Low-Frequency Gravitational Wave Astronomy with LISA

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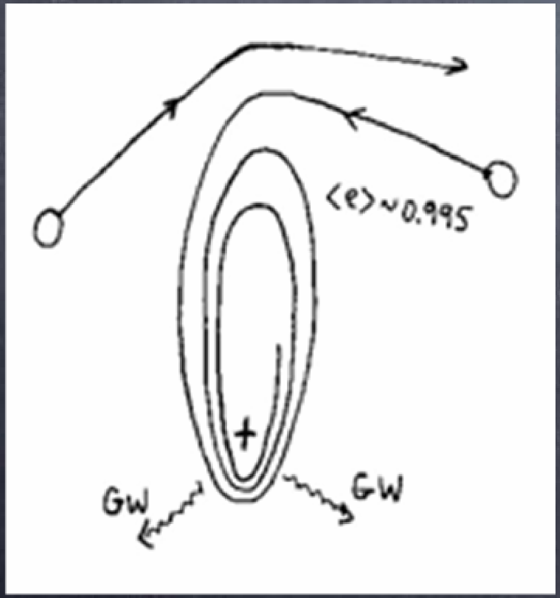
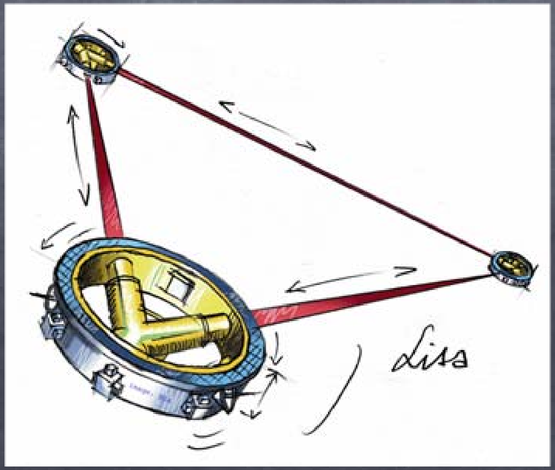
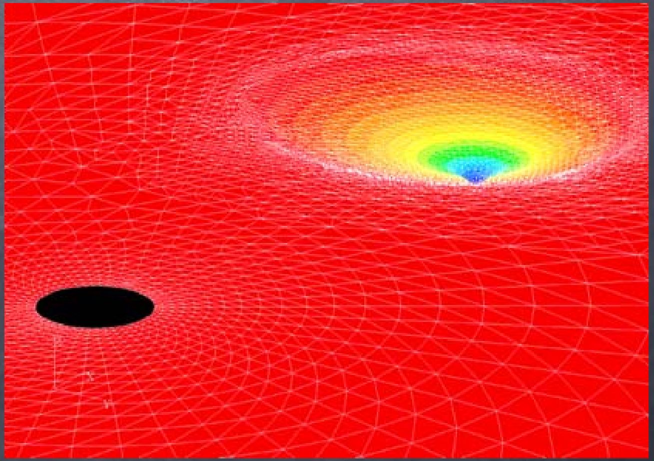




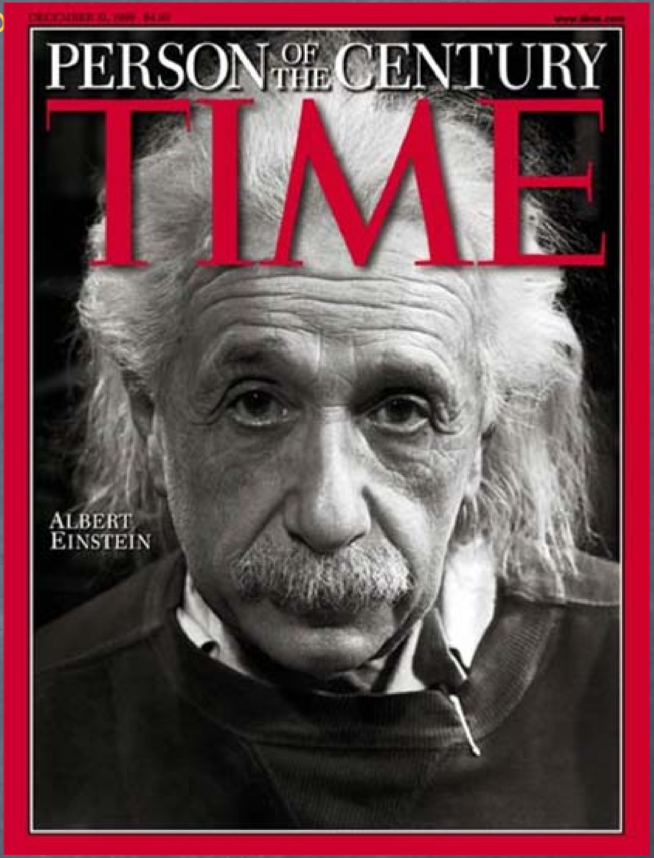


Outline

- Basics of Gravitational Wave Astronomy.
- Sources of Gravitational Waves for LISA and their impact on Astrophysics, Cosmology, and Fundamental Physics.
    - Binary Black Hole Mergers
    - Capture of stellar compact objects by MBHs
- Final Remarks.

Basics of Gravitational Wave Astronomy

- What are Gravitational Waves?
  - They are ripples of spacetime, produced by moving masses, that propage at the speed of light far away from the sources.
  - Proper distance between test masses change as: $\Delta L \sim$ (GW strain)xL = hL.
  - They are transverse waves and have two independent polarization states:



QuickTime™ and a
GIF decompressor
are needed to see this picture.

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GIF decompressor
are needed to see this picture.

They are the only prediction of Einstein that awaits for <u>direct</u> confirmation.

Basics of Gravitational Wave Astronomy

- What are Gravitational Waves?
  - We will detect wave amplitudes (h~1/r), not energy fluxes (dE/dt ~ (dh/dt)x(dh/dt) ~ 1/r^2).
  - An enhancement in the detector sensitivity of a factor 2 increases the visible volume of the sky in a factor 8!
  - They are never significantly absorbed or scattered. Therefore, they carry almost uncorrupted information from the sources, but are hard to detect!   (Warning: GWs from cosmological sources at z>2 suffer significantly from weak lensing).
  - They are direct probes of spacetime curvature and strong gravity regimes.
  - They will provide observations of strong gravity regions not transparent to EM waves

Basics of Gravitational Wave Astronomy

* Comparison with EM Waves

EMWs are generated by accelerated charges

GWs are generated by accelerated masses

Dipole is the lowest order time-dependent distribution that can generate EMWs (charge conservation)

Quadrupole is the lowest order time-dependent distribution that can generate GWs (mass and linear momentum conservation)

EMWs arise from interactions of atoms, nuclei, etc. within the astrophysical source: $\lambda_{\rm EM} \ll L_{\rm source}$

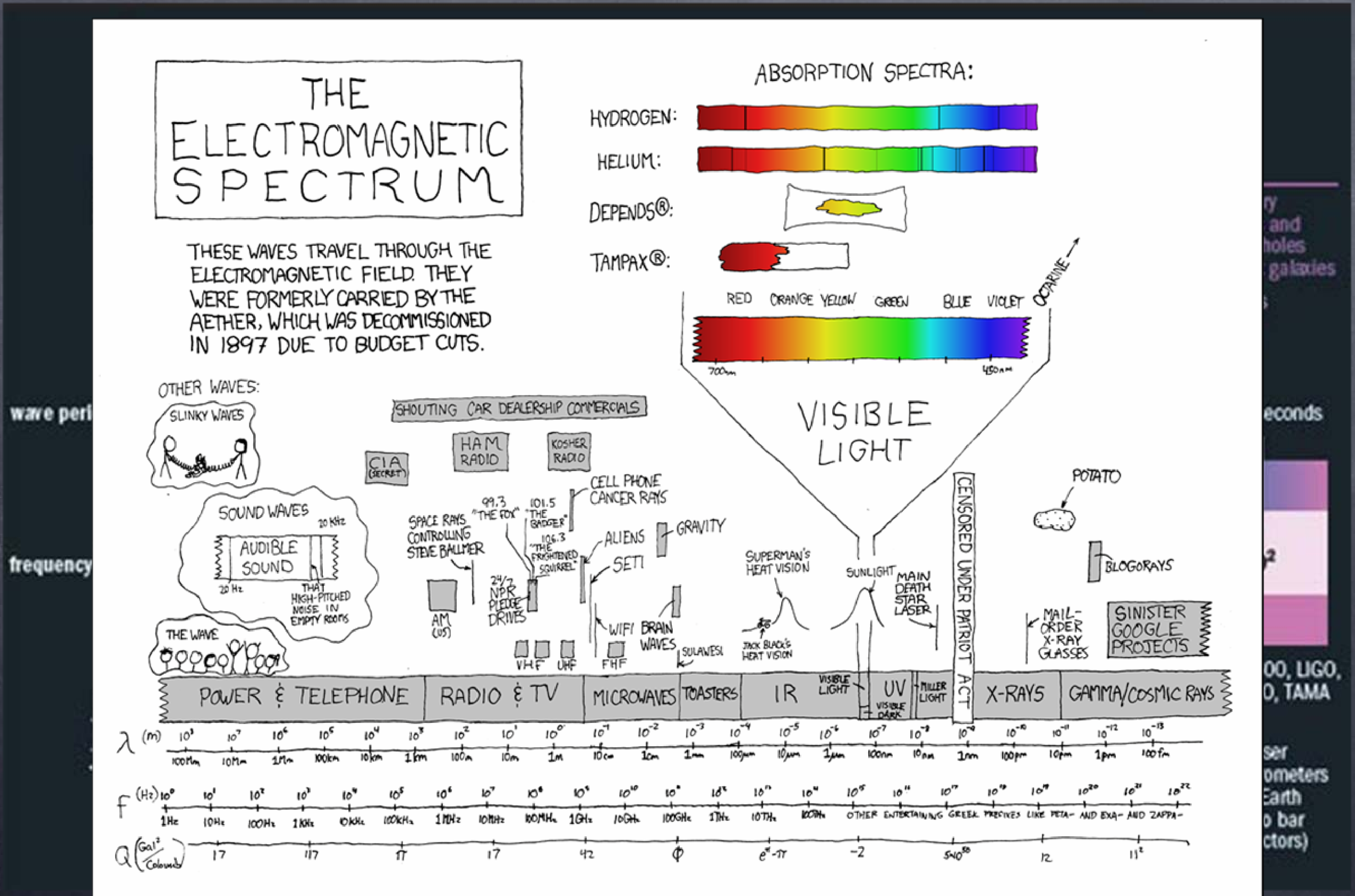
GWs are generated by the bulk mass distribution of the sources: $\lambda_{\rm GW} \sim L_{\rm source}$

