Institute of Physics
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The Violent Universe

Gravitational Wave Astronomy

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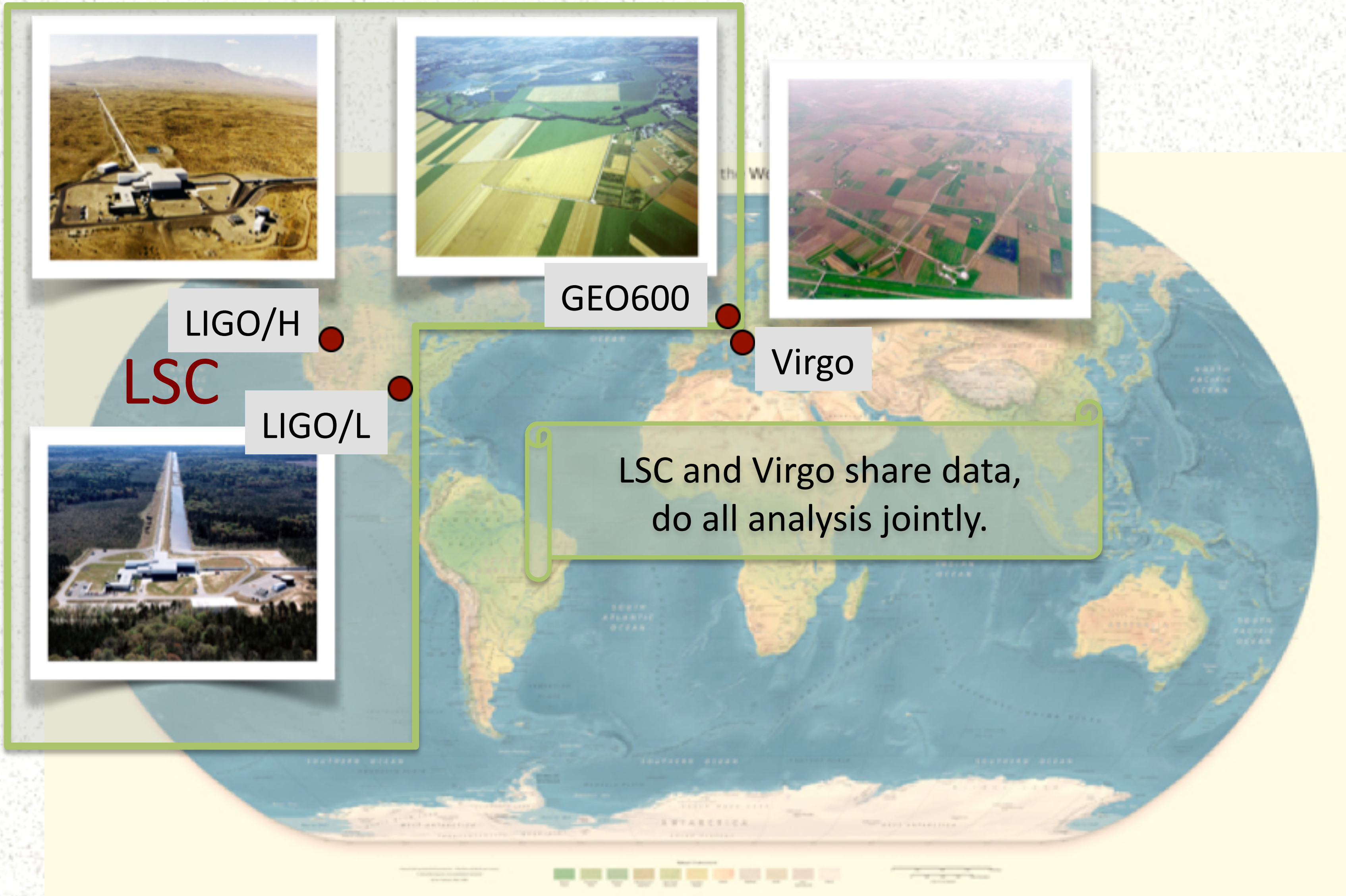
Gravitational Wave Detection



