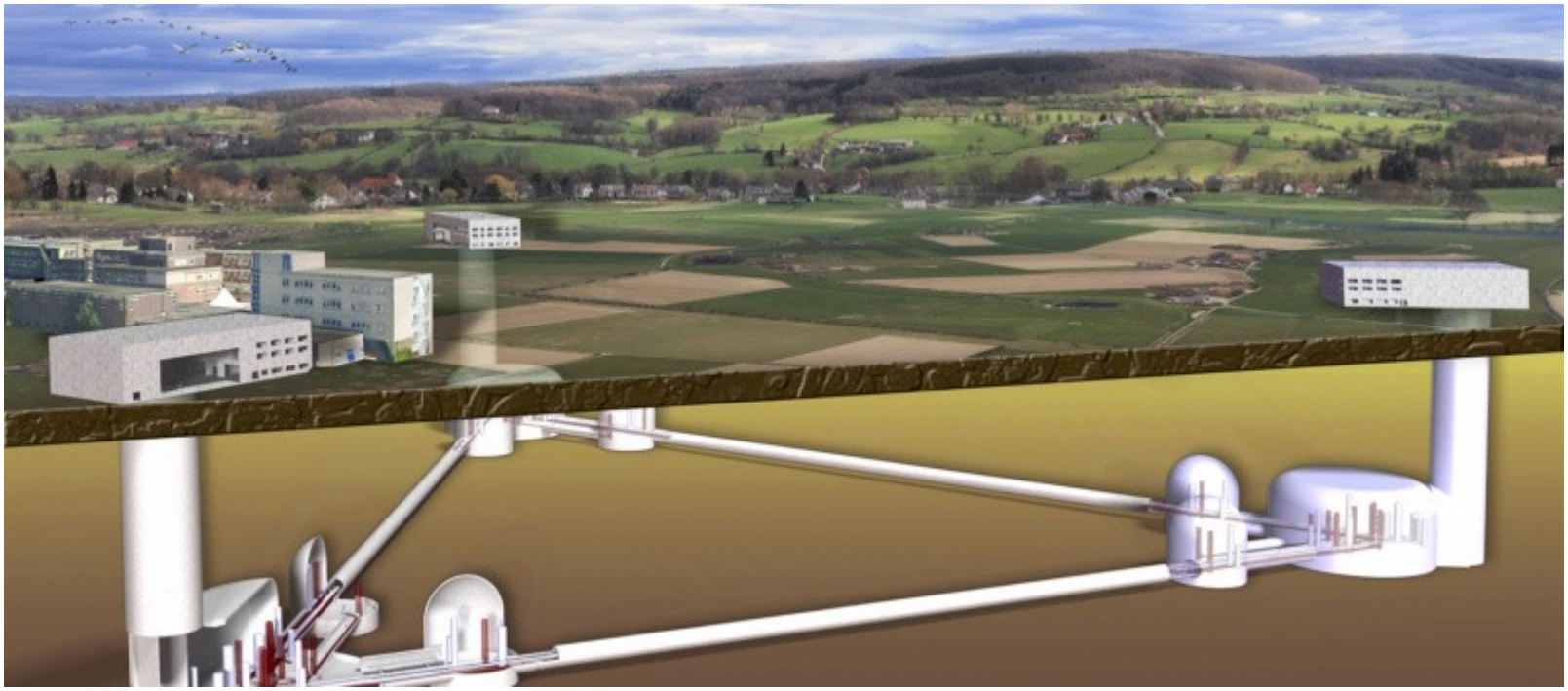
GW Science with 3G detectors

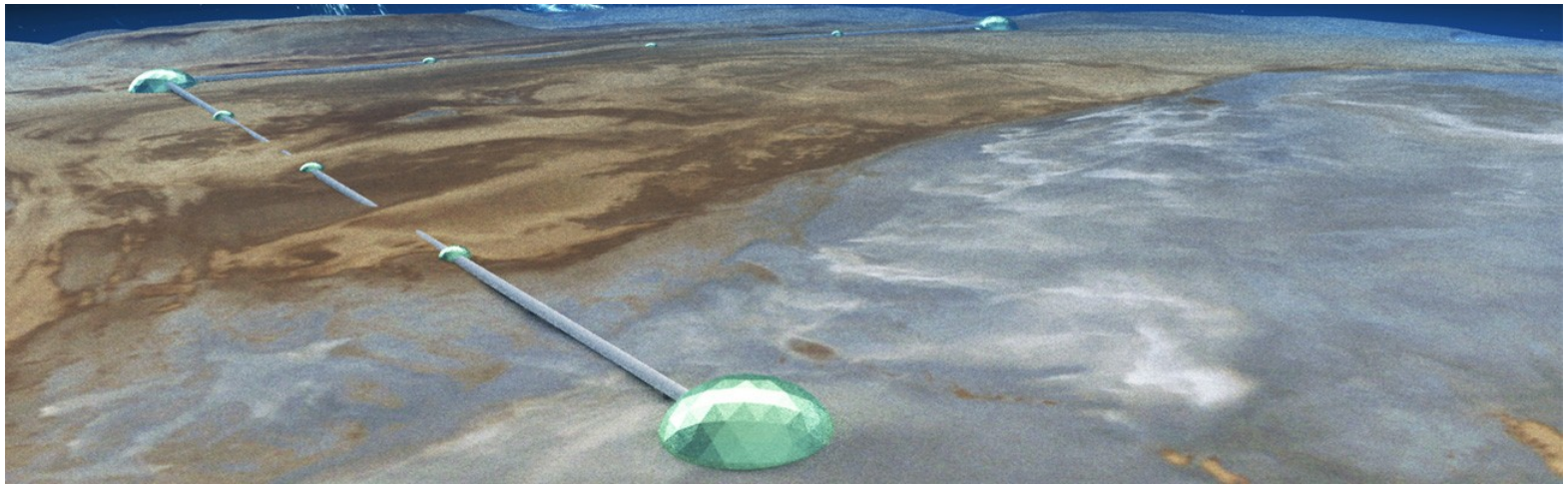
T Bulik
University of Warsaw
and
Astrocent, NCAC

Current state of GW studies

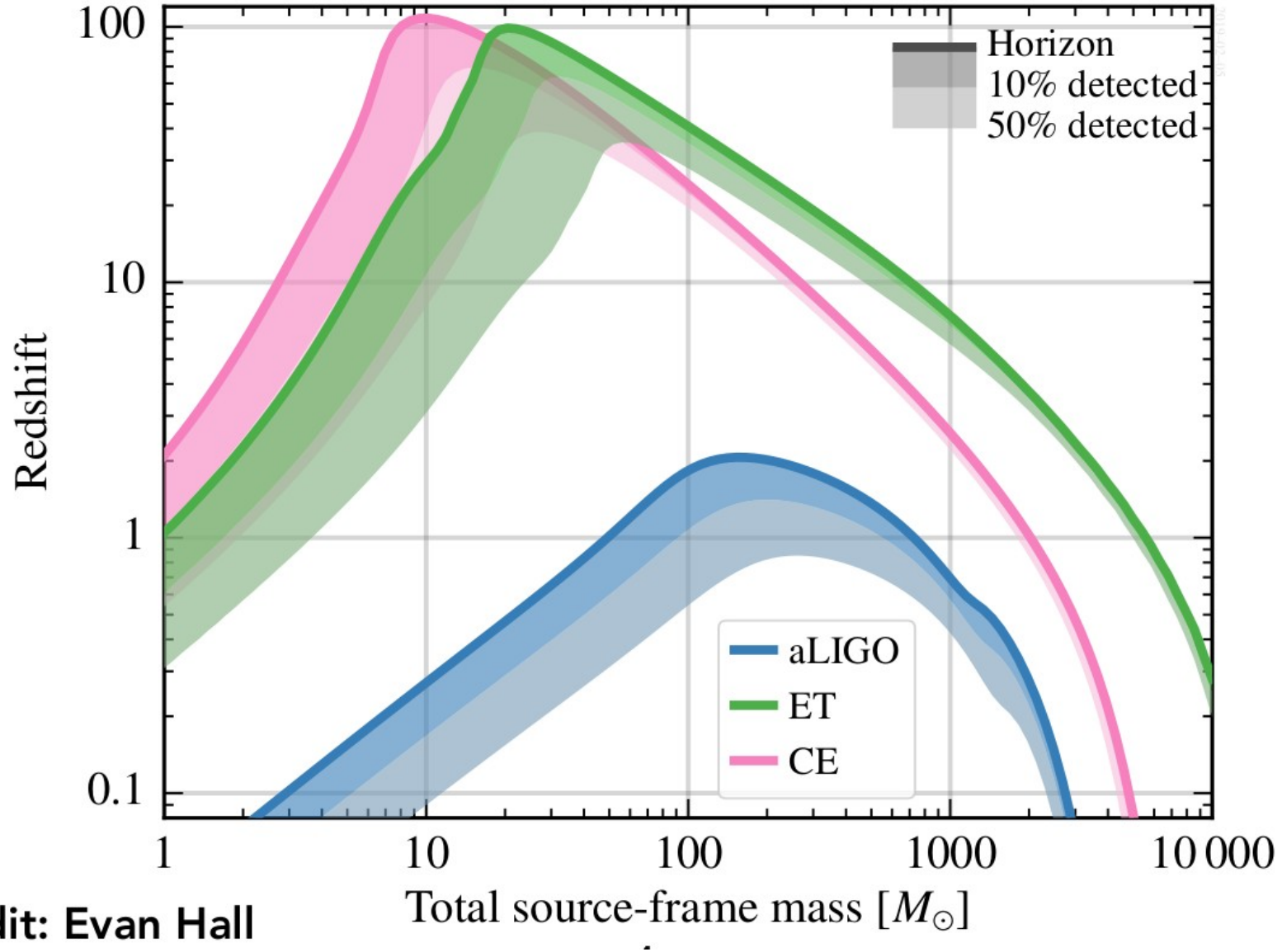
- Start of the new astronomy
  - Existence of merging BBH
  - Mergers of BNS
    - Neutron EOS constraints
- GW generation beyond the quadrupole approximation
- New class of BH – with masses above 30Msun, and small spins
- Origin of SGRBs solved
  - Heavy element production
  - Speed of gravitational waves

