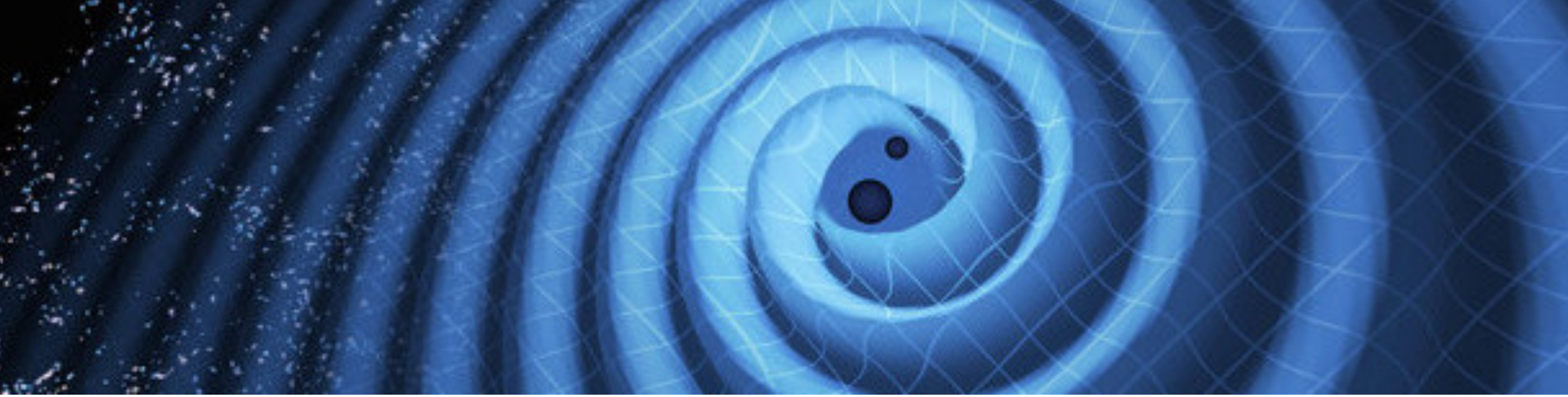


FUNDAMENTAL PHYSICS WITH GRAVITATIONAL WAVES

B.S. SATHYAPRAKASH

Penn State and Cardiff University

Credits: GWIC 3G Science Case Committee and Science Case Consortium

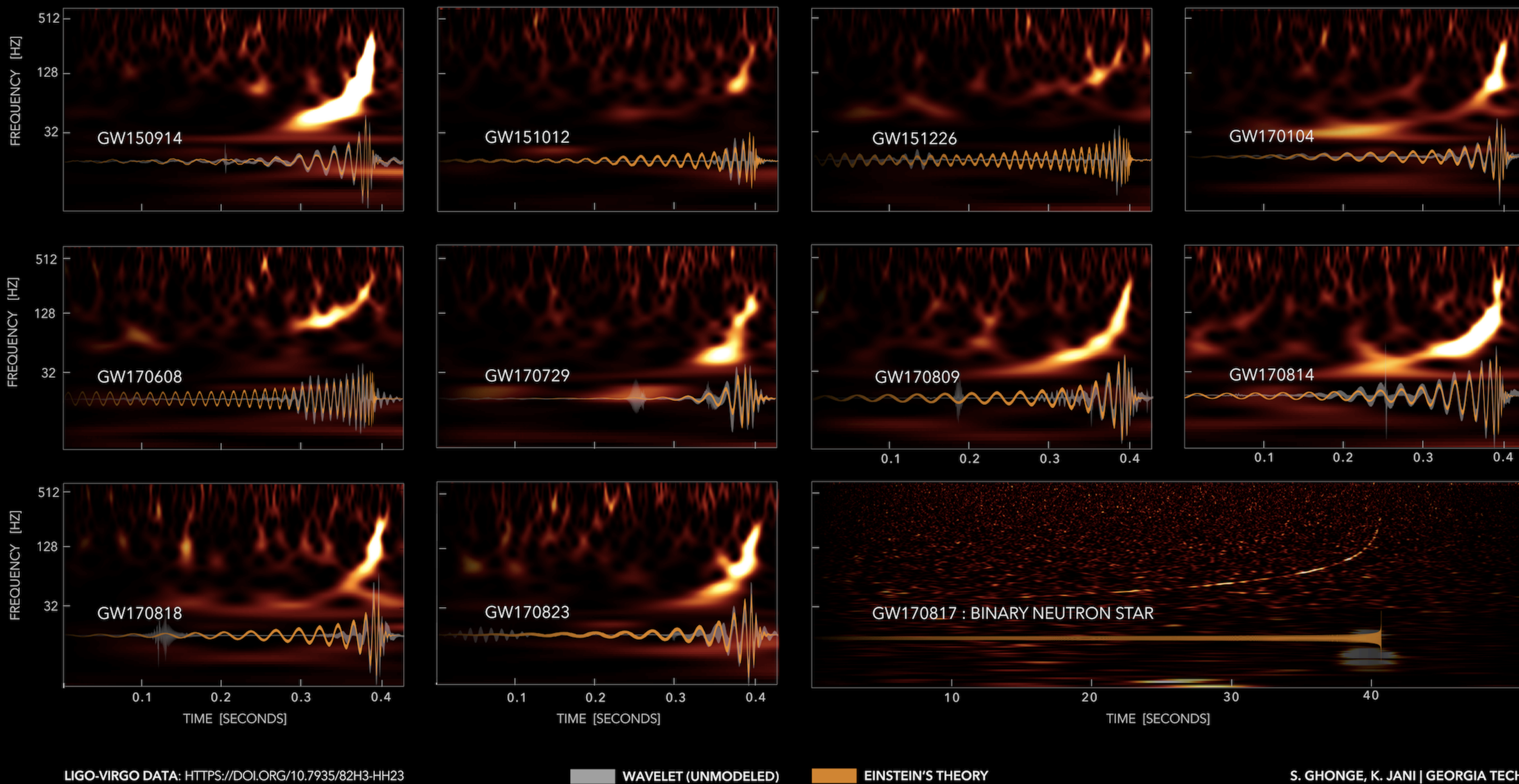
PennState

European Strategy Update

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

LIGO-VIRGO DISCOVERIES:

A NEW ERA IN FUNDAMENTAL PHYSICS, ASTROPHYSICS AND COSMOLOGY



PUBLIC ALERTS IN THE 3RD OBSERVING RUN

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 14 May 2019 07:44:56 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

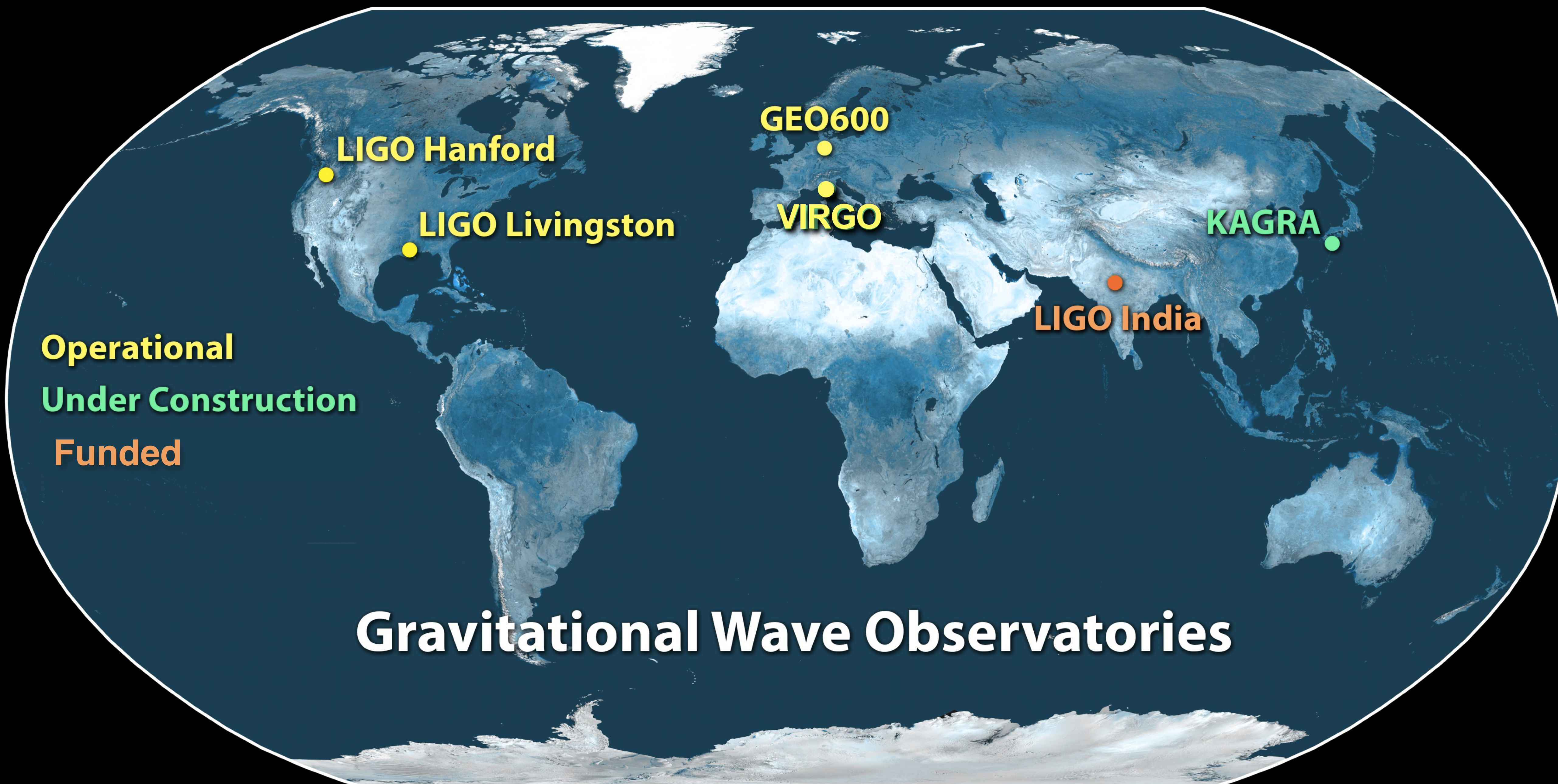
Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

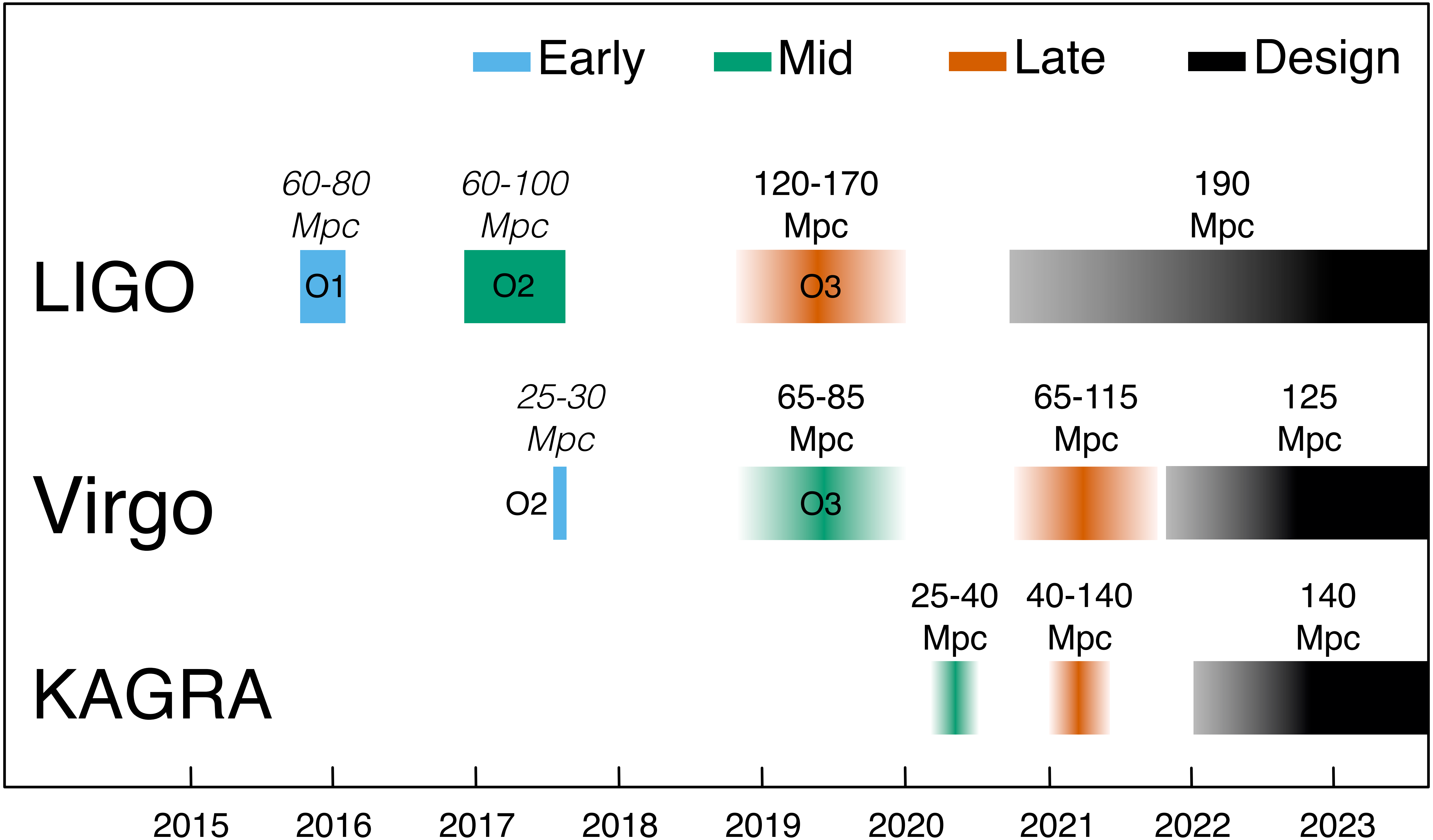
LIGO VIRGO LSC

LASER INTERFEROMETER GRAVITATIONAL WAVE DETECTORS



Credit: LVC/EPO

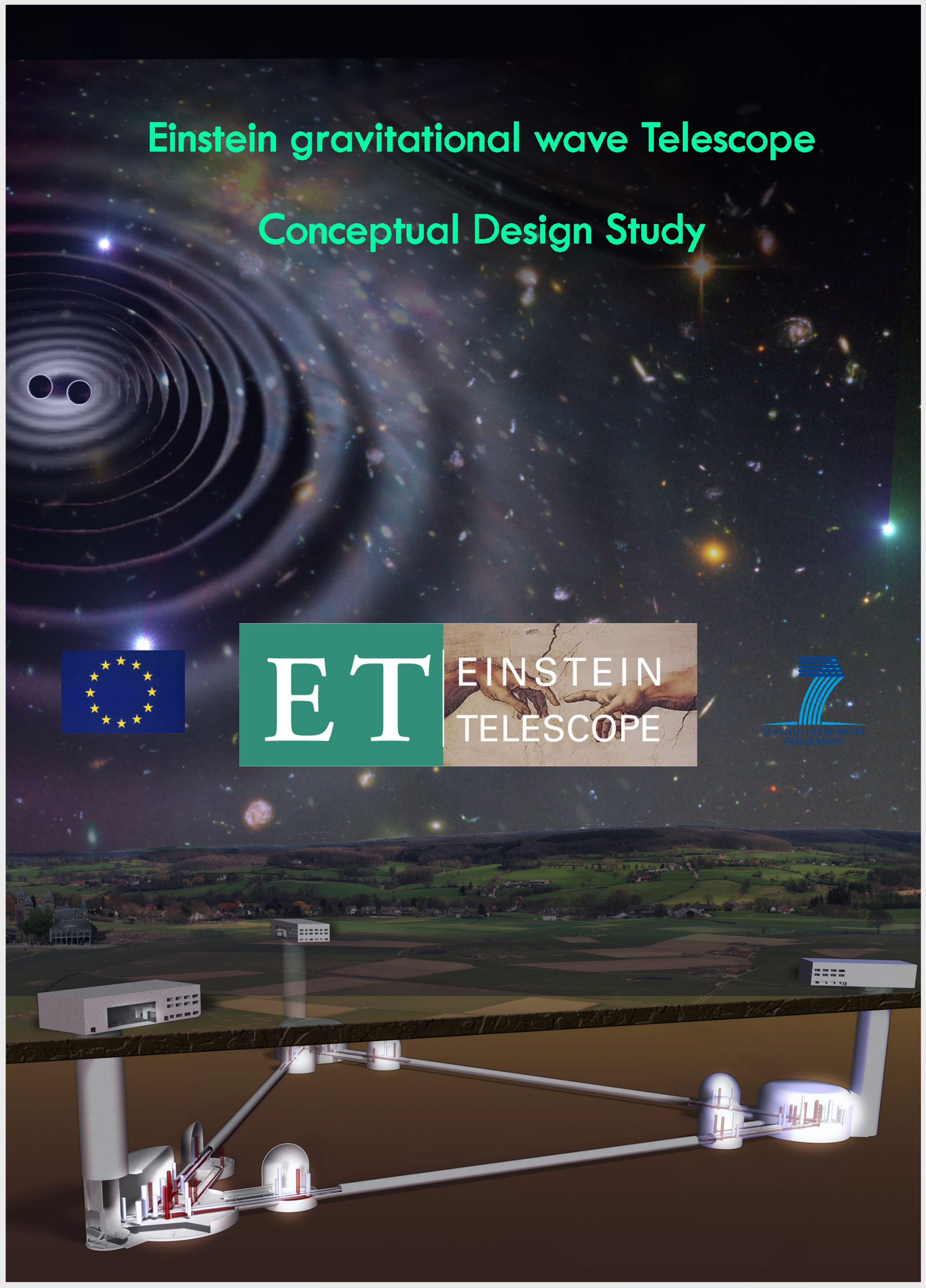
UPCOMING RUNS AND SENSITIVITIES



Abbott+, Living Rev. Relativity (2018) 21:3

EINSTEIN TELESCOPE

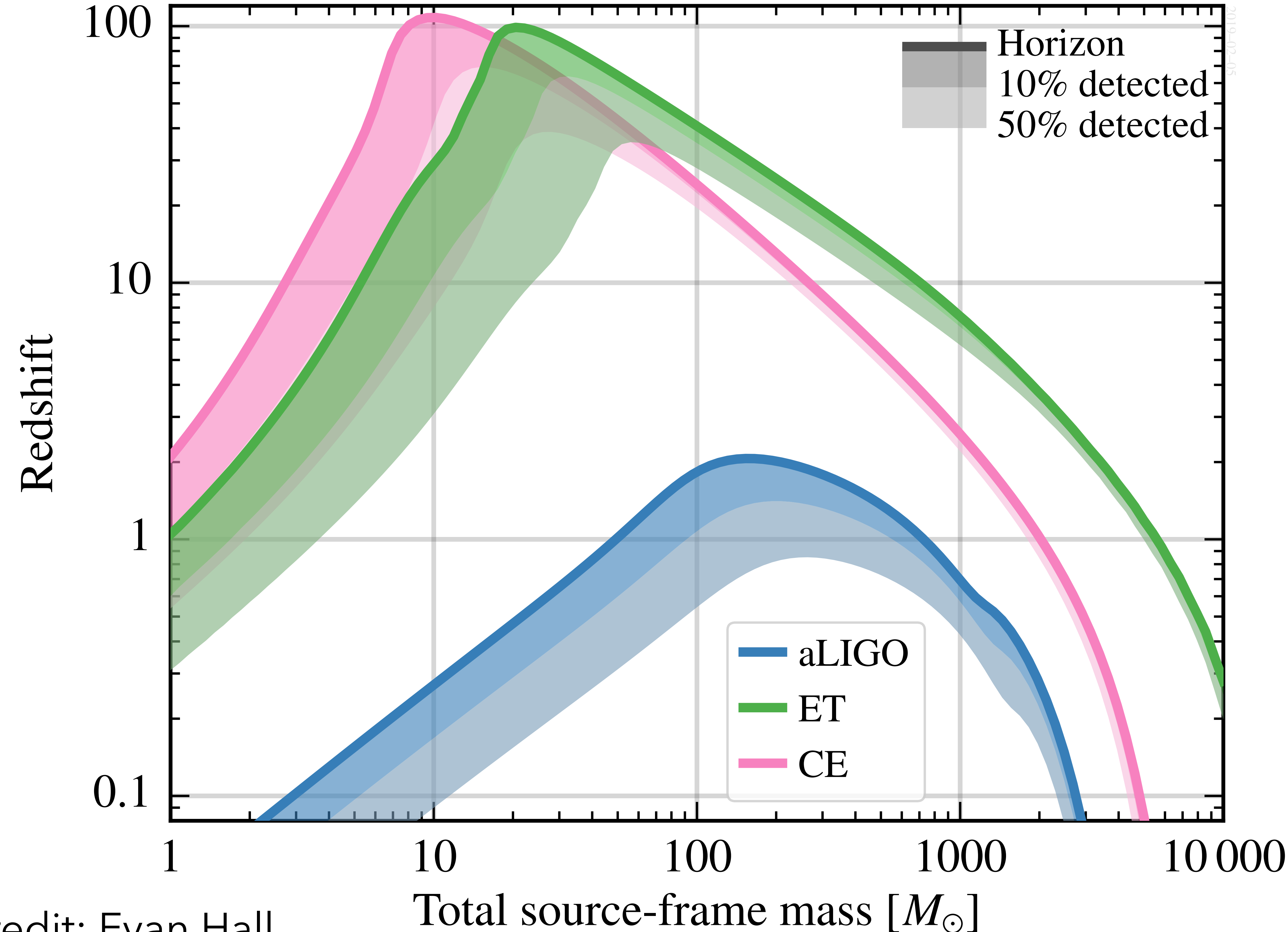
- FP7 conceptual design study
  - underground, 10-km side triangle
  - design study completed in ’11
- clearly defined project
  - roadmap presented to APPEC, ET collaboration formed ’19, enter ESFRI Roadmap in ’20, site selection in ’22, technical design ’23, construction ’25-’31, commission ’31+
- ET needs CERN
  - underground infrastructure, cryogenics, vacuum, material and surface science, electronics and data acquisition, computing



