Compact Binaries as Sources for Ground-Based Gravitational-Wave Detectors

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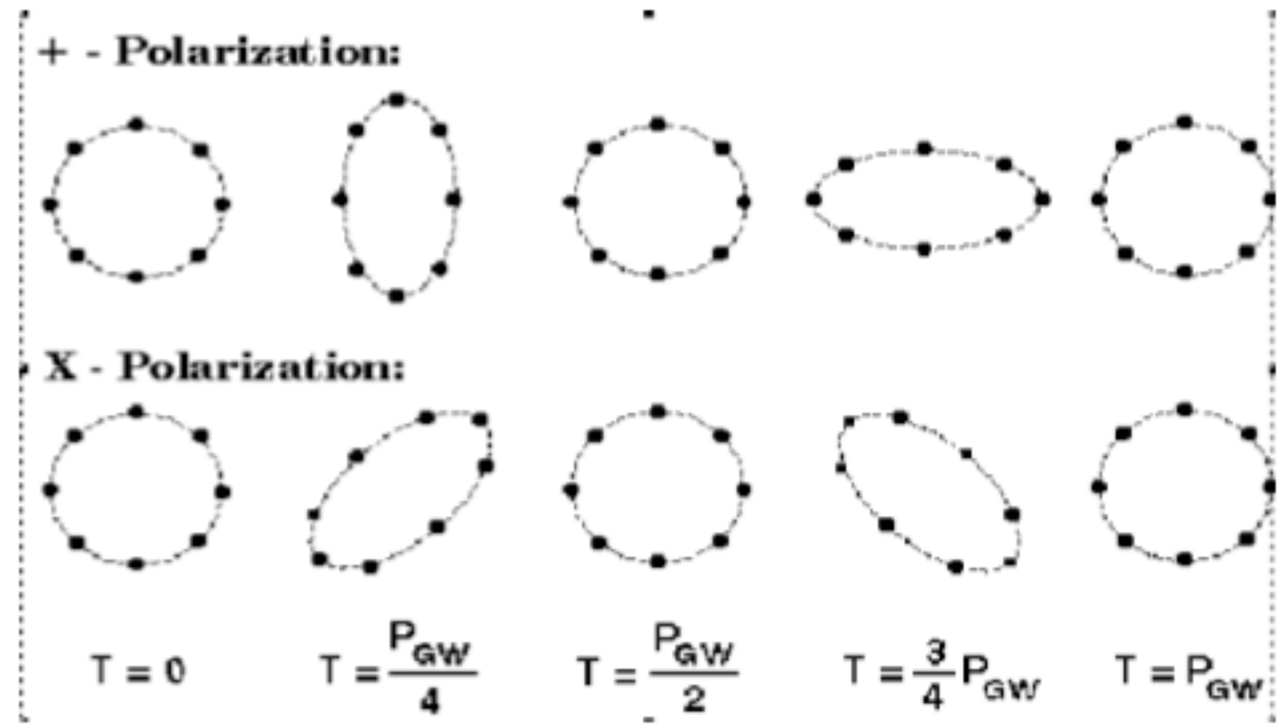
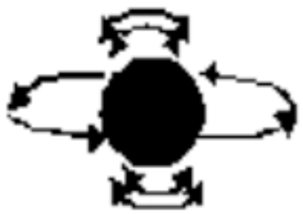
Gravitational Waves

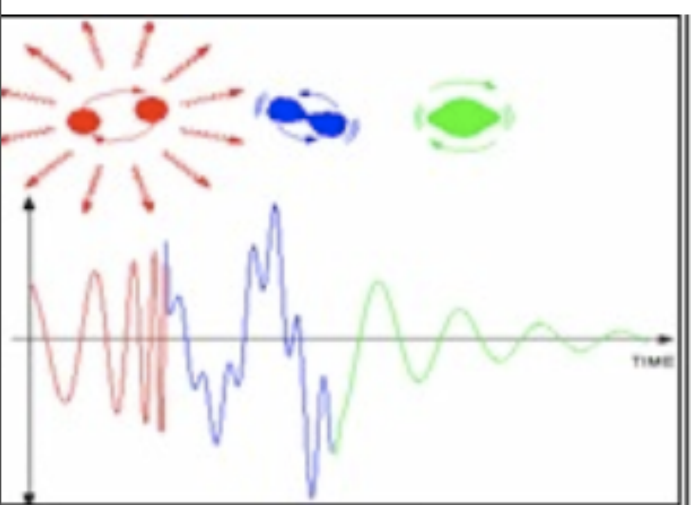
- Ripples in spacetime:

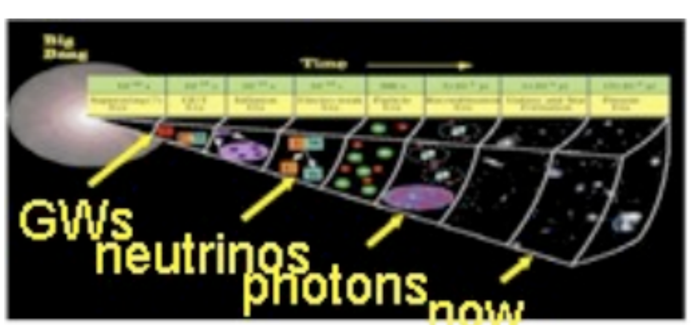


- Caused by time-varying mass quadrupole moment
- Indirectly detected by Hulse & Taylor [binary pulsar]
- Huge amounts of energy released: 5% of mass-energy of a supermassive black hole binary is more than the electromagnetic radiation emitted from an entire galaxy over the age of the universe!