Future – 3G detectors



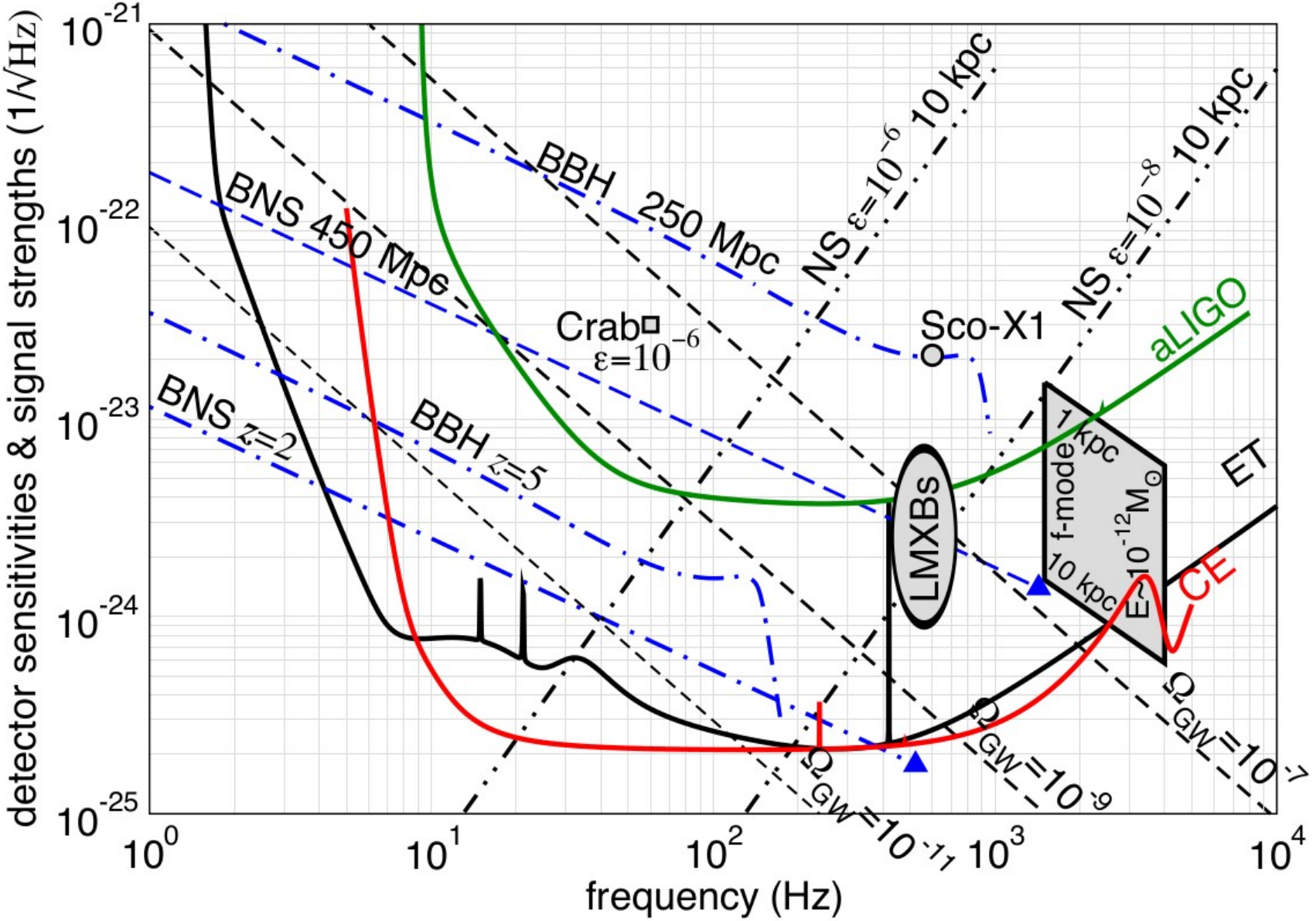


Future sensitivities: ET and CE



Credit: Evan Hall

Sources

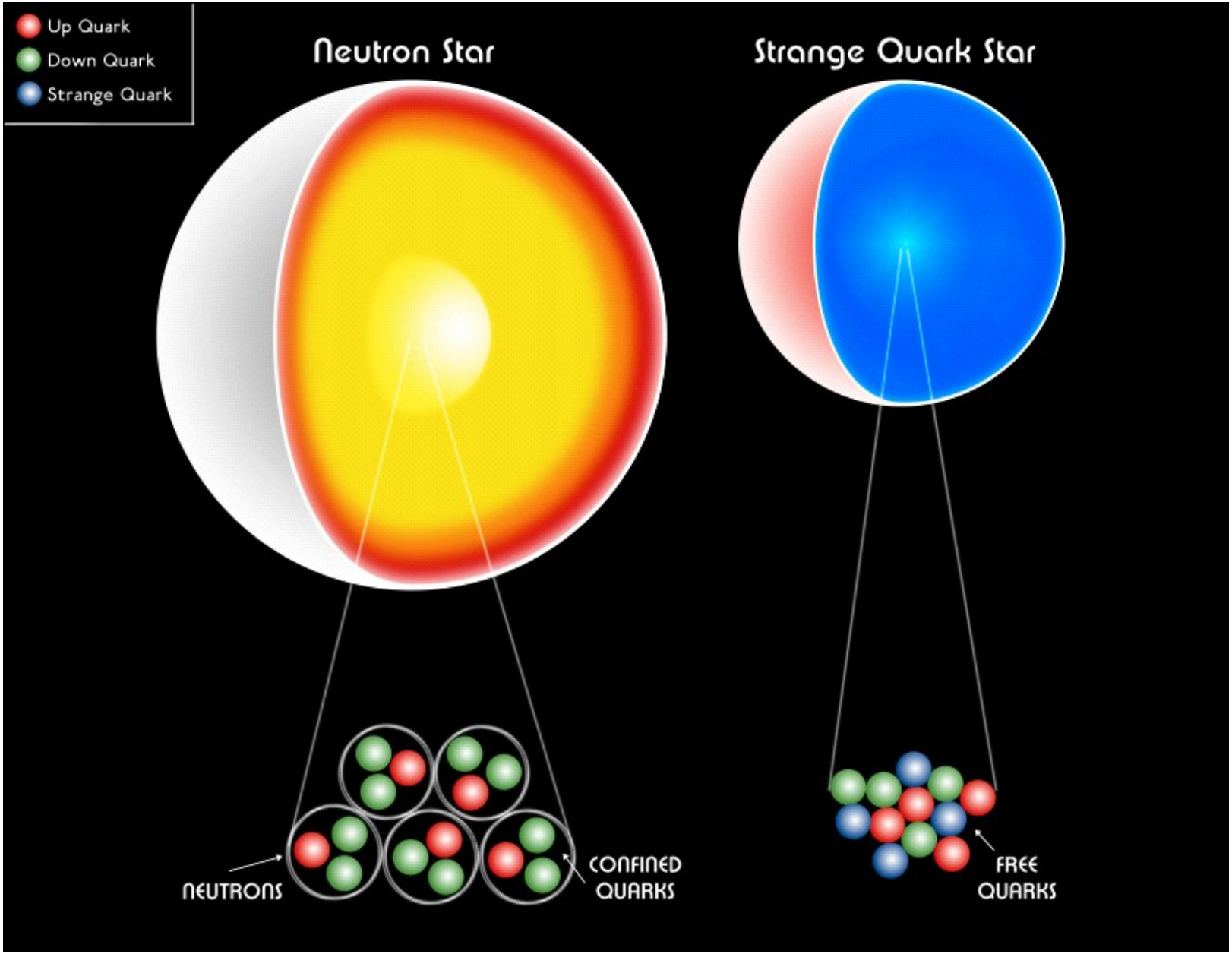


Credit: S. Bangalore

Outline

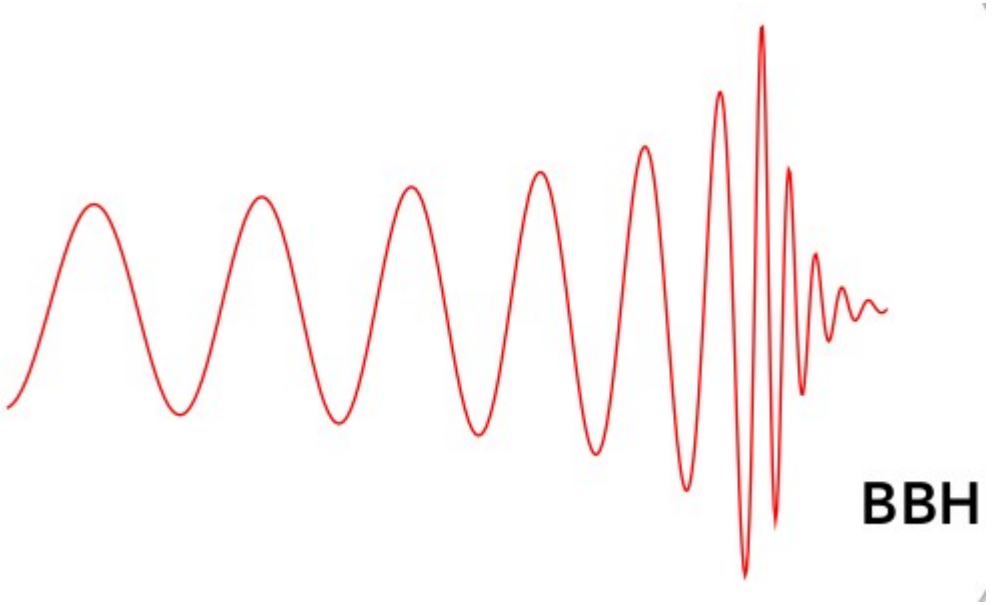
- Dense matter
- Multimessenger astronomy
- Stellar Astrophysics
- Strong gravity, modified gravity
- Stochastic backgrounds

Dense matter

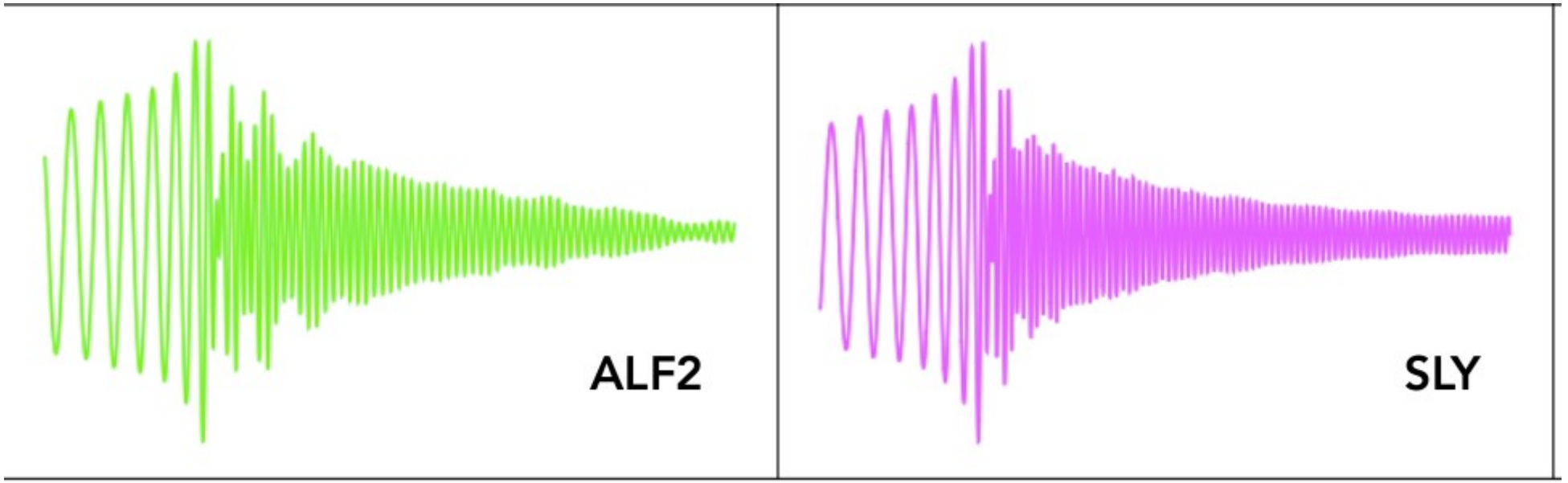


Problems

- What is the EOS; does stable quark matter exist?
- Measuring radii of NS down to 1% accuracy
- Waveforms, post merger phase, calibration

