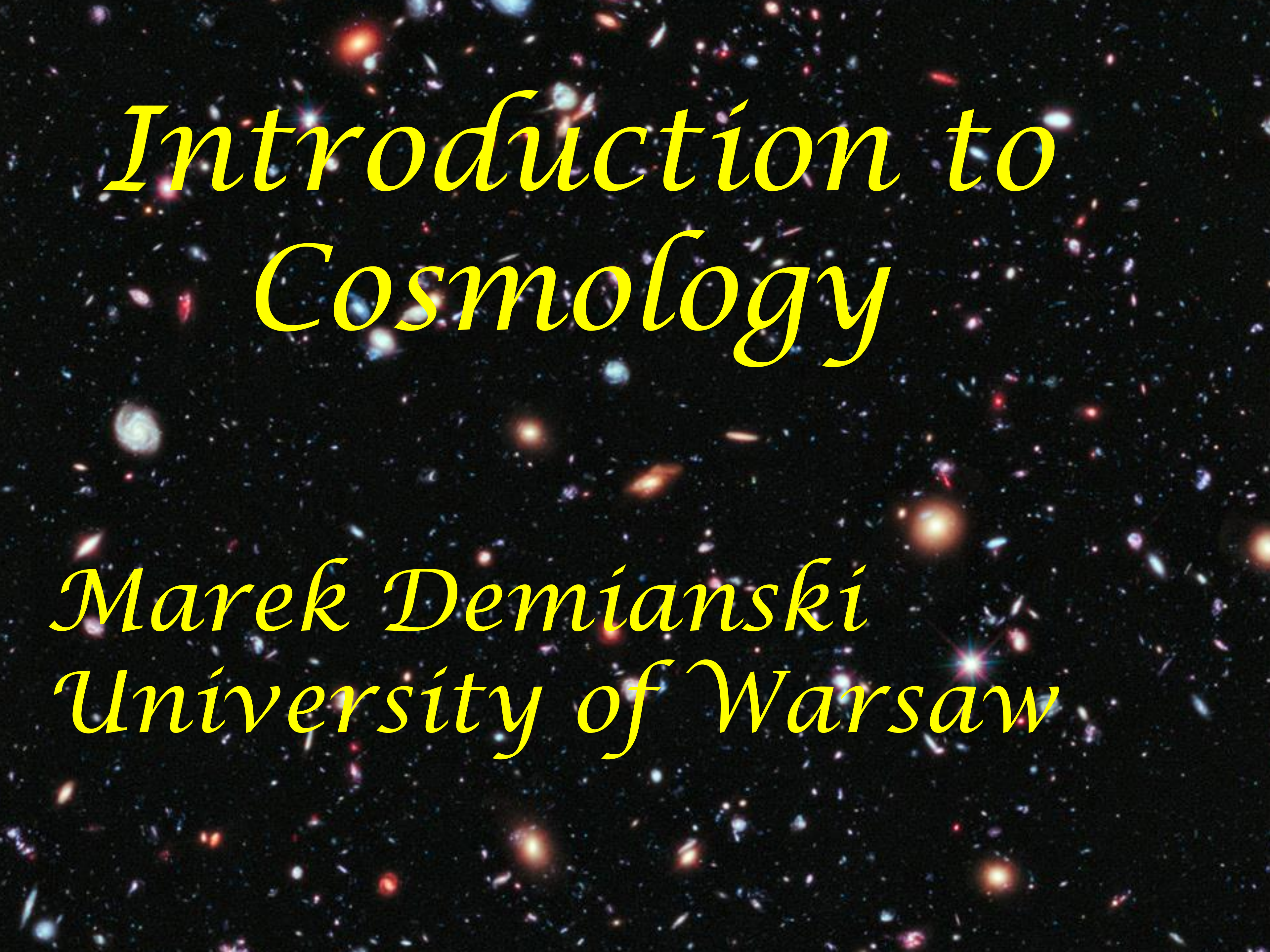
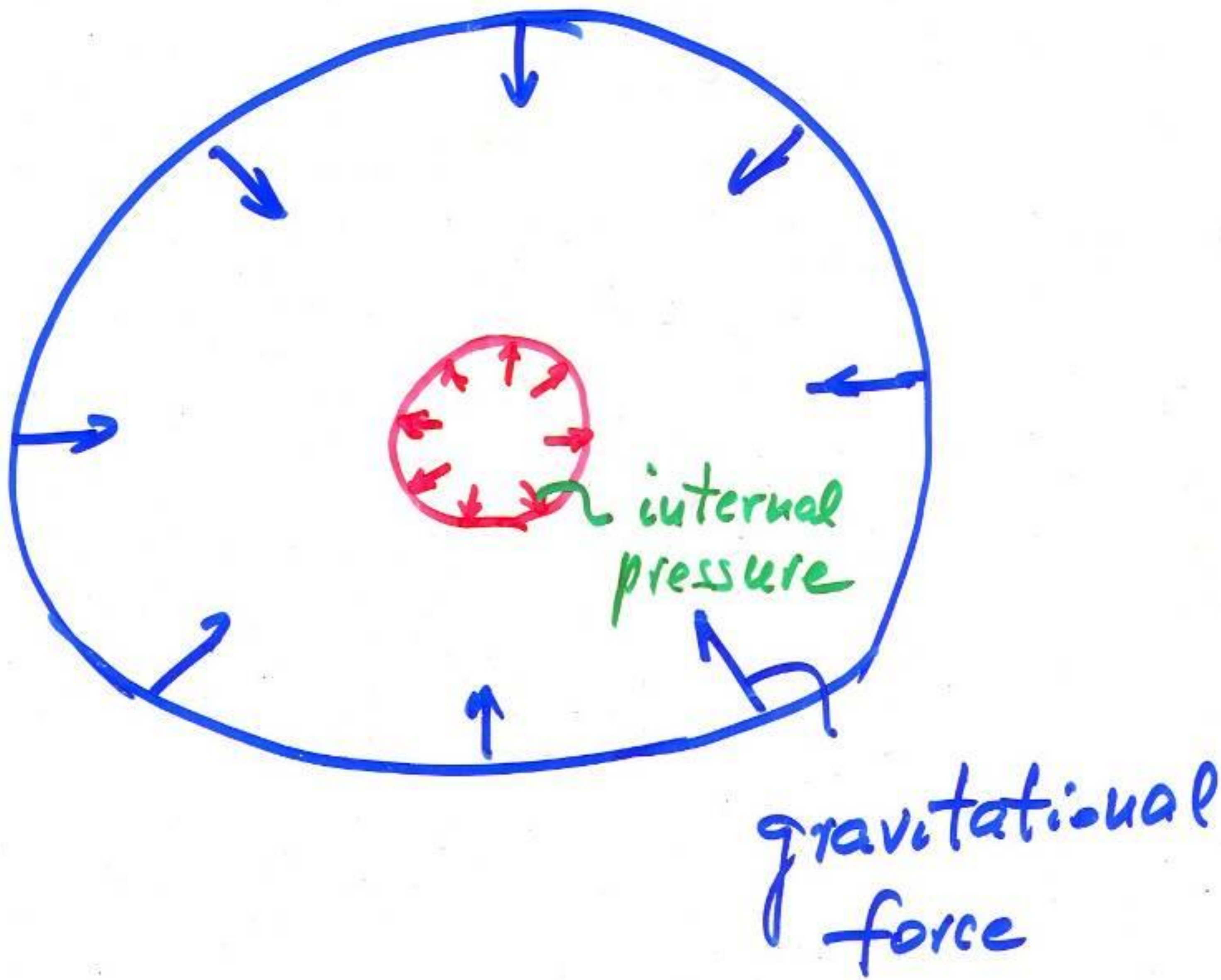

Introduction to
Cosmology
Marek Demianski
University of Warsaw



internal pressure
gravitational force

The virial theorem:

$\frac{1}{2}$ of the released GPE is used to heat up the center of a star,

the other $\frac{1}{2}$ has to be radiated away

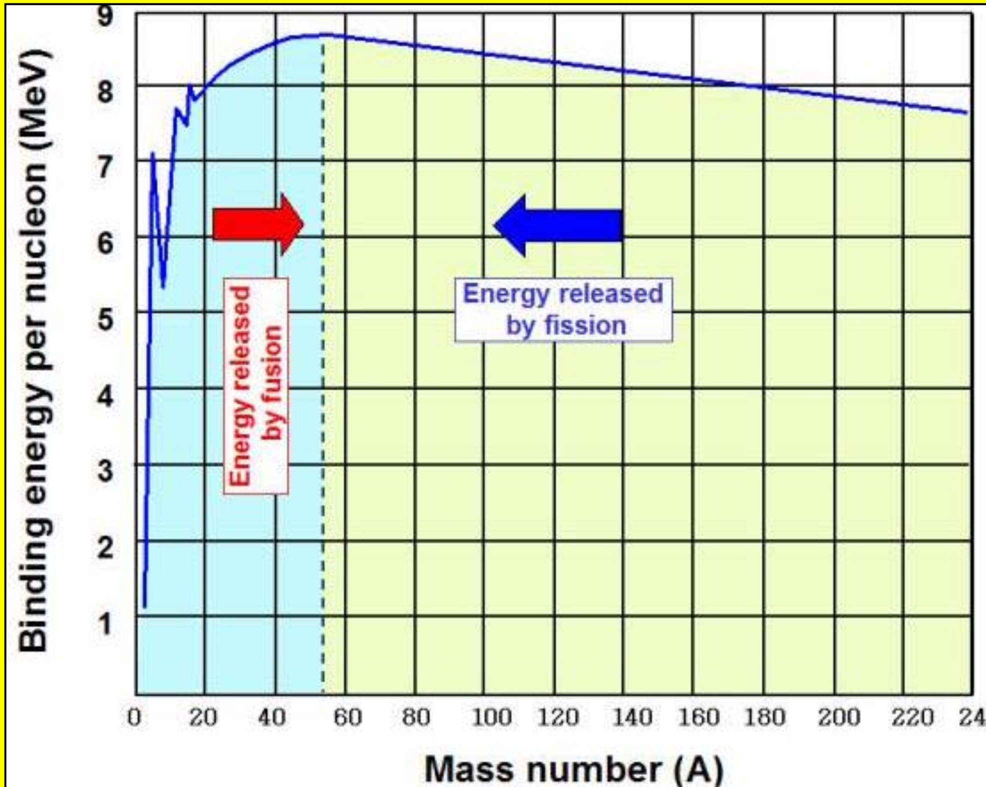
Massive Stars Cook Heavy Elements

The carbon core of a massive star becomes **hot enough (T>7 x 10^8 K) for carbon to fuse**:

$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma$ and $^{16}O + ^{4}He \rightarrow ^{20}Ne + \gamma$

These reactions produce less E per reaction, consuming fuel faster and faster…

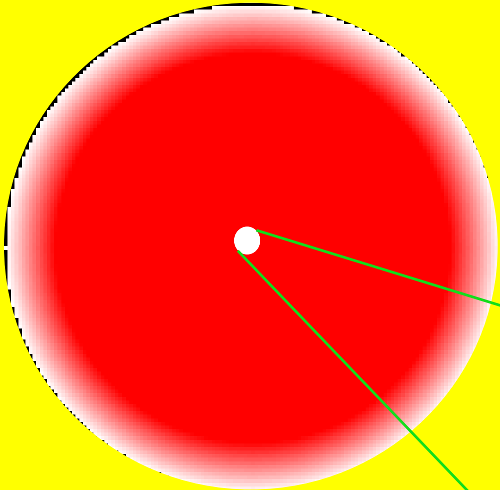
→***evolution accelerates***

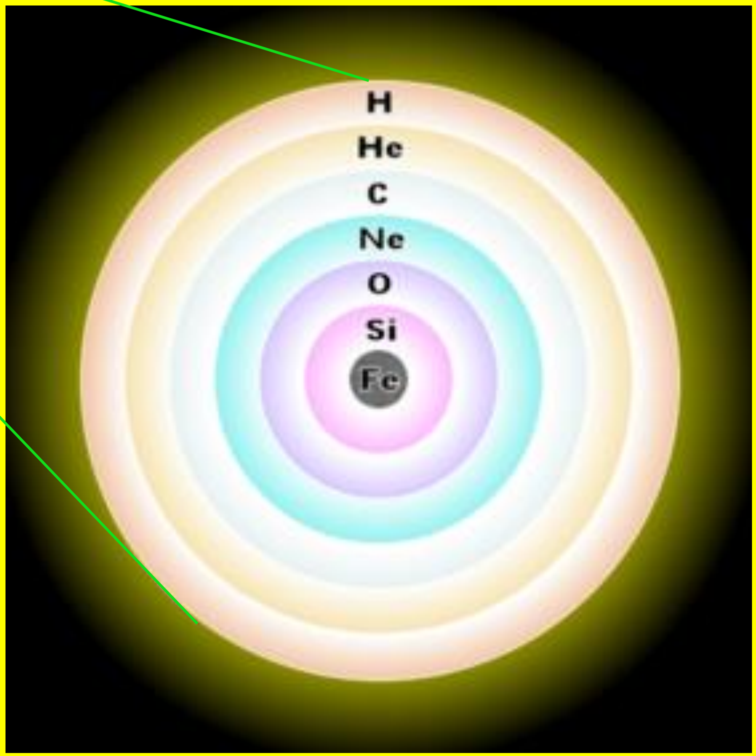


http://web.mit.edu/people/jinseok/notes/notes_20031217/notes_20031217.shtml

Multiple Shell Burning Stages

Advanced nuclear burning proceeds in a series of nested shells, giving rise to an “onion skin” structure





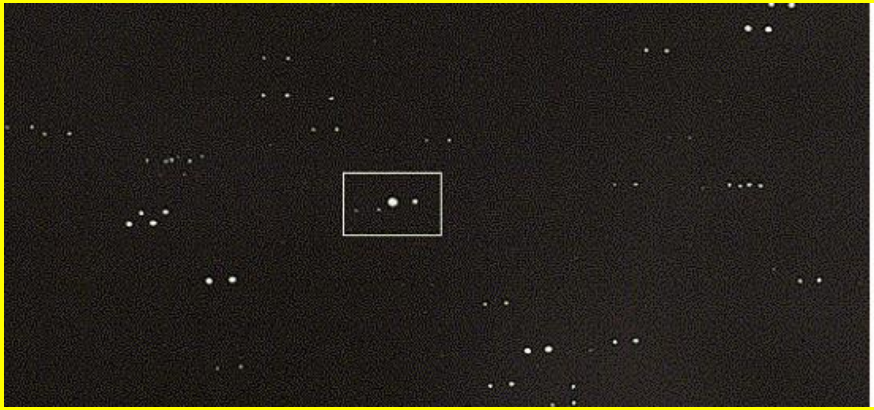
http://www.physics.uc.edu/~hanson/ASTRO/LECTURENOTES/W07/Death/OnionSkin.png

Digression: Cepheid Variables

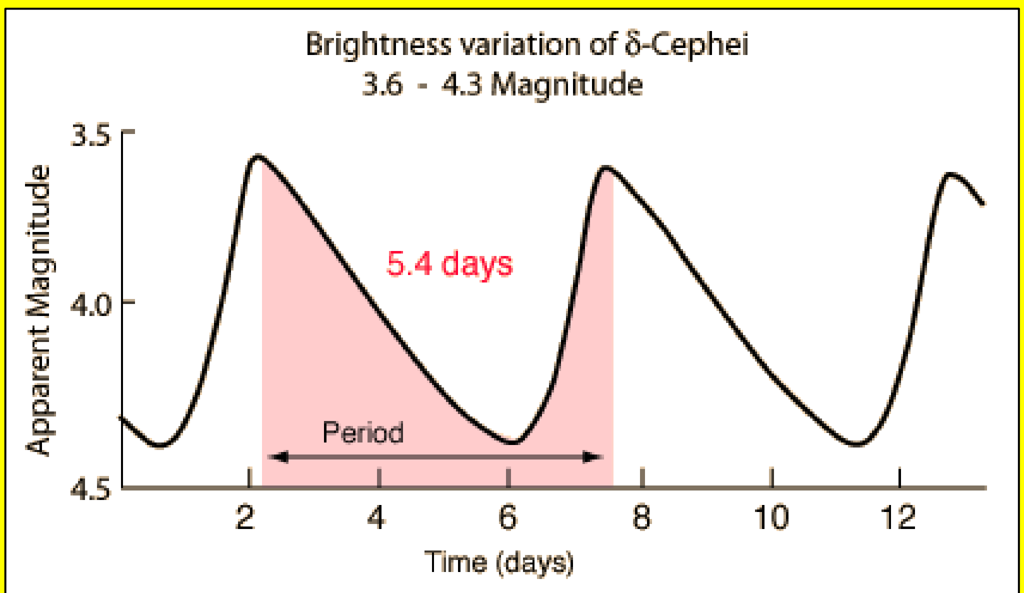
- Young, yellow supergiants with periodic L variation.
- Periods range from 2 days to about 100-120 days.
- 2-10 $M_\odot$ ~ $10^4 L_\odot$ T_{eff} = 5000-6400K
- Brightness fluctuations ~1 magnitude, surface velocities ~ 40-60 km/s.
- Located in the disks of spiral galaxies.

