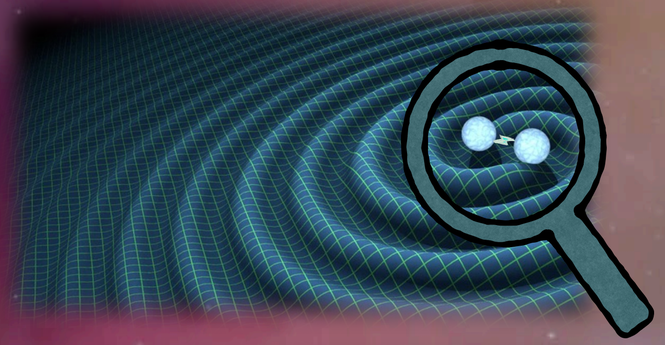
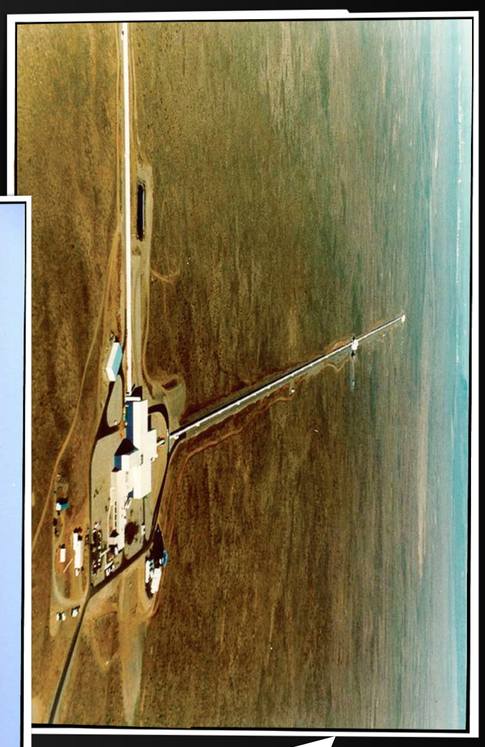
Testing the Predictions of General Relativity with Gravitational Waves

