Gravitational-wave progenitors

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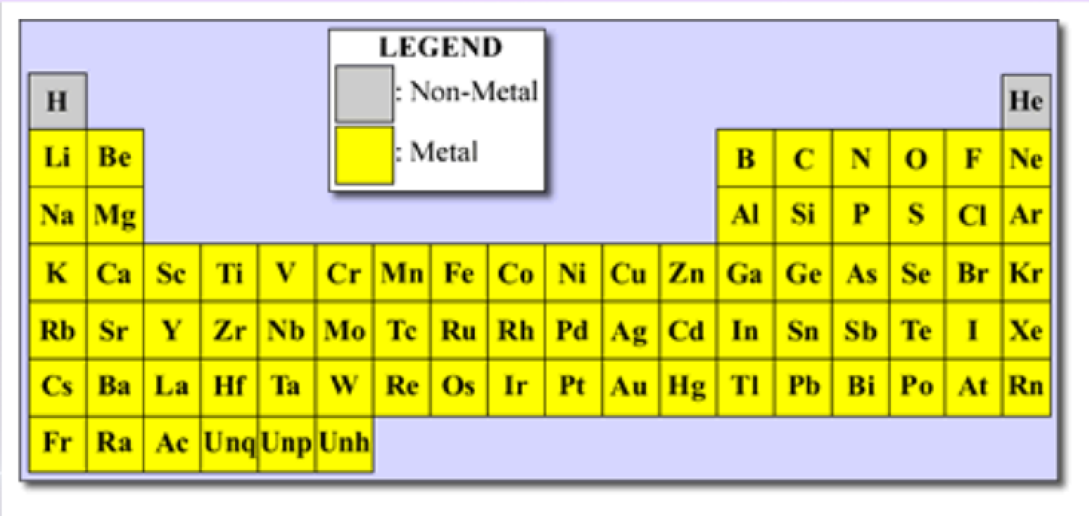
Lecture #3

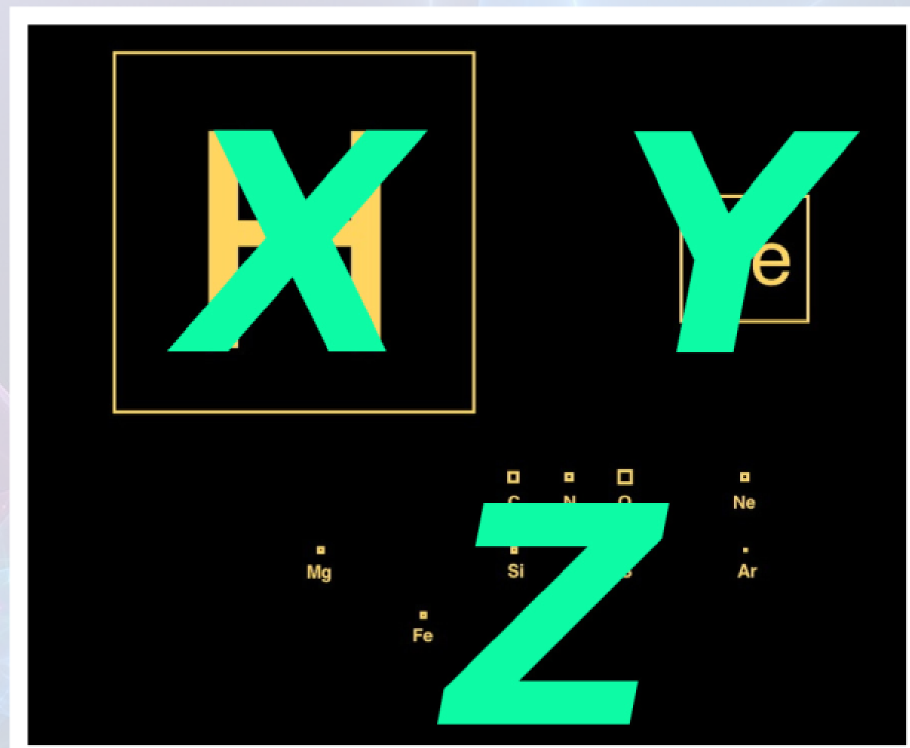
NCU, Summer Semester 2022

Previously
on GW-progenitors...

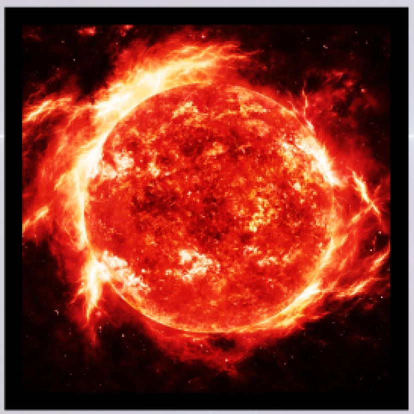
Astronomers and metal

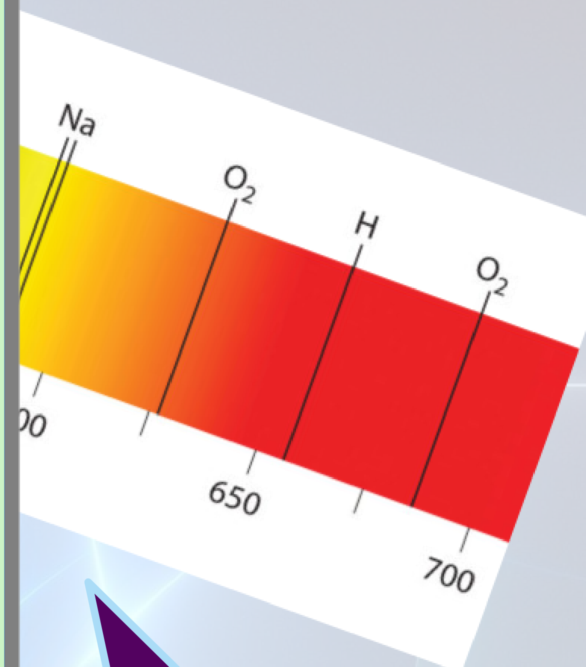


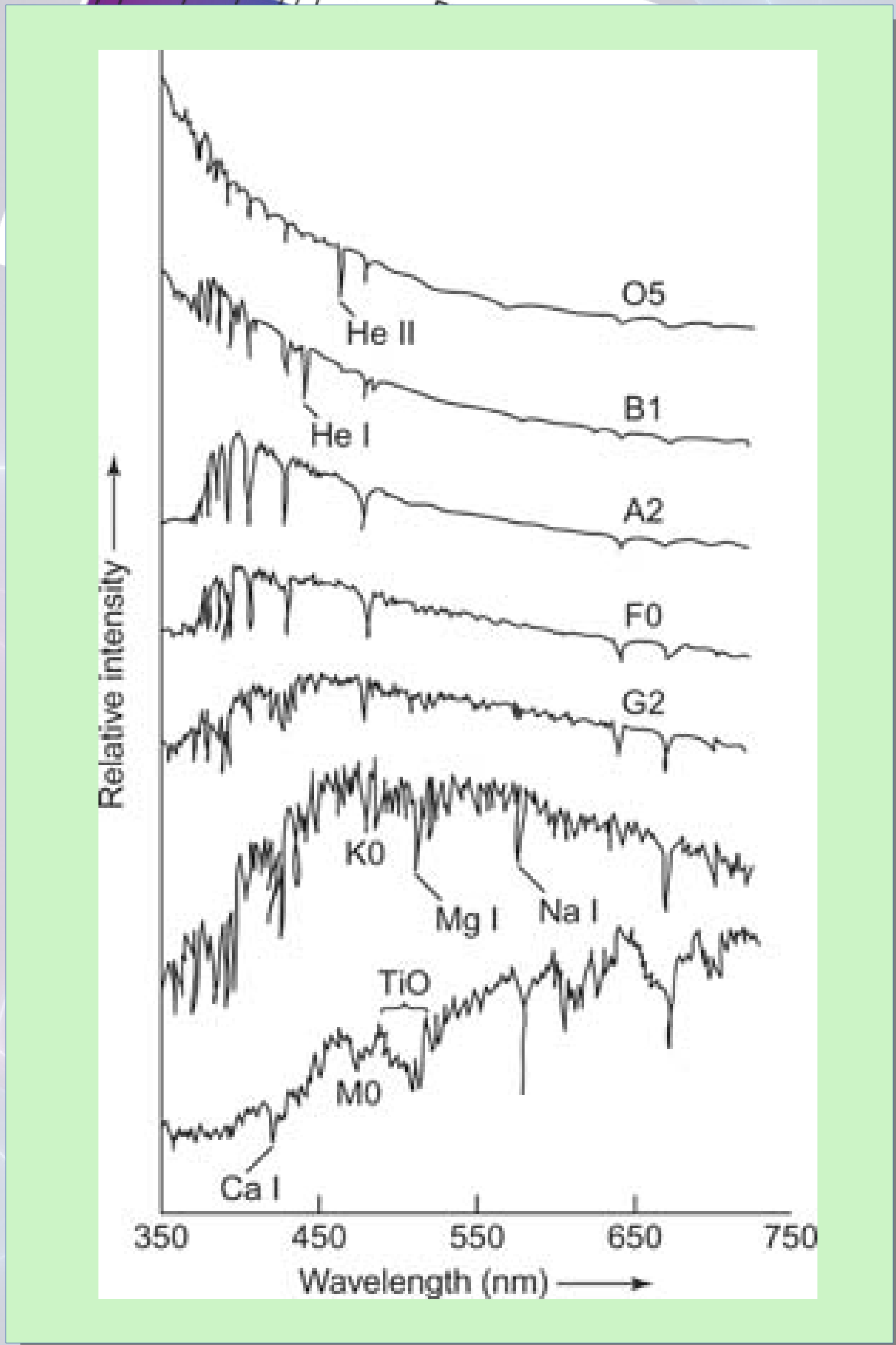
"Z: metallicity"



How to measure composition?







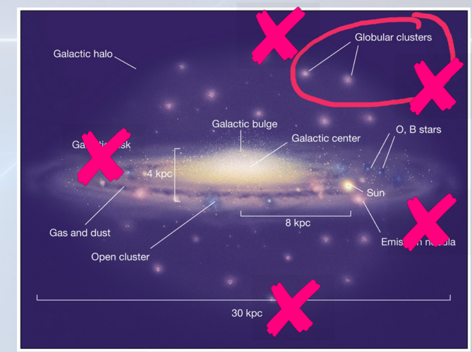
Spectroscopy :)

Where can we find stars*

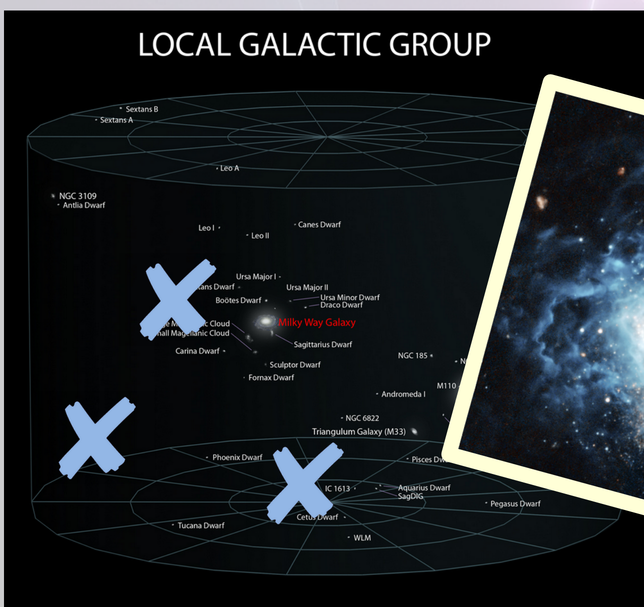
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

