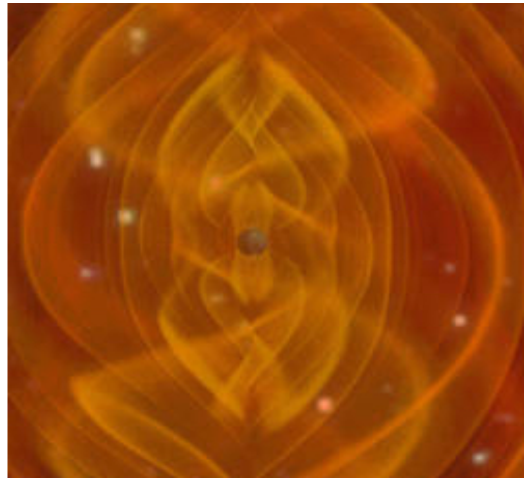


The direct detection of gravitational waves: Scientific pay-off

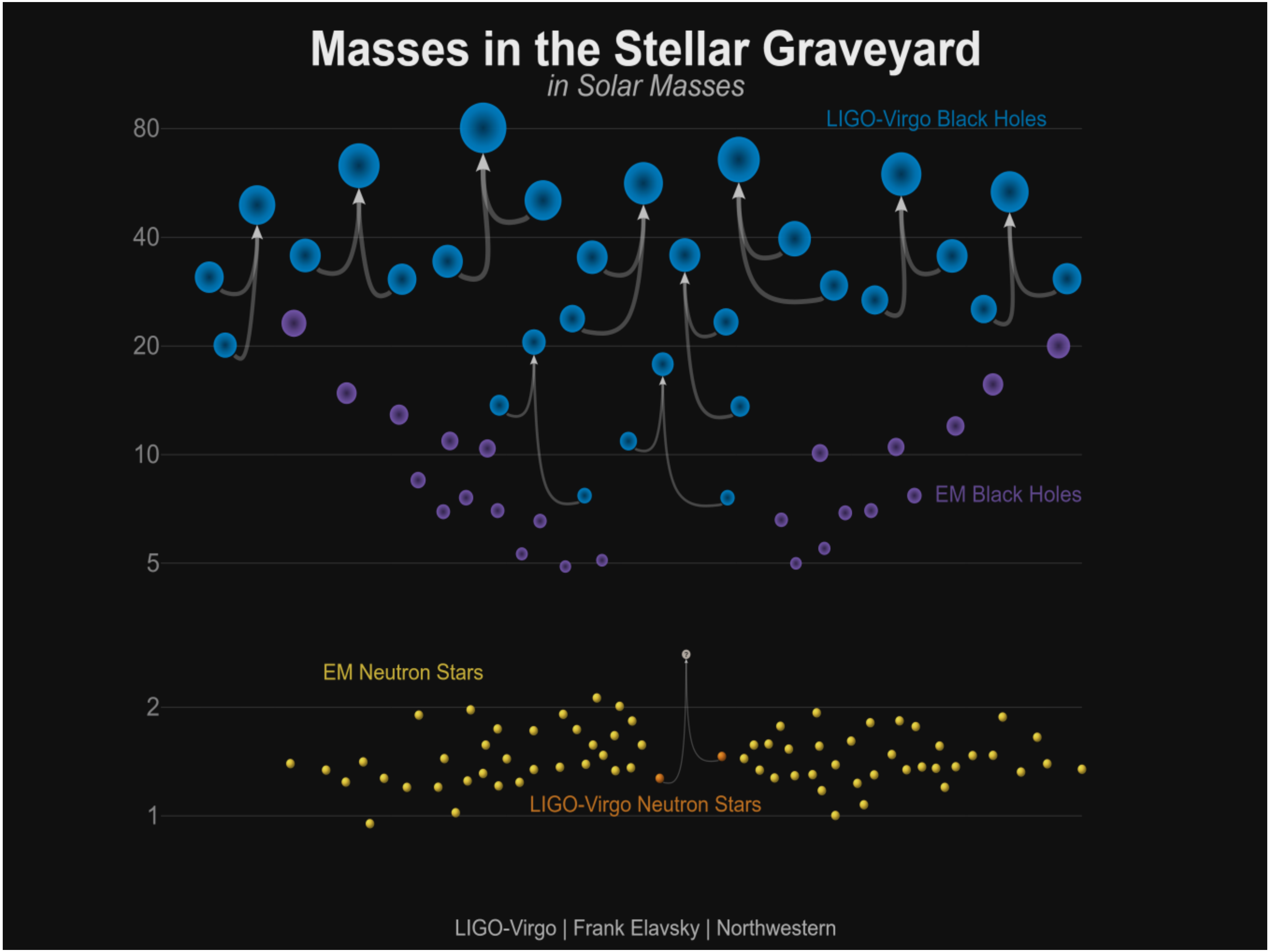
Chris Van Den Broeck

Utrecht University

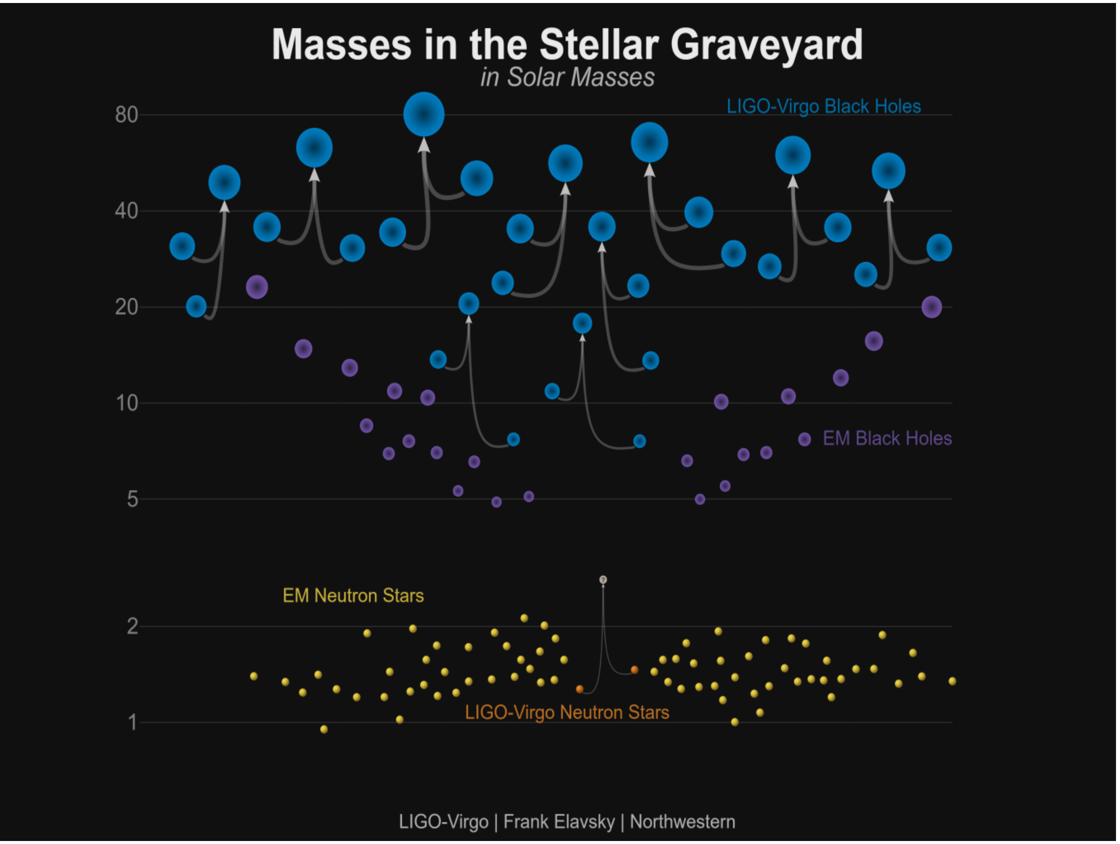
LIGO VIRGO

Nikhef

Lectures on gravitational waves, 21-22/01/2020, UCL, Belgium


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
LIGO-Virgo | Frank Elavsky | Northwestern

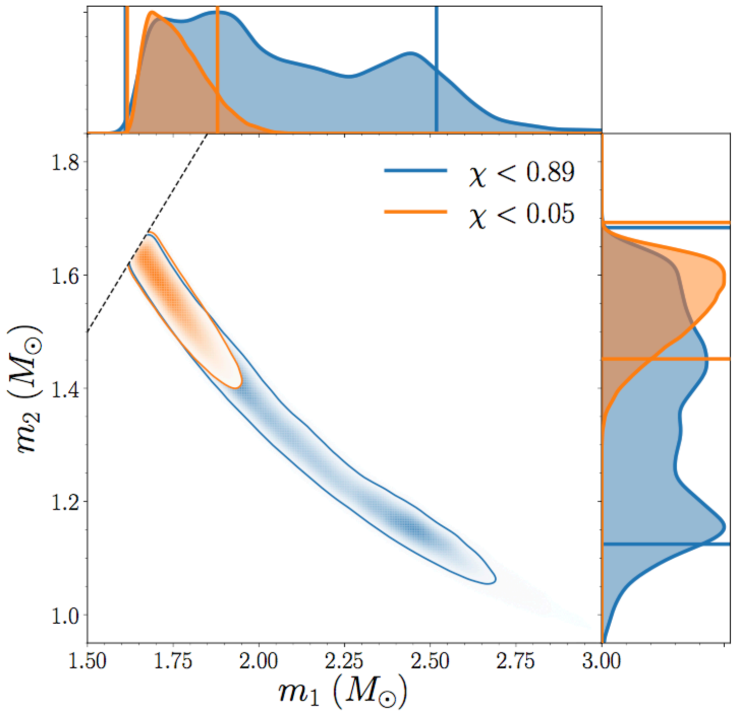
How are black hole masses distributed?

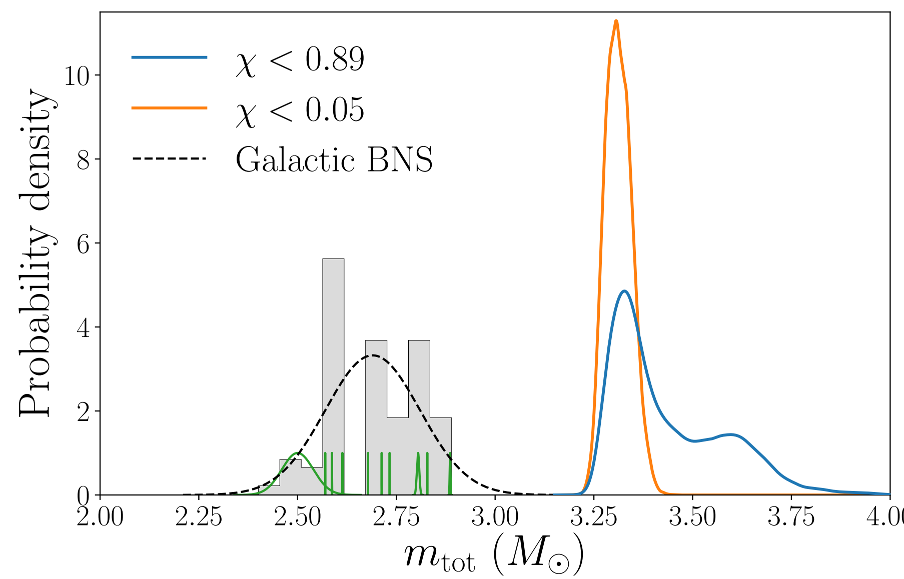


- **Pair instability gap**
  - Black holes with masses above ~60 M_{sun} can not directly originate from collapsing stars
- Black holes **below 1 M_{sun}**?
  - Almost guaranteed primordial origin!
- Is there a **mass gap** between neutron stars and black holes?
  - X-ray observations indicate no black holes with masses in the range 3 - 5 M_{sun}
  - Is this gap real, and if so what is the explanation?

