Gravitational-wave progenitors

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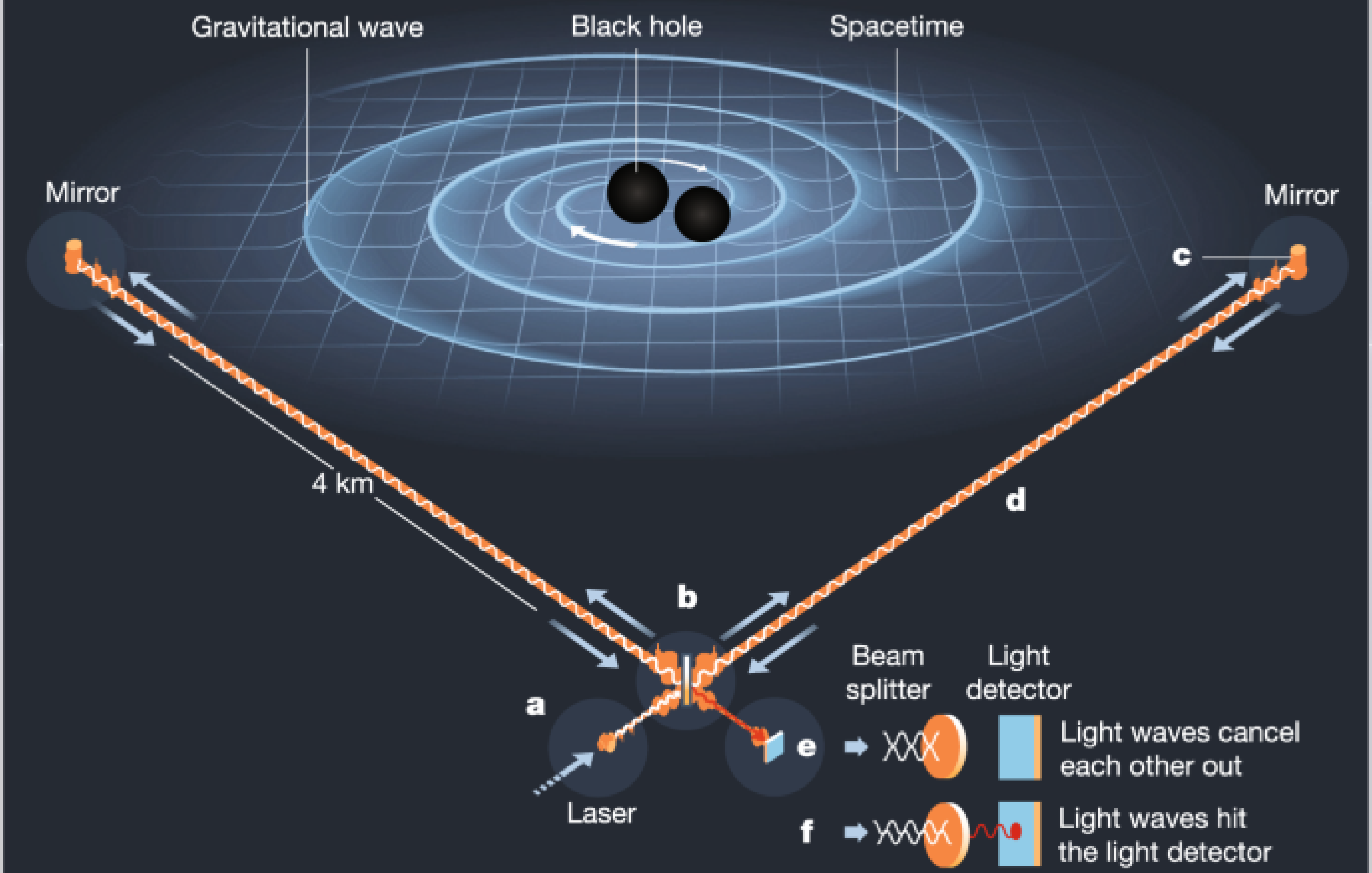
Lecture #2

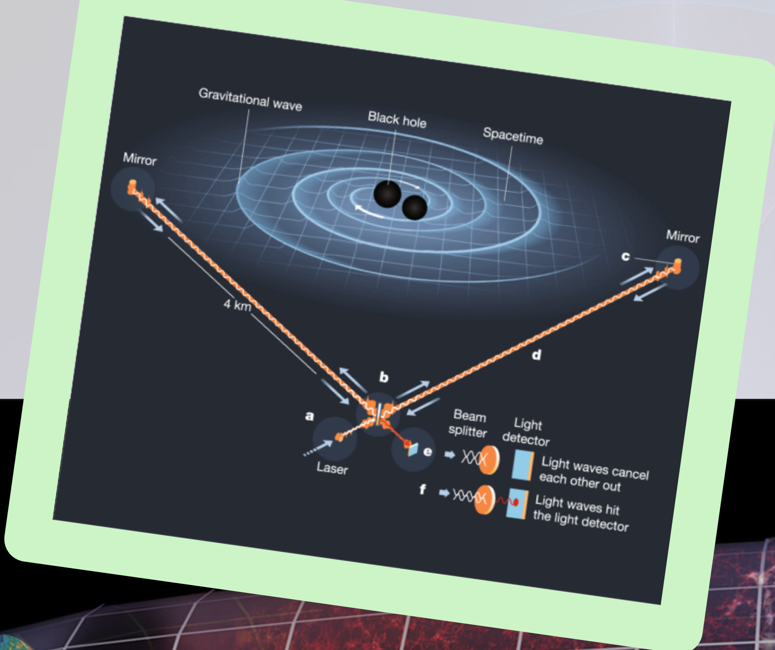
NCU, Summer Semester 2022

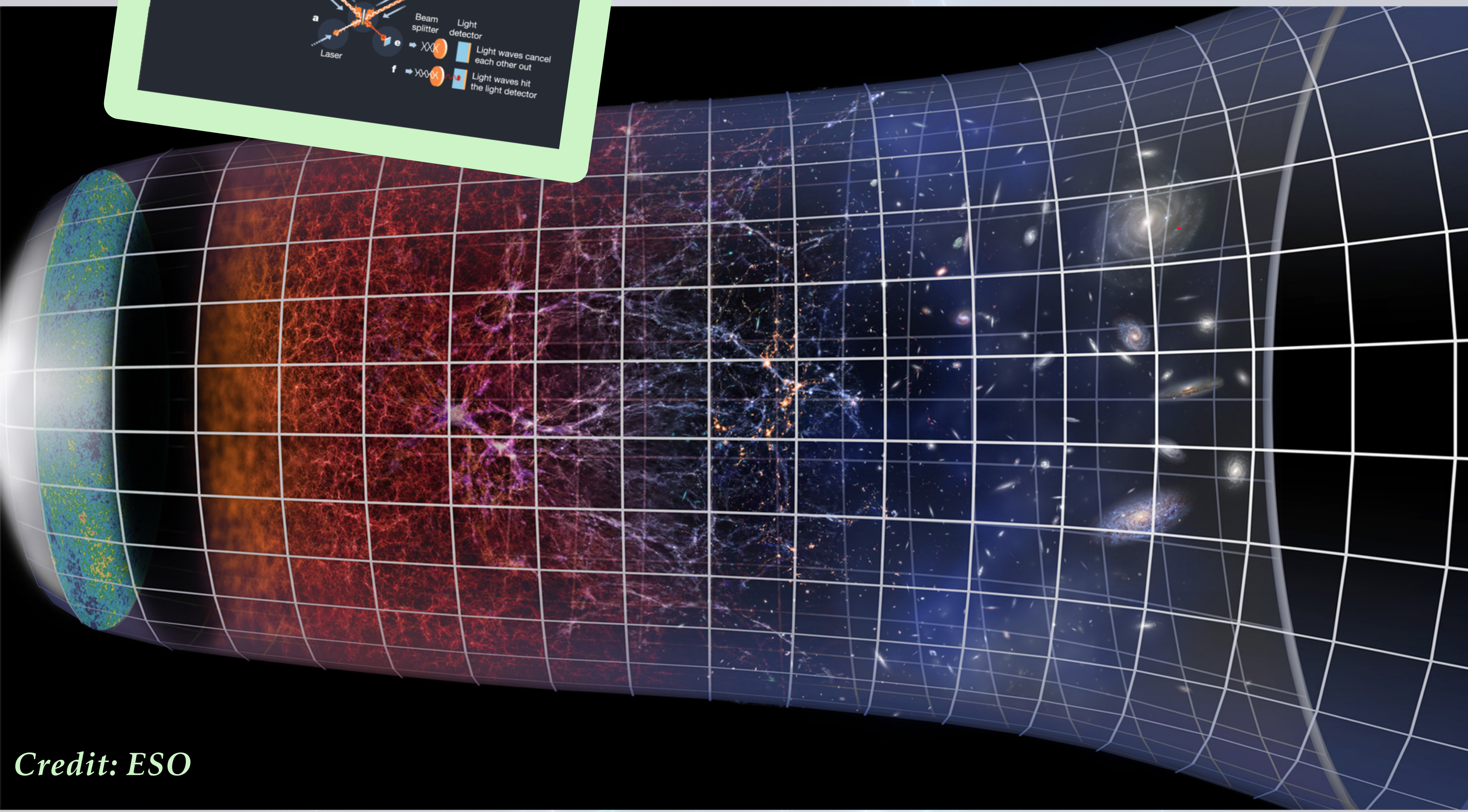
Previously

on GW-progenitors…



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

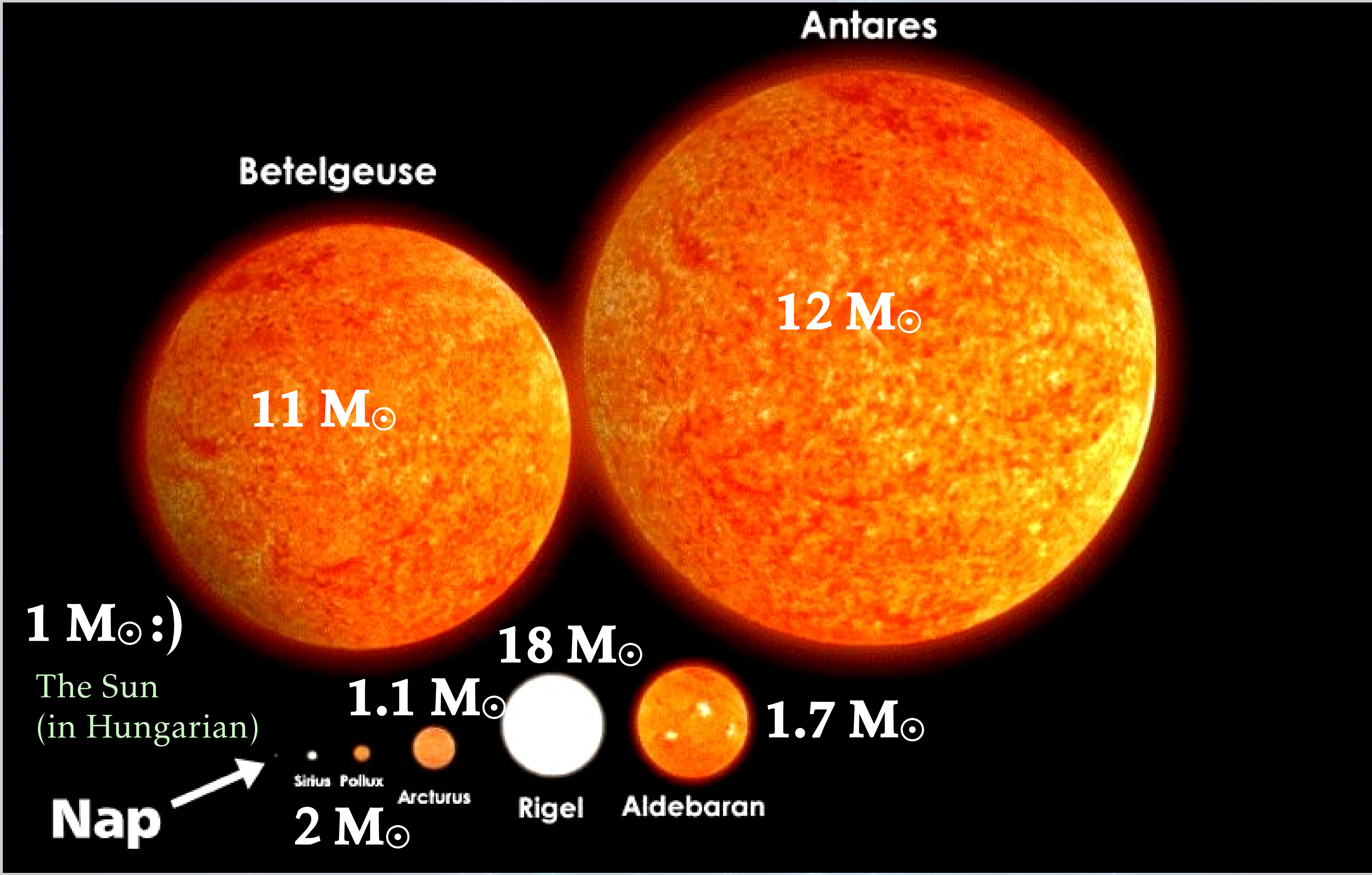

Gravitational wave
Black hole
Spacetime
Mirror
Mirror
c
4 km
d
b
a
Beam splitter
Light detector
Laser
e
Light waves cancel each other out
f
Light waves hit the light detector



