On the origin of gravitational wave sources

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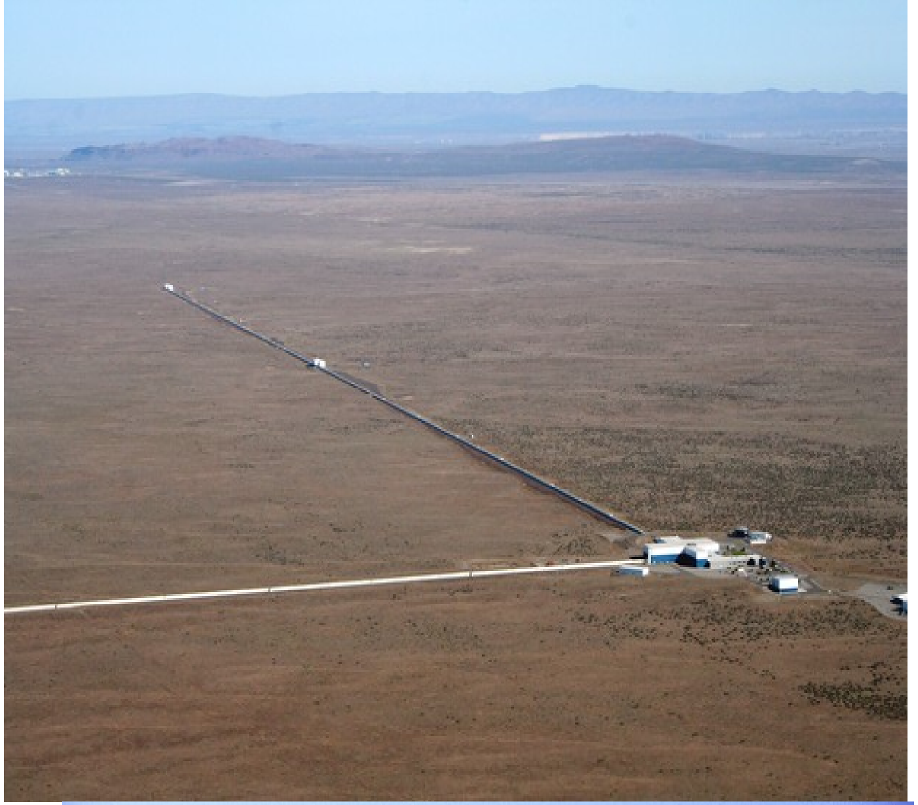
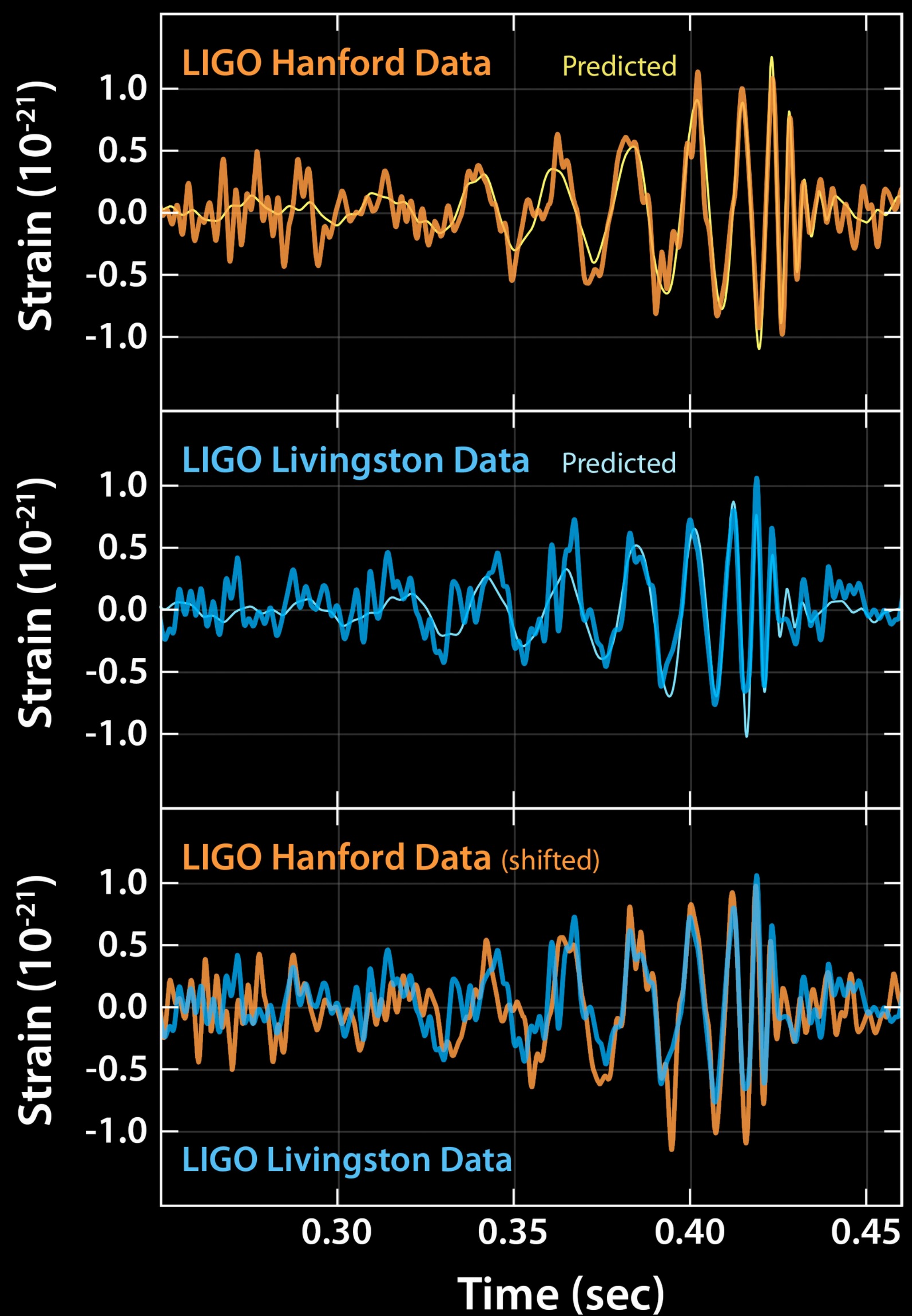
Outline

- GW detections
- Source properties
- Models and their predictions
- Models vs data
- What next?

