The Path Forward for Gravitational-wave Astrophysics

Damour Fest

13 October 2021

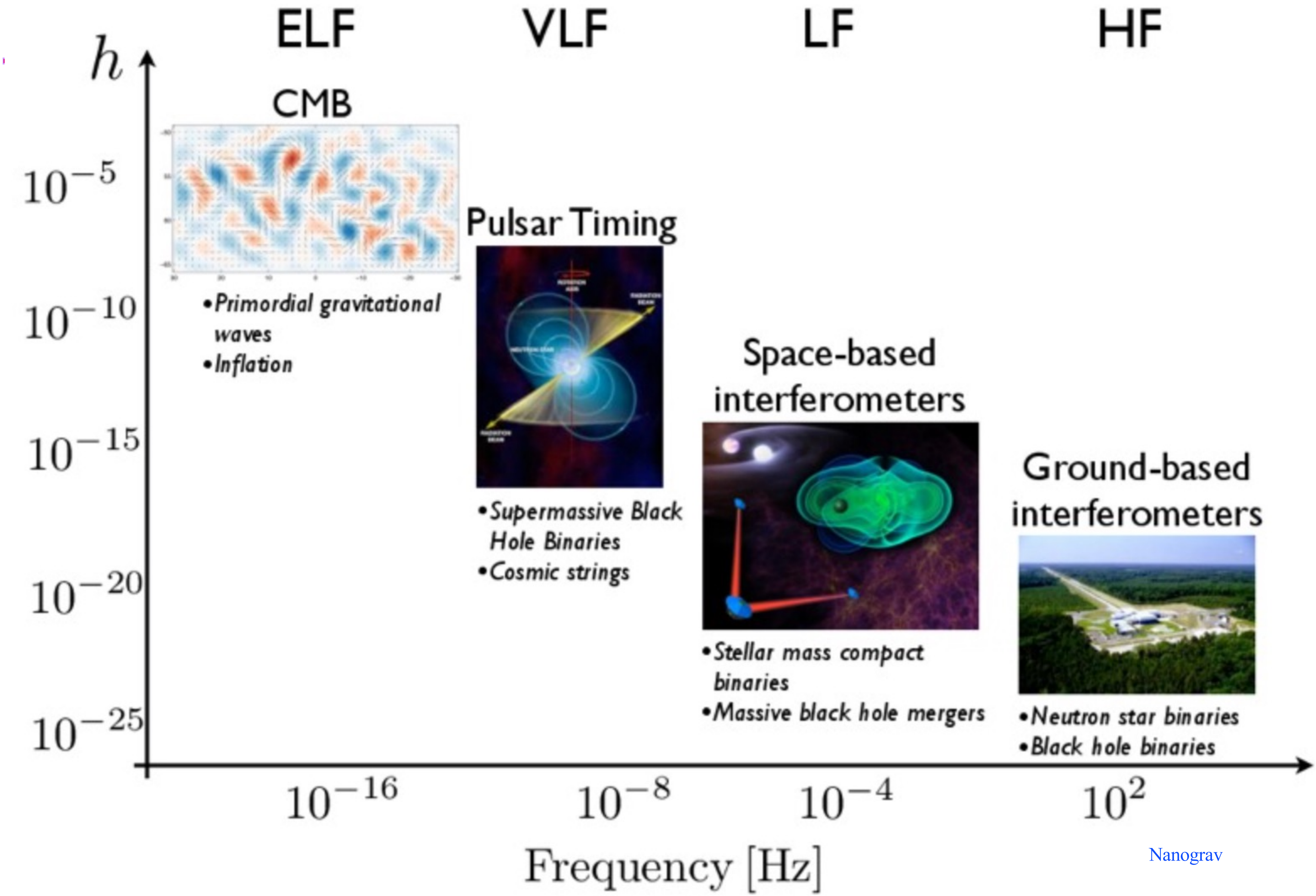
David Shoemaker

MIT

G2102164

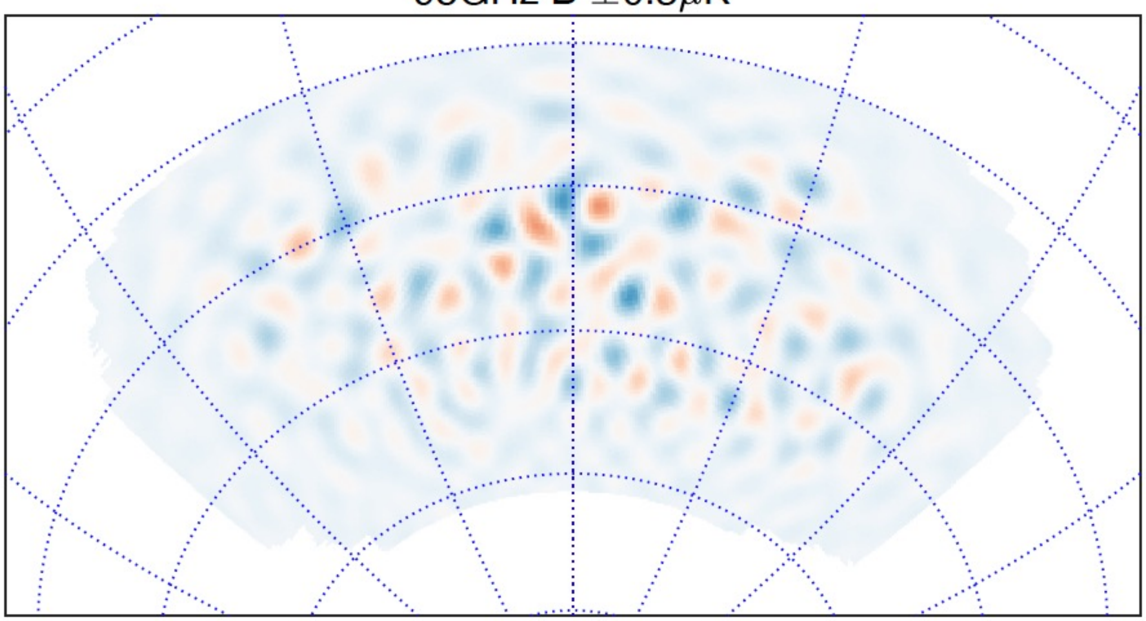
- Plans and dreams for the future of detecting/exploiting
  - FemtoHz: CMB B-mode primordial stochastic background
  - NanoHz: signals via Pulsar test masses
  - MilliHz: signals via inter-satellite timing
  - HectoHz: signals via ground interferometry
- GWIC Roadmap in Nature for more detail

The big picture of gravitational wave astronomy



CMB B-mode

- The signal of gravitational waves from inflation is the holy grail of cosmology
- Measuring *primordial* CMB B-modes is likely our best opportunity for indirectly observing gravity operating on a quantum scale
- Current limit: tensor to scalar ratio $r < 0.036$ (BICEP/Keck+WMAP/Planck, PRL **127**, 151301)
- …no detection to date – foreground of galactic dust is challenging



$r = (E/3.3*10^{16}\ \mathrm{GeV})^4$
where E is the scale of inflation

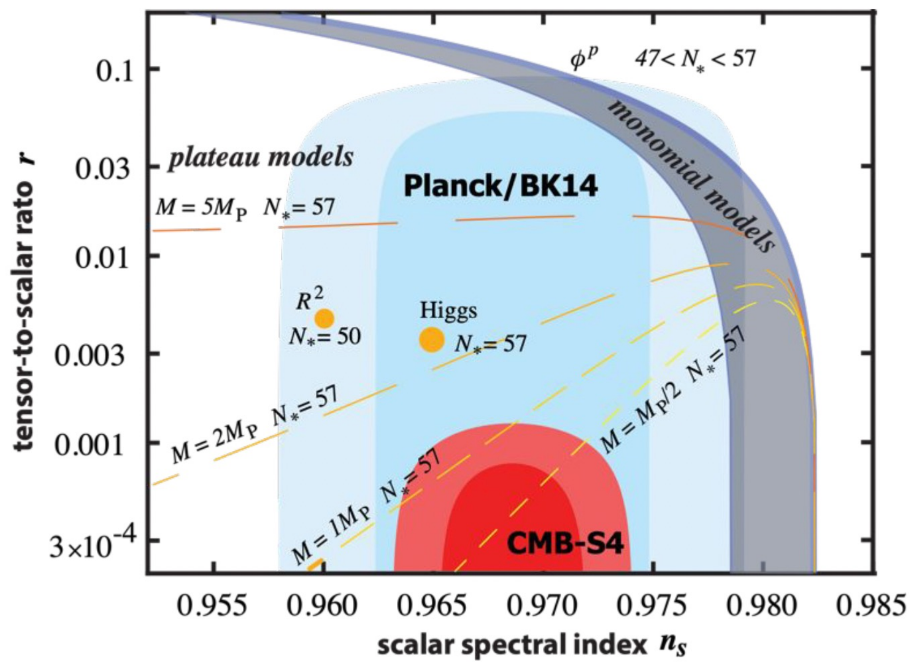
E, 10^{16} GeV	r
3.3	0.1
1	0.01
0.6	0.001