Credit: ESO

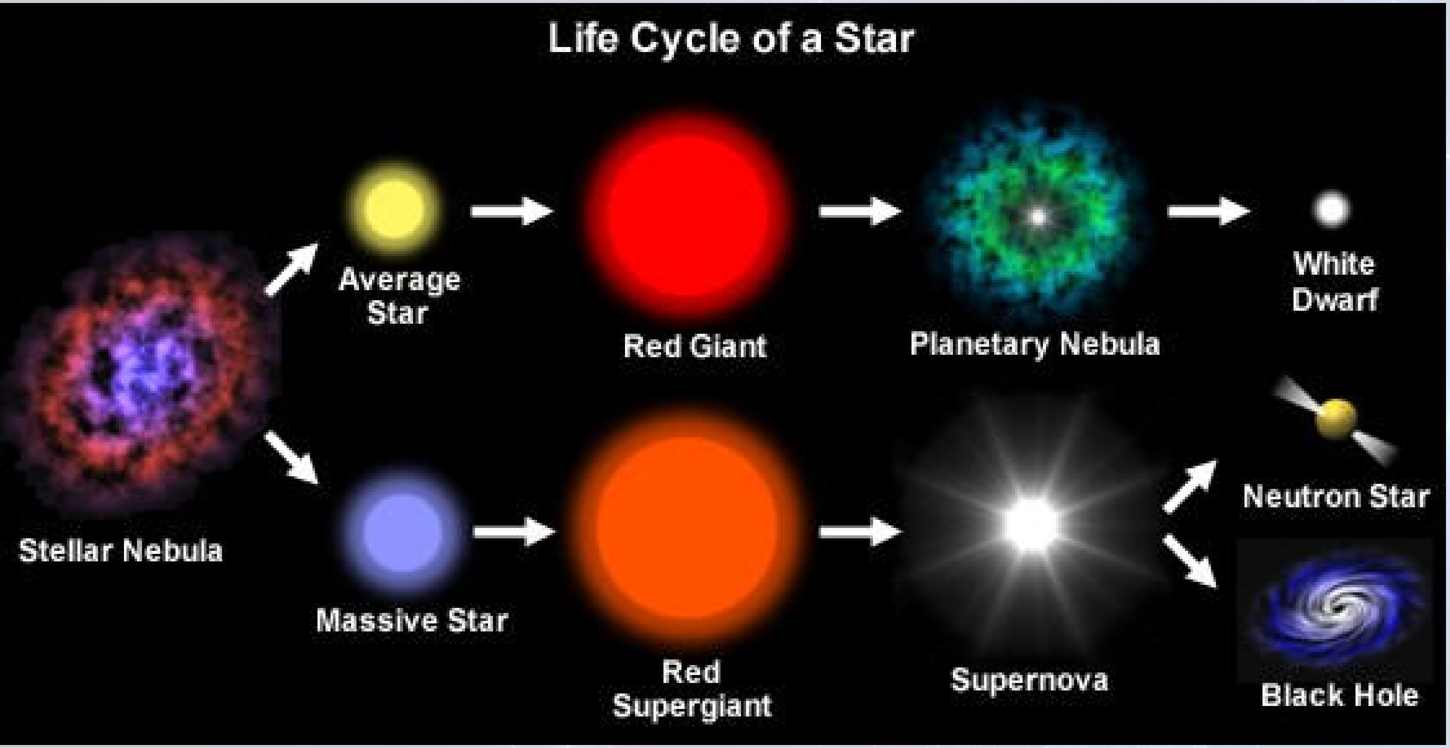
Credit: ESO/M. Kornmesser

Massive stars vs. low-mass stars



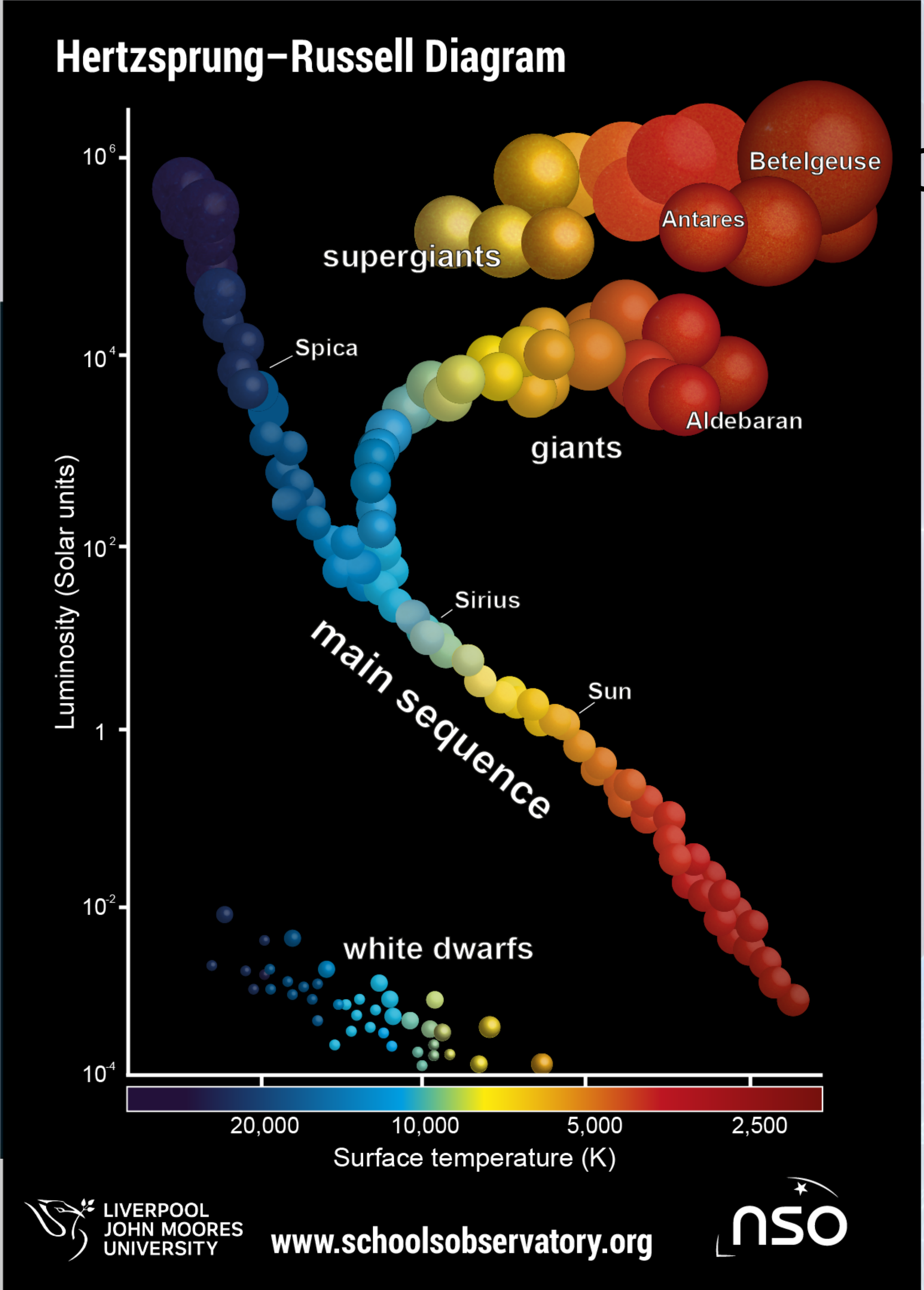
Reason: stars evolve

→ stellar evolution



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

massive: $> 8\ M_\odot$



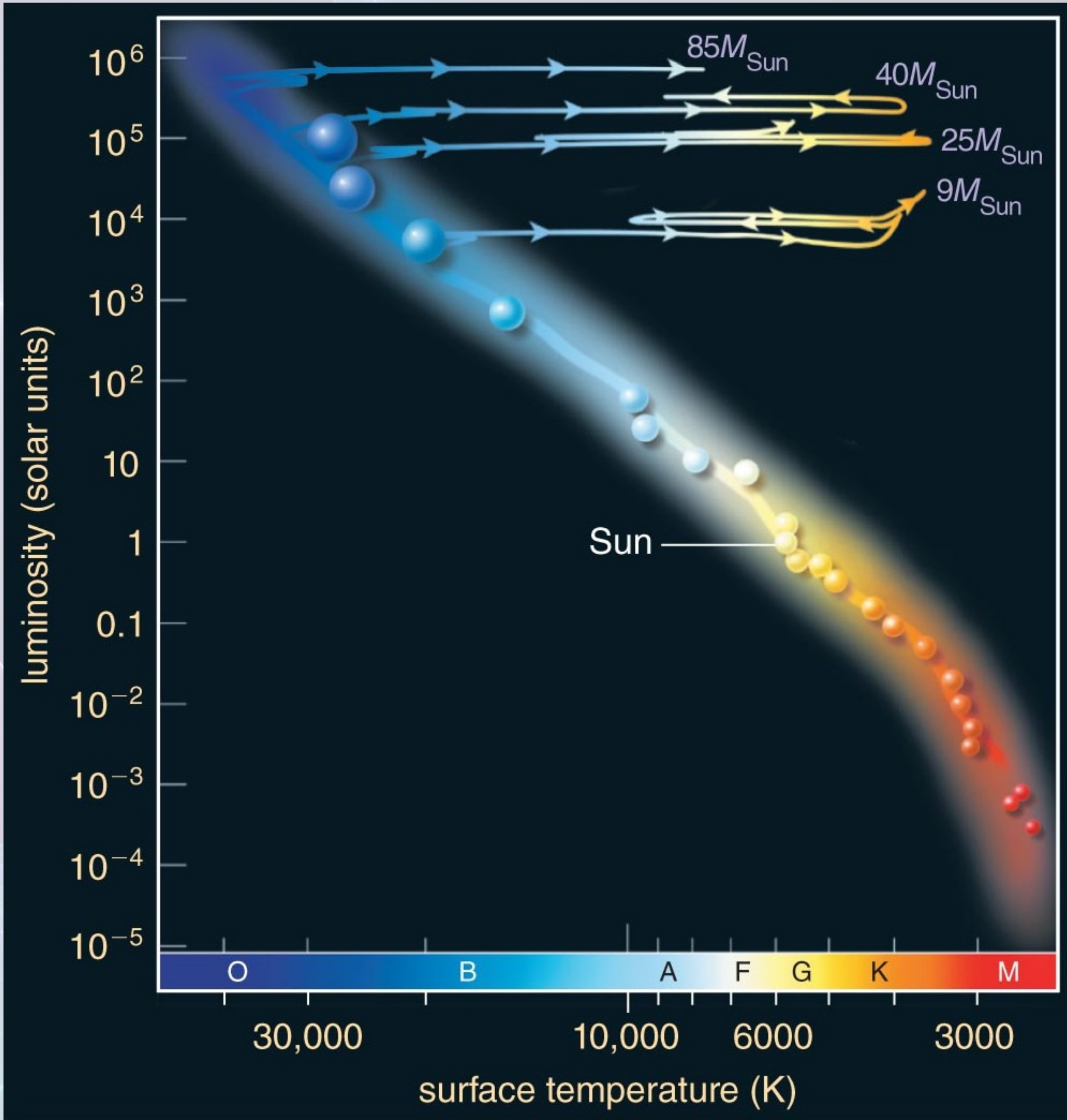
…of the HRD

radius can be easily read out
- equiradial lines due to Stephan-Bolzmann law

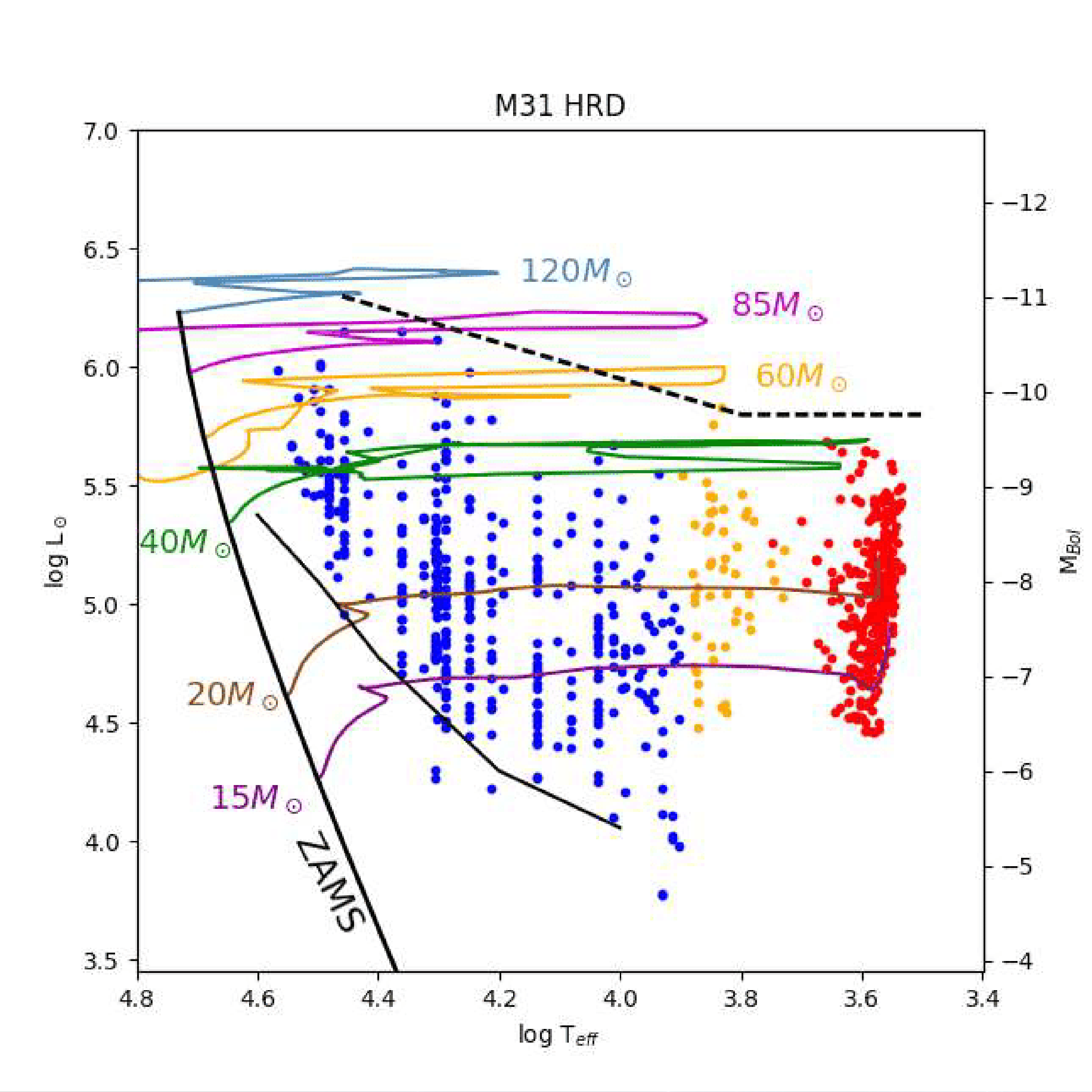
color of the star can be easily read out (~surface temp.)
brightness: ~luminosity

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: $\lg T_{eff}$ [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.)

Theoretical modelling of the stellar structure

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

ec 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

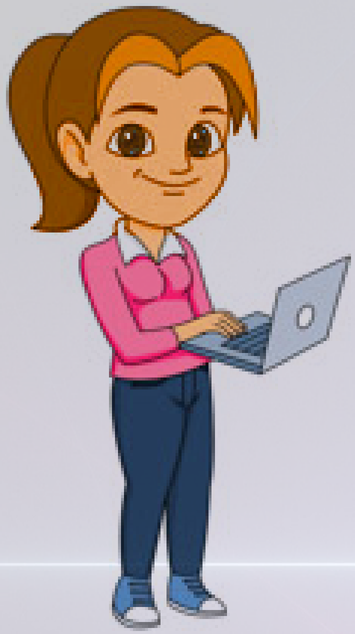
$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

Guilera+ 11

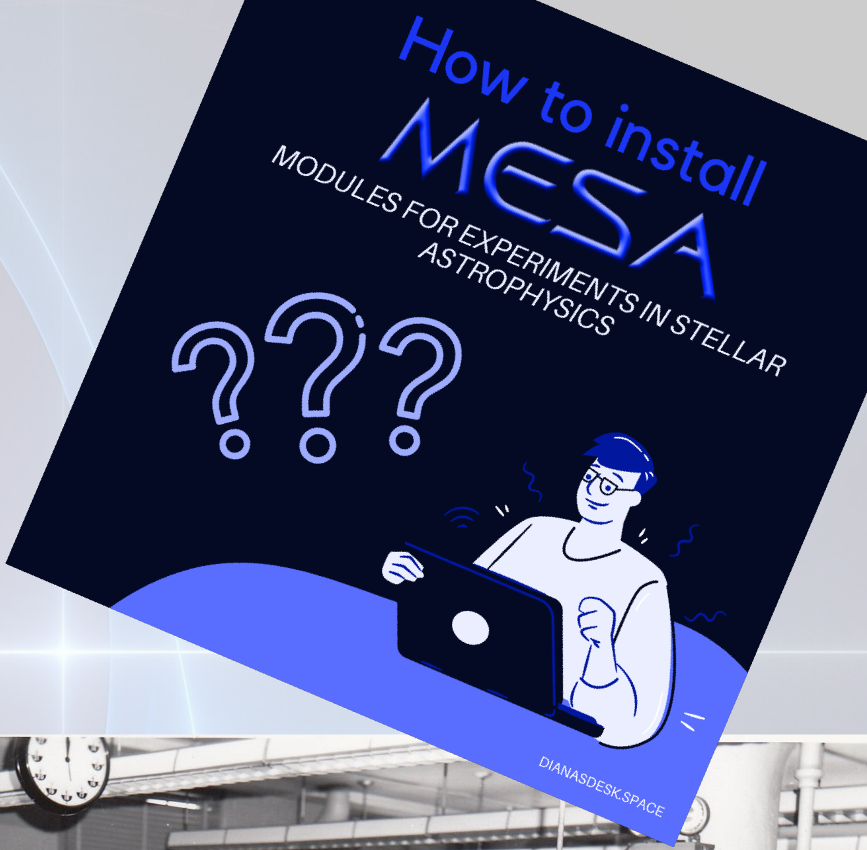
composition change due to nuclear burning:

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



MESA Summer School 2022: August 8th-12th (University of California, Santa Barbara)

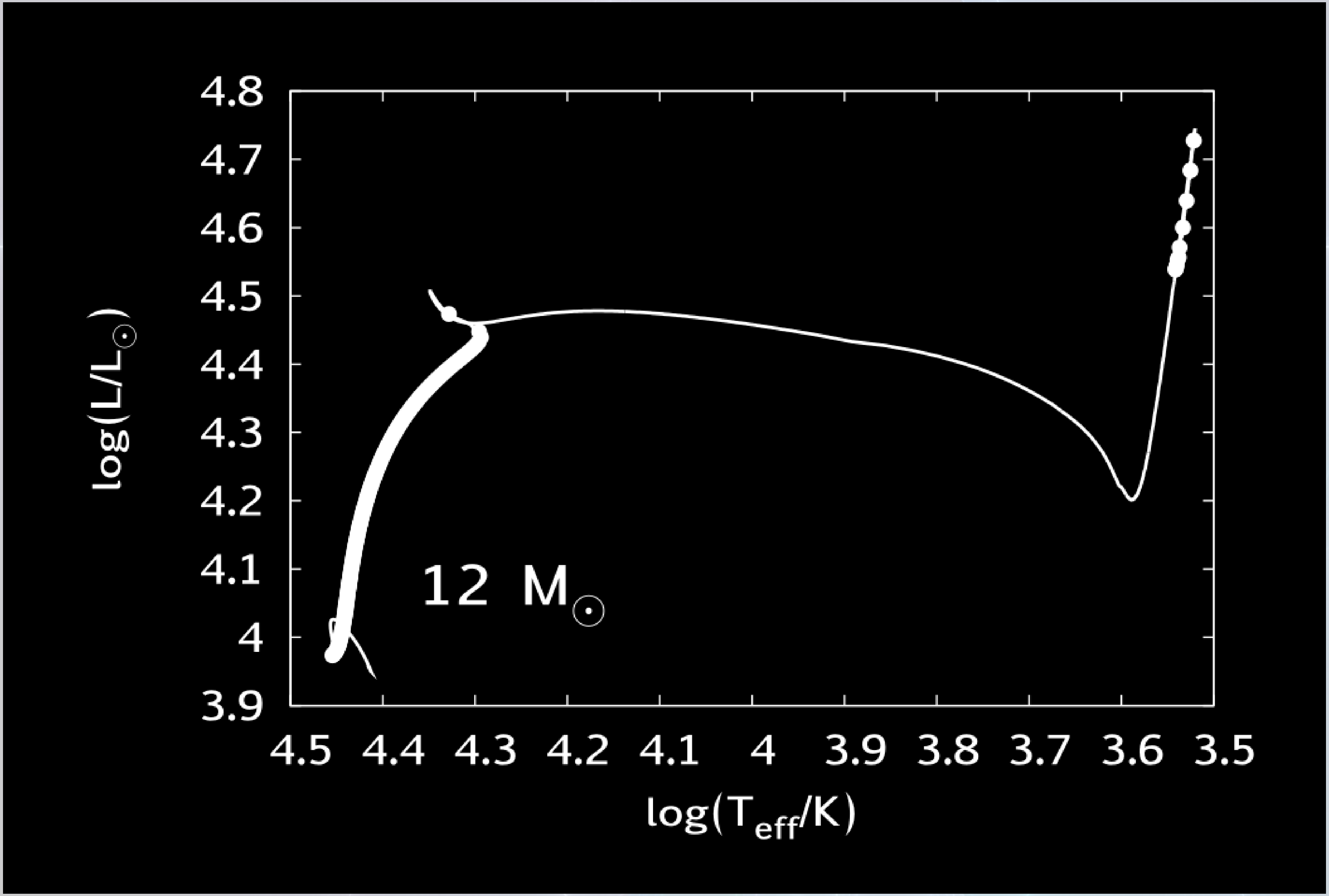
https://mesahub.github.io/summer-school-2022/application/



Where to start:

https://docs.mesastar.org/en/latest/index.html

https://cococubed.com/mesa_market/education.html



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log(L/L☉)
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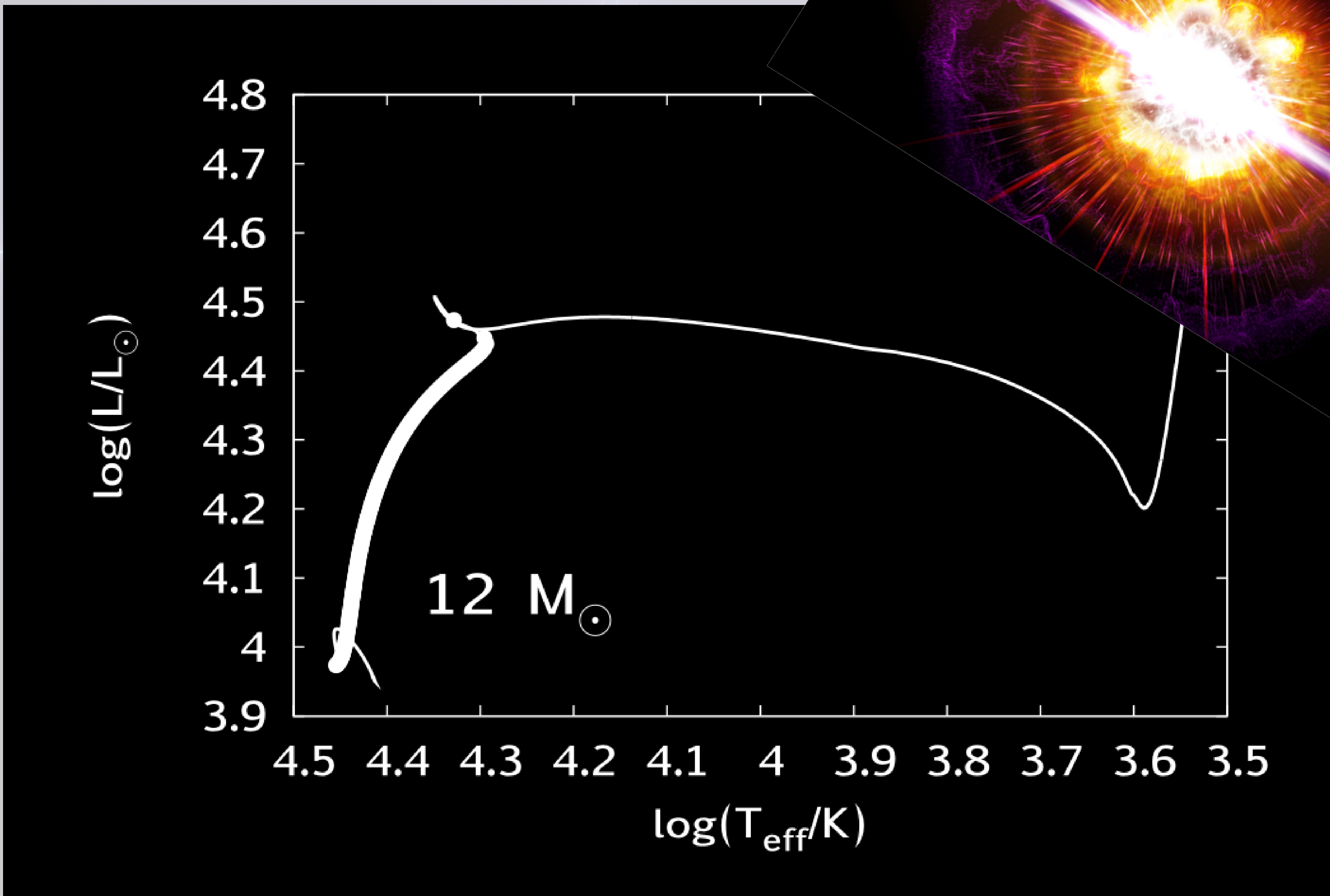
3.5
log(Teff/K)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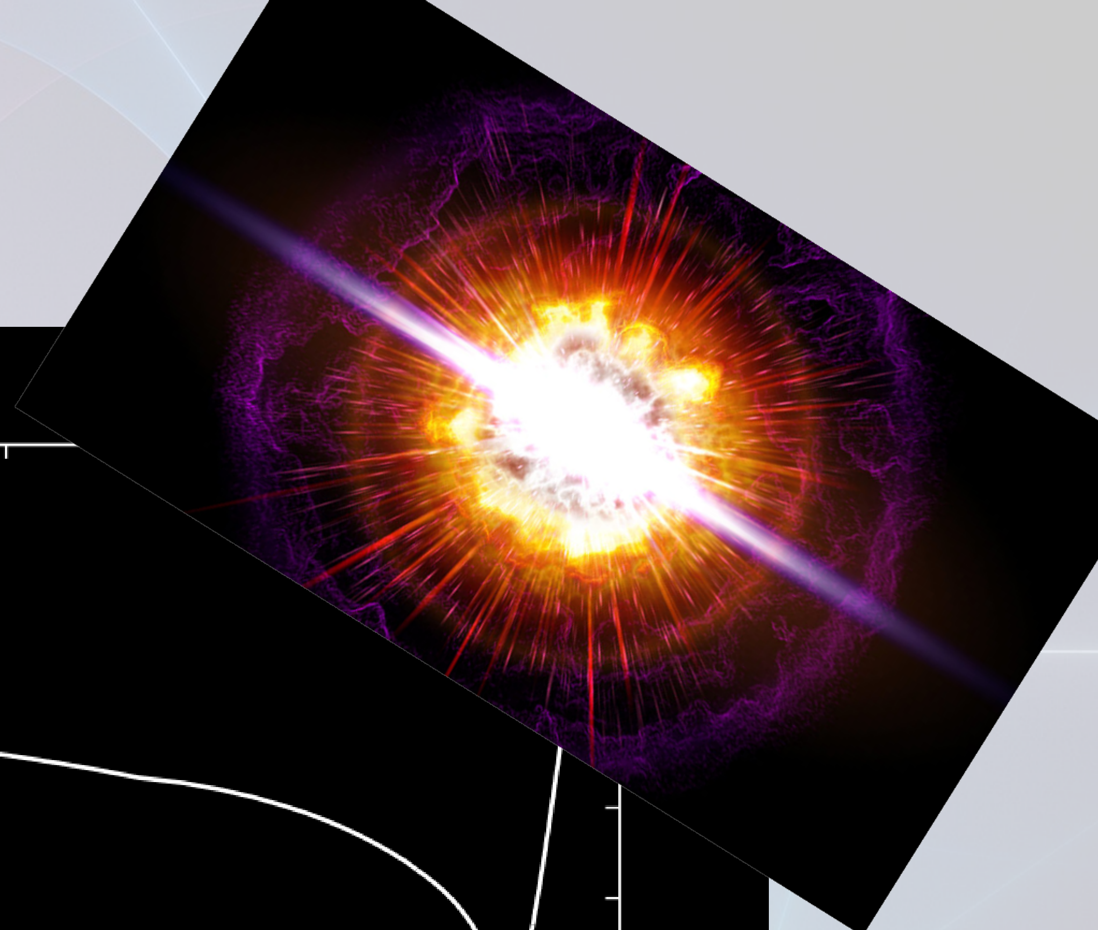
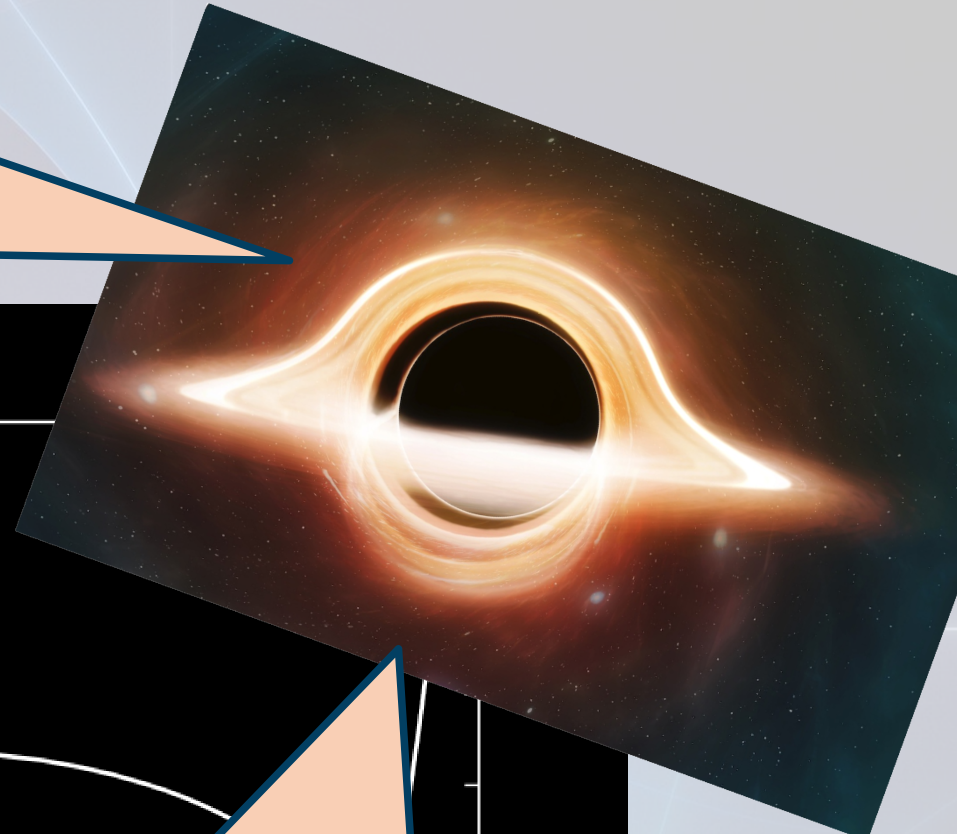
$\log(L/L_\odot)$
4.5 4.4 4.3 4.2 4.1 4 3.9 3.8 3.7 3.6 3.5
$\log(T_{eff}/K)$
$12\ M_\odot$