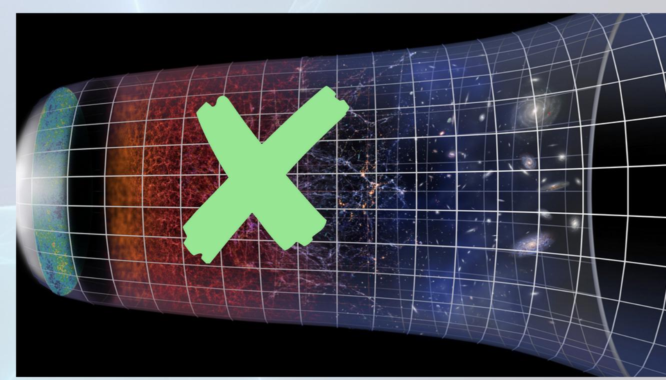
Globular clusters



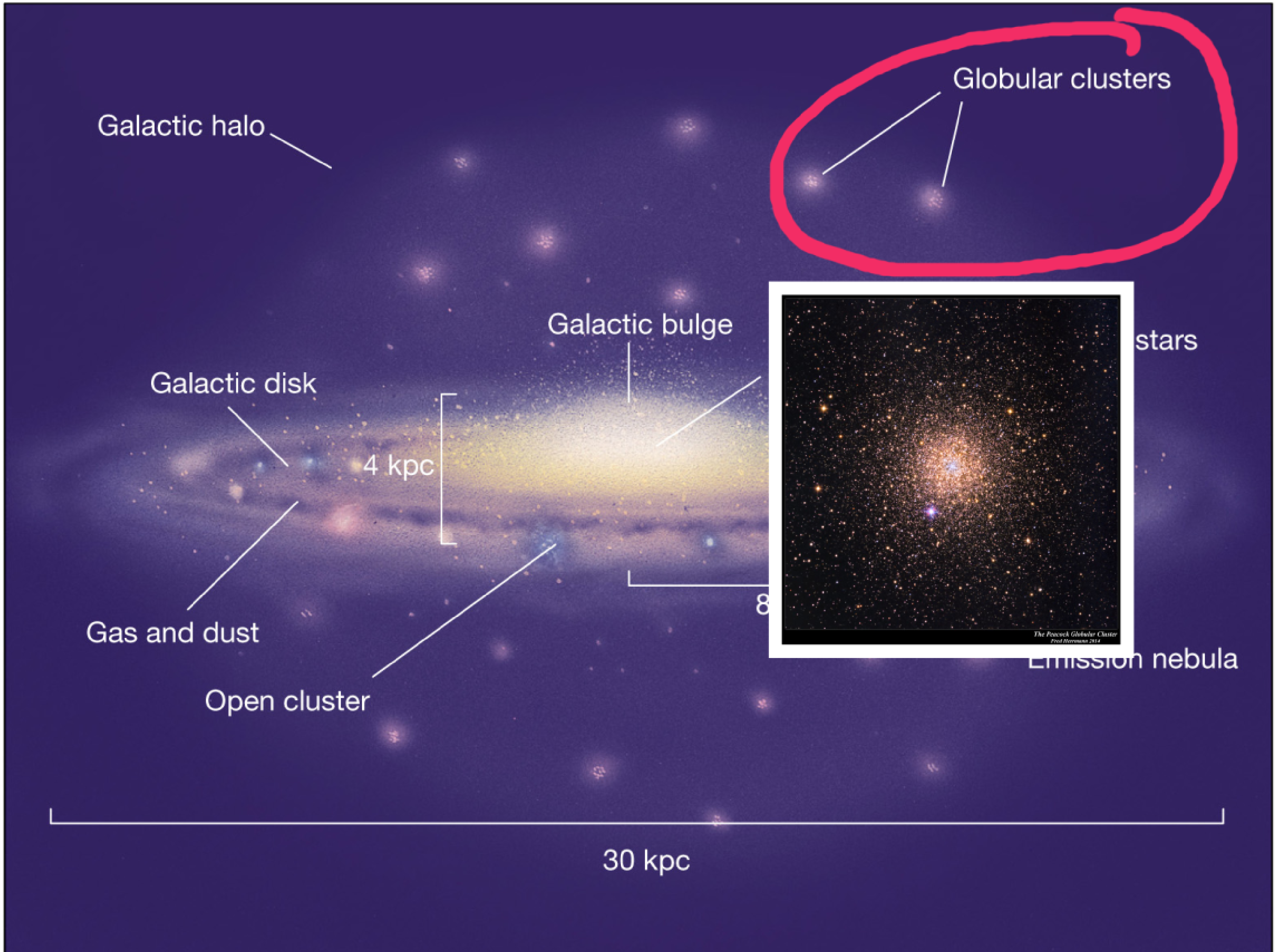
Dwarf galaxies



Early Universe

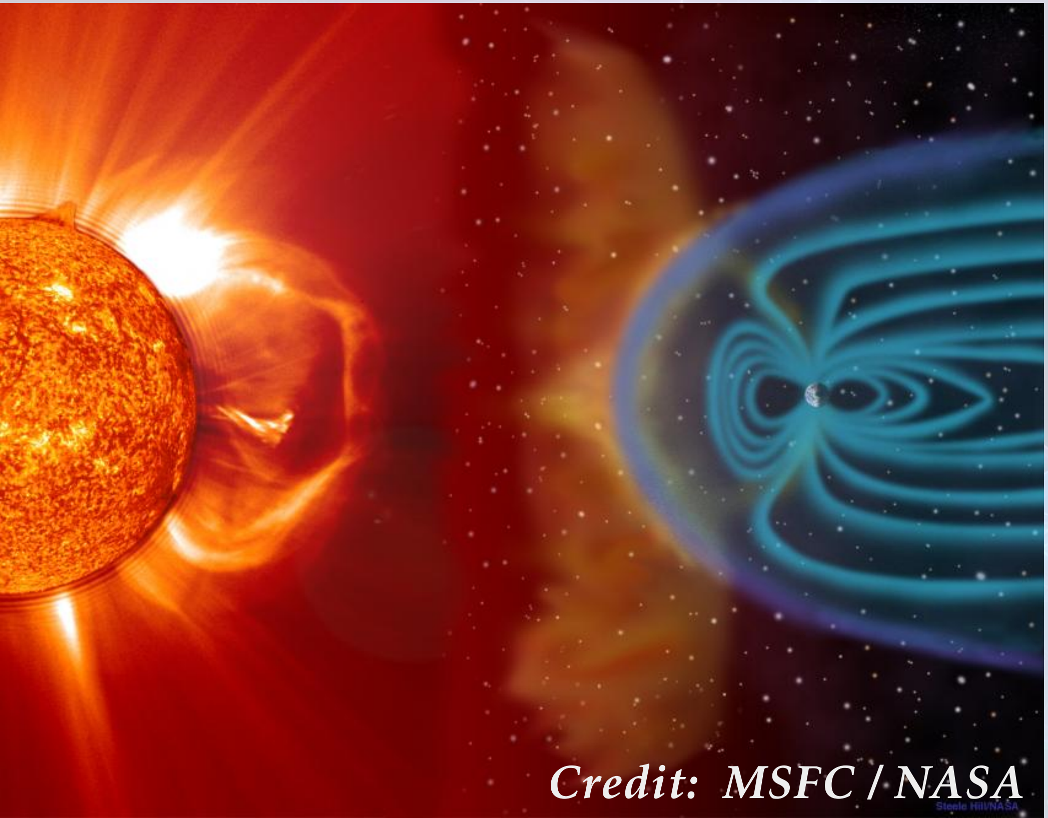


Globular Clusters



How does Z come to GWs though?

- Stellar evolution! (what else… :P)
  - more precizely: ***stellar winds***



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.

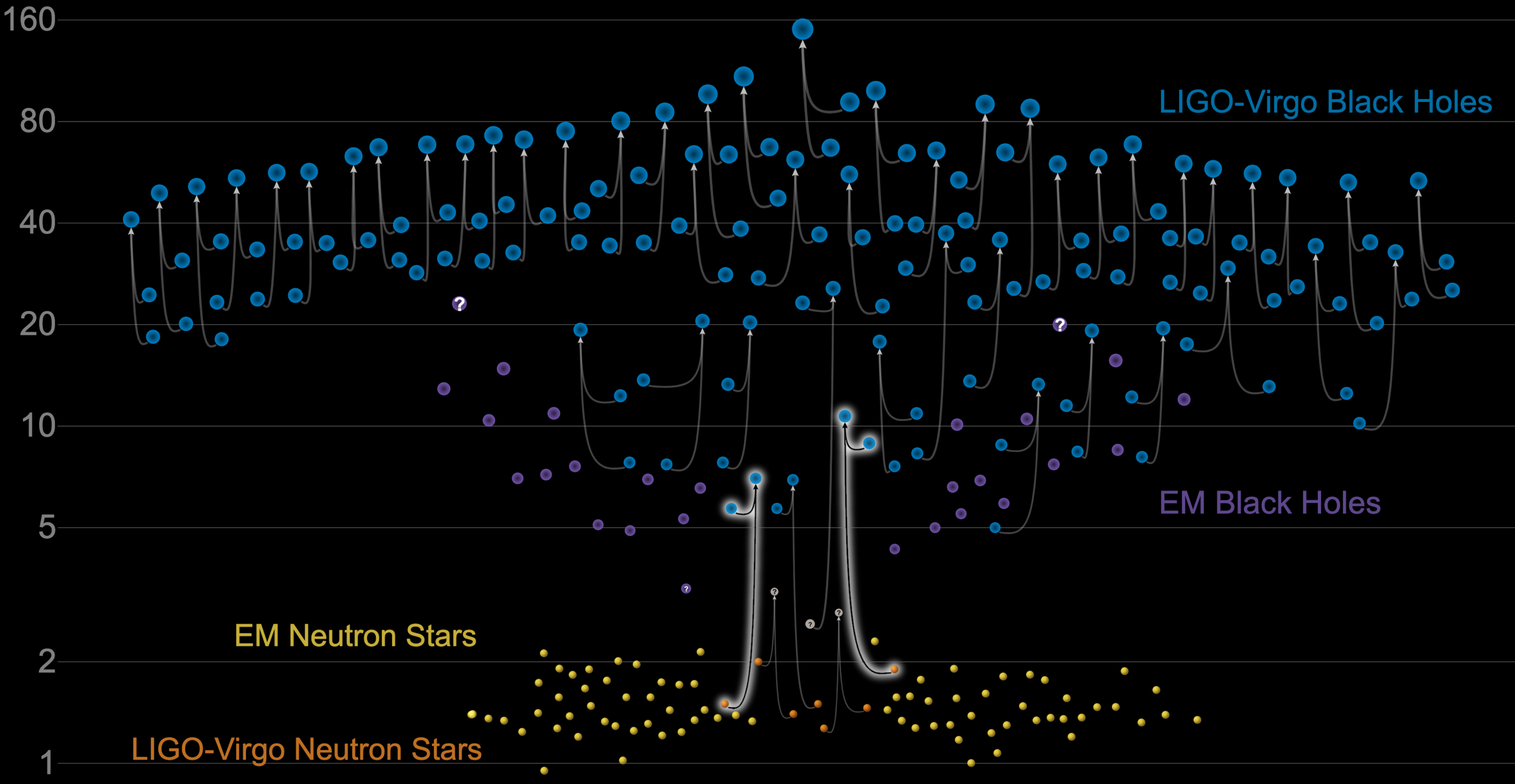
Wolf-Rayet star WR 124 with its surrounding nebula known as M1-67.
The nebula came ***from the star***!

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

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

Masses in the Stellar Graveyard

in Solar Masses



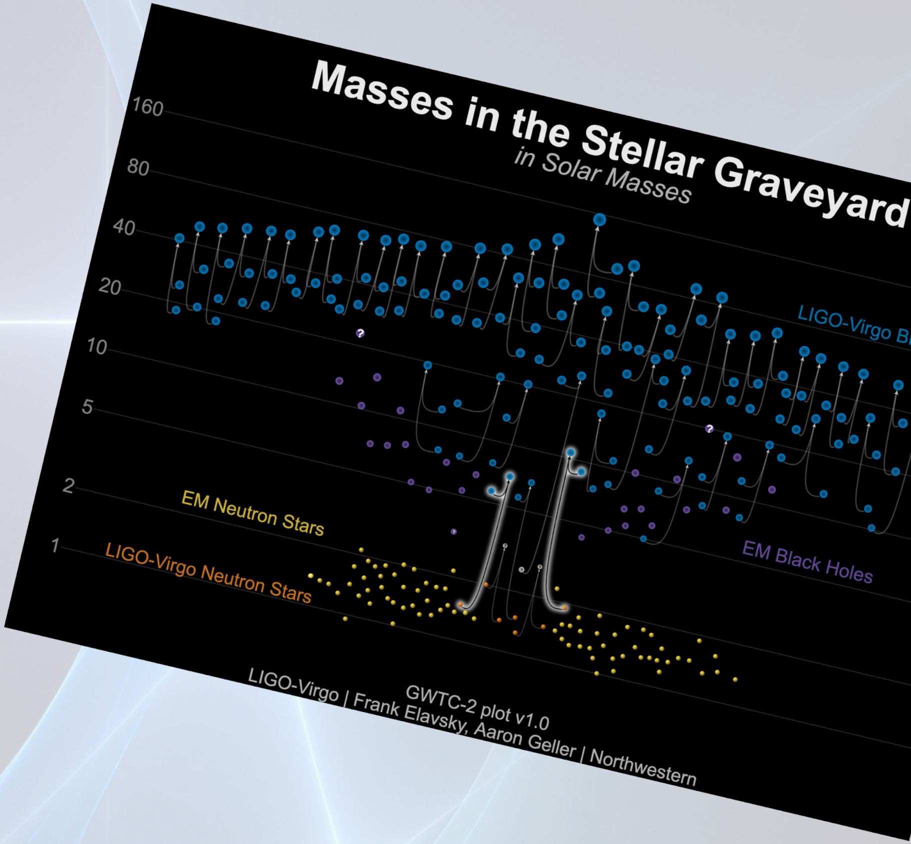
GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

To form a $60\ M_\odot$ black hole…

- start with a very-very massive star*

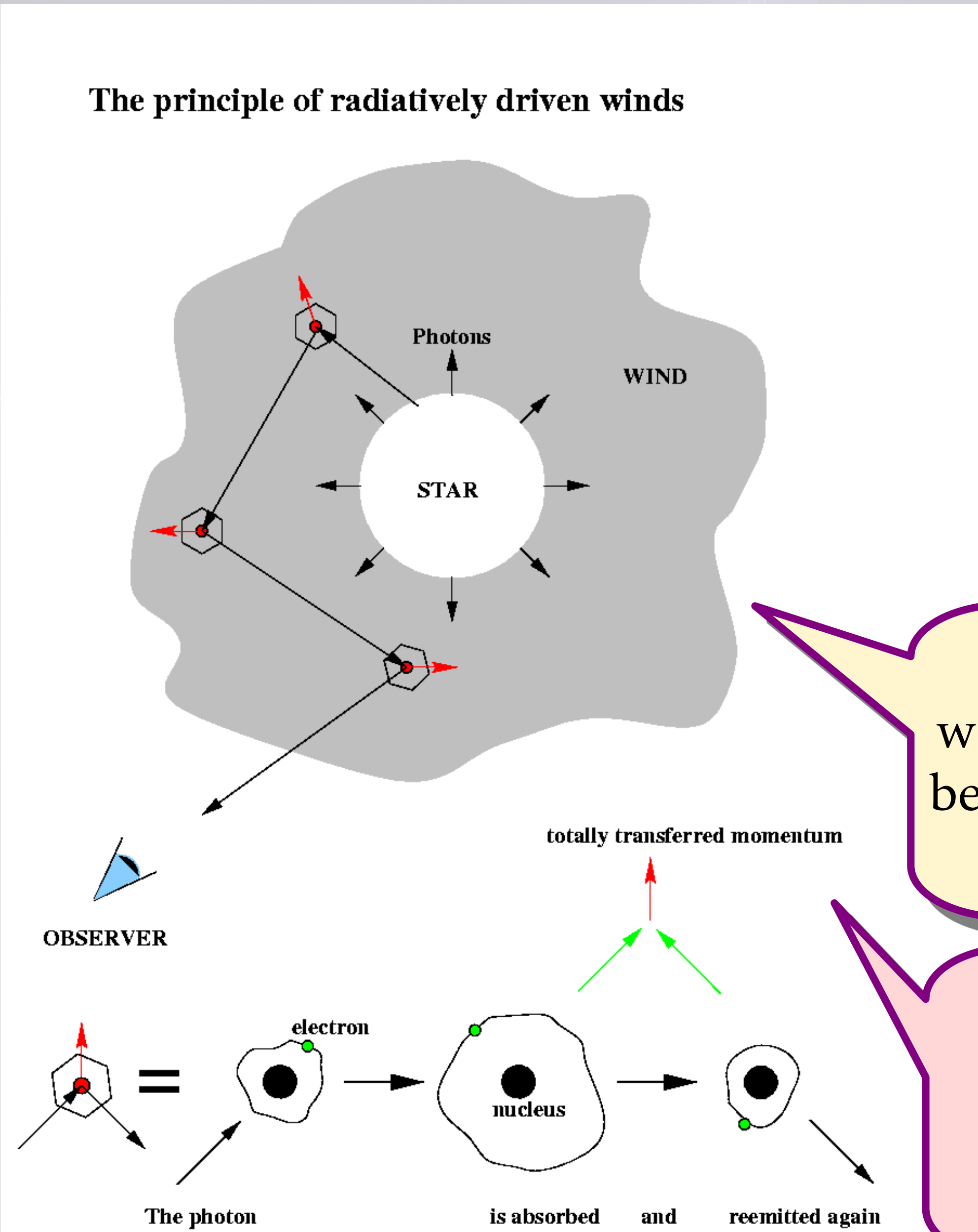
*later
(IMF, mass limits…)



or

- decrease the strength of the wind somehow?

What drives the wind?



