Putting Einstein to the test with Gravitational Wave Observations

eXtreme Gravity Institute

Neil J. Cornish

NANOGrav

LSC LIGO Scientific Collaboration

VIRGO

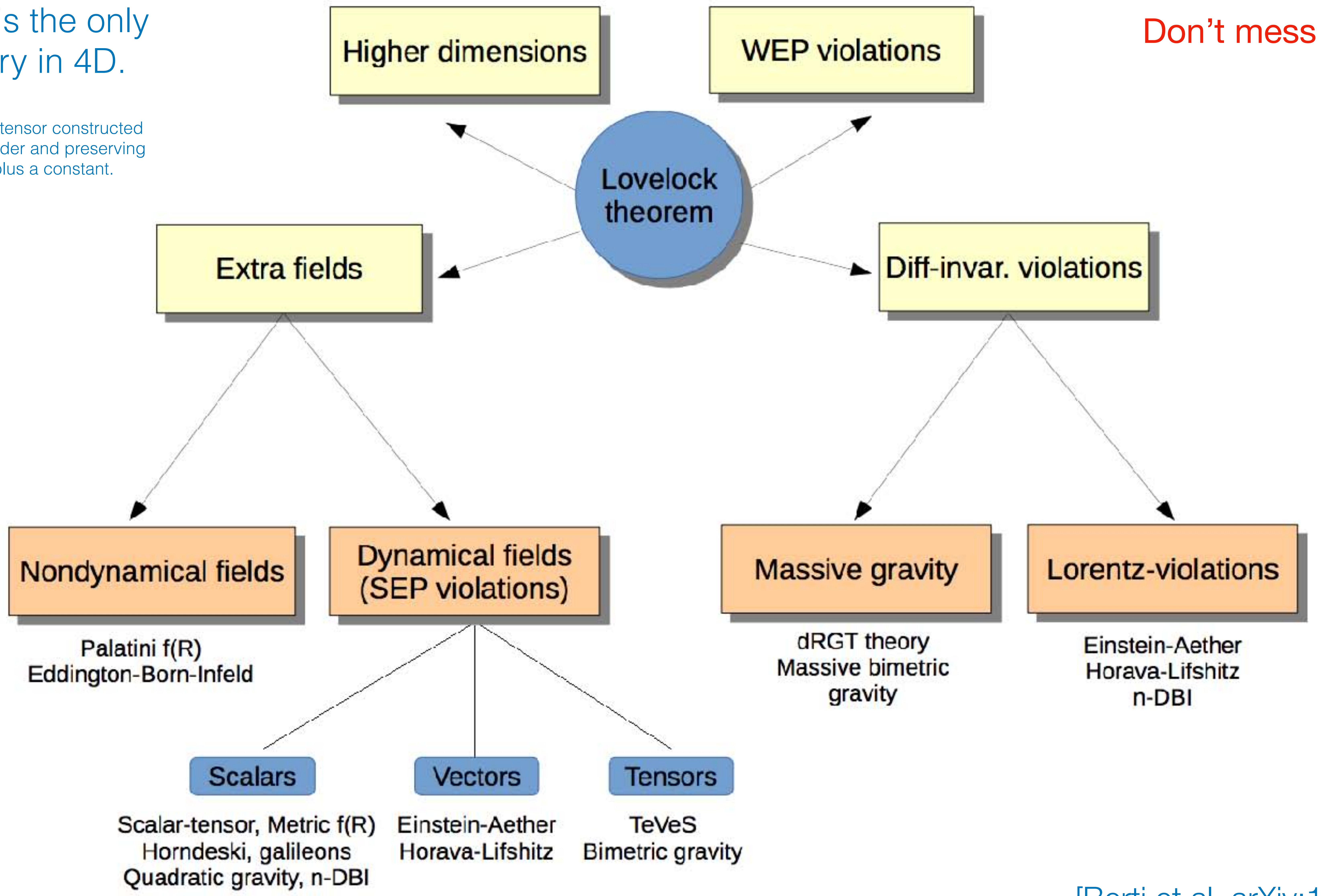
Outline

- Theoretical Landscape
- Observational landscape
- First look at dynamical strong field gravity
- Polarization
- Future prospects

Theoretical Landscape

Lovelock theorem: GR is the only "nice" purely metric theory in 4D.

In 4D, the only divergence free symmetric rank-2 tensor constructed only by the metric and its derivatives up to 2nd order and preserving diffeomorphism invariance is the Einstein tensor plus a constant.



Don't mess with WEP!

[Berti et al, arXiv:1501.07274]

Rouges Gallery of Alternative Theories

Theory	Field content	Strong EP	Massless graviton	Lorentz symmetry	Linear $T_{\mu\nu}$	Weak EP
Extra scalar field						
Scalar-tensor	S	✗	✓	✓	✓	✓
Multiscalar	S	✗	✓	✓	✓	✓
Metric $f(R)$	S	✗	✓	✓	✓	✓
Quadratic gravity						
Gauss-Bonnet	S	✗	✓	✓	✓	✓
Chern-Simons	P	✗	✓	✓	✓	✓
Generic	S/P	✗	✓	✓	✓	✓
Horndeski	S	✗	✓	✓	✓	✓
Lorentz-violating						
Æ-gravity	SV	✗	✓	✗	✓	✓
Khronometric/ Hořava-Lifshitz	S	✗	✓	✗	✓	✓
n-DBI	S	✗	✓	✗	✓	✓
Massive gravity						
dRGT/Bimetric	SVT	✗	✗	✓	✓	✓
Galileon	S	✗	✓	✓	✓	✓
Nondynamical fields						
Palatini $f(R)$	–	✓	✓	✓	✗	✓
Eddington-Born-Infeld	–	✓	✓	✓	✗	✓

[Berti et al, arXiv:1501.07274]

Popular Examples

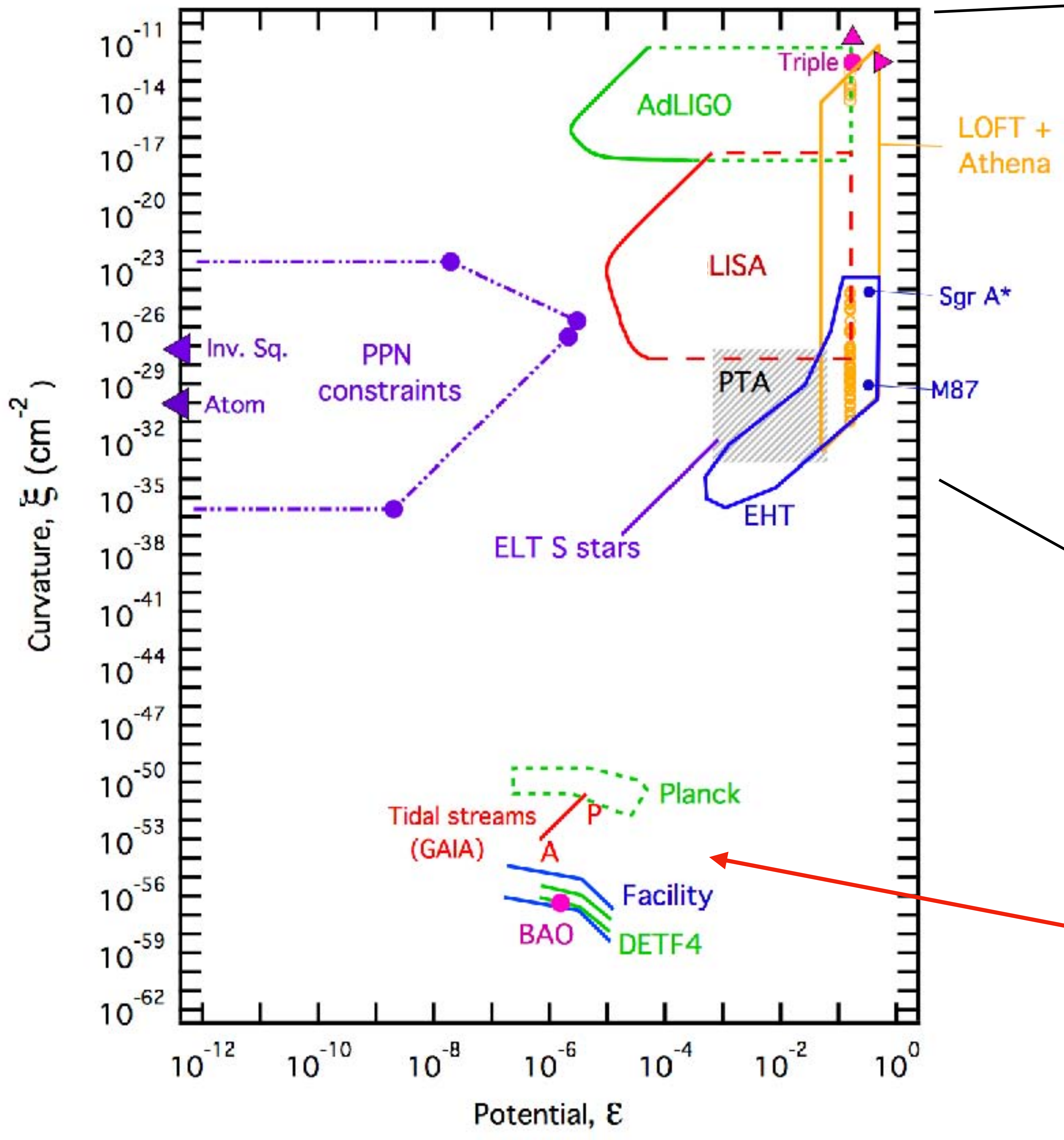
Ultraviolet Modifications (e.g. EdGB, dCS)

$$S = \frac{1}{16\pi}\int \sqrt{-g}\, d^4x \Big[R - 2\nabla_\mu\phi\nabla^\mu\phi - V(\phi) + S_{\rm mat}\left[\Psi,\, \gamma(\phi) g_{\mu\nu}\right] + f_1(\phi)R^2 + f_2(\phi)R_{\mu\nu}R^{\mu\nu} + f_3(\phi)R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + f_4(\phi)\,{}^*RR \Big]$$

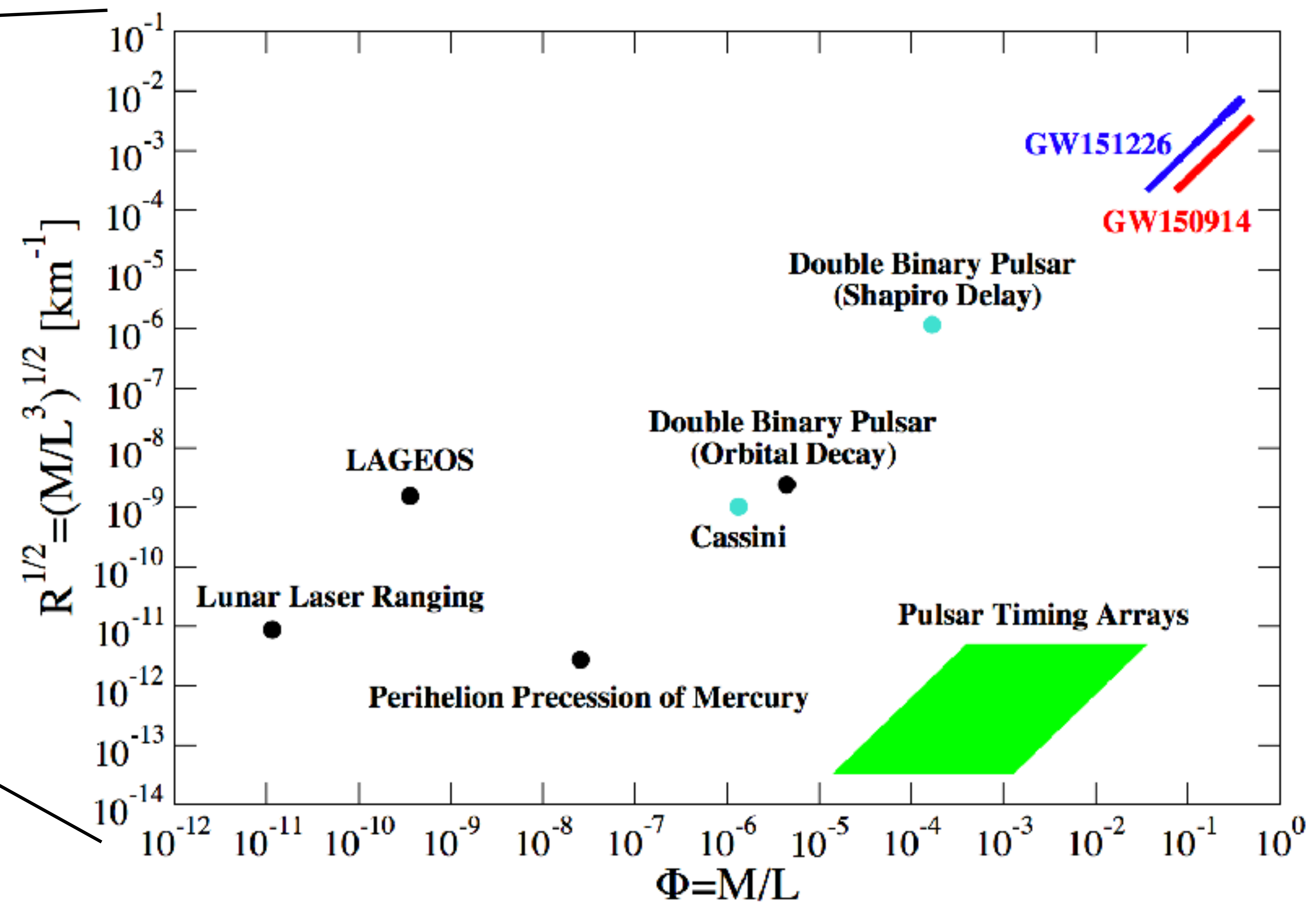
Infrared (screened) Modifications (e.g. Horndeski)

$$\begin{aligned} S = \int d^4x\sqrt{-g}\Big\{ & K(\phi, X) - G_3(\phi, X)\Box\phi \\ & + G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right] \\ & + G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}(\phi, X)}{6}\big[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) \\ & + 2(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla_\sigma\phi)(\nabla^\nu\nabla^\sigma\phi)\big]\Big\} \end{aligned}$$

Observational Landscape



[Baker, Psaltis, Skordis, arXiv:1412.3455]



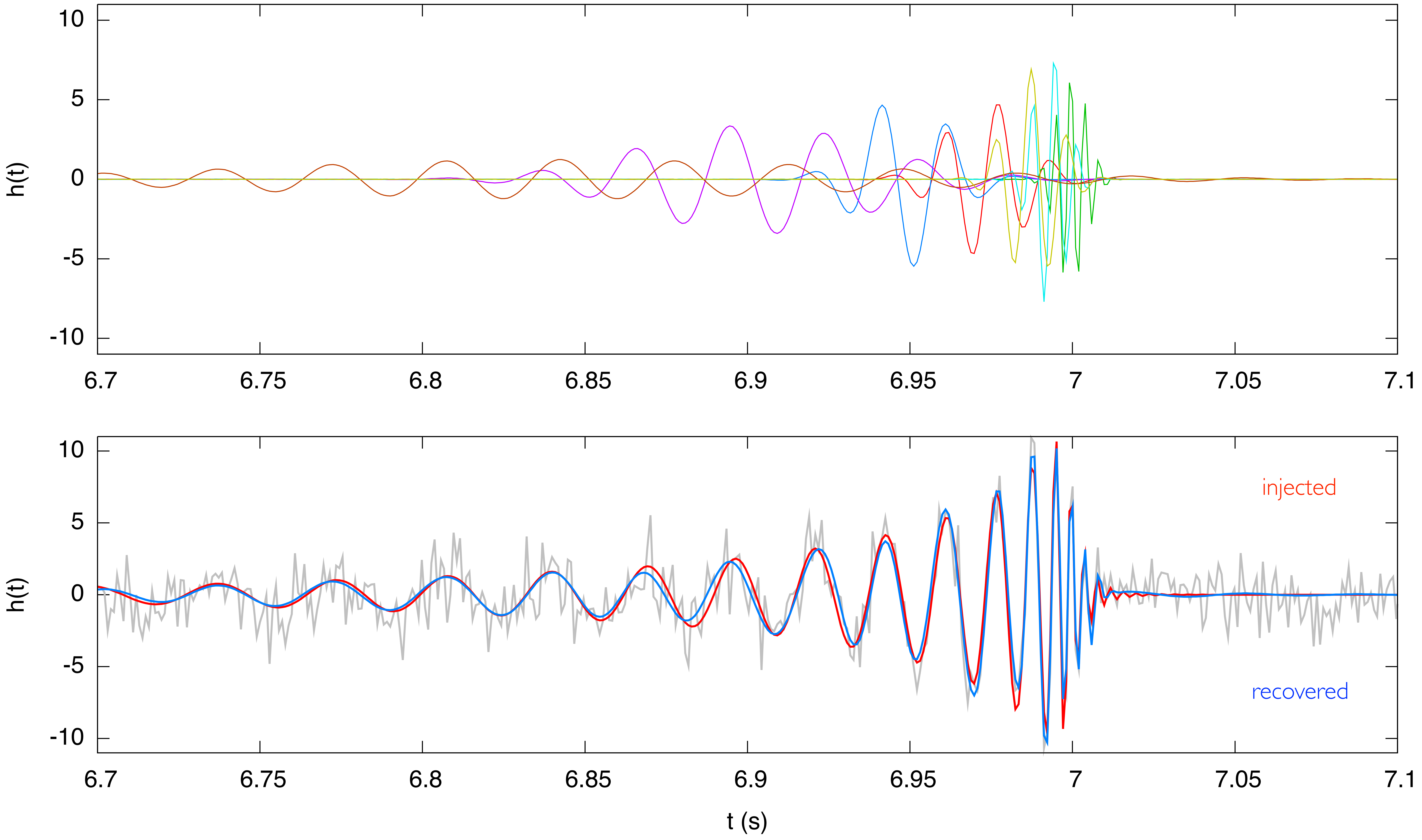
[Yunes, Yagi, Pretorius, arXiv:1603.08955]