LIGO i Virgo





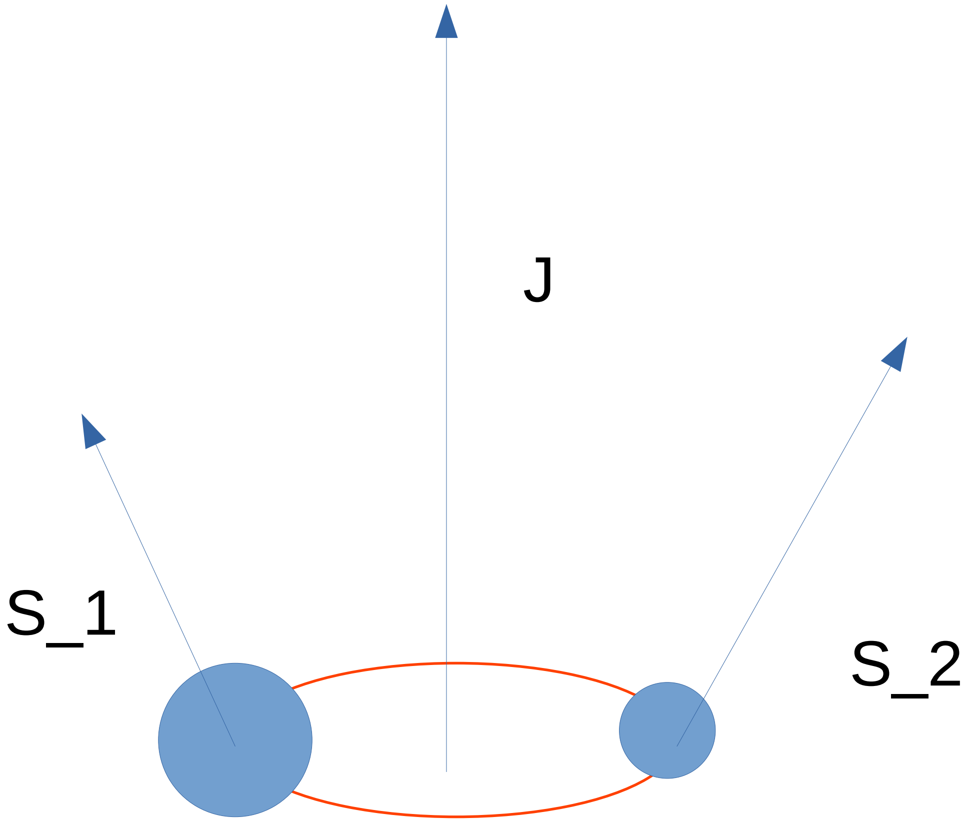
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Current status of detections

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

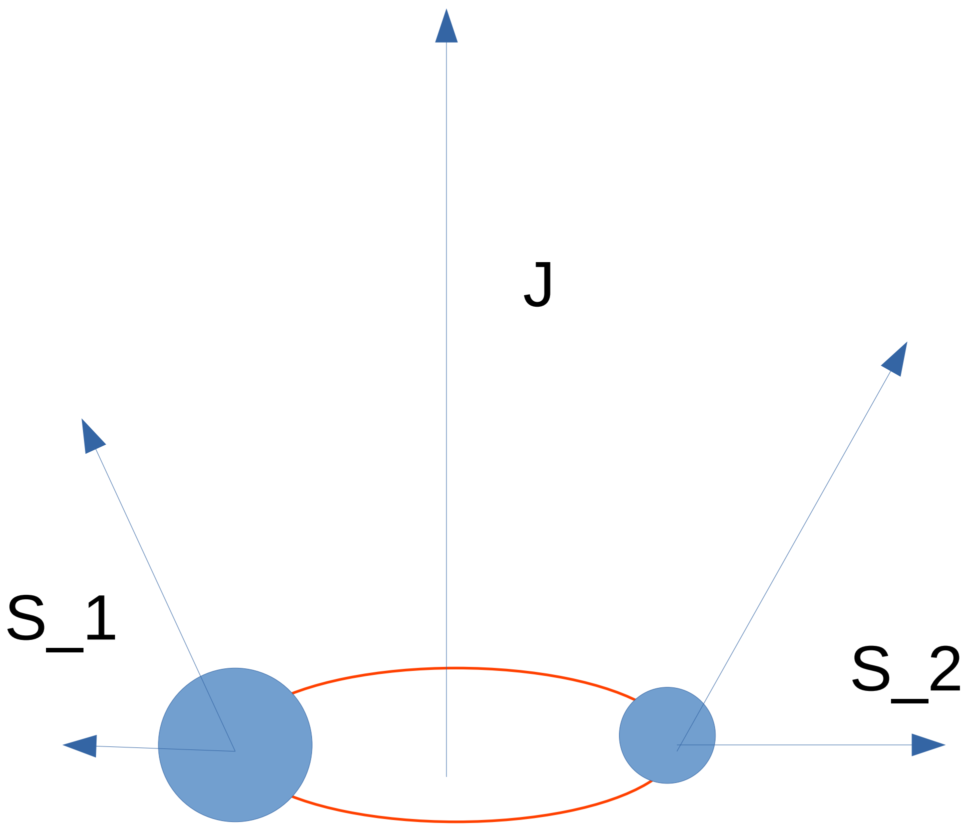
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$

