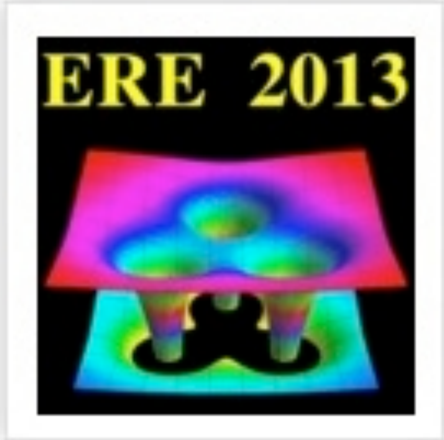
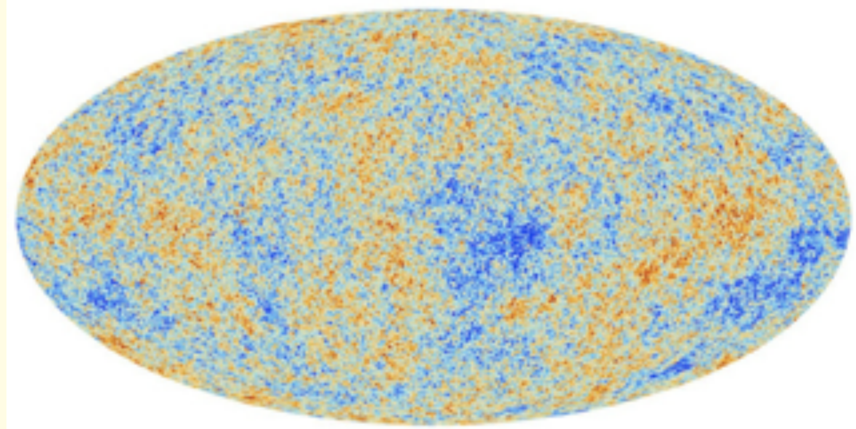
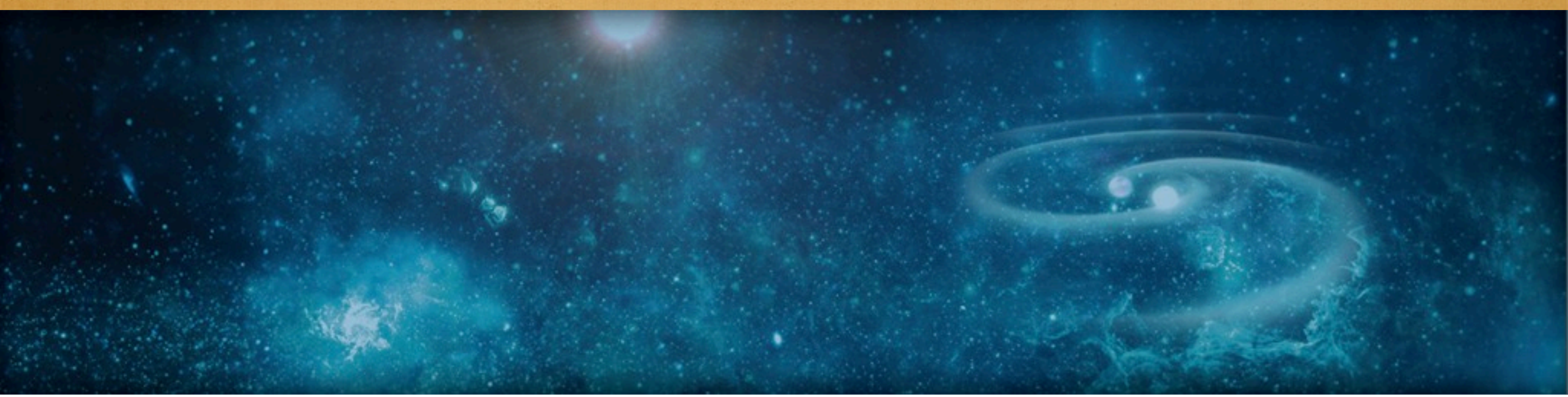



