Advanced Interferometers and their Science Reach

David Shoemaker,
MIT – LIGO

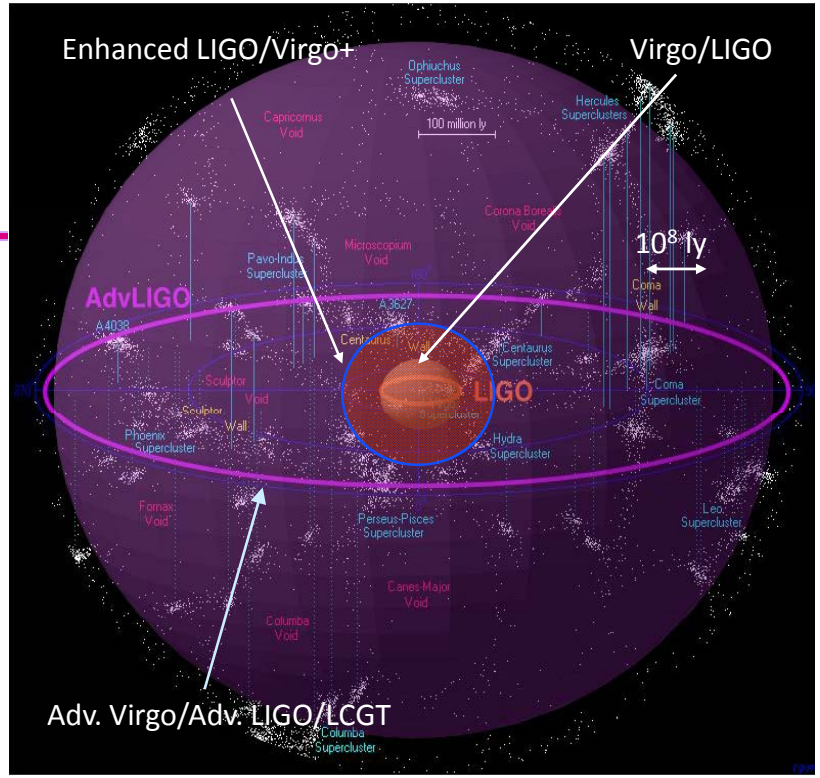
Amaldi, June 2009 – Columbia University

The next phase

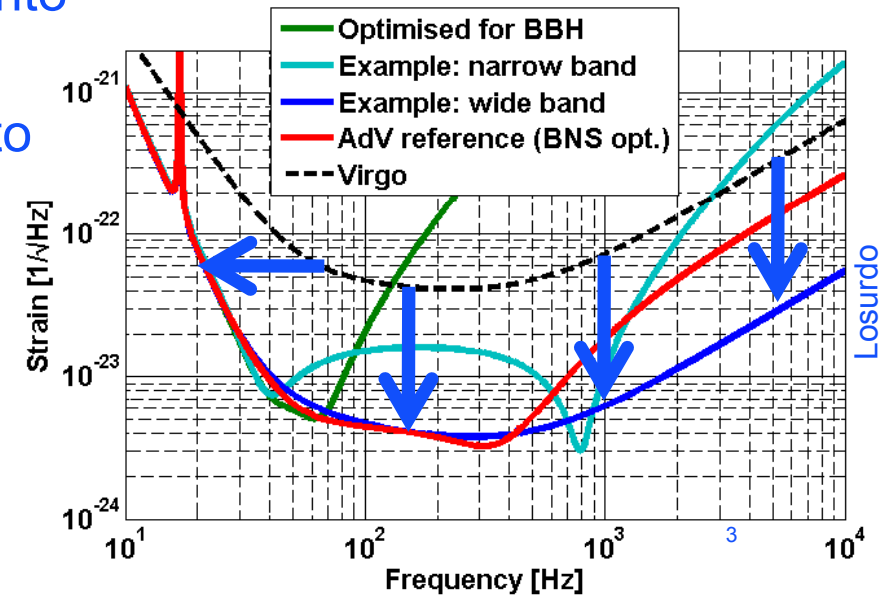
- Initial instruments worked remarkably well
  - » Delivered the instrument science
  - » Established the infrastructure
  - » Reached their design sensitivities
  - » Developed the paradigms for data analysis
  - » Did real astrophysics – provided new upper limits, made important non-detections
- …but they have not (yet) detected gravitational waves
  - » Some analyses of existing high-sensitivity data not yet complete
  - » May still find a gem in the rough!
- Community impatient to move to frequent detections, use of GWs as an observing tool
- What's needed?

Advanced Detector goals

- A factor of ~10 improvement in linear strain sensitivity over the initial instruments
  - » Just about at the current practical limit of instrument science
  - » A nice round number (if we had 12 fingers, we'd do a bit better yet)
- Corresponds to Strain sensitivity *h* of ~3×10^{-23} in a 100 Hz bandwidth
- By itself, brings ~10^3 more candidates into reach
- Can also push down in frequency, say to 10 or 20 Hz
- …and, quite importantly, growing the network
  - » Extracting polarization, position
  - » Increasing uptime, SNR



Credit: R.Powell, B.Berger

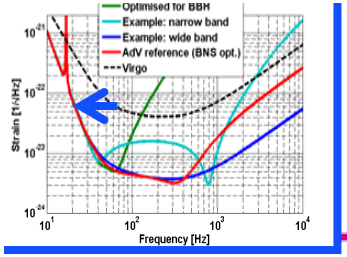


A tour of the challenges and innovations

- What are the limits to performance and the concepts for addressing them?
- What solutions have been adopted for the ‘Advanced’ detectors – and their immediate predecessors, the ‘enhanced’ or ‘+’ versions?

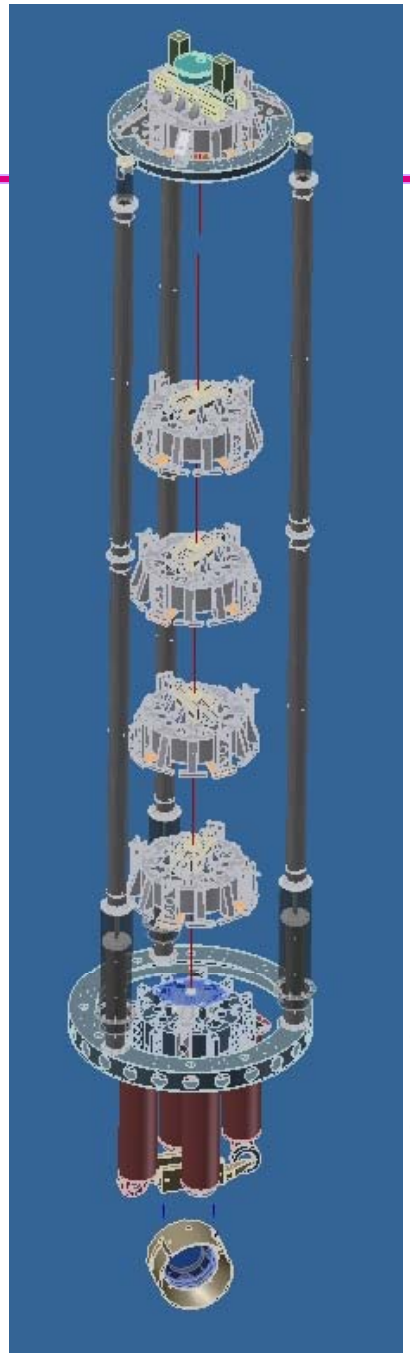
Introduction to the Characters:

- Virgo+: a 3km-arm **1.5** generation instrument, testing and exploiting 2nd generation approaches
- Enhanced LIGO: two 4km-arm **1.5** generation instruments, testing and exploiting 2nd generation approaches
- Advanced Virgo: a 3km-arm **2nd** generation instrument, developed by the Virgo collaboration and EGO, sited in Cascina, Italy
- Advanced LIGO: three 4km-arm **2nd** generation instruments, developed by the LIGO Scientific Collaboration, sited at Hanford, Washington and Livingston, Louisiana USA.
- GEO-HF: a 600m-arm **2+nd** generation instrument, developed by the GEO collaboration, sited near Hannover, Germany
- LCGT: a 3km-arm **2+nd** generation instrument, developed by a Japanese consortium, underground at Kamioka, Japan
- ACIGA – potential for a multi-km system in Australia on 2nd-generation time scales



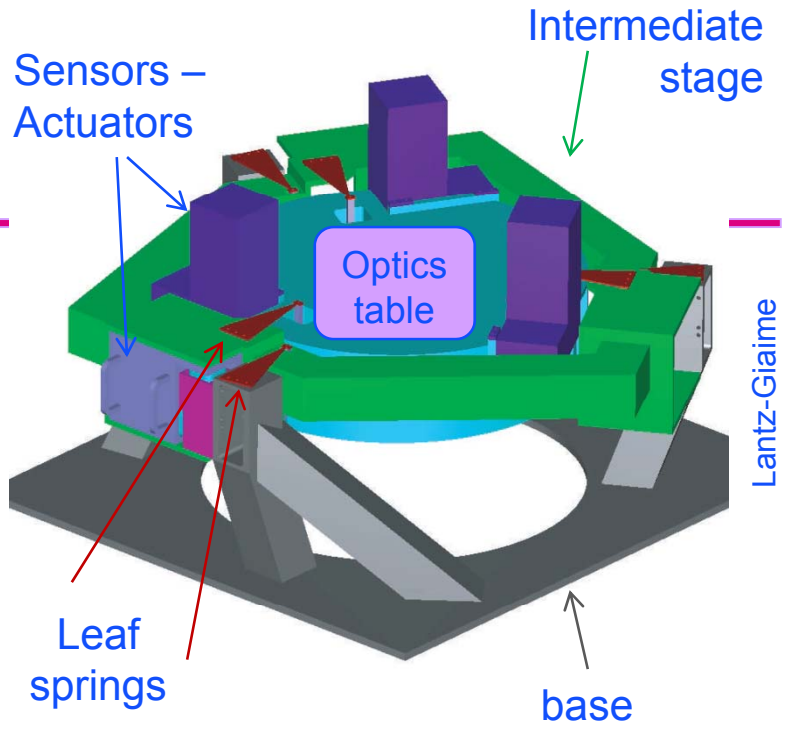
Some challenges:
Seismic Noise

- An obvious way to mask gravitational waves: seismic noise
  - » Noise spectrum grows rapidly toward low frequencies --- requires something like 9 orders of magnitude of suppression at 10 Hz
- All instruments using a pendulum suspension of the optic, one or more layers, to give final isolation (more later)
- Most instruments using initial instrument approach: multiple passive pendulums in series
  - » Prime Example: Virgo 'Superattenuator' to serve for the Advanced Virgo instrument
  - » Virgo+, AdvVirgo, LCGT also use this approach
  - » Masses and springs, similar in principle: GEO-HF

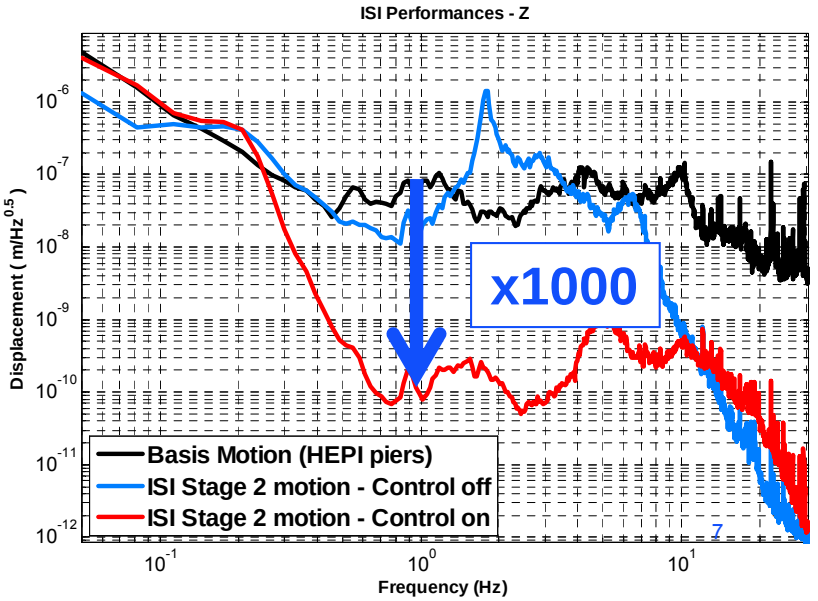


Losurdo

Active seismic isolation

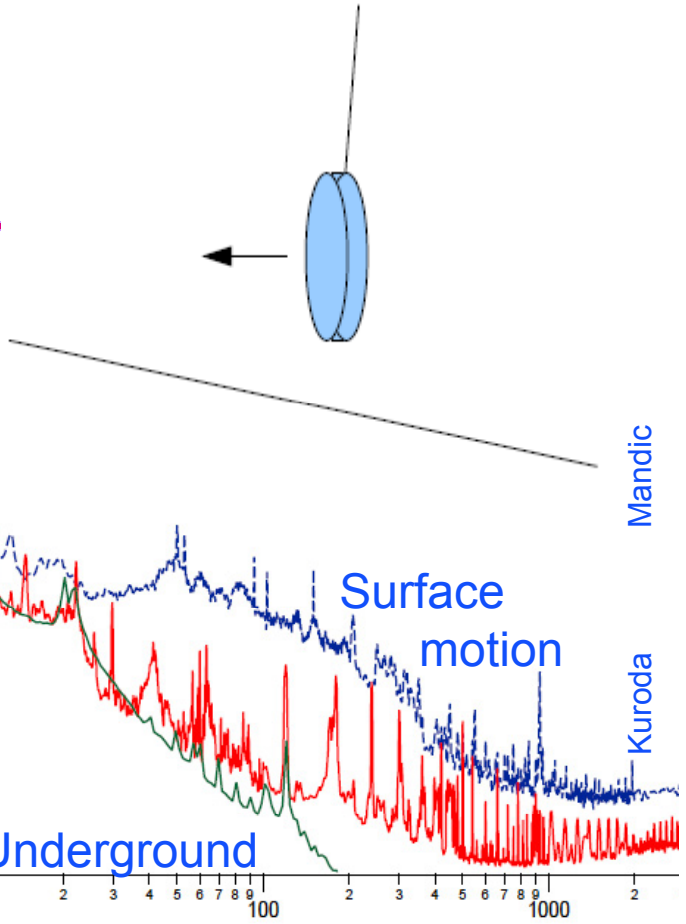


- One new approach is ‘active’ suppression, used in Advanced LIGO
  - » Low-noise seismometers on payload detect motion in all six degrees-of-freedom
  - » Actuators push on payload to eliminated perceived motion
  - » Multiple 6-DOF stages to achieve desired suppression, allocation of control
- Challenges in structural resonances, sensor performance
- Nice to have a quiet table to mount lots of stuff on
- Enhanced LIGO using this approach for one chamber per interferometer
  - » Meets requirements, will remain in place for AdvLIGO



Newtownian background

- Fluctuations in the local gravity gradient
- Test mass can't distinguish from GWs
- Starts to limit Advanced detectors ~15 Hz
- Could put down an array of seismometers, try to regress out the background…
- Or move underground
  - » Reduced level of seismic activity
  - » Symmetrization of earth-air interface
- LCGT to be placed next to Kamiokande, 1000 m underground
- Many orders of magnitude quieter – due to simple seismic noise reduction, and
- ~1 order quieter in gradients