Effective spin

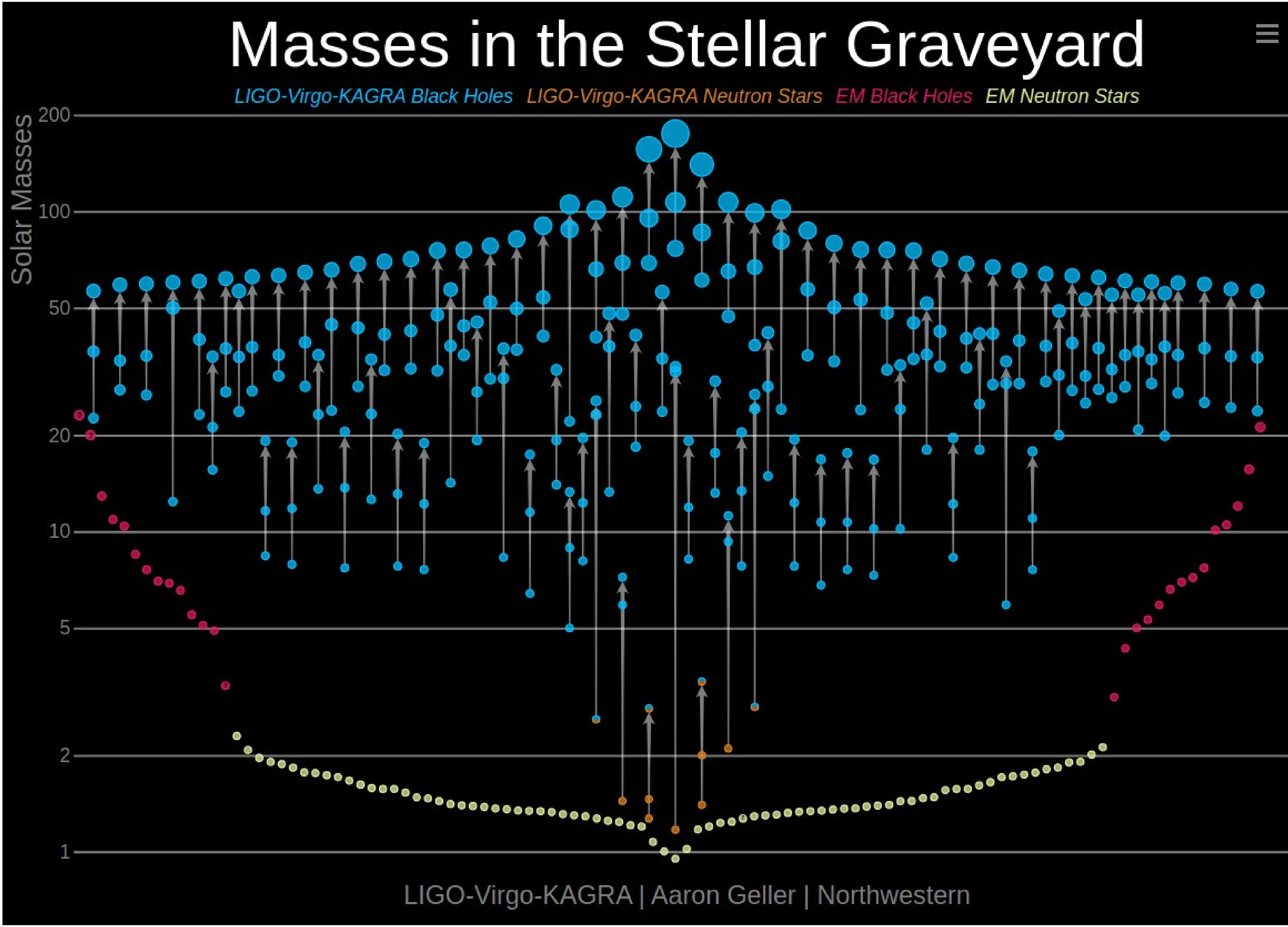


$$\chi_{eff} = \frac{m_1\vec{s}_1 + m_2\vec{s}_2}{m_1 + m_2}\frac{\vec{J}}{|J|}$$

Effective precession spin

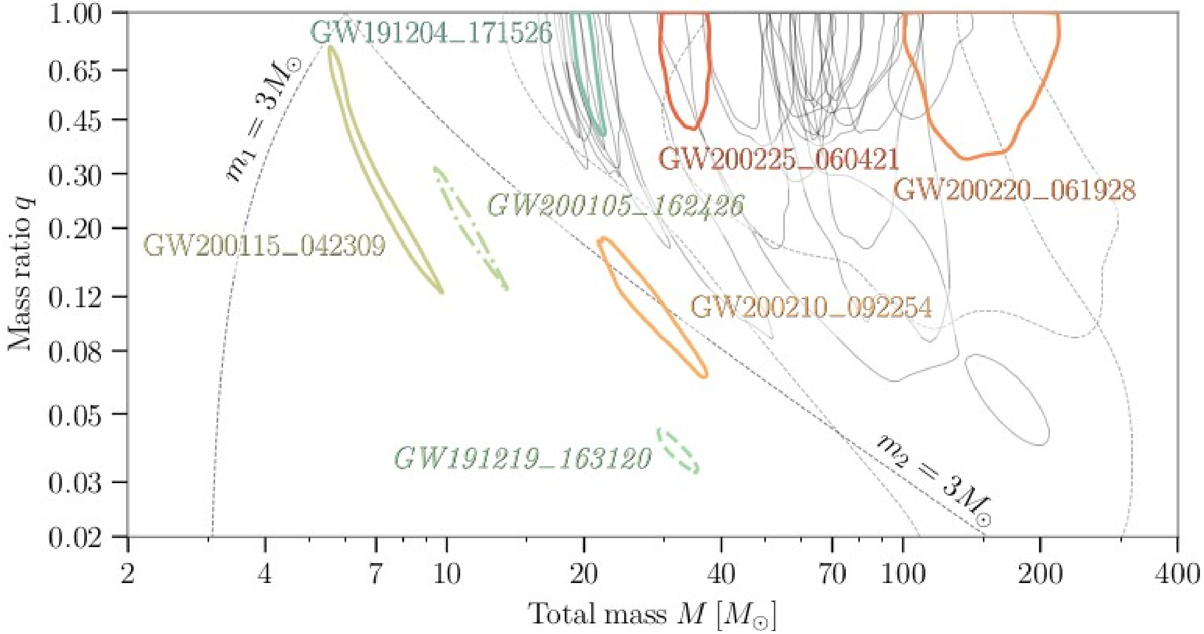


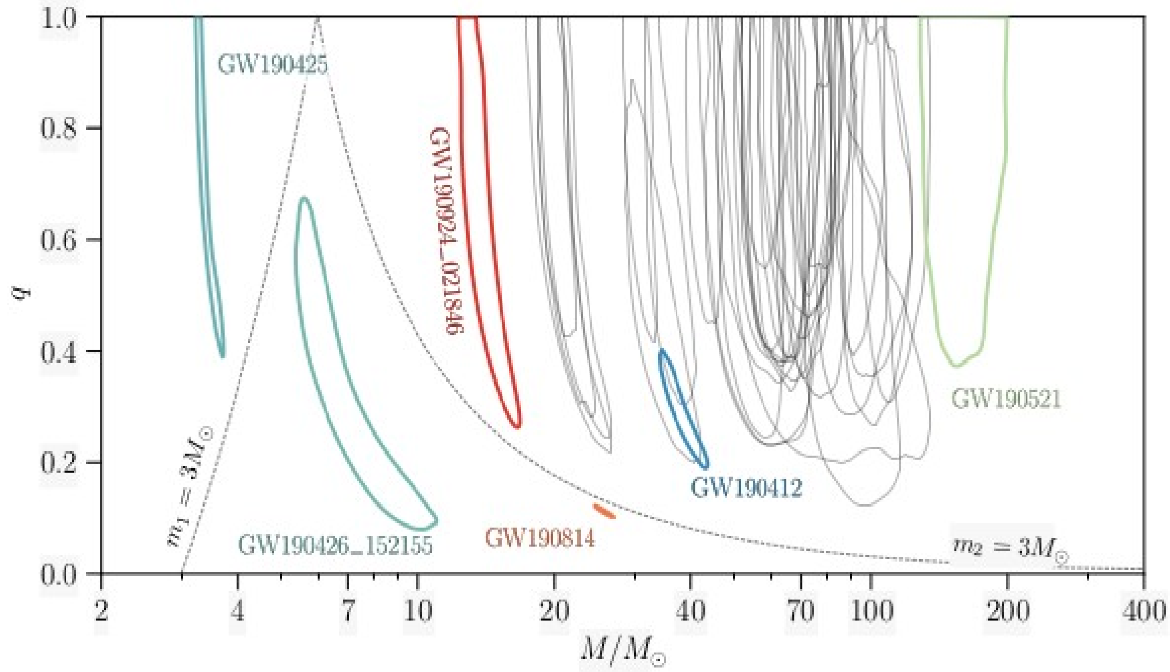
$$\chi_p = \max\left[|s_1|\sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q|s_2|\sin\theta_2\right]$$



