Csillagok keletkezése és halála

Bevezetés az asztrofizikába

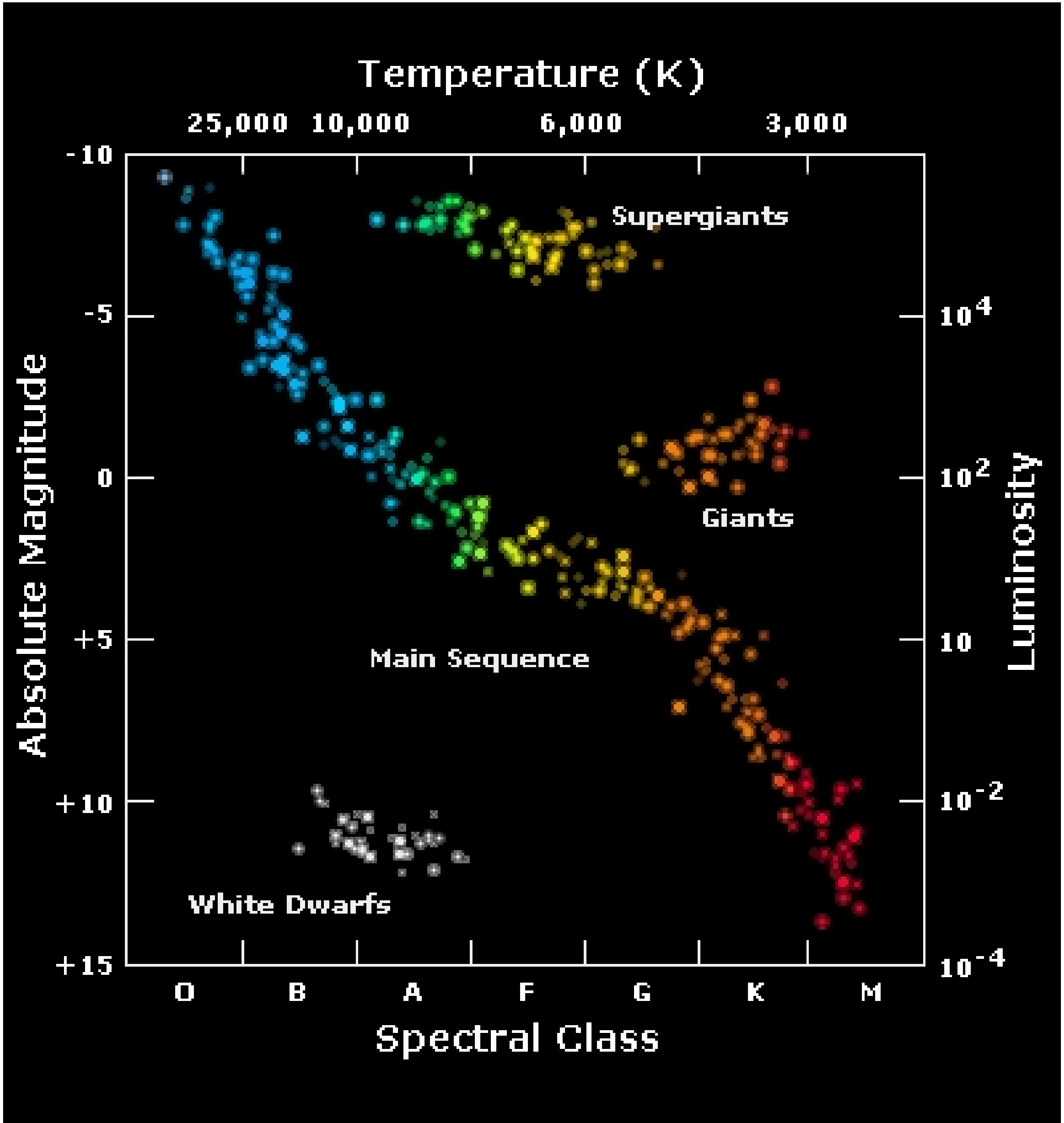
Kocsis Bence

Előző óra

- Csillagok sugárzása
  - Fúzió: pp lánc, CNO ciklus, tripla alpha folyamat
  - spektrum: fekete test “kontinuum” + vonalak
- Nukleoszintézis
  - Nap: [H] = 71%, [He] = 27%, [Z] = 2% (fém = minden más)
- Tömegeloszlás
  - $dN / dM \sim M^{-2.35}$
  - $M > 0.08$ Msun
  - $M < 100$ Msun
- Hertsprung-Russel diagramm
  - Hőmérséklet – Luminozitás
  - sugár és tömeg ebből számítható (hogyan?)
  - színképosztály OBAFGKM

$L = 4\pi r^2 \; \sigma T^4$

dM/dt = M^(−2.5)



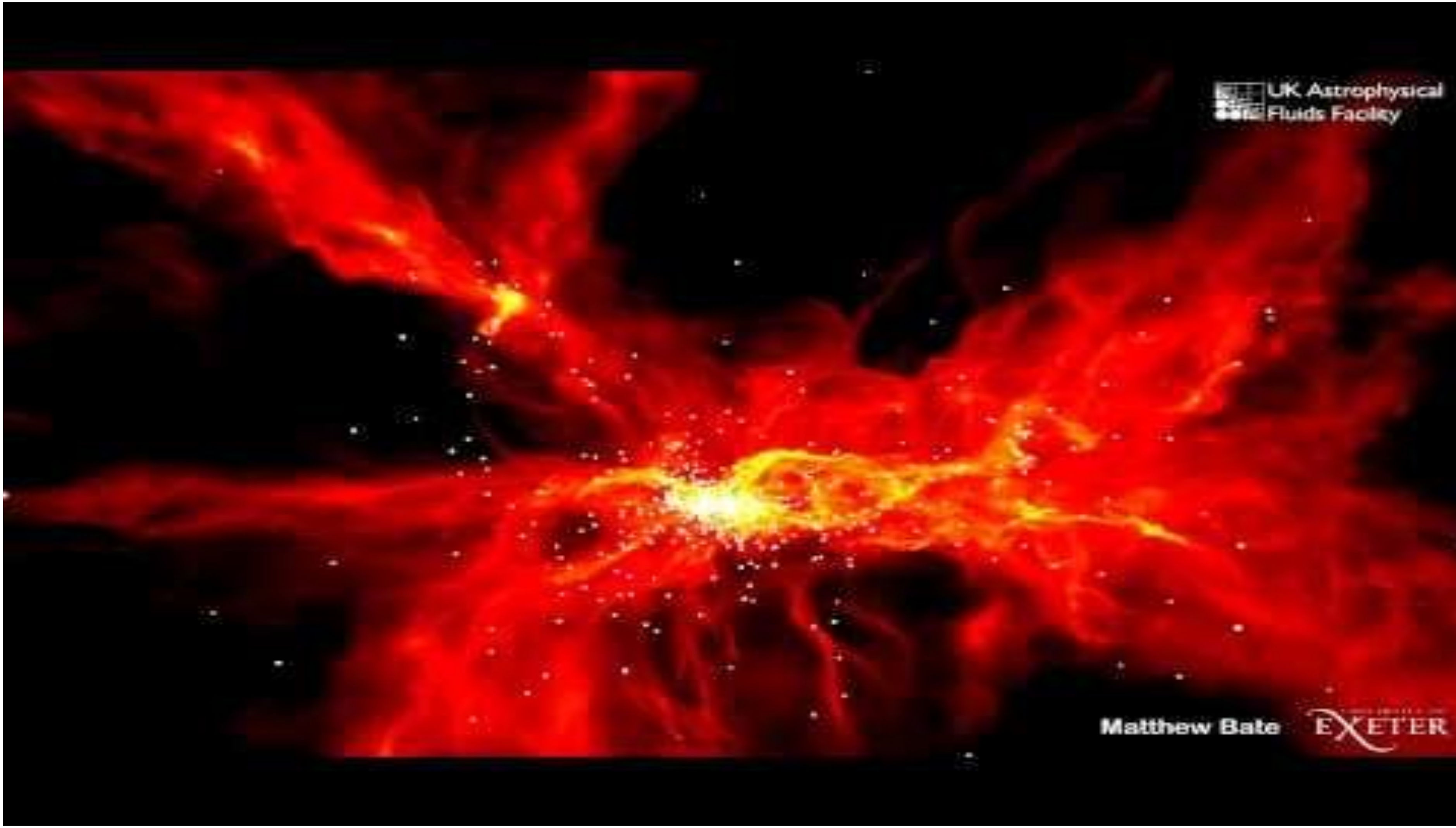
Temperature (K)
25,000
10,000
6,000
3,000
-10
-5
0
+5
+10
+15
Absolute Magnitude
10^4
10^2
10
10^{-2}
10^{-4}
Luminosity
Supergiants
Giants
Main Sequence
White Dwarfs
O
B
A
F
G
K
M
Spectral Class

Csillagkeltekezés

- Fúzióhoz nagy sűrűség kell
- Gáz sugárzás miatt energiát veszít, hül, nyomás csökken, gravitációsan csomósodik
- Hűlés közben molekulák alakulhatnak ki (H2 felhők)
- Csillagképződés egy kritikus tömeg felett gravitációs instabilitás miatt (Jeans tömeg)
  - Segít ha egy lökéshullám keresztülhalad a rendszeren
  - Pl. masszív csillagok erős UV sugárzása kisöpri a gázt és lökéshullám frontok alakulnak ki

Szimuláció

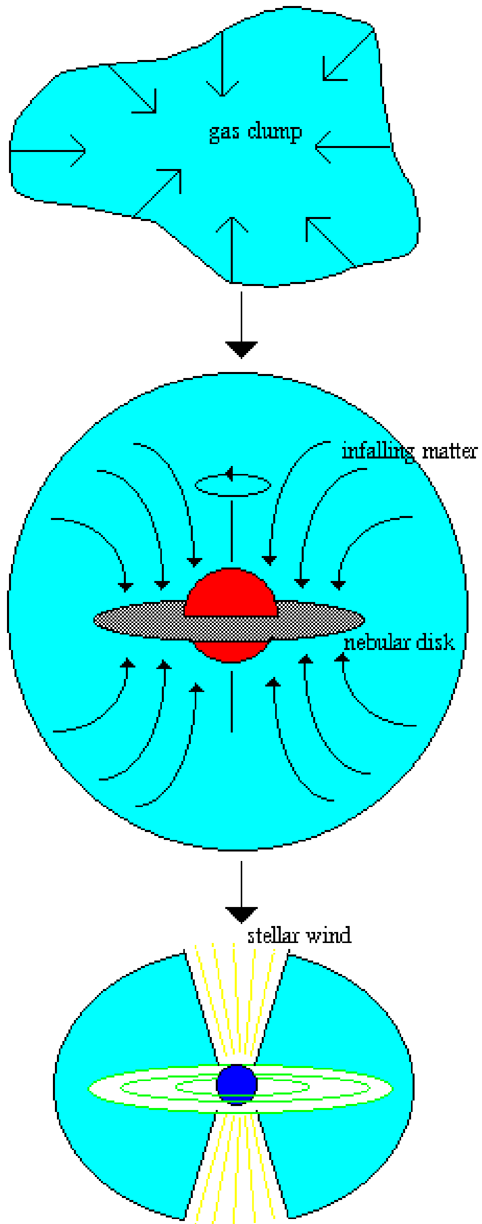
https://youtu.be/3z9ZKAkbMhY



Szimulációs nehézségek

- Felbontás – nagyon széles mérettartomány skála
  - Óvatosnak kell lenni mit hanyagolunk el
- Sugárzás energia transzport
  - opacitást több százezer fém-vonal dominálja
- nemegyensúlyi termodinamika
- magnetohidrodinamika
- turbulencia
- Impulzusmomentum megmaradás → fragmentáció?
- Sűrű részek gravitációja a gázfelhőkben állóhullámokat kelt, ami a sűrű részek vándorlásához, ütközéséhez vezet

Protostar Formation



A dense gas clump breaks off from molecular cloud and collapses Angular momentum turns the irregular clump into a rotating disk

The central region is denser and forms into a protostar, the nebular disk forms slower to become a planetary system. Infalling matter increases the size of the protostar by a factor of 100

Infall is stopped when the protostar begins thermonuclear fusion and produces a strong stellar wind

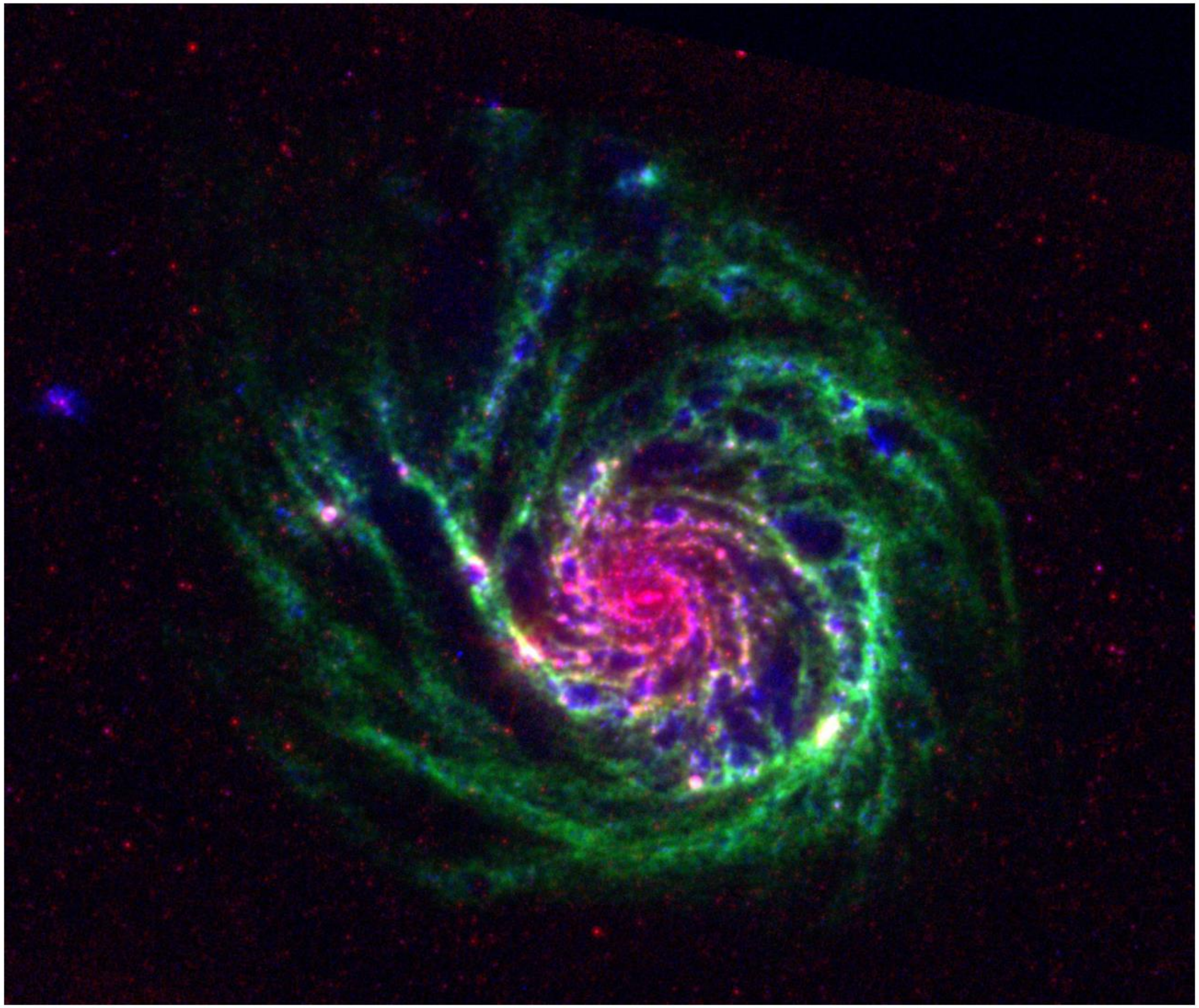
Nearby galaxy with HI gas disc

Green = HI Gas
Blue = star-formation
Red = warm dust

Ionised gas is constantly accreting onto galaxies from the IGM, as it does so it cools and recombines to create neutral gas (HI) shown here in green.

Star-formation shown in blue occurs in regions where the HI is densest and where H_2 can form.

