

# Všechno jednou končí aneb zánik hvězd

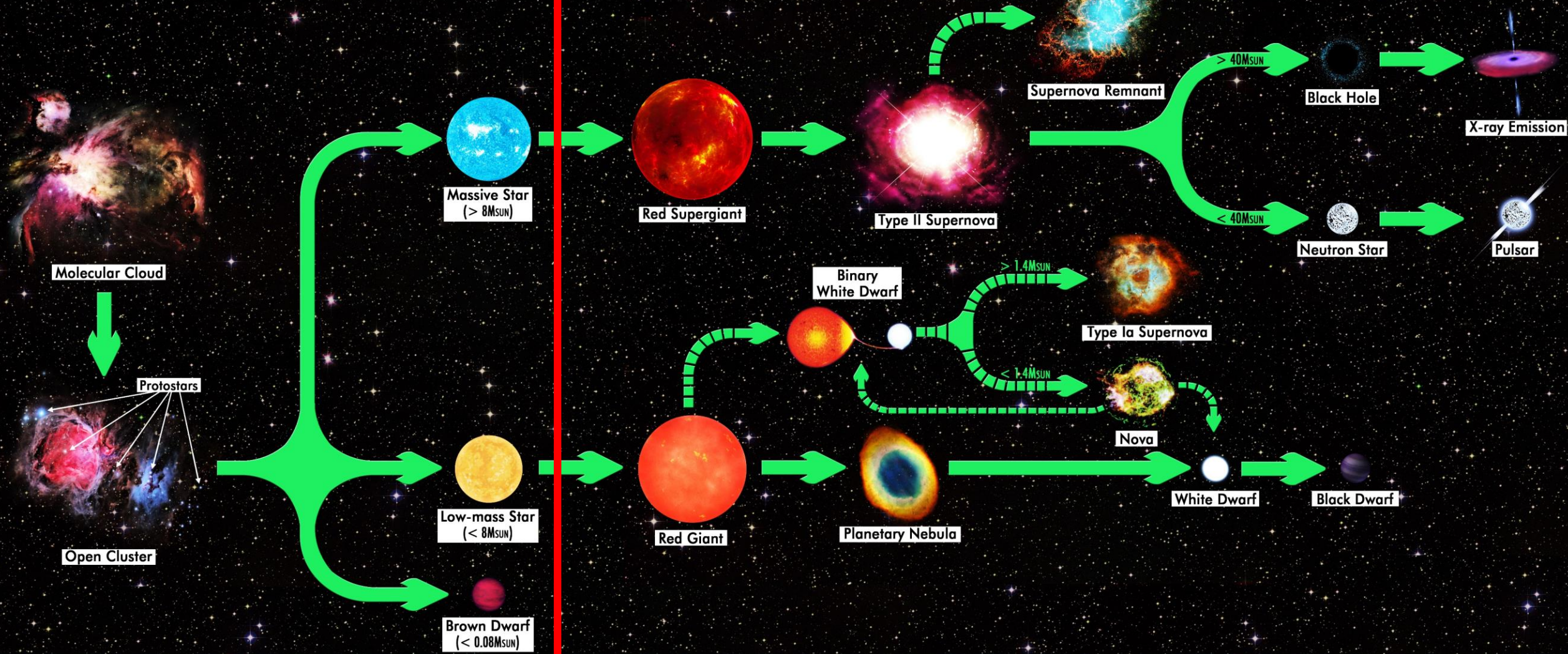
Ing. Petr Dvořák, Ph.D.

[petr.dvorak@ceitec.vutbr.cz](mailto:petr.dvorak@ceitec.vutbr.cz)

16. listopadu 2021, Astronomie aneb jak žijí hvězdy, U3V, Brno

Obsah naší přednášky

# STELLAR LIFE CYCLE



Birth

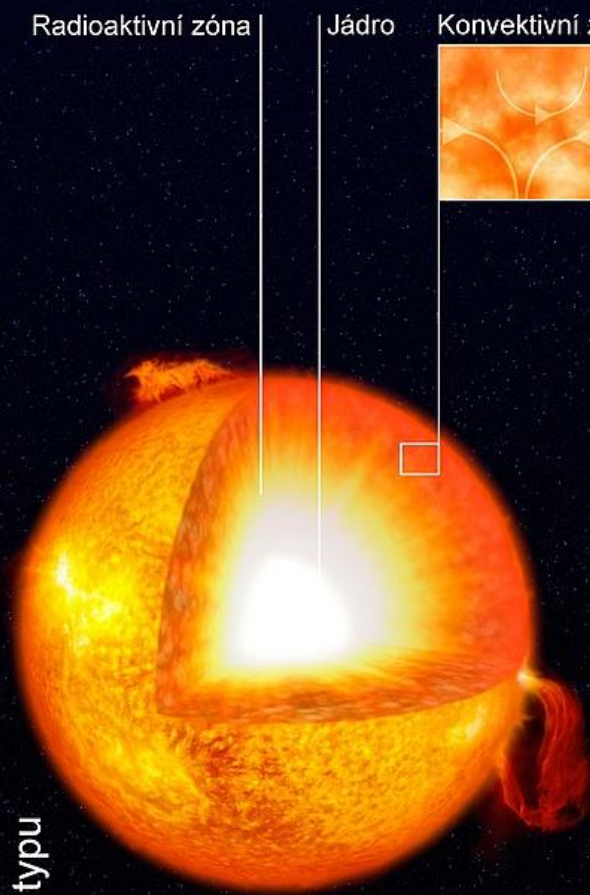
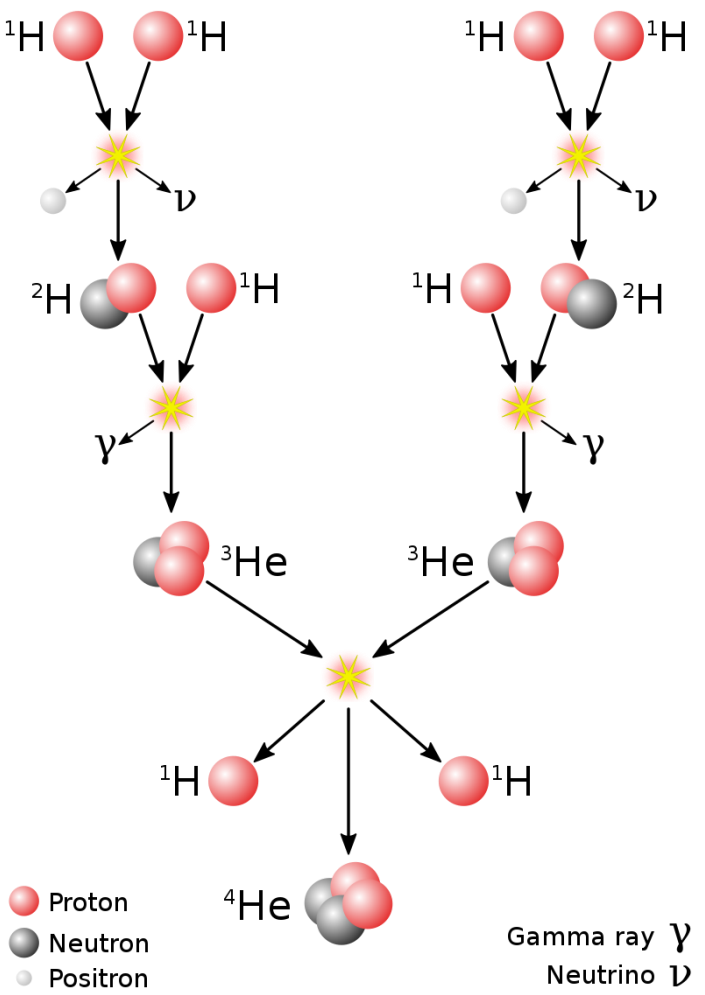
Main Sequence

Old Age

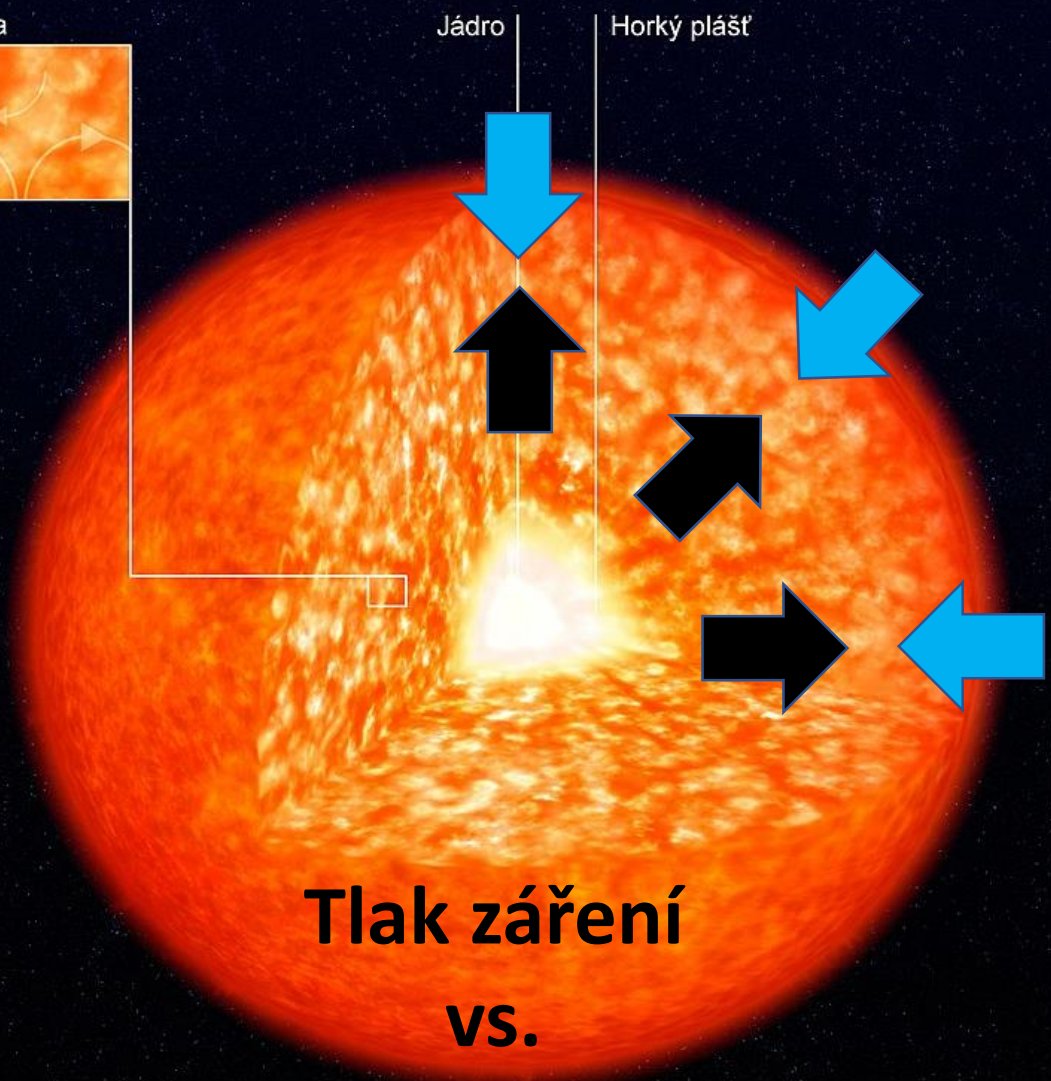
Death

Remnant

# Hvězdy (připomenutí)



Hvězda slunečního typu



Rudý obr

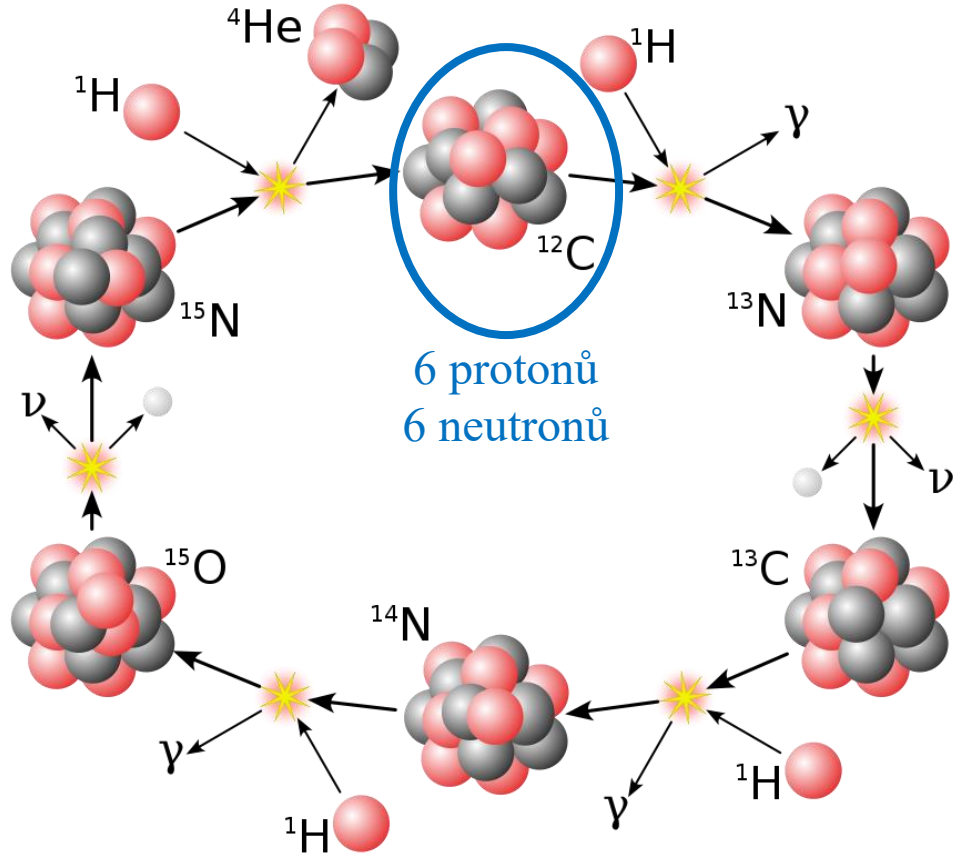


Měřítko → 200 poloměrů Země

Energy Production in Stars\*

H. A. BETHE  
 Cornell University, Ithaca, New York  
 (Received September 7, 1938)

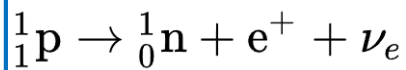
CNO cyklus



- Proton
- Neutron
- Positron

Gamma ray  $\gamma$   
 Neutrino  $\nu$

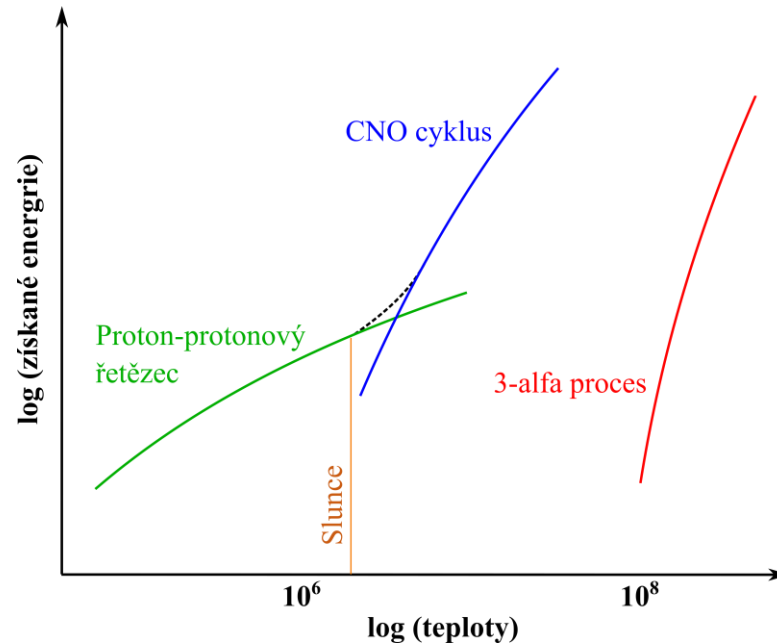
Beta rozpad (plus)