Dark energy alternatives,
screening mechanisms required

Null Tests, Generic Tests

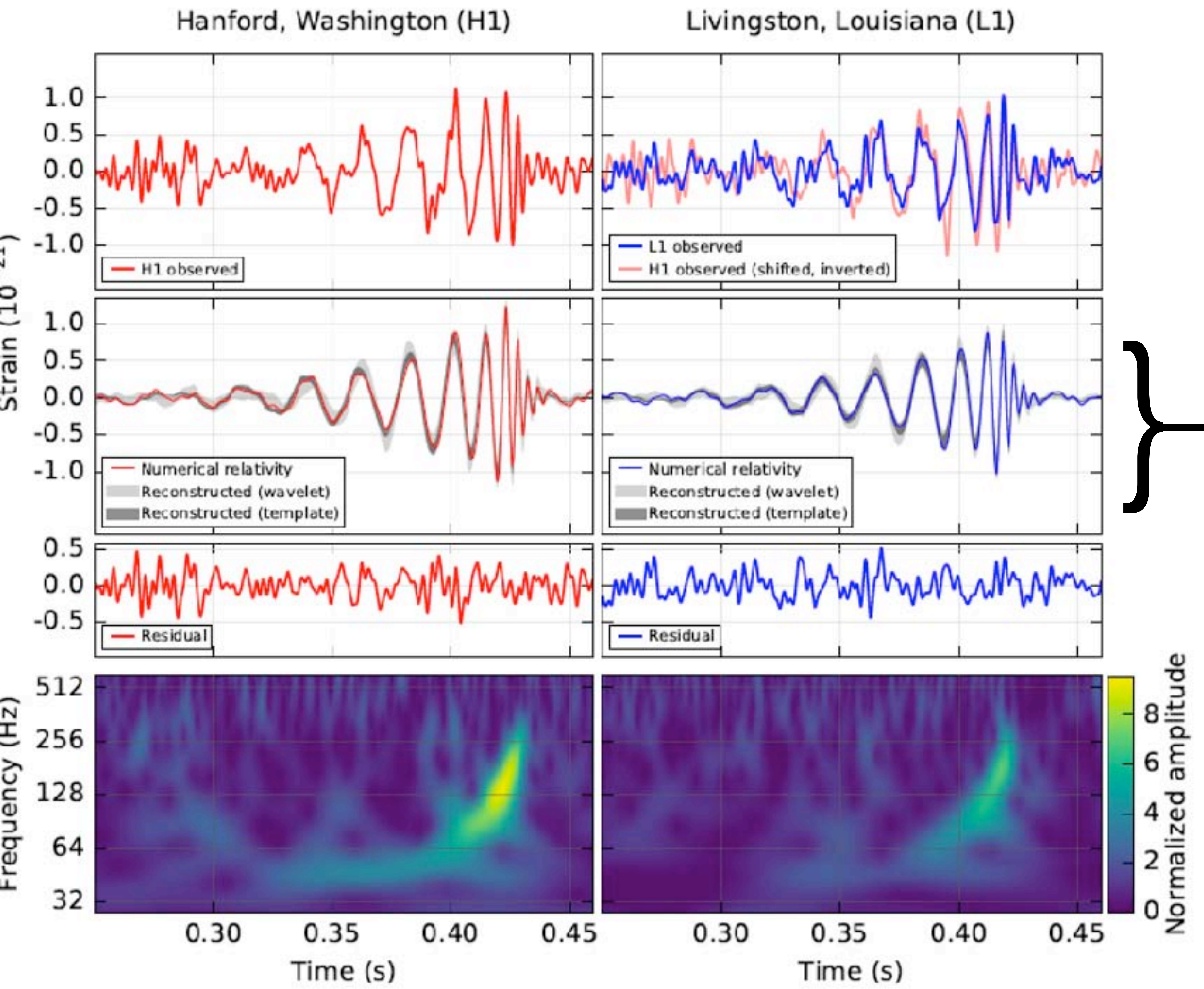
- Lacking compelling alternatives, prefer generic null tests
- Do GR models leave behind a residual signal?
- Parameterize possible departures from GR waveforms
- Search for additional polarization states
- Ringdown - GR predicts unique relationship between harmonics

Morphology-independent signal reconstruction

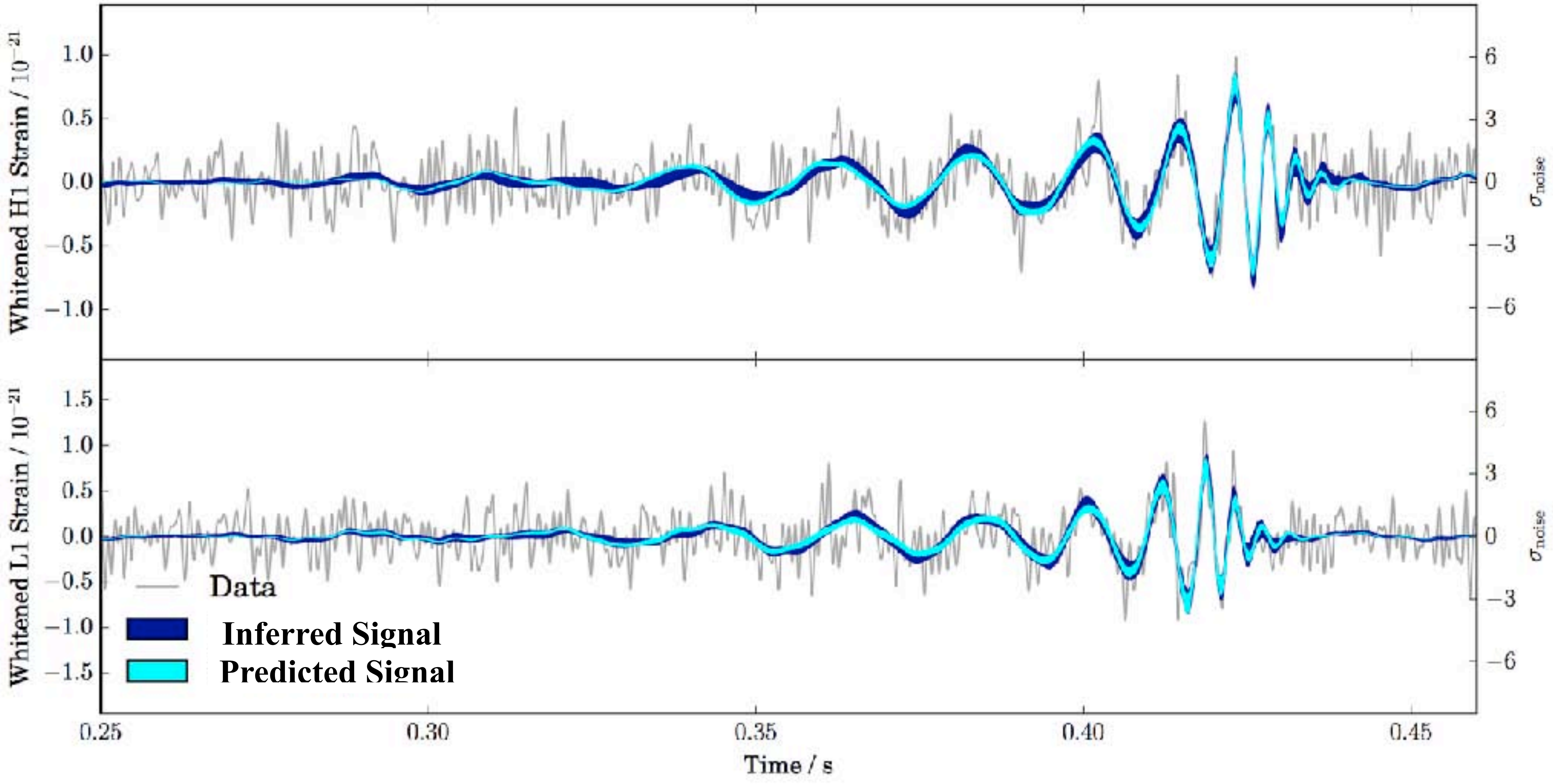


[Cornish & Littenberg, arXiv:1410.3835]

Extracting signals without templates



The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1,
olumn panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series



94% match with GR waveform

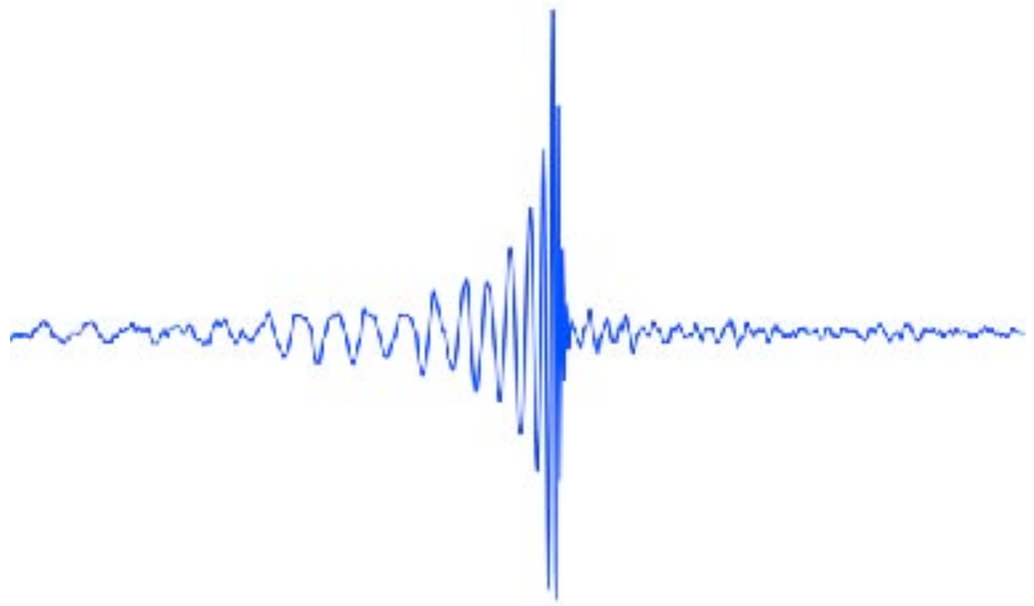
(discrepancy consistent with what we expect from noise)

[LVC, PRL**116**, 061102 (2016); PRL **116** 221101, (2016)]

Search for Residual Signals

data

-



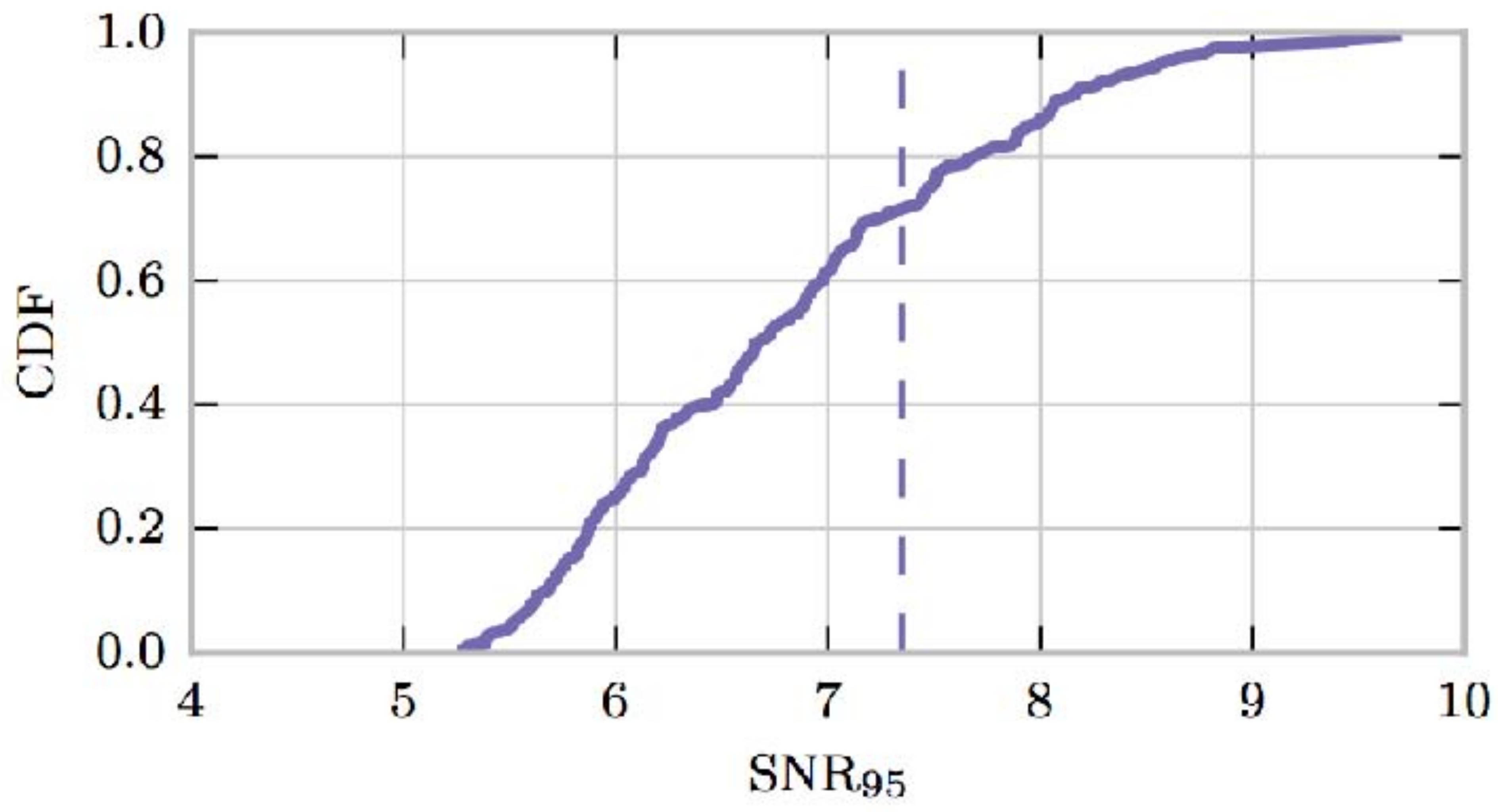
signal

=

noise

$$\mathcal{F} = \sqrt{1 - \frac{\mathrm{SNR}^2_{\mathrm{res}}}{\mathrm{SNR}^2}} > 0.96$$

Deviations from GR < 4%



$\mathrm{SNR}_{\mathrm{res}} < 7.3$

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

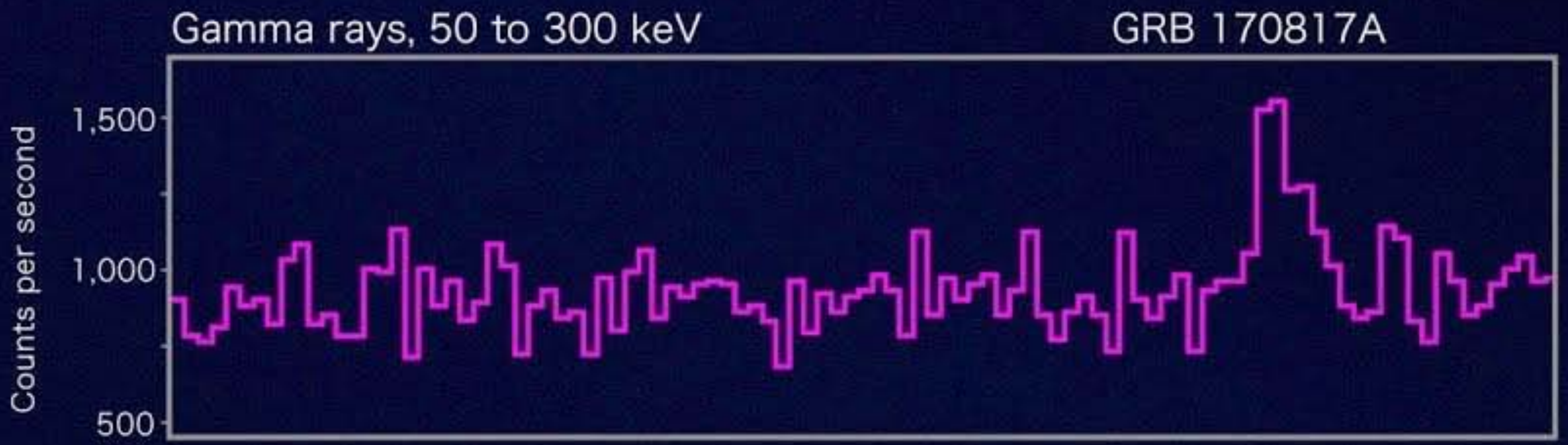
Gravitational Wave Observations

- Do gravitational waves travel at the speed of light?
- Is the emission of energy and angular momentum as predicted by GR?
- Is the graviton massless?
- Are gravitational waves transverse?
- Additional polarization states?
- Did anyone hear an echo?

