# A critical review of the origin gravitational wave sources

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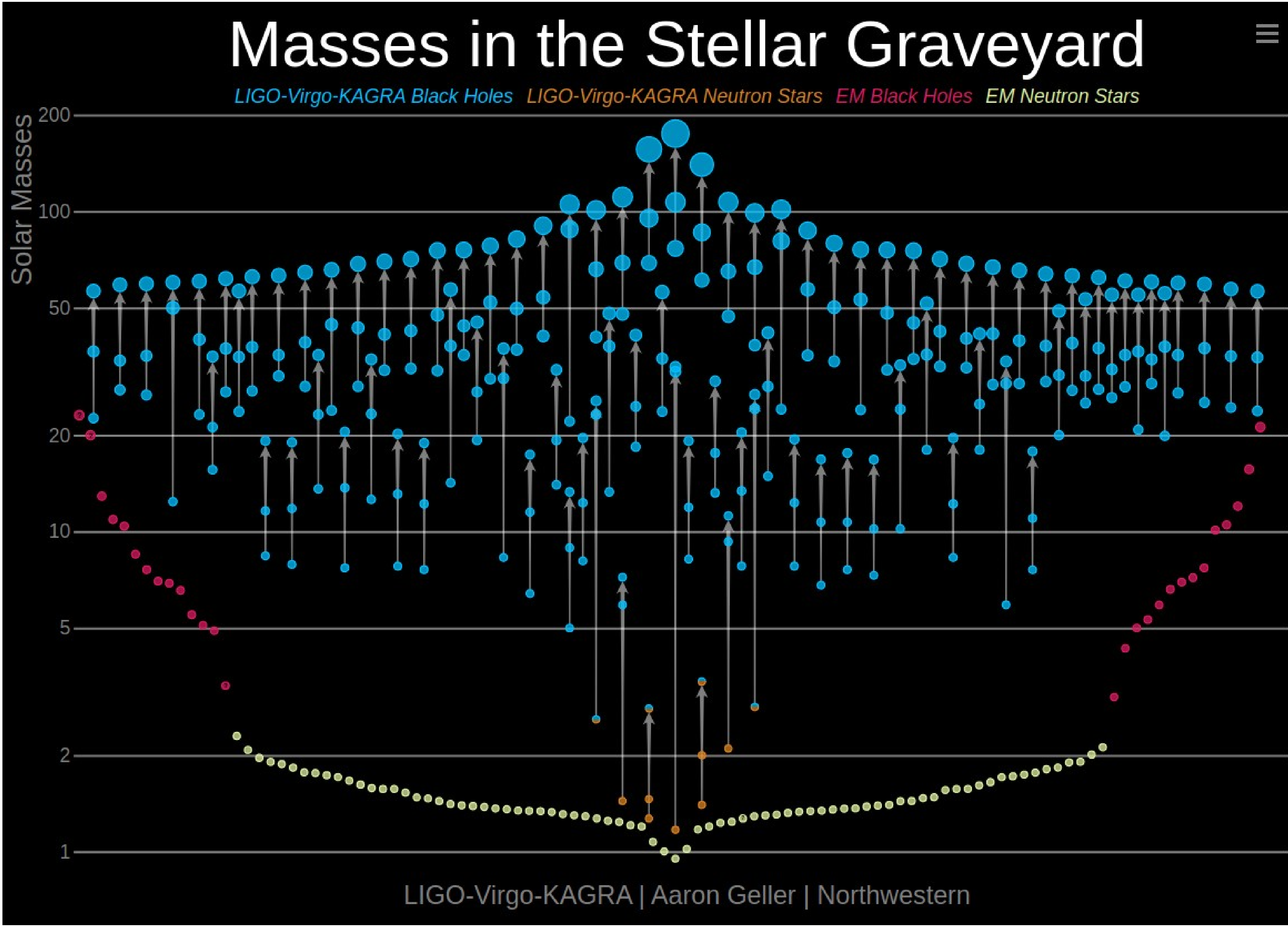
# Current status of detections