Capabilities

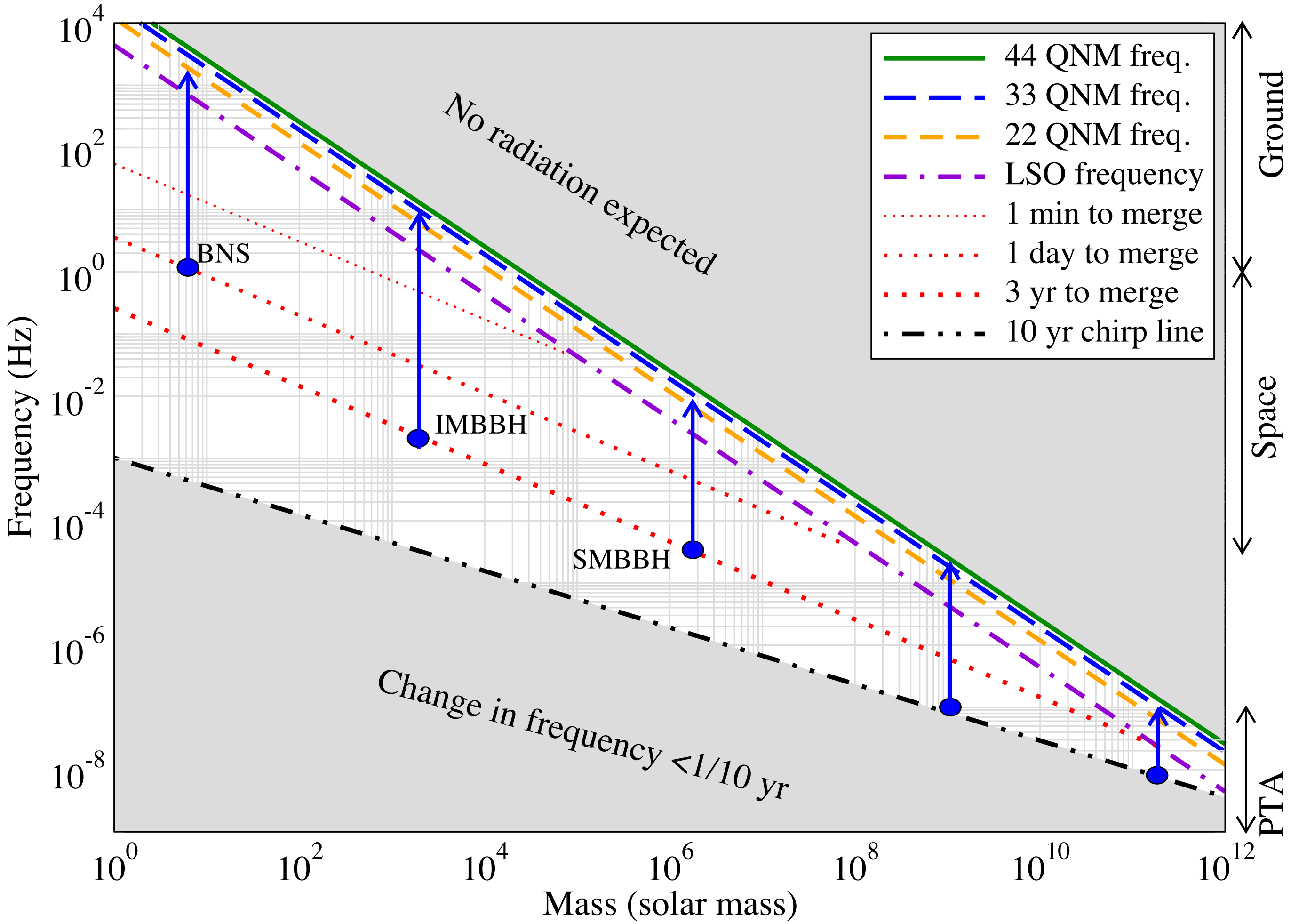
- Initial detectors (1G)
  - ★ $h_{burst} \sim 10^{-21}$
  - ★ BNS <mean range> ~ 20 Mpc
- Advanced detectors (2G): Shoemaker's talk
  - ★ $h_{burst} \sim 10^{-22}$
  - ★ BNS <mean range> ~ 200 Mpc
- Beyond advanced (2.5-3G): Rowan's talk
  - ★ $h_{burst} \sim 10^{-23}$
  - ★ BNS <mean range> ~ z = 1+

Then and now

- LIGO's 1992 "definition"paper: Abramovici et al, *Science* **256**, 325-333. (Shoemaker an author!)
- LIGO's first detector system might see gravitational waves, and the advanced detectors discussed above are highly likely to see them. Success will probably come between the first-detector level and the advanced level, that is, a few years after LIGO goes into operation.
- The uncertainty in the waves' strength arises solely from the uncertain distance to the nearest such sources. The observed statistics of binary neutron stars in our own galaxy, extrapolated to include distant galaxies, give a best estimate (32, 33) of 200 Mpc (650 million light years) for the distance to which LIGO must look to see three neutron star inspirals per year.

