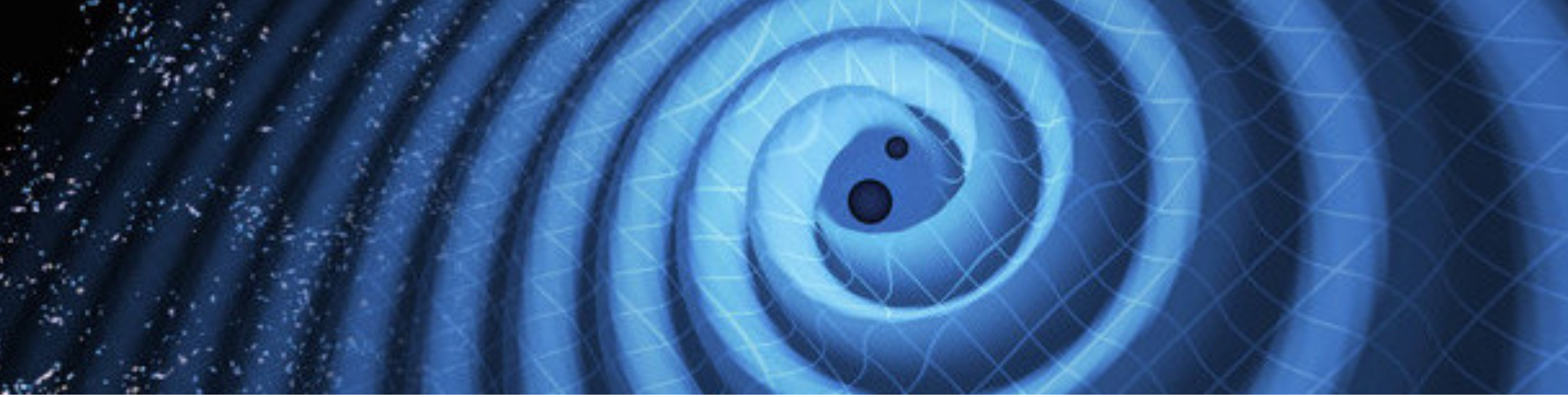


GWIC-3G SCIENCE CASE

https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0

B.S. SATHYAPRAKASH

Penn State and Cardiff

GWIC 3G Science Case Team and Consortium

GWIC

Gravitational Wave International Committee

ASTRO2020 WHITE PAPERS

1. **Astro2020 Science White Paper: Populations of Black Holes in Binaries**
   Thomas J. Maccarone (Texas Tech. U.) *et al.*. Apr 26, 2019. 8 pp.
   e-Print: **arXiv:1904.11842 [astro-ph.HE] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Extreme Gravity and Fundamental Physics**
   B.S. Sathyaprakash (Penn State U. & Cardiff U.) *et al.*. Mar 25, 2019. 14 pp.
   e-Print: **arXiv:1903.09221 [astro-ph.HE] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record - Cited by 1 record

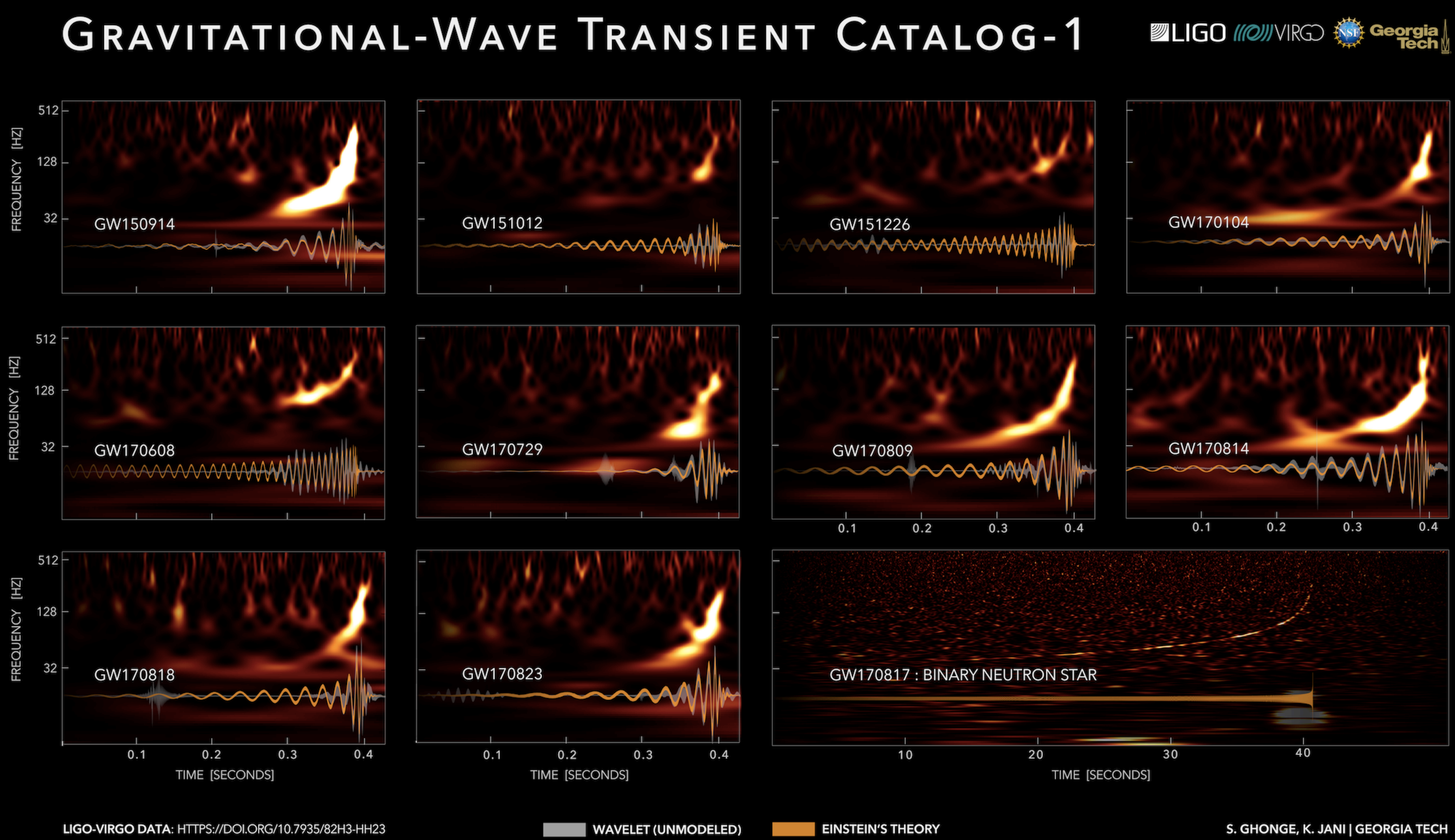
3. **Multimessenger Universe with Gravitational Waves from Binaries**
   B.S. Sathyaprakash (Penn State U. & Cardiff U.) *et al.*. Mar 22, 2019. 11 pp.
   e-Print: **arXiv:1903.09277 [astro-ph.HE] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

4. **Deeper, Wider, Sharper: Next-Generation Ground-Based Gravitational-Wave Observations of Binary Black Holes**
   Vassiliki Kalogera (Northwestern U. (main)) *et al.*. Mar 21, 2019. 14 pp.
   e-Print: **arXiv:1903.09220 [astro-ph.HE] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record - Cited by 1 record

5. **Cosmology and the Early Universe**
   B.S. Sathyaprakash (Penn State U.) *et al.*. Mar 21, 2019. 13 pp.
   e-Print: **arXiv:1903.09260 [astro-ph.HE] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

LIGO-VIRGO DISCOVERIES:

A NEW ERA IN FUNDAMENTAL PHYSICS, ASTROPHYSICS AND COSMOLOGY

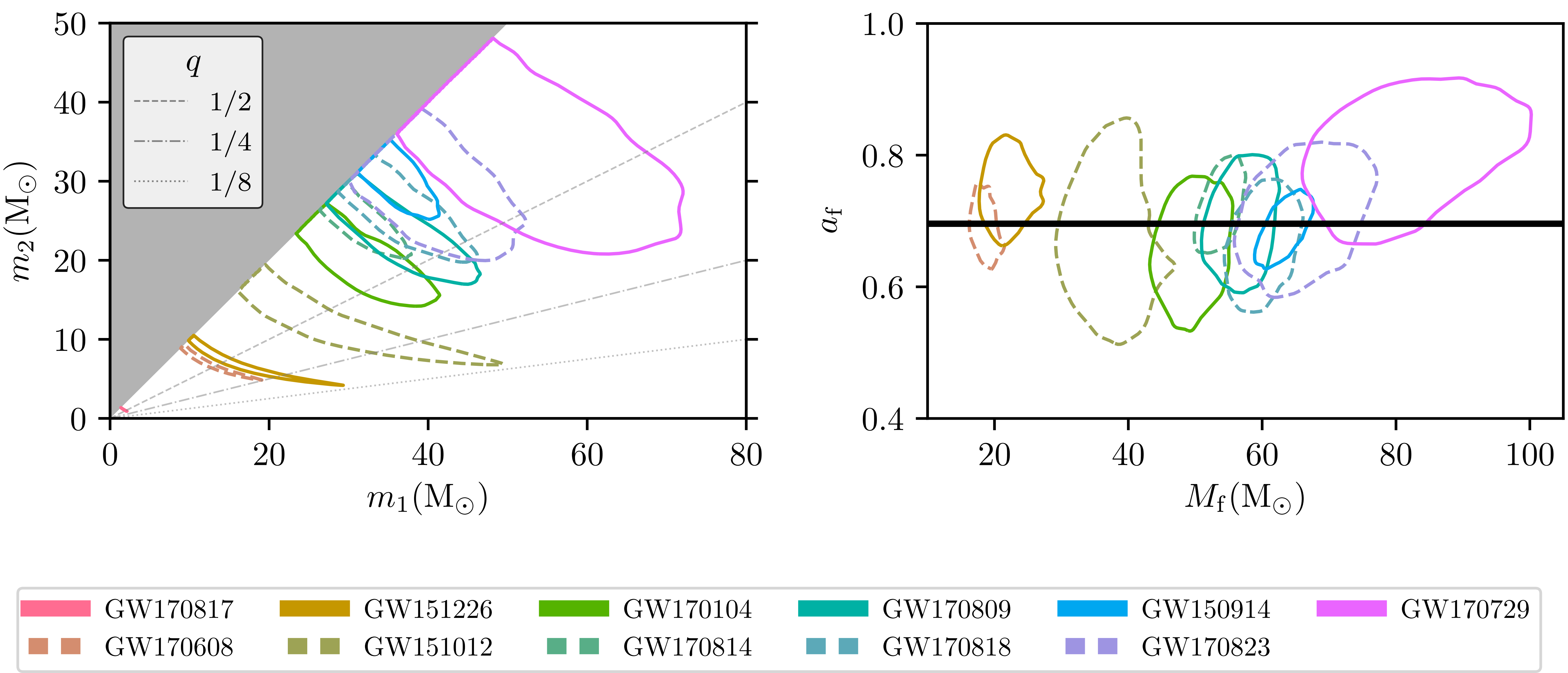


GROUNDBREAKING SCIENCE FROM GW DISCOVERIES - THE STORY SO FAR

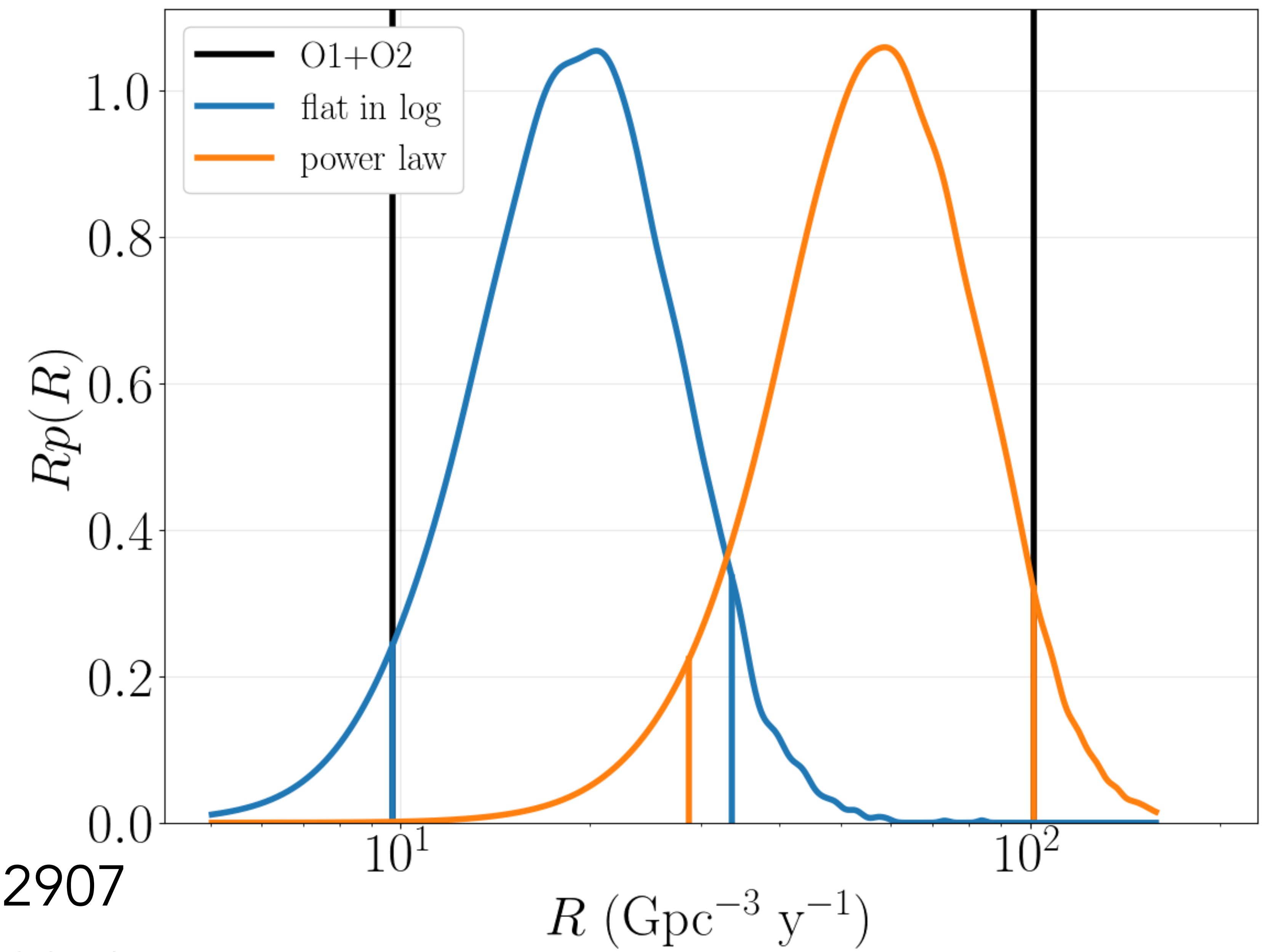
- opened a new window to observe the dark sector, inaccessible to others
  - confirmed existence of merging binary black holes, rate well constrained
    - the most luminous sources in the Universe
  - matter under extreme environs
    - highest densities and greatest temperatures but for the big bang
- confirmed gravitational wave generation beyond quadrupole formula
  - tails of gravitational waves, absorption of radiation by black holes, …
- discovered a completely new class of black holes
  - totally unexpected properties:
    - > 30 $M_\odot$ black holes, spins ~ 0 (?), a challenge to theory
- origin of short GRBs resolved by GW170817 and GW170817
  - helped identify sites of heavy element production
  - constrained the speed of gravitational waves to 1 part in 10^{16} of light speed

SOURCE PROPERTIES

- maximum dimensionless spin of remnant BH when two non-spinning black holes merge ~ 0.69



COALESCENCE RATES



arXiv:1811.12907

arXiv:1811.12940

BBH Rate: 9.7 – 101 Gpc^{-3} y^{-1}

BNS Rate: 110 – 3840 Gpc^{-3} y^{-1}

PUBLIC ALERTS IN THE 3RD OBSERVING RUN

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created
S190524q	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	ADVOK DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
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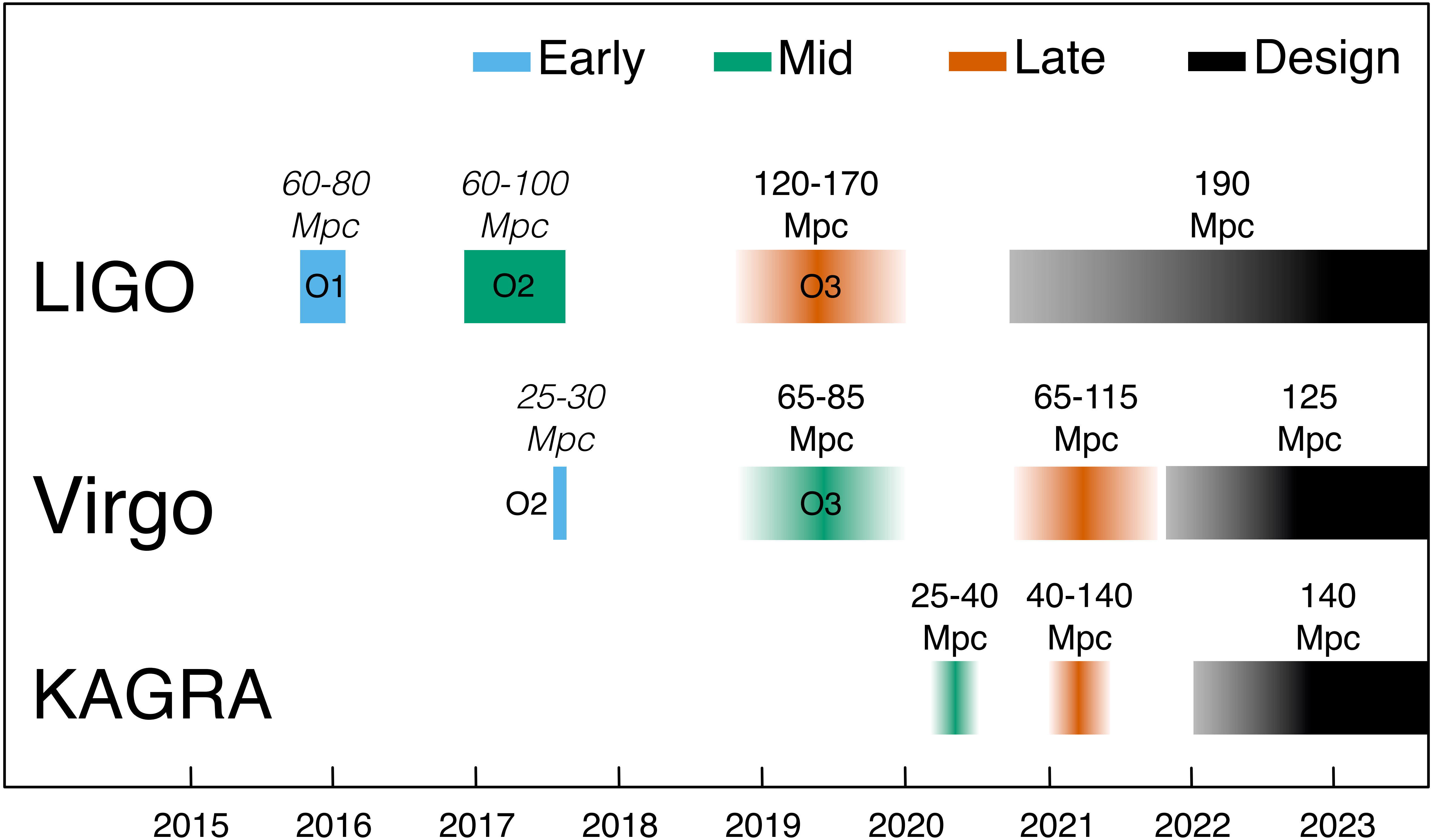
S190517h	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	DQOK PASTRO_READY EMBRIGHT_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT PE_READY	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT ADVOK PE_READY	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVNO	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