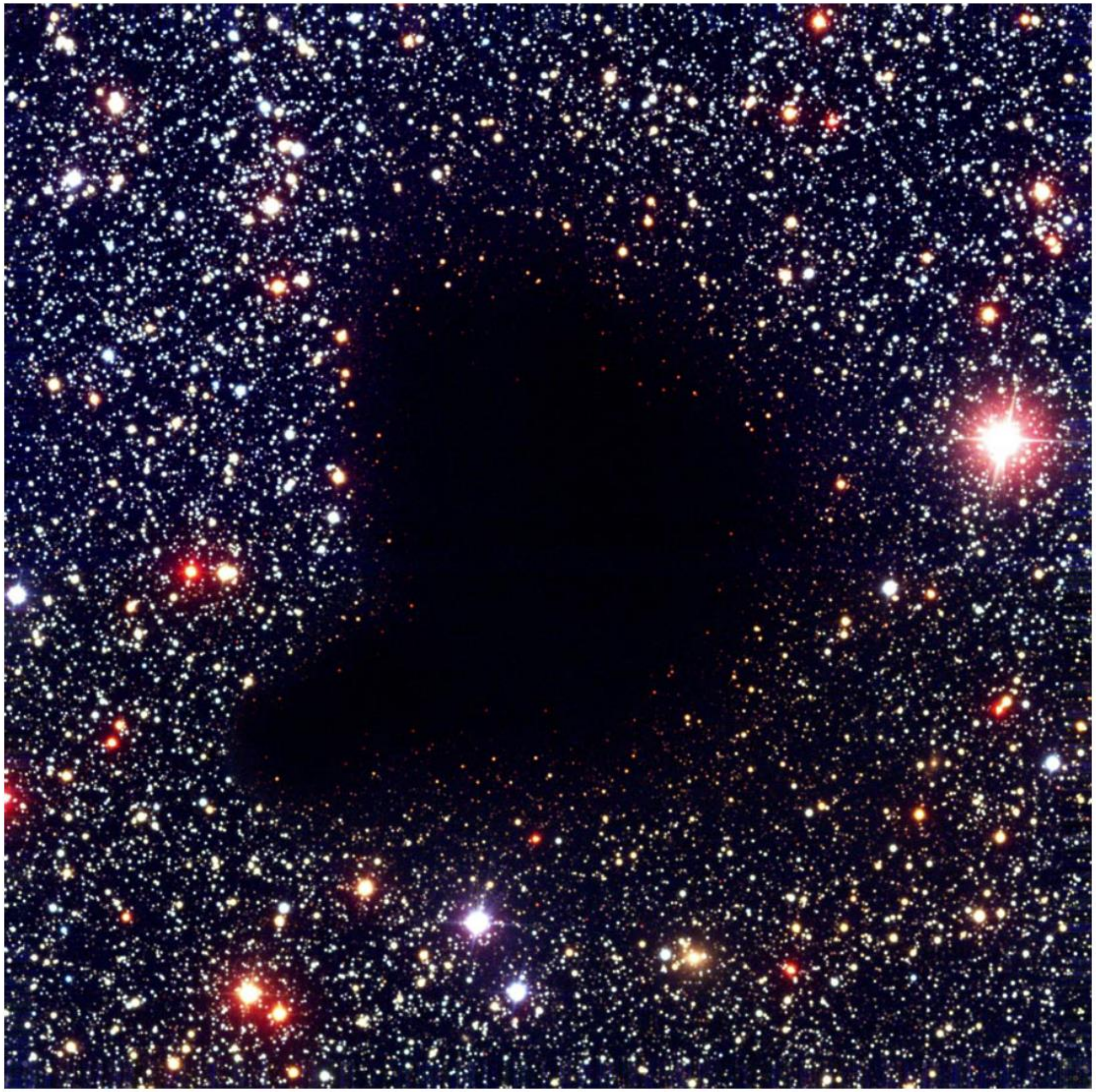
Stars then form from H_2



Giant Molecular Cloud

H_2 is not directly detectable but one can take images of other molecules such as CO or see the impact of dust grain attenuation on background light

Here we see a dense clump of foreground dust blocking the background light

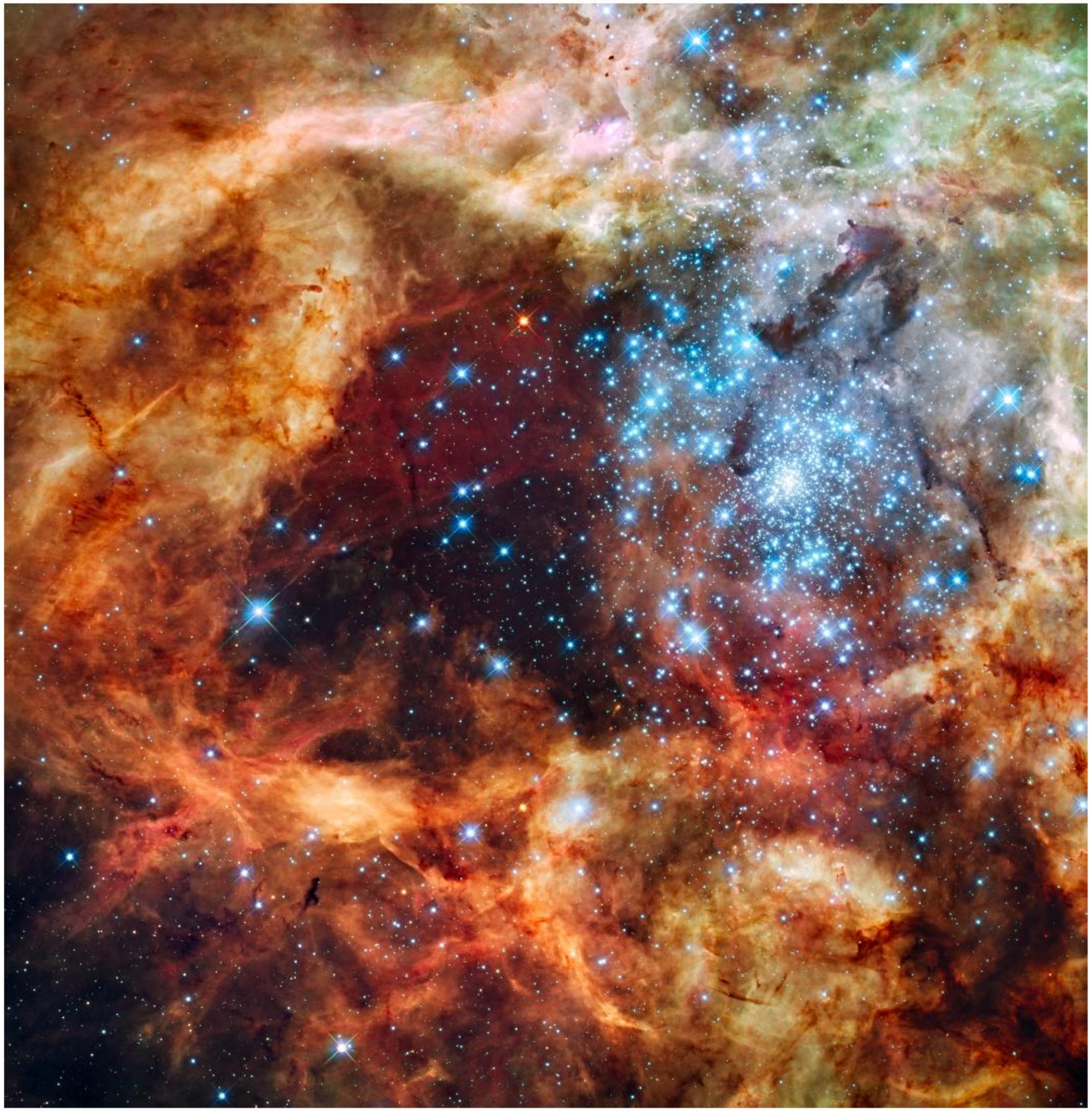


Giant Molecular Cloud

Many examples exist of opague regions of molecular gas which become visible when viewed in far-IR wavelengths

Emerging star cluster

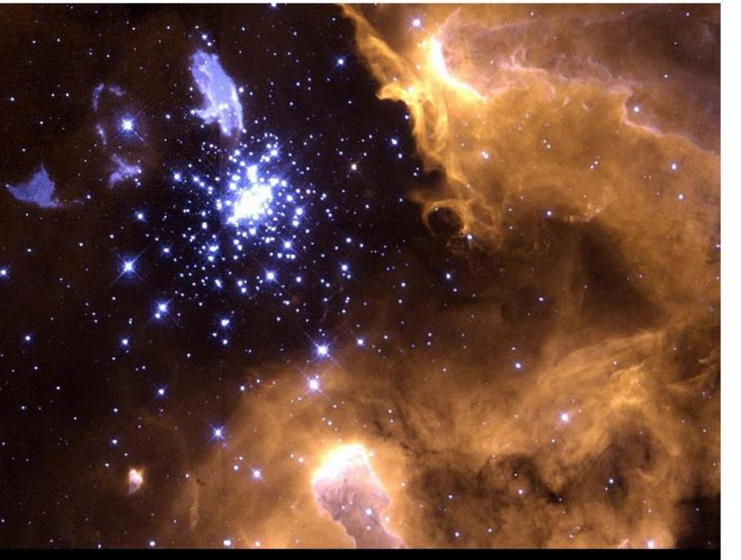
As stars form they first generate UV radiation ionising the surrounding gas and then SN shocks which push the material away revealing the young star cluster.

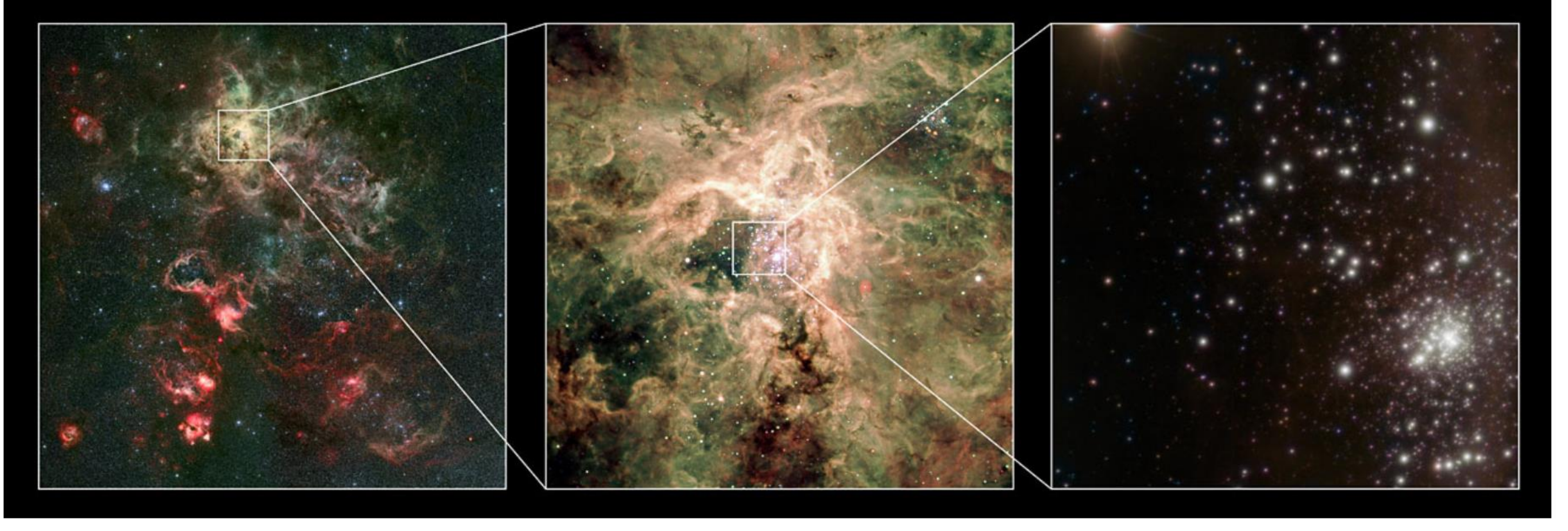


Early Supernovae

Process continues until star cluster is entirely distinct from the originally cloud.

Typically only a small fraction of the original gas cloud has been converted into stars, the rest survives for now…

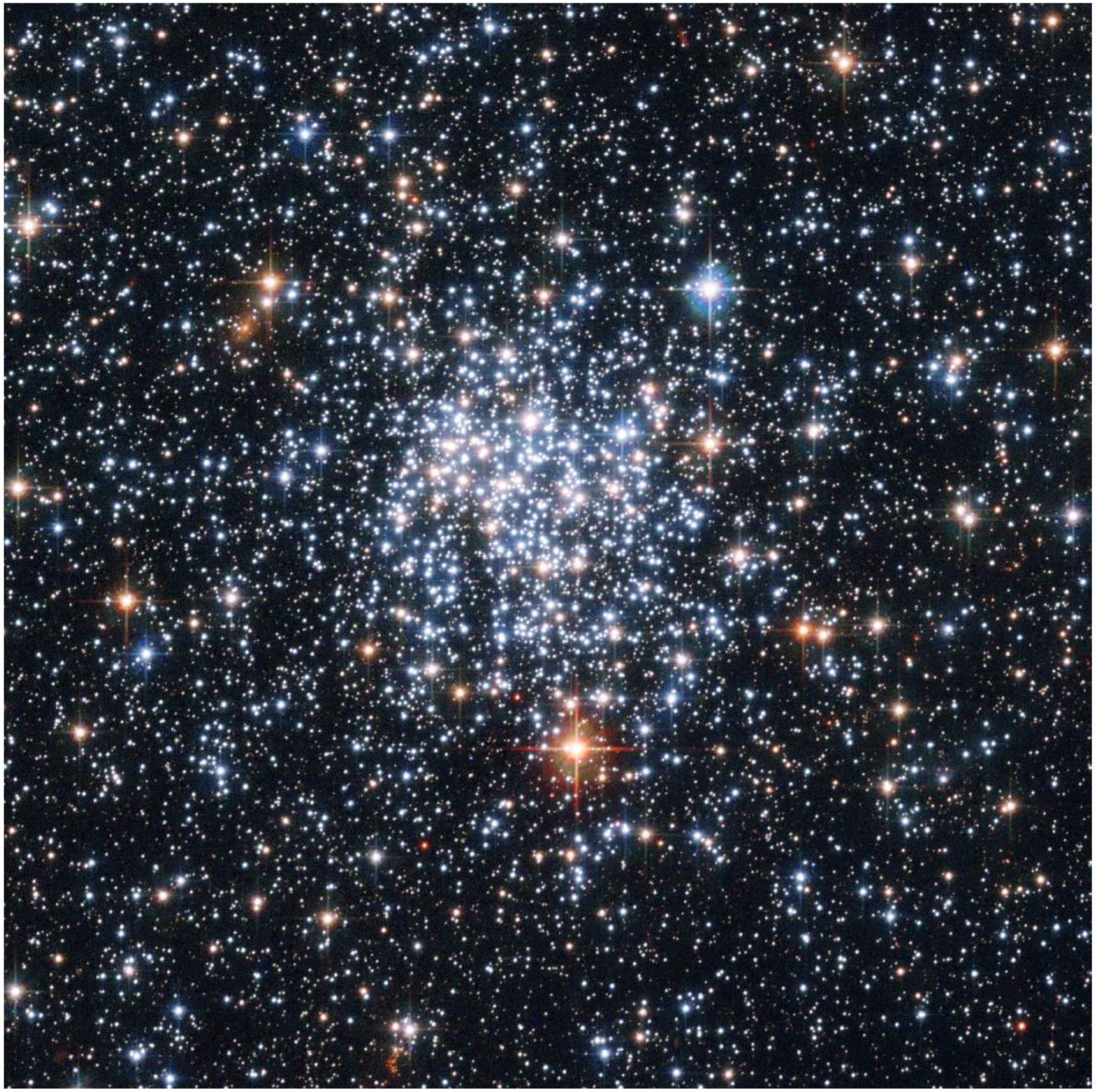




Young star cluster

In a young star cluster the stars appear to be quite concentrated but are not gravitational bound

As time goes by the stars will dissipate and moving apart to form an Open Cluster



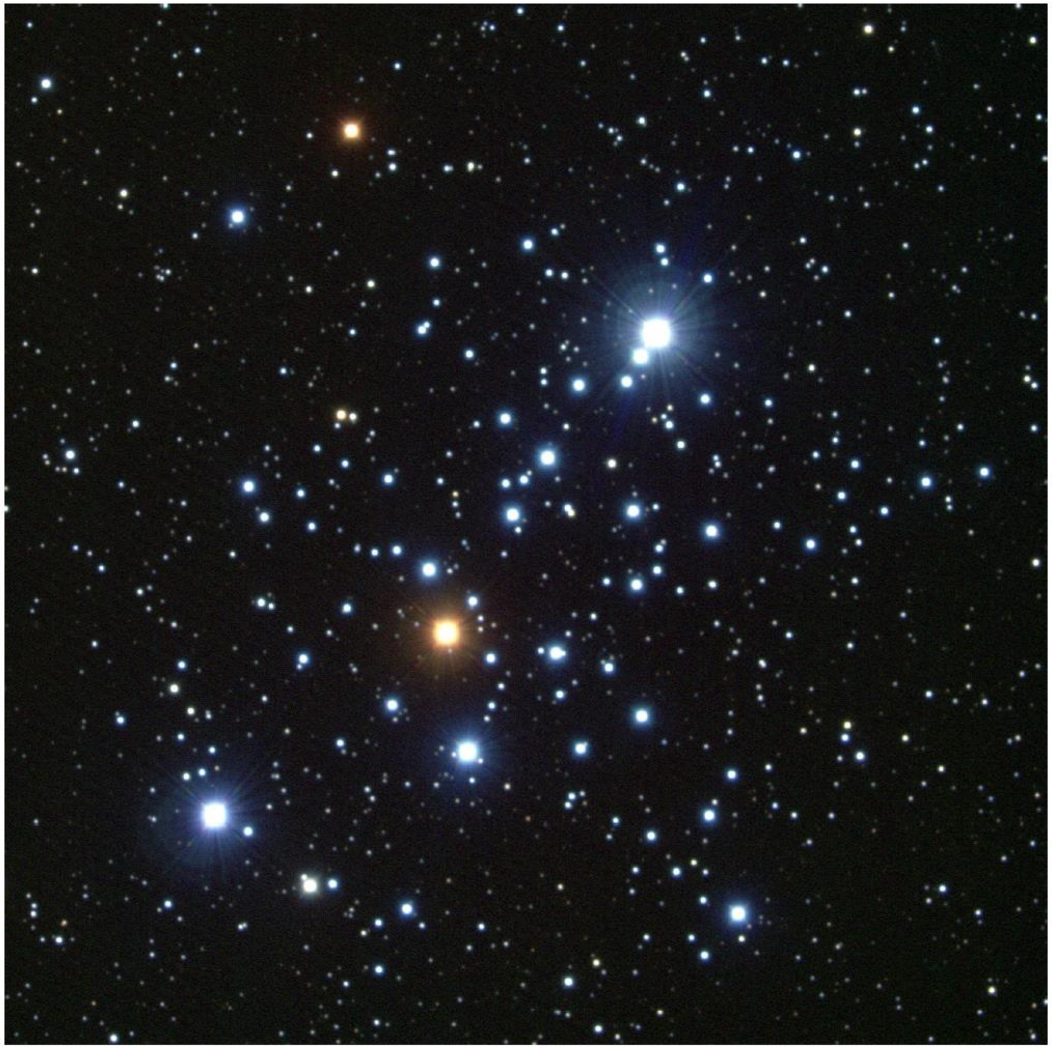
Open cluster

After a ~billion years the cluster has integrated into the galaxy as a whole.

