Evolucija zvezda i nastanak hemijskih elemenata

Odakle sve ovo?

Big Bang (veliki prasak)...

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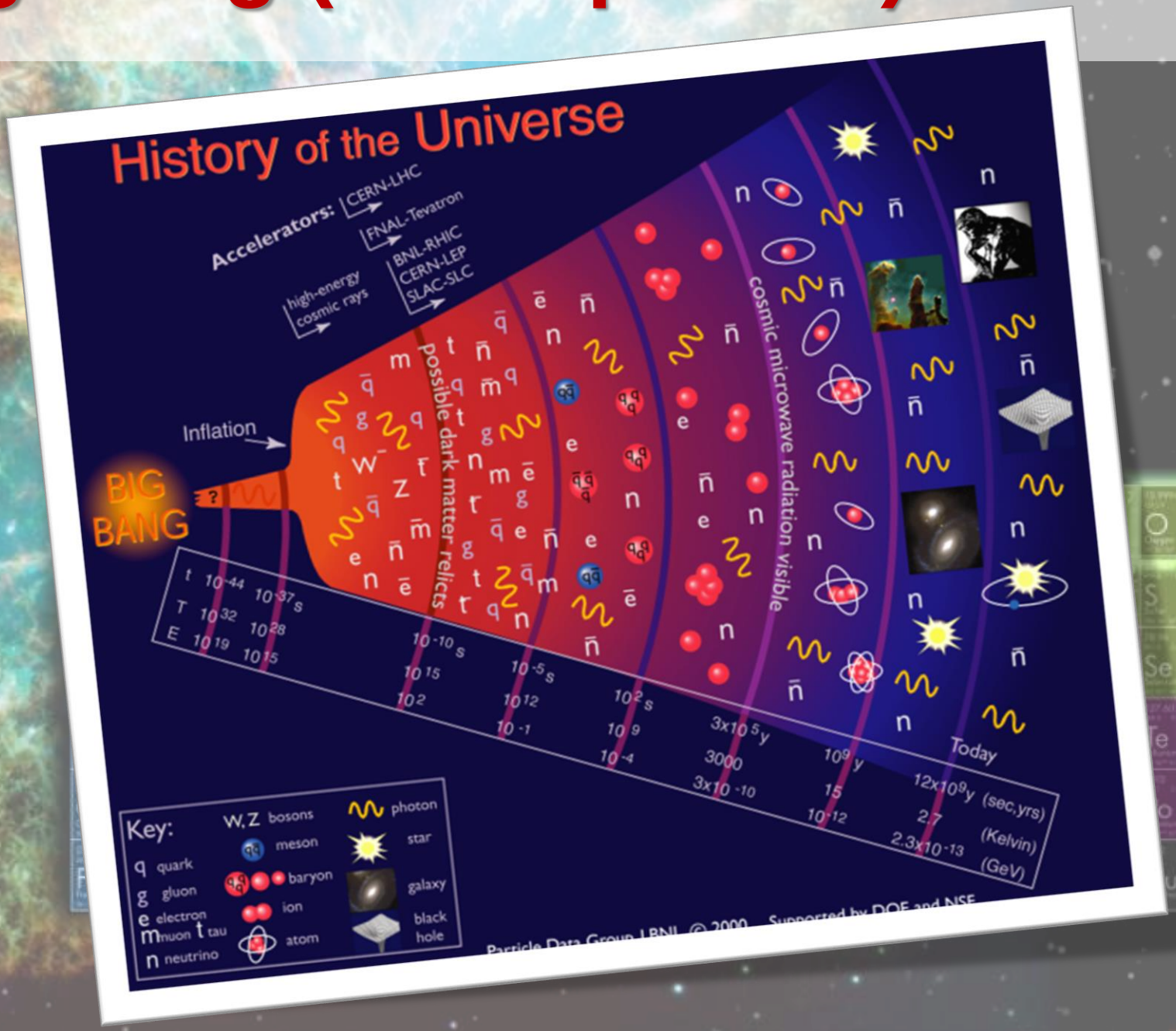


Periodic Table of the Elements

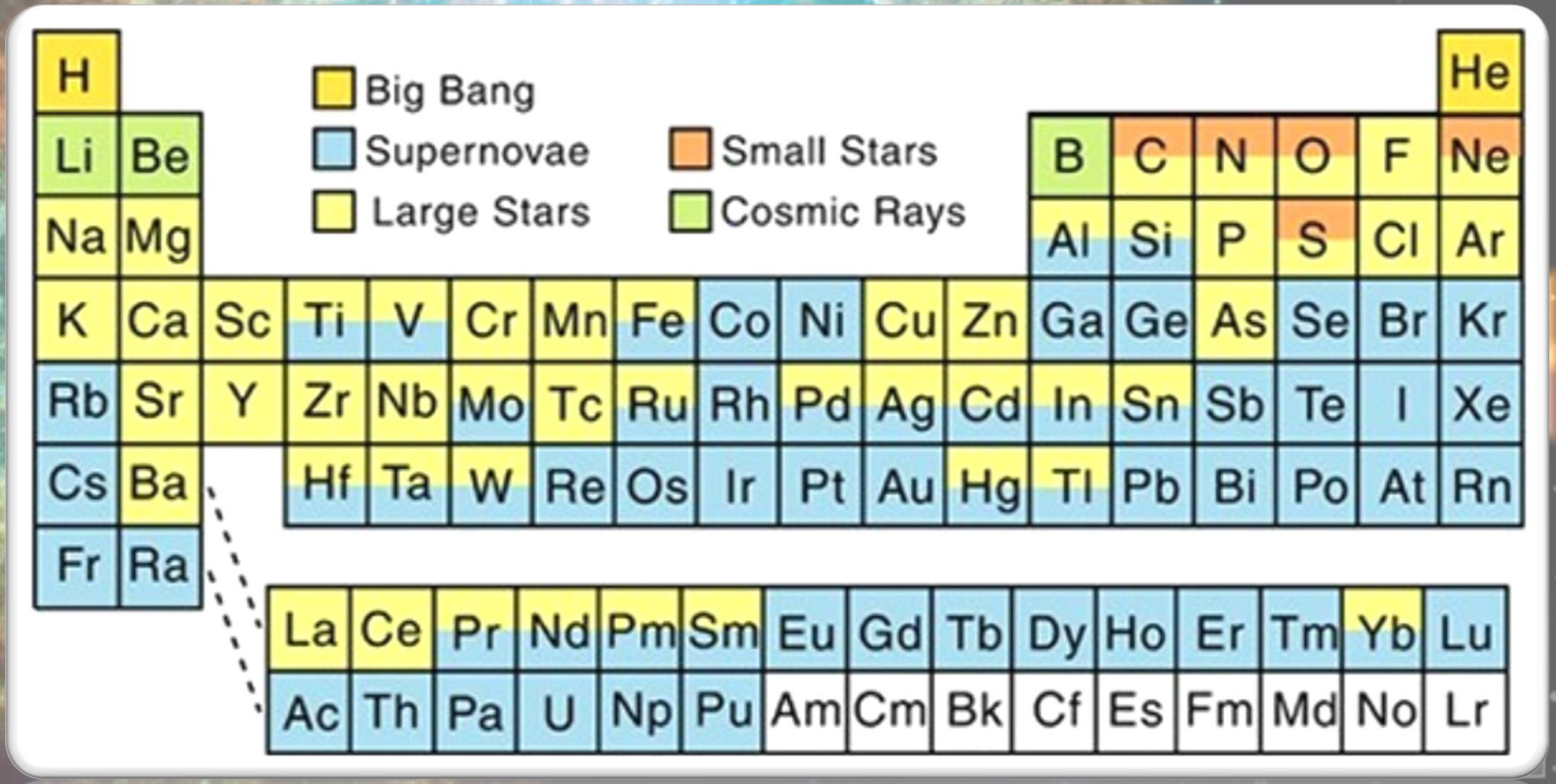
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Svaki atom na Zemlji...

... nekada je bio deo jedne zaboravljene zvezde!



Nukleosinteza

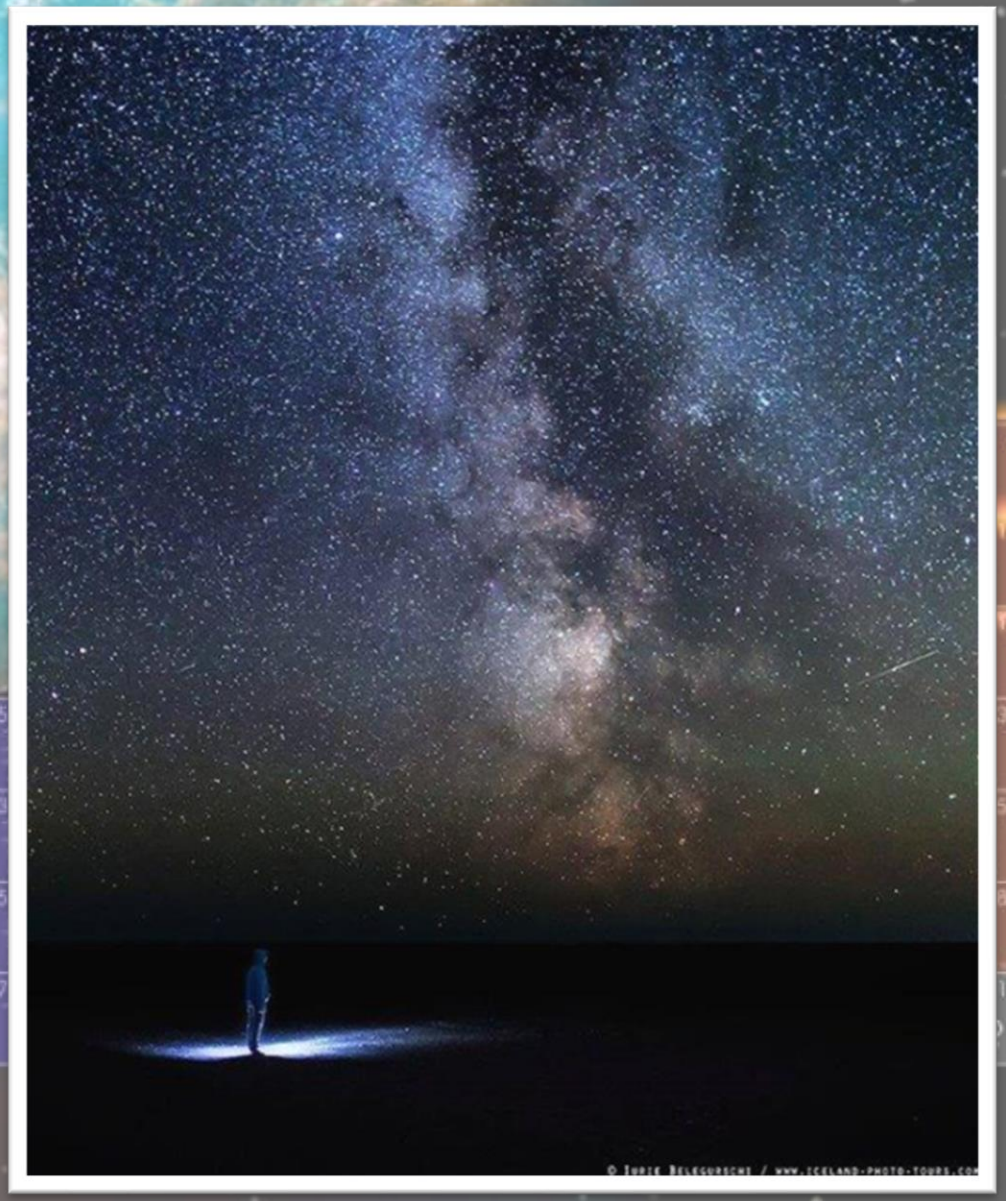
- Prva ideja – elementi nastali kad i svemir
- *H* i *He* – najrasprostranjeniji (ostali samo 2% mase Sunčevog sistema); ledeći *O* i *C.*
- Artur Edington (1920) – prva ideja o fuziji vodonika u zvezdama; mogu i ostali – slabo prihvaćena ideja.
- Hans Bete (1938) – nuklearne reakcije --> kako sija Sunce
- Fred Hojl – nastanak težih elemenata
- E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle, *Synthesis of the Elements in Stars*, Rev. Mod. Phys. 29, 547 (1957) https://doi.org/10.1103/RevModPhys.29.547

Nukleosinteza

- Veliki prasak (*H*, *He*, *Li, Be*)
  - 100-300 sekundi nakon Velikog praska
- Nukleosinteza u zvezdama:
  - p-p ciklus, 3-alfa-proces, CNO ciklus, *s*-proces, fotodezintegracija
- „Eksplozivna“ nukleosinteza
  - Tokom supernova
- Sudar neutronskih zvezda
  - Glavni izvor *r*-procesa
- Kosmičko zračenje

Zvezde su uvek iste?

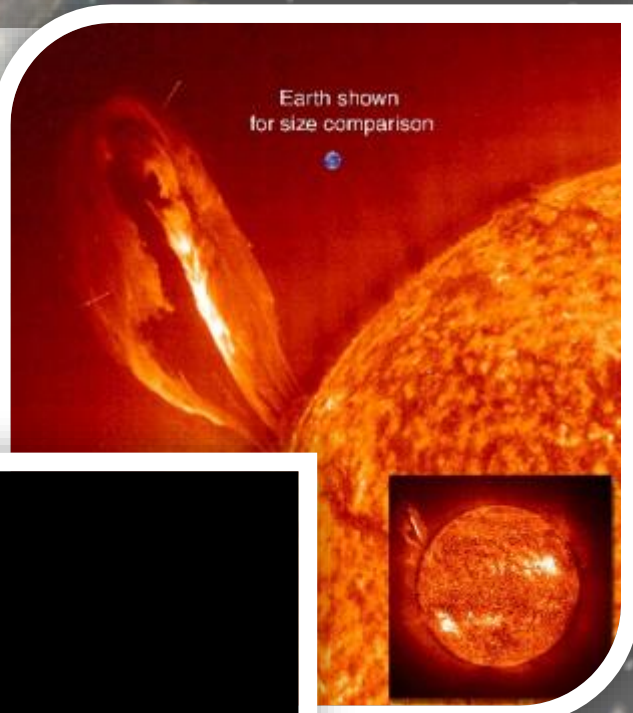
- “Tačkice” na nebu
- Ogromne lopte vrelog gasa
- Toplota nastaje u njihovom centru
- Različite boje



http://vimeo.com/57130400

Naša zvezda - Sunce

Ali...



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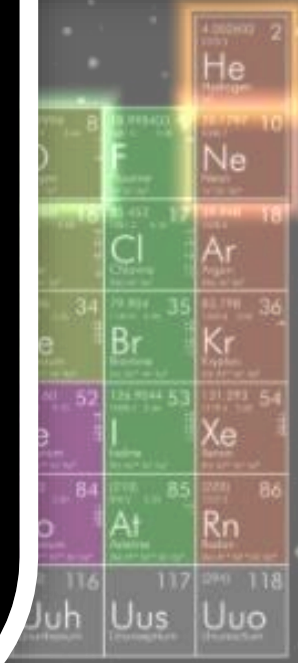

Slike nam pričaju priču...

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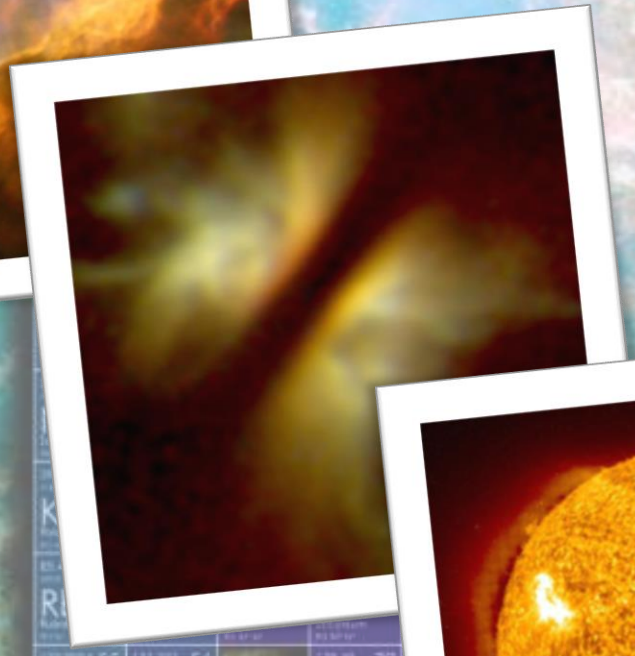
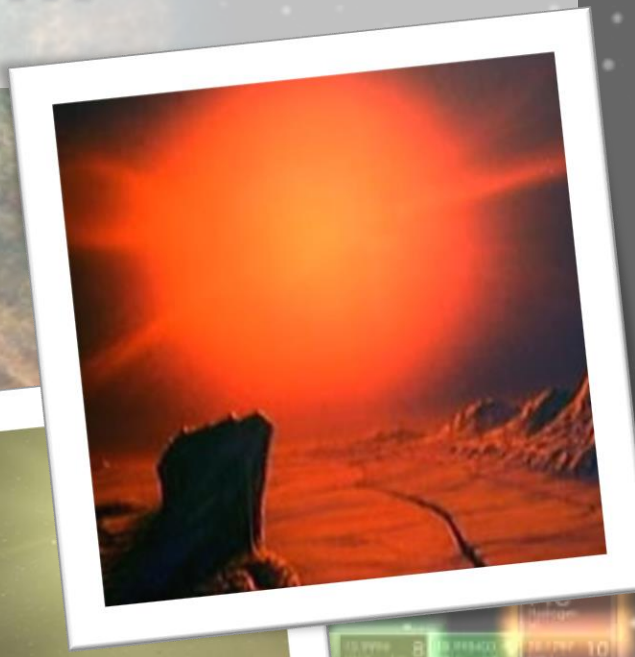
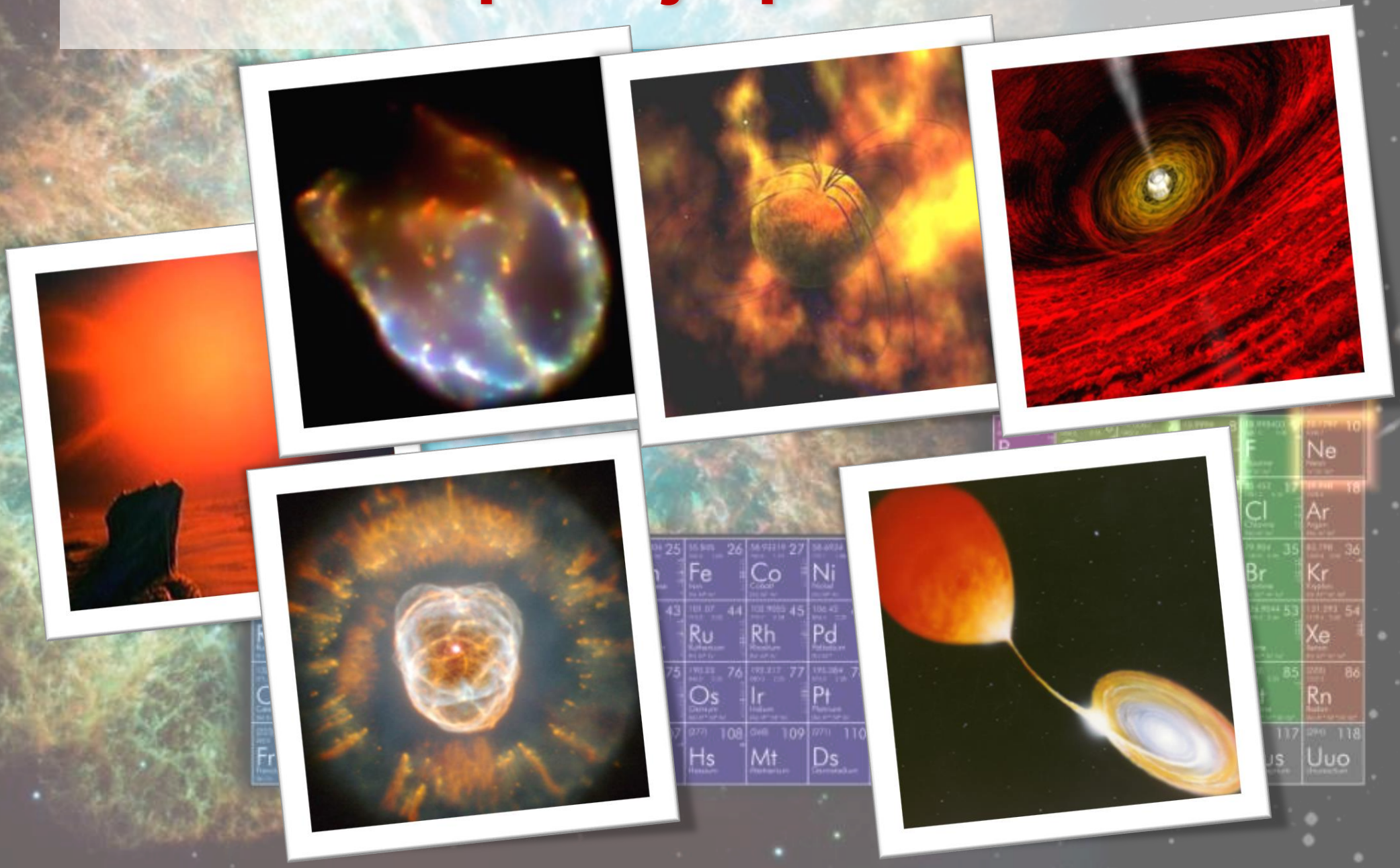




Slike nam pričaju priču...

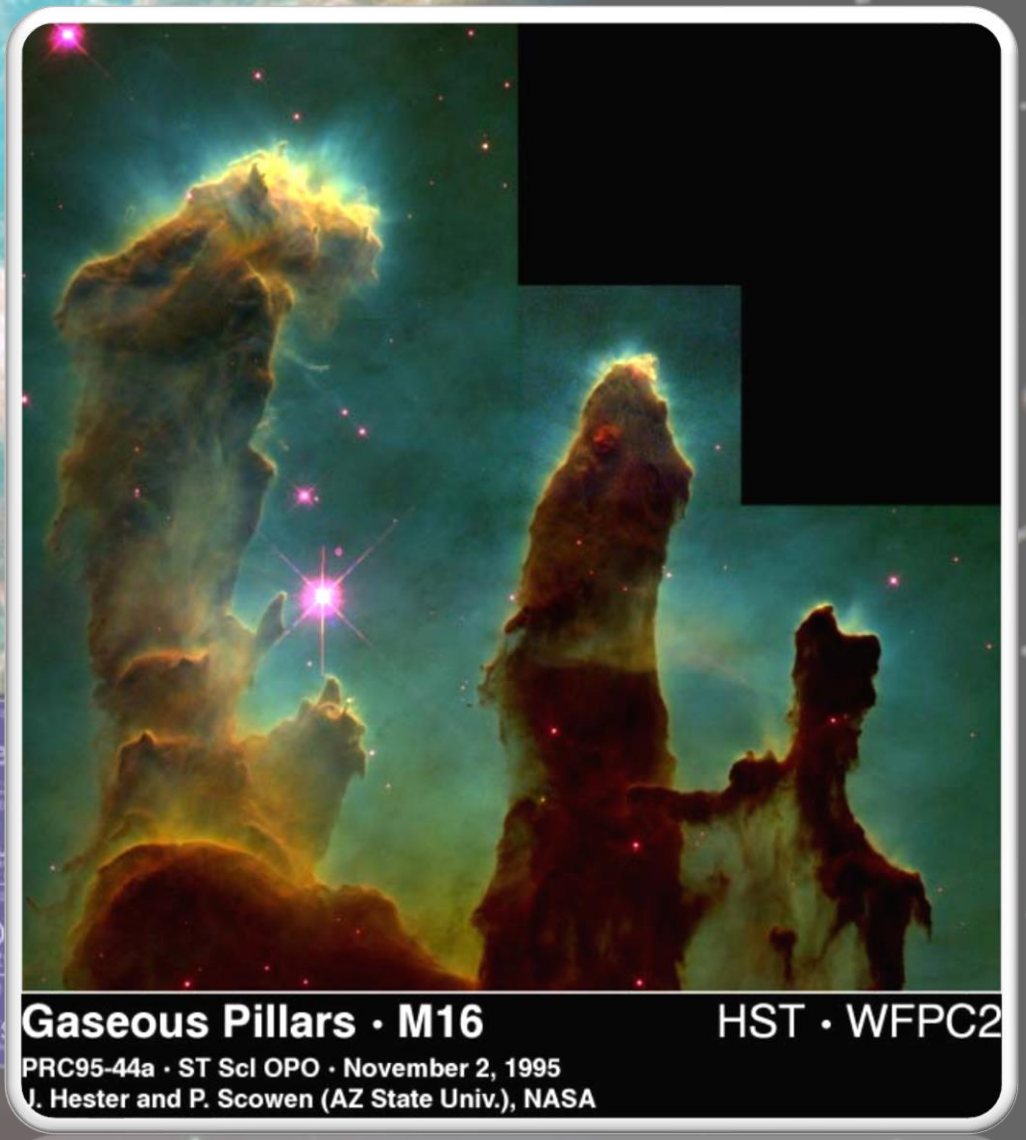


Kako stvoriti zvezdu?