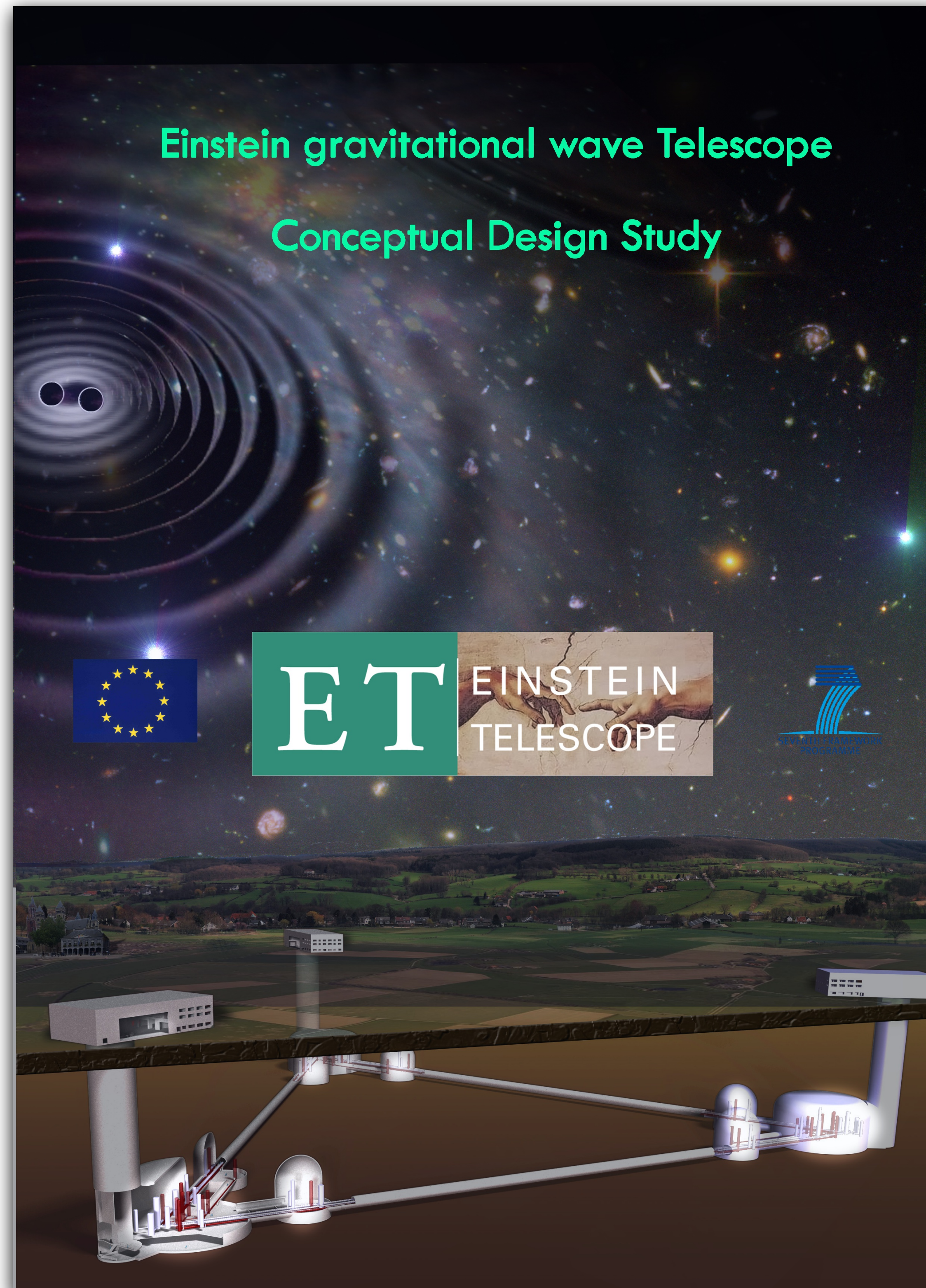
UPCOMING RUNS AND SENSITIVITIES



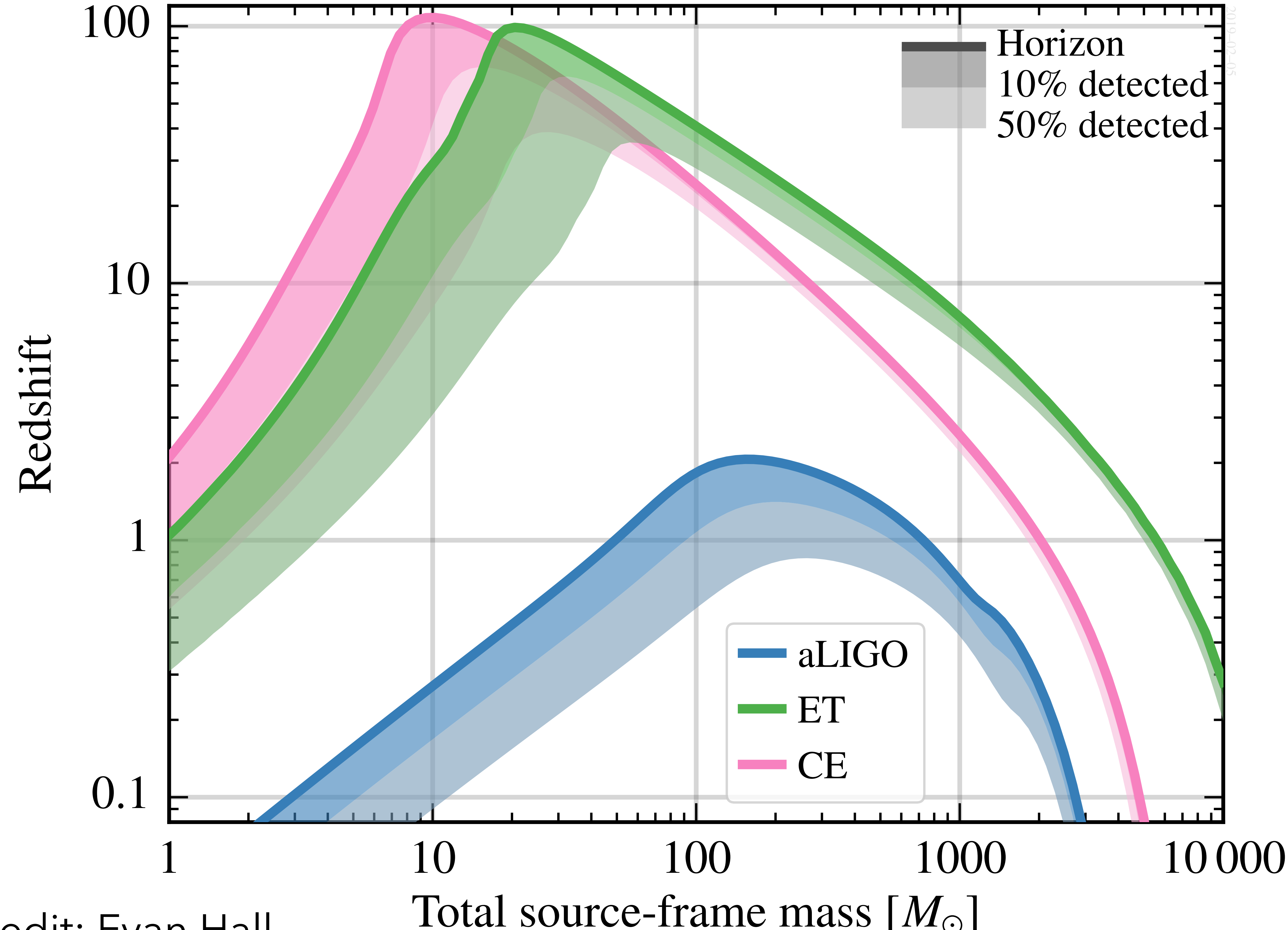
Abbott+, Living Rev. Relativity (2018) 21:3

EINSTEIN TELESCOPE AND COSMIC EXPLORER

- Einstein Telescope
  - FP7 conceptual design study
  - underground, 10-km arm triangle
  - design study completed in ’11
  - 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+
- Cosmic explorer
  - 40 km arm ground-based
  - NSF funded design study: 2018-2021



3G NETWORK SENSITIVITY

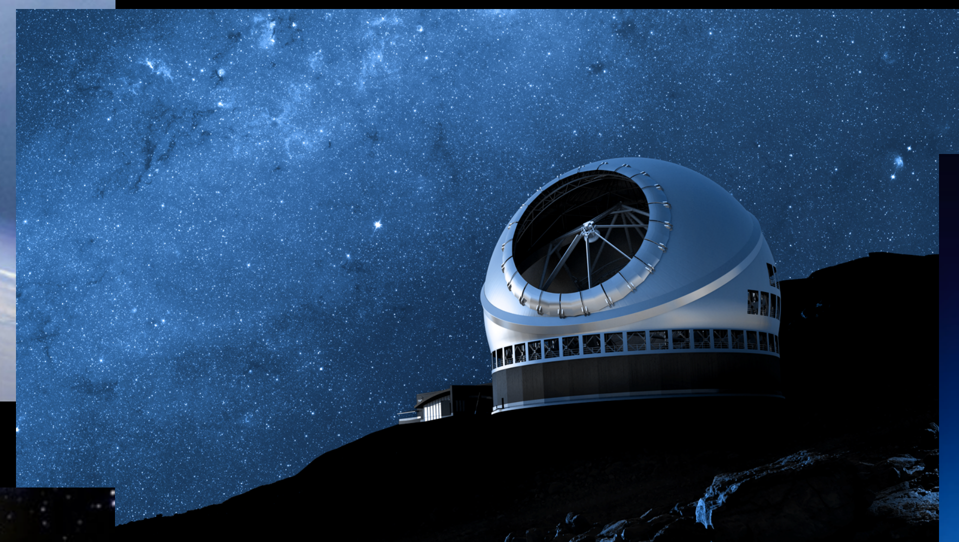


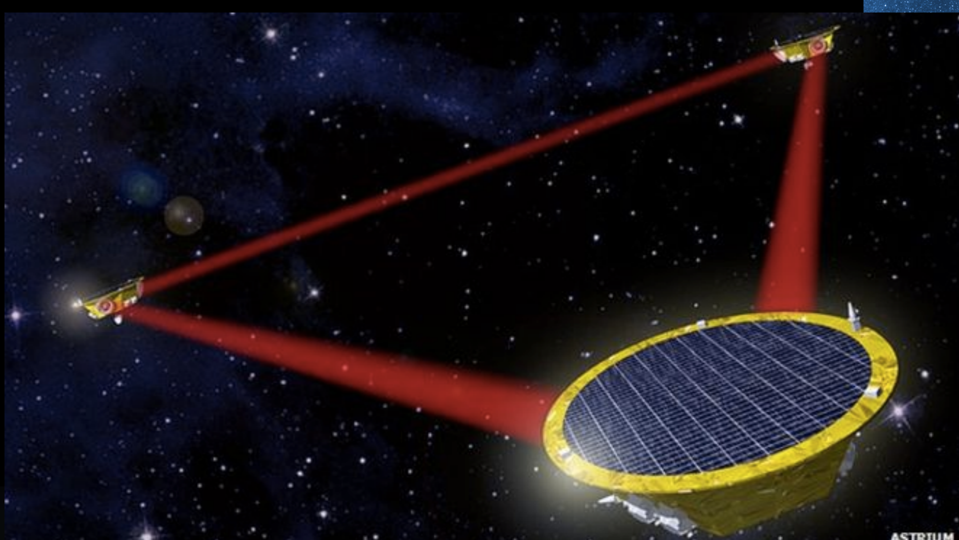
Credit: Evan Hall

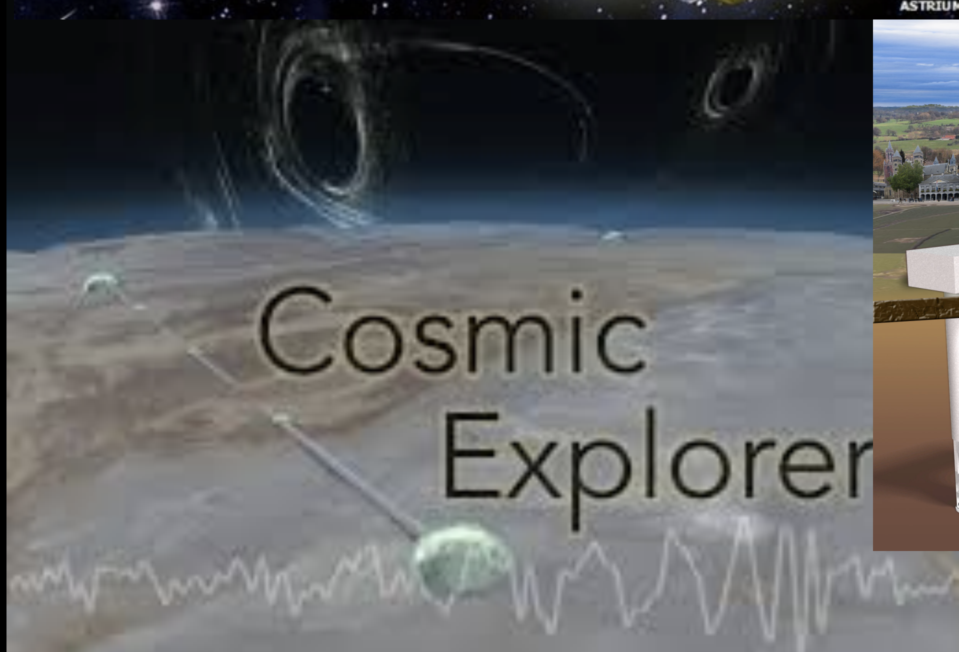
WITH 3G WE WILL EXPLORE FUNDAMENTAL PROPERTIES OF SPACETIME AND MATTER

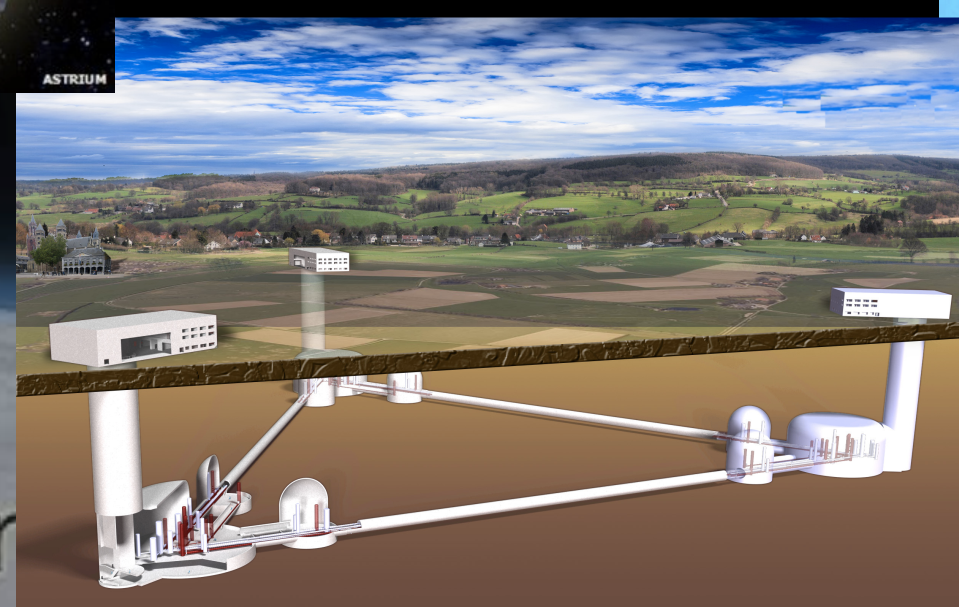
- multimessenger astronomy
  - sites of r-process heavy element production, BNS vs NSBH, etc.
- equation of state of dense nuclear matter
  - size of neutron stars; are there phase transitions beyond nucleons
- standard siren cosmology
  - Hubble parameter, dark energy equation of state and its variation with z
- 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, …
- 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.