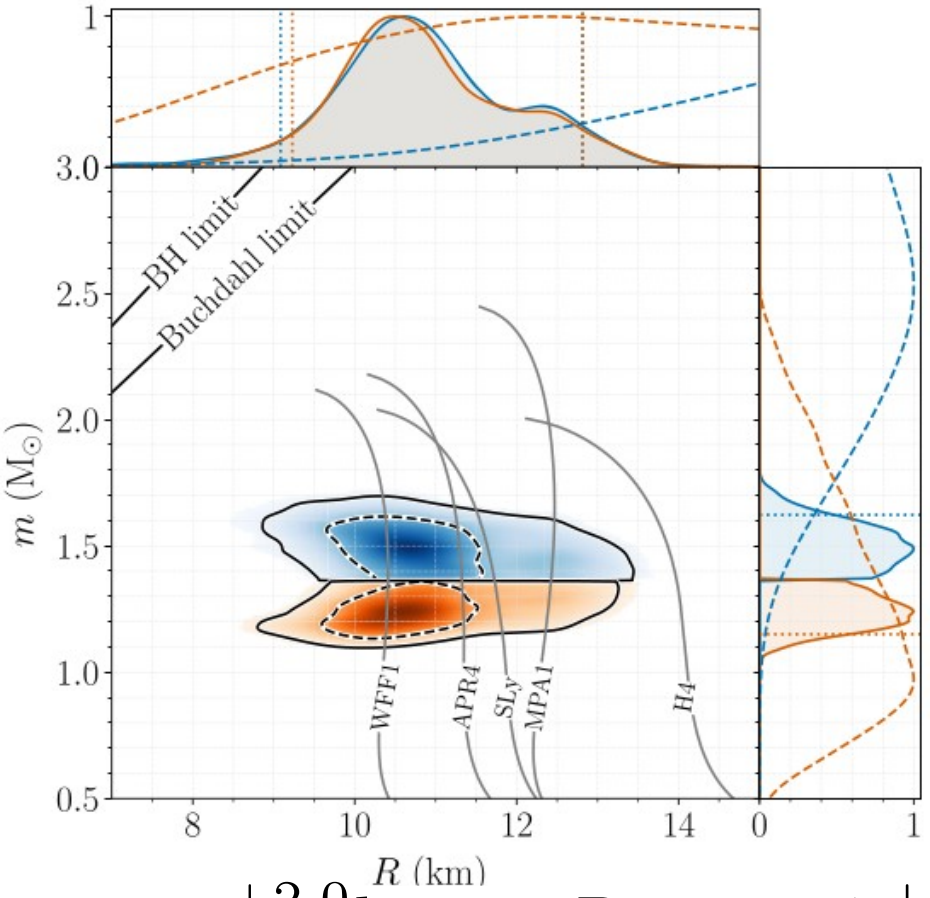


Neutron stars



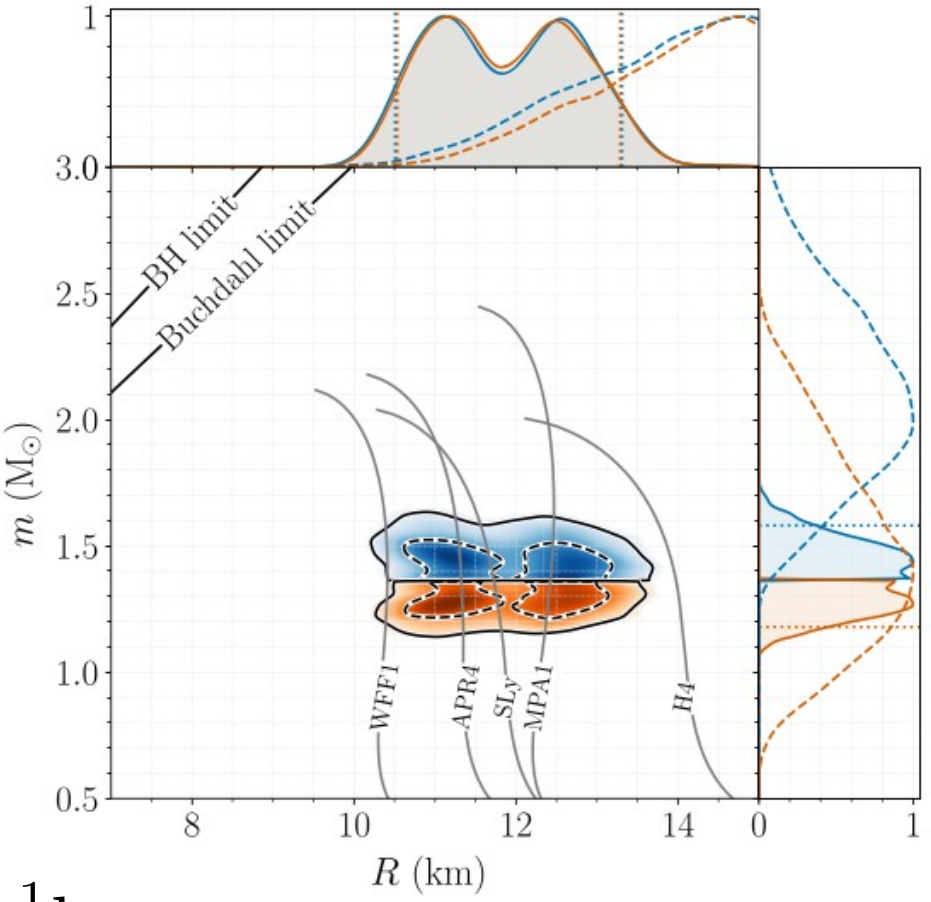
Mass radius plot

EOS insensitive



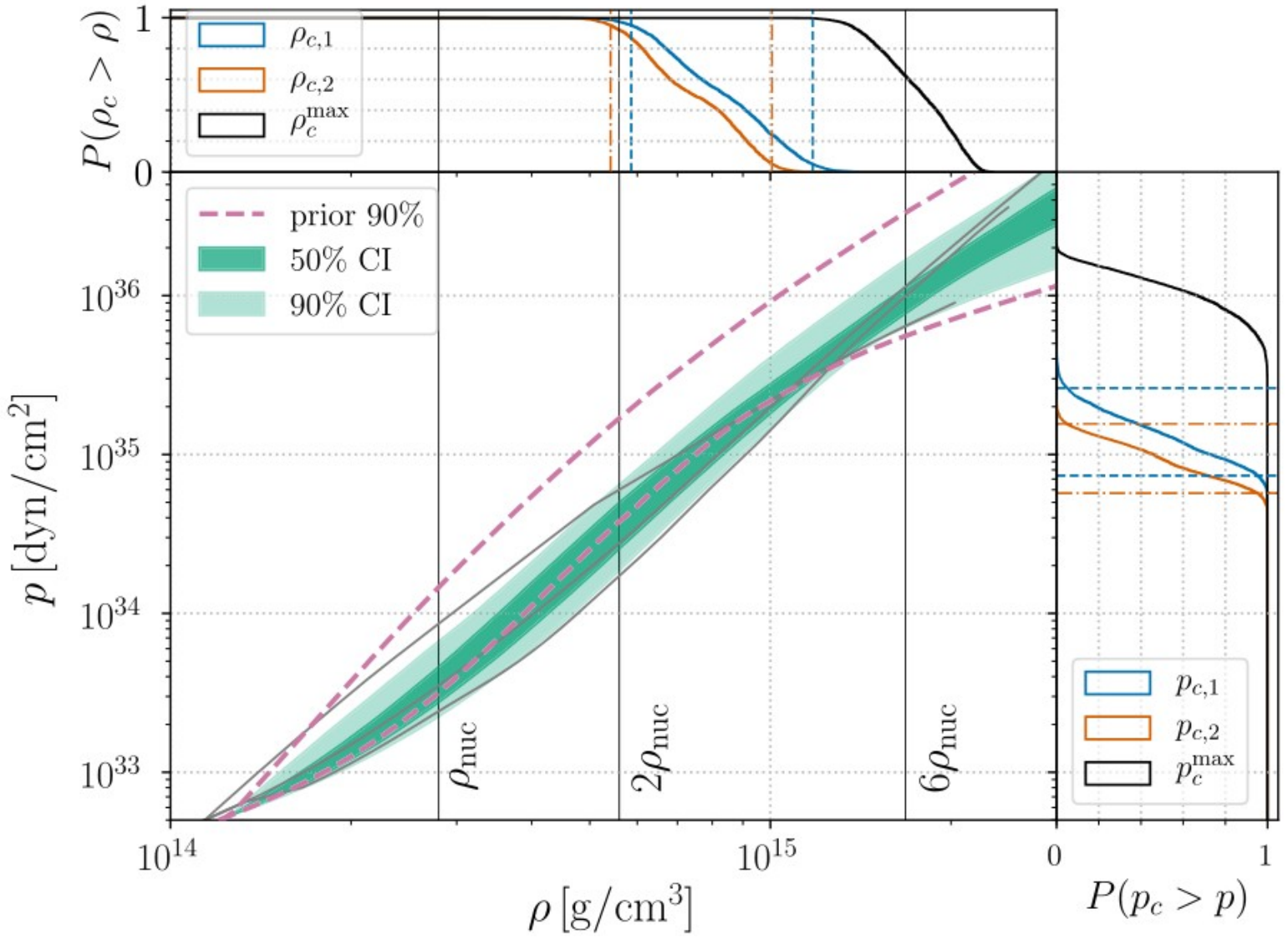
$$R_1 = 10.8^{+2.0}_{-1.7}\mathrm{km}, \quad R_2 = 10.7^{+2.1}_{-1.5}\mathrm{km}$$

Parameterized EOS



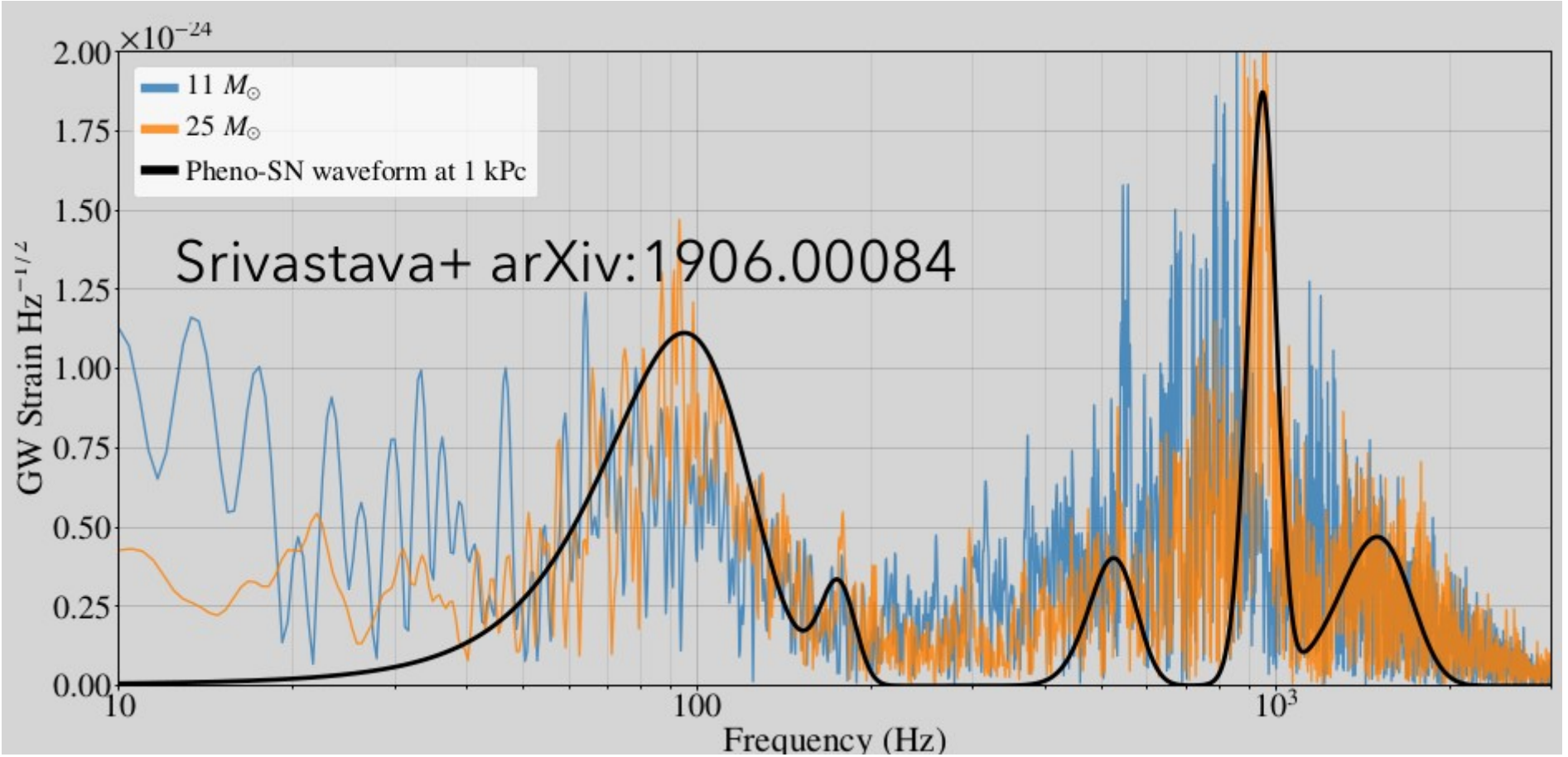
$$R_1 = 11.9^{+1.4}_{-1.4}\mathrm{km}, \quad R_2 = 11.9^{+1.4}_{-1.4}\mathrm{km}$$