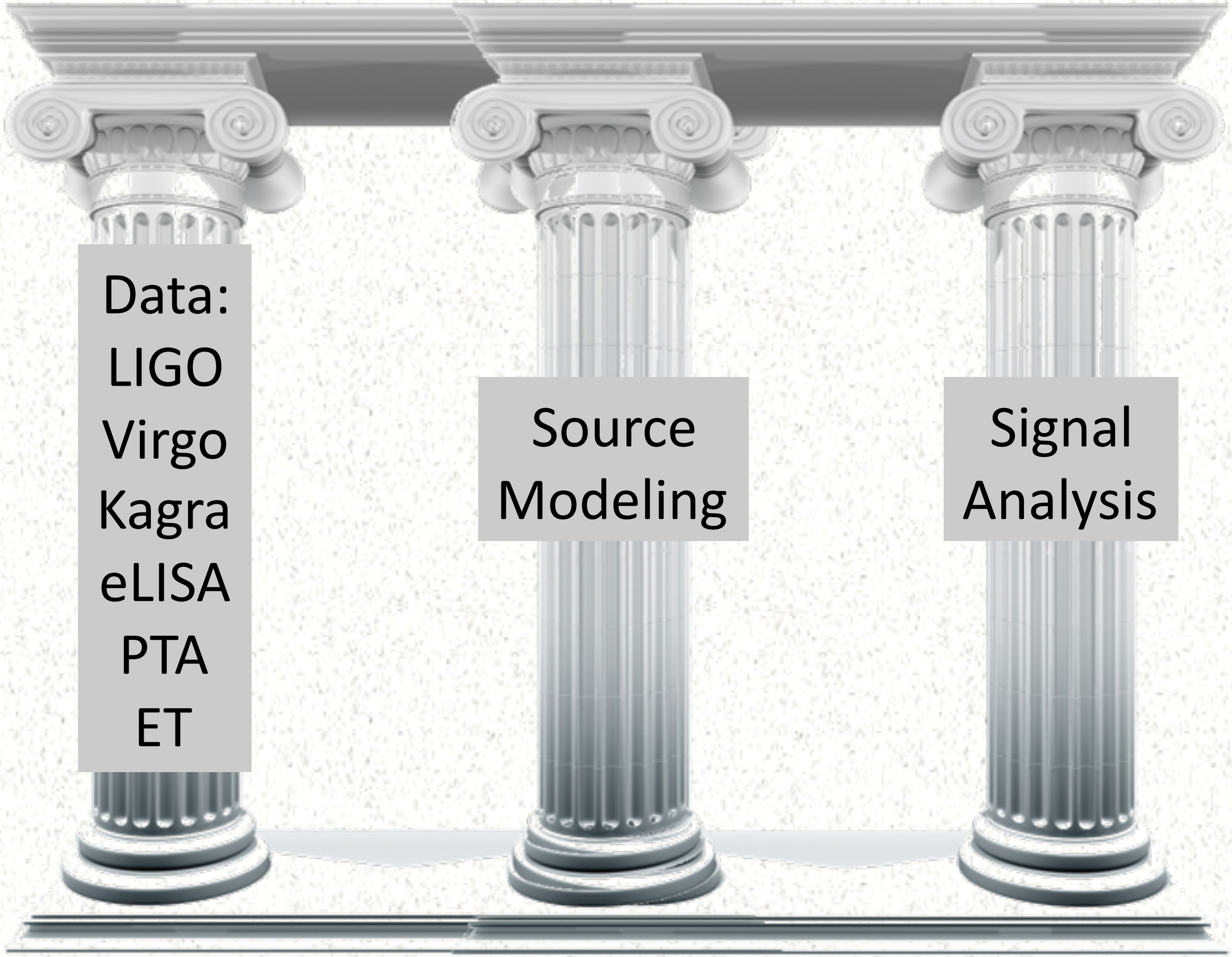
- LV "Observing Scenarios" paper arXiv:1304.0670, subm. *Living Reviews Relativity.*
- Initial detectors made no detections; advanced detectors very likely to do so.
- Advanced detectors will increase sensitivity in stages. By 2019 the mean range should be 200 Mpc and the expected number of binary neutron star detections will be 0.2-200 per year, with a best estimate of 40 per year.

The GW Spectrum



(B. S. Sathyaprakash)

Three Pillars of GW Detection



Binaries with LIGO-Virgo

- Binaries all merge within a few minutes
  - ★ BNS: best estimate rate 40/yr at 200 Mpc
  - ★ BBH: very uncertain, rate maybe 50% of BNS
  - ★ NS-BH: maybe rare?
- Initial detectors have set upper limits
  - ★ BNS: none to 20 Mpc, rate < 1.3×10^{-4} Mpc^{-1} yr^{-1}, for Adv LIGO ~ 10^3 yr^{-1}. [Phys. Rev. D 85, 082002 (2012)]
  - ★ BBH: none to 300 Mpc, rate < 3.3×10^{-7} Mpc^{-1} yr^{-1}, for Adv LIGO ~ 10^3 yr^{-1}. [Phys. Rev. D 87, 022002 (2013)]

GW Pulsars with LIGO-Virgo

- Spinning NSs are long-lived, so GWs must be weak. Need to integrate months of data.
- Searches for known pulsars use radio timing. See arXiv:1309.4027.
  - ★Crab: $h < 2.3 \times 10^{-25}$, $dE/dt_{GW} < 0.01\ dE/dt_{tot}$
  - ★Vela: $h < 1.1 \times 10^{-24}$, $dE/dt_{GW} < 0.1\ dE/dt_{tot}$
- All-sky searches(Einstein@Home): no detections, limits around 10^{-24}, depends on f. [Phys. Rev. D 87, 042001 (2013)].