MULTIMESSENGER OBSERVATIONS



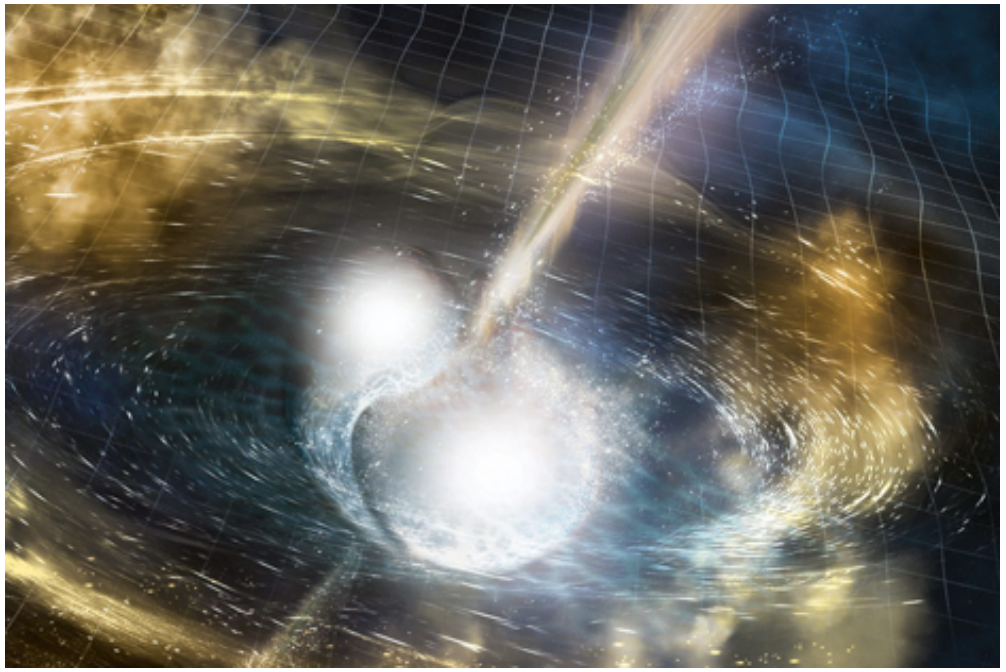


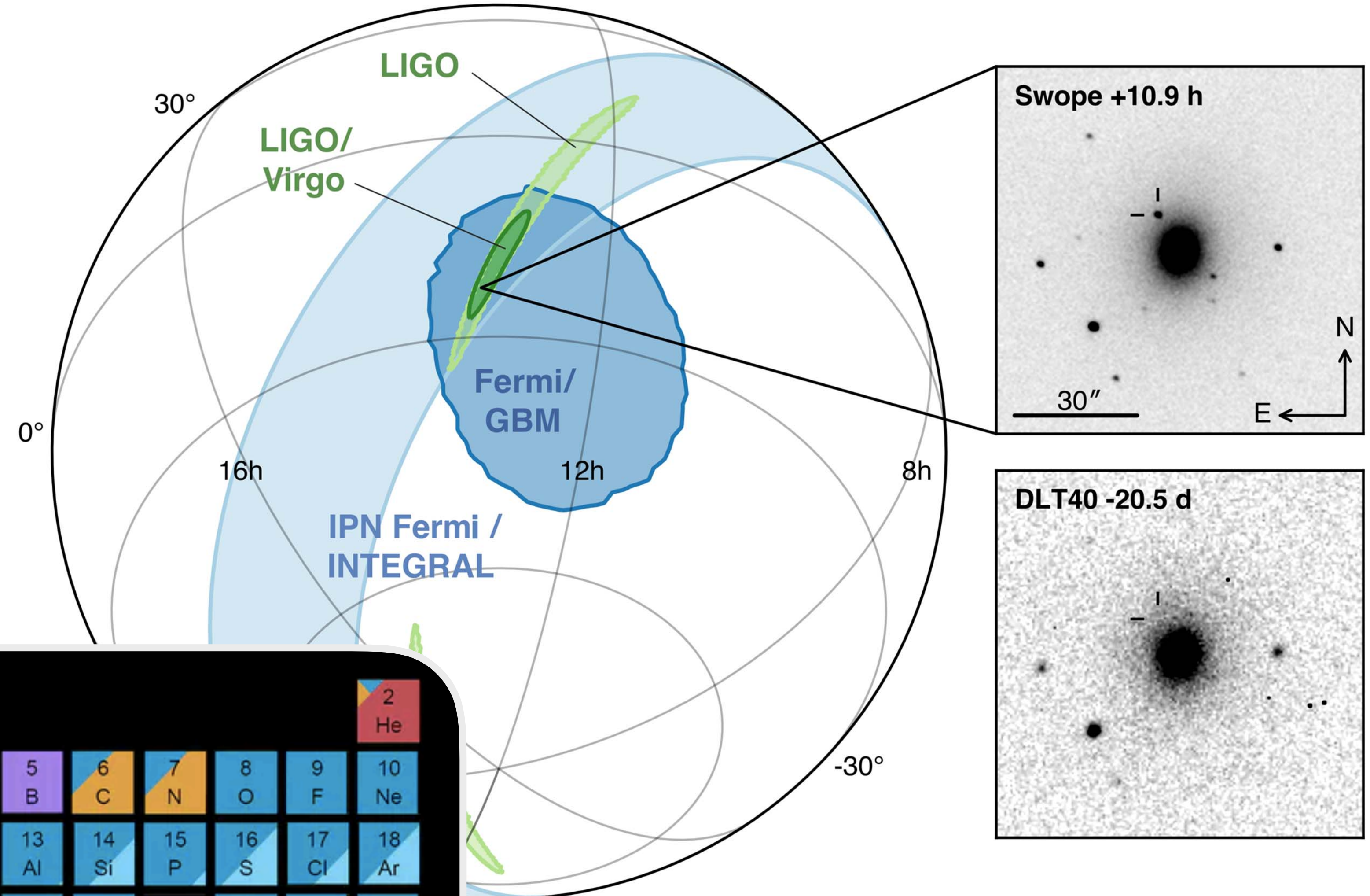


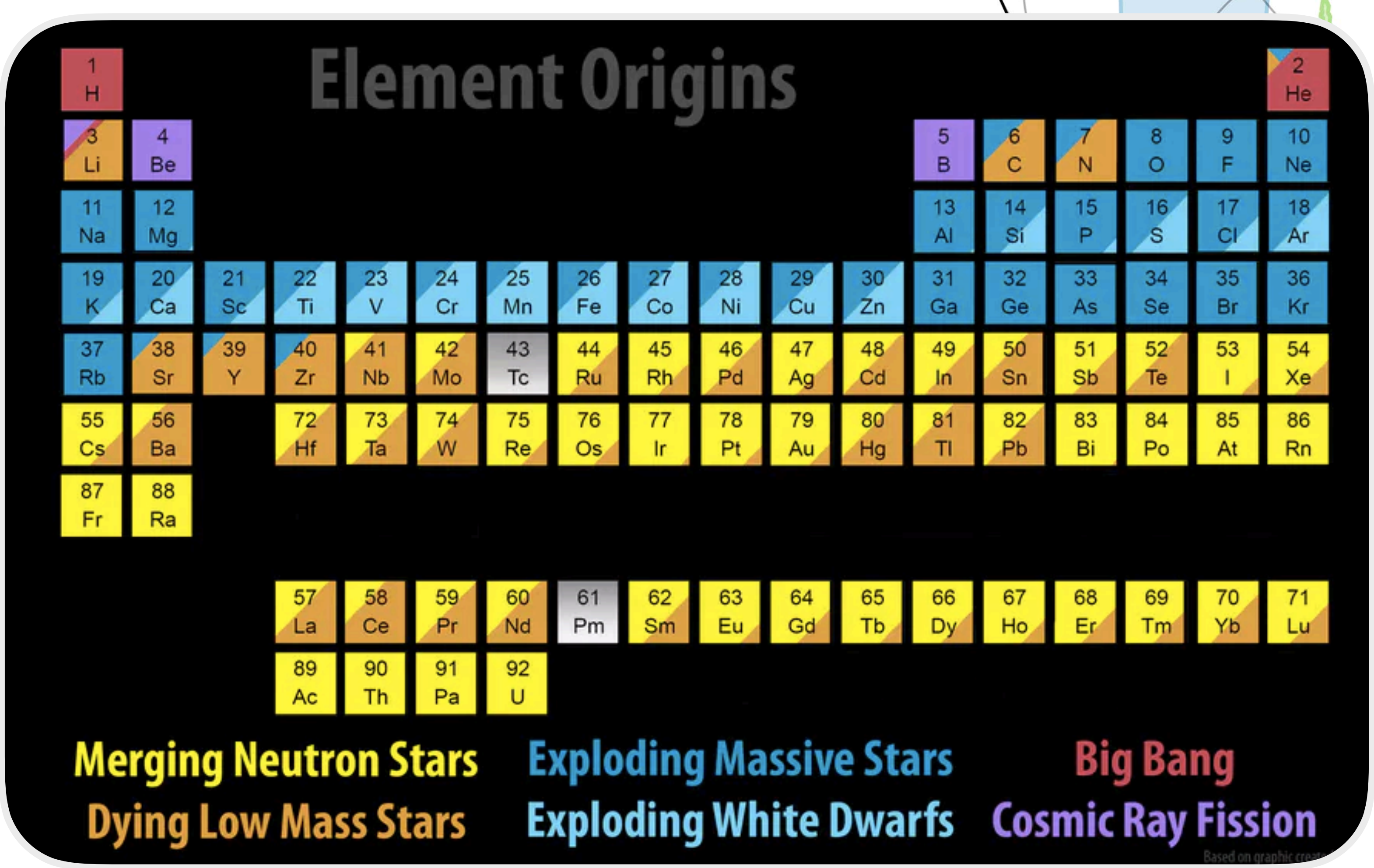


ORIGIN OF HEAVY ELEMENTS

Abbott+ ApJ Letters, 848, L12 (2017)

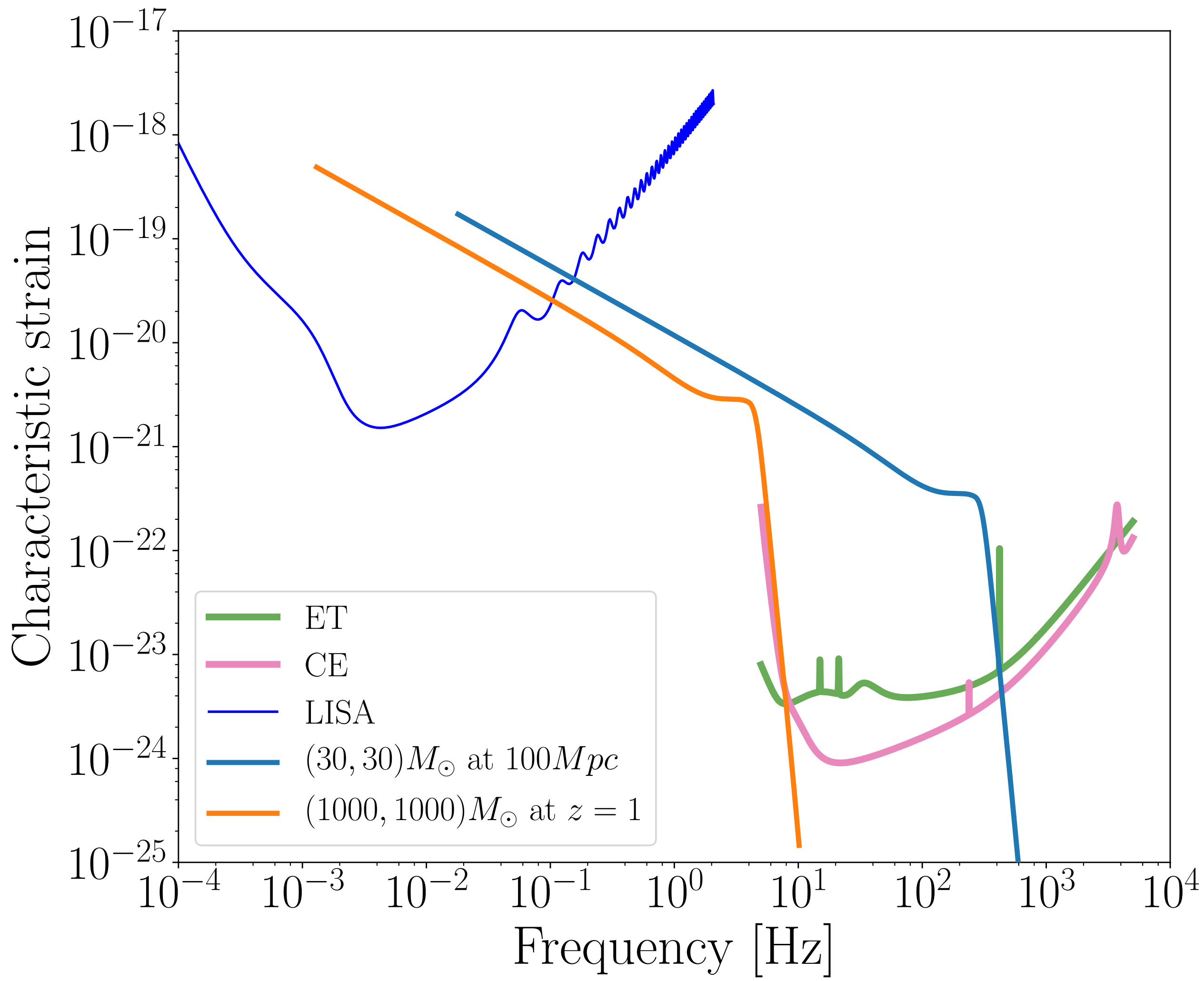




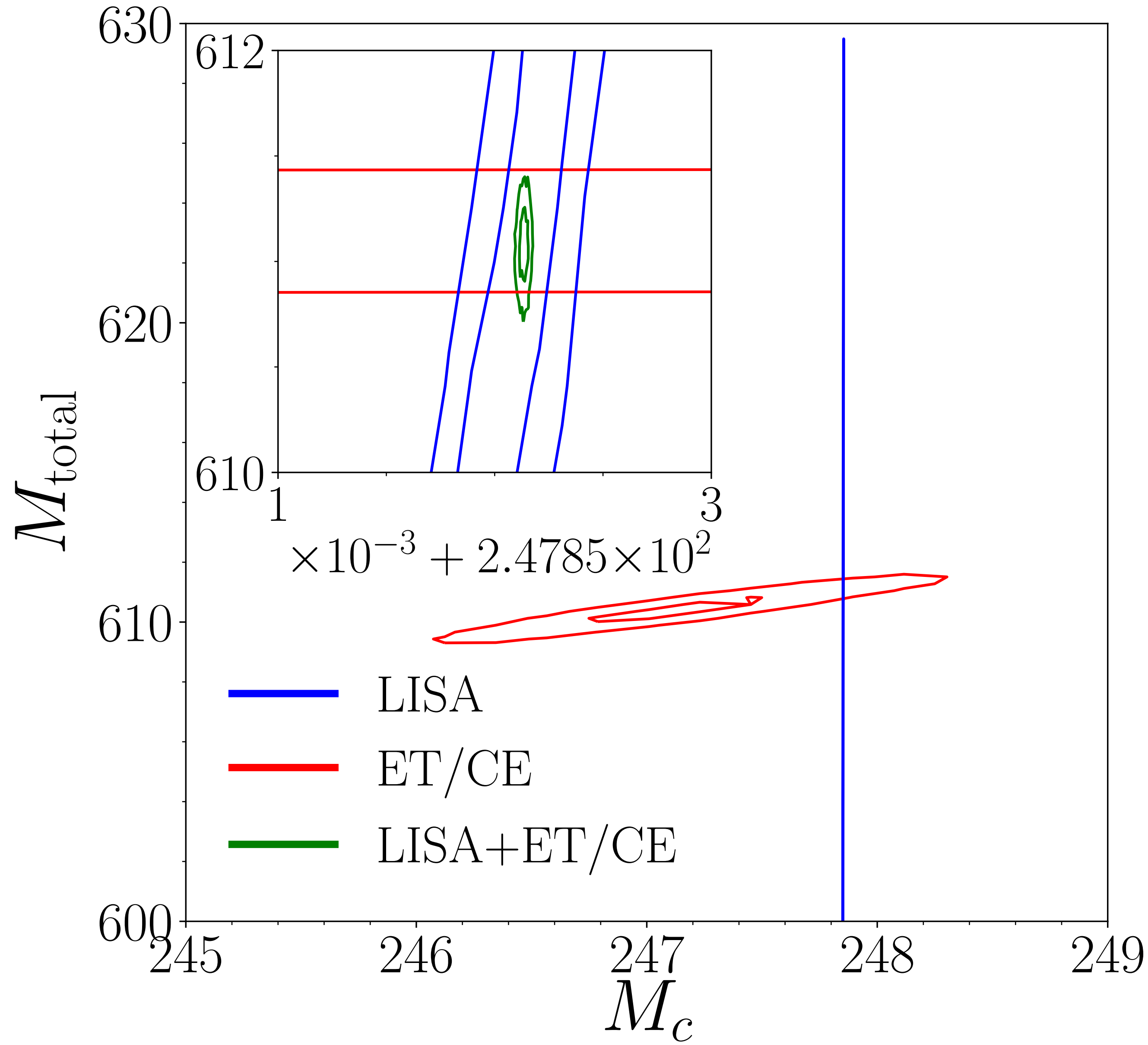


3G network will help identify thousands of kilonova and trace the origin of heavy elements