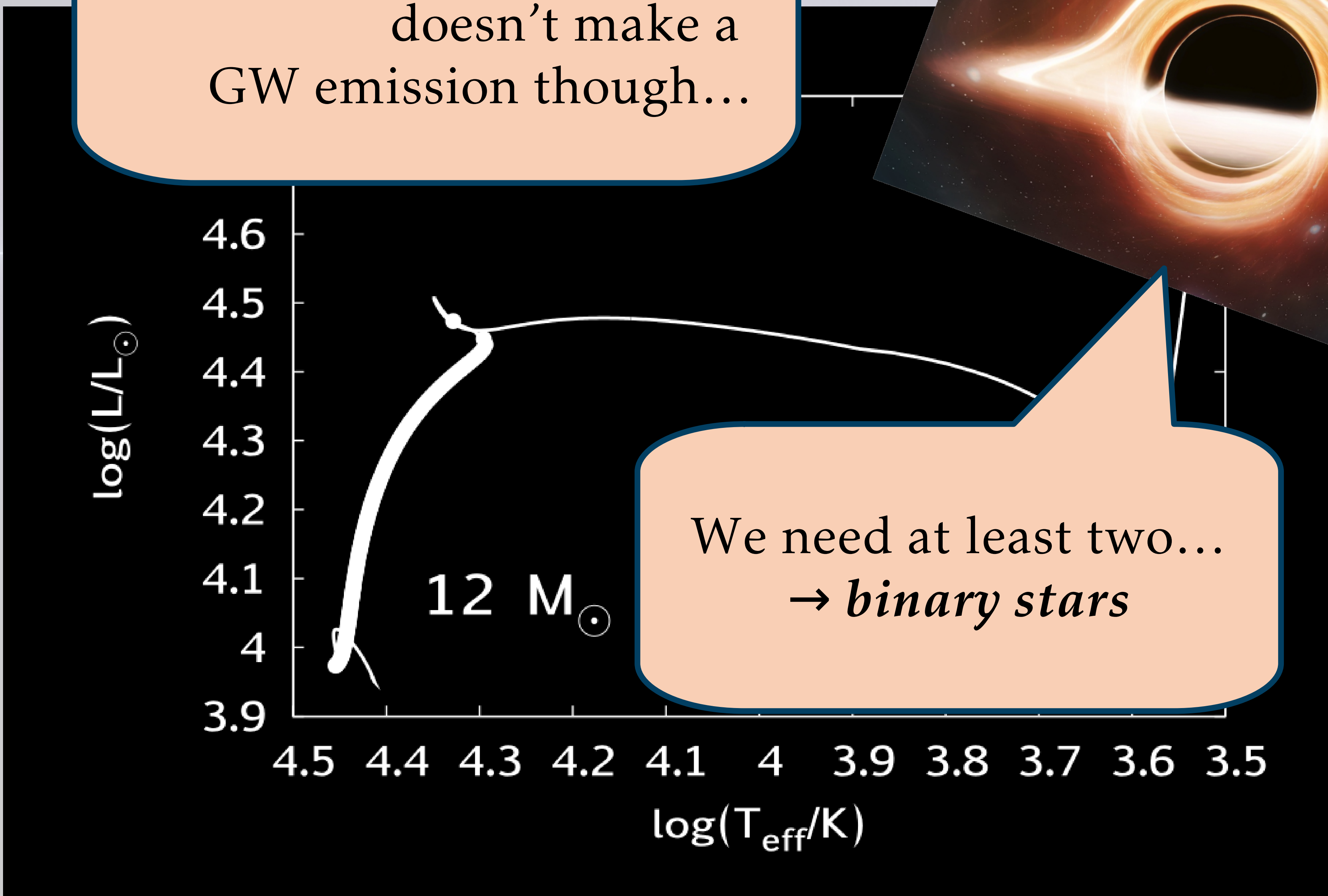


One Black Hole*

*Neutron Star

doesn't make a GW emission though…



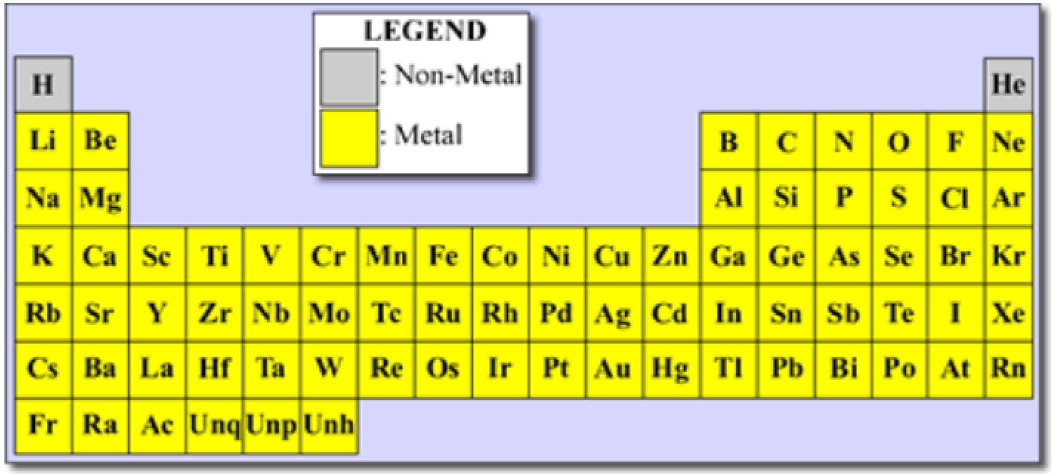


We need at least two…

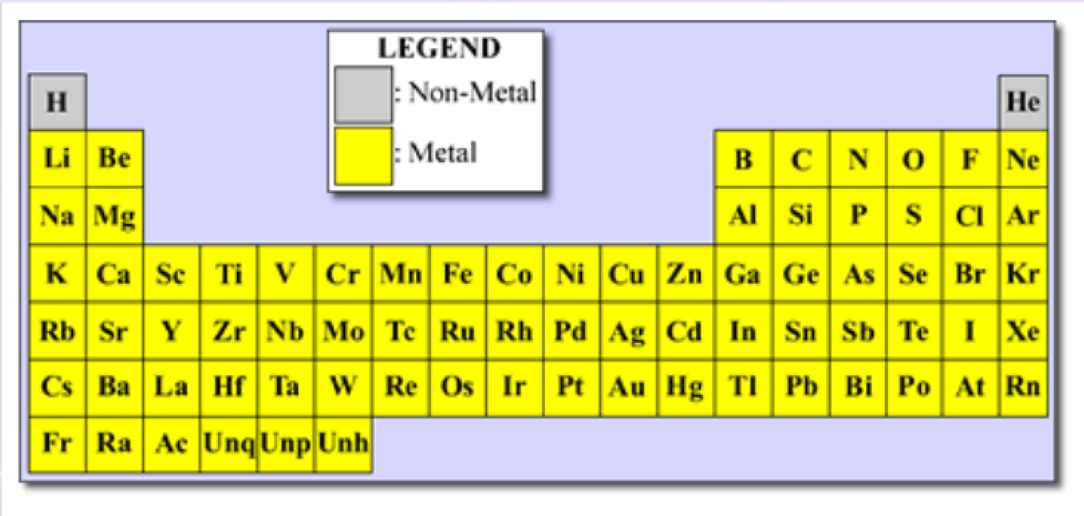
→ ***binary stars***

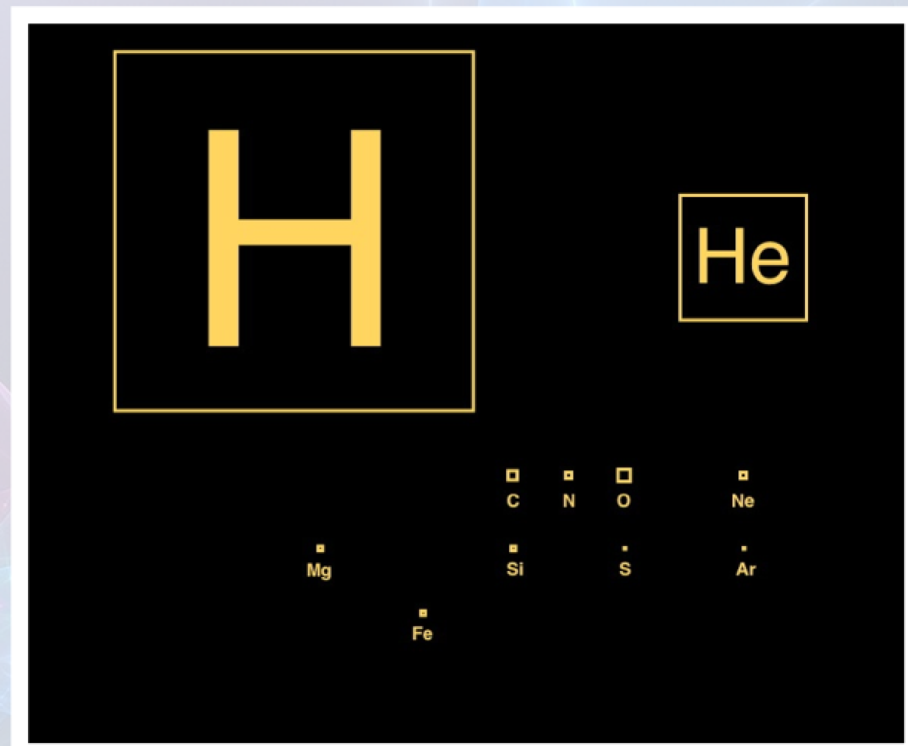
Metallicity

Astronomers and metal

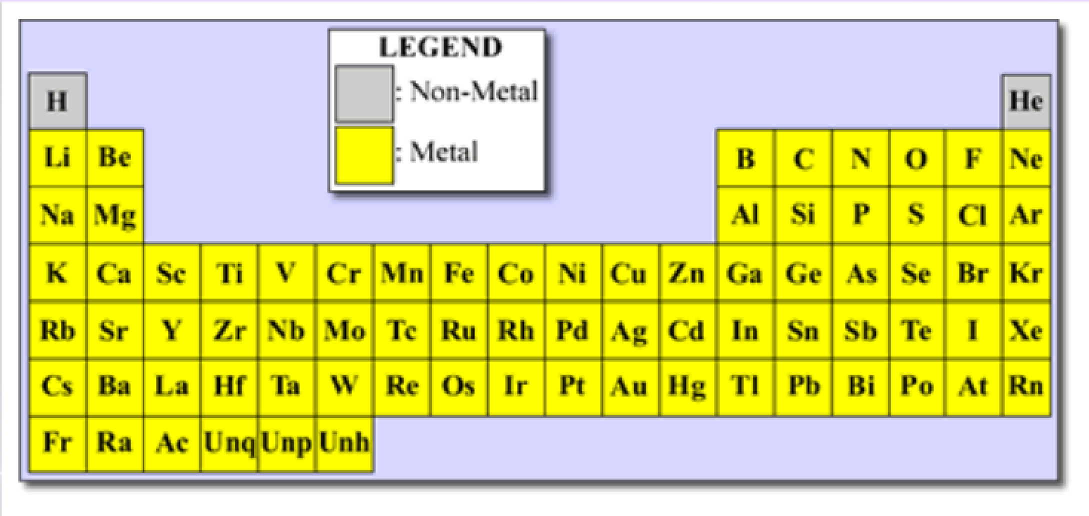


Astronomers and metal

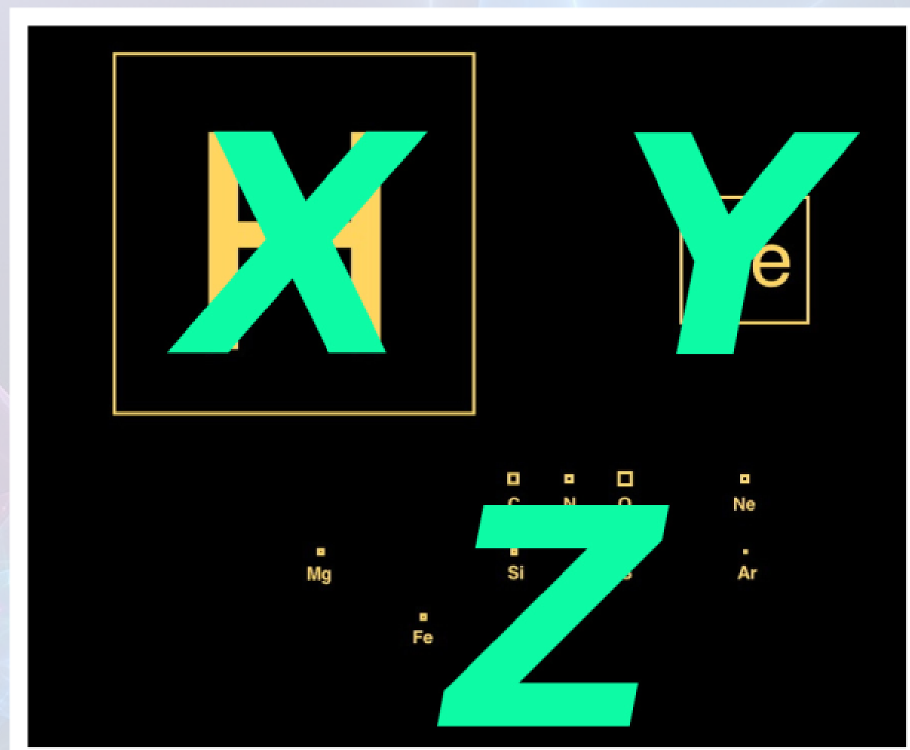




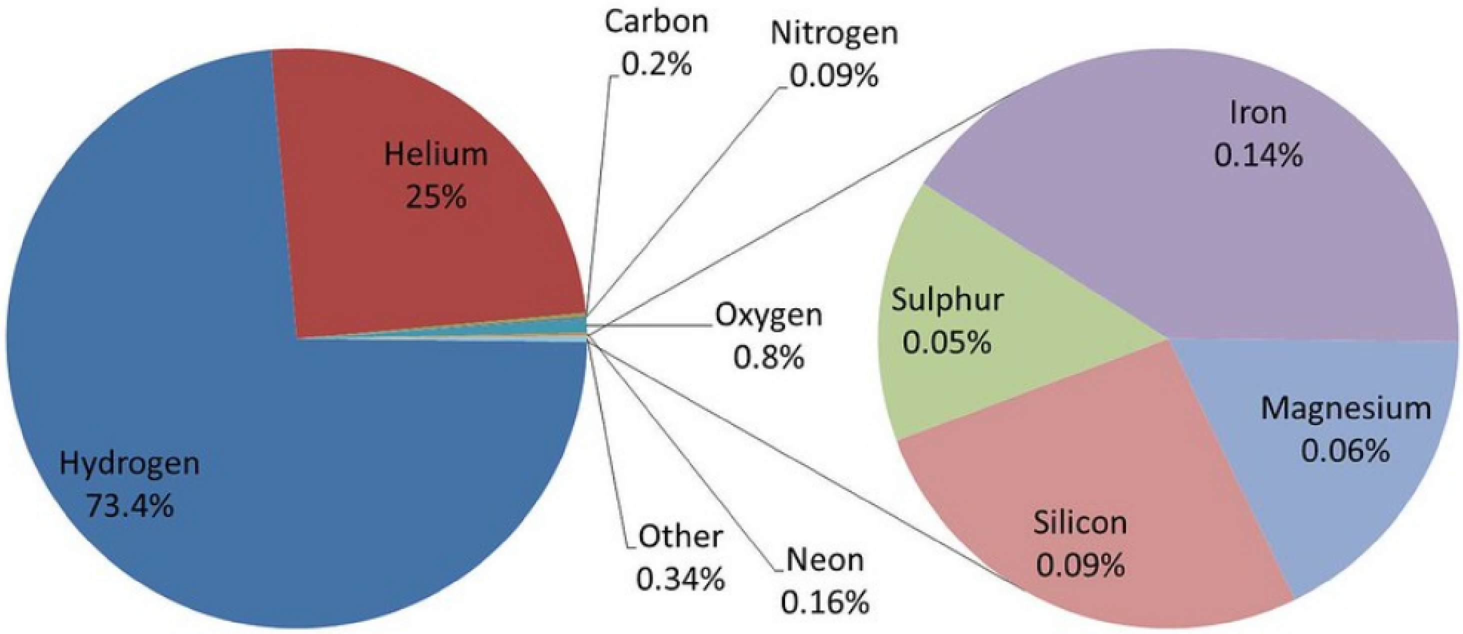
Astronomers and metal



"Z: metallicity"

