On the origin of merging compact object binaries

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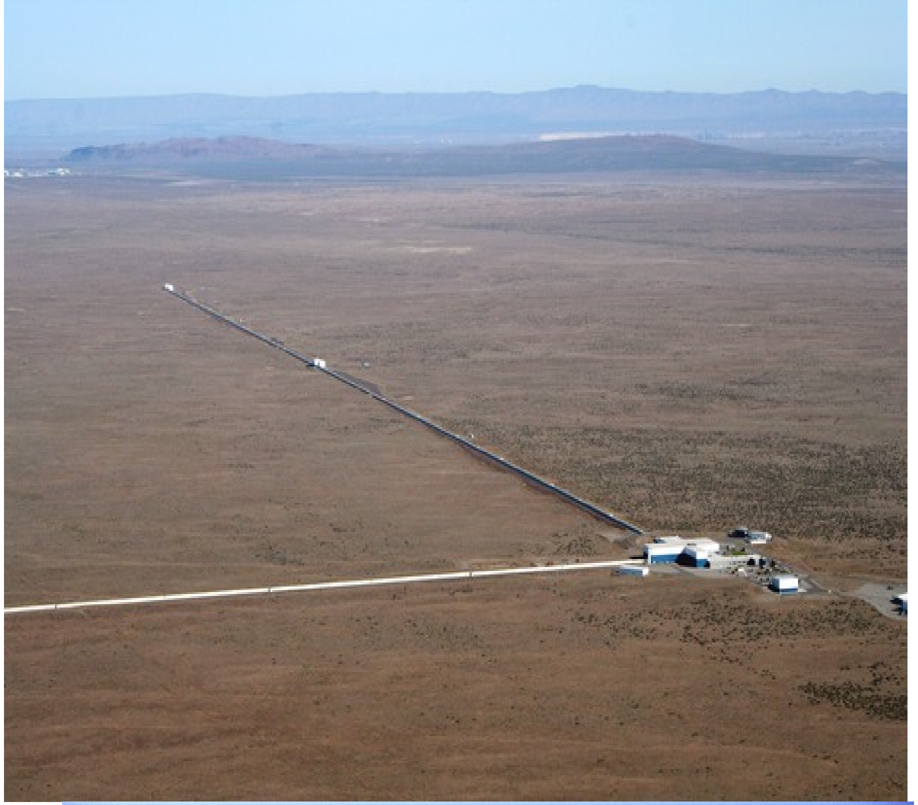
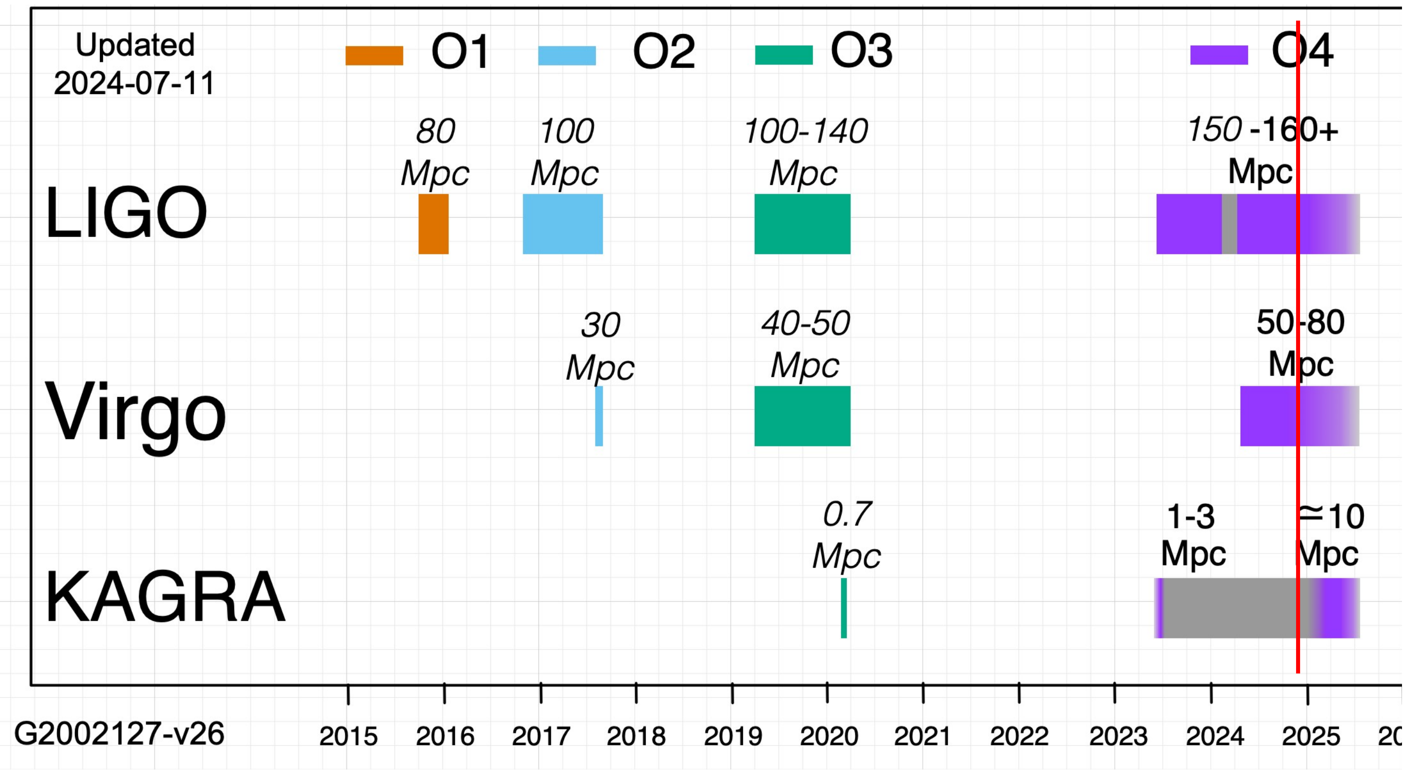
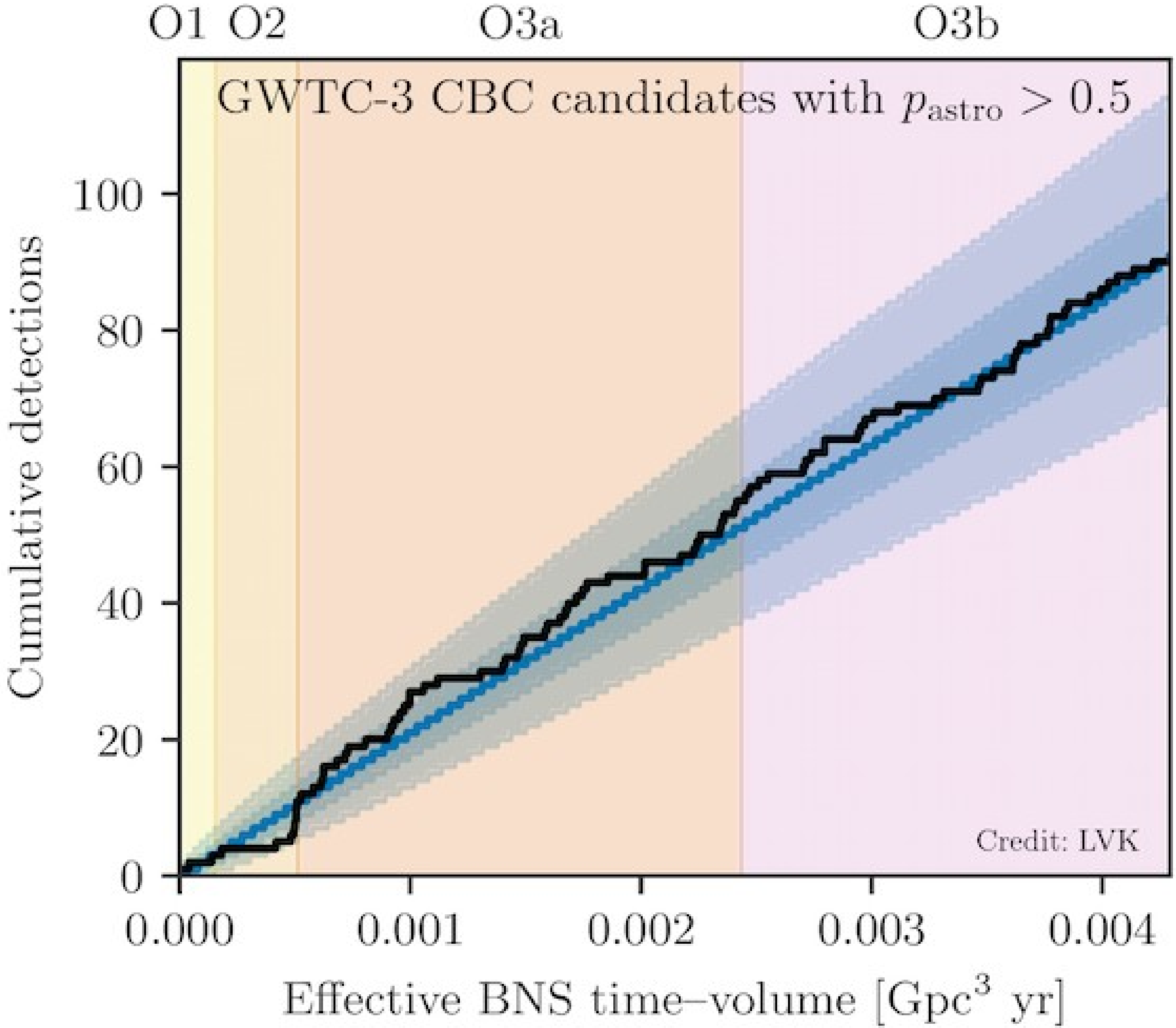
LIGO, Virgo



GW observations:





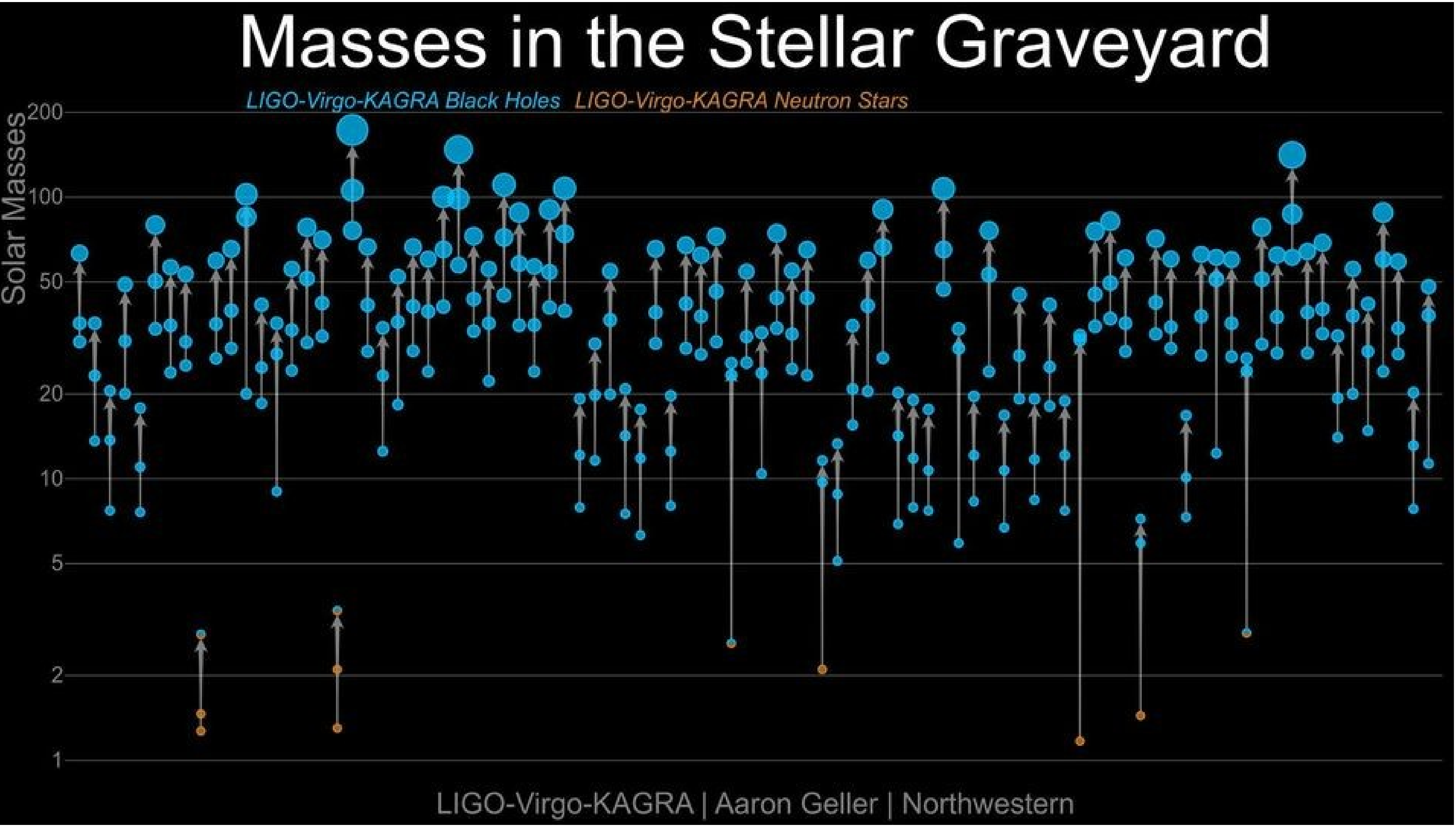
O1
O2
O3a
O3b
GWTC-3 CBC candidates with $p_{astro} > 0.5$
Cumulative detections
0
20
40
60
80
100
0.000
0.001
0.002
0.003
0.004
Effective BNS time–volume [Gpc^3 yr]
Credit: LVK

Current status of detections

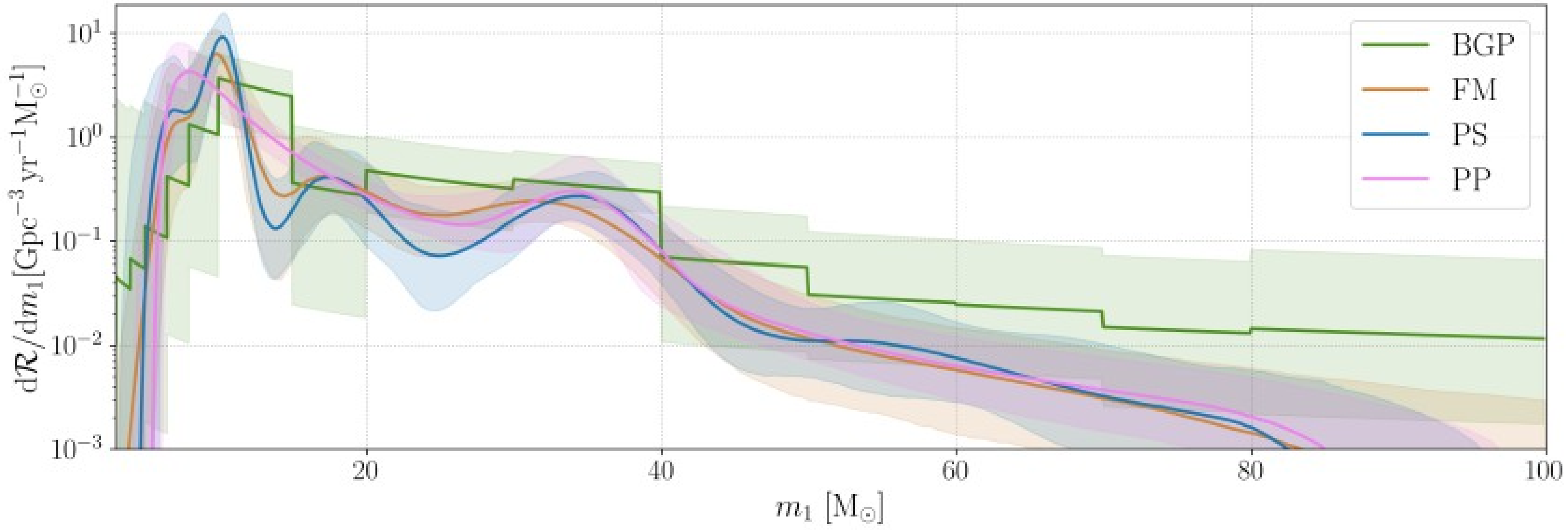
- What can be measured:
  - Chirp mass
  - Mass and mass ratio
  - Effective spin
  - Effective precession
  - Statistical properties

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

BH detections



Primary mass

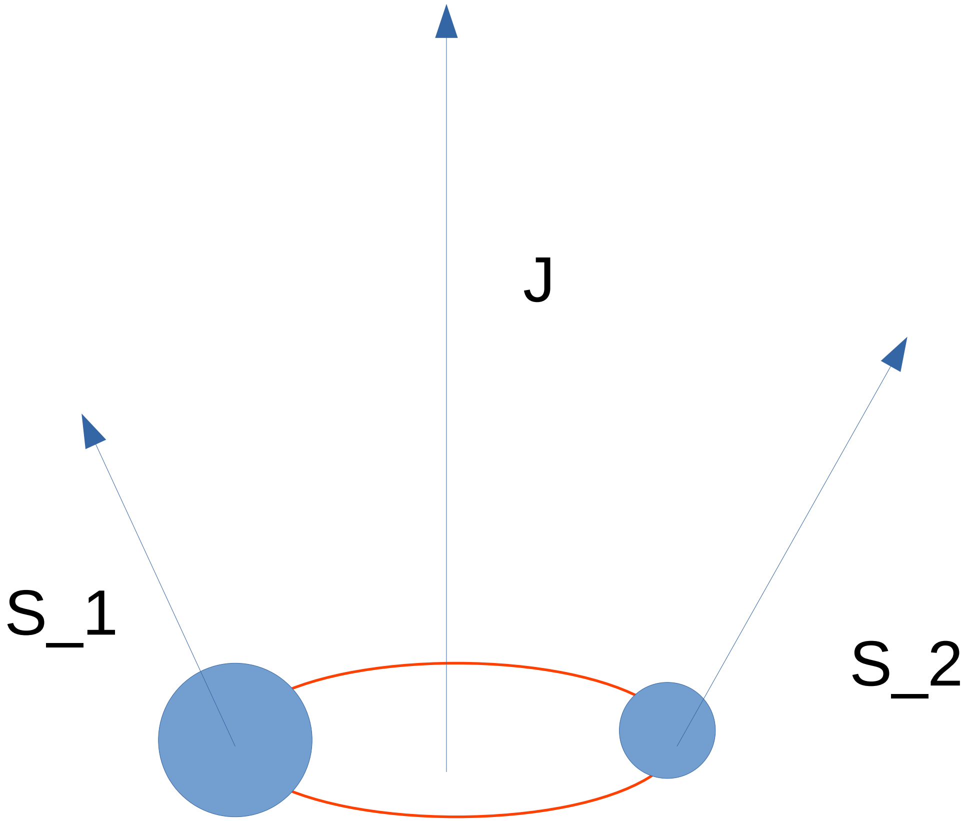


Peaks in the stellar mass region

Long tail to high masses

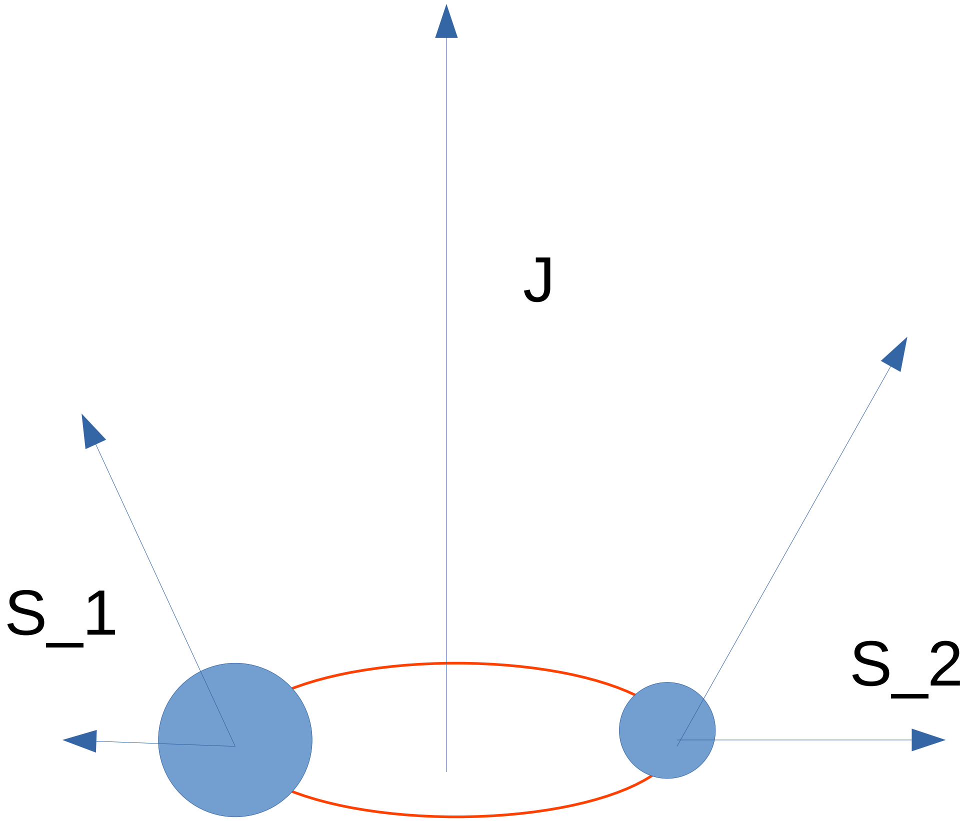
Exponential fall-off.