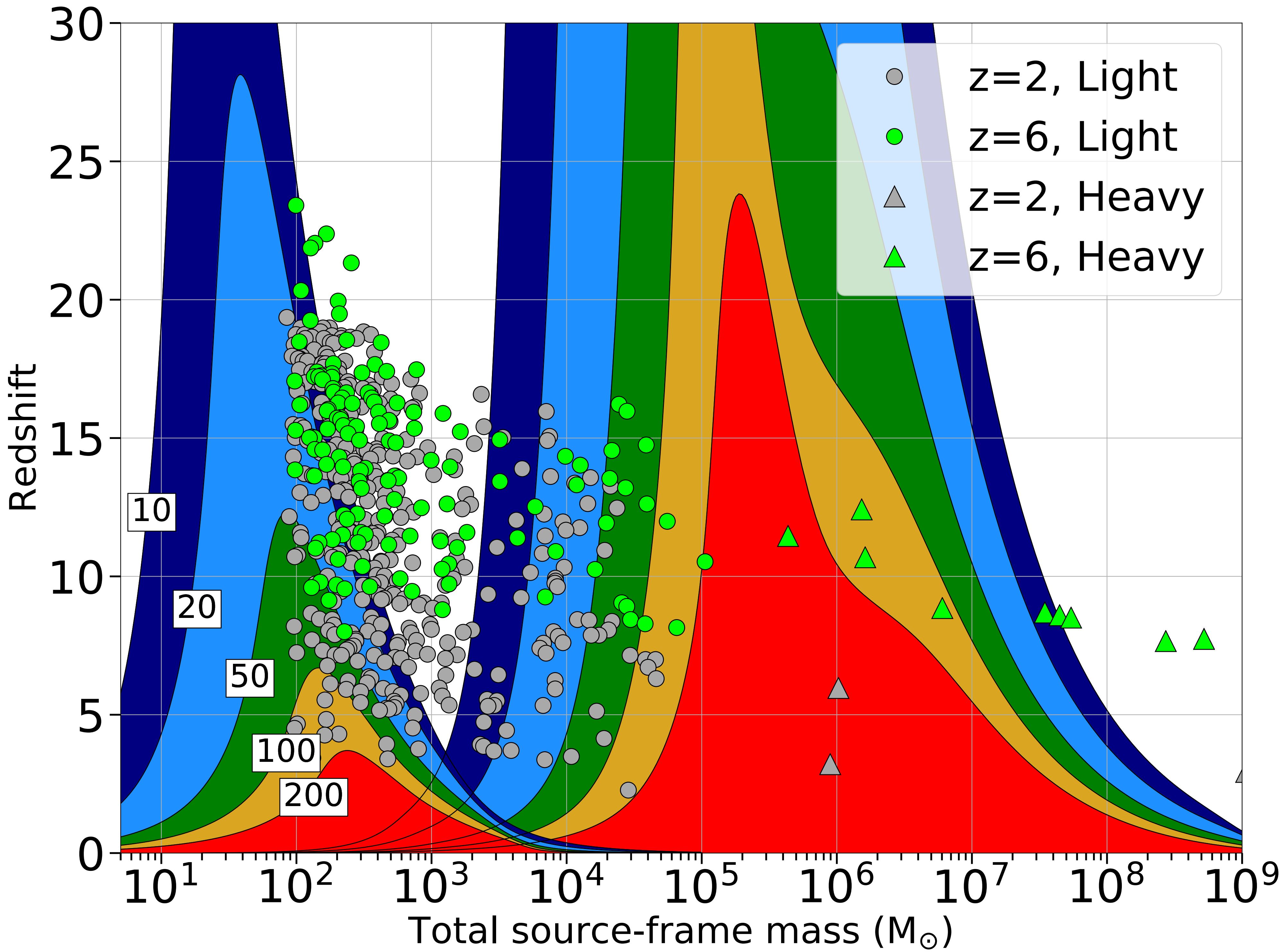
MULTIBAND - LISA AND 3G



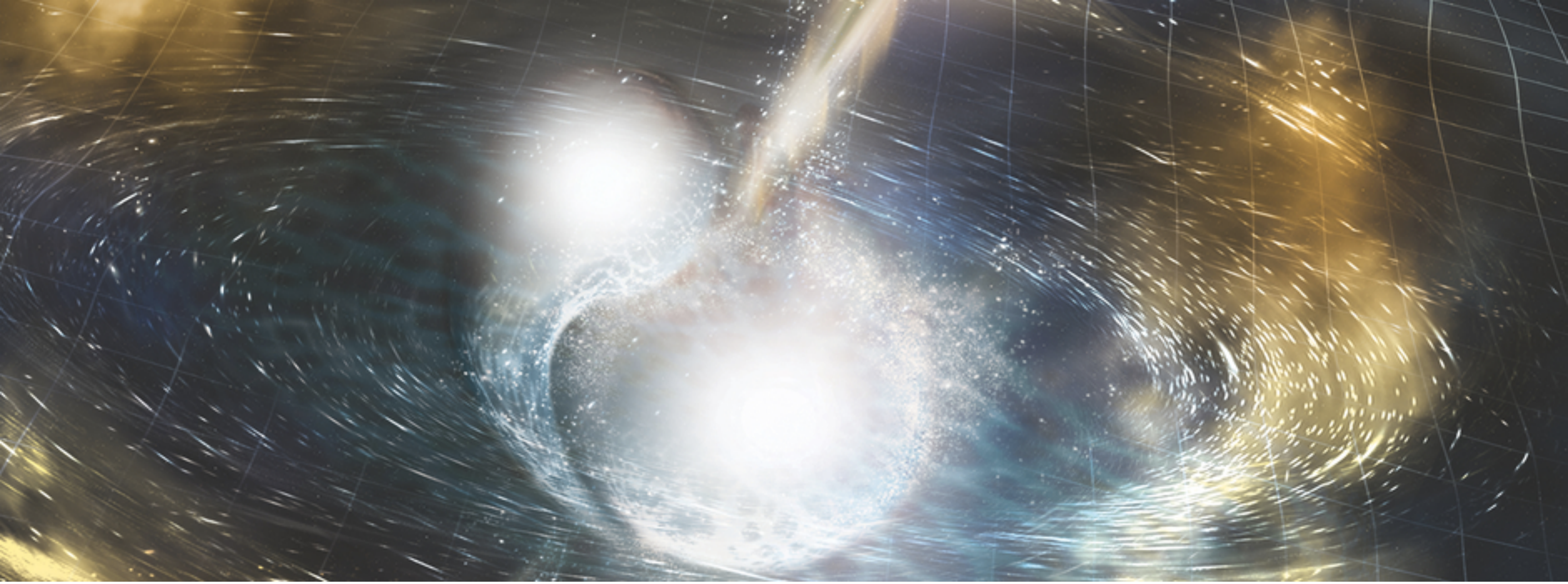
Cutler+ arXiv:1903.04069



ORIGIN & EVOLUTION OF SEED BLACK HOLES

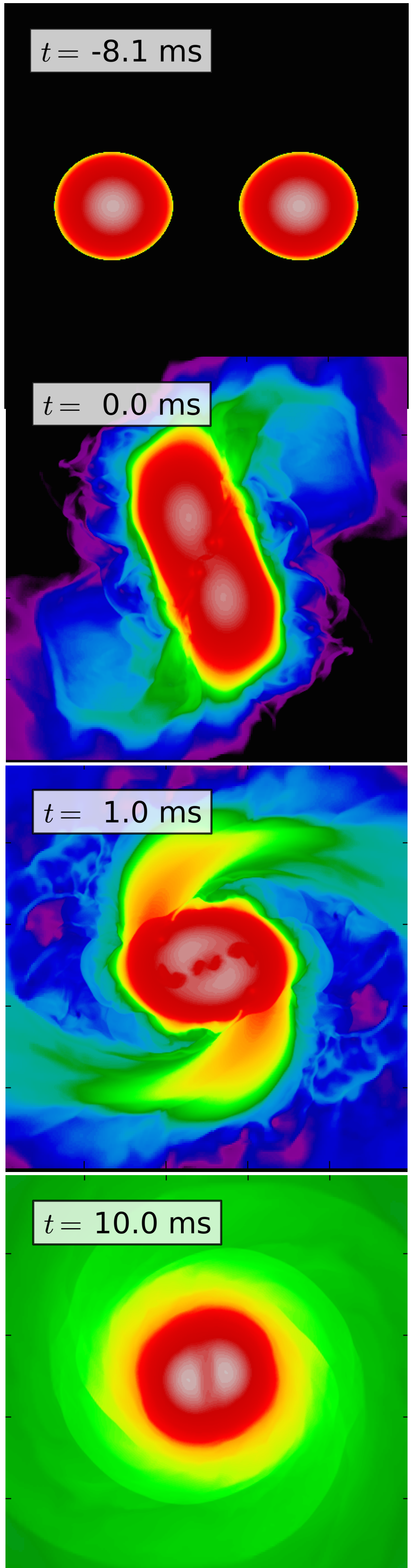


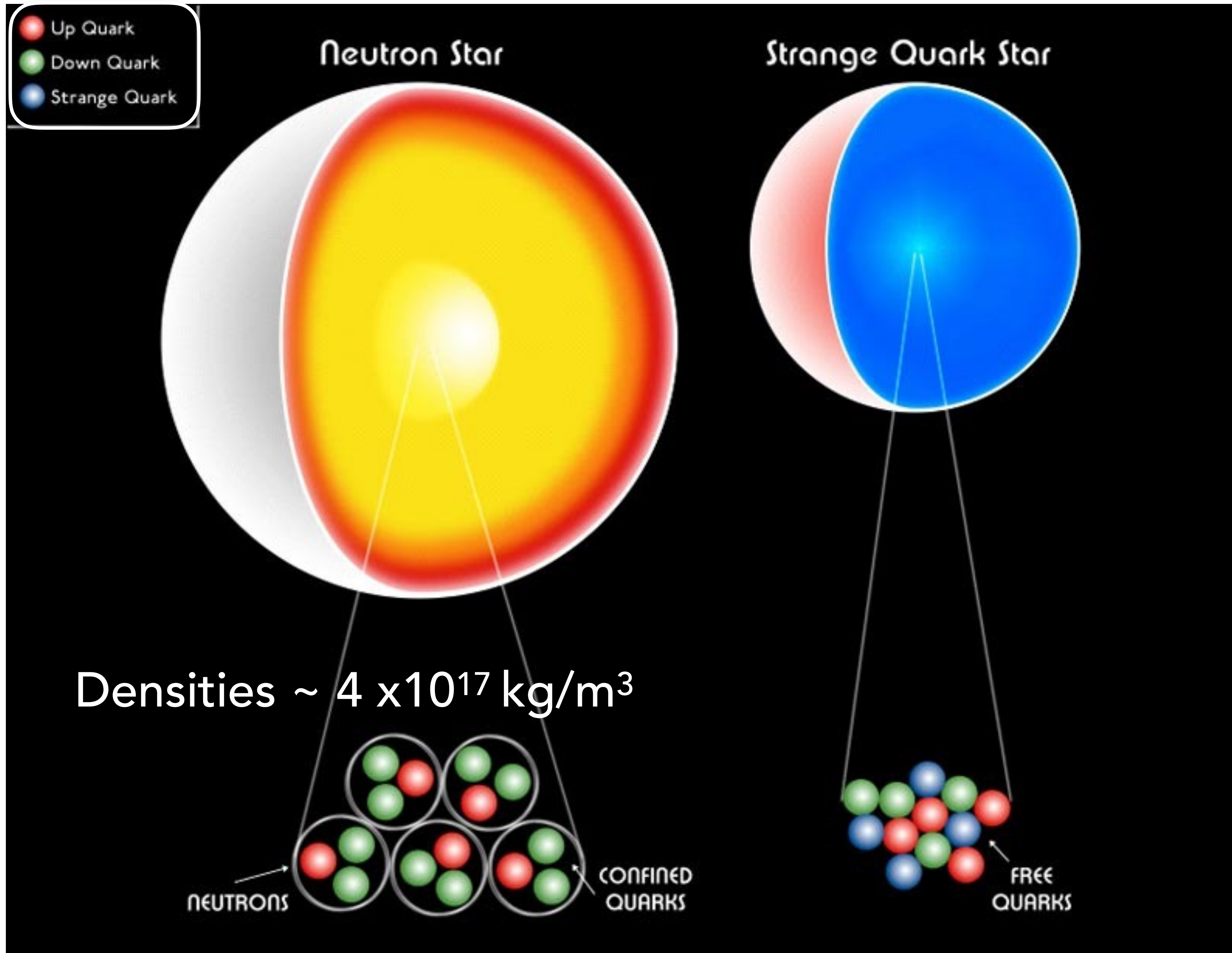
Credit: Alberto Mangiagli



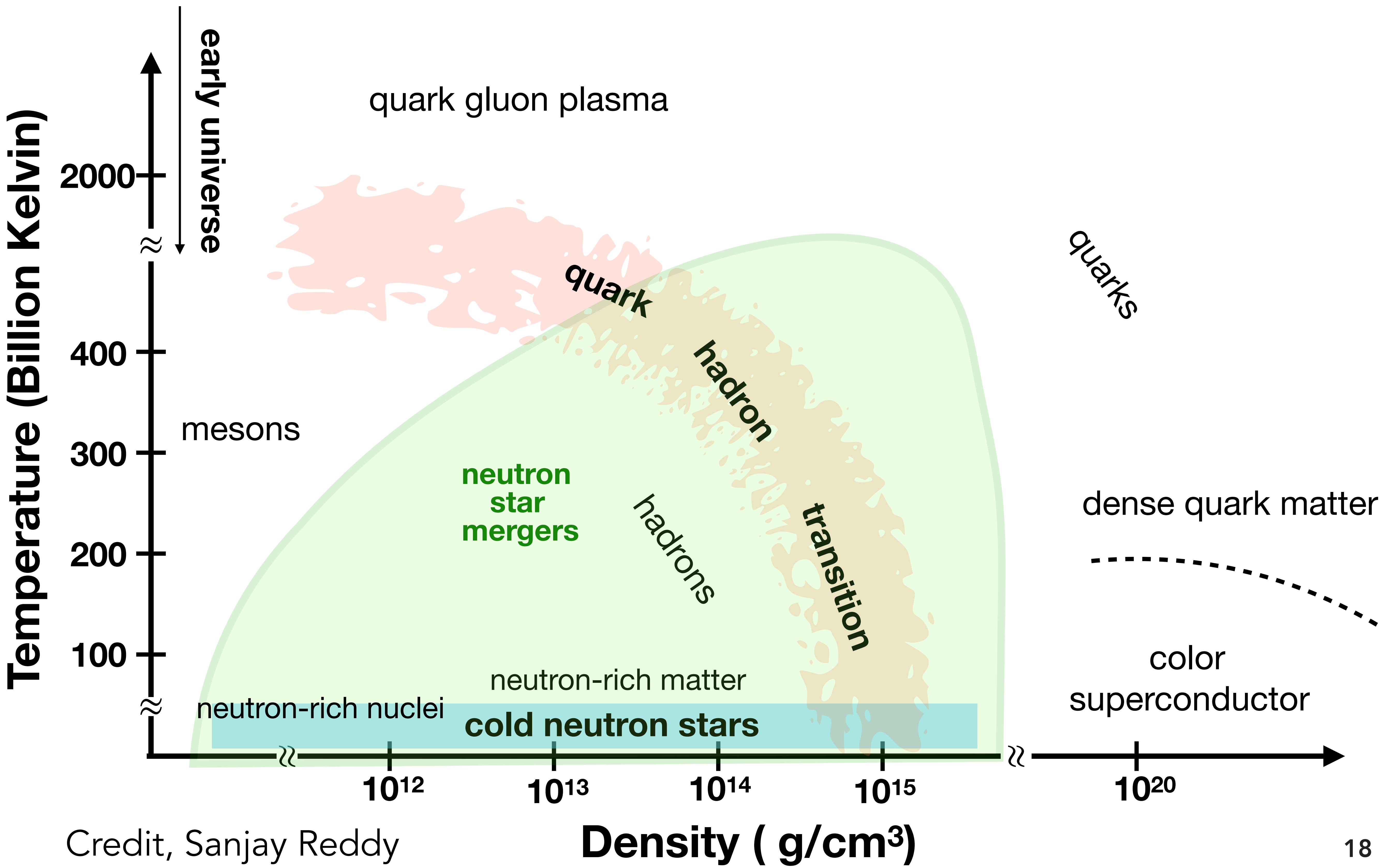
EXTREME MATTER IN EXTREME ENVIRONS

EQUATION OF STATE OF HOTTEST AND DENSEST MATTER



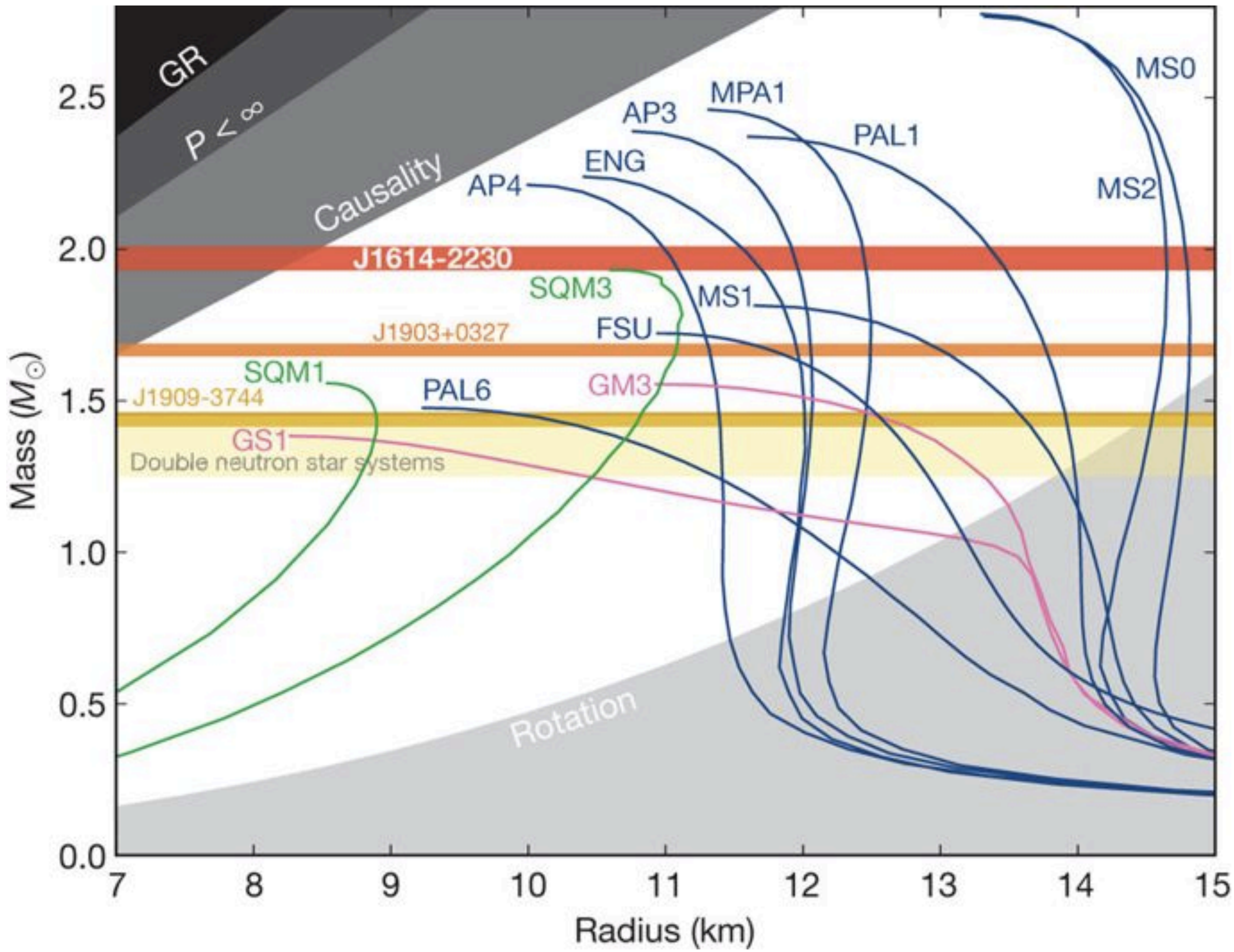


NEUTRON STARS IN THE QCD PHASE DIAGRAM



Credit, Sanjay Reddy

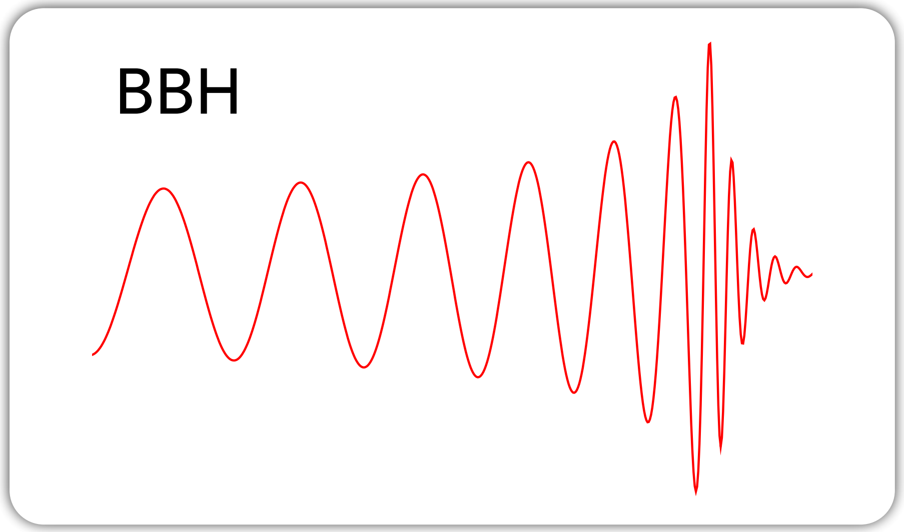
STATE OF DENSE MATTER - TOTALLY UNKNOWN



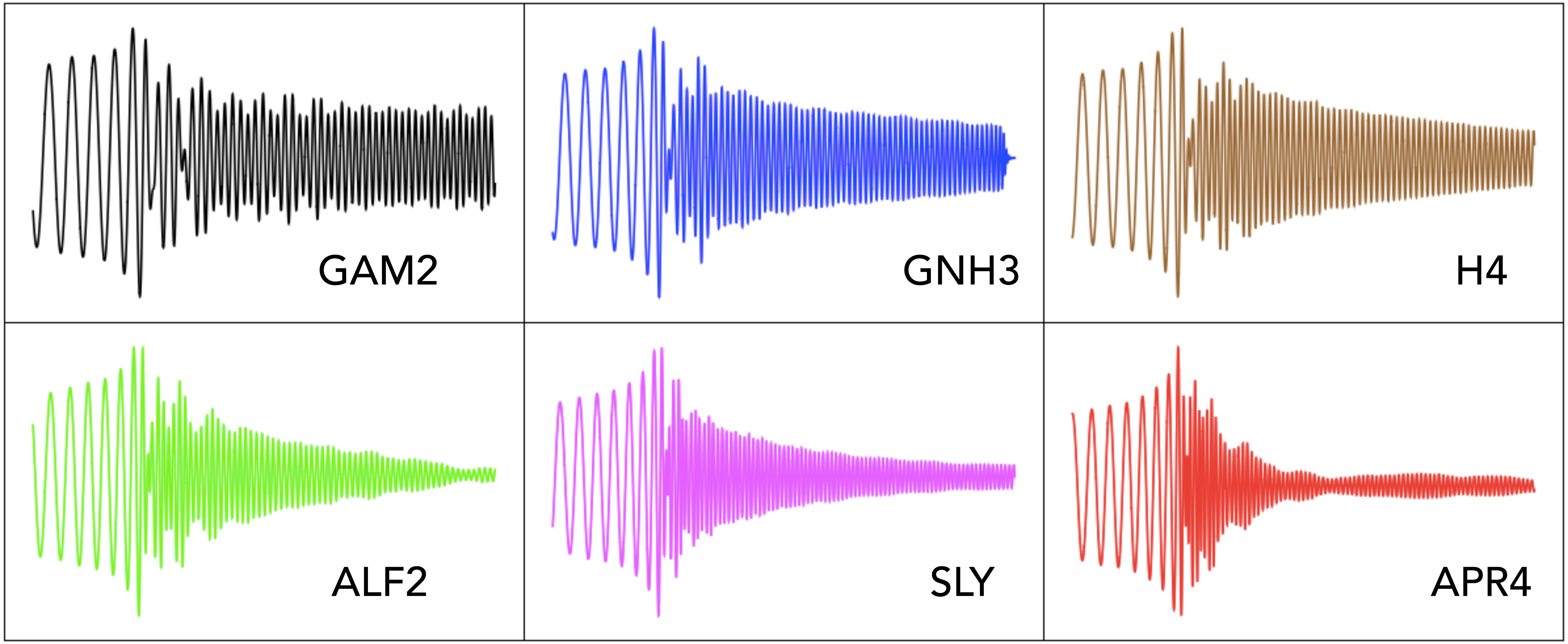
Strange quark **Nucleons plus exotic matter** **Nucleons**

Demorest+, Nature 2010

BINARY NEUTRON STAR MERGER IS VERY DIFFERENT FROM BLACK HOLE MERGER



- inspiral phase: well described by post-Newtonian approximation + tides
- post-merger bar-deformed hyper-massive neutron star