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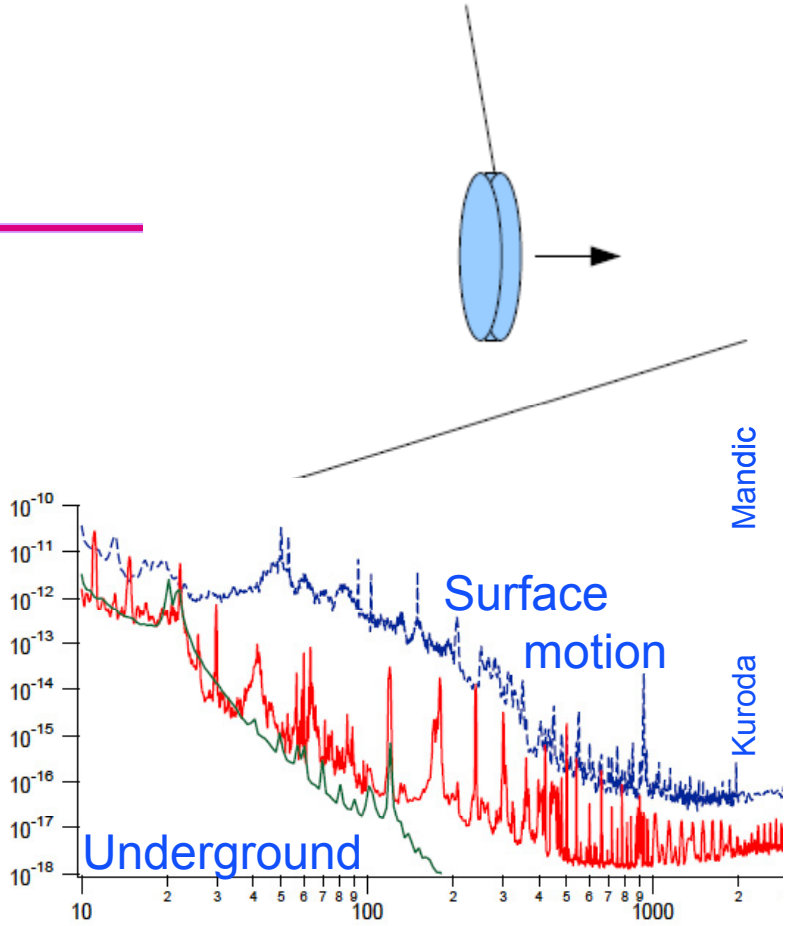
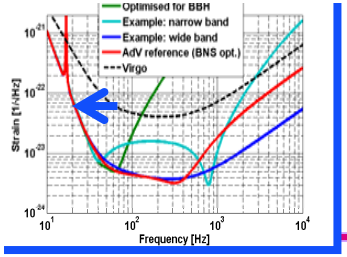
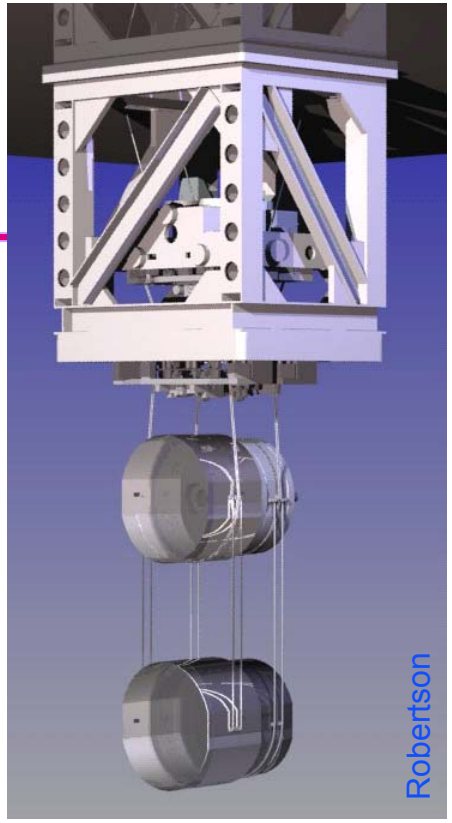
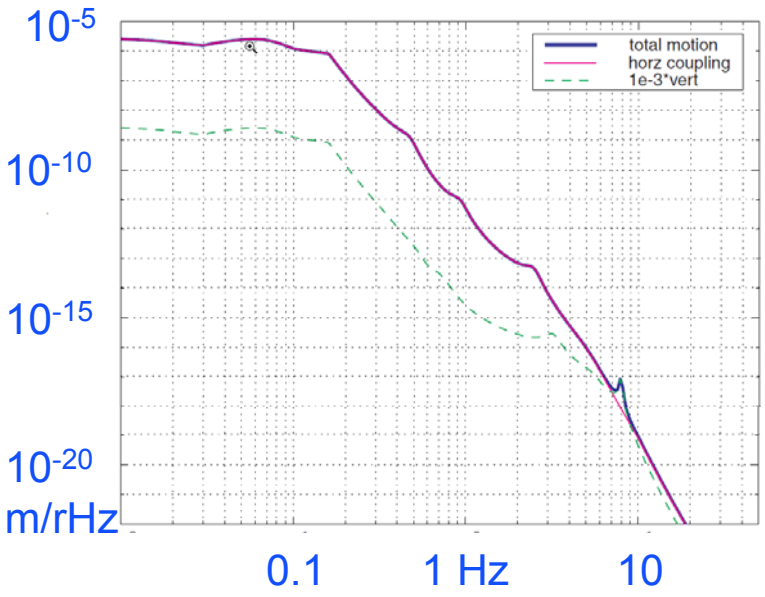




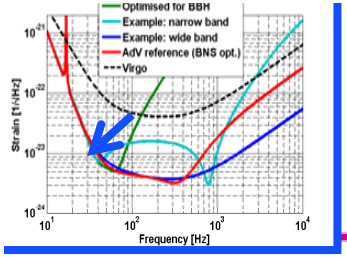
Test mass isolation and control



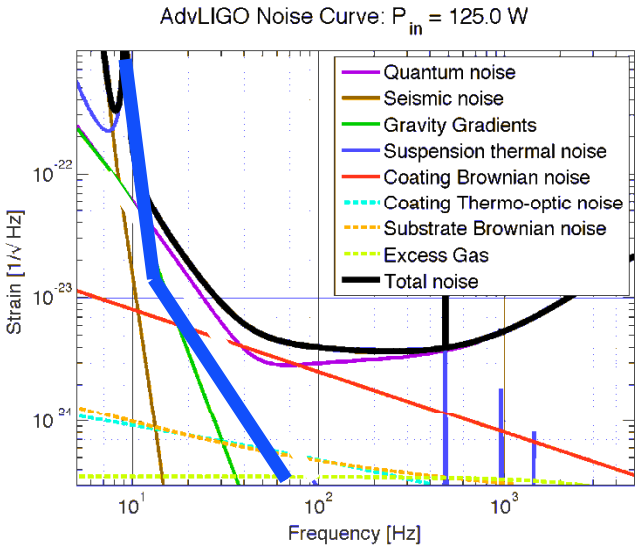
- Test mass suspension complements seismic isolation
- All instruments using several pendulums in series for improved isolation, staging of control forces and dynamic range
- Glasgow has championed multiple-stage pendulums, and UK Consortium has designed and is fabricating suspensions for Advanced LIGO
  - » 4 stages; sensors and actuators as needed to manage forces and dynamic range