Types of GW sources







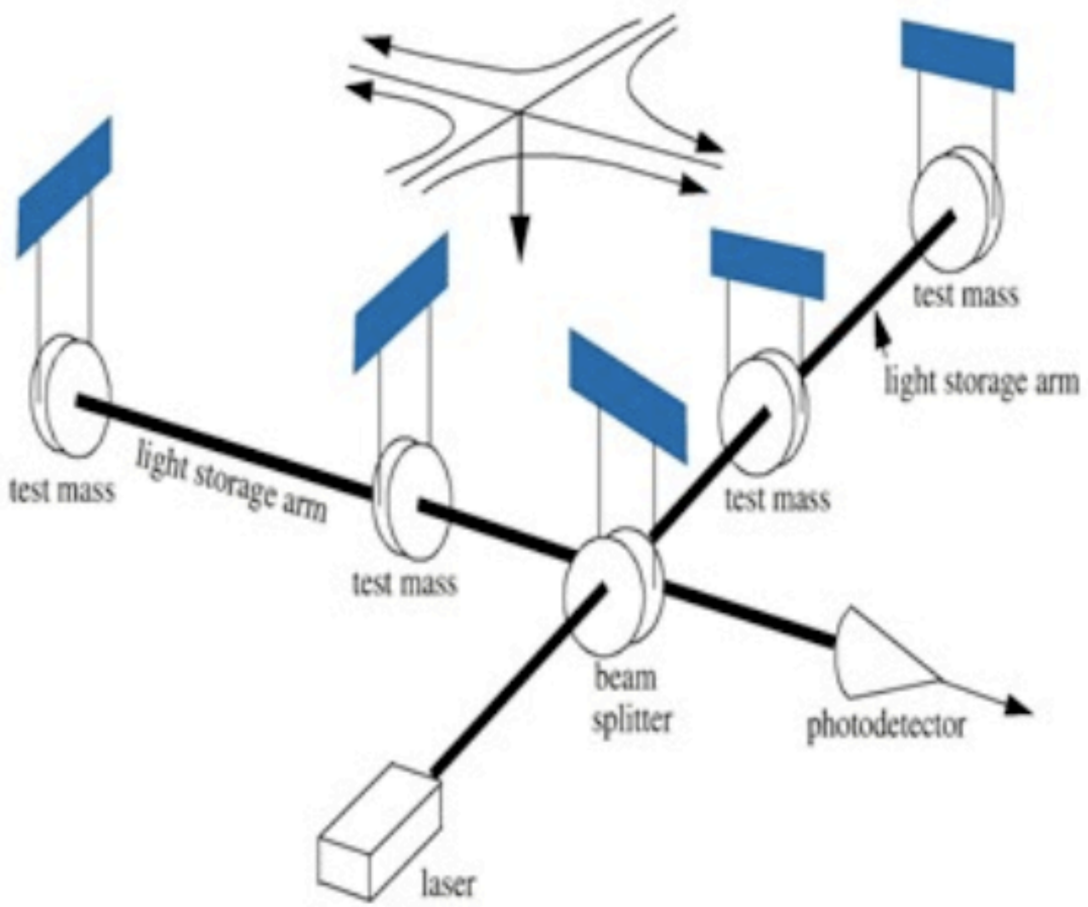
- Continuous sources [sources with a slowly evolving frequency]: e.g., non-axisymmetric neutron stars, slowly evolving binaries
- Coalescence sources: compact object binaries
- Burst events [unmodeled waveforms]: e.g., asymmetric SN collapse, cosmic string cusps
- Stochastic GW background [early universe]
- ??? [expect the unexpected]

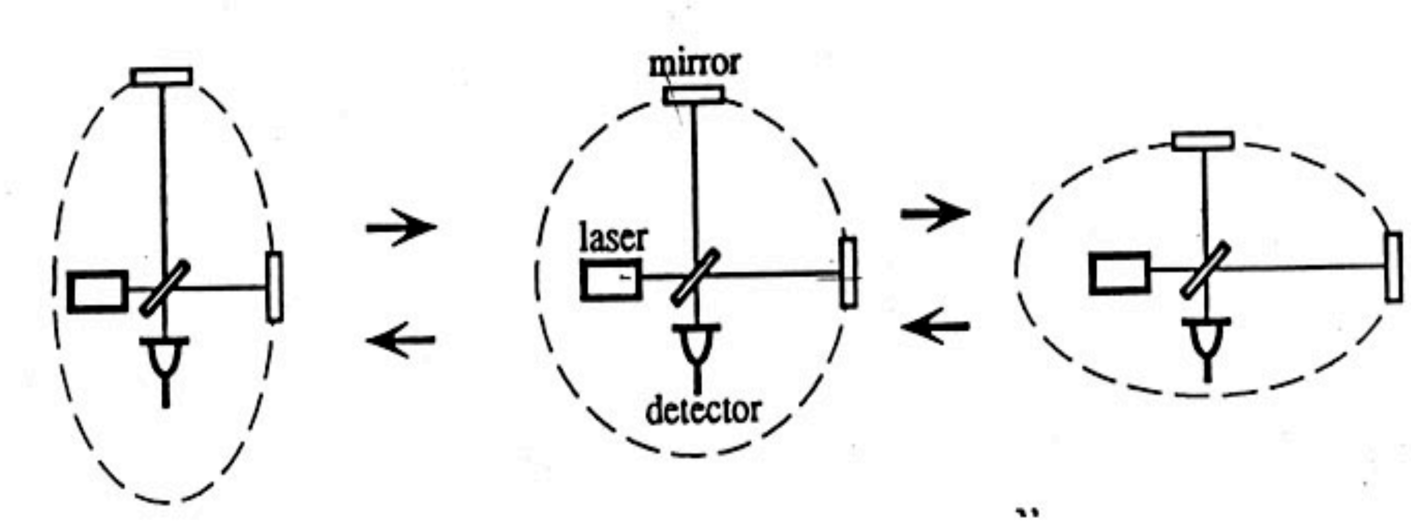
Why do we want to see GWs?

