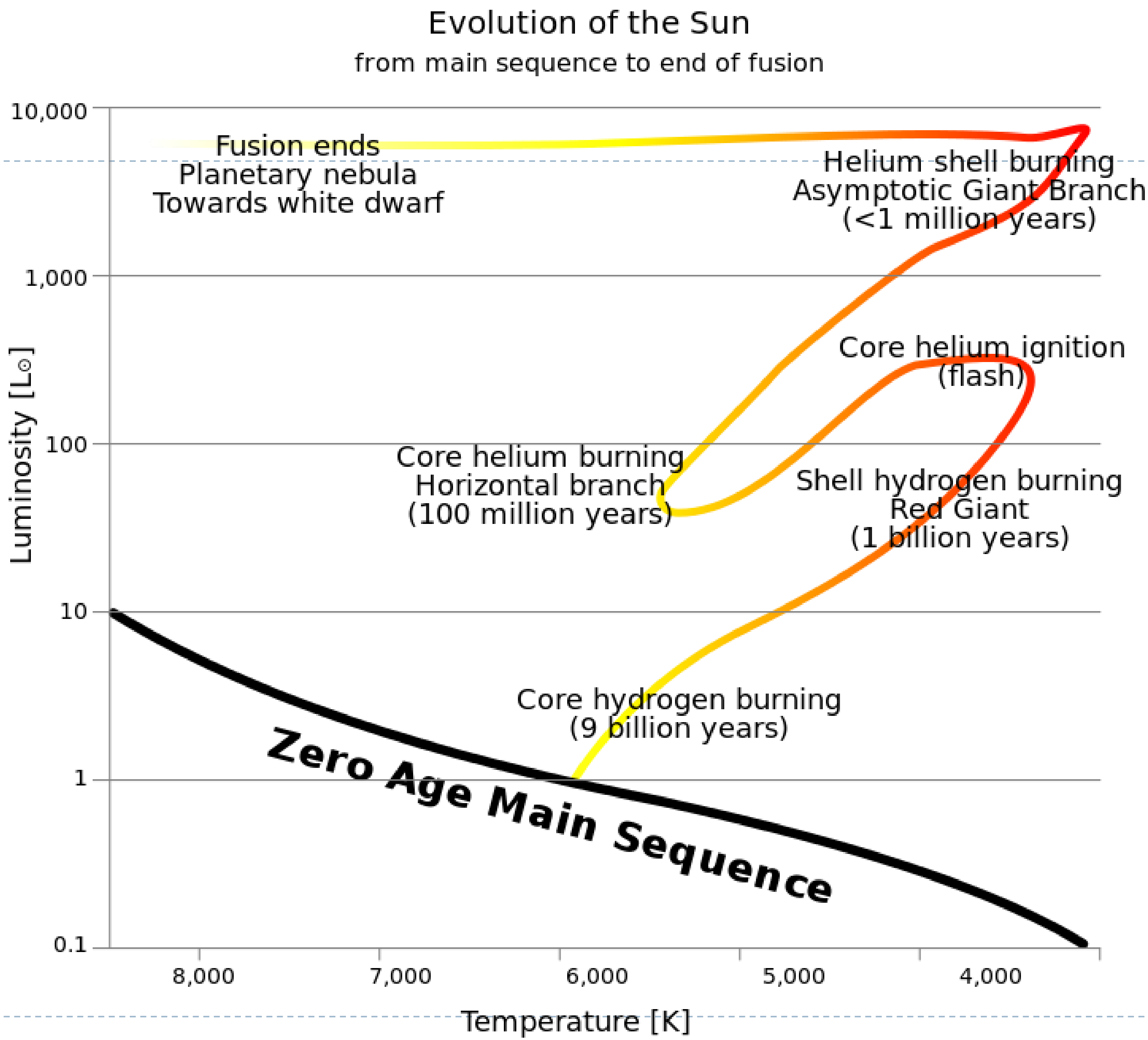
- Expanding (~20 km/s) gas shells around old stars.
- The whole outer atmosphere of a star is ejected into space by stellar winds, ionized by UV emission.
- In a few ten thousand years the central star cools to become a white dwarf, and the planetary nebula disappears into the interstellar medium.



HERTZSPRUNG-RUSSELL DIAGRAM



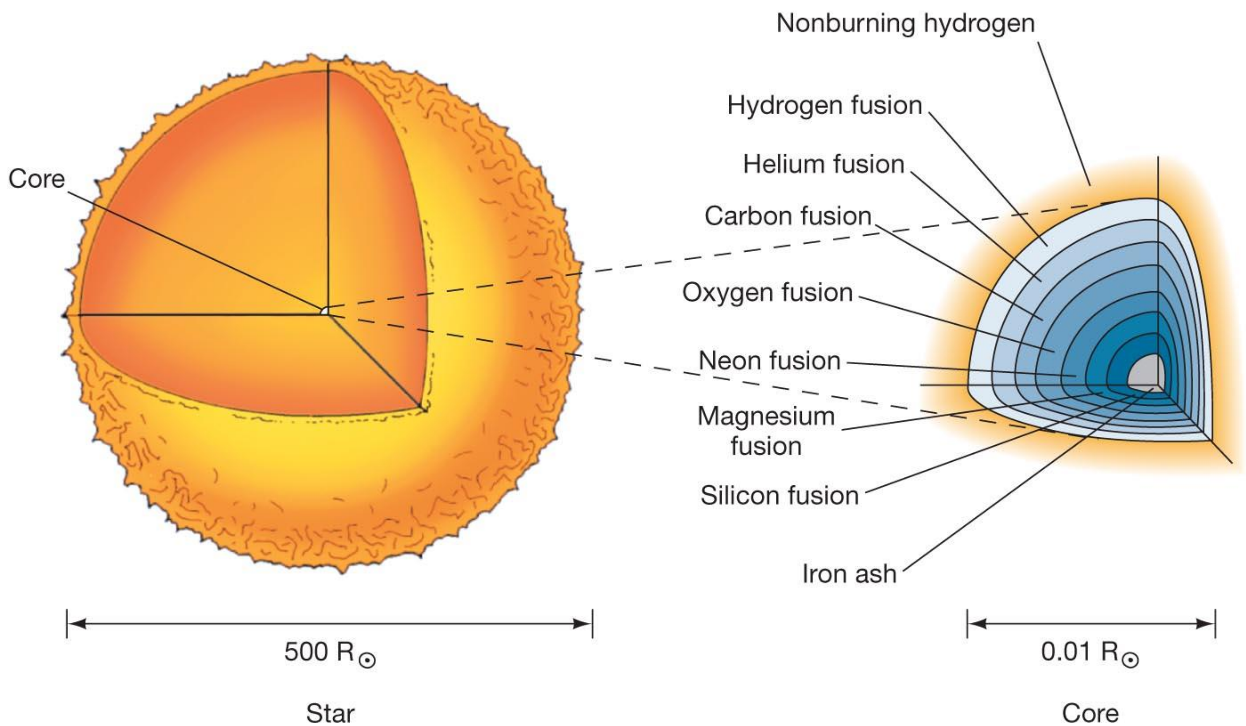
- The star moves in the HR diagram, depending on its current temperature and brightness (in other words, its stage of evolution).
- Stars spend 90% of their time in the main sequence. This is millions of years for very large stars, or several hundreds of billion years (more than the age of the universe) for the very low-mass stars.
- The Sun is 5 billion years old now and has approx. 5 more billion years left in the main sequence.