- Combined attenuation of seismic noise ~10 orders of magnitude at 10 Hz

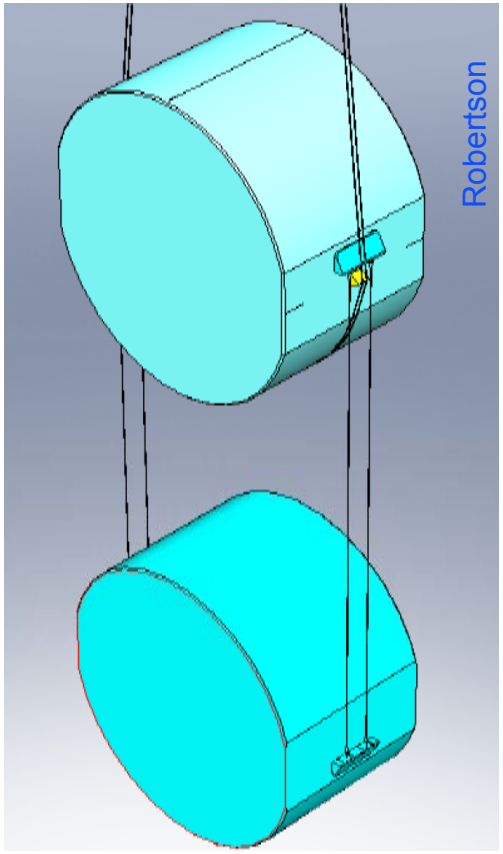


Suspension Thermal Noise



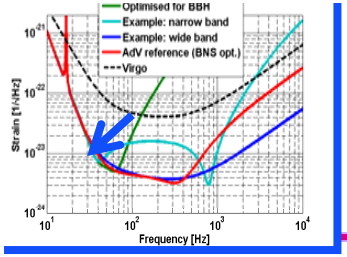
Harry

- ½ kT of energy in each mode, expressed according to the Fluctuation-Dissipation theorem
- Managed by
  - » gathering noise power into a narrow band around suspension resonances, via…
  - » Use of very high quality factor (low loss) materials,
  - » push fundamental resonances below observation band



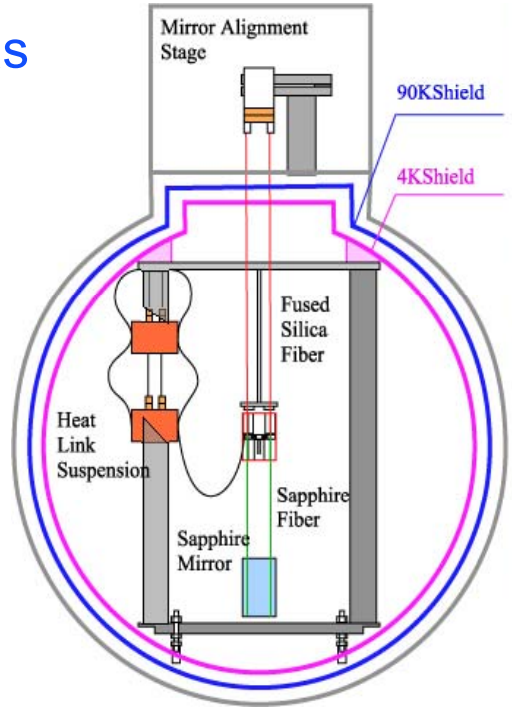
Robertson

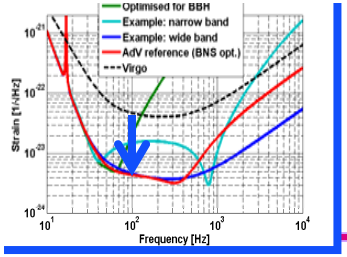
- Fused Silica suspension fibers, as pioneered by GEO (Glasgow) in the GEO600 instrument
  - » Advanced LIGO: as the final stage of suspensions delivered by the UK consortium
  - » In Advanced Virgo, using somewhat different connection approaches, same principle
  - » In Virgo+ -- as early as late 2009/early 2010



Suspension thermal noise

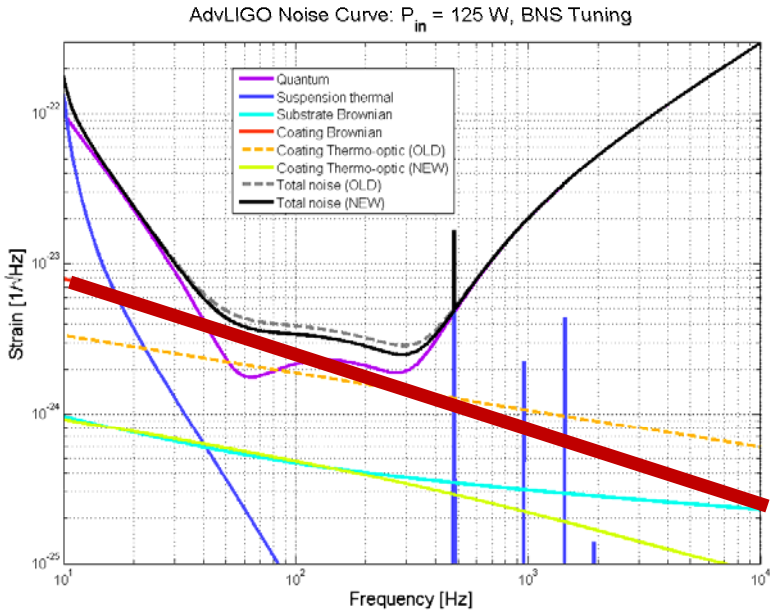
- ½ kT…suppose we lower the temperature? (thermal noise scales as √T)
- Sapphire suspension fibers, pioneered by the Japanese consortium/ICRR, planned for LCGT,
- motivated by cryogenic cooling of suspension and mirrors
- High thermal conductivity, to draw heat from test mass deposited by laser beam
- Mechanical losses decrease as temperature drops – some cancellation of noise sources
- Challenges in quiet refrigeration confronted
- An important candidate for 3rd generation instruments



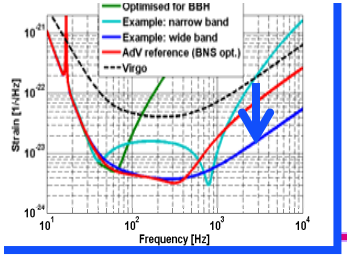


Test Mass and Coating thermal noise

- Again, thermal energy of mechanical modes of the optic substrate which serves as the test mass cause motions of surface
- LCGT paving the way for 3rd generation instruments with a cryogenically cooled sapphire mirror – lowering noise by sqrt(T)
- Most instruments using fused silica as the substrate material as for initial instruments
  - » Virgo+, AdvVirgo, eLIGO, AdvLIGO, GEO600
  - » Loss values of ~10^{-8} …
  - » Substrate thermal noise not a problem
- Mirror coatings: loss values of ~10^{-4}
- THE dominant mid-range noise
- Meets 10x improvement, barely
- Continuing work well rewarded!

