GRAVITATIONAL WAVE DETECTORS AND SEARCHES

LXI CRACOW SCHOOL OF THEORETICAL PHYSICS: PROBING THE VIOLENT UNIVERSE WITH MULTIMESSENGER EYES:

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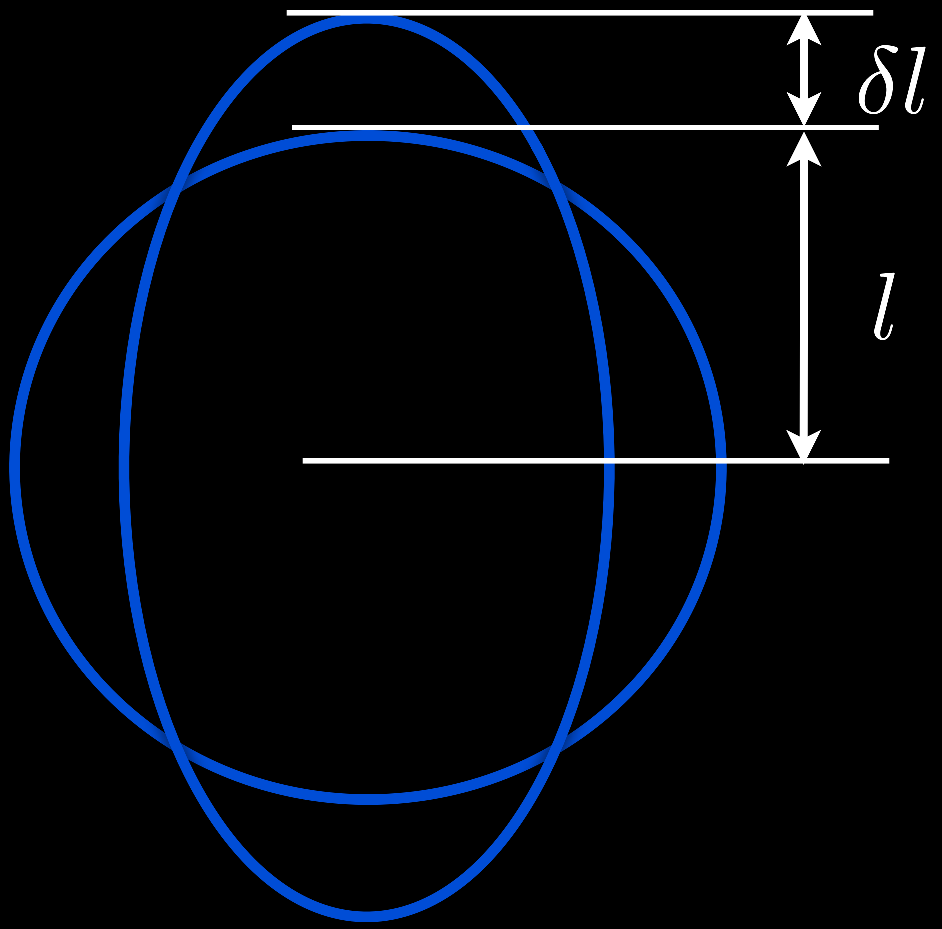
GRAVITATIONAL WAVE AMPLITUDE

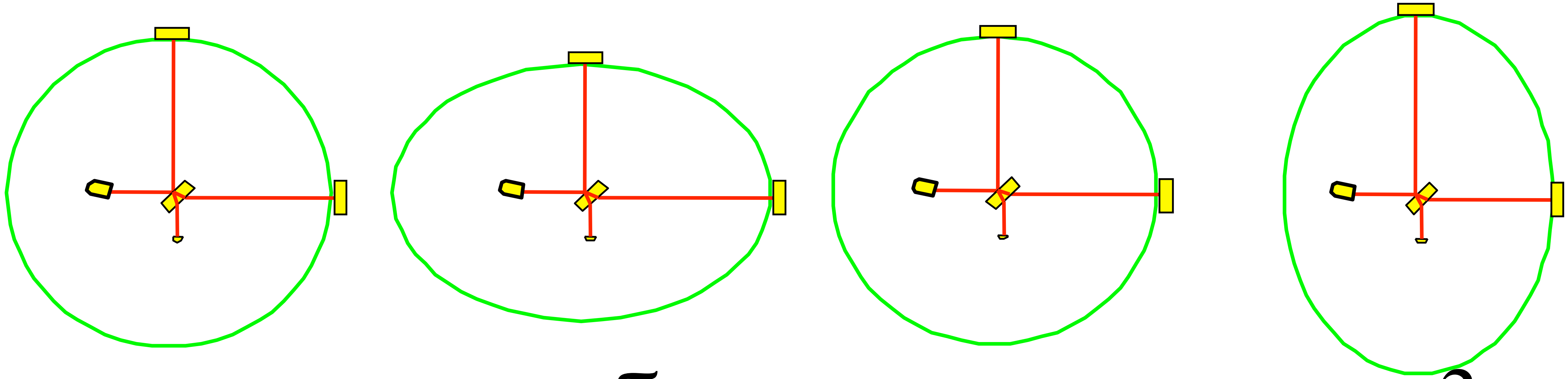
- gravitational waves cause strain in space as they pass
- measurement of the strain gives the amplitude of gravitational waves



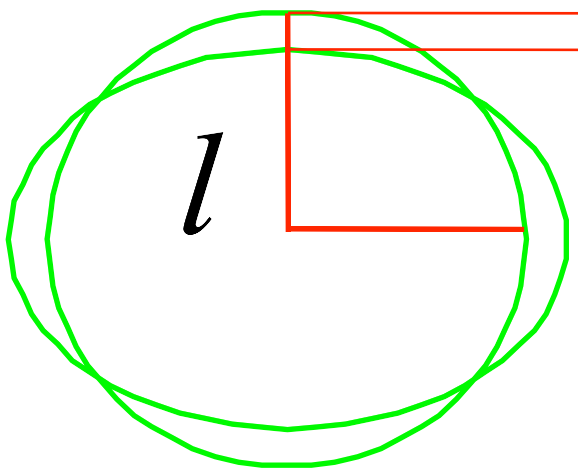
$$\frac{\delta l}{l} = h \sim 10^{-21};\ \delta l \sim 10^{-18}\left(\frac{l}{\mathrm{km}}\right)\mathrm{m}$$

- strain caused by a pair of colliding black holes at 1.3 billion light years

Interferometric gravitational-wave detectors

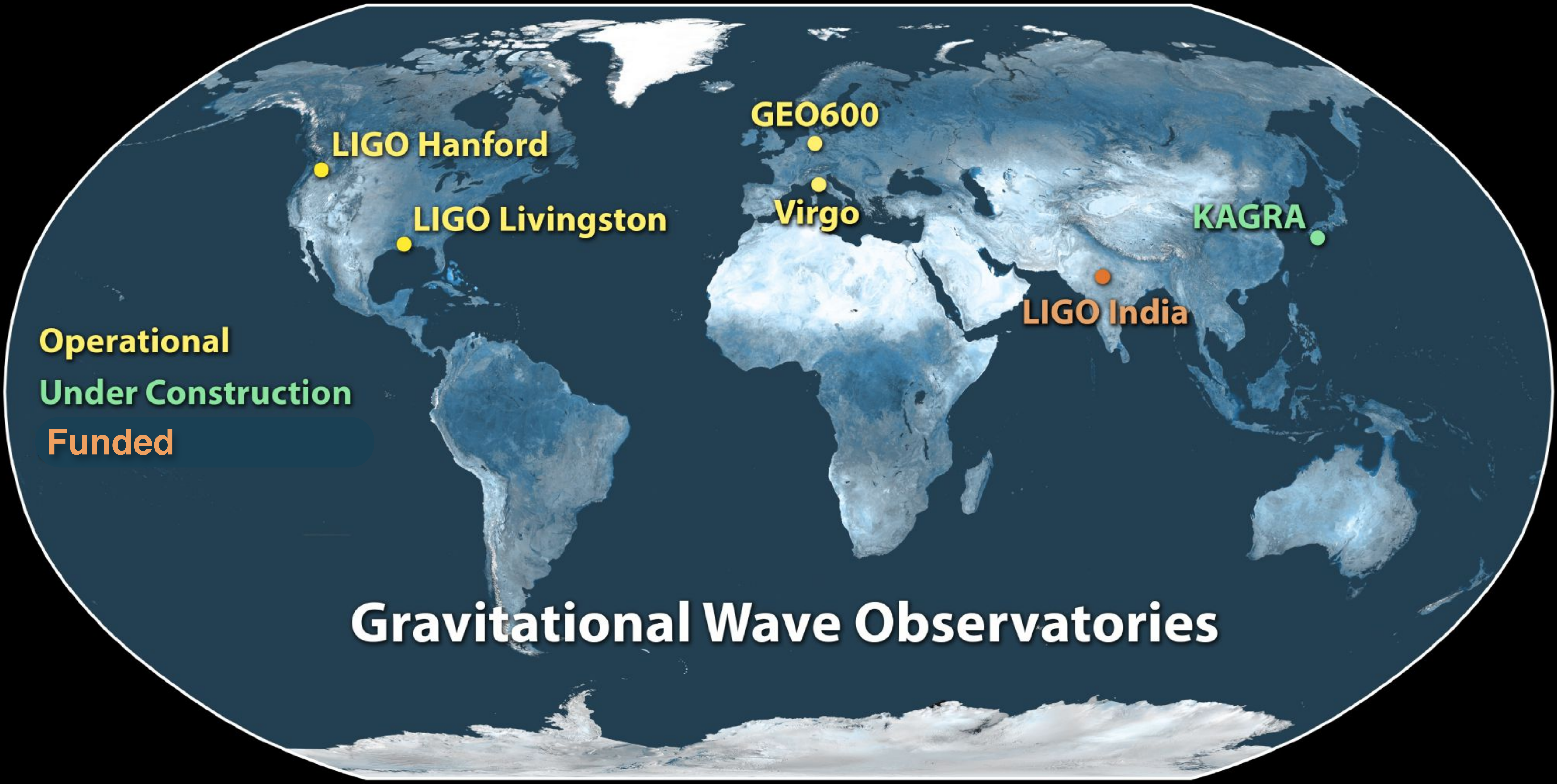


$$t = 0 \qquad t = \frac{\tau}{4} \qquad t = \frac{\tau}{2} \qquad t = \frac{3\tau}{4}$$



$$\delta l = \frac{h}{2} l$$

LASER INTERFEROMETER GRAVITATIONAL WAVE DETECTORS

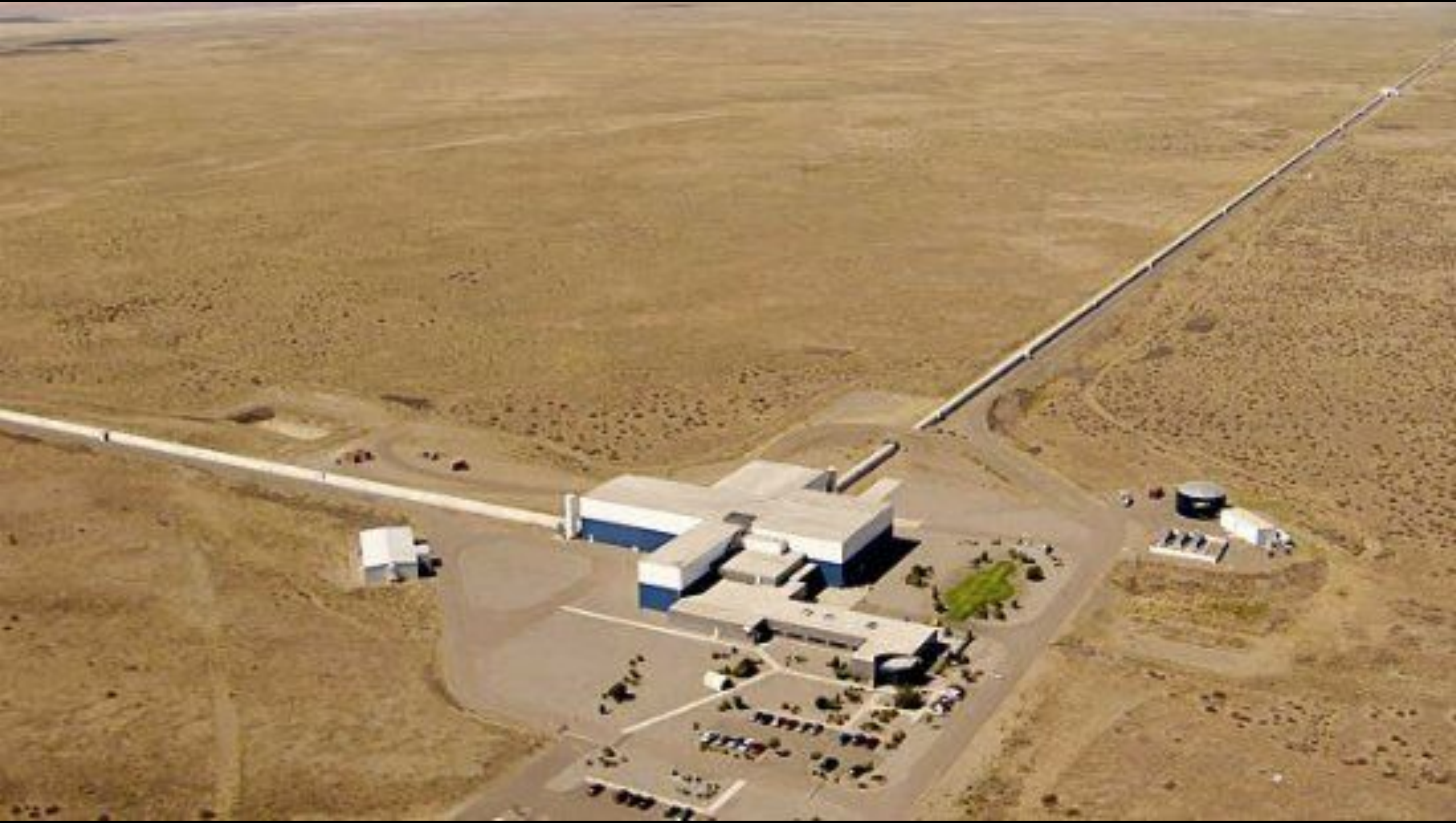


Credit: LVC/EPO

LIGO-LIVINGSTON OBSERVATORY

Credit: LIGO Livingston

LIGO-HANFORD OBSERVATORY



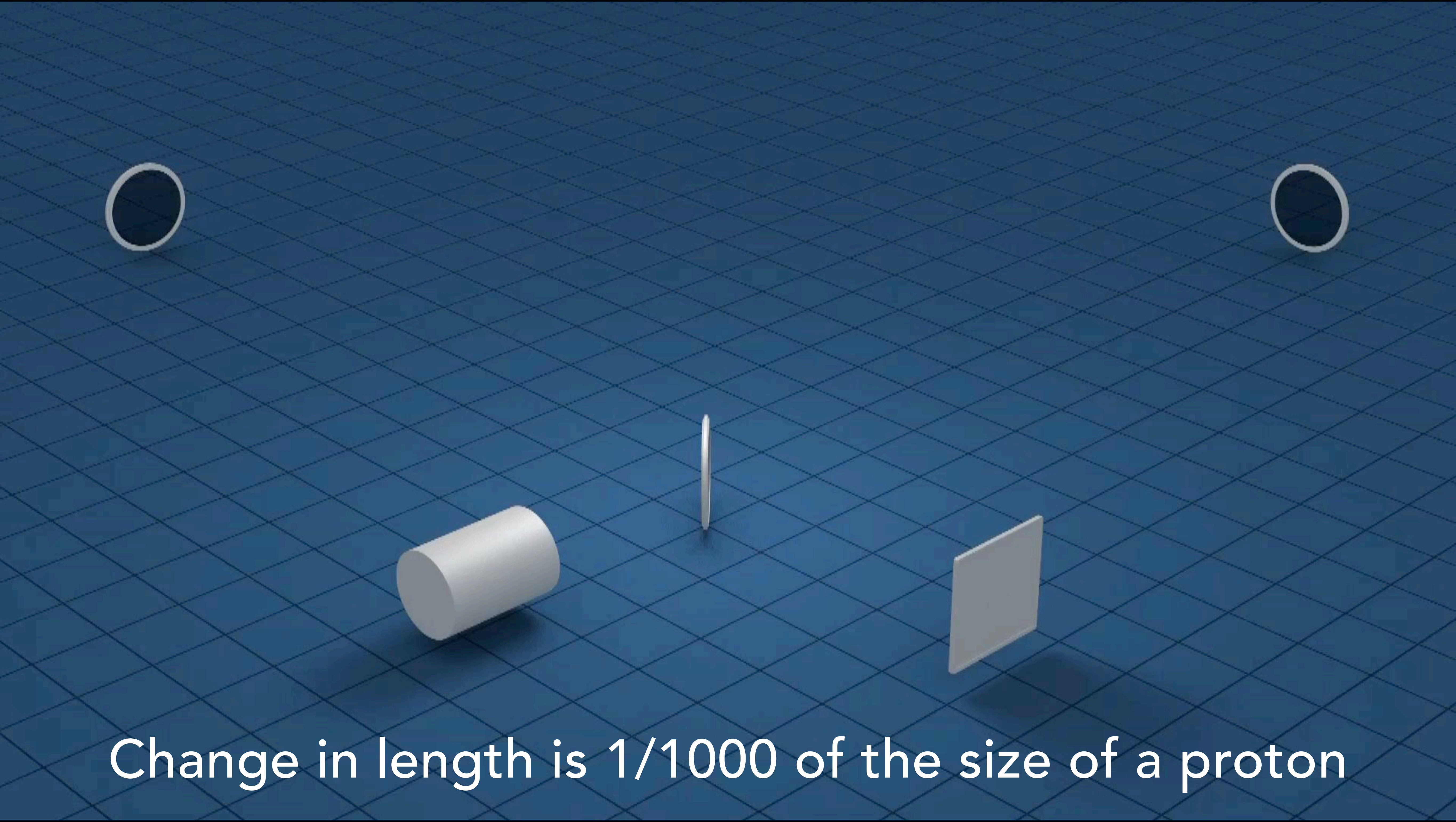
Credit: LIGO Hanford

VIRGO AT CASCINA, ITALY

Credit: Virgo

KAGRA - KAMIOKA OBSERVATORY

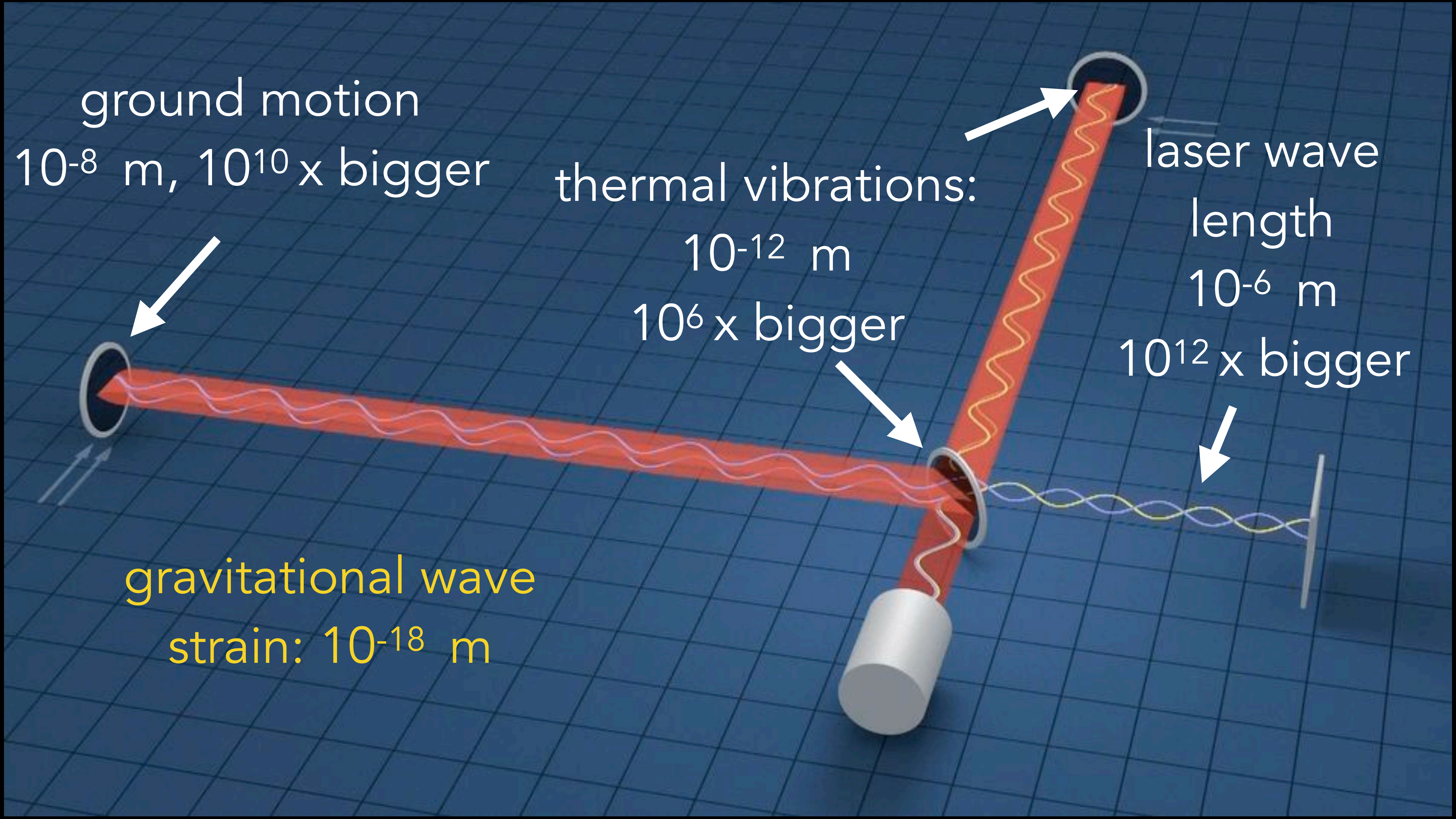
HOW LIGO DETECTS GRAVITATIONAL WAVES



Change in length is 1/1000 of the size of a proton

Credit: LIGO

MAIN NOISE COMPONENTS



ground motion
10^{-8} m, 10^{10} x bigger

thermal vibrations:
10^{-12} m
10^{6} x bigger

laser wave
length
10^{-6} m
10^{12} x bigger

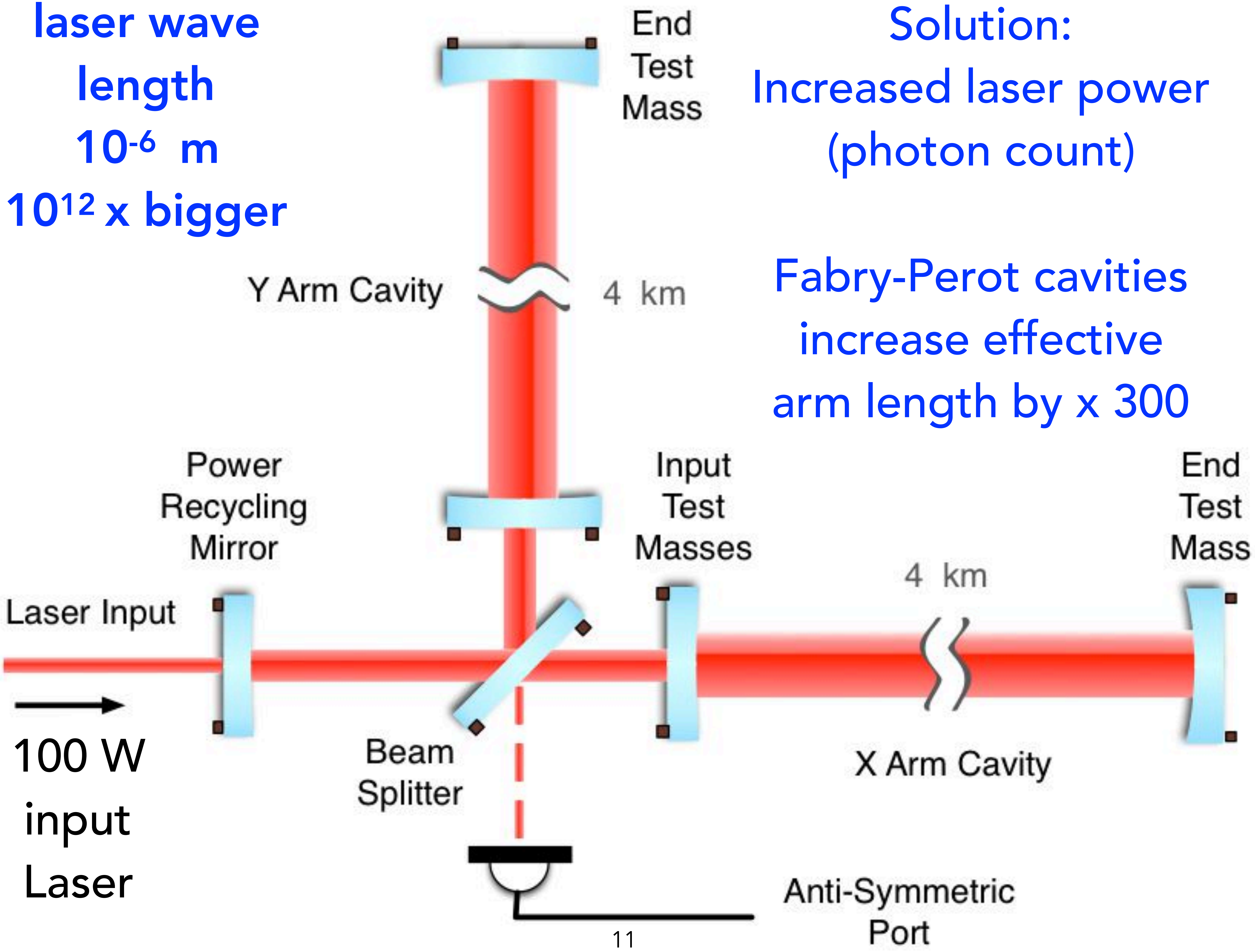
gravitational wave
strain: 10^{-18} m

Credit: LIGO

laser wave
length
10^{-6} m
10^{12} x bigger

Solution:
Increased laser power
(photon count)

Fabry-Perot cavities
increase effective
arm length by x 300



100 W
input
Laser

laser wave length

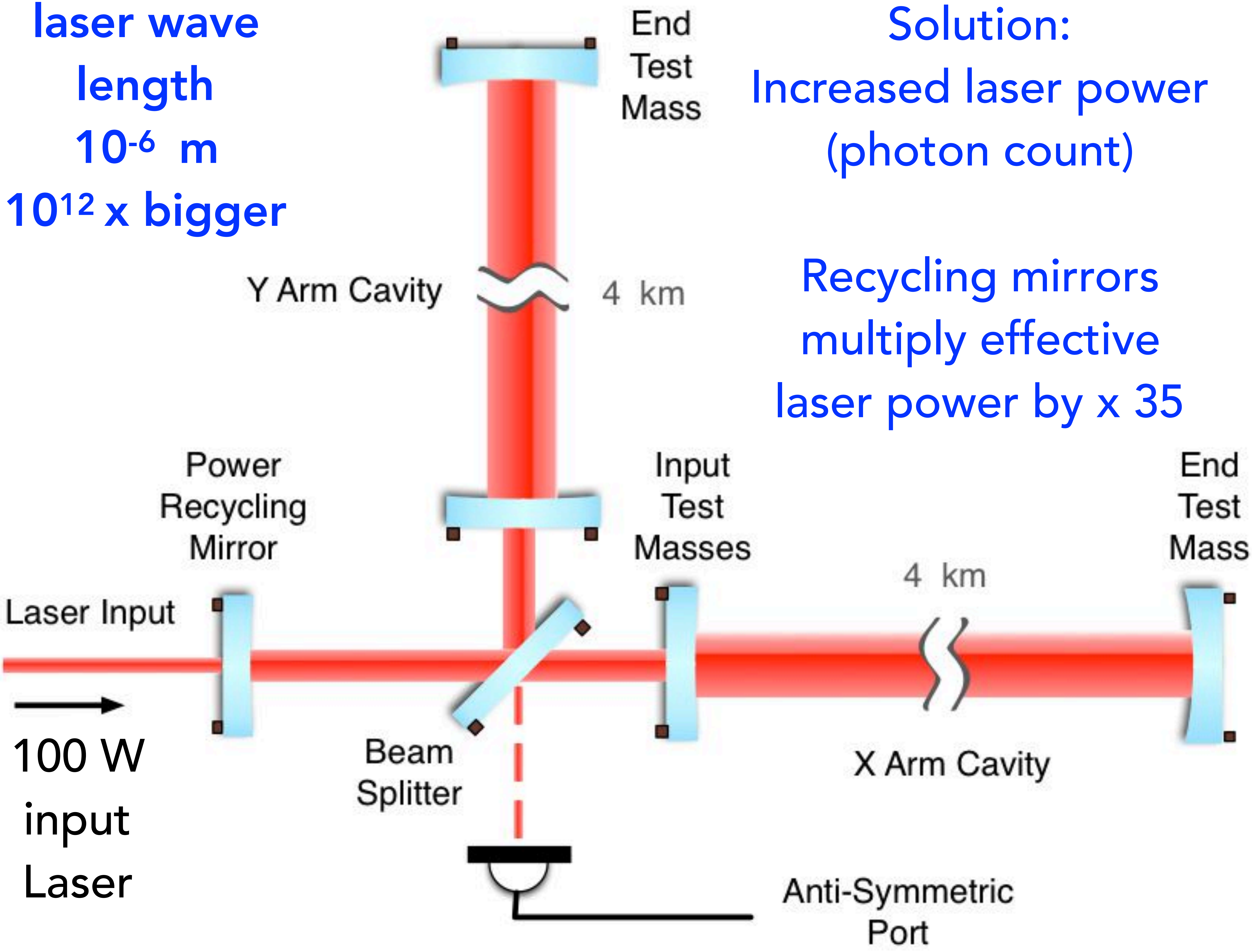
10^{-6} m

10^{12} x bigger

Solution:

Increased laser power (photon count)

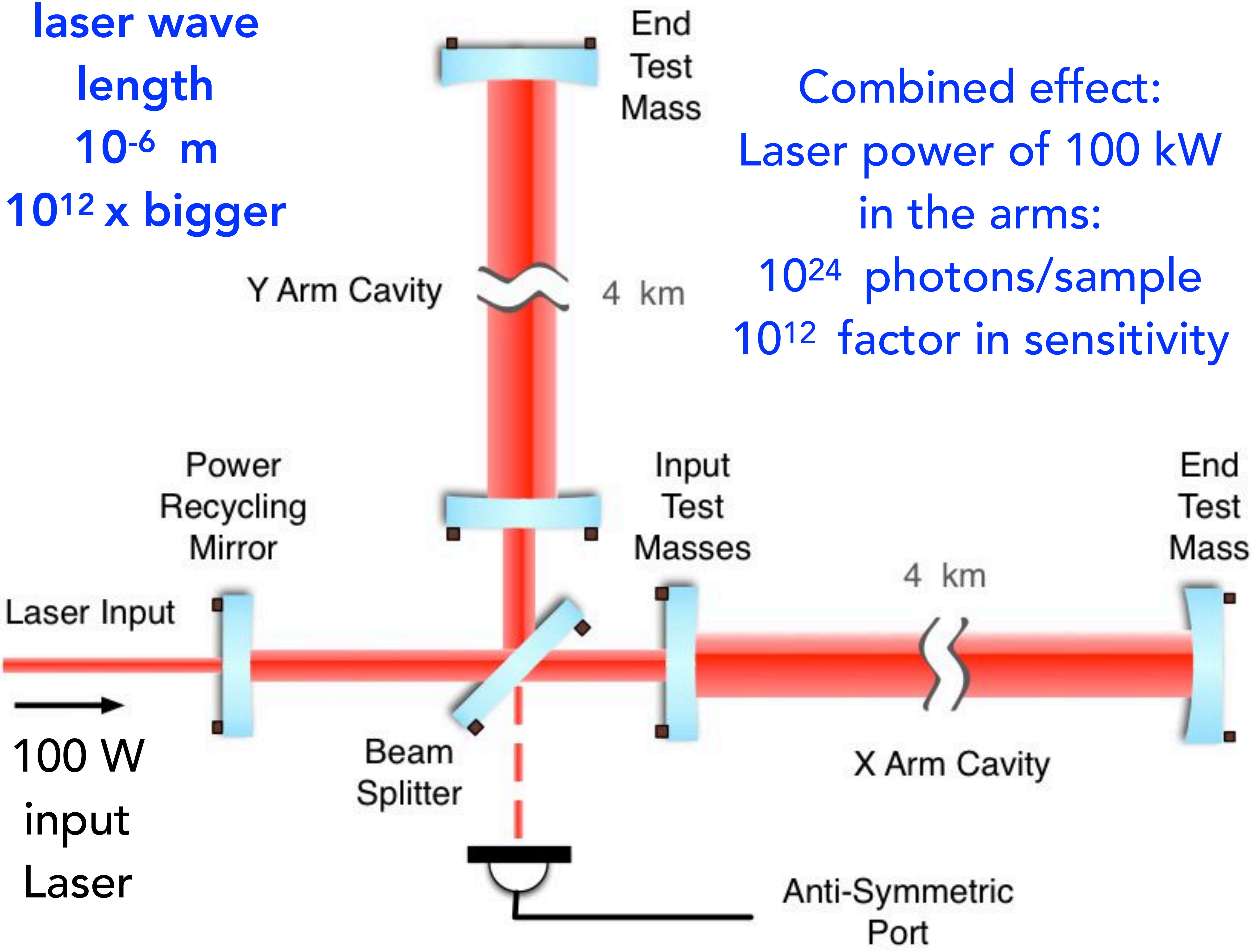
Recycling mirrors multiply effective laser power by x 35



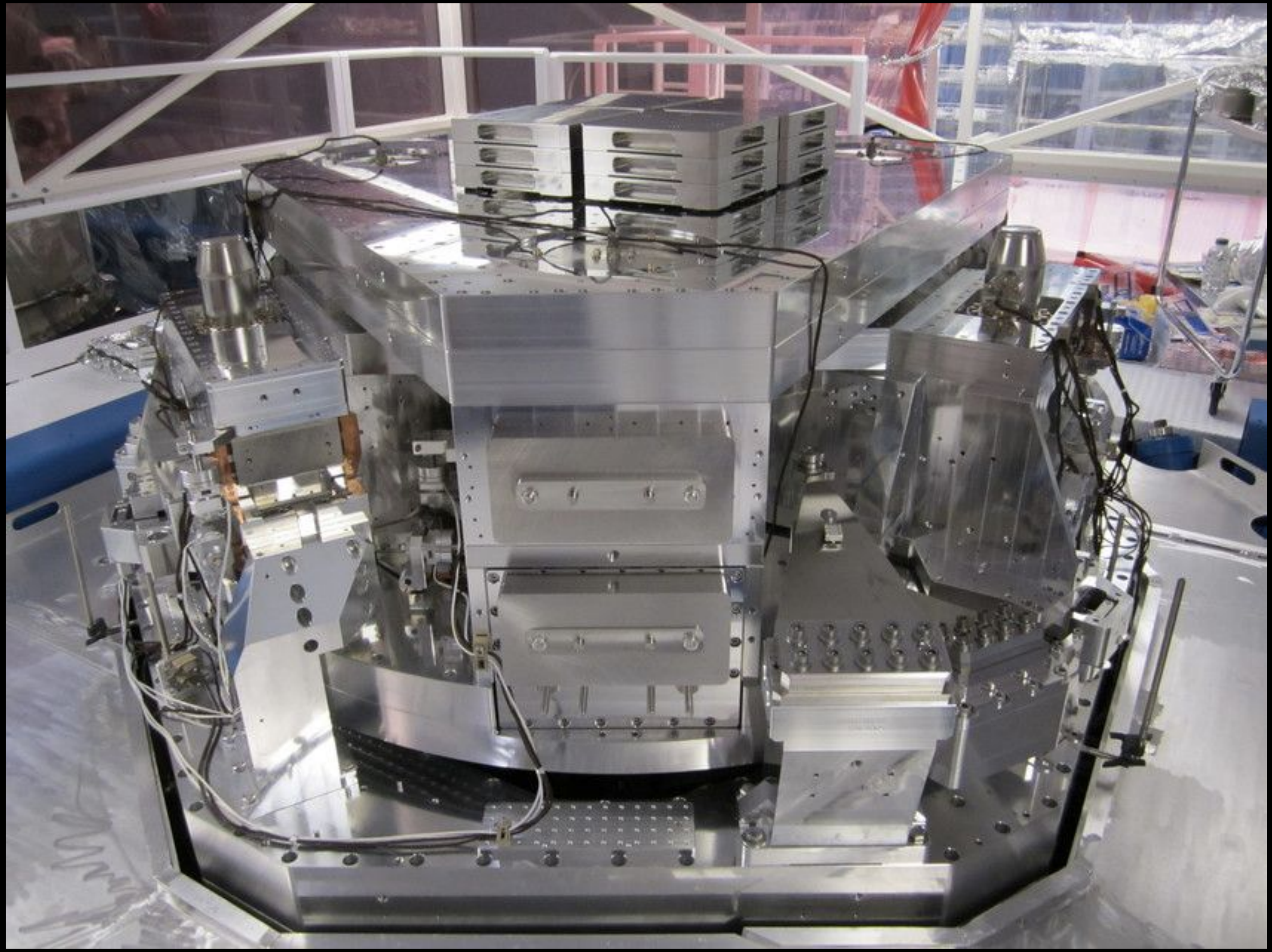
100 W input Laser

laser wave
length
10^{-6} m
10^{12} x bigger

Combined effect:
Laser power of 100 kW
in the arms:
10^{24} photons/sample
10^{12} factor in sensitivity



100 W
input
Laser



Ground motion:

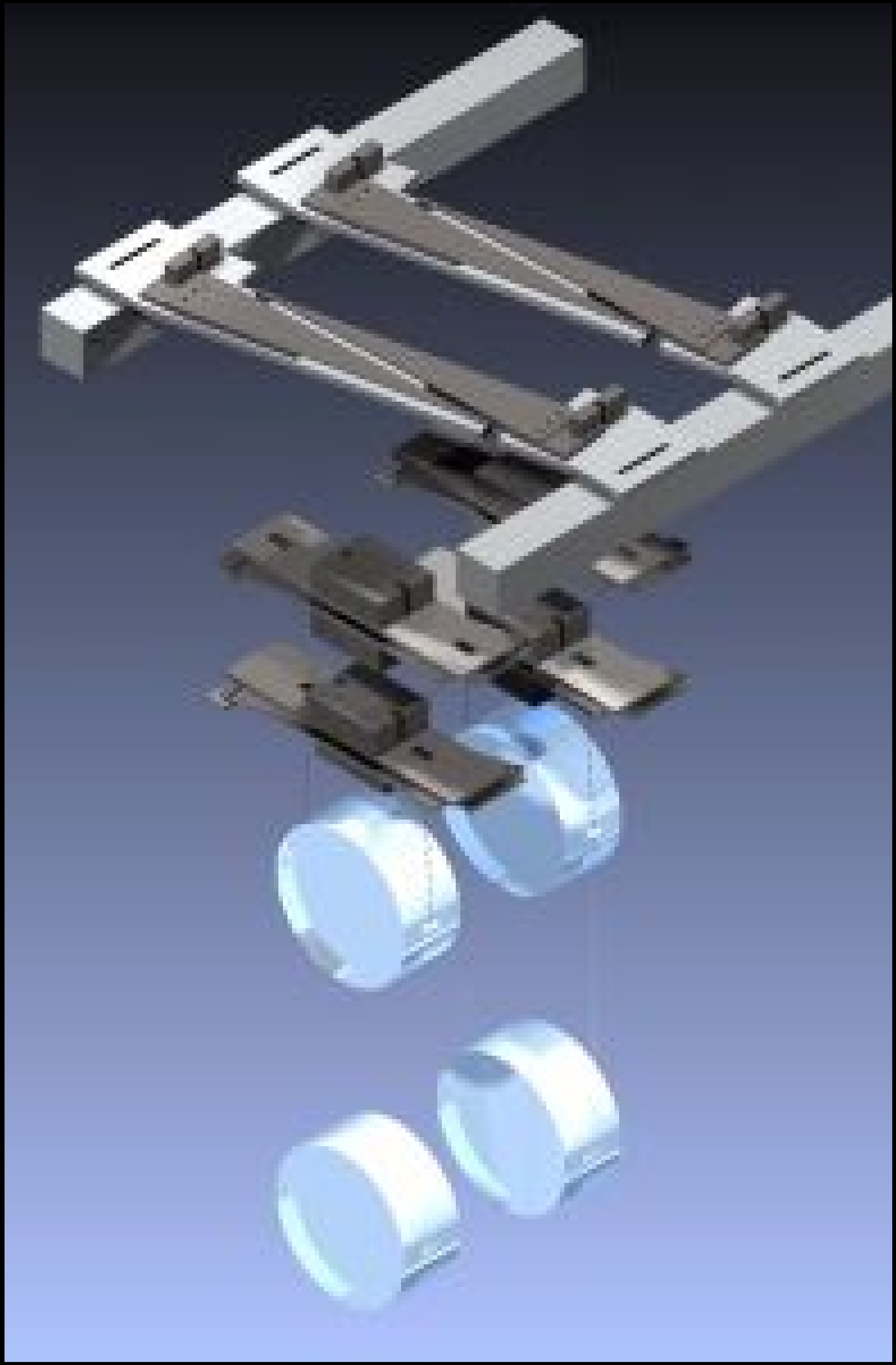
10^{-8} m

10^{10} x bigger

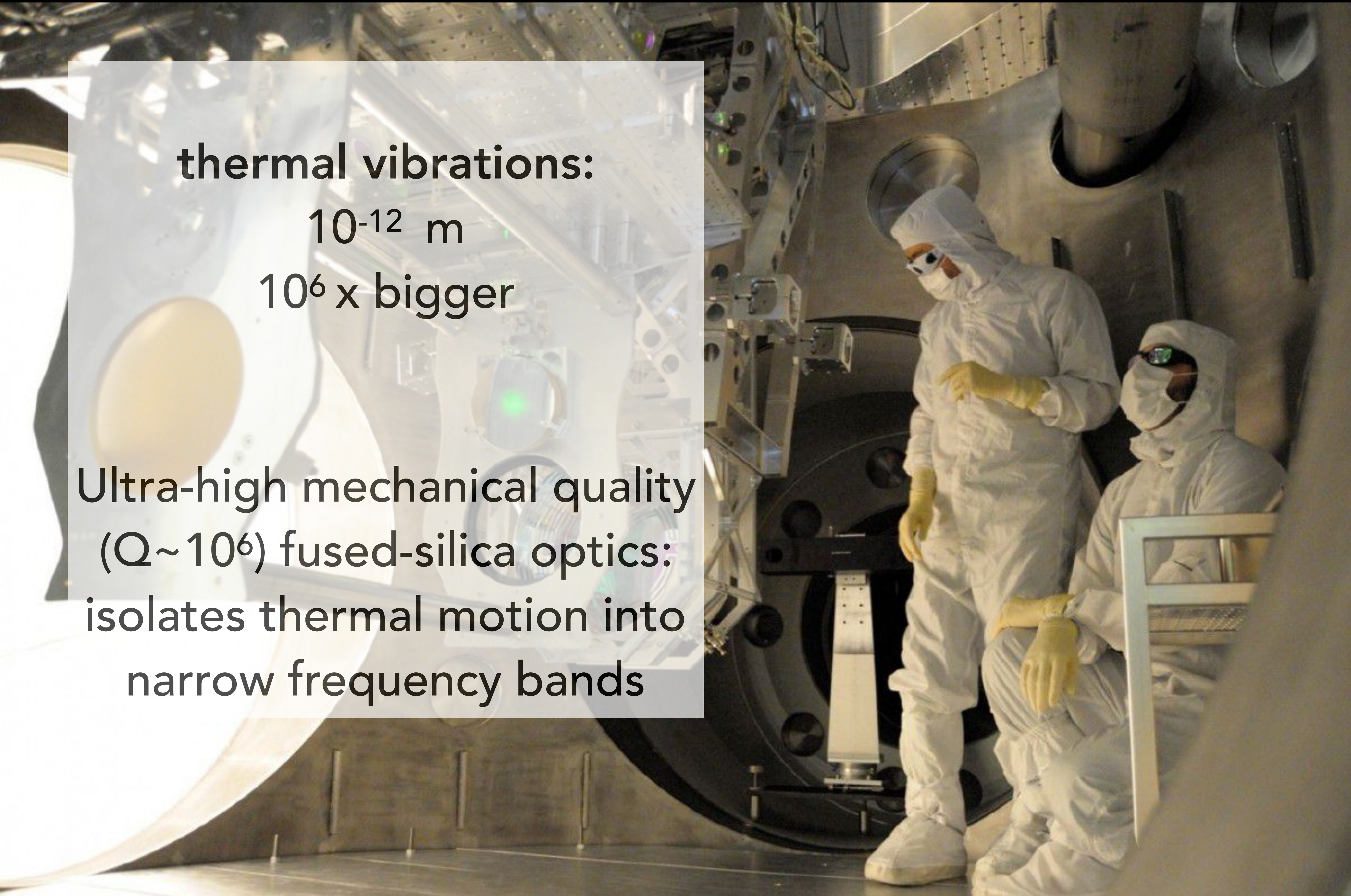
Active seismic isolation: 10^{3}

x

Quadruple pendulum suspension system:10^{7} m



ULTRA-HIGH VACUUM TO AVOID LIGHT DIFFUSION



thermal vibrations:

10^{-12} m

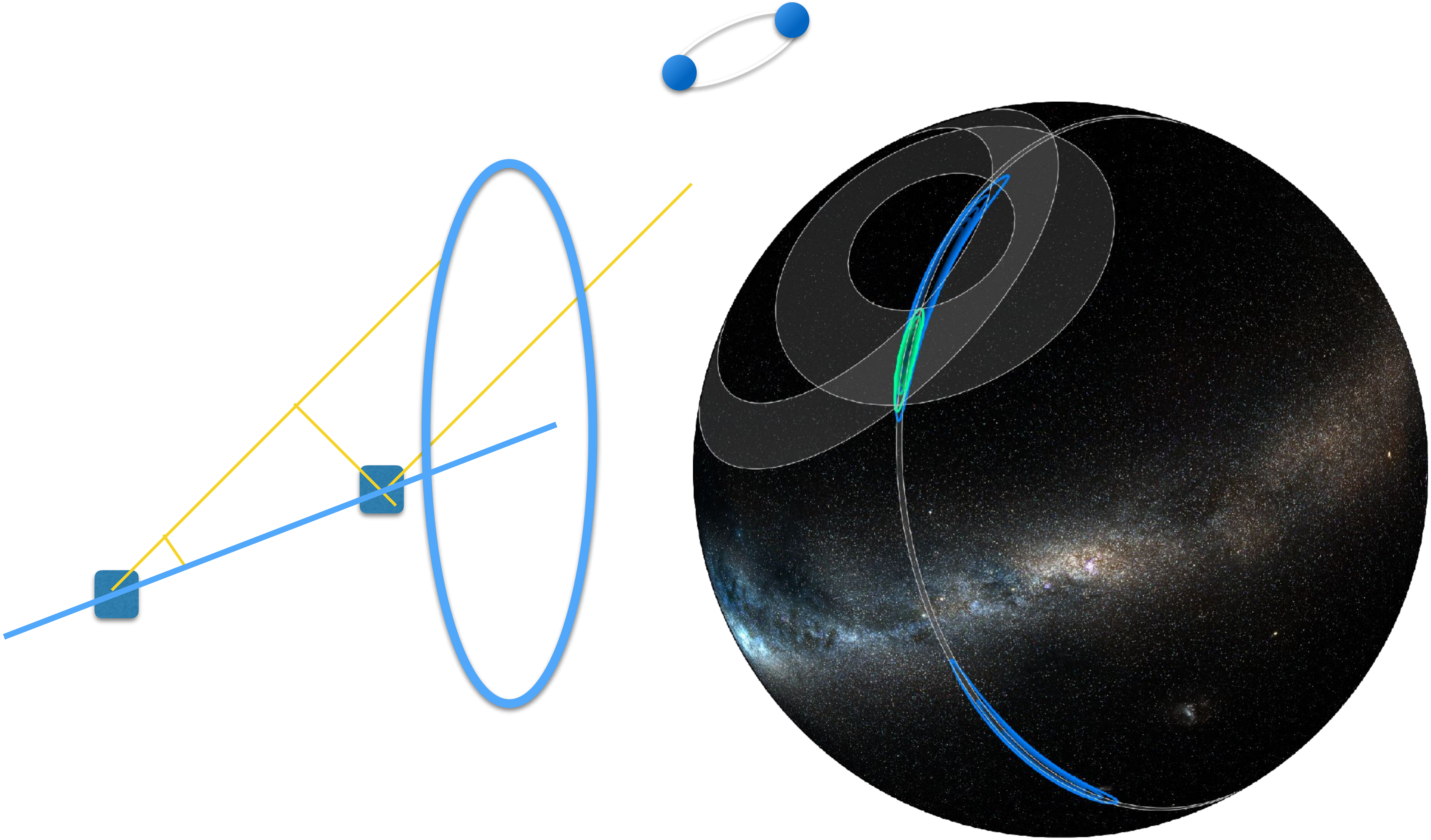
10^6 x bigger

Ultra-high mechanical quality ($Q \sim 10^6$) fused-silica optics: isolates thermal motion into narrow frequency bands

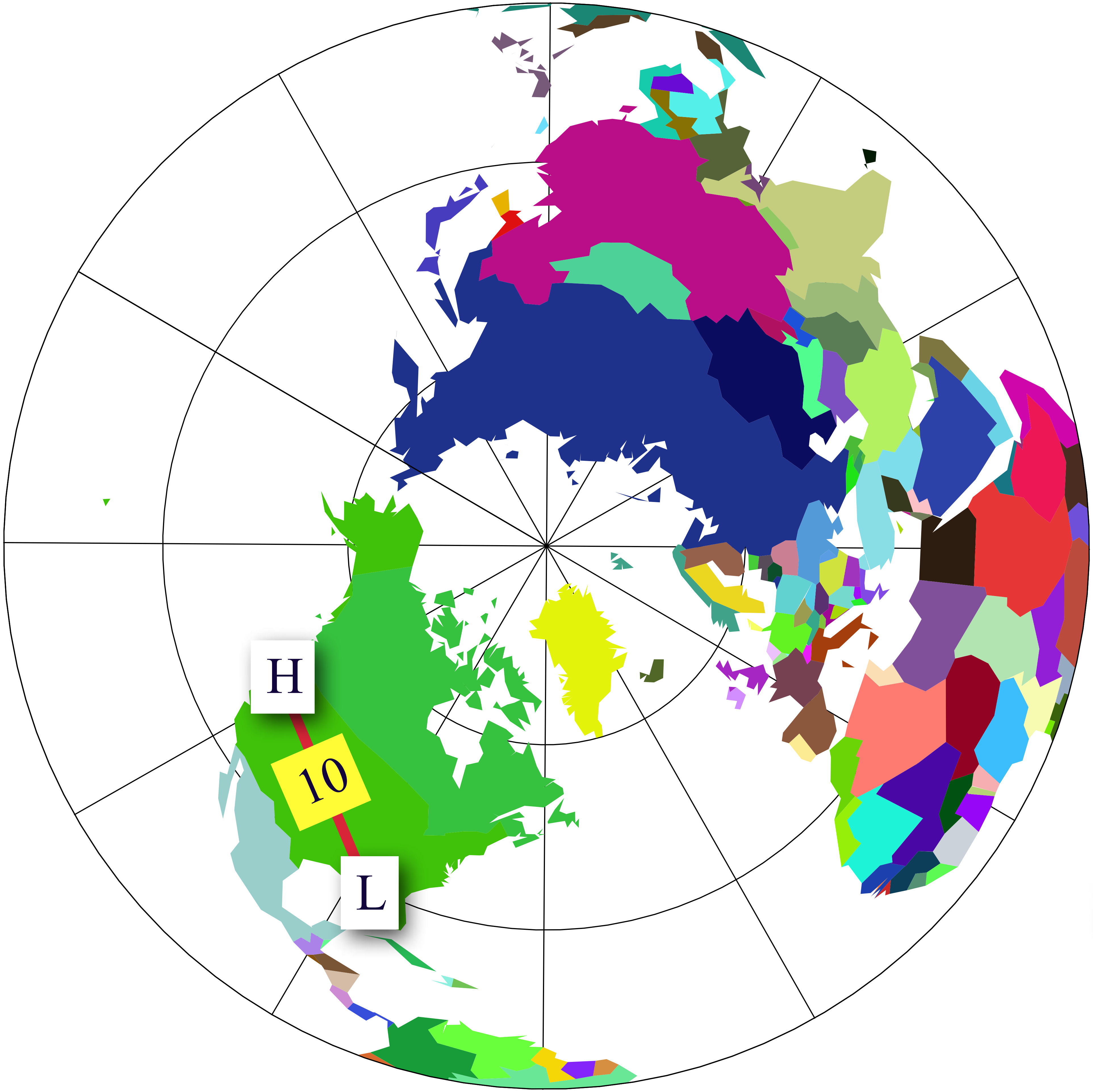
FROM DETECTION TO SOURCE: ANALYSIS AND INFERENCE

- Source localization
  - by triangulation and antenna pattern
- Detection
  - is there a signal of known shape in the data?
- Measurement
  - if so, what are its properties?
- Waveform Models
  - Analytical and numerical models of binary coalescence waveforms
- Model Selection
  - amongst a set of competing models, which model best fits the data?