Only the dynamical and chemical information provide relic signatures of its point of origin.

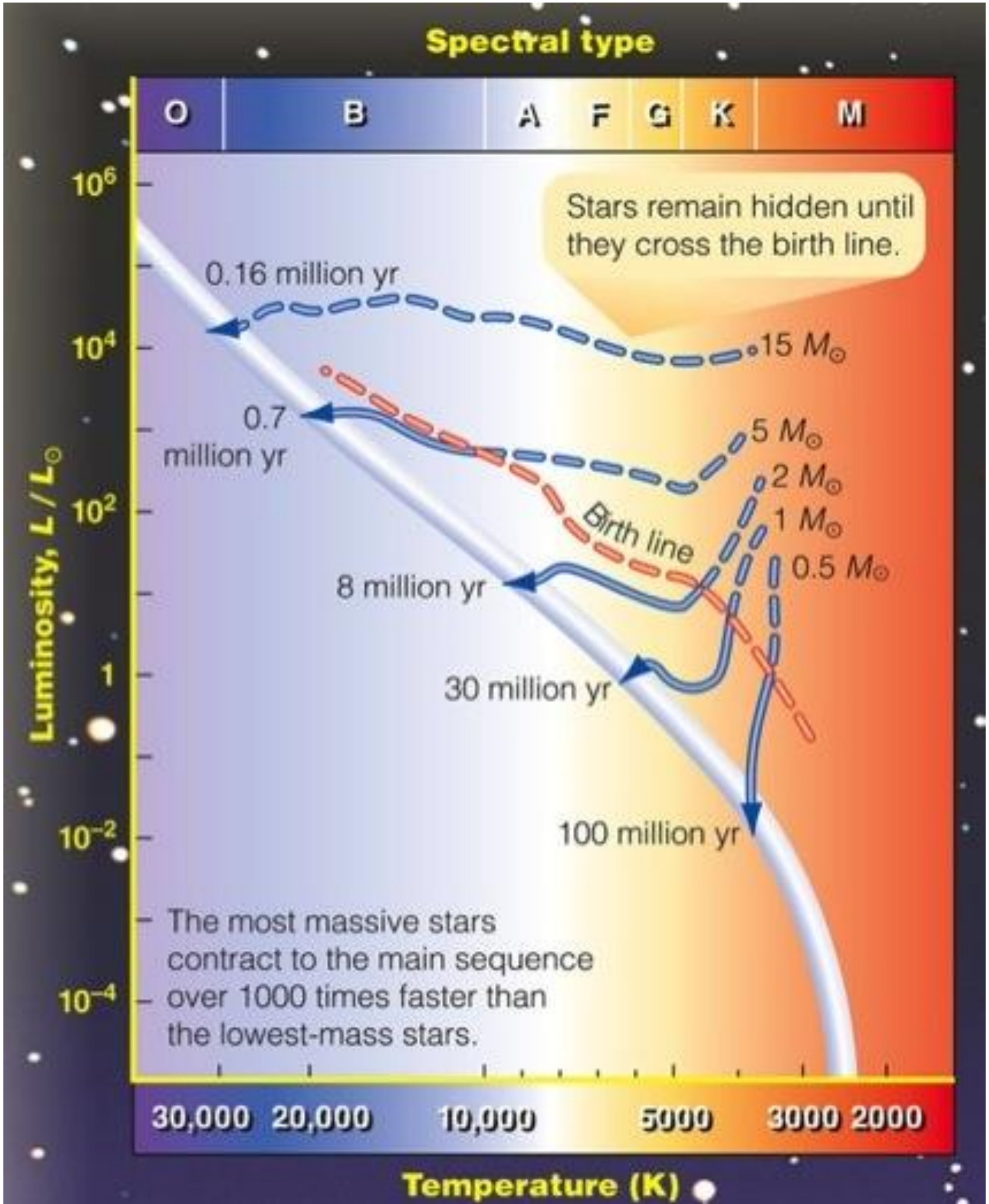
All stars formed from a cloud will carry a distinctive chemical tag reflecting the composition of the parent cloud

Projects are underway to tag all stars in the Galaxy to determine their origins.



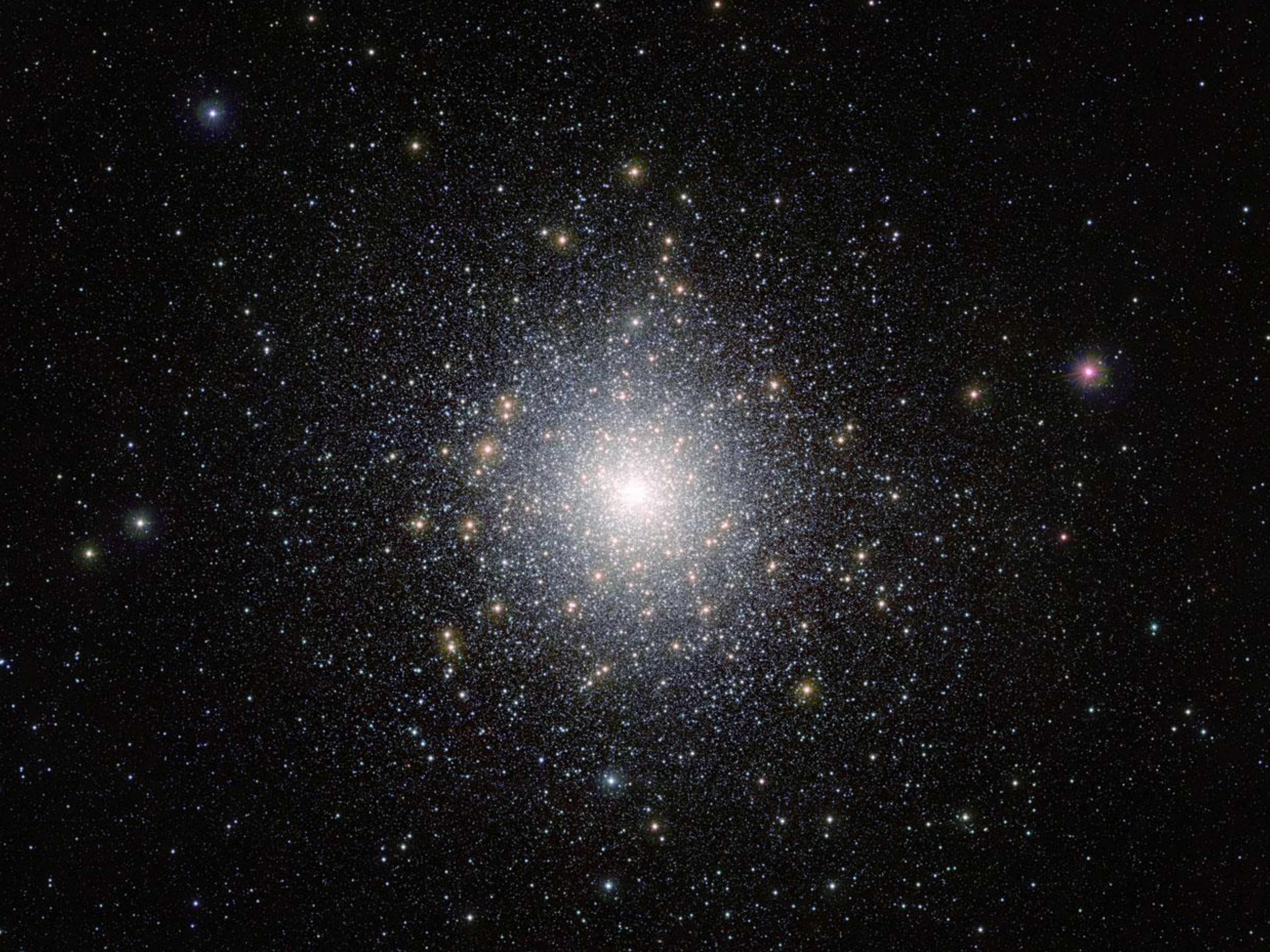
https://www.youtube.com/watch?v=_mr9y4F6ME4

6144 stars, credit Simon Zwart & Frank Summers

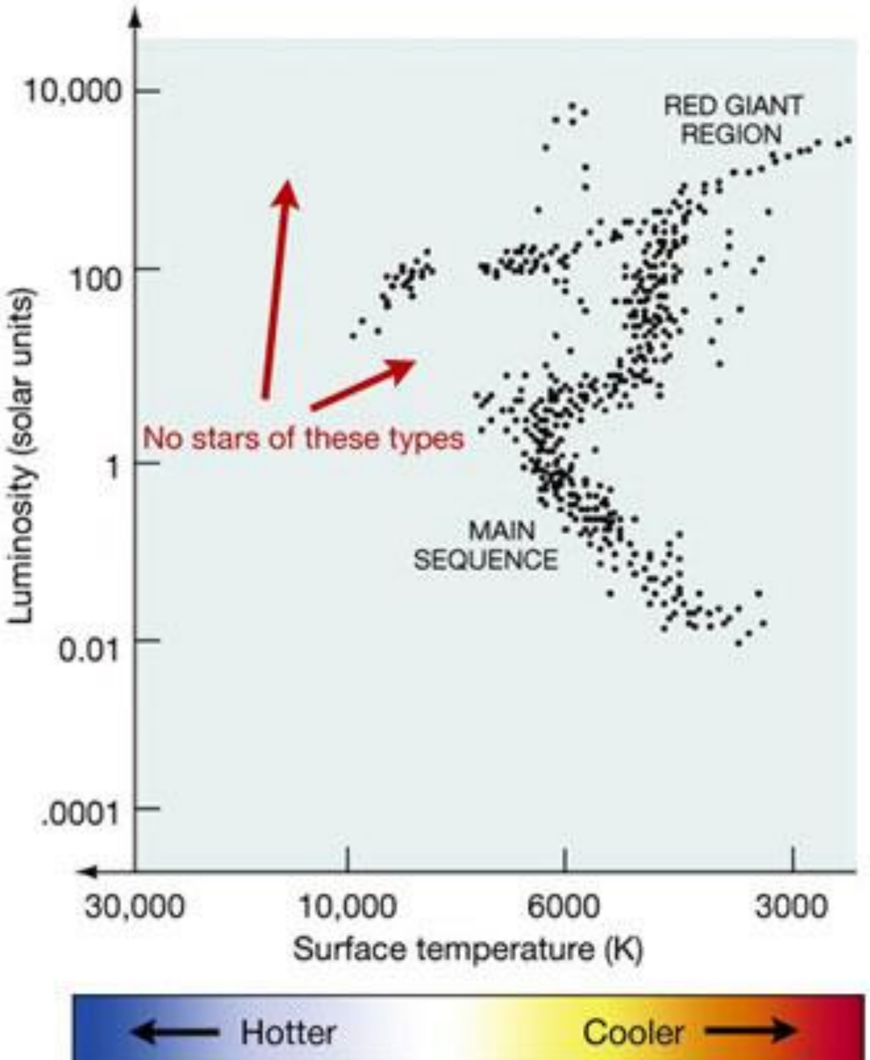


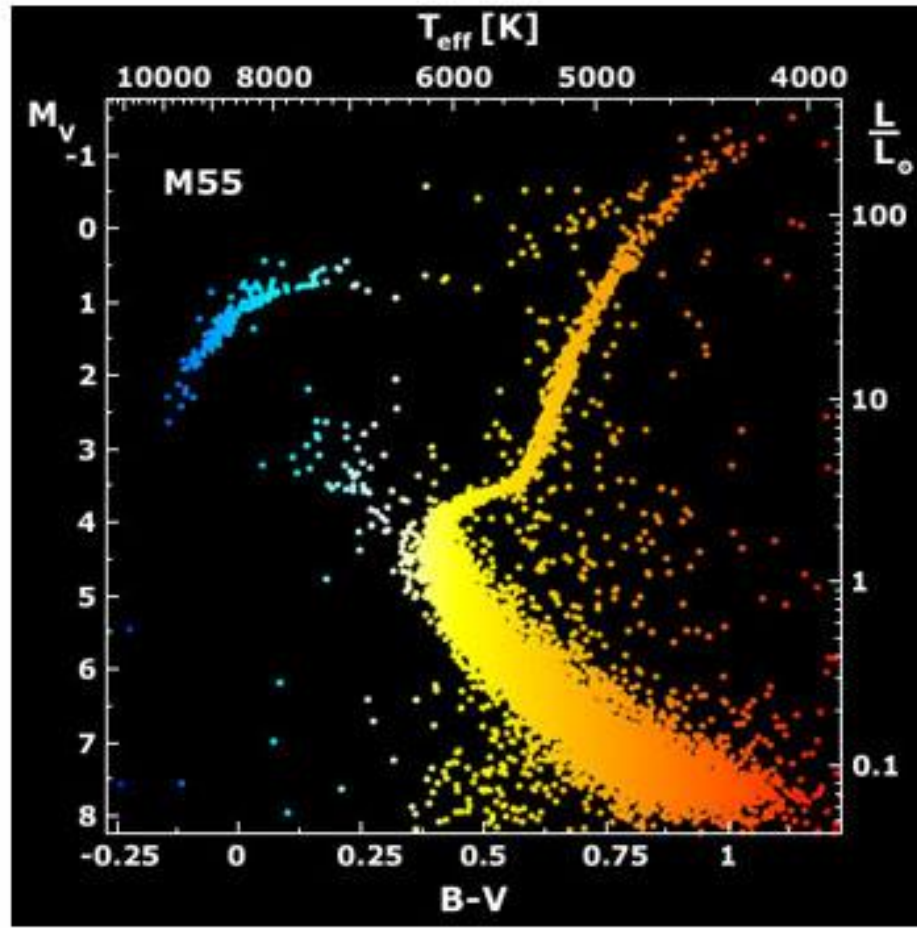
Spectral type
O
B
A
F
G
K
M
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity, $L / L_\odot$
Stars remain hidden until they cross the birth line.
0.16 million yr
15 $M_\odot$
0.7 million yr
5 $M_\odot$
2 $M_\odot$
1 $M_\odot$
0.5 $M_\odot$
Birth line
8 million yr
30 million yr
100 million yr
The most massive stars contract to the main sequence over 1000 times faster than the lowest-mass stars.
30,000
20,000
10,000
5000
3000
2000
Temperature (K)