Michalis Agathos - Kavli Research Fellow KICC/DAMTP



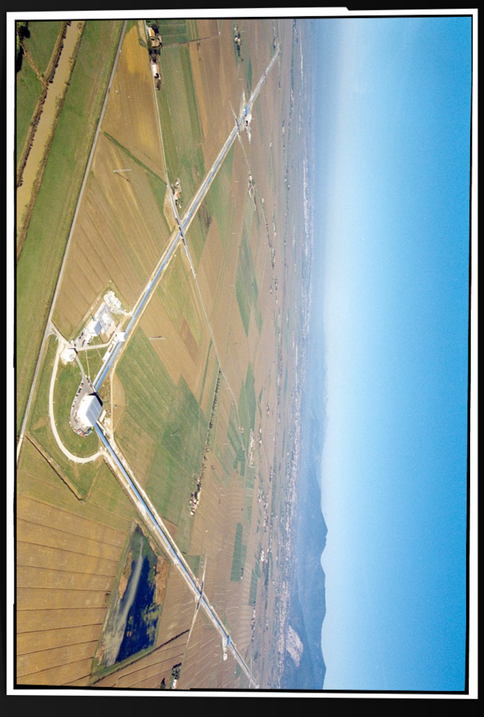
Cambridge - 30 Sep 2021

LIGO Hanford

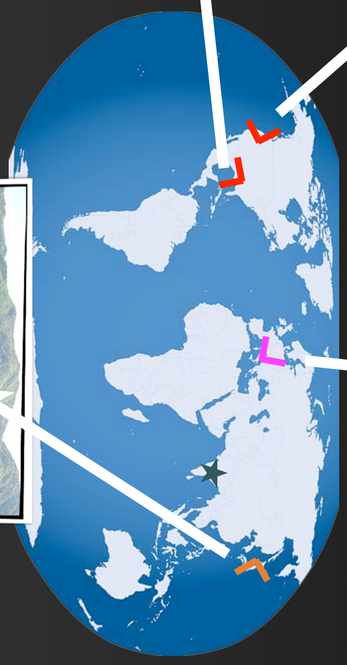


LIGO Livingston

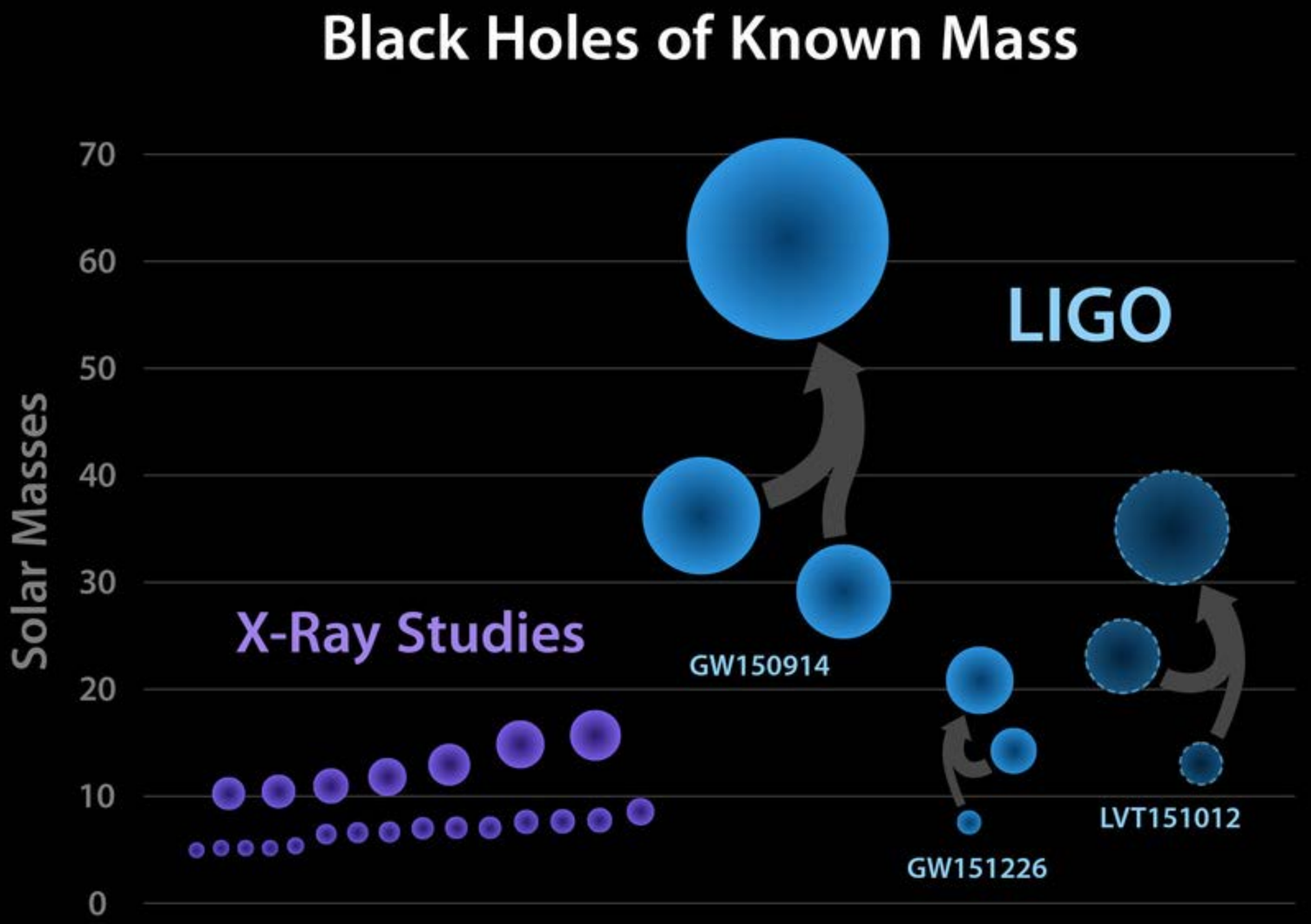
VIRGO



KAGRA

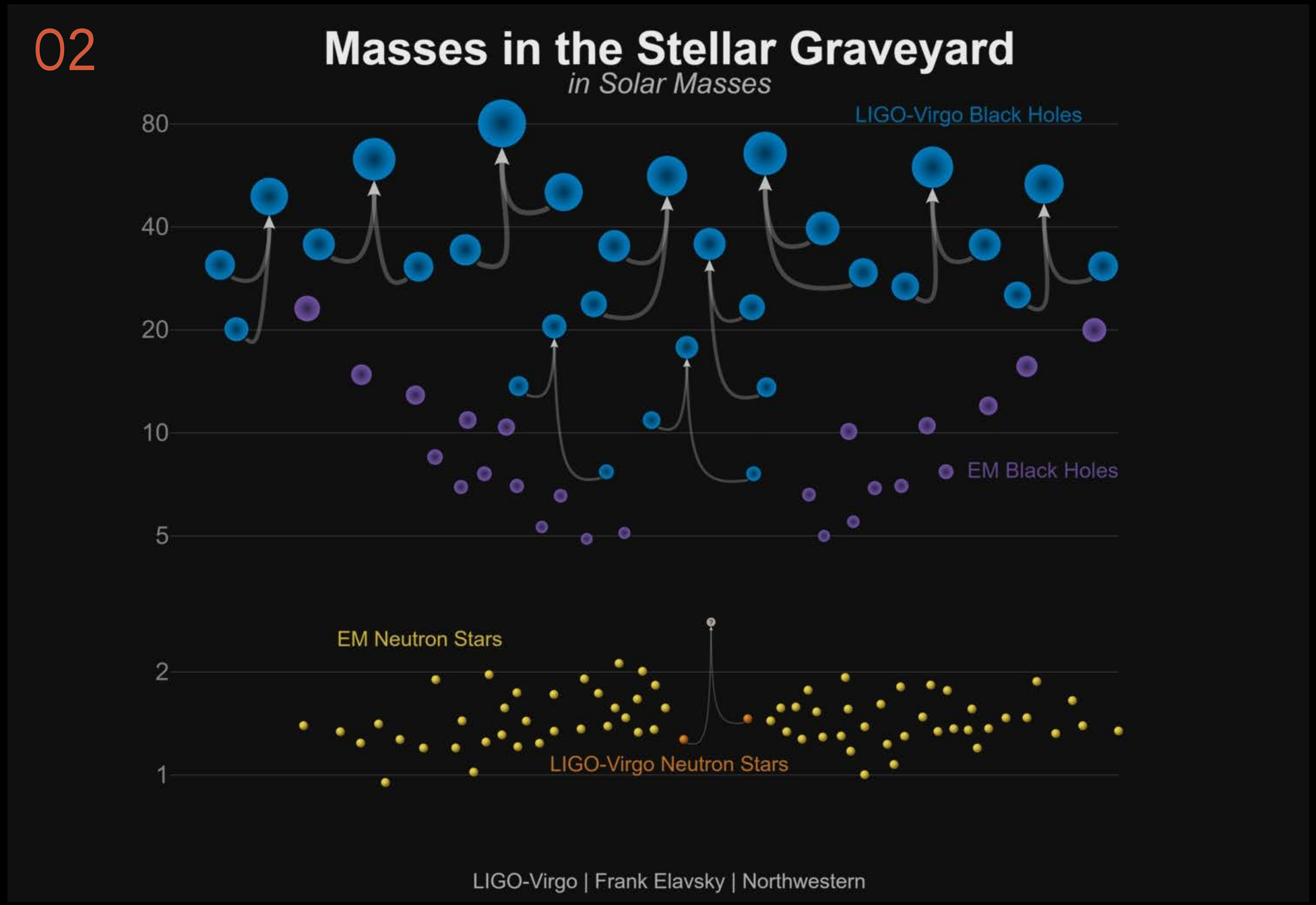


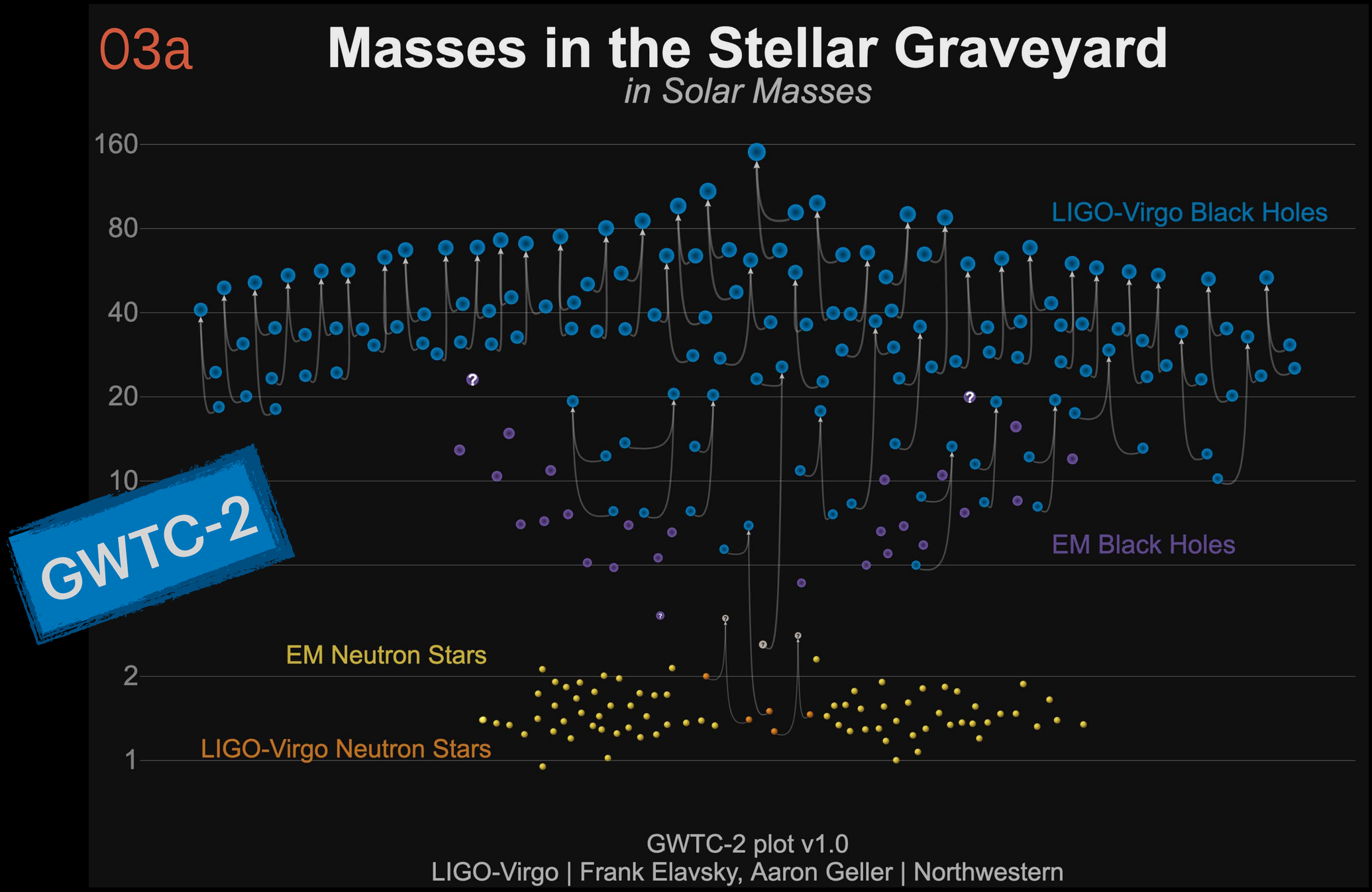
01


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
GW151226
LVT151012

LIGO

02


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

