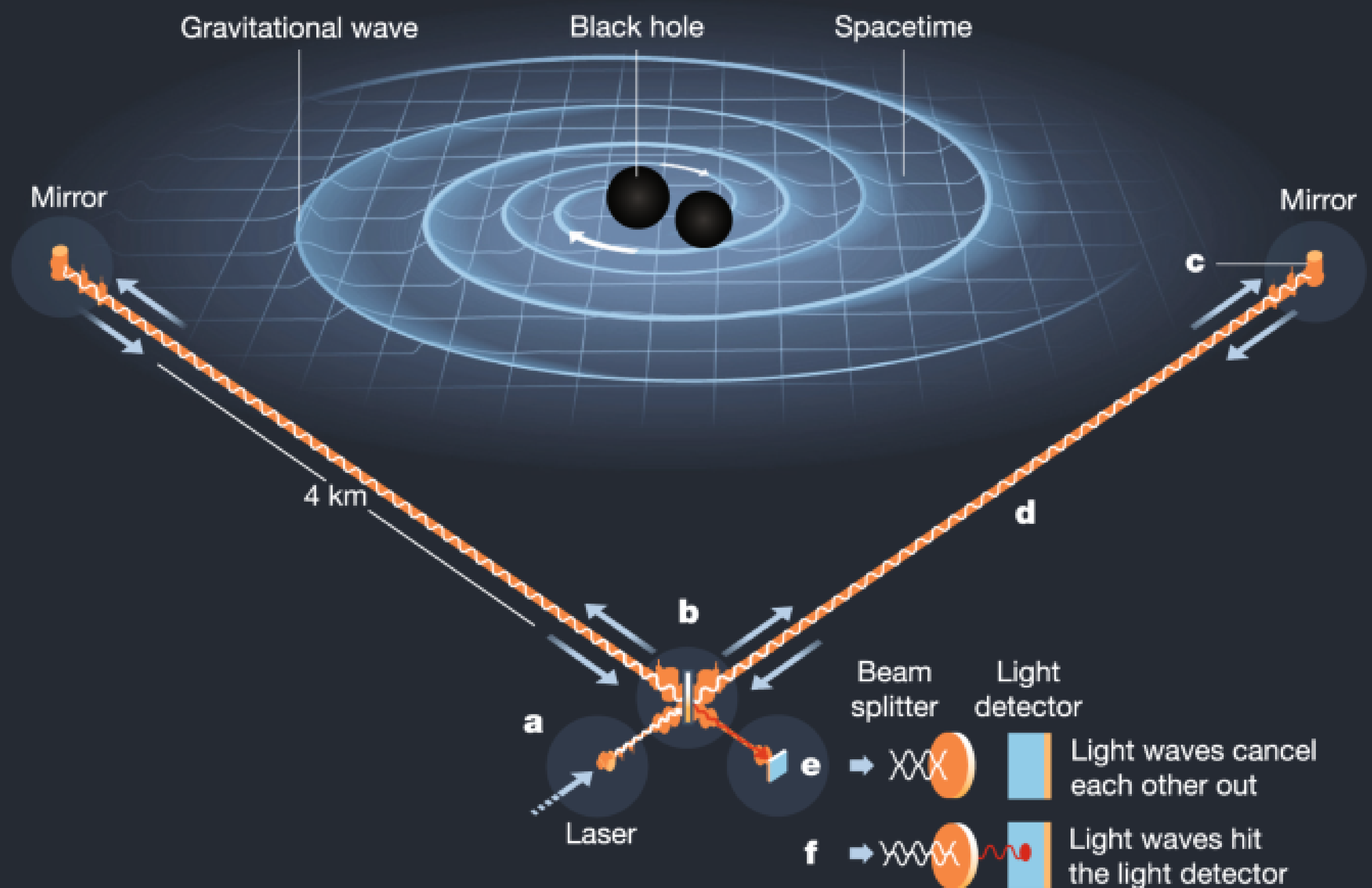
Gravitational-wave progenitors

Dorottya Szécsi

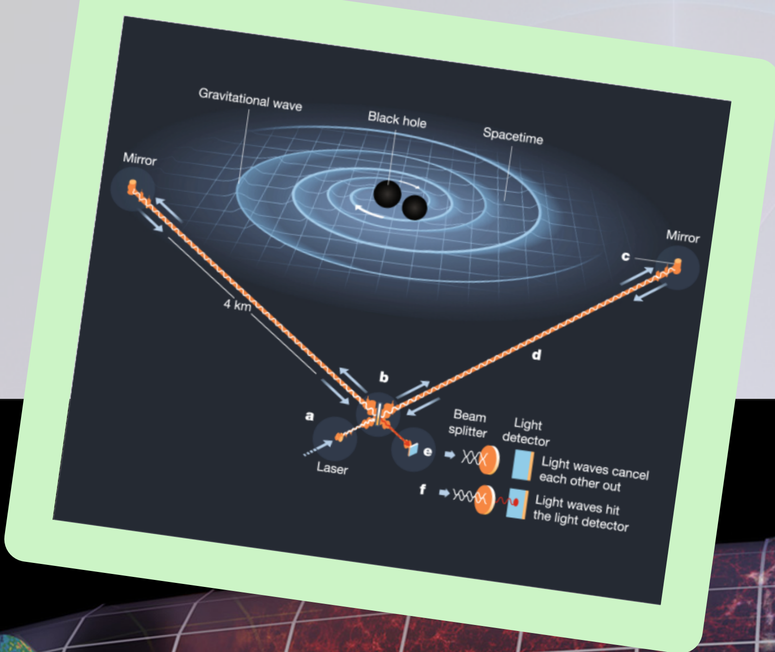
NCU, Summer Semester 2022

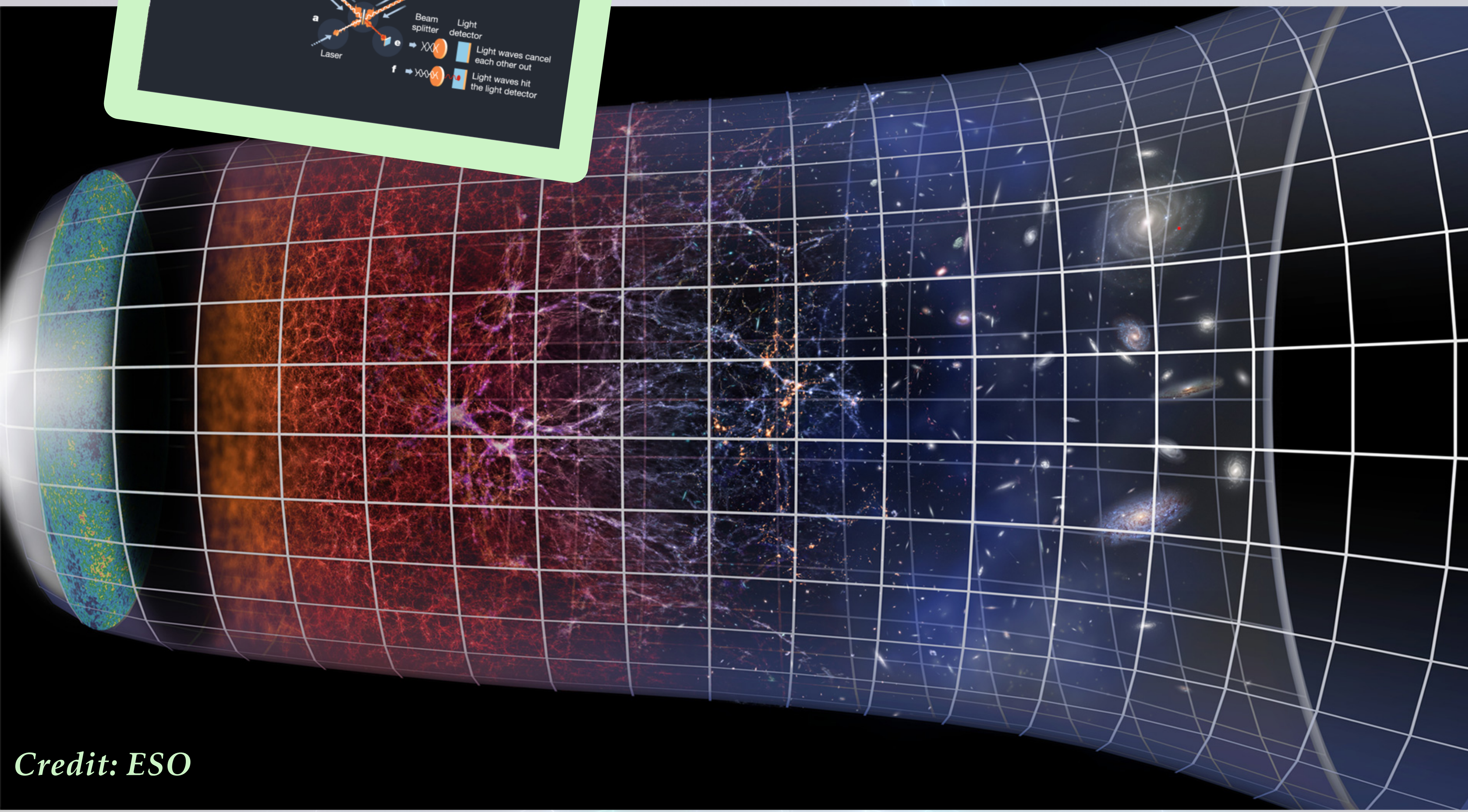
What are we going to talk about?

- the **PROGENITORS** of gravitational-waves:
  - compact object progenitors: black holes, neutron stars…
  - stellar progenitors: massive stars, binaries…
- **birth environments** of GW progenitors:
  - stellar populations in clusters and galaxies
  - ‘sister’ phenomena: supernovae, gamma-ray bursts
  - cosmology, star-formation in the early Universe
- General Relativity, Einstein equations
- GW-detectors in past, present, future (LIGO/Virgo etc.)



Credit: Miller & Yunes (2019, Nature 568, 469–476)

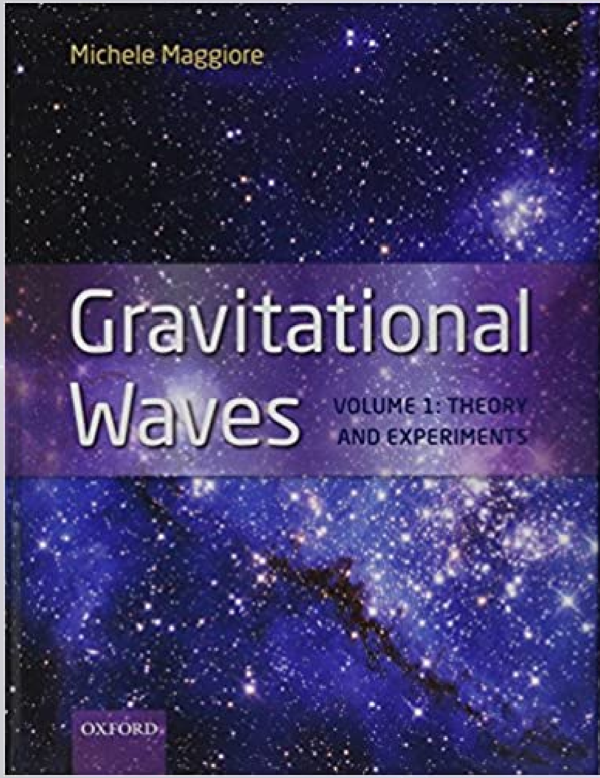

Gravitational wave
Black hole
Spacetime
Mirror
Mirror
4 km
a
b
c
d
e
f
Laser
Beam splitter
Light detector
Light waves cancel each other out
Light waves hit the light detector