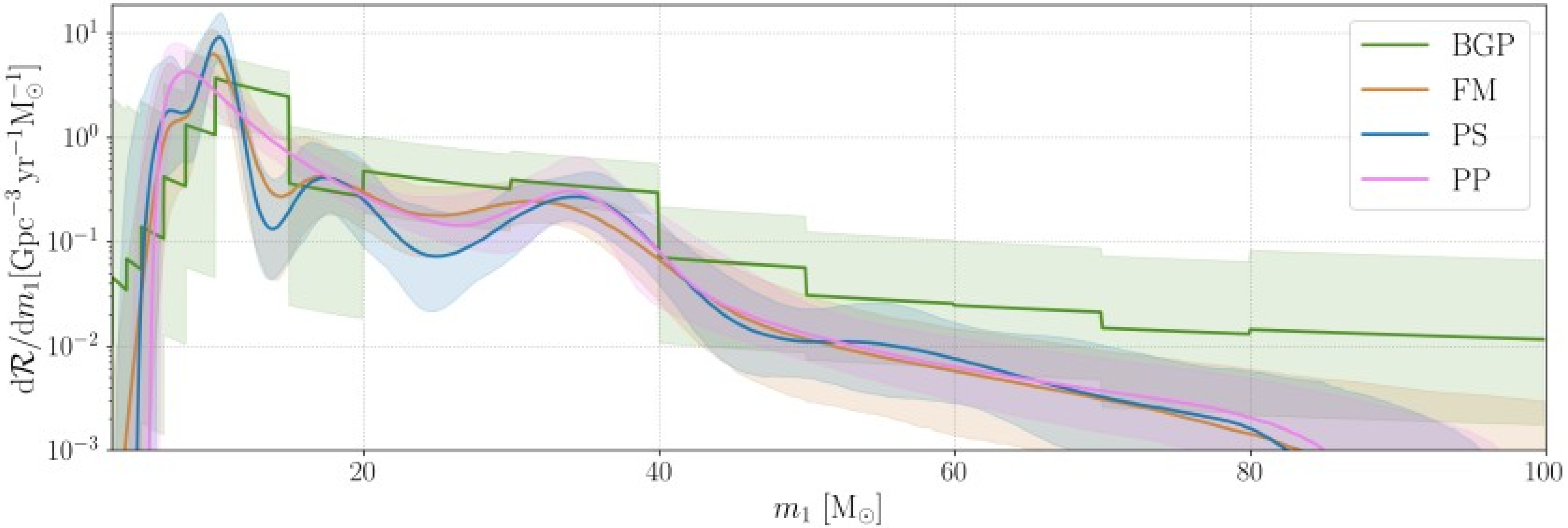
Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses and mass ratios