# Digging for Gravitational Waves

*Bernard Schutz*
*MPI Gravitational Physics (Albert Einstein Institute), Germany*
*and Cardiff University, Wales*



# The Foundation Years

- Joseph Weber started building his bar detector in the early 1960s. He considered and rejected detecting GWs by interferometry because the technology was not yet ready.
- Narrow-band bars got the field started, but their dependence on resonance at ~ 1 kHz limited their physical size, sensitivity. Bars still operating in Rome and Legnaro, will stop when aLIGO comes up. Spheres, an outgrowth of bar technology, have the same limitation.
- The development of adequate technology to allow interferometers (IFOs) to detect gravitational waves has taken around 40 years. Key prototype detectors at Glasgow, Garching, MIT, later at Caltech.
- During this time, astronomers motivated GW detection by discovering pulsars, binary neutron stars, black holes, and the big bang.

# The Foundation Years

- The development of sensitive data analysis methods for GW detection supported detector improvements. Some very early milestones:
  - 1987: Kip Thorne's seminal chapter in the book *300 Years of Gravitation*. The first comprehensive description of how we have to DIG into the detector noise to find the signals! This was a big departure from the way bar data had been analysed.
  - 1987: first Gravitational Wave Data Analysis conference took place in Cardiff, proceedings published by Kluwer 1989. Bar and IFO community participated. Article by signal analysis expert M.H.A. Davis on nonlinear filtering is still worth reading.
  - 1989: first coincidence experiment and data analysis between IFOs (Glasgow and Garching prototypes), known as the "100 hour run", upper limits published in *Physics Letters A* **218** , 175-180 (1996).
  - 1994: first published search of IFO data for a NS-NS chirp signal, done by Allen et al at the Caltech prototype, published in *Physical Review Letters* **83**, 1498-1501 (1999).
- It was during this foundation period that Alberto Lobo joined the GW community.

