Gravitational-wave progenitors

Rafia Sarwar
rafia.sarwar@doktorant.umk.pl

Lecture 13

NCU, Summer Semester 2024

Previously on GW-progenitors...

Population synthesis on ***binaries***

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

meaning: ‘detailed’ evolutionary computations e.g. with MESA

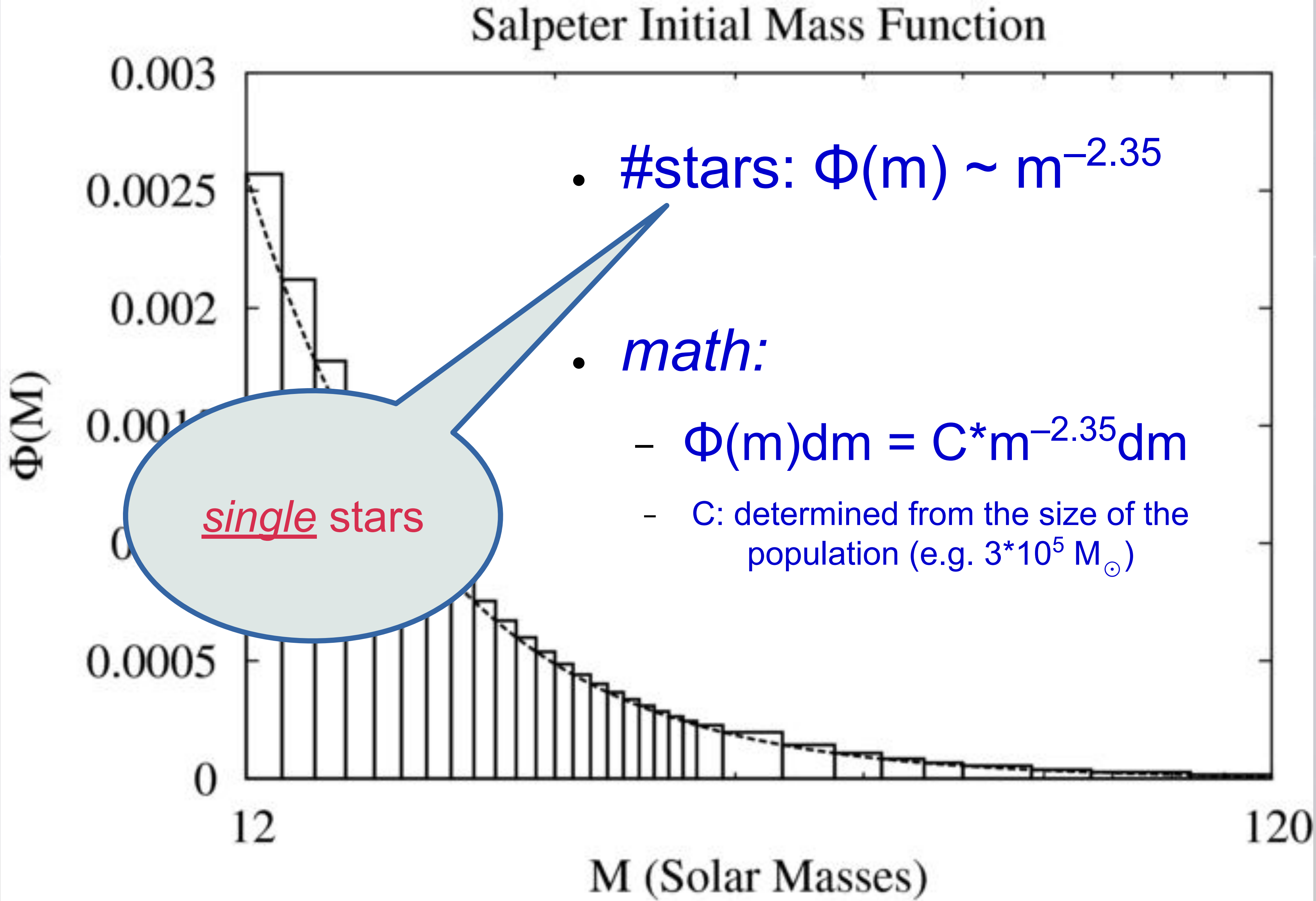
(yes, MESA can run binaries too)

Remember the Initial Mass Function (IMF)?

Pop.synth. starts with that.

But binaries make life complicated.

REMINDER: The Initial Mass Function (IMF)

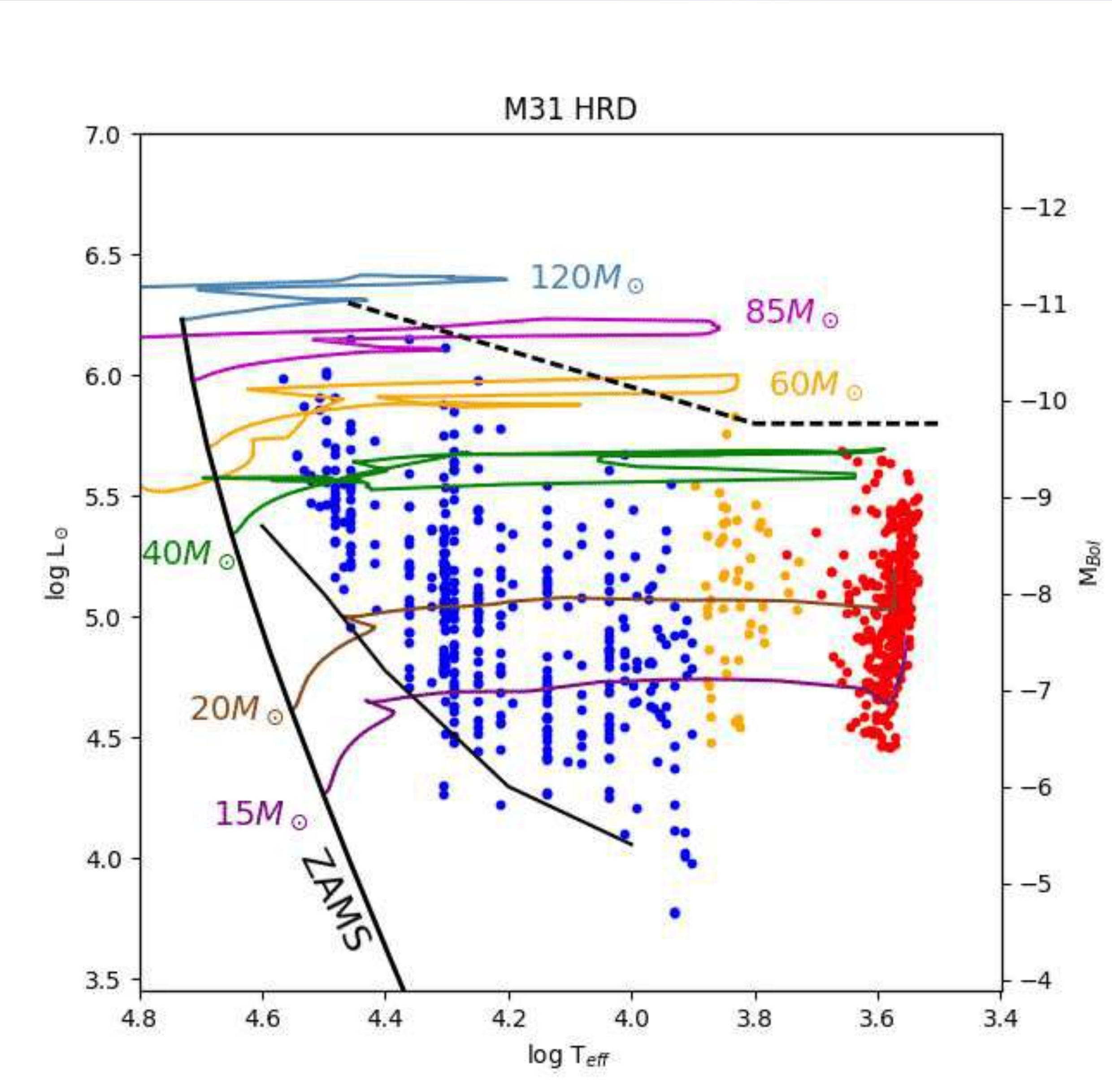


- #stars: $\Phi(m) \sim m^{-2.35}$
- *math:*
  - $\Phi(m)dm = C*m^{-2.35}dm$
  - C: determined from the size of the population (e.g. $3*10^5\ M_\odot$)

single stars

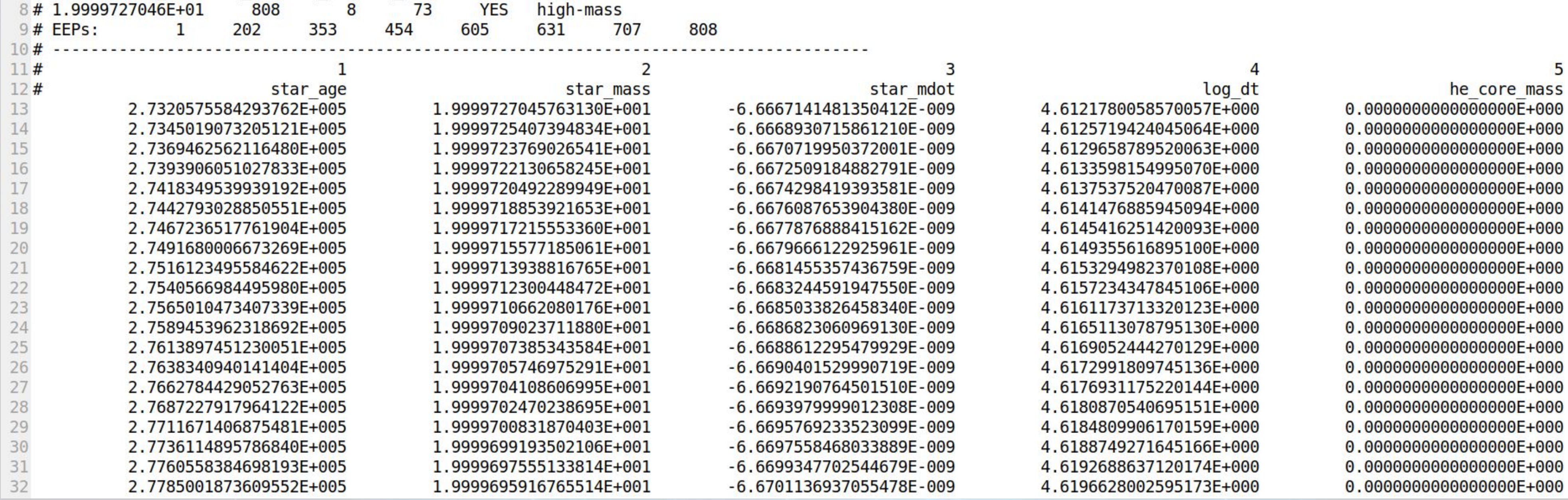
(*single* stars)

Let’s think!