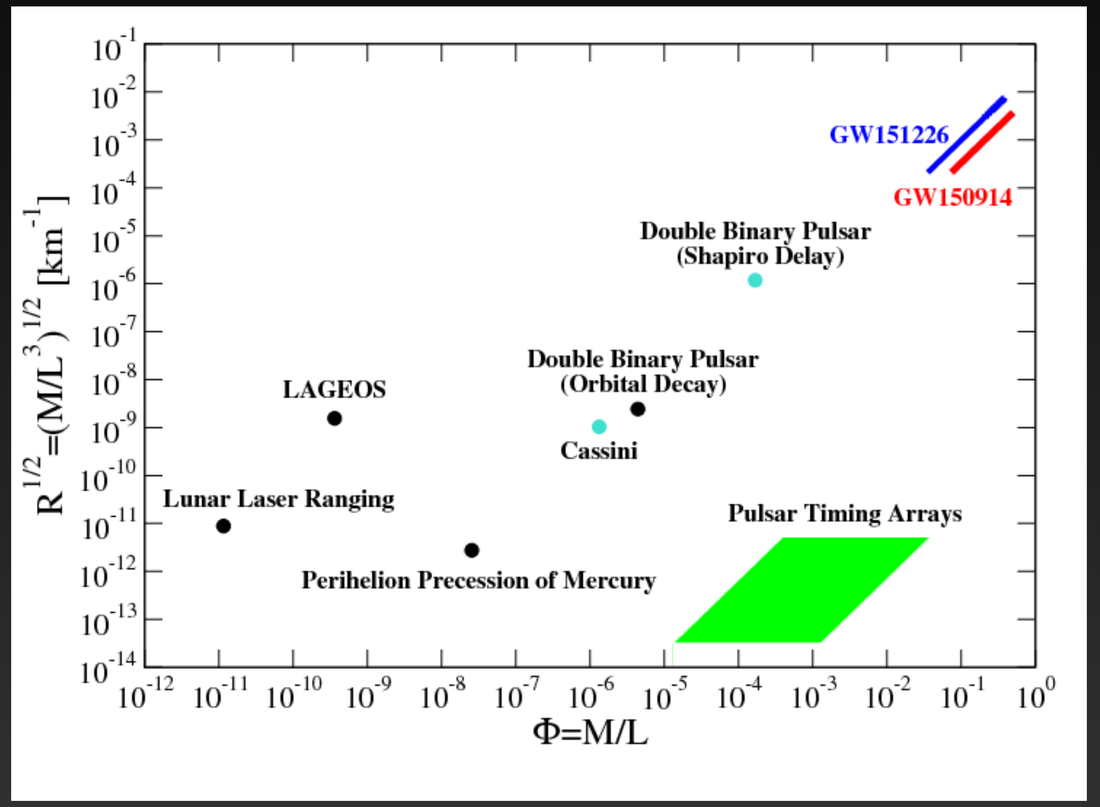

03a
Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

“

You may want to try to test GR with those

-Captain Obvious

Testing GR: Motivation



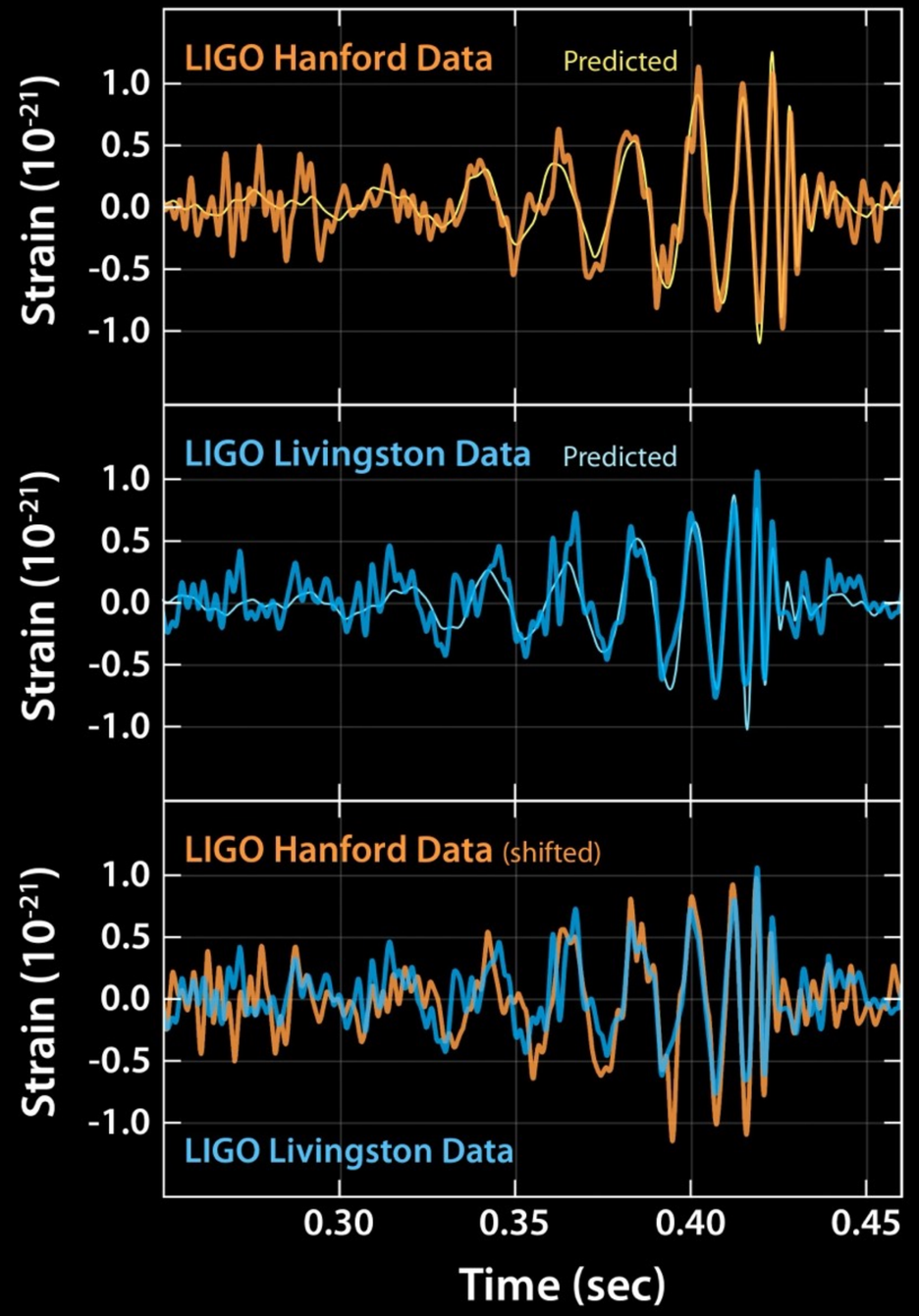
[Yunes+ PRD 94 084002 (2016)]

GW150914

- fgw: 30→132→250 Hz within < 0.2s
- v/c: 0.03→0.13→0.5

☑ Strong-field

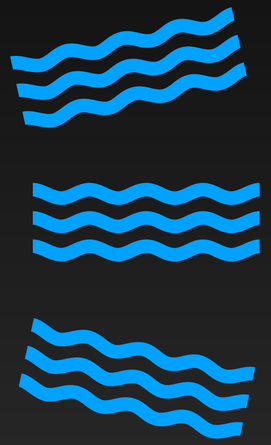
☑ Highly relativistic



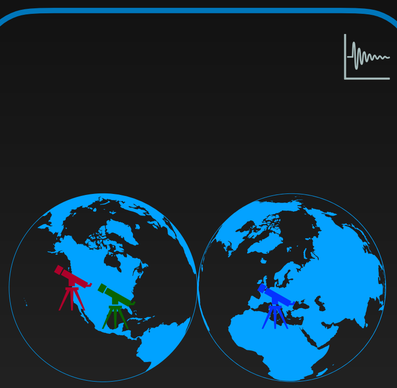
Testing GR with Gravitational Waves

What are we testing?

