Gravitational-wave progenitors

Dorottya Szécsi

dorottya.szecsi@gmail.com

Lecture #12

NCU, Summer Semester 2022

Previously on GW-progenitors…

Let's play!

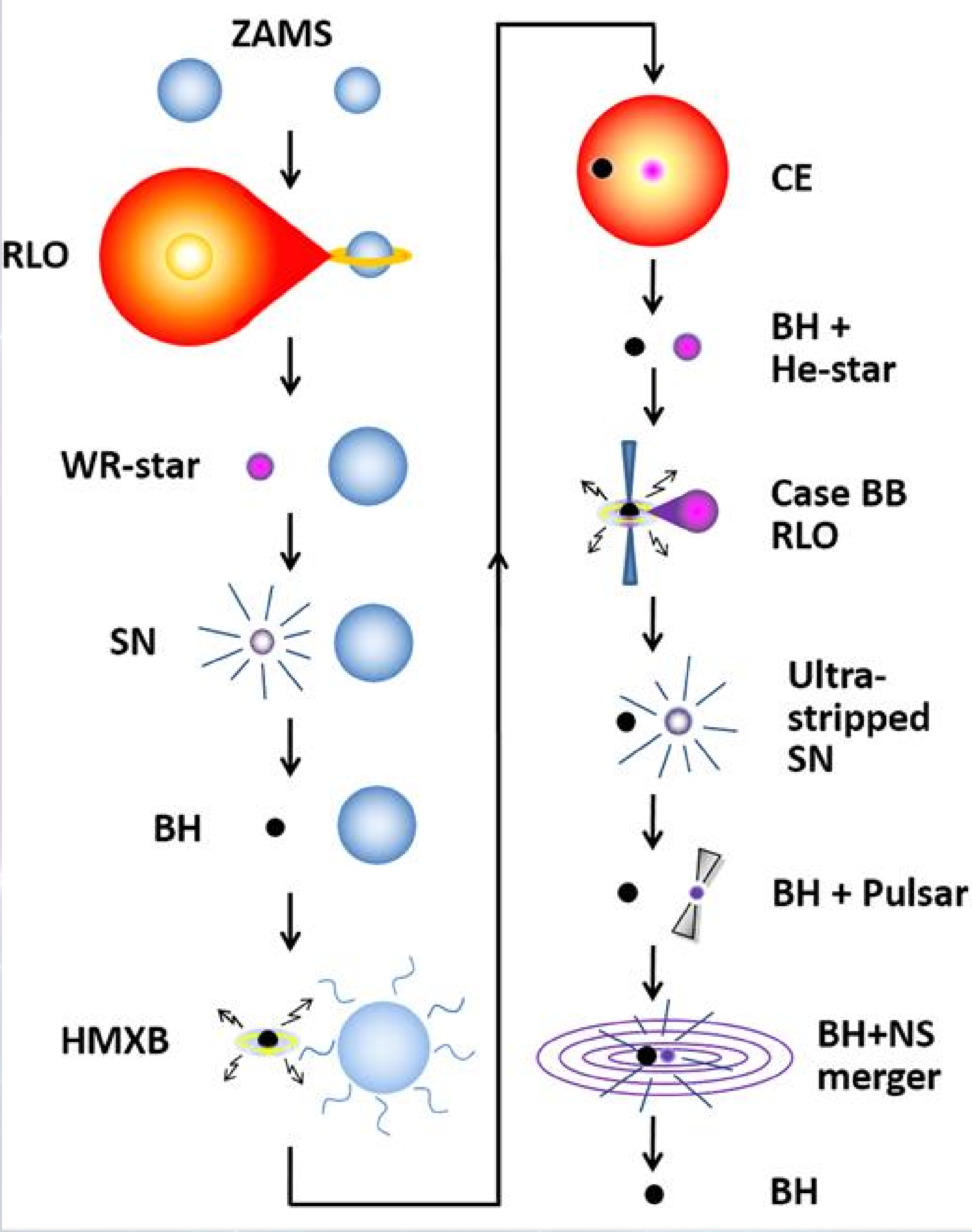
Zero-age Main Seq.

Roche-lobe overflow: stable mass transfer

Wolf-Rayet star (naked He-star with strong emission lines)

Supernova may kick out the companion! Survival rate?

Accreting black hole: High-Mass X-ray Binary (observed: periodic pulsations in X-rays)



Common Envelope! 😳

Probably a HMXB?

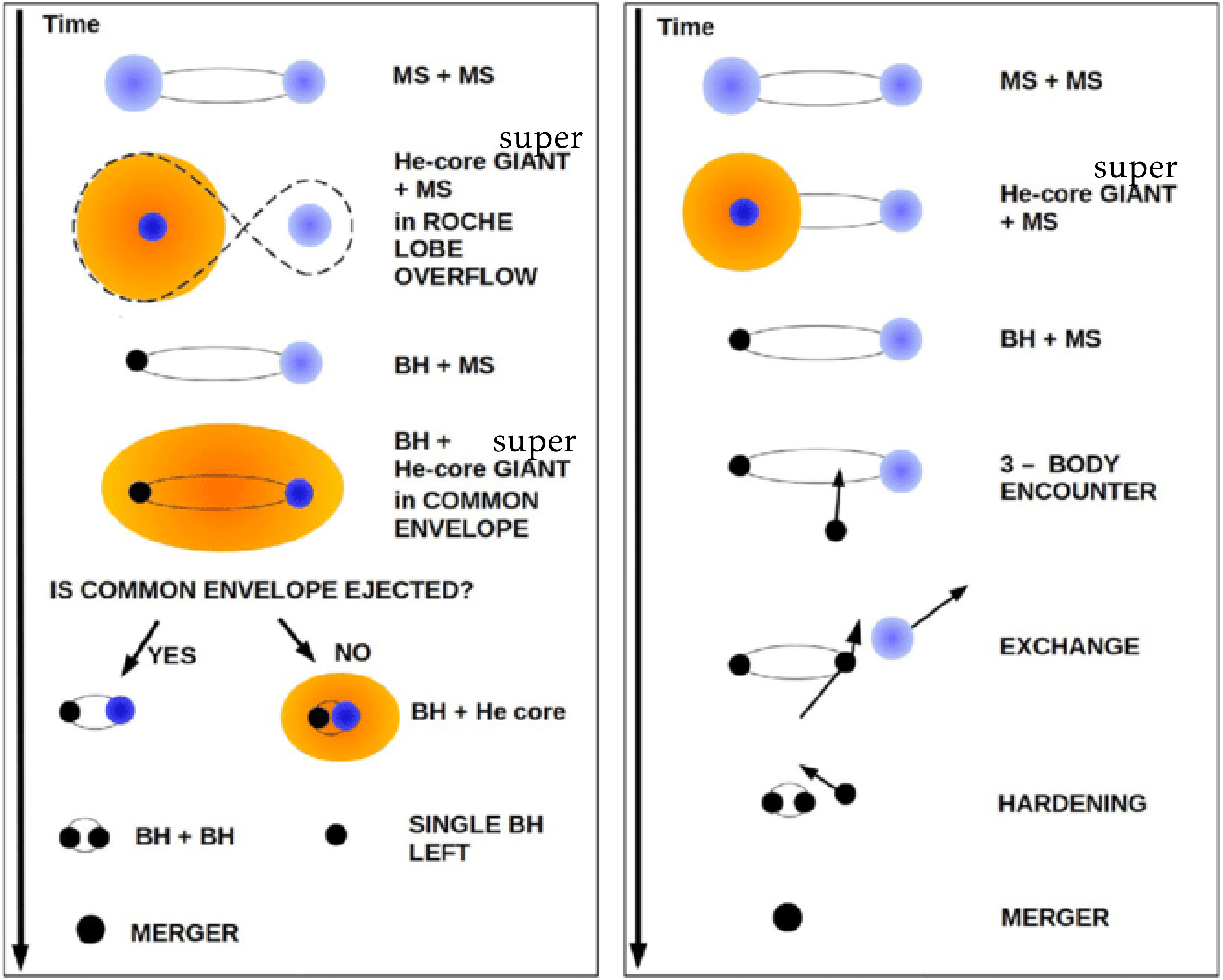
Stripped = type Ib
Ultra-stripped = type Ic

(Pulsar: a rotating, magnetized neutron star

GRAV. WAVES!!!

Credit: Kruckow+18

Some other scenarios...

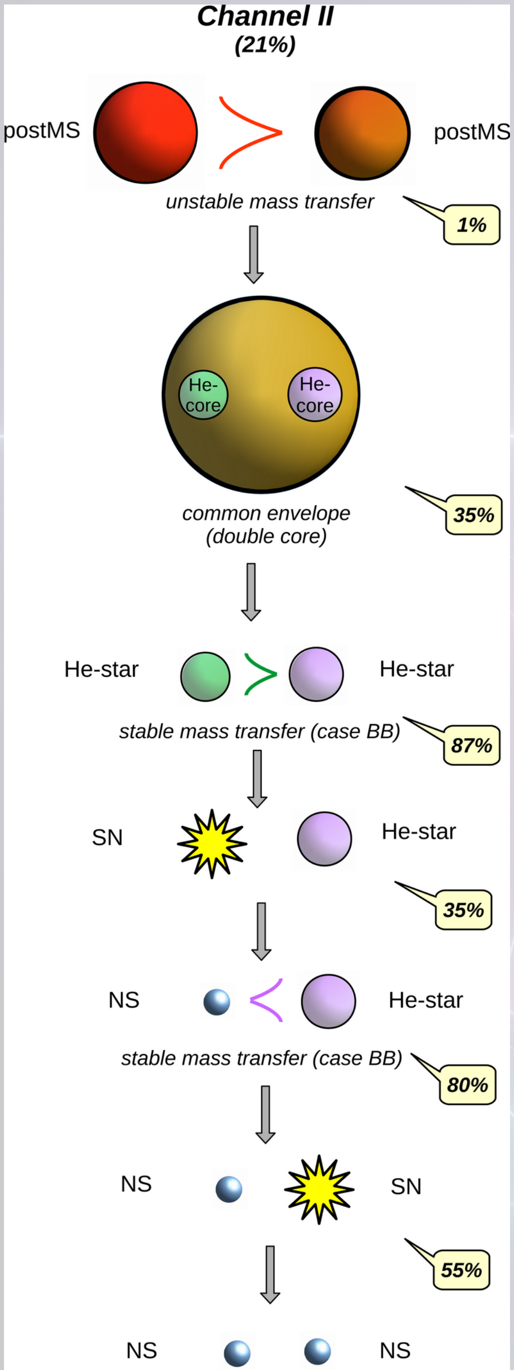


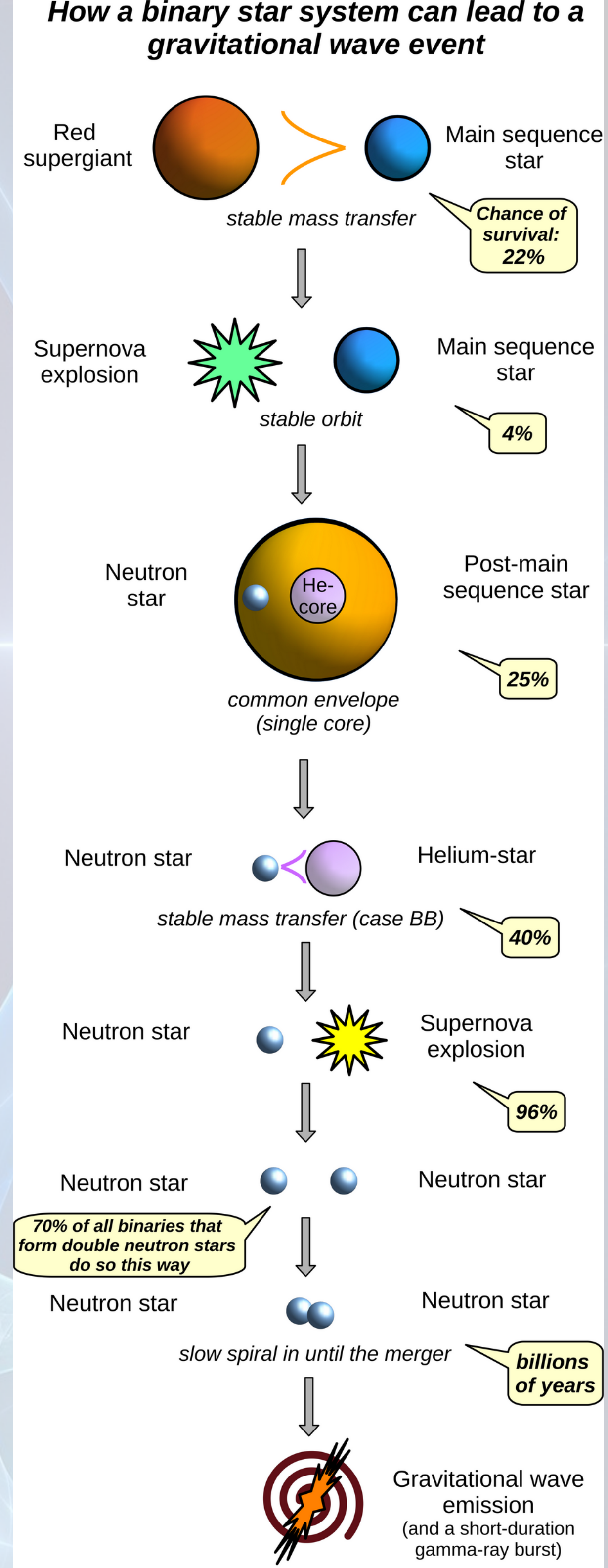
a triple!

= orbit shrinks

Credit: Mapelli'21

There are more... :D



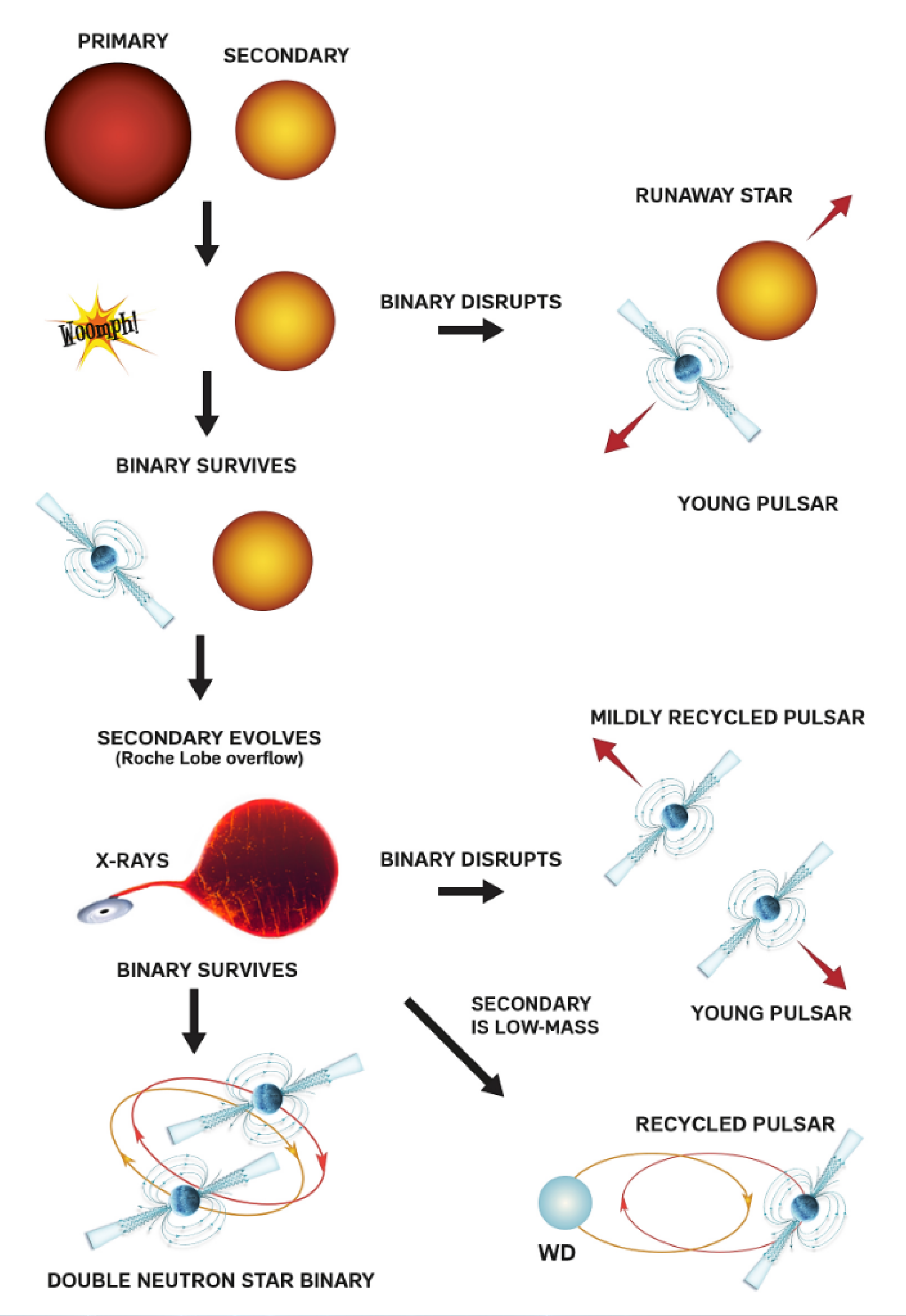


Credit: Vigna-Gomez+18

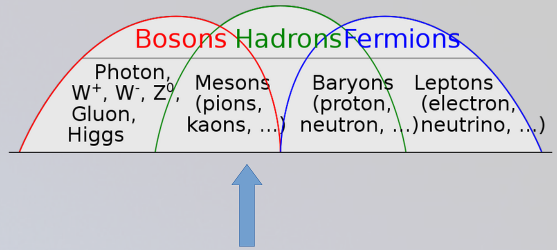
And even more…

This one makes it clear that there are various outcomes based on the SN kick.

Credit: Alice Froll



Degeneracy

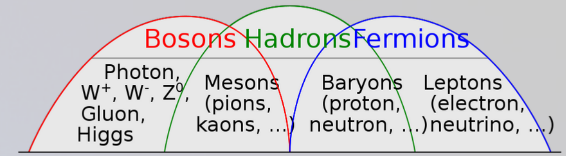


remember: γ is a boson

- Imagine: plasma (of fermions, i.e.: e^-,p^+,n^0…)
  - at normal densities: thermal pressure (ideal gas)
  - let's cool it and compress it repeatedly!
  - at some point, ***Pauli exclusion principle*** turns on
    - forbids the fermions to occupy identical quantum states
    - thus, if they are forced closer, they must be be placed at different energy levels → extra pressure (a ***very*** strong one)
- can happen to: only e^- (=WD) **or** p^+&n^0&e^- (=NS)

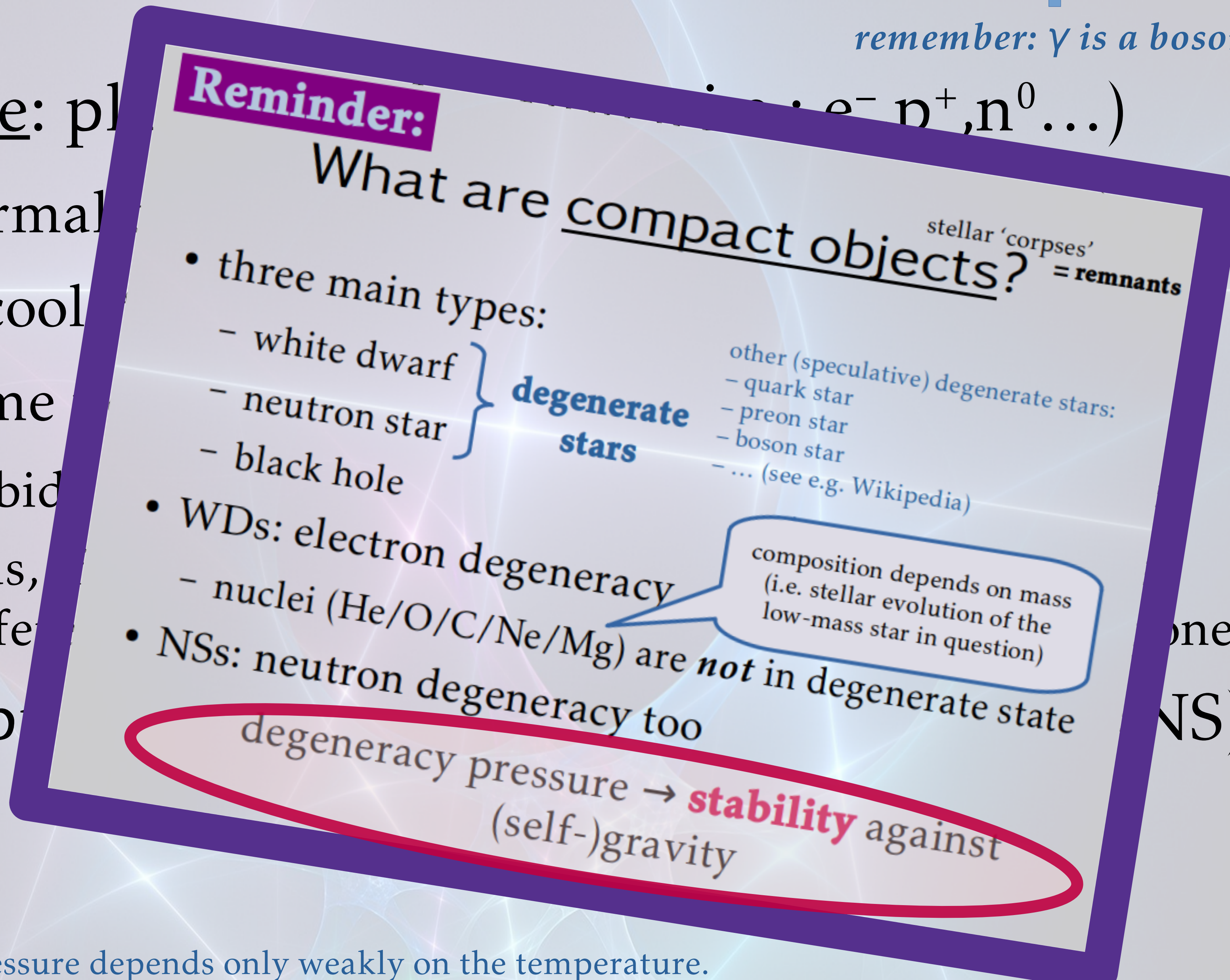
Funfact: degeneracy pressure depends only weakly on the temperature.
Increasing the temperature of degenerate stars has a minor effect on the structure.

Degeneracy



remember: γ is a boson

- Imagine: pl … e^-, p^+, n^0 …)
  - at normal
  - let's cool
  - at some
    - forbid
    - thus, … diffe … one)
- can hap … NS)



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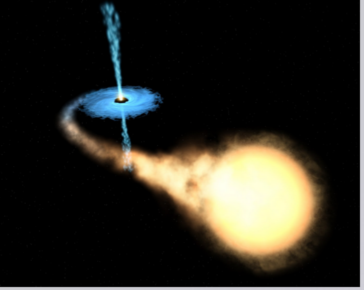


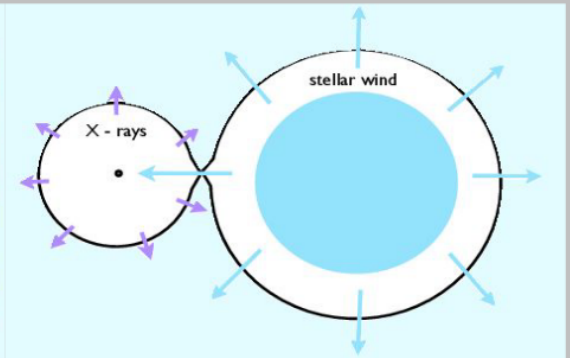
HMXB = High-mass X-ray binary

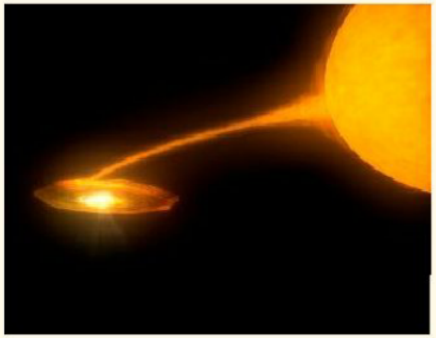
Observed:
~ 200 LMXB in the MW
some more in other gals.
> 100 HMXB in MW
e.g. ***Cygnus X-1***

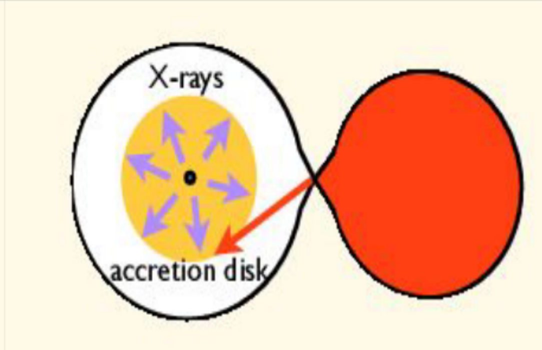
- sister object: LMXB = Low-mass X-ray binary
- X-rays are produced by the matter falling from the (stellar) companion to the NS or BH
  - if the companion is a low-mass star (or a WD): LMXB
  - if it's a massive star: HMXB
- Massive stars have strong winds! It contributes.

periodic X-ray pulses

HMXB's | **LMXB's**







Microquasars

- basically HMXBs which also emit in radio
  - the source of the radio emission is two jets* (*see next slide)
  - Cygnus-X1 is also a microquasar

- name comes from 'quasars' also known as 'quasi-stellar object" (QSO) – discovered in the 50s as radio sources of unknown origin
  - ***galaxies where the central BH eats up the stars…***
  - → active galactic nucleus (AGN)
  - powered by a ***supermassive*** BH ($\gtrsim 10^6$–10^9 $M_\odot$)
    (as opposed to a ***stellar mass*** BH as in a HMXB/microquasar)
  - **THIS WEEK'S MOST EXCITING NEWS!!**
    Capturing our MW's central BH by the "Event Horizon Telescope" (not a real telescope; but a collaboration of radio observatories & clevera data reduction techniques :D)

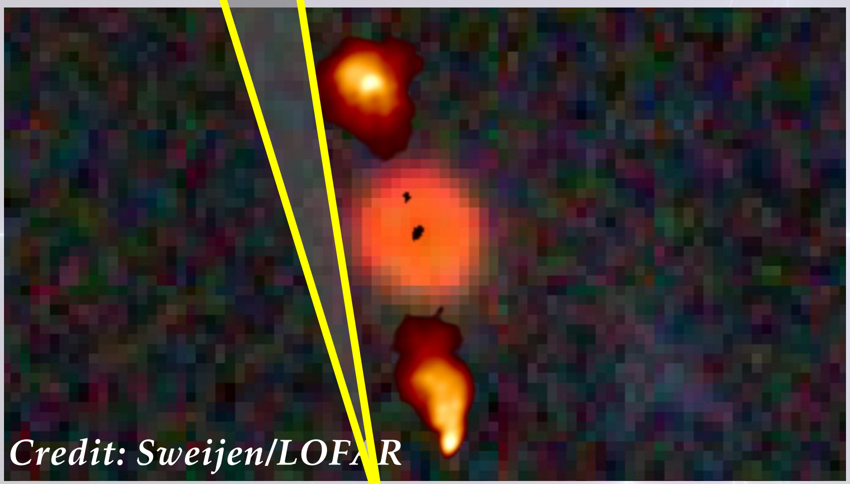
Sgr A*
4x10^6 $M_\odot$

not a very active nucleus (fortunately)

Jets (in astronomy)

And also microquasars, of course.

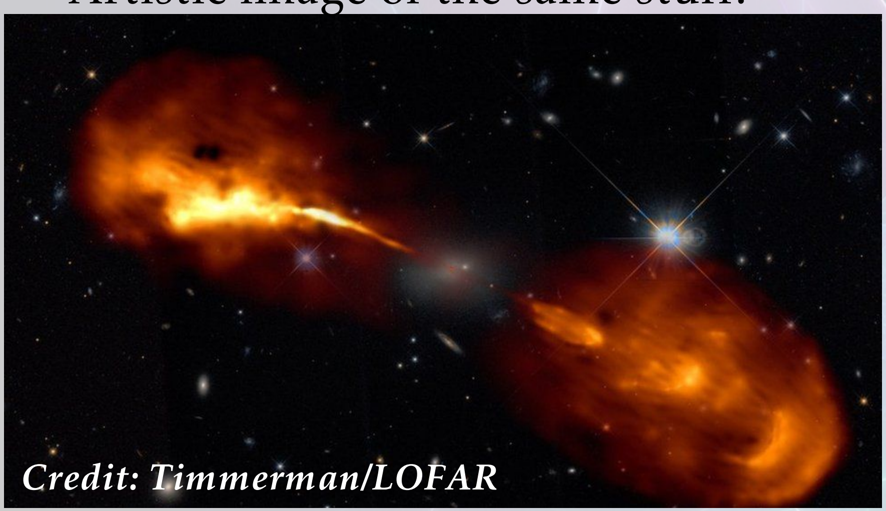
Actual observation (2021, LOFAR):



Credit: Sweijen/LOFAR

AGNs

Artistic image of the same stuff:



Credit: Timmerman/LOFAR

??

spectral features (breaking)
high energies cannot be explained otherwise

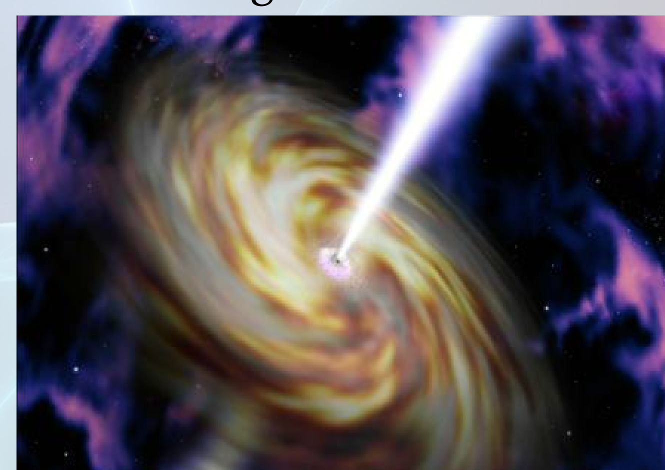
short-living

long-living

(timescales are proportional to the mass of the central BH)

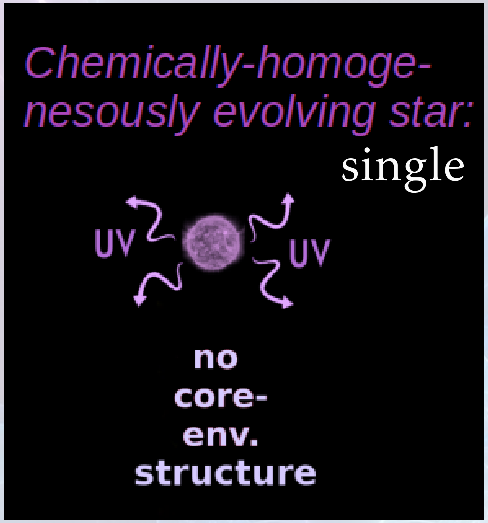
GRBs

Artistic image:



→ sub-Solar metallicities? ✓
→ fast-rotating stars? ✓
→ stars in a binary system? ✓

What about a metal-poor, fast rotating binary system?



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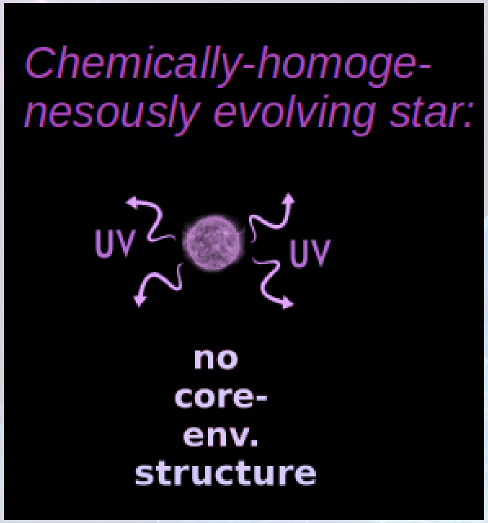
What about a metal-poor, fast rotating binary system?

Let's put two of them next to each other on a (very) close orbit!



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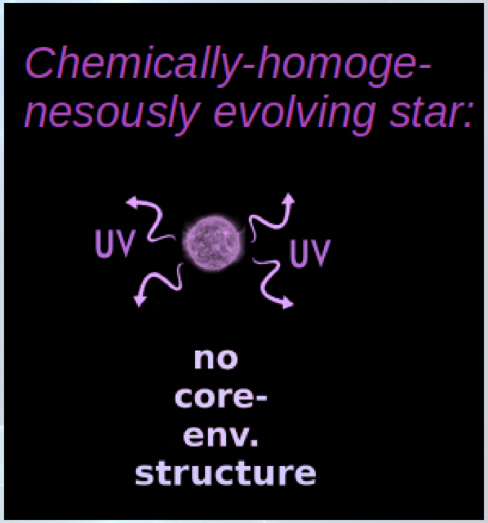
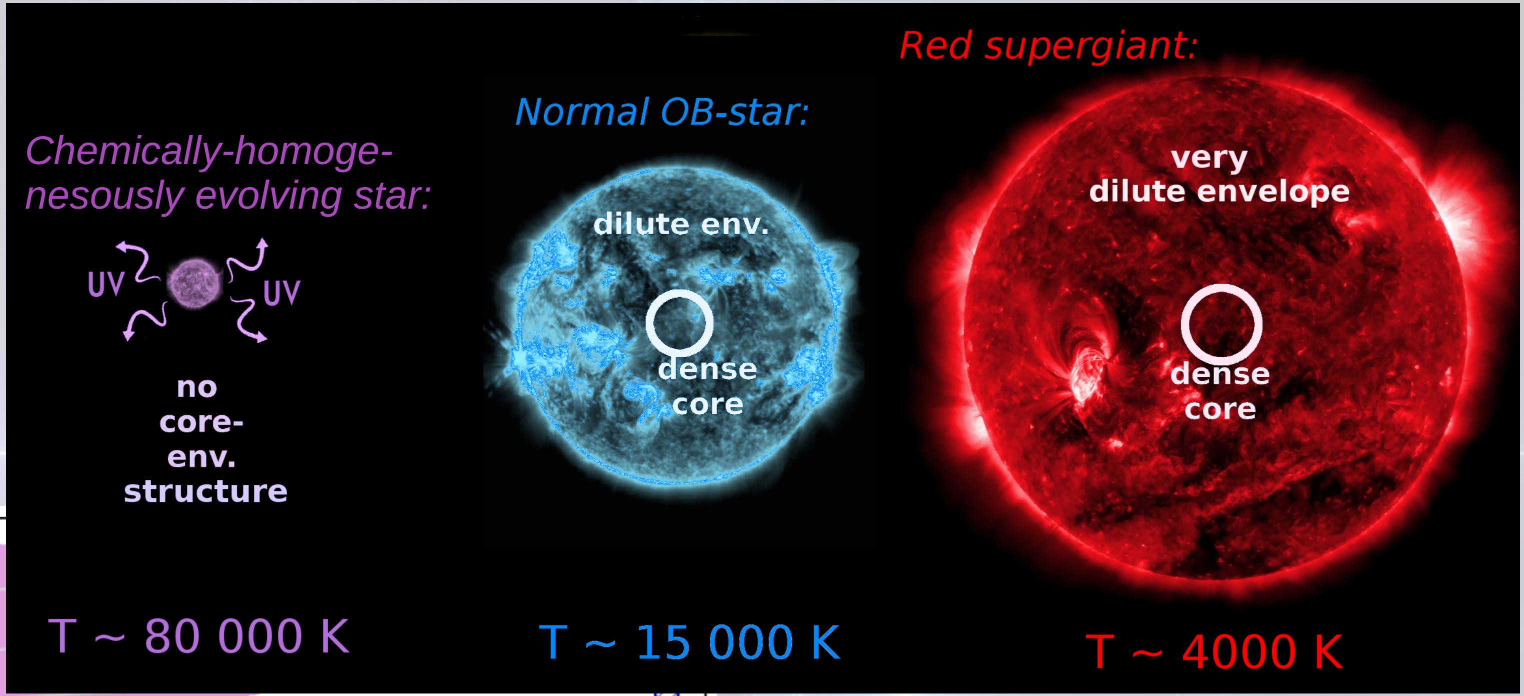
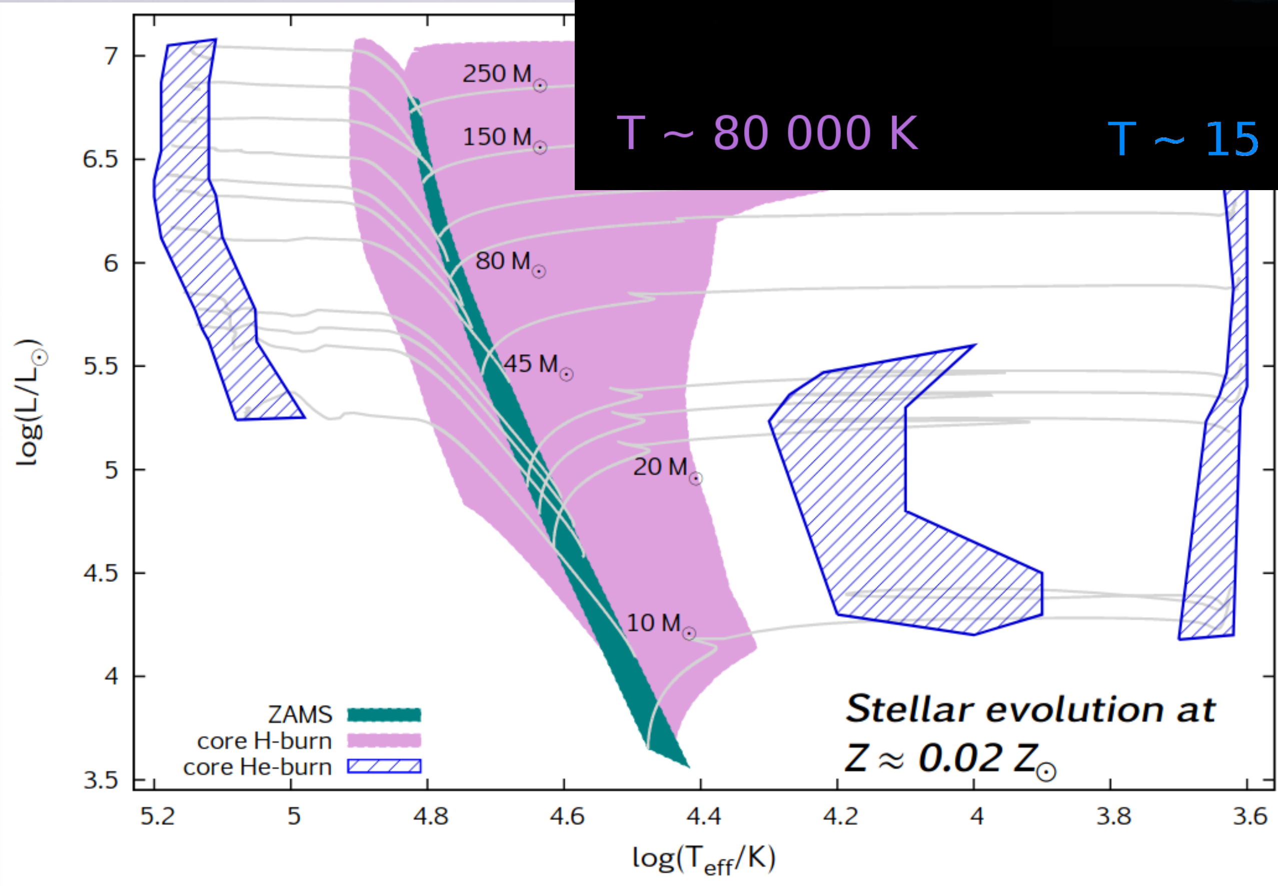
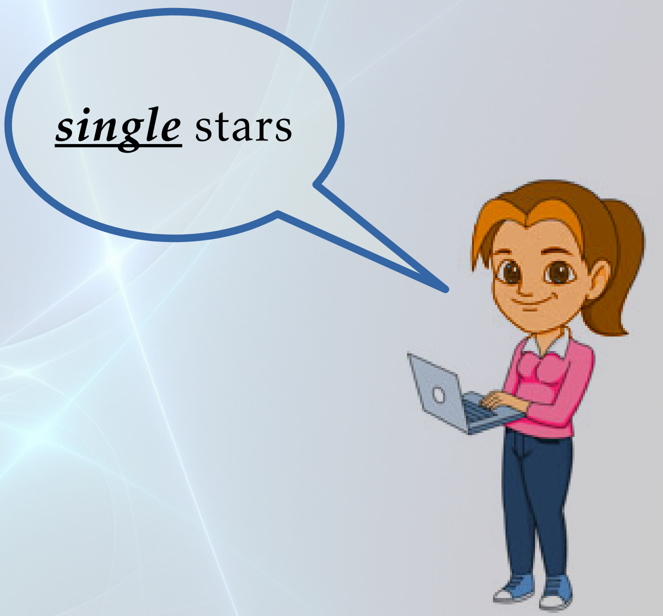


= ?

What do chem.hom. evolving stars look like?







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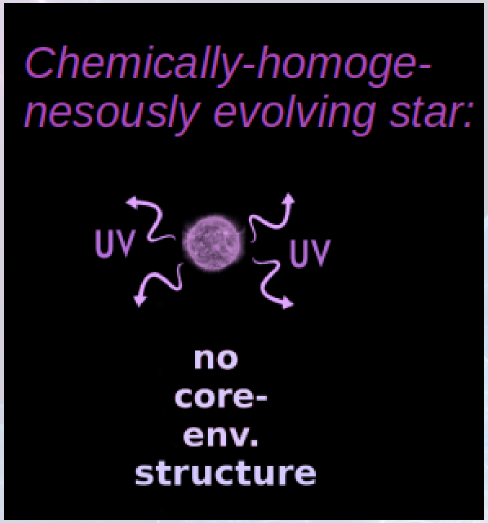

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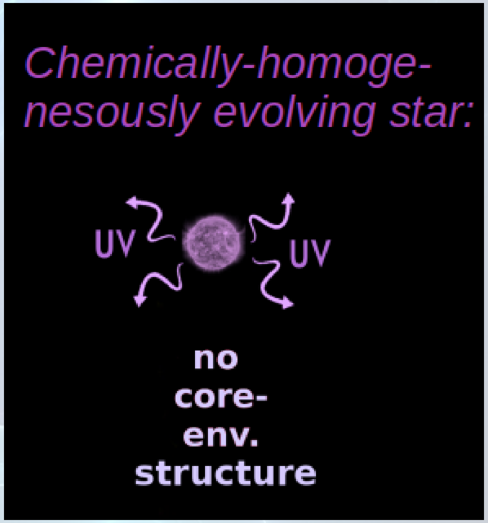
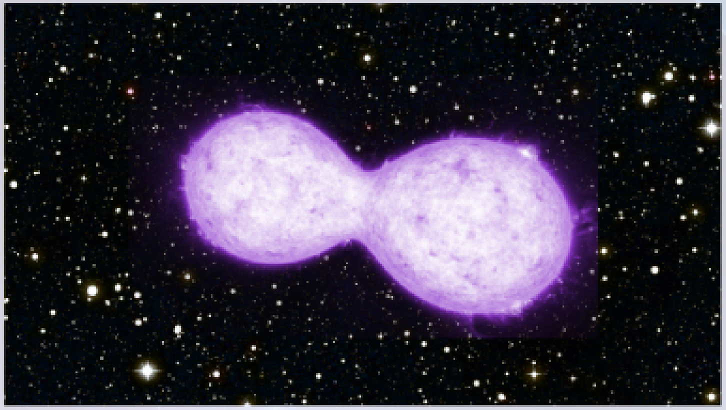


= ?

Gravitational waves... theoretical origin!



e.g. **Szécsi**'17a

Szécsi'17b

Bagoly,**Szécsi**+16

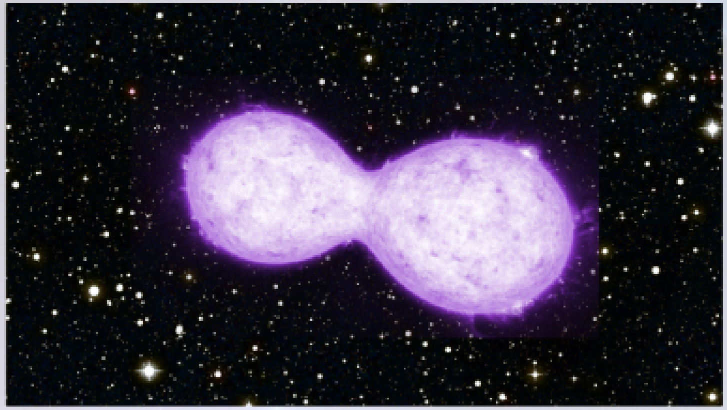
Marchant+16,17

Gravitational waves... theoretical origin!

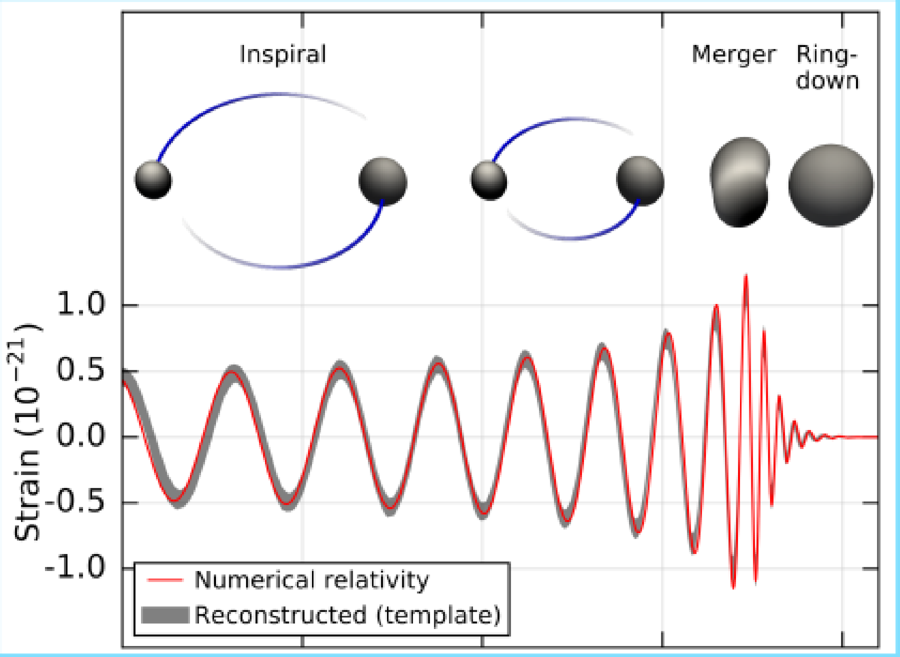
Life — Massive binaries

Death — Explosions

Afterlife — 2 Black Holes (or Neutron Stars)



'Second death' — **Merger**



Credit: http://gallatin.physics.lsa.umich.edu

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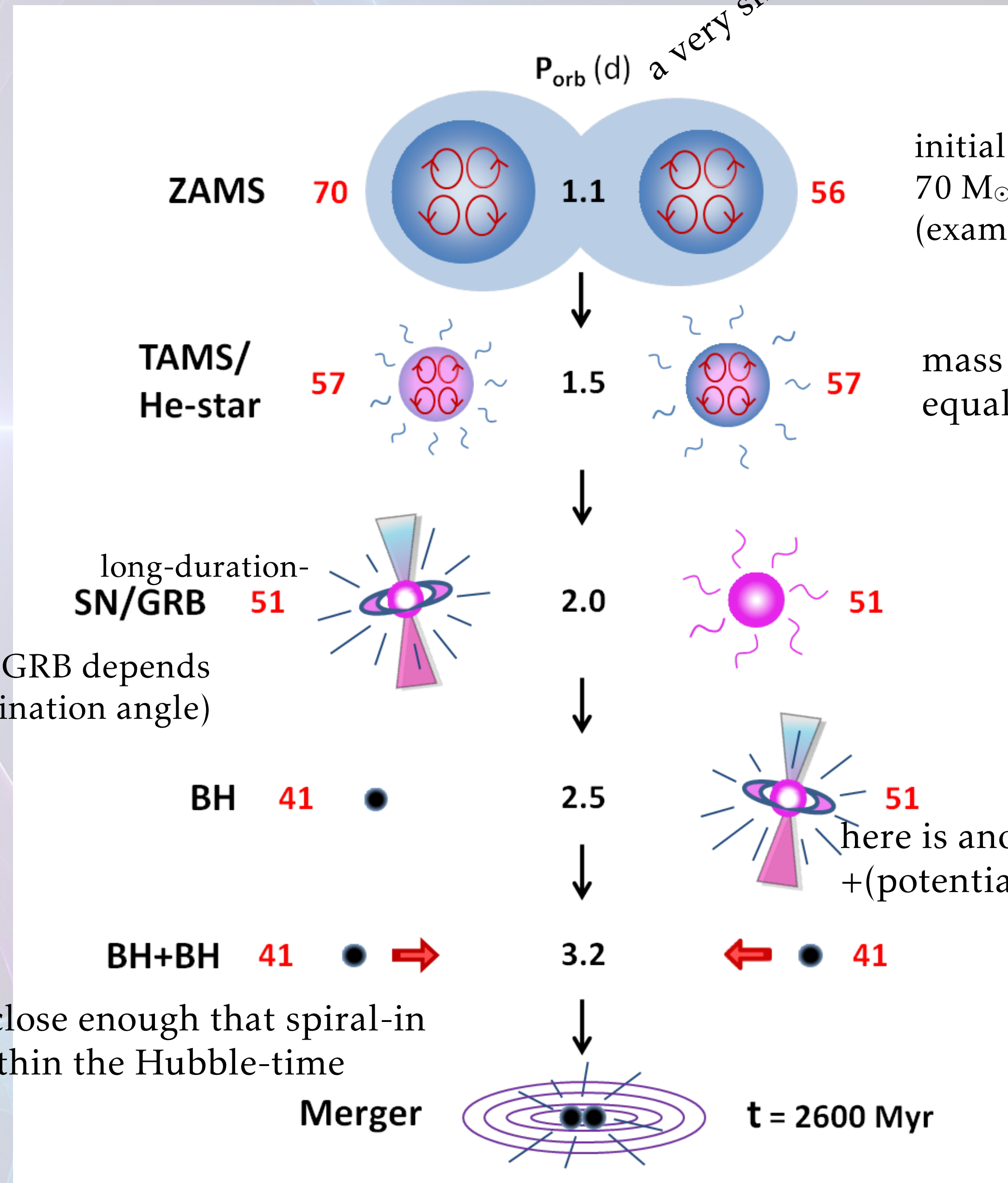
Bagoly,Szécsi+16

Marchant+16,17

To “cartoonize” the scenario:



a very short orb.period!

initial masses
70 M☉ + 56 M☉
(example)

mass ratio (*q*) equalizes

long-duration-

(seeing the L-GRB depends on the inclination angle)

Remember: to see a GRB, we need to look right into the jet!

here is another SN +(potential) L-GRB

system is still close enough that spiral-in can happen within the Hubble-time

Credit: Marchant+16

Possible exam question ;)

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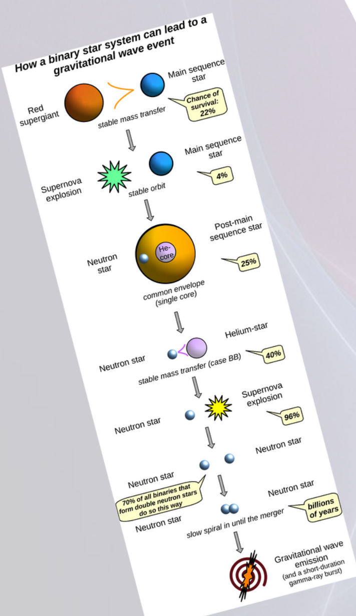
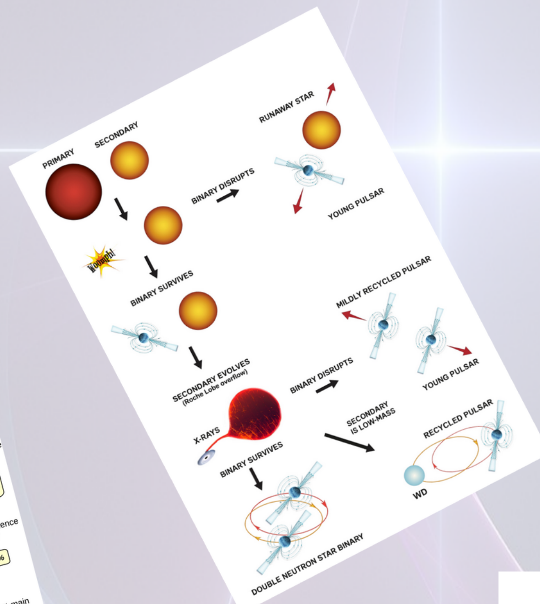
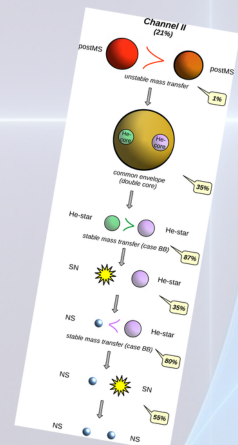
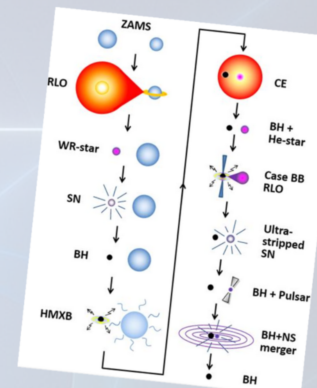
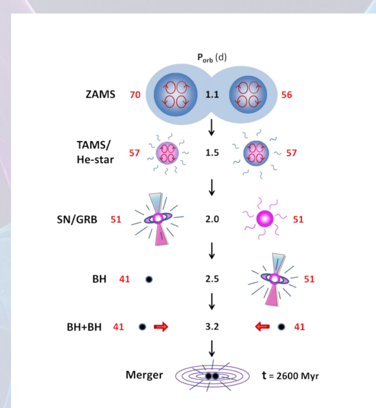
- explain a binary evolution cartoon scientifically!

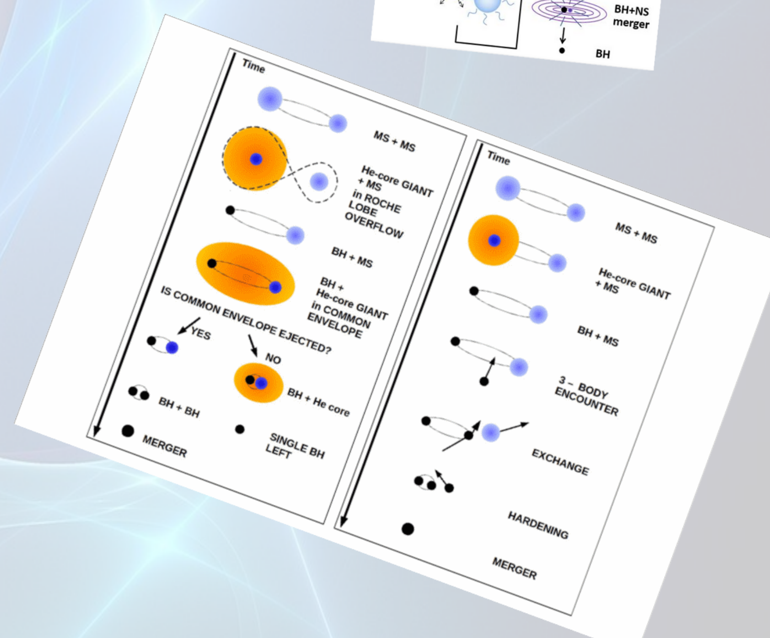












Today…

Population synthesis on ***binaries***

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- **NOT** the same thing as binary evolutionary simulations

meaning: 'detailed' evolutionary computations e.g. with MESA

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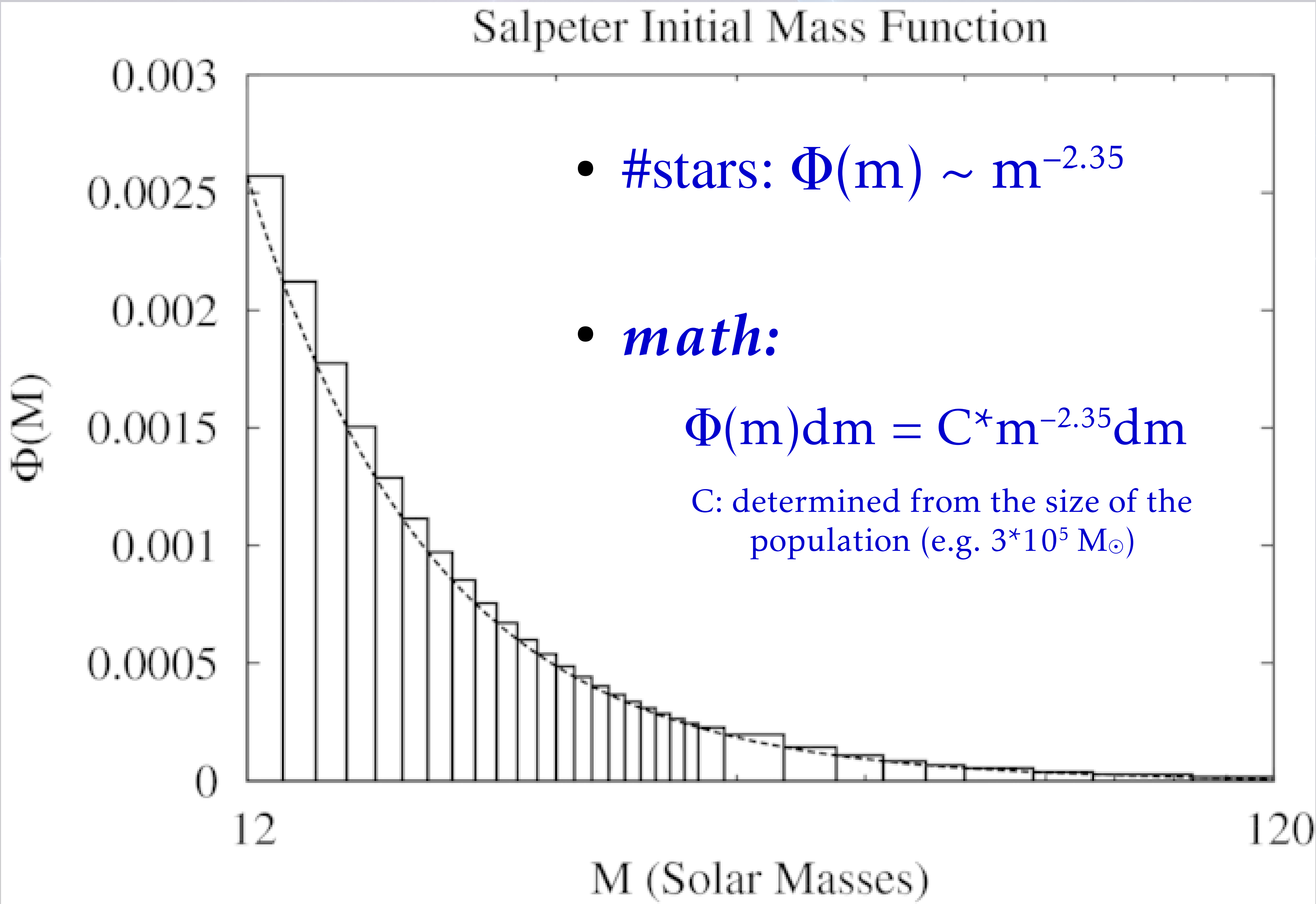
Remember the Initial Mass Function (IMF)?

Pop.synth. starts with that.

But binaries make life complicated.

REMINDER: The Initial Mass Function (IMF)

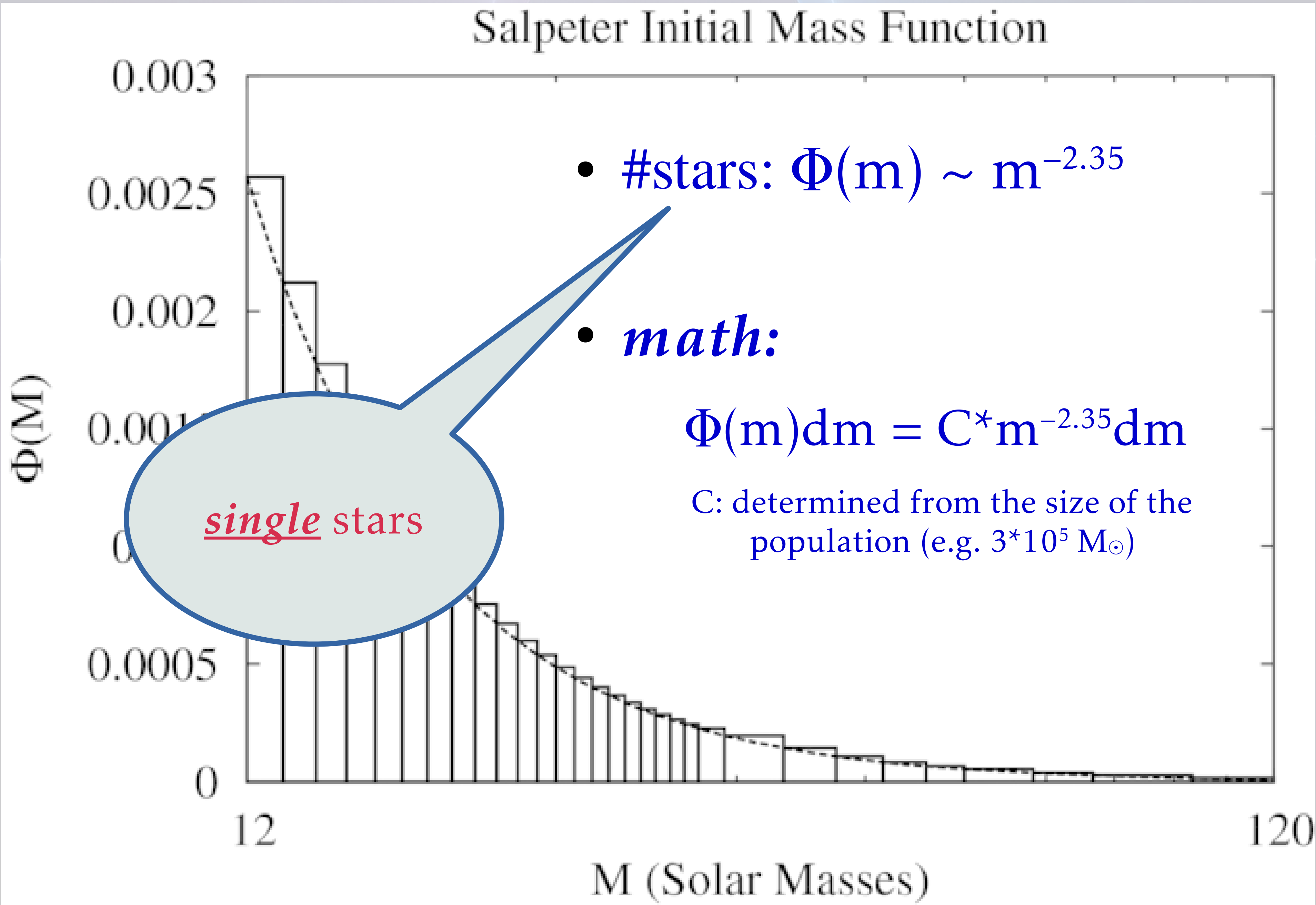


- #stars: $\Phi(m) \sim m^{-2.35}$
- ***math:***

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

C: determined from the size of the population (e.g. $3^{*}10^{5}\ M_{\odot}$)

REMINDER: The Initial Mass Function (IMF)



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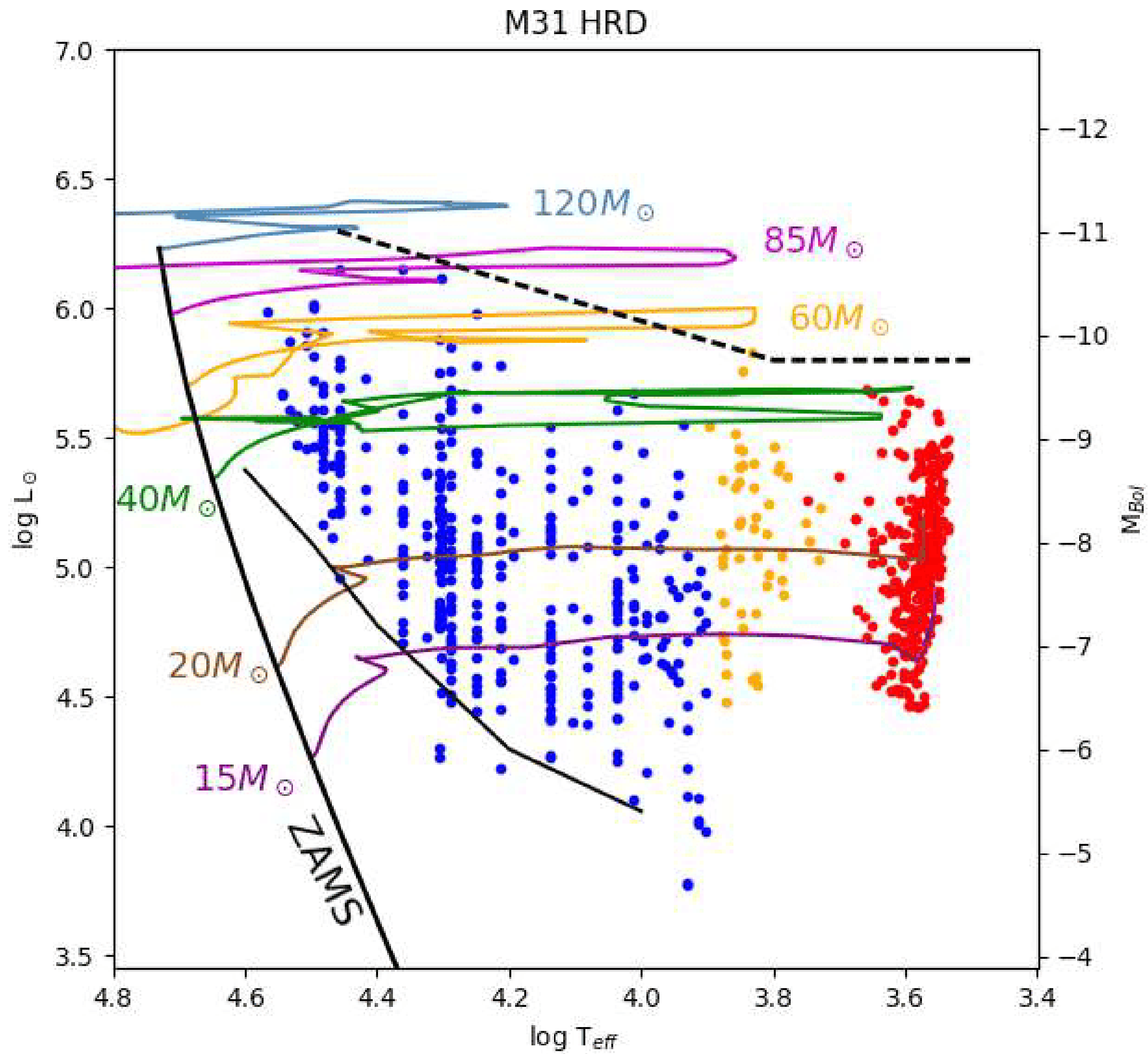
- ***math:***

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

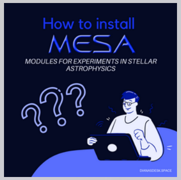
C: determined from the size of the population (e.g. $3{*}10^5\ M_\odot$)

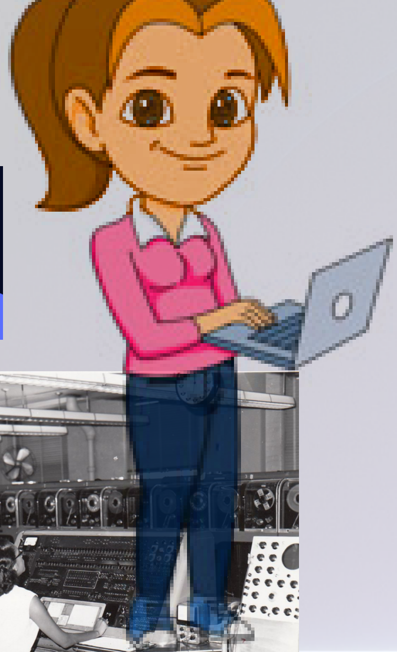
(*single* stars)

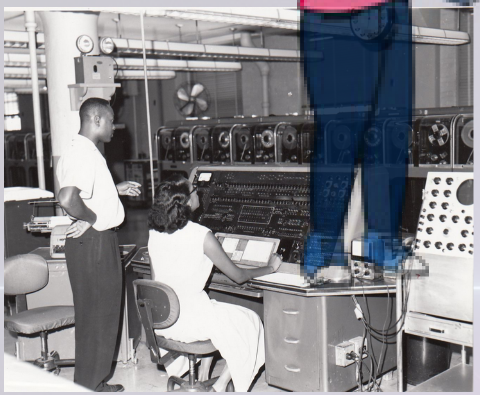
Let's think!



- How would you "convert" between the lines and the dots?
- ***Meaning***:
  - how would you compare theoretical predictions with observations?







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# MESA revision number =     11701
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#  Yinit        Zinit    [Fe/H]    [a/Fe]  v/vcrit
# 0.2511  1.42857E-03    -1.00     0.00     0.00
# --------------------------------------------------------------------------------------
#     initial_mass   N_pts   N_EEP   N_col   phase        type
# 1.9999727046E+01     808       8      73     YES   high-mass
# EEPs:        1     202     353     454     605     631     707     808
# --------------------------------------------------------------------------------------
#                              1                                2                                3                                4                                5
#                        star_age                        star_mass                        star_mdot                           log_dt                     he_core_mass
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         2.7345019073205121E+005          1.9999725407394834E+001         -6.6668930715861210E-009          4.6125719424045064E+000          0.0000000000000000E+000
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         2.7393906051027833E+005          1.9999722130658245E+001         -6.6672509184882791E-009          4.6133598154995070E+000          0.0000000000000000E+000
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         2.7442793028850551E+005          1.9999718853921653E+001         -6.6676087653904380E-009          4.6141476885945094E+000          0.0000000000000000E+000
         2.7467236517761904E+005          1.9999717215553360E+001         -6.6677876888415162E-009          4.6145416251420093E+000          0.0000000000000000E+000
         2.7491680006673269E+005          1.9999715577185061E+001         -6.6679666122925961E-009          4.6149355616895100E+000          0.0000000000000000E+000
         2.7516123495584622E+005          1.9999713938816765E+001         -6.6681455357436759E-009          4.6153294982370108E+000          0.0000000000000000E+000
         2.7540566984495980E+005          1.9999712300448472E+001         -6.6683244591947550E-009          4.6157234347845106E+000          0.0000000000000000E+000
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         2.7589453962318692E+005          1.9999709023711880E+001         -6.6686823060969130E-009          4.6165113078795130E+000          0.0000000000000000E+000
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         2.7687227917964122E+005          1.9999702470238695E+001         -6.6693979999012308E-009          4.6180870540695151E+000          0.0000000000000000E+000
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         2.7760558384698193E+005          1.9999697555133814E+001         -6.6699347702544679E-009          4.6192688637120174E+000          0.0000000000000000E+000
         2.7785001873609552E+005          1.9999695916765514E+001         -6.6701136937055478E-009          4.6196628002595173E+000          0.0000000000000000E+000
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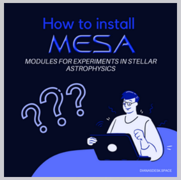
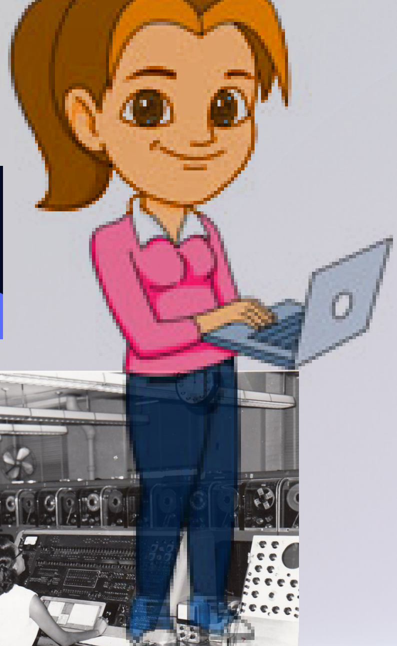
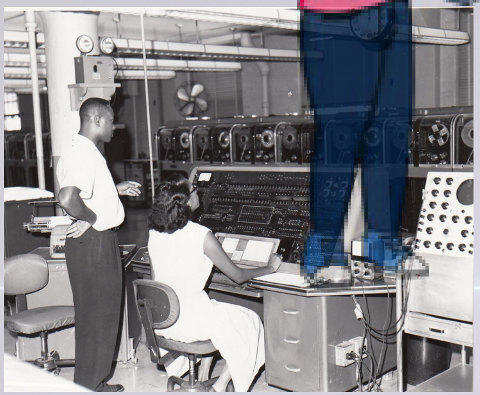
Age, Mass, Radius, T_{eff} [K], $\log(L/L_{\odot})$, Massloss rate…







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#                 star_age                 star_mass                 star_mdot                    log_dt              he_core_mass
         2.7320575584293762E+005   1.9999727045763130E+001  -6.6667141481350412E-009   4.6121780058570057E+000   0.0000000000000000E+000
         2.7345019073205121E+005   1.9999725407394834E+001  -6.6668930715861210E-009   4.6125719424045064E+000   0.0000000000000000E+000
         2.7369462562116480E+005   1.9999723769026541E+001  -6.6670719950372001E-009   4.6129658789520063E+000   0.0000000000000000E+000
         2.7393906051027833E+005   1.9999722130658245E+001  -6.6672509184882791E-009   4.6133598154995070E+000   0.0000000000000000E+000
         2.7418349539939192E+005   1.9999720492289949E+001  -6.6674298419393581E-009   4.6137537520470087E+000   0.0000000000000000E+000
         2.7442793028850551E+005   1.9999718853921653E+001  -6.6676087653904380E-009   4.6141476885945094E+000   0.0000000000000000E+000
         2.7467236517761904E+005   1.9999717215553360E+001  -6.6677876888415162E-009   4.6145416251420093E+000   0.0000000000000000E+000
         2.7491680006673269E+005   1.9999715577185061E+001  -6.6679666122925961E-009   4.6149355616895100E+000   0.0000000000000000E+000
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         2.7565010473407339E+005   1.9999710662080176E+001  -6.6685033826458340E-009   4.6161173713320123E+000   0.0000000000000000E+000
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         2.7662784429052763E+005   1.9999704108606995E+001  -6.6692190764501510E-009   4.6176931175220144E+000   0.0000000000000000E+000
         2.7687227917964122E+005   1.9999702470238695E+001  -6.6693979999012308E-009   4.6180870540695151E+000   0.0000000000000000E+000
         2.7711671406875481E+005   1.9999700831870403E+001  -6.6695769233523099E-009   4.6184809906170159E+000   0.0000000000000000E+000
         2.7736114895786840E+005   1.9999699193502106E+001  -6.6697558468033889E-009   4.6188749271645166E+000   0.0000000000000000E+000
         2.7760558384698193E+005   1.9999697555133814E+001  -6.6699347702544679E-009   4.6192688637120174E+000   0.0000000000000000E+000
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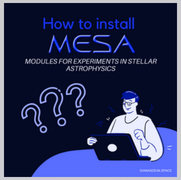

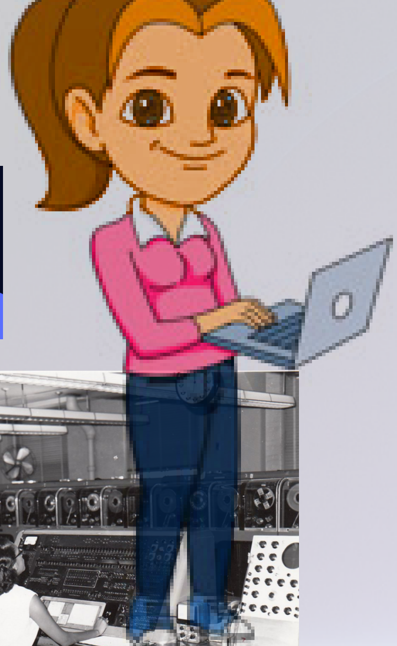

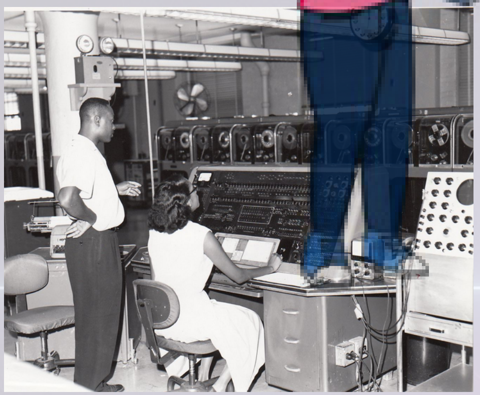

HR-diagram

Age, Mass, Radius, $\mathbf{T_{eff}}$ **[K]**, $\mathbf{log(L/L_\odot)}$, Massloss rate…

```
# MIST version number  = 10.1
# MESA revision number =    11701
# ---------------------------------------------------------------------------------------
#  Yinit        Zinit   [Fe/H]   [a/Fe]  v/vcrit
# 0.2511  1.42857E-03    -1.00     0.00     0.00
# ---------------------------------------------------------------------------------------
#     initial_mass   N_pts   N_EEP   N_col    phase        type
# 1.9999727046E+01     808       8      73      YES   high-mass
# EEPs:          1     202     353     454      605     631      707      808
# ---------------------------------------------------------------------------------------
#                               1                               2                               3                               4                               5
#                        star_age                       star_mass                       star_mdot                          log_dt                    he_core_mass
         2.7320575584293762E+005         1.9999727045763130E+001        -6.6667141481350412E-009         4.6121780058570057E+000         0.0000000000000000E+000
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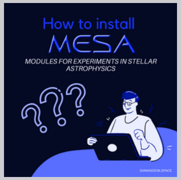

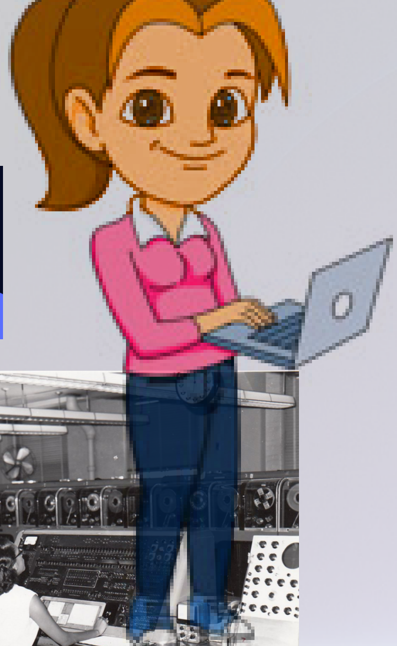

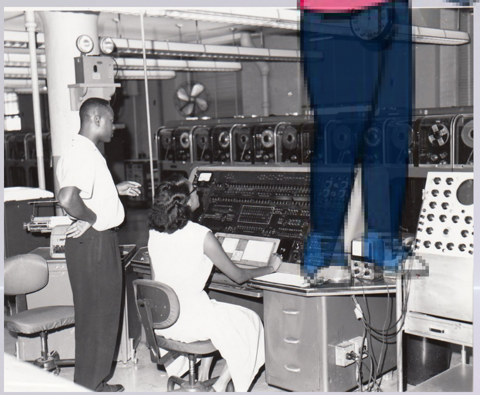

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         2.7369462562116480E+005          1.9999723769026541E+001         -6.6670719950372001E-009          4.6129658789520063E+000          0.0000000000000000E+000
         2.7393906051027833E+005          1.9999722130658245E+001         -6.6672509184882791E-009          4.6133598154995070E+000          0.0000000000000000E+000
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```

(*single* stars)

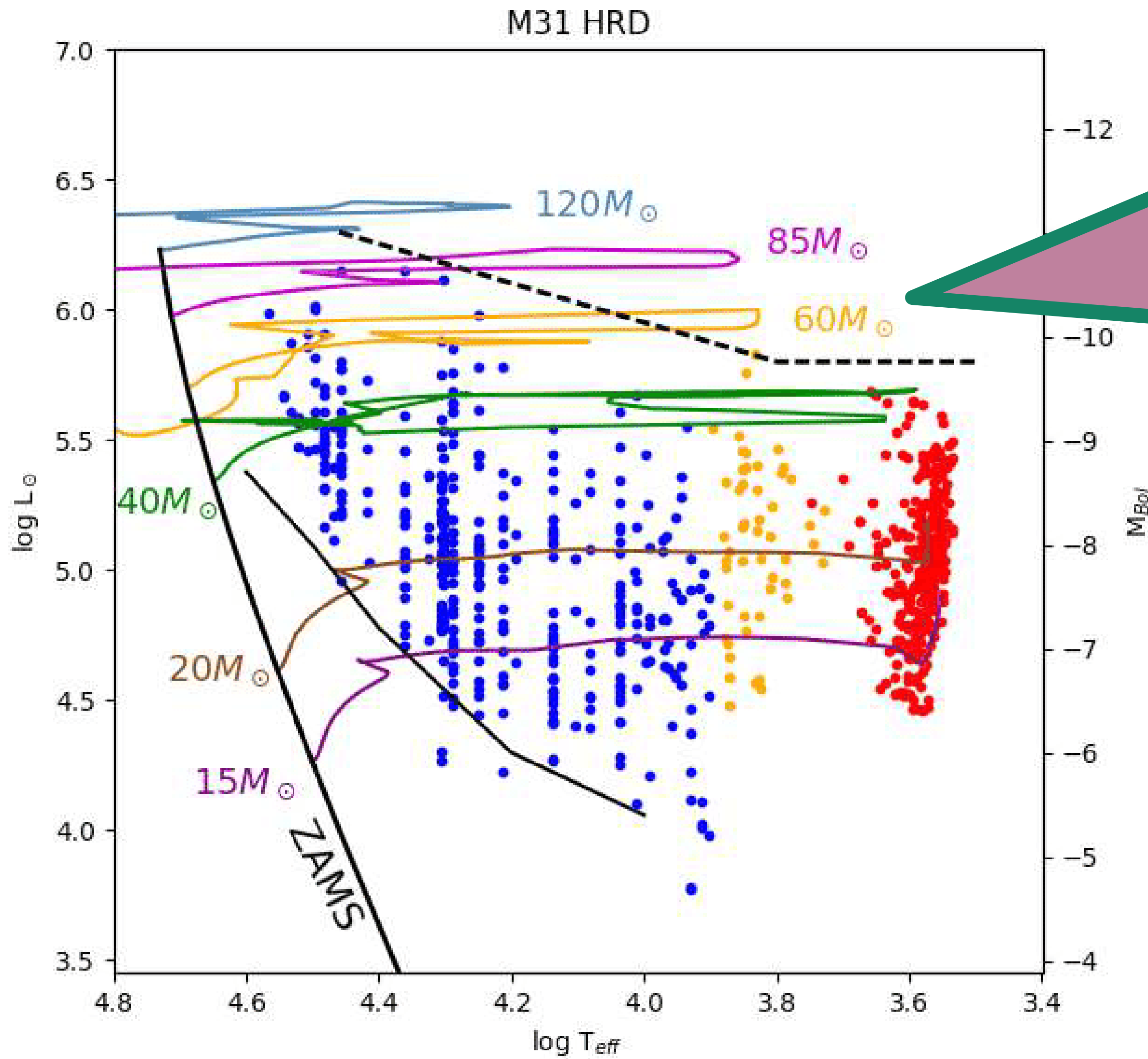
Let's think!

number ratio of MS vs. RSG stars

– pick lines according to IMF *(cf. initial mass column)*

– compute how much time they all spend as blue stars

– and how much as red stars



- ***Meaning***:
  - how would you compare theoretical predictions with observations?

(*single* stars)

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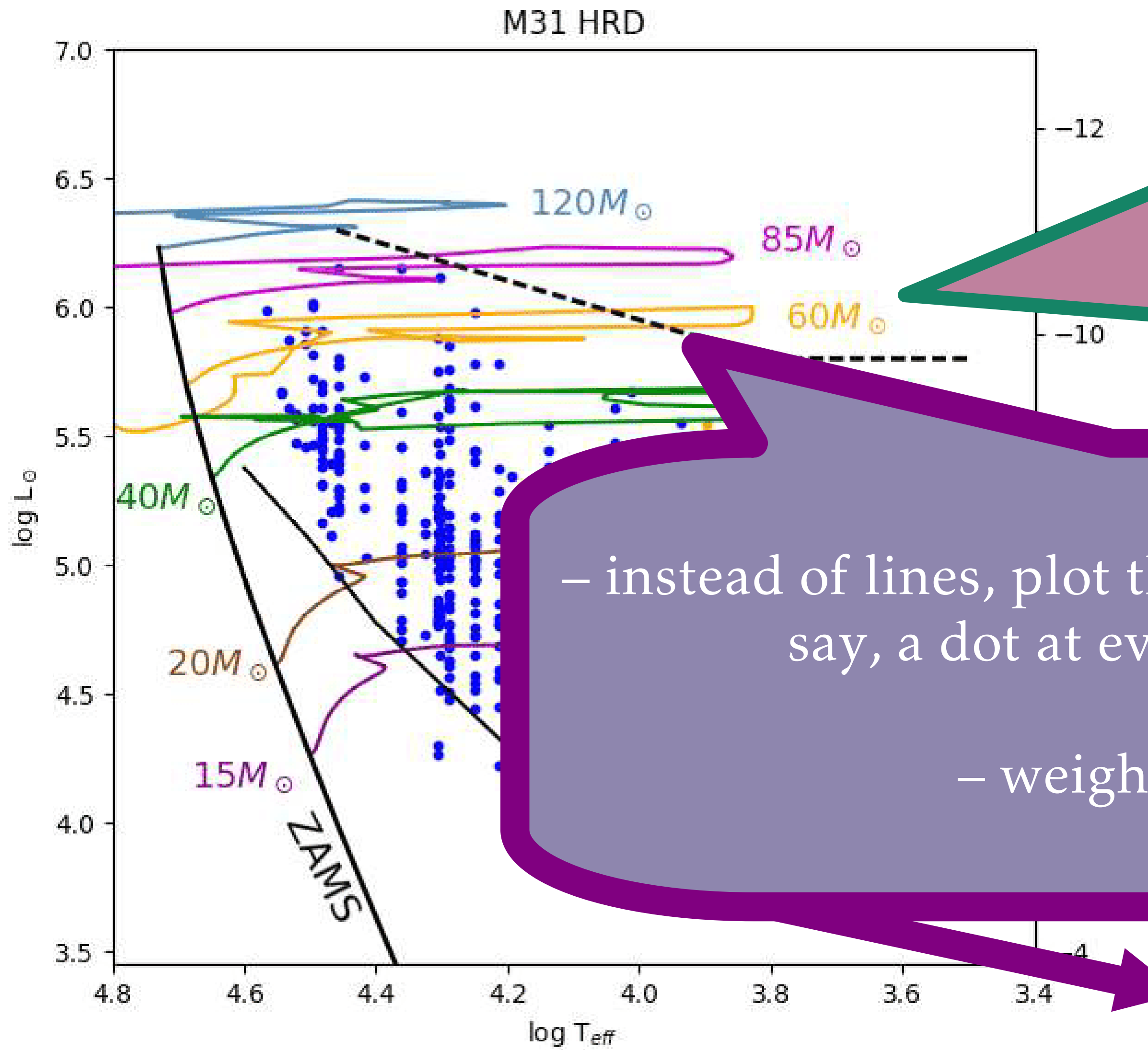
number ratio of MS vs. RSG stars



– pick lines according to IMF *(cf. initial mass column)*

– compute how much time they all spend as blue stars

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– instead of lines, plot the evolutionary tracks as dots! say, a dot at every 10 thousand year

– weight with the IMF

an actual (simulated) stellar population!

simulated = "synthetic"

IMPORTANT

- Stellar evolution modelling

- Synthetic population modelling

IMPORTANT

- Stellar evolution modelling
  - based on first principles ***(5 stellar equations)***
  - follows one star's life at the time
  - IMF is not yet considered
  - result is ***a line*** ('track') in the HR-diagram

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  - <u>***relies***</u> on stellar evolution modelling
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Exam warning! :P

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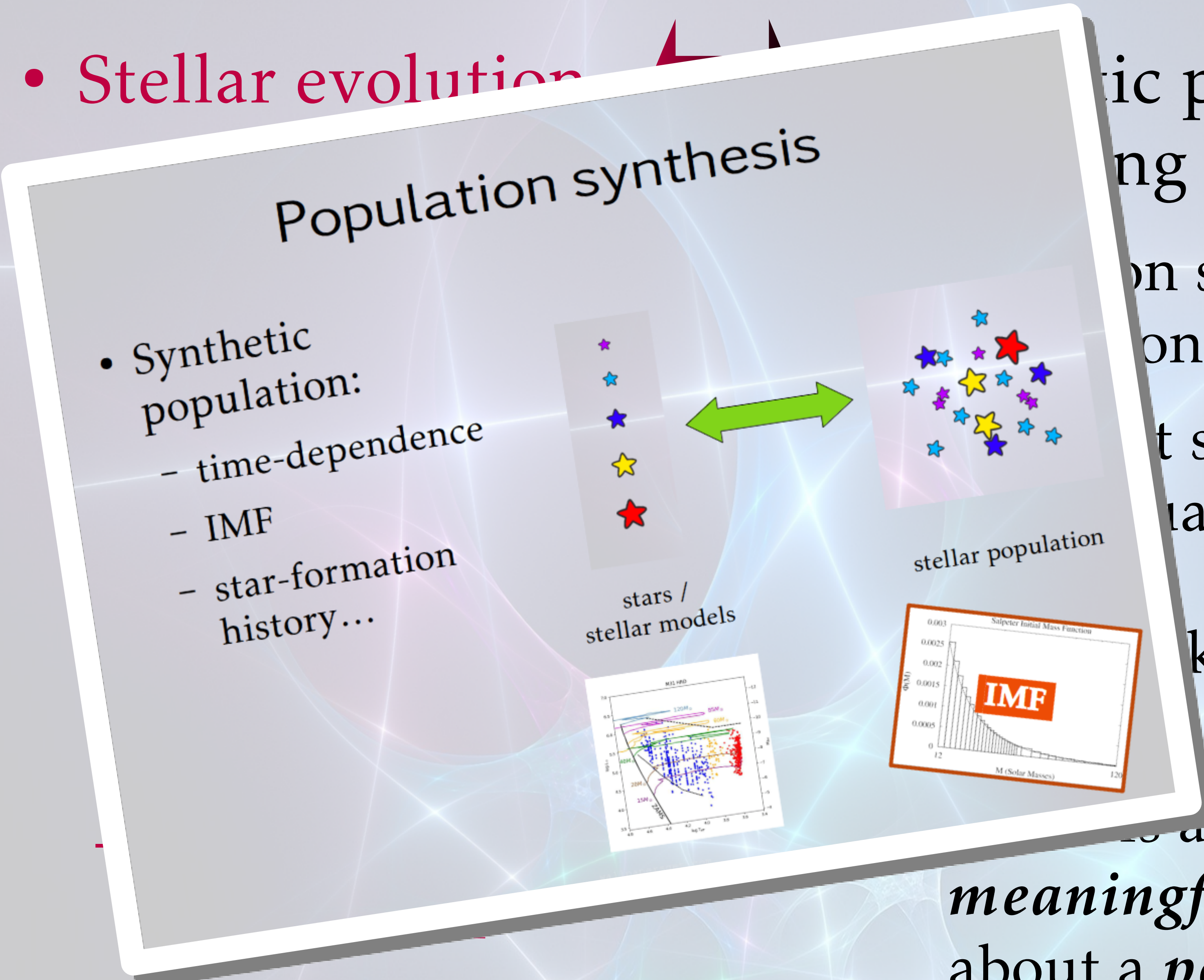


What about binaries??

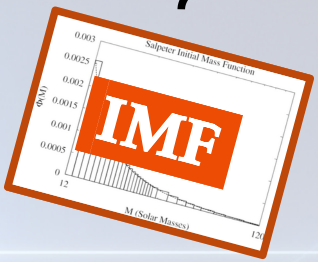
Population synthesis on ***binaries***

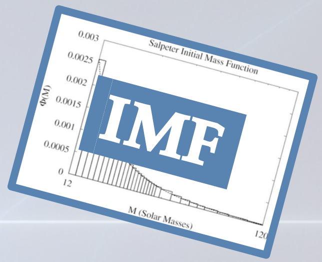
- 2 stars instead of 1

Population synthesis on ***binaries***

- 2 stars instead of 1
  - both have their individual IMFs

(related?)





Population synthesis on ***binaries***

- 2 stars instead of 1
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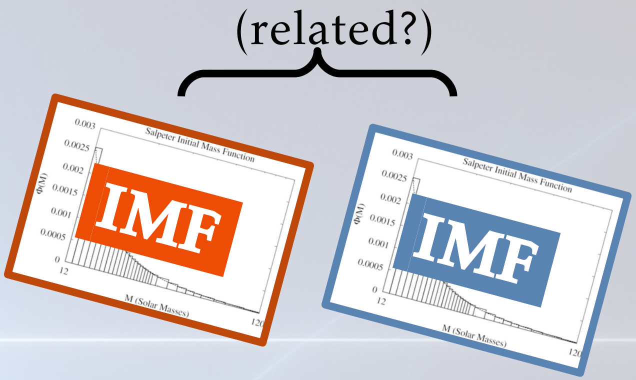
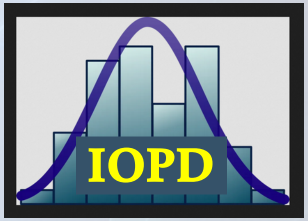
- orbital separation!
  - Initial Orbital Period Distribution
    same kind of thing as the IMF but for the period,
    i.e. an observation-based statistical distribution





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- plus a ***lot*** of assumptions about the evolution

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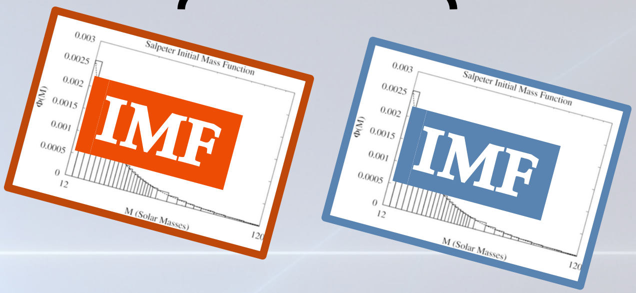

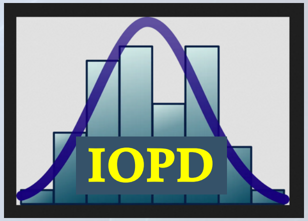

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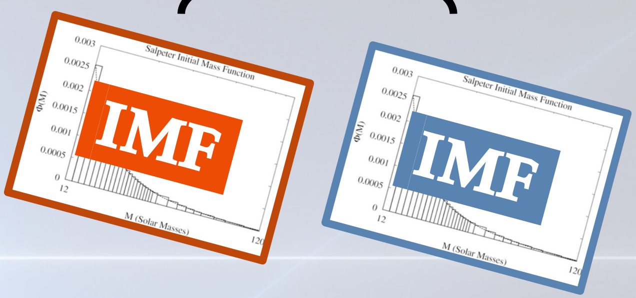

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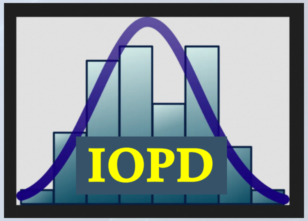

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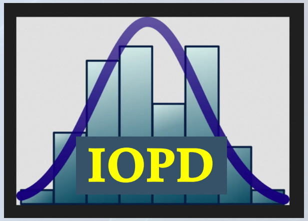

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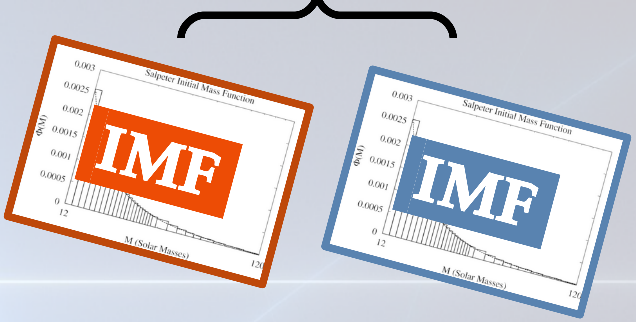

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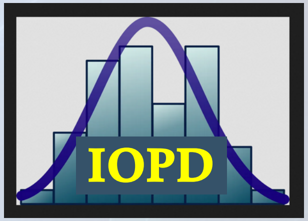

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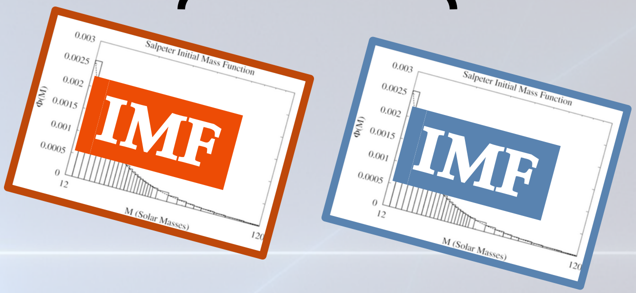
Population synthesis on ***binaries***

(related?)



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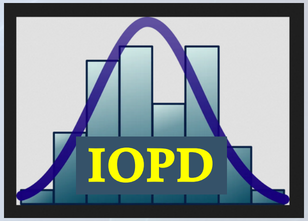

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on top of what we already don't know about ***single*** stars' evolution

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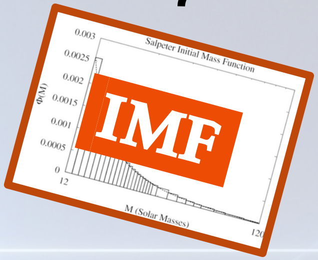
under active research

(related?)



on top of what we already don't know about *single* stars' evolution

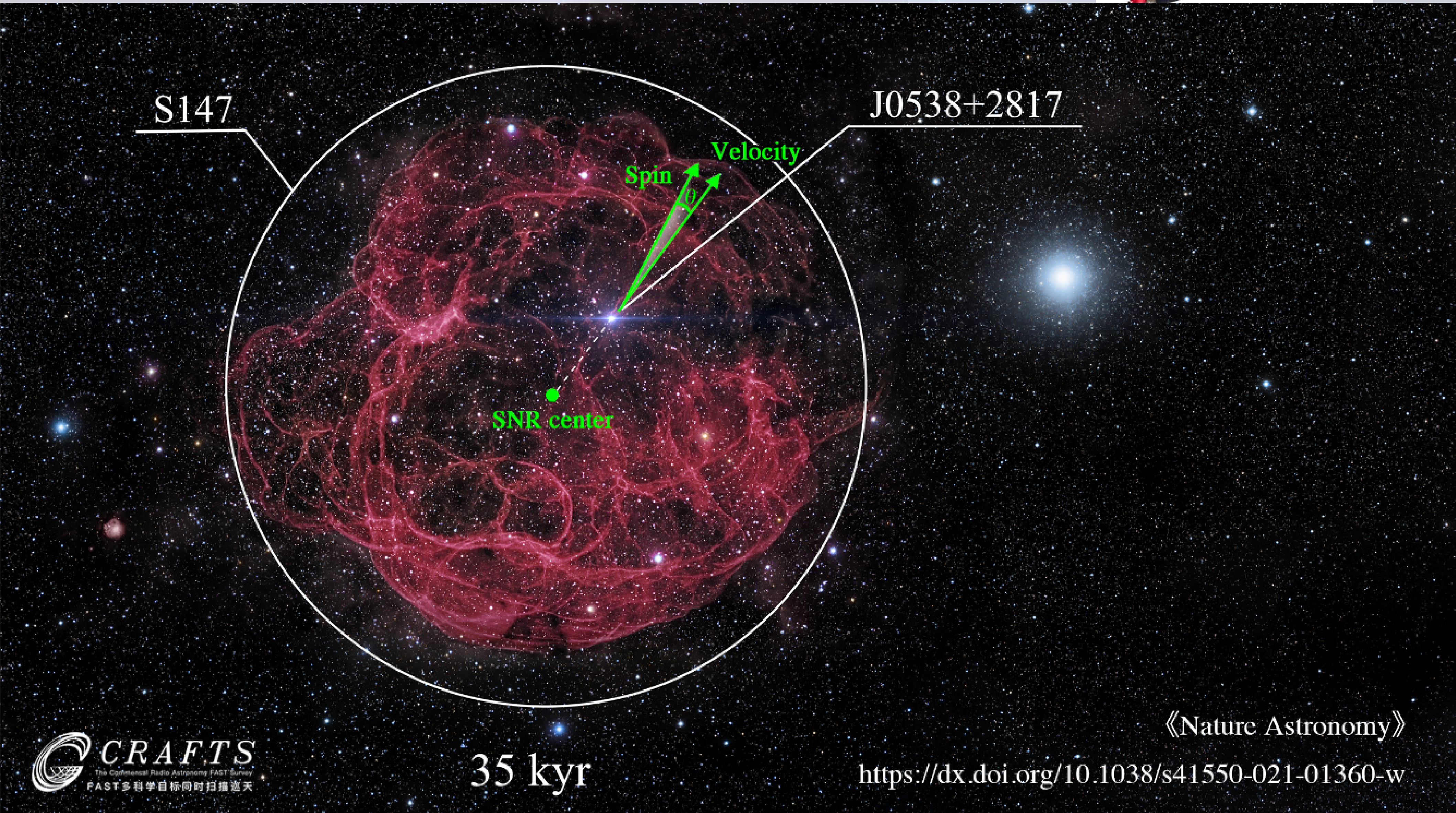
Kicks

= natal kicks

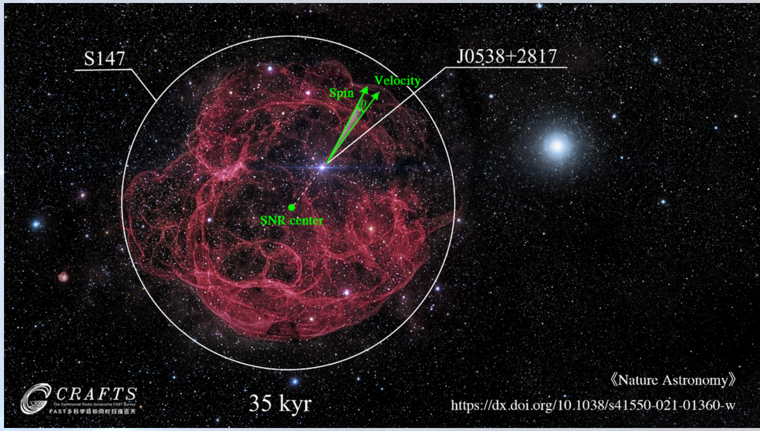
which happen when the NS is born

also see: pulsar kick, NS kick, SN kick

Kicks


S147
J0538+2817
Velocity
Spin
θ
SNR center
35 kyr
《Nature Astronomy》
https://dx.doi.org/10.1038/s41550-021-01360-w
CRAFTS
FAST多科学目标同时扫描巡天

Kicks


S147
J0538+2817
Spin
Velocity
SNR center
CRAFTS
35 kyr
《Nature Astronomy》
https://dx.doi.org/10.1038/s41550-021-01360-w

Kicks

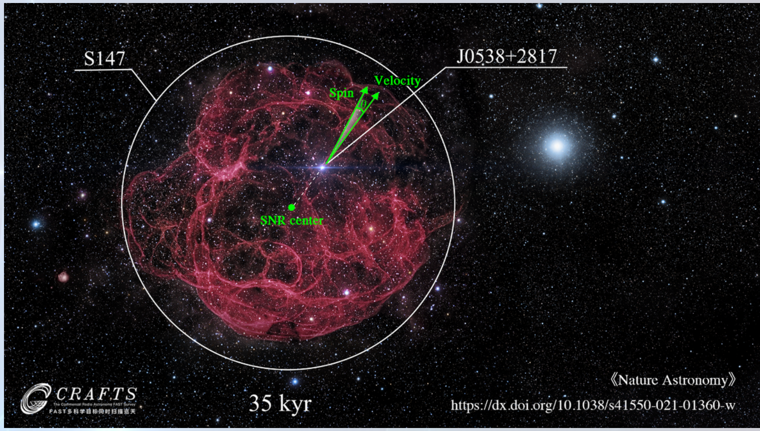
- happens for single-star supernovae too

  = natal kick

  which happen when the NS is born

  also see: pulsar kick, NS kick, SN kick

  – needs: assymetric explosion



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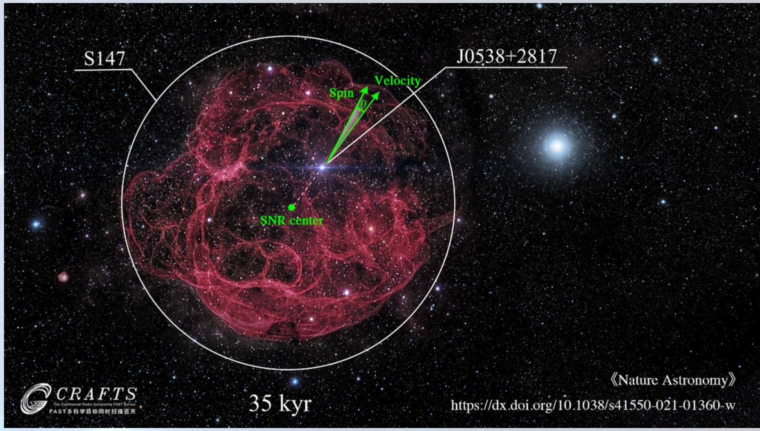

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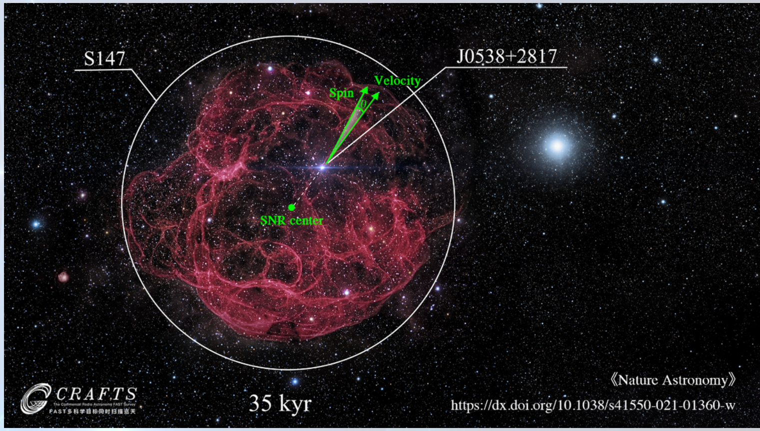

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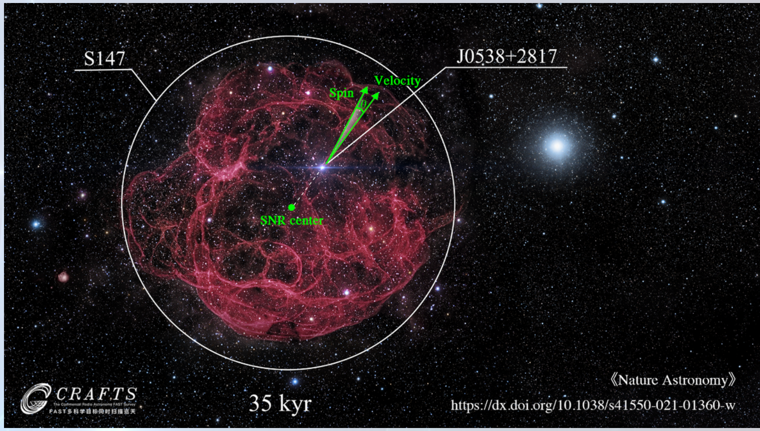

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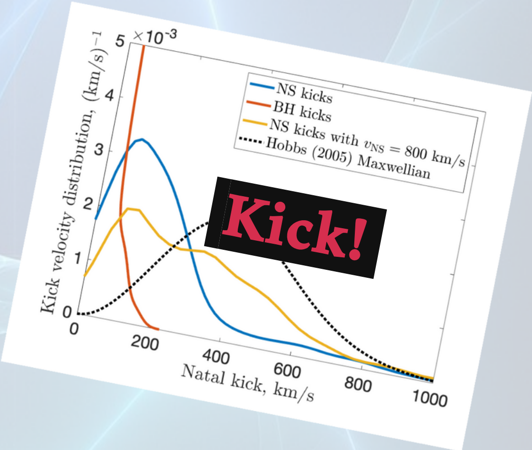
  - but in pop.synth., drawn from a – ***you guessed it*** – statistical distribution :D



cf. Mandel & Müller (2020)