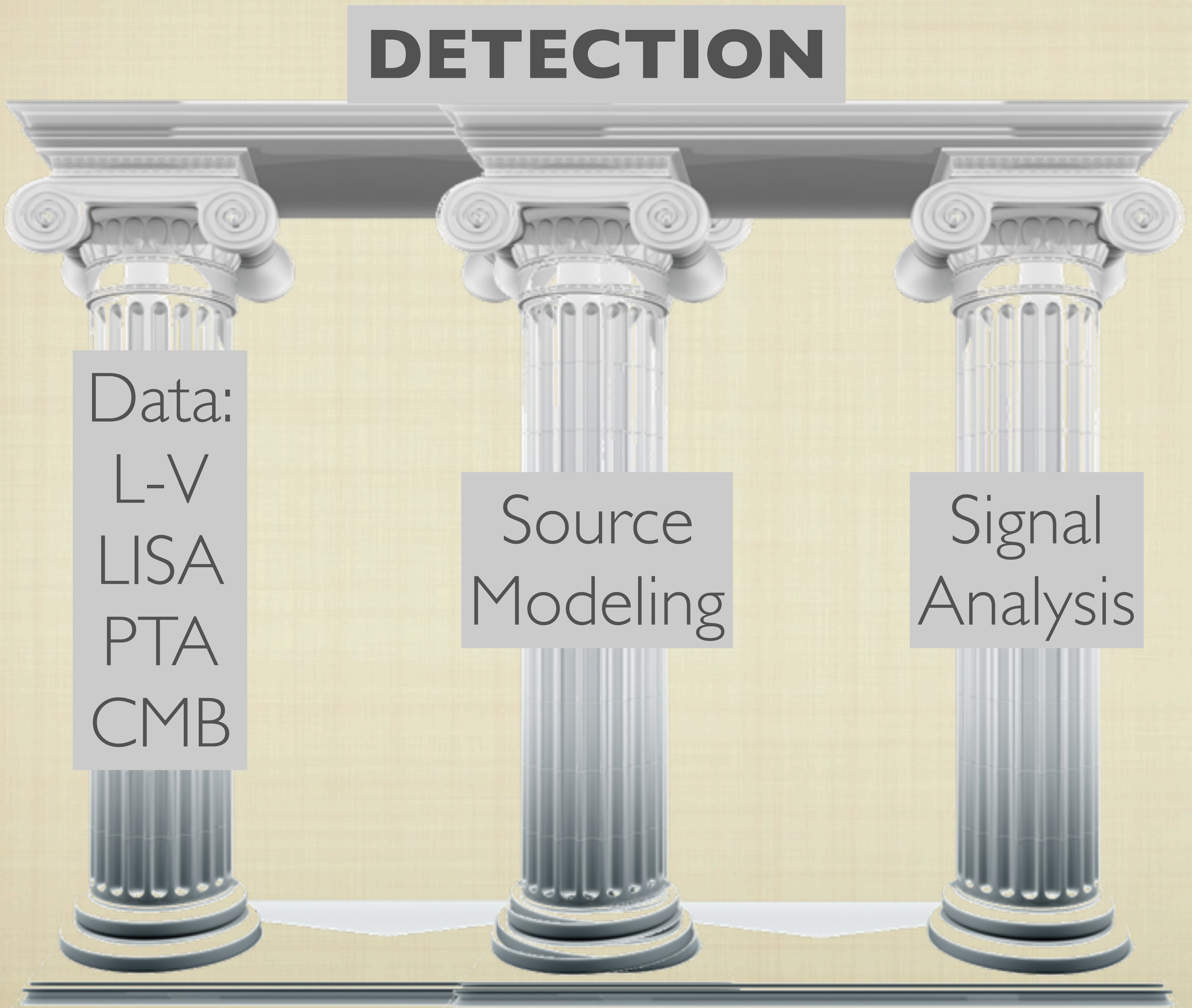
# Alberto Lobo in the Foundation Period

- Switched from n-body theory to GW data analysis in 1980s.
- Frequent visitor to Cardiff, teamed up with Krolak, Dhurandhar, Meers.