- Probing stellar dynamics and evolution via stellar-mass compact-object binary measurements (NS-NS, NS-BH, BH-BH)
- Studying galactic structure formation by measuring mass and spin distributions of massive black holes (MBHs); measuring high-redshift mergers of MBH progenitors; understanding galactic mergers (e.g., kicks)
- Direct probes of early-universe cosmology by measuring GWs emitted soon after the Big Bang
- Mapping cosmology with GW events as standard candles (especially with electromagnetic counterparts to binary mergers)
- Studying structure of neutron stars and white dwarfs
- Studying compact objects falling into massive black holes in galactic nuclei

Opportunity and Challenge

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



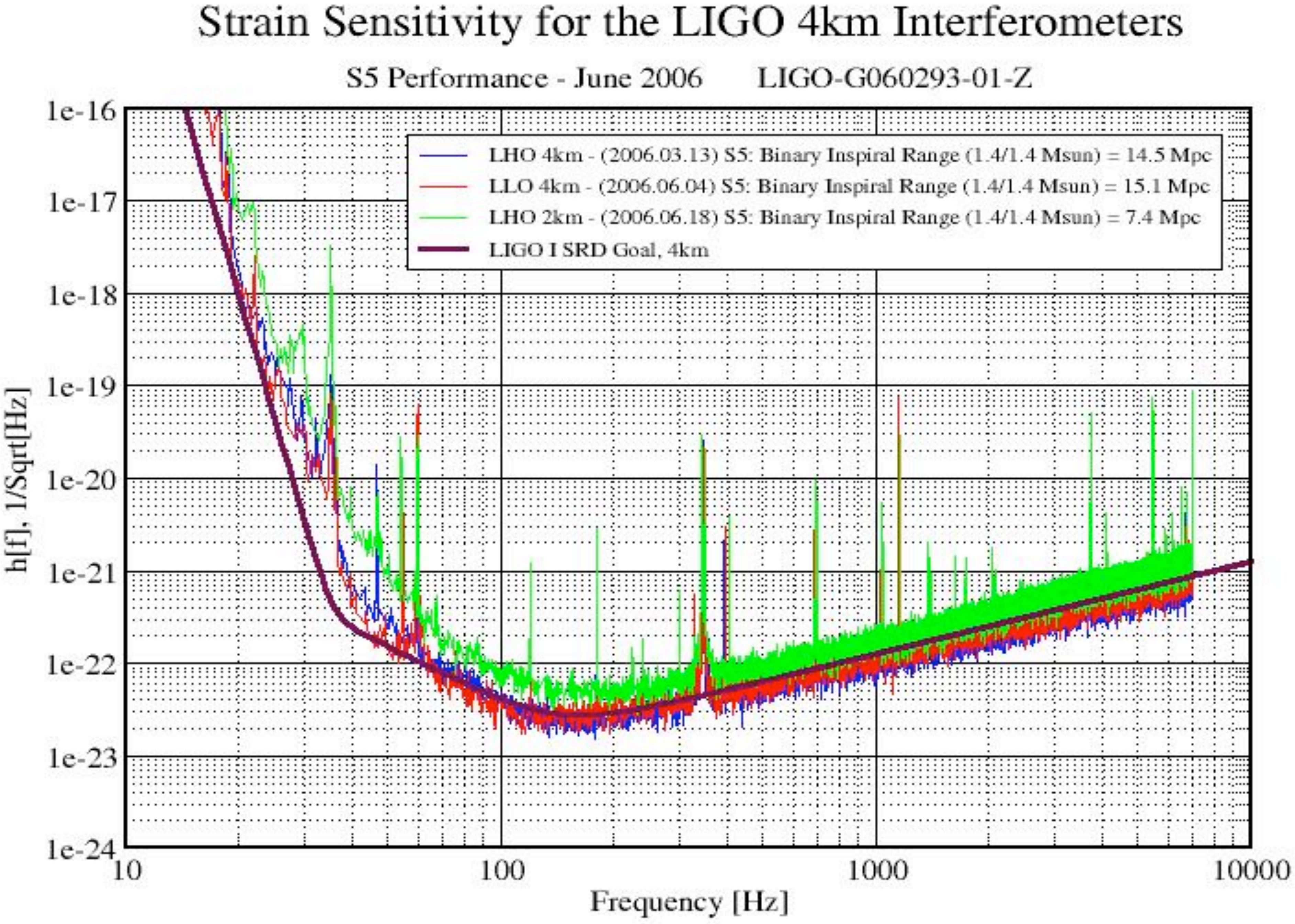


Michelson-type interferometers

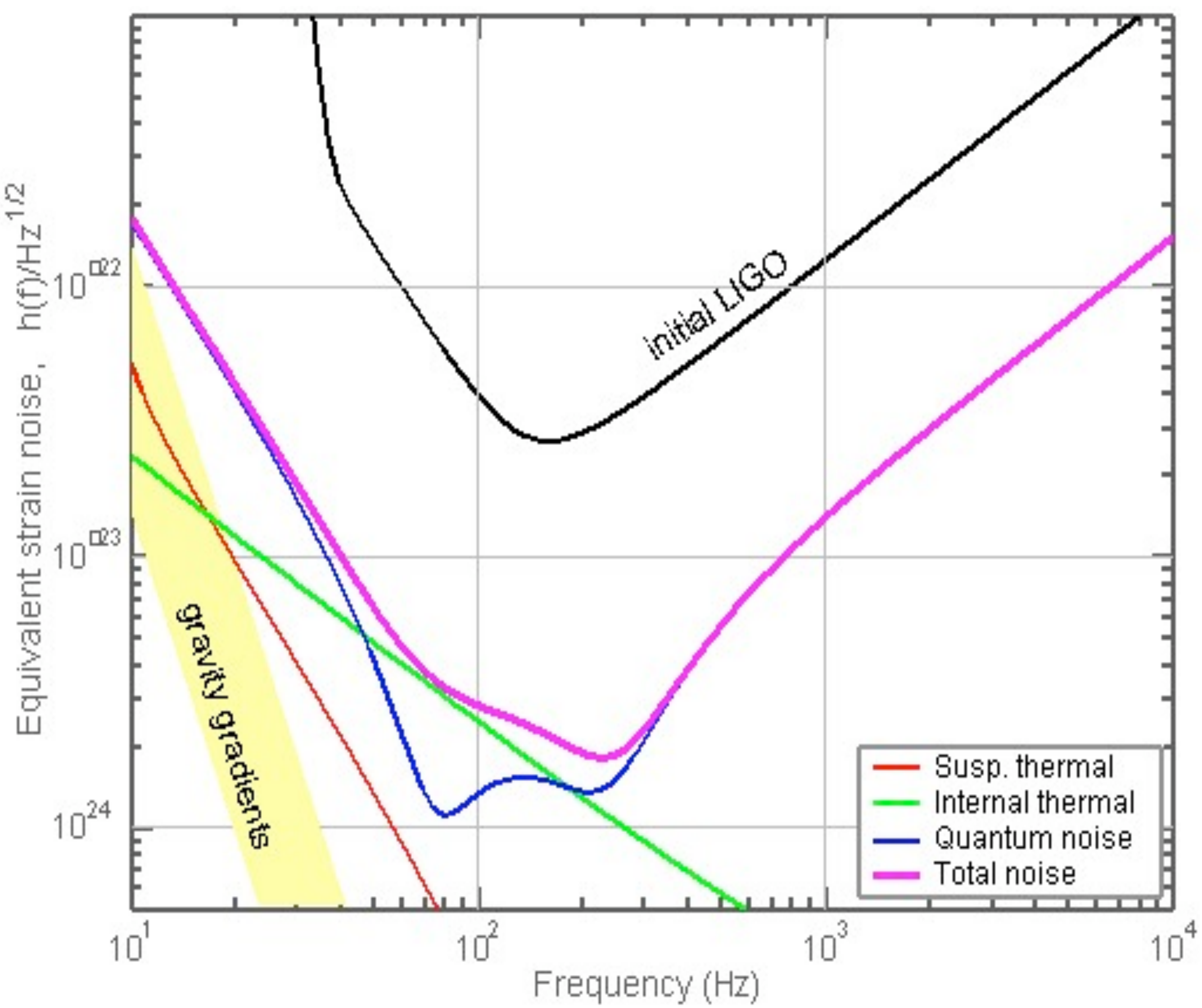
LIGO (Laser Interferometer GW Observatory)

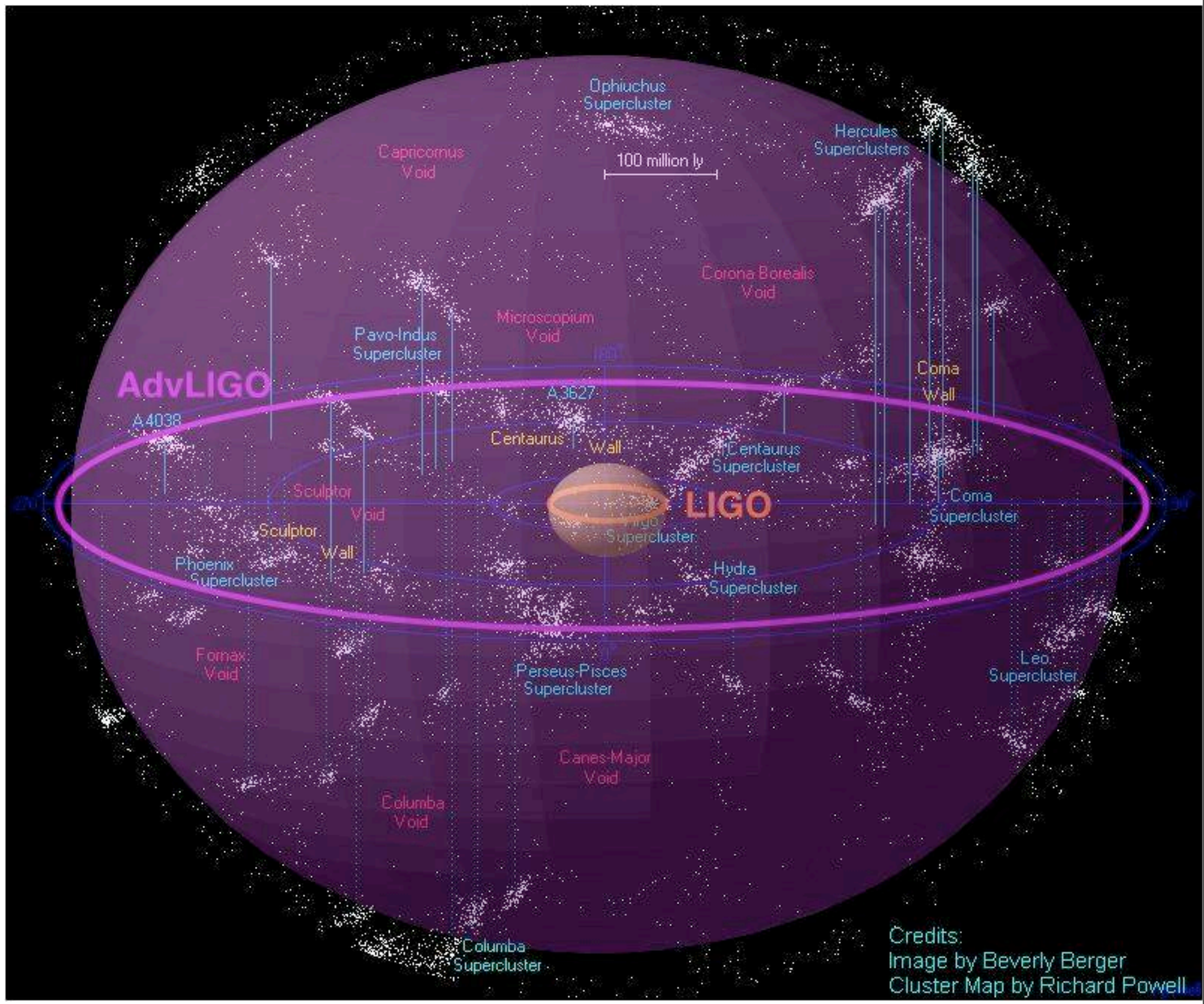
- 4 km long arms
- Typical strains $h = \Delta L / L \sim 10^{-22}$ (NS-NS in Virgo)
- Needs to measure $\Delta L = hL \sim 10^{-17}$ m
- 2 LIGO detectors in US + Virgo, GEO

