Gravitational-wave progenitors

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Lecture #13

NCU, Summer Semester 2022

Previously
on GW-progenitors...

Population synthesis on ***binaries***

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

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

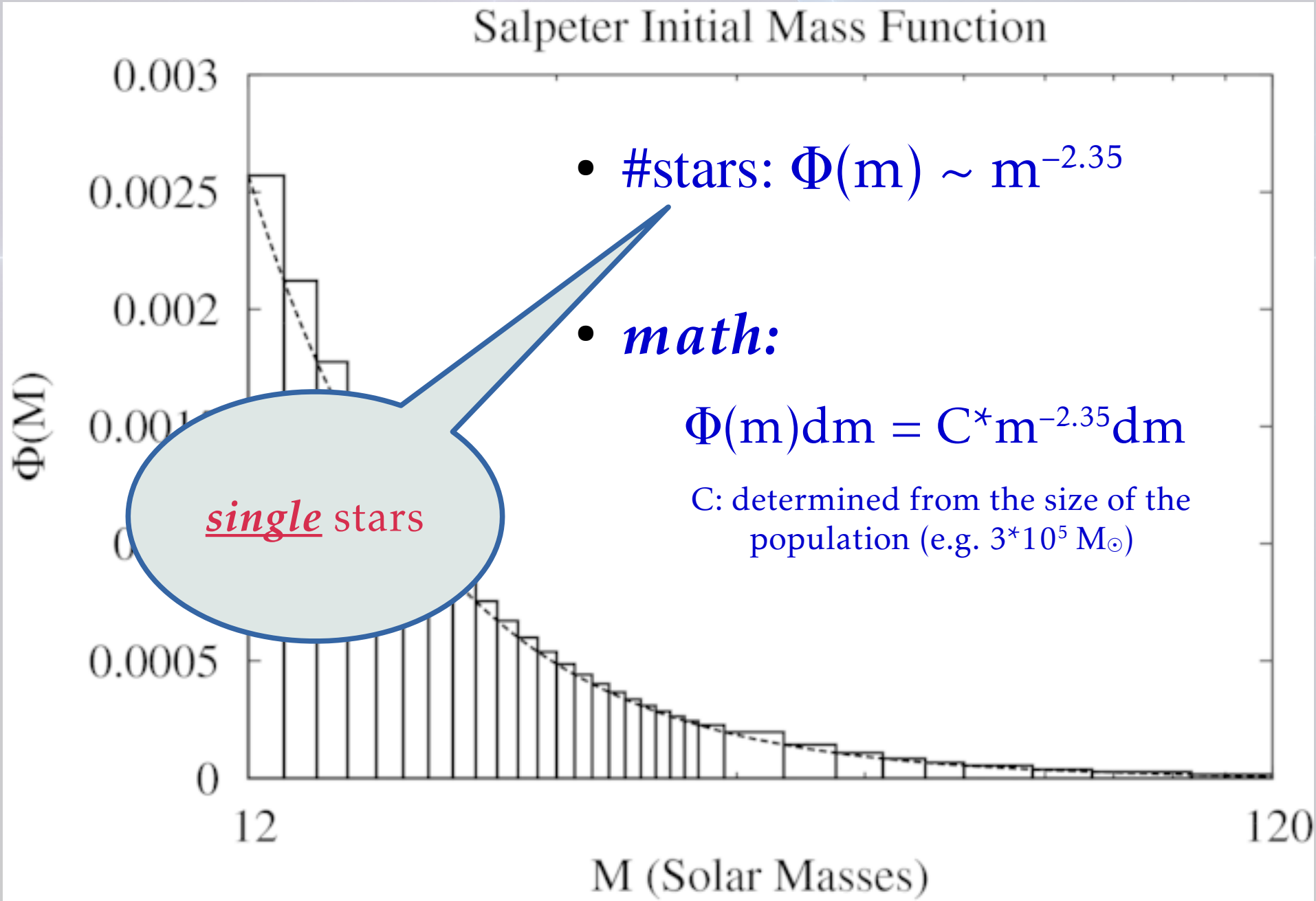
(yes, MESA can run binaries too)

Remember the Initial Mass Function (IMF)?

Pop.synth. starts with that.

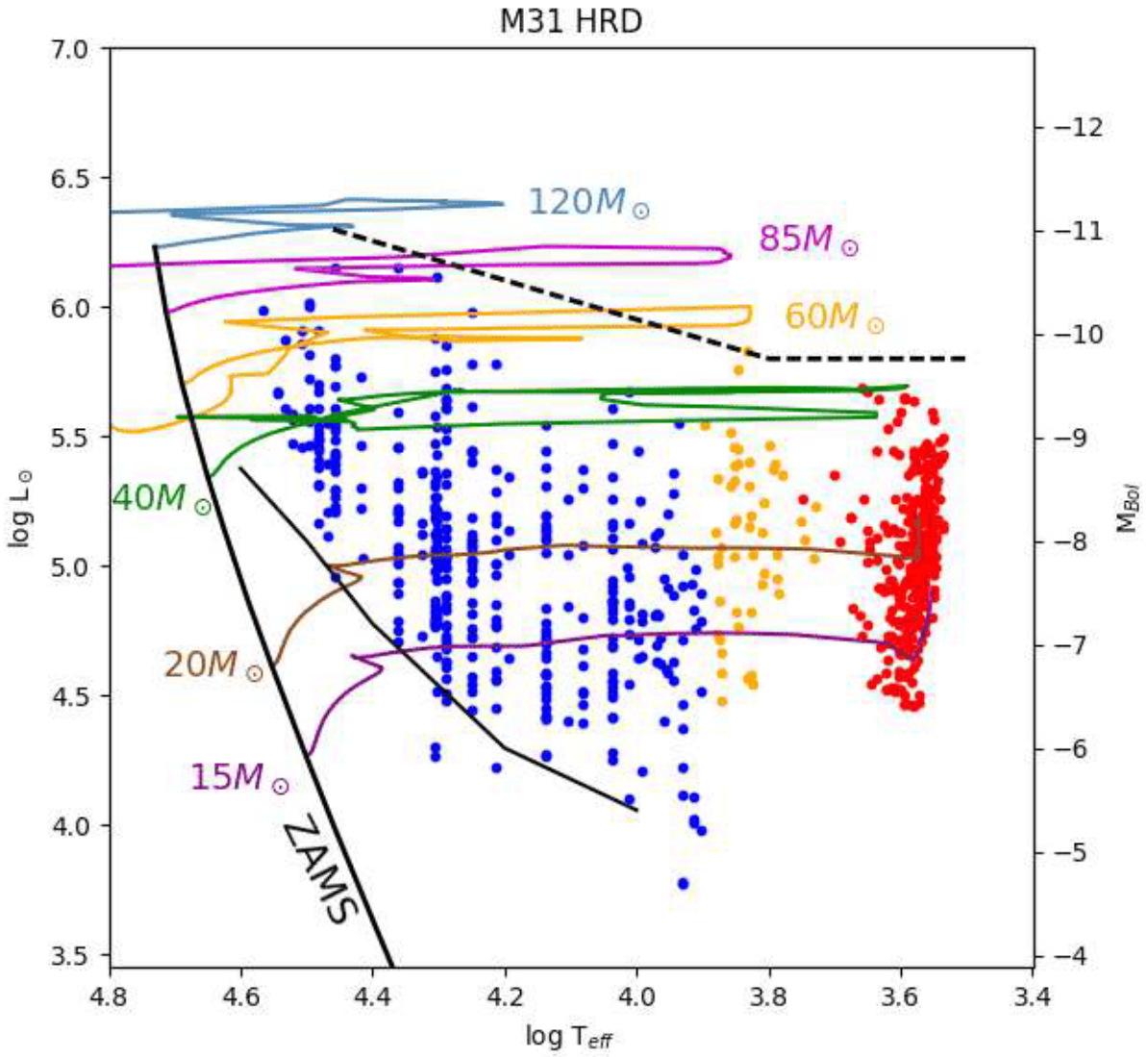
But binaries make life complicated.

REMINDER: The Initial Mass Function (IMF)

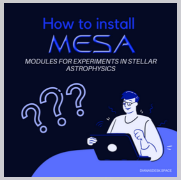


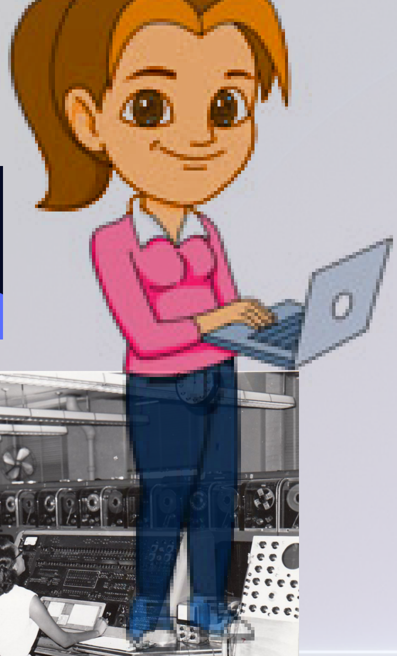
(*single* stars)

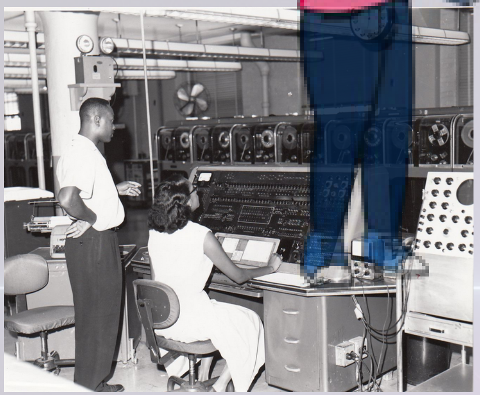
Let's think!