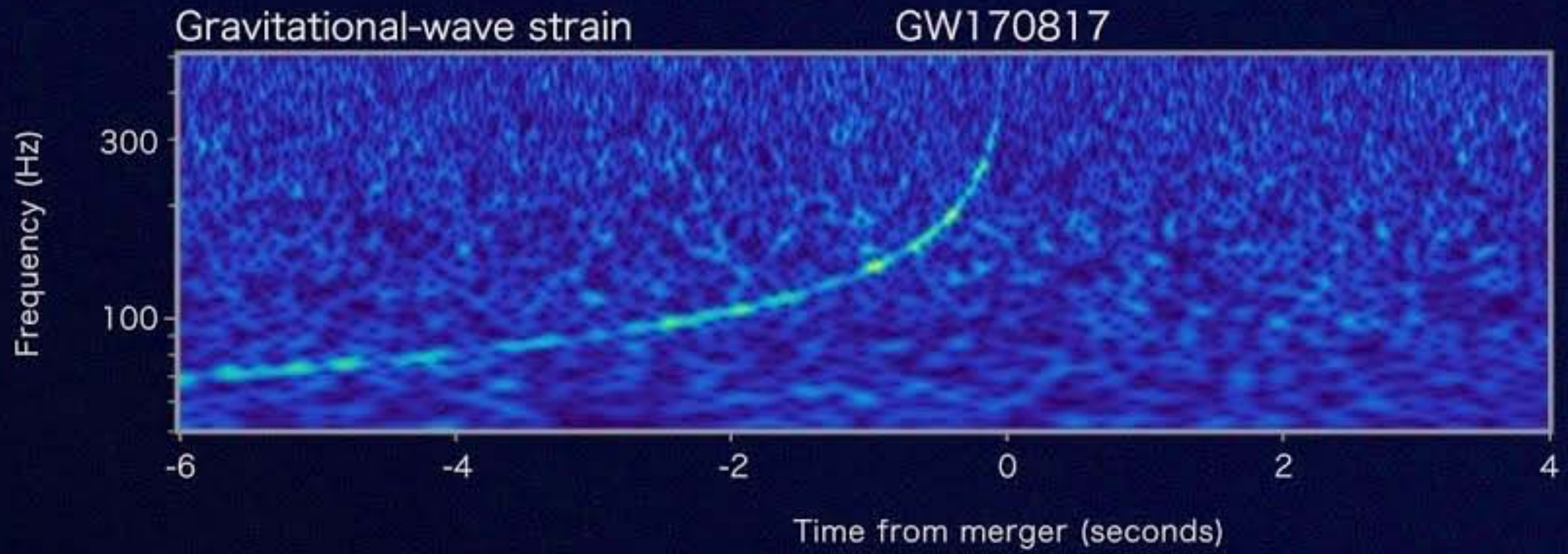
Gravitational Waves Travel at the Speed of Light

$$c_{\rm gw} = 1^{+7\times10^{-16}}_{-3\times10^{-15}}$$

Fermi



LIGO



[LIGO/Virgo/Fermi, ApJ Lett 848 (2017)]

Bad news for many dark energy alternatives

e.g. Horndeski

$$S = \int d^4x\sqrt{-g}\Big\{K(\phi,X) - G_3(\phi,X)\Box\phi$$

$$+ G_4(\phi,X)R + G_{4,X}(\phi,X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right]$$

$$+ G_5(\phi,X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}(\phi,X)}{6}\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right.$$

$$\left. + 2(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla_\sigma\phi)(\nabla^\nu\nabla^\sigma\phi)\right]\Big\}$$

[Creminelli, Vernizzi, arXiv:1710.05877, Sakstein, Jain, arXiv:1710.05893, Baker et al, arXiv:1710.06394]

Many models that could potentially explain the accelerated expansion yet evade solar system constraints via screening have been ruled out

One way out might be to build models that change behavior with length scale rather than density since $\lambda_{\rm gw} \ll R_H, \quad D_L \ll R_H$

[Battye, Pace, Trinh, arXiv:1802.09447]

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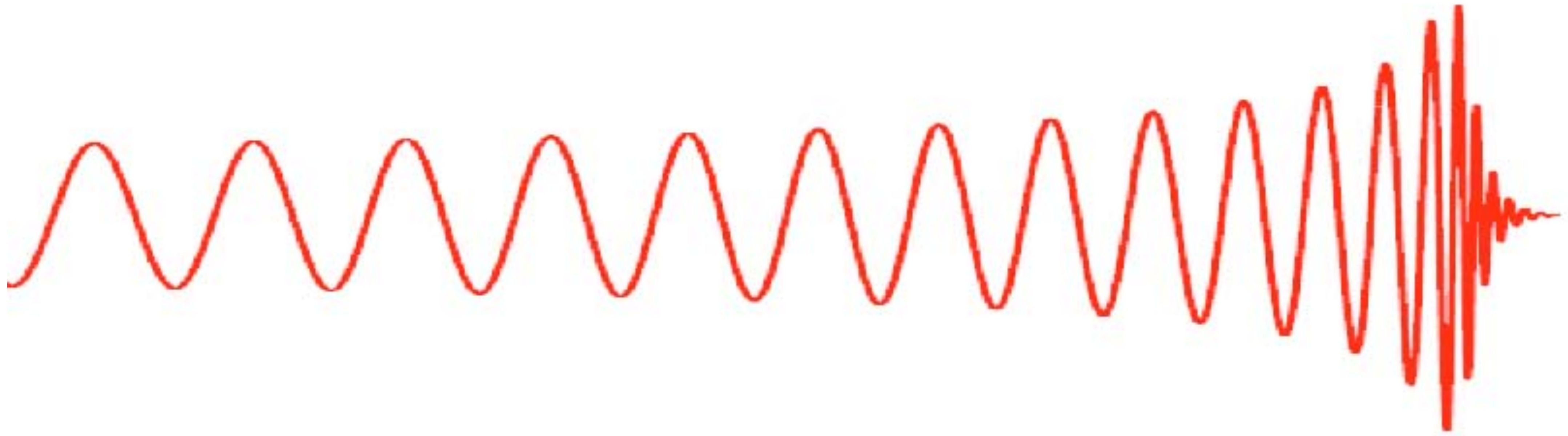
Is the emission of energy and angular momentum as predicted by GR?



$$h(f) = \mathcal{A}(f)\, e^{i\Psi(f)}$$

Post-Newtonian Inspiral

$$\mathcal{A}_{\rm GR}(f) = \sqrt{\frac{5}{96}} \frac{\mathcal{M}^{5/6}}{D\,\pi^{2/3}}\, f^{-7/6}$$

$$\Psi_{\rm GR} = 2\pi f t_c + \Phi_c + \frac{\pi}{4} + \sum_{k=-5} \psi_k\, u^k$$

$$u = (\pi \mathcal{M} f)^{1/3} \sim v$$

Modified Waveforms

$$\mathcal{A}(f) = \sqrt{\frac{5}{96}\frac{\mathcal{M}^{5/6}}{D\,\pi^{2/3}}} f^{-7/6}\left(1 \;\; -\frac{5}{512}\dot{G}\mathcal{M}u^{-8} \;\; + \left(\frac{743}{672} + \frac{11}{8}\eta\right)\eta^{-2/5}u^2 + \ldots\right)$$

Variable G

Scalar Field

$$\Psi(f) = 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}u^{-5}\Big[1 \;\; -\frac{25}{1536}\dot{G}\mathcal{M}u^{-8} \;\; -\frac{5}{84}\frac{S^2}{\omega_{\mathrm{BD}}}\eta^{3/5}u^{-2}$$

$$+\left(\frac{3715}{756} + \frac{55}{9}\eta\right)\eta^{-2/5}u^2 - 16\pi\eta^{-3/5}u^3 \;\; -\frac{128}{3}\frac{\pi^2 D\mathcal{M}}{\lambda_g^2(1+z)}u^2 \;\; + \ldots\Big]$$

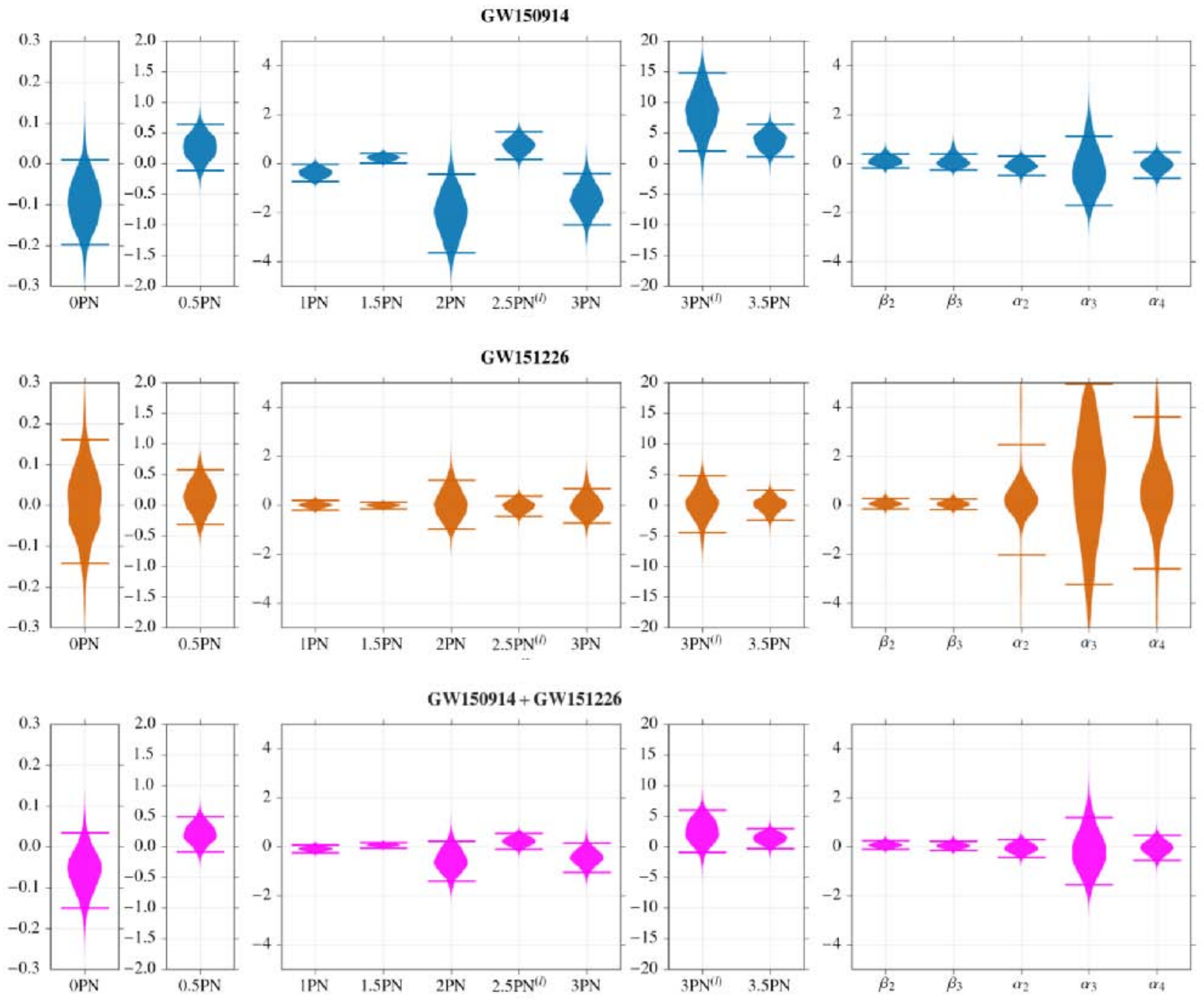
Massive Graviton

$$h(f) = (1 + \delta\mathcal{A}(f))\, e^{i\delta\Psi(f)}\, h_{\mathrm{GR}}(f)$$

Parametrized Post-Einsteinian

[Yunes, Pretorius, arXiv:0909.3328]
[Arun, Iyer, Qusailah, Sathyaprakash, arXiv:gr-qc/0604018]

No deviations seen from GR phasing



$\frac{\delta\psi_k}{\psi_k}$

Inspiral

Merger-ringdown

[LVC, arXiv:1602.03841, arXiv:1606.04856]

Caveat emptor:

These bounds are term-by-term (not jointly allowed to vary)

Bounds would be weaker if all terms allowed to vary together

[Sampson, Cornish, Yunes, arXiv:1303.1185]

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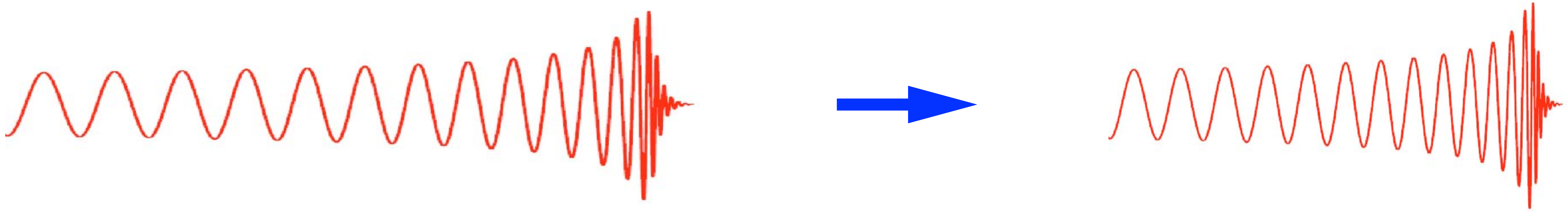
Is the graviton massless?

"Chirp Squeezing" - higher frequency signal from near the merger travels faster and arrive earlier

$$c_{\rm gw}^2 = c_{\rm gw,0}^2 \left(1 - \frac{m_g^2}{E^2}\right)$$



$$\Psi(f) = 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128} u^{-5} \left[1 + \left(\frac{3715}{756} + \frac{55}{9}\eta\right) \eta^{-2/5} u^2 - 16\pi\eta^{-3/5} u^3 - \frac{128}{3} \frac{\pi^2 D \mathcal{M}}{\lambda_g^2 (1+z)} u^2 + \ldots\right]$$

Partially degenerate with changing the total mass
Degeneracy mostly broken by higher PN terms and merger

$$m_g < 1.2 \times 10^{-22}\ \mathrm{eV}$$

[LVC, arXiv:1602.03841, arXiv:1606.04856]

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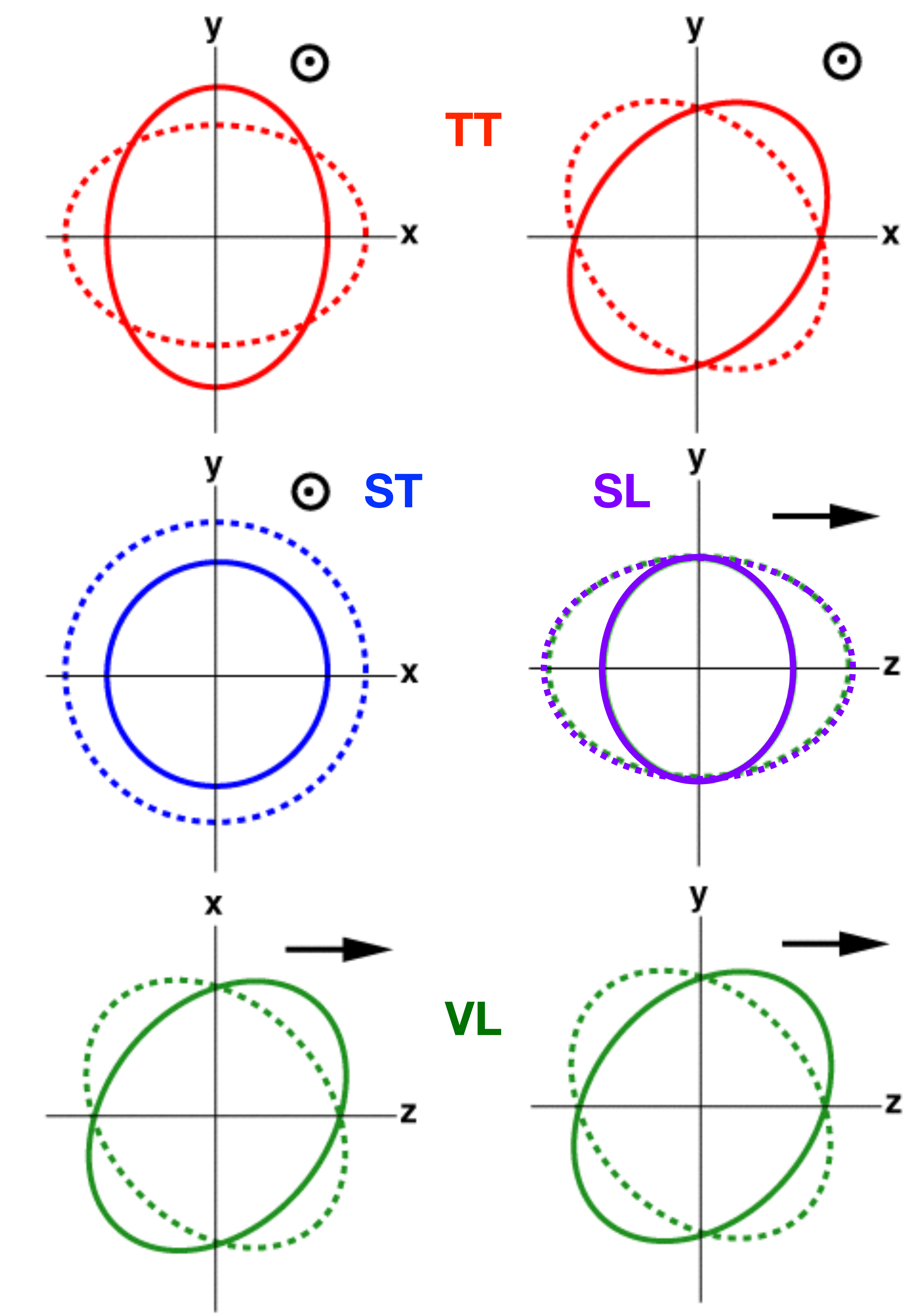
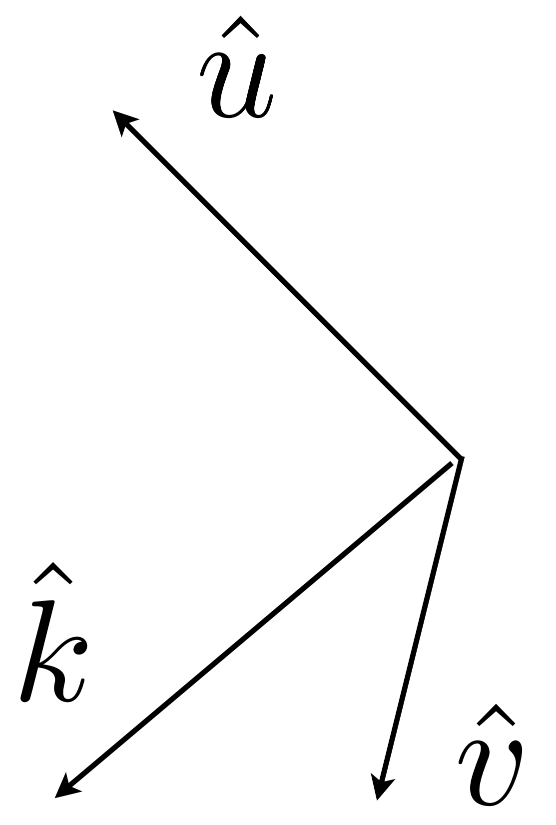
Alternative Theories Predict additional Polarization States