Effective spin



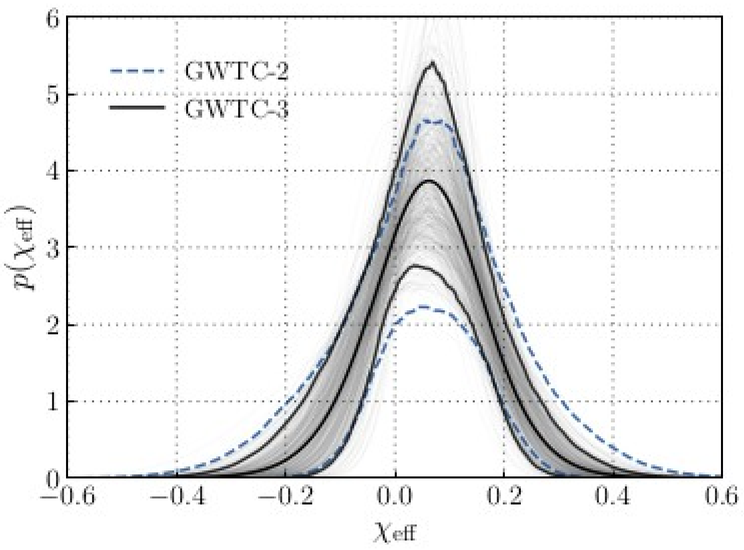
$$\chi_{eff} = \frac{m_1 \vec{s}_1 + m_2 \vec{s}_2}{m_1 + m_2} \frac{\vec{J}}{|J|}$$

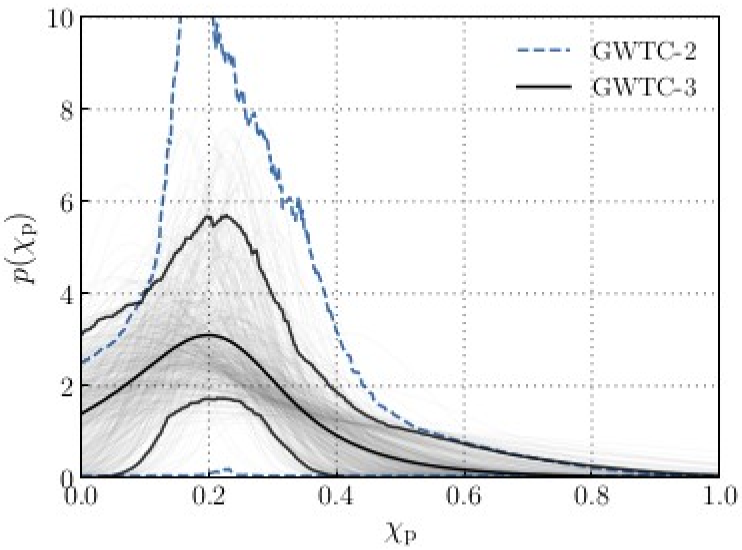
Effective precession spin



$$\chi_p = \max\left[|s_1|\sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q|s_2|\sin\theta_2\right]$$

Spin distribution

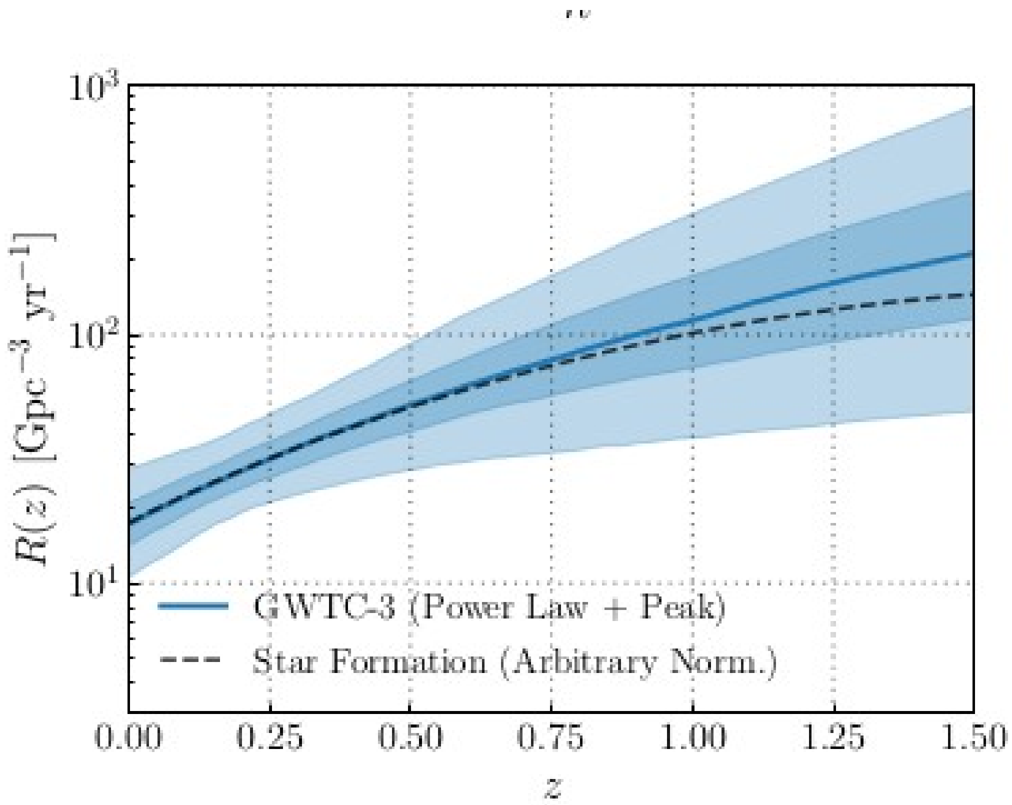


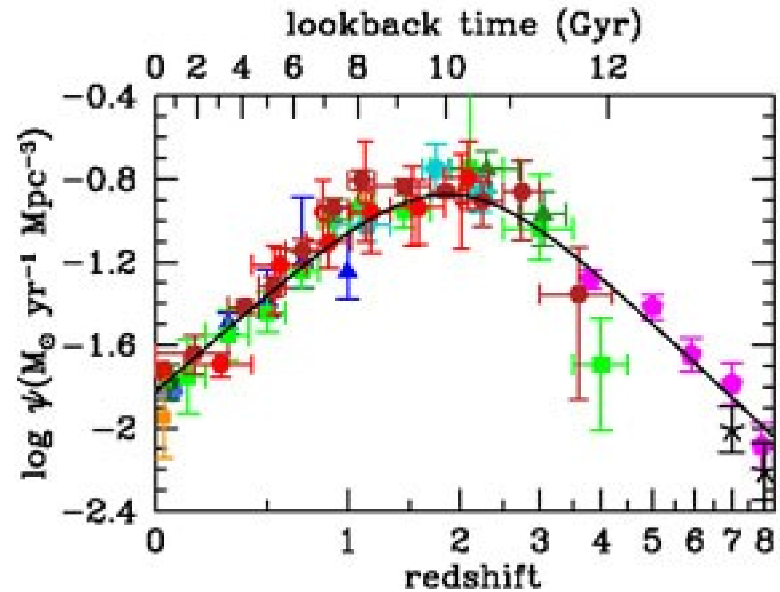


Slight tendency toward positive values

Spins are small

Rates vs redshift





Rates follow **roughly** star formation rate.

BH mass challenge

- BH masses limited by PISN and winds
- Hierarchical mergers?

Belczynski et al.