Hazumi&Lee; Page

The Future: CMB-S4

- CMB-S4 is the next-generation ground-based cosmic microwave background experiment.
- 21 telescopes at the South Pole and in the Chilean Atacama desert
- Multi-band detectors to be able to remove contamination from galactic foregrounds
- DOE + NSF joint construction project
- Commissioning in the late 2020s
- 7 years of operations through 2030s
- >10x improvement in sensitivity

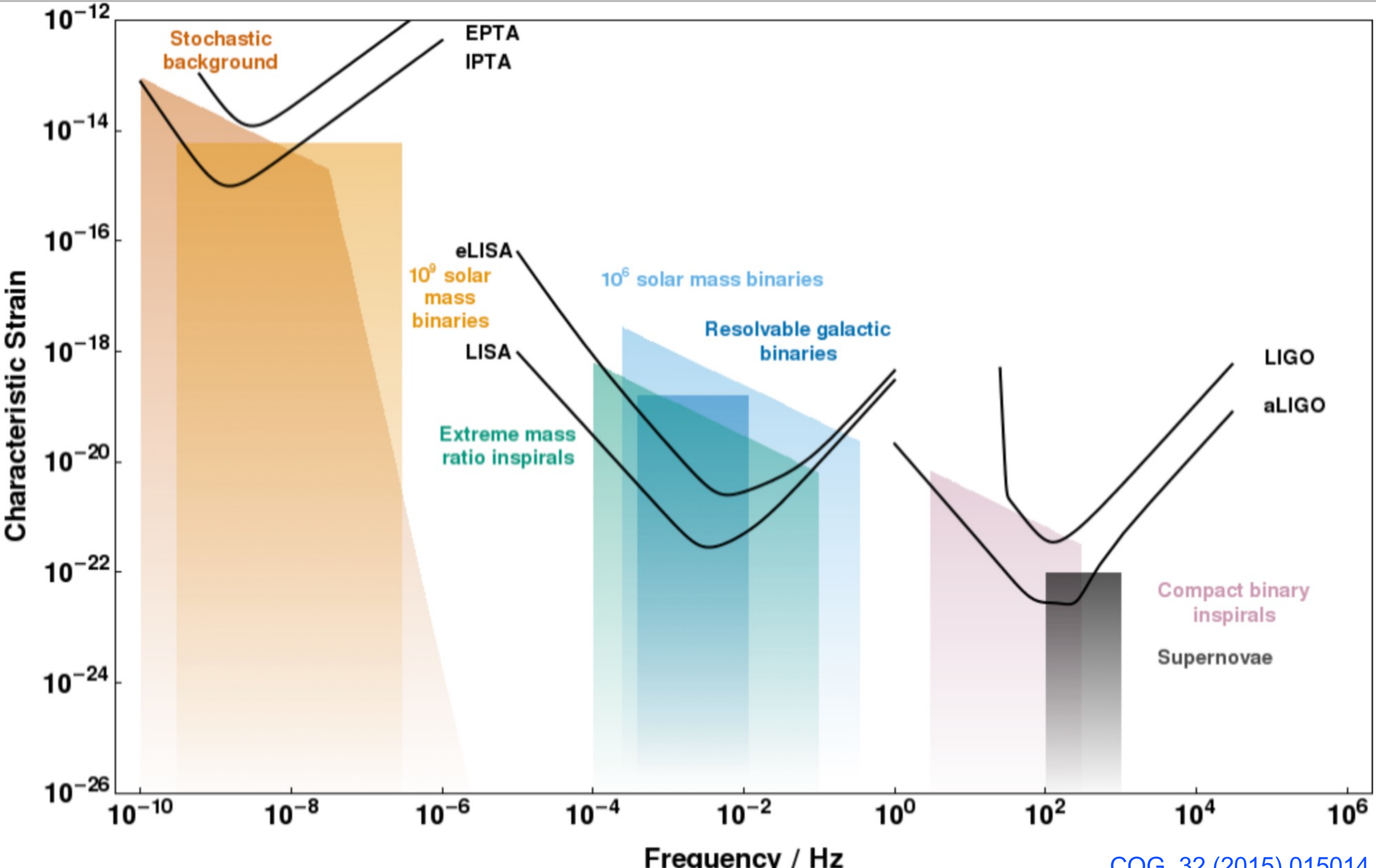
- CMB-S4 sensitivity ensures that a non-detection of r would rule out the leading inflationary models, and motivate alternate models for the origin of the universe



CMB-S4 Science Requirement 1.0:

- If r > 0.003: measure at 5σ
- If r = 0: set r ≤ 0.001 at 2σ

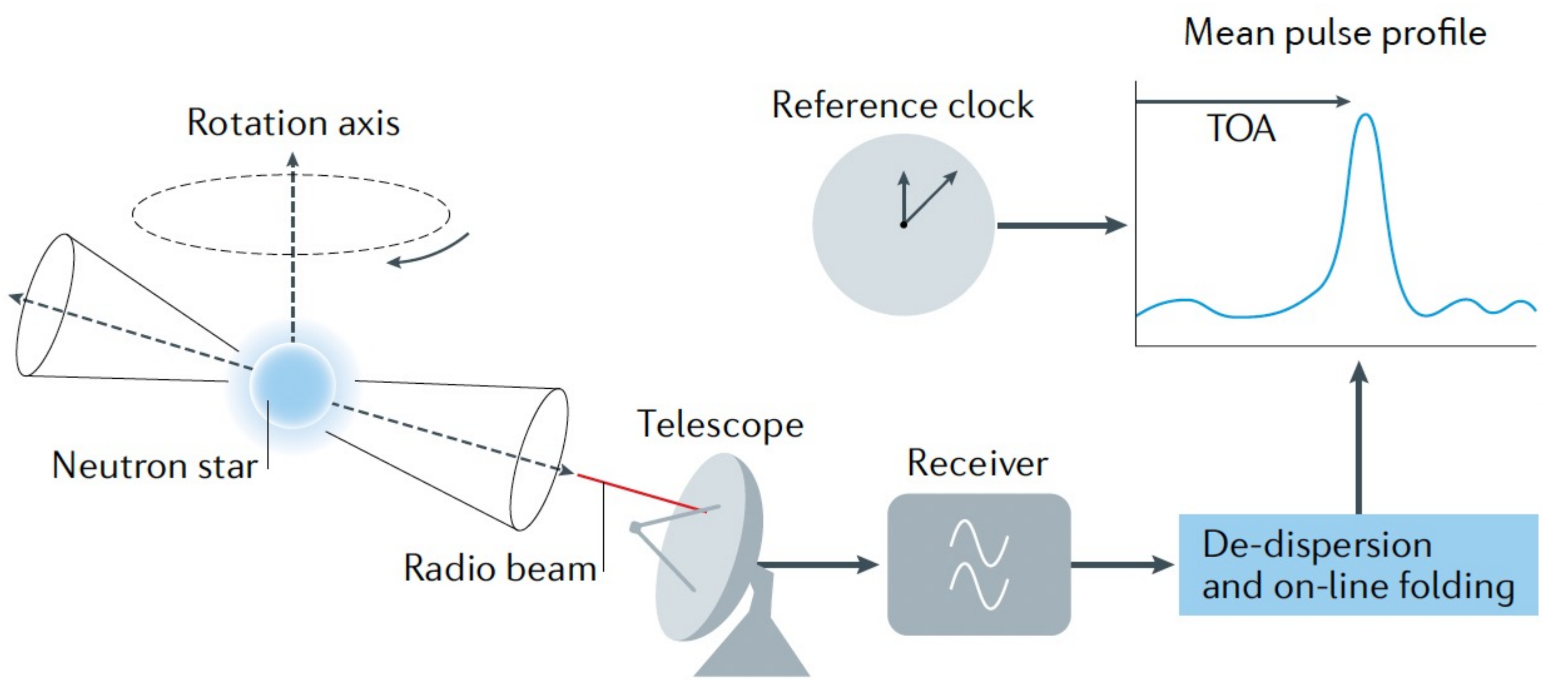
A spectrum of GW Sources and Sensors (trimming off CMB B-modes)