- Sastojci:
  - Vodonik
  - Gravitacija
  - Vreme... mnogo vremena

Zvezdano porodilište

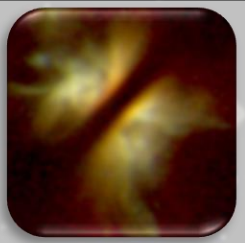
- Gustina:
  - 10 atoma vodonika/cm^3
  - 16 vodonika – 1 helijum
  - (vazduh - $30x10^{18}$ at./cm^3)
- Temperatura: 100K ($-173^{O}C$)

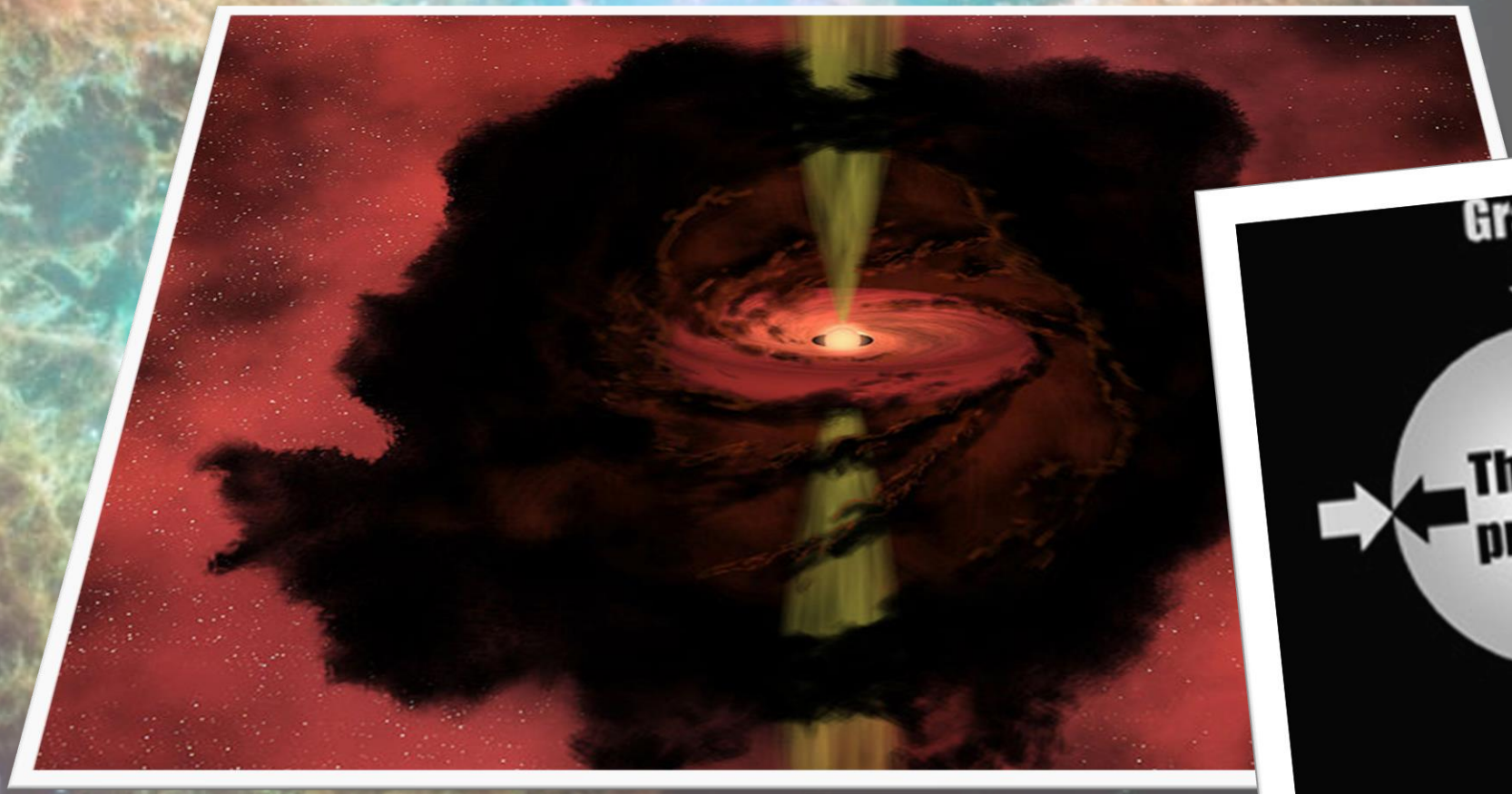


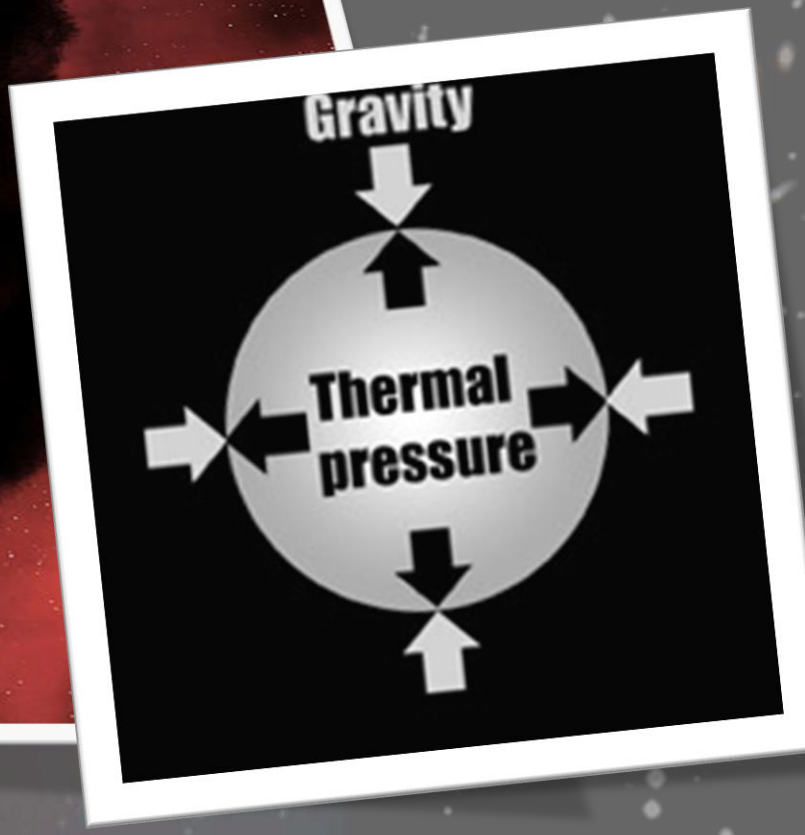
Tamna maglina

Globula

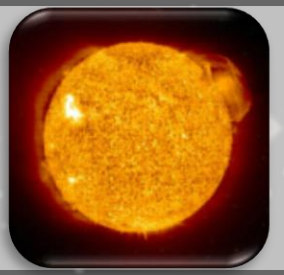
Protozvezda

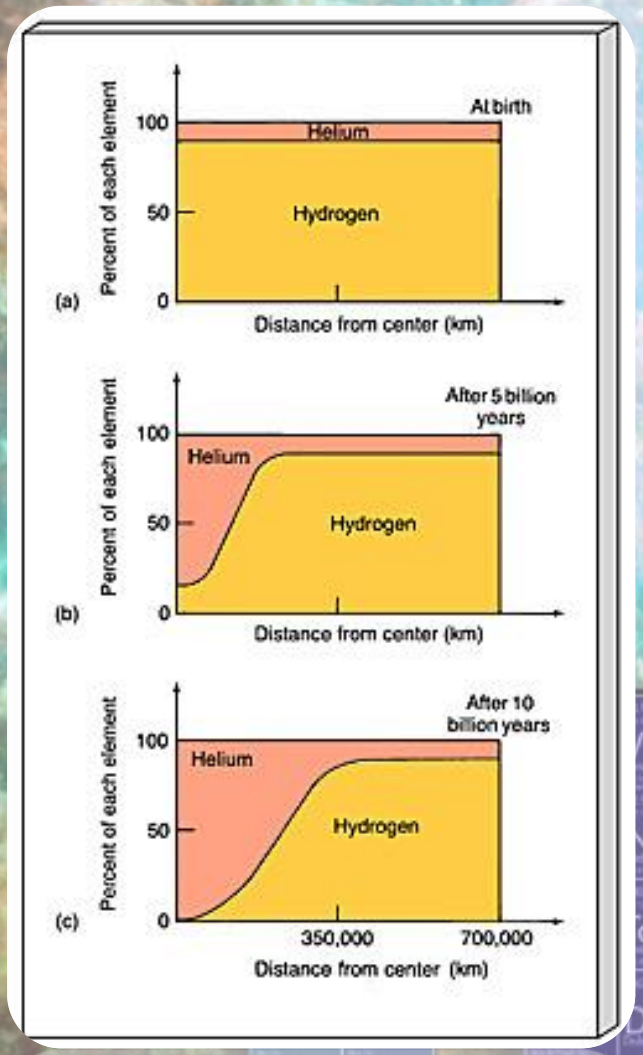






Zvezda je rođena

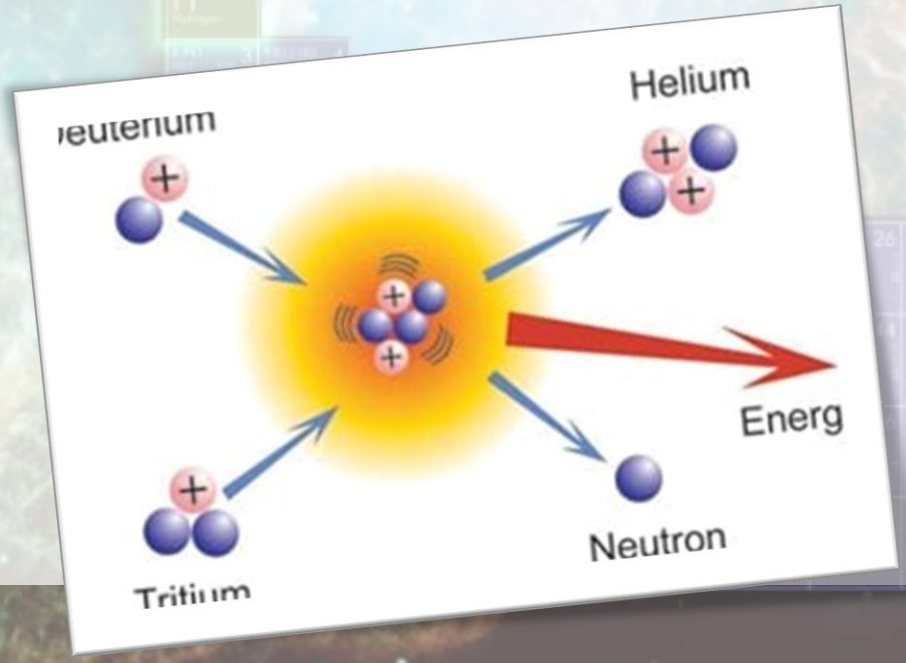


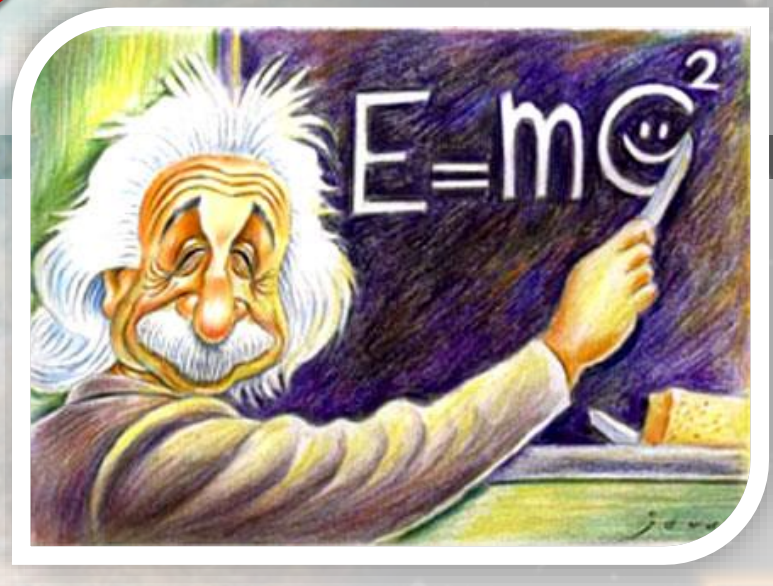


- Temperatura: 10 miliona stepeni

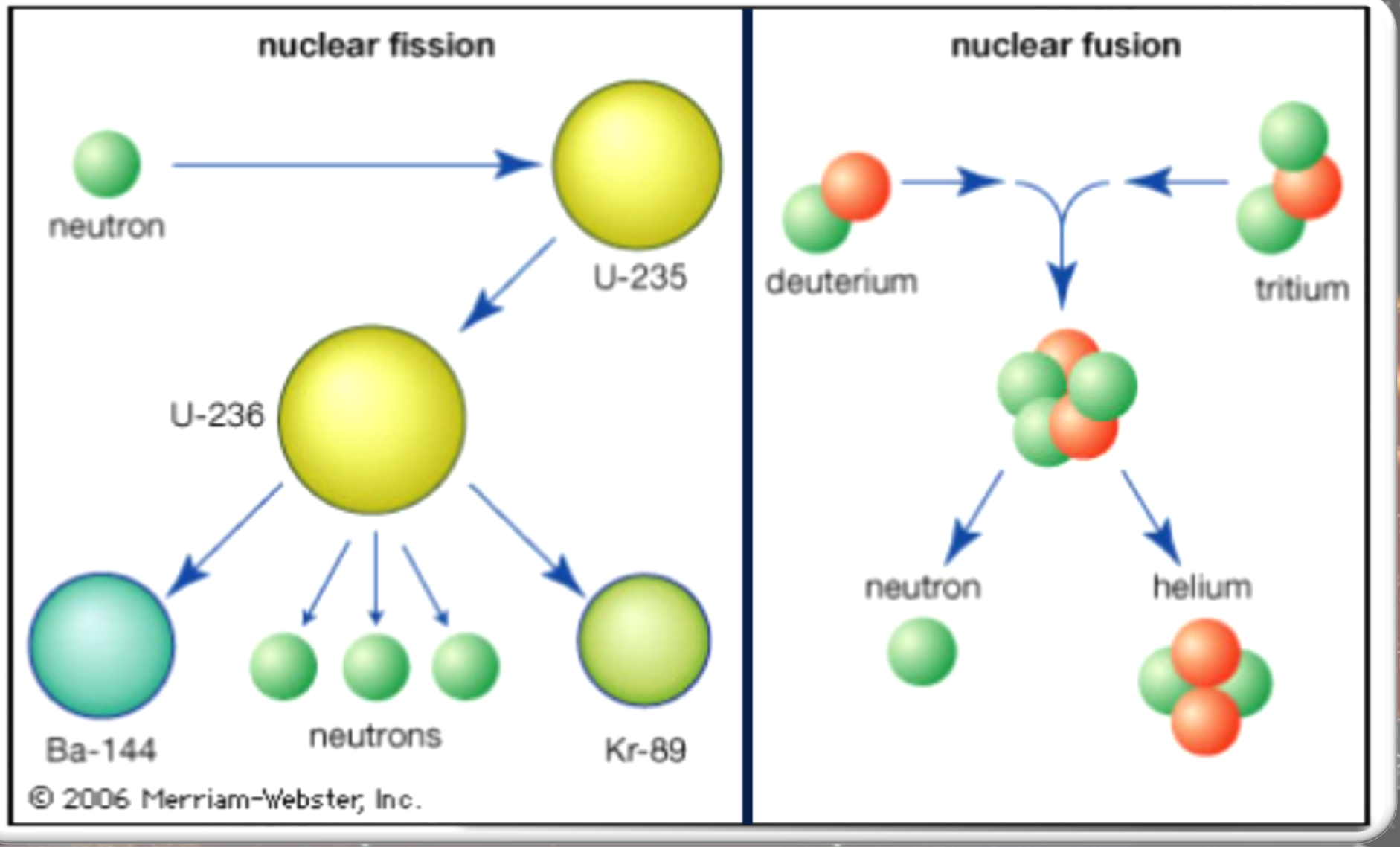
Kako sijaju zvezde?

- Vatra? Ne ☹
  - Energija Sunca: $2 \cdot 10^{-4} \frac{J}{kg \cdot s}$
- Hemijska reakcija? Ne ☹
- Fuzija! DA! ☺





Nuklearna fuzija vs fisija



Nuklearna fuzija

- Spajanje lakih jezgara i dobijanje jezgra veće mase
- Jezgro 1 + jezgro 2 -> jezgro 3 + energija
- Tokom fuzione reakcija ukupna masa se smanjuje – masa jezgra 3 manja je od zbira masa jezgra 1 i jezgra 2
- Ekvivalencija mase i energije: $E = mc^2$
  - 1 kg --> 9×10^{16} J
- Zakon održanja mase i energije

Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

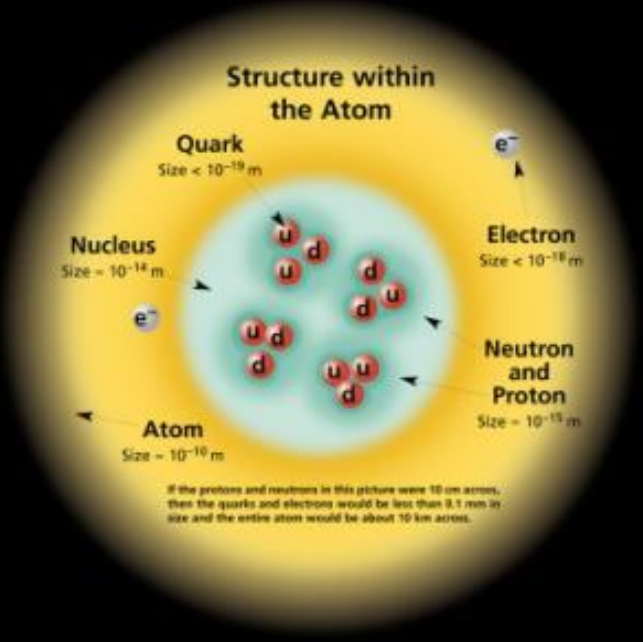
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag. for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag. for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

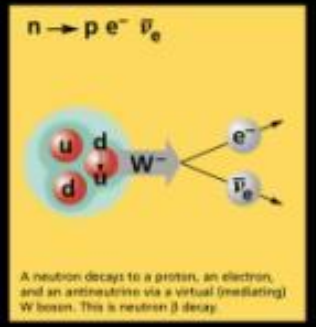
Mesons $q\bar{q}$

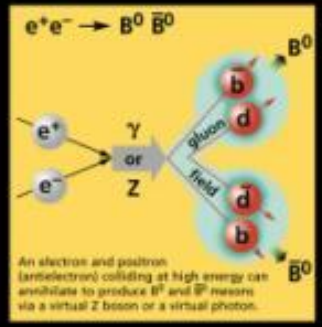
Mesons are bosonic hadrons. There are about 140 types of mesons.

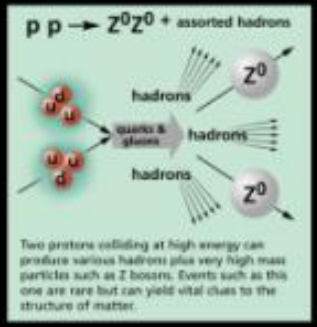
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are **not** exact and have **no** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



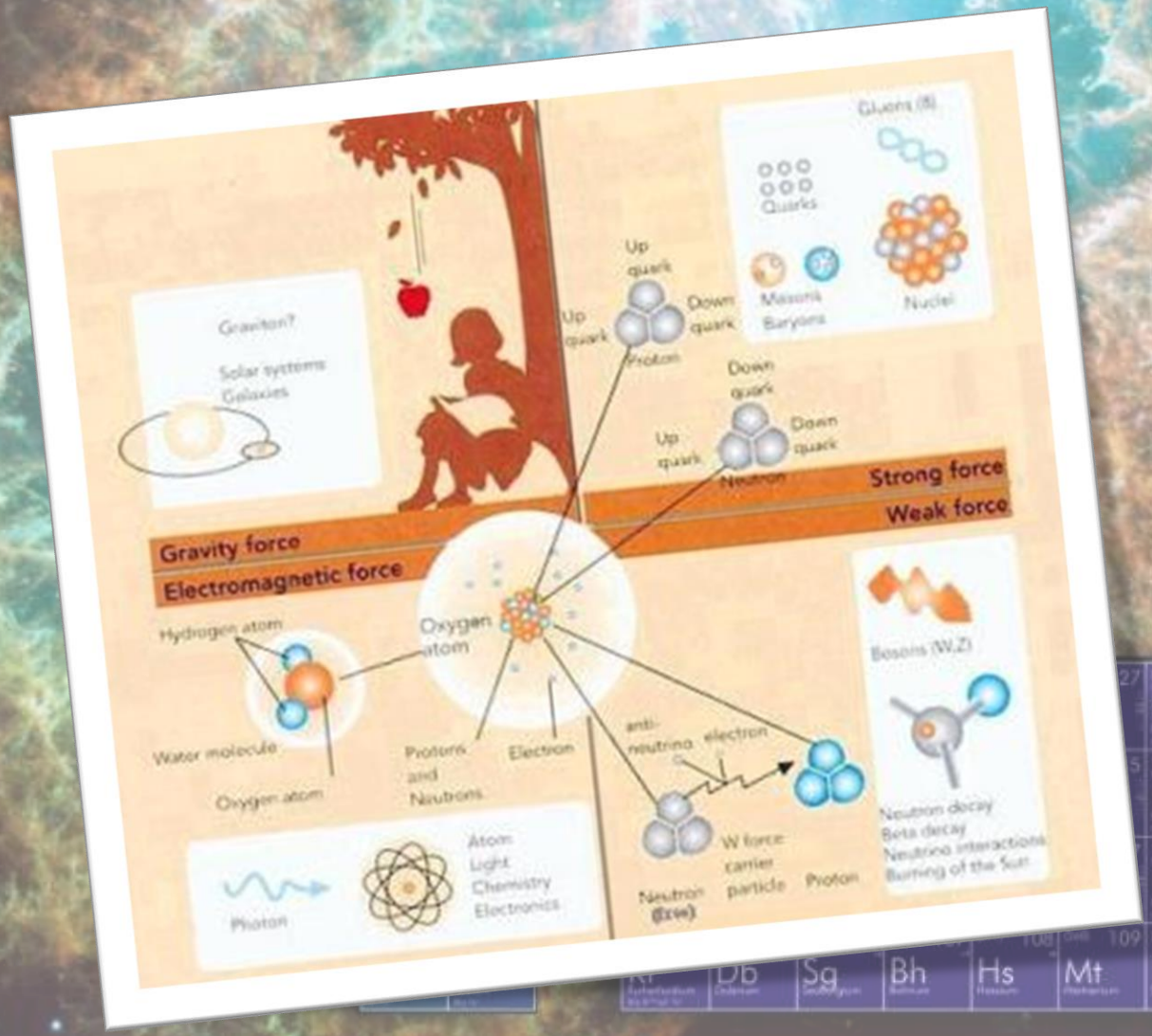


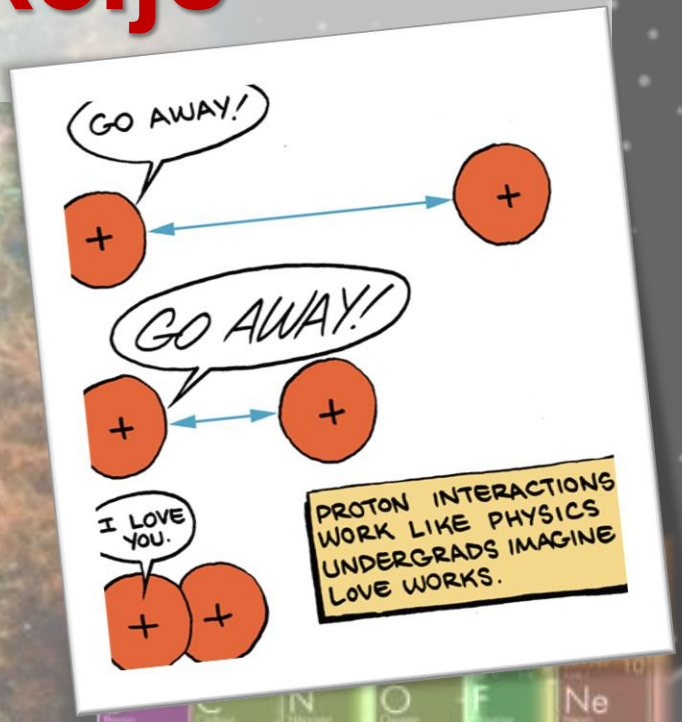


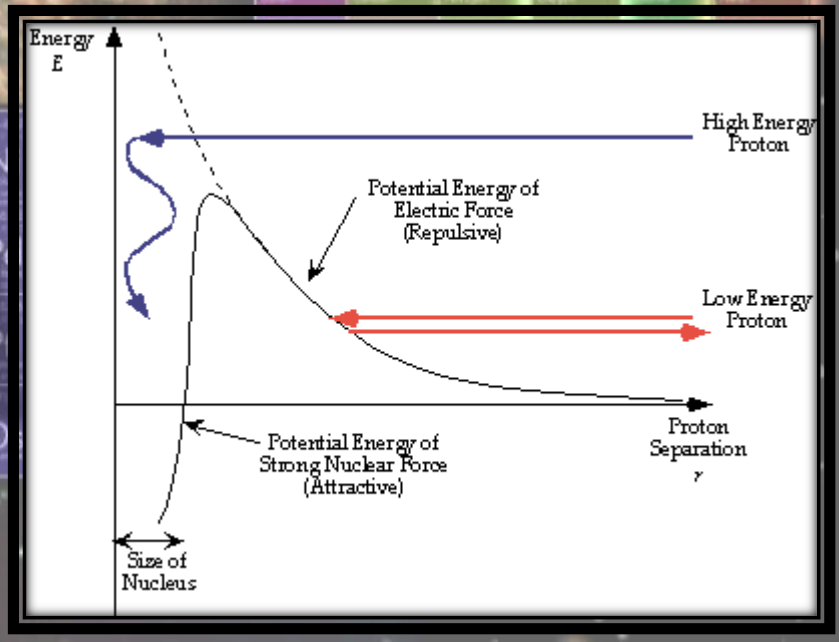
The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Fundamentalne interakcije

