THE HUNT FOR GRAVITATIONAL WAVES AND BLACK HOLES

DEIRDRE SHOEMAKER

The mess at the beginning of the radiation graph is junk radiation since they don't solve the initial data perfectly.

We have change in length over length is like 10^{-21}. Tiny!

Signal to noise ratio is 58... but is tiny. But need models for it. Also, more detectors give better directionality and polarization.

The Hunt for Gravitational Waves and Black Holes

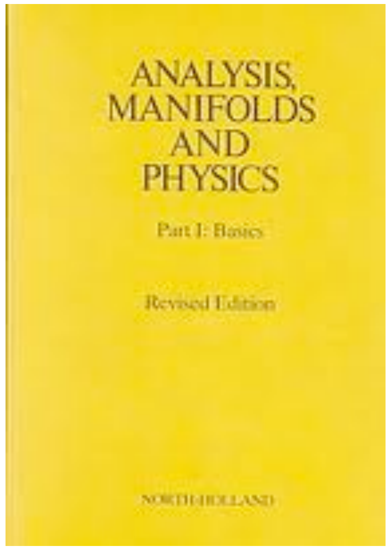
"It's black, and it looks like a hole. I'd say it's a black hole."

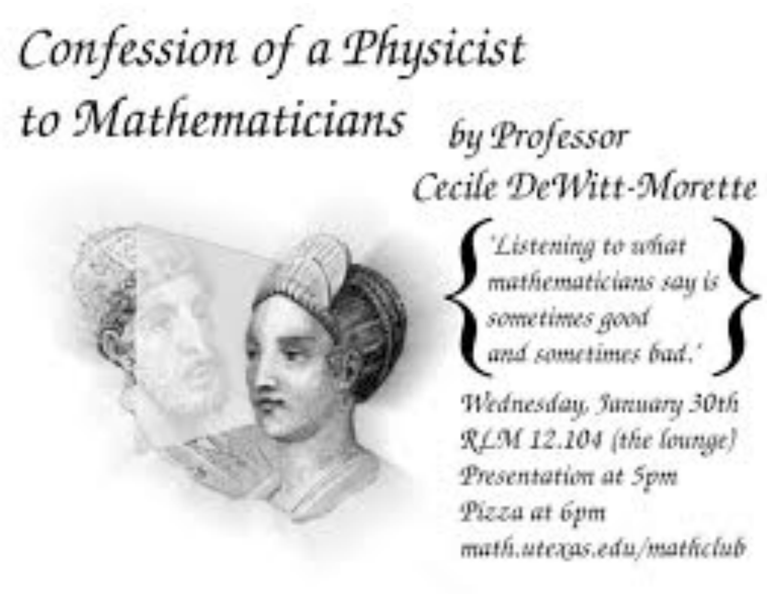
Deirdre Shoemaker
Center for Relativistic Astrophysics
School of Physics
Georgia Tech

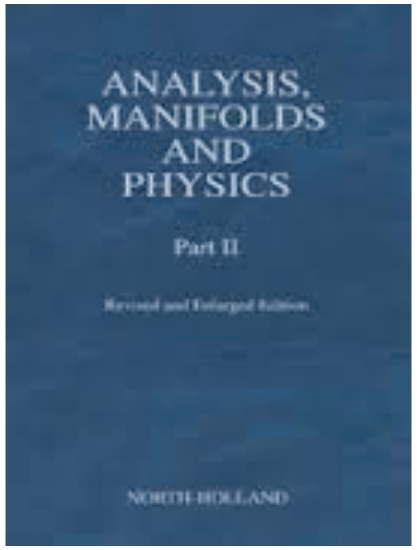
Connections for Women: Mathematical Relativity

Cecile Dewitt-Morette

Yvonne Choquet-Bruhat

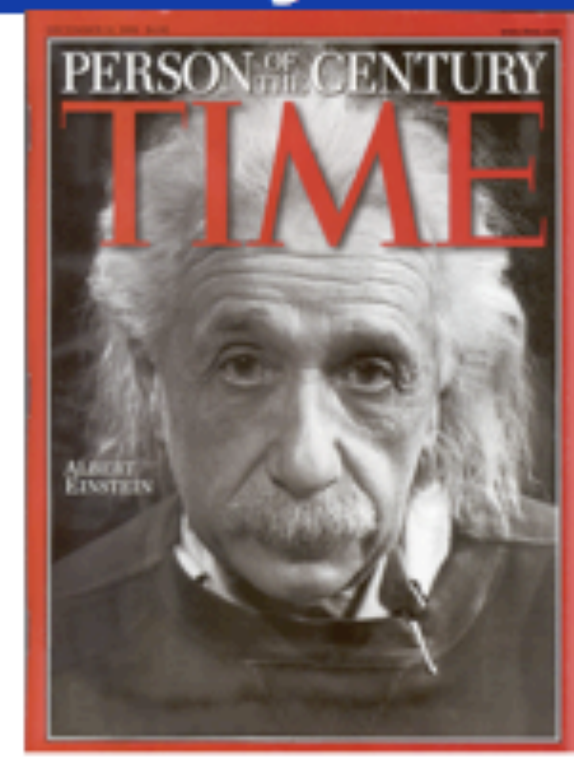






A Brief History by Larry Smarr

The Problem of the Century
Posed by the Person of the Century



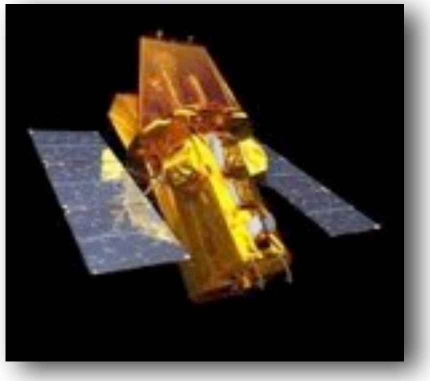
- 1910s-General Theory; Schwarzschild
- 1920s-Equation of Motion Posed
- 1930s-Two Body Problem Posed
- 1940s-Cauchy Problem Posed
- 1950s-Numerical Relativity Conceived
- 1960s-Geometrodynamics; First Numerical Attempts
- 1970s-Head-On Spacetime Roughed Out
- 1980s-Numerical Relativity Becomes a Field
- 1990s-Head-On Nailed; 3D Dynamics Begin
- 2000s-3D Dynamics Nailed; Grav. Wave Astronomy

Institute of Theoretical Physics

Larry Smarr, 1/18/00

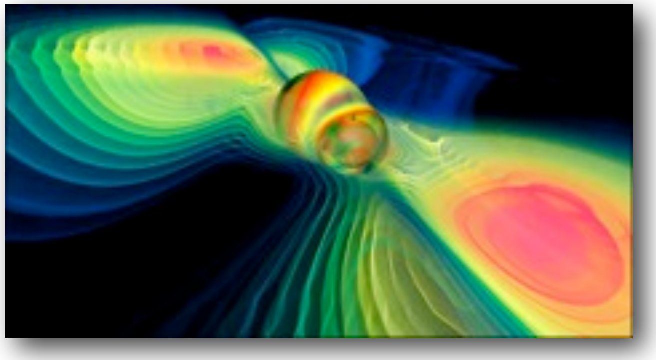
New Era in Gravity

- Gravitational physics will be driven by data.
- That data is gravitational waves coupled with other messengers.
- Numerical relativity plays a fundamental role in this new era by
  - predicting and characterizing sources of gravitational radiation and
  - unveiling strong-field gravity in the universe
- I will focus on Binary Black Hole Systems (BBH)



SWIFT

LIGO, Livingston



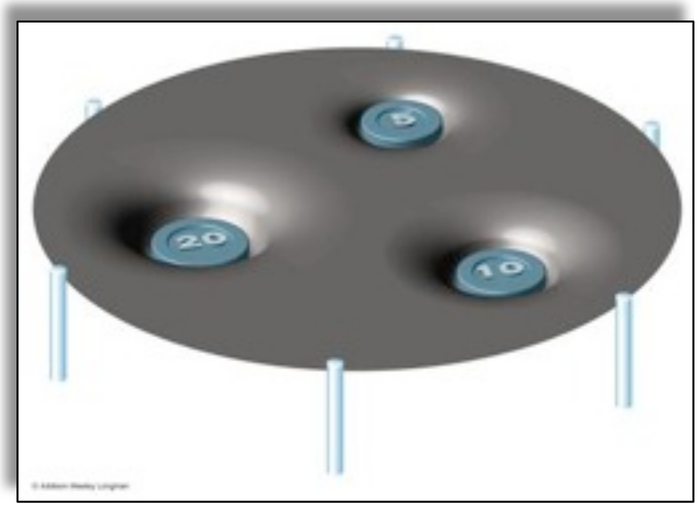
Gravitational Waves from BBH
(credit: MPI for Gravitational Physics/W.Benger-ZIB)