Burst searches with LIGO-Virgo

- There have been many searches with data 2005-10:
  - ★ Untriggered all-sky searches set upper limits around 10^{-21} in 1 year: Phys. Rev. D 85, 122007 (2012).
  - ★ Searches triggered by gamma-ray bursts have found no GW counterparts. See arXiv:1309.6160, Astrophys. J. 760 (2012) 12, Astrophys. J. 755 (2012) 2.
  - ★ Swift did searches triggered by GW candidate events, also with no positives: Astrophys. J. Suppl. 203 (2012) 28
  - ★ Searches for coincidences between GW and neutrino events with Antares: JCAP 1306 (2013) 008.
  - ★ Searches for optical counterparts to GW candidate events: arXiv:1310.2314, Astron. Astrophys. 541 (2012) A155
- These have prepared software, techniques, protocols for searches with advanced detectors.

Other LIGO-Virgo Searches

- Many other searches have been performed:
  - ★ Stochastic background (isotropic and directed)
  - ★ Cosmic strings
  - ★ GWs from pulsar glitches (NS ringdown modes)
  - ★ GWs from pulsars near Galactic Center
  - ★ Ringdowns of black holes

Einstein@Home Finds Radio and Gamma-ray Pulsars

- Volunteer computing system Einstein@Home delivers 470 Tflops continuously.
- GW software was developed for deep searches for periodic signals.
- Bruce Allen and team (AEI) applying similar techniques and finding pulsars in data from Aricebo [Astrophys. J. Lett. 732, i.d. L1 (2011)] and Fermi/LAT [Astrophys. J. 744, i.d. 105 (2012)].
- Recent Parkes analysis found 24 pulsars, including 6 in binaries[Astrophys. J. 774, i.d. 93 (2013)]