Credit: Kudritzki & Puls (2000)

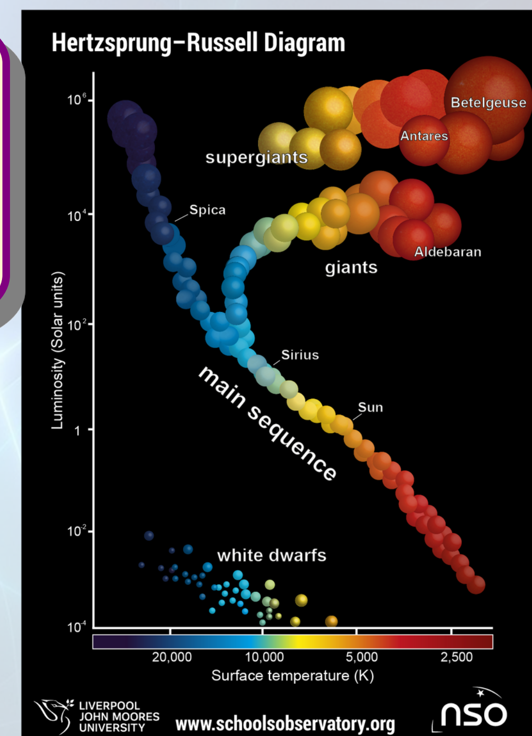
Massive stars:

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

Cause they are bright, cf.:

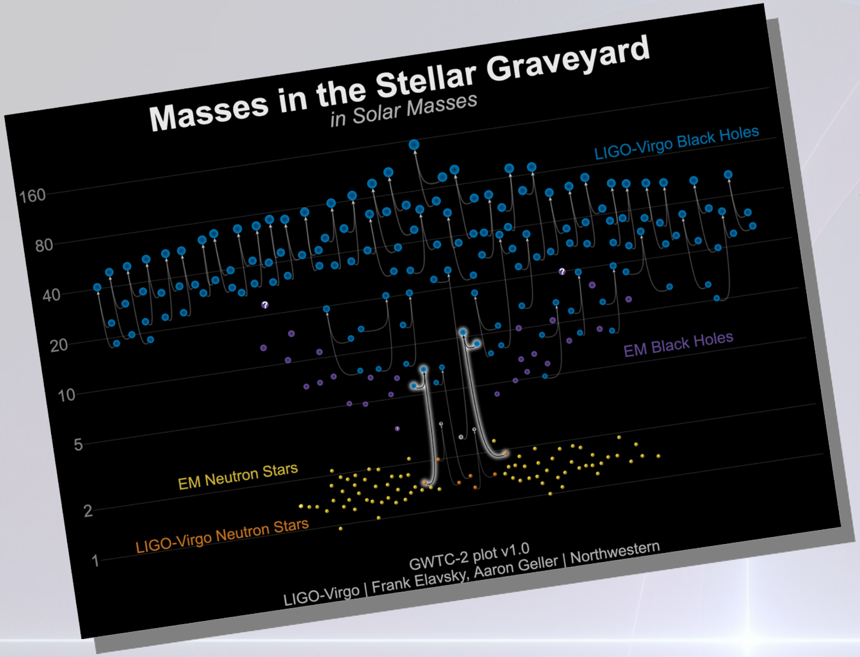
Question:
which star's wind will be stronger: a low-Z or a high-Z star's?

Answer:
dM/dt ~ Z

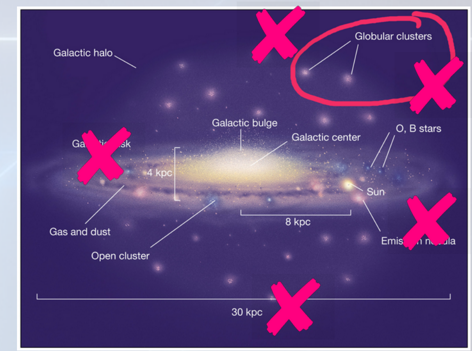


To explain the mass distribution of GW-emitting compact object mergers, we need to understand low-Z environments! (And low-Z stellar evolution, of course.)

to research...



Globular clusters



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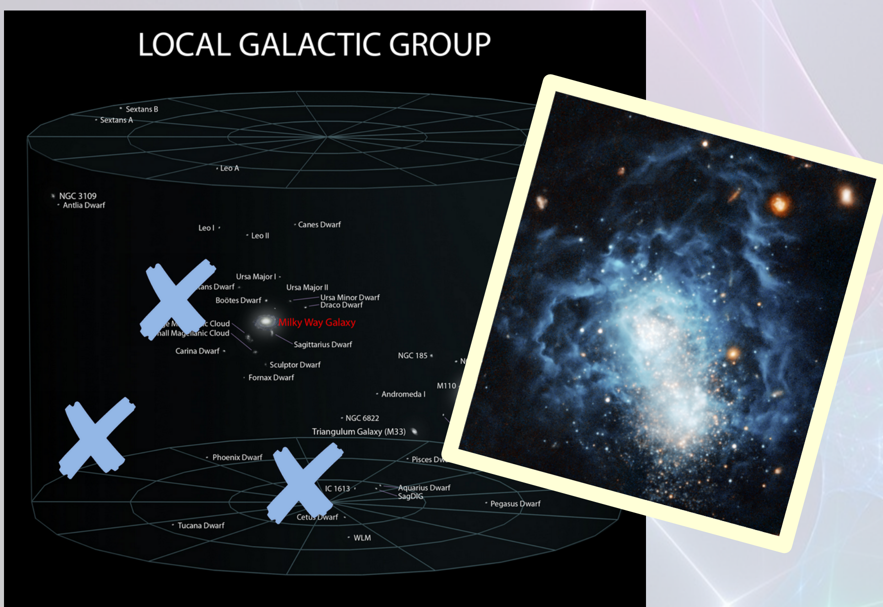

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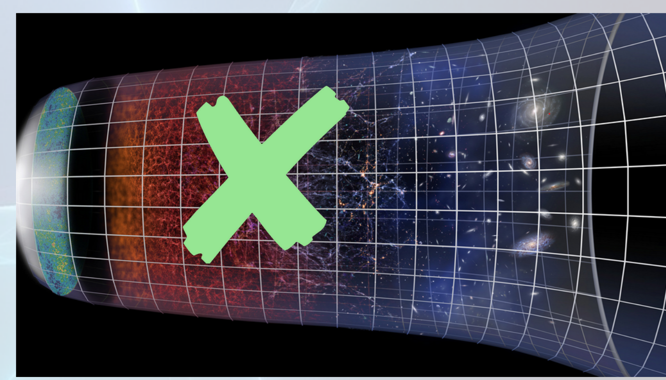

Today…

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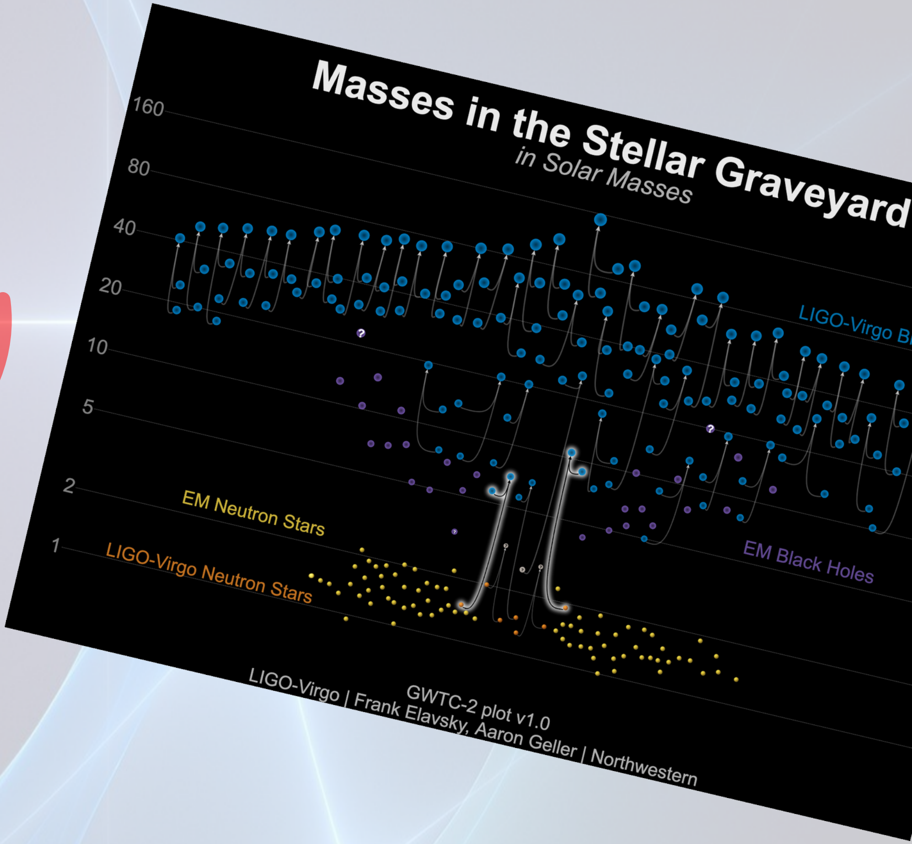
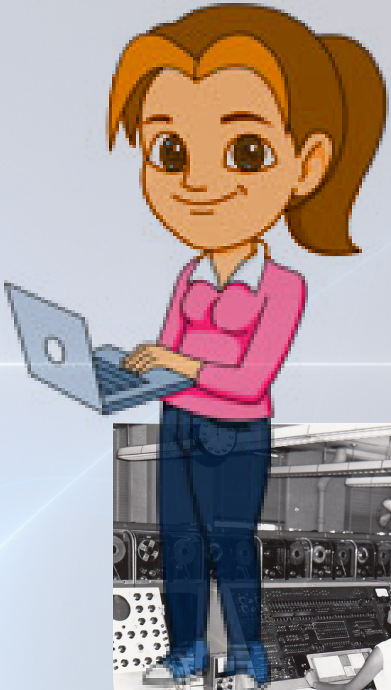


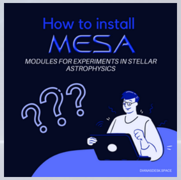
(Stellar) Populations

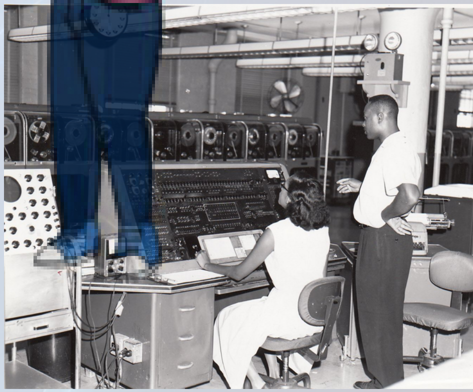
...and the Initial Mass Function (IMF)

a star-cluster or galaxy:

(e.g.) $10^7\ M_\odot$







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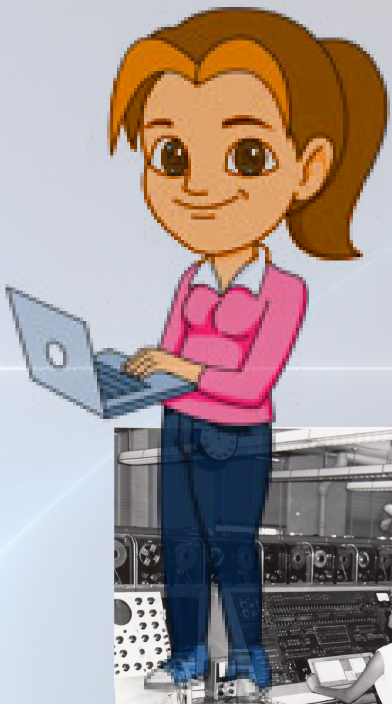

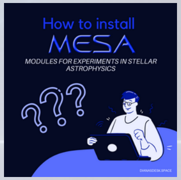

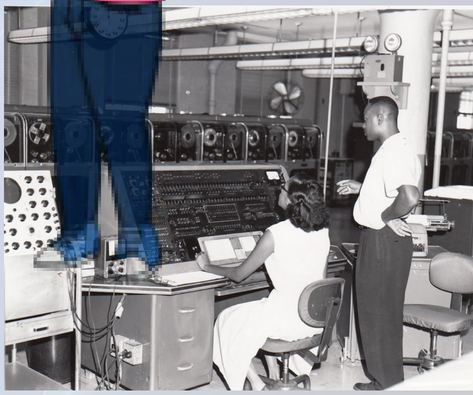

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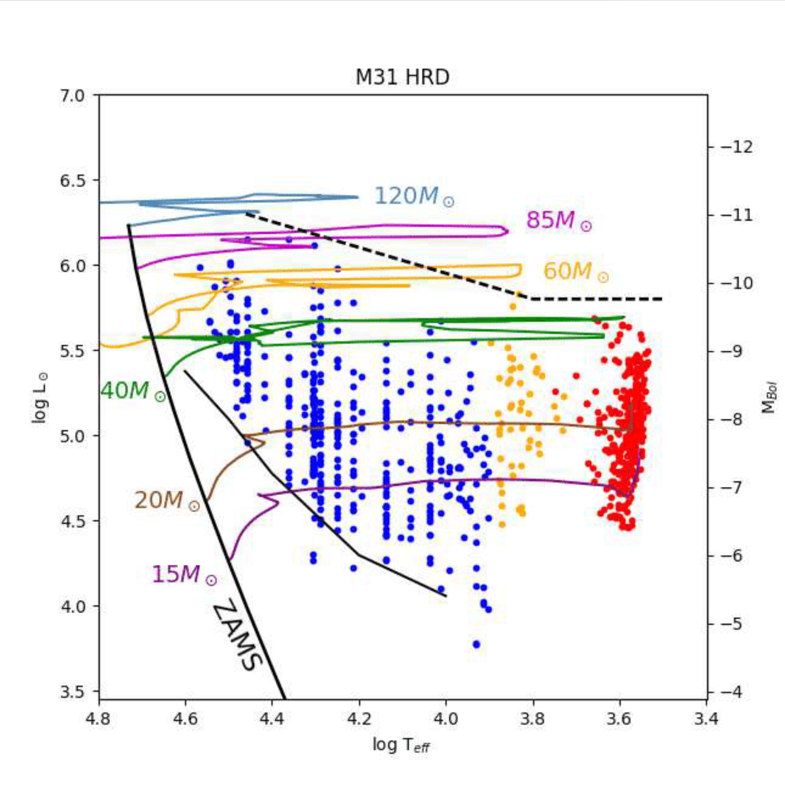
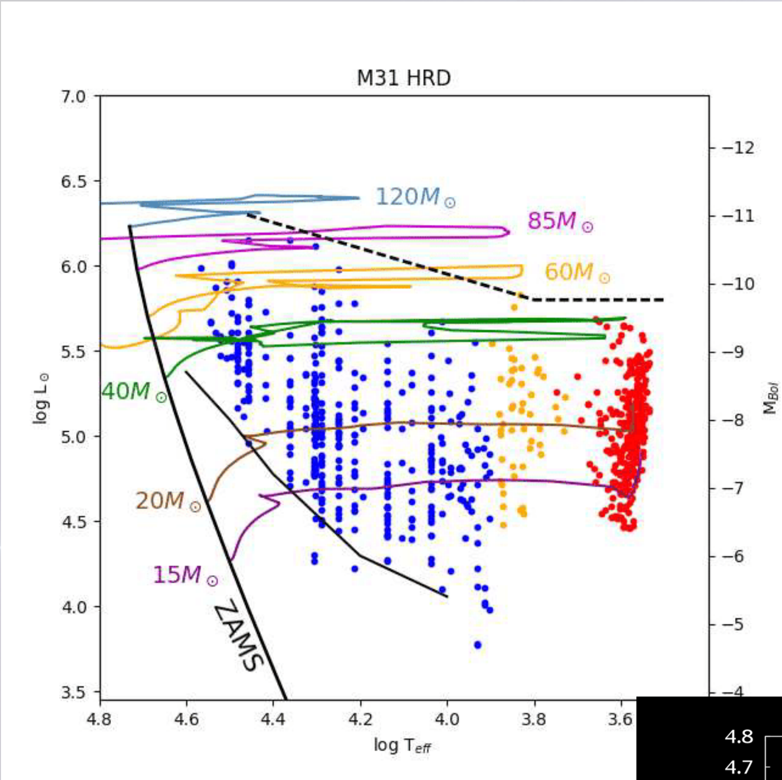
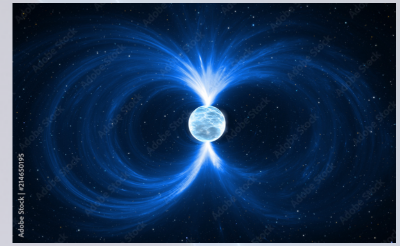


stellar evolution models → ? → type of explosion?? → ? → mass of remnant?? (BH?, NS?)





