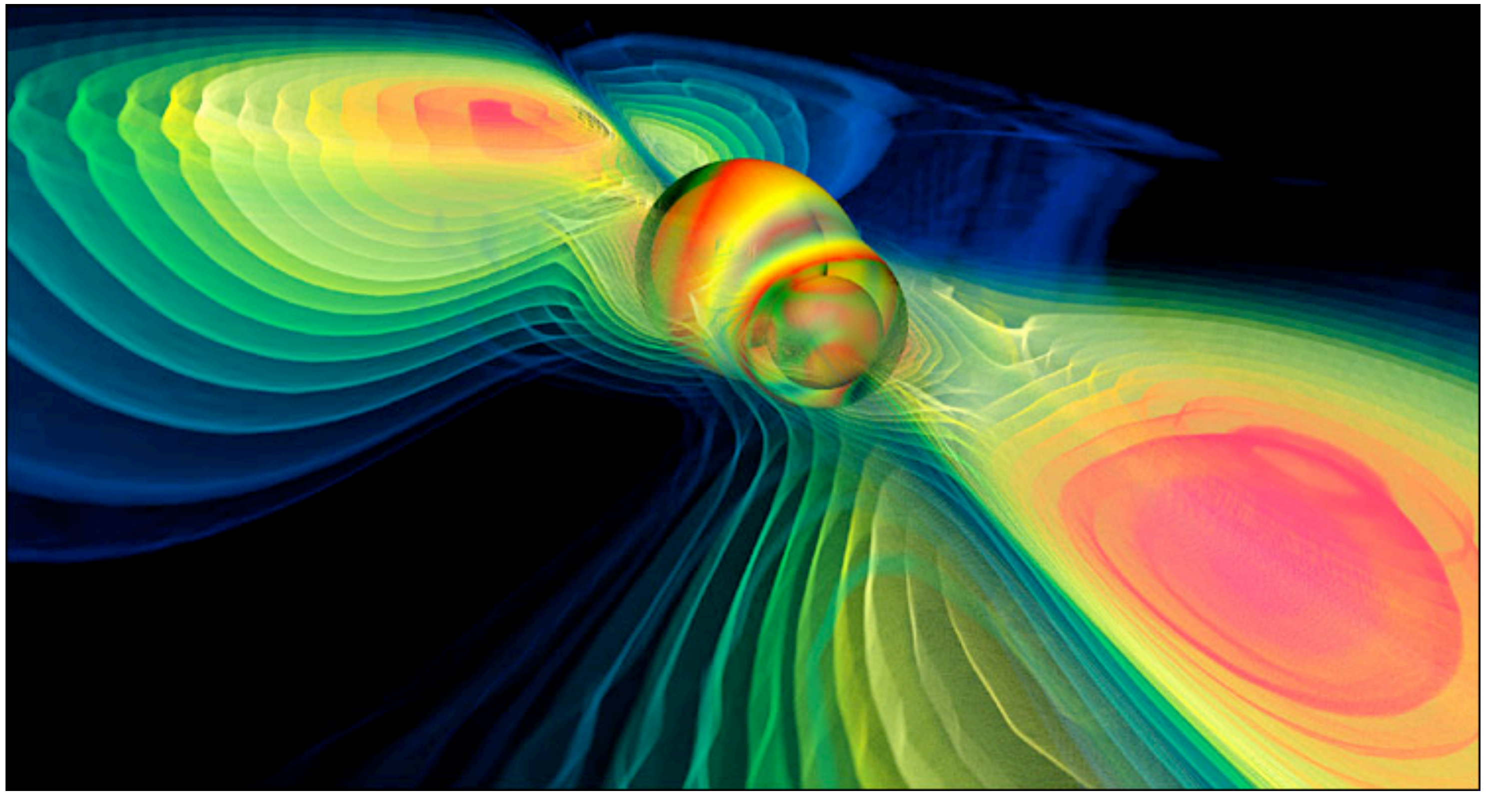
LIGO-Virgo Searches for Gravitational Waves from Binary Systems Containing Intermediate-Mass Black Holes



(Image: MPI for Gravitational Physics / W.Benger-ZIB)

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LIGO-G0900244

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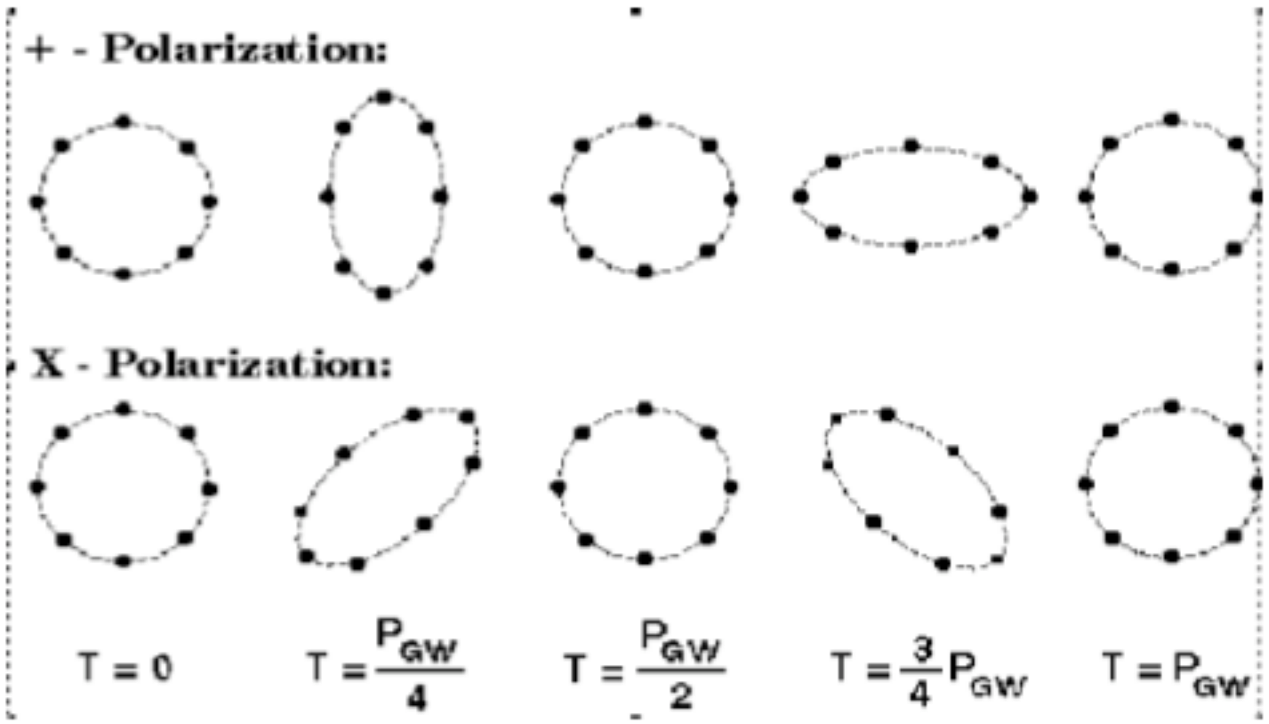
- Gravitational waves
- Ground-based gravitational-wave detectors
- LIGO/Virgo sources involving IMBHs
- LIGO/Virgo searches for GWs from high-mass sources