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

Age, Mass, Radius, $\overbrace{\mathbf{T_{eff}\ [K]},\ \mathbf{\log(L/L_{\odot})}}^{\textbf{HR-diagram}}$, 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
          2.7540566984495980E+005          1.9999712300448472E+001         -6.6683244591947550E-009          4.6157234347845106E+000          0.0000000000000000E+000
          2.7565010473407339E+005          1.9999710662080176E+001         -6.6685033826458340E-009          4.6161173713320123E+000          0.0000000000000000E+000
          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
          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
```

(*single*
stars)

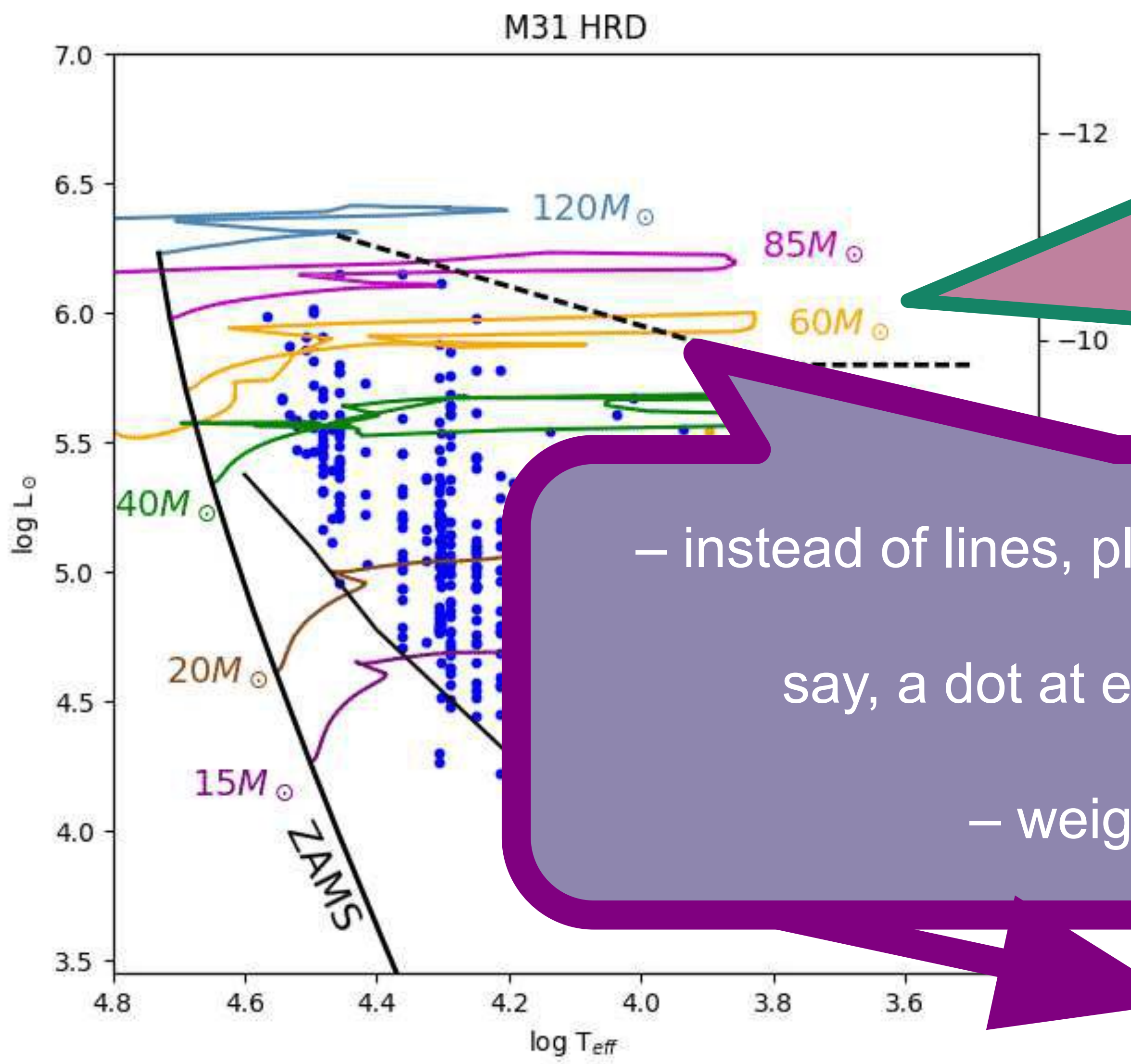
Let’s think!

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!

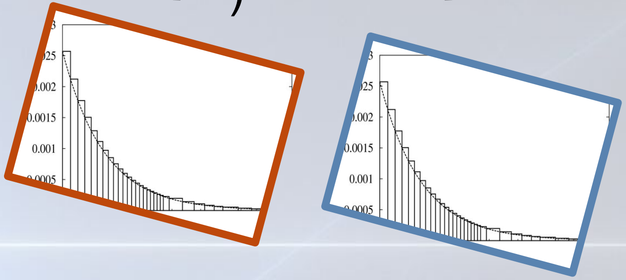
*simulated =
“synthetic”*

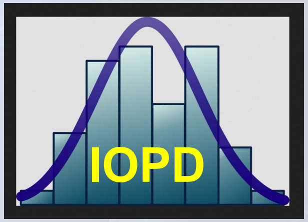
Population synthesis on ***binaries***

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

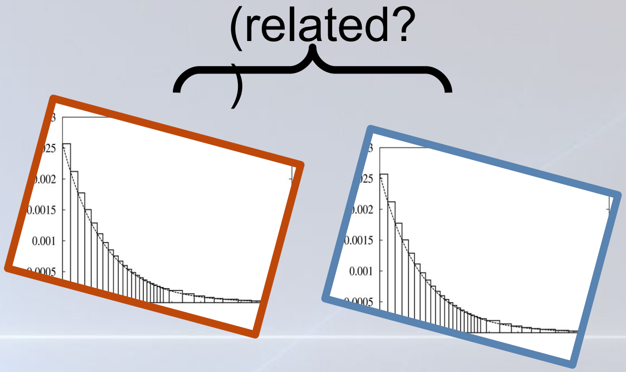
(related?)





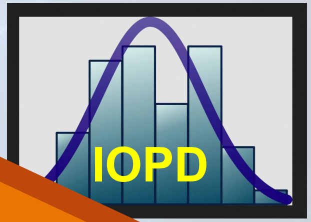
Population synthesis on ***binaries***

- 2 stars instead of 1
  - both ha individual IMFs



- orbital sep
  - Initial Orbital Peri

    same kind of thing as the IM
    i.e. an observation-based stati



- plus a *lot* of assumptions abo t n
  - mass transfer (stable/unstable? co rvative/non-con vative? ...)
  - Common Envelope phase (outcome: me separation afterwards?)
  - supernova physics… and the kick.

under active research

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

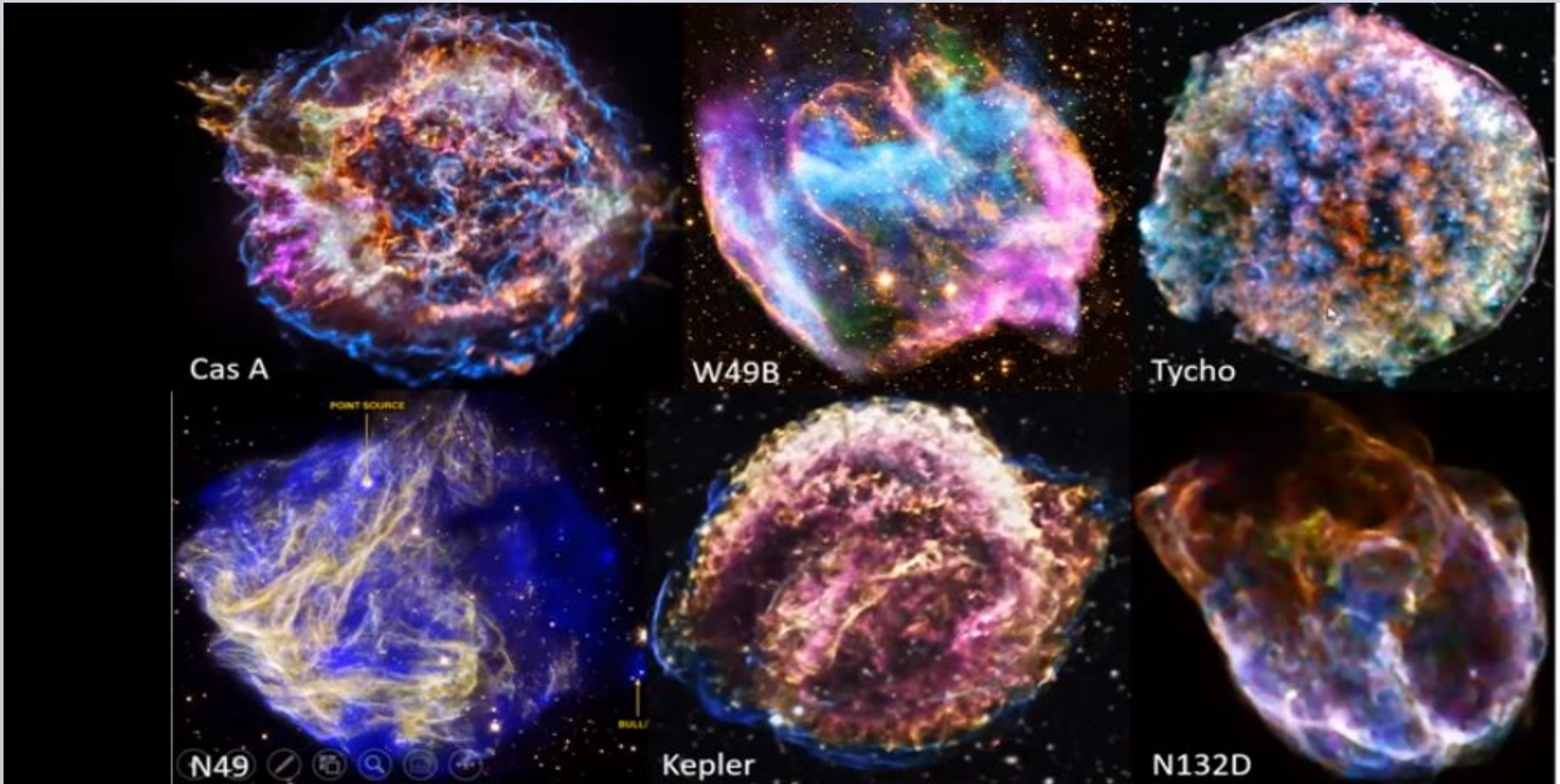
Kicks

- happens for single-star supernovae too

  = natal kick

  which happen when the NS is born

Each color corresponds to different emission process.



Kicks

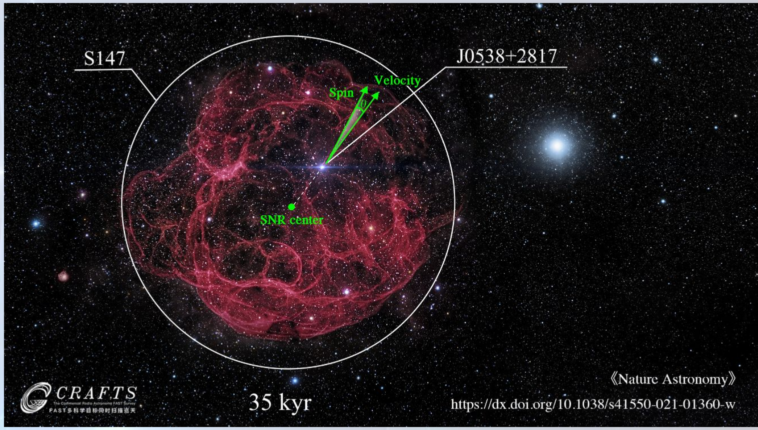
- happens for single-star supernovae too

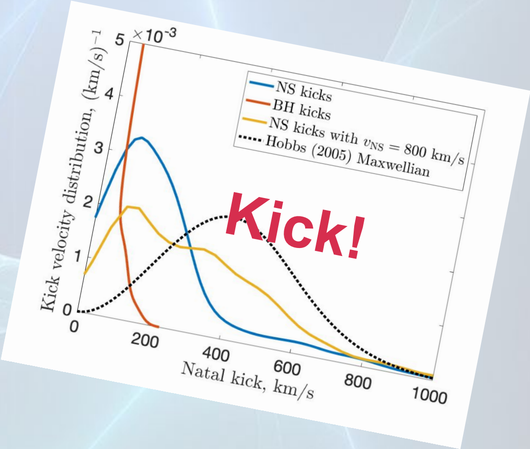
  = natal kick

  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

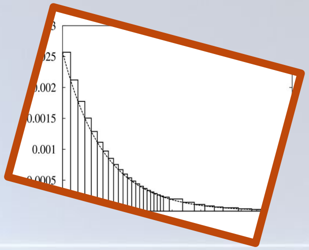
- Stellar evolution modelling
  - based on first principles *(5 stellar equations)*
  - follows one star's life at the time
  - IMF is not yet considered
  - result is *a line* ('track') in the HR-diagram

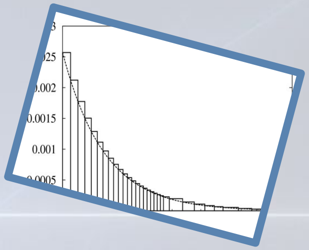
- Synthetic population modelling
  - *relies* on stellar evolution modelling