HST

A Cepheid at max and min



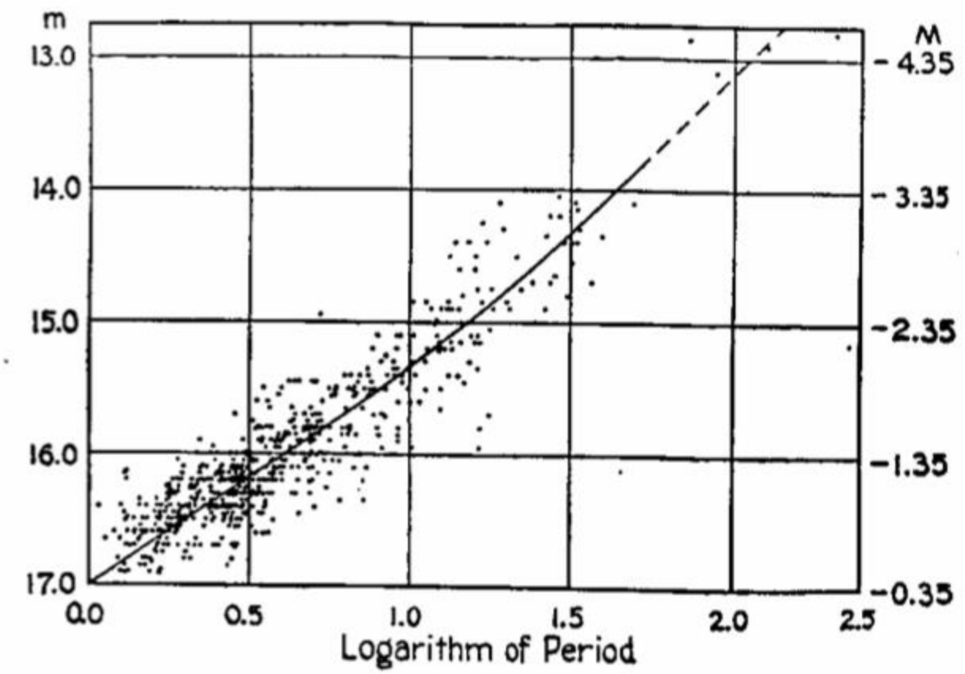
Composite Cepheid photograph at maximum (left) and minimum (right) brightness



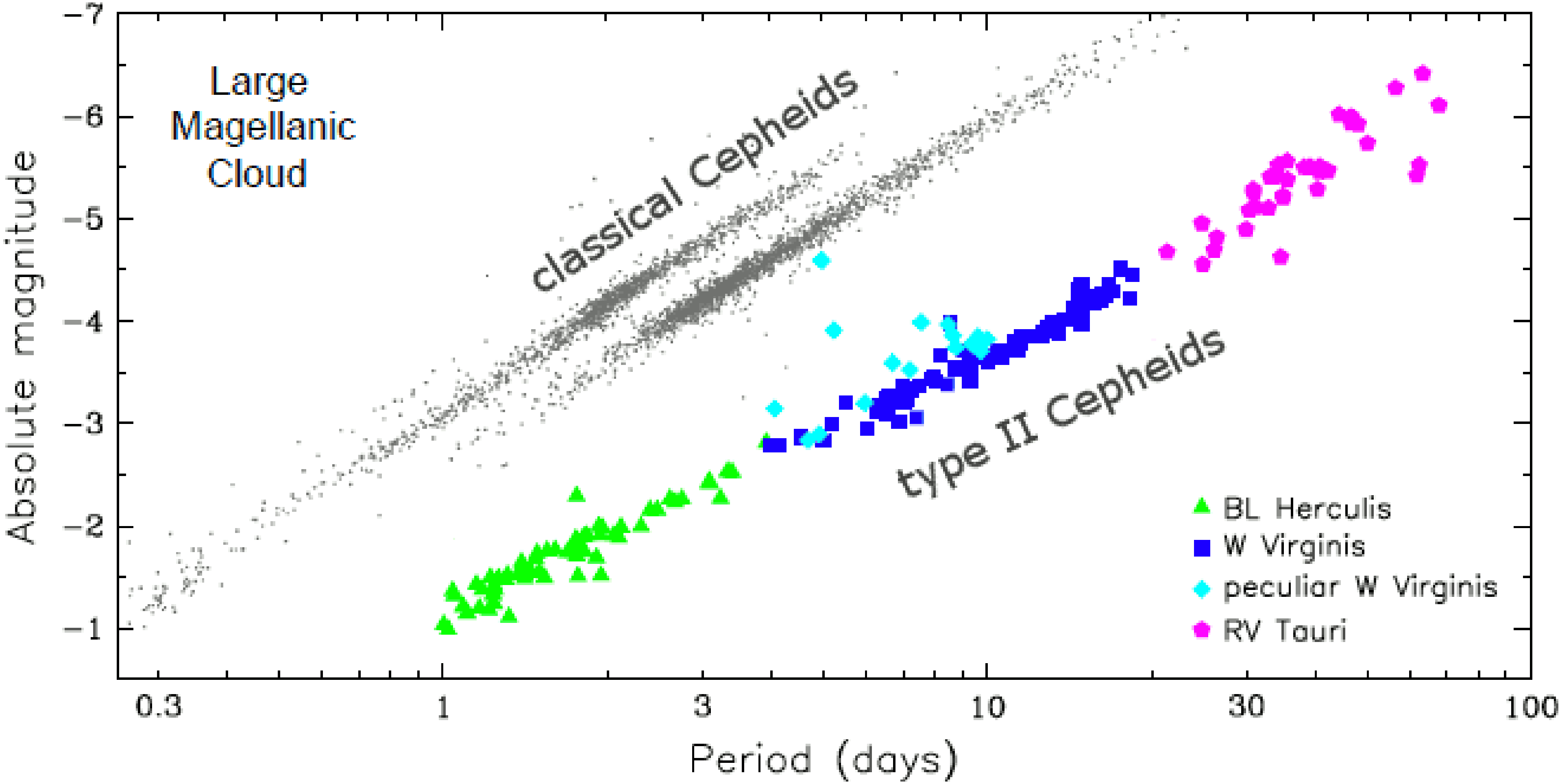
http://hyperphysics.phy-astr.gsu.edu/hbase/astro/cepheid.html

Leavitt's Data

Henrietta Leavitt's SMC Cepheids

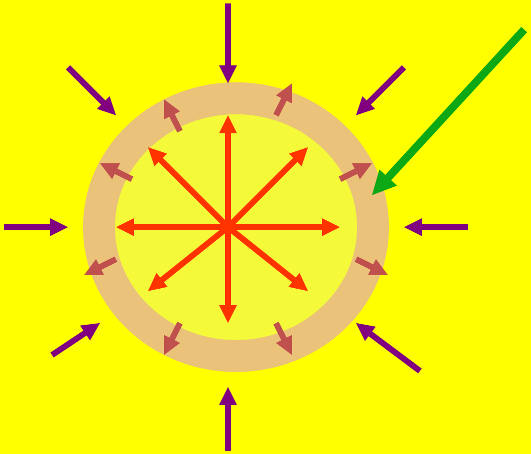


(From Carroll and Ostlie, *Modern Astrophysics*)



Large Magellanic Cloud
classical Cepheids
type II Cepheids
BL Herculis
W Virginis
peculiar W Virginis
RV Tauri
Absolute magnitude
Period (days)
−7
−6
−5
−4
−3
−2
−1
0.3
1
3
10
30
100

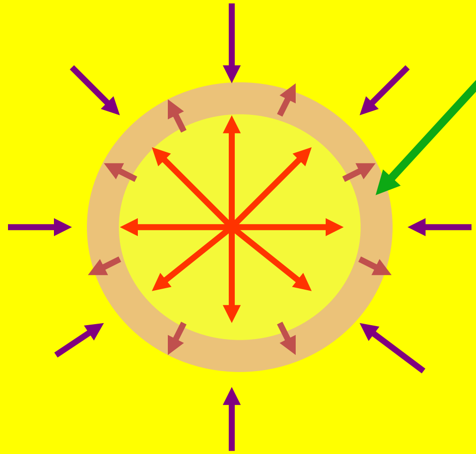
Cepheid Broken Valve Mechanism



Partial He^{+} ionization zone* is opaque and absorbs more energy than necessary to balance the weight from higher layers.
→ ***Expansion***

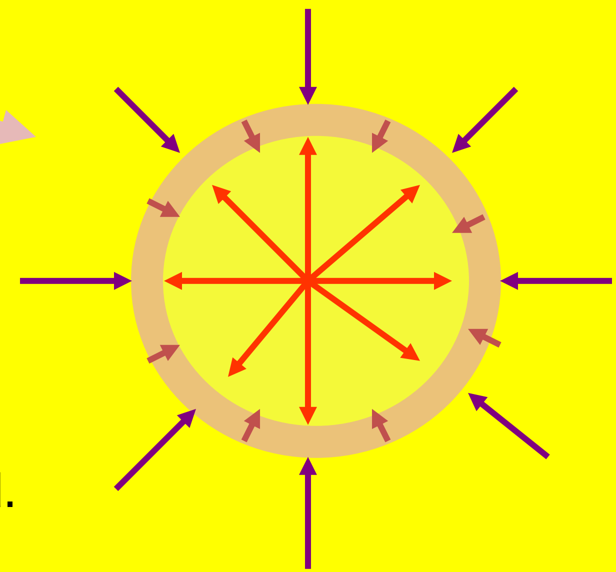
***region below surface where helium is partly He^{+} and partly He^{++}**

The Valve Mechanism

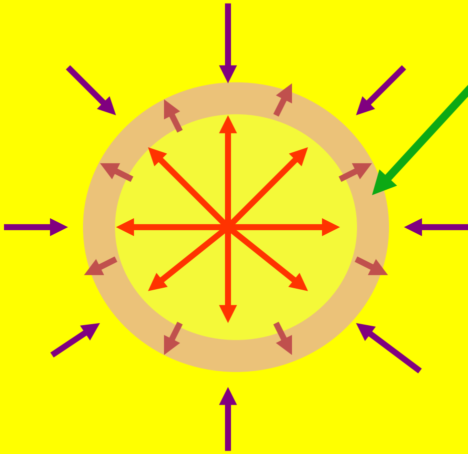


Partial He ionization zone is opaque and absorbs more energy than necessary to balance the weight from higher layers.
→ ***Expansion***

Upon expansion, partial He ionization zone becomes more transparent, absorbs less energy → weight from higher layers pushes it back inward.
→ ***Contraction***

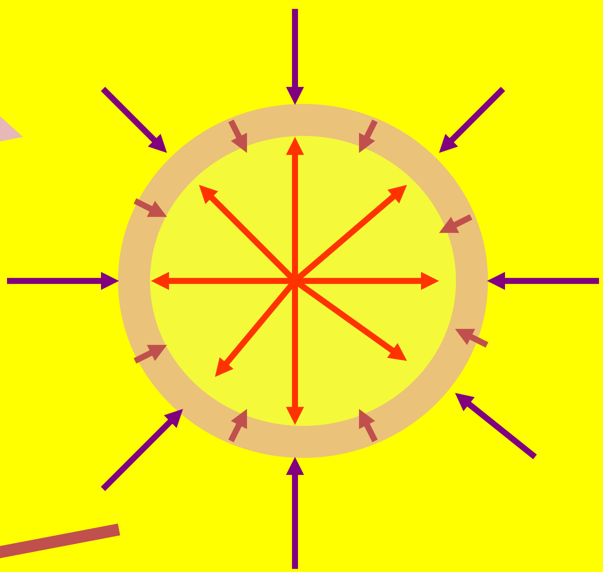


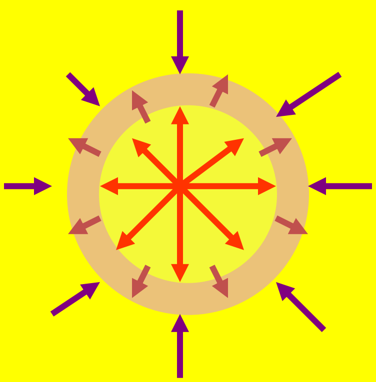
The Valve Mechanism



Partial He ionization zone is opaque and absorbs more energy than necessary to balance the weight from higher layers.
→ ***Expansion***

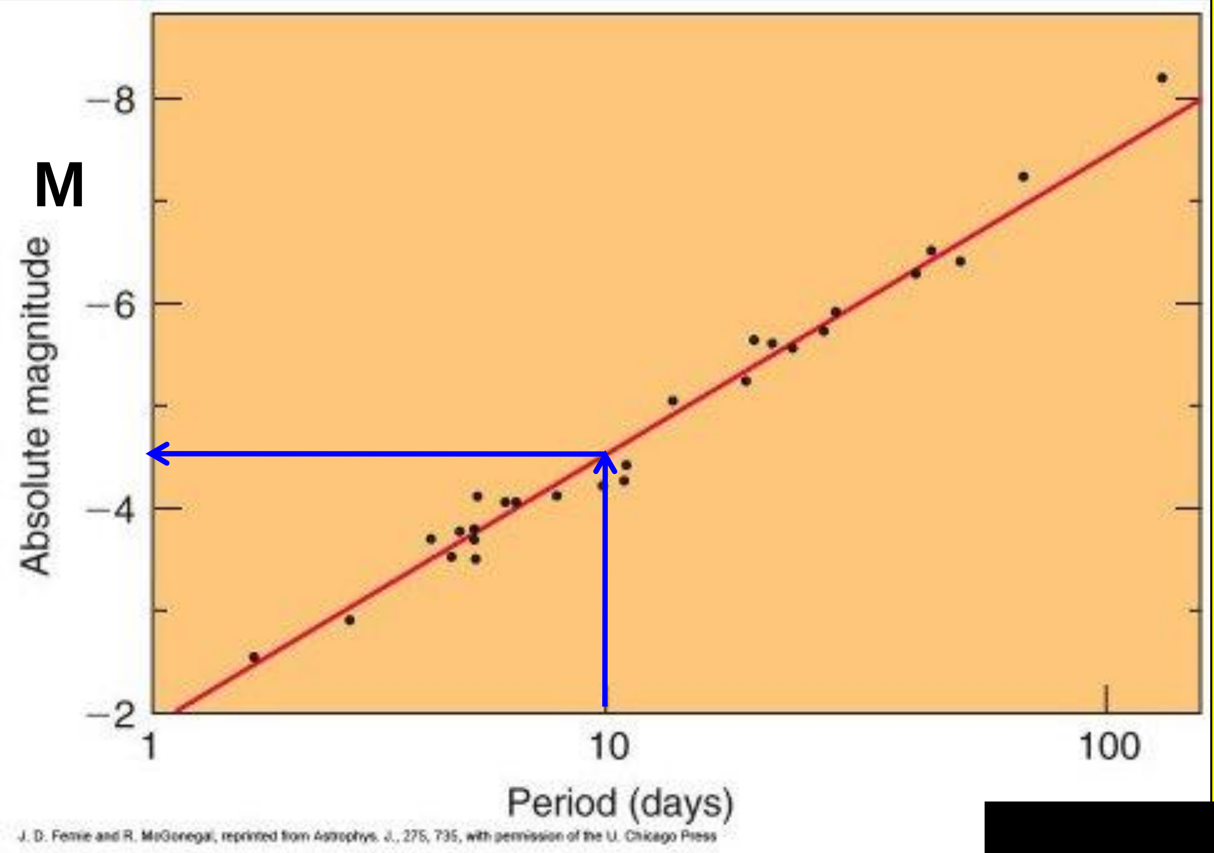
Upon expansion, partial He ionization zone becomes more transparent, absorbs less energy → weight from higher layers pushes it back inward.
→ ***Contraction***