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

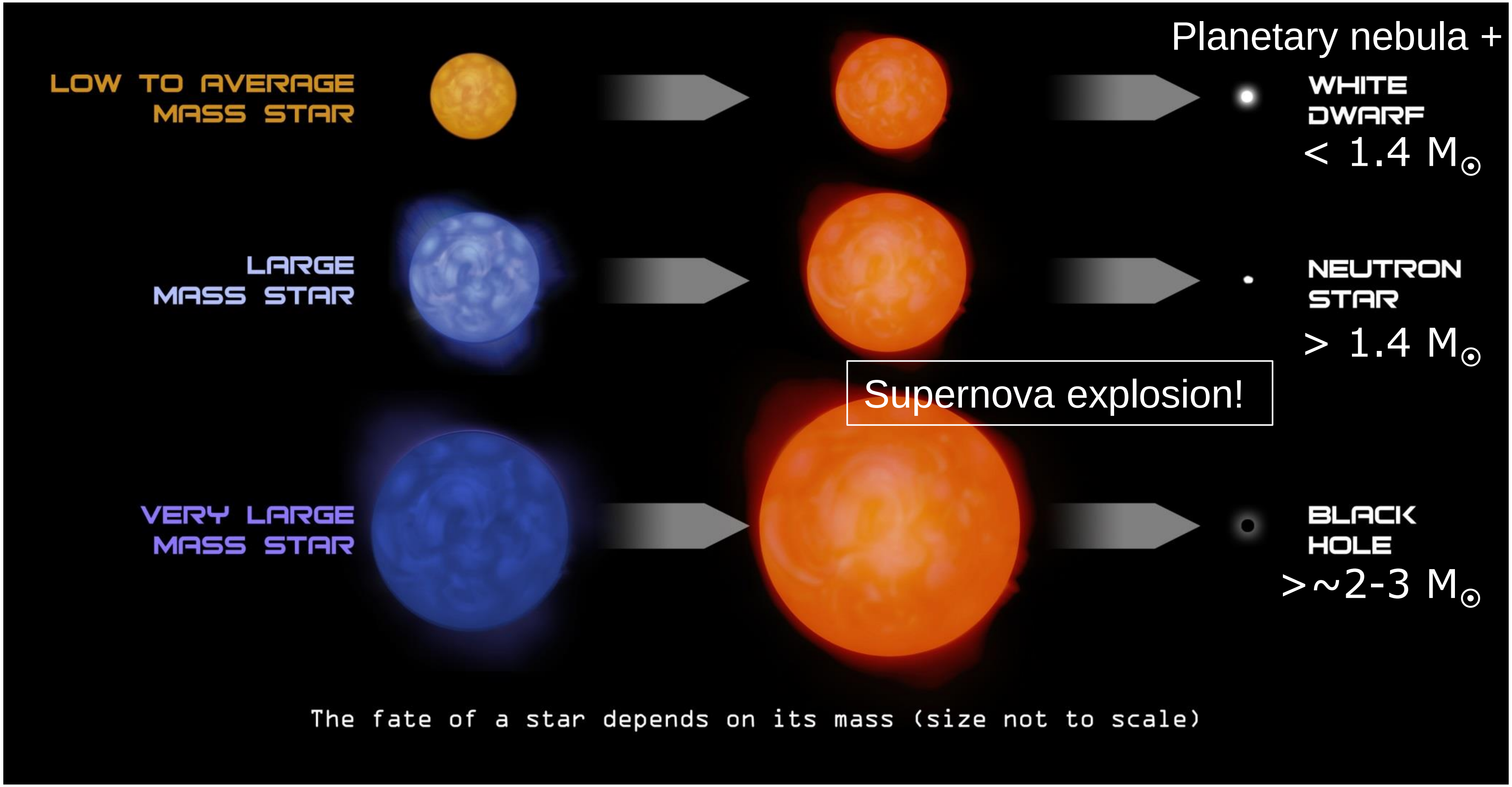
Szczureq

STELLAR EVOLUTION

- High-mass stars (core > 3 $M_\odot$):
  - Continuous fusion of elements halt collapse.
    - Now also heavier elements as the temperatures are higher.
  - Finally the core collapses because after the fusion of iron ends, nothing resists the gravitational collapse: supernova explosion.



STELLAR EVOLUTION: THE END



NASA/CXC/M.Weiss

Stars either cool down to white dwarfs or explode as supernovae, depending on their mass.

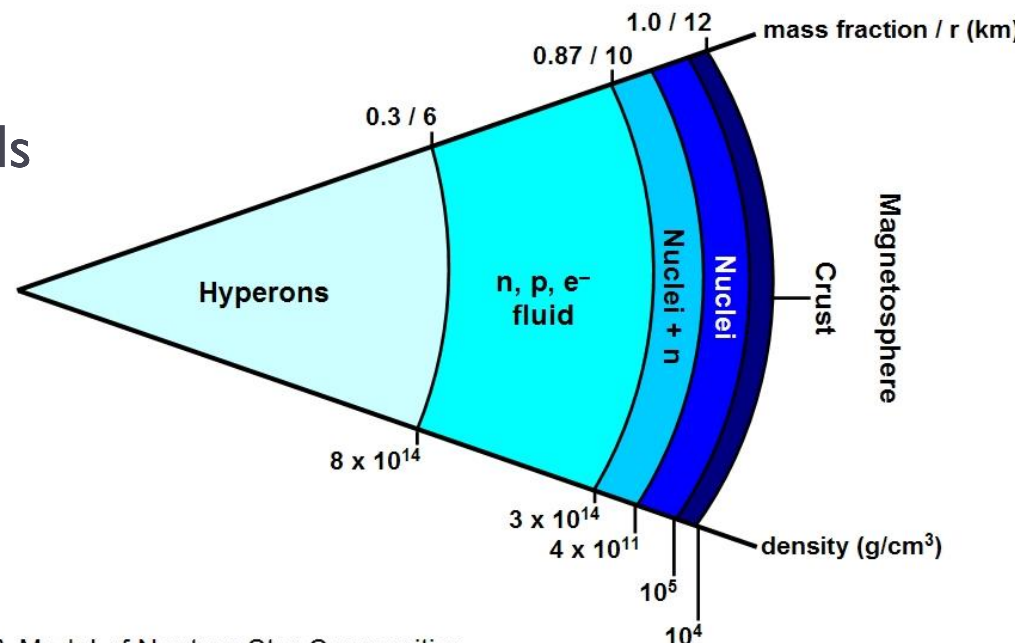
Links to stellar evolution

- https://www.physics.rutgers.edu/analyze/wiki/stellar_evolution.html
- https://en.wikipedia.org/wiki/Stellar_evolution
- Stellar evolution in a nutshell http://astronomy.swin.edu.au/cosmos/S/Stellar+Evolution

- https://en.wikipedia.org/wiki/Supernova
- https://en.wikipedia.org/wiki/Planetary_nebula

NEUTRON STARS

- If the mass of the collapsing star is >1.4 $M_{\odot}$, a rapidly rotating neutron star is formed in a supernova explosion.
- Electrons and protons combine to form neutrons
  - Neutron degeneracy vs. gravitational pressure
- Diameter typically 12 km, solid crust & surface.
- Very high rotation speeds
  - from milliseconds to seconds
- High magnetic field.

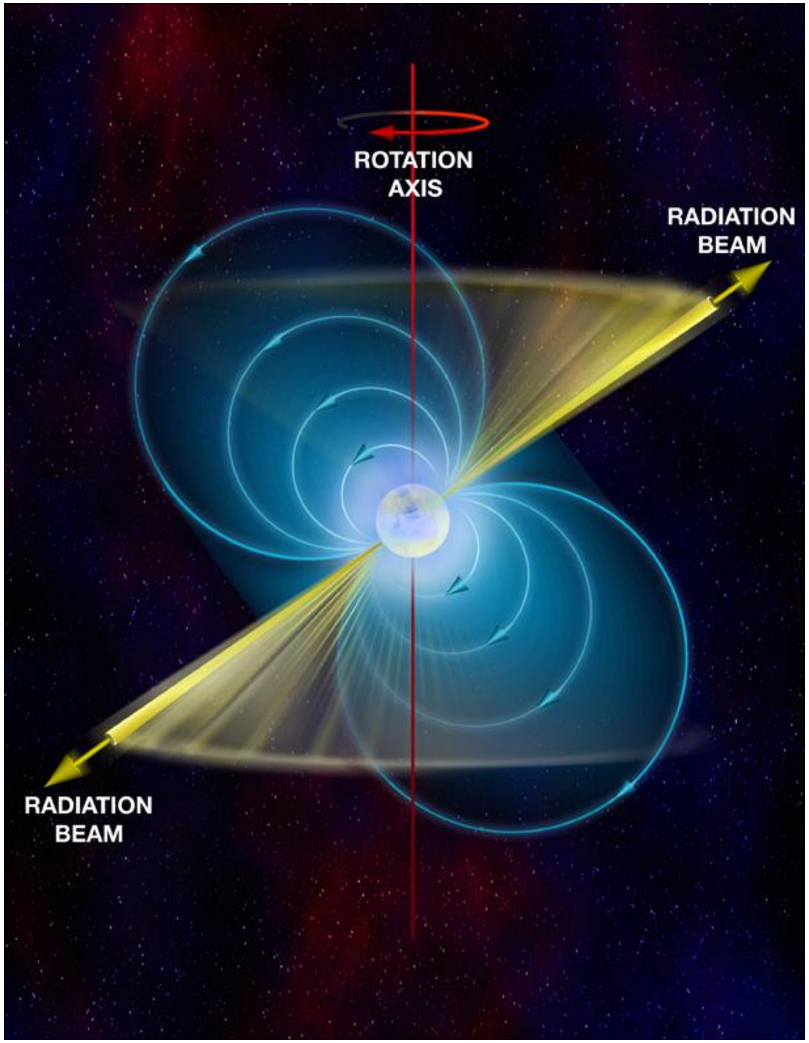


A Model of Neutron Star Composition

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

PULSARS
(more about these on the Radio Astronomy course)

- High magnetic field combined with the high rotation speed of the neutron star produces a flashing beam of synchrotron emission.



Bill Saxton, NRAO/AUI/NSF

KEEP IN MIND THAT THERE EXISTS TWO MAIN TYPES OF BLACK HOLES. Stellar black holes are generated in supernova explosions of large stars and supermassive black holes evolve (in a so far unknown way) in the centres of galaxies.

