Gravitational wave astrophyics at the onset of O4

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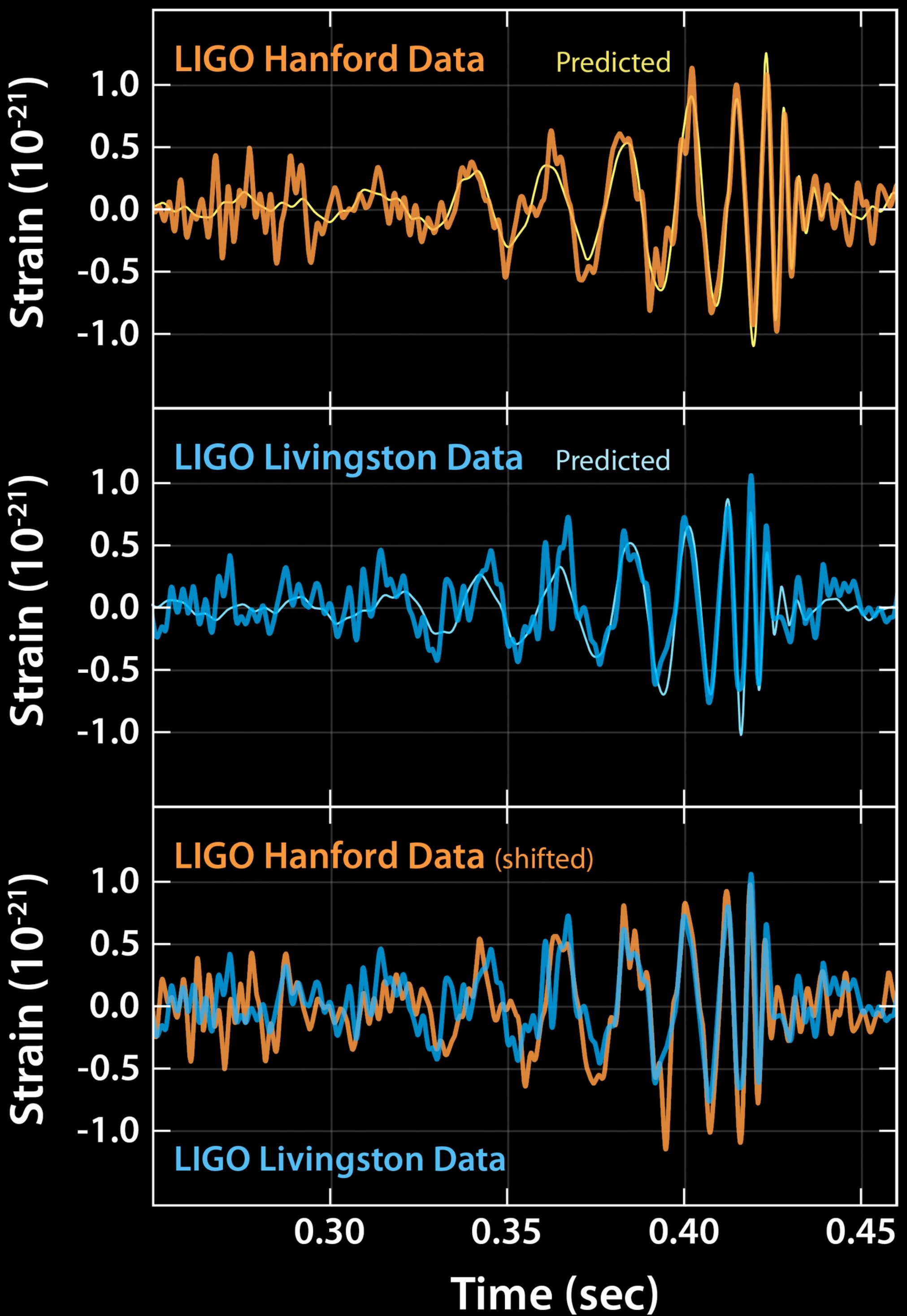
Outline

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

LIGO, 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)

A list of breakthroughs

- Detection of gravitational waves
- Detection of a black hole
- Detection of black hole binary
- Evidence for BHs with masses of 30 and and up to 60 solar masses
- Possibility to test General Relativity
- Possibility to test Quantum Gravity(?)
- The brightest source ever seen in the sky:

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

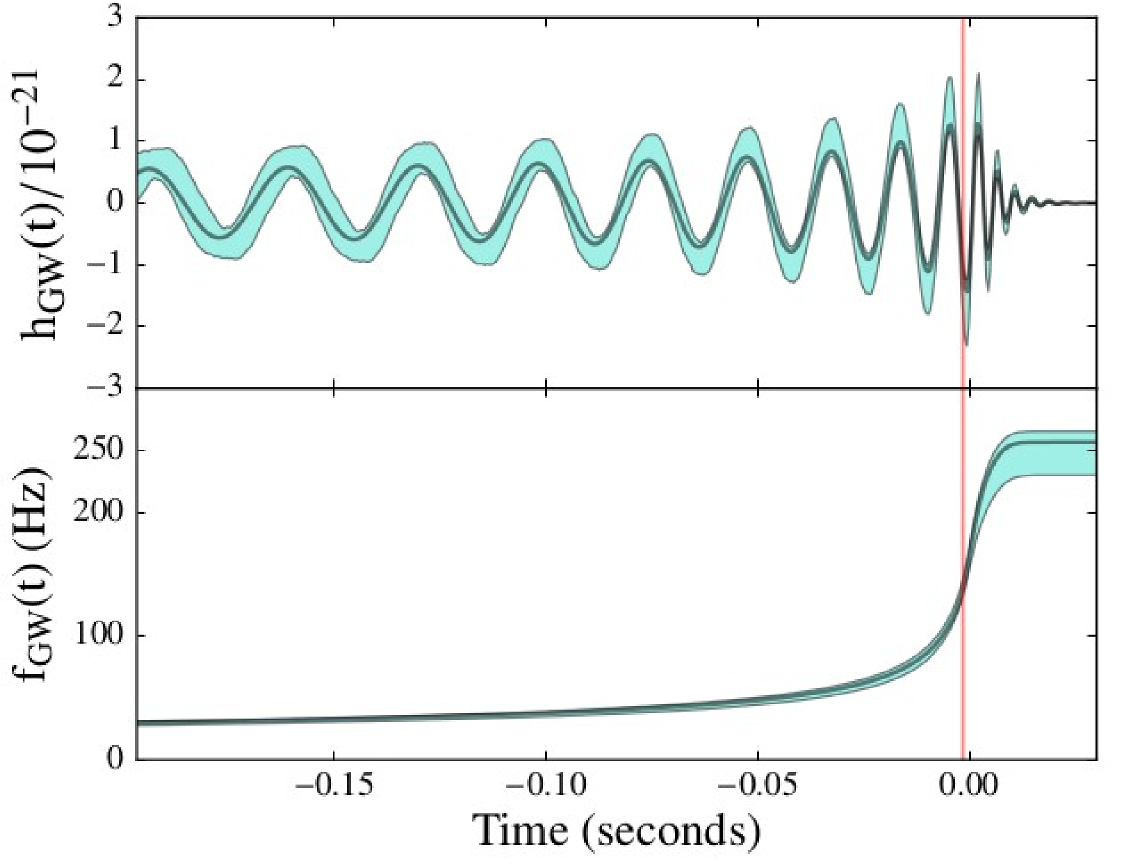
Physics

The reconstructed waveform allows to place lmits on fundamental physics:

Graviton mass

General relativity

Probe no hair theorem



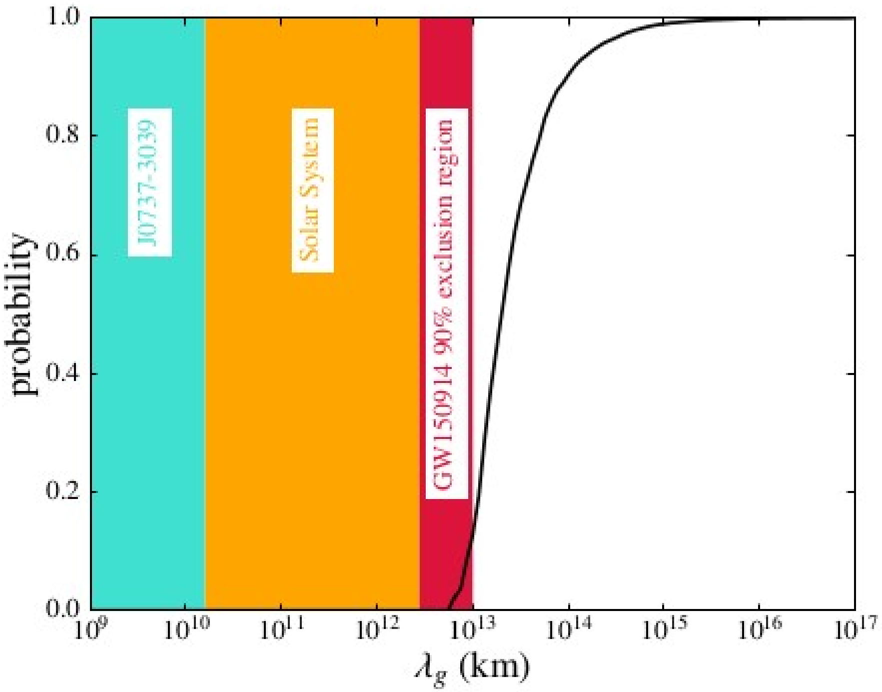
Graviton

- Graviton mass limits

$$\frac{v_g}{c} = \sqrt{1 - \frac{h^2 c^2}{\lambda_g^2 E^2}}$$

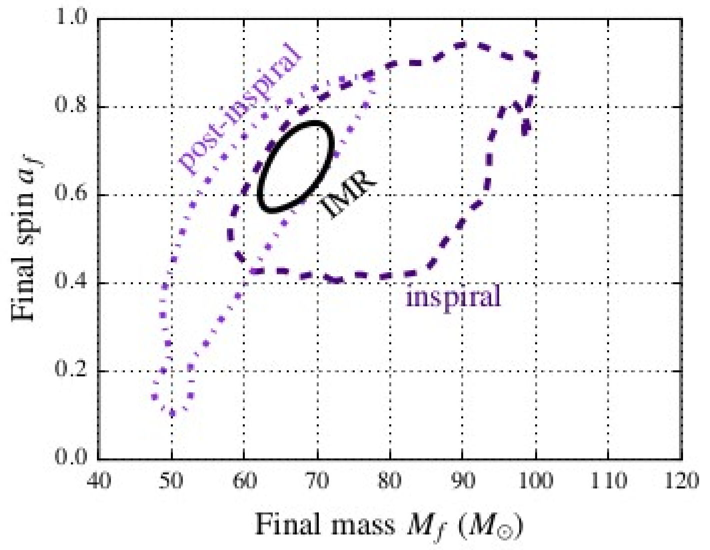
$$\lambda_g > 10^{13}\mathrm{km}$$

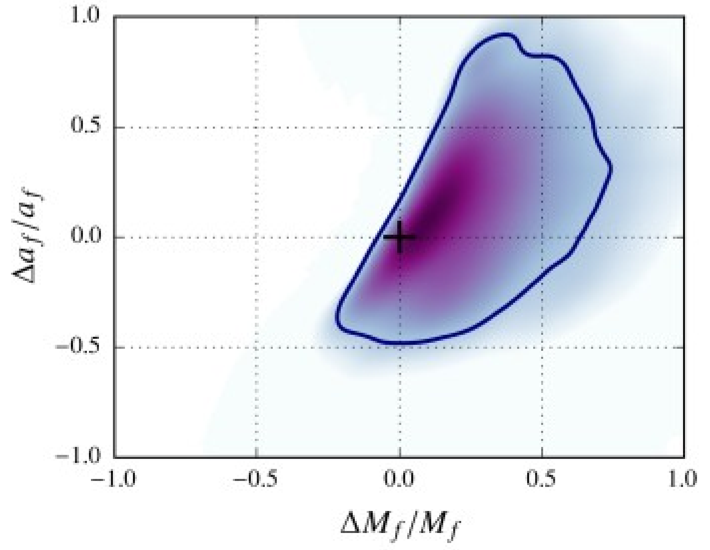
$$m_g < 10^{-22}\mathrm{eV/c^2}$$



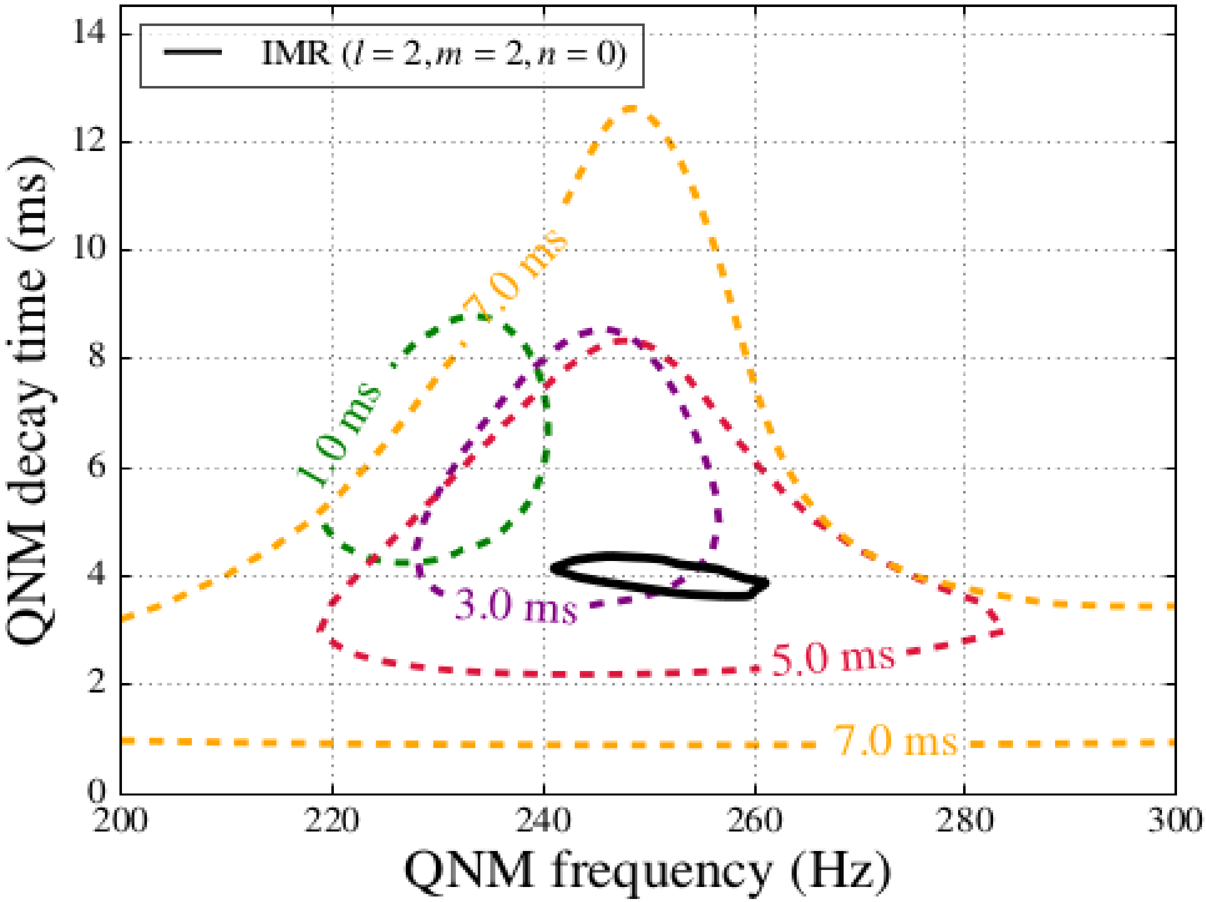
Tests of General Relativity

- The final mass and spin is implied by the the initial ones.
- Measure the mass in the inspiral phase
- Measure the final mass and spin with quasi normal modes
- Check consistency





Ringdown of the new BH

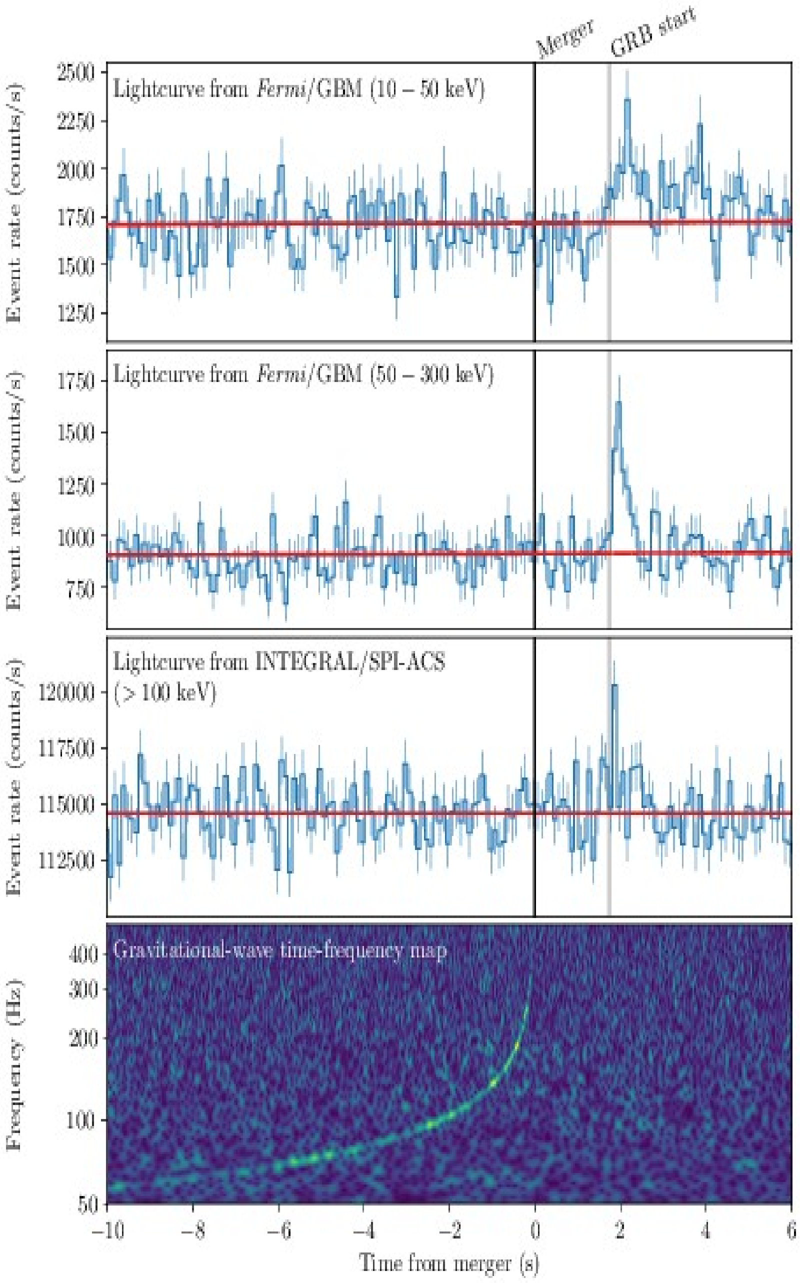


Model and measurements – assuming diffferent time of formation of the single BH

Double neutron star GW170817

- Origin of short GRBs
- Speed of gravity
- Origin of heavy metals
- Hubble constant
- NS equation of state through deformation measurement