COSMIC EXPLORER

- 40 km ground-based interferometer
  - NSF funded design study: 2018-2021
- GWIC-3G Study
  - a network of three detectors is essential for achieving science goals
  - ET in Europe, Cosmic Explorer in the US and Australia

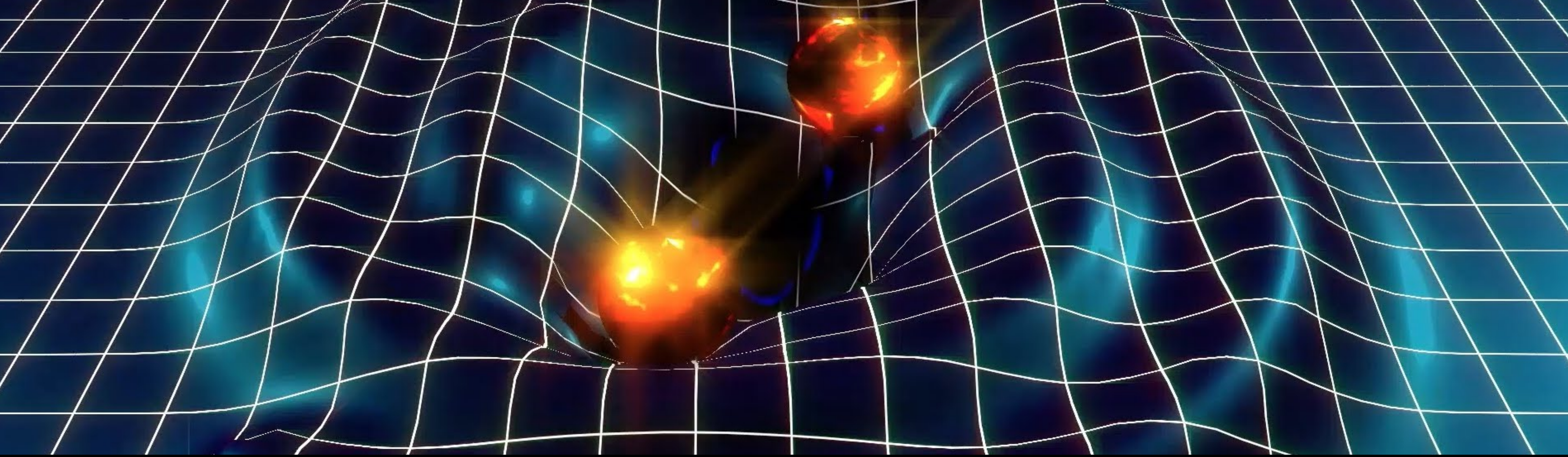
3G NETWORK SENSITIVITY



Credit: Evan Hall

EXPLORE FUNDAMENTAL PROPERTIES OF SPACETIME AND MATTER

- strong field tests of general relativity
  - binary black hole orbital dynamics
- testing the black hole hypothesis of LIGO's detections
  - BH no-hair theorem, horizon structure, echoes, …
- equation of state of dense nuclear matter
  - size of neutron stars; are there phase transitions beyond nucleons
- standard siren cosmology
  - Hubble parameter, dark energy equation of state and its variation with z
- new fields and novel compact objects
  - ultra-light bosonic fields, axions, boson stars, extremely compact objects
- primordial stochastic backgrounds
  - early universe phase transitions, cosmic strings, etc.



EXTREME GRAVITY AND THE NATURE OF SPACETIME

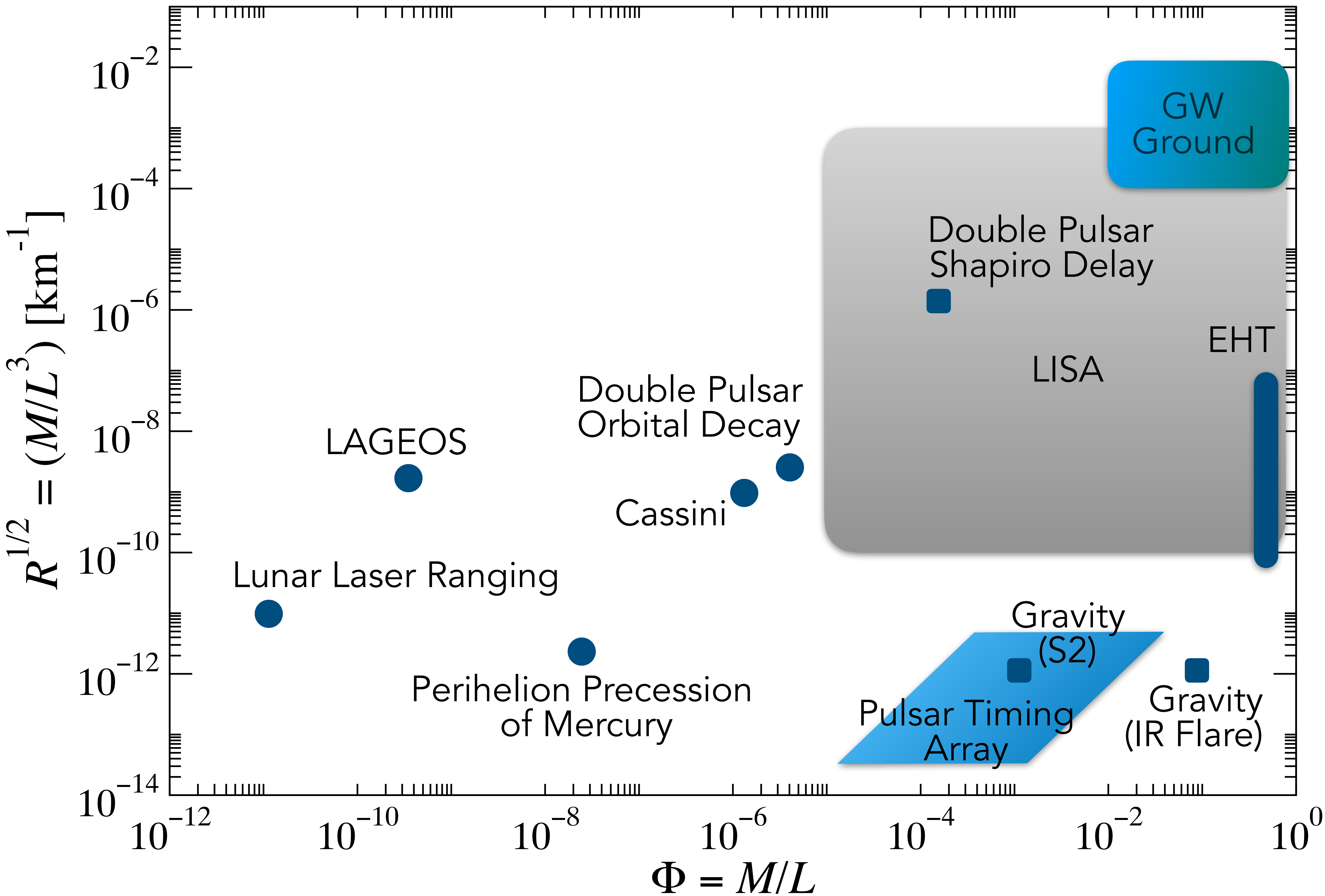
WHY TEST GENERAL RELATIVITY

- so far GR has passed all experimental and observational tests
  - solar system tests, binary pulsars, black hole orbital dynamics, …
- but theoretical and observational problems exist
  - generic prediction of singularity, black hole information loss, accelerated expansion of the Universe, non-detection of dark matter, …
- GR is violated in quantum gravity theories
  - birefringence of gravitational waves in Chern-Simons theory
  - violation of Lorentz invariance in Loop quantum gravity
  - Planck-scale structure of black hole horizons

BINARY BLACK HOLES AS TESTBEDS OF GENERAL RELATIVITY

$$G_{\mu\nu} = \frac{1}{\kappa} T_{\mu\nu}, \quad \kappa = \frac{c^4}{8\pi G} \sim 5 \times 10^{49}\,\mathrm{dynes}$$

$$L \sim \frac{32\eta^2 c^5}{5G}\left(\frac{v}{c}\right)^{10}, \quad \eta = \frac{m_1 m_2}{(m_1+m_2)^2}, \quad \frac{2c^5}{5G} \simeq 10^{59}\,\mathrm{erg\,s^{-1}}$$



Credit: Nico Yunes

TYPES OF TESTS

- null tests of GR
  - assume that GR is correct and look for small deviations from GR
    - e.g. search for tails of gravitational waves
- tests of modified theories of gravity
  - modified phase evolution or propagation
  - could potentially arise from a modified gravity theories
    - e.g. massive graviton, dipole radiation, scalar modes, Lorentz violation…

3G network will test general relativity in regions of greatest curvature and surface gravity of any experiment

TESTS OF GRAVITATIONAL WAVE PROPAGATION

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

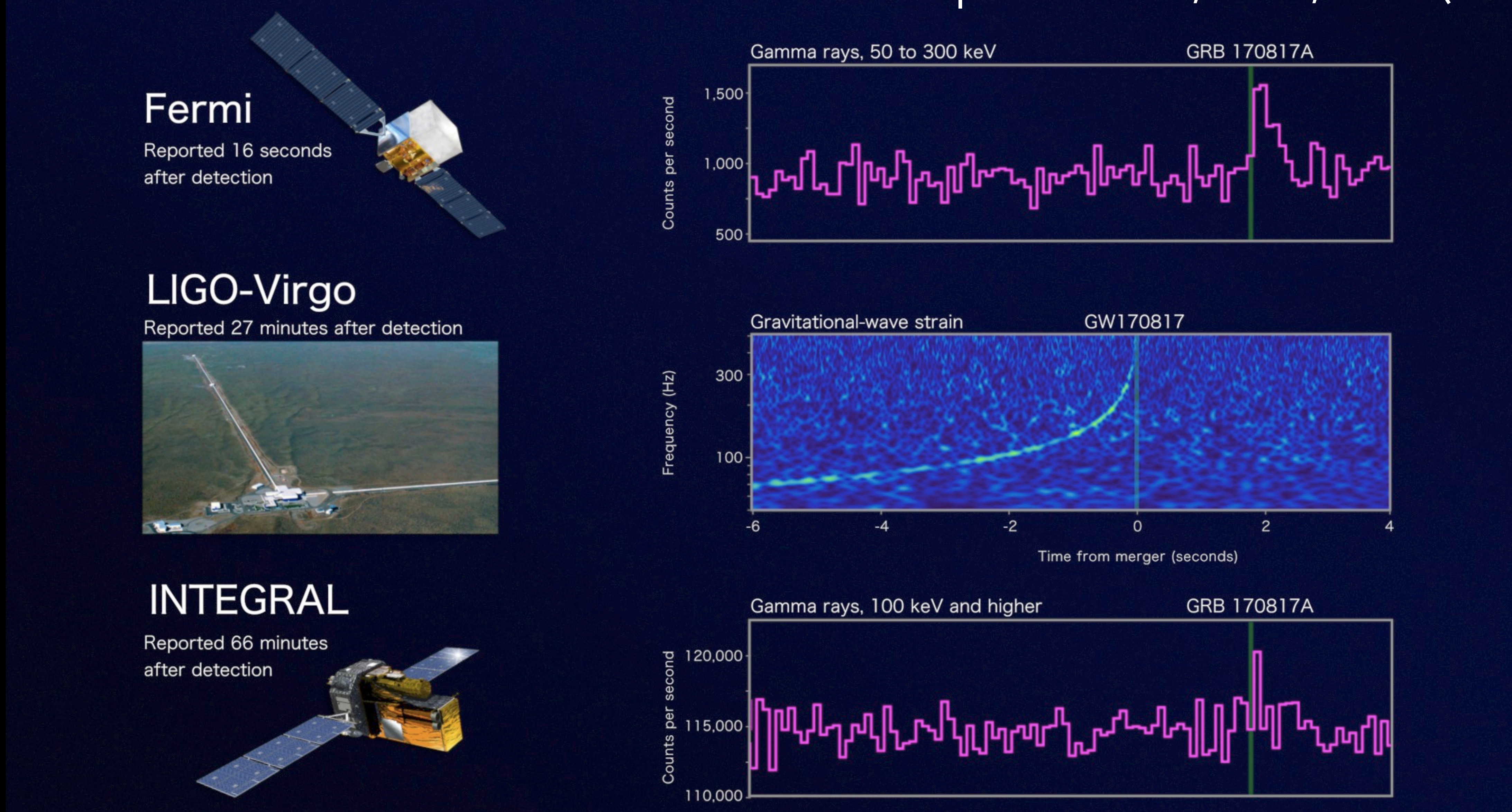
- modified theories of gravity predict dispersion
- dispersion modifies the phase and frequency
- best constraints in the gravity sector for superluminal gravitational waves
  - **GW170104 bound on graviton mass:**
- **$m_g < 7.7 \times 10^{-23}$ eV**

Abbott+ PRL, 118, 221101 (2017)

3G network will observe sources @ z~20 and improve limit on graviton mass by three orders of magnitude

SPEED OF GRAVITATIONAL WAVES FROM GW170817 AND GRB170817A

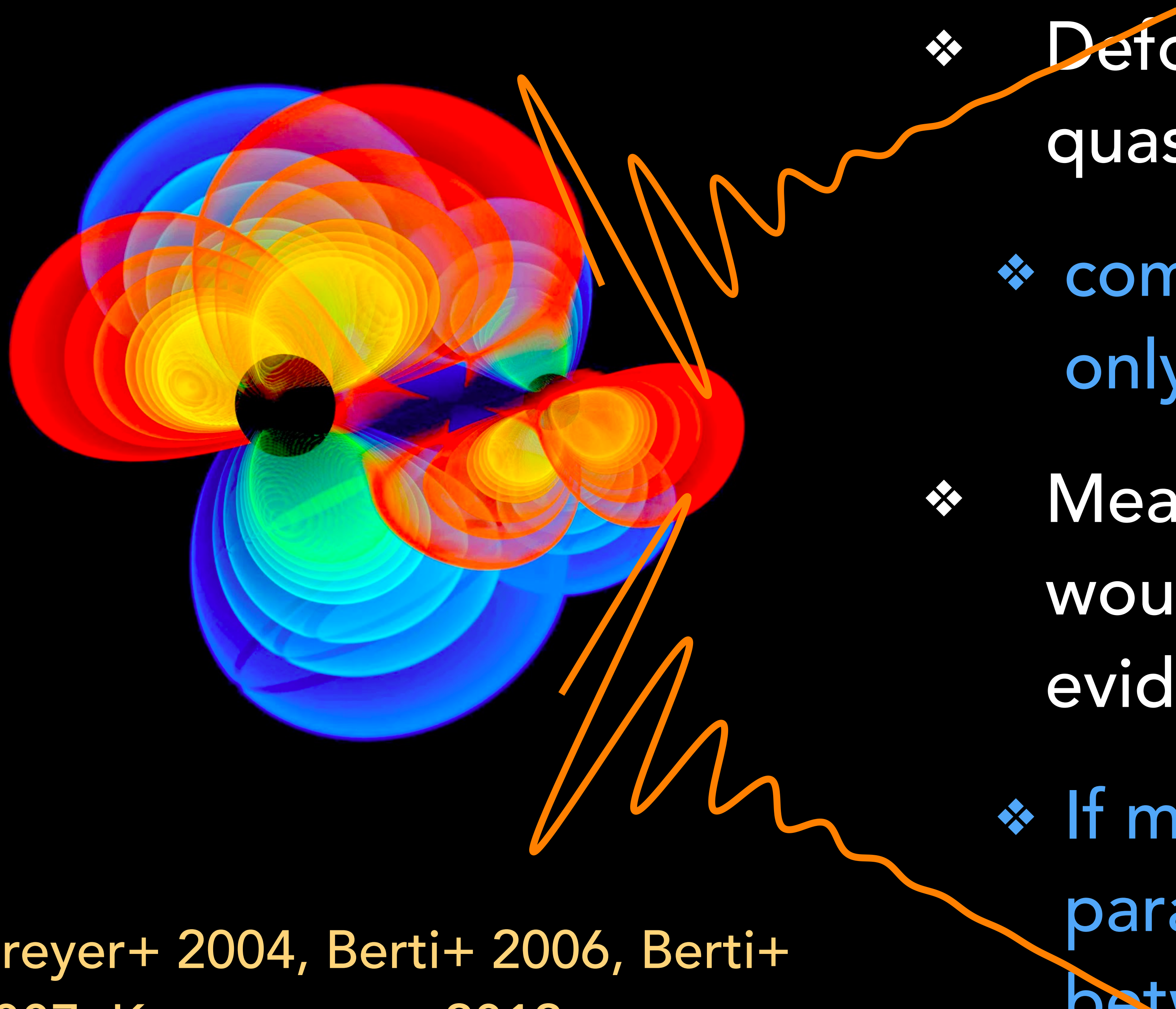
Abbott+ ApJ Letters, 848, L12 (2017)