LOCALIZING SOURCE



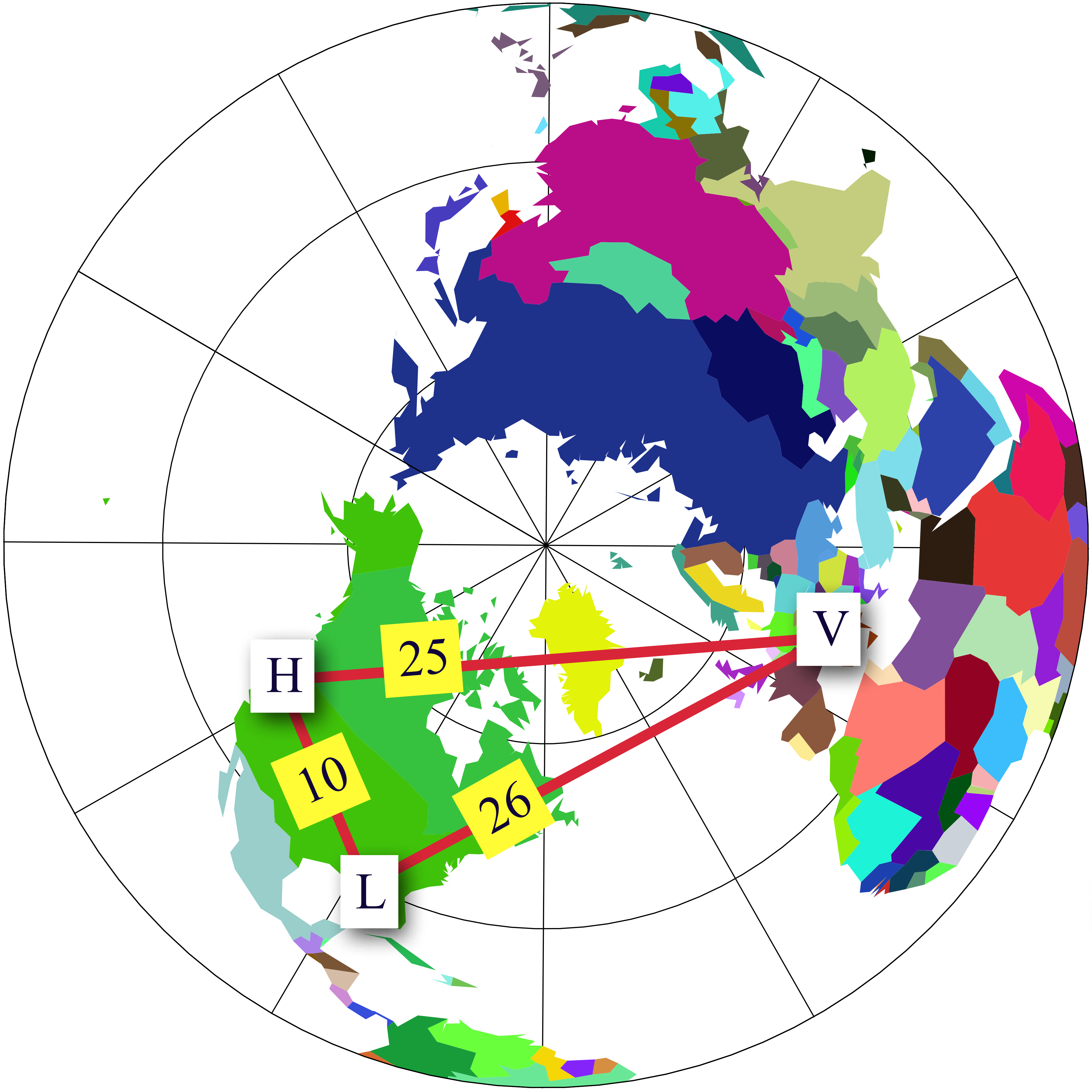
Detector Networks 2015+



Baselines

in light travel time (ms)

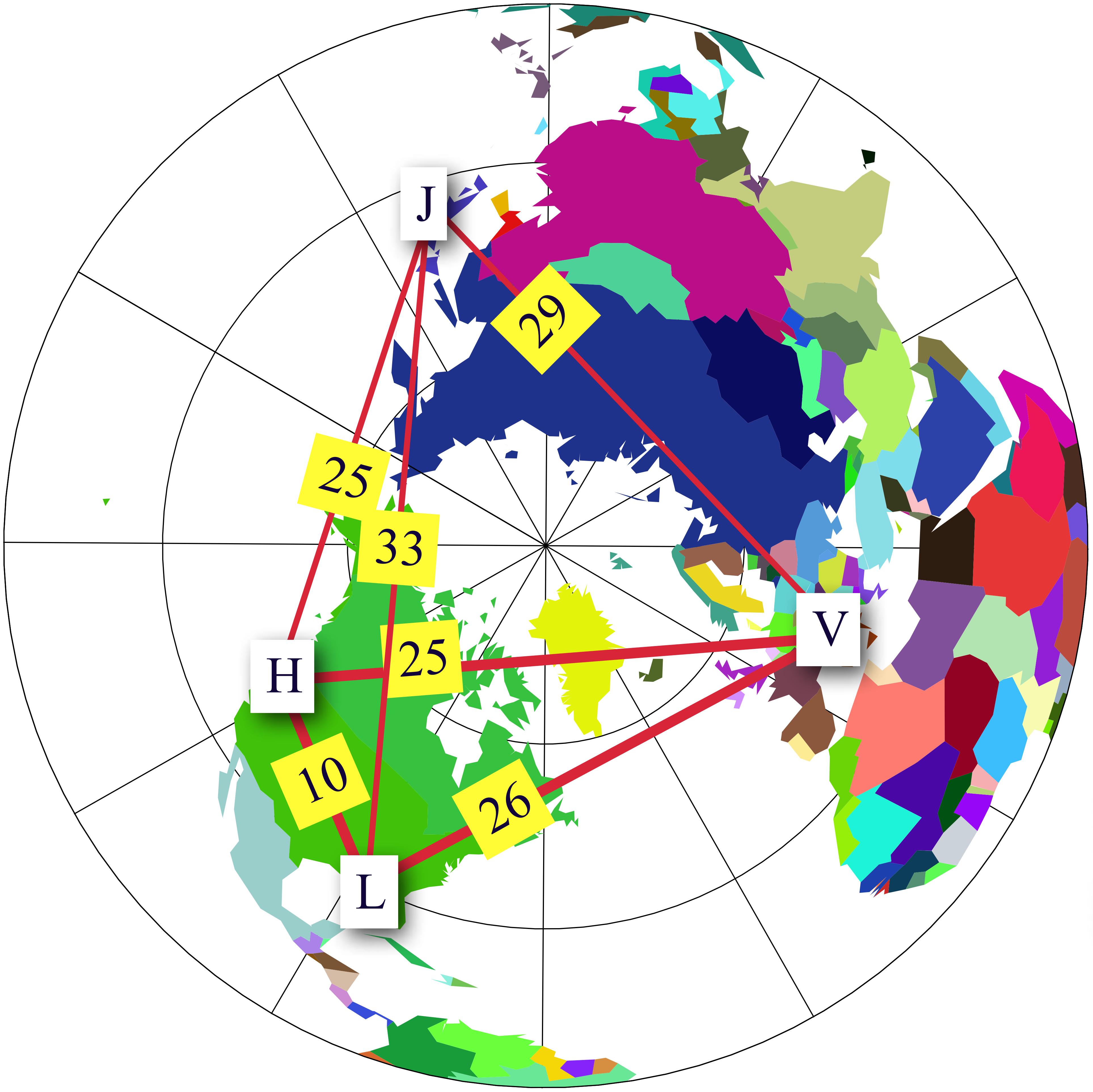
Detector Networks 2016+



Baselines

in light travel time (ms)

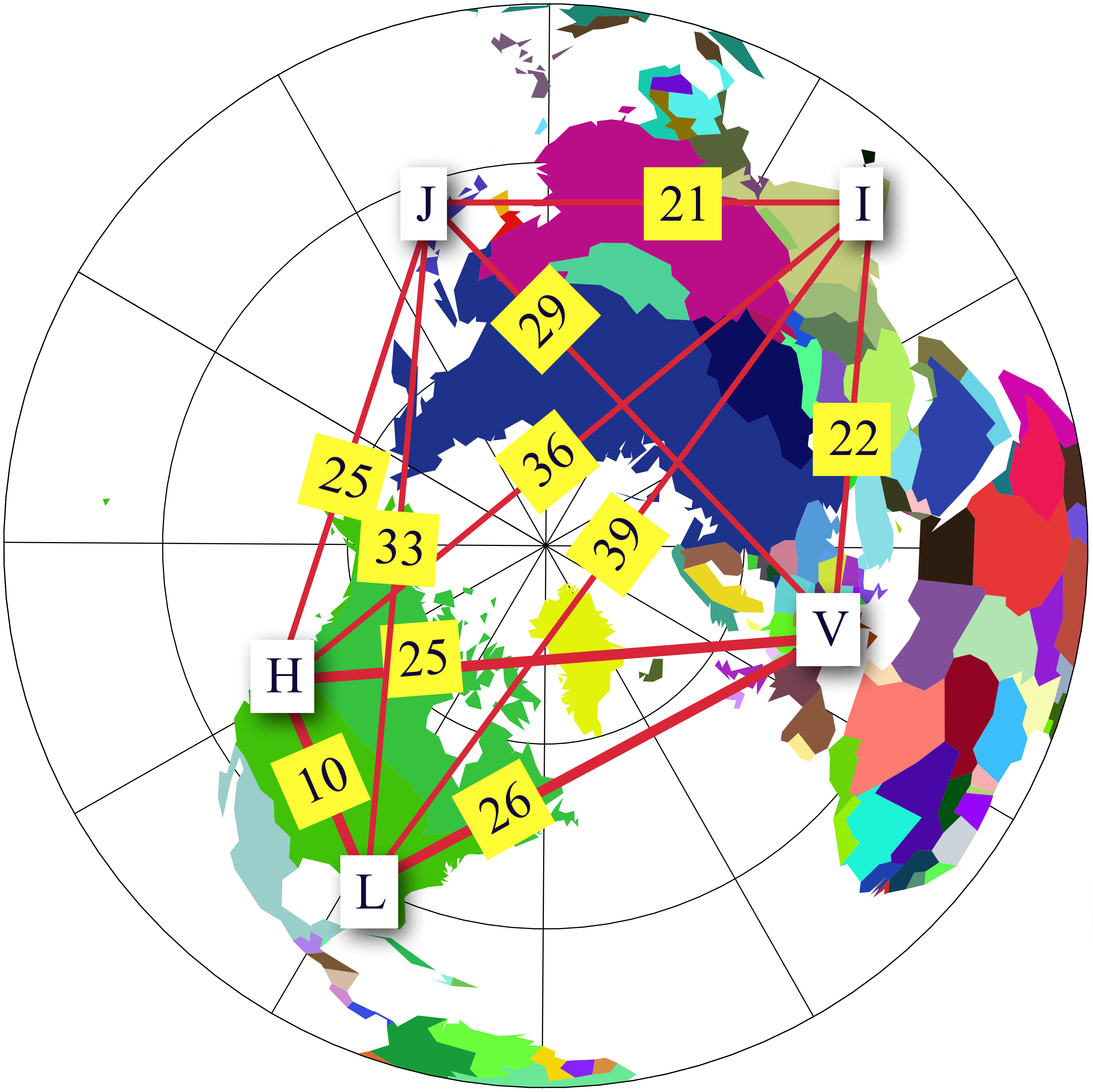
Detector Networks 2019+



Baselines

in light travel time (ms)

Detector Networks 2025+

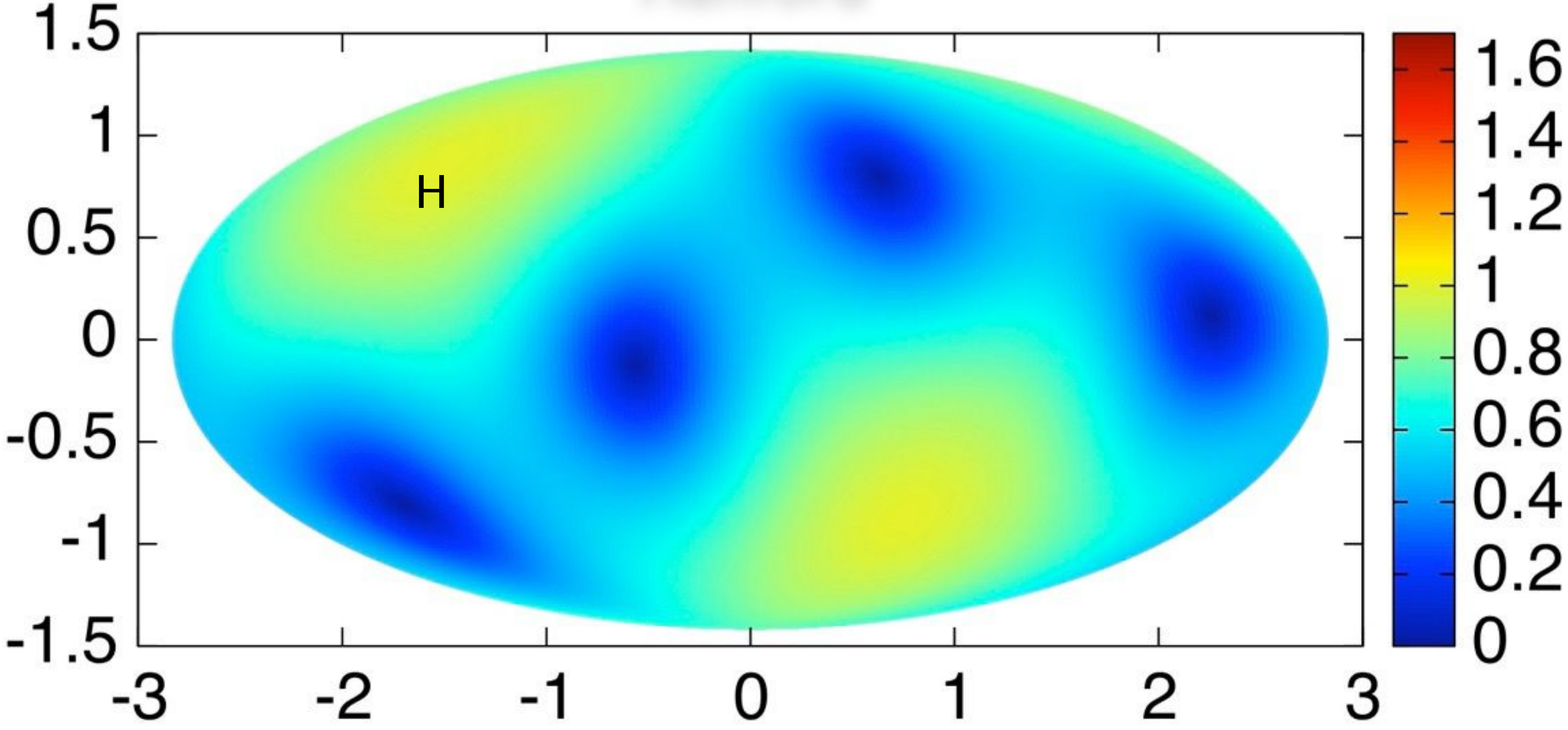


Baselines

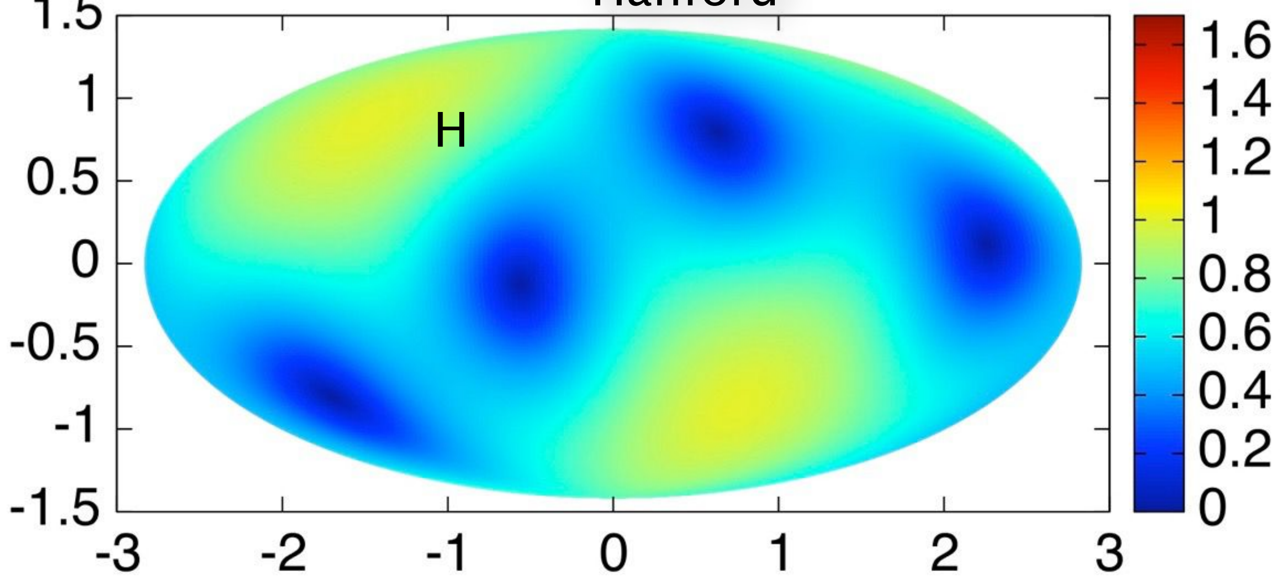
in light travel time (ms)

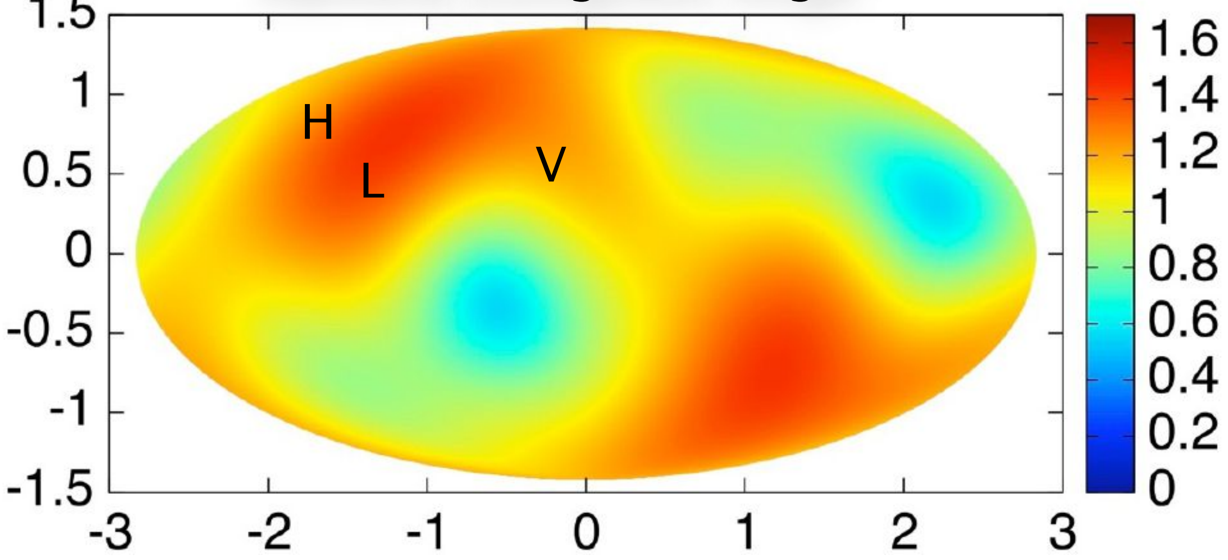
ANTENNA PATTERN OF AN INTERFEROMETER

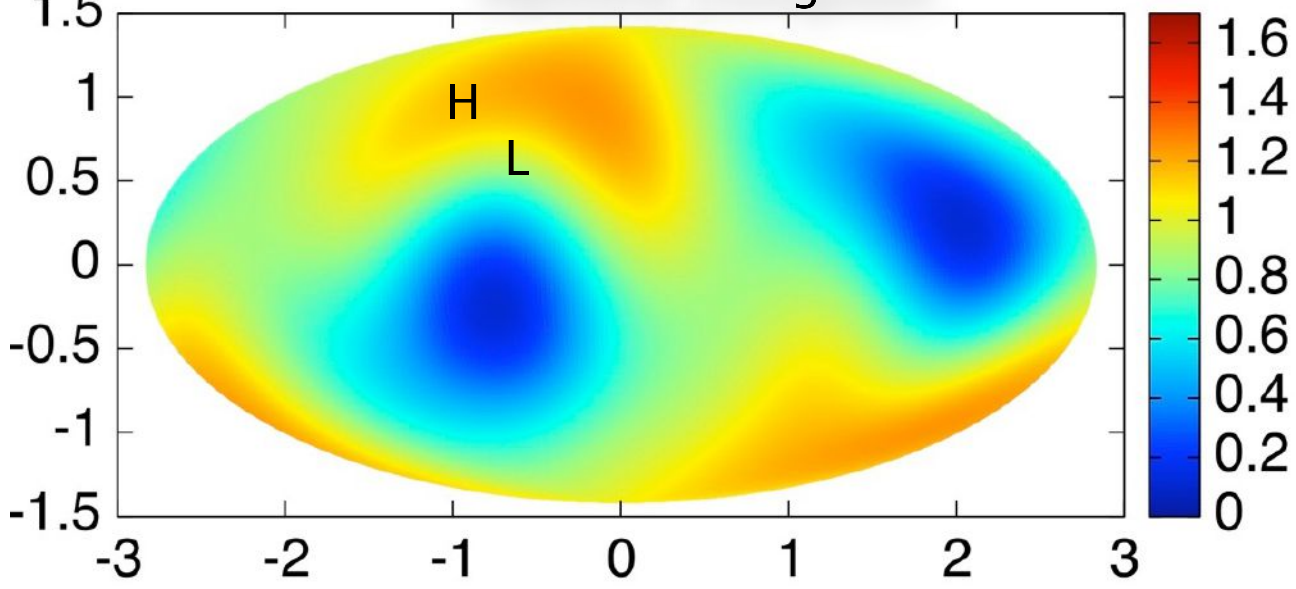
Hanford

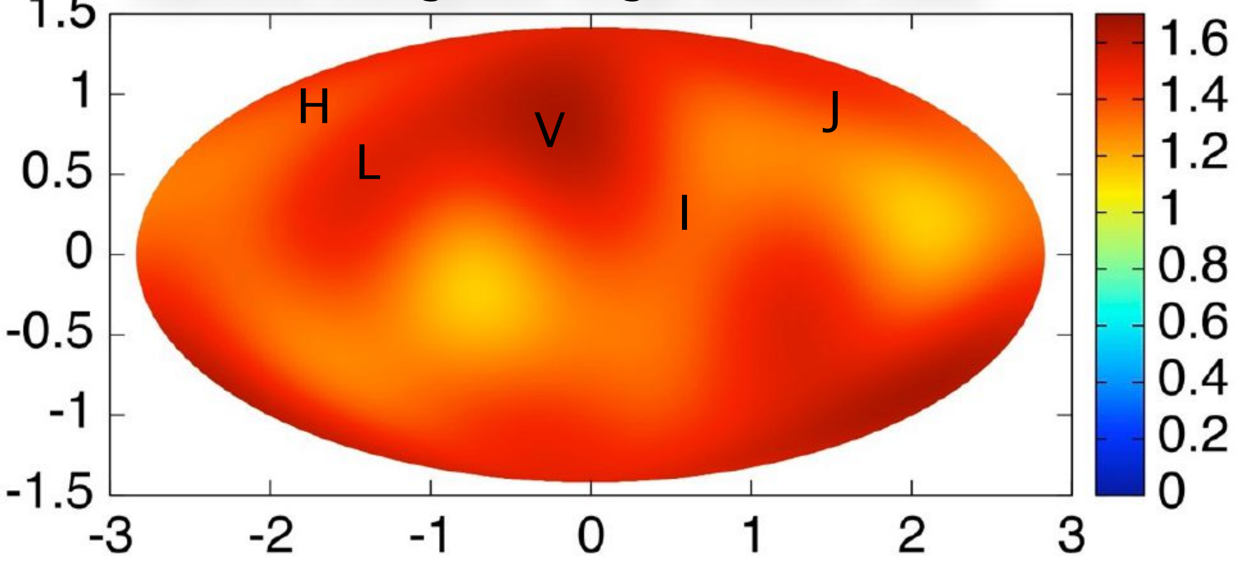


BEAM PATTERNS OF NETWORKS


Hanford


Hanford_Livingston_Virgo


Hanford_Livingston


Hanford_Livingston_Virgo_KAGRA_India

DETECTION

STATEMENT OF THE PROBLEM

- detector output consists of:
  - only background noise: $x(t) = n(t)$
  - noise + some interesting signal: $x(t) = h(t) + n(t)$
  - given a detector output which of the two possibilities is more likely given that the noise background is Gaussian and stationary
- formulate the problem as Bayes' theorem:

$$P(h|x) = \frac{P(x|h)P(h)}{P(x)}$$

- posterior prob. = likelihood x prior / evidence

- denominator is: $P(x) = P(x|h)P(h) + P(x|\bar{h})P(\bar{h})$
- define likelihood ratio:

$$\Lambda = \frac{P(x|h)}{P(x|n)}$$

- if signals are rare then

$$P(h) \ll 1 \text{ and } P(\bar{h}) = 1 - P(h) \simeq 1$$

- in that case the posterior prob. of a signal given data is:

$$P(h|x) = \frac{\Lambda P(h)}{1 + \Lambda P(h)}$$

- for confident detection

$$\Lambda \gg 1/P(h)$$

- rarer the signal larger should be the likelihood for a given confidence: for 5-sigma detection $P(h|x) \simeq 0.999\,999$

one in a million

COMPUTING THE LIKELIHOOD RATIO

- noise is a Gaussian random process, so at any instant *t*k

$$P(n_k) = \frac{1}{\sqrt{2\pi}\sigma_k} e^{-n_k^2/2\sigma_k^2}$$

- it is more convenient to deal with Fourier domain quantities Nk (similarly, Xk and Hk):

$$P(N_k) = \frac{1}{\sqrt{2\pi}S_k} e^{-N_k^2/2S_k^2}$$

- so the probability of getting a sequence $P(\{N_k\})$

$$P(\{N_k\}) = \prod_k \frac{1}{\sqrt{2\pi}S_k} e^{-N_k^2/2S_k^2} \propto e^{-\frac{1}{2}\langle n,n\rangle}$$

$$< a, b >= \sum |N_k|^2/S_k^2$$

- if signal is absent n=x, if signal is present n=x-h:

$$\Lambda = \frac{P(x|h)}{P(x|n)} = \frac{e^{-\frac{1}{2}\langle x-h,x-h\rangle}}{e^{-\frac{1}{2}\langle x,x\rangle}} = e^{\langle x,h\rangle-\frac{1}{2}\langle h,h\rangle}$$

DIFFICULTIES …

- the likelihood ratio is computationally very expensive:
  - <x, h> would need to be computed at 10's of millions of points in the parameter space (parameters μ) before giving up - signal
  - a scheme would be needed to compute P(x|n) - background
- noise is not Gaussian or stationary
  - nothing much can be done about non-stationarity: detector behavior is assumed to be stable over periods ~ days
  - non-Gaussian and non-stationary data is rejected
    - glitch rejection, signal consistency checks, coincidence and coherent analysis, etc.
  - will not address this latter problem here

A GEOMETRICAL FORMULATION OF DATA ANALYSIS: SIGNAL MANIFOLD

- detector outputs can be thought of as vectors
  - the set of all detector outputs forms a vector space
- signals are also vectors that live in this vector space
  - space of signals forms a manifold: signal parameters (e.g. masses and spins of black holes) are coordinates that determine the dimension of the manifold
- the scalar product <a,b> can be used to induce a metric on the manifold: $g_{\alpha\beta} = \langle h_\alpha, h_\beta \rangle$, where $h_\alpha = \delta h / \delta \mu_\alpha$
  - the signal space now acquires a shape

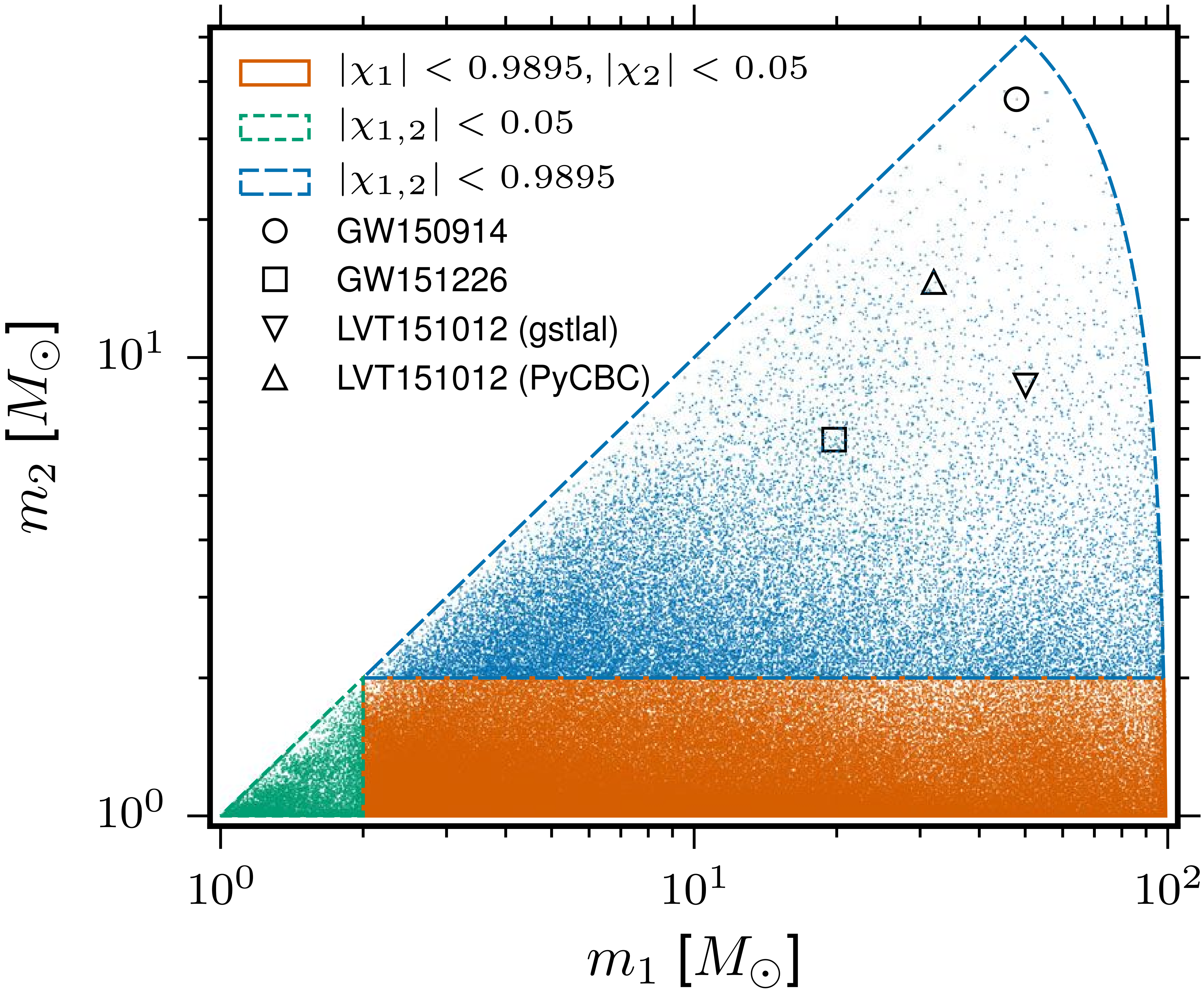
TEMPLATE BANKS FOR COMPUTING <x,h(μ)>

- volume of the parameter space is: $V = \int \sqrt{g}\, \mathrm{d}^n \mu$
- if each template covers a volume V then the number of templates is:

$$N = \frac{1}{\Delta V} \int \sqrt{g}\, \mathrm{d}^n \mu$$

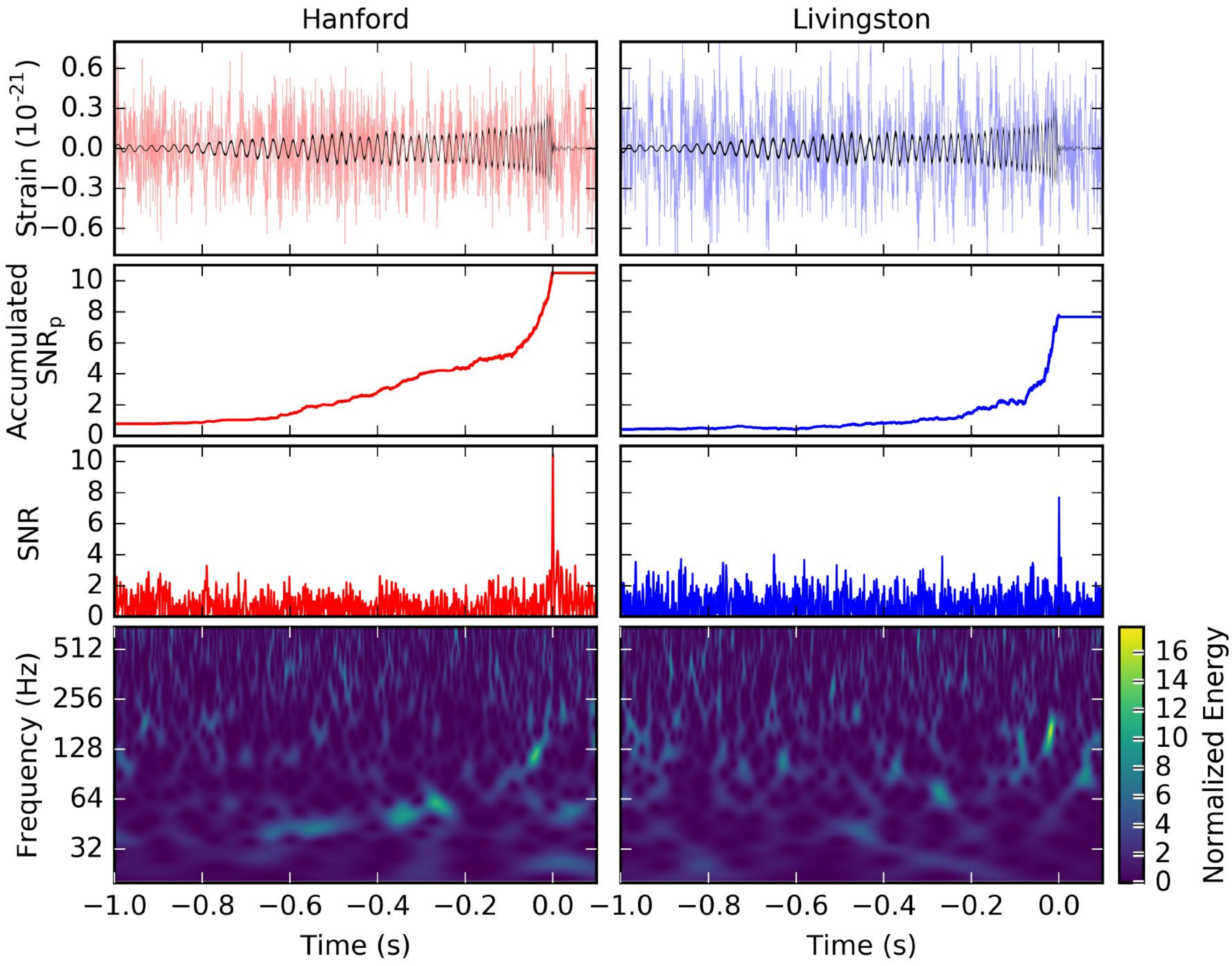
- but how to choose templates … template placement problem, a hard problem with only sub-optimal solutions
  - a uniform grid, say, in the space of masses and spins, or something more fancy?
  - a hexagonal lattice, stochastic method, …
- O1 search deployed 250,000 templates for compact binary coalescence searches

TEMPLATE BANK USED IN O1 SEARCH FOR COMPACT BINARY COALESCENCES



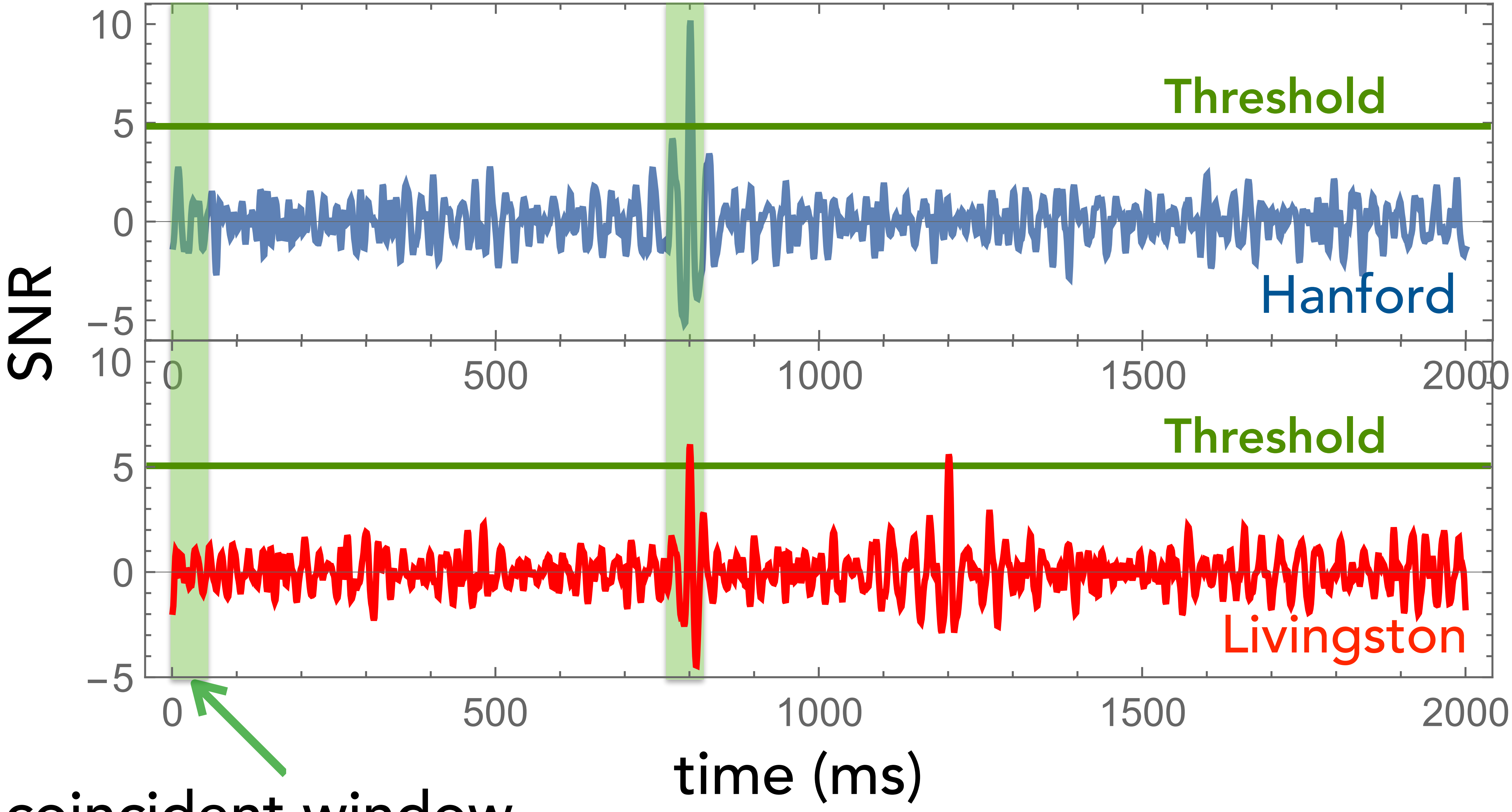
Matched filtering and waveform models were critical for detection and signal reconstruction

GW151226



COINCIDENT DETECTION

- coincidence detection: look for triggers coincident within light-travel time in a network of detectors

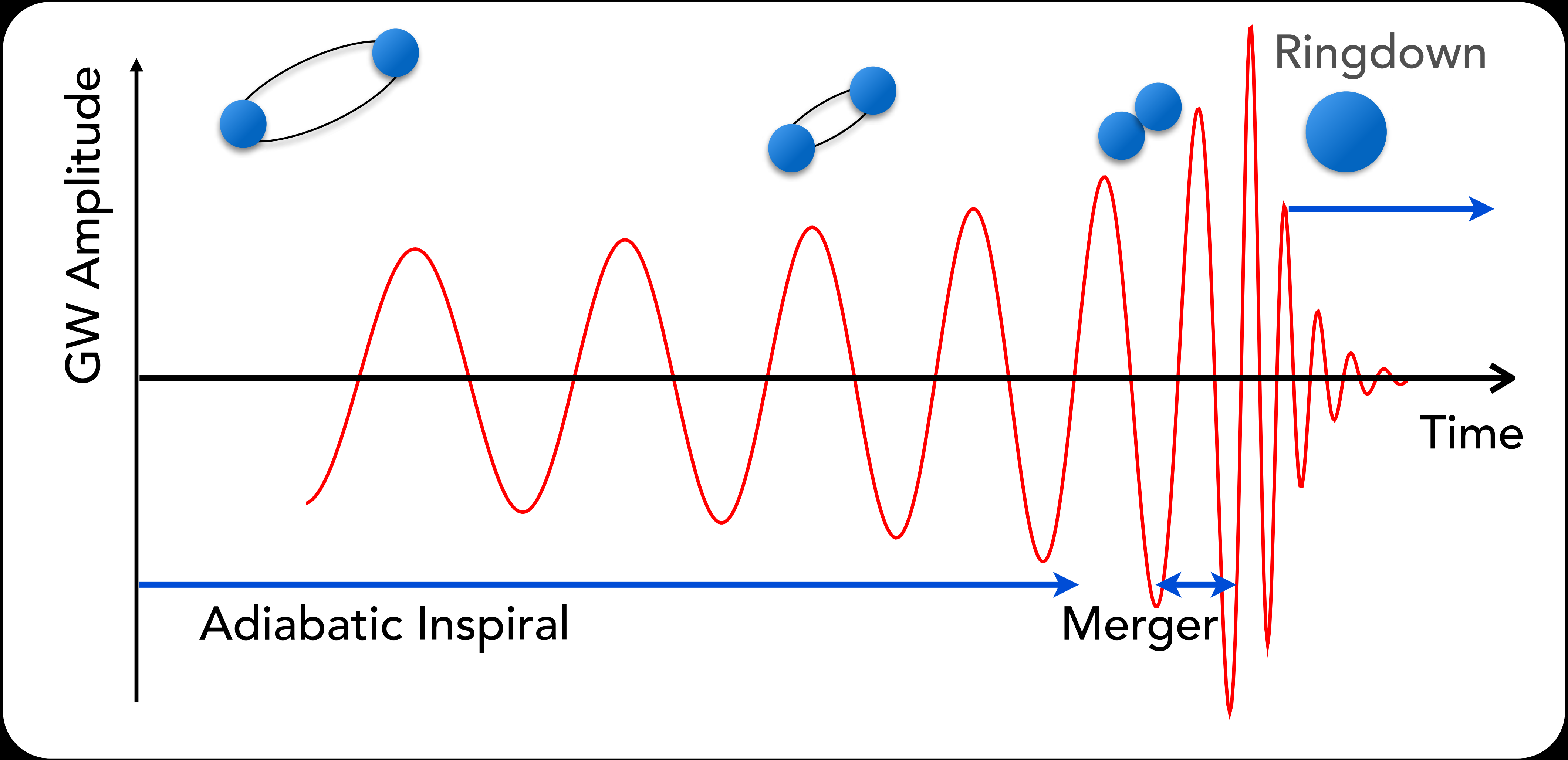


coincident window

WAVEFORMS

BINARY BLACK HOLE WAVEFORM

- waveform characterised by
  - slow adiabatic inspiral, fast and luminous merger, rapid ringdown
- very large parameter space
  - mass ratio, large BH spins misaligned with orbit, eccentricity
- waveform shape can tell us about component masses, spins and eccentricity
- waveform amplitude (in a detector network) can tell us about source’s orientation, sky position, polarisation and distance



POST-NEWTONIAN THEORY

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

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

(Abbott et al. arXiv:1606.04856)

post-Newtonian expansion is known to order $(v/c)^7$

capture a lot of interesting physical effects

Blanchet, Living Reviews

wave tails

mass asymmetry

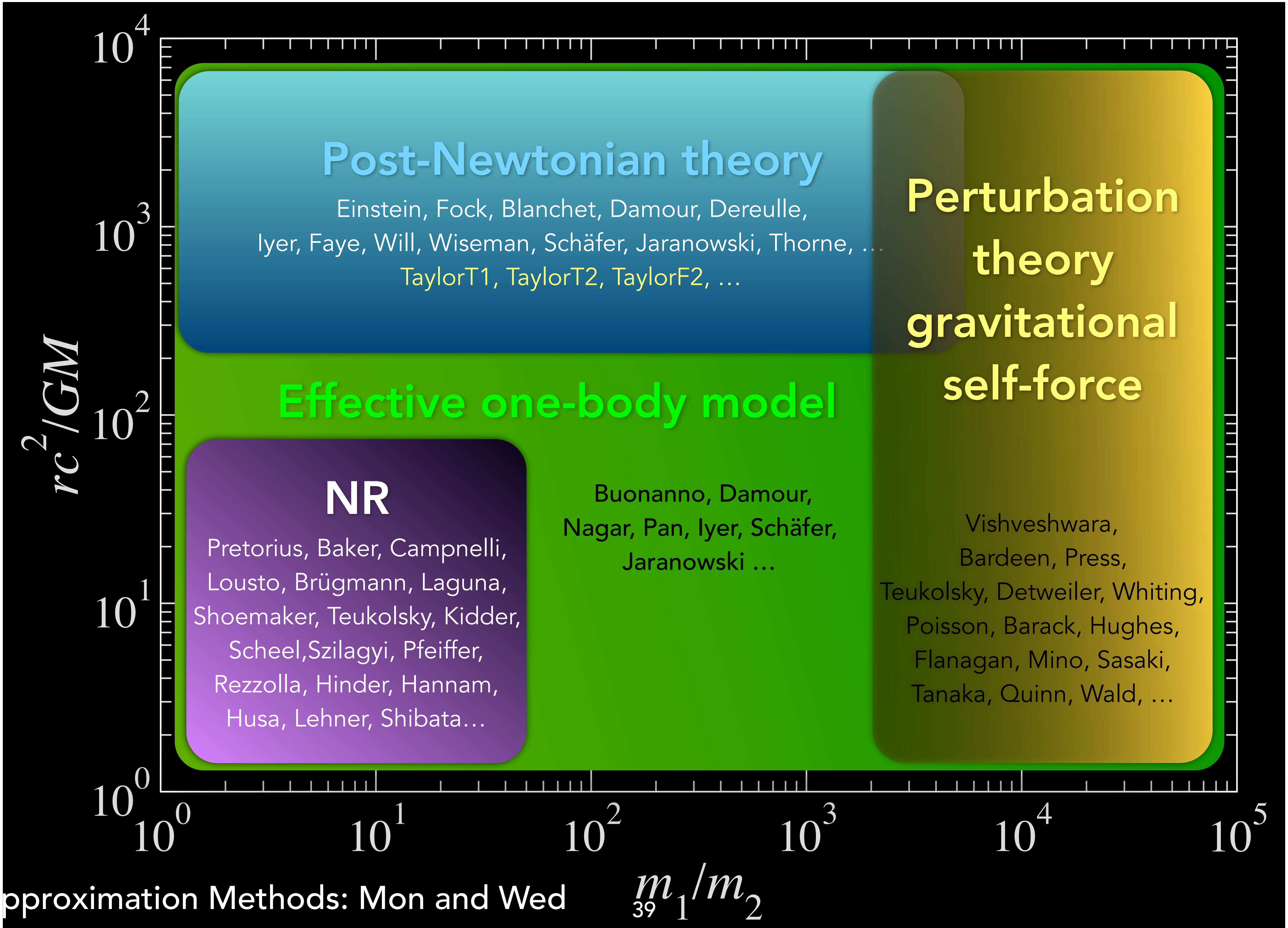
spin-spin coupling

spin-orbit coupling

hereditary terms

spin precession

absorption of radiation by black hole



Post-Newtonian theory

Einstein, Fock, Blanchet, Damour, Dereulle,
Iyer, Faye, Will, Wiseman, Schäfer, Jaranowski, Thorne, …
TaylorT1, TaylorT2, TaylorF2, …

Perturbation theory gravitational self-force

Effective one-body model

NR

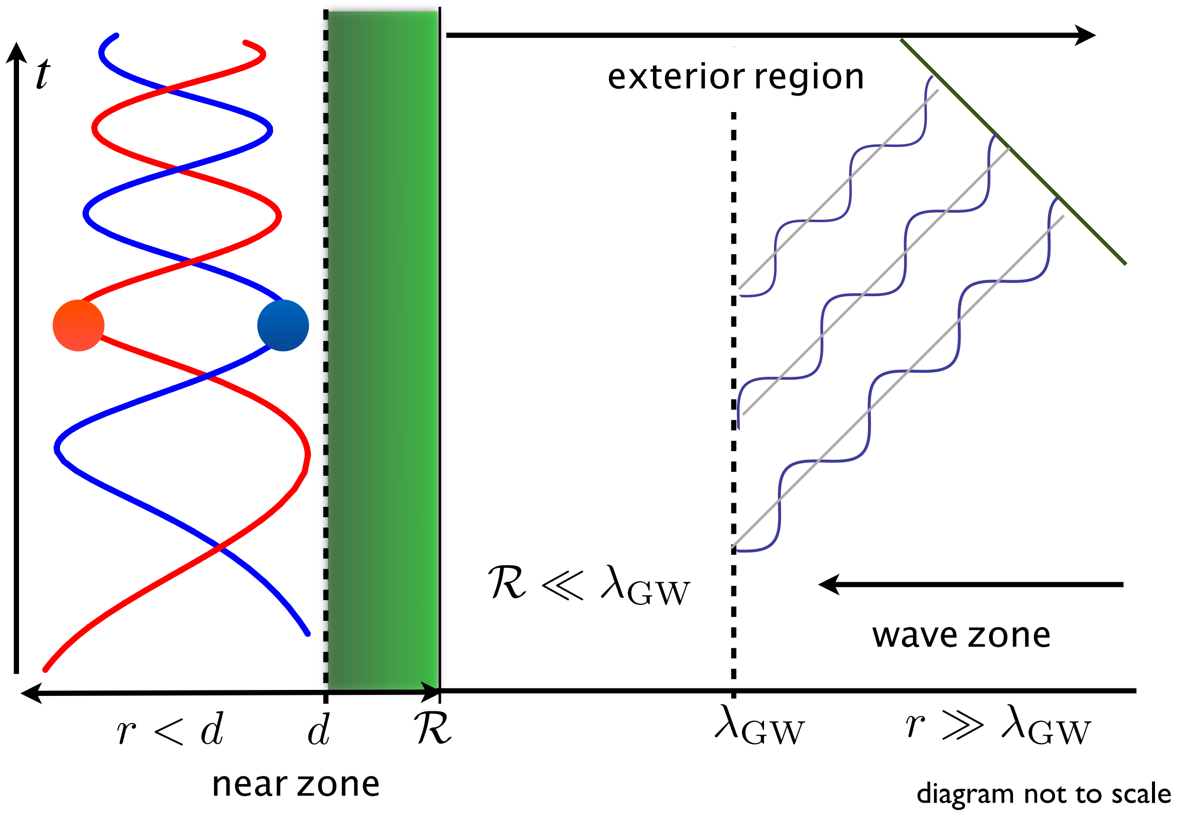
Pretorius, Baker, Campnelli,
Lousto, Brügmann, Laguna,
Shoemaker, Teukolsky, Kidder,
Scheel,Szilagyi, Pfeiffer,
Rezzolla, Hinder, Hannam,
Husa, Lehner, Shibata…

Buonanno, Damour,
Nagar, Pan, Iyer, Schäfer,
Jaranowski …

Vishveshwara,
Bardeen, Press,
Teukolsky, Detweiler, Whiting,
Poisson, Barack, Hughes,
Flanagan, Mino, Sasaki,
Tanaka, Quinn, Wald, …

PROGRESS IN TWO-BODY PROBLEM

- Caltech group pointed out the importance of computing phasing beyond leading order; followed by very impressive progress in post-Newtonian computation of two-body dynamics
- construction of LIGO, Virgo, GEO600 and TAMA brought theory and observations closer
- effective one-body approach developed: bold prediction for the late inspiral, merger and ringdown
- first successful NR simulations broke conventional wisdom - a far simpler merger than anyone predicted
- remarkable interactions between GW data analysts, astrophysicists and theorists to open a new observational window