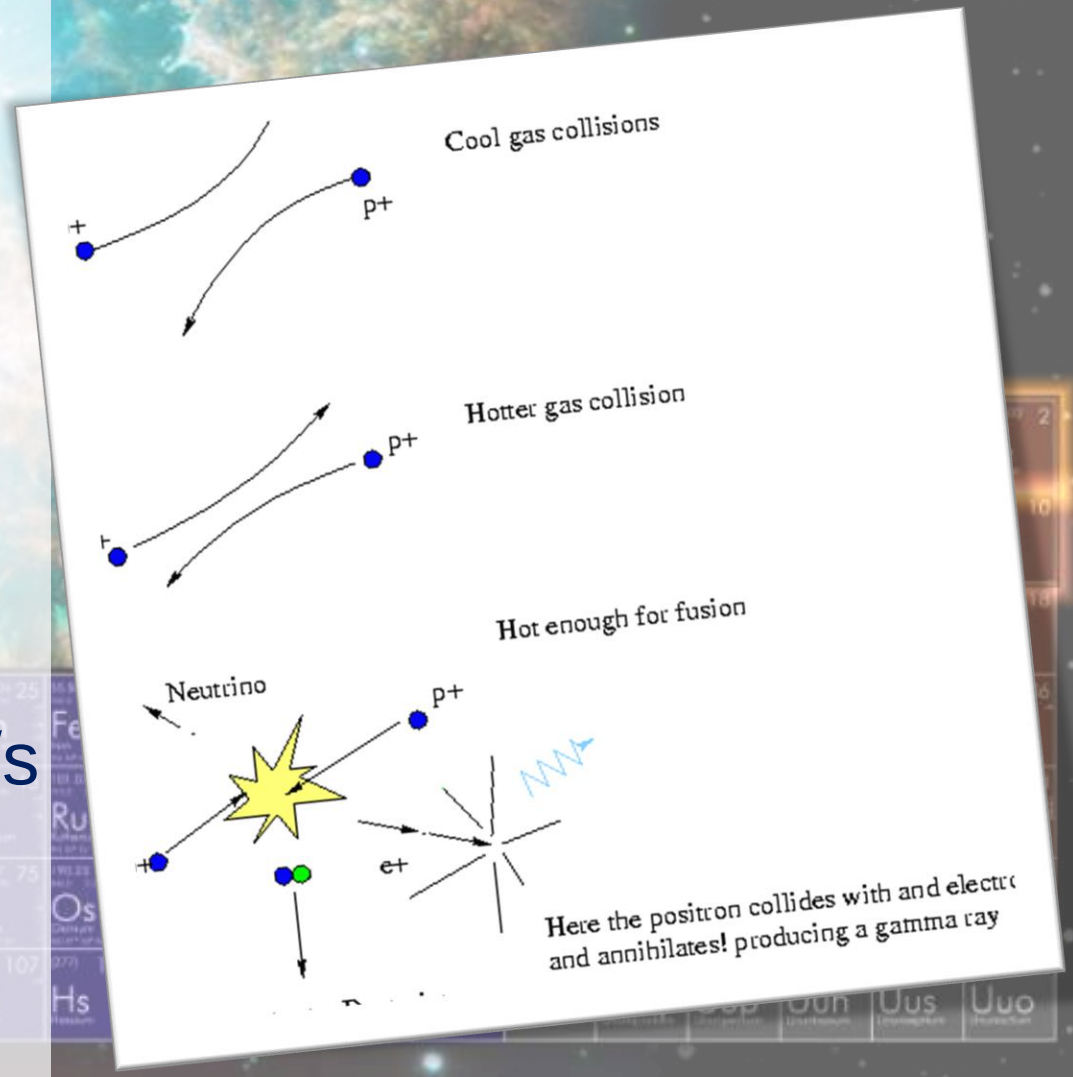




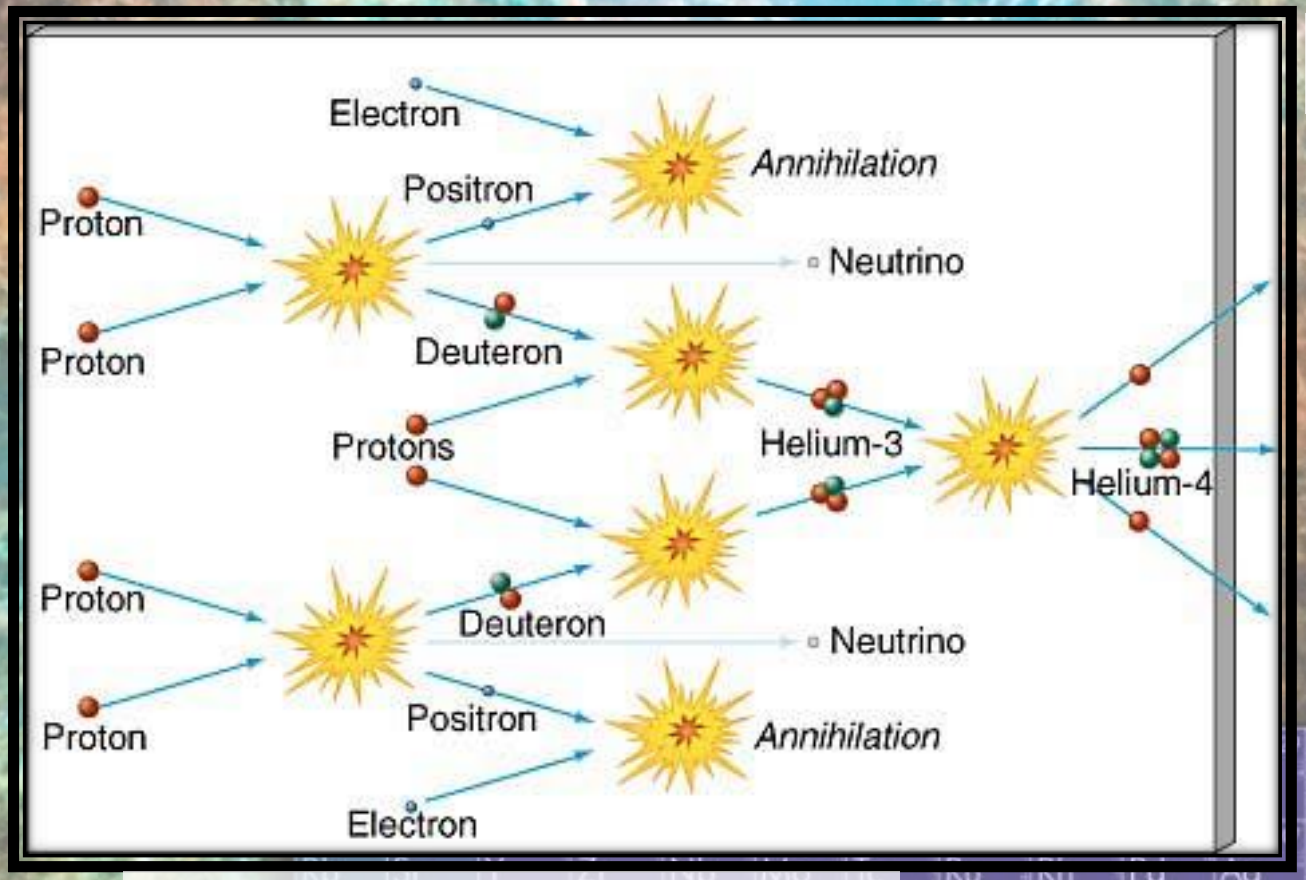


Nuklearna fuzija

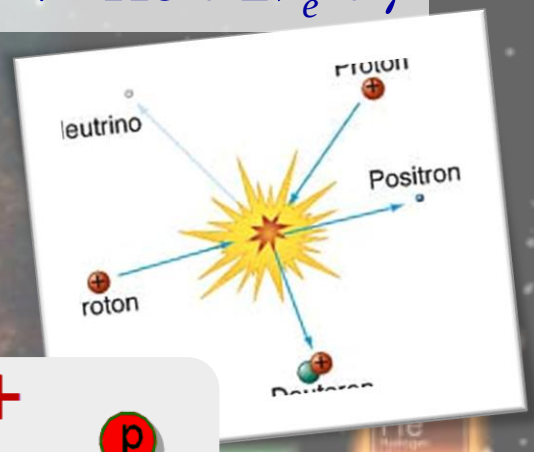
- Velika brzina
- Jaka nuklearna sila
- Rastojanje: 10^{-15} m
- Brzina: nekoliko 100 km/s
- Temperatura: 10^{7} K

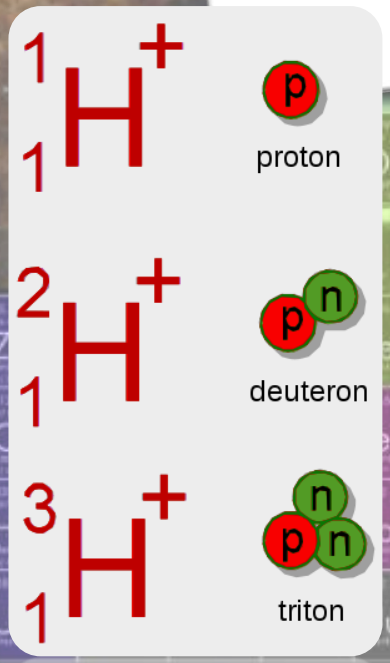


Proton-protonski ciklus



$$4(^1H) \rightarrow {}^4He + 2\nu_e + \gamma$$



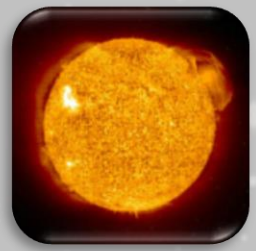


$$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$$

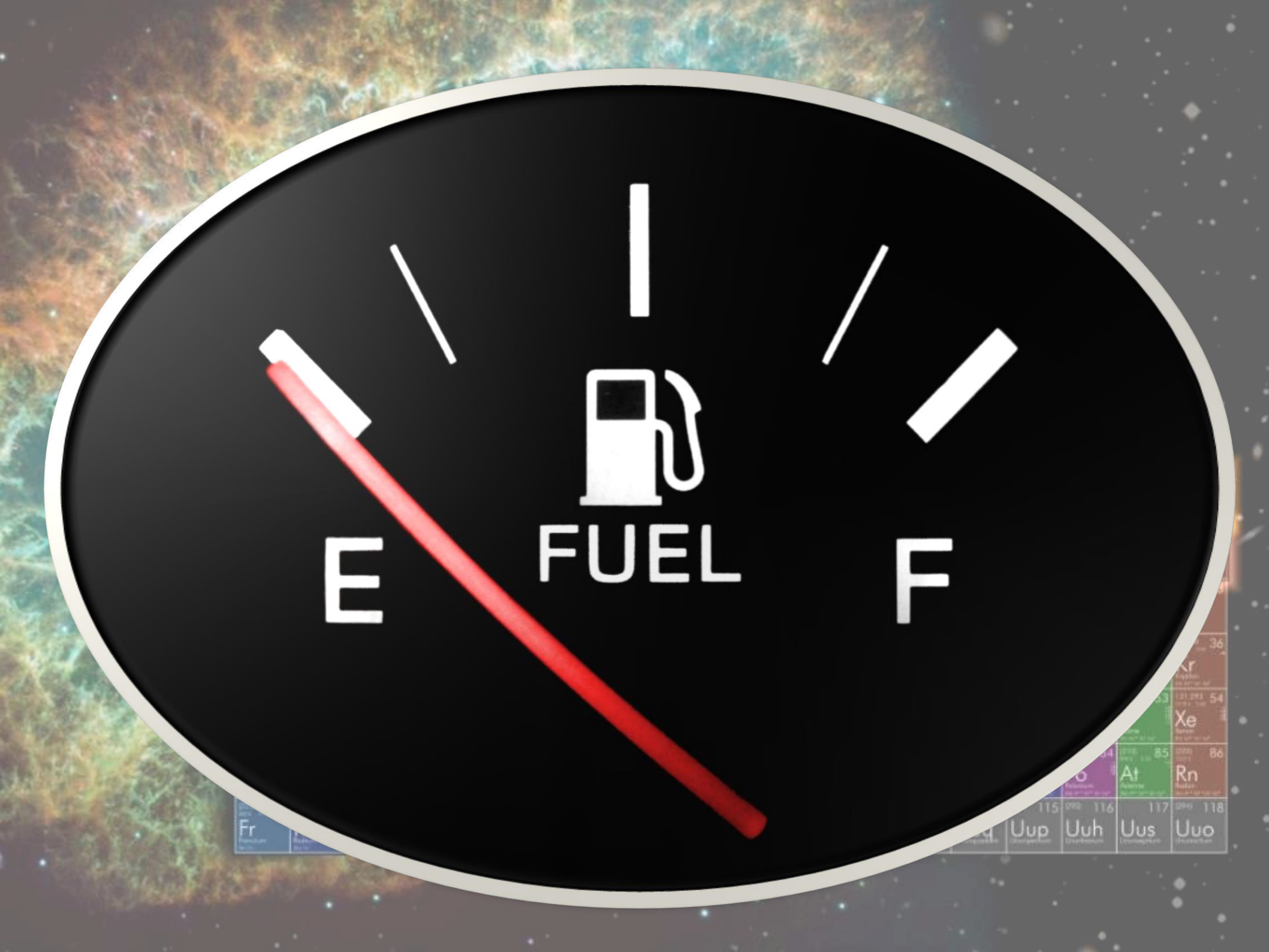
$$^2H + {}^1H \rightarrow {}^3He + \gamma$$

$$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H + \gamma$$

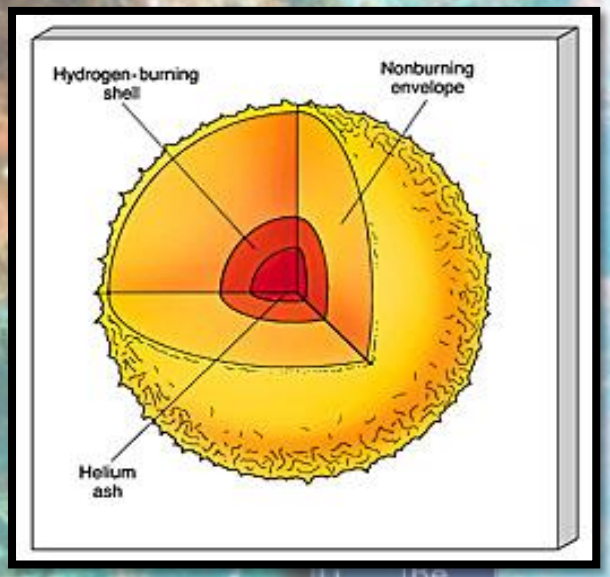
Koliko energije?

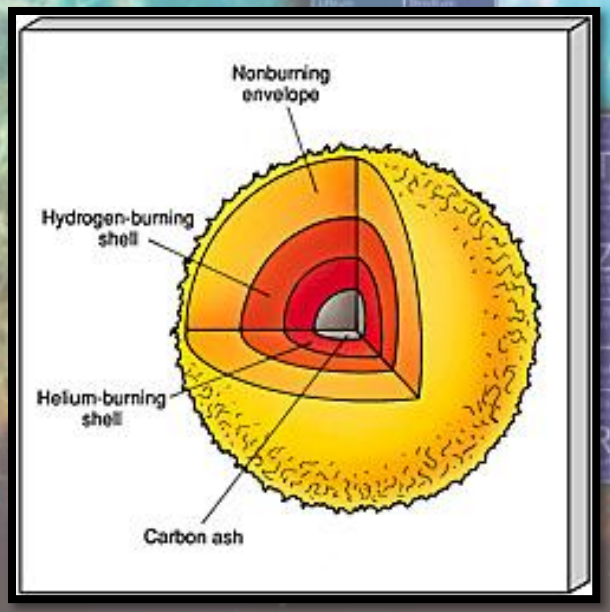


- Precizni eksperimenti na Zemlji - određene mase svih čestica u p-p ciklusu
- 4 protona - $6{,}6943 \circ 10^{-27}$kg
- jezgro helijuma - $6{,}6466 \circ 10^{-27}$kg
- defekt mase - $0{,}048 \circ 10^{-27}$kg => $4{,}3 \circ 10^{-12}$J (26,7 MeV)
- 1 kg vodonika => $6{,}4 \circ 10^{13}$ J (više nego dovoljno)
- svake sekunde **700 miliona tona** vodonika fuzijom prelazi u **695 miliona tona** helijuma, a od **5 miliona tona** nastaje energija
- ***1 sekunda = 500000 godina potrošnje na Zemlji!***


E
FUEL
F

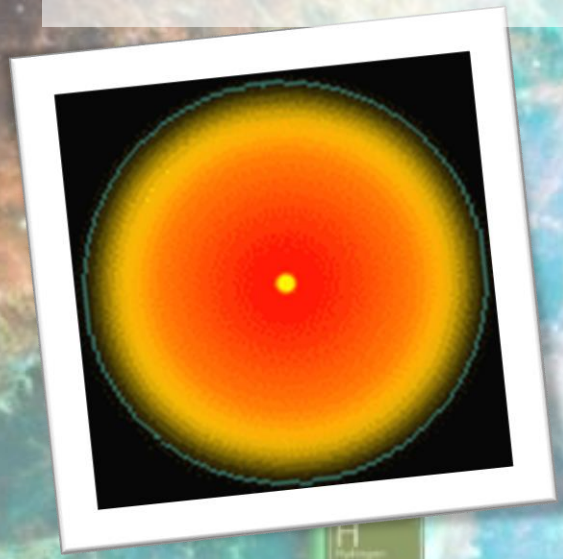
Početak kraja

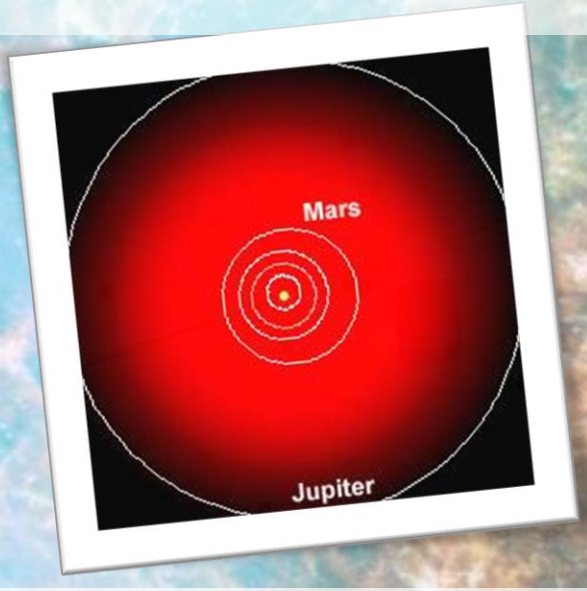


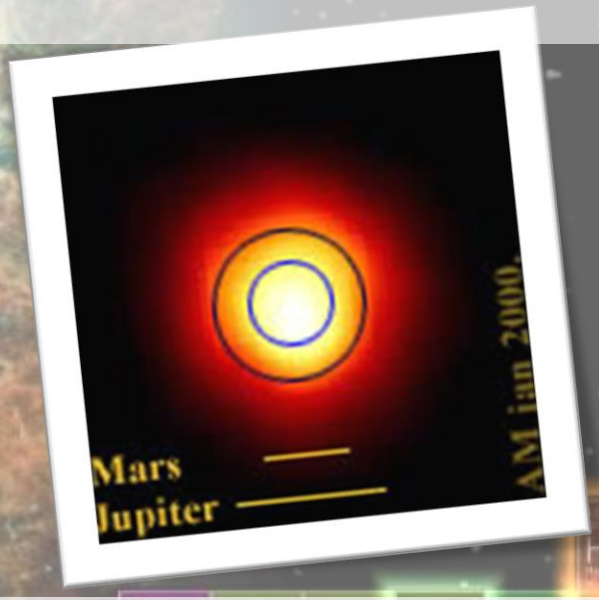


- “Sagorevanje” vodonika u ljusci oko jezgra
- Jezgro
  - Temperatura ***100 miliona*** stepeni
  - “sagorevanje” helijuma
  - “pepeo”: ugljenik i kiseonik
- Zvezda raste, površina hladi
- Zapremina oko ***milijardu puta*** veća
- **Crveni džin**

Crveni džin







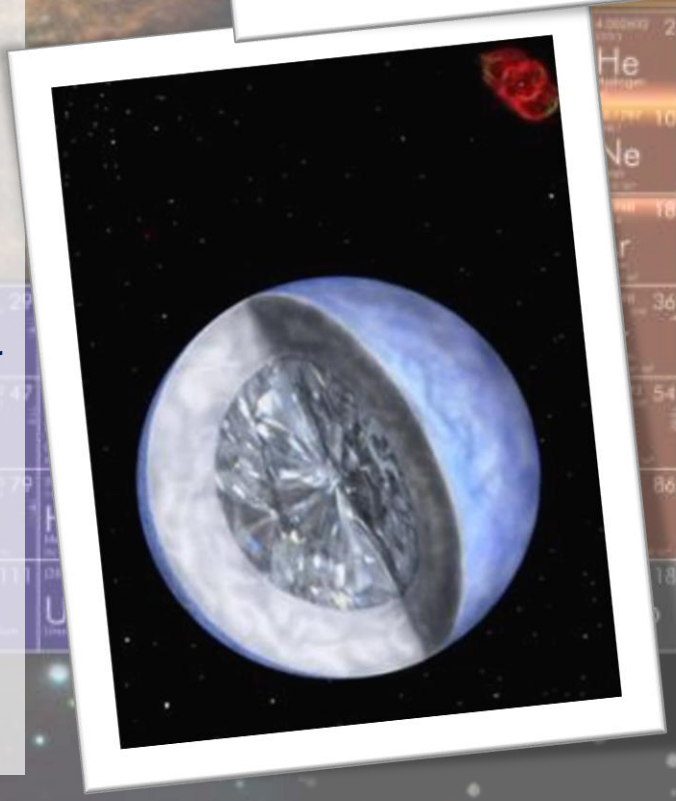
- Aldebaran (Bik)
  - 15 najsjajnijih zvezda, 15x veći od Sunca; orbita Merkura
- Antares (Škorpija)
  - 13. po sjaju, 12000x sjajniji od Sunca, ¾ rastojanja do Jupitera
- Betelgez (Orion)
  - 11. po sjaju, 15000x sjajniji od Sunca, 20x veća masa

Planetarna maglina

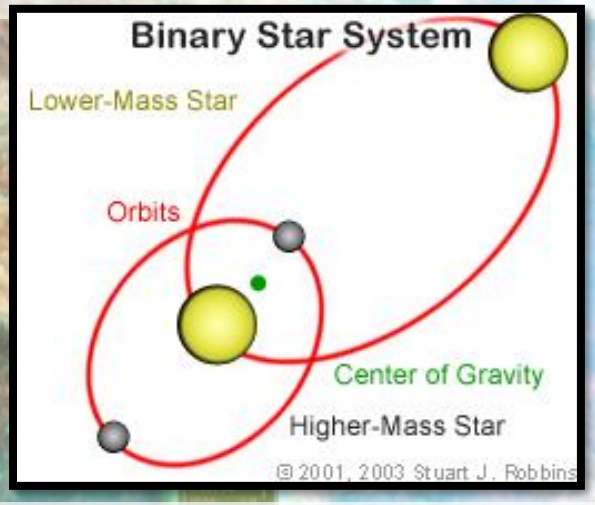
“Mačije oko”