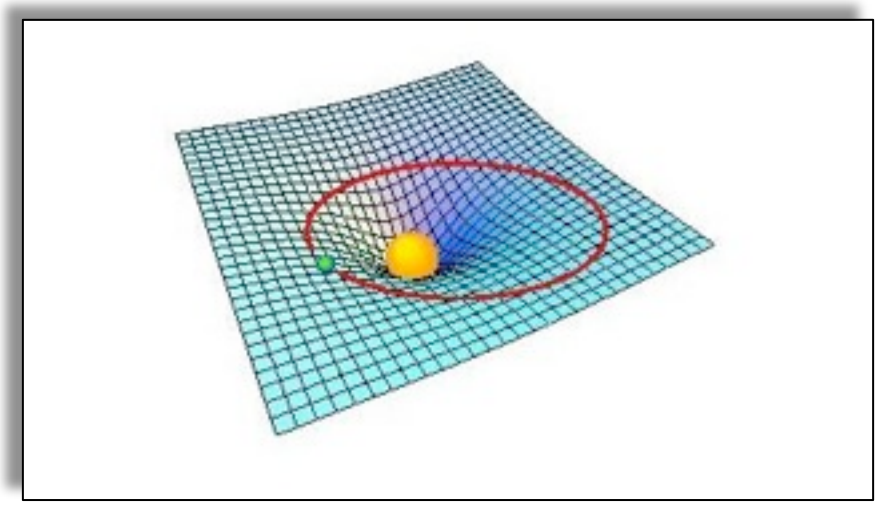
NASA

Einstein's Theory of General Relativity

Space-Time Curvature = Matter-Energy

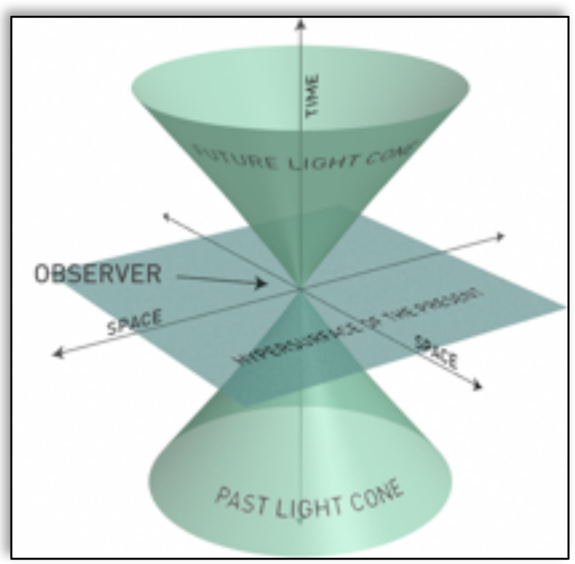
$$G_{\mu\nu} = 8\pi\, T_{\mu\nu}$$



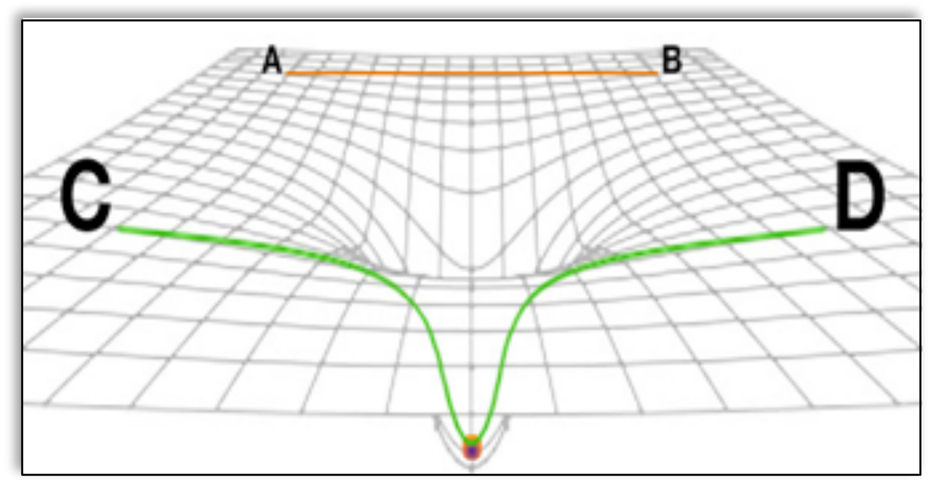


Matter tells space-time how to curve

Space-time curvature tells Matter how to move



$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

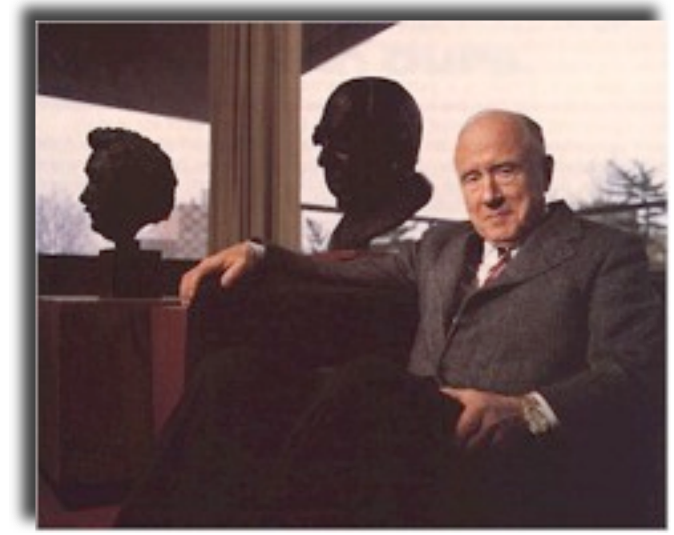


Solutions to Einstein's Equations: Black Holes

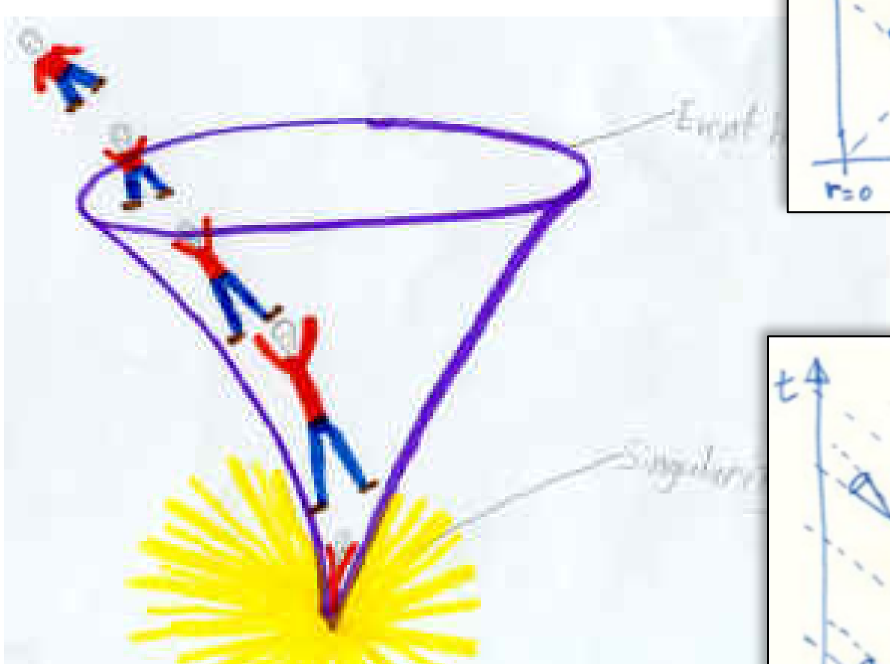
Schwarzschild 1915

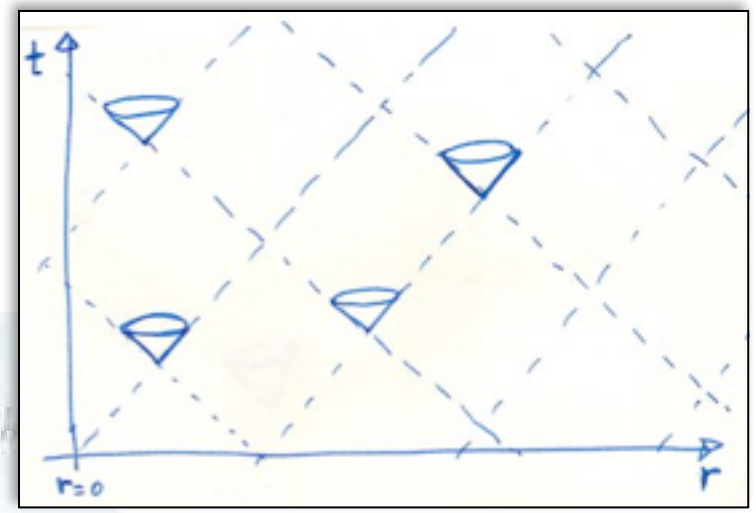
$$g_{\mu\nu} = \begin{vmatrix} -\left(1-\frac{2M}{r}\right) & 0 & 0 & 0 \\ 0 & \left(1-\frac{2M}{r}\right)^{-1} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta \end{vmatrix}$$

Issues at
r = 2M and r = 0!

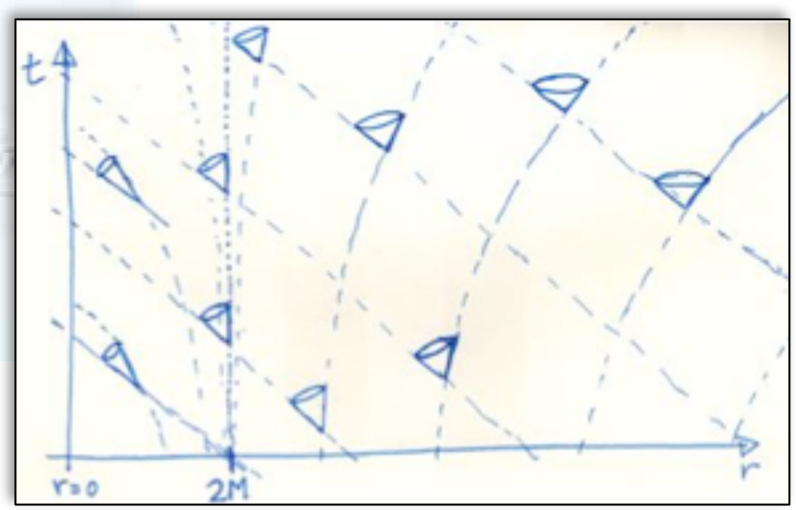


John A. Wheeler 1967



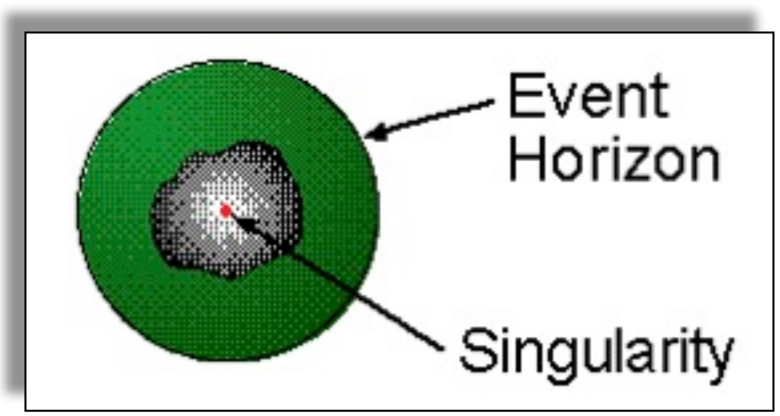


In flat spacetime



Schwarzschild spacetime

Black Hole: A region of space-time inside which the gravitational field is so intense that it prevents all matter and radiation from escaping.



Kerr Black Holes

Black holes are macroscopic objects with masses varying from a few solar masses to millions of solar masses. To the extent they may be considered as stationary and isolated, to that extent, they are all, every single one of them, described exactly by the Kerr solution. This