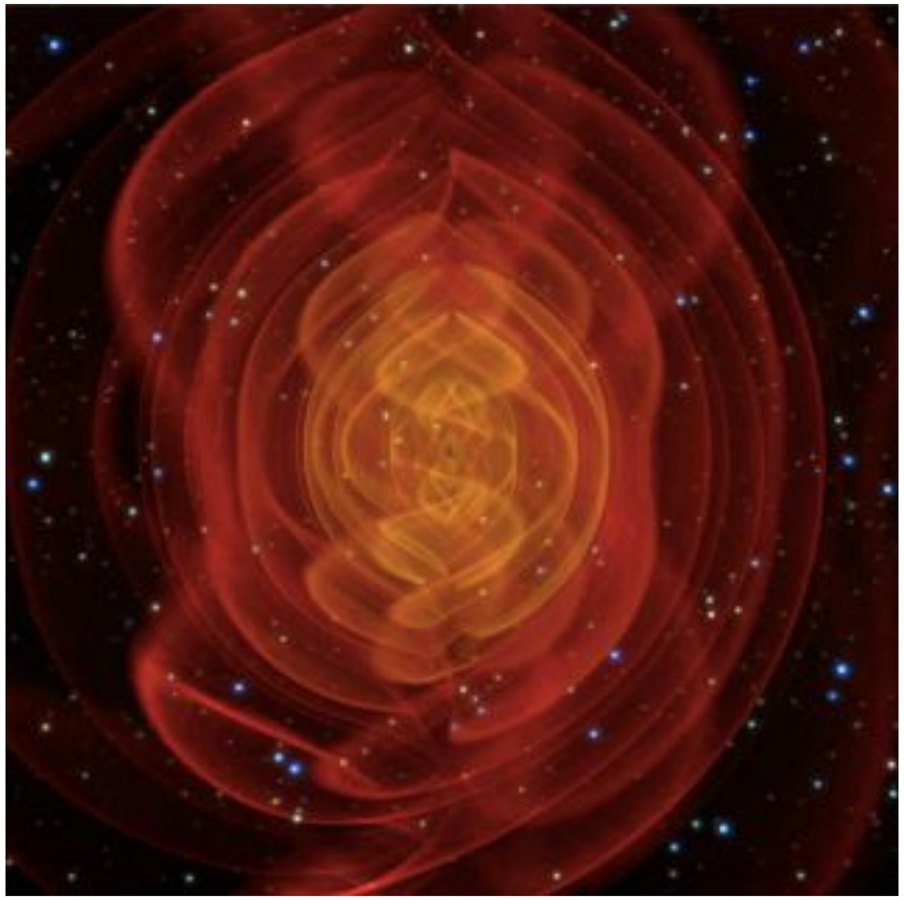


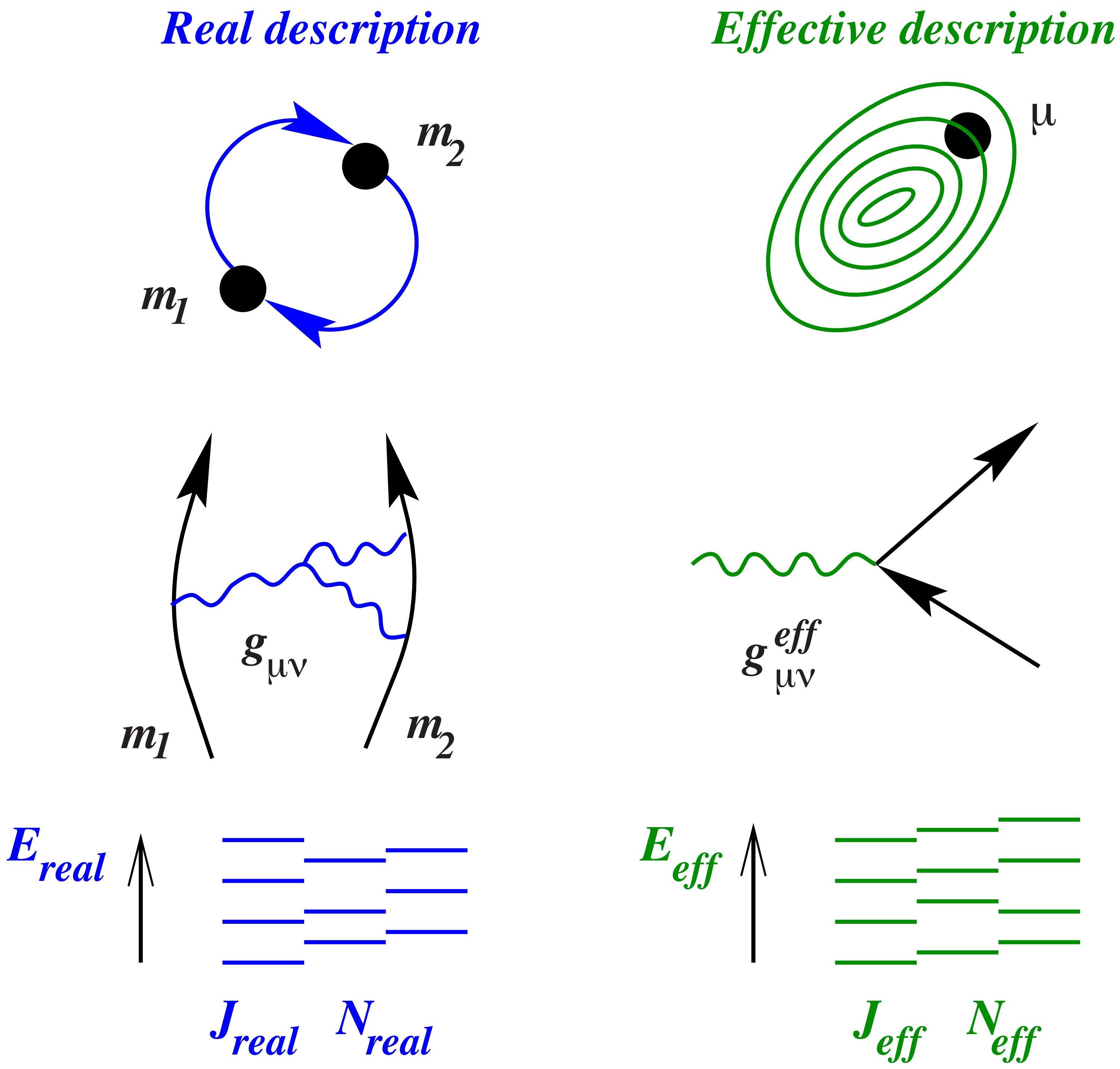
image curtsey NASA/C. Henze

CURRENT STATUS OF PN CALCULATIONS

	No Spin	Spin-Linear	Spin-Squared	Tidal
Conservative Dynamics	4PN	3.5PN	3PN	7PN
Energy Flux at Infinity	3.5PN	4PN	2PN	6PN
RR Force	4.5PN	4PN	4.5PN	6PN
Waveform Phase	3.5PN	4PN	2PN	6PN
Waveform Amplitude	3PN	2PN	2PN	6PN
BH Horizon Energy Flux	5PN	3.5PN	4PN	–

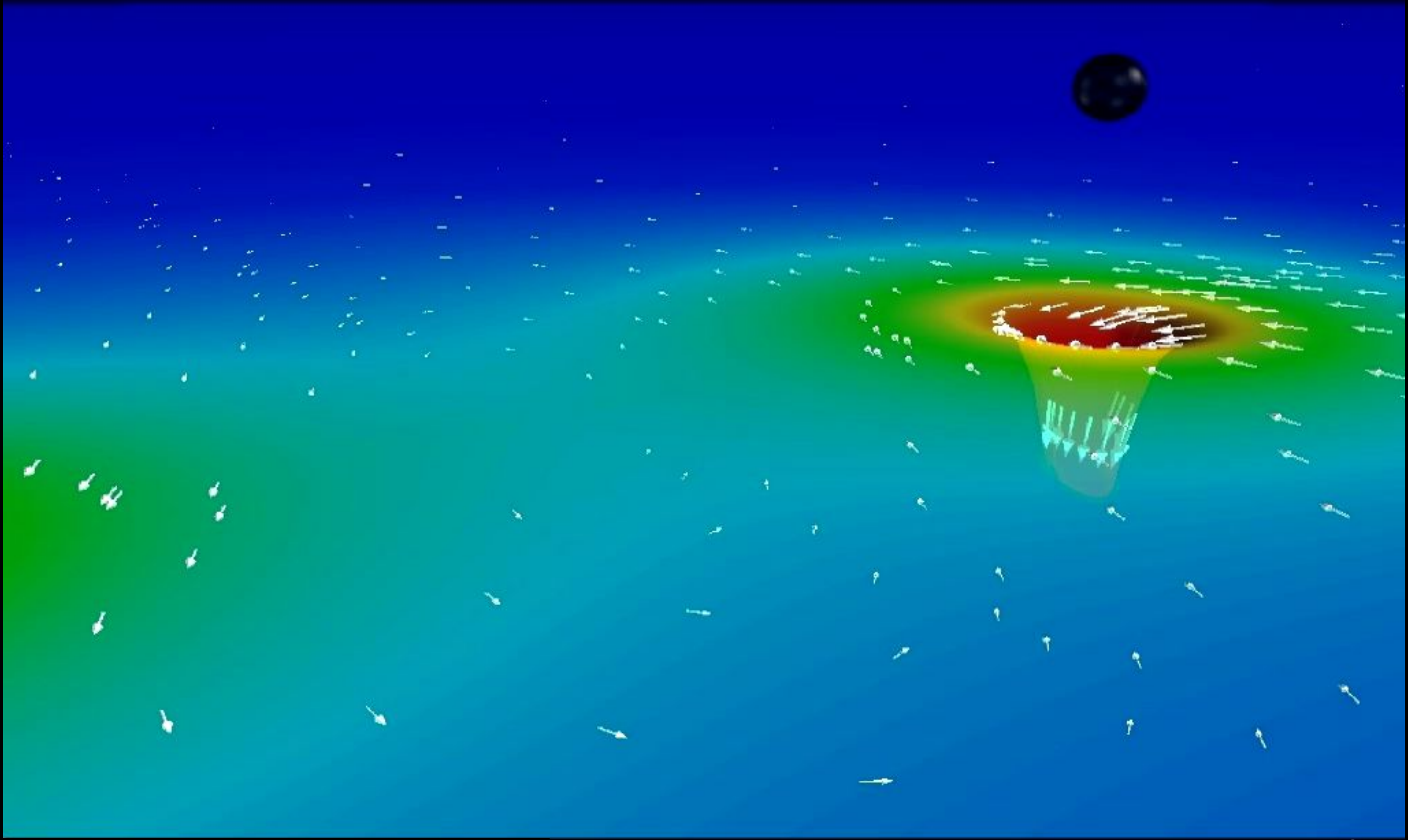
Table from Buonanno and BSS 2014

BEYOND INSPIRAL: EFFECTIVE ONE BODY FORMALISM



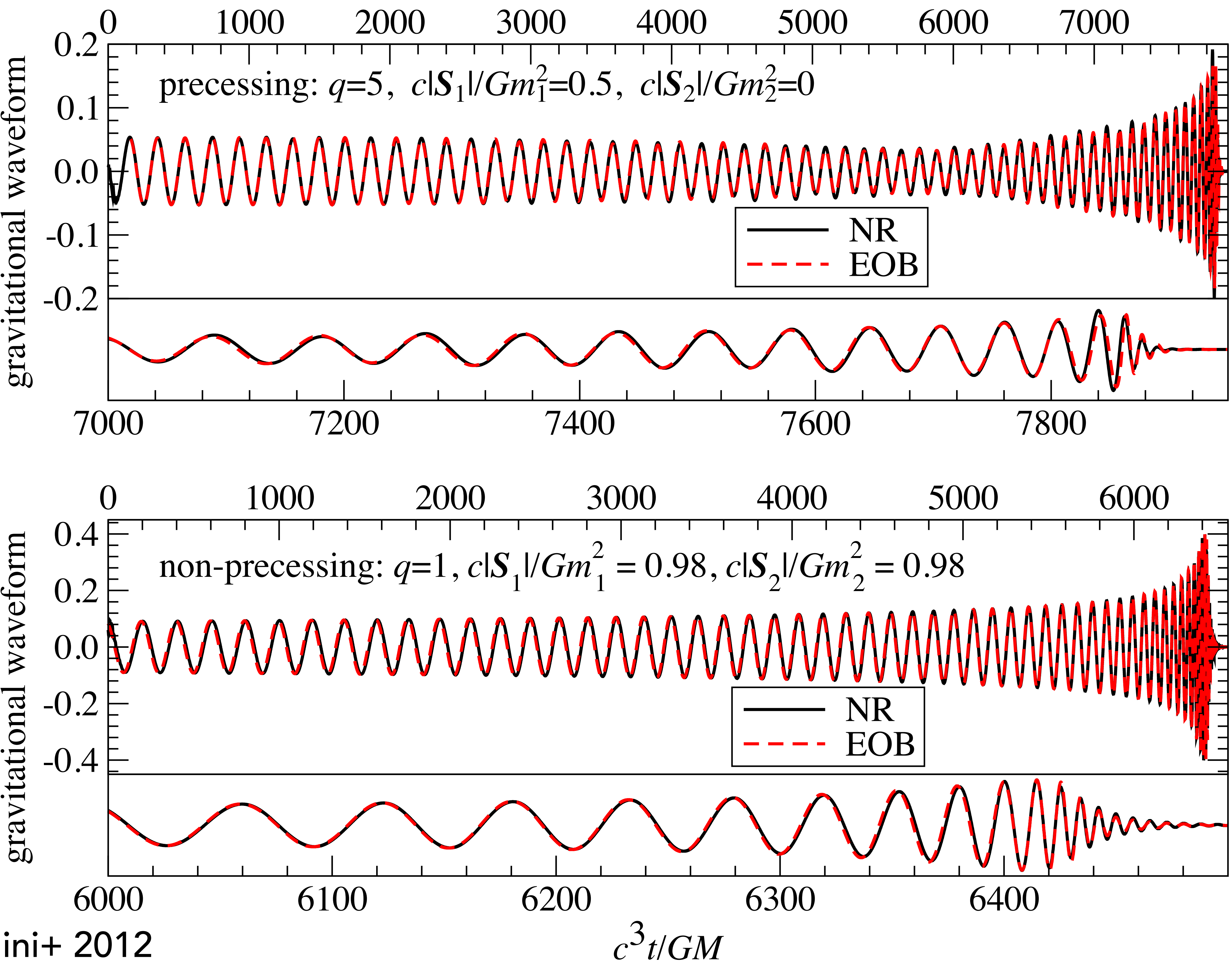
Buonanno and Damour 1999

NUMERICAL SIMULATIONS OF BBH



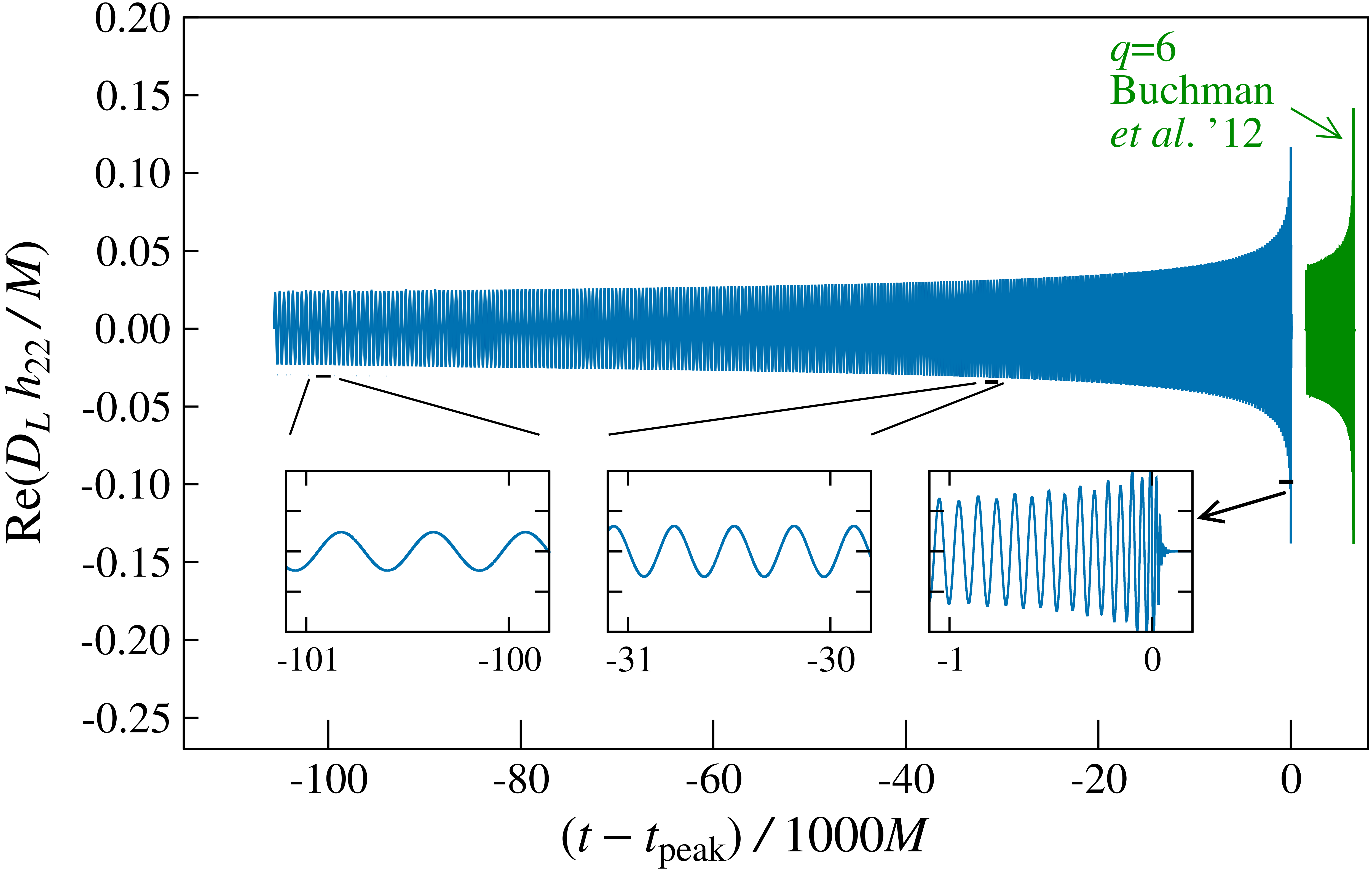
Caltech-Cornell simulation, 2009

EOB VIS-A-VIS NR SIMULATIONS



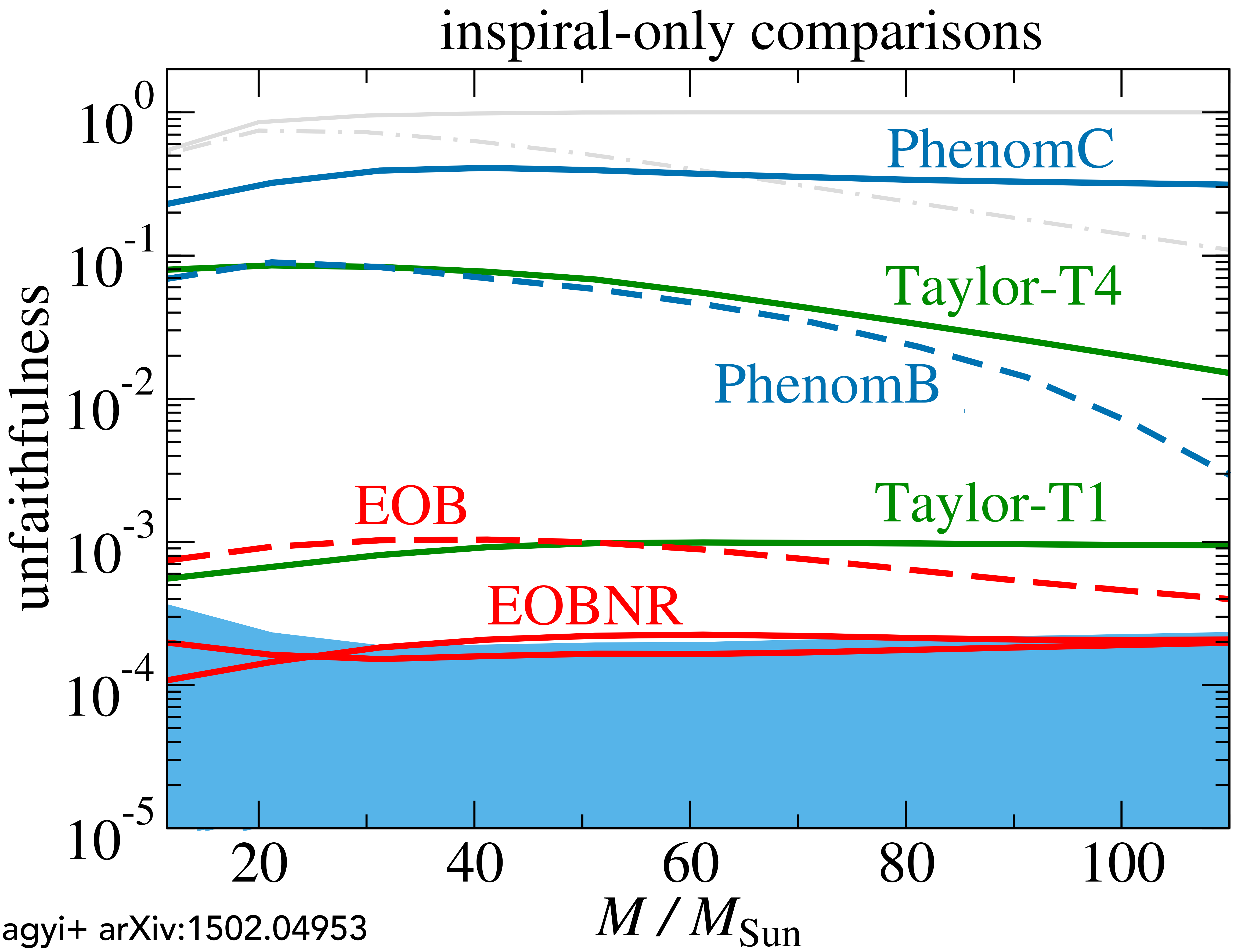
Taracchini+ 2012

LONGEST SO FAR: 170-ORBITS, MASS RATIO 1:7, NON-SPINNING



Szilagyi+ arXiv:1502.04953

UNFAITHFULNESS OF EOB < 0.1%



Szilagyi+ arXiv:1502.04953

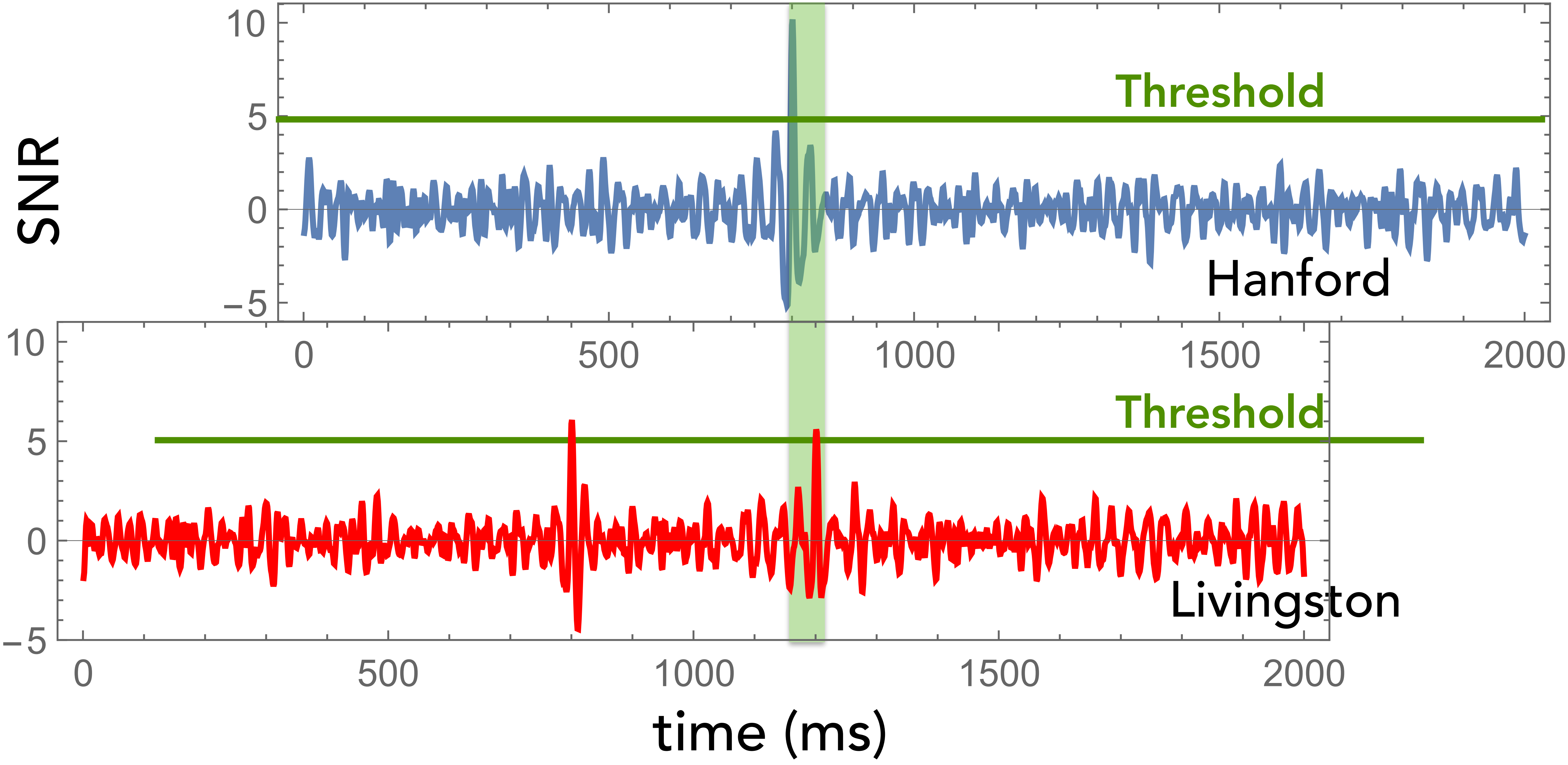
BACKGROUND

COMPUTING THE BACKGROUND

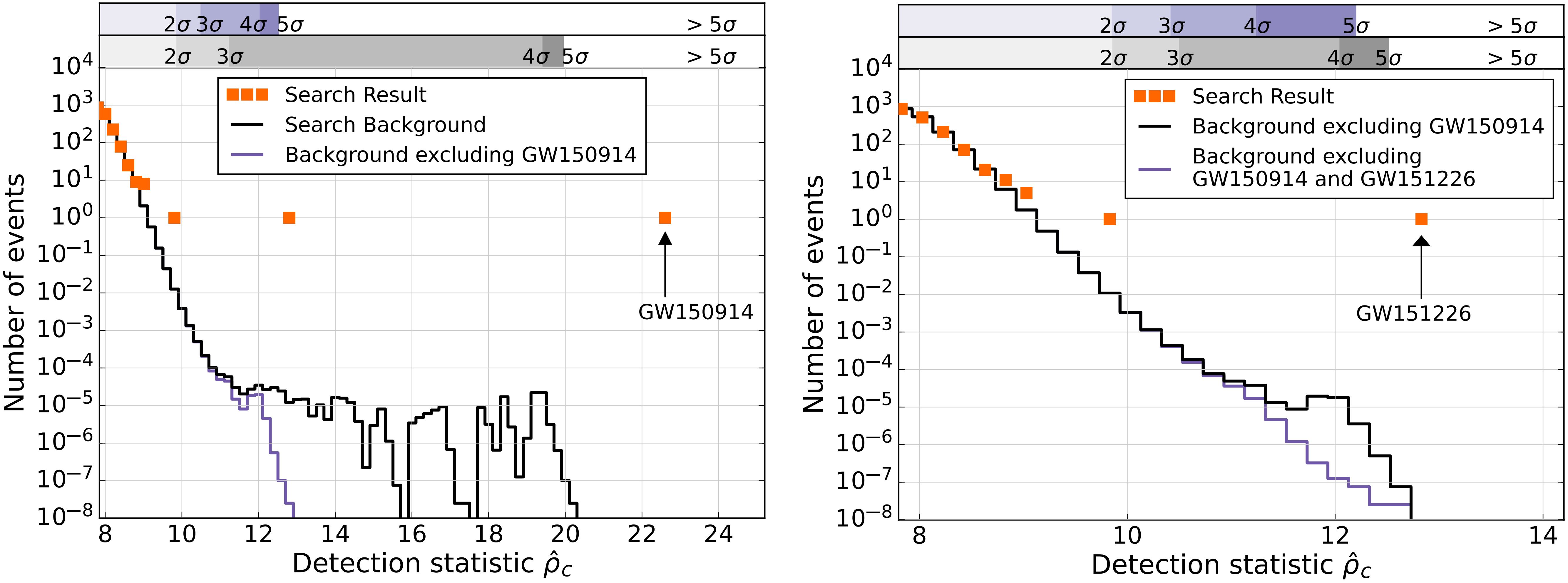
- a tale of two methods
  - time-shift method using triggers from coincidence analysis
    - background computed from fake coincidences in data from a pair of detectors one of whose time stamps are shifted artificially
  - likelihood method using triggers from single detectors
    - triggers from non-coincident single detector triggers are used used to compute the probability distribution of triggers for each detector
    - one then draws triggers from each distribution to estimate fake coincidences and their likelihoods compared to likelihoods of true coincidences

TIME-SHIFT METHOD FOR BACKGROUND ESTIMATION

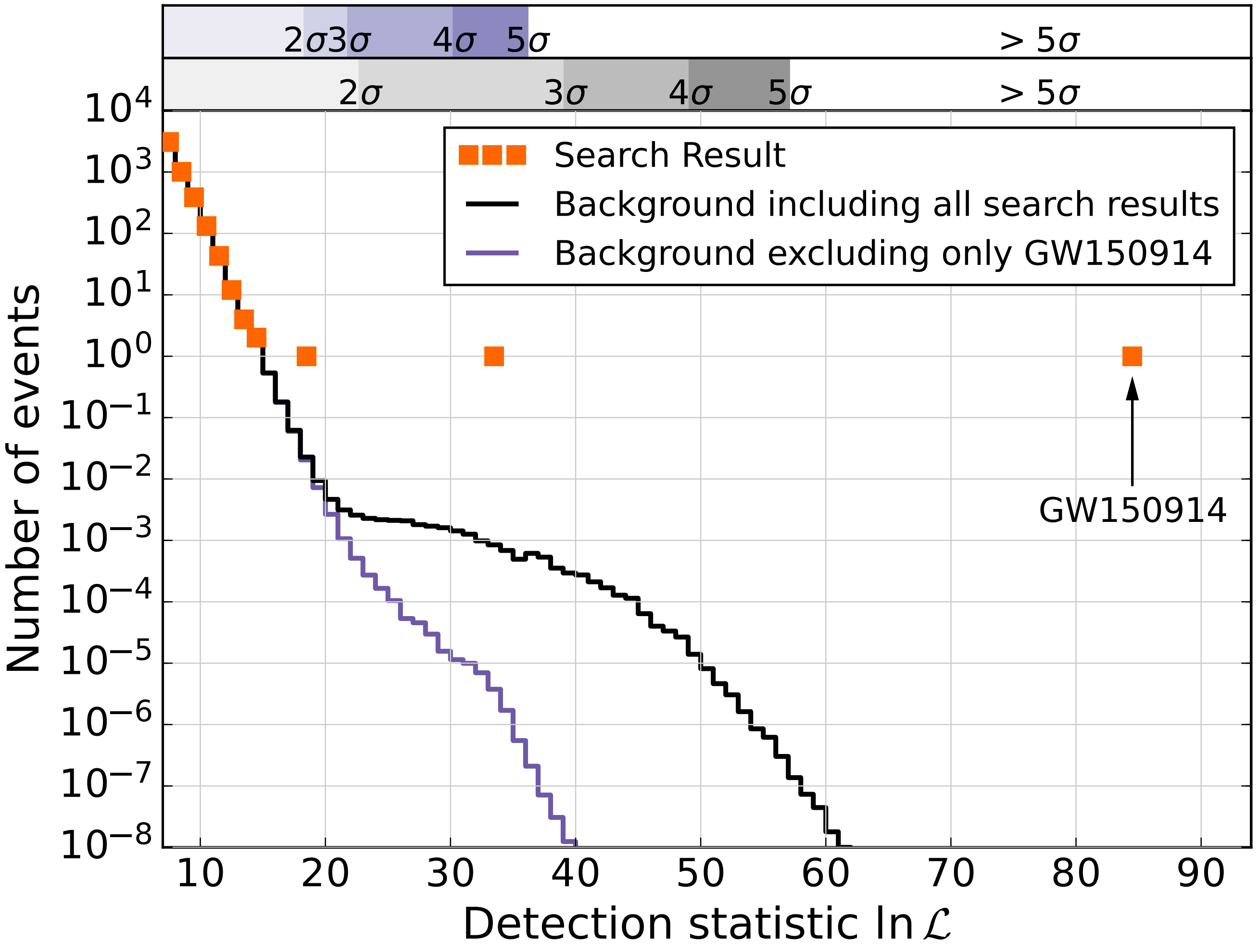
- shift one of the data sets with respect to the other and then look for coincidence - any coincidence now is a false alarm

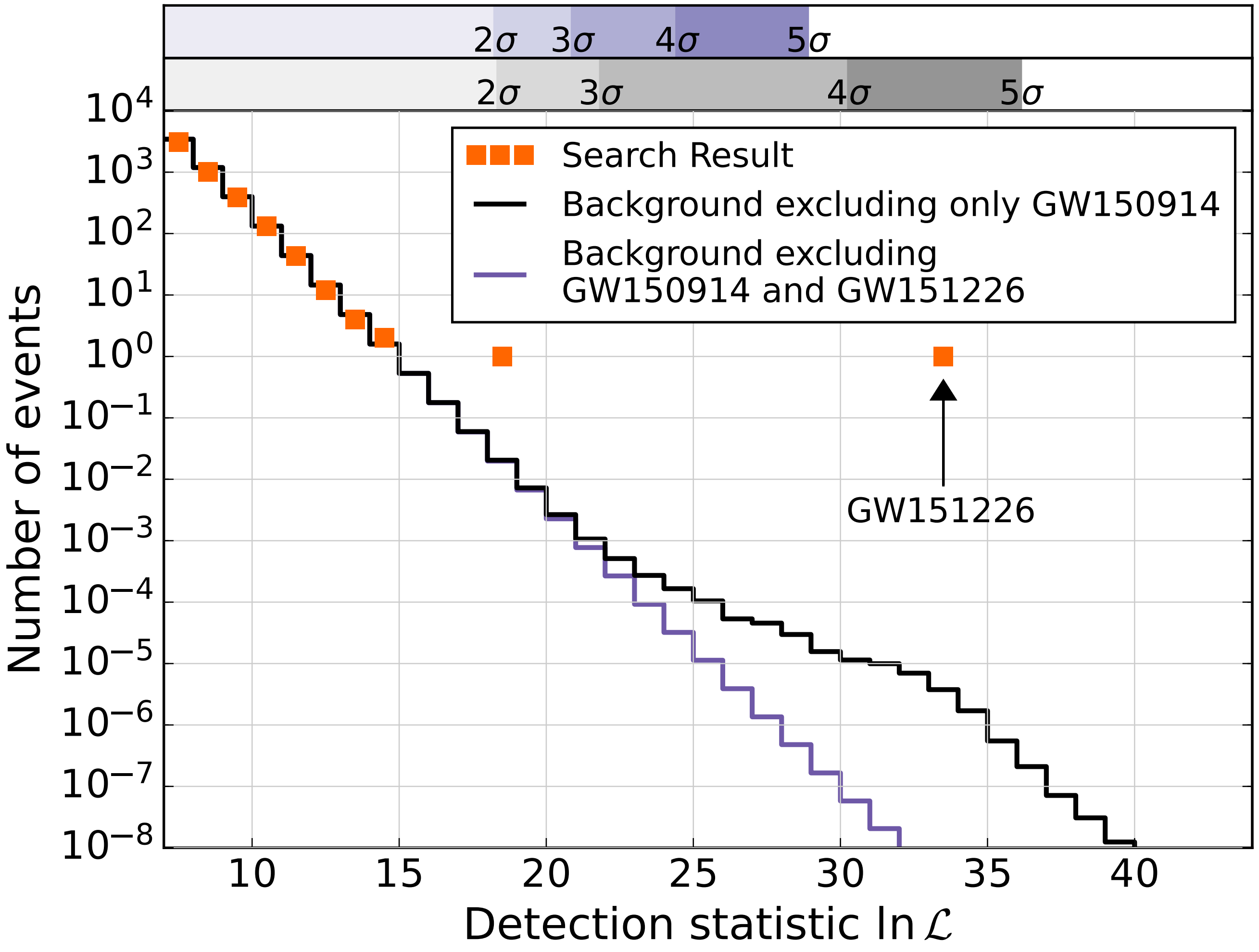


NOISE BACKGROUND: METHOD OF TIME SHIFTS



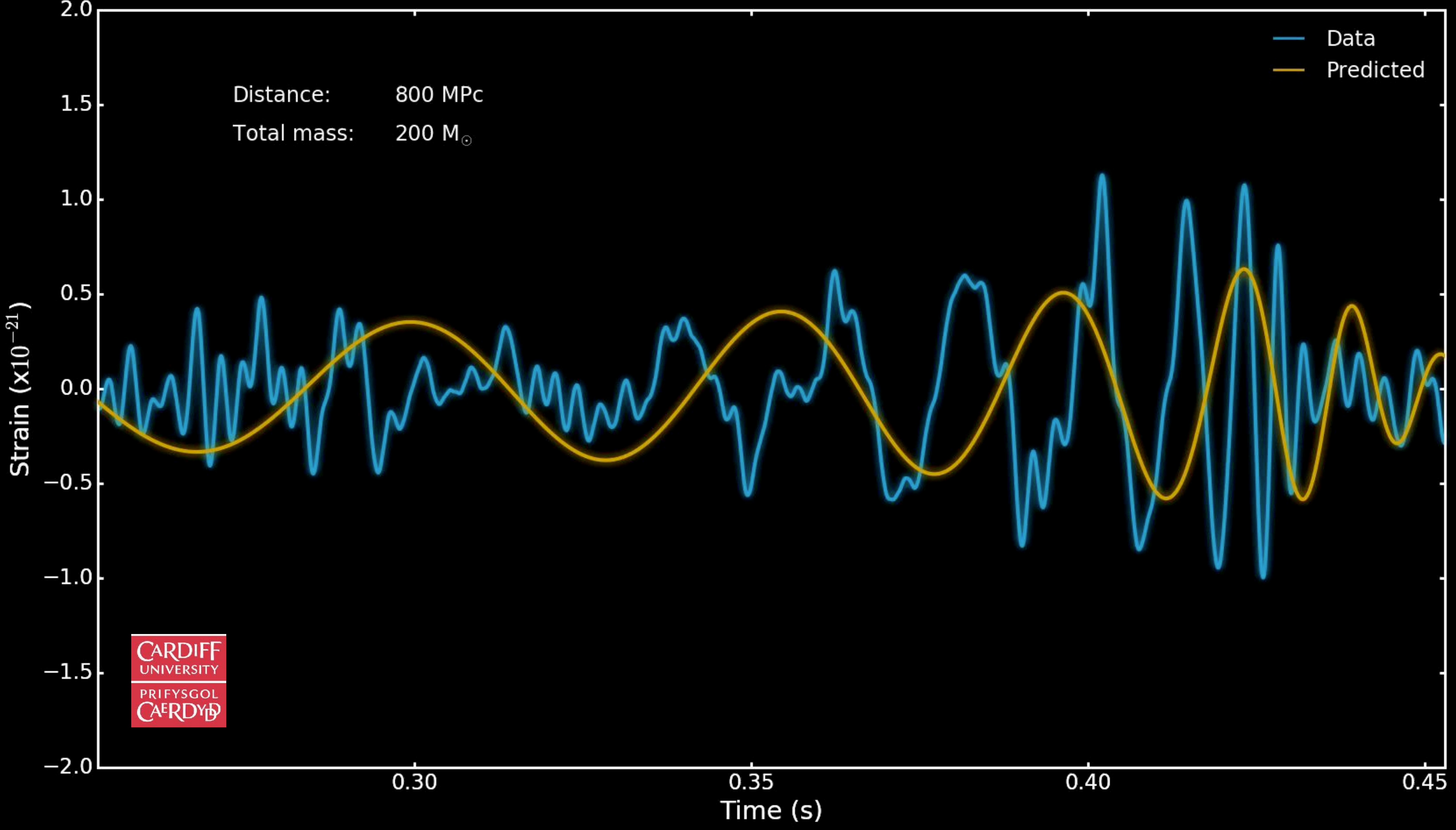
NOISE BACKGROUND: THE METHOD OF LIKELIHOOD





PARAMETER ESTIMATION

HOW DO WE MEASURE SOURCE PARAMETERS?



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff

PROBLEM OF PARAMETER ESTIMATION

- Bayesian analysis is used to infer the posterior probability density of parameters $\mu = \{\mu_1, \mu_2, \ldots, \mu_n\}$ given the data x:

$$P(\mu|x) = \frac{P(x|\mu)P(\mu)}{P(x)}$$

- in the case of binary black holes signal parameters are masses (m_1,m_2), spins $(\mathbf{S}_1,\mathbf{S}_2)$, eccentricity (e), sky position $(\boldsymbol{\theta},\boldsymbol{\varphi})$, distance (D), binary orientation angles $(\boldsymbol{\iota},\boldsymbol{\delta})$, time of and phase at coalescence $(t_c,\boldsymbol{\varphi}_c)$
- the choice of prior could significantly influence the posterior when the likelihood is small (and there is no such thing as “uniform” or “uninformative” prior as this is a parameter-dependent statement; if the likelihood is large (or if we have a large number of observations) then prior doesn’t matter

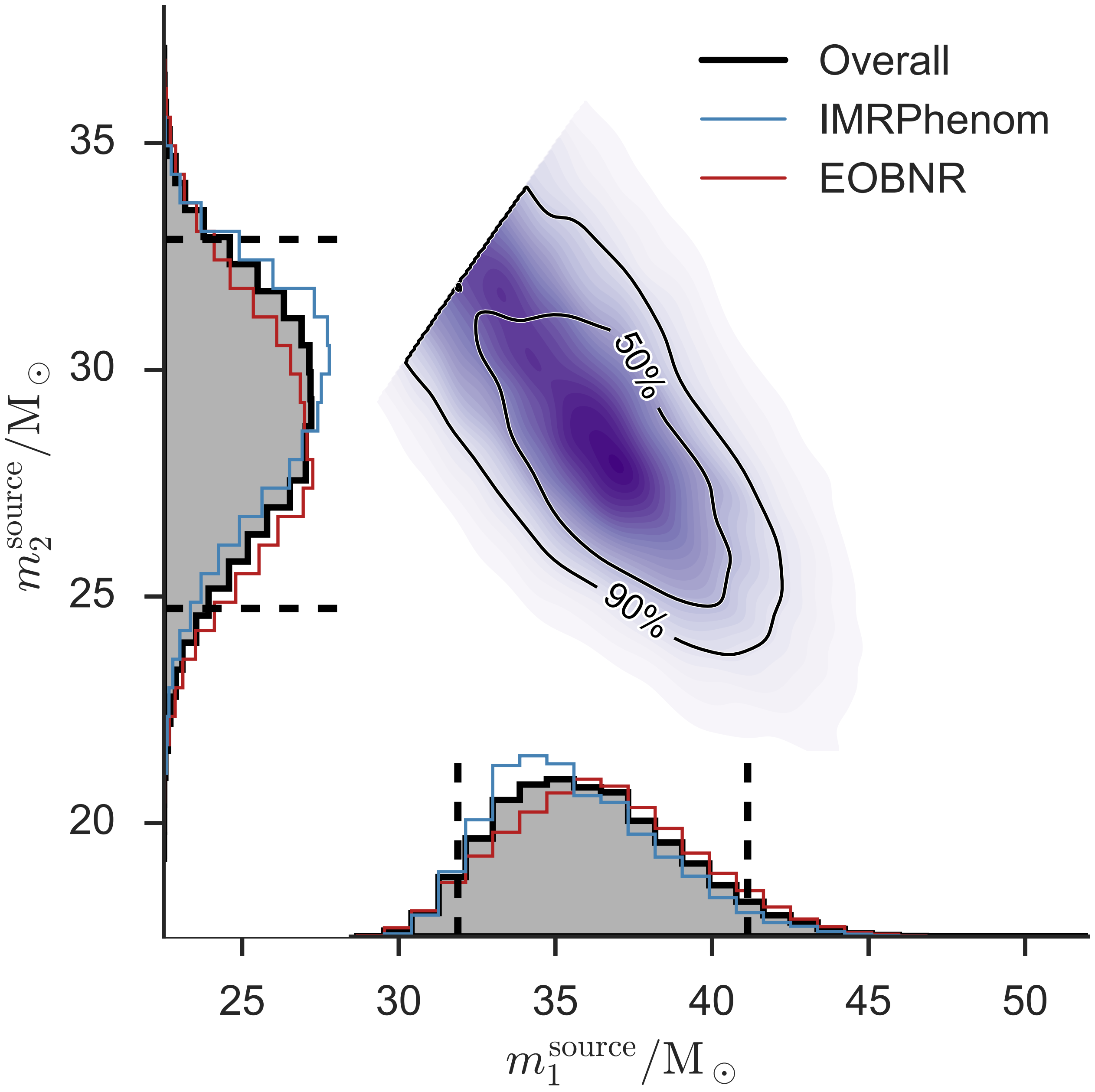
ONE-D AND TWO-D DISTRIBUTIONS

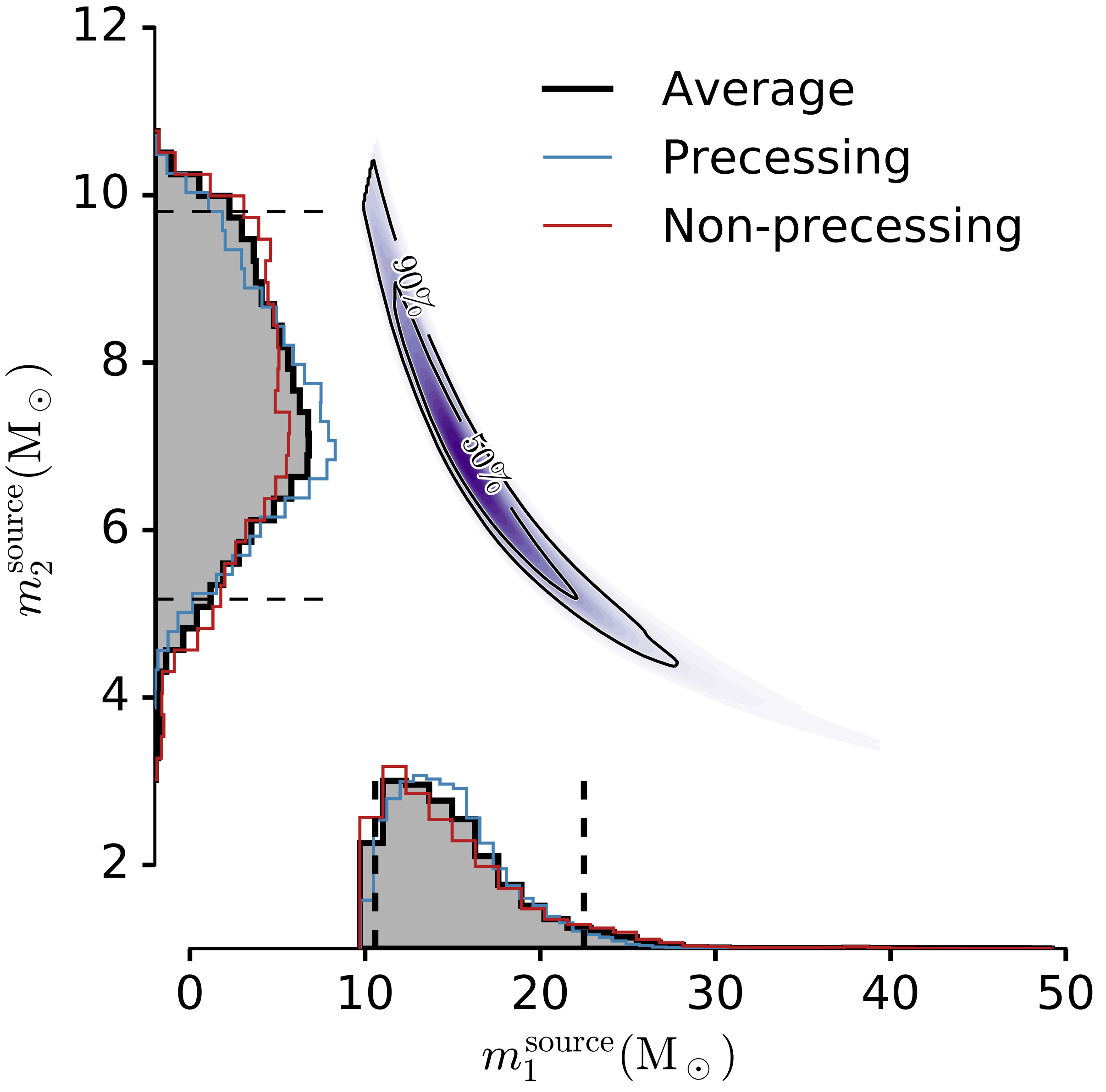
- one can integrate the multivariate posterior distributions to obtain one-d and two-d distributions to compute mean, median, mode, confidence interval, etc.