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

3G network will improve this limit by three orders of magnitude

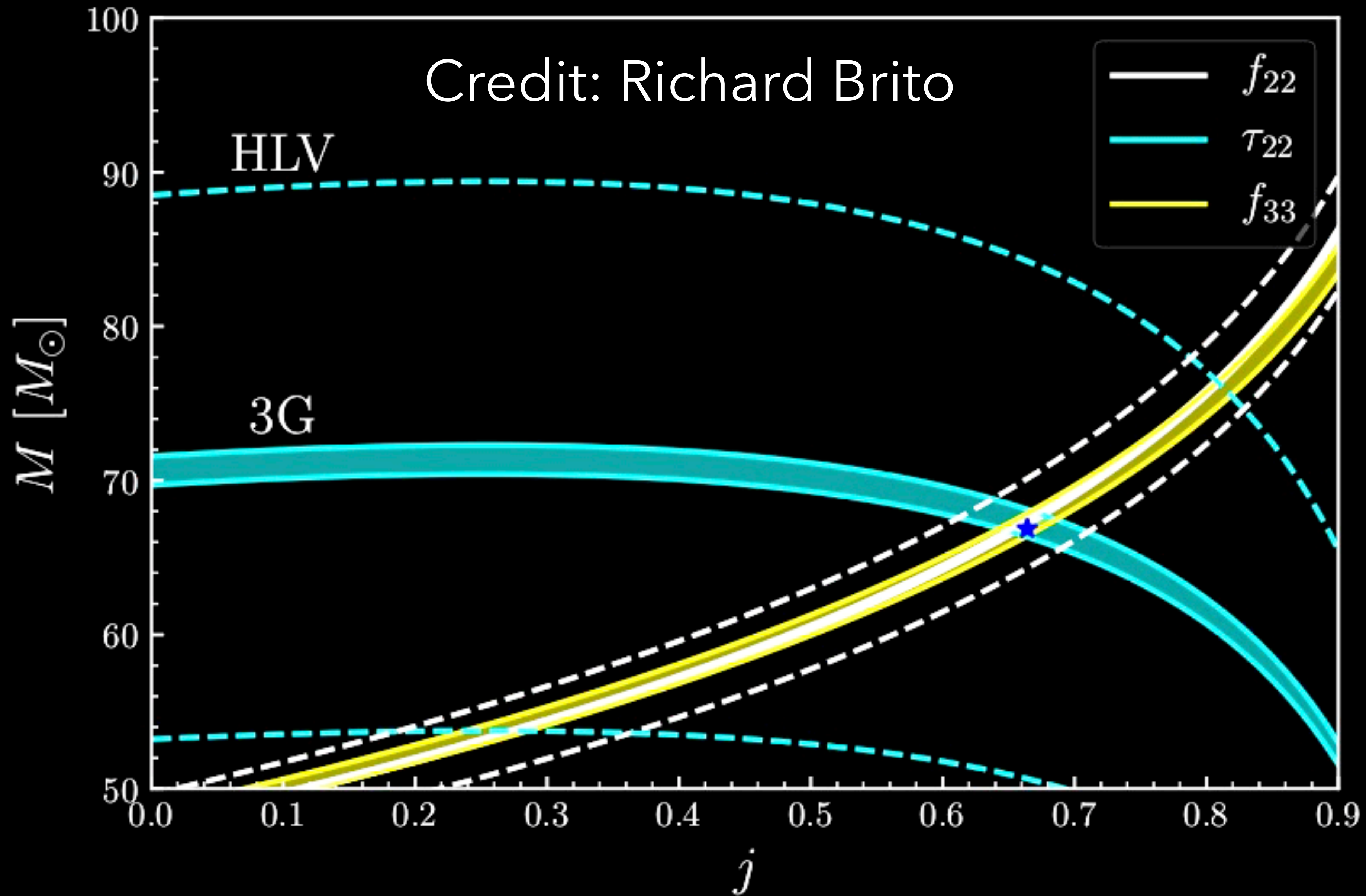
QUASI-NORMAL MODES AND NO-HAIR TESTS



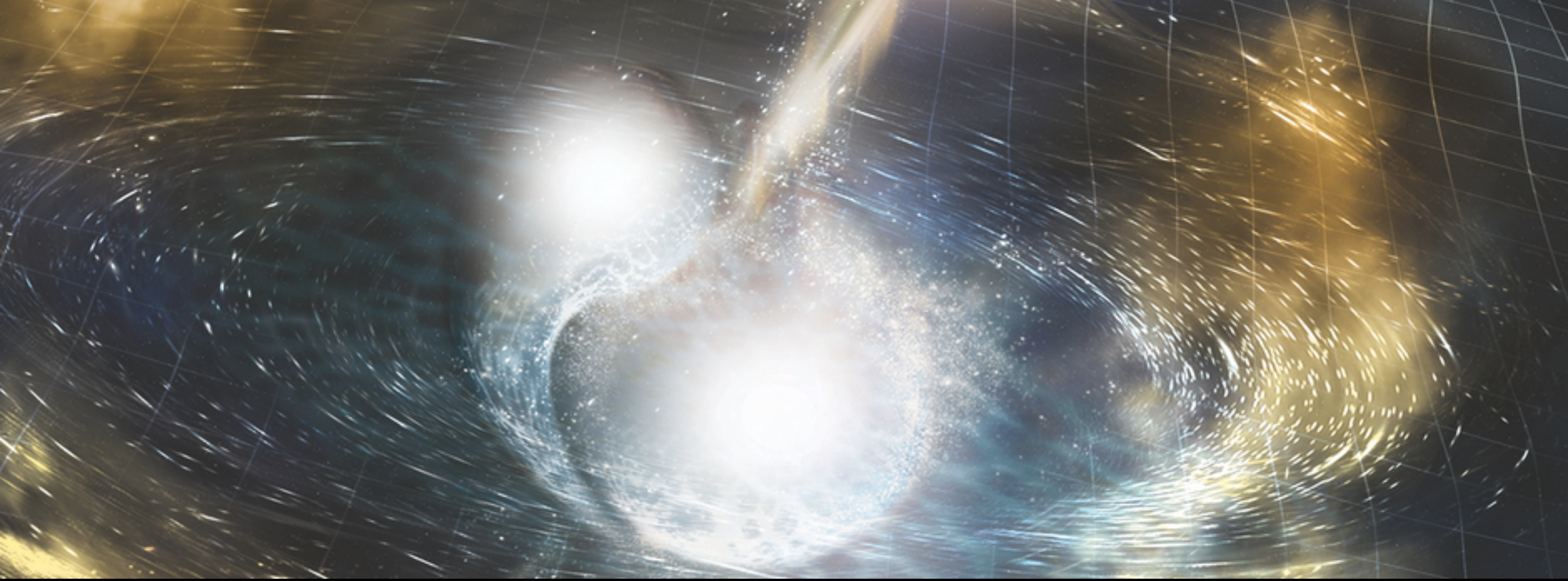
- Deformed black holes emit quasi-normal modes
    - complex frequencies depend only on the mass and spin
- Measuring two or modes would provide a smoking gun evidence of Kerr black holes
    - If modes depend on other parameters, consistency between different mode frequencies would fail

Dreyer+ 2004, Berti+ 2006, Berti+ 2007, Kamaretsos+ 2012, Gossan+2012, Bhagwat+ 2017, Brito+ 2018

TESTING THE NO-HAIR THEOREM WITH 3G NETWORK

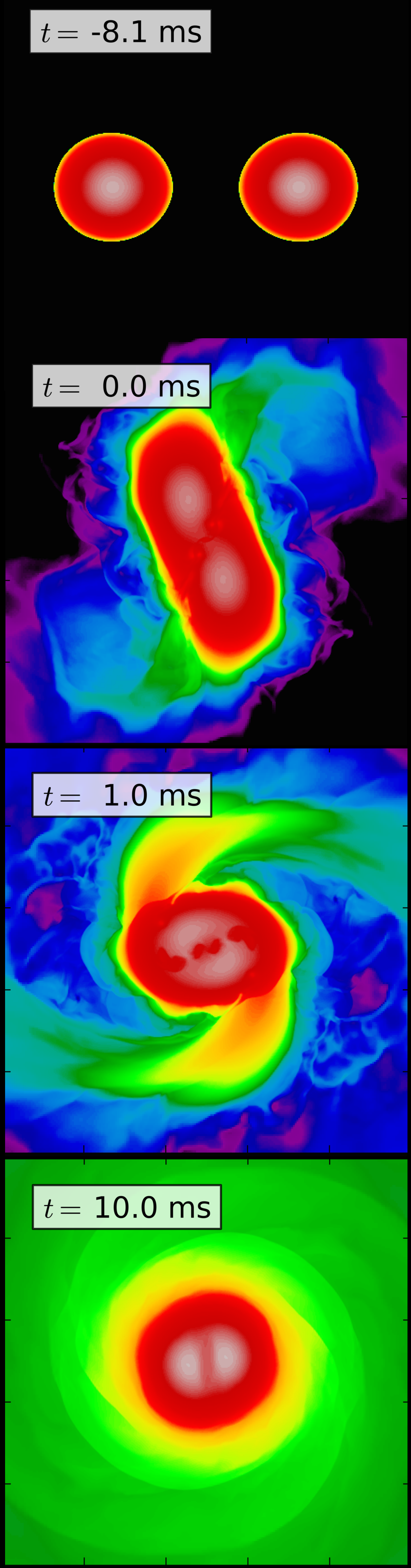


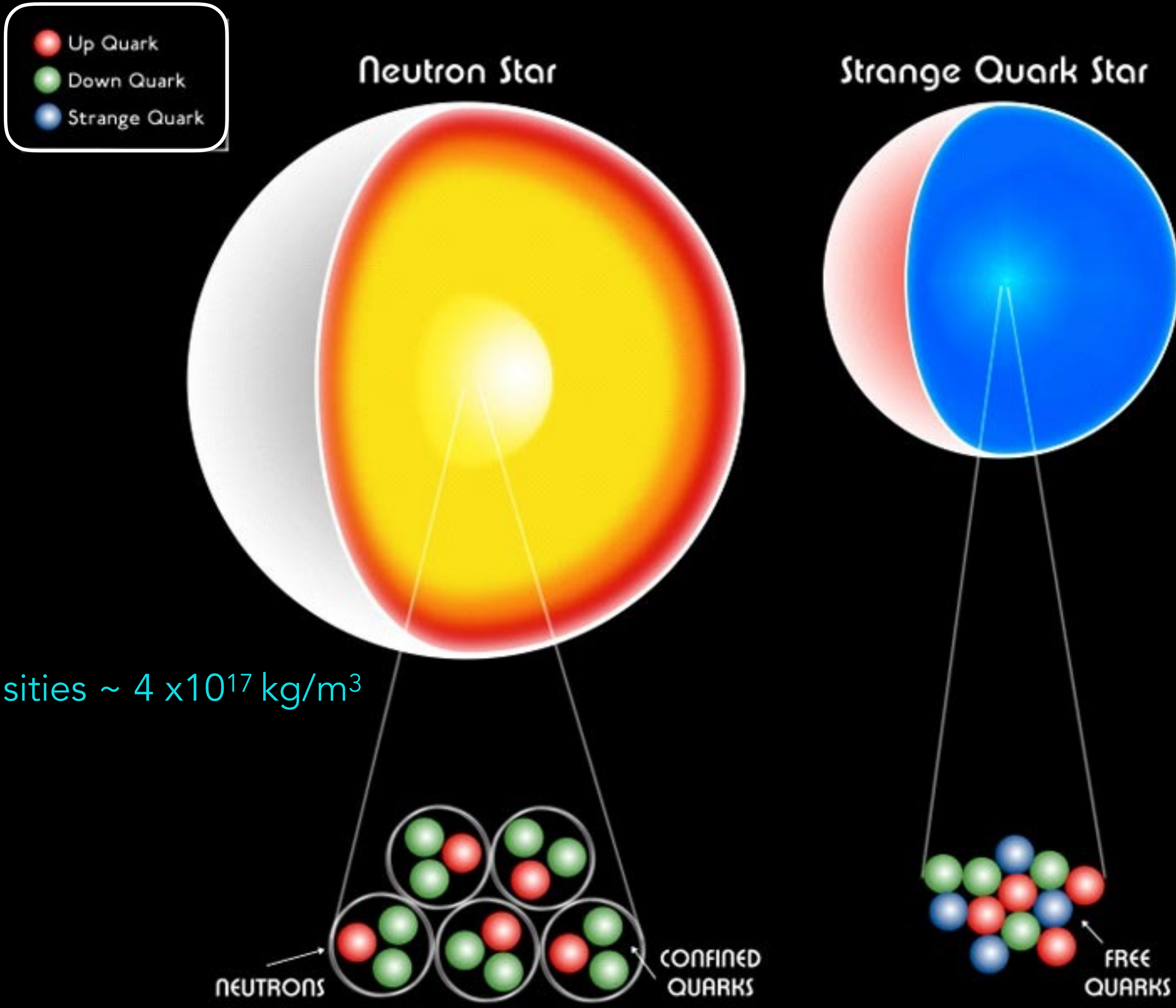
3G network is critical for unambiguous proof of the existence black holes and to explore structure of horizons



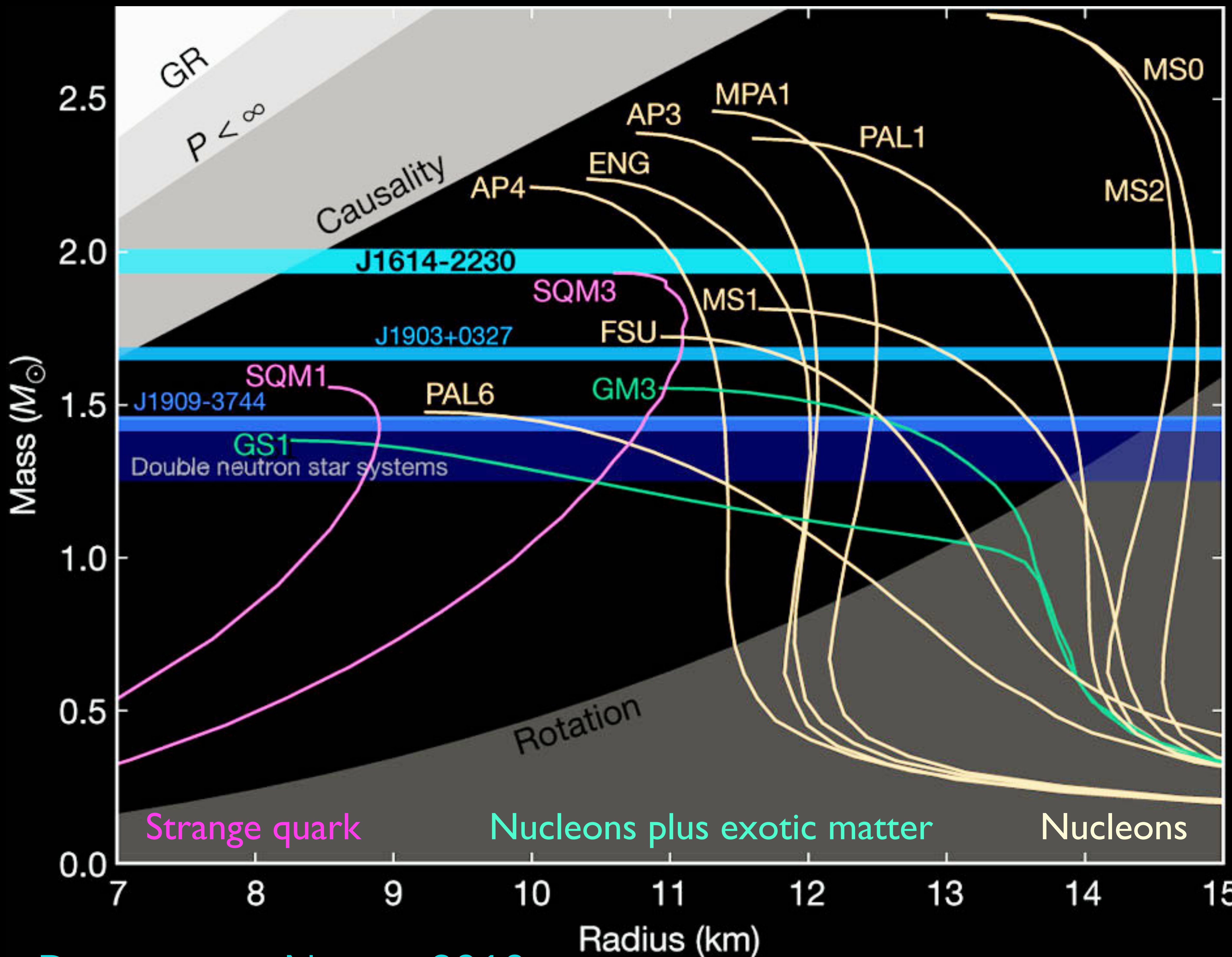
EXTREME MATTER IN EXTREME ENVIRONS

EQUATION OF STATE OF DENSE NUCLEAR MATTER



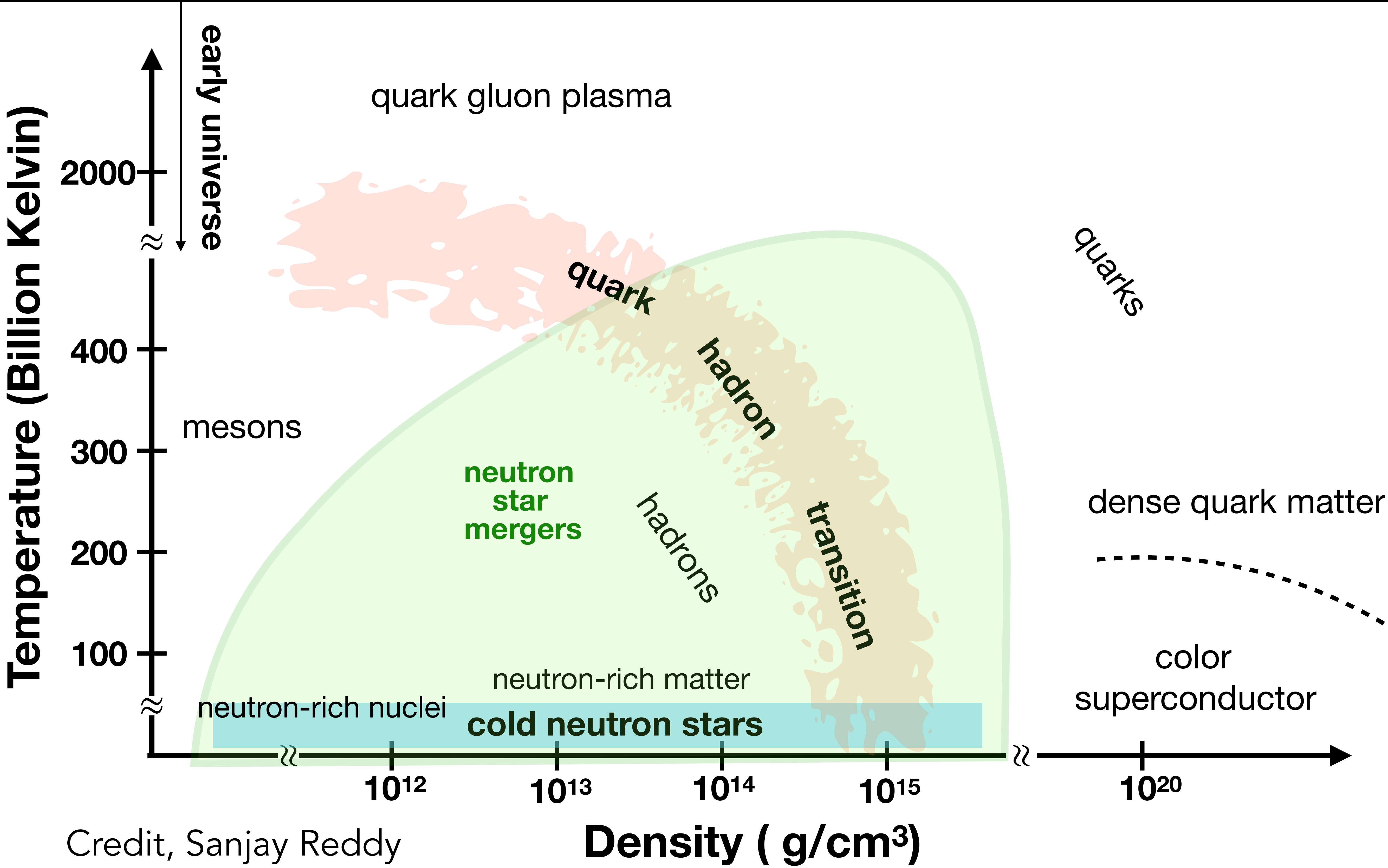


Densities ~ 4 x10^{17} kg/m^3



Demorest+, Nature 2010

NEUTRON STARS IN THE QCD PHASE DIAGRAM

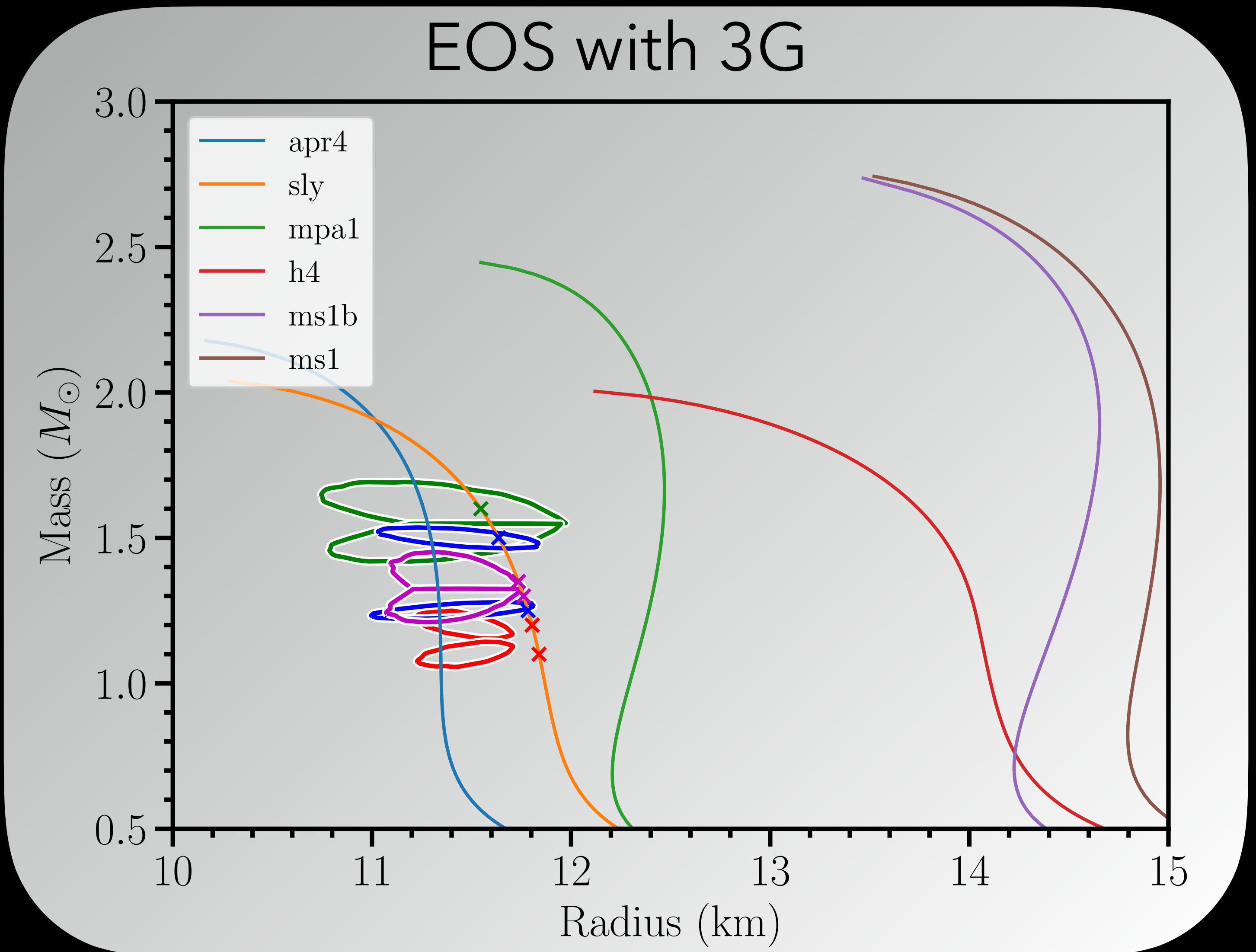


Credit, Sanjay Reddy

MEASUREMENT OF NEUTRON STAR RADIUS

- constraints on NS radius : 9.1 km < R_1, R_2 < 13.3 km
- softer EoS preferred (e.g. APR4) over stiffer ones (e.g. H4)