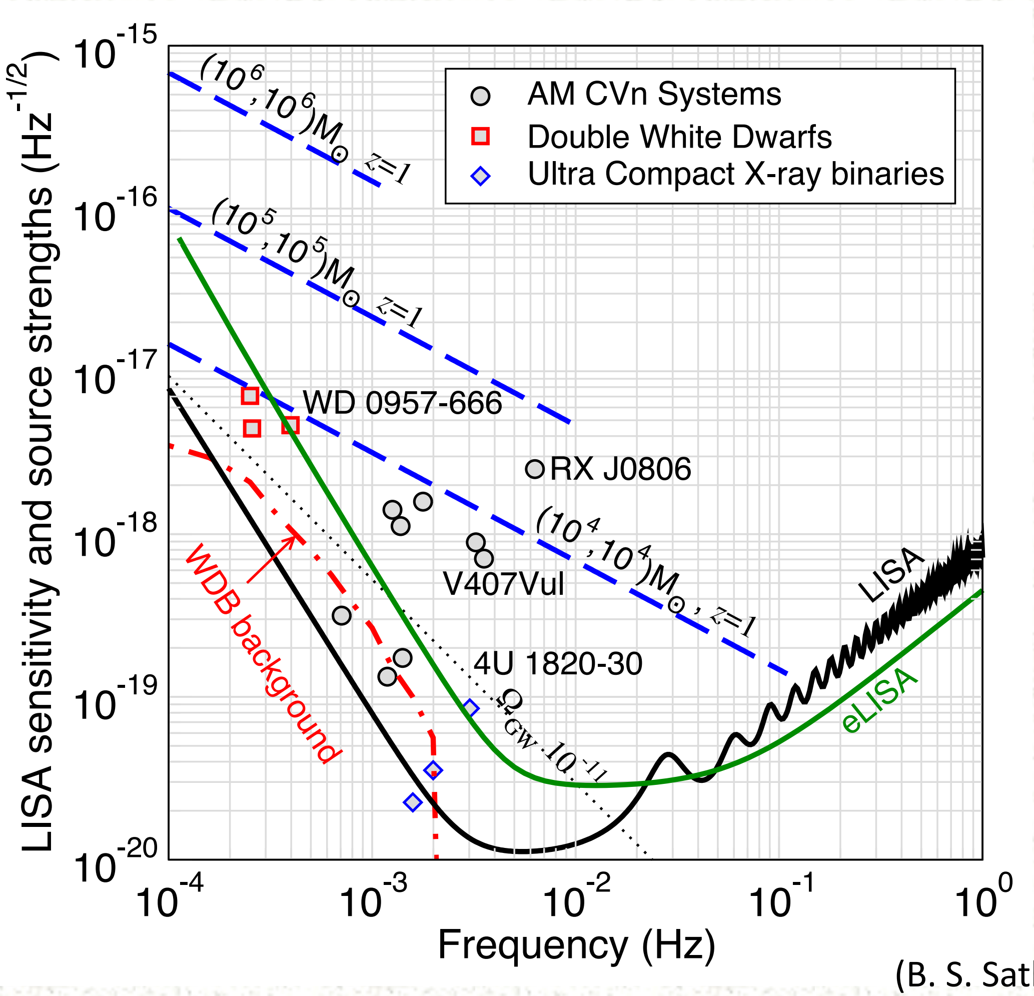
Advanced Detector Observing

- From 2015 onward, LIGO will have periods of observing alternating with periods of improving sensitivity.
- If all goes well and the “best estimate” rates are correct, first detection should happen 2016-17. (Shoemaker talk)
- Multimessenger should be a feature of the observing scenario from the start.
- Patrick Sutton reviewed our preparations and expectations.
- The promise of GW detection is now very close to being realised.

GW Sources for eLISA

- eLISA seems likely to be adopted for ESA's L3 launch around 2034.
- Long arms mean high amplitude SNR: 50-1000+.
- Important sources include
  - ★ MBH binary mergers out to redshifts of 20, tracers of beginning of galaxy formation.
  - ★ EMRI: a MBH swallows an "ordinary" BH, strong test of GR, probe of clusters around central BHs.
  - ★ WD-WD binaries: with thousands of systems, mapping the Galaxy and examining a principal end phase of stellar evolution.

LISA/eLISA Sensitivity



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Pulsar Timing

- Worldwide IPTA collaboration of three main groups: EPTA, NANOGRAV, PPTA.
- Accumulating good data on more and more millisecond pulsars, closing in on predictions.
- First detection of an astrophysical stochastic background due to SMBH binaries could happen as early as 2016.
- Pulsar timing comes into its own with SKA: possibility of identifying individual systems.
- Remember: at frequencies 1/yr, we only get a few cycles of each waveform. Principal pay-off likely to be the statistics of SMBH systems 10^8-10^{10} $M_\odot$.

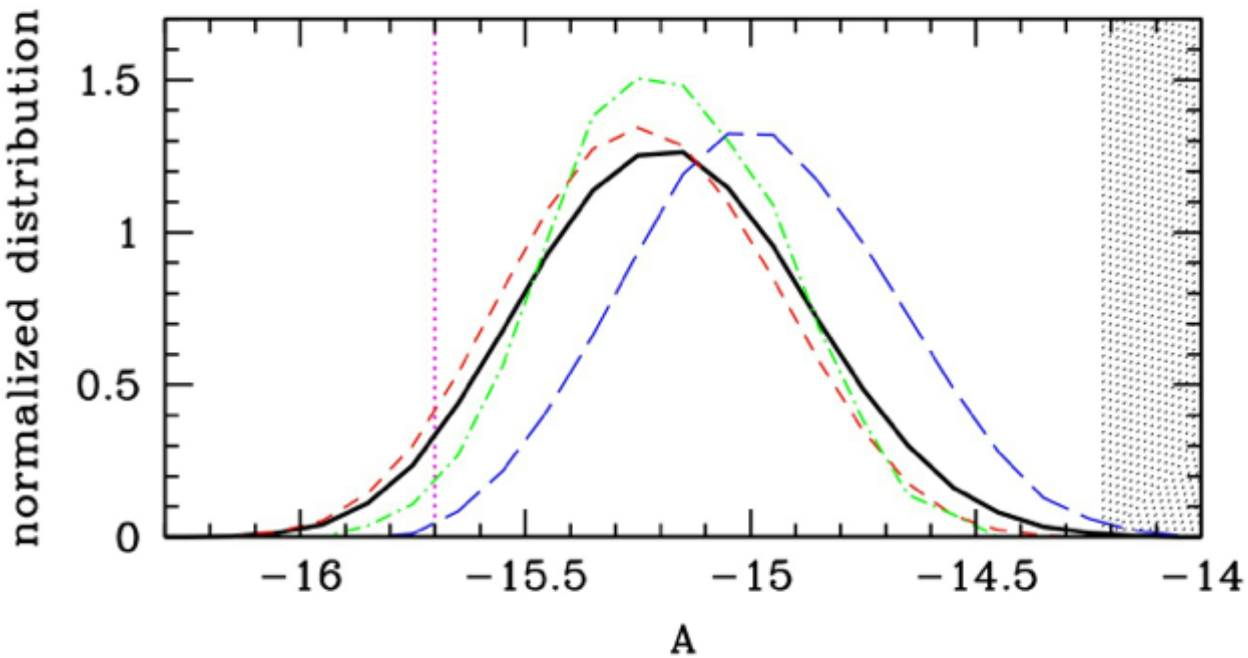
PTA: Predictions vs Sensitivity

GW amplitude pdf based on large ensemble of evolutionary models.

Shaded: current PTA limits.

Black: PTA with 20 MSPs for 10 years.