is the only instance we have of an exact description of a macroscopic object. Macroscopic objects, as we see them all around us, are governed by a variety of forces, derived from a variety of approximations to a variety of physical theories. In contrast, the only elements in the construction of black holes are our basic concepts of space and time. They are, thus, almost by definition, the most perfect macroscopic objects there are in the universe. And since the general theory of relativity provides a single unique two-parameter family of solutions for their description, they are the simplest objects as well.

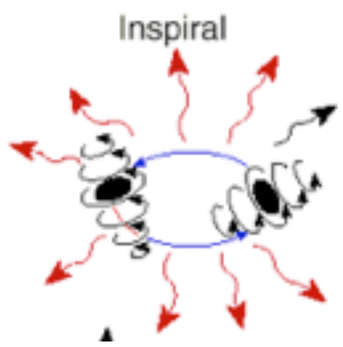
—S. Chandrasekhar

BHs in the universe are expected to rotate but be neutral; and, therefore they are described by Kerr's 2 parameters of mass and spin.

But nature produces binaries

BBH spacetime: equations of motion telling us how the black holes are moving and the gravitational radiation (waves) that are emitted as they interact.

Approximated with post-Newtonian models assume slow moving point particles



total mass, mass ratio, orbital angular momentum, individual spins, eccentricity, sky location

Many parameters

Black holes move rapidly & the nature of the black holes becomes important
Numerical relativity solves the full Einstein equations

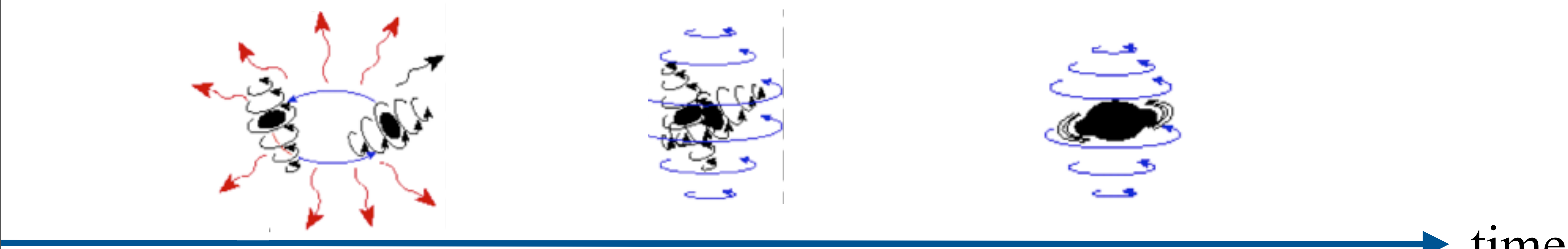
- gravitational waves (GWs)