CQG, 32 (2015) 015014

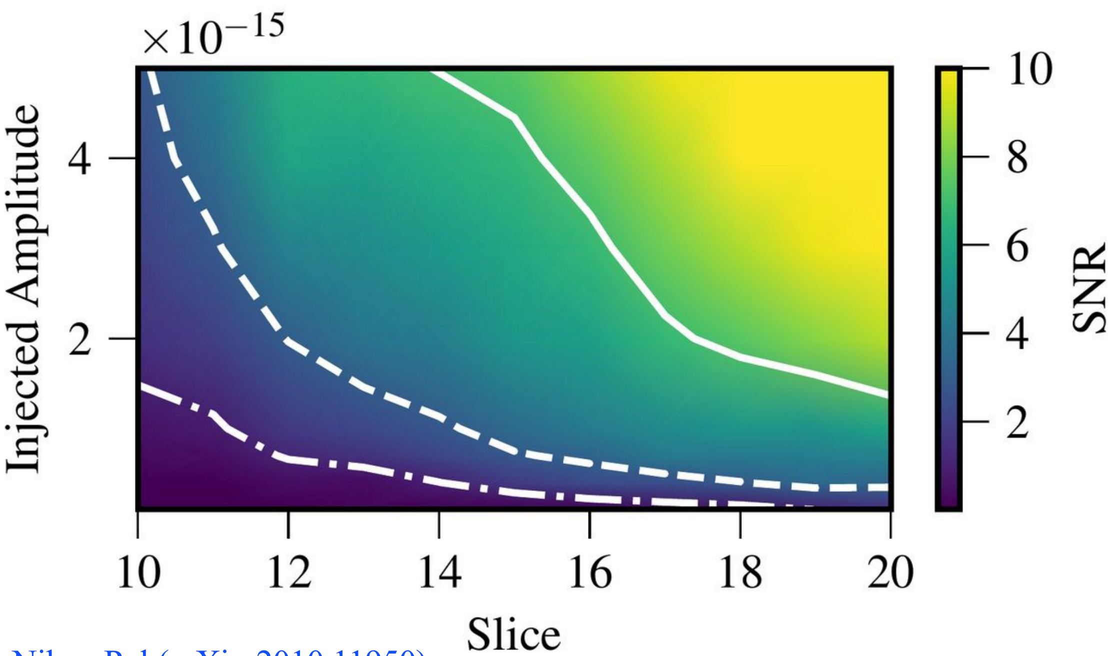
Pulsar Timing Array GW Detectors

- Prime target: the stochastic background signal from the cosmological population of gravitationally bound supermassive black hole binaries
  - May also be able to see some SMBHB inspirals as individual sources
- Technique: observe well-characterized msec pulsars, infer distortions of space-time from coherent shifts in timing
- Uses an array of ground-based Radio Antennas
- Requires search for, and deep understanding of, very stable pulsars

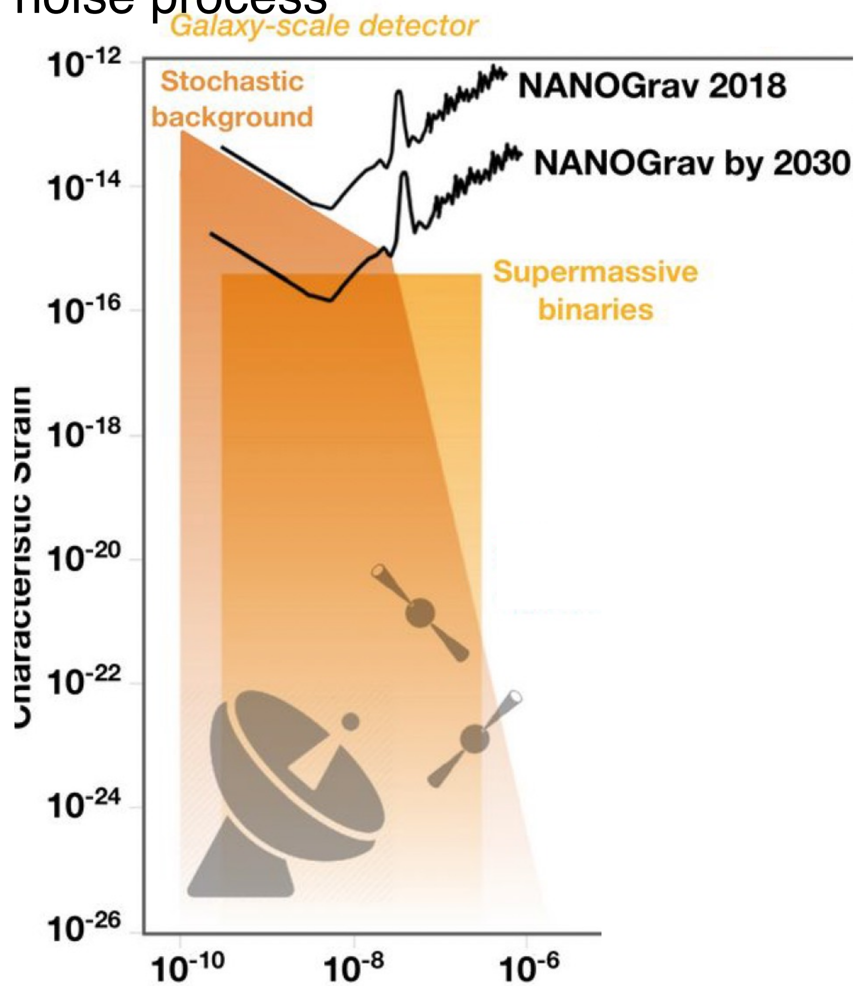


PTA: Projection going forward

- The most recent PTA results are from NANOGrav's analysis of [12.5 years of precision timing data from 47 pulsars]
- Strong evidence for *uncorrelated* common red noise process
- (GW would show a spatial correlation)
- Already constraining Galaxy Formation
- Loss of Arecibo…gain of Tianyan, Chime
- Foresee ~factor 10 improvement in ~10 years

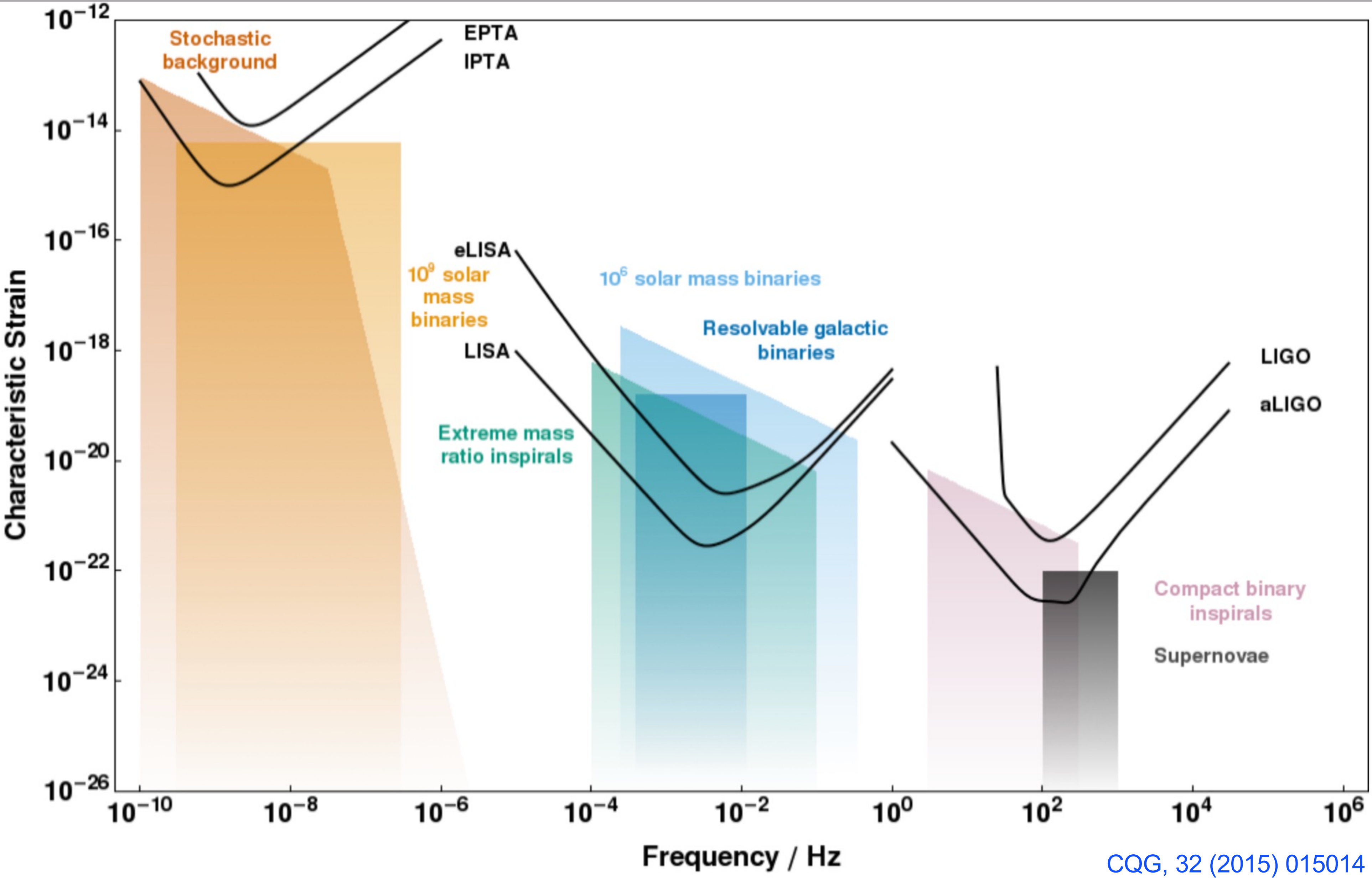


Nihan Pol (arXiv:2010.11950)