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







HR-diagram

Age, Mass, Radius, $\mathbf{T_{eff}}$ **[K]**, **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
         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
         2.7516123495584622E+005         1.9999713938816765E+001        -6.6681455357436759E-009         4.6153294982370108E+000         0.0000000000000000E+000
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         2.7589453962318692E+005         1.9999709023711880E+001        -6.6686823060969130E-009         4.6165113078795130E+000         0.0000000000000000E+000
         2.7613897451230051E+005         1.9999707385343584E+001        -6.6688612295479929E-009         4.6169052444270129E+000         0.0000000000000000E+000
         2.7638340940141404E+005         1.9999705746975291E+001        -6.6690401529990719E-009         4.6172991809745136E+000         0.0000000000000000E+000
         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
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```

(*single* stars)

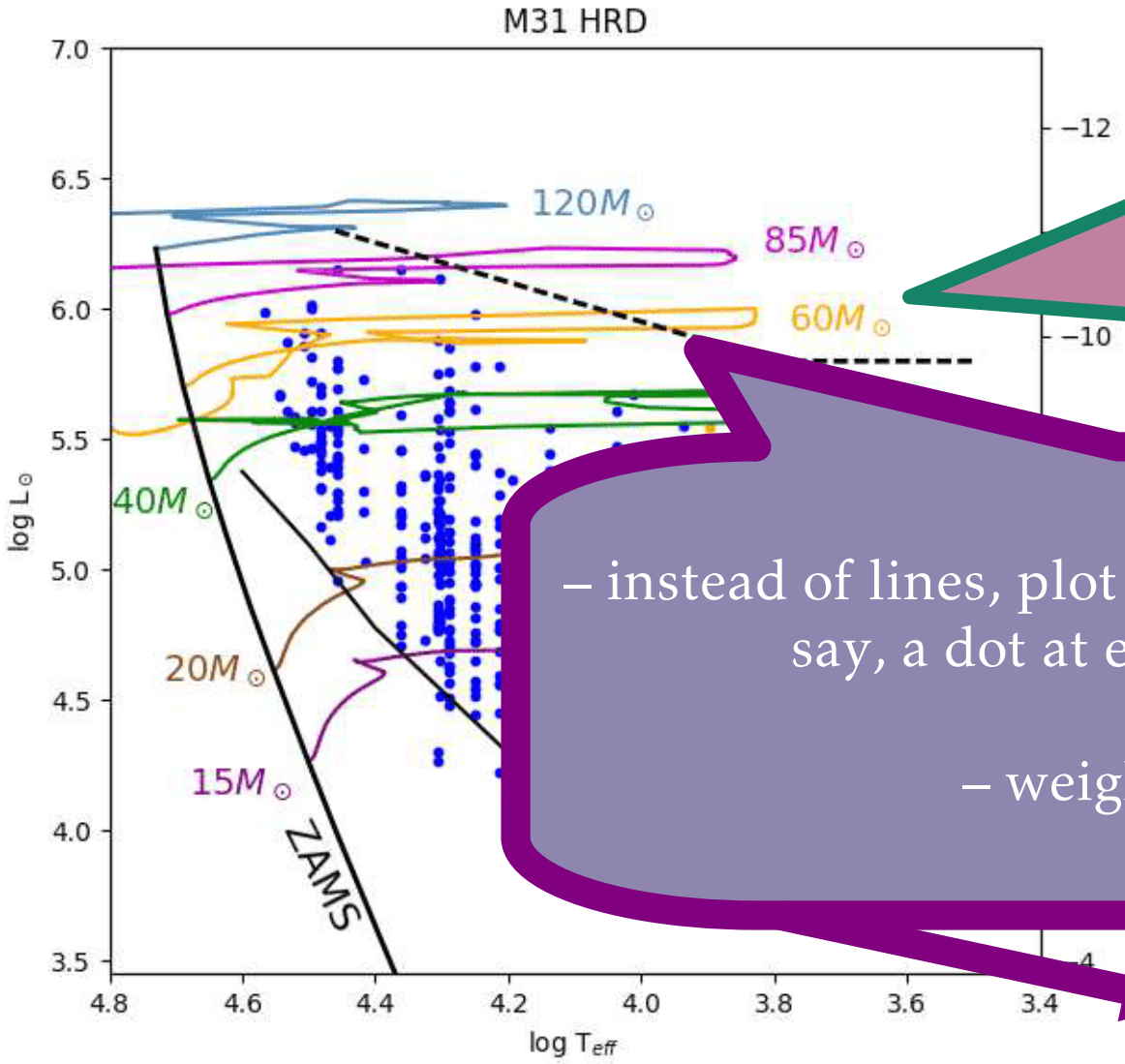
Let's think!

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



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

– weight with the IMF

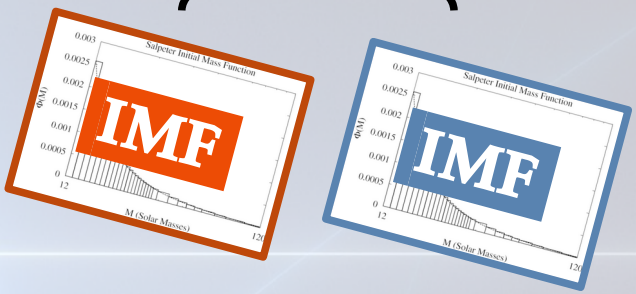
an actual (simulated)
stellar population!

***simulated* = "synthetic"**

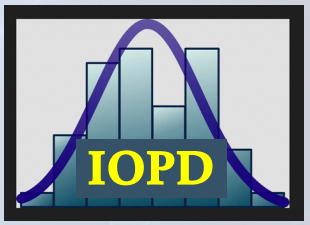
Population synthesis on ***binaries***

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

(related?)



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



- plus a ***lot*** of assumptions about the evolution
  - mass transfer (stable/unstable? conservative/non-conservative? ...)
  - Common Envelope phase (outcome: merger or survival?
    separation afterwards?)
  - supernova physics… and the kick.

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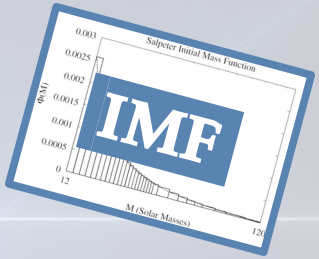
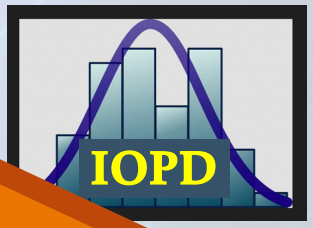


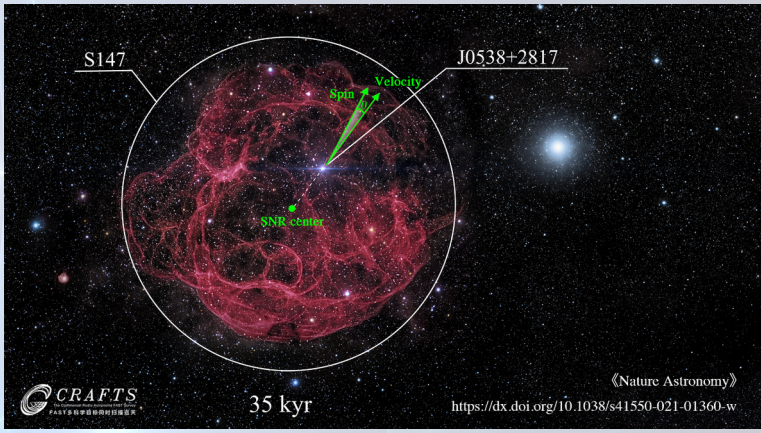


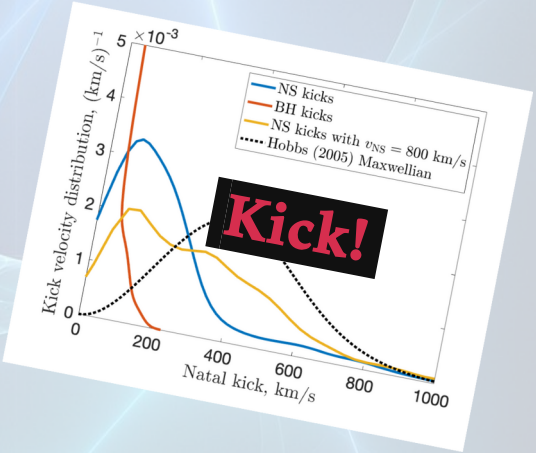
under active research

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

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
- in binaries, one SN may kick out the companion
- survival rate is uncertain
  - but in pop.synth., drawn from a – ***you guessed it*** – statistical distribution :D



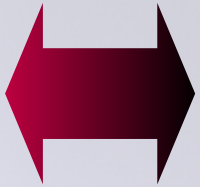


cf. Mandel & Müller (2020)

IMPORTANT

Exam warning! :P

- 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

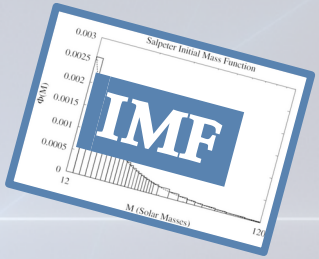


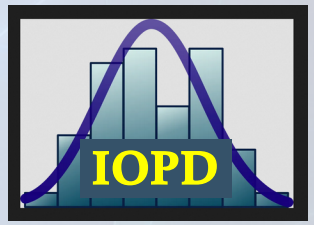
- Synthetic population modelling
  - ***relies*** on stellar evolution modelling
  - does not simulate the individual star's life (typically)
  - IMF is taken into account
  - result is a ***statistically meaningful*** prediction about a ***population***

Today…

…the last steps!

Star-formation history

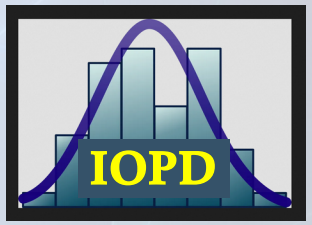




Not enough!

Star-formation history

- We need to know the ***history*** of how the stars are being born…



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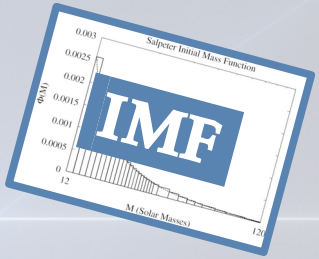
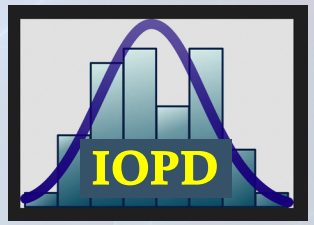
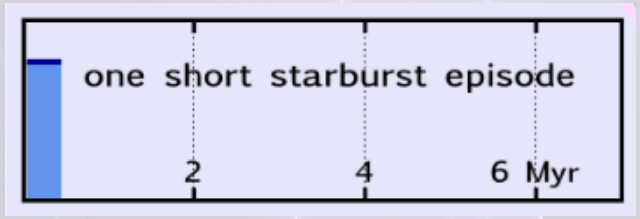




Not enough!

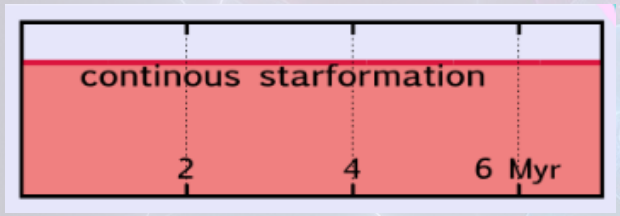
SFR

star-formation rate



or anything else

SFR



Unit:
$M_\odot/yr$

Star-formation history

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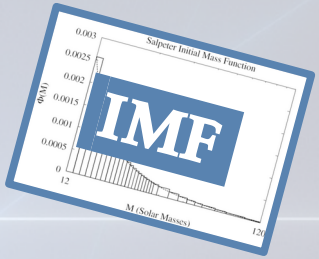