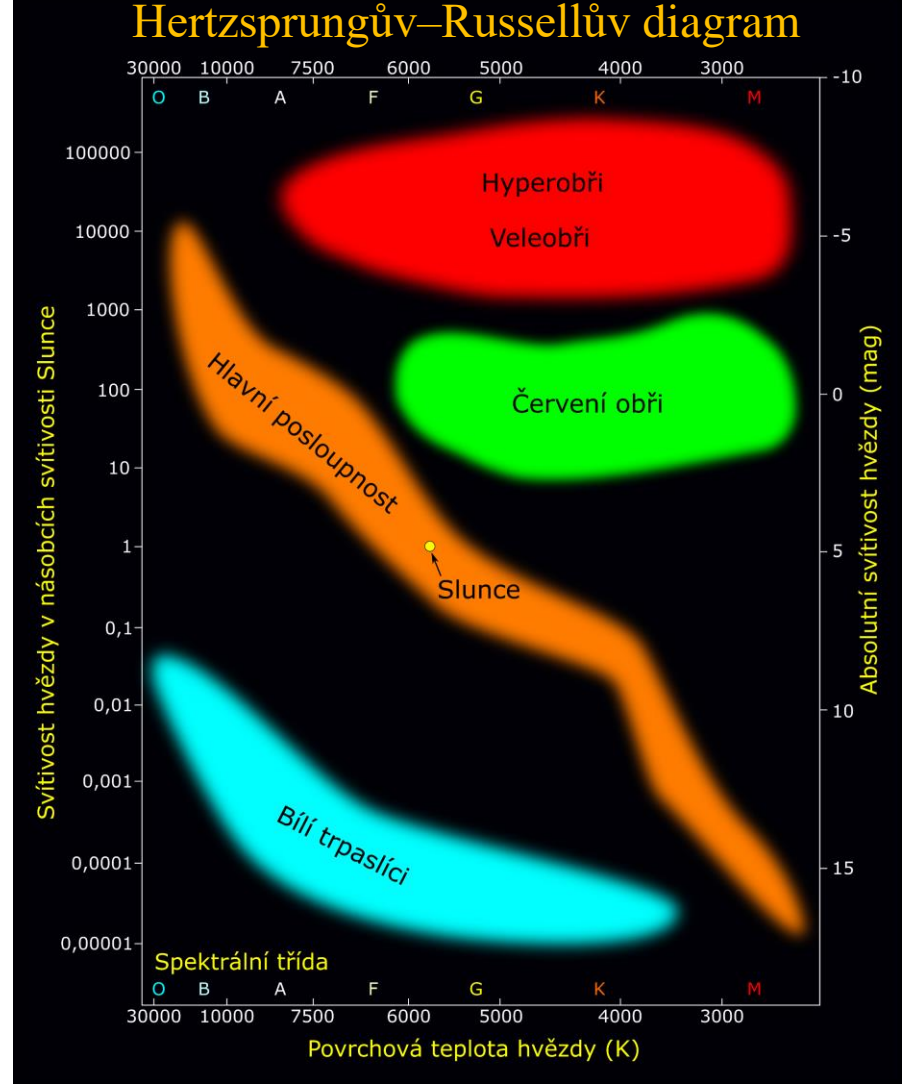
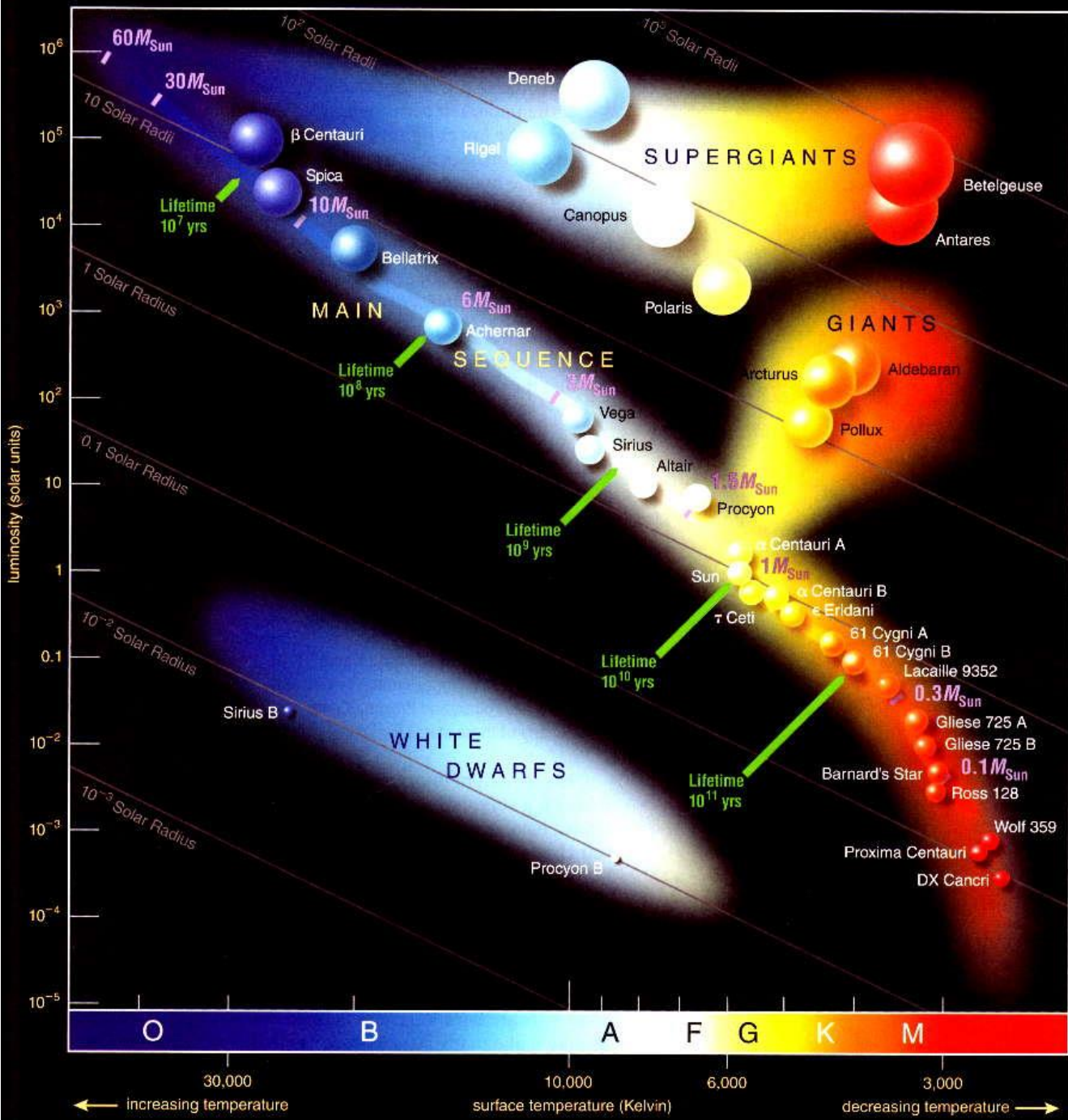
It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced, viz.  $\text{C}^{12} + \text{H} = \text{N}^{13}$ ,  $\text{N}^{13} = \text{C}^{13} + e^+$ ,  $\text{C}^{13} + \text{H} = \text{N}^{14}$ ,  $\text{N}^{14} + \text{H} = \text{O}^{15}$ ,  $\text{O}^{15} = \text{N}^{15} + e^+$ ,  $\text{N}^{15} + \text{H} = \text{C}^{12} + \text{He}^4$ . Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an  $\alpha$ -particle (§7).

integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

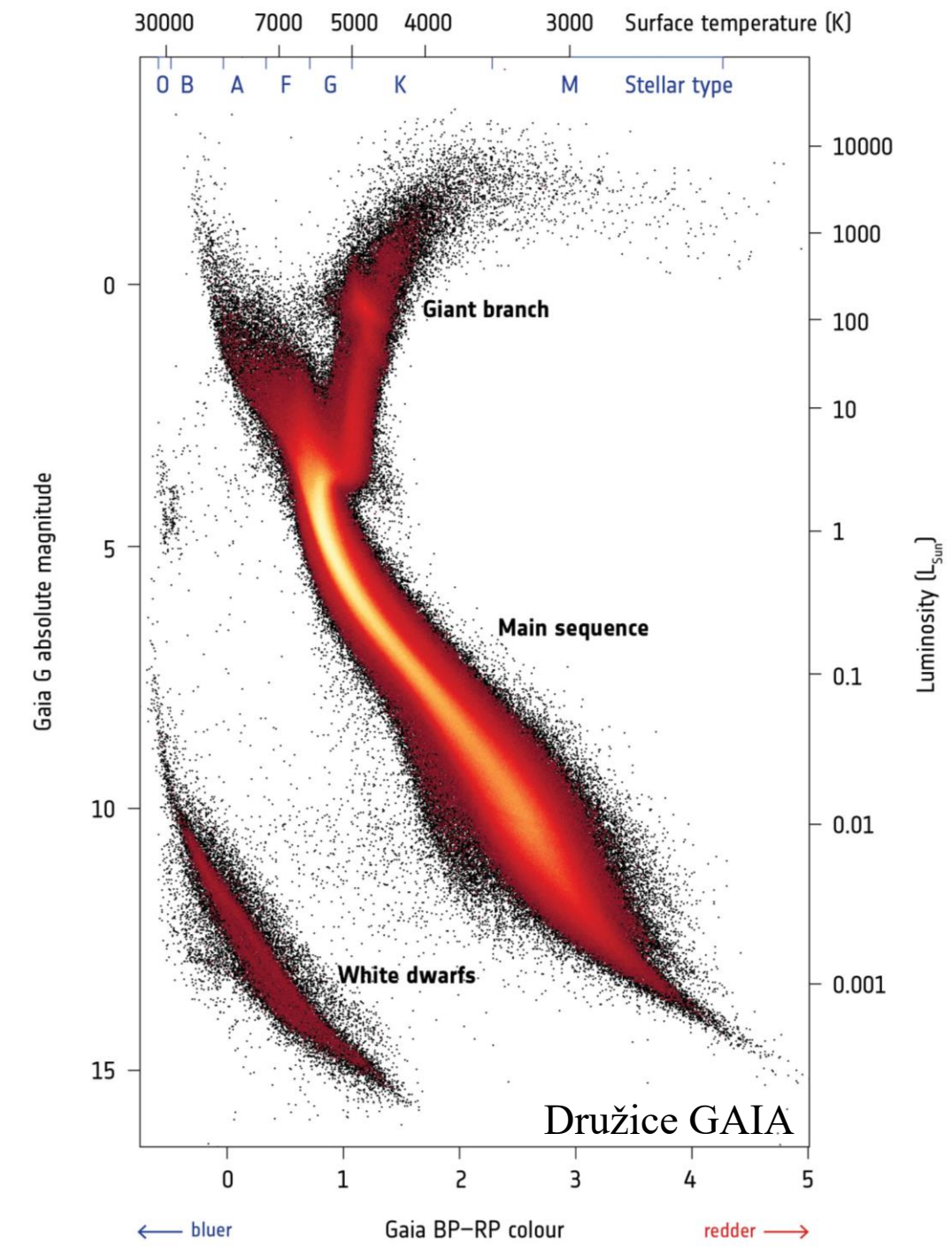
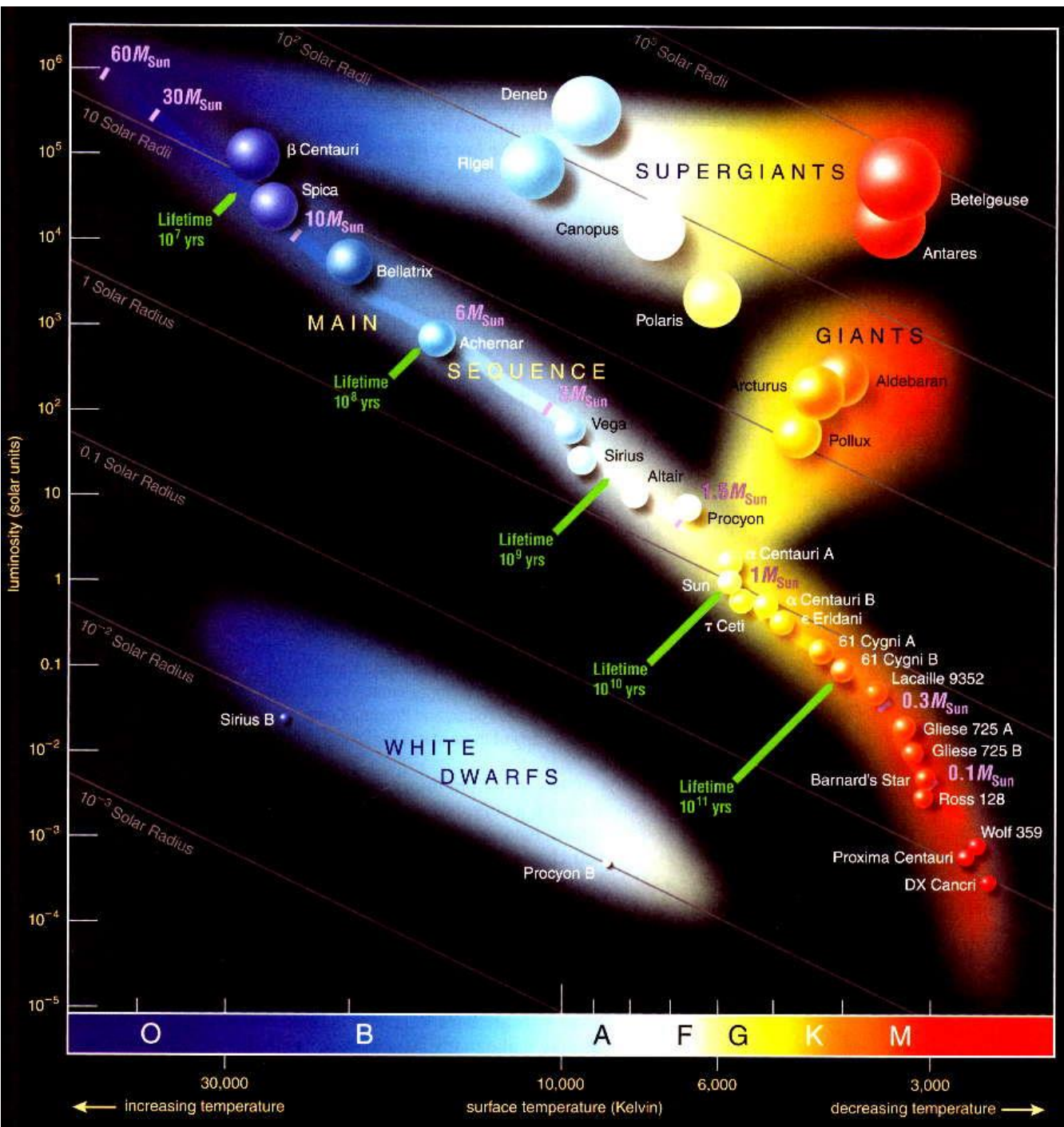
For fainter stars, with lower central temperatures, the reaction  $\text{H} + \text{H} = \text{D} + e^+$  and the reactions following it, are believed to be mainly responsible for the energy production. (§10)