Sesana, MNRAS 433, L1-L5 (2013)



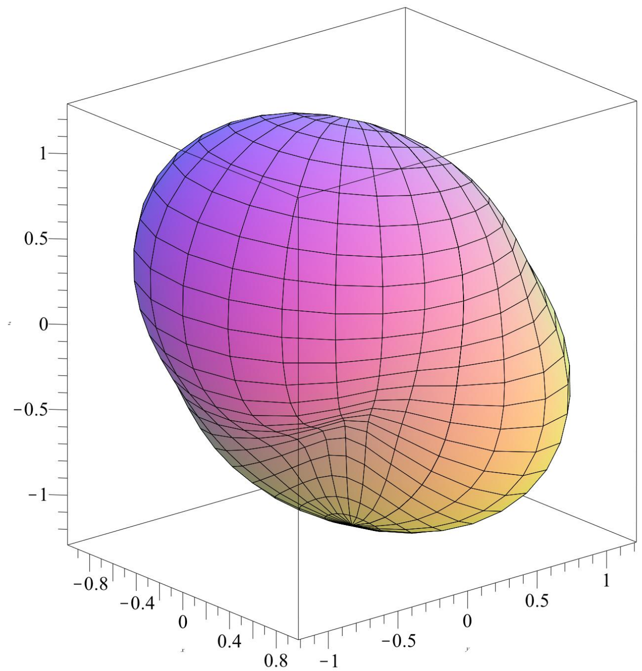
Expanded Network

- The advanced interferometer network will be increased by KAGRA in Japan (2018+) and LIGO-India (after 2020).
- Brings many benefits:
  - ★ longer baselines leading to better positions, easier follow-up, more counterpart identifications;
  - ★ better sky-coverage;
  - ★ better time-coverage (duty cycle);
  - ★ better vetoes against instrument “glitches” because of redundancy of GW data with 3+ detectors.