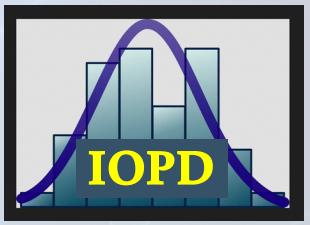

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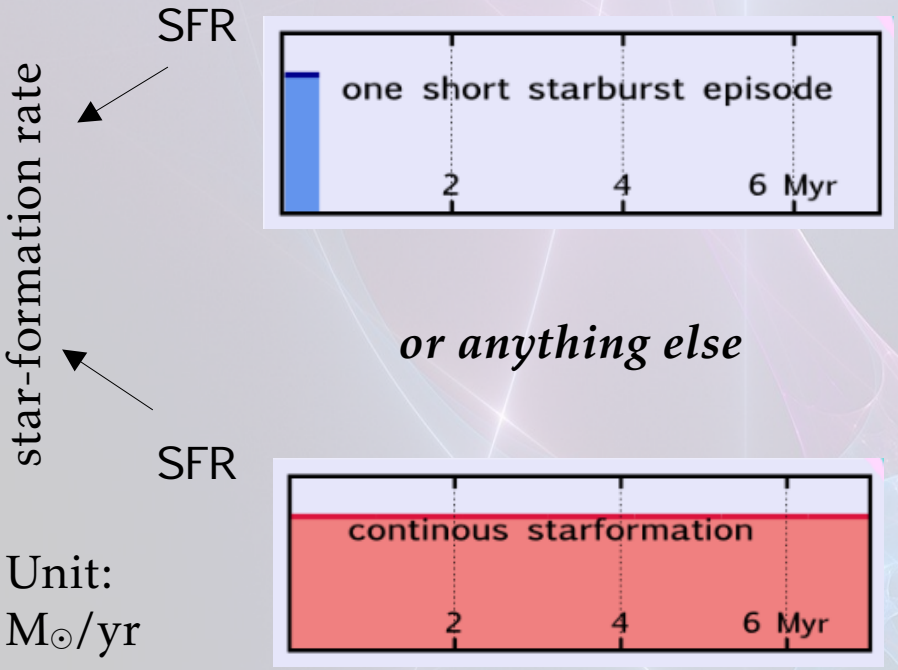
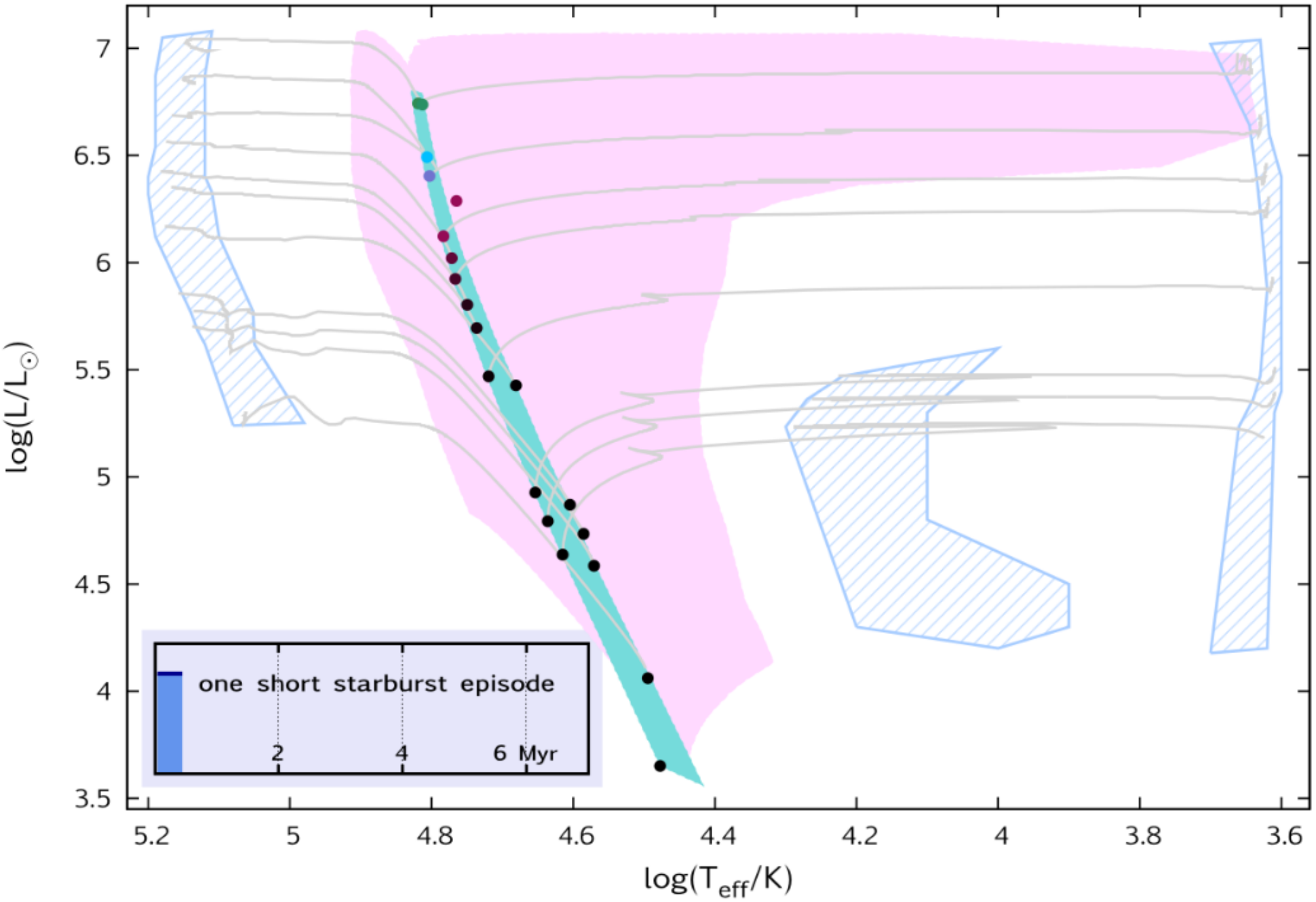


We need all these to do (binary) population synthesis.

Simulating a galaxy... or starcluster



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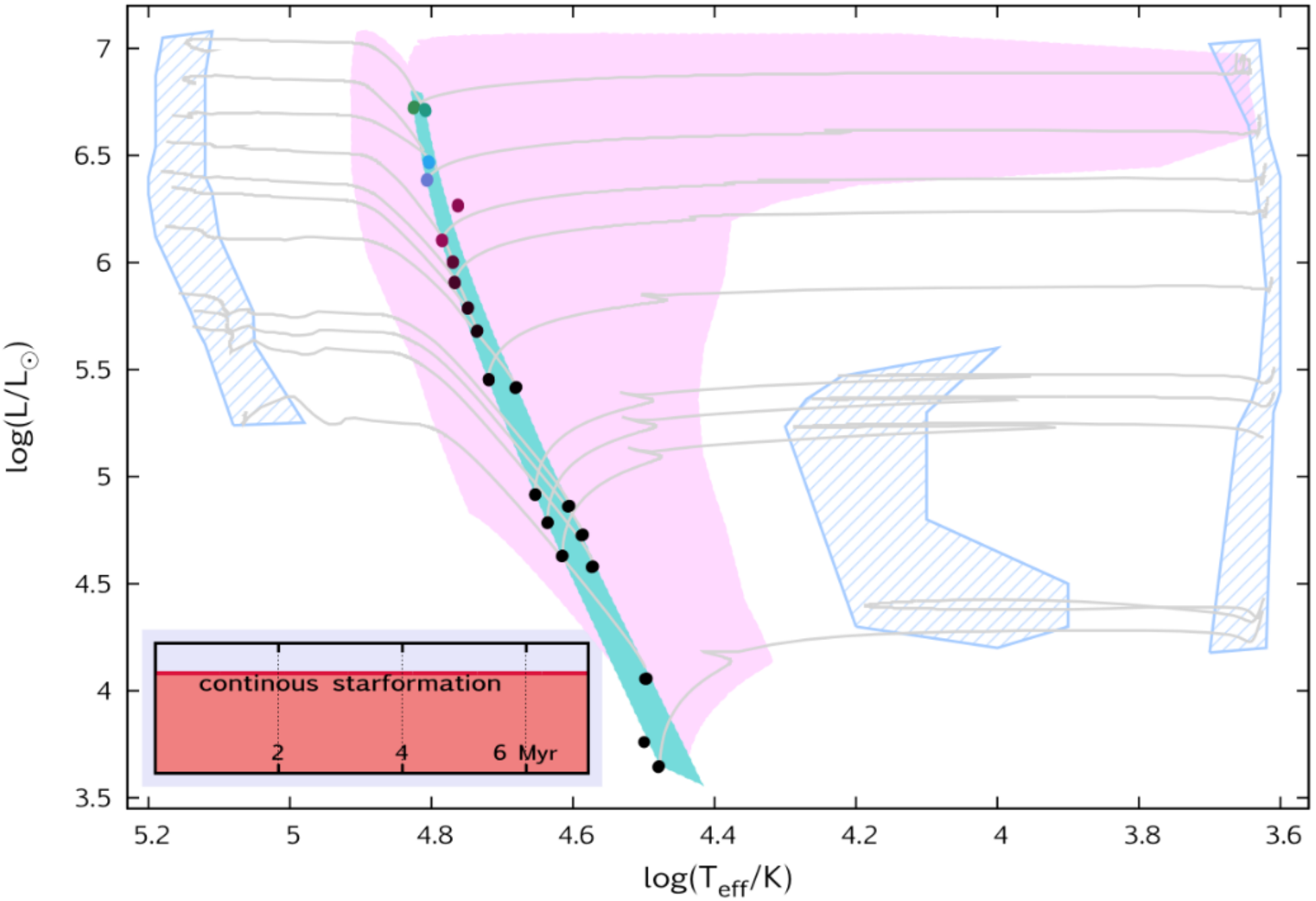
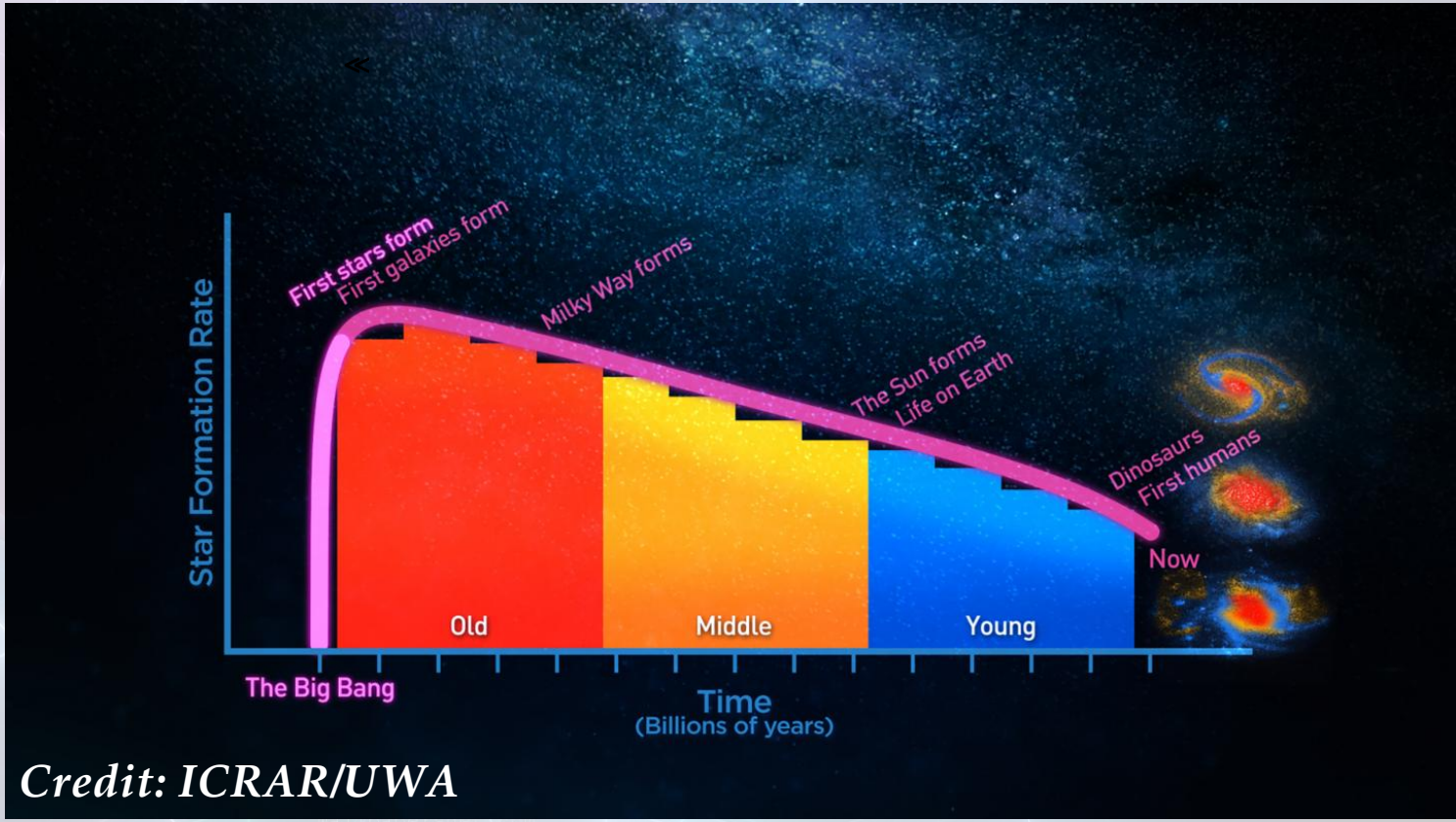