LIGO Noise Curve



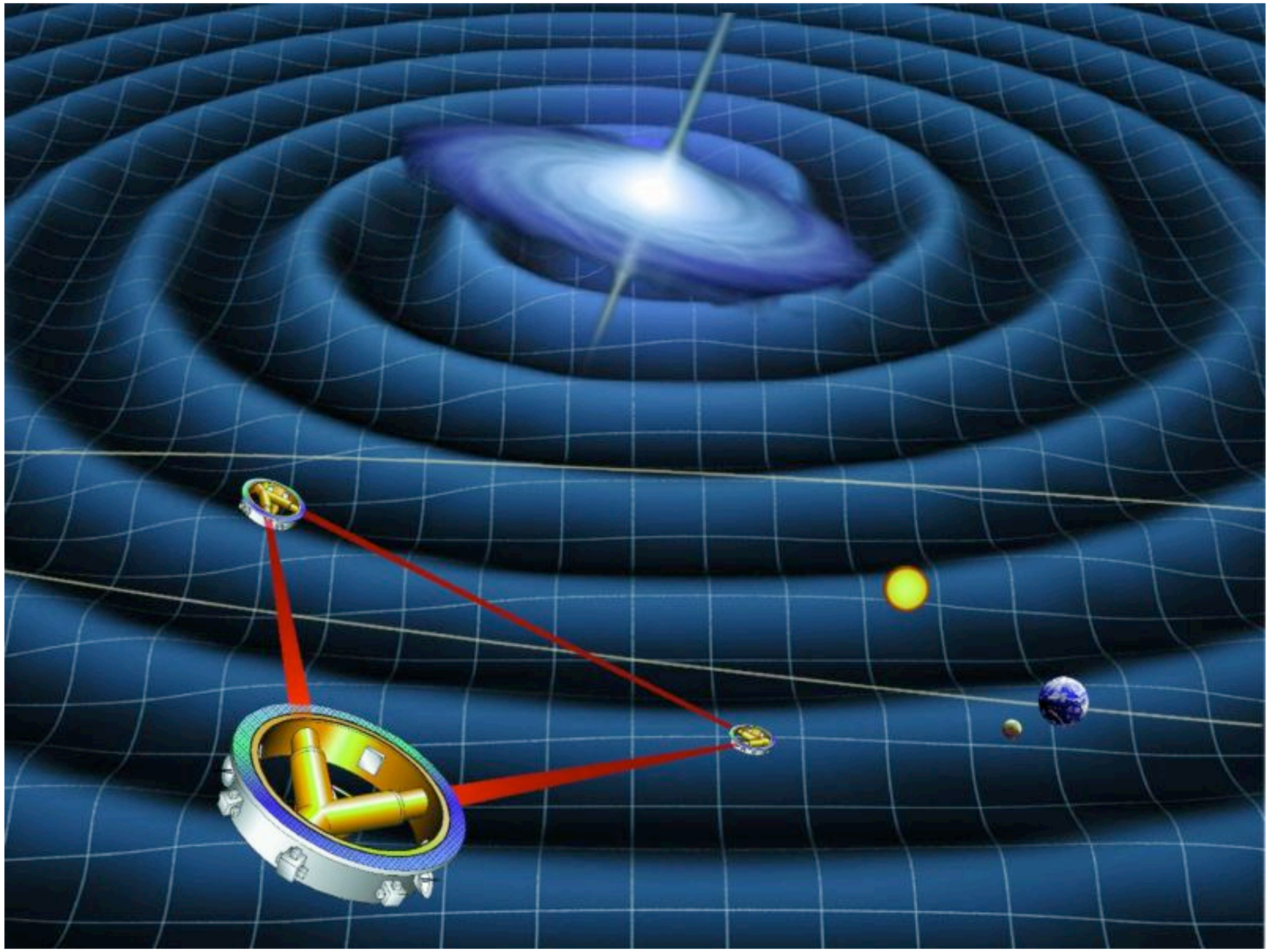
Advanced LIGO





- x10 in range -> x1000 in event rate
- 10 Hz low frequency cutoff

LISA (Laser Interferometer Space Antenna)



- 3 spacecraft following Earth around sun, 5 million km apart

LIGO and LISA binary sources

- LIGO sensitive @ a few hundred Hz

  NS-NS, NS-BH, BH-BH binaries

- LISA sensitive @ a few mHz

  supermassive black-hole binaries

  galactic white dwarf binaries

  extreme-mass-ratio inspirals
  of WDs/NSs/BHs into SMBHs

Other detectors (3-g)

- 3rd-generation ground-based: Einstein Telescope, DECIGO
- space-based: Big Bang Observer, ALIA
- Pulsar Timing Arrays

Rates predictions

All astrophysical rates estimates depend on limited observations and/or models with many ill-constrained parameters, and are still significantly uncertain at present

LIGO Rates: NS-NS binaries

- Best NS-NS merger-rate estimates come from observed Galactic binary pulsars
- Small-number statistics: only four systems should merge in a Hubble time under radiation reaction; are these representative?
- Selection effects unclear, particularly pulsar luminosity distribution
- Uncertainties in age of pulsar, beaming factor, etc.
- Kalogera et al., 2004

LIGO Rates: NS-BH, BH-BH binaries

- Predictions based on population-synthesis models
- *Thirty* poorly constrained parameters, including seven important ones (e.g., winds, birth kicks, etc.)
- Constraints from observations (binary pulsars, supernovae, etc.)
- Complicated simulations with StarTrack (Belczynski et al.) or similar codes, average over models that satisfy constraints
- O'Shaughnessy et al., 2005, 2008

Coalescence Rates per Galaxy

Source	$N_{\rm low}$	$N_{\rm re}$	$N_{\rm pl}$
NS-NS (L_{10}^{-1} Myr^{-1})	0.6	50	500
NS-BH (L_{10}^{-1} Myr^{-1})	0.03	2	60
BH-BH (L_{10}^{-1} Myr^{-1})	0.02	0.4	60