$$\mathbf{e}_{\mathrm{TT}}^{+} = \mathbf{u} \otimes \mathbf{u} - \mathbf{v} \otimes \mathbf{v}$$

$$\mathbf{e}_{\mathrm{TT}}^{\times} = \mathbf{u} \otimes \mathbf{v} + \mathbf{v} \otimes \mathbf{u}$$

$$\mathbf{e}_{\mathrm{ST}}^{\odot} = \mathbf{u} \otimes \mathbf{u} + \mathbf{v} \otimes \mathbf{v}$$

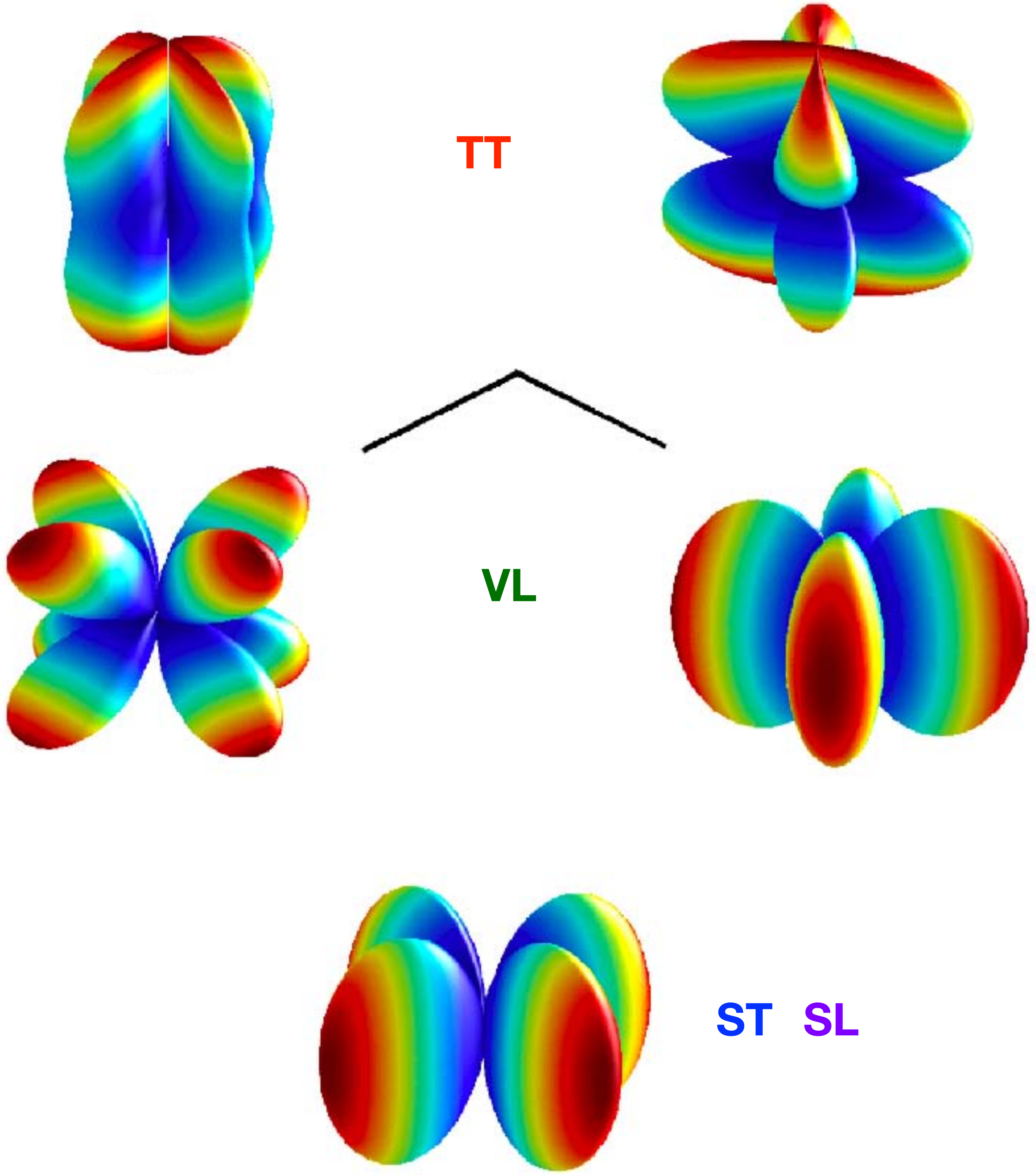
$$\mathbf{e}_{\mathrm{SL}}^{\odot} = \mathbf{k} \otimes \mathbf{k}$$

$$\mathbf{e}_{\mathrm{VL}}^{u} = \mathbf{u} \otimes \mathbf{k} + \mathbf{k} \otimes \mathbf{u}$$

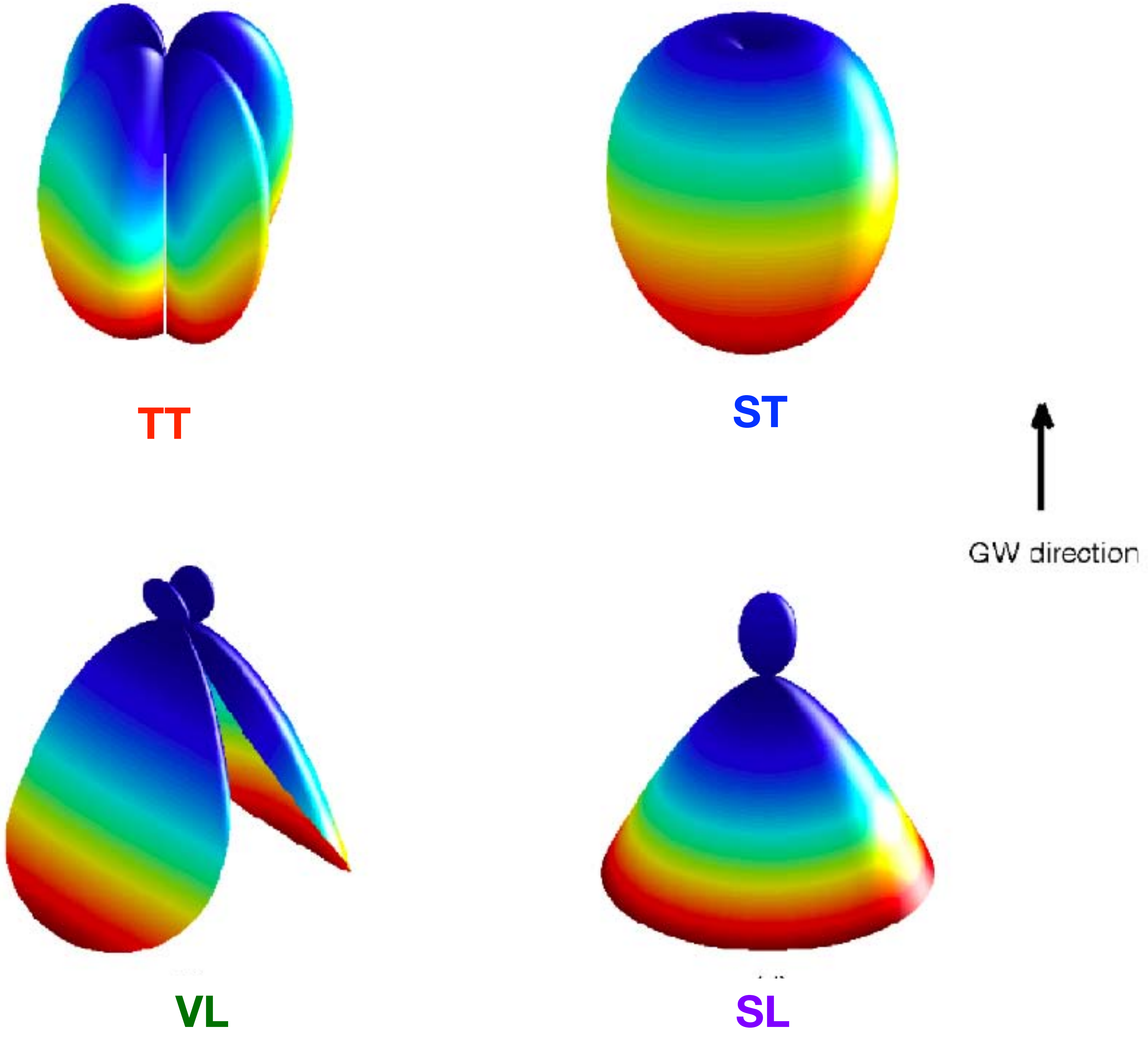
$$\mathbf{e}_{\mathrm{VL}}^{v} = \mathbf{v} \otimes \mathbf{k} + \mathbf{k} \otimes \mathbf{v}$$

Antenna Patterns

Interferometers

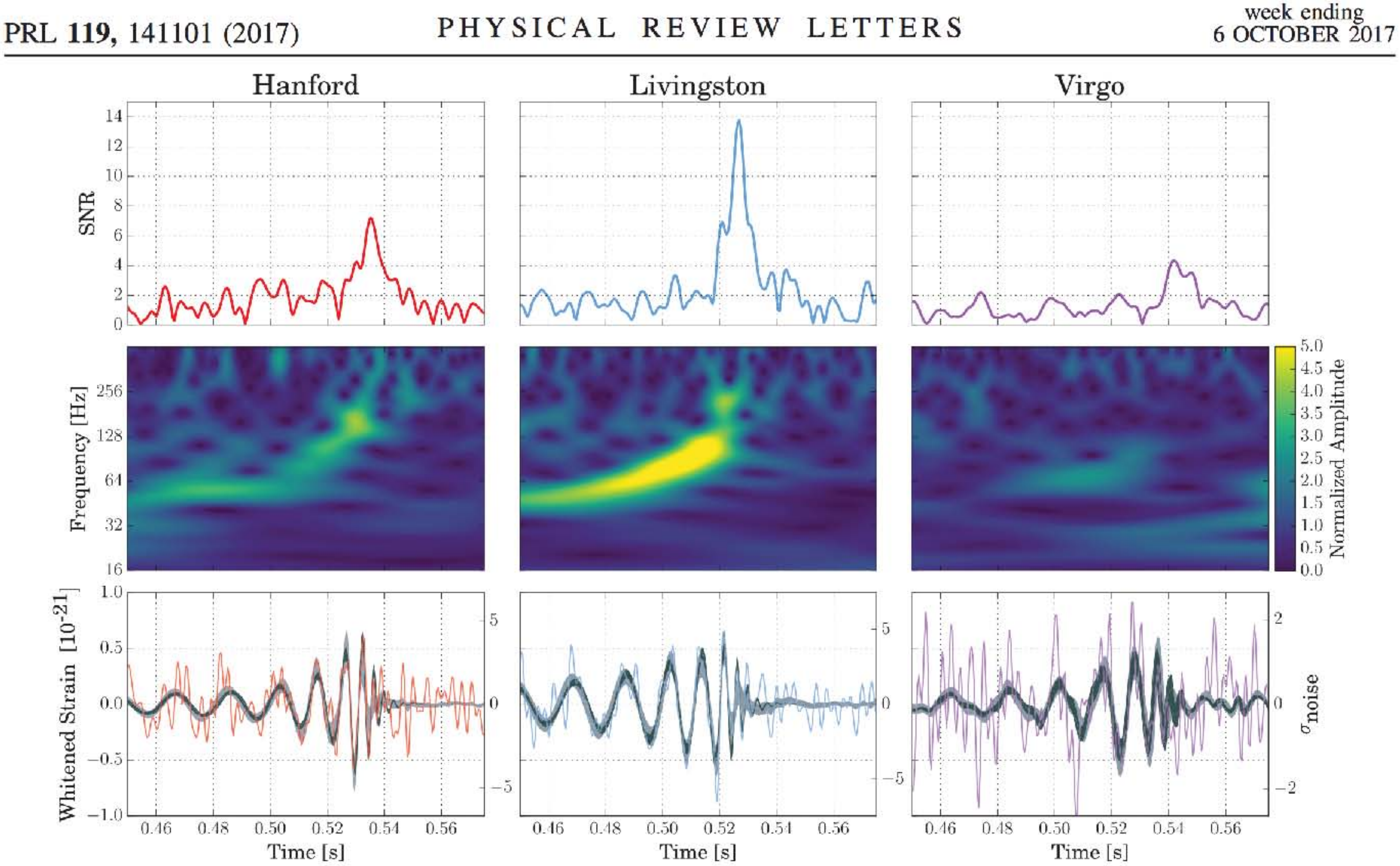


Pulsar Timing



[Yunes & Siemens, Living Rev.Rel. 16, 9 (2013)]

Binary Black Hole Merger GW170814 - First Constraints on Polarization



[LIGO/Virgo PRL 119, 141101 (2017)]