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

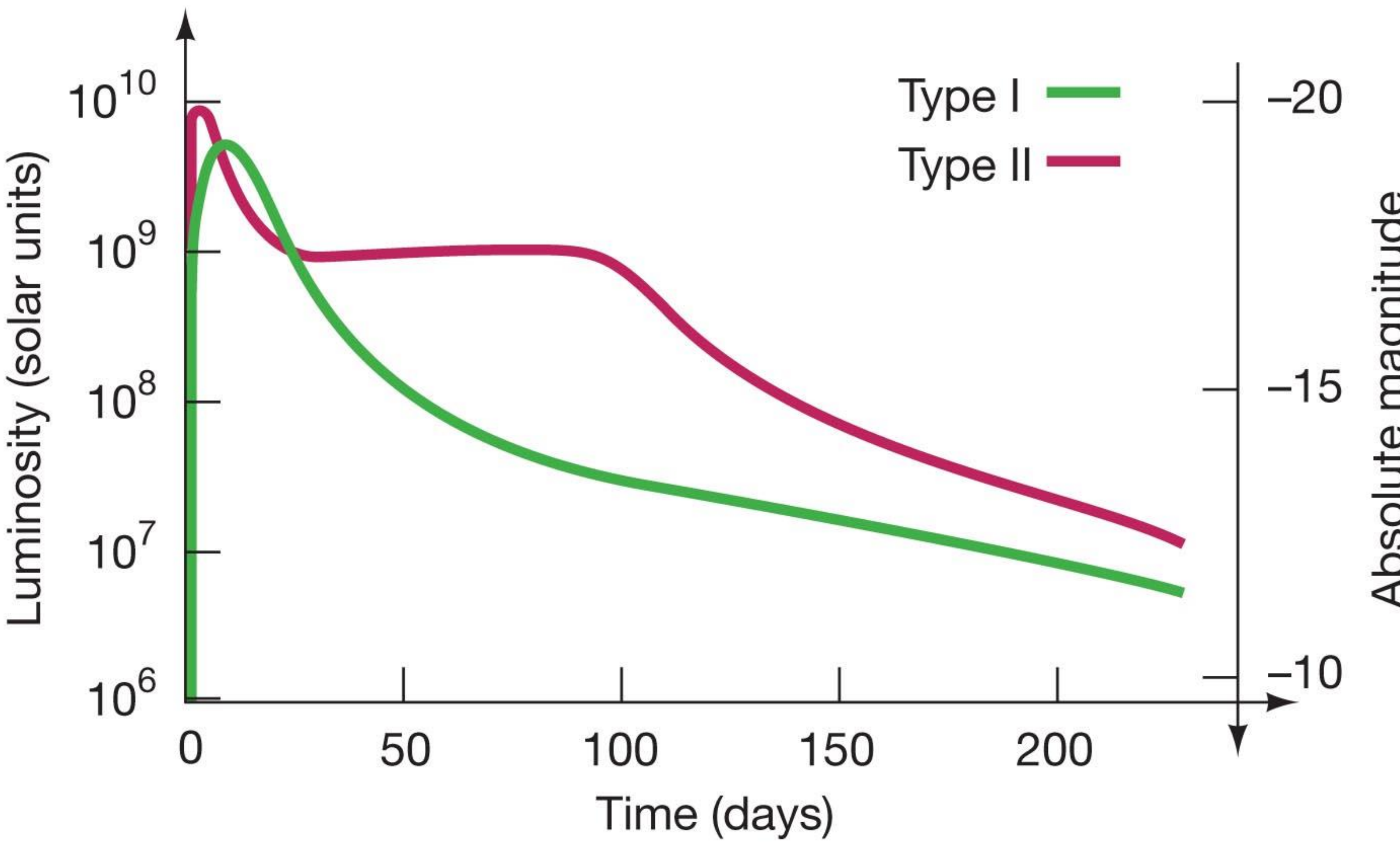
DIFFERENT TYPES OF SUPERNOVAE

- 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.
- **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).

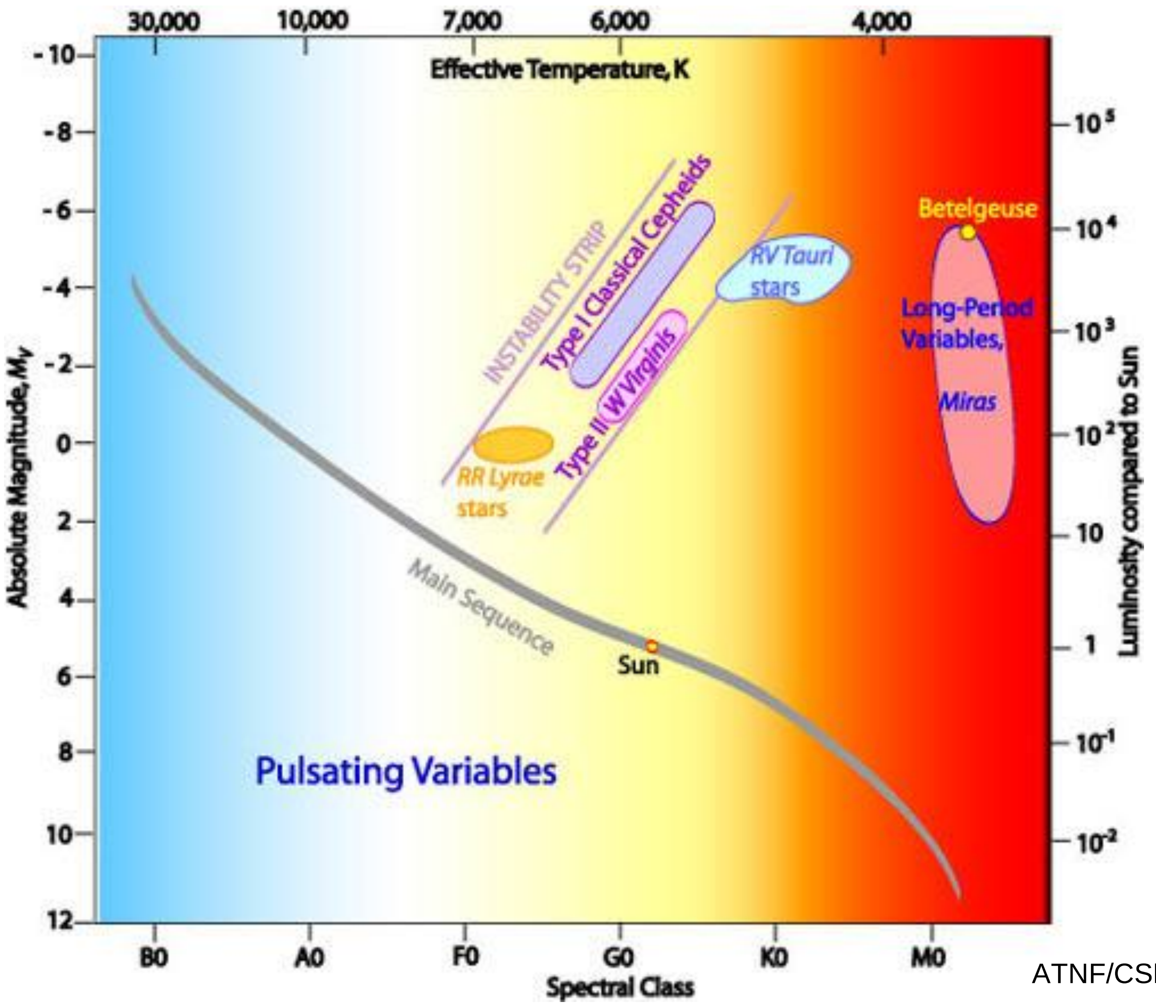
Evolution of a supernova explosion/remnant over time, depending on its type



VARIABLE STARS

- **Pulsating stars** expand and shrink because of their evolution (giants)
  - Mira variables: variability period 100 – 500 days, variations in brightness approx. 6 mag
  - Cepheids: 1 – 50 days, variations 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 that causes nova-like behaviour)
  - Supernovae
- **Eclipsing stars** (binary/multiple stars, extrasolar planets)
  - No changes in the stars themselves, they just eclipse each other.

Location of pulsating variable stars in the HR diagram



ATNF/CSIRO

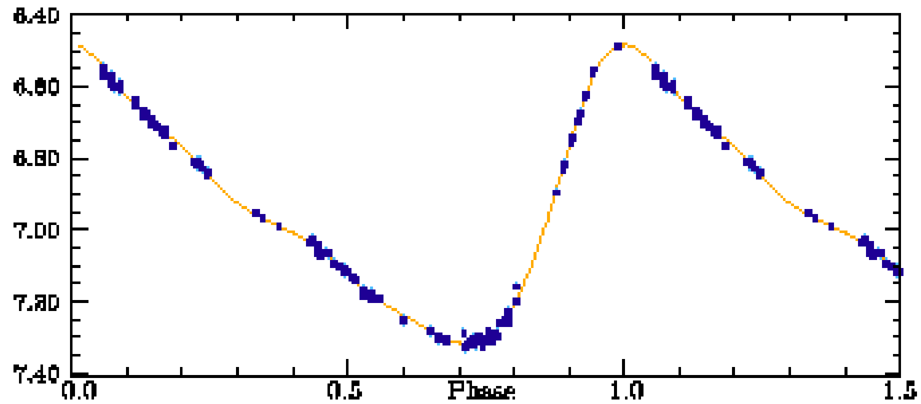
CEPHEID PERIOD-LUMINOSITY RELATION

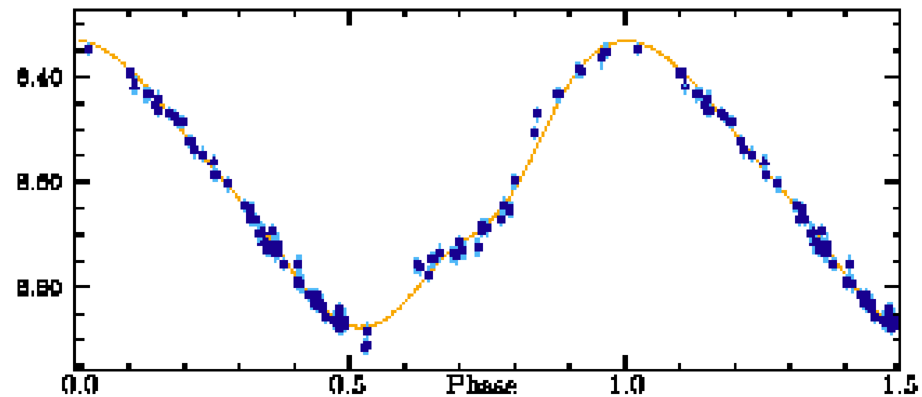
- The period-luminosity relation enables the determination of distances to stars and nearby galaxies.