Gravitational wave speed



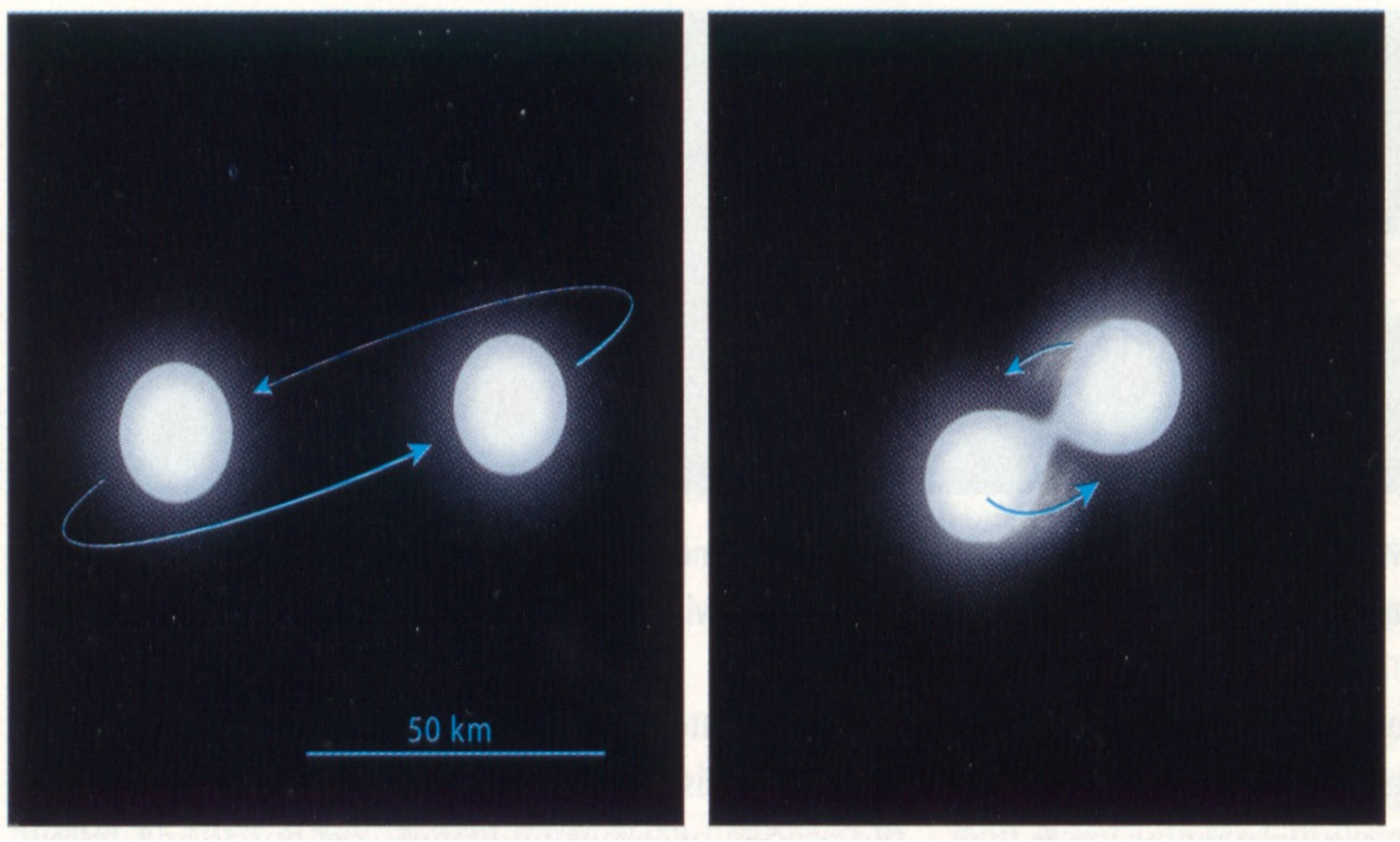
Time delay - 1.7 s, let us assume it is less than 10s

Distance 40 Mpc = 4.10 x 10^{15} light s, let us assume a lower limit of 26Mpc

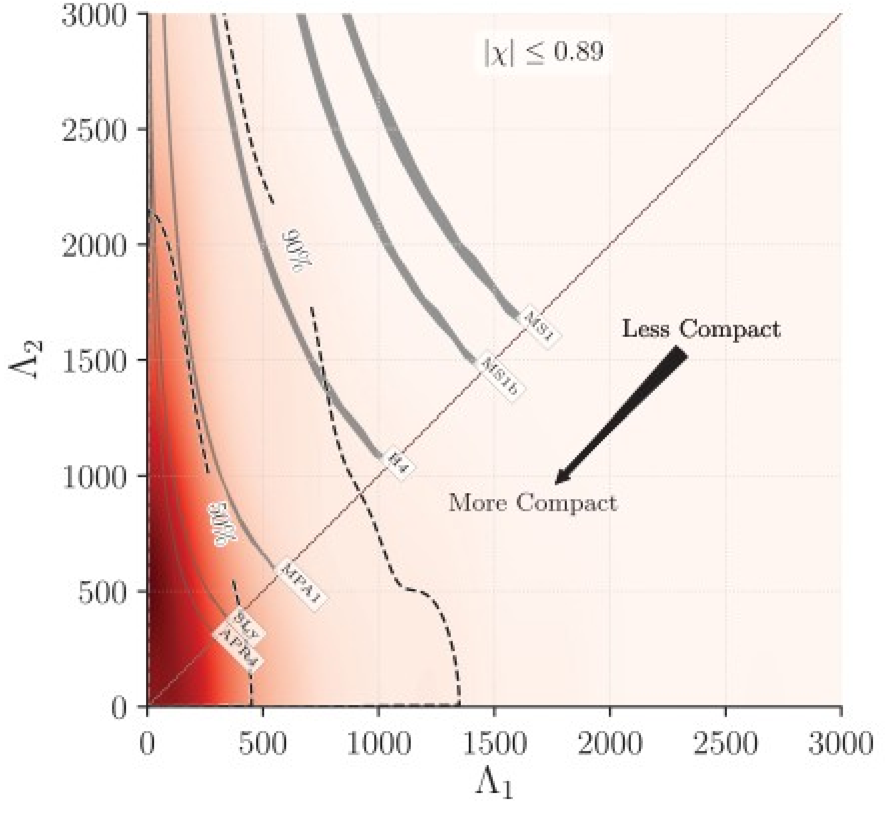
Relative difference of speed

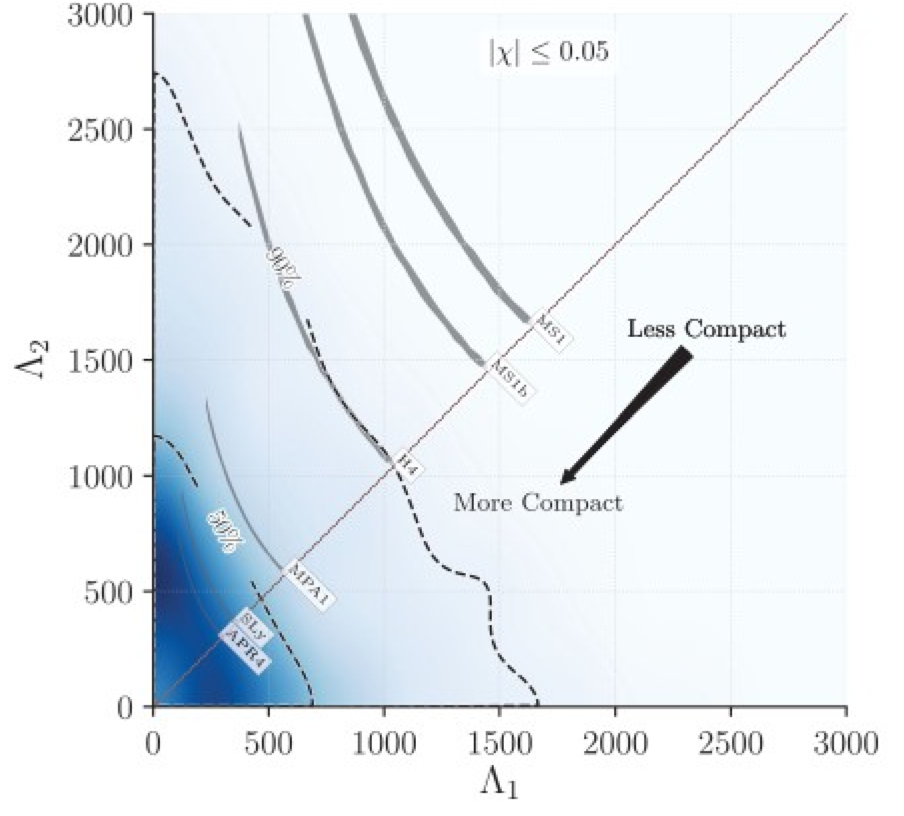
$$-3 \times 10^{-15} < \frac{\delta c_g}{c} < 7 \times 10^{-15}$$