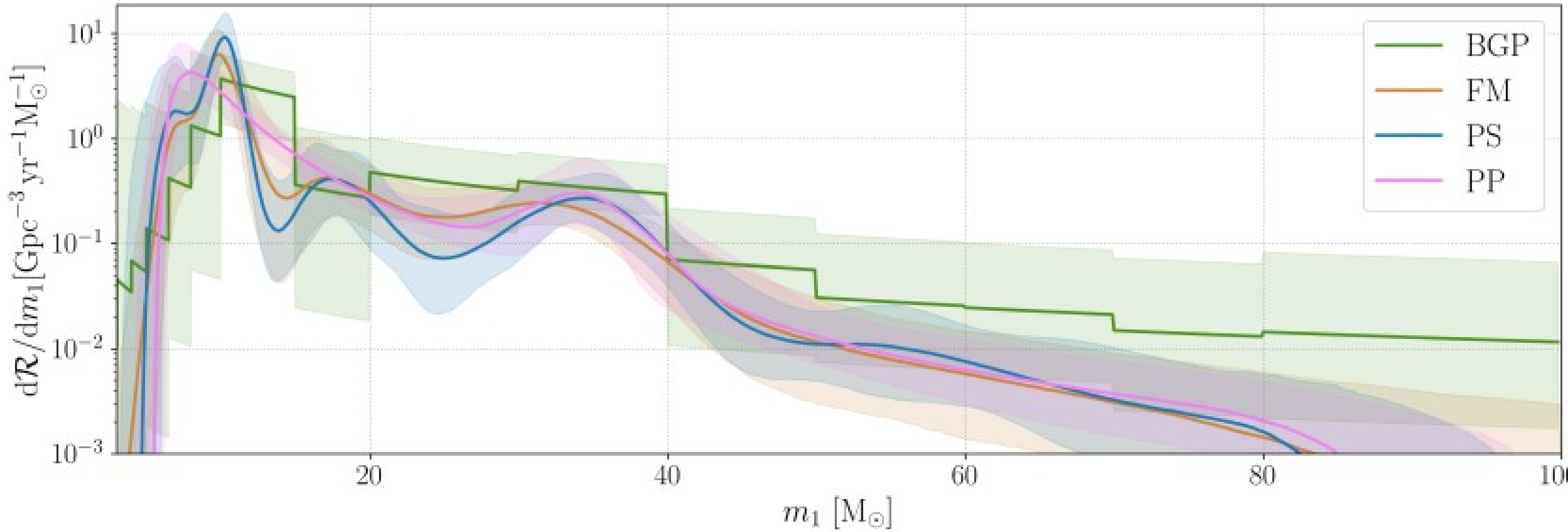
- What can be measured:
  - Chirp mass
  - Mass and mass ratio
  - Effective spin
  - Effective precession
  - Statistical properties