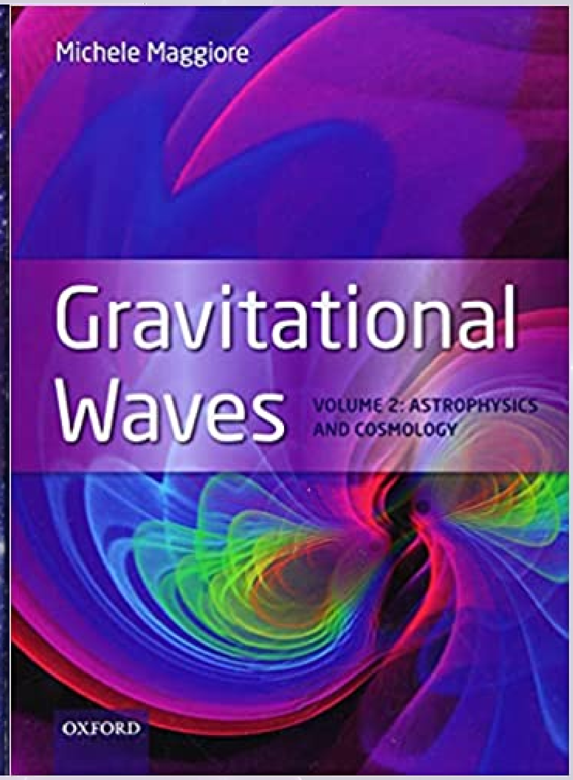


Credit: ESO

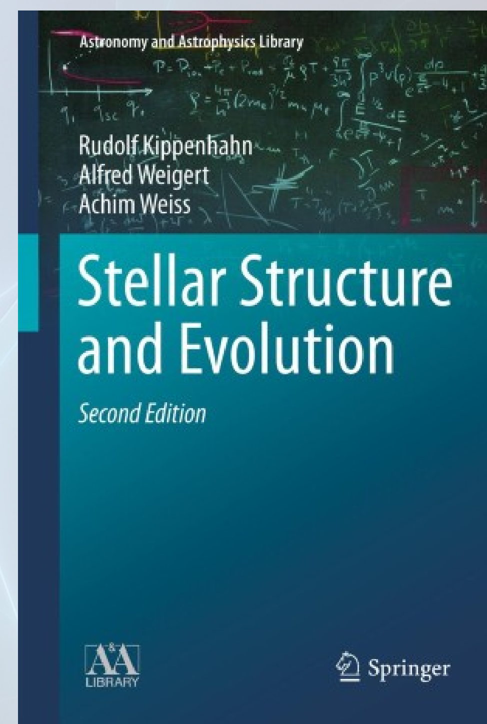
Credit: ESO/M. Kornmesser

Suggested literature





Gravitational Waves
Vol. 1 (2007) & Vol. 2 (2018)
– by **Michele Maggiore**



Stellar Structure and Evolution
2nd Edition (2012)
– by **Kippenhahn, Weigert & Weiss**

Suggested literature (free)

https://iopscience.iop.org/article/10.1088/1742-6596/1263/1/012008

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Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Lecture Notes on Gravitational Waves

Alex Nielsen[1]

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Journal of Physics: Conference Series, Volume 1263, ISAPP-Baikal Summer School 2018: Exploring the Universe through multiple messengers 12–21 July 2018, Bol'shie Koty, Russian Federation

Citation Alex Nielsen 2019 *J. Phys.: Conf. Ser.* **1263** 012008

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References

Article information

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Abstract

References

Abstract

These lectures notes give a overview of gravitational wave astrophysics and the role they play in particle astrophysics and multi-messenger astronomy. The lecture notes are organised into three main topics: the theoretical background of gravitational waves in general relativity, how gravitational waves

Lecture Notes on Gravitational Waves (2019)
– by **Alex Nielsen**
(J. Phys.: Conf. Ser. 1263 012008)

Merging stellar-mass binary black holes (2022)
– by **I. Mandel & A. Farmer**
(arXiv:1806.05820, Physics Reports, in press)

arXiv > astro-ph > arXiv:1806.05820

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Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 15 Jun 2018 (v1), last revised 19 Jan 2022 (this version, v3)]

Merging stellar-mass binary black holes

Ilya Mandel, Alison Farmer

The LIGO and Virgo detectors have directly observed gravitational waves from mergers of pairs of stellar-mass black holes, along with a smaller number of mergers involving neutron stars. These observations raise the hope that compact object mergers could be used as a probe of stellar and binary evolution, and perhaps of stellar dynamics. This colloquium-style article summarises the existing observations, describes theoretical predictions for formation channels of merging stellar-mass black-hole binaries along with their rates and observable properties, and presents some prospects for gravitational-wave astronomy.

Comments: Version accepted by Physics Reports

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References & Citations

- INSPIRE HEP

Exam & grading

Oral examination.
Assessment criteria:

- fail: below 50 pts (below 50%)
- satisfactory: 50 pts (50%)
- satisfactory plus: 60 pts (60%)
- good: 70 pts (70%)
- good plus: 75 pts (75%)
- very good: 80 pts (80%)

Extra options...

- active participation*: +20%
- paper presentation**: +40%

*asking questions during class, thinking out loud, showing interest

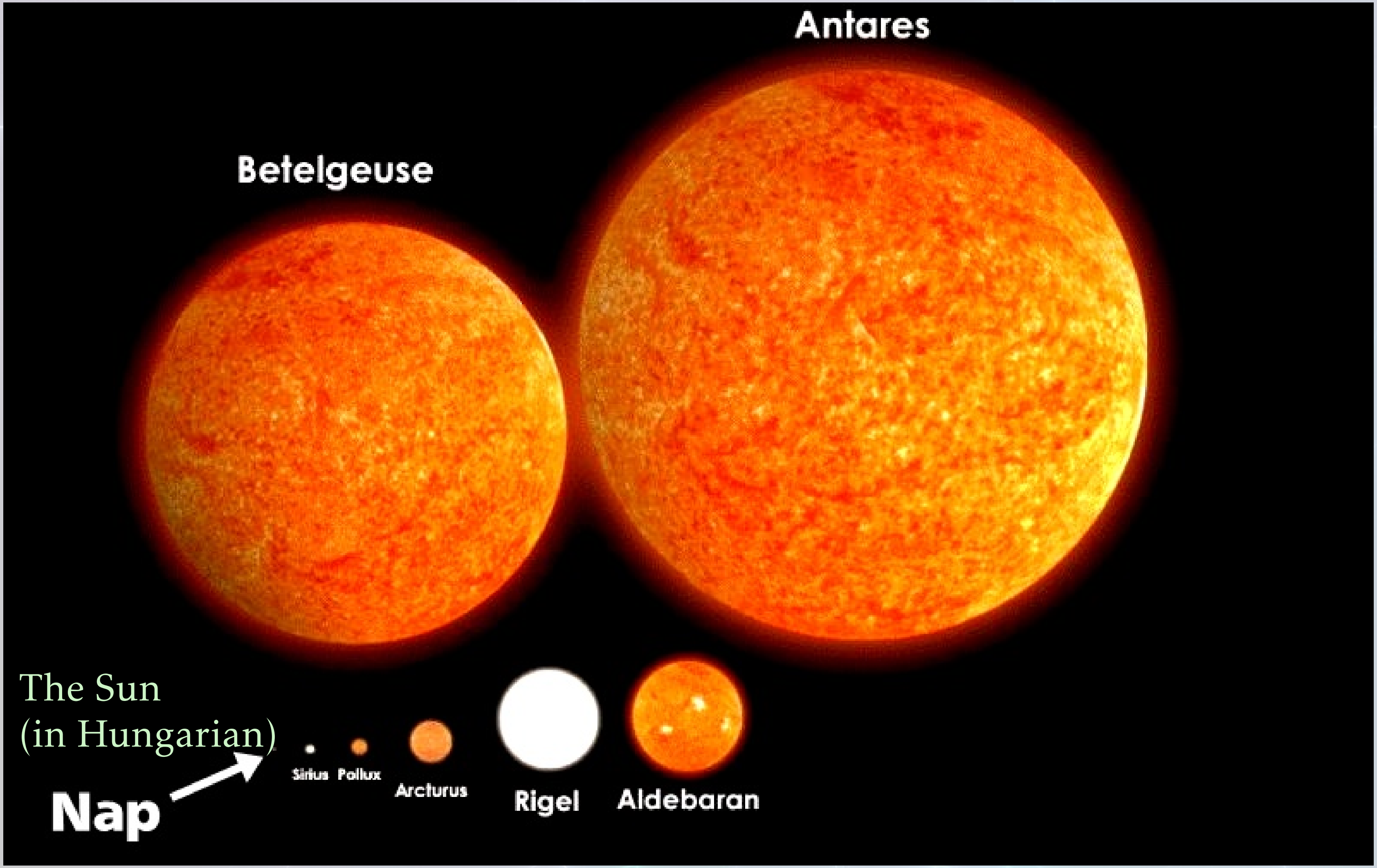
**chosing a GW-related paper from arXiv (accepted for publication after 24.01.2022) and giving a “journal club” style presentation (with slides) of ~30 min

Massive stars

Massive stars vs. low-mass stars

massive: > 8 $M_\odot$

low-mass: < 8 $M_\odot$



Question:

SIZE vs. MASS

Are these the same?

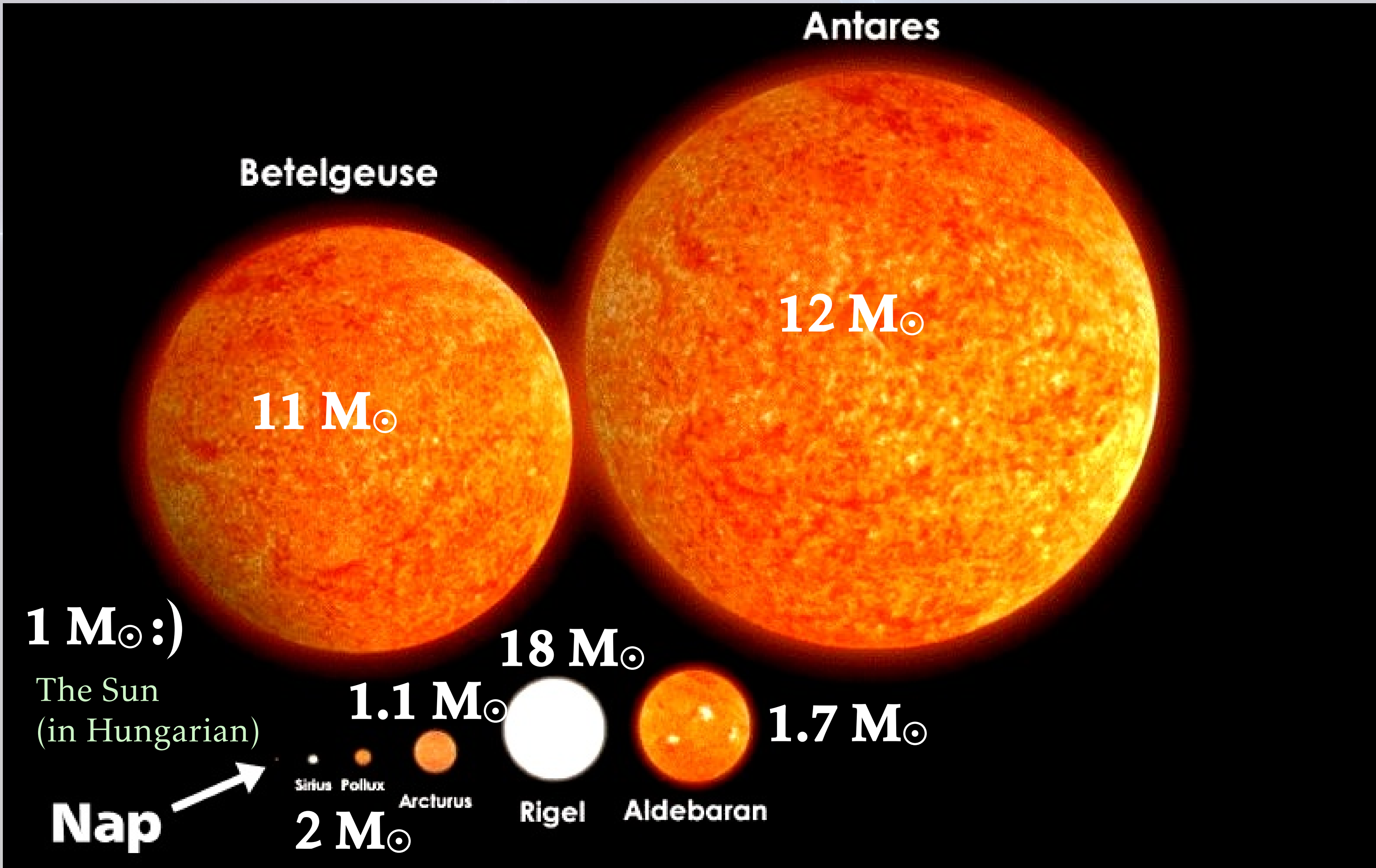
Question:

SIZE vs. MASS

Are these the same?

