GRAVITATIONAL WAVES: observational forays into fundamental physics

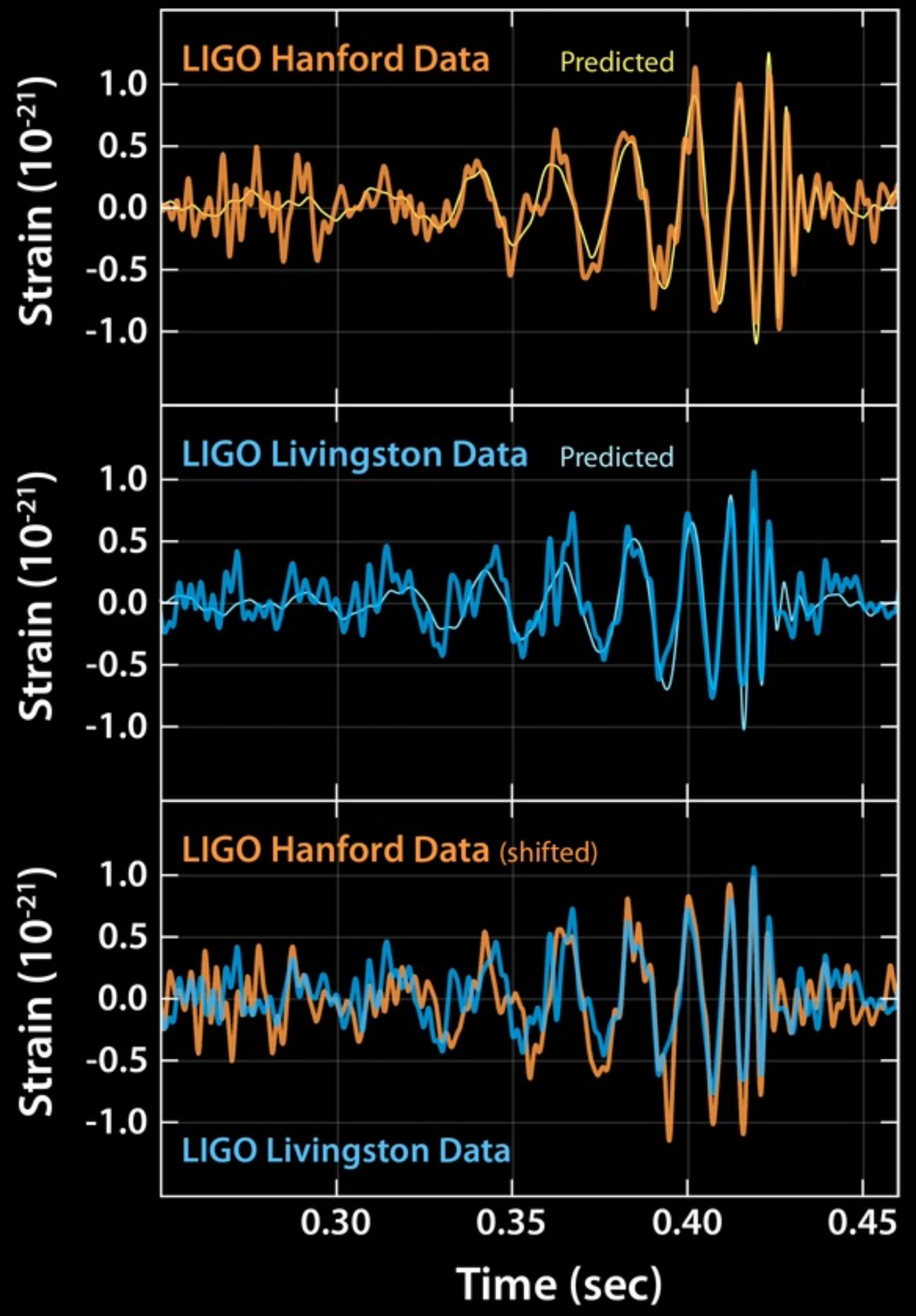
Michalis Agathos

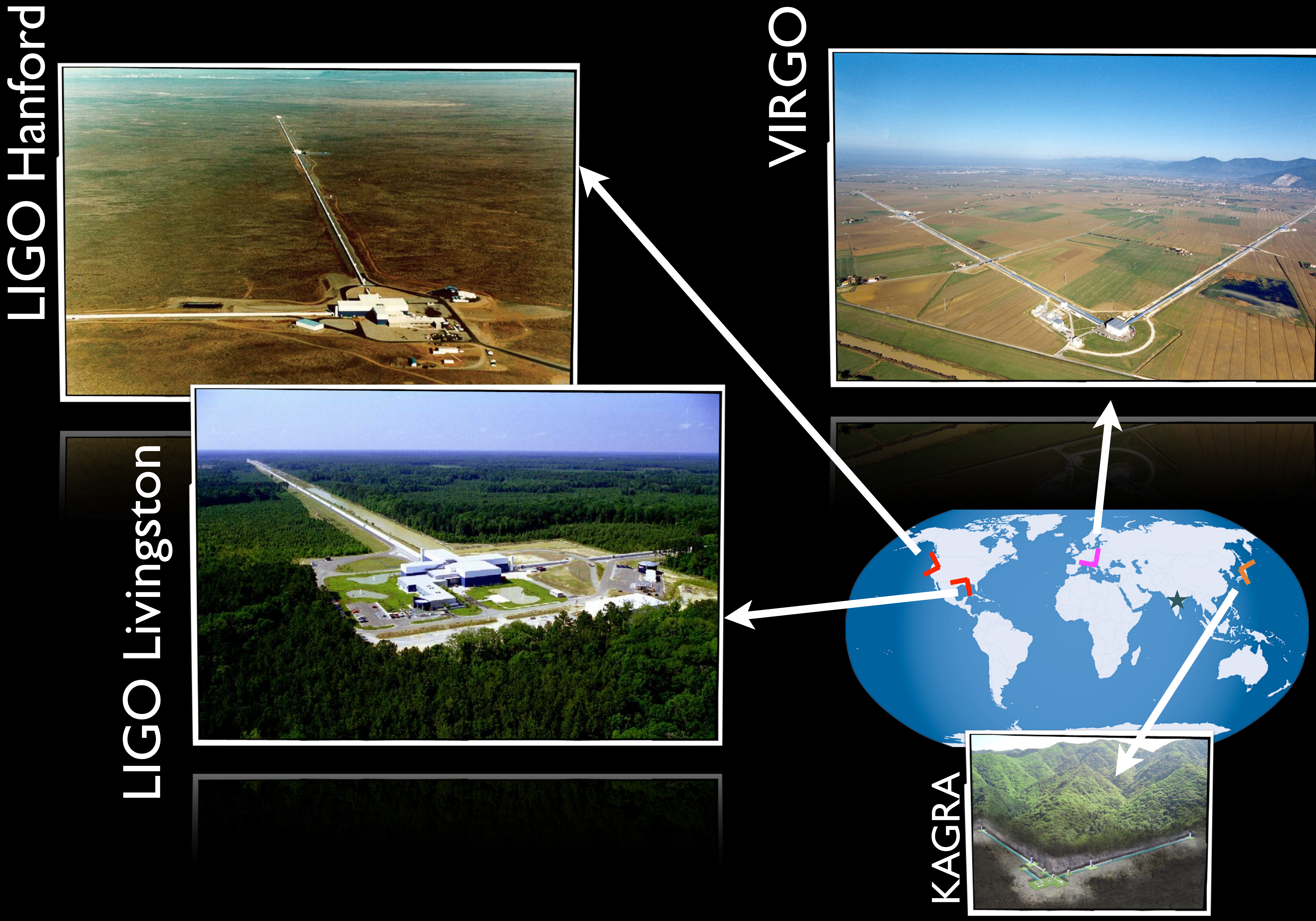
SUSY 2022 - Ioannina

UNIVERSITY OF CAMBRIDGE

Outline

- GW detections
- Tests of GR
- Fundamental fields
- Peculiar observations
- Stochastic GW Background
- Next generation