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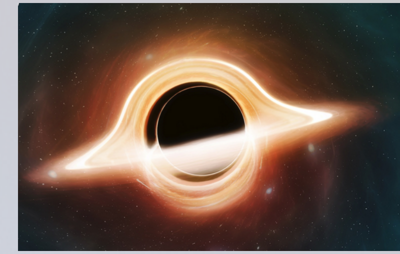
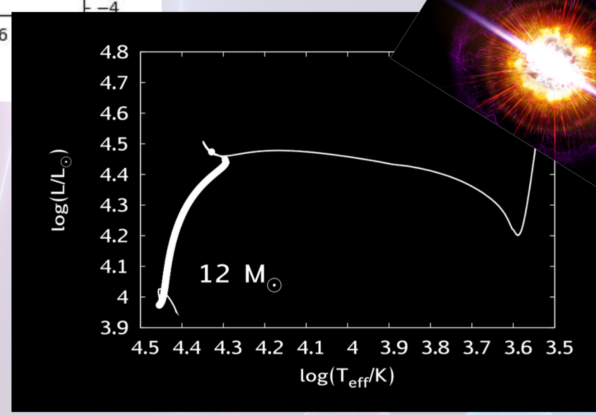


SN??



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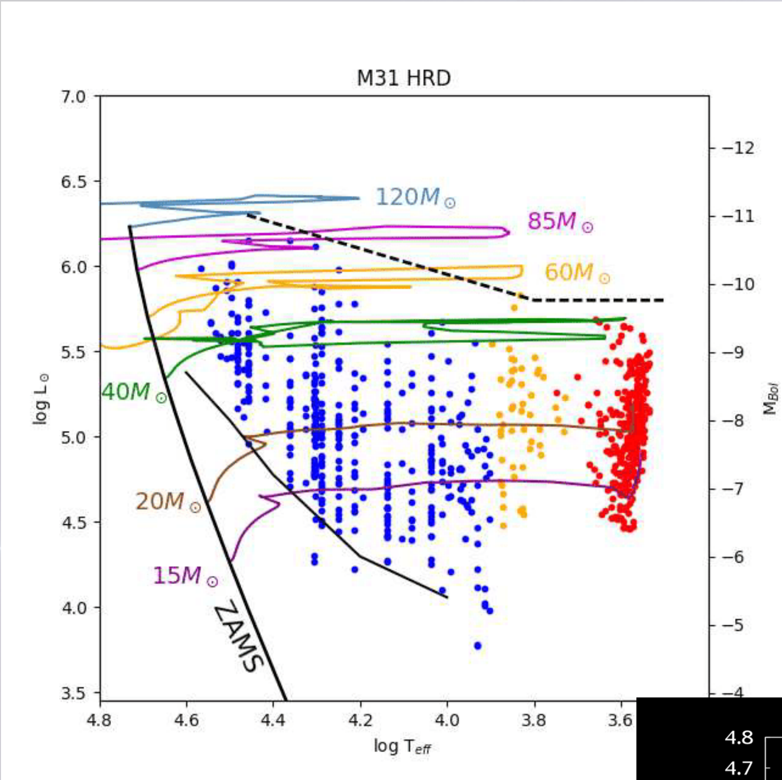

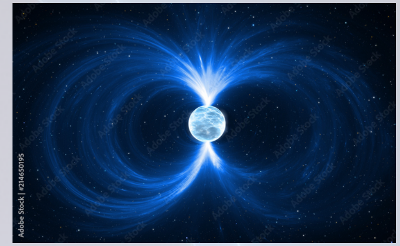

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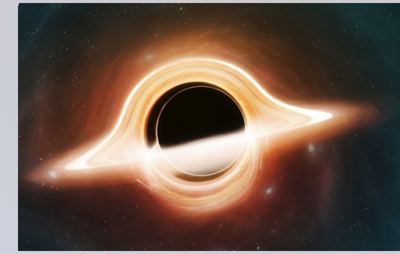

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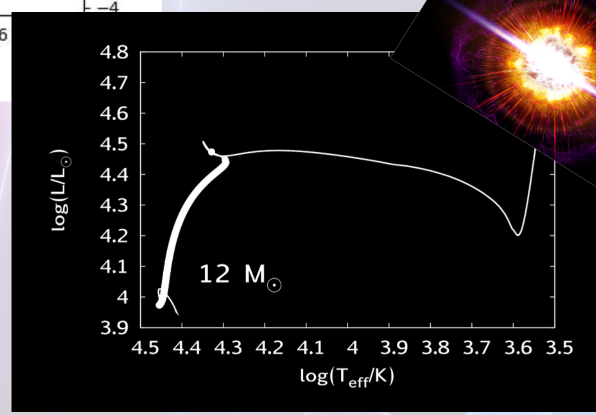
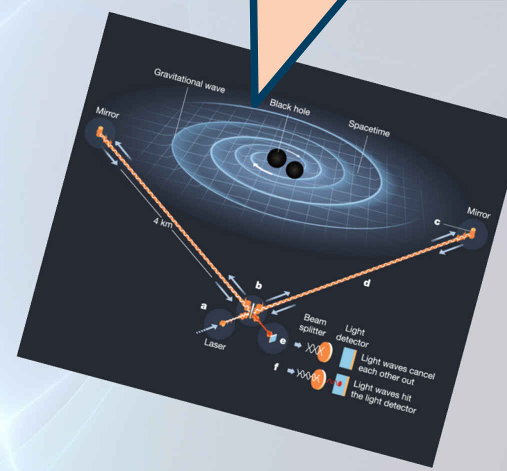


We need at least two...



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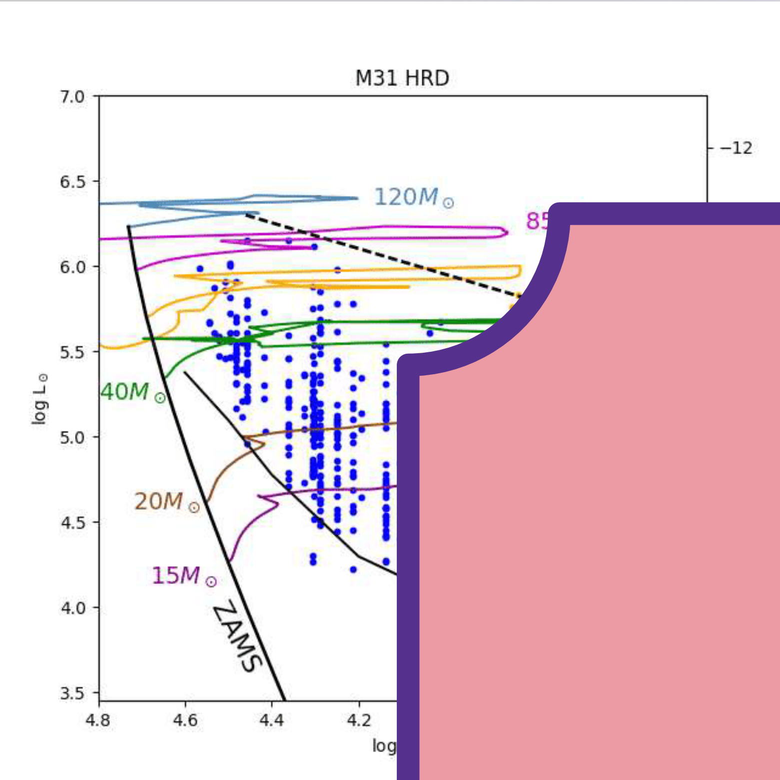

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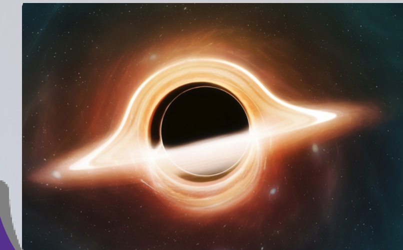

Later.

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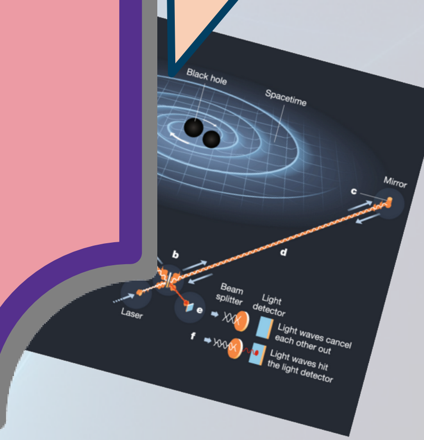

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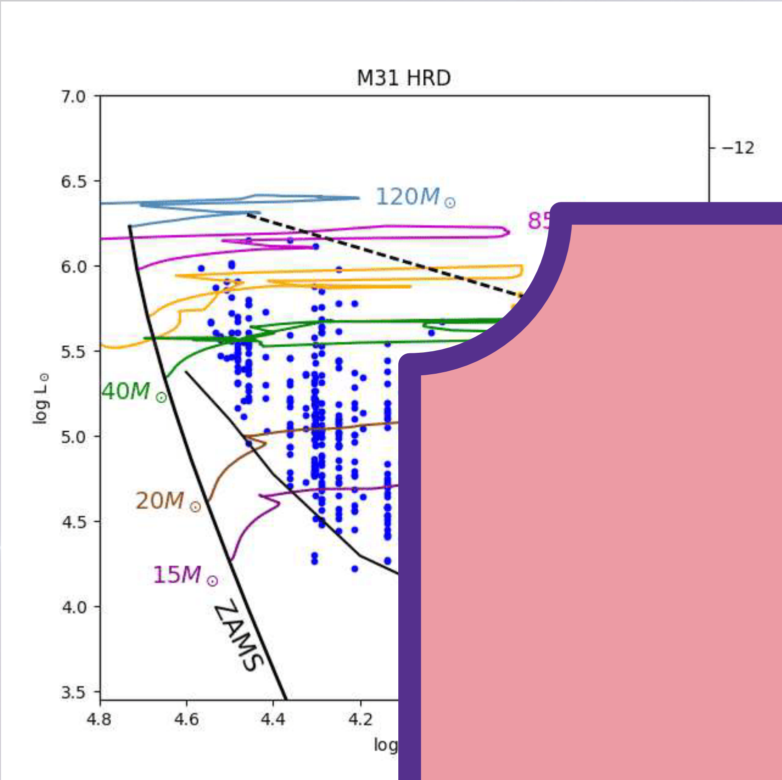
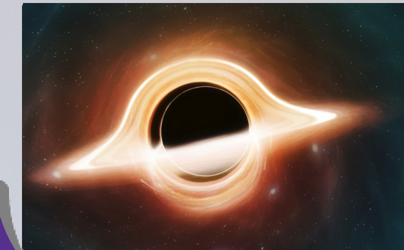


?



Later.

For now:
massive star → compact object

We need
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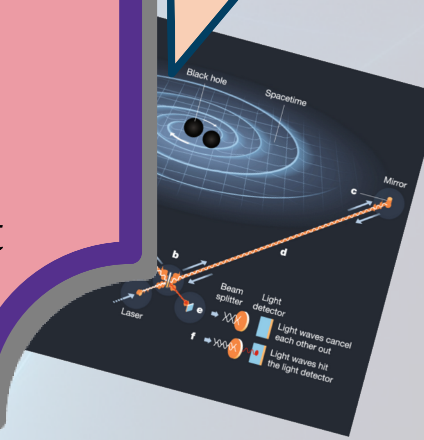

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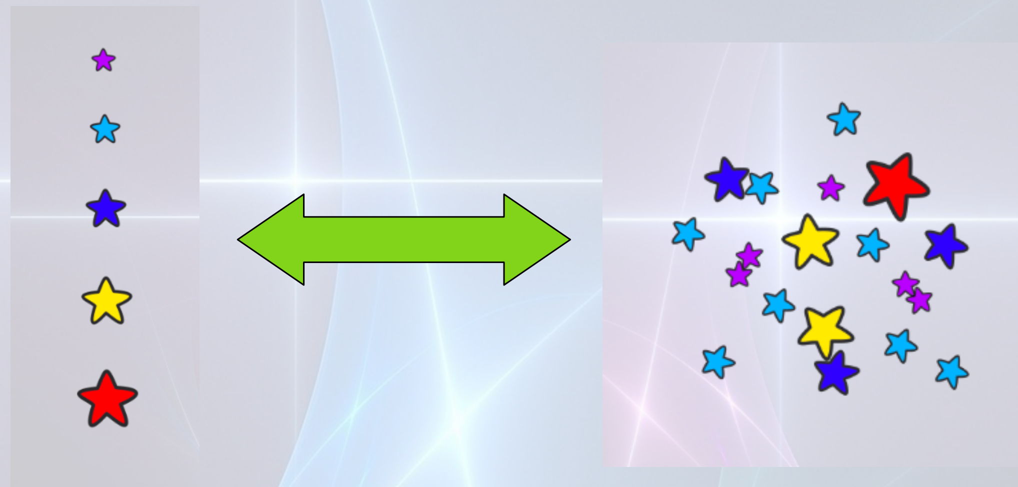

stars

stellar population

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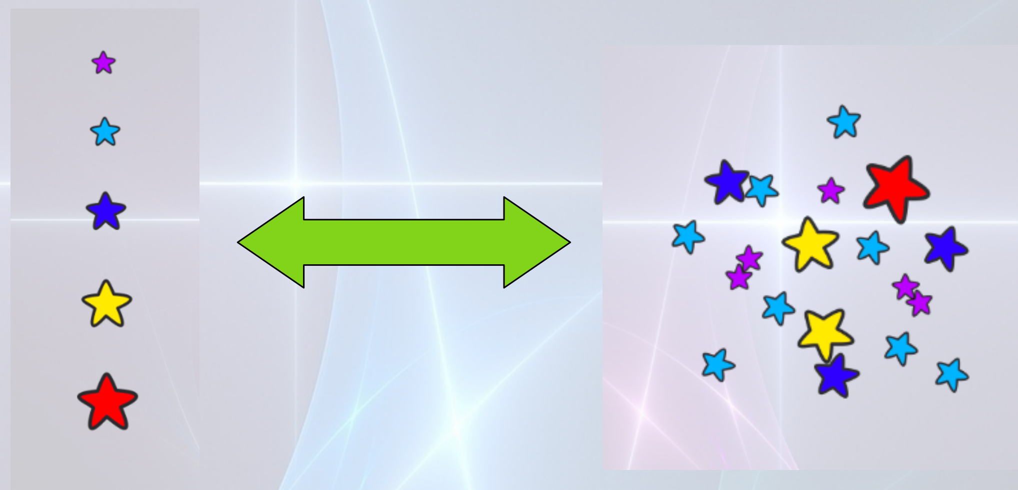

stars

stellar population

How many stars with 8 $M_\odot$?