Neutron star deformability



Limits on the deformability of neutron stars



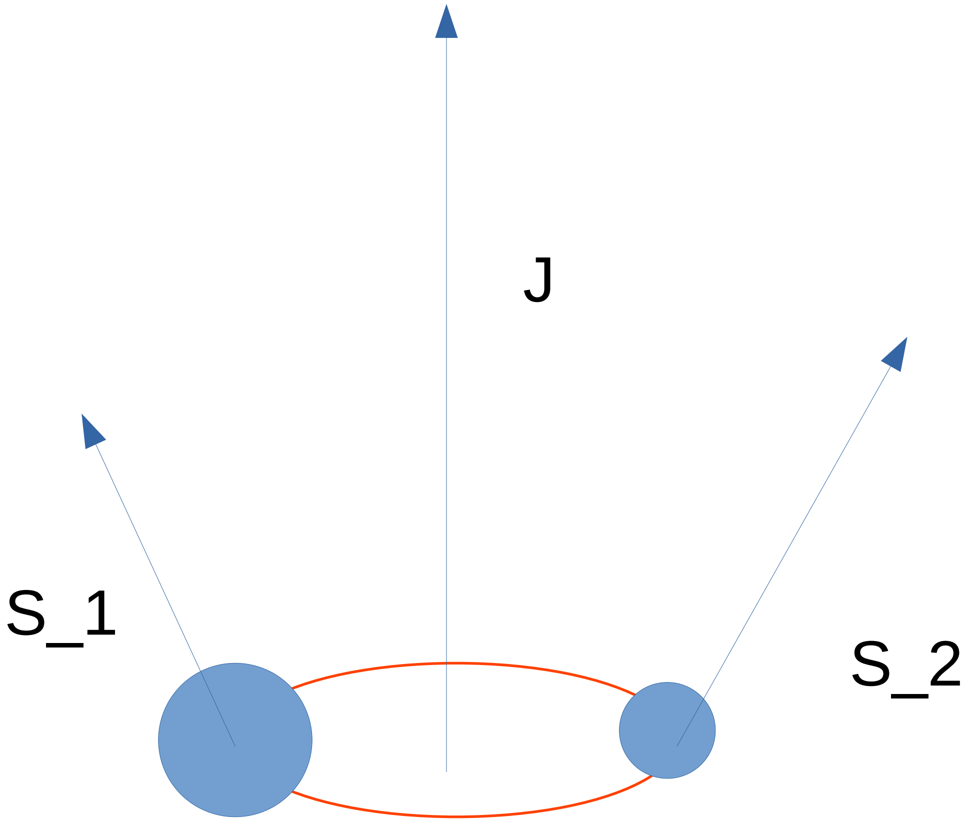


Current status of detections

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

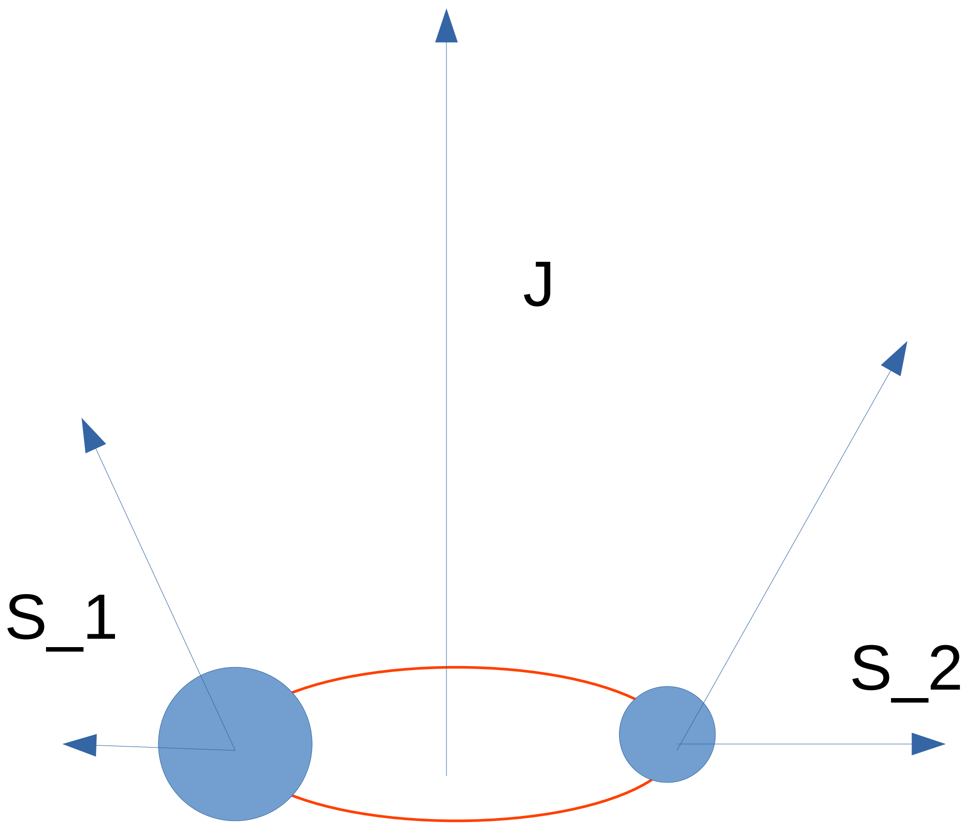
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$

Effective spin

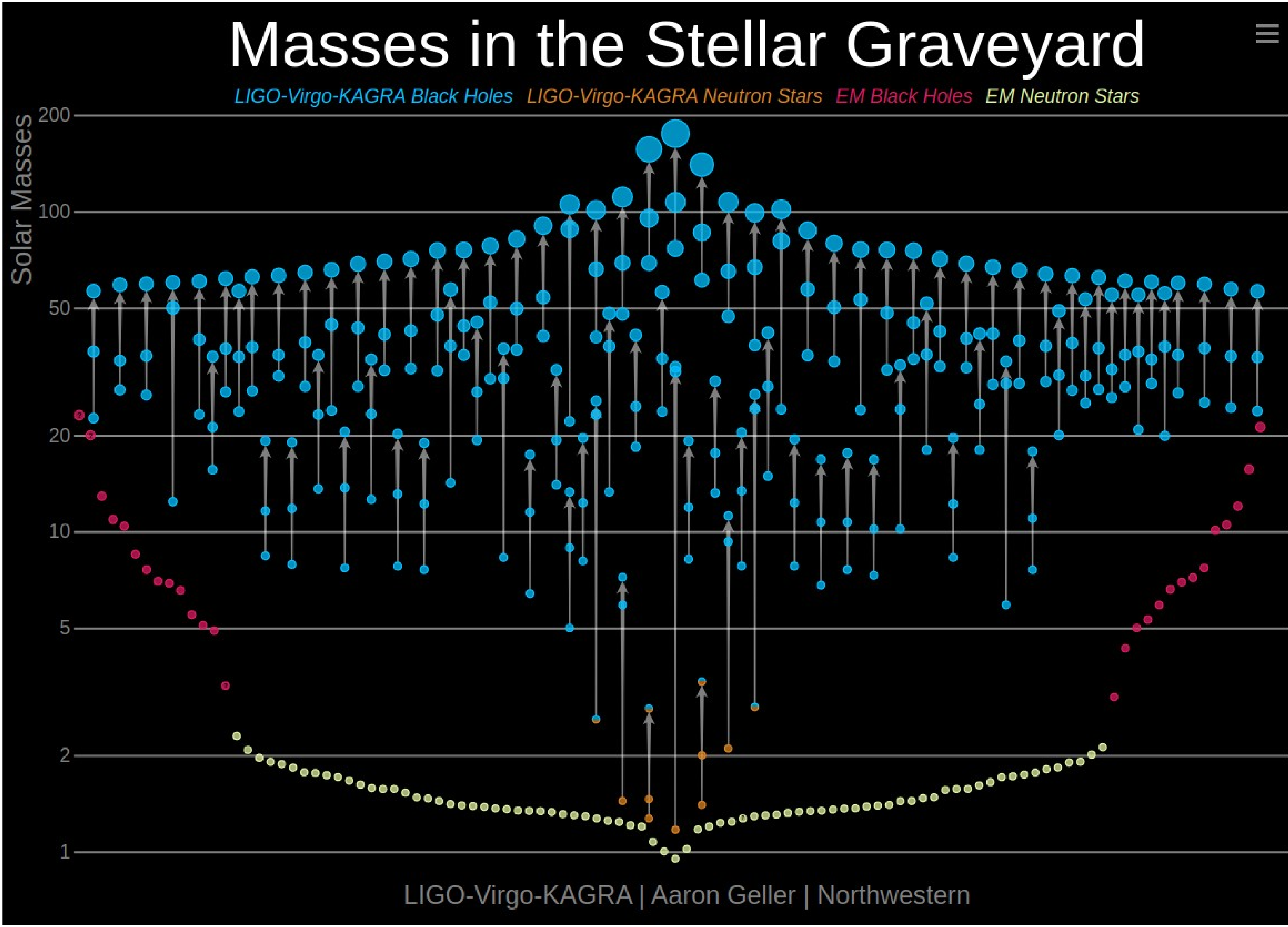


$$\chi_{eff} = \frac{m_1\vec{s}_1 + m_2\vec{s}_2}{m_1 + m_2}\frac{\vec{J}}{|J|}$$