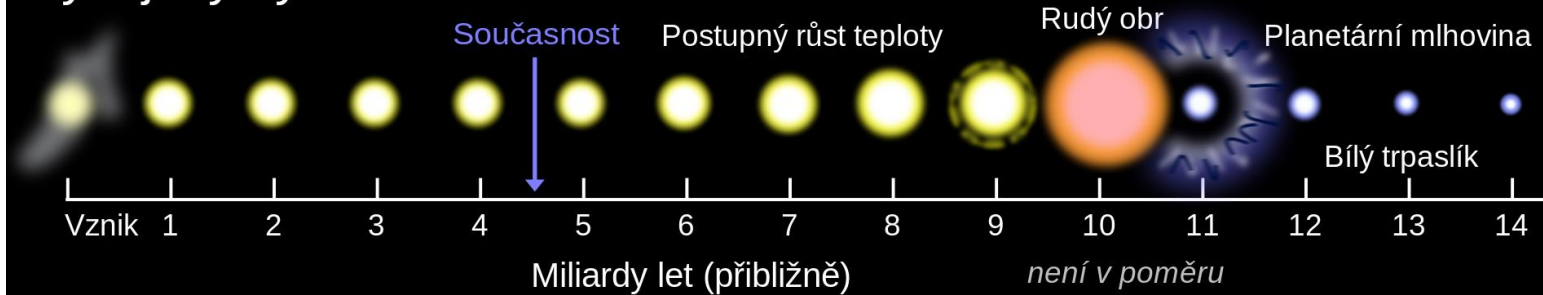
Hans Albrecht Bethe  
 (1906 – 2005)



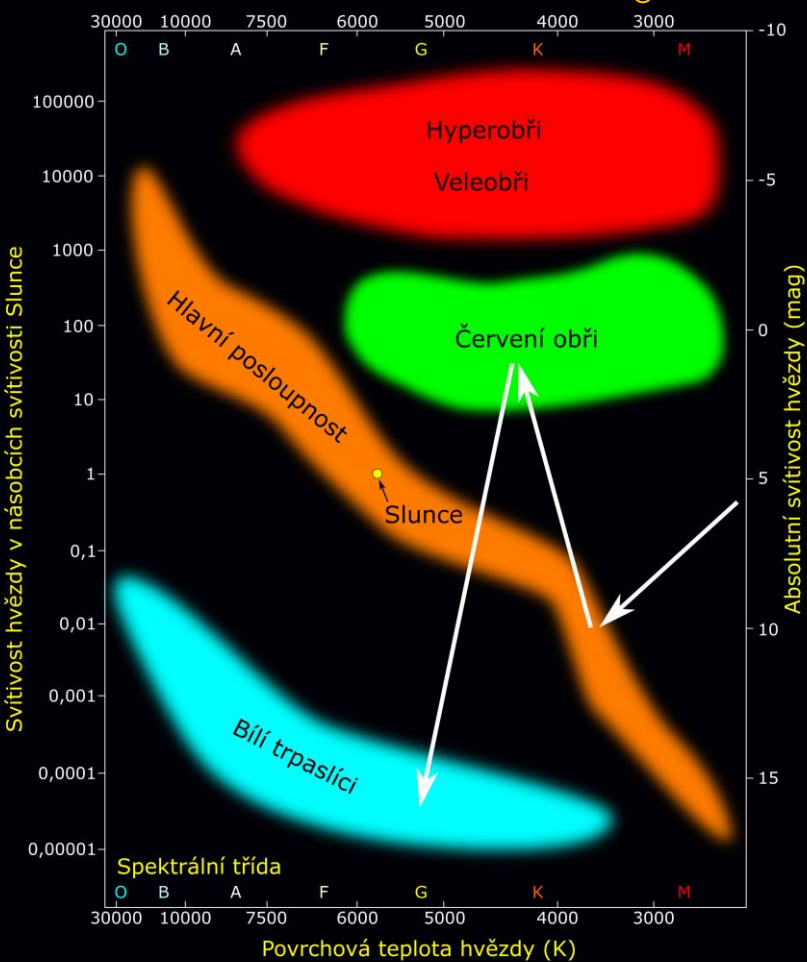
Hmotnost hvězdy (hmotností Slunce)	Délka života (let)	Spektrální typ
60	3 milióny	O3
30	11 miliónů	O7
10	31 miliónů	B4
3	370 miliónů	A5
1,5	3 miliardy	F5
1	10 miliard	G2
0,1	1 bilión	M7



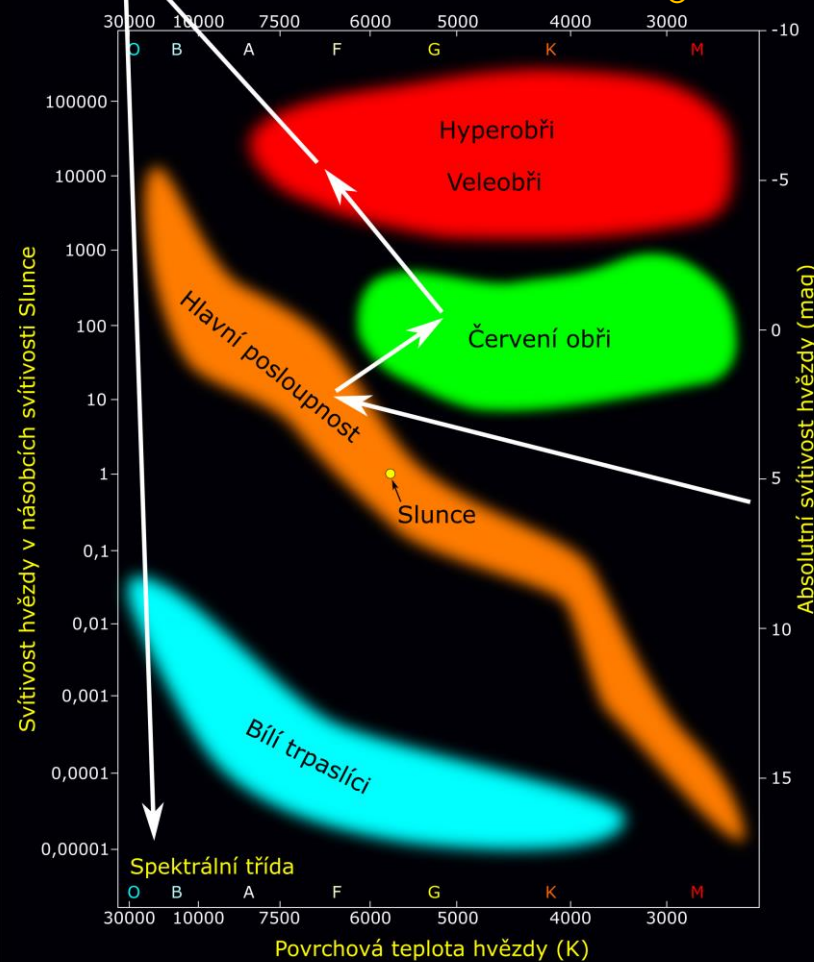
# Vývojový cyklus Slunce



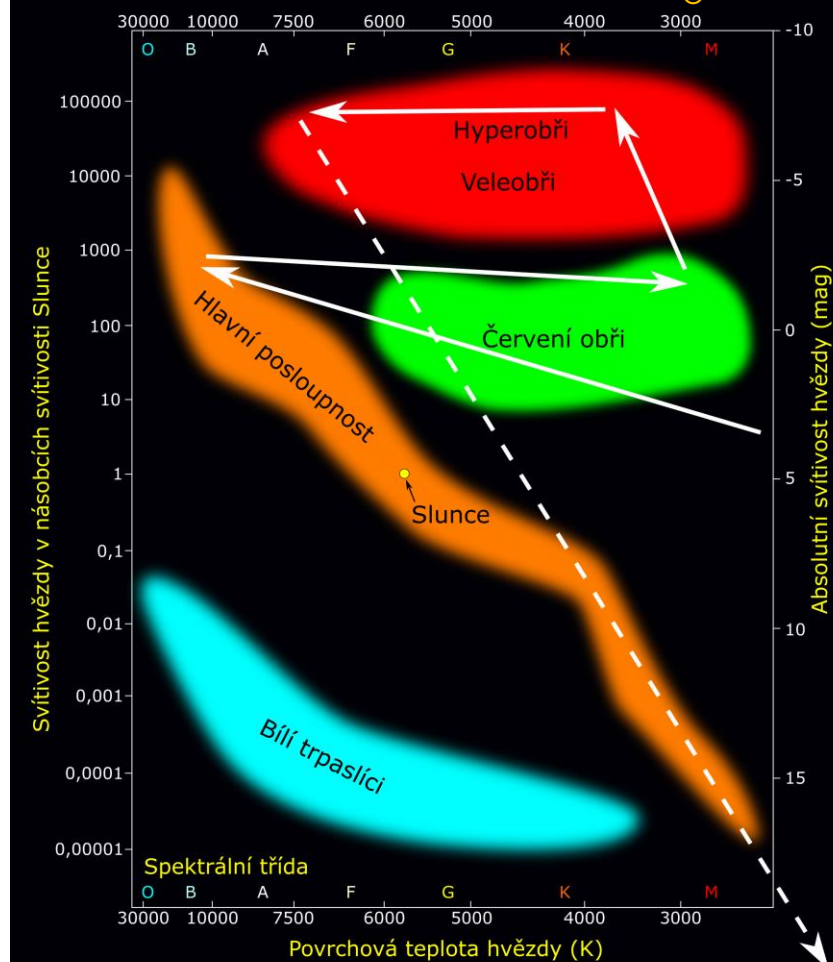
## Hmotnost hvězd do $8M_{\odot}$



## Hmotnost hvězd nad $8M_{\odot}$



## Hmotnost hvězd nad $40M_{\odot}$



# Hvězdy s hmotností $0,6 - 8M_{\odot}$

Degenerovaný (elektronový) plyn



Vlivem teploty nafouknutí obalu  
Červený obr



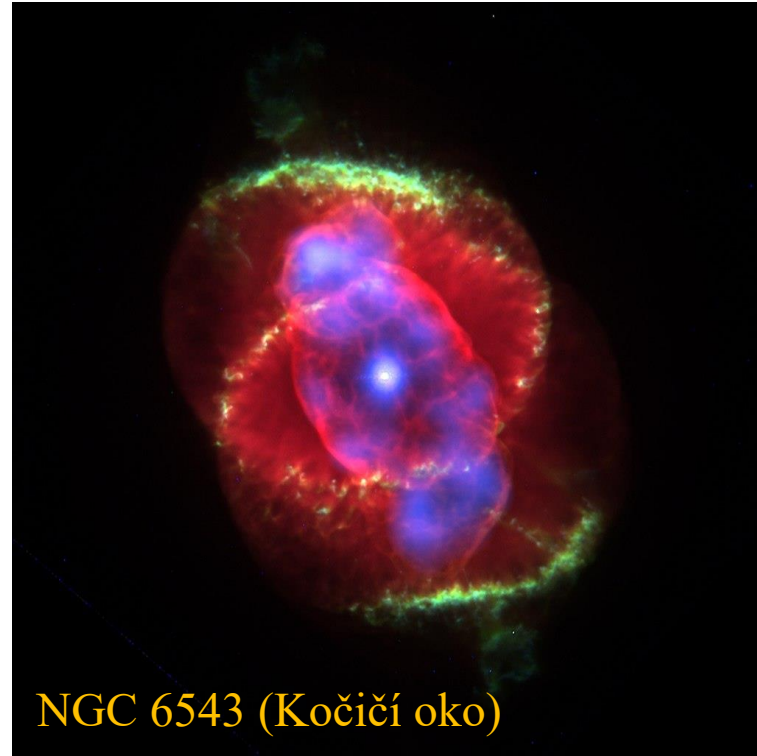
Jádro  $T \sim 10^8$  K



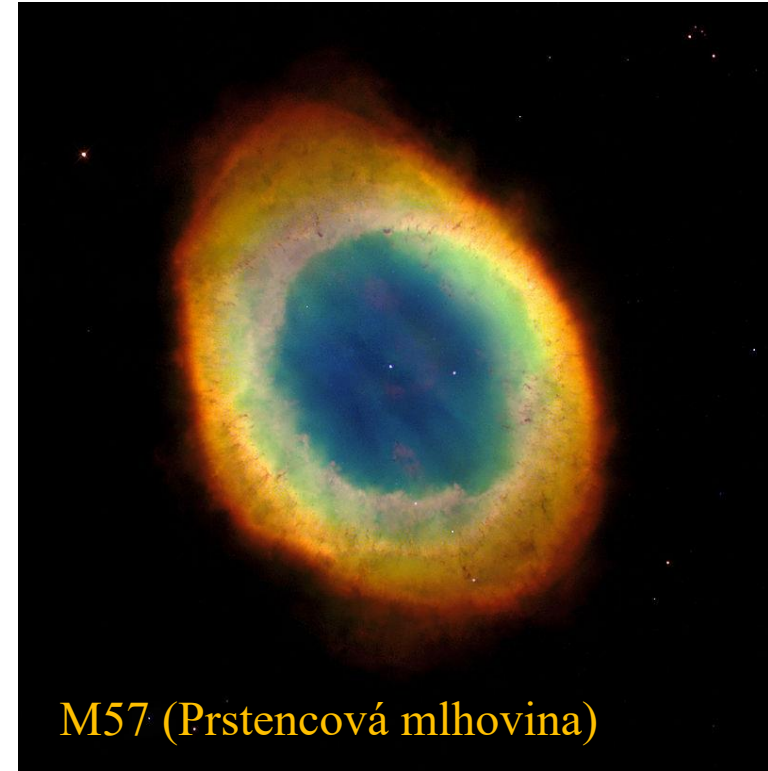
Heliový záblesk a slučování hélia



Bílý trpaslík a planetární mlhovina

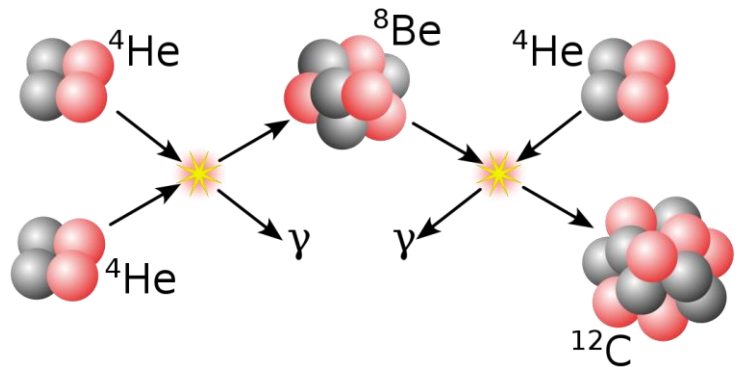


NGC 6543 (Kočičí oko)