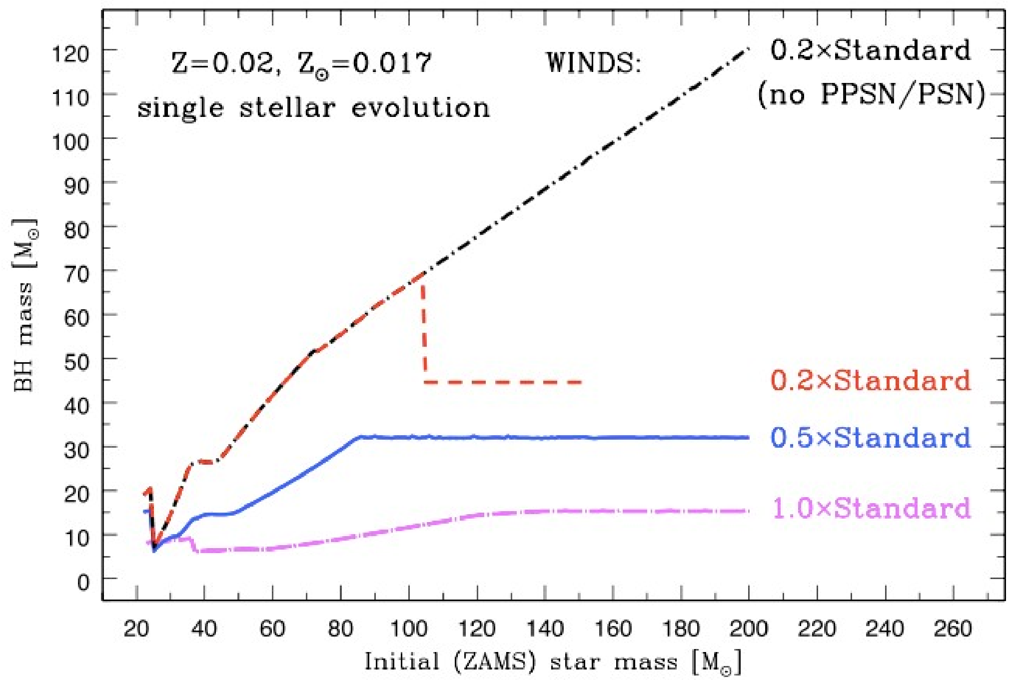


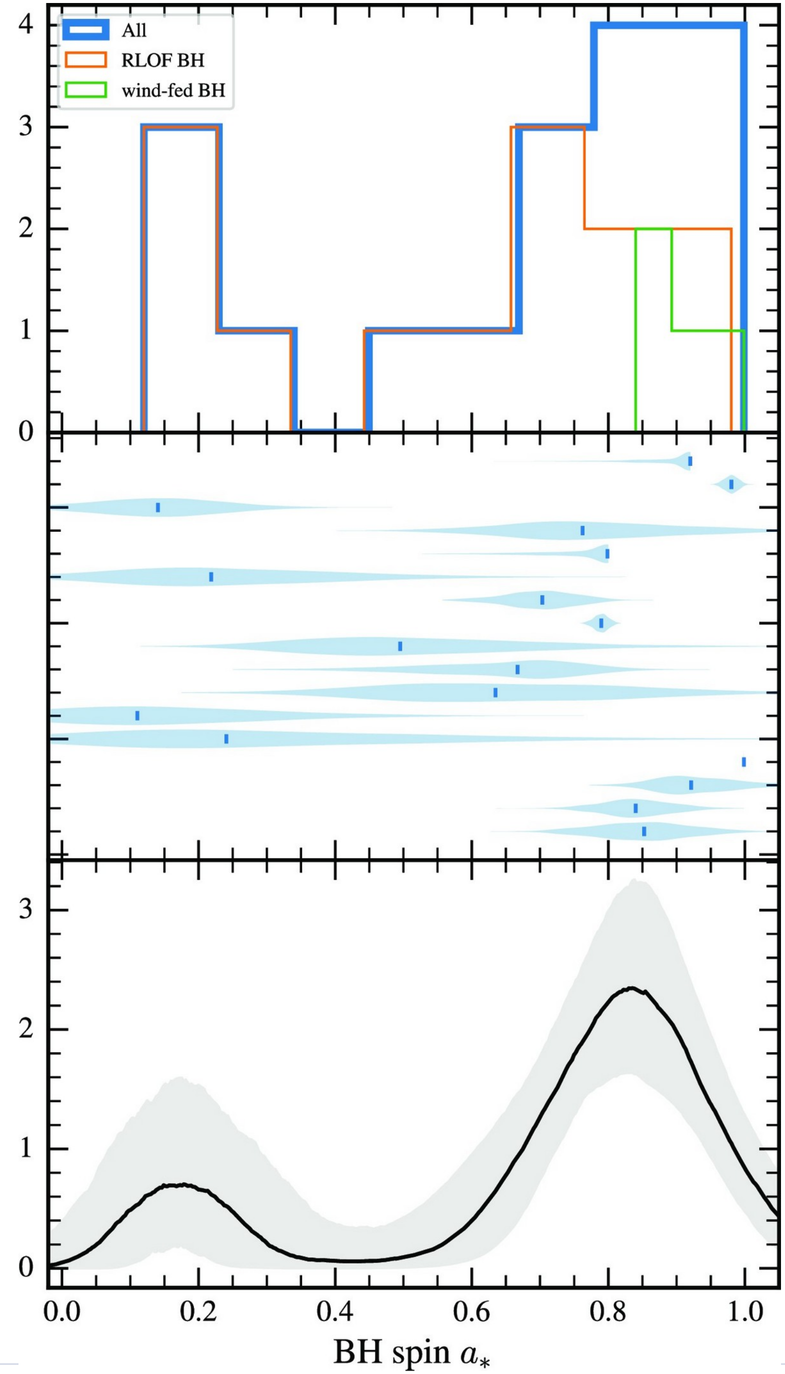
Figure 1. Black hole mass for single stars at metallicities estimated for LB-1 as a function of initial star mass. For standard wind mass-loss prescriptions only low-mass black holes are predicted: $M_{\rm BH} < 15\ M_\odot$. For reduced wind mass loss, however, much heavier black holes are formed: $M_{\rm BH} = 30\ M_\odot$ for winds reduced by factor of two, and $M_{\rm BH} = 70\ M_\odot$ for winds reduced by factor of five of the standard values. Note that to reach even higher masses it is necessary to switch off pair-instability pulsation supernovae that severely limit black hole masses.

BH spin challenge

- BH spins in GW sources small
- BH spins in accreting binaries large
- Why?

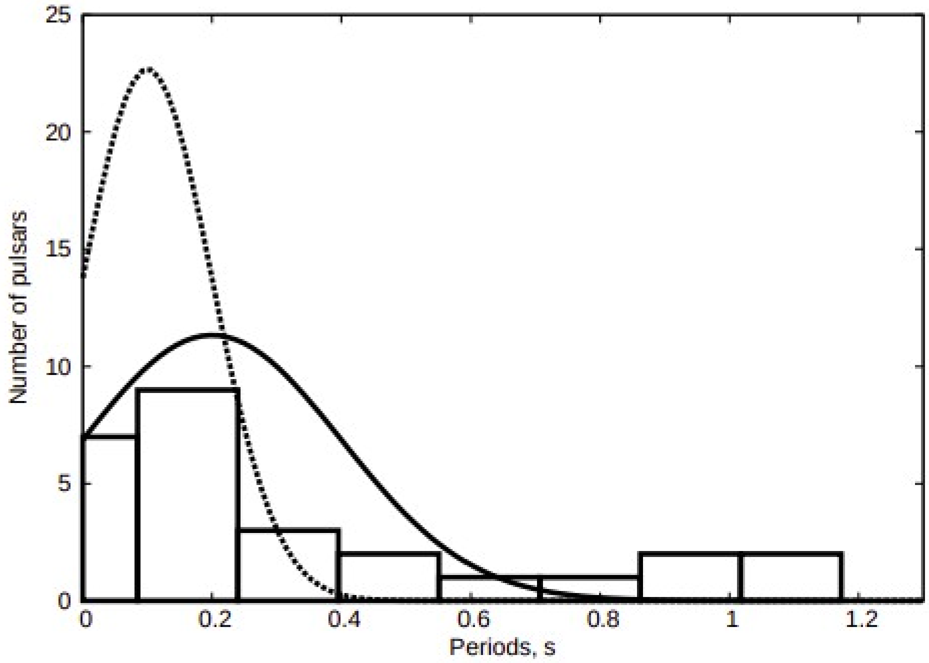
BH spins in accreting binaries

Top: the distribution of the measured spin parameters a* of BH XRBs. Middle: resampling the data by considering the errors and upper/lower limits. Bottom: the double Gaussian distribution and the 1σ range.



Mon Not R Astron Soc, Volume 524, Issue 3, September 2023, Pages 4562–4573, https://doi.org/10.1093/mnras/stad2063

But spins of young NS...



Young NS spin slowly!   Typical values P~0.1- 0.2 s

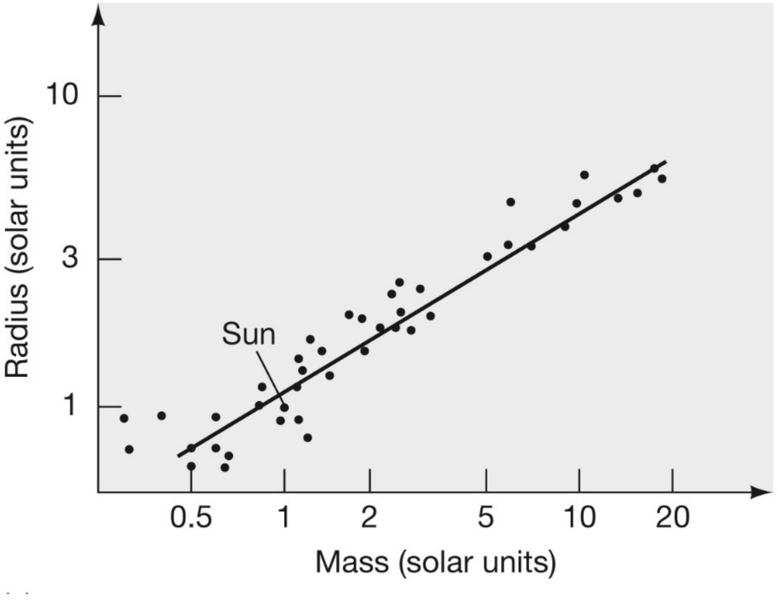
Fast spins – P< 1ms !

Argument based on long GRBs

- Supernova rate 1Hz in the Universe
- GRB rate ~0.01 Hz in the Universe
- If GRBs are caused by spinning BH in stars than most BH are not spinning fast

BH initial separation

- 30+30Msun binary: separation less than 28Rsun for merger n Hubble time
- Radius of 30Msun ~10sun



The merger rate densities

- BBH estimate $R = 17 - 45 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BNS estimate $R = 13 - 1900 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BHNS estimate $R = 7.4 - 320 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The local supernova rate ~ $10^5 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The BH formation rate is ~ $10^4 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- About 1 black hole in a 100-1000 ends up in a merging binary
- Similarly NS: 1 in 100-1000 is in a merging binary!

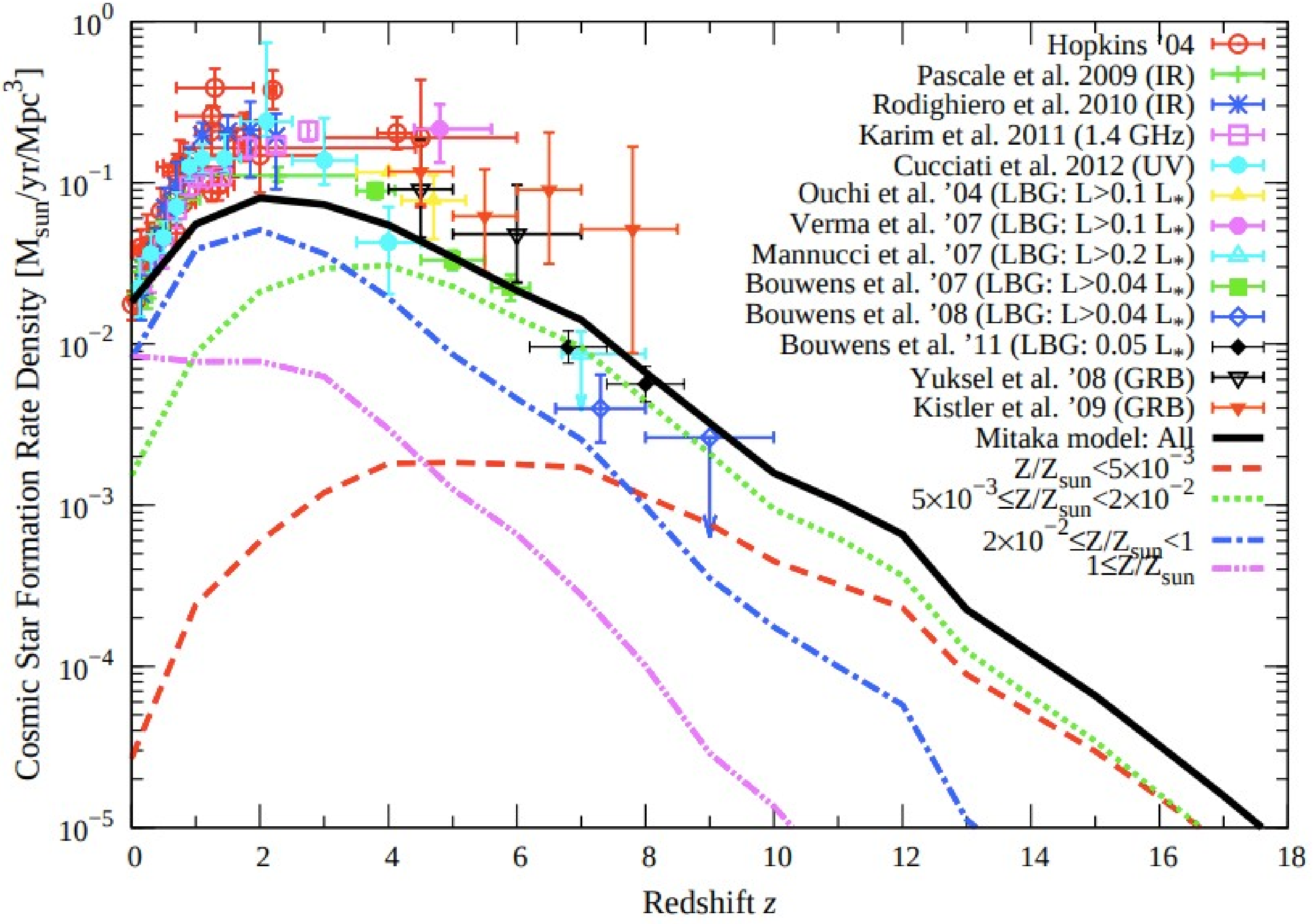
Challenges in formation

- Black hole masses and spins
  - Not a real problem...
- Orbital separation to merge in Hubble time
  - Need to work a little…
- Rate
  - There is quite a lot of them...