Abbott+, arXiv 1805.11581

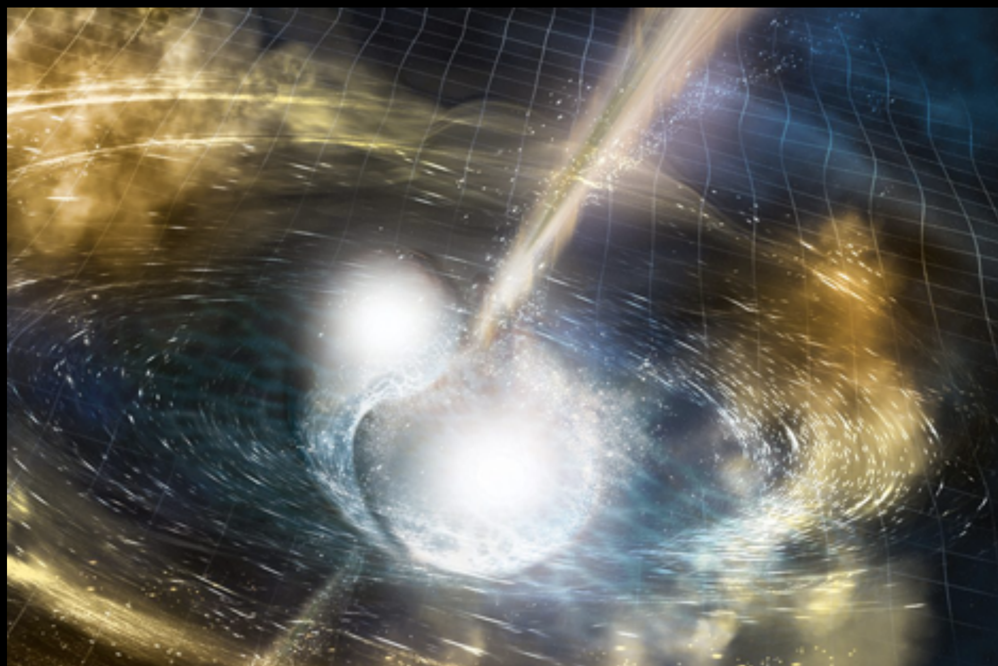


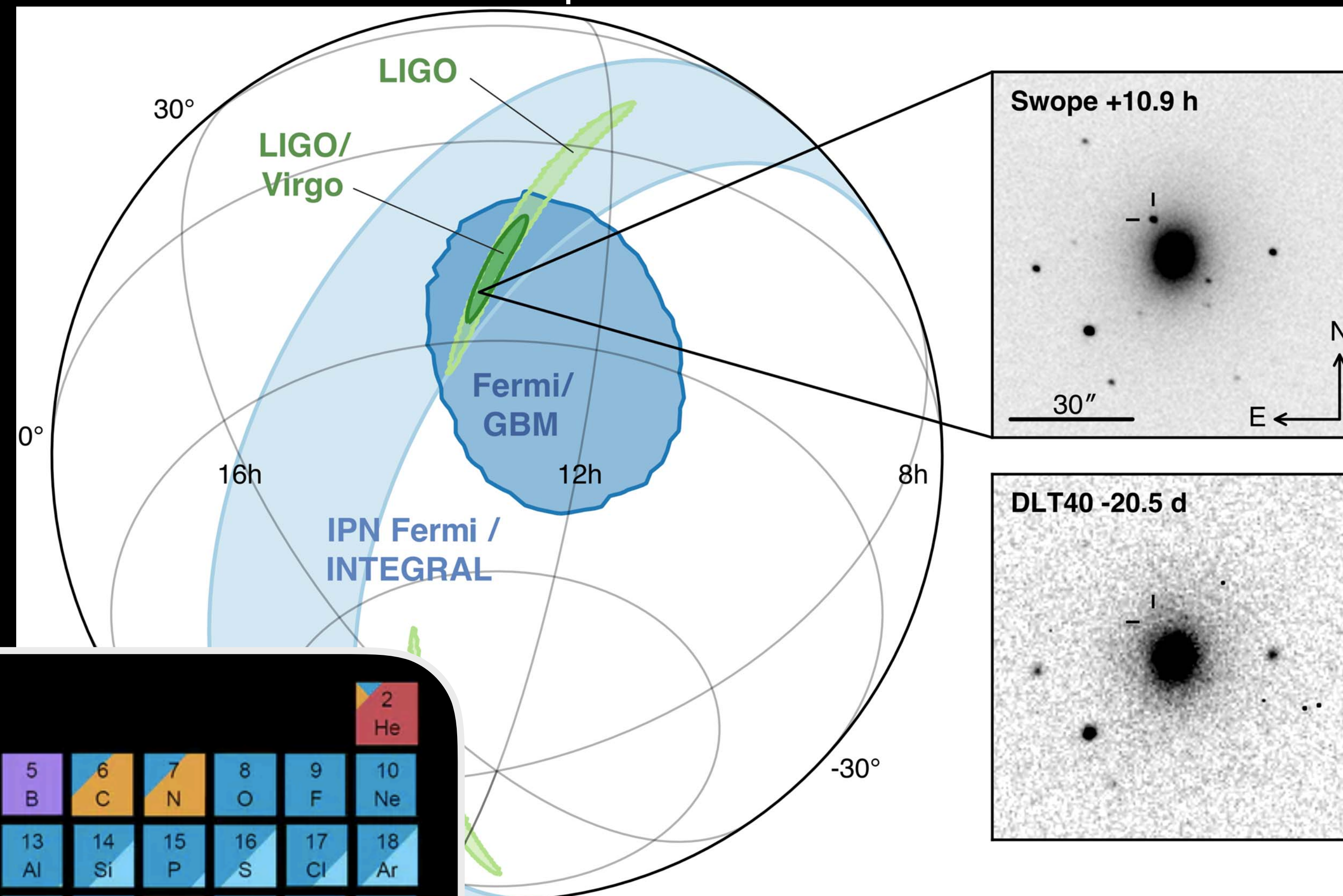
Credit:Ben Lackey

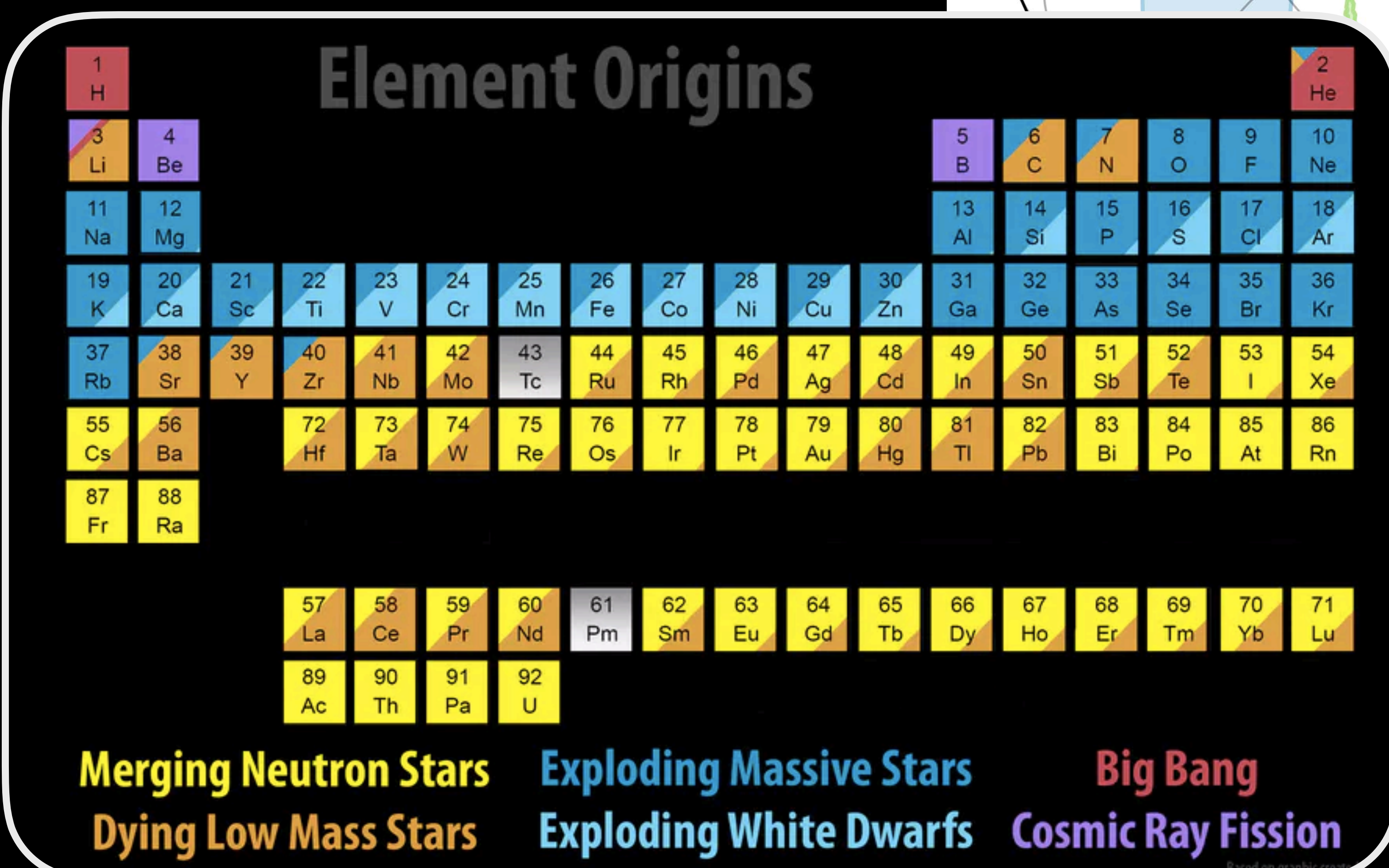
3G network will determine the equation of state of ultra-dense matter and could reveal new states of matter in the QCD phase diagram

ORIGIN OF HEAVY ELEMENTS

Abbott+ ApJ Letters, 848, L12 (2017)



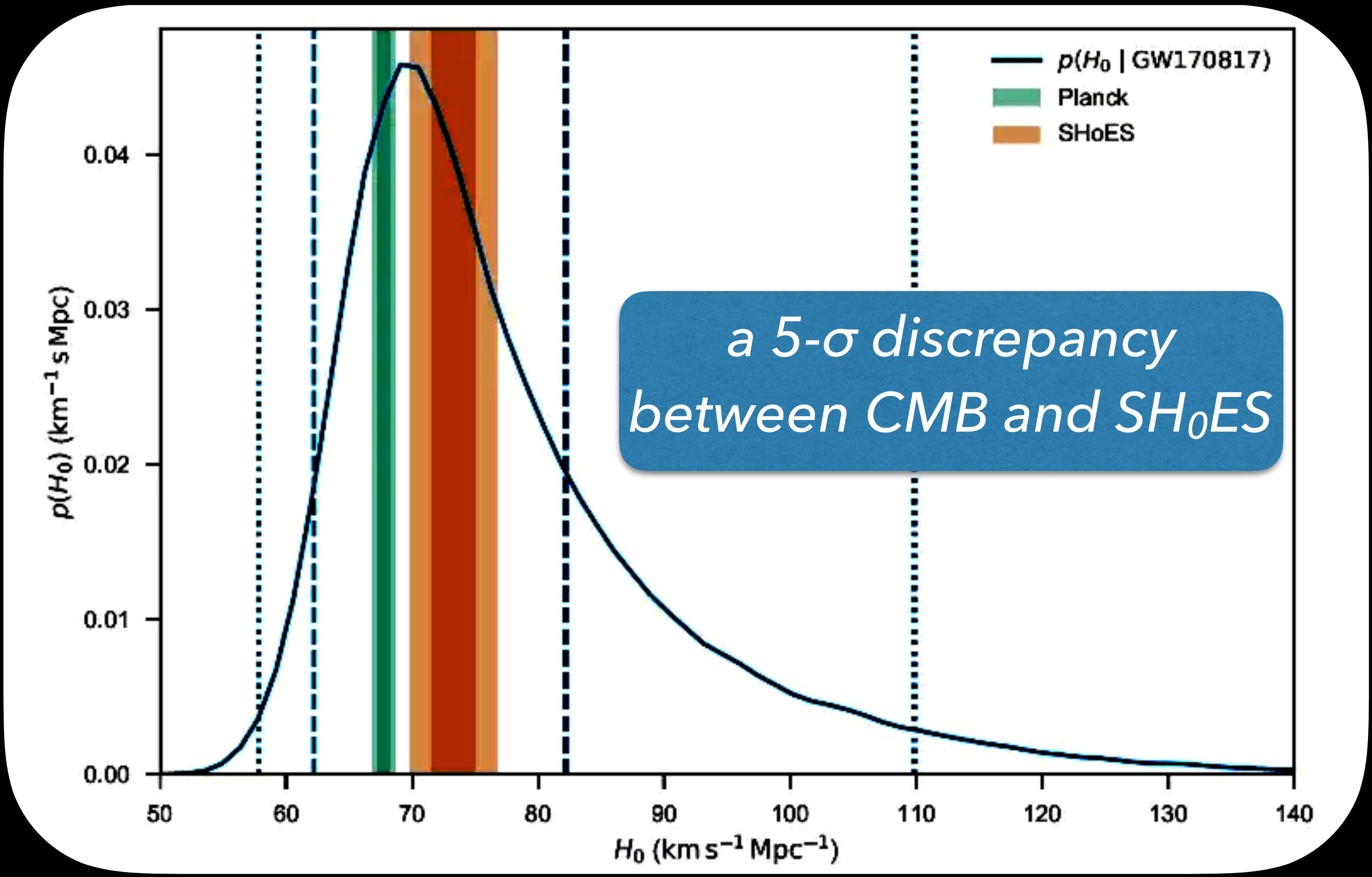




3G network will help identify thousands of kilonova and trace the origin of heavy elements

STANDARD SIREN COSMOLOGY

TENSION IN H_0 MEASUREMENT FROM CMB AND SH_0ES PROJECT

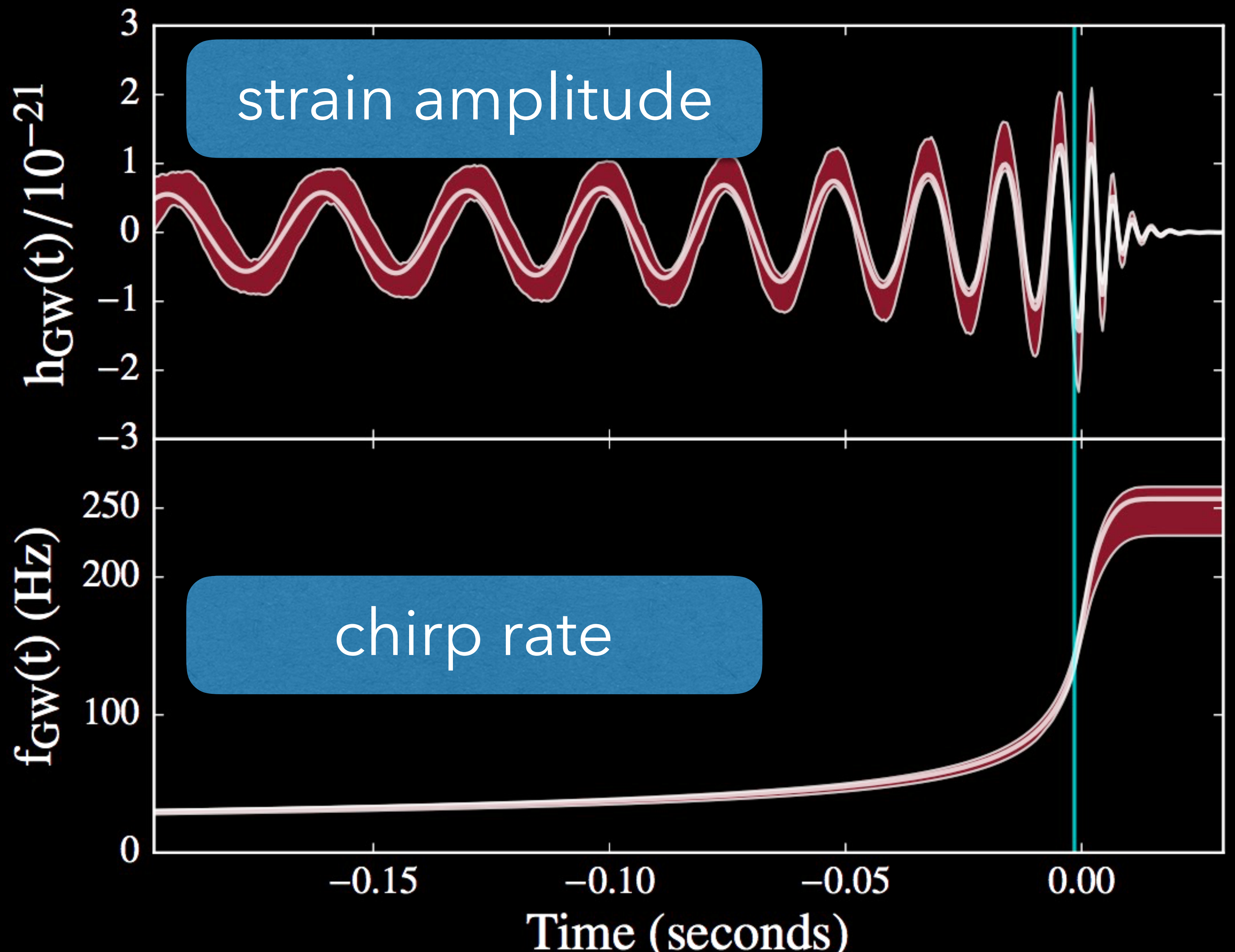


❖ evidence of new/missing physics?