Two parameters

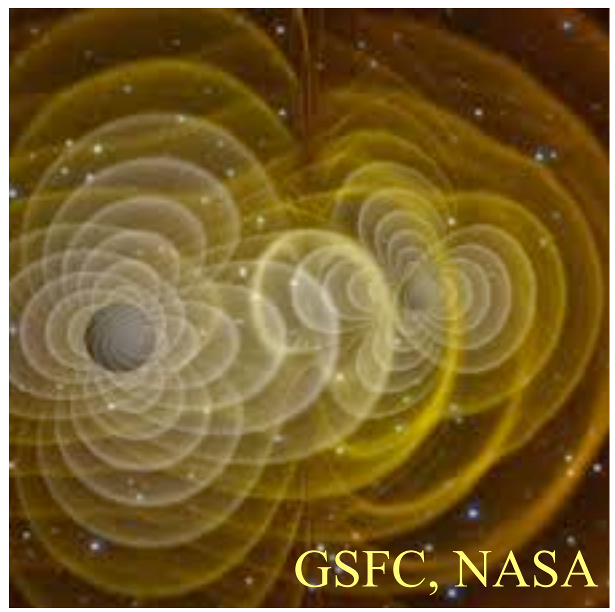
Single Kerr black hole
Perturbation theory approximates

final mass and spin vector

Gravitational Waves



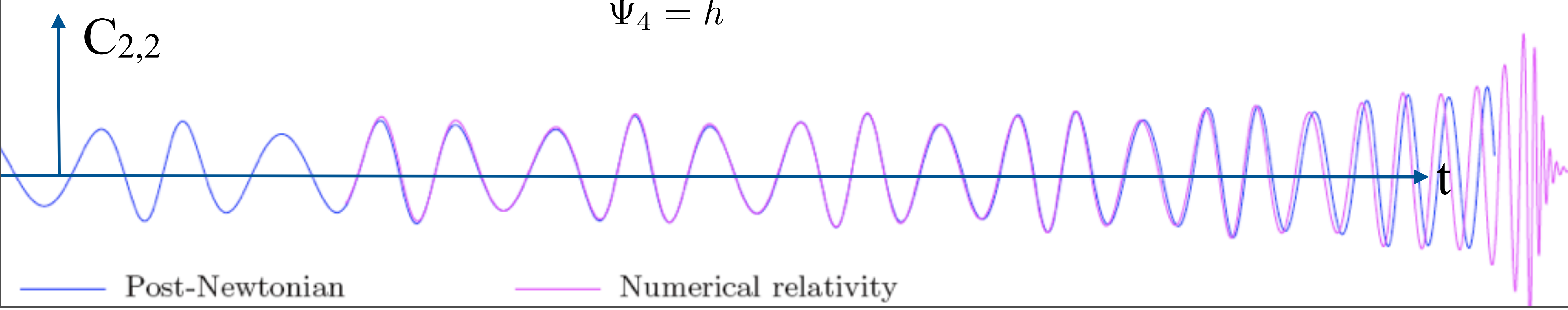
total mass, mass ratio, angular momentum, individual spins, eccentricity...



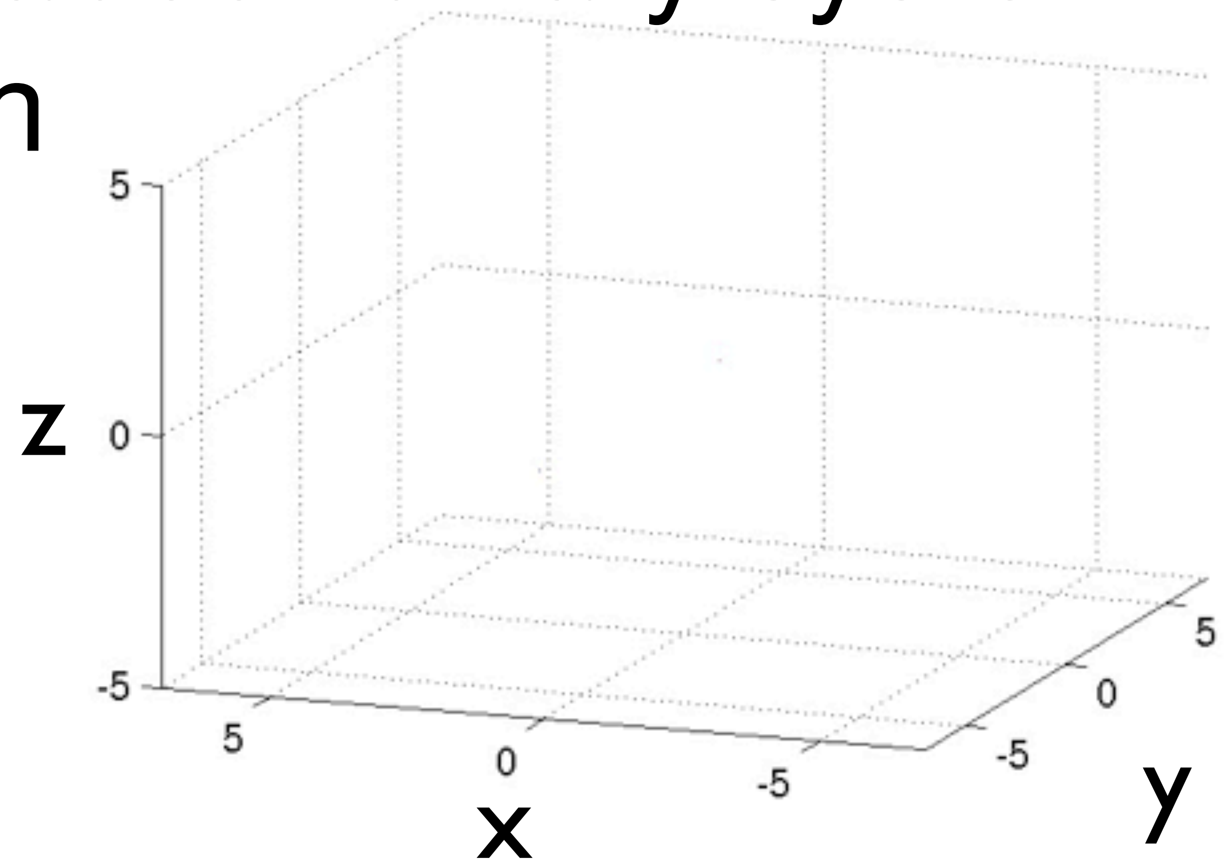
final mass and spin vector

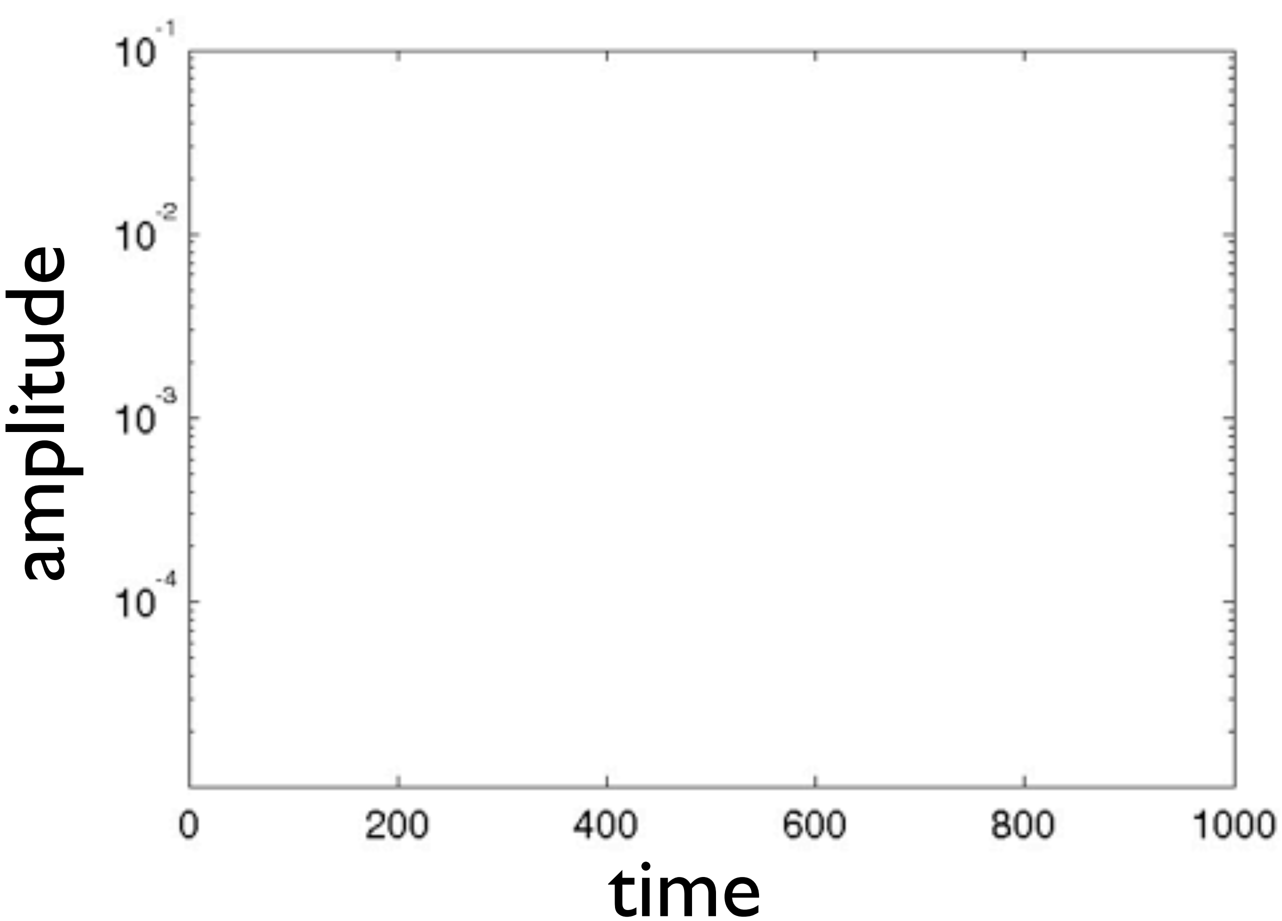
$$rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t)$$