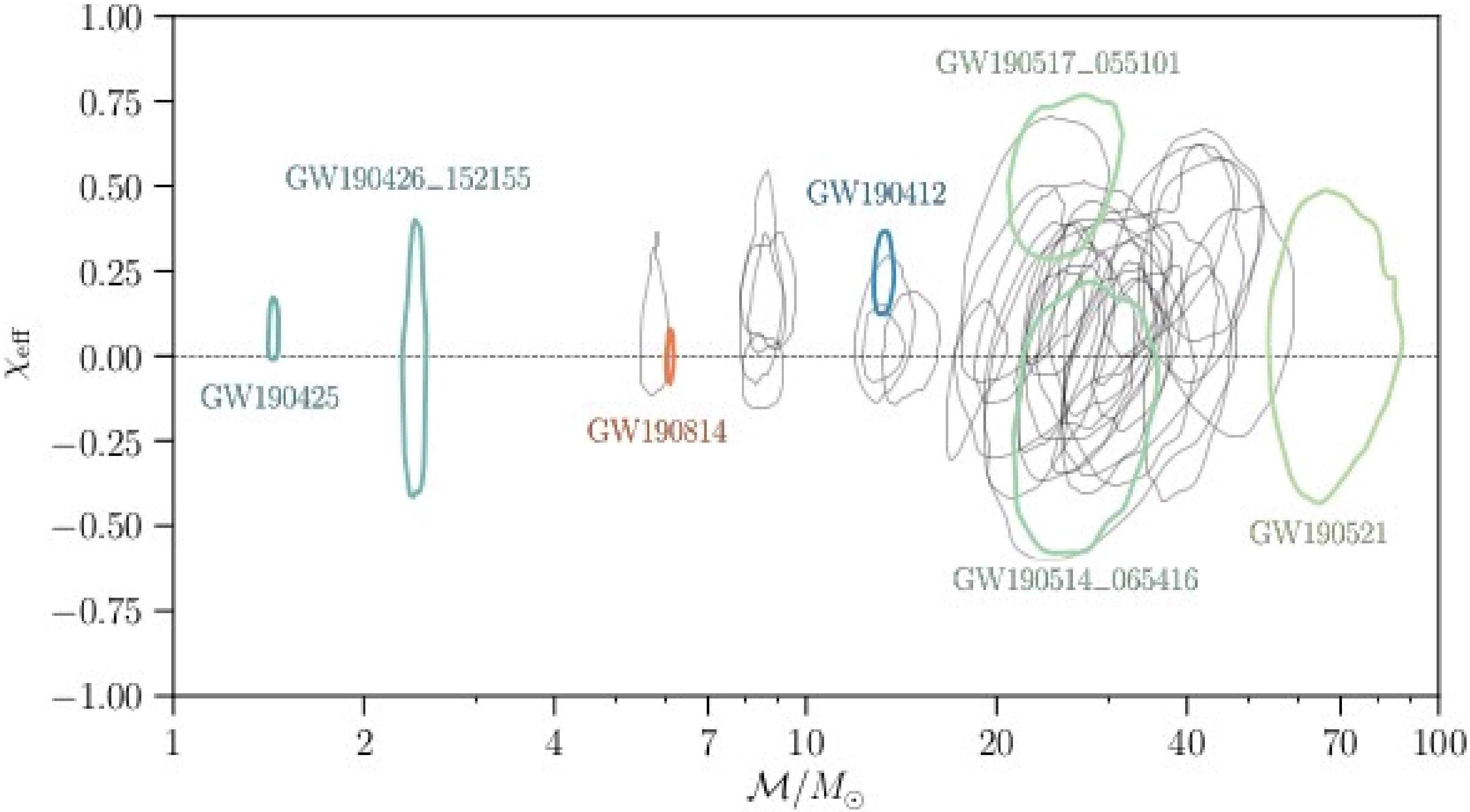
Primary mass



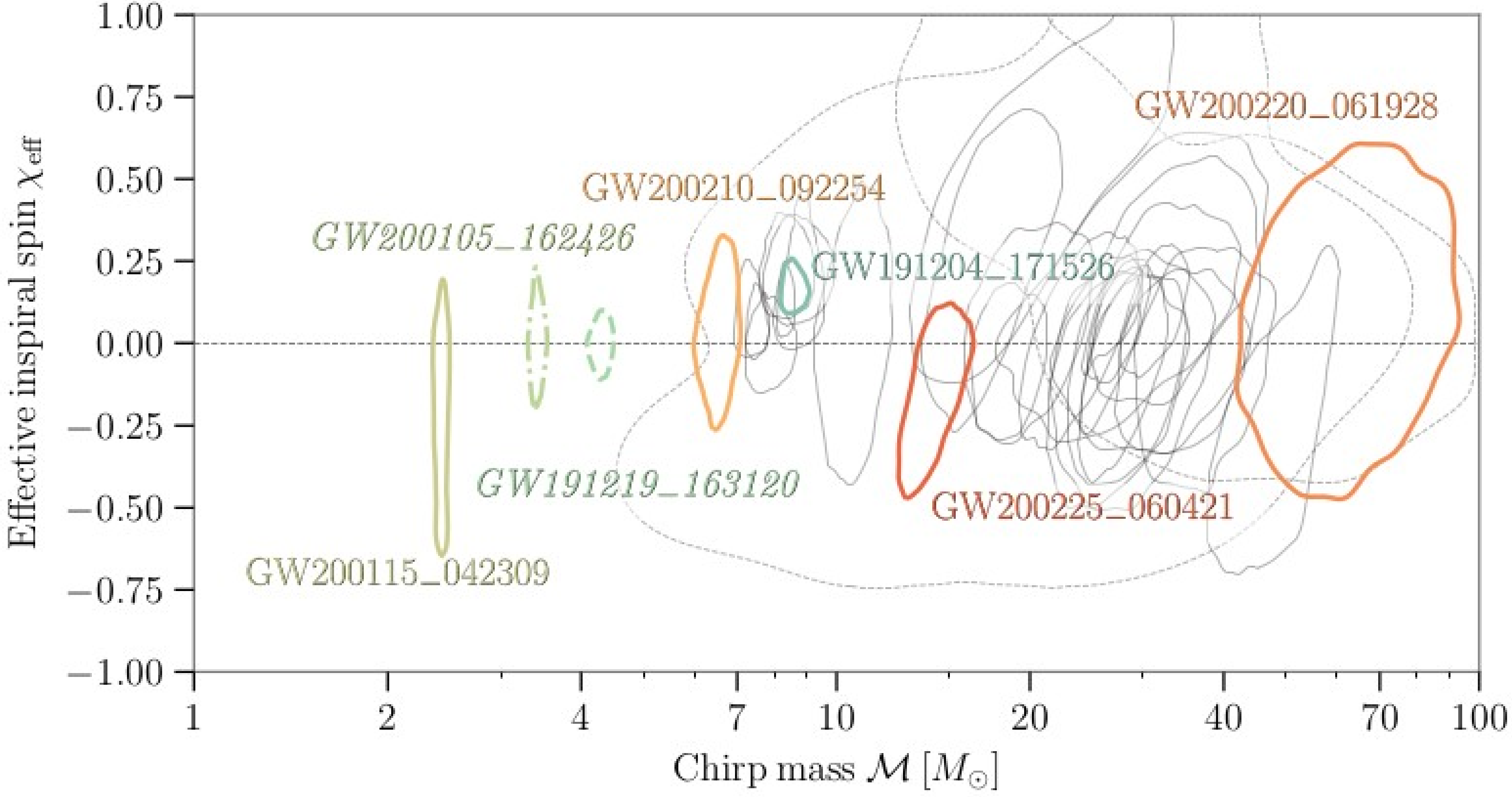
Peaks in the stellar mass region

Long tail to high masses

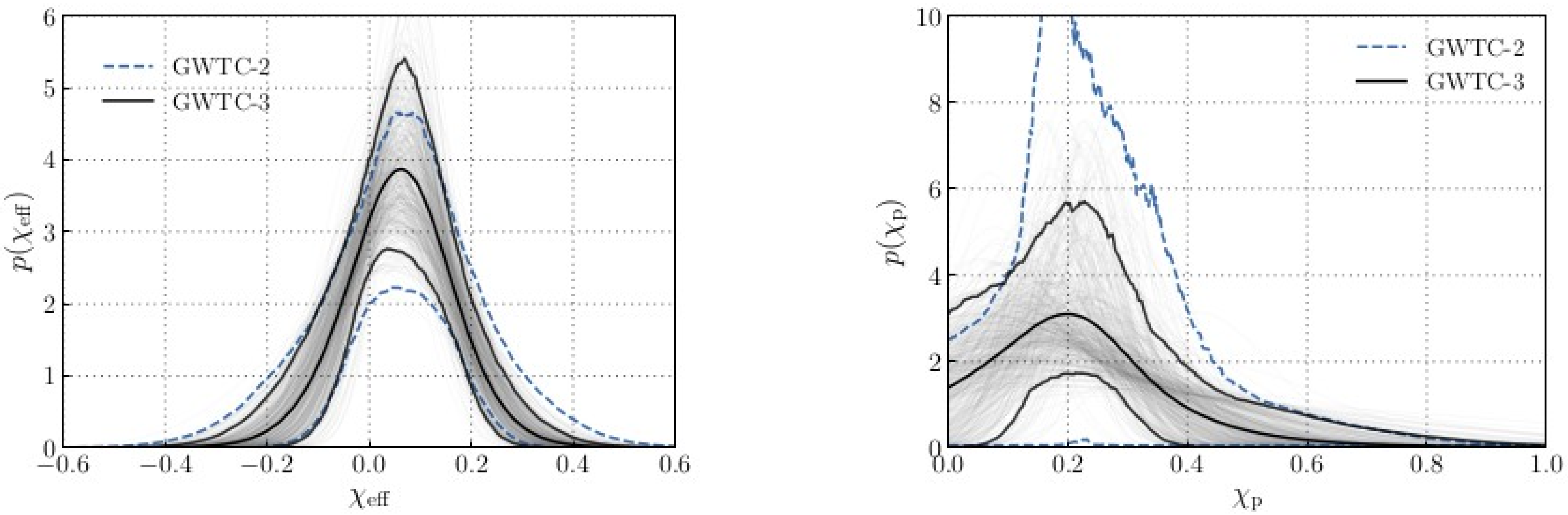
Spins and masses



Spins and masses



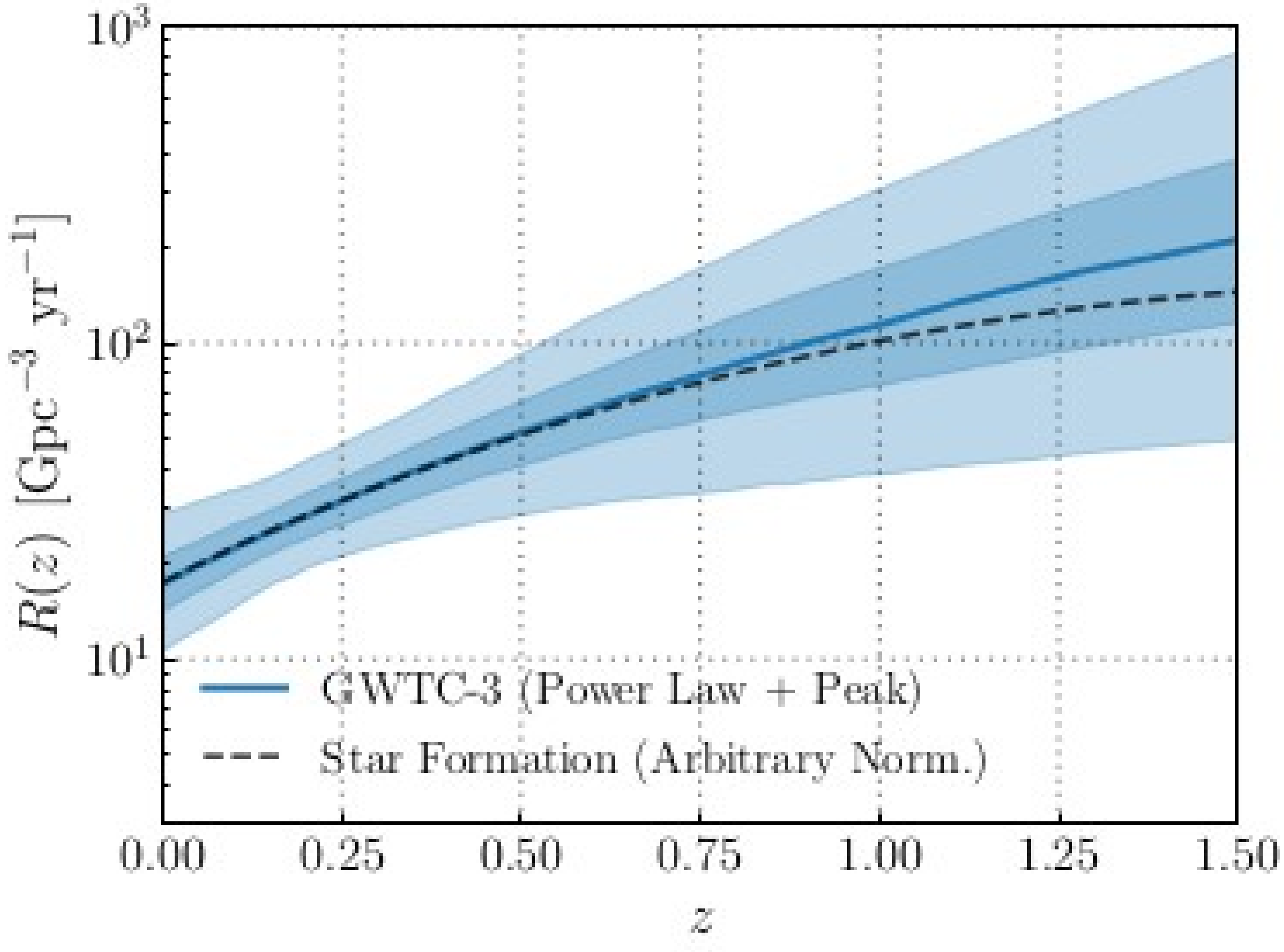
Spin distribution



Slight tendency toward positive values