From star-formation history to ***cosmic*** star-formation history

- This is what we need to predict GW-event rates from synthetic populations

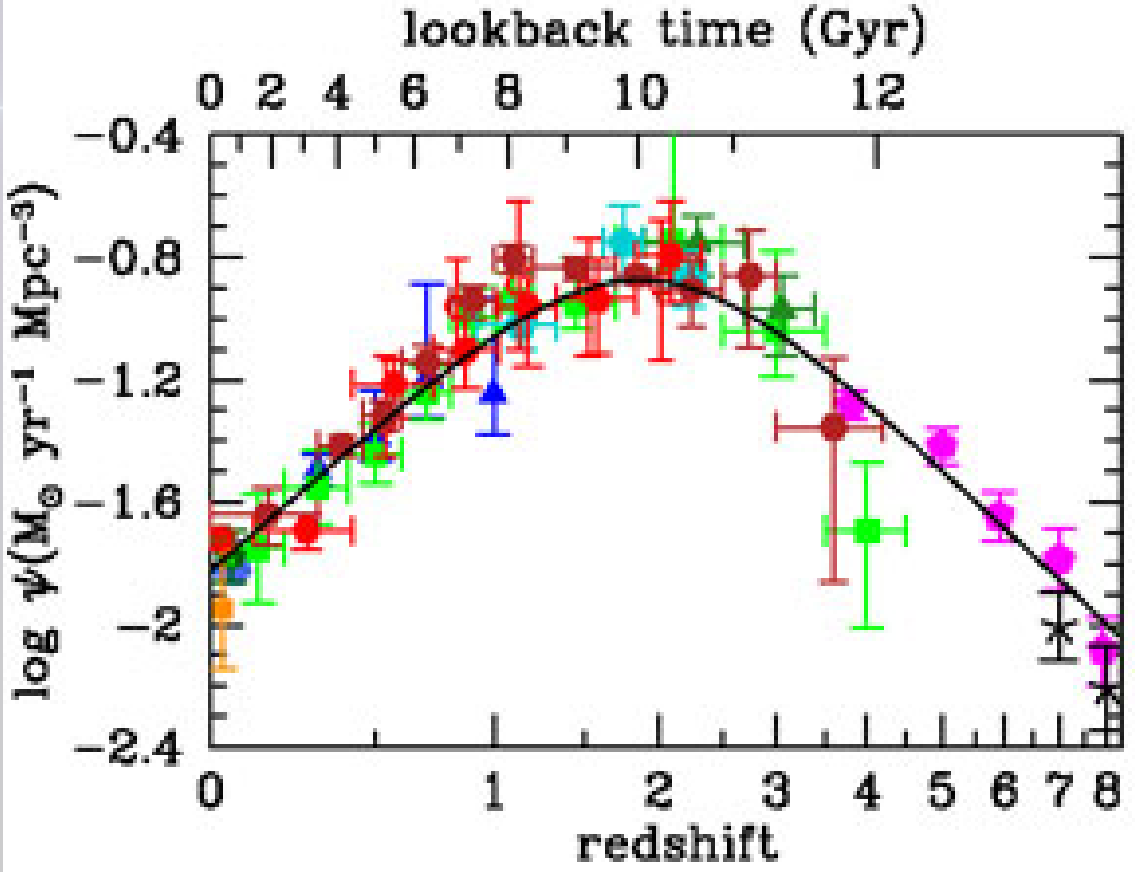


Credit: ICRAR/UWA

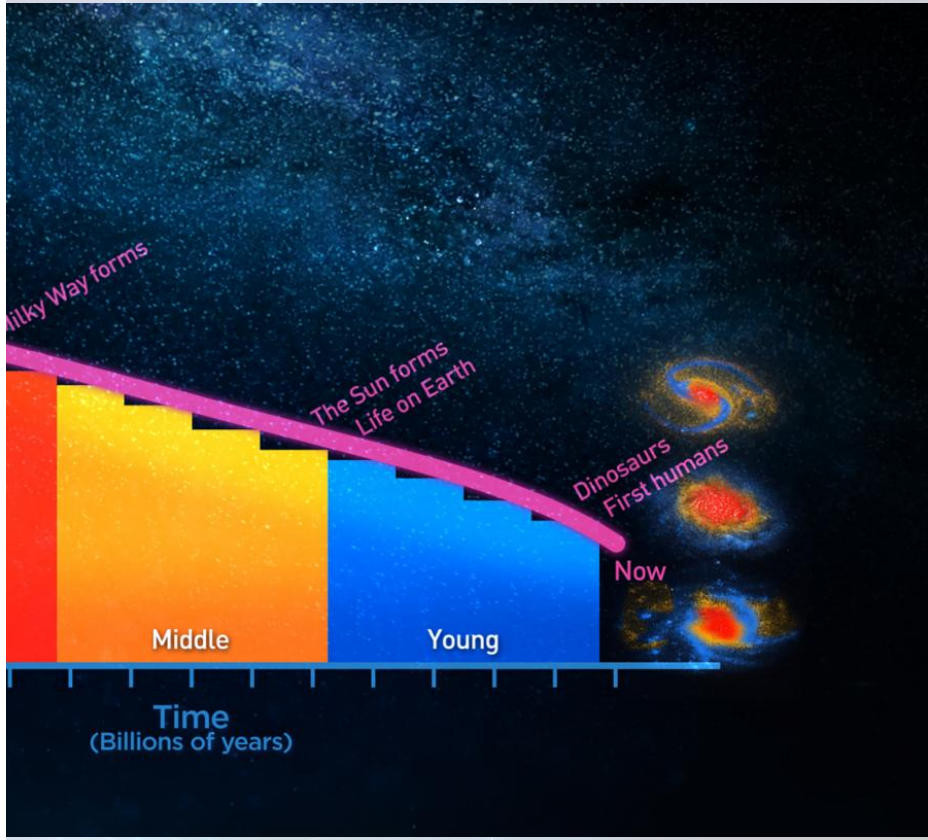
From star-formation history to ***cosmic*** star-formation history

edict GW-event rates

s



Credit: Madau & Dickinson (2014)



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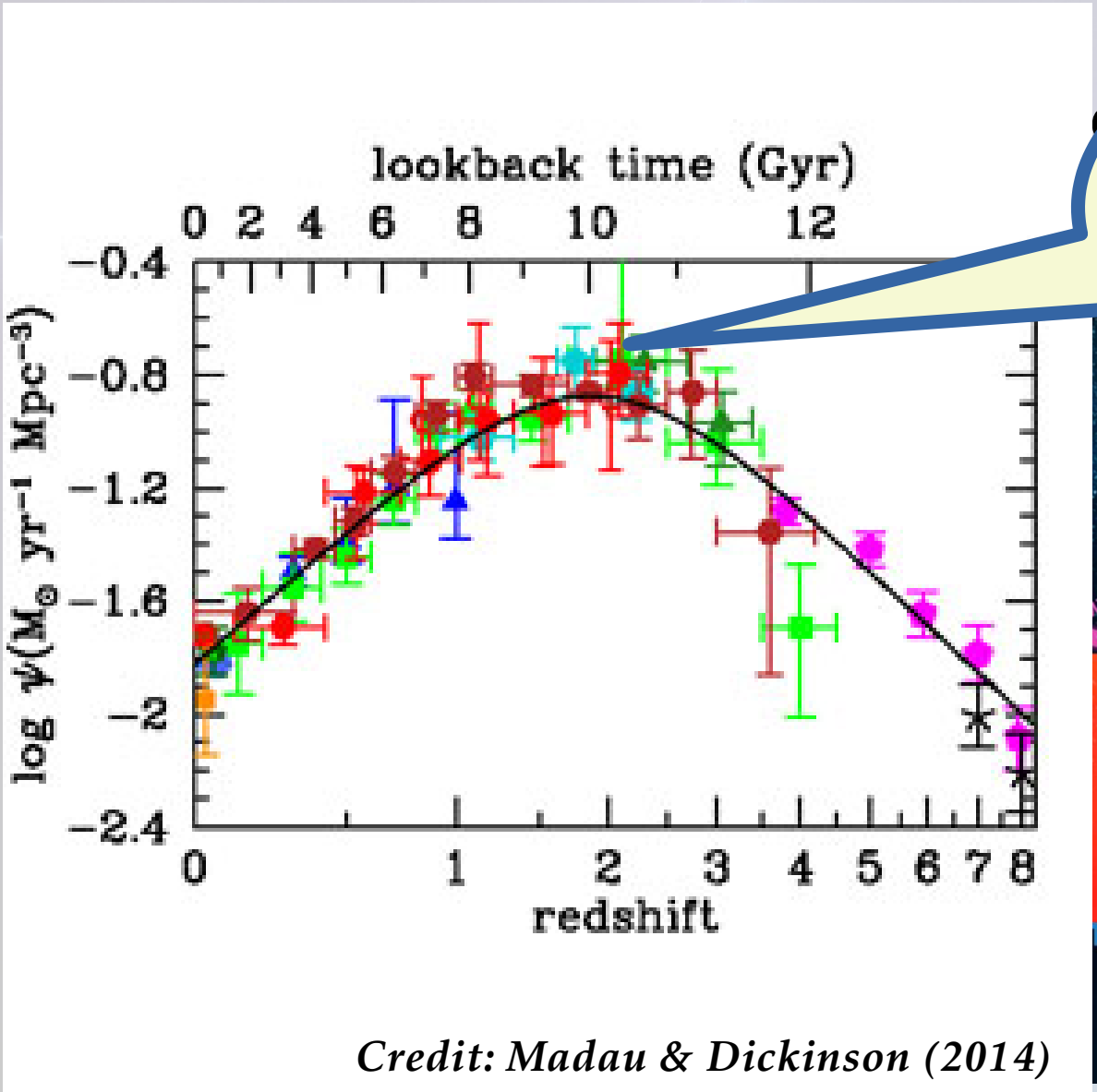