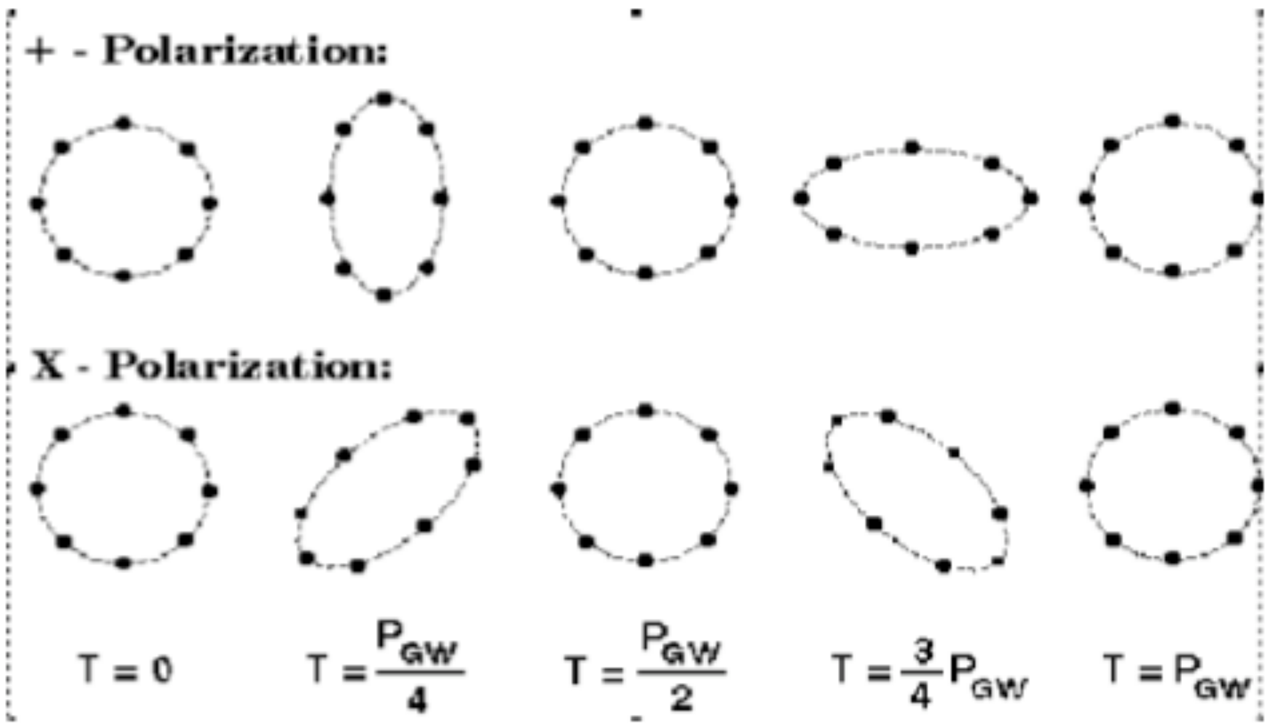
Gravitational Waves

- Ripples in spacetime:



- Caused by time-varying mass quadrupole moment
- Indirectly detected by Hulse & Taylor [binary pulsar]
- Huge amounts of energy released: 5% of mass-energy of a supermassive black hole binary is comparable to the electromagnetic radiation emitted from an entire galaxy over the age of the universe!

Gravitational Waves



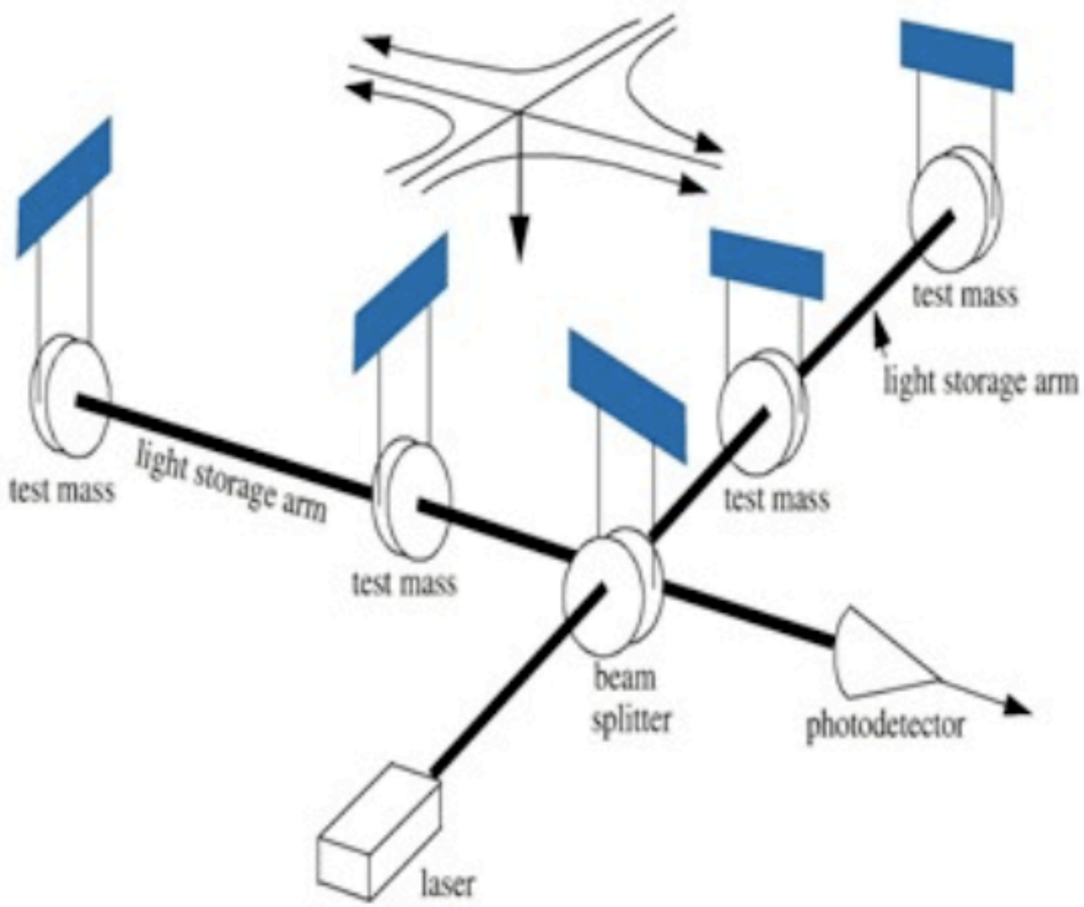
- Ripples in spacetime:

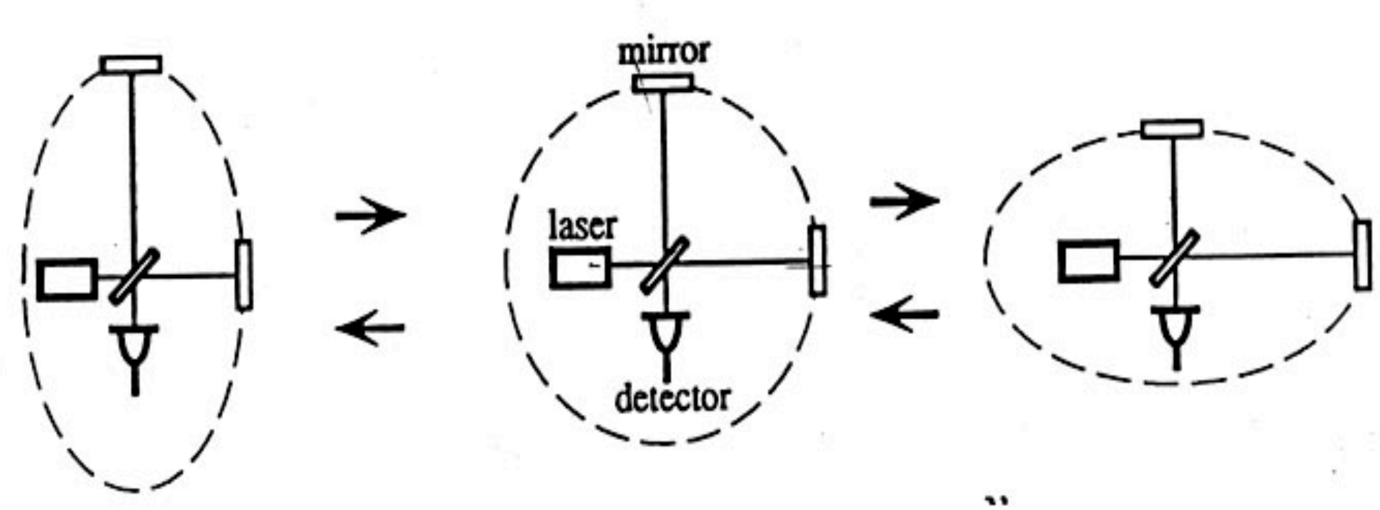
Inspiral sound borrowed from Scott Hughes

- Caused by time-varying mass quadrupole moment
- Indirectly detected by Hulse & Taylor [binary pulsar]
- Huge amounts of energy released: 5% of mass-energy of a supermassive black hole binary is comparable to the electromagnetic radiation emitted from an entire galaxy over the age of the universe!