$$P(\mu_1) = \int P(\mu|x)\,\mathrm{d}\mu_2\,\mathrm{d}\mu_3, \ldots$$

$$P(\mu_1, \mu_2) = \int P(\mu|x)\,\mathrm{d}\mu_3\,\mathrm{d}\mu_4, \ldots$$

MASSES OF GW150914 AND GW151226 FROM BAYESIAN ESTIMATION

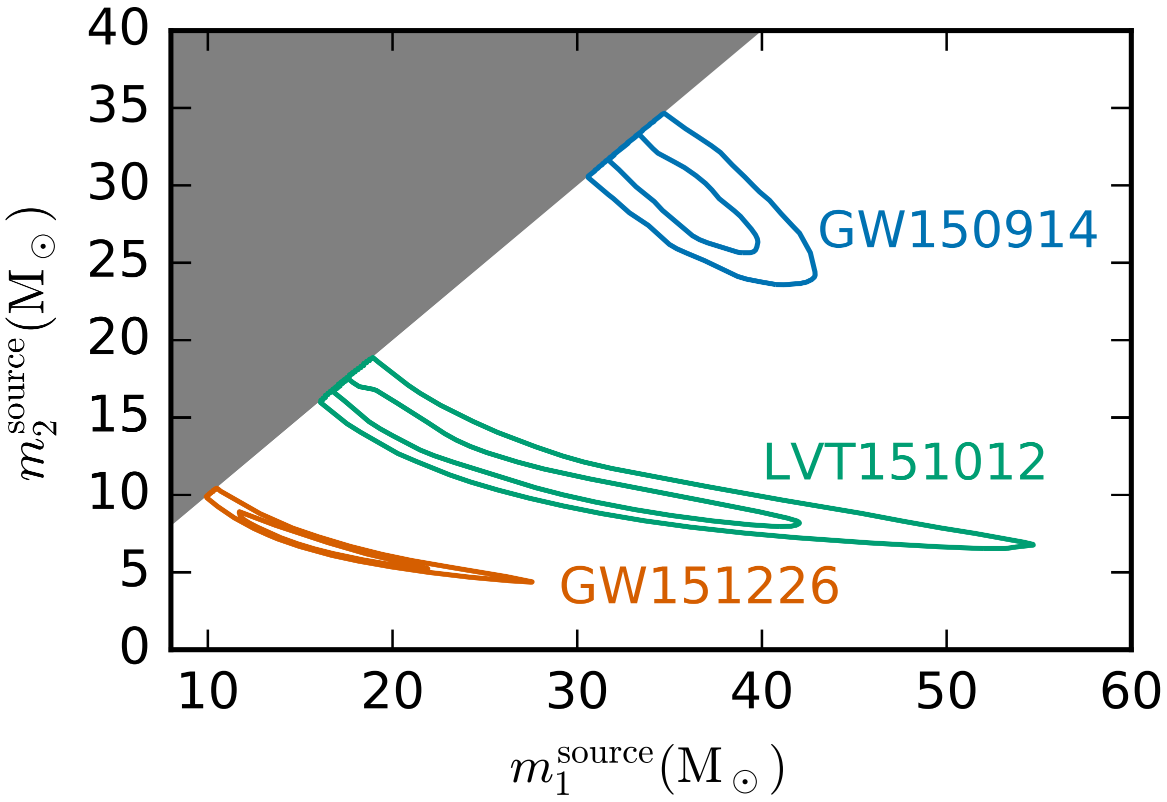


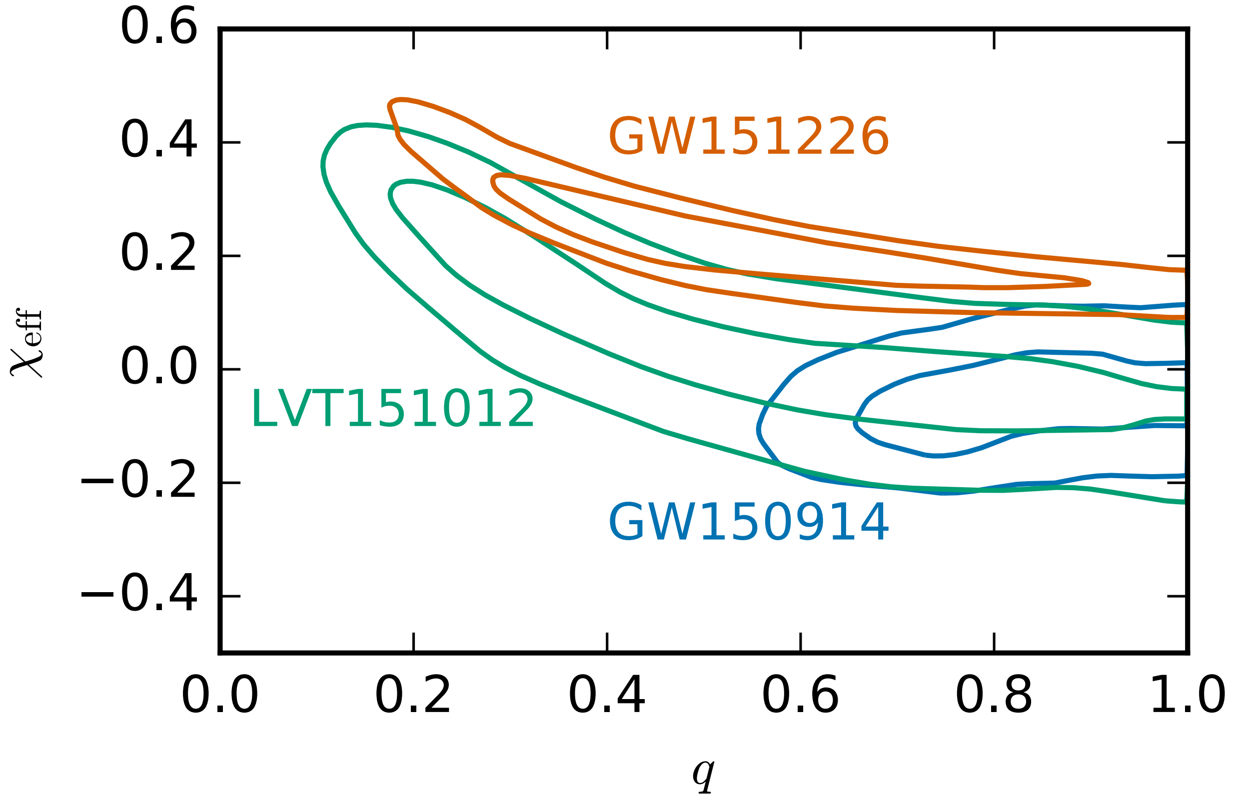


MASSES AND SPINS: ALL EVENTS

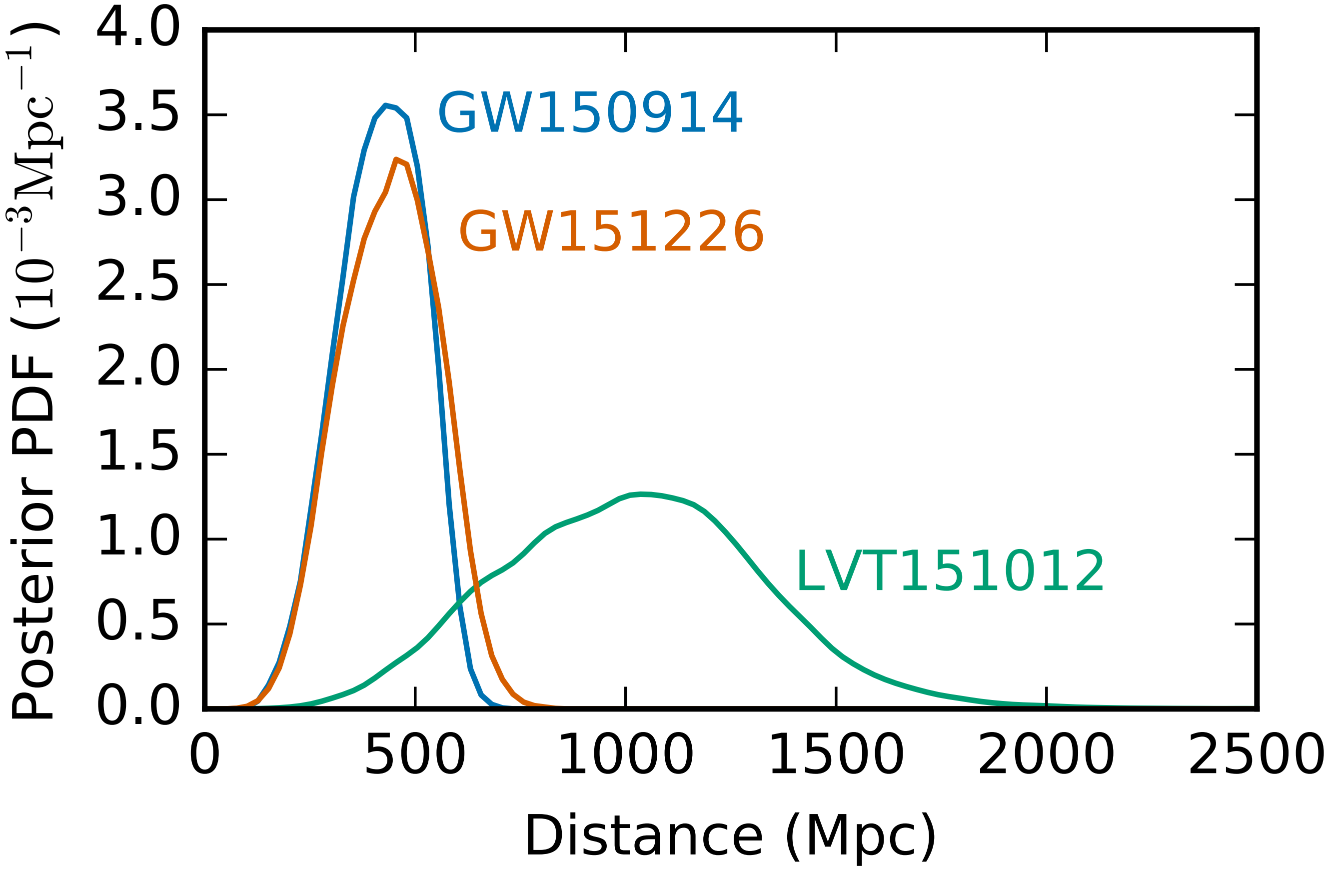
- GW150914
  - (36, 29) solar mass
- GW151226
  - (14, 8) solar mass
  - one of the BHs has nonzero spin
- LVT151012
  - (23, 13) solar mass

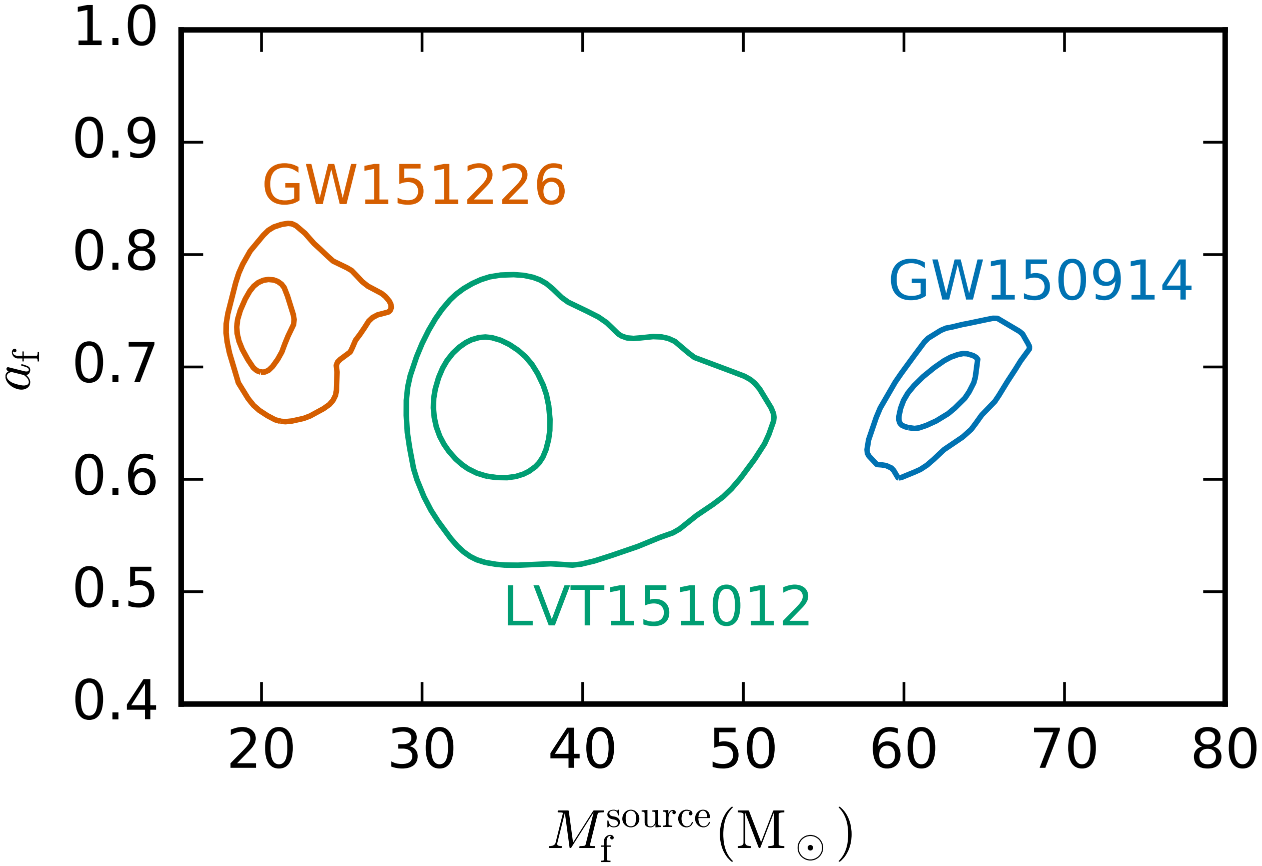
Abbott+ PRL, PRD, 2016





DISTANCE AND REMNANT MASSES & SPINS





Abbott+ PRD, 2016

MODEL SELECTION

ODDS RATIO FOR MODEL INFERENCE

- if H_1 and H_2 are two alternative models (or hypotheses), which of the two is preferred by data? in Bayesian language this is given by the *odds ratio,* ratio of posterior probabilities for the two hypothesis

$$\mathcal{O}_2^1 \equiv \frac{P(\mathcal{H}_1|x)}{P(\mathcal{H}_2|x)} = \frac{P(\mathcal{H}_1)}{P(\mathcal{H}_2)} \mathcal{B}_2^1, \qquad \mathcal{B}_2^1 \equiv \frac{P(x|\mathcal{H}_1)}{P(x|\mathcal{H}_2)}$$

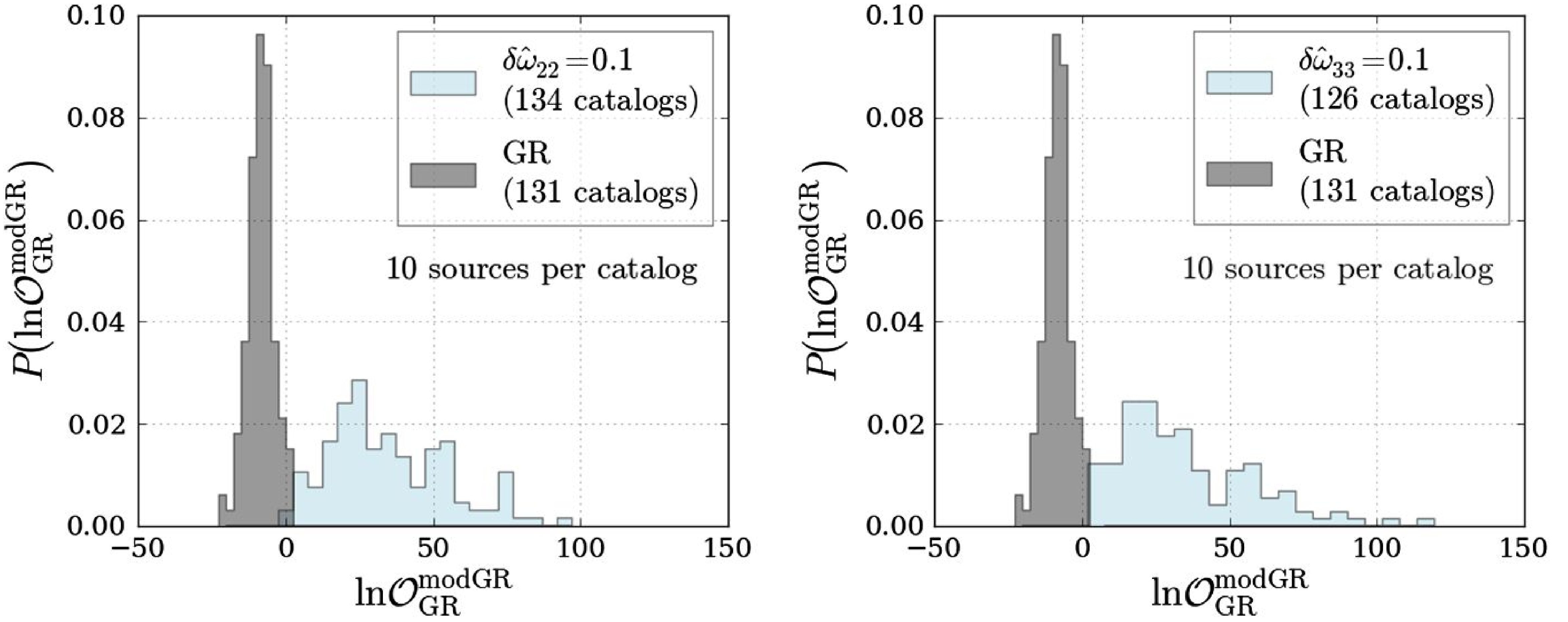
  - if $\ln(\mathcal{O}^1{}_2) \gg 0$, then model/hypothesis H_1 is preferred to H_2
  - if $\ln(\mathcal{O}^1{}_2) \ll 0$, then model/hypothesis H_2 is preferred to H_1
  - if $\ln(\mathcal{O}^1{}_2) \sim 0$, then the data has no discriminatory power
- $\mathcal{B}^1{}_2$ is the Bayes factor, the ratio of posterior odds to prior odds for the two competing models:

$$\mathcal{B}_2^1 = \frac{P(\mathcal{H}_1|x)/P(\mathcal{H}_2|x)}{P(\mathcal{H}_1)/P(\mathcal{H}_2)}$$

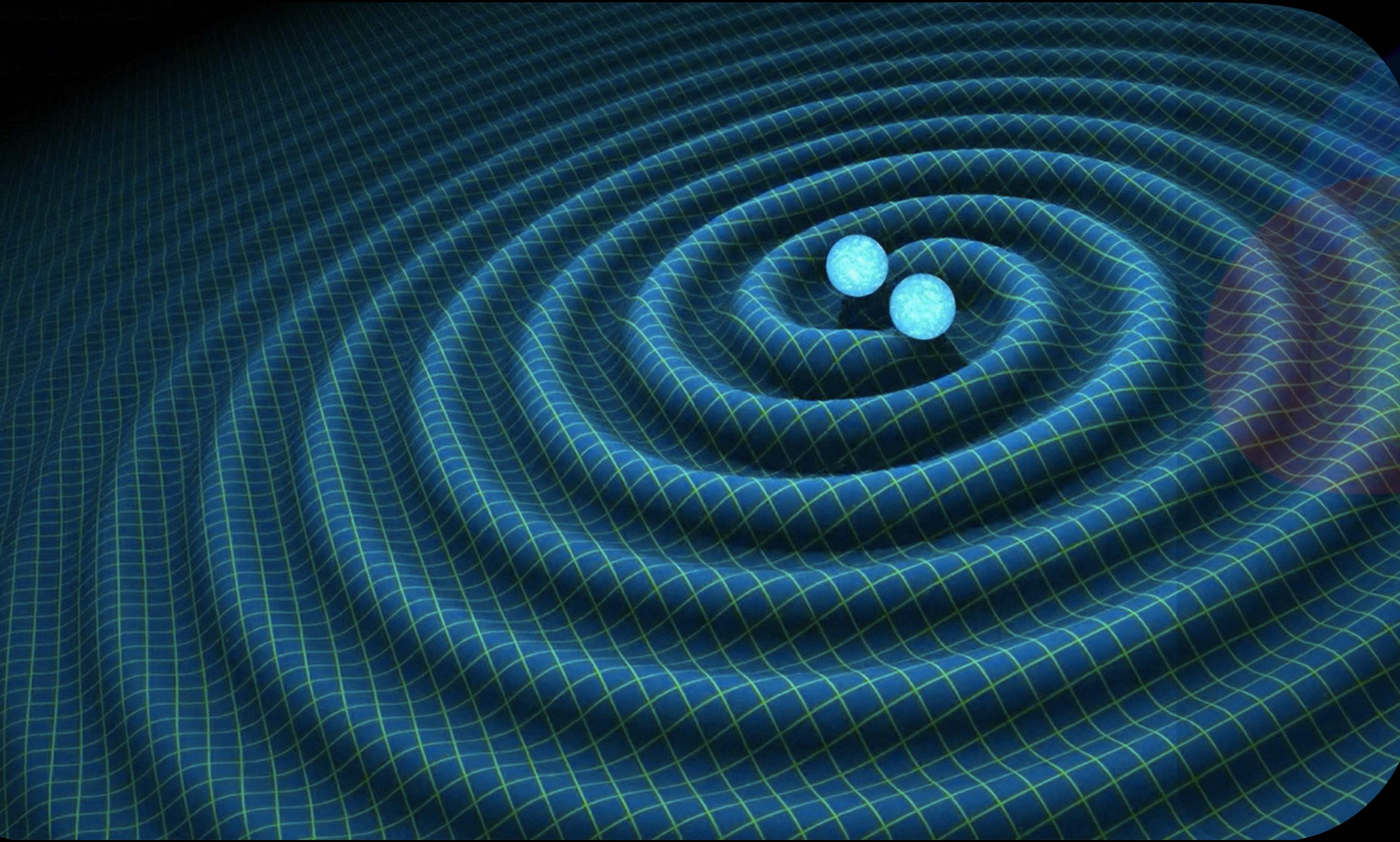
TESTING THE BLACK HOLE PARADIGM WITH MODEL SELECTION

- an example of model selection is to test if ringdown signals are black hole quasi-normal modes; this is done by introducing extra hairs to describe black holes (in addition to their mass and spin)

- the following example shows the odds ratio that uses 10 detections for two alternative hypothesis: H1 ringdown is described GR, H2 ringdown is described by an additional parameter



A NEW ASTRONOMY

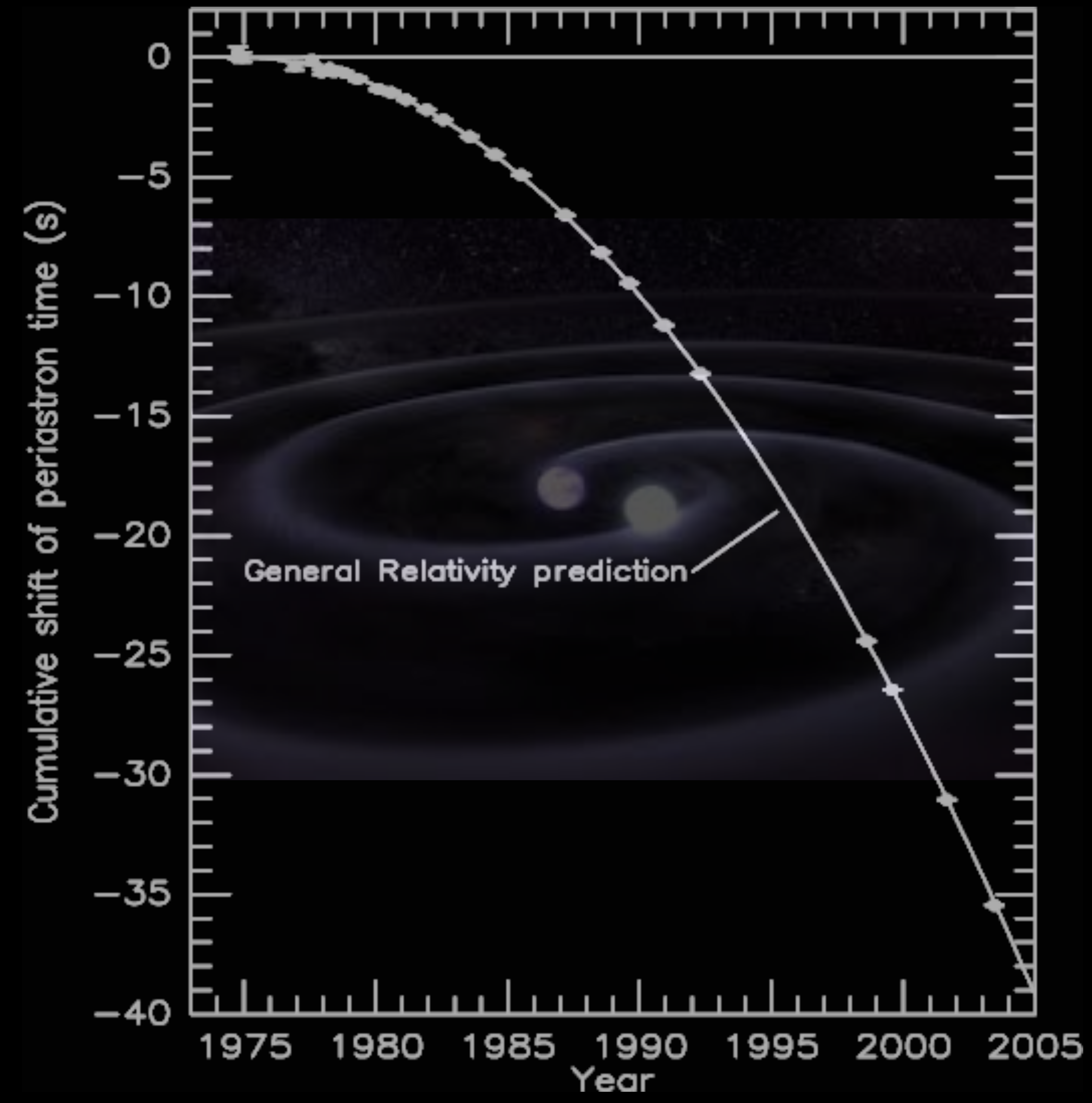


GRAVITATIONAL WAVES FROM HULSE-TAYLOR BINARY PULSAR

Observed decrease in period - about 76 μs per year

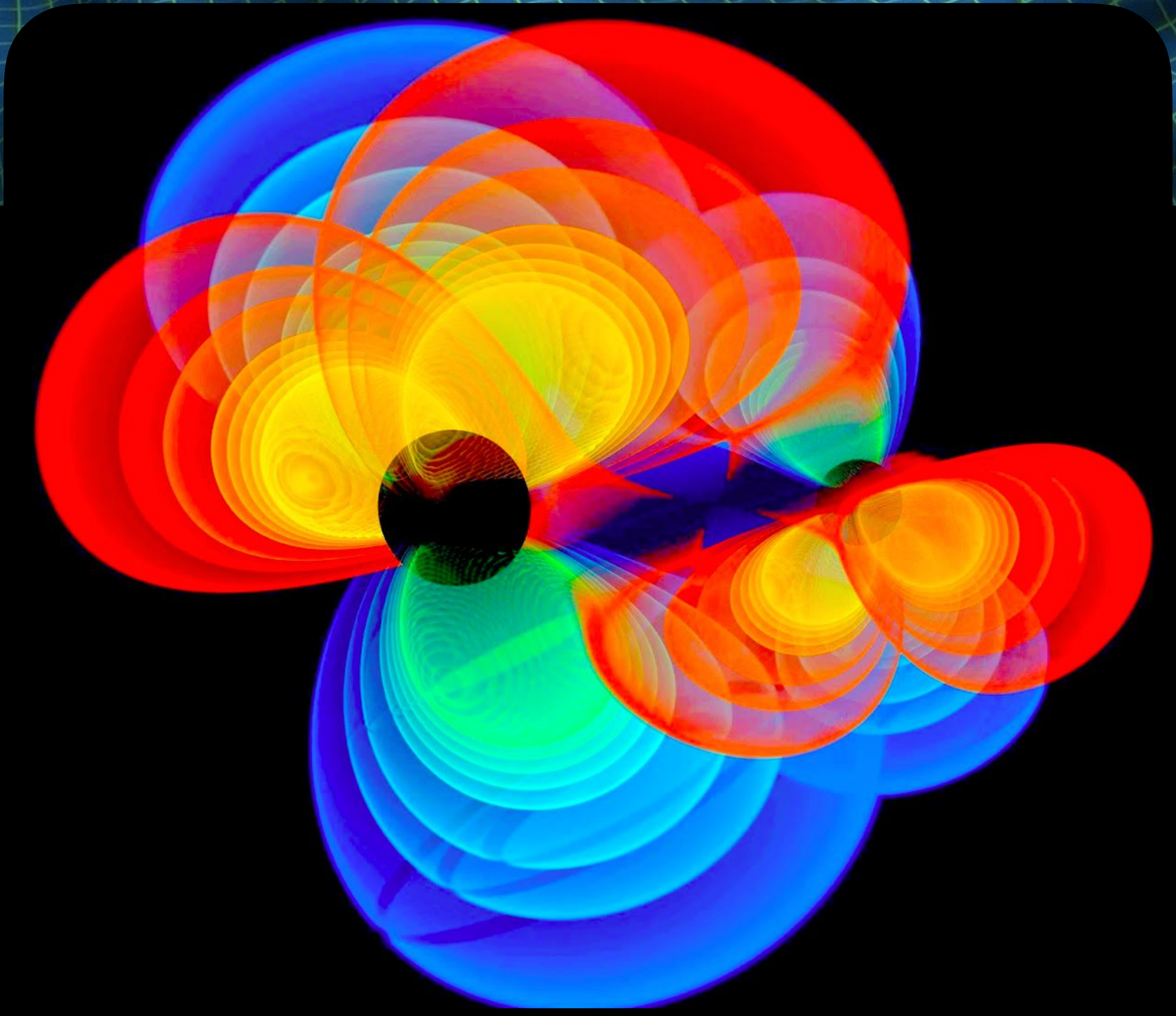
Credit: Michael Kramer

HULSE-TAYLOR BINARY PULSAR AND TEST OF THE QUADRUPOLE FORMULA

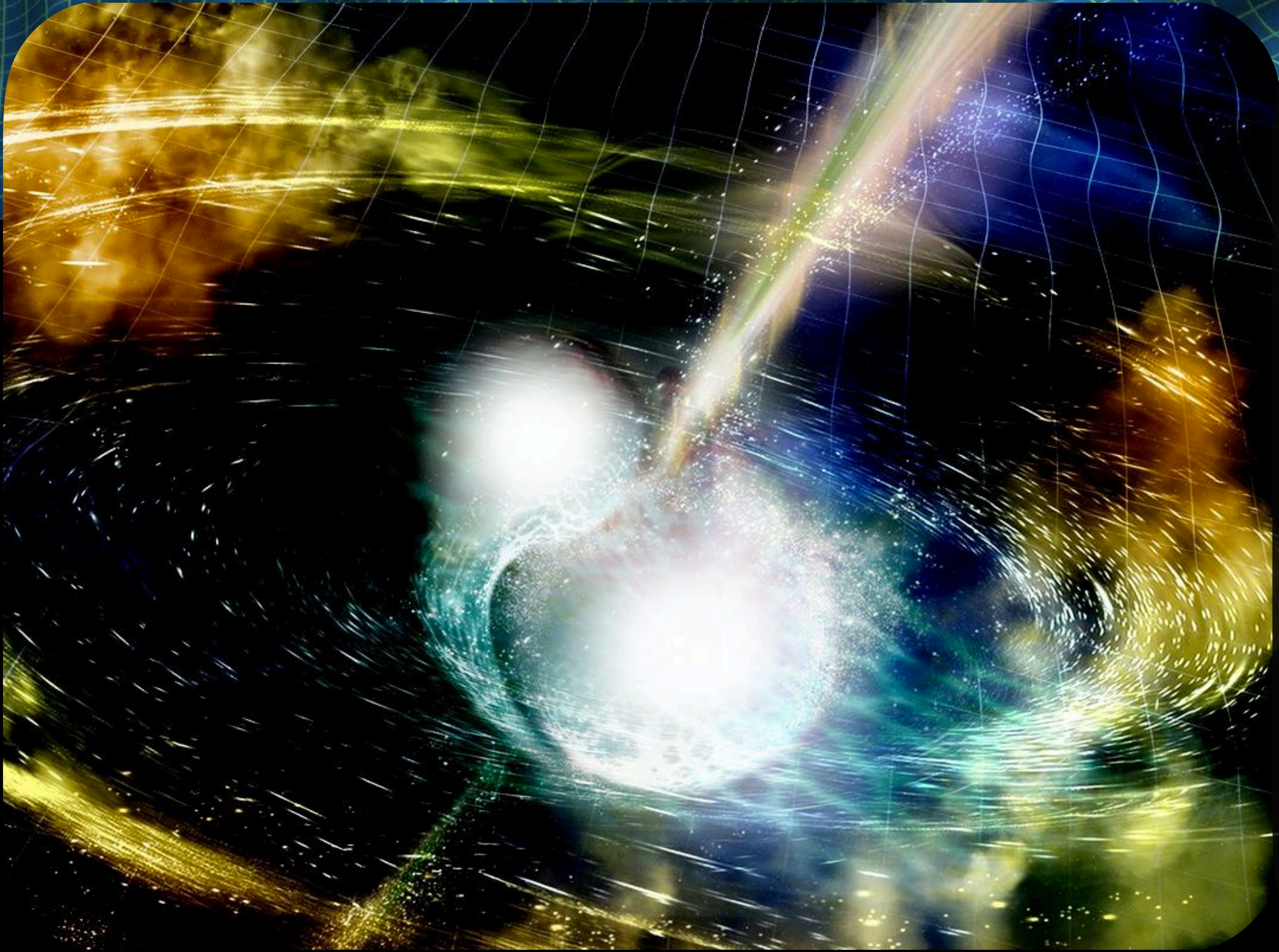


Plot: Weisberg+, Image: NASA

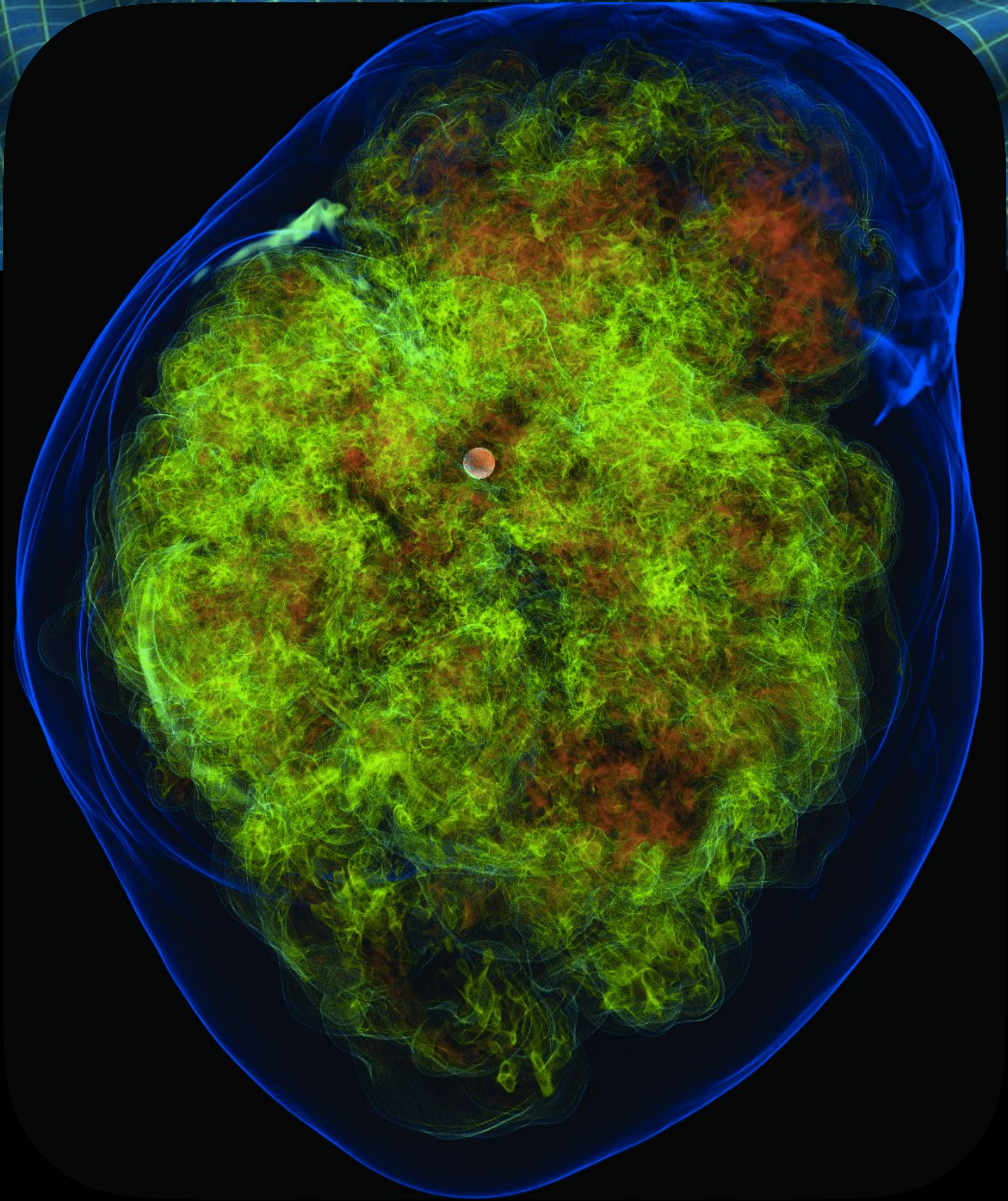
A NEW ASTRONOMY



A NEW ASTRONOMY



A NEW ASTRONOMY



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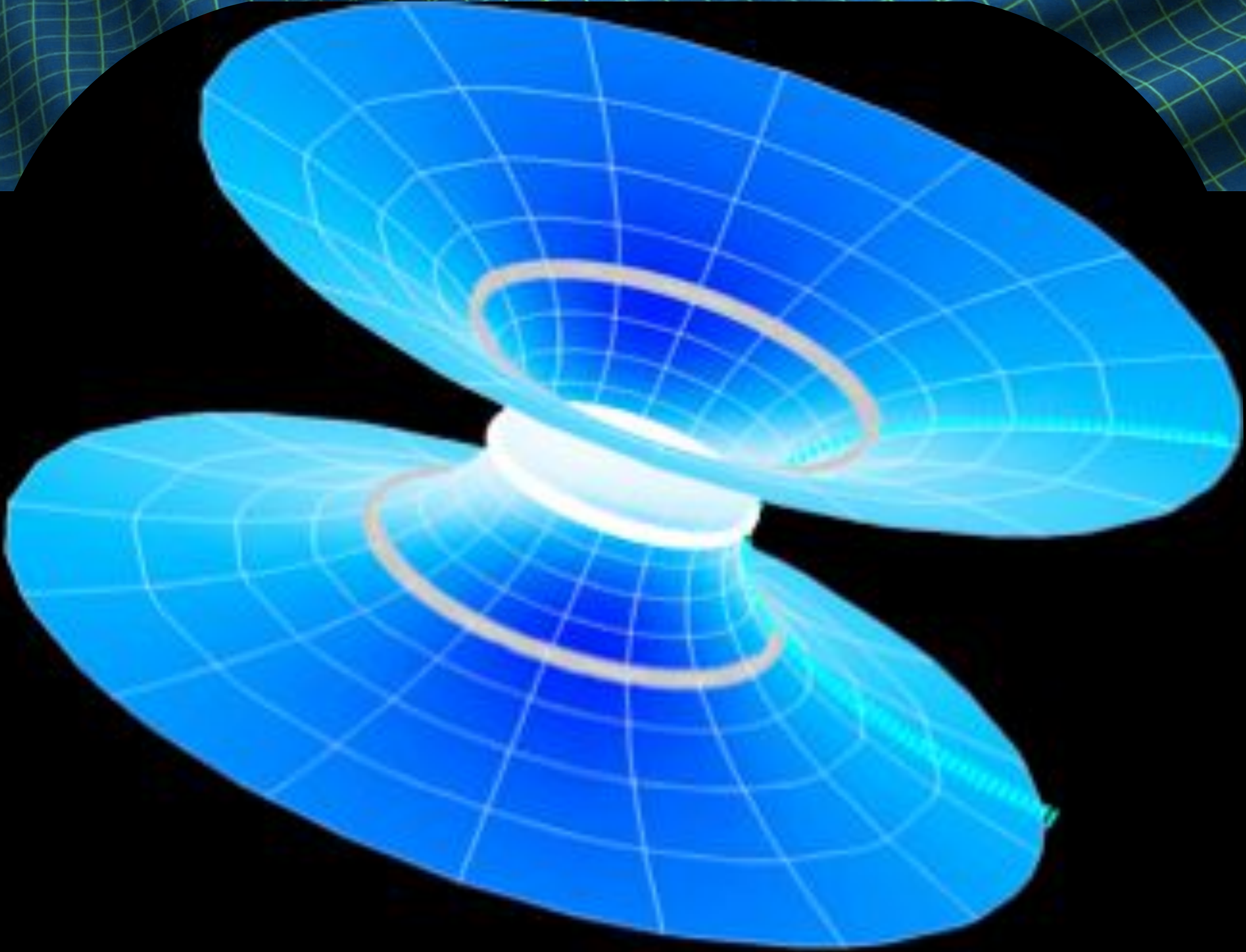
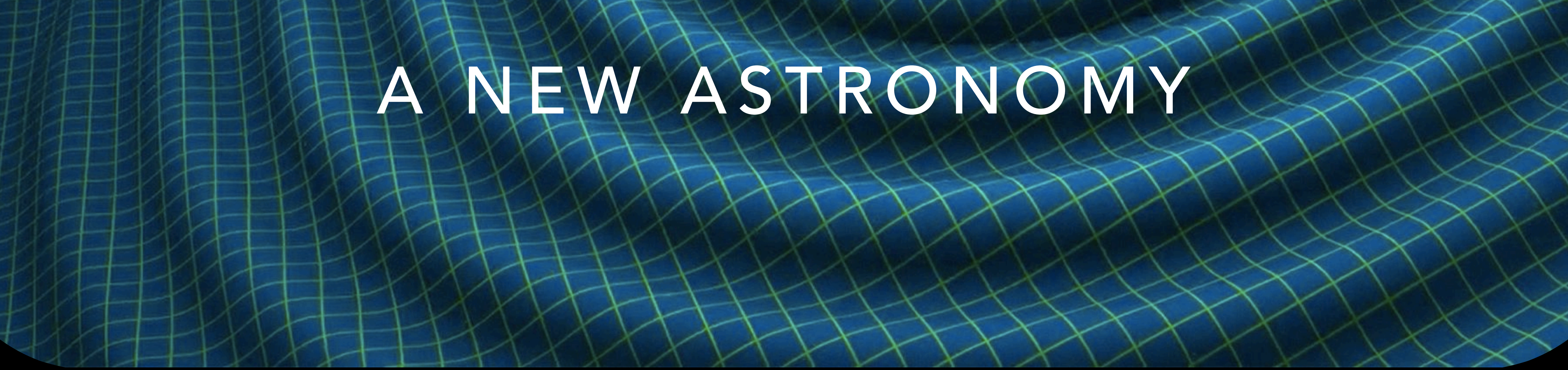
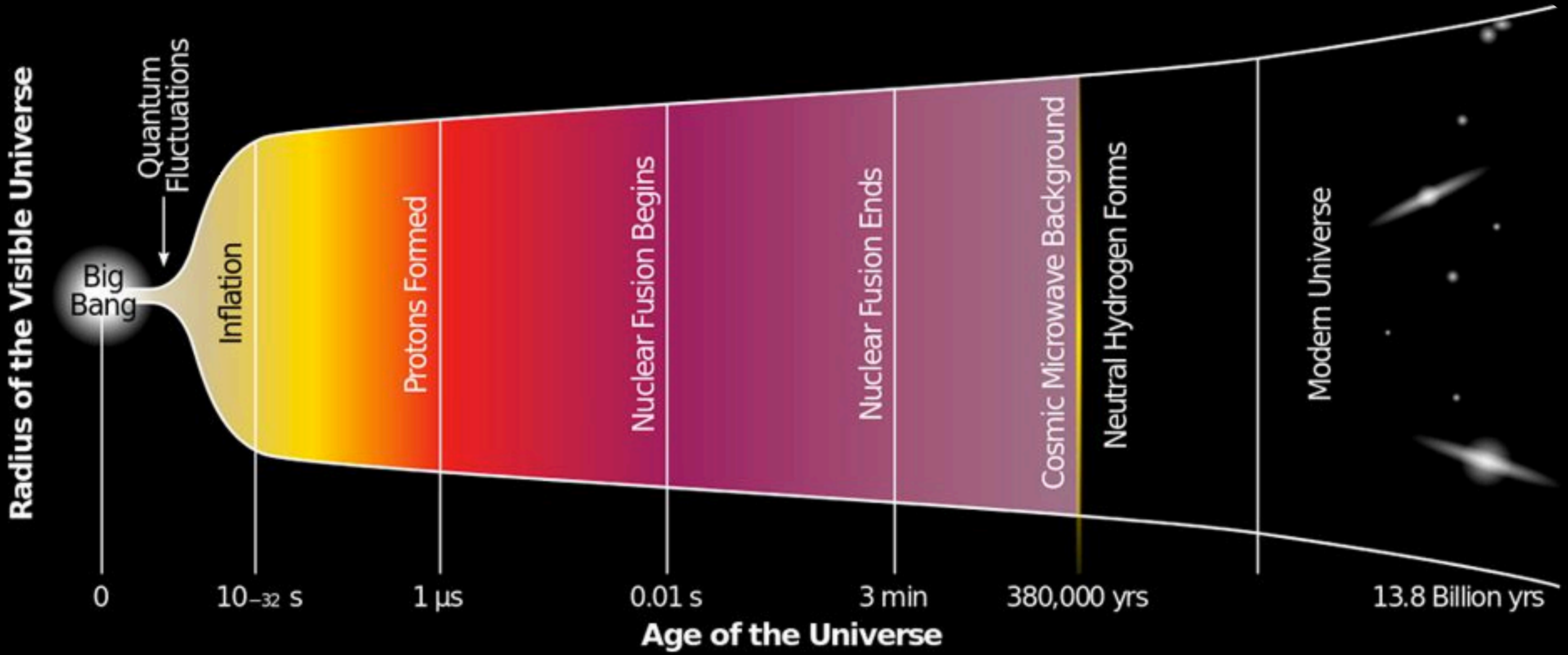
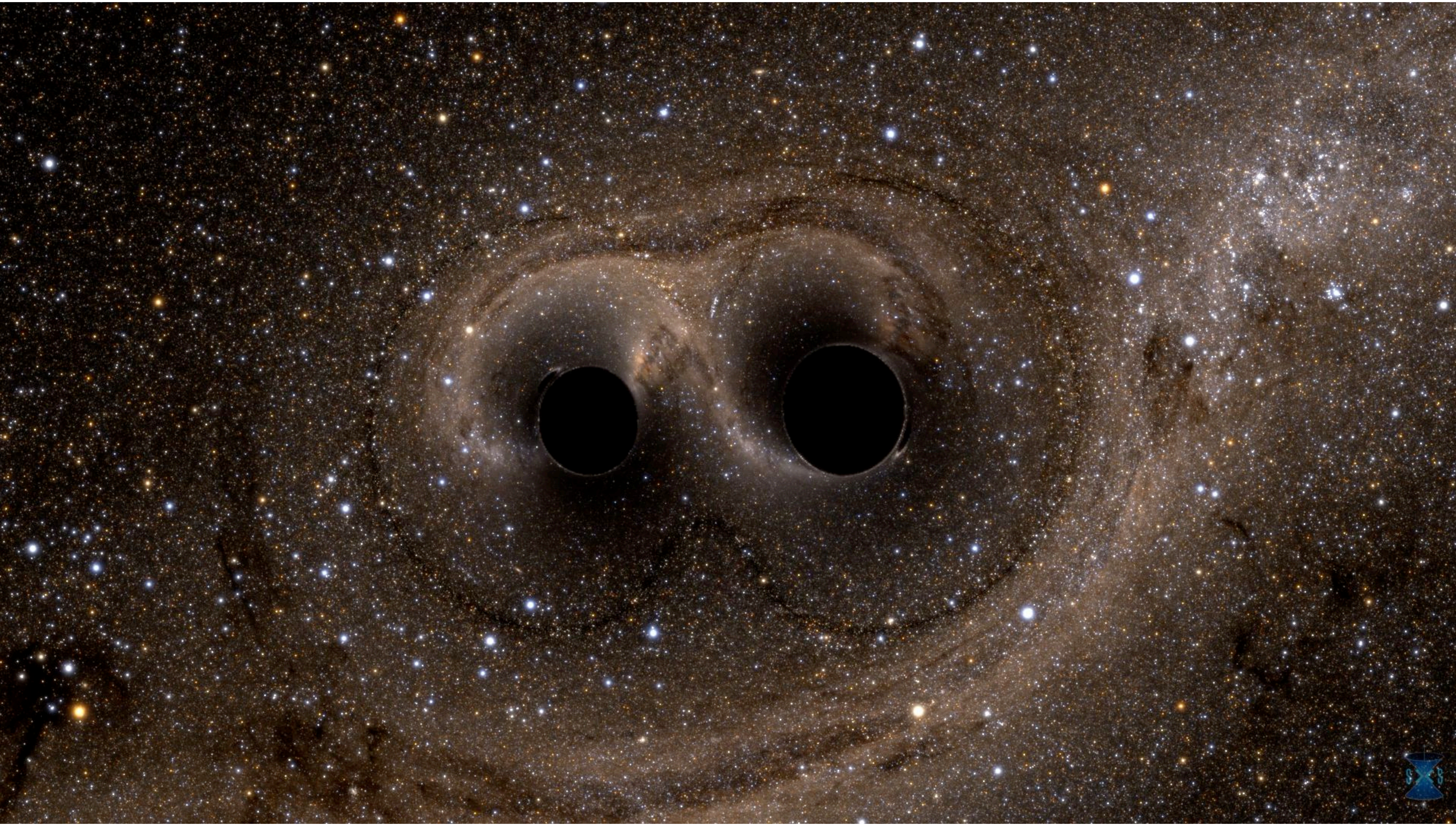
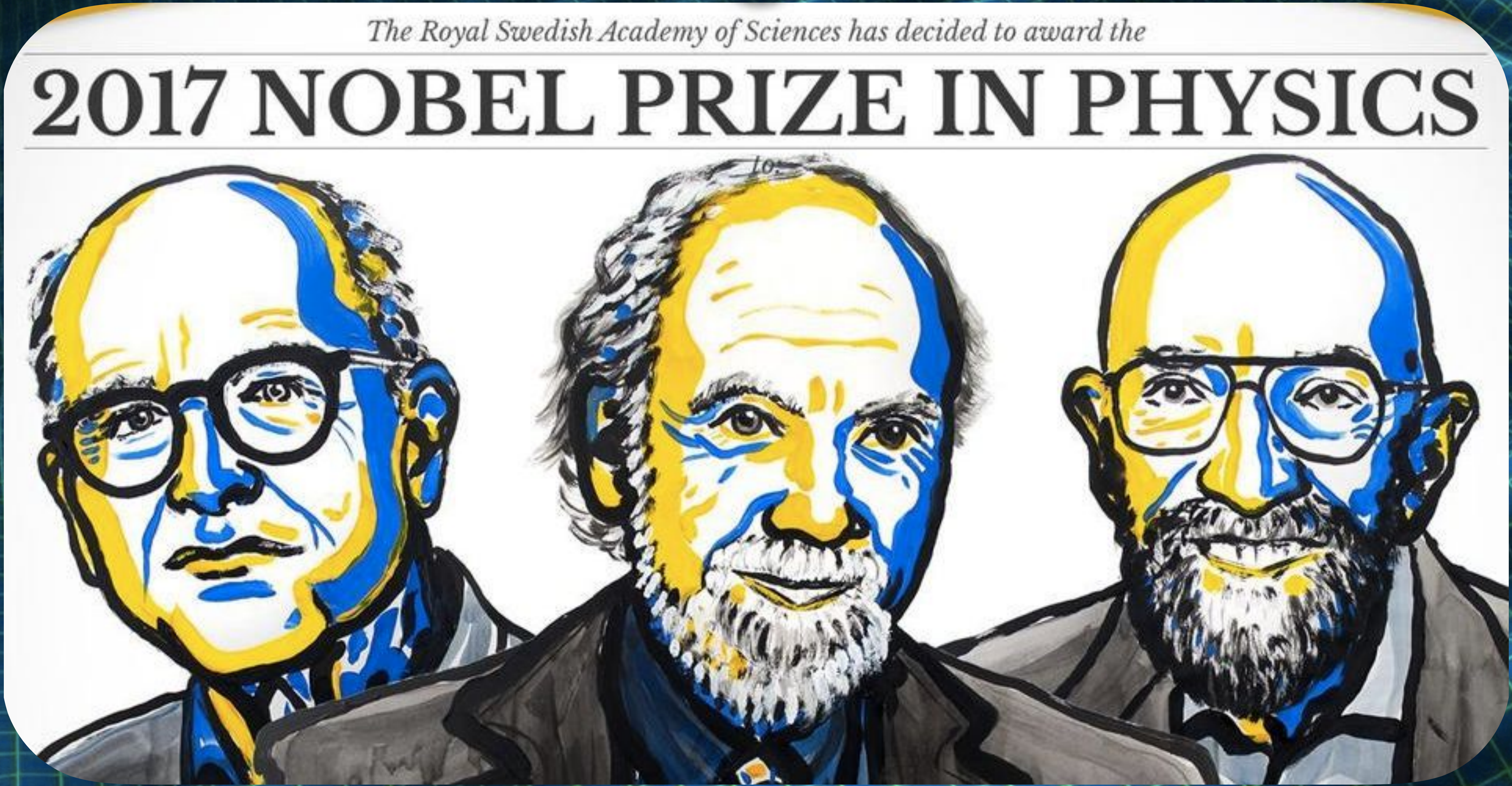


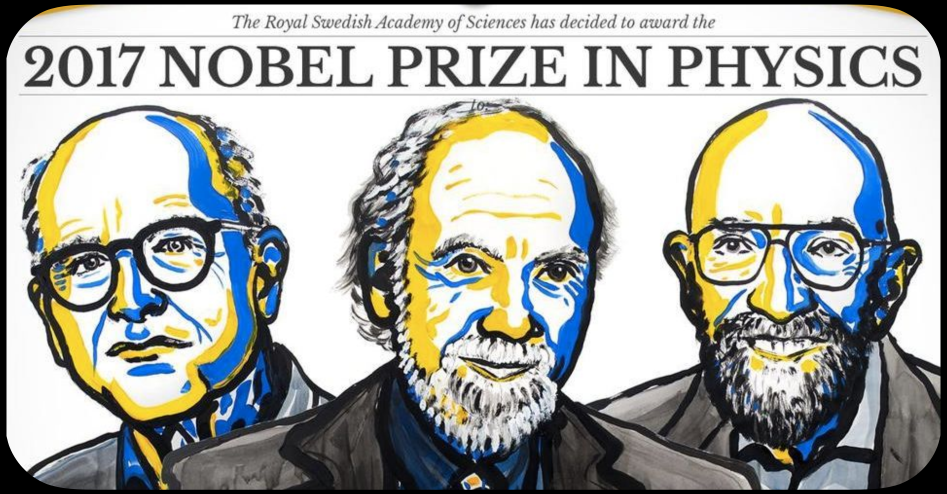
A NEW ASTRONOMY



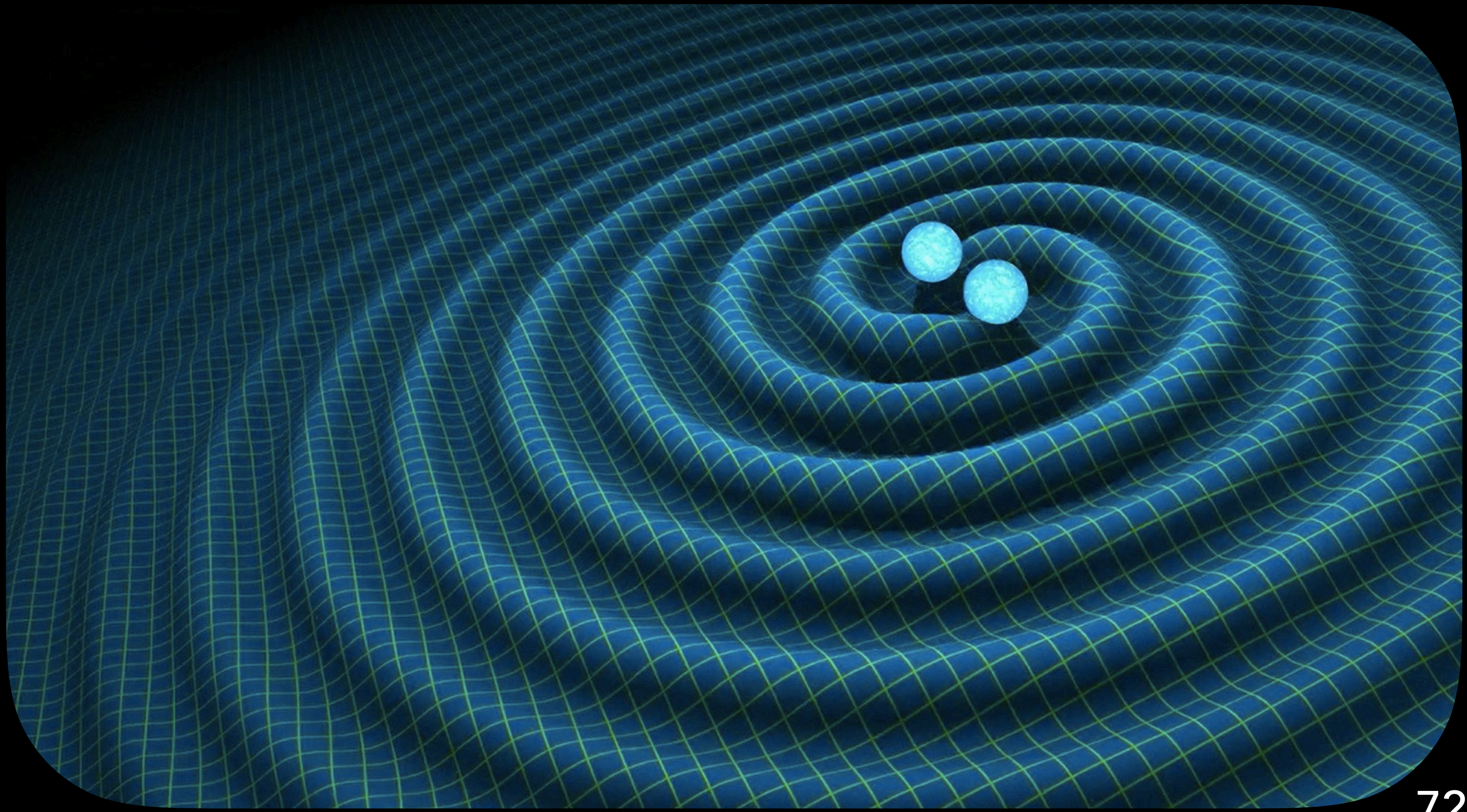





The Royal Swedish Academy of Sciences has decided to award the
2017 NOBEL PRIZE IN PHYSICS
to:

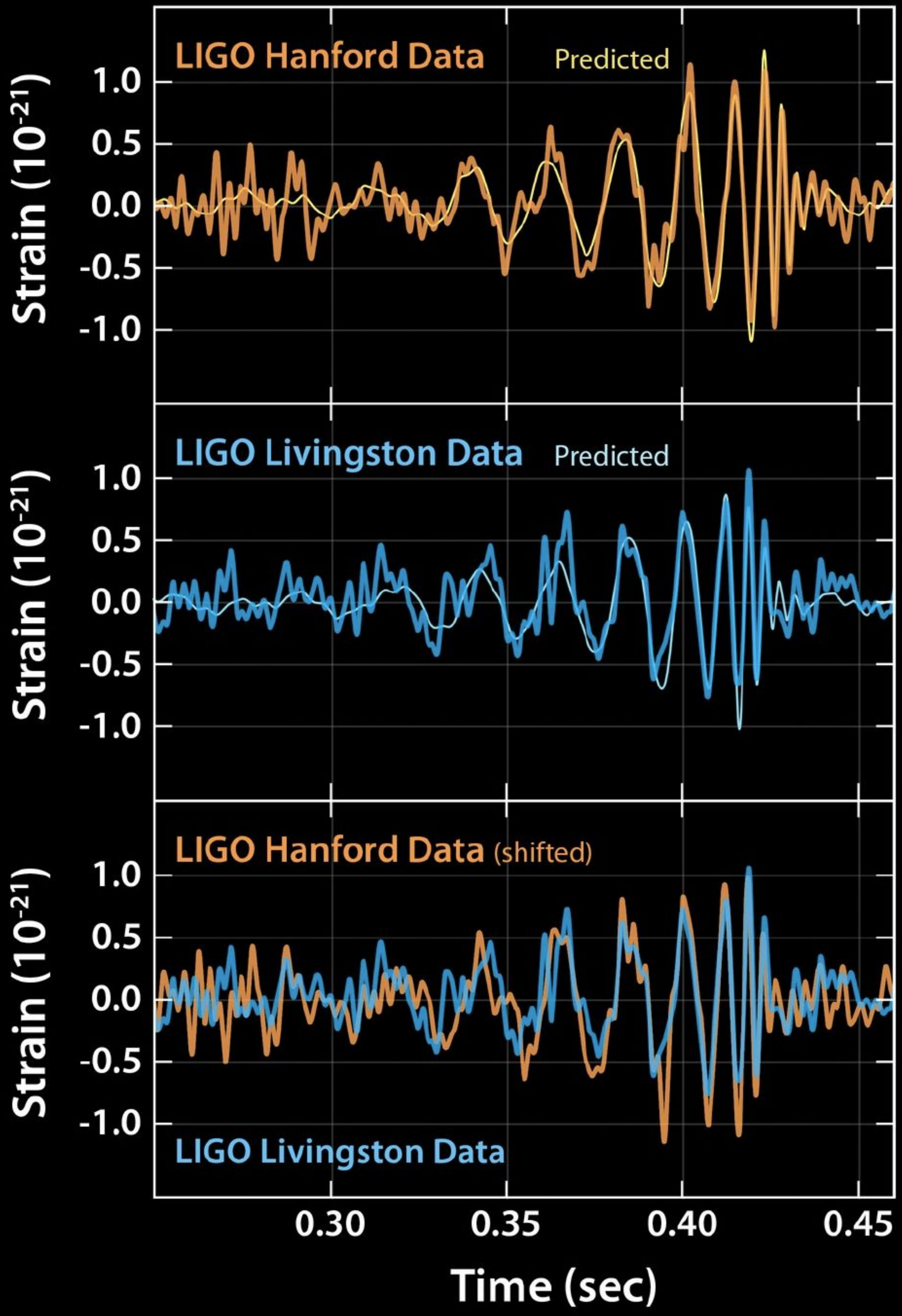


- first direct detection of gravitational waves
- first observation of a black hole binary
- first direct observation of a black hole

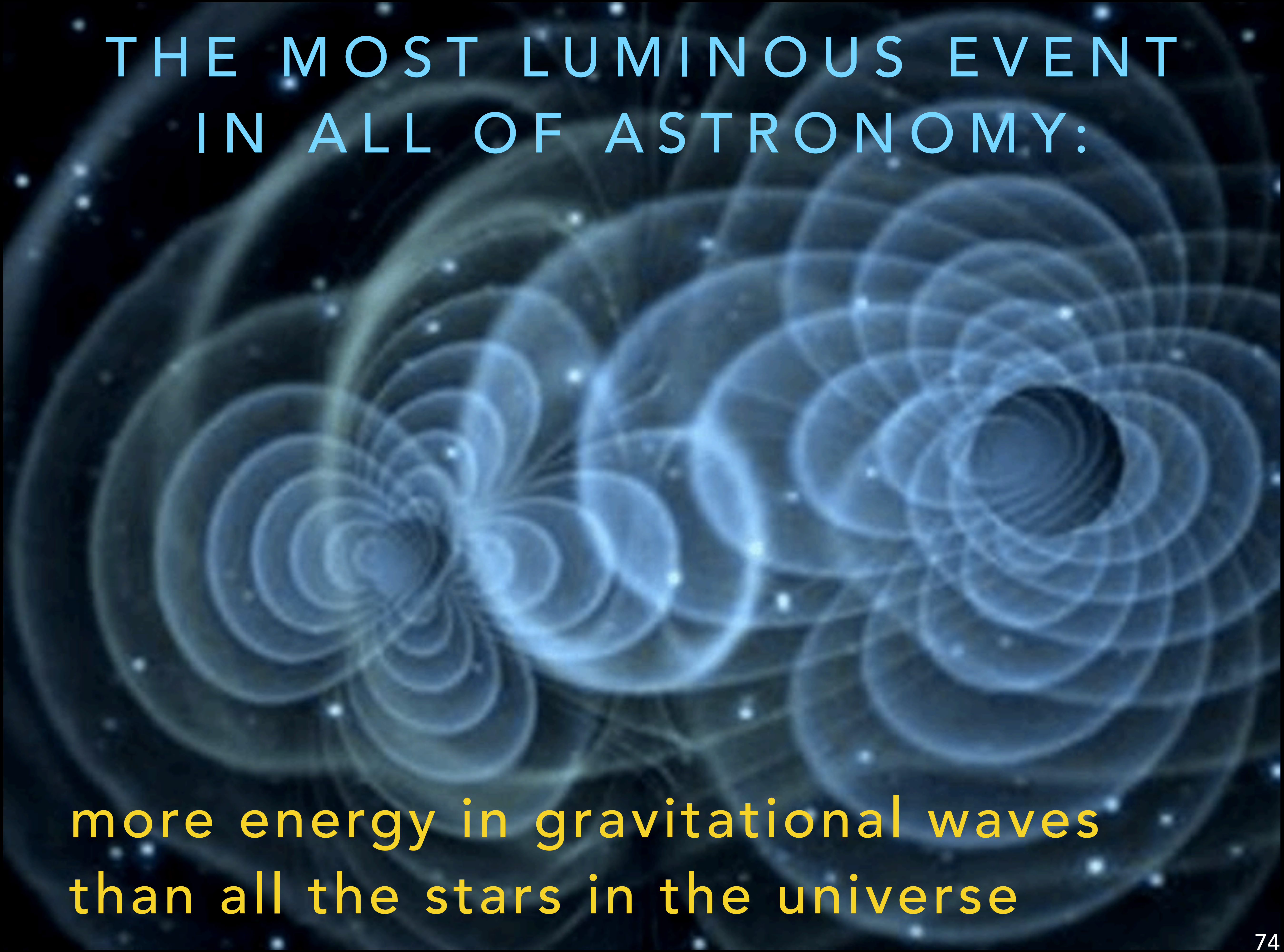


GW150914: FIRST DIRECT DETECTION

- detection and characterization uses matched filtering
- requires very accurate waveforms
- >3 decades of effort on analytical and numerical modeling of waveform and still ongoing



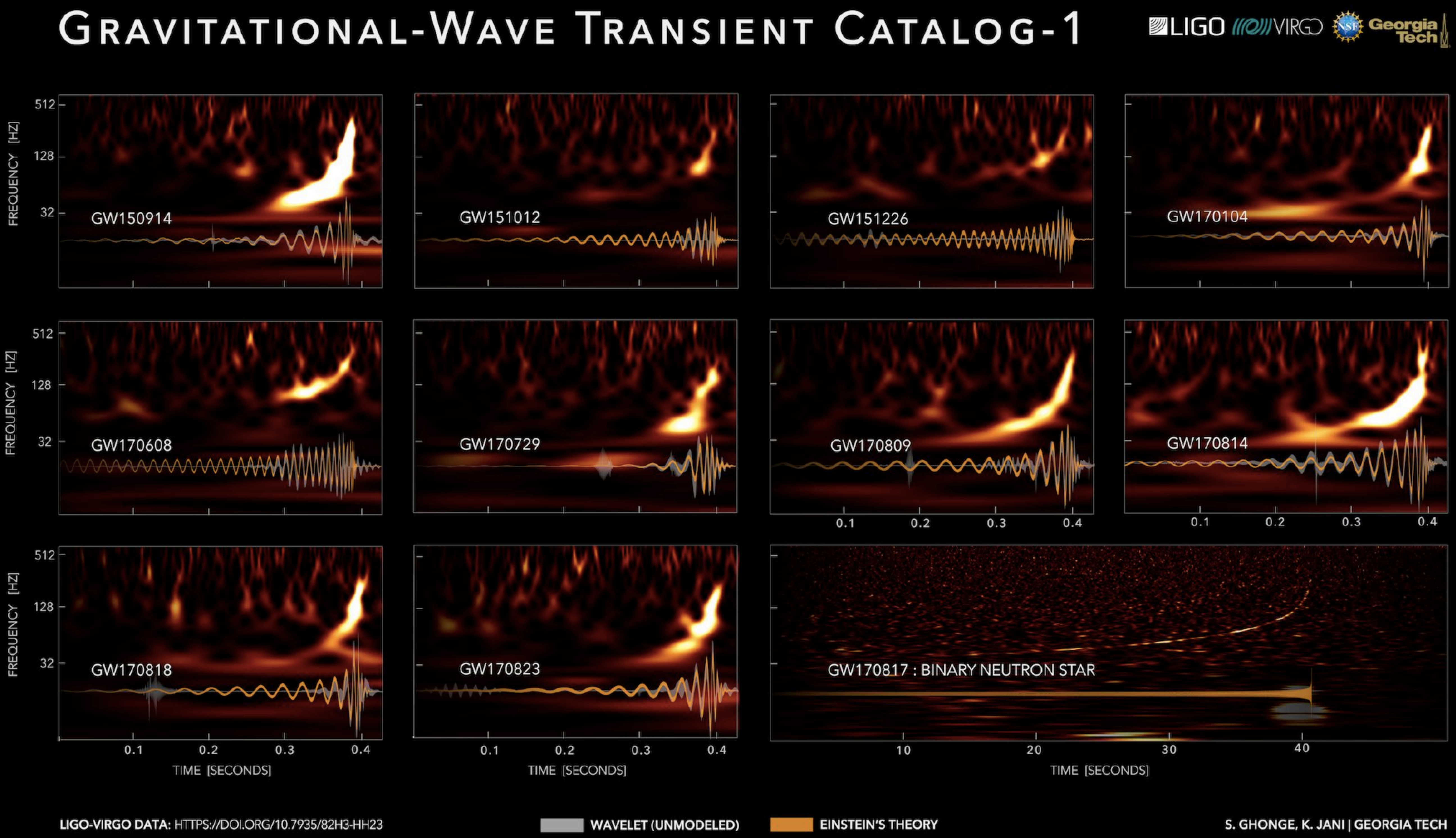
THE MOST LUMINOUS EVENT IN ALL OF ASTRONOMY:



more energy in gravitational waves than all the stars in the universe

LIGO-VIRGO DISCOVERIES:

A NEW ERA IN FUNDAMENTAL PHYSICS, ASTROPHYSICS AND COSMOLOGY

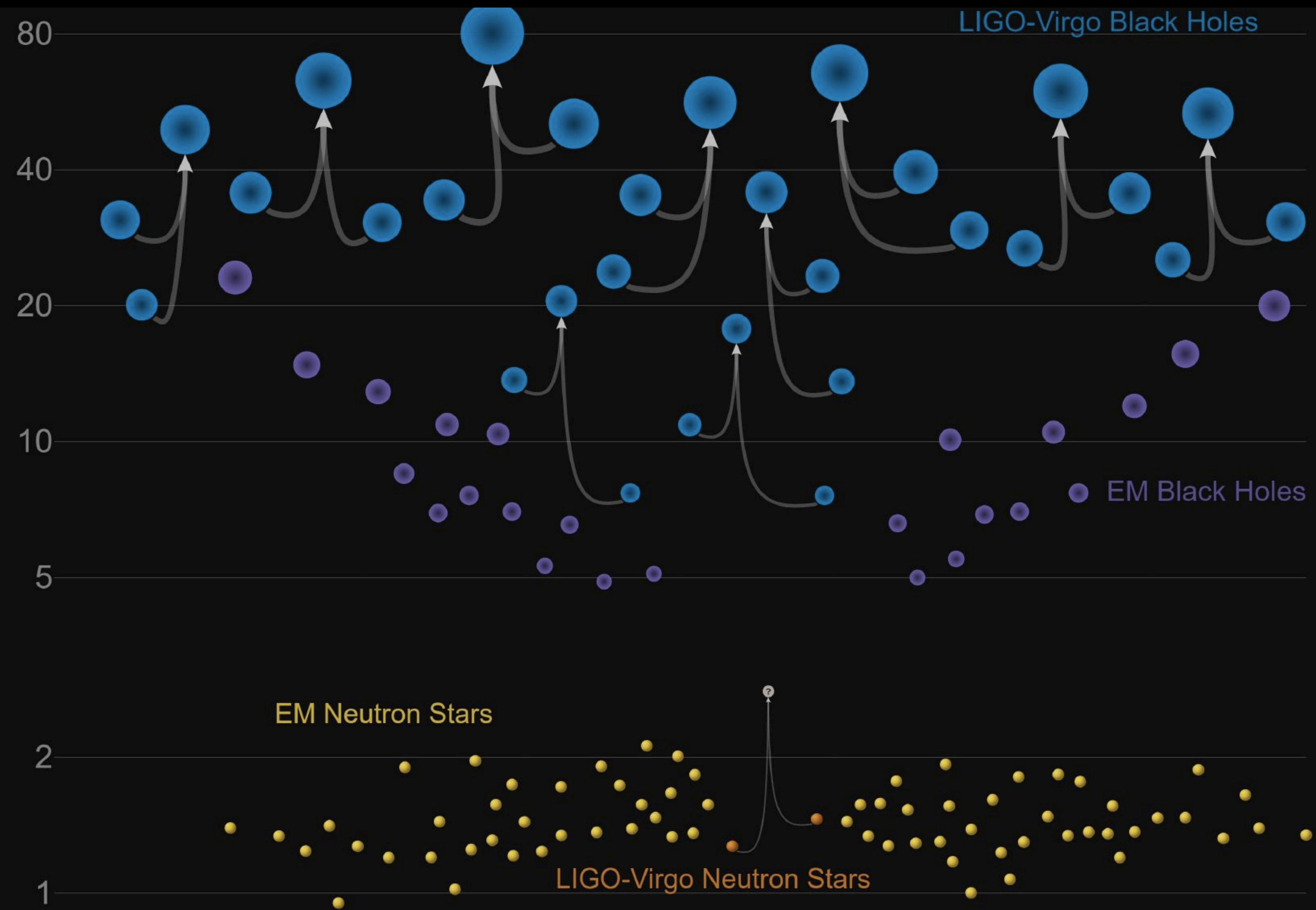


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1

LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

S. GHONGE, K. JANI | GEORGIA TECH

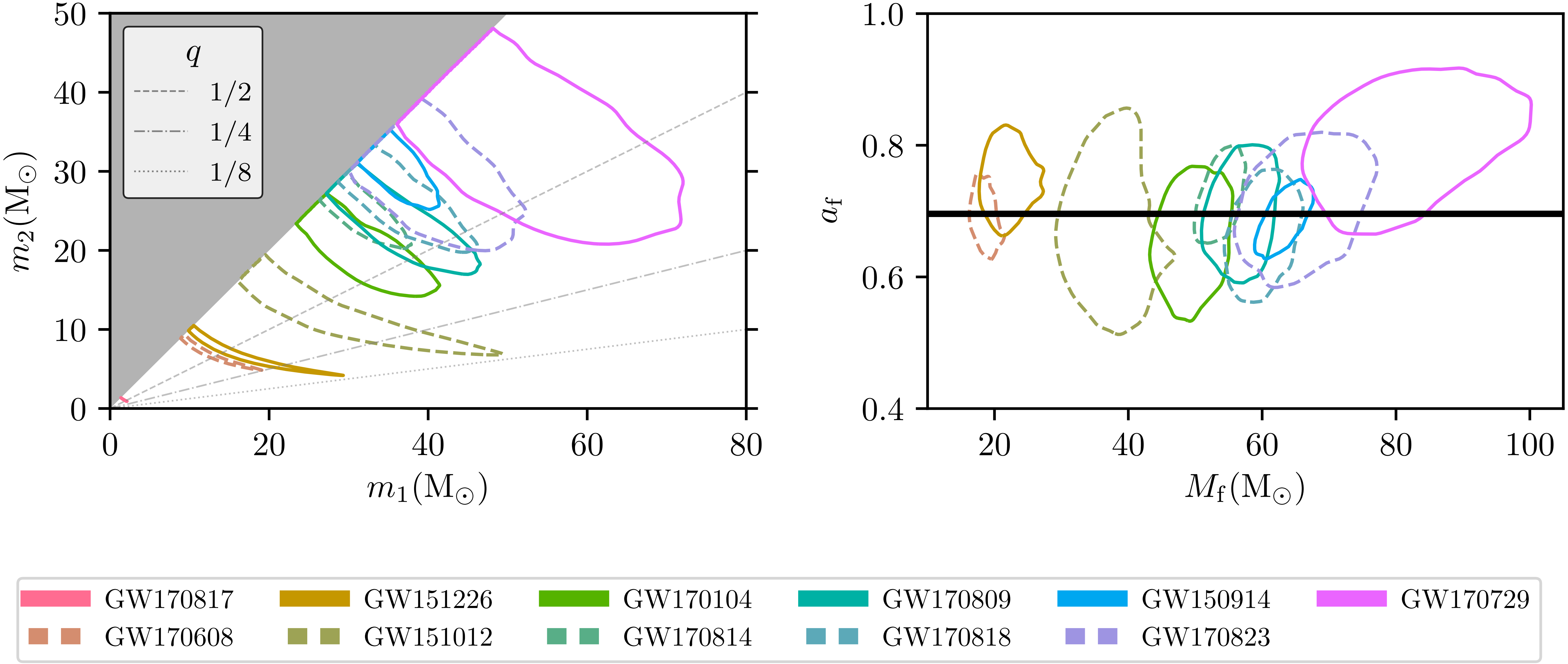
BINARY MERGERS DETECTED BY LIGO



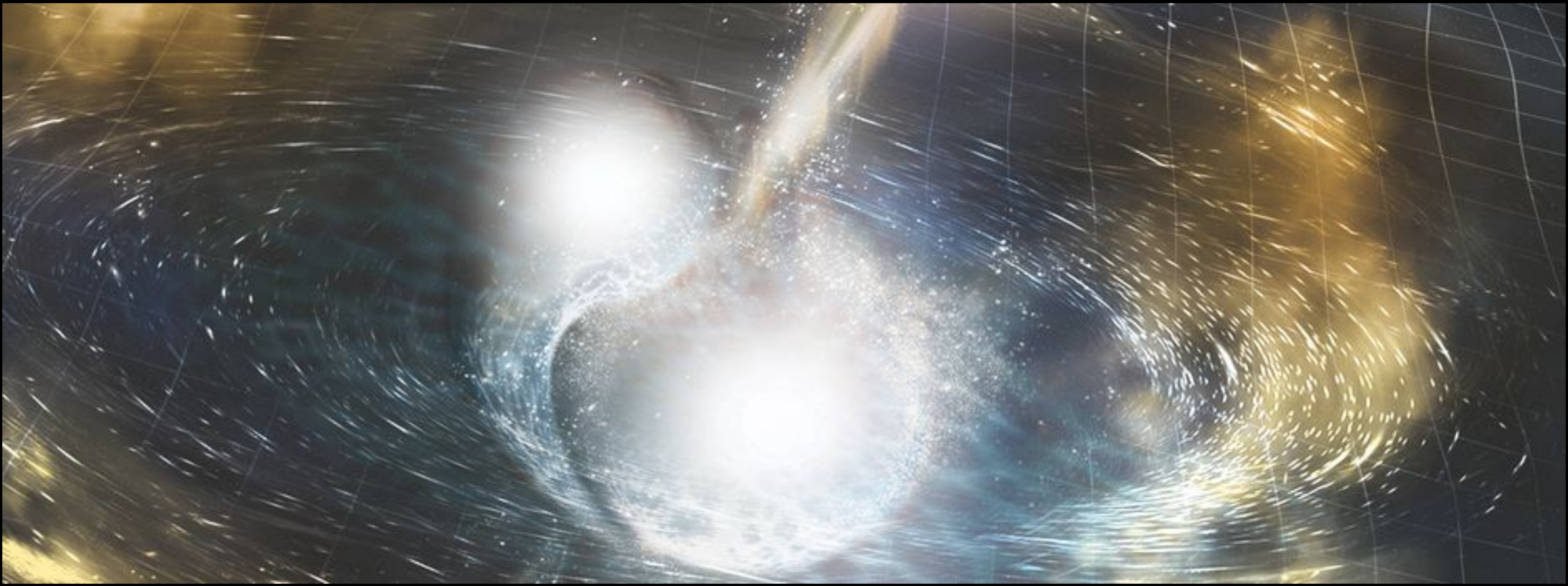
LIGO-Virgo | Frank Elavsky | Northwestern

SOURCE PROPERTIES

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



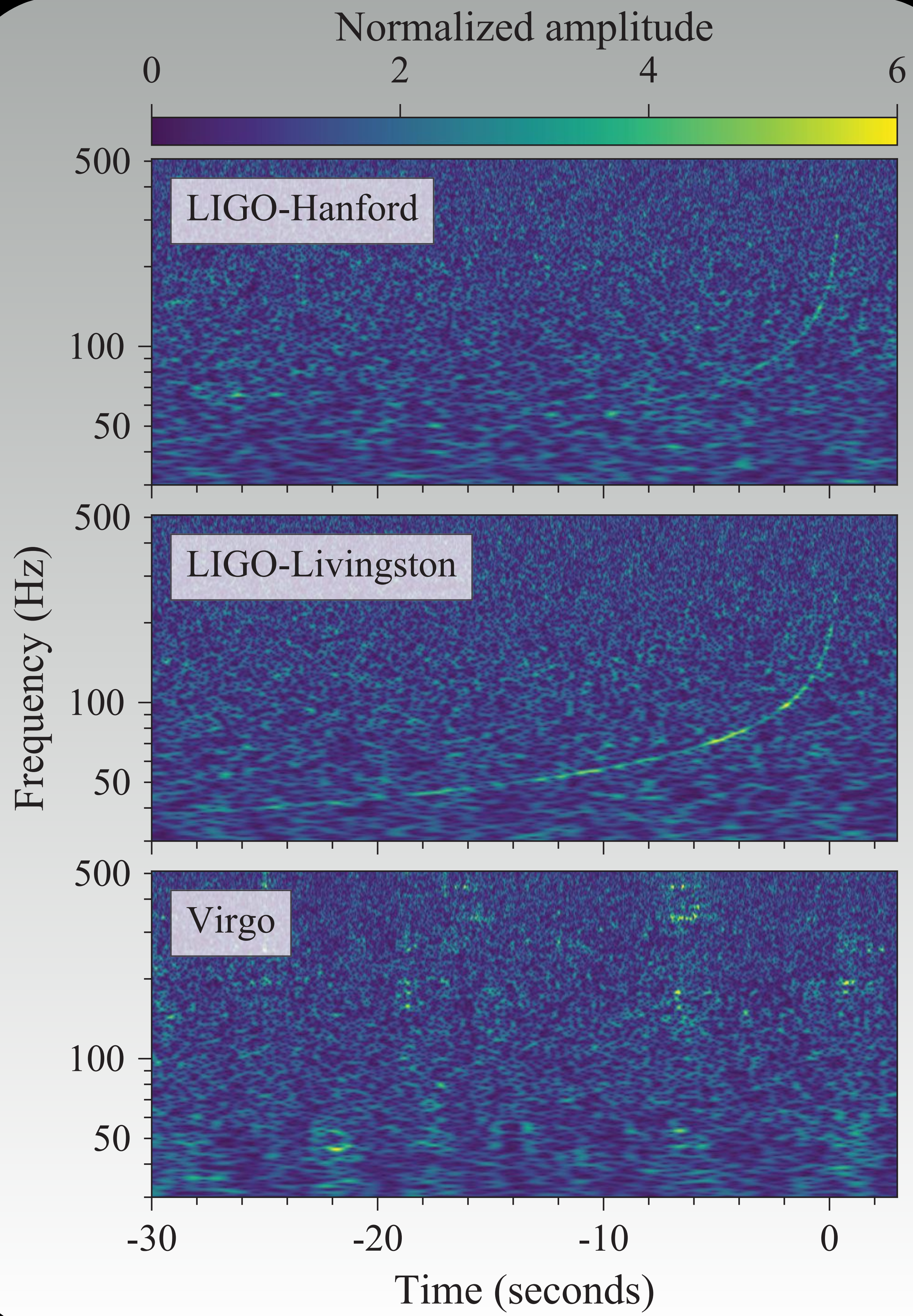
GW170817:DISCOVERY OF INSPIRALLING BINARY NEUTRON STARS



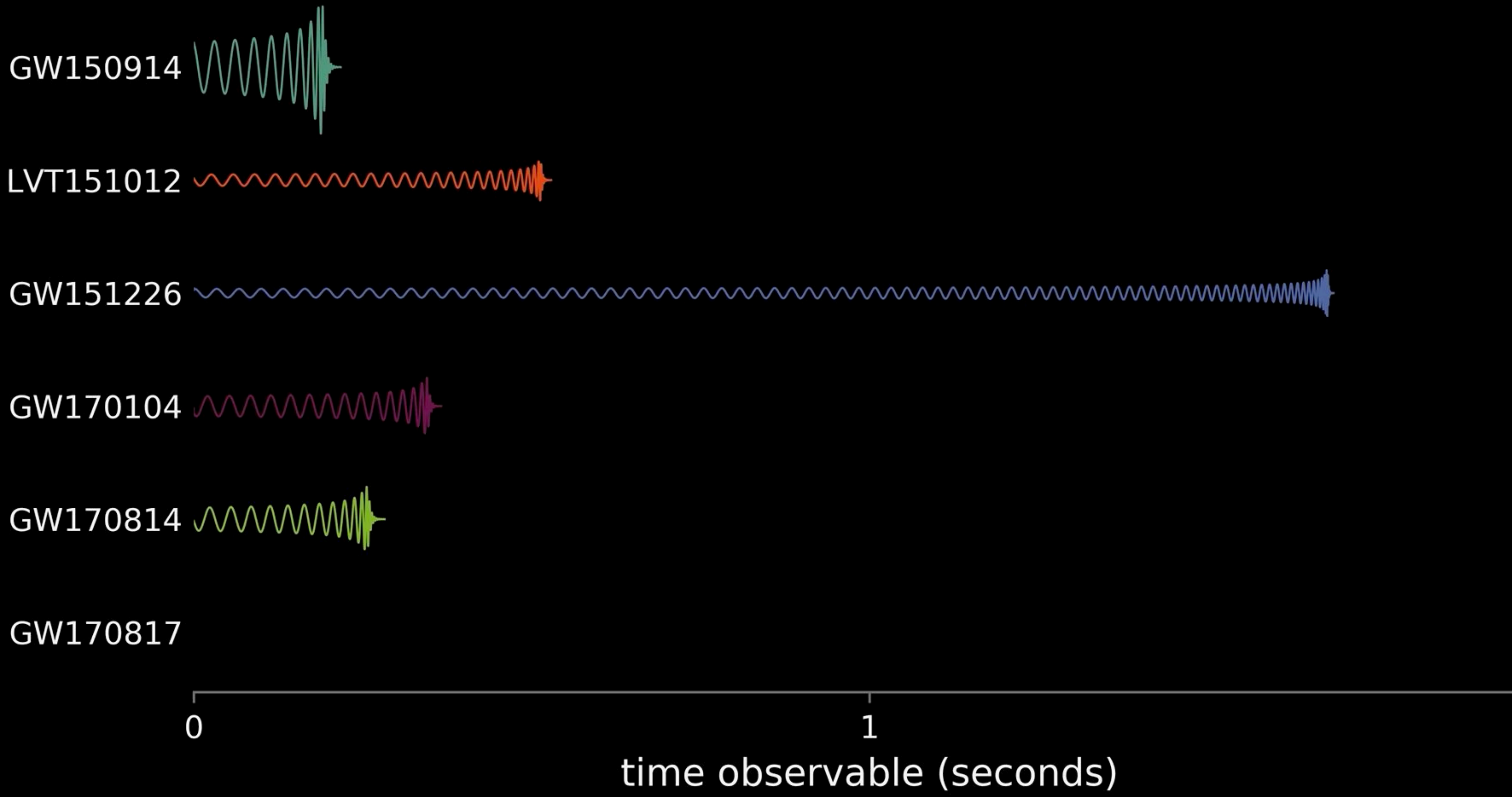
TIME FREQUENCY PLOT OF GW170817

- Signal-to-noise ratio of 32.4
  - loudest yet
- False alarm rate of 1 in 10^6 yrs
  - most significant of all

Abbott+, PRL 119, 161101 (2017)

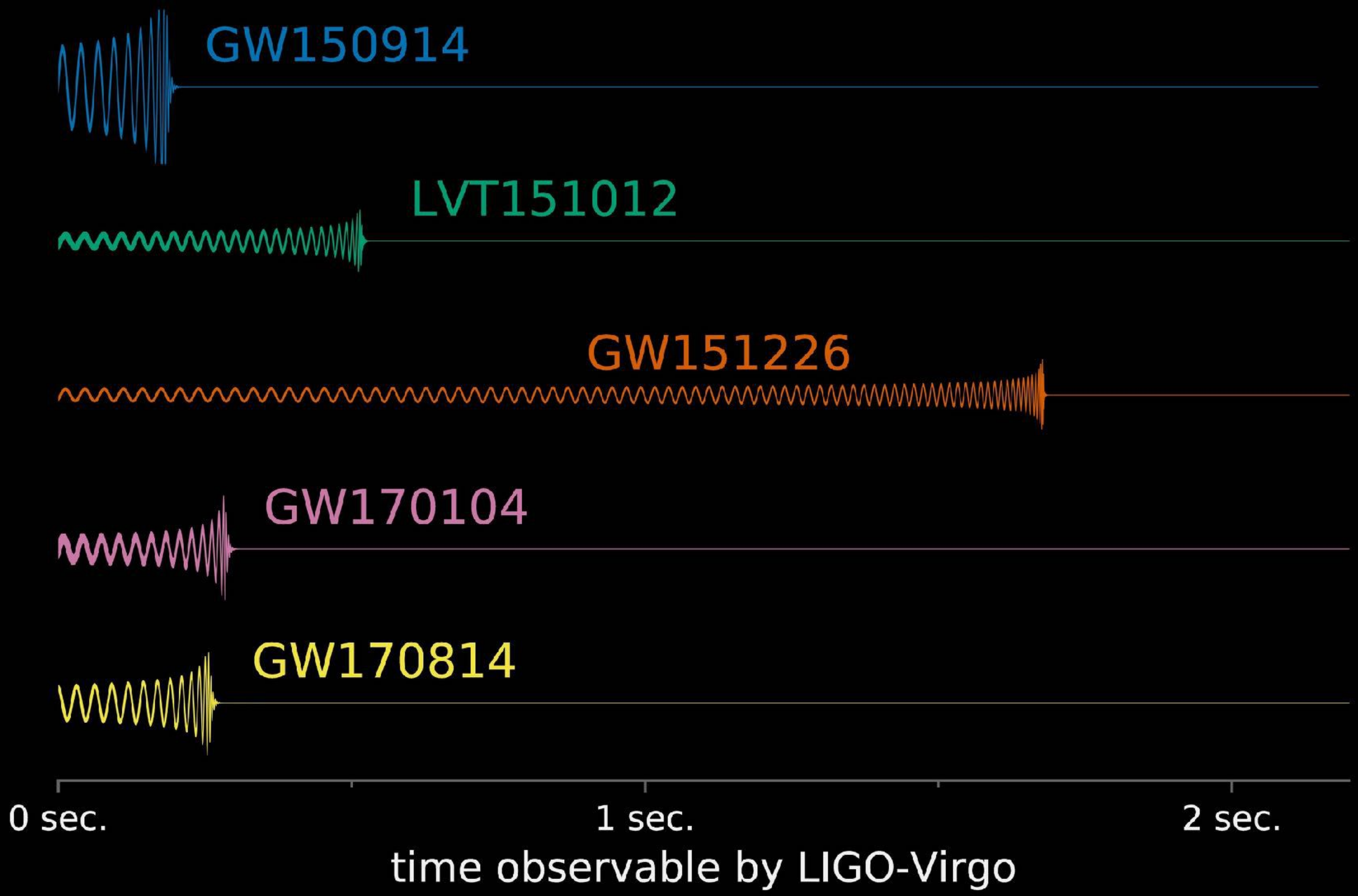


SIGNAL LASTED FOR SEVERAL MINUTES IN BAND



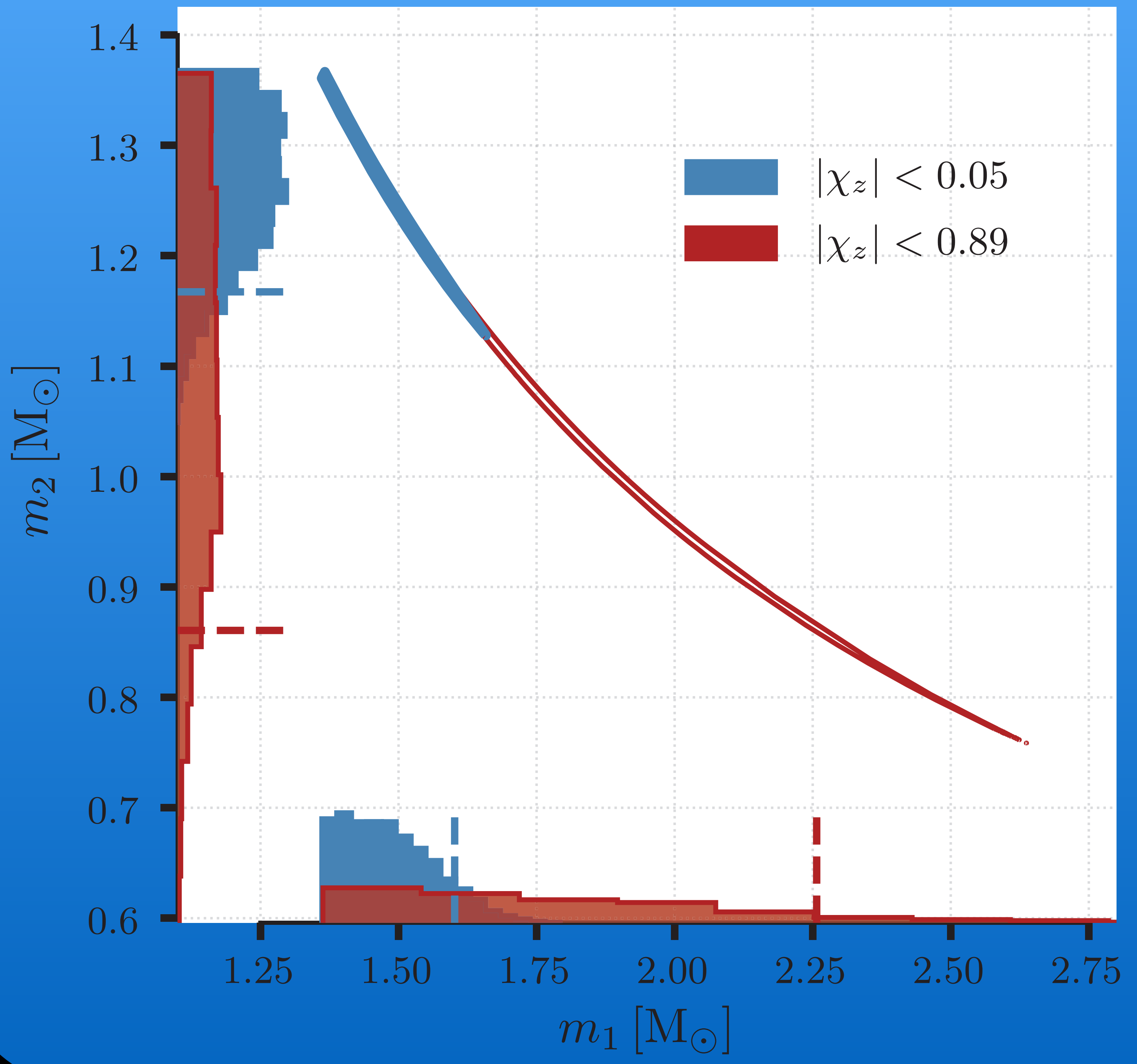
LIGO/University of Oregon/Ben F

HOW LONG DO THEY LAST?



waveforms: LSC/Ben Farr

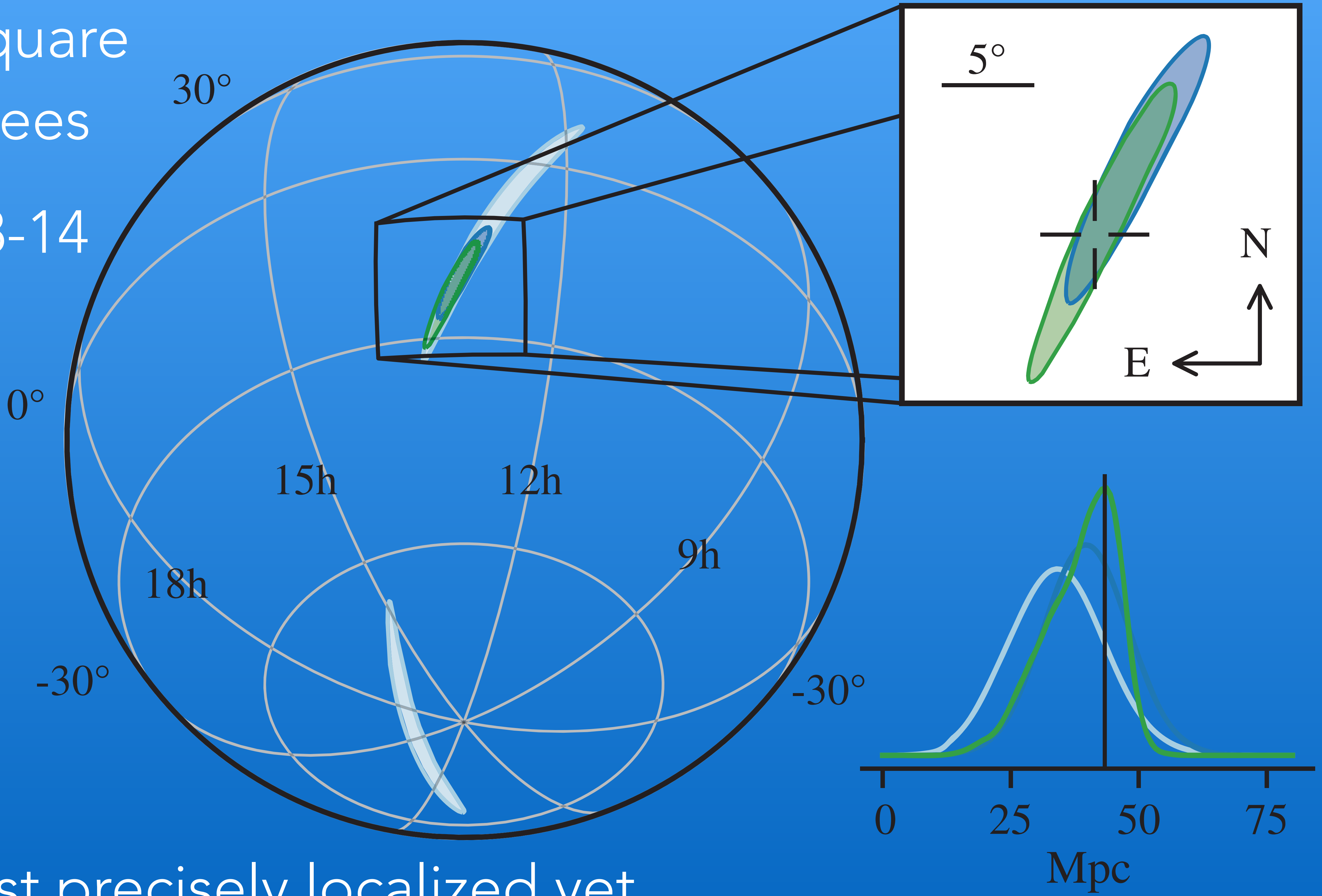
COMPONENT MASSES



Abbott+, PRL 119, 161101 (2017)

SKY POSITION AND DISTANCE

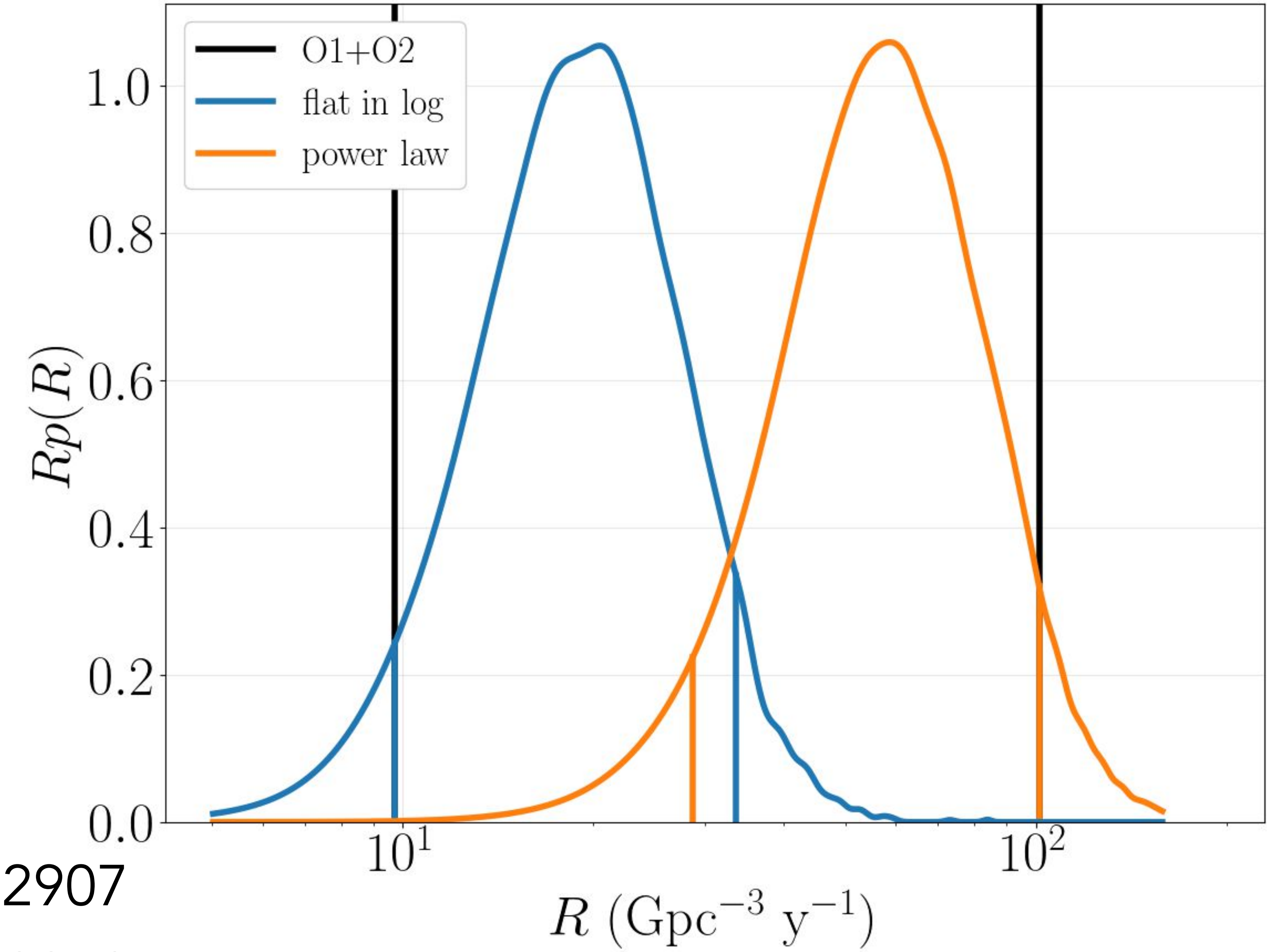
- 28 square degrees
- 40+8-14 Mpc



- most precisely localized yet

Abbott+, PRL 119, 161101 (2017)

COALESCENCE RATES



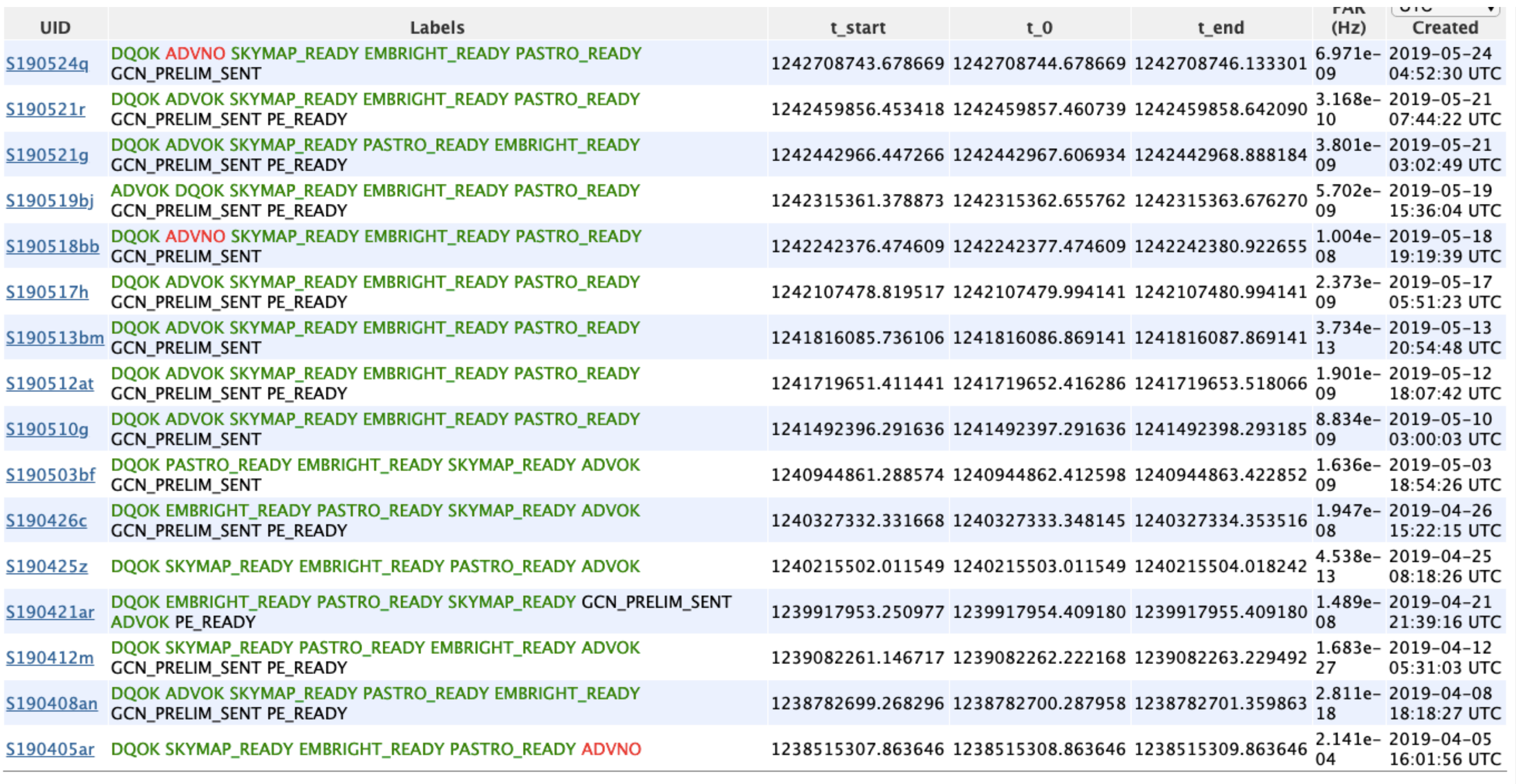
arXiv:1811.12907

arXiv:1811.12940

BBH Rate: $9.7 - 101$ Gpc^{-3} y^{-1}

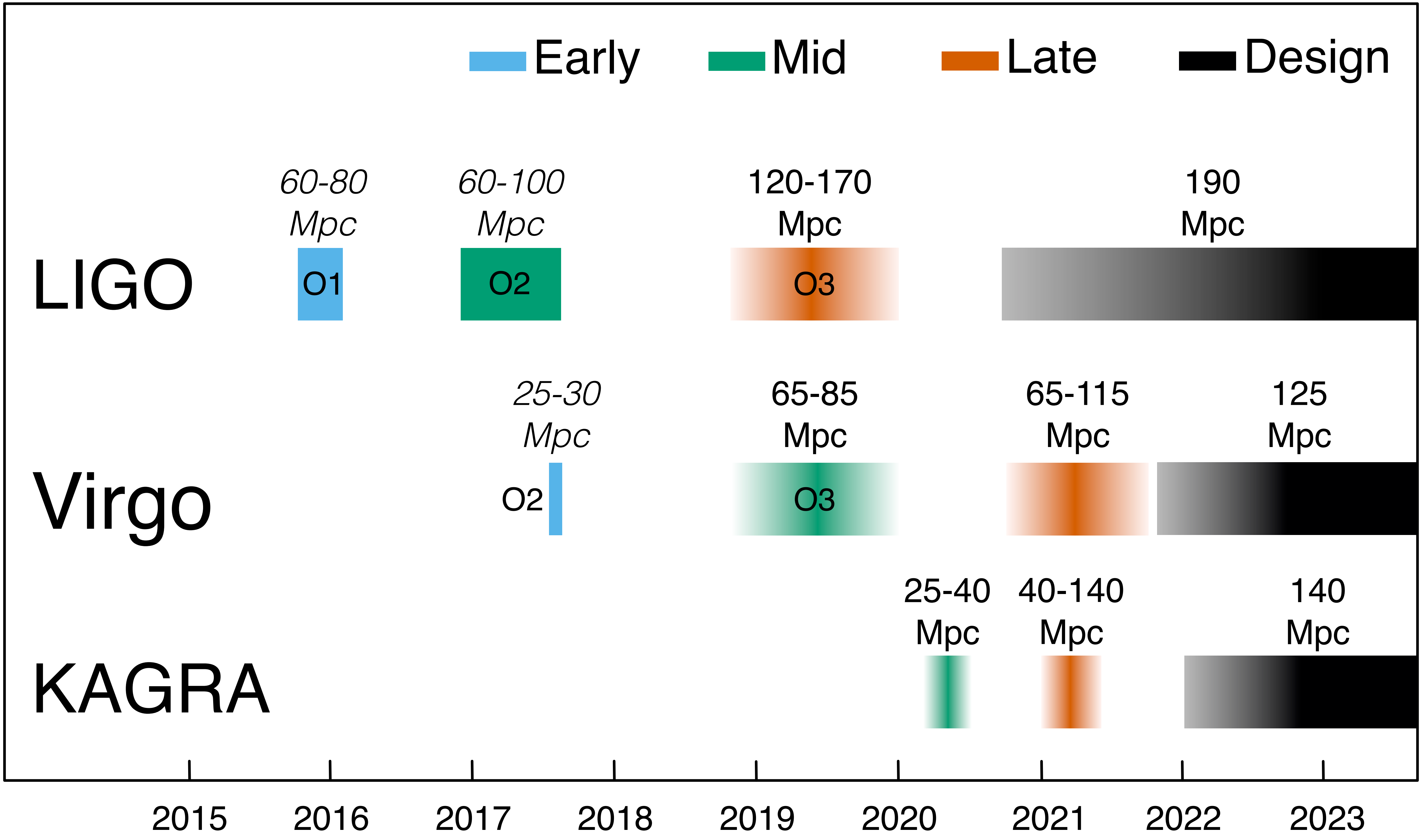
BNS Rate: $110 - 3840$ Gpc^{-3} y^{-1}

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
S190518bb	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
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