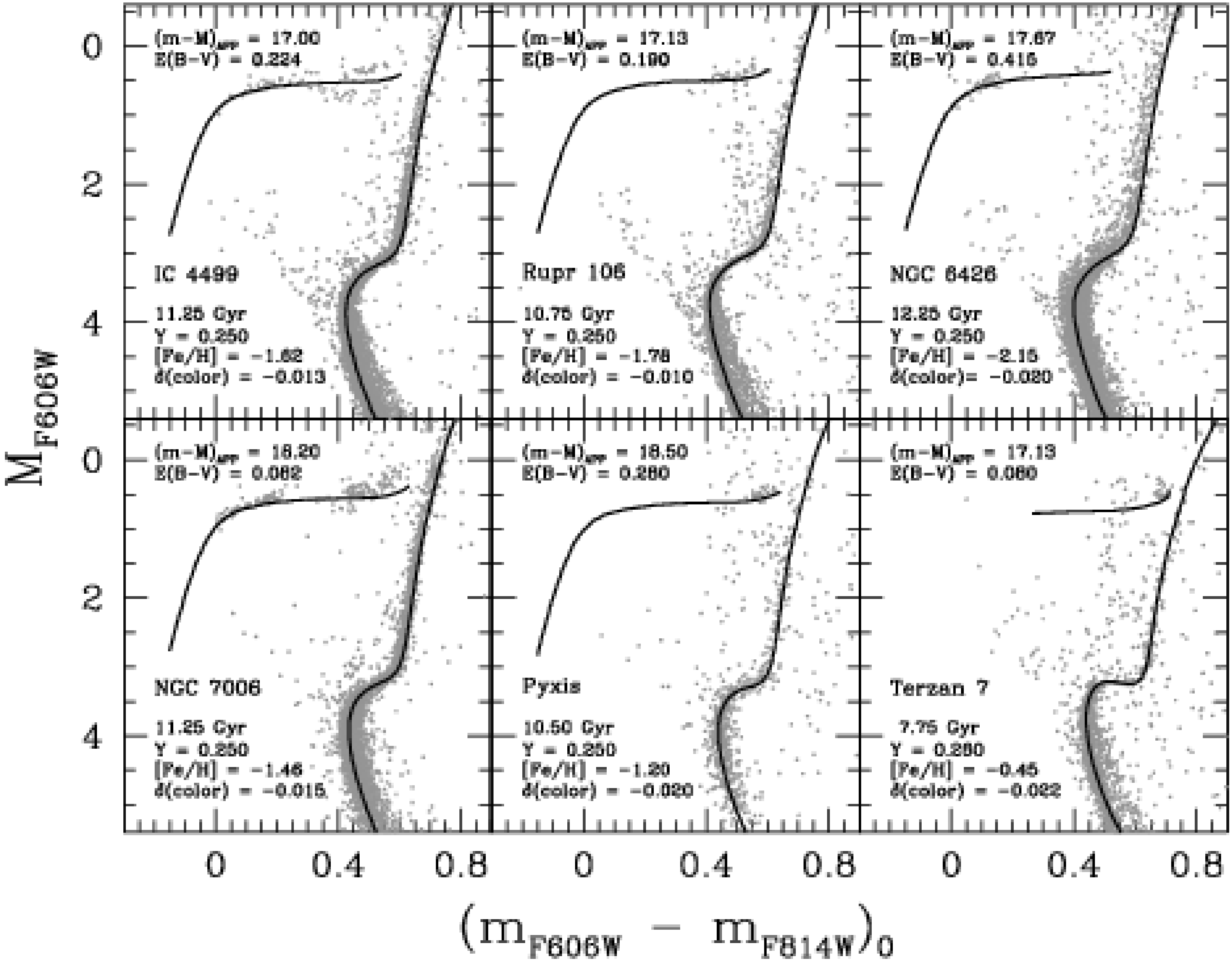
Ősi gömbhalmazok (globular cluster)



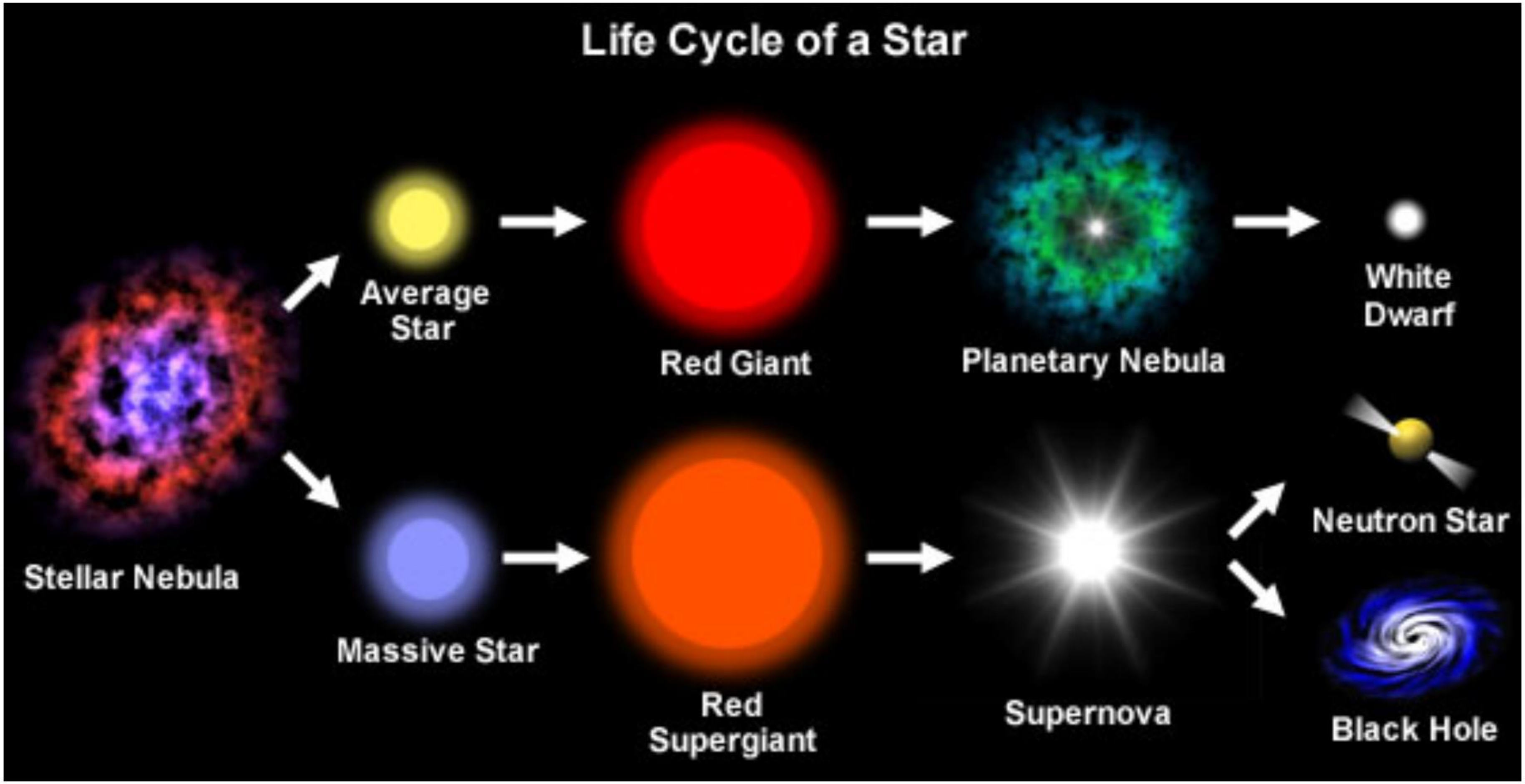
Gömbhalmazok H-R diagrammja



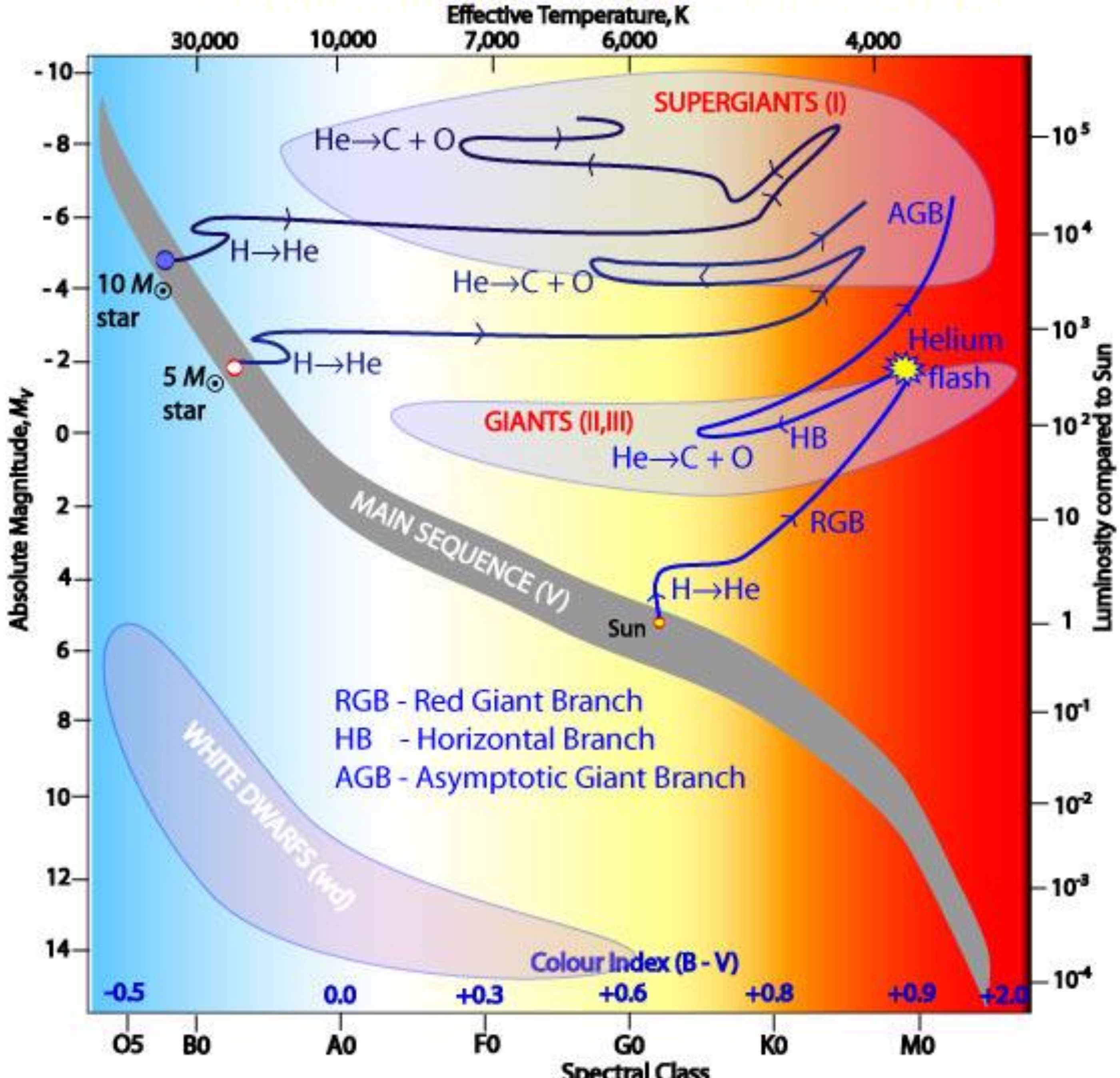




$(m-M)_{app}$ = 17.00
E(B−V) = 0.224
IC 4499
11.25 Gyr
Y = 0.250
[Fe/H] = −1.62
δ(color) = −0.013
$(m-M)_{app}$ = 17.13
E(B−V) = 0.190
Rupr 106
10.75 Gyr
Y = 0.250
[Fe/H] = −1.78
δ(color) = −0.010
$(m-M)_{app}$ = 17.67
E(B−V) = 0.416
NGC 6426
12.25 Gyr
Y = 0.250
[Fe/H] = −2.15
δ(color)= −0.020
$(m-M)_{app}$ = 18.20
E(B−V) = 0.082
NGC 7006
11.25 Gyr
Y = 0.250
[Fe/H] = −1.46
δ(color) = −0.015
$(m-M)_{app}$ = 18.50
E(B−V) = 0.280
Pyxis
10.50 Gyr
Y = 0.250
[Fe/H] = −1.20
δ(color) = −0.020
$(m-M)_{app}$ = 17.13
E(B−V) = 0.080
Terzan 7
7.75 Gyr
Y = 0.280
[Fe/H] = −0.45
δ(color) = −0.022
M_{F606W}
$(m_{F606W} - m_{F814W})_0$
0
2
4
0
0.4
0.8