Abbott+, Nature (2017)

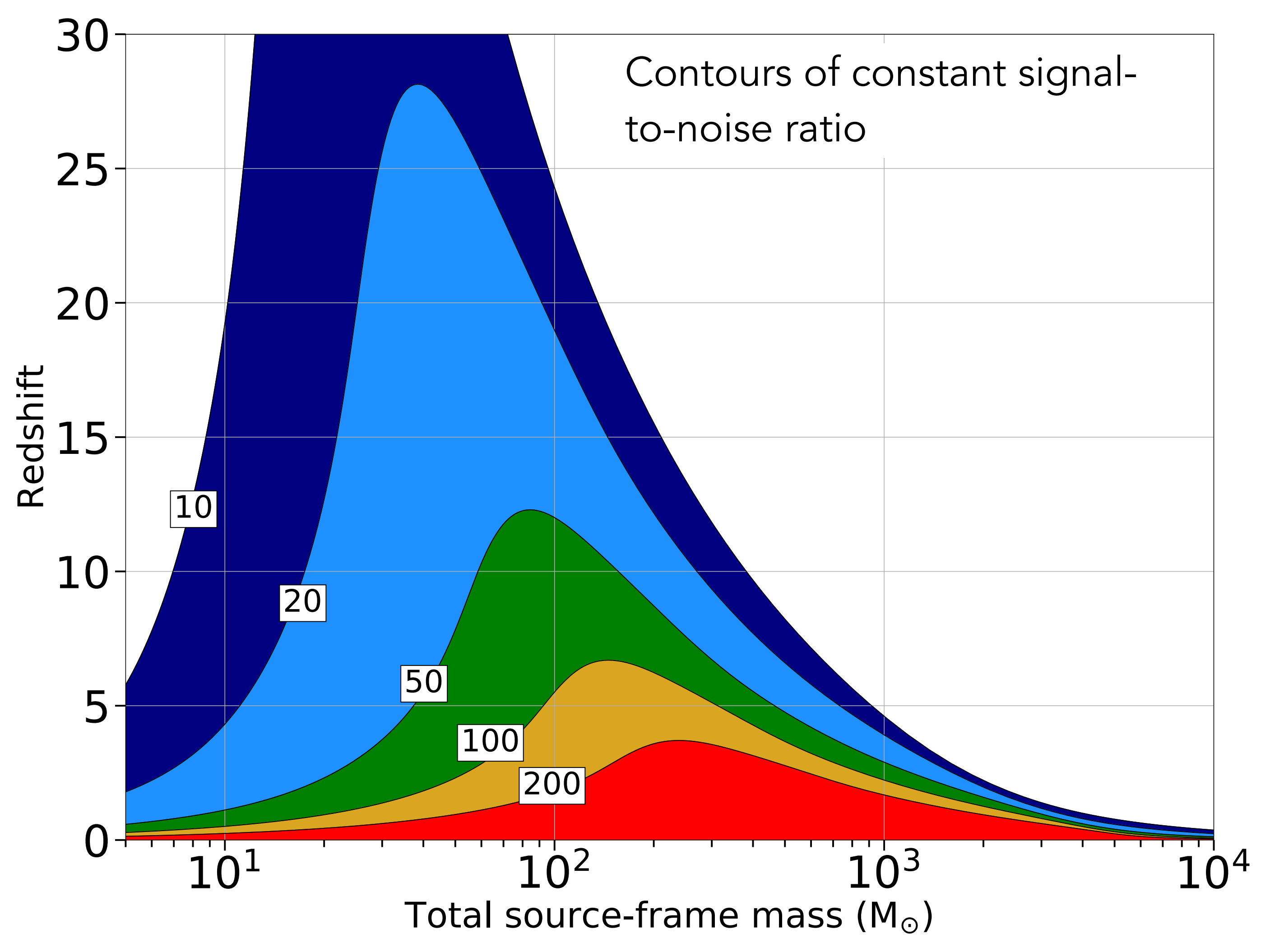
STANDARD SIREN COSMOLOGY

strain gives apparent luminosity, chirp rate gives absolute luminosity; luminosity distance inferred by GW observations alone

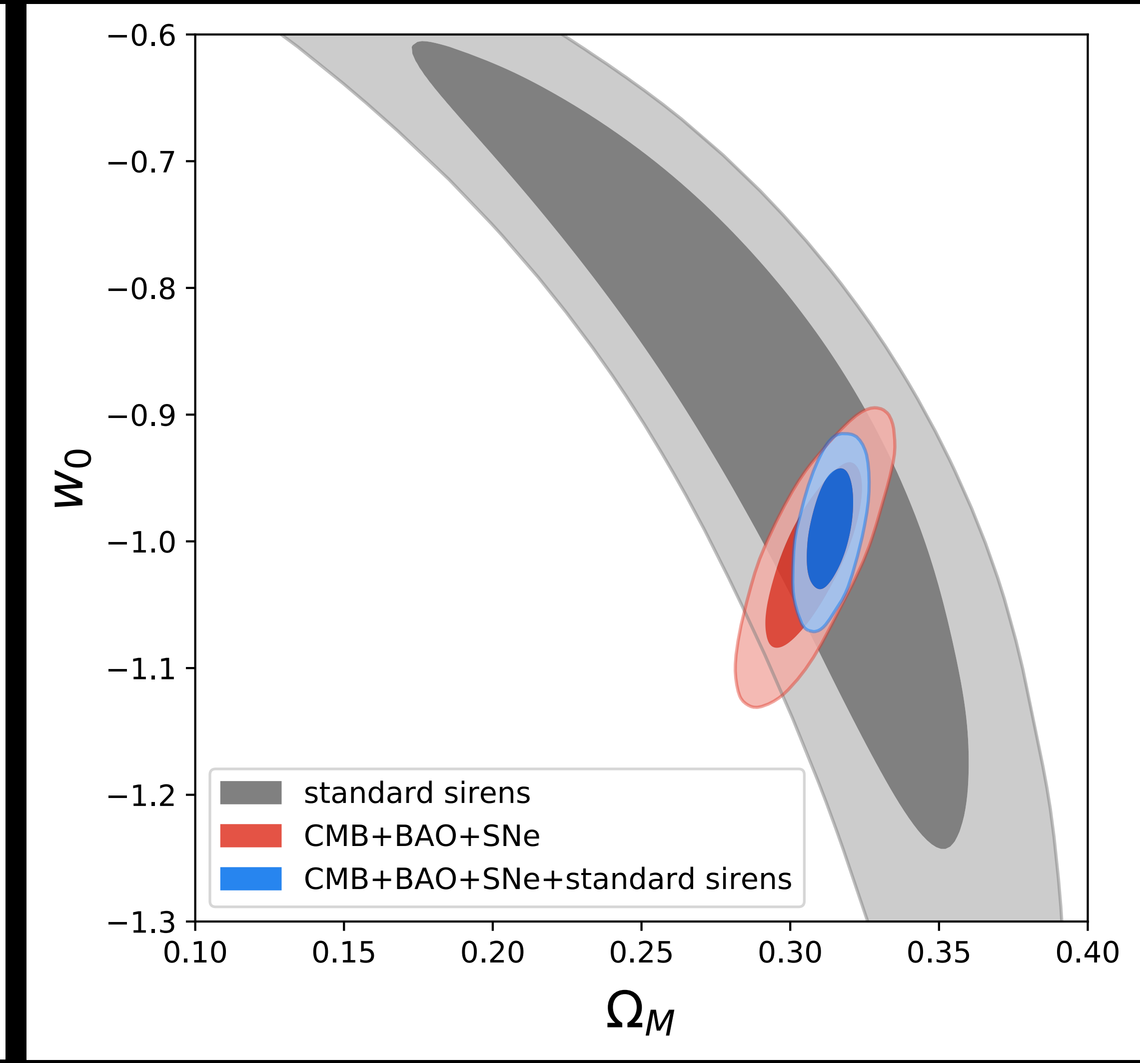


Abbott+ PRL, 116 (2016)

3G NETWORK WILL DETECT MILLIONS OF MERGERS



Credit: Alberto Mangiagli

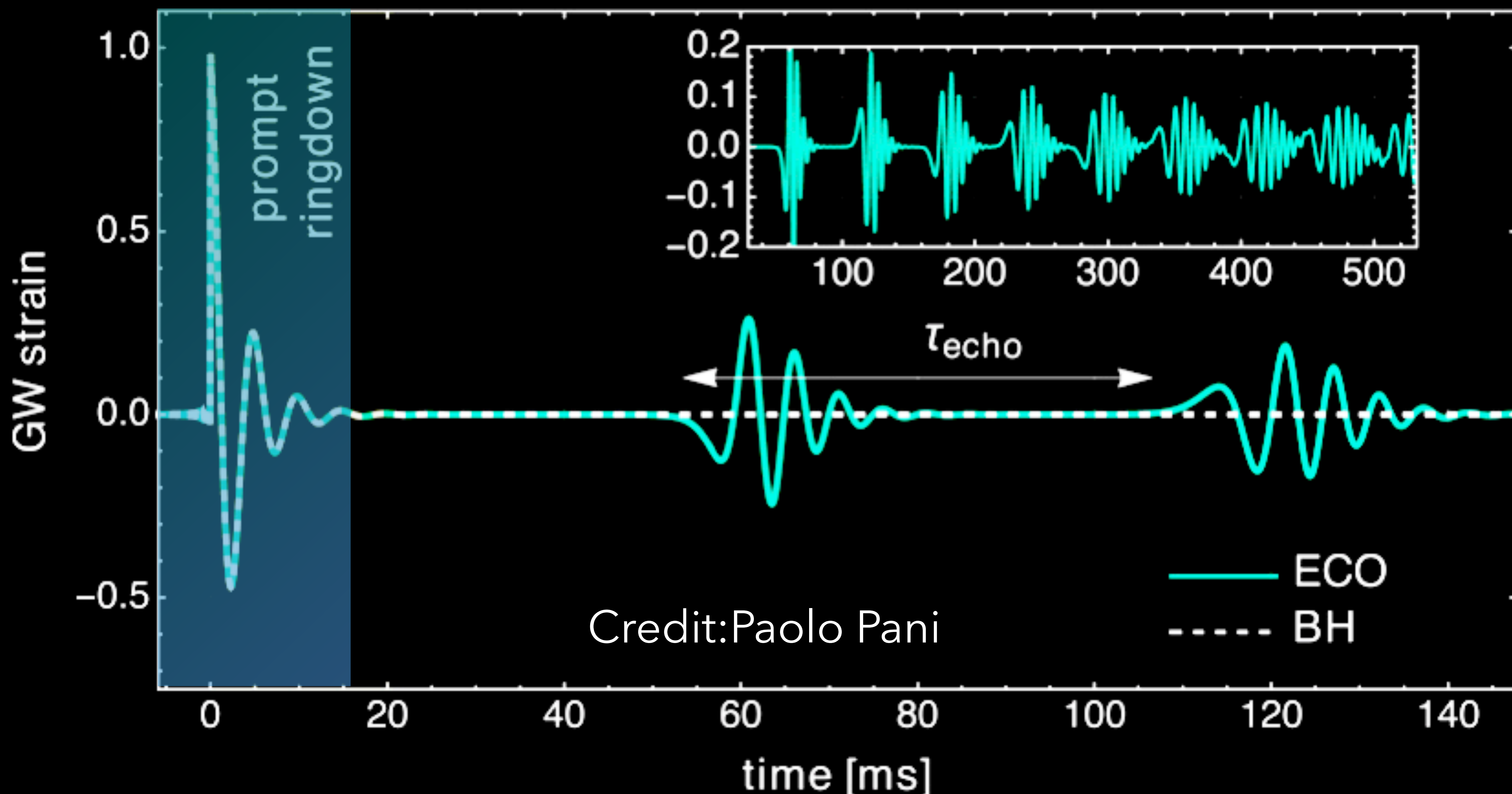


Credit: Michele Maggiore

3G network will calibrate nearby supernovae, determine dark energy equation of state and its variation with redshift

EXOTIC OBJECTS, NEW FIELDS AND PARTICLES

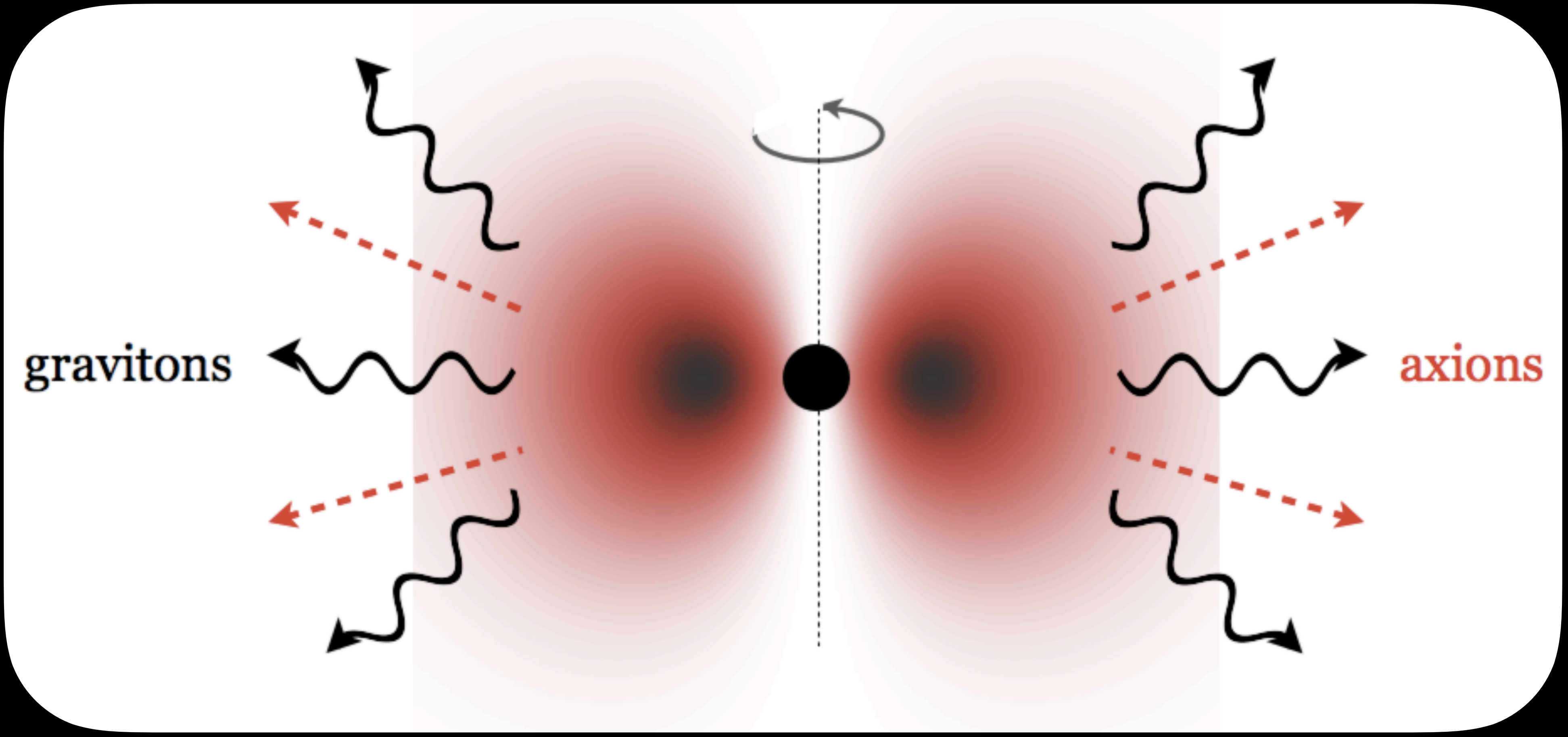
EXTREMELY COMPACT OBJECTS



3G network could discover extremely compact objects such as Boson stars, strange stars, gravastars, worm holes, …

GRAVITATIONAL ATOMS AND BLACK HOLE SUPER RADIANCE

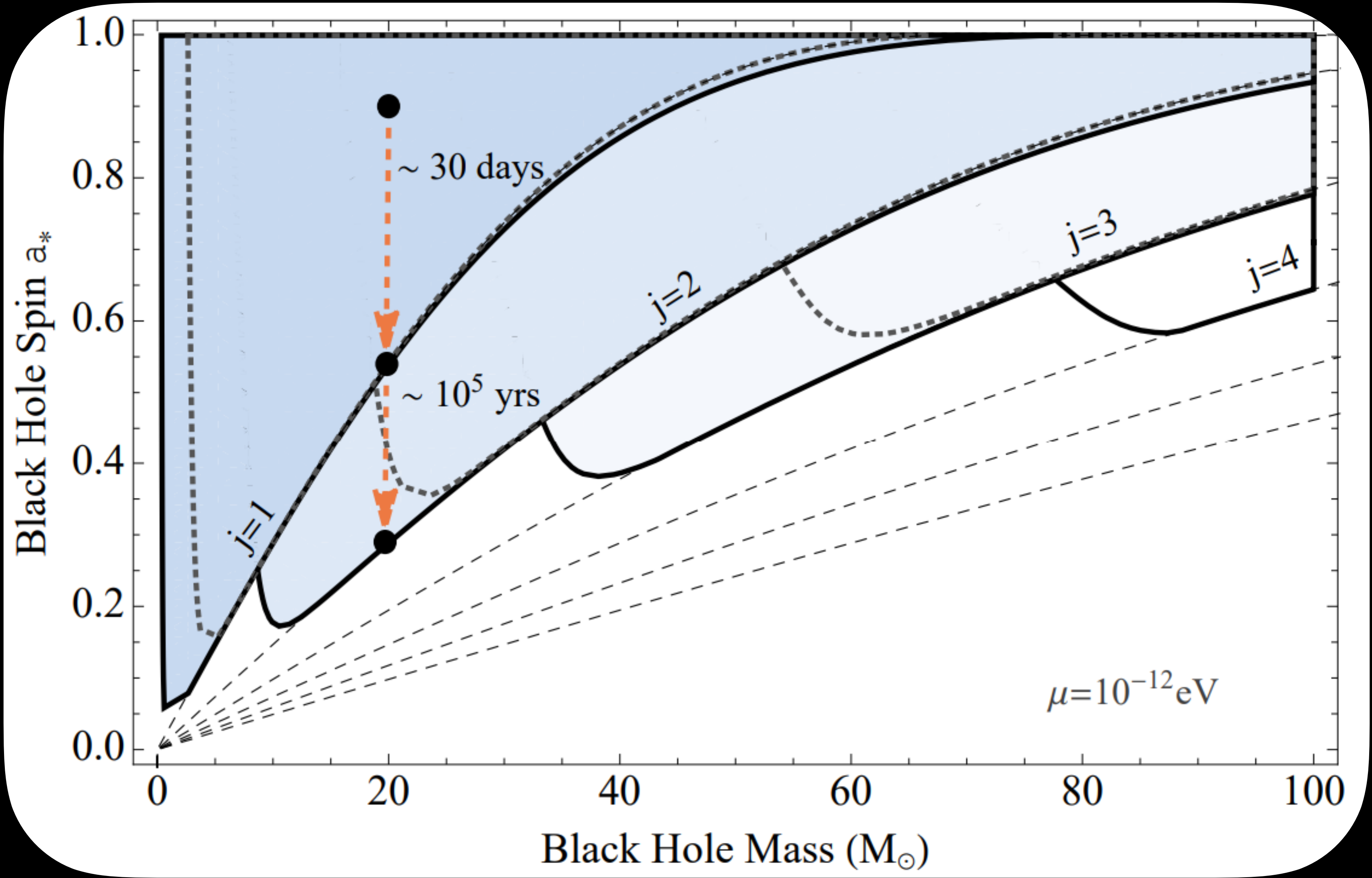
Arvanitaki+ Phys. Rev. D83 (2011)



- axionic fields of Compton wavelength ~ black hole horizon form a gravitational atom
- they can extract black hole's angular momentum via superradiance

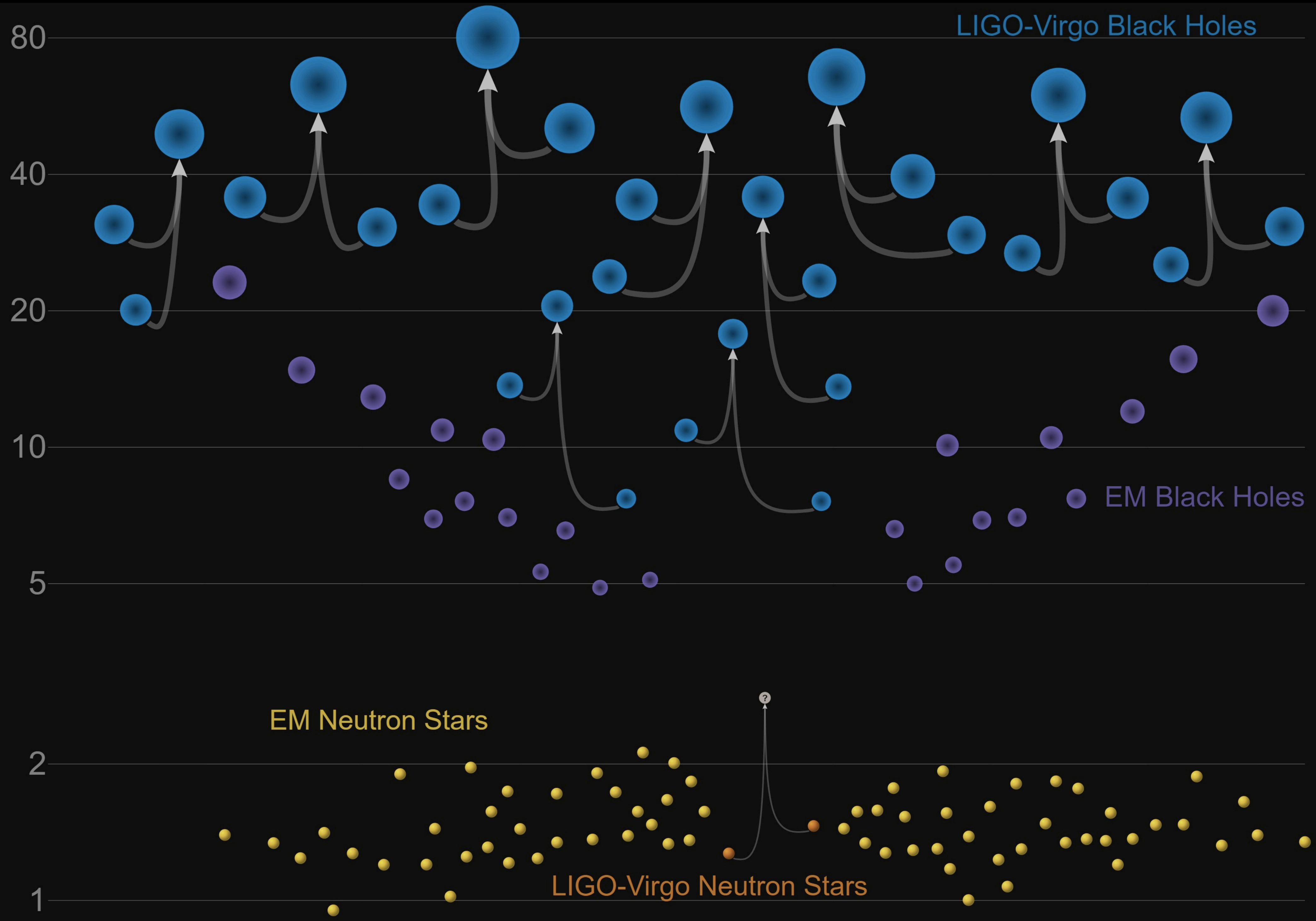
GRAVITATIONAL ATOMS AND SUPER RADIANCE

Baryakhtar+ Phys. Rev. D96 (2017)



3G network will explore properties of dark matter not accessible to any other experiment

ARE LIGO-VIRGO BLACK HOLES DARK MATTER?