$$\Psi_4 = \ddot{h}$$



Information about binary system is encoded on waveform





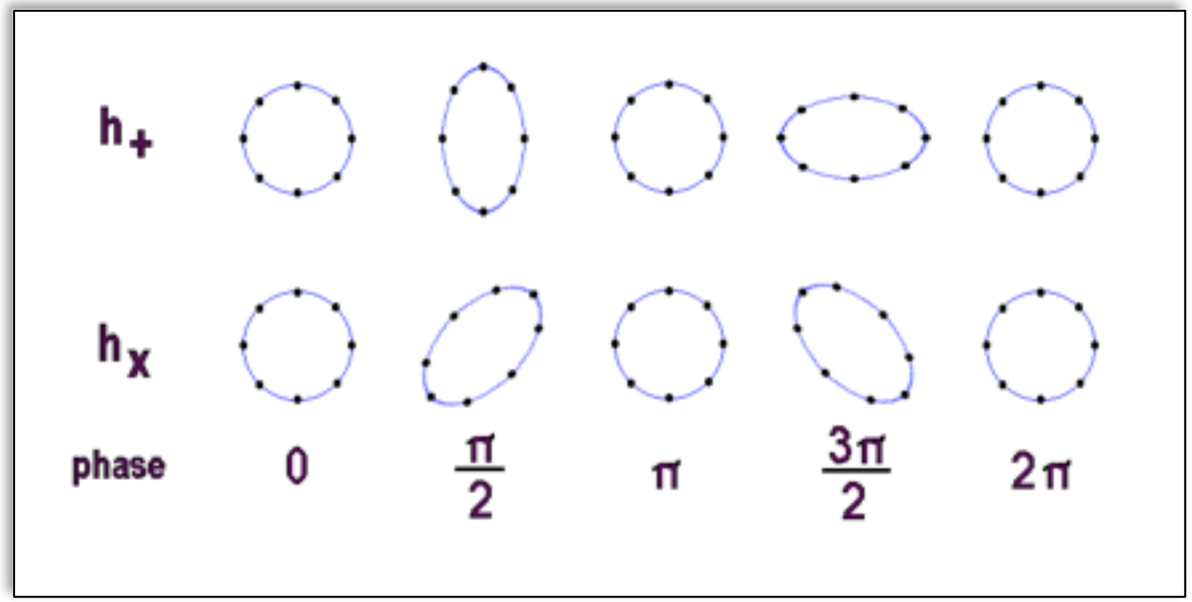
Solutions to Einstein's Equations: Gravitational Waves

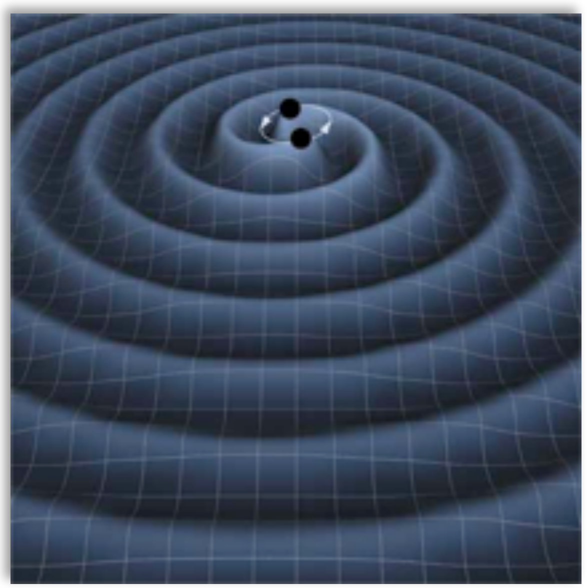
$$g_{\mu\nu} = \begin{vmatrix} -1 & 0 & 0 & 0 \\ 0 & 1+h_+ & h_\times & 0 \\ 0 & h_\times & 1-h_+ & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$-\frac{\partial^2}{\partial t^2} h_{\alpha\beta} + c^2 \nabla^2 h_{\alpha\beta} = \tau_{\alpha\beta}$$

h_+ and h_x obey a wave equation

Polarizations





Ripples in Space-Time

For a binary system

$$h_+ = -\frac{1}{r}\frac{G^2}{c^4}\frac{2m_1m_2}{R}\cos[2\omega(t-r)]$$

$$h_\times = -\frac{1}{r}\frac{G^2}{c^4}\frac{2m_1m_2}{R}\sin[2\omega(t-r)]$$

$$\omega = \sqrt{G(m_1+m_2)/r^3}$$

Orbital Frequency

ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

I. APPROXIMATE SOLUTION OF THE PROBLEM OF PLANE WAVES AND THE PRODUCTION OF GRAVITATIONAL WAVES.

It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = -T_{\mu\nu}. \quad (1)$$

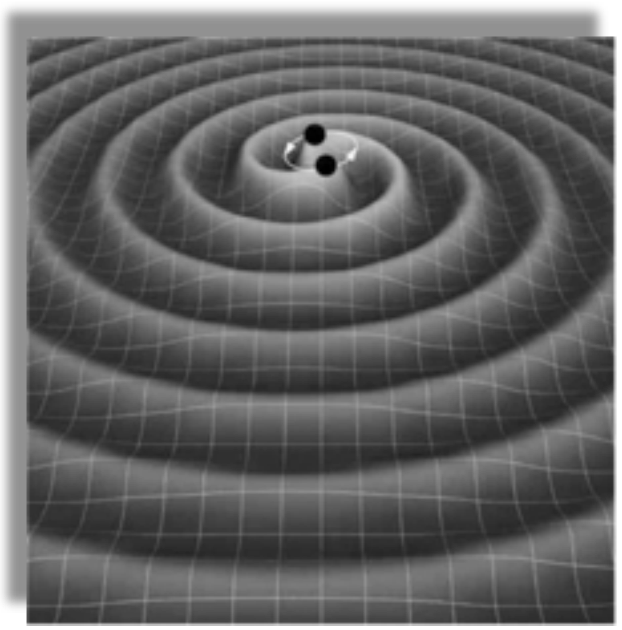
We consider that the $g_{\mu\nu}$ are replaced by the expressions