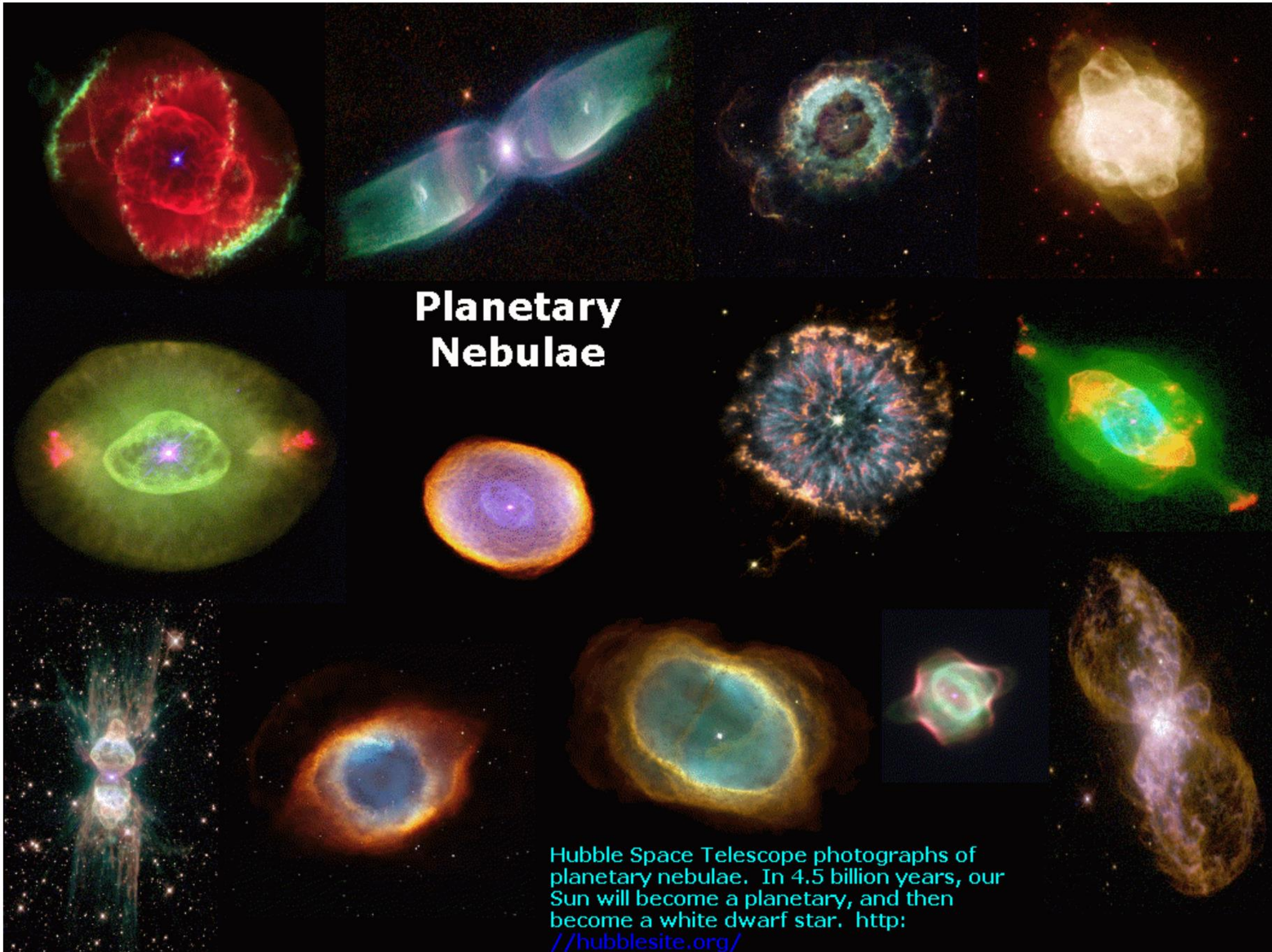

Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole

Evolutionary Tracks off the Main Sequence



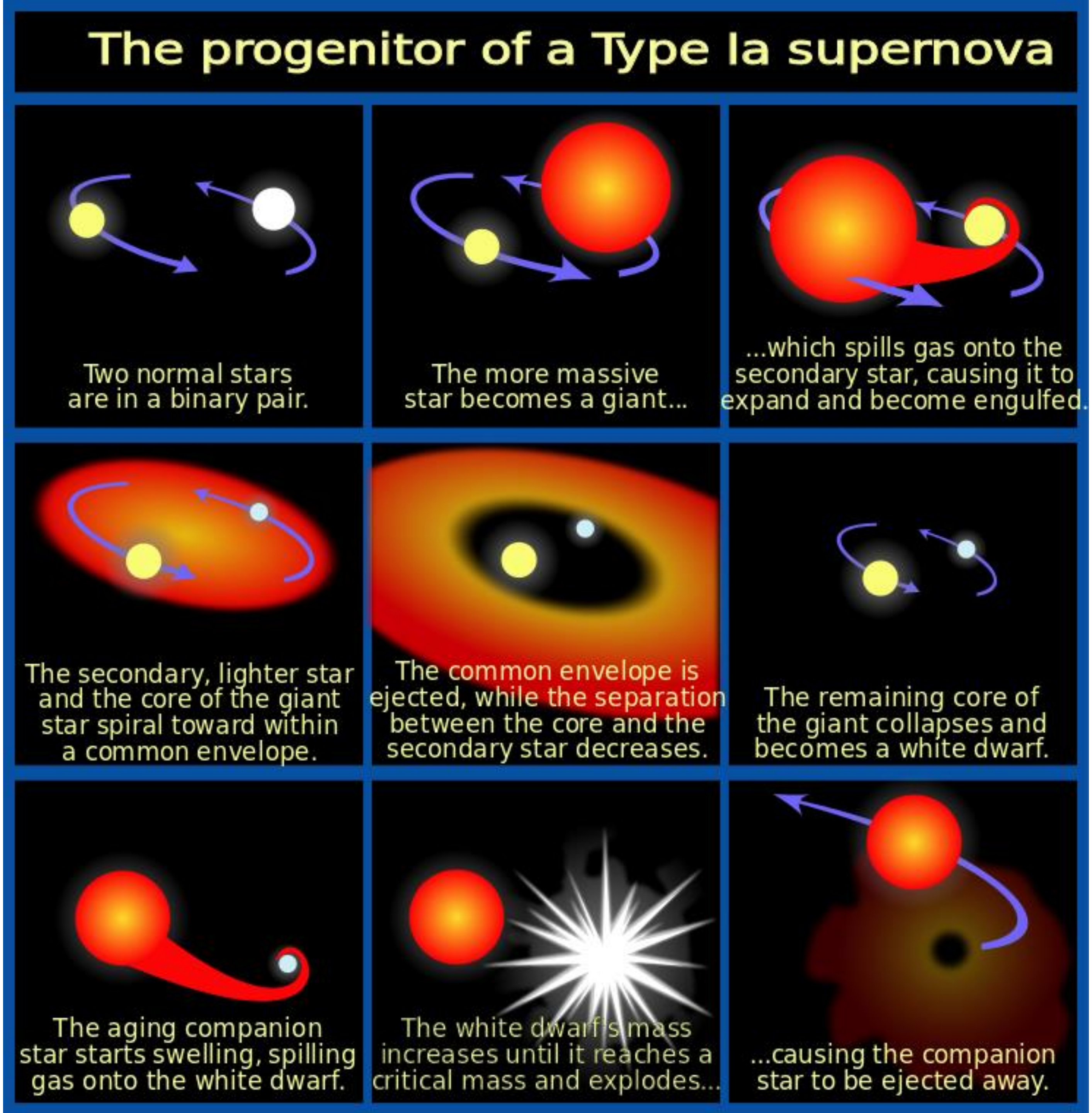
Final stages for low mass stars

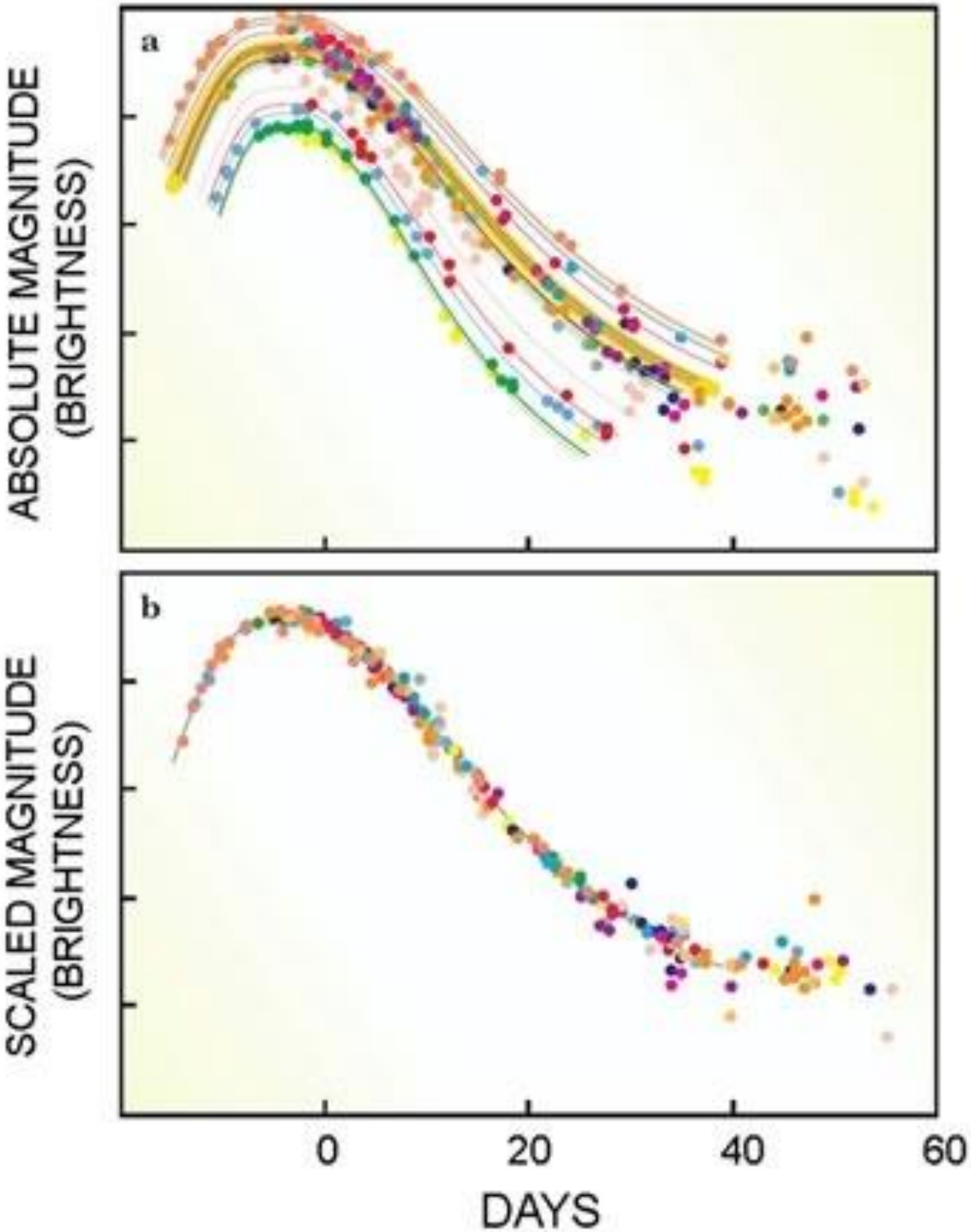
- Low mass stars with ZAMS mass < $4.0M_o$
  - Core continues to collapse but temperature not high enough for Carbon & Oxygen to ignite (fuse)
  - Core stops collapsing when all electrons are in the lowest energy states (Fermi Gas) allowed by the Pauli Exclusion principle
  - Electrostatic pressure prevents further collapse
  - Equilibrium is now restored as gravity v electrostatic pressure
  - Holds for core mass < $1.4M_o$ (the Chandrasakar Limit)
  - Independent of T so as star cools no further change
  - Outer shells slowly ejected giving rise to Planetary Nebulae
  - Stellar core is all that remains and dubbed a White Dwarf
  - Material locked up in core essentially now out of play unless mass is accreted, e.g., via binary (potentially leading to Type Ia Supernova)
  - One teaspoon of WD material = 5000 tons


Planetary
Nebulae
Hubble Space Telescope photographs of planetary nebulae. In 4.5 billion years, our Sun will become a planetary, and then become a white dwarf star. http://hubblesite.org/

Final stages for high mass stars

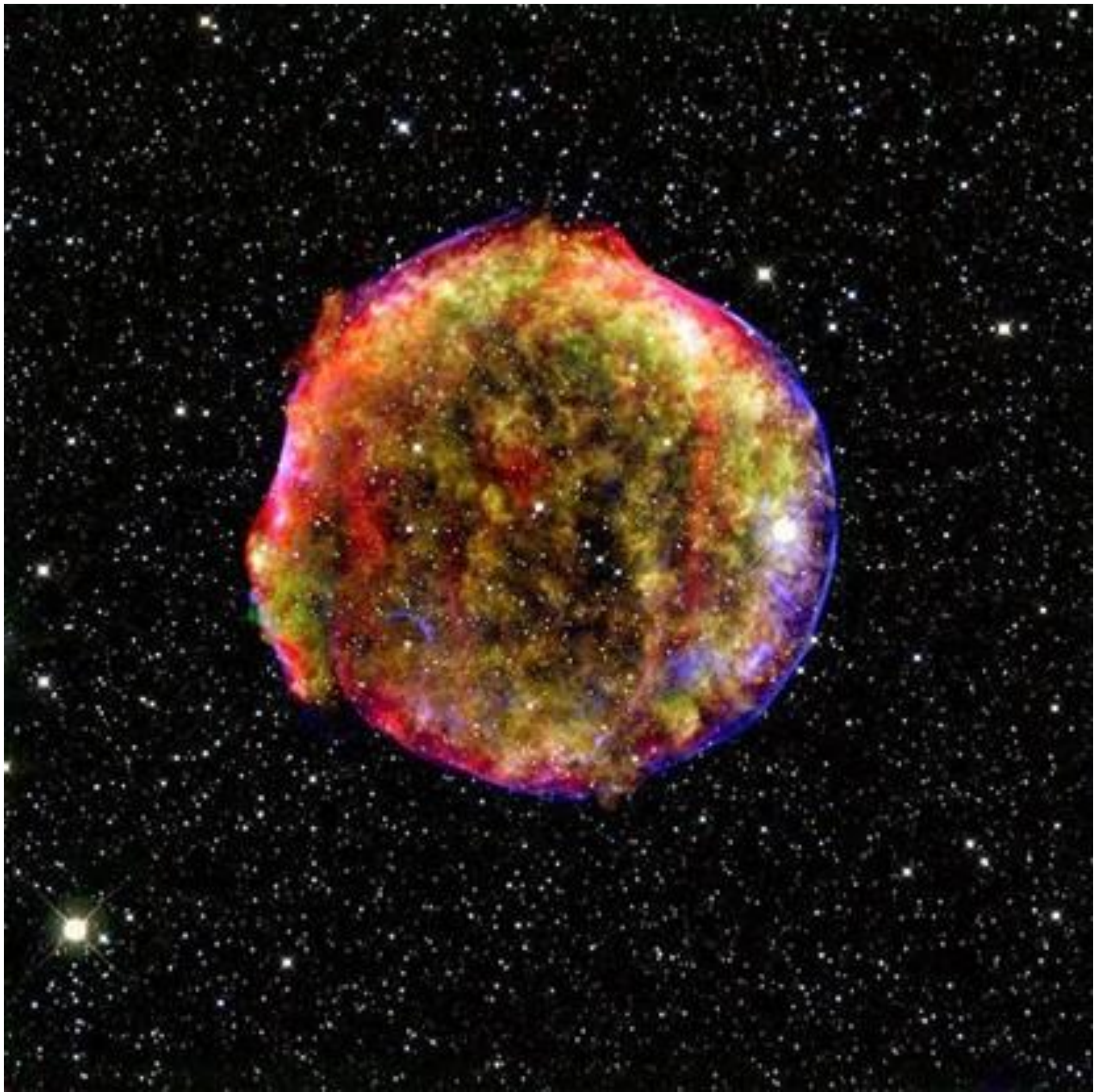
- If core > 1.4M_o gravitational force is sufficient to force electrons into nucleus resulting in further core compression
- Compression heats core and C&O undergoes fusion → Ne
- If M_{ZAMS}<8M_o fusion stops after C and O core depleted
  - Shell ejected rapidly (Supernova) and core reaches equilibrium once all electrons are forced into nuclei creating a Neutron Star
- If M_{ZAMS}>8 then Ne, O, Si can fuse → Fe
  - Shell ejected explosively (Supernova) and core collapses beyond neutron star to form a Black Hole
- Each successive phase of fusion progresses faster as temperature gets ever higher

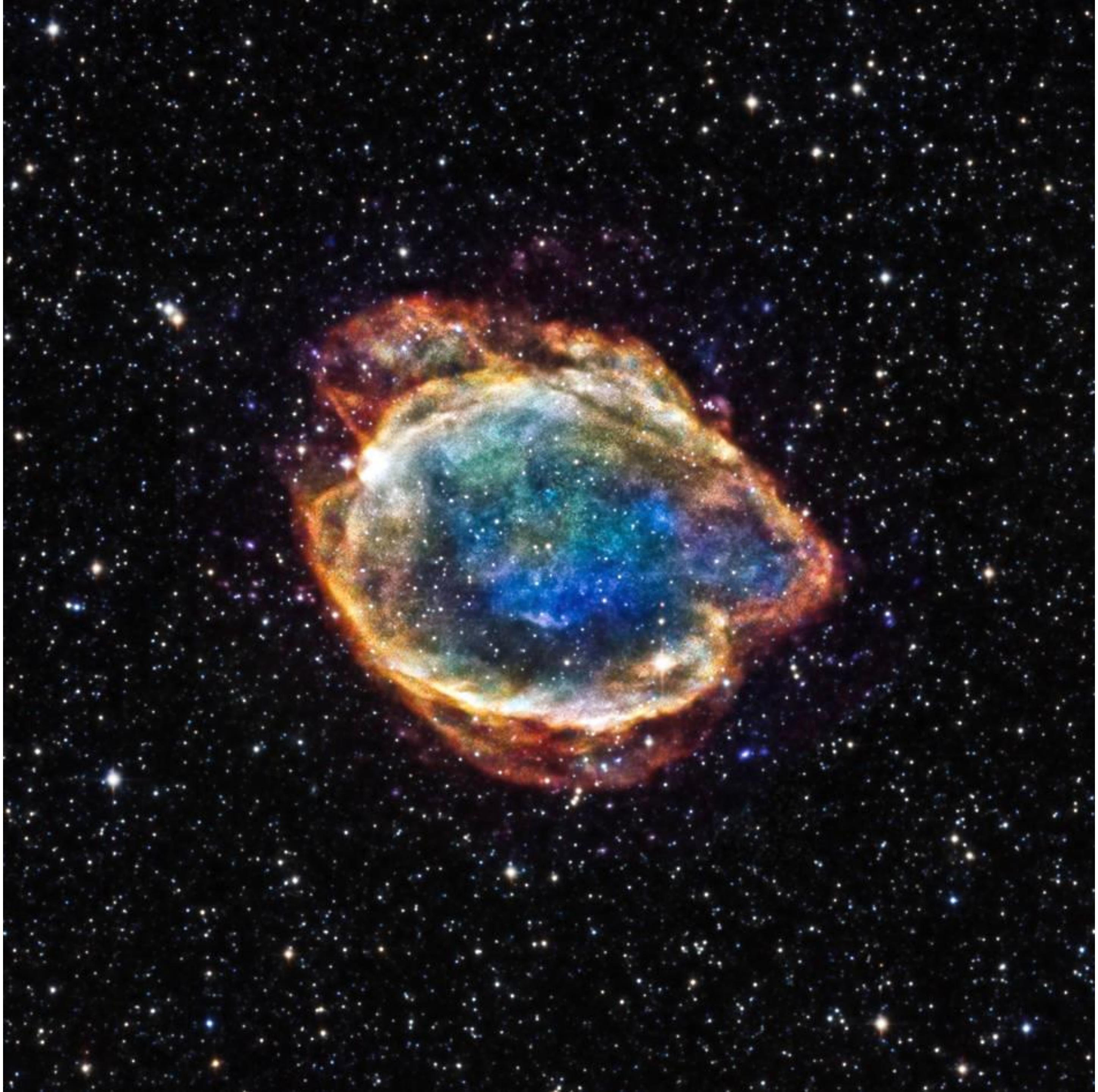

The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.