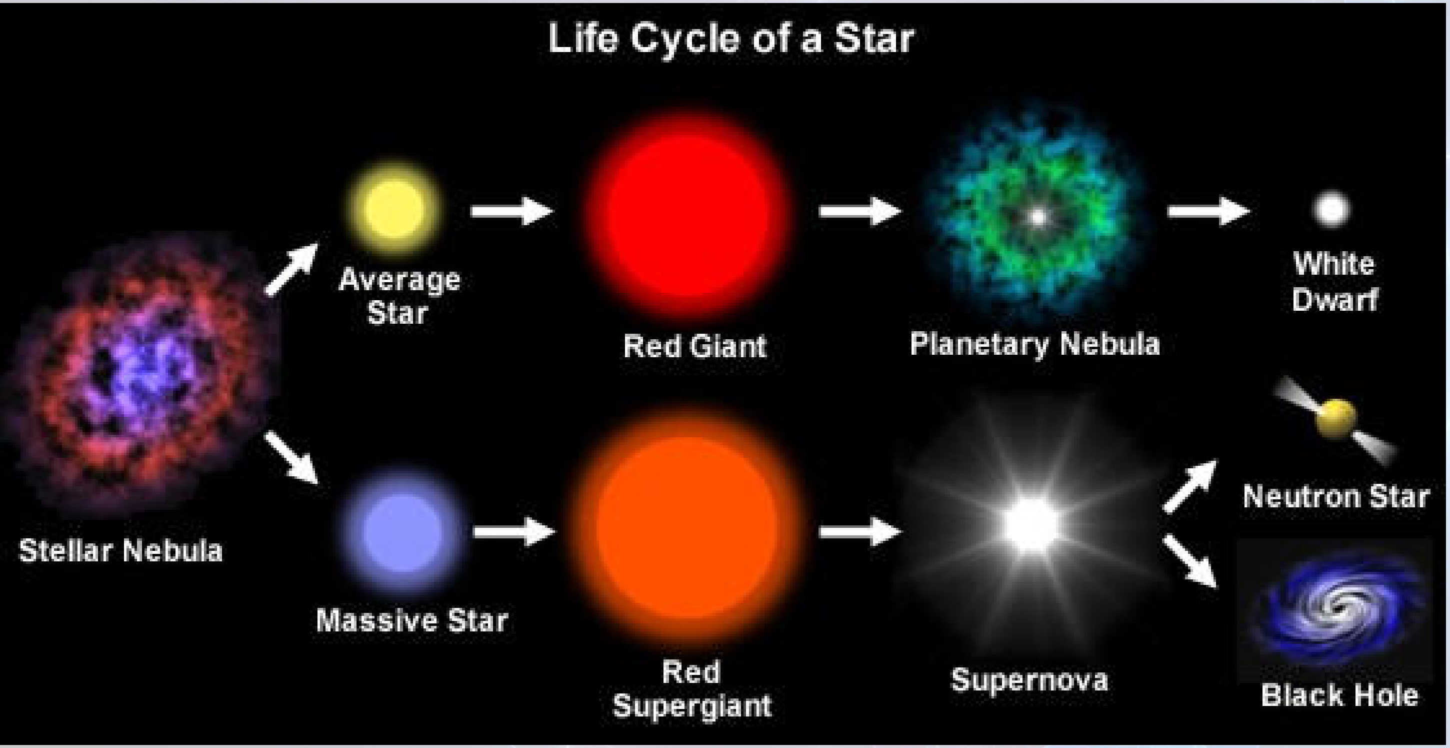
No.

Massive stars vs. low-mass stars



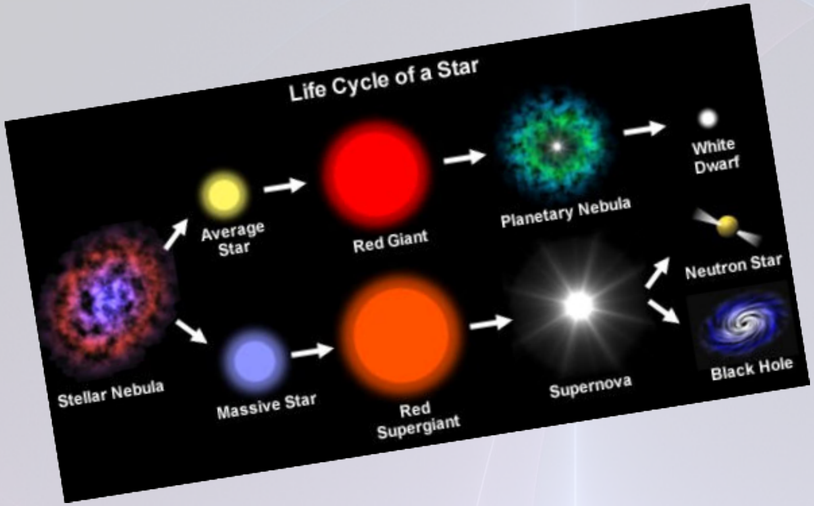
Reason: stars evolve

→ stellar evolution



low-mass: $< 8\ M_\odot$

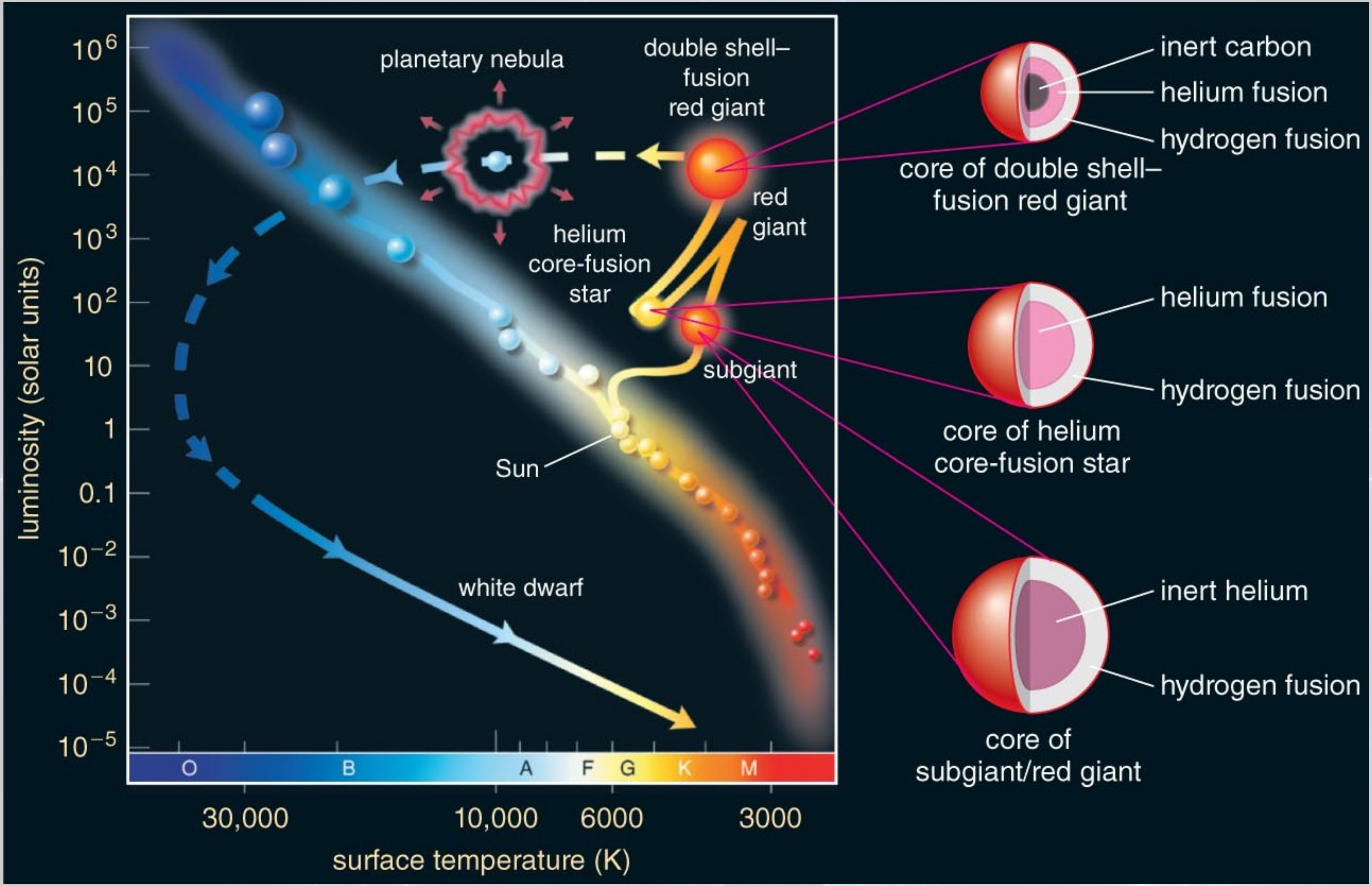
massive: $> 8\ M_\odot$



How to do it more scientifically?