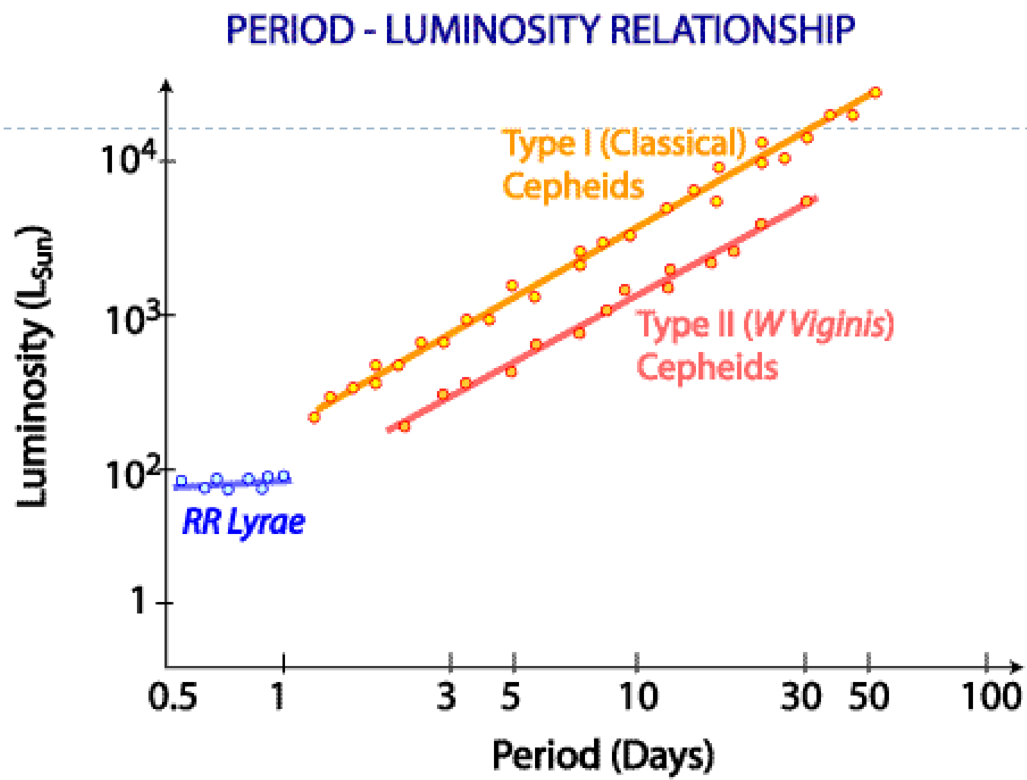
- Classical cepheids
- W Virginis cepheids

- 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, that is, M.
- **RR Lyrae** stars all have the same M. If M is known (~+0.6 for all) we can calculate m and the distance of the star.
- Also supernova Type I (decay rate vs. brightness, that is, M)

Various ways of 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!

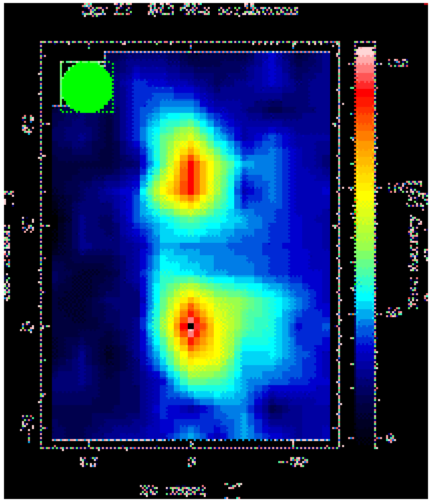
INTERSTELLAR MEDIUM, ISM

- 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.

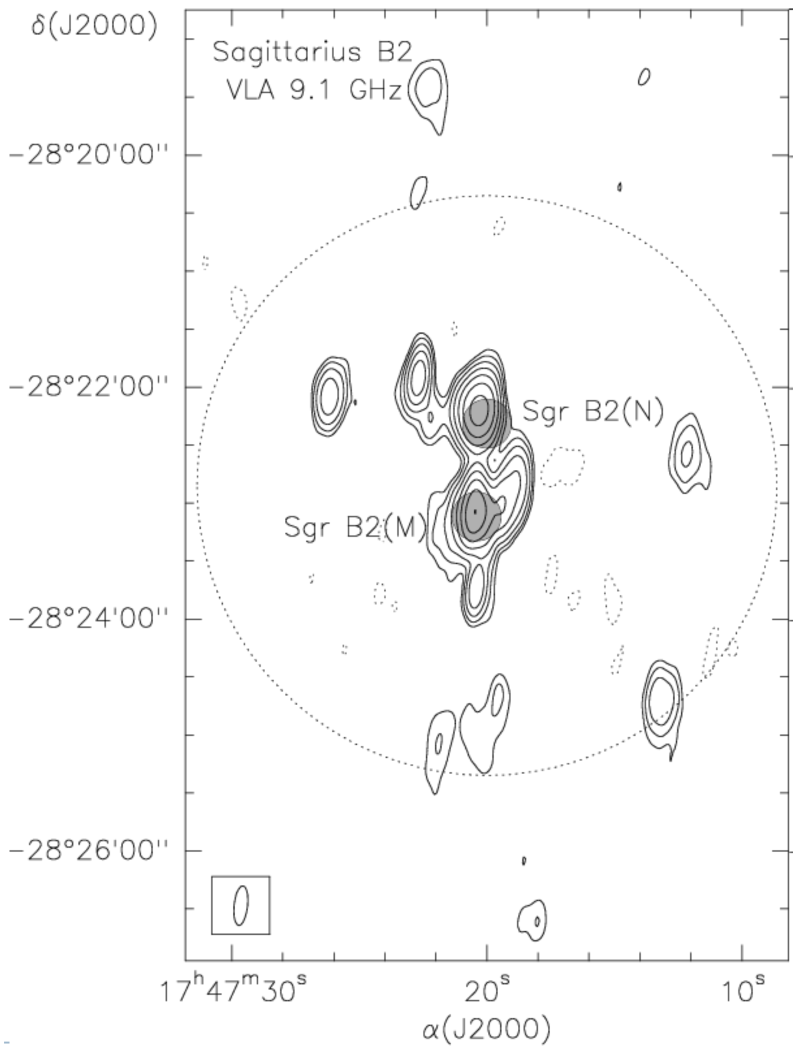
- Interstellar matter is raw material for star formation, and further may develop into planetary systems.
- Seems diffuse but there are enormous amounts of it.

EXAMPLE: INTERSTELLAR MEDIUM

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



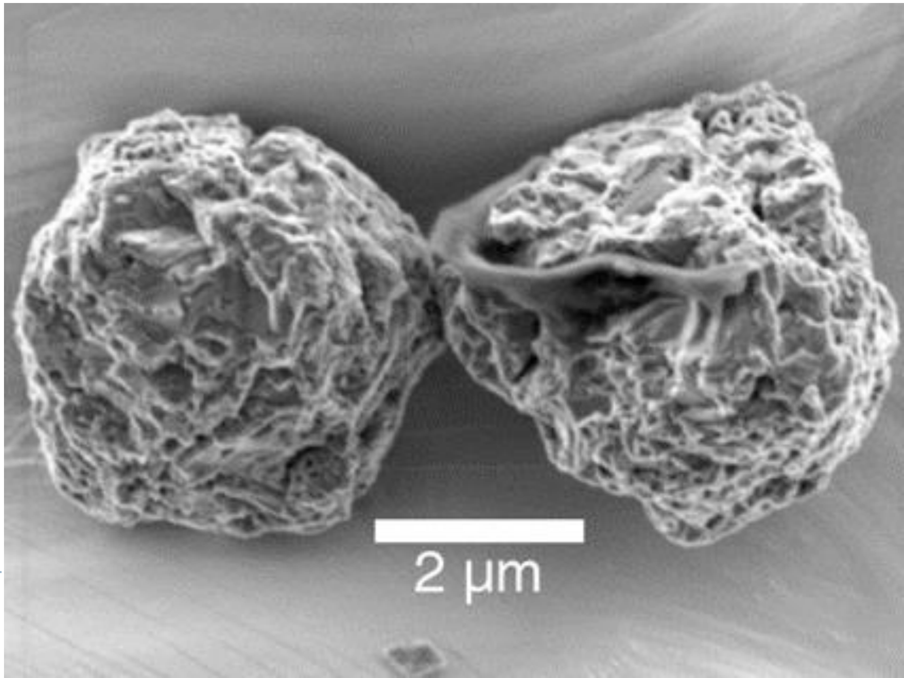
343 GHz



DUST

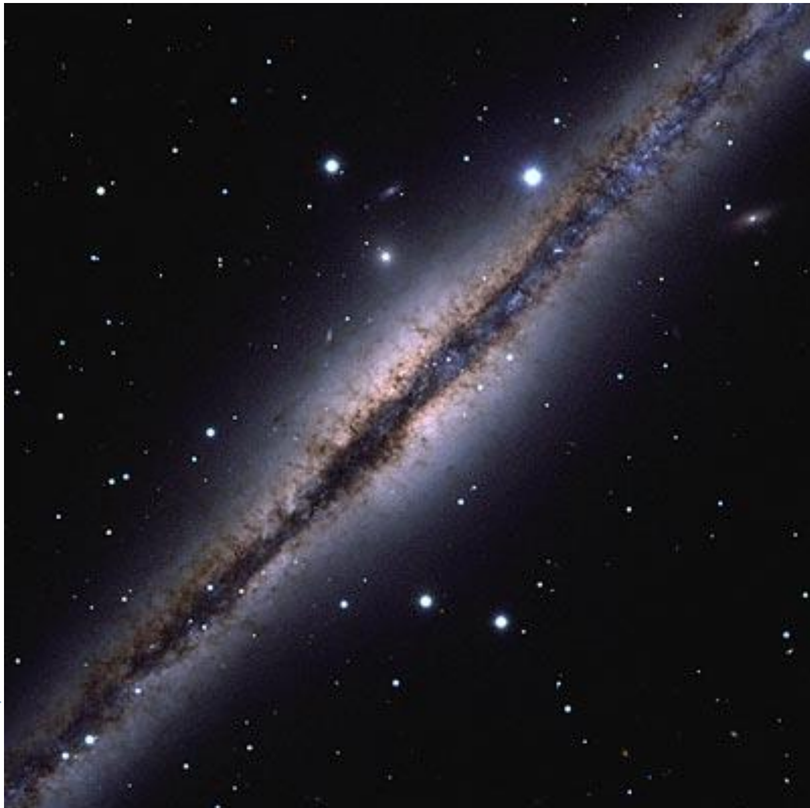
- The amount of dust is 1 % of the amount of gas.
- There is dust particulatly at the inner edges of spiral arms and also in individual clouds.
- Composition: at least water ice, silicates, graphite.
- Particle size is usually < 1μm. We can get information about the dust grain sizes from the scattering and extinction of emission.