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



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

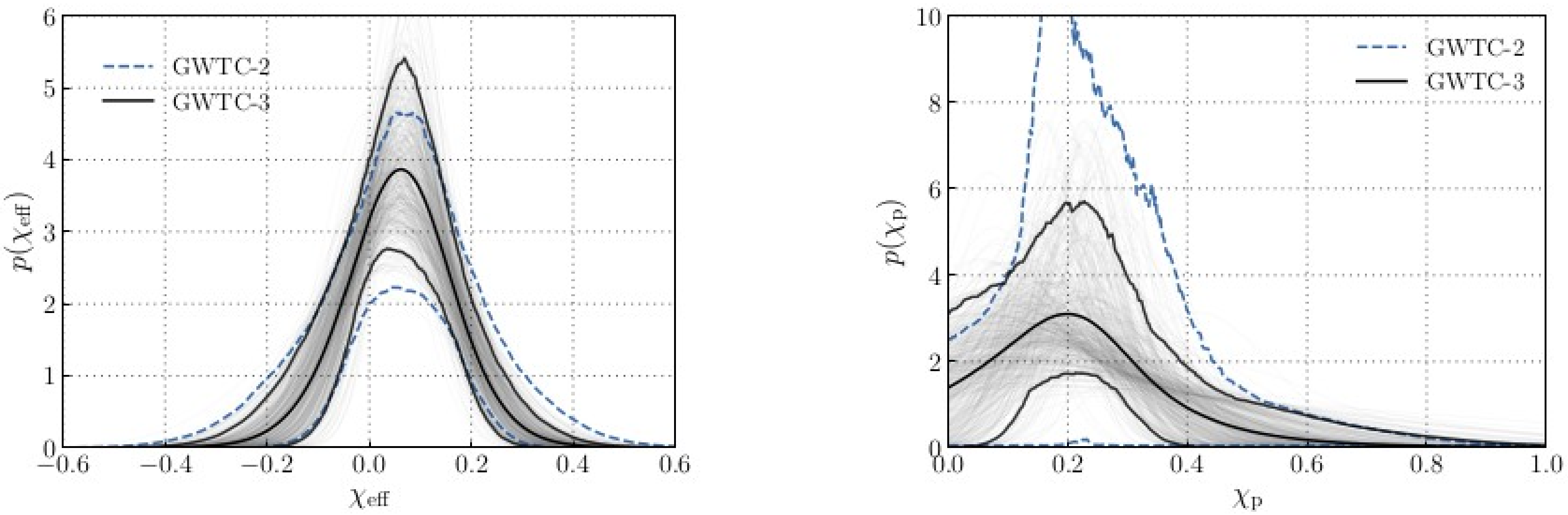
# Primary mass




Peaks in the stellar mass region

Long tail to high masses

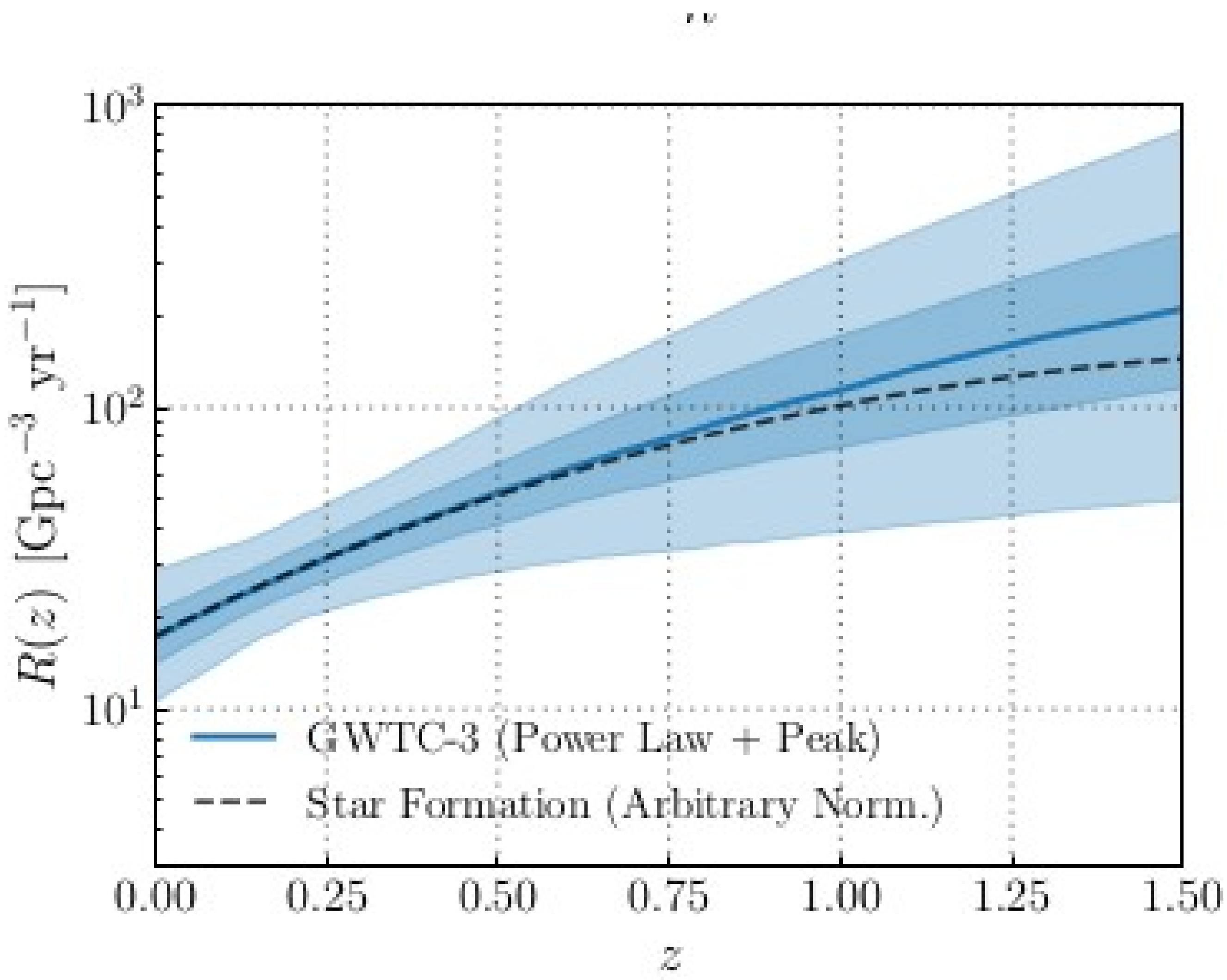
# Spin distribution




Slight tendency toward positive values

Spins are small