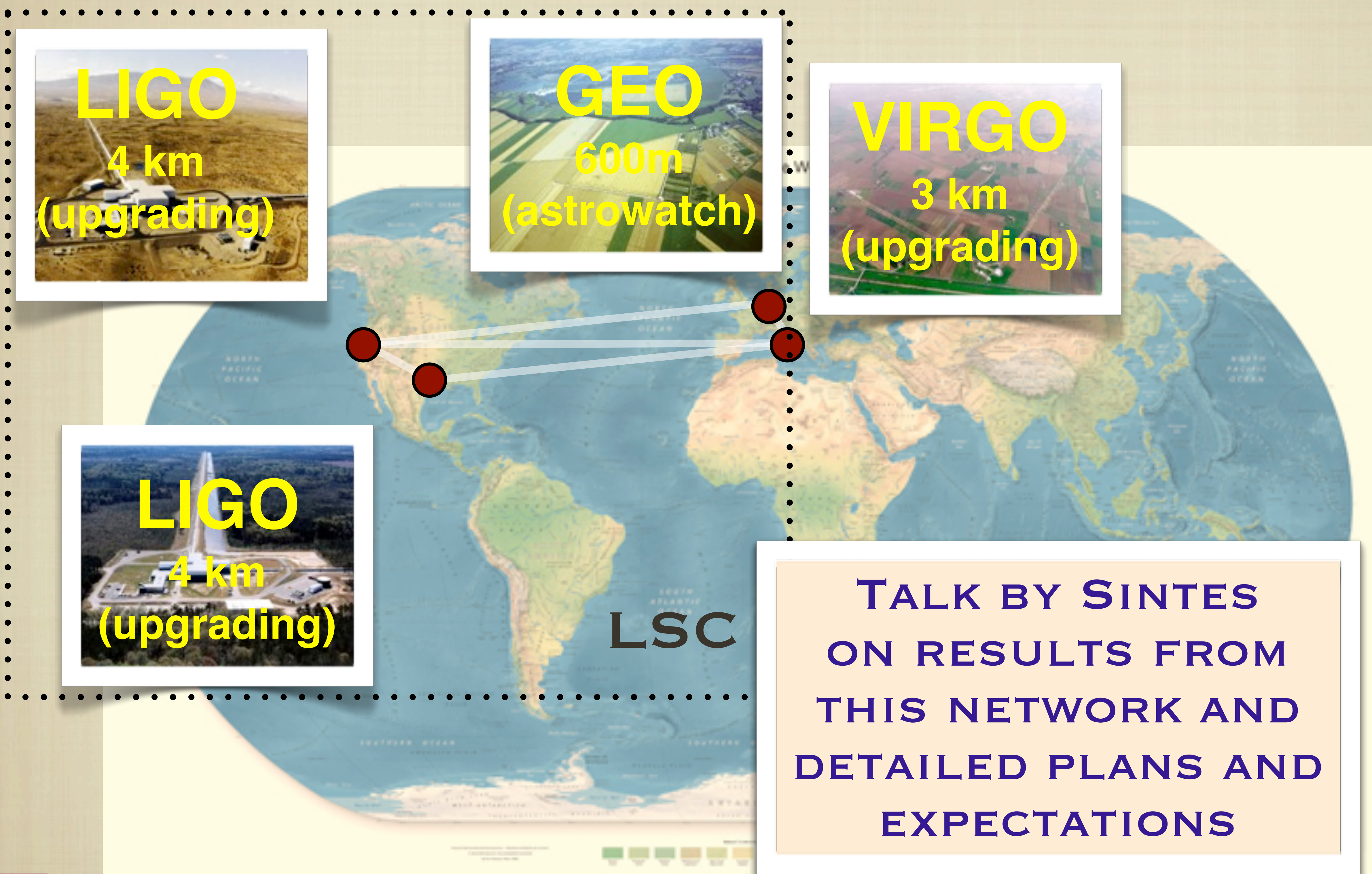
# Lobo’s evolution

- Early work with Meers and others on dual recycling and its potential for the detection of coalescing binaries. All this is now part of the standard detection methodology.
- Became strongly interested in spherical antennas, did a lot to help us understand how to extract science from them.
- Led the Spanish contribution to LISA Pathfinder -- theorist turns experimentalist!!