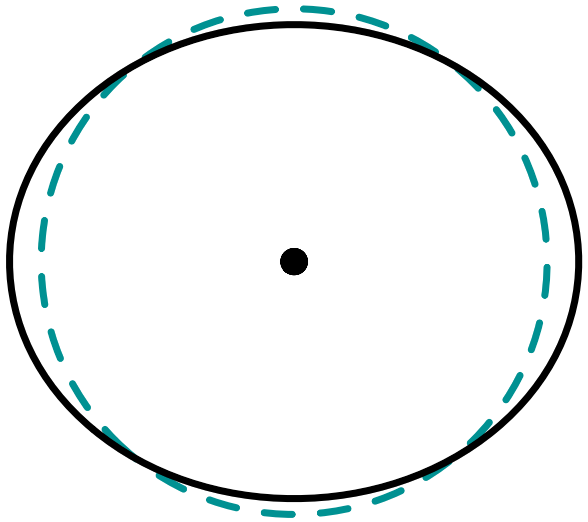


SIGNATURE OF EOS IN INSPIRAL AND POST-MERGER WAVEFORMS

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

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

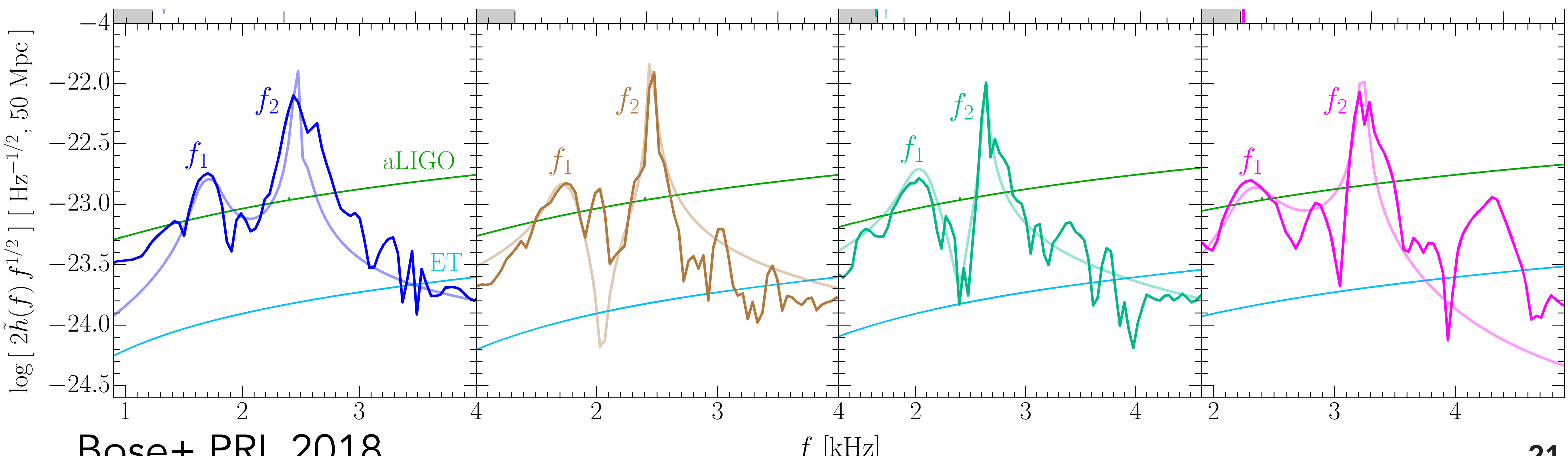
- **$\lambda(m)$** is tidal deformability, **$k_2(m)$** is the Love number and **R** is the NS radius
- post-merger oscillations, stability, extraction of radius, mass and compactness



sketch: J. Read

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

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

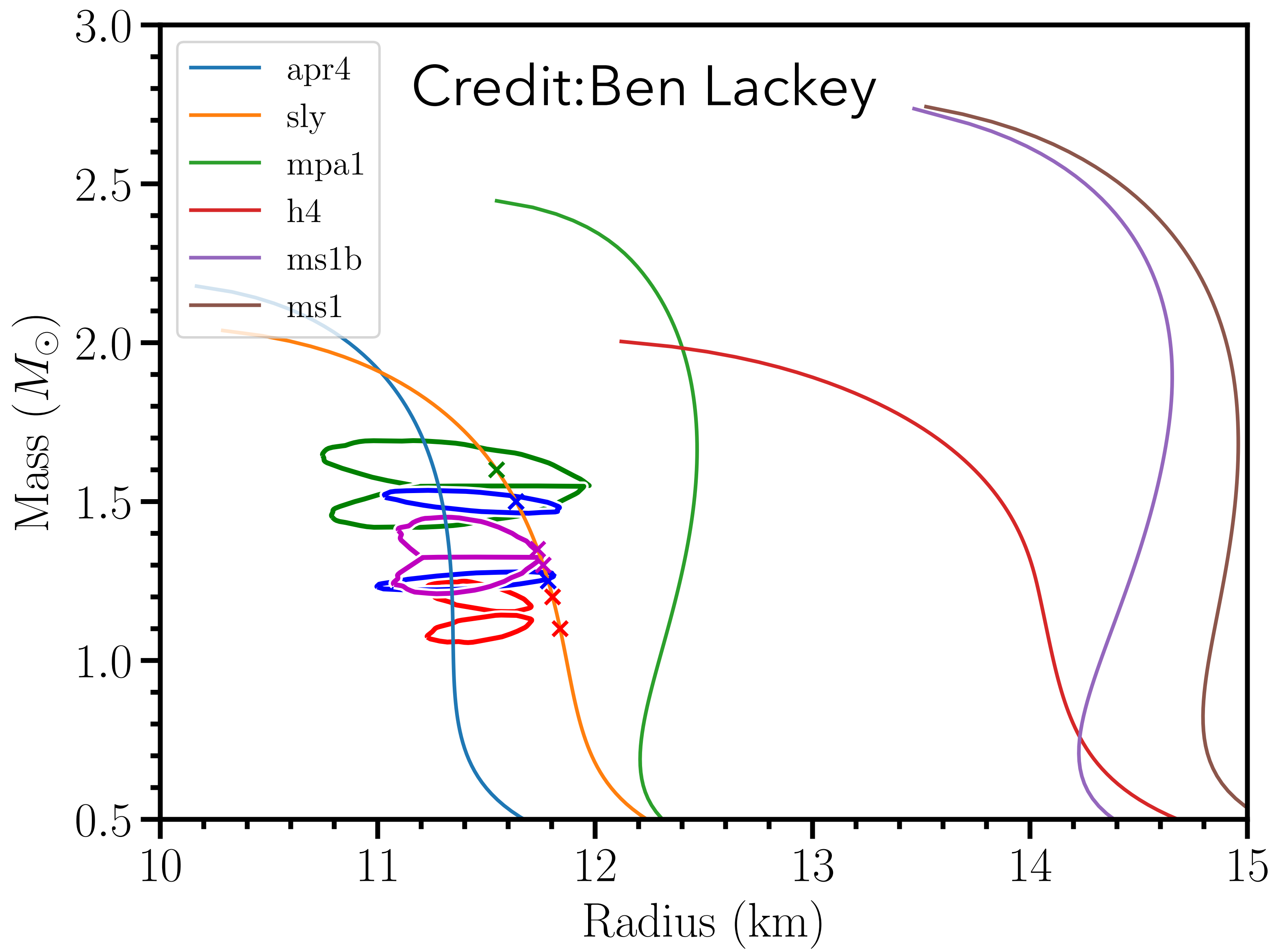


Bose+ PRL 2018

MEASUREMENT OF NEUTRON STAR RADIUS

EOS with 3G

- 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)

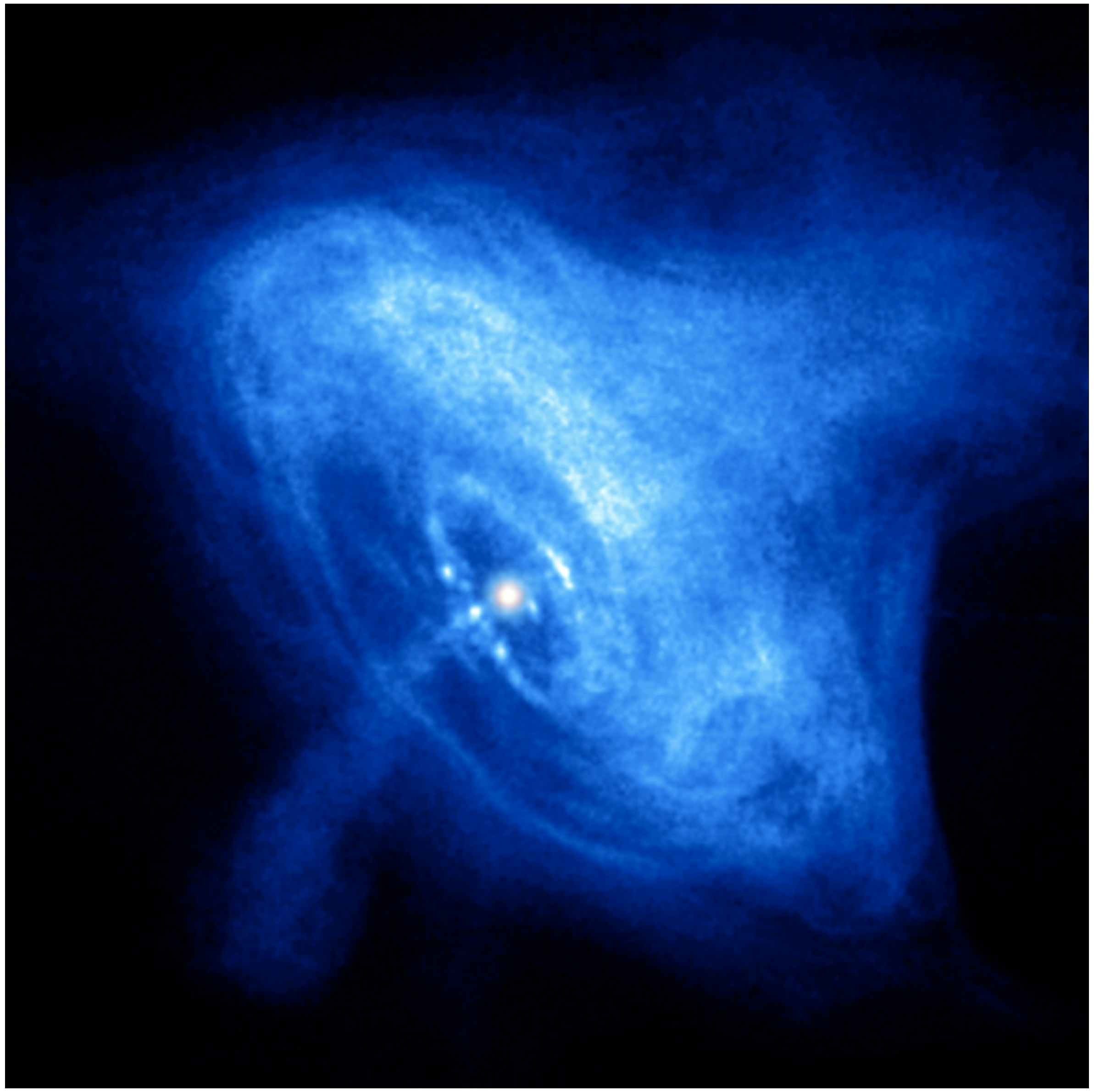


Abbott+, arXiv 1805.11581

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

CONTINUOUS WAVES, PULSAR GLITCHES, MAGNETAR FLARES, ...

- continuous wave sources
  - EOS, elasticity (mountains) of phases; deformations and precession
  - microphysics input: transport in cold matter (shear, bulk viscosities), neutrino cooling
  - GR modeling of oscillations, stability and dependence on EoS
  - effect of magnetic fields, spin-evolution, magnetically induced deformations
  - binary systems: dynamics, X-rays, spin-evolution, QPOs

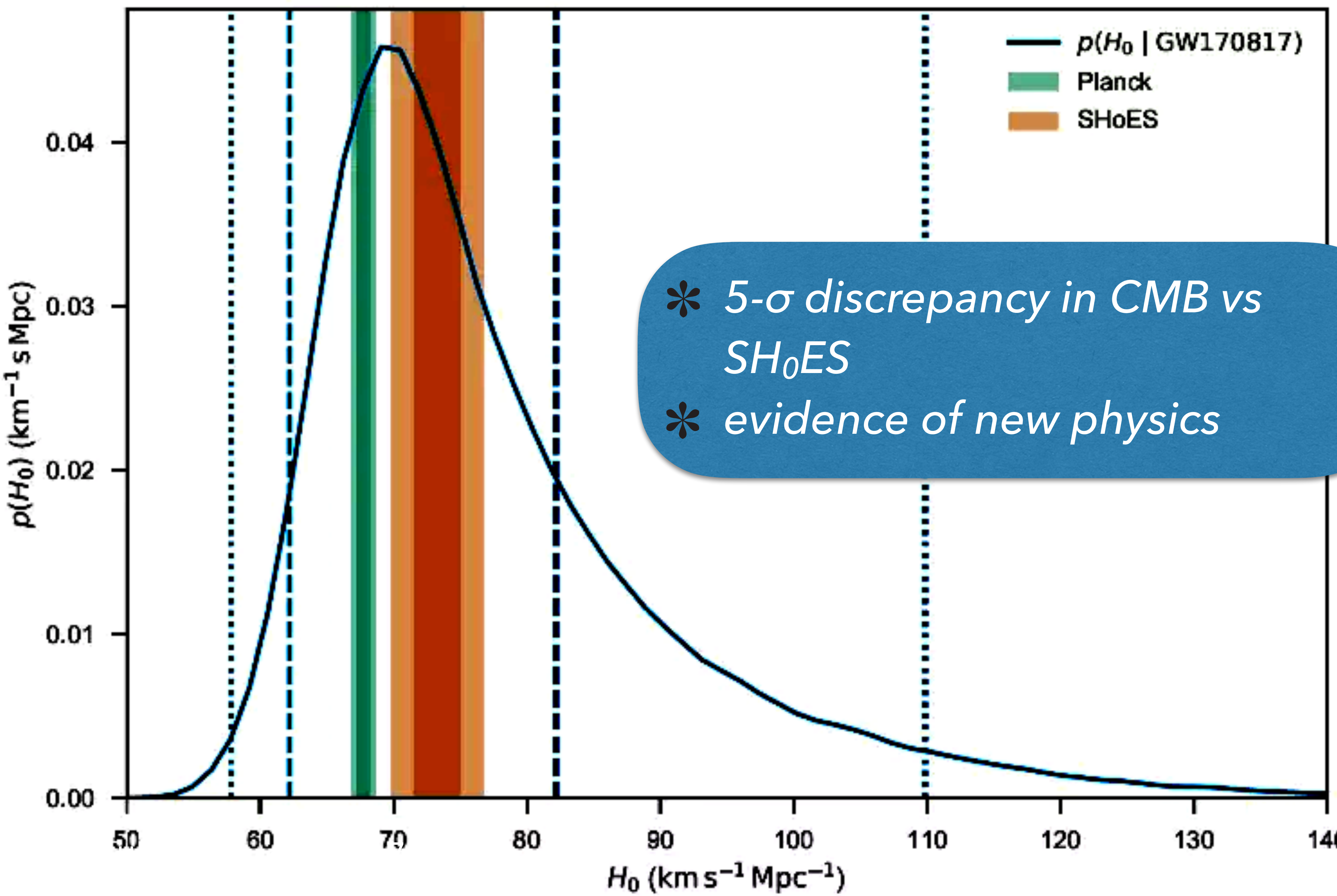


NEUTRON STAR QUAKES

- transients
  - EOS of cold matter, superfluidity for glitches and relaxations, hot-matter in core-collapse
  - microphysics of neutrino interactions in core-collapse, mutual friction in superfluids
  - modelling magnetar oscillations and bursts
  - modeling pulsar glitches, precession, elasticity
- beyond standard model physics GR
  - effects of dark matter particles
  - testing GR with observations of GW
  - modeling phenomena in theories beyond GR