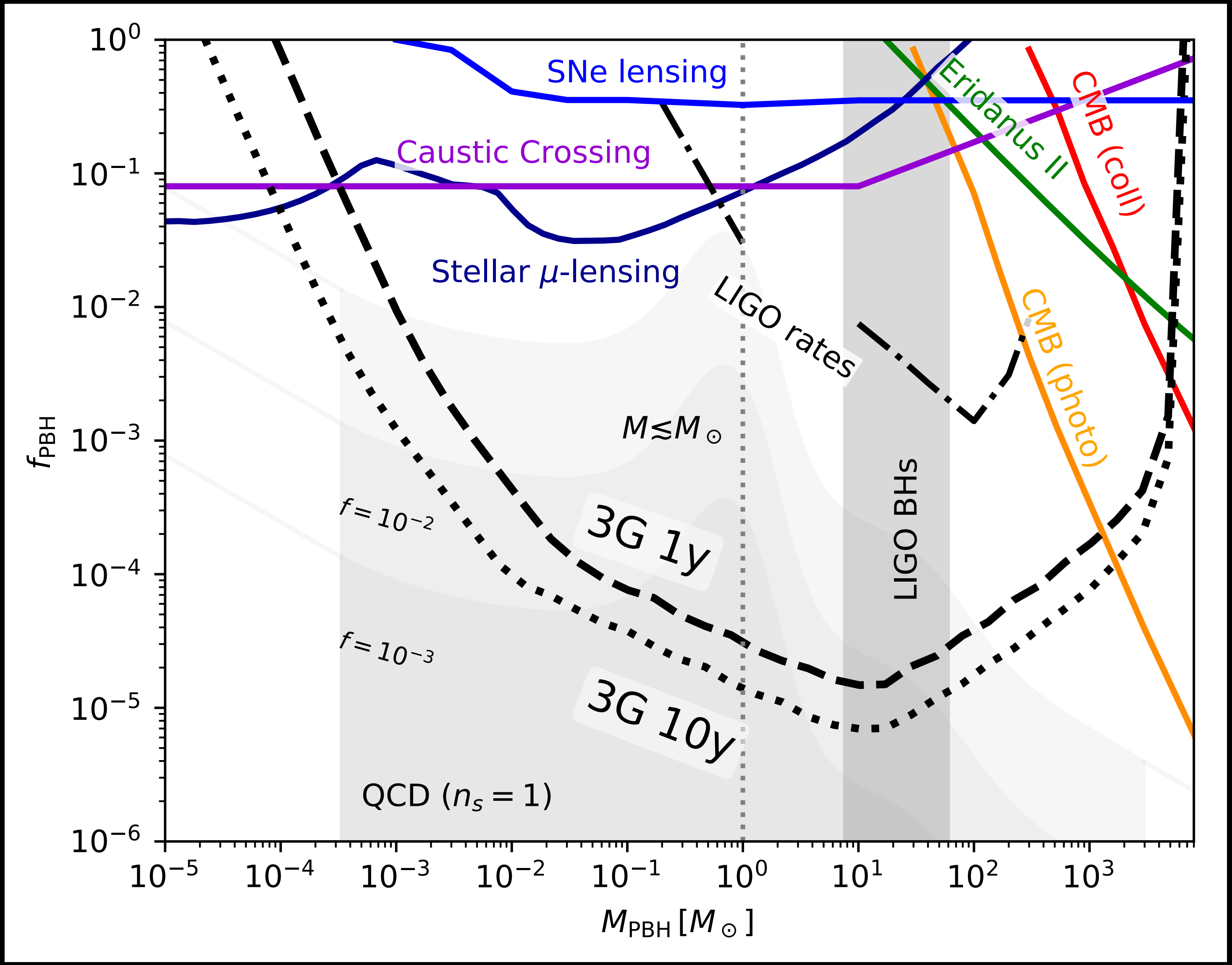


LIGO-Virgo | Frank Elavsky | Northwestern

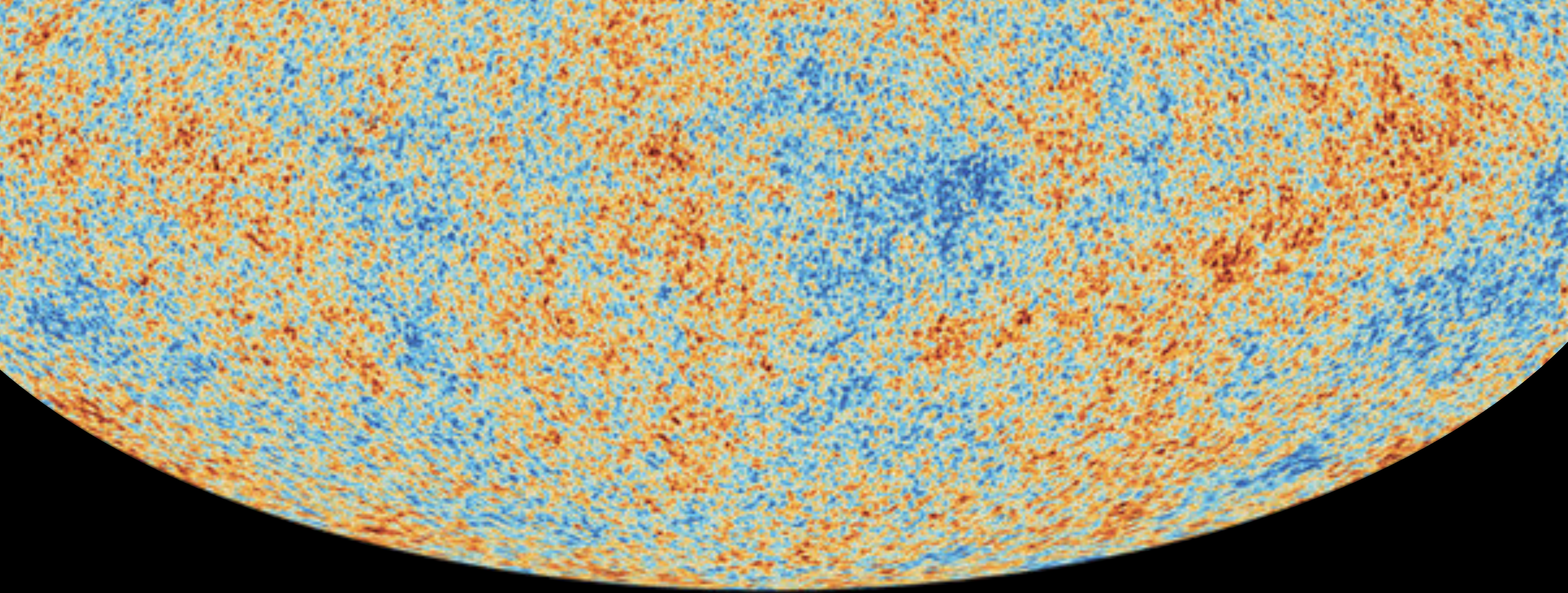
PRIMORDIAL BLACK HOLES AS DARK MATTER

- sub-solar black holes cannot form by stellar evolution
- must be primordial in origin
- 3G detectors can probe existence of light black holes

Credit:Miguel Zumalacarregui



3G network would settle the question if LIGO-Virgo black holes constitute dark matter and are primordial in origin

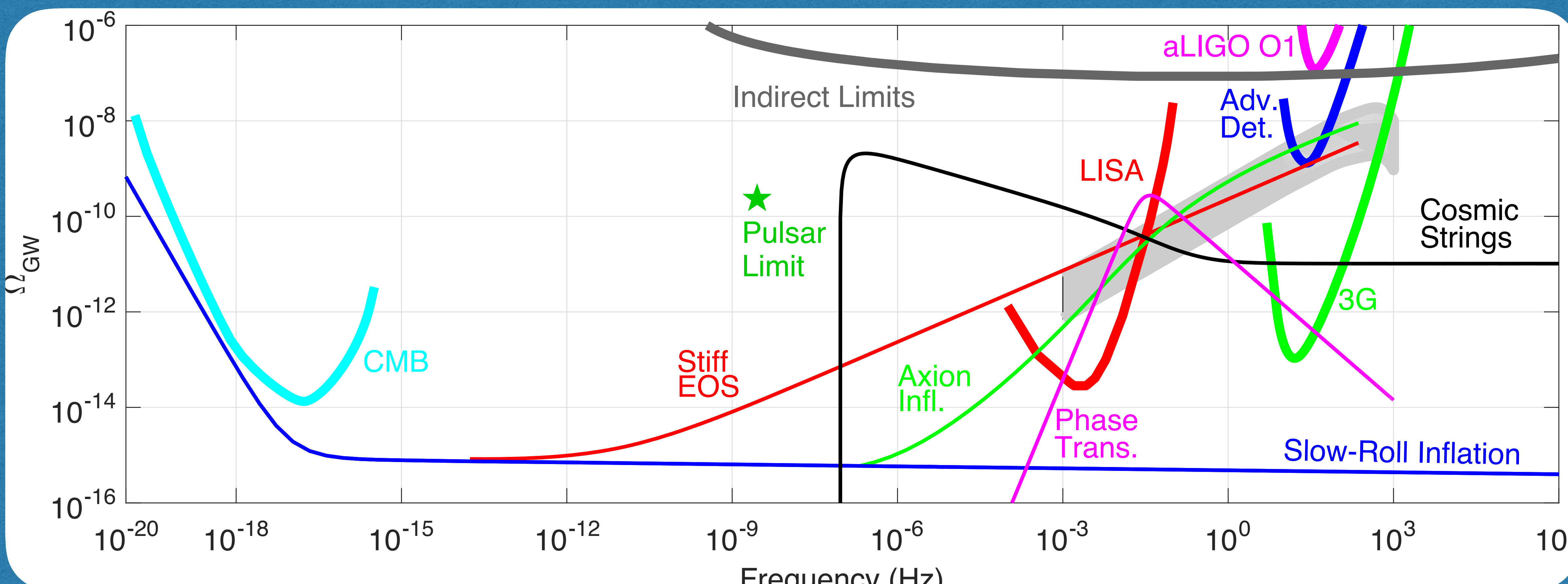


PRIMORDIAL UNIVERSE

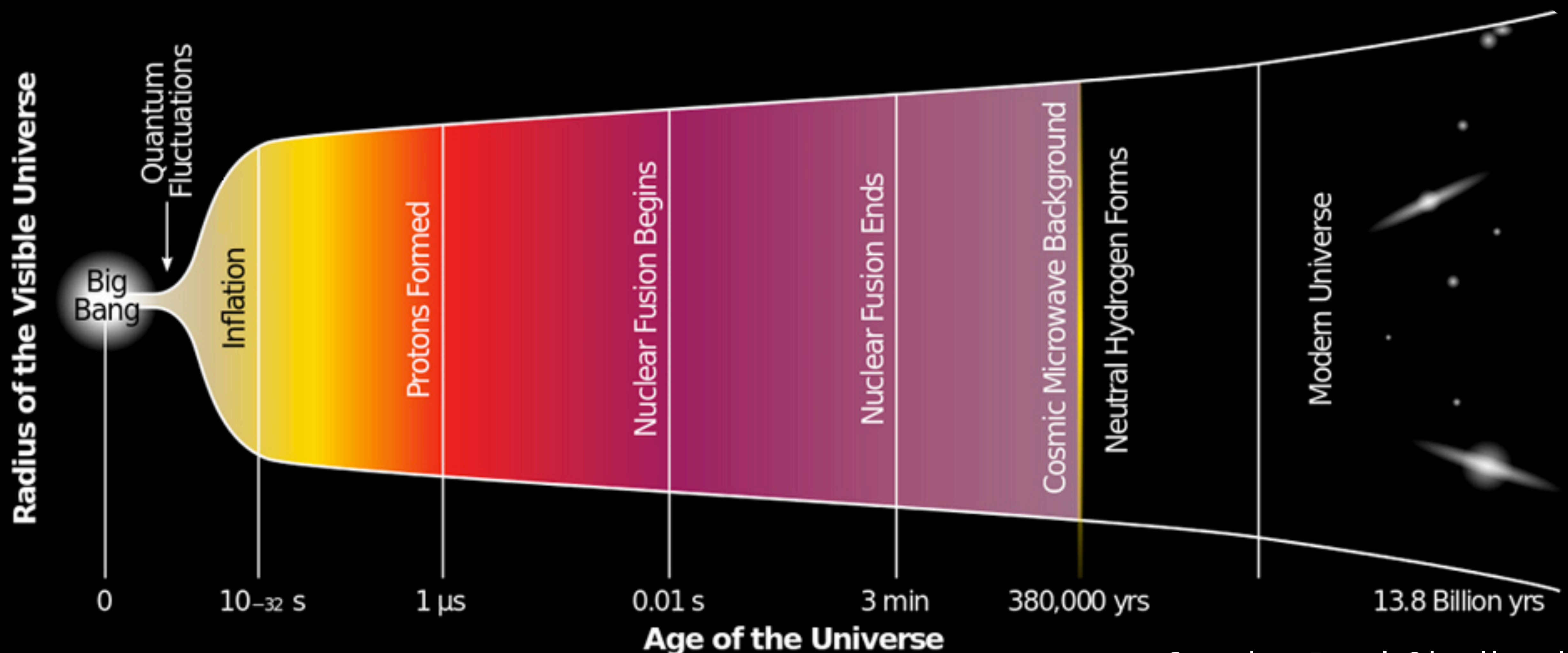
STOCHASTIC BACKGROUND LANDSCAPE

- slow-roll inflation
- stiff equation of state
- axion inflation
- early universe phase transitions
- cosmic strings

Credit: Vuk Mandic



EXPLORE FUNDAMENTAL PHYSICS AT HIGHEST ENERGY SCALES



Credit: Paul Shellard

3G network will explore laws of physics at energy scales inaccessible to particle accelerators and potentially discover remnants of phase transitions and new physics

SUMMARY

- study the nature of black holes, state of ultra dense nucleons and the origin of heavy elements
- reveal phase transition from nucleons to free quarks and insight into the QCD phase diagram
- determine H_0 and the nature of dark energy equation of state and its variation with redshift
- explore extremely compact objects, ultra-light bosonic clouds such as axions near black holes
- the early history of the universe and the physics at energy scales inaccessible to terrestrial experiments
- GW technology needs CERN - many opportunities for collaboration and cooperation

SPARE SLIDES

PHASE SPACE OF TESTS OF GR

❖scale of curvature

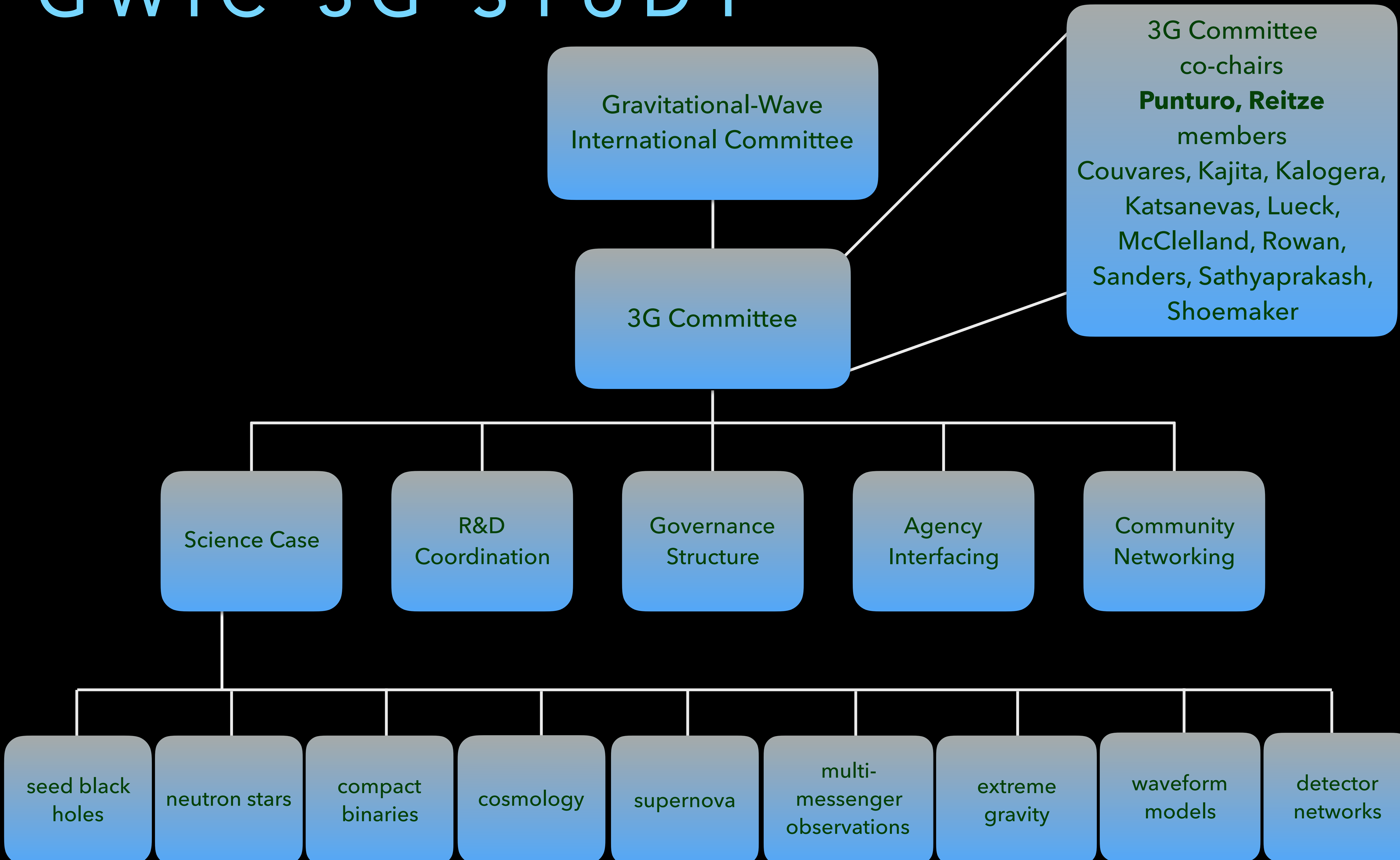
$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

- ❖scale of curvature ~ matter density ~ M/L^3, define $R = (L^3/M)^{1/2}$

❖strength of surface gravity, also compactness and orbital speed

- ❖scale of surface gravity determined by compactness, $v^2 \sim M/L \sim \Phi$

GWIC 3G STUDY



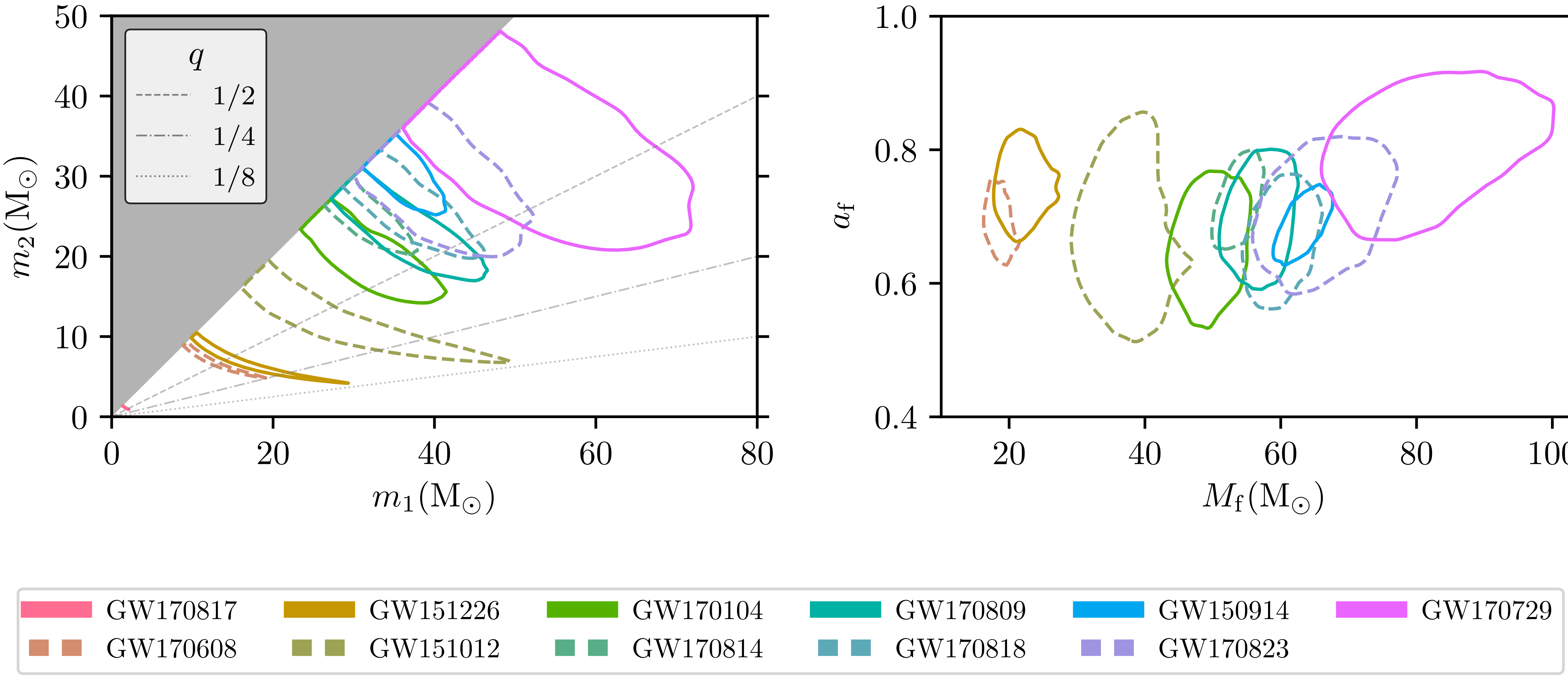
for membership of committees see: https://gwic.ligo.org/3Gsubcomm/