Opportunity and Challenge

GWs carry a lot of energy, but interact weakly: can pass through everything, including detectors!



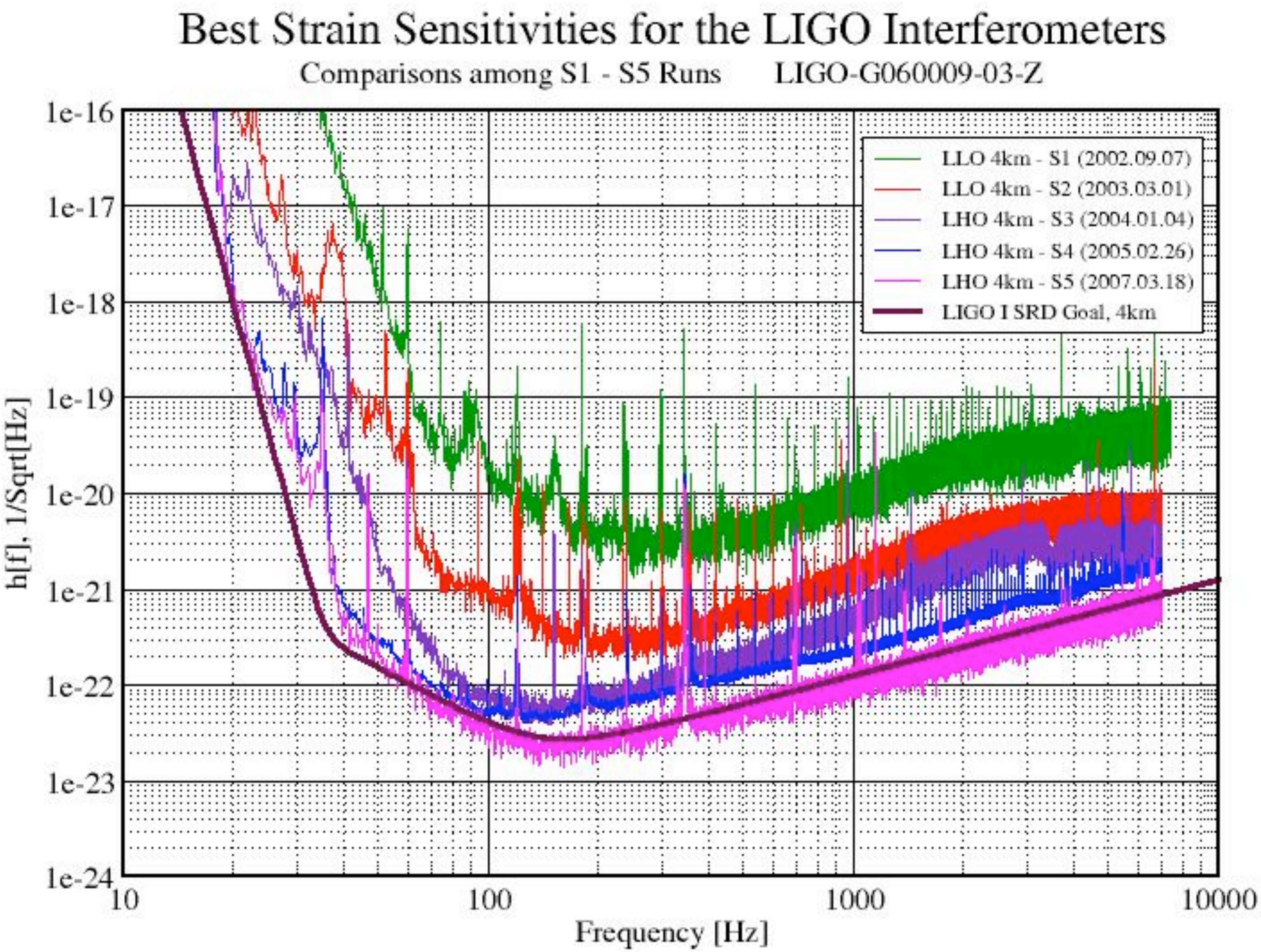


Michelson-type interferometers

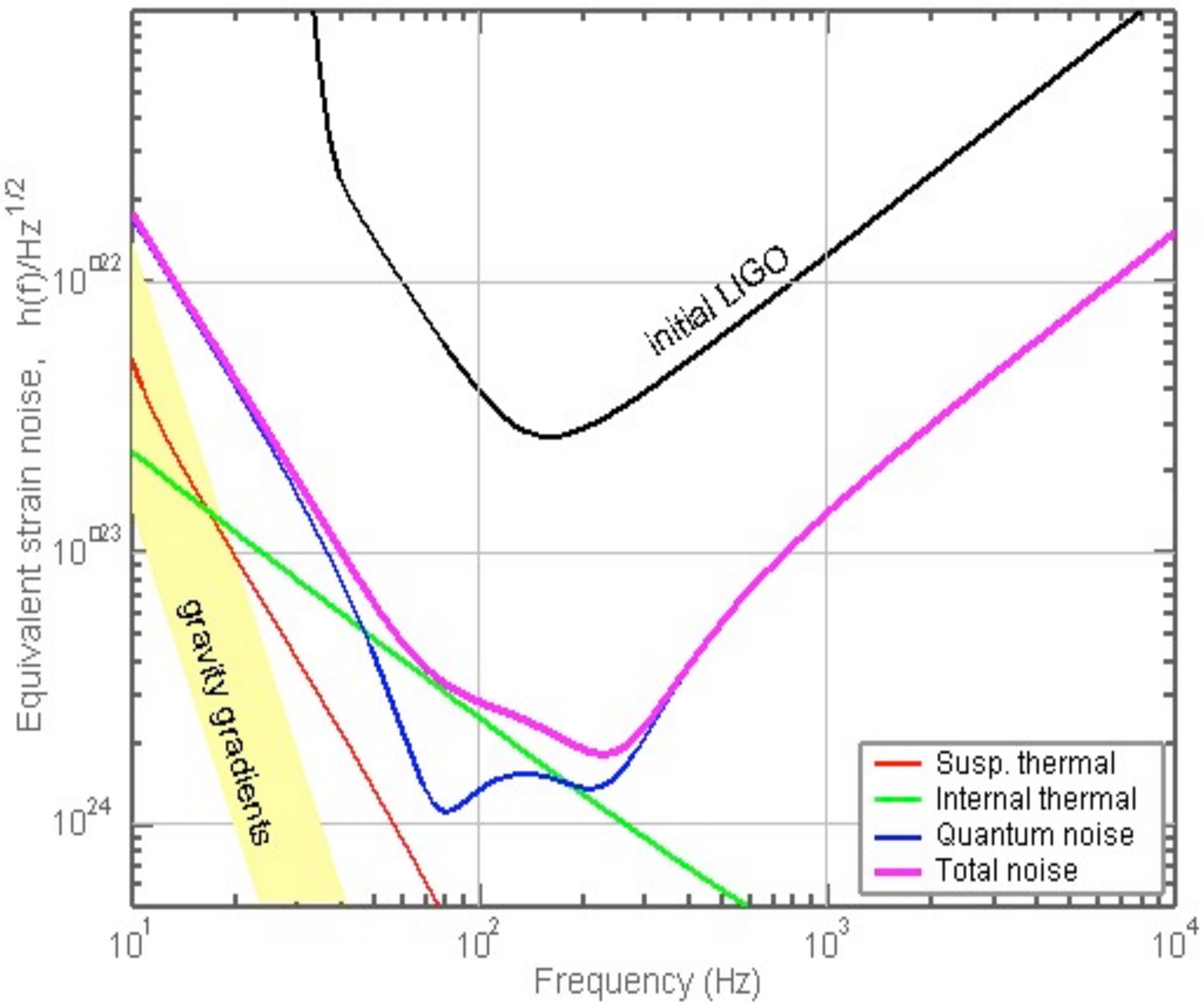
LIGO (Laser Interferometer Gravitational-Wave Observatory)