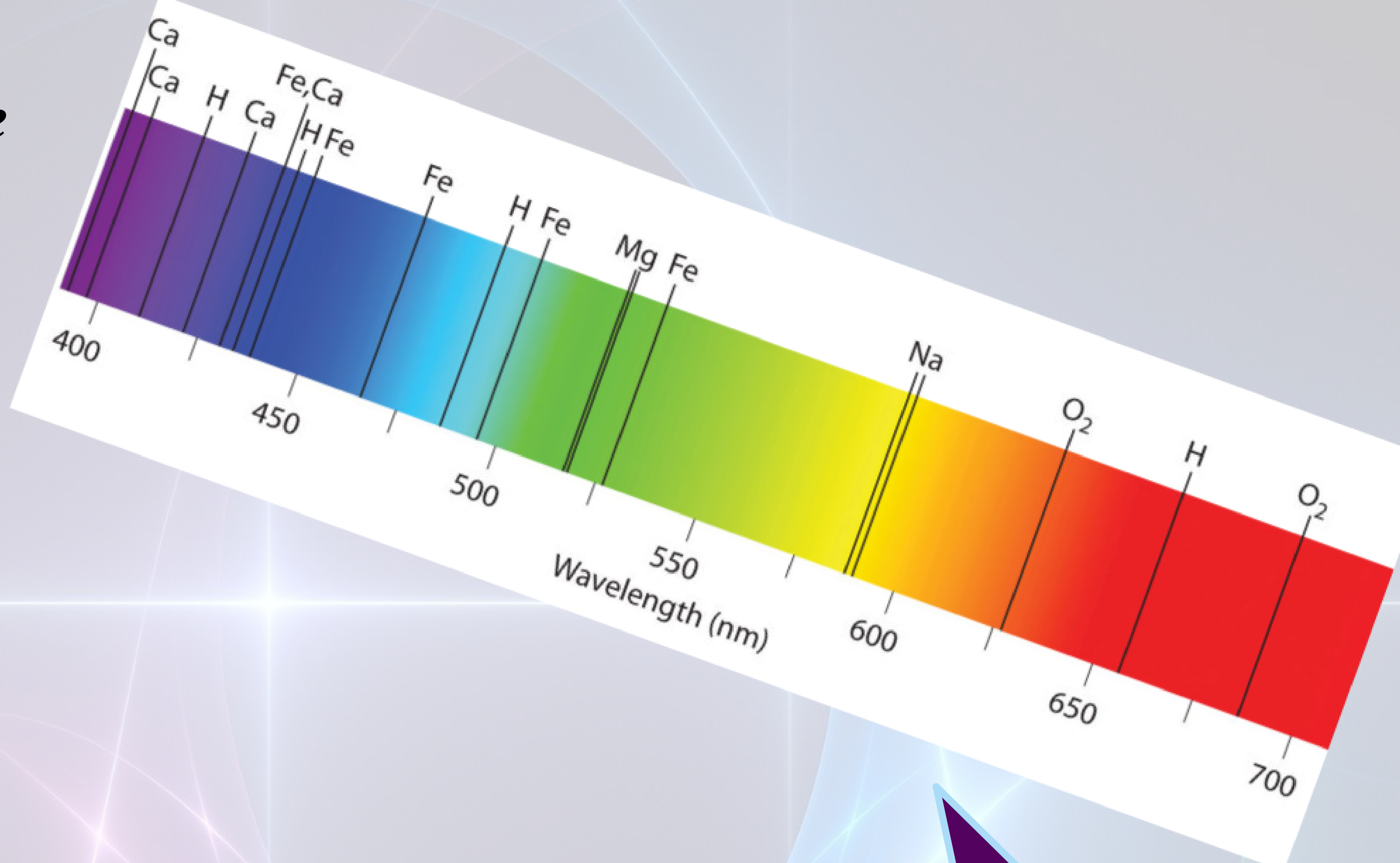


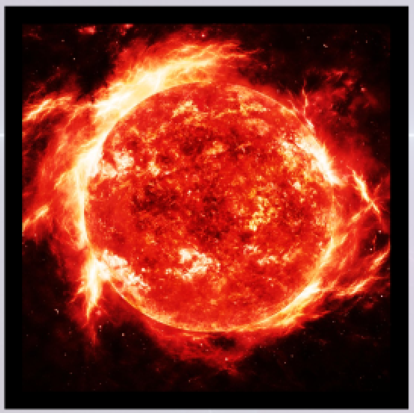
The Sun's composition



Less than 2% heavy elements,
i.e. *high* metal content, metal-*rich*

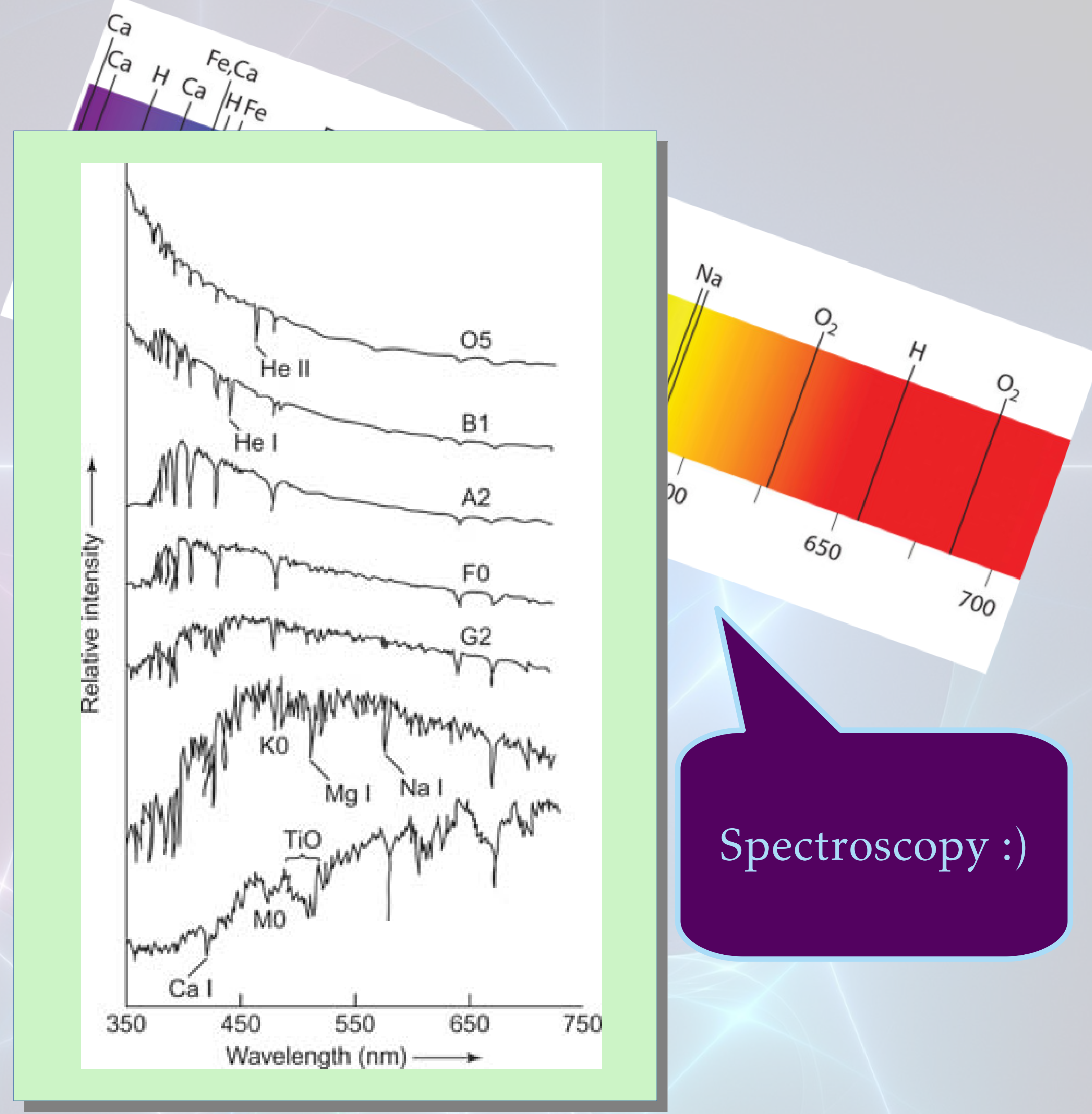
How to measure composition?





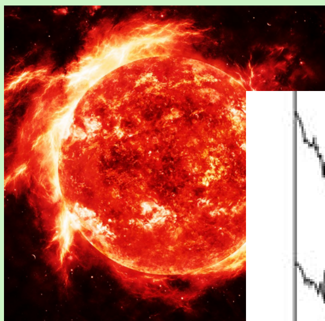
Spectroscopy :)

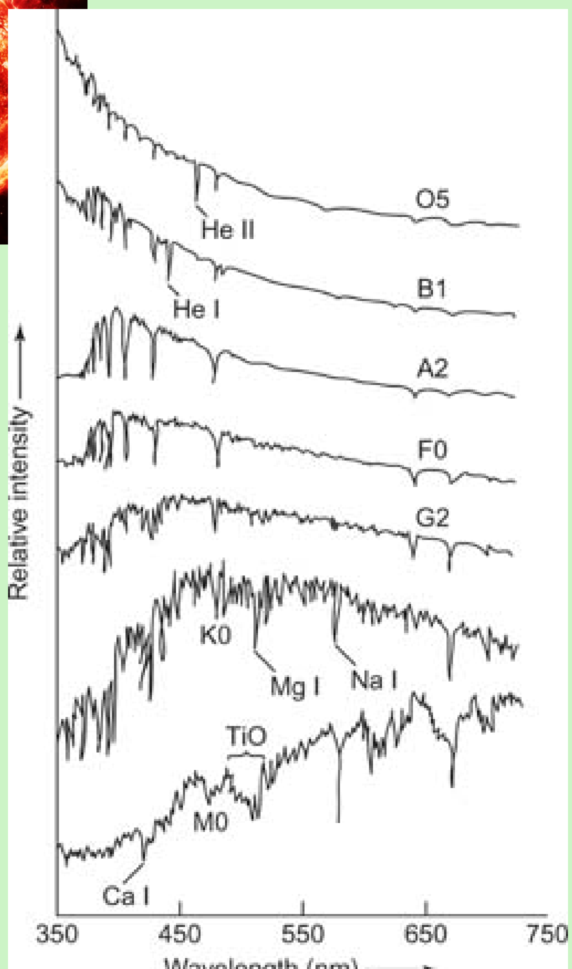
How to measure composition?



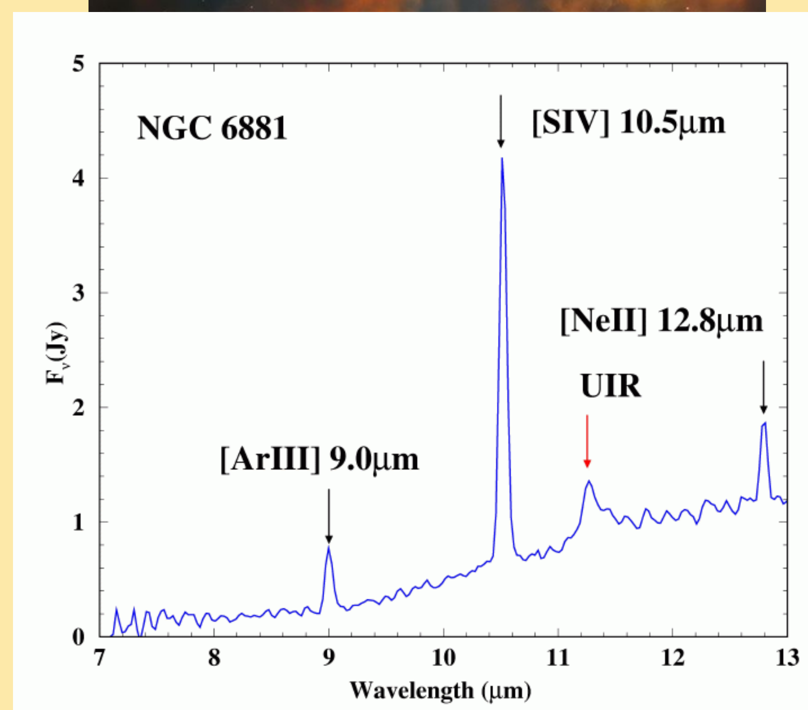
Spectroscopy :)

- Stellar spectra
  - absorption lines (mostly)





- Nebular spectra
  - emission lines (a light source needed for the excitation)

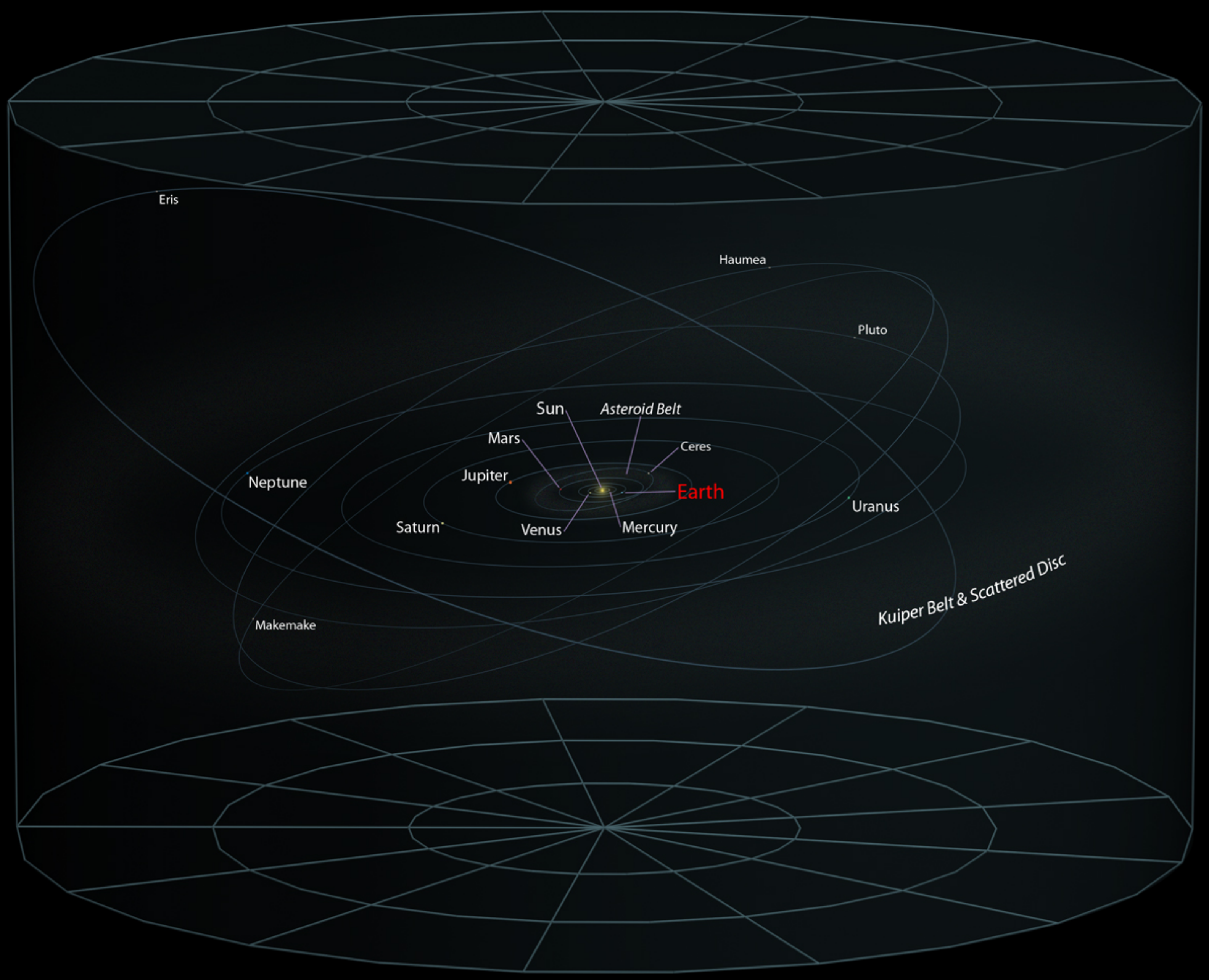


Where can we find stars*

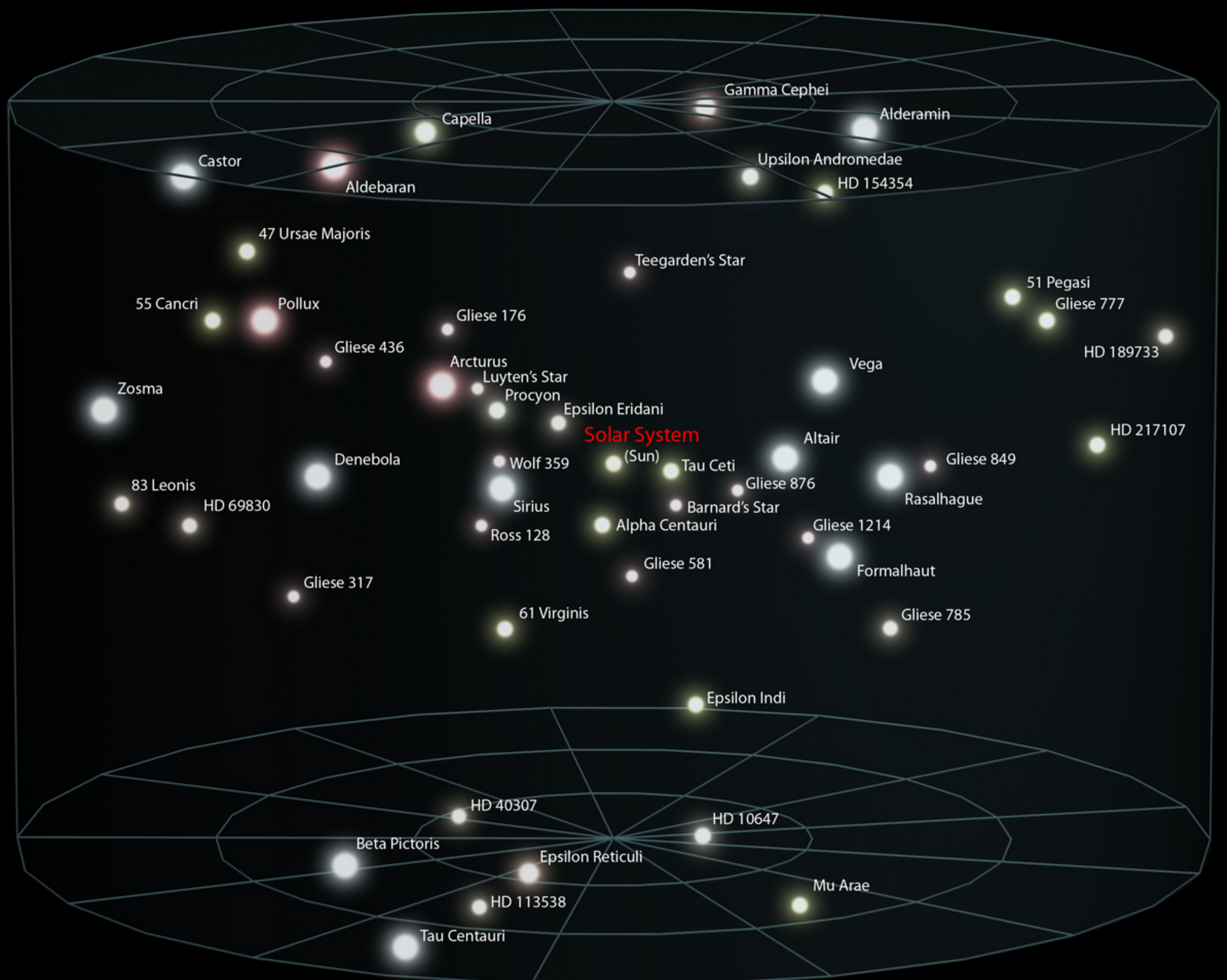
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