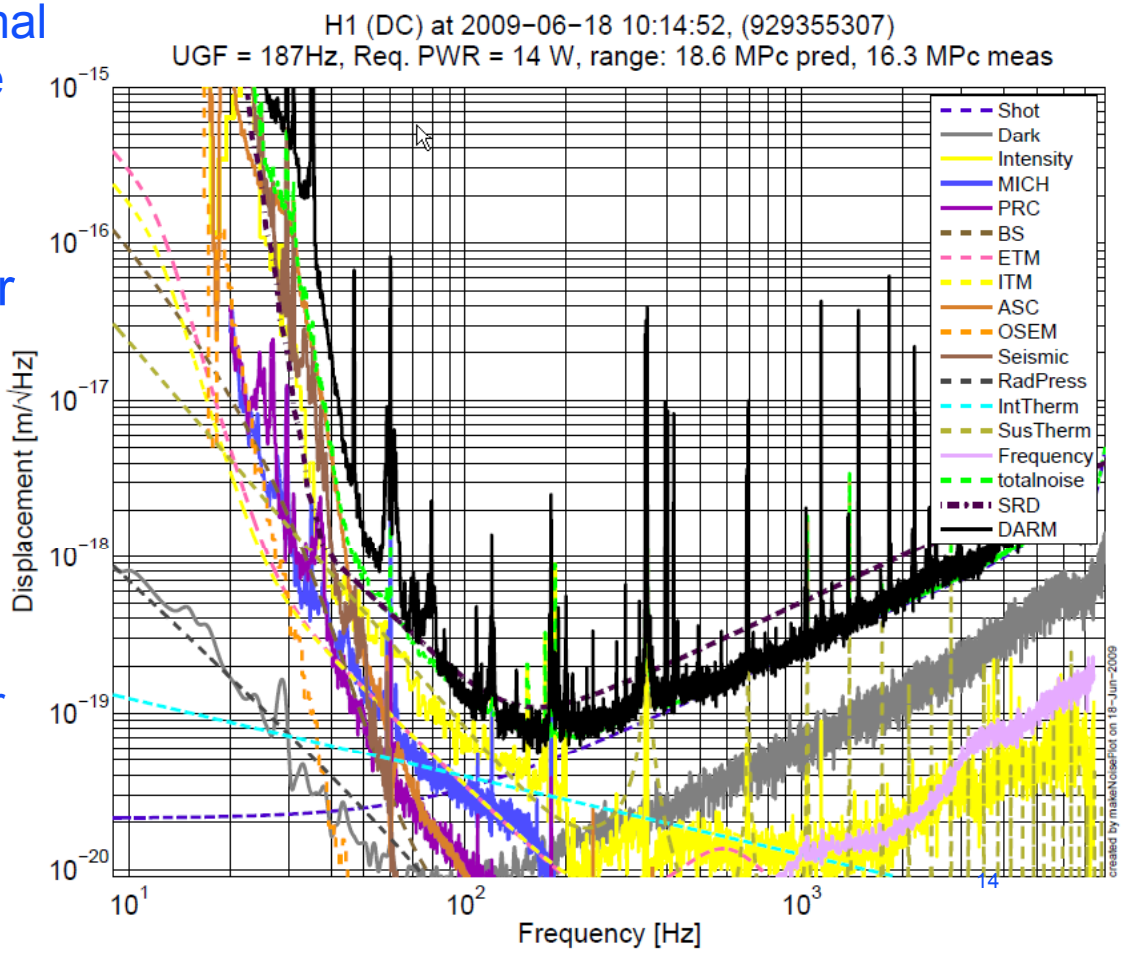


M. Evans



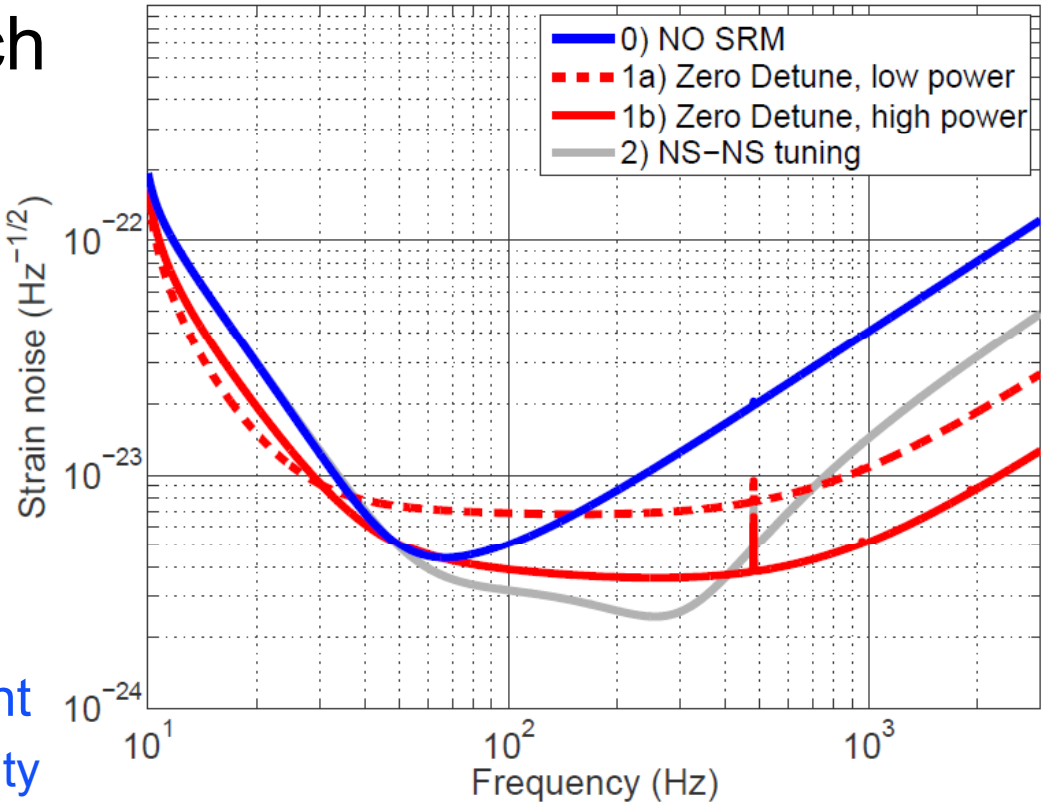
Laser light sources

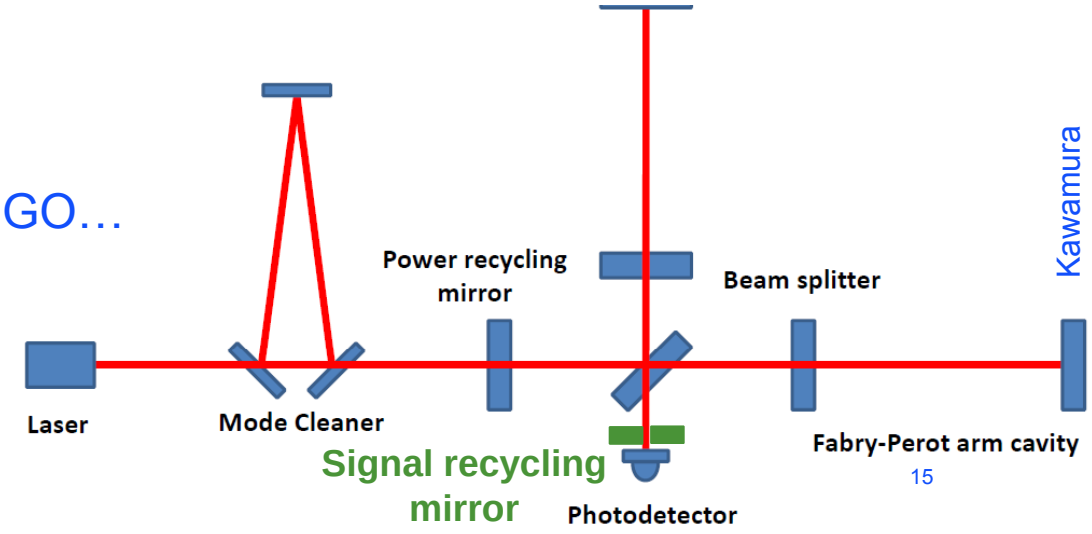
- Need order of ~150-200W to achieve Advanced sensitivities
- GEO-HF, Adv LIGO, LCGT -- 150-200W Nd-Yag lasers
  - » Max Planck Hannover-developed solution for the laser for several projects
  - » modulators, isolators, thermal compensation schemes are advanced for a factor ten
- eLIGO – 35W front end laser
  - » Starting to see success in using this light!
- Adv Virgo – keeping option of a fiber laser open
  - » Valuable path to explore for 3rd generation instruments