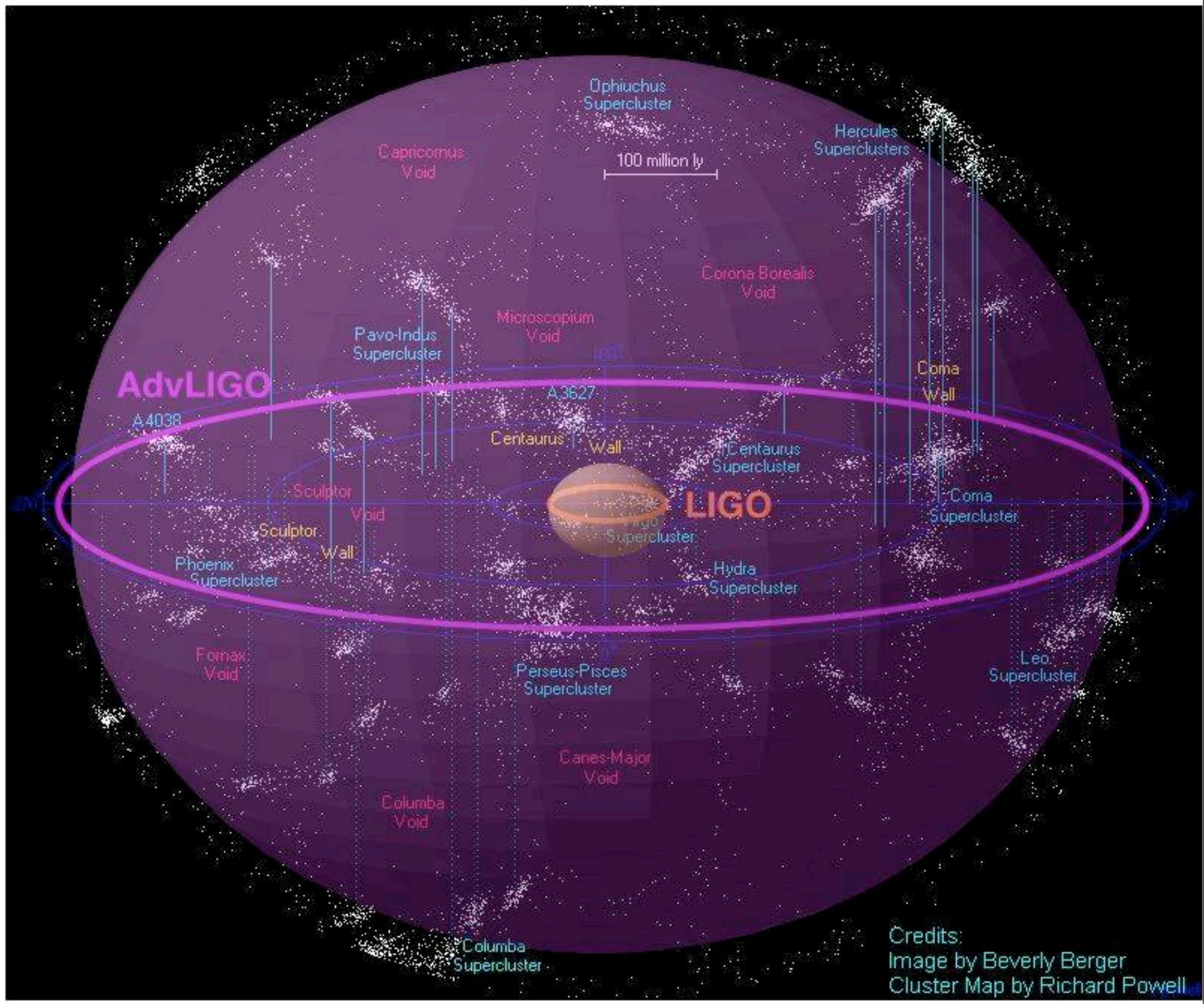
- 4 km long arms
- Typical strains $h = \Delta L / L \sim 10^{-21}$ (NS-NS in Virgo cluster)
- Needs to measure $\Delta L = hL \sim 10^{-18}$ m
- 2 LIGO detectors in US + Virgo, GEO in Europe
- Virgo has 3 km baseline; data-sharing agreement with LIGO

LIGO Noise Curve



Advanced LIGO





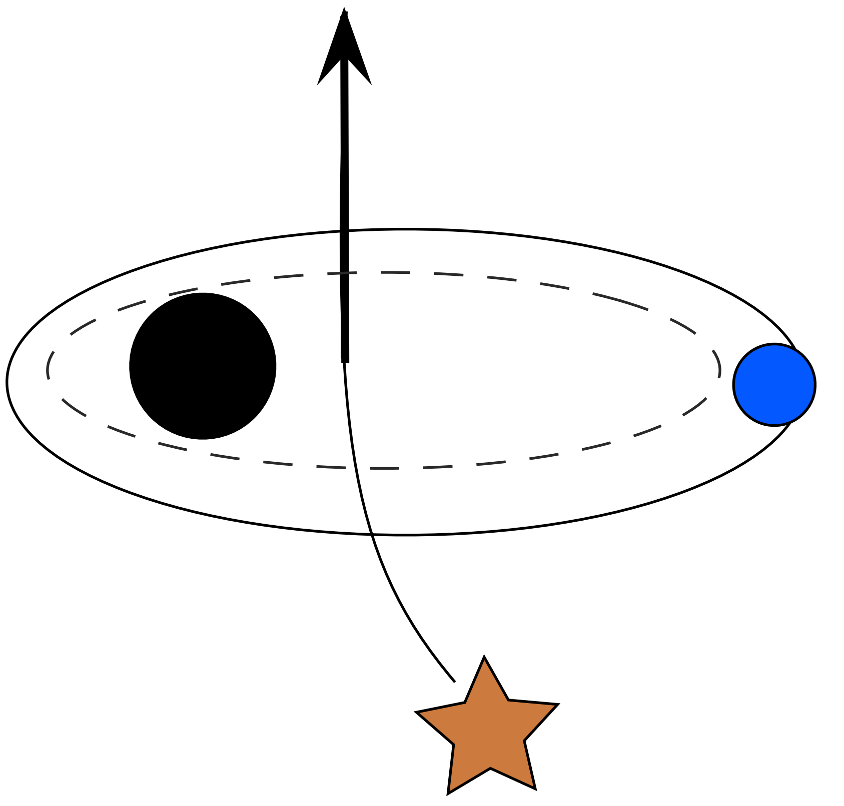
- ~ x10 in range -> ~ x1000 in event rate
- 10 Hz low frequency cutoff
- (Enhanced LIGO will have ~ x2 in range, simultaneous data collection with Virgo)

Intermediate-mass-ratio inspirals (IMRIs)