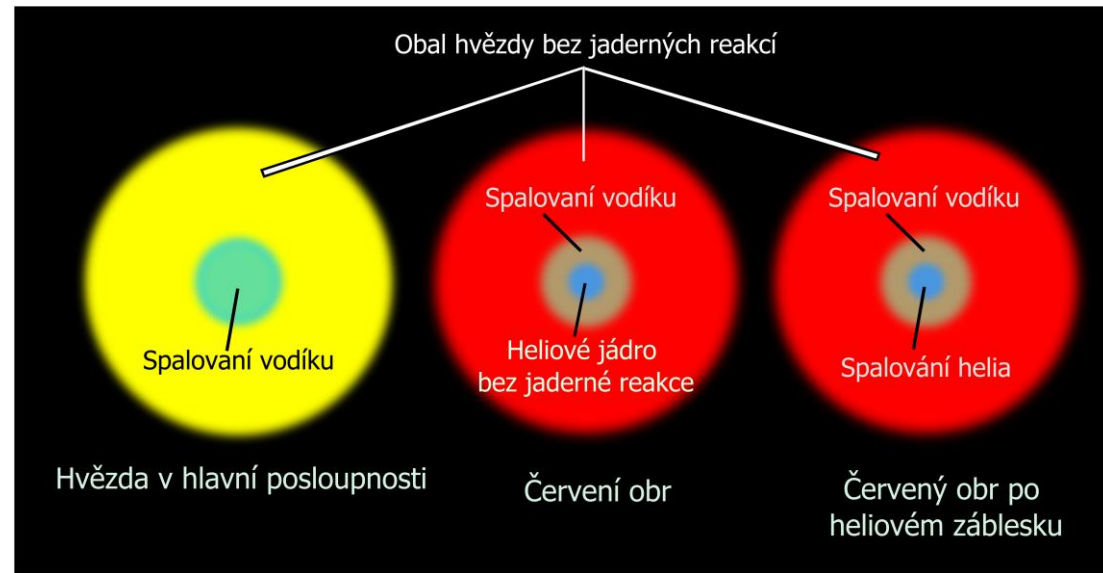
M57 (Prstencová mlhovina)

## 3-alfa proces



● Proton  
● Neutron

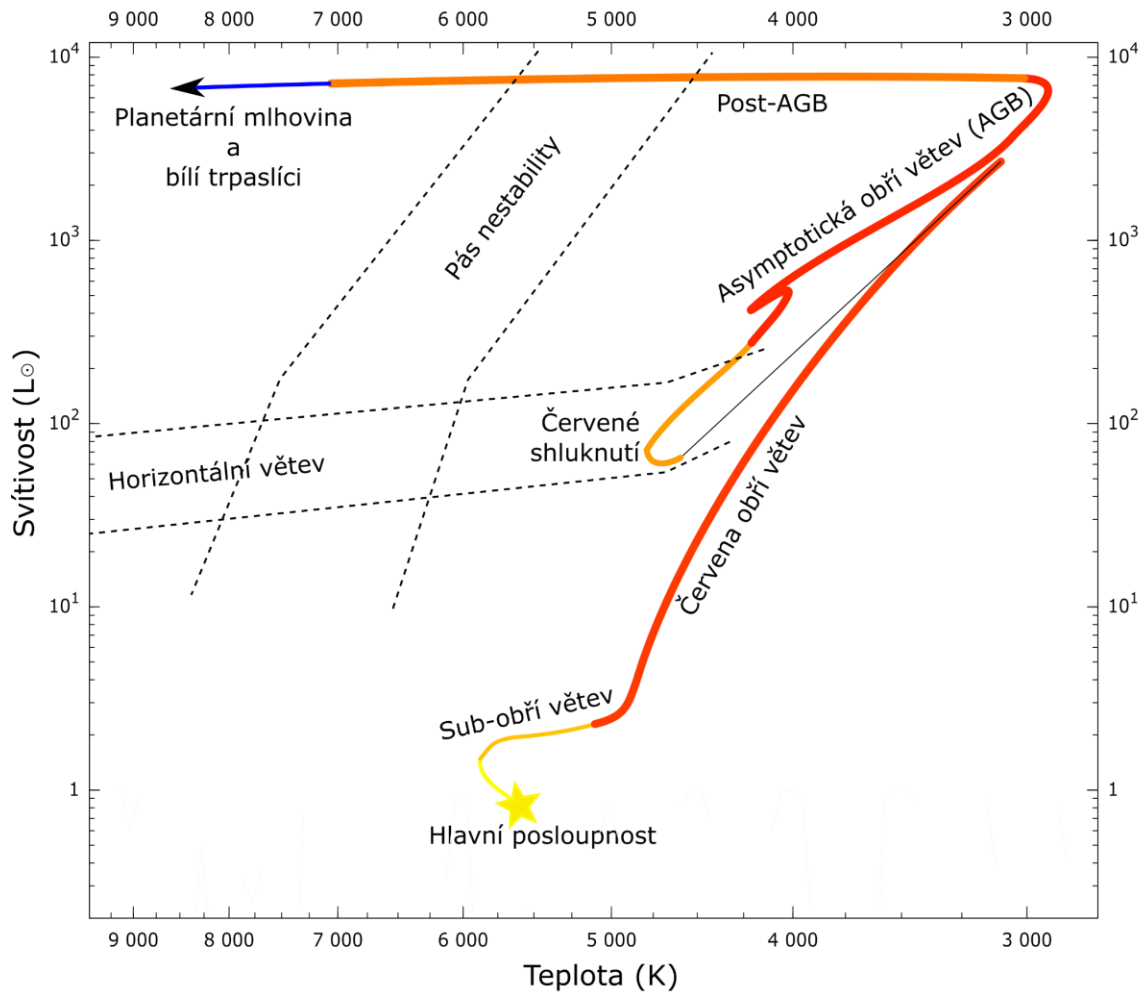
Gamma ray  $\gamma$



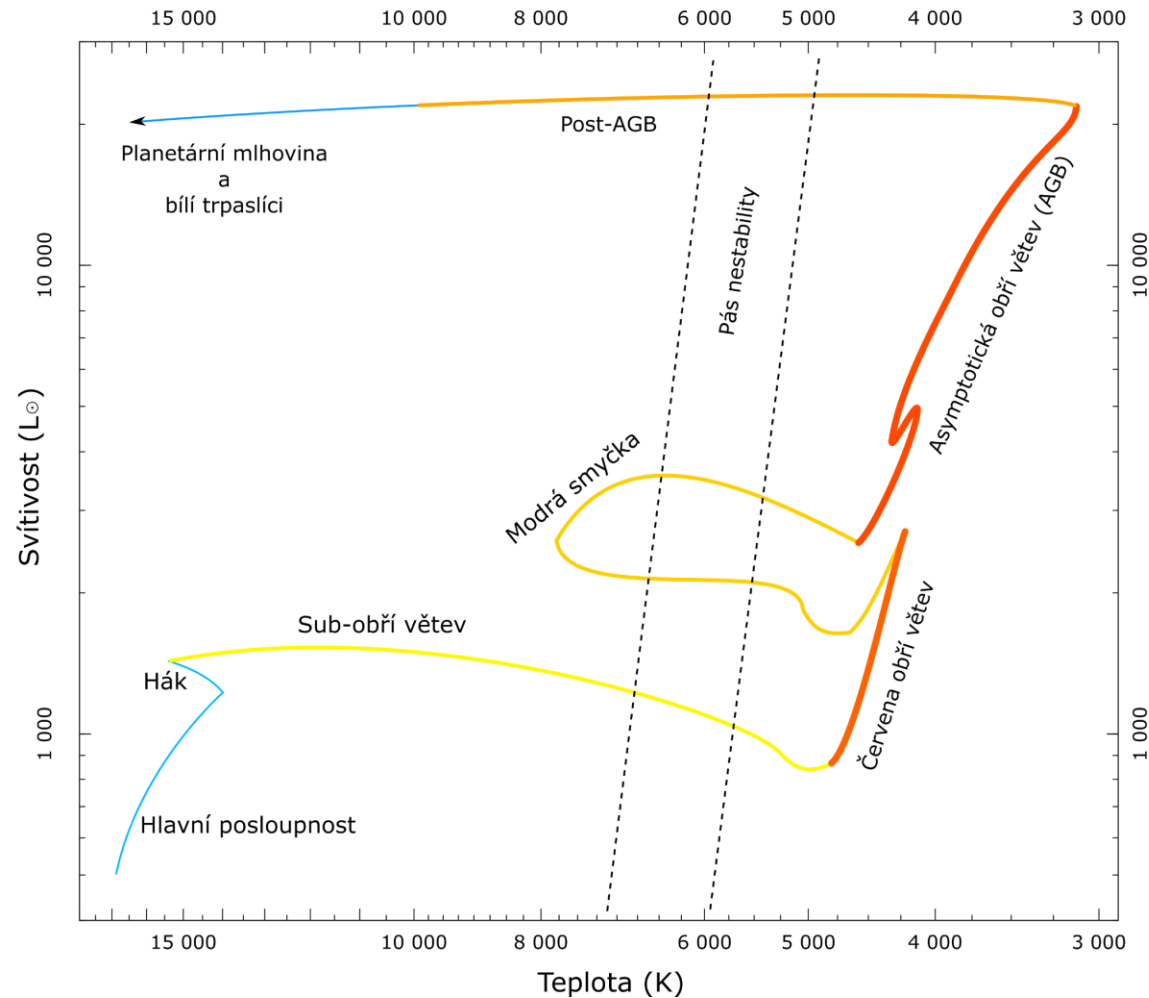
NGC 6302



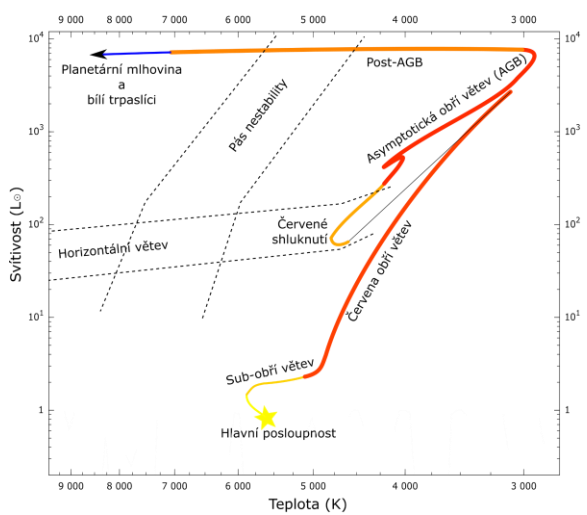
Závěrečná stádia hvězdy o hmotnosti  $1M_{\odot}$