  - does not simulate the individual star's life (typically)
  - IMF is taken into account
  - result is a *statistically meaningful* prediction about a *population*

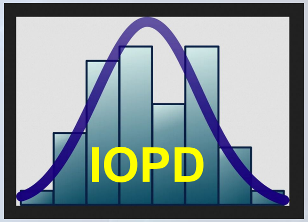
Today…

…the last steps!

Star-formation history



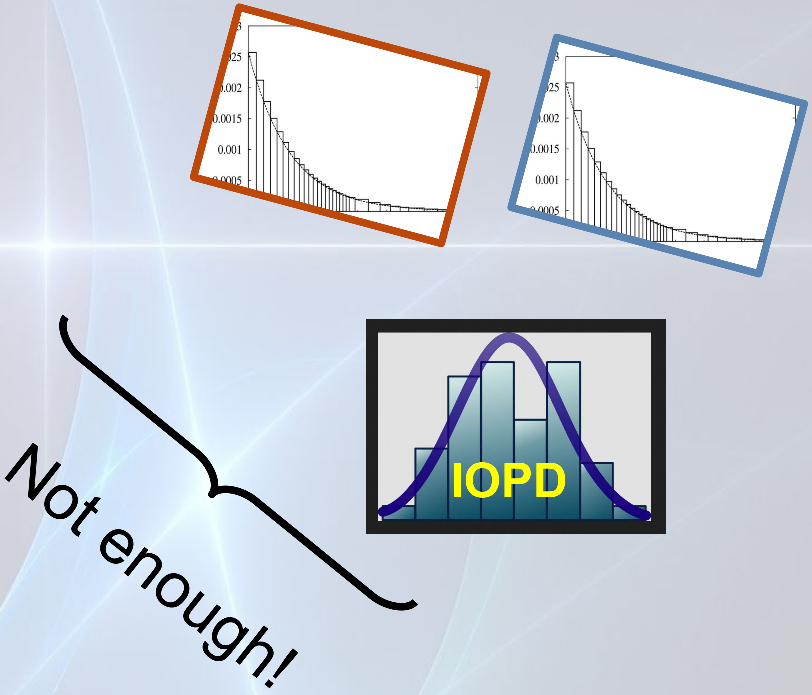




Not enough!

Star-formation history

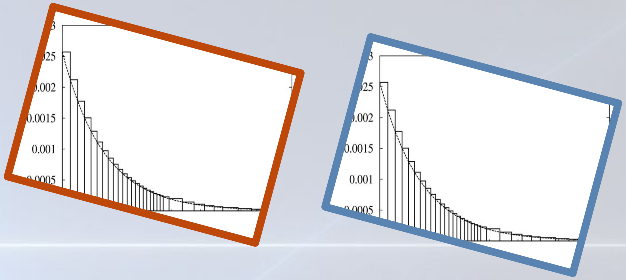
- We need to know the *history* of how the stars are being born…

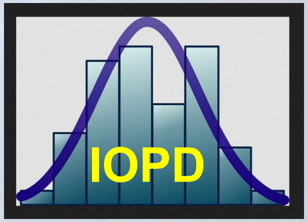


Not enough!

Star-formation history

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





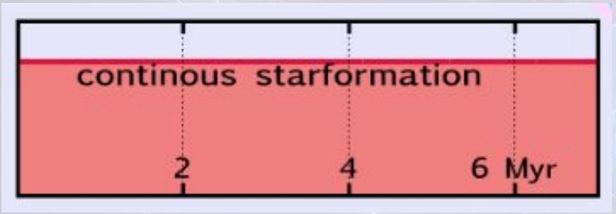
Not enough!

star-formation rate

SFR

or anything else

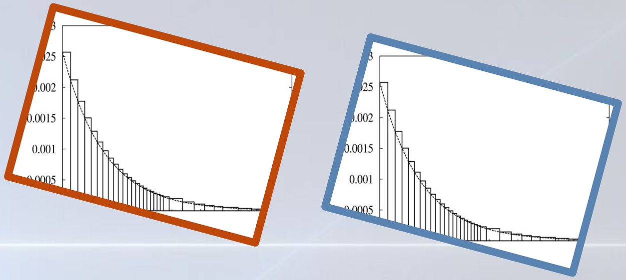
SFR

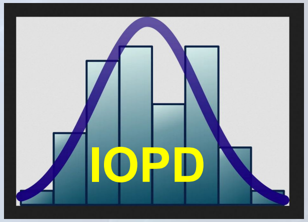


Unit:
$M_\odot$/yr

Star-formation history

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





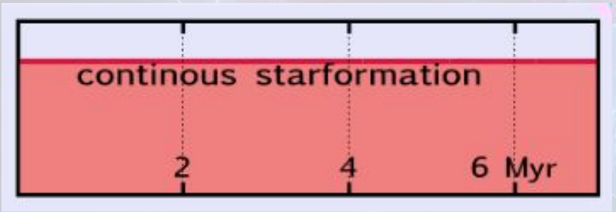
Not enough!

star-formation rate

SFR

or anything else

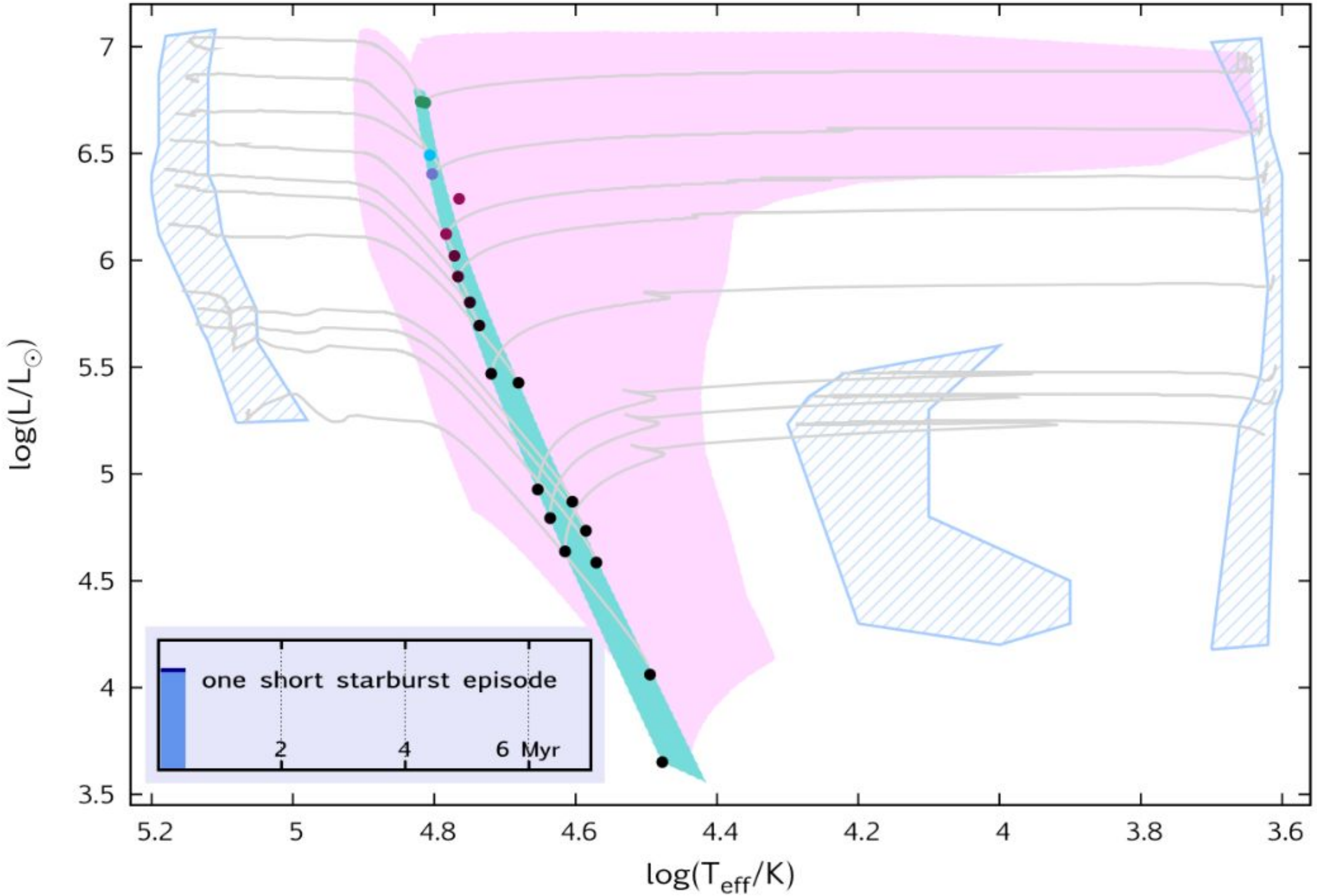
SFR



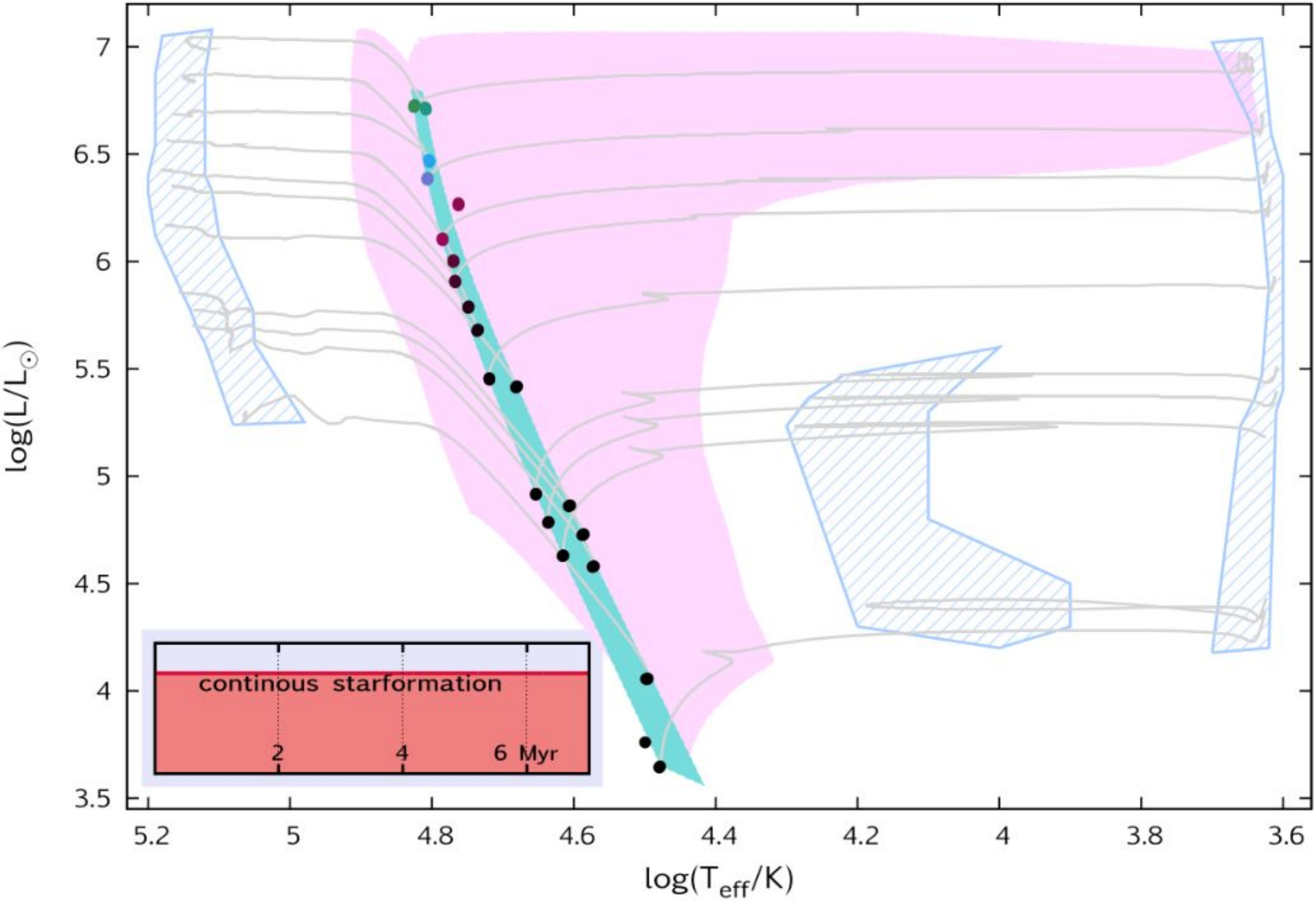
Unit: $M_\odot$/yr

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

Simulating a galaxy… or starcluster

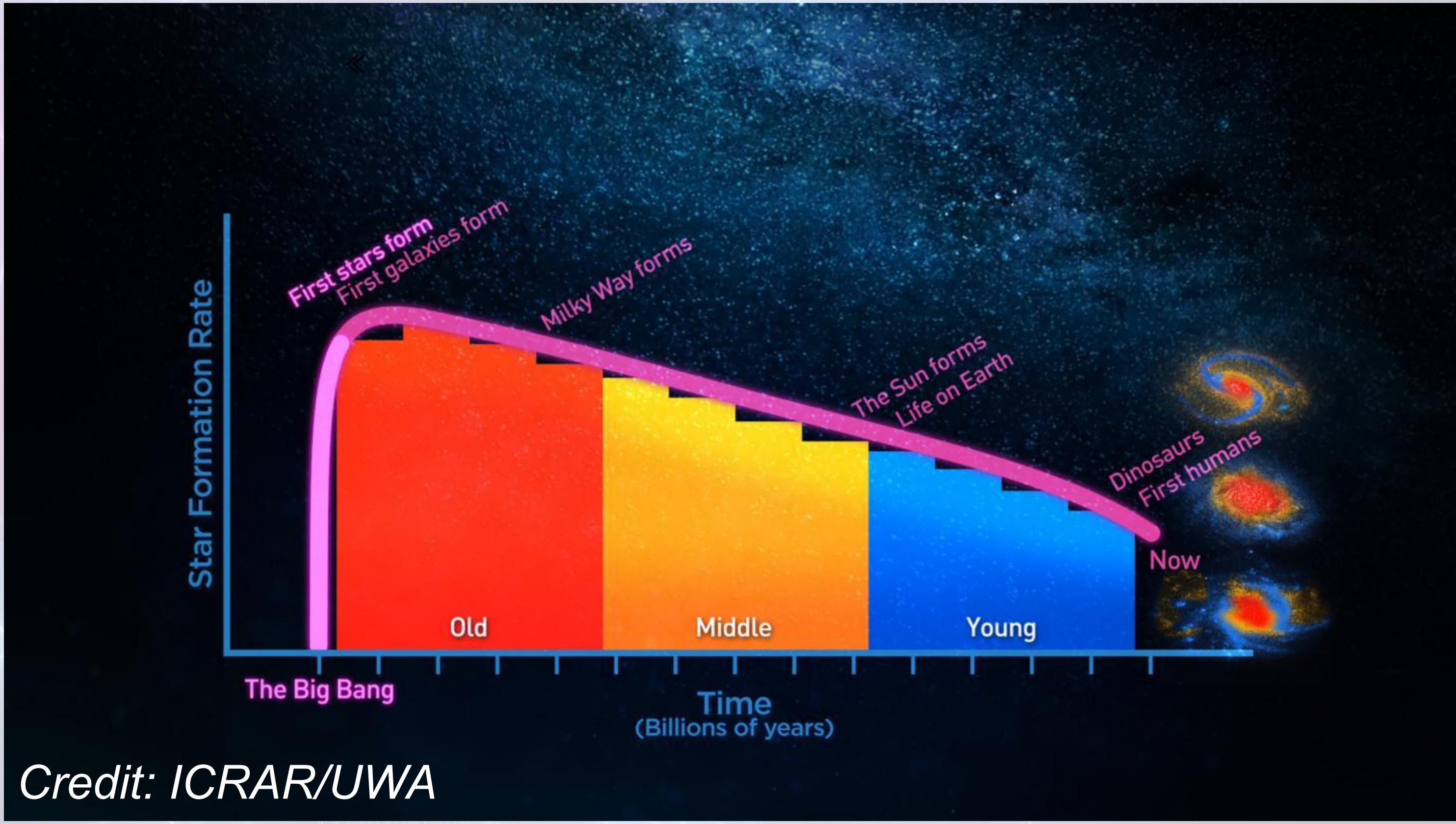


Simulating a galaxy… or starcluster



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

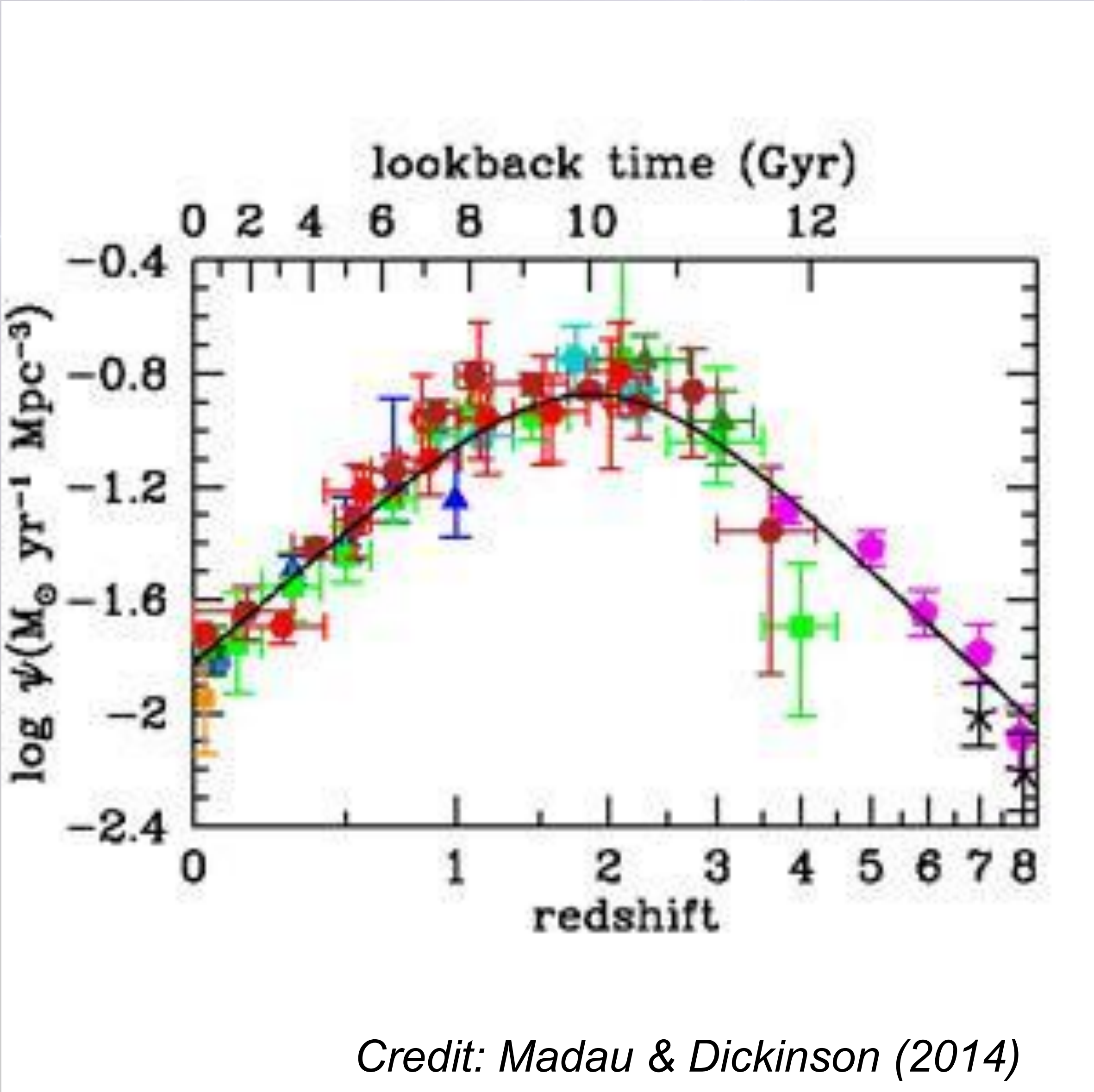
- This is what we need to predict GW-event rates from synthetic populations



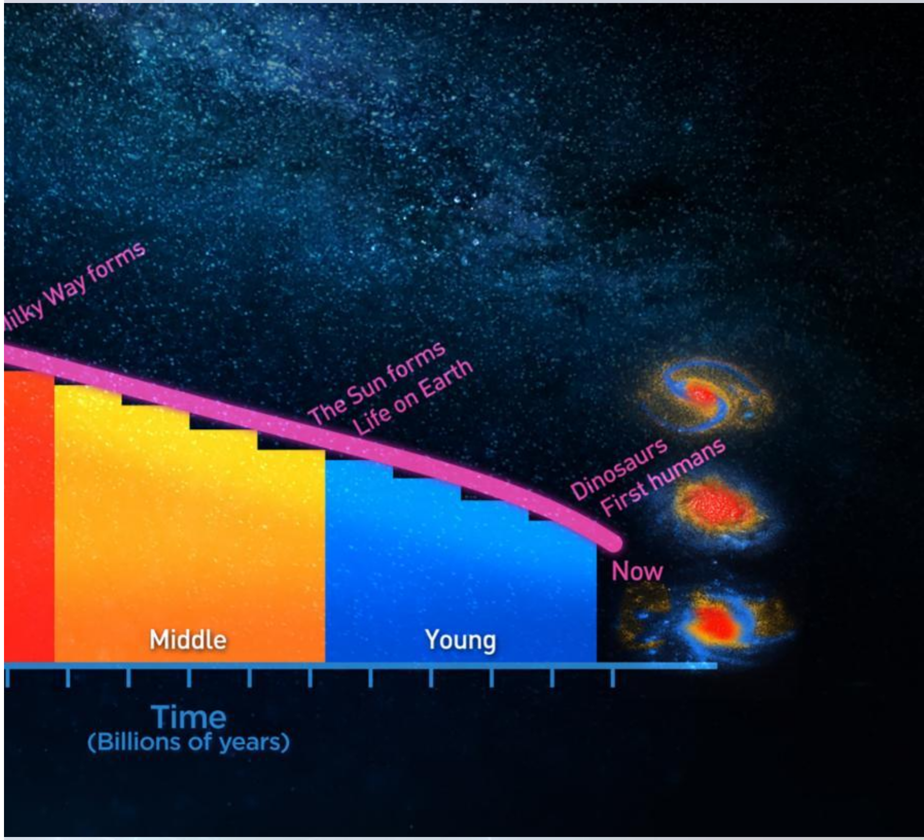
Credit: ICRAR/UWA

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

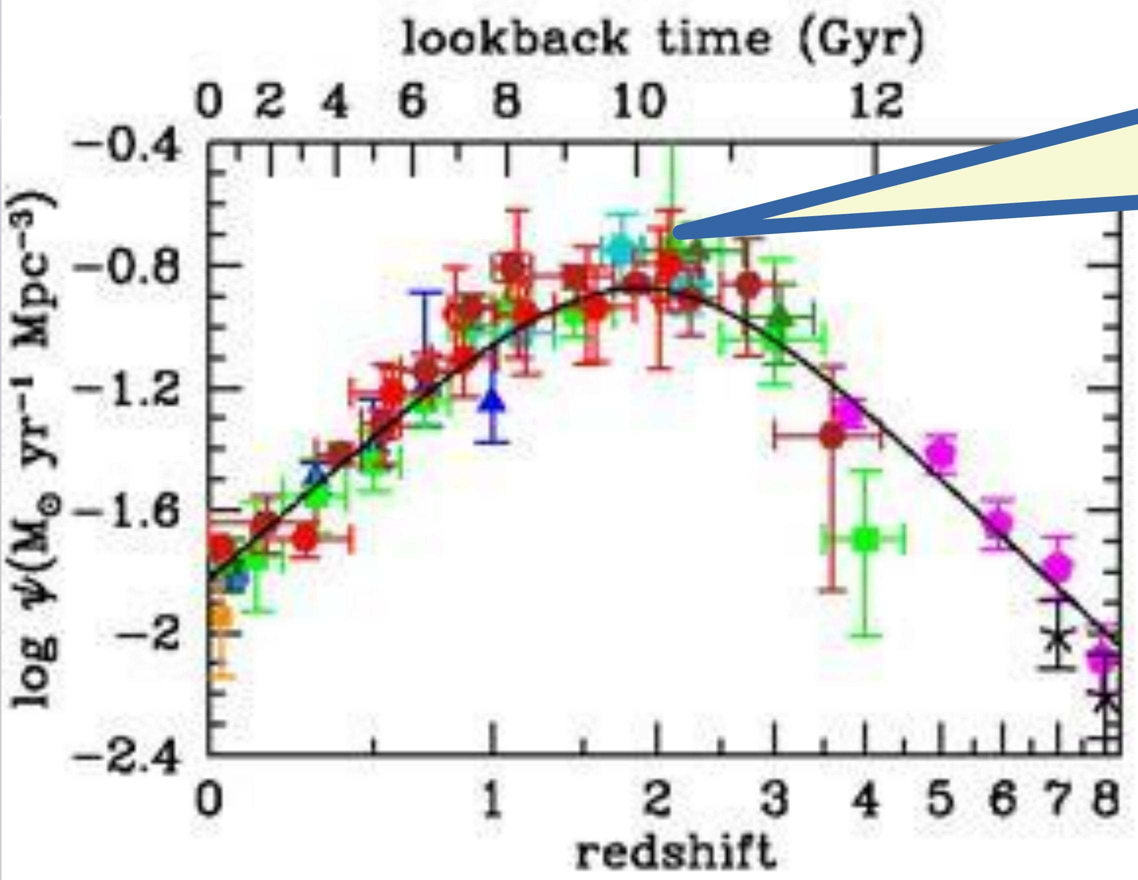
edict GW-event rates



Credit: Madau & Dickinson (2014)

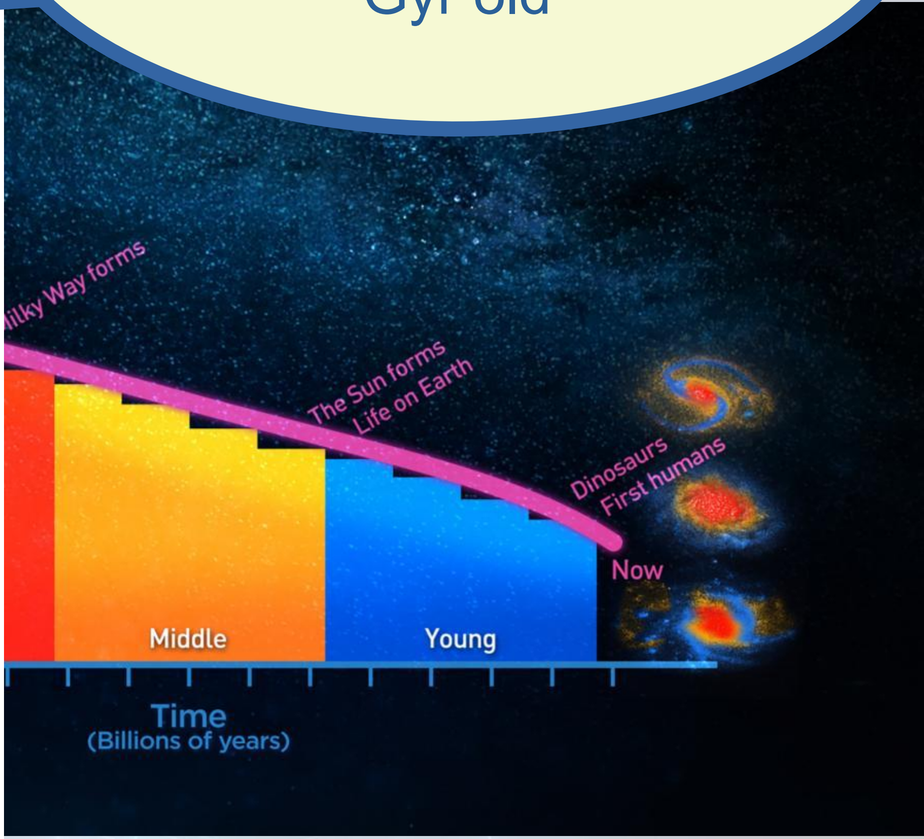


From star-formation history to ***cosmic*** star-formation history

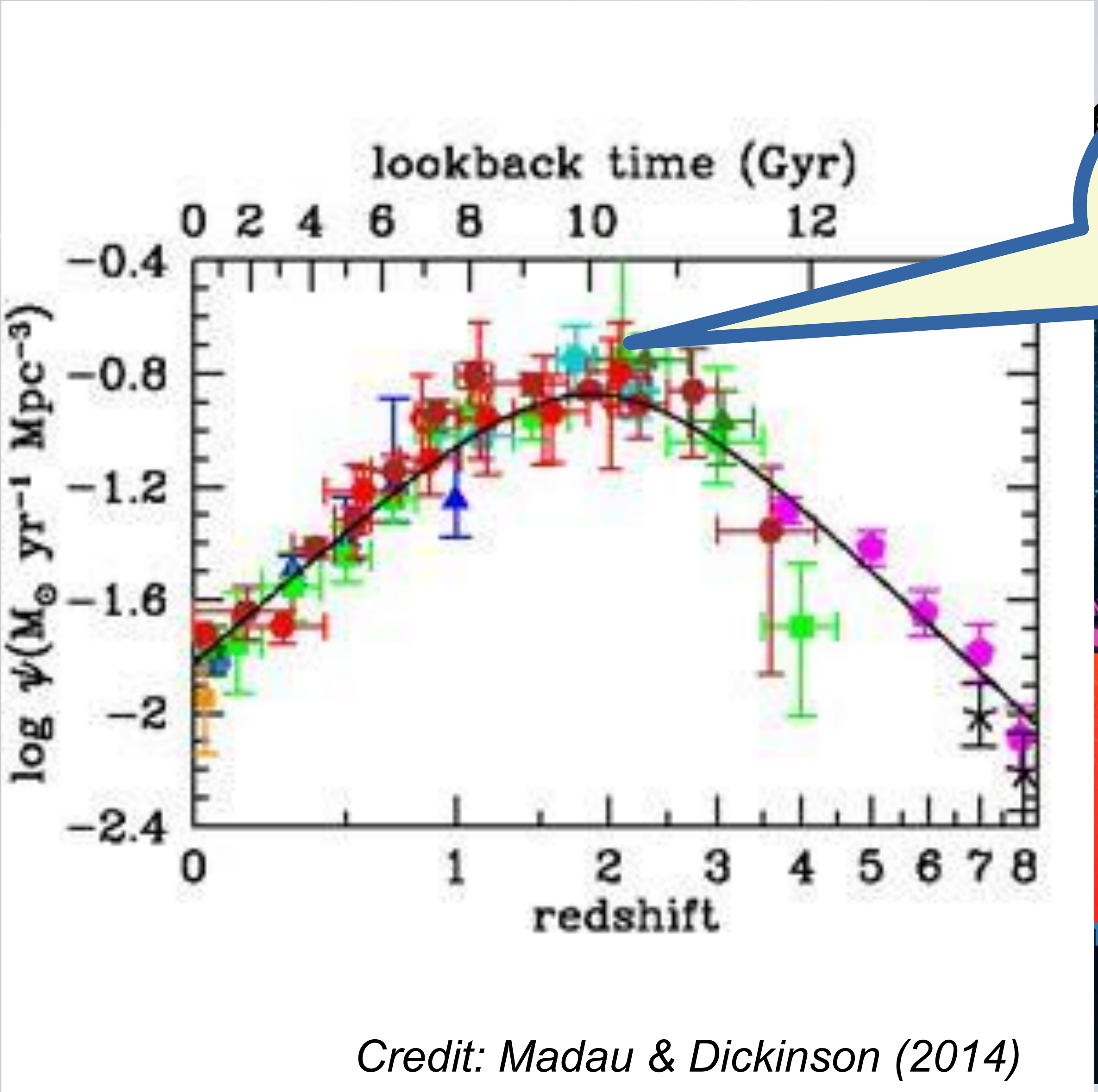


Credit: Madau & Dickinson (2014)

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

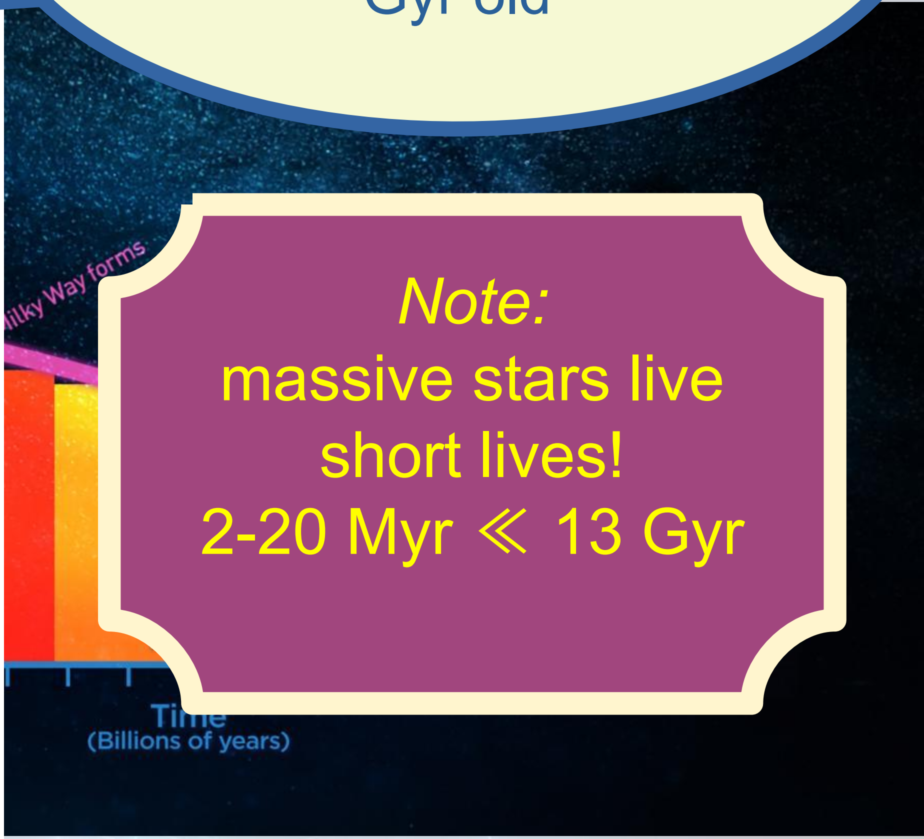


From star-formation history to ***cosmic*** star-formation history



Credit: Madau & Dickinson (2014)

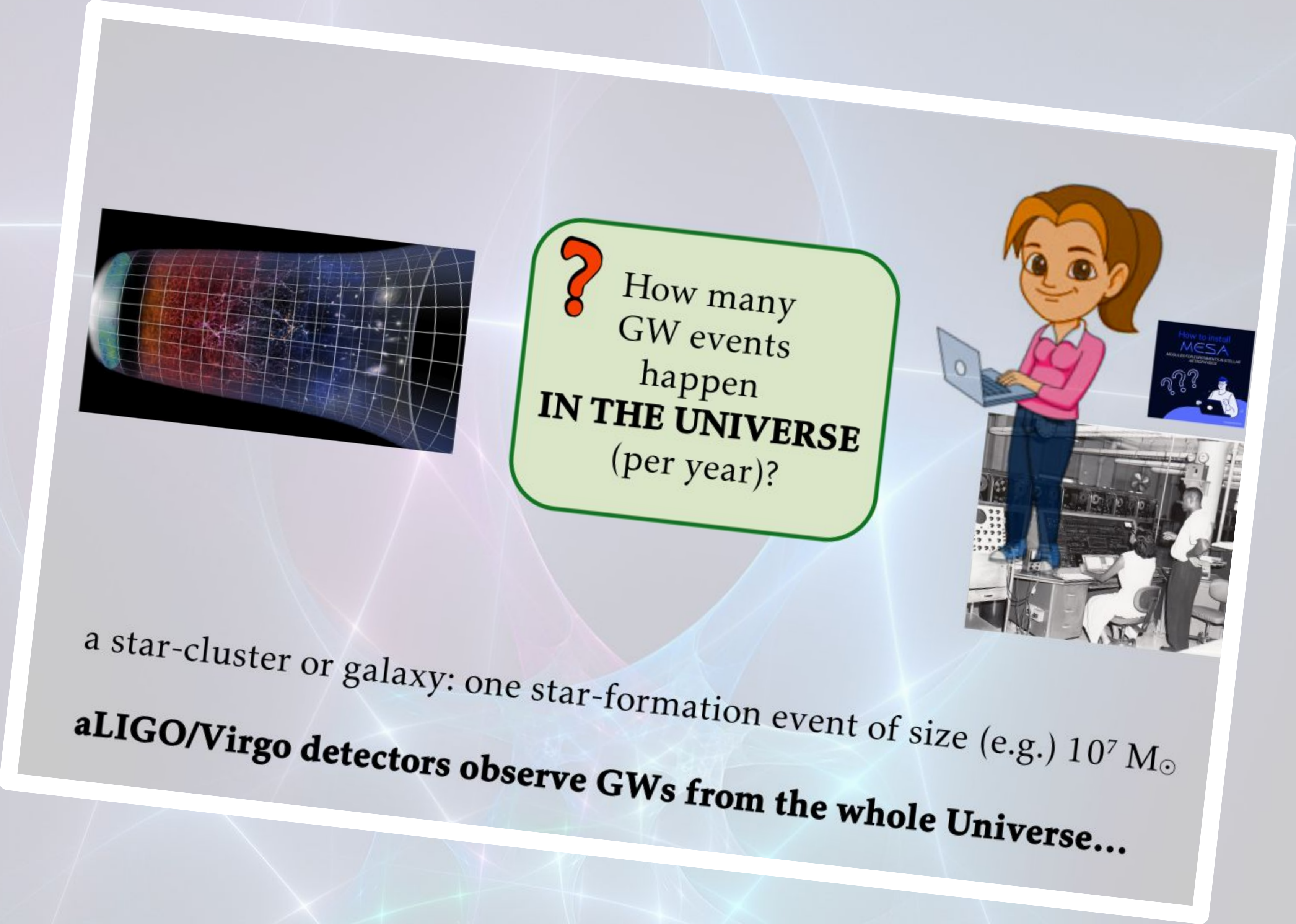
Peaking: somewhere around z = 2, when the Universe was ~3.5 Gyr old



Note:
massive stars live short lives!
2-20 Myr $\ll$ 13 Gyr

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

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