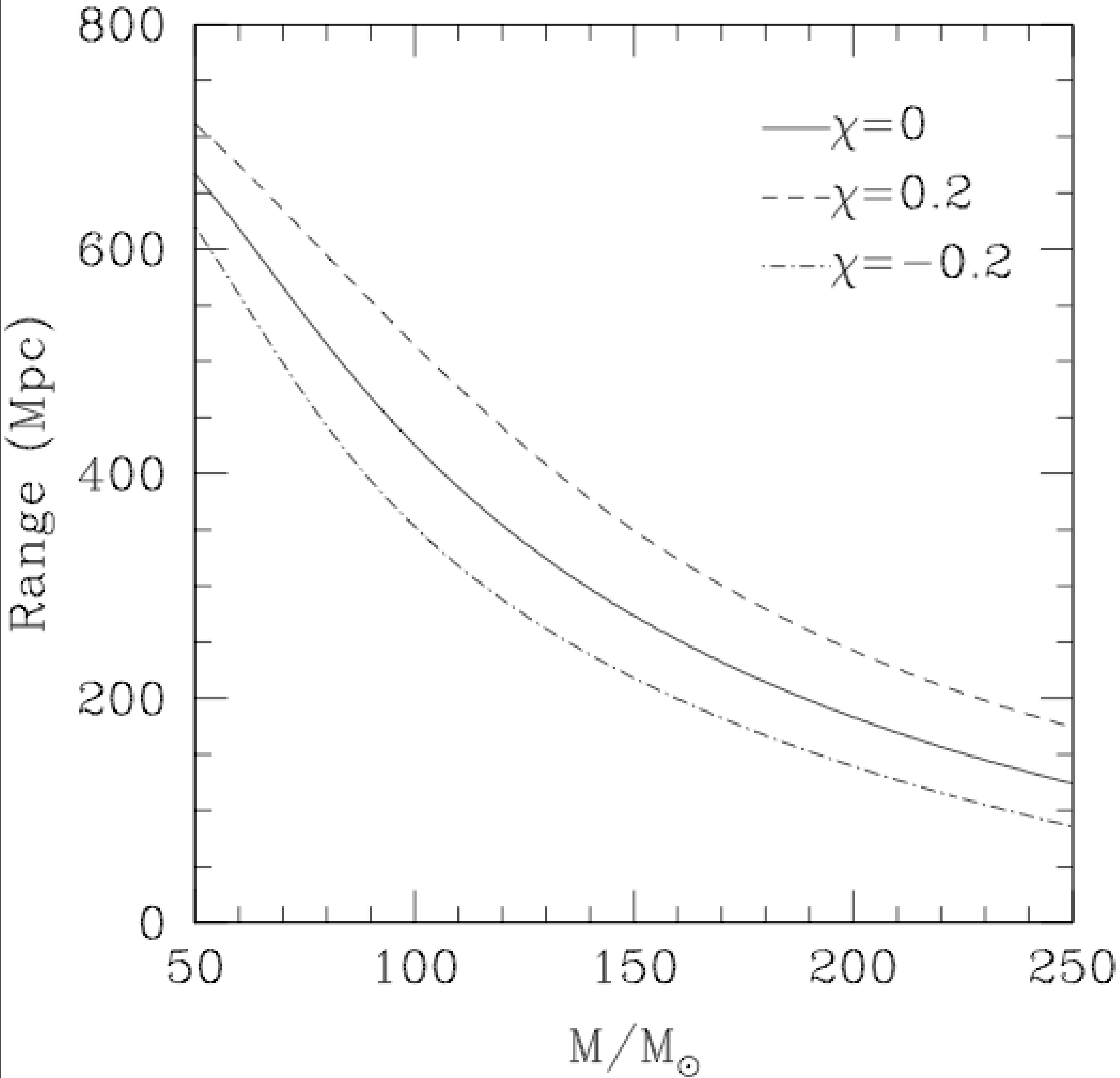
[IM, Brown, Gair, Miller; 2008; ApJ 681 1431. arXiv:0705.0285]

- Inspirals of compact objects (1.4 solar-mass Neutrons Stars to 10 solar-mass Black Holes) into intermediate mass black holes (IMBHs, 50-350 solar masses) in globular clusters
- Dominant formation mechanism: three-body interactions: IMBH swaps into binaries, forms CO-IMBH binaries which are tightened via three-body interactions with other stars, then merge via GW radiation reaction
- 3-body interaction rate is $dN/dt=n\sigma v$;

  $n \sim 10^{5.5}\ pc^{-3}$; $v \sim 10$ km/s; $\sigma \sim \pi a(2GM/v^2)$
- $T_{harden} \sim O(M/m)\ (dN/dt)^{-1} \sim 10^8\ (AU/a)$ yr
- $T_{merge} \sim 5*10^8\ (M_o/m)\ (100M_o/M)^2\ (a/AU)^4$ yr
- To maximize rate, minimize $T=T_{harden}+T_{merge}$
- Rate per globular cluster is $\sim 3*10^{-9}\ yr^{-1}$ for NS, $5*10^{-9}\ yr^{-1}$ for BH



Advanced LIGO IMRI sensitivity



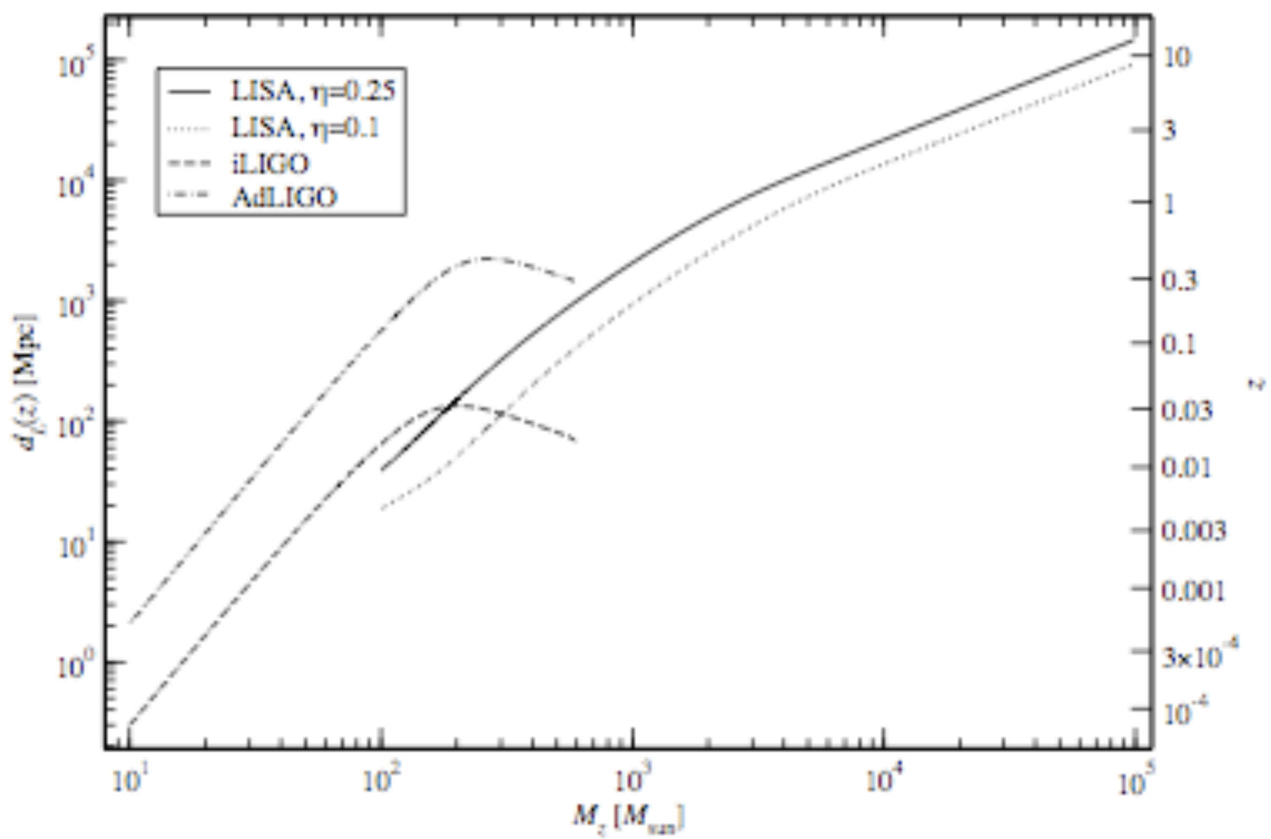
$$\frac{R}{\mathrm{Mpc}} \approx \left[1 + 0.6\,\chi^2\left(\frac{M}{100\,M_\odot}\right)\right]\sqrt{\frac{m}{M_\odot}}\left[800 - 540\left(\frac{M}{100\,M_\odot}\right) + 107\left(\frac{M}{100\,M_\odot}\right)^2\right]$$

[IM, arXiv:0707.0711; IM, Brown, Gair, Miller, 2008]

- Assume 10% of all globular clusters hold suitable IMBH (mass ~ 100 Msun, spin~0.2)
- If inspiraling object is 1.4 Msun NS, Advanced LIGO could detect one IMRI per 3 years
- If inspiraling object is 10 Msun BH, Advanced LIGO could detect 10 IMRIs per year
- Range could be increased by x1.5 by tuning Advanced LIGO; rates could go up to 1/year and 30/year
- Could be sensitive to ringdowns of more massive objects

IMBH-IMBH mergers

[Fregeau, Larson, Miller, O'Shaughnessy, Rasio; 2006; ApJL 646 L135. arXiv:astro-ph/0605732]