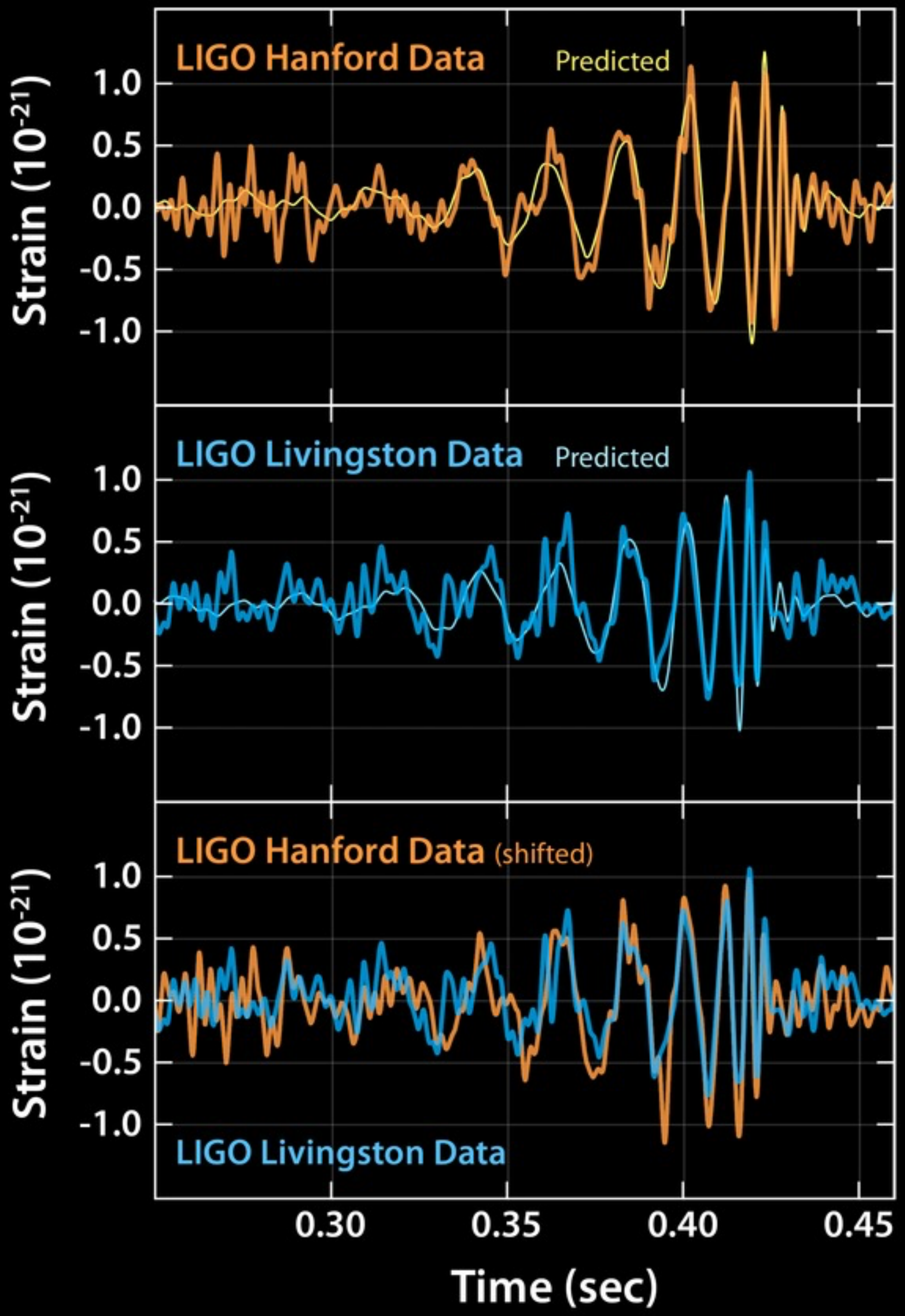

LIGO Hanford
VIRGO
LIGO Livingston
KAGRA

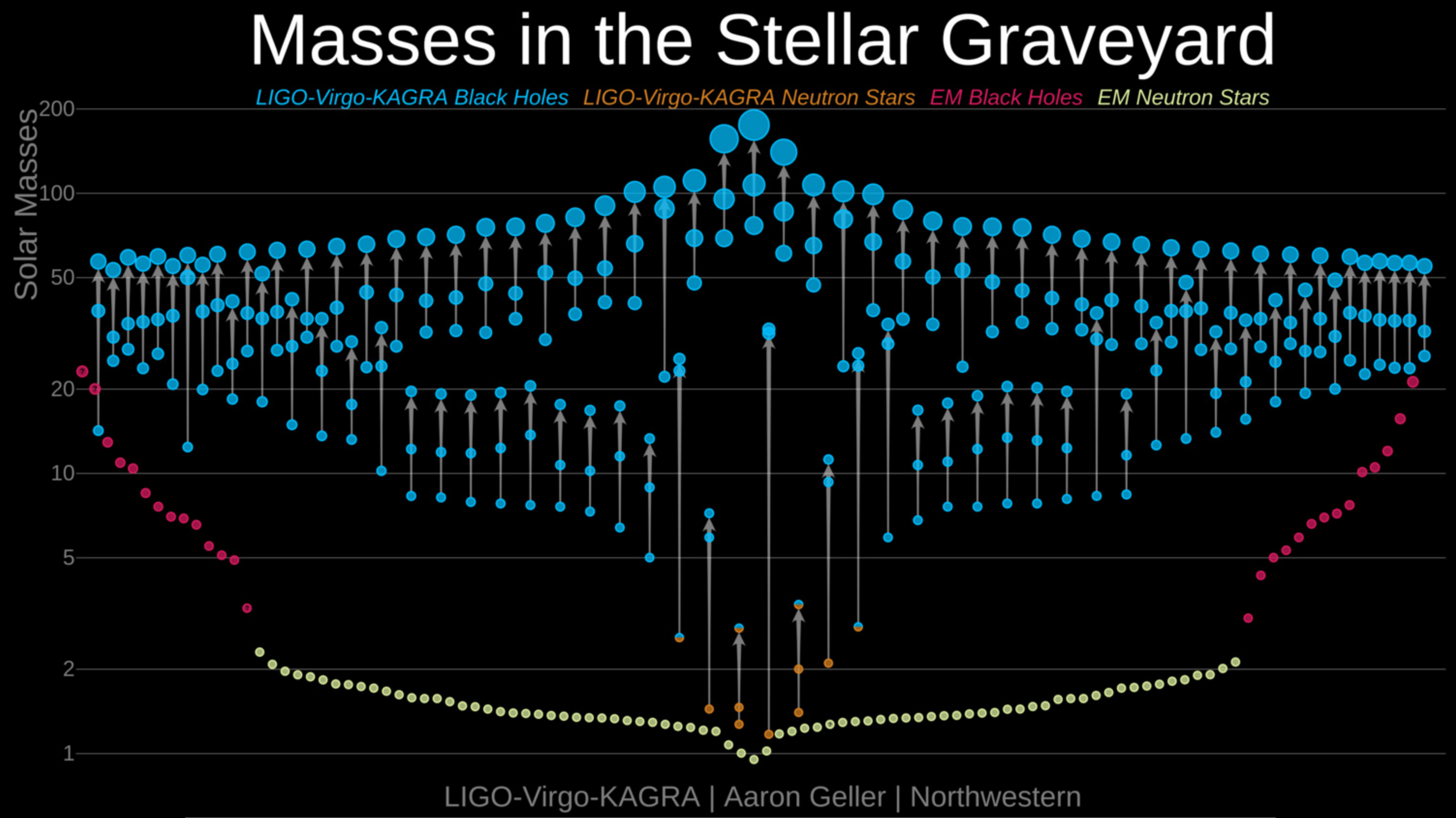
LIGO Scientific Collaboration

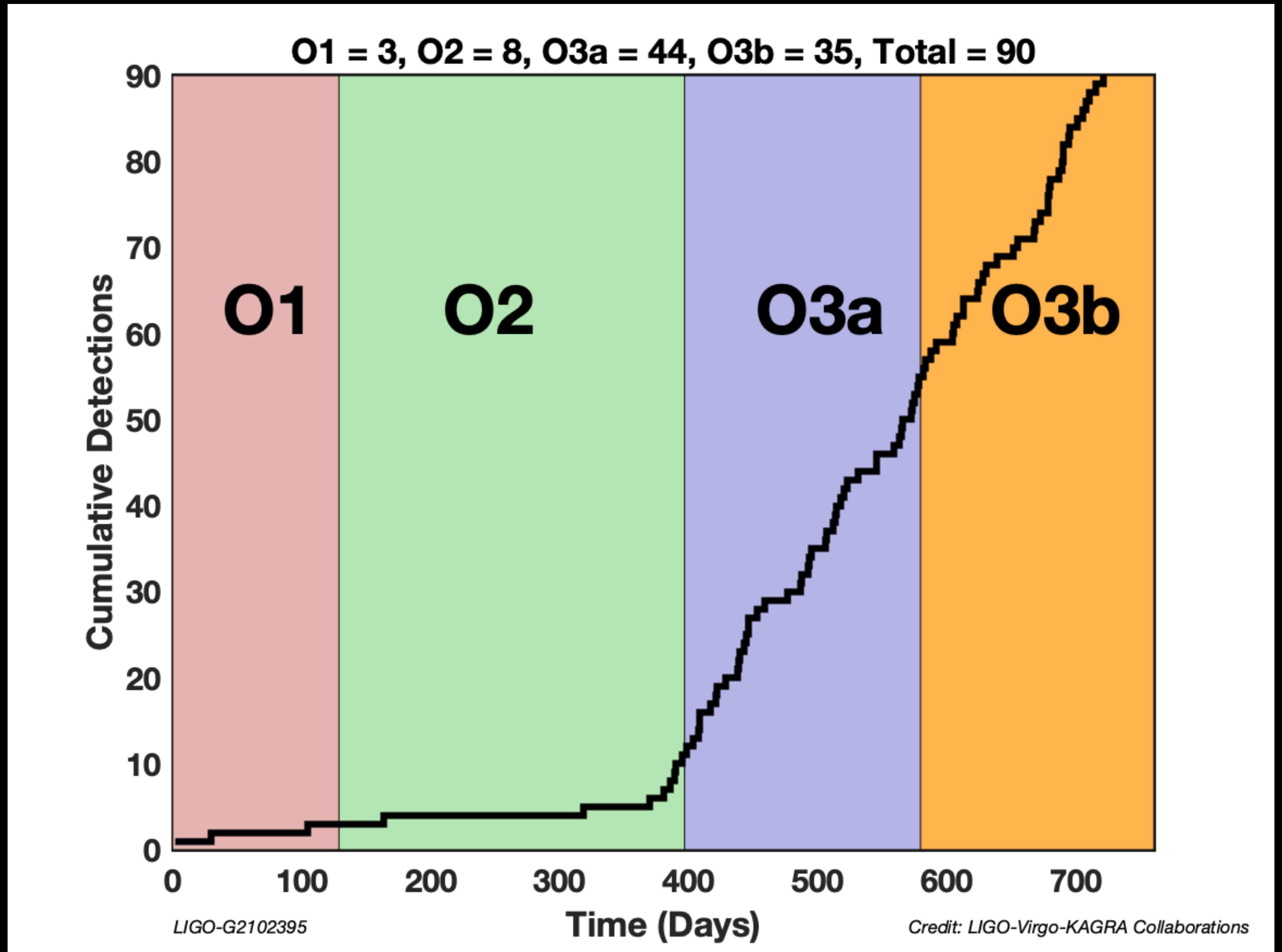
LIGO

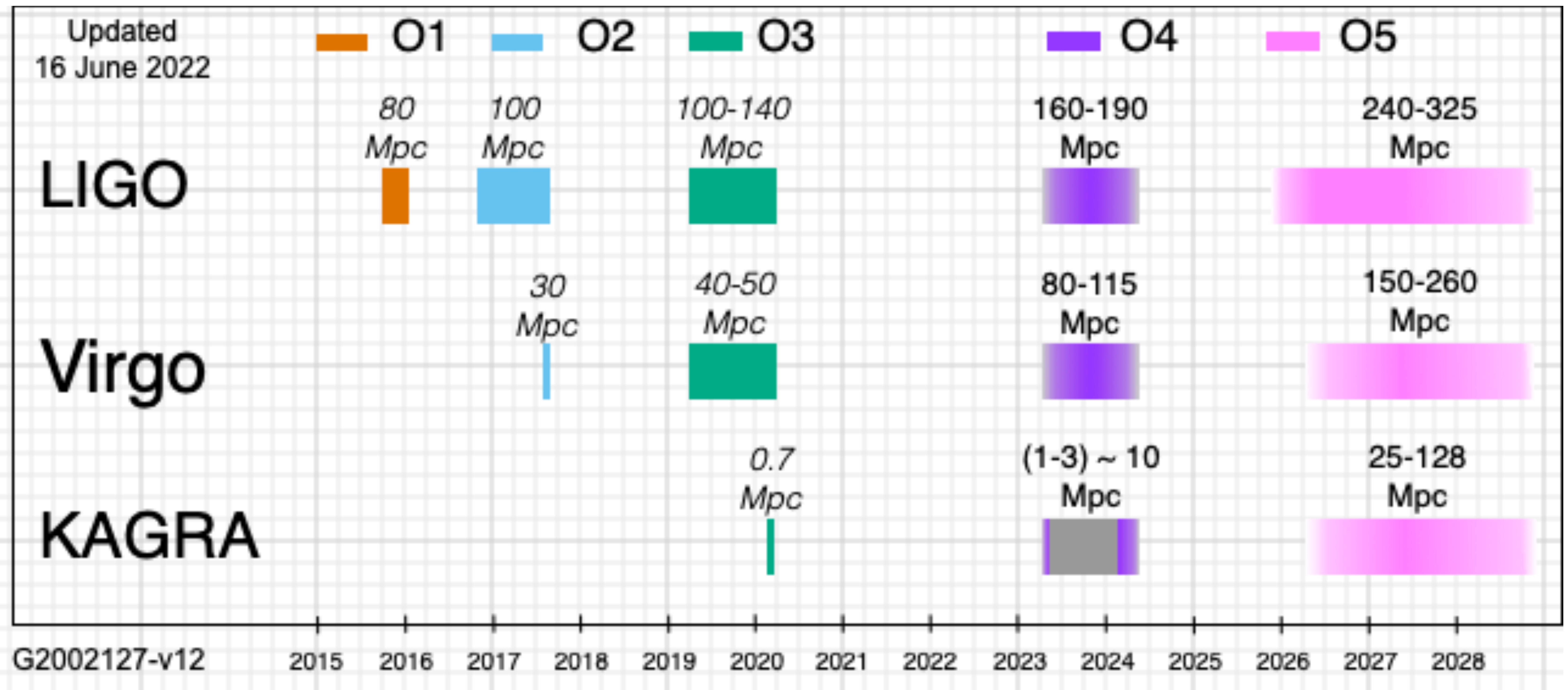
LSC

Caltech
Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut
American University Washington, DC
Andrews University
Bar-Ilan University
Bard College
Bellevue College
California State University Fullerton
Cal State LA
Carleton College
MIT
Christopher Newport University
Colorado State University
Columbia University in the City of New York
Concordia University Wisconsin
Embry-Riddle Aeronautical University
Georgia Tech
NASA Goddard Space Flight Center
INPE
Haverford College
Hillsdale College
Hobart & William Smith Colleges
International Institute of Physics
LSU Louisiana State University
Maastricht University
Marquette University Be The Difference.
NASA Marshall Space Flight Center
Missouri S&T
Montana State University
Montclair State University
Lomonosov Moscow State University
Northwestern
PennState
RIT
Sonoma State University
Flatiron Institute Center for Computational Astrophysics
Science & Technology Facilities Council Rutherford Appleton Laboratory
King's College London
Southern University and Agricultural & Mechanical College
Stanford University
Stony Brook University
University of the West of Scotland UWS
University of Birmingham
Australian National University
Charles Sturt University
Monash University
Texas Tech University
Polytechnique Montréal Université d'ingénierie
The University of Arizona
University of Arkansas
University of Portsmouth
University of Glasgow
Cardiff University Prifysgol Caerdydd
OzGrav
Swinburne University of Technology
UBC
Berkeley University of California
The University of Chicago
Universität Hamburg Der Forschung | Der Lehre | Der Bildung
University of Southampton
The University Of Sheffield.
GEO 600
The University of Adelaide
The University of Melbourne
The University of Western Australia
Universität Bonn
University of Maryland
University of Michigan
University of Minnesota
The University of Mississippi
University of Oregon
The University of Rhode Island
USC Universidade de Santiago de Compostela
UF University of Florida
University of Cambridge
Leibniz Universität Hannover
Texas The University of Texas at Austin
UTRGV
UIB Universitat de les Illes Balears
東京大学 The University of Tokyo
The University of Utah
University of Washington
W Bothell
UWM University of Wisconsin Milwaukee
Lancaster University
University of Zurich
IISER Kolkata
tifr
ICTS International Centre for Theoretical Sciences Tata Institute of Fundamental Research
IISER Pune
Vanderbilt University
Villanova University
VU Vrije Universiteit Amsterdam
West Virginia University
University of Strathclyde Glasgow
CMI Chennai Mathematical Institute
DCSEM
RRCAT
NIMS National Institute for Mathematical Sciences | South Korea
KISTI 한국과학기술정보연구원 Korea Institute of Science and Technology Information
한양대학교 Hanyang University
서울대학교 Seoul National University
UNIST
인제대학교 Inje University
LISC LIGO–India Scientific Collaboration
IIT Hyderabad
IUCAA
KASI Korea Astronomy and Space Science Institute
Pusan National University
Sungkyunkwan University
Ewha
Korean Gravitational-Wave Group


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


O1 = 3, O2 = 8, O3a = 44, O3b = 35, Total = 90
Cumulative Detections
O1
O2
O3a
O3b
Time (Days)
LIGO-G2102395
Credit: LIGO-Virgo-KAGRA Collaborations



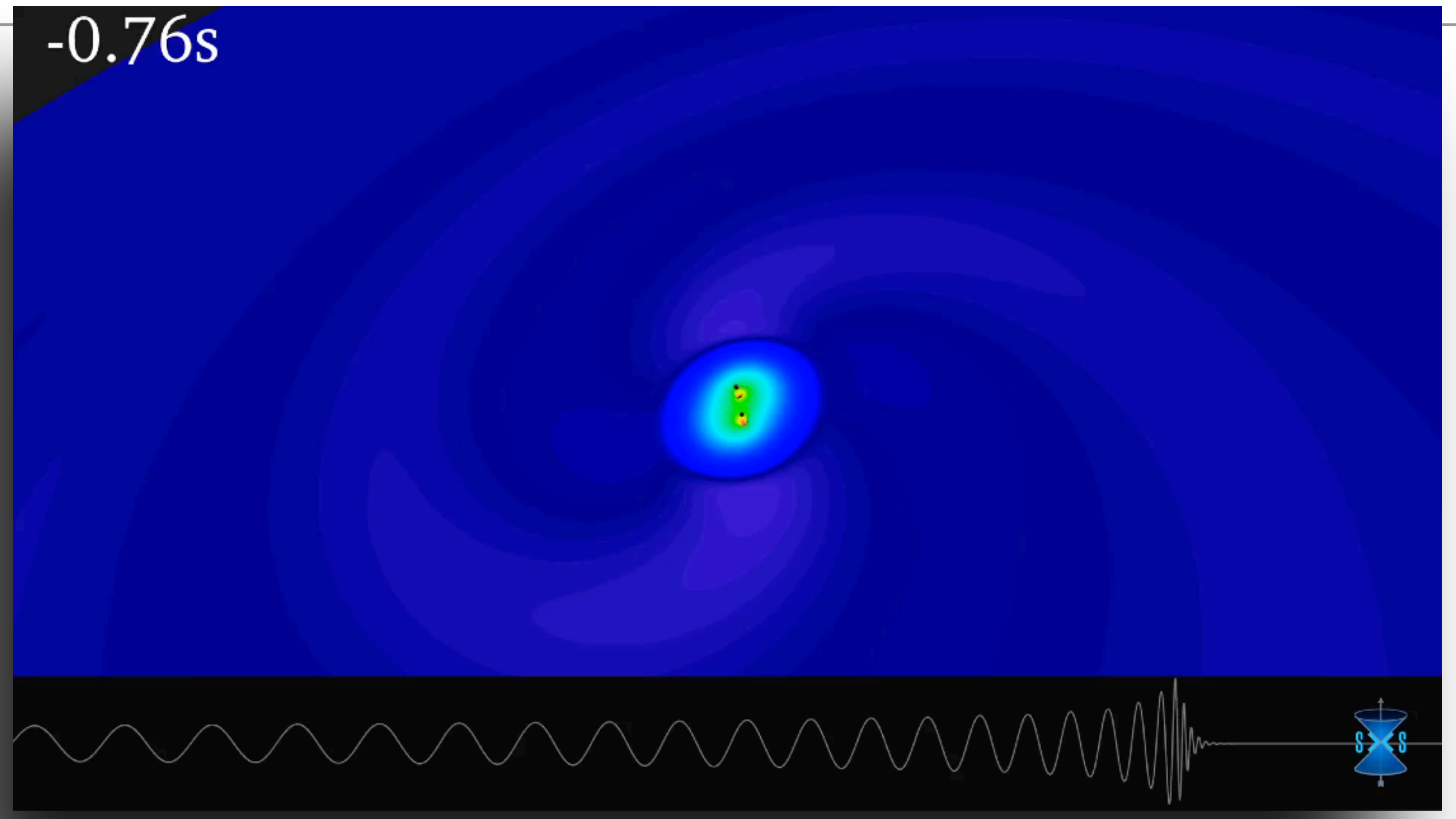
LIGO | Virgo | KAGRA Observing Plan

Coming up

Gravitational wave Data analysis

- I) Direct problem (source modelling):

“Given a GW source of known properties (e.g. BBH of known masses, spins, etc), what is the emitted gravitational wave signal?”

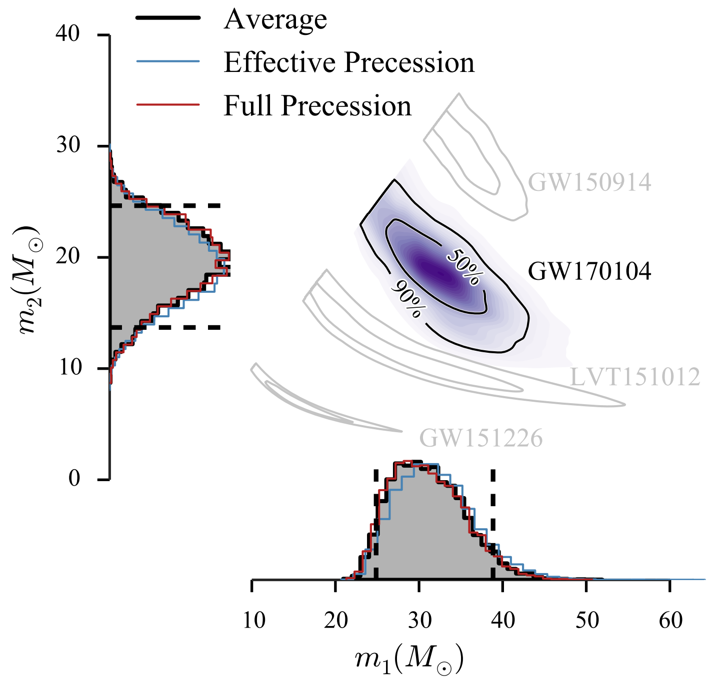


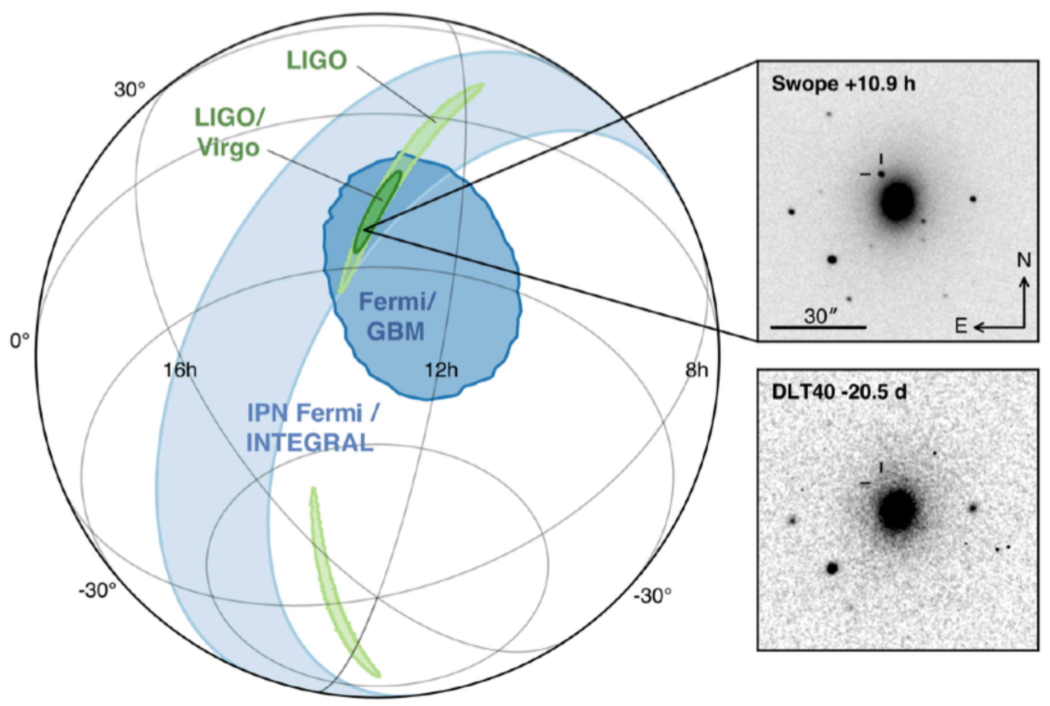
https://www.ligo.caltech.edu/video/ligo20160211v10

- II) Inverse problem (data analysis):

“Given a stretch of noisy data and the stochastic properties of noise, can you reconstruct a signal and estimate the properties of the source?”

$$\vec{\theta}_{CBC} = \left(m_1, m_2, \vec{S}_1, \vec{S}_2, D, \alpha, \delta, \iota, \psi, t_c, \varphi_c\right)$$

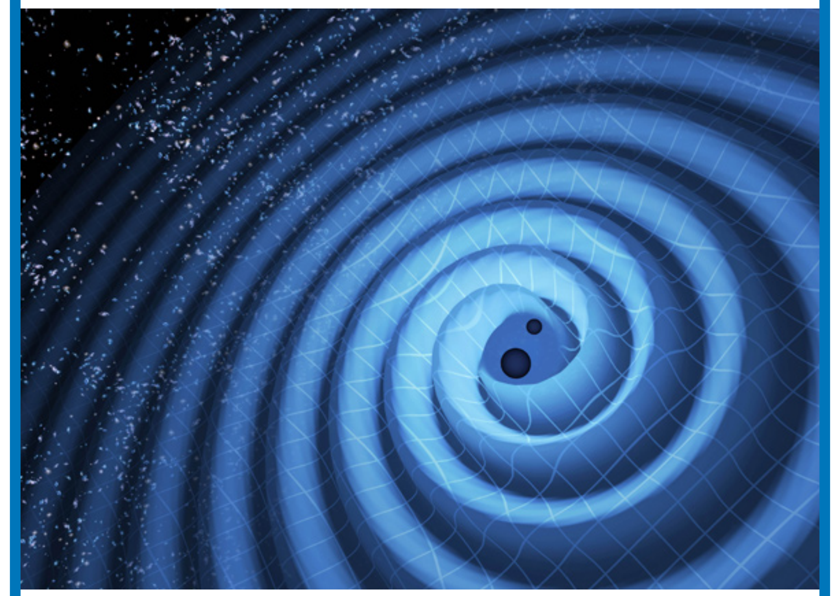




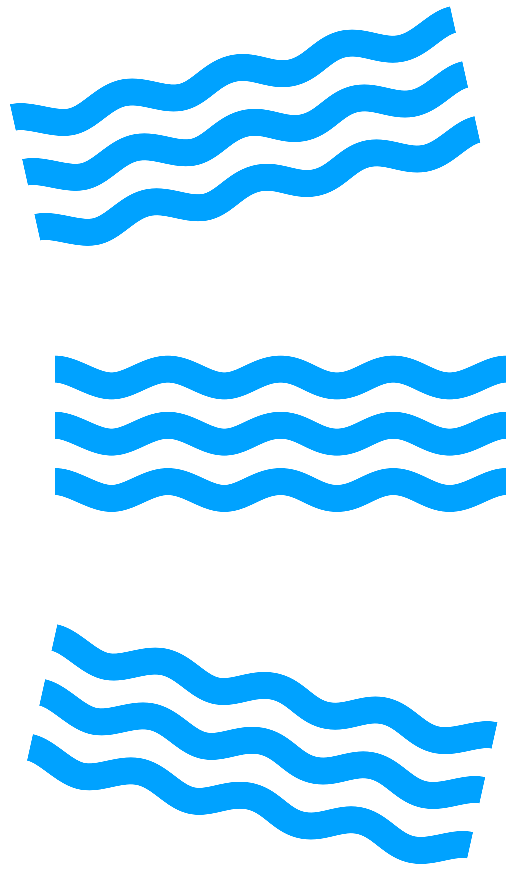
[LVC PRL 119, 161101 (2017)]

Testing GR with Gravitational Waves

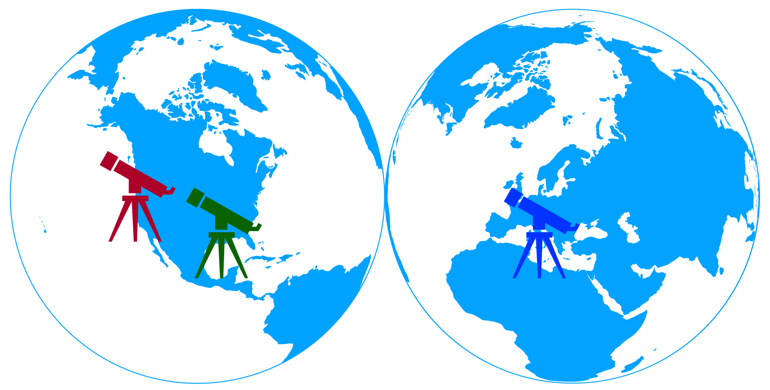
What are we testing?



