ASTROPHYSICAL IMPLICATIONS OF THE FIRST LIGO AND VIRGO DETECTIONS

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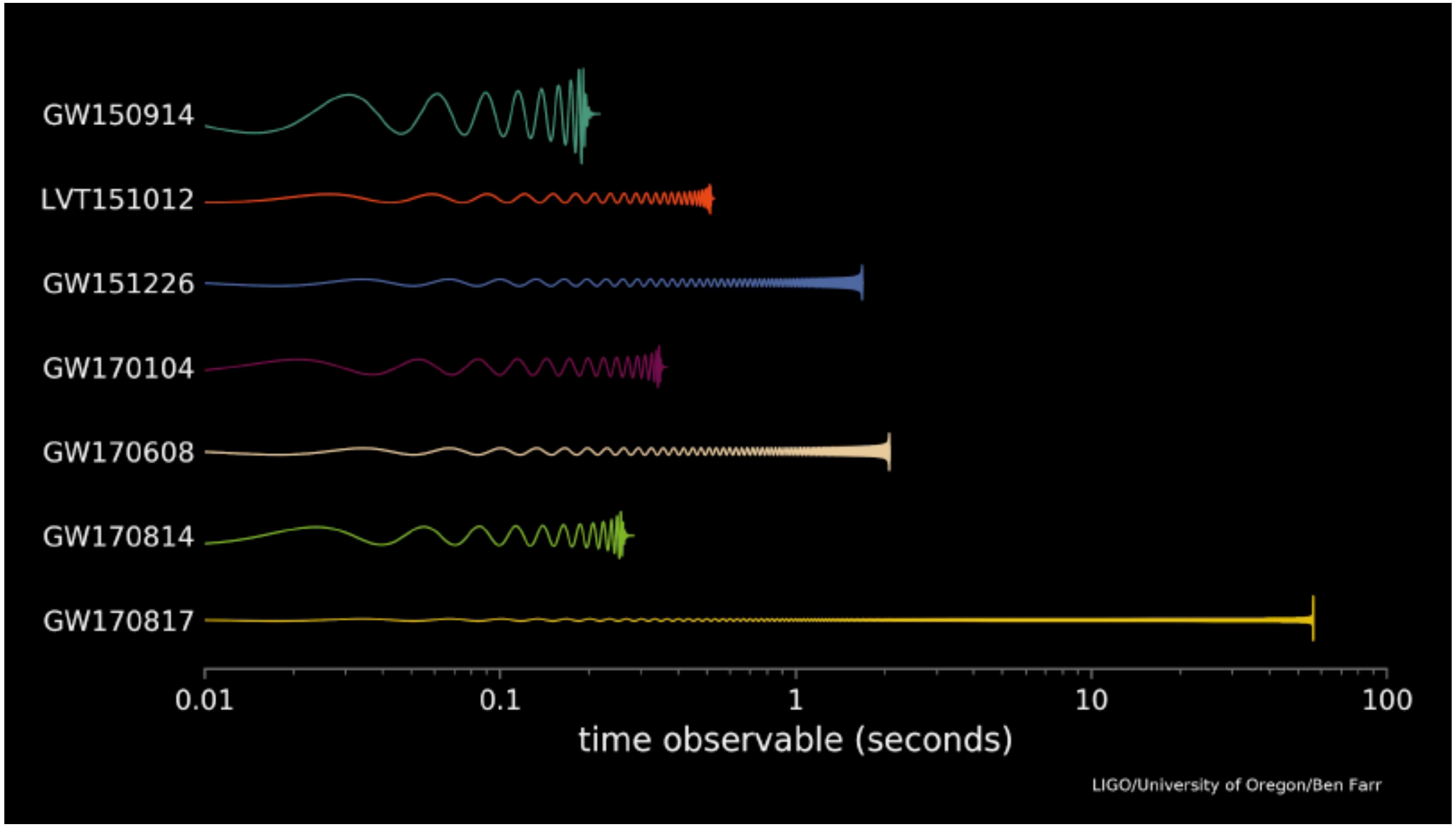
LIGO Current Detections

LIGO and Virgo have already observed 5 (+1?) BBHs and 1 BNS.



Possible Formation Scenarios

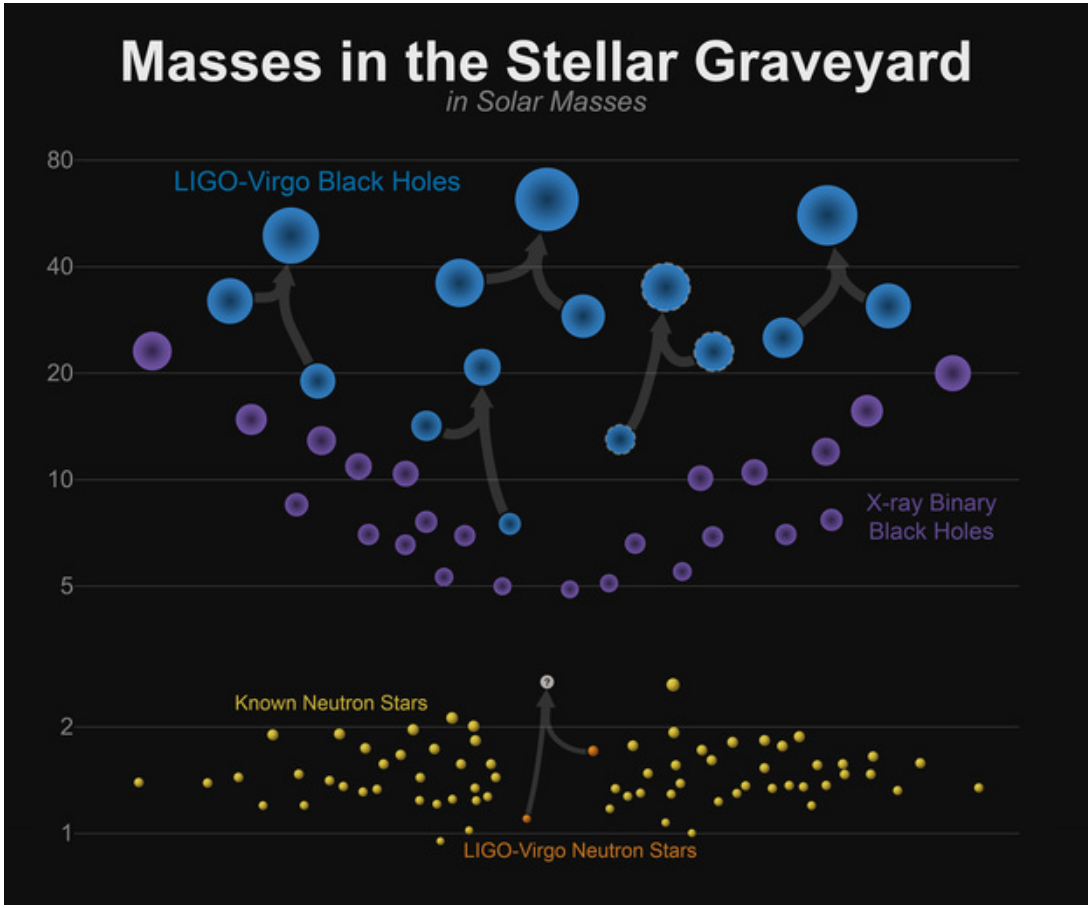
- Field: formed from stars born in a binary system that remain bounded after the two supernovas (short or long delays).
- Dynamical: formed by capture in a dense environment through mass segregation that move NSs and BHs to the center
- Primordial BBH: formed by the collapse of dense regions in the very early Universe (hypothetical). Expected to have a large mass distribution.
- We need more data to reconstruct the mass, spin (eccentricity) distribution

Compact objects masses

▪Black hole masses (m~7-30 Mo) can be larger than previously observed in XR-binaries. Must have been created in low metallicity environment.