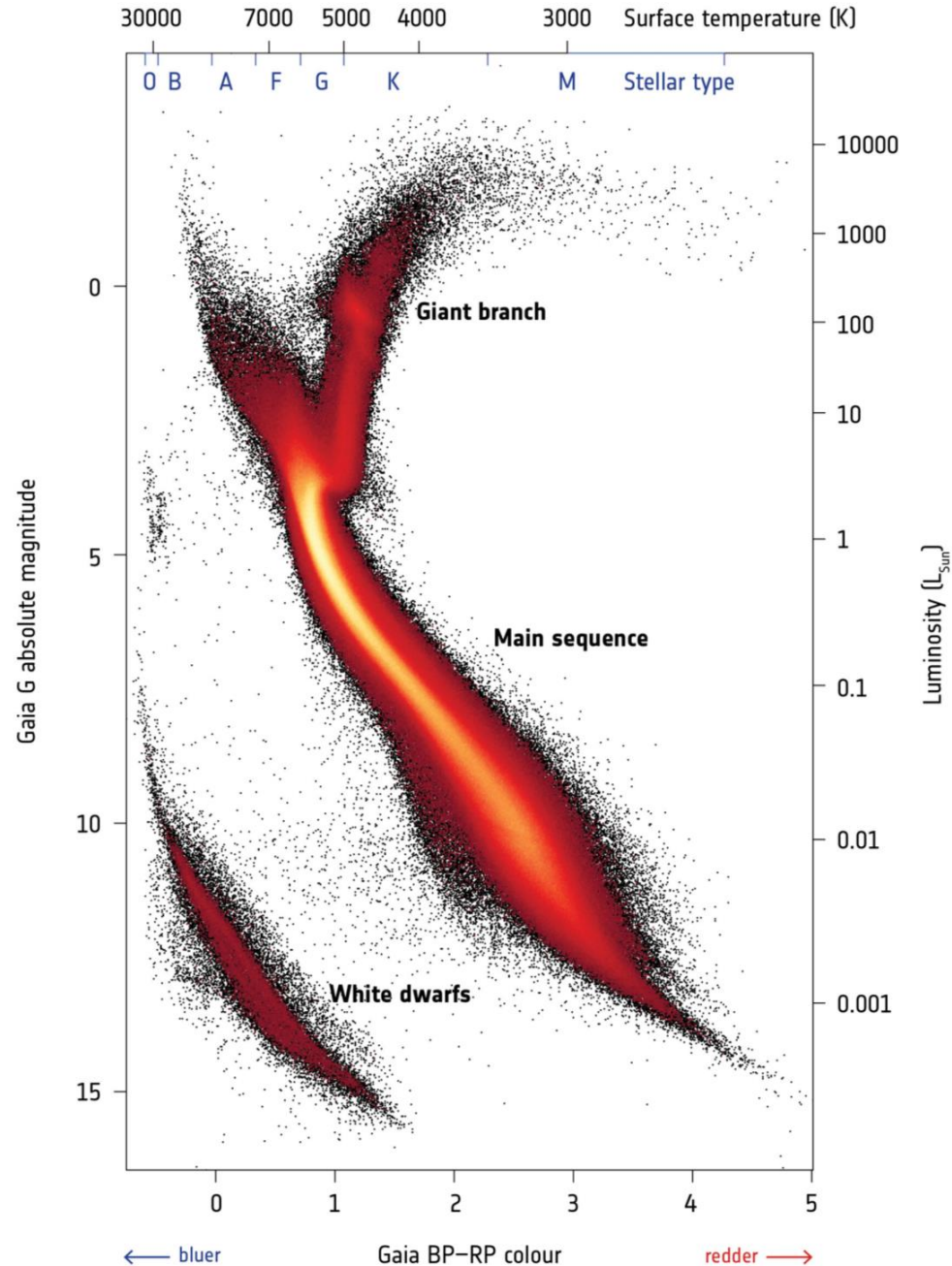
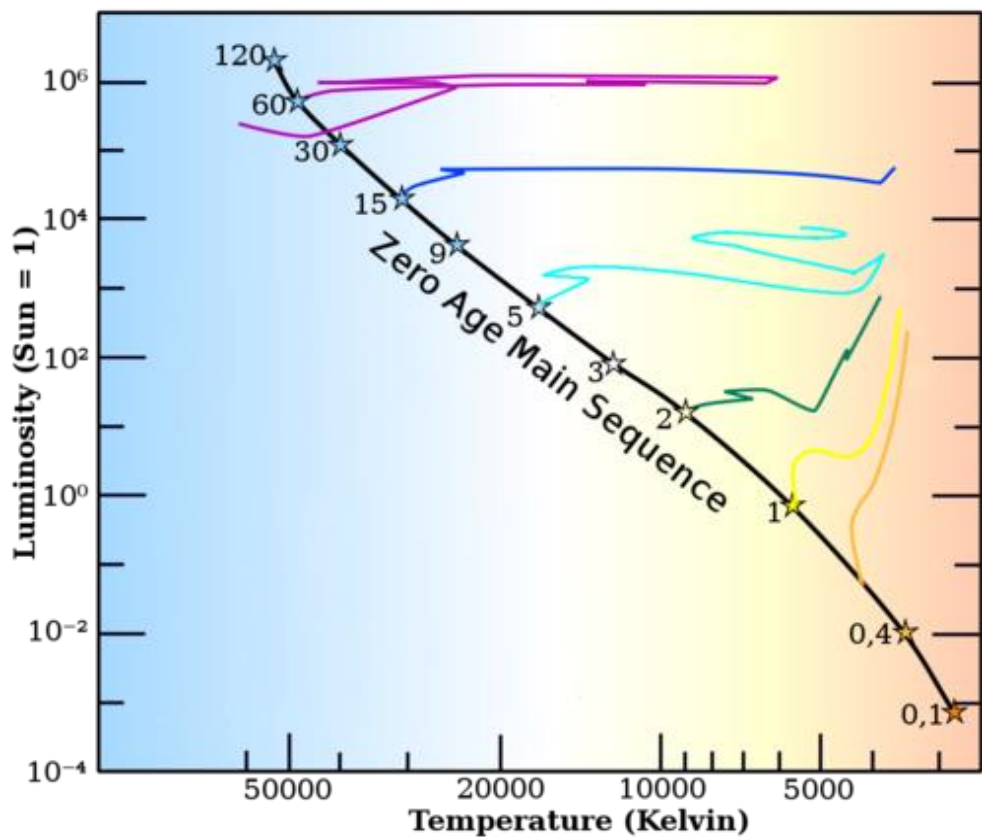
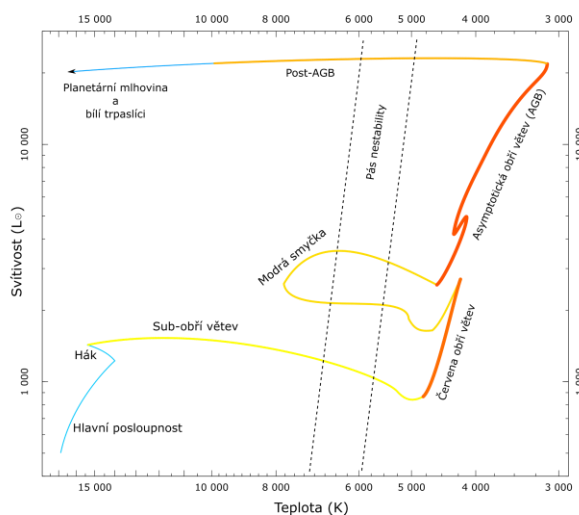
Závěrečná stádia hvězdy o hmotnosti  $5M_{\odot}$



Závěrečná stádia hvězdy o hmotnosti  $1M_{\odot}$



Závěrečná stádia hvězdy o hmotnosti  $5M_{\odot}$



# Hvězdy s hmotností nad $8M_{\odot}$

Po spotřebování He => slučování C



Přesun z červených obrů do veleobrů



Jádro bohaté na uhlík a kyslík  
slučování dalších těžších prvků



Odražené rázové vlny rozmetají obal



Supernova

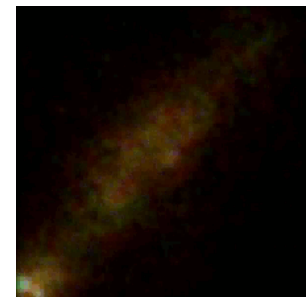
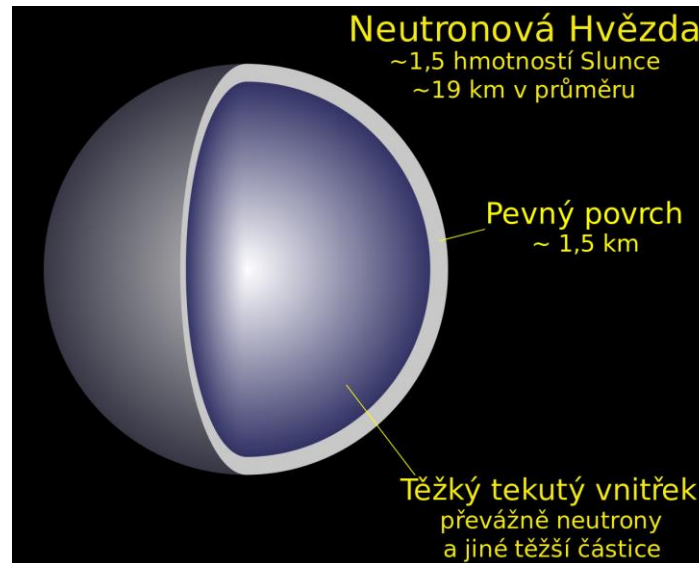
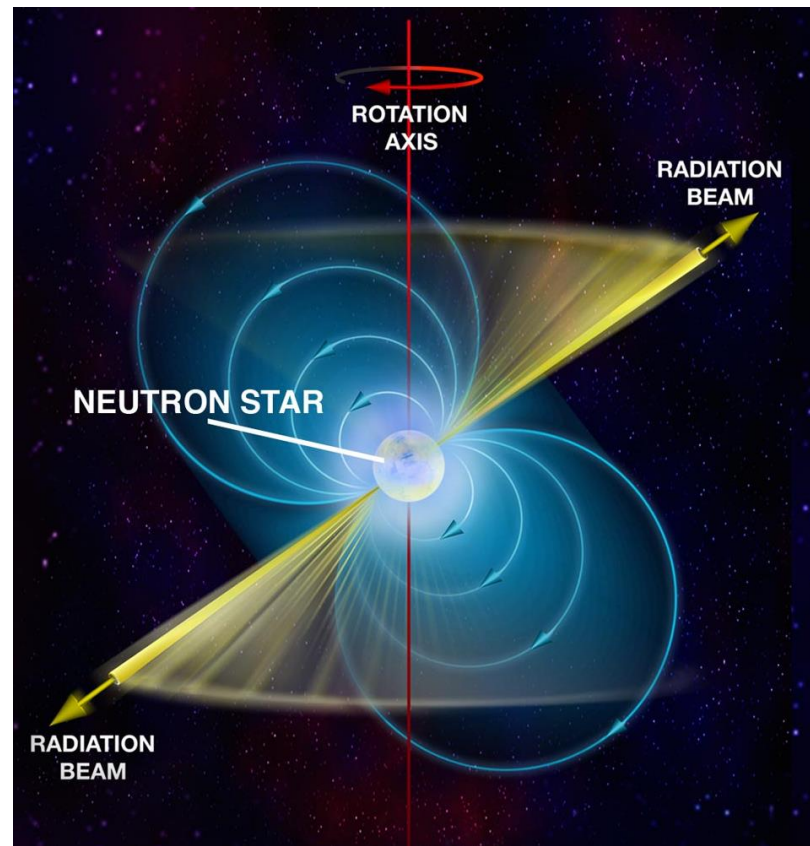


Zůstatek jádro s hmotností cca  $1,4 - 2,5M_{\odot}$

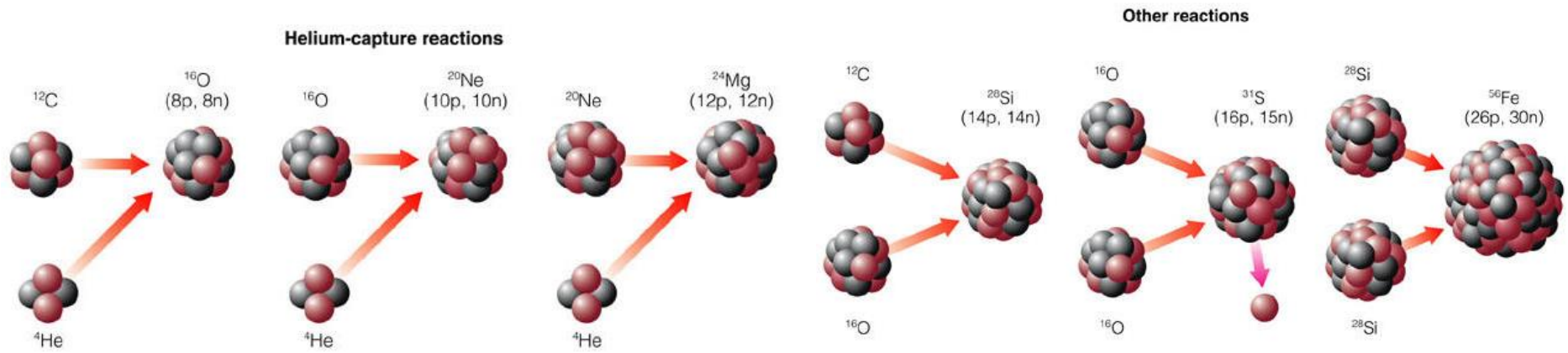
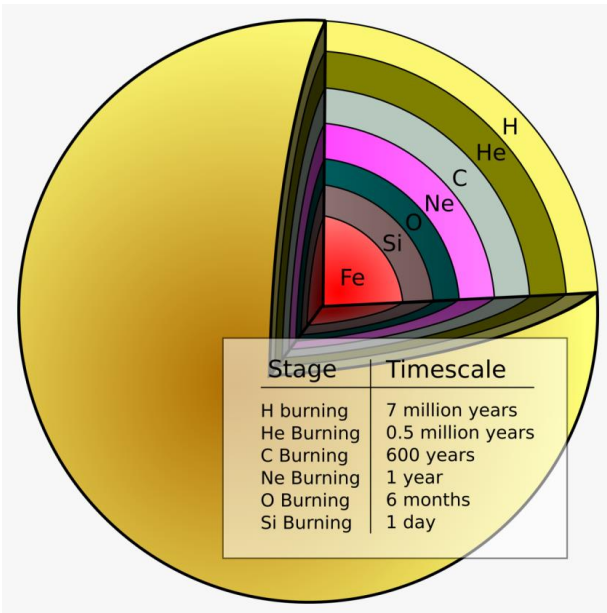
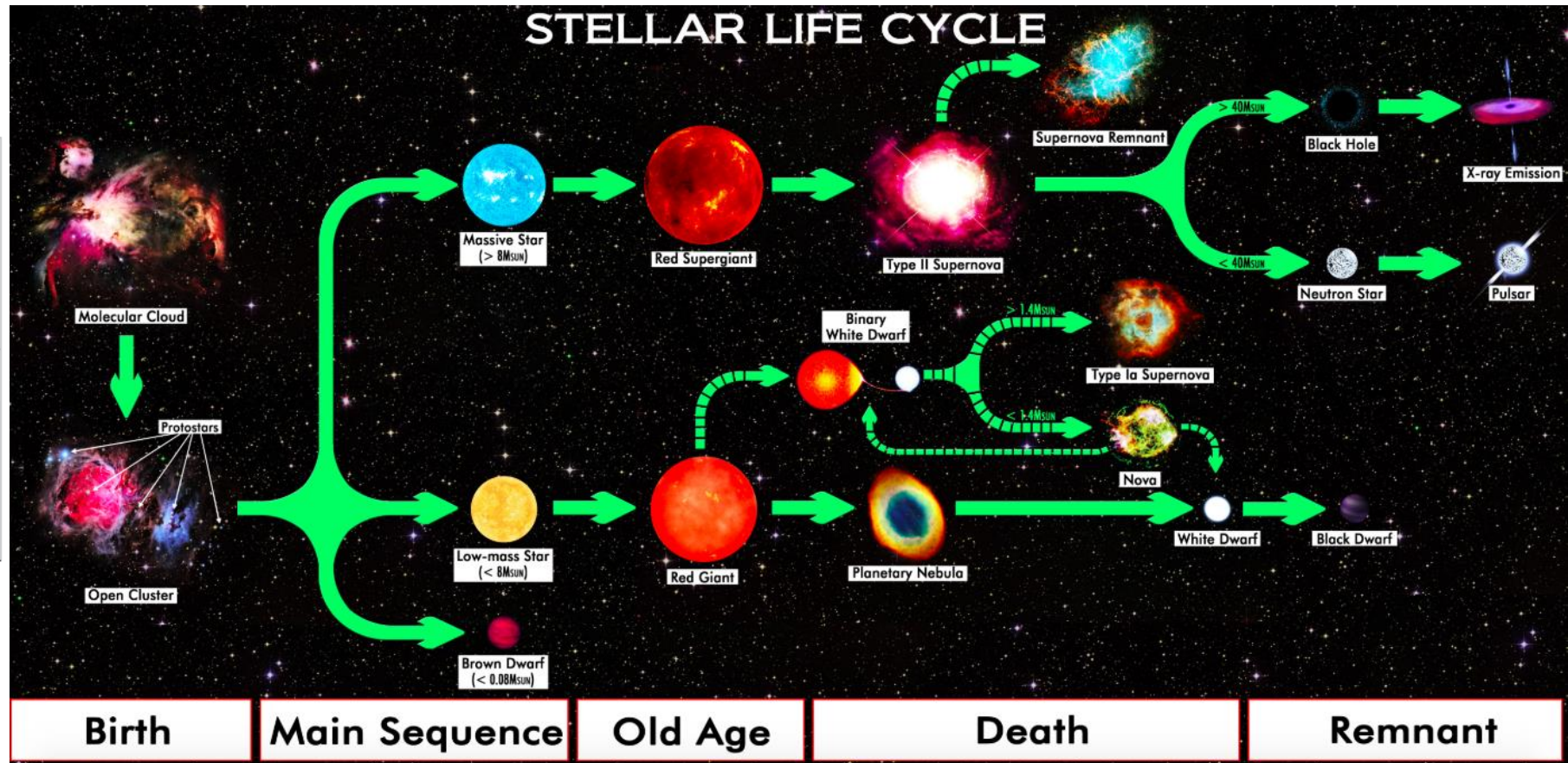
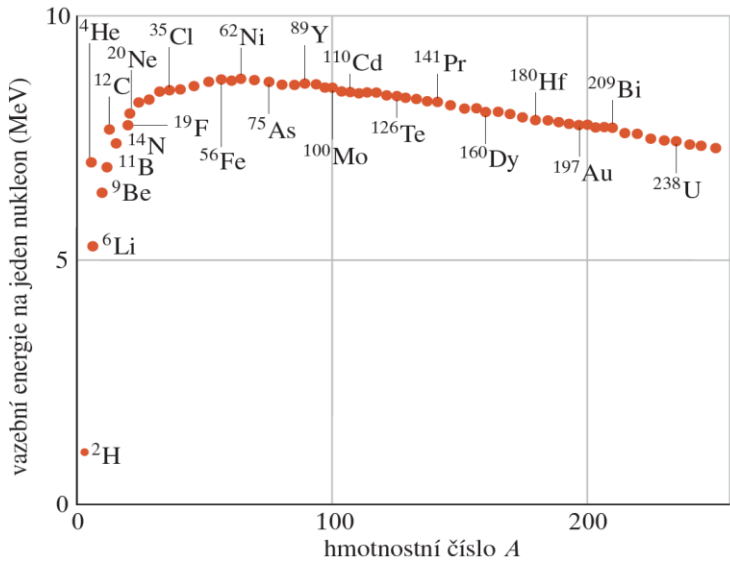