What models do we have?

- Stellar models
  - Binary evolution (field, chemically homogenous, pop III)
  - Cluster evolution (including nuclear cluster
  - AGN disk model
- Primordial BHs

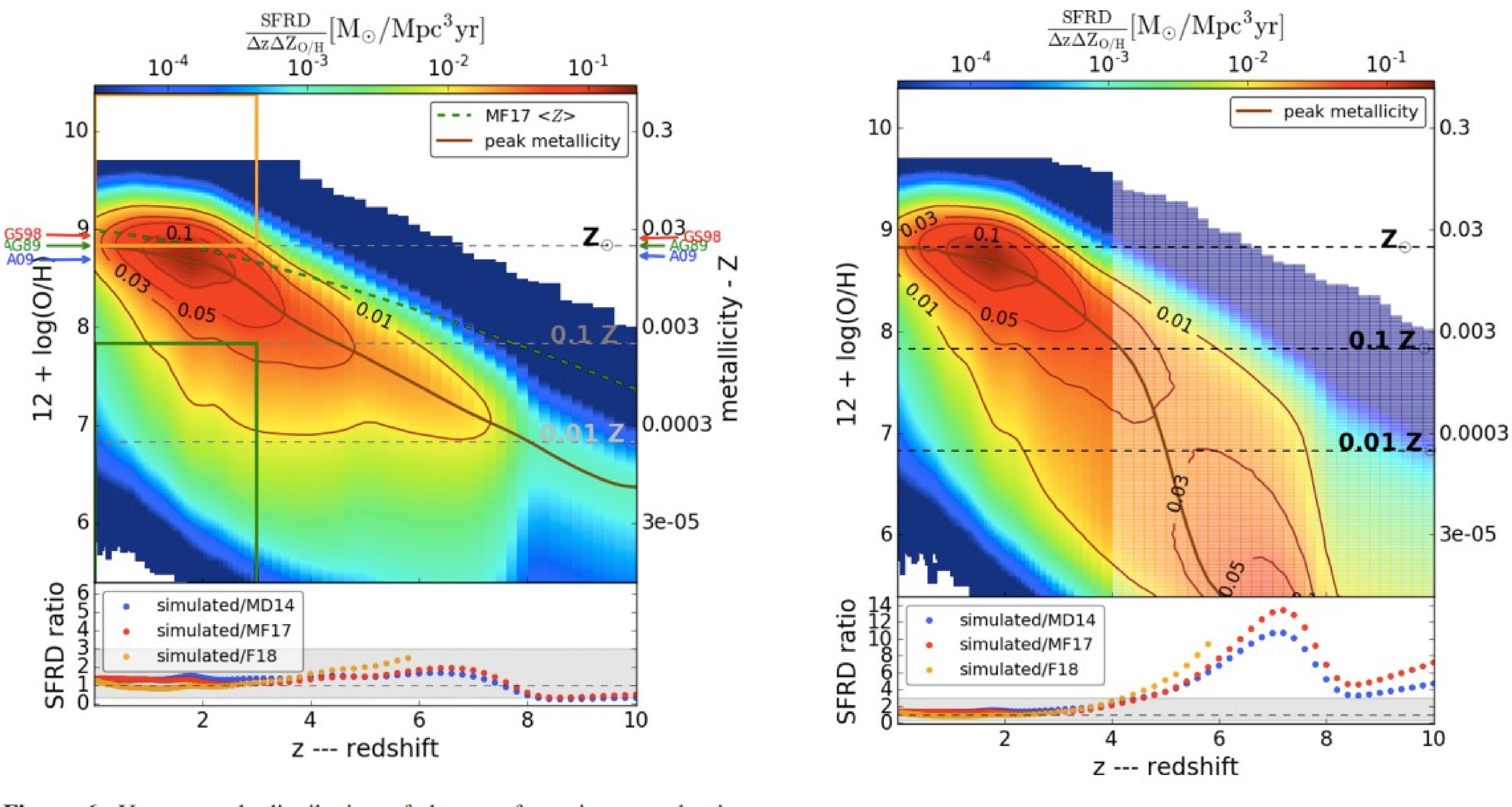
Star formation rate



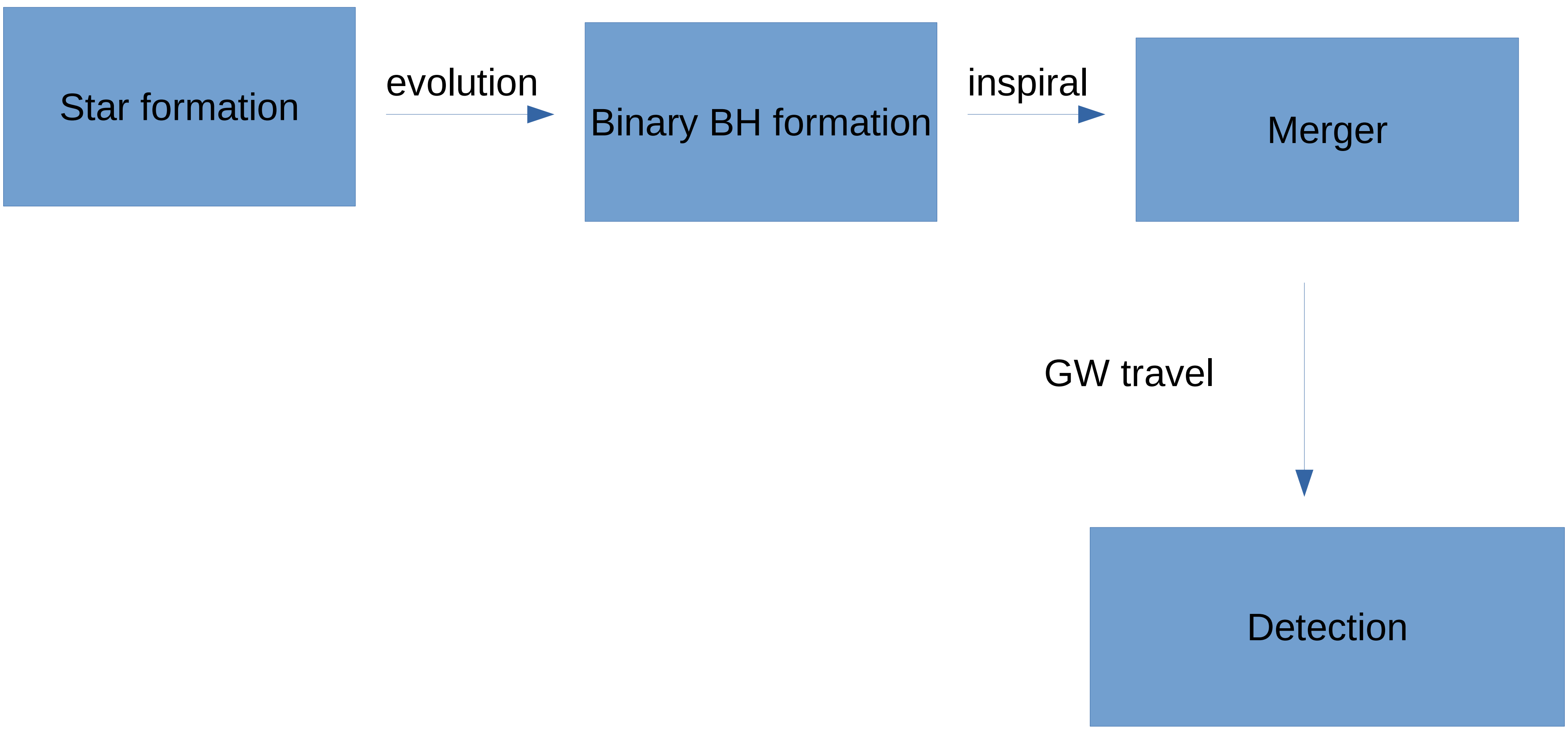
Inoue et al

SFR and metallicity

5312 *M. Chruslinska and G. Nelemans*



Scenario


Star formation
evolution
Binary BH formation
inspiral
Merger
GW travel
Detection

Isolated binary evolution

- Masses
  - must come from stellar evolution
  - PPS mass maximum ~ 60-70 Msun
- Effective spins
  - should be aligned at least partially
  - Small or large?
- Rates
  - Should follow SFR