Current constraints on EOS



Supernovae

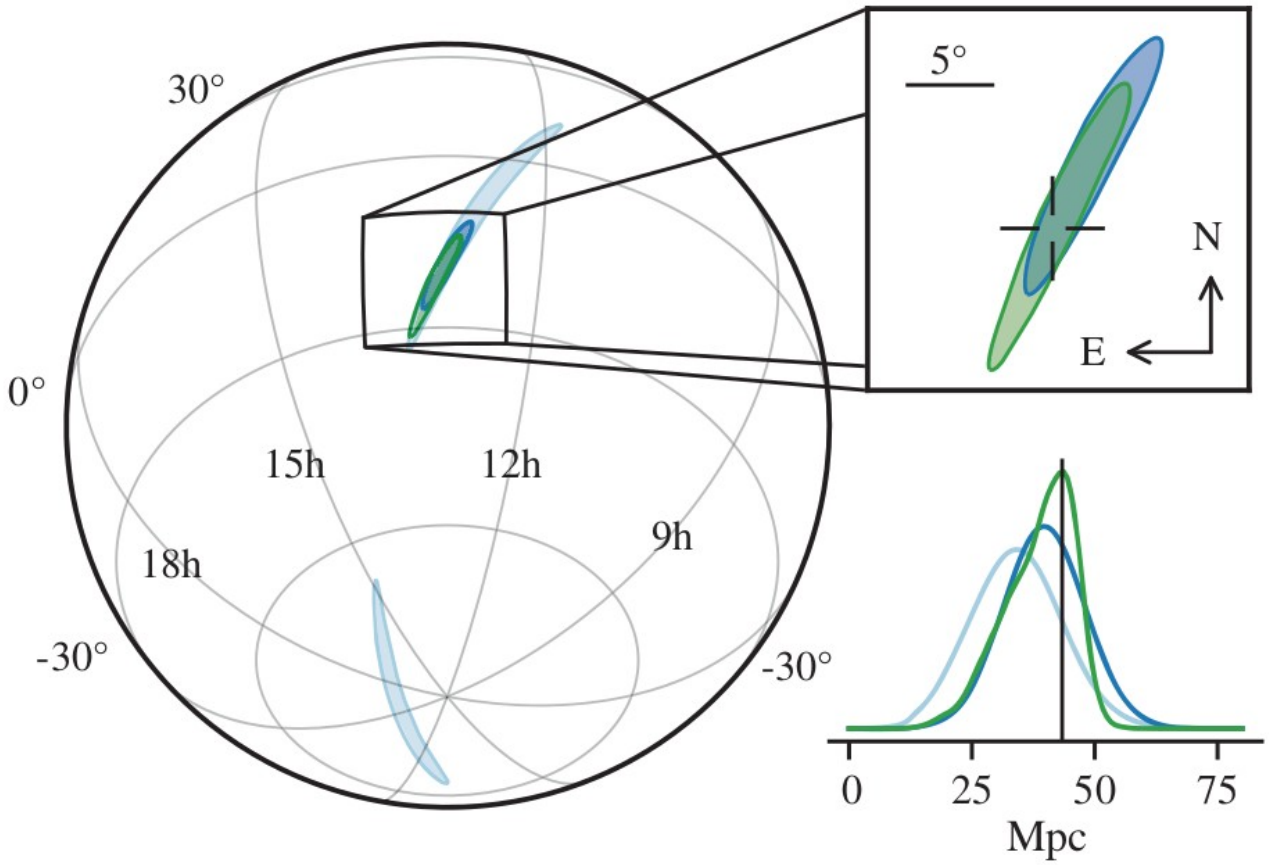
- Peek into a supernova
- Oscillations, rotation
- Geometry of collapse
- NS EOS – hot matter
- 3G rate 1-2 per century



Continuous wave sources

- Elasticity, persistence of magnetic fields
- Magnetar flares
- NS oscillations
- Binaries – spin evolution

Multimessenger astronomy



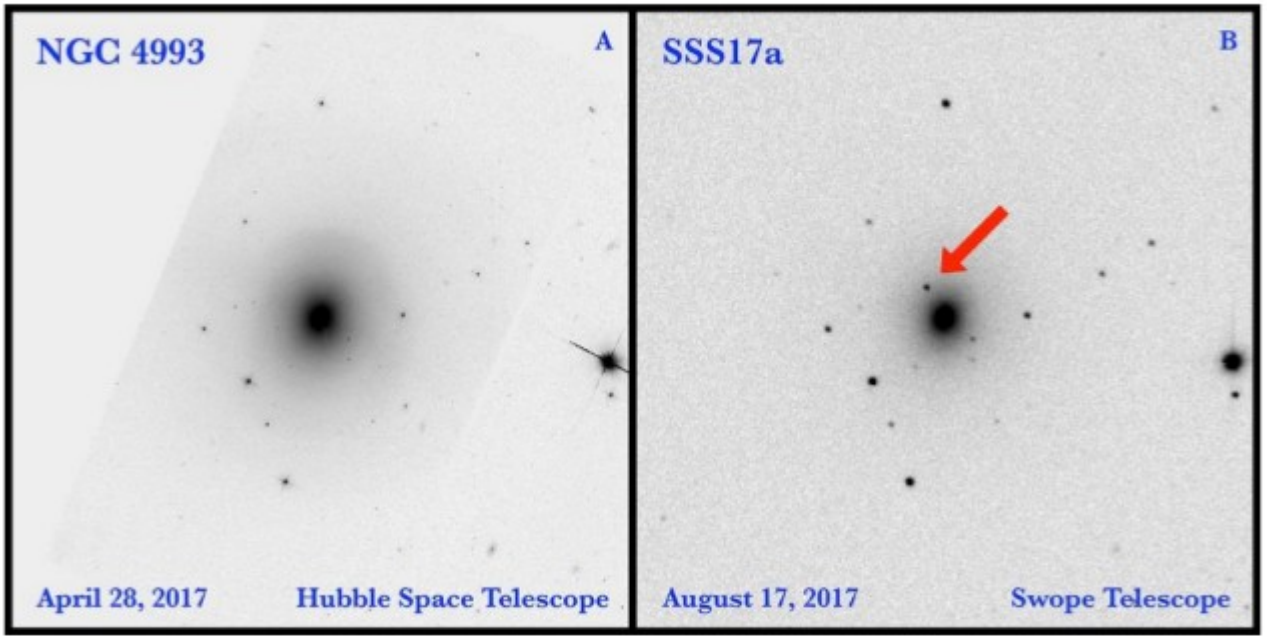
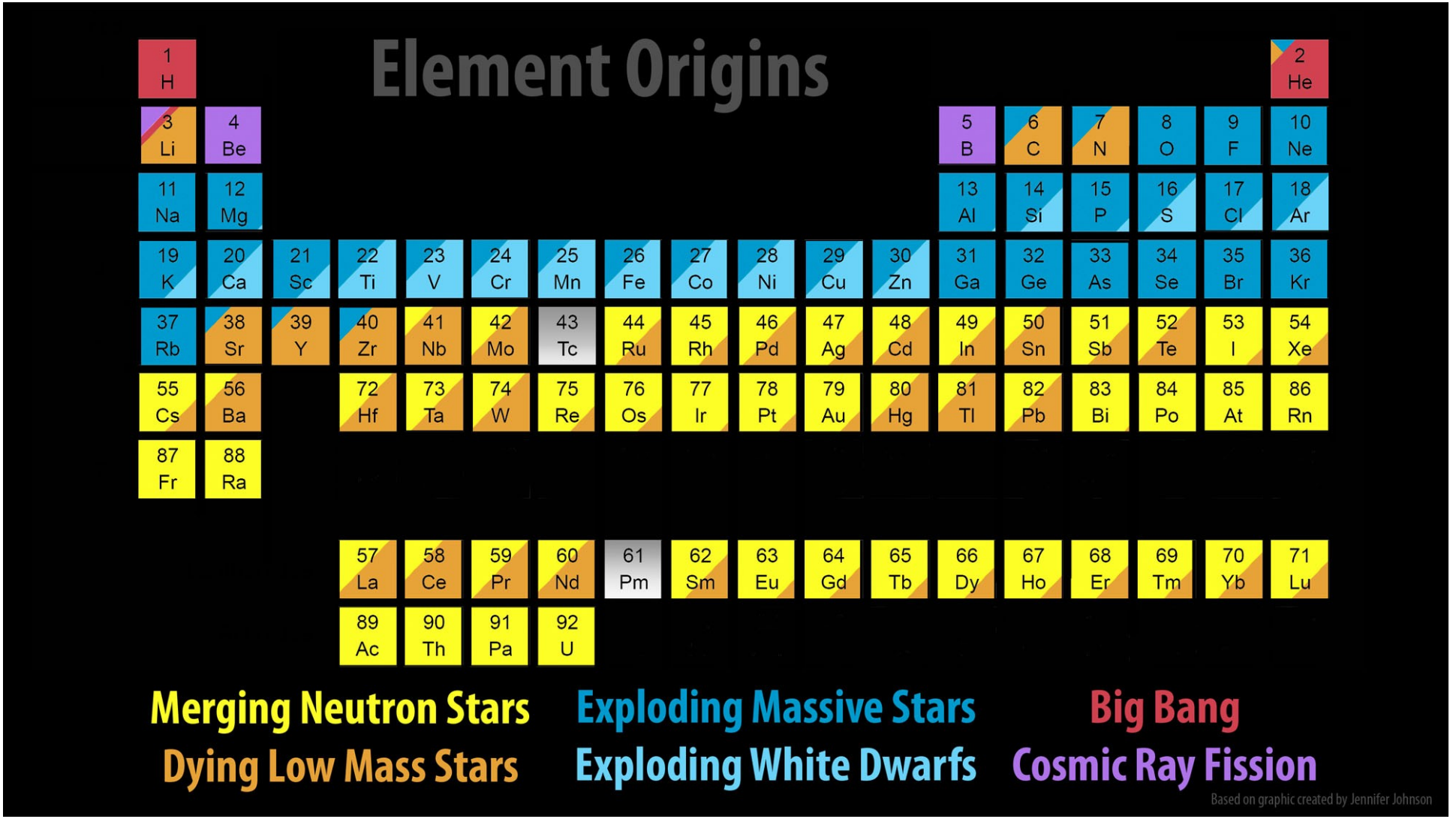
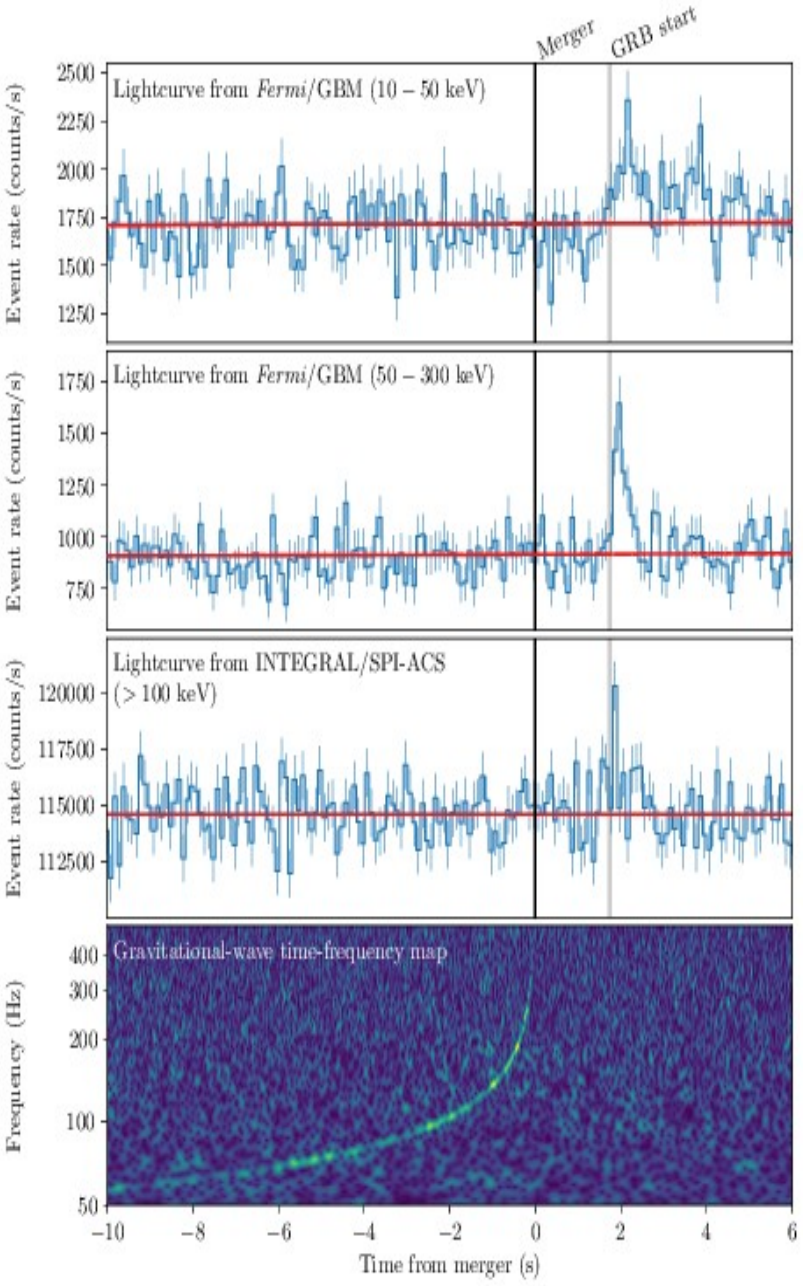