# The beginning is in sight!!



# Current IFO network




Talk by Sintes on results from this network and detailed plans and expectations

# First-generation IFOs

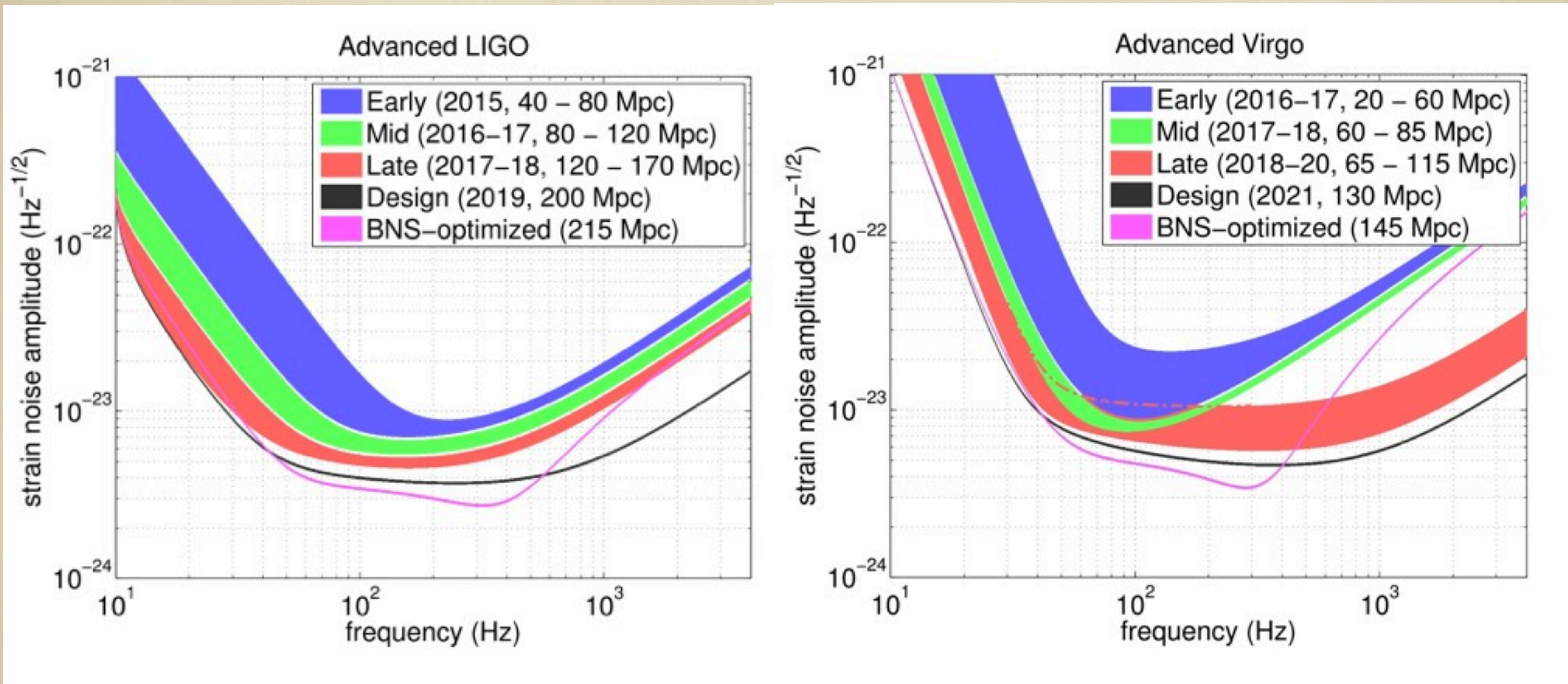
- Observing by LIGO, Virgo, GEO600 2005-2010 has laid foundations for success with Advanced Detectors:
  - Demonstration that large IFOs can be controlled with duty cycle ~ 70%.
  - Organizing data analysis teams, proving of data analysis algorithms, verifying code, establishing the results review process, agreeing detection criteria, even writing a specimen paper.
  - Development in GEO600 of Advanced technologies: monolithic suspensions, high-power lasers, signal recycling, squeezed light.
  - Significant upper limits on GW pulsars (Crab, Vela), stochastic background radiation, compact binary coalescence.

# Current upgrade

- LIGO and Virgo are upgrading by installing Advanced technologies.
- Advanced LIGO (aLIGO) will be handed to commissioners by 2014. Advanced Virgo (AdV) will be 1-2 years later. Likely to be a significant difference between AdV and aLIGO sensitivity for some time.
- Commissioning will alternate with science runs until full sensitivity is reached by 2020.
- If upgrade projections and estimated event rates are both correct, first detections expected by 2017, very likely by 2020.
- LSC-Virgo are actively developing collaborations with EM and neutrino observatories for following up GW observations and triggering GW observations. LoI meetings Amsterdam, Chicago.

# Projected progress

arXiv:1304.0670




Ranges are polarization- and antenna-pattern-averaged detection distance for NS-NS binary coalescence.