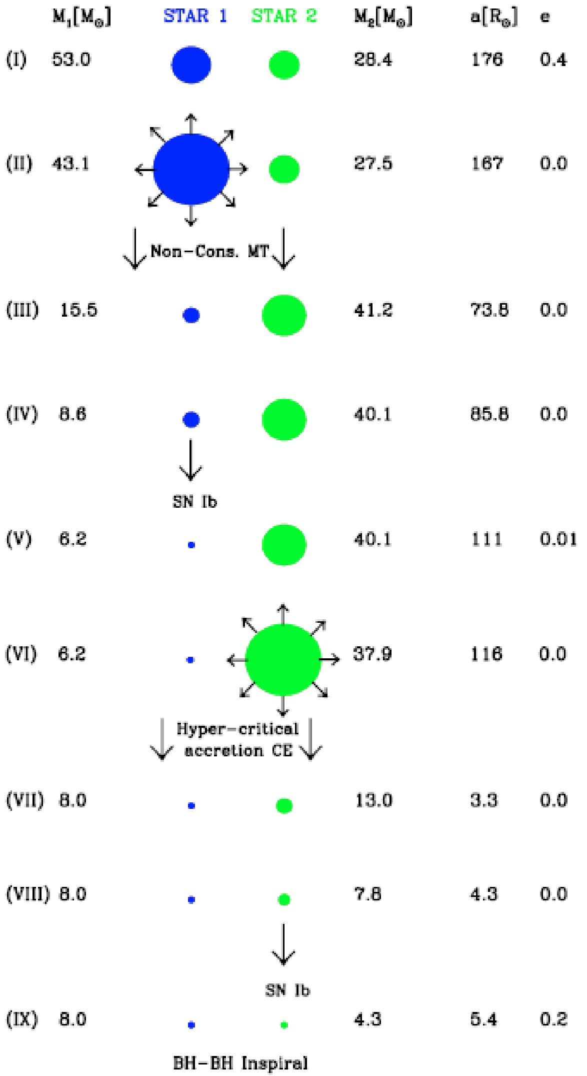


Fig. 1. An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

Globular clusters

Dense stellar systems

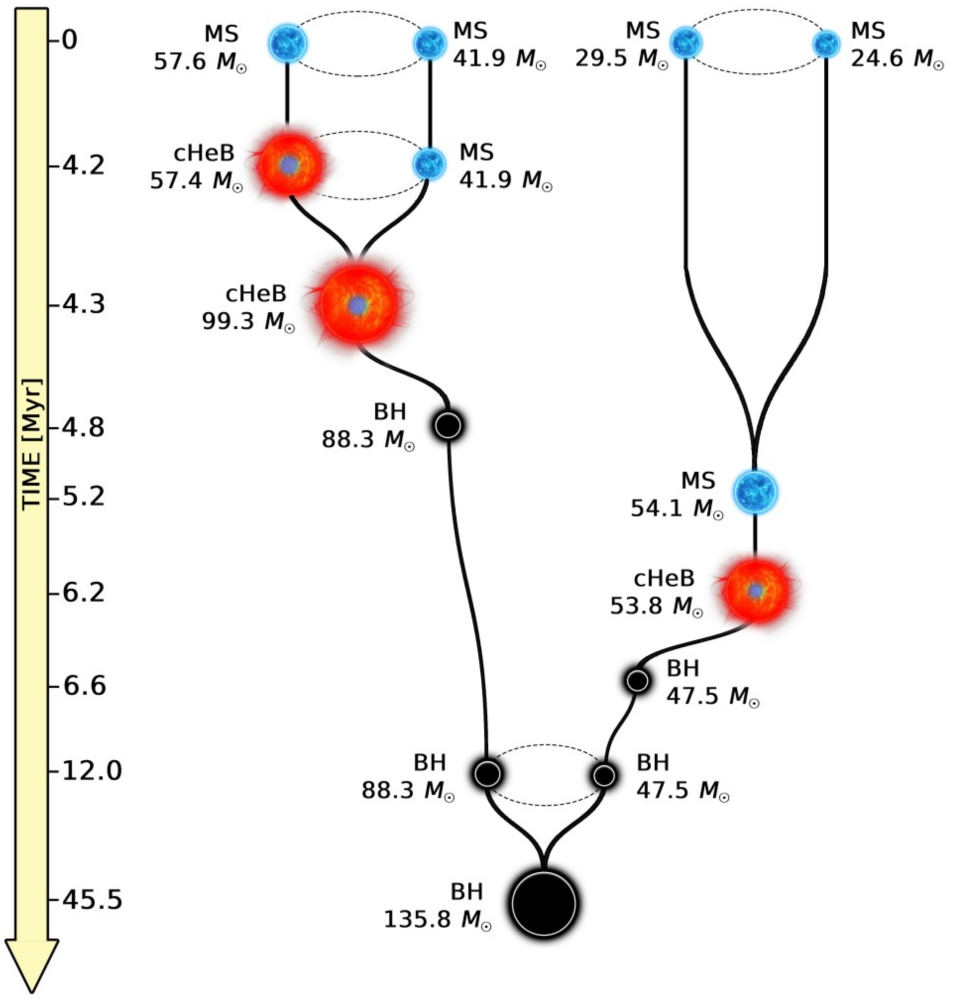
10^4 – 10^7 solar masses

Stellar collisions possible

Low escape velocity

Cluster evolution

- Masses
  - Can be much larger (hierarchical mergers)
- Spins
  - Random – not aligned
  - Small, large (2nd generation)
- Rates
  - Should peak at higher redshift (peak of GC formation)



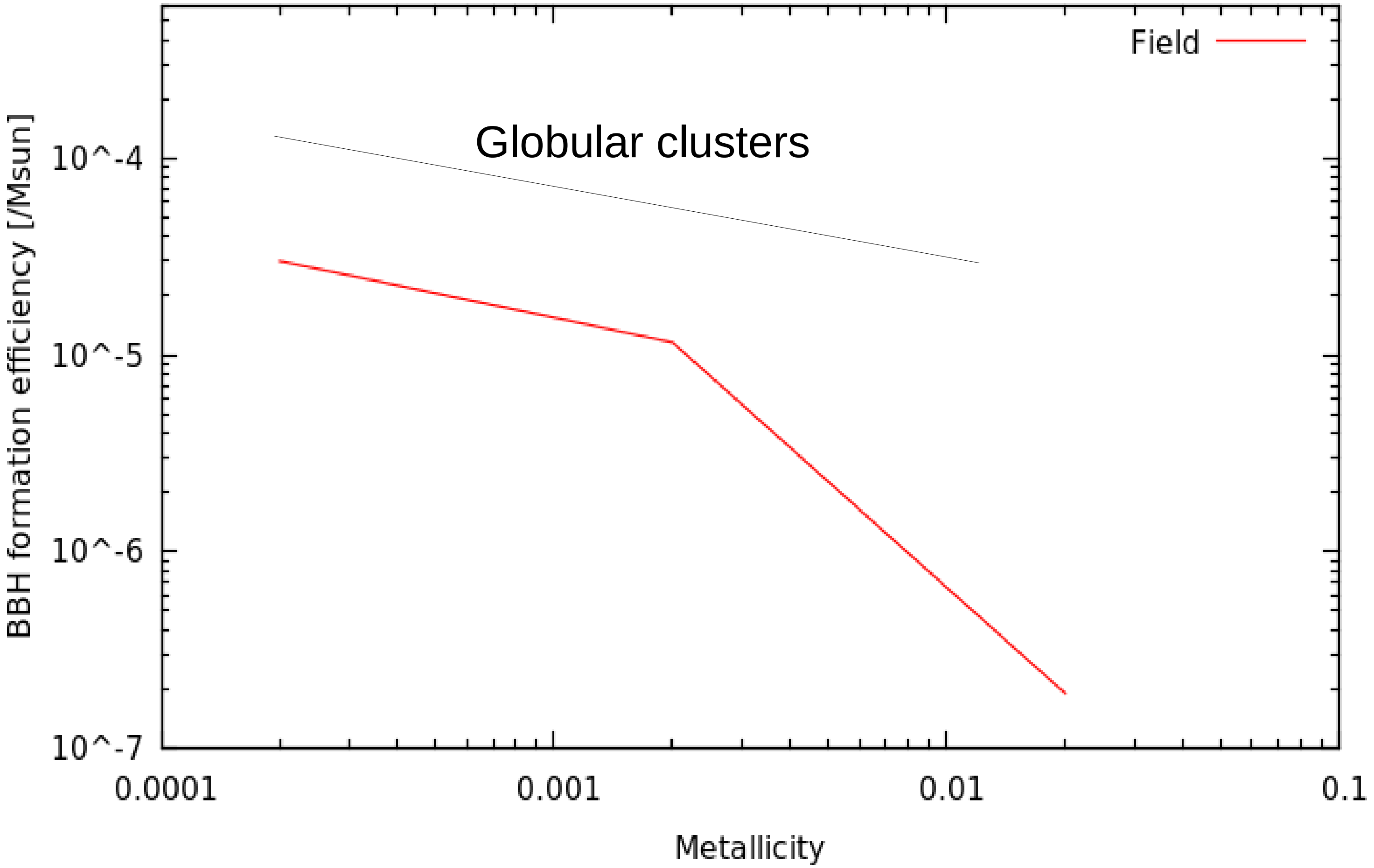
Mapelli, 21

BHBH formation efficiency

$$X_{BHBH} = \frac{N_{BHBH}}{M_*}$$

If all BHs end up in merging binaries and with Salpeter IMF

$$X^{max}_{BHBH} = 1.8 \times 10^{-3} M_\odot^{-1}$$



AGN disk model

- BH born in stellar evolution
- BBH formed in multi-body interaction in AGN disks –
- Mergers in disk
- Spins isotropic
- Rate - small

Primordial binaries

- Masses
  - Correspond to phase transitions in the Early universe (generally below 1Msun)
- Spins
  - Random, small
- Rates
  - Do not have to follow SFR
  - Very uncertain, scale as f^2 (f - fraction of BH as DM)

Comparison with observations

Basic rate arguments

- Formation scenario must be generic
- Exceptional environments must produce BBH and BNS with very high efficiency
- Dense stellar regions can contribute
- I am skeptical about exotic models

Binary evolution

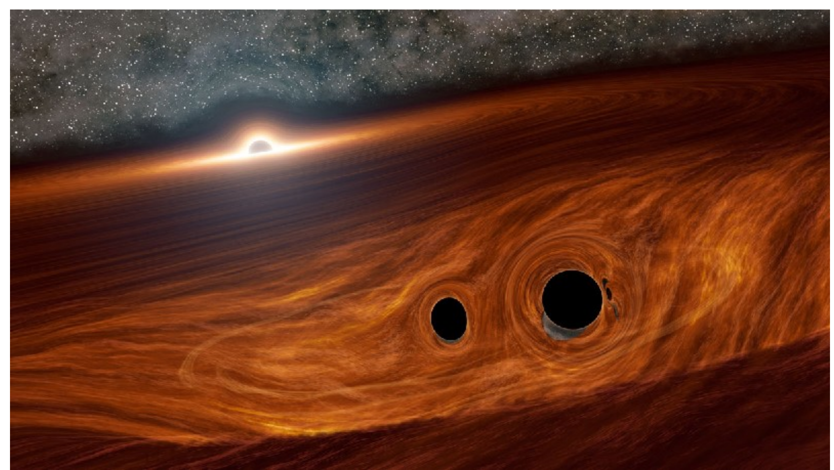
- Masses –we see too heavy BHs
- Spins
  - slightly positive
  - are small spins a problem?
- Rates increase with z

Cluster evolution

- Masses – extend above PPSN gap
- Spins
  - why positive?, consistent with an isotropic subpopulation
  - In hierachical merges should be ~0.7
- Rates
  - increase but follow SFR
  - Is there a peak at z=2-3?