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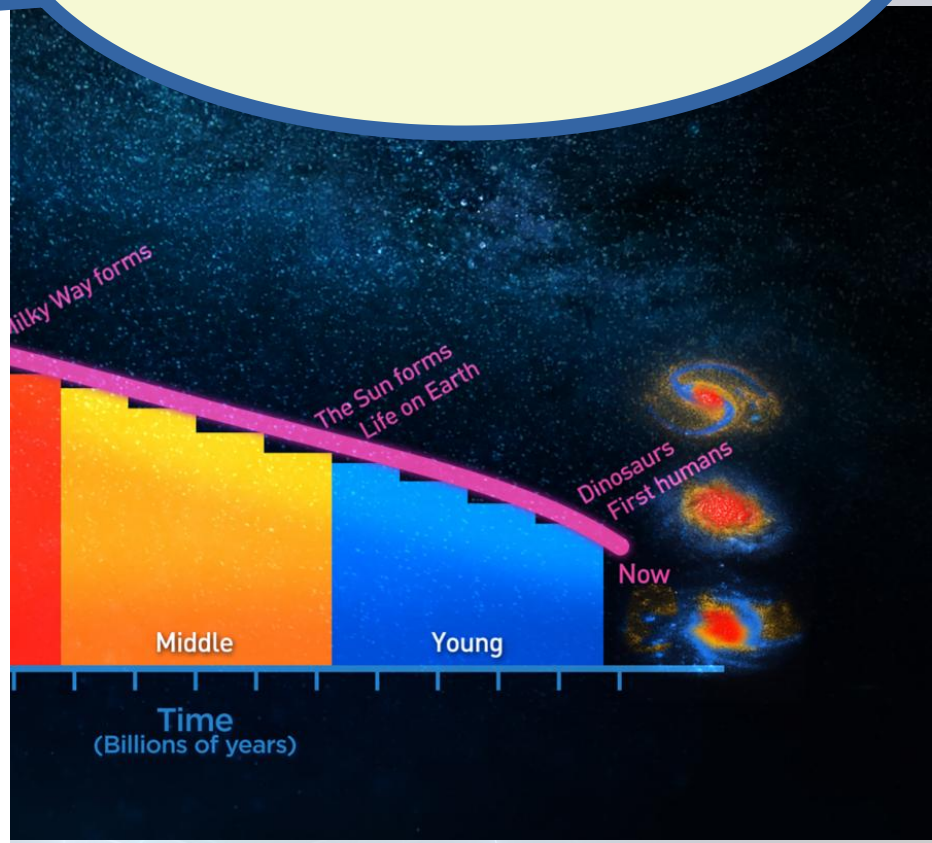
Peaking: somewhere around z = 2, when the Universe was ~3.5 Gyr old



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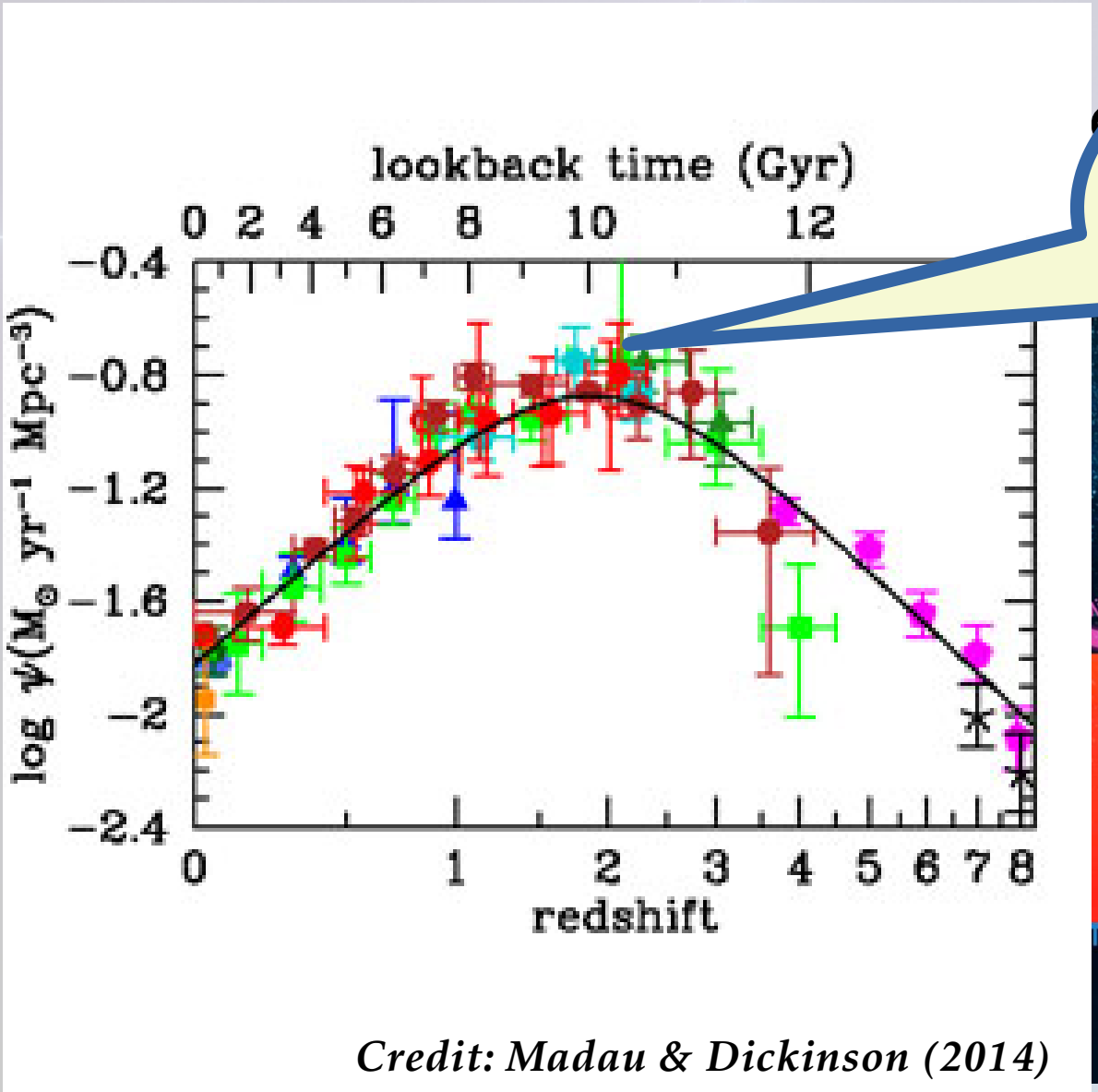

Credit: Madau & Dickinson (2014)

Peaking: somewhere around z = 2, when the Universe was ~3.5 Gyr old

Note:
massive stars live short lives!
2-20 Myr ≪ 13 Gyr

Now we can answer the original question of this whole lecture series *(kind of)*

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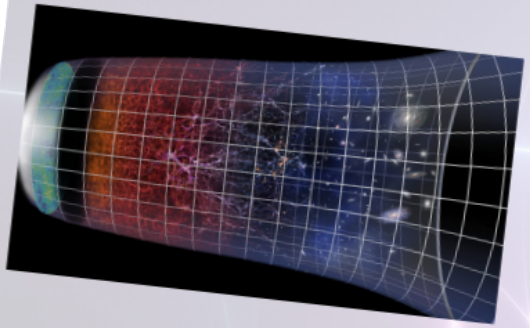
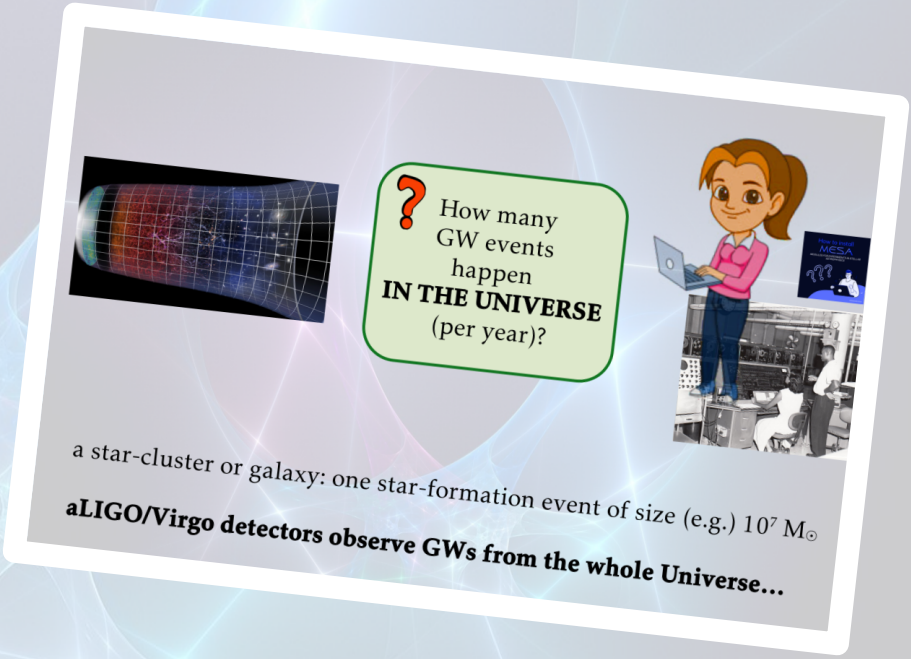


How many GW events happen **IN THE UNIVERSE** (per year)?

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...

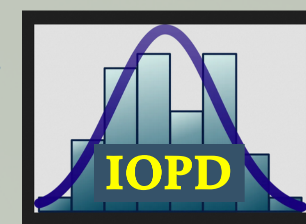
Now we can answer the original question of this whole lecture series *(kind of)*



Now we can answer the original *(kind of)* question of this whole lecture series

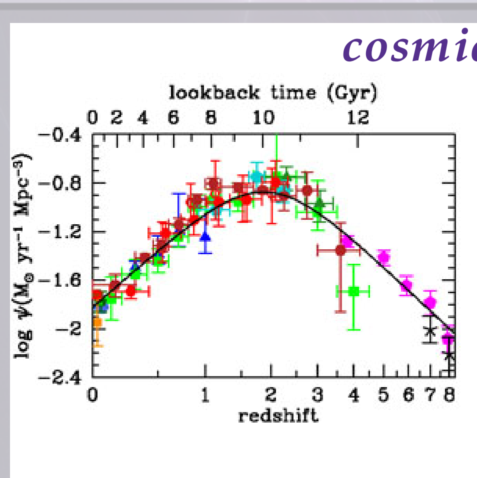
stellar models

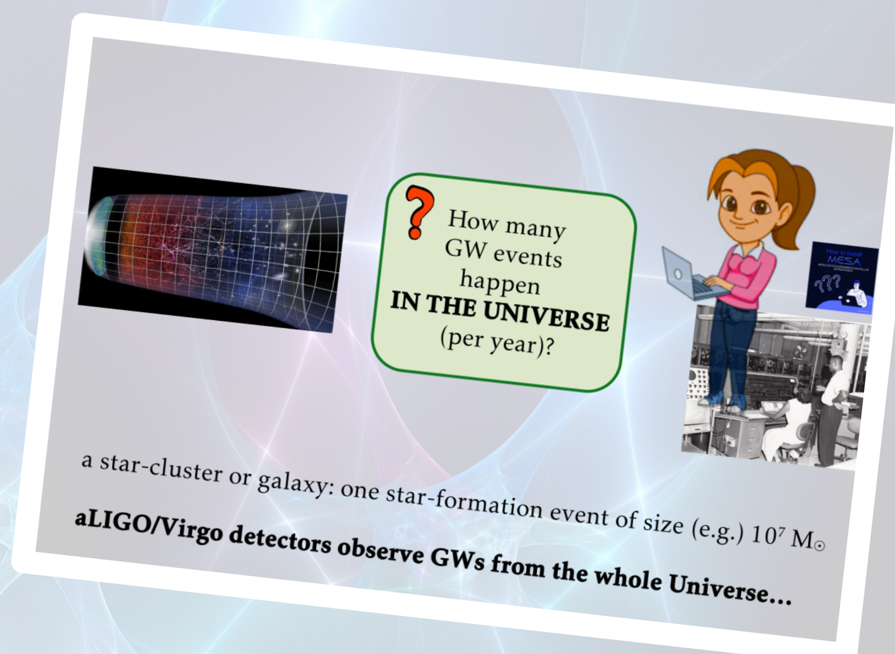
initial distributions



+ a lot of assumptions about binary physics

cosmic SFH





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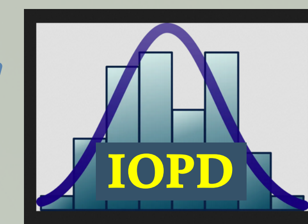