Neutronová hvězda

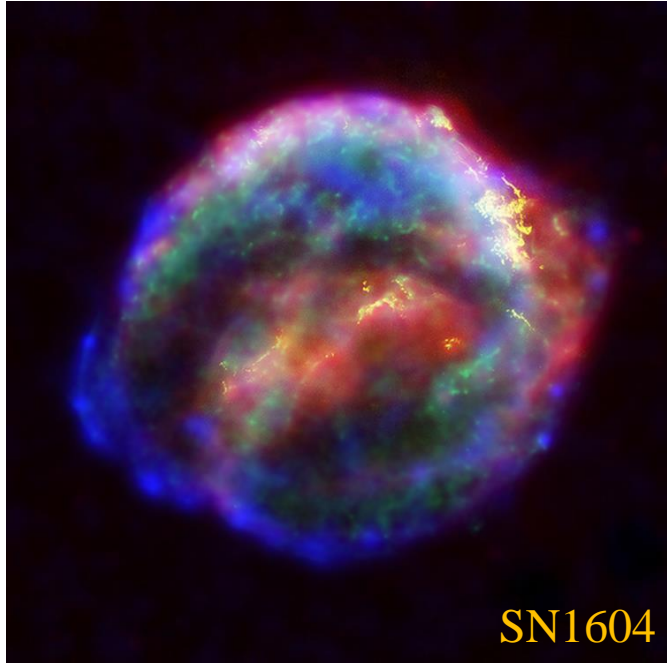
hustota až  $10^{17} \text{ kg/m}^3$   
mag. pole až  $10^{11} \text{ T}$



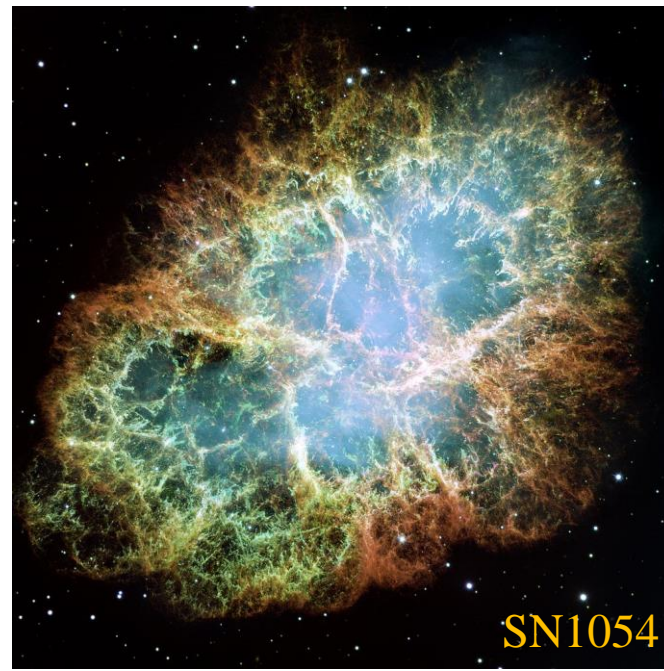
# Hvězdy s hmotností nad $40M_{\odot}$



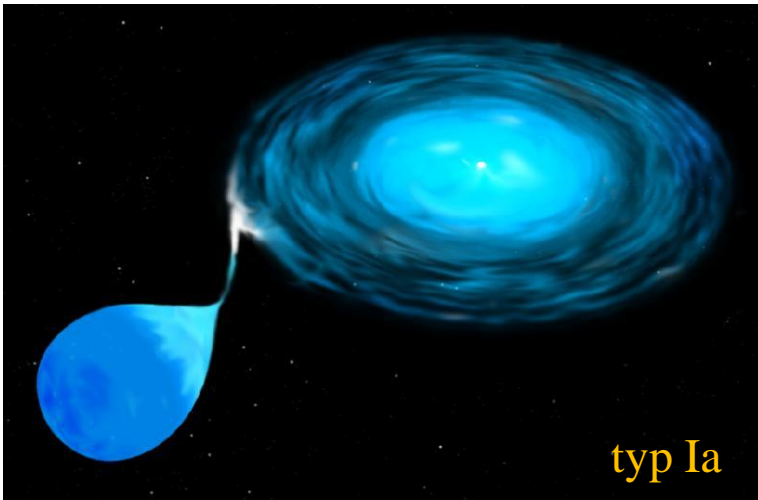
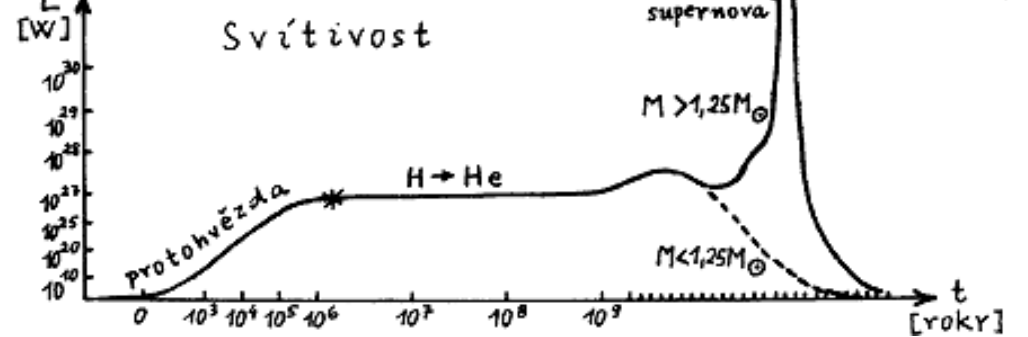
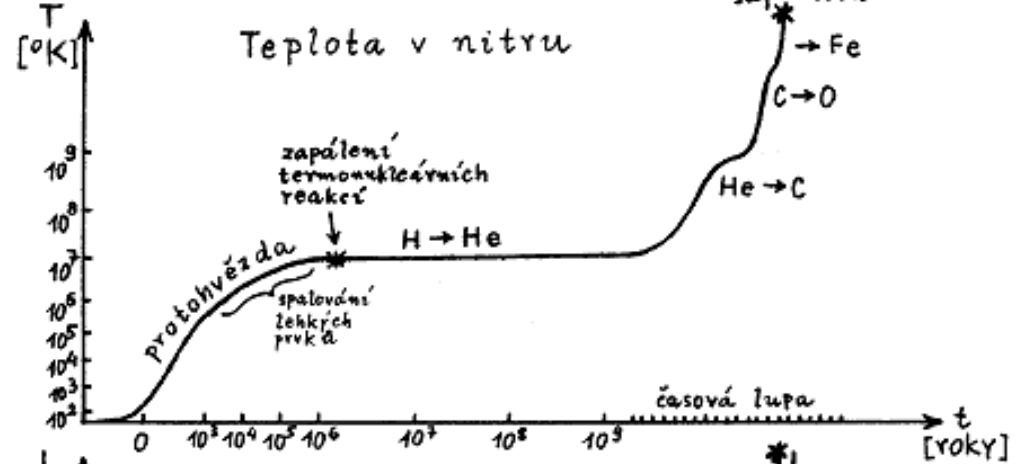
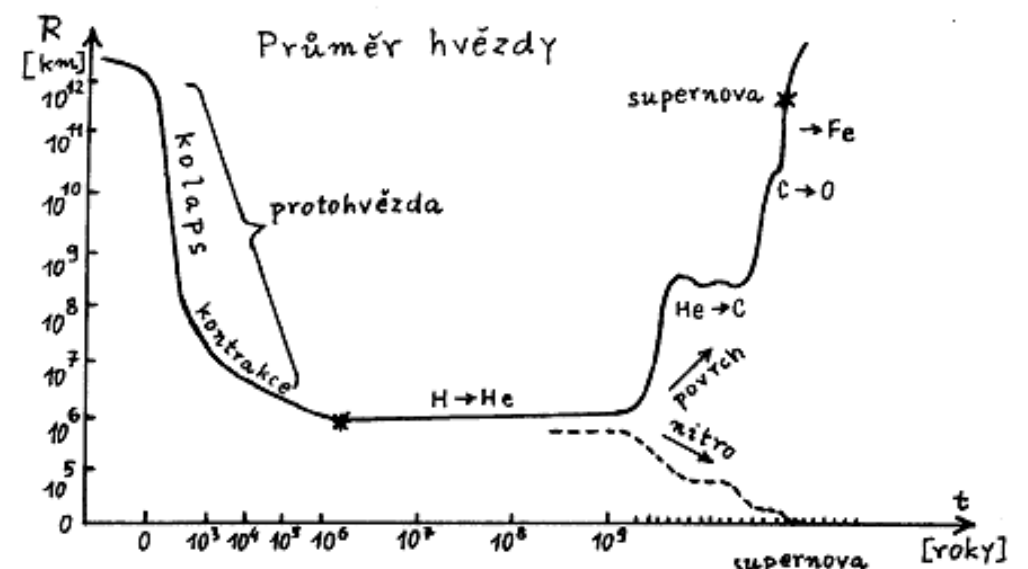
# Supernovy



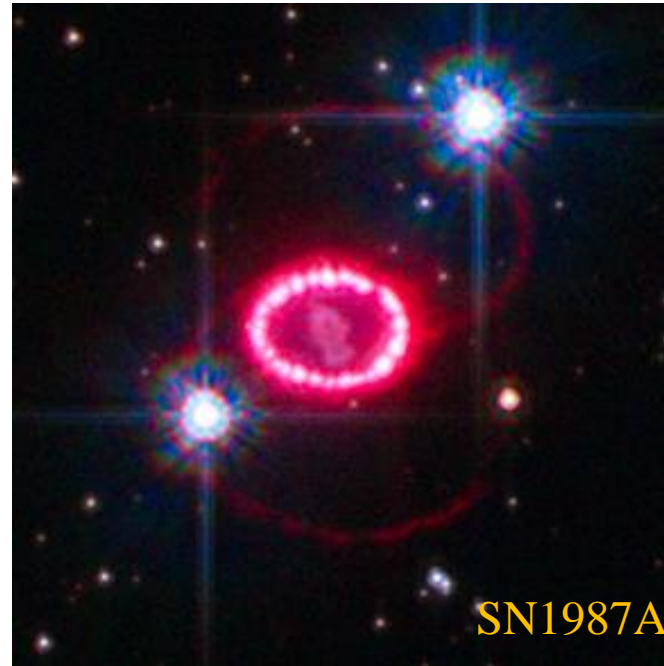
SN1604



SN1054



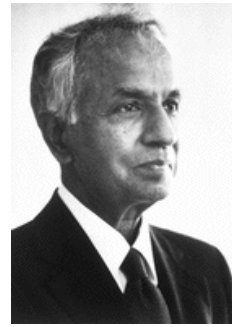
typ Ia



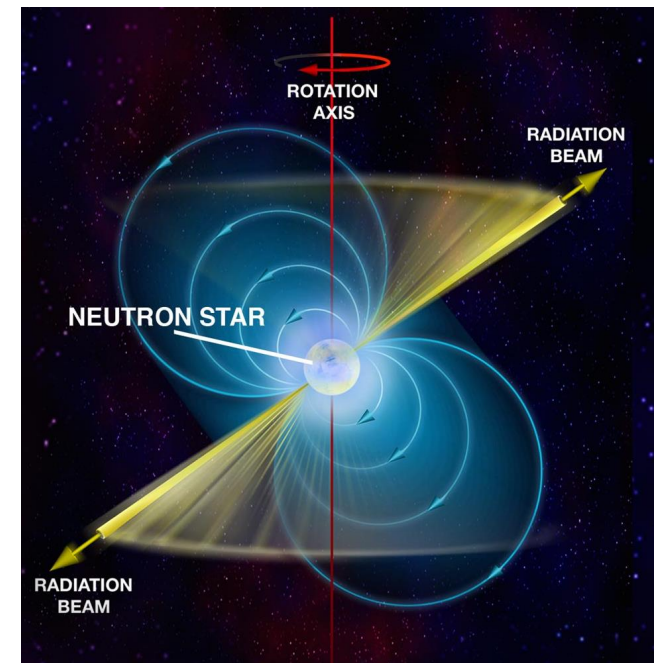
SN1987A

## Zbytky po hvězdách (a po supernovách)

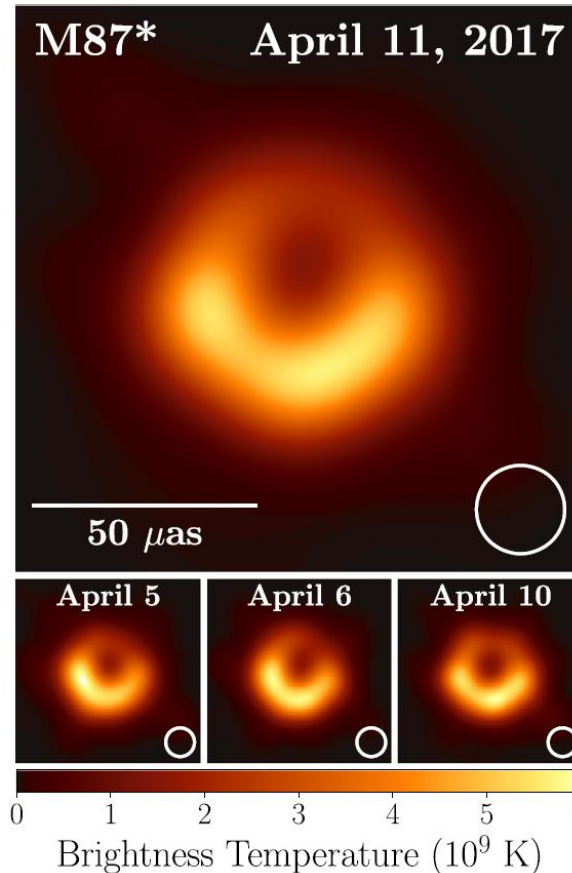
Chandrasekharův limit:  $1,44 - 2,58 M_{\odot}$