The HRD

Hertzsprung–Russell diagram

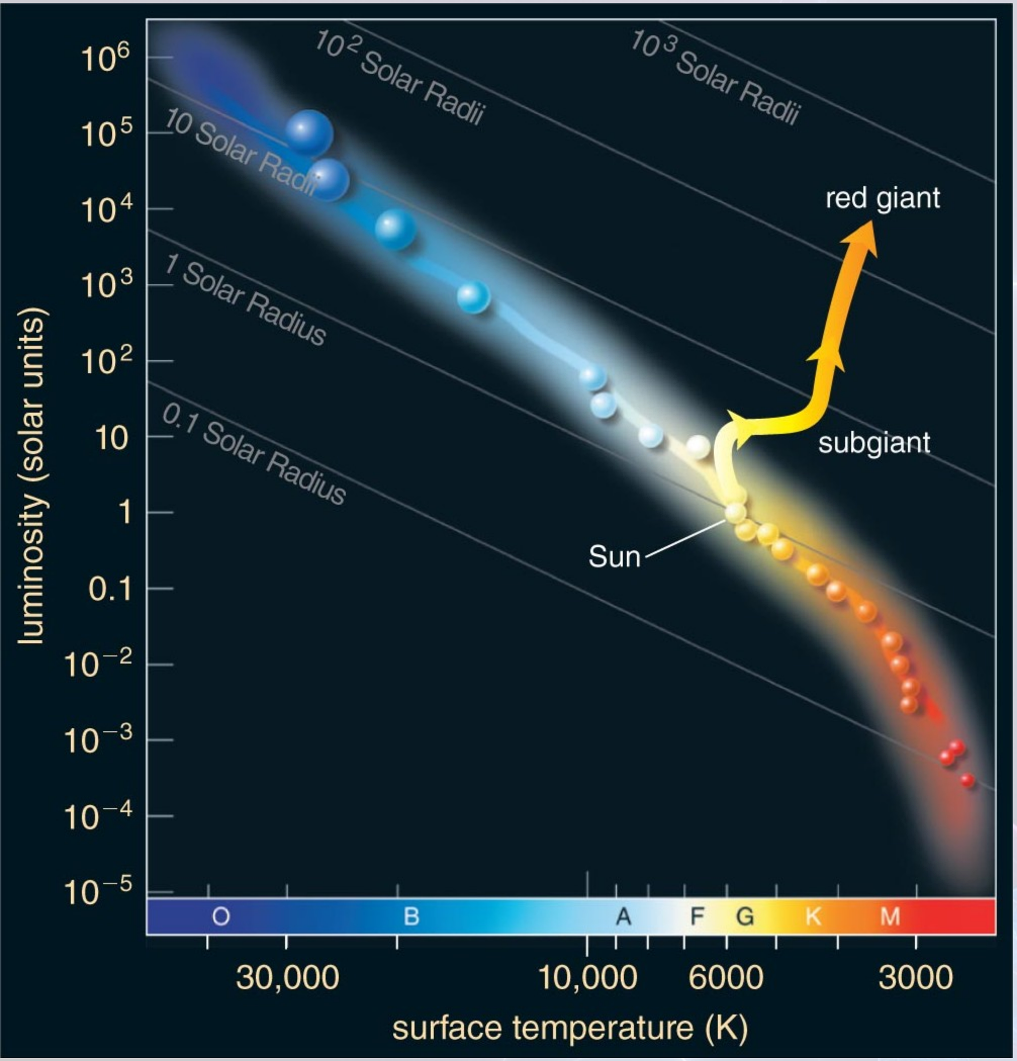


Credit: https://jila.colorado.edu/~ajsh/courses/astr1200_18/starevol.html

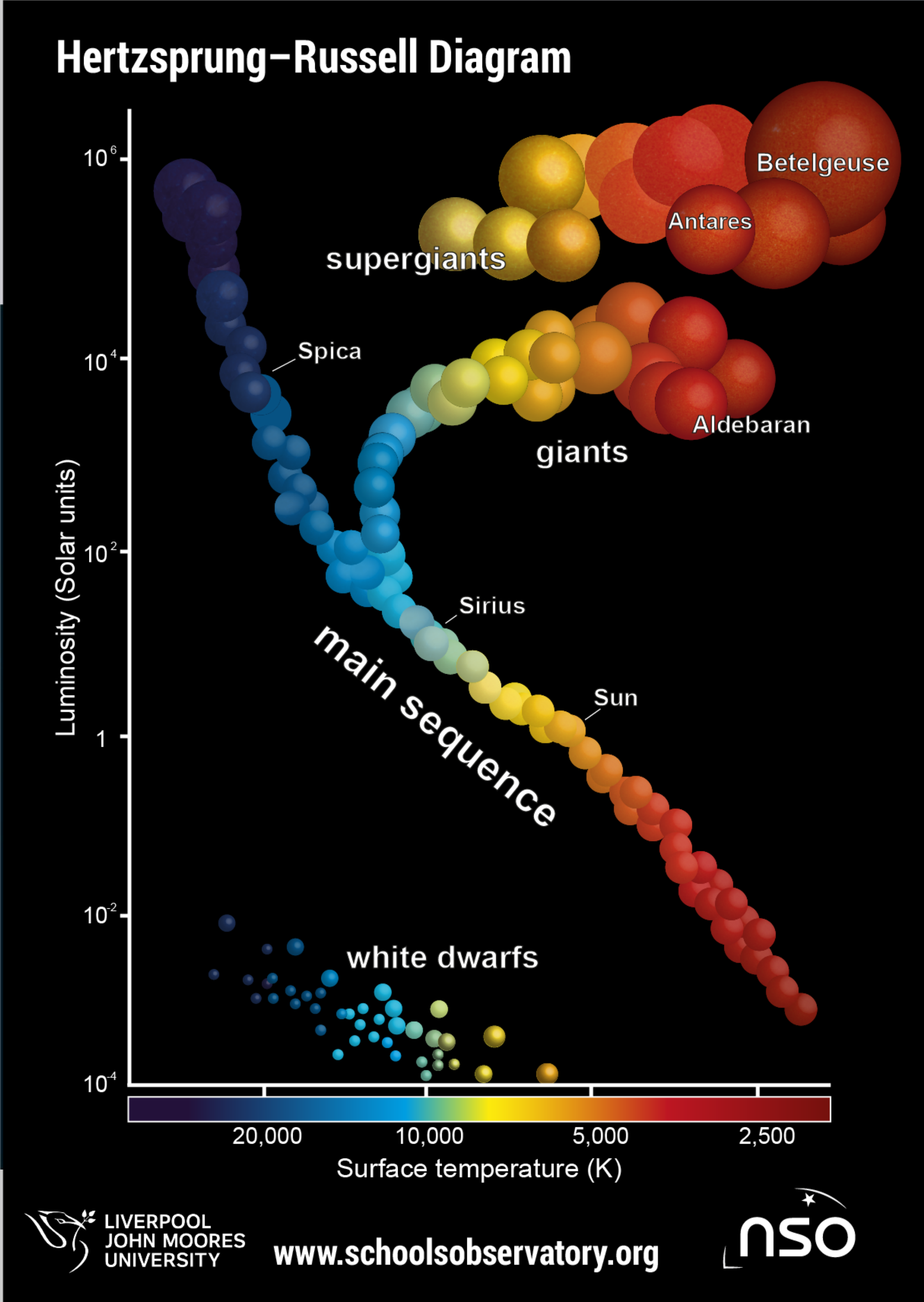
The HRD

Hertzsprung–Russell diagram

Advantages of the HRD



- radius can be easily read out
  - equiradial lines
  - due to Stephan-Bolzmann law (stars are practically Black Bodies…)
- color of the star can be easily read out (~surface temp.)
- brightness: ~luminosity

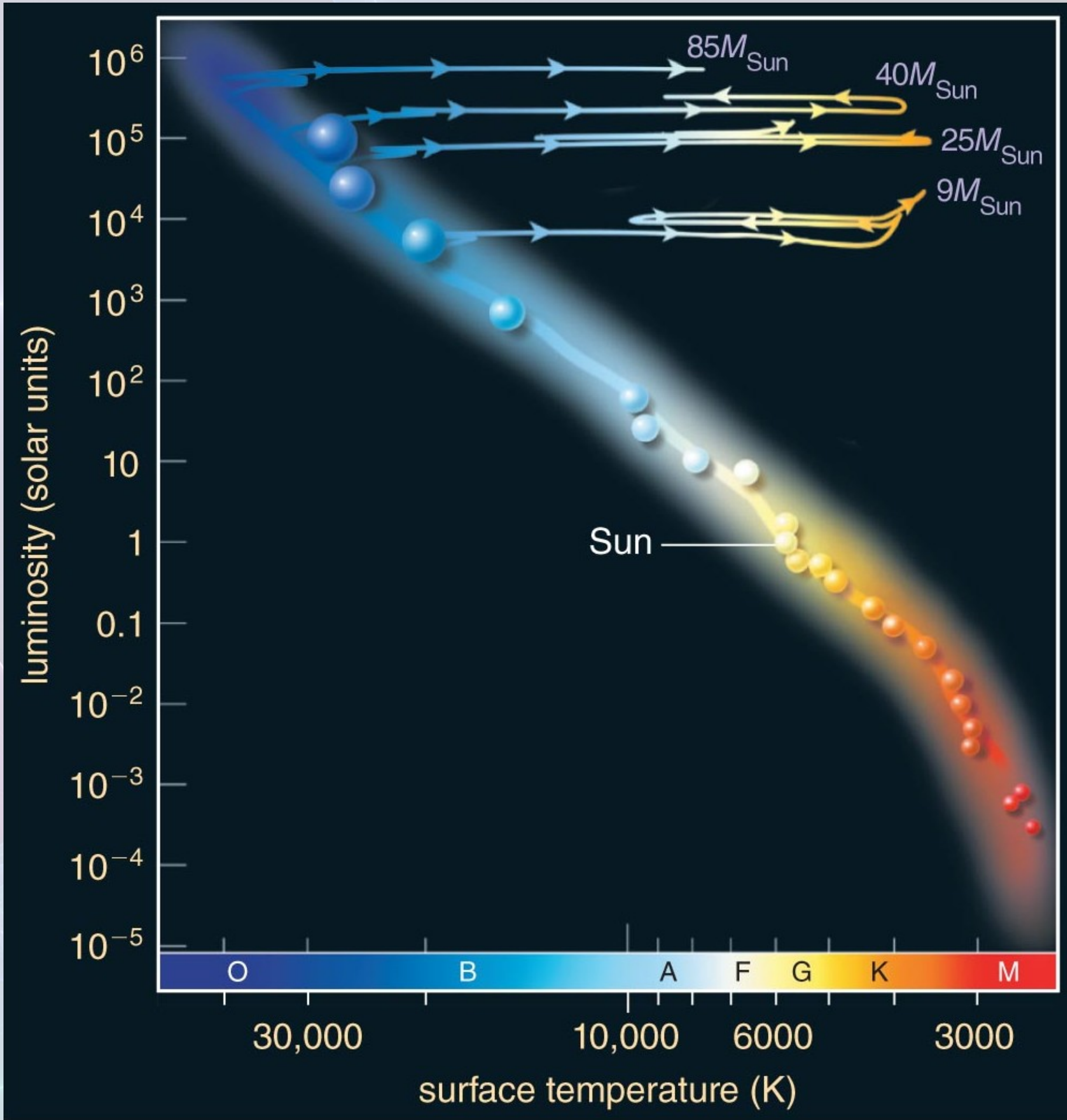


of the HRD

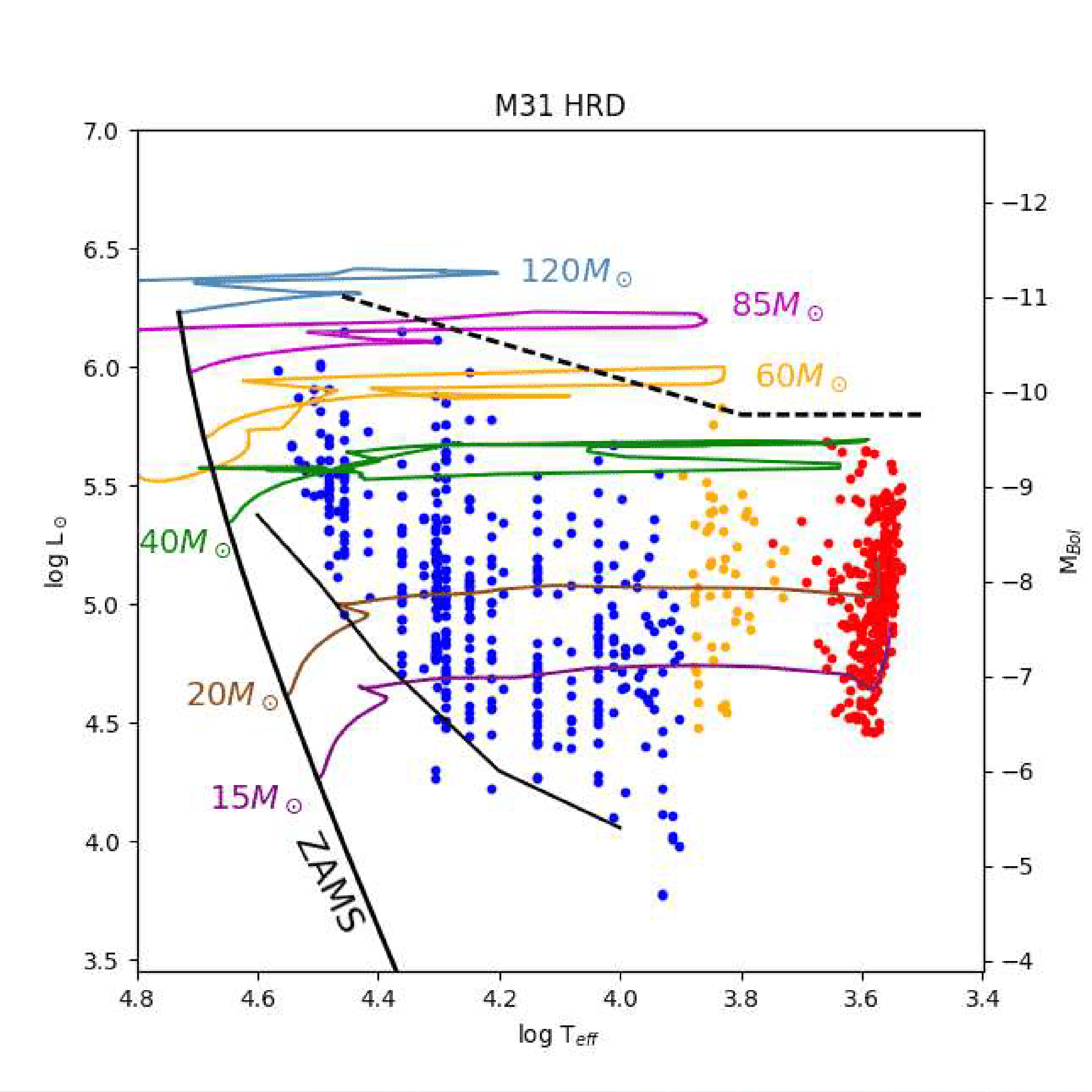
- radius can be easily read out
  - equiradial lines due to Stephan-Bolzmann law
- color of the star can be easily read out (~surface temp.)
- brightness: ~luminosity

Further advantages of the HRD

- allows comparison of an observed ***star*** and its corresponding ***stellar evolutionary model***
- allows comparison of low-mass stars vs. massive stars



The real (boring) scientific version:



- X: $\lg T_{\mathrm{eff}}$ [K]
  - logarithmic & upside down (historical reasons)
- Y: $\lg(L/L_\odot)$
  - lines: theoretical models (not always, but usually)
  - dots: observed stars (not always, but usually)
  - ZAMS: Zero-Age Main Sequence

Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

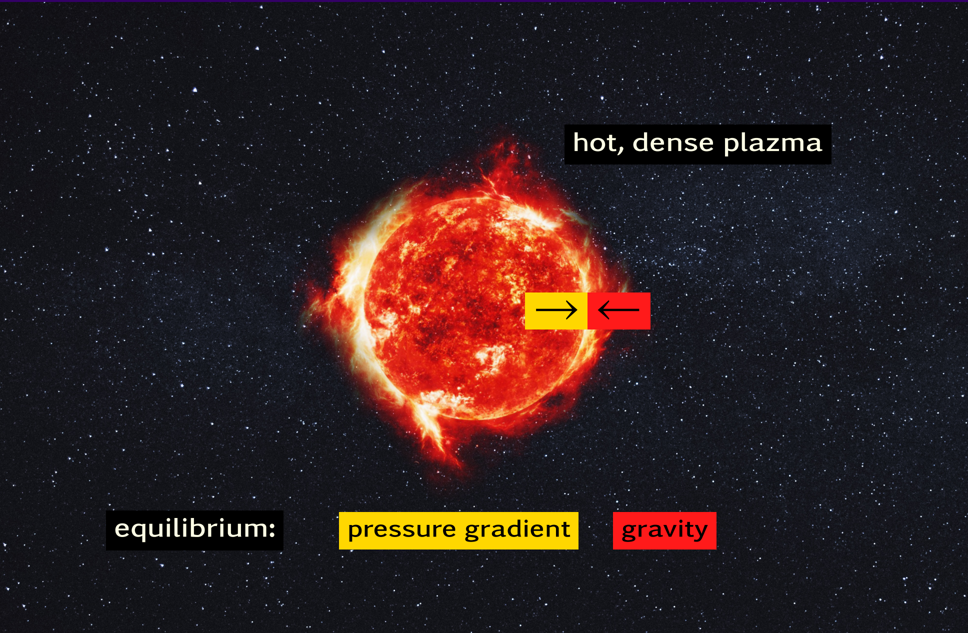
COFFEE BREAK :)


What is a star?