EMWs are good for imaging the source

GWs are not good for imaging the source. Information is extracted by means of audio-like methods

Basics of Gravitational Wave Astronomy

- Comparison with EM Waves



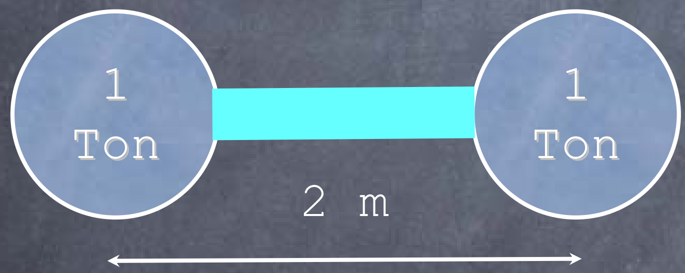
Basics of Gravitational Wave Astronomy

How strong are they?

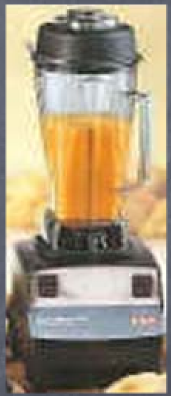
- Let us use the lowest-order approximation: Quadrupole approximation:

$$\frac{\Delta L}{L} = h \sim \frac{G\ddot{Q}}{c^4\, r}\,, \quad Q \sim M R^2 \;\Rightarrow\; \ddot{Q} \sim M v^2$$

- Can we generate them on Earth?



$$\begin{aligned} f &\sim 1kHz \\ h &\sim 10^{-37}\frac{1km}{r} \\ \Delta L_{\text{LIGO}} &\sim 10^{-33} m \frac{1km}{r} \\ \ell_{\text{Planck}} &\sim 10^{-35} m \end{aligned}$$



- For relativistic astrophysical sources:

$$M \sim 1\, M_\odot\,, \quad v \sim c\,, \quad r \sim 15Mpc \;\longrightarrow\; h \sim 10^{-21}$$

$$\Delta L = h\, L_{\text{LIGO}} \;\sim\; 10^{-15} - 10^{-16}\, cm$$

$$R_{\text{atomic nuclei}} \;\sim\; 10^{-16} cm$$

Basics of Gravitational Wave Astronomy

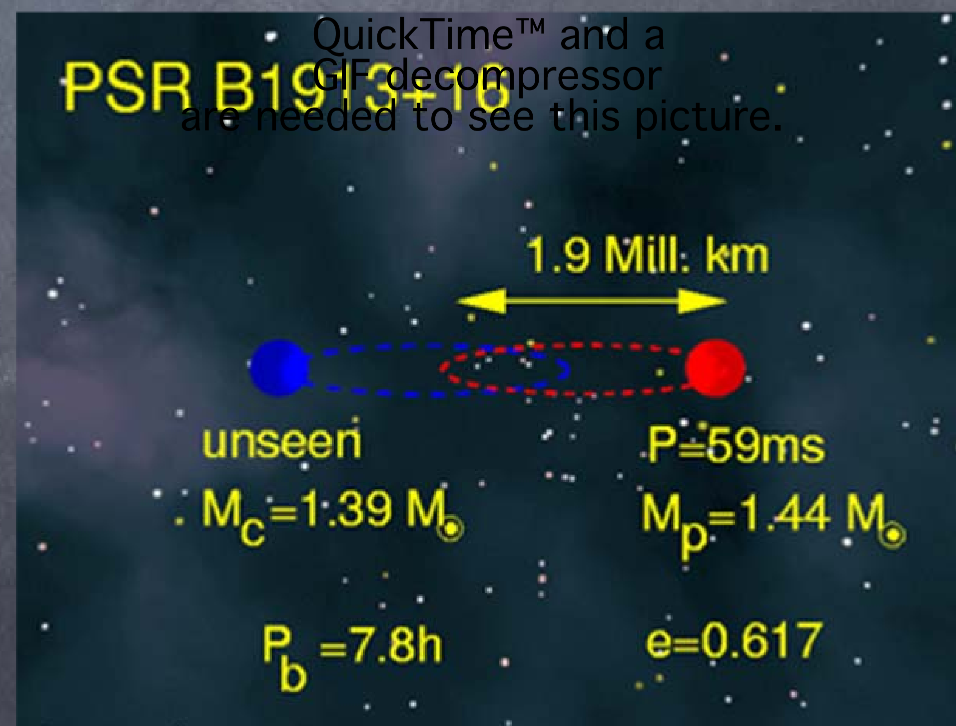
- Are we sure they exist?

1993 Nobel Prize in Physics

Russell A. Hulse

Joseph H. Taylor

... for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.



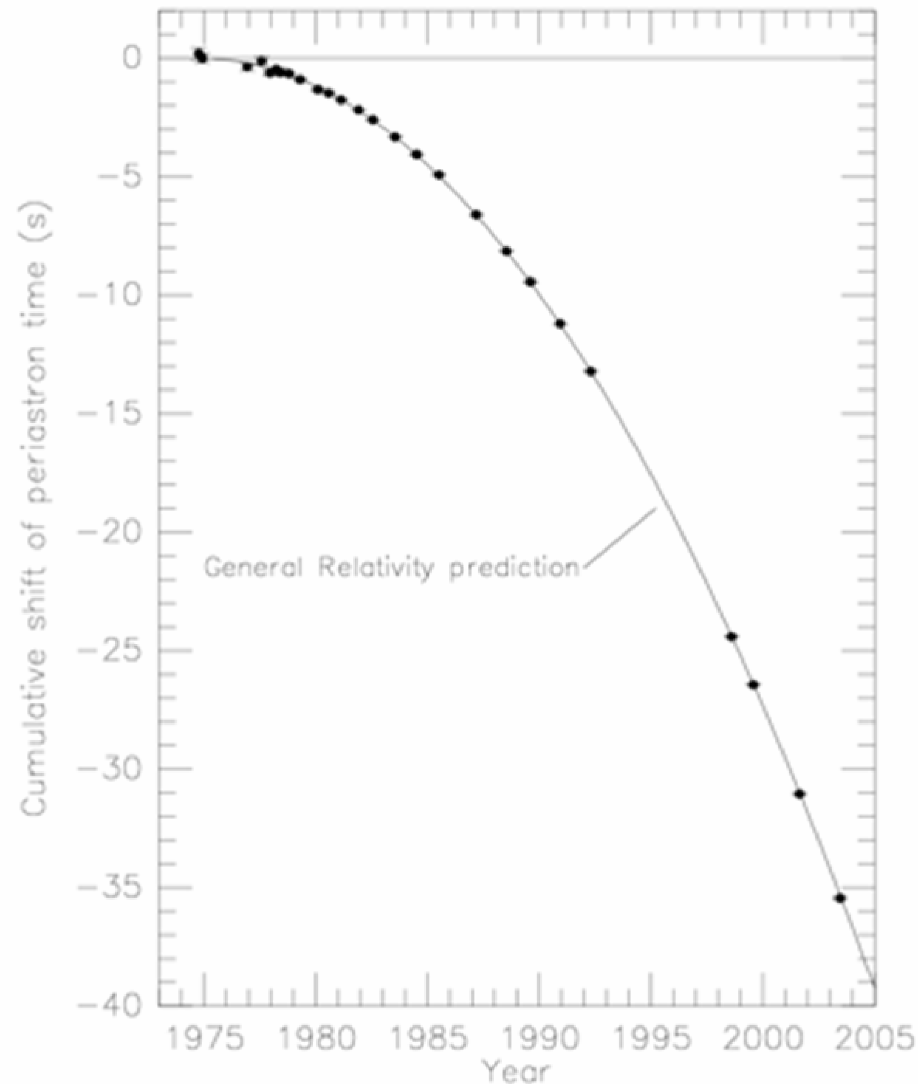
Basics of Gravitational Wave Astronomy

- Are we sure they exis

Measured Orbital Parameters for B1913+16 System

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

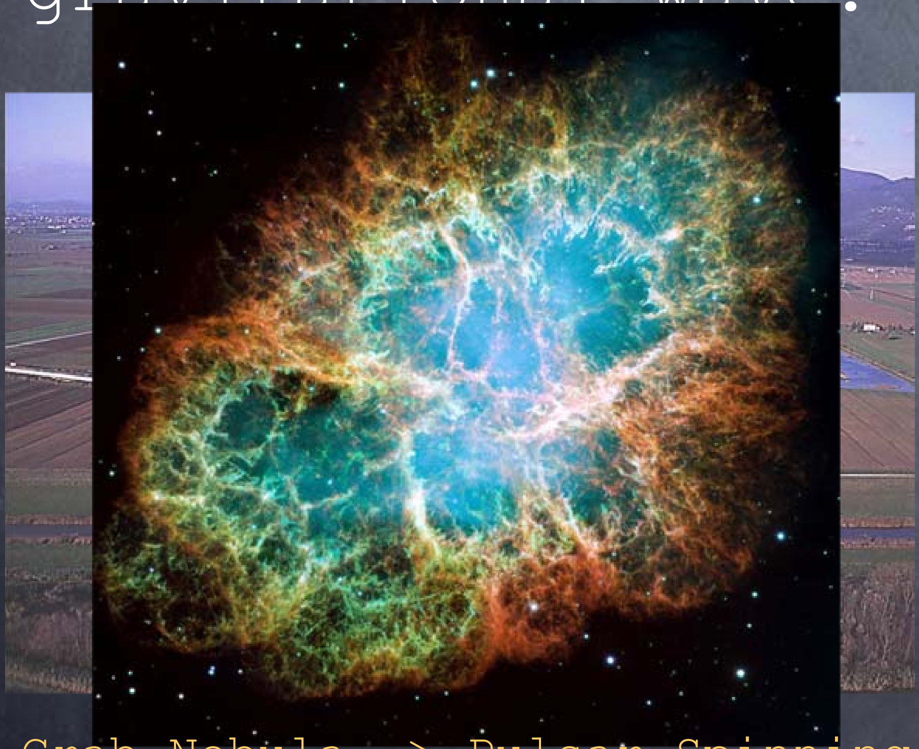
... The measured rate of change of orbital period agrees with that expected from the emission of gravitational radiation, according to general relativity, to within about 0.2 percent. ...