Fig. 4. 3×3 arcminute images centered on NGC 4993 with North up and East left. (**A**) *Hubble Space Telescope* F606W-band (broad *V*) image from 4 months before the GW trigger (*25*, *35*). (**B**) Swope image of SSS17a. The *i*-band image was obtained on 2017 August 17 at 23:33 UT by the Swope telescope at Las Campanas Observatory. SSS17a is marked with the red arrow. No object is present in the *Hubble* image at the position of SSS17a (*25*, *35*).


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
Based on graphic created by Jennifer Johnson

Speed of gravity



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

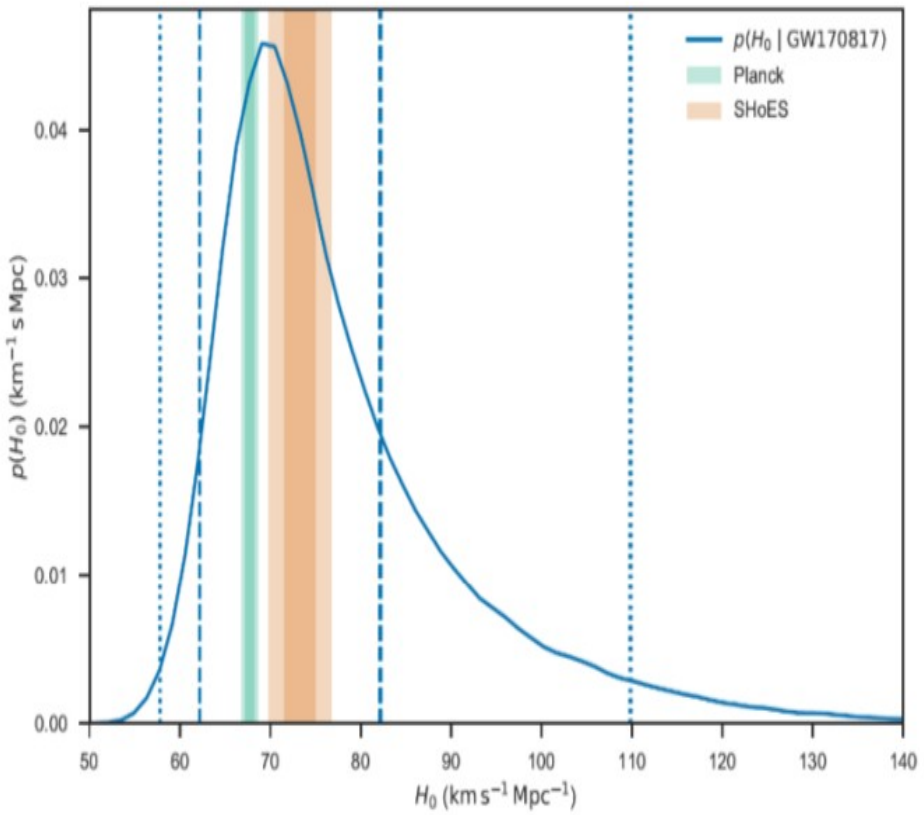
Relative difference of speed

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

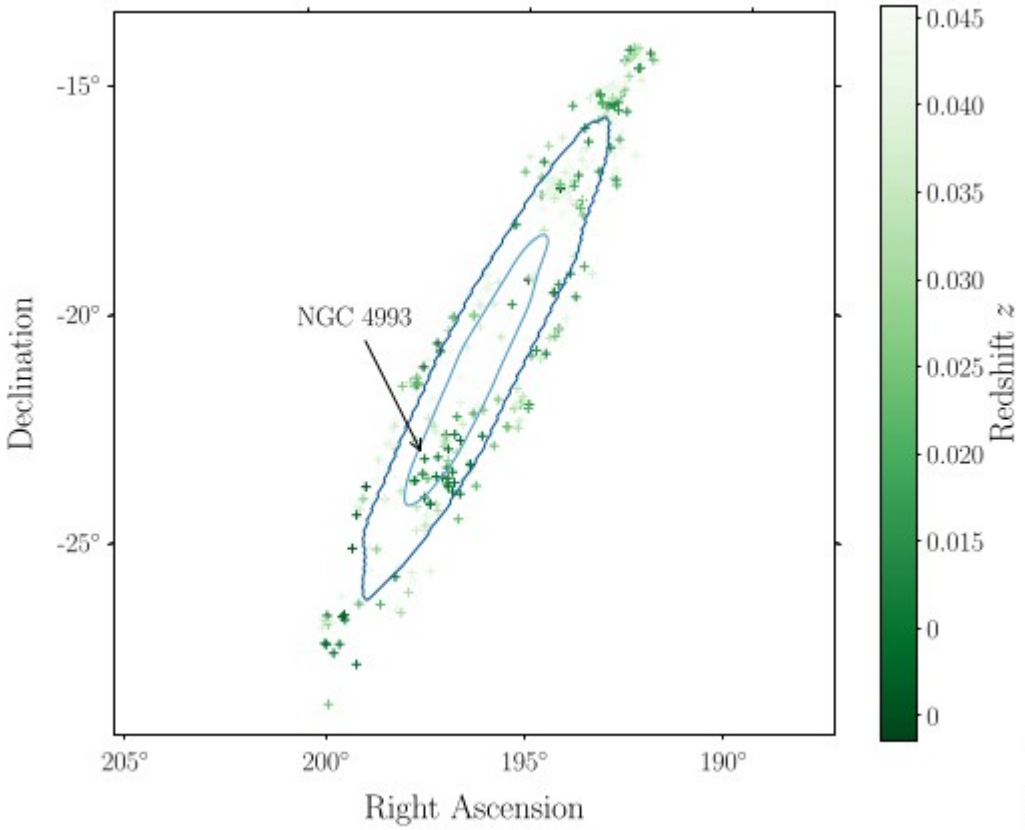
Cosmology

Binary as a standard siren:
Location and orientation needed
LHV: detection, location
From GW: distance
Optical detection: redshift
Together – Hubble constant !!!