Effective precession spin

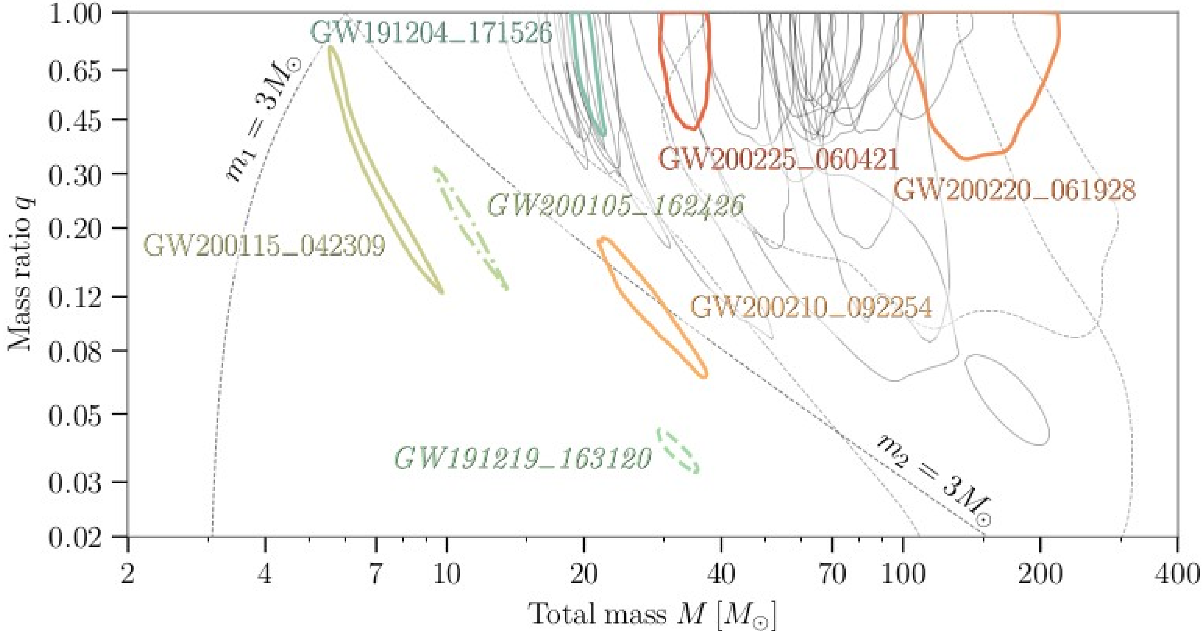


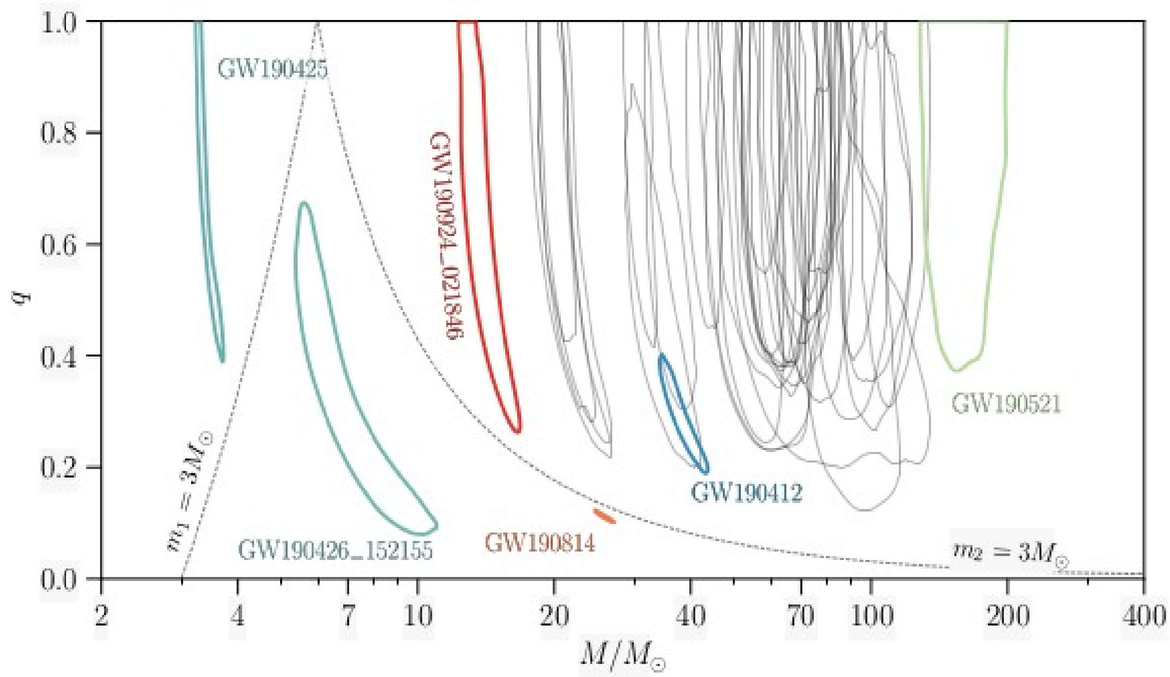
$$\chi_p = \max\left[|s_1|\sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q|s_2|\sin\theta_2\right]$$



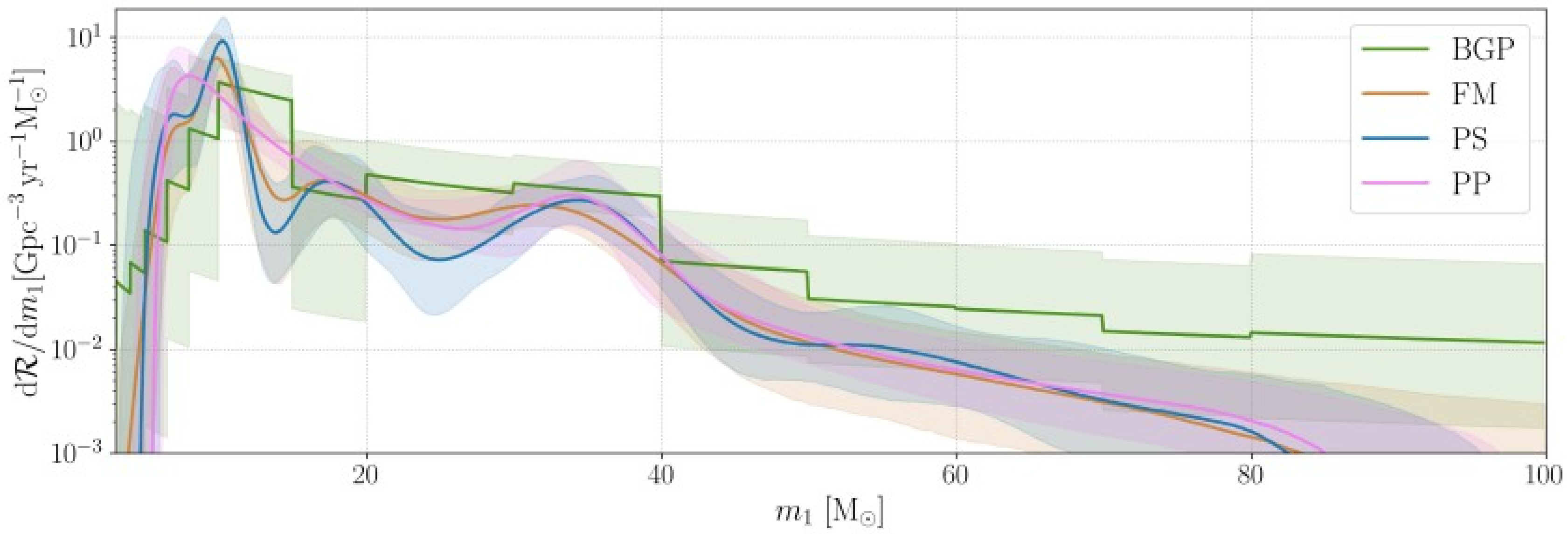
Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses and mass ratios