Generation



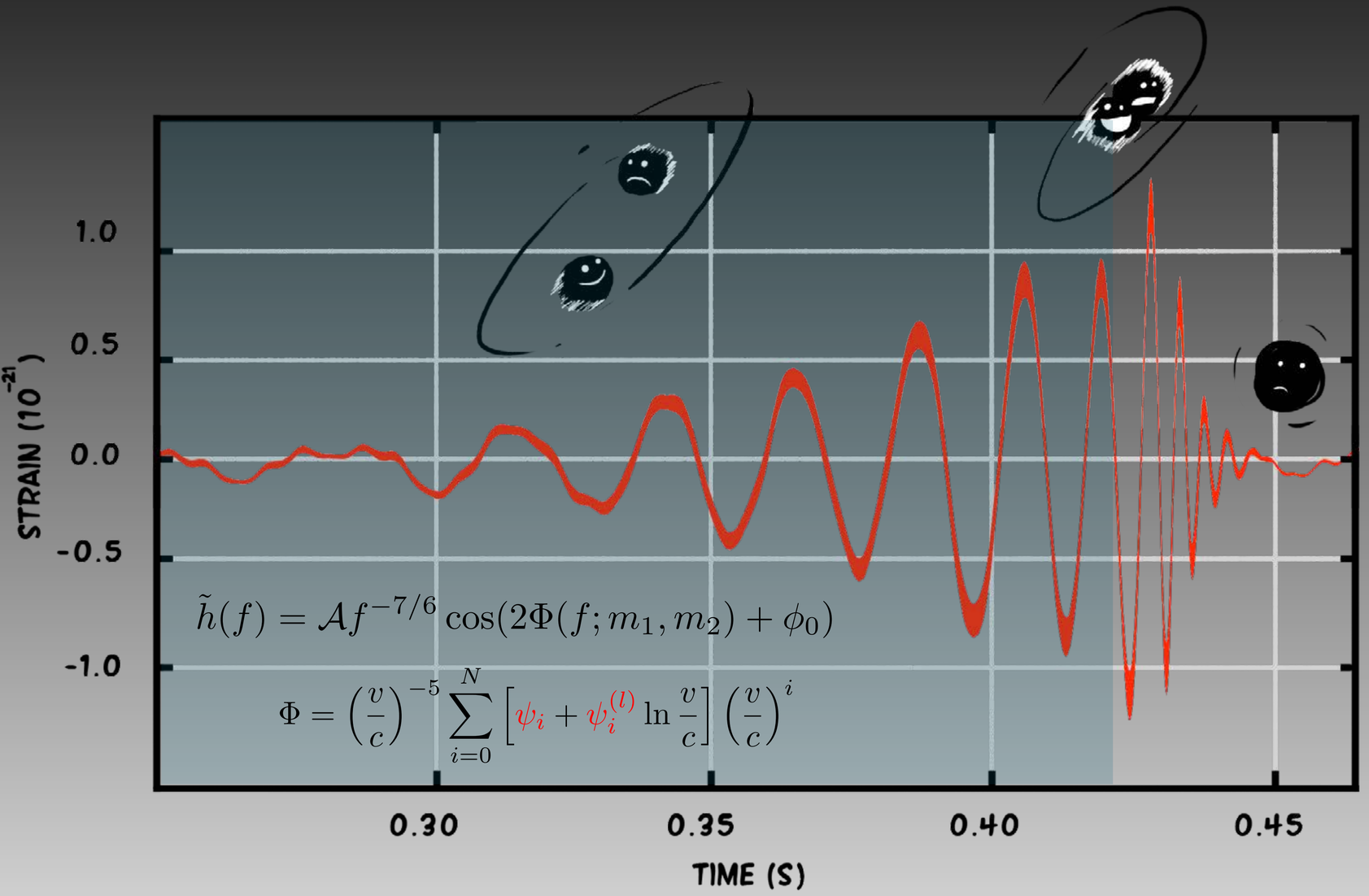
Propagation



Detection

+ *waveform systematics*
+ *noise model & calibration*

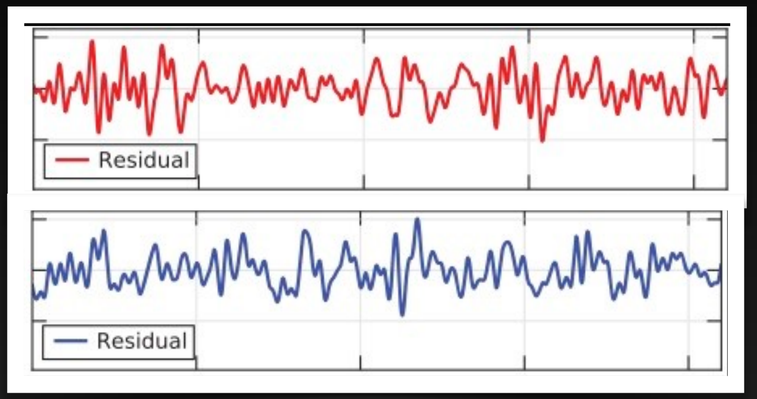
Inspiral - Merger - Ringdown

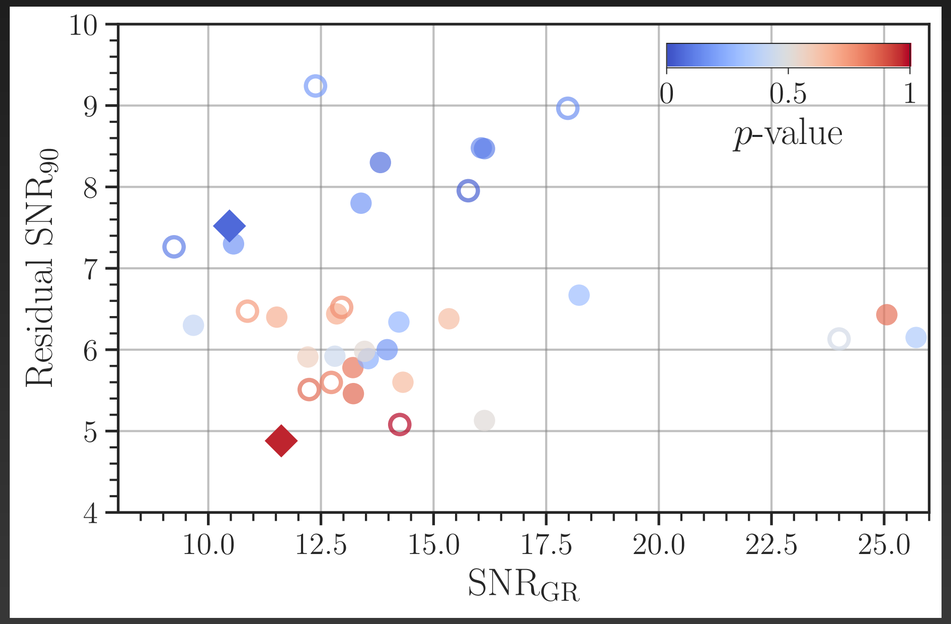


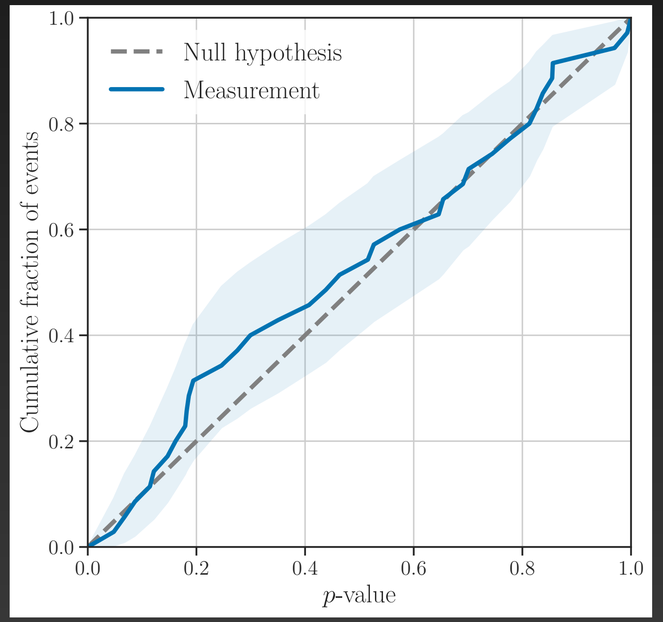
GWTC-2: Analysis on residuals

LVC PRD **103**, 122002 (2021) [arXiv:2010.14529]

- Residual SNR consistent with noise
- No significant trend with overall SNR
- p-value statistics are regular



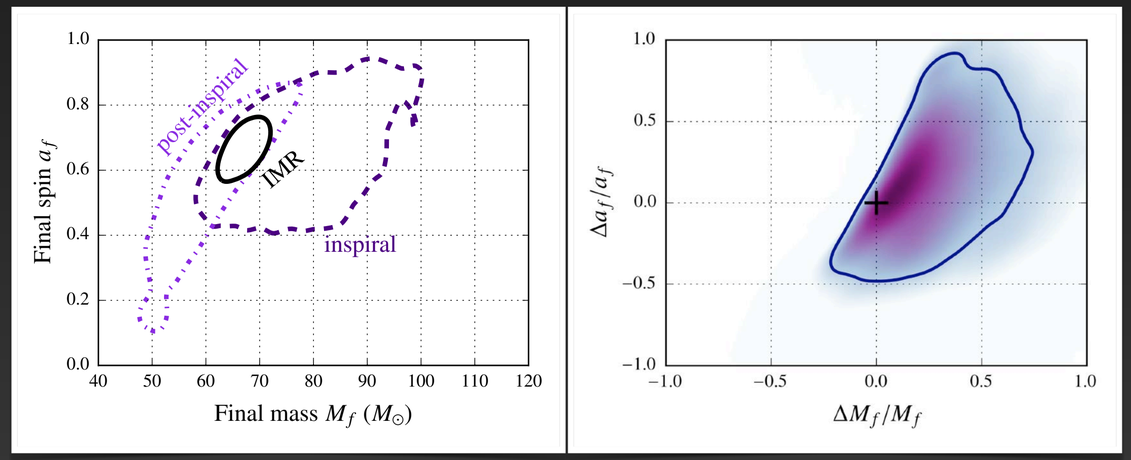


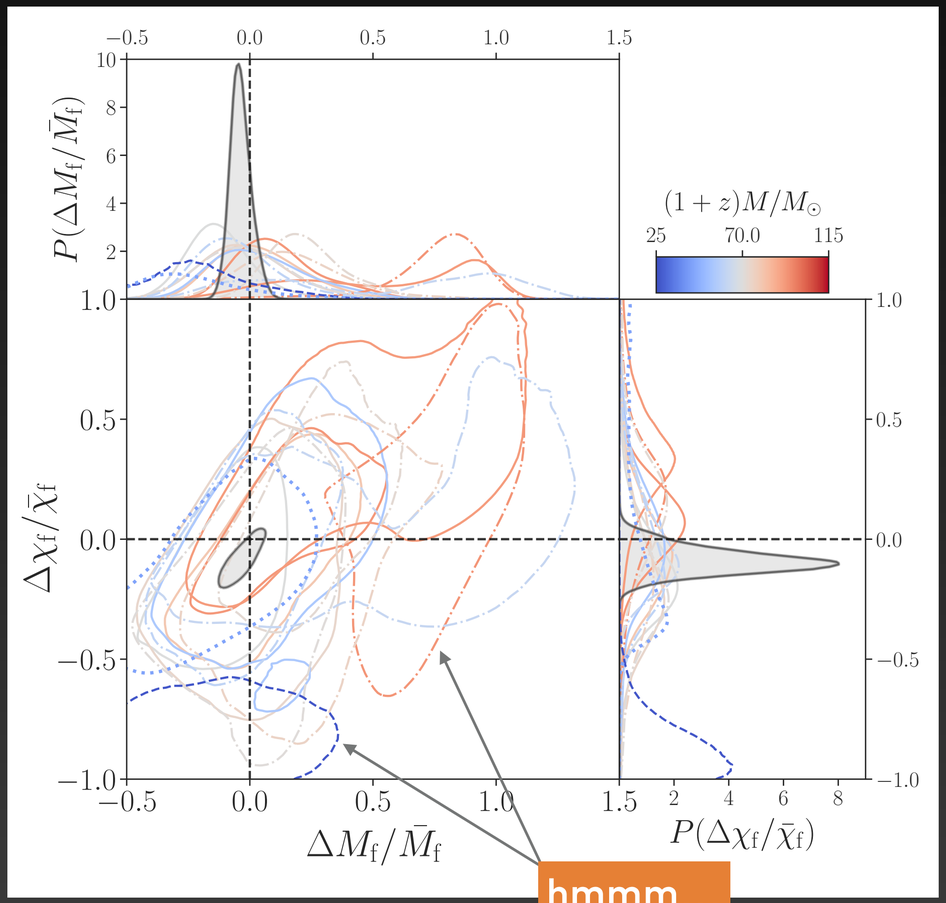


Inspiral - Merger-Ringdown consistency

LVC PRD **103**, 122002 (2021)
[arXiv:2010.14529]

- Inspiral signal gives progenitor masses & spins
- Post-inspiral signal gives final BH mass & spin
- GR (NR) gives relation between masses and spins between progenitor and final BH



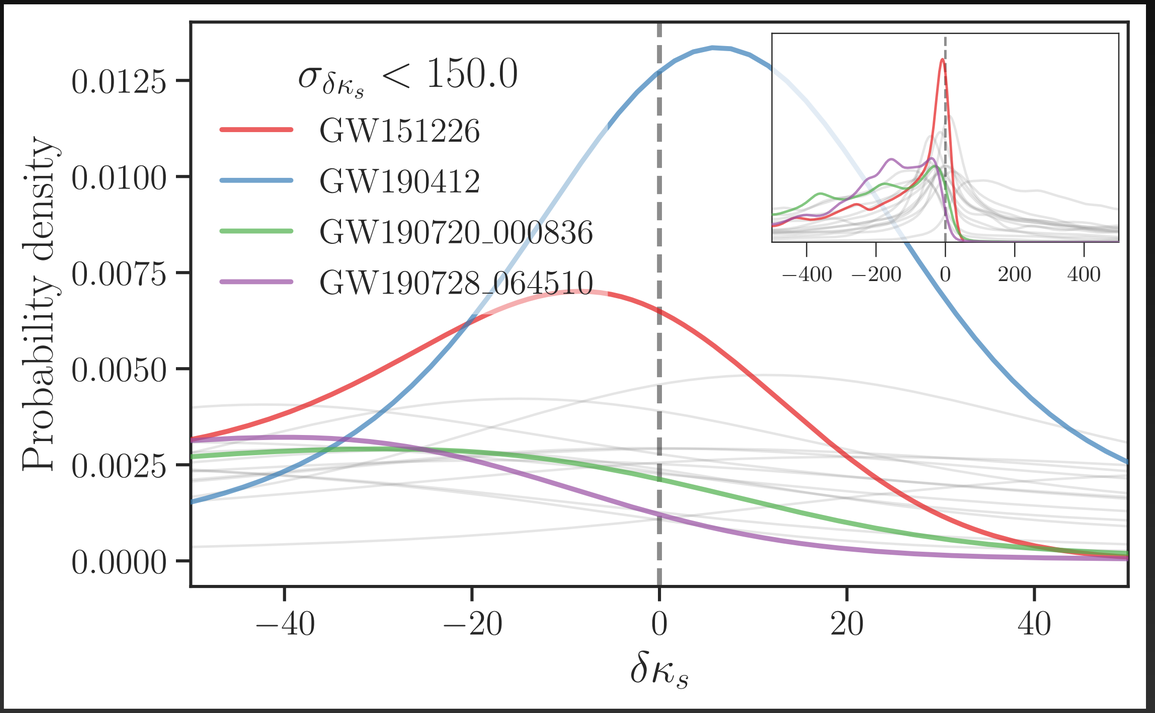


GWTC-2 Black Hole Quadrupole

- All properties of a Kerr BH are uniquely determined by knowing its **mass** and **spin**
- Spin-induced quadrupole:

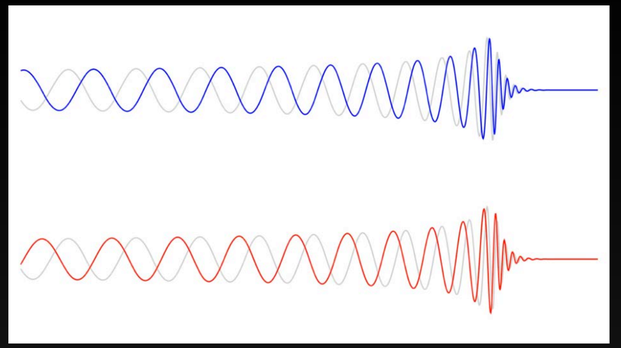
$$Q = -\kappa \chi^2 M^3 , \quad \kappa_{\rm BH} = 1$$

- Non-Kerr compact objects will in general have $\kappa \neq 1$, e.g. neutron-/boson-/grava- stars, etc.
- We measure a combination of κ to be **consistent with the Kerr BH** value



LVC PRD **103**, 122002 (2021)
[arXiv:2010.14529]

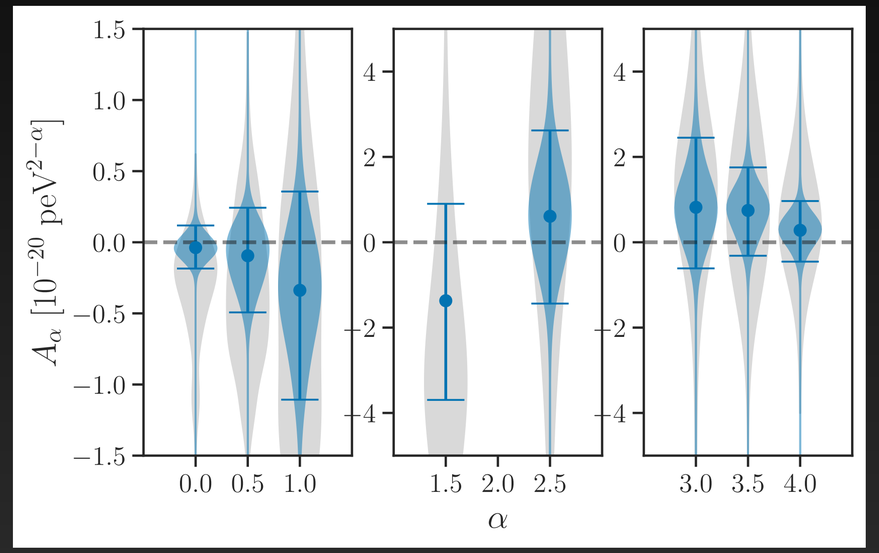
GW propagation
Modified Dispersion Relation



- Massive graviton: $E^2 = p^2c^2 + m_g^2c^4$
- Generalization: $E^2 = p^2c^2 + \mathbb{A}\, p^\alpha c^\alpha$
- Phase modification:

[Will 1994]
[Mirshekari+ 2011]

$$\delta\Psi_\alpha(f) = -\cancel{\beta(\pi M f)} - \frac{\pi D_\alpha}{(1-\alpha)\lambda_{\mathbb{A}}^{2-\alpha}(1+z)^{1-\alpha}} f^{\alpha-1} \qquad \alpha \neq 1$$



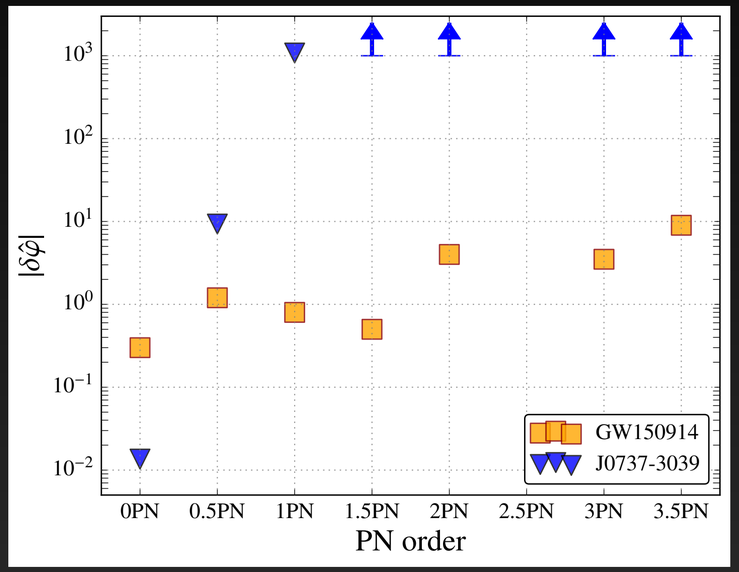
LVC PRD **103**, 122002 (2021)
[arXiv:2010.14529]

	m_g [10^{-23} eV/c^2]	$\lvert\bar{A}_0\rvert$ < [10^{-45}]	$\lvert\bar{A}_0\rvert$ > [10^{-45}]	Q_{GR} [%]	$\lvert\bar{A}_{0.5}\rvert$ < [10^{-38}]	$\lvert\bar{A}_{0.5}\rvert$ > [10^{-38}]	Q_{GR} [%]	$\lvert\bar{A}_1\rvert$ < [10^{-32}]	$\lvert\bar{A}_1\rvert$ > [10^{-32}]	Q_{GR} [%]	$\lvert\bar{A}_{1.5}\rvert$ < [10^{-26}]	$\lvert\bar{A}_{1.5}\rvert$ > [10^{-26}]	Q_{GR} [%]	$\lvert\bar{A}_{2.5}\rvert$ < [10^{-14}]	$\lvert\bar{A}_{2.5}\rvert$ > [10^{-14}]	Q_{GR} [%]	$\lvert\bar{A}_3\rvert$ < [10^{-8}]	$\lvert\bar{A}_3\rvert$ > [10^{-8}]	Q_{GR} [%]	$\lvert\bar{A}_{3.5}\rvert$ < [10^{-2}]	$\lvert\bar{A}_{3.5}\rvert$ > [10^{-2}]	Q_{GR} [%]	$\lvert\bar{A}_4\rvert$ < [10^{4}]	$\lvert\bar{A}_4\rvert$ > [10^{4}]	Q_{GR} [%]
GWTC-1	4.70	7.99	3.39	79	1.17	0.70	73	2.51	1.21	70	6.96	3.70	86	5.05	8.01	28	2.94	3.66	25	2.01	3.73	35	1.44	2.34	34
GWTC-2	1.76	1.75	1.37	66	0.46	0.28	66	1.00	0.52	79	3.35	1.47	83	1.74	2.43	31	1.08	2.17	17	0.76	1.57	12	0.64	0.88	25