▪We need more data to investigate the mass gap between NS and BH.

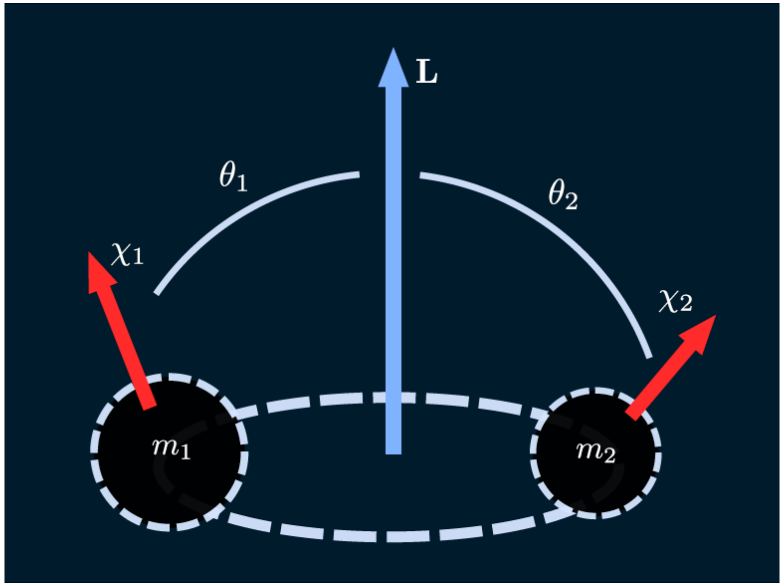
▪Already evidence for the heavy BH mass gap between 40-135 Mo (pulsational pair instability supernovae)



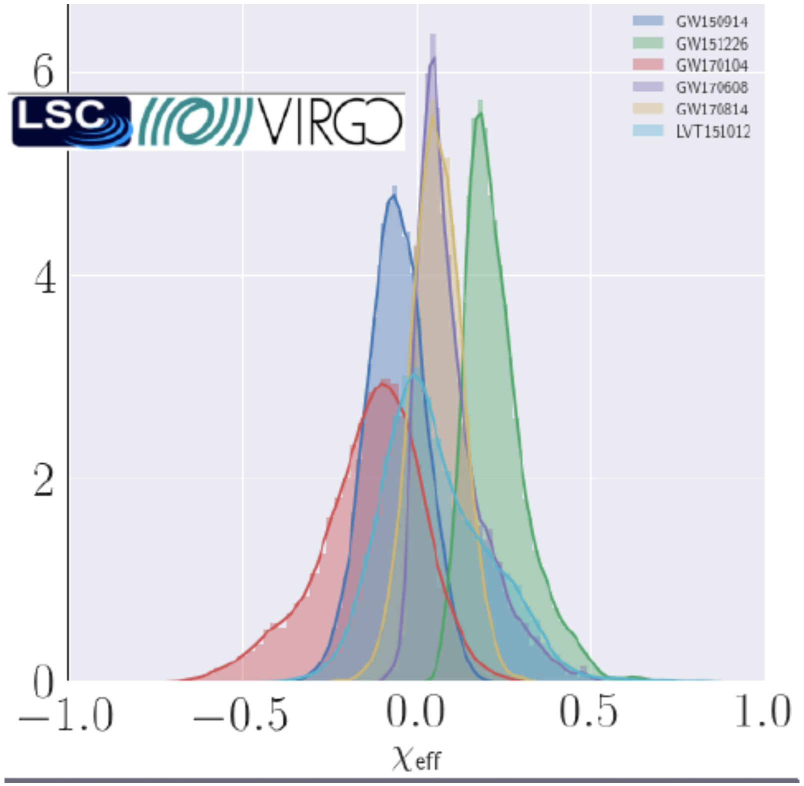
Spins

Spin is the most promising parameter to distinguish between formation channels.

$$\chi_{\text{eff}} \equiv \left(\frac{m_1 \boldsymbol{\chi}_1 + m_2 \boldsymbol{\chi}_2}{m_1 + m_2} \right) \cdot \hat{\mathbf{L}}$$



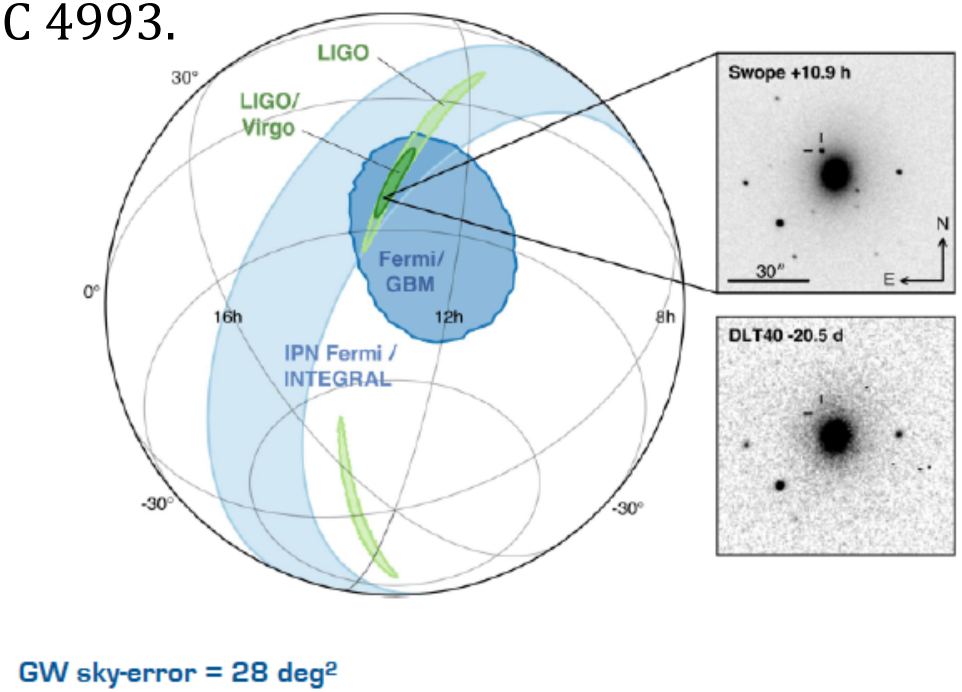
Weak aligned spins favored



Rosetta stone GW170817

GW170817 was observed in both gravitational and electromagnetic waves (gamma, X-ray, ultraviolet, infrared, optical, radio).