$$g_{\mu\nu} = \delta_{\mu\nu} + \gamma_{\mu\nu}. \quad (2)$$

Strength and Frequency of Gravitational Waves

$$h_+ = -\frac{1}{r}\frac{G^2}{c^4}\frac{2m_1m_2}{R}\cos[2\omega(t-r)]$$

$$h_\times = -\frac{1}{r}\frac{G^2}{c^4}\frac{2m_1m_2}{R}\sin[2\omega(t-r)]$$



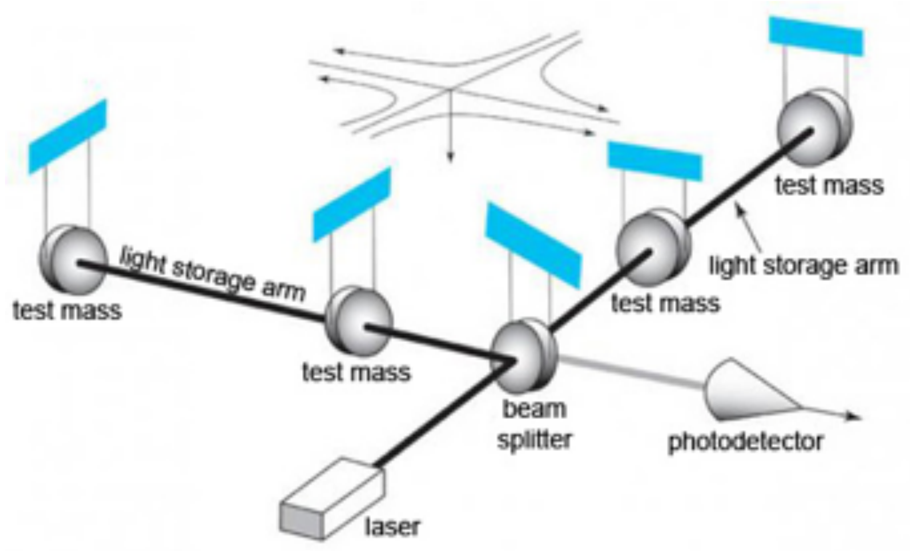
$$\frac{\delta L}{L} \approx h$$

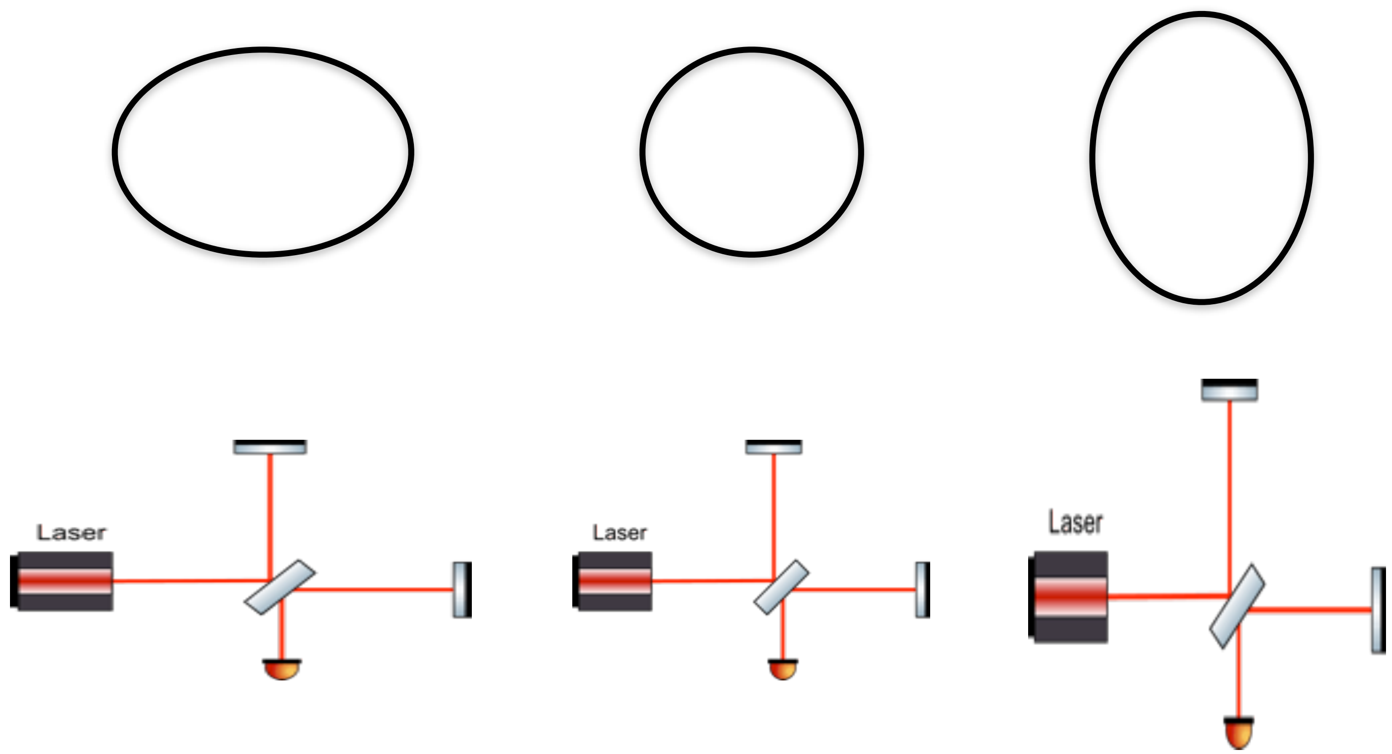
For a black hole binary system

$$m \sim 10\, M_\odot$$
$$R \sim 100\,\mathrm{km}$$
$$r \sim 100\,\mathrm{Mpc}$$

$$h \sim 10^{-21}$$
$$\nu \sim 10^2\,\mathrm{Hz}$$

Detecting Gravitational Waves





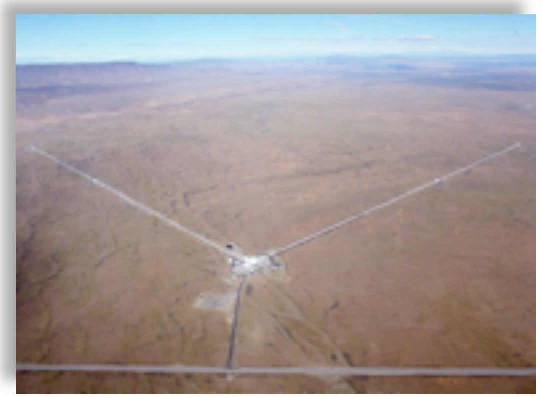
One measures the changes in the distance between the mirrors:

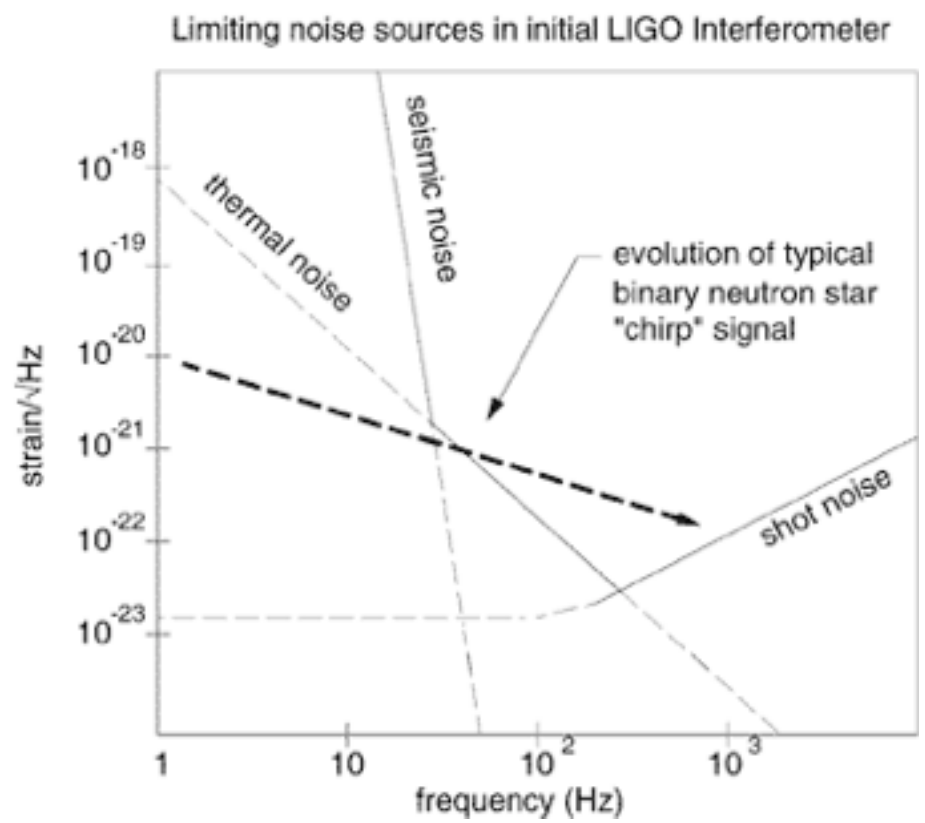
- Not by measuring the changes in the wavelength of the light from the lasers.