Upon compression, partial He ionization zone becomes more opaque again, absorbs more energy than needed for equilibrium → ***Expansion***

= **positive feedback (like pushing someone on a swing; perpetuates instability**



http://www.ifa.hawaii.edu/~barnes/ast110_06/trotn/1128a.jpg

- **observe m**
- **observe P**
- **read off M**

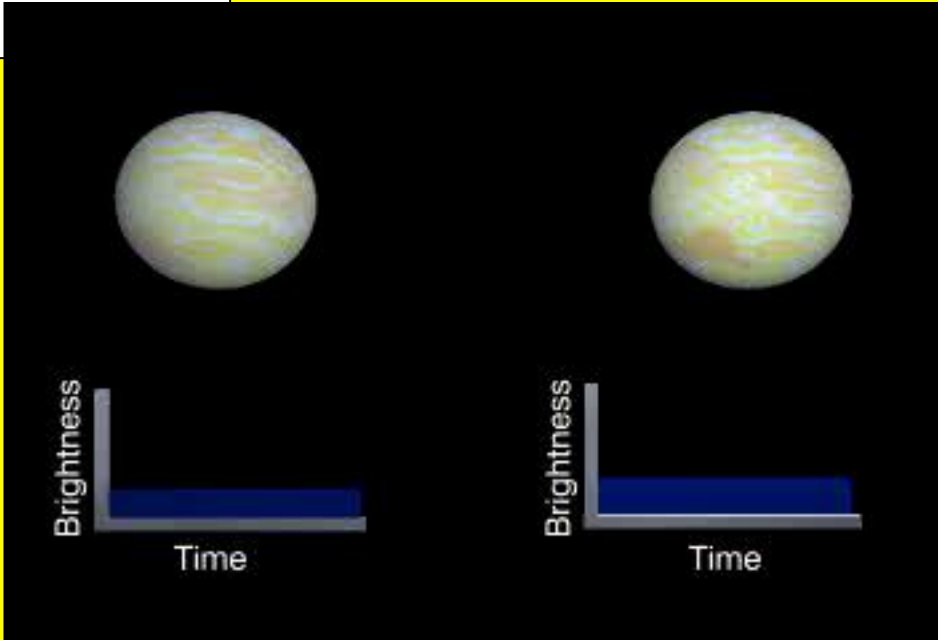
→ determine distance:

$$m - M = 5(\log d) - 5$$

$$d(pc) = 10^{\frac{(m - M + 5)}{5}}$$

Period ~ time for a sound wave to travel the diameter of the star

Changes in R and T ~10-20%



http://www.aavso.org/sites/default/files/cepheid.mpeg

Steps to a Supernova

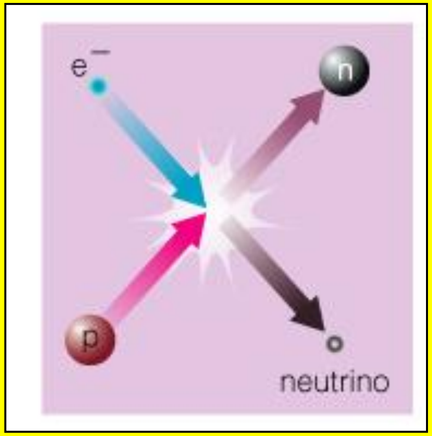
- ^{56}Fe core means *no more E can be extracted*
- $M_{core} > 1.44\ M_{\odot}$ (Chandrasekhar Limit)
- → **CORE COLLAPSE!**
- Core still heats up as it collapses, but to no avail, *except* **photodisintegration**!
- $^{56}\mathrm{Fe} + \gamma \rightarrow 13(^{4}\mathrm{He}) + 4\ \mathrm{n}$ and $^{4}\mathrm{He} + \gamma \rightarrow 2\mathrm{p} + 2\mathrm{n}$

Think about it … All the star's previous nucleosynthesis over many millions of years is undone in seconds!

Neutronization and Collapse

- **photodisintegration** occurs in < 0.1 second!
- Density is so high that protons and electrons are crushed into neutrons, which also produces huge numbers of neutrinos:

$$p^+ + e^- \rightarrow n + \nu$$



- Atoms disappear and become nuclear matter, with density about 4×10^{14} g/cm^3 !
- … as if a whole sun collapsed to city size: 10^9 tons/tsp!

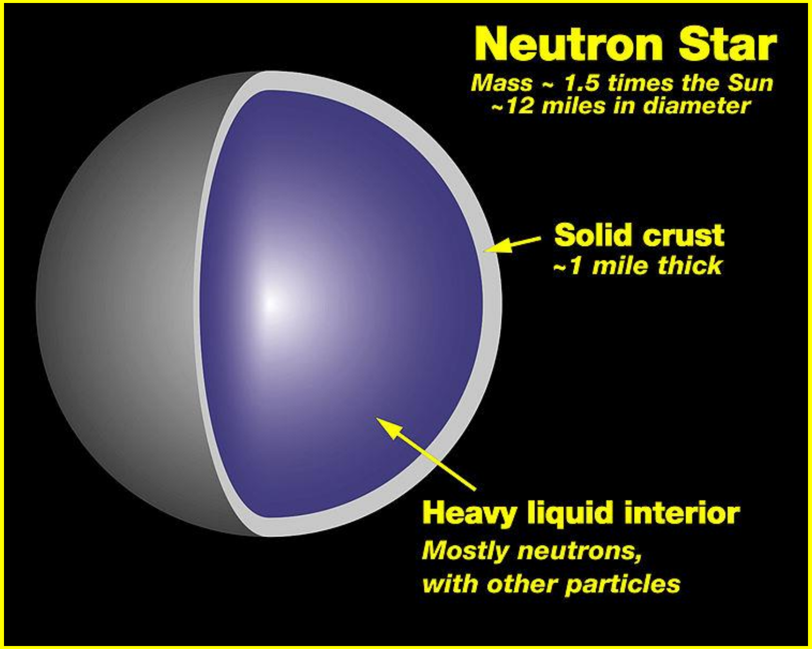
→

Getty Images

Core Collapse, continued

- When *neutronization* is nearly complete, core collapse is halted by a combination of **neutron degeneracy pressure**, and strong-force repulsion.

- The core, with R ~ 10 km, has become a ***NEUTRON STAR.***

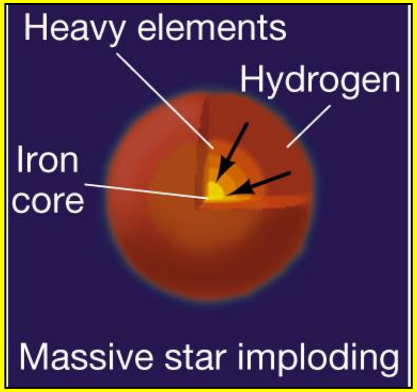


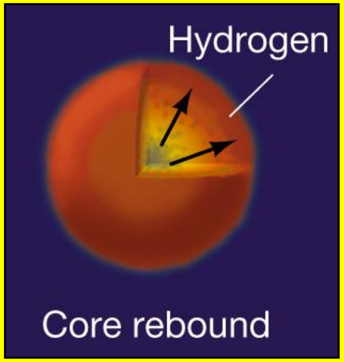
n : p : e = 8 : 1 : 1

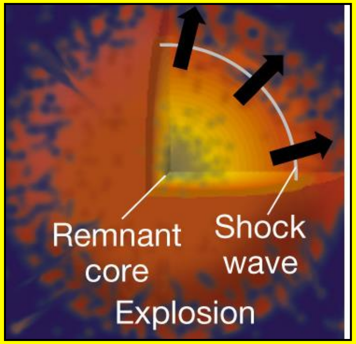
NASA

But what about the rest of the star??

- **Ca, Si, S, Mg, Ne, O, C** layers obliviously continue to burn, until…
- When core collapses, they collapse onto it.
- “Stiff” core, plus **pressure from all the ν** produce a **bounce** and an outgoing shock wave that blasts off the outer layers
- Energy released allows ***explosive nucleosynthesis***, producing elements beyond the Fe peak in binding energy
- The rapidly-expanding outer layers get very luminous, very quickly, producing a **TYPE II SUPERNOVA**

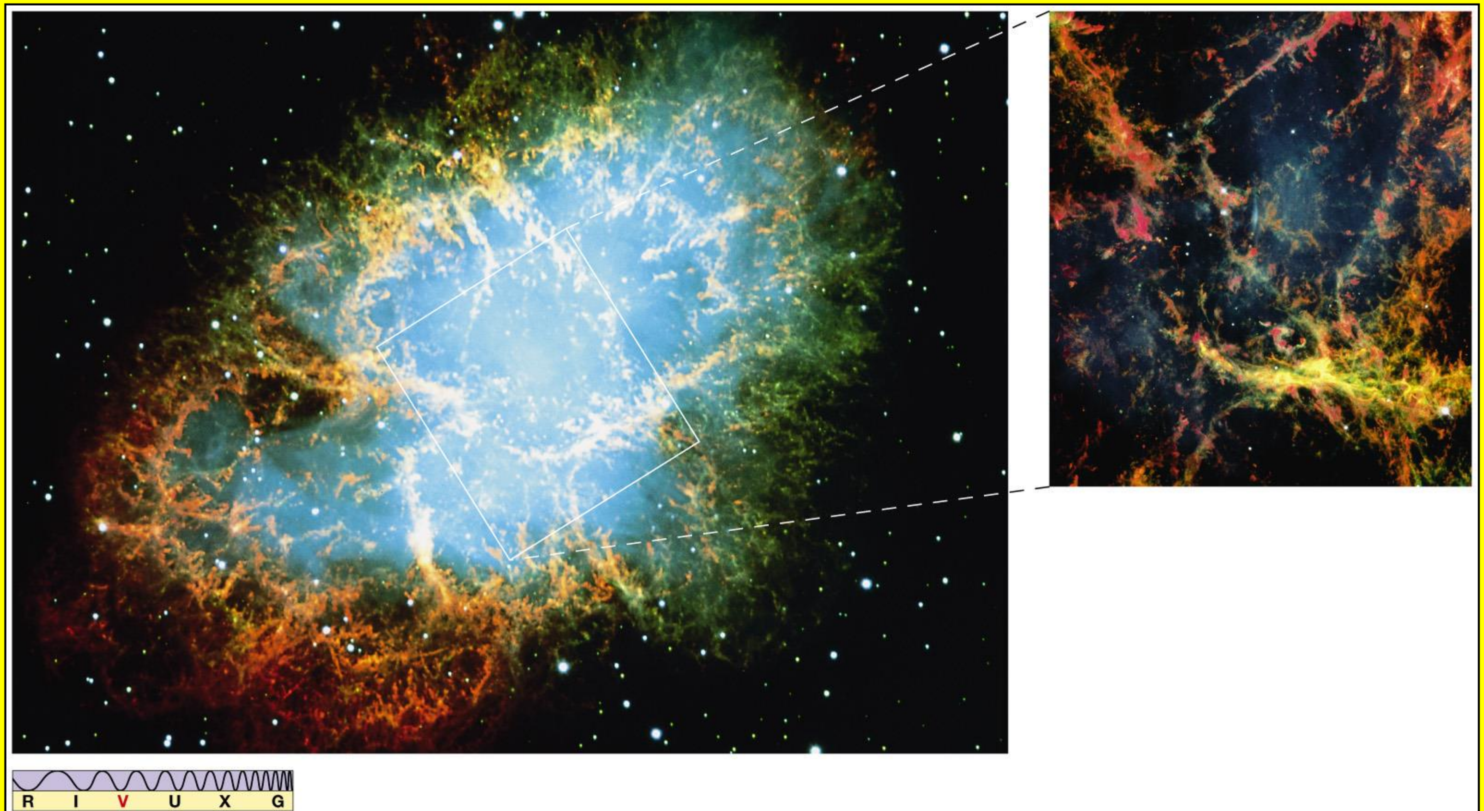






Supernova Remnants

- The expelled gas interacts with the ISM to make a **SUPERNOVA REMNANT**, which glows for $\sim 10^5$ years
- CRAB SN was seen in 1054 CE – appears in Chinese records



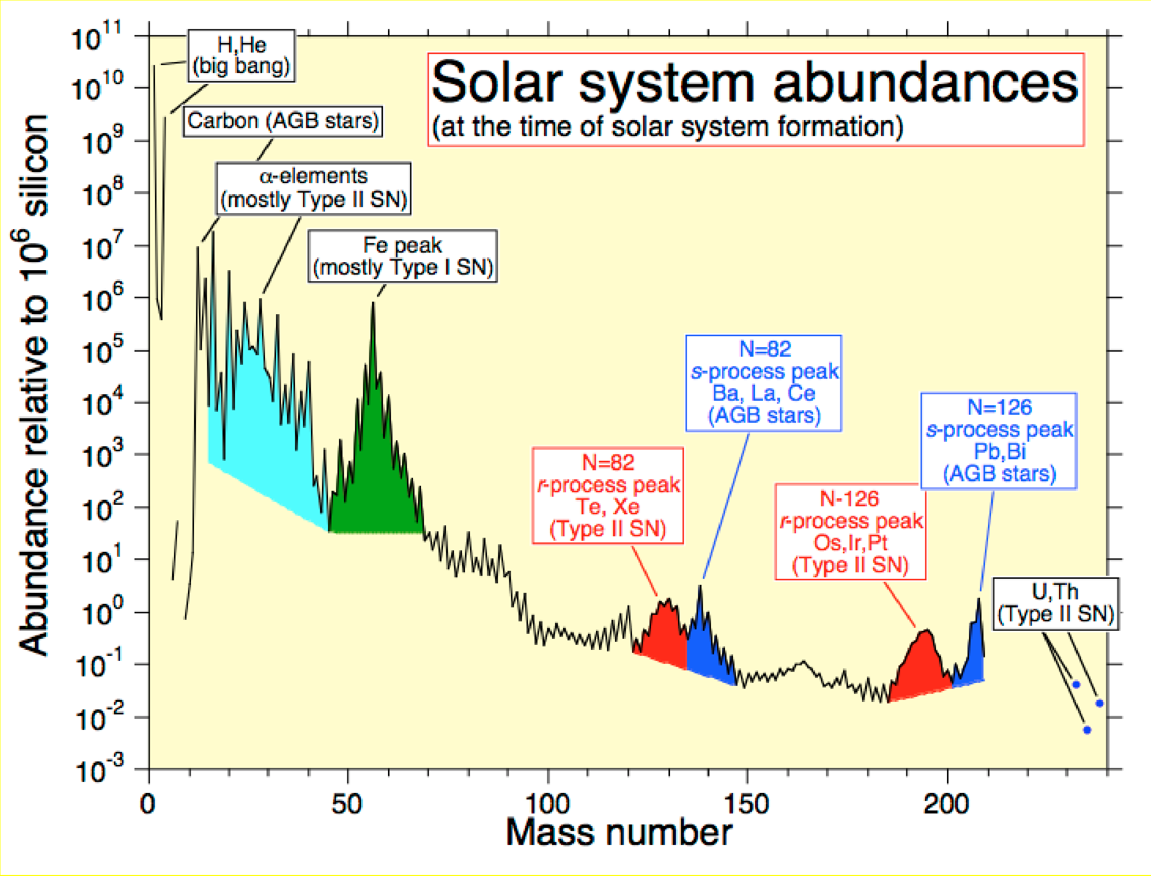
3 Main Nucleosynthesis Sites & Timescales