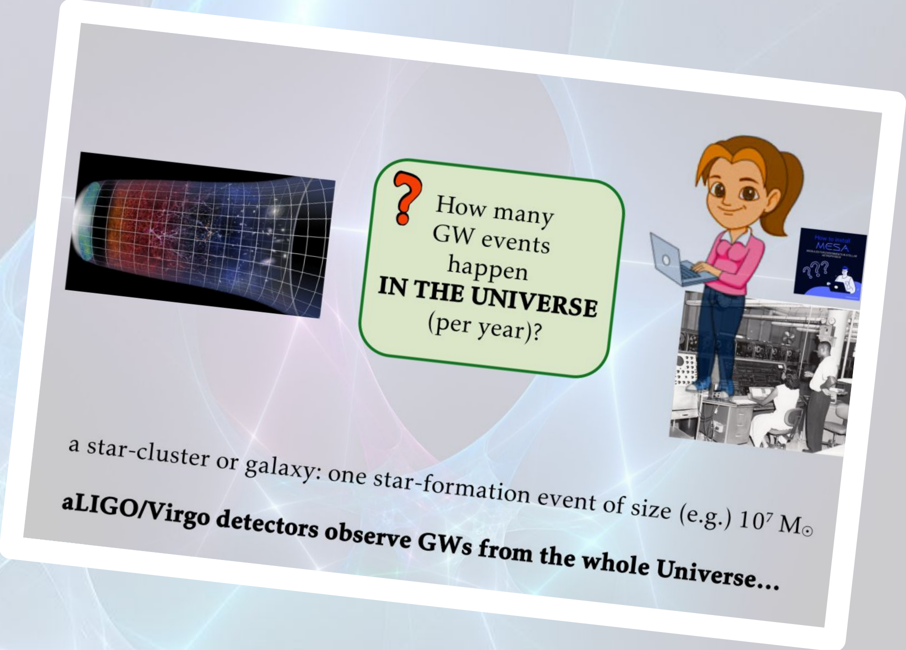


How many GW events happen **IN THE UNIVERSE** (per year)?

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 *(kind of)* question of this whole lecture series

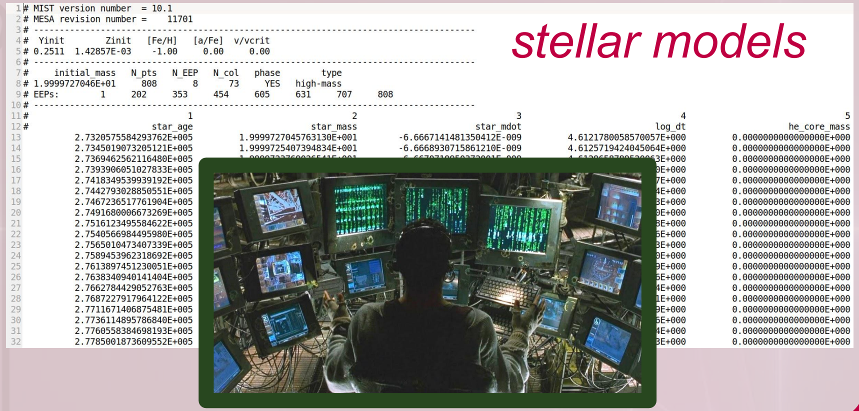


How many GW events happen **IN THE UNIVERSE** (per year)?

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...

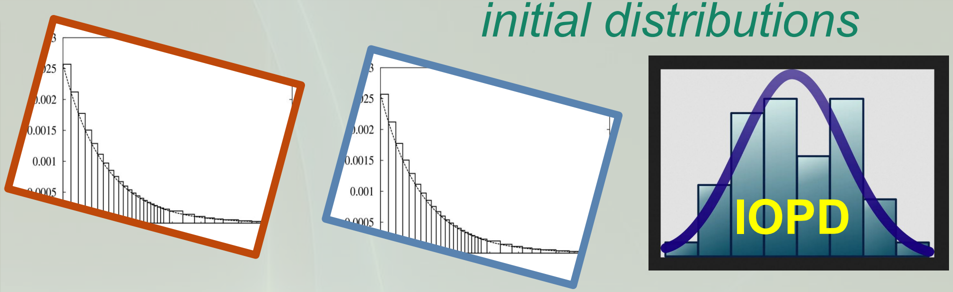
Now we can answer the original *(kind of)* question of this whole lecture series



stellar models

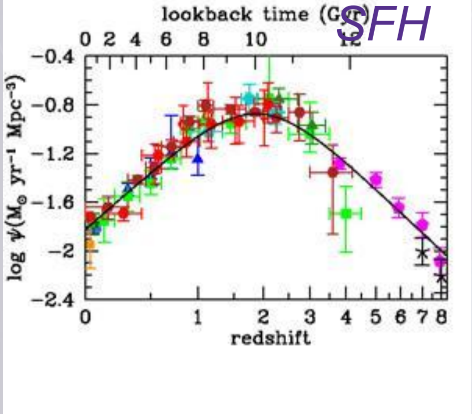
```
# MIST version number  = 10.1
# MESA revision number =    11701
# ---------------------------------------------------------------------------------------
#  Yinit        Zinit   [Fe/H]   [a/Fe]  v/vcrit
# 0.2511  1.42857E-03    -1.00     0.00     0.00
# ---------------------------------------------------------------------------------------
#     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                                                                            3E+000    0.0000000000000000E+000
       2.7393906051027833E+005                                                                            0E+000    0.0000000000000000E+000
       2.7418349539939192E+005                                                                            7E+000    0.0000000000000000E+000
       2.7442793028850551E+005                                                                            4E+000    0.0000000000000000E+000
       2.7467236517761904E+005                                                                            3E+000    0.0000000000000000E+000
       2.7491680006673269E+005                                                                            0E+000    0.0000000000000000E+000
       2.7516123495584622E+005                                                                            3E+000    0.0000000000000000E+000
       2.7540566984495980E+005                                                                            6E+000    0.0000000000000000E+000
       2.7565010473407339E+005                                                                            3E+000    0.0000000000000000E+000
       2.7589453962318692E+005                                                                            0E+000    0.0000000000000000E+000