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.
- Dust generates thermal emission so we can study it with IR observations.
- Image on the right: Note the heavy dust lane in the plane of the galaxy. Our galaxy has a similar feature (remember the Galactic continuum from last week).



DUST NEBULAE

- Dark nebulae (cold, 10 - 20 K)
  - Can be seen as star-poor regions (dust covers the stars)
- 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 (=interstellar dust grains scattering light from stars) constitutes 20 - 30 % of the total brightness of the Galaxy.

Left: reflection nebulae

Right: dark nebulae

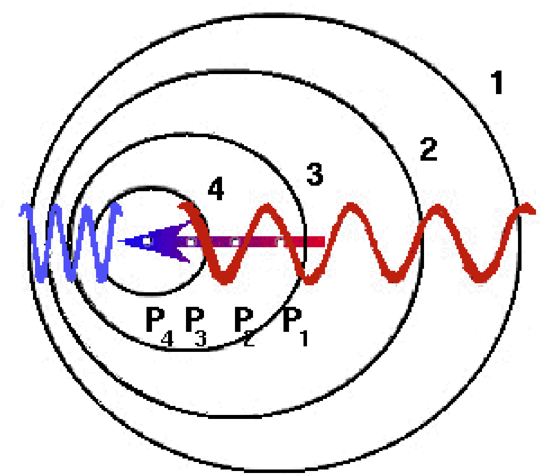
INTERSTELLAR GAS

- The amount of gas is 10 % of the total mass of the Galaxy.
- Does not induce extinction, yet is difficult to observe optically (via only a few spectral lines).
- Most elements are ionized, caused by UV emission from stars and cosmic rays.
- Composed of ~30 elements, however, most of it is hydrogen and helium (~90 % H, ~10 % He). There seems to be less of the heavier elements in interstellar gas than in the Sun or in stars; this is because it is incorporated in dust grains and does not produce absorption lines.

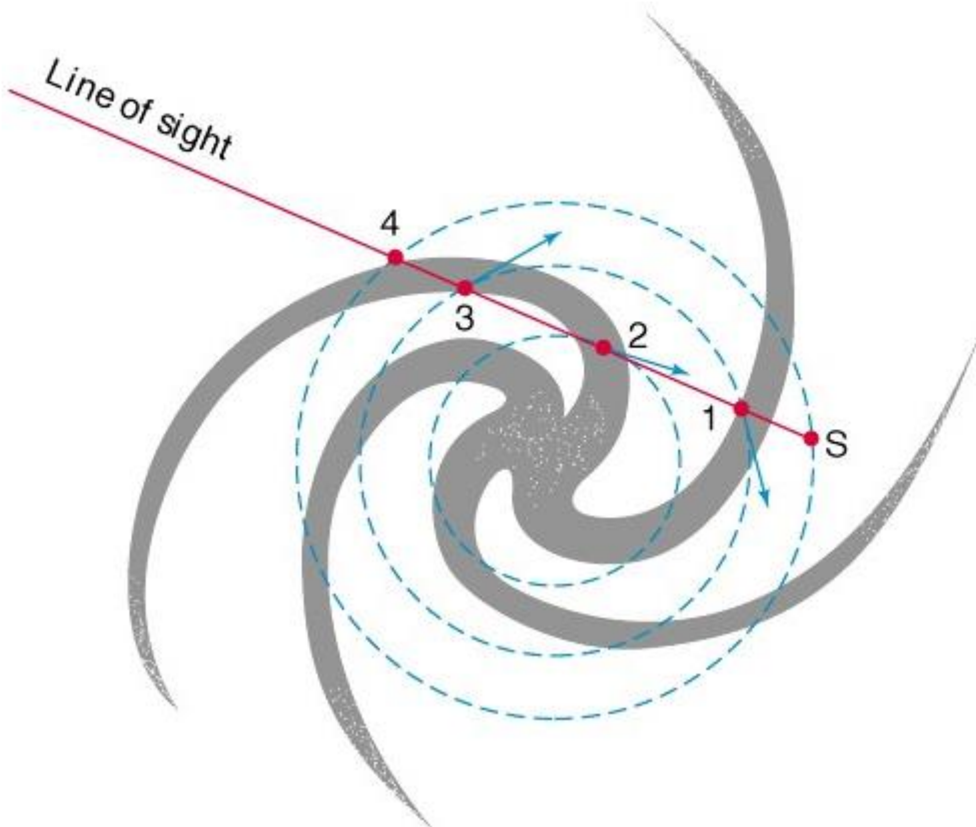
DISTRIBUTION OF INTERSTELLAR MATTER

- We can study the distribution of interstellar matter by determining the distances and the numbers 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)

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

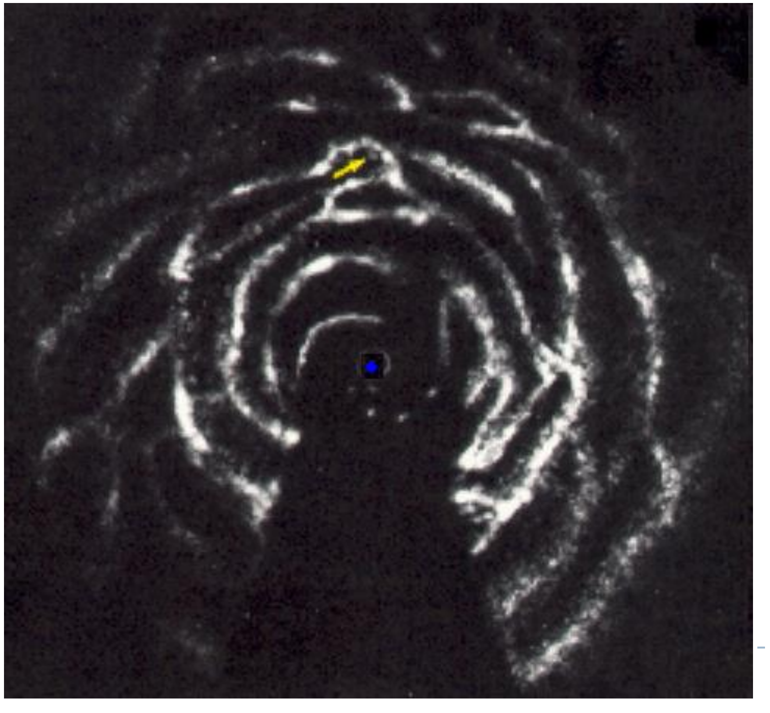


- We can measure radiation at different locations of the Galaxy using, for example, radio astronomy.



H I (neutral = atomic hydrogen)

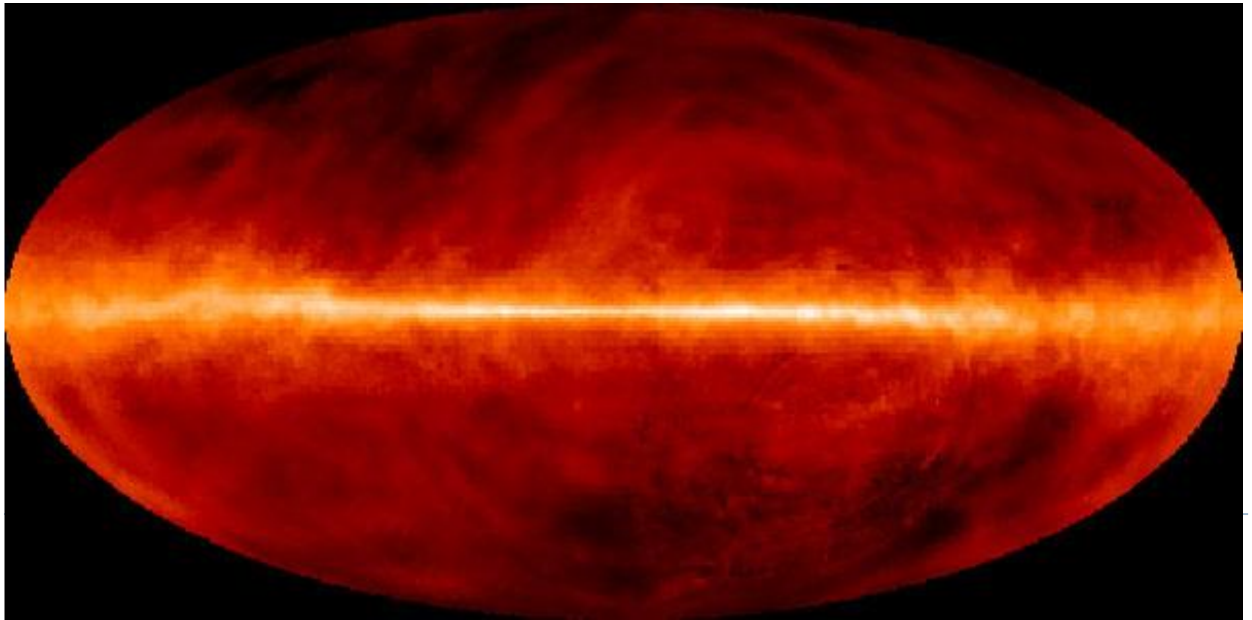
- Abundant (~90% or everything in the universe), suits very well for studying the ISM and the Galaxy .
- Mapping of HI reveals:
  - The Galaxy is a spiral galaxy, HI concentrated in the spiral arms.
  - Density and distribution.
  - Temperature.
  - Rotation.