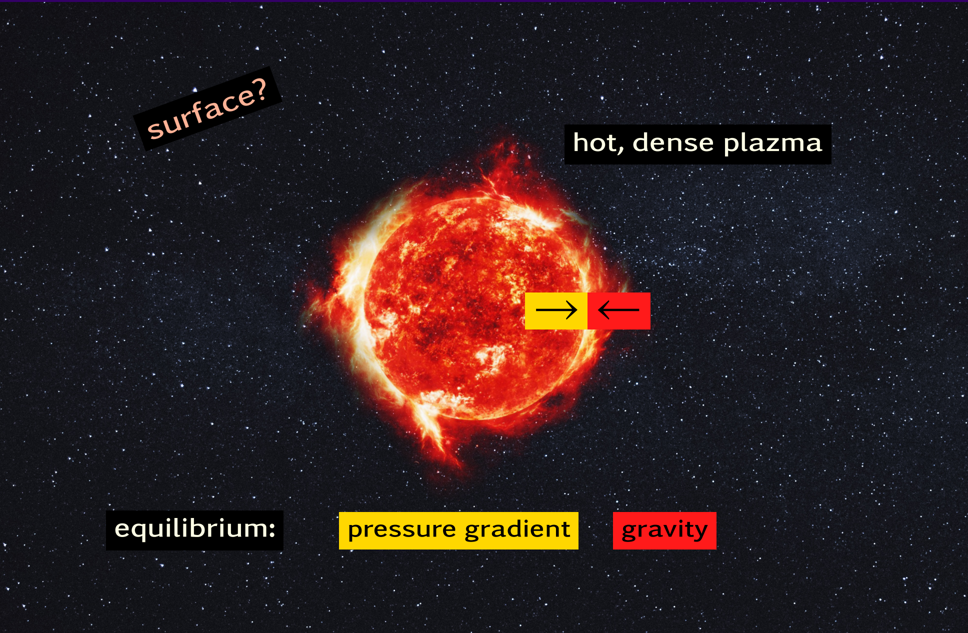
What is a star?

What is a star?

What is a star?



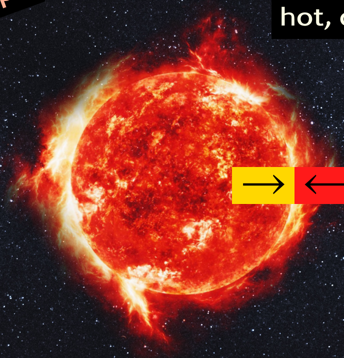
What is a star?



What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



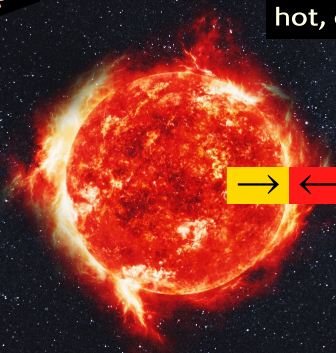
→ ←

equilibrium: pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



→ ←

equilibrium: pressure gradient gravity

What is a star?

surface?
→ photons escape
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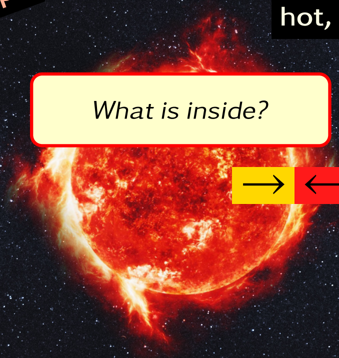


What is inside?

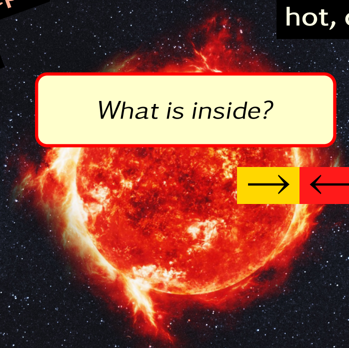
→ ←

equilibrium: pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



What is inside?

⟶ ⟵

theoretical modelling of the stellar structure

equilibrium: pressure gradient gravity

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \quad \text{equation of definition of mass} \qquad (1)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \quad \text{equation of hydrostatic equilibrium} \qquad (2)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T \frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \qquad (3)$$

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P} \nabla \quad \text{equation of energy transport,} \qquad (4)$$

Guilera+ 11

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad \text{mass conservation} \qquad (1)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad \text{equation of hydrostatic equilibrium} \qquad (2)$$

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Theoretical modelling of the stellar structure

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$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$ momentum conservation (2)

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t}$$ energy conservation (3)

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$ equation of energy transport, (4)

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Theoretical modelling of the stellar structure

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mass conservation

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \quad (2)$$

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transport of energy

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Theoretical modelling of the stellar structure

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momentum conservation

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energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \quad (4)$$

transport of energy

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composition change due to nuclear burning:

Theoretical modelling of the stellar structure

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mass conservation

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad (2)$$

momentum conservation

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad (3)$$

energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

Guilera+ 11

composition change due to nuclear burning:

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \qquad (5)$$

How to solve a set of
joint partial differential equations?

Numerical integration.

Henyey, Forbes & Gould (1964)
Astrophysical Journal, vol. 139, p.306

A NEW METHOD OF AUTOMATIC COMPUTATION OF STELLAR EVOLUTION

L. G. Henyey, J. E. Forbes, and N. L. Gould
Berkeley Astronomical Department, University of California

Received July 26, 1963

ABSTRACT

A method is described for obtaining time sequences of stellar models describing evolutionary changes. This method is a modified version of an earlier one described by Henyey, Wilets, Böhm, LeLevier, and Levée (1959). The modifications involve the evaluation of all quantities at the same discrete points. The technique provides for coupling the interior integrations to those for model atmospheres based on mixing-length theory. The scope of the formalism is such as to provide for a wide range of calculations for spherically symmetric configurations in hydrostatic equilibrium.

Henyey, Forbes & Gould (1964):

A New Method of Automatic Computation of Stellar Evolution

II. THE BASIC DIFFERENTIAL EQUATIONS

The development of the modified form of the computational technique requires that the basic equations be put into a suitable form. Let ξ be a Lagrangian variable and let $m(\xi)$ be the mass inclosed within a sphere designated by ξ, that is,

$$m = m(\xi)\,, \qquad 0 \leq \xi \leq 1\,. \tag{1}$$

Here it is understood that

$$m(0) = 0\,, \quad \text{and} \quad m(1) = M\,, \tag{2}$$

where M is the total mass.

$$\frac{\partial P}{\partial \xi} + \frac{G m \rho}{r^2}\frac{\partial r}{\partial \xi} = 0\,,$$

$$m' - 4\pi r^2 \rho \frac{\partial r}{\partial \xi} = 0\,,$$

$$\frac{\partial l}{\partial \xi} - m'\left[\epsilon - \frac{\partial E}{\partial t} - P\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right)\right] = 0\,;$$

and for radiative-conductive transfer of energy

$$\frac{\partial T}{\partial \xi} + \frac{3\kappa\rho l}{64\pi\sigma T^3 r^2}\frac{\partial r}{\partial \xi} = 0\,, \tag{6}$$

(where κ, the opacity, includes the effect of electron conduction) or for convection

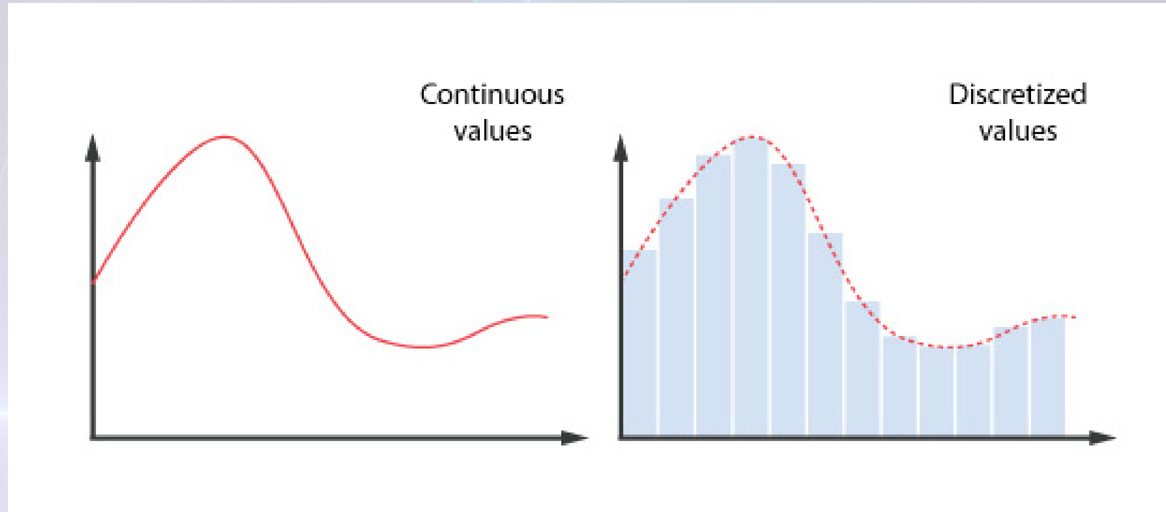
$$\frac{\partial E}{\partial \xi} + P\frac{\partial}{\partial \xi}\left(\frac{1}{\rho}\right) = 0\,. \tag{7}$$

The symbol m' represents the ordinary derivative of $m(\xi)$ with respect to ξ. As usual ρ represents the density, P the pressure, T the temperature, l the luminosity, and r the radius at any interface within the star. E is the internal energy per unit mass and ϵ the thermonuclear energy release per unit mass and time. M, R, and L are the mass, radius, and luminosity of the whole star.