A new binary neutron star (?) detection

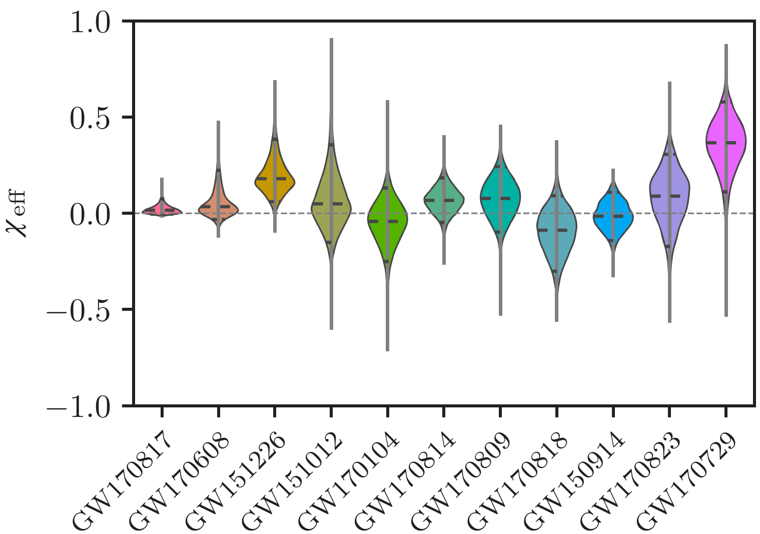
- **GW190425**
  - Only LIGO Livingston; bad sky localization; no EM counterpart found
  - Consistent with binary neutron star, but also with one of the two objects being a light black hole!
  - More massive than any galactic binary neutron star observed with radio that will merge in a Hubble time

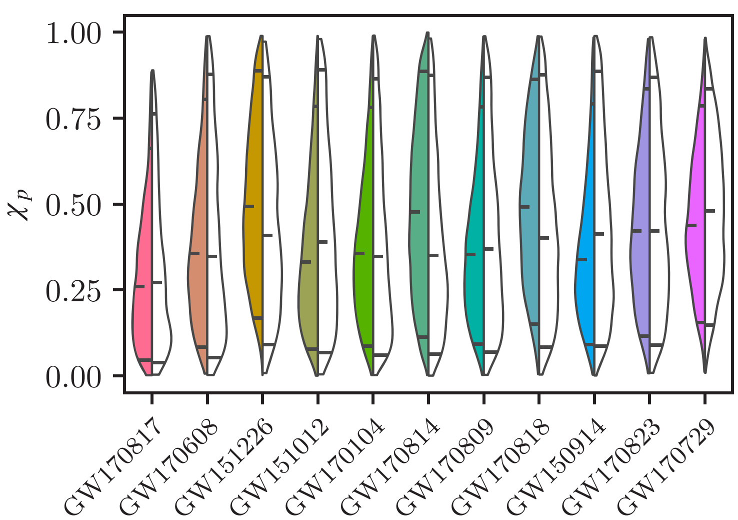




LIGO + Virgo, arXiv:2001.01761

How are black hole spins distributed?

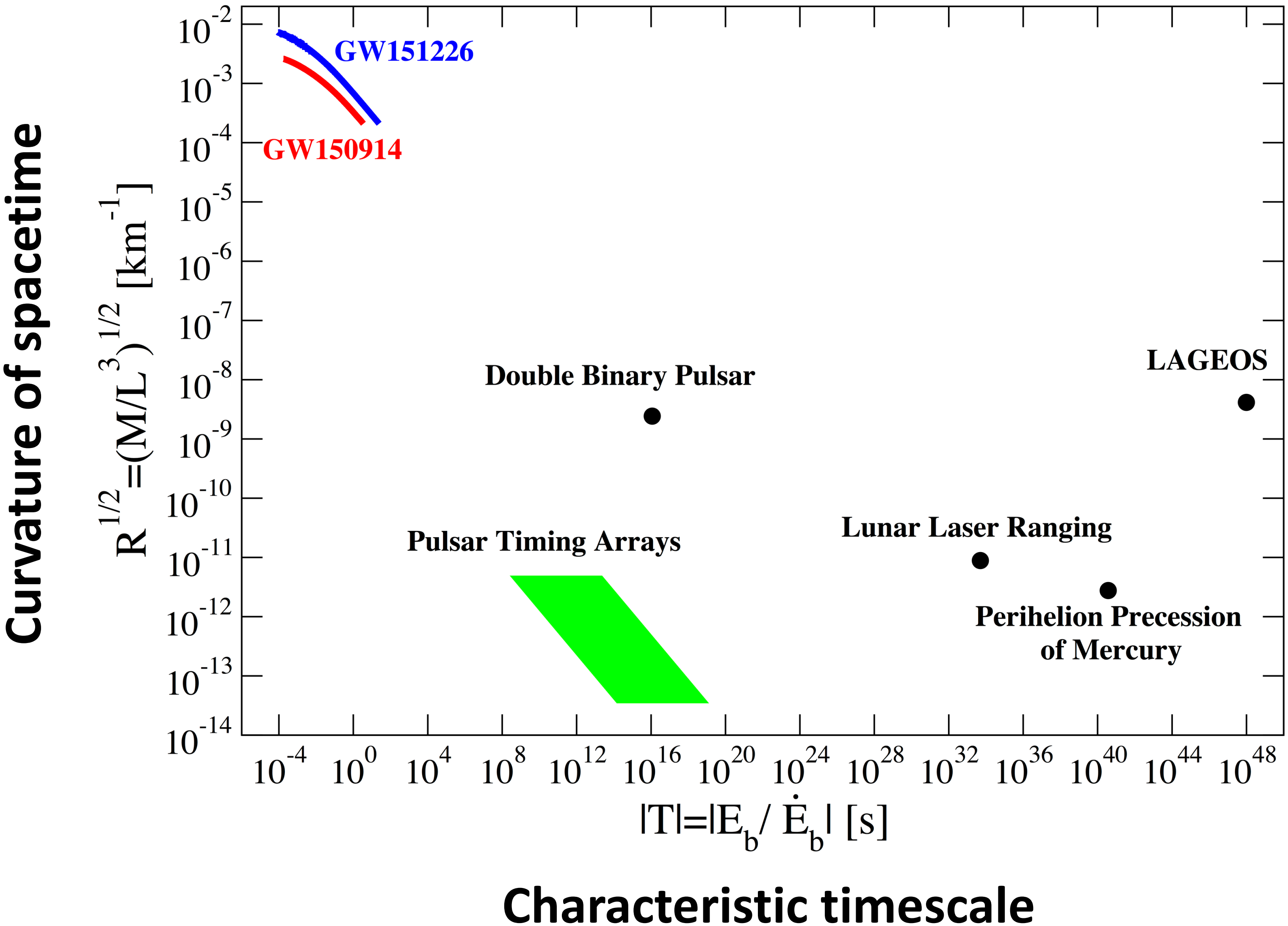




- Spins can be used to distinguish between **formation mechanisms**
  - **Field binaries**:
    Binary black holes originating directly from a heavy binary star system
    - Expect aligned spin vectors
  - **Dynamical formation**:
    Two black holes form separately in a dense stellar environment, then dynamically form a binary
    - Expect misaligned spin vectors
  - **Primordial black holes**:
    If generated during QCD phase transition, expect small spins

LIGO + Virgo, PRX **9**, 031040 (2019)

Access to strongly curved, dynamical spacetime



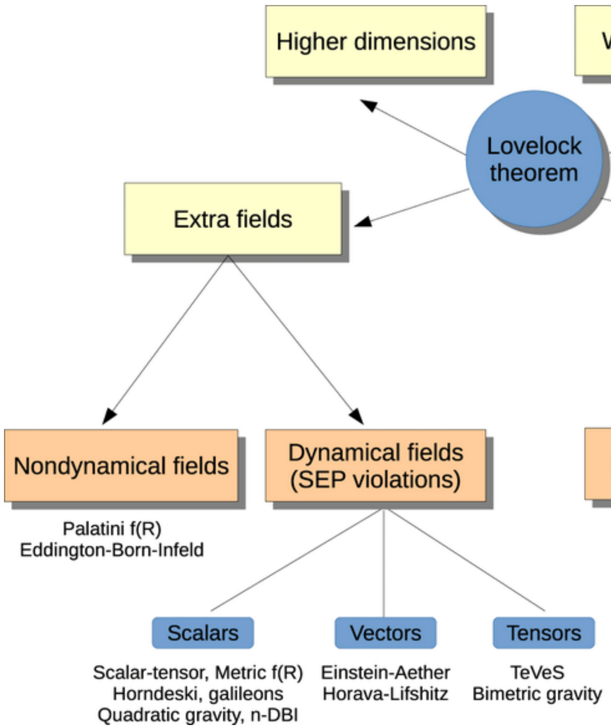
Yunes et al., PRD **94**, 084002 (2016)

The nature of gravity

- Lovelock's theorem:

  "In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term."

- Relaxing one or more of the assumptions allows for a plethora of alternative theories:



Berti et al., CQG **32**, 243001 (2015)

- Most alternative theories: no full inspiral-merger-ringdown waveforms known
  - Most current tests are **model-independent**

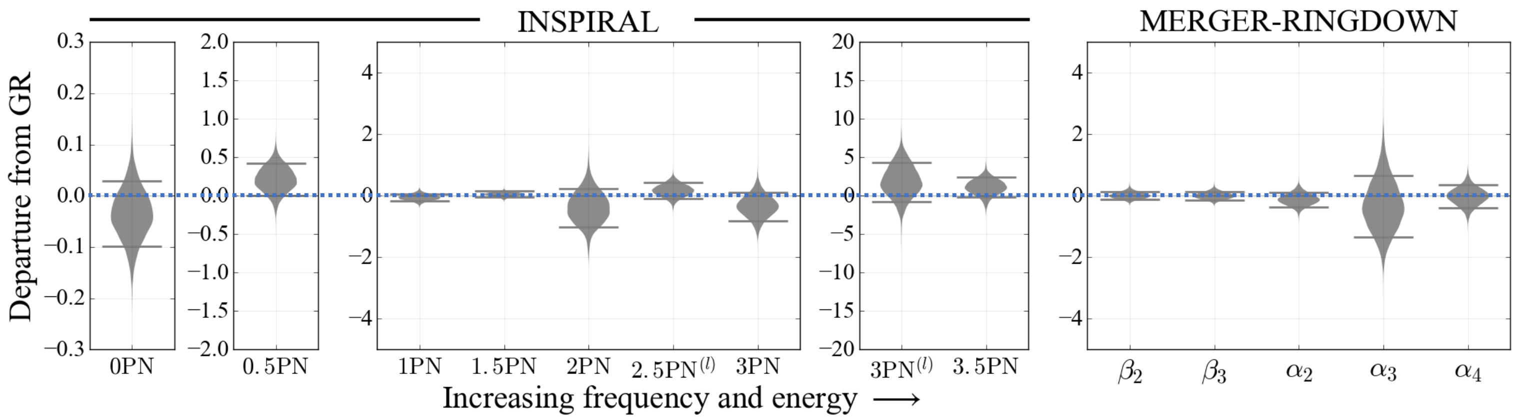
The strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}} \left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}} \left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}} \log\left(\frac{v}{c}\right) \left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}} \left(\frac{v}{c}\right)^7 \right]$$