From: Weisberg & Taylor, astro-ph/0407149

Basics of Gravitational Wave Astronomy

- **How to detect them?**
  - Interferometric Detectors: They use the invariance of the speed of light to measure the change in relative spatial distance of two axes caused by a passing gravitational wave.



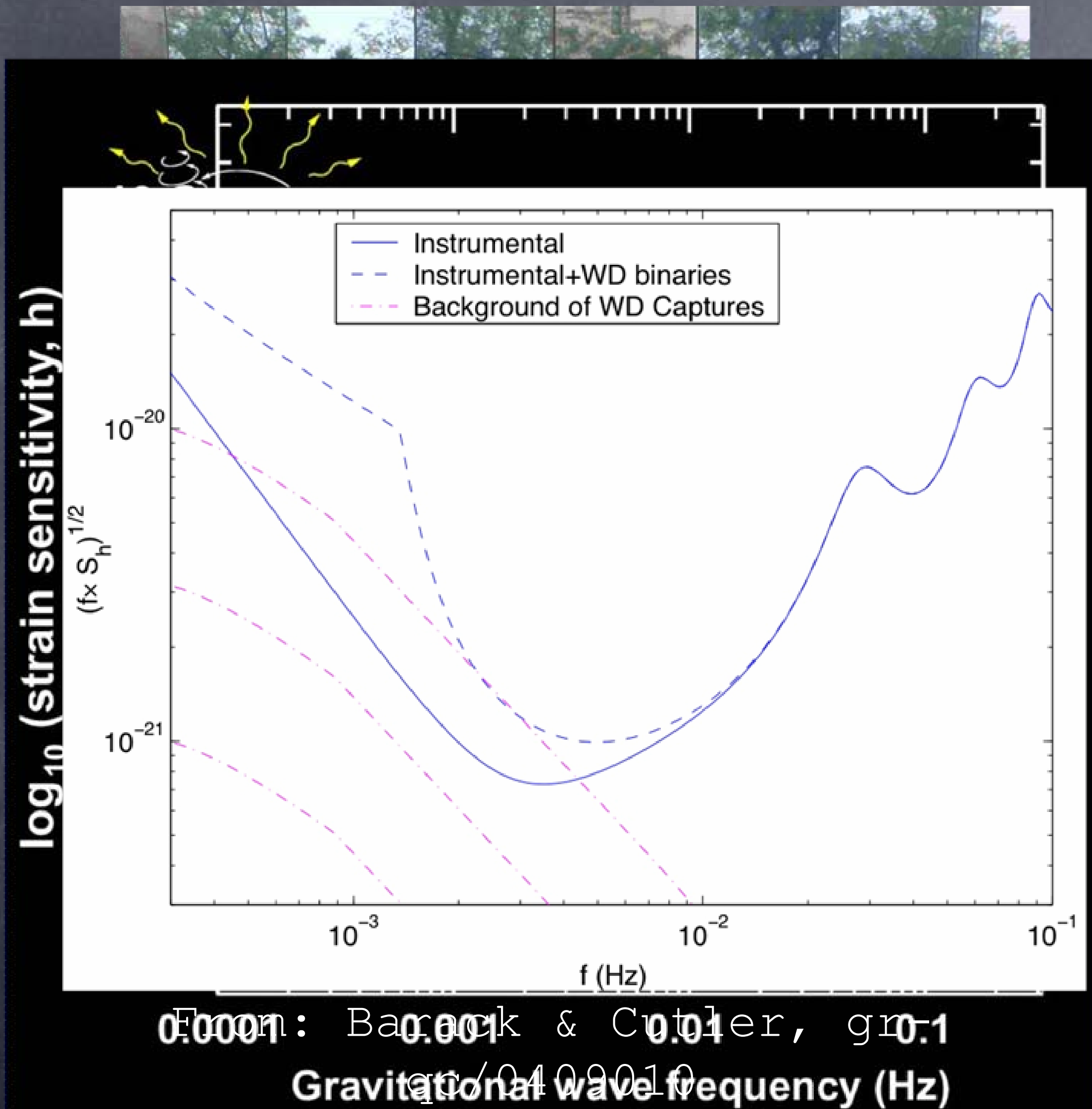
Crab Nebula -> Pulsar Spinning down

VIRGO

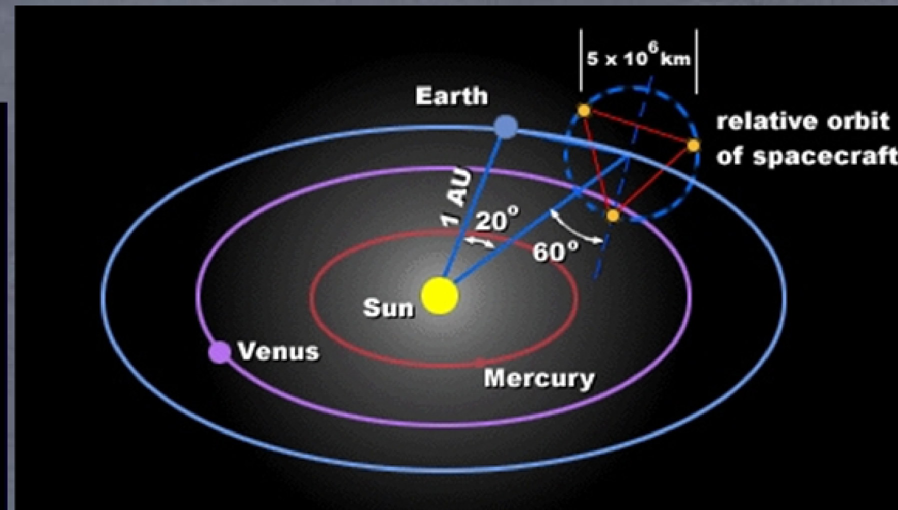
LIGO

Basics of Gravitational Wave Astronomy

✳ How to detect them?



From: Barack & Cutler, gr-qc/0409010



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onboard processing of phasemeter data.

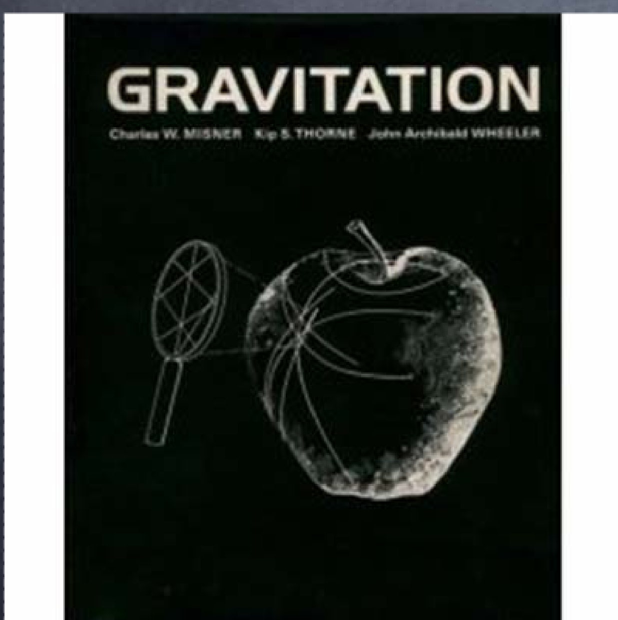
Basics of Gravitational Wave Astronomy

* Key Topics in GW Astronomy:
  * Generation of Gravitational Waves: We need to understand the sources in order to have an understanding of the waves they produce. In particular, we need theoretical waveform templates to separate the signal from the detector noise (typically via match filtering techniques).
  * Propagation of Gravitational Waves: We need to understand how gravitational waves propagate through spacetime.
  * Detection of Gravitational Waves: In addition to the detector problem, we need to develop the necessary statistical tools to extract the signals, and more importantly, the physical parameters that characterize the sources of the waves.