AGN model of formation

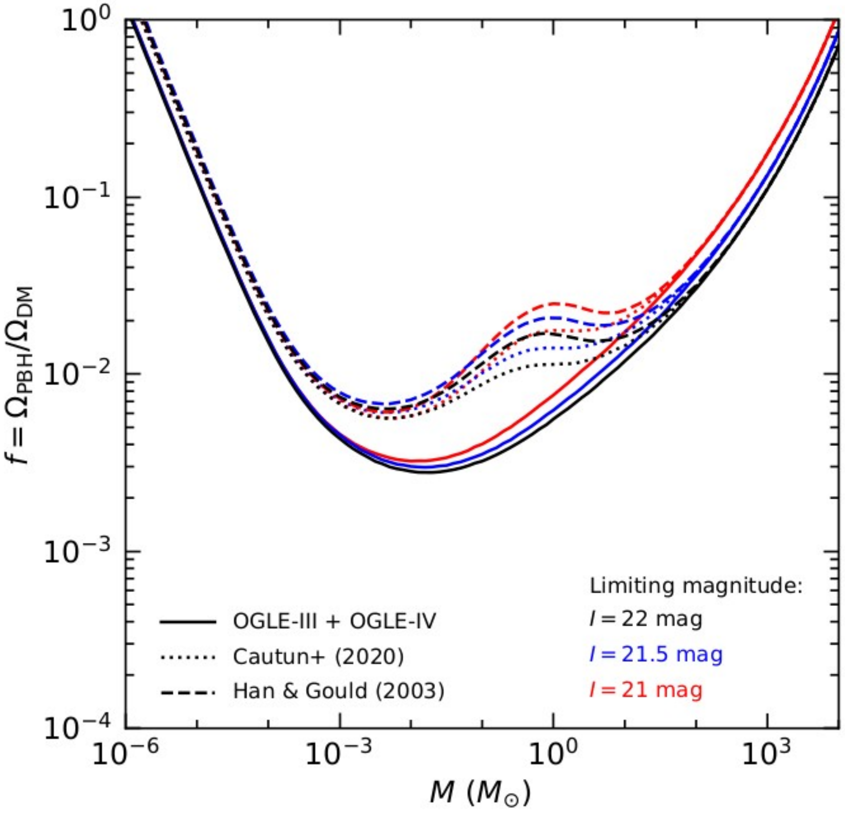
- GW190521 – quasar flare after 35 days.
- Possibility of forming rare eccentric/high mass binaries
- Rates – very low… (in my opinion)



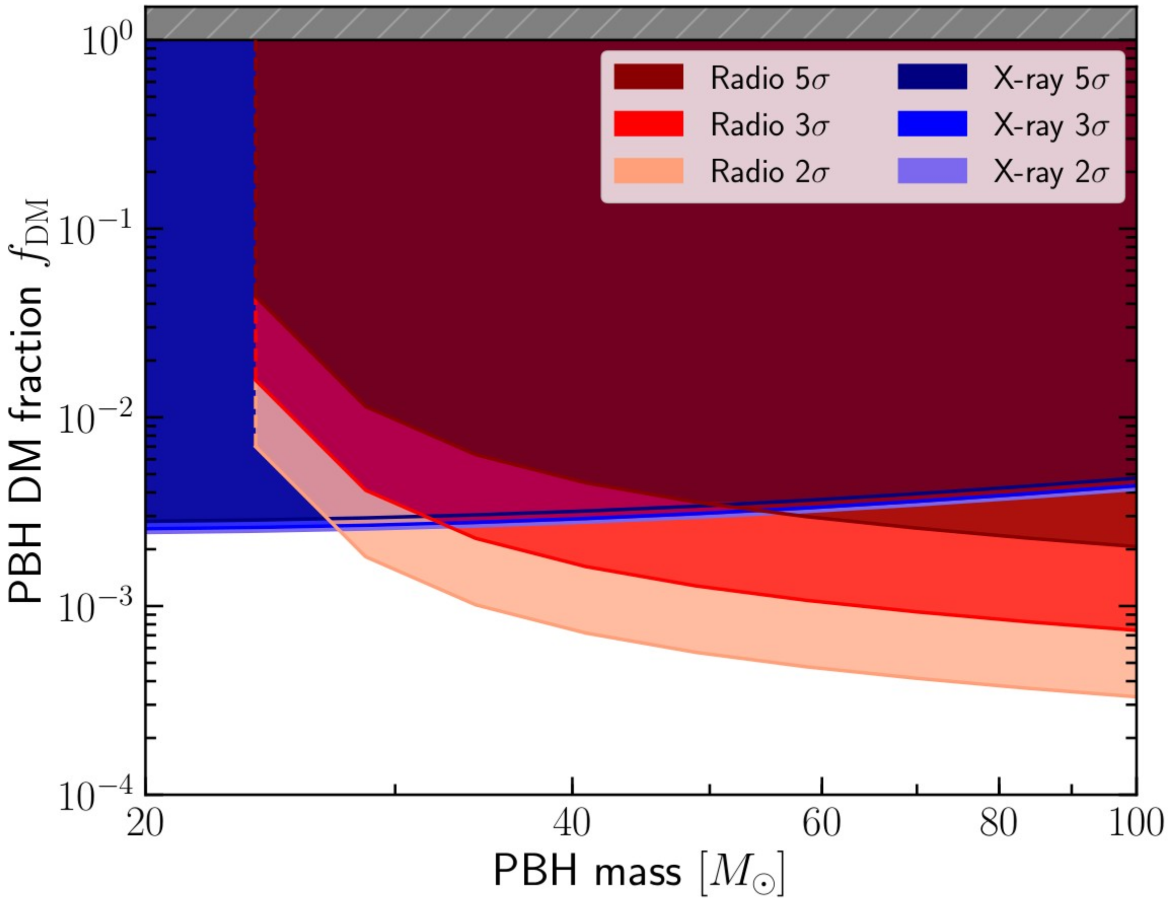
Primordial

- Distribution of masses, lack of BHs below the stellar limit.
- Spins positive
  - But a sub-population possible
- Why do the rates follow SFR?
  - Rate conspiracy?

Primordial BH as part of DM



Mroz etal 2023



Manshanden etal. 2019

Black holes can be only a small fraction of DM.

Probability of formation BBH in halo is very low.

Rates ~ 0.0001 /Gpc^3 /yr

Primordial BHs

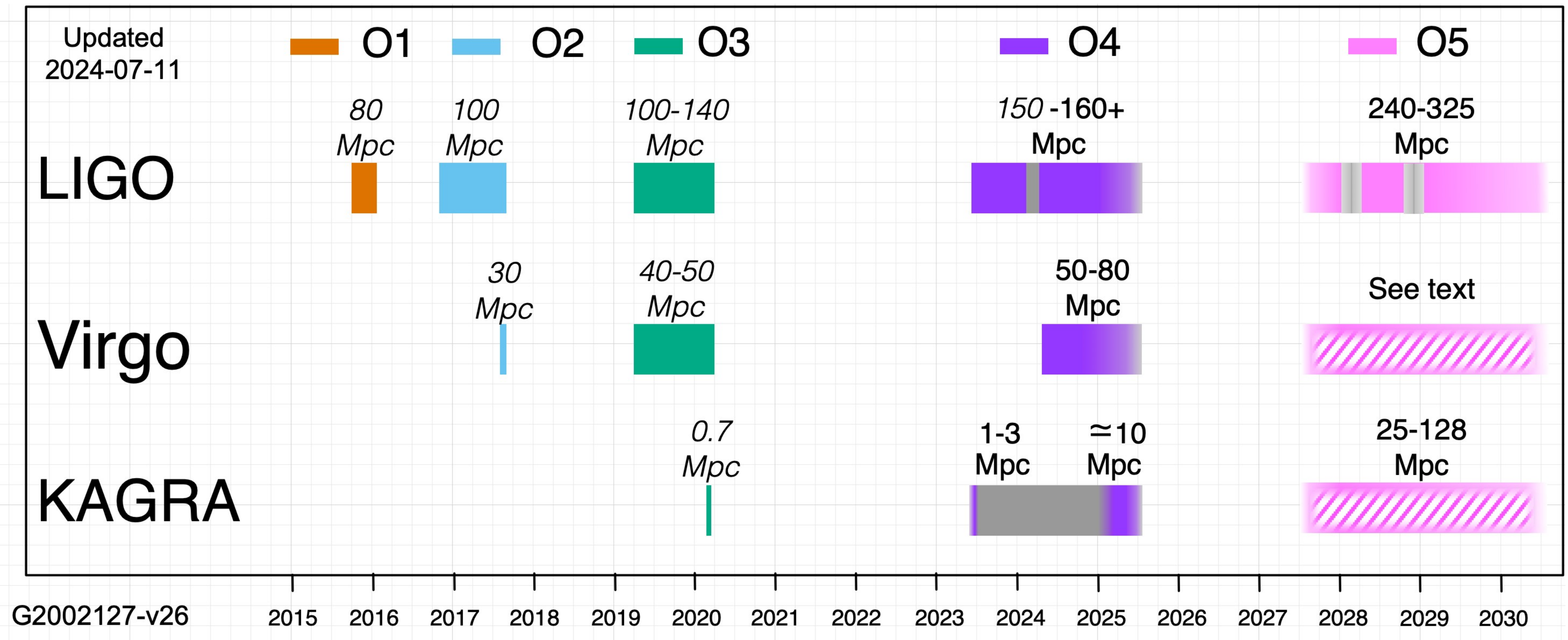
- Scenarios:
  - Early Universe capture
  - Late capture in halos
- Rates scale as n^2 – very low
- Rate as function of redshift
- Positive effective spins – not expected