Generation



Propagation

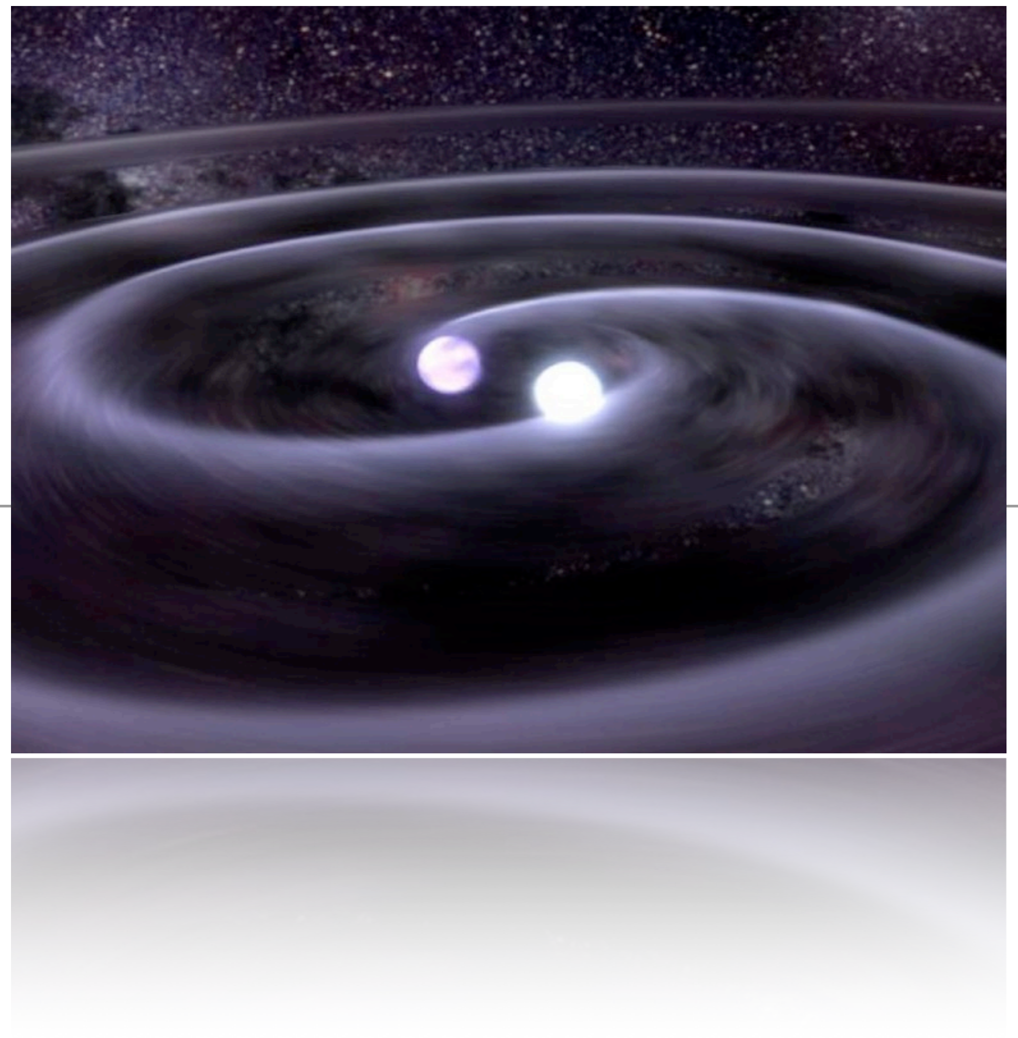


Detection

\+ *waveform systematics*

\+ *noise model & calibration*

GW Source modelling



- A **post-Newtonian** (PN) expansion gives approximate solutions to the 2-body problem in GR
- Accurate analytic solution for the best part of the ***quasicircular Inspiral***
- Simple frequency-domain waveform:

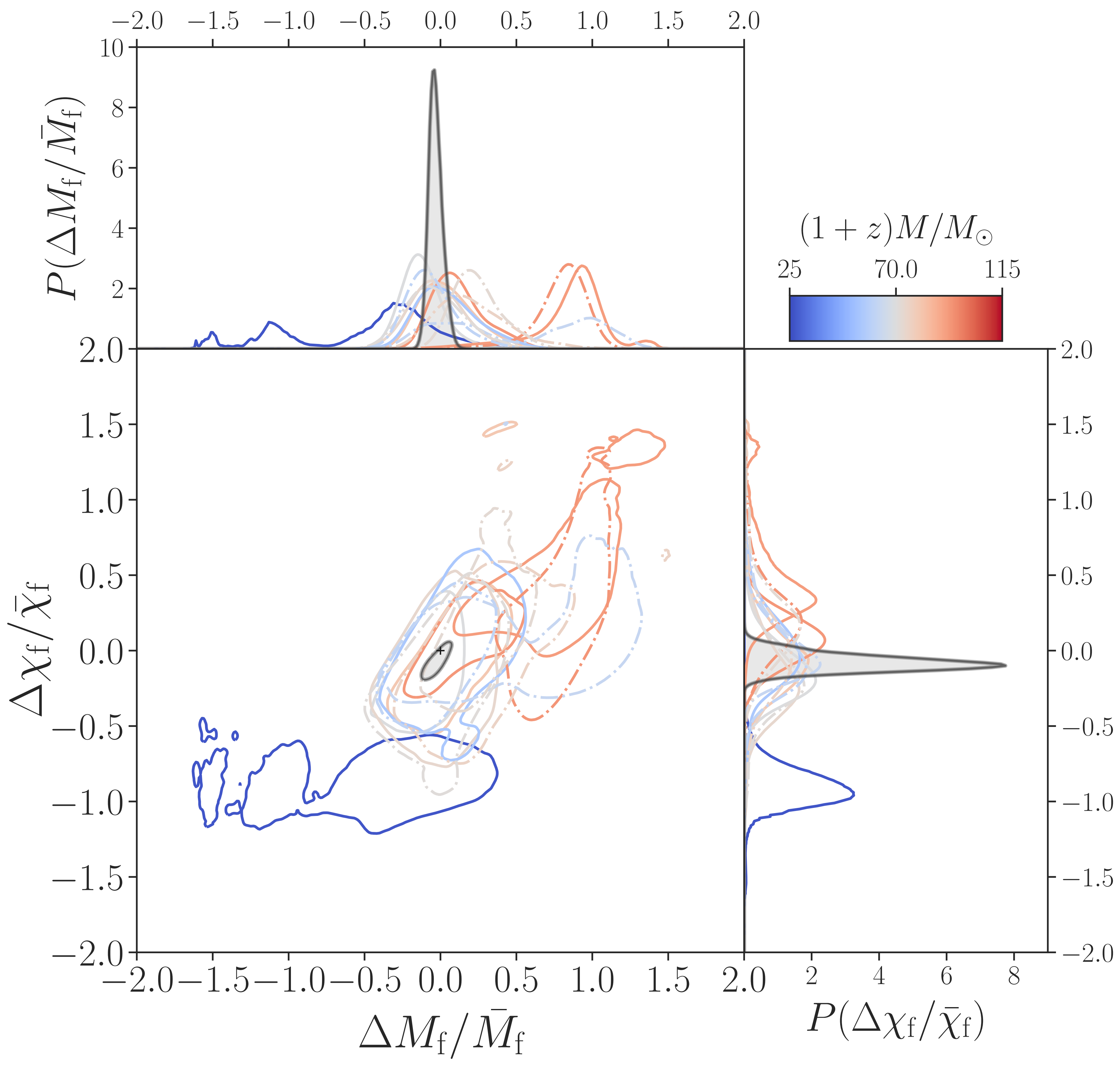
$$\tilde{h}(f) = \mathcal{A} f^{-7/6} \cos(2\Phi(f; m_1, m_2) + \phi_0) \qquad v = (\pi M f)^{1/3}$$

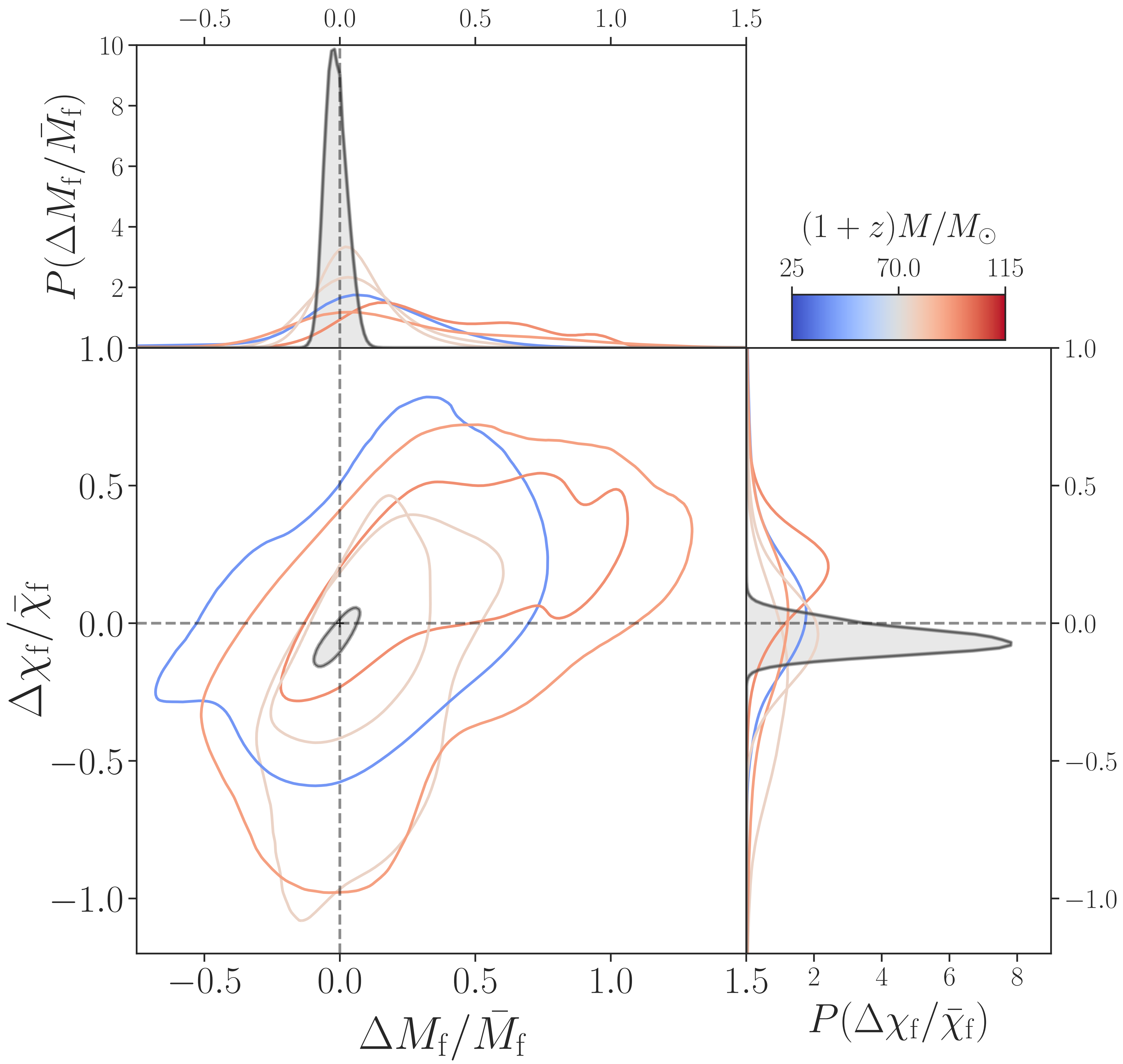
$$\Phi = \left(\frac{v}{c}\right)^{-5} \sum_{i=0}^{N} \left[\psi_i + \psi_i^{(l)} \ln \frac{v}{c}\right] \left(\frac{v}{c}\right)^i$$

- Calculations in GR give PN phase coefficients ψ_i (m_1, m_2, $\mathbf{S}_1$, $\mathbf{S}_2$), $\psi_i^{(l)}$ (m_1, m_2, $\mathbf{S}_1$, $\mathbf{S}_2$)
- **Numerical Relativity** simulations complete the model close to/during ***Merger***, where perturbative expansions fail
- **BH perturbation** theory informed by NR gives model for the ***Ringdown***
- **IMR** models are used in full LVK analyses

Inspiral - Merger-Ringdown consistency

LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

- Posteriors show consistency with GR predictions
- 

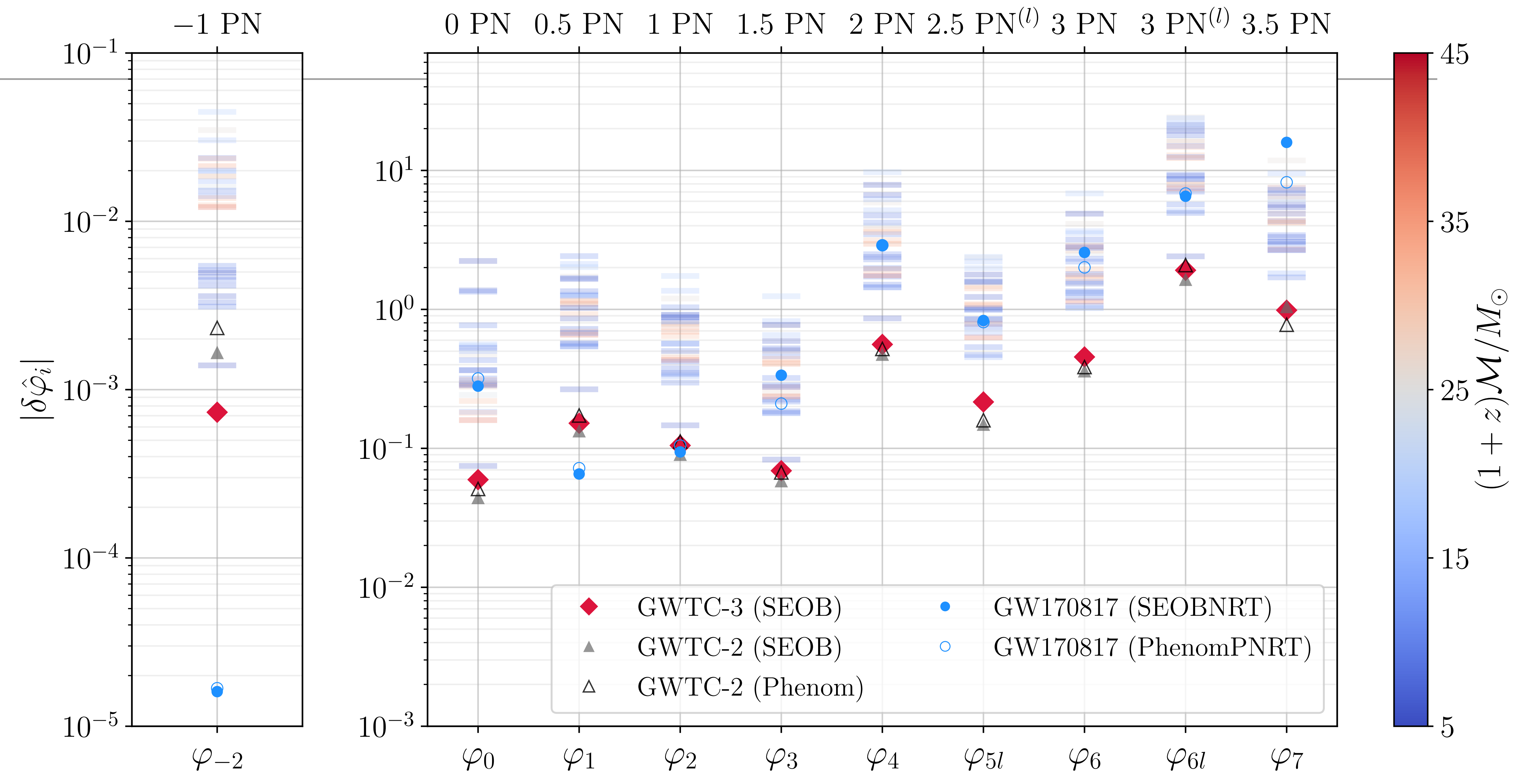


LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

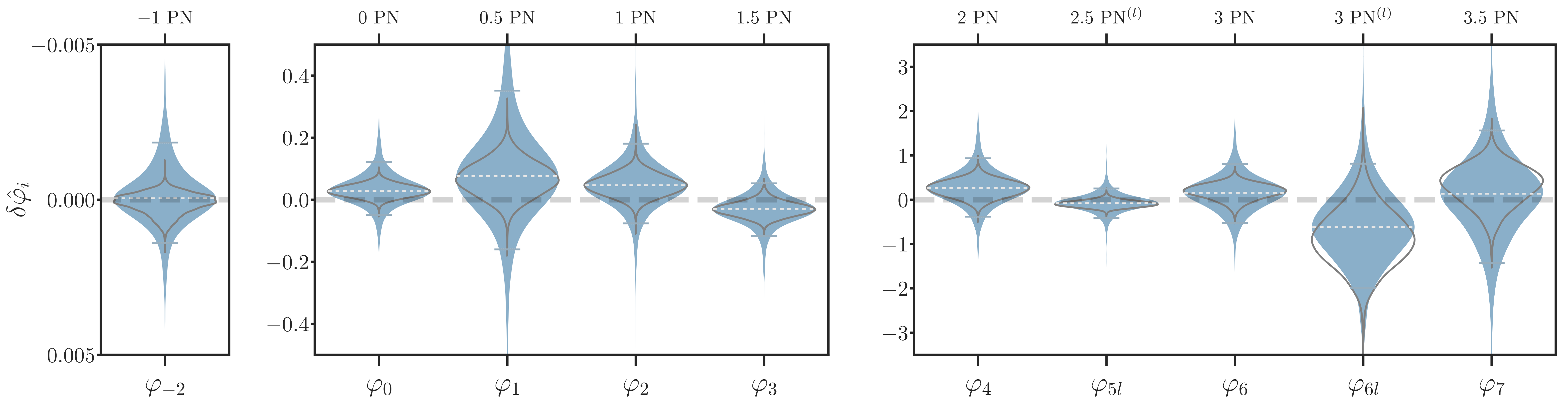
Parameterized tests of GR

- Phase evolution of the binary is dictated by GR
- Violation of GR would modify **inspiral** dynamics
- Allow for parameterized violations of GR in post-Newtonian phase coefficients and measure them:

$$\varphi_i \to \varphi_i(1 + \delta\hat{\varphi}_i)$$



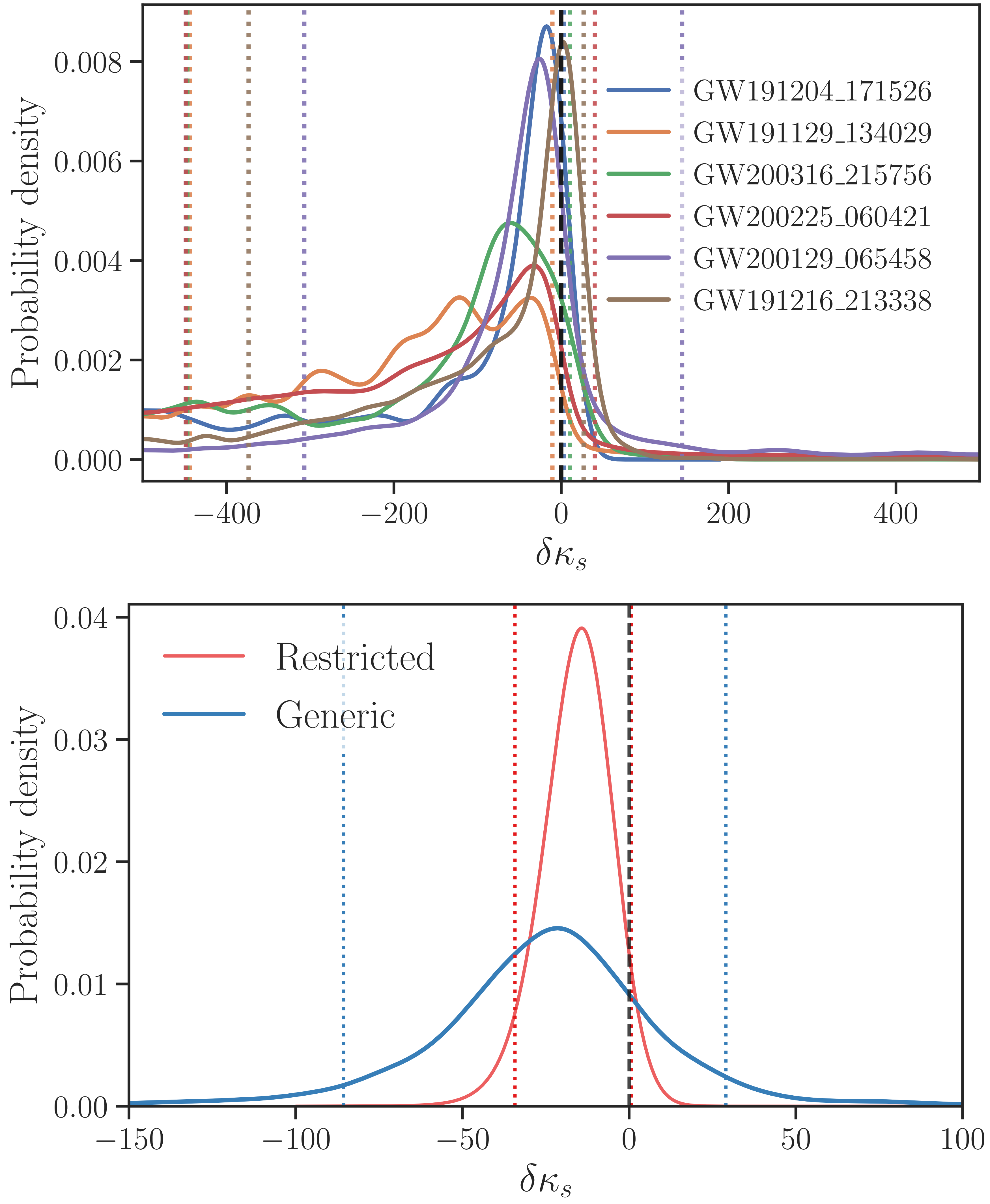
Arun+ [PRD 74, 024006 (2006)]
Yunes+ [PRD 80, 122003 (2009)]
Li, MA+ [PRD 85, 082003 (2012)]
MA+ [PRD 89, 082001 (2014)]
Meidam, MA+ [PRD 97, 044033 (2018)



Black Hole Quadrupole

LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

- All properties of a Kerr BH are uniquely determined by knowing its mass and spin
- Simple formula for mass and current multipoles
- Spin-induced mass quadrupole:
  $$Q = -\kappa\chi^2 M^3\,, \quad \kappa_{\rm BH} = 1$$
- Introduces modification in the GW phase that enters @2PN
- Non-Kerr compact objects will in general have $\kappa \neq 1$, e.g. neutron-/boson-/grava- stars, etc.
- We measure a combination of κ to be consistent with the Kerr BH value



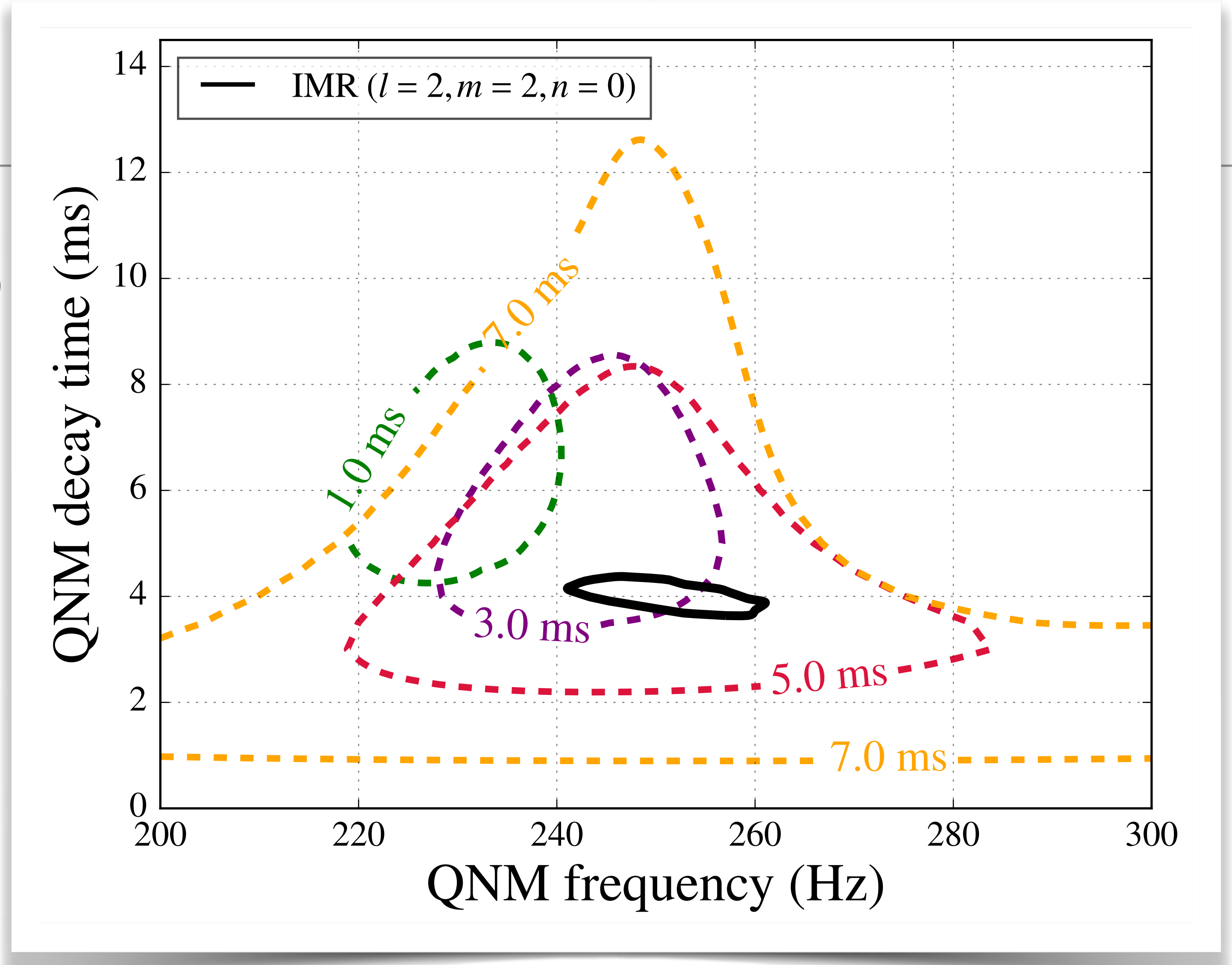
Ringdown analysis

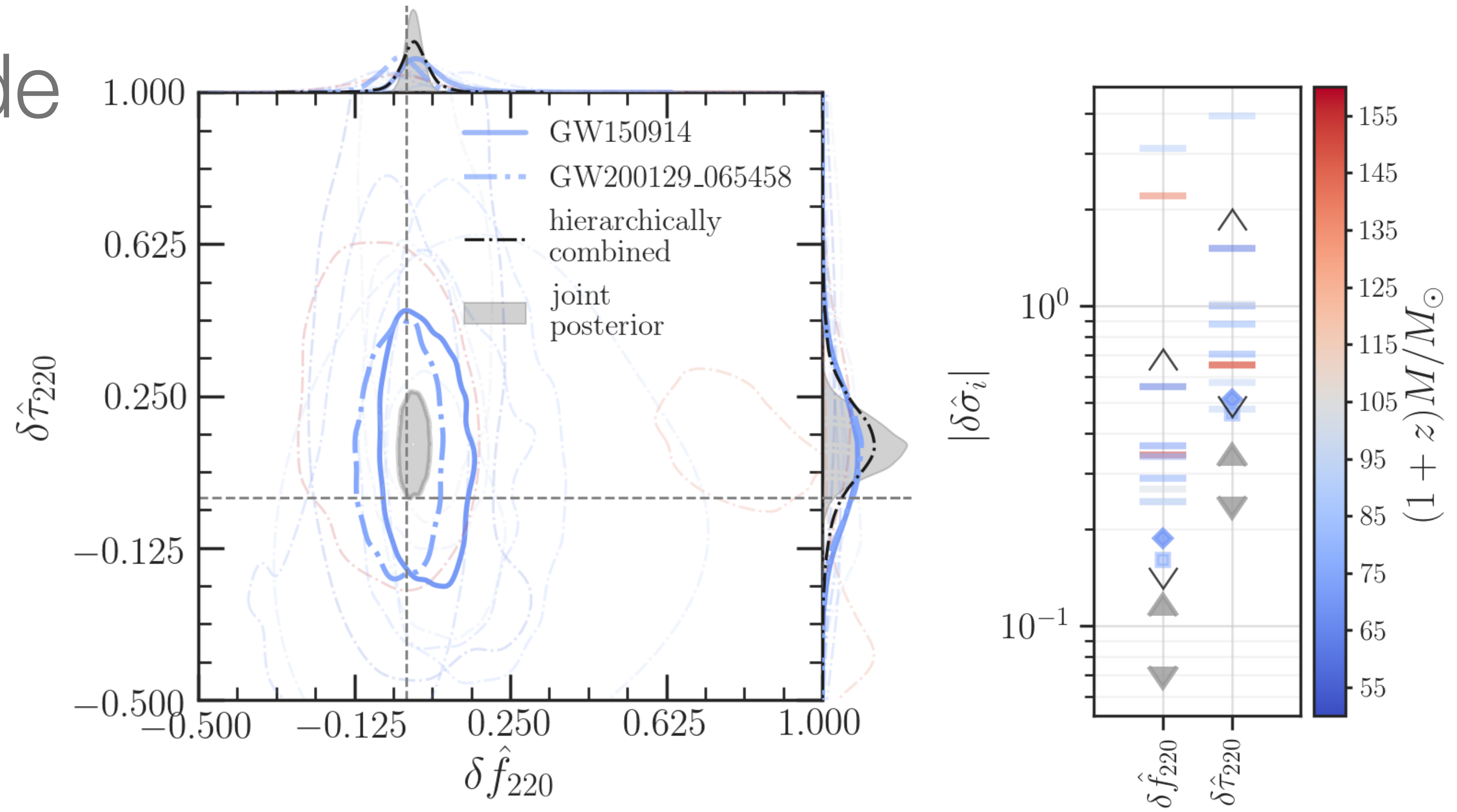
- "Is there clear evidence of a quasi-normal ringdown?"
- Final BH radiates damped sinusoids

$$h_+(t) - ih_\times(t) = \sum_{\ell=2}^{+\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{+\infty} \mathcal{A}_{\ell mn} \exp\left[-\frac{t-t_0}{(1+z)\tau_{\ell mn}}\right] \exp\left[-\frac{2\pi i f_{\ell mn}(t-t_0)}{1+z}\right] {}_{-2}S_{\ell mn}(\theta, \phi, \chi_f),$$

- Estimate f & τ of **dominant** (`l=2 m=2`) mode
-

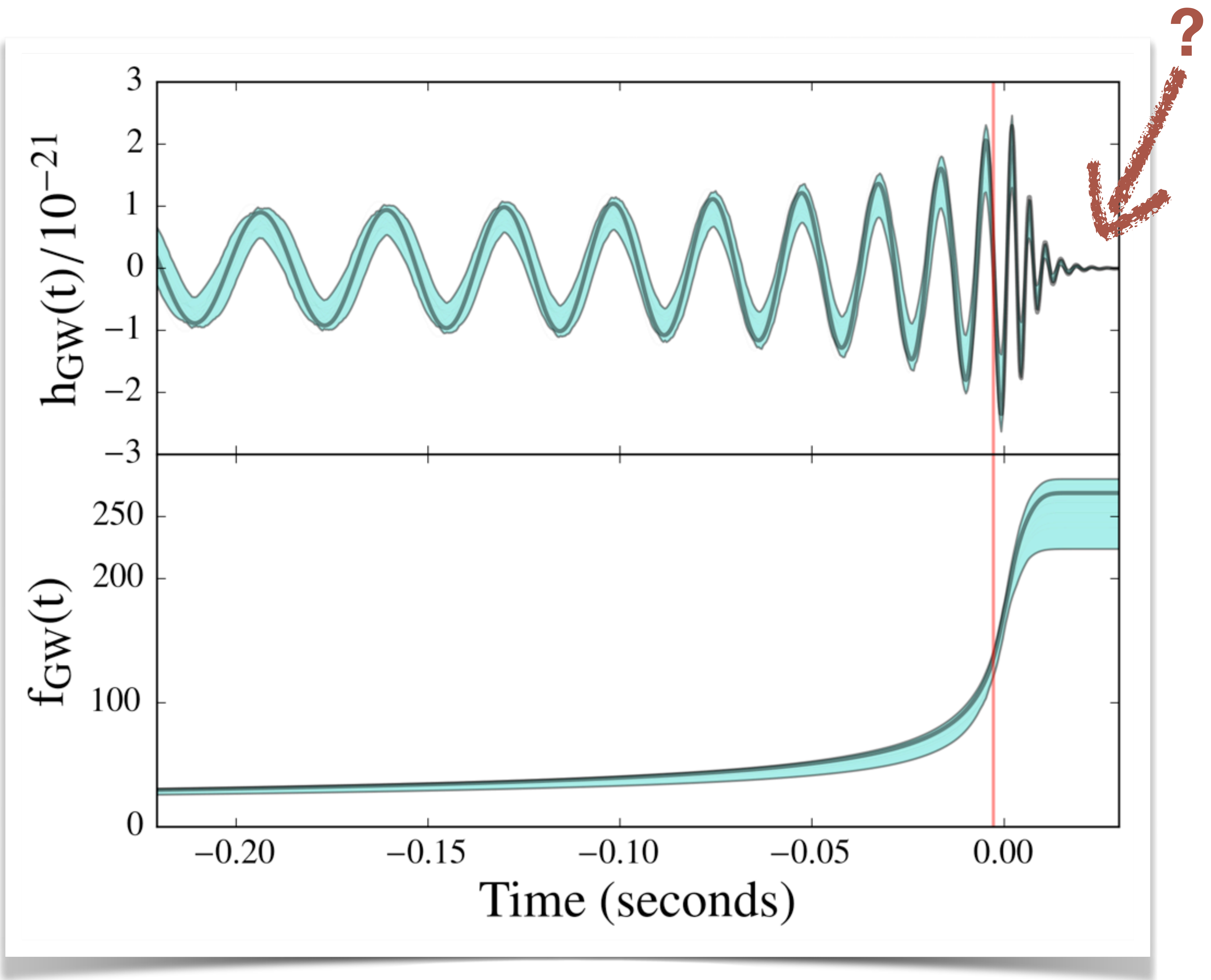
[LVC PRL 116, 221101 (2016)]





LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

Is there anything beyond ringdown?