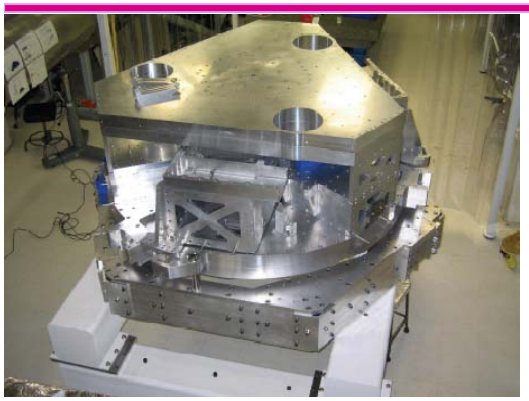
Strain sensing approach

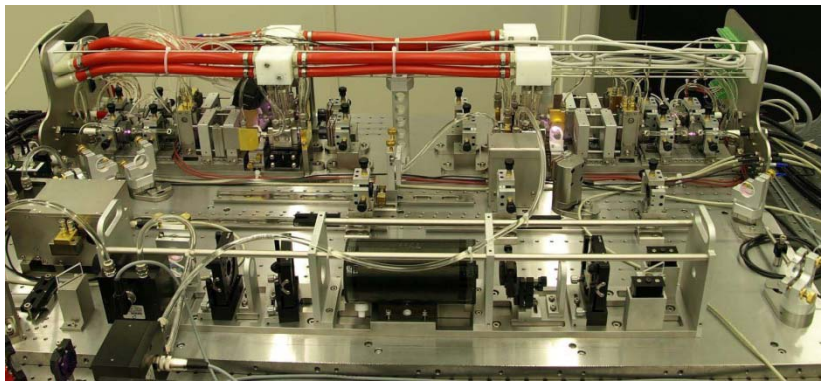
- Adv Virgo, AdvLIGO, LCGT – signal recycling, Pioneered in GEO600
- Allows some tuning, used to balance technical limitations and astrophysical signatures
- GEO-HF – will use squeezed light
  - » Can achieve e.g., same sensitivity for less light power
  - » pathfinding for 3rd Generation (or 2.5 or 2.3….)
  - » May test in LIGO/eLIGO/AdvLIGO…

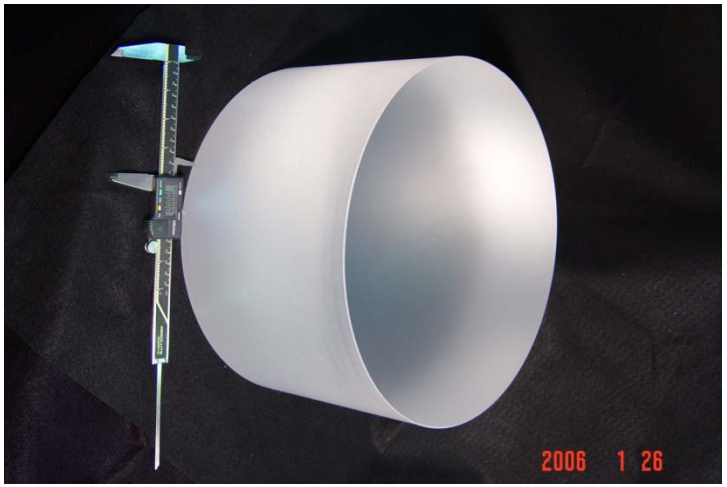




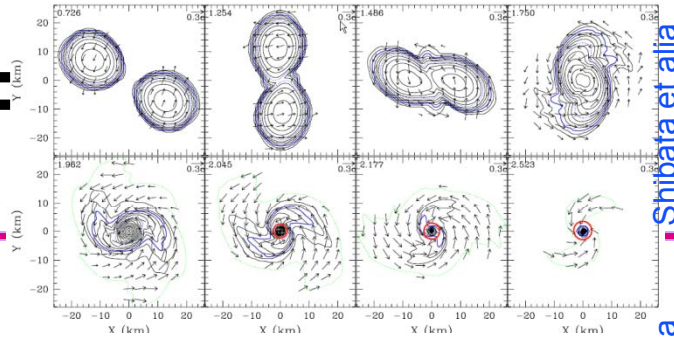
And hardware exists!

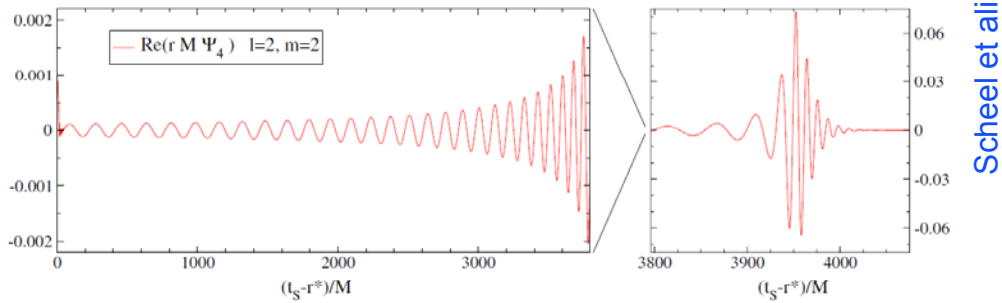






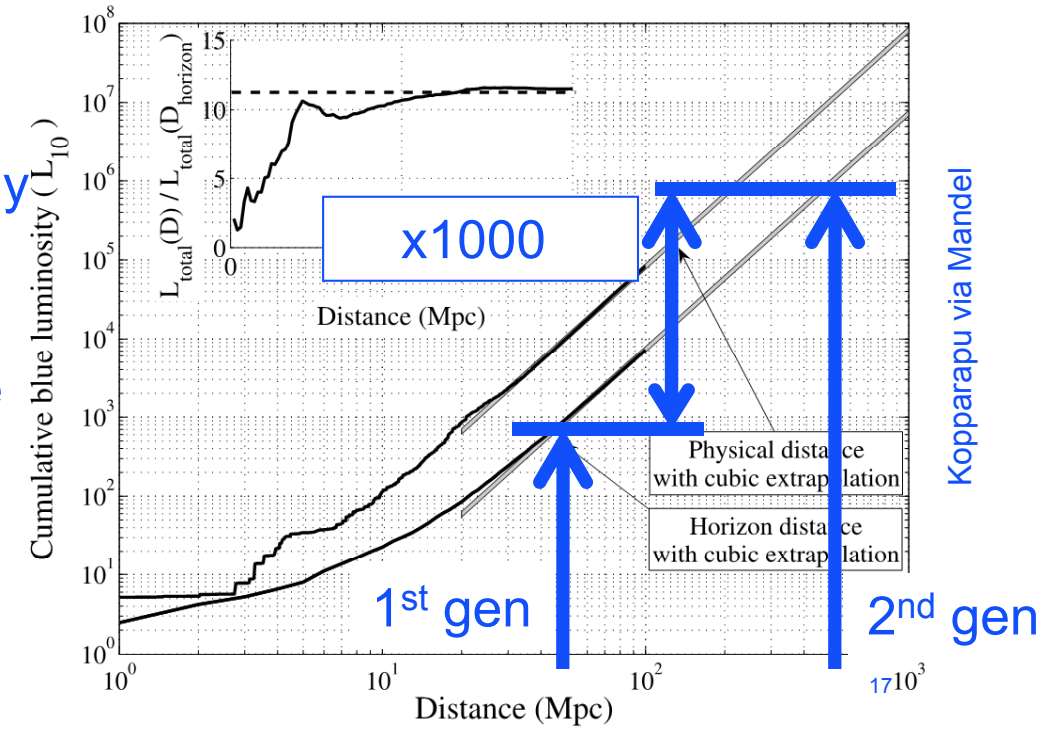
A bit on the astrophysical targets:
Neutron-star binary coalescence





- The source for which we have the best templates, and now also an idea of the coalescence/ ringdown…