Massive stars (M>10 $M_\odot$) and SNe II: synthesis of most of the nuclear species from oxygen through zinc, and the r-process heavy elements (*τ < 10^8 years*)

Red G/AGB Stars: (1<M<10 $M_\odot$) synthesis of heavy s-process elements (*τ > 10^9 years*)

SNe Ia: synthesis of ~ 50-70% of Fe-peak nuclei not produced by SNe II (*τ > 1.5-2 x10^9 years*)

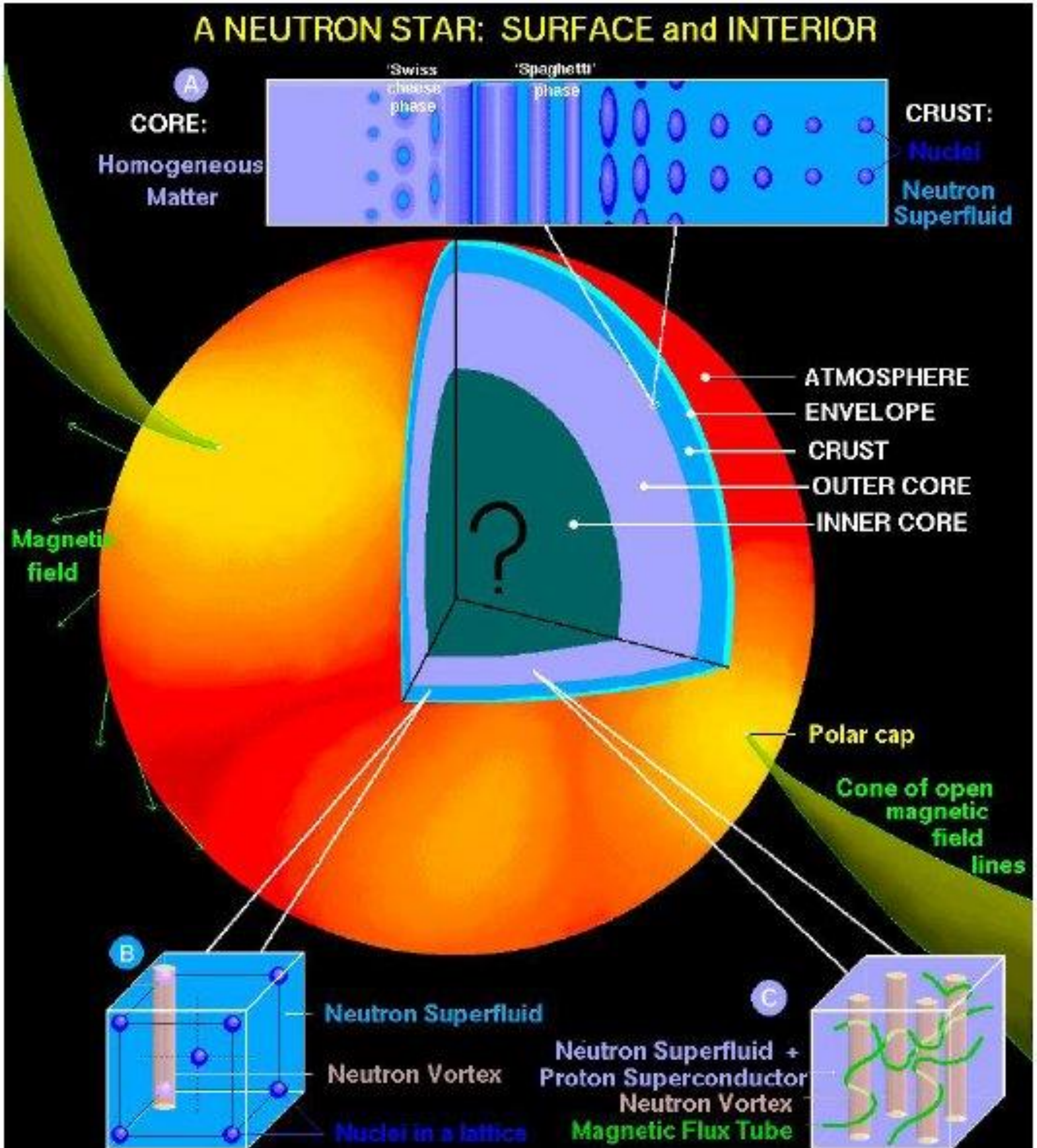
NS-NS mergers τ ~ sec



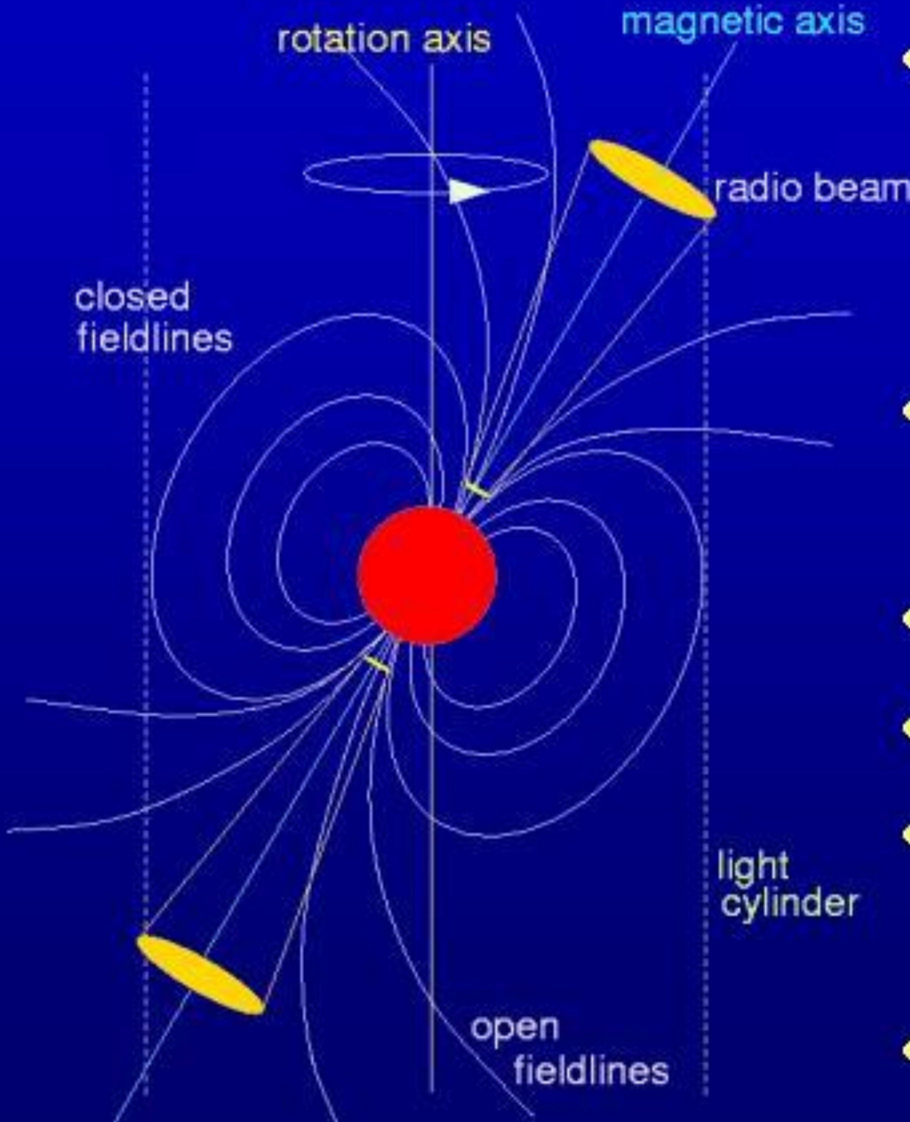
Adapted from J. Truran

Expected characteristics of neutron stars

- Mass ~ 1.4 $M_\odot$
- Radius ~ 10 - 20 km !
- Density ~ 10^{17} kg/m^3
- Initial temperature ~ 10^{11} K


A NEUTRON STAR: SURFACE and INTERIOR
A
'Swiss cheese' phase
'Spaghetti' phase
CORE:
Homogeneous Matter
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

Pulsar - Magnetosphere



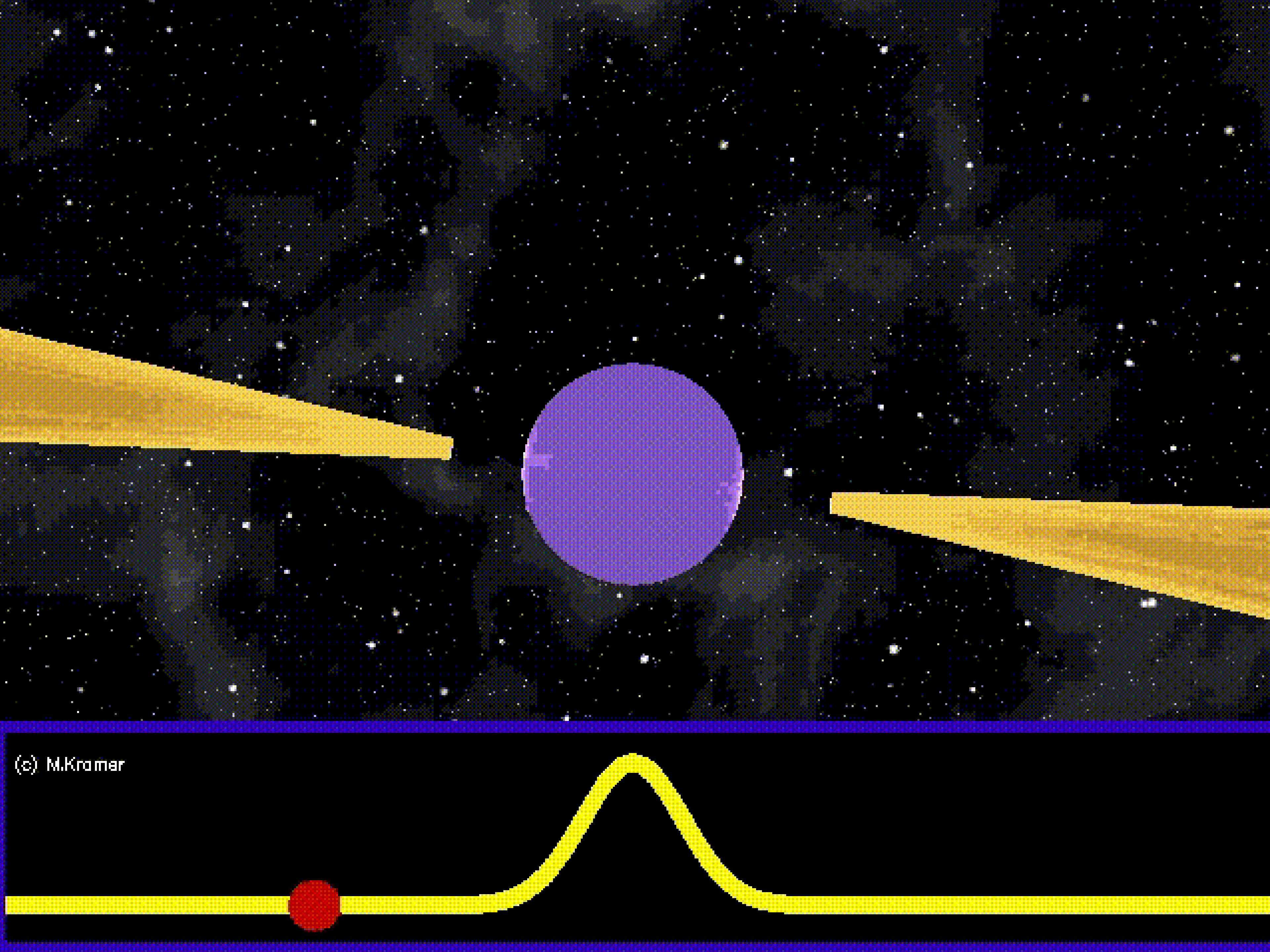
- rotation induces electric quadrupole field

$$F_{el} / F_{grav} = 10^{12}$$

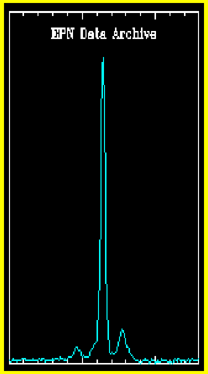
- charges pulled out of surface, shielding force
- plasma fills surrounding
- co-rotation with pulsar
- light cylinder:

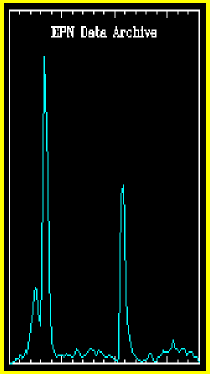
$$v = R_L \Omega = c$$

- open and closed fieldlines


(c) M.Kramer

Sound of pulsars





PSR B0329+54
1.4 Hz

typical pulsar

Crab
Pulsar

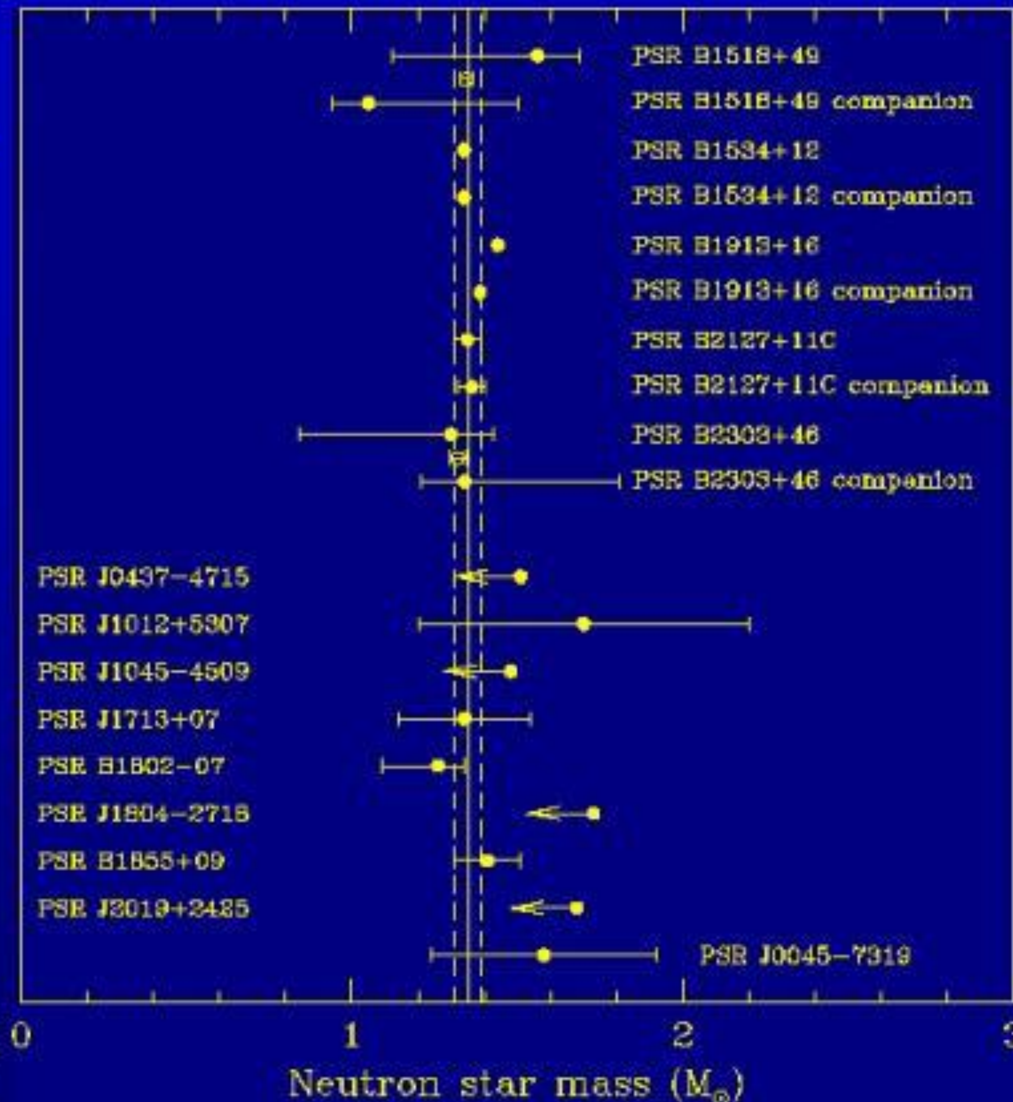
30 Hz

PSR 1937
645 Hz

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Masses

- QM predicts 1.4 $M_{\odot}$
- Depends on Equation-of-State (EOS)
- Accretion can increase mass
- Observations show mean values ~1.35$M_{\odot}$