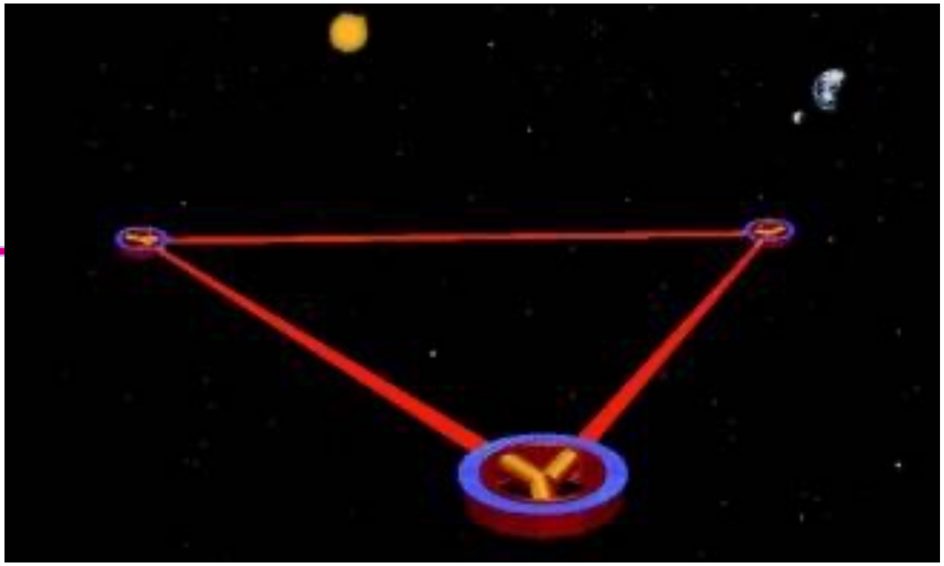
S. Taylor, C. Mingarelli

A spectrum of GW Sources and Sensors

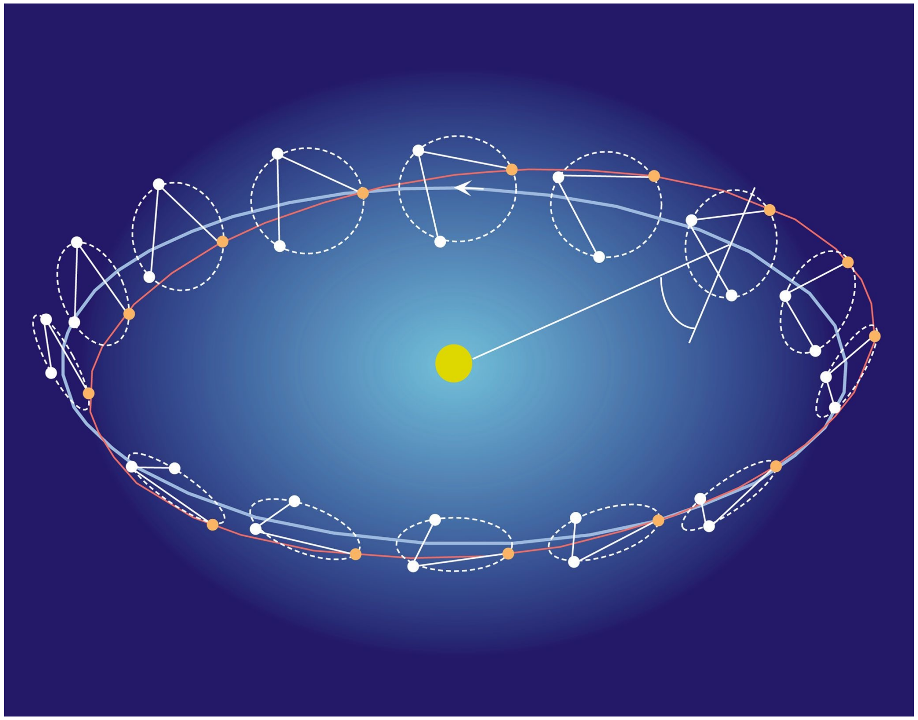


CQG, 32 (2015) 015014

LISA

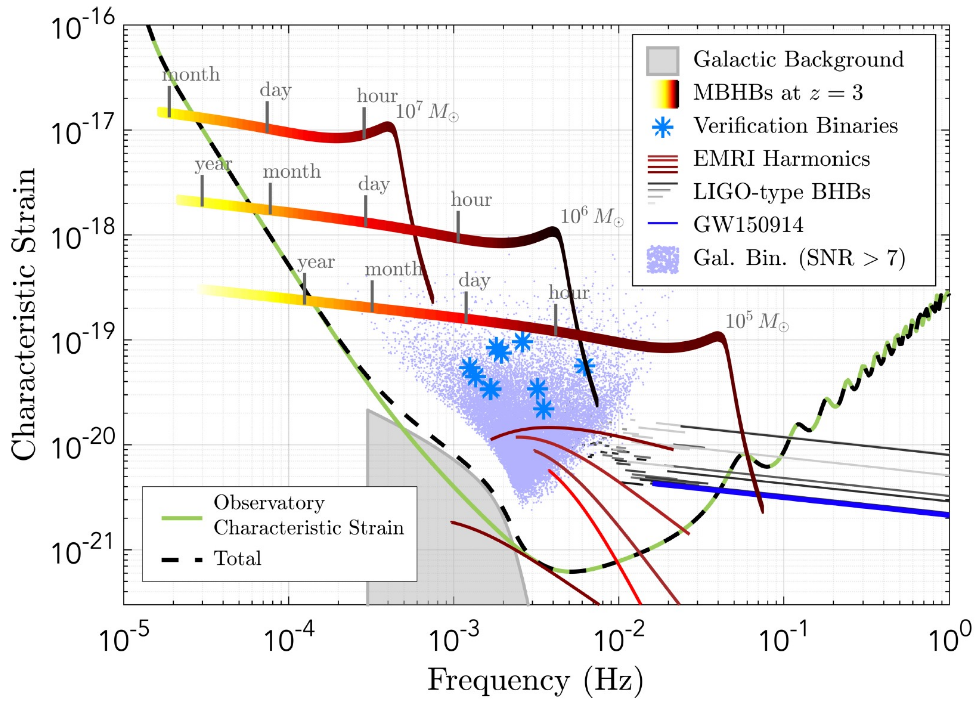


- Notion of a space-based interferometric detector dates from 1974
  - » Rai Weiss and Peter Bender; napkin
- Basically a timing measurement between test masses in space
- Take advantage of vacuum in space: make very long arms
  - » $\Delta L = h \cdot L$; L can be ~10^9 m, making ΔL ~10^{-11} m workable (not LIGO's 10^{-19})
  - » Best sensitivity to milliHz sources – targets 10^3 – 10^9 $M_\odot$
- Triangular configuration
- Sums and differences around the triangle
  - » Allows both polarizations of the gravitational waves to be measured
  - » Provides signals to remove laser frequency noise
- Earth-trailing orbit provides scan of the sky, provides sky localization