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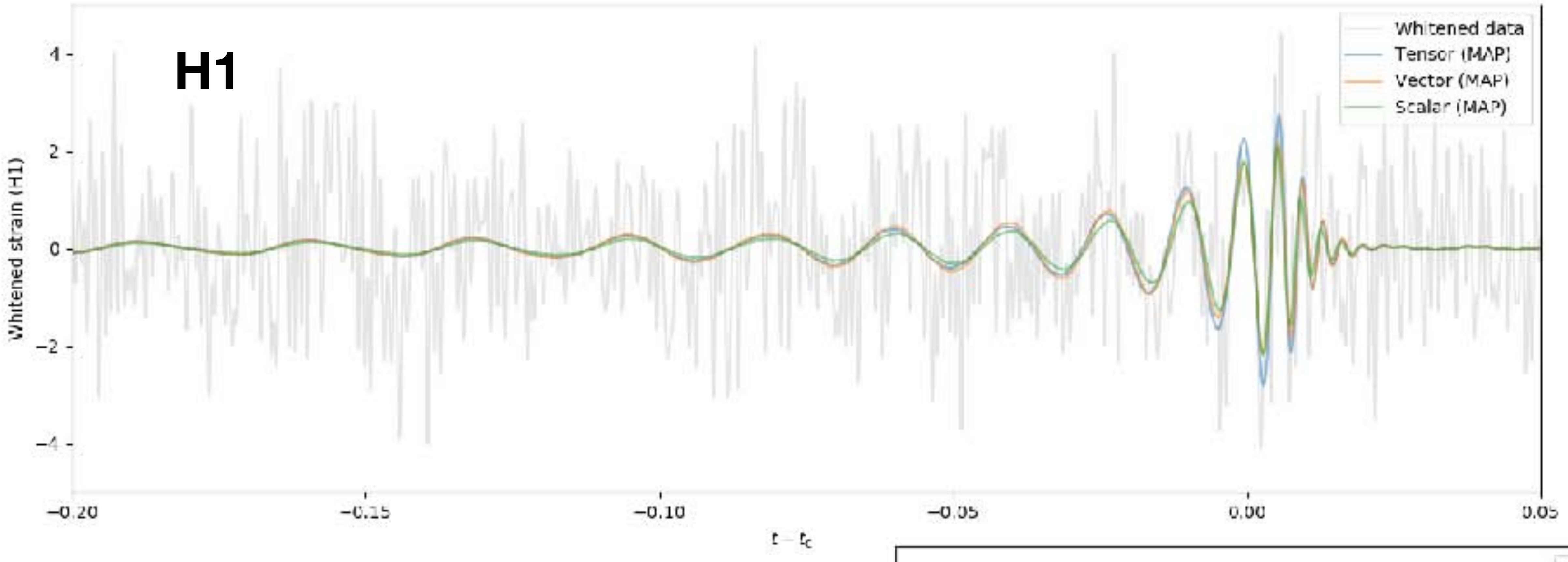
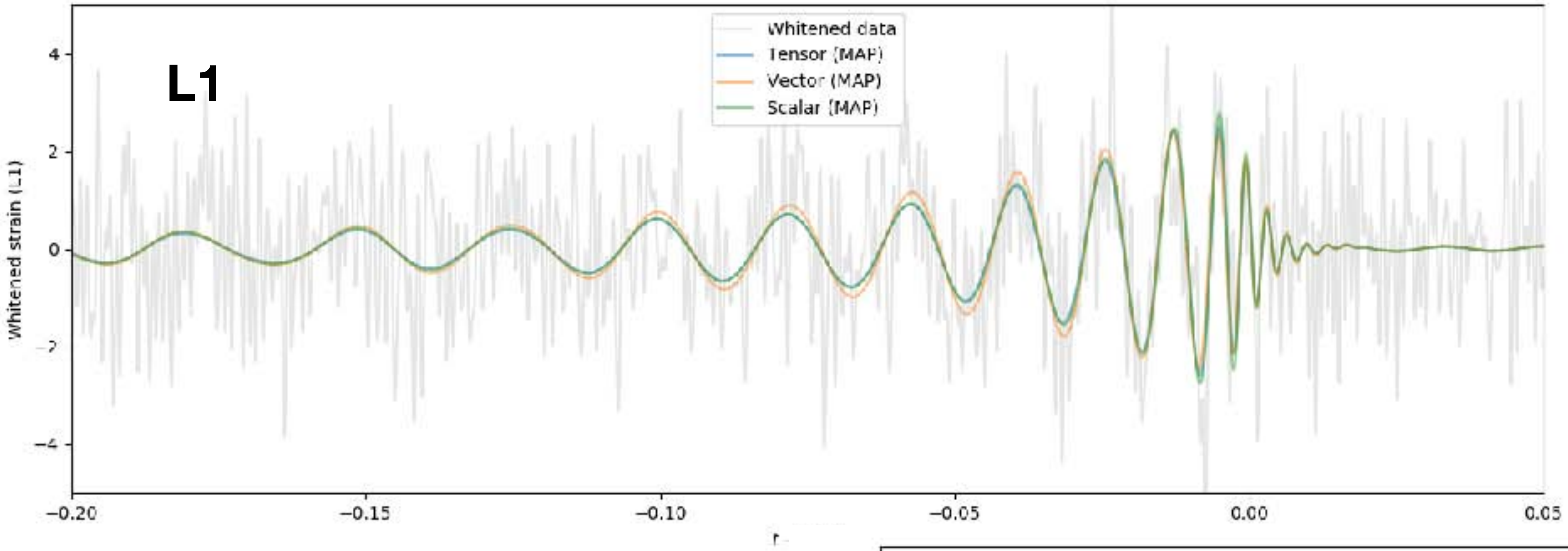
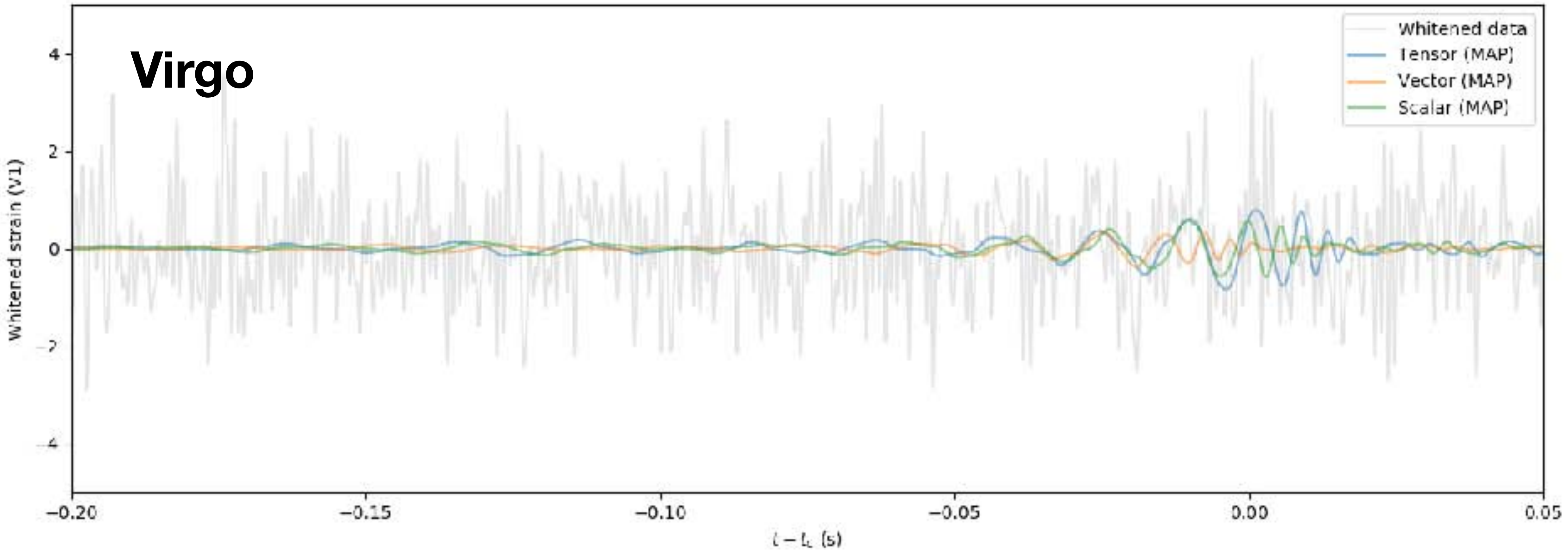


[LIGO/Virgo PRL 119, 141101 (2017)]

Tensor favored over Vector by 200:1

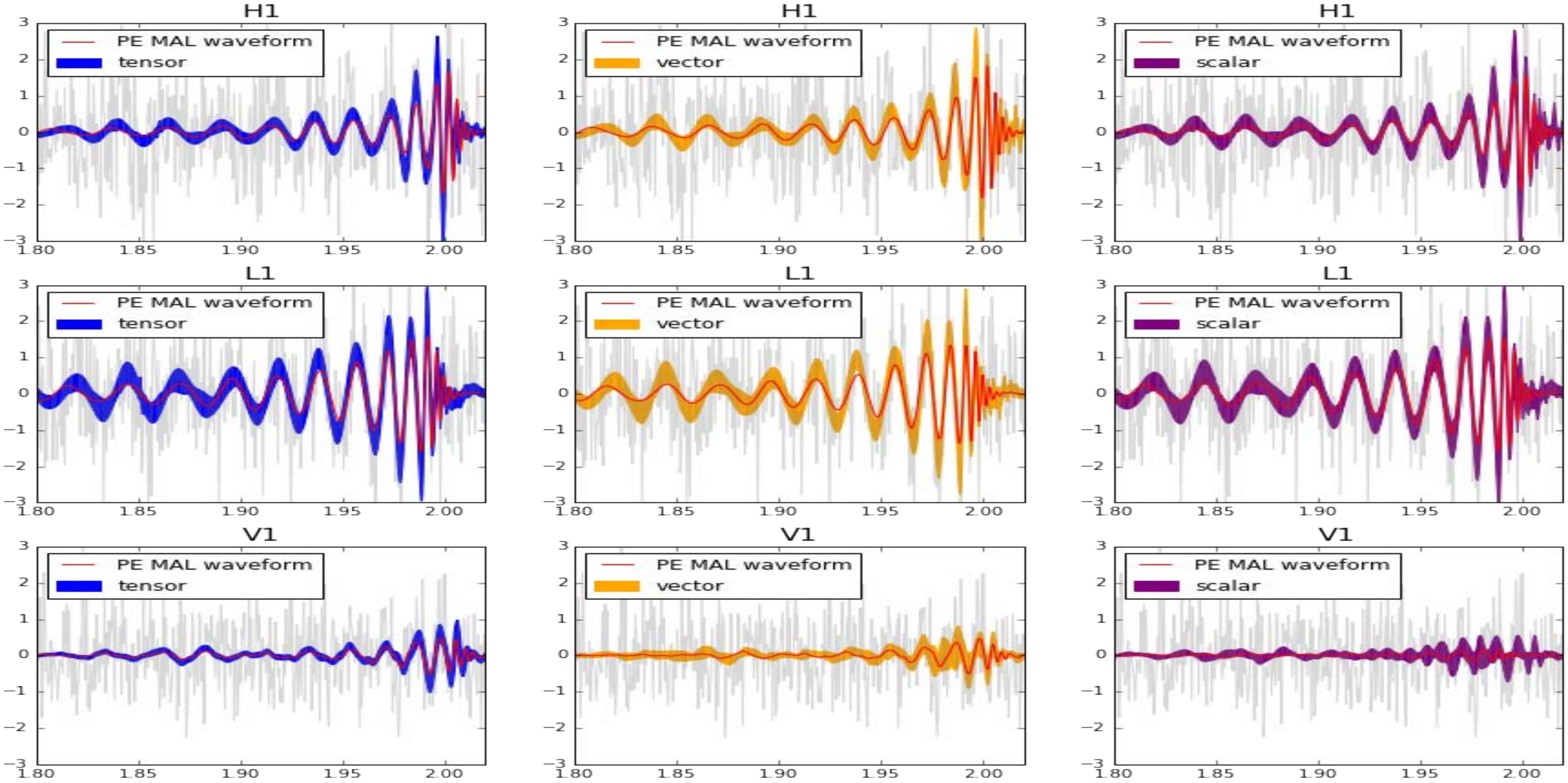
Tensor favored over Scalar by 1000:1





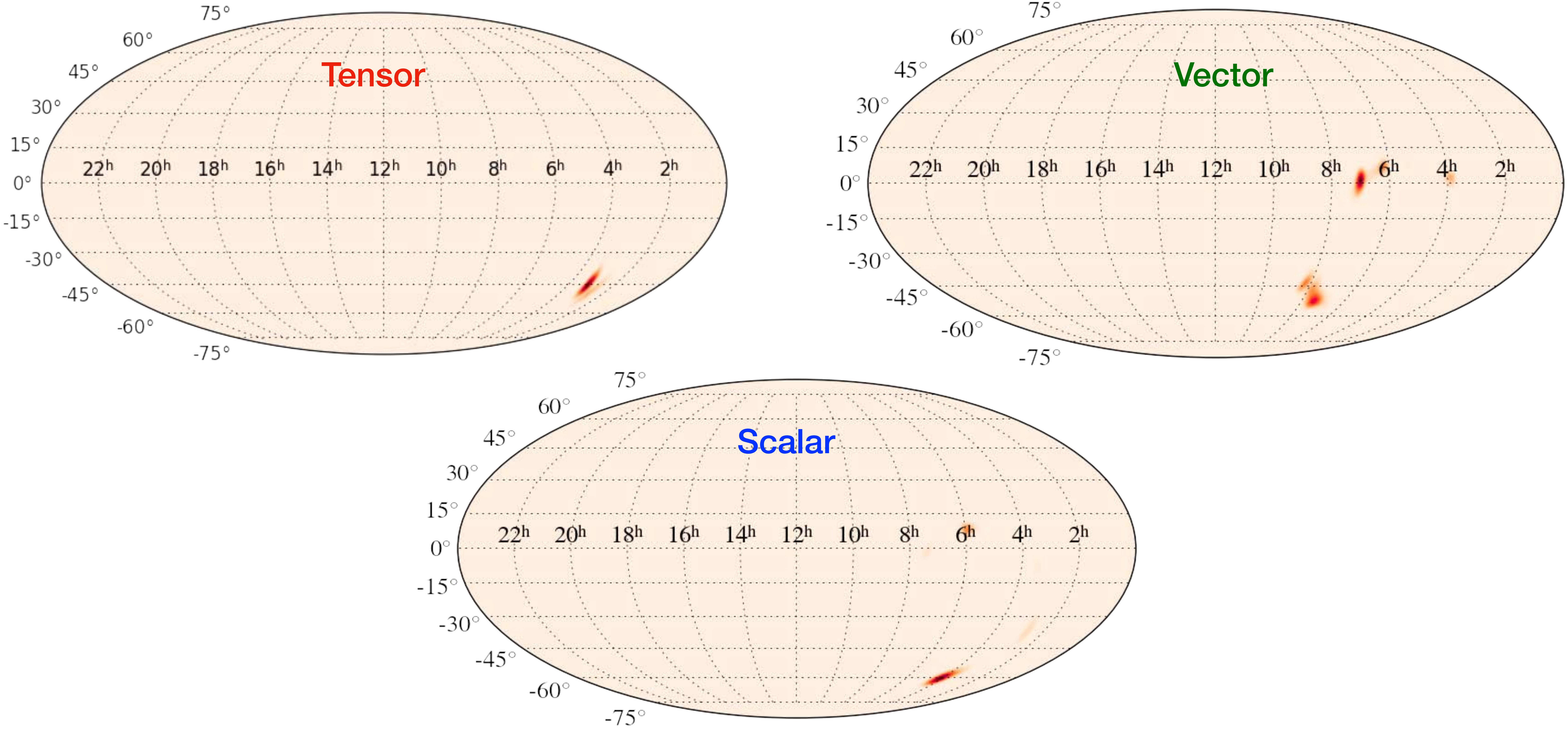
[Isi & Weinstein, arXiv:1710.03794 (2017)]

Binary Black Hole Merger GW170814 - BayesWave Constraints on Polarization



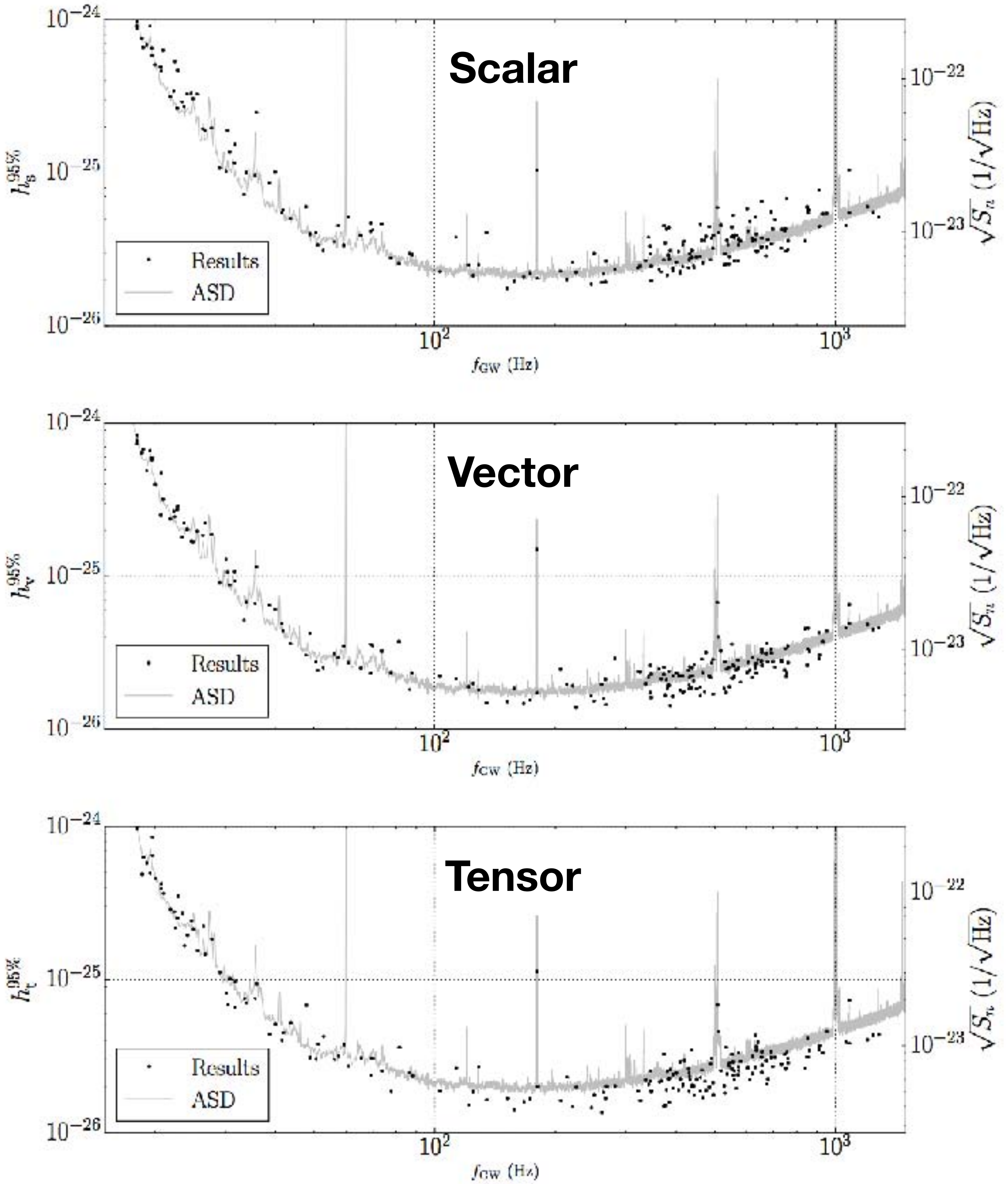
Bayes Factors between models similar to those form template based analysis