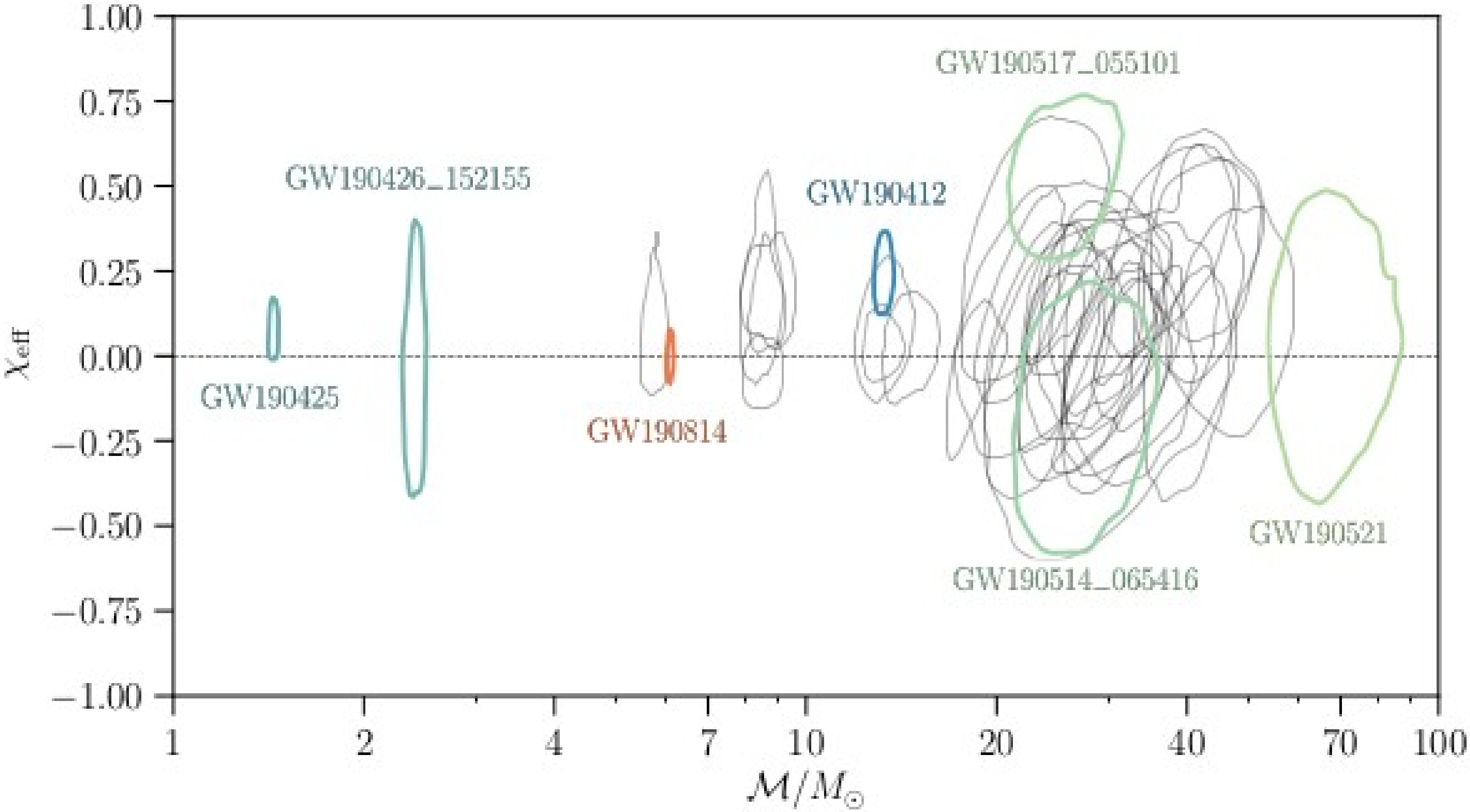
Primary mass



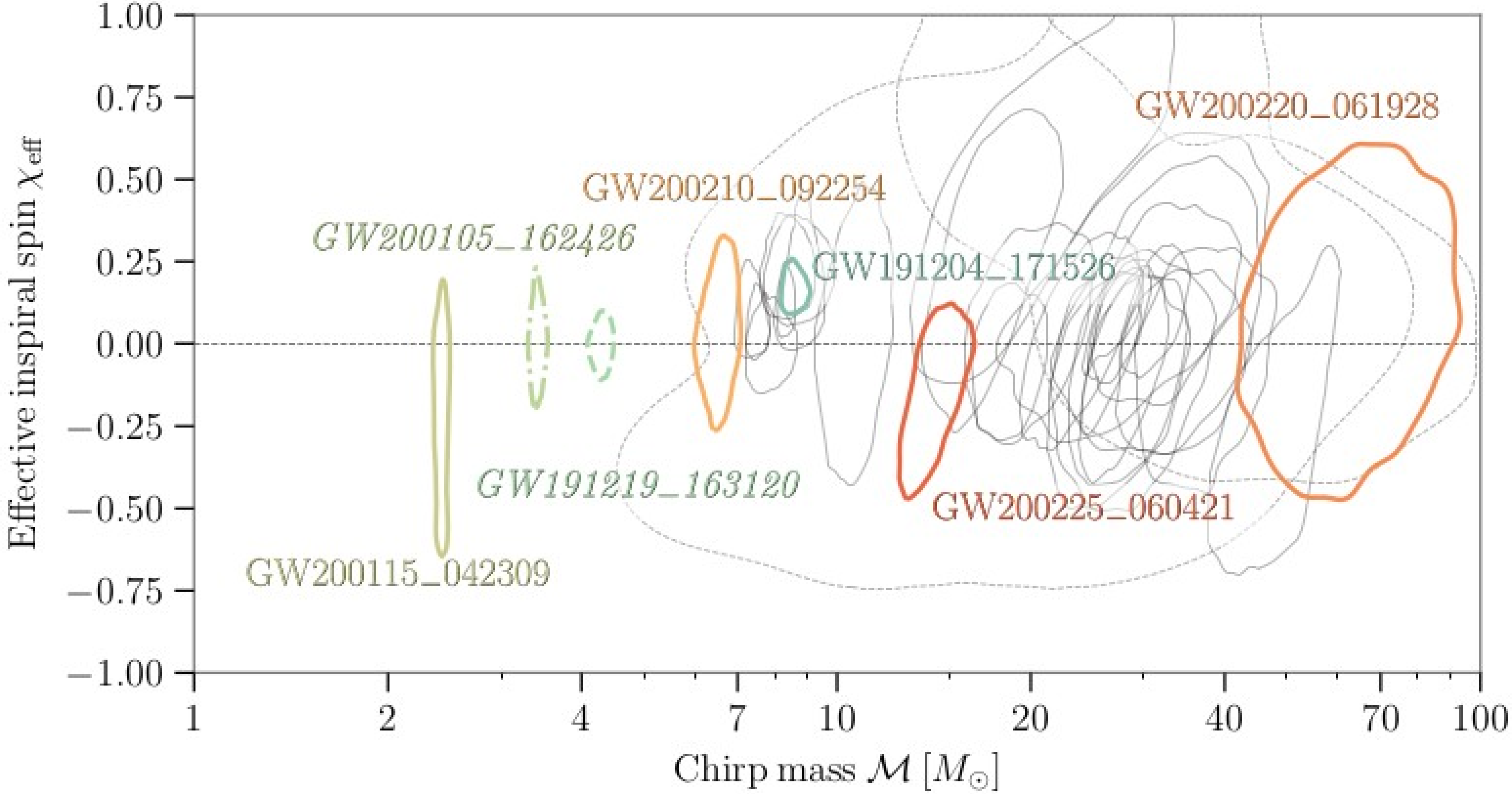
Peaks in the stellar mass region

Long tail to high masses

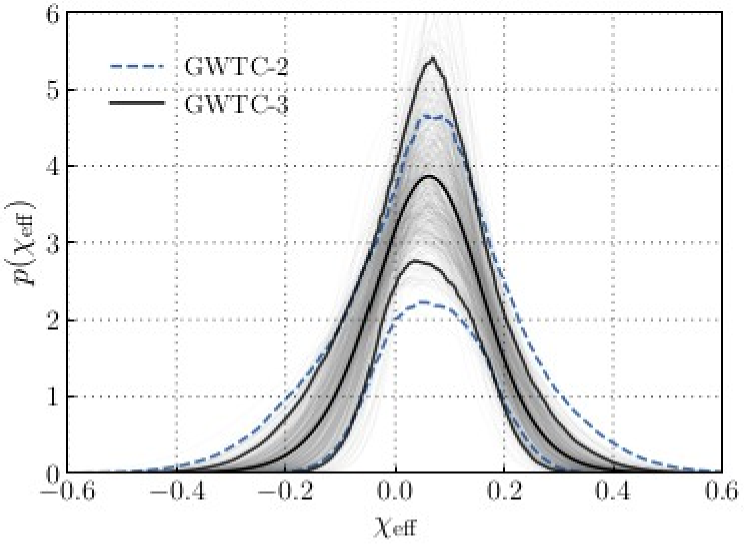
Spins and masses

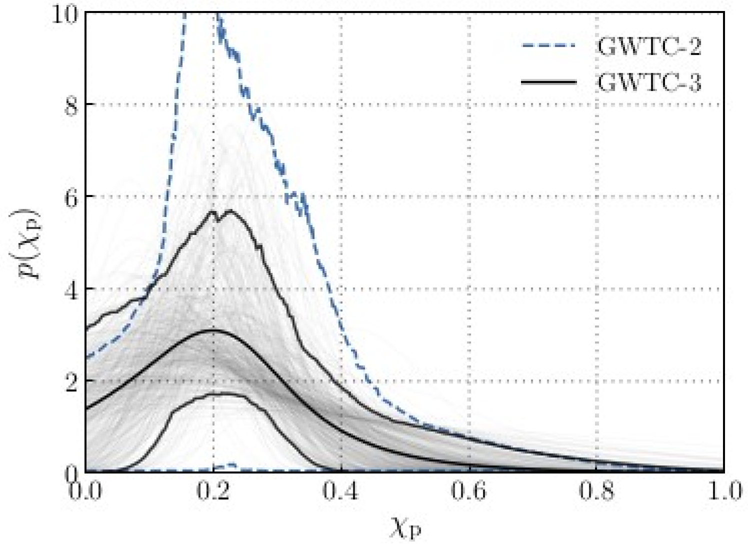


Spins and masses



Spin distribution

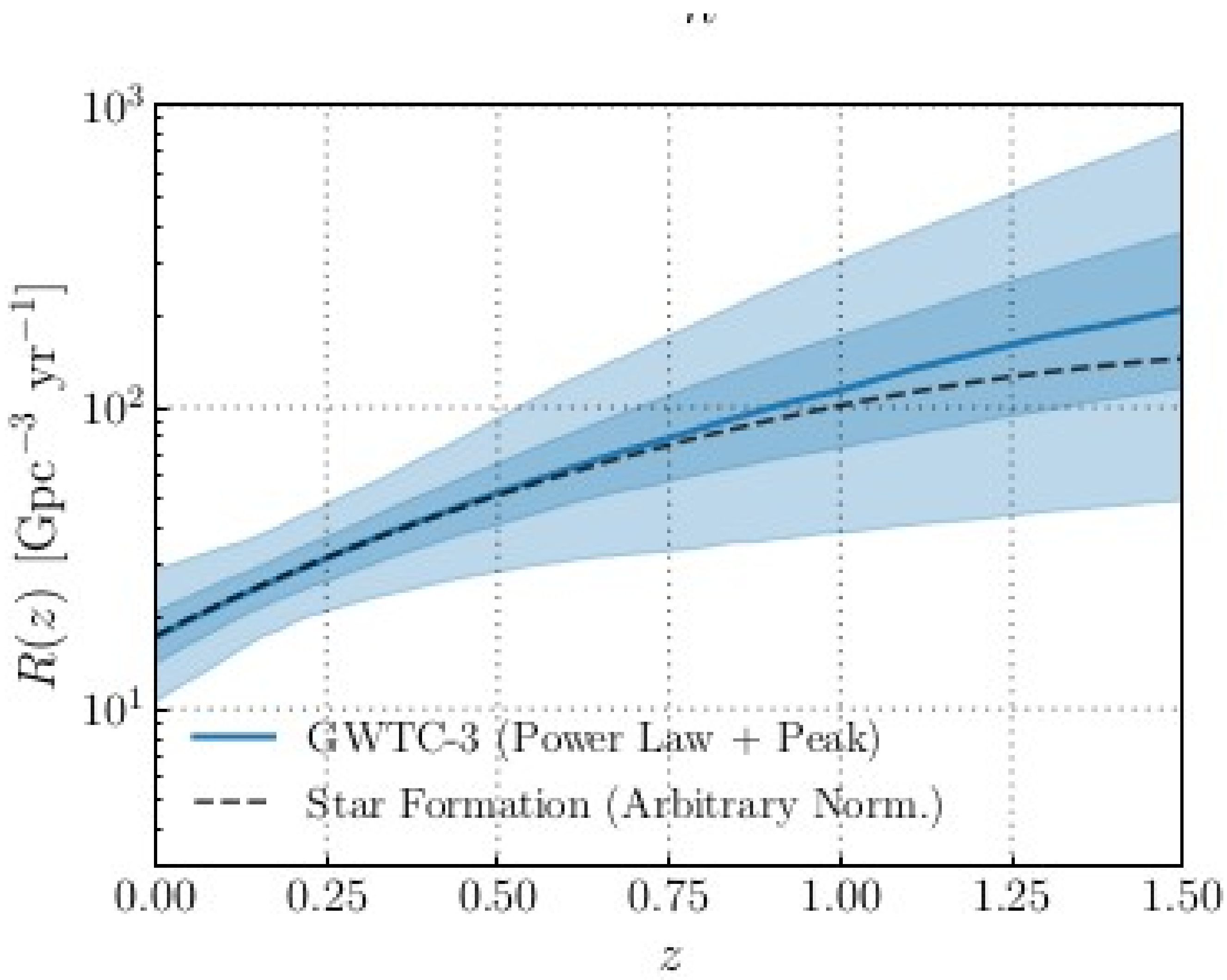




Slight tendency toward positive values

Spins are small

Rates vs redshift



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 is their origin?