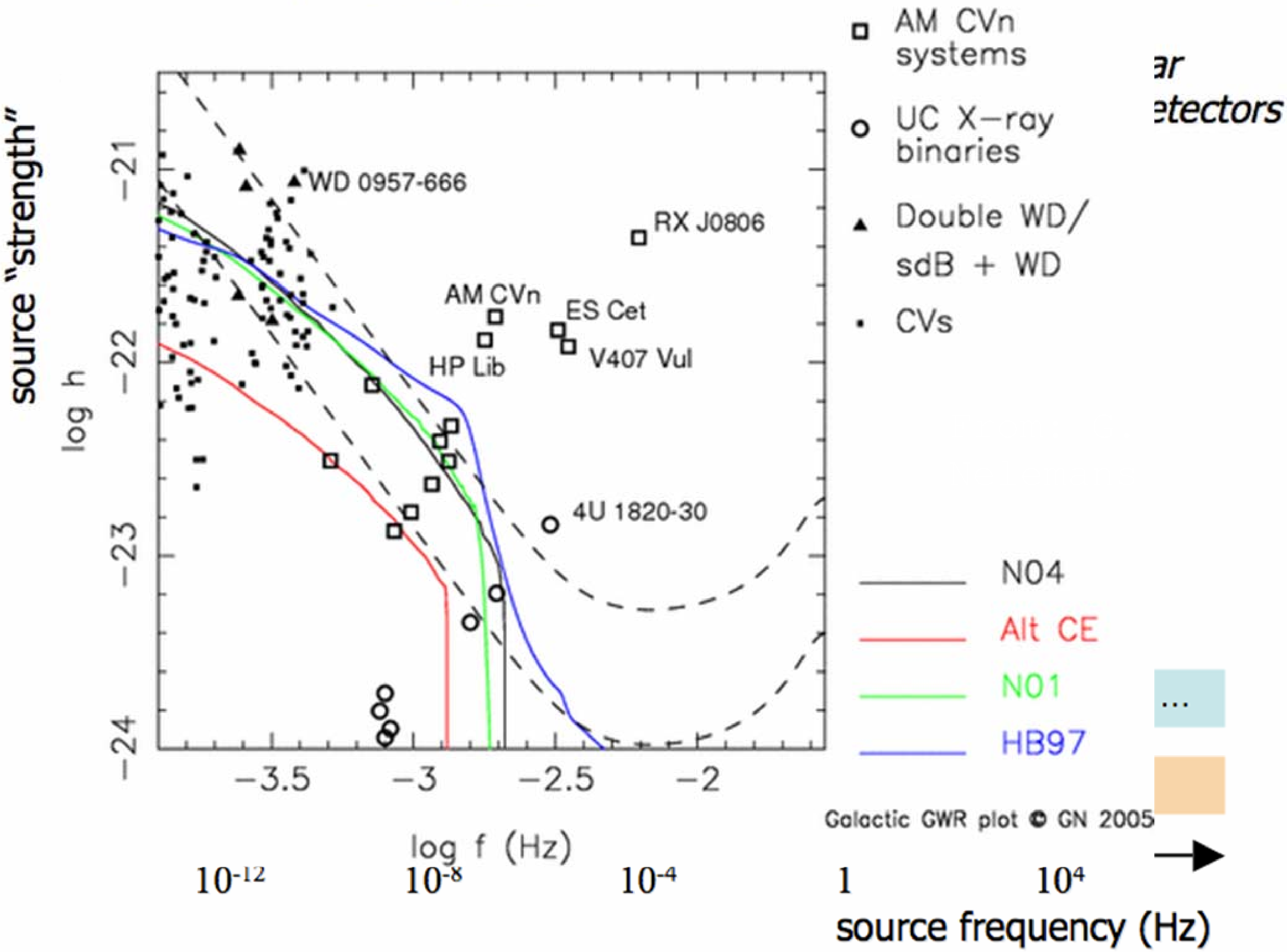
Basics of Gravitational Wave Astronomy

- Key Topics in GW Astronomy:

Theory ⟷ Experiment ⟷ Computation



Overview of expected gravitational wave sources



Binary Massive Black Hole Mergers

- Massive Black Holes:
  - There is accumulating evidence that (super)massive Black Holes populate the centers of nearly all galaxies.
  - In a Λ-CDM cosmogony, the growth of this population of Massive Black Holes (MBHs) is thought to be associated with a multistage process of Binary Black Hole Mergers and Accretion.
  - Observations have revealed tight relations between the MBH and the bulge of the host galaxy and indicate that the MBH mass may be determined by the mass of the host dark matter halo.
  - These facts indicate that there must be a deep relation between the formation mechanisms of the MBH and its host galaxy that is not yet completely understood.

Binary Massive Black Hole Mergers

Massive Black Holes:

- LISA will detect gravitational radiation from MBHs with masses:

$$10^4\,M_\odot \lesssim M_\bullet \lesssim 10^7\,M_\odot$$

and mass ratios:

$$\frac{1}{20} \lesssim \frac{M_2}{M_1} \leq 1$$

The event rate of MBH binaries has been estimated to be:

$$60-70\ \mathrm{events\,yr}^{-1} \begin{cases} \sim 50 & \text{for } M_\bullet < 10^5\,M_\odot \text{ and } z \gtrsim 10 \\ \sim 10 & \text{for } 10^5 M_\odot \lesssim M_\bullet \lesssim 10^6 M_\odot \text{ and } 2 \lesssim z \lesssim 6 \end{cases}$$

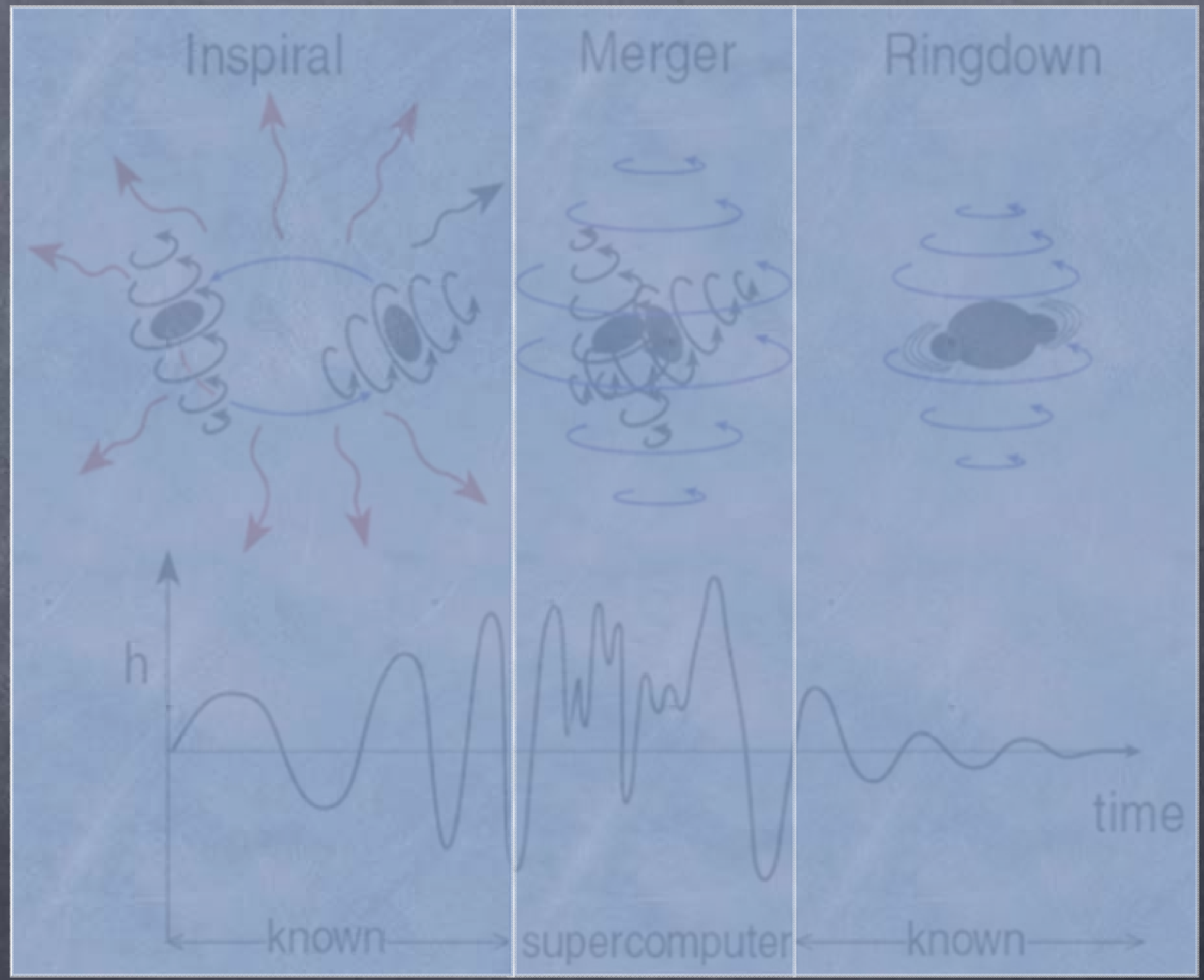
Binary Massive Black Hole Mergers

- The last stages of the evolution of a Black Hole Binary will be driven by gravitational-

The system here

This stage has resembles a perturbed single Black Hole. The evolution can be followed using BH perturbation theory (evolution of damped sinusoids, i.e. Quasi-normal modes).

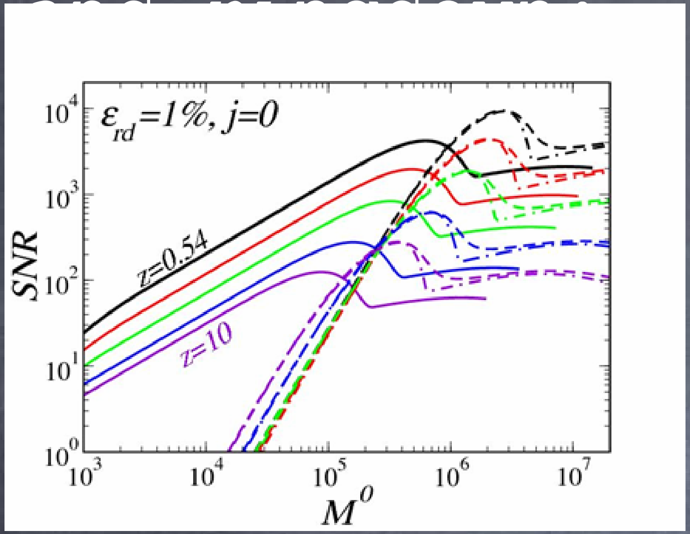
(2005)]