# Rates vs redshift



# Challenges in formation

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

# What models do we have?

- Stellar models
  - Binary evolution (filed, chemically homogenous, etc.)
  - Cluster evolution (including nuclear cluster
  - AGN disk model
- Primordial BHs

# 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

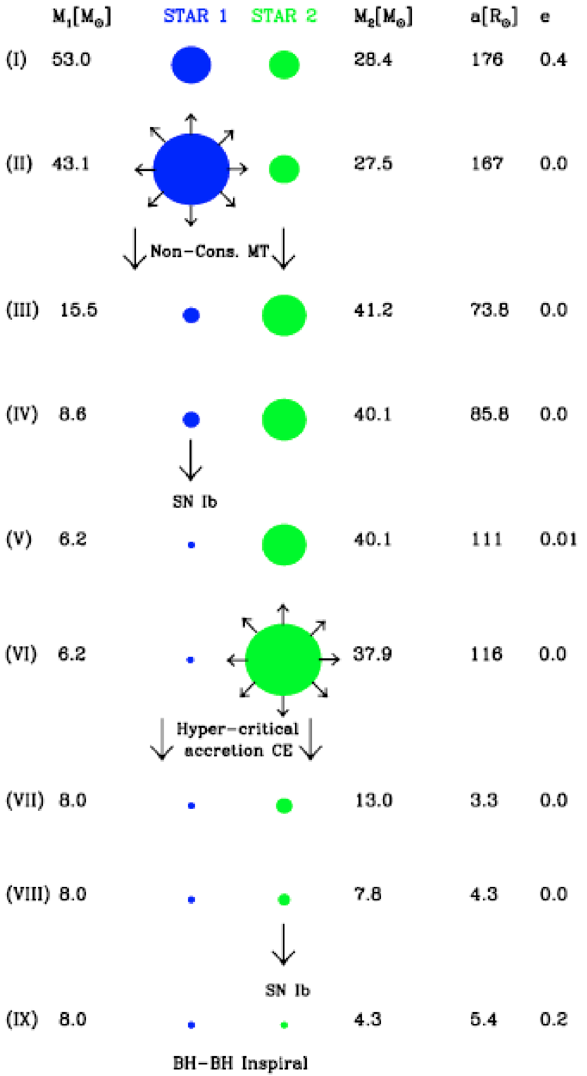
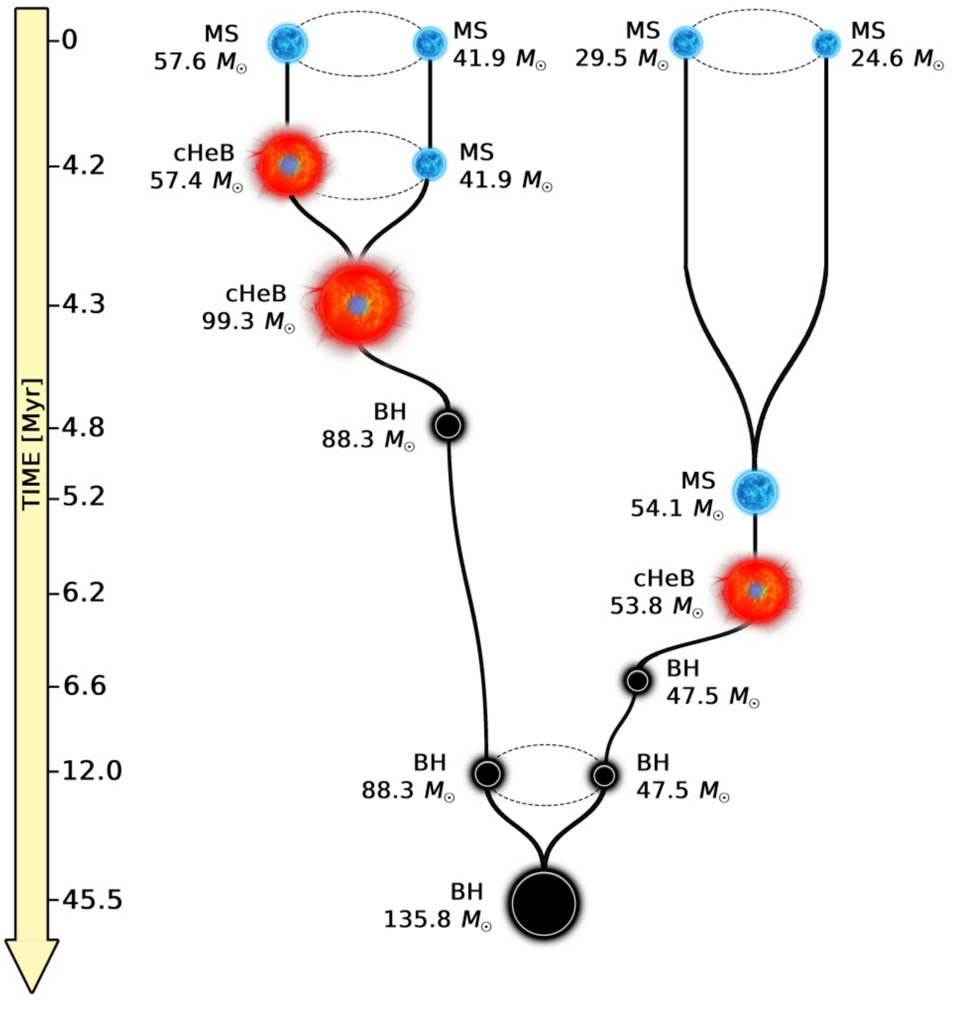