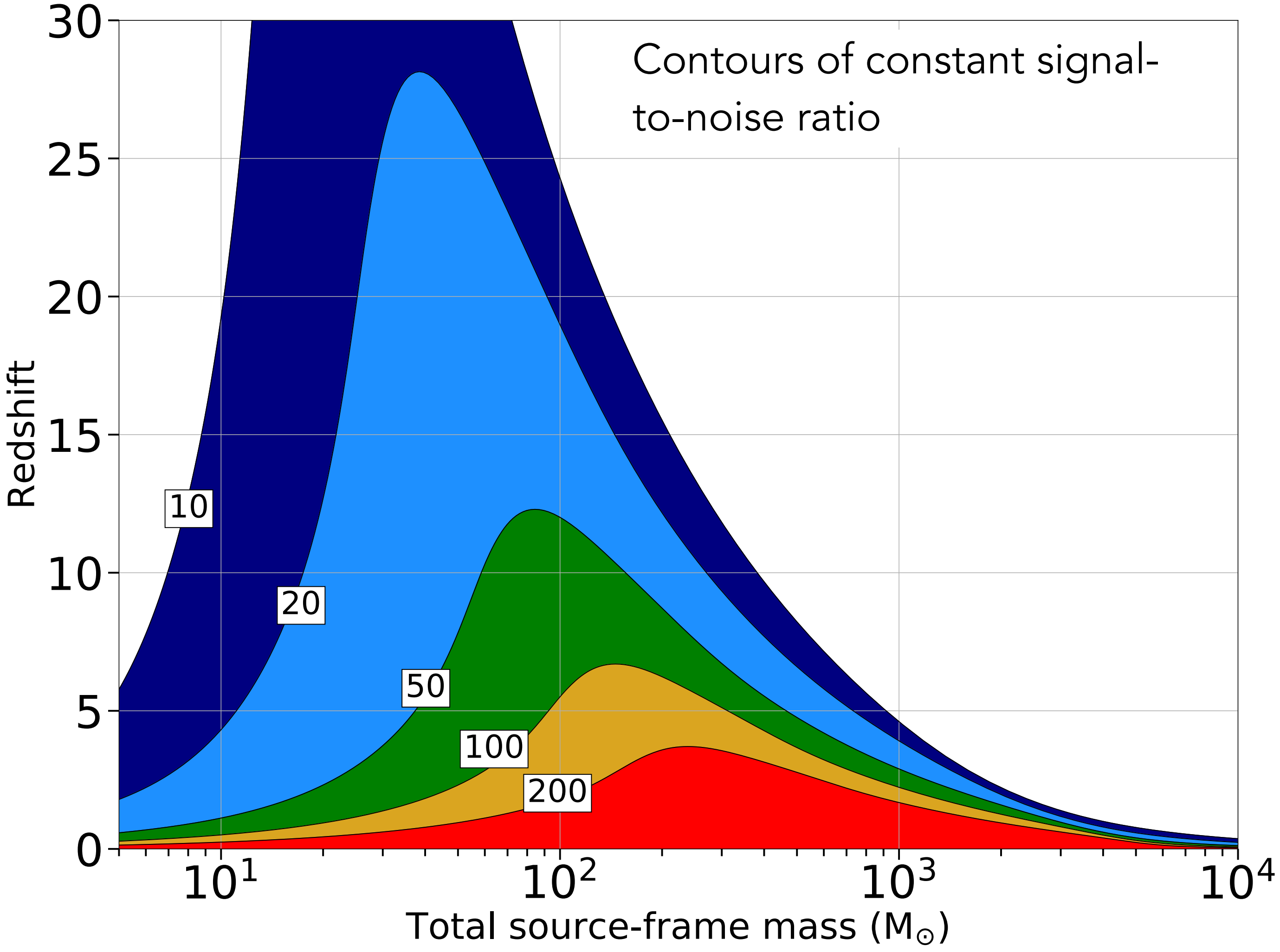
STANDARD SIREN COSMOLOGY

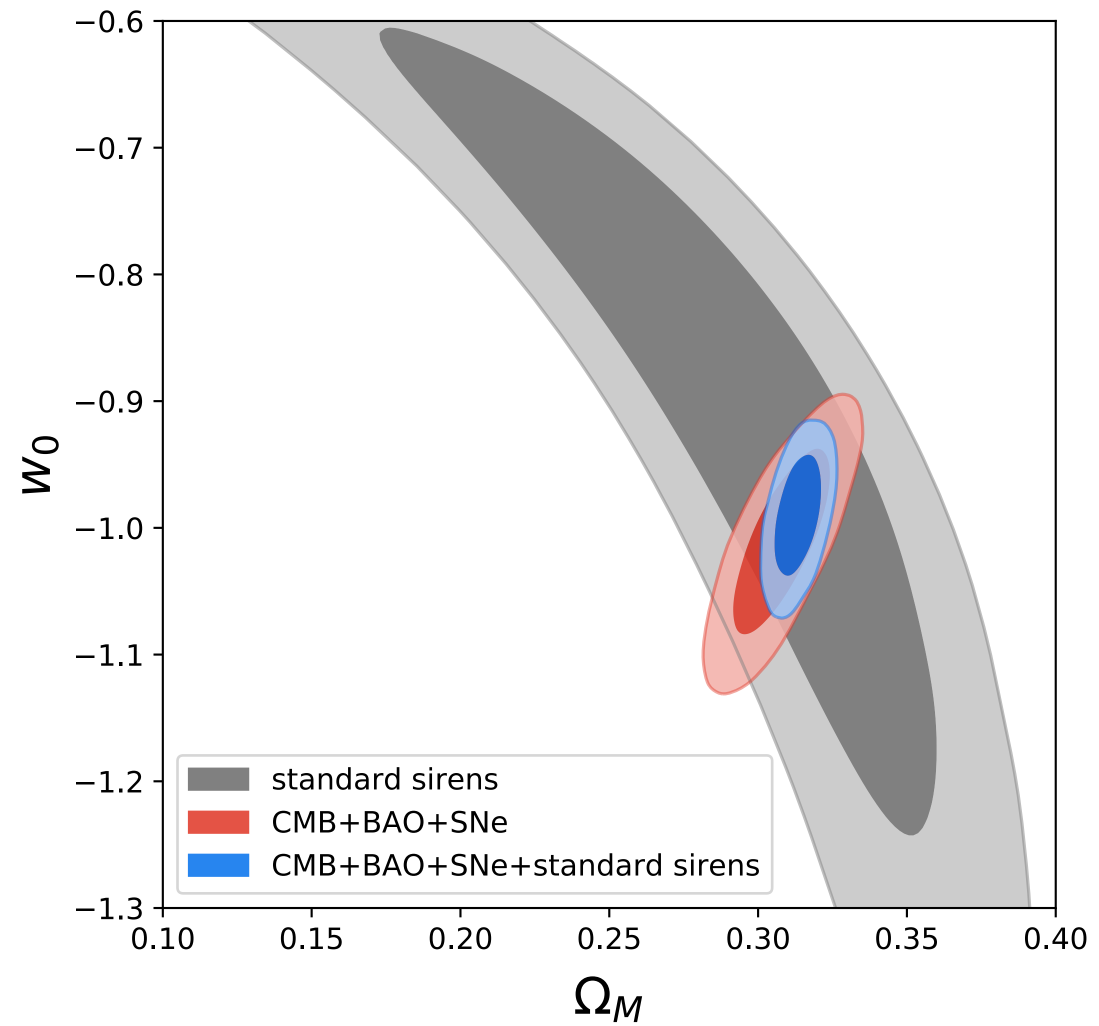
TENSION IN H_0 MEASUREMENT FROM CMB AND SH_0ES PROJECT



- *5-σ discrepancy in CMB vs SH_0ES*
- *evidence of new physics*

3G NETWORK WILL DETECT MILLIONS OF MERGERS

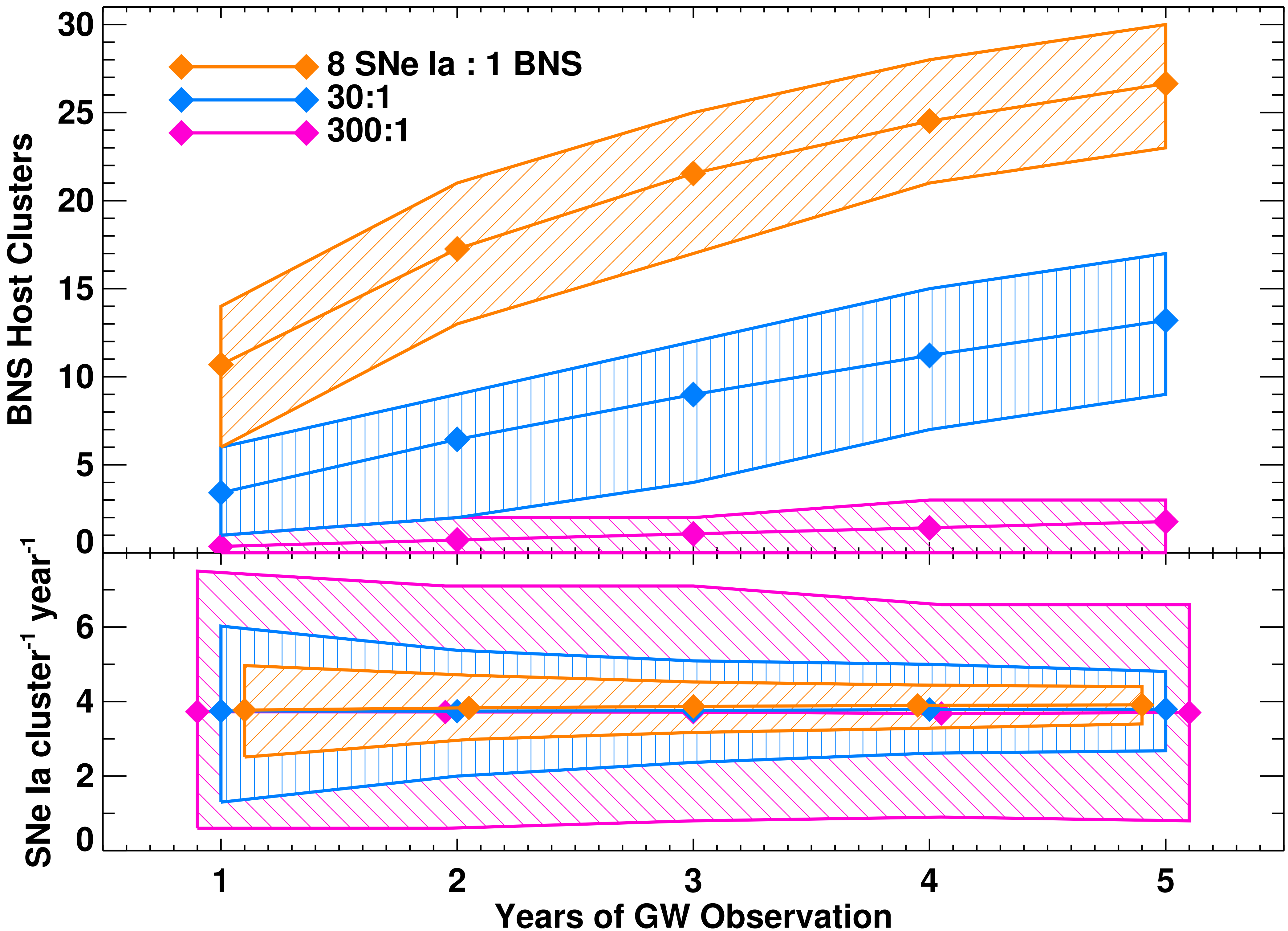




3G network will calibrate nearby supernovae, determine dark energy equation of state and its variation with redshift

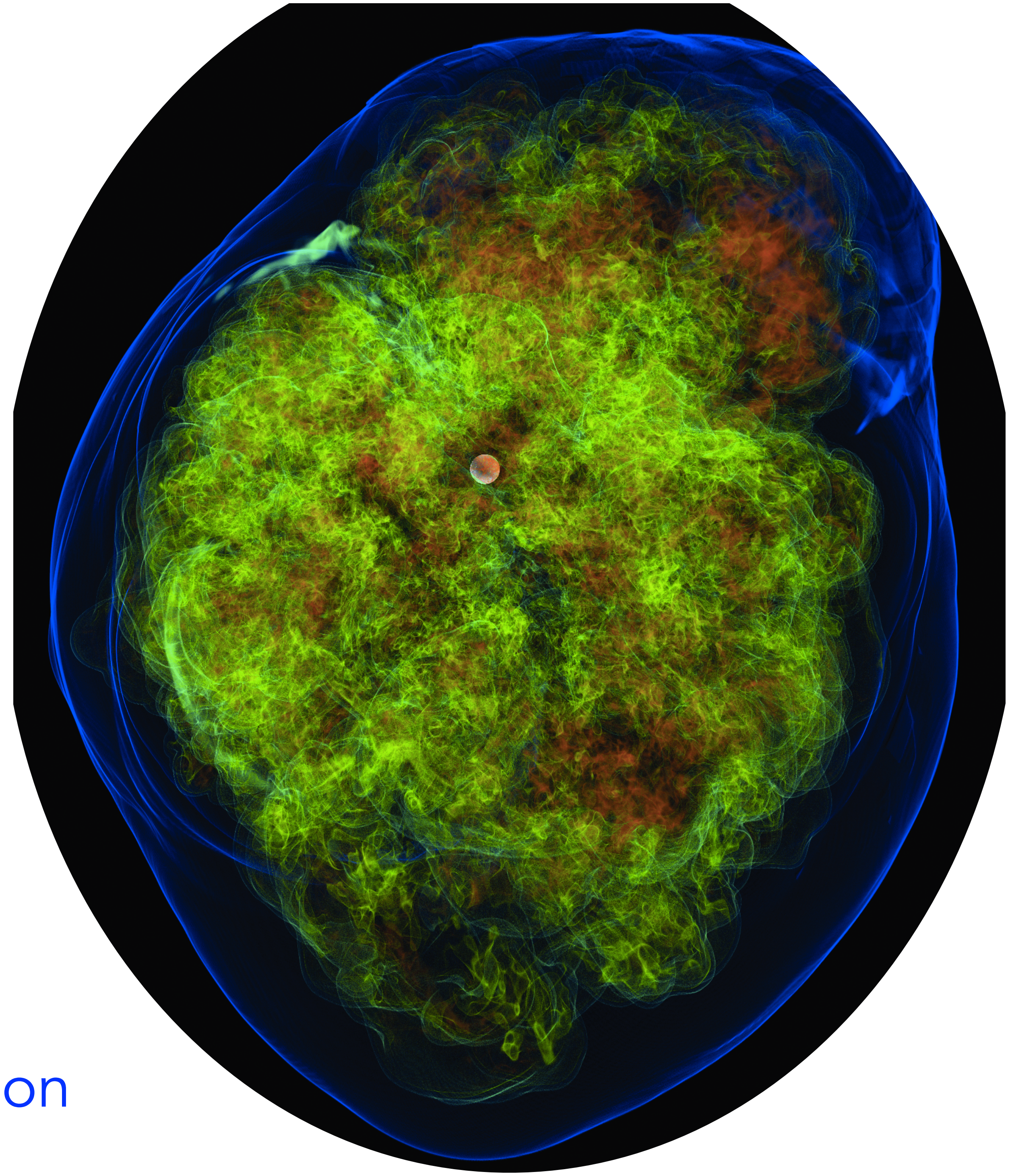
DIRECT CALIBRATION OF SNe IA

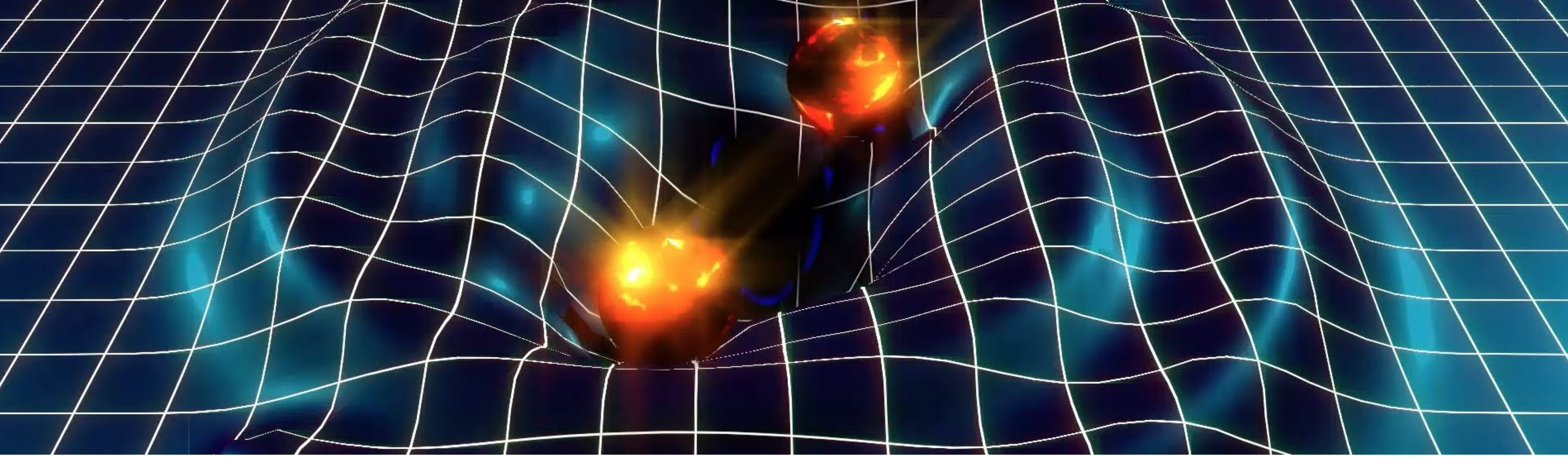
Gupta+, in preparation



SUPERNOVAE

- signature of physics of supernova
  - progenitor mass
  - proto-NS core oscillation modes
  - core rotation rate
  - mass accretion rate from shock
  - geometry of collapse
- NS equation of state
  - spectrum of GW signal
  - following the phase evolution
- fate of collapse
  - neutron star vs black hole formation





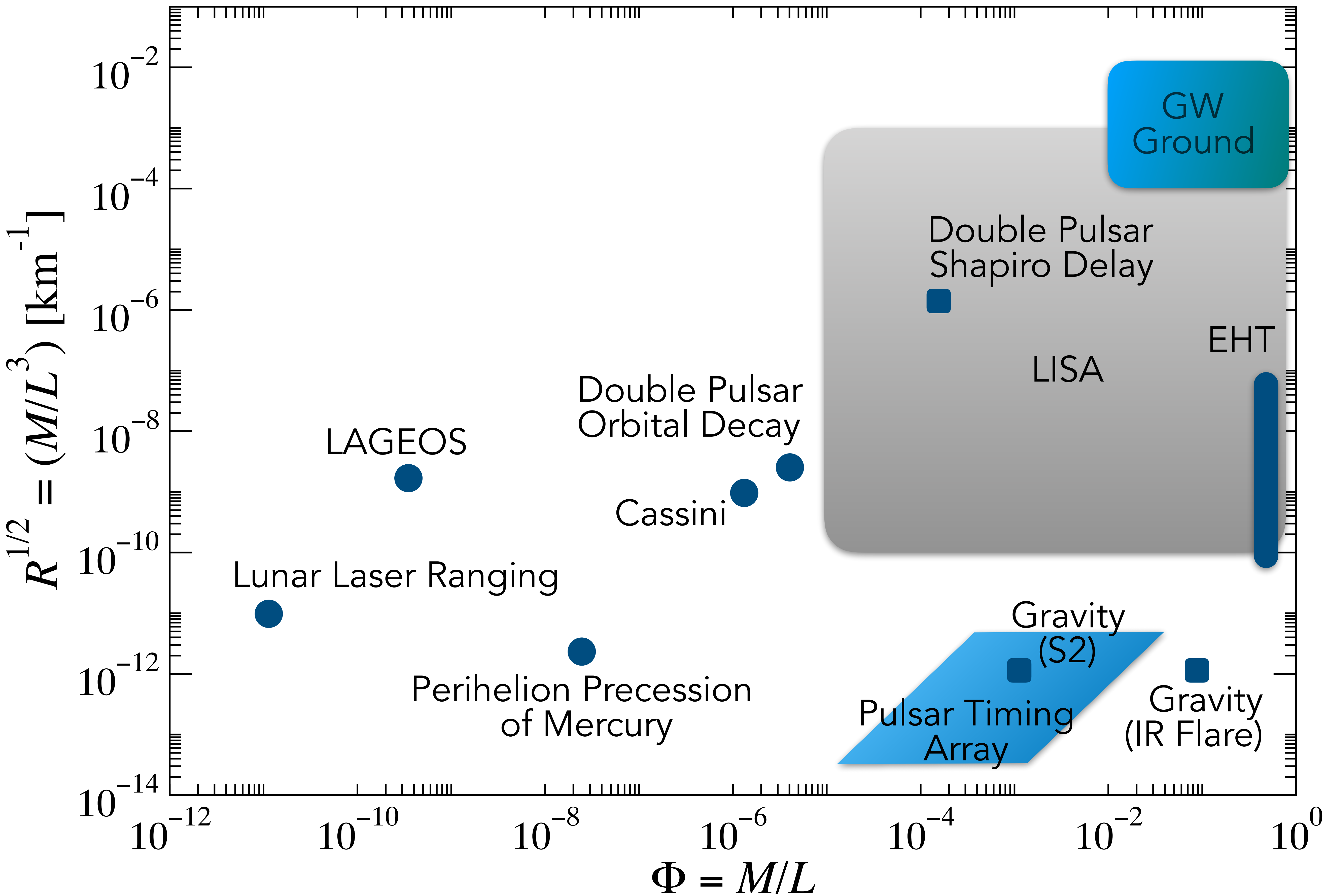
EXTREME GRAVITY AND THE NATURE OF SPACETIME

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

PHASE SPACE OF TESTS OF GR

- scale of curvature
  - scale of curvature
    - matter density ~ M/L^3, $R = (L^3/M)^{1/2}$
- strength of surface gravity, also compactness and orbital speed
  - scale of surface gravity determined by compactness, $v^2 \sim M/L \sim \Phi$



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

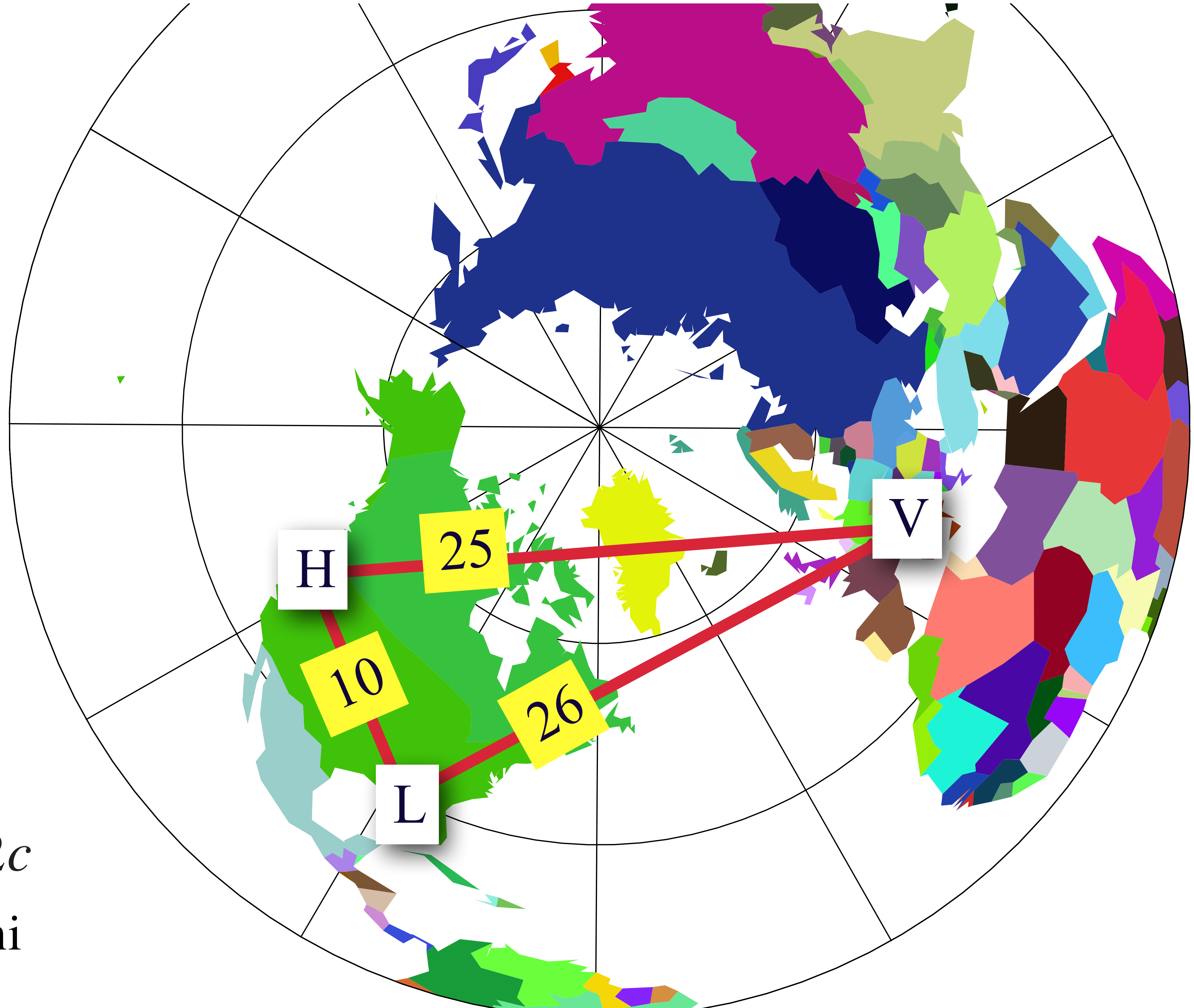
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

- 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

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

TEST OF THE SPEED OF GRAVITATIONAL WAVES

BASELINES IN LIGHT TRAVEL TIME (MS)