Henyey, Forbes & Gould (1964):

A New Method of Automatic Computation of Stellar Evolution

Discretization:



Discretized version ('difference equations') is solved by standard numerical solvers on modern computers

$$p_{j+1} - p_j + \frac{G m_{j+1/2} (q_{j+1}+q_j)^3 (r_{j+1}-r_j)}{(p_{j+1}+p_j)^3 (r_{j+1}+r_j)^2} = 0\,.$$

$$\frac{8}{\pi} m_{j+1/2}' (\xi_{j+1}-\xi_j) - (q_{j+1}+q_j)^3 (r_{j+1}+r_j)^2 (r_{j+1}-r_j) = 0\,.$$

$$\begin{aligned} &F_{j+1}(\xi_{j+1}+\xi_j)(3\xi_{j+1}-\xi_j) + F_j(\xi_{j+1}+\xi_j)(\xi_{j+1}-3\xi_j) \\ &\quad - 2 m_{j+1/2}'(\xi_{j+1}-\xi_j)\Big[2(\epsilon_{j+1}\epsilon_j)^{1/2} - \frac{E_{j+1}+E_j-E_{j+1}{}^n-E_j{}^n}{\Delta t} \\ &\quad + 3\left(\frac{p_{j+1}+p_j}{q_{j+1}+q_j}\right)^4 \frac{q_{j+1}+q_j-q_{j+1}{}^n-q_j{}^n}{\Delta t}\Big] = 0\,. \end{aligned}$$

$$T_{j+1} - T_j - \frac{(K_{j+1}+K_j)(\xi_{j+1}+\xi_j)^2 (F_{j+1}+F_j)(p_{j+1}-p_j)}{m_{j+1/2}} = 0\,.$$

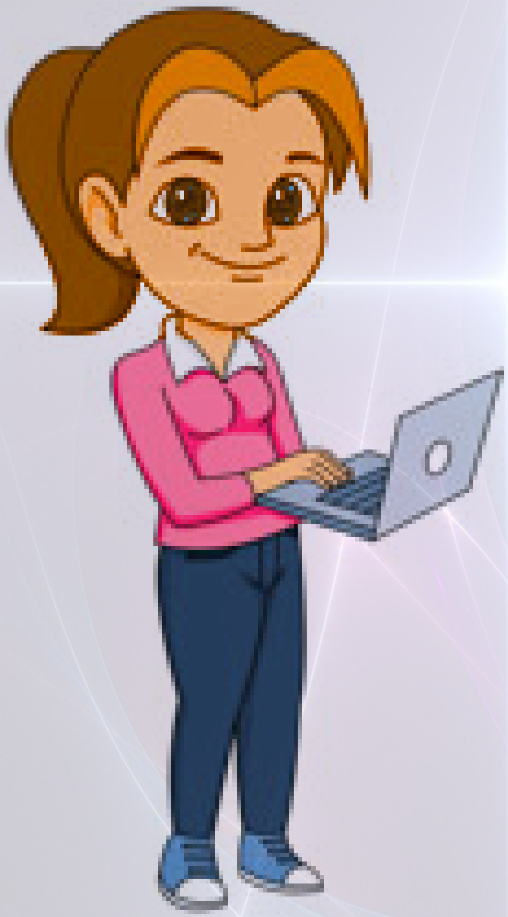
$$E_{j+1} - E_j - 3\left(\frac{p_{j+1}+p_j}{q_{j+1}+q_j}\right)^4 (q_{j+1}-q_j) = 0\,.$$

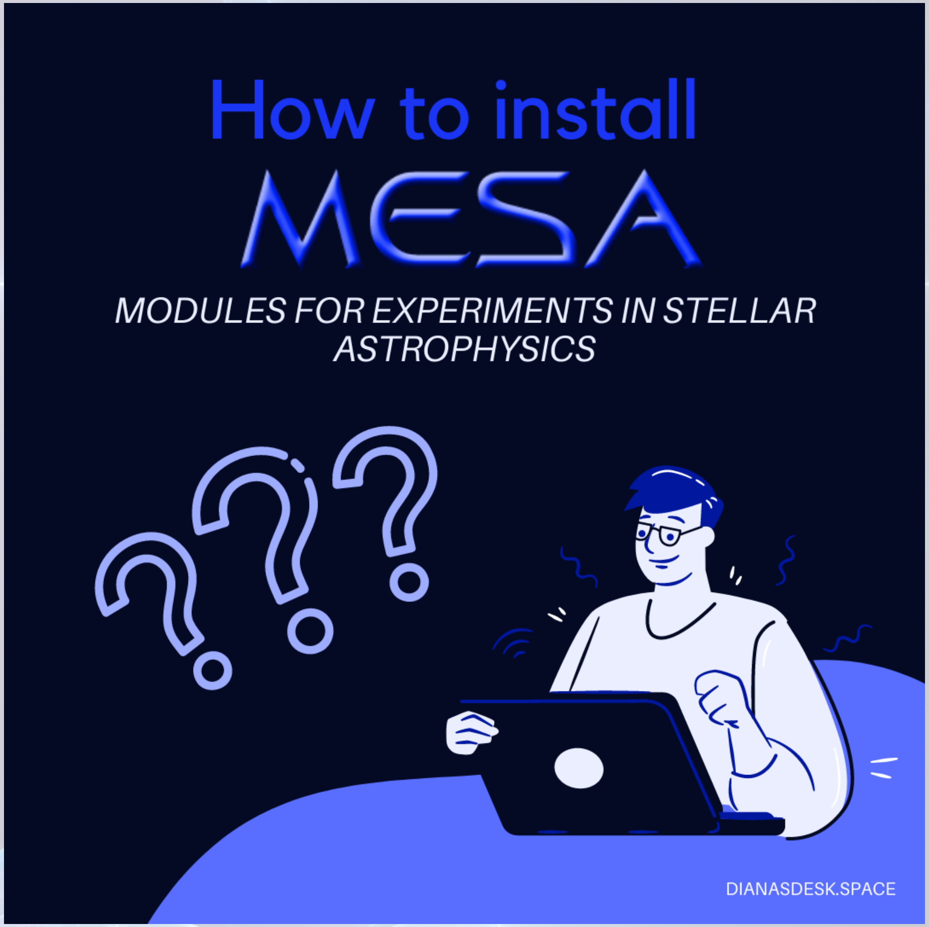
UNIVAC = UNIVersal Automatic Computer (Livermore Radiation Laboratory)

36 Williams tubes with a capacity of 1024 bits each

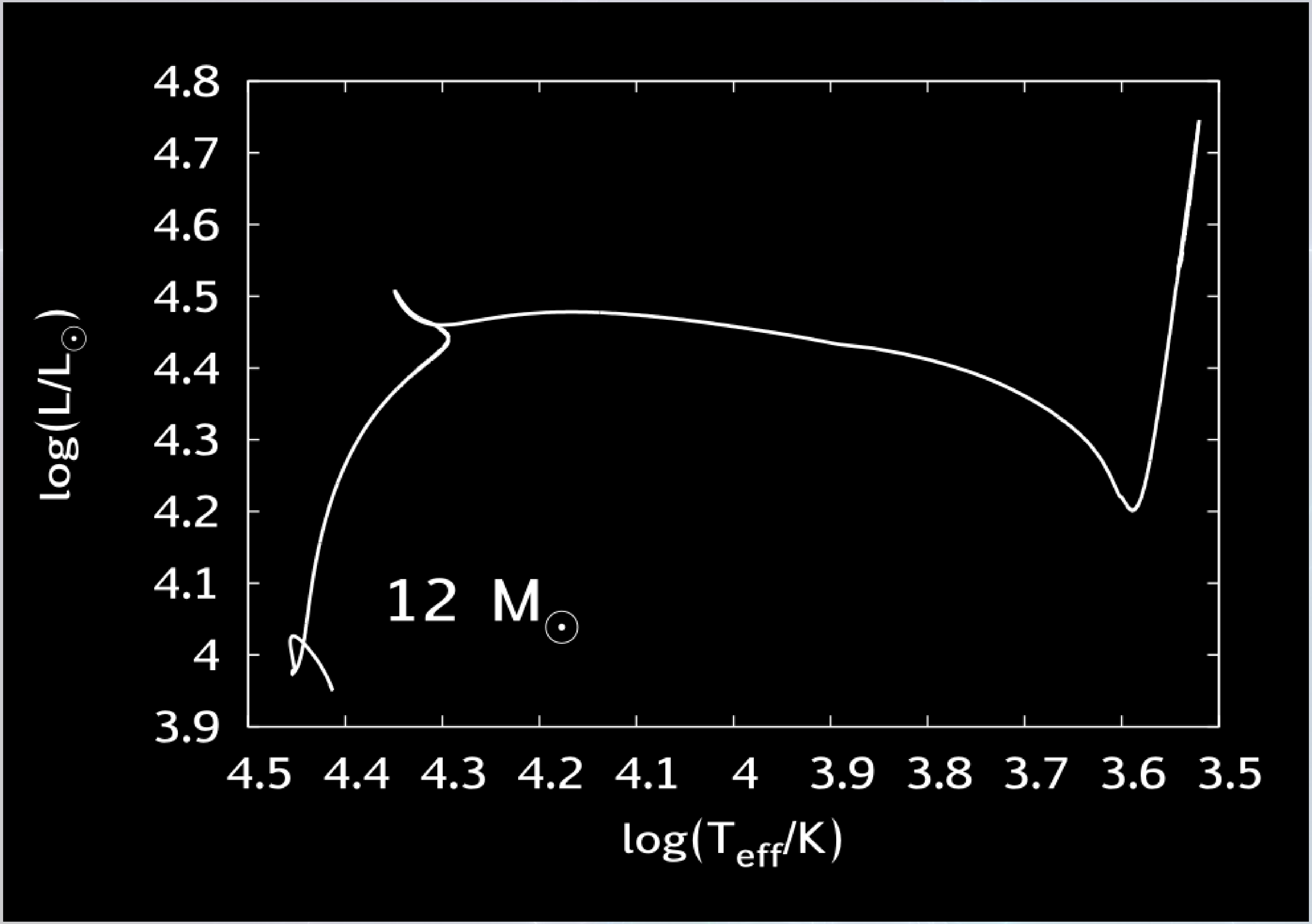
1 Williams tube was five inches in diameter

These days…




How to install
MESA
MODULES FOR EXPERIMENTS IN STELLAR ASTROPHYSICS
DIANASDESK.SPACE

Explosions!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log(L/L$_\odot$)
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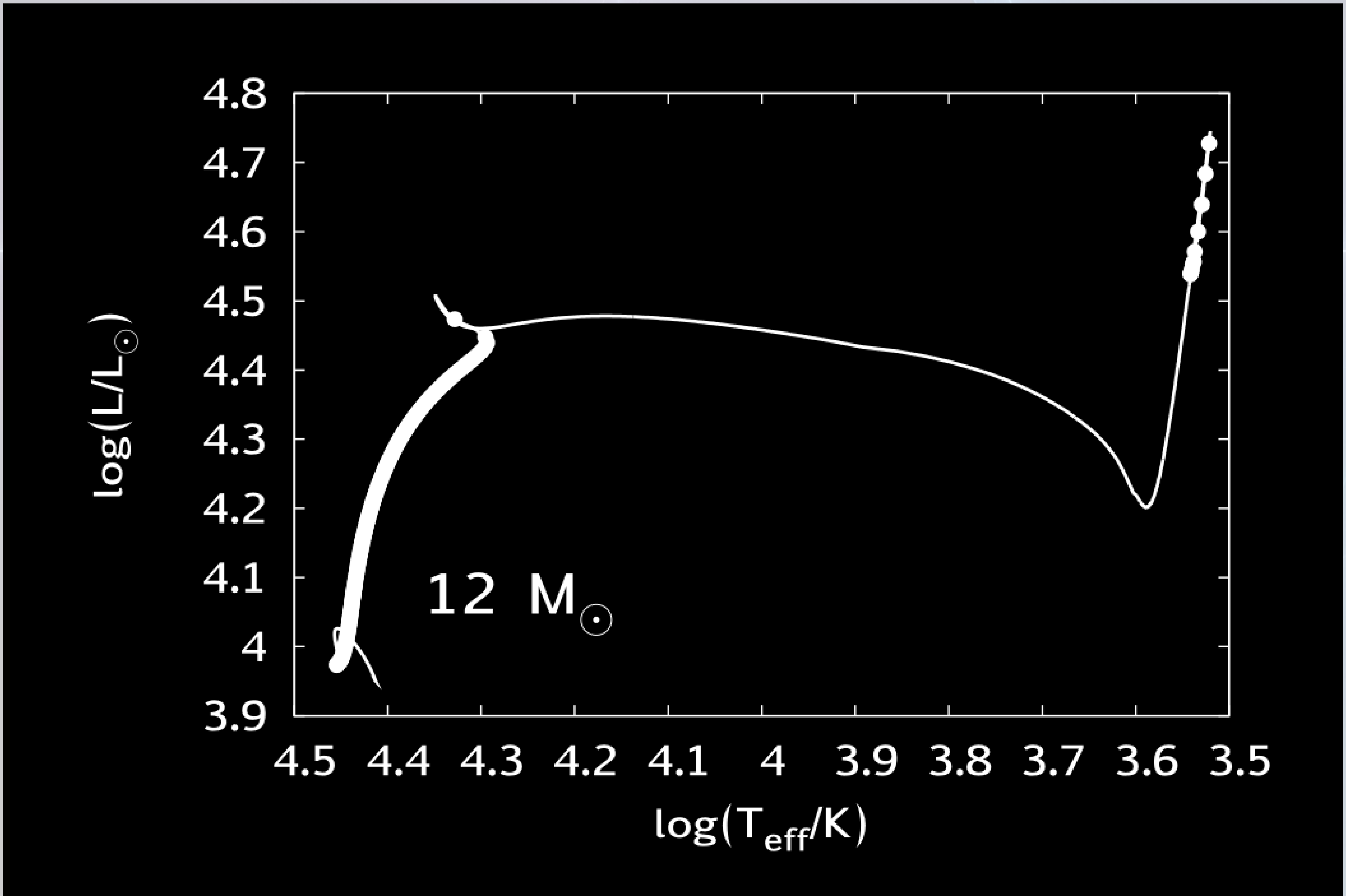
log(T$_{eff}$/K)