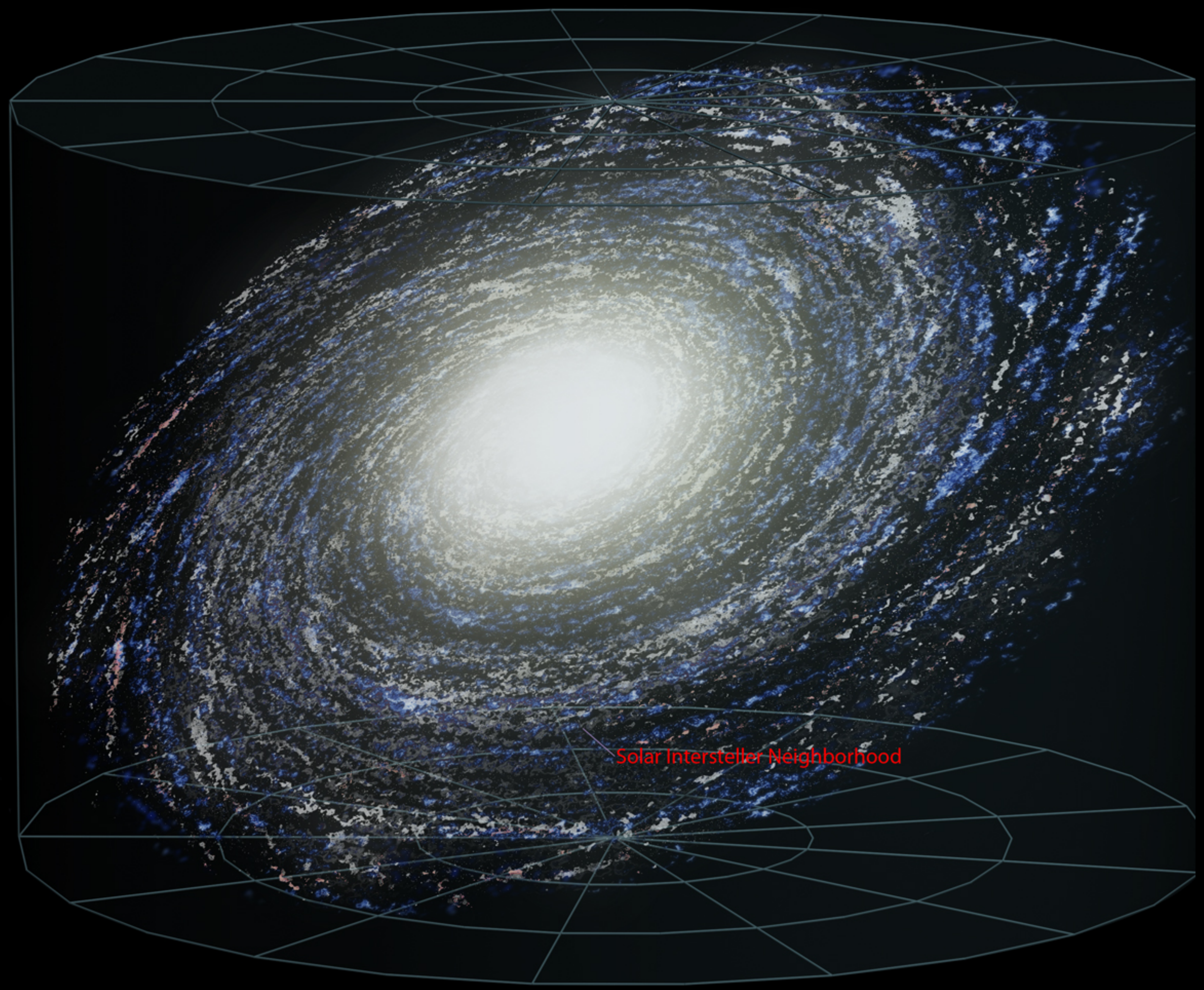
SOLAR SYSTEM



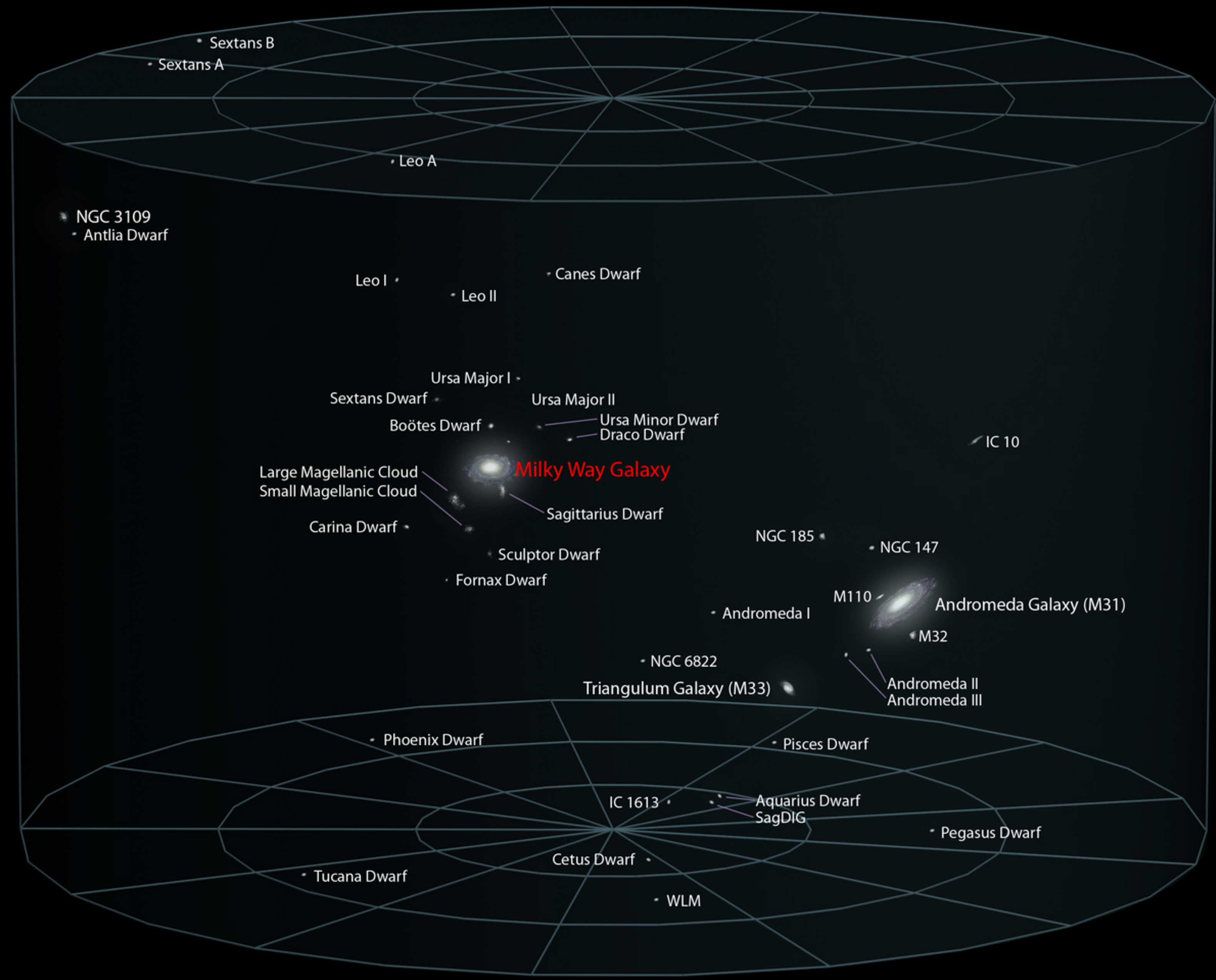
INTERSTELLAR NEIGHBORHOOD



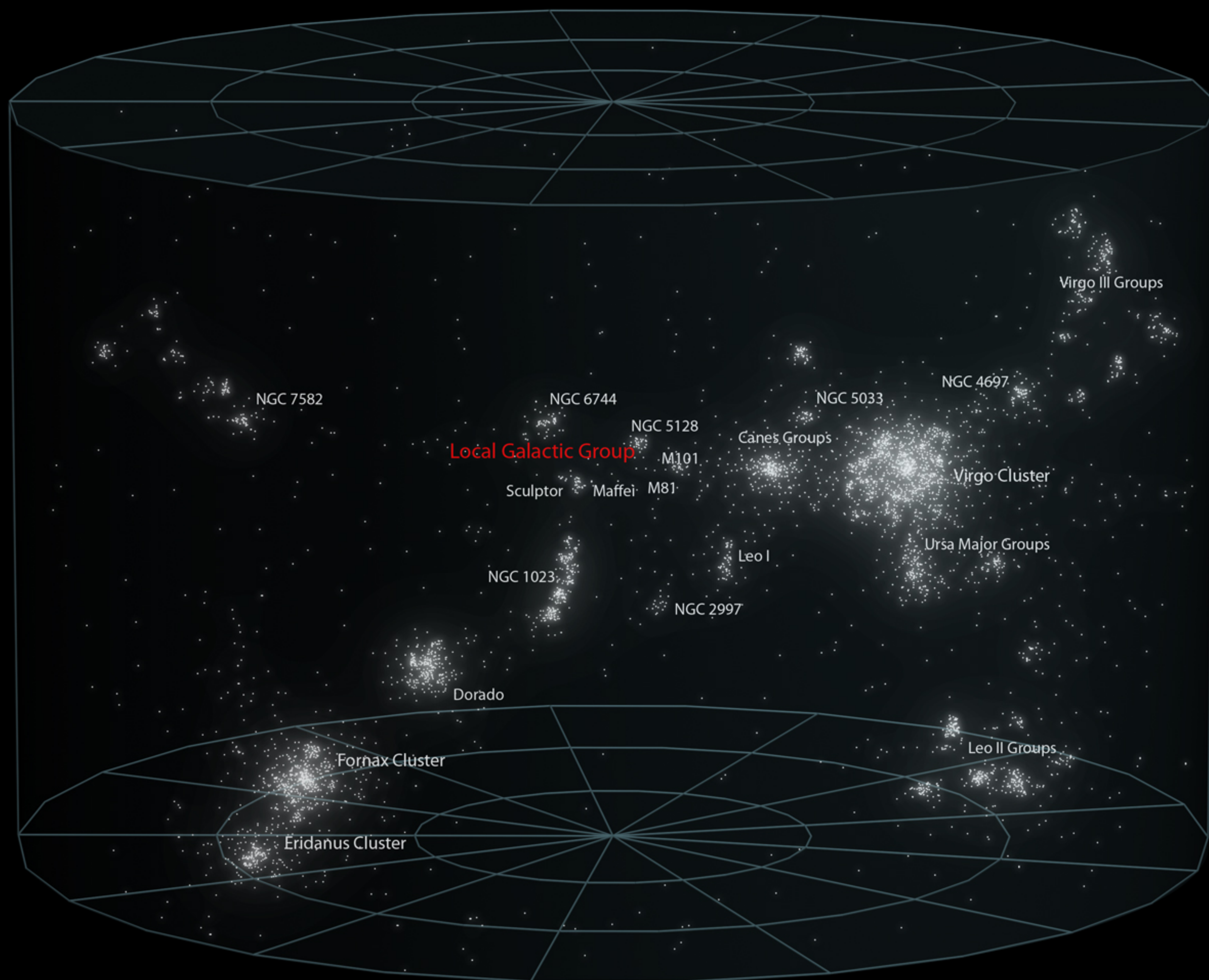
MILKY WAY GALAXY



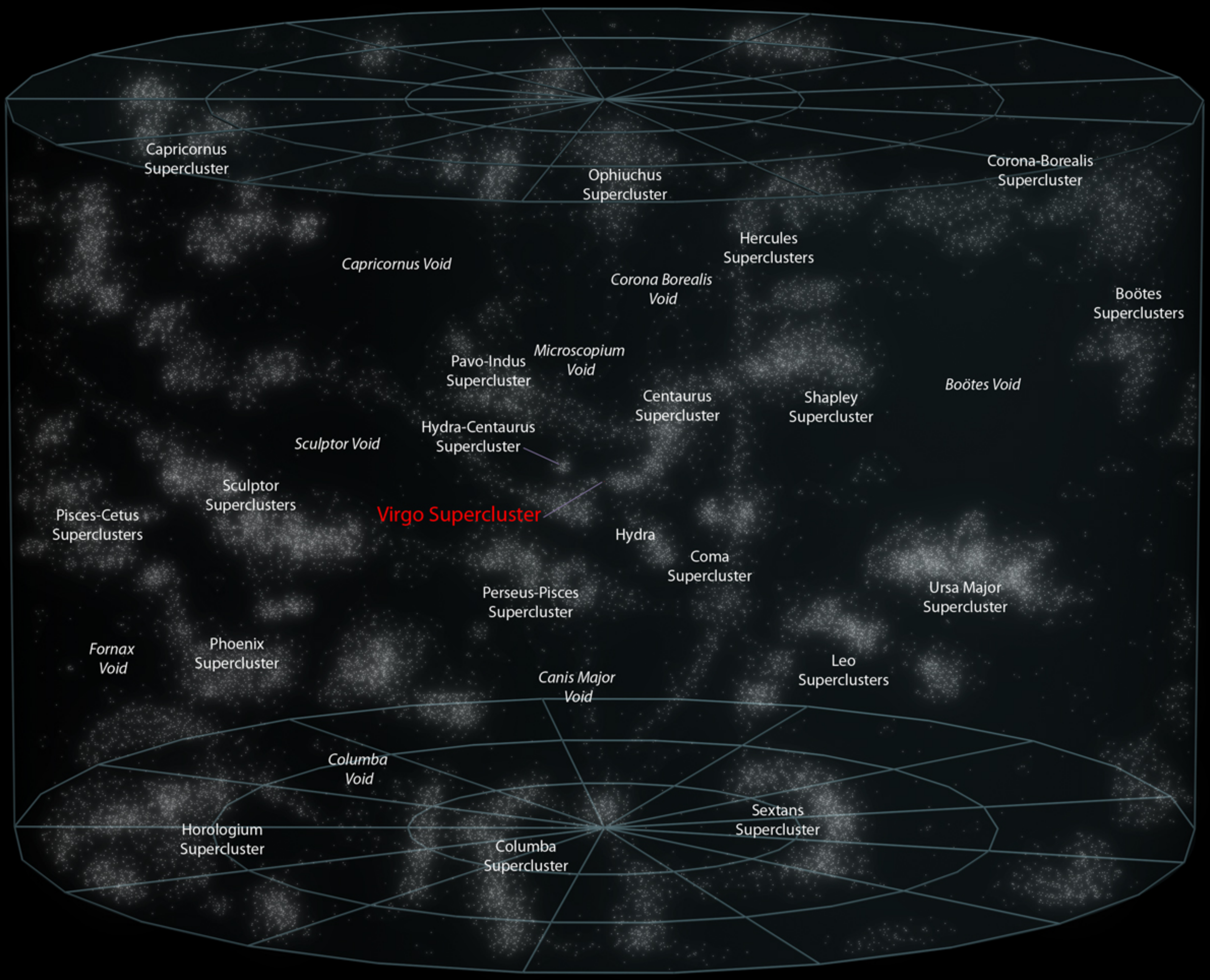
LOCAL GALACTIC GROUP



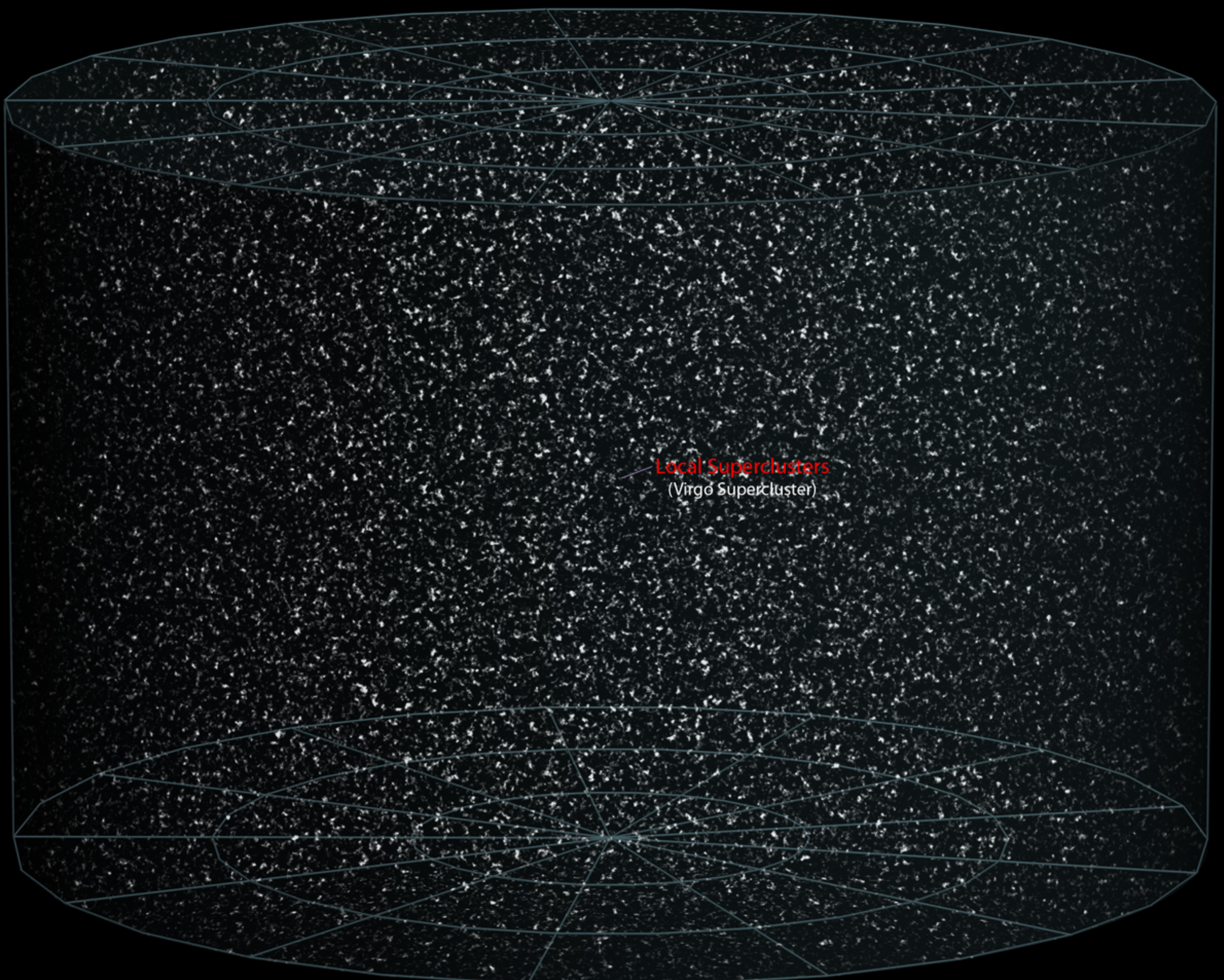
VIRGO SUPERCLUSTER



LOCAL SUPERCLUSTERS



OBSERVABLE UNIVERSE



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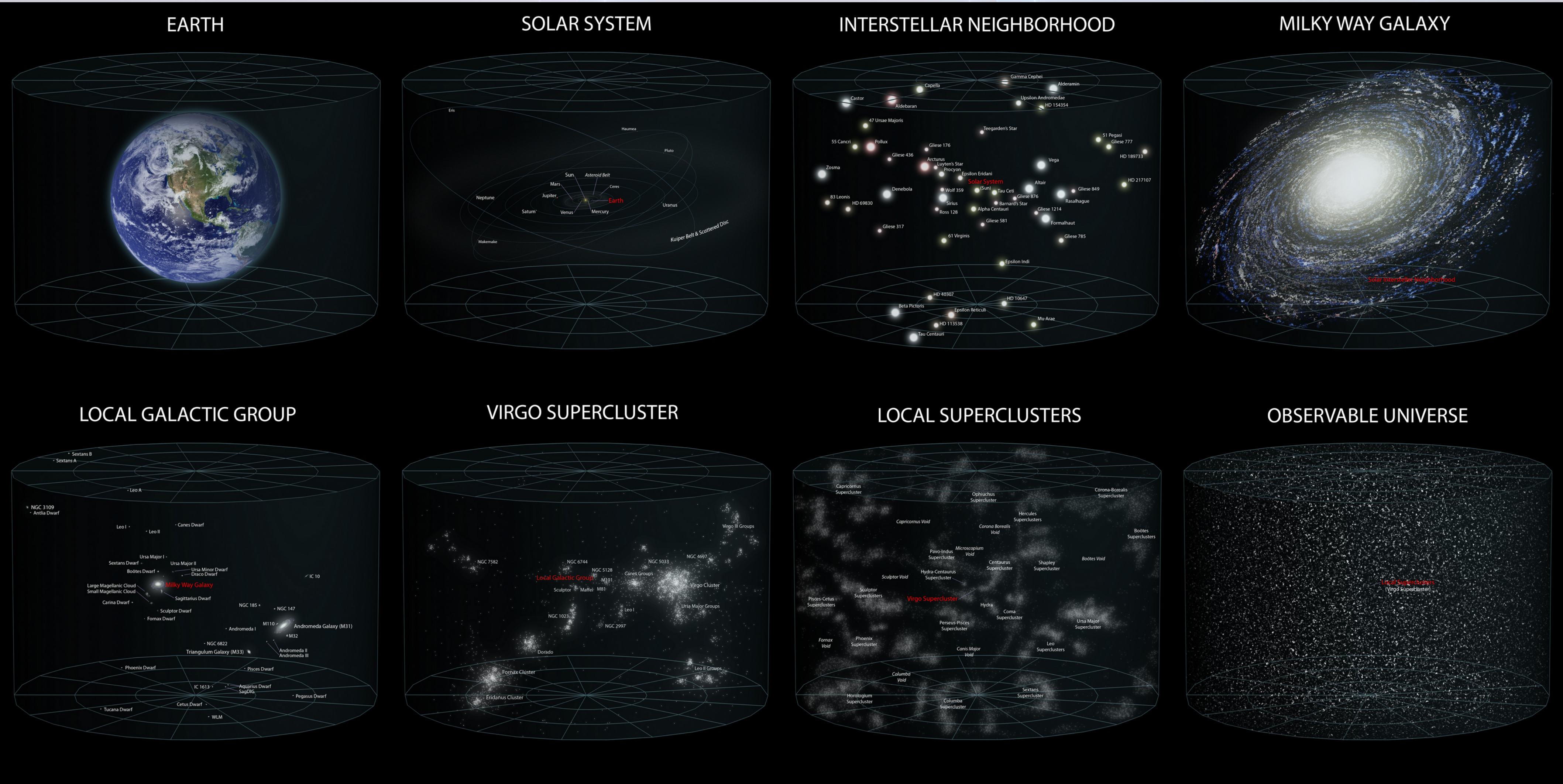


Where can we find stars*

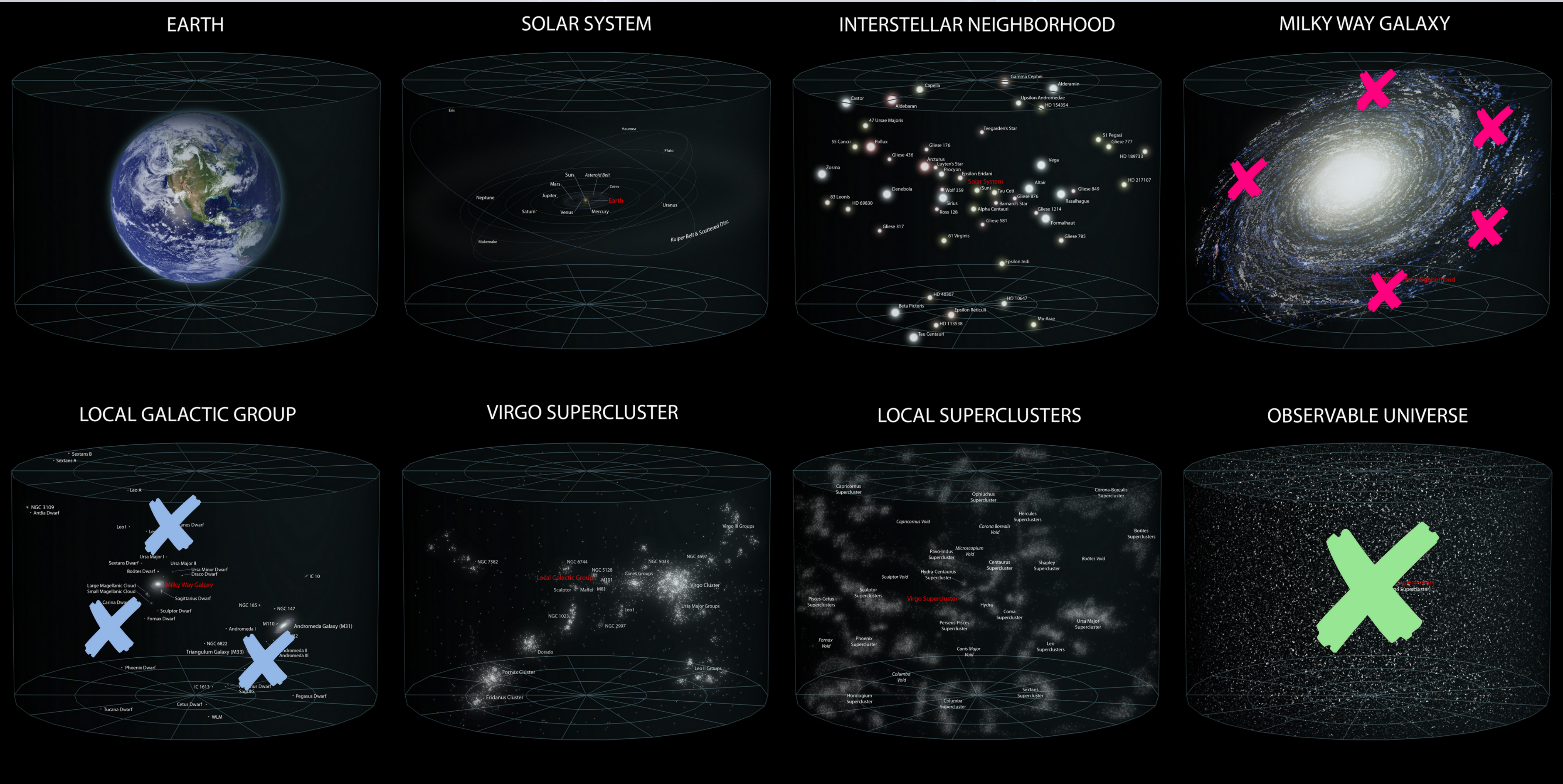
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