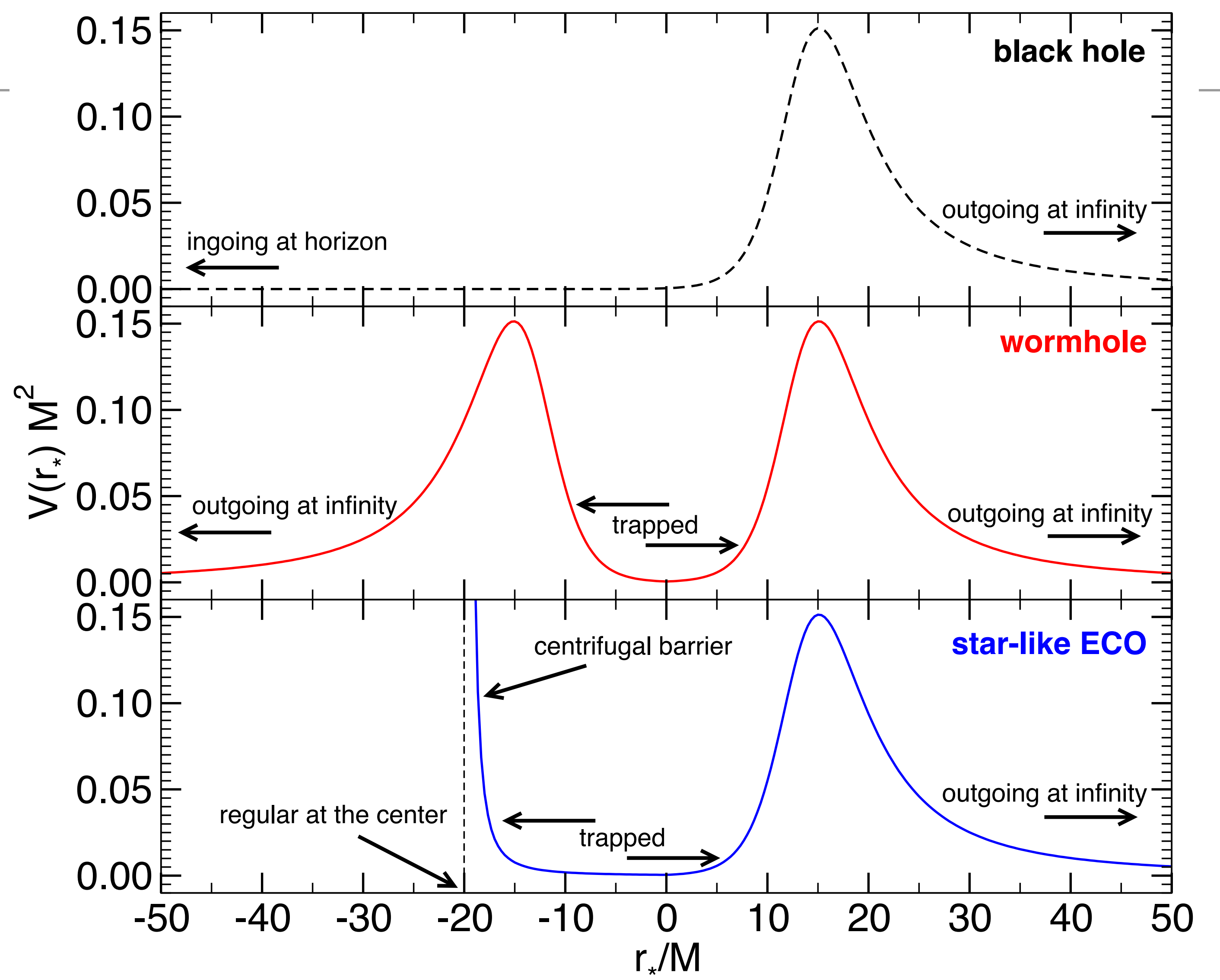


Echoes from Exotic Compact Objects

Cardoso et al. 2016

- Are we still sure these are BHs?
- Alternative: objects that
  - are compact enough
  - have the same light-ring structure as a BH **but** no horizon
- Candidates: Wormholes, thin-shell Gravastars, other?
- GW signature: echoes at fixed time intervals Δt

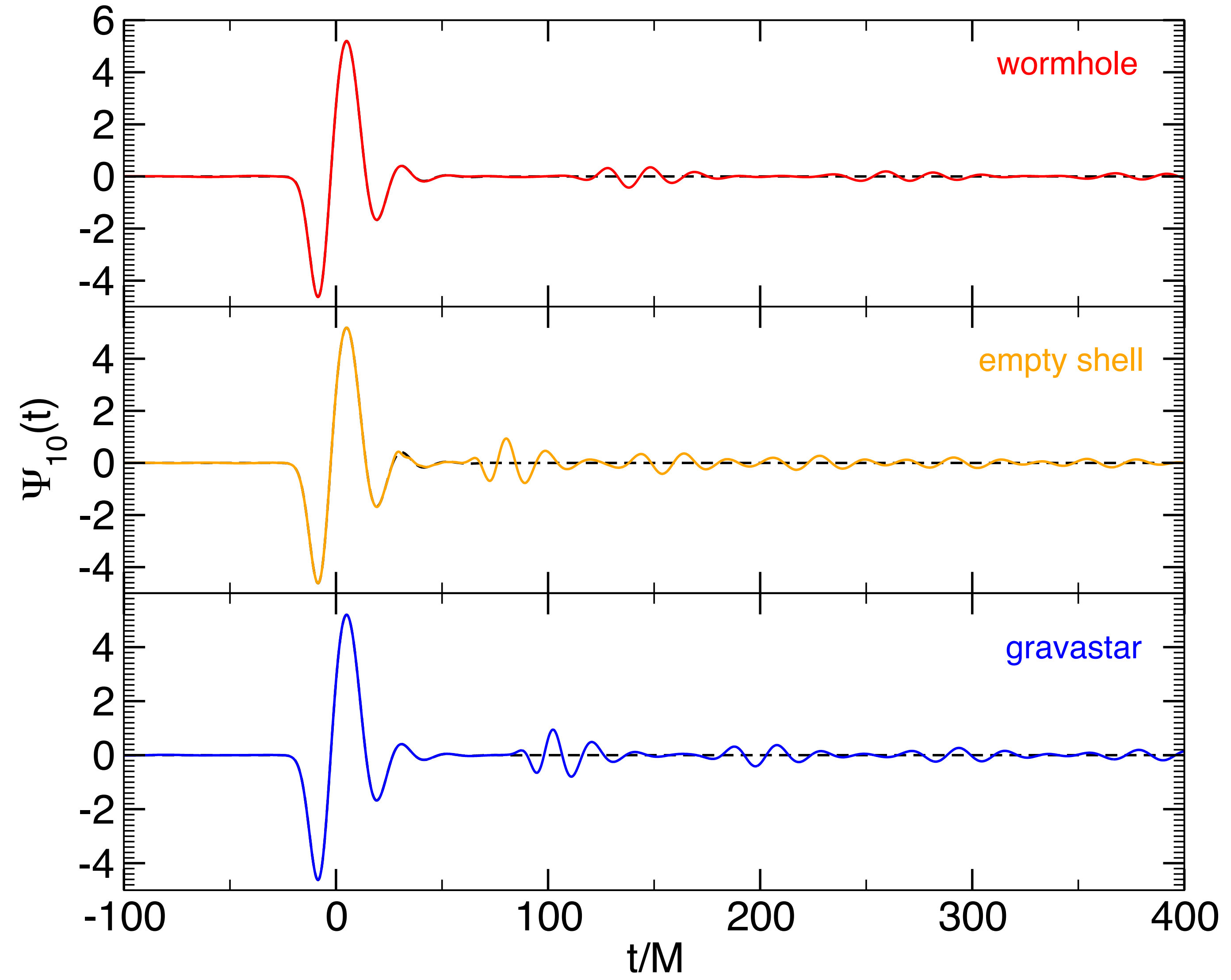
$$\Delta t \sim -nM \log\left(\frac{\ell}{M}\right), \quad \ell \ll M$$



n=8

n=4

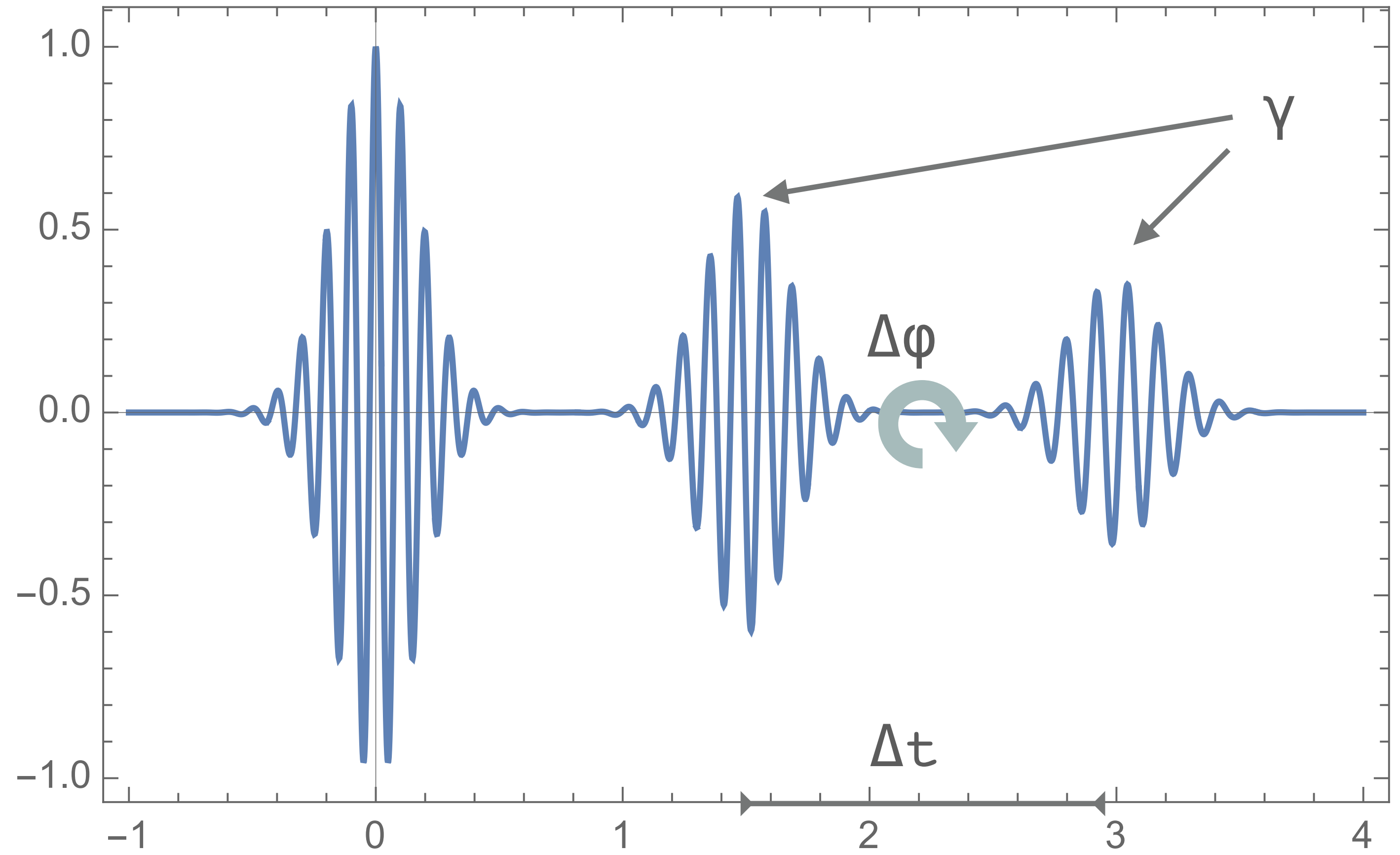
n=6



GWTC-2 searches for echoes

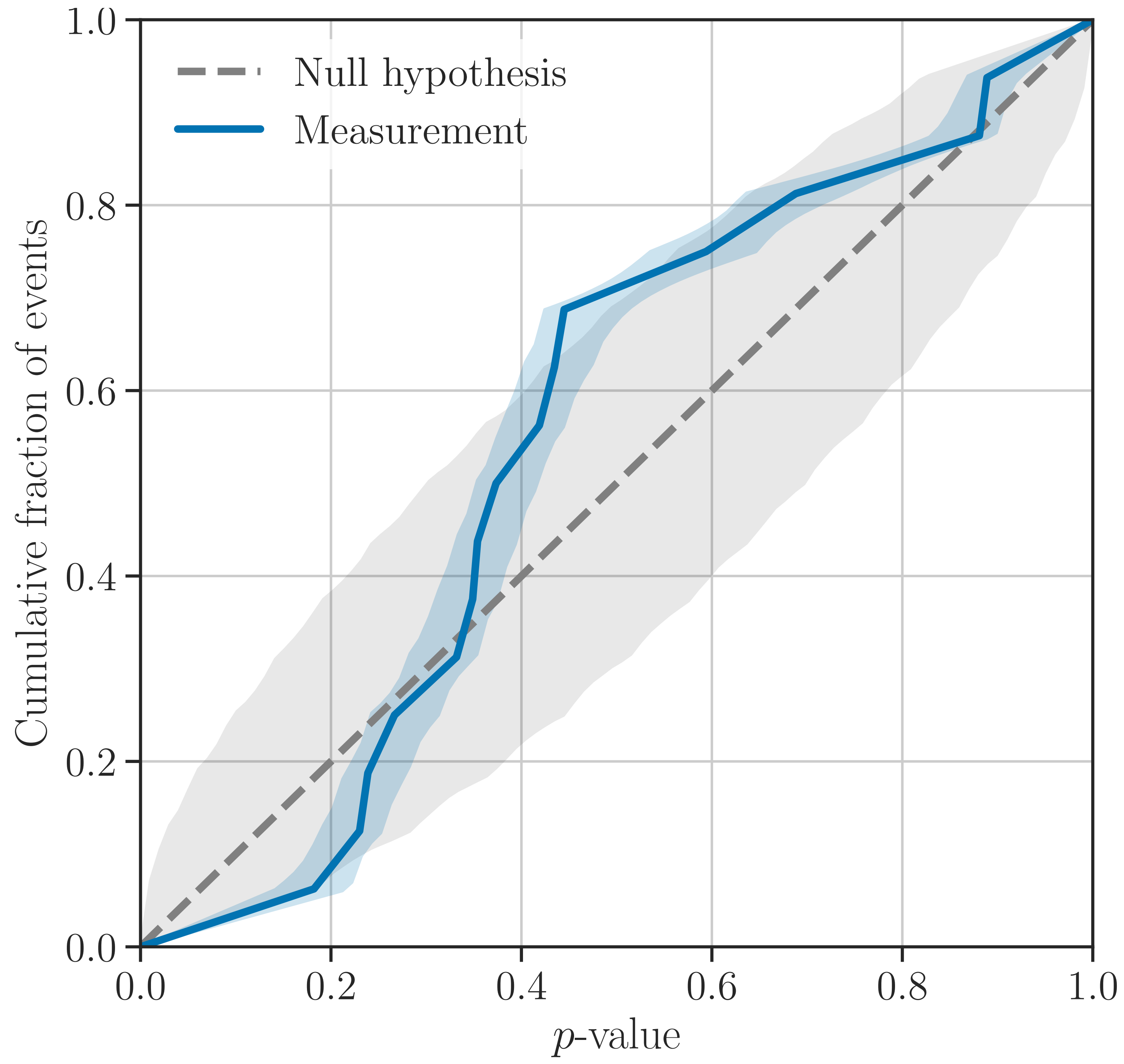
LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

- Look for quasi-periodic bursts of GWs after the ringdown
- Template-based analysis using ringdown signal as basis that is modulated and repeated in echoes [Lo+ arXiv:1811.07431]
- No support for echoes in data



- Earlier model-independent searches also gave null results in O1 and O2

[Cornish & Littenberg arXiv:1410.3835]
[Tsang,…,MA+ arXiv:1804.04877]
[Tsang,…,MA+ arXiv:1906.11168]



Massive graviton effect on propagation

Will (1998) [gr-qc/9709011]

- "Massive graviton": GWs propagate along timelike geodesics under the dispersion relation

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = \frac{h}{m_g c}$$

- Waveform undergoes dispersion:
  - (early) low-f waves get delayed w.r.t. (late) high-f waves

$$\left(\frac{v_g}{c}\right)^2 = 1 - \frac{h^2c^2}{\lambda_g^2 E^2}$$

  - "Chirp"-like signals get squeezed together

$$\Delta t_a = (1+Z)\left[\Delta t_e + \frac{D}{2\lambda_g^2}\left(\frac{1}{f_e^2} - \frac{1}{f_e'^2}\right)\right]$$

- Phase modification in the frequency domain:

$$\delta\Phi_{\mathrm{MG}}(f) = -\frac{\pi D c}{\lambda_g^2(1+z)f}$$

Lorentz-Invariance-Violating dispersion

LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

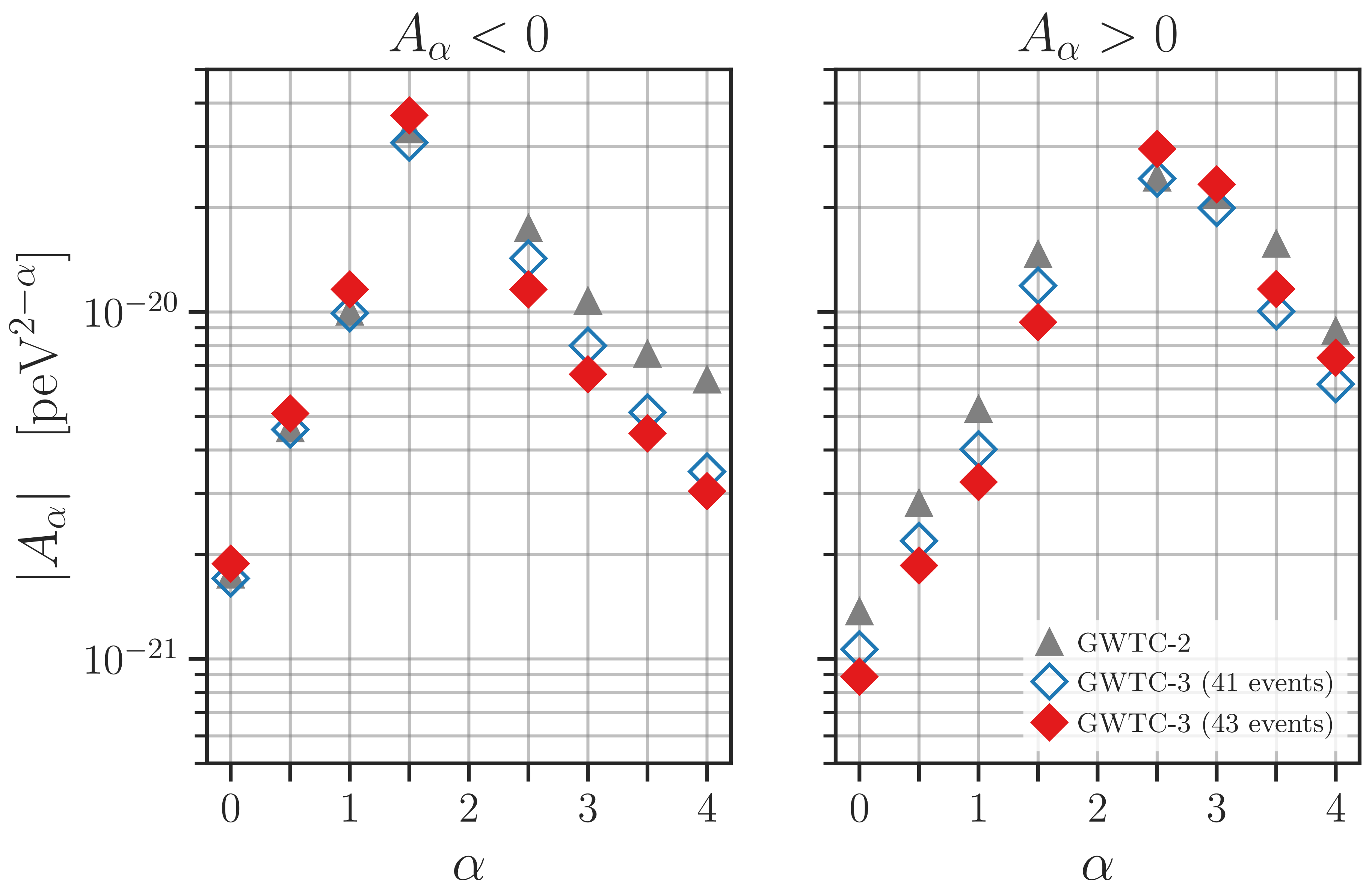
- More general form of modified dispersion relation:
  - α=0 : massive graviton [de Rham LRR-2014-7]
  - α=2 : no dispersion, non-LIV
  - other: Lorentz invariance violating, some motivated by approaches to quantum gravity, e.g. dSR (α=3) [Amelino-Camelia 2002,2010], extra dims & Horava-Lifshitz (α=4) [Blas&Sanctuary 2011]
  - More general forms include vector/tensor contractions with p^μ
- GW phase modification:

[Mirshekari, Yunes, Will 2011]

$$E^2 = p^2c^2 + \mathbb{A}\, p^\alpha c^\alpha$$

$$\lambda_{\mathbb{A}} = h\, \mathbb{A}^{\frac{1}{\alpha-2}}$$

	m_g $[10^{-23}$ $\mathrm{eV}/c^2]$
GWTC-2	1.76
GWTC-3	1.27



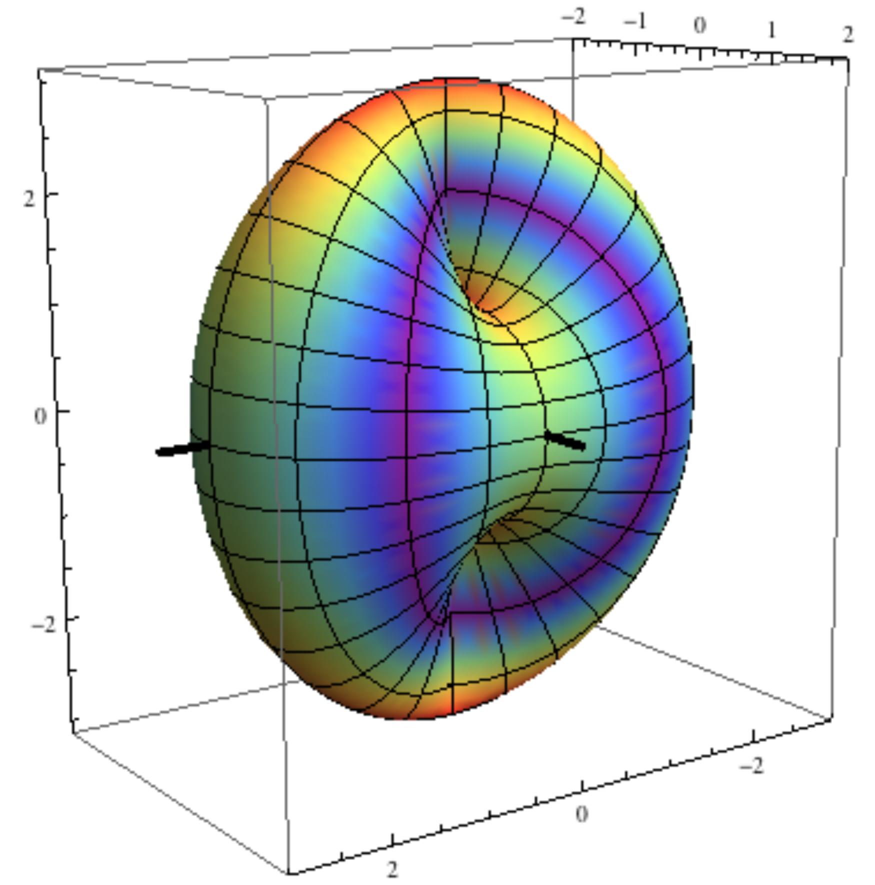
$$\delta\Psi_\alpha(f) = -\beta(\pi\mathcal{M}f) \quad - \frac{\pi D_\alpha}{(1-\alpha)\lambda_{\mathbb{A}}^{2-\alpha}(1+z)^{1-\alpha}} f^{\alpha-1} \qquad \alpha \neq 1$$

Gravitational Wave Detection

- Detector arms stretch and squeeze in a different way

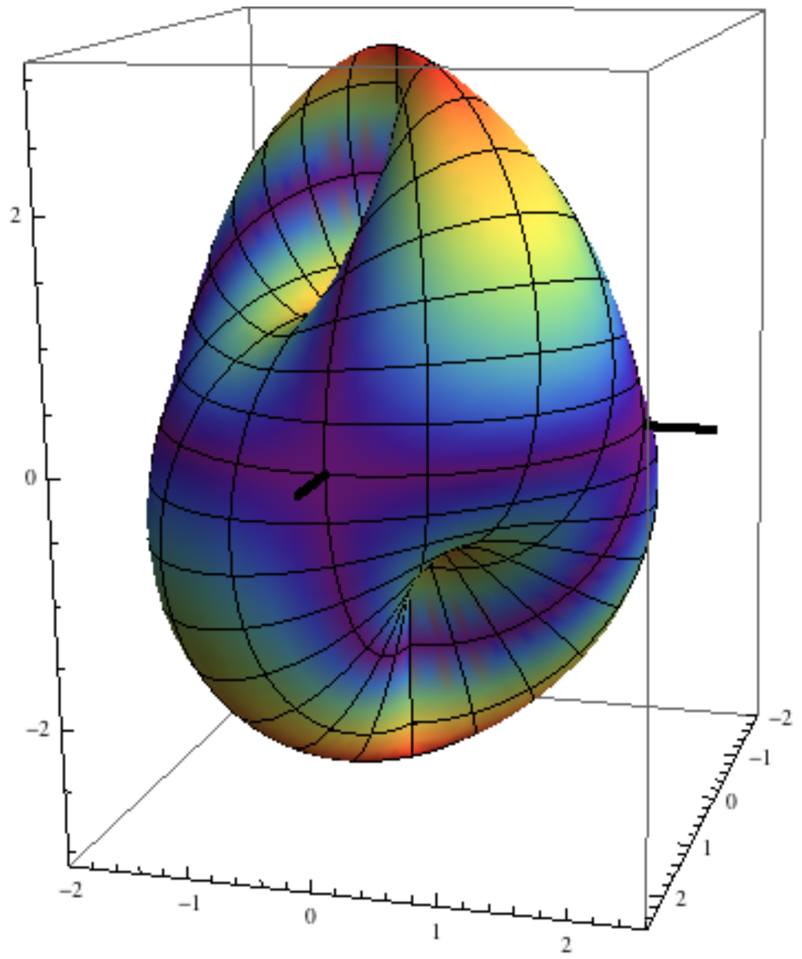
- Antenna pattern gives detector response that depends on direction of propagation

$$h(t) = F_+(\hat{n})\, h_+(t) + F_\times(\hat{n})\, h_\times(t)\,,$$
$$F_P(\hat{n}) = D^{ij}\, \epsilon^P_{ij}(\hat{n}) \quad , \; P = +, \times$$



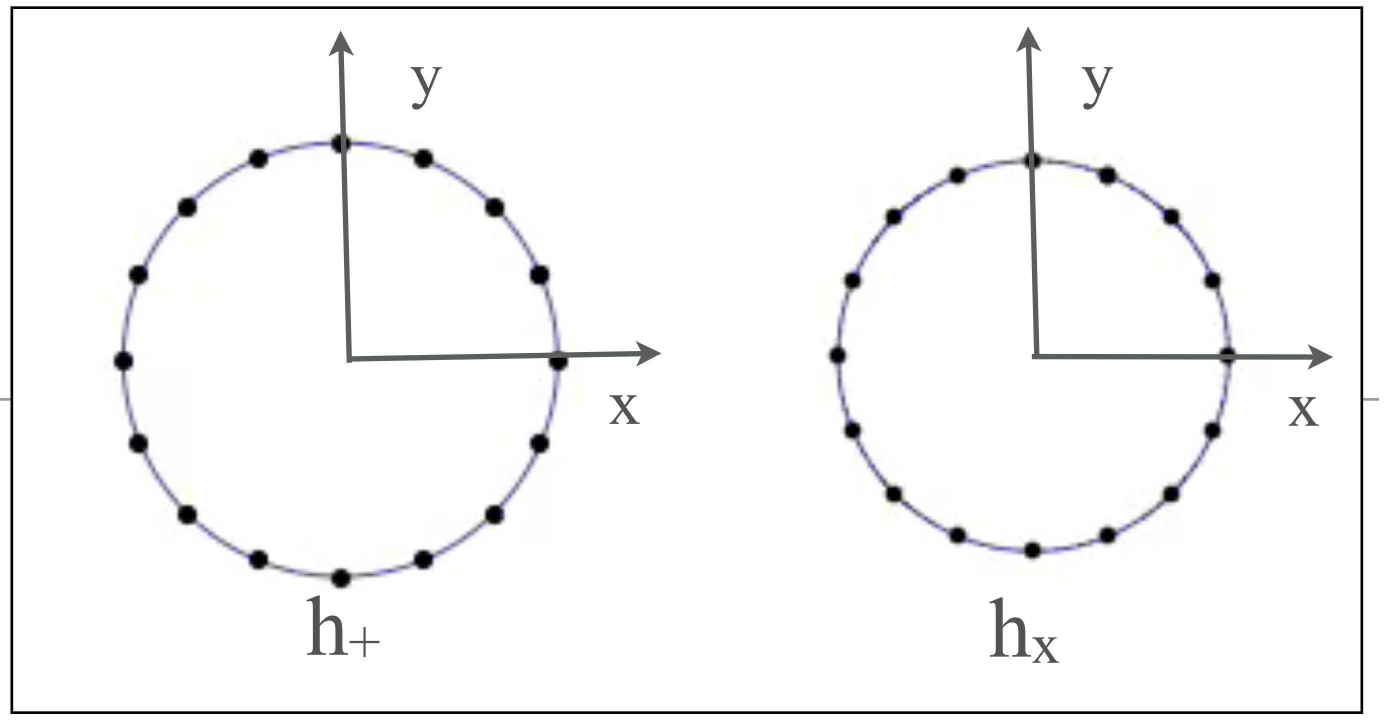
- Detector output (strain) is the differential deformation of arms

$$D^{ij} = \frac{1}{2}(\hat{x}_i \hat{x}_j - \hat{y}_i \hat{y}_j)$$

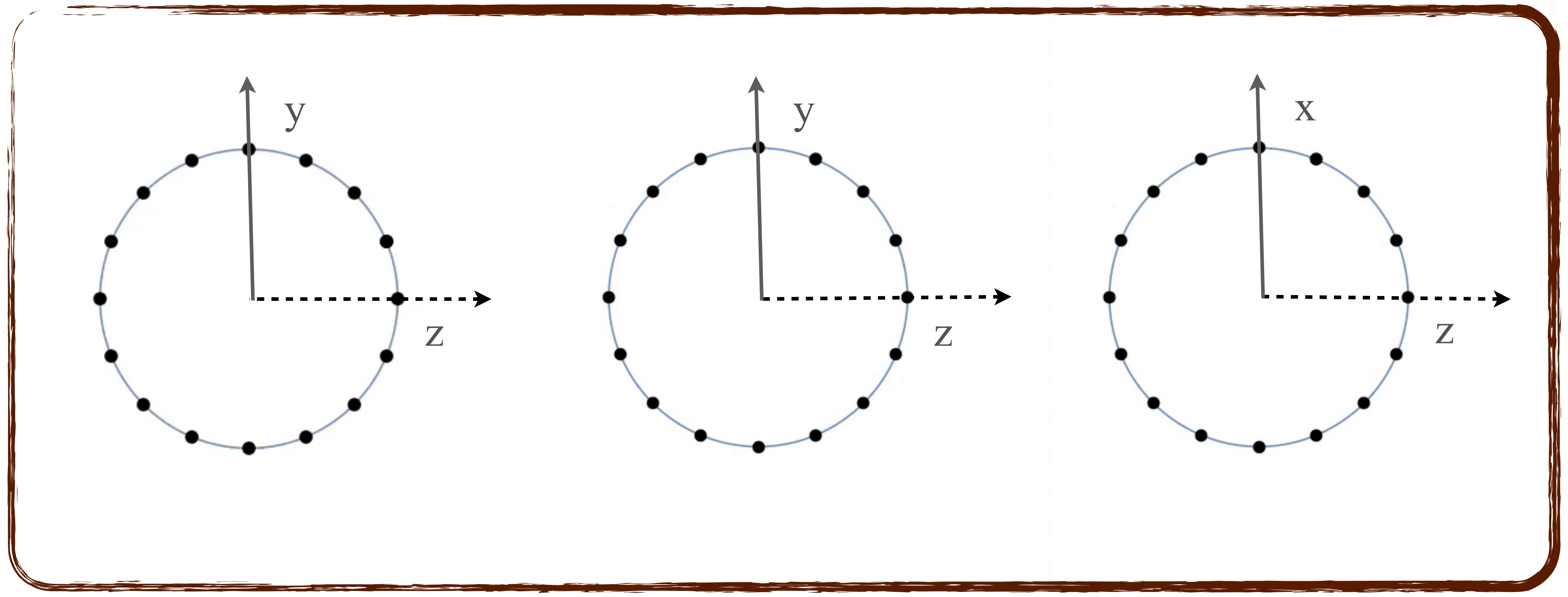


- With many IFOs we can resolve polarizations

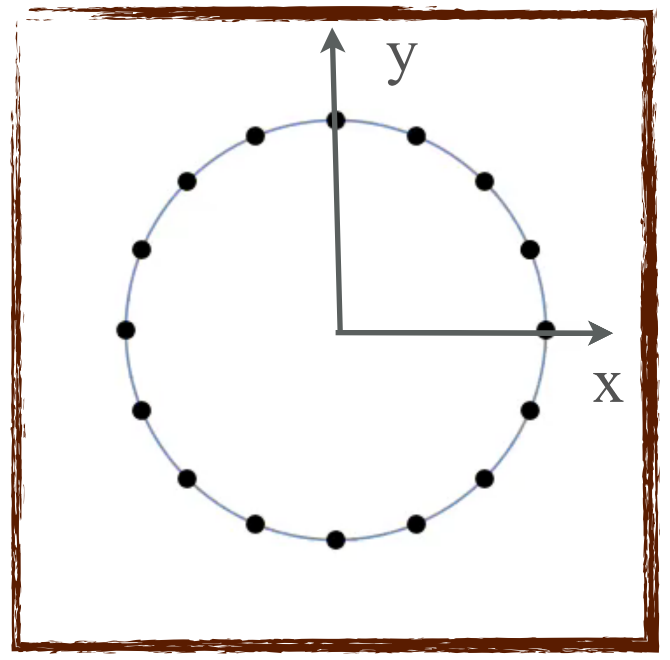
Anomalous polarizations



- GR predicts 2 transverse GW polarizations (+,x)
- Alternative metric theories allow for additional:
  - longitudinal modes
  - breathing mode



- With the 2 LIGO detectors: cannot tell the difference!
- Virgo, KAGRA (2019) and IndIGO will help resolve degeneracies between polarizations



[LVC PRL 119, 141101 (2017)]
[LVC arXiv:1811.00364]
[Isi, Weinstein arXiv:1710.03794]

Testing presence of nontensorial polarizations

LVC PRD **103**, 122002 (2021)
LVK [arXiv:2112.06861]

- Null-stream test without modelling the actual signal
- Any residual signal must be non-tensorial
- No evidence for nontensorial signal in data; scalar is more disfavoured

Events	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{S}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{V}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TV}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{VS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TVS}}$
O1	-0.04 ± 0.07	0.09 ± 0.07	0.04 ± 0.07	0.09 ± 0.07	0.09 ± 0.07	0.07 ± 0.07
O2	-0.42 ± 0.12	0.04 ± 0.12	0.08 ± 0.12	0.22 ± 0.12	0.09 ± 0.12	0.35 ± 0.12
O3a	-1.85 ± 0.21	-1.04 ± 0.20	0.25 ± 0.20	0.07 ± 0.20	-1.05 ± 0.20	-0.18 ± 0.20
O3b	-1.93 ± 0.17	-0.79 ± 0.17	-0.17 ± 0.17	-0.07 ± 0.17	-0.86 ± 0.17	-0.32 ± 0.17
Combined	-4.24 ± 0.30	-1.70 ± 0.30	0.20 ± 0.30	0.31 ± 0.30	-1.73 ± 0.30	-0.08 ± 0.30

Tests of Gravity with GW170817

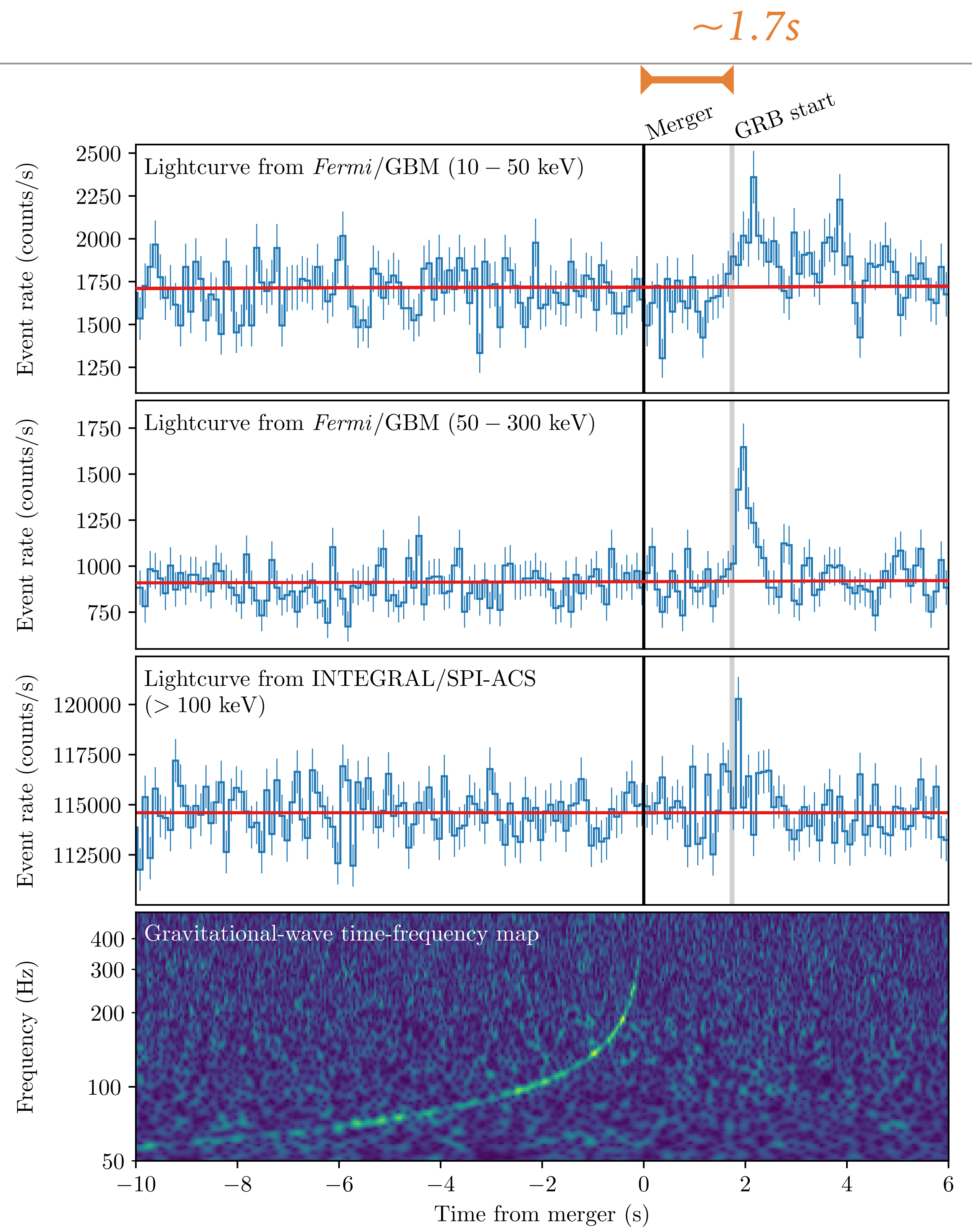
- Coincident GWs and γ-ray detections
- Distance travelled ~40 Mpc
- GW -> GRB time delay (+ reasonable astrophysical priors) =>