Beli patuljak

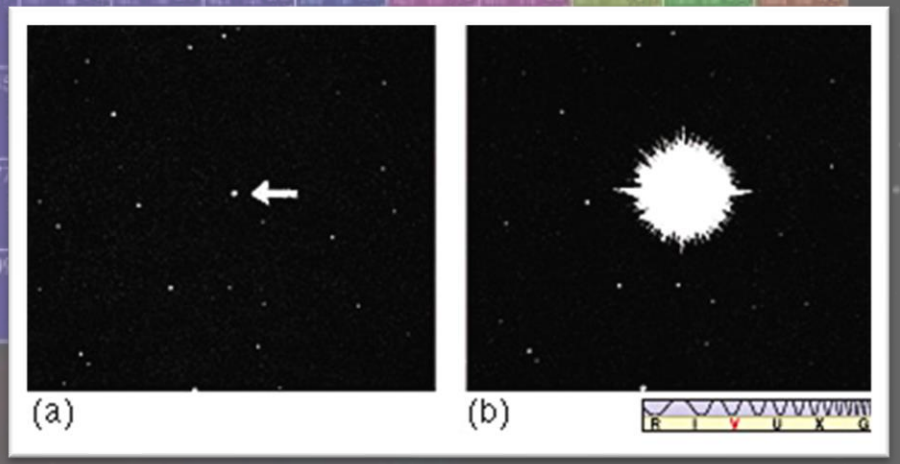
- Mnogo praznog prostora...
- “Pritisak” elektrona
- 1,4 solarne mase, 10.000 km;
- 1 cm^3 → 60 tona!
- Beli patuljci se hlade → temperatura međuzvezdanog prostora, mrki patuljci
- Neki beli patuljci – zanimljiva sudbina



Nova

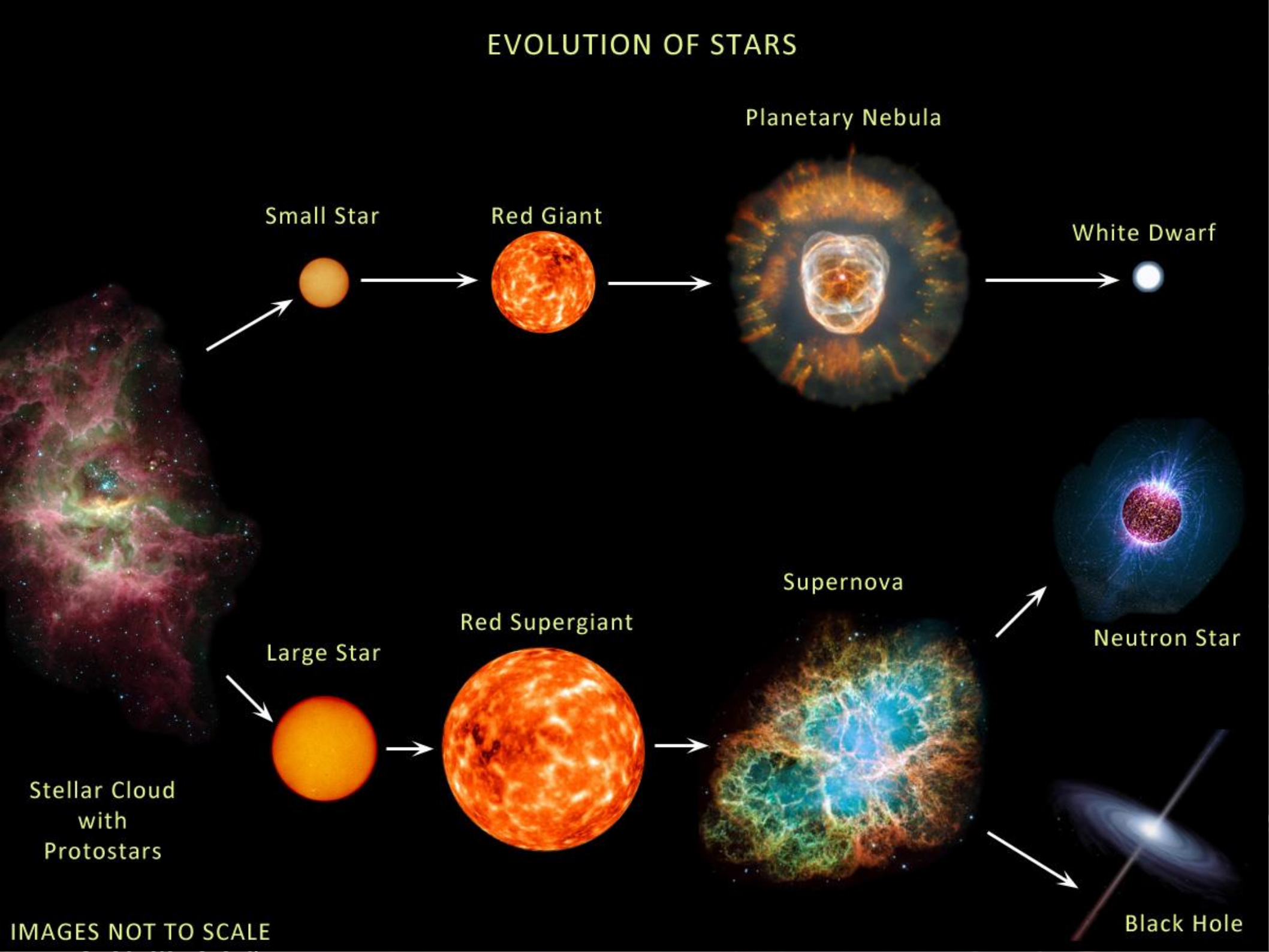


- Sjaj - 10 hiljada puta!
- Masa – 1/10 solarne
- beli patuljci – objašnjeni ~1930
- Čandrasekar
- Granica 1,4 solarne mase
- Svake godine 6-10



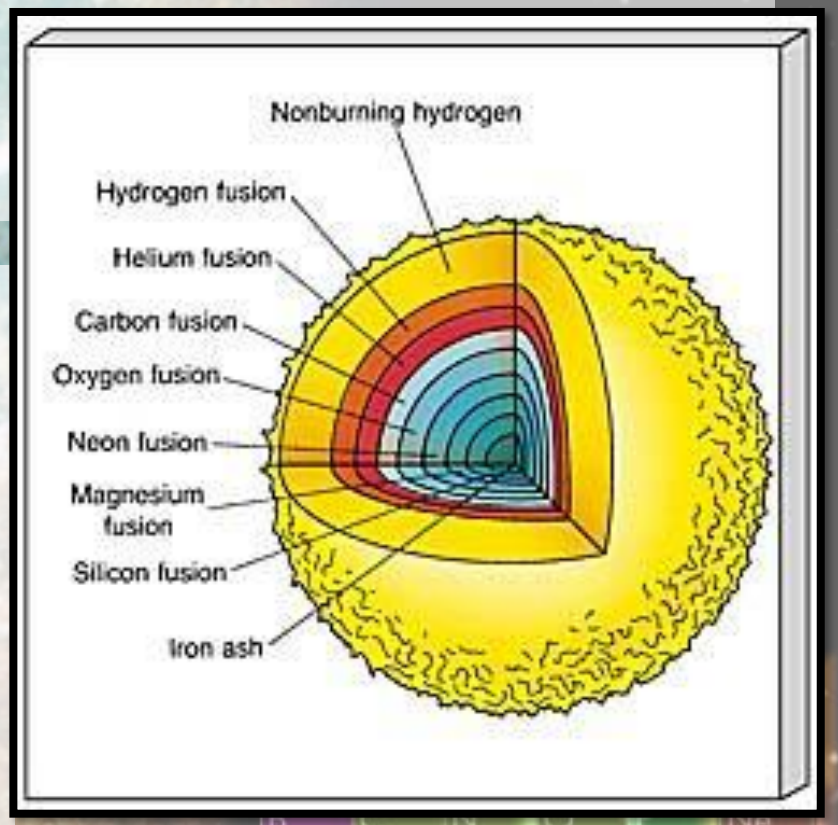
Male i velike zvezde

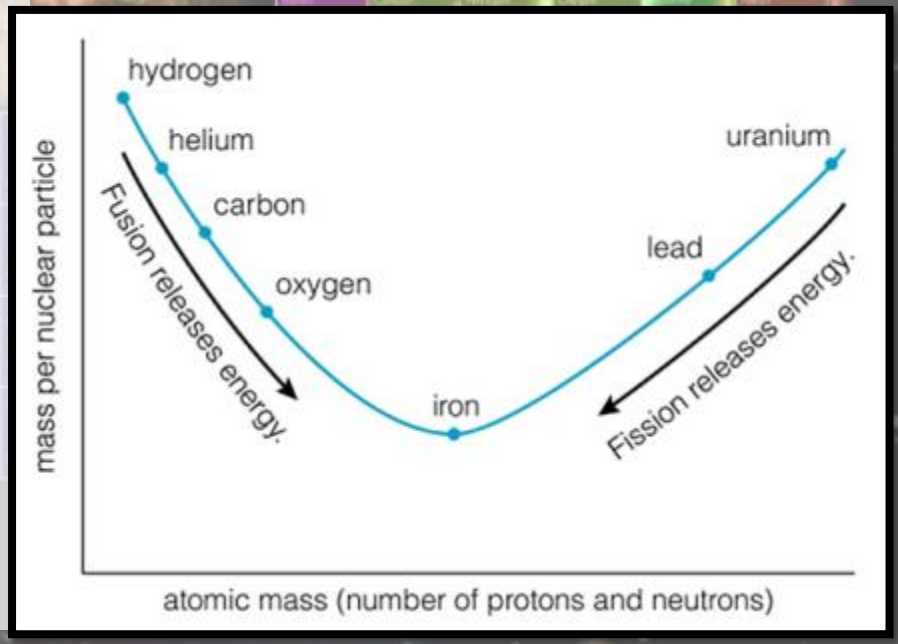
- Većina zezda – slične Suncu
- Postoje i druge zvezde – plavičaste, blještavo sjajne
- Spika (Devica), Aherar (Eridan), skoro sve sjajne u Orionu
- Masa zvezda:
- mala – žive dugo, evoluiraju polako
- velika – žive kratko, evoluiraju brzo
- Crveni džin – teško se razlikuju
- Mala masa – jezgro (ugljenik, kiseonik) – inertno
- Velika masa – termonuklearne reakcije se nastavlja


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Red Supergiant
Large Star
Neutron Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

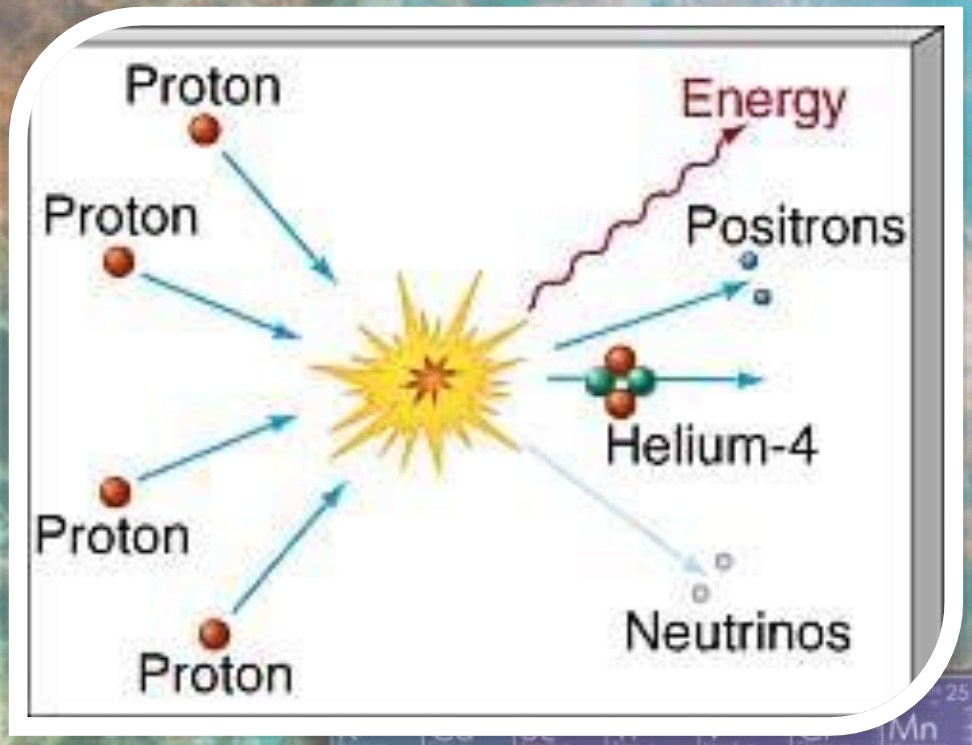
Velike brzo žive...

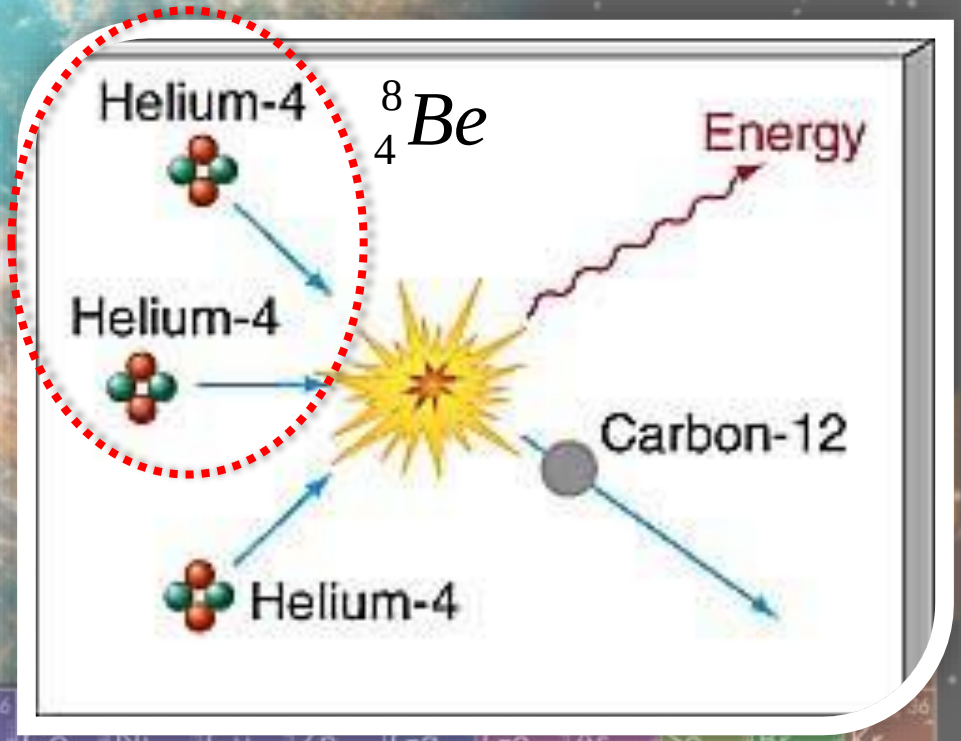
- Brzina:
  - 20 solarnih masa
  - vodonik - 10 miliona god.
  - helijum – milion godina
  - Ugljenik – 1000 godina
  - Kiseonik – 1 godina
  - Silicijum → gvozdeno jezgro za 1 dan
- Temperatura raste
  - 700 miliona – ugljenik
  - milijardu – kiseonik
  - 3 milijarde – silicijum
- Inertno gvožđe!





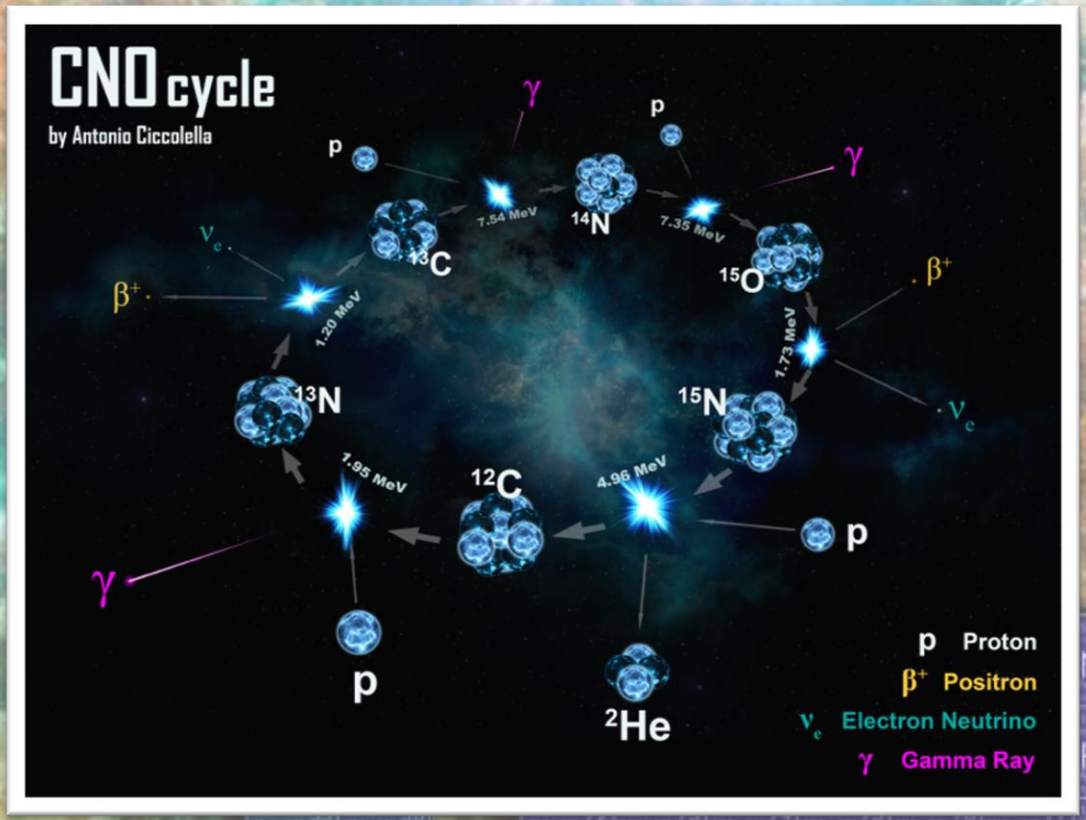
Fuzija vodonika i helijuma





- Proton-protonski ciklus, temperatura 10^7K
- Tri-alfa proces, temperatura 10^8K

CNO ciklus



$$^{6}C + {}^{1}H \rightarrow {}^{13}N + \text{energy}$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \text{energy}$$

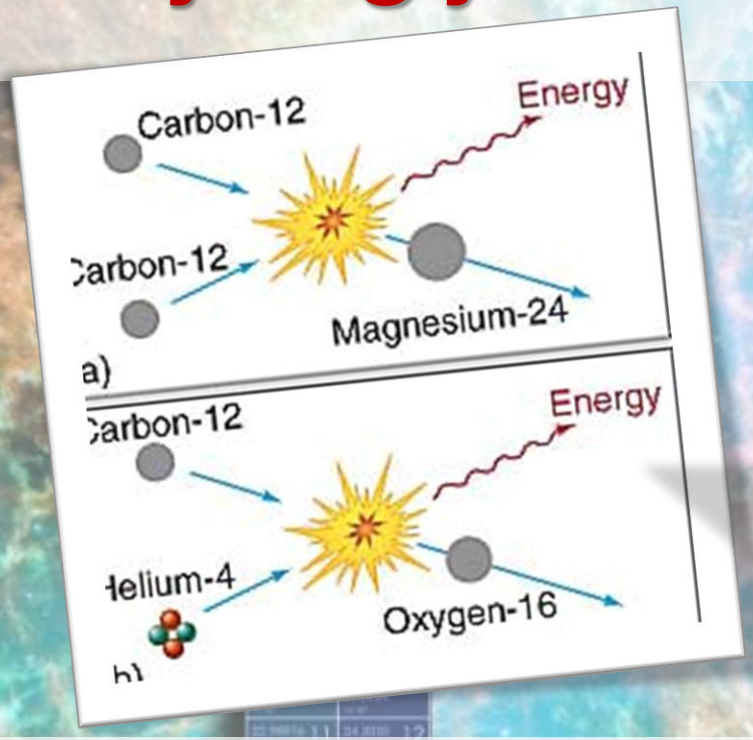
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \text{energy}$$

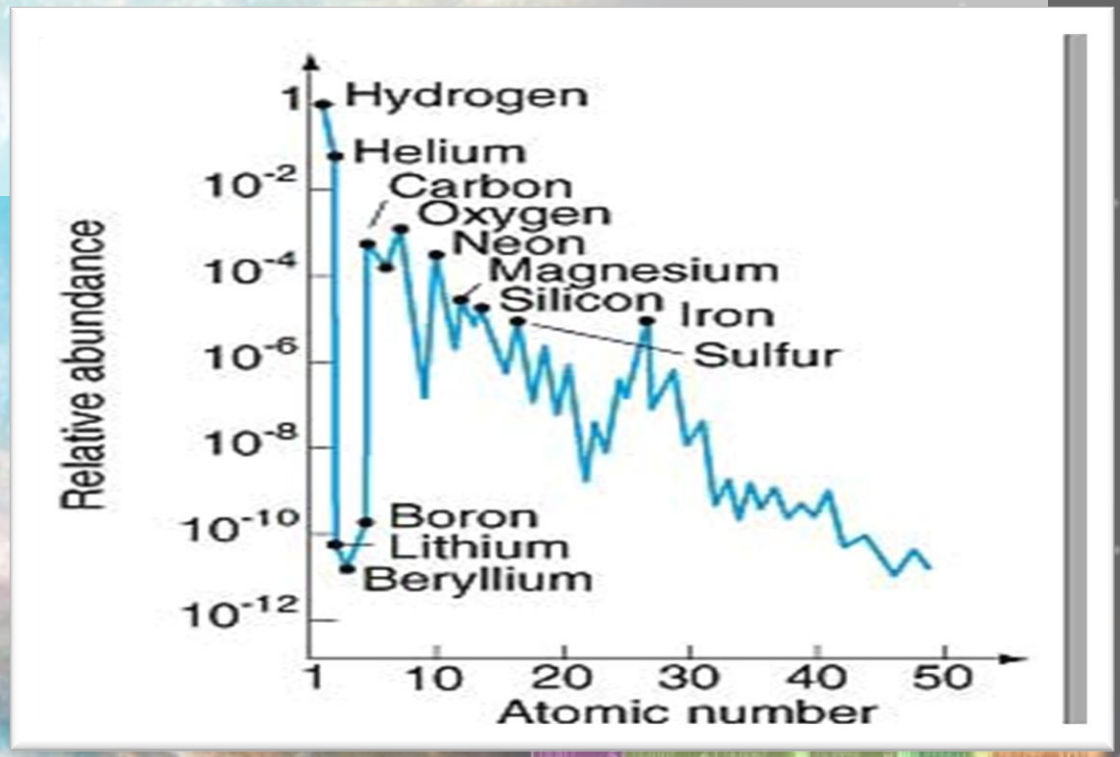
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \text{energy}$$

- Dominantan u zvezdama 1,3 puta veće mase od Sunca

Fuzija ugljenika





- Temperatura 10^9K
- Teža jezgra → veći broj protona → ogromne temperature
- Fuzija ugljenik-helijum, temperatura $6 \cdot 10^8$K

  $^{16}O + {}^{16}O \rightarrow {}^{32}S + energija$

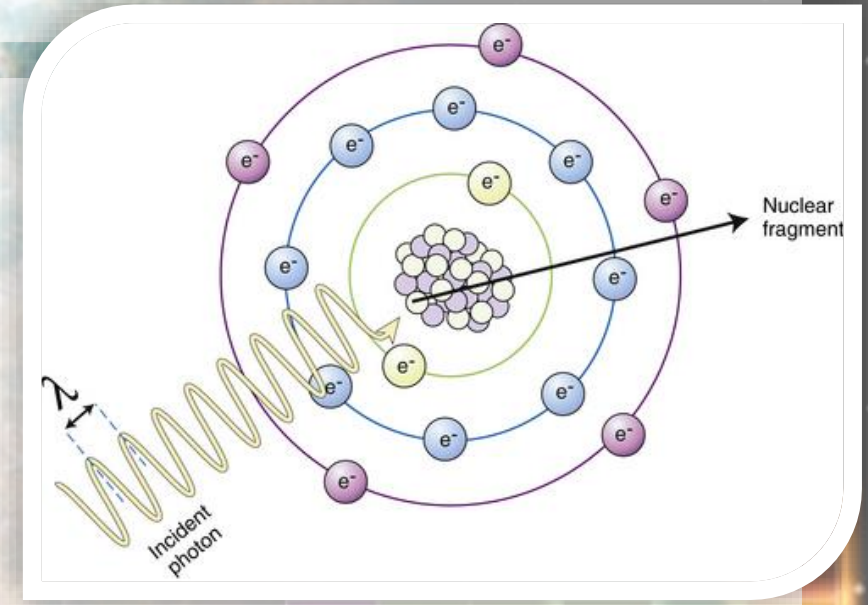
  $^{16}O + {}^{4}He \rightarrow {}^{20}Ne + energija$