How many with 20 $M_\odot$?
How many with 100 $M_\odot$?
...

The Initial Mass Function (IMF)

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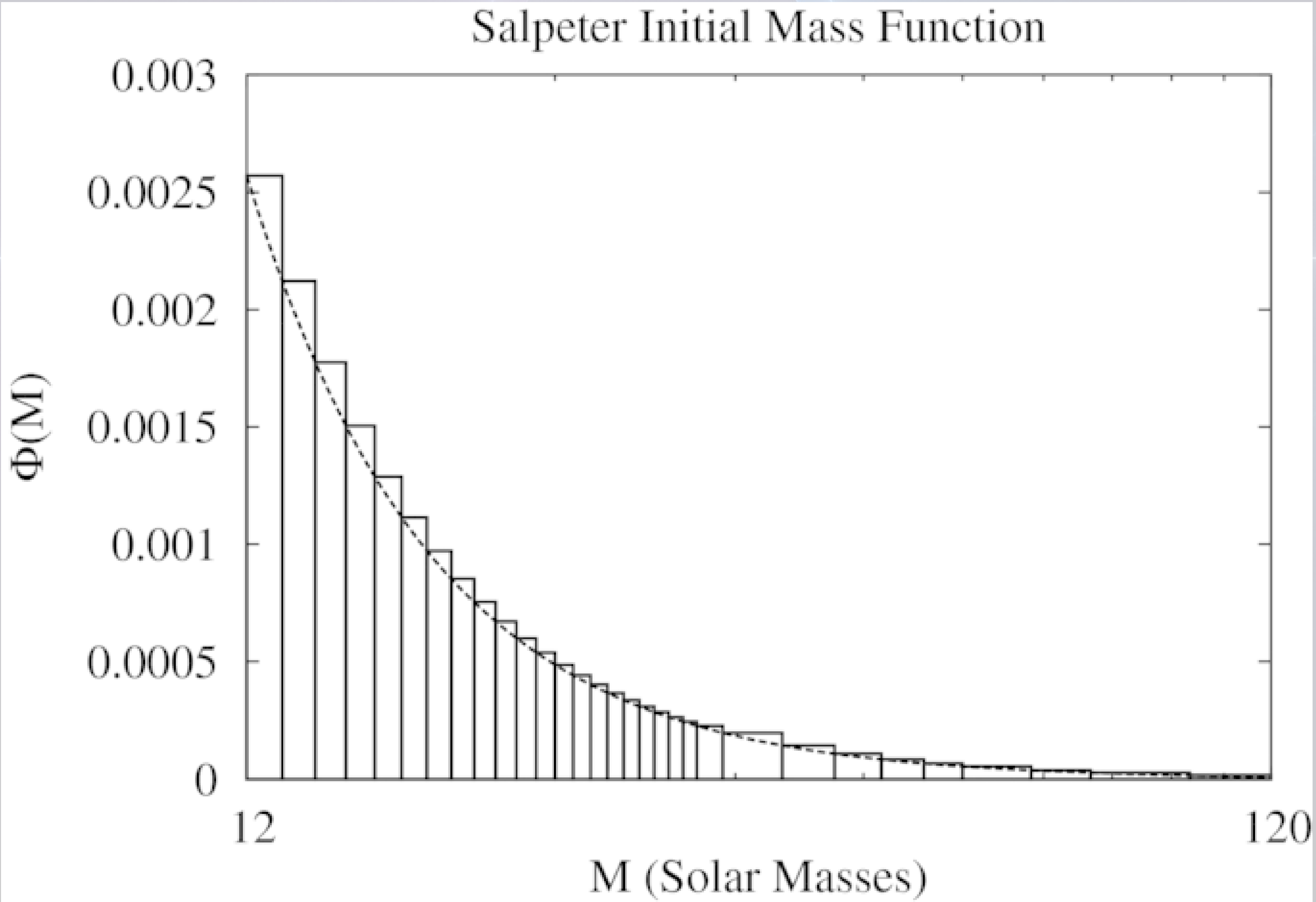

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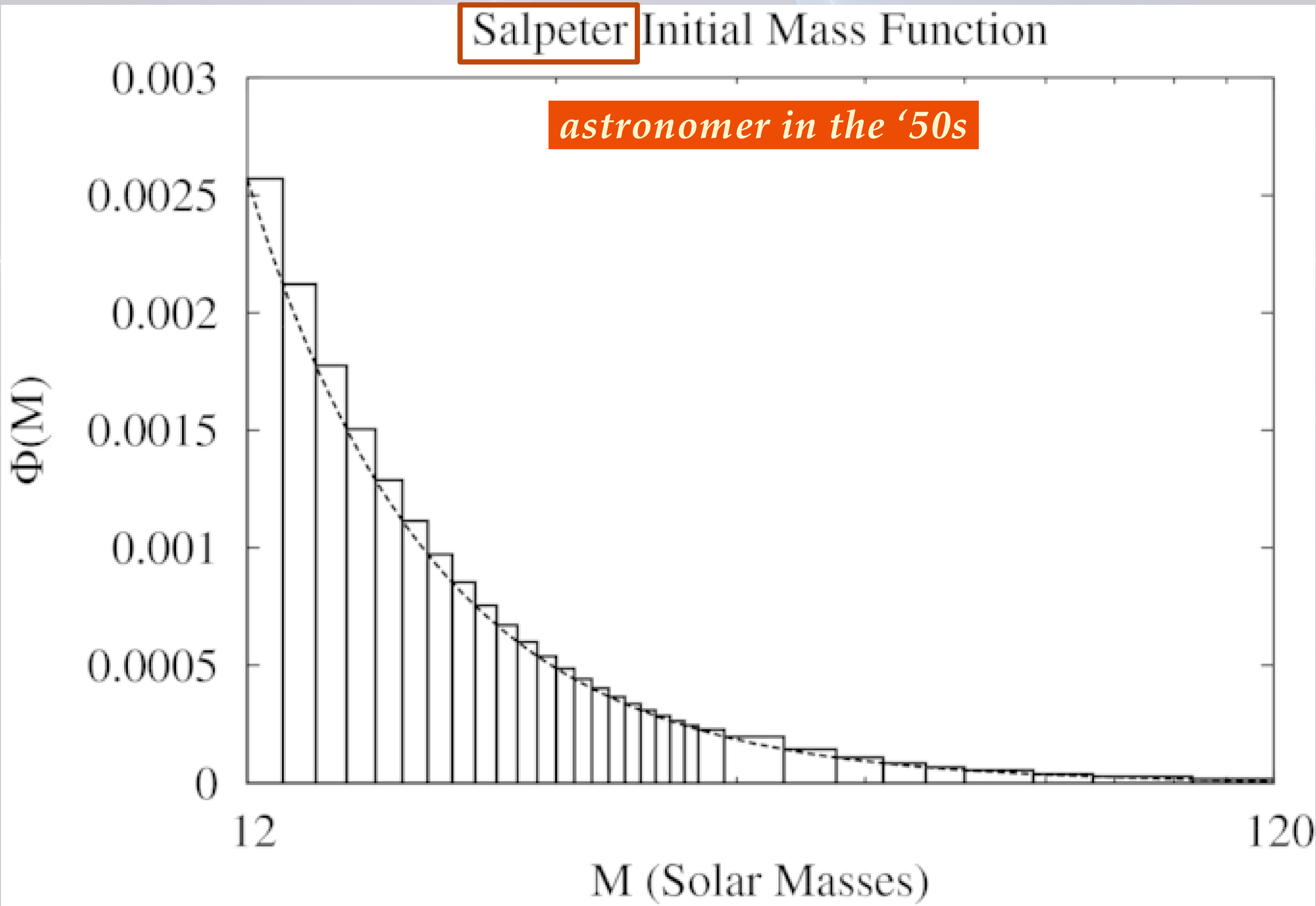

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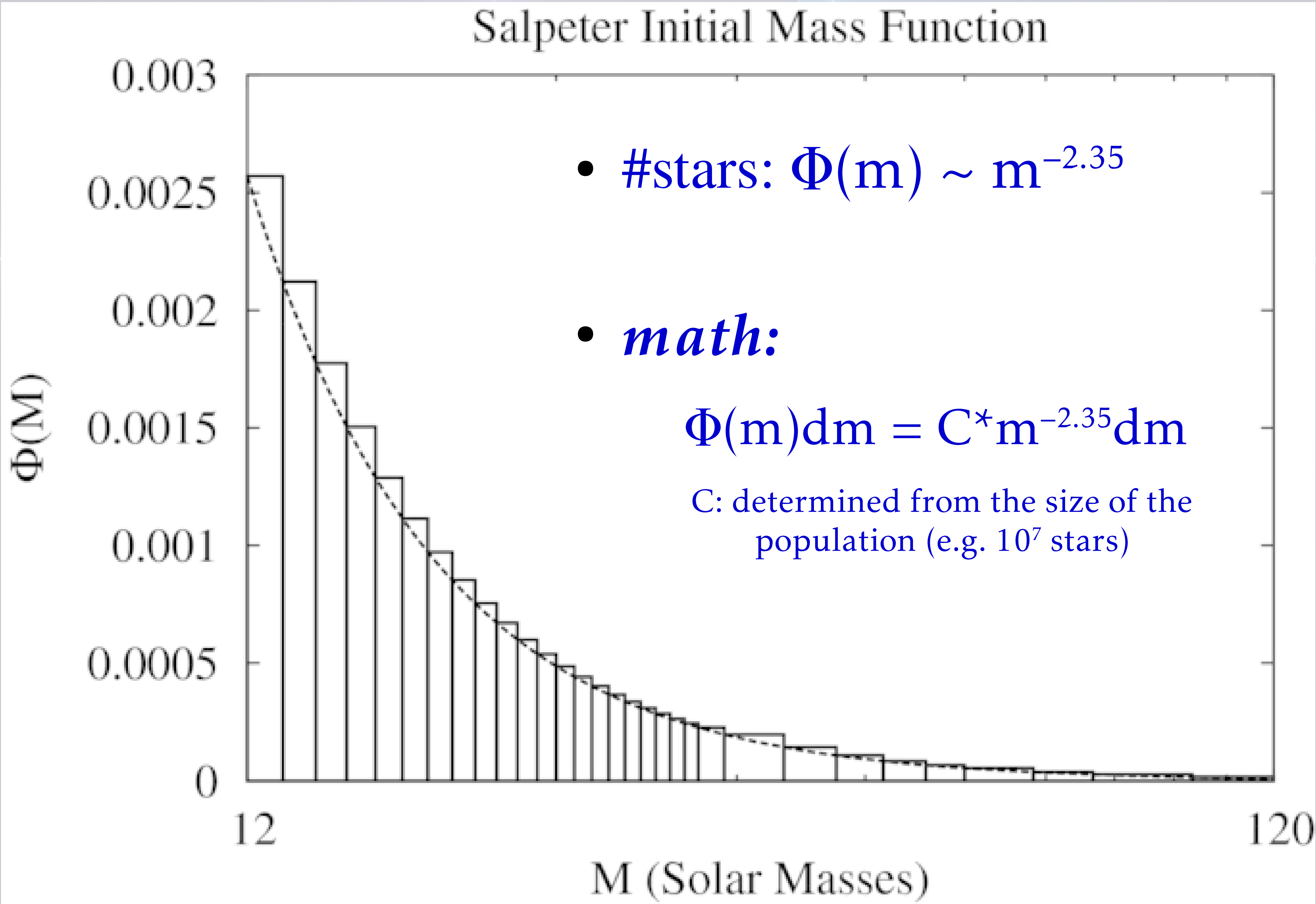

- #stars: $\Phi(m) \sim m^{-2.35}$
- ***math:***

$$\Phi(m)dm = C^{*}m^{-2.35}dm$$

C: determined from the size of the population (e.g. 10^7 stars)

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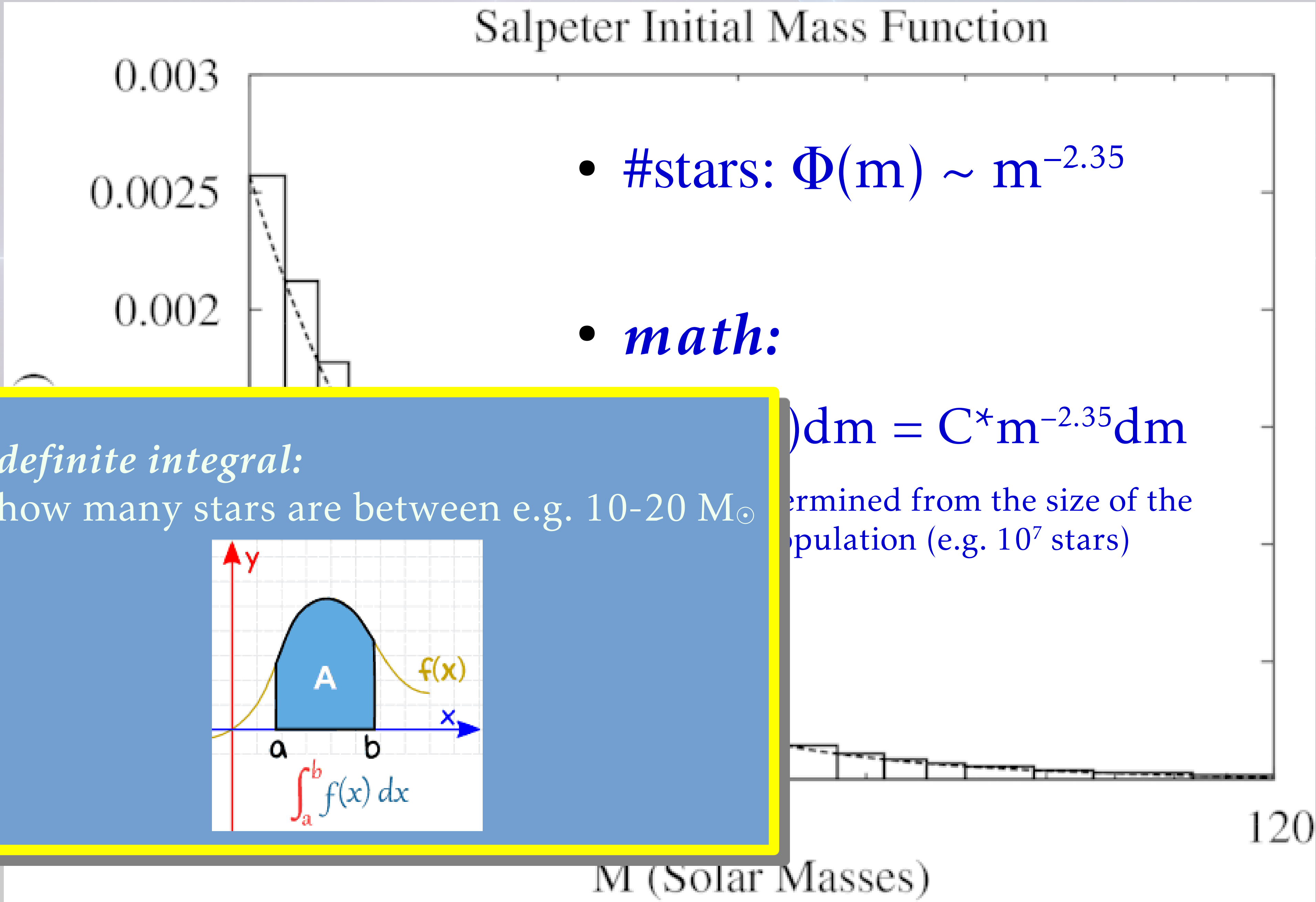