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

- Test of the equivalence principle (Shapiro time delay):

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

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



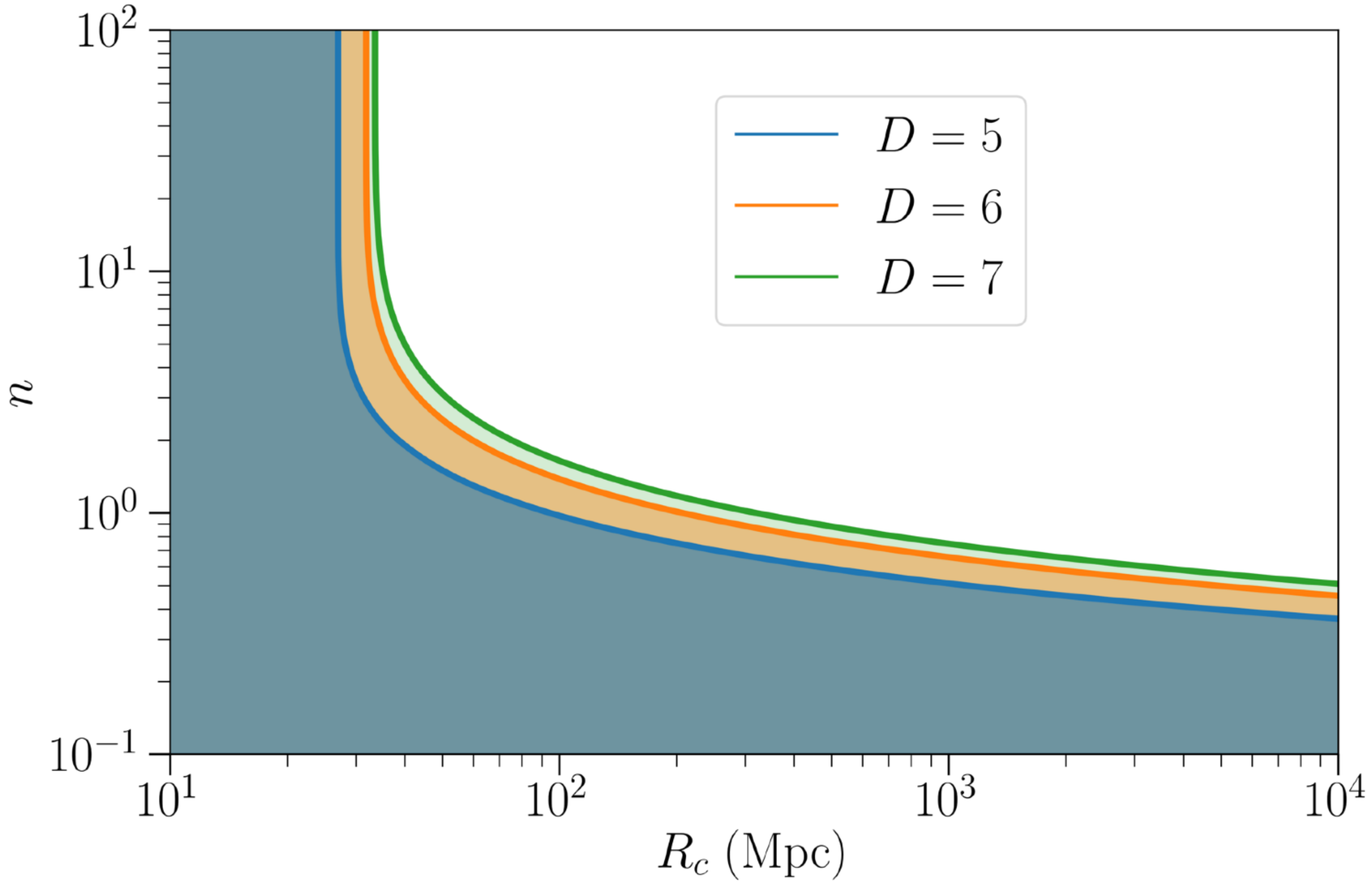
[LVC ApJ Lett. 848, L13 (2017)]

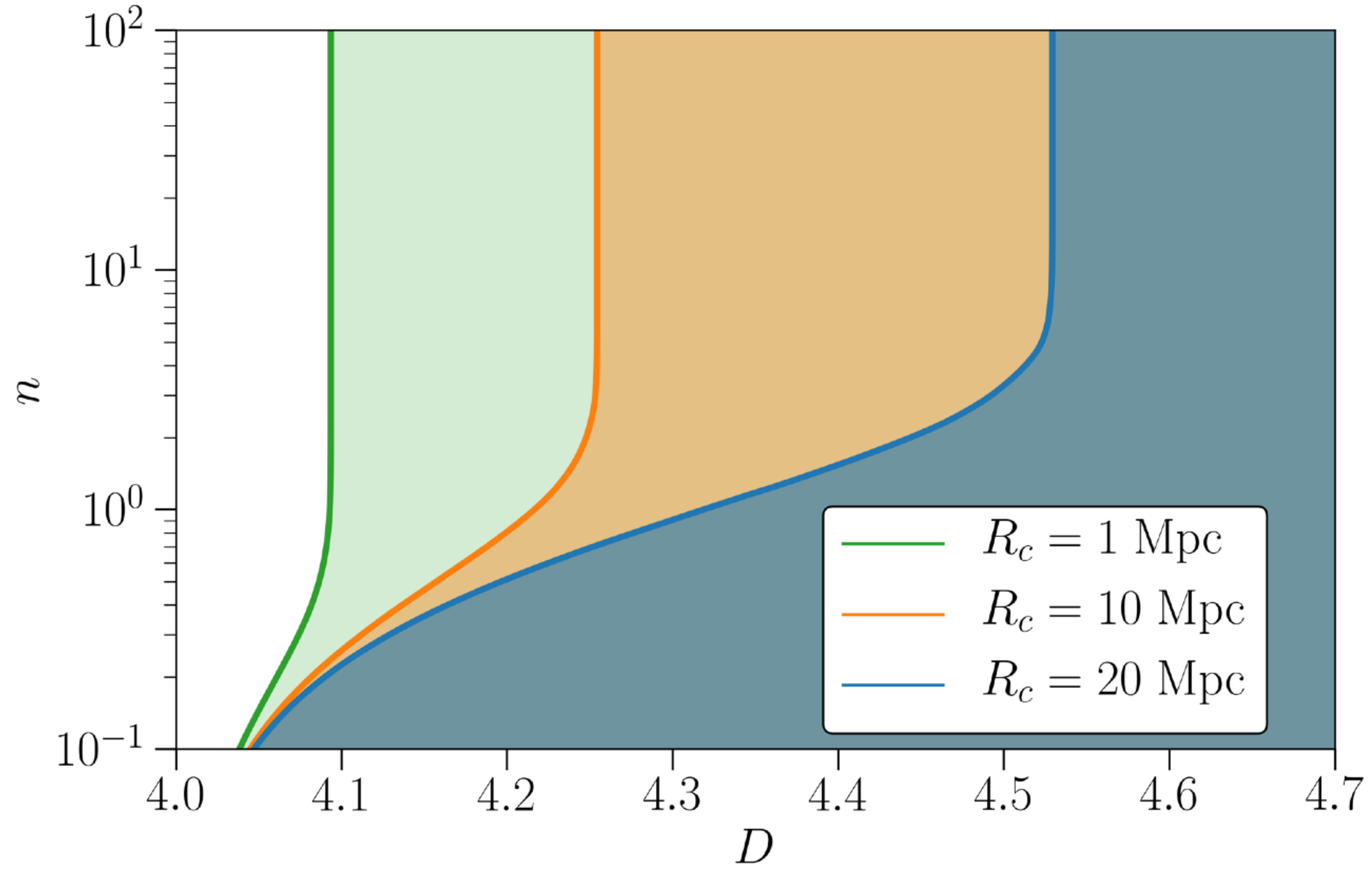
LVC 2018 [arXiv:1811.00364]

GW170817: Test of extra dimensions

- GW detection + EM identification of host galaxy -> independent measurements of distance to source
- In higher-dim gravity, GWs may “leak” into extra dimensions (larger effective distance)

$$h \propto \frac{1}{d_L^{GW}} = \frac{1}{d_L^{EM}}\left[1+\left(\frac{d_L^{EM}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

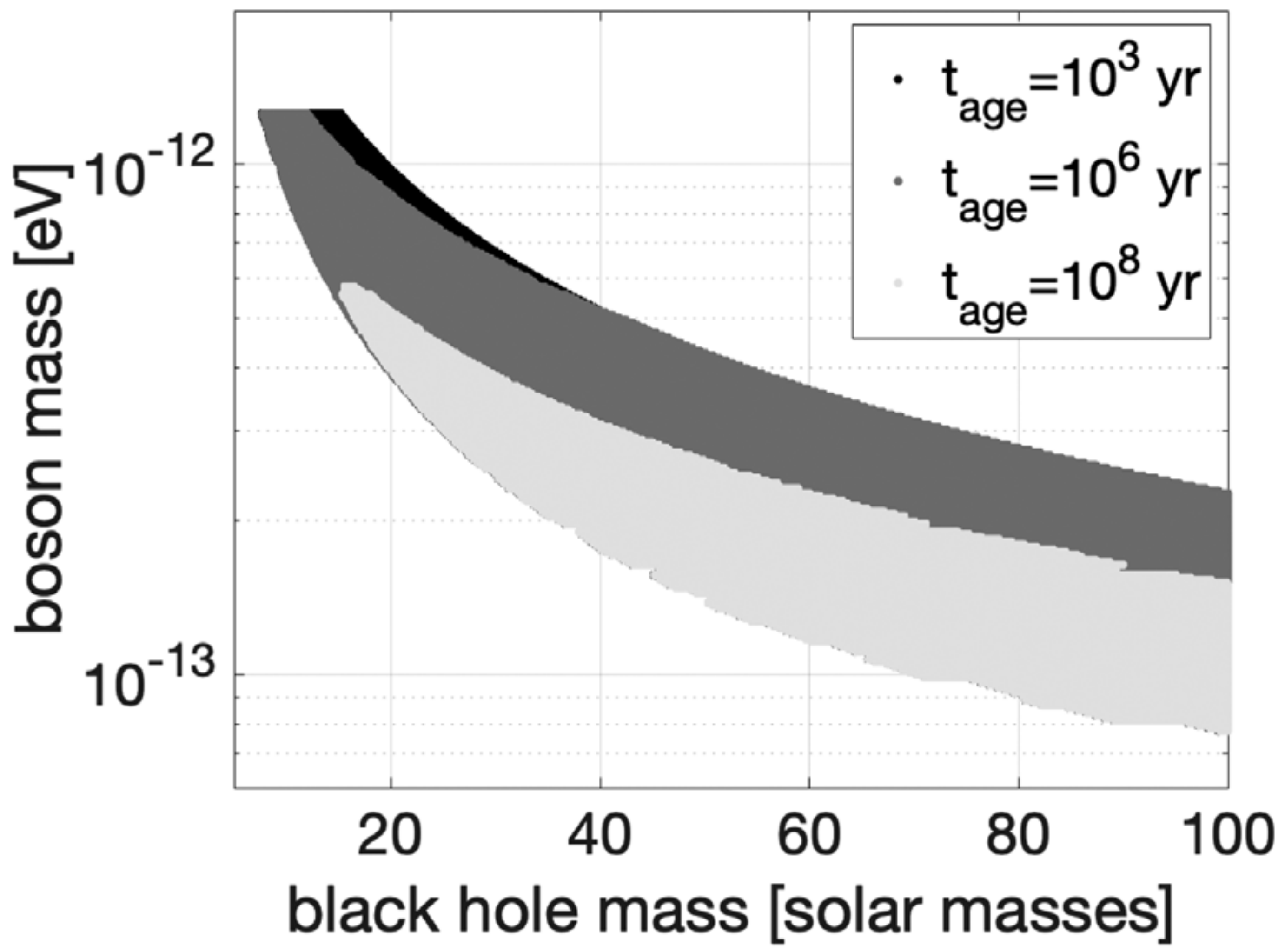




- screening out to “activation radius” R_c
- n: transition steepness
- Astrophysical length scales -> D=4
- Cosmological length scales ($R_c \sim R_H$):
  - slow transition (n~0.1): D=4
  - steep transition: unconstrained

Light bosons & BH Superradiance

- Growth of bosonic field with $\frac{\bar{h}c}{m_b} \simeq \frac{GM_{BH}}{c^2}$, stimulated by BH spin
  - Direct detection via CW emission
  - Indirect detection in population statistics (mass-spin plane)



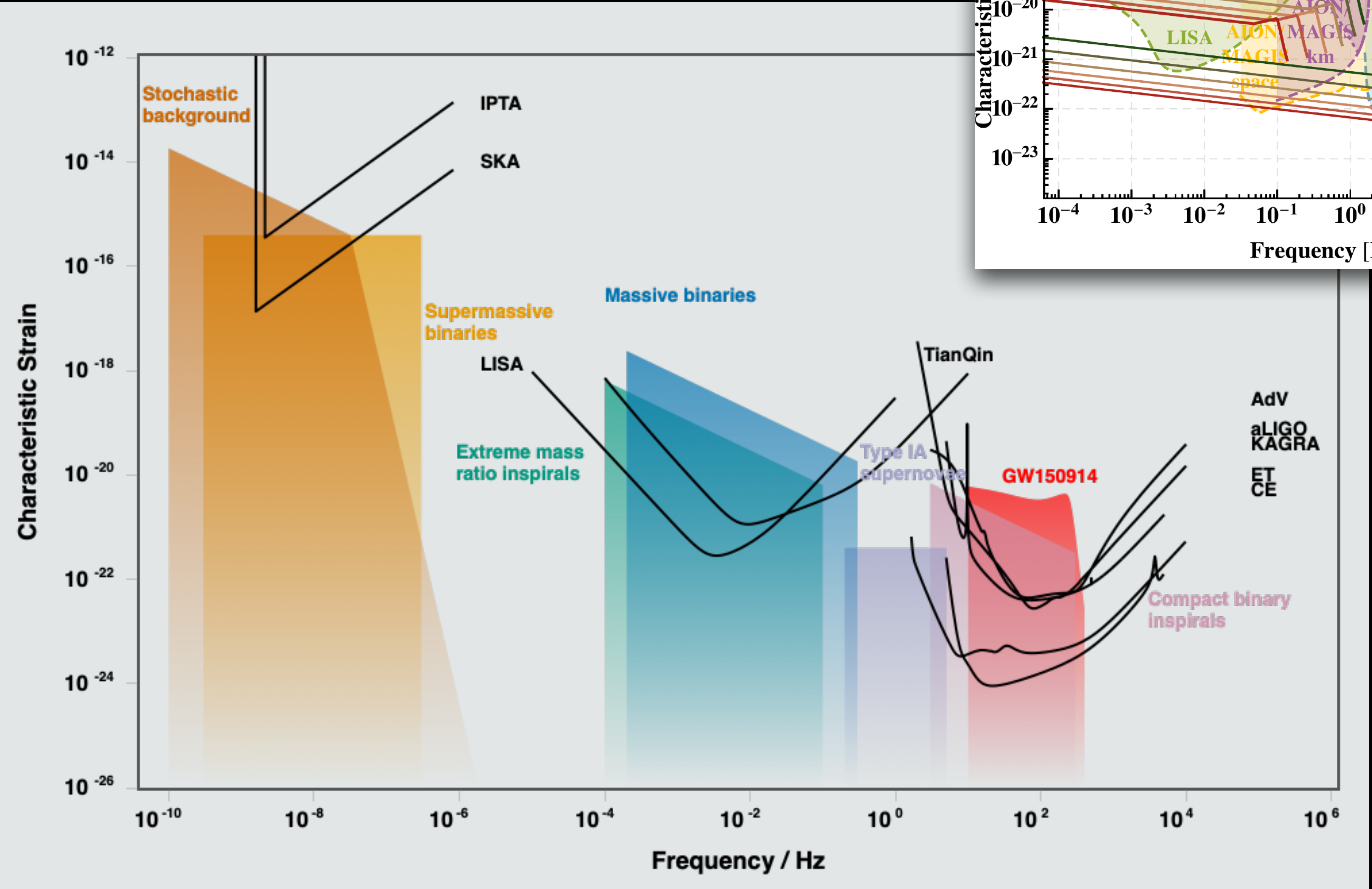
- LVK sets bounds on long-duration signals from UL scalars [PRD 105, 102001]
- Continuous wave emission during cloud decay phase
- Axionic case fits with mass ~ 10^{-13} - 10^{-12} eV

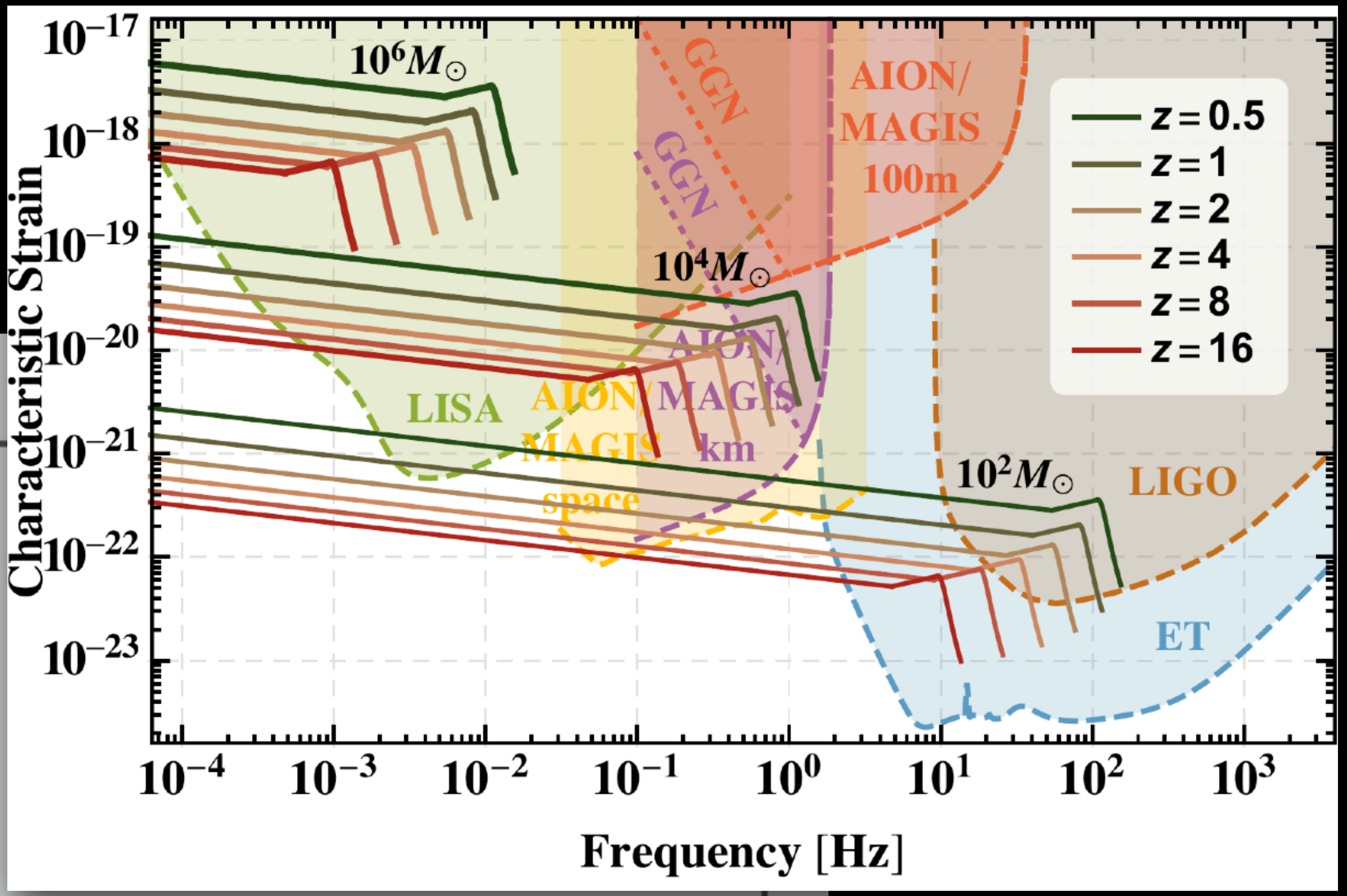
GW Phenomenology of New Physics

- Modified BH geometry (multipolar structure, QNMs)
- Modified binary dynamics
- Alternative polarizations (scalar, vector)
- Modified Dispersion Relation (massive, LIV)
- Speed of Gravity
- Superradiance (light boson)
- **Stochastics GW Background (cosmological/astrophysical)**
- **Phase transitions / topological defects**
- **Neutron star matter (composition, phase transitions)**
- **Stellar evolution**