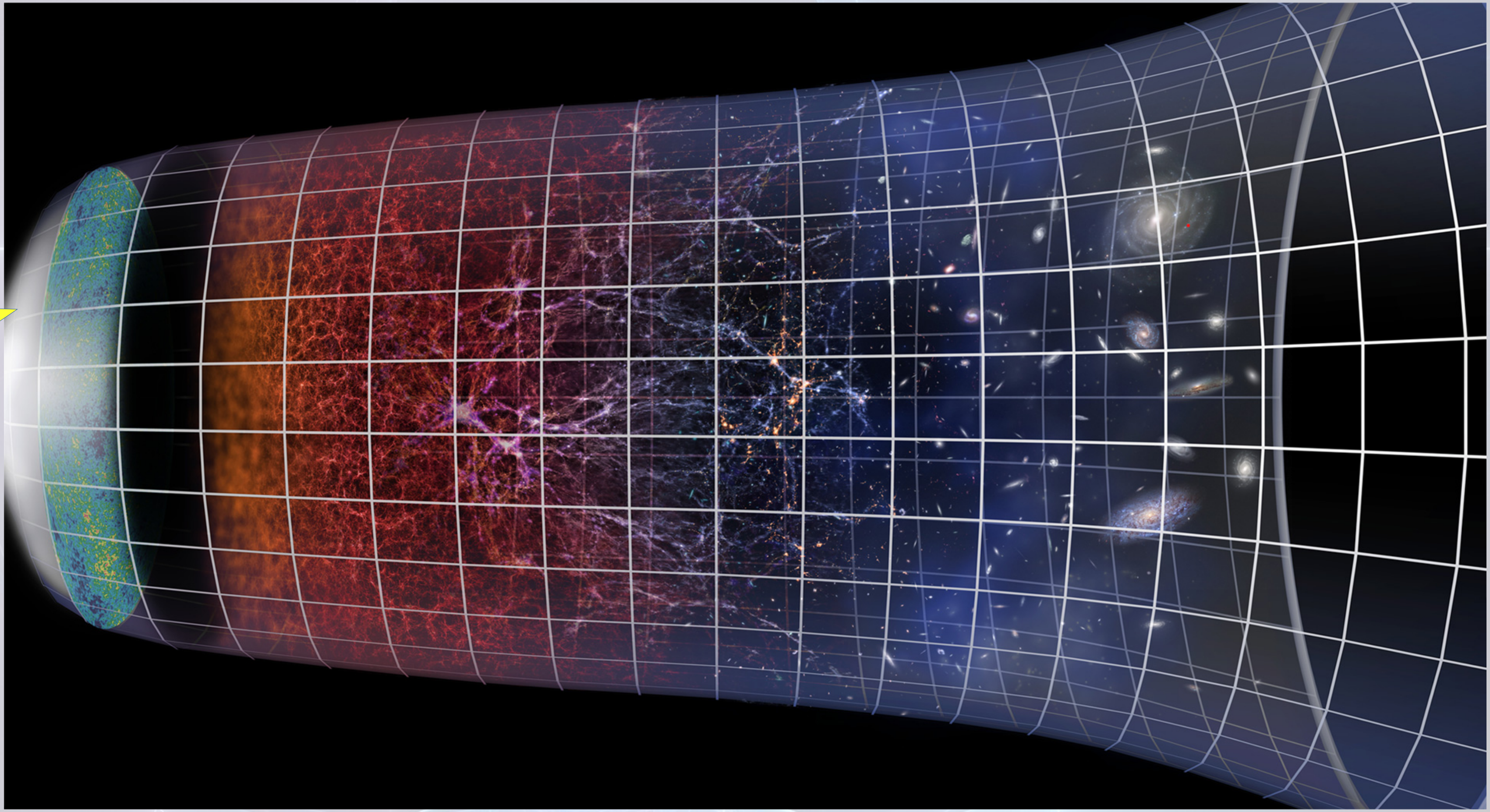
Globular clusters

Dwarf galaxies

Early Universe



Early Universe...

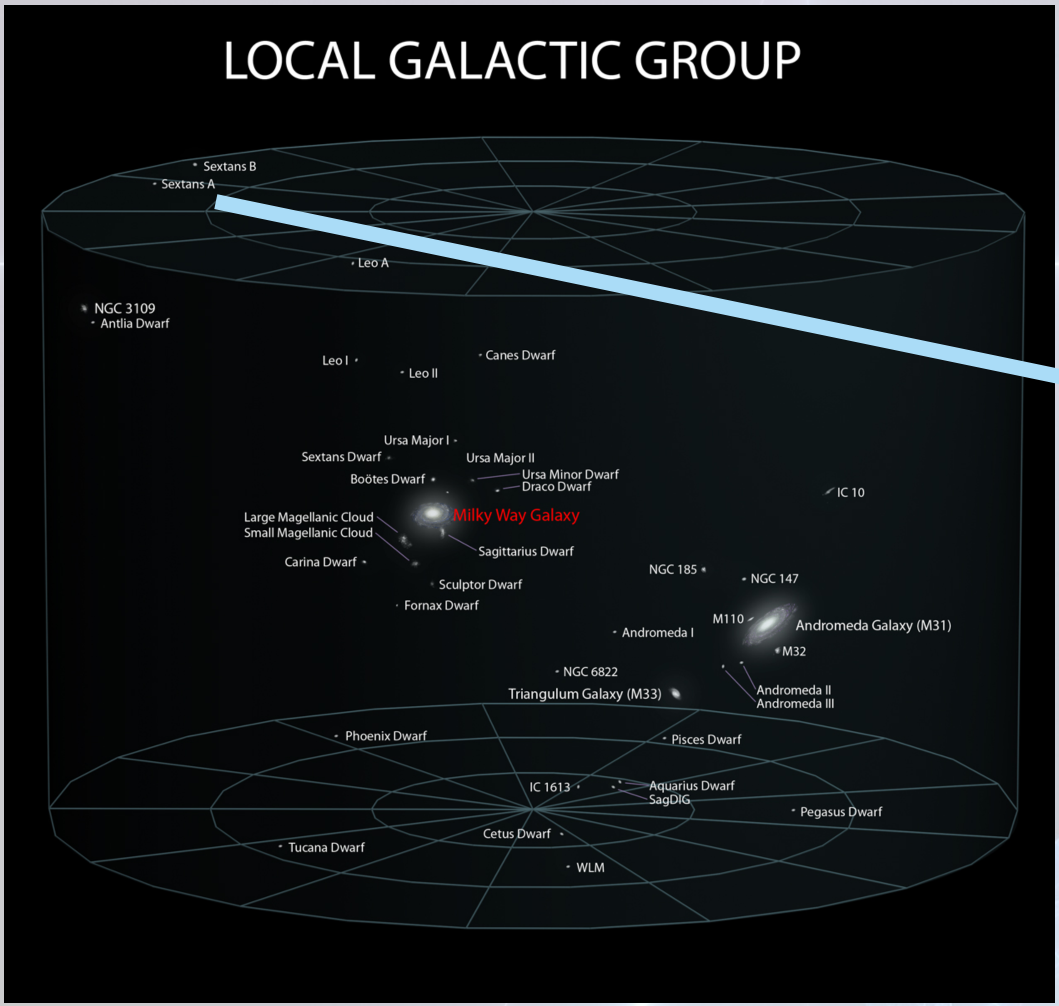


BB-
nucleo-
synthesis

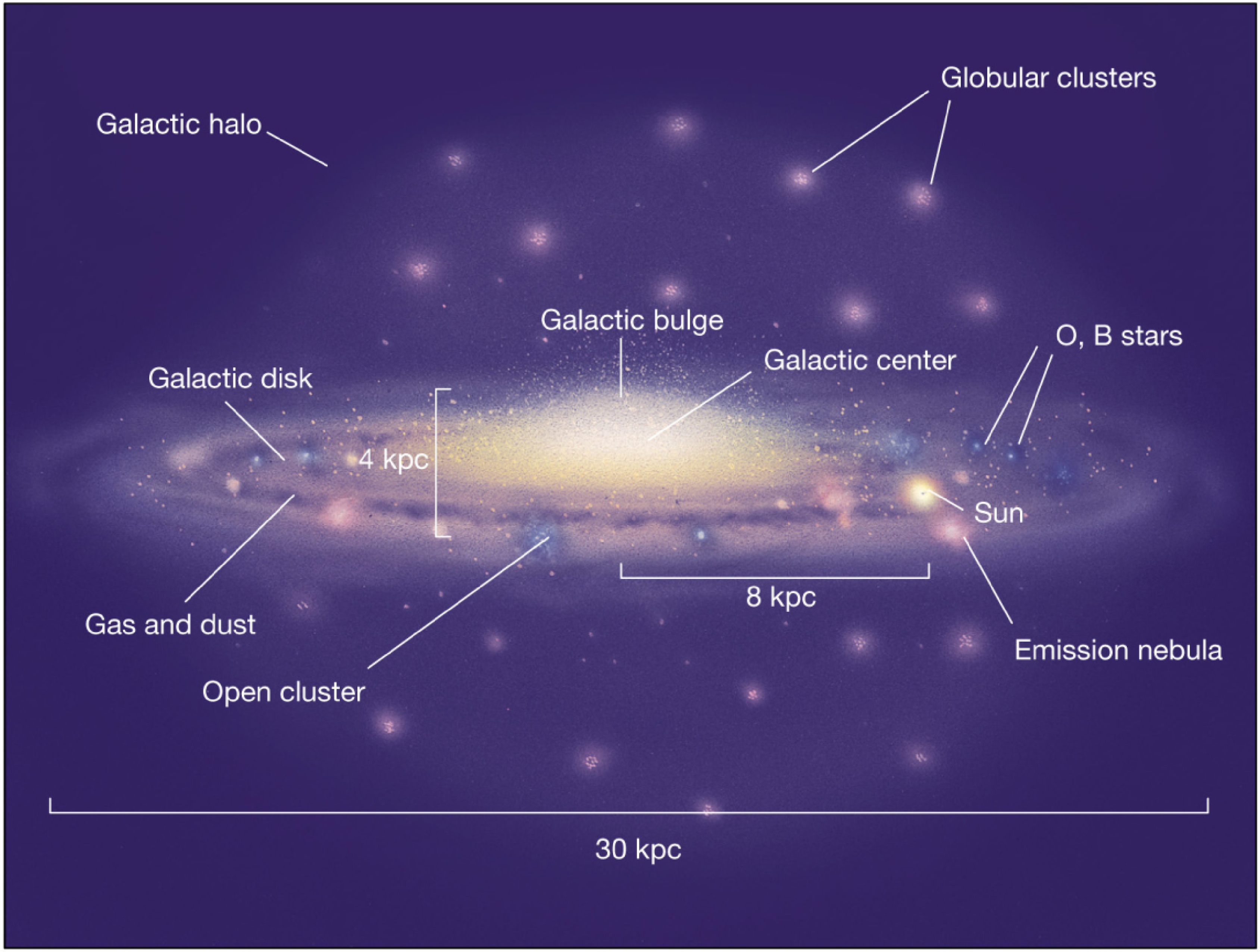
H & He

Looking into the past…

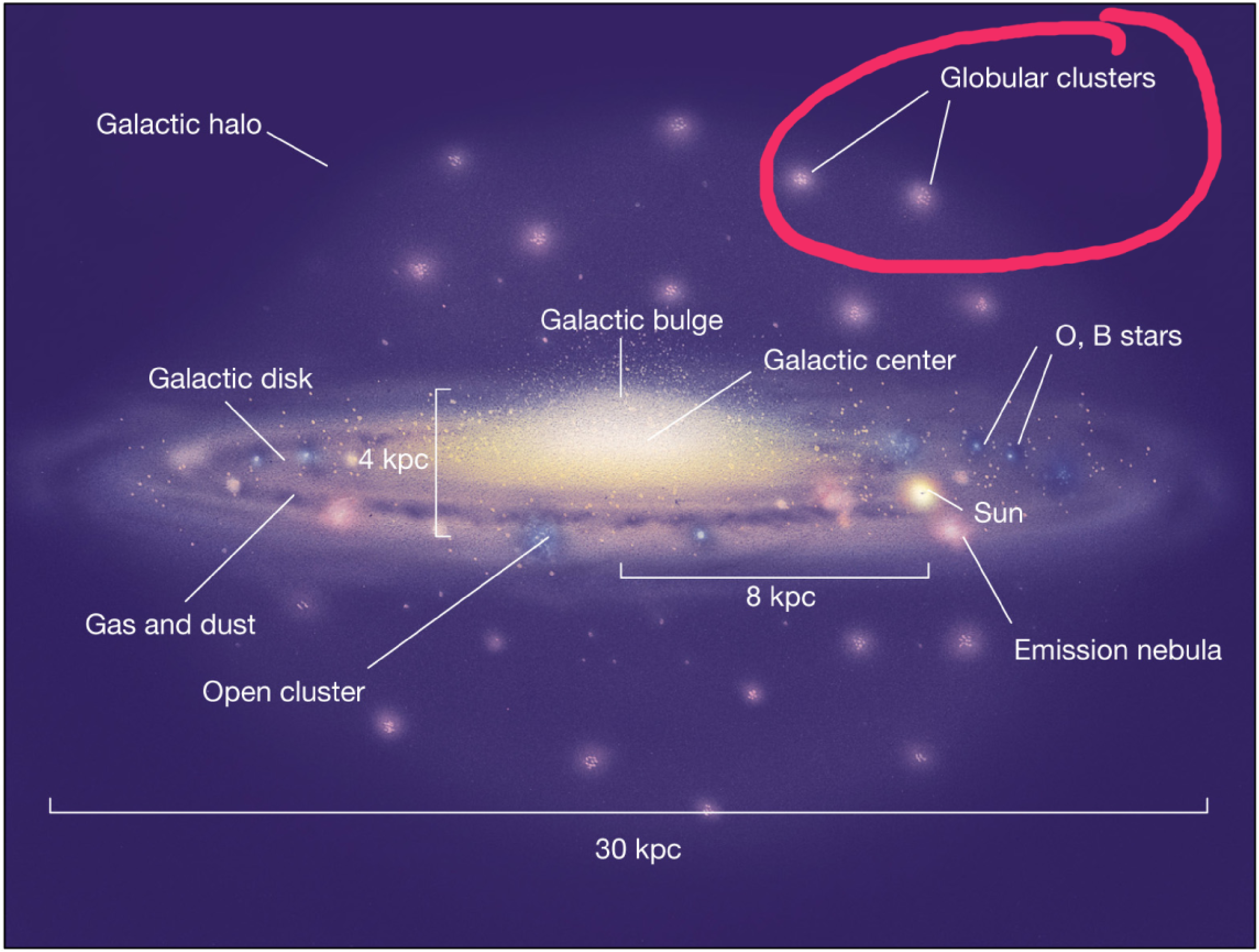
Dwarf galaxies...



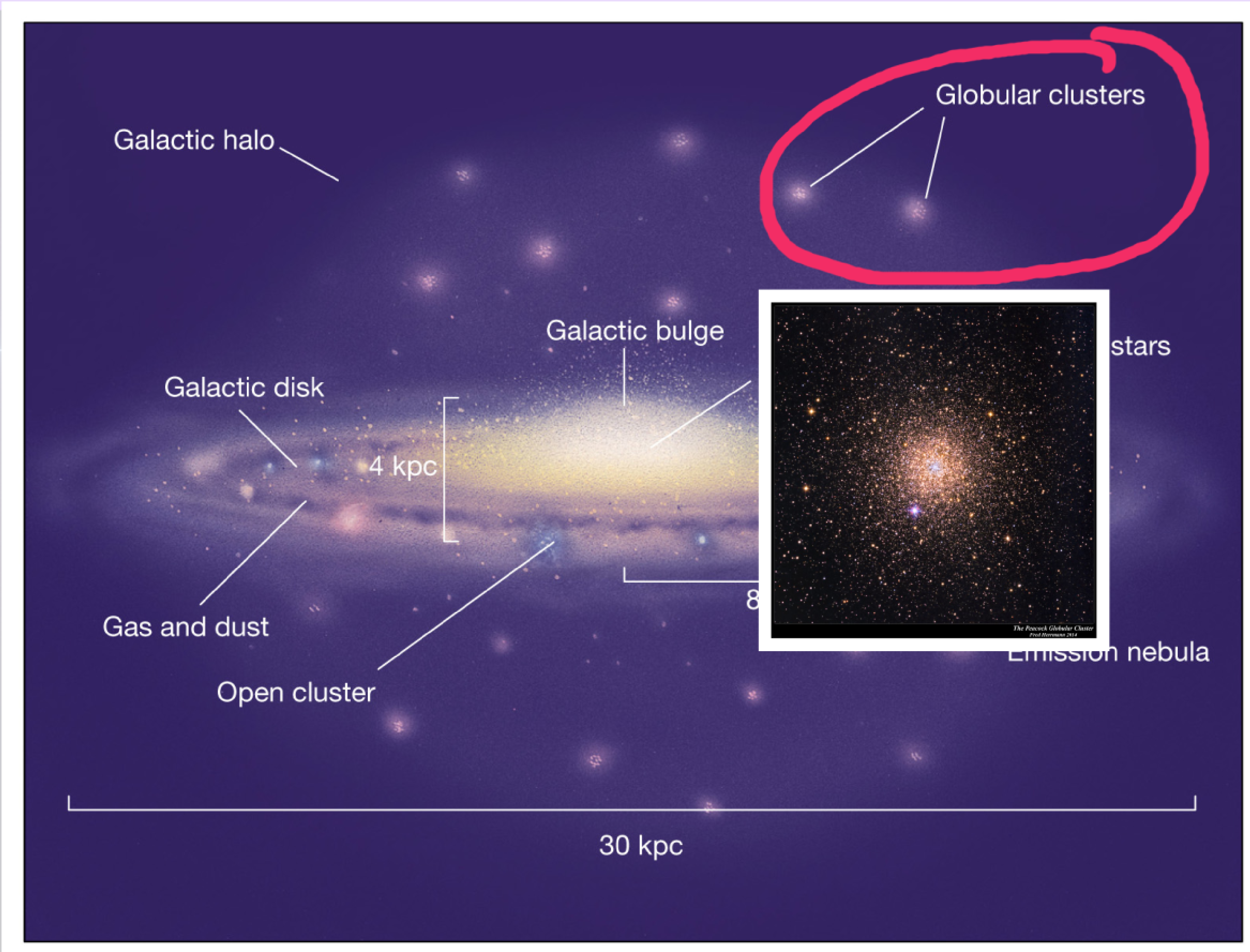
Globular Clusters



Globular Clusters



Globular Clusters



How does Z come to GWs though?

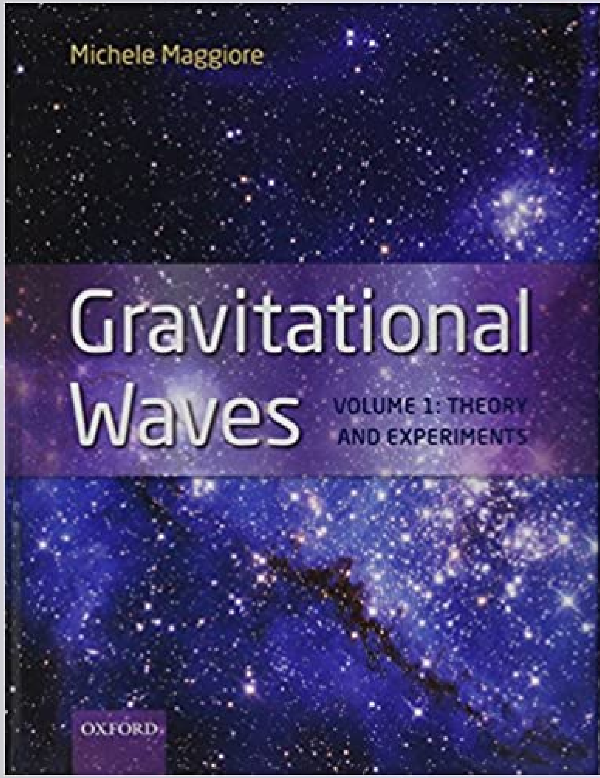
- Well…

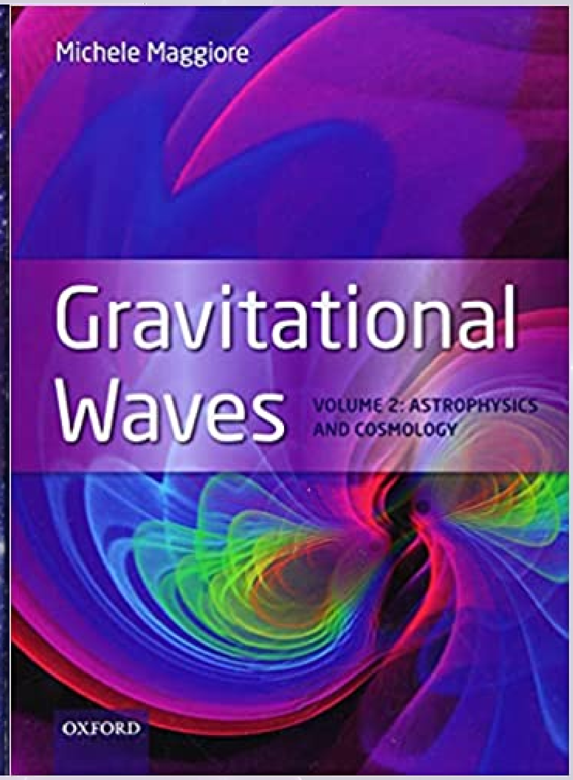
How does Z come to GWs though?