  - Merger-ringdown governed by additional parameters β_n, α_n

- Look for possible deviations in these parameters:



LIGO + Virgo, PRL **118**, 221101 (2017)

- Rich physics:
  Dynamical self-interaction of spacetime, spin-orbit and spin-spin interactions

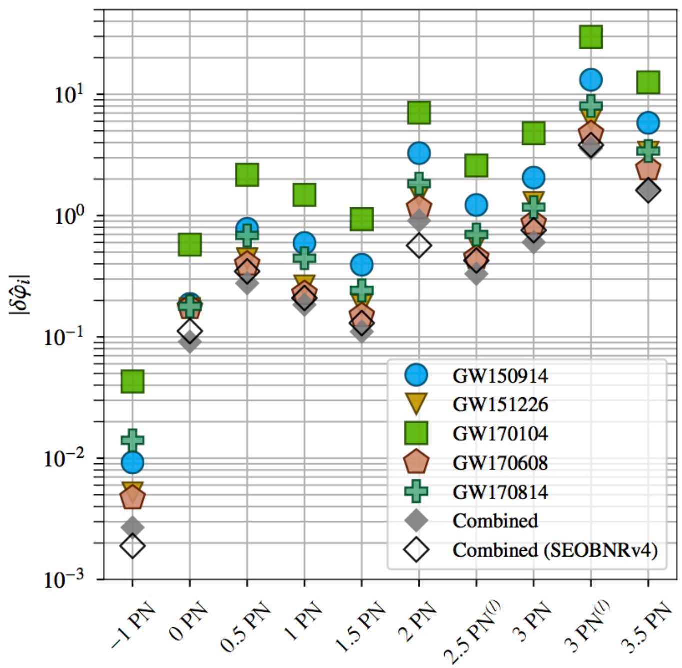
The strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}}\log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^7\right]$$

  - Merger-ringdown governed by additional parameters β_n, α_n

- Combine information from multiple sources:

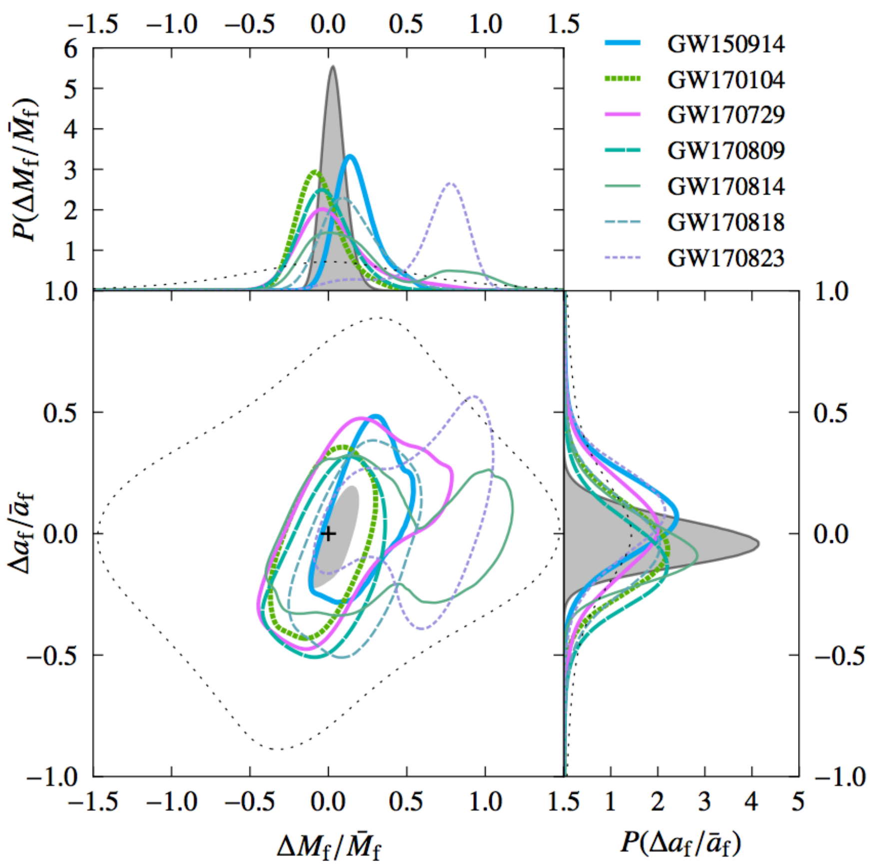


LIGO + Virgo, arXiv:1903.04467

The strong-field dynamics of spacetime

- Consistency between inspiral and merger-ringdown?
  - Masses and spins during inspiral can be used to predict masses and spins of the final object
  - Compare prediction from inspiral with what follows from merger-ringdown

- Here too, combine information from multiple sources



LIGO + Virgo, arXiv:1903.04467

The propagation of gravitational waves

- Dispersion of gravitational waves?
  E.g. as a result of **non-zero graviton mass**:
  - Dispersion relation:

$$E^2 = p^2c^2 + m_g^2c^4$$

  - Group velocity:

$$v_g/c = 1 - m_g^2c^4/2E^2$$

  - Modification to gravitational wave phase:

$$\delta\Psi = -\pi Dc/[\lambda_g^2(1+z)\, f] \qquad \lambda_g = h/(m_g c)$$

- Bound on graviton mass:

$$\boxed{m_g \leq 5.0 \times 10^{-23}\,\mathrm{eV}/c^2}$$

LIGO + Virgo, arXiv:1903.04467

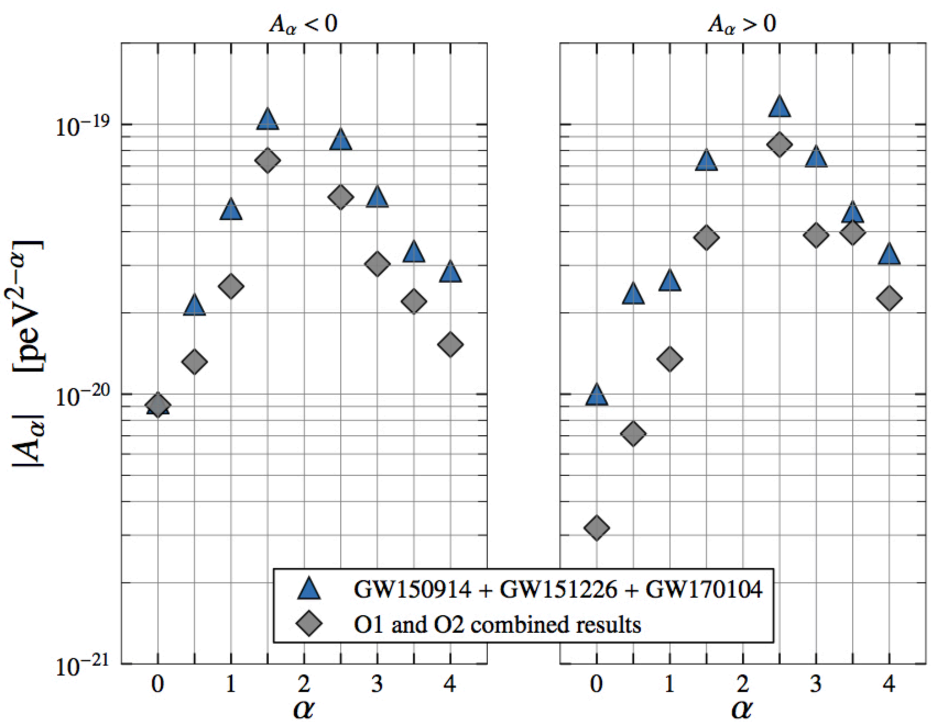
The propagation of gravitational waves

- More general forms of dispersion:

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

$\alpha \neq 0$ corresponds to violation of local Lorentz invariance

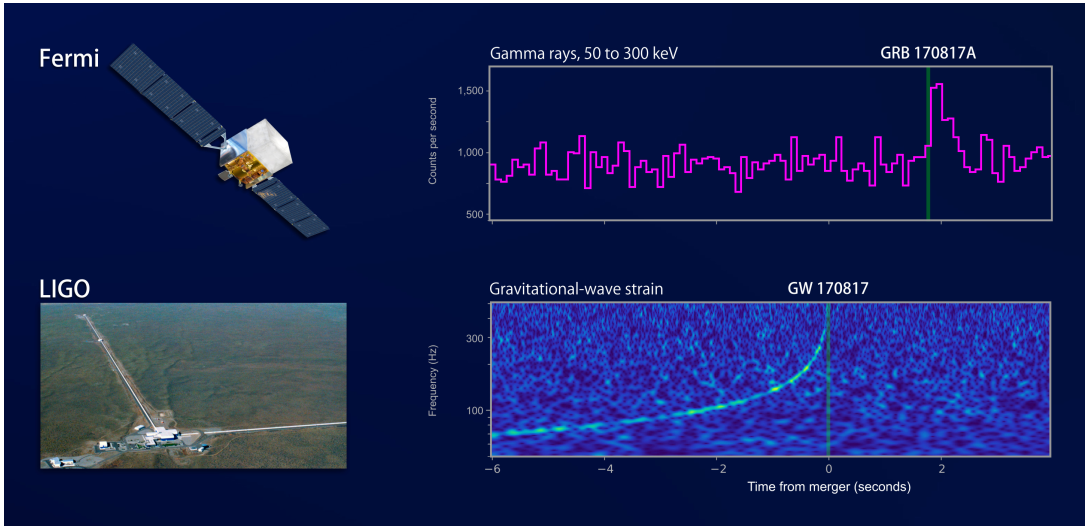
  - $\alpha = 2.5$ multi-fractal spacetime
  - $\alpha = 3$ doubly special relativity
  - $\alpha = 4$ higher-dimensional theories



LIGO + Virgo, arXiv:1903.04467

The propagation of gravitational waves

- Does the speed of gravity equal the speed of light?
- The binary neutron star coalescence GW170817 came with gamma ray burst, **1.74 seconds afterwards**