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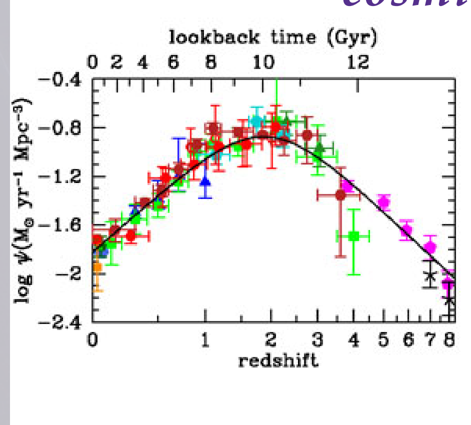

Important piece of math:
Convolution
of two functions

$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau) g(t - \tau) \, d\tau.$$

Some more terms

- Lookback time:
  - difference between the age of the Universe ***now*** (at observation) and the age te of the Universe when the photons* were emitted (from the given object).

**grav.waves*

- Delay time:
  - the time it takes for a binary system to ***(1)*** evolve both stars, then ***(2)*** spiral in due to the emission of (undetectably weak) gravitational waves, and then ***(3)*** merge (emitting ((potentially)) detectable grav.waves). Typically: ~10 Myr – 13.77 Gyr

Even some more terms

- Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

this is what can be directly derived from a measured GW-signal

to derive m_1 and m_2, a strong signal with good resolution is needed

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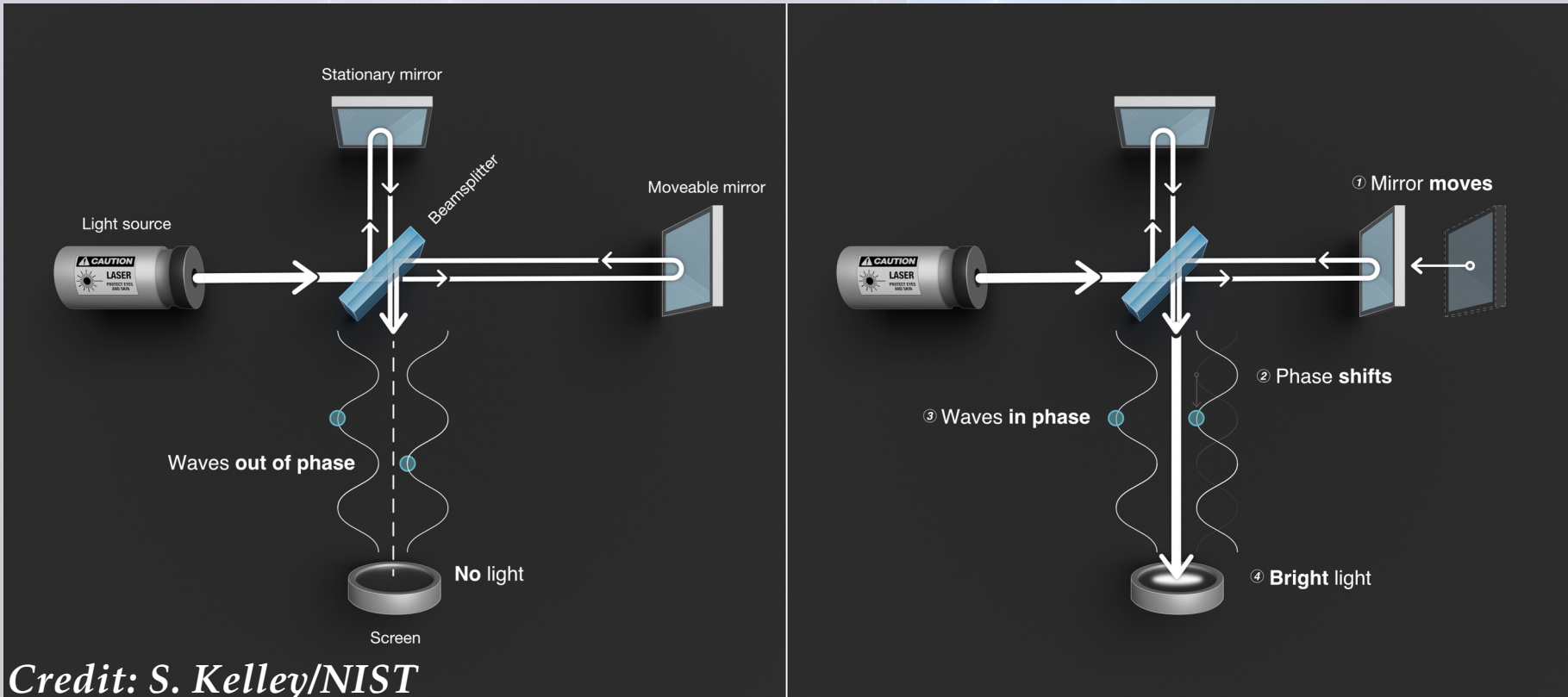
- Interferometer:



Credit: S. Kelley/NIST

Even some more terms

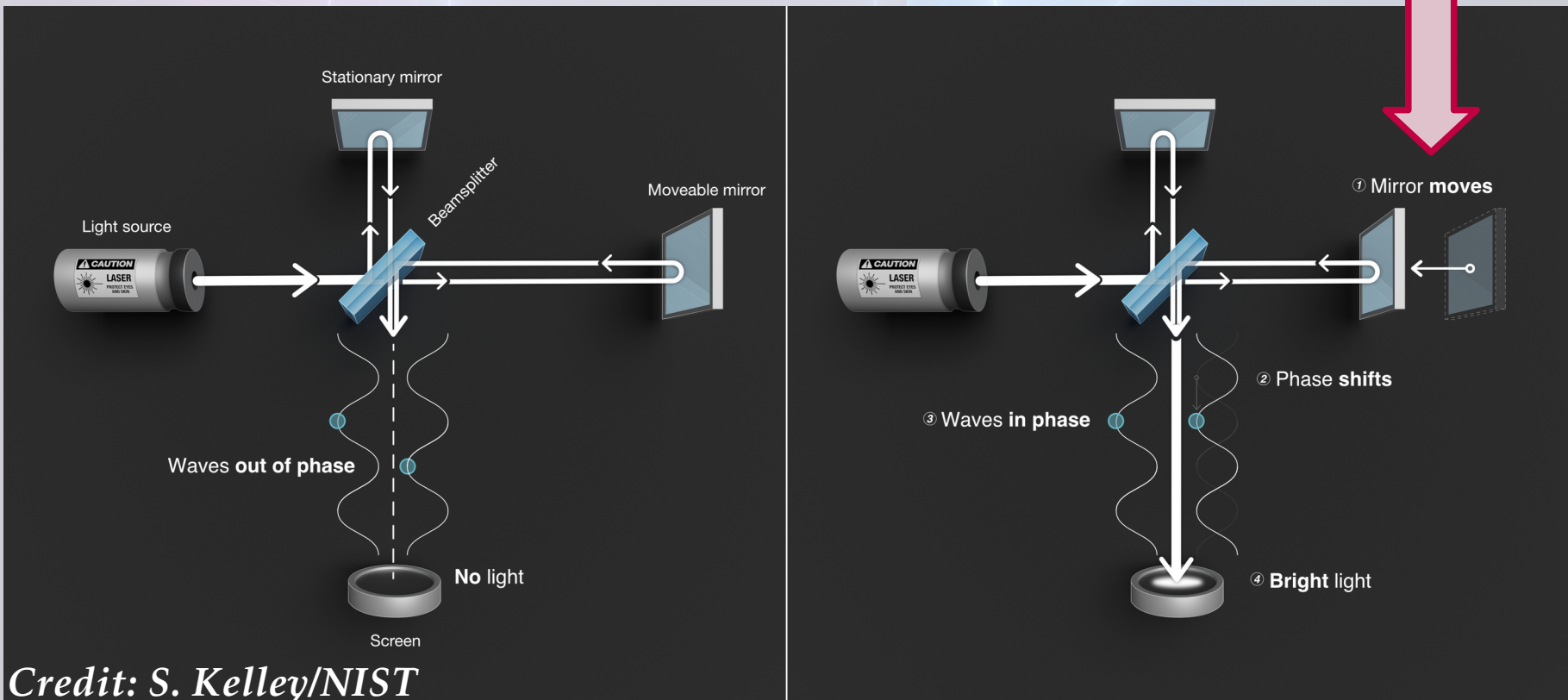
- Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

this is what can be directly derived from a measured GW-signal

to derive m_1 and m_2, a strong signal with good resolution is needed

- Interferometer:

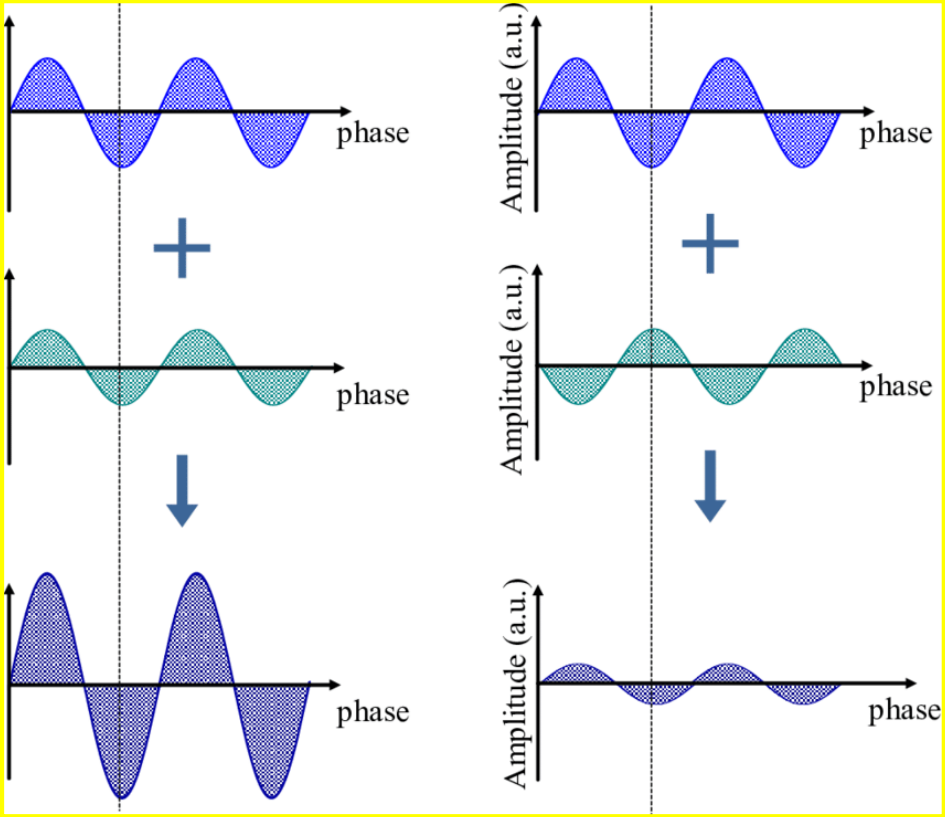
GW!