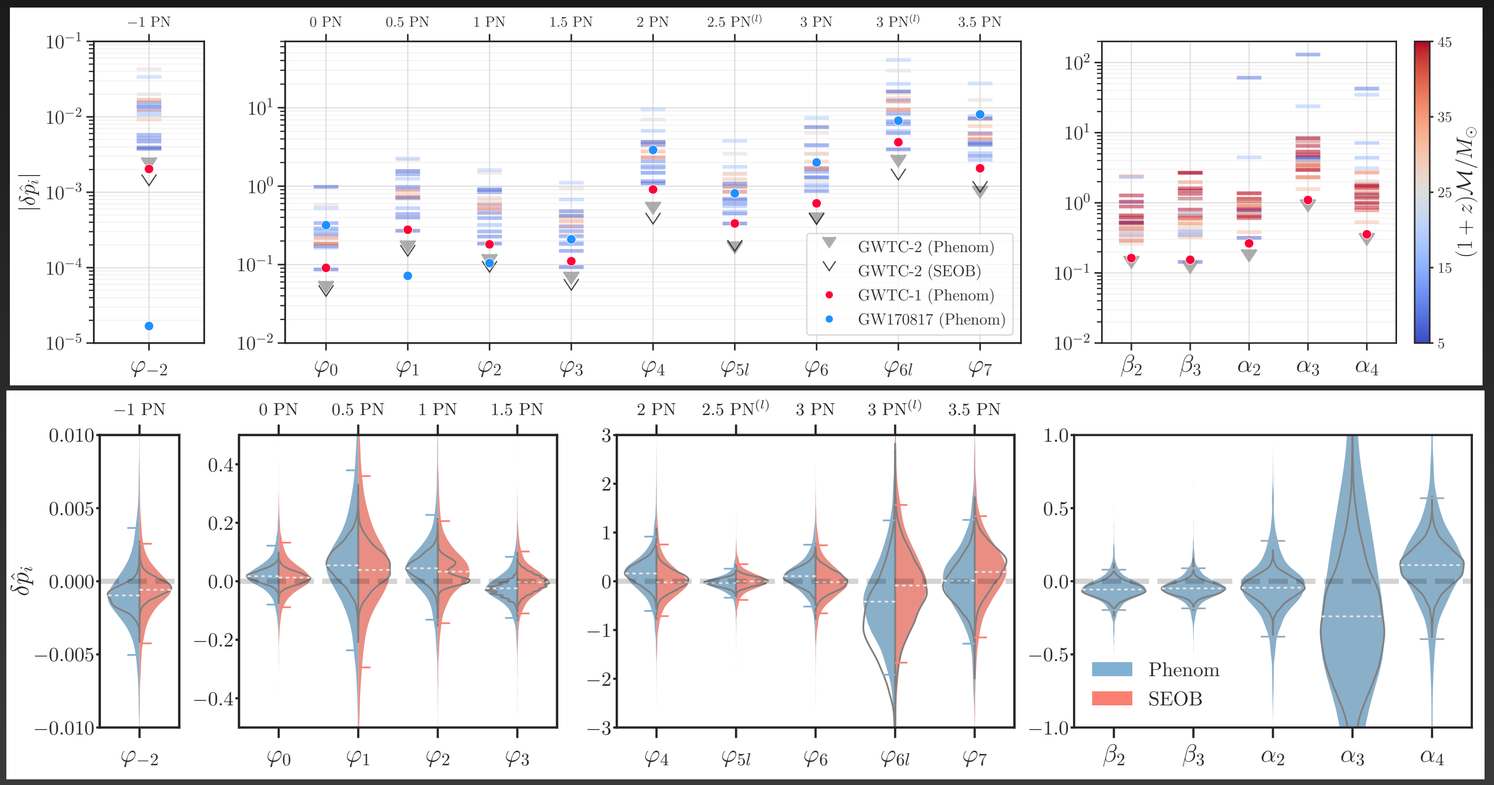
GW150914: Parameterized tests of GR

- Phase evolution of the binary is dictated by GR
- Violation of GR would modify **inspiral** dynamics
- Allow for parameterized violations of GR and constrain

[LVC PRL 116, 221101 (2016)]



LVC PRD **103**, 122002 (2021) [arXiv:2010.14529]



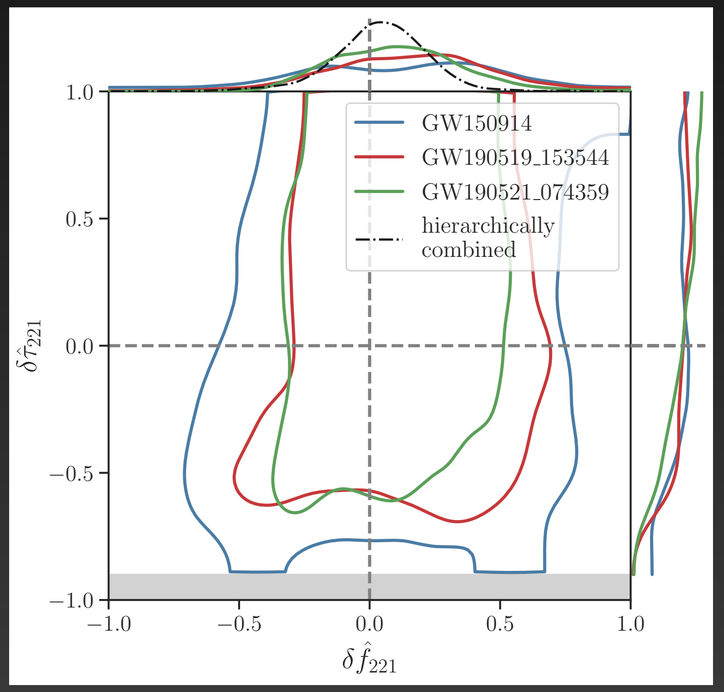
Arun+ [PRD 74, 024006 (2006)]
Yunes+ [PRD 80, 122003 (2009)]
Li, MA+ [PRD 85, 082003 (2012)]
MA+ [PRD 89, 082001 (2014)]
Meidam, MA+ [PRD 97, 044033 (2018)

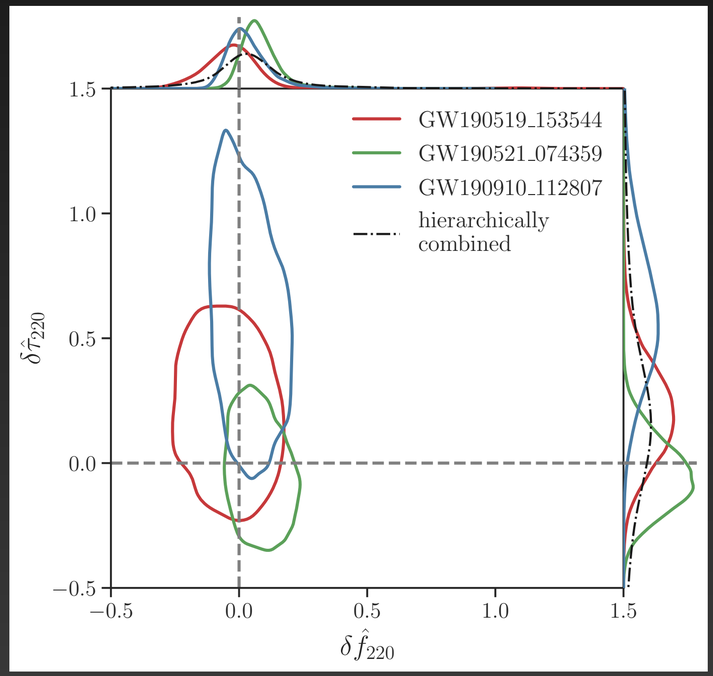
Ringdown analysis

Testing the no-hair theorem

$$f_{lmn} = f^{GR}_{lmn}(M, J)(1 + \delta\hat{f}_{lmn})$$

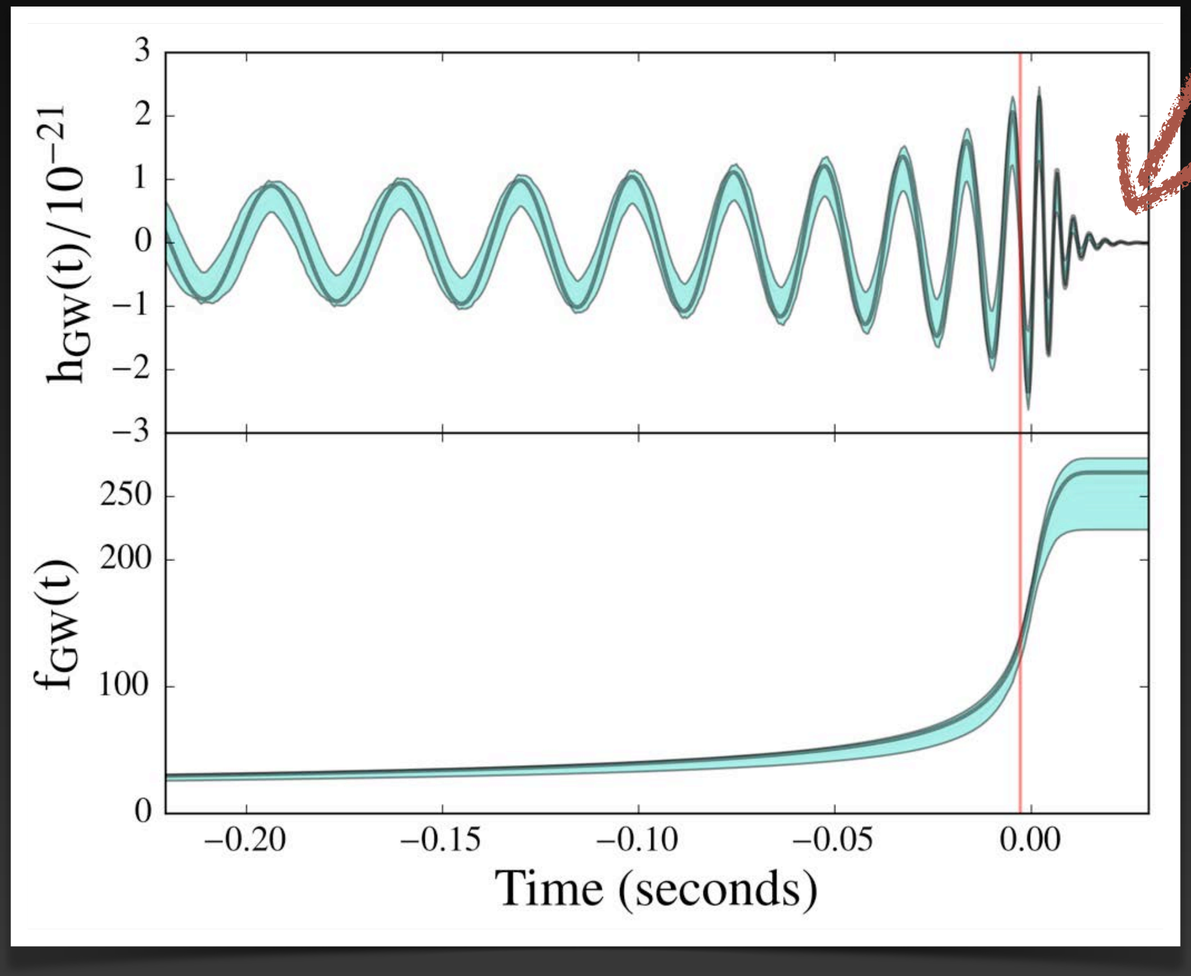
$$\tau_{lmn} = \tau^{GR}_{lmn}(M, J)(1 + \delta\hat{\tau}_{lmn})$$





Is there anything beyond ringdown?