- 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

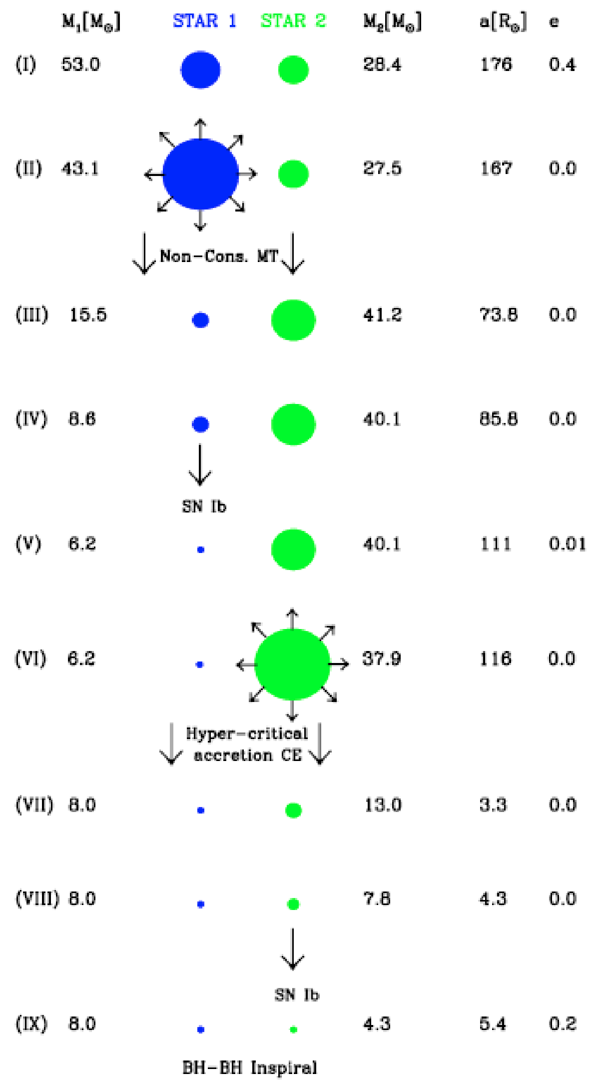
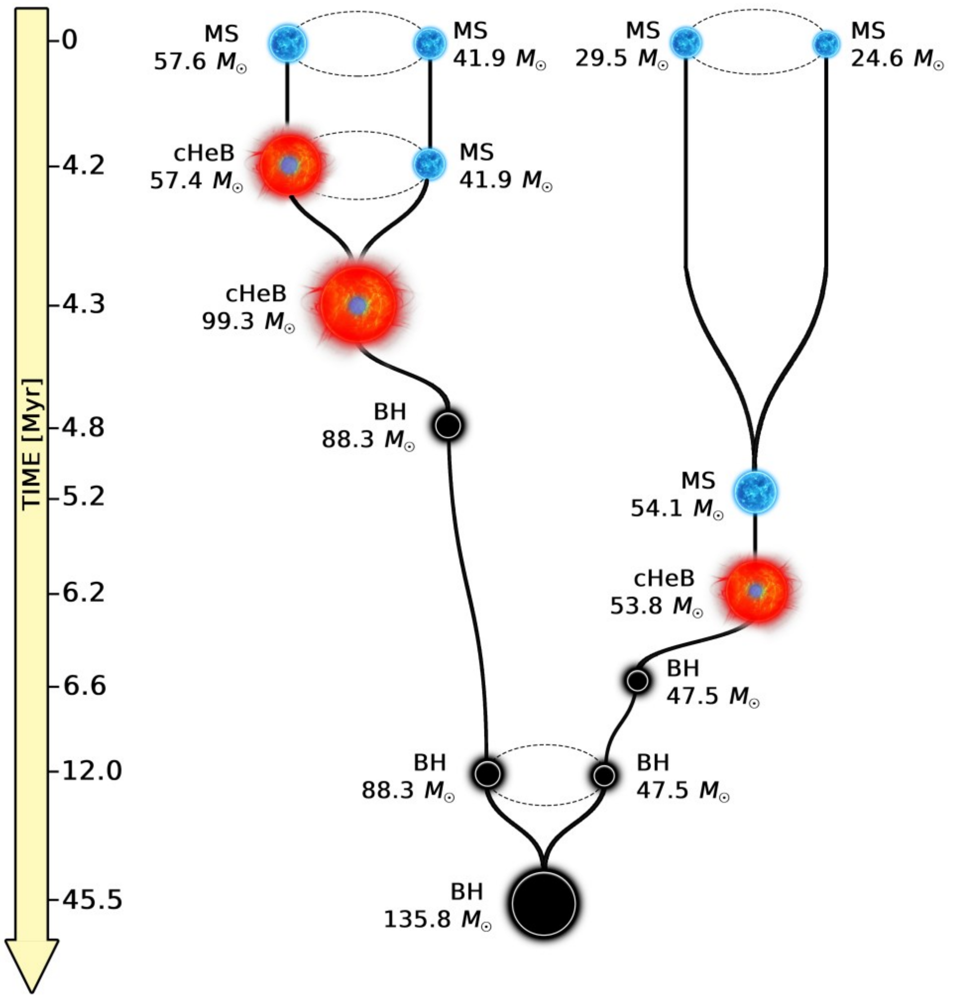


Fig. 1. An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

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!

The rate implications

- The supernova rate density

$$R_{SN} \approx 10^5 \mathrm{Gpc}^{-3} \mathrm{yr}^{-1}$$

- The production of NSNS mergers must be very efficient
- Total GW luminosity density in the sky from NSNS mergers

$$\mathcal{L}_{GW} = 1560 \frac{0.025 M_\odot c^2}{3.1 \times 10^7 \mathrm{s}} \approx 2.5 \times 10^{48} \mathrm{erg s}^{-1} \mathrm{Gpc}^{-3}$$

- The luminosity density of BHBH mergers is about 10 times larger
- EM luminosity density of all galaxies:

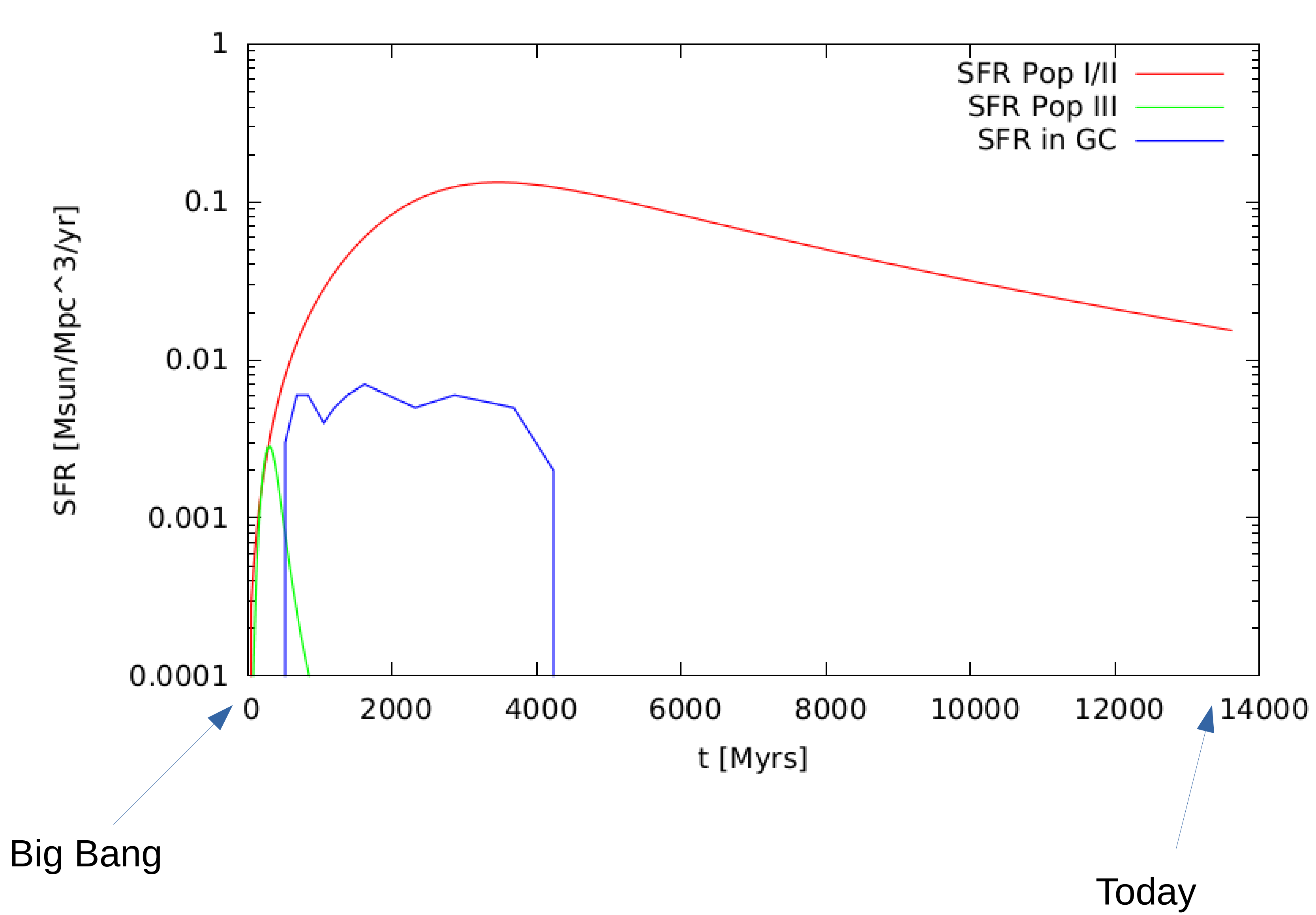
$$\mathcal{L}_{EM} \approx 10^{50} \mathrm{erg\, s}^{-1} \mathrm{Gpc}^{-3}$$