$$H_0 = 70^{+12}_{-8}\mathrm{km\,s^{-1}Mpc^{-1}}$$

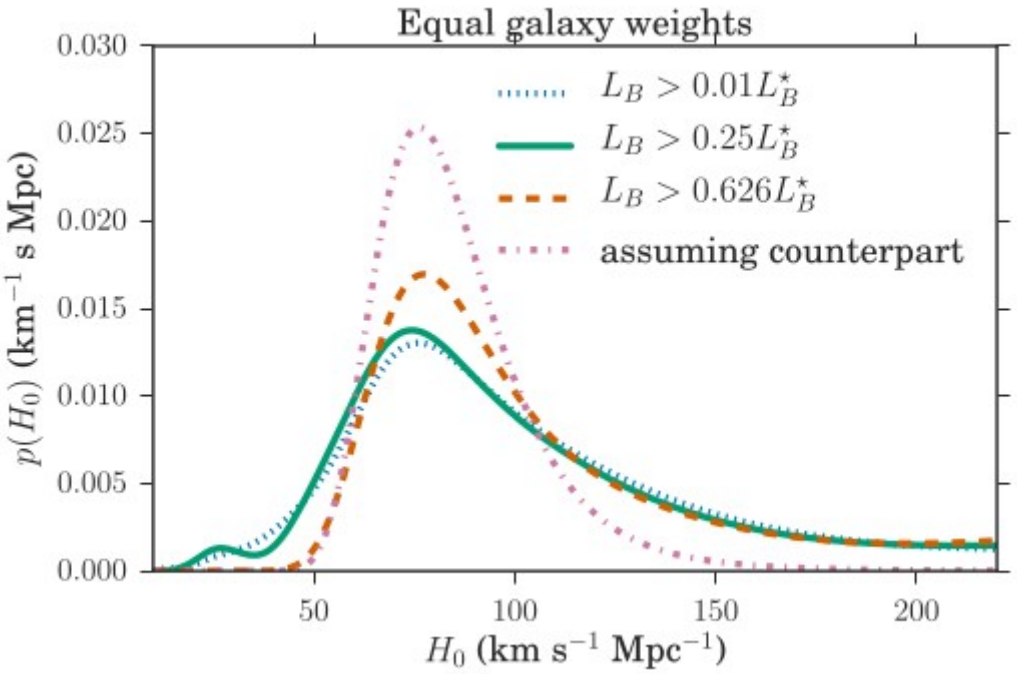


Hubble without EM

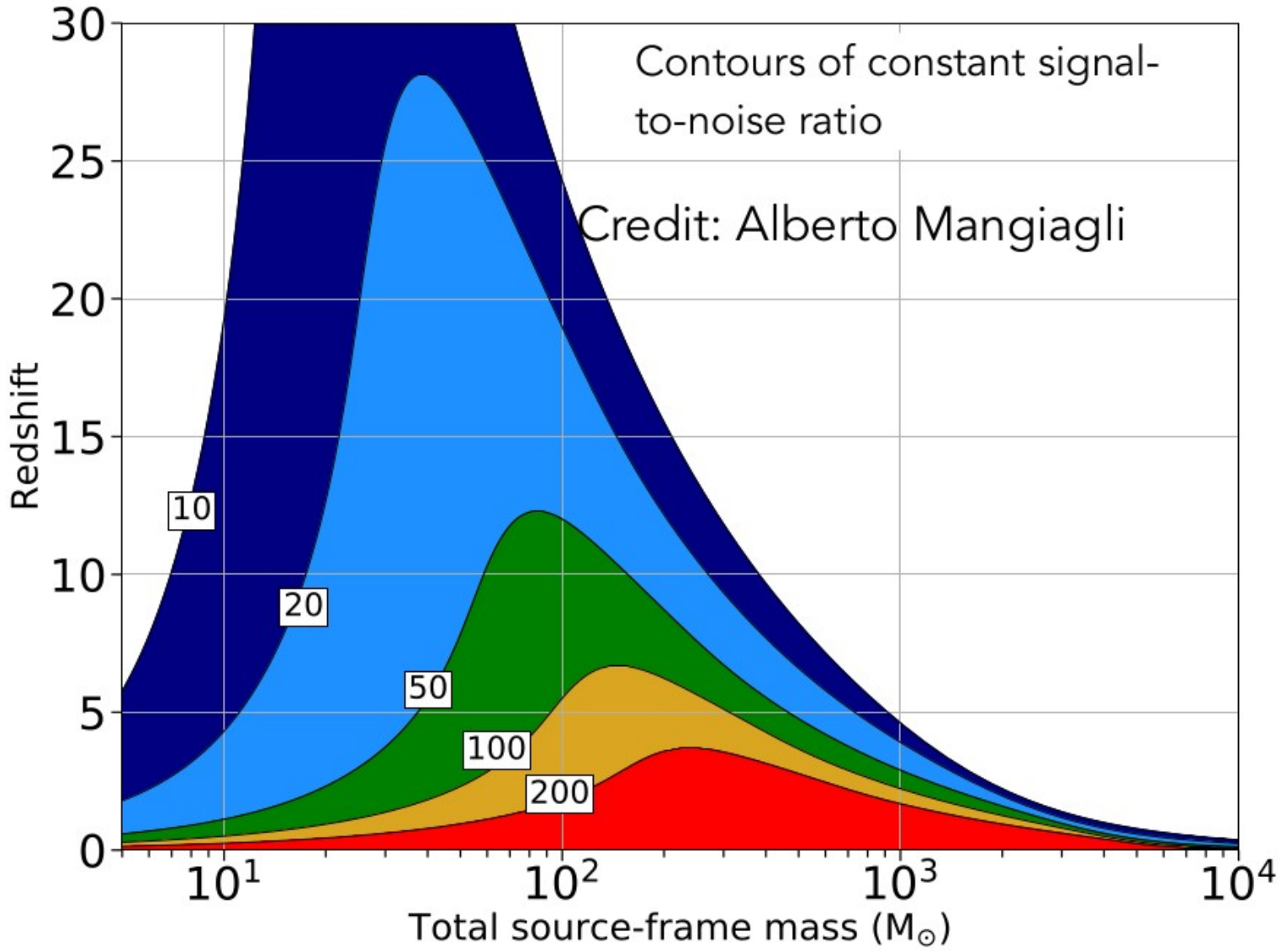


Great potential for future observations.