a
ABSOLUTE MAGNITUDE (BRIGHTNESS)
b
SCALED MAGNITUDE (BRIGHTNESS)
0
20
40
60
DAYS

Tycho Brache szupernovája (Type I) SN1572

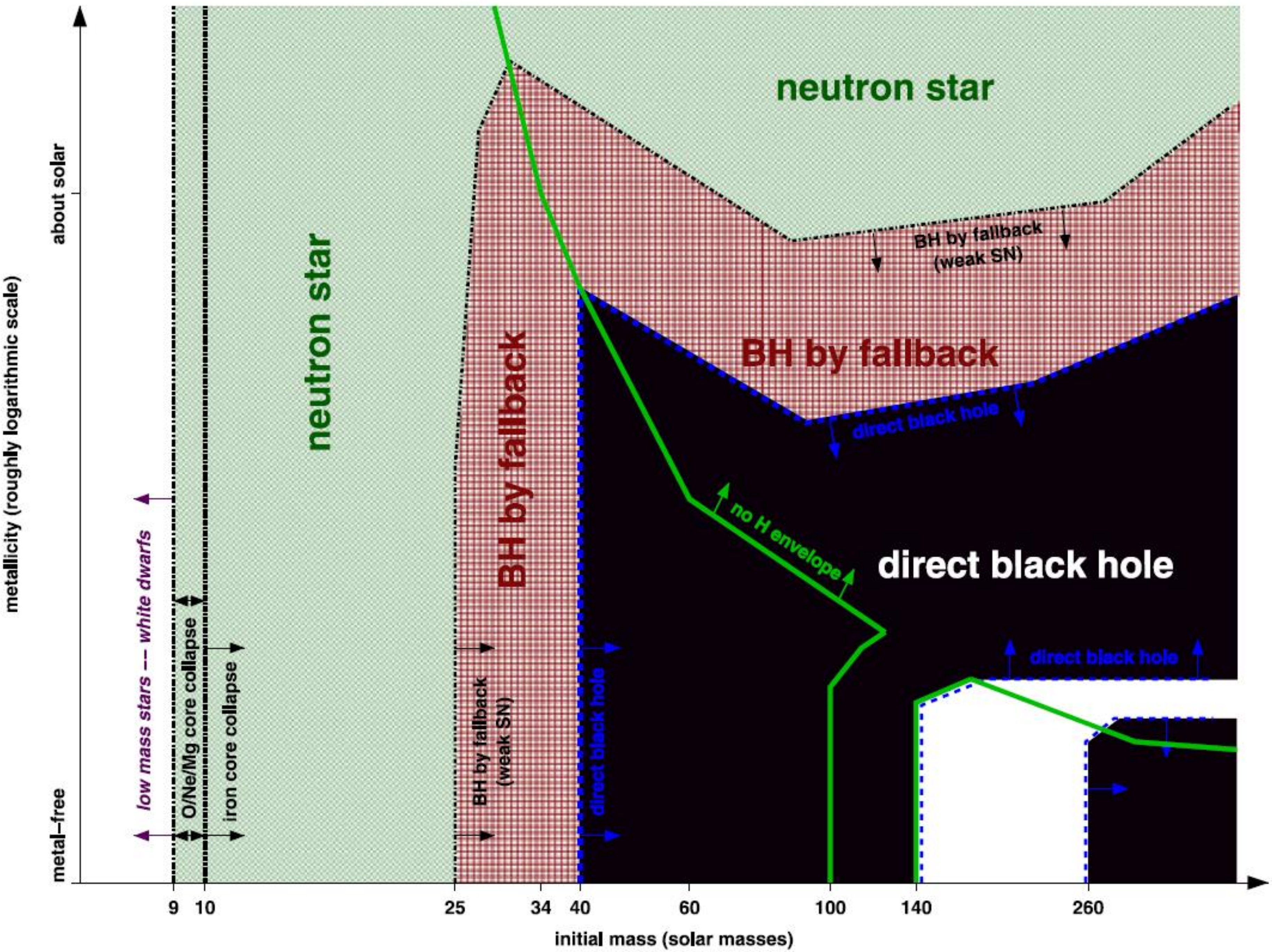




Core collapse Supernova (Type II)

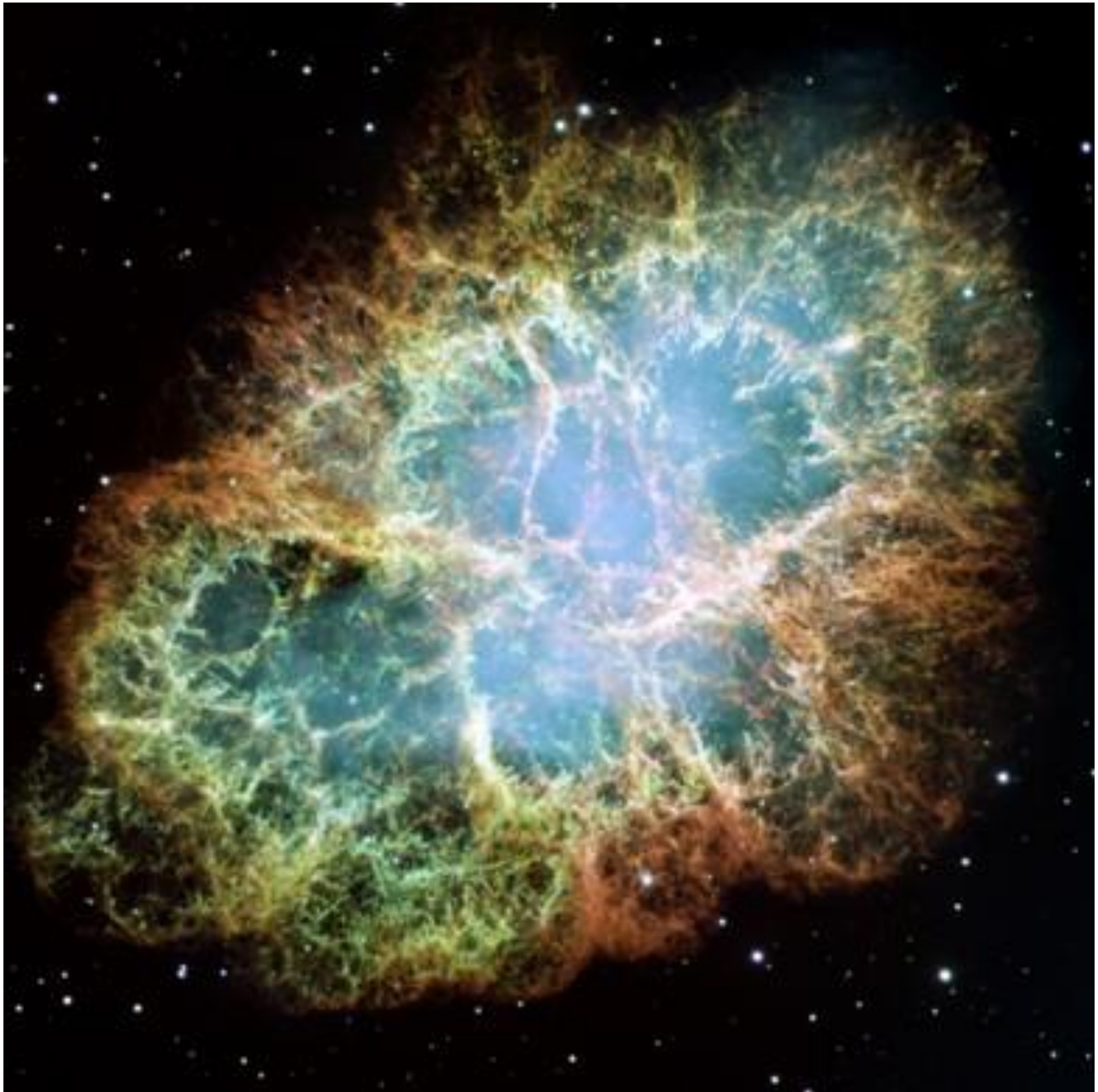
- When core contracts beyond WD phase electrons are forced into nucleus and combine with protons releasing neutrinos
- Neutrinos carry away energy allowing core collapse to accelerate
- Core rapidly contracts until all electrons are packed into the nucleus at which point core becomes rigid and infalling material bounces creating an outward pressure wave pushed on by neutrinos
- As pressure wave propagates into lower density (lower opacity) it accelerates to become a high velocity shockwave: a supernova

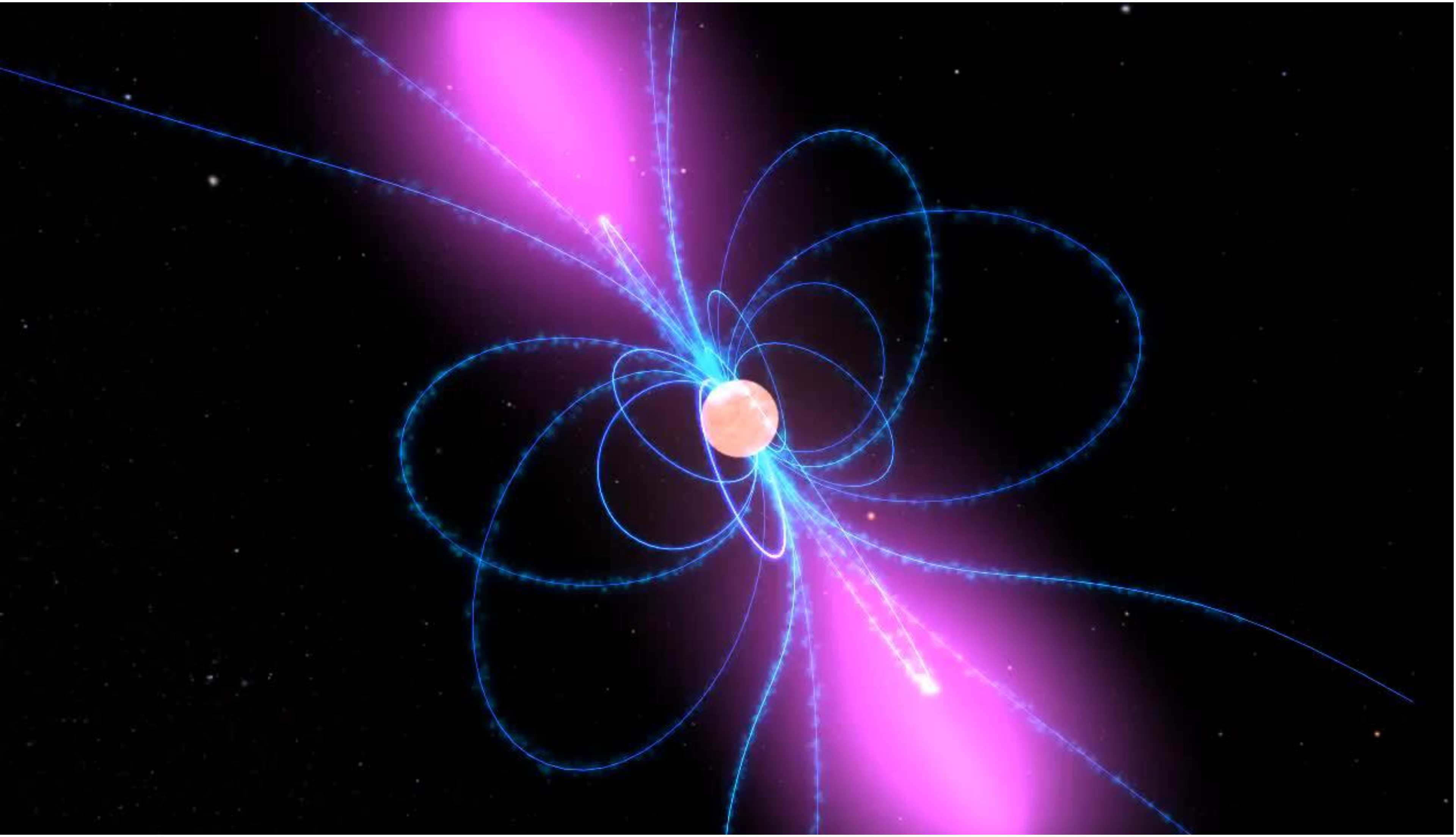
Note: Above scenario developed via theoretical and numerical models. Some elements, e.g., high neutrino flux confirmed via SN1987A



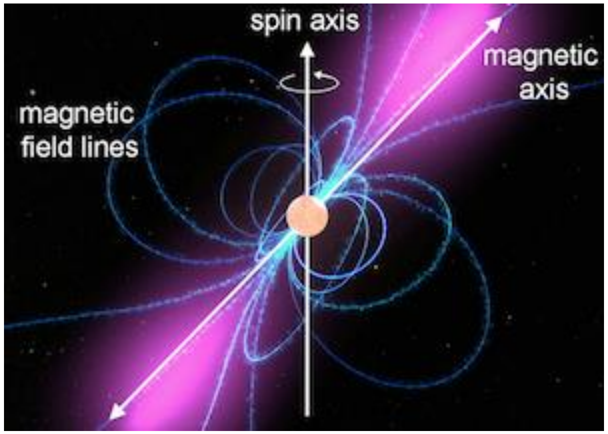
neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback
(weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
BH by fallback
(weak SN)
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
about solar
metal-free
metallicity (roughly logarithmic scale)
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

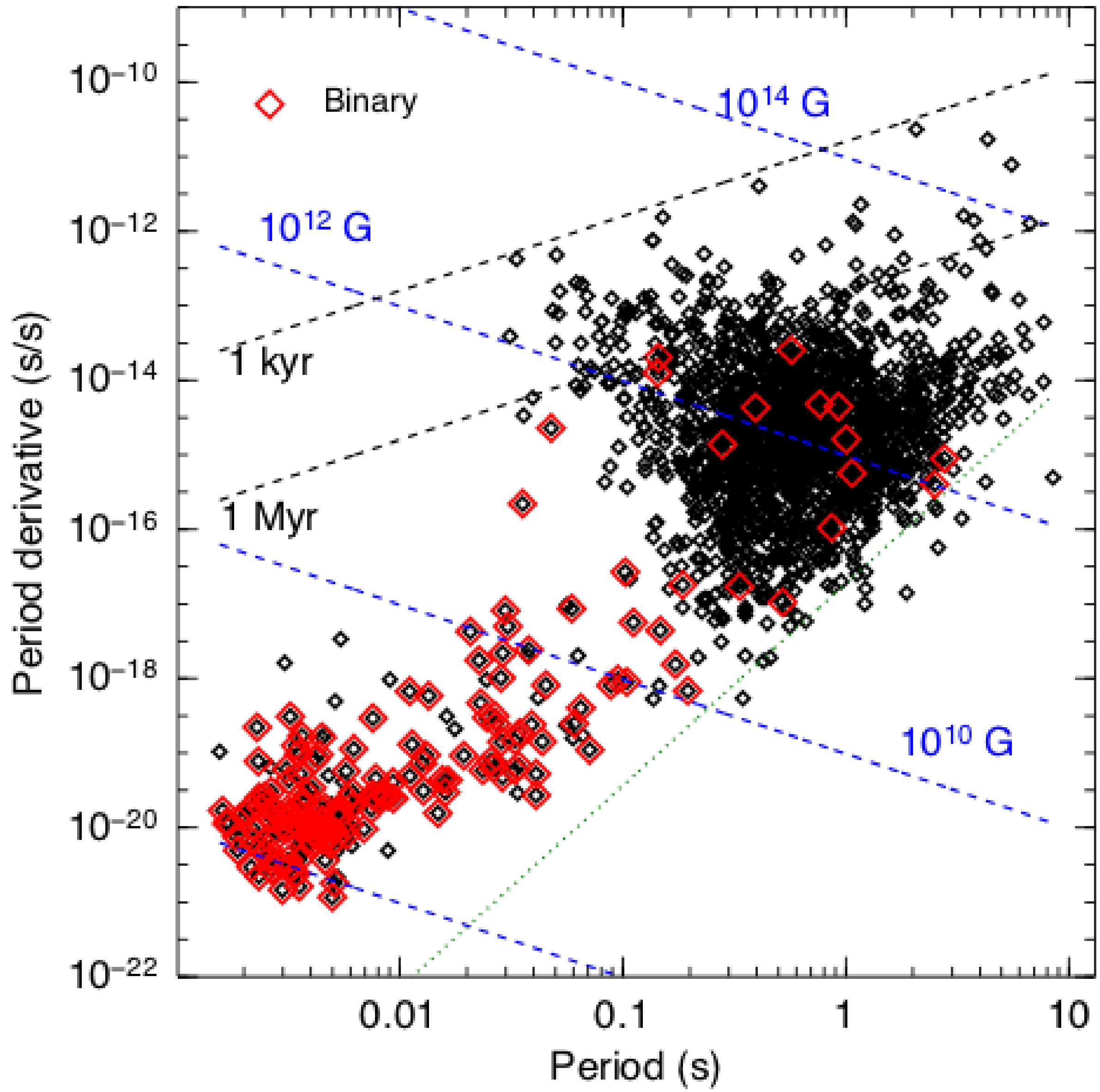
Type-II szupernova (rák köd)