**Neutronová hvězda**  
pulzary a magnetary  
hustota až  $10^{17} \text{ kg/m}^3$   
mag. pole až  $10^{11} \text{ T}$



Tolmanův–Oppenheimerův–Volkoffův limit:  $2,17 - 2,27 M_{\odot}$  (teoreticky  $3,0 M_{\odot}$ )

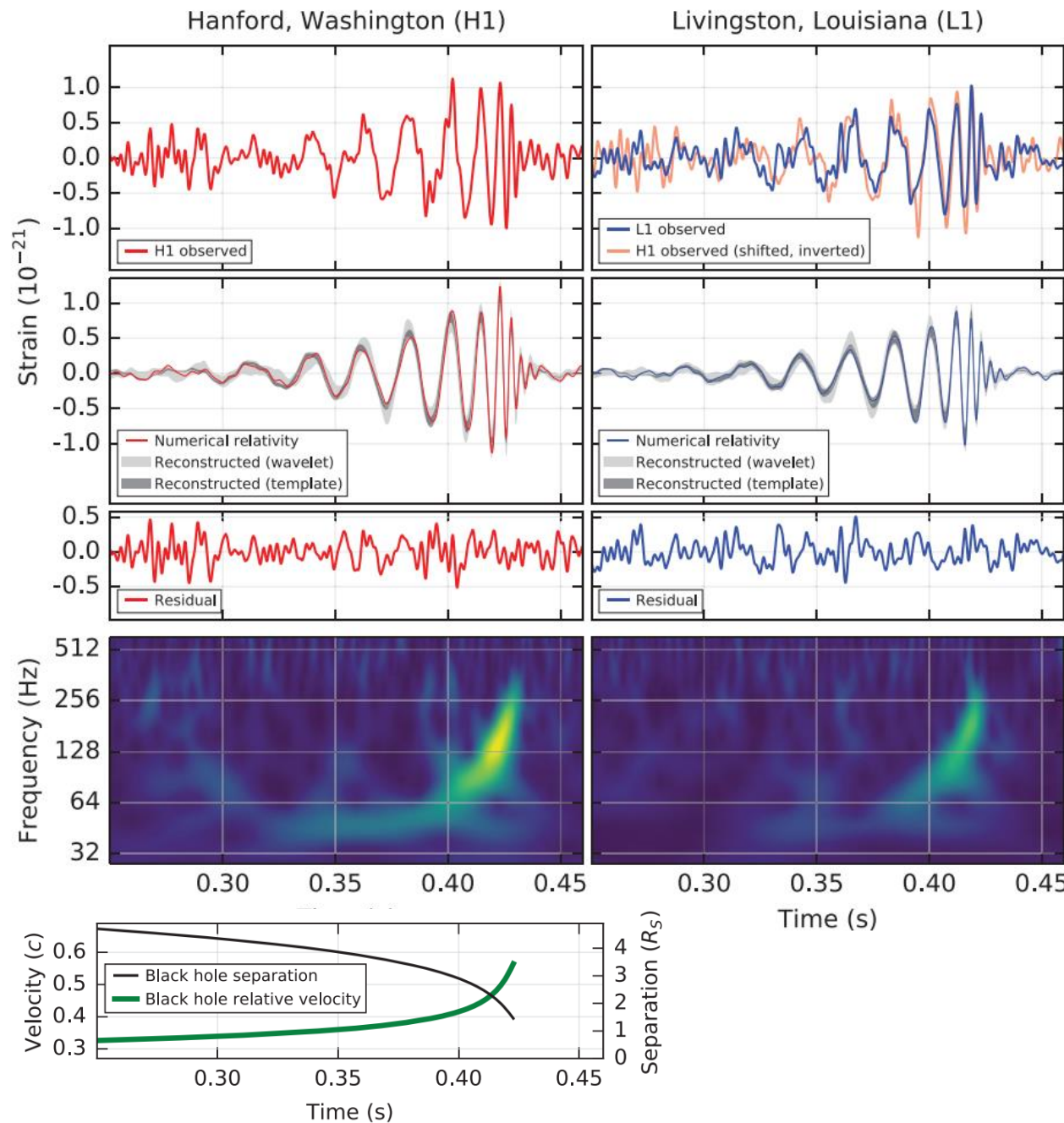


**Černá díra**  
horizont událostí  
akreční disk  
relativistické výtrysky

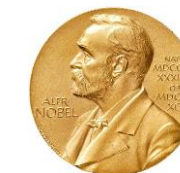


The Event Horizon Telescope:  
*The Astrophysical Journal Letters*, **875**, (2019)

# Srážky neutronových hvězd a černých děr



Ondrej Nepela (1972)



2017



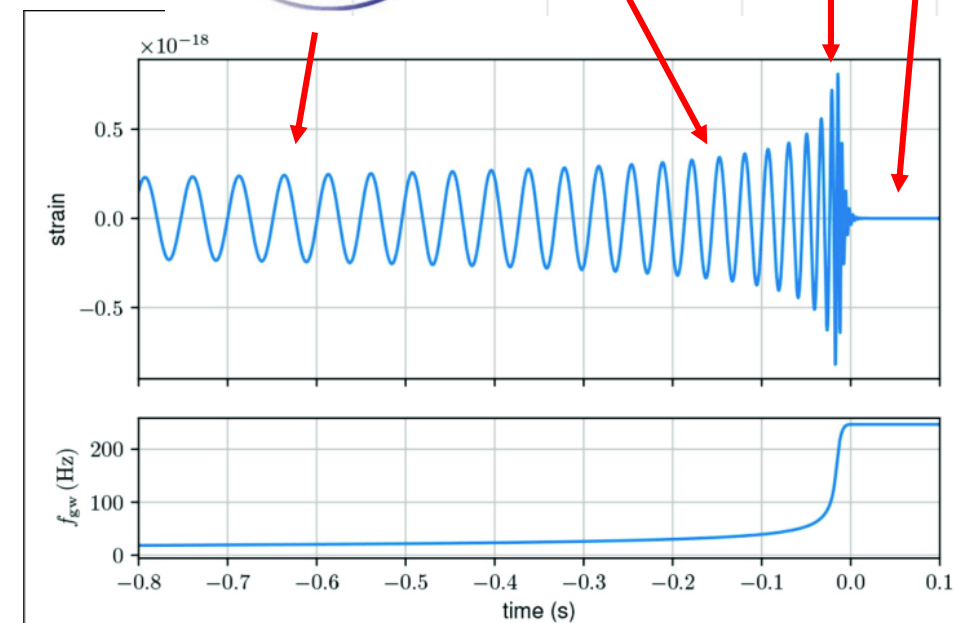
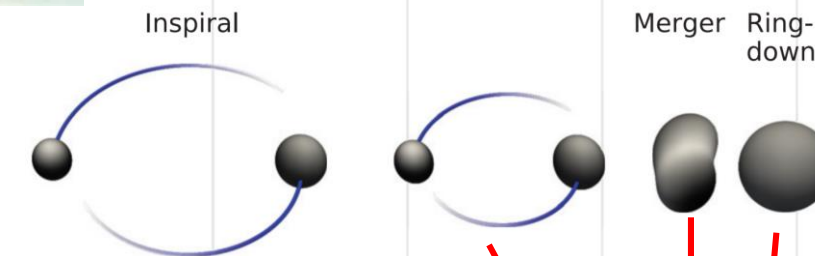
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**Rainer Weiss**  
Prize share: 1/2



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**Barry C. Barish**  
Prize share: 1/4



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**Kip S. Thorne**  
Prize share: 1/4



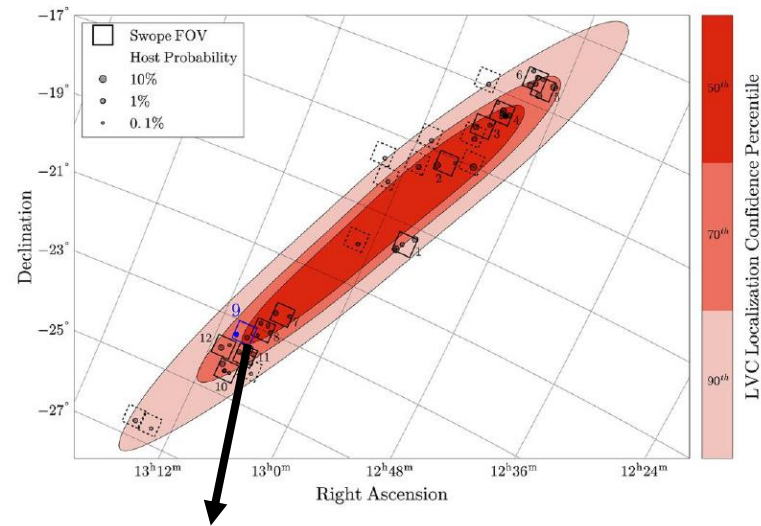
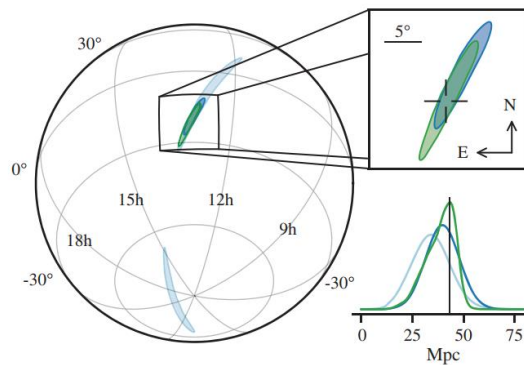


# GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*  
 (LIGO Scientific Collaboration and Virgo Collaboration)

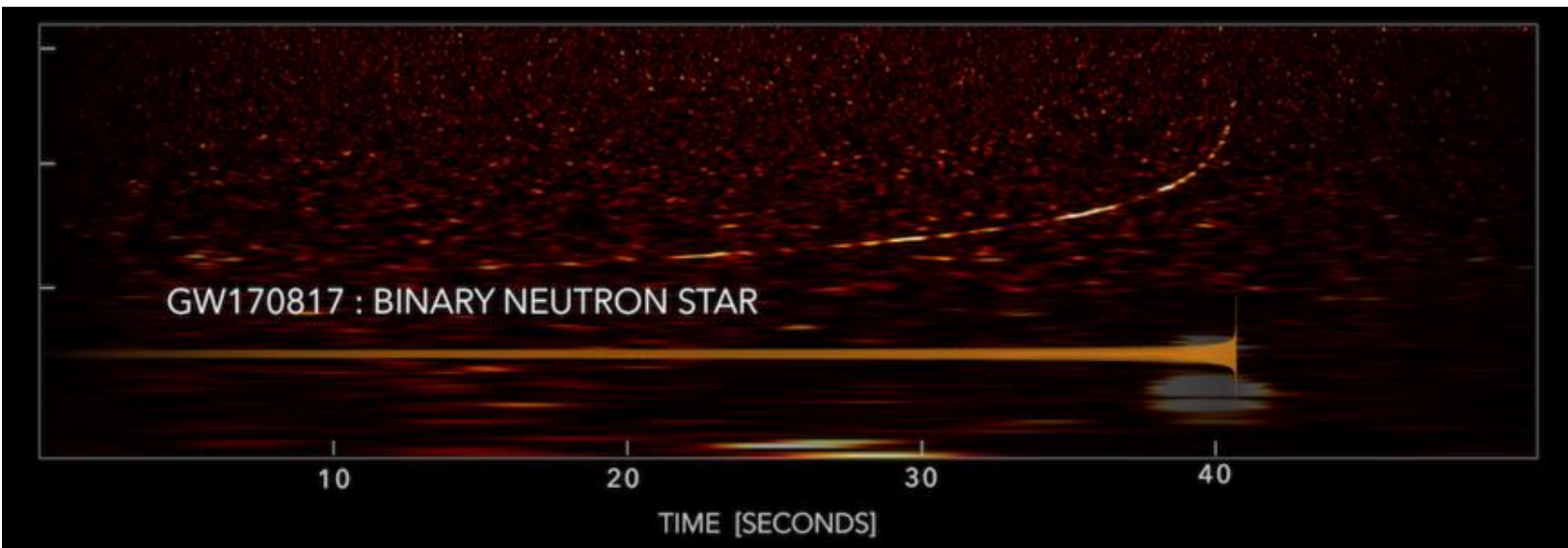
## Low-spin priors ( $|\chi| \leq 0.05$ )

Primary mass $m_1$	1.36–1.60 $M_\odot$
Secondary mass $m_2$	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio $m_2/m_1$	0.7–1.0
Total mass $m_{\text{tot}}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\text{rad}}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_L$	130 mil. ly = $40^{+8}_{-14}$ Mpc
Viewing angle $\Theta$	$\leq 55^\circ$
Using NGC 4993 location	$\leq 28^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leq 800$
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	$\leq 800$