FUTURE OF GW

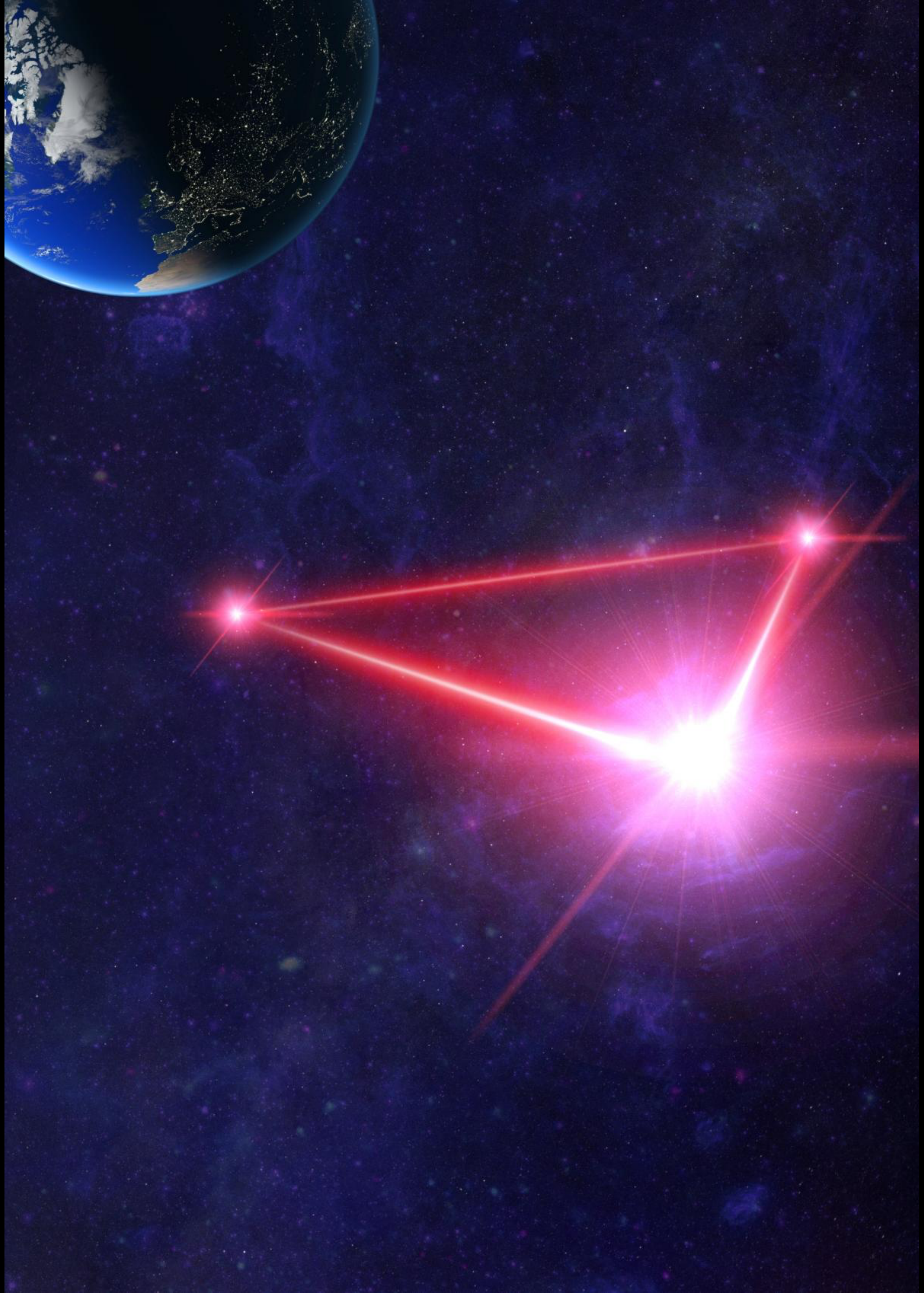
Detectors & Sources





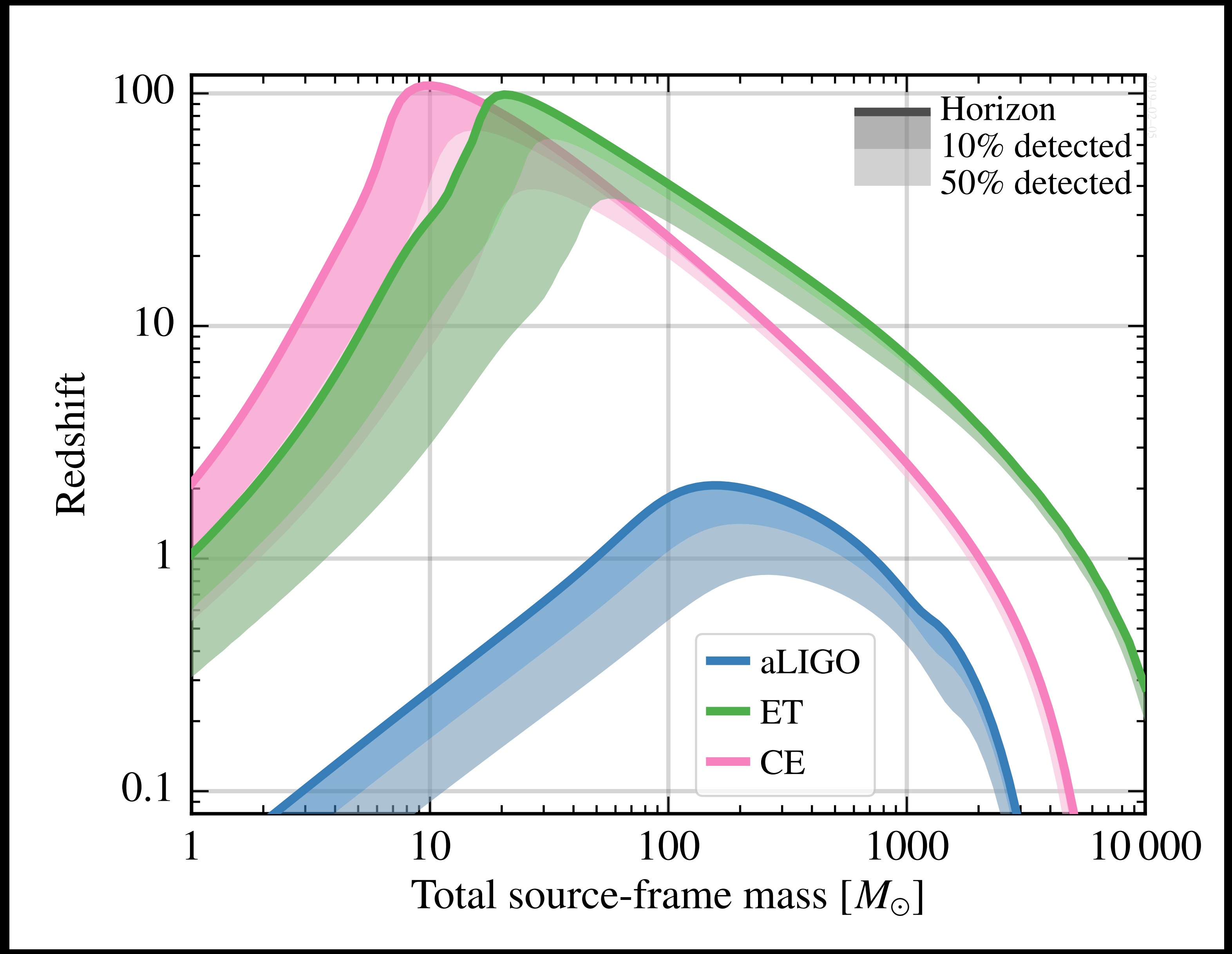
LISA (2034+)

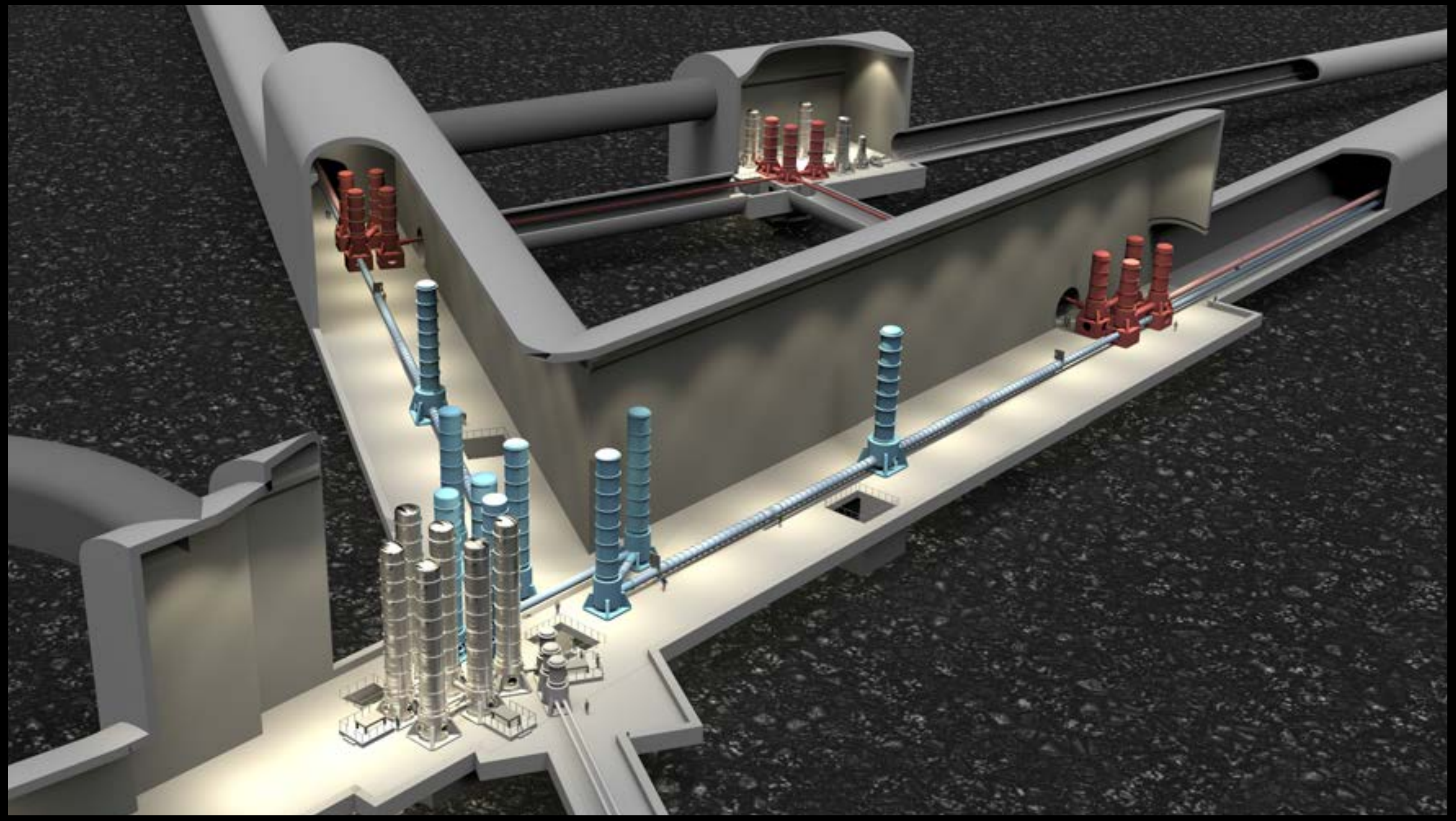
- Massive - Supermassive BBH mergers
- Horizon out to $z \sim 10 - 20$
- MMA for transients
- Tests of GR
- Precision Black-Hole Spectroscopy
- Probe of MBH environment, DM halos, disks, etc
- Cosmology
- Physics in the Early Universe
  - Phase transitions
  - Cosmic string networks



EINSTEIN TELESCOPE

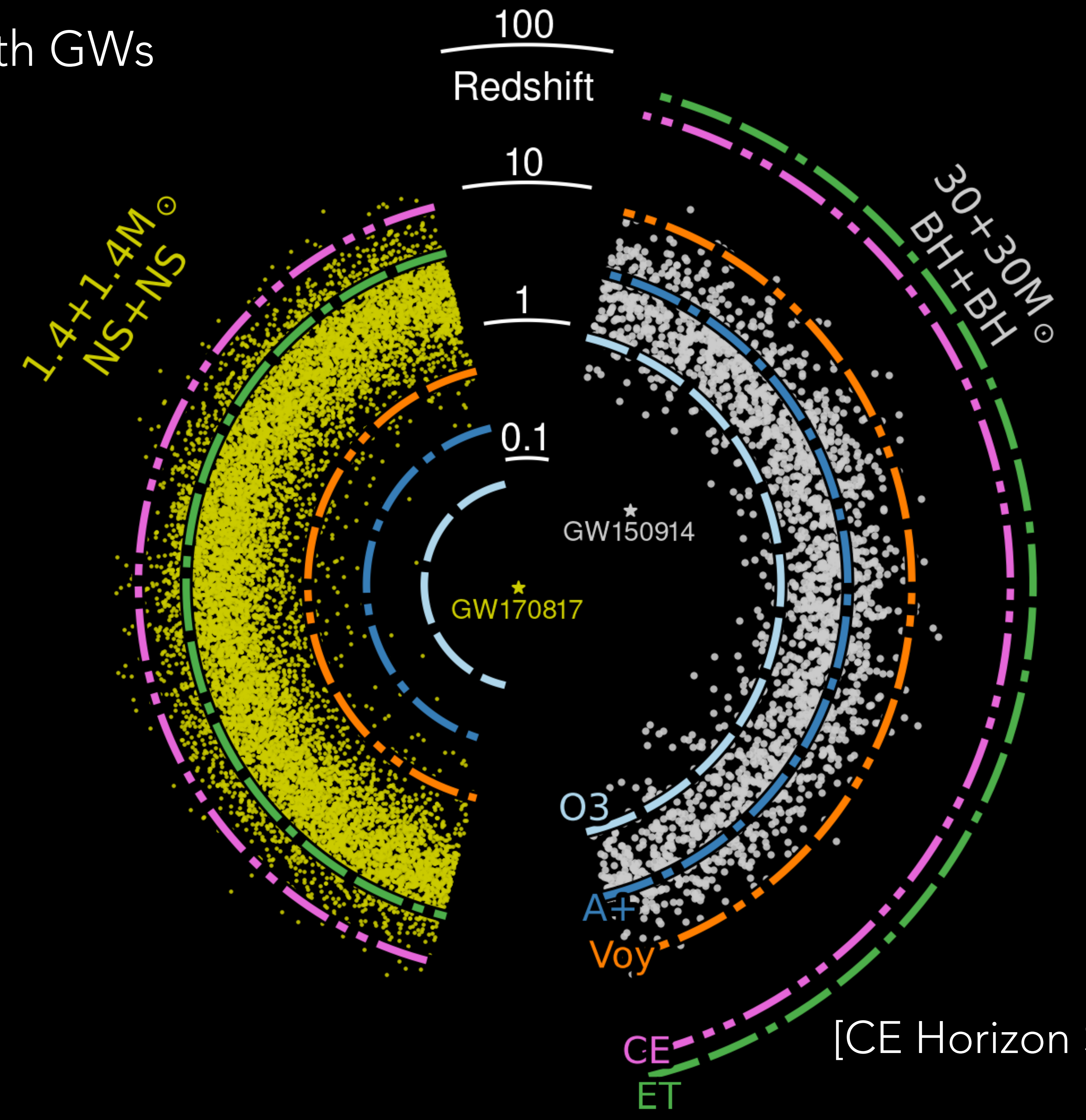
- On the ESFRI Roadmap
- Candidate Sites:
  i. Euregio Meuse-Rhine (NL) ii. Sardinia (IT)
- Scientific Consortium forming NOW!
- 10 km arm lengths
- Triangular shape
- Underground
- Cryogenic optics
- Improved sensitivity @ high- & low-freq
- Increase in sensitivity by O(10)





THE SCIENCE OF 3G DETECTORS

- Multimessenger Astronomy with GWs
  - 100,000 - 1,000,000 CBC sources/yr
  - Improved Sky Localization for EM-bright transients
  - Early warning for transient events (e.g. BNS)
  - Multi-band detections (LISA -> AION -> ET/CE)
  - Supernova event detection
- Fundamental Physics
  - Tests of GR vs Modified Gravity
  - Precision BH Spectroscopy
  - Near-horizon physics & Exotic Compact Objects
  - Fundamental fields, DM, DE
  - Tight constraints on NS matter and EoS (pre- & post-merger)
- Cosmology
  - Cosmography with high-z population of sources
  - Stochastic backgrounds (cosmological/astrophysical)
  - Tests of ΛCDM with GWs
  - Cosmic strings
  - GW Lensing



[CE Horizon Study 2021]

DATA AVAILABLE ONLINE!

- Detector strain data & more
  www.gw-openscience.org
- Data release GWTC-2
  https://dcc.ligo.org/LIGO-P2000438/public
- Full posterior samples GWTC-2
  https://zenodo.org/record/5172704#.YTOaSC1h2Zw