Map of the Galaxy at 21 cm (1.4 GHz, the frequency of HI) + UV

GALACTIC H I

- Mass ~3 – 5 x 10^9 $M_\odot$
- Mostly in the galactic plane, but not smoothly distributed $\rightarrow$ 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

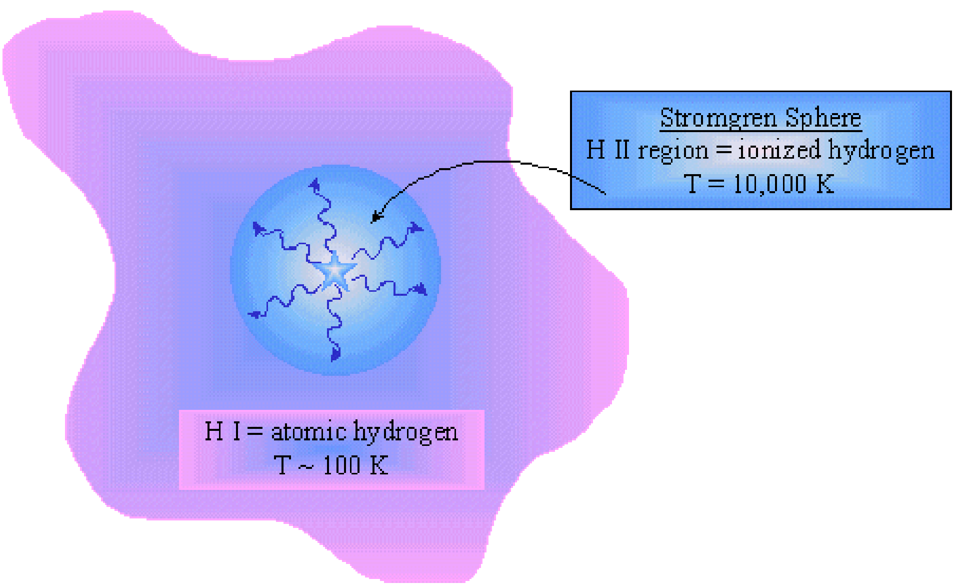


H II (ionized hydrogen)

- HII clouds are called also HII regions and emission nebulae.
- They can typically be found around hot O type stars.
- H is ionized by UV radiation, temperature 8000 – 10 000 K.
  - H atom remains ionized for hundreds of years, neutral for only a few months.
  - In the image: Orion nebula

H II

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

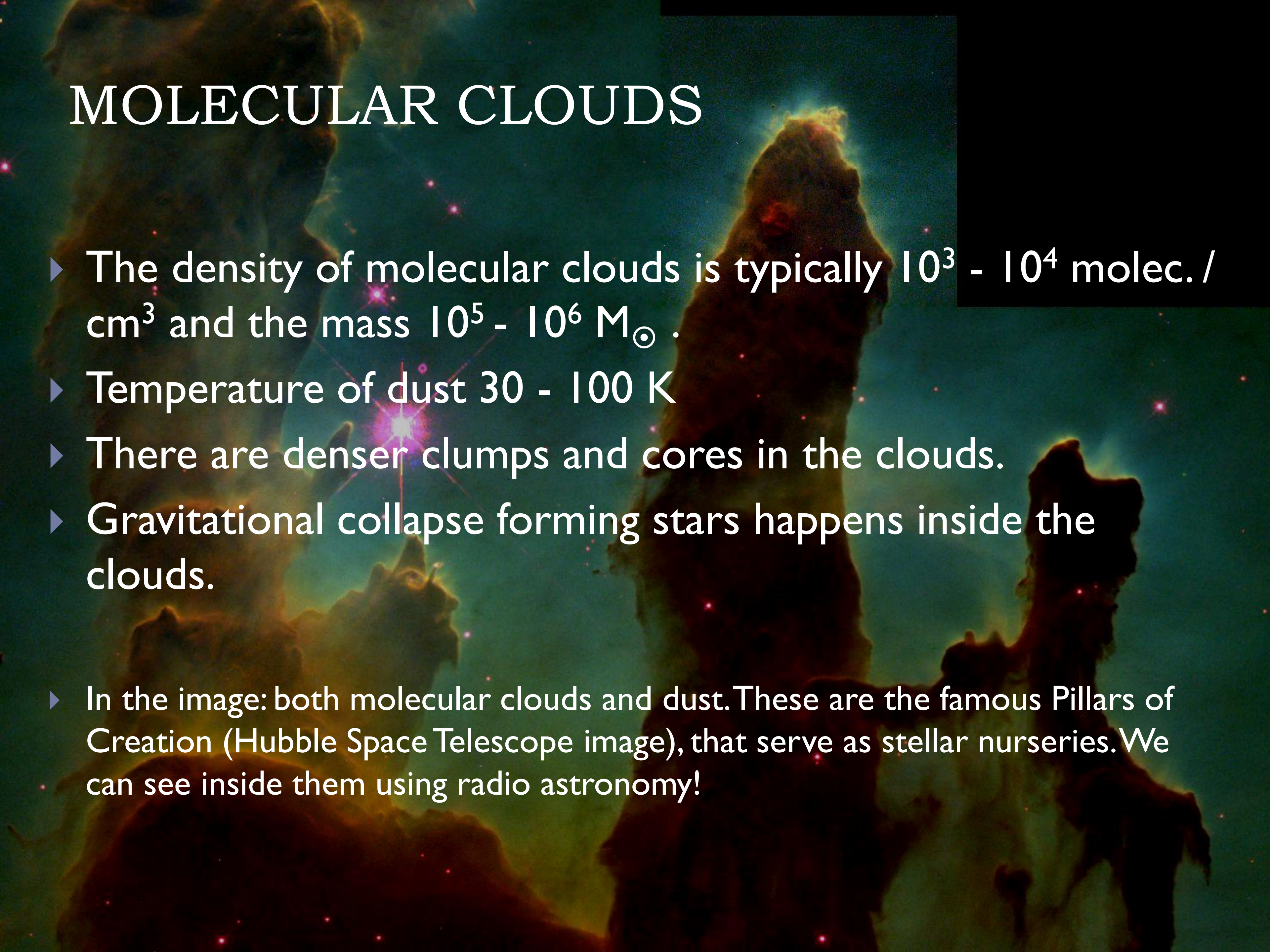


INTERSTELLAR MOLECULES

- 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 that shield them from disintegrating UV radiation.
- Form through collisions or on the surface of dust grains (or in gas clouds). The dust also absorbs the UV emission that easily destroys the molecules.
- Dark nebulae or dense molecular clouds in the vicinity of HII regions are the most favourable environment for interstellar molecules.



MOLECULAR CLOUDS

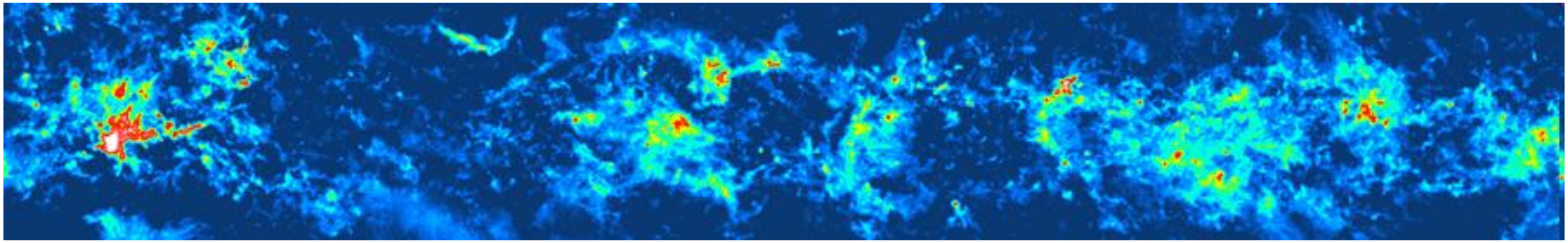
- The density of molecular clouds is typically 10^3 - 10^4 molec. / cm^3 and the mass 10^5 - 10^6 $M_\odot$.
- Temperature of dust 30 - 100 K
- There are denser clumps and cores in the clouds.
- Gravitational collapse forming stars happens inside the clouds.

- In the image: both molecular clouds and dust. These are the famous Pillars of Creation (Hubble Space Telescope image), that serve as stellar nurseries. We can see inside them using radio astronomy!

MOLECULAR CLOUDS

- The most abundant molecule is H_2, second CO.
- Significant fraction of all hydrogen is molecular, H_2.
- The fraction of H_2 increases strongly with density and extinction, because it is formed on the surface of interstellar dust grains. It therefore also enables studies of the relation between gas and dust.