Credit: S. Kelley/NIST

Interference

(of the ***light*** from the laser, not the GW signal!!)



n be directly
measured GW-signal

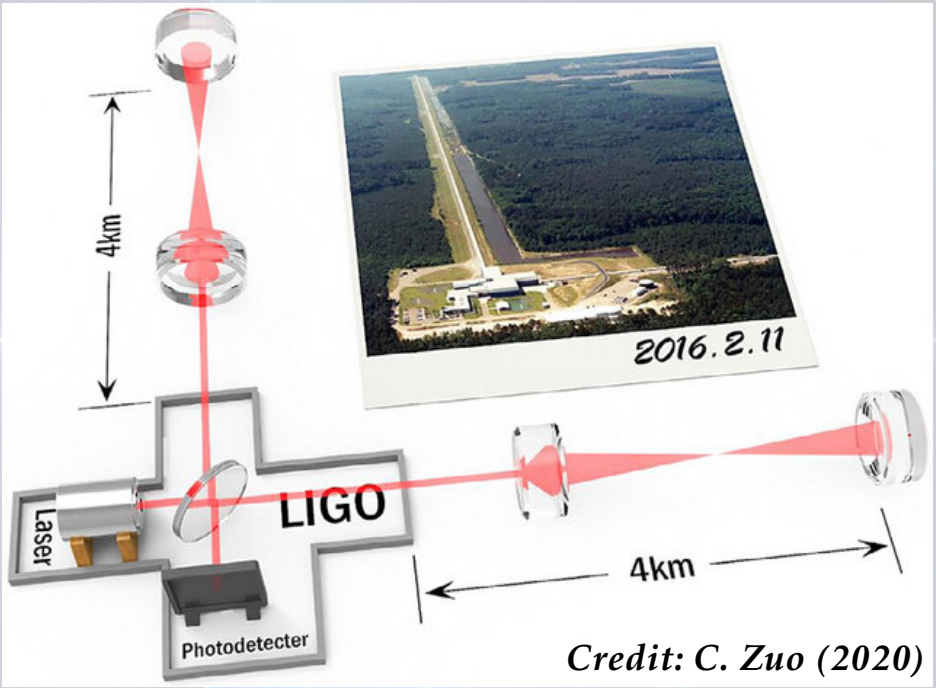
d m_2, a strong signal
lution is needed

GW!

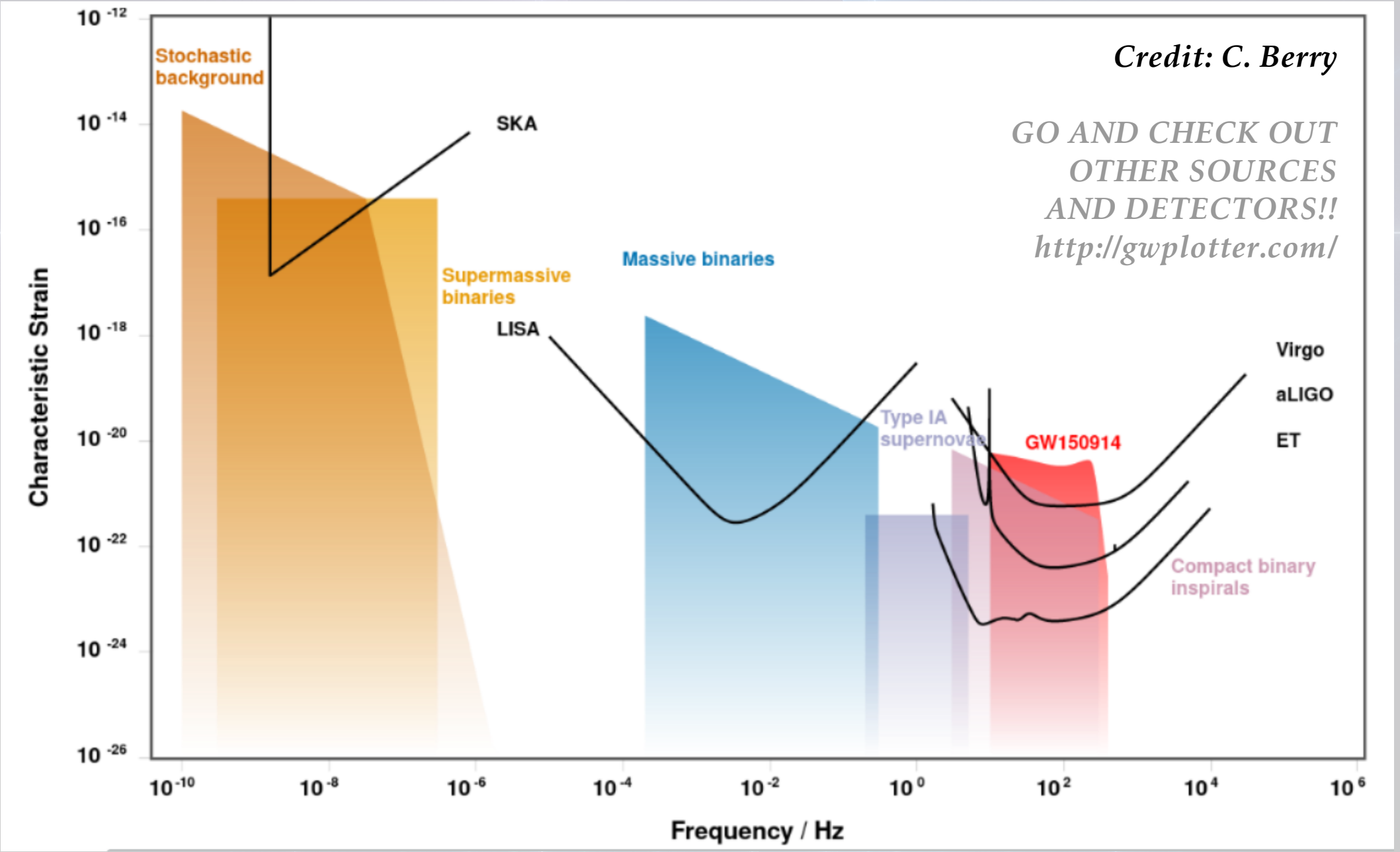
Credit: S. Kelley/NIST

And some names you MUST know

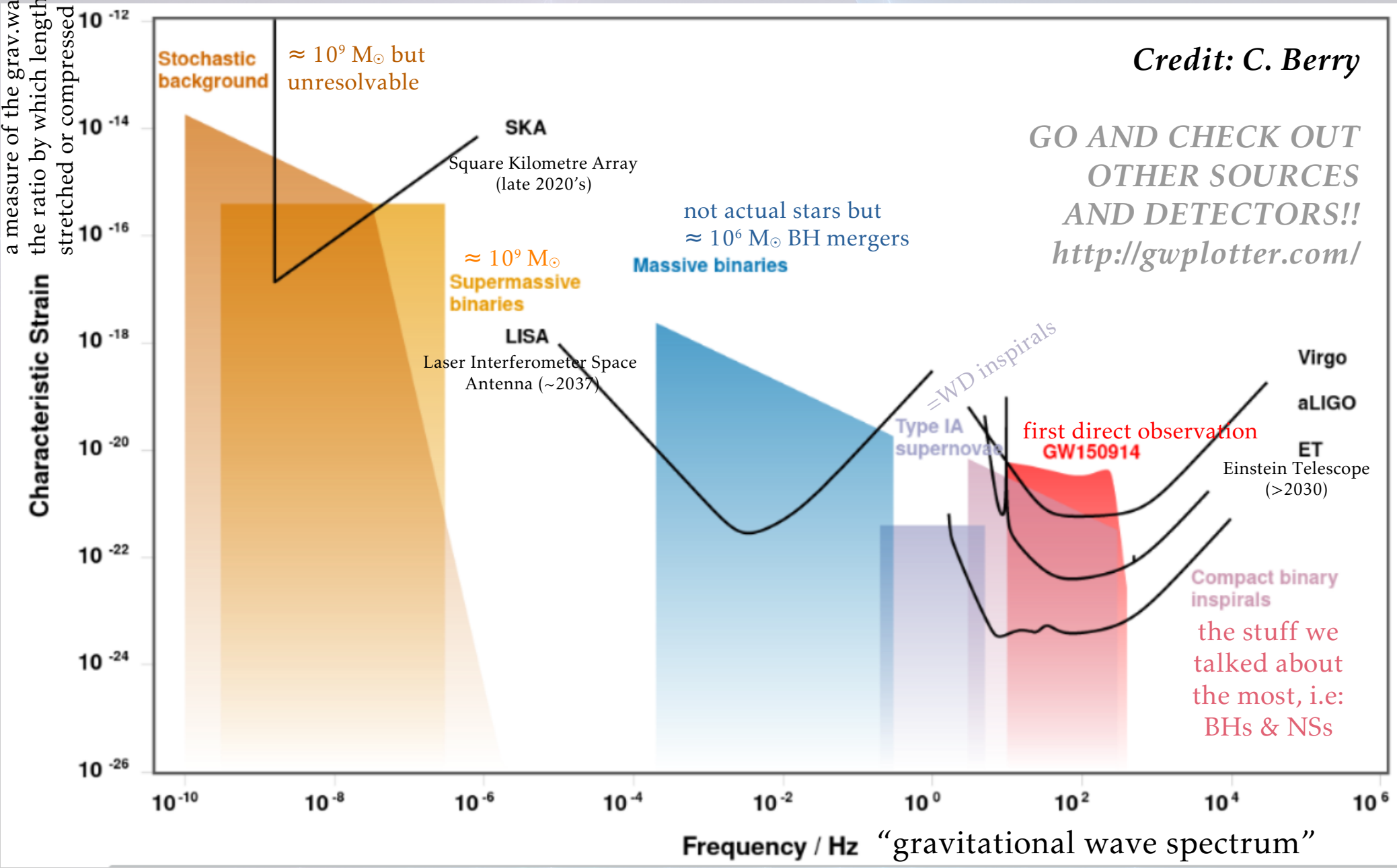
- LIGO:
  - Laser Interferometer Gravitational-wave Observatory (USA)
- **aLIGO**
  - advanced LIGO
  - the current version
- **Virgo**
  - LIGO's important little sister in Europe