       2.7613897451230051E+005                                                                            9E+000    0.0000000000000000E+000
       2.7638340940141404E+005                                                                            6E+000    0.0000000000000000E+000
       2.7662784429052763E+005                                                                            4E+000    0.0000000000000000E+000
       2.7687227917964122E+005                                                                            1E+000    0.0000000000000000E+000
       2.7711671406875481E+005                                                                            9E+000    0.0000000000000000E+000
       2.7736114895786840E+005                                                                            6E+000    0.0000000000000000E+000
       2.7760558384698193E+005                                                                            4E+000    0.0000000000000000E+000
       2.7785001873609552E+005                                                                            3E+000    0.0000000000000000E+000
```

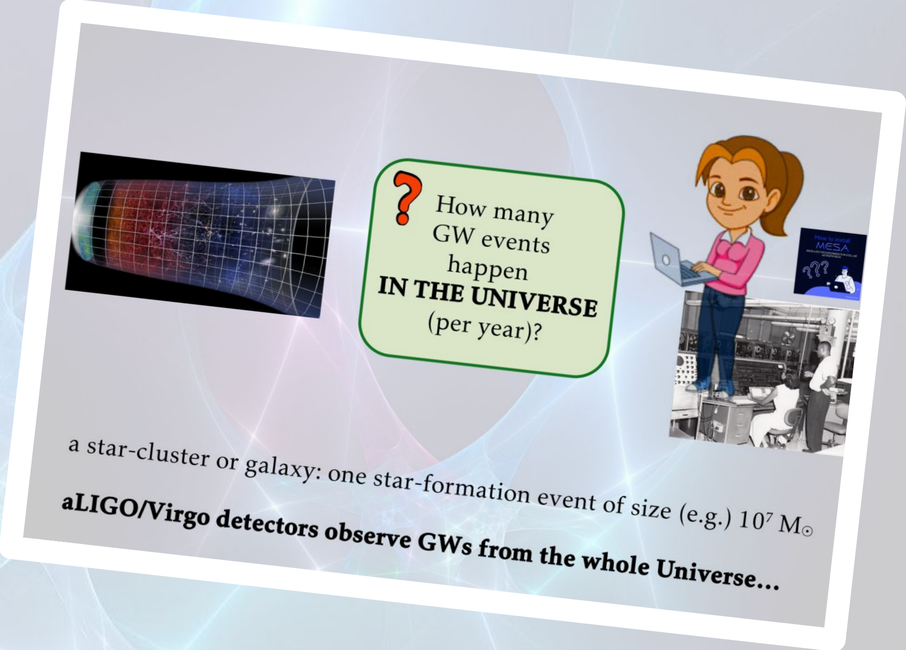
initial distributions



+ a lot of assumptions about binary physics

cosmic SFH



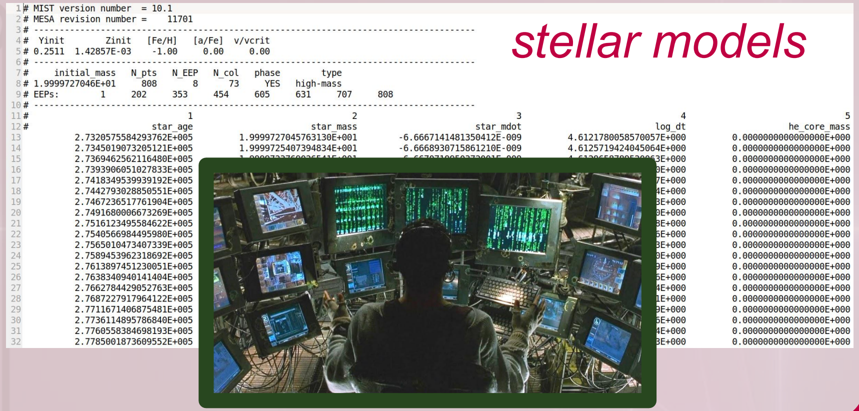


? How many GW events happen **IN THE UNIVERSE** (per year)?

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...

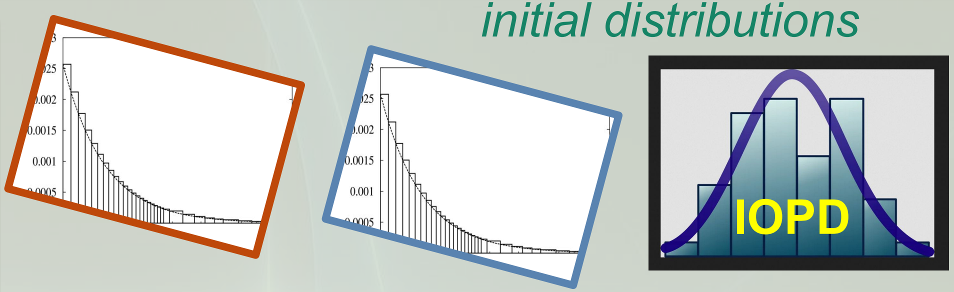
Now we can answer the original *(kind of)* question of this whole lecture series



stellar models

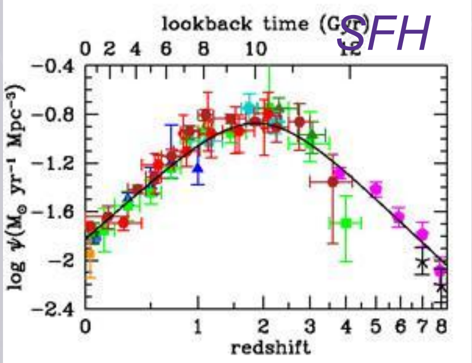
```
# MIST version number  = 10.1
# MESA revision number =    11701
# ---------------------------------------------------------------------------------------
#  Yinit        Zinit   [Fe/H]   [a/Fe]  v/vcrit
# 0.2511  1.42857E-03    -1.00     0.00     0.00
# ---------------------------------------------------------------------------------------
#     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                                                                                                     0.0000000000000000E+000
             2.7393906051027833E+005                                                                                                     0.0000000000000000E+000
             2.7418349539939192E+005                                                                                                     0.0000000000000000E+000