Searching for Exotic Compact Objects



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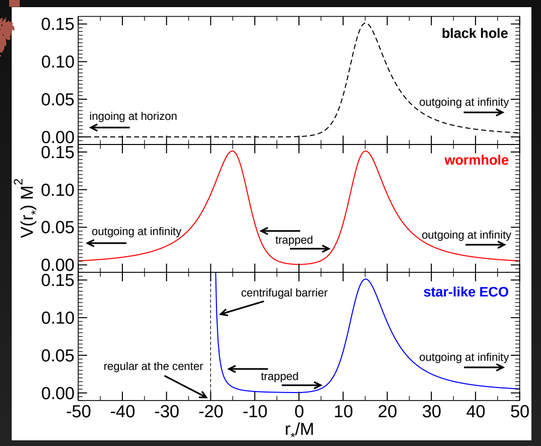
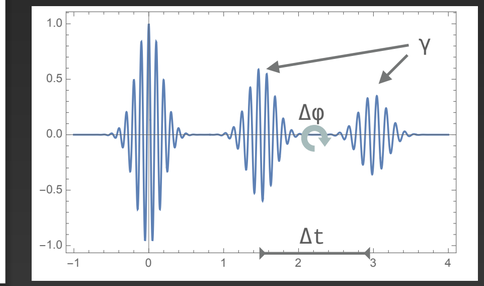


[Cardoso+ 2017]
[Tsang, MA+ arXiv:1804.04877]
[Tsang, MA+ arXiv:1906.11168]
[Lo+ arXiv:1811.07431]



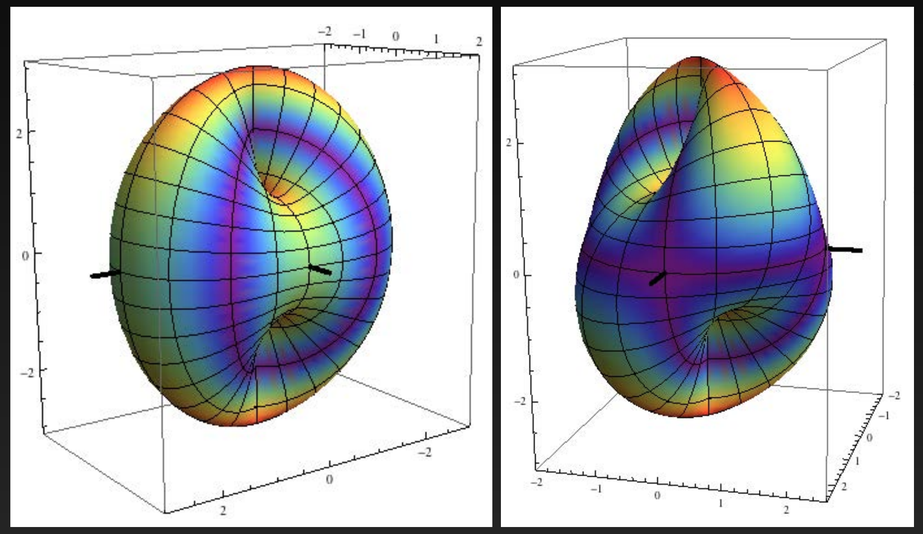
LVC PRD **103**, 122002 (2021)
[arXiv:2010.14529]

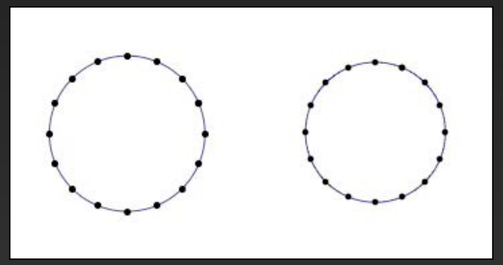
Event	$\log_{10}\mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$	Event	$\log_{10}\mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		

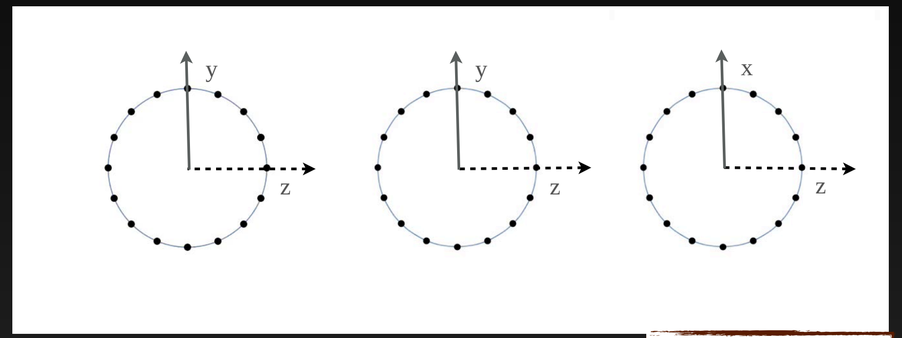
GW Polarizations

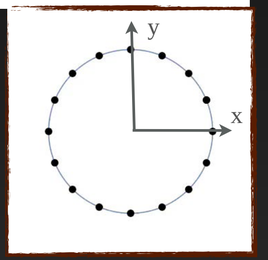
GR

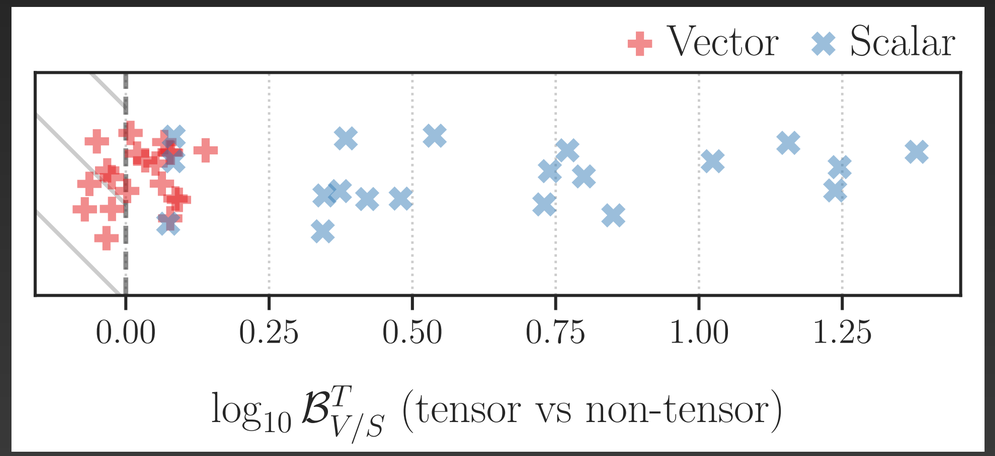
non-GR











LVC PRD **103**, 122002 (2021)
[arXiv:2010.14529]

GW170817

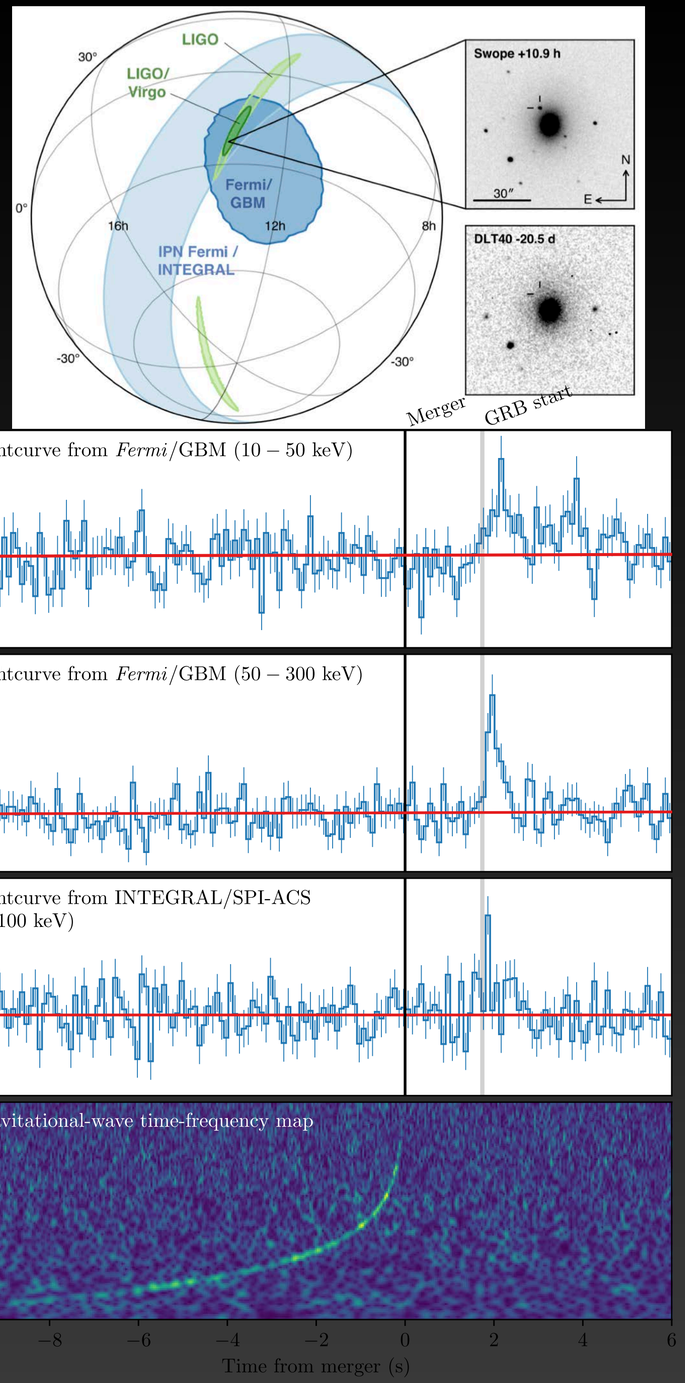
- Speed of gravity VS speed of light!

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

- Shapiro time delays

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3} \int_{r_{\mathrm{e}}}^{r_{\mathrm{o}}} U(\boldsymbol{r}(l))\, dl$$

$$-2.6 \times 10^{-7} \leqslant \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leqslant 1.2 \times 10^{-6}$$



But wait, there's more!