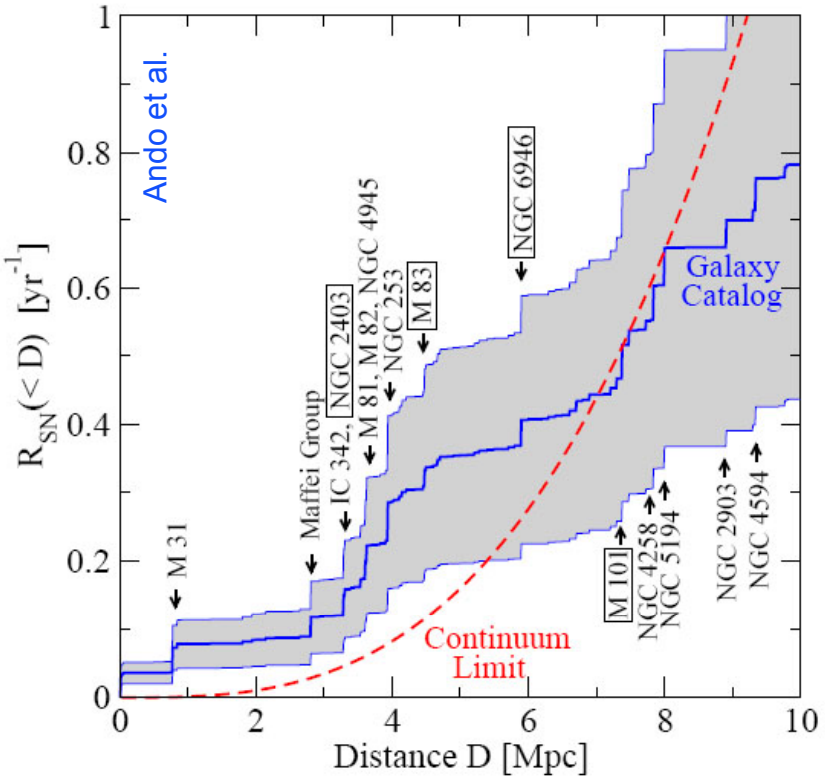
- …and the best rate estimates.
- Advanced detector rates are likely to be 40 /year but still uncertain to a factor 10 in either direction
- Rates for other species less sure
  - » NS-BH – best guess 10 /year
  - » BHBH – best guess 20 /year



Supernovae (one example of a 'burst' source)

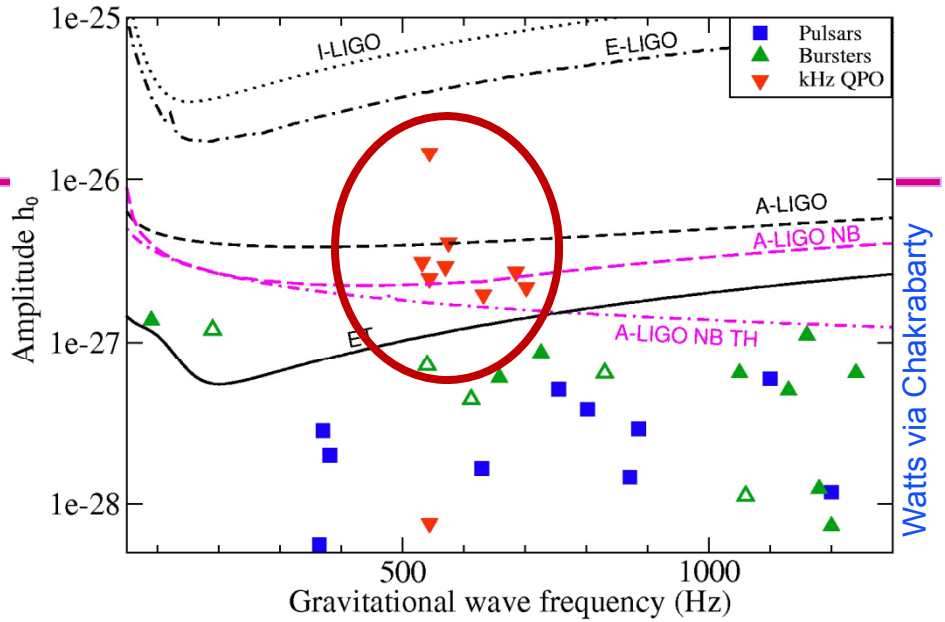
- Know of ~1-3 per year out to the Virgo cluster
- Advanced detectors can see ~10^{-6} M_s out to 1 Mpc -- ~1/150 yr

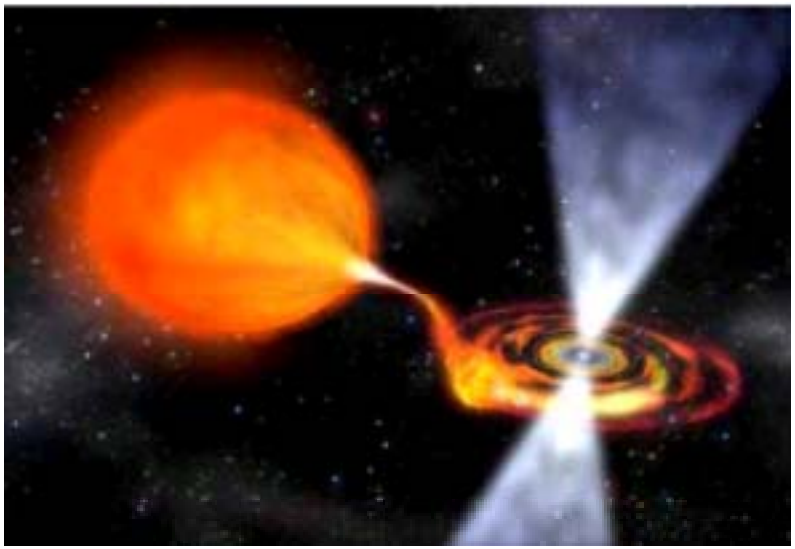
- But some proposed mechanisms release more energy than this, and
- May be more that we do not yet see
- Great target for multi-messenger astrophysics with neutrinos – increases reach and confidence



Periodic sources

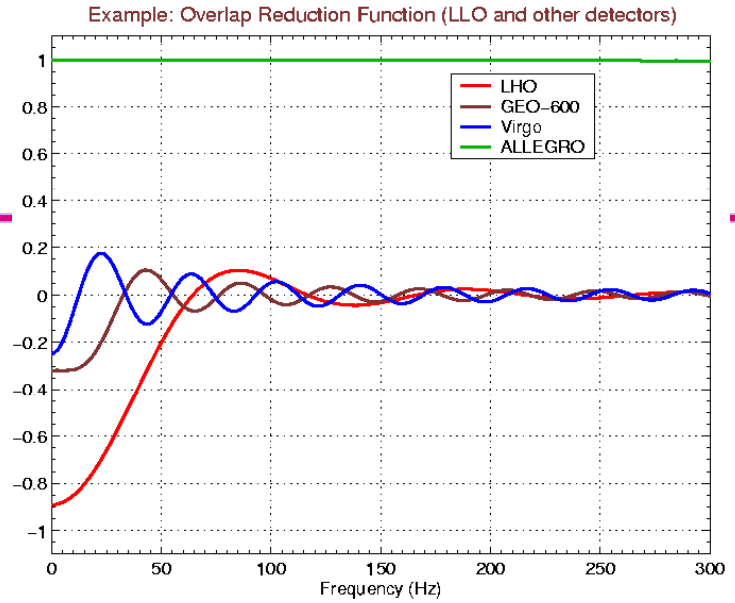
- Pulsars will emit GWs if asymmetric; lots of discussion about the stiffness of the shell
- One mechanism for Low-mass X-ray binaries: GW emission (due to “mountains”) balances long-term accretion torque
- Handful of known pulsars appear to be in reach for a 2-year observation
- Will continue all-sky search using Einstein@home screen-saver approach