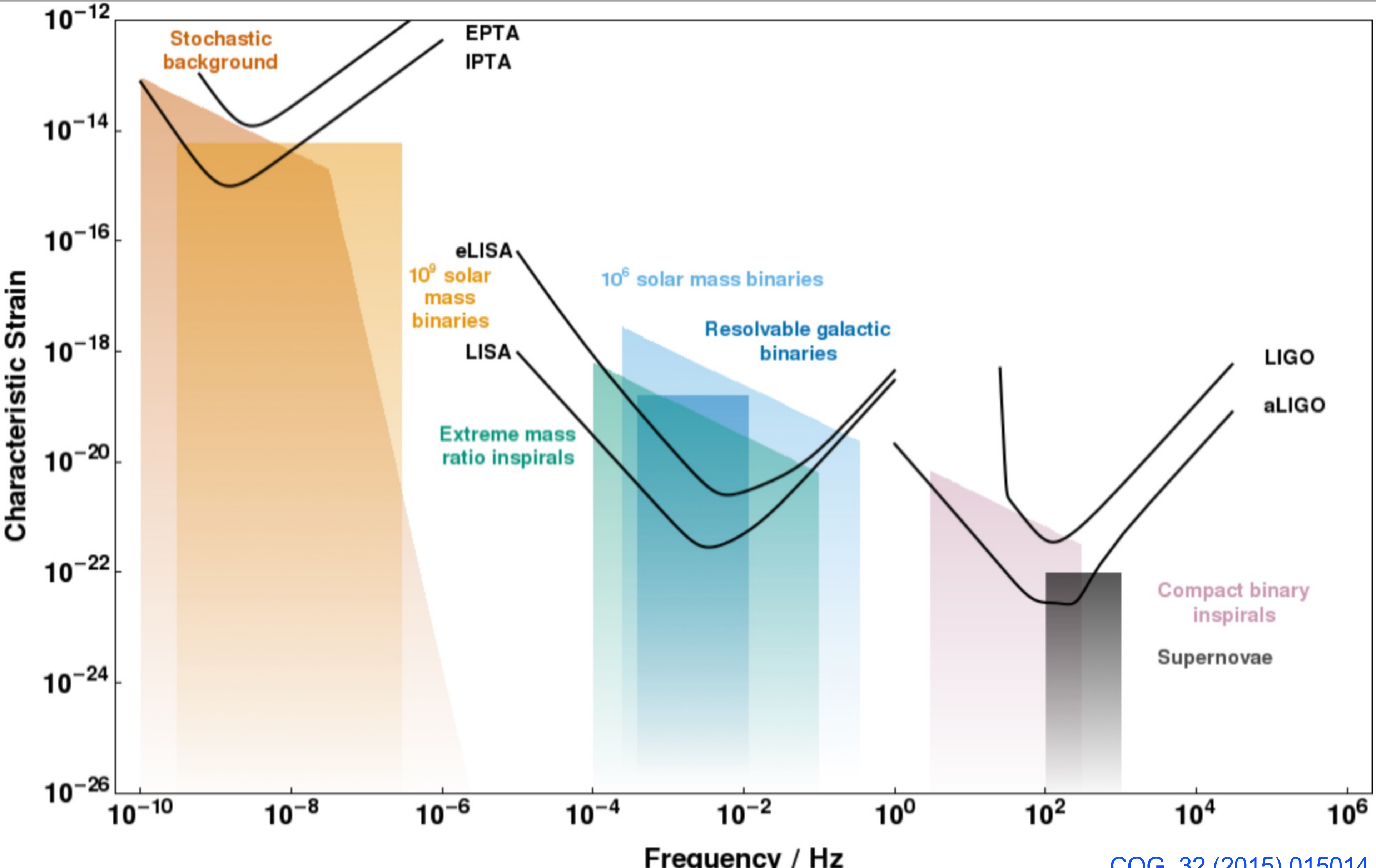


LISA Status

- LISA's Projected science capabilities are breathtaking – mapping of SMBH by IMBH test particles, understanding galaxy formation, unprecedented tests of GR via Thibault's waveforms…
- Key 'free-fall' technology beautifully demonstrated by LISA Pathfinder
  - Telescope is the principal untested instrument element
  - Systems challenges – alignment, cross-couplings
  - Mostly just making it robust, redundant, and making 3 satellites, 6 transponders, in time for launch
- ESA 'L' mission, broad European member-state participation, NASA a junior partner
- Mission Formulation Review underway; on track for
  - 2025 adoption
  - Mid-2030's launch
- 4 year mission, 10-year consumables



A spectrum of GW Sources and Sensors

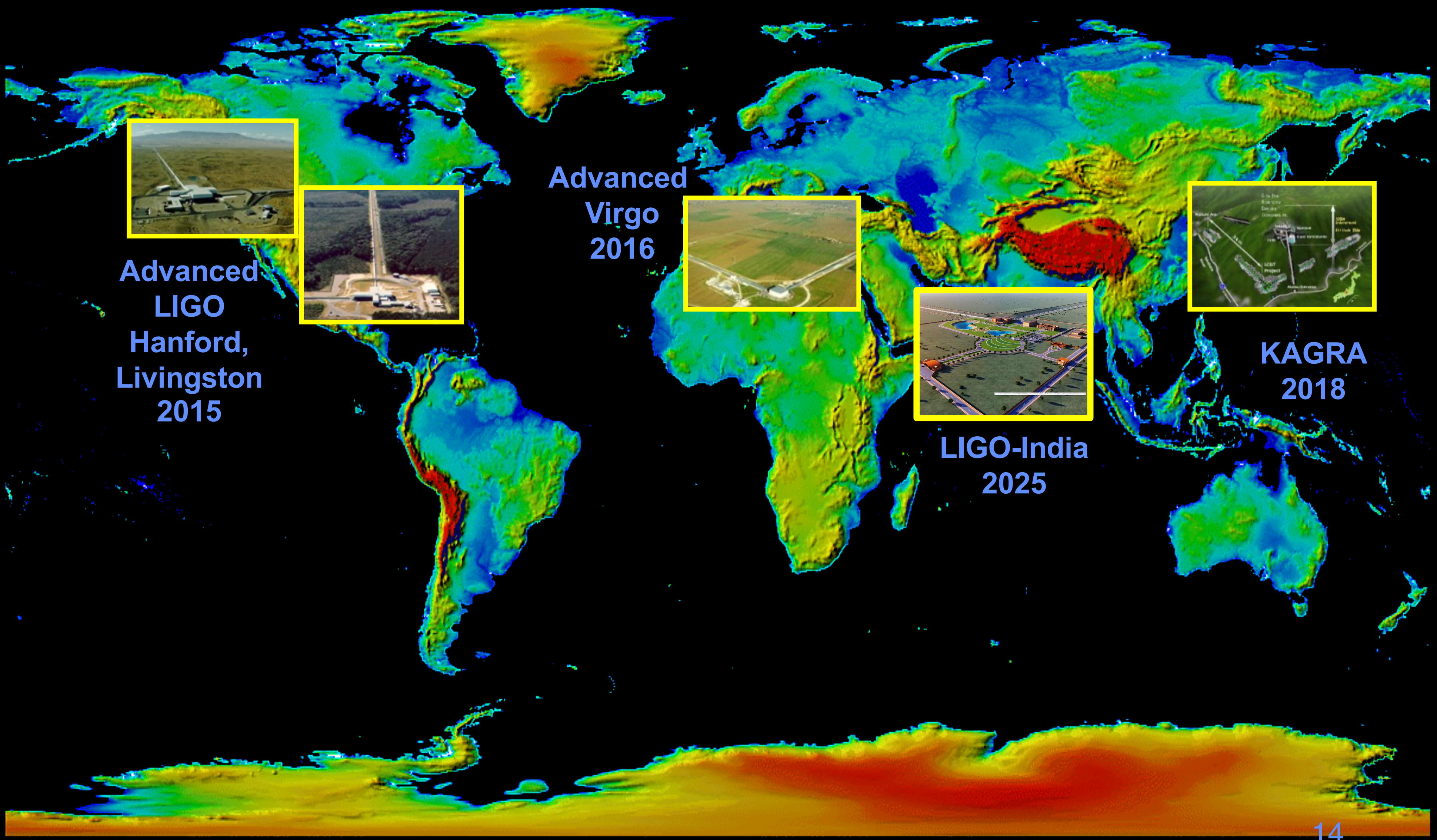


CQG, 32 (2015) 015014

Ground-based instruments

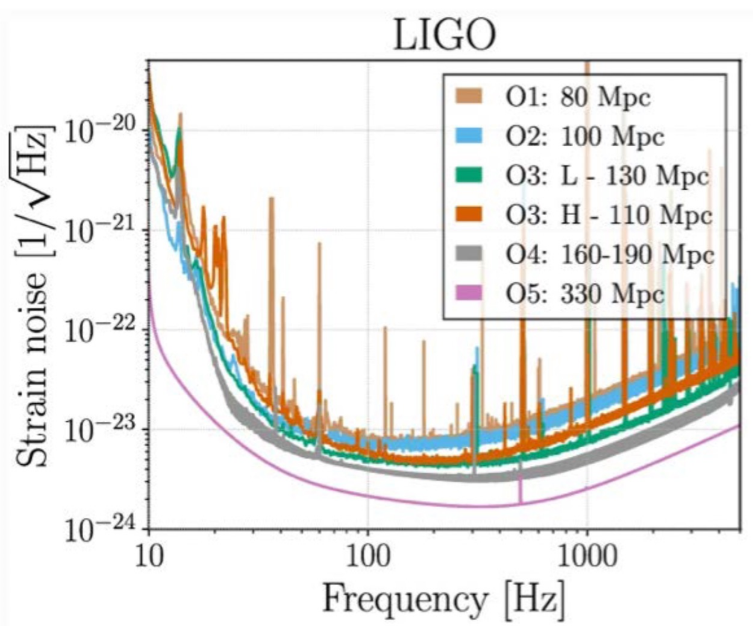
- 3 Epochs relevant for this ‘future’ discussion:
  - Building out the network of current ‘Advanced Detectors’
  - Full exploitation of the present observatories
  - 3^{rd} generation instruments in New Observatories
- I’ll just use binaries to indicate sensitivities
  - Obviously a wide range of GR, astrophysics, and cosmology can be explored
- …Building out the network:

The advanced GW detector network



What can we do in a 4km infrastructure?