Spins are small

Rates vs redshift



What is their origin?

- Stellar models
  - Binary evolution (filed, chemically homogenous, etc.)
  - Cluster evolution (including nuclear cluster
- 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

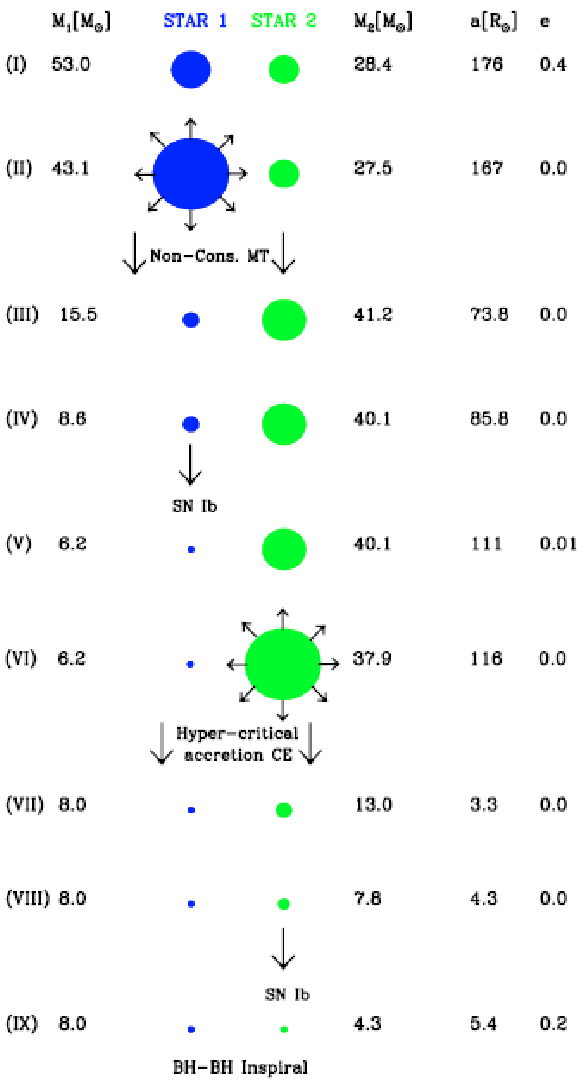
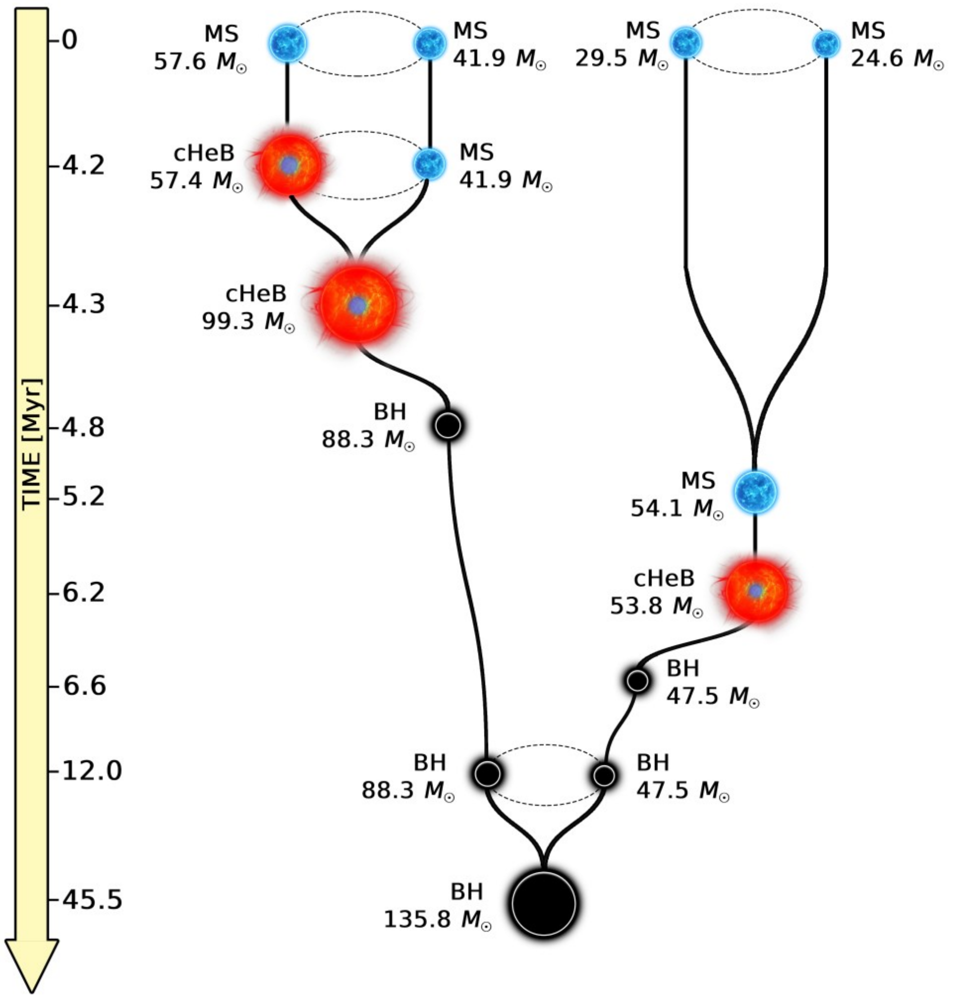