- *proces zahvata helijuma*

Alfa proces

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{16}_{8}\mathrm{O} + \gamma && E = 7.16\ \mathrm{MeV} \\
{}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma && E = 4.73\ \mathrm{MeV} \\
{}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{24}_{12}\mathrm{Mg} + \gamma && E = 9.32\ \mathrm{MeV} \\
{}^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{28}_{14}\mathrm{Si} + \gamma && E = 9.98\ \mathrm{MeV} \\
{}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{32}_{16}\mathrm{S} + \gamma && E = 6.95\ \mathrm{MeV} \\
{}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{36}_{18}\mathrm{Ar} + \gamma && E = 6.64\ \mathrm{MeV} \\
{}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{40}_{20}\mathrm{Ca} + \gamma && E = 7.04\ \mathrm{MeV} \\
{}^{40}_{20}\mathrm{Ca} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{44}_{22}\mathrm{Ti} + \gamma && E = 5.13\ \mathrm{MeV} \\
{}^{44}_{22}\mathrm{Ti} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{48}_{24}\mathrm{Cr} + \gamma && E = 7.70\ \mathrm{MeV} \\
{}^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{52}_{26}\mathrm{Fe} + \gamma && E = 7.94\ \mathrm{MeV} \\
{}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{56}_{28}\mathrm{Ni} + \gamma && E = 8.00\ \mathrm{MeV}
\end{aligned}
$$

Nije sve tako jednostavno

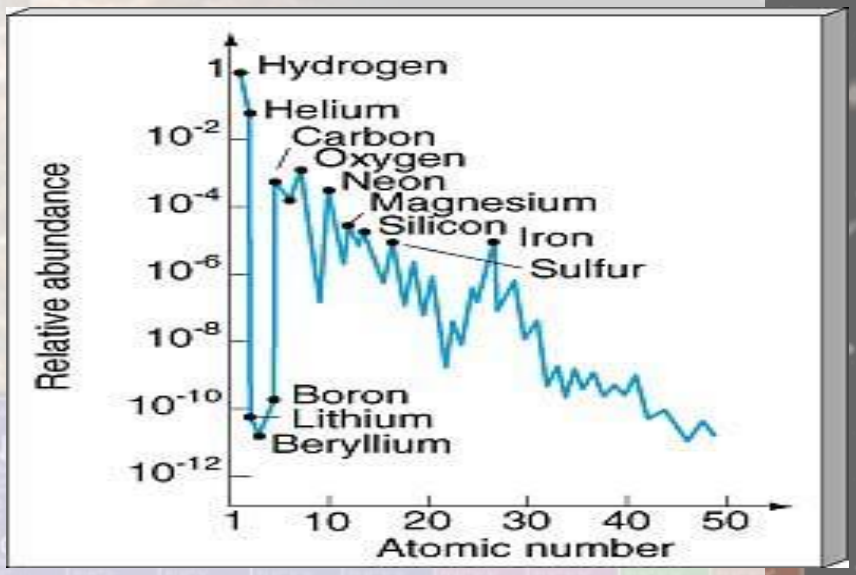


- Helijum nije jedini element koji učestvuje u fuzionim reakcijama sa drugim elementima
- Emisija i apsorpcija protona i neutrona
- Kad se pojavi ***silicijum*** – temperatura $3 \cdot 10^9 K$
- Razaranje jezgara, gama zracima, na jezgra helijuma (**fotodisintegracija**)
- Ne samo da uništava silicijum, omogućava nastanak težih jezgara

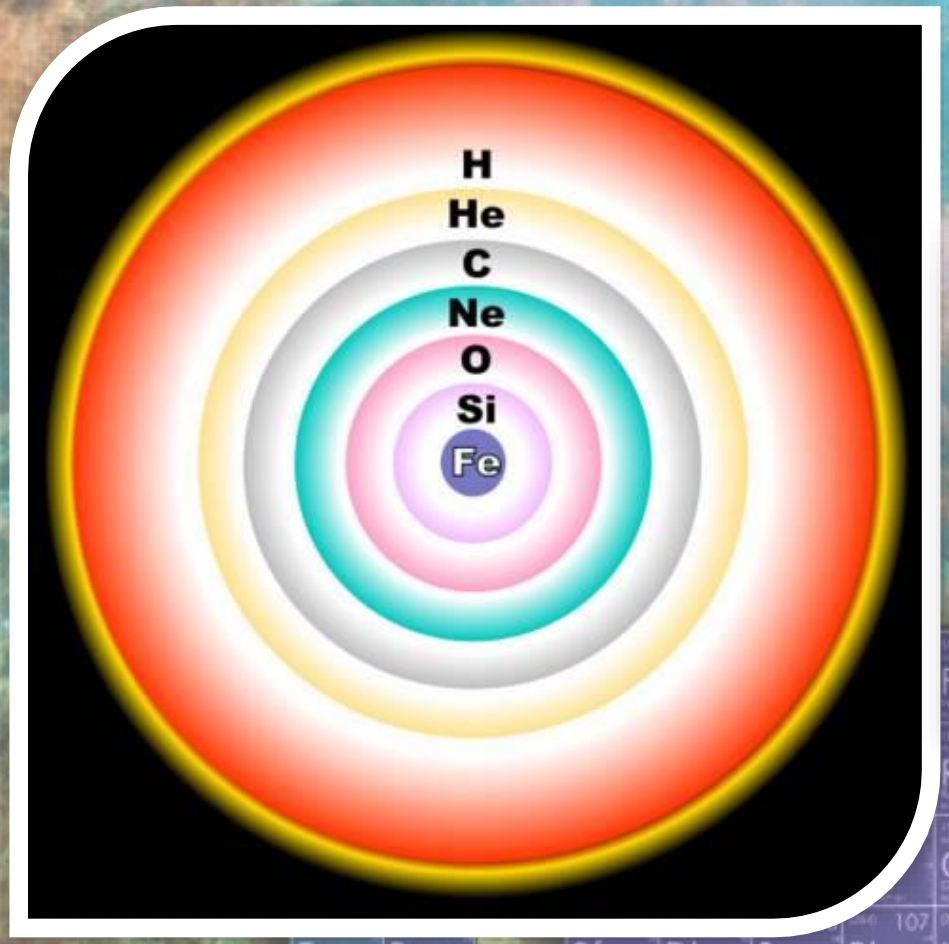
- Silicijum zahvata neku od nastalih alfa-čestica
- Proces u nekoliko etapa, konačno

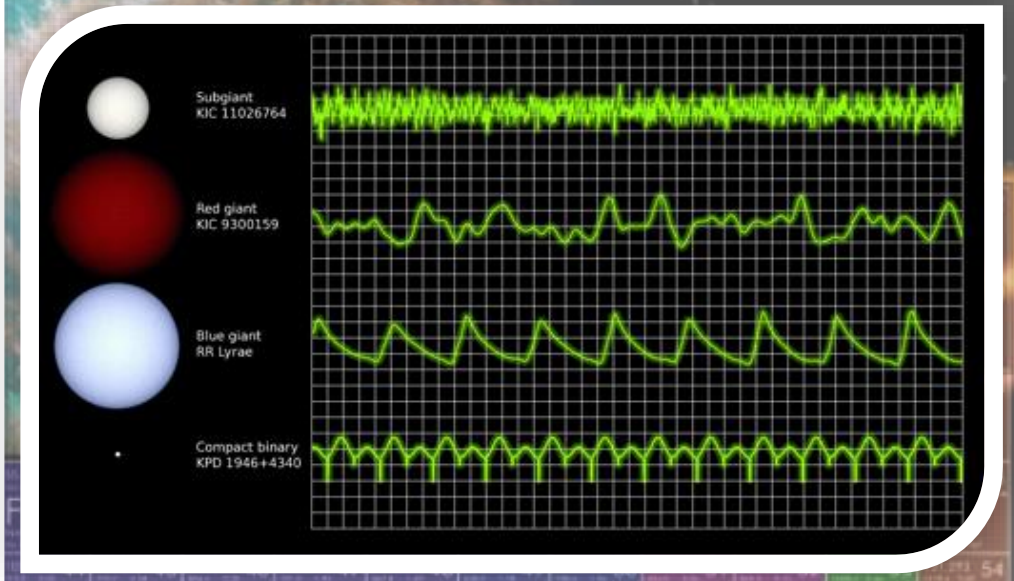
$$^{28}Si + 7(^{4}He) \rightarrow {}^{56}Ni + energija$$

- *Alfa-proces*
- *nikl-56 → kobalt-56 → gvožđe-56*
- **gvožđe-56 „najjače“ vezano atomsko jezgro**
  - 26 protona, 30 neutrona
  - Najveća energija veze jezgra
  - Nagomilava u jezgru zvezde
  - Elementi grupe gvožđa – veća rasprostranjenost



Pre eksplozije

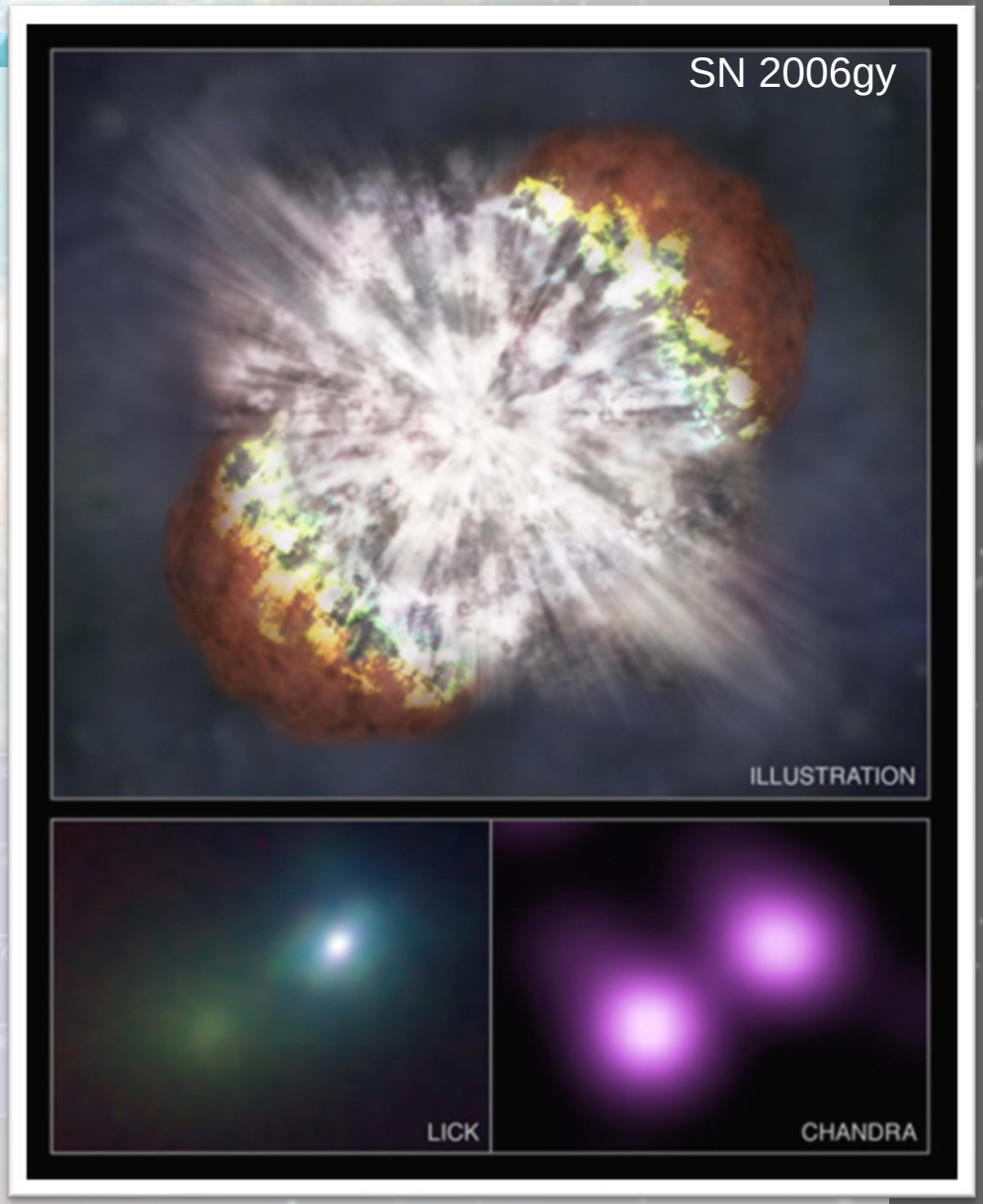




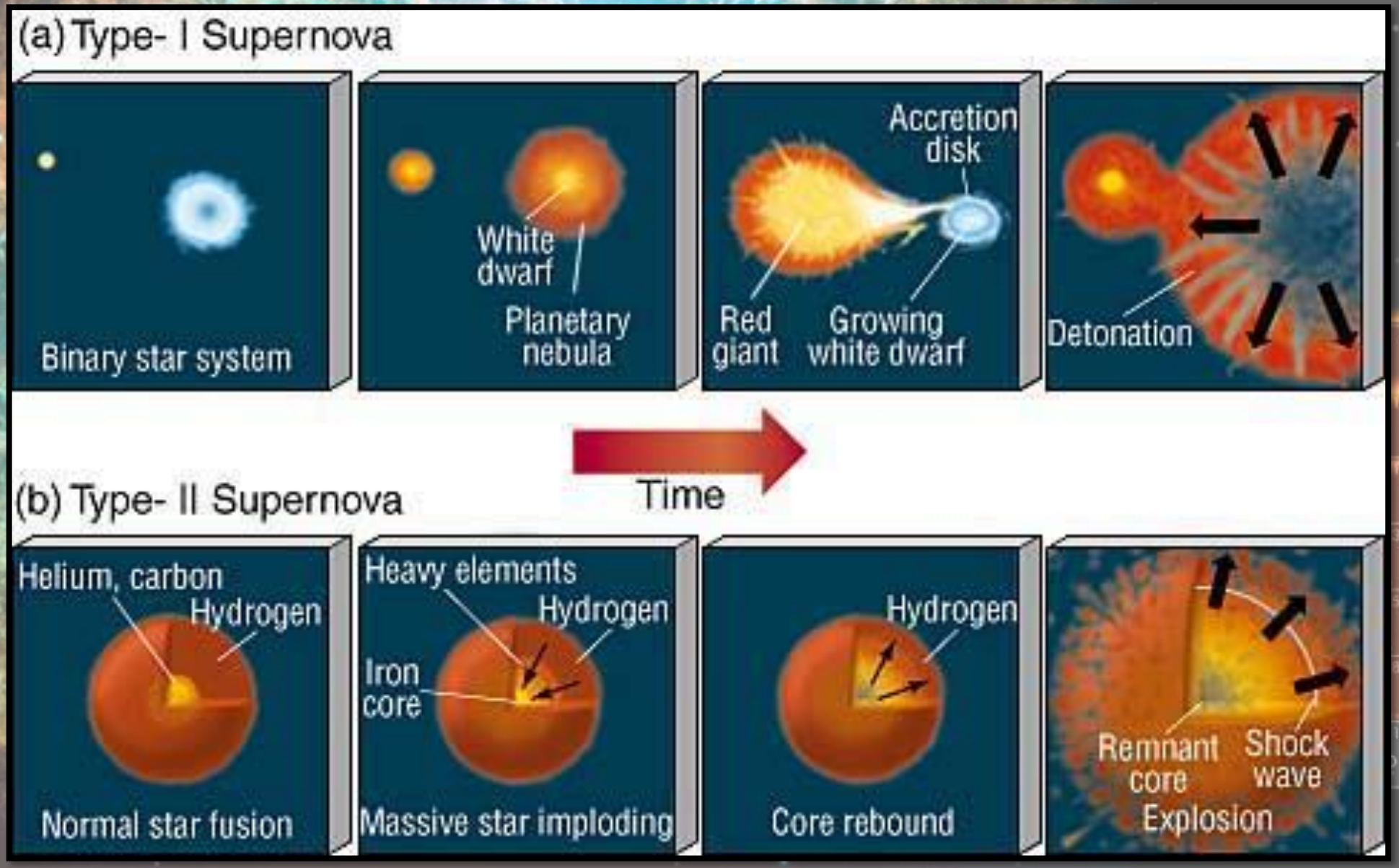

100 miliona
milijardi triliona
atomskih bombi

Supernova

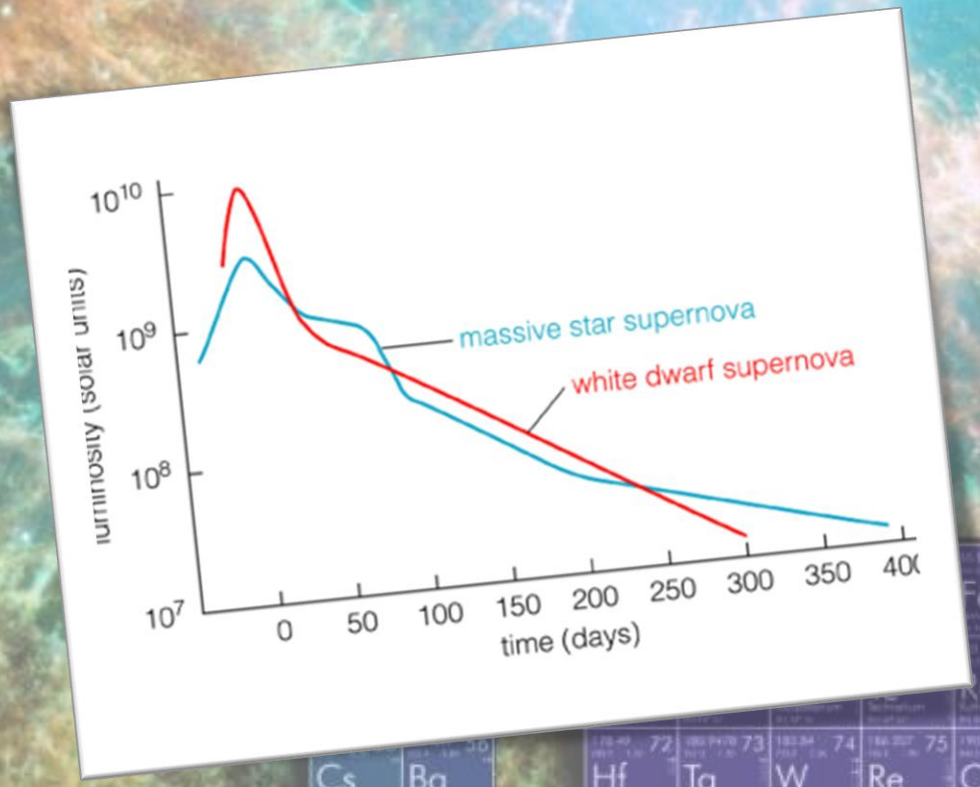
- Udarni talas – brzina nekoliko desetina hiljada km/s
- Eksplozija – odbacivanje spoljašnjih slojeva
- Ogromna oslobođena energija
- Sjajnija od čitave galaksije!
- Bljesak svetlosti jednak sjaju milijardi Sunaca i taj sjaj dostiže za nekoliko sati.
- Ista zvezda može postati nova nekoliko puta, ali zvezda može biti supernova samo jednom!