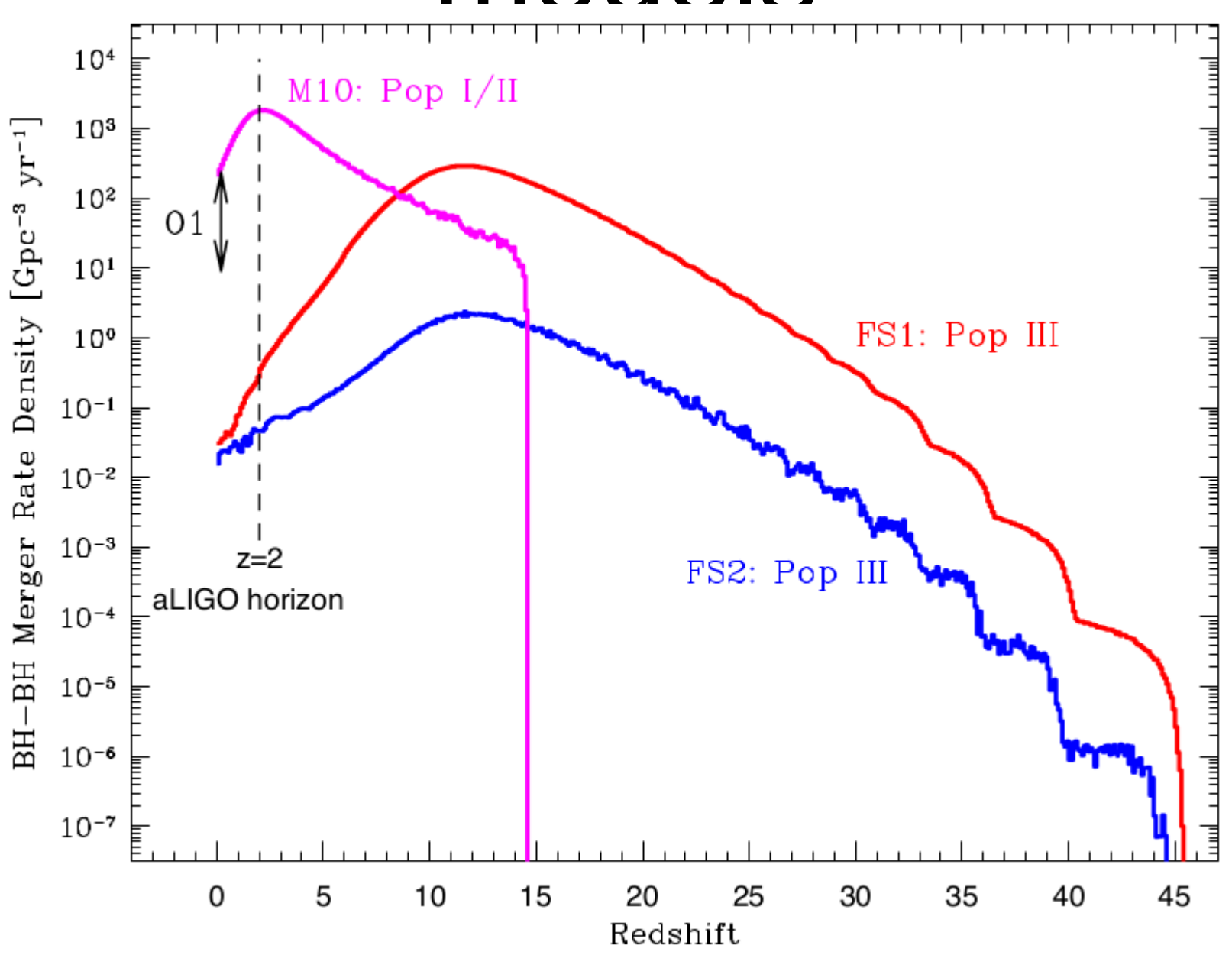
May solve the Hubble constant proble,



Stellar astrophysics



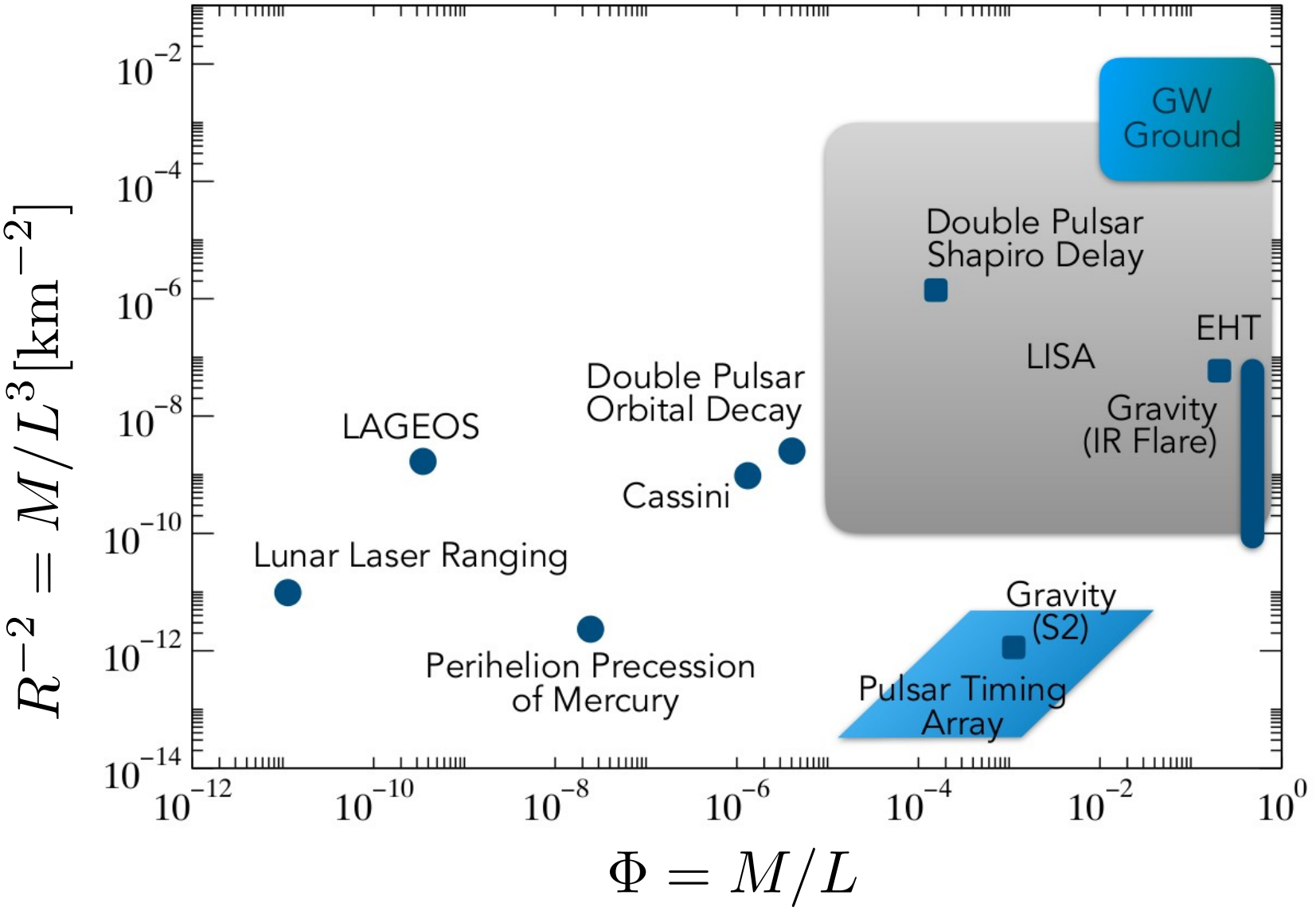
Merger rate density history, models



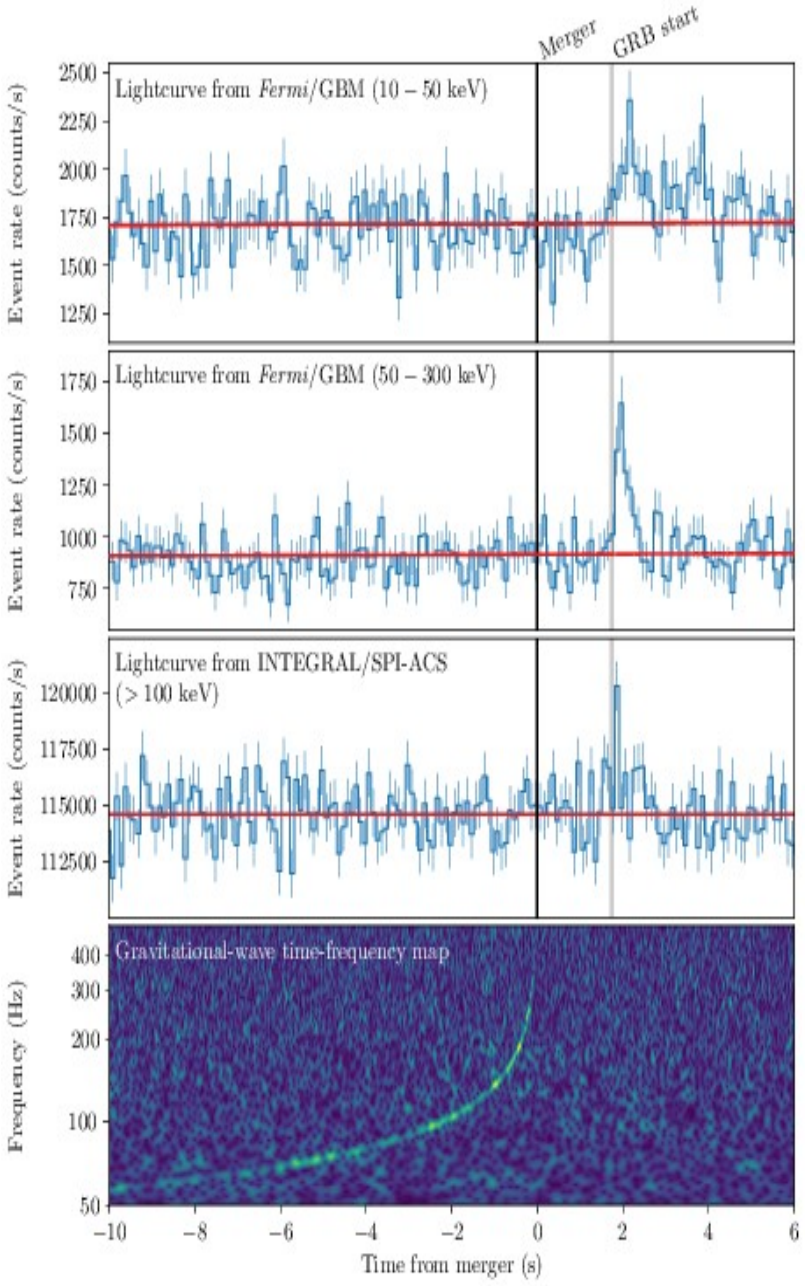
Strong gravity, modified theories

- So far GR succesful
- But problems persist:
  - BH information loss,
  - GR vs quantum theory
  - Planck scale structure of horizons
  - Etc.

GR testing


$R^{-2} = M/L^3 [\mathrm{km}^{-2}]$
$\Phi = M/L$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
GW Ground
Double Pulsar Shapiro Delay
EHT
LISA
Gravity (IR Flare)
Double Pulsar Orbital Decay
LAGEOS
Cassini
Lunar Laser Ranging
Gravity (S2)
Perihelion Precession of Mercury
Pulsar Timing Array

Speed of gravity - again



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

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

Will improve by a factor of up 1000!

Search for systematic shift in delay – measureemnt of difference?

Dispersion relation

- Does speed of GW depend on frequency?