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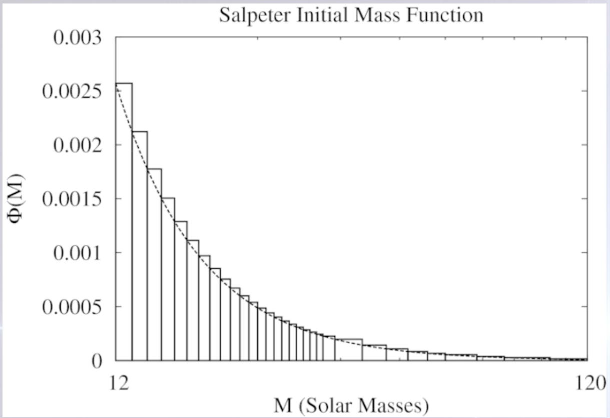
definite integral:

how many stars are between e.g. 10-20 $M_\odot$

Homework



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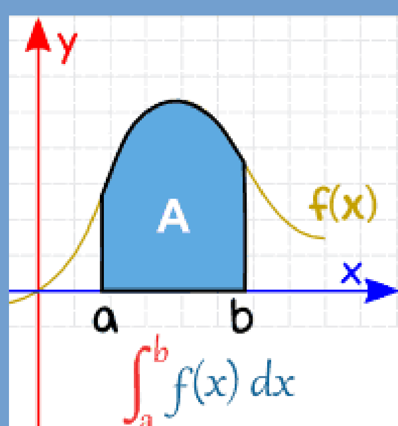
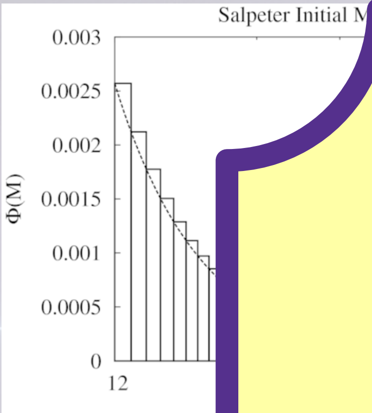


Compute the number (and mass) of stars between 10-20 $M_\odot$ in a stellar population of 10^7 stars!

Suppose that in this star-cluster the lower mass limit is 1 $M_\odot$ and the upper mass limit is 120 $M_\odot$.

Homework

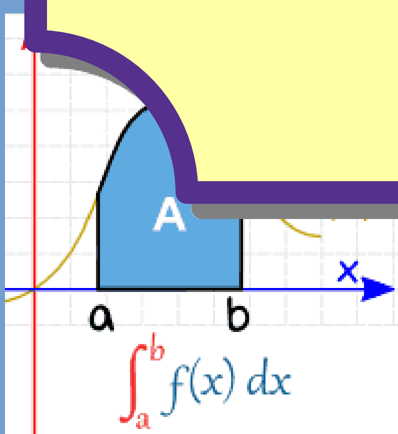


35

^{5}dm

population

definite integ
how many st



Homework++

Write a code that does the same for you numerically! ;)

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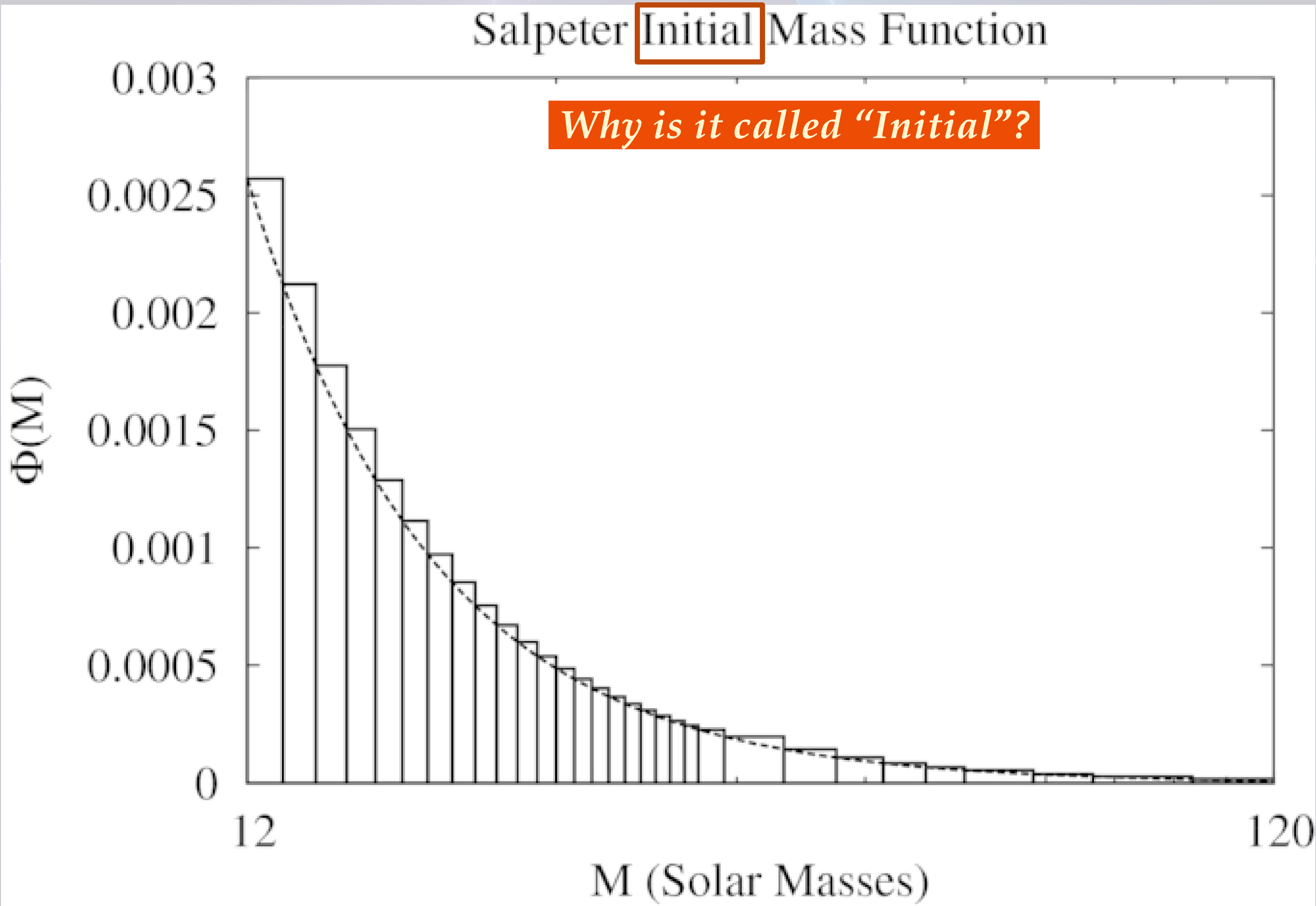
The Initial Mass Function (IMF)



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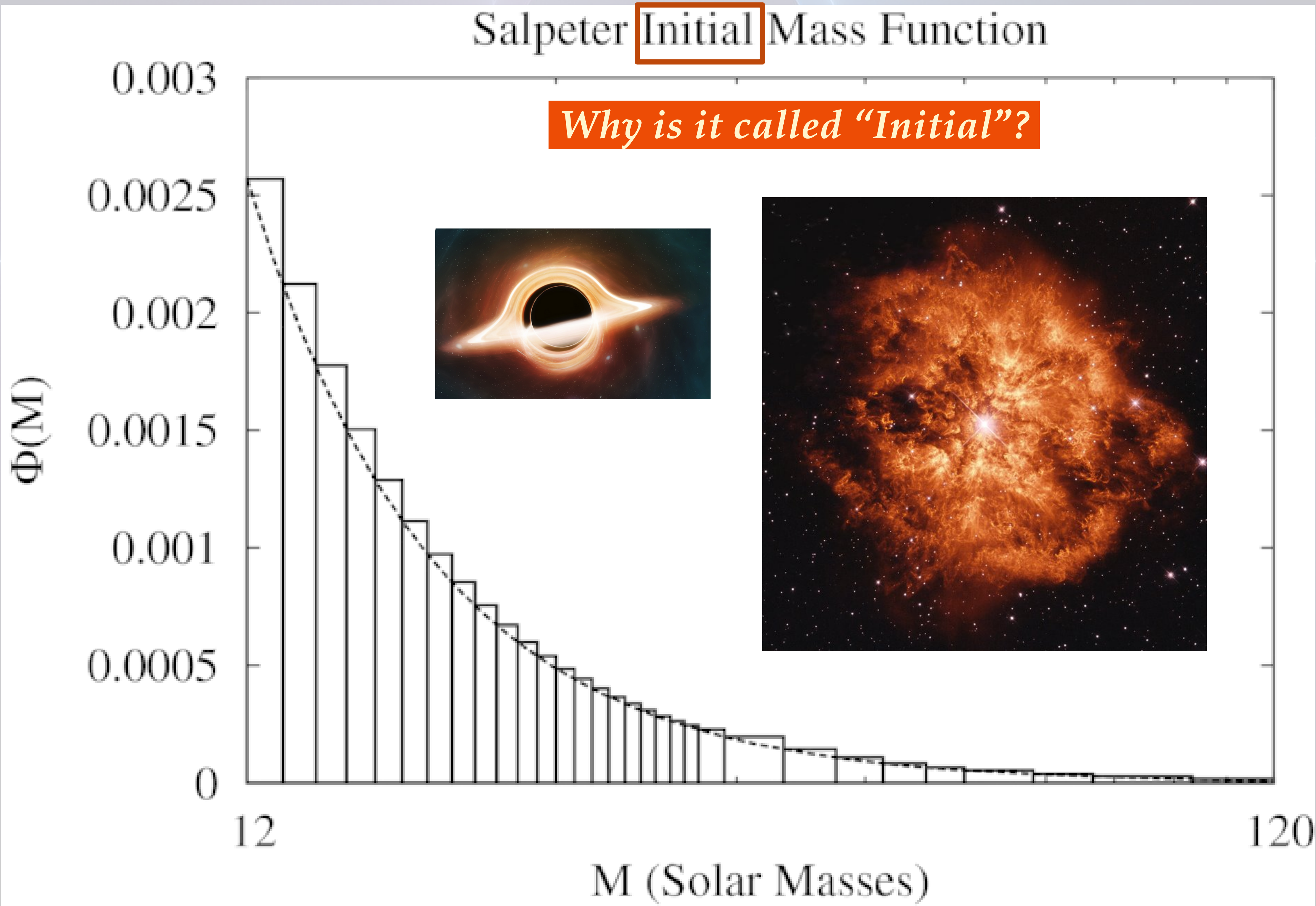
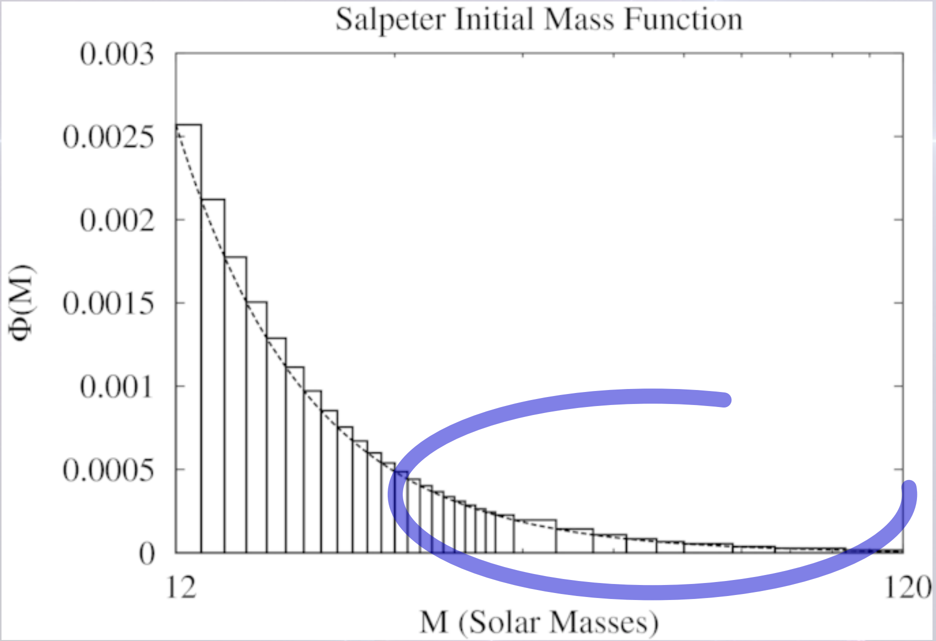


What changed since the ‘50s?