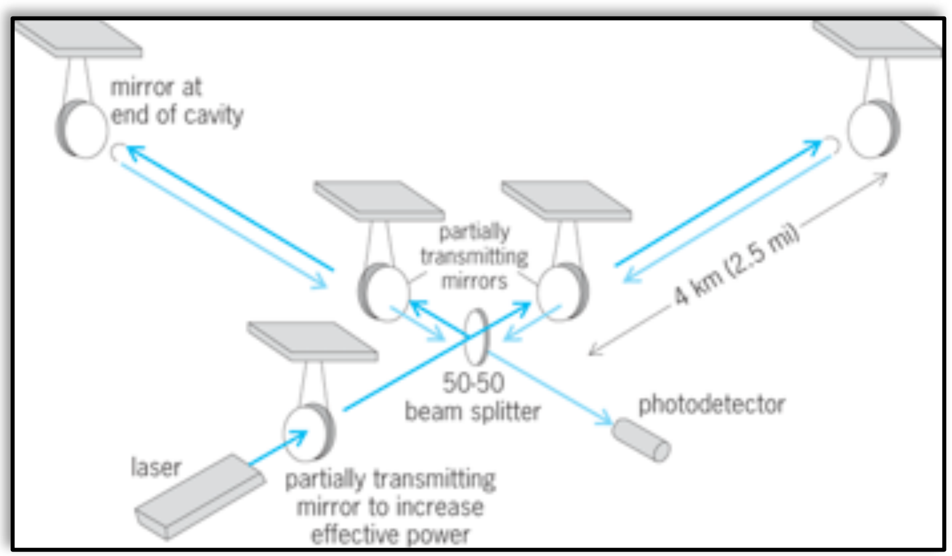
- But the shift in the arrival time of the wavelength crests of the light from the lasers.

P. Saulson, American Journal of Physics (vol. 65, issue 6, pp. 501-505)

Laser Interferometer Gravitational-Wave Observatory (LIGO)