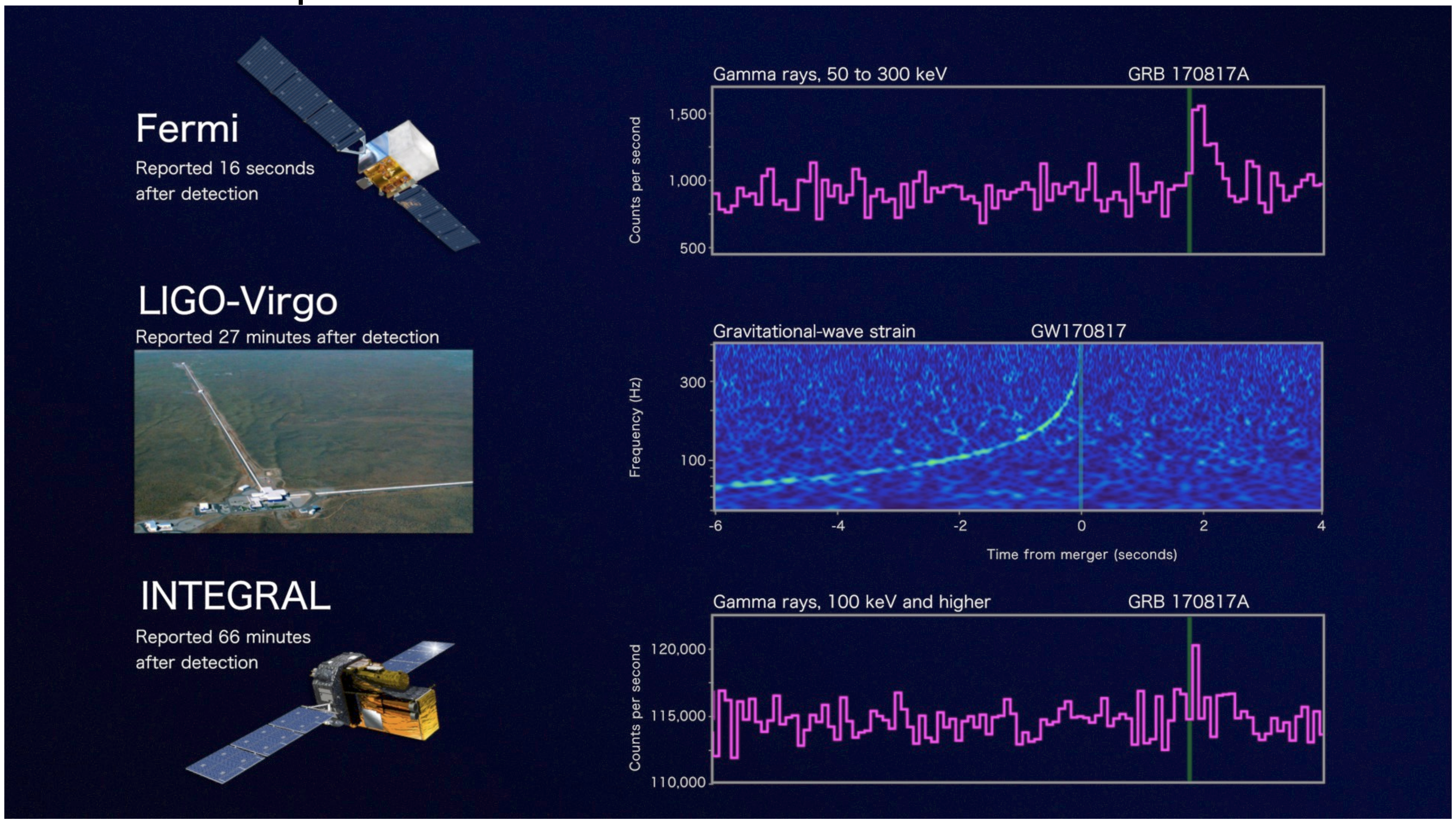
USING GW150914, GW151226, GW170104

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

Cornish, Blas Nardini
PRL **119,** 161102 (2017)

SPEED OF GRAVITATIONAL WAVES FROM GW170817 AND GRB170817A

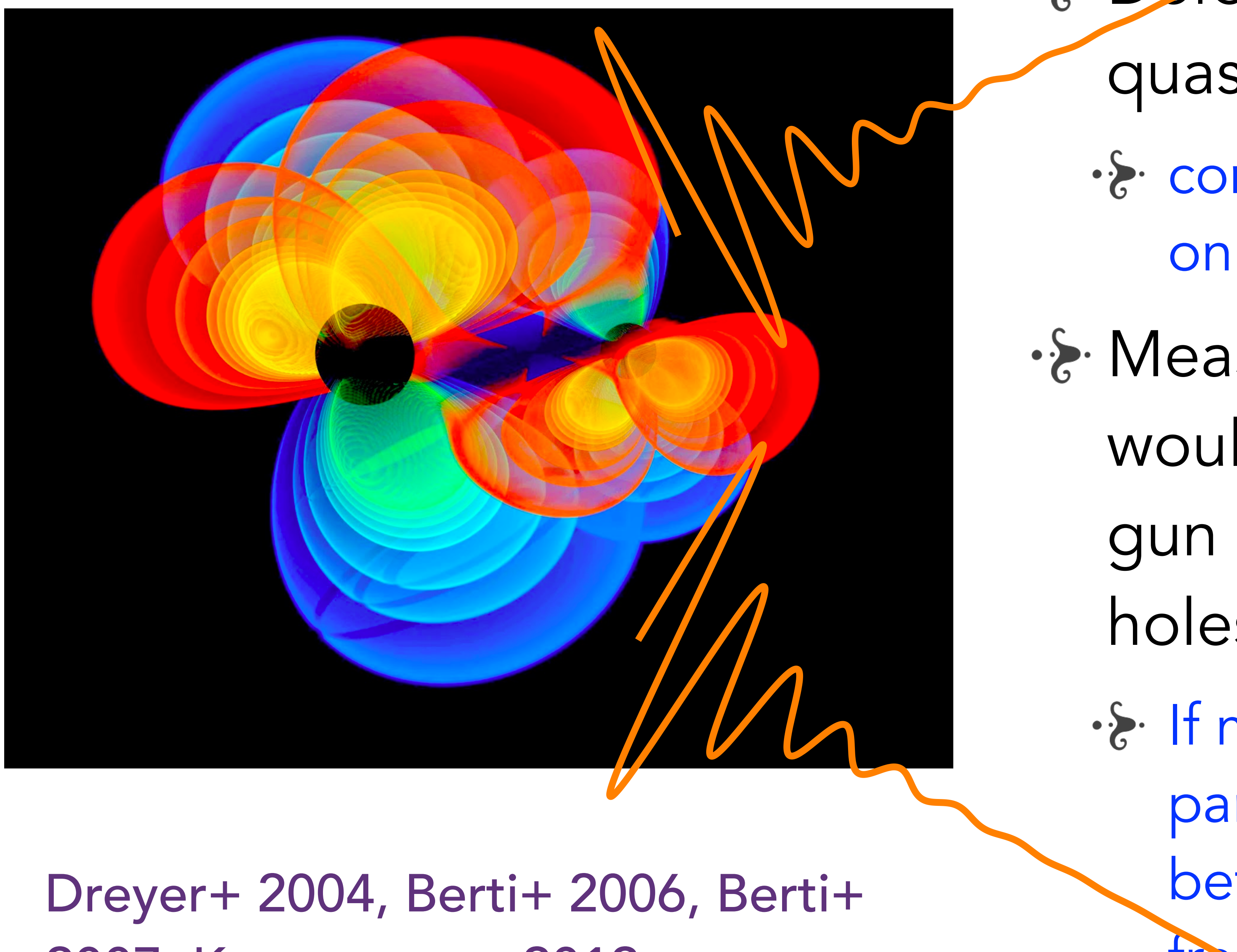
Abbott+ ApJ Letters, 848, L12 (2017)



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

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

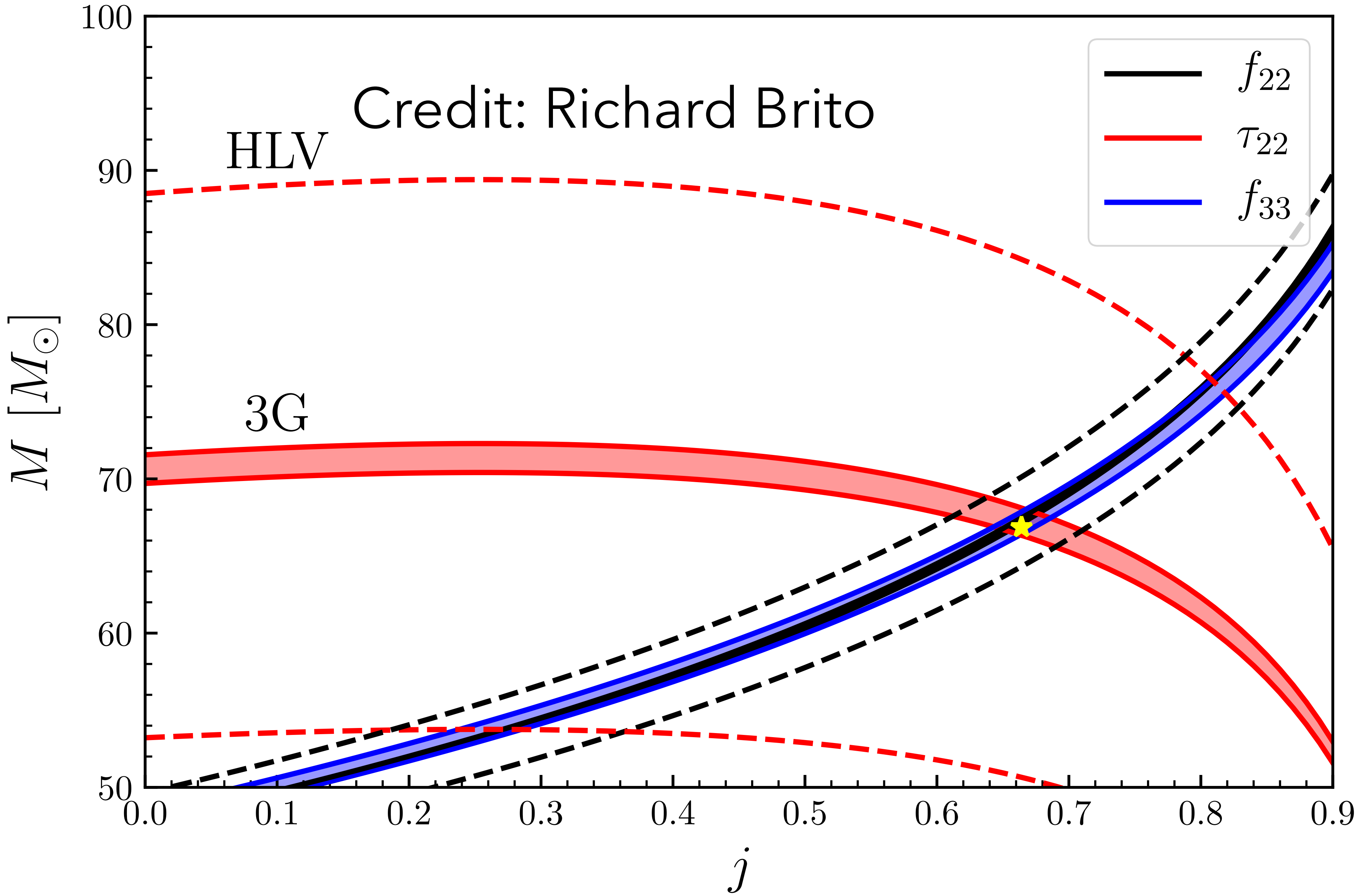
QUASI-NORMAL MODES AND NO-HAIR TESTS



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

- 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

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

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:

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

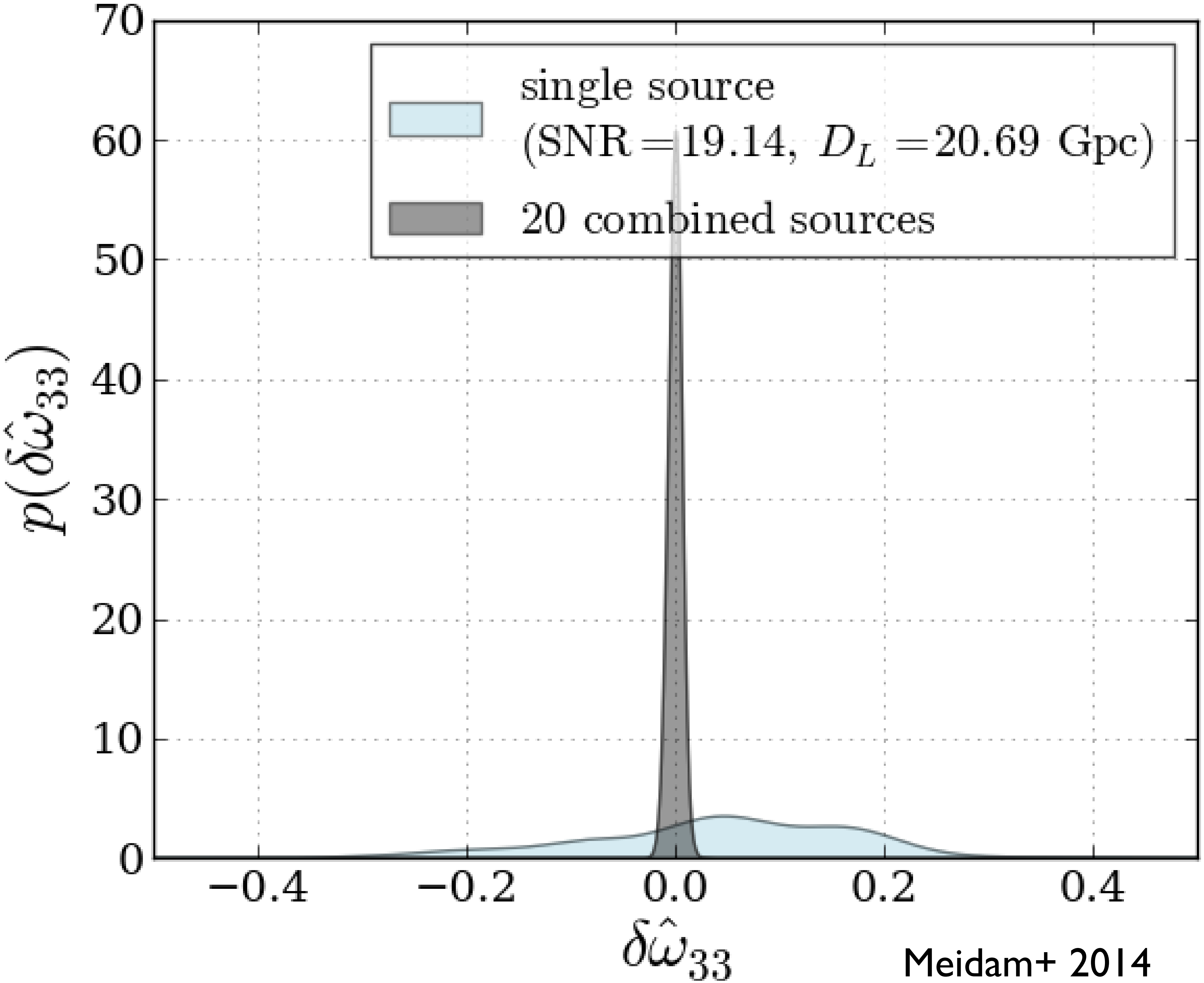
$$\begin{aligned}H_1 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{22}\},\\ H_2 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{33}\},\\ H_3 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\tau}_{22}\},\\ H_{12} &\longleftrightarrow \{\vec{\theta}_{\rm GR},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

→

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

Gossan+ 2012, Meidam+ 2014

HOW WELL CAN WE MEASURE

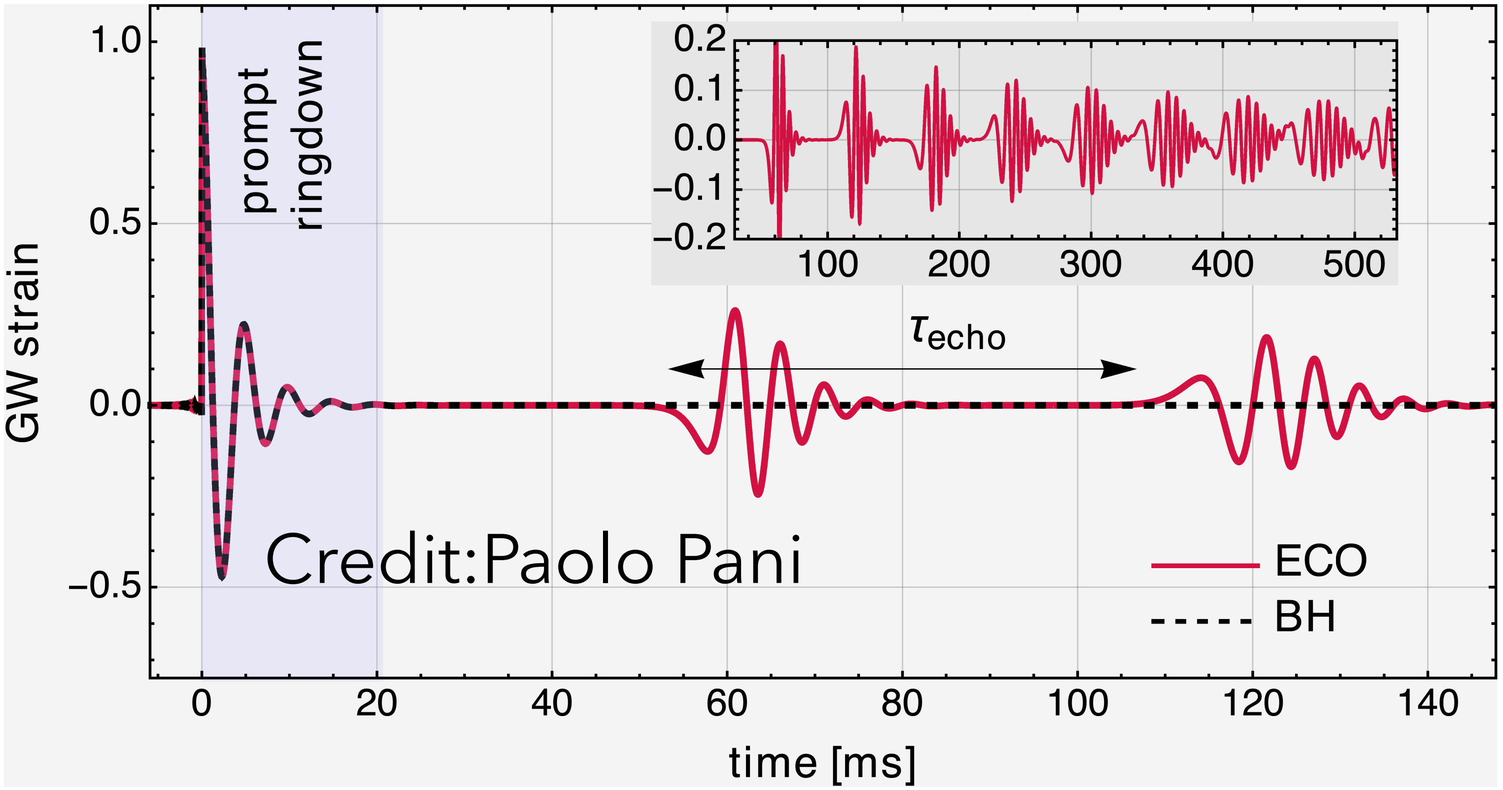


Meidam+ 2014

EXOTIC OBJECTS, NEW FIELDS AND PARTICLES

EXTREMELY COMPACT OBJECTS

- exploring particle physics theories
  - axions, ultra-light bosons, consequence of new interactions on two-body dynamics and population characteristics
- objects made of new matter
  - fundamental strings, boson stars, strange stars, gravastars

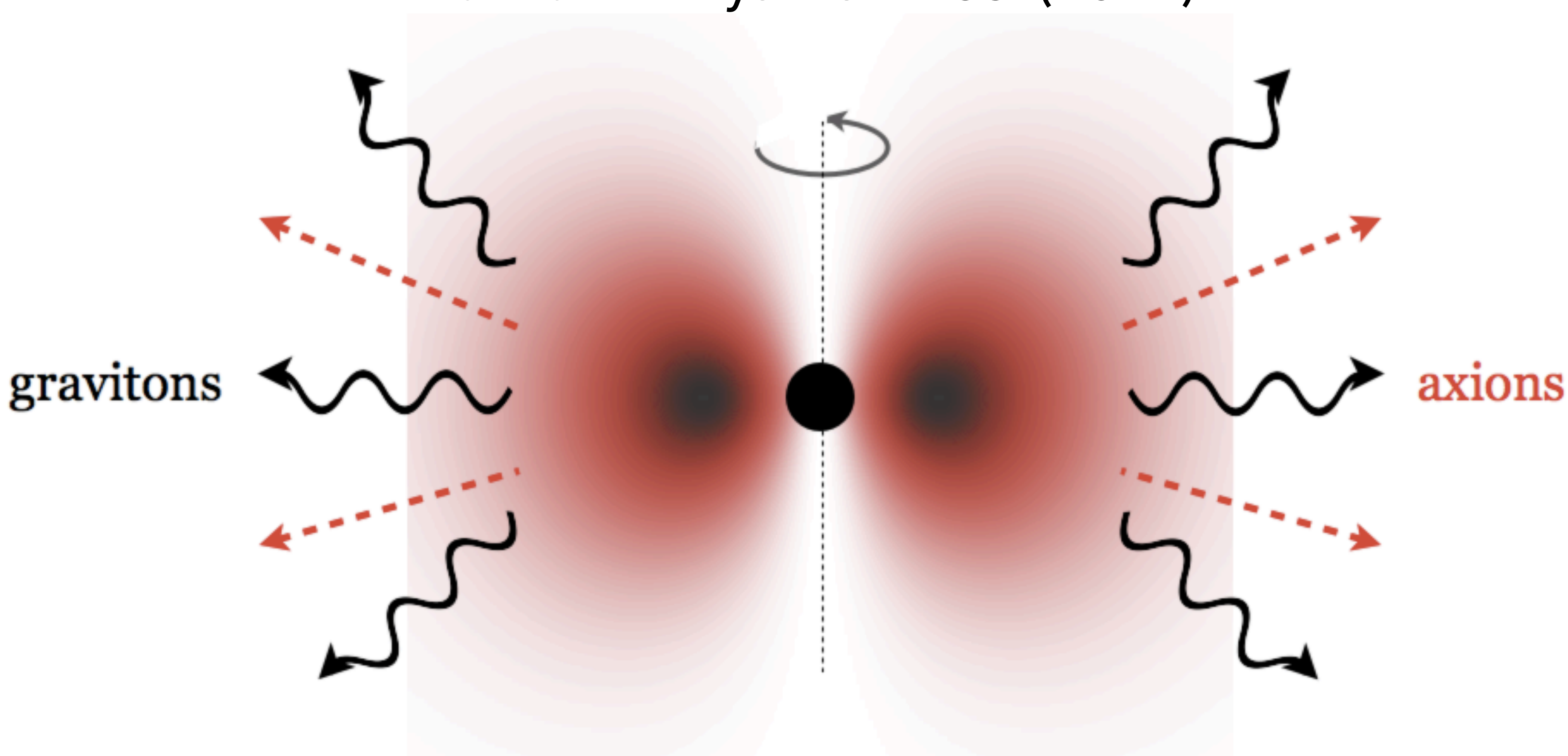


3G network could discover extremely compact objects such as Boson stars, strange stars, gravastars, worm holes, ...