# Understanding the data

- All the predicted GW signals are well below noise. We have to dig into the noise to find any signals at all.
- Matched filtering -- correlating with a predicted signal waveform (the "template") -- is essential for the most predictable source, coalescing compact binaries.
- Template families are large, computationally demanding. Fitting "best" template determines parameter values. But noise is very non-gaussian, so analysis is closely coupled to understanding the experiment's hardware.
- Toughest problem: CW signals (GW pulsars).
- Einstein@Home is devoted to CW searches, provides 1 Petaflop continuously!
- Bruce Allen and team have applied GW search techniques to look for pulsars in radio and gamma data. They have found 50 new pulsars, including one new double neutron-star binary. This proves the effectiveness of the algorithms that the GW community has developed.

# First science: mergers

- When the aLIGO range reaches 120 Mpc, the “best estimate” NS-NS merger rate (CQG 27, 173001, 2010) suggests a detection rate of 4 per year. This could happen in 2016 but more likely 2017. The real rate might be as low as 0.04 per year or as high as 40 per year.
- The first NS-NS detections will be intensively followed up by EM observatories looking for afterglows, but if AdV is not observing, or has lower sensitivity, then error box is very big. About 1 in 30 detections is expected to be associated with a detected gamma-ray burst (depends on beam-width of gamma burst).
- BH-BH merger rate more uncertain, but “expected” rate is about 50% of NS-NS rate.
- The network SNR threshold for these detections should be about 12. Median SNR will be 1.3 times this ~ 15 ⇒ typical parameters measured to 7% accuracy.
- After the first 4 confirmed events, LIGO and Virgo will begin publicly releasing alerts (including data) on all strong candidates. Before this, only collaborators who sign MOUs with LIGO and Virgo will get alerts. With a 2-year delay, all signal data will be made public.

# New detectors

- KAGRA plans a very short iKAGRA observing run in 2015 at low sensitivity. According to its development schedule it will reach full advanced-level sensitivity by 2018. This is a very challenging deadline.
  - KAGA will provide longer baselines, improving position-finding.
  - KAGRA will fill in sky coverage: fewer nearby events will be missed.
- LIGO-India is almost fully approved, but recent financial restrictions in India will stretch out the time-line. Full aLIGO sensitivity probably not before 2020.
  - With LIGO-India the network will have an almost isotropic antenna pattern.
  - Improved reliability: even if individual detectors have duty cycles of ~70%, there will be at least three on for 90% of the time.
- GEO-HF will be competitive with aLIGO until the final sensitivity upgrade of aLIGO uses its full laser power ~2019.

# Expanded IFO network 2020+

# Science with the full network

- With the full sky coverage of 5 detectors, the NS-NS event rate could climb to ~100 per year. The strongest such event each year will have a network SNR ~ 4.6 times threshold, or > 50.
- With this accuracy, strong tests of GR are possible:
  - Cosmic censorship can be tested by measuring quasi-normal mode frequencies of the final black hole.
  - Look for evidence of non-GR propagation effects (v<c, Chern-Simons).
- Statistics will return mass and spin distributions for NSs and BHs in binaries.
- With 50 NS-NS merger events, network could determine $H_0$ to better than 1%.
- Multiple detectors creates null streams, linear combinations that contain no GW signal and are good vetoes against glitches. This will make unmodelled burst detection much more sensitive. This is where the first really unexpected discoveries could come.
- Searches for GW pulsars will push down to being able to detect asymmetries of order $10^{-7}$ or smaller.
- Stochastic background searches will probably be best done with the 2 LIGO instruments, which might reach $\Omega_{gw} \sim 10^{-9}$. A first-order GUTs phase transition might produce such a background. Or an inflationary model with an unusual fluctuation spectrum.
- After 2020, aLIGO and AdV may begin to upgrade again, to "2.5G" sensitivity. Factors of 2-5 are possible in range improvements.