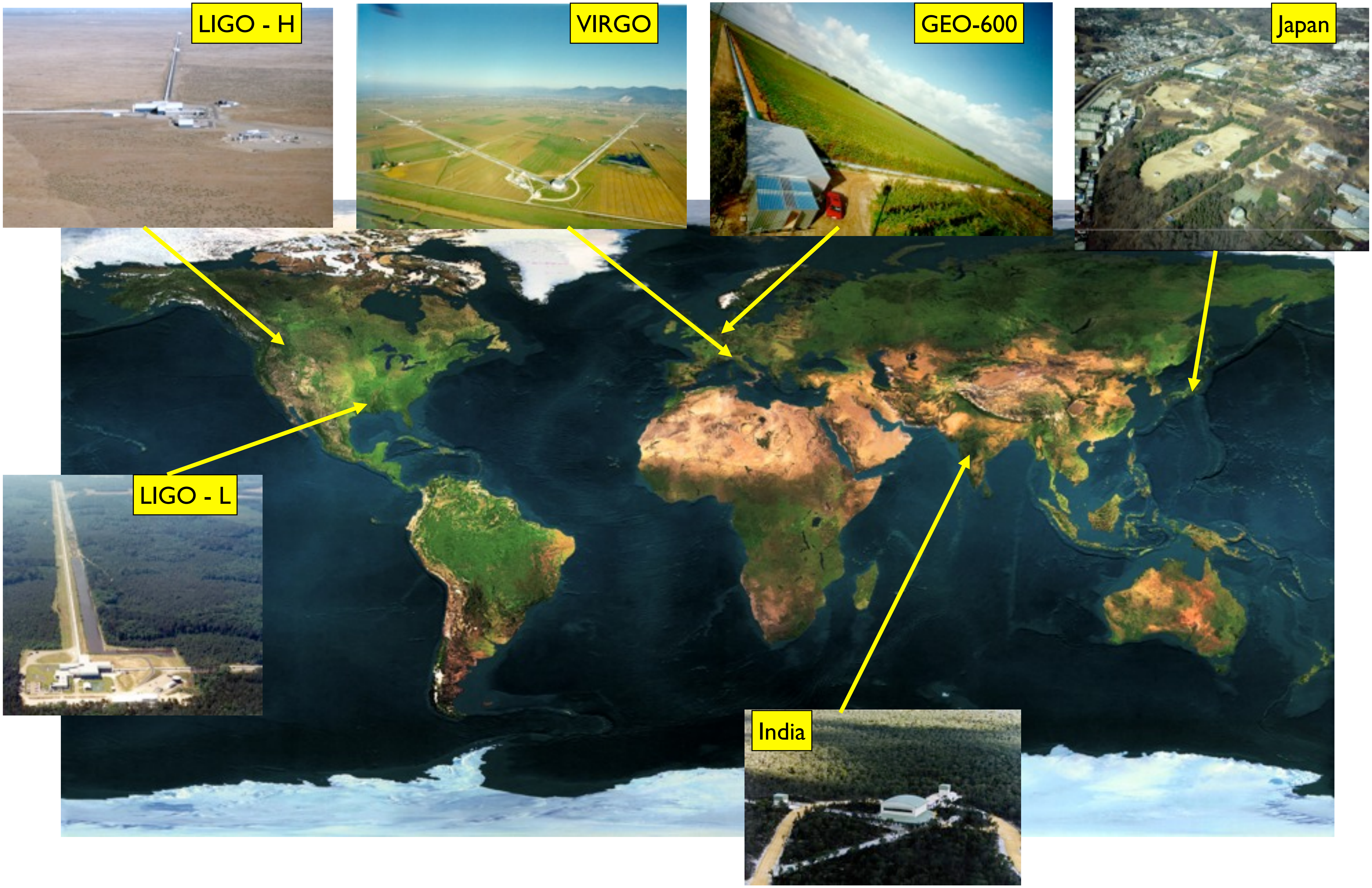




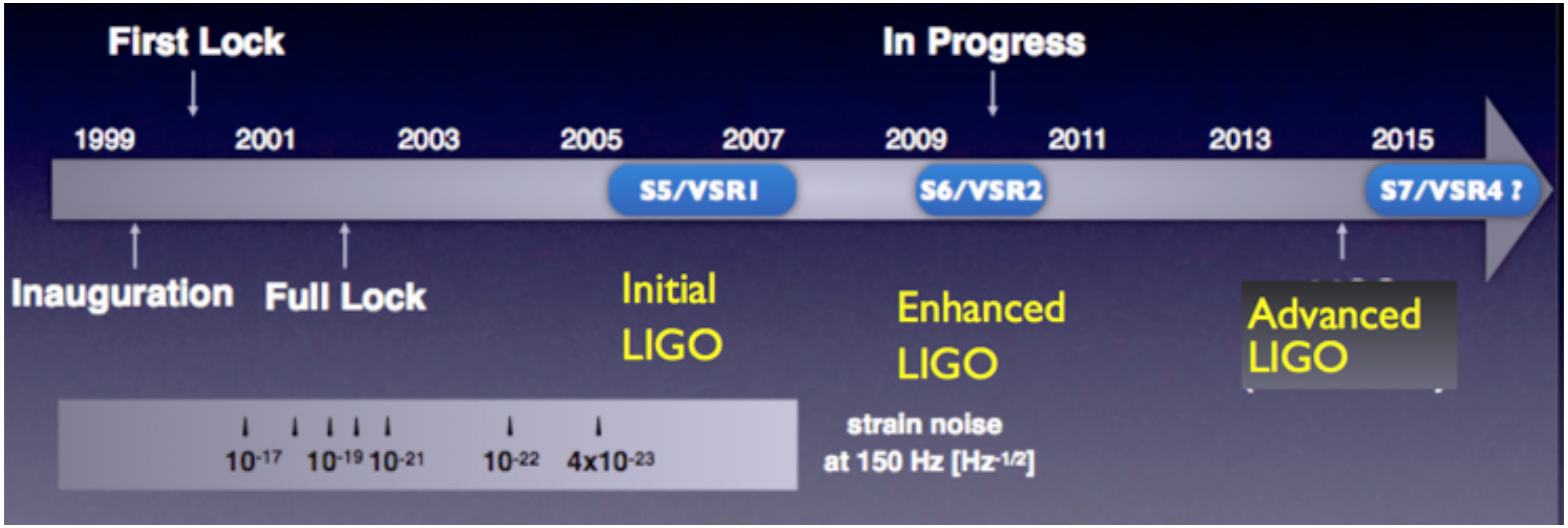


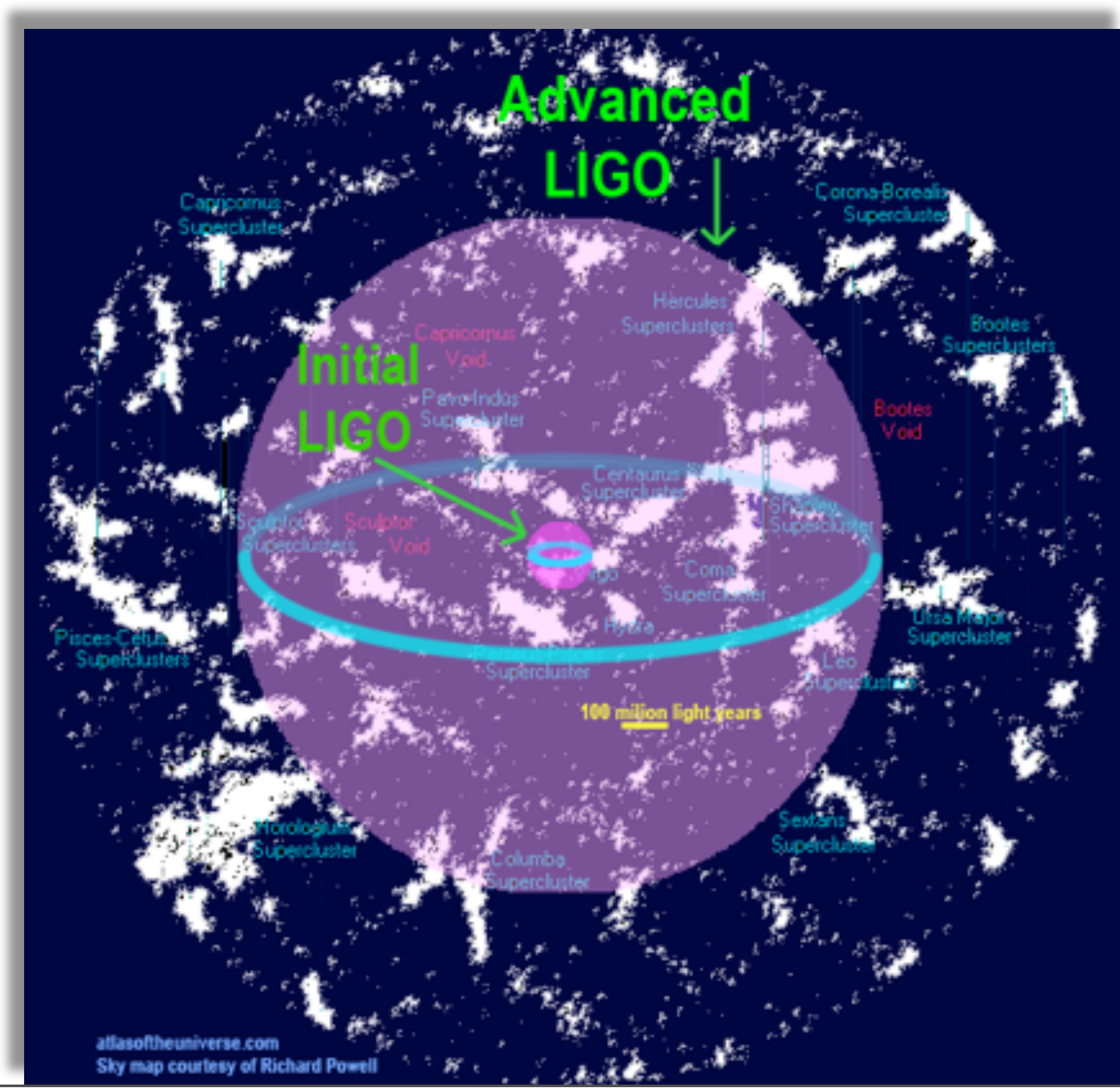
- Hanford, WA (4 km & 2 km) and Livingston, LA (4 km)
- Fabry-Perot cavities to increase its effective length
- Power-recycling' mirror to improved shot noise sensitivity
- 8 Watt Nd:YAG lasers
- 25 cm aperture l/1000 fused silica mirrors
- Advanced seismic isolation systems
- World's largest high-vacuum system

A Network of Detectors



LIGO Reach

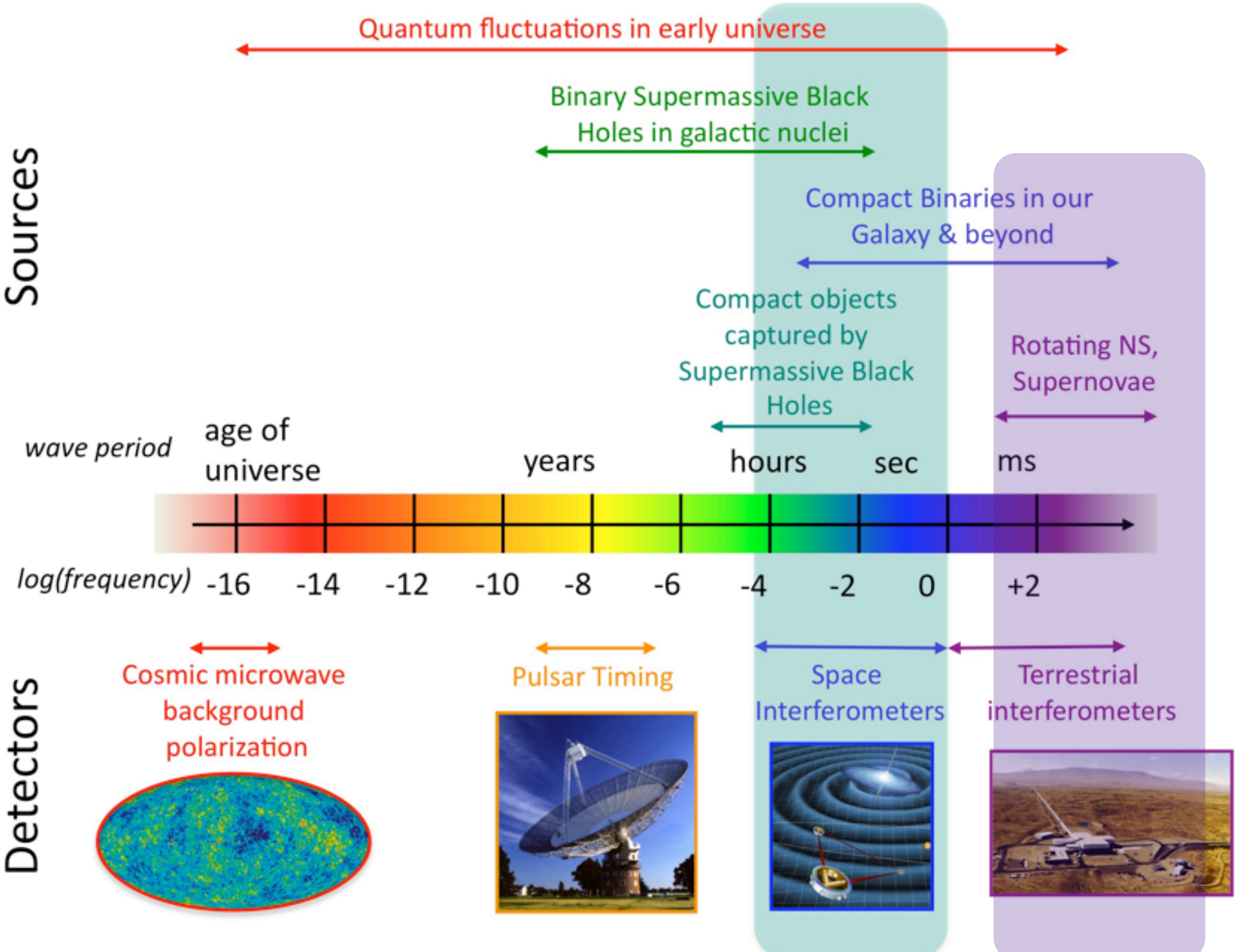