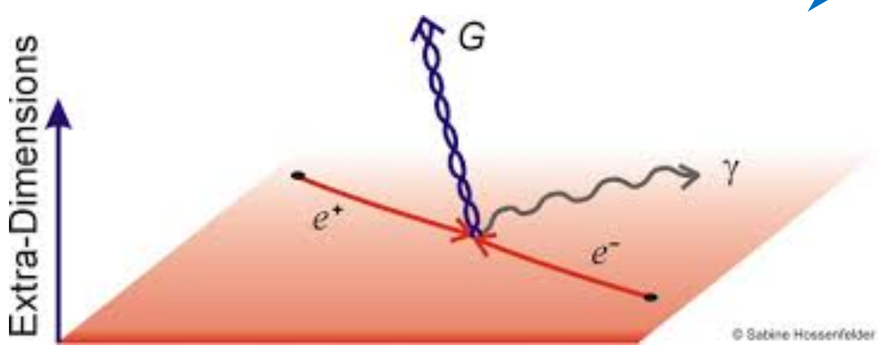
- With a conservative lower bound on the distance to the source:

$$\boxed{-3 \times 10^{-15} < \Delta v / v_{EM} < +7 \times 10^{-16}}$$

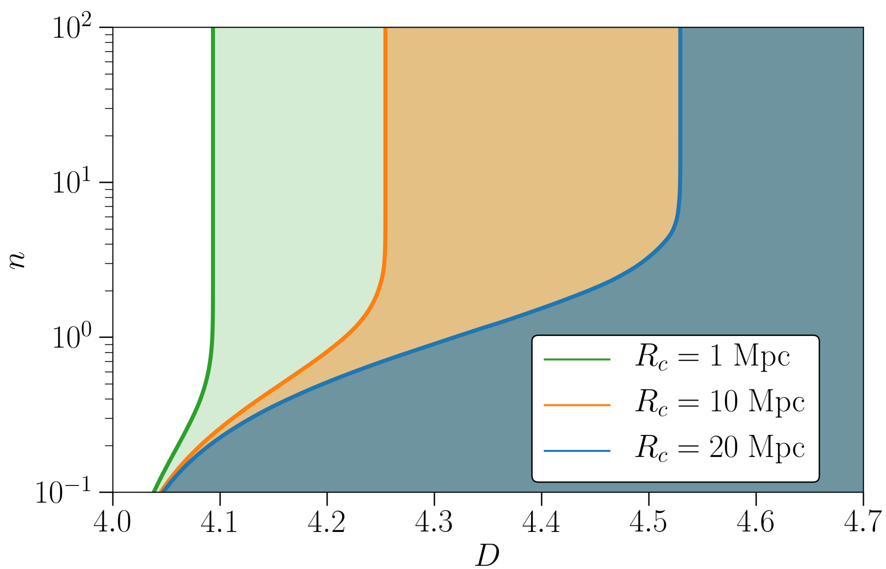
- Excluded certain alternative theories of gravity designed to explain dark matter or dark energy in a dynamical way

LIGO + Virgo + Fermi-GBM + INTEGRAL, ApJ. **848**, L13 (2017)

The propagation of gravitational waves



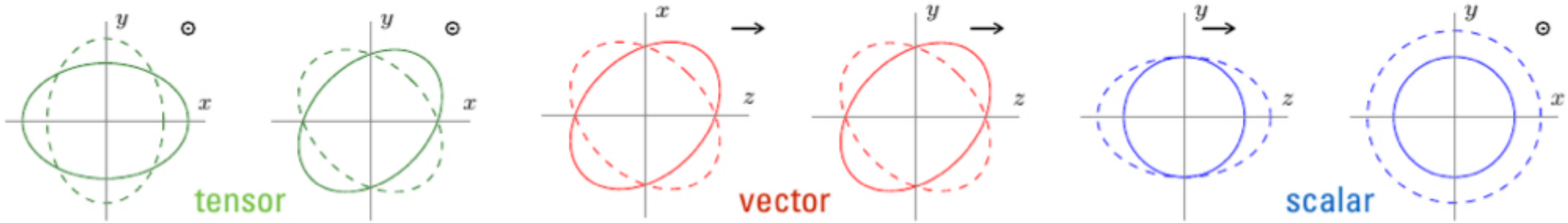
- "Braneworld" model
  - Standard model physics confined to the 3D brane
  - Gravity can propagate into the bulk (which would explain why it is the weakest interaction)



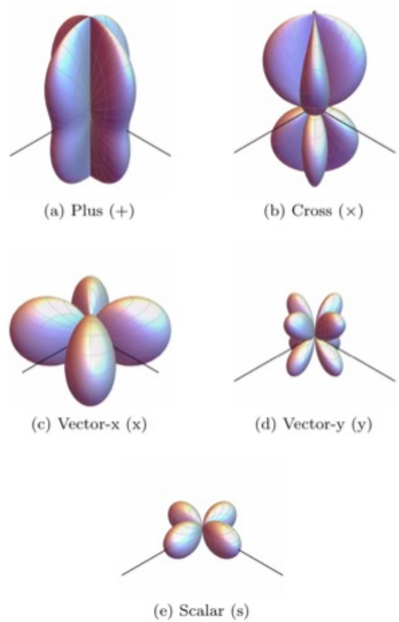
- "Leakage" of gravitational waves into large extra dimensions would cause deviations from expected 1/distance drop-off
  - Compare distance inferred from GW signal with distance to host galaxy
  - Exclude extra dimensions depending on length scale of possible screening mechanism, and transition steepness

LIGO + Virgo, PRL **123**, 011102 (2019)

The propagation of gravitational waves



- Metric theories of gravity allow up to 6 polarizations
- Distinct antenna patterns:



$$|F_{\rm t}^I(\alpha,\delta)| \equiv \sqrt{F_+^I(\alpha,\delta)^2 + F_\times^I(\alpha,\delta)^2}\,,$$

$$|F_{\rm v}^I(\alpha,\delta)| \equiv \sqrt{F_{\rm x}^I(\alpha,\delta)^2 + F_{\rm y}^I(\alpha,\delta)^2}\,,$$

$$|F_{\rm s}^I(\alpha,\delta)| \equiv \sqrt{F_{\rm b}^I(\alpha,\delta)^2 + F_{\rm l}^I(\alpha,\delta)^2}$$

Isi & Weinstein, PRD **96**, 042001 (2017)

- In the case of GW170817, sky position was known from EM counterpart
  - Pure tensor / pure vector = 10^{21} / 1
  - Pure tensor / pure scalar = 10^{23} / 1

LIGO + Virgo, PRL **123**, 011102 (2019)

What is the nature of compact objects?

- Black holes, or still more exotic objects?
  - Boson stars
  - Dark matter stars
  - Gravastars
  - Wormholes
  - Firewalls, fuzzballs
  - *The unknown*

Ringdown and the no-hair conjecture

- Assuming vacuum Einstein equations:
  "Stationary black holes are completely characterized by mass and spin"

- Ringdown regime: Kerr metric + linear perturbations
  - Ringdown signal is superposition of "quasi-normal modes"

    $$h(t) = \sum_{nlm} \mathcal{A}_{nlm} e^{-t/\tau_{nlm}} \cos(\omega_{nlm} t + \phi_{nlm})$$

  - Characteristic frequencies and damping times completely determined by mass M_f and spin a_f :

    $$\omega_{nlm} = \omega_{nlm}(M_f, a_f)$$

    $$\tau_{nlm} = \tau_{nlm}(M_f, a_f)$$

  - **Empirically checking these dependences can be viewed as an indirect test of the no-hair conjecture**

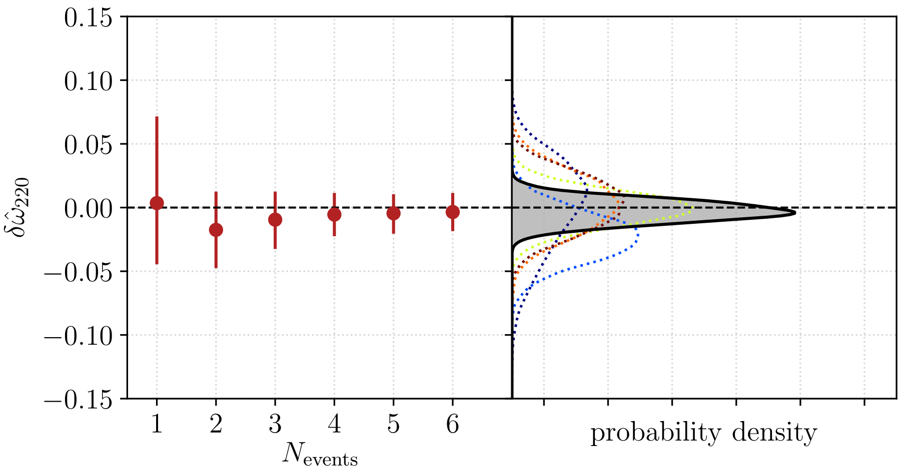
Ringdown and the no-hair conjecture

- Given a waveform model, (indirectly) test the no-hair theorem by allowing for deviations:

$$\omega_{lmn}(M_f, a_f) \;\rightarrow\; (1+\delta\hat{\omega}_{lmn})\,\omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \;\rightarrow\; (1+\delta\hat{\tau}_{lmn})\,\tau_{lmn}(M_f, a_f)$$

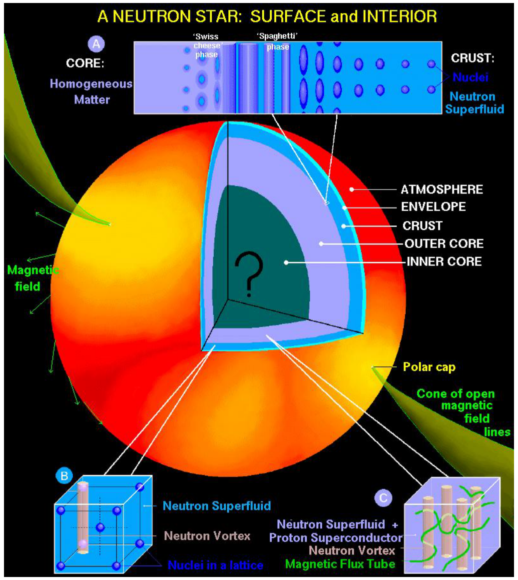
- Let the different $\delta\hat{\omega}_{lmn}$ and $\delta\hat{\tau}_{lmn}$ vary in turn, and measure them together with all other parameters in the problem
  - Obtain probability density distributions
  - Combine information from multiple signals

- Assuming Advanced LIGO/Virgo at design sensitivity, and 6 sources similar to GW150914:
  - $\delta\hat{\omega}_{220}$ measurable to **O(2%)**
  - $\delta\hat{\tau}_{220}$ measurable to **O(10%)**

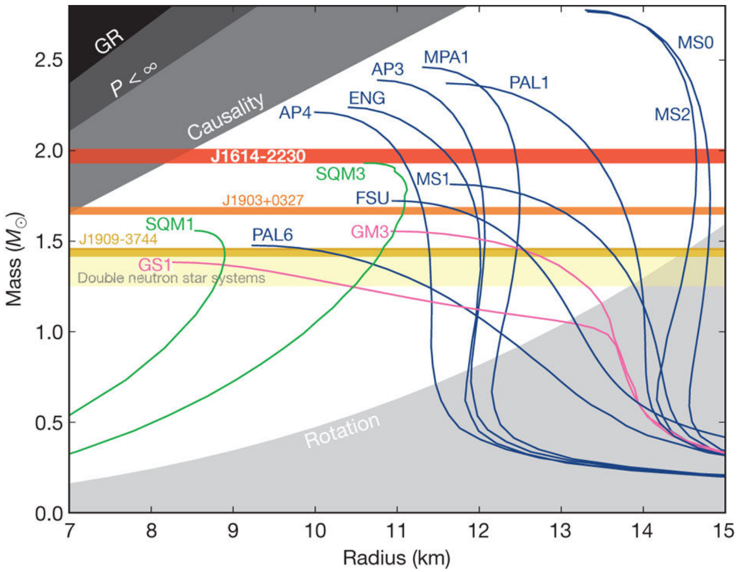


Carulllo et al., PRD **98**, 104020 (2018)

The equation of state of neutron stars



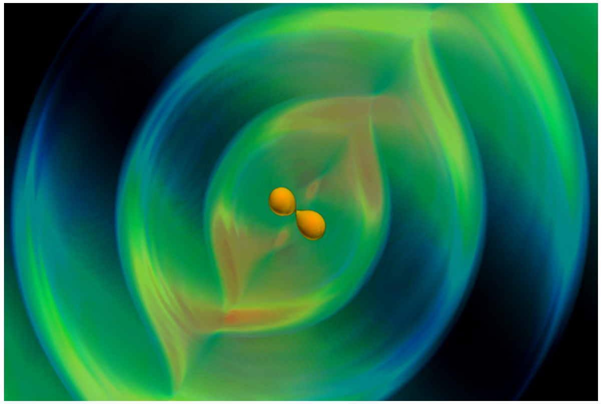
- Structure of neutron stars?
  - Structure of the crust?
  - Proton superconductivity
  - Neutron superfluidity
  - “Pinning” of fluid vortices to the crust
  - Origin of magnetic fields?
  - More exotic objects?