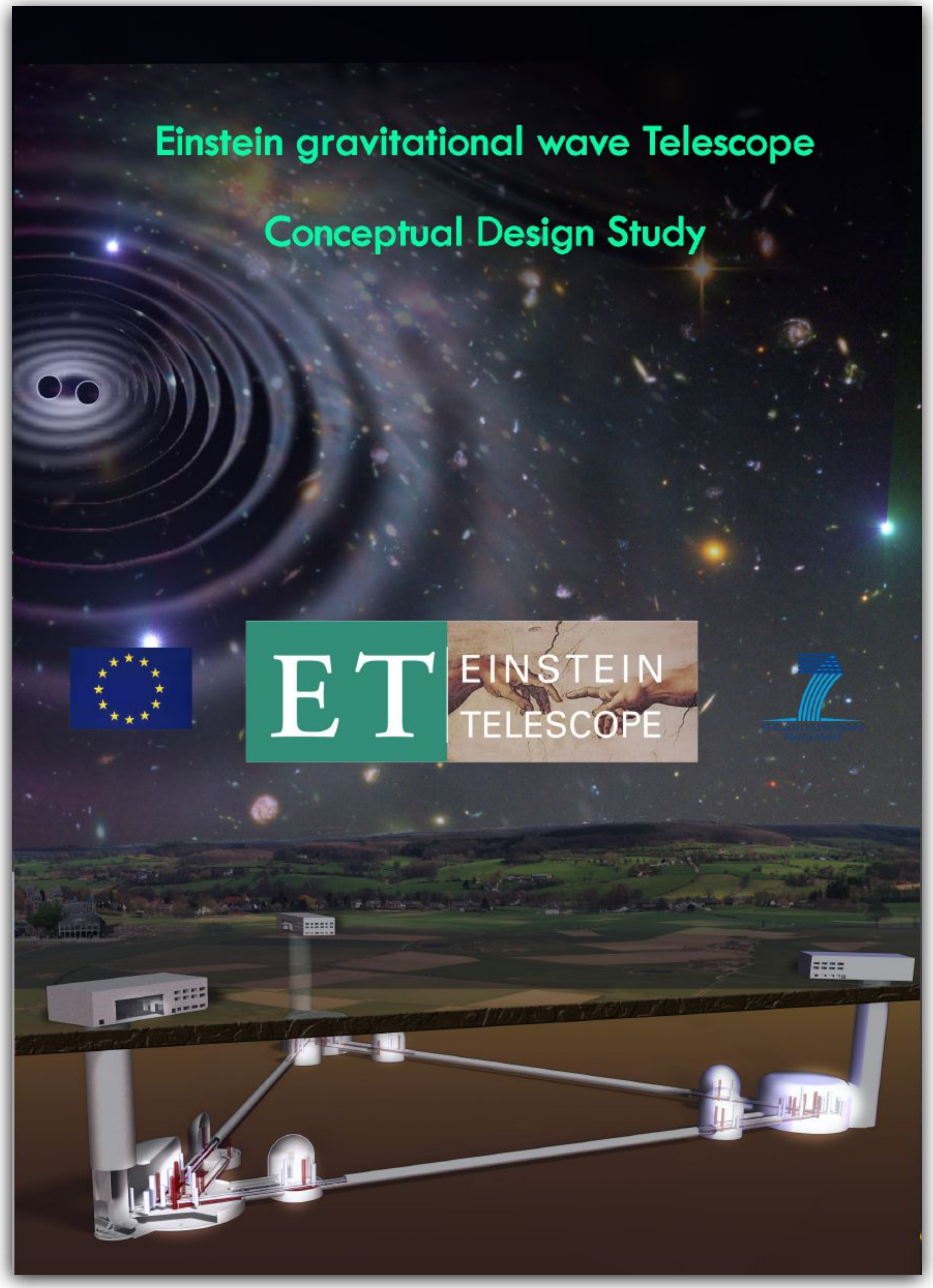
UPCOMING RUNS AND SENSITIVITIES



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

EINSTEIN TELESCOPE AND COSMIC EXPLORER

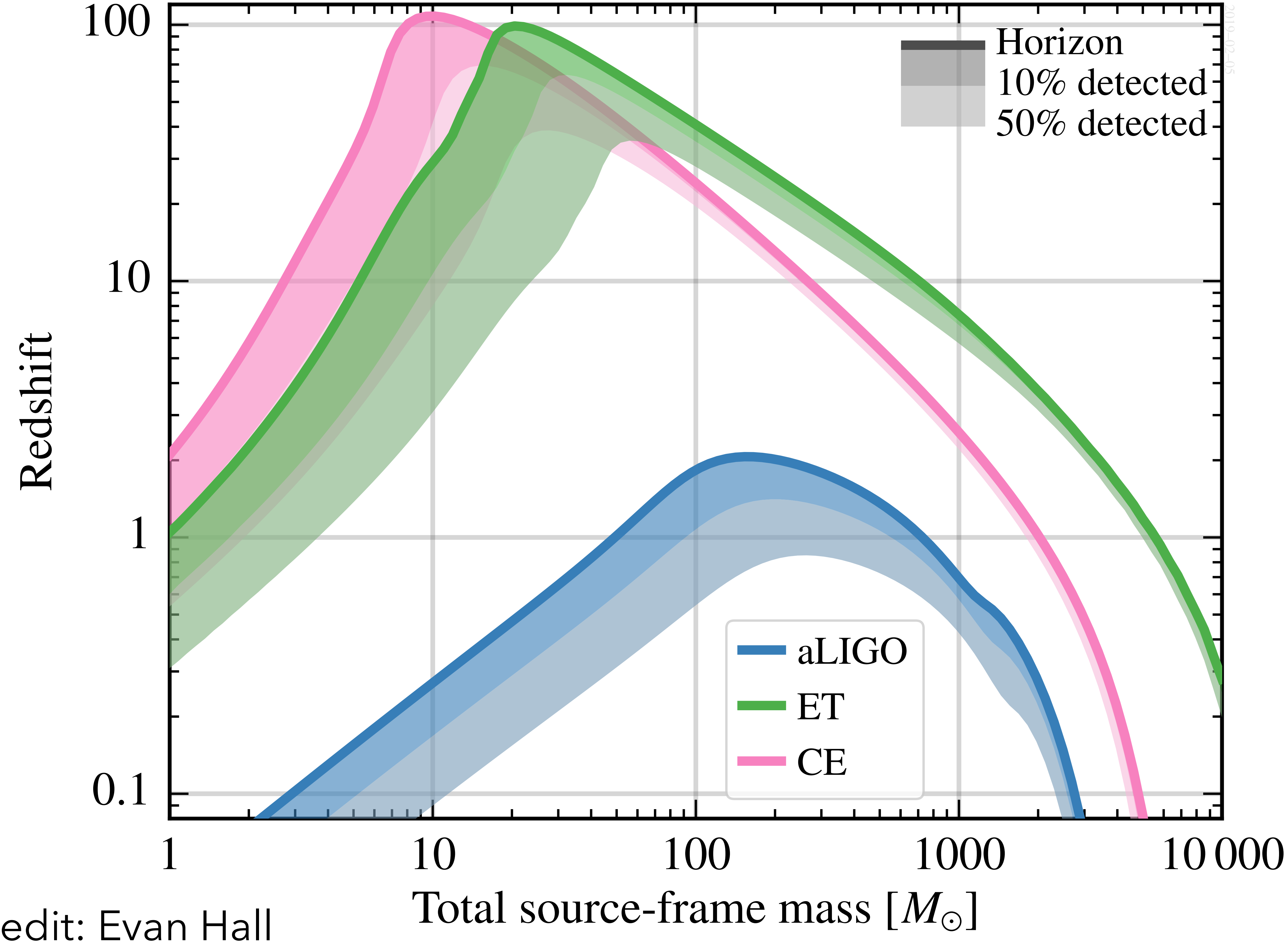
- Einstein Telescope
  - FP7 conceptual design study
  - underground, 10-km arm triangle
  - design study completed in ’11
  - roadmap presented to APPEC, ET collaboration formed ’19, enter ESFRI Roadmap in ’20, site selection in ’22, technical design ’23, construction ’25-’31, commission ’31+
- Cosmic explorer
  - 40 km arm ground-based
  - NSF funded design study: 2018-2021



Einstein gravitational wave Telescope

Conceptual Design Study

3G NETWORK SENSITIVITY



Credit: Evan Hall

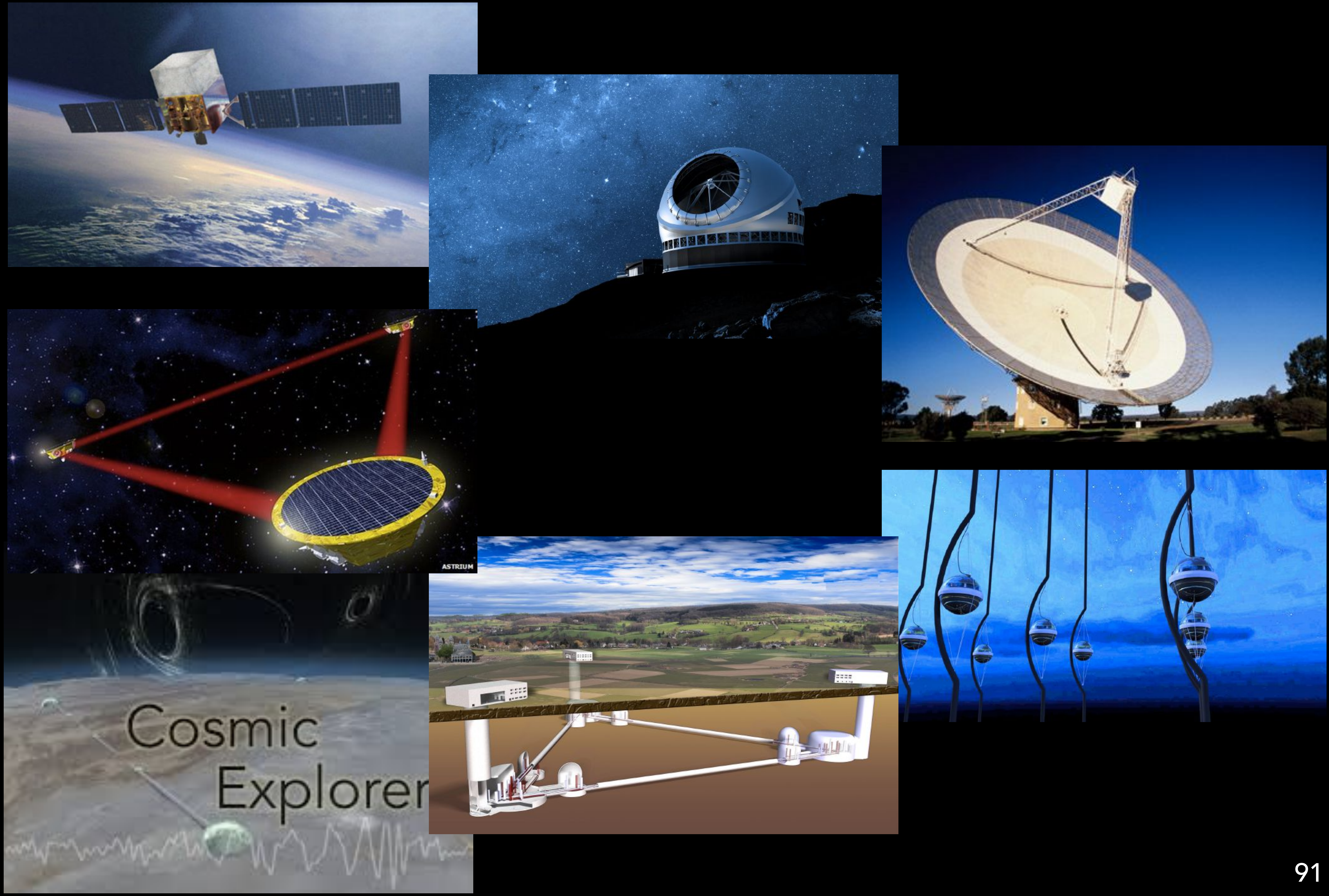
WITH 3G WE WILL EXPLORE FUNDAMENTAL PROPERTIES OF SPACETIME AND MATTER

- 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.

GROUNDBREAKING SCIENCE FROM GW DISCOVERIES - THE STORY SO FAR

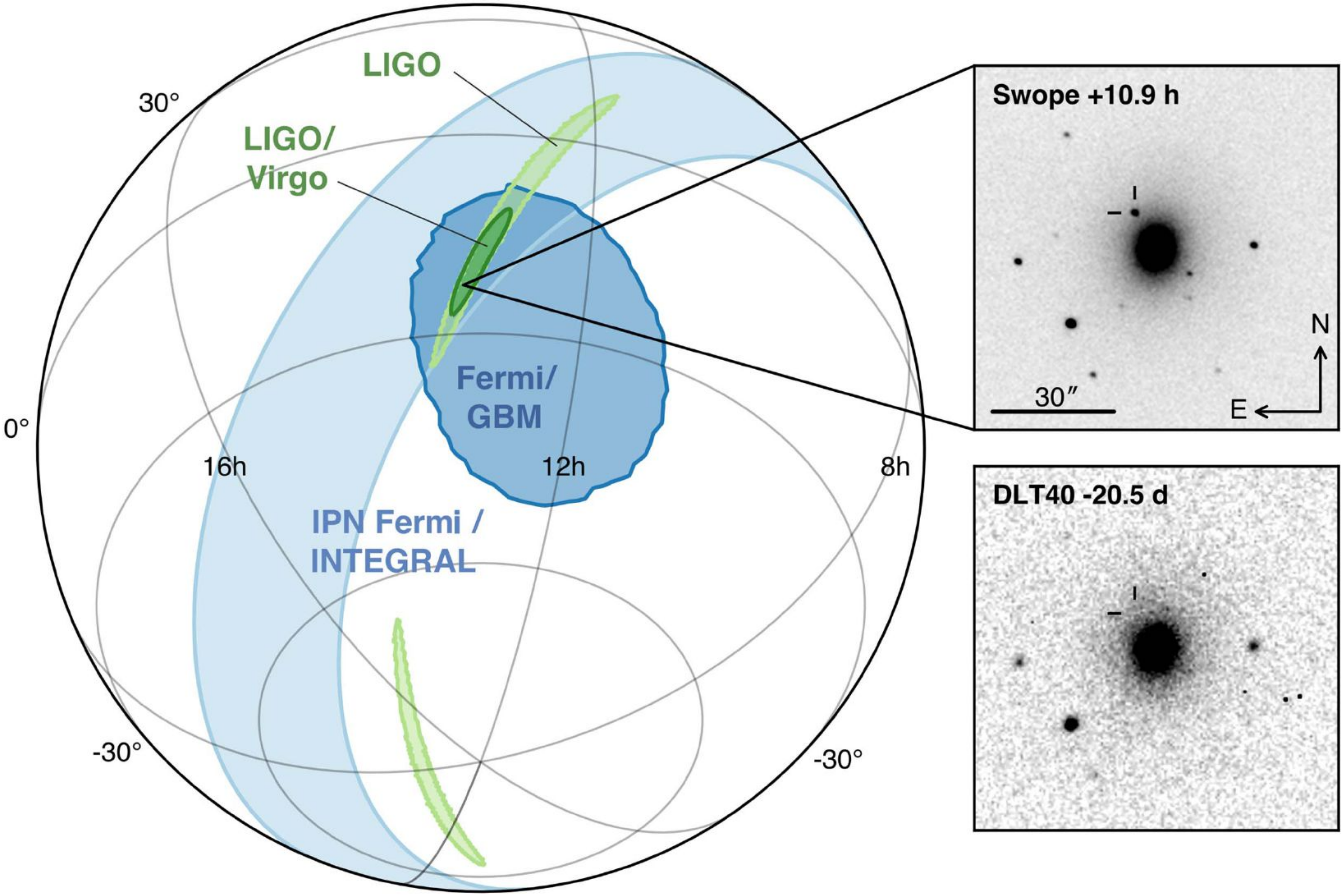
- opened a new window to observe the dark sector, inaccessible to others
  - confirmed existence of merging binary black holes, rate well constrained
    - the most luminous sources in the Universe
  - matter under extreme environs
    - highest densities and greatest temperatures but for the big bang
- 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 GRB170817A
  - helped identify sites of heavy element production
  - constrained the speed of gravitational waves to 1 part in 10^{16} of light speed

MULTIMESSENGER OBSERVATIONS

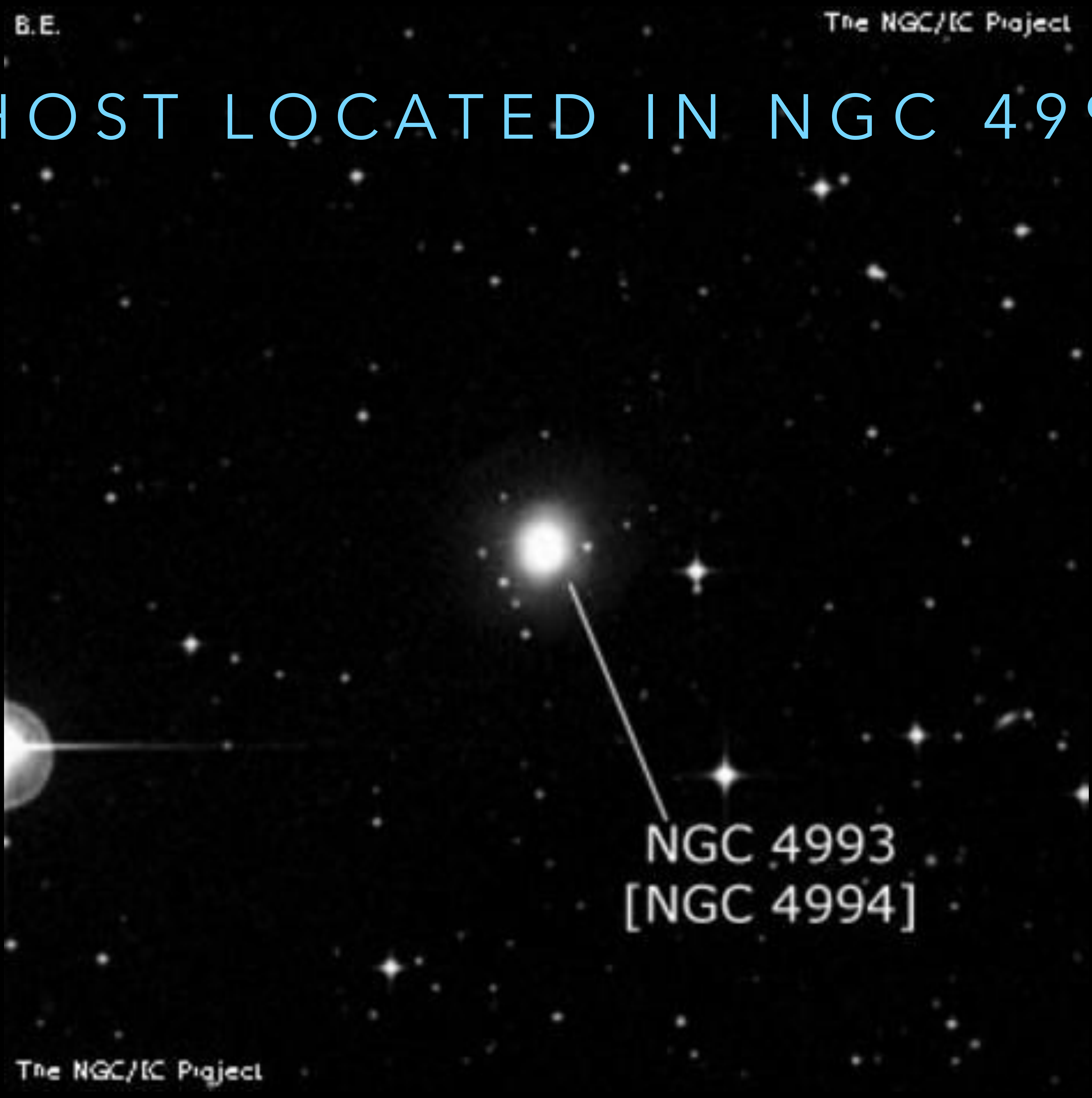


KILONOVA AND MULTI-BAND OBSERVATIONS - A NEW ERA IN MULTI-MESSENGER ASTRONOMY

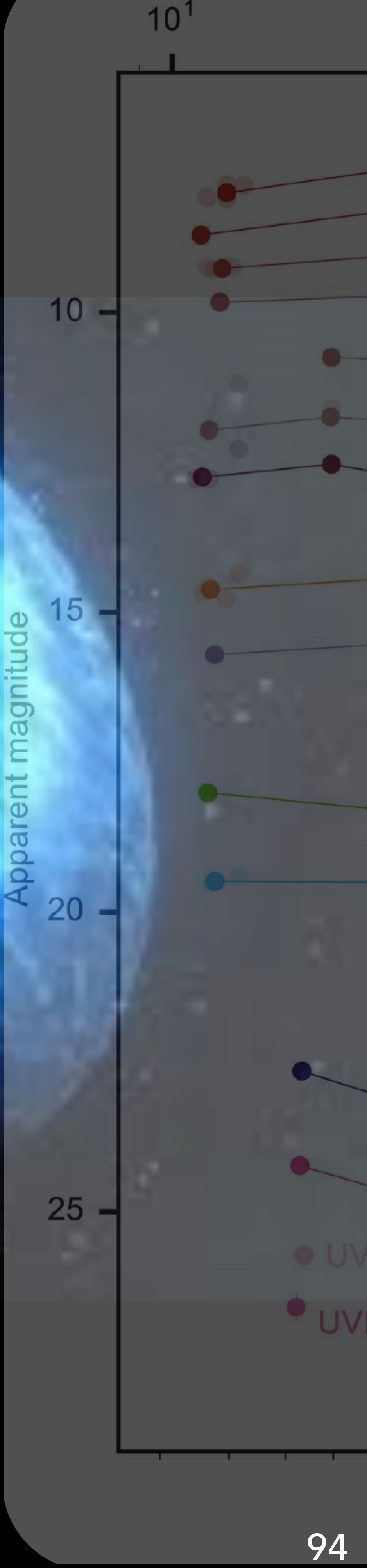
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20



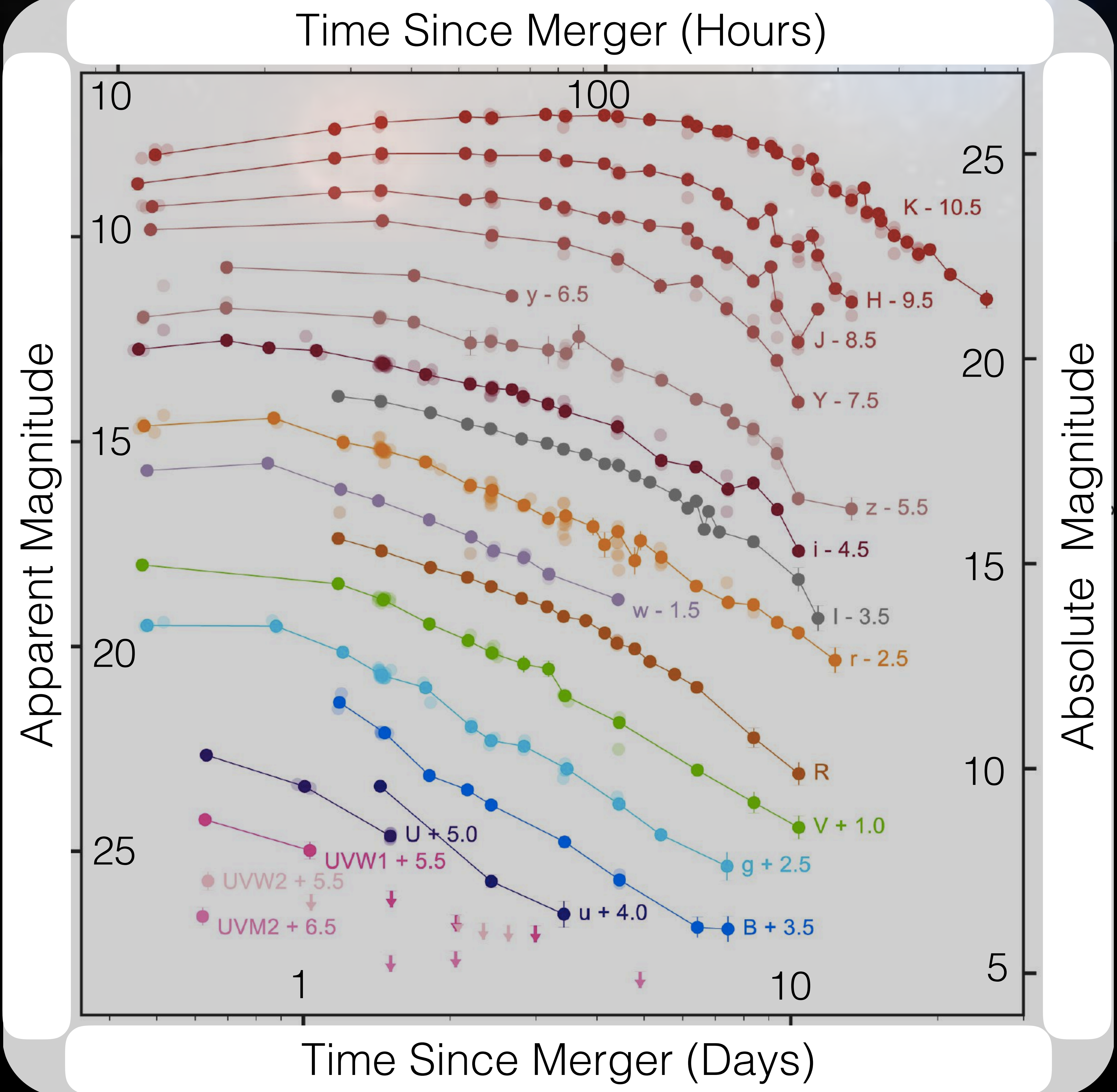
HOST LOCATED IN NGC 4993



PRODUCTION OF HEAVY ELEMENTS

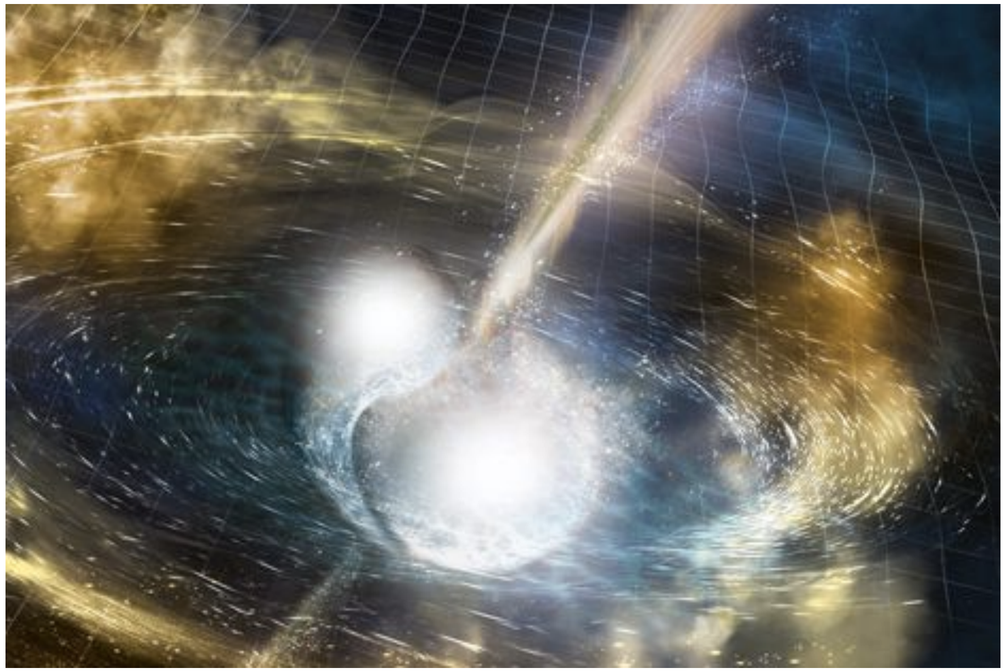


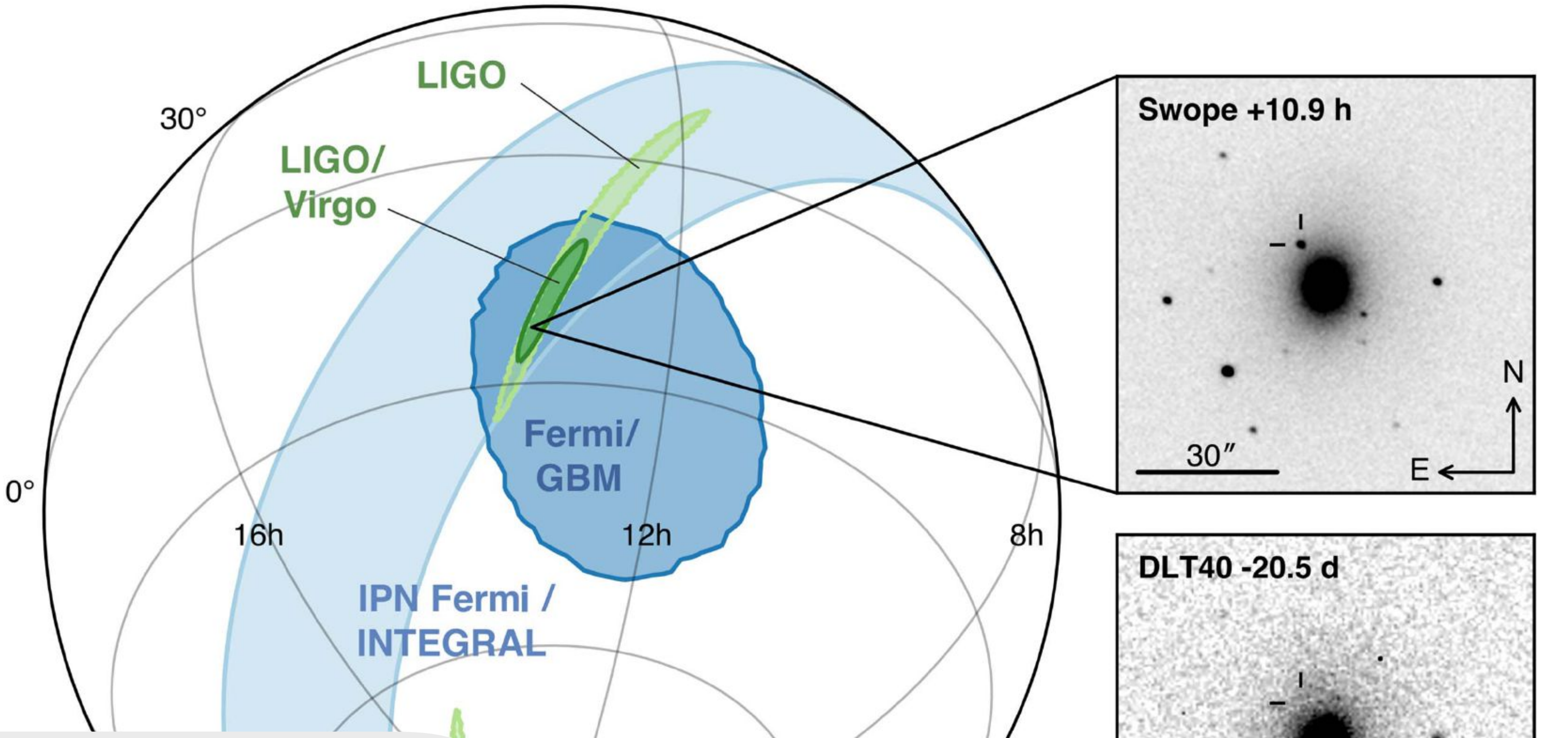
- in the aftermath of merger heavy elements are produced by r-process
- many of these heavy elements are unstable and radioactively decay
- the process produces a fireball called kilonova

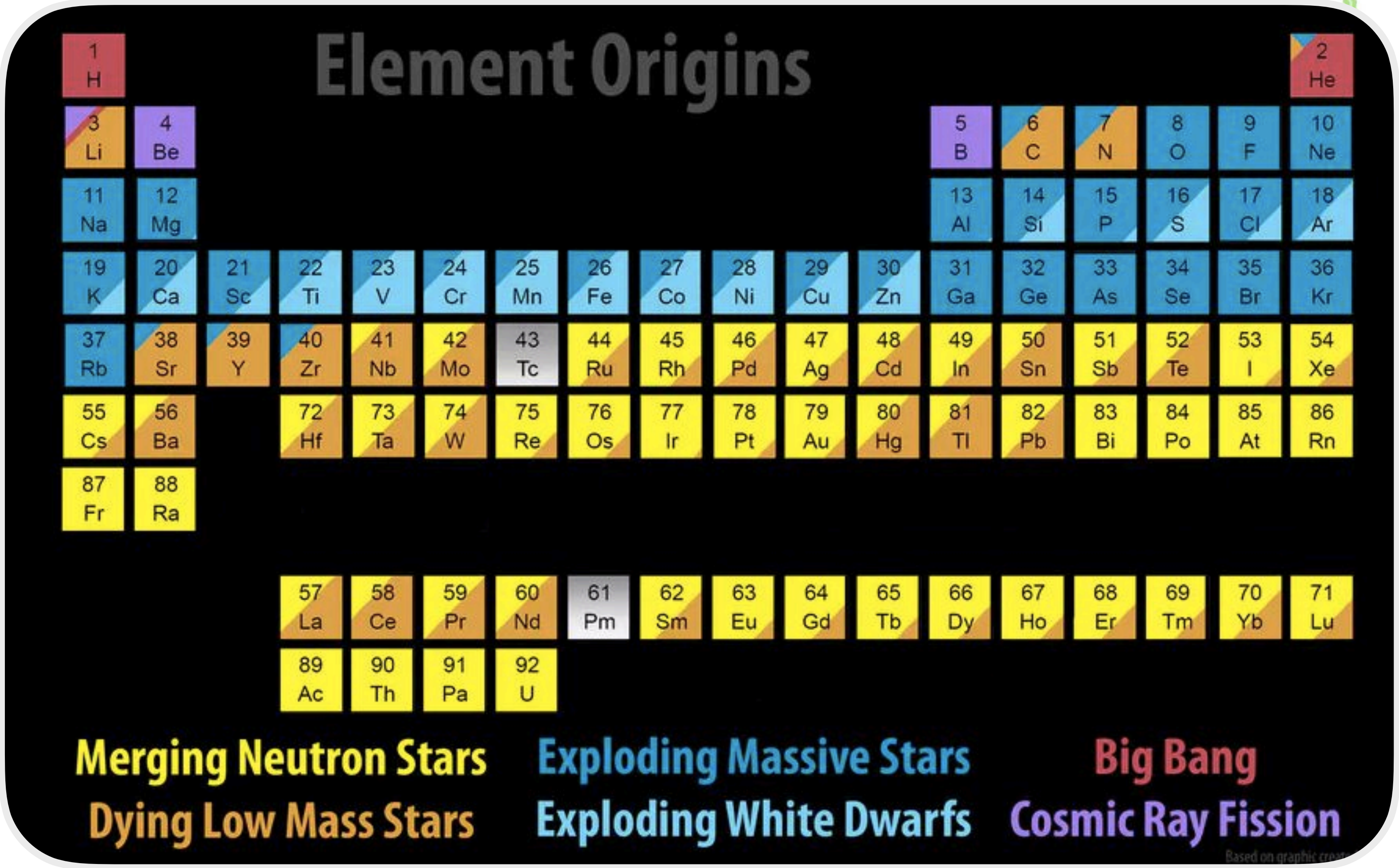

Time Since Merger (Hours)
10
100
Apparent Magnitude
10
15
20
25
Absolute Magnitude
25
20
15
10
5
K - 10.5
H - 9.5
J - 8.5
y - 6.5
Y - 7.5
z - 5.5
i - 4.5
I - 3.5
w - 1.5
r - 2.5
R
V + 1.0
g + 2.5
U + 5.0
UVW1 + 5.5
UVW2 + 5.5
UVM2 + 6.5
u + 4.0
B + 3.5
1
10
Time Since Merger (Days)

ORIGIN OF HEAVY ELEMENTS

Abbott+ ApJ Letters, 848, L12 (2017)

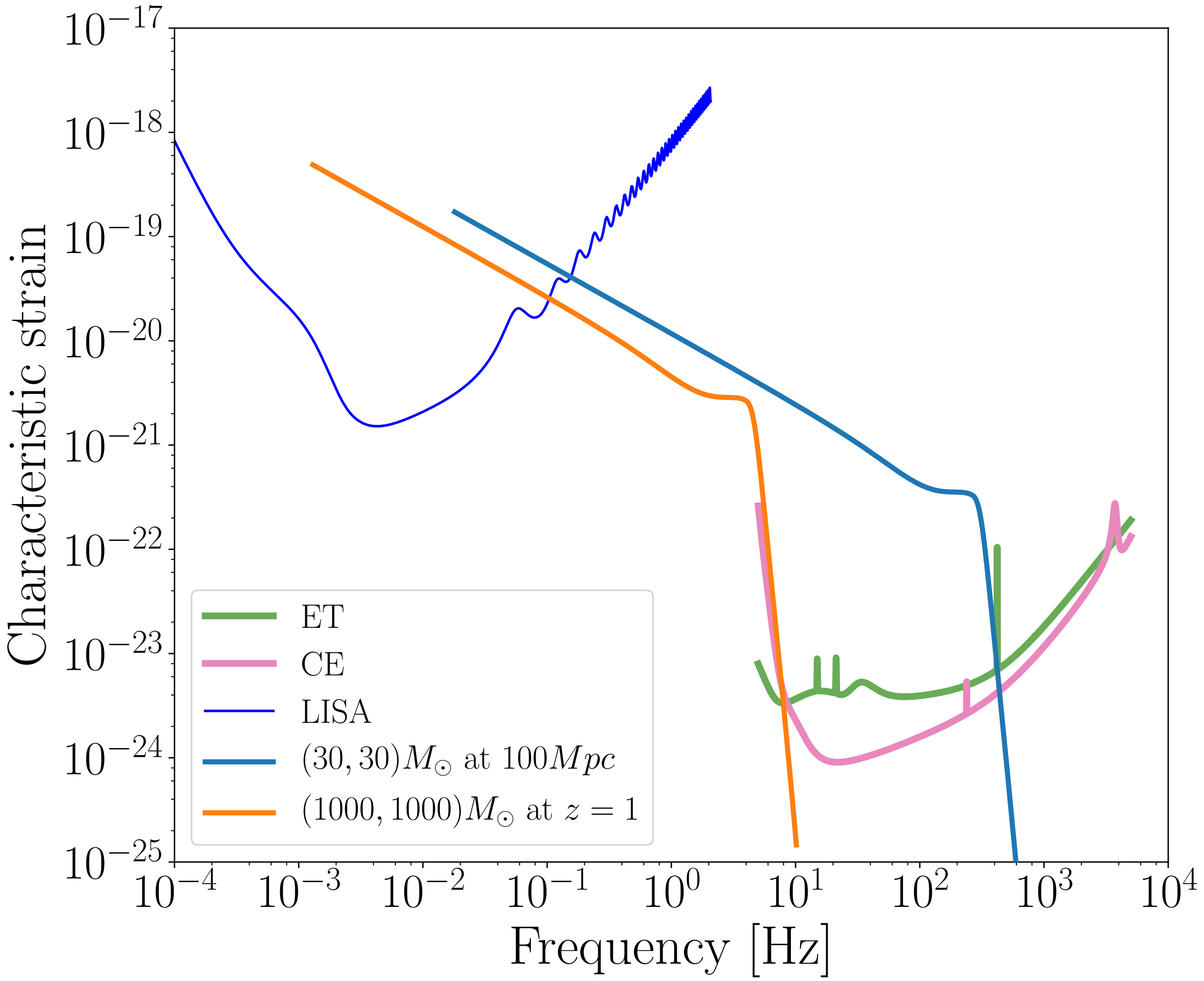


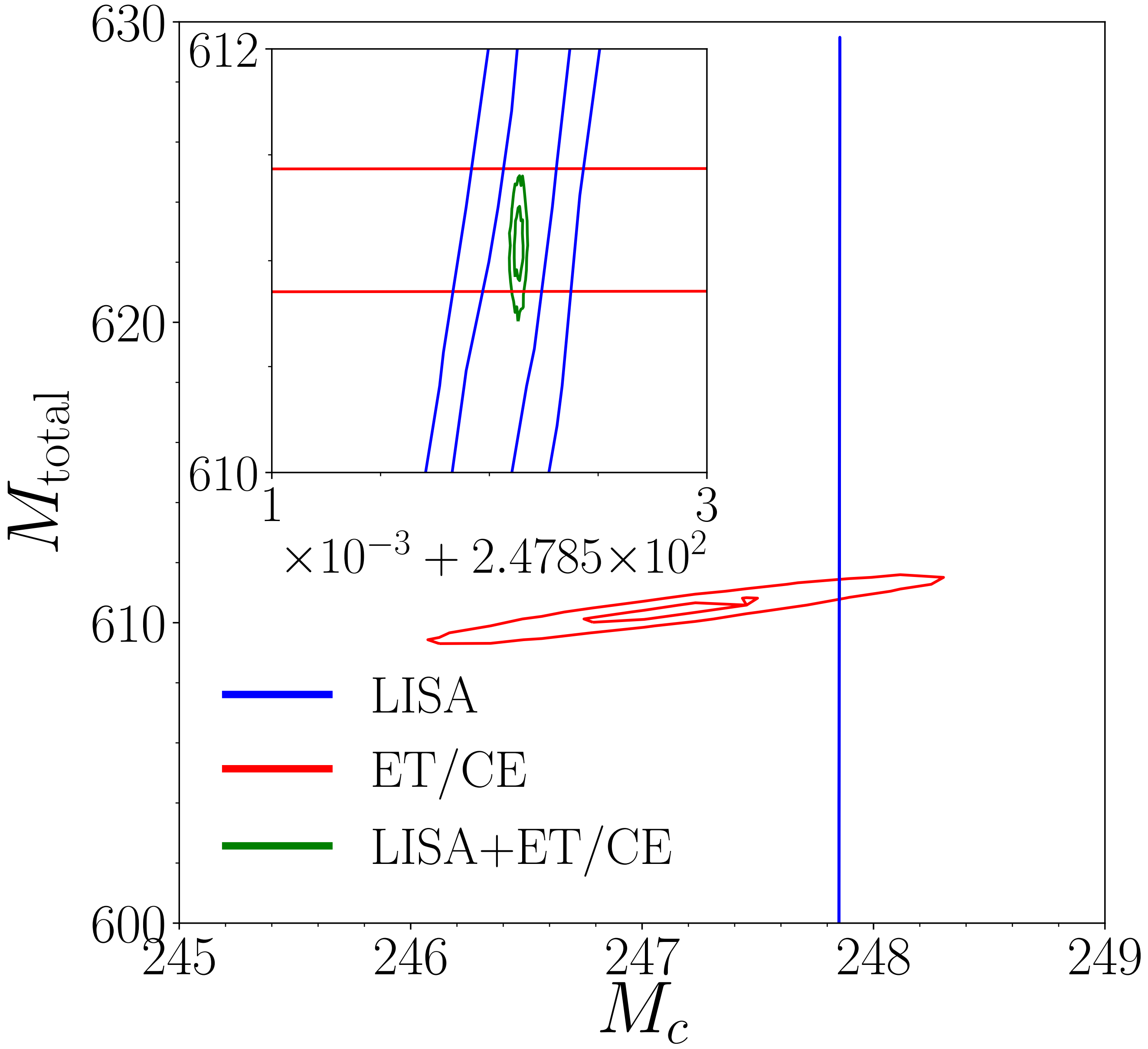




3G network will help identify thousands of kilonova and trace the origin of heavy elements