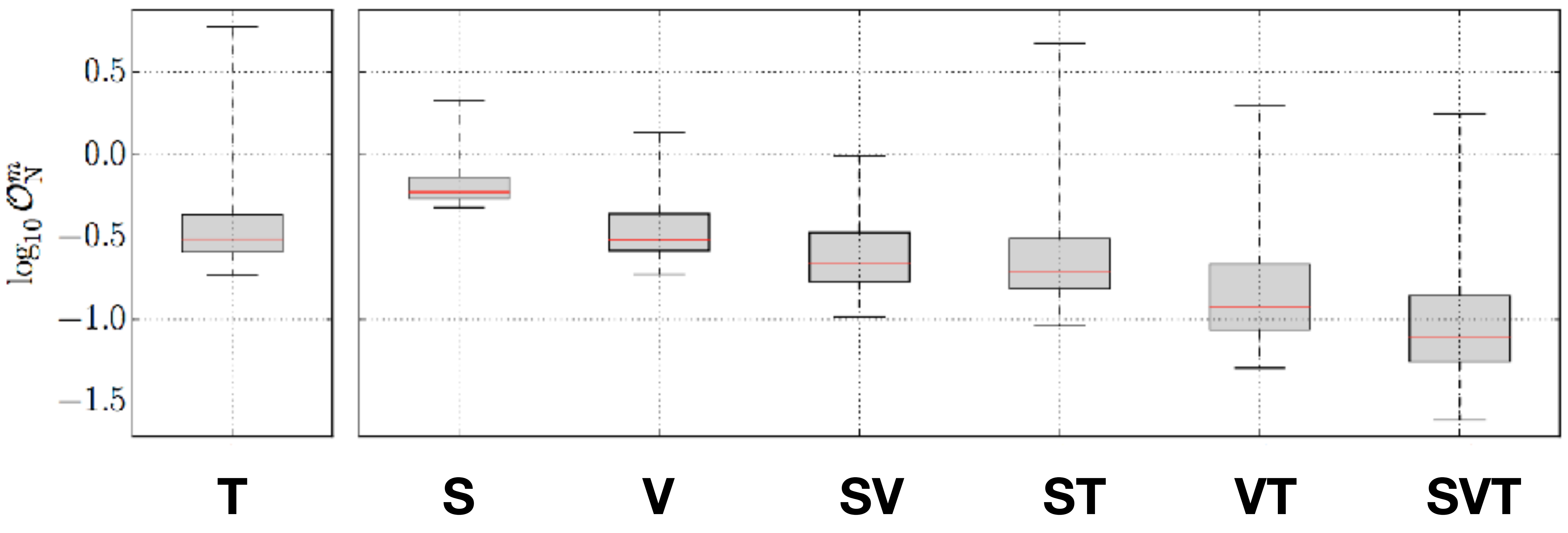
Binary Black Hole Merger GW170814 - First Constraints on Polarization



LIGO/Virgo Antenna Patterns

First search for nontensorial gravitational waves from known pulsars





No detections so far, so bounds are weak

Note: The analysis assumed that $f_{\rm gw} = 2 f_{\rm orb}$, which is not always the case for dipole emission

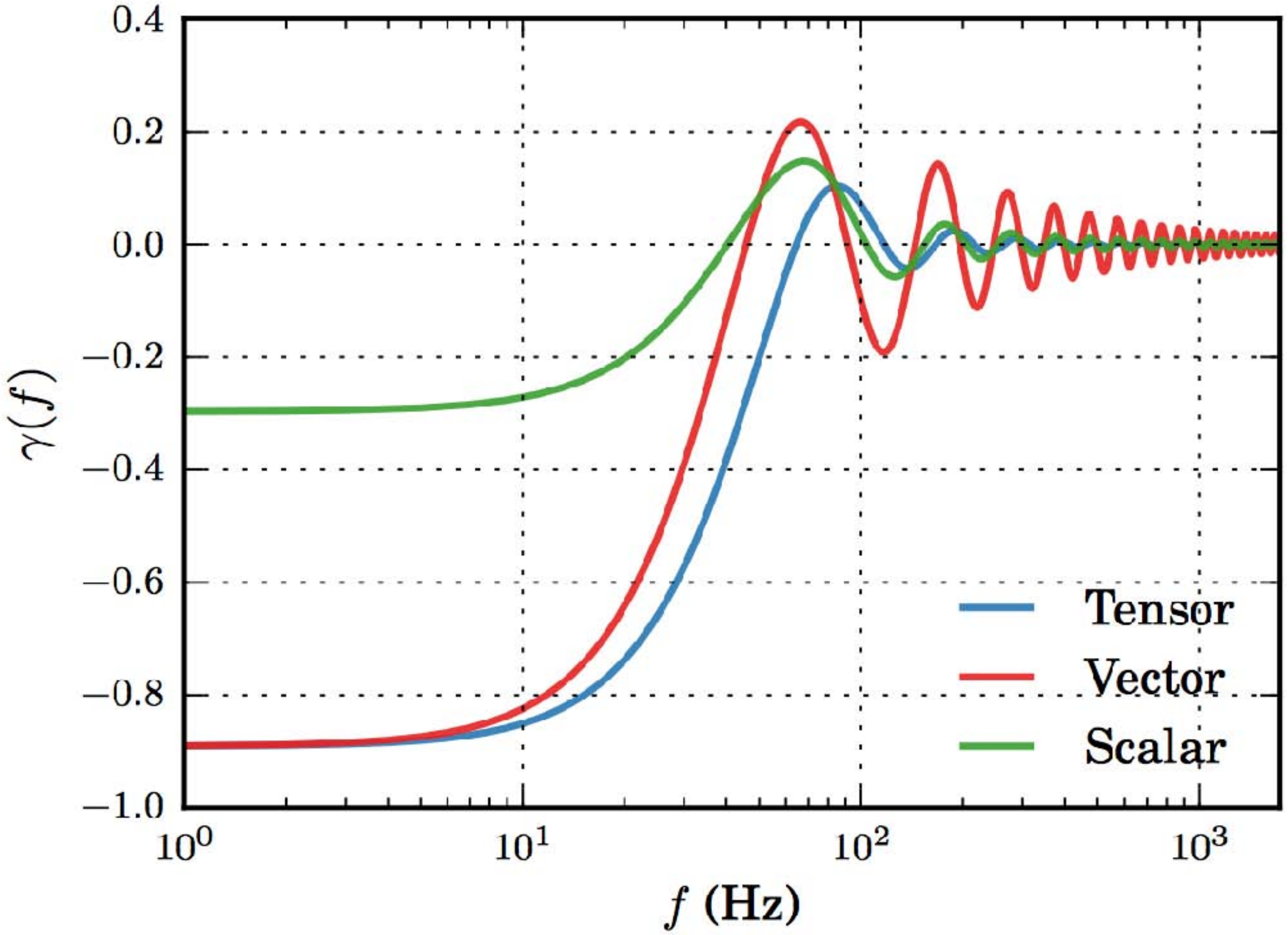
[LIGO/Virgo PRL 120, 031104 (2018)]

A Search for Tensor, Vector, and Scalar Polarizations in the Stochastic Gravitational-Wave Background

$$\langle \tilde{s}_1(f)\tilde{s}_2^*(f')\rangle = \delta(f-f')\sum_A \gamma_A(f)H^A(f).$$

$$\Omega(f) = \frac{20\pi^2}{3H_0^2} f^3 H(f)$$

$$\Omega(f) = \Omega_0^T\left(\frac{f}{f_0}\right)^{\alpha_T} + \Omega_0^V\left(\frac{f}{f_0}\right)^{\alpha_V} + \Omega_0^S\left(\frac{f}{f_0}\right)^{\alpha_S}$$



[LIGO/Virgo arXiv:1802.10194 (2018)]

A Search for Tensor, Vector, and Scalar Polarizations in the Stochastic Gravitational-Wave Background

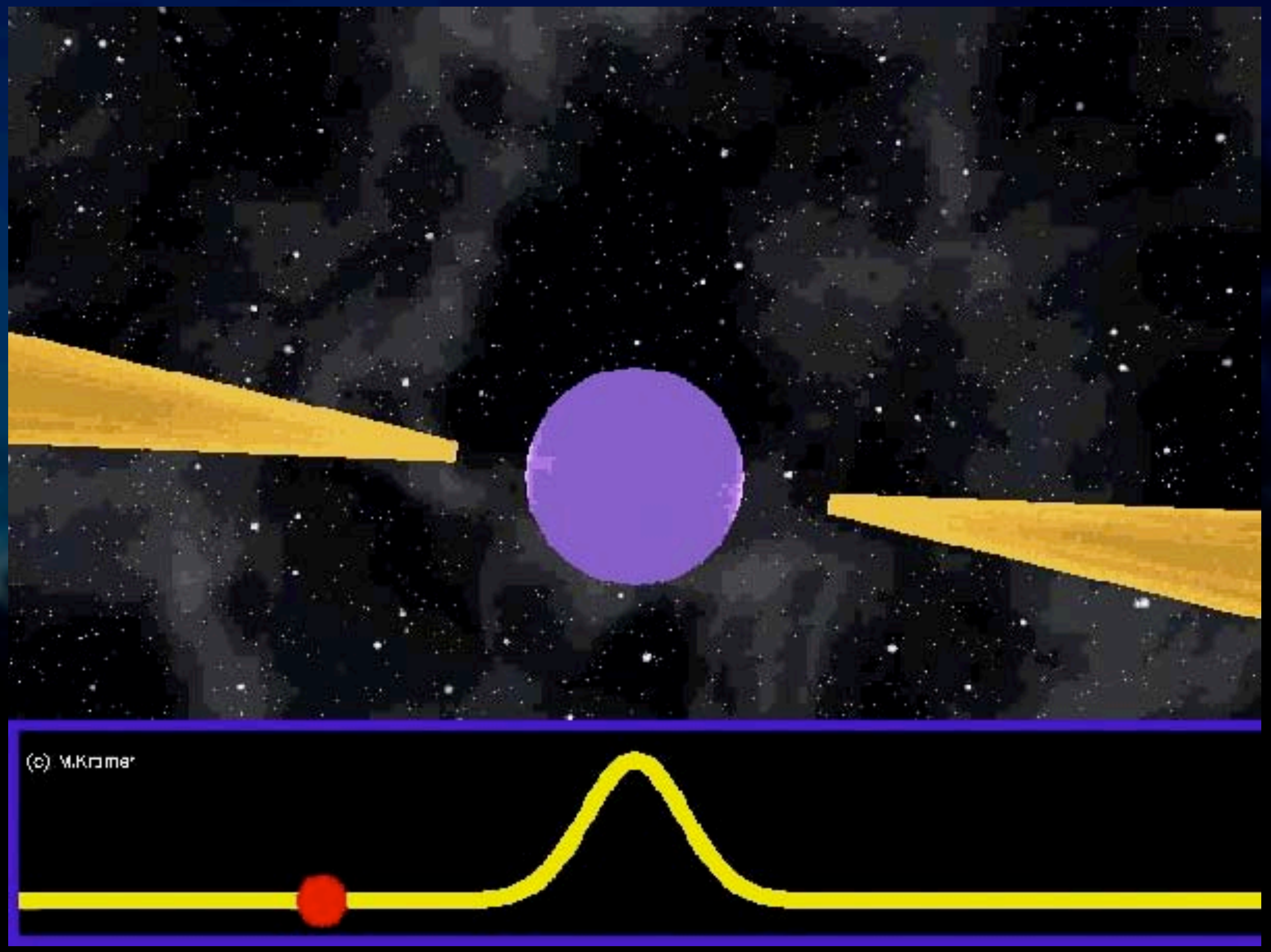
$$\Omega(f) = \Omega_0^T \left(\frac{f}{f_0}\right)^{\alpha_T} + \Omega_0^V \left(\frac{f}{f_0}\right)^{\alpha_V} + \Omega_0^S \left(\frac{f}{f_0}\right)^{\alpha_S}$$

LIGO O1 Limits: (Marginalized over spectral slope) $f_0 = 25\mathrm{Hz}$

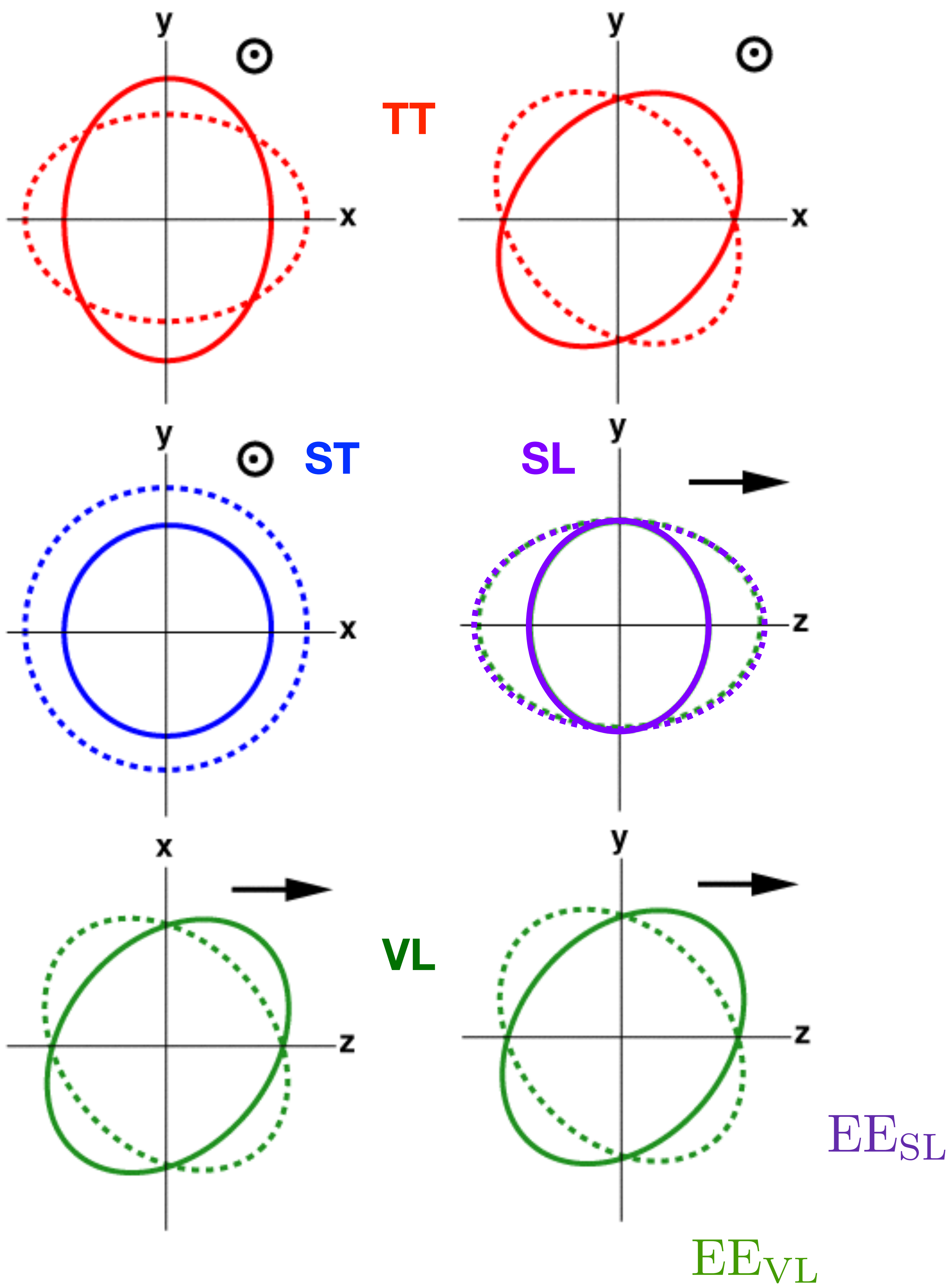
$\Omega_0^T < 2.0 \times 10^{-7}$ $\Omega_0^V < 2.5 \times 10^{-7}$ $\Omega_0^S < 8.4 \times 10^{-7}$