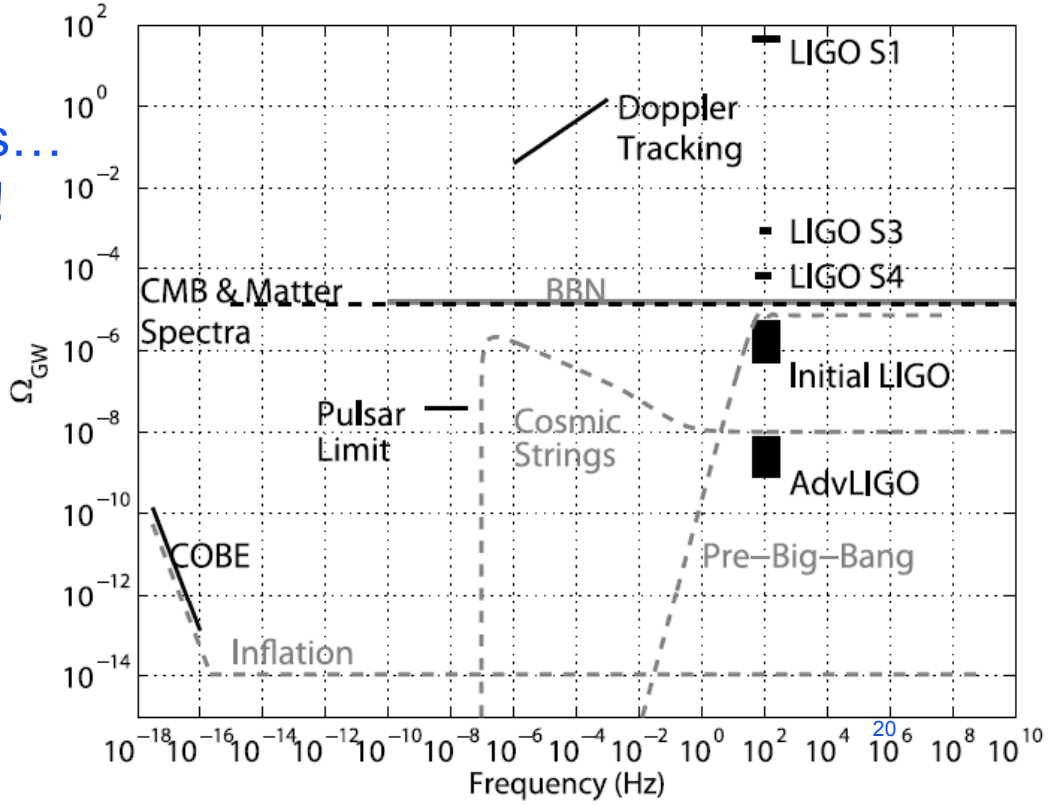


Stochastic sources

- Have already 'beat' the Big-Bang nucleosynthesis upper limit
- Huge increase in sensitivity for the AdvLIGO pair despite overlap function – due to improvement in low-frequency sensitivity

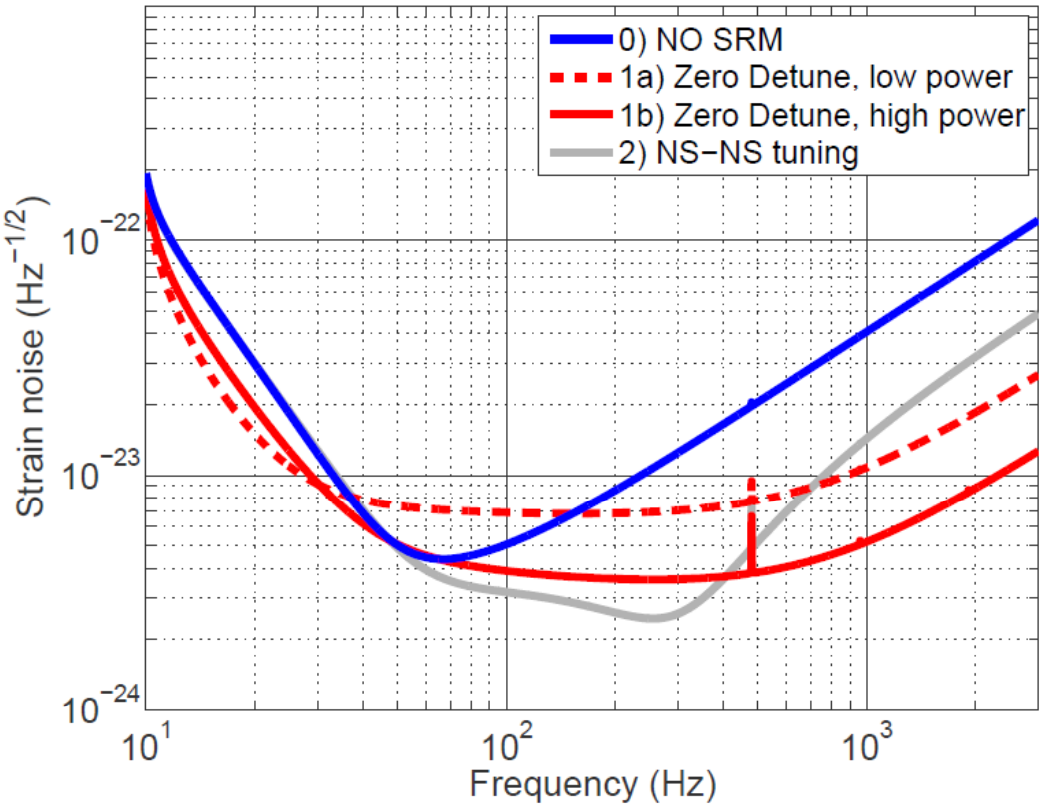


- Standard inflationary models out of reach for 2nd gen detectors… have to wait for 3rd gen or space!
- But some Cosmic String models, defects, etc. can be tested
- …and surprises to be found



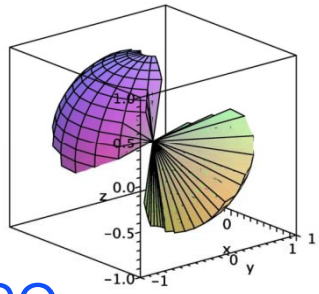
Surprises

- Broad sensitivity of the Advanced detectors, multiple detectors for confidence and coverage, and the sheer number of candidate systems convinces me we will see lots of signals!

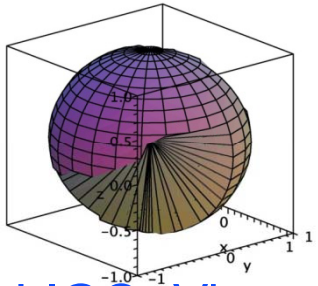


The Network

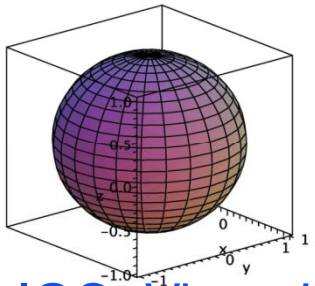
Network sensitivity For 50% Sensitivity Coverage



LIGO



LIGO+Virgo



LIGO+Virgo+LCGT

Schutz

So….

- There is a range of nice new technologies which appear to be able to deliver the desired 10x sensitivity, <1000x volume
- There are a number of sources waiting to be detected
- eLIGO and Virgo+ will start observing with some enhanced sensitivity this summer – and with many parts of Advanced Instruments being explored, exploited, refined
- ACIGA, other groups, establishing plans for instruments
- Advanced Virgo plans a start this summer, LCGT also has optimism for a start in the near future
- …not just plans: The Advanced LIGO Project is underway since April 2008 (Thank you, NSF!)

2015 will be a very good year!