             2.7442793028850551E+005                                                                                                     0.0000000000000000E+000
             2.7467236517761904E+005                                                                                                     0.0000000000000000E+000
             2.7491680006673269E+005                                                                                                     0.0000000000000000E+000
             2.7516123495584622E+005                                                                                                     0.0000000000000000E+000
             2.7540566984495980E+005                                                                                                     0.0000000000000000E+000
             2.7565010473407339E+005                                                                                                     0.0000000000000000E+000
             2.7589453962318692E+005                                                                                                     0.0000000000000000E+000
             2.7613897451230051E+005                                                                                                     0.0000000000000000E+000
             2.7638340940141404E+005                                                                                                     0.0000000000000000E+000
             2.7662784429052763E+005                                                                                                     0.0000000000000000E+000
             2.7687227917964122E+005                                                                                                     0.0000000000000000E+000
             2.7711671406875481E+005                                                                                                     0.0000000000000000E+000
             2.7736114895786840E+005                                                                                                     0.0000000000000000E+000
             2.7760558384698193E+005                                                                                                     0.0000000000000000E+000
             2.7785001873609552E+005                                                                                                     0.0000000000000000E+000
```

initial distributions



+ a lot of assumptions about binary physics

cosmic SFH



Important piece of math:
Convolution
of two functions

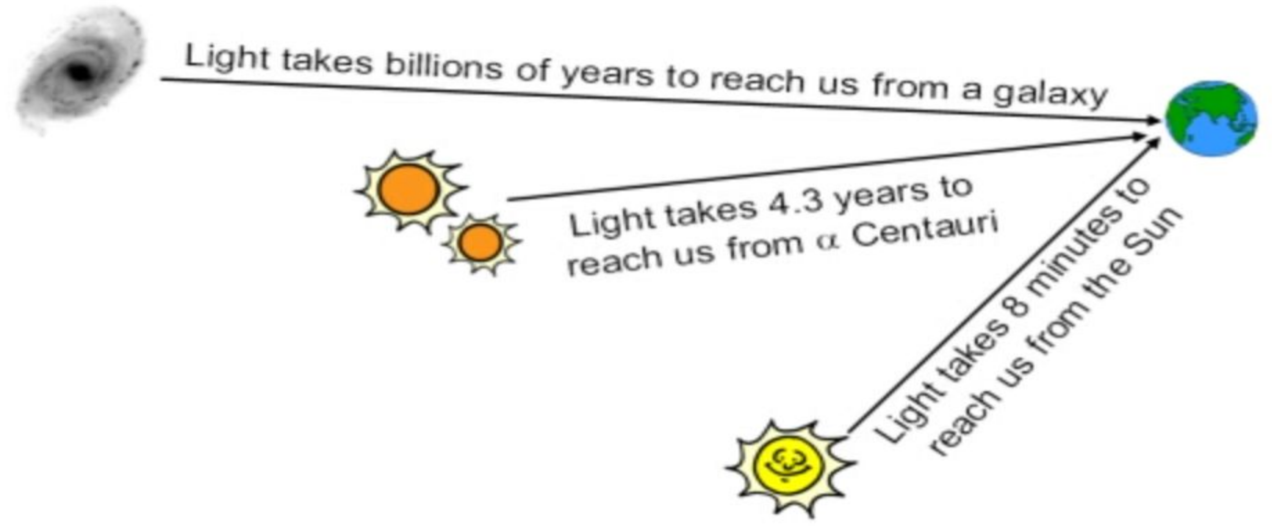
$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau)g(t-\tau)\,d\tau.$$

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*

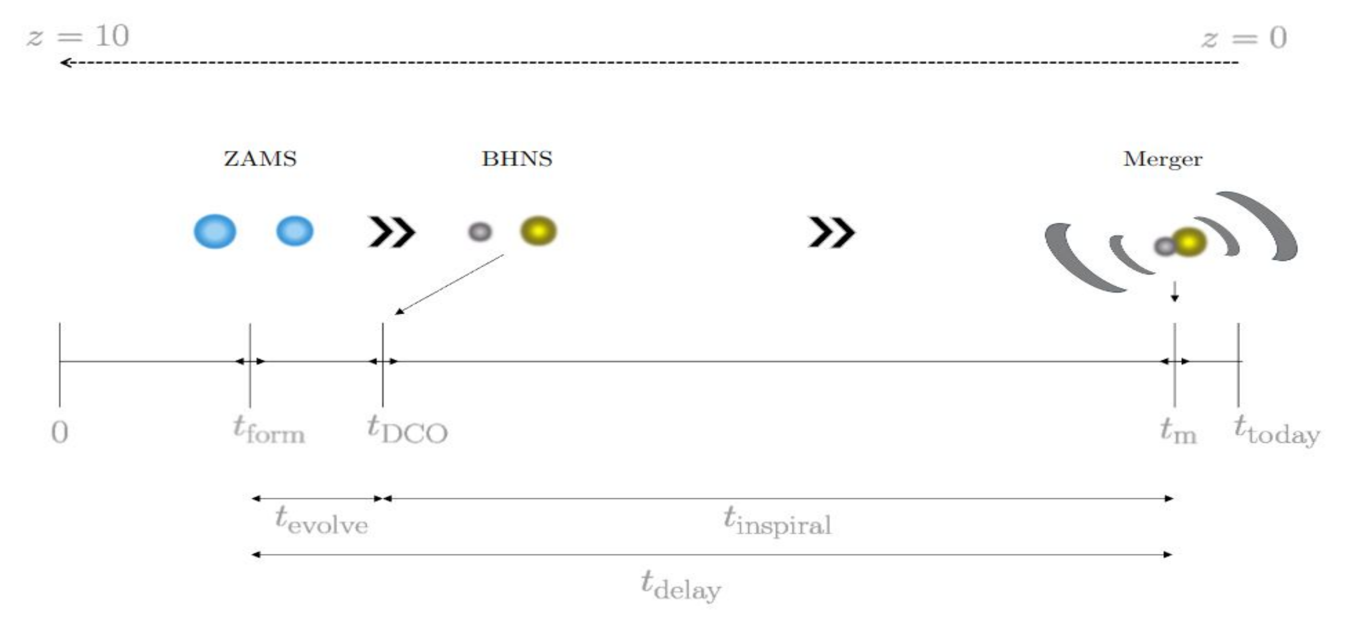


$$t_L(z) = \frac{2}{3H_0}\left(1 - \frac{1}{(1+z)^{3/2}}\right)$$

Some more terms

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**

$$\mathcal{M}_c \equiv \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- **Effective spin**

$$\chi_{\text{eff}} = \frac{M_1 \mathbf{a}_1 + M_2 \mathbf{a}_2}{M_1 + M_2} \hat{\mathbf{L}}$$

- **Orbital frequency**

$$f_{\text{orb}} = \frac{1}{2\pi} \sqrt{\frac{G(m_1 + m_2)}{a^3}}$$

- **Merger time**

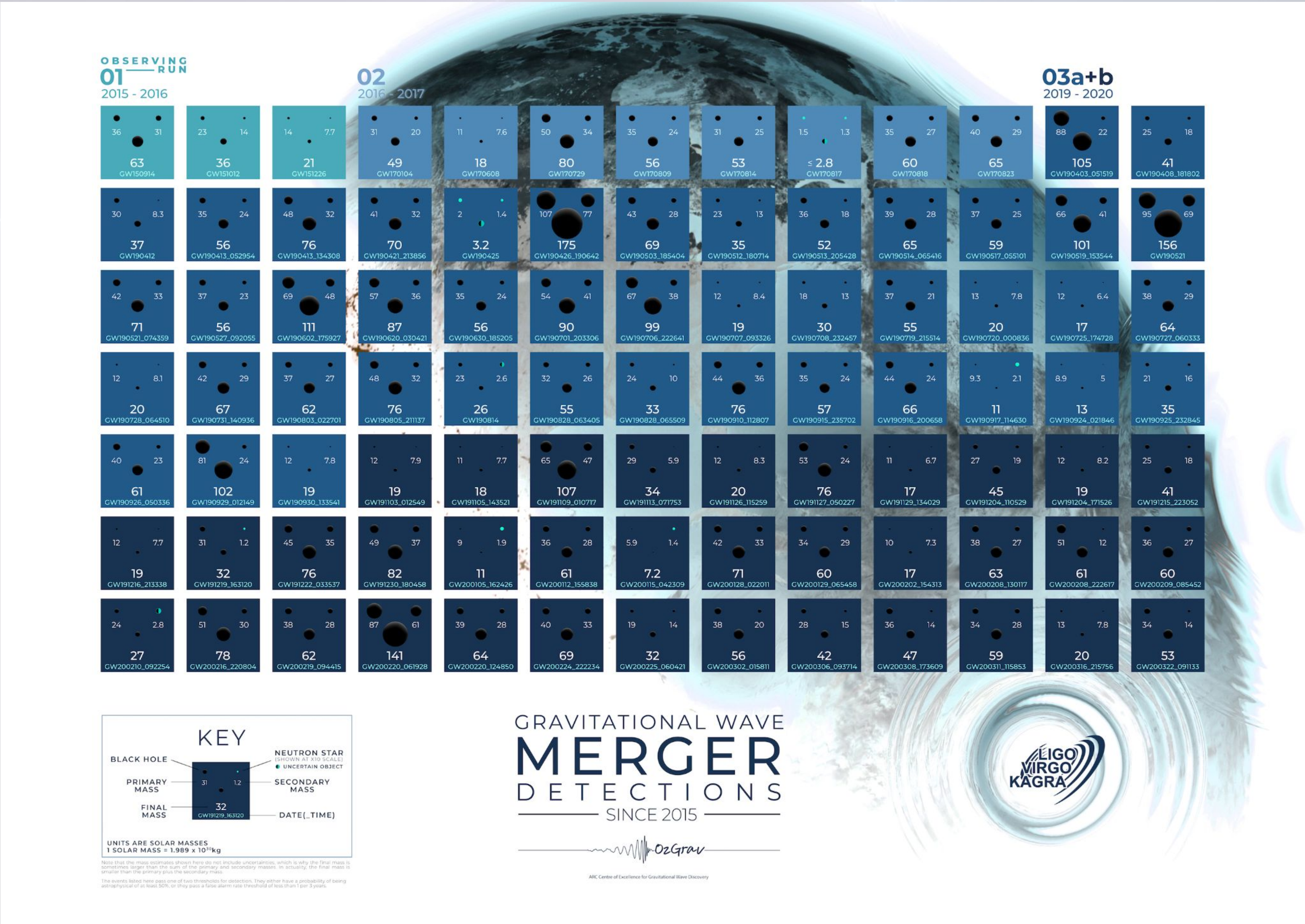
$$t_{\text{merge}} = \frac{12}{19} \frac{c_0^4}{\beta} \int_0^{e_0} \frac{\left[1 + (121/304)e^2\right]^{\frac{1181}{2299}}}{e^{-29/19} \left(1 - e^2\right)^{3/2}} \mathrm{d}e$$

- **Delay time . . .**

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

The Gravitational-Wave Transient Catalogue 3 (GWTC-3)



OBSERVING RUN

01 2015 - 2016

02 2016 - 2017

03a+b 2019 - 2020

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤ 2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

KEY

UNITS ARE SOLAR MASSES
1 SOLAR MASS = $1.989 x 10^{30}$kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

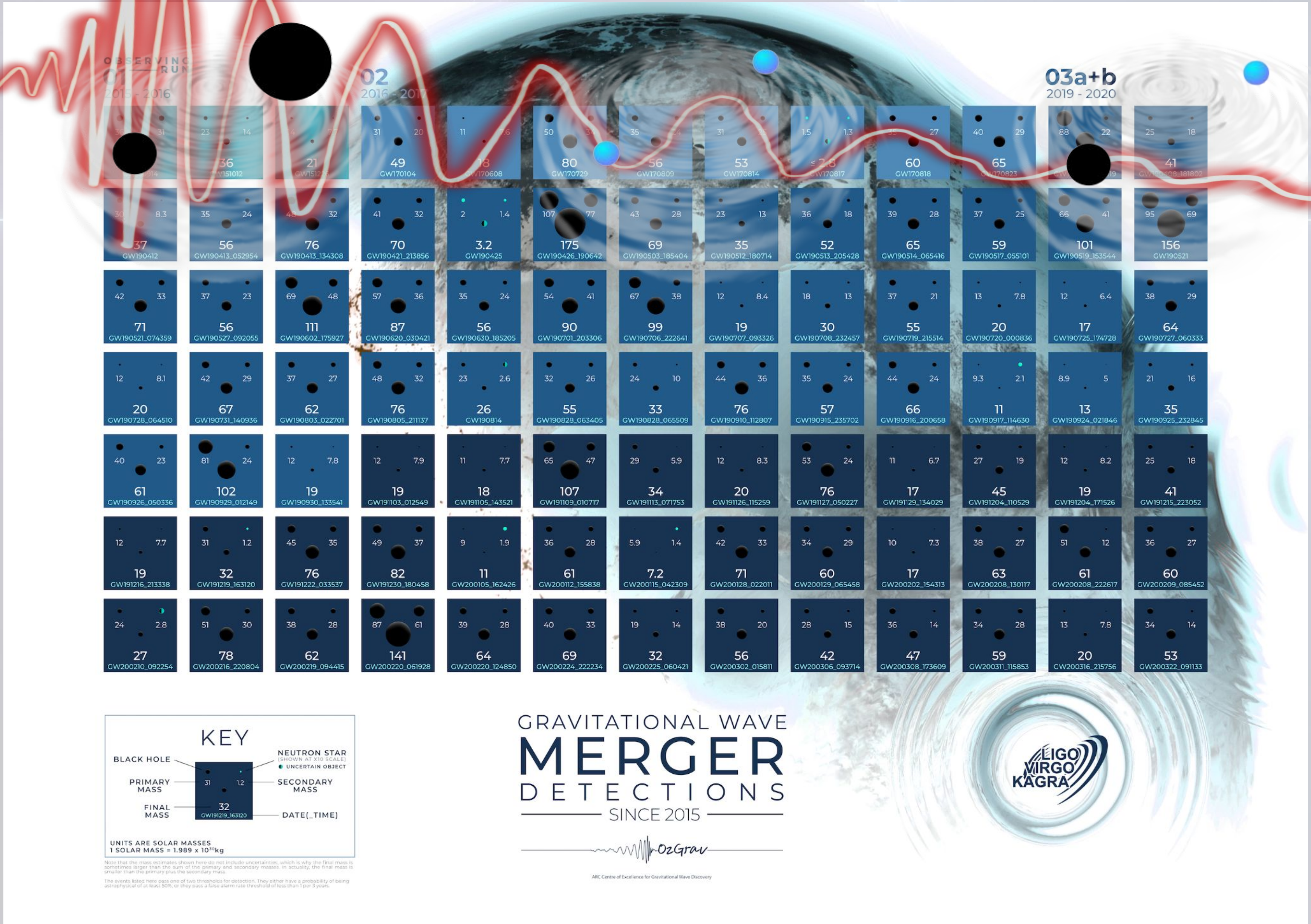
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

The Gravitational-Wave Transient Catalogue 3 (GWTC-3)



OBSERVING RUN
O1
2015 - 2016

O2
2016 - 2017

O3a+b
2019 - 2020

[illegible] 31 [illegible] [illegible]	23 14 36 GW151012	[illegible] 21 [illegible]	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤ 2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 [illegible] [illegible]	25 18 41 [illegible]
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

KEY

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

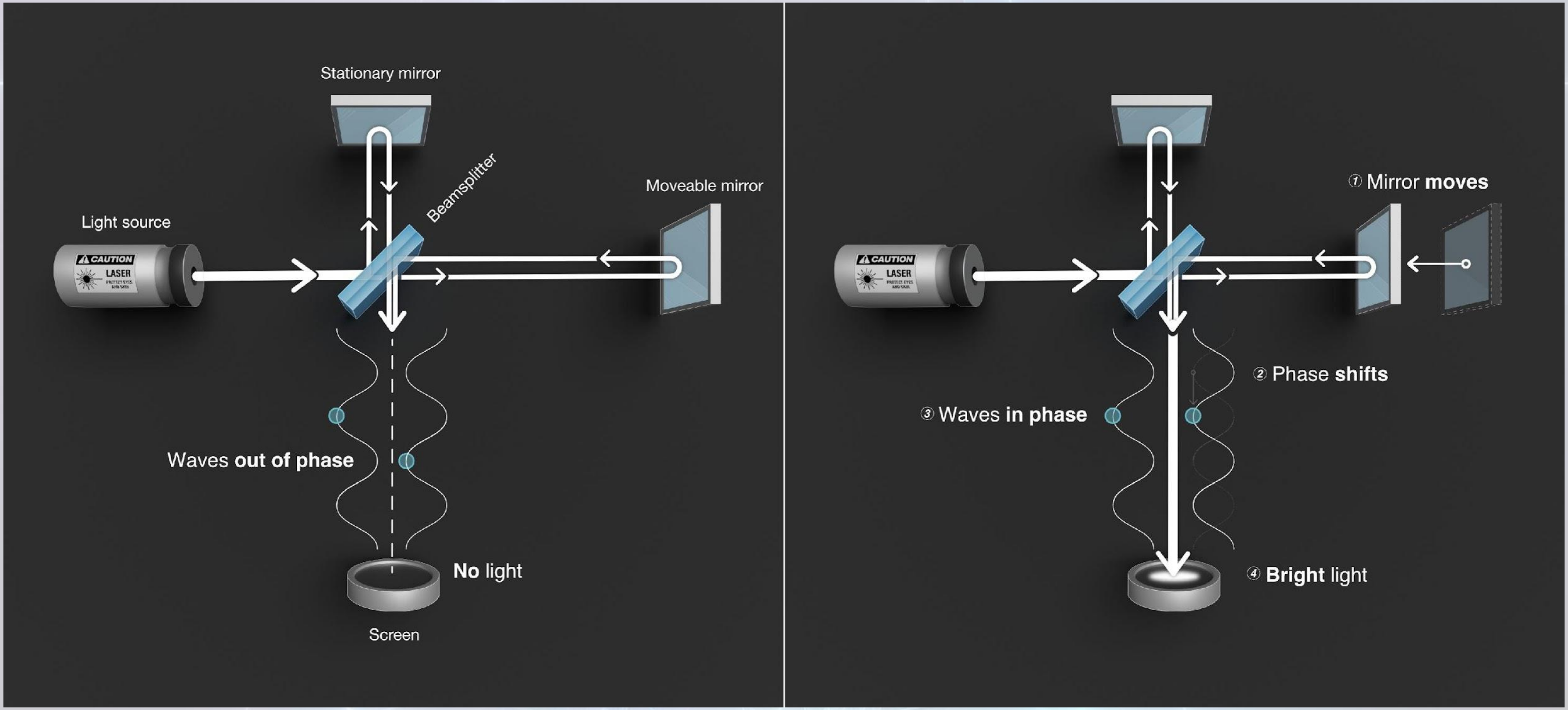
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

Detector

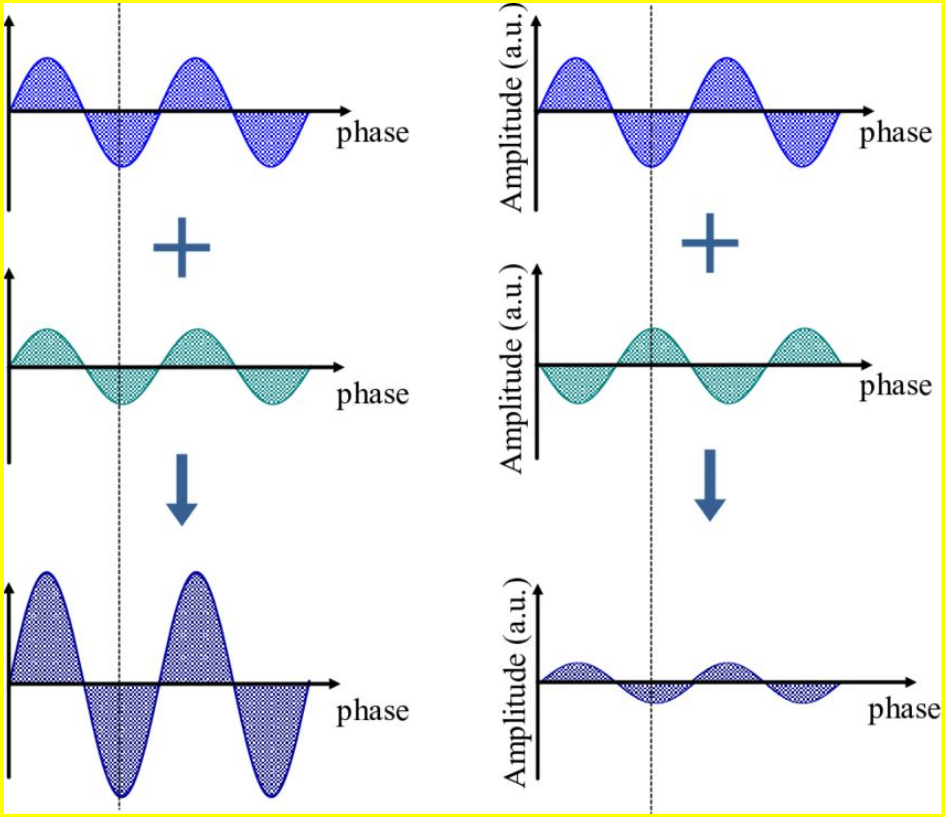
Interferometer:



Credit: S. Kelley/NIST