In simplest models, coalescence rates are proportional to stellar-birth rates in nearby spiral galaxies, so we quote rates in units of L_{10} (blue-light luminosity of 10^{10} Suns)

LIGO Rates: Other Compact-Binary Sources

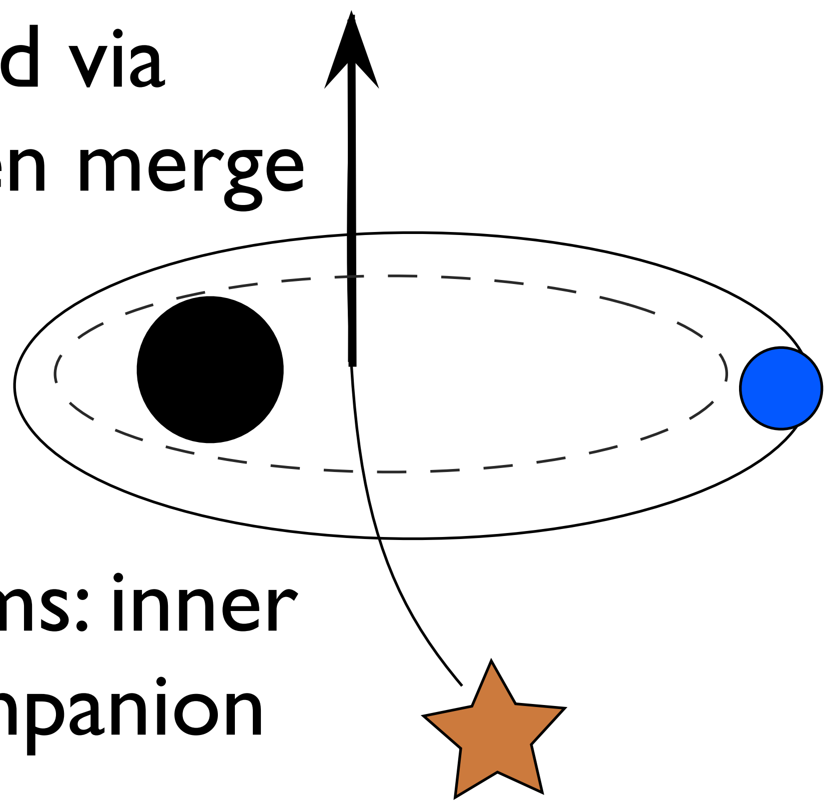
- Intermediate-mass-ratio inspirals into IMBHs: a few per year with Advanced LIGO? (Mandel et al., 2008)
- IMBH-IMBH mergers in globular clusters: 0.1 to 1 per year with Advanced LIGO? (Fregeau et al., 2006)

Intermediate-mass-ratio inspirals (IMRIs)

- IMRIs have mass ratios between 10 and 10^4
- LIGO IMRIs: 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)
- Indirect evidence for IMBH existence in globular clusters (50 – 10^4 solar masses)
  - Observational evidence (e.g. Macarone et al.)
  - Simulations (e.g. McMillan et al., O'Leary et al.)
  - Simulations vs. Observations (e.g. Trenti)
- GWs from IMRIs could provide the first proof of IMBH existence!

Event Rates: Mechanisms

- 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



- Direct capture via energy loss to GWs
- Kozai resonances in hierarchical triple systems: inner binary eccentricity is driven up by outer companion
- Tidal capture of MS star that evolves into CO while in orbit
- Tidal interactions (orbital-vibrational coupling) for NS inspirals

Event Rates: Mechanisms

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IMRI Event rates per G.C.

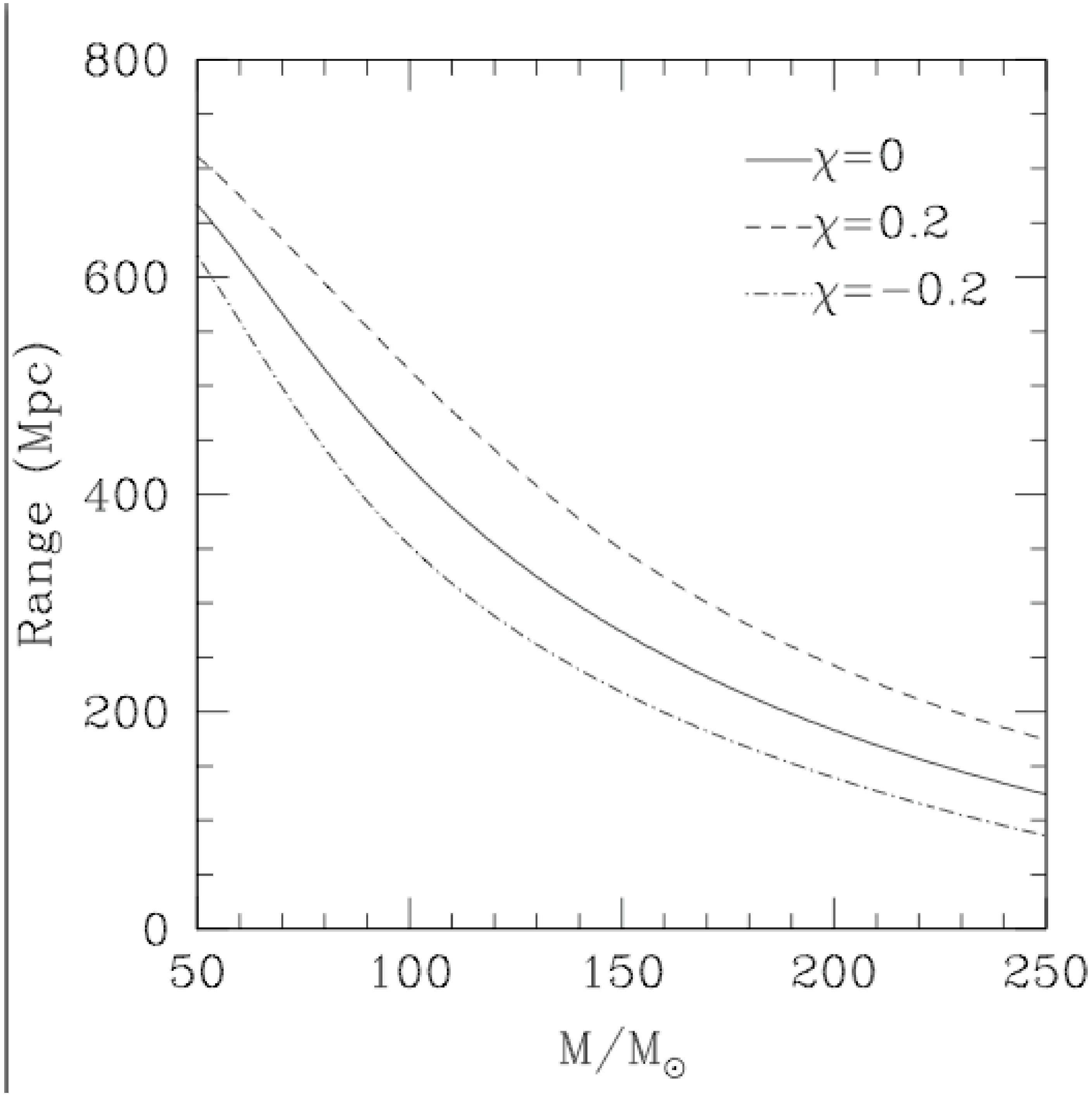
- Binary tightening via 3-body interaction
- 3-body interaction rate is $dN/dt=n\sigma v$;