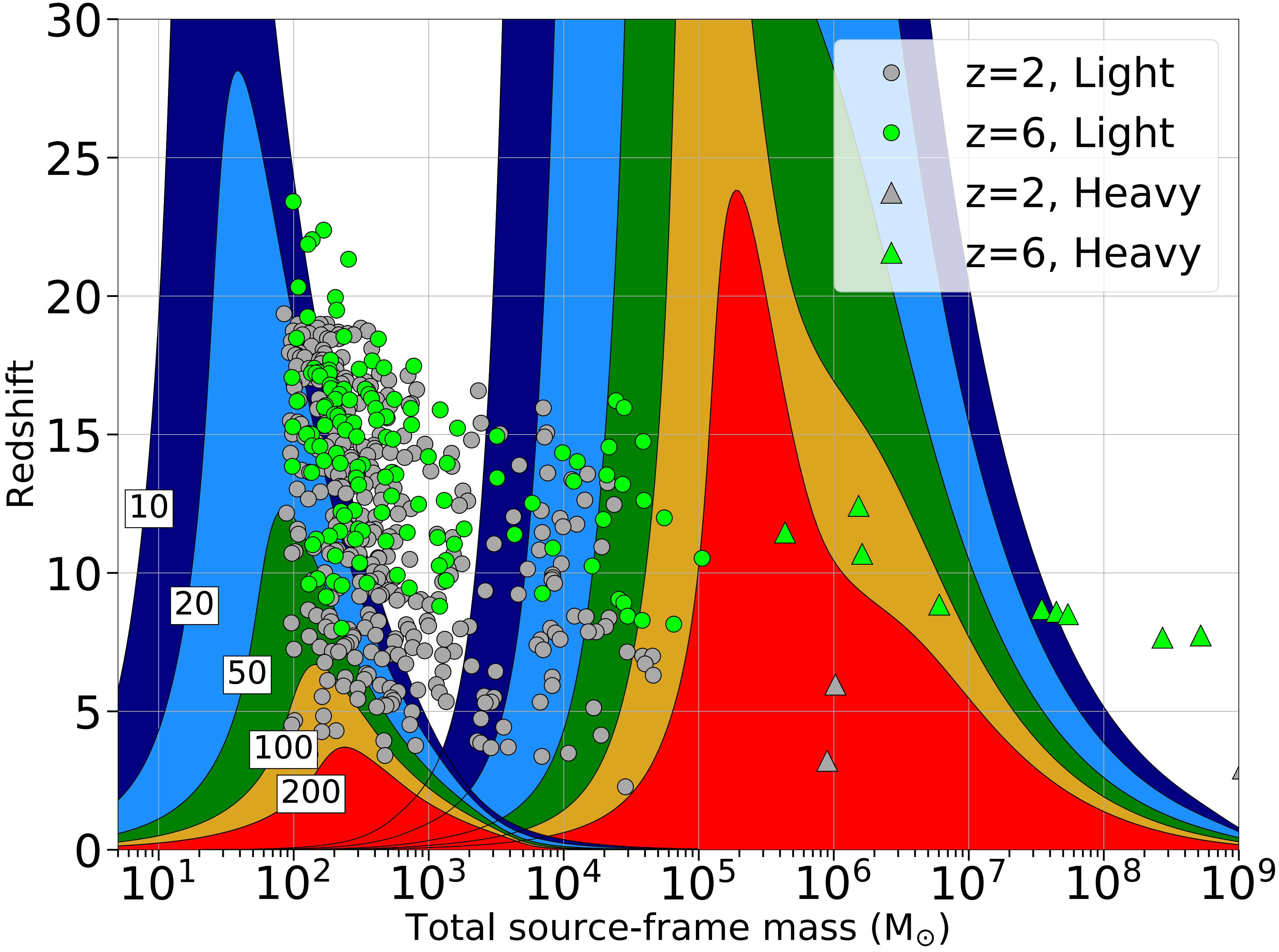
MULTIBAND - LISA AND 3G



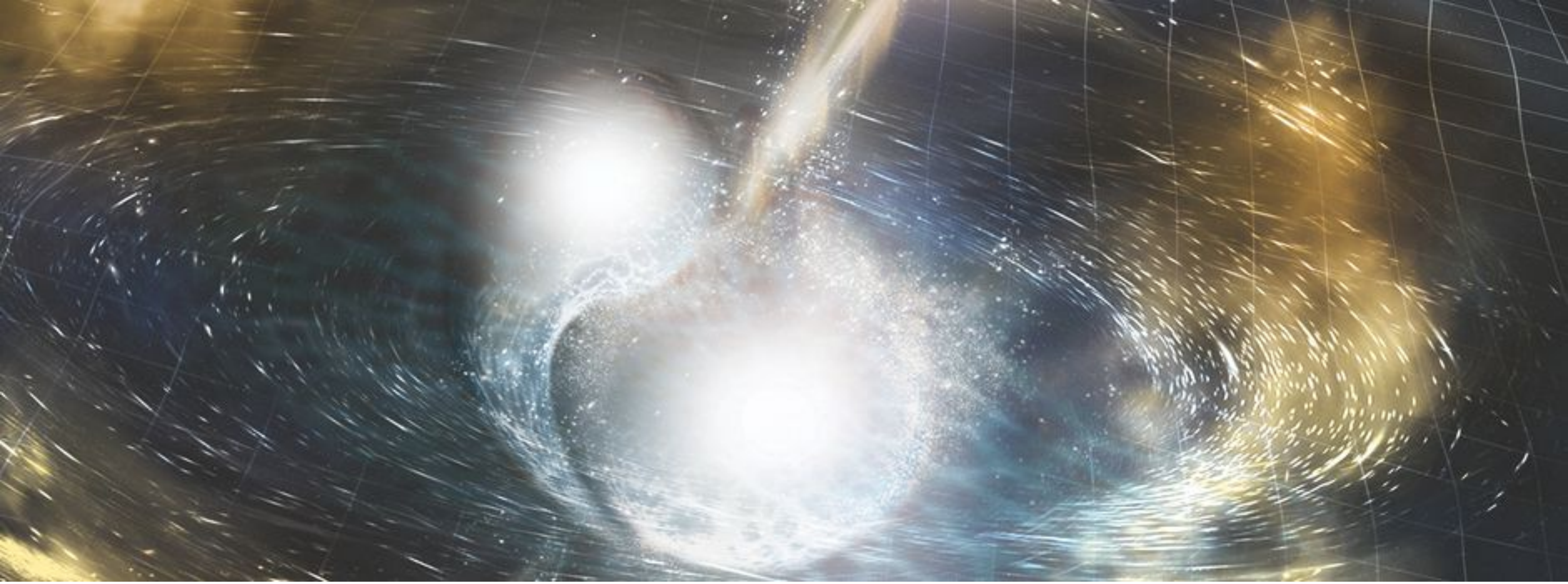


Cutler+ arXiv:1903.04069

ORIGIN & EVOLUTION OF SEED BLACK HOLES

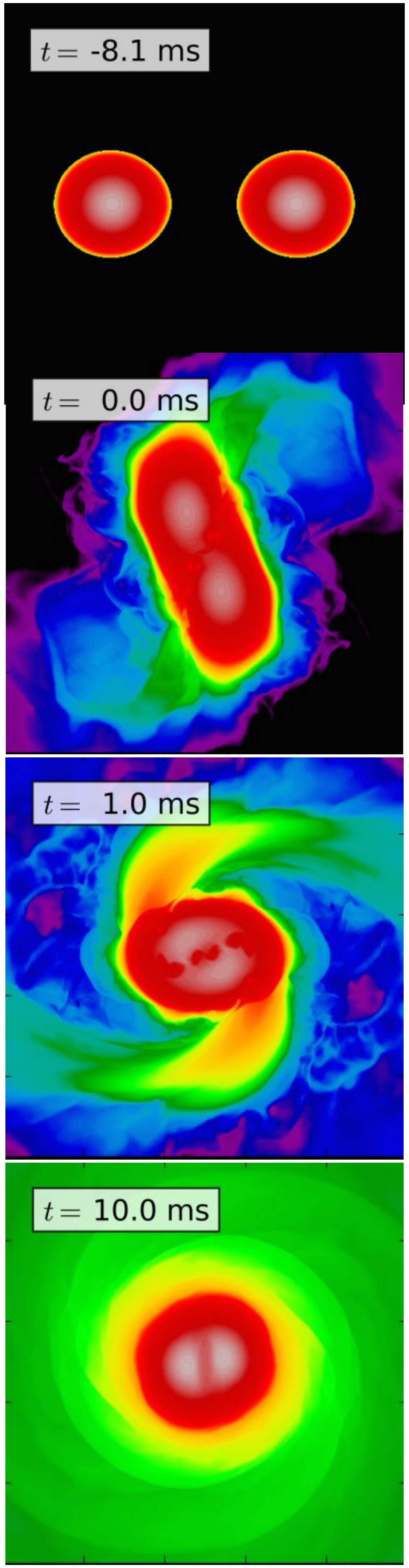


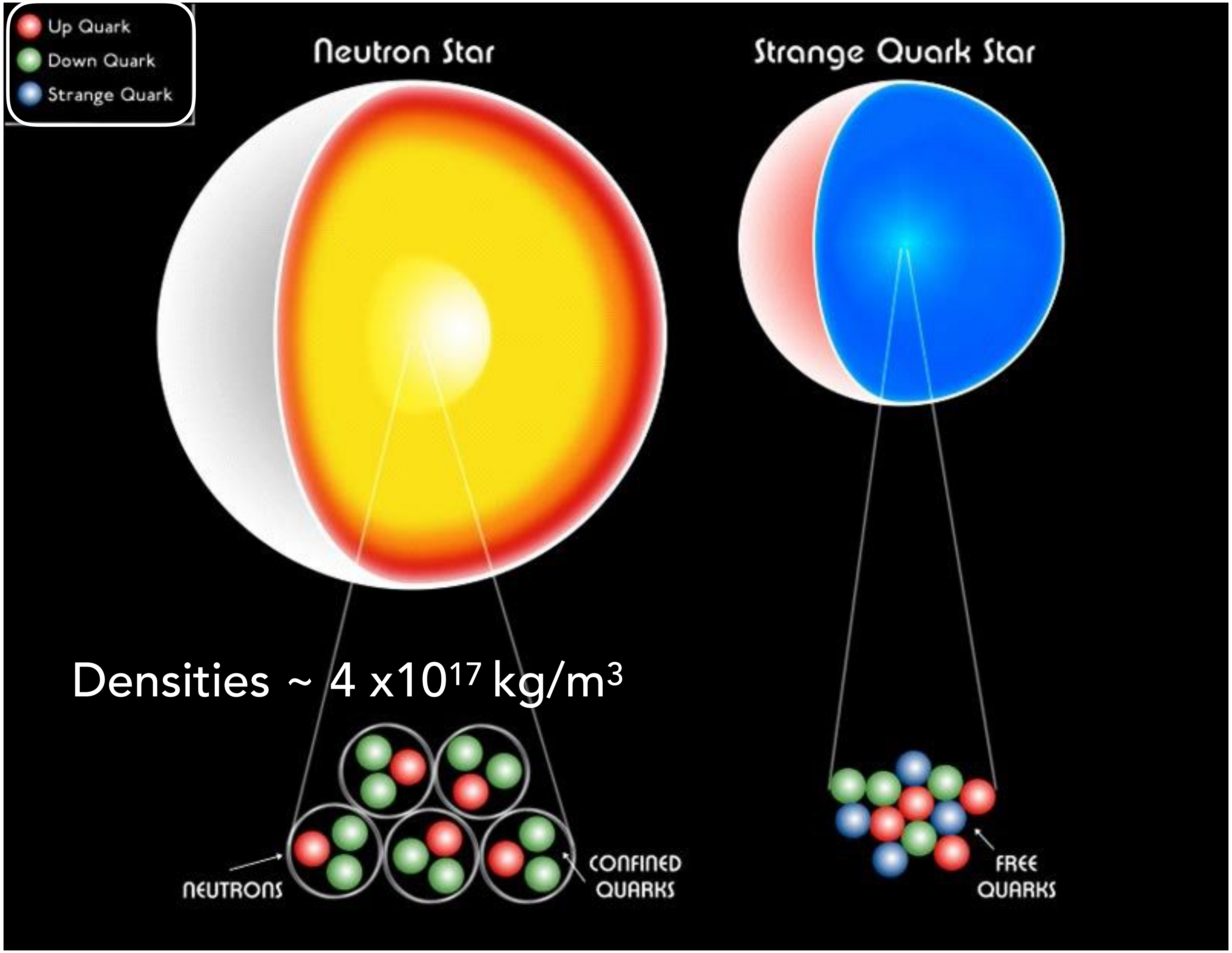
Credit: Alberto Mangiagli



EXTREME MATTER IN EXTREME ENVIRONS

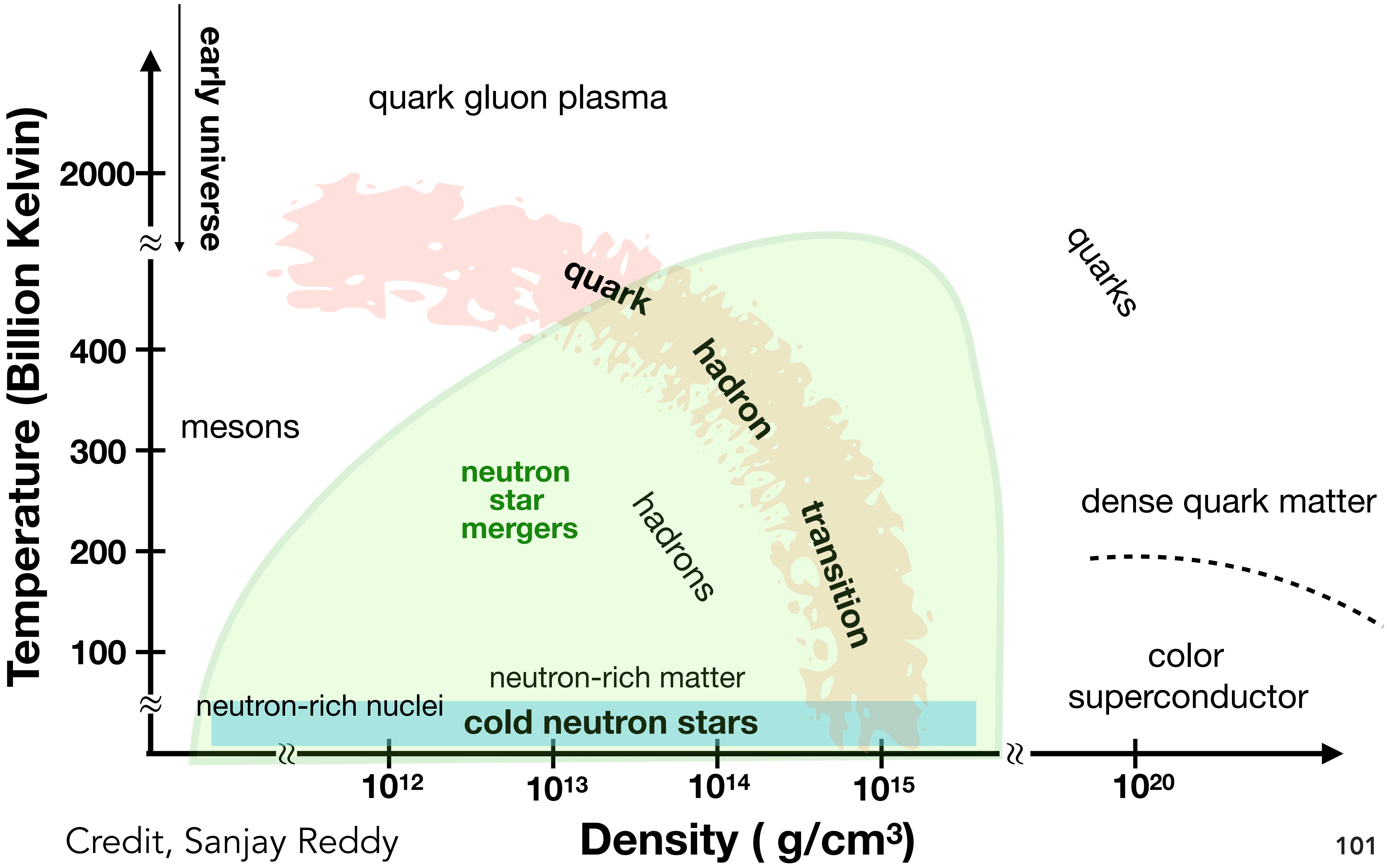
EQUATION OF STATE OF HOTTEST AND DENSEST MATTER





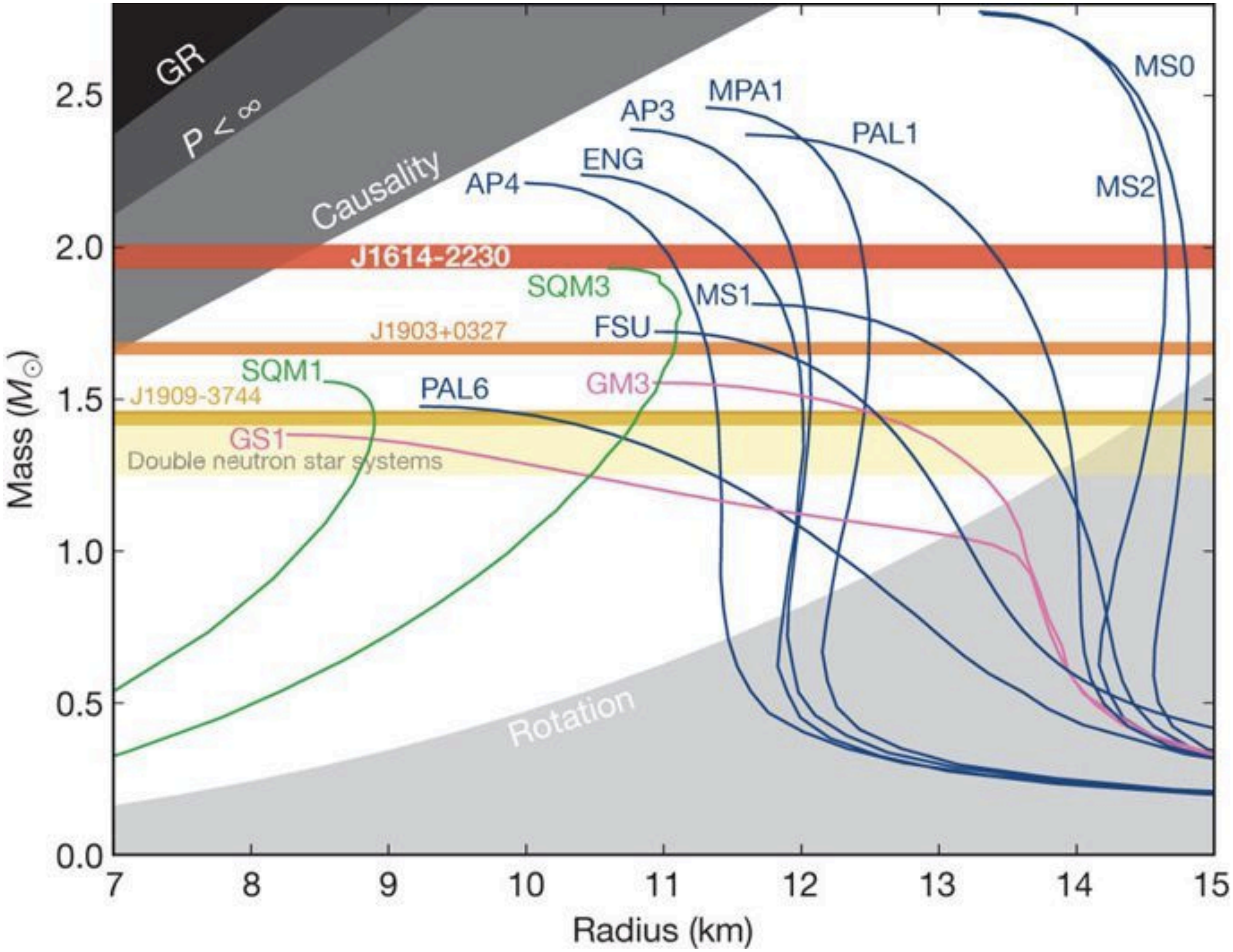
Densities ~ 4 x10^{17} kg/m^3

NEUTRON STARS IN THE QCD PHASE DIAGRAM



Credit, Sanjay Reddy

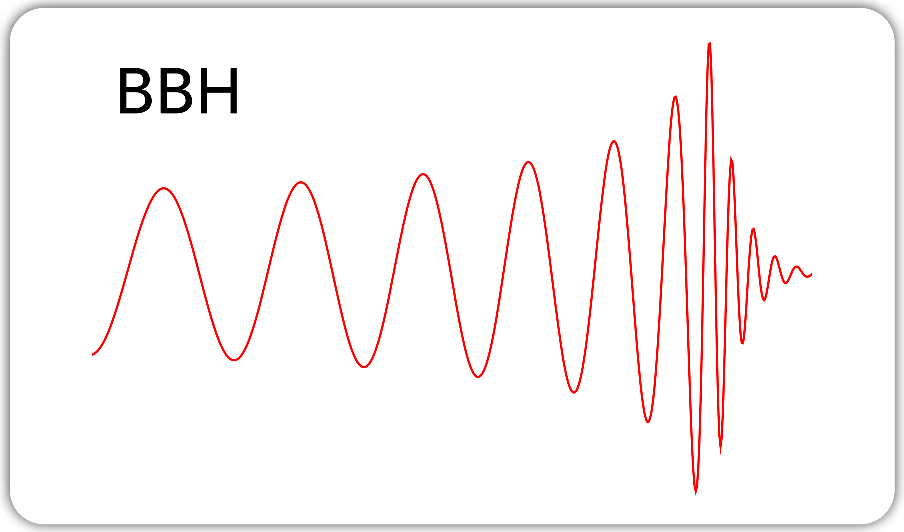
STATE OF DENSE MATTER - TOTALLY UNKNOWN



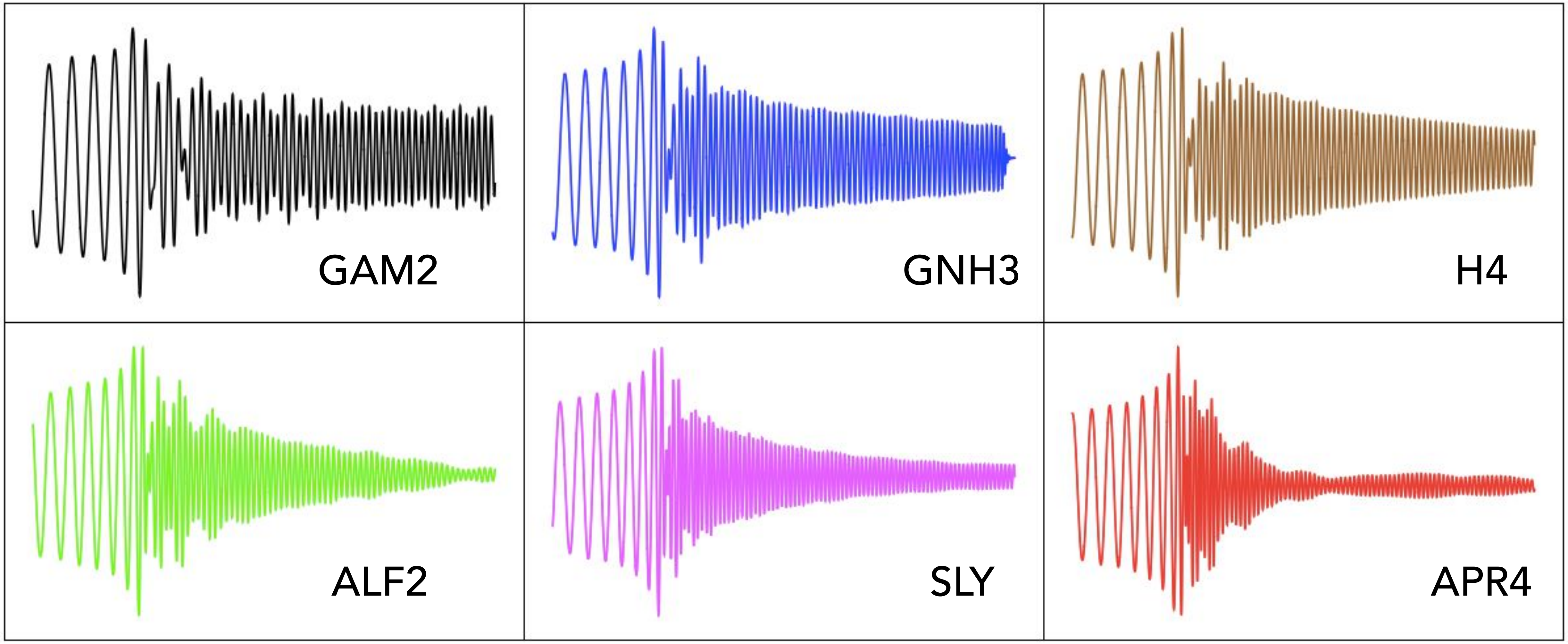
Strange quark **Nucleons plus exotic matter** **Nucleons**

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

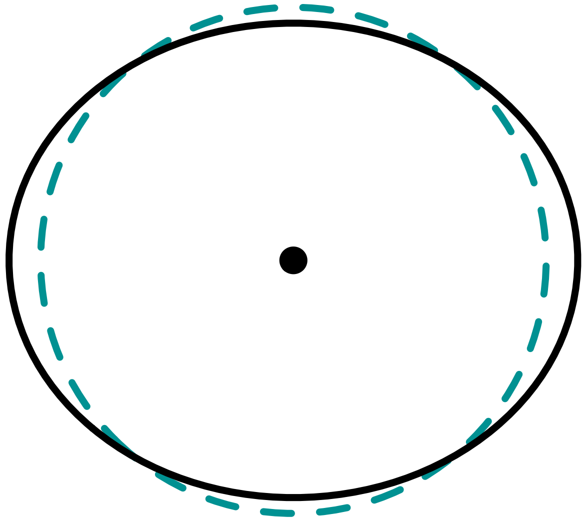


SIGNATURE OF EOS IN INSPIRAL AND POST-MERGER WAVEFORMS

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

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

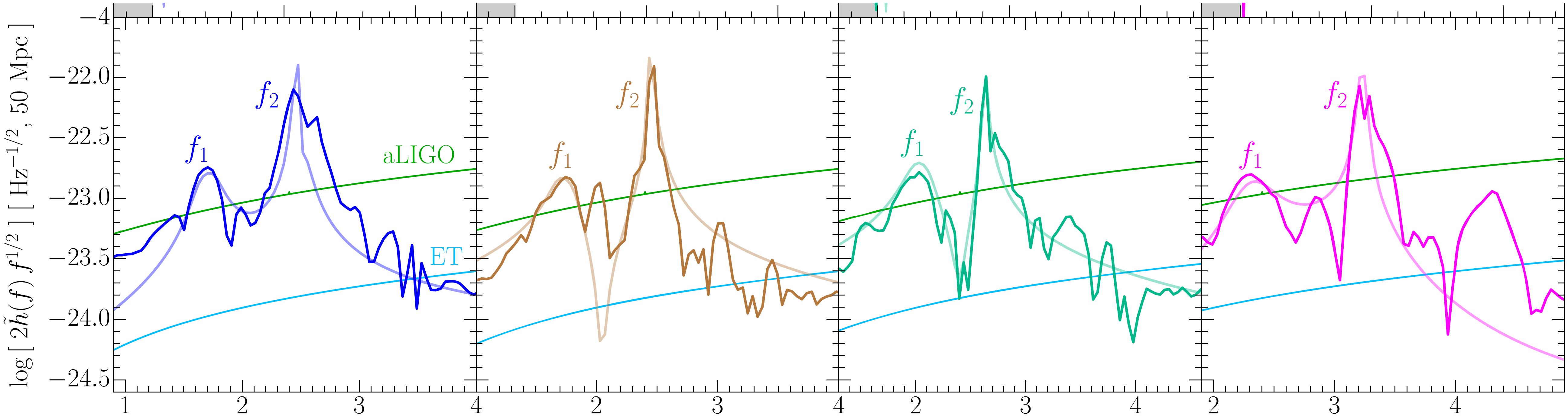
- **$\lambda(m)$** is tidal deformability, **$k_2(m)$** is the Love number and **R** is the NS radius
- post-merger oscillations, stability, extraction of radius, mass and compactness



sketch: J. Read

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

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



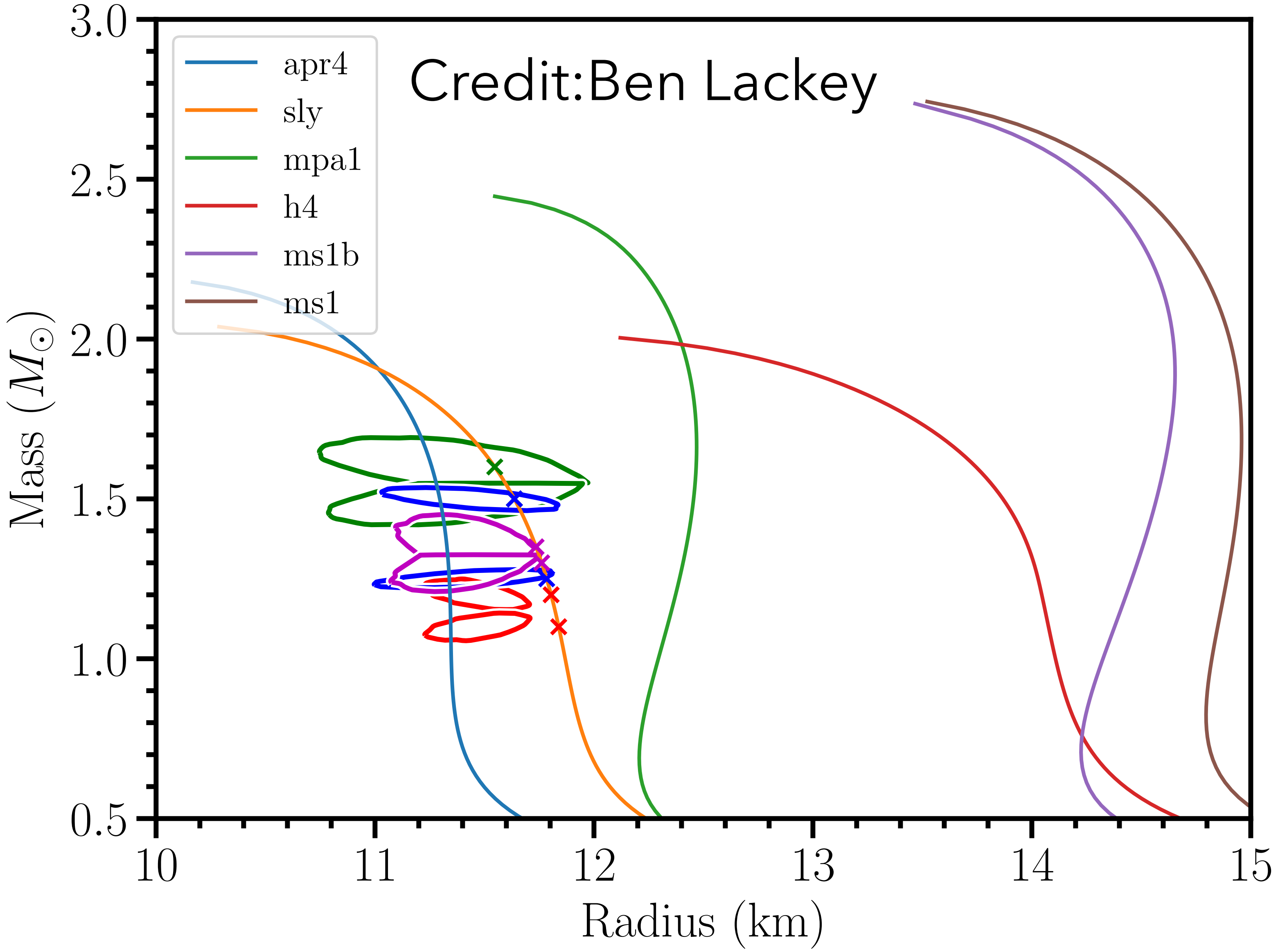
Bose+ PRL 2018

MEASUREMENT OF NEUTRON STAR RADIUS

- 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

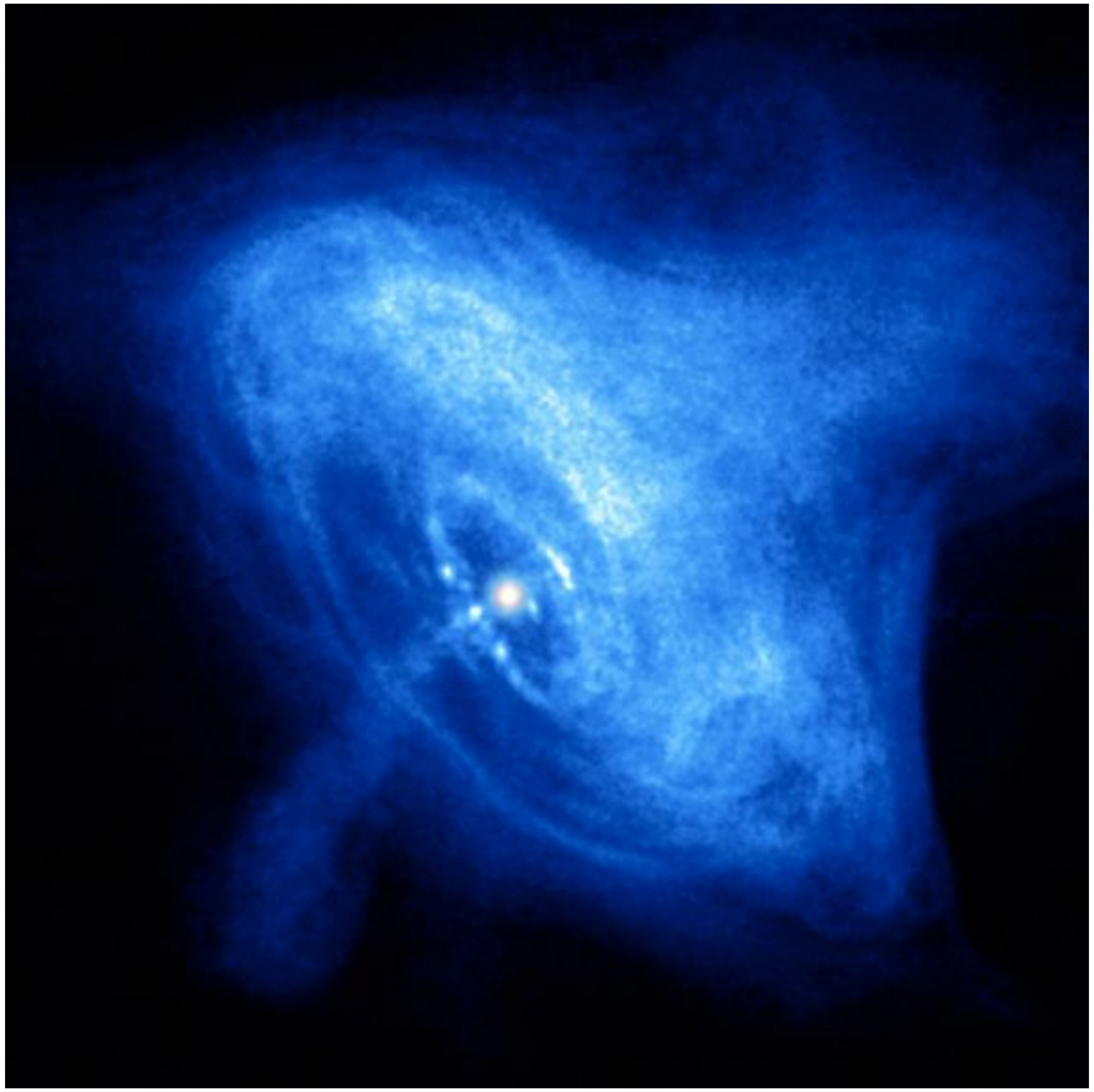
EOS with 3G



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

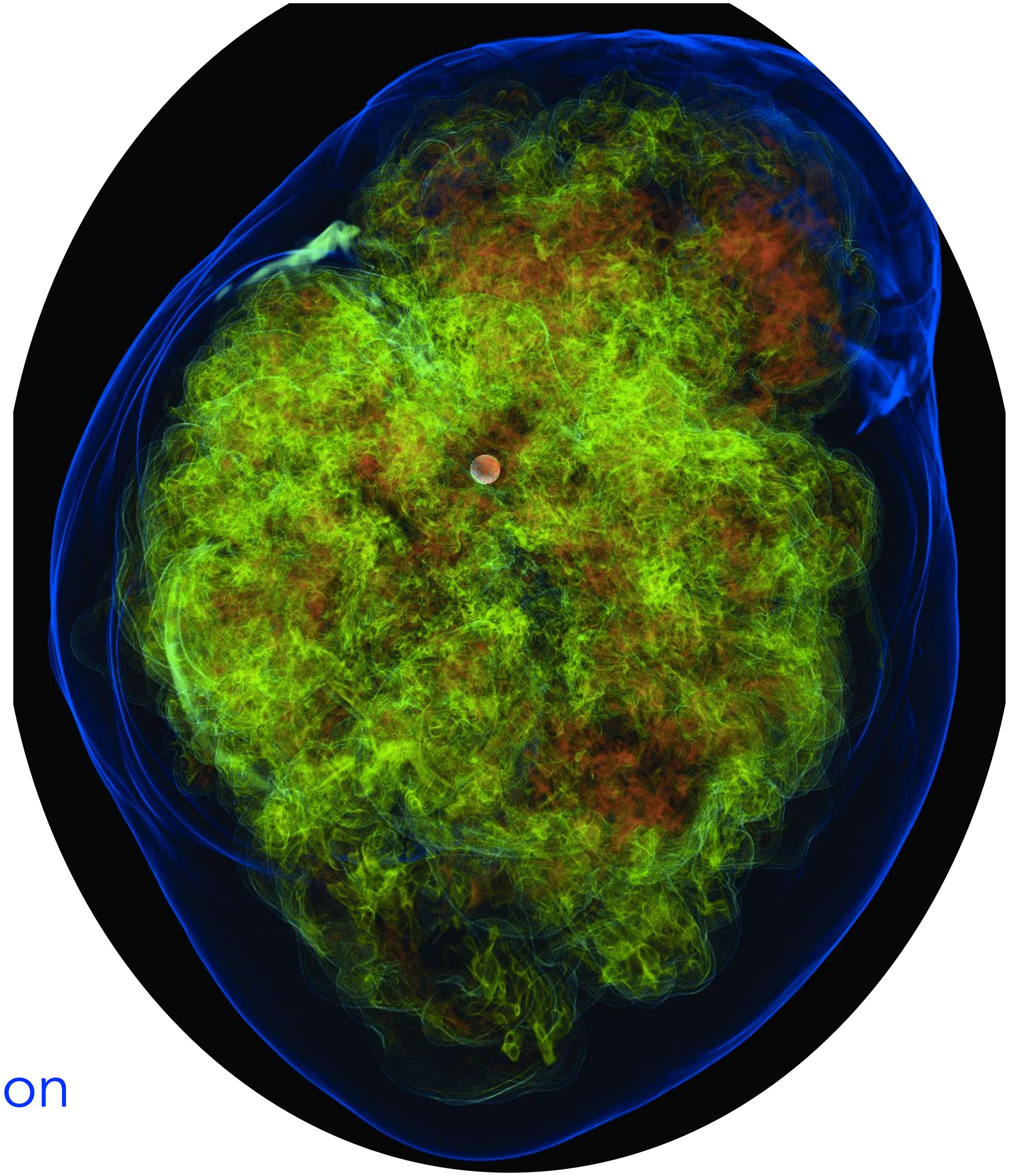


NEUTRON STAR QUAKES

- 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

SUPERNOVAE

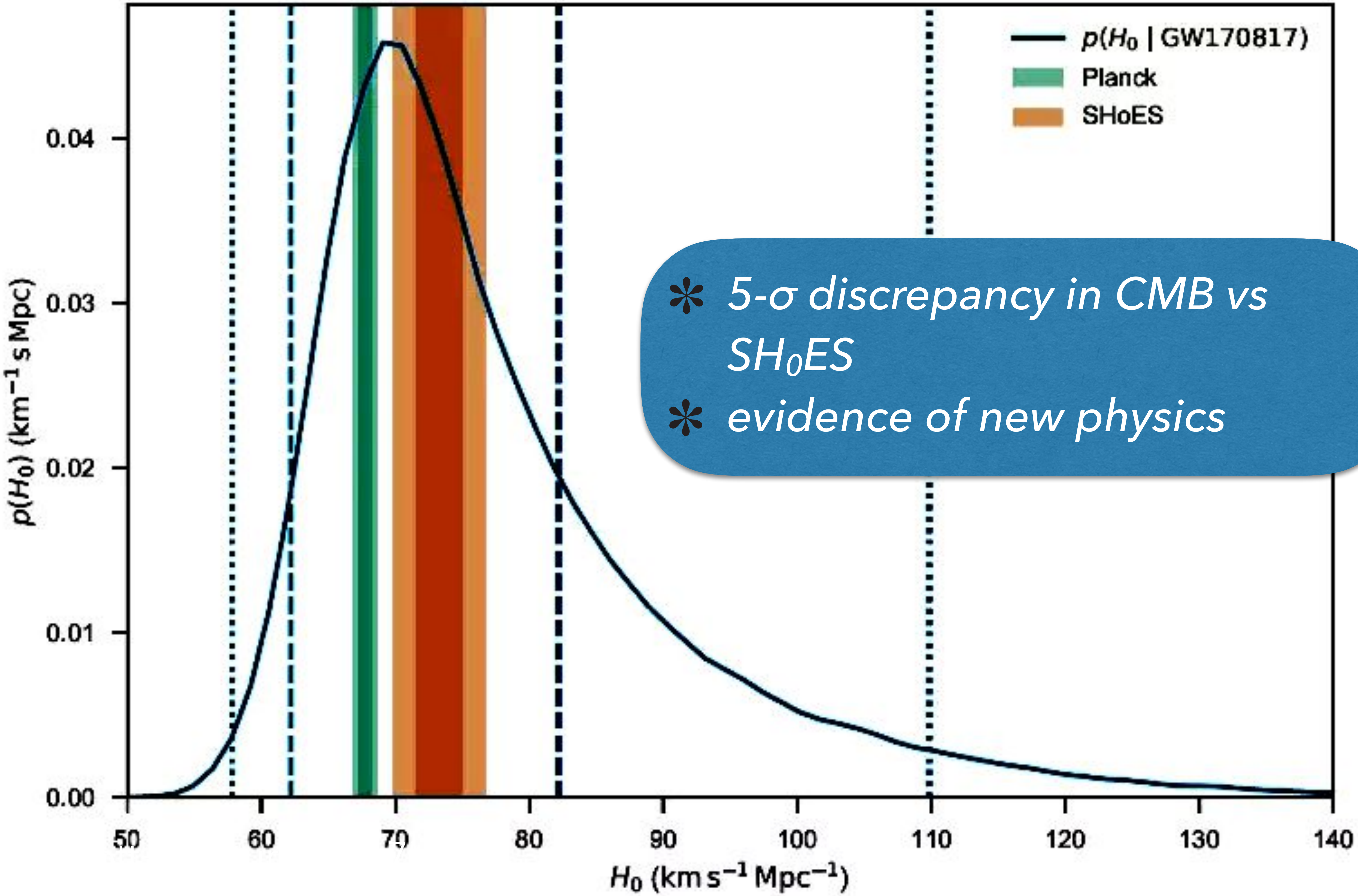
- signature of physics of supernova
  - progenitor mass
  - proto-NS core oscillation modes
  - core rotation rate
  - mass accretion rate from shock
  - geometry of collapse
- NS equation of state
  - spectrum of GW signal
  - following the phase evolution
- fate of collapse
  - neutron star vs black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



STANDARD SIREN COSMOLOGY

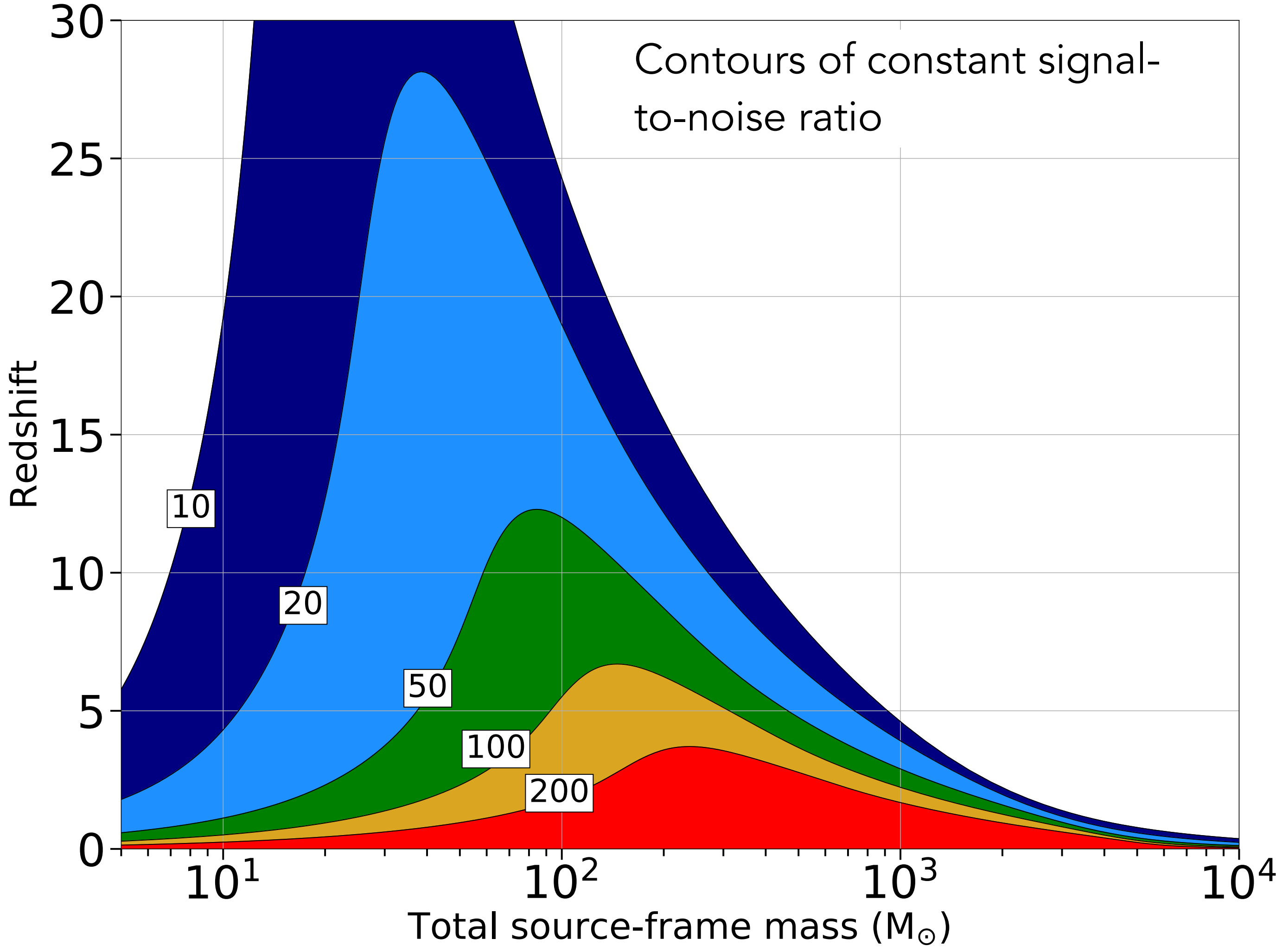
GRAVITATIONAL WAVES FROM COMPACT BINARIES ARE STANDARD SIRENS

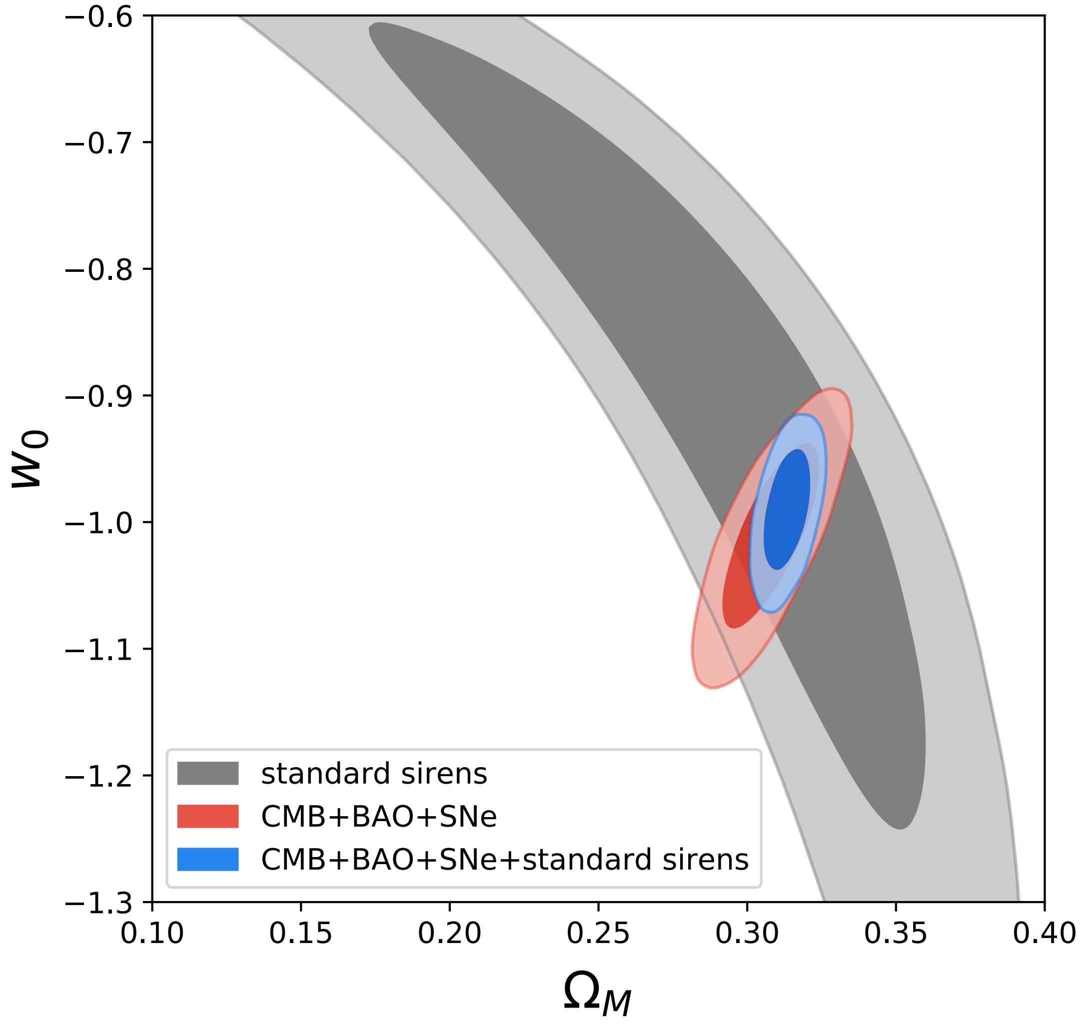
TENSION IN H_0 MEASUREMENT FROM CMB AND SH_0ES PROJECT



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

3G NETWORK WILL DETECT MILLIONS OF MERGERS

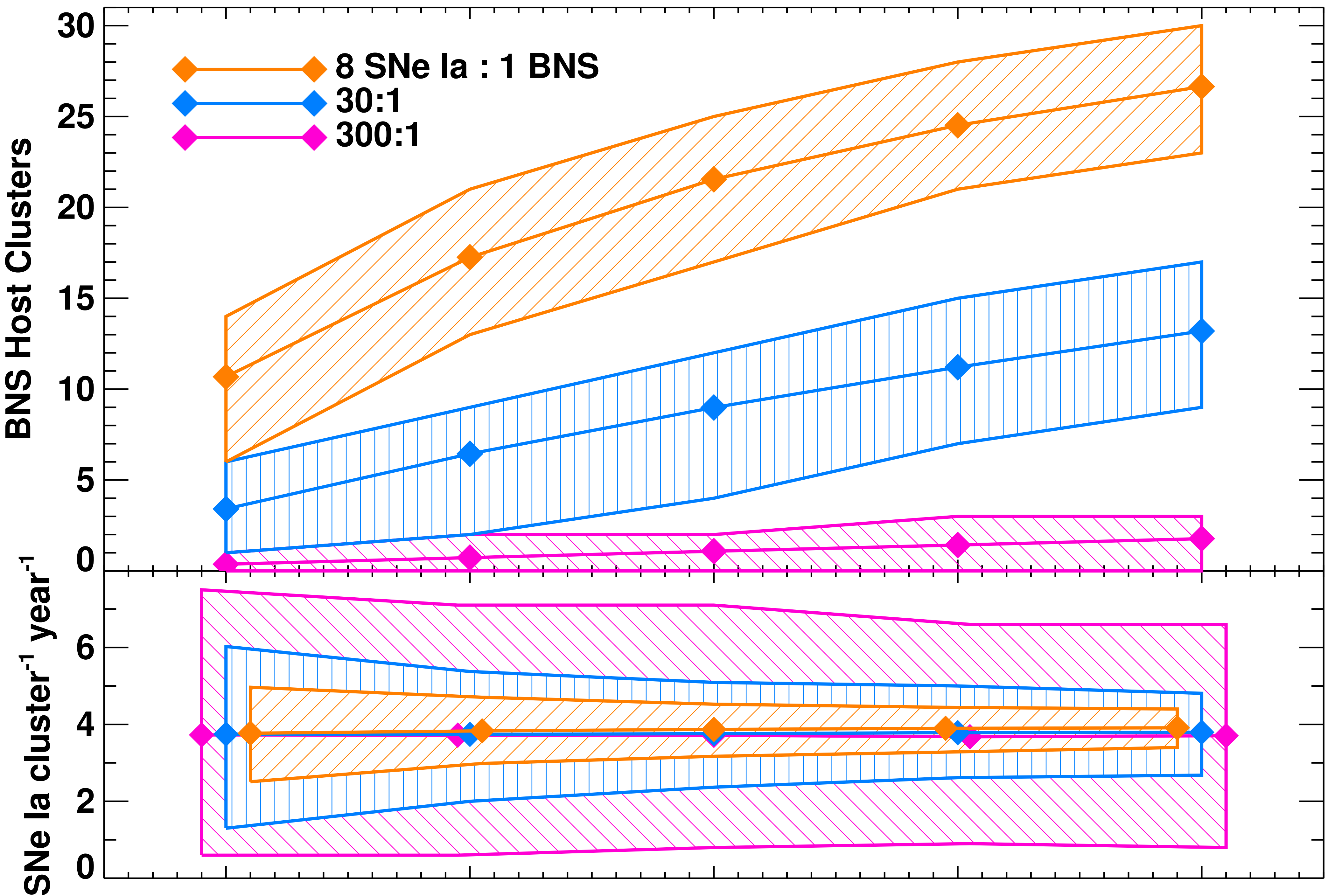


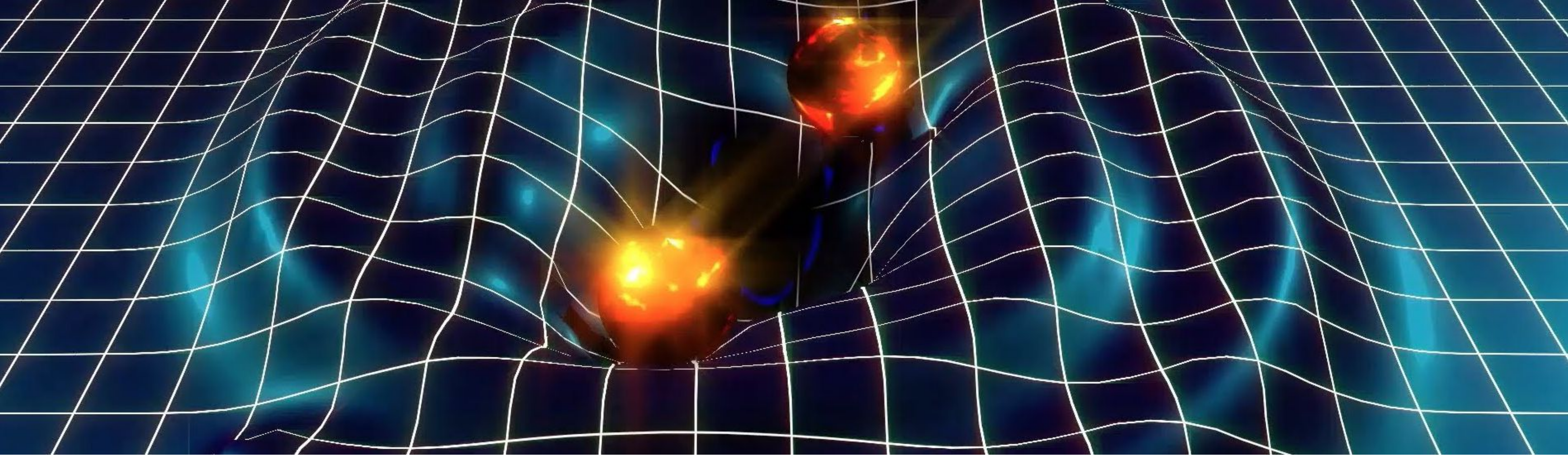


3G network will calibrate nearby supernovae, determine dark energy equation of state and its variation with redshift

DIRECT CALIBRATION OF SNe IA

Gupta+, in preparation





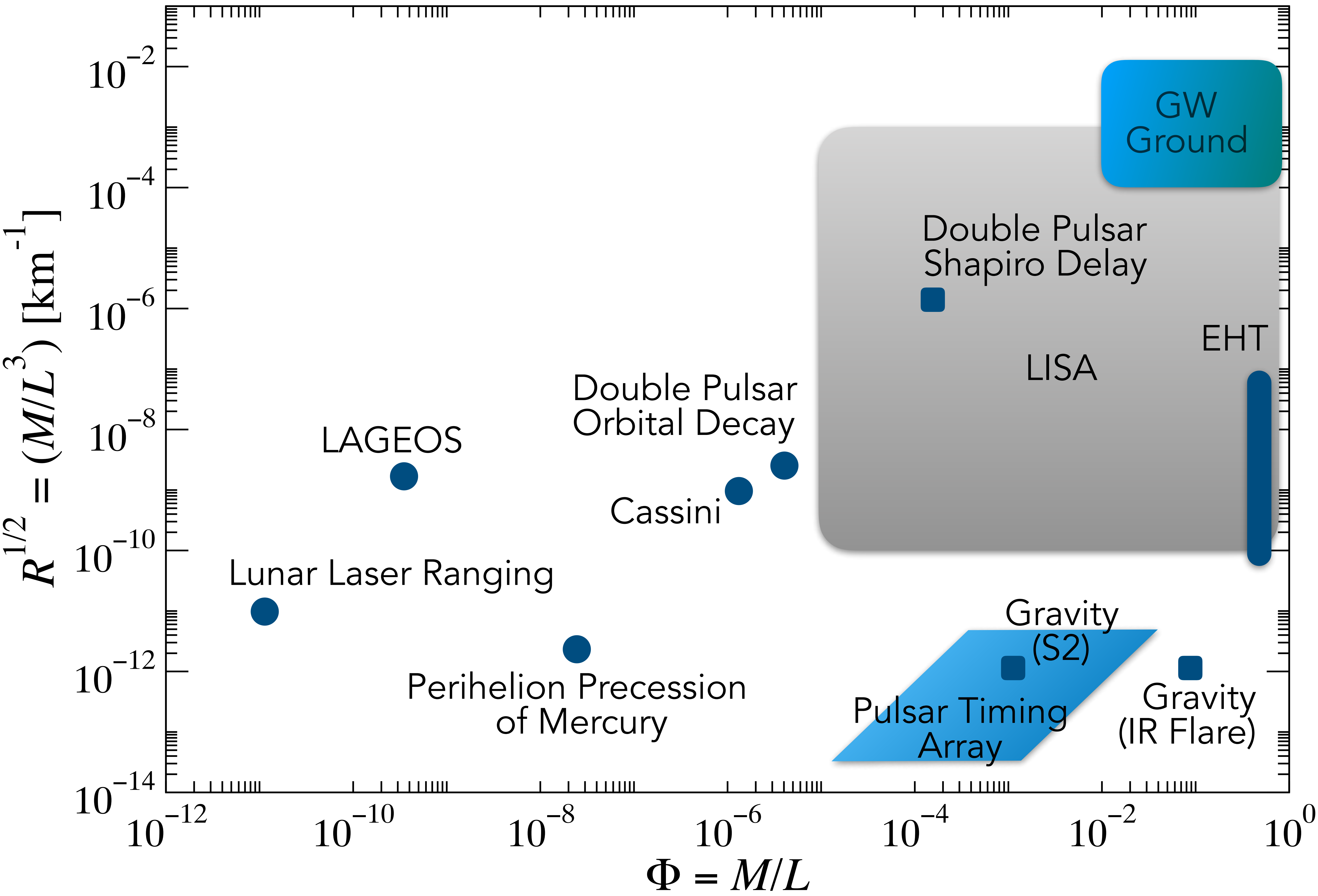
EXTREME GRAVITY AND THE NATURE OF SPACETIME

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 THE BINARY BLACK HOLE INSPIRAL DYNAMICS

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

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

(Abbott et al. arXiv:1606.04856)

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

$$\varphi_{\mathrm{Newt}} \rightarrow \varphi_{\mathrm{Newt}} + \delta\varphi_{\mathrm{Newt}}$$