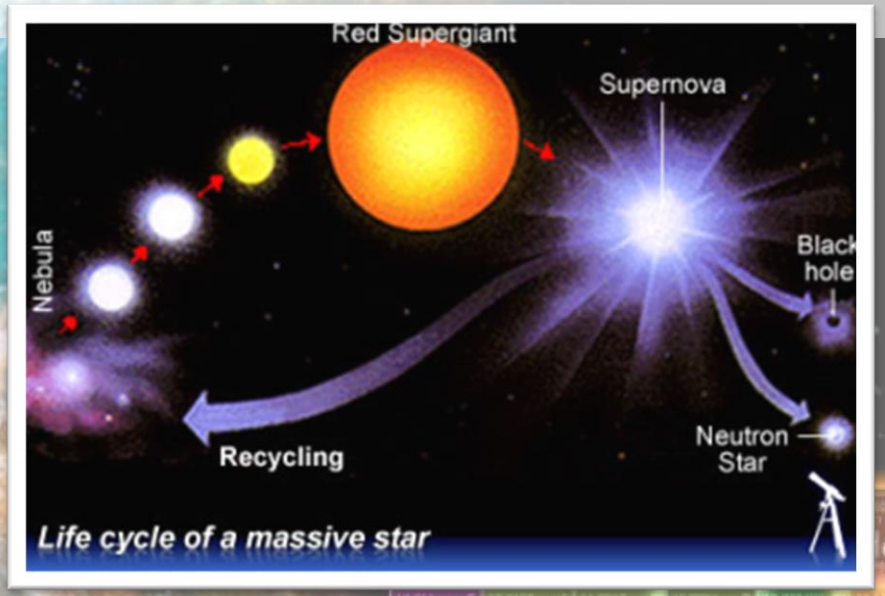


Dva tipa supernovih

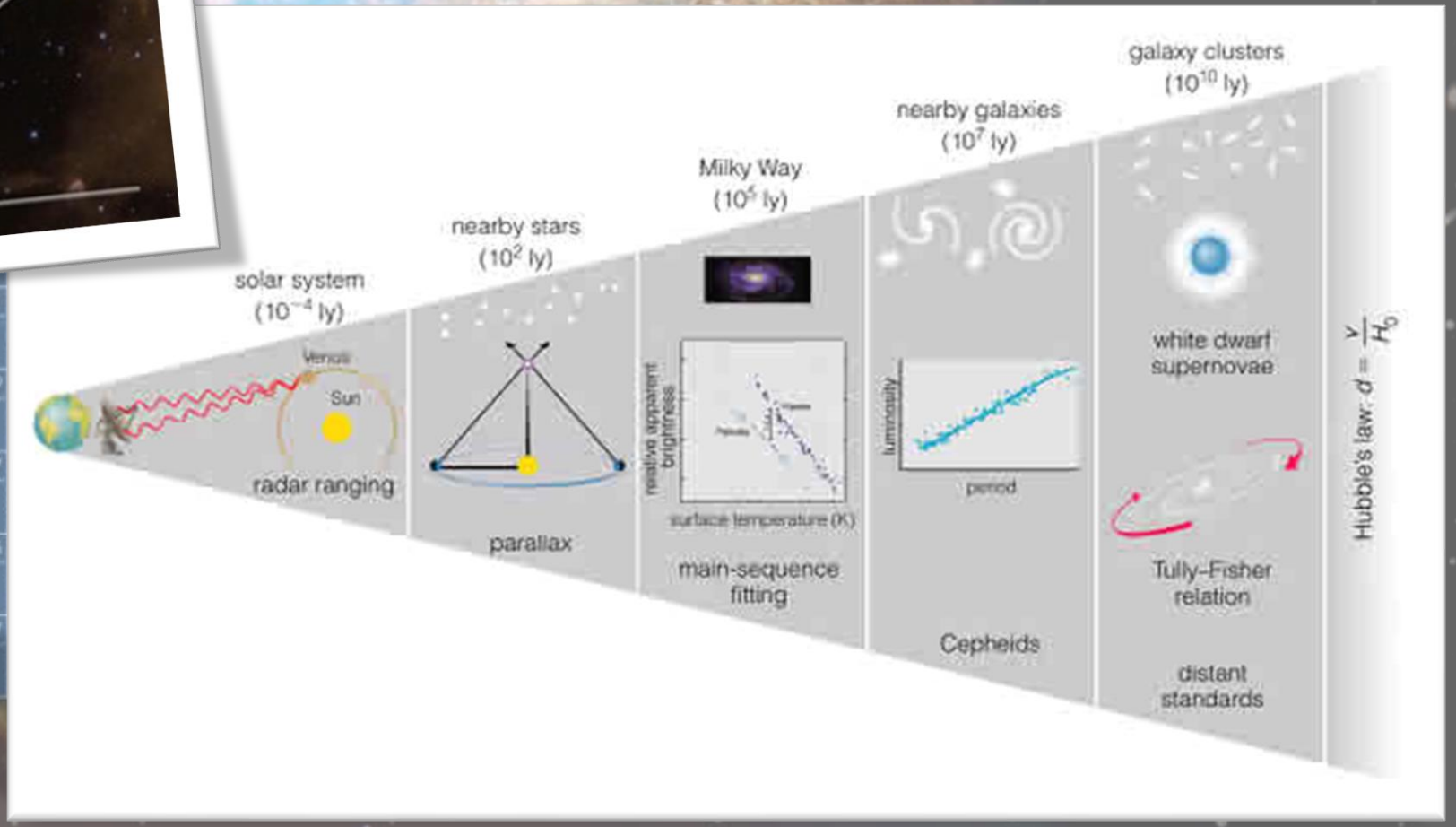


Dva tipa supernovih



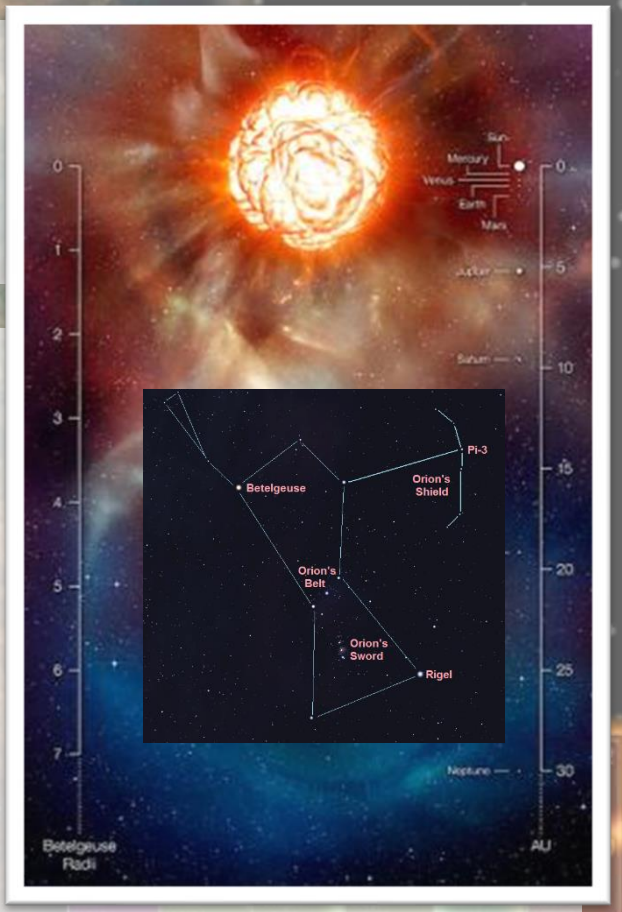


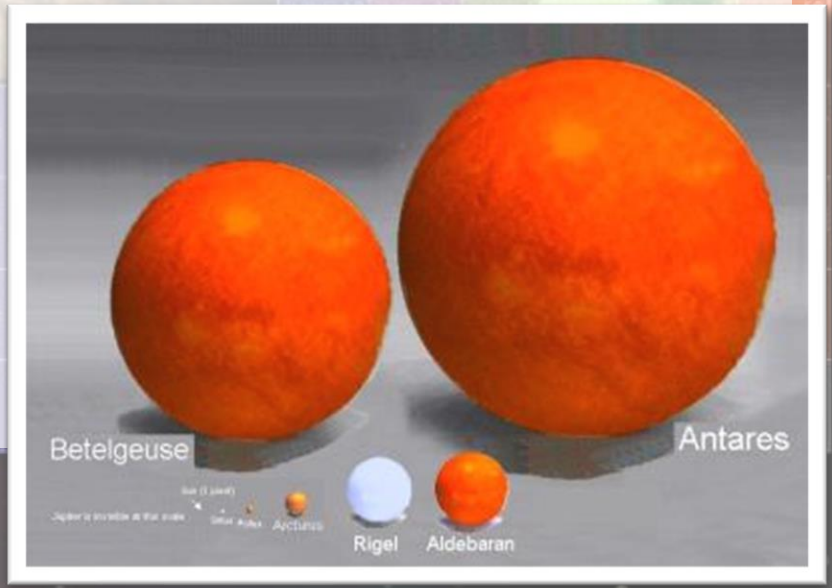
Standardne “sveće” – tip Ia



Betelgez – Alfa Orionis

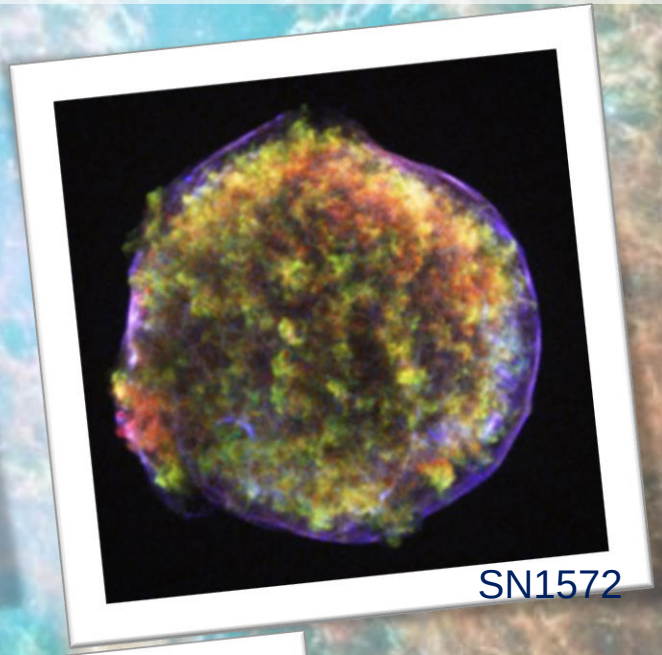
- Masa: 18-19 masa Sunca
- Prečnik: ~1000 puta veći Sunca
- Sjaj: ~150.000 puta veći
- Temperatura: 3500K
- Daljina: 650 sv. godina





Kako znamo?


SN1054

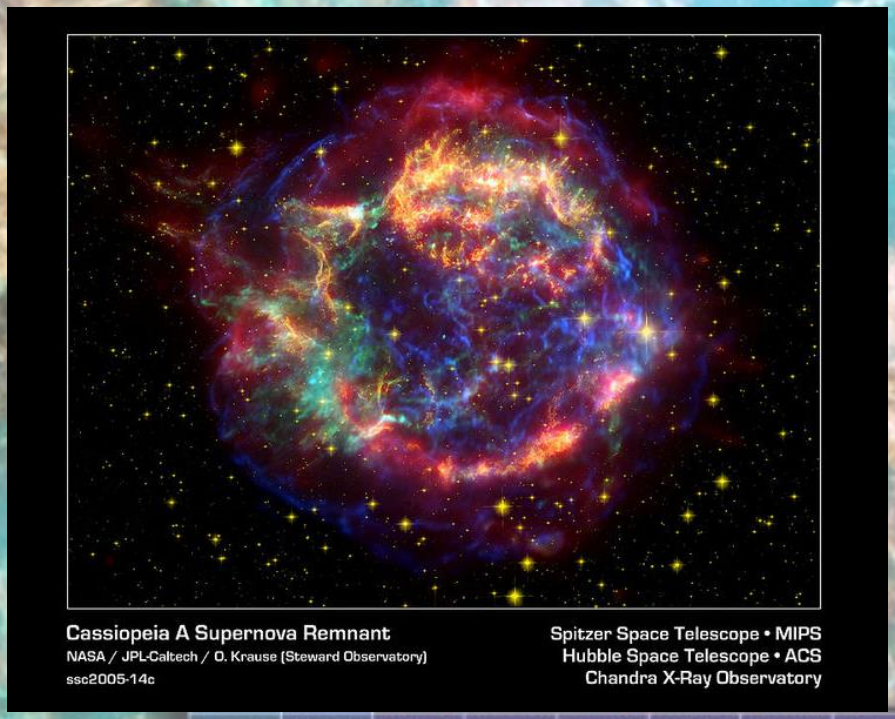

SN1572

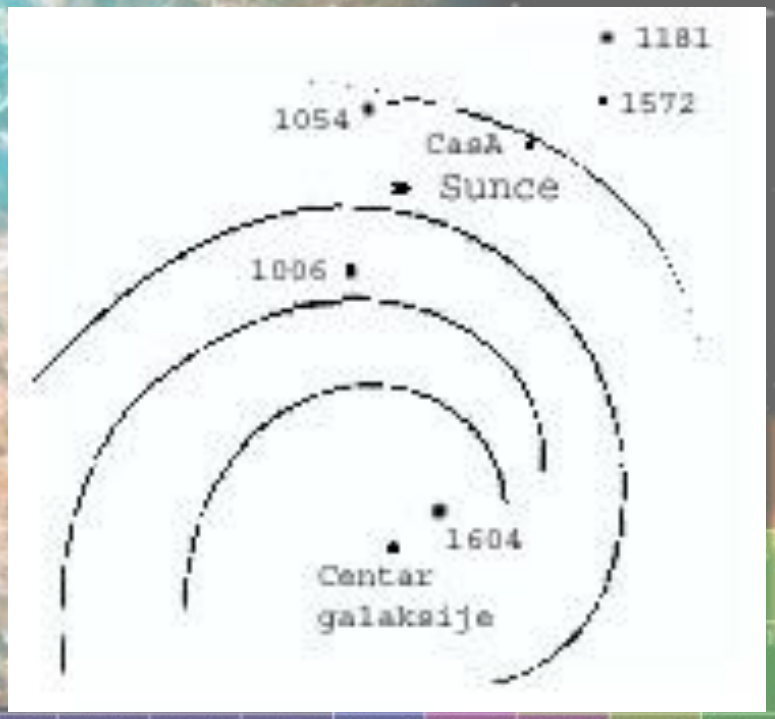

SN1604


SN1006


SN1987

Supernove u našem komšiluku

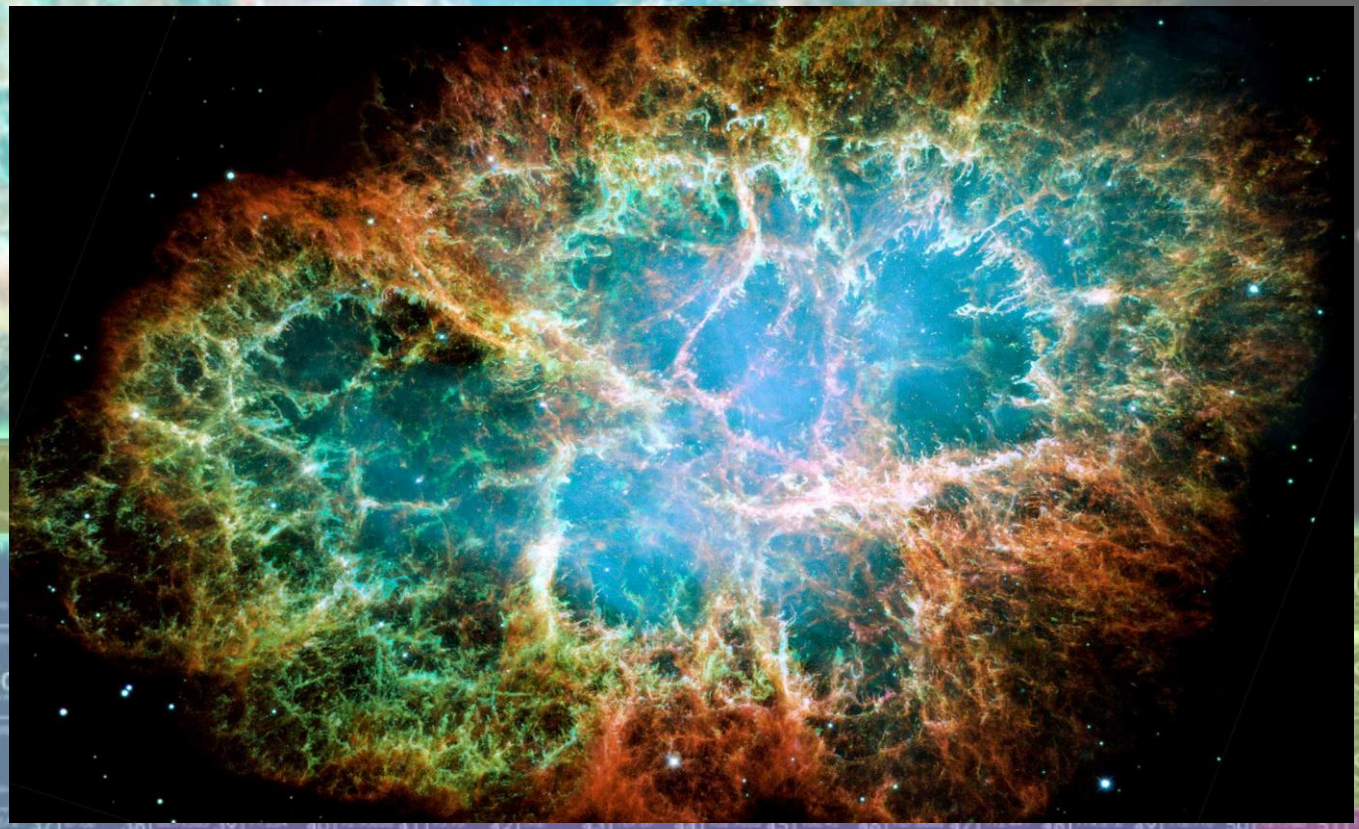




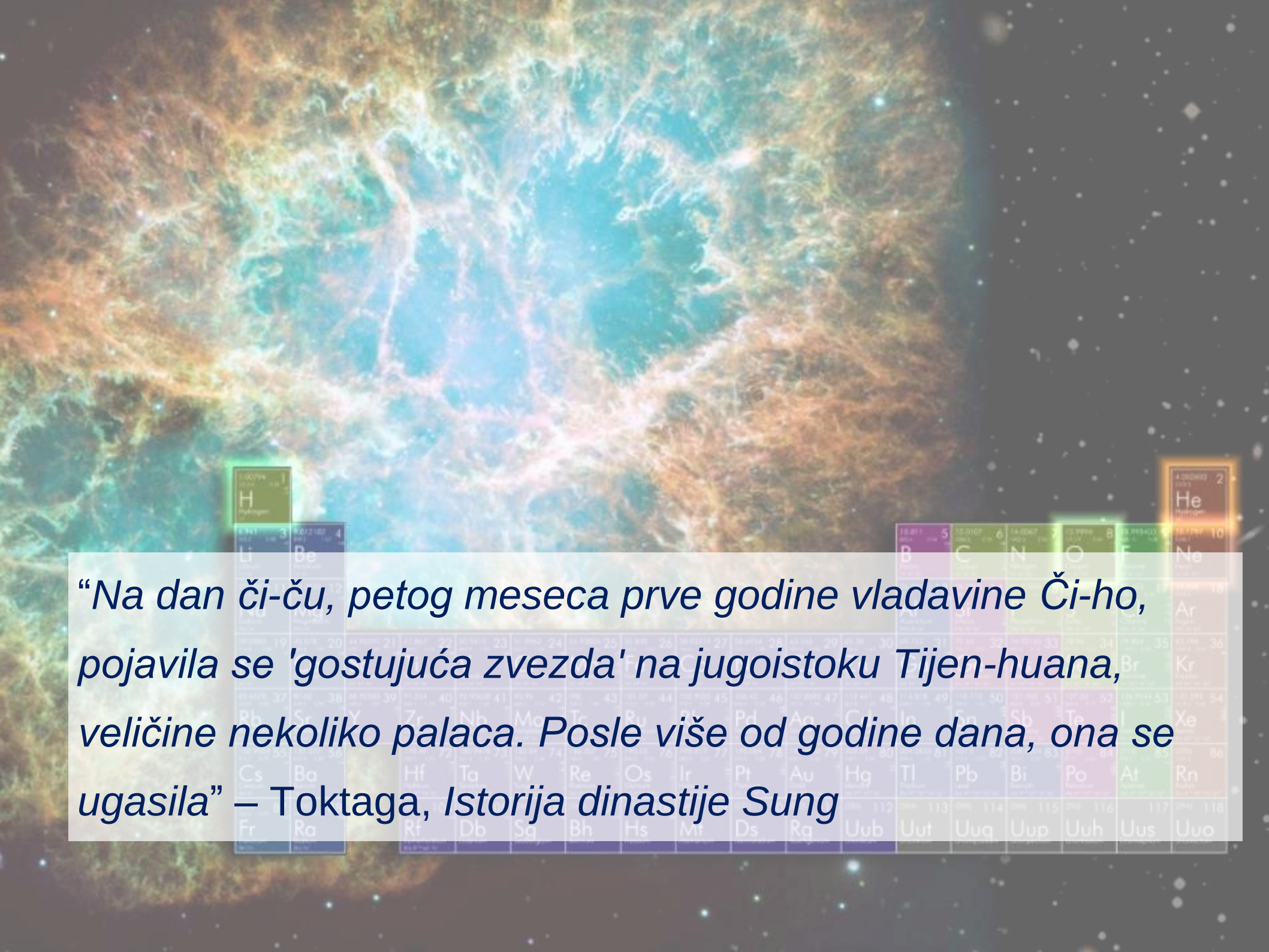
- 10 supernova u našoj galaksiji u poslednjih 1000 godina
- CasA – nema je u istoriji, radio posmatranja - videla se u VII veku
  - Najjači radio izvor, 10.000 sg, stara 300 god (možda 16. avgust 1680 – nova zvezda u katalogu)
- Svaka – bar 100 pc ispod ili iznad galaktičke ravni
- Krug 100 pc – 1 supernova svakih 500.000 god.
- Najmlađa SNR G1.9+0.3 (1868. god; otkrivena 1985, starost određena 2008)

M1 – Maglina Rak (SN1054)

(NGC 1952; Taurus; +8,4 mag; 6300 s.g.)



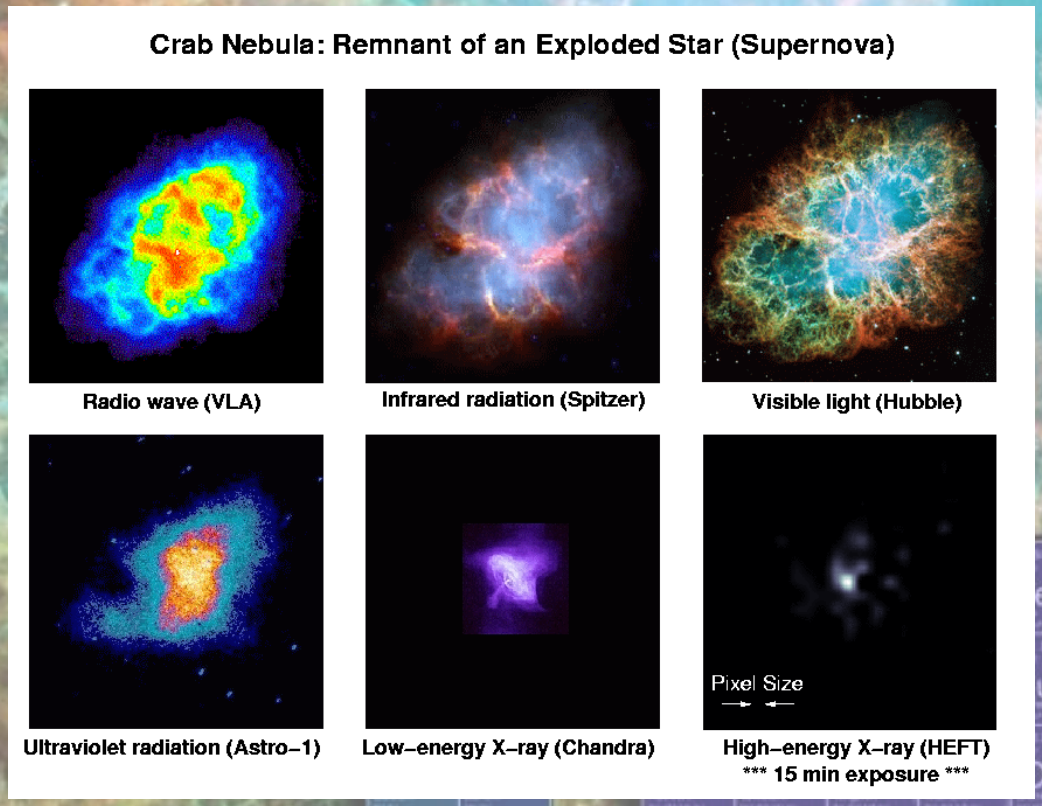
- 4. jula 1054. g. kineski astronomi na istočnom delu neba
- Dostigla -6^{m} (1/4 Meseca)
- naredna 23 dana – videla po danu
- opažena i na drugom kraju sveta – iznad današnjeg Novog Meksika i Arizone, zabeležili je indijanski slikari



“Na dan či-ču, petog meseca prve godine vladavine Či-ho, pojavila se 'gostujuća zvezda' na jugoistoku Tijen-huana, veličine nekoliko palaca. Posle više od godine dana, ona se ugasila” – Toktaga, *Istorija dinastije Sung*

M1 – Maglina Rak (SN1054)

(NGC 1952; Taurus; +8,4 mag; 6300 s.g.)

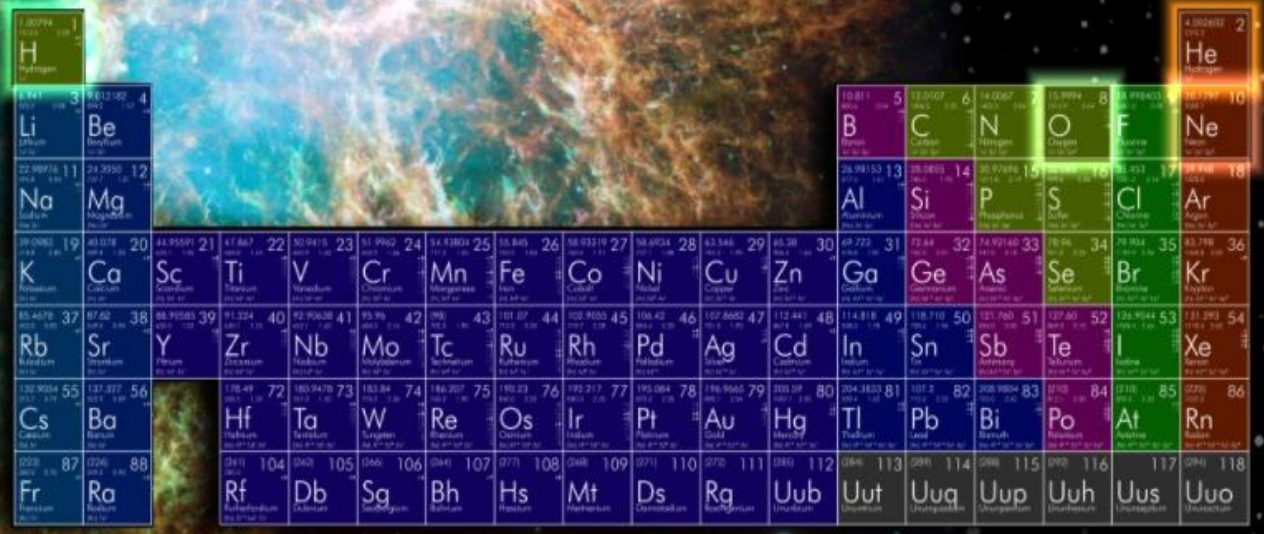


- Daljina 6.300 s.v. god.
- 28. avgust 1758. – Š. Mesije
- maglina 10 s.g. u prečniku, brzina 1800 km/s
- Sjaj -3.2^{m} (1000 x Sunce)
- 1948. – jak radio izvor
- 1964. – izvor X-zraka

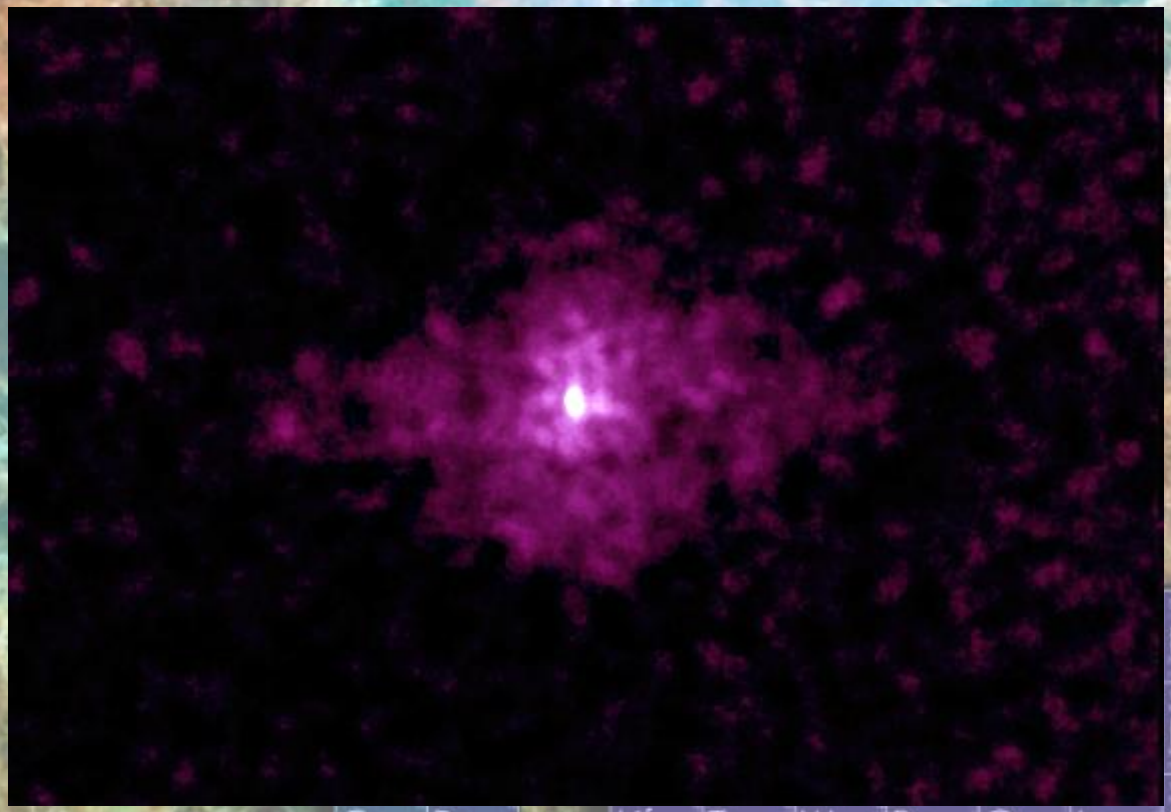
M1 – Maglina Rak (SN1054)

(NGC 1952; Taurus; +8,4 mag; 6300 s.g.)