Fig. 1. An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

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

Primordial binaries

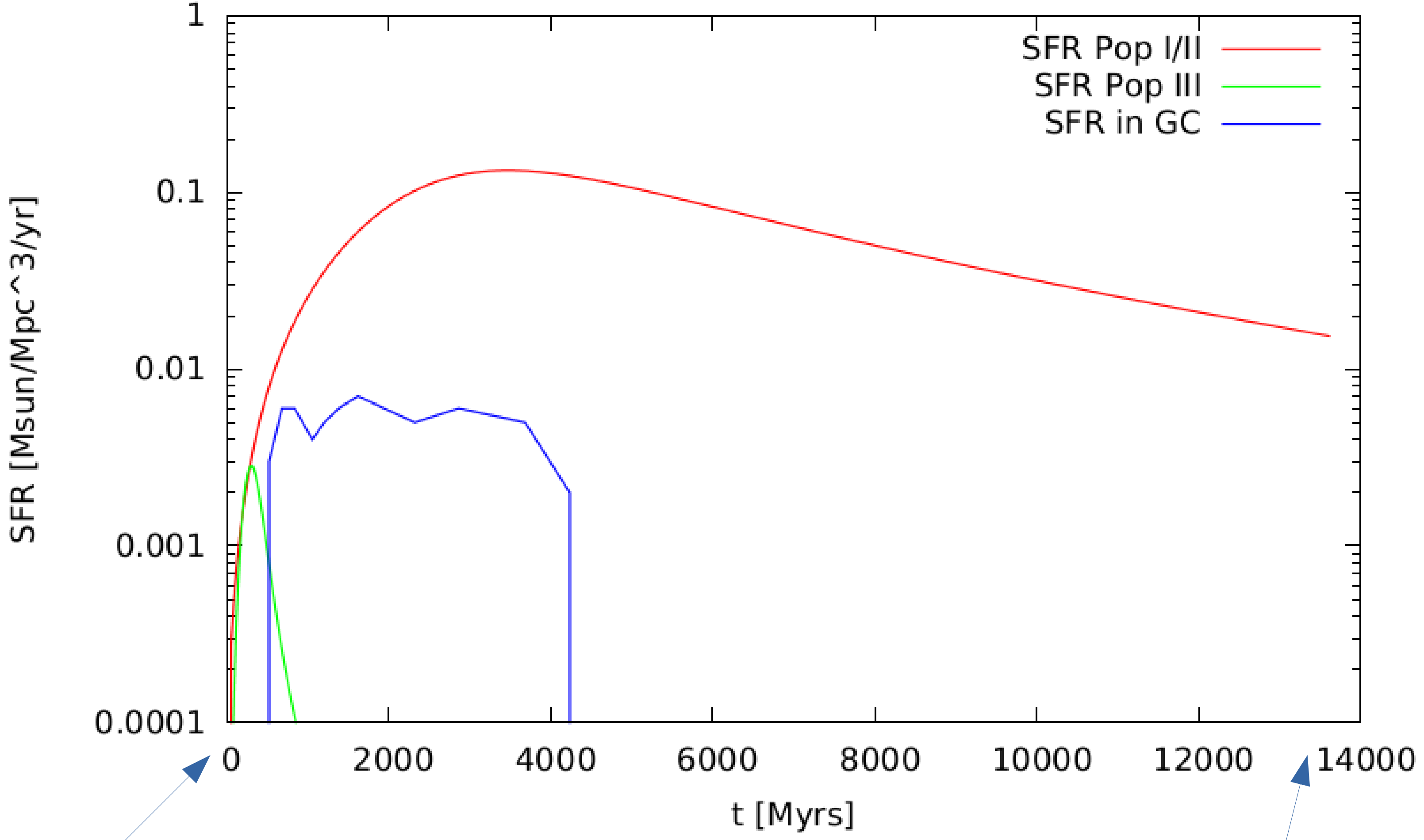
- Masses
  - Correspond to phase transitions in the Early universe (can be below 3Msun)
- Spins
  - Random, small
- Rates
  - Do not have to follow SFR

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
- Similarily NS: 1 in 100-1000 is in a merging binary!