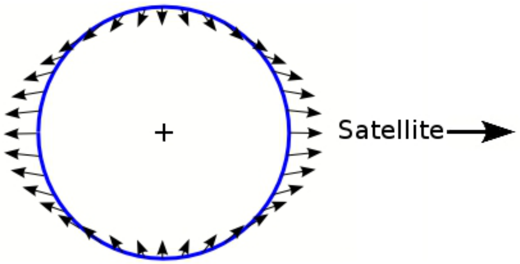
- Widely differing theoretical predictions for **equation of state**
  - Pressure as a function of density
  - Mass as a function of radius
  - **Tidal deformability** as a function of mass

Demorest et al., Nature **467**, 1081 (2010)

Tidal deformations in binary neutron stars



- Gravitational waves from inspiraling neutron stars:
  - When close, the stars induce tidal deformations in each other
  - These affect orbital motion, which modifies the gravitational wave signal



- Tidal field of one star causes quadrupole deformation in the other:

  $$Q_{ij} = -\lambda(\mathrm{EOS}; m)\, \mathcal{E}_{ij}$$

  where $\lambda(\mathrm{EOS}; m)$ depends on internal structure (equation of state)

- Enters inspiral phase at 5PN order, through

  $$\lambda(m)/m^5 \propto (R/m)^5$$

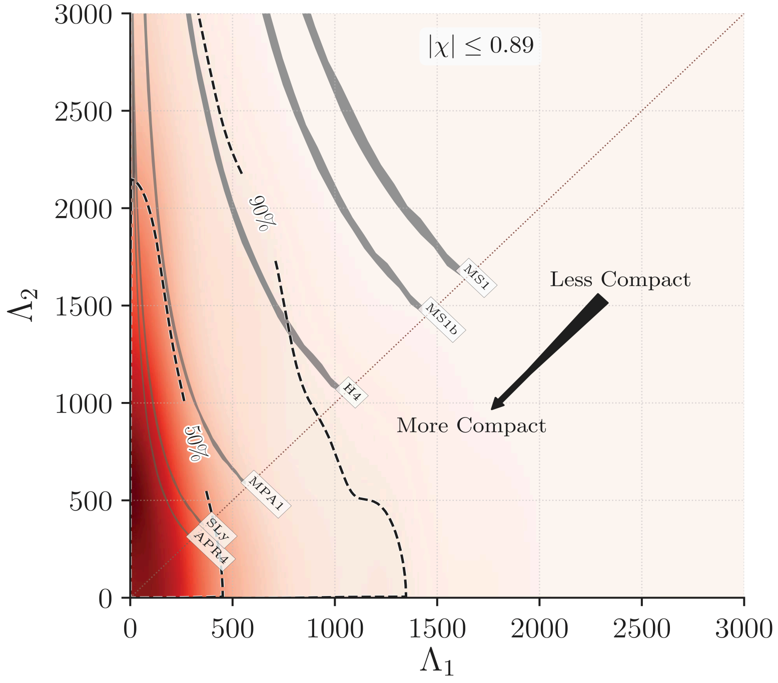
  - $O(10^2 - 10^5)$ depending on mass and EOS

Probing the structure of neutron stars

- Measurement of tidal deformations on GW170817
  - Free parameters in the waveform:

$$\{m_1, m_2, \vec{S}_1, \vec{S}_2, \alpha, \delta, \iota, \psi, d_L, t_c, \varphi_c, \Lambda_1, \Lambda_2\} \qquad \Lambda_i \equiv \frac{\lambda_i}{m_i^5} \qquad i = 1, 2$$

  - First results: more compact neutron stars favored



LIGO + Virgo, PRL **119**, 161101 (2017)

  - Since then more detailed investigations:
    LIGO + Virgo, PRL **121**, 161101 (2018)

Equations-of-state: model selection

- Given two hypotheses $\mathcal{H}_1, \mathcal{H}_2$ we can calculate the **odds ratio**:

$$
\begin{aligned}
O^{\mathcal{H}_X}_{\mathcal{H}_Y} &= \frac{p(\mathcal{H}_X|d)}{p(\mathcal{H}_Y|d)} \\
&= \frac{p(d|\mathcal{H}_X)}{p(d|\mathcal{H}_Y)} \frac{p(\mathcal{H}_X)}{p(\mathcal{H}_Y)}
\end{aligned}
$$

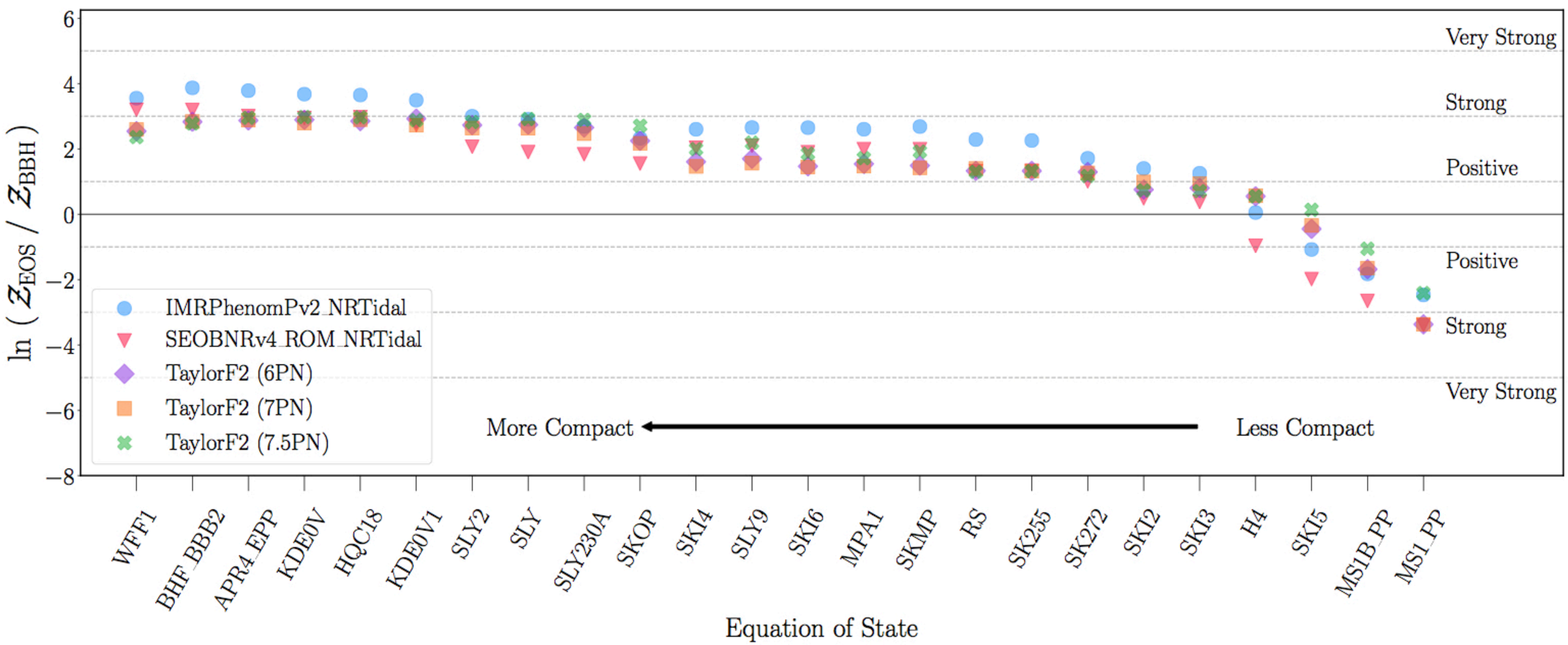
  - $p(\mathcal{H}_X)/p(\mathcal{H}_Y)$ ratio of prior odds
  - $p(d|\mathcal{H}_X)/p(d|\mathcal{H}_Y)$ ratio of evidences

- Consider hypotheses $\mathcal{H}_A$, $A = 1, \ldots, N$ corresponding to different theoretical predictions for the equation of state
  - For a given equation of state $\mathcal{H}_A$, one has a waveform model in which the tidal deformations depend on component masses in a specific way: $\Lambda_1 = \Lambda^{(A)}(m_1)$, $\Lambda_2 = \Lambda^{(A)}(m_2)$
  - The free parameters in each model are $\{m_1, m_2, \vec{S}_1, \vec{S}_2, \alpha, \delta, \iota, \psi, d_L, t_c, \varphi_c\}$

- Define some reference model $\mathcal{H}_{\rm ref}$, e.g. one in which $\Lambda^{(\rm ref)}(m) \equiv 0$, and compute $O^{\mathcal{H}_A}_{\mathcal{H}_{\rm ref}}$ for $A = 1, \ldots, N$

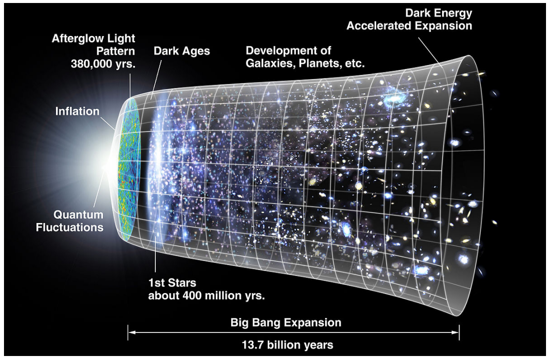
Equations-of-state: model selection

➢ Results from GW170817:

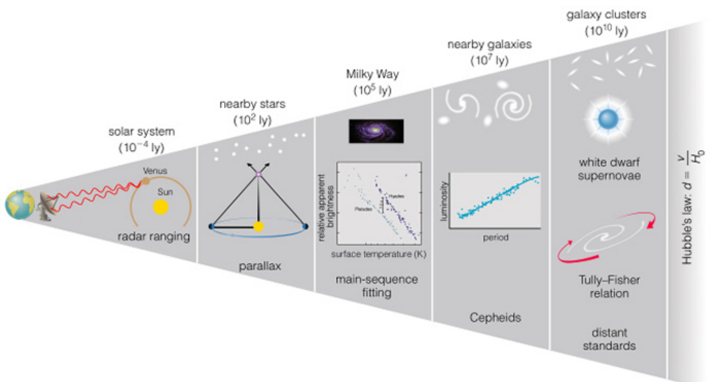


LIGO + Virgo, arXiv:1908.01012

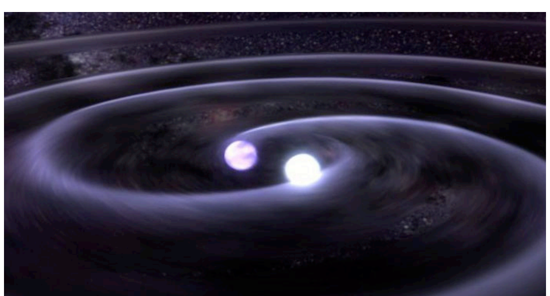
A new cosmic distance ladder



- Mapping out the large-scale structure and evolution of spacetime by comparing:
  - Distance
  - Redshift