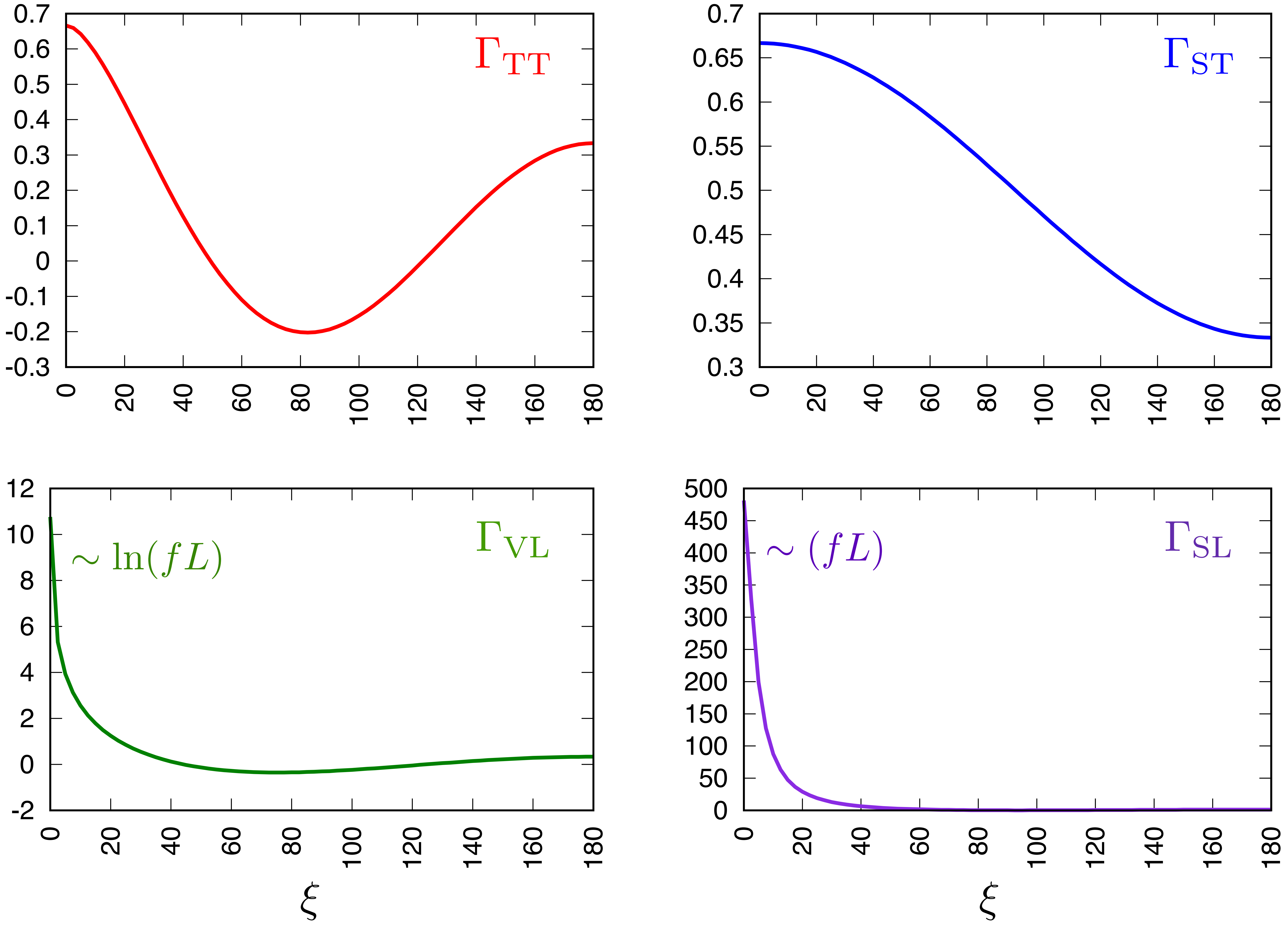
[LIGO/Virgo arXiv:1802.10194 (2018)]

Pulsar Timing



PTA Two-Point Correlations

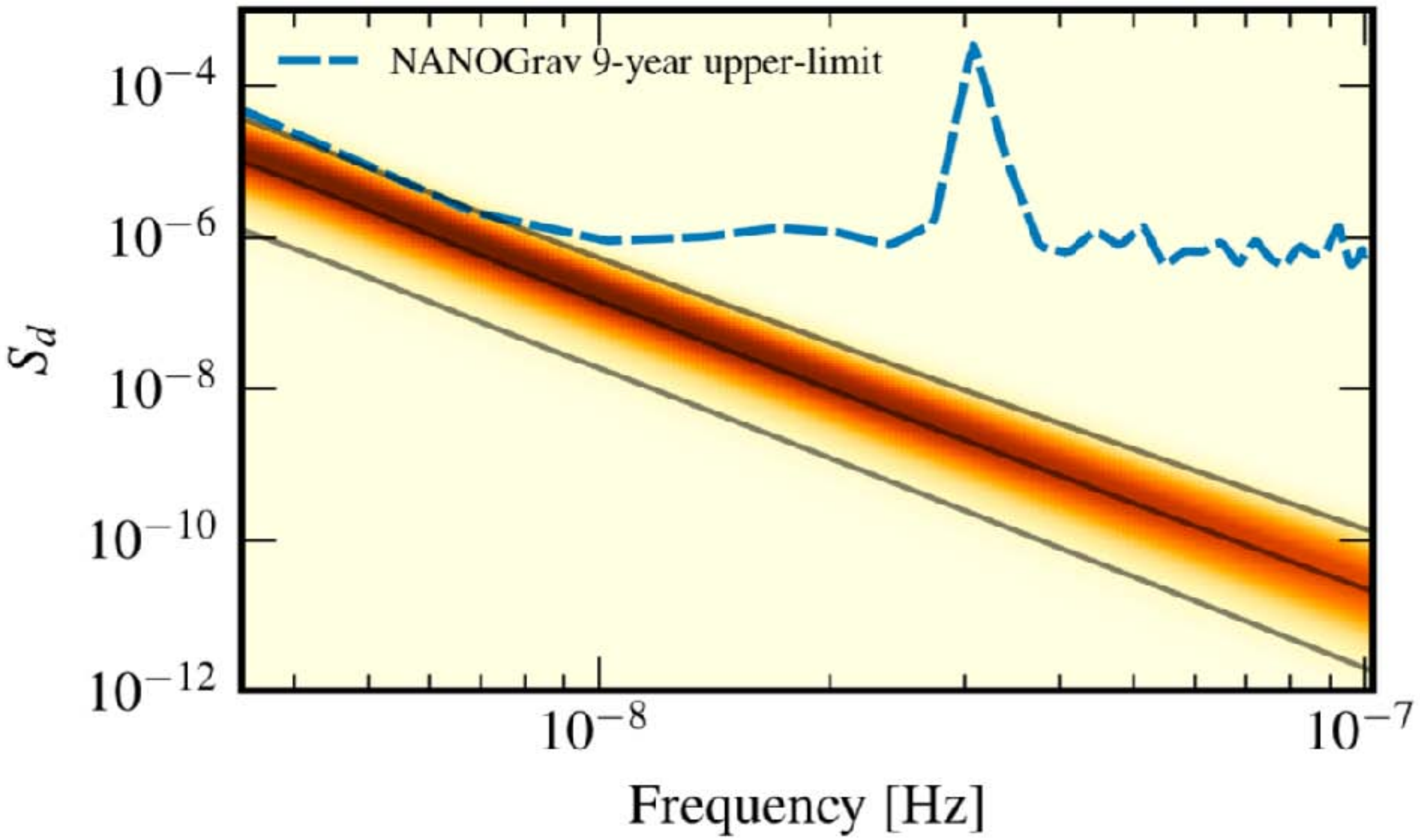


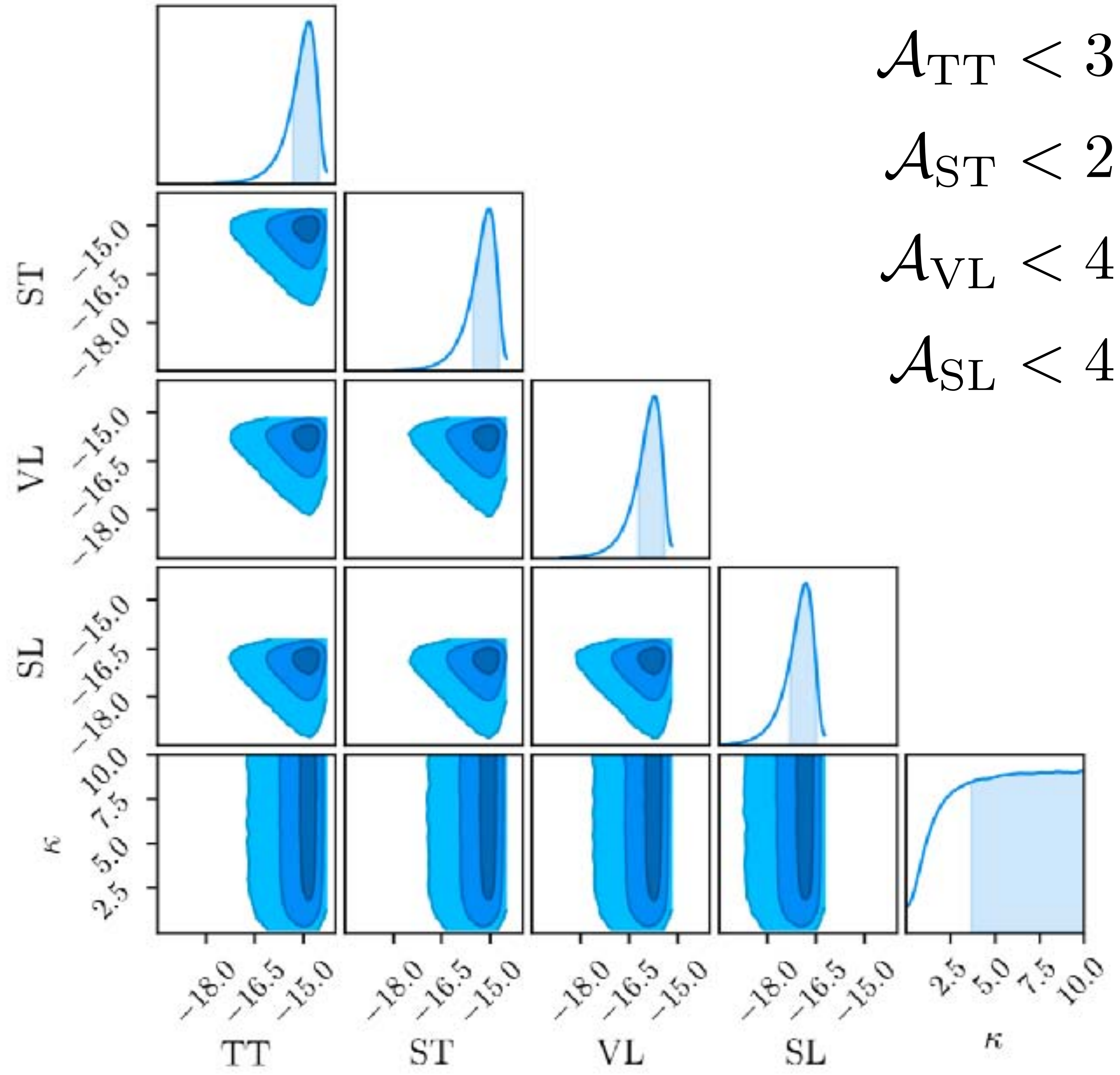


[Chamberlin & Siemens Phys.Rev. D**85,** 082001 (2012)]
[Lee, Jenet & Price, Ap.J. **685,** 1304 (2008)]

Upper Limit using NANOGrav 9-year results

$$S_{ab}(f) = \frac{\Gamma_{ab}^{\rm TT}\,\mathcal{A}_{\rm Q}^2\,(f/f_y)^{-4/3} + (\,\Gamma_{ab}^{\rm ST}\,{\mathcal{A}_{\rm ST}}^2 + \Gamma_{ab}^{\rm VL}\,{\mathcal{A}_{\rm VL}}^2 + \Gamma_{ab}^{\rm SL}\,{\mathcal{A}_{\rm SL}}^2)\,(f/f_y)^{-2}}{(1+\kappa^2(f/f_y)^{-2/3})}$$





$\mathcal{A}_{\rm TT} < 3 \times 10^{-15}$

$\mathcal{A}_{\rm ST} < 2 \times 10^{-15}$

$\mathcal{A}_{\rm VL} < 4 \times 10^{-16}$

$\mathcal{A}_{\rm SL} < 4 \times 10^{-17}$

[Cornish, O'Beirne, Taylor, Yunes, PRL (2018)]

Gravitational Wave Observations

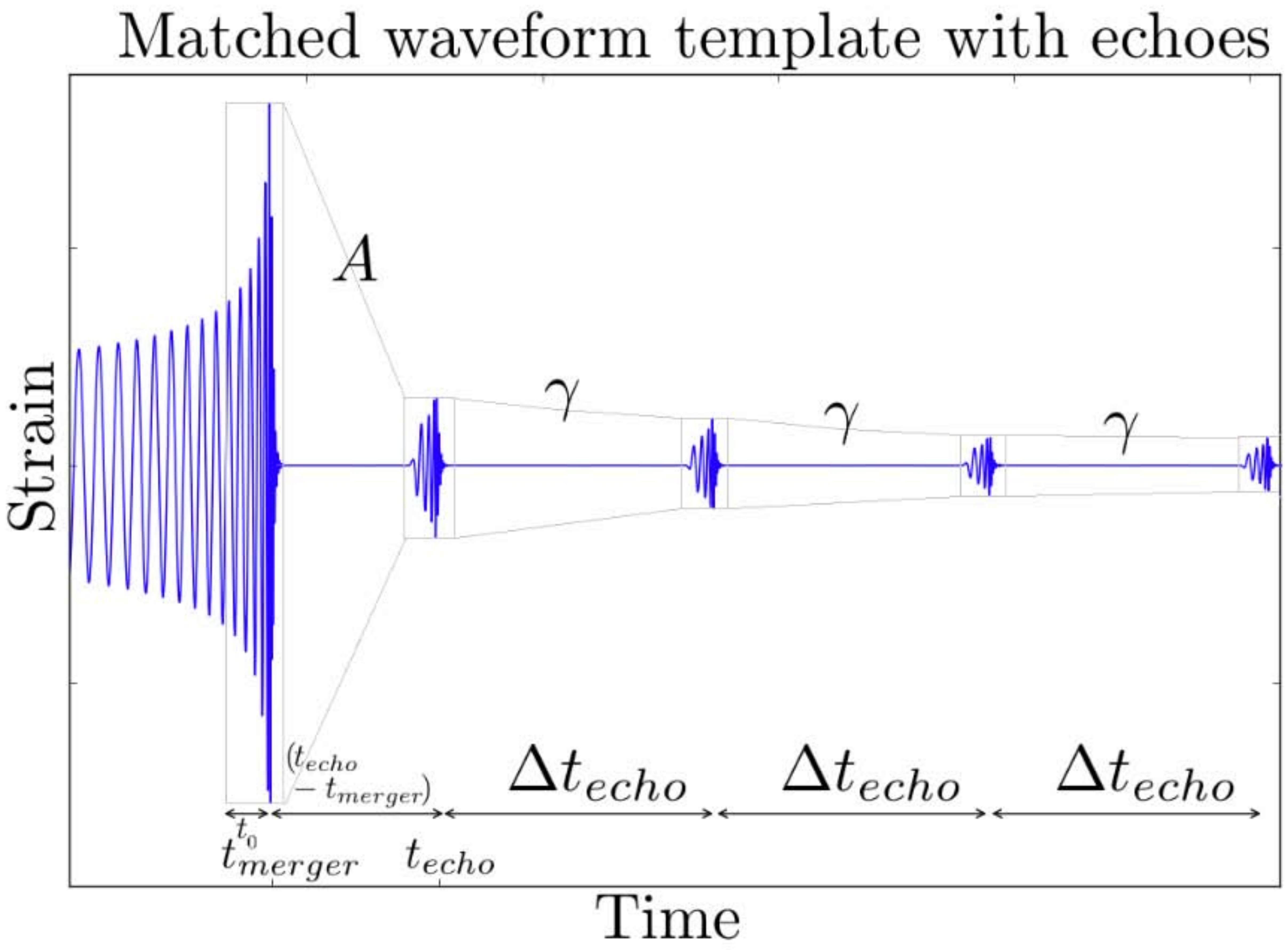
- Do gravitational waves travel at the speed of light? ✓
- Is the emission of energy and angular momentum as predicted by GR? ✓
- Is the graviton massless? $m_g < 1.2 \times 10^{-22}$ eV
- Are gravitational waves transverse? **no evidence to contrary**
- Additional polarization states? ✗
- Did anyone hear an echo?

Echoes from the abyss?

BH perturbation theory - structure of QN modes depends on inner boundary conditions. Any reflections from inside the light ring produce echoes

[Cardoso, Hopper, Macedo, Palenzuela, Pani, arXiv:1608.08637]

Echoes from the abyss?