Thorsett & Chakrabarty '99

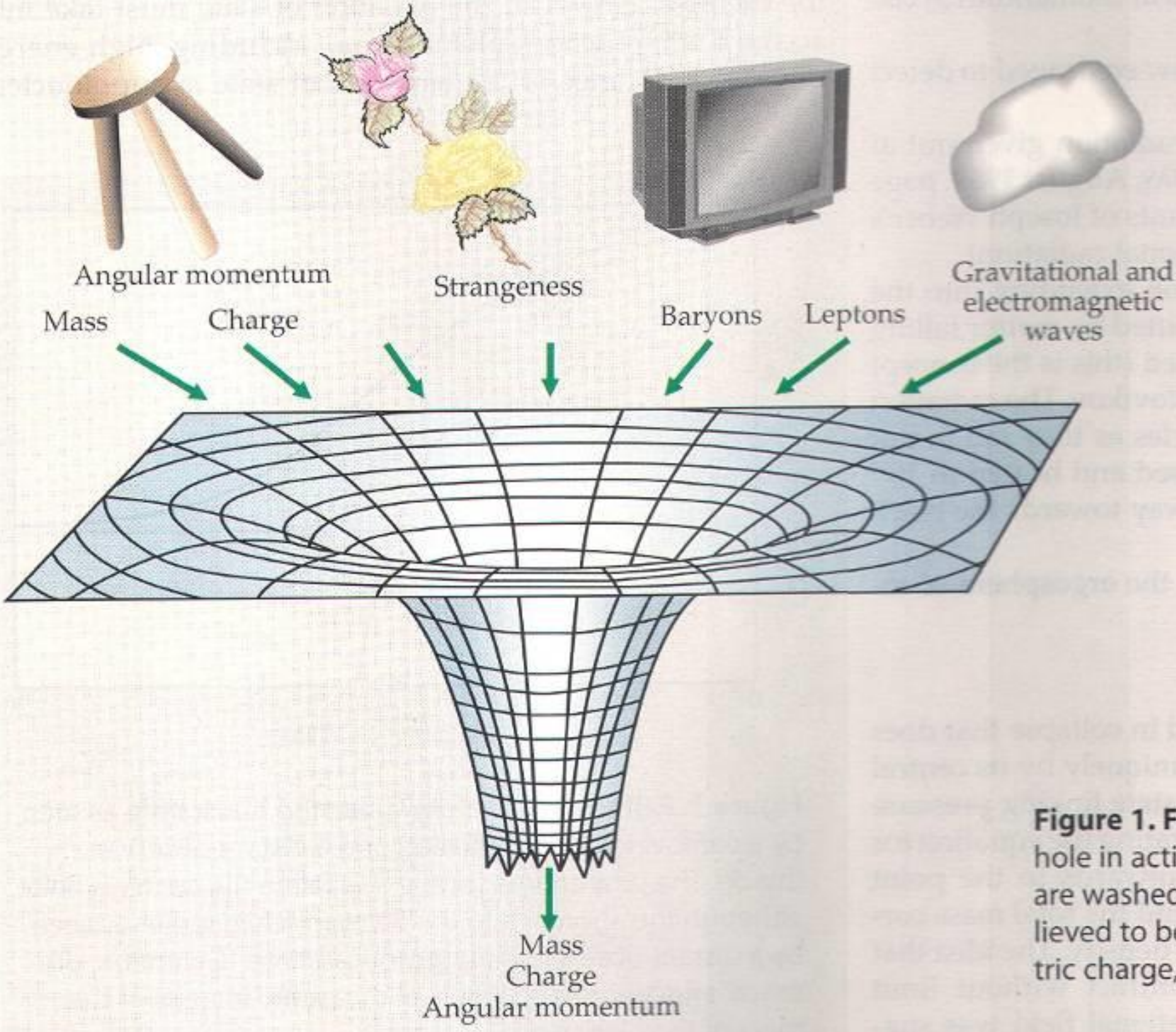


Figure 1. Figu
hole in action.
are washed ou
lieved to be ur
tric charge, an

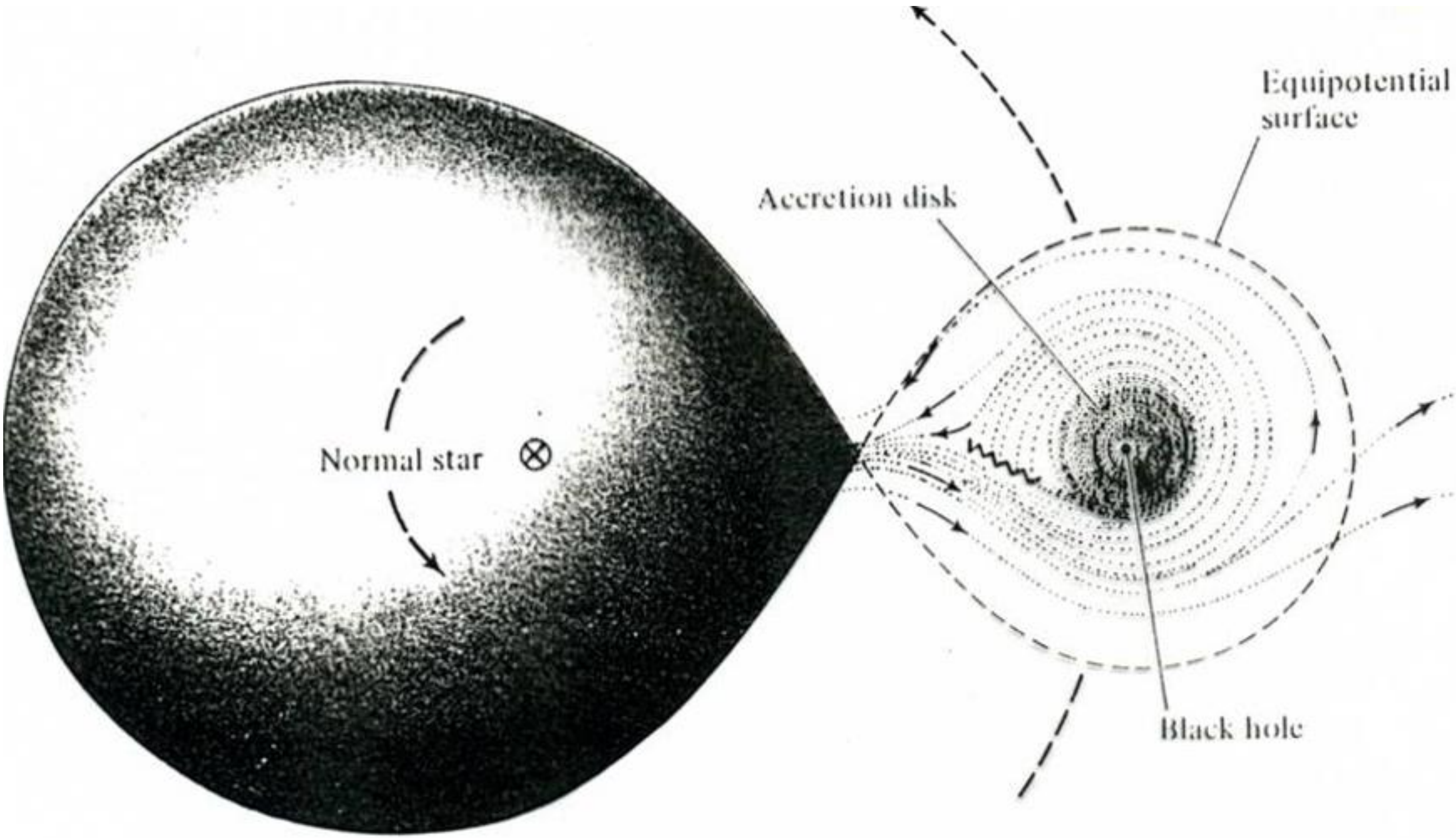
Black holes

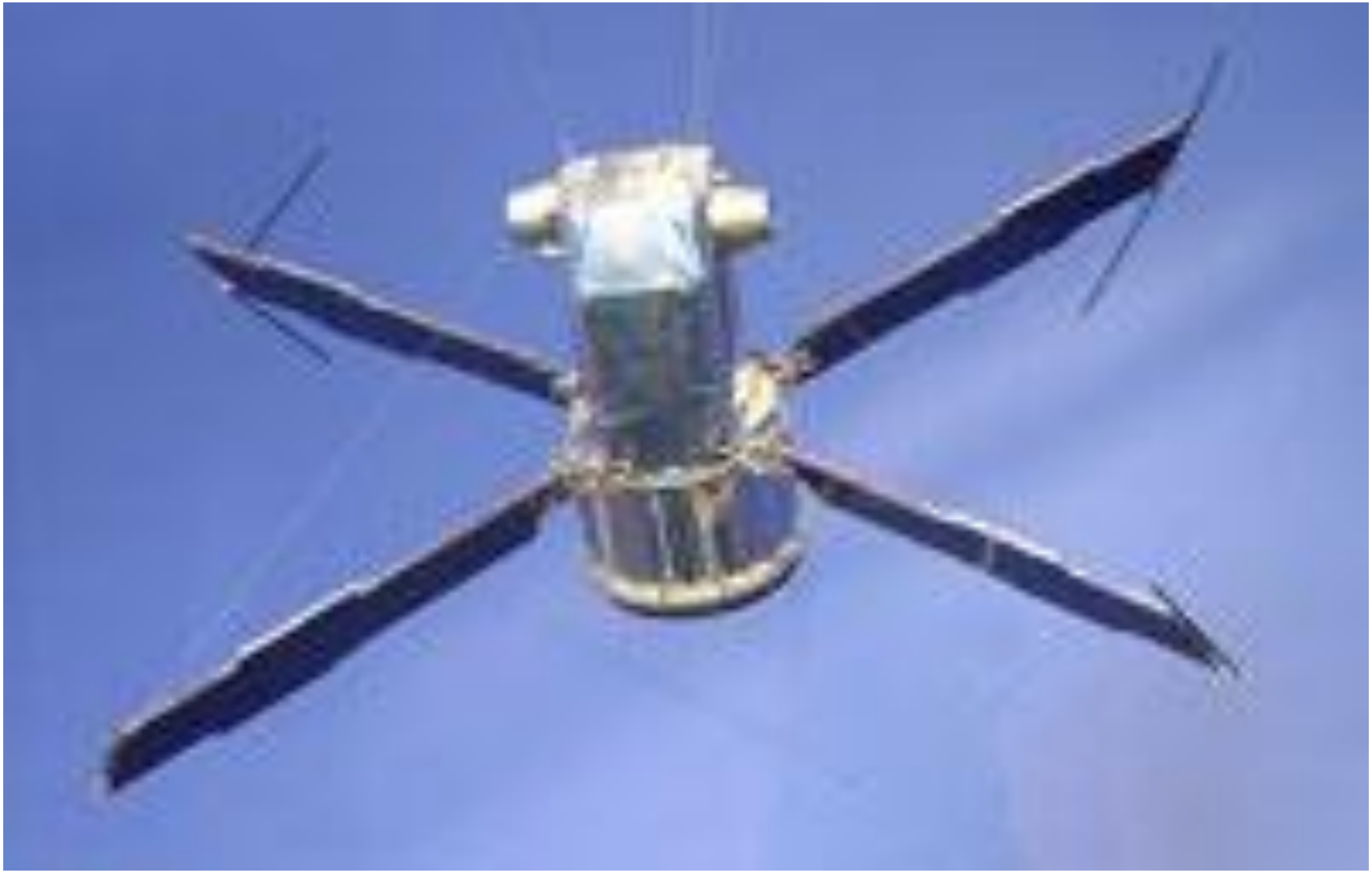
1. Mass $> 3M_\odot$
2. Electric charge ≈ 0
3. Rotation period could be as small as 0.001 s
4. Does not radiate !!
5. Strong gravitational field

How to find them ??