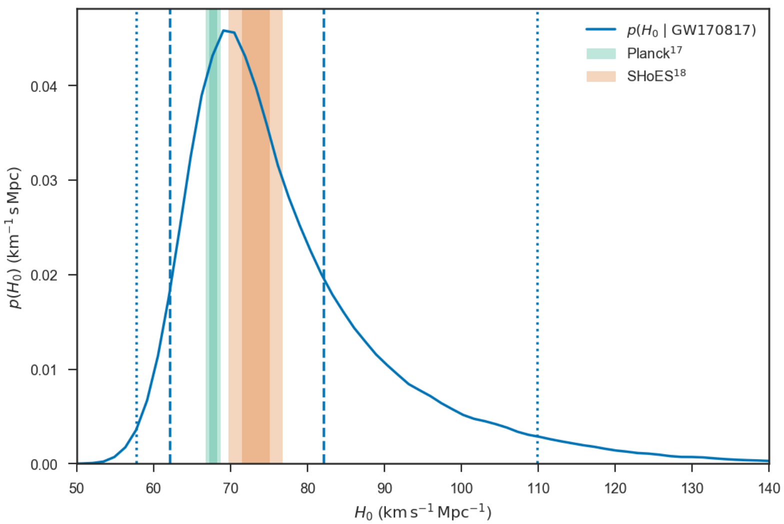


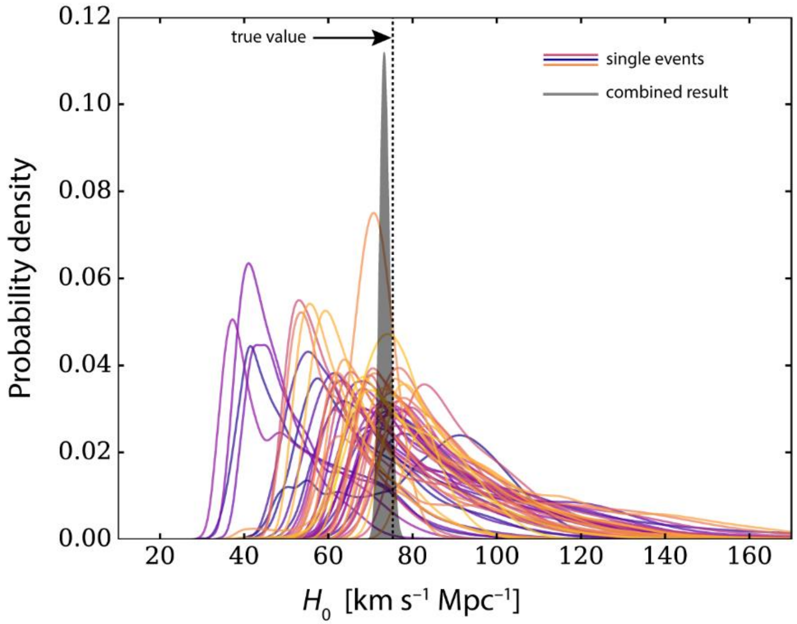
- Current measurements depend on **cosmic distance ladder**
  - Intrinsic brightness of e.g. supernovae determined by comparison with different, closer-by objects
  - Possibility of systematic errors at every "rung" of the ladder



- Gravitational waves from binary mergers: **Distance can be measured directly from the gravitational wave signal!**

A new cosmic distance ladder





- Measurement of the local expansion of the Universe: the Hubble constant
  - Distance from GW signal
  - Redshift from EM counterpart (galaxy NGC 4993)

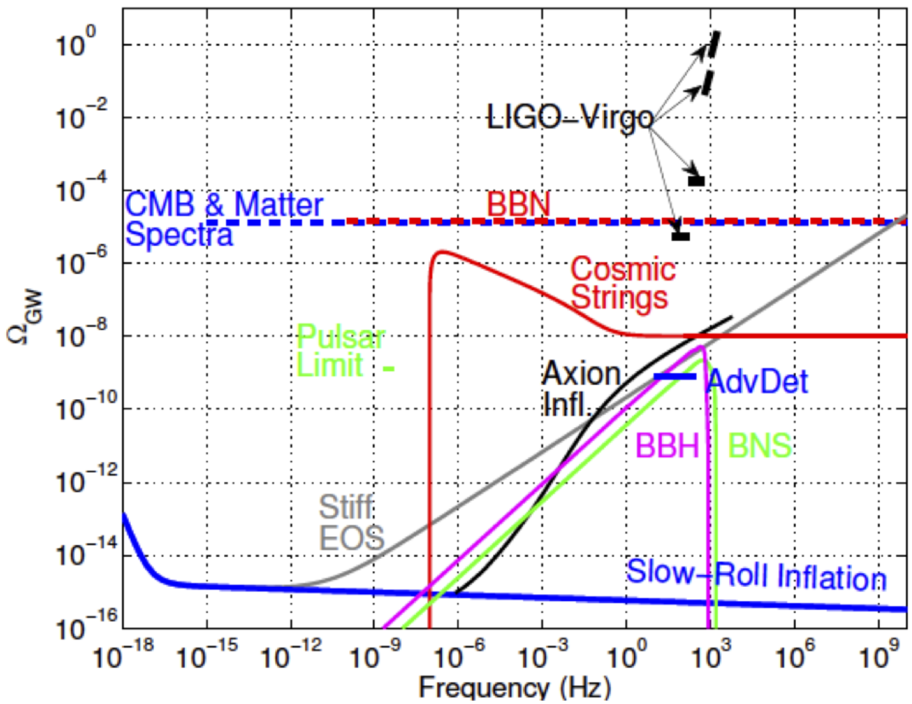
LIGO + Virgo, Nature **551**, 85 (2017)

- One detection: limited accuracy
- Few tens of detections: O(1%) accuracy

Del Pozzo, PRD **86**, 043011 (2012)
Chen et al., Nature **562**, 7728 (2018)
Feeney et al., PRL **112**, 061105 (2019)

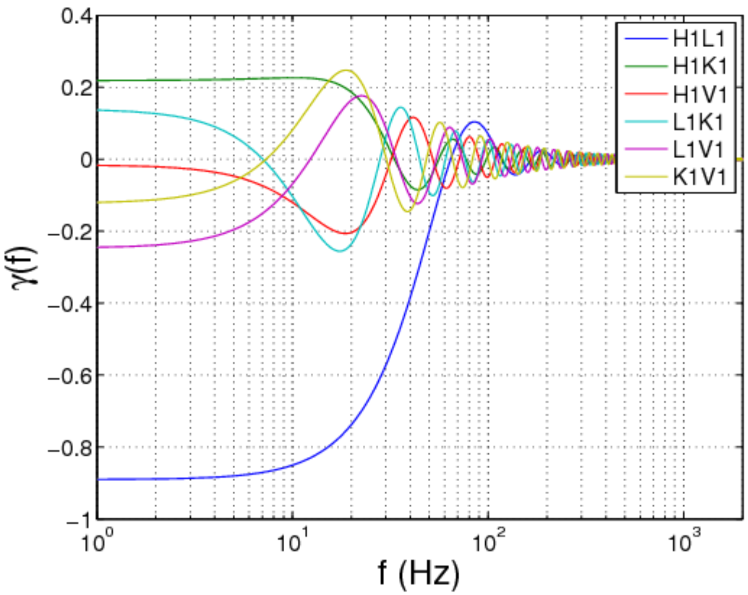
Stochastic gravitational waves

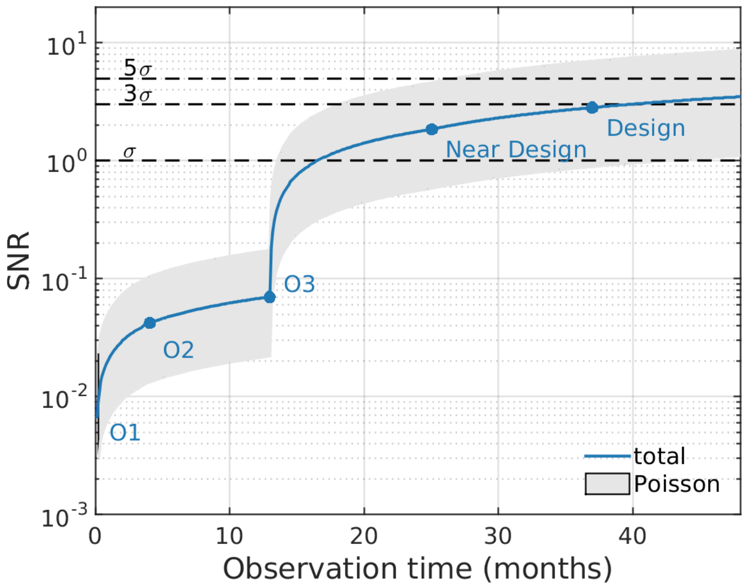
$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$



- Gravitational wave backgrounds of a fundamental nature
  - Inflation: period of exponential growth of the Universe
  - Phase transitions: fundamental forces splitting off
  - Cosmic strings
  - …
- Combined background of weak signals from astrophysical sources
  - Coalescing binaries out to arbitrary distances
  - All the continuous waves sources in the Milky way
  - …

Stochastic gravitational waves





- Takes the form of "noise" that is correlated between detectors
  - Searched for by cross-correlating between detectors:

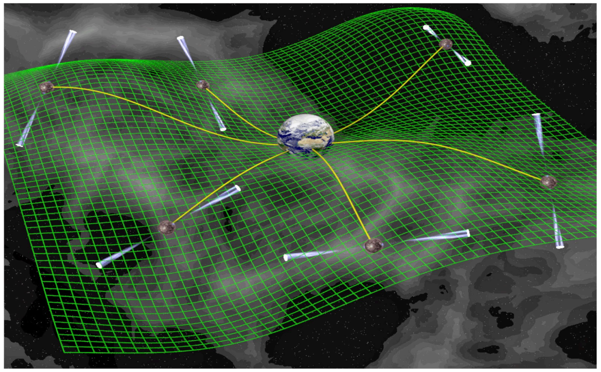
$$Y = \int \tilde{s}_1(f)\,\tilde{K}(f)\,\tilde{s}_2(f)\,df$$

  - Optimal filter:

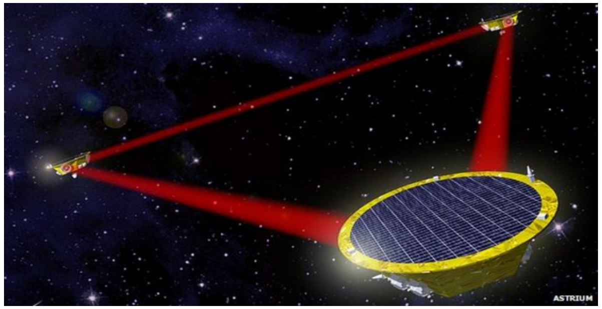
$$\tilde{K}(f) \propto \frac{\gamma(f)\,\Omega_{gw}(f)}{f^3\,S_{n,1}(f)\,S_{n,2}(f)} \qquad \Omega_{gw}(f) \equiv \Omega_0\,f^{\alpha}$$

- In the case of astrophysical stochastic background from binary coalescences:
  Detection in a few years' time?