Host galaxy identified NGC 4993.

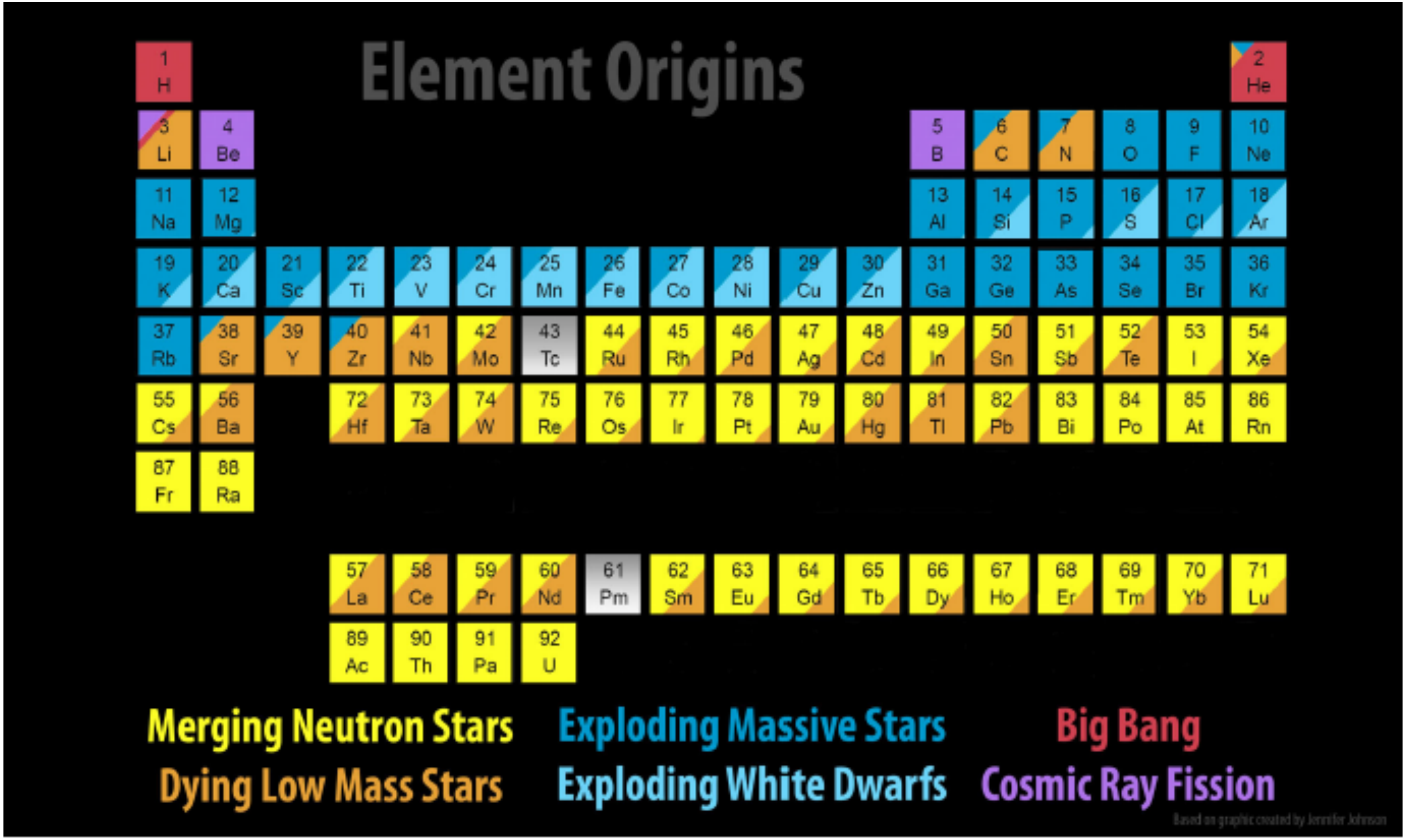


www.ligo.caltech.edu/images

Rosetta stone GW170817

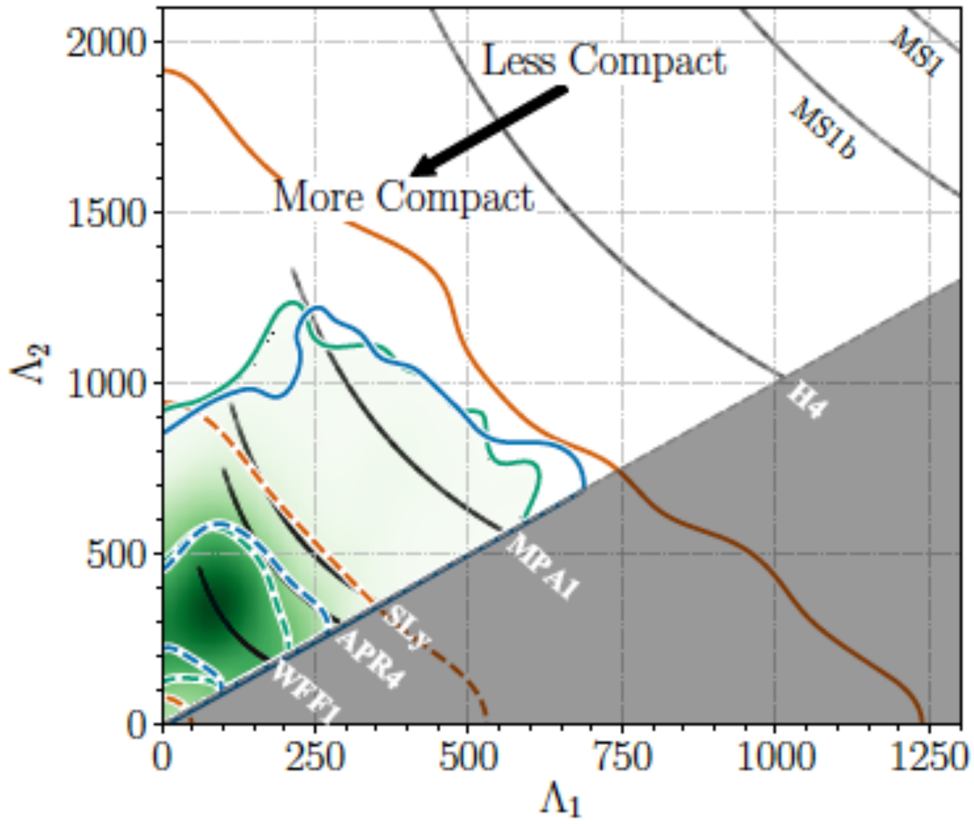
GW170817 was observed in both gravitational and electromagnetic waves (gamma, X-ray, ultraviolet, infrared, optical, radio).