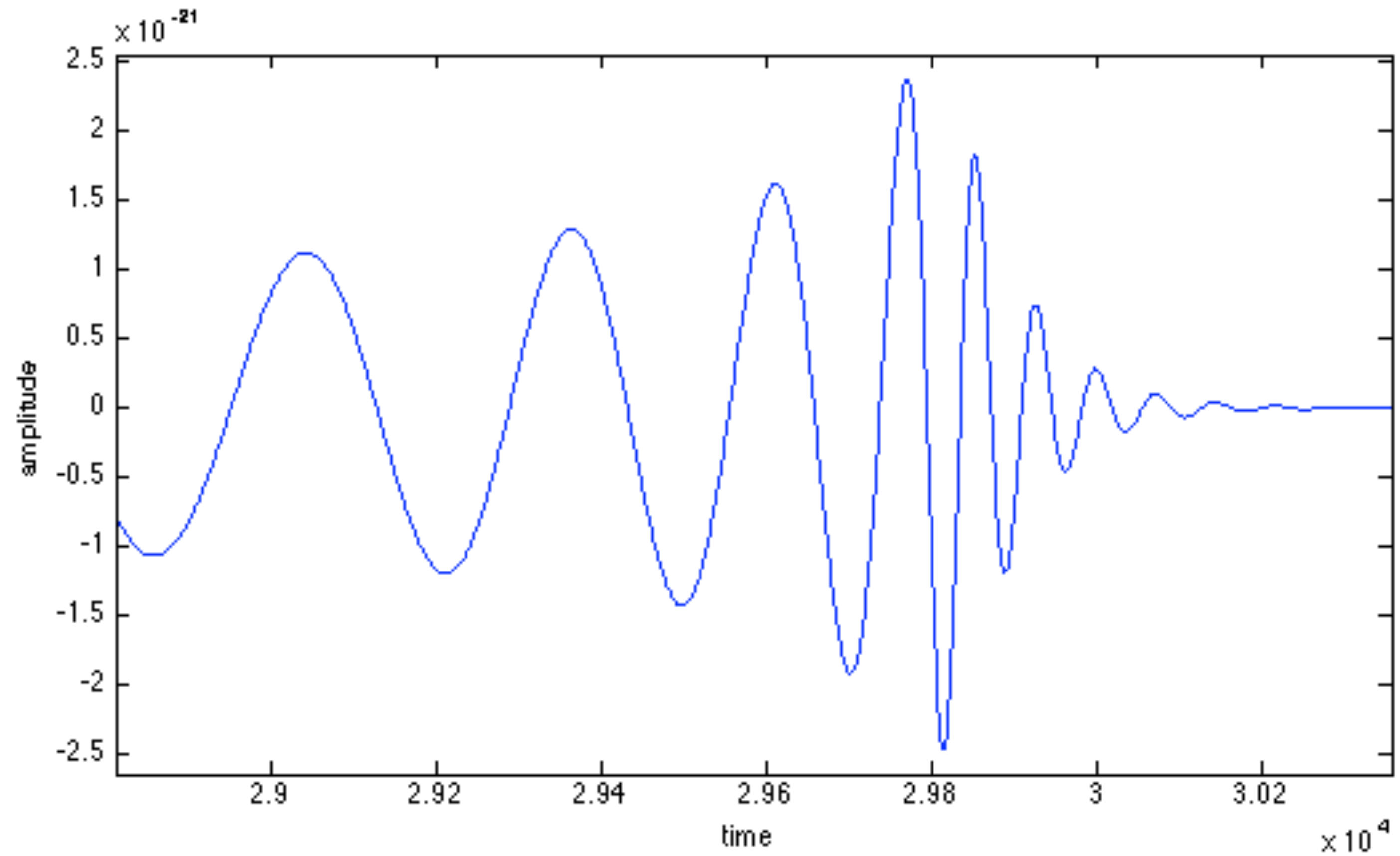
Most of the possible Advanced LIGO signal is in the ringdown

- Two very massive stars could form in star clusters with sufficient binary fractions through runaway collisions [Gurkan et al., 2006]; they could then form 2 IMBHs in the same cluster

- Depending on assumptions about cluster mass functions and binary fractions, rates of order 1/year are possible for Advanced LIGO

- IMBH binaries could also form when globular clusters merge: P. Amaro-Seoane and M. Freitag, ApJL 653, L53 (2006), arXiv:astro-ph/0610478.

Gravitational waves from high-mass systems



INSPIRAL: post-Newtonian approximate waveforms

MERGER: need Numerical Relativity!

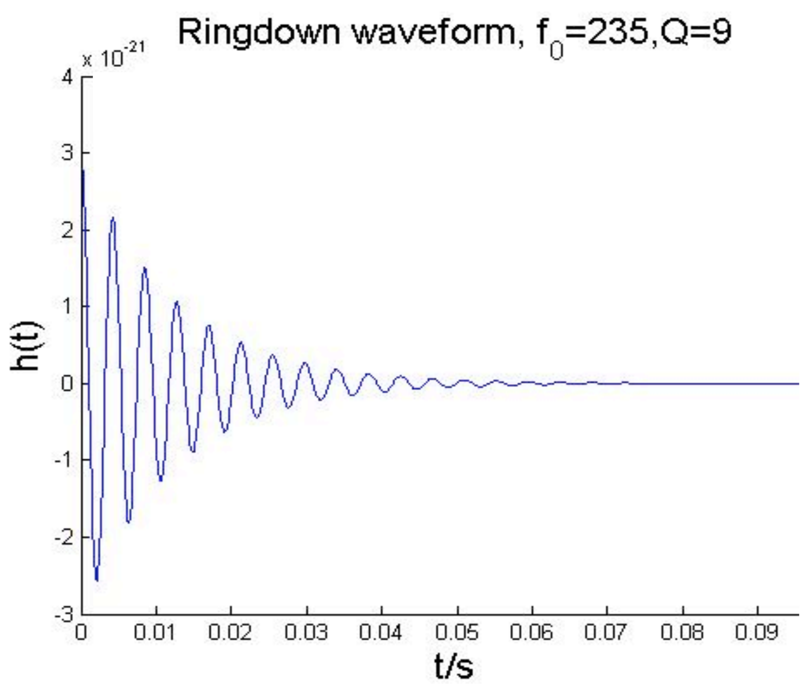
RINGDOWN: perturbative solutions

- Typical frequency scales as 1/Mass
- For massive systems, merger and ringdown contribute significantly to signal-to-noise ratio (SNR); inspiral alone can be below detector's frequency band
- Post-Newtonian, inspiral-only waveforms are inadequate

Searching for GWs from high-mass systems

- Can use perturbative ringdown waveforms; they are well-understood (quasi-normal mode ringing), but include the ringdown only
- Can fit extensions of post-Newtonian waveforms to numerical-relativity results.
  - At least two such extensions exist:
    1. Phenomenological IMR waveforms [Ajith et al.; PRD 77 (2008) 104017; arXiv:0710.2335]
    2. Effective one-body numerical relativity (EOBNR) waveforms [Buonanno et al.; PRD 76 (2007) 104049; arXiv:0706.3732]
  - These describe the complete coalescence, but are only tested against numerical relativity at comparable mass ratios and do not include spin
- Can use unmodeled searches for coherent excess power (gravitational-wave bursts); these could capture sources that are not covered by the existing template families, but require higher thresholds for a given false alarm rate (may be harder to distinguish from glitches)