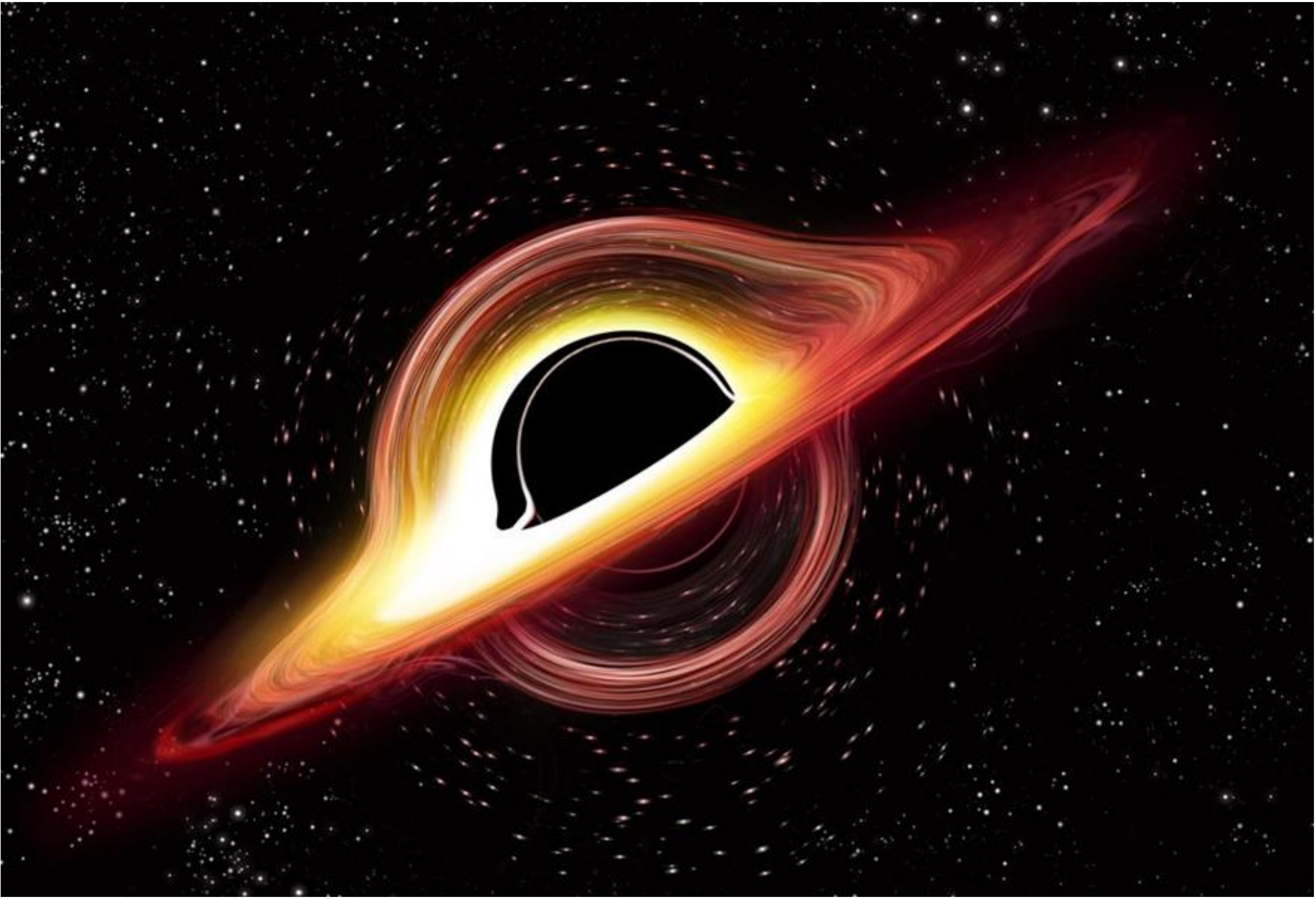


Neutroncsillag – pulzár periódus



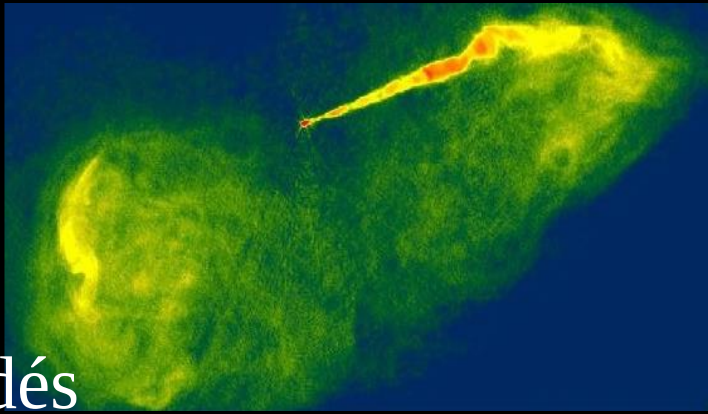


Fekete Lyuk

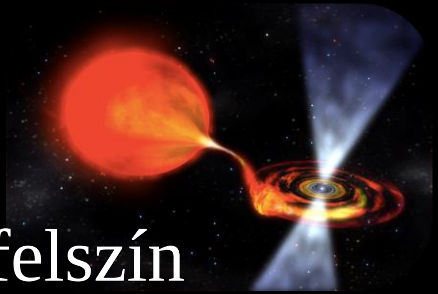


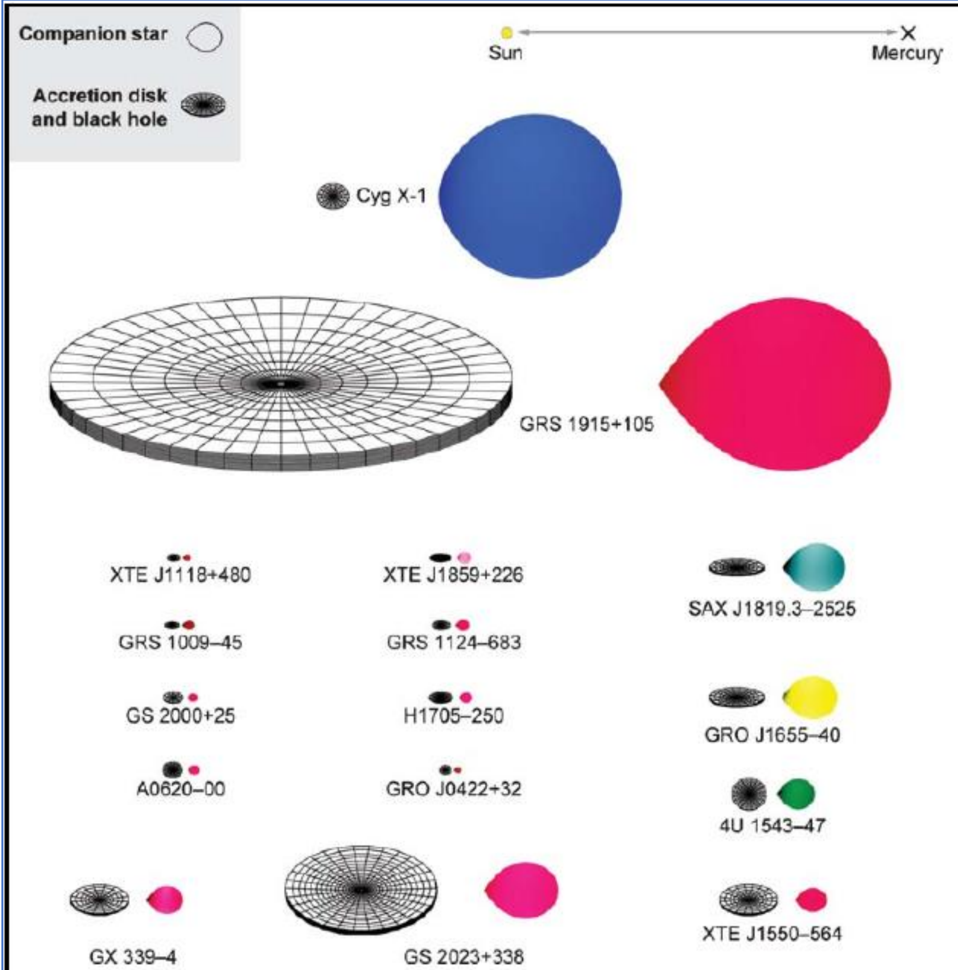
Világító fekete lyukak

- Aktív galaxismag
  - Nagyon kis tértartomány túlragyogja a galaxist
  - hónapos időkálán változik
  - relativisztikus jetek 0.999c
  - Gáz keringési sebesség 0.1c
  - relativisztikus vonalkiszélesedés



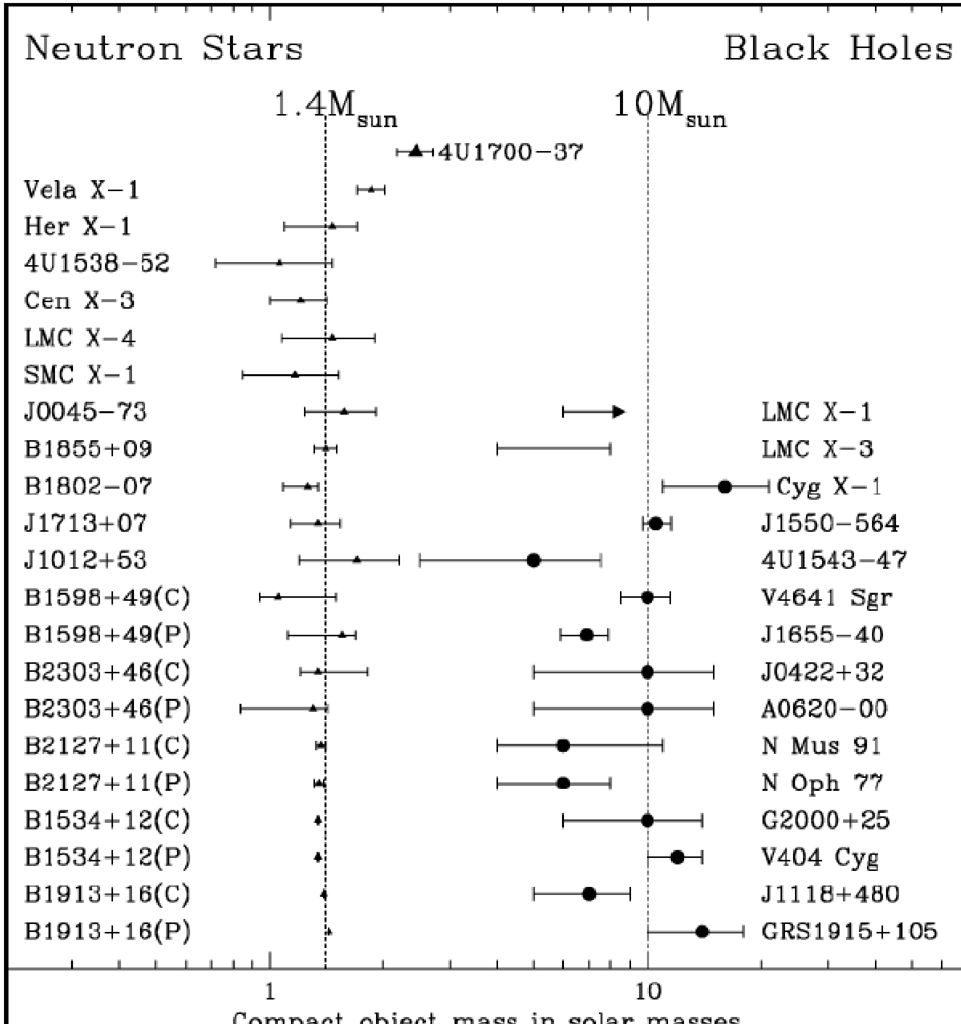
- Fekete lyuk kettősök (naptömegű)
  - csillag + fekete lyuk
  - változó röntgen emisszió
  - spektrum arra utal, hogy nincs felszín