Interference

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

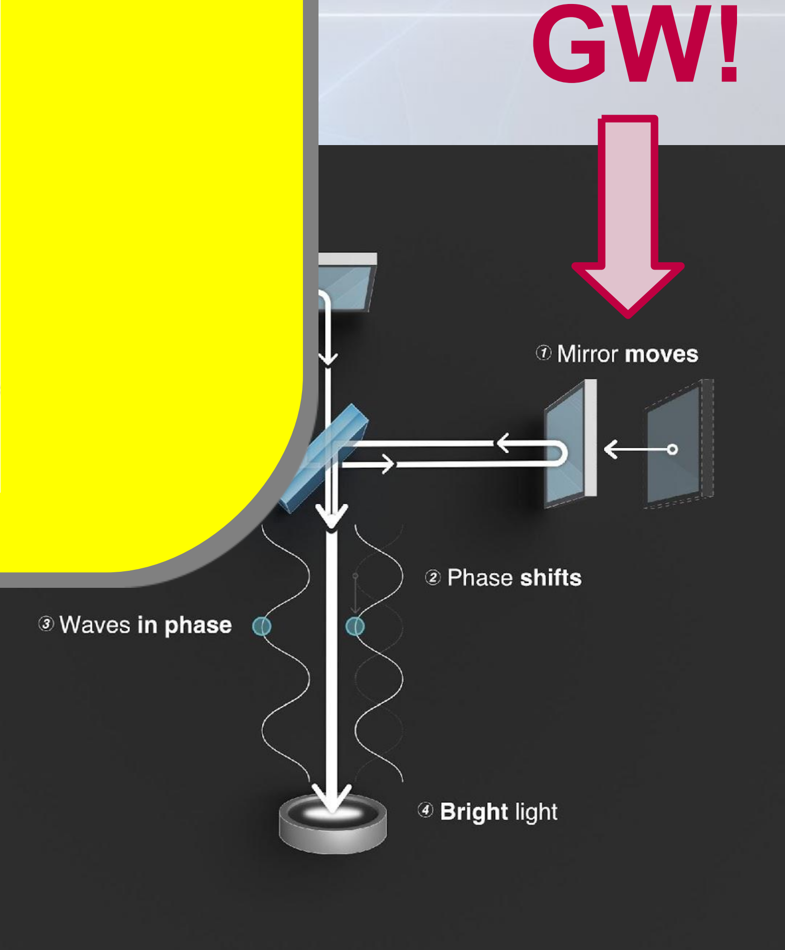


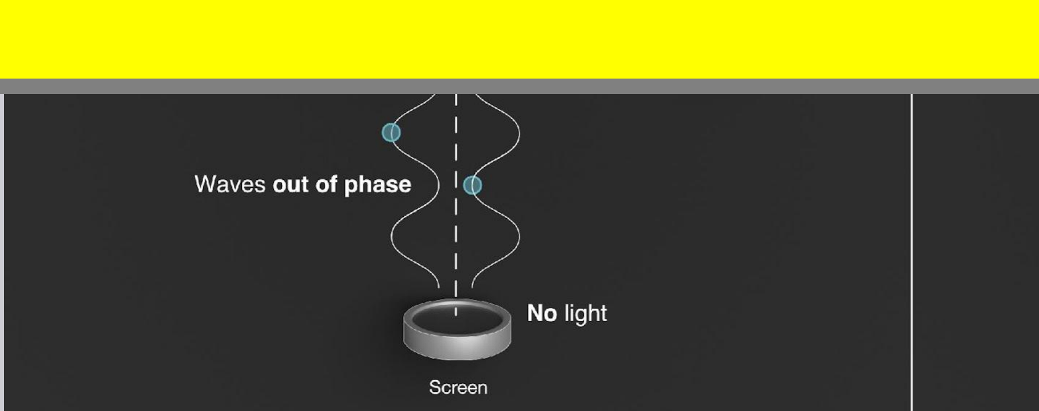
s

n be directly
measured GW-signal

nd m_2, a strong

lution is needed

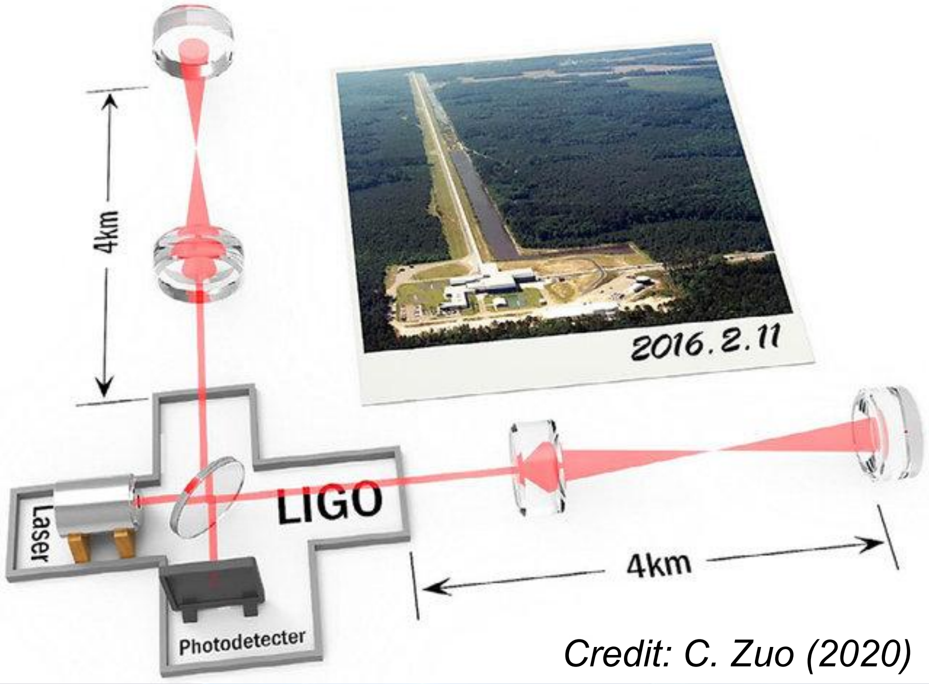




Credit: S. Kelley/NIST

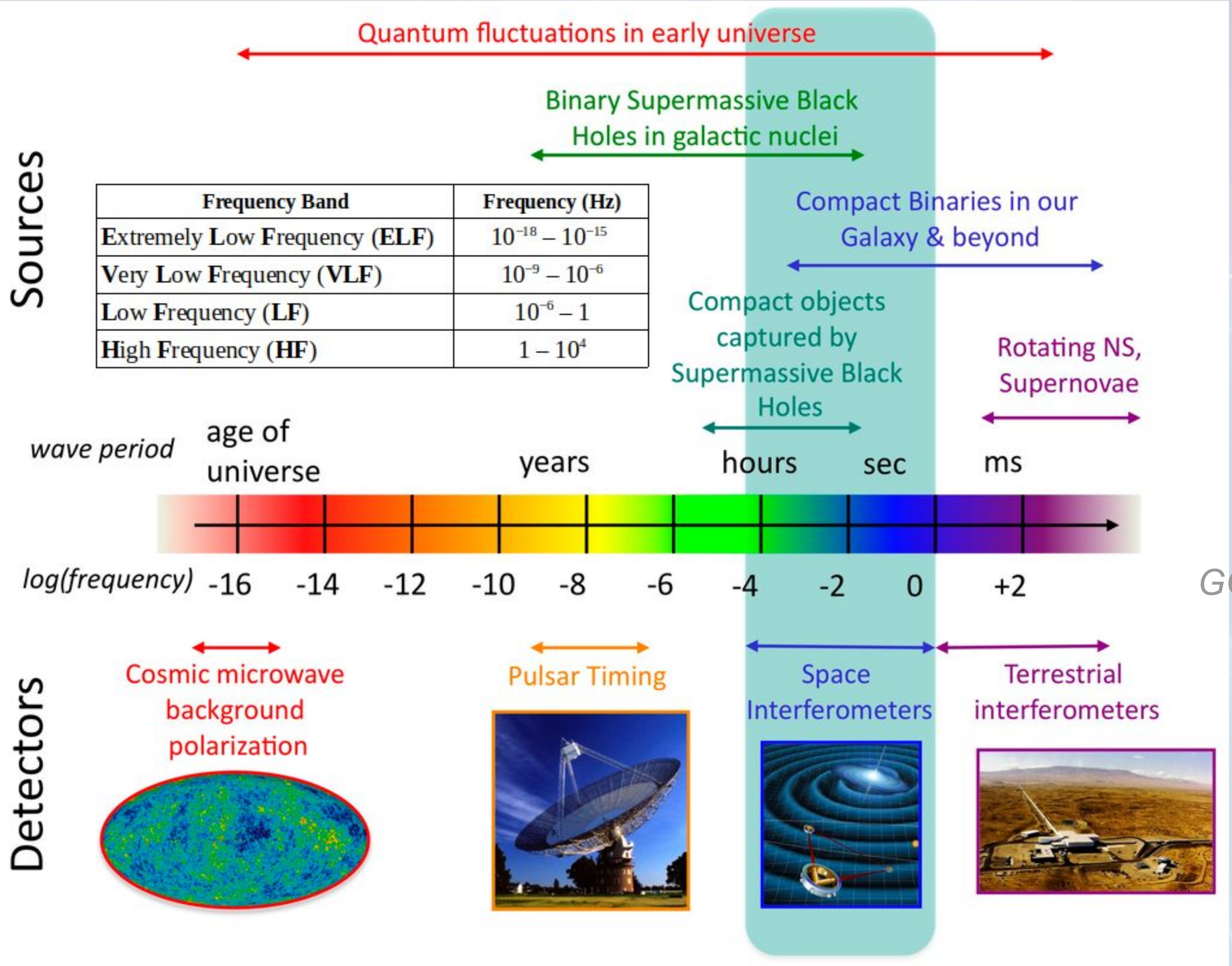
And some names you MUST know

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



Credit: C. Zuo (2020)

Gravitational wave spectrum

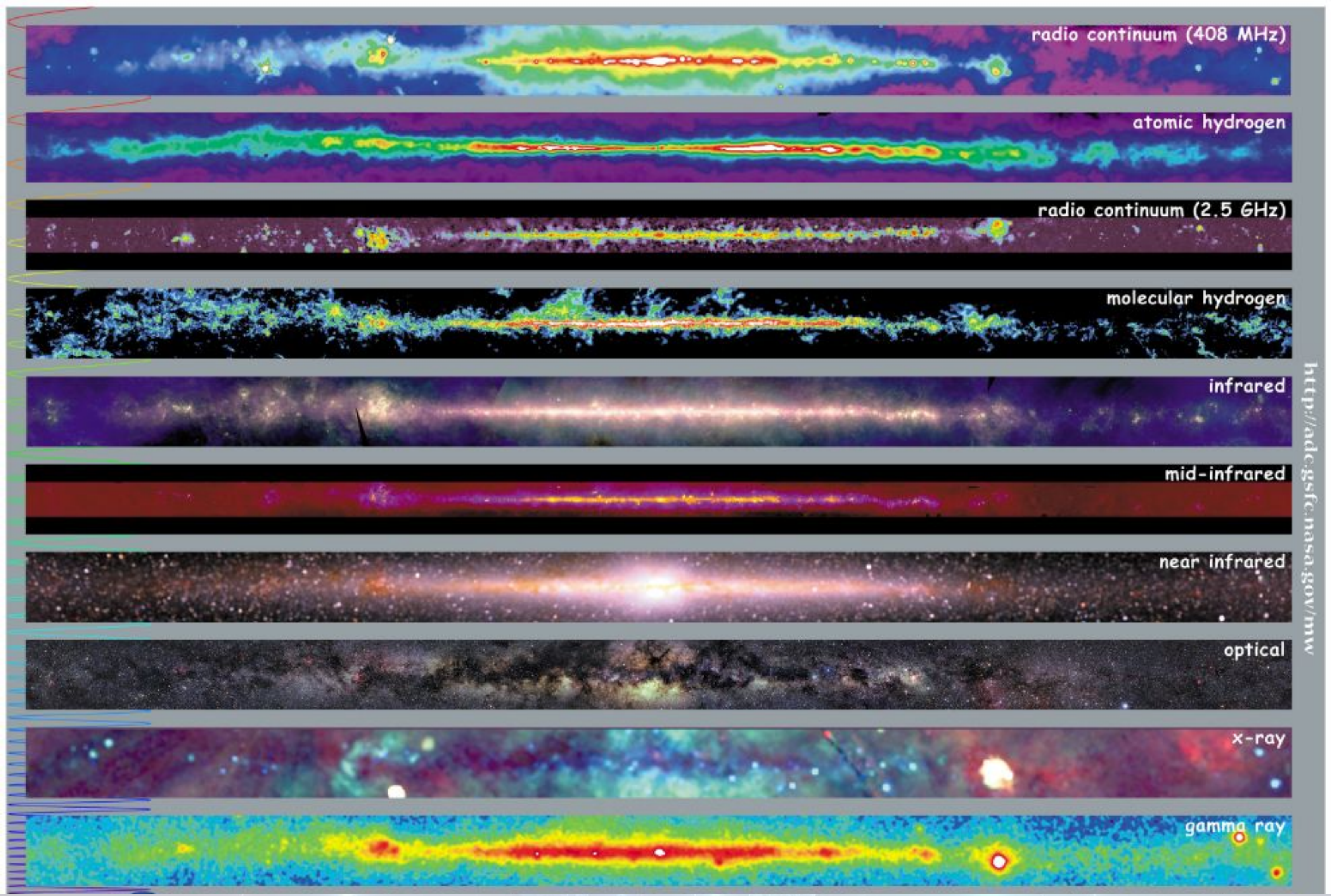


Frequency Band	Frequency (Hz)
Extremely Low Frequency (ELF)	$10^{-18} - 10^{-15}$
Very Low Frequency (VLF)	$10^{-9} - 10^{-6}$
Low Frequency (LF)	$10^{-6} - 1$
High Frequency (HF)	$1 - 10^{4}$

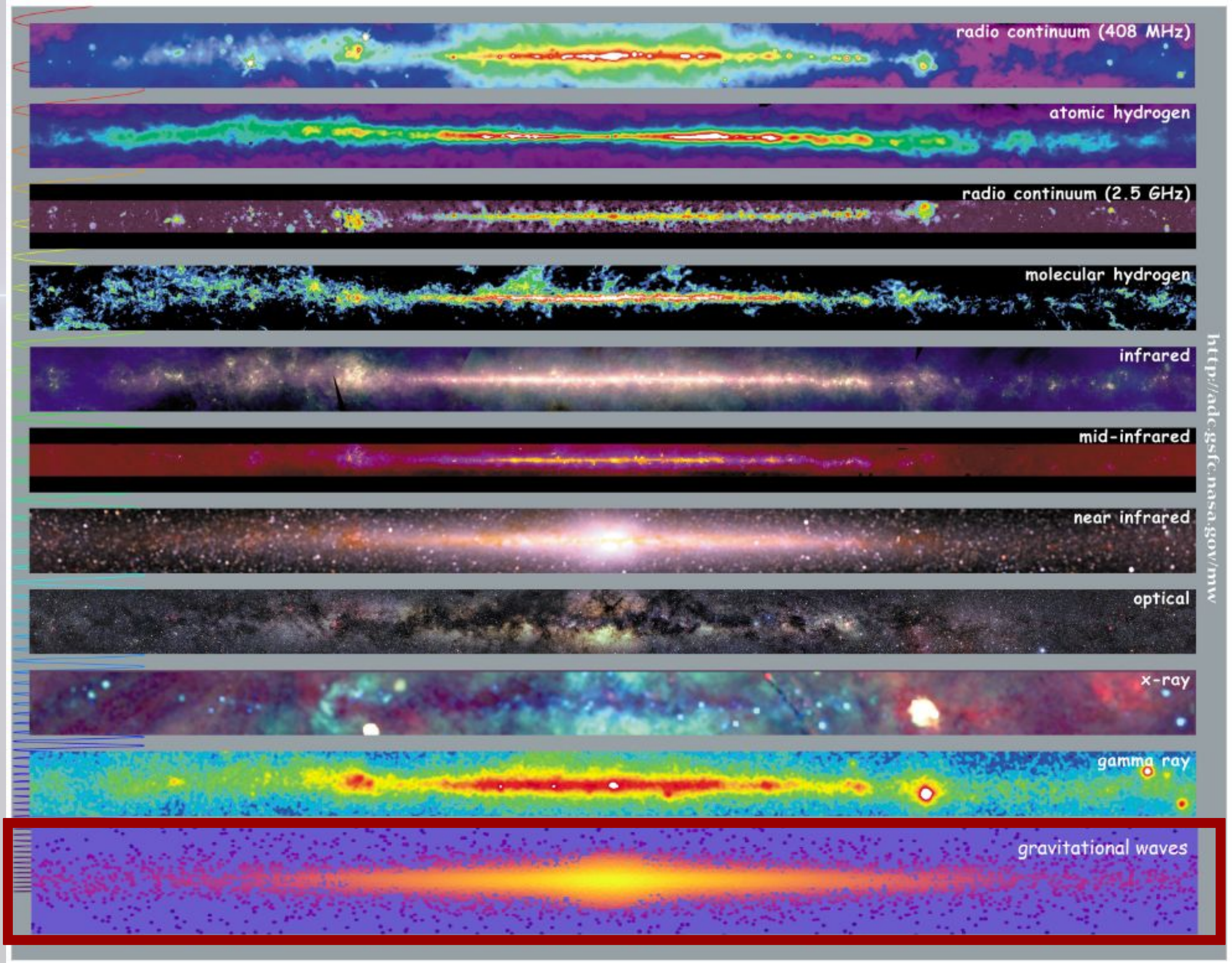
Credit: C. Berry

GO AND CHECK OUT OTHER SOURCES AND DETECTORS!!
http://gwplotter.com/

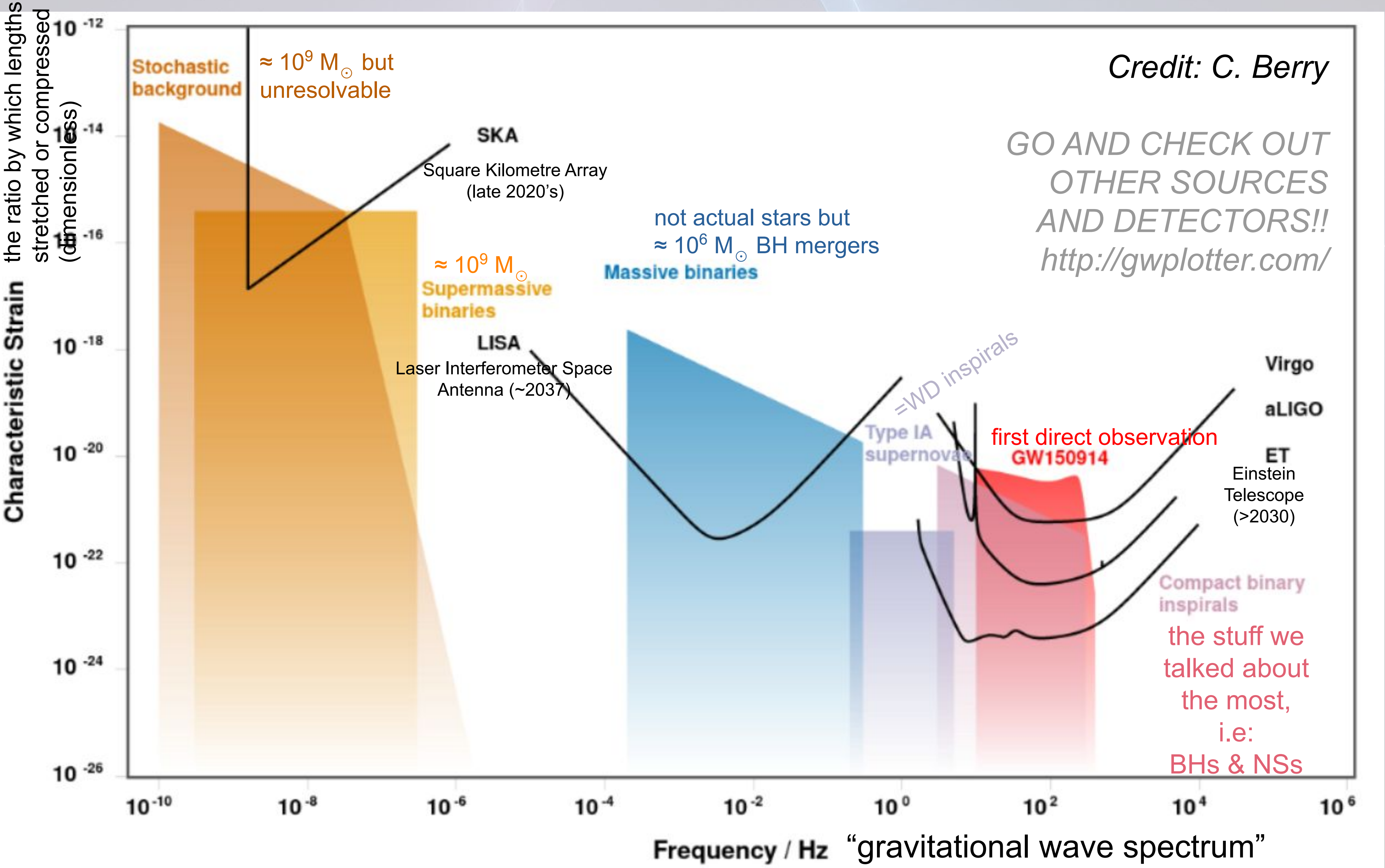
Gravitational wave spectrum



Gravitational wave spectrum



Detector sensibility



a measure of the grav.wave's effect: the ratio by which lengths are stretched or compressed (dimensionless)

≈ 10^9 M$_\odot$ but unresolvable

Square Kilometre Array (late 2020's)

≈ 10^9 M$_\odot$

Laser Interferometer Space Antenna (~2037)

not actual stars but ≈ 10^6 M$_\odot$ BH mergers

=WD inspirals

first direct observation

Einstein Telescope (>2030)

the stuff we talked about the most, i.e: BHs & NSs

Credit: C. Berry

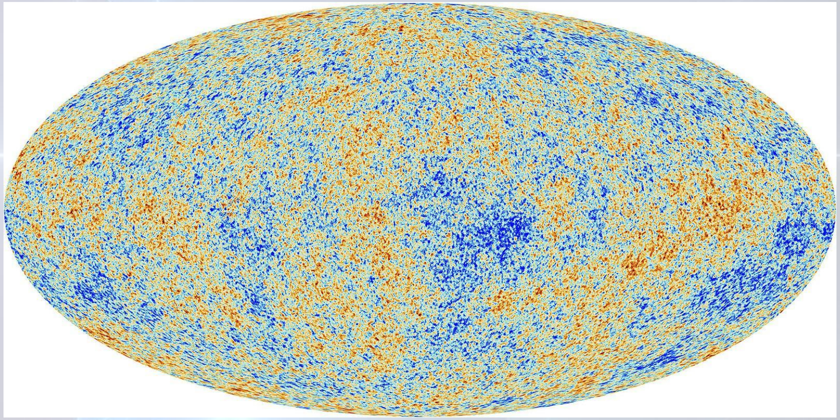
GO AND CHECK OUT OTHER SOURCES AND DETECTORS!!

http://gwplotter.com/

“gravitational wave spectrum”

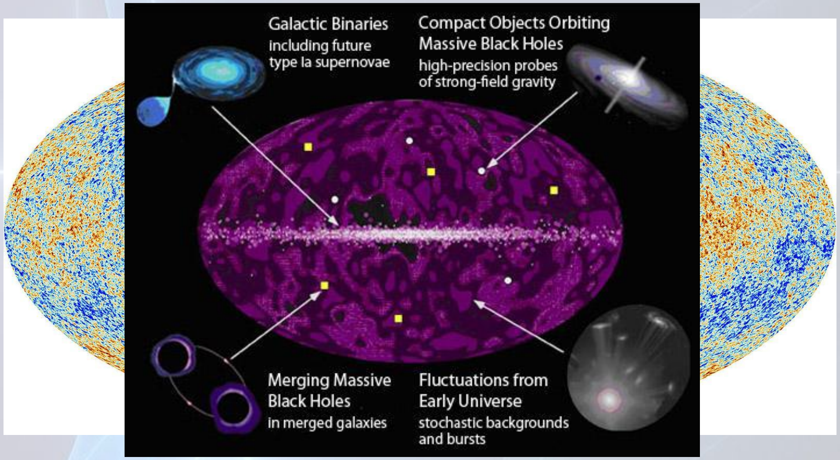
Cosmic grav.wave background

- Heard about the cosmic microwave background?



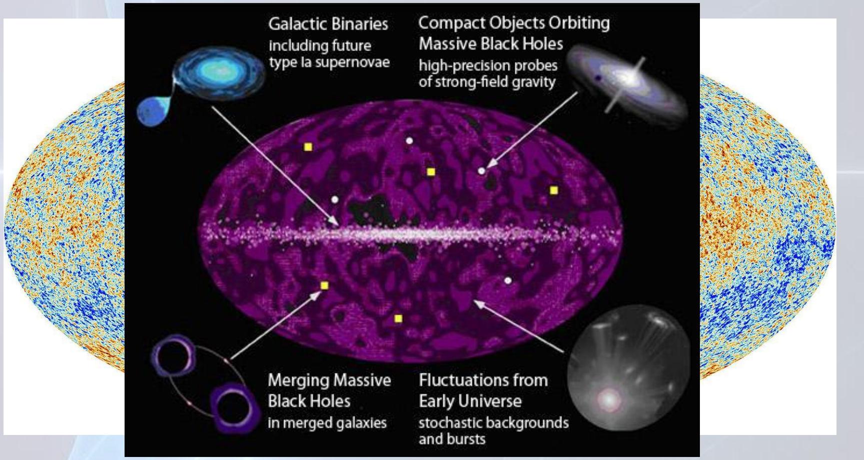
Cosmic grav.wave background

- Heard about the cosmic microwave background?
- GW-background:
  - undetected (yet)

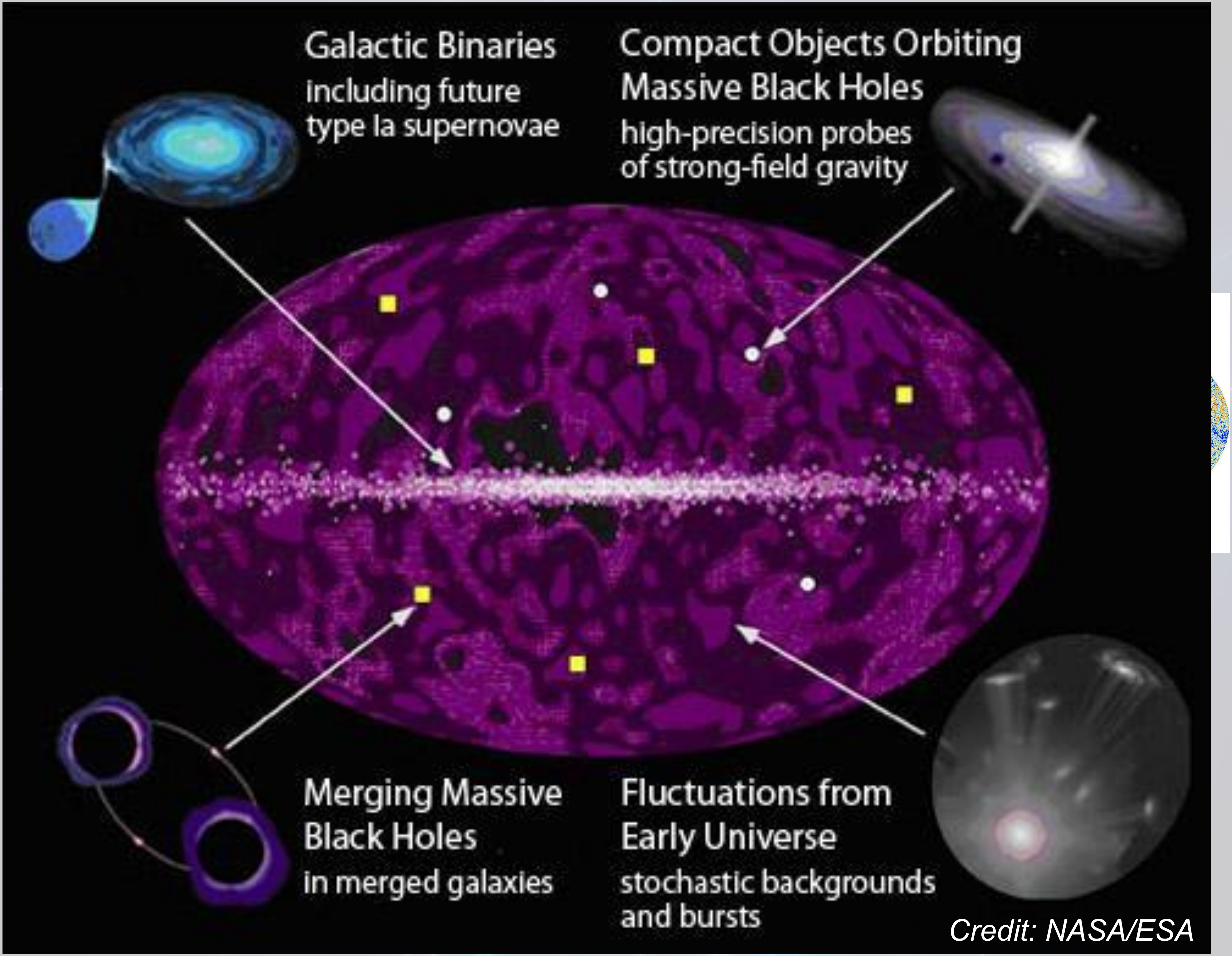


Cosmic grav.wave background

- Heard about the cosmic <u>microwave</u> background?
- GW-background:



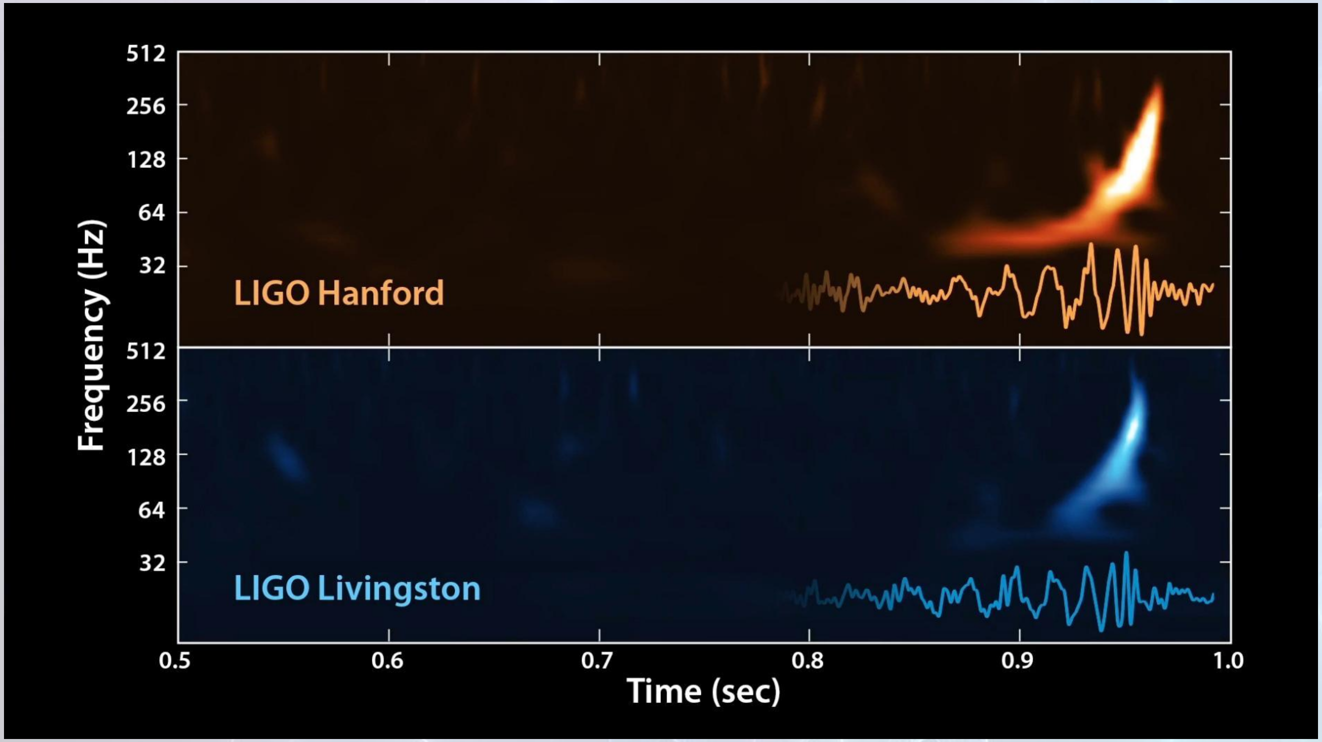
  - undetected (yet)
  - cosmological sources
    - processes during e.g. the cosmic inflation (10^{-36}–10^{-33} sec after the Big Bang)
  - astrophysical sources
    - large number of *unresolvable* BH-BH (or BH-NS, or NS-NS) mergers; additional WD-WD mergers, supernova explosions…



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!