# Einstein Telescope

- The ET design study, funded by the EU, led to a feasible plan for a 3G detector.
- With two such detectors on the globe, and with 2.5G Advanced detectors still operating, the network could essentially detect all the NS-NS events in the entire universe.
- High-precision measurements of dark energy, strong tests of gravity.
- Europeans are now preparing a further study proposal for ET. Funding probably will not be approved before first LIGO detections. Construction might start in early 2020’s, first operation hopefully before 2030.

# LISA, eLISA and LPF

- The mHz frequency window is the richest part of the GW spectrum. Massive black hole binaries, close WD binaries in our Galaxy, captures of small black holes by massive ones.
- Danzmann's talk reviewed the status today.
- Data analysis for eLISA very different from ground IFOs, so the original Thorne 1987 article is not a good guide. Signals do stand above noise, so are easy to detect, but overlap, and there are many thousands of detectable ones. So the data problem is one of searching the parameter space of ALL signals simultaneously, trying to separate them one from another. Very compute-intensive. Mock LISA Data Challenges very useful!
- Reminder: the eLISA whitepaper is arXiv:1305.5720. There is a website for the proposal: http://www.elisascience.org. Please visit it and sign up as a supporter! See the whitepaper for the updated science case, placed in the context of physics and astronomy in 2028.