Rates

- BHBH production efficiency:
  - Number of merging BBH per unit mass
- Delay times
- Mass distribution
  - Intrinsic vs observed: range and redshift effect

- Rate density: local and as a function of redshift

SFR



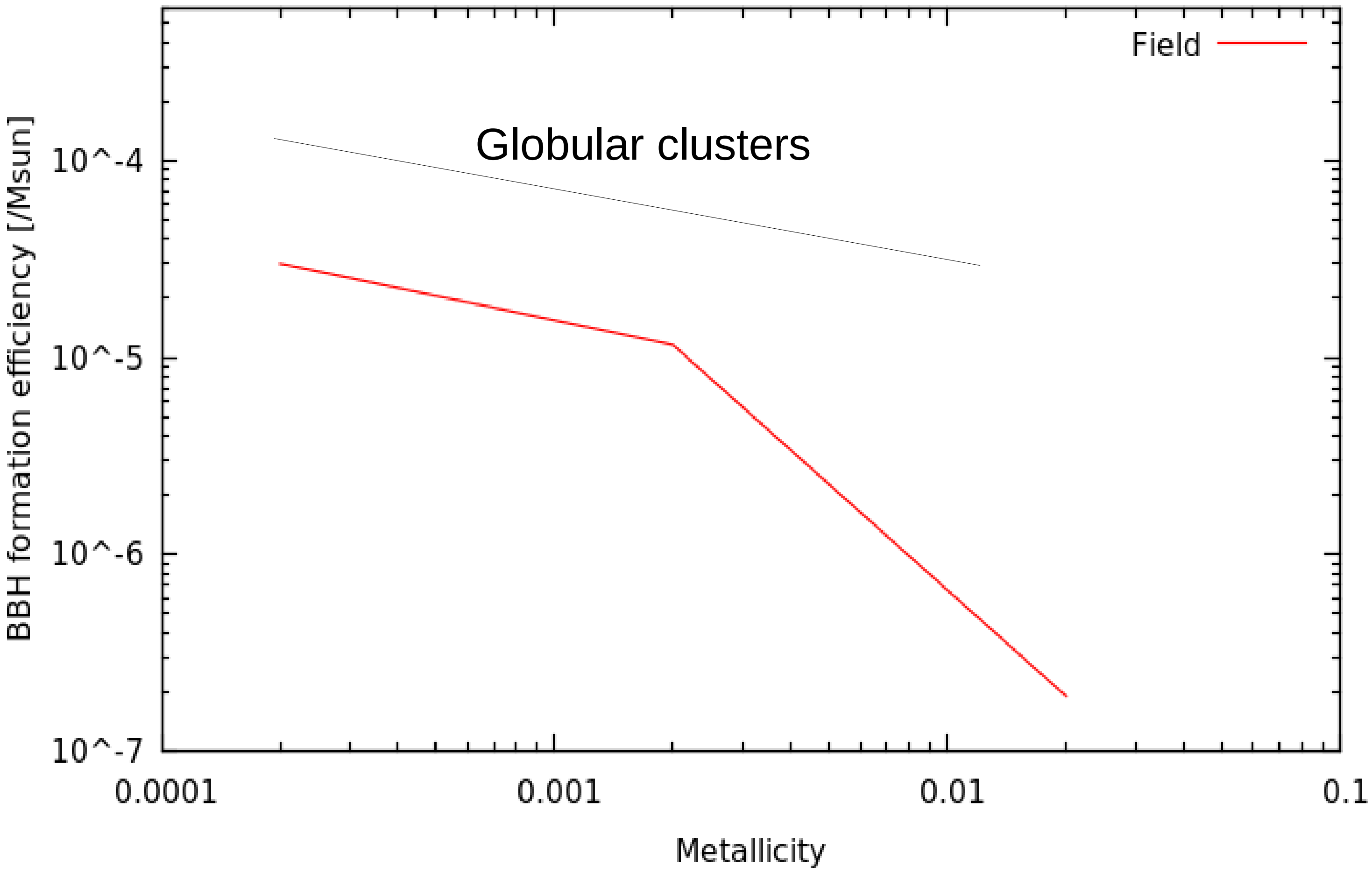
SFR Pop I/II
SFR Pop III
SFR in GC
SFR [Msun/Mpc^3/yr]
1
0.1
0.01
0.001
0.0001
0
2000
4000
6000
8000
10000
12000
14000
t [Myrs]
Big Bang
Today

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 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

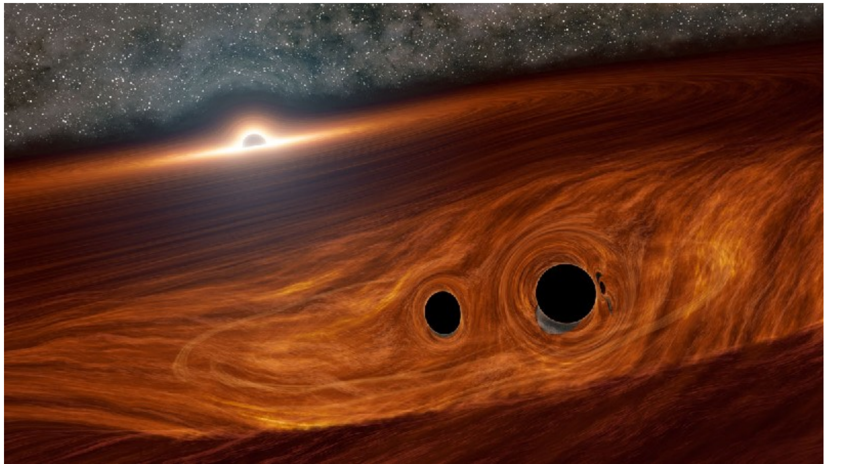
- BH spins measured in accreting binaries are large
- But:
  - Spins of young pulsars
  - Supernova vs GRB rate → spins

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

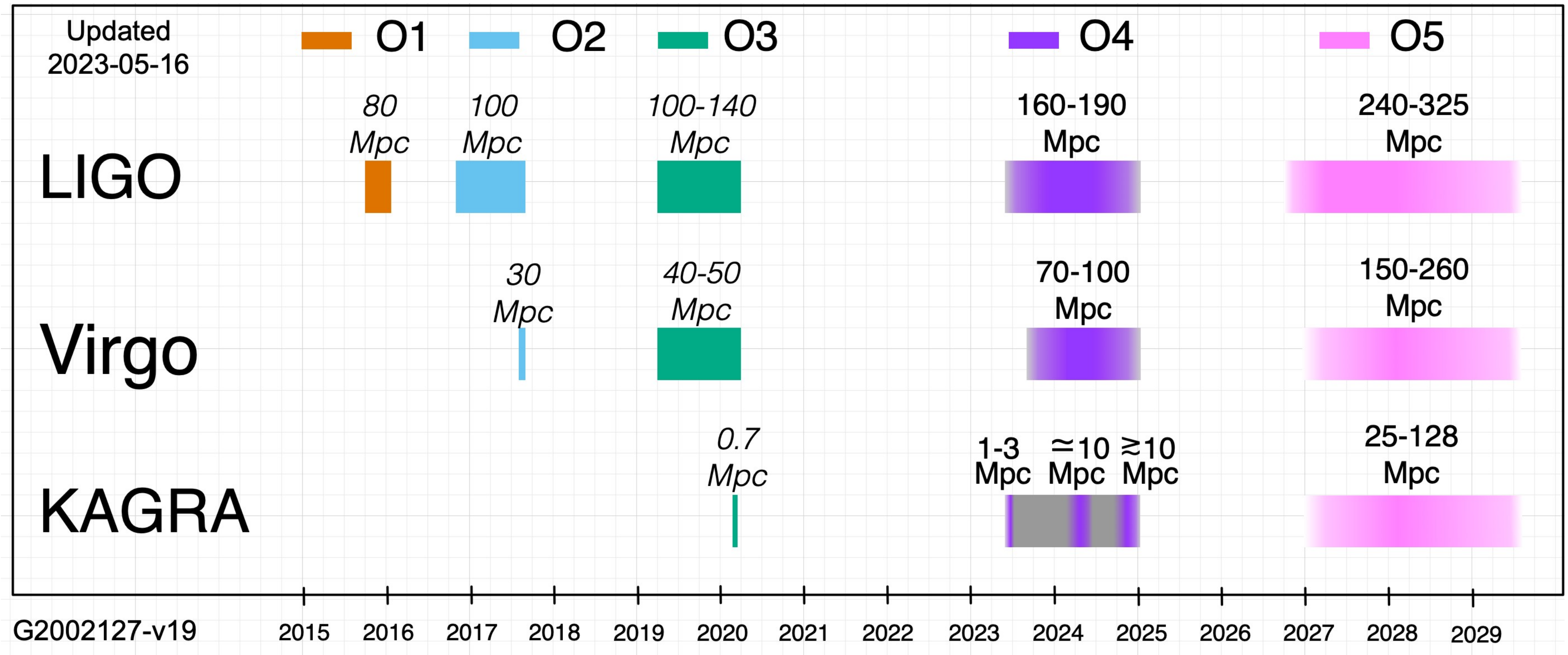
- Distribution of masses, lack of BHs below the stellar limit.
- Spins positive
  - But a sub-population possible
- Why do the rates follow SFR?
  - Rate conspiracy?

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.

Current and future observations



ET and Cosmic Explorer needed!