Galaxie NGC 4993 (suhvězdí Hydra)  
 134 mil. ly

Kilonova







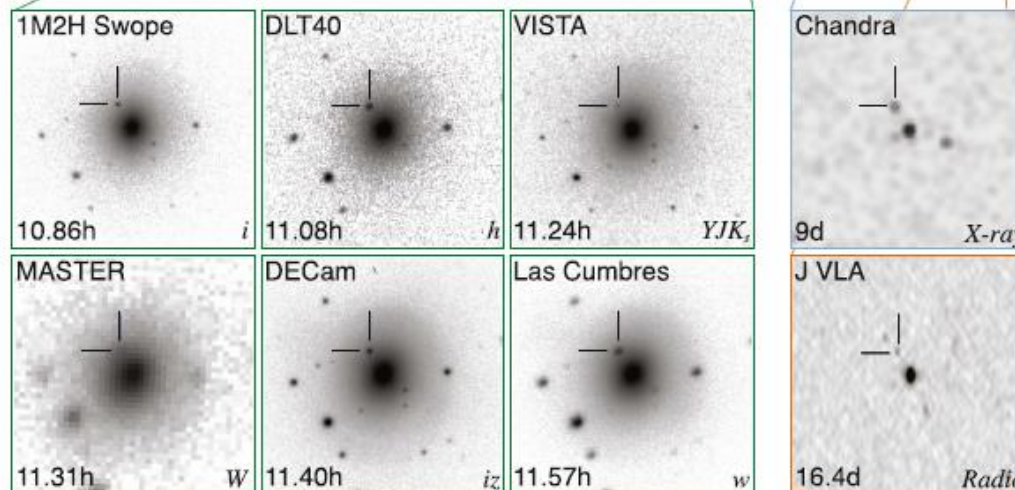
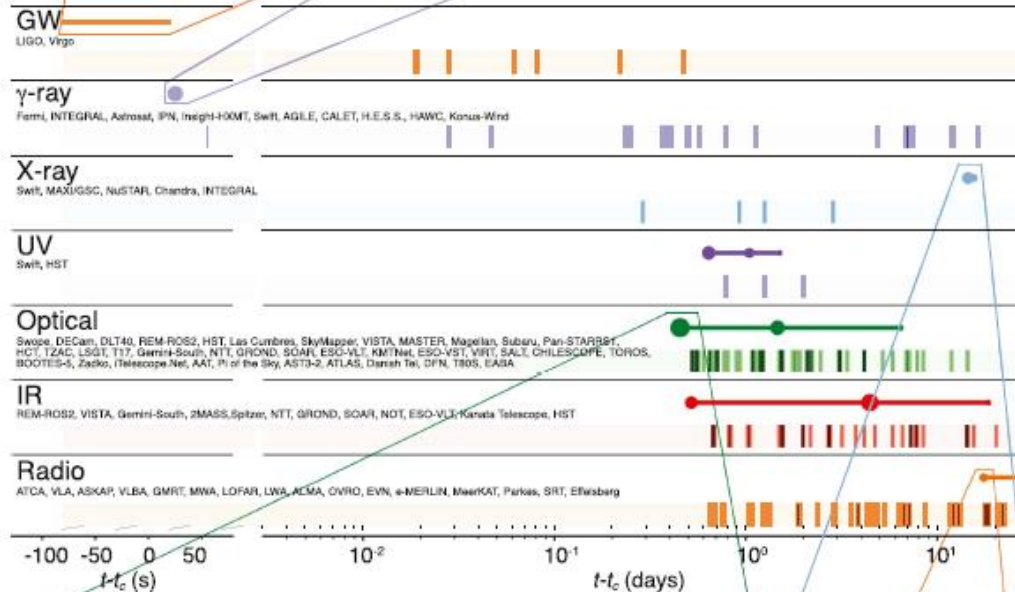
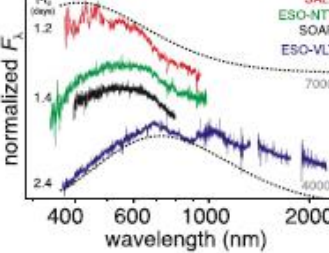
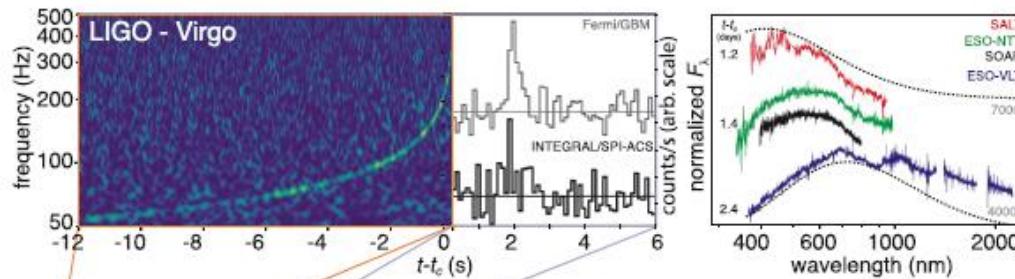
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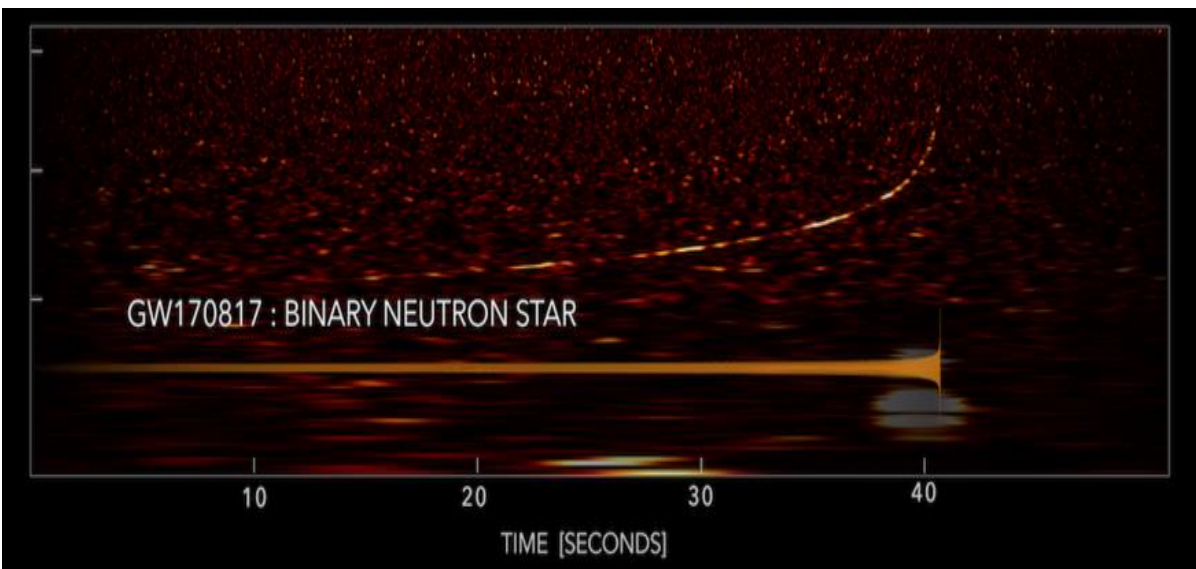
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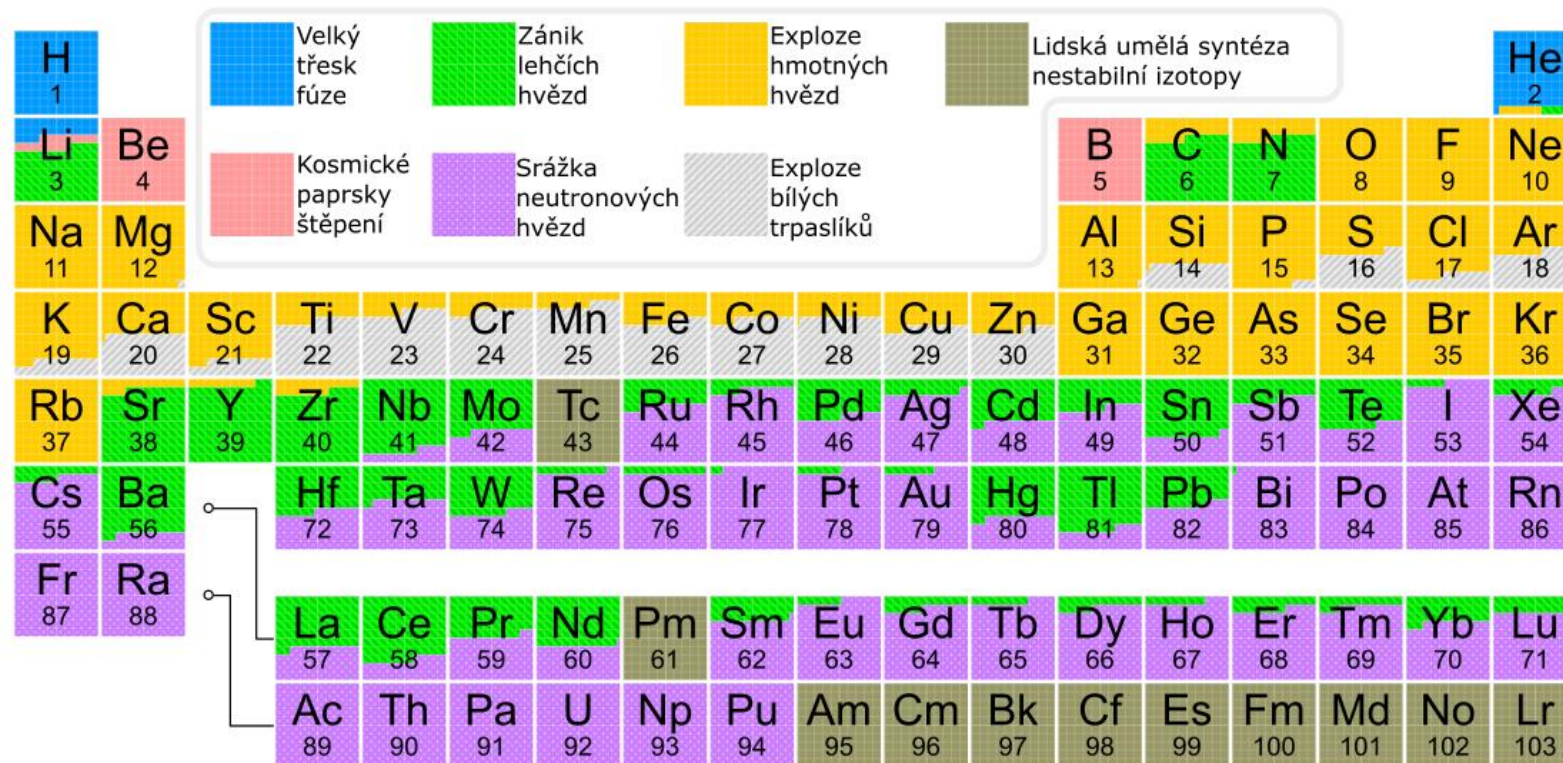
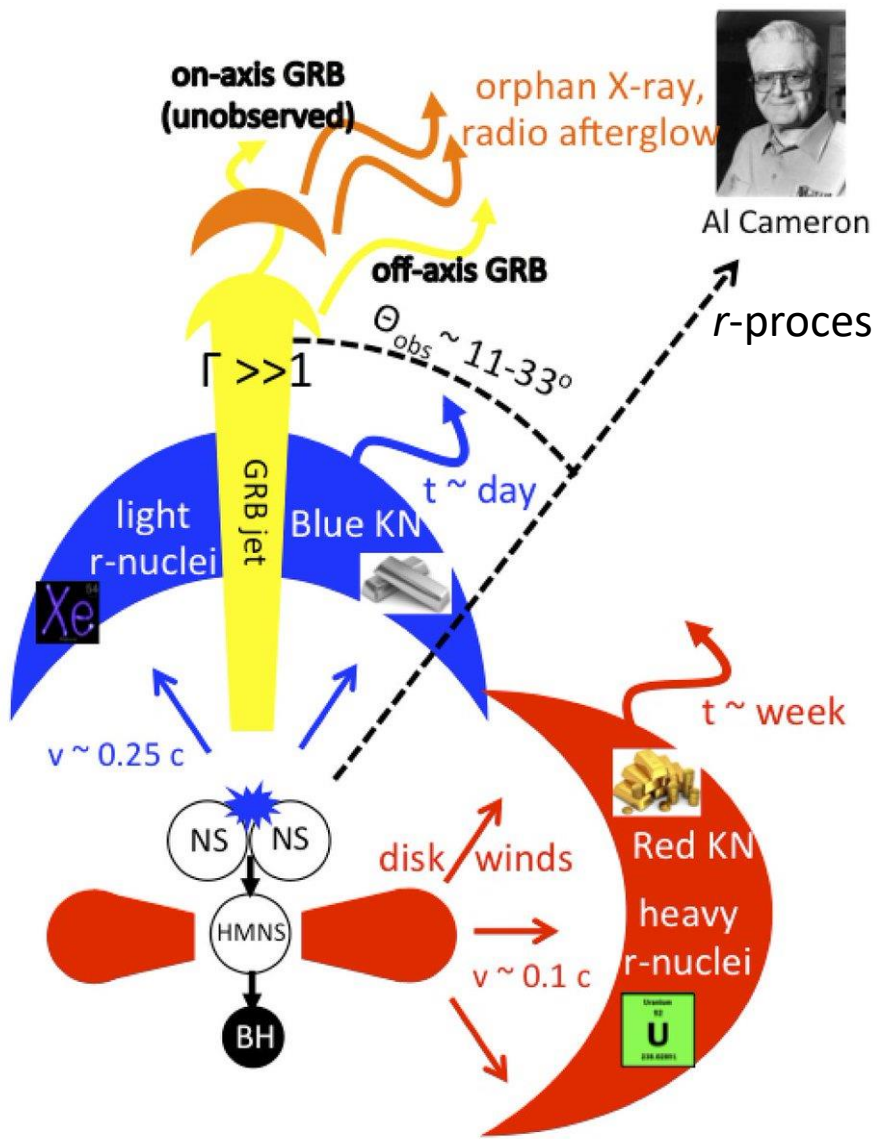
130 mil. ly =  $40^{+8}_{-14}$  Mpc



Pozorování v celém elektromagnetickém i gravitačním spektru!



# Každý konec je začátek něčeho nového



B. D. Metzger, *arXiv:1710.05931*, (2017)

A. Cameron, *PASP*, vol. **69**, (1957)

M. R. Drout *et al.*, *Science* 10.1126/science.aaq0049 (2017)

**Každý konec je začátek něčeho nového...**