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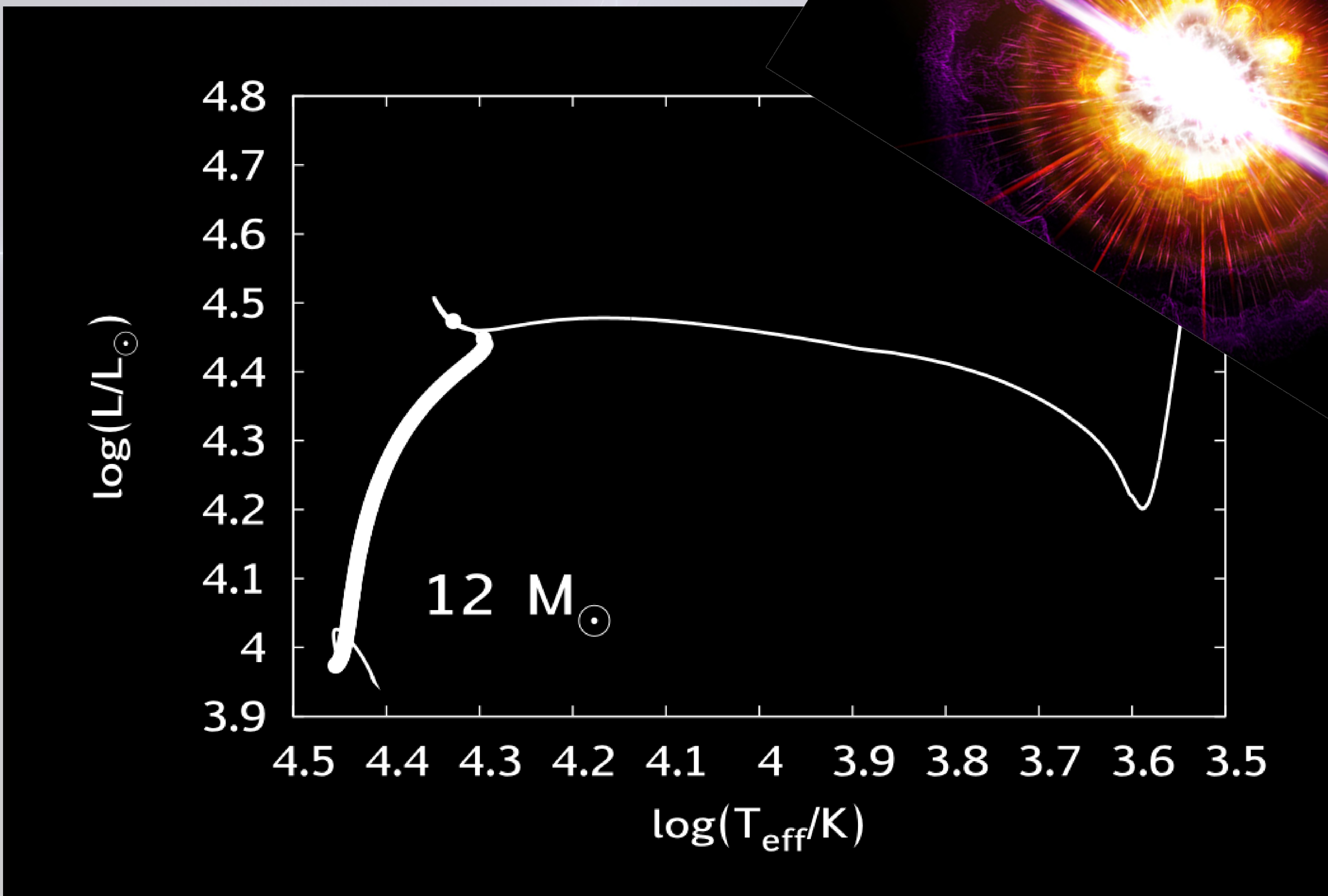

$\log(L/L_\odot)$
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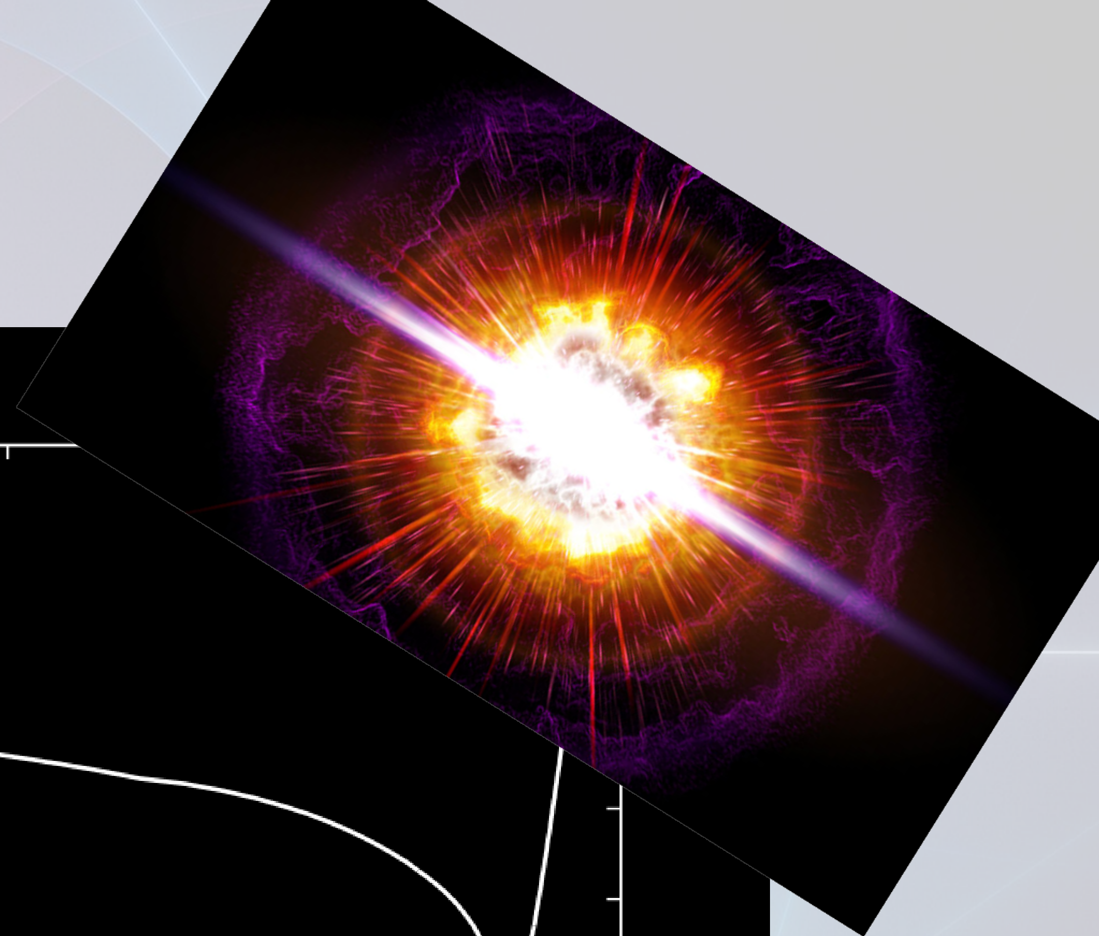
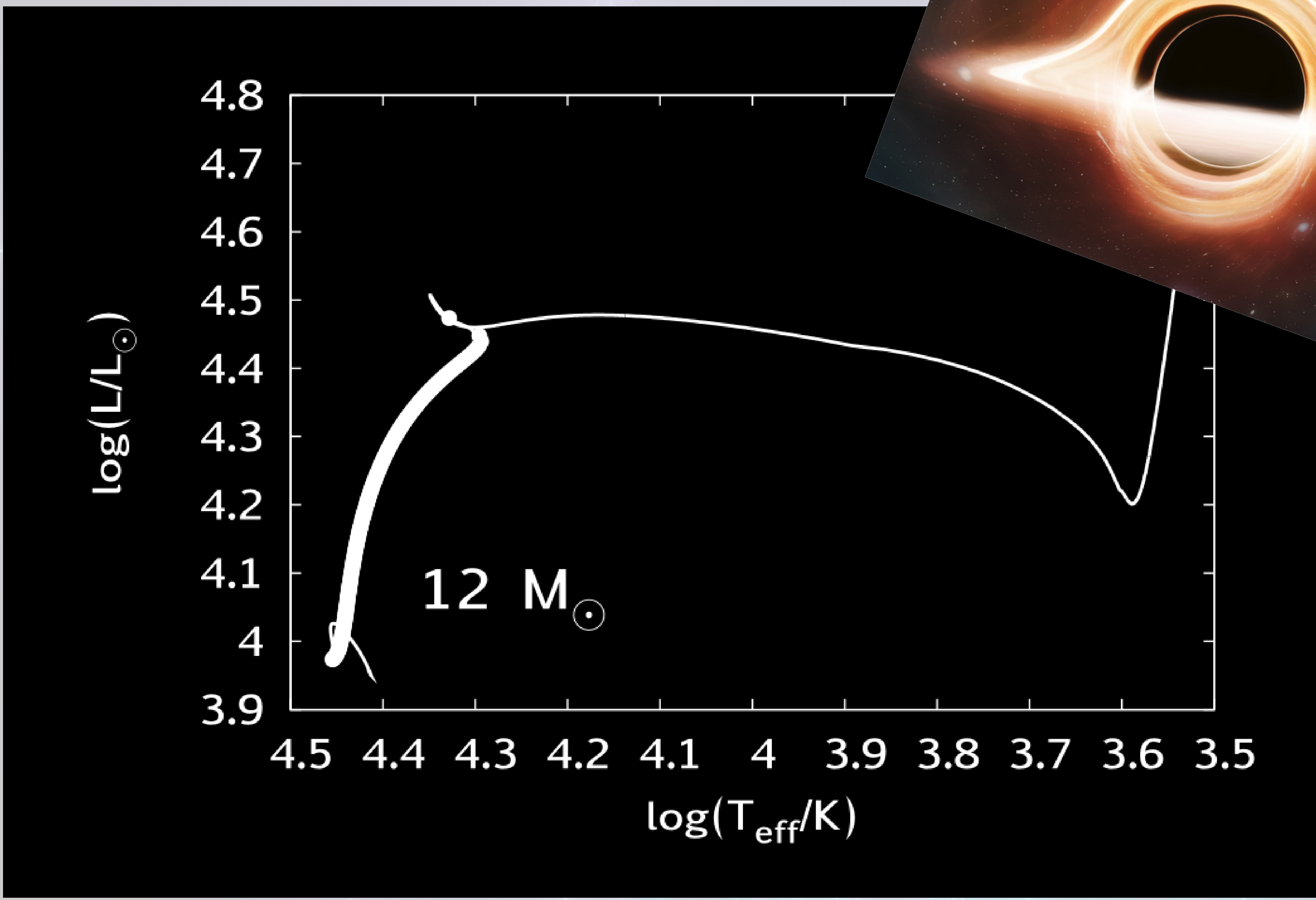
$\log(T_{eff}/K)$
12 $M_\odot$