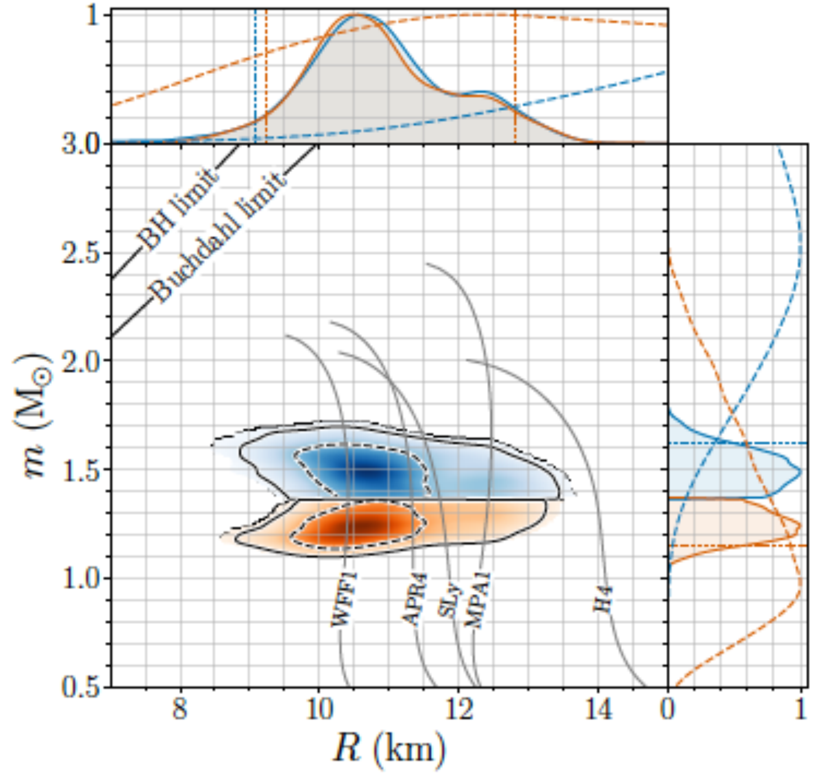
- sGRBs/BNS merger association (Fermi GRB 1.74 s delay)
- kilonova/BNS (r process induced optical transient)
- remnant objecy of 2.74 M_s, light BH or heavy NS?


Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission

NS equation of state

Small defomability parameter
and then soft EOS favored





Abbott et al. Nature, 551, 85 (2017)

Measurement of the Hubble Constant

- Direct measurement of the luminosity distance with GWs

Compared to supernovas, no need for distance ladder.

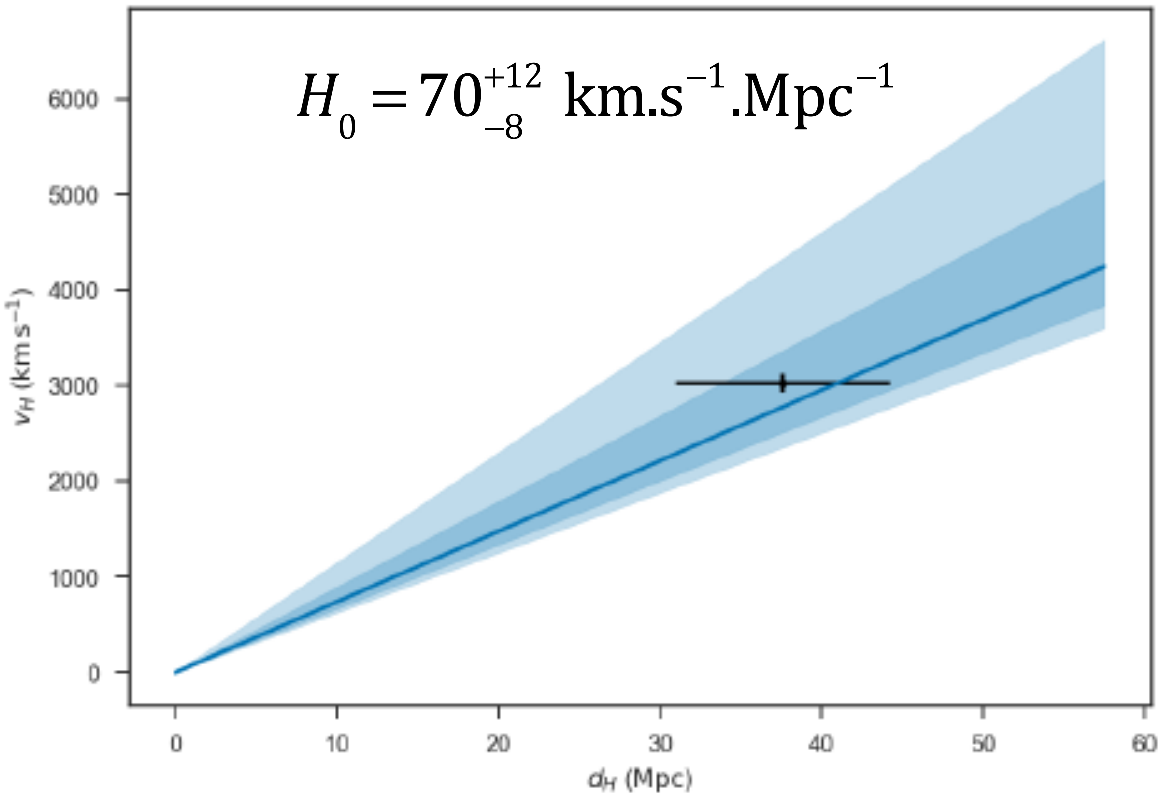
$$d_L = 40^{+8}_{-14} \text{ Mpc}$$

- Optical identification of the host galaxy NGC4993. Measurement of the Hubble flow from the position and the redshift. Need to correct for the local peculiar velocity (~10%).

- Hubble law: $v_H = H_0 d$ (d<50 Mpc)

Abbott et al. Nature, 551,85 (2017)