**Fig. 1.** An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

# 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

# AGN disk model

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

# Primordial binaries

- Masses
  - Correspond to phase transitions in the Early universe (can be below 3Msun)
- Spins
  - Random, small
- Rates
  - Do not have to follow SFR

# Comparison with observations

# 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!

# Basic rate arguments

- Formation scenario must be generic
- Exceptional environments must produce BBH and BNS with very high efficiency
- Dense regions are not favored, but do 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

# Small spins

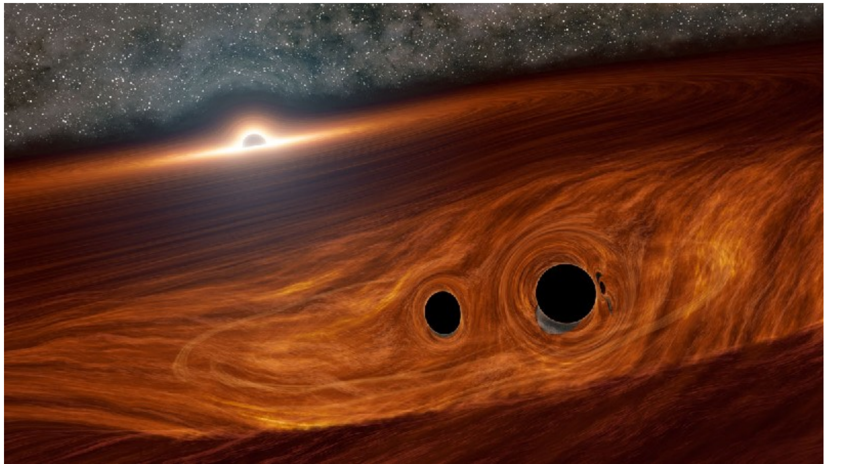
- BH spins measured in accreting binaries are large
- But:
  - Spins of young pulsars
  - Supernova vs GRB rate → spins

# 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 eccentric 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?

# How does it look

| Model | Masses | Spins | Rates |
|---|---|---|---|
| Binary | | | |
| Cluster | | | |
| Primordial | | | |

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

# Things I have overlooked

- A hint of three eccentric binaries
  - triple interaction in dense systems if true
- Delay time distribution from studies of GRBs
  - does not fit pop synthesis