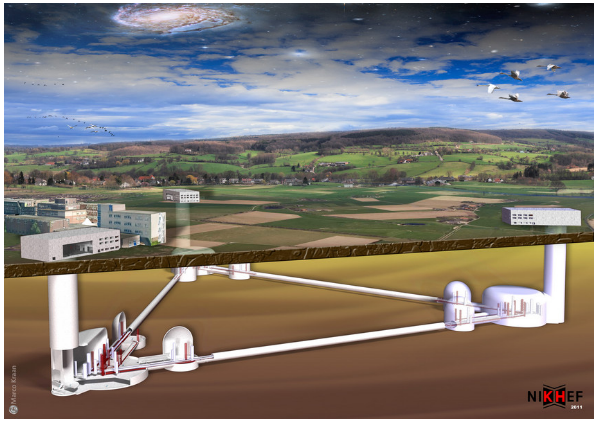
New (types of) detectors



- Pulsar timing arrays

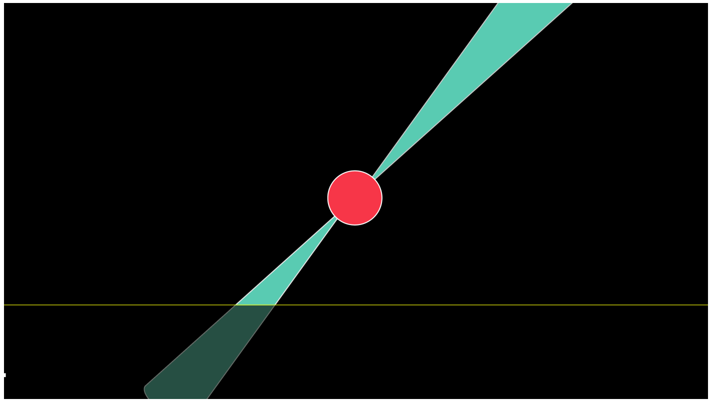


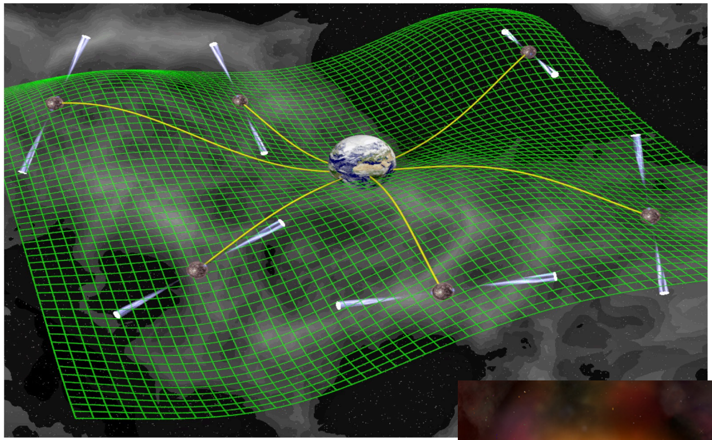
- Laser Interferometer Space Antenna (LISA)

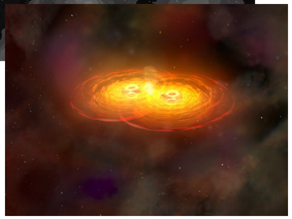


- Einstein Telescope

Pulsar timing







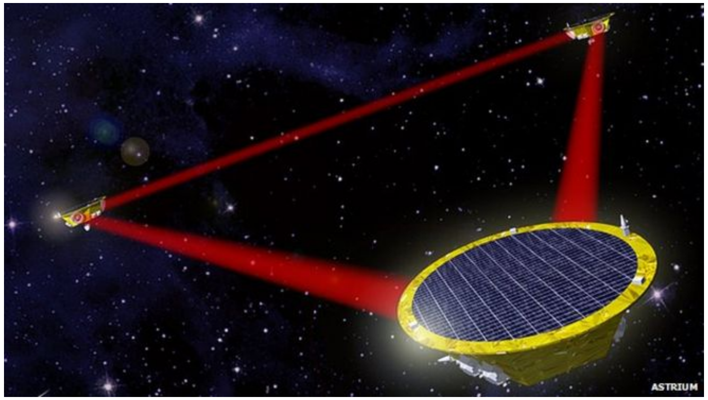
- Radio astronomers monitor pulsars:
  - Neutron stars as “lighthouses”
  - Period can be measured with great accuracy
- When a gravitational wave passes by, time runs faster/slower
- Large number of pulsars in the Milky Way together form a gravitational wave detector
  - Sensitive to ultra-low frequencies: $10^{-9} – 10^{-6}$ Hz
  - Observations of supermassive binary black holes long before they merger?
    - Possible first detection 2020-2030
  - Primordial background of GWs?

Pulsar timing

- International pulsar array
  - European Pulsar Timing Array: 4 largest radio telescopes in Europe (including Westerbork)
  - NANOGrav: United States, Australia (Green Bank, Arecibo, Parkes)

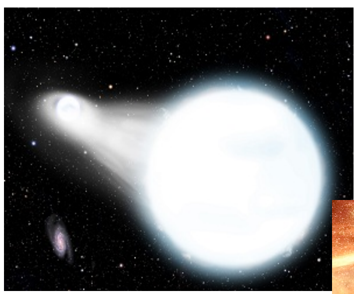
- Near future: Square Kilometer Array

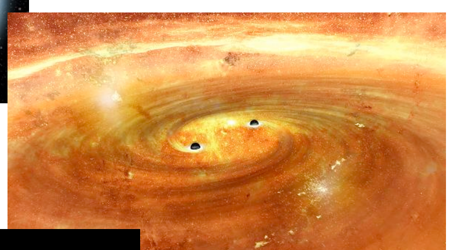
Laser Interferometer Space Antenna (LISA)

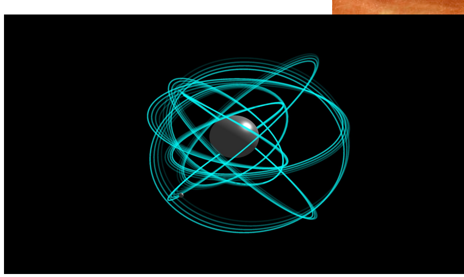


- Project of the European Space Agency, to be launched in 2034

- Three probes in orbit around the Sun, exchanging laser beams
  - Triangle with sides of a few million km
  - Sensitive to low frequencies: $10^{-4} – 10^{-1}$ Hz

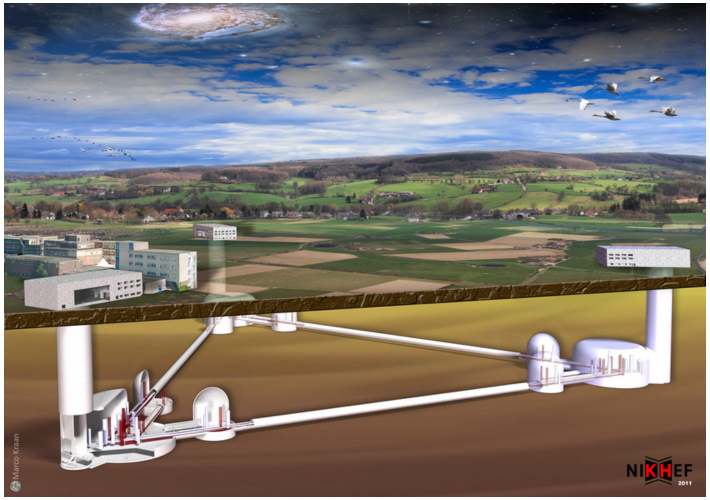


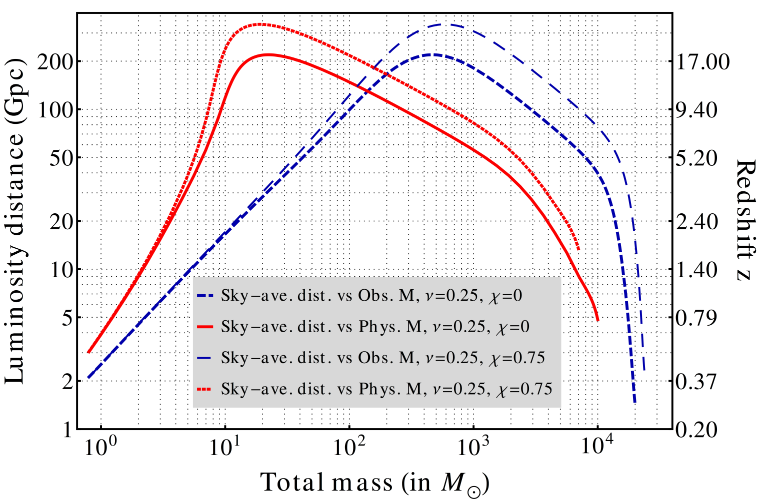




- Different types of sources:
  - Binary white dwarfs in the Milky Way
  - Mergers of supermassive black holes
  - Smaller objects in complicated orbit around supermassive black hole
  - Primordial background of GWs?