- Well…

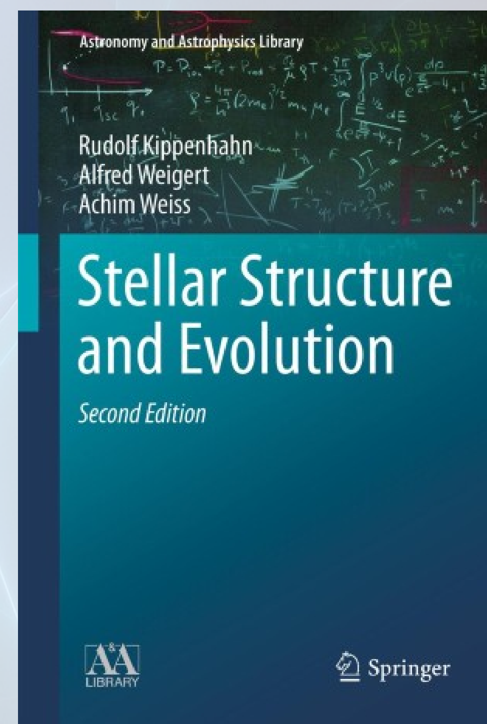
AFTER THE COFFEE BREAK :D

Suggested literature



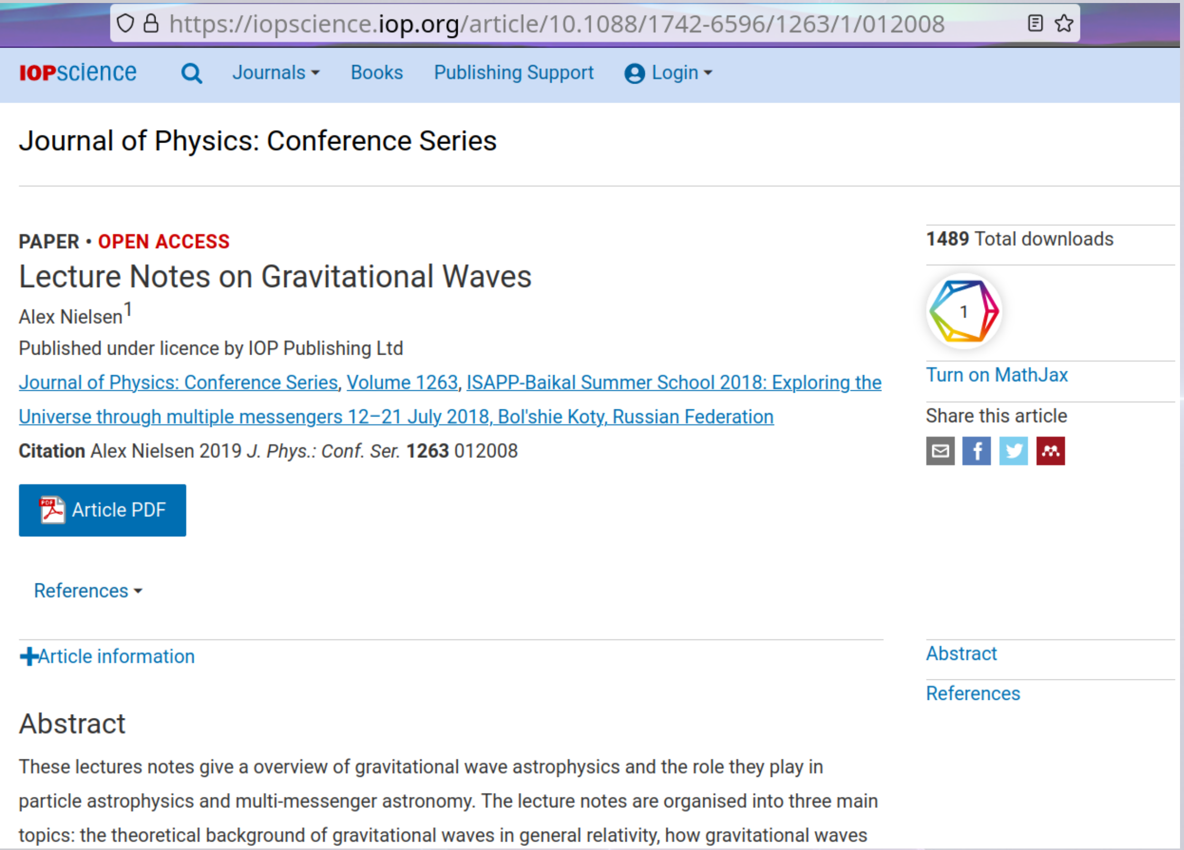


Gravitational Waves
Vol. 1 (2007) & Vol. 2 (2018)
– by **Michele Maggiore**



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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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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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)

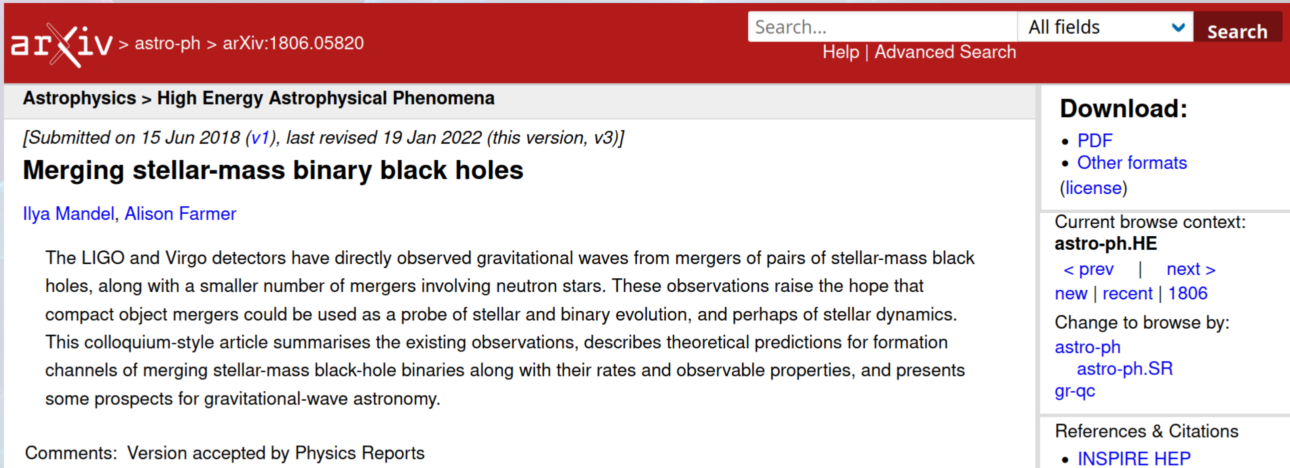
– by **Alex Nielsen**

(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/ADS (accepted for publication after 24.01.2022) and giving a "journal club" style presentation (with slides) of ~30 min

Exam & grading

Oral examination.
Assessment criteria:

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

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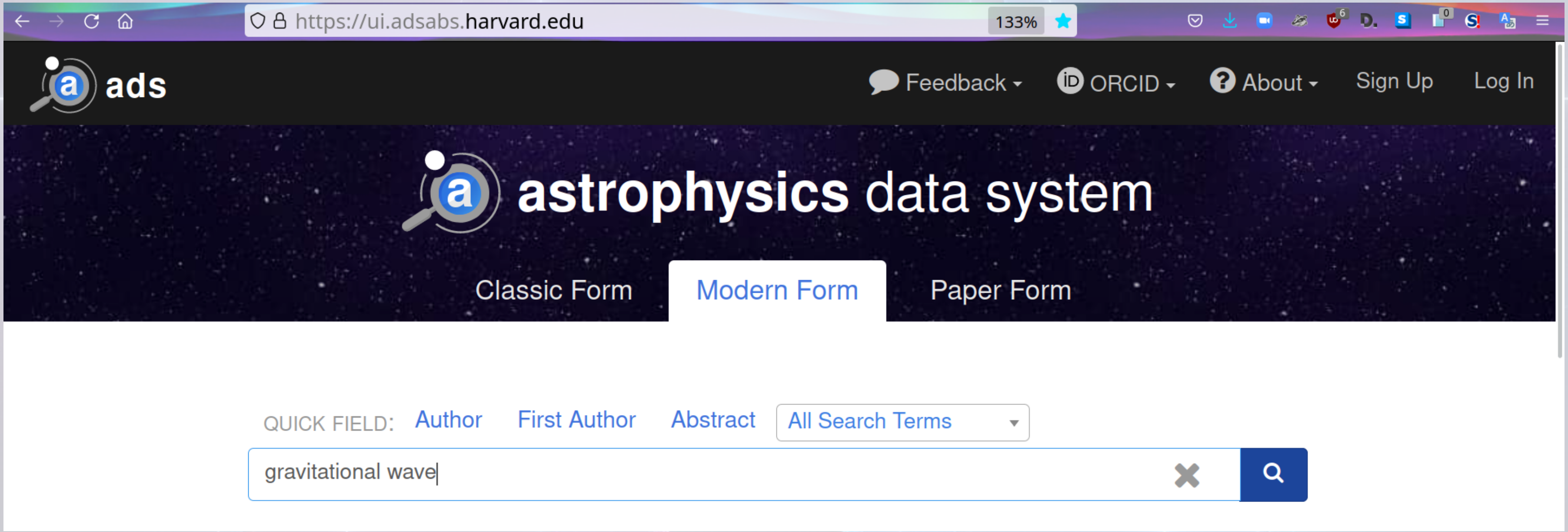
Where to find the relevant papers?

- NASA ADS: https://ui.adsabs.harvard.edu/



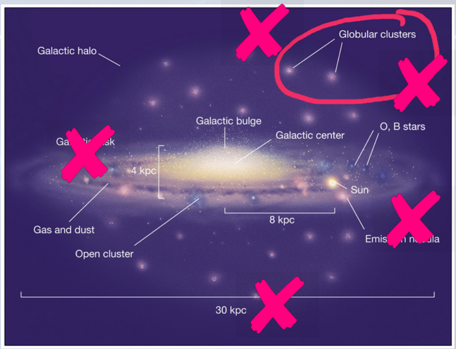
- arXiv: https://arxiv.org/ (preprints...)

Where can we find stars*

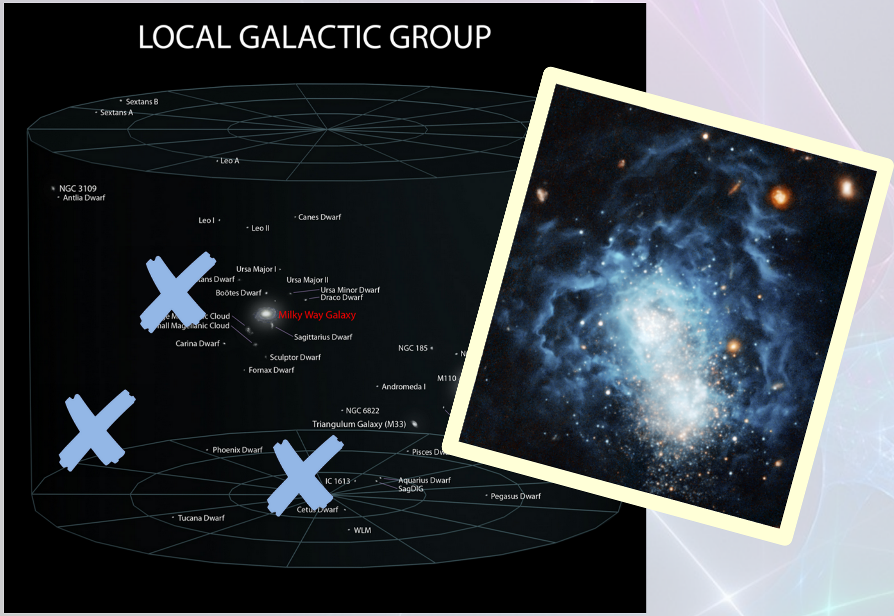
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

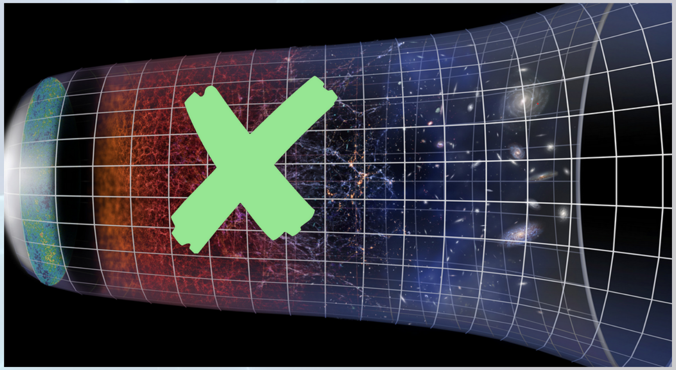
Globular clusters



Dwarf galaxies



Early Universe



How does Z come to GWs though?

- …

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- Stellar evolution! (what else… :P)

Credit: MSFC / NASA

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  - more precizely: ***stellar winds***

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How does Z come to GWs though?

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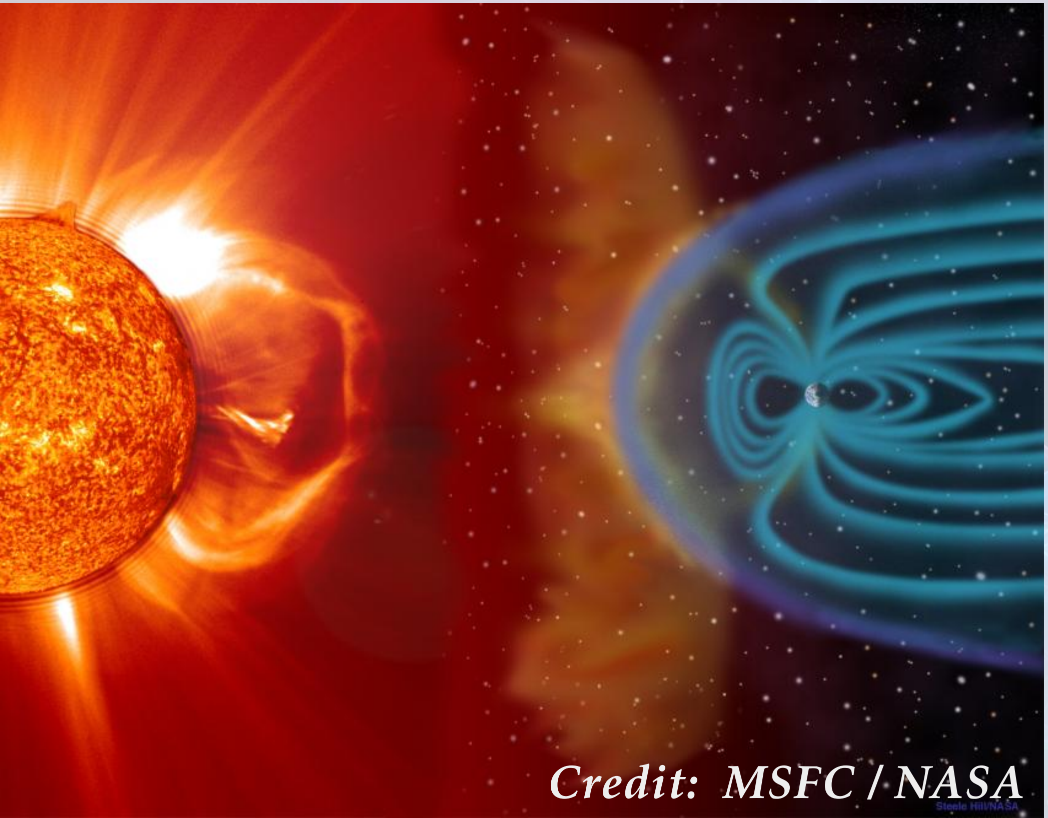


Credit: MSFC / NASA

The solar wind is a stream of charged particles released from the upper atmosphere of the Sun. ***#northernlights***

low-mass: < 8 $M_\odot$

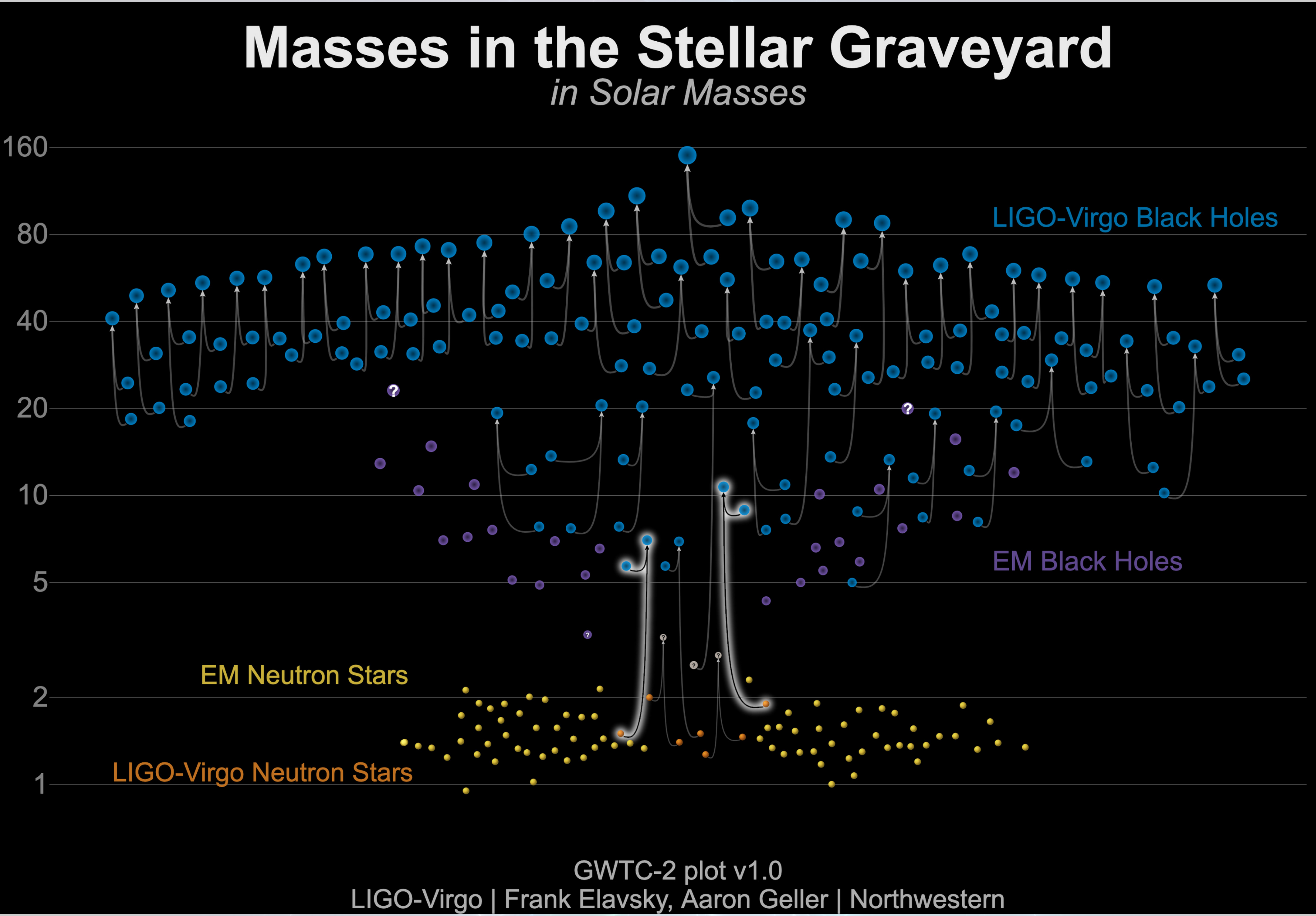
massive: > 8 $M_\odot$

The winds of *massive* stars are… strong.

Wolf-Rayet star WR 124 with its surrounding nebula known as M1-67.
The nebula came ***from the star***!

$10^{-7} - 10^{-3}\ M_{\odot}/yr$
→
loss of 10-70% of material over lifetime…

(Sun: $\sim 10^{-14}\ M_{\odot}/yr$)

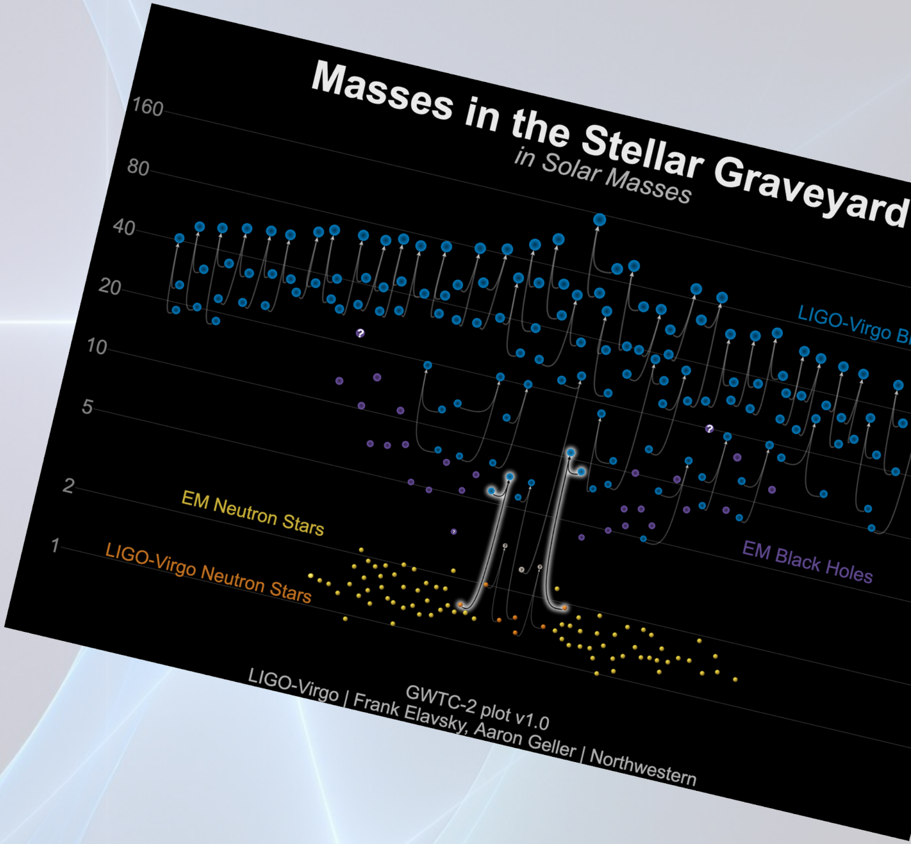


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

To form a 60 $M_\odot$ black hole…

- start with a very-very massive star*

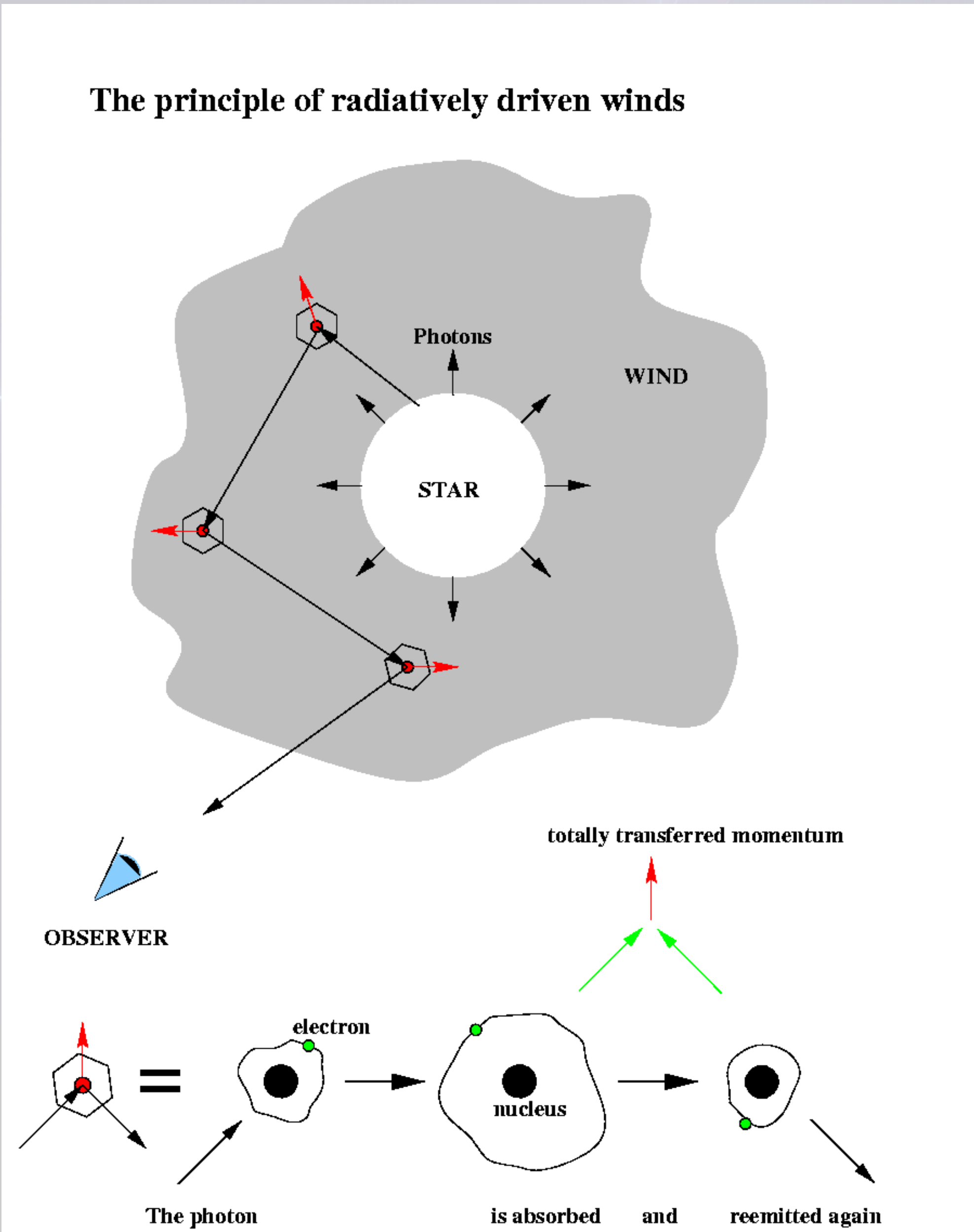
*later
(IMF, mass limits…)



or

- decrease the strength of the wind somehow?

What drives the wind?

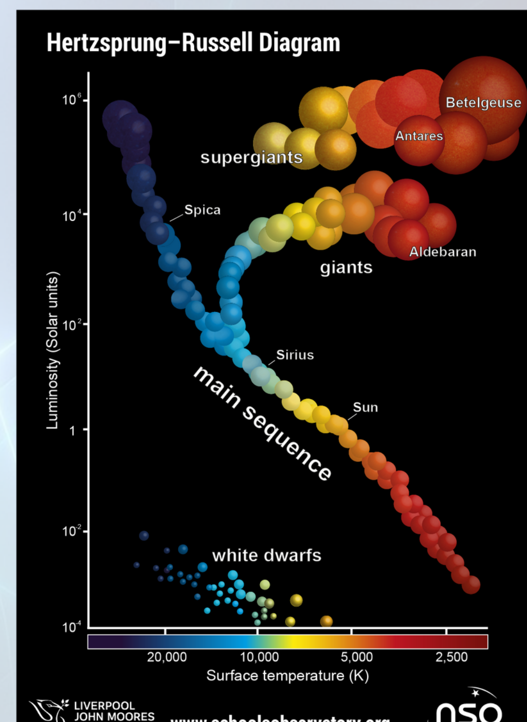


Credit: Kudritzki & Puls (2000)

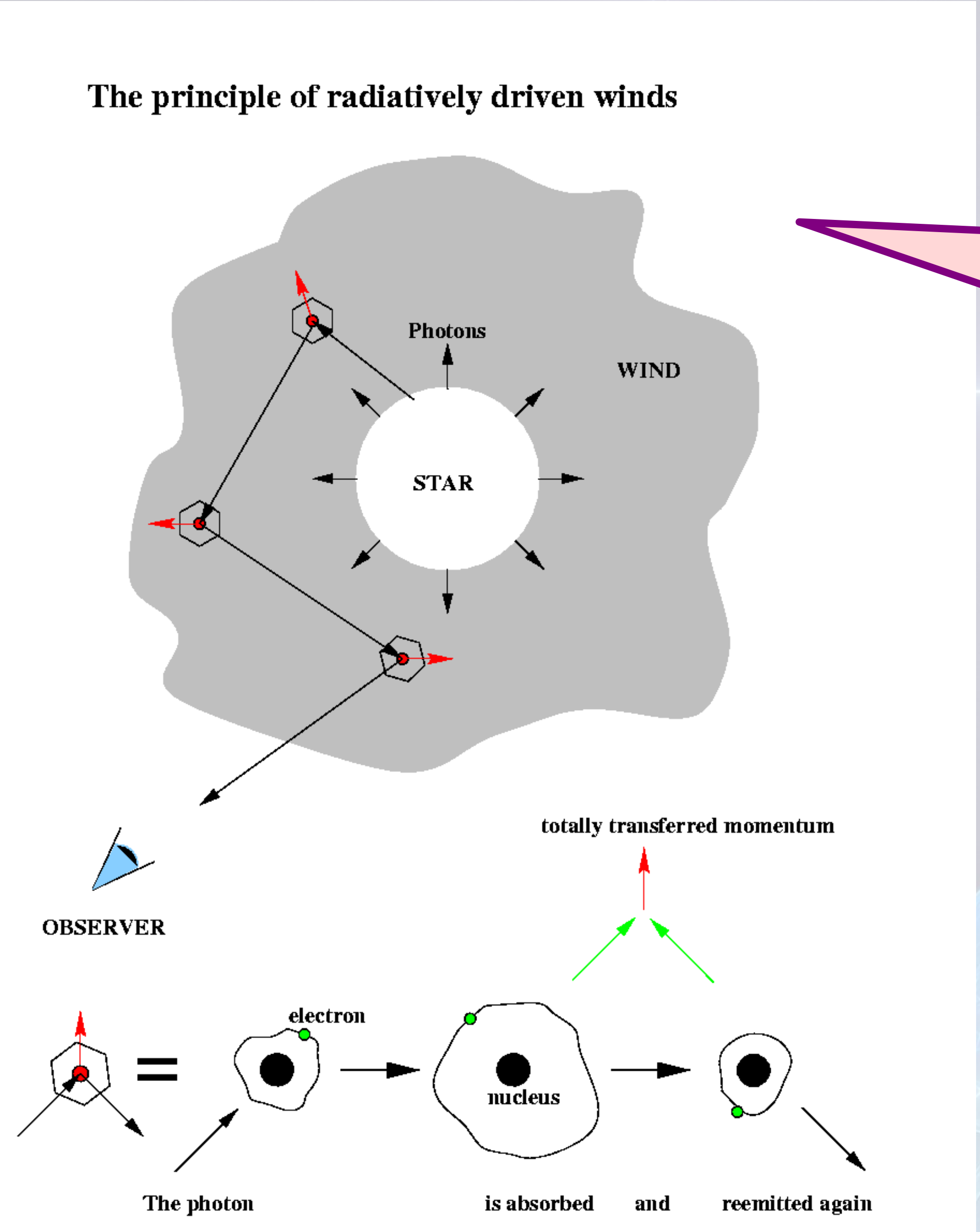
Massive stars:

line-driven
(i.e. radiation-driven)
winds

Cause they are bright, cf.:



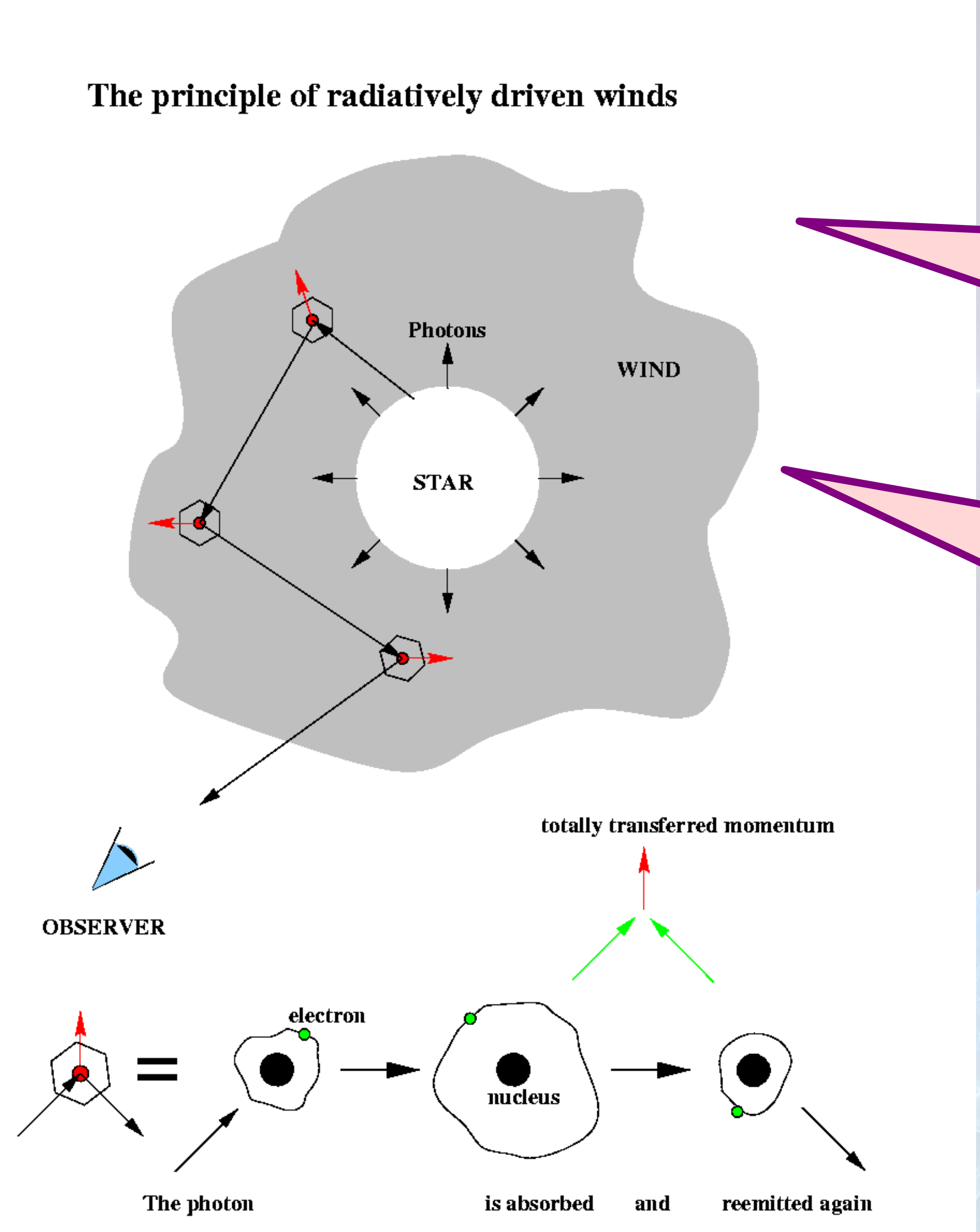
What drives the wind?



Question:
how many electrons does a H-atom have?

Credit: Kudritzki & Puls (2000)

What drives the wind?

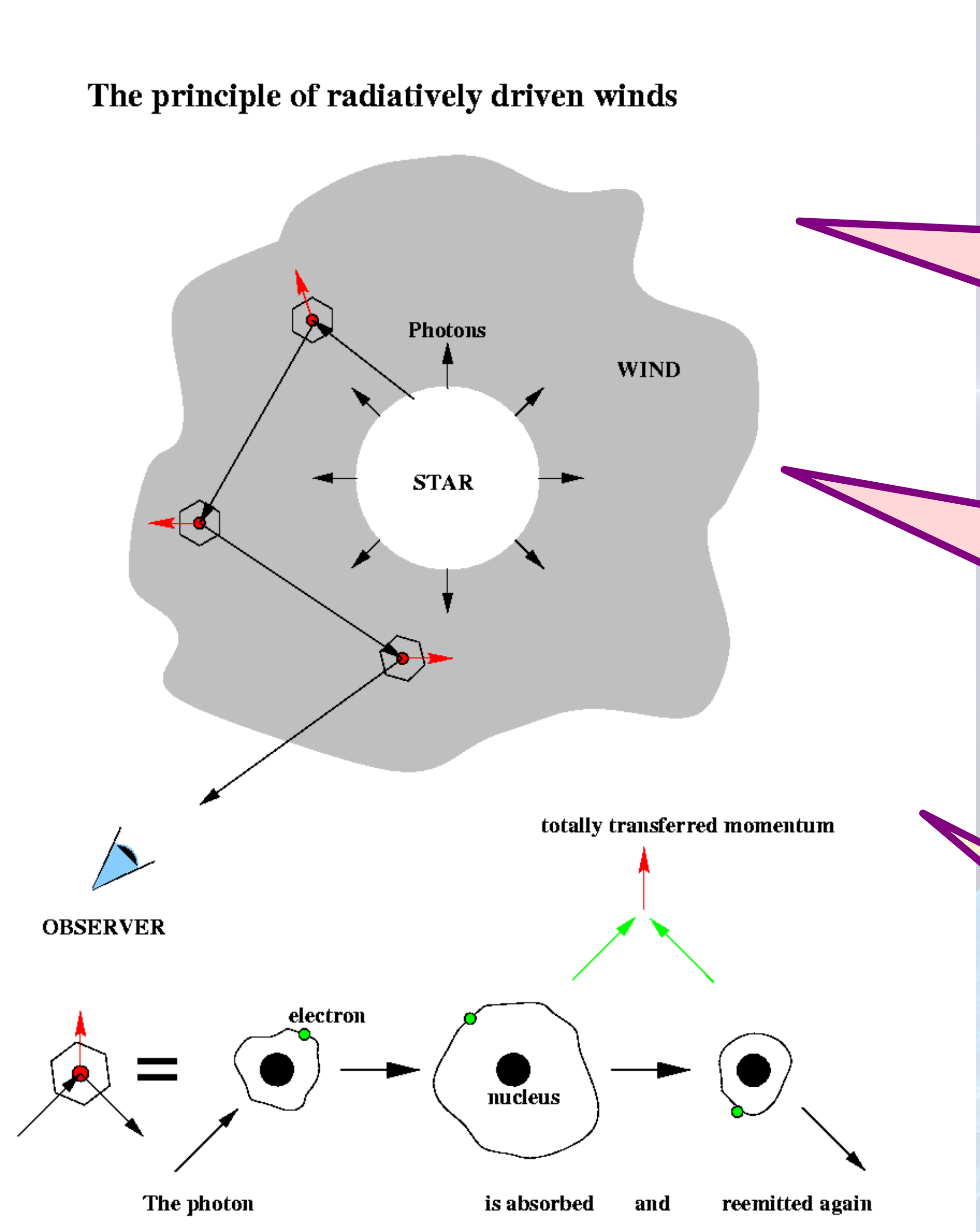


Question:
how many electrons does a H-atom have?

Question #2:
how many electrons does an Fe-atom have?

Credit: Kudritzki & Puls (2000)

What drives the wind?



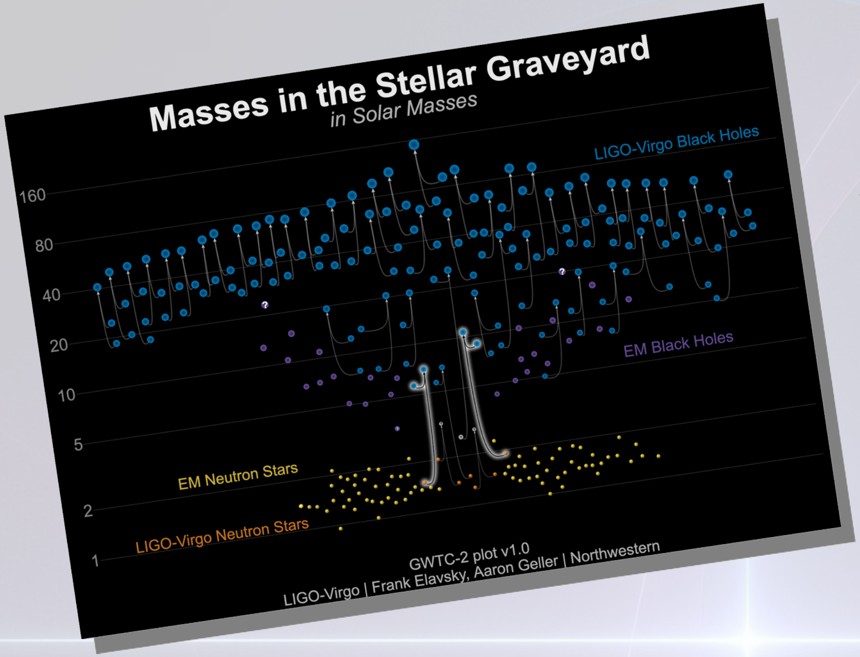
Question:
how many electrons
does a H-atom have?

Question #2:
how many electrons
does an Fe-atom have?

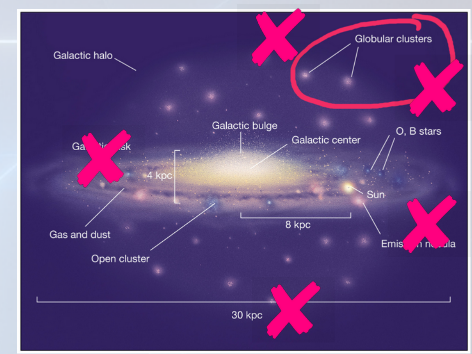
Question #3:
which star's wind will
be stronger: a low-Z or
a high-Z star's?

Credit: Kudritzki & Puls (2000)

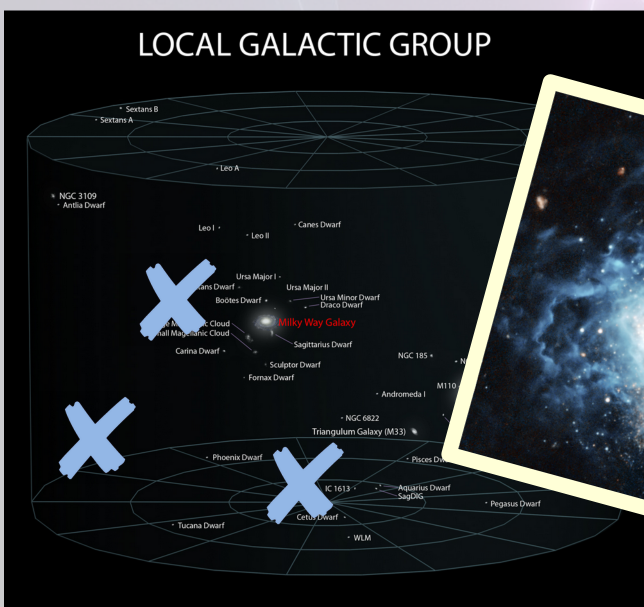
To explain the mass distribution of GW-emitting compact object mergers, we need to understand low-Z environments! (And low-Z stellar evolution, of course.)



Globular clusters



Dwarf galaxies



Early Universe