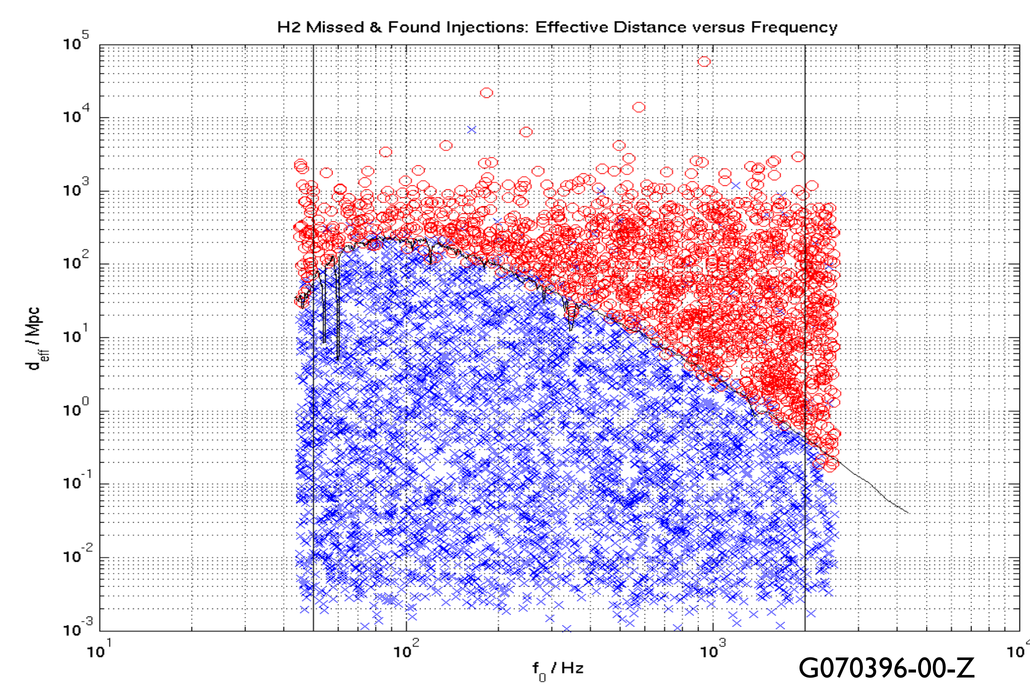
Ringdown searches



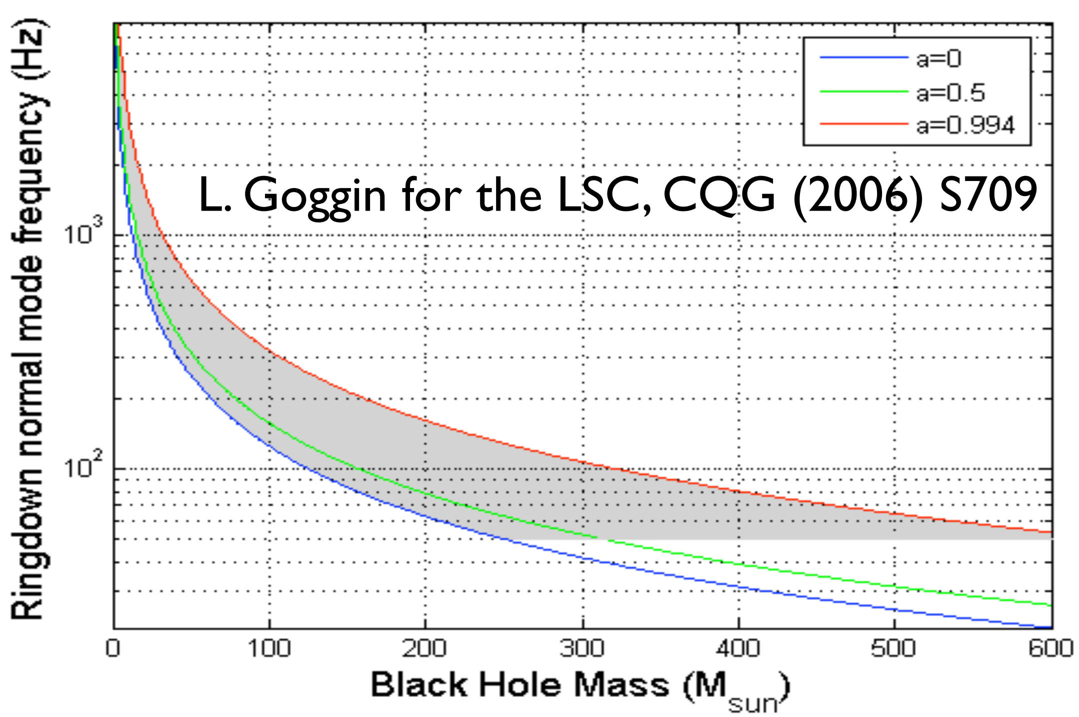
Matched-filtering search:

$$\mathrm{SNR}^2 = 4\Re \int_{\mathrm{flow}}^{\mathrm{fISCO}} \frac{\tilde{h}(f)\tilde{g}^*(f)}{S_n(f)} df$$

Use time-slides to measure background; use injections to measure detection efficiency; set detection thresholds based on desired False Alarm Probability (FAP)



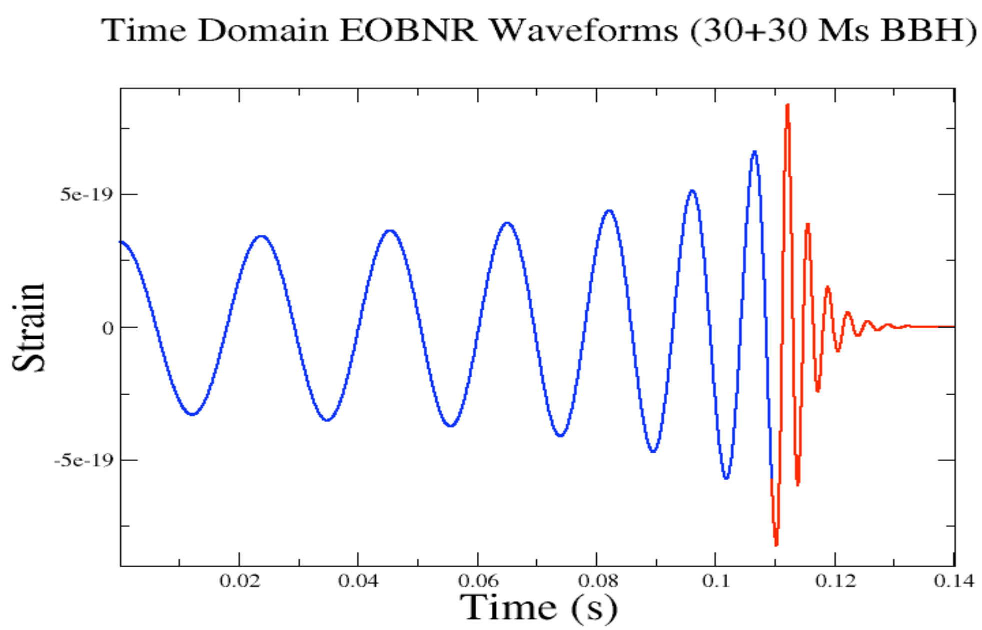
Frequency and quality factor of dominant l=m=2 mode depend on remnant mass and spin