Measurement of the Hubble Constant



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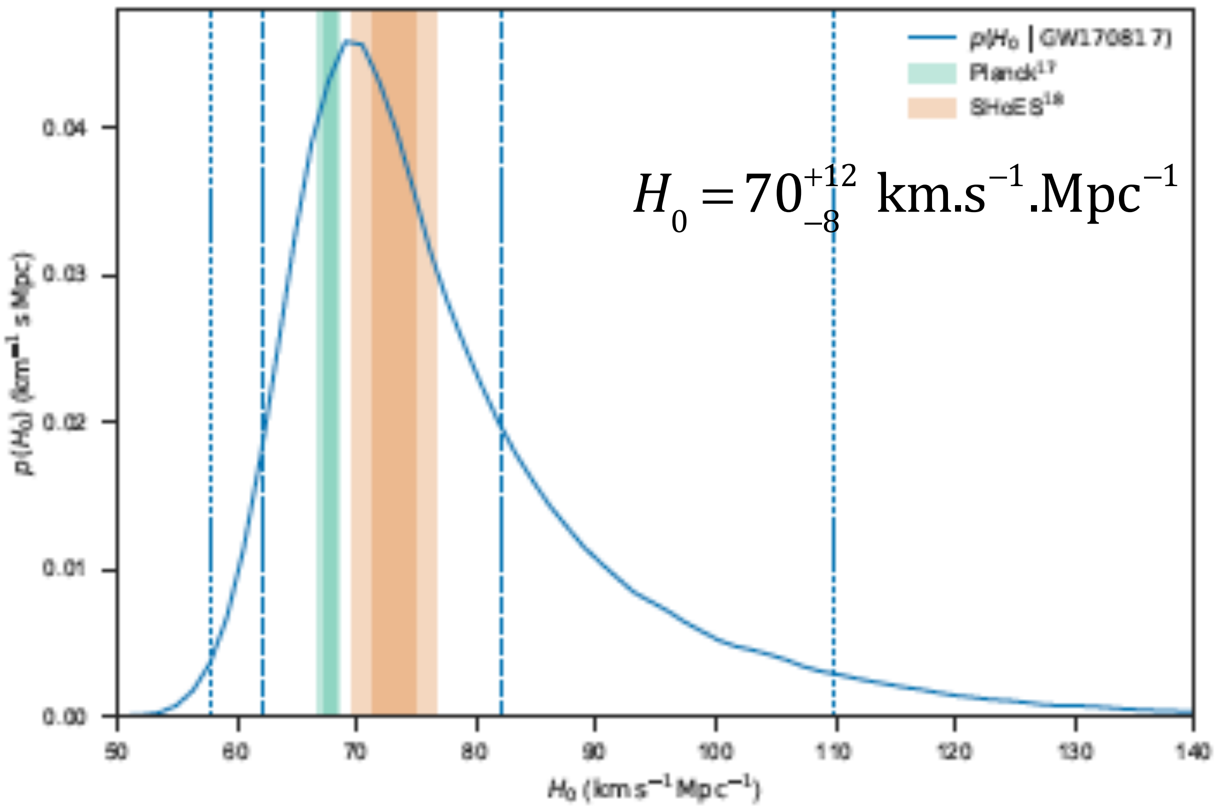
Measurement of the Hubble Constant



The Cosmological Population

- Many more individual sources at larger distance
- Contribute to create a stochastic background, which could be the next milestone for LIGO/Virgo
- Carries lots of information about the star formation history, the metallicity evolution, the average source parameters (and then the main evolution scenarios).
- Using information from the first observations, we were able to revise previous predictions of the GW background from BBHs and BNSs.

SGWB = noise

SGWB = symphony of the Universe

The Background Spectral Properties

- Energy density in GWs characterized by:

$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}(f)}{df}$$

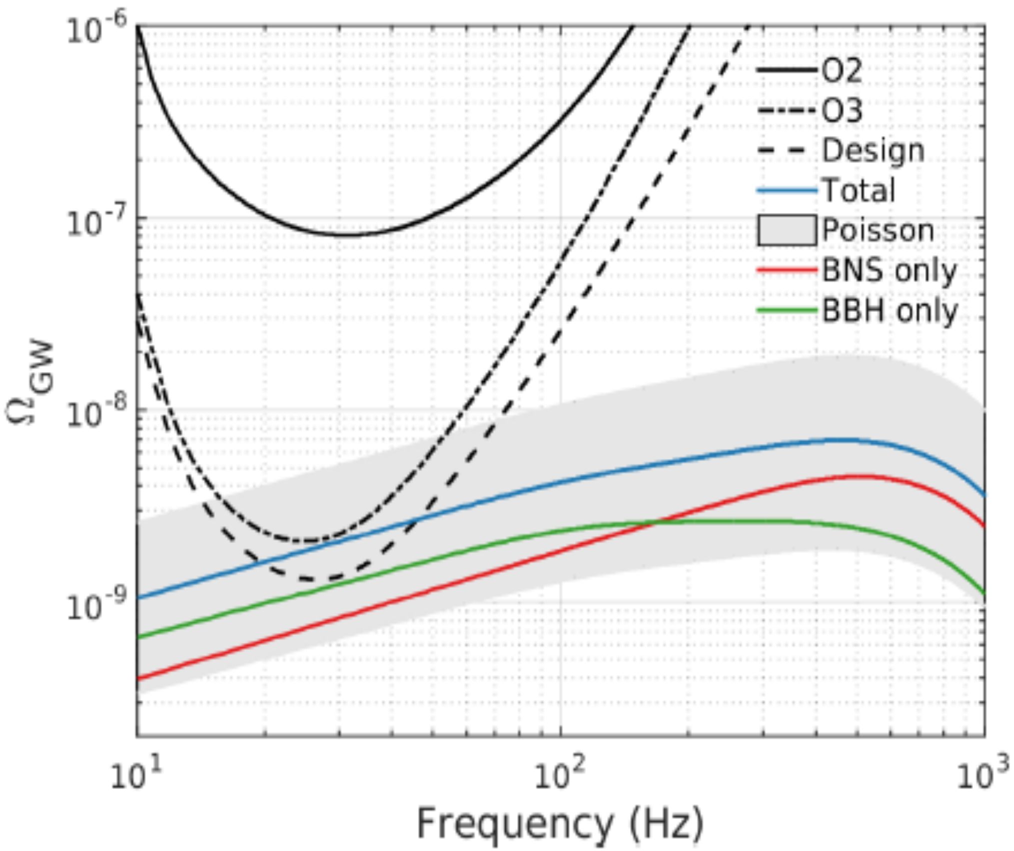
- For a population distributed in the parameter space $\theta=(m_1,m_2,\chi_{eff})$

$$\Omega_{gw}(f,\theta) = \frac{f}{\rho_c}\int d\theta P(\theta)\int_0^{10} dz R_m(z,\theta)\frac{\frac{dE_{gw}}{df}(\theta,f(1+z))}{4\pi r^2(z)}$$

With rate:

$$R_m(z,\theta) = \int_{t_{\min}}^{t_{\max}} R_f(z,\theta)P(t_d,\theta)dt_d$$

Estimate from Detected Sources

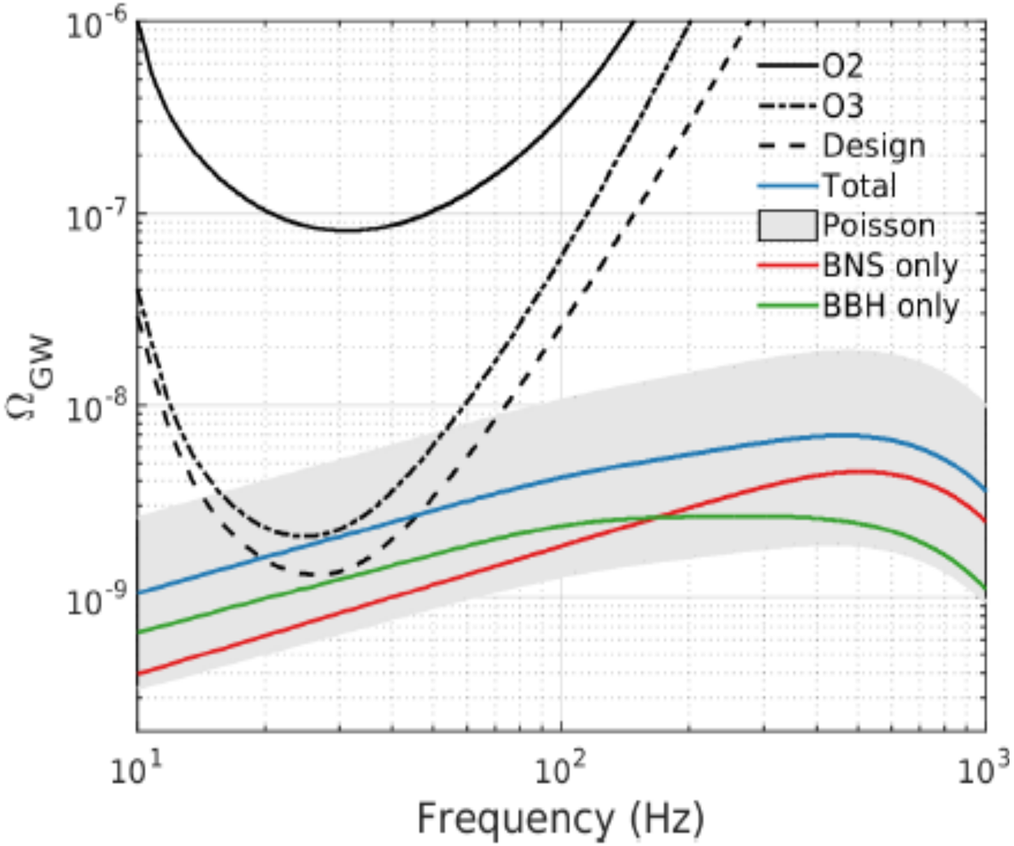


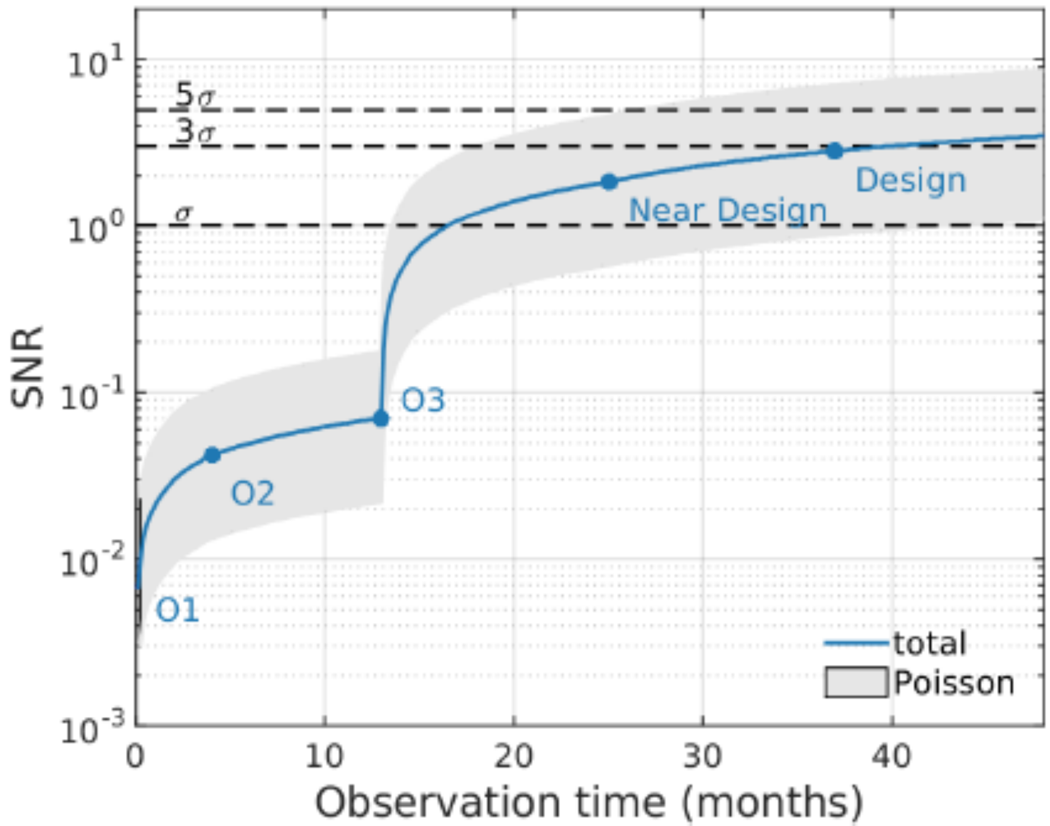
$$\Omega_{gw}^{bbh}(25\text{Hz}) = 1.1_{-0.7}^{+1.2} 10^{-9}$$

$$\Omega_{gw}^{bns}(25\text{Hz}) = 0.7_{-0.6}^{+1.5} 10^{-9}$$

Estimate from Detected Sources

The background could be detected before the detectors reach design sensitivity!





Constraints on cosmic strings models

- Topological defects which can be formed in GUT-scale phase transitions in the early Universe. They can produce large amount of GWs through the production of loops (cusps and kinks)