SFR



Big Bang

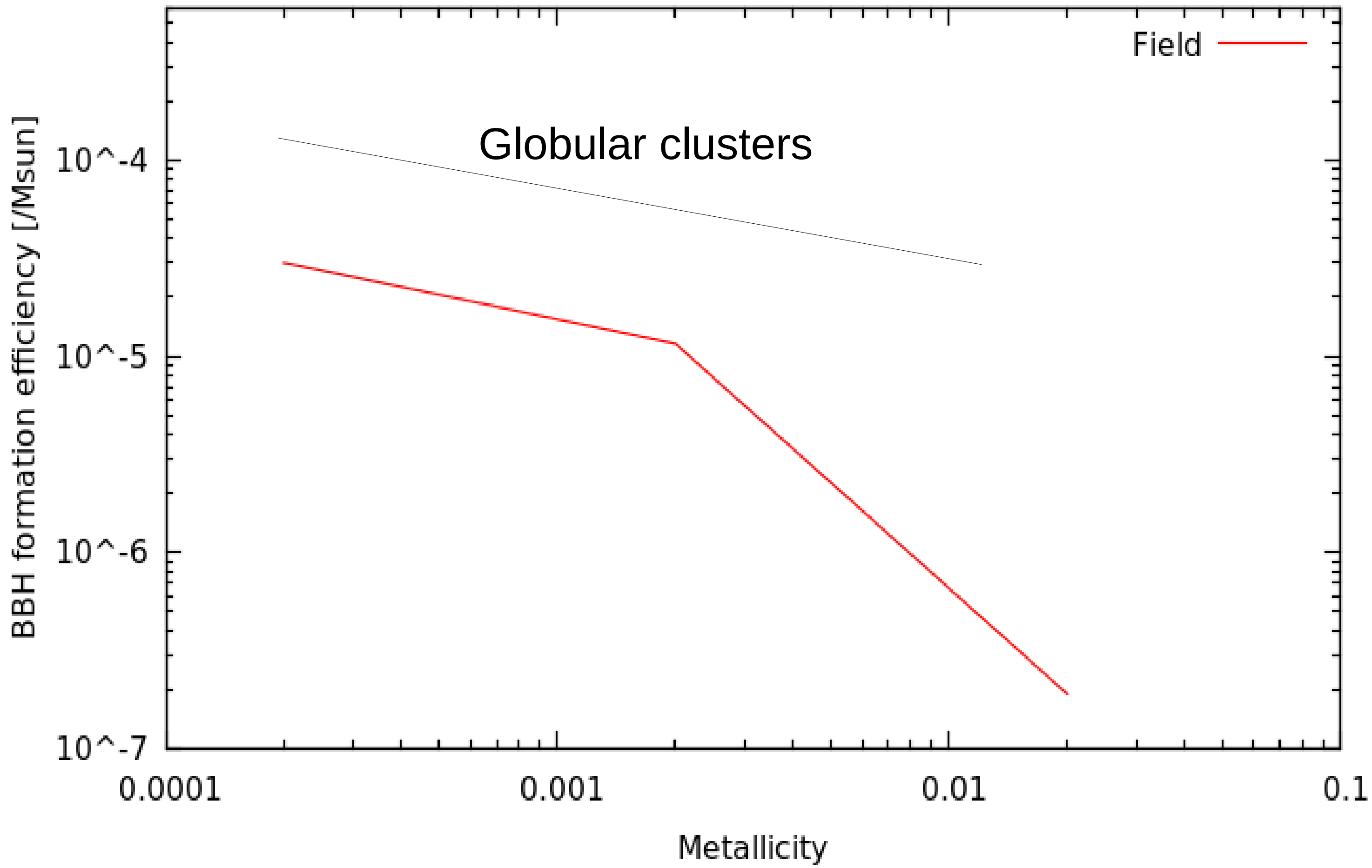
Today

BHBH formation efficiency

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

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

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



Basic rate arguments

- Formation scenario must be generic
- Exceptional environments must produce BBH and BNS with very high efficiency
- Dense rebions are not favoured, but do contribute
- I am sceptical 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
- Rates
  - increase but follow SFR
  - Is there a peak at z=2-3?

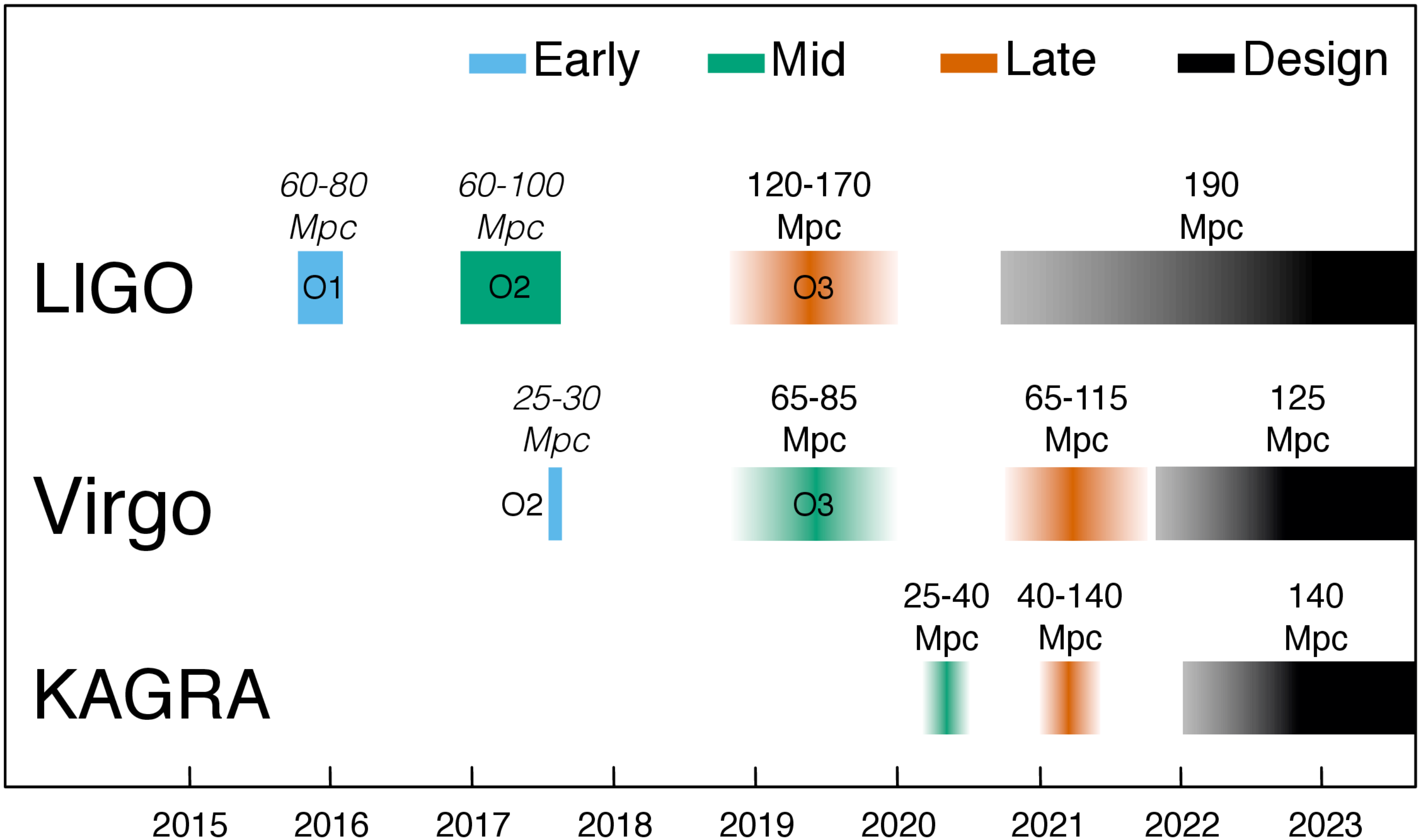
Primordial

- 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			
Promordial			

What next



ET and Cosmic Explorer needed!