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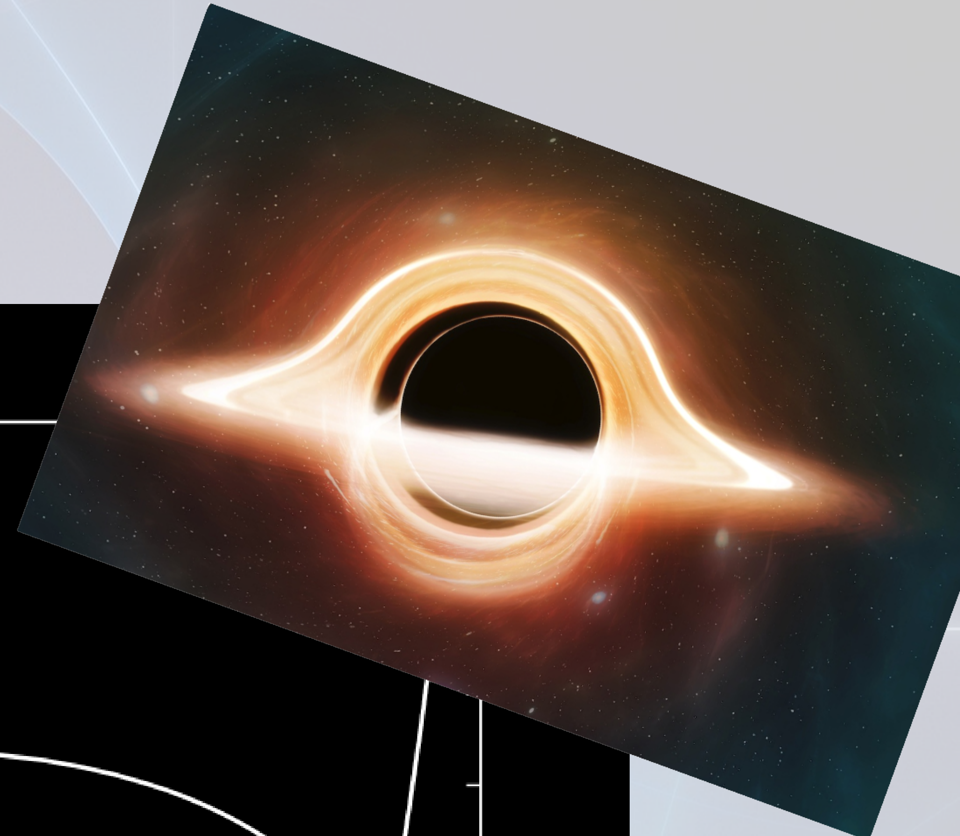
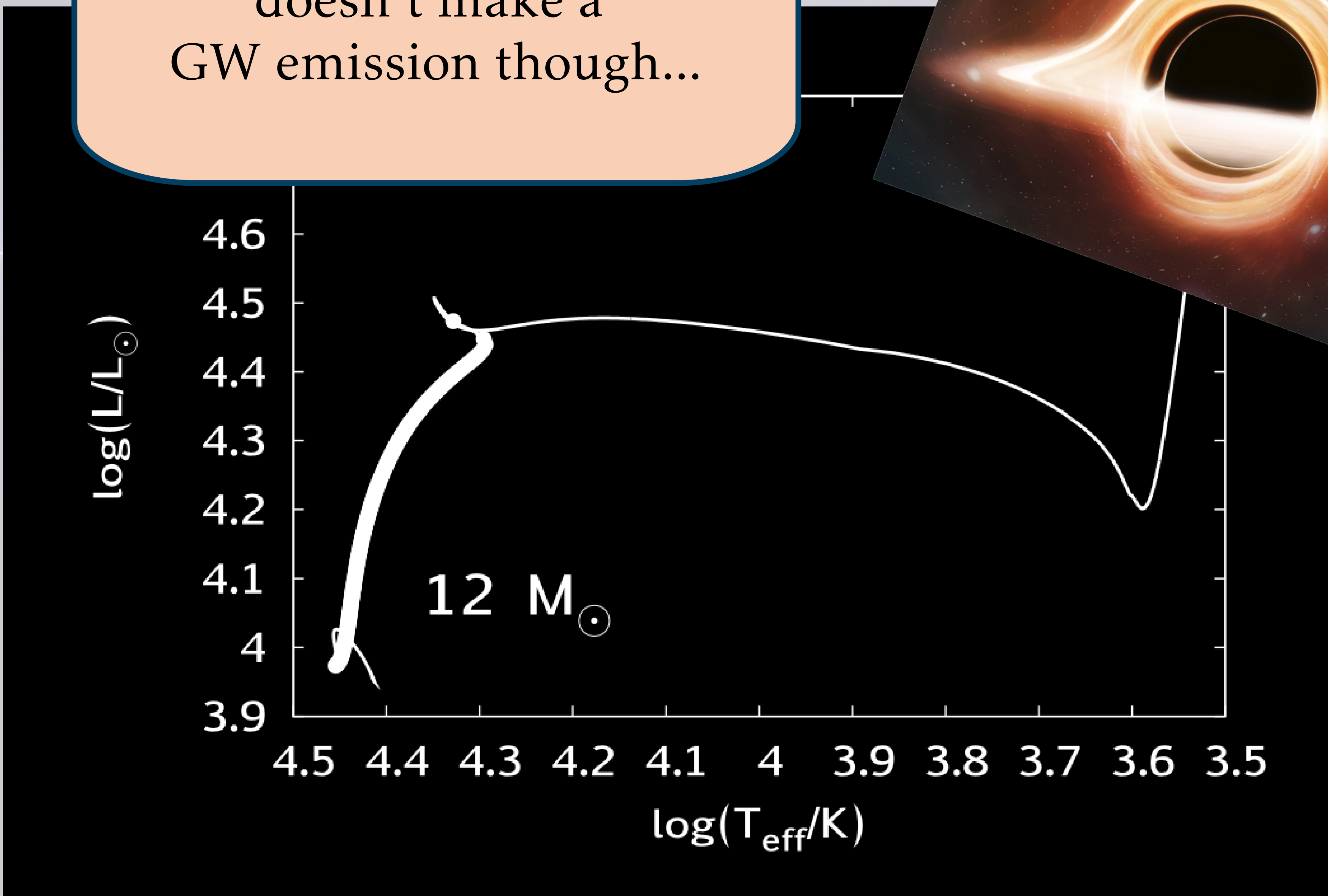
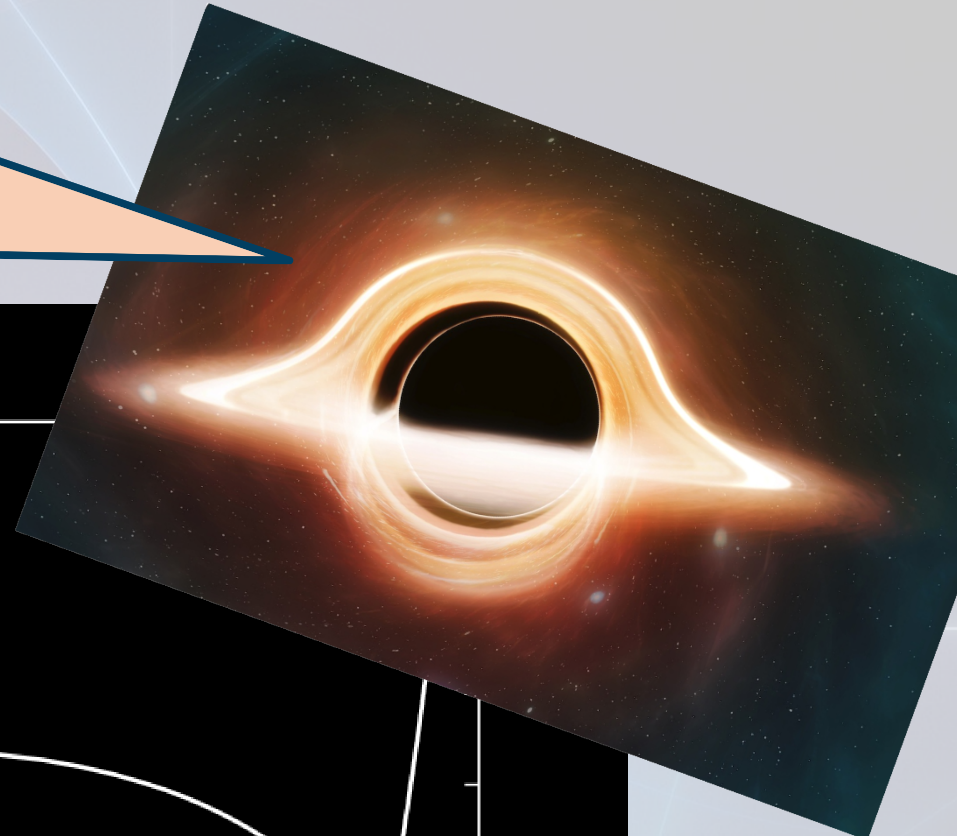
log(L/L☉)
12 M☉
4.5 4.4 4.3 4.2 4.1 4 3.9 3.8 3.7 3.6 3.5
log(T_eff/K)

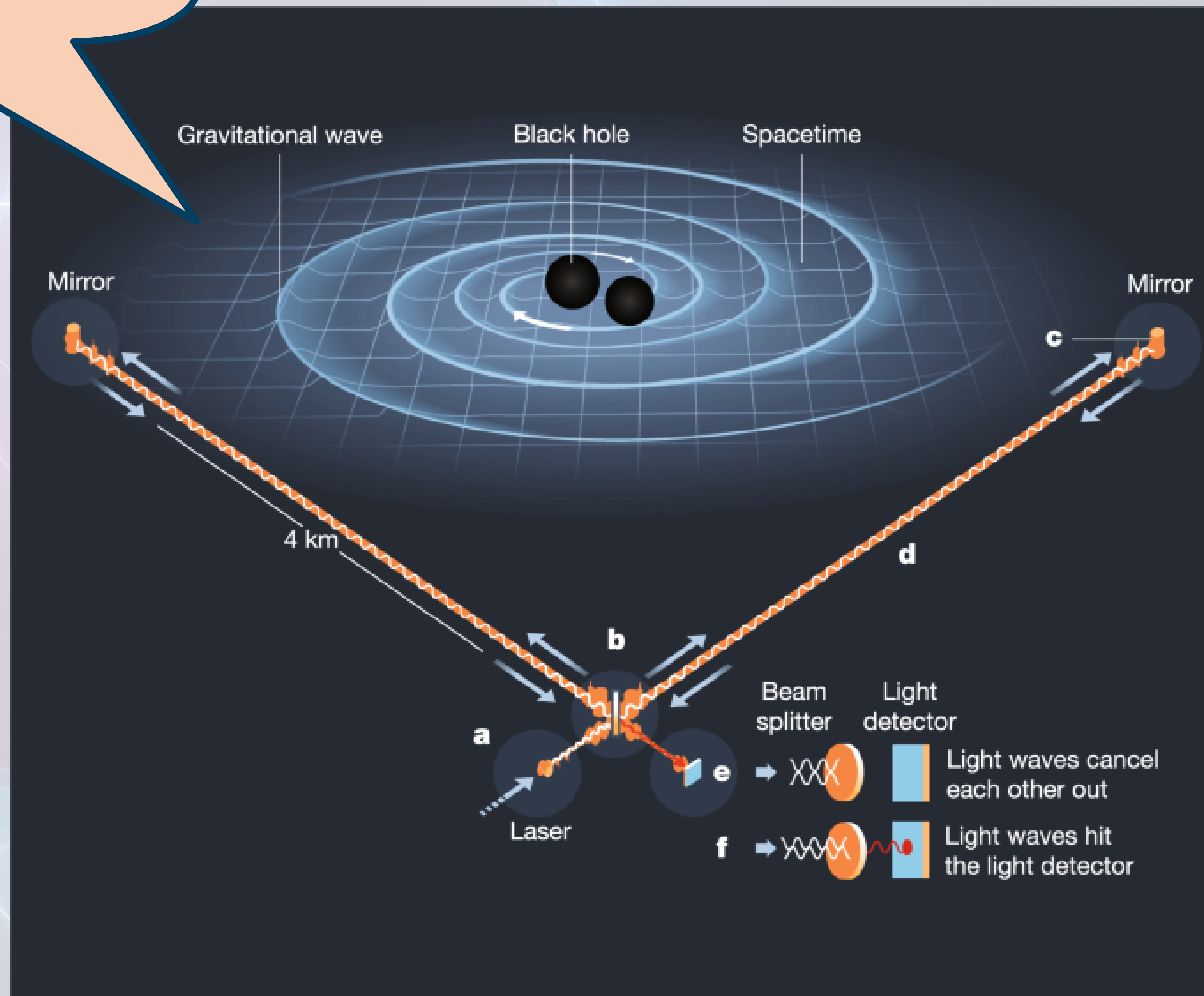


One Black Hole
doesn't make a
GW emission though...





We need at least two...



Binary stars...

...next time.