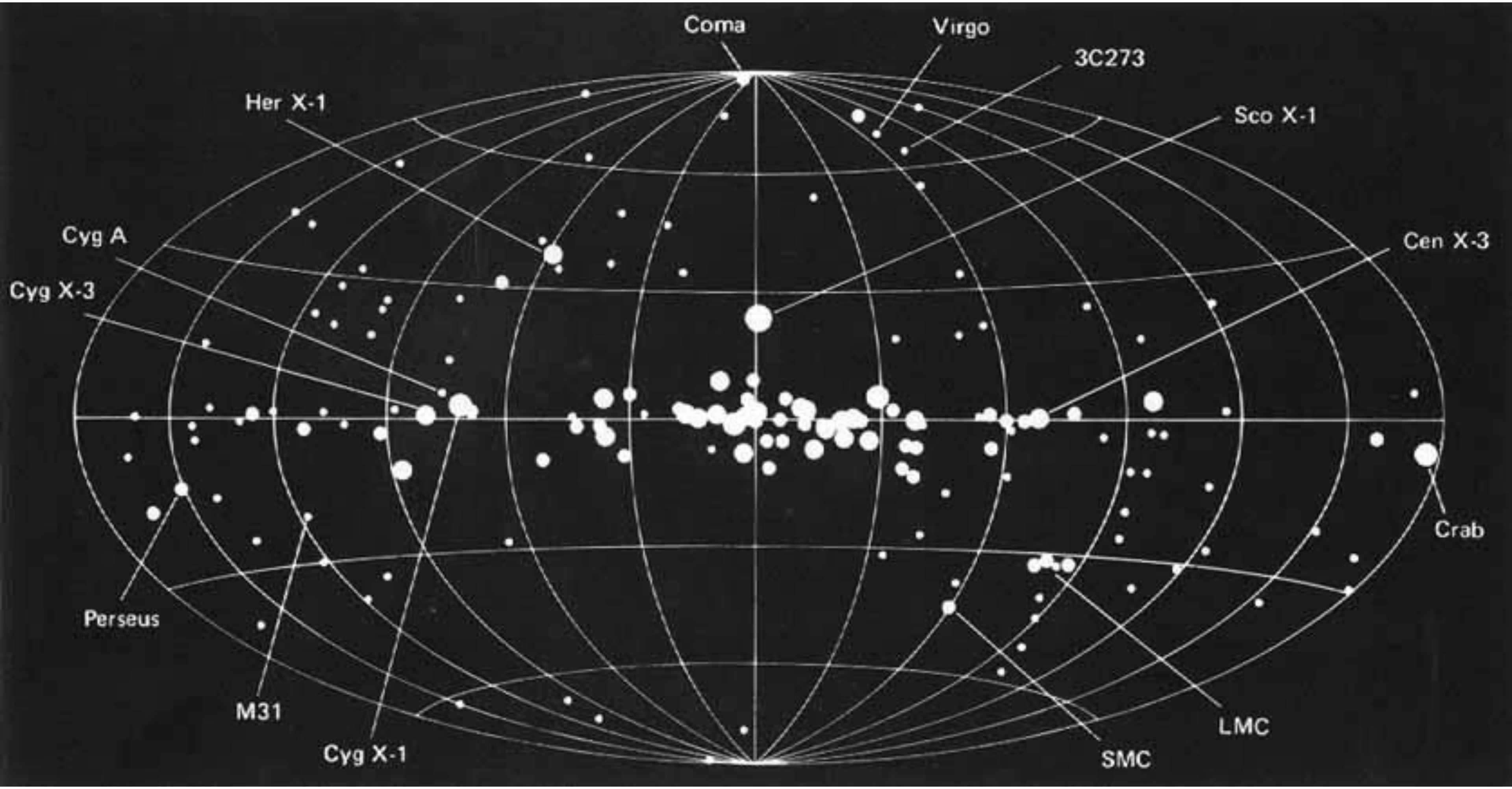
$T \sim 10^6\ K$

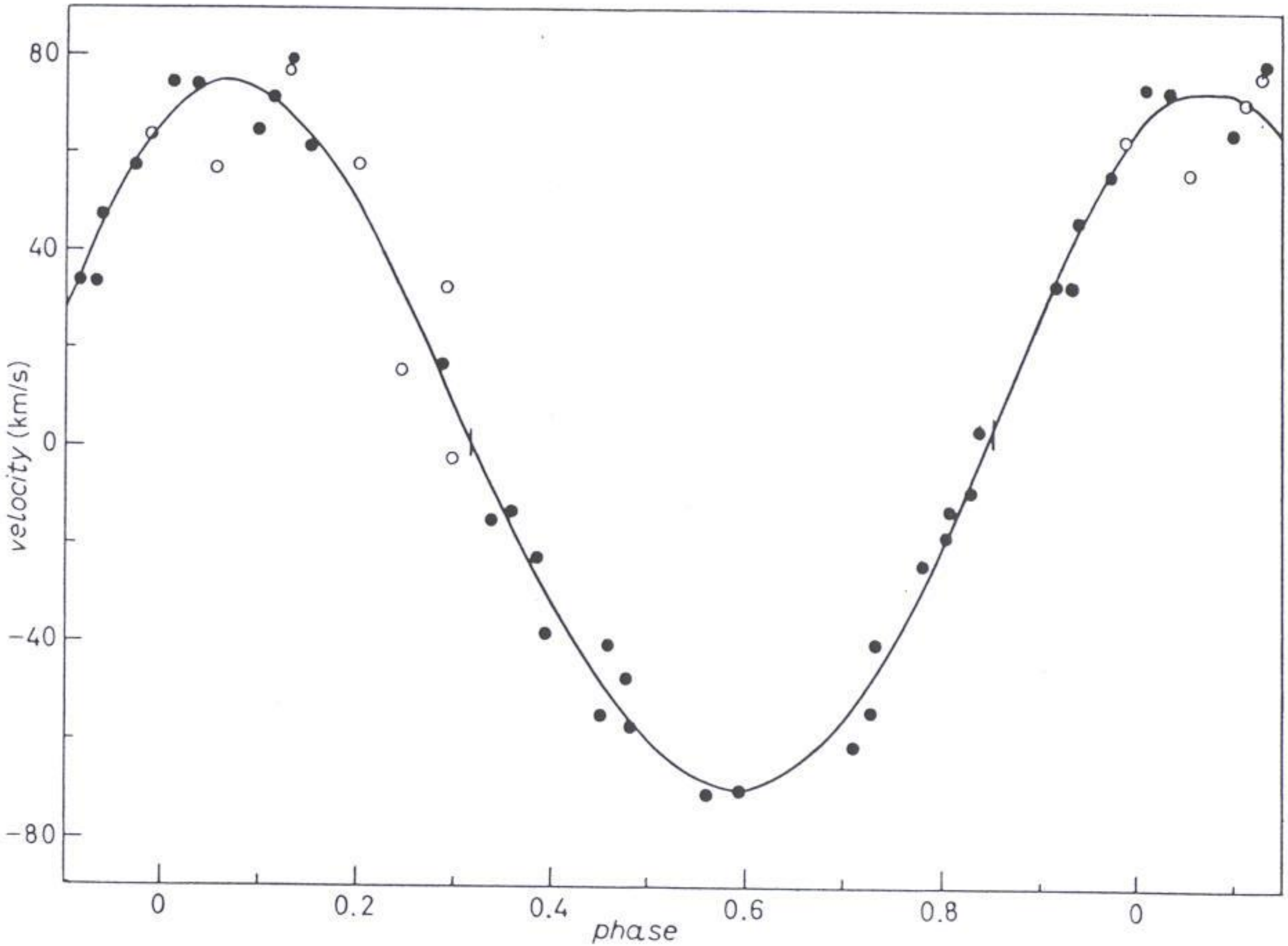
X - rays



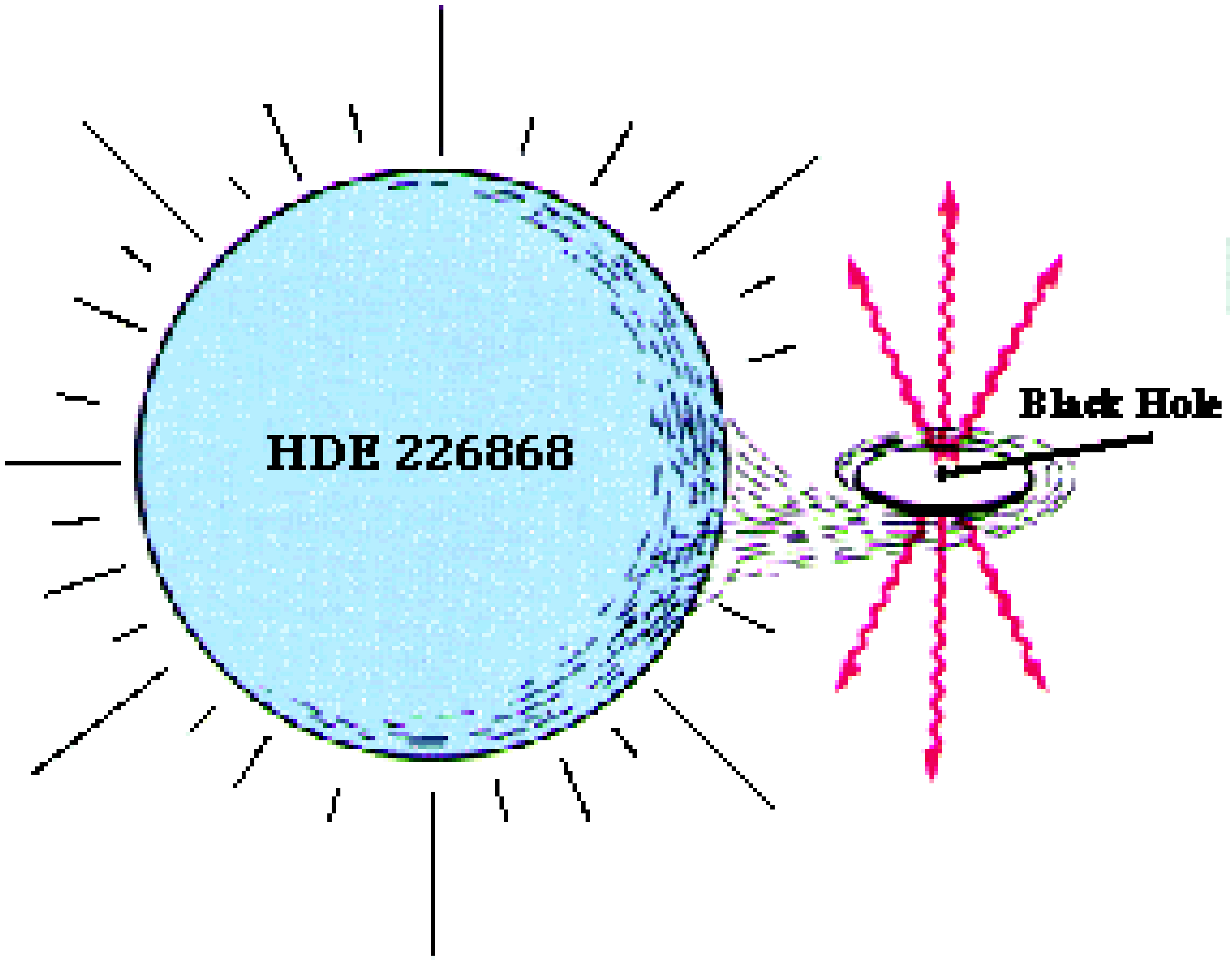


UHURU – the first X-ray satellite


Coma
Virgo
3C273
Her X-1
Sco X-1
Cyg A
Cen X-3
Cyg X-3
Crab
Perseus
M31
Cyg X-1
LMC
SMC



80
40
0
-40
-80
velocity (km/s)
0
0.2
0.4
0.6
0.8
0
phase


HDE 226868
Black Hole

Remnants of stellar evolution

$0.001 < M_{in}/M_\odot < 0.085$ → brown dwarfs

$0.085 < M_{in}/M_\odot < 8 \sim 12$ → white dwarf

planetary nebula $M_{WD} < 1.4 M_\odot$

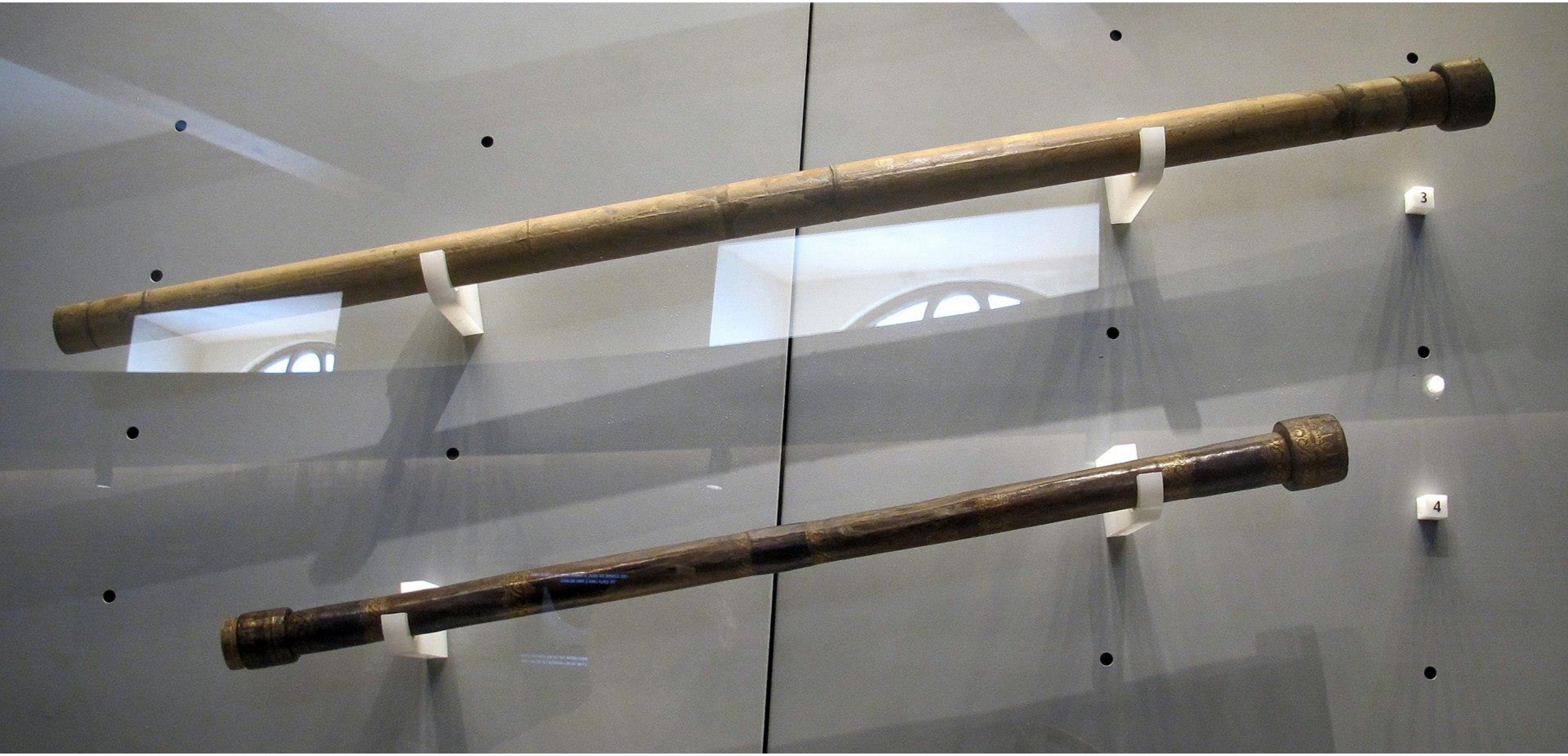
$8 \sim 12 < M_{in}/M_\odot < \sim 20$ → neutron star

supernova explosion $M_{NS} < 3 M_\odot$

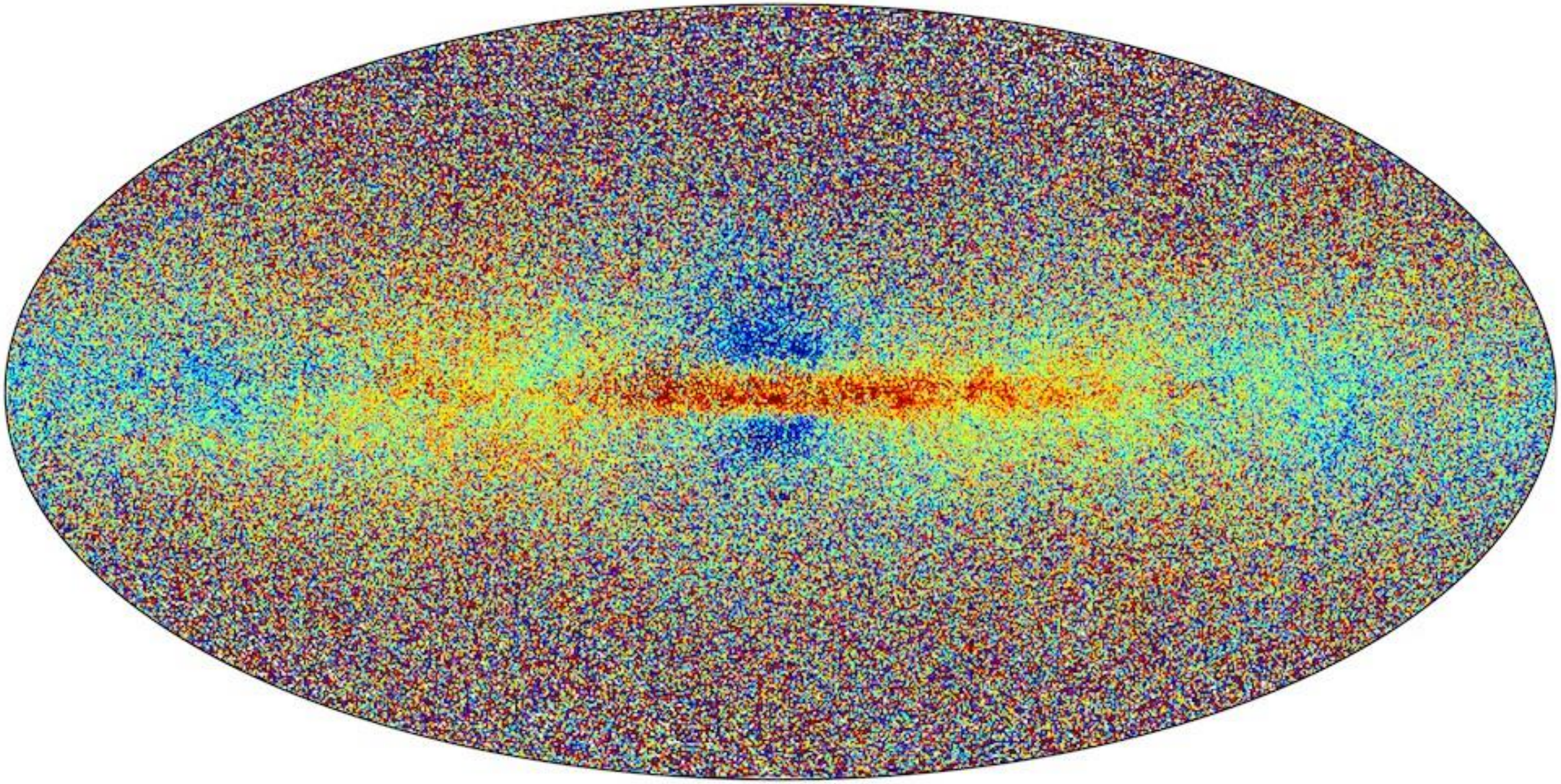
$M_{in}/M_\odot > \sim 20$ → black hole

supernova explosion $M_{BH} > 3 M_\odot$

Galileo
1564 - 1642


3
4

Chemical evolution



Astronomical Mendeleev table:

X – fraction of hydrogen (by weight)

Y – fraction of helium

Z – fraction of all other elements (astronomers call them metals)

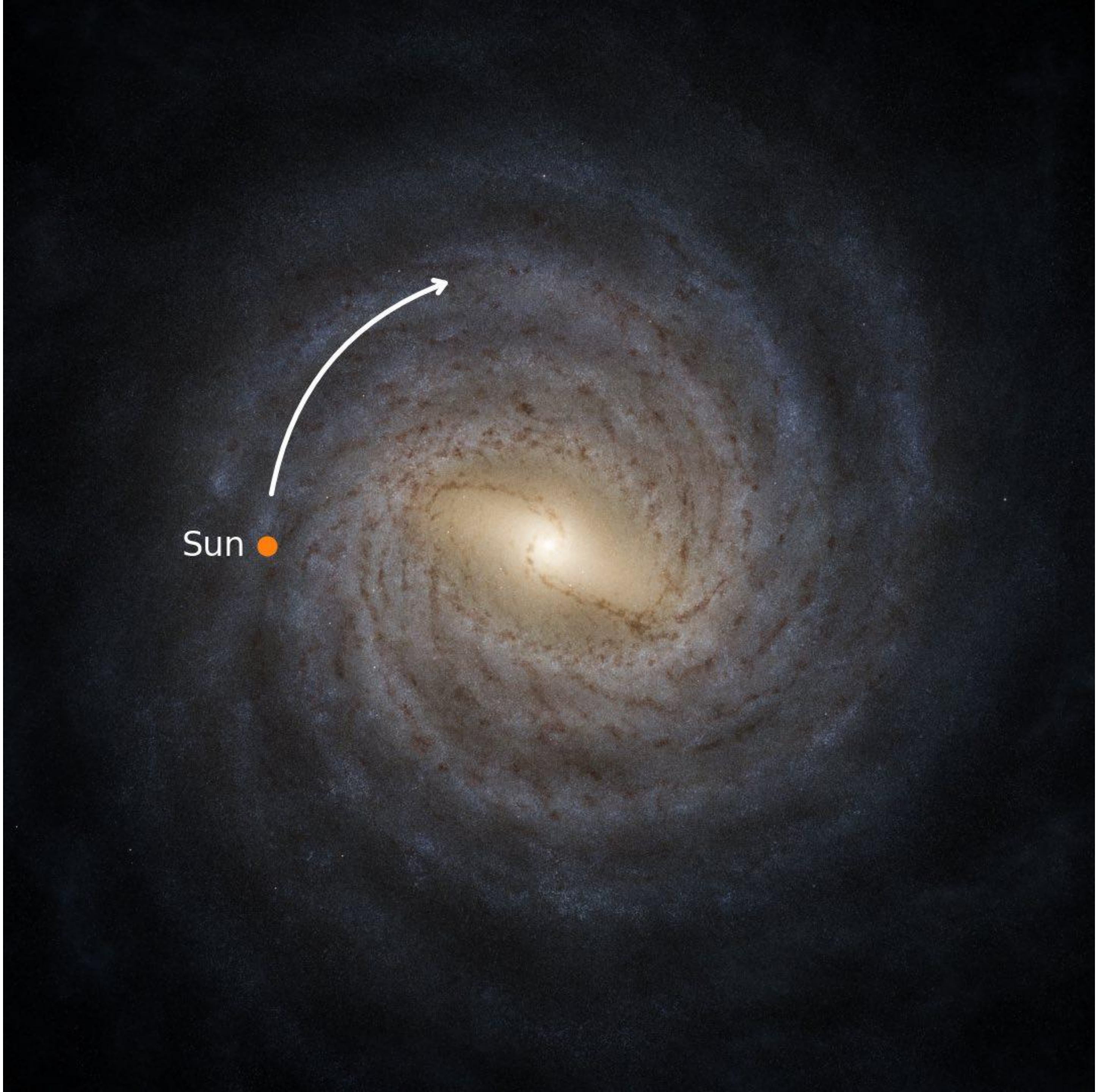
$$X + Y + Z = 1$$

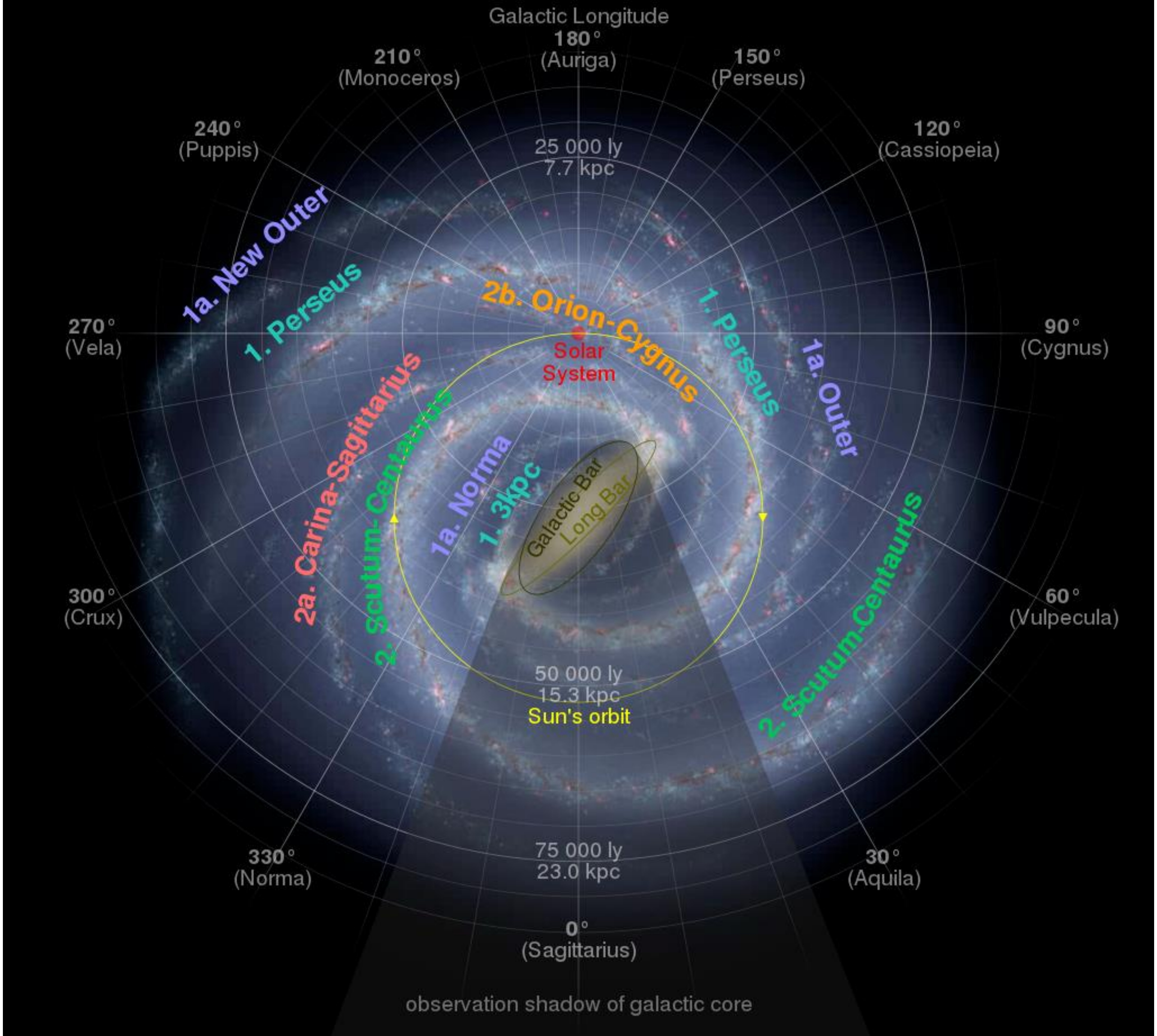
$$X_{\odot} = 0.73,\ Y_{\odot} = 0.24\ Z_{\odot} = 0.03$$

Population I stars, are, the young stars confined to the disk of the galaxy and of metal abundances near the solar value $Z \sim 0.03$

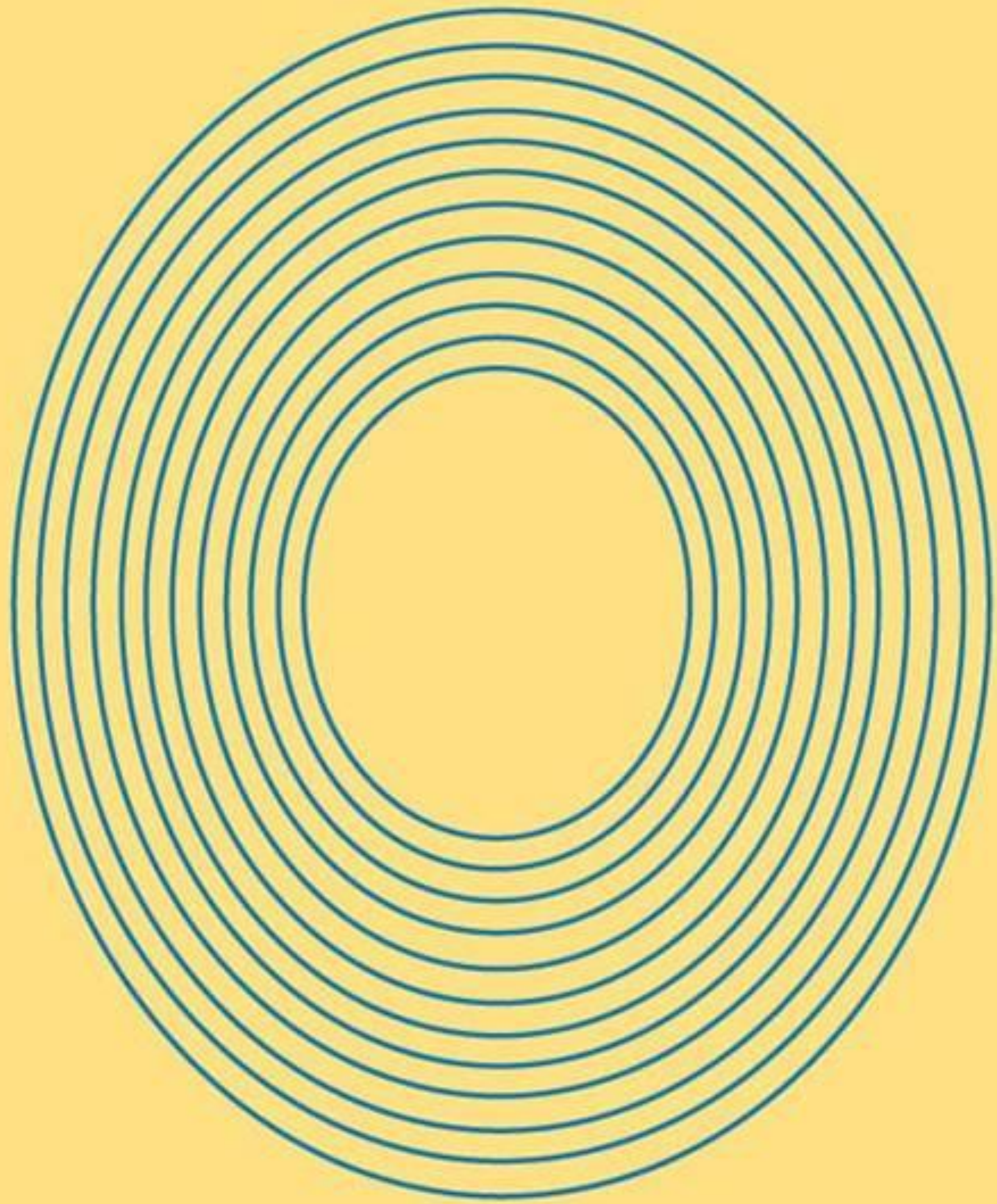
Population II stars - the old stars that appear in the galactic halo and of very low metal abundance $Z \leq 0.01$