Einstein Telescope

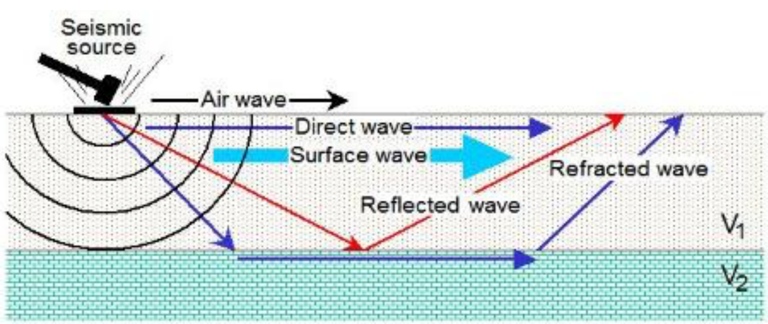




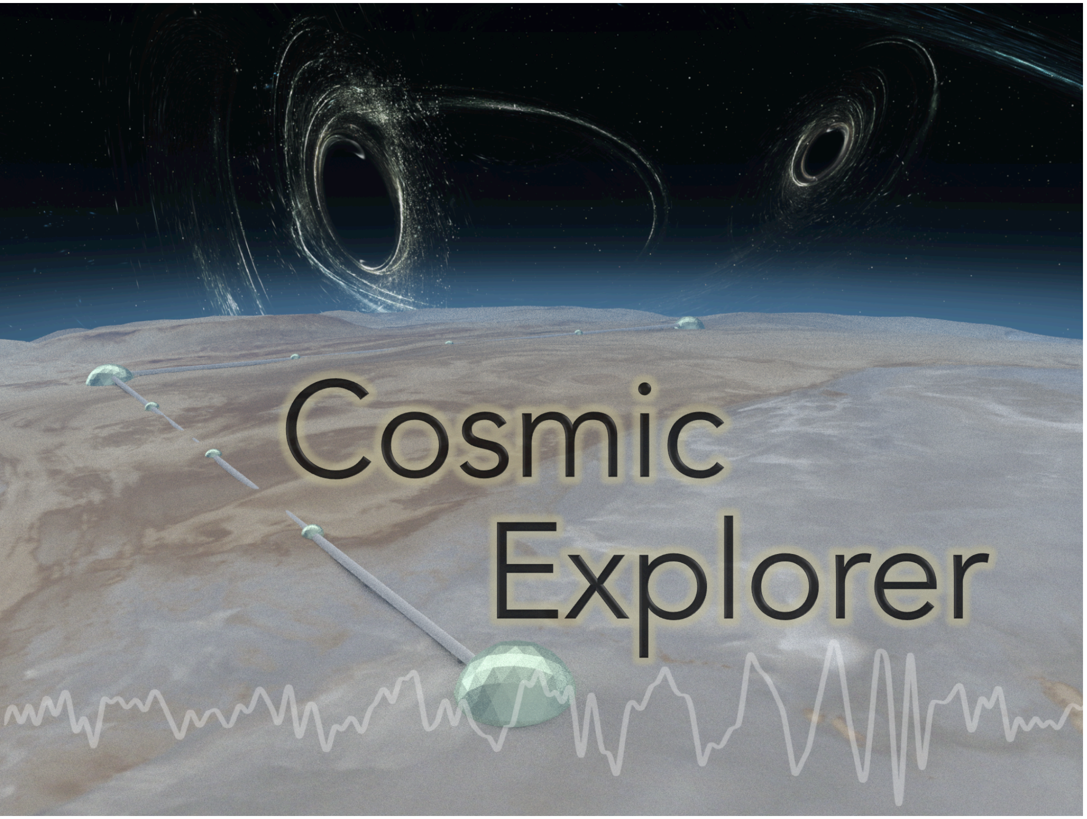
- EU-funded conceptual design study in 2011
  - Triangular, sides of 10 km
  - Underground
  - Superior noise suppression
  - More sensitive optics
  - Six interferometers:
    - High frequencies (high laser power)
    - Low frequencies (cryogenic)
- Factor 10 improvement over LIGO/Virgo at design sensitivity
  - Access to the entire visible Universe
  - 100,000 merger detections per year
    - How did stellar mass binary black holes arise?
    - Are there primordial black holes?
    - Detailed probe of neutron star interiors
    - Cosmology
      - Large-scale structure and evolution of spacetime
      - Primordial background of GWs?

Einstein Telescope in the Belgian-Dutch-German border region?

- Location in the south of Limburg
  - Clay with hard rock underneath
  - Well-suited for damping of seismic vibrations
  - Drilling to depth of 320 meters to prove quality of the site

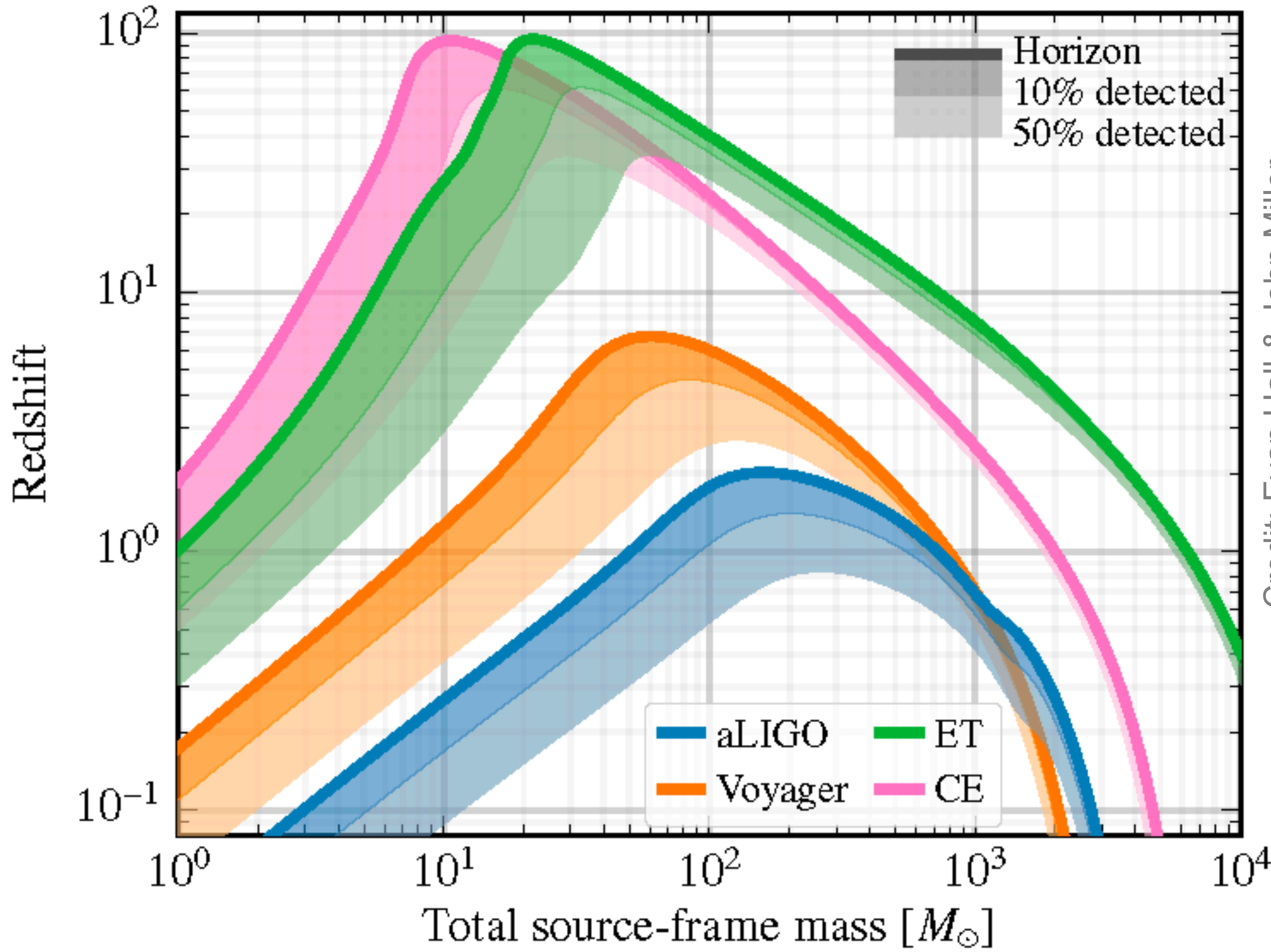


Plans in the United States: Cosmic Explorer



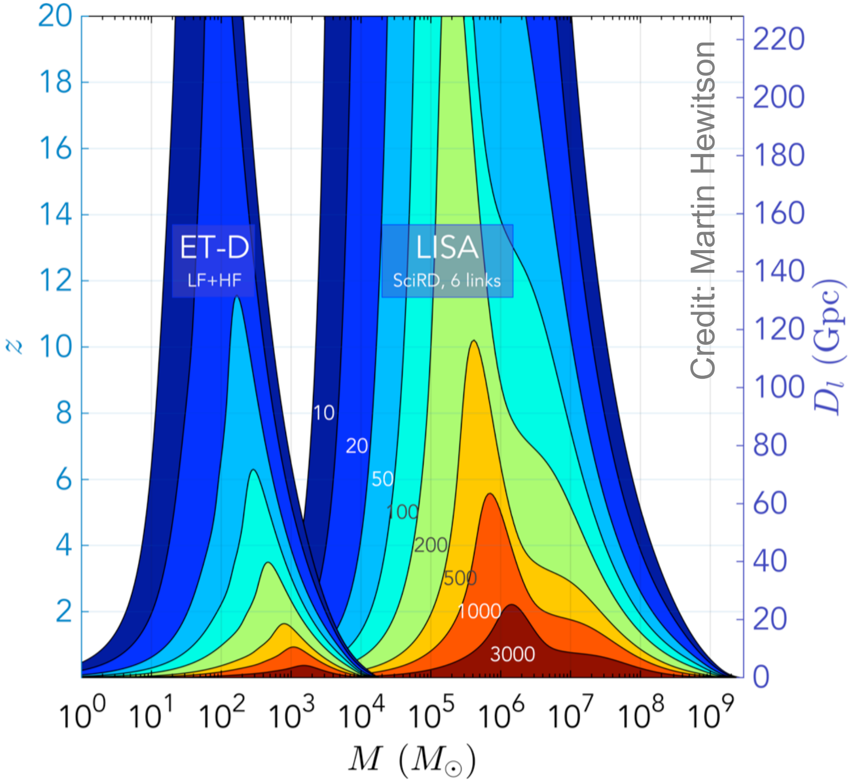
- 40 km arm length
- (Mostly) above ground
- Single L-shaped detector
  - Or two, in different locations
- Partially cryogenic
- Recent idea
  (after first detections)
- Together with ET:
  sky localization

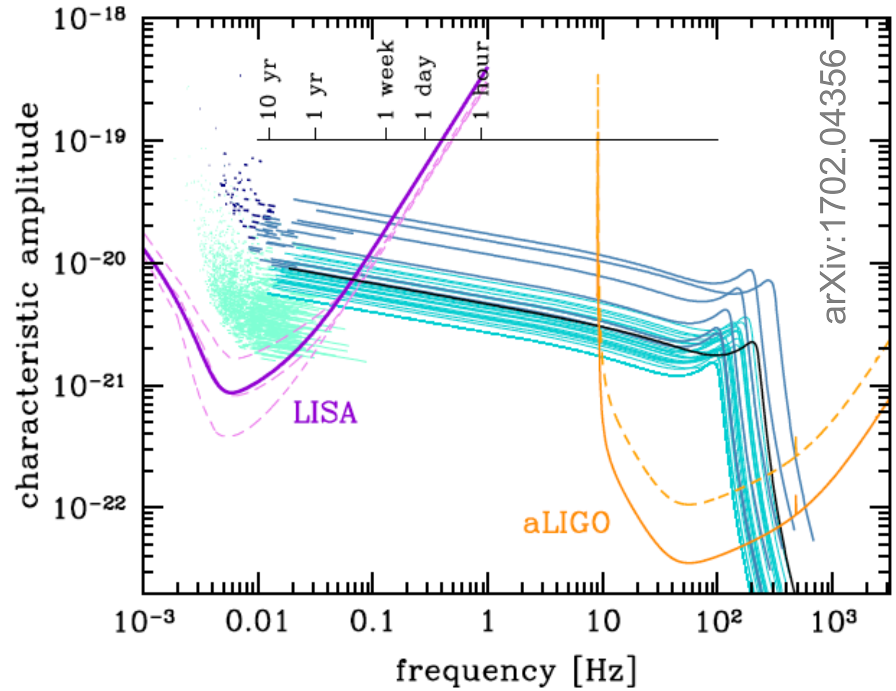
Plans in the United States: Cosmic Explorer



Credit: Evan Hall & John Miller

Advantages in having Einstein Telescope, Cosmic Explorer running at the same time as LISA





- LISA has a planned launch in 2034
- Make sure ET and CE have consistent timelines

Into the future