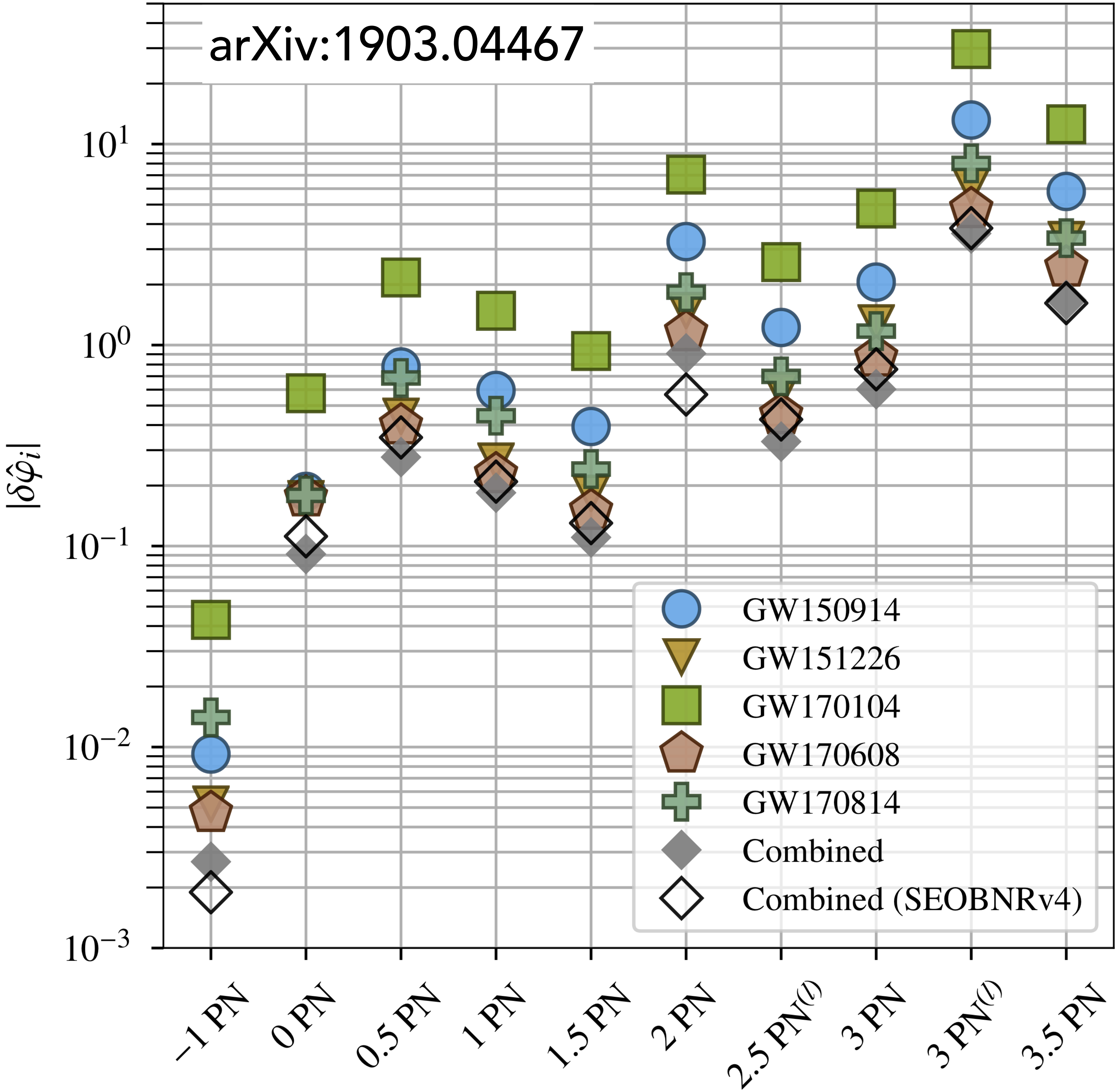
BINARY BLACK HOLE DETECTIONS

arXiv:1903.04467

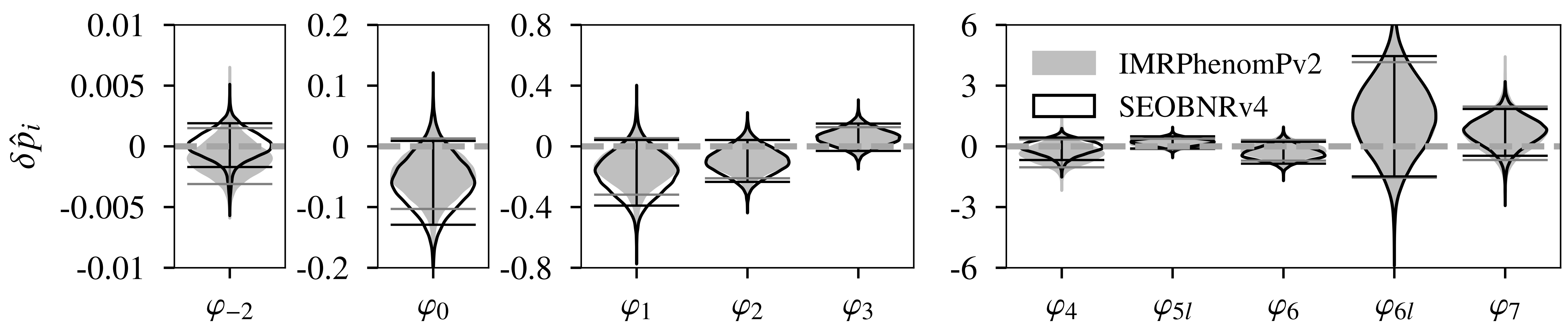
Event	Properties			
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$
GW151226[b,c]	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$
GW170729[d]	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$

BINARY BLACK HOLE EVENTS



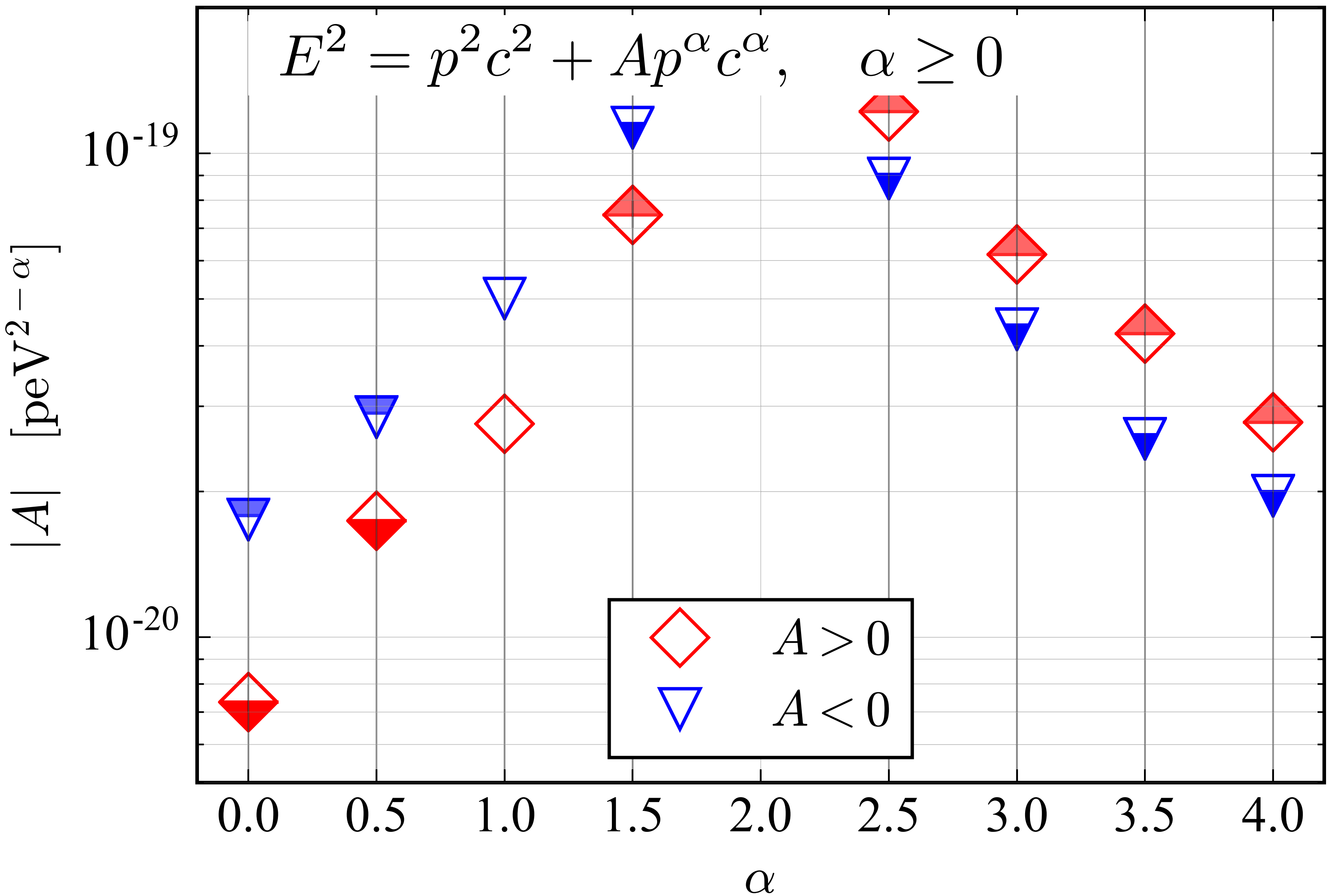

arXiv:1903.04467
$|\delta\hat{\varphi}_i|$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
−1 PN
0 PN
0.5 PN
1 PN
1.5 PN
2 PN
2.5 PN$^{(l)}$
3 PN
3 PN$^{(l)}$
3.5 PN
GW150914
GW151226
GW170104
GW170608
GW170814
Combined
Combined (SEOBNRv4)

LIMITS ON DEVIATIONS IN POST-NEWTONIAN PARAMETERS FROM O1-O2 POPULATION



arXiv:1903.04467

CONSTRAINTS ON DISPERSION OF GRAVITATIONAL WAVES



massive-graviton theories (α=0, $A > 0$), multifractal spacetime (α=2.5), doubly special relativity (α=3), and Hořava-Lifshitz and extra-dimensional theories (α=4).

Abbott+ PRL, 118, 221101 (2017)

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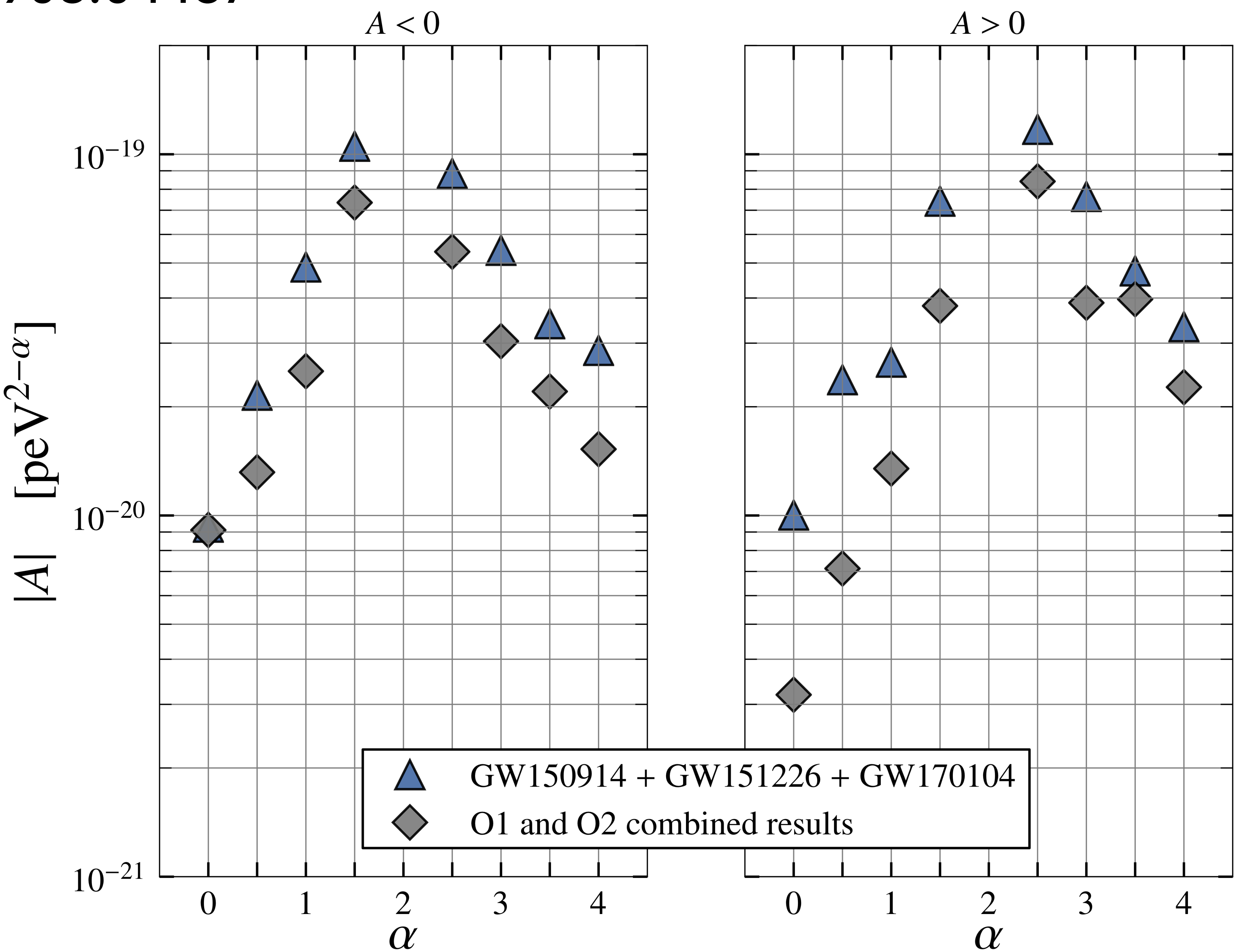

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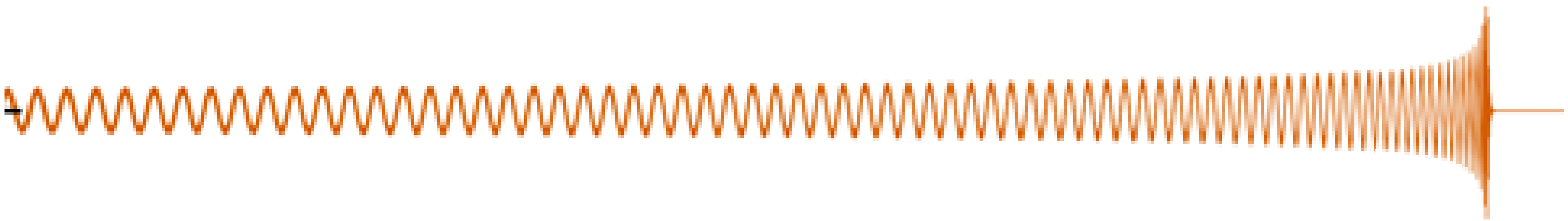
IS THE SIGNAL CONSISTENT WITH A BLACK HOLE REMNANT



m1, m2, S1, S2, …

Abbott+ PRL, 118, 221101 (2017)

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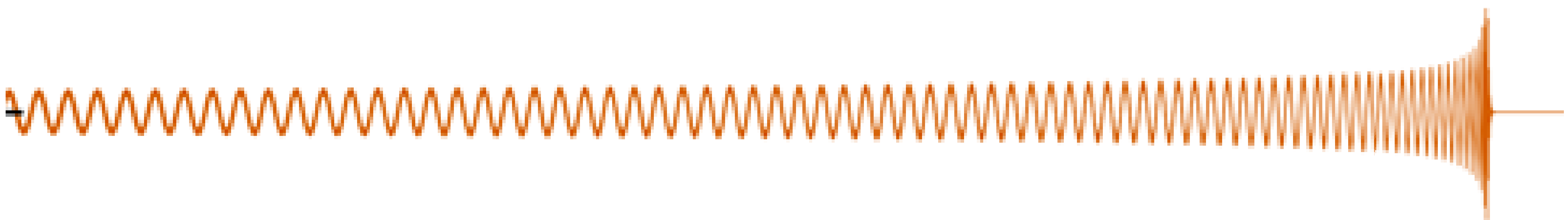