- LIGO, Virgo, and KAGRA will continue to interleave observing and improving sensitivity until the next generation of detectors is in place
  - » …or beyond if there is a good scientific reason
- LIGO as example….Near term (to ~2028): well-defined program, leading to ~20x greater event rate, ~2.75x better SNR for given event
- Longer term, in 4km infrastructure: Just starting to think about what's possible, with improvements of another factor 2 in sensitivity, 8 in rate

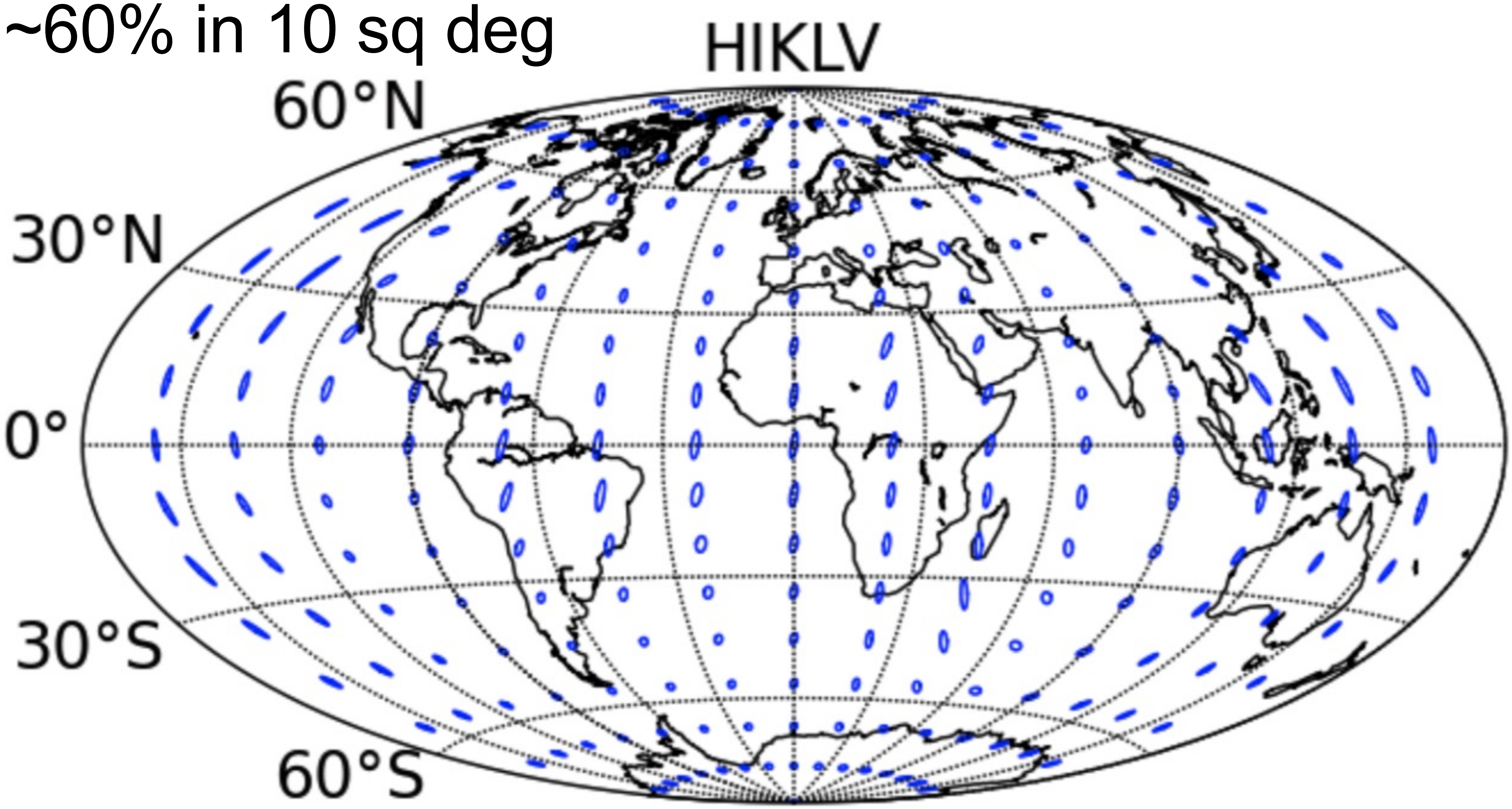


	Range / Mpc	
	BNS	BBH
A+	340	2565
A++ (A+)	450	3095
A++ (AlGaAs)	670	4005
Voyager	720	4085

Kevin Kuns

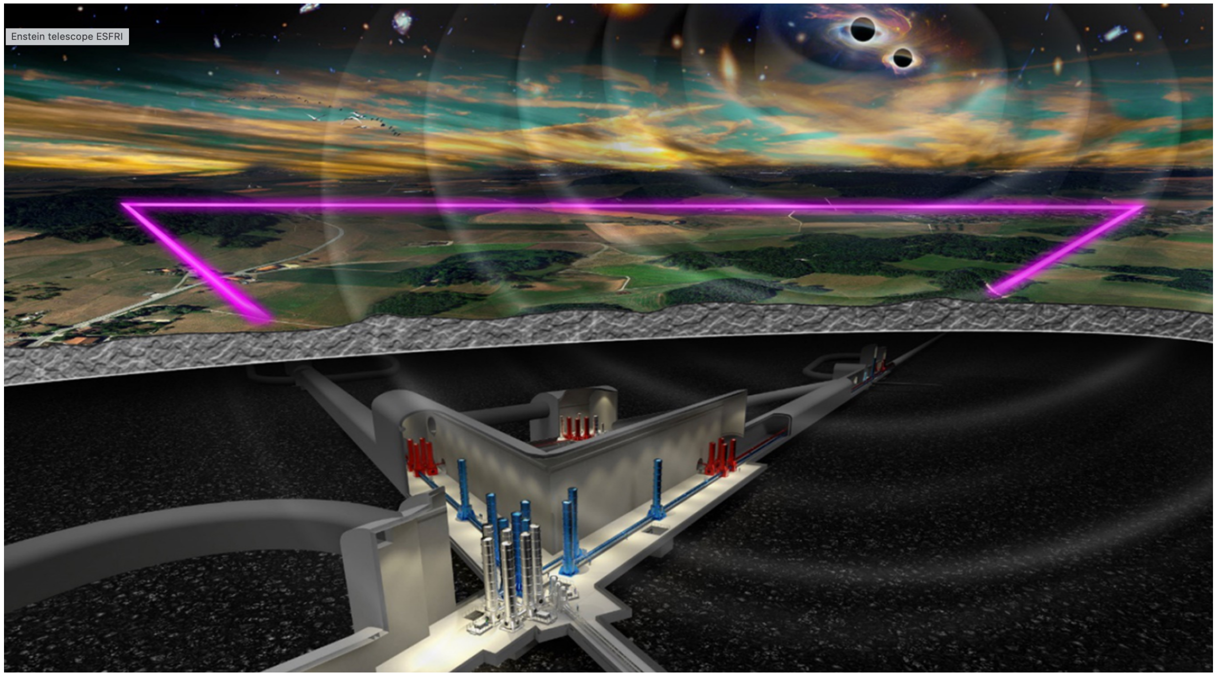
Ability to localize sources with 5 detectors

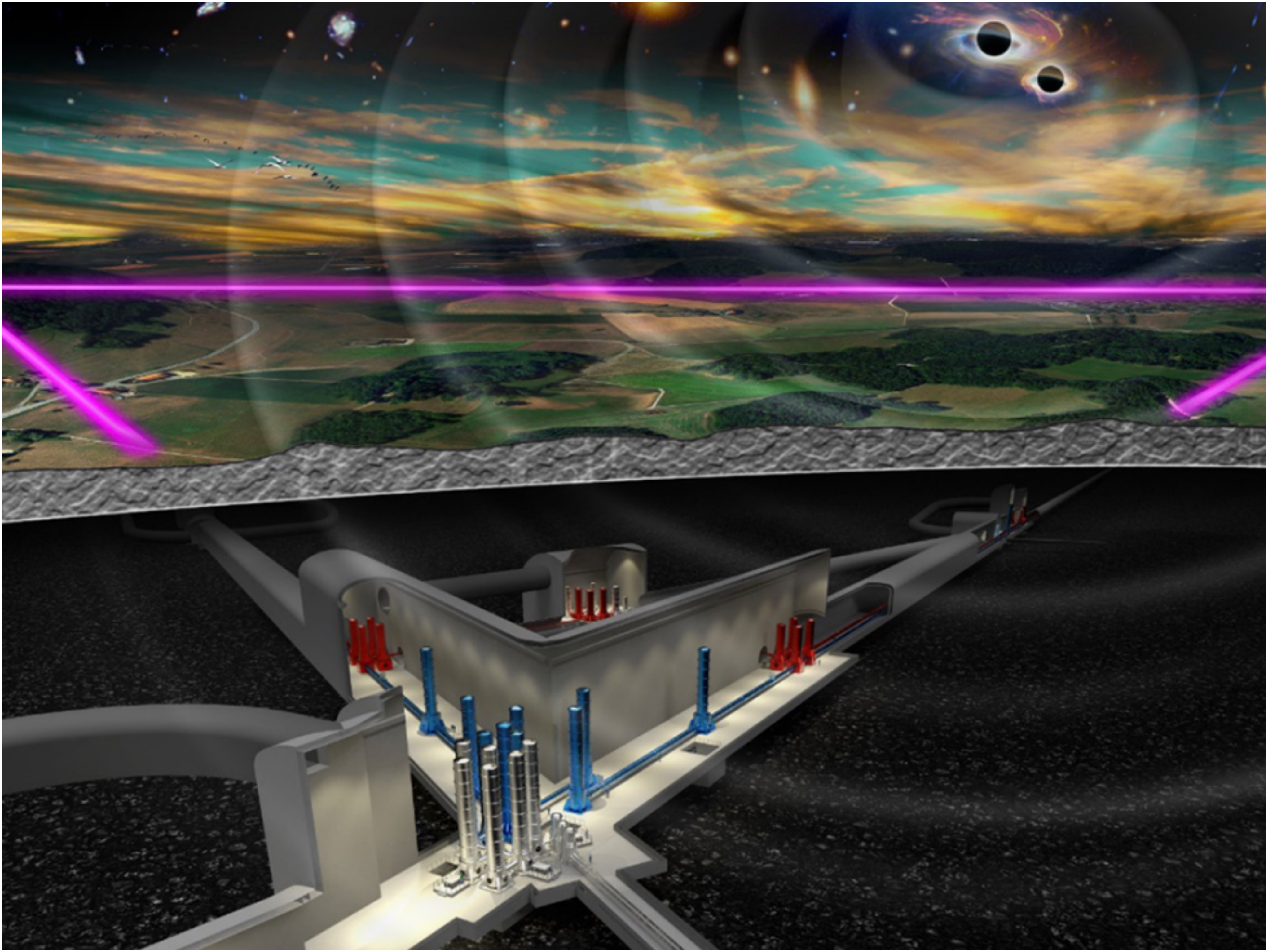
~60% in 10 sq deg



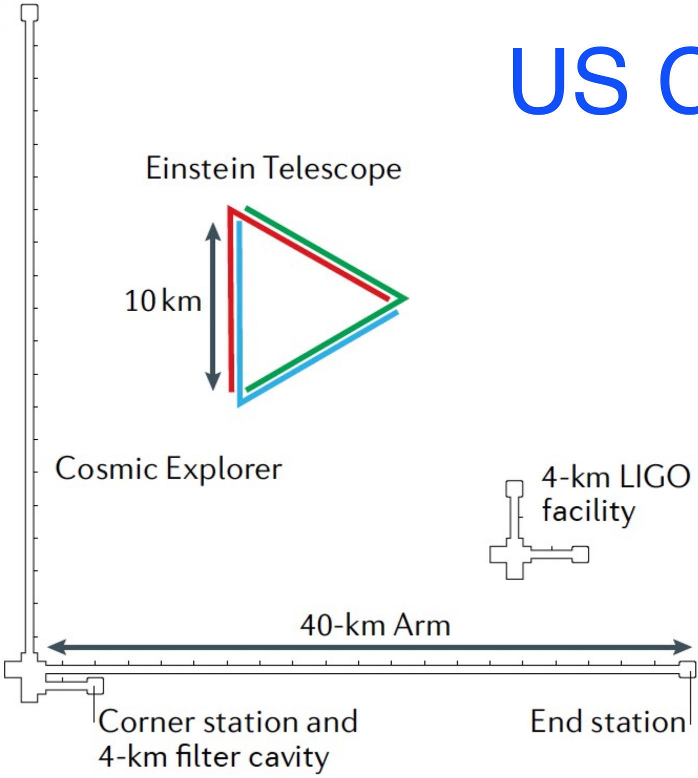
Further Future Improvements: Next Generation Observatories

- European Concept: Einstein Telescope
- Significant design study undertaken for both Facility and Instruments
- Underground construction proposed to reduce Newtonian Background
  - (and be compatible with densely-populated Europe)
- Triangle – LISA-like – with 10km arms; one-site polarization measurement
- Multiple instruments in a 'Xylophone' configuration
  - Allows technical challenges for low- and high-frequency to be separated
- Designed to accommodate a range of detector topologies and mechanical realizations
  - Including squeezing and cryogenics
- **News: placed on the ESFRI Roadmap; Significant step forward!**





US Concept: Cosmic Explorer

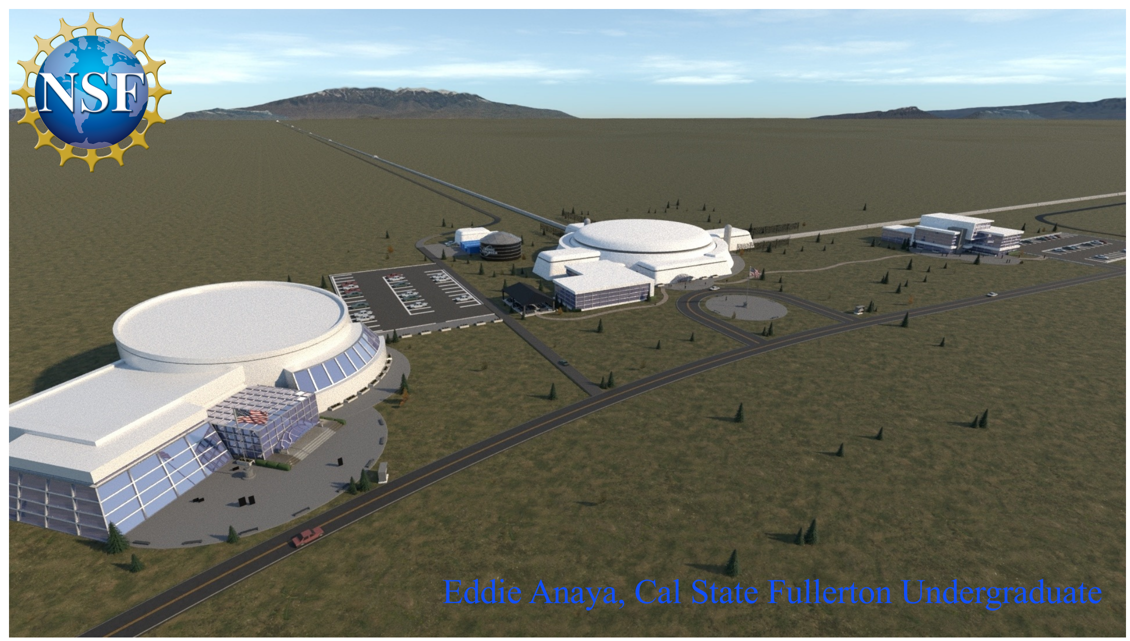


- Make Advanced LIGO 10x longer, 10x more sensitive
- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Signal grows with length –

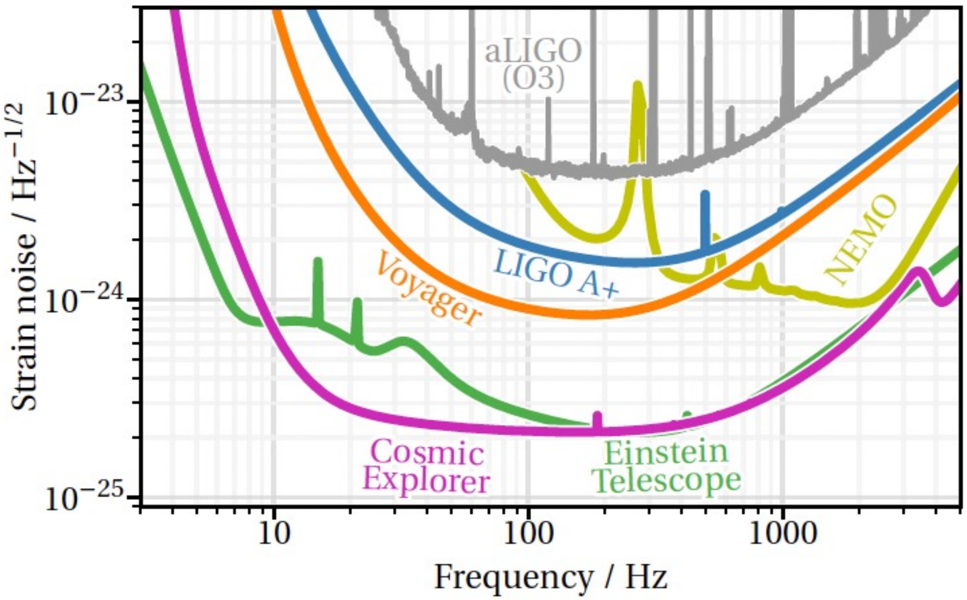
$$\Delta L = h \cdot L$$

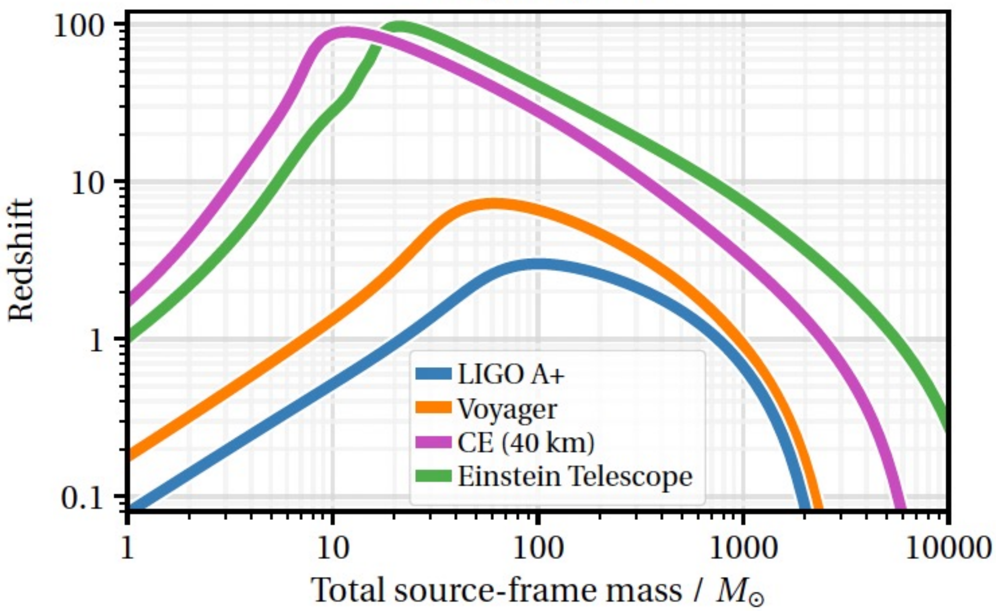
– For wavelengths shorter than the arms; 20km ideal for NS-NS tidal signal detection

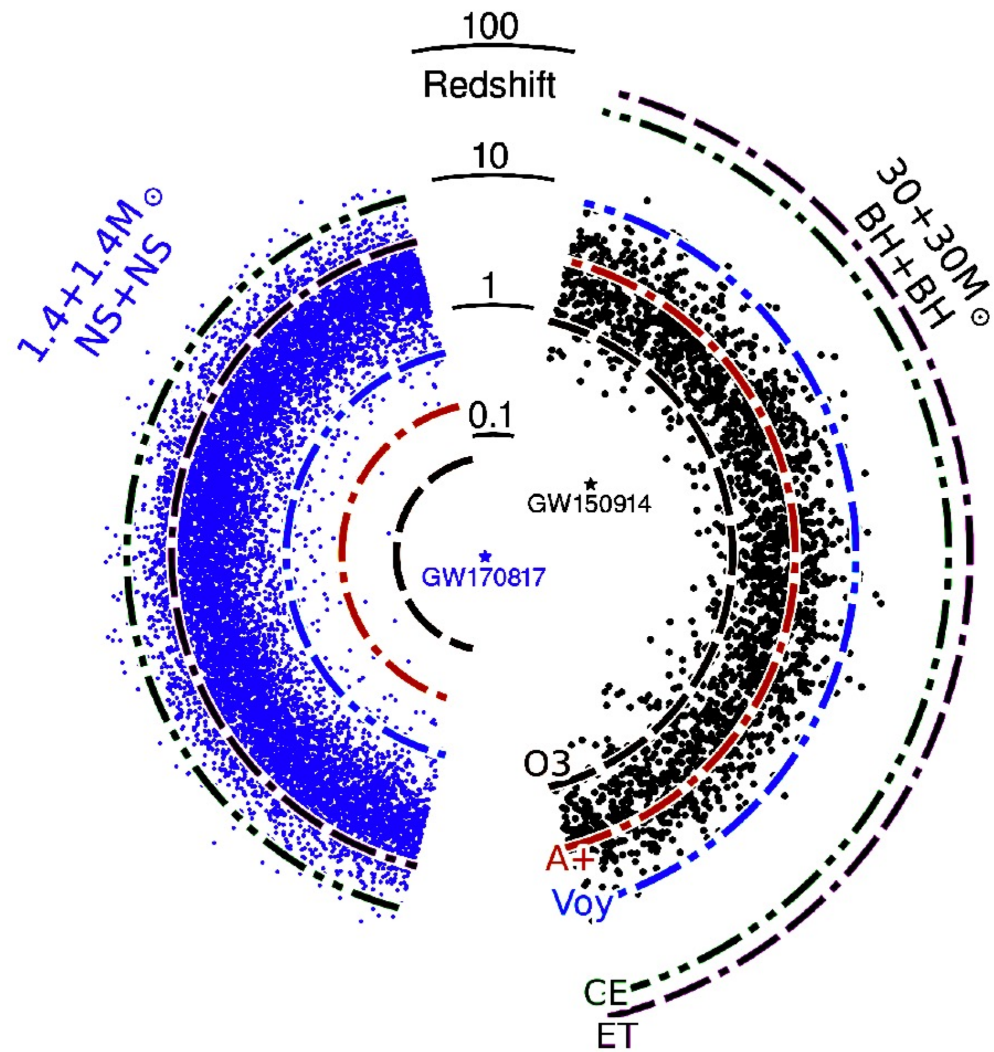
- Two sites, 40km and 20km; on earth's surface (needs some earthmoving)
- 40km ideal for BH-BH horizon
- Concept offers sensitivity without new measurement challenges; could start at room temperature, modest laser power, etc
- Recently completed 'Cosmic Explorer Horizon Study'
- Eager to catch up with Einstein Telescope



Reach of ET and CE







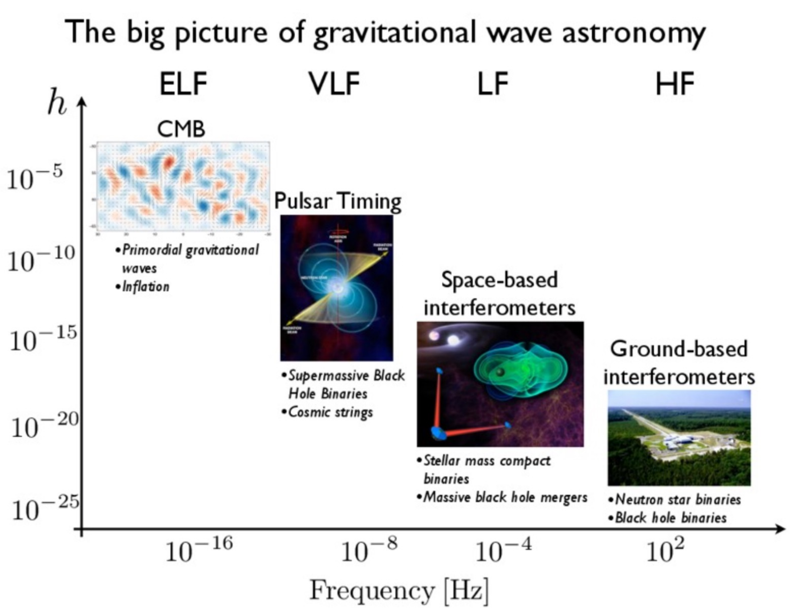
Next Generation Observatories

- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - Advanced LIGO: 1999 White Paper, GW150914 in 2015
- Modulo funding, could envision…
  - Einstein Telescope in the early 2030's
  - Cosmic Explorer in the mid-2030s
- Should hope – and strive and plan – to have great instruments ready to 'catch' the end phase of binaries seen in LISA (ref. Sesana)

- Crucial for all these endeavors: to grow the scientific community planning on exploiting these instruments far beyond the GR/GW enclave
  - Costs are like TMT – needs a comparable audience

Onward!

- Wonderful GW science opportunities within the reach of technology
- Let's hope – and conspire – to cause our funding agencies to support these initiatives
- …and thanks to Thibault for contributing in so many ways!



Nanograv