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

$$m_g < 9.51 \times 10^{-22}\mathrm{eV}$$

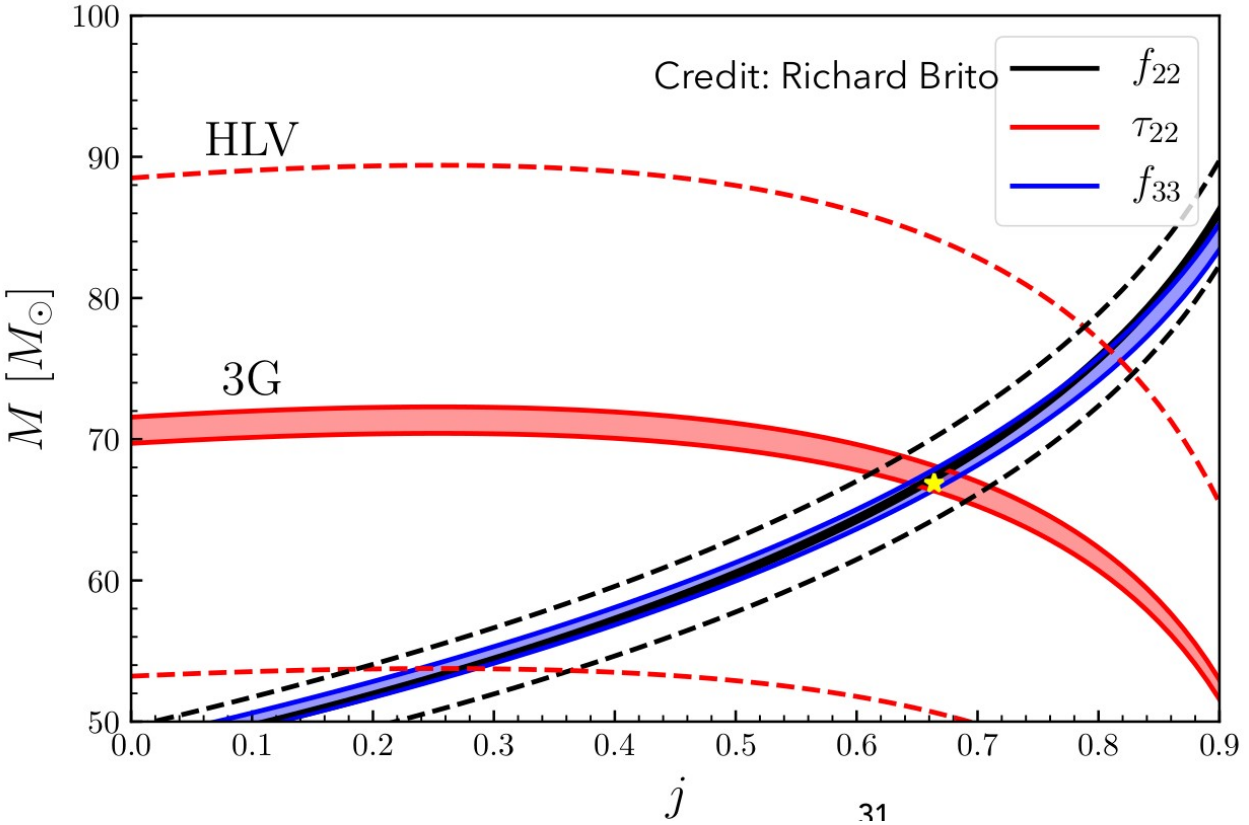
Quasi normal modes

BH emit QNMs when excited

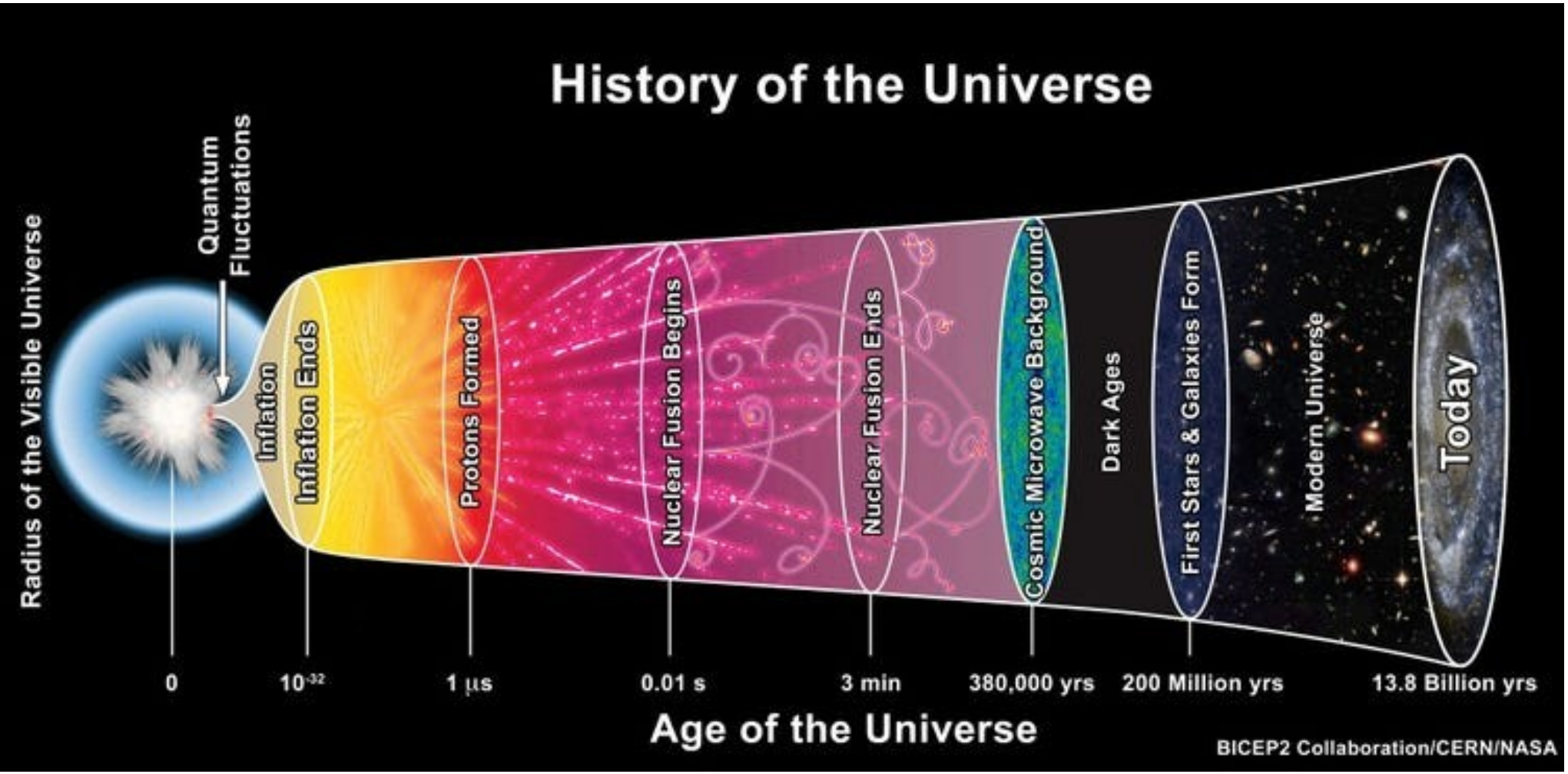
Only two parameters M, J

Measurement of more than two is a rtest of consistency of GR

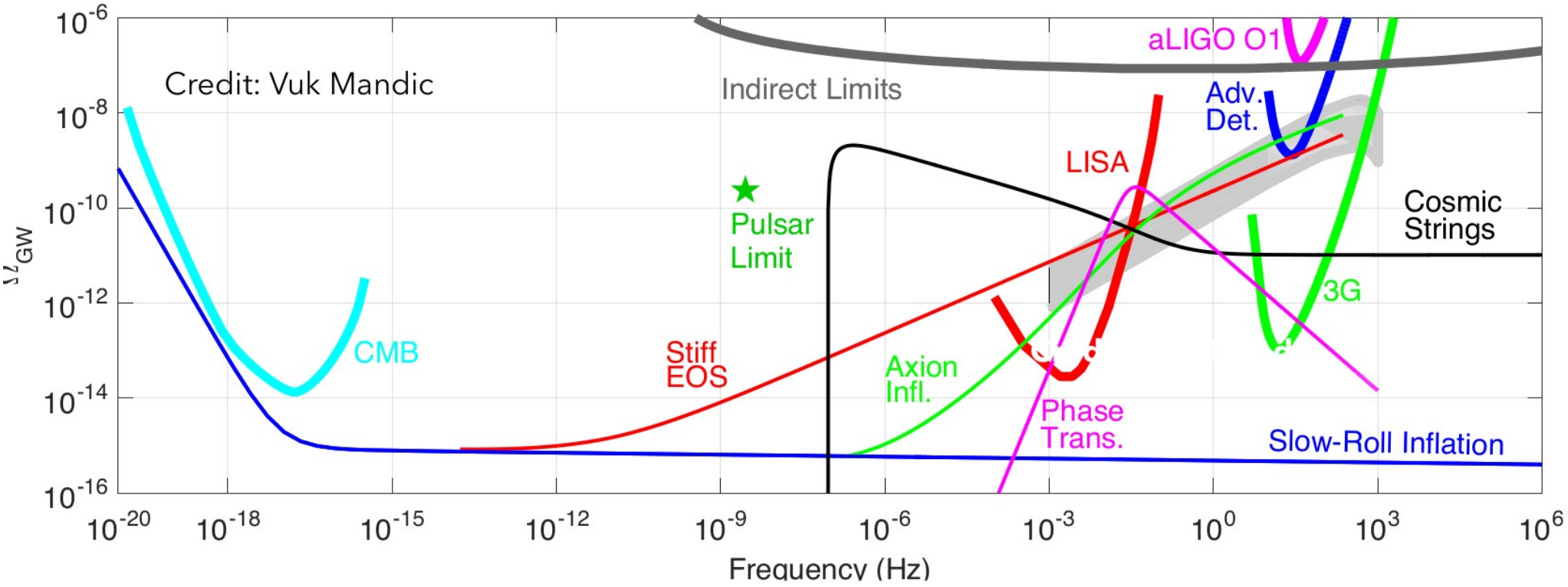
Silver bullet for Kerr BHs



Stochastic backgrounds



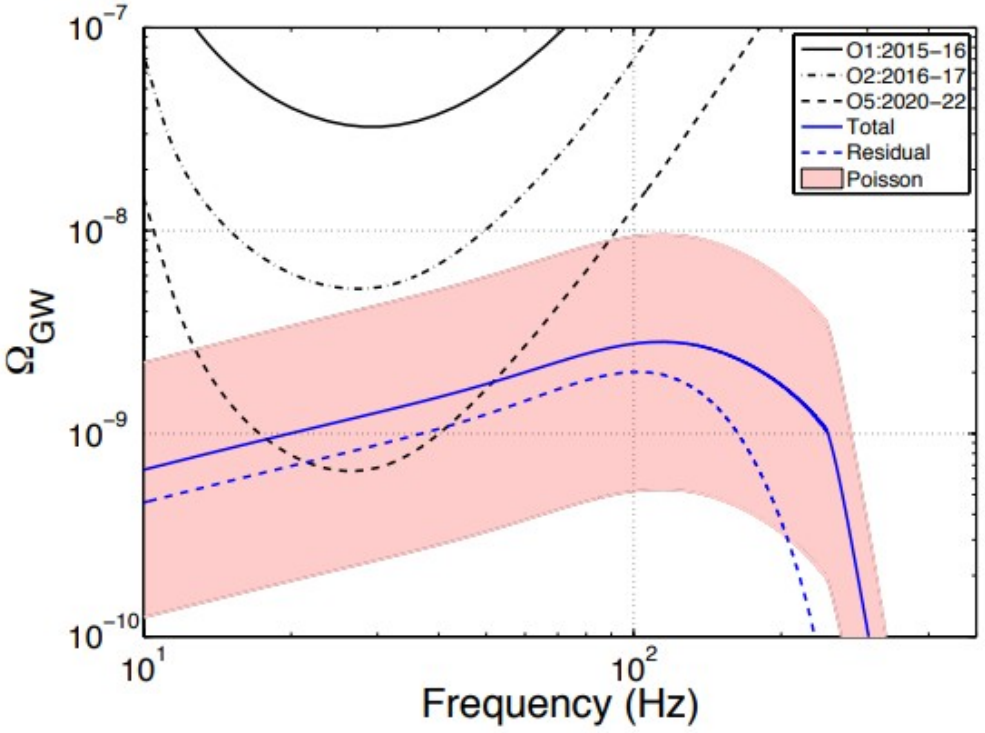
Stochastic background

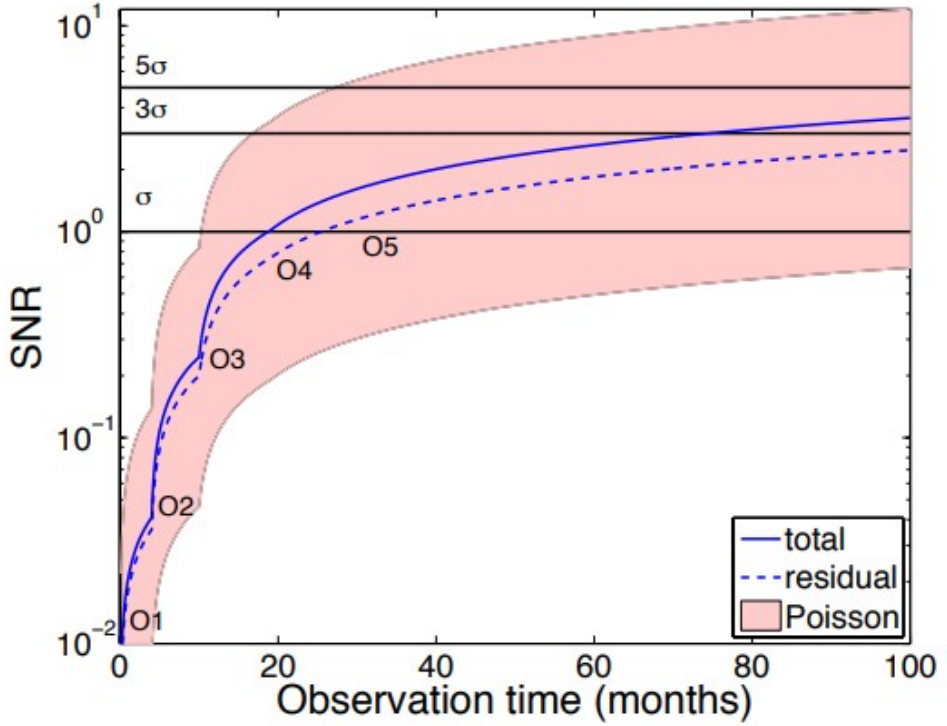


Lots of possibilities

Foregrounds subtraction is a challenge

Stochastic foreground





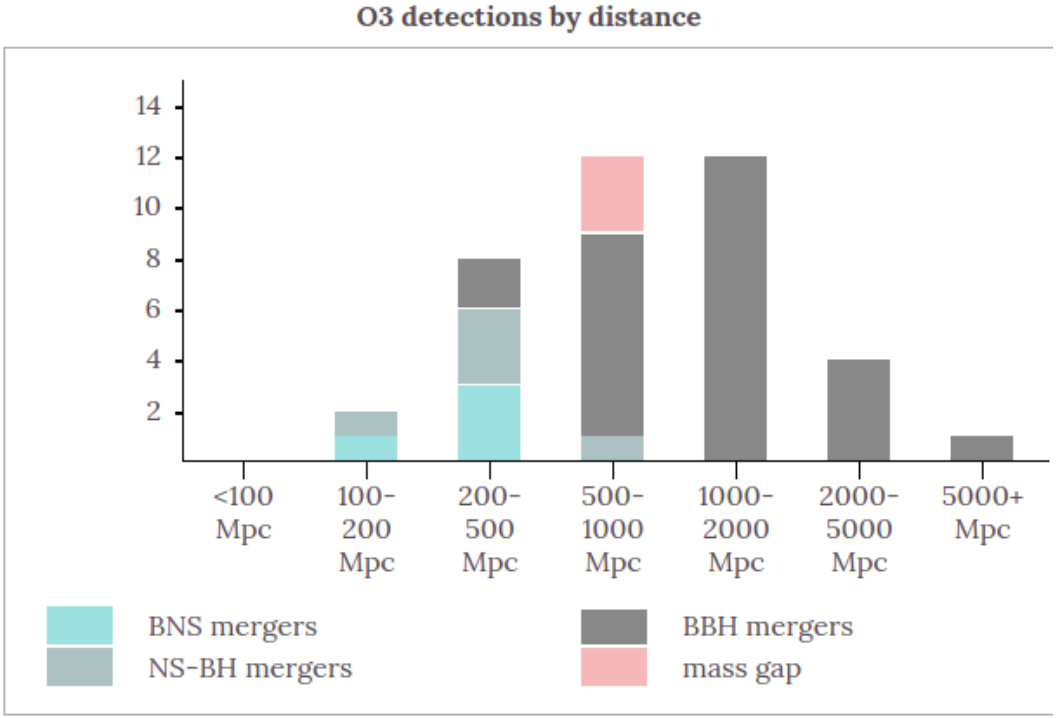
Current runs..

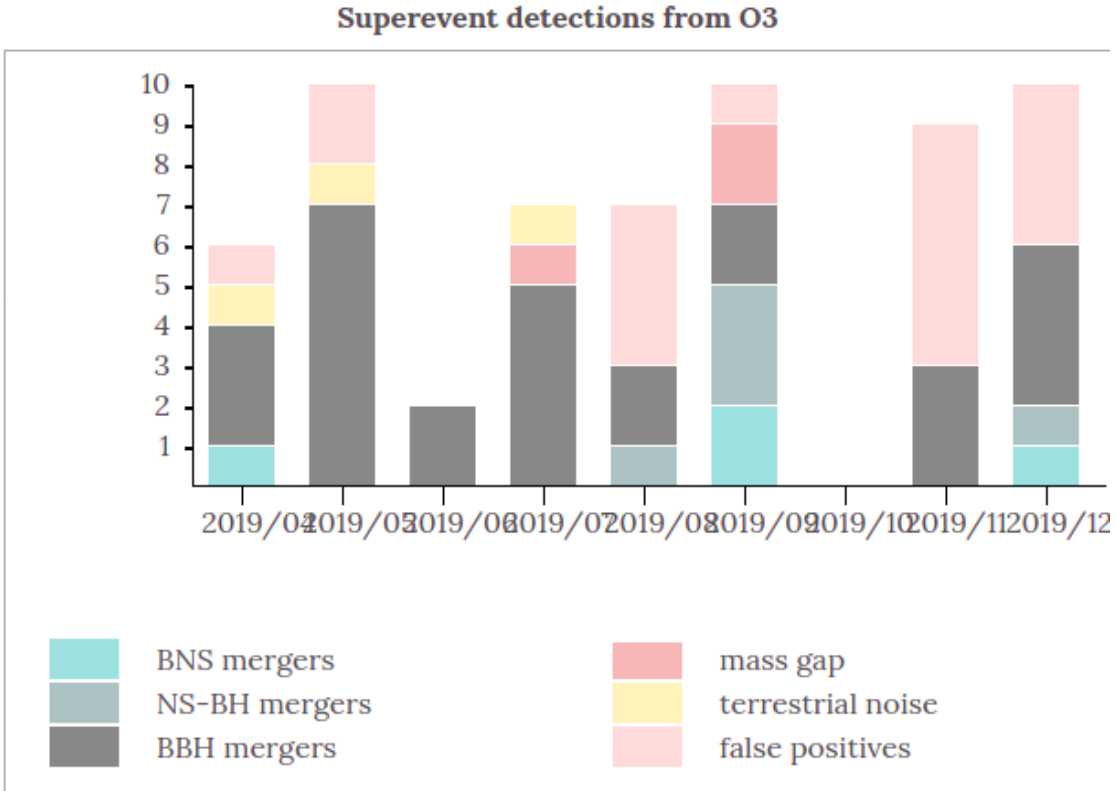
$$N(O4) \approx 2 \times 1.5^3 N(O3) \approx 2 \times 3.37 \times N(O3) = 6.7 \times N(O3)$$

Current detection alerts

For more information see

http://gracedb.ligo.org





Summary

- 3G science will be exciting !
- Ultra dense matter
- Phase transitions and quark matter
- Expansion of the Universe and dark matter
- Nature of black holes
- Core collapse supernovae
- New tool for measuring cosmic distances
- And a lot more!!!