- X-zračenje oko 100 puta intenzivnije nego VIS
- 1968 - pulsar (NP0532)
- 30 obr/sec – najmlađi pulsar
- mala zvezda, apsolutni sjaj približno kao Sunce

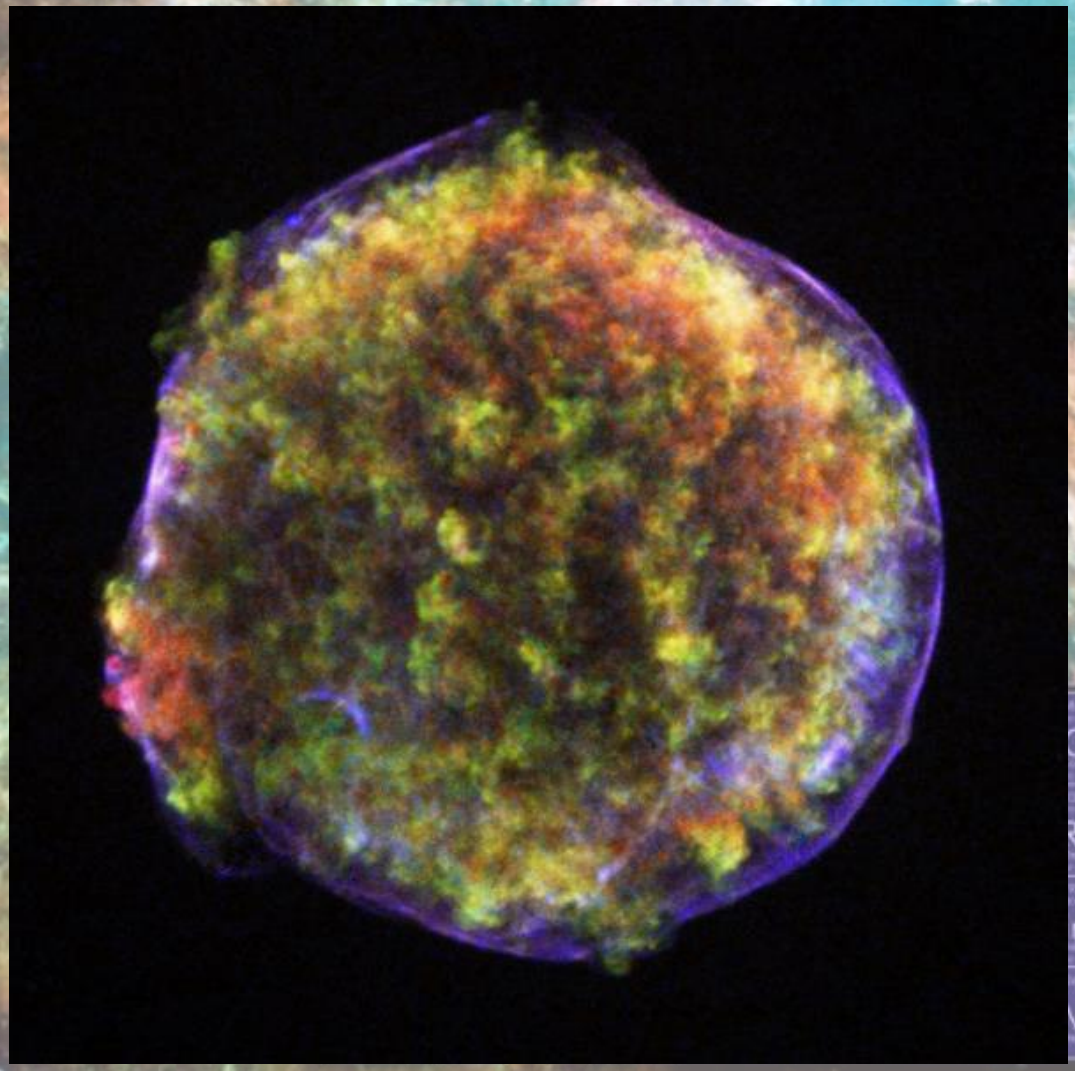


SN 1181



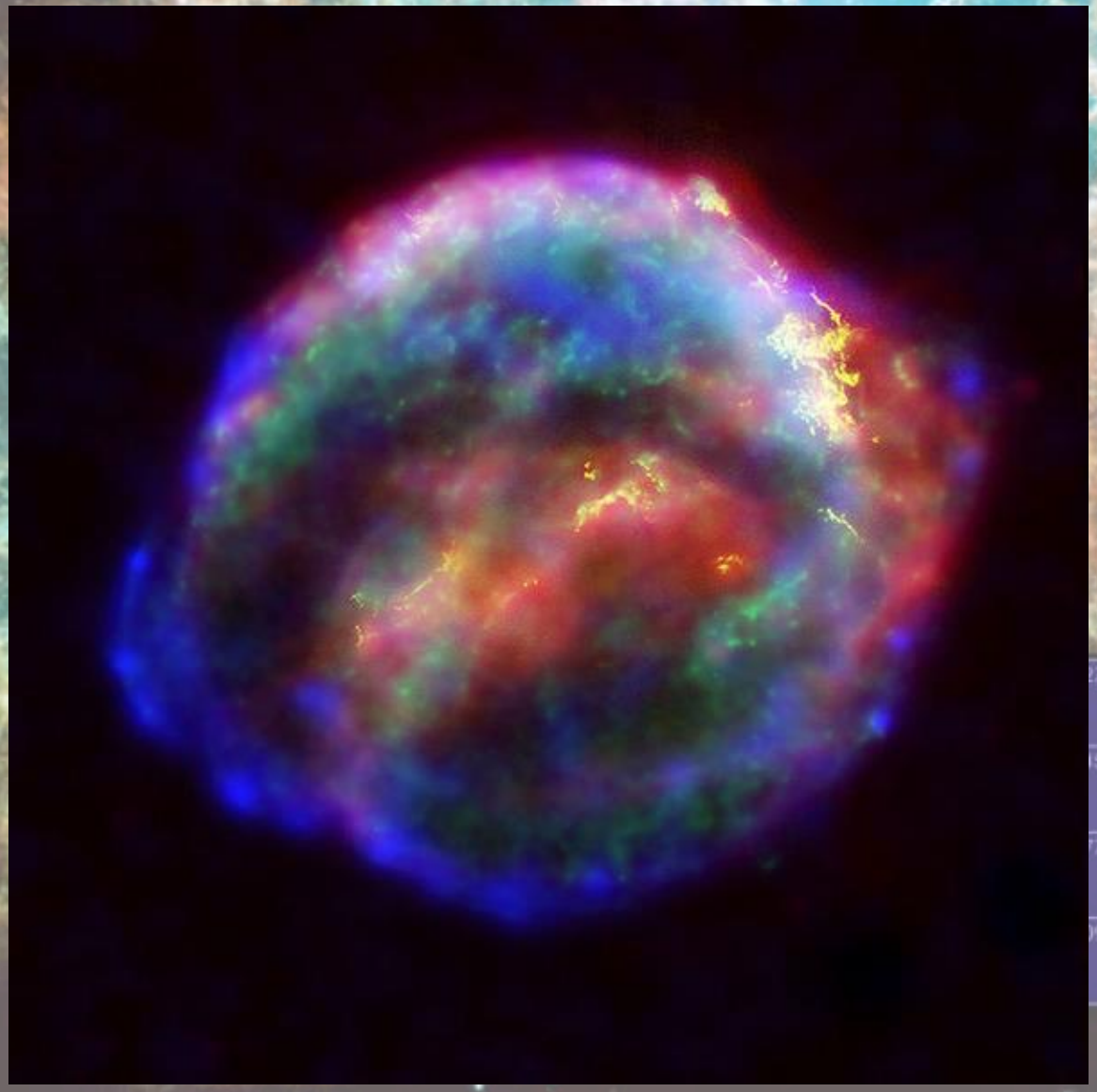
- 4 – 6 avgusta
- Kineski i Japanski astronomi
- Sazvežđe: Cassiopeia
- Vidljiva 185 dana
- Radio izvor 3C58
  - Rotira 15 puta u sec
  - Prva “kvark-zvezda”
- Sjaj supernove: -1^{m}

SN 1572



- 11. novembar
- Tiho Brahe
- Sjajnija od Venere (-4^m)
- Mart 1574 – nevidljiva golim okom
- Mlečni put, Cassiopeia
- Supernova Ia
- Gas – 9000 km/h
- Zvezda – G2
  - “pomogla” nastanku SN
  - 10.000 svetlosnih godina

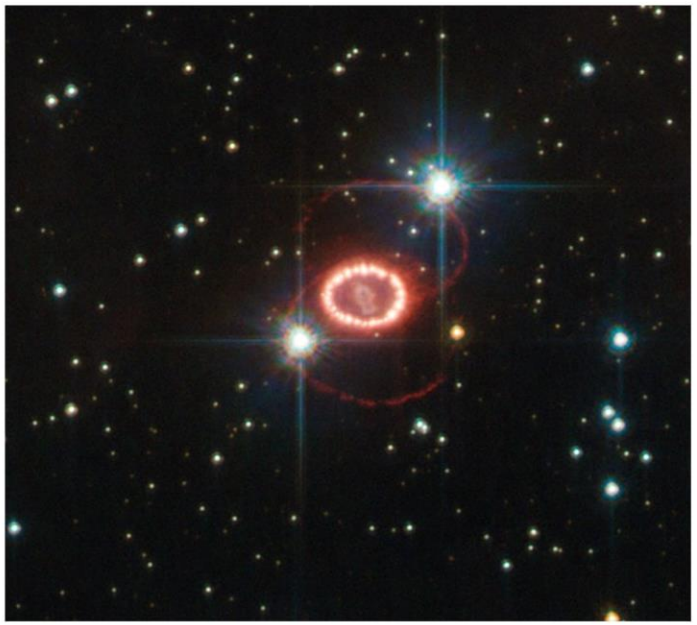
SN 1604



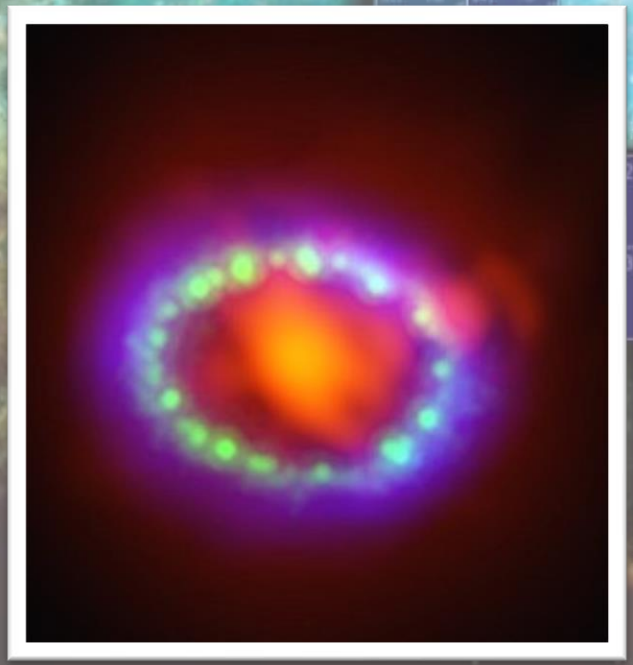
- 9. oktobra 1604
- Keplerova SN (zvezda), 17. oktobar 1604
- 20.000 svetlosnih godina
- Sjajnija od svih planeta osim Venere (-2.5^{m})

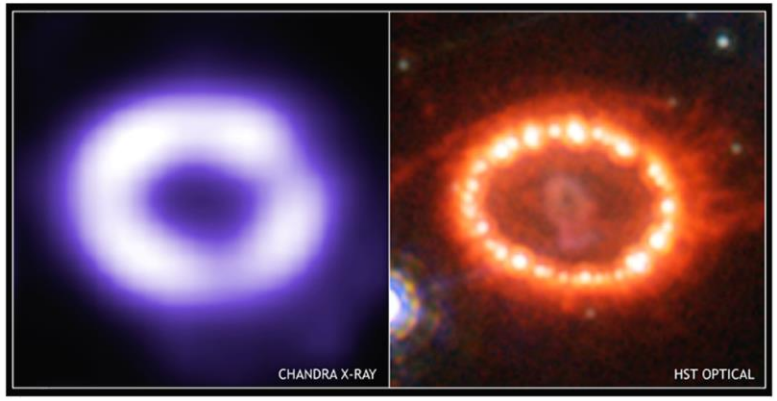
Supernova SN1987A

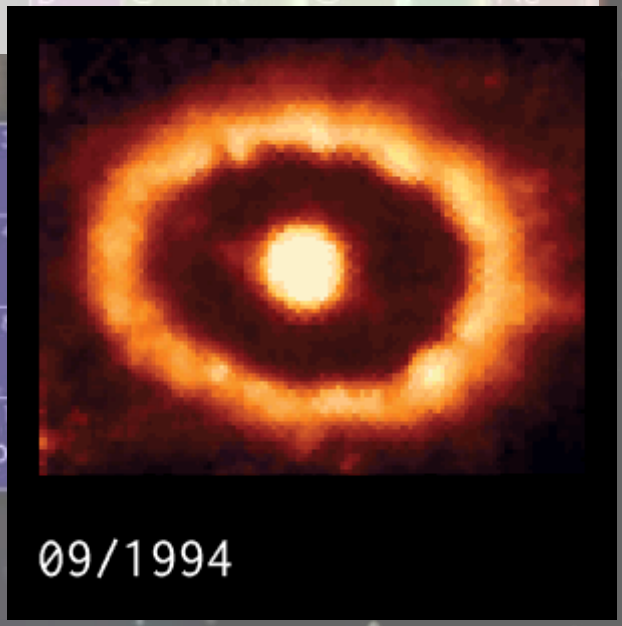
- Noć 23.-24. februar 1987. godine
- Jan Šelton, opservatorija Las Kampanas (čileanski Andi)
- Veliki Magelanov oblak
- Rudnik cinka – Kamioka (Japan)
  - 11 događaja u istoj sekundi
  - Rudnik u Ohaju – istovremeno 6 događaja
  - Verovatnoća nezamislivo mala!
  - Sudar sa neutrinima
- Nekoliko sati kasnije – australijski astronomi prepoznali zvezdu:
  - super-džin B3, 40 puta veći prečnik od Sunca
  - Sanduleak-69202



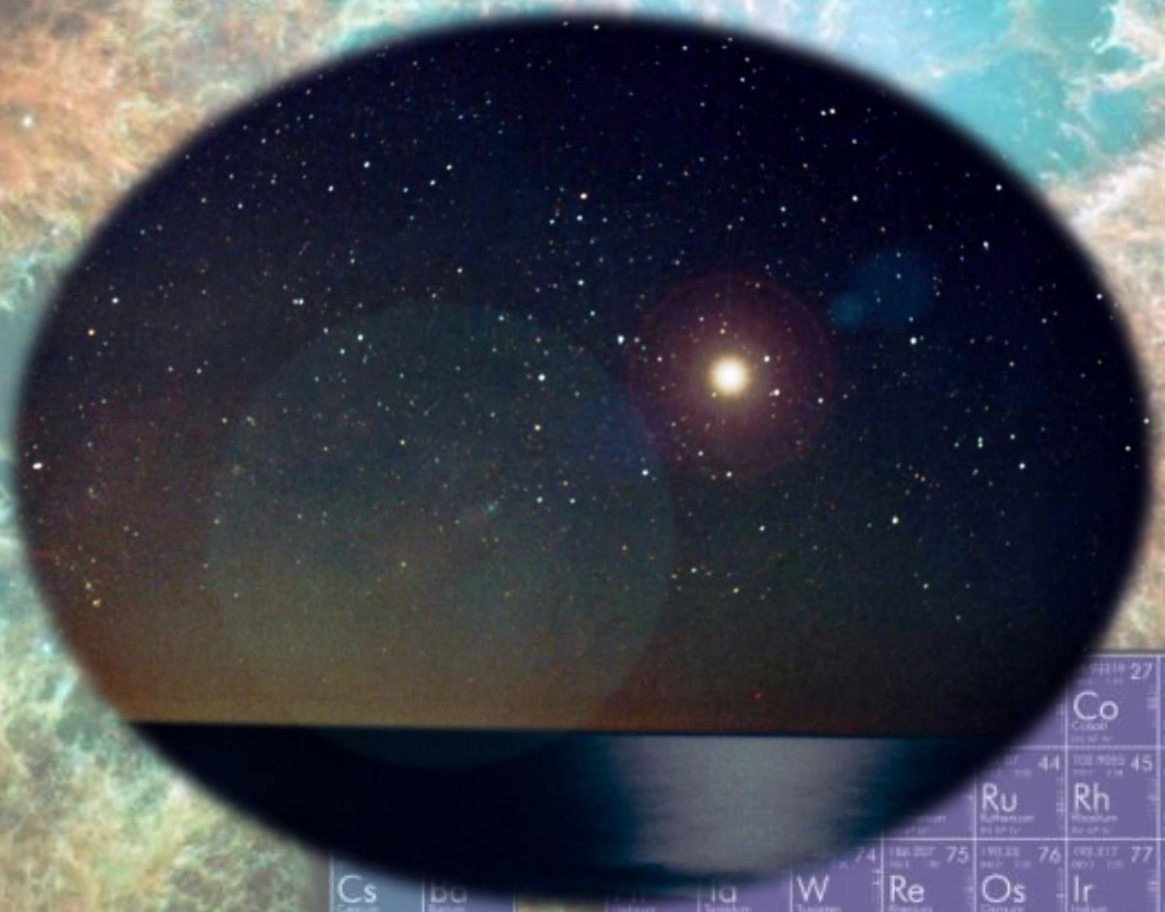
- Daljina 168.000 svetlosnih godina
- Sjaj $+3^m$
- Prva fotografija snimljena HST-om, kraj 1990. god
- Tri prstena
- 2001 – izbačeni materijal „udario“ prvi prsten; jaka emisija X zračenja (3 puta veći fluks, 2001-2009)
- HST i VLT (fotografije 1994-2014) – sjaj bledi, udarni talas uništio prsten. Izbledeće 2020-2030.





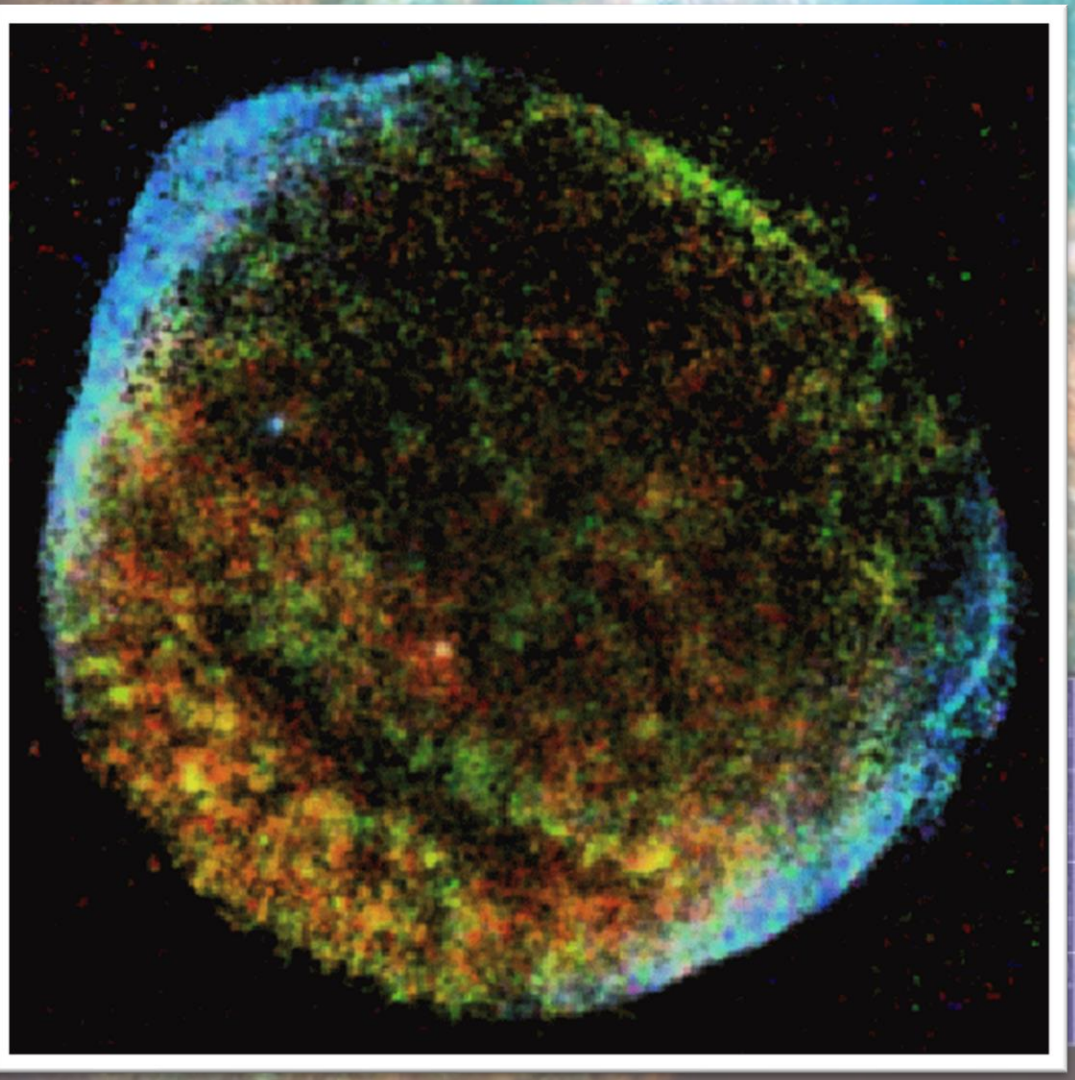


SN1006



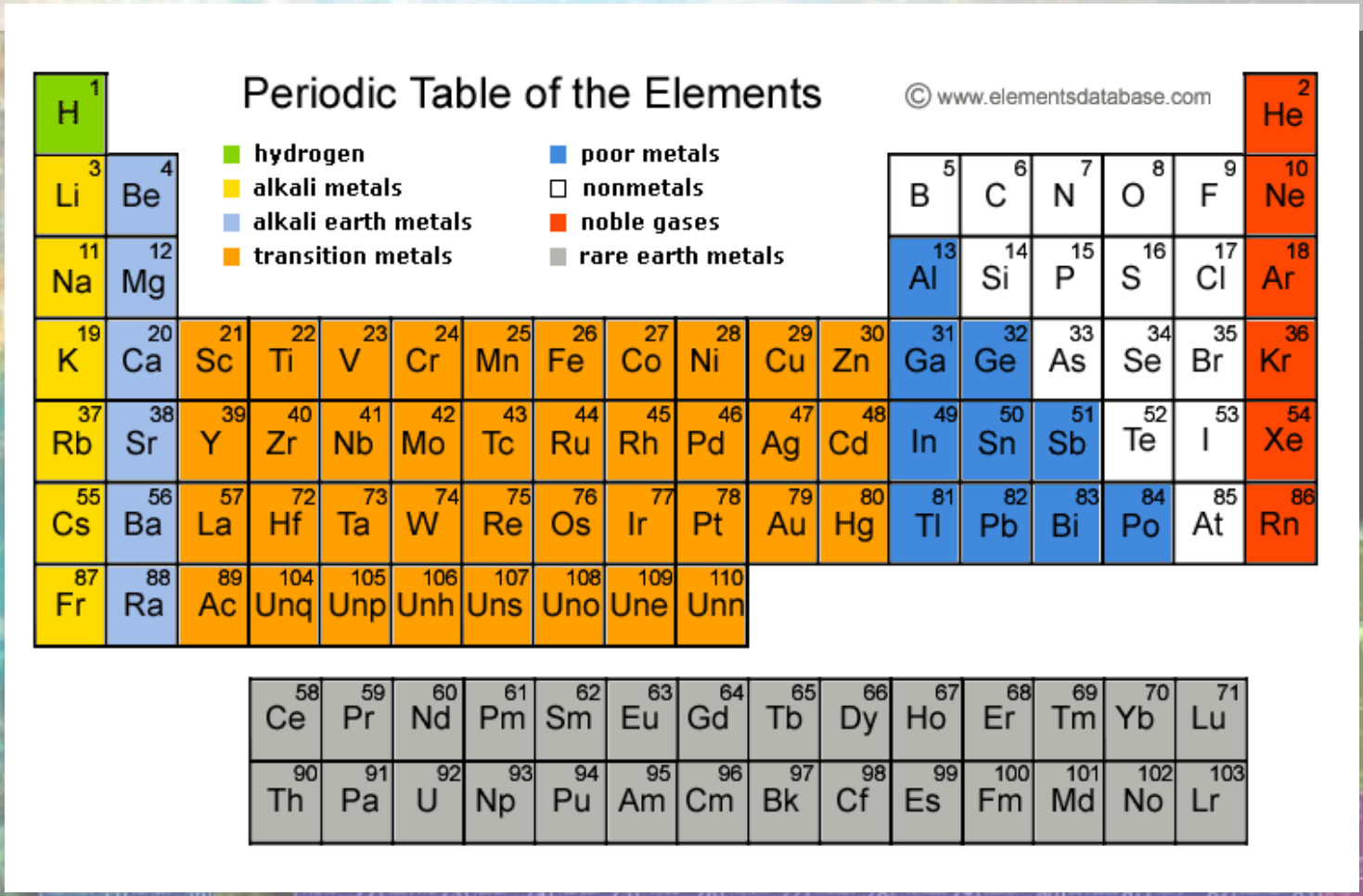
- Najsjajniji događaj u istoriji
- 1. maj 1006. godine
- Švajcarska, Egipat, Irak, Kina, Japan, S. Amerika
- Egipatski astrolog Ali bin Ridwan
  - 2.5-3 puta veći disk od Venere
  - ¼ sjaja Meseca
- Supernova tipa Ia
- Neki izvori - senka

SN 1006



- Sjaj -7.5^{m}
- U centru – pulsar ili crna rupa – nepoznato
- Oblak – 2.800 km/h

Elementi „iza“ gvožđa?