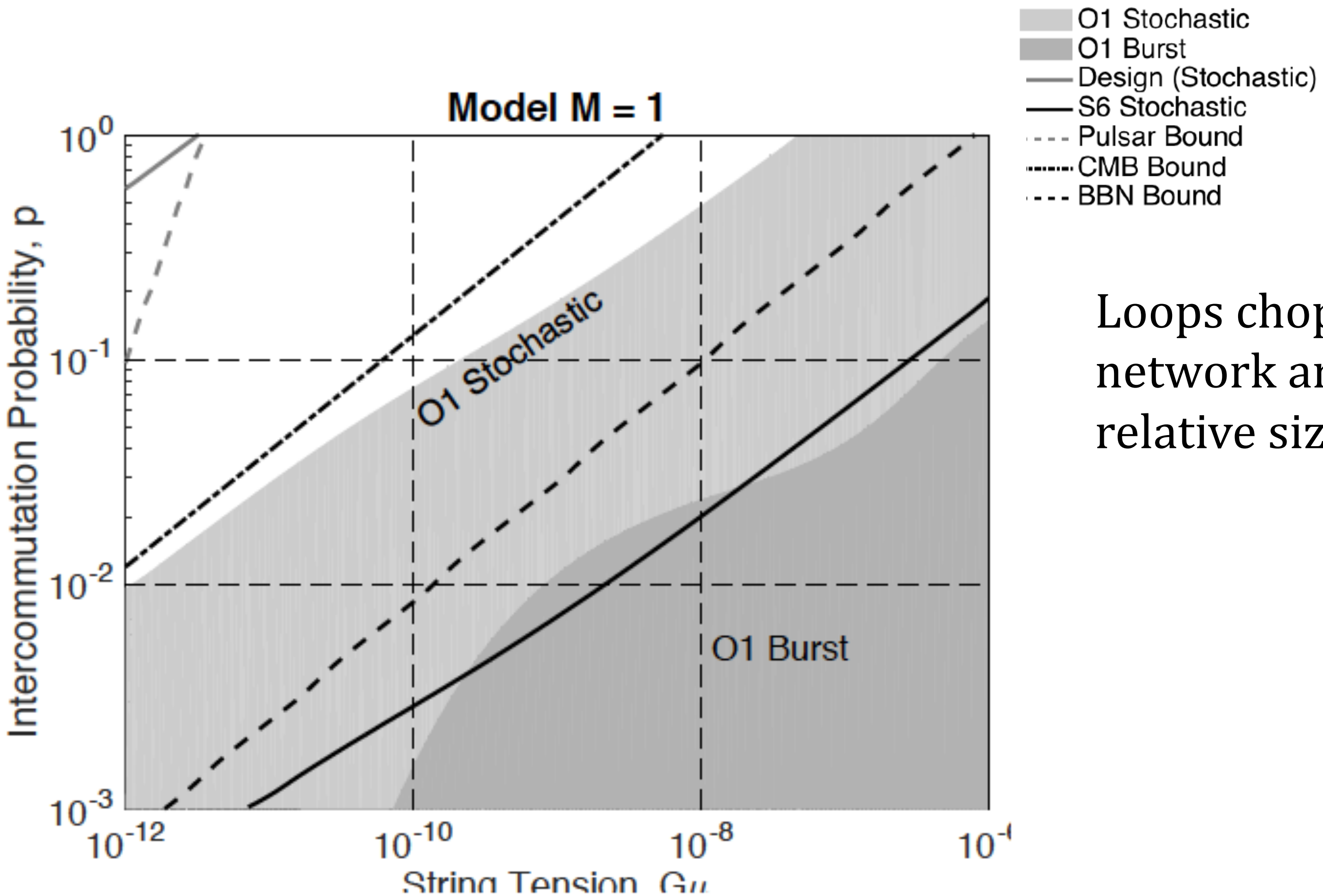
- Strings are charactarized by 2 parameters: tension $G\mu$ and intercommutation probability p

- We consider 3 different models of the number density *n(l,t)* based on Numbo-Goto numerical simulations (*p=1*), and extend to *p<1* assuming

$$n(l,t,p<1) = n(l,t,p=1)/p$$

Abbott et al. arXiv:1712.0116

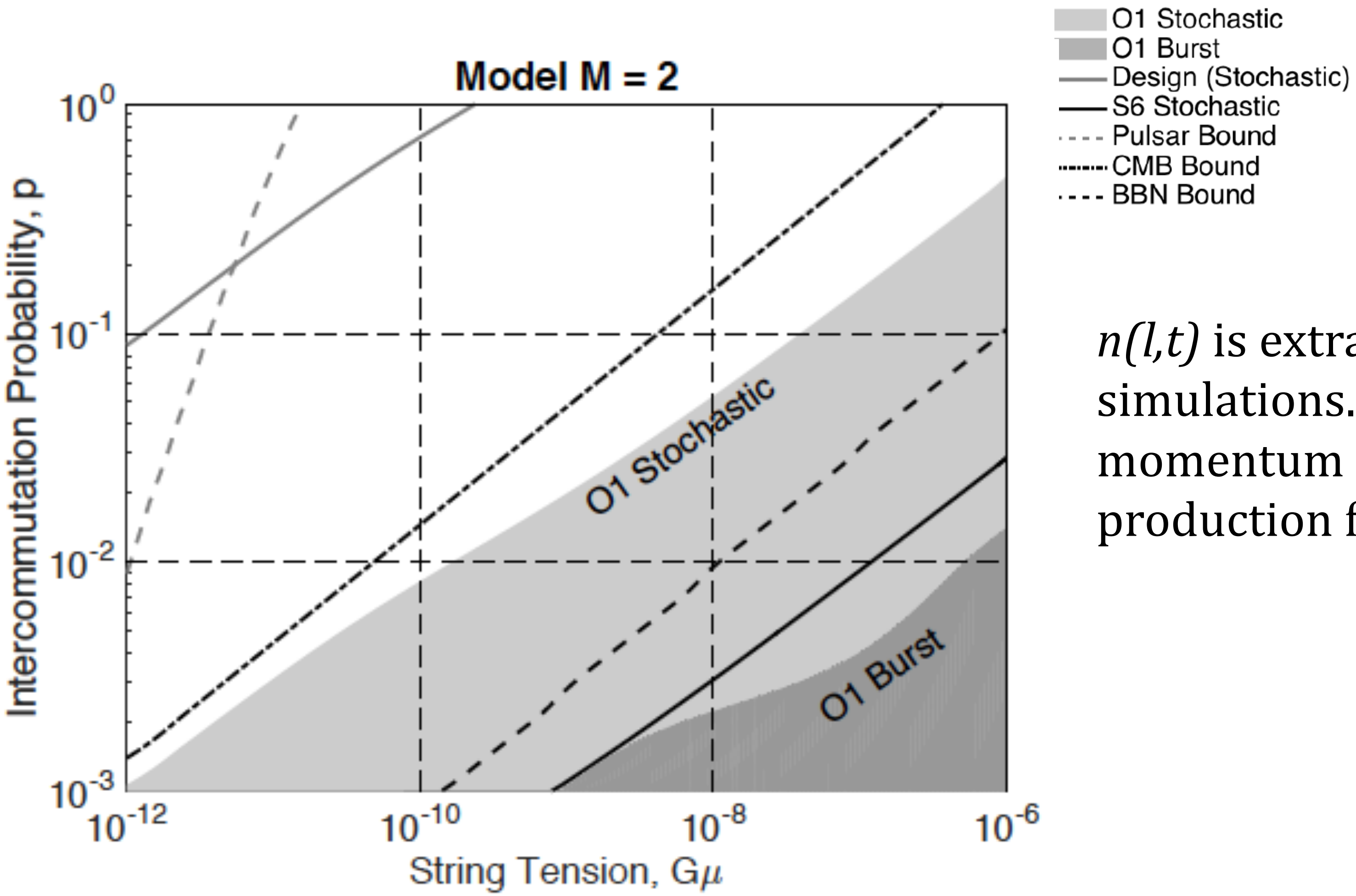
Original Large Loop Distribution



Loops chopped off the infinite string network are formed with the same relative size:

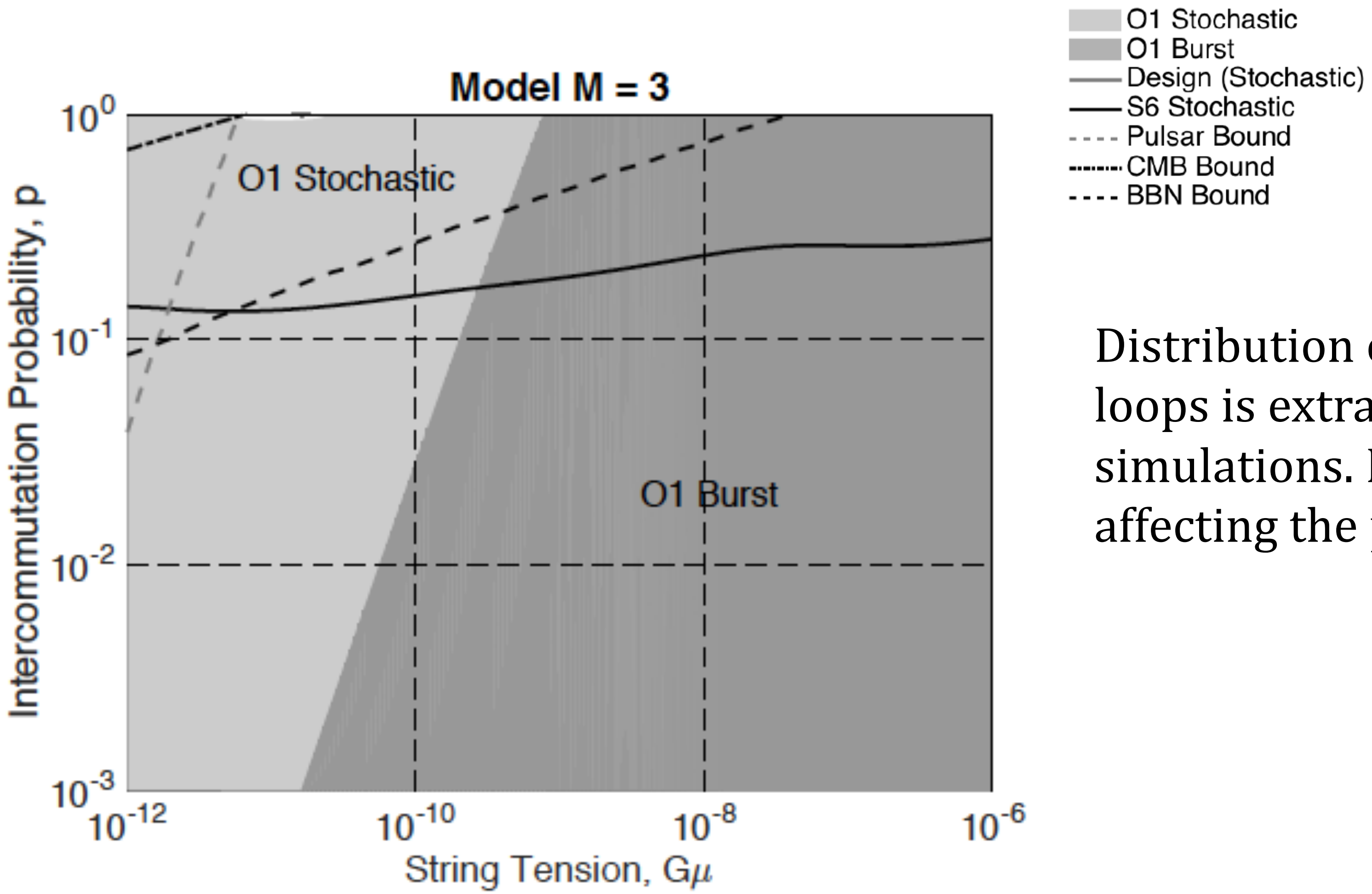
$$l(z) = \alpha t(z)$$

Large loop distribution of Blanco Pillado et al.

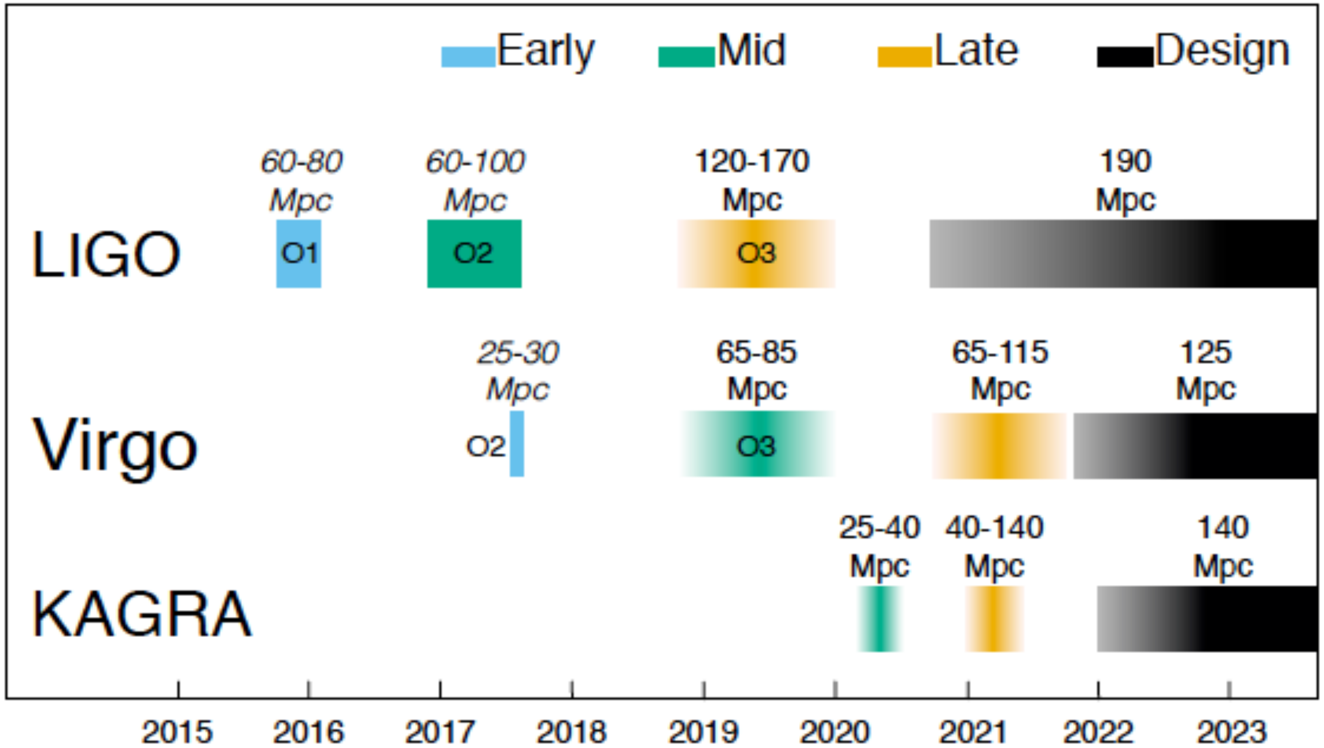


n(l,t) is extrapolated from numerical simulations. Assume that the momentum dependance of the loop production function is weak.

Large Loops Distribution of Ringeval et al.



Distribution of non self interacting loops is extrapolated from numerical simulations. Include GW back reaction affecting the production of small loops.


Early
Mid
Late
Design
LIGO
60-80 Mpc
O1
60-100 Mpc
O2
120-170 Mpc
O3
190 Mpc
Virgo
25-30 Mpc
O2
65-85 Mpc
O3
65-115 Mpc
125 Mpc
KAGRA
25-40 Mpc
40-140 Mpc
140 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023