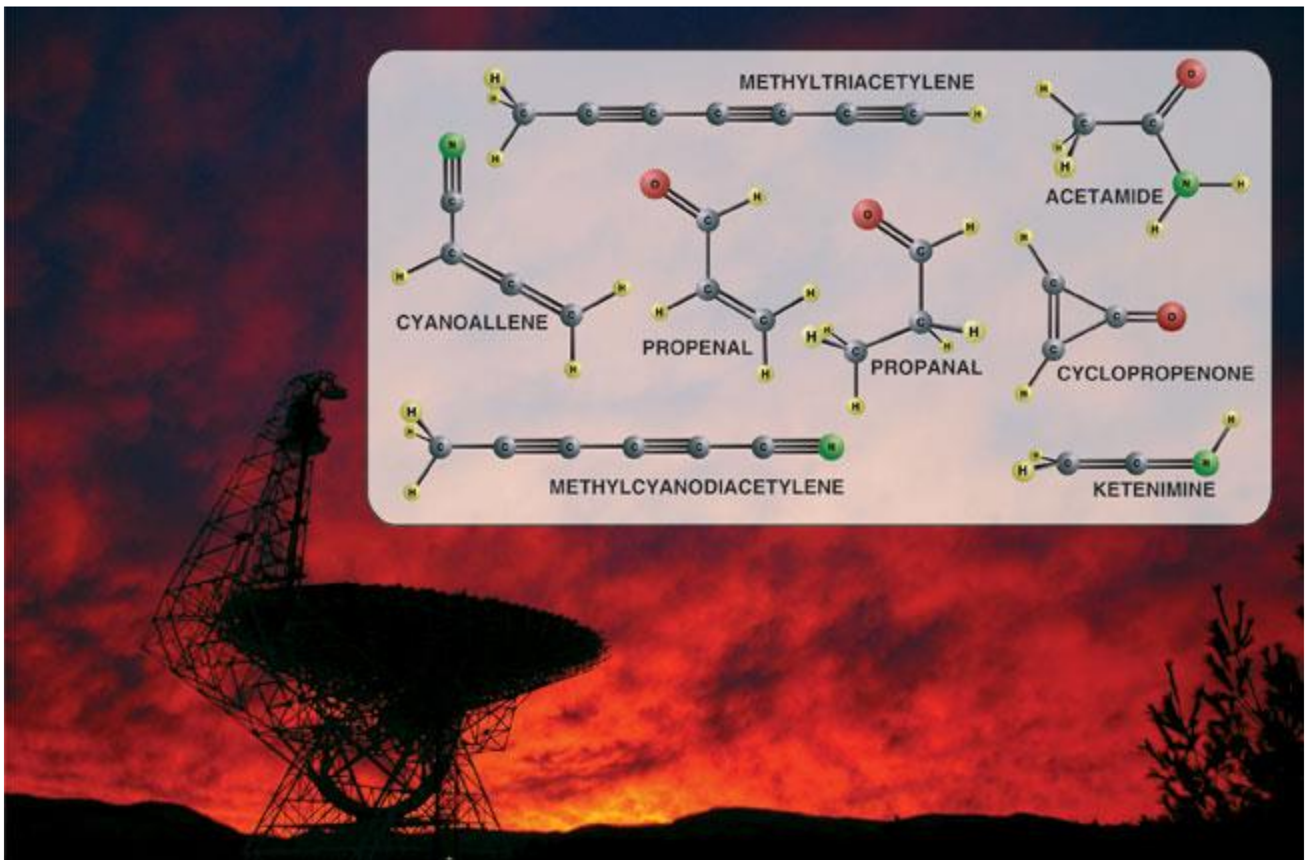
- *For example, Sgr B2 contains almost all interstellar molecules found. Some molecules are found *only* in Sgr B2! It's an amazing little bugger!*



Galactic ring of CO at 110 GHz

ORGANIC MOLECULES

- Organic molecules have also been found in space. They are usually complex with weak emission and therefore hard to measure. However, five have been found in Sgr B2.



NRAO

VARIOUS 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 is difficult to observe, but we know it's there because we see how it effects its environment. Sometimes theories do not work unless we include dark matter.

The amount of matter that we **can** observe is only a small fraction of the whole mass of the universe.

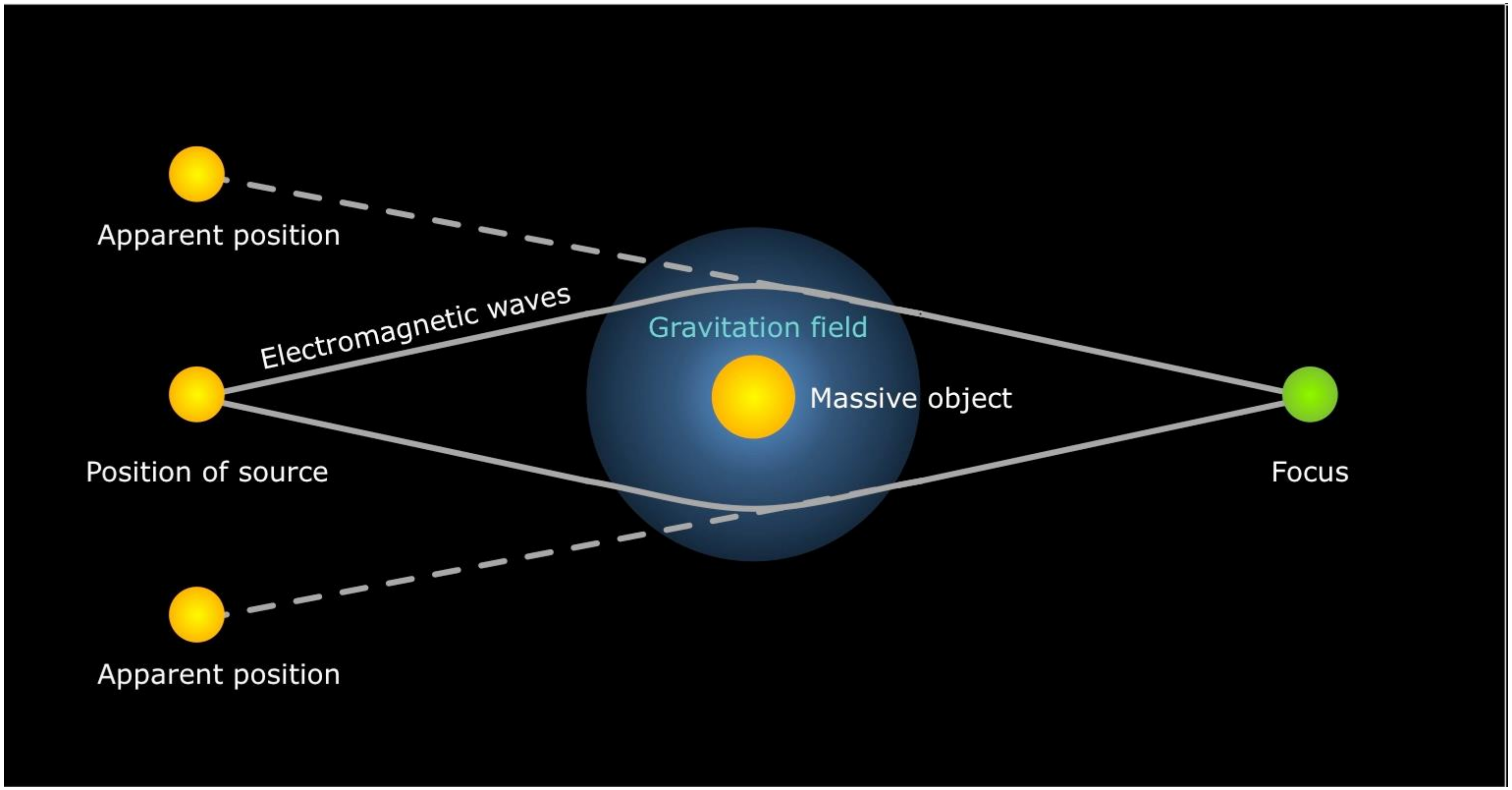
EVIDENCE FOR DARK MATTER

1. The outer part of the Galaxy is rotating "too fast" (rotation curve!).
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.

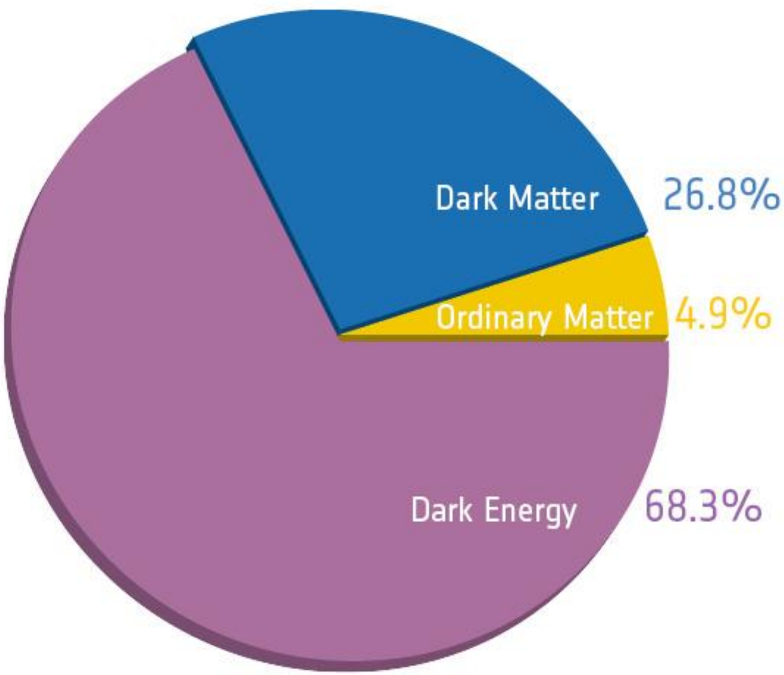
GRAVITATIONAL LENSING

- https://en.wikipedia.org/wiki/Gravitational_lens



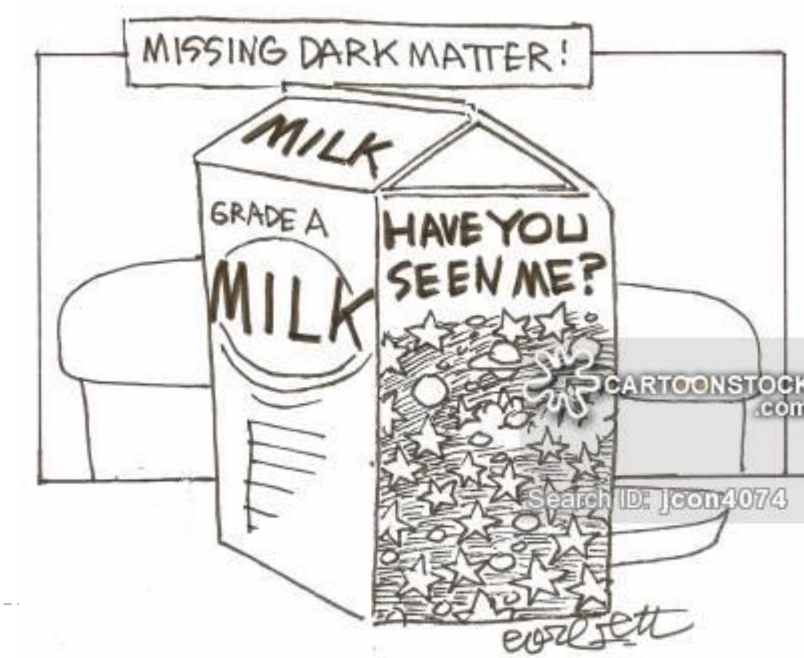
CONTENTS OF THE UNIVERSE

- Read more about dark matter and its properties:
  - https://en.wikipedia.org/wiki/Dark_matter
- Dark energy is "nice-to-know" material, no need to go into details unless you are interested:
  - https://en.wikipedia.org/wiki/Dark_energy