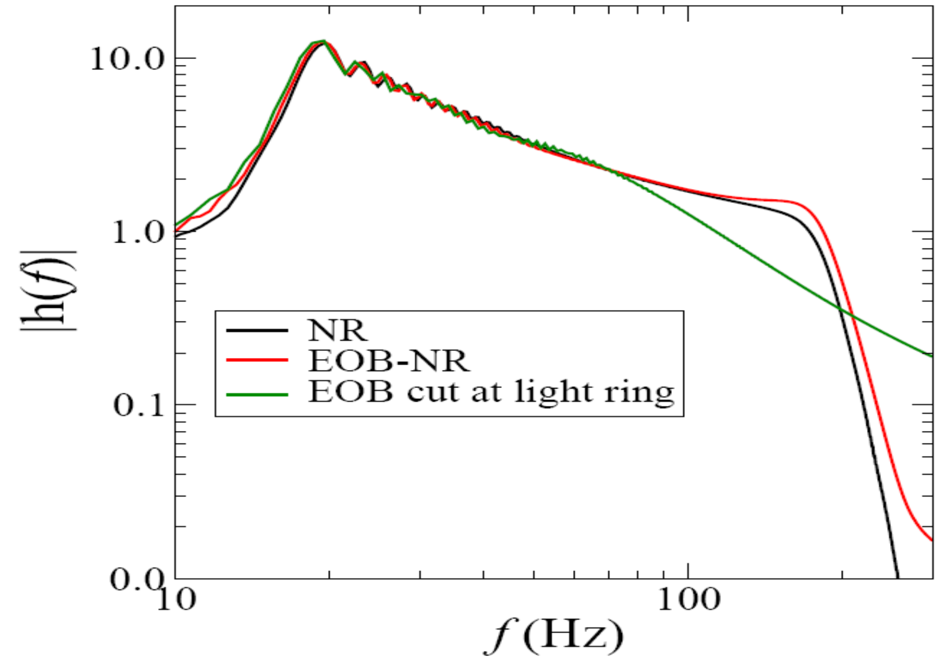


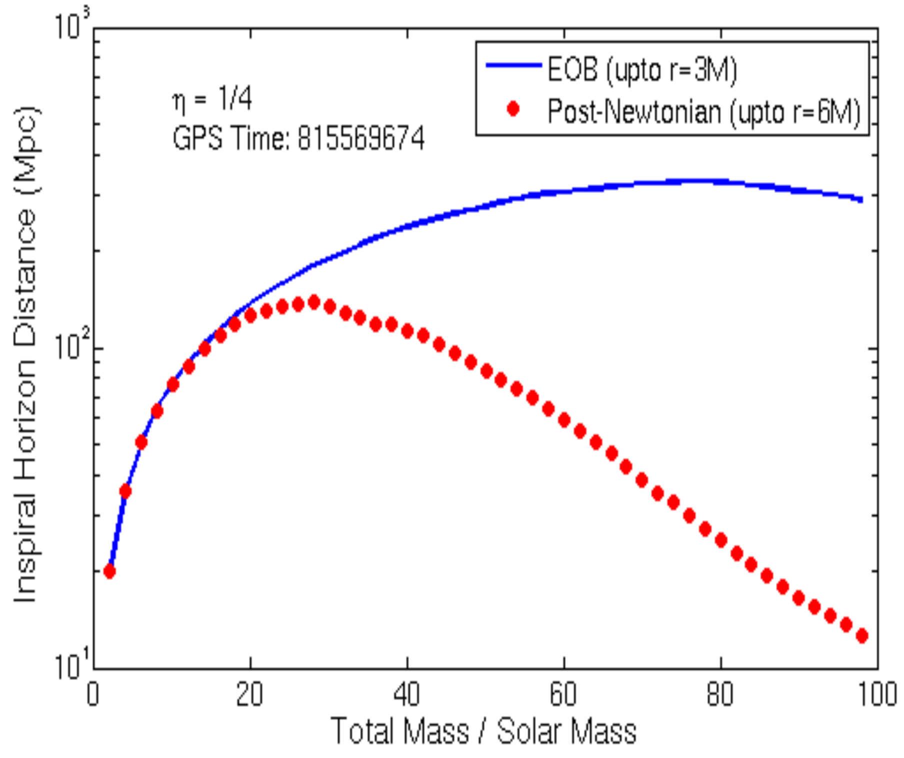
L. Goggin for the LSC, CQG (2006) S709

Ringdown search for data from the fourth LIGO science run (S4; 2005) is complete and undergoing review; search for data from S5 (2005-2007) is ongoing

EOBNR searches





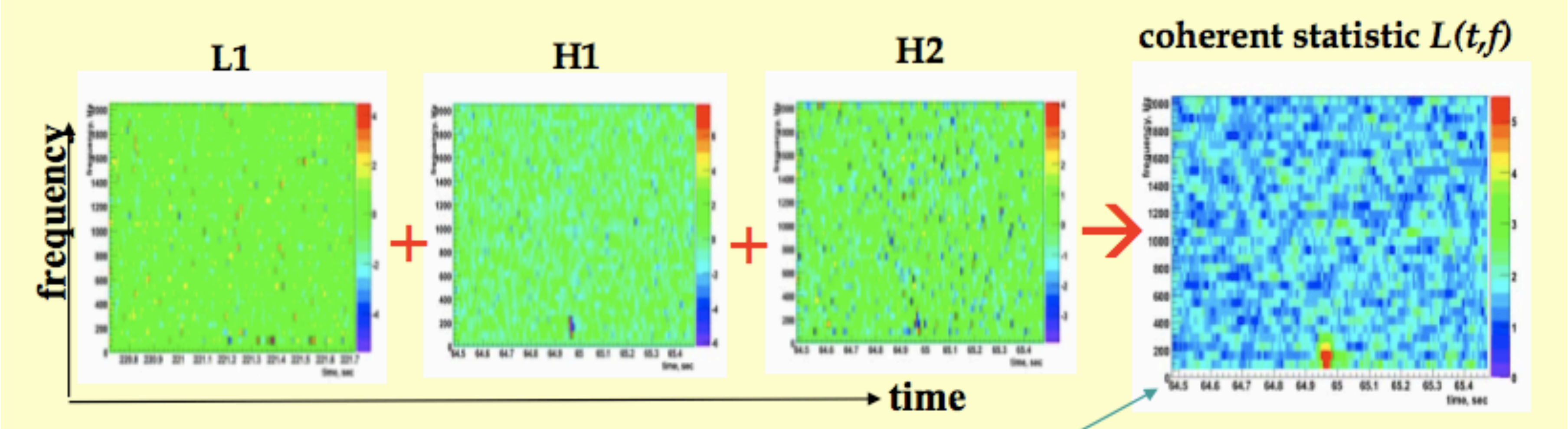


A search based on waveform templates that include the inspiral, merger, and ringdown waveforms; the templates are tuned to non-spinning numerical-relativity simulations with mass ratios up to 4:1

Total mass: 25-100 Msun
Individual masses: 1-99 Msun

Burst searches

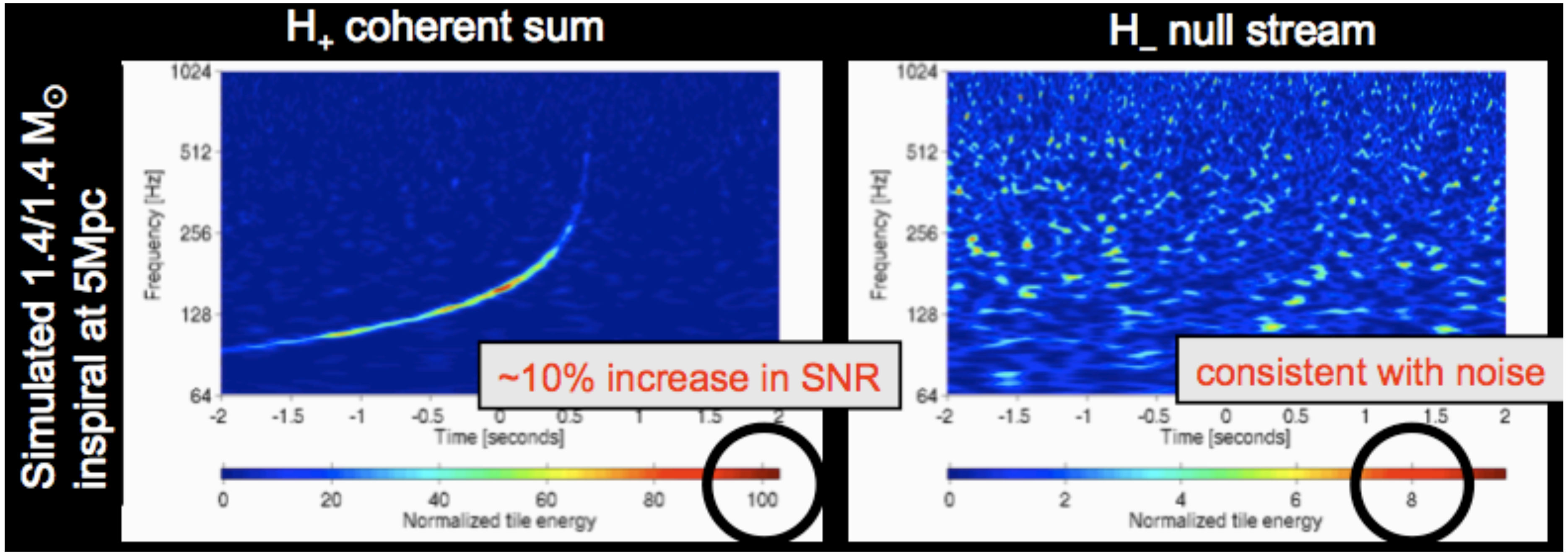
- Coherent WaveBurst: An algorithm which is used for unmodeled searches in a wide parameter space that could detect all parts of the coalescence event



$$L(t,f) = \max_{h_+ h_\times \theta\varphi} \sum_k \frac{1}{2\sigma_k^2(f)} \left[x_k^2[t,f] - (x_k[t,f] - \xi_k[t,f])^2 \right]$$

$$\xi_k = h_+ F_{+k} + h_x F_{xk}$$

- Omega pipeline: Multi-resolution time-frequency search, equivalent to a template-based search for sinusoidal Gaussians in whitened data



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G070801-00

Conclusion

- LIGO/Virgo can realistically detect GWs from coalescences involving intermediate-mass black holes
- A variety of search techniques are already being employed to search for signals from massive sources
- Enhanced LIGO will start collecting data in a few months
- Stay tuned!