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

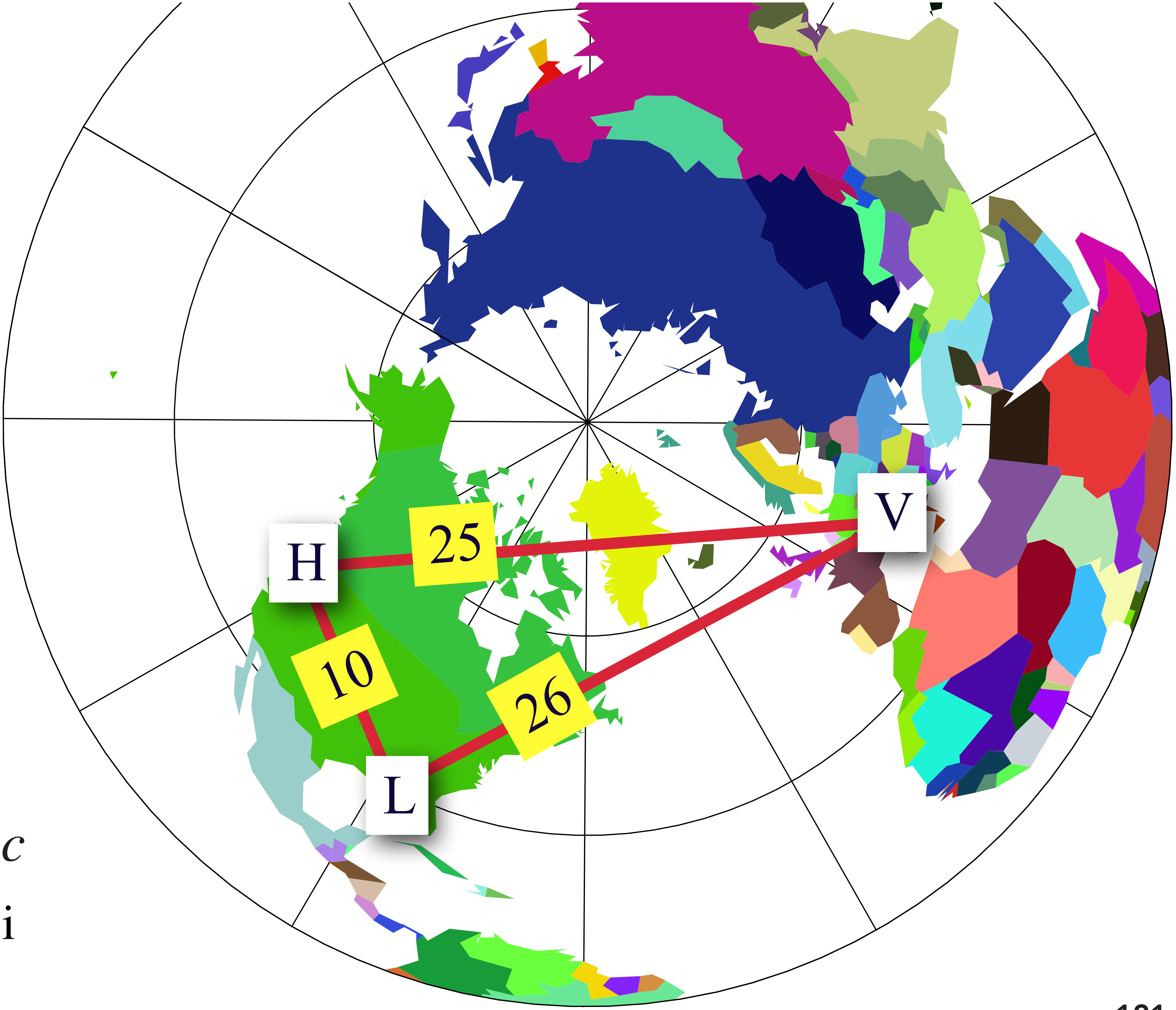
TESTS OF GRAVITATIONAL WAVE PROPAGATION

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

- 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)

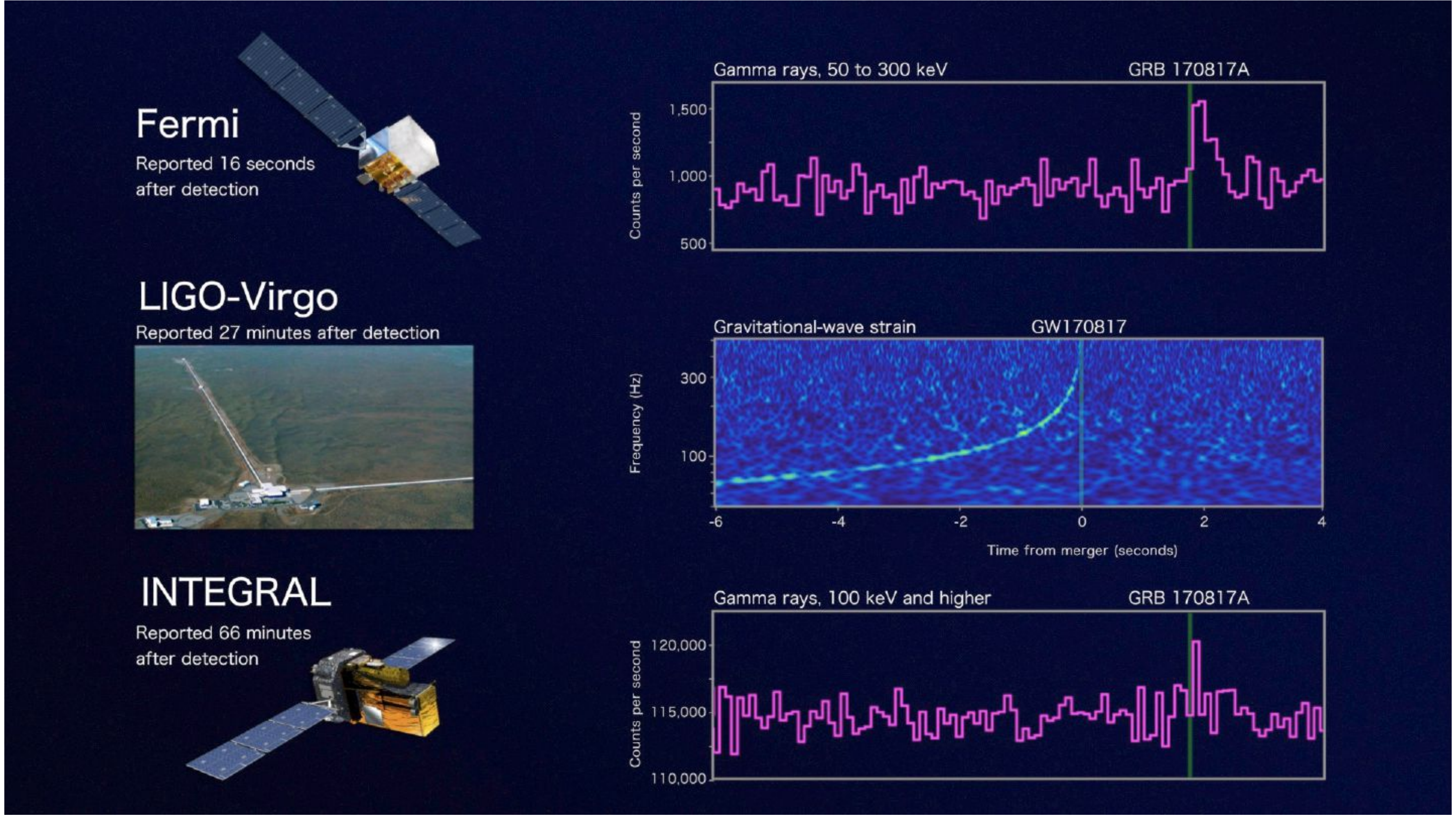
USING GW150914, GW151226, GW170104

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

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

SPEED OF GRAVITATIONAL WAVES FROM GW170817 AND GRB170817A

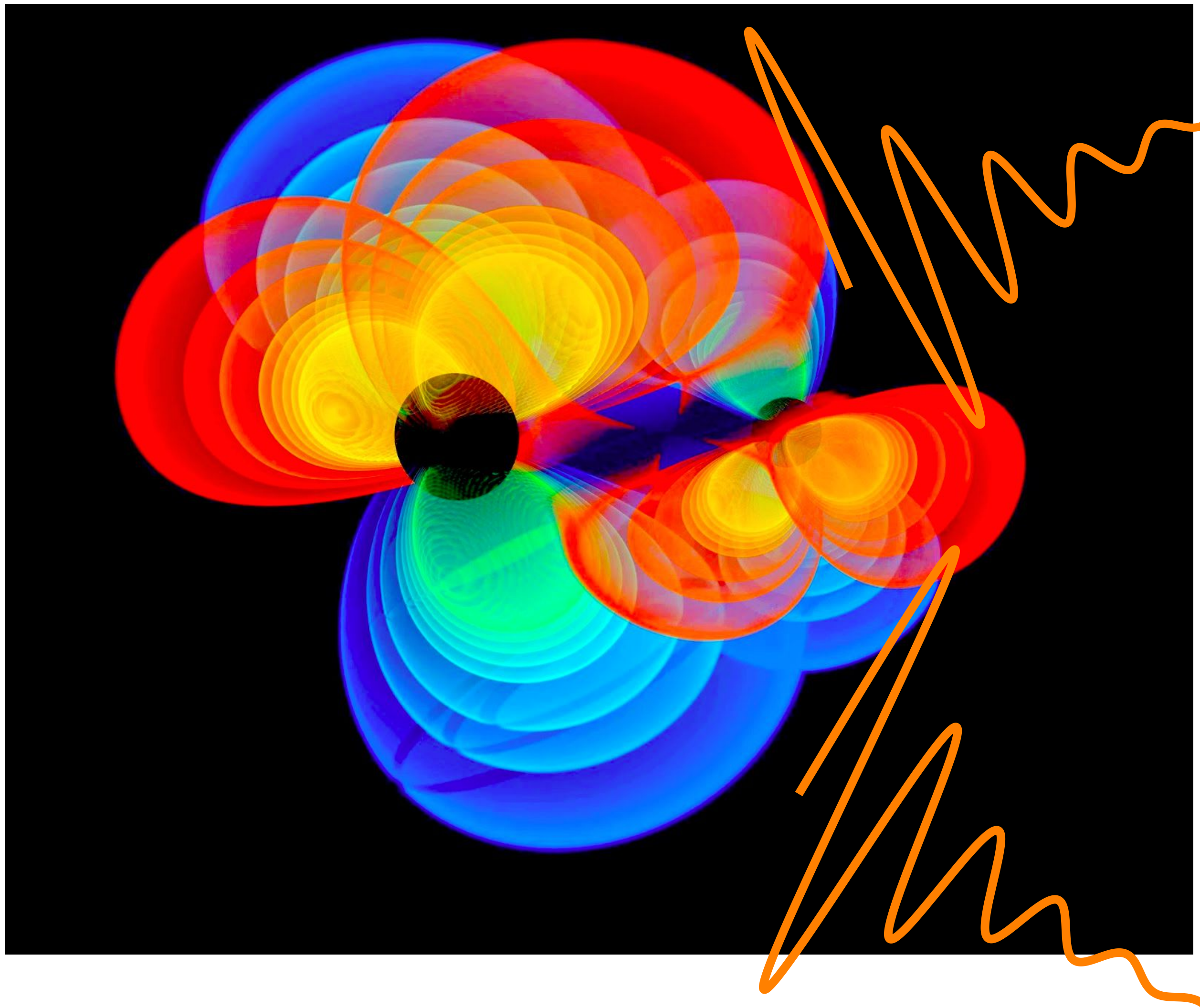
Abbott+ ApJ Letters, 848, L12 (2017)



$$-3\times10^{-15}\leq\frac{v_{\rm GW}-v_{\rm EM}}{v_{\rm EM}}\leq7\times10^{-16}$$

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

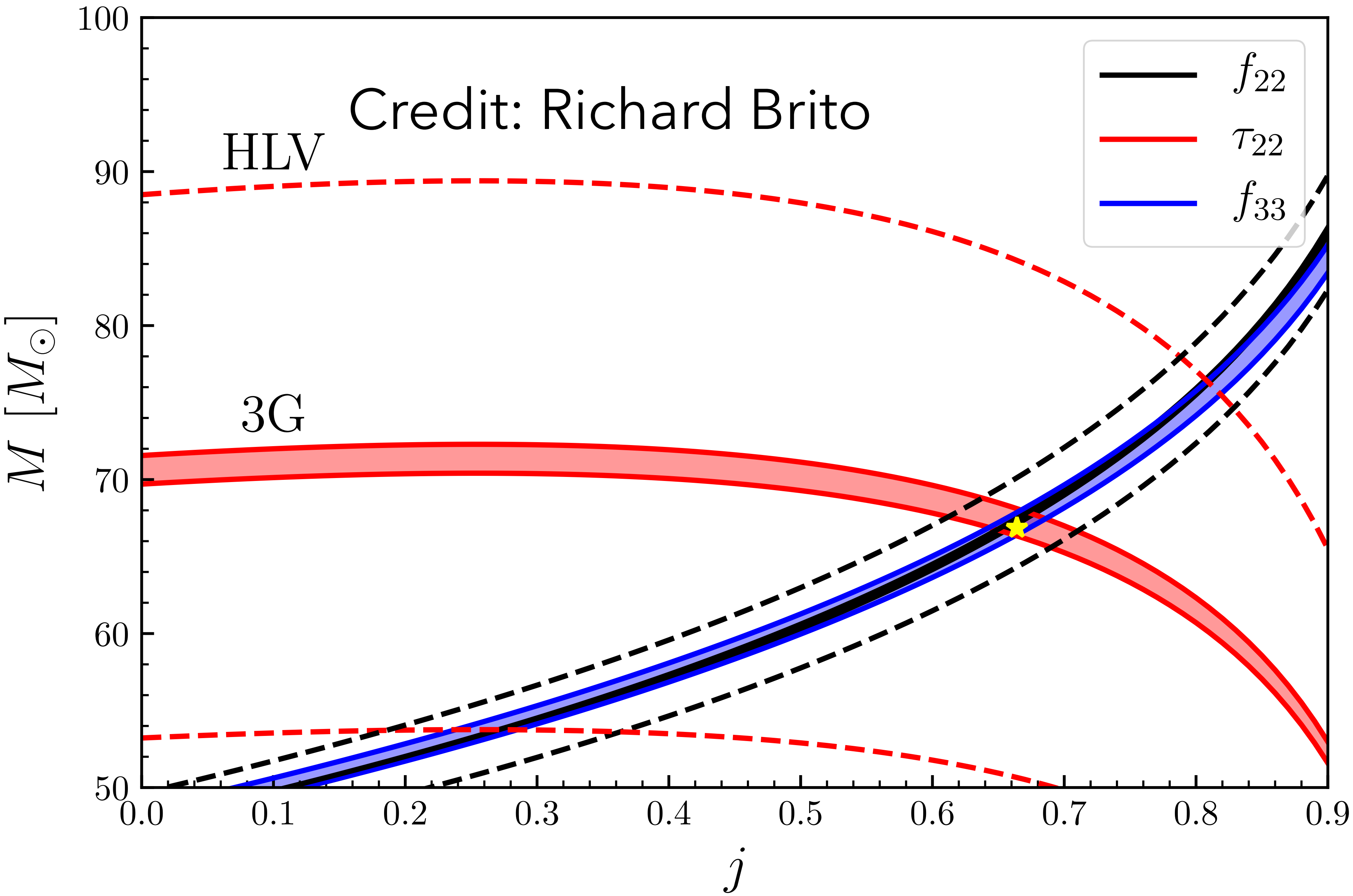
QUASI-NORMAL MODES AND NO-HAIR TESTS



- 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

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:

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

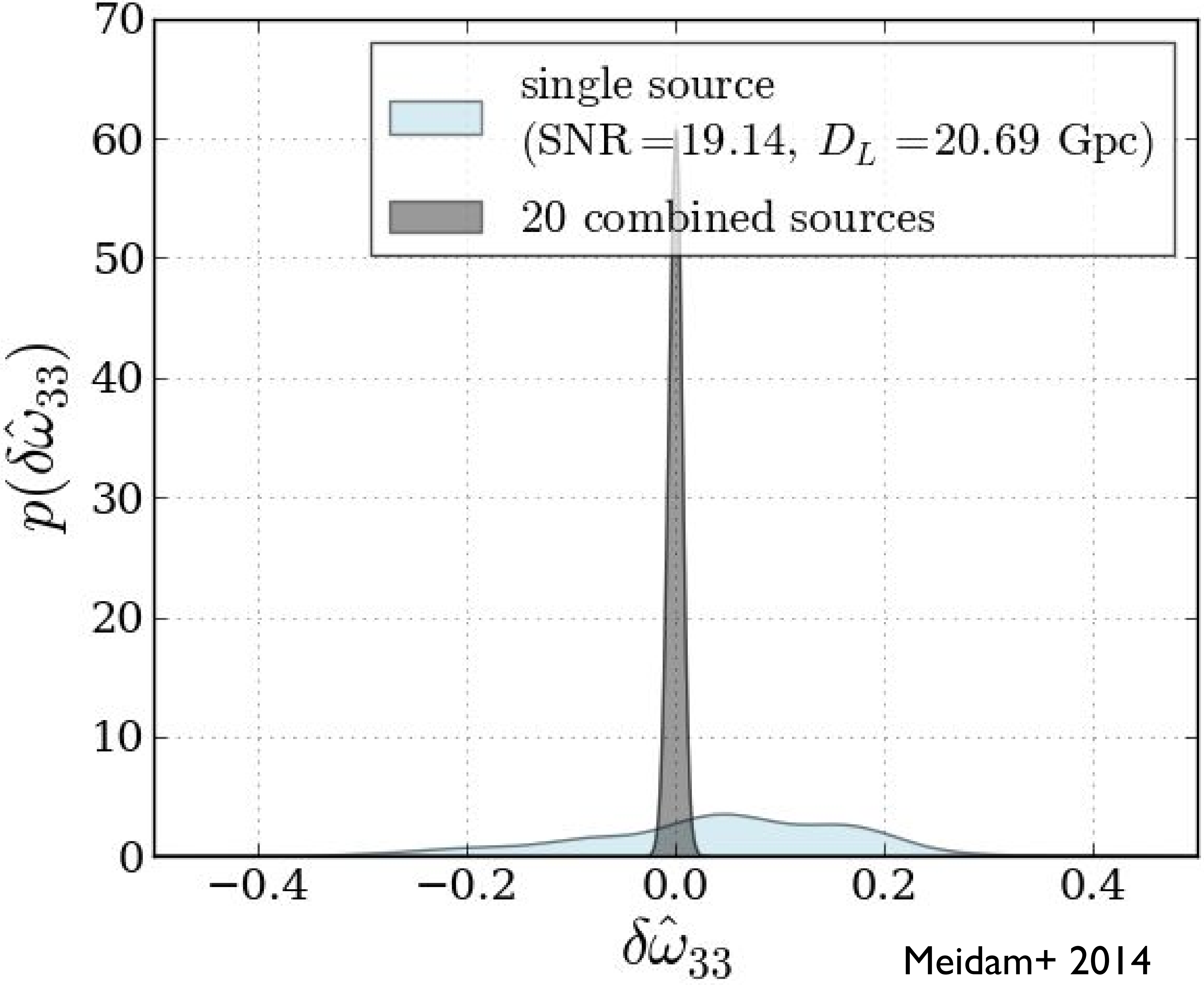
$$\begin{aligned} H_1 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{22}\}, \\ H_2 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\omega}_{33}\}, \\ H_3 &\longleftrightarrow \{\vec{\theta}_{\rm GR}, \delta\hat{\tau}_{22}\}, \\ H_{12} &\longleftrightarrow \{\vec{\theta}_{\rm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

➡

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

Gossan+ 2012, Meidam+ 2014

HOW WELL CAN WE MEASURE

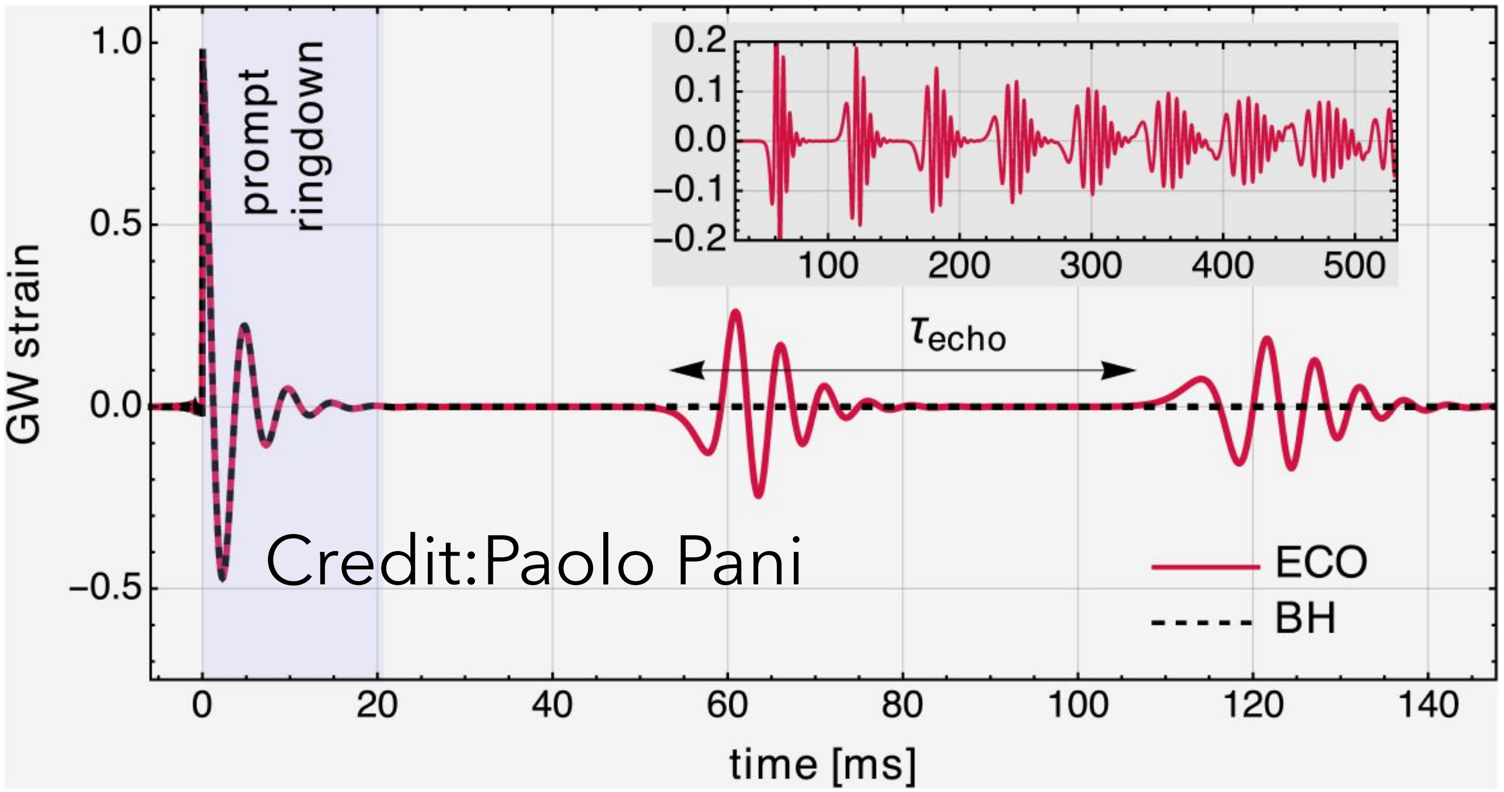


Meidam+ 2014

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



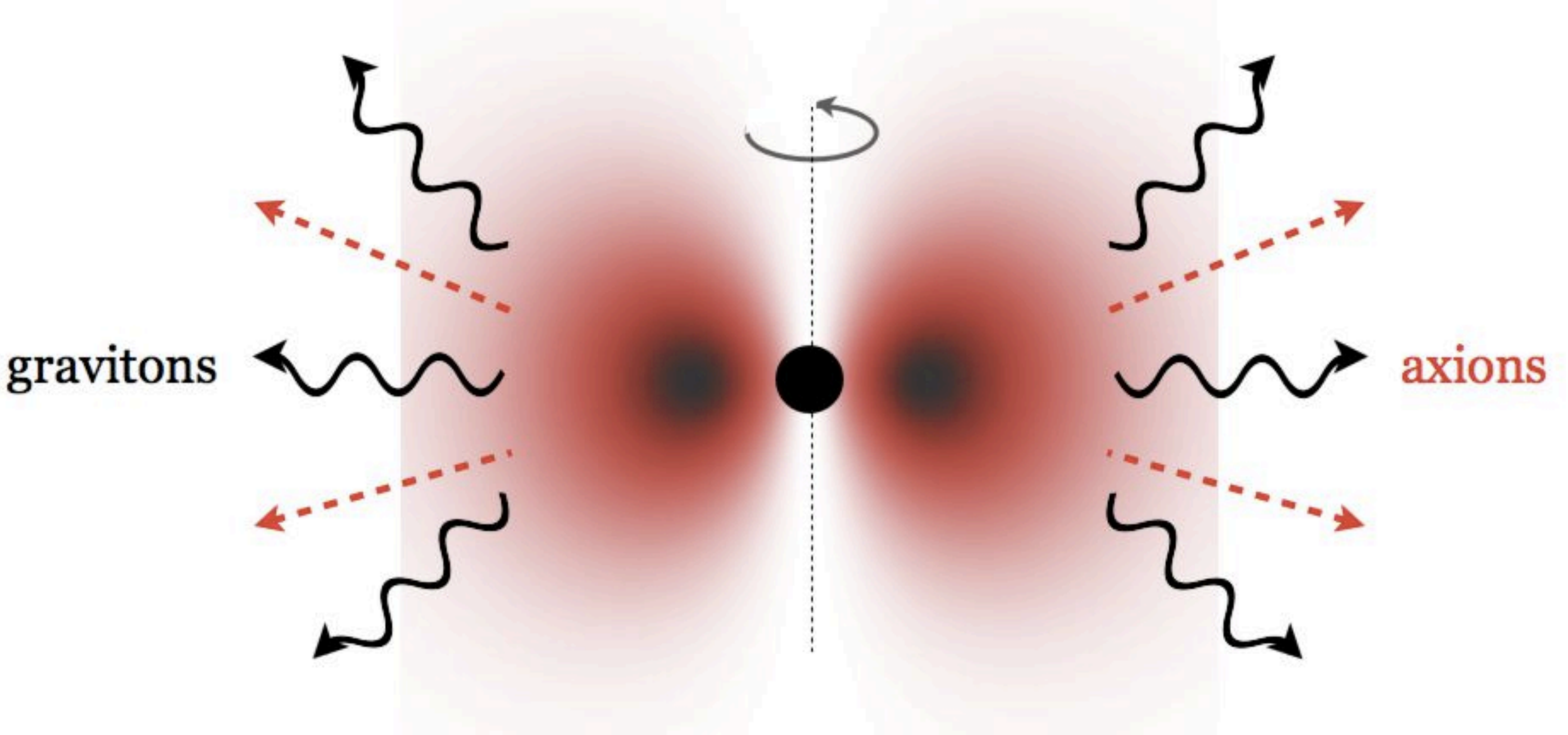
Credit:Paolo Pani

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)

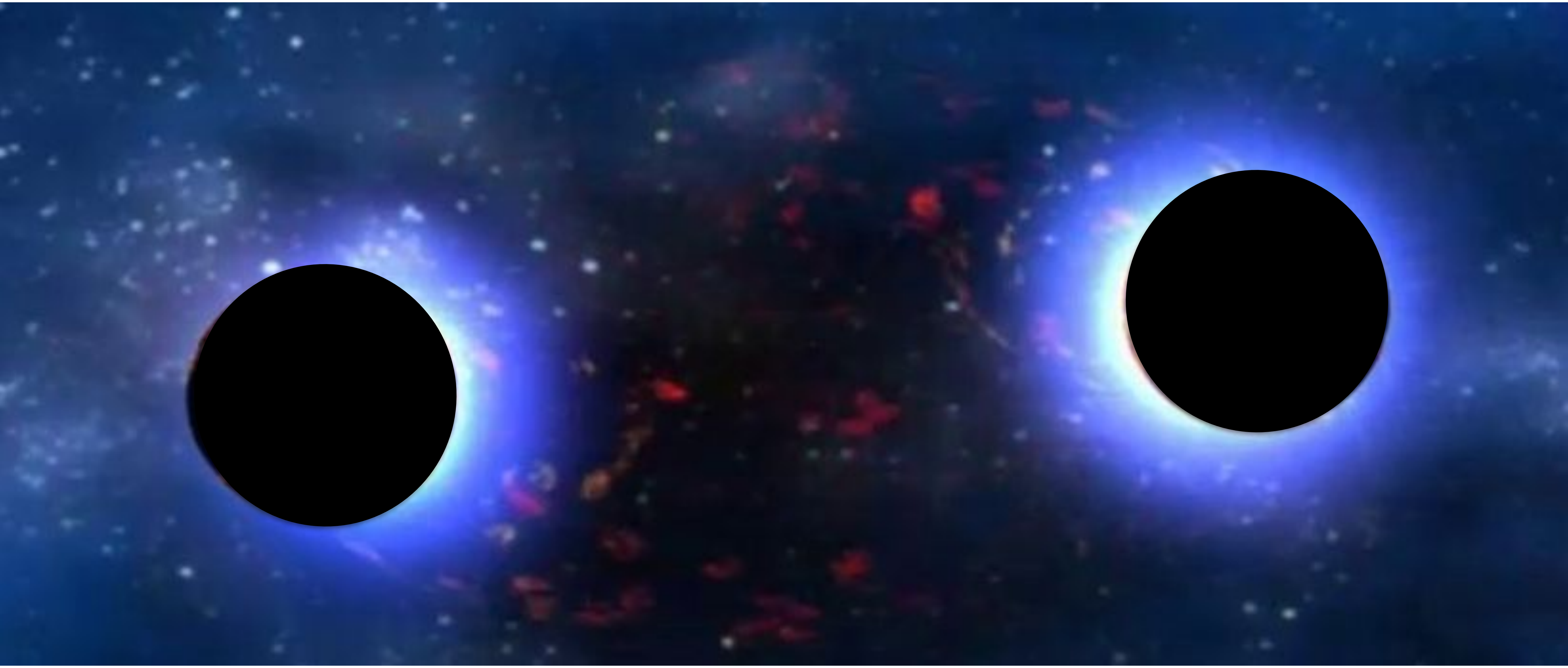


NEUTRON-STAR IMPLODING DARK MATTER

Gupta+, in preparation

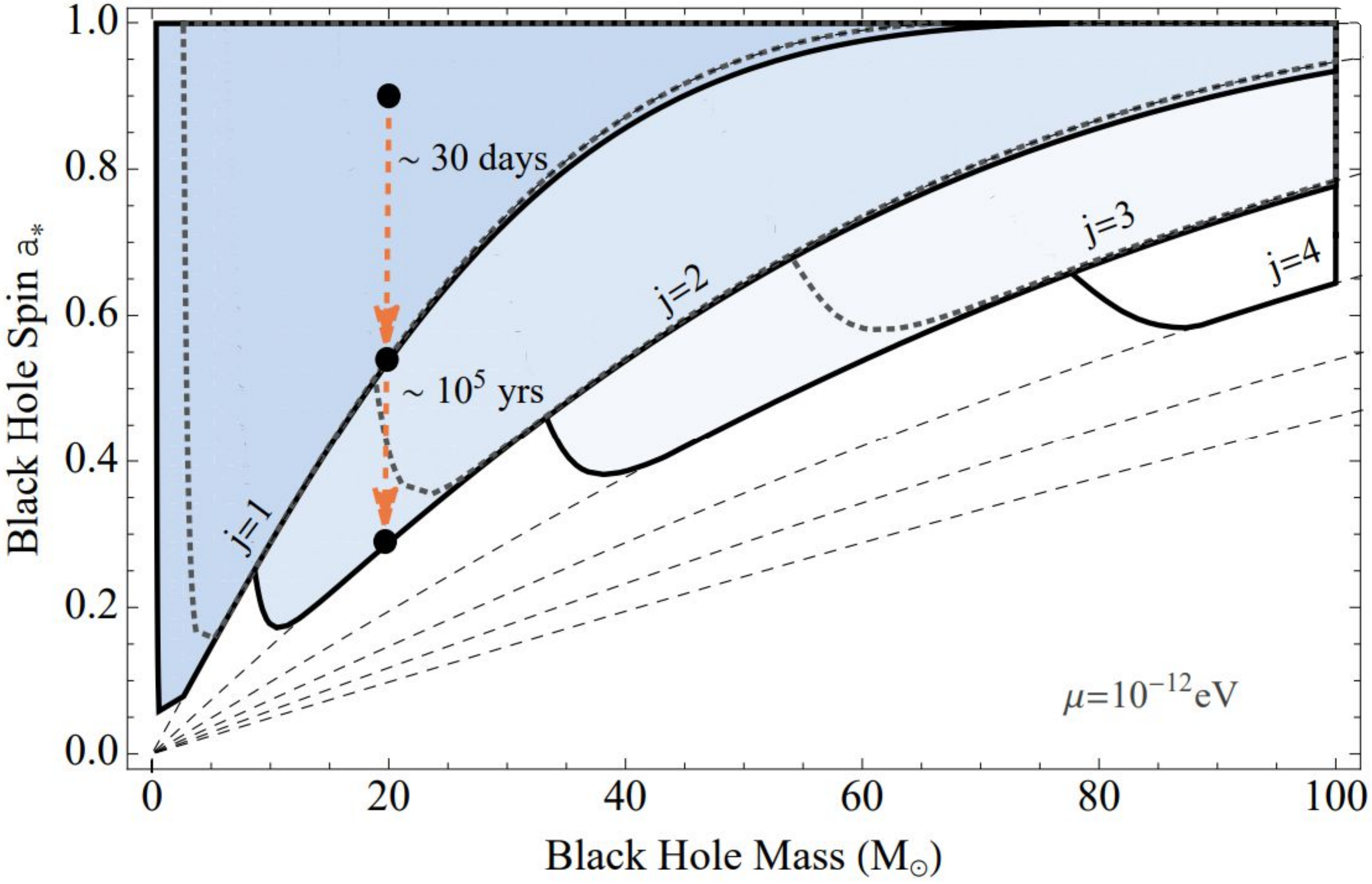
NEUTRON-STAR IMPLODING DARK MATTER

Gupta+, in preparation



GRAVITATIONAL ATOMS AND SUPER RADIANCE

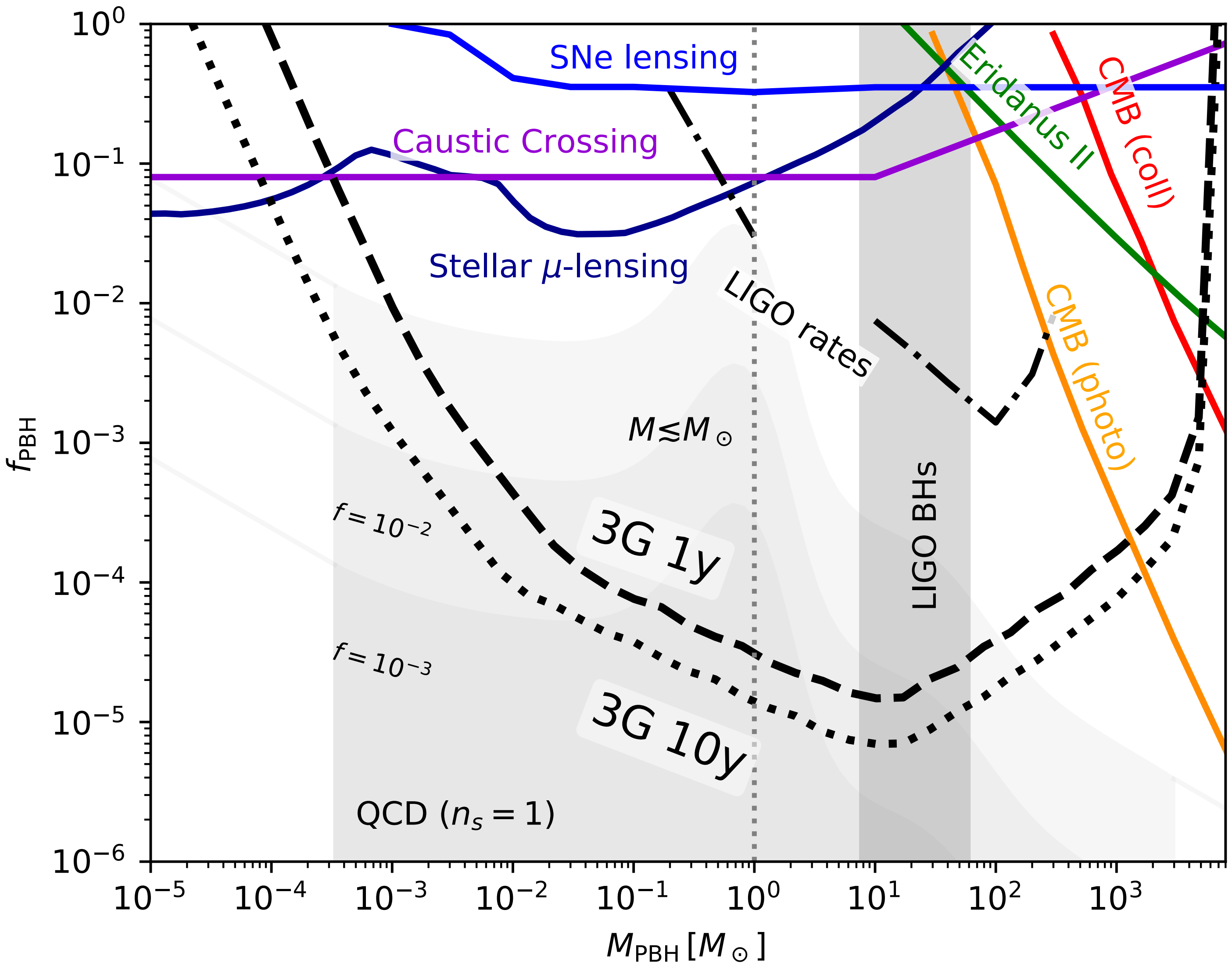
Baryakhtar+ Phys. Rev. D96 (2017)



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

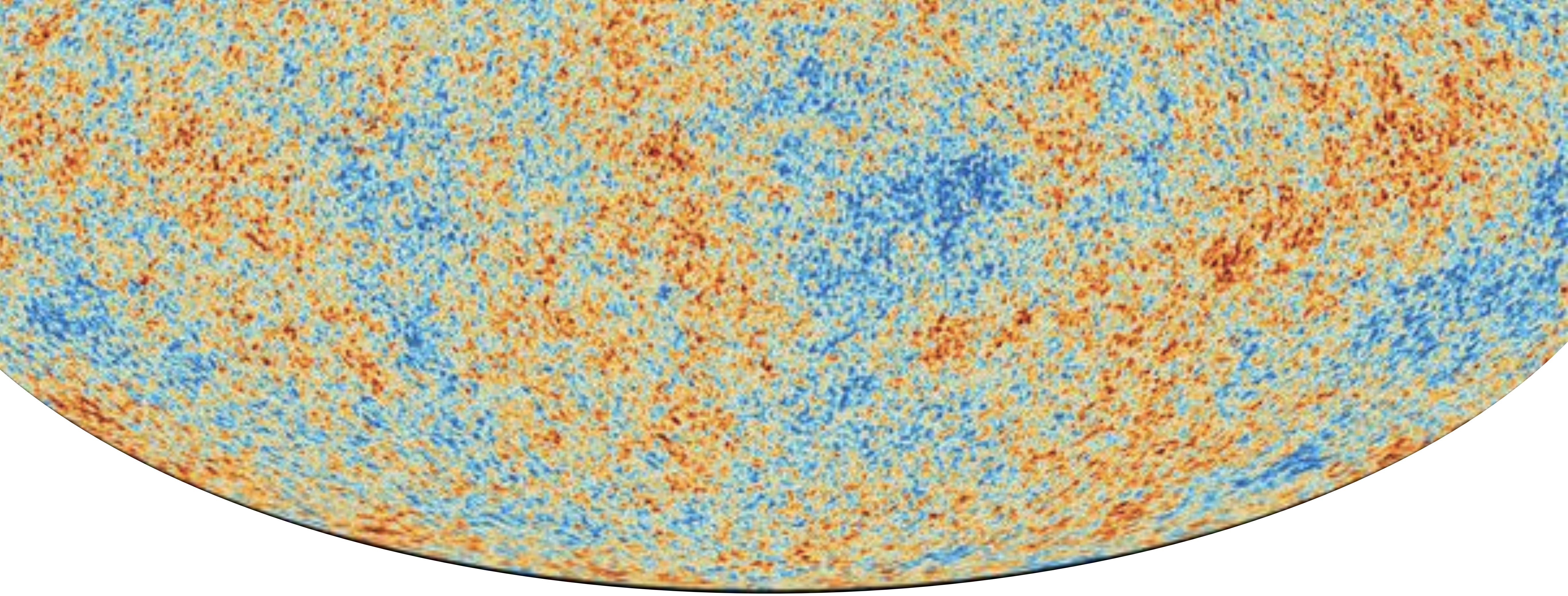
PRIMORDIAL BLACK HOLES AS DARK MATTER

- 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

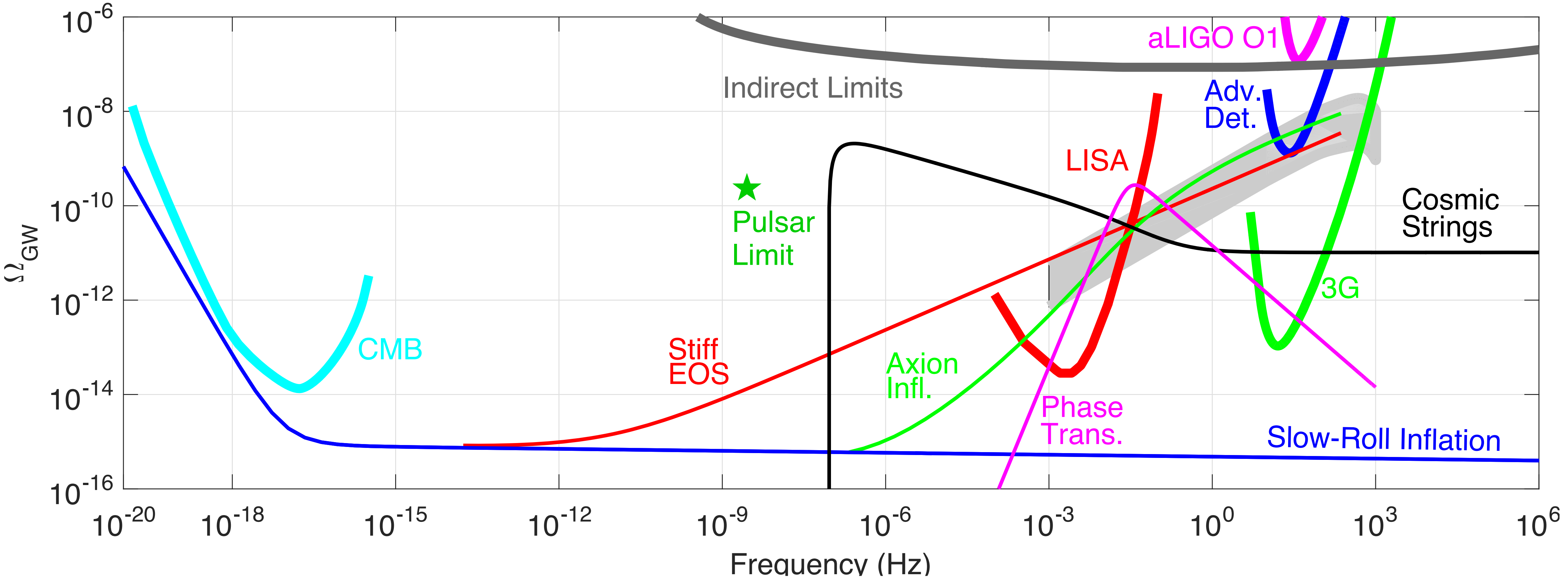
3G network would settle the question if LIGO-Virgo black holes constitute dark matter and are primordial in origin



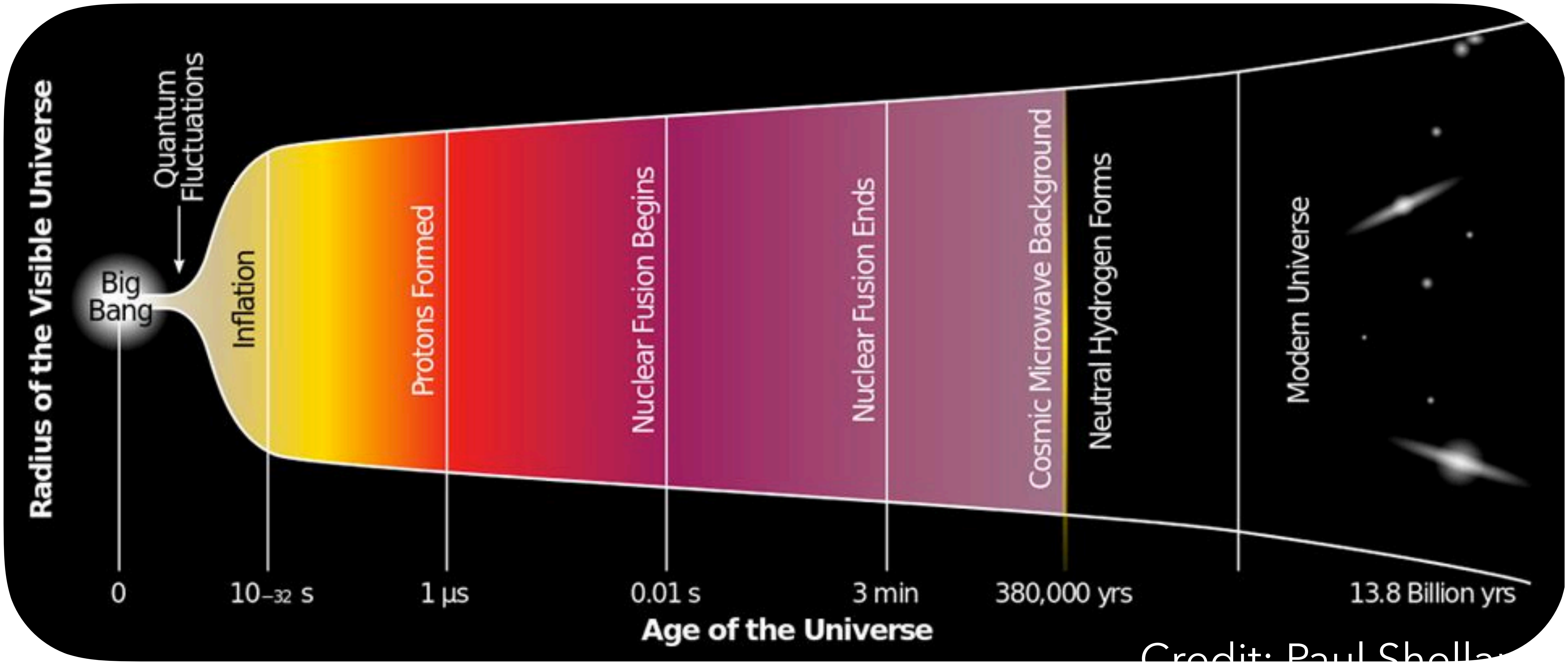
PRIMORDIAL UNIVERSE

STOCHASTIC BACKGROUND LANDSCAPE

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



EXPLORE FUNDAMENTAL PHYSICS AT HIGHEST ENERGY SCALES



Credit: Paul Shella

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

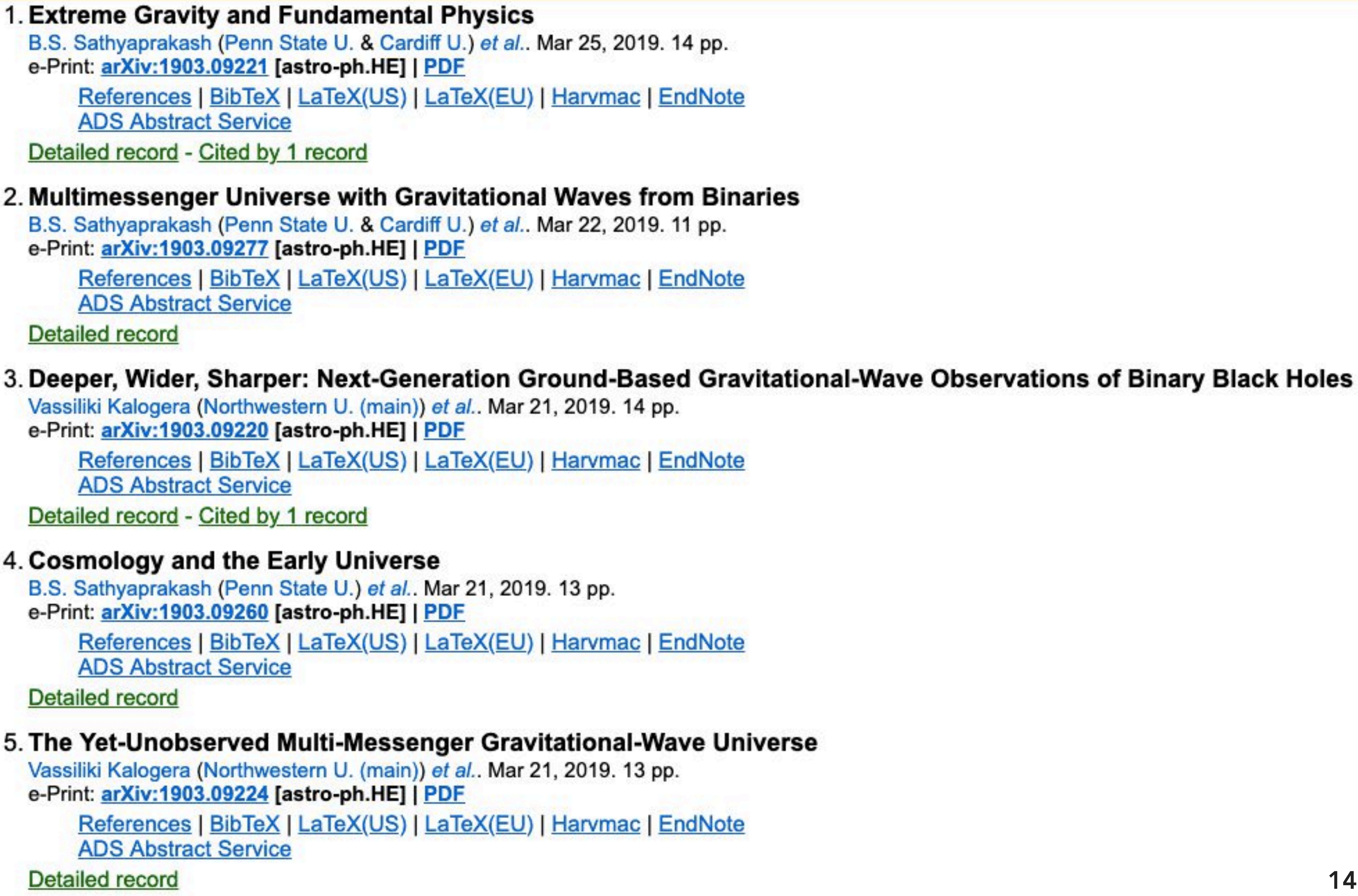
OPPORTUNITY FOR NEW DISCOVERIES

- 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

WHAT CAN GW OBSERVATIONS TEACH US?

- fundamental physics
  - equation of state of ultra dense matter, dark energy EoS
  - gravastars, wormholes, …, testing non-BH paradigms?
- astrophysics
  - formation and evolution of compact binaries, GRB engines, supernovae
- cosmology
  - primordial and astronomical GW backgrounds
  - primordial origin of black hole binaries
  - standard siren cosmography

ASTRO2020 WHITE PAPERS



1. **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

2. **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
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   Detailed record

3. **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
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   Detailed record - Cited by 1 record

4. **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
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5. **The Yet-Unobserved Multi-Messenger Gravitational-Wave Universe**
   Vassiliki Kalogera (Northwestern U. (main)) *et al.*. Mar 21, 2019. 13 pp.
   e-Print: **arXiv:1903.09224** **[astro-ph.HE]** | **PDF**
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清華大学

Tsinghua University

Université de Montréal

MONASH University

UIB Universitat de les Illes Balears

INTERNATIONAL INSTITUTE OF PHYSICS

Federal University of Rio Grande do Norte

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BELLEVUE COLLEGE

MONTANA STATE UNIVERSITY

UNIVERSITY OF CAMBRIDGE

UNIVERSITY OF Southampton

POLYTECHNIQUE MONTRÉAL

LE GÉNIE EN PREMIÈRE CLASSE

THE UNIVERSITY OF ADELAIDE AUSTRALIA

NCSA

UNIVERSITY of WISCONSIN UWMILWAUKEE

UNIVERSITY OF THE WEST of SCOTLAND UWS

W BOTHELL

MICHIGAN

ACU

TRINITY UNIVERSITY

Australian National University

UNIVERSITY OF STRATHCLYDE

University of Glasgow

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

LOMONOSOV MOSCOW STATE UNIVERSITY

SYRACUSE UNIVERSITY FOUNDED AD 1870

OzGrav

CARDIFF UNIVERSITY

PRIFYSGOL CAERDYDD

THE UNIVERSITY OF WESTERN AUSTRALIA

R·I·T

SONOMA STATE UNIVERSITY

PAH

UNIVERSITY OF MINNESOTA

CARLETON COLLEGE NORTHFIELD, MINN. A.D. 1866

RRCAT

CORNELL UNIVERSITY FOUNDED A.D. 1865

NASA

THE UNIVERSITY OF CHICAGO

IIT Hyderabad

UNIVERSITY OF WASHINGTON

Università degli Studi del Sannio

LSU LOUISIANA STATE UNIVERSITY

Colorado State University

CHARLES STURT UNIVERSITY

Marshall Space Flight Center

CHENNAI MATHEMATICAL INSTITUTE

東京大学

THE UNIVERSITY OF TOKYO

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ICTS INTERNATIONAL CENTRE for THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

UNIVERSITY OF BIRMINGHAM

Georgia Institute of Technology

Korean Gravitational-Wave Group

UH Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

THE UNIVERSITY OF MELBOURNE

EMBRY-RIDDLE Aeronautical University

UNIVERSITAS VILLANOVANA IN STATU PENNSYLVANIAE 1842

WHITMAN COLLEGE

Northwestern

UF UNIVERSITY of FLORIDA

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THE PURI FOUNDATION FOR EDUCATION IN INDIA

SWINBURNE UNIVERSITY OF TECHNOLOGY

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INPE

UNIVERSITY OF SOUTHERN CALIFORNIA 1880

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Max Planck Institute for Gravitational Physics

ALBERT EINSTEIN INSTITUTE

Leibniz Universität Hannover

University of Zurich

IISER THIRUVANANTHAPURAM

CITA ICAT

Canadian Institute for Theoretical Astrophysics

L'institut Canadien d'astrophysique théorique

KING'S College LONDON

IISER KOLKATA

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