  $n \sim 10^{5.5}$ pc^{-3}; $v \sim 10$ km/s; $\sigma \sim \pi a(2GM/v^2)$
- $T_{harden} \sim O(M/m)\ (dN/dt)^{-1} \sim 1.5 \times 10^{8}\ (AU/a)$ yr [Quinlan]
- $T_{merge} \sim 5 \times 10^{17}\ M_\odot^3/(M^2 m)\ (a/AU)^4\ (1-e^2)^{7/2}$ yr

  $\sim 5 \times 10^{8}\ (M_\odot/m)\ (100M_\odot/M)^2\ (a/AU)^4$ yr [Peters & Mathews]
- To maximize rate, minimize $T=T_{harden}+T_{merge}$
- Rate per globular is $\sim 3 \times 10^{-9}$ yr^{-1} for NS,

  5×10^{-9} yr^{-1} for BH

Advanced LIGO IMRI sensitivity



- Use EMRI-like waveforms, including non-quadrupolar harmonics, to determine range

- Range is spin-dependent

$$R \approx \left[1 + (\chi^2/2)\left(\frac{M}{100\,M_\odot}\right)^{1.5}\right]\sqrt{\frac{m}{M_\odot}}\left[800 - 540\left(\frac{M}{100\,M_\odot}\right) + 107\left(\frac{M}{100\,M_\odot}\right)^2\right].$$

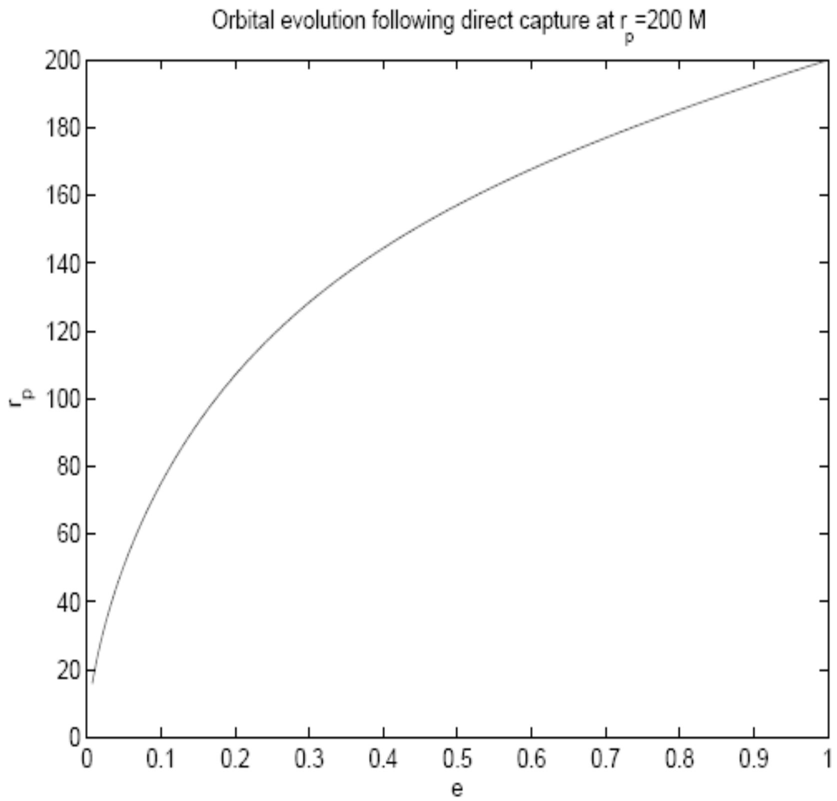
IM, arXiv:0707.0711

- Range could be increased by x1.5 by tuning Advanced LIGO

Advanced LIGO IMRI rates

- Assume 10% of all globular clusters hold suitable IMBH (typical 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
- If Advanced LIGO is IMRI-optimized, rates could go up to 1/year and 30/year