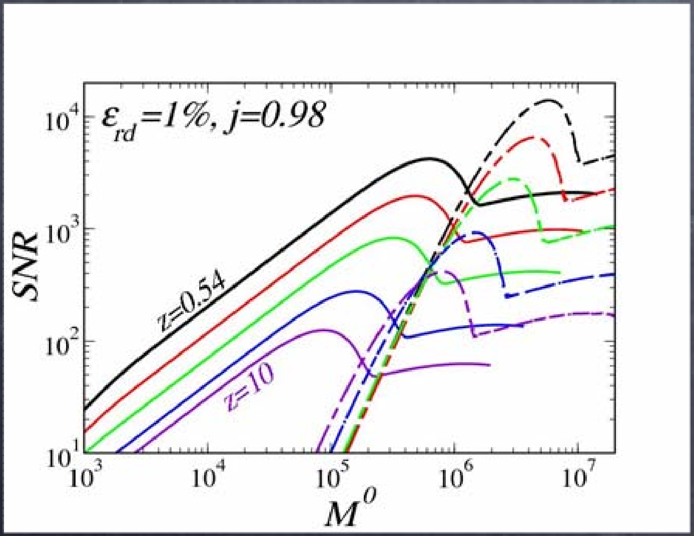


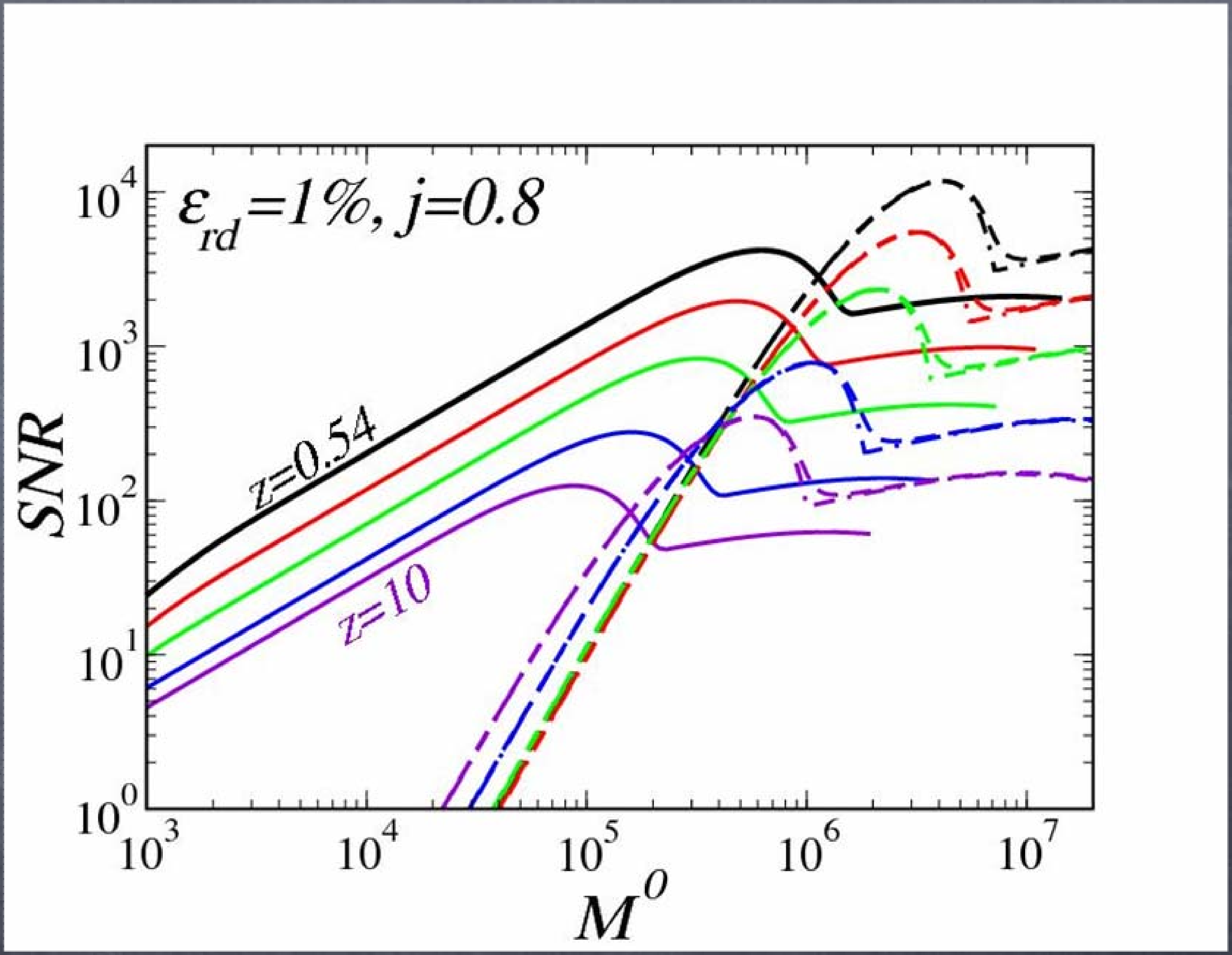
From: Kip Thorne

Binary Massive Black Hole Mergers

- **Massive Black Holes:** LISA SNR for inspiral and ringdown:







From: Berti, Cardoso & Will, PRD **73** 064030 (2006)

Binary Massive Black Hole Mergers

- Massive Black Holes: Astrophysics & Cosmology with LISA:
  - Binary Black Hole Mergers are standard sirens (calibration provided by general relativity), and therefore can provide information about the expansion history of the Universe (they provide absolute distances). Electromagnetic counterparts are very important to determine the redshift location of the host galaxy (to break the degenaracy between mass and redshift: M(z) = (1+z) x M). Weak gravitational lensing degrades the precision in the distance(from ~ 1% to a few %).
  - To trace the merger history of the Black Holes, and hence of the host galaxies.

Binary Massive Black Hole Mergers

Massive Black Holes: Astrophysics & Cosmology with LISA:

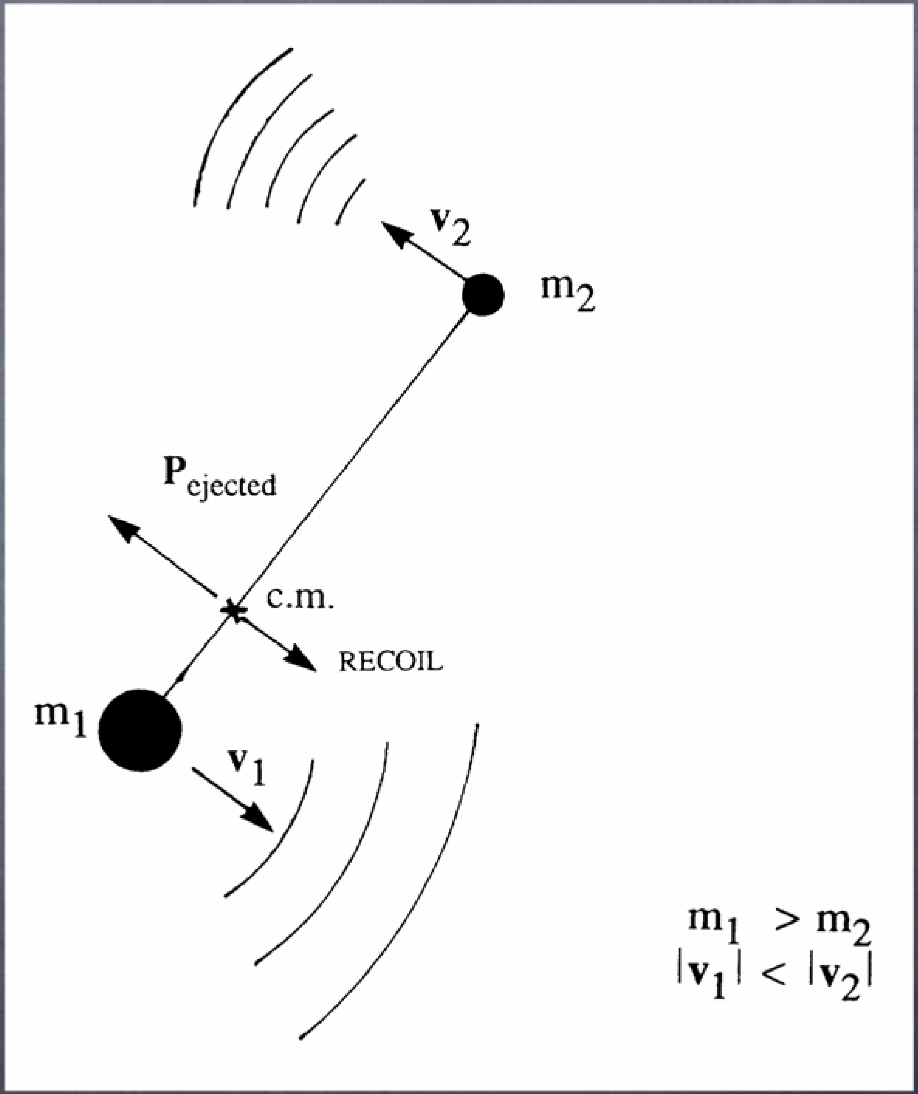
- Tests of no-hair theorem (via detection of multiple harmonics in the ringdown). The precision in measuring the spin parameter is ~ 0.1%.
- Tests of strong gravity, and in particular, of alternative theories of gravity (for instance, determination of the graviton mass and bounds on the Brans-Dicke parameter of scalar-tensor theories).
- Etc.

Binary Massive Black Hole Mergers

Massive Black Holes: The Gravitational Recoil

- For unequal-mass Mergers, apart from energy and angular momentum, GWs carry linear momentum. Then, momentum conservation implies that the resulting Black Hole will experience a recoil.