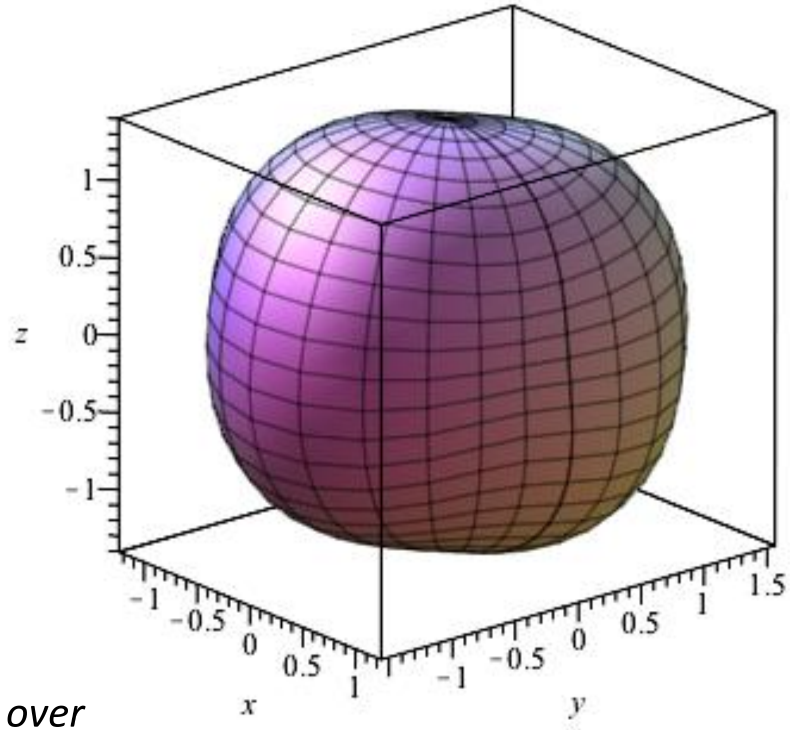
Worldwide Network 2020+

Antenna Amplitude Patterns

Hanford-Livingston-Virgo

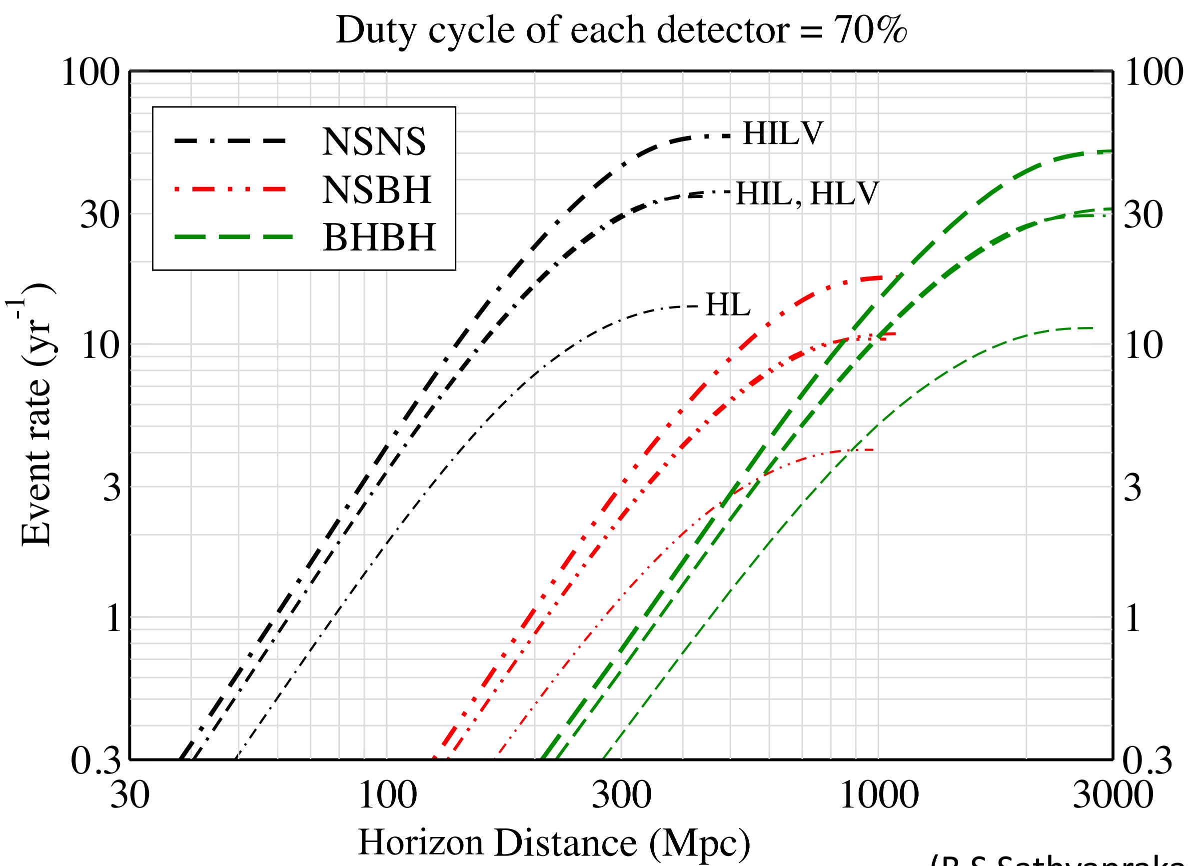


5 Advanced Detectors



Viewpoint over North Atlantic

Expected Event Rate



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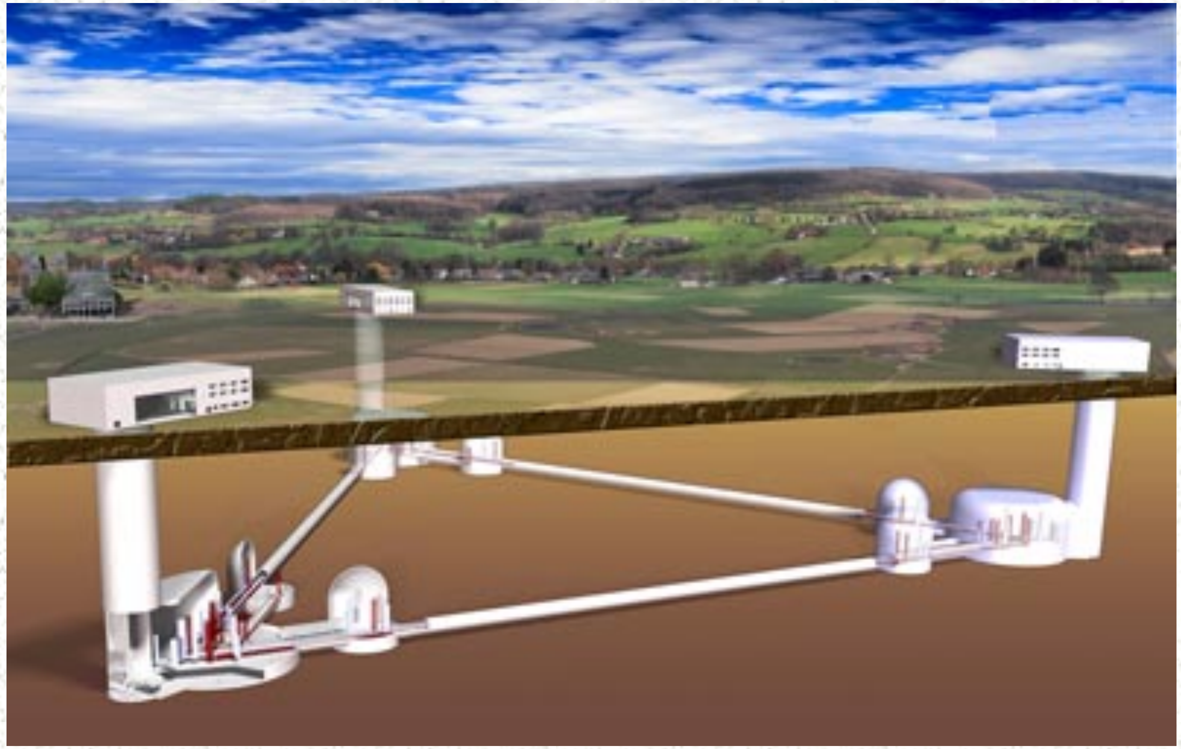
Worldwide Network Science 2023