GW190521

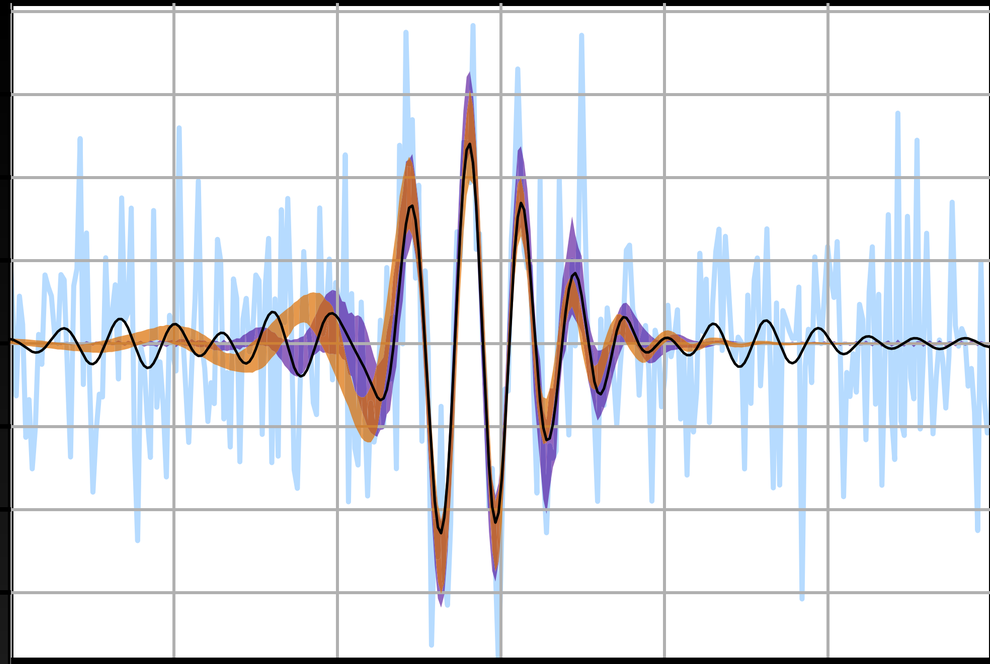
So massive...

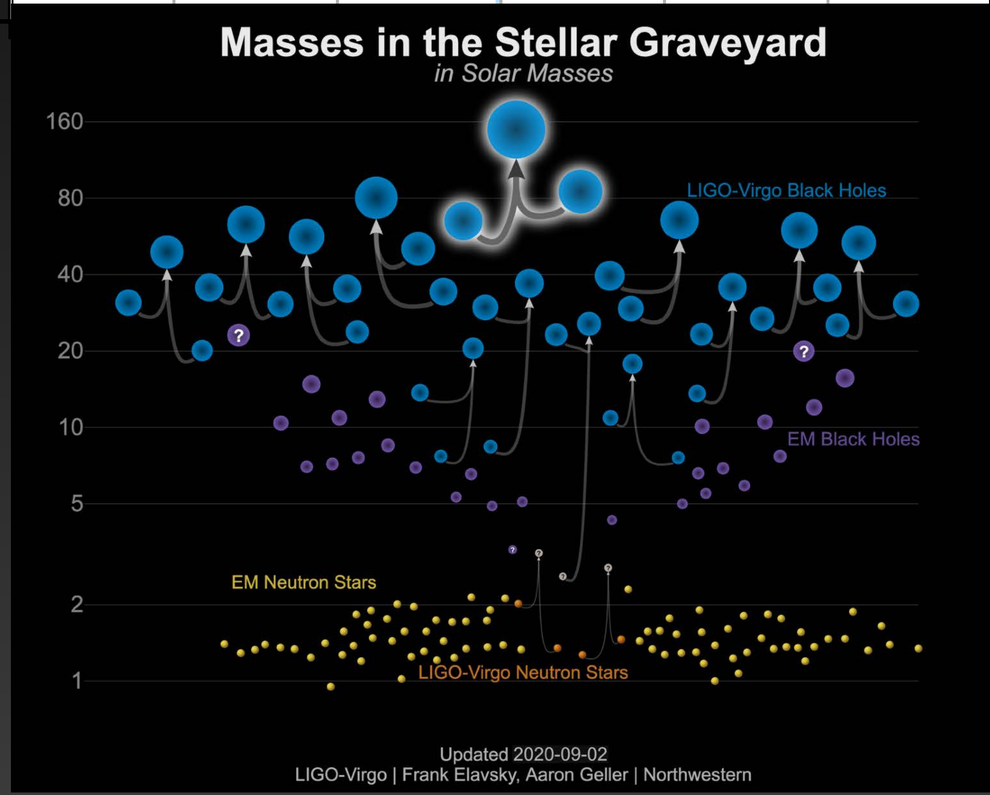
- Component masses at

$$m_1 = 85^{+21}_{-14} M_\odot \, , \, m_2 = 66^{+17}_{-18} M_\odot$$

- Not supposed to be there (pair-instability)

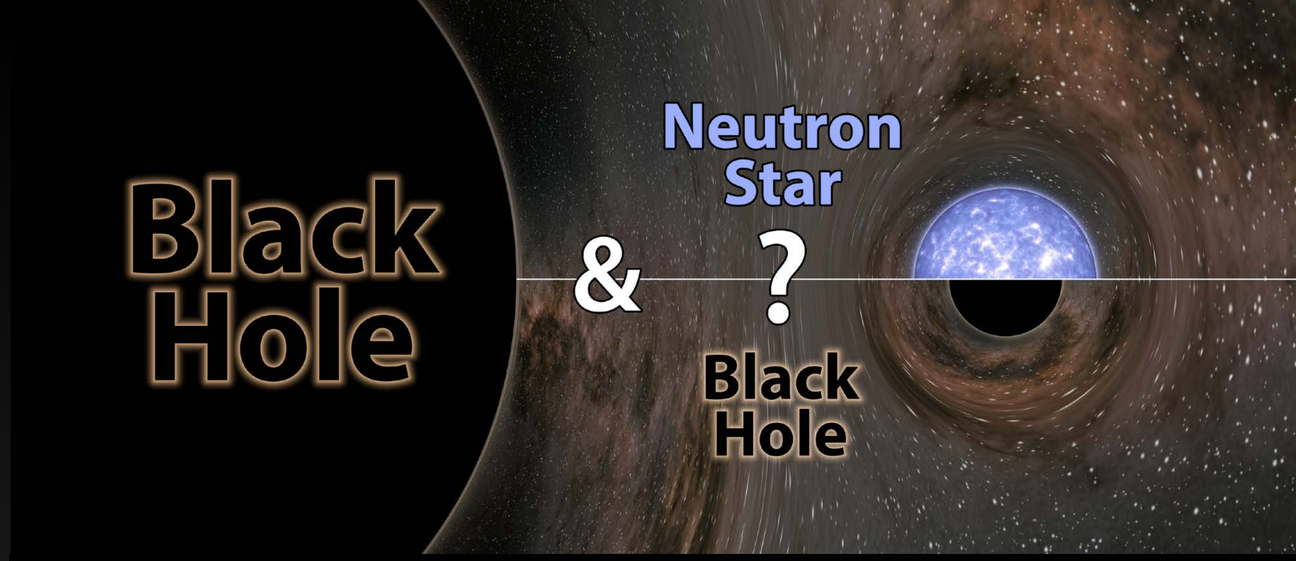
- Is it really what we think it is?

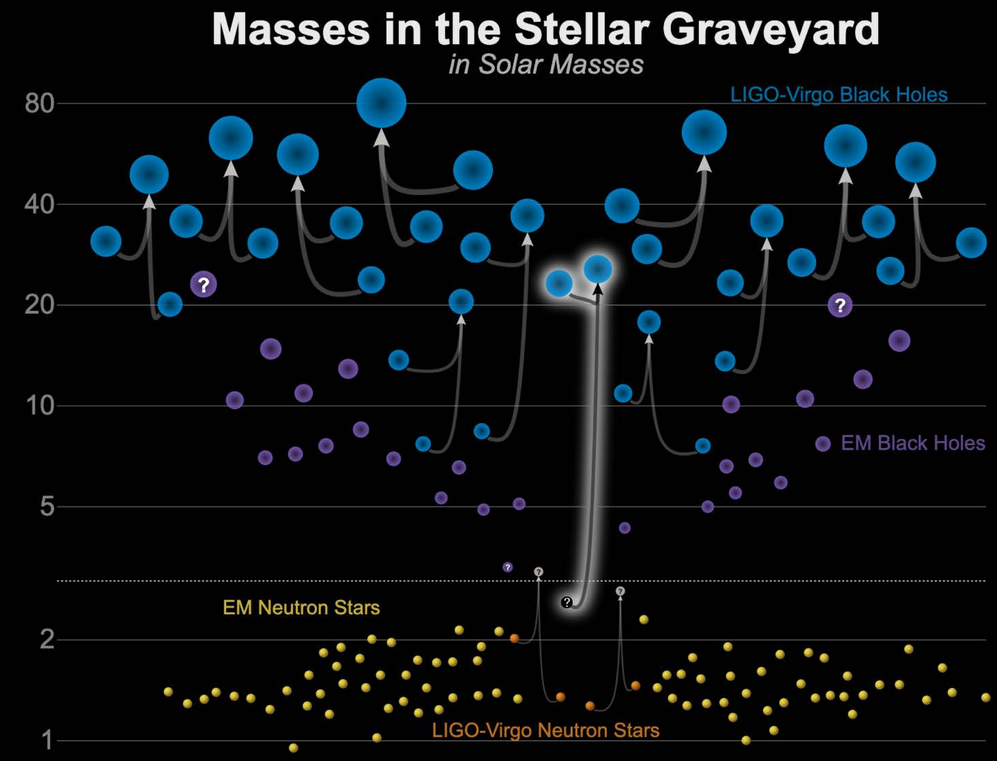




GW190814
What is it?

- High mass-ratio binary
- Secondary mass at $\sim 3 - 5\, M_\odot$





Can’t wait for O4!

...and O3b

...and Einstein Telescope

...and Cosmic Explorer

...and LISA

...