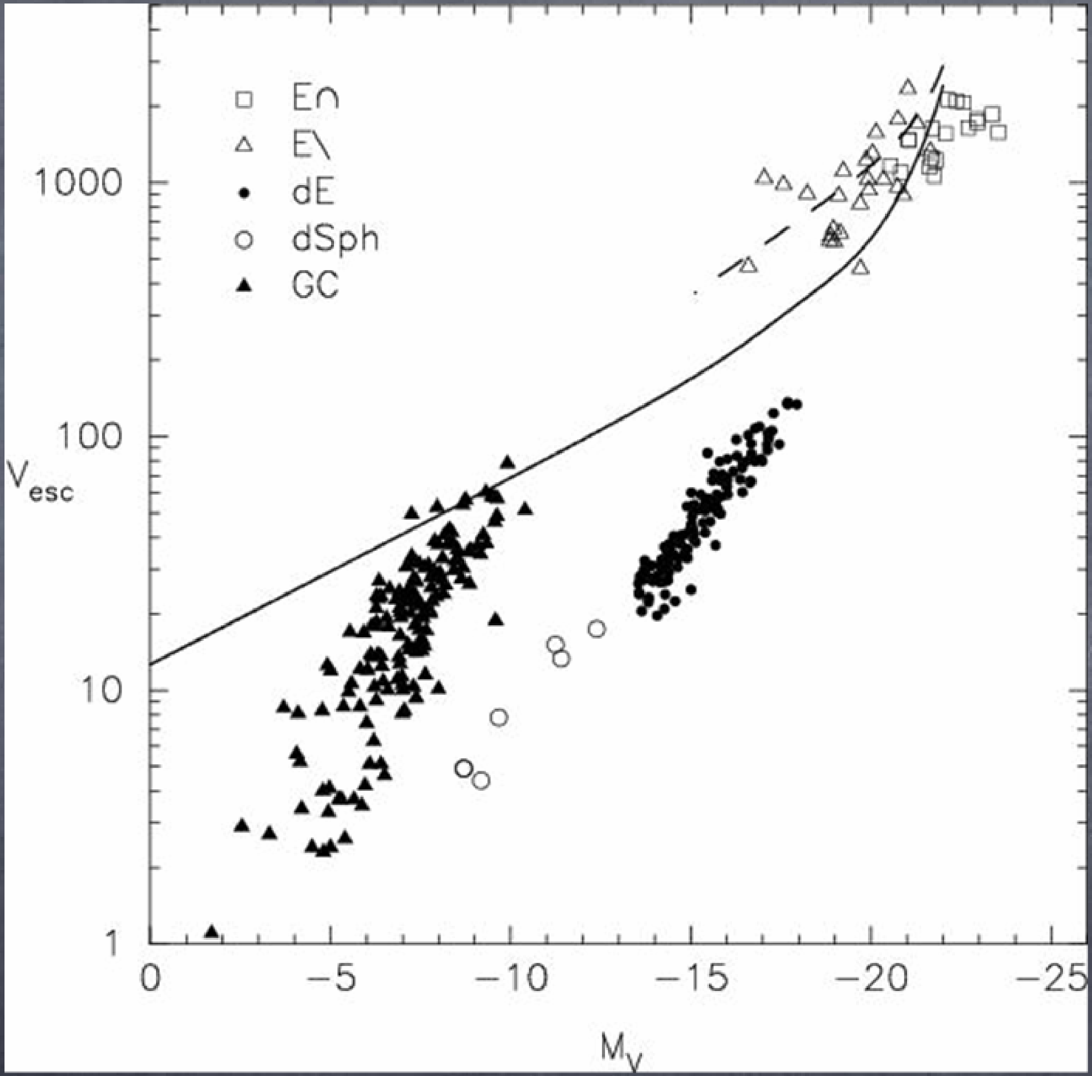
- Depending on its magnitude, this recoil can have important astrophysical and cosmological consequences.



From: Wiseman, PRD **46** 1517 (1992)

Binary Massive Black Hole Mergers

- Massive Black Holes: The Gravitational Recoil

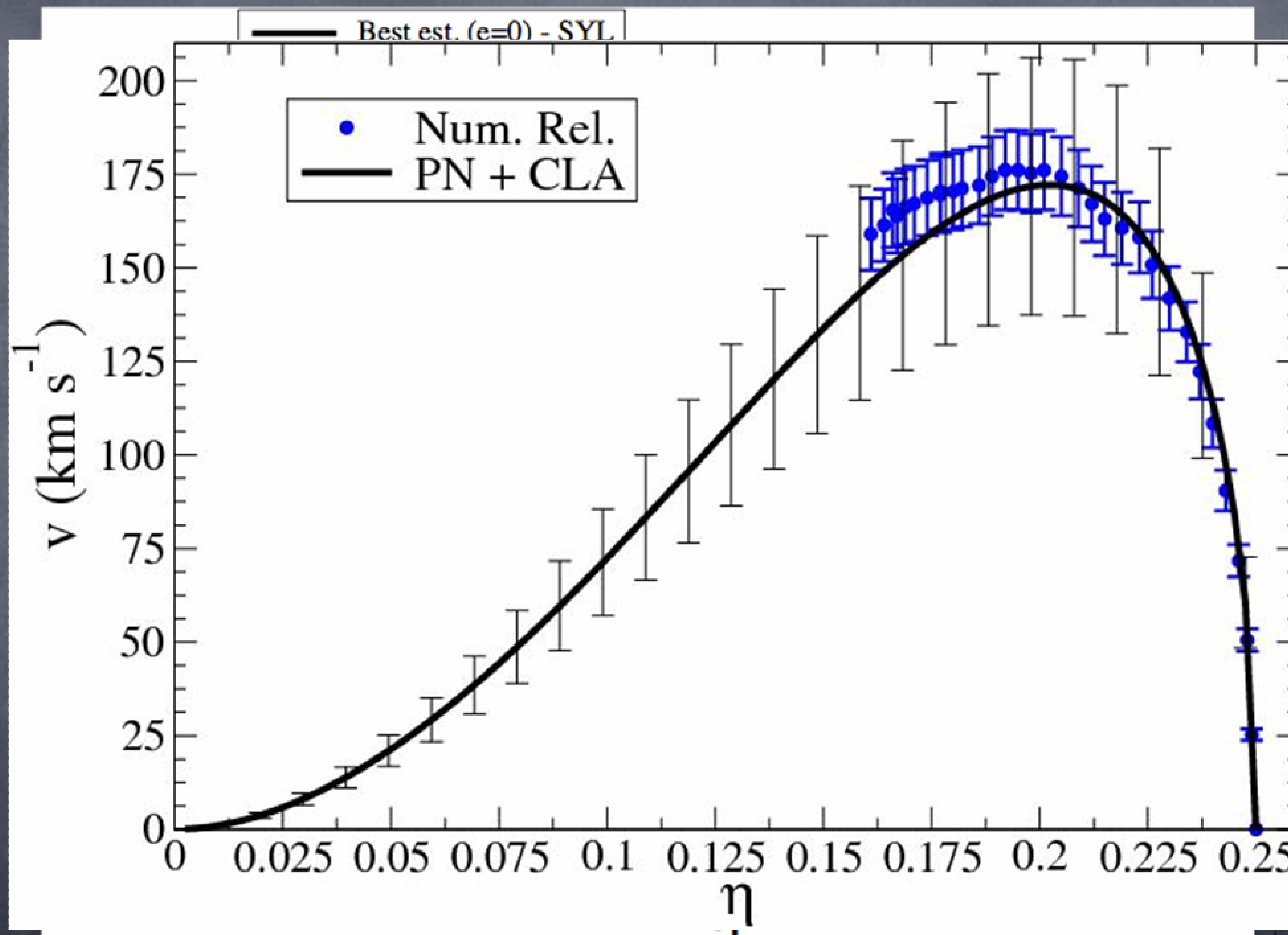


From: Merritt, Milosavljevic, Hughes & Favata, ApJ **607** L9 (1992)

Binary Massive Black Hole Mergers

Massive Black Holes: The Gravitational Recoil

$$\eta = \frac{M_1 M_2}{(M_1+M_2)^2}$$



Comparison with Gonzalez et al, PRL 98 091101 (2007)

From CFS, Yunes & Laguna, PRD 74 124010 (2006)

Binary Massive Black Hole Mergers

- **Massive Black Holes:** The Gravitational Recoil

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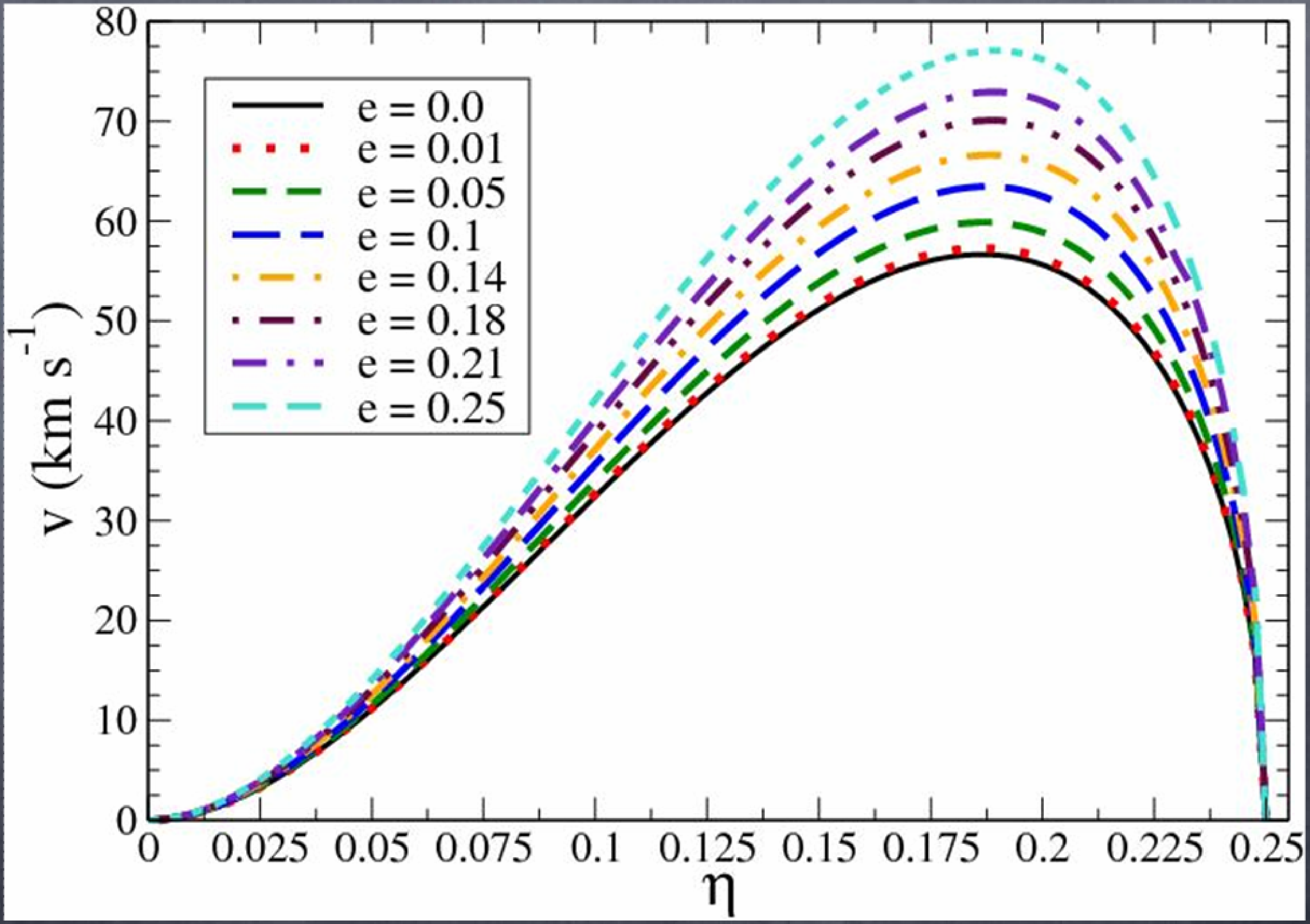