- **Prvih 81** – stabilni, nalaze na Zemlji, izgrađuju većinu objekata u vasioni
- **Sledeći…** – radioaktivno, nalaze na Zemlji, dug period poluraspada (milion ili milijardu godina); prilično retki, nisu zabeleženi na drugim zvezdama
- **Poslednji** – radioaktivni, samo veštački, mnogo kraći period poluraspada

Elementi teži od gvožđa

- Zahvat neutrona
- Neutroni – sporedni produkti nuklearnih reakcija
- Nemaju naelektrisanje – nema odbojnih sila
- „Spajanje“ sa gvožđem → izotop veće mase
- *S*-proces (*slow neutron capture*)
  - Jezgro postaje nestabilno, raspada se

    $^{56}Fe + n \rightarrow {}^{57}Fe$

    $^{57}Fe + n \rightarrow {}^{58}Fe$

    $^{58}Fe + n \rightarrow {}^{59}Fe$

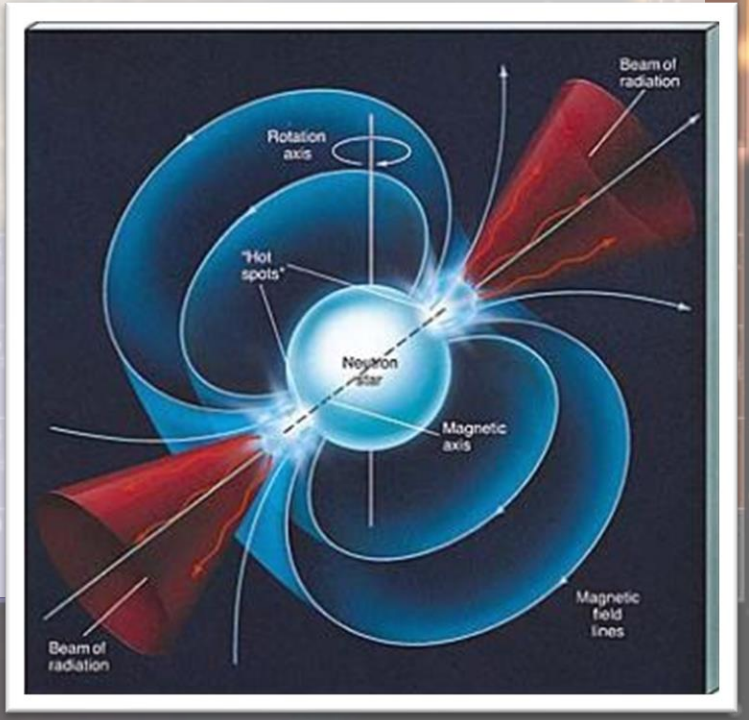
  - *^{59}Fe – radioaktivno, raspada se na kobalt-59, stabilan*
  - Svaki uspešan zahvat – oko godinu dana, nestabilna jezgra imaju dovoljno vremena da pređu u stabilna
  - Nastali: olovo, bakar, srebro, zlato

Najteži elementi

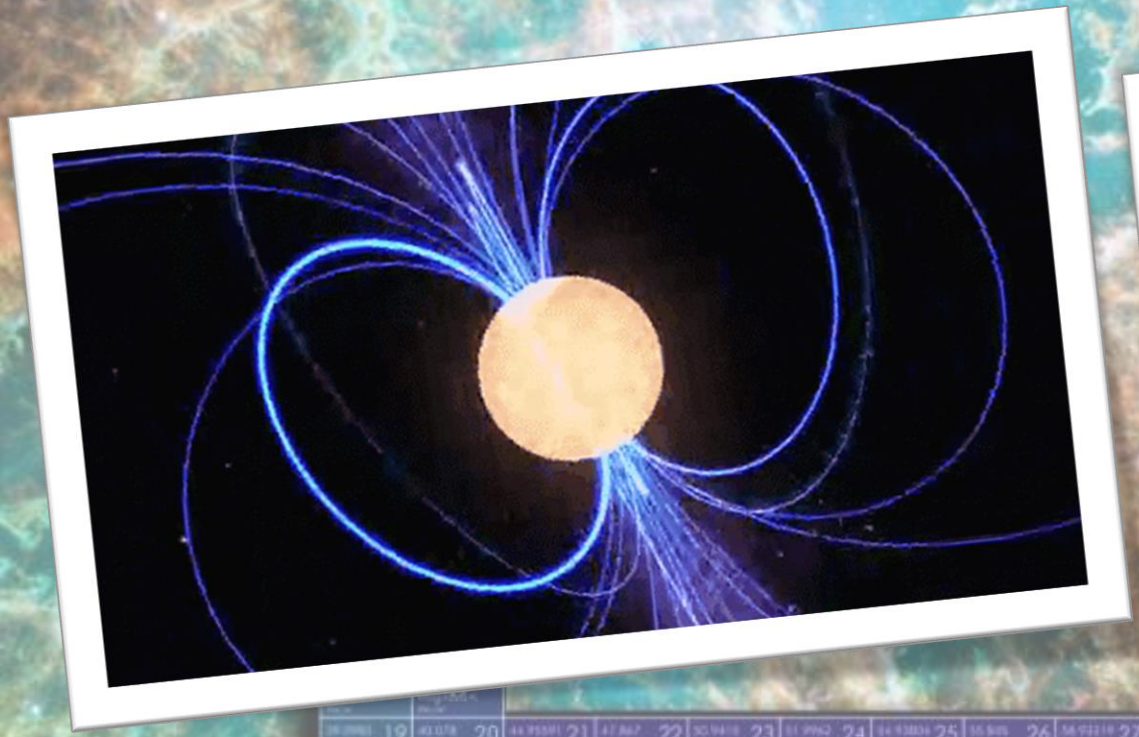
- S-proces – do bizmuta-209 (najteži neradioaktivan element)
- Ne može torijum, uran, plutonijum
- S-proces nemoguć – novo jezgro raspada za kraće vreme nego što je potrebno za nastanak
- *r*-proces (*rapid*)
  - prvih 15 minuta eksplozije, broj slobodnih neutrona raste
- Stopa zahvata neutrona – velika
- Najteži elementi nastaju nakon smrti matične zvezde
- Rasprostranjenost oko milijardu puta manja nego vodonika i helijuma

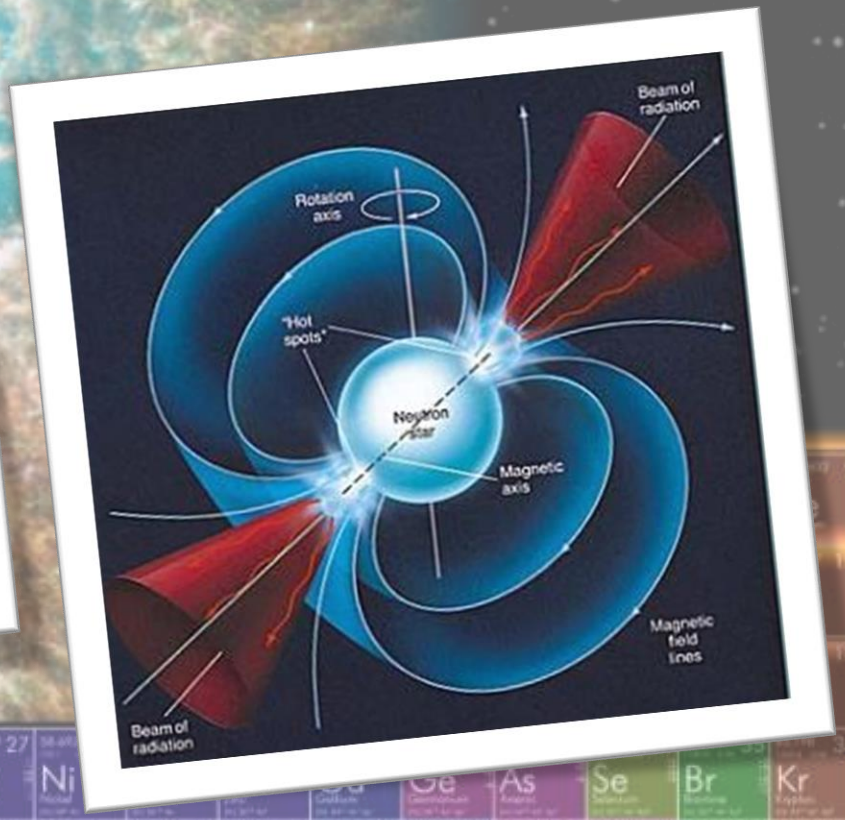
Neutronska zvezda

- “Pritisak” neutrona
- Uvećana verzija belog patuljka
- Beli patuljak 10.000 km, neutronska zvezda 30 km.
- Kašičica materijala – 40 milijardi tona



Pulsari

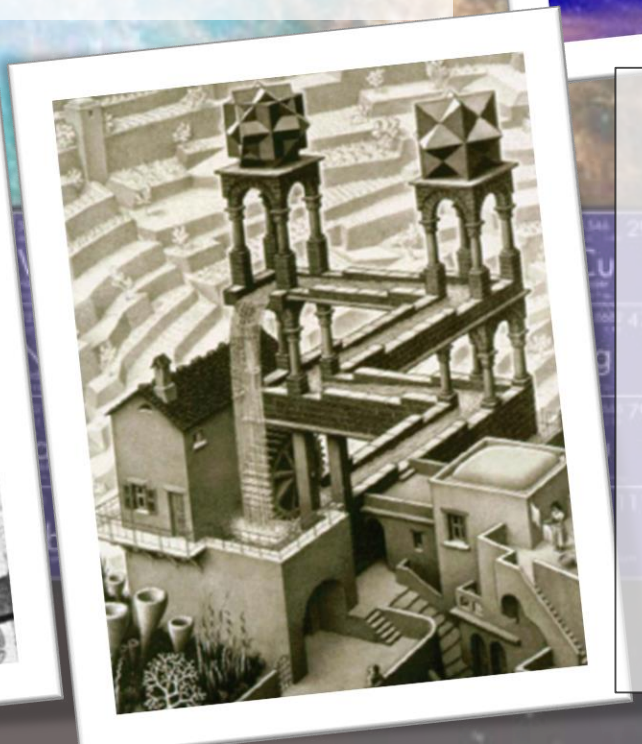




- 1967. godina → LGM1 → pulsari
- LGM – *Little Green Man*

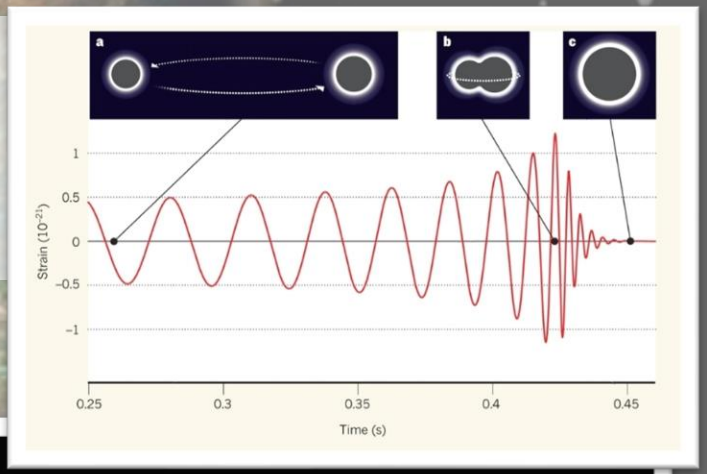
Crne rupe

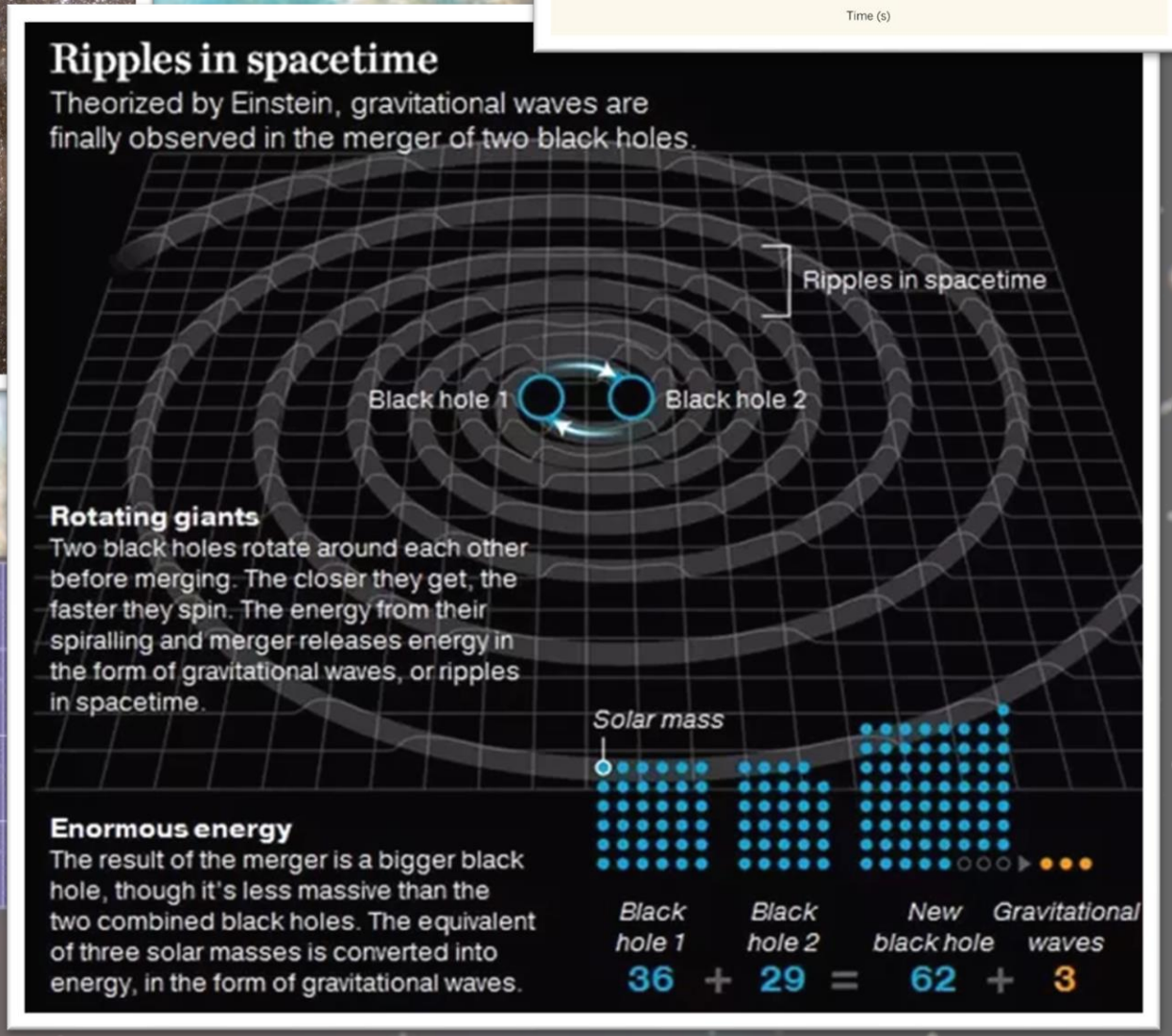
- Neutronske zvezde – do 2,5 solarne mase
- Jedno od najznačajnijih teorijskih otkrića XX veka
- 40-50 puta veća masa



- Maurits Cornelis Escher (1898-1972)
- Relativity, 1953.
- Waterfall, 1961.

Sudar dve crne rupe…



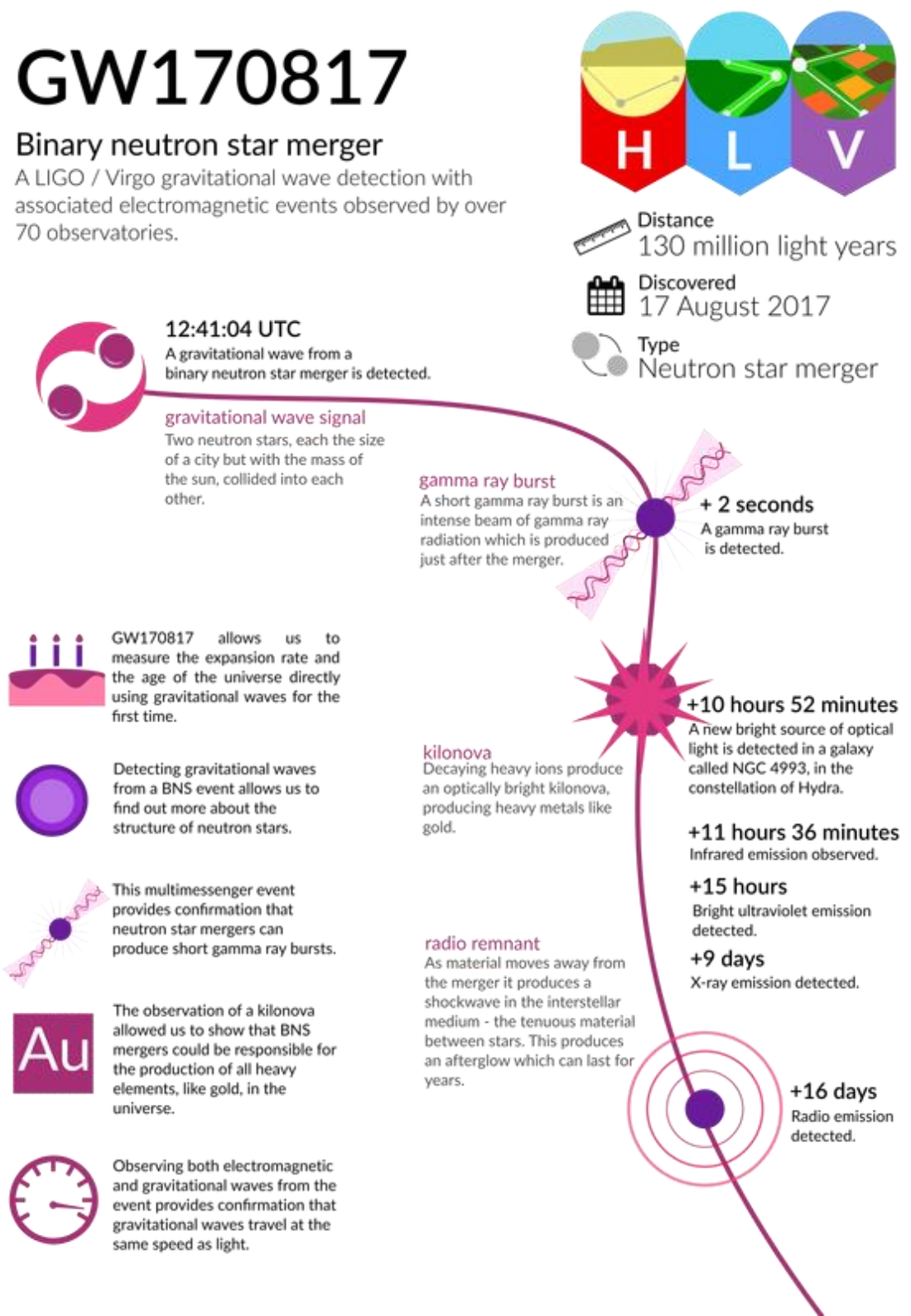


… gravitacioni talasi!

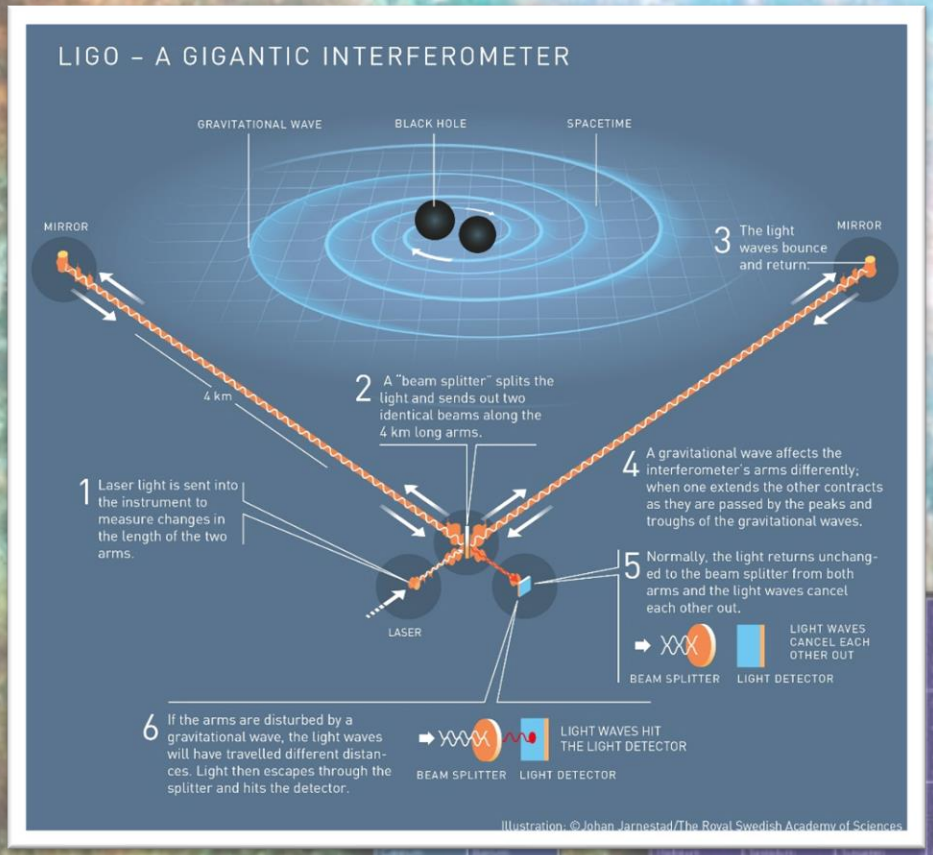
GW150914

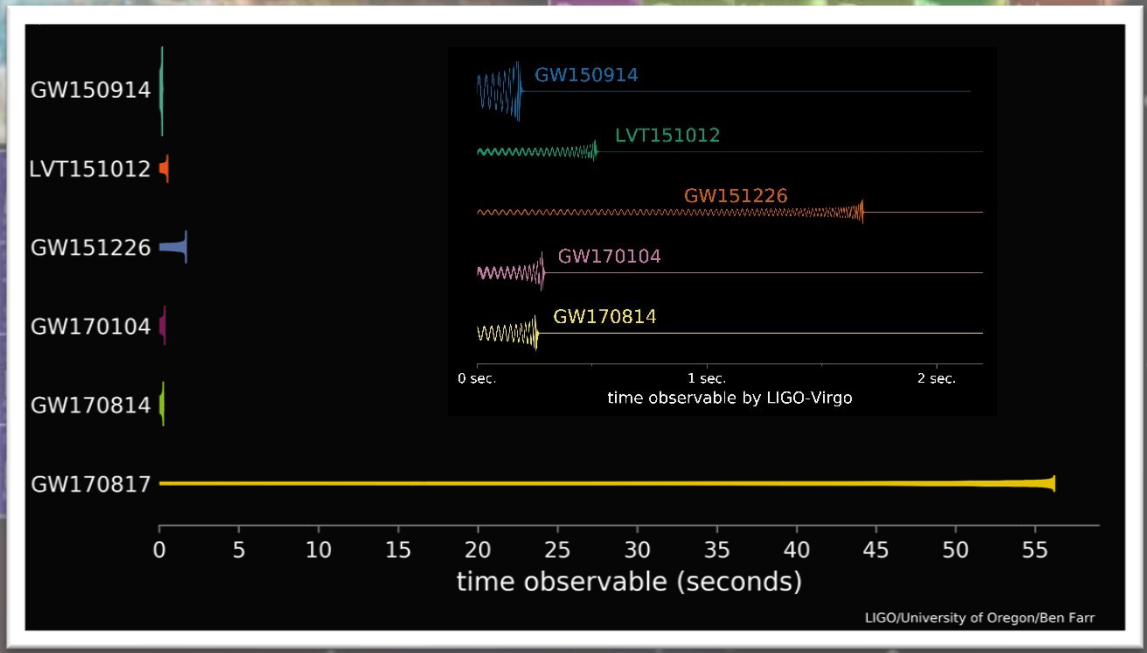
Sudar dve neutronske zvezde

- Gravitacioni talasi
  - GW170817
  - GW170814
  - GW170104
  - GW151226
  - GW150914
- Nobelova nagrada iz fizike za 2017. godinu



Gravitacioni talasi





http://www.ligo.org/detections/GW170817.php

Svaki atom na Zemlji...

... nekada je bio deo jedne zaboravljene zvezde!