Eccentricities in AdvLIGO band



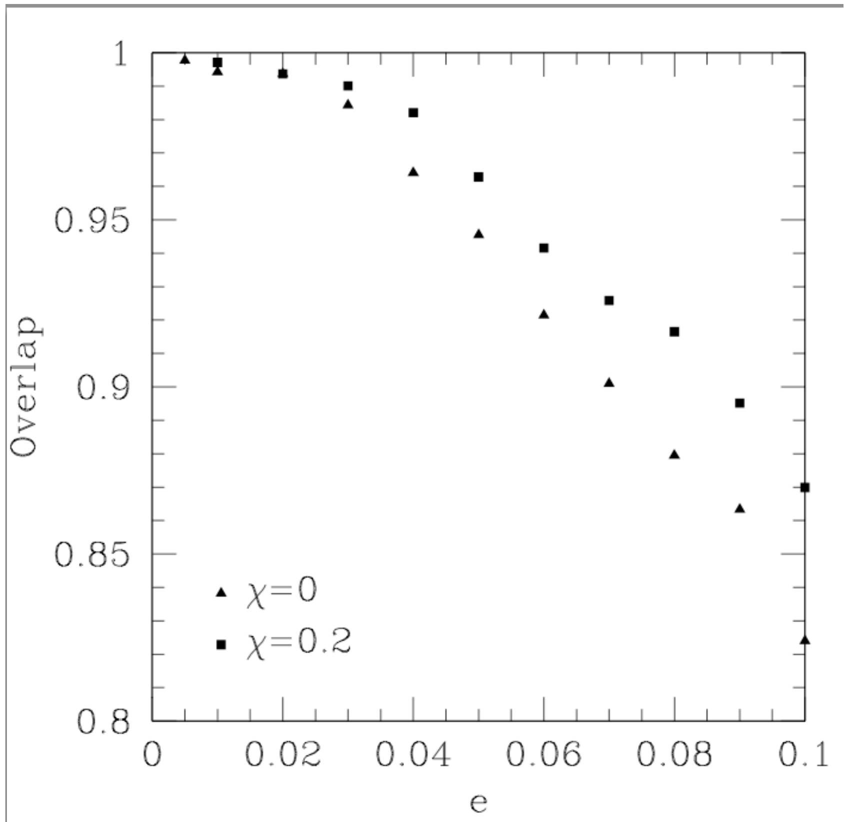
- Hardening via 3-body interactions

  Eccentricity ~ few*10^{-5} when f_{GW}=10 Hz

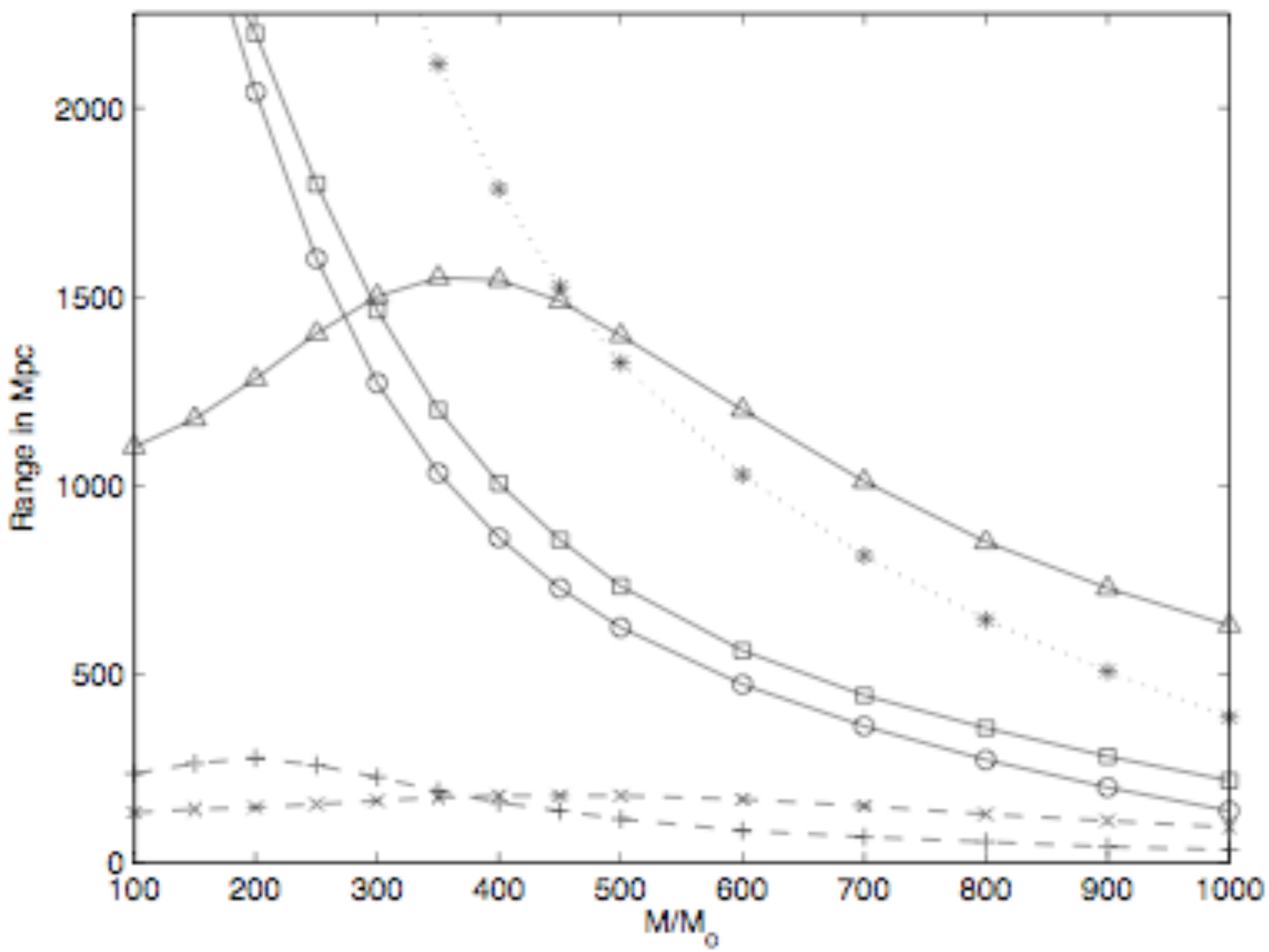
- Direct capture

  90% of IMRIs circularize to e<0.1 by 10 Hz, 67% circularize to e<0.01 by f_{GW}=10 Hz

- At e=0.01, overlap between eccentric and circular templates is >0.99, so circular templates can be used for detection



Ringdowns



Could complement IMRIs
if higher CO and IMBH masses are prevalent