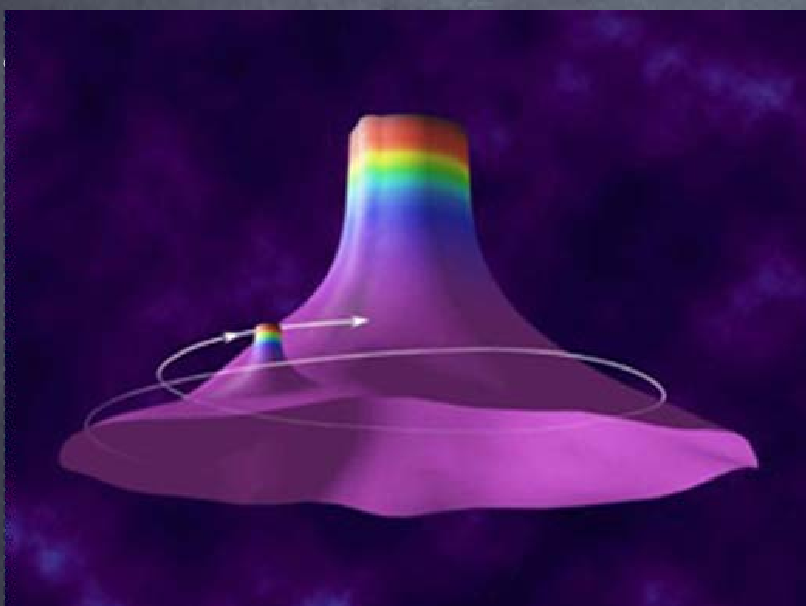
From: CFS, Yunes & Laguna, ApJ **656** L9 (2007)

Binary Massive Black Hole Mergers

- Massive Black Holes: The Gravitational Recoil
  - The end of the story: Recently, several Numerical Relativity groups have reported recoil velocities (equal mass and opposite spins) up to 4000 km/s !!! [González et al, PRL 98, 231101 (2007); Campanelli et al, PRL 98, 231102 (2007)]
  - However, it is still unclear whether the configurations of these mergers are astrophysically very likely. [Bogdanovic, Reynolds & Miller, ApJ 661, L147 (2007)]
  - More to come...

Capture of Stellar Compact objects by MBHs

- **Extreme-Mass-Ratio Inspirals (EMRIs):** They consist of a Stellar-mass Compact Object (SCO) $(m \sim 1 - 10^2 M_{\odot})$ orbiting a Massive Black Hole (MBH) $(M_{\bullet} \sim 10^5 - 10^7 M_{\odot})$



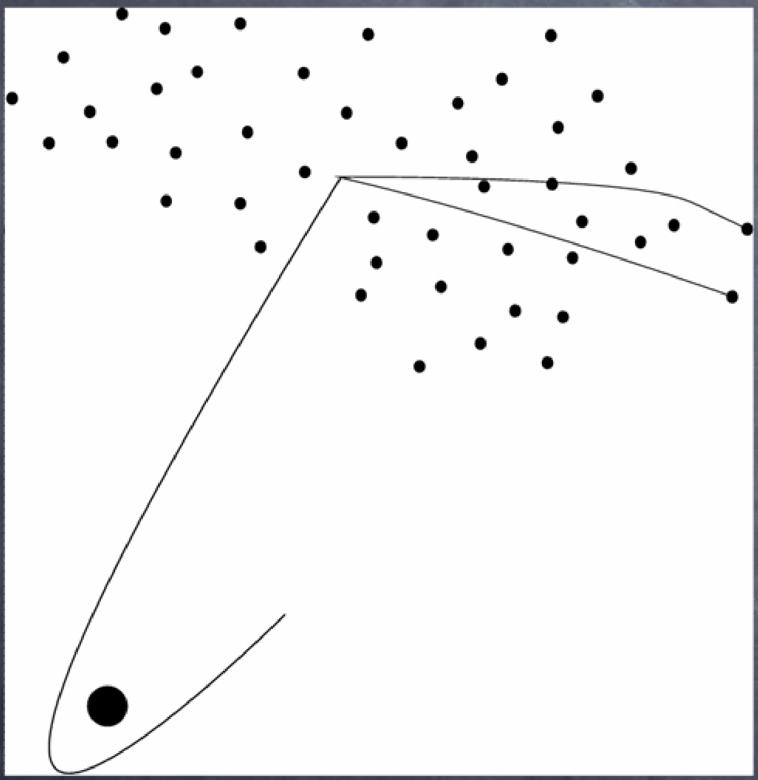
- Therefore, the mass ratios of interest are in the range:

$$\mu = \frac{m}{M_{\bullet}} \sim 10^{-3} - 10^{-7}$$

- There are several astrophysical mechanisms that can produce EMRI events.

Capture of stellar compact objects by MBHs

* First Mechanism: Single Captures (classical EMRIs)



- Scattering of a Stellar-mass Compact Object (through 2-body or multi-body encounters) to highly eccentric orbits around a MBH:

$$M_\bullet \sim 10^5 - 10^7 M_\odot\,, \;\; 1-e \sim 10^{-3} - 10^{-6}\,.$$

- They expend the last year before plunging inside the LISA band:

$$e \sim 0.5 - 0.9\,, \;\; \text{no. cycles} \sim 10^5\,.$$

- It has been estimated that LISA will see:

$$\sim 10 - 10^3\ \text{EMRIs}/yr$$

Capture of stellar compact objects by MBHs

✳ First Mechanism: Single Captures (Classical EMRIs)

- The orbits probe the strong-field region of the central MBH:

$$e = 0.9\,,\quad p = 7.8001\quad [r = pM_{\bullet}/(1+e\cos\chi)]$$

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Capture of stellar compact objects by MBHs

* First Mechanism: Single Captures (Classical EMRIs)

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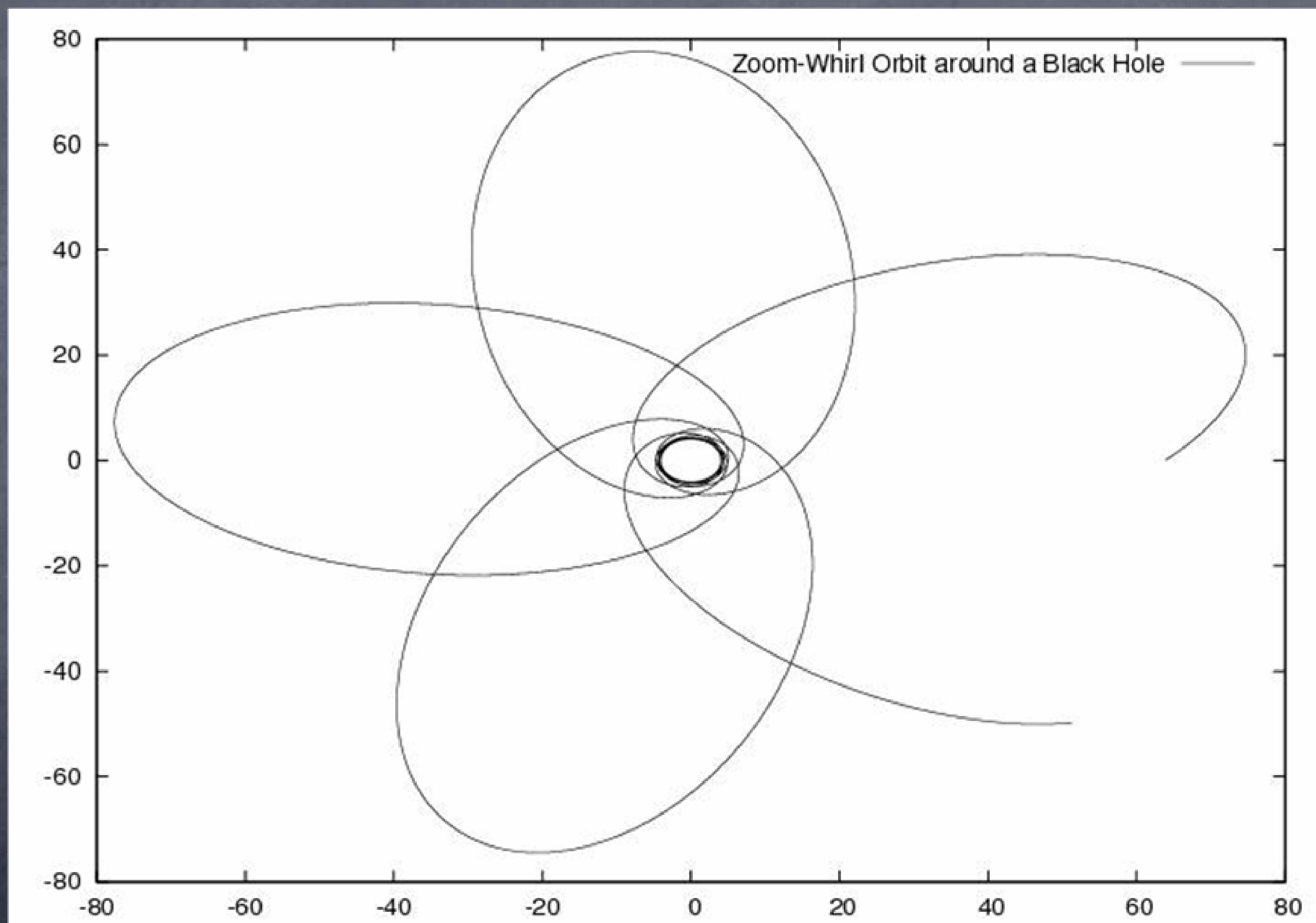


$$e = 0.9\,, \quad p = 7.8001 \quad [r = pM_\bullet/(1 + e\cos\chi)]$$

Capture of Stellar Compact objects by MBHs

Other EMRI Mechanisms:

- Stellar-Mass Compact Binaries passing close to the MBH can be tidally separated. One component gets bound to the MBH and the other one escapes to infinity.
- Capture of cores of giant stars close to the MBH by tidal stresses.
- Inspiral of black holes produced in an accretion disc around the MBH (at distances ~ 0.1-1 pc).
- Inspirals of intermediate-mass black holes (IMBHs; with masses in the range $10^2 - 10^4 M_\odot$ located in globular clusters near the central MBH.
- Extreme-Mass-Ratio Bursts: long-period, nearly-radial orbits of compact objects around a central MBH. Relevant for systems in our Galaxy.

Capture of stellar compact objects by MBHs

How well we need to understand EMRIs?

- We need precise waveform templates to dig the signals out from the detector noise (instrumental + confusion noise) and for estimation of physical parameters:

$$\delta\phi_{GW}^{Detection} \sim 1\,, \quad \text{over 3 weeks}$$

$$\delta\phi_{GW}^{Parameter\ Estimation} \sim 1\,, \quad \text{over 1 year}$$

- The construction of the waveforms requires a very precise estimation of the gravitational backreaction in the motion of the stellar compact object. This is a challenge for the theory and for the numerical computations.

Capture of stellar compact objects by MBHs

* Challenges for the numerical simulations:

• To compute the perturbations (1st- & 2nd-order perturbations) created by the SCO -> To Solve a set of (coupled) linear PDEs coupled to the ODEs describing the motion of the SCO.

• The equations to be solved have (highly) singular source terms: The solutions are not smooth; they may be discontinuous, or even singular, at the particle location -> Numerical regularization at the particle location required.

• The problem involves a vast range of spatial scales: The MBH horizon; the SCO size; typical gravitational radiation wavelength; etc. -> Numerical simulations need to incorporate (dynamical) adaptivity.

• The problem also has different temporal scales: Orbital time-scale; Radiation-reaction

Capture of stellar compact objects by MBHs

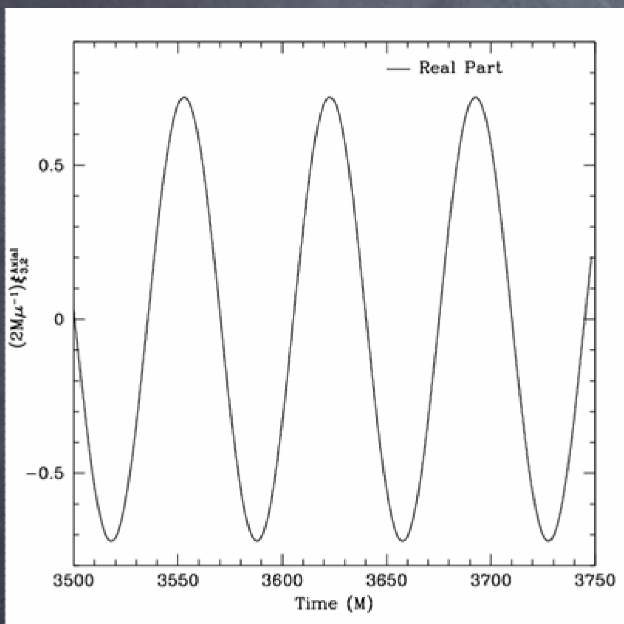
Status of the Computations:

- We can produce waveforms, including radiation-reaction, for Schwarzschild and Kerr MBHs in the adiabatic approximation (may be good enough for LISA detection but probably not good enough for parameter estimation).

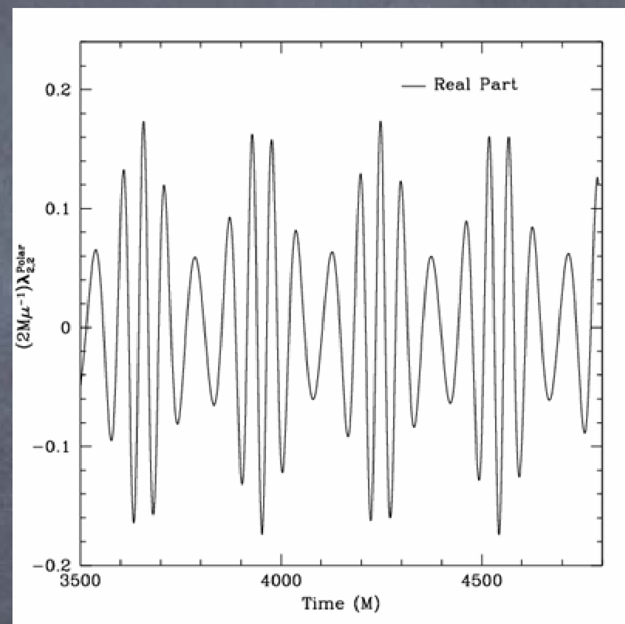
- With proper radiation-reaction (self-force), we can handle only circular motion around a Schwarzschild MBH (no spin yet), but no waveform production yet.

Capture of stellar compact objects by MBHs

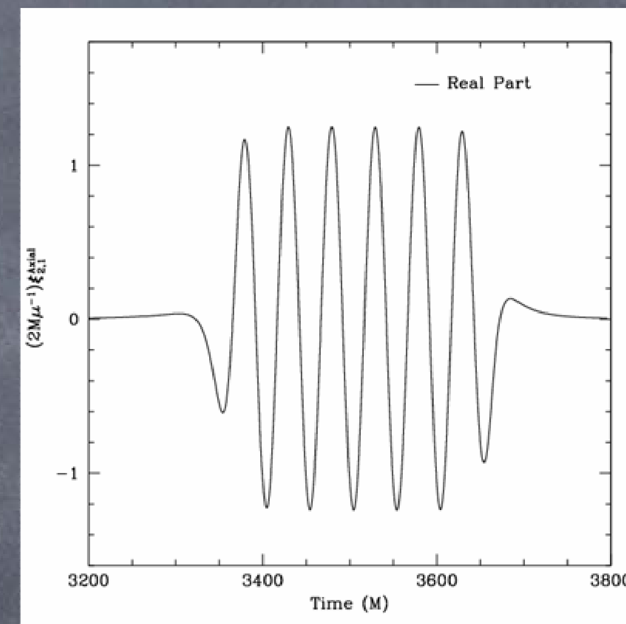
- Some examples: From [CFS & Laguna, PRD 73, 044028 (2006)]
  - Some Waveforms:



Circular Orbits



Elliptic Orbits with e=0.188



Zoom-whirl Orbits

Capture of stellar compact objects by MBHs

- Some examples: From [CFS & Laguna, PRD 73, 044028 (2006)]
- Computations of the total energy and angular momentum radiated, both to infinity and into the horizon in parabolic orbits (e=1). We show the relative difference with respect the results obtained by [Martel, PRD 69, 044025 (2004)] in the Time domain.

p	E^{∞}	L^{∞}	E^{H}	L^{H}
8.00001	3.5603 [3.1%]	29.415 [2.5%]	$1.8884 \cdot 10^{-1}$ [0.05%]	1.5112 [0.7%]
8.001	2.2212 [2.7%]	18.704 [2.1%]	$1.1339 \cdot 10^{-1}$ [0.7%]	$9.0783 \cdot 10^{-1}$ [0.5%]

Capture of stellar compact objects by MBHs

Science from LISA observations of EMRIs:

- The Gravitational Waves emitted carry a map of the MBH spacetime (the MBH multipole moments). LISA is expected to measure 3-5 moments with high precision:

$$\Delta(\ln M_\bullet)\,,\ \Delta\left(\ln\frac{m}{M_\bullet}\right)\,,\ \Delta\left(\frac{S_\bullet}{M_\bullet^2}\right)\ \sim\ 10^{-4}\,,\quad \Delta\Omega\ \sim\ 10^{-3}\,.$$

- Opportunity to test the no-hair theorem and constraint theories on the MBH growth mechanism (galaxy formation mechanisms). Tests of alternative theories of Gravity.
- To create census of masses and spins of MBHs and masses of the inspiraling compact objects, which can tell us about the stellar mass function and mass segregation in the central parsec of galactic nuclei.

Capture of stellar compact objects by MBHs

- Science from LISA observations of EMRIs:
  - EMRIs are also standard GW sirens. We can study the acceleration history of the Universe up to z~1. Electromagnetic counterparts are needed for redshift estimation.
  - Precision Cosmology: Measurement of the Hubble constant [MacLeod & Hogan, PRD 77, 043512 (2007)] by combining LISA observations of EMRIs events with Galaxy redshift surveys (they would provide statistical redshift information of the EMRI events).

It has been estimated that for 20 or more EMRI events to z = 0.5, it is possible to obtain a measurement of the Hubble constant better than one percent precision.

Conclusions

- Gravitational Wave Astronomy will open a new window to the exploration of the Universe.
- Combination with Electromagnetic windows will be crucial for success.
- LISA observations of Massive Binary Black Hole mergers are powerful tools to understand better galaxy formation, and also for cosmology.
- EMRIs are high precission tools that can provide robust tests of the no-hair theorem.
- Unexpected physics (early universe, high-energy physics phenomena, ...).