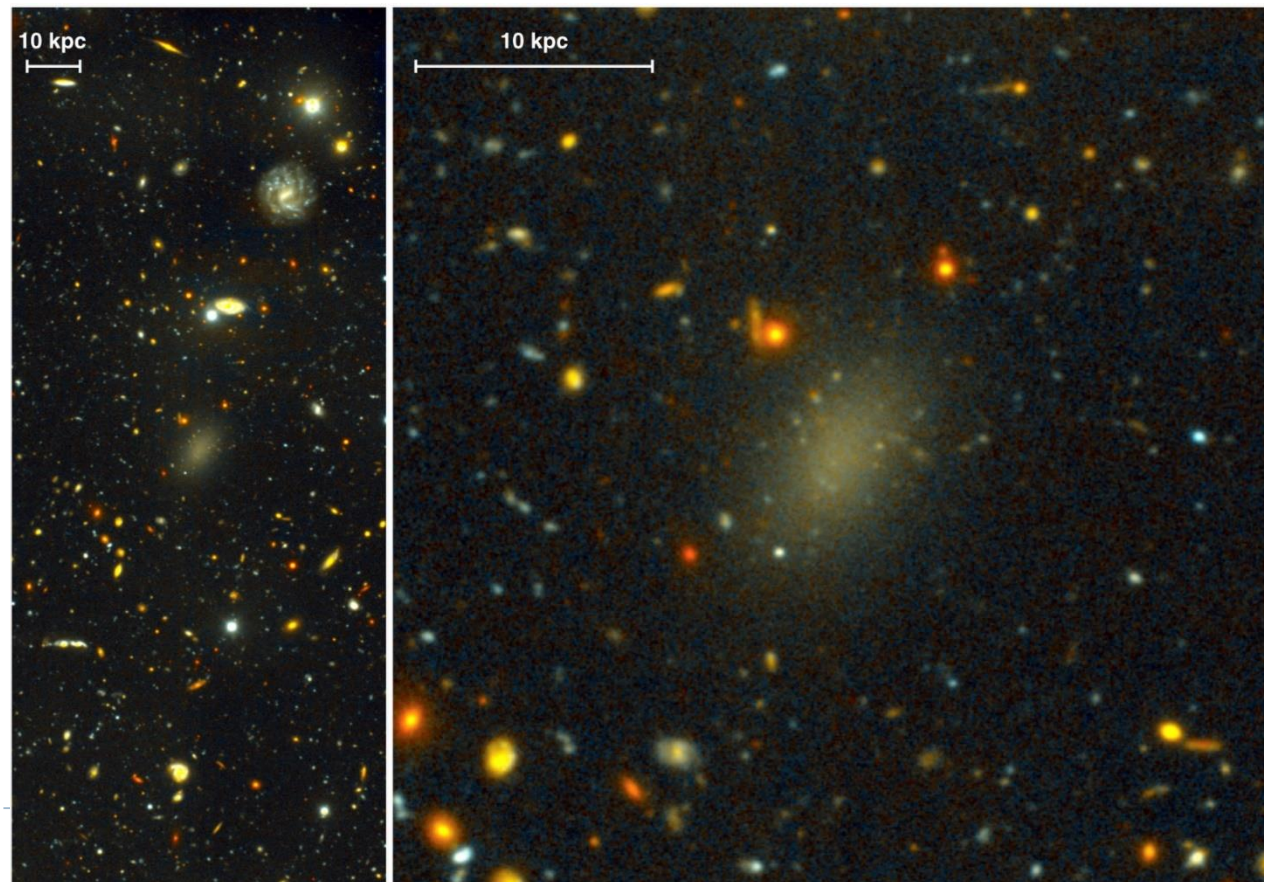
DARK MATTER

- 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 weakly interacting massive particles (WIMPs)…?
- Baryonic vs. **non-baryonic** ???



A DARK MATTER GALAXY: DRAGONFLY 44

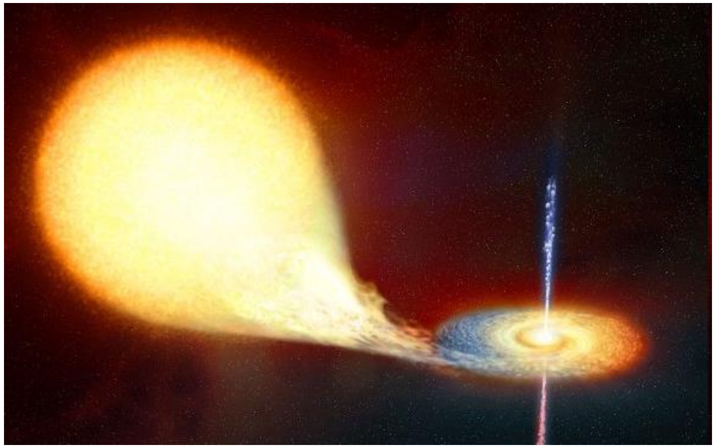
- Very diffuse, "fluffy" galaxy made 99.99% of dark matter but still about the size of the Milky Way. The stars that can be seen could not hold the galaxy gravitationally together.



Pieter van Dokkum, Roberto Abraham, Gemini Observatory/AURA

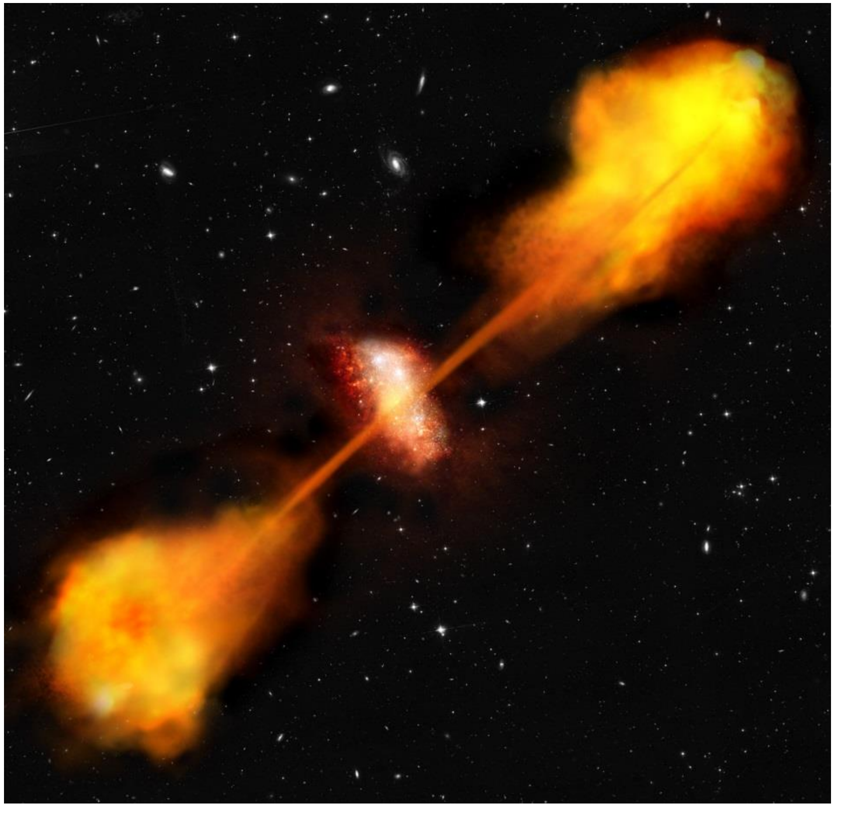
TODAY

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



NEXT WEEK 30.11.2020

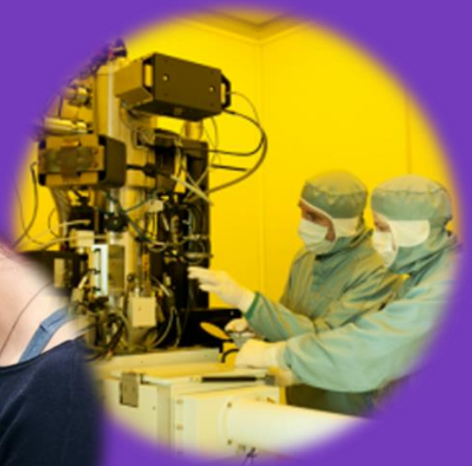
- Extragalactic astronomy & Cosmology as self-study materials (no live lecture)



- Reminder: Exam on **8.12.2020 at 13-16** online in MyCourses!
- Retake exam on 1.2.2021

ELE’s 2021 Summer jobs

Open for application 8 Dec 2020!



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