Distribution of neutral hydrogen - radio

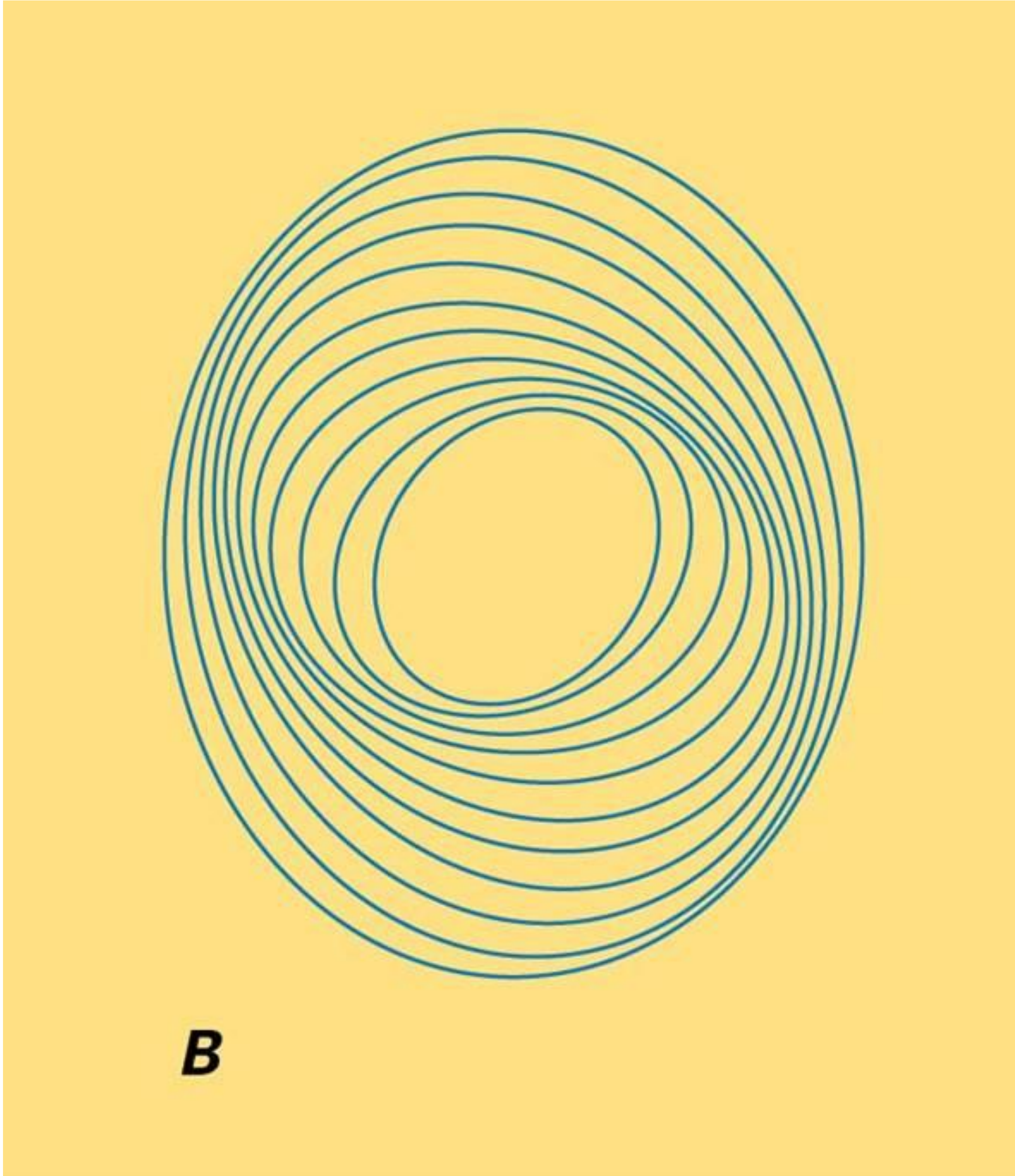

Sun

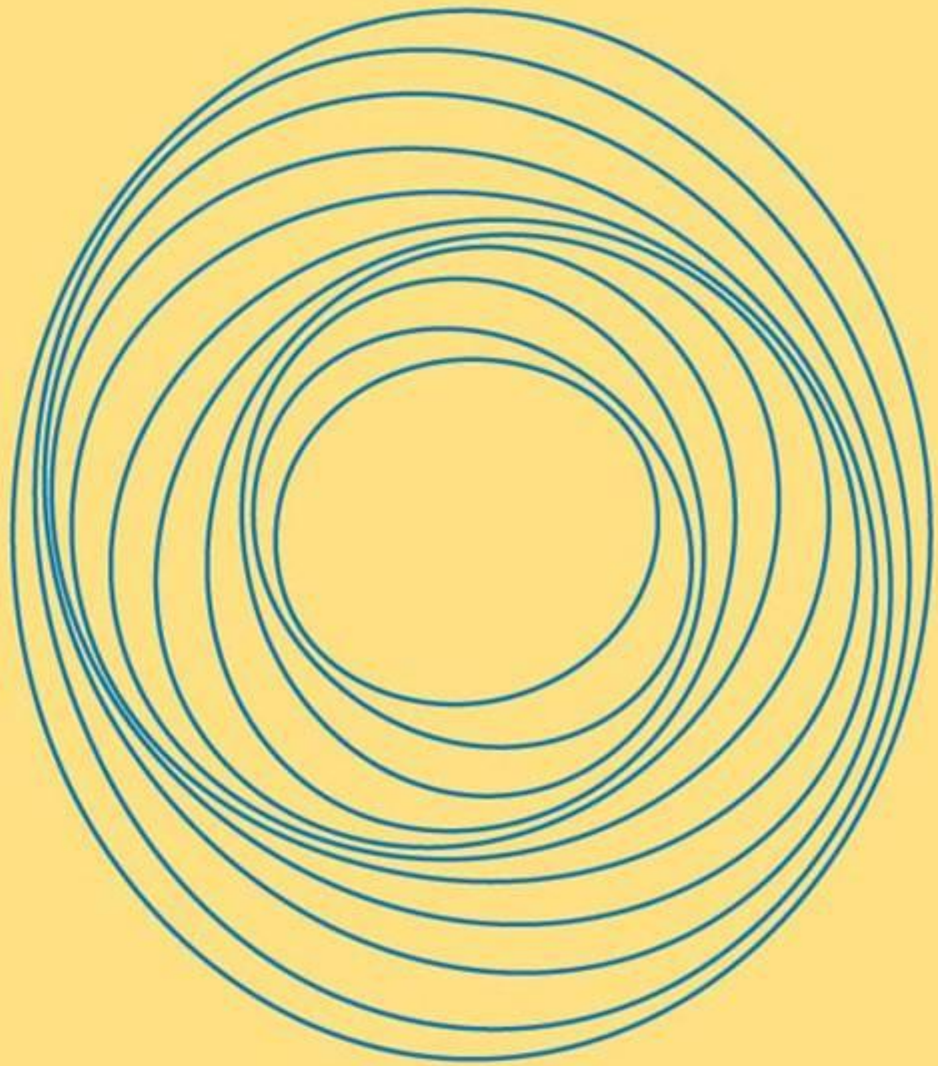


Galactic Longitude
180°
(Auriga)
210°
(Monoceros)
150°
(Perseus)
240°
(Puppis)
120°
(Cassiopeia)
270°
(Vela)
90°
(Cygnus)
300°
(Crux)
60°
(Vulpecula)
330°
(Norma)
30°
(Aquila)
0°
(Sagittarius)
25 000 ly
7.7 kpc
50 000 ly
15.3 kpc
75 000 ly
23.0 kpc
1a. New Outer
1. Perseus
2b. Orion-Cygnus
1. Perseus
1a. Outer
Solar
System
2a. Carina-Sagittarius
2. Scutum-Centaurus
1a. Norma
1. 3kpc
Galactic Bar
Long Bar
2. Scutum-Centaurus
Sun's orbit
observation shadow of galactic core

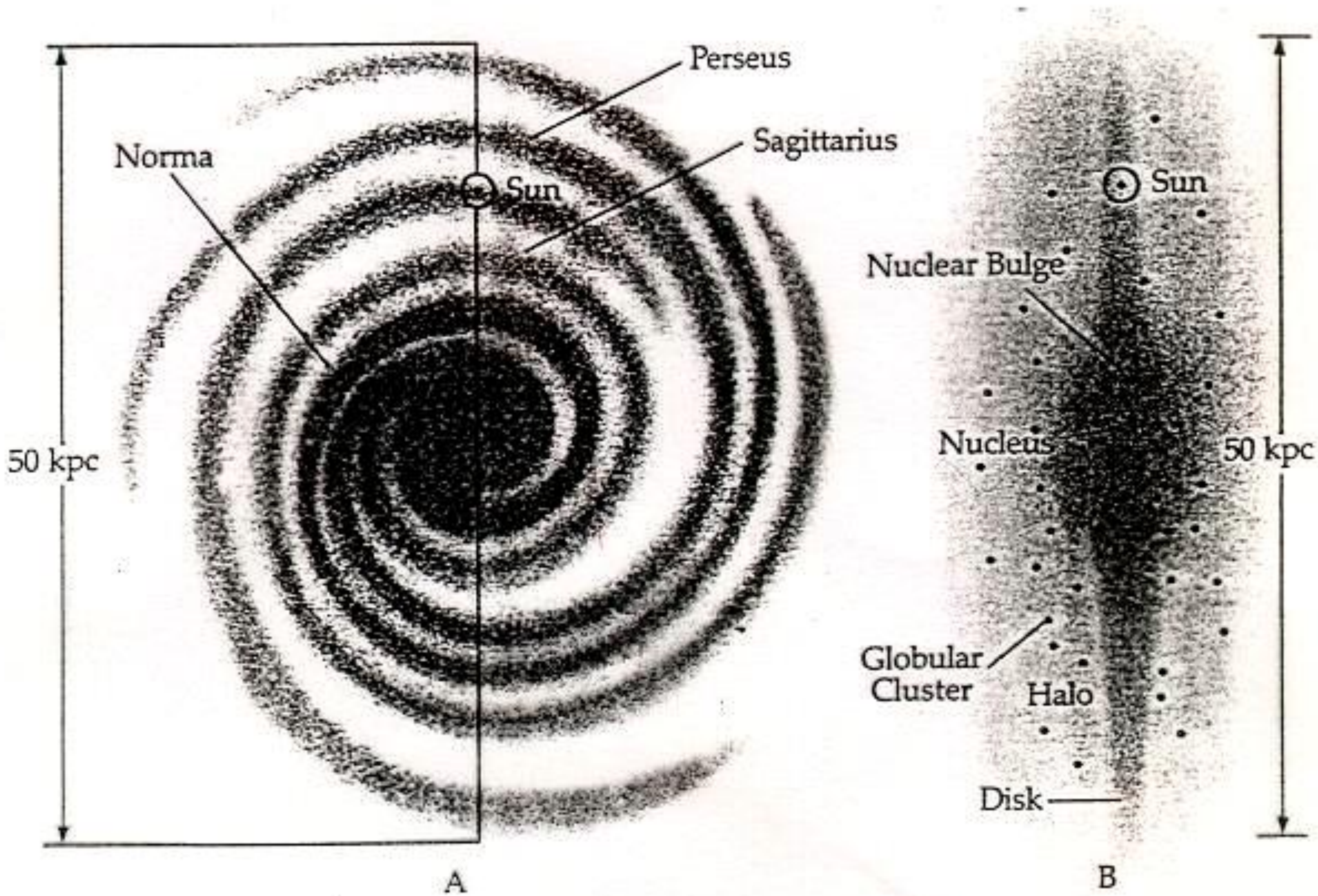


A

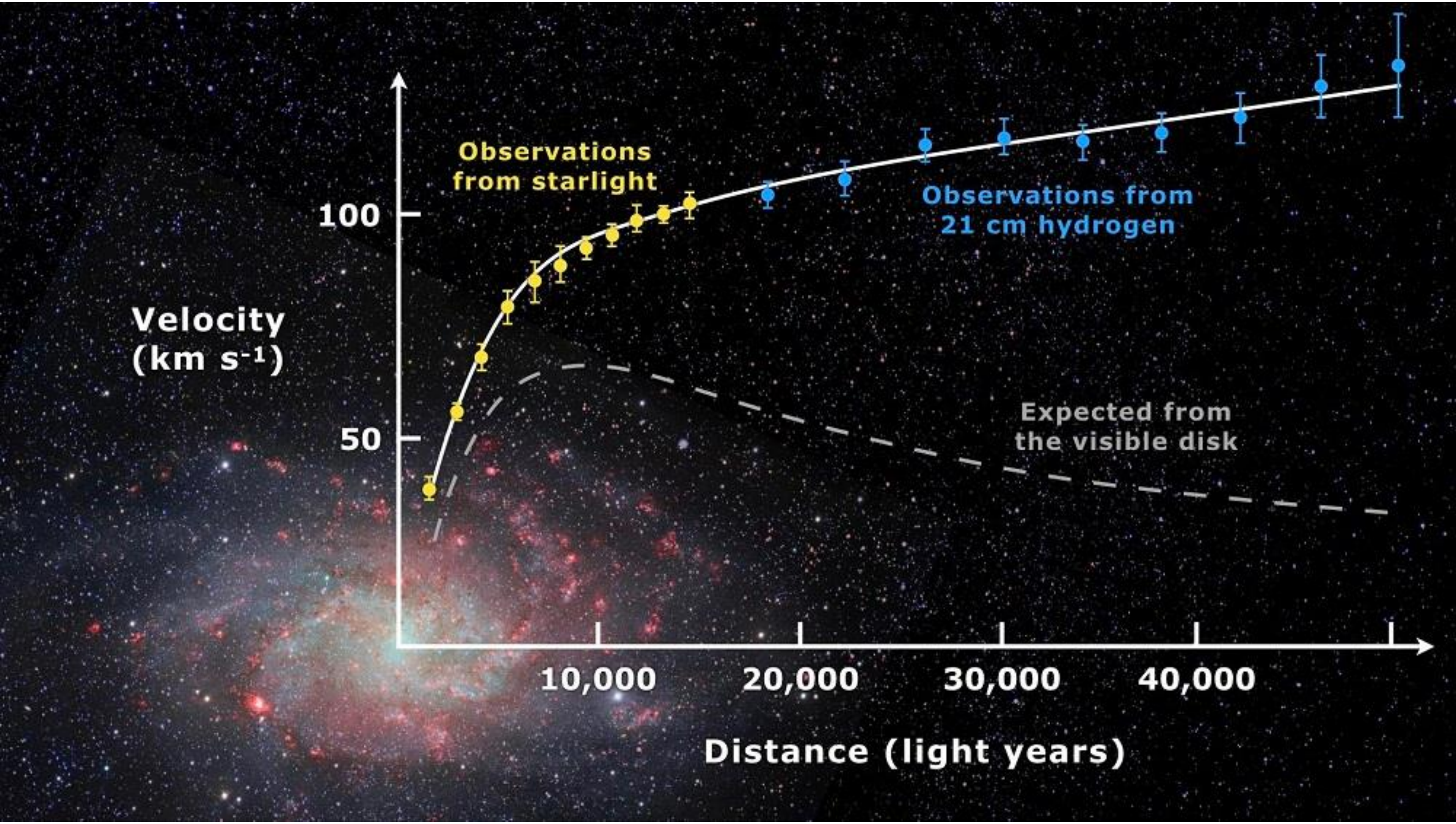

B



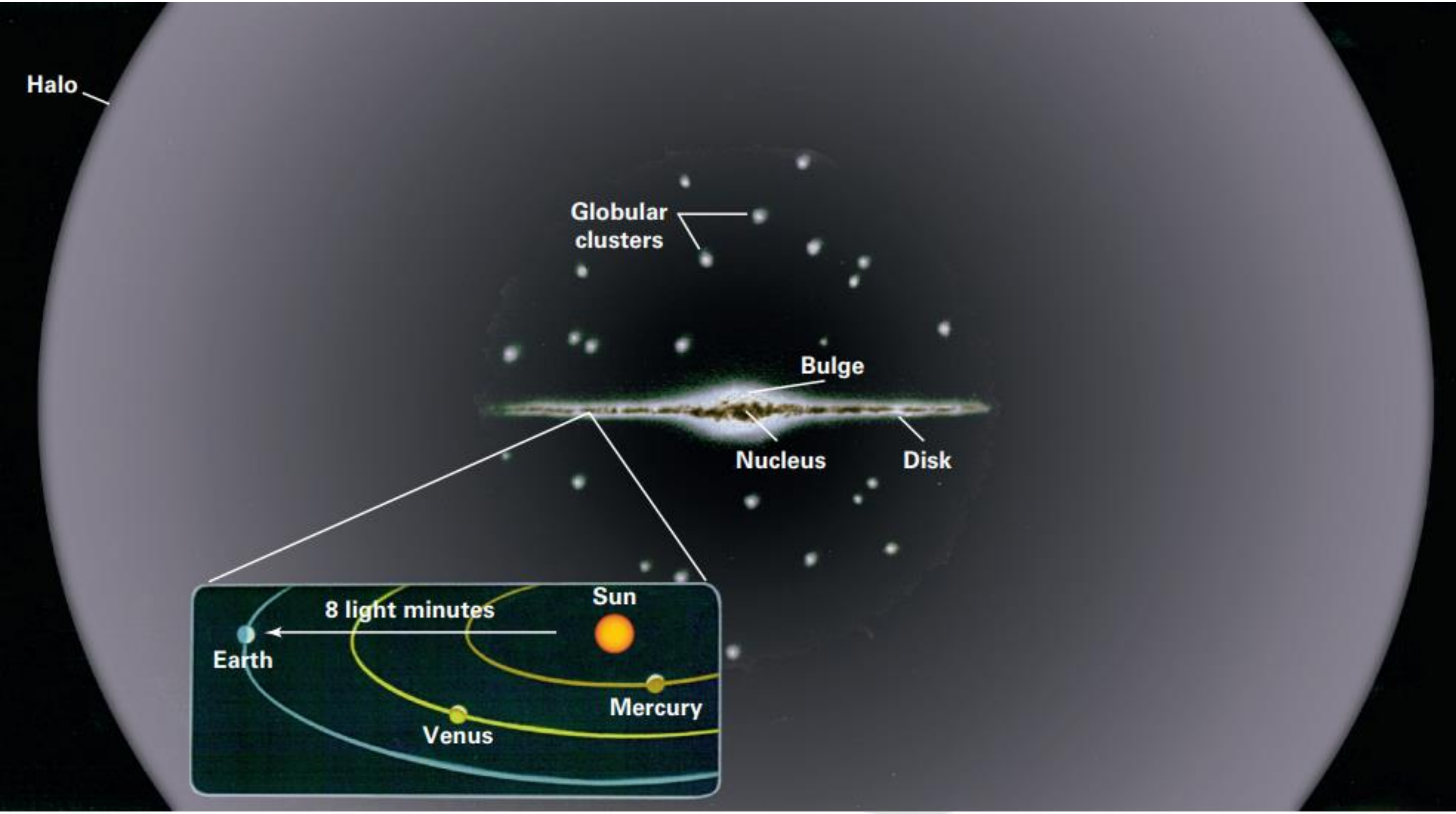
c



50 kpc
Norma
Perseus
Sagittarius
Sun
A
Sun
Nuclear Bulge
Nucleus
50 kpc
Globular
Cluster
Halo
Disk
B



Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s-1)
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)



The Milky Way + dark matter halo

Size of the Milky Way

- Diameter of the disk 120000 ly
- Thickness of the disk 1000 ly
- Diameter of the galactic halo 300000 ly
- Distance of the Sun from the galactic center ~ 25000 ly
- Mass ~ $120\times10^{9}\ M_{\odot}$