GRAVITATIONAL ATOMS AND BLACK HOLE SUPER RADIANCE

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

Arvanitaki+ Phys. Rev. D83 (2011)



NEUTRON-STAR IMPLODING DARK MATTER

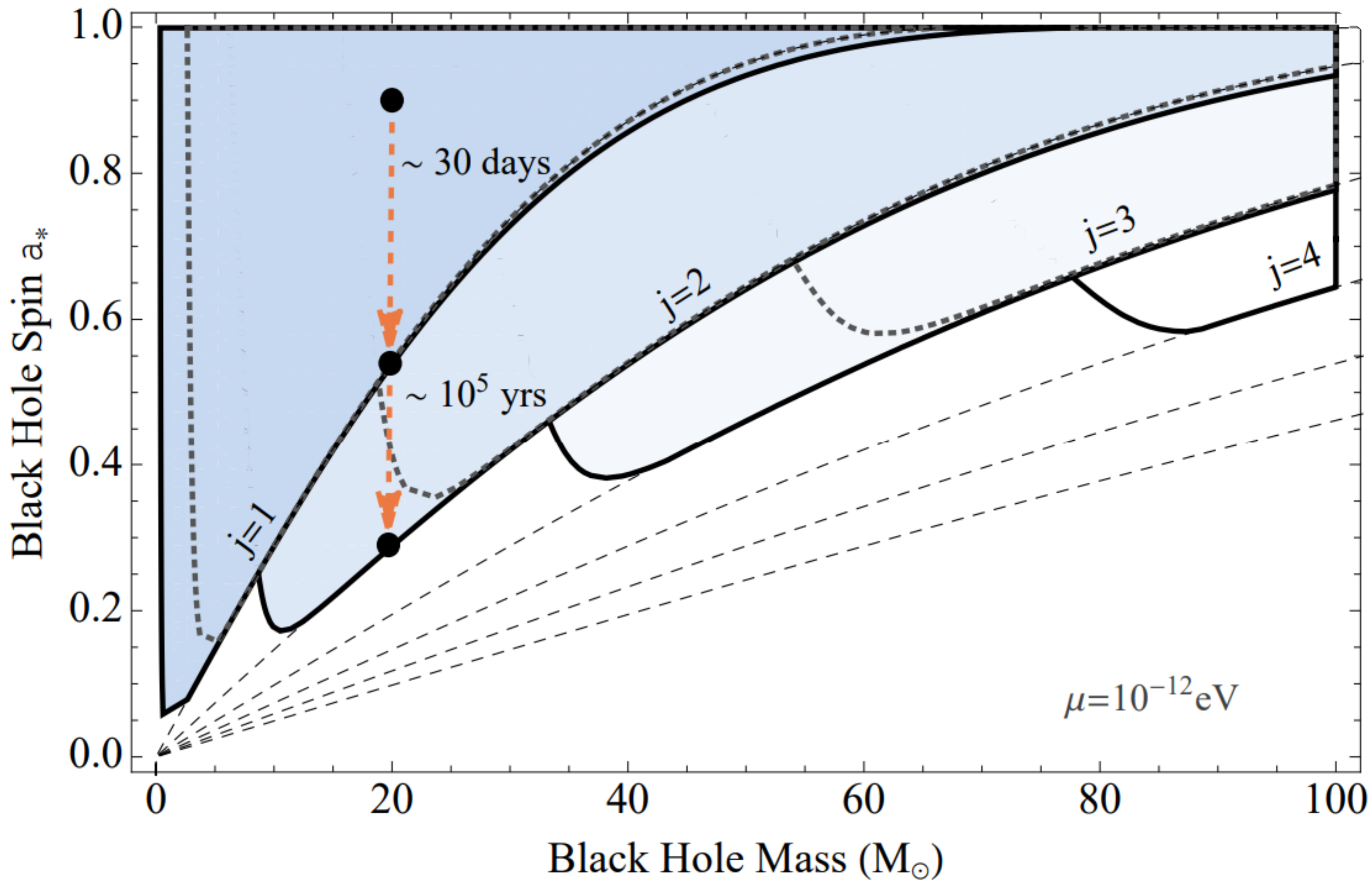
Gupta+, in preparation

NEUTRON-STAR IMPLODING DARK MATTER

Gupta+, in preparation

GRAVITATIONAL ATOMS AND SUPER RADIANCE

Baryakhtar+ Phys. Rev. D96 (2017)

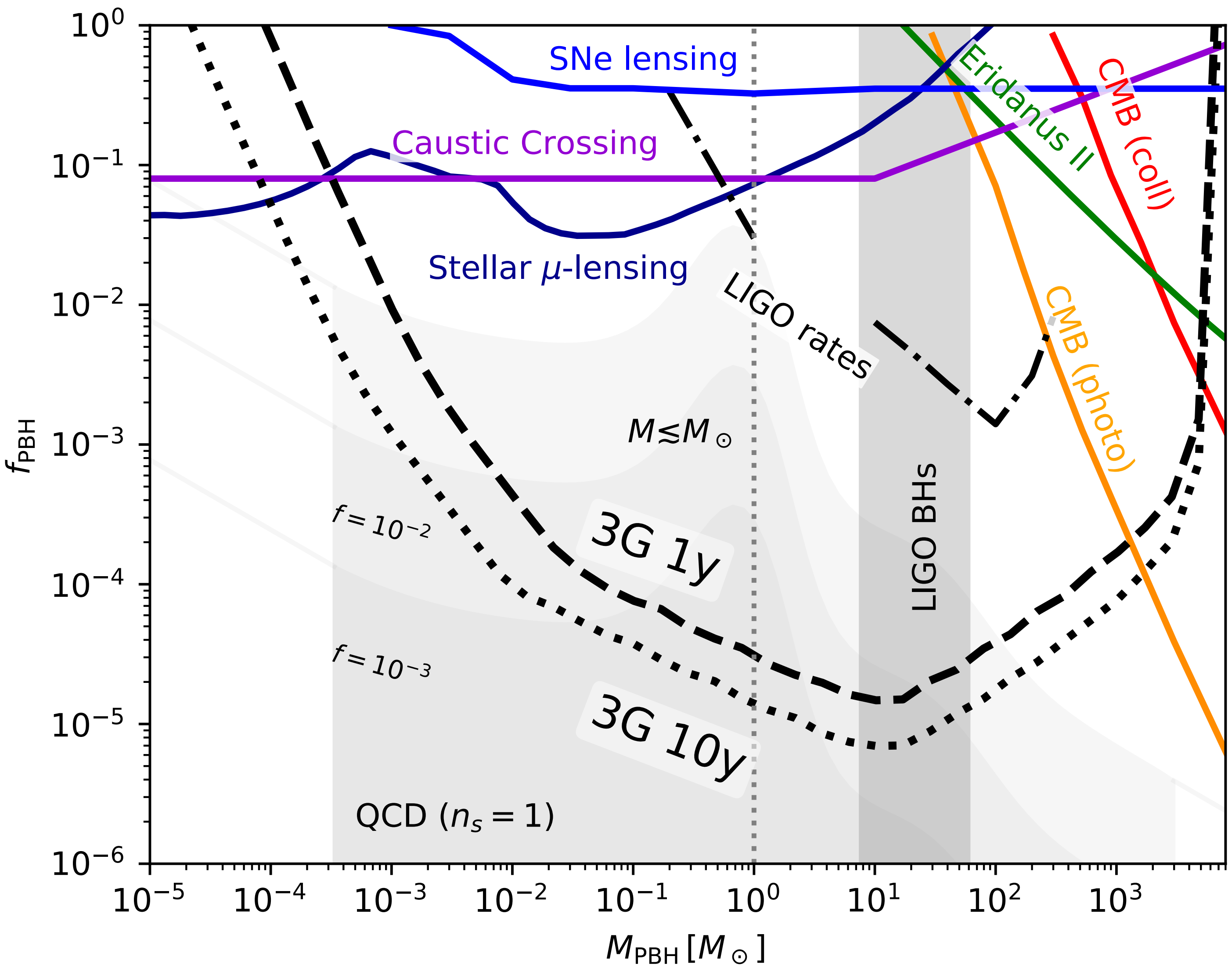


3G network will explore properties of dark matter not accessible to any other experiment

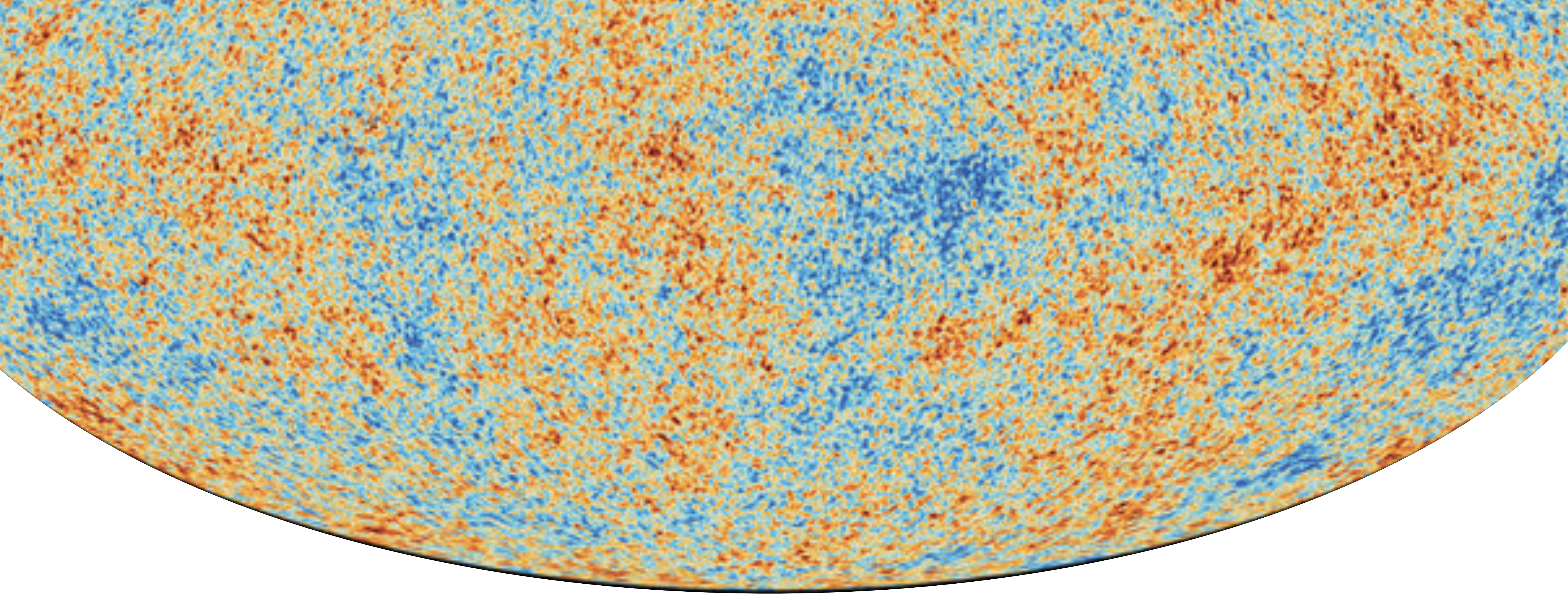
PRIMORDIAL BLACK HOLES AS DARK MATTER

Credit:Miguel Zumalacarregui

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



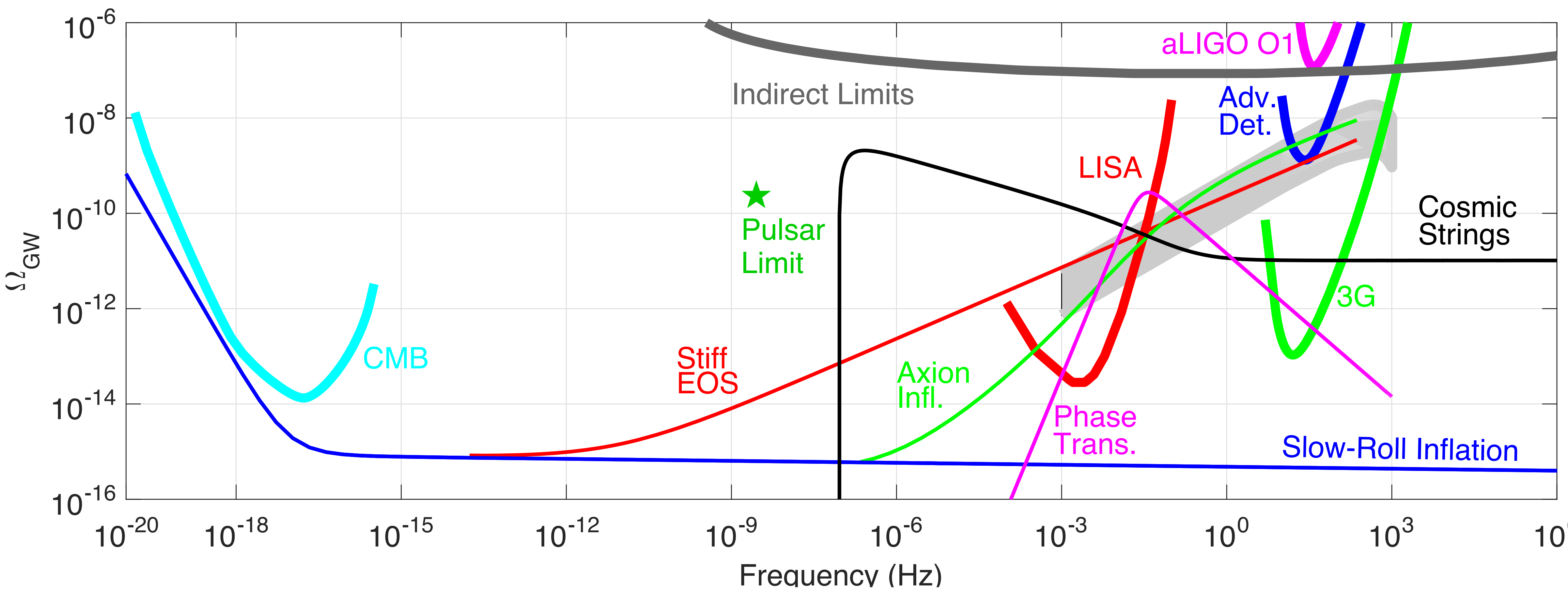
3G network would settle the question if LIGO-Virgo black holes constitute dark matter and are primordial in origin



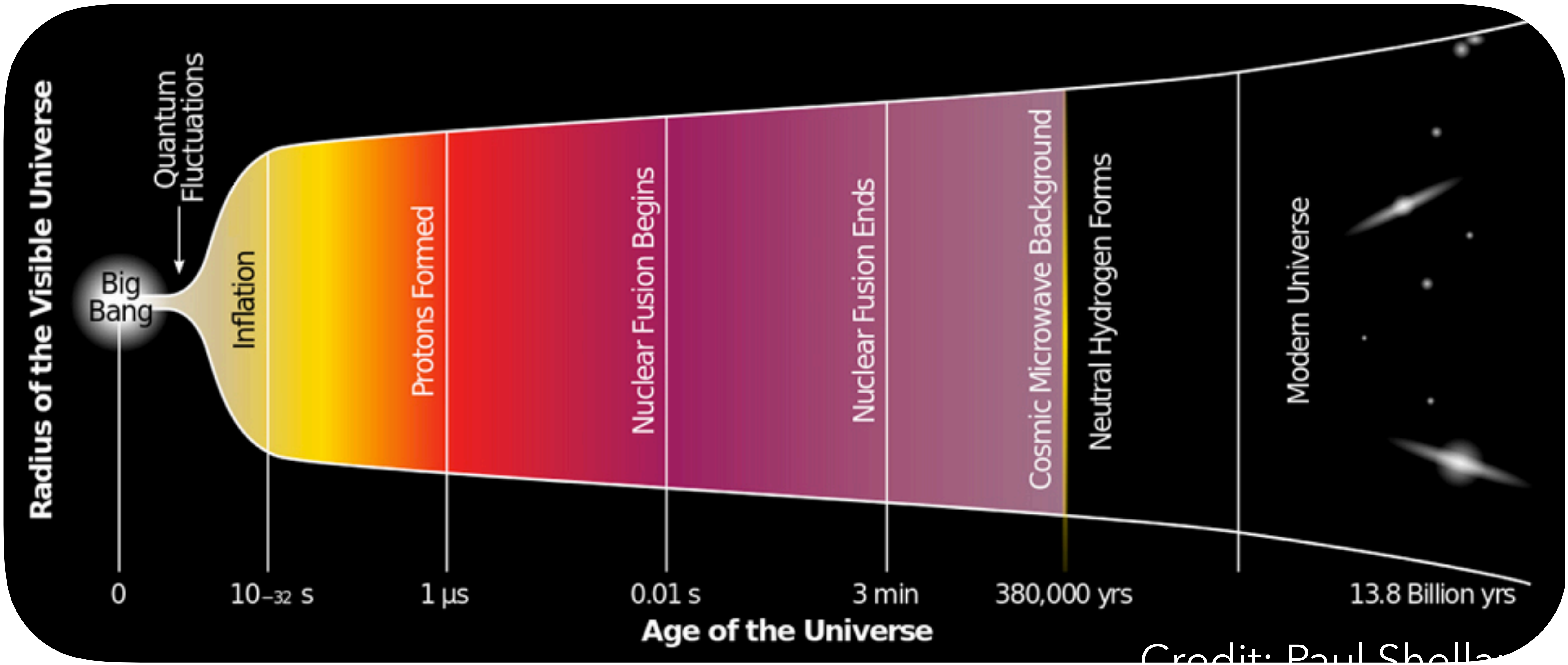
PRIMORDIAL UNIVERSE

STOCHASTIC BACKGROUND LANDSCAPE

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



EXPLORE FUNDAMENTAL PHYSICS AT HIGHEST ENERGY SCALES



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

GUARANTEED SCIENCE RETURNS

- study the nature of black holes, test the no-hair theorem and gravity in ultra strong fields
- explore the 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
- detect gravitational waves from supernova and determine the physics of core-collapse supernova
- provide a new tool for measuring distances to cosmological sources

OPPORTUNITY FOR NEW DISCOVERIES

- gravitational window is a completely different observational tool compared to em window
  - experience tells us that each observational window had led to discoveries never imagined before
    - x-ray, radio, infra-red, gamma-ray, cosmic rays, …
- gravitational wave detectors, especially at good sensitivities, should be expected to make new discoveries
  - could lead to new physics that help us understand missing links in fundamental physics and astrophysics

SUMMARY AND OUTLOOK

- compelling science case:
  - address questions of foundational importance in fundamental physics, astrophysics and cosmology, questions uniquely addressed by the GW window
- broad scientific community
  - relativity, astrophysics (across the entire EM window), particle physics, neutrinos, nuclear physics, cosmology, quantum gravity, early universe - a new probe of physics
- what is the best way to present the science case

TESTS OF THE BINARY BLACK HOLE INSPIRAL DYNAMICS

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

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

(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