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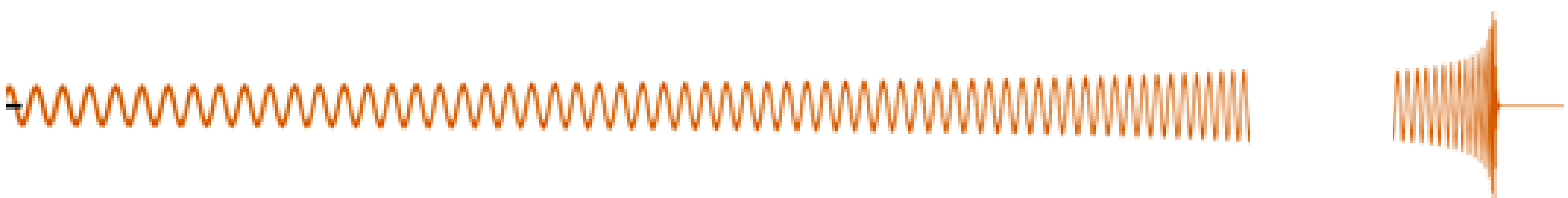
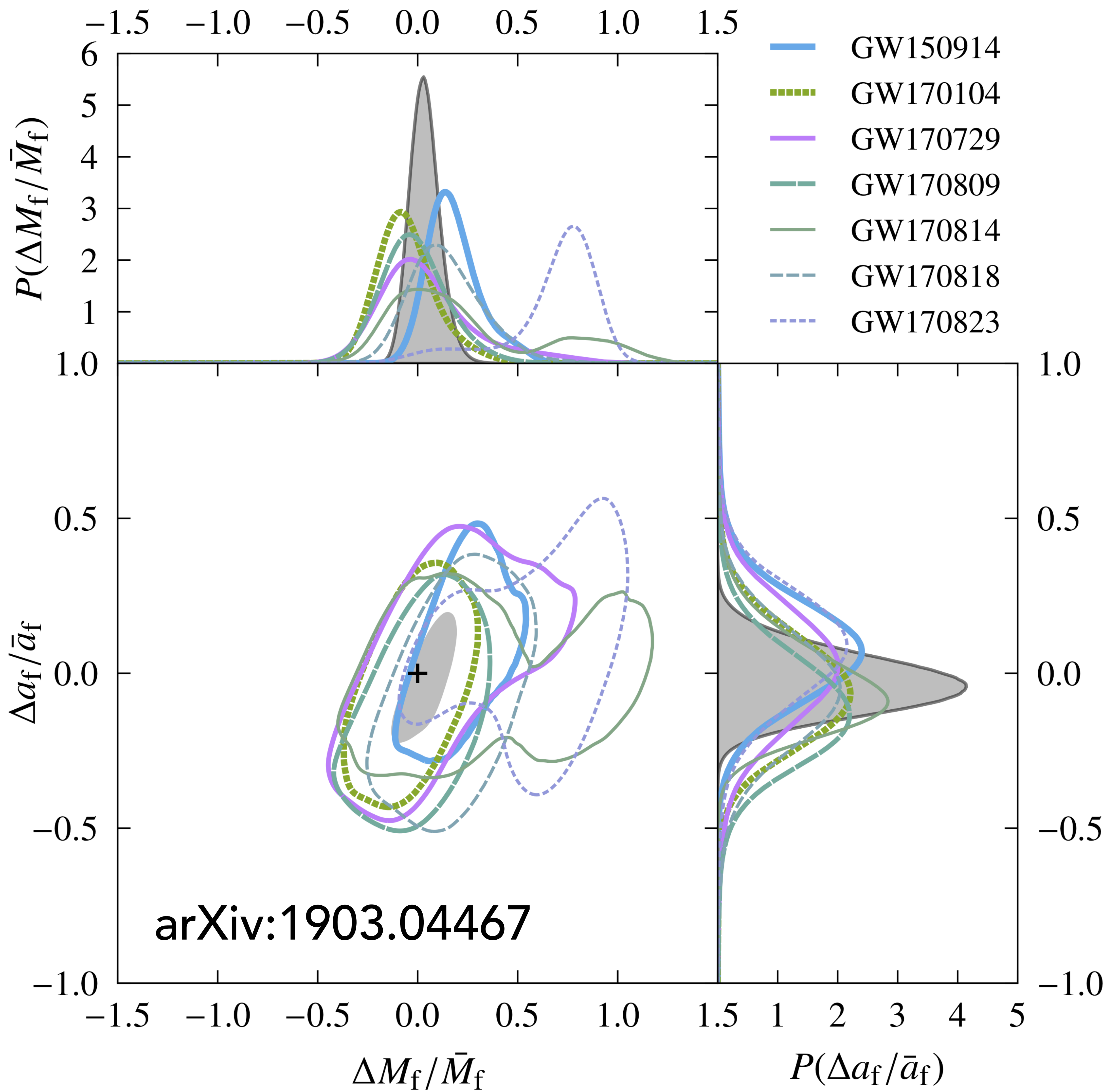
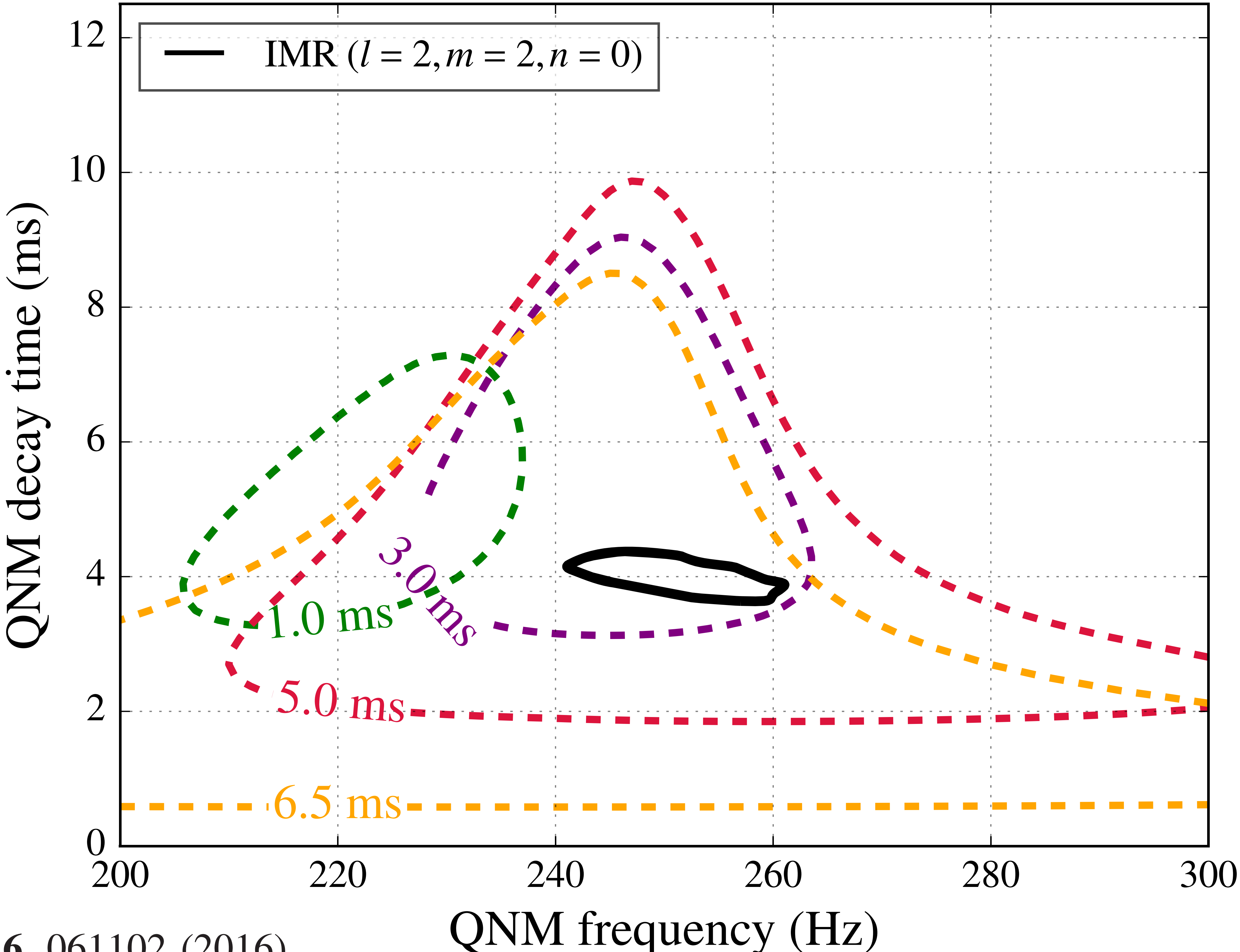


m1, m2, S1, S2, … m1, m2, S1, S2, …

Abbott+ PRL, 118, 221101 (2017)


GW150914
GW170104
GW170729
GW170809
GW170814
GW170818
GW170823
$P(\Delta M_f/\bar{M}_f)$
$\Delta a_f/\bar{a}_f$
$\Delta M_f/\bar{M}_f$
$P(\Delta a_f/\bar{a}_f)$
arXiv:1903.04467

QUASI-NORMAL MODES IN LIGO'S BLACK HOLES? GW150914



PRL **116,** 061102 (2016)

TEST OF THE SPEED OF GRAVITATIONAL WAVES

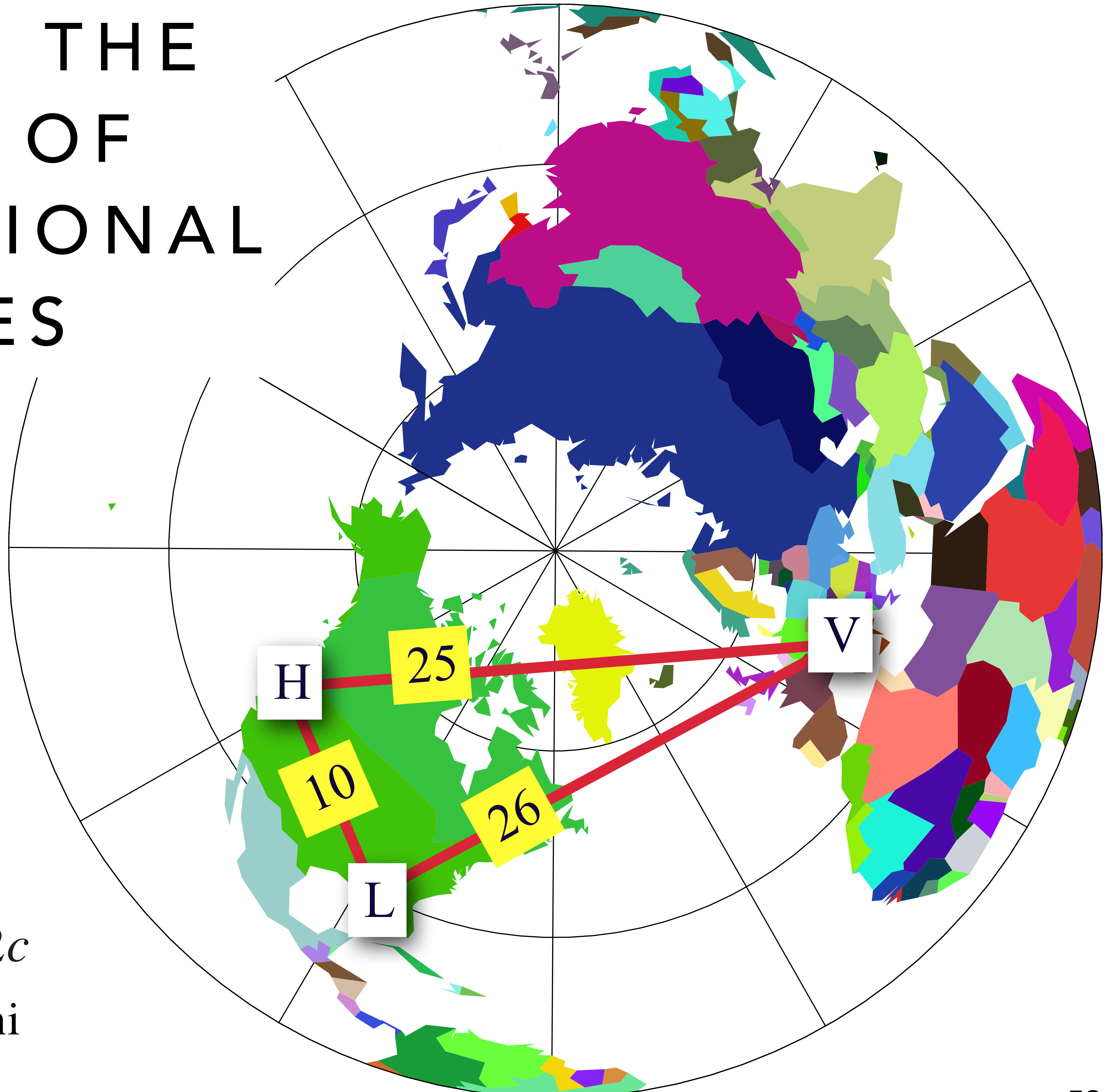
BASELINES IN LIGHT TRAVEL TIME (MS)

USING GW150914, GW151226, GW170104

$$0.55c < c_{\mathrm{gw}} < 1.42c$$

Cornish, Blas Nardini

PRL **119**, 161102 (2017)



NO-HAIR TEST WITH A POPULATION OF BINARY BLACK HOLE SIGNALS

- in general relativity the parameters of QNM signal are

$$\vec{\theta}_{\rm GR} = \{M, \nu, j, \chi_{\rm eff}, D_{\rm L}, \theta, \varphi, \psi, \iota, \phi, t_0\}\,,$$

- extra hair:

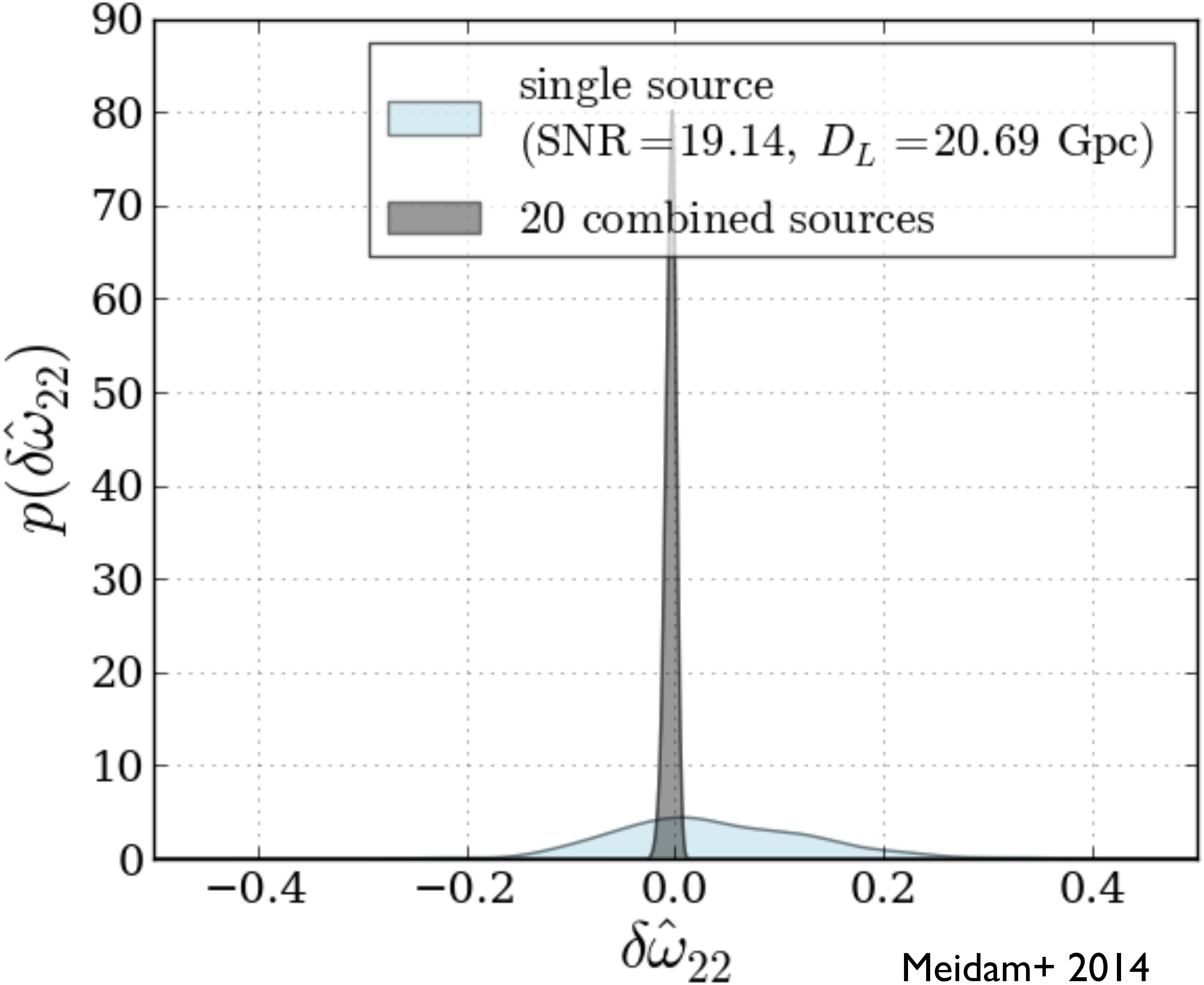
$$\begin{aligned}
\omega_{lm} &= \omega_{lm}^{\rm GR}(M,J)\,(1+\delta\hat{\omega}_{lm}),\\
\tau_{lm} &= \tau_{lm}^{\rm GR}(M,J)\,(1+\delta\hat{\tau}_{lm}),
\end{aligned}$$

$$\begin{aligned}
H_1 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{22}\},\\
H_2 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{33}\},\\
H_3 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\tau}_{22}\},\\
H_{12} &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{22}, \delta\hat{\omega}_{33}\},
\end{aligned}$$

$$B^{123}_{\rm GR} = \frac{P(d|H_{123}, I)}{P(d|\mathcal{H}_{\rm GR}, I)}.$$

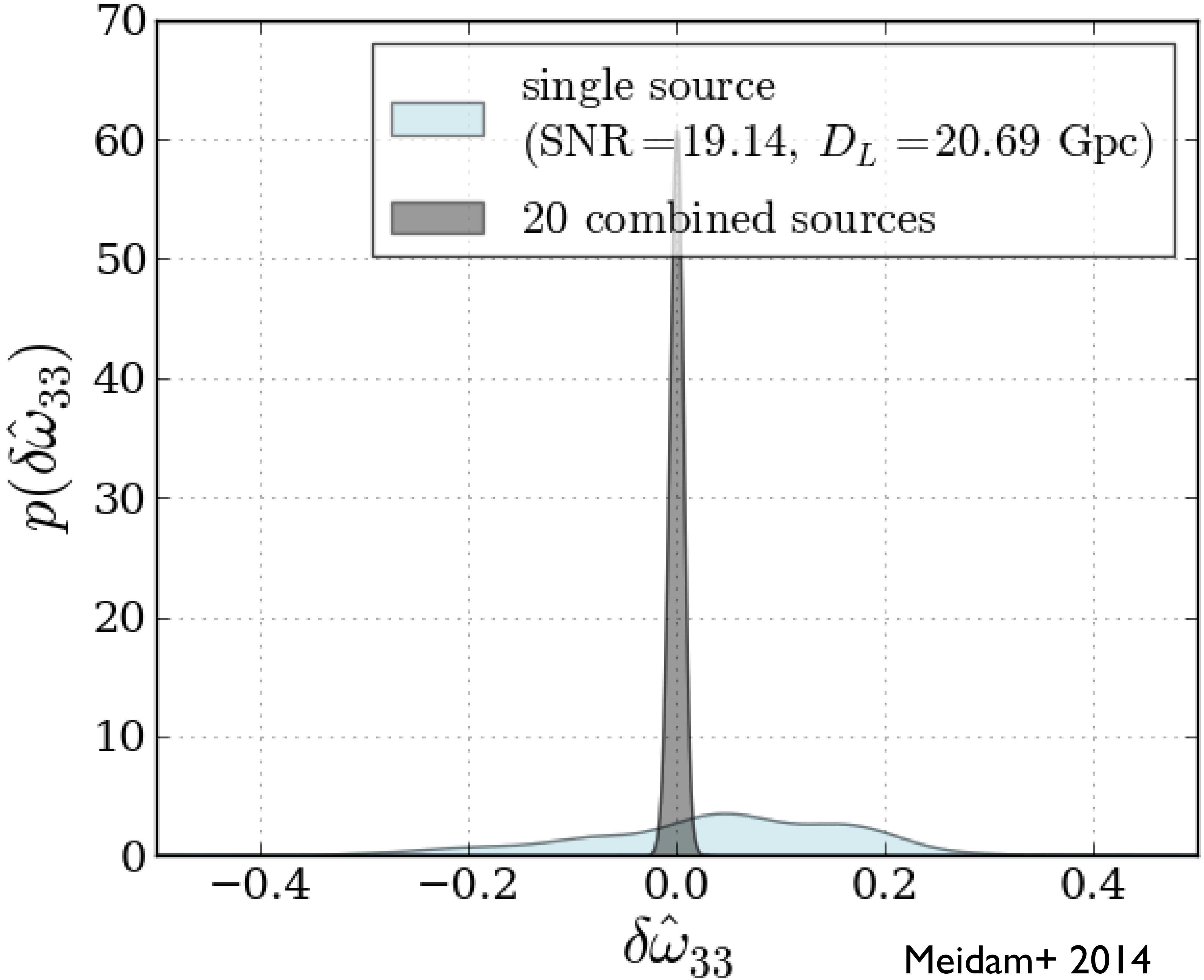
Gossan+ 2012, Meidam+ 2014

HOW WELL CAN WE MEASURE NON-GR



Meidam+ 2014

HOW WELL CAN WE MEASURE NON-GR

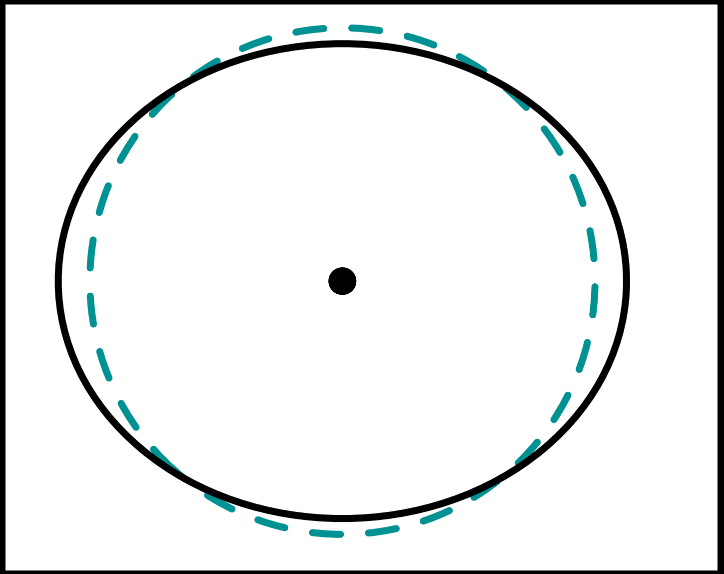


Meidam+ 2014

SIGNATURE OF EQUATION OF STATE IN BINARY NEUTRON STAR WAVEFORMS

- tidal field $\mathcal{E}$ of one companion induces a quadrupole moment Q in the other
- in the adiabatic approximation

$$Q_{ij} = -\lambda(m)\,\mathcal{E}_{ij}, \qquad \lambda(m) = (2/3)\,k_2(m)\,R^5(m)$$



sketch: J. Read

- **$\lambda(m)$** is tidal deformability, **$k_2(m)$** is the Love number and **R** is the NS radius

$$\Lambda \equiv G\lambda(Gm_{\rm NS}/c^2)^{-5}$$

$$\Lambda \in [300, 600]$$

TESTS OF THE BINARY BLACK HOLE INSPIRAL DYNAMICS

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\varphi(f)}$$

$$\begin{aligned}\varphi(f) =& \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} \\ &+ \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} \\ &+ \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots\end{aligned}$$

(Abbott et al. arXiv:1606.04856)

deform PN coefficients from their GR value and look for these deviations; e.g.

$$\varphi_{\rm Newt} \to \varphi_{\rm Newt} + \delta\varphi_{\rm Newt}$$

Blanchet and BS 1995
Arun+ 2006, Mishra+ 2010,
Yunes and Pretorius 2009, Li+ 2012

wave tails
mass asymmetry
spin-spin coupling
spin-orbit coupling
hereditary terms
spin precession
absorption of radiation by black hole