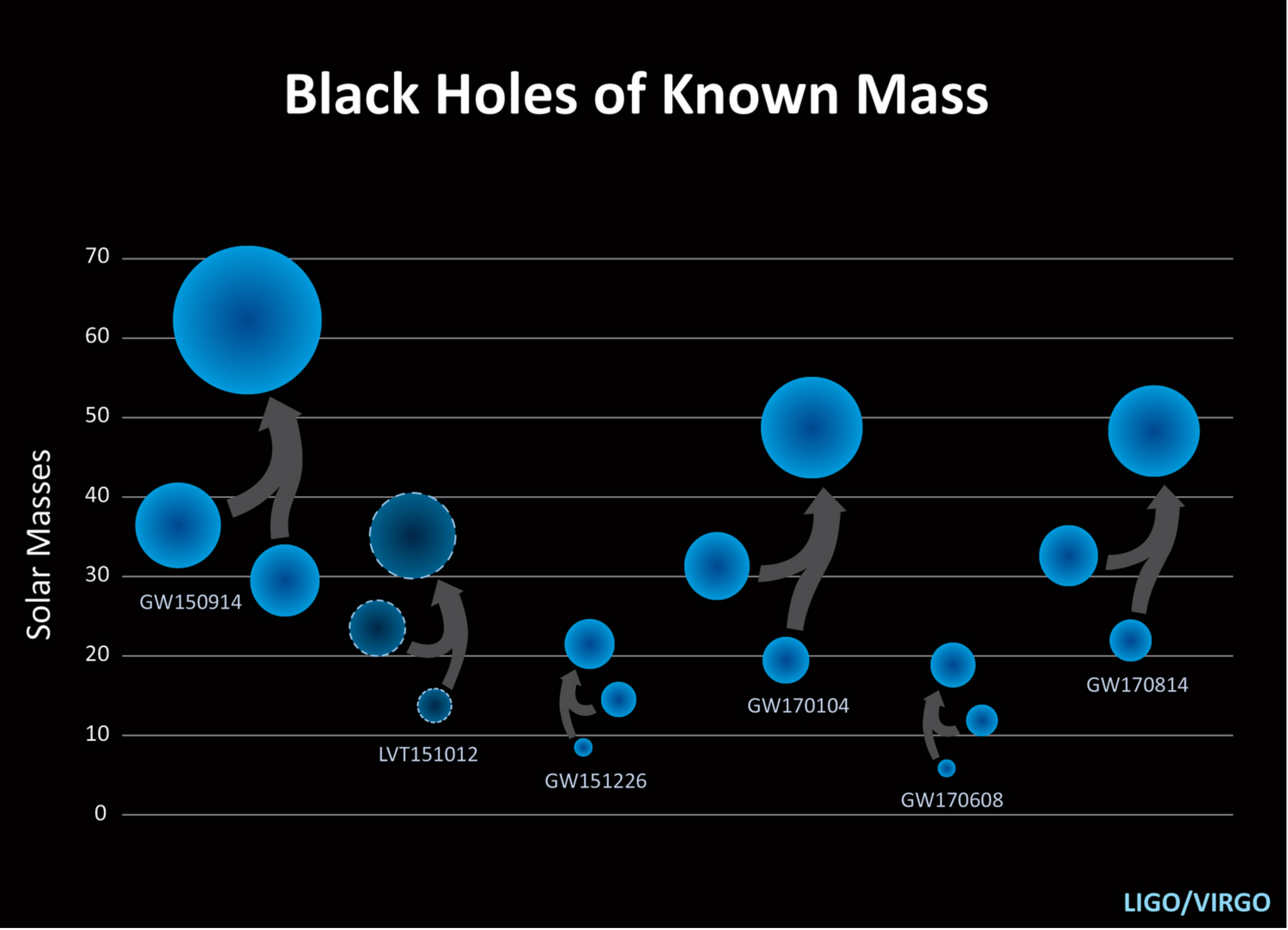


Binary systems with massive compact objects

Ordinary star + "something else" – a neutron star or BH

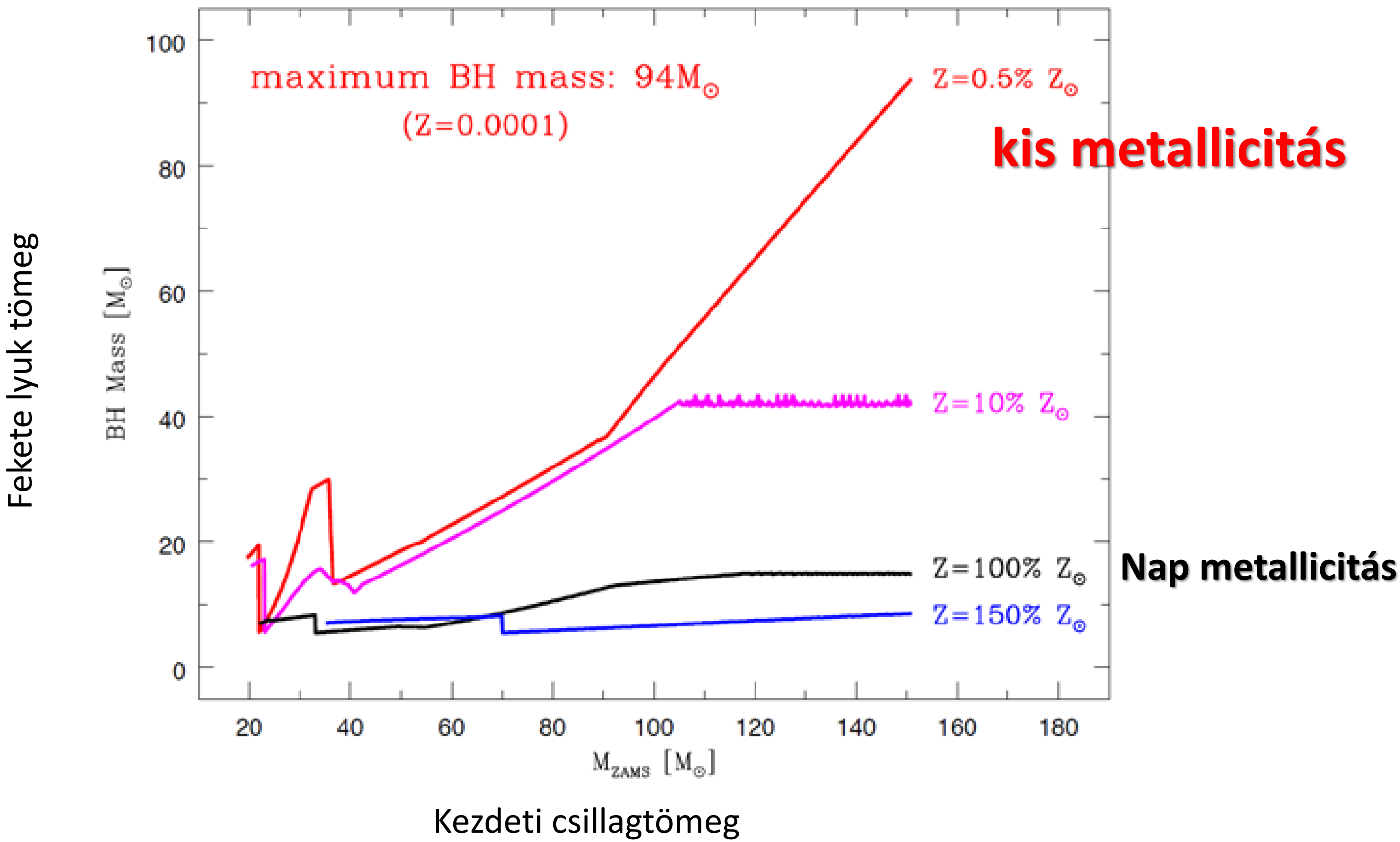


About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
LIGO/VIRGO

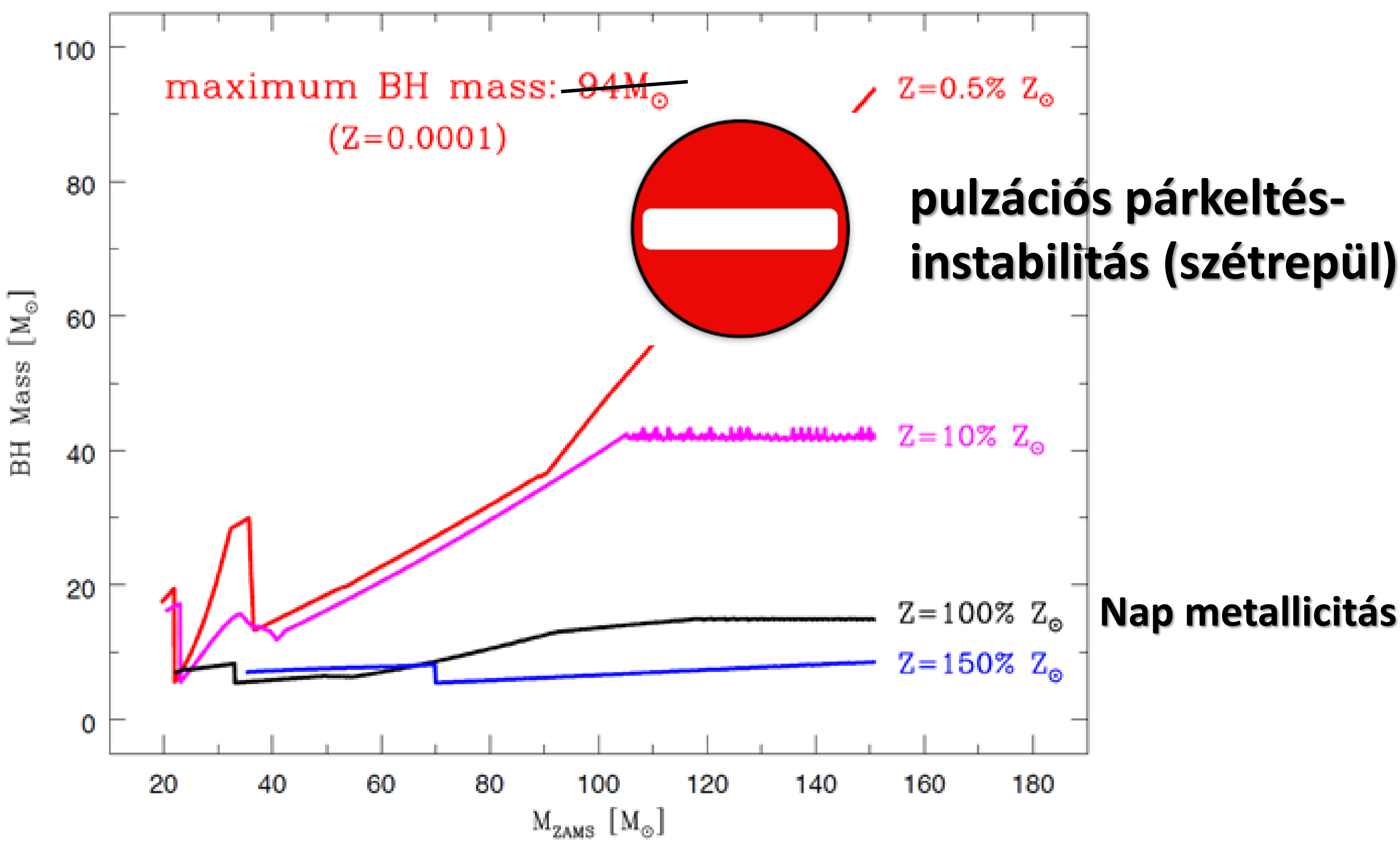
Milyen tömegű lesz a fekete lyuk?

Belczynski et al. 2010a (ApJ 714, 1217)



Milyen tömegű lesz a fekete lyuk?

Belczynski et al. 2010a (ApJ 714, 1217)



Fekete lyuk tömeg

Kezdeti csillagtömeg

Eddington luminozitás

Hidrodinamikai egyensúly:

a sugárzás nyomása ellentart a gravitációnak

sugárnyomás → fluxus → luminozitás

Eddington luminozitás

$$\frac{du}{dt} = -\frac{\nabla p}{\rho} - \nabla \Phi = 0$$

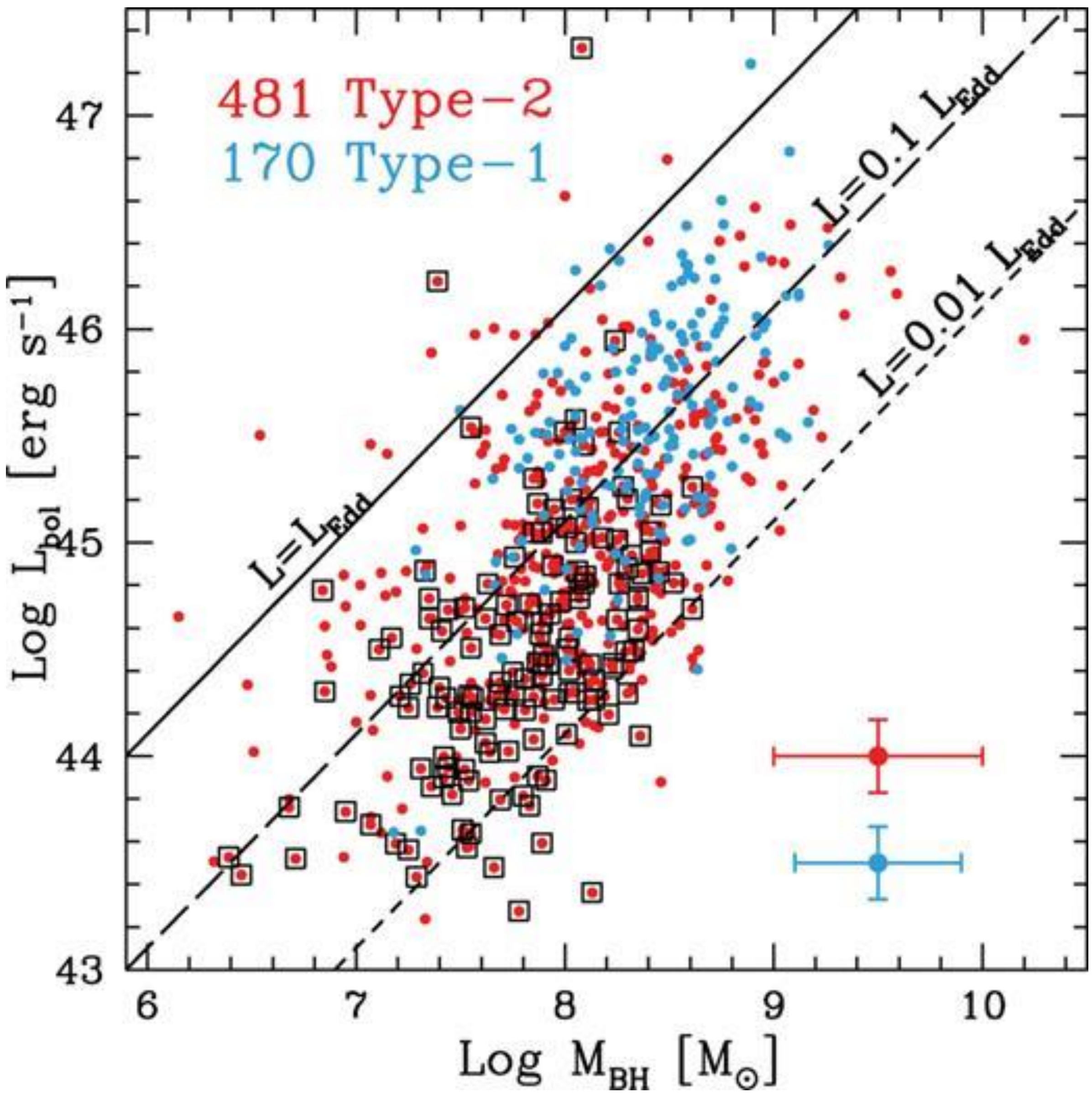
$$-\frac{\nabla p}{\rho} = \frac{\kappa}{c} F_{\rm rad}$$

$$L = \int_S F_{\rm rad} \cdot dS = \int_S \frac{c}{\kappa} \nabla \Phi \cdot dS$$

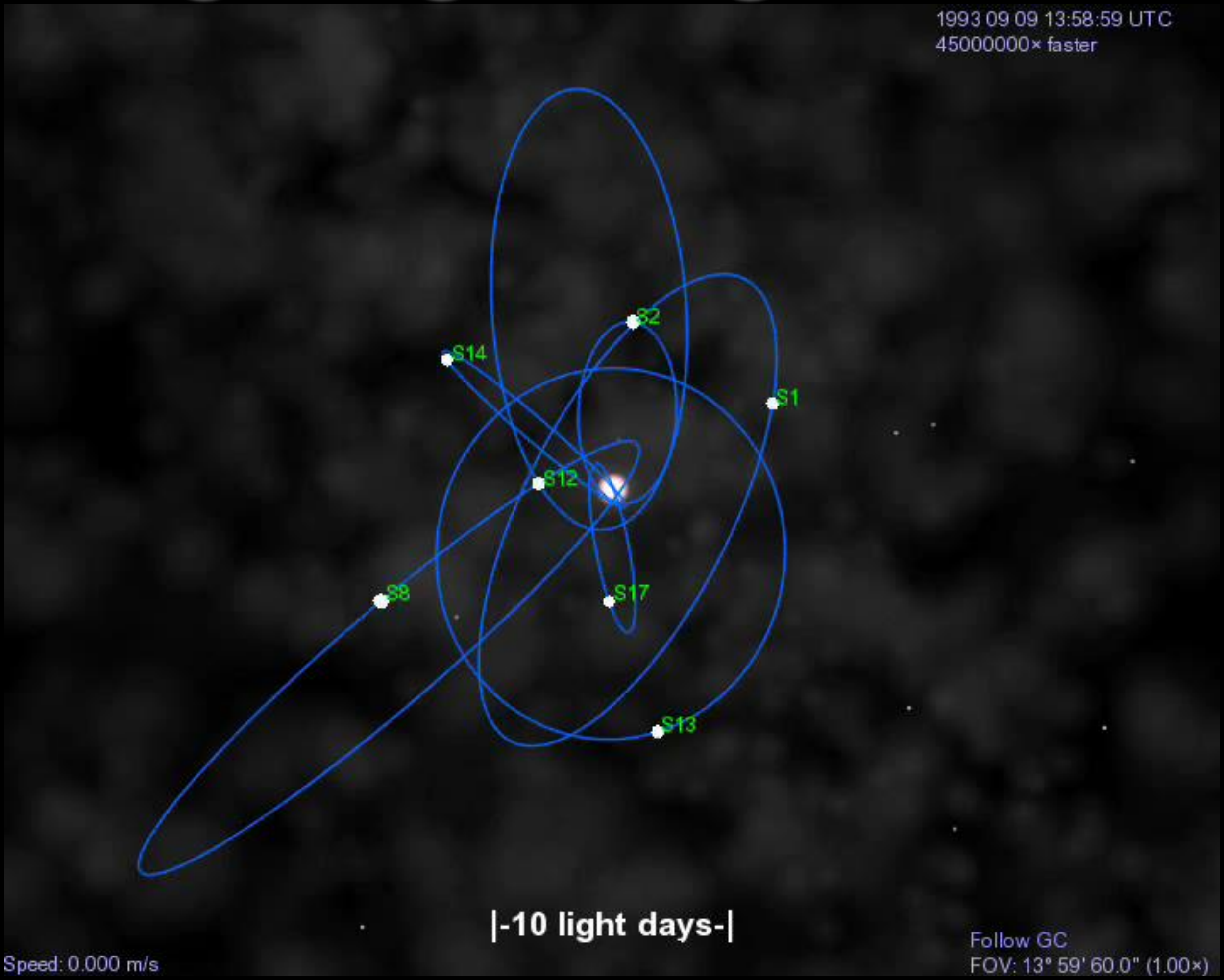
$$= \frac{c}{\kappa} \int_V \nabla^2 \Phi \, dV = \frac{4\pi G c}{\kappa} \int_V \rho \, dV = \frac{4\pi G M c}{\kappa}$$

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}} = 1.26 \times 10^{38} \left(\frac{M}{M_\odot}\right) {\rm erg/s} = 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right)$$

Kvazárok megfigyelt luminozitása



Csillagmozgás a SgrA* körül



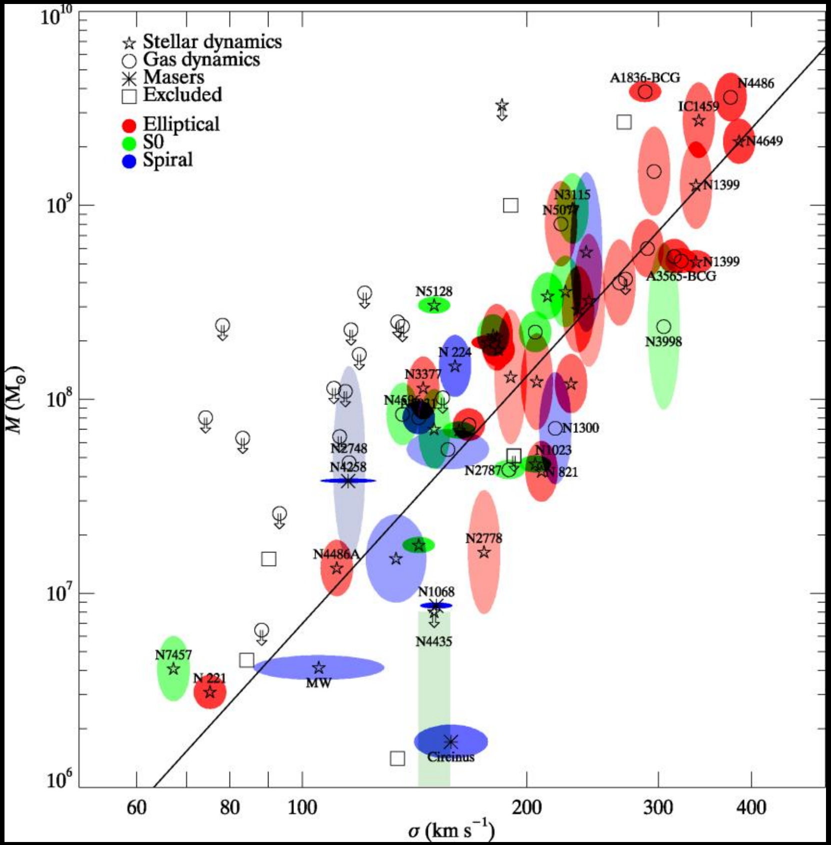
$$M_{\rm BH} = (4.5 \pm 0.4) \times 10^6 M_\odot$$

Ghez et al. 2008; Genzel et al. 2008

Szupermasszív fekete lyukak (SMBH) és galaxisaik

0.2% galaxismag tömeg = SMBH fekete lyuk

Fekete lyuk tömeg



Csillagok random sebessége