$2.5\,\sigma$ hint of detection claimed using LIGO O1 detections

[Abedi, Dykaar, Afshordi, arXiv:1612.00266]

More careful reanalysis by some LIGO researchers found nothing

[Westerweck et al, arXiv:1712.09966]

$4.2\,\sigma$ claim of detection using BNS GW170817 data

[Abedi, Afshordi, arXiv:1803.10454]

Detection of echoes also claimed for GW151226, GW170104, GW170606, GW170814, GW170817

[Conklin, Holdom, Ren, arXiv:1712.06517]

I'm waiting for the analysis to be re-done using the specialized BayesWave search [Tsang et al, arXiv:1804.04877]

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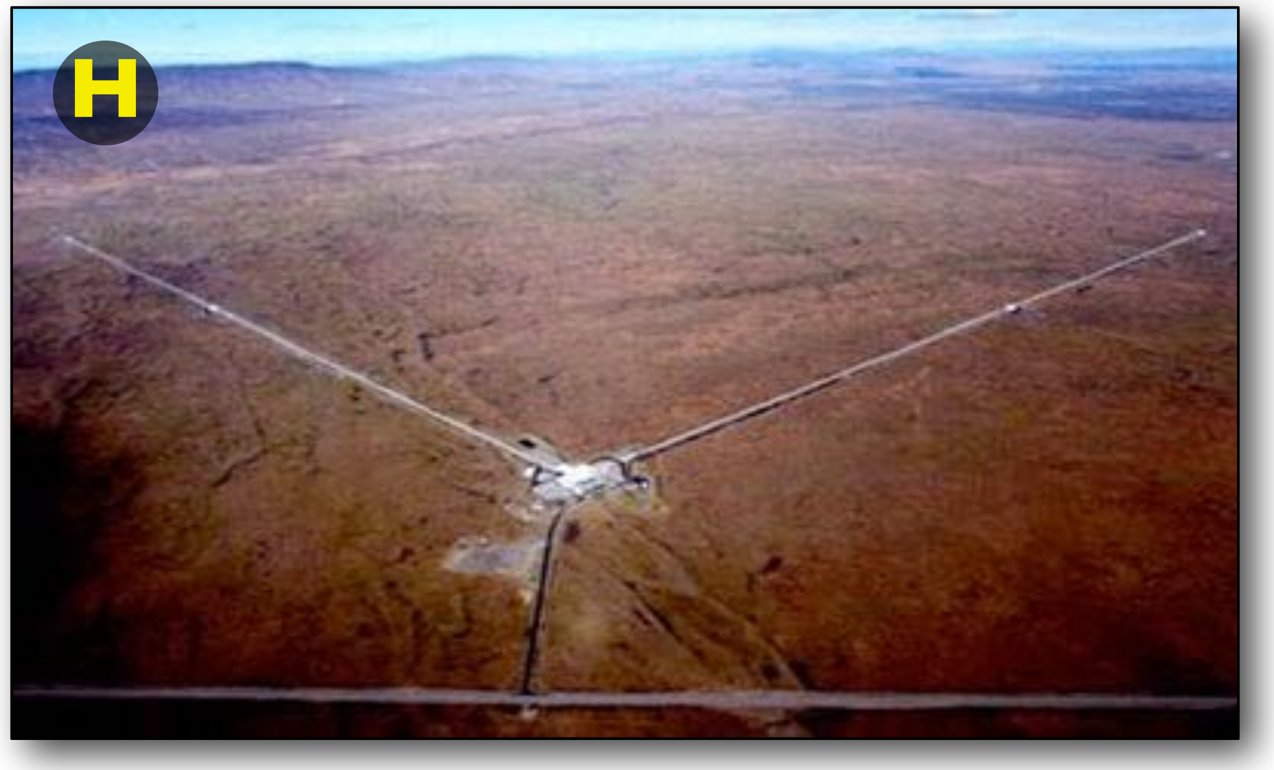
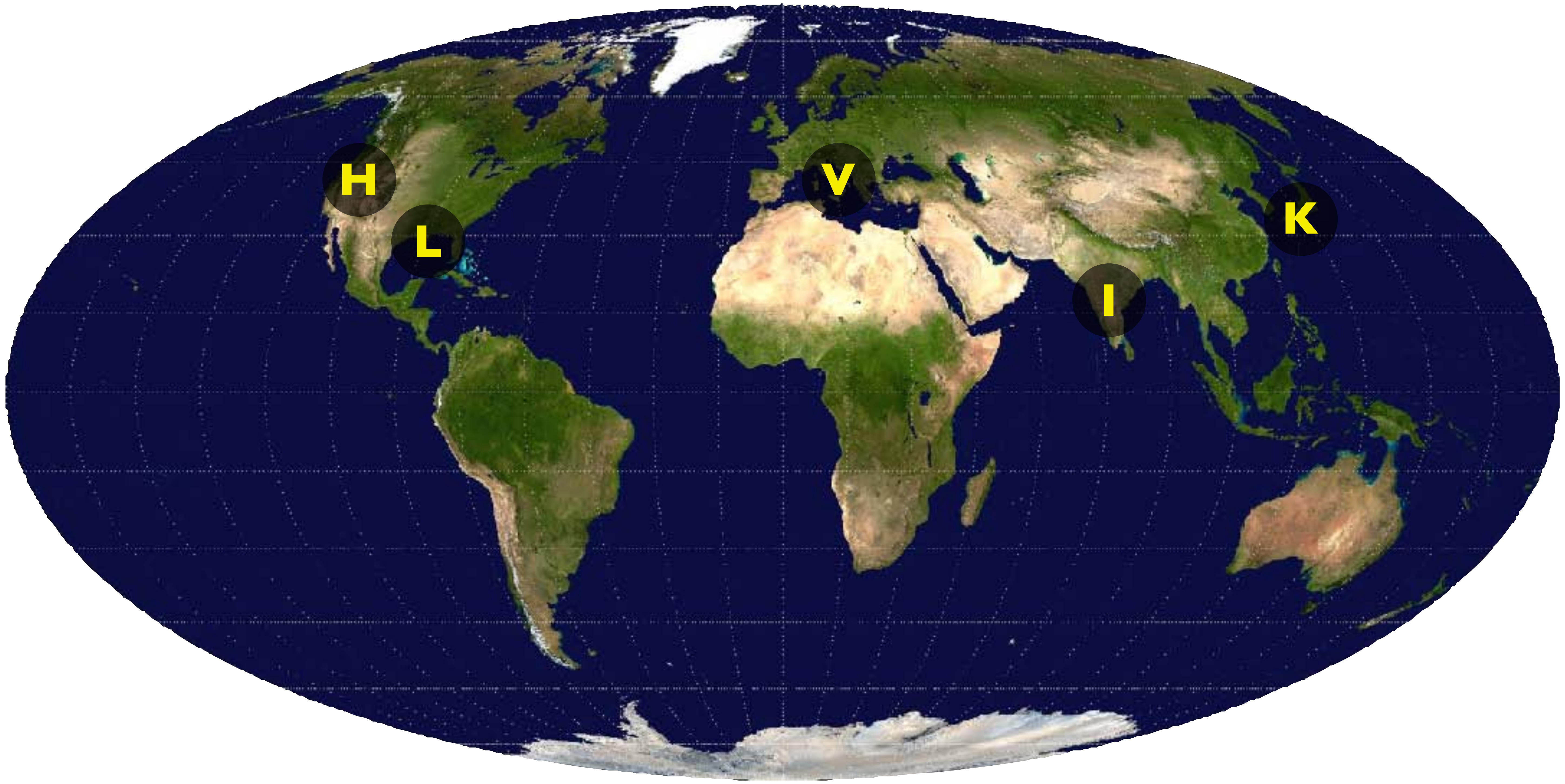
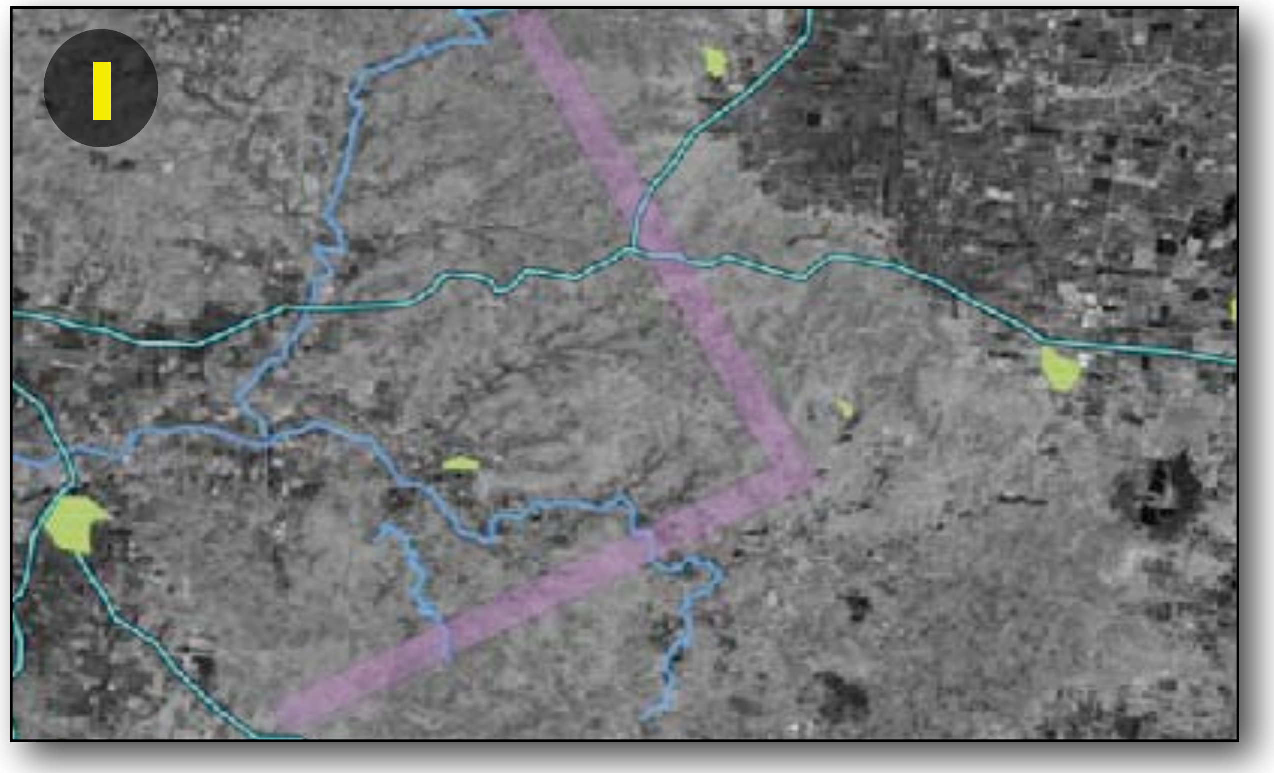
- Do gravitational waves travel at the speed of light? ✓
- Is the emission of energy and angular momentum as predicted by GR? ✓
- Is the graviton massless? $m_g < 1.2 \times 10^{-22}$ eV
- Are gravitational waves transverse? **no evidence to contrary**
- Additional polarization states? ✗
- Did anyone hear an echo? ✗

Future Prospects

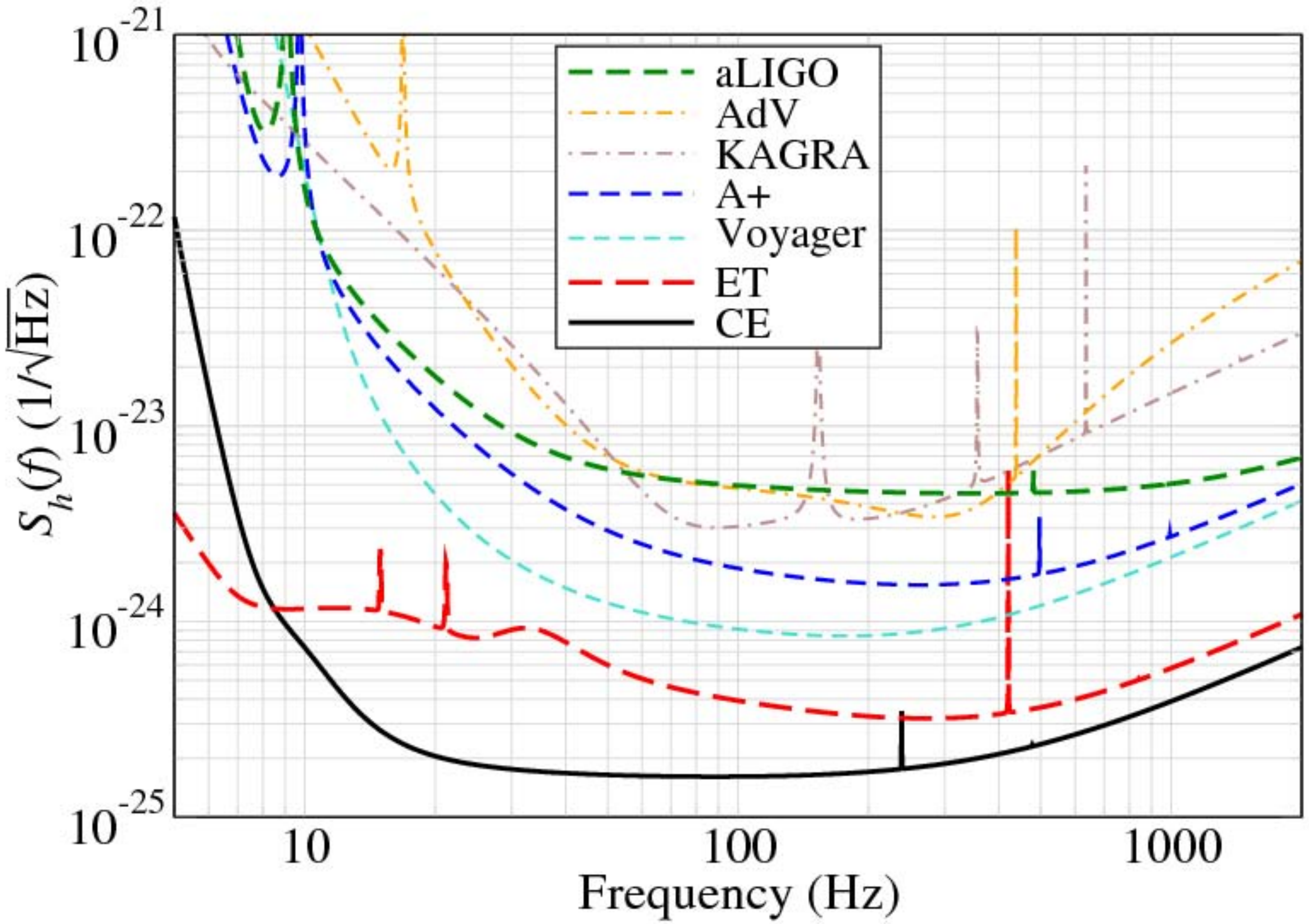
Next steps - a worldwide network

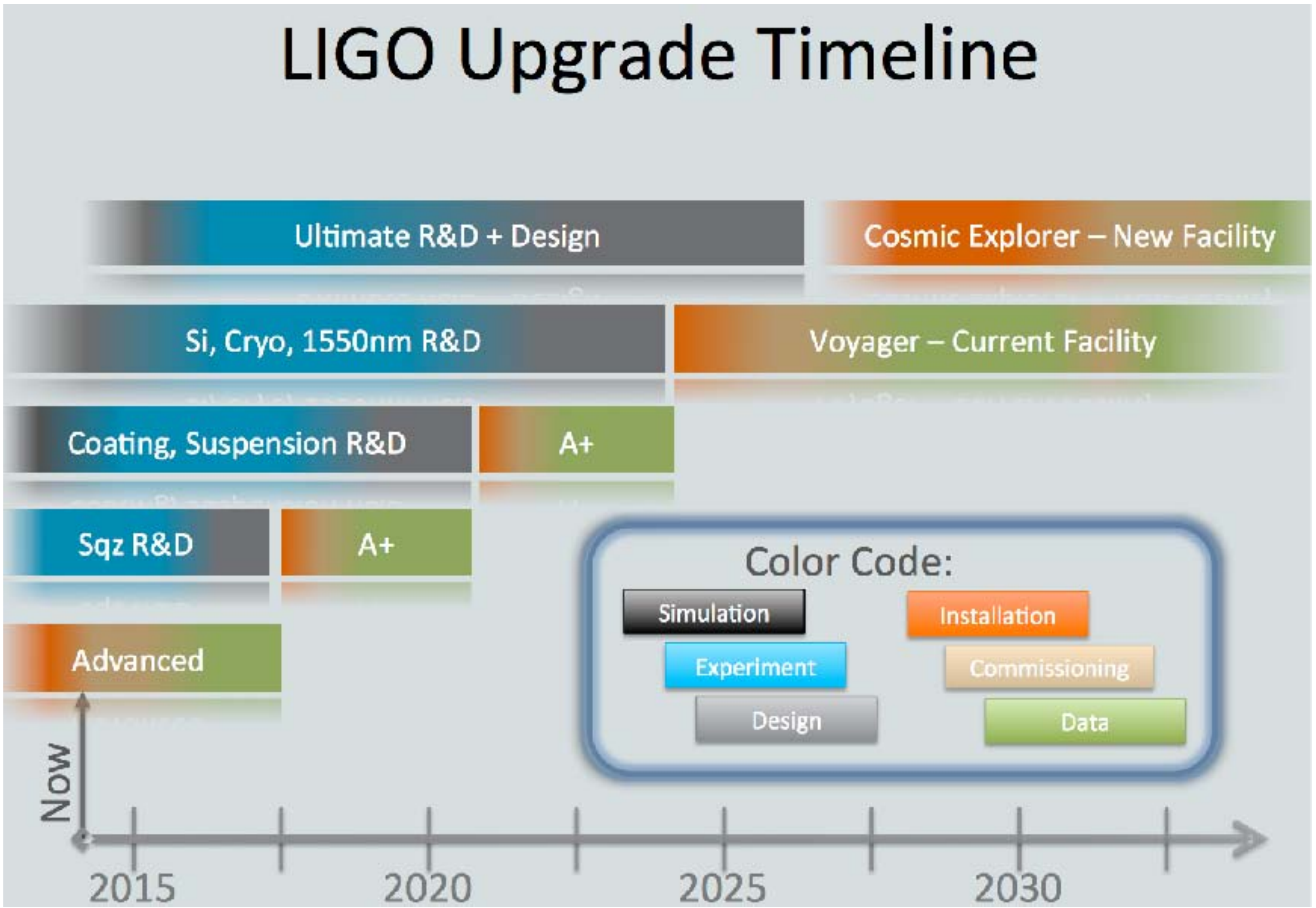






3rd and 4th generation ground-based instruments





A+: aLIGO upgrade, freq. dep. squeezing, heavier mirrors, more powerful lasers

Voyager: aLIGO upgrade, same facility, cryogenic, more powerful lasers

Einstein Telescope: Underground, 10 km, triangular, cryogenic

Cosmic Explorer: New facility, 40 km arms, squeezing etc

The International Pulsar Timing Array

EPTA

PPTA

NANOGrav







Next steps: Chime, FAST, MeerKAT, and the SKA

June 2017, LISA mission selected by ESA