- Salpeter, Kroupa, top-heavy…

top-heavy:

$$\Phi(m) \sim m^{-\alpha}$$

$$\alpha = 1.9 \ (?)$$

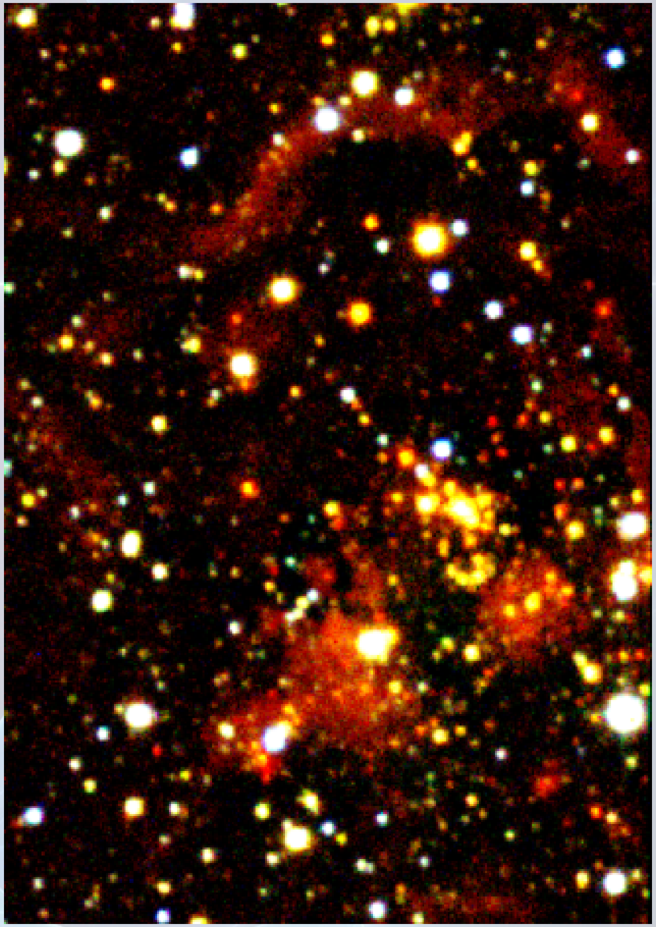
  - helps with massive stars ;)

...and massive BHs too!

- What is the most massive star known?

Highest mass star in the Universe?

- Westerhout 49-2:
  - 250 (±120) $M_\odot$
  - W49: star-forming region in the Milky Way…
- low Z ??
  - mass loss is weaker…
  - hard to observe individual objects
  - Population III stars [next slide]
- Practice:
  - IMF with $M_{up} = 120\ M_\odot$ (or 250 $M_\odot$ or 500 $M_\odot$ or ...)



UKIDSS JHK image of W49

“Population III” stars: *first stars*

- Historically: 3 stellar “populations”

    Population I = stars around the Sun (solar Z)

    Population II = stars in Globular Clusters (low Z)

    Population III = primordial stars, metal-free (H&He)

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    - low-metallicity massive stars / metal-poor massive stars
    - e.g. in dwarf galaxies or the early Universe

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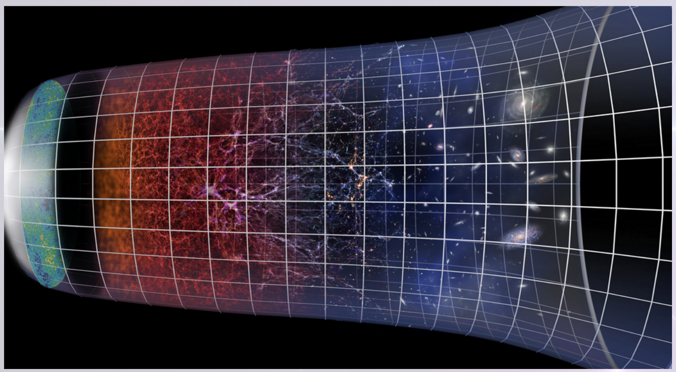
- 'Stellar Population' today:
  - stars in a star-cluster or galaxy

HARDCORE STUFF



How many
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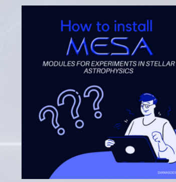
IN THE UNIVERSE
(per year)?

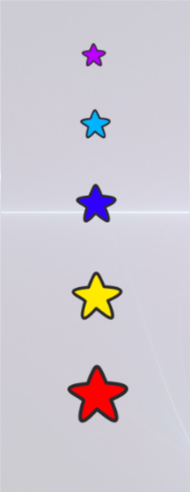


a star-cluster or galaxy: one star-formation event of size (e.g.) $10^7\ M_\odot$

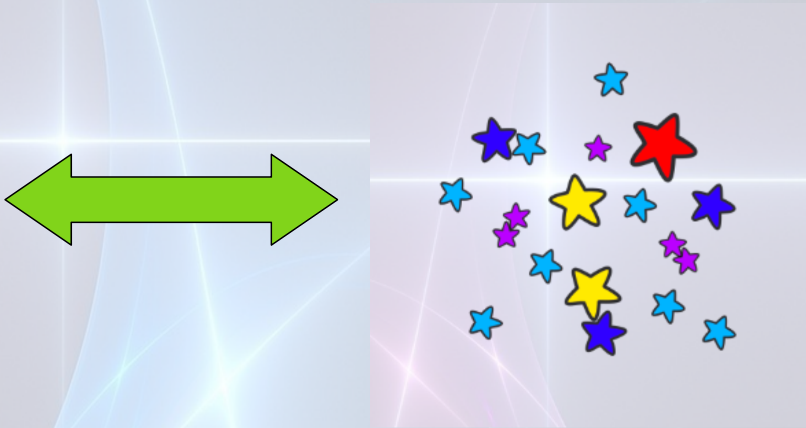
aLIGO/Virgo detectors observe GWs from the whole Universe…

Population synthesis

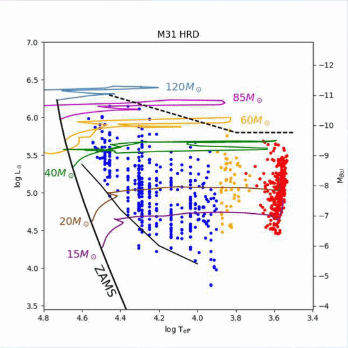
- Synthetic population:
  - time-dependence
  - star-formation history…



stars /
stellar models

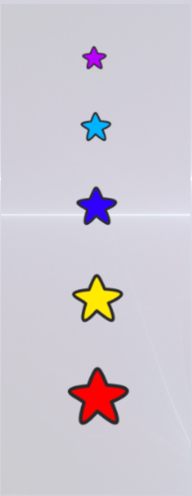


stellar population



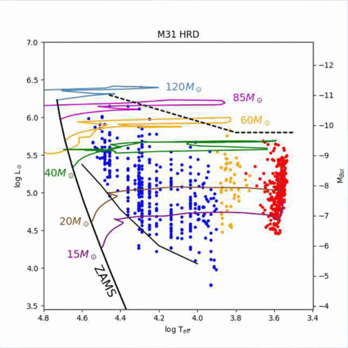
Population synthesis

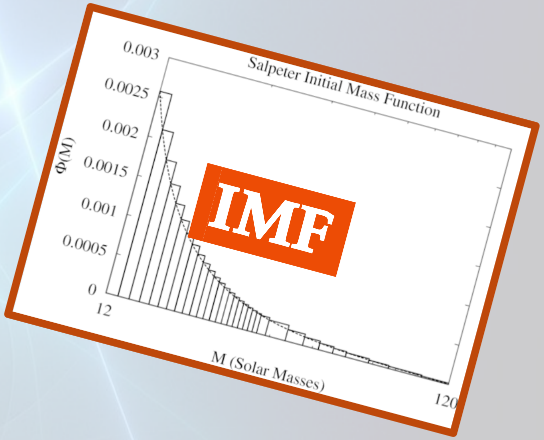
- Synthetic population:
  - time-dependence
  - IMF
  - star-formation history…



stars /
stellar models

stellar population





Question:

Which star lives longer?

A low-mass star or a massive star?

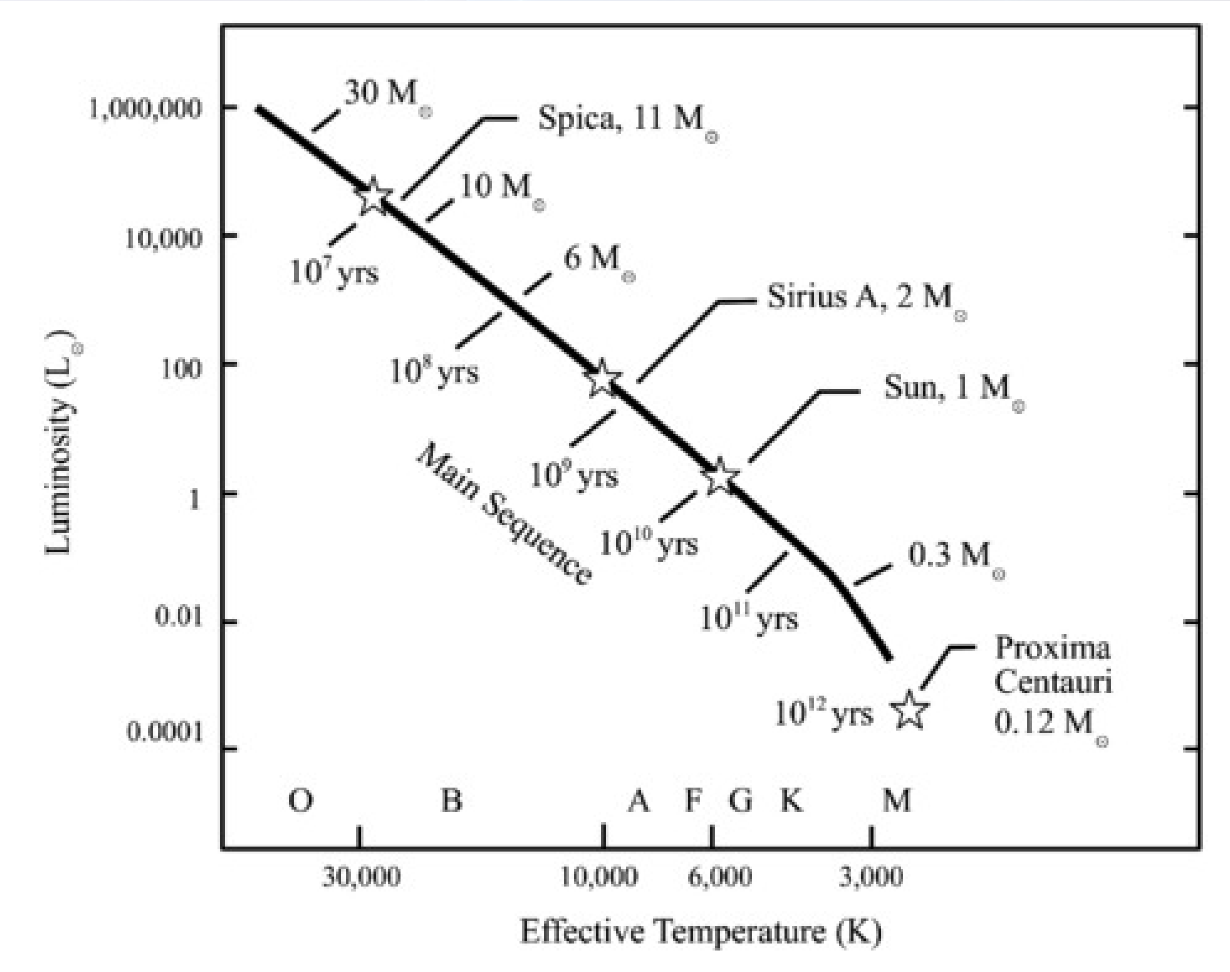
Why?

Lifetime of stars

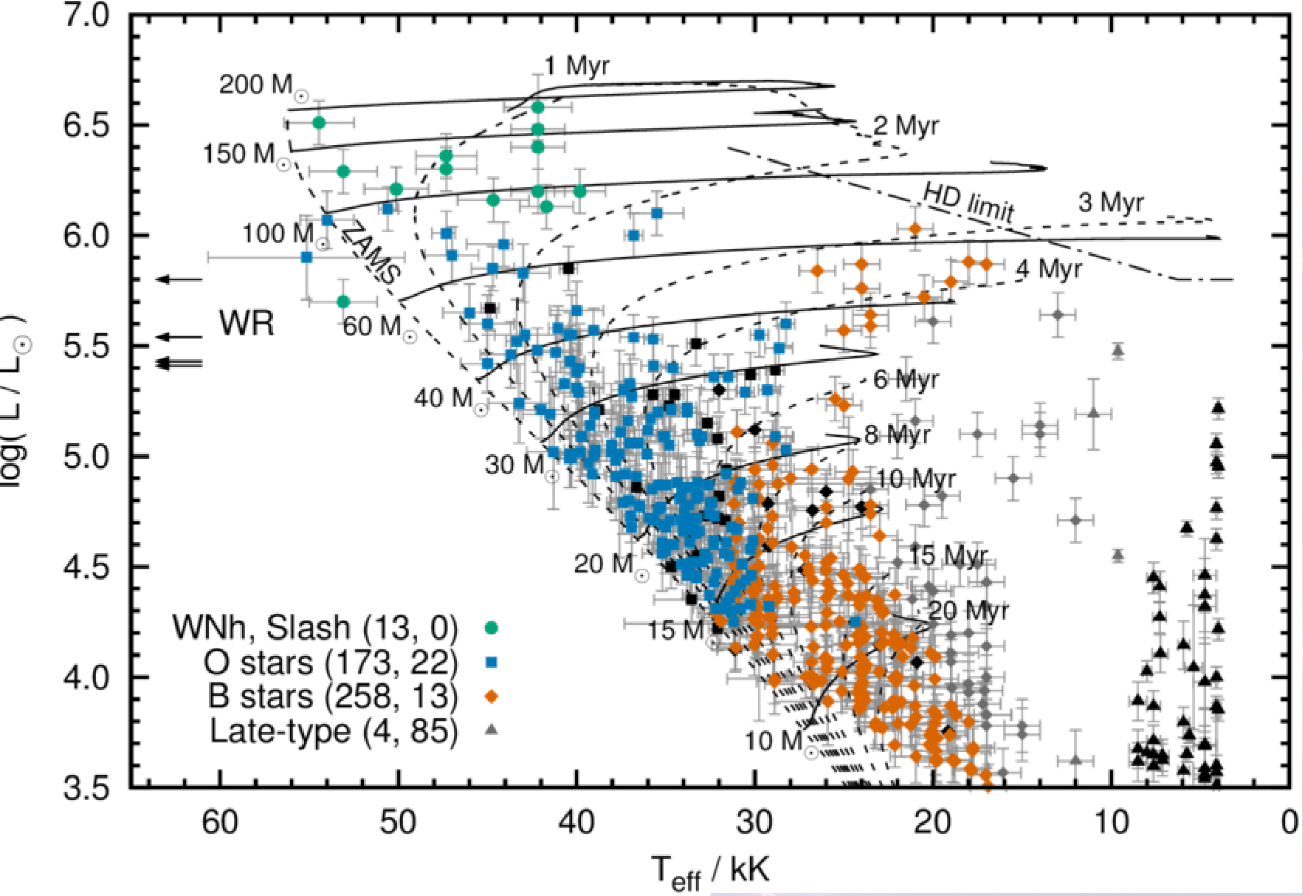
- $\tau(m) \sim m^{-2.5}$
  - Sun's lifetime: $\sim 10 \cdot 10^9$ yrs
  - an 8 $M_\odot$ star's lifetime: $\sim 5 \cdot 10^7$ yrs
  - a 100 $M_\odot$ star's lifetime: $\sim 2 \cdot 10^6$ yrs

Stars of higher mass are more luminous. They burn their fuel at a faster rate.