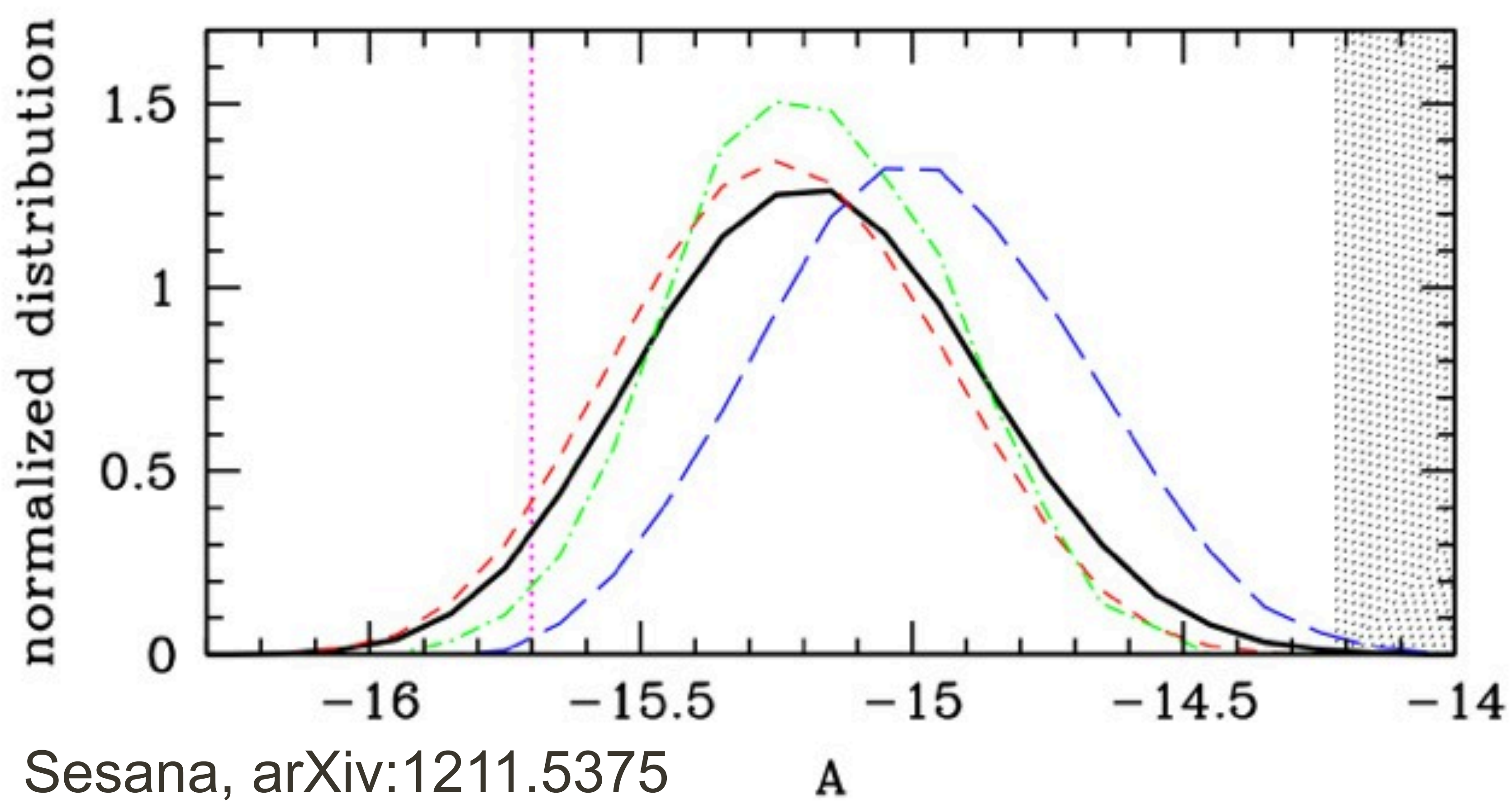
# Pulsar Timing Arrays

- The three PTA projects in Australia, Europe, and N America are making rapid progress pooling their data and getting more observing time for the stablest millisecond pulsars.
- Their sensitivity is already beginning to constrain the most optimistic predictions of the level of a stochastic background at nHz frequencies due to binary SMBHs (McWilliams et al, arXiv1211.4590).
- SKA (2020+) will take PT to a new level: individual SMBH binaries will be identified.

GW amplitude pdf based on large ensemble of evolutionary models.

Shaded: current PTA limits.

Black: PTA with 20 MSPs for 10 years.




Sesana, arXiv:1211.5375

# CMB polarization signal

- Inflationary models generally predict tensor (GW) perturbations as well as the scalar ones that create the temperature anisotropies measured in the CMB.
- GWs create polarization patterns that are visible in the “curl” part of the CMB polarization map.
- Planck’s polarization map is expected next year. Small chance of a positive signal.
- Future ground-based, balloon, and space mission instruments (eg CMBPol) will eventually detect this signal, and chances are good in the time-frame 2020-25.
- This detection would strongly confirm inflation and constrain the inflationary model and scalar field potential. It would also predict levels of this background in the LIGO frequency band, but almost certainly undetectably low.

# The 2013-23 Crystal Ball

- 2013-2015: Advanced LIGO upgrade continues.
  - Commissioning and science runs alternate from 2015 on.
- 2013-2016+: Advanced Virgo upgrade continues.
  - Virgo joins LIGO science runs in 2016-17.
- 2013+: PTAs pool data, increase number of MSPs.
- 2015: iKAGRA science run.
- 2015-2020: Pulsar timing arrays get first nHz detection.
- 2015: LISA Pathfinder launched.
- 2016-2020: Advanced IFOs get first 100 Hz detection.
- 2017: LISA confirmed by ESA for 2028 launch.
- 2017: CMB: first measurement of $\Omega_{gw}$ at z ~ 1000.
- 2018: KAGRA data at Advanced-level sensitivity.
- 2018: ET approved in Europe, construction begins 2020.
- 2020: LIGO-India data at Advanced-level sensitivity.
- 2020+: Advanced detectors upgrade to 2.5G sensitivity, PTAs/SKA study individual SMBH binary systems.

## Verifying Expectations

Population of SMBHS at $10^9\ M_\odot$

Pop of mergers: NS-NS, BH-BH (< 100 $M_\odot$)
Assoc. w GRBs. Poss GWPSR.

Confirm inflation, restrict models

More events, identifications.
Hubble const measured to 1%

Even more events & IDs. Good
tests of GR: Kerr, GW propagation.

GWPSRs, stochastic, cosmic strings,
unexpected events all more likely.

## Discovery Space