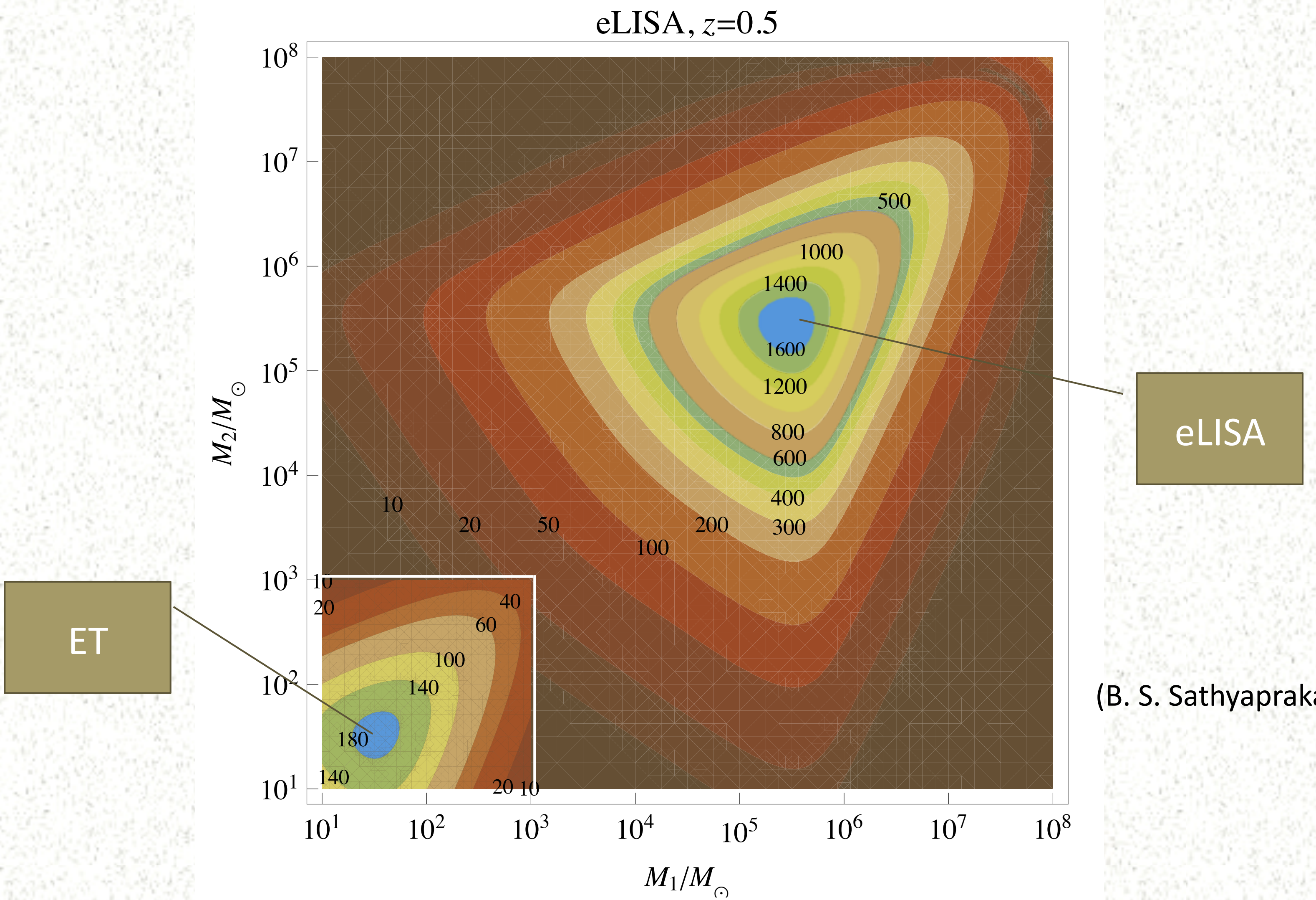
- With 100s of BNS, BBH events per year:
  - ★GRB-BNS association – look directly into engine.
  - ★Statistics of BNS masses, BBH masses & spins
  - ★Strongest signal per year amplitude SNR ~ 60
    - Tests of GR, evidence about NS EOS
  - ★Good positions, identifications – precise distances, measure local H_0 to better than 1%.
- Discovery space: enough sensitivity to identify something completely unexpected.

And after that …

- Third generation detectors like ET can finally extend the reach of BNS detection out to cosmological distances, z > 1. (Talk by Rowan)



eLISA and ET Work Together at z = 0.5



(B. S. Sathyaprakash)