How do the models look

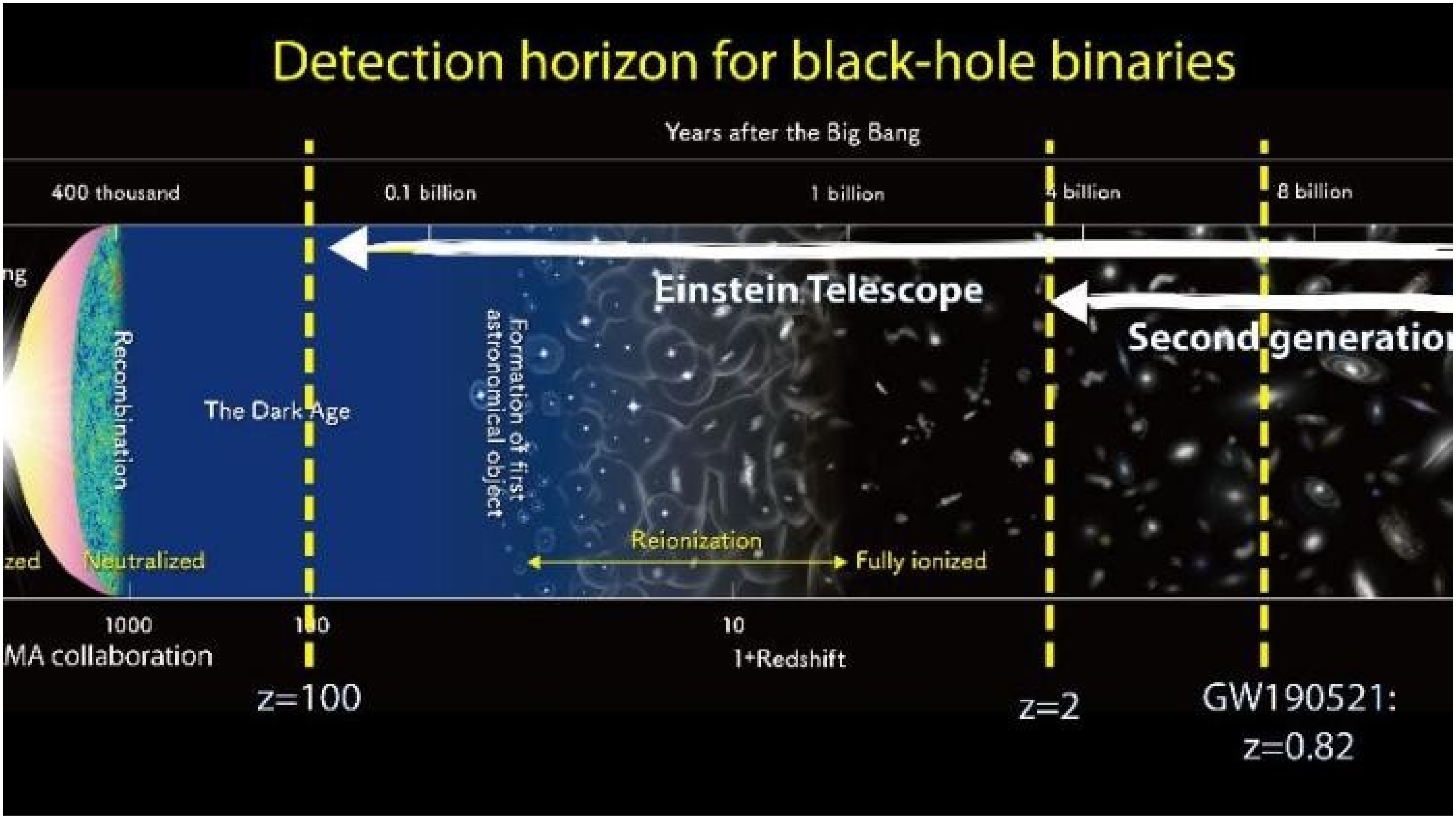
Model	Masses	Spins	Rates
Binary			
Cluster			
Primordial			

My conclusion is that we may need more than one scenario to explain observations.

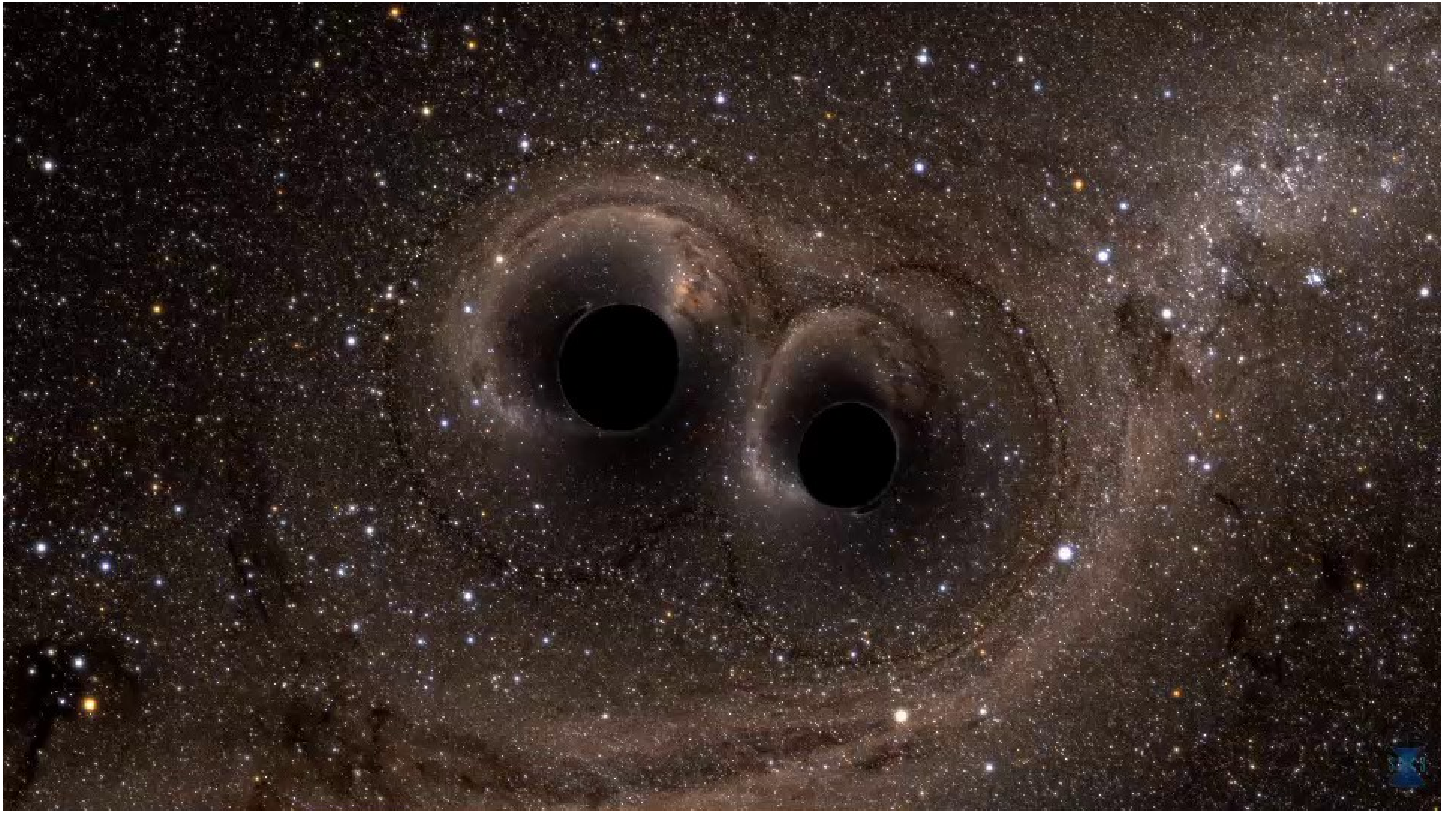
GW observations: future



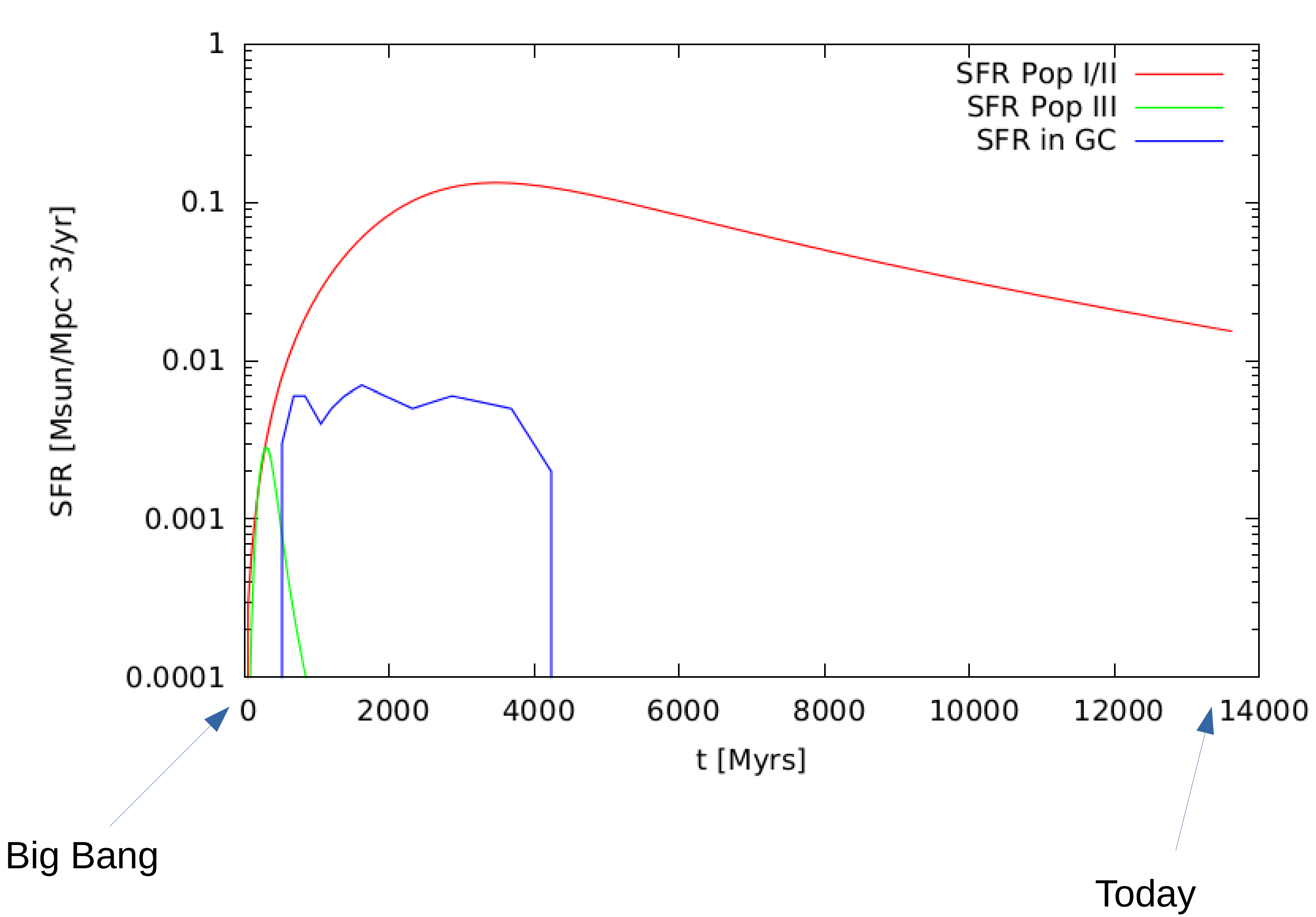
Einstein Telescope



Thank you !



SFR


SFR [Msun/Mpc^3/yr]
1
0.1
0.01
0.001
0.0001
0
2000
4000
6000
8000
10000
12000
14000
t [Myrs]
SFR Pop I/II
SFR Pop III
SFR in GC
Big Bang
Today