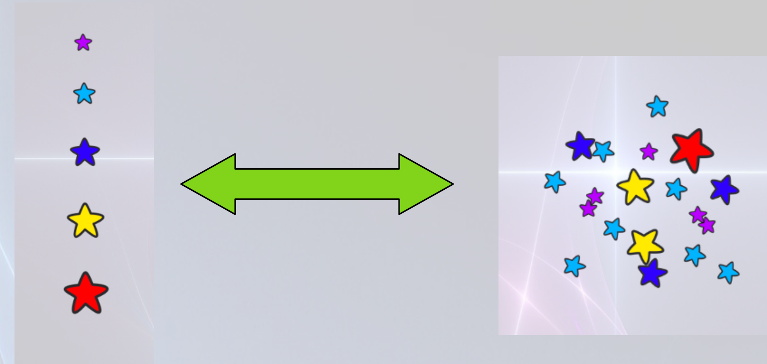
→ shorter lifetimes



Credit: ase.tufts.edu/cosmos



30 Doradus star-cluster in the Large Magellanic Cloud galaxy (VFTS survey, 2018)



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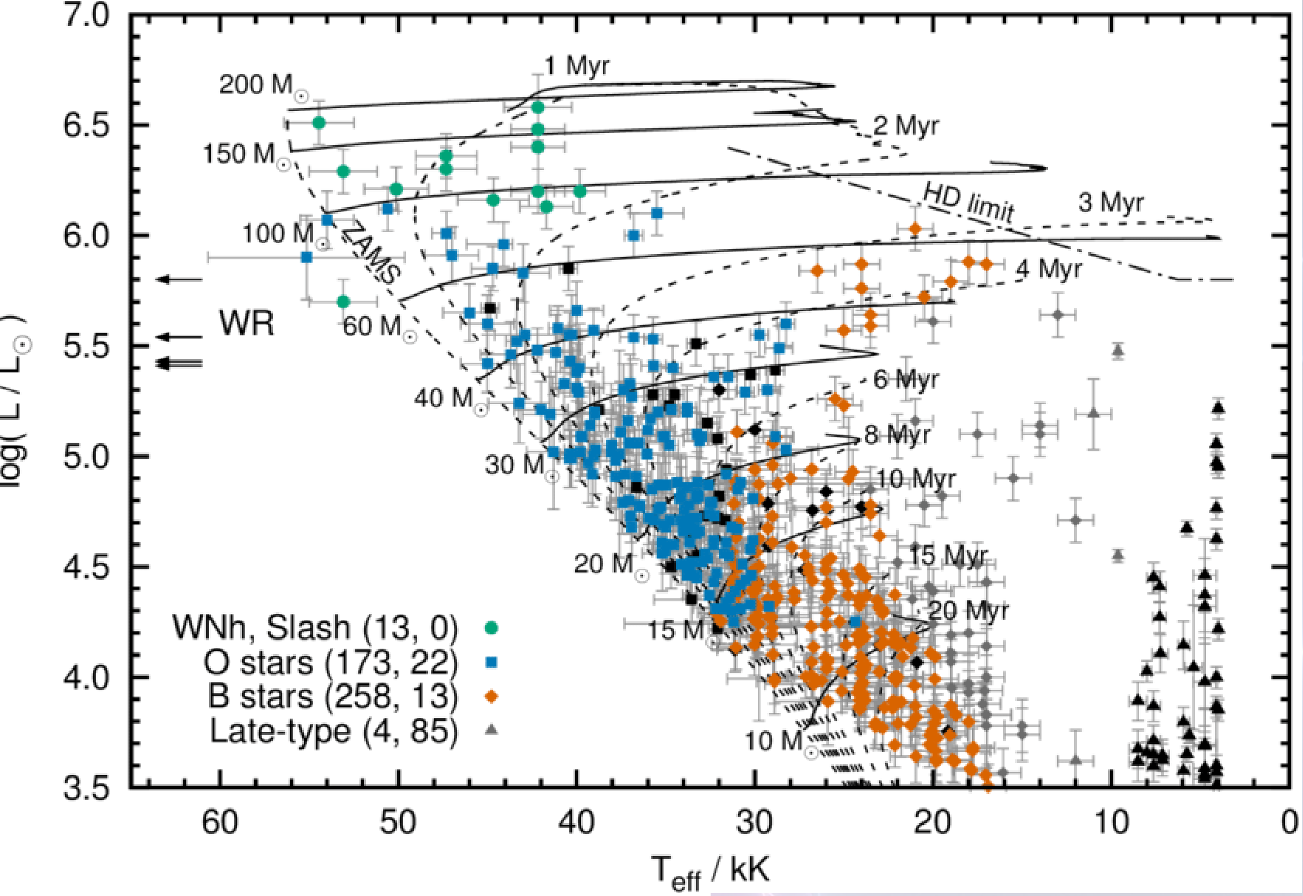

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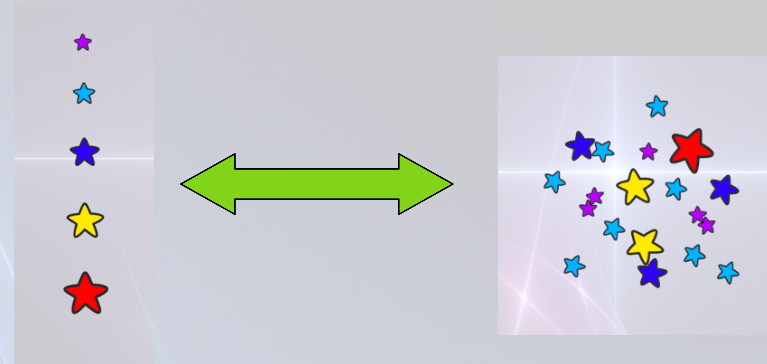

A star-cluster of 10^5 yrs (young) will look really different from a star-cluster of 10^8 yrs (old).

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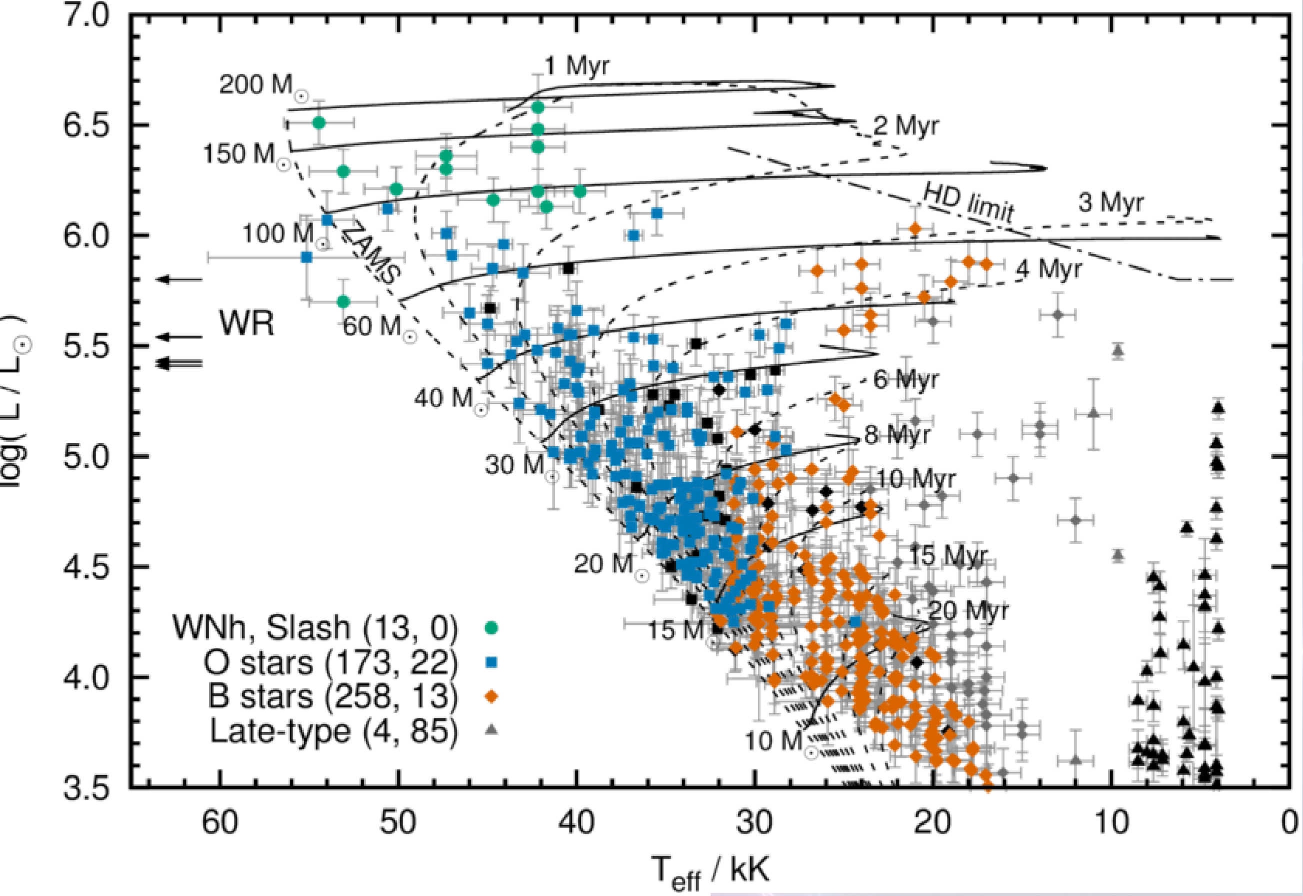

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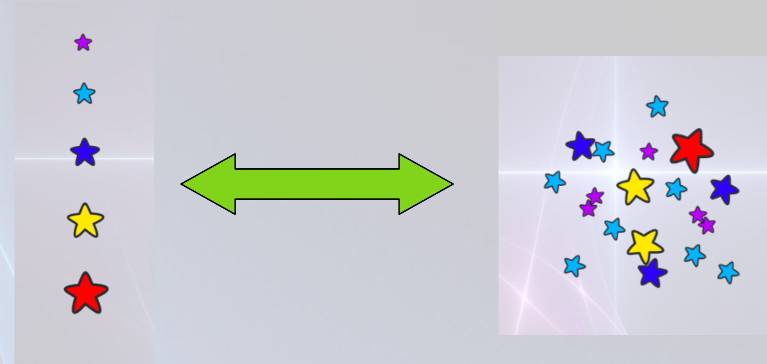

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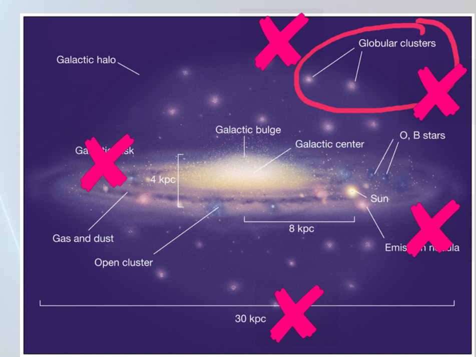
Dwarf galaxies

vs.

Globular clusters



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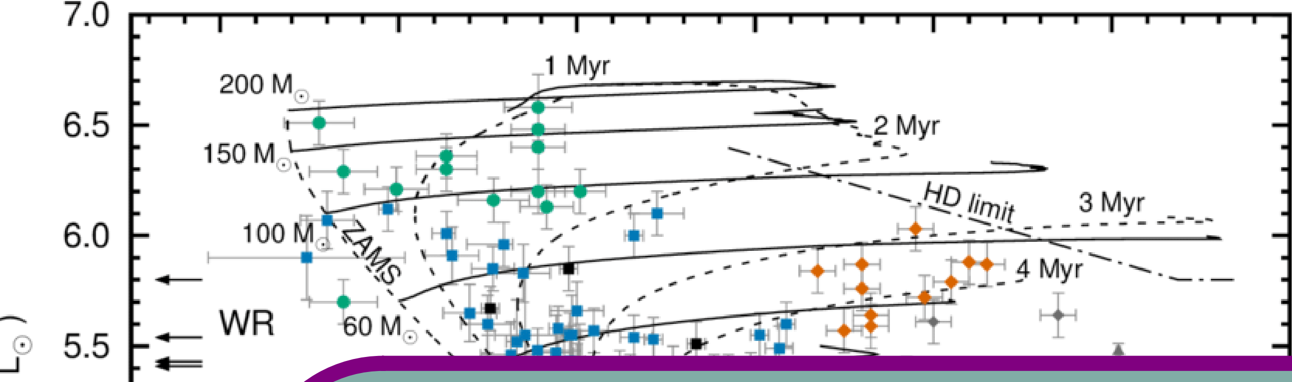
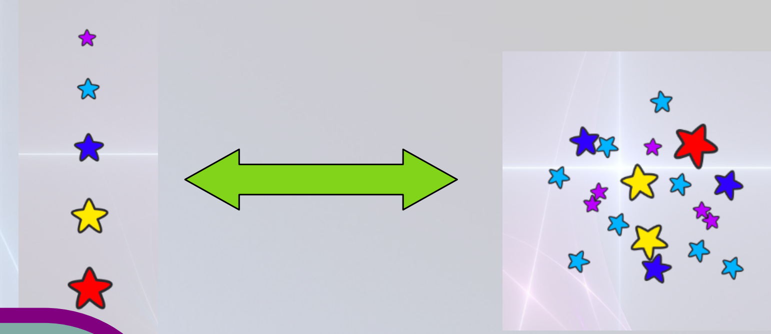
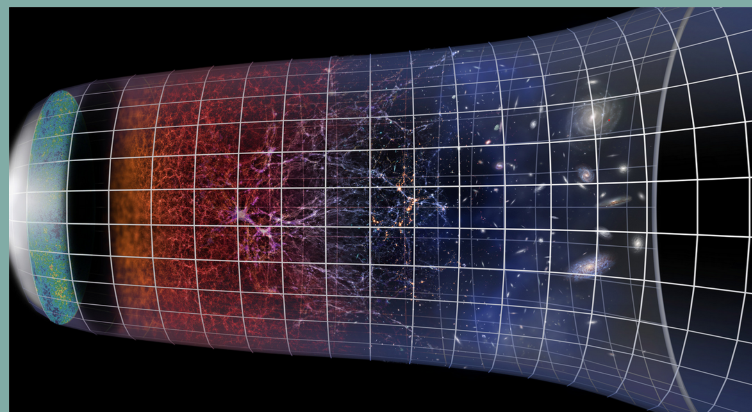


30 Doradu
Large Mage





aLIGO/Virgo detectors observe GWs from the whole Universe…

…population synthesis

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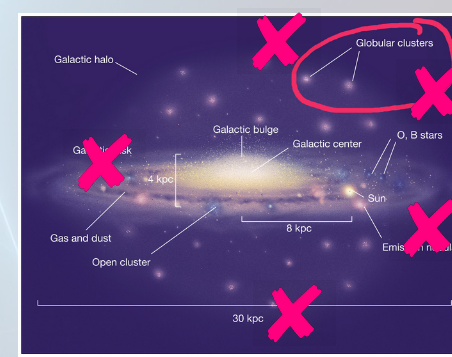

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Important exam question :D

- What is the difference between stellar evolution and population synthesis?