Detector sensibility

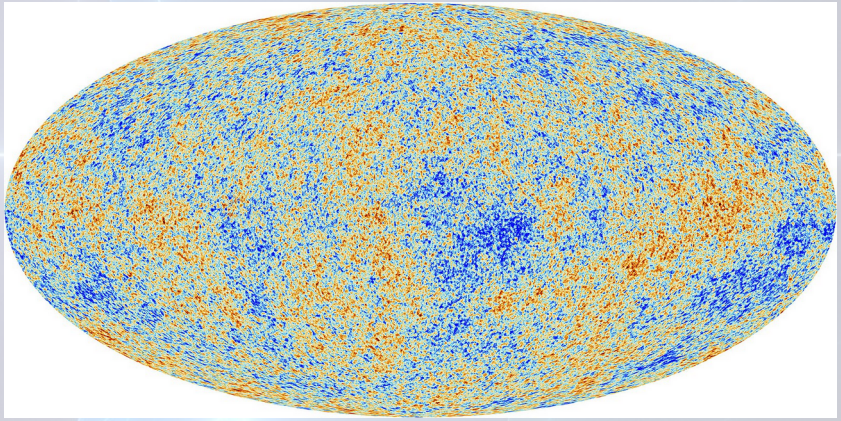


Detector sensibility



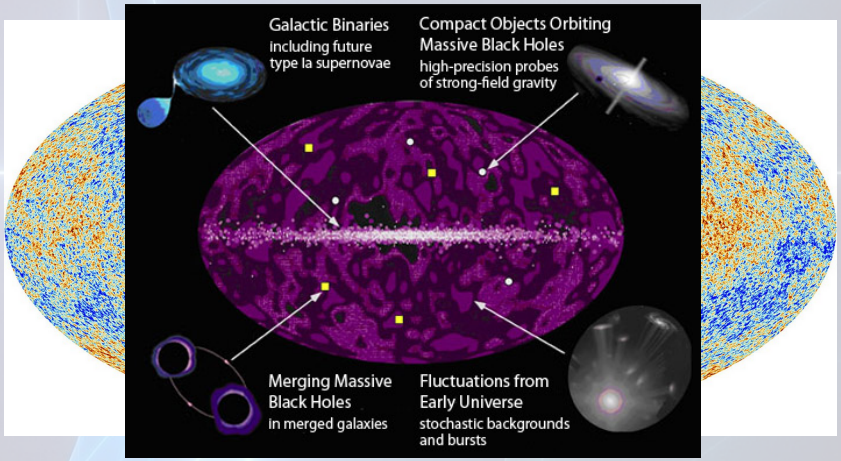
Cosmic grav.wave background

- Heard about the cosmic microwave background?



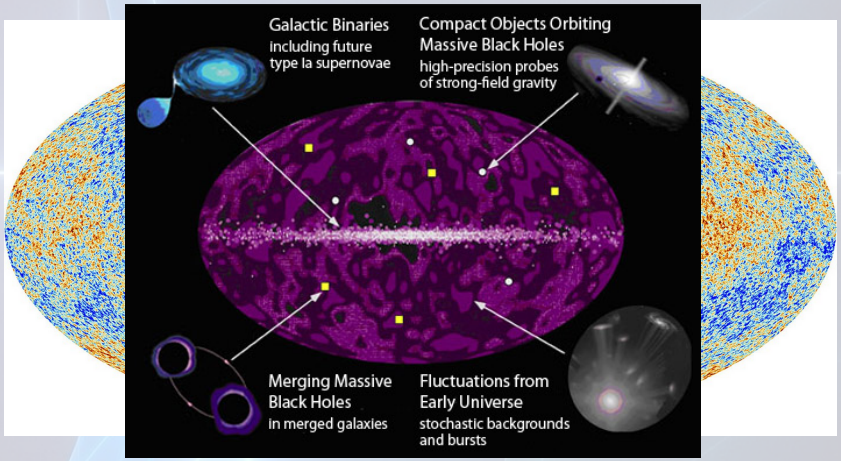
Cosmic grav.wave background

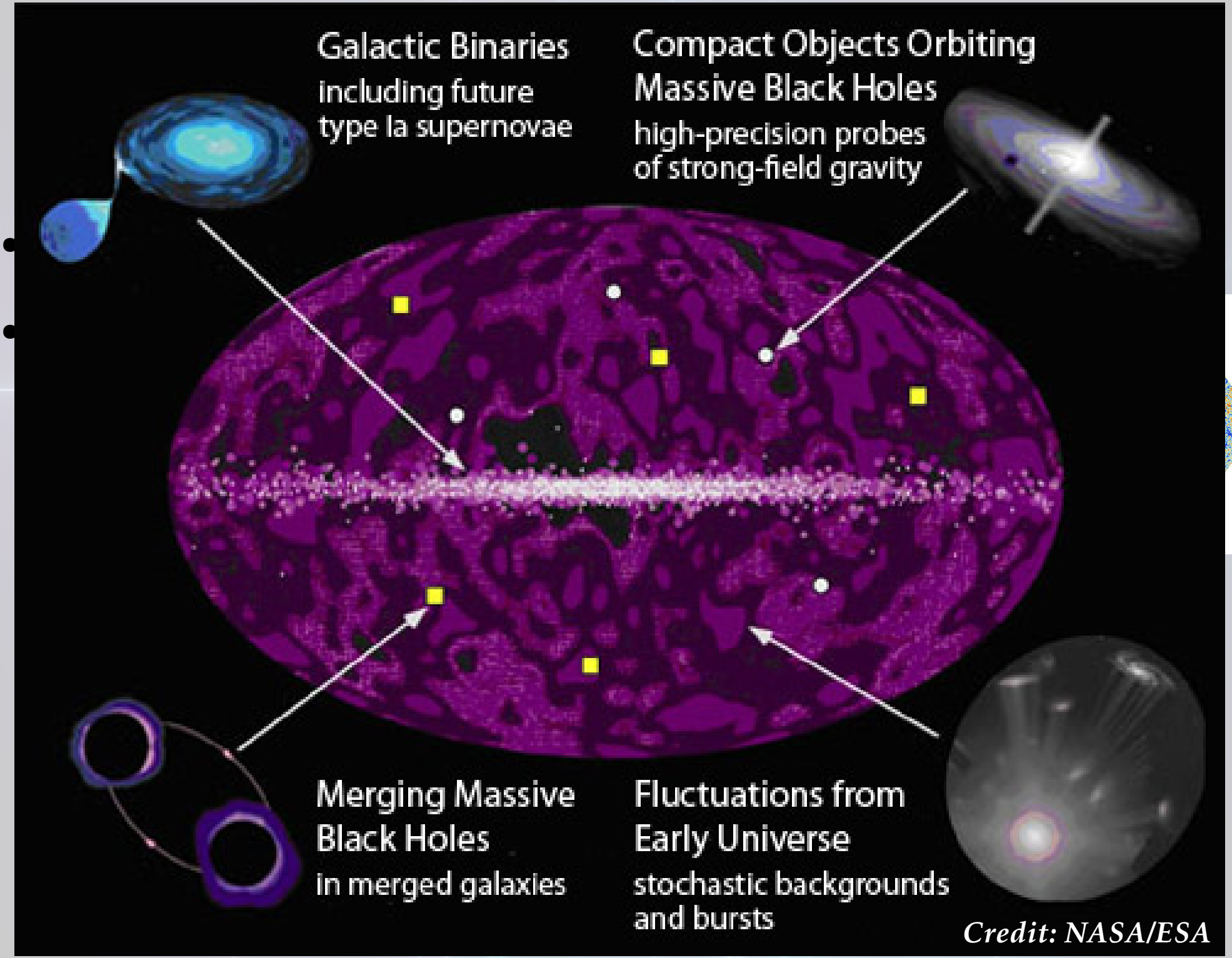
- Heard about the cosmic <u>microwave</u> background?
- GW-background:
  - undetected (yet)



Cosmic grav.wave background

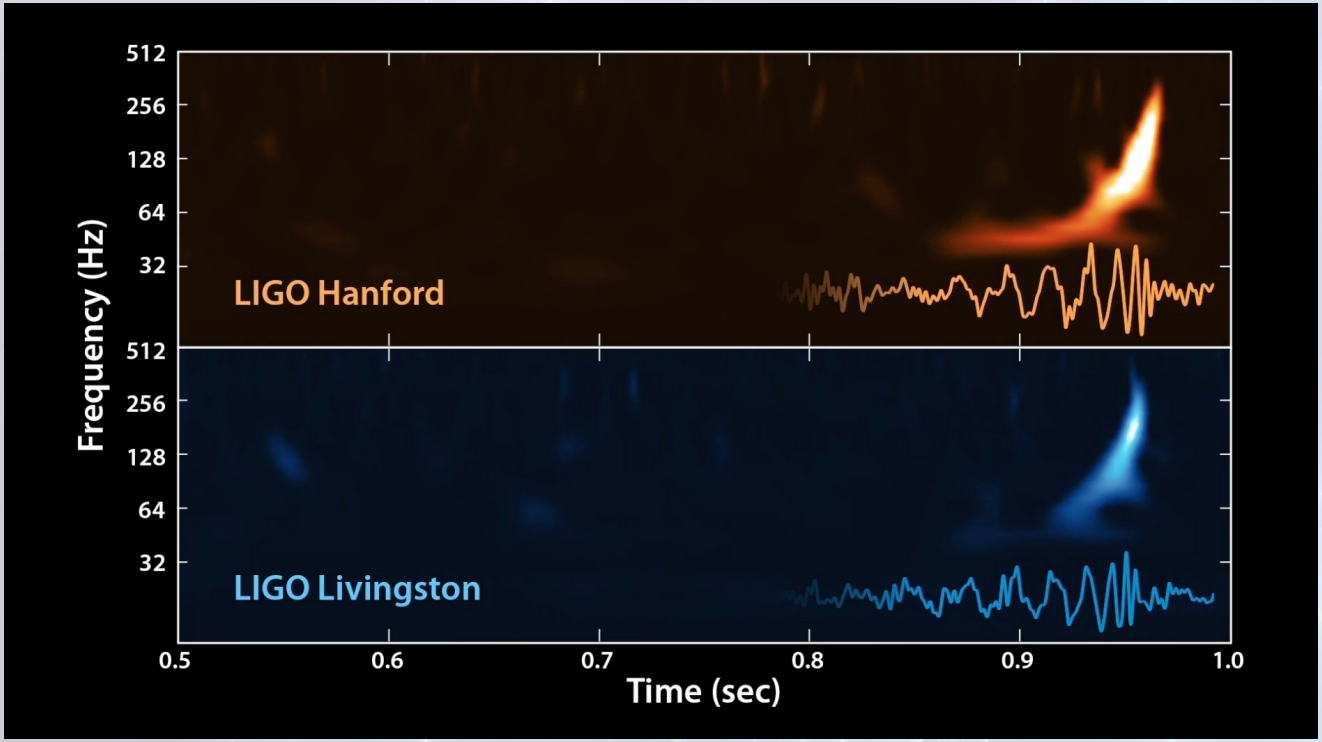
- Heard about the cosmic <u>microwave</u> background?
- GW-background:
  - undetected (yet)
  - cosmological sources
    - processes during e.g. the cosmic inflation (10^{-36}–10^{-33} sec after the Big Bang)
  - astrophysical sources
    - large number of ***unresolvable*** BH-BH (or BH-NS, or NS-NS) mergers; additional WD-WD mergers, supernova explosions…




Galactic Binaries
including future
type Ia supernovae
Compact Objects Orbiting
Massive Black Holes
high-precision probes
of strong-field gravity
Merging Massive
Black Holes
in merged galaxies
Fluctuations from
Early Universe
stochastic backgrounds
and bursts
Credit: NASA/ESA

The whispering of the Universe

https://www.youtube.com/watch?v=2PzbYK1x3Vo



'GW150914'

35 $M_\odot$ & 30 $M_\odot$

(BH+BH)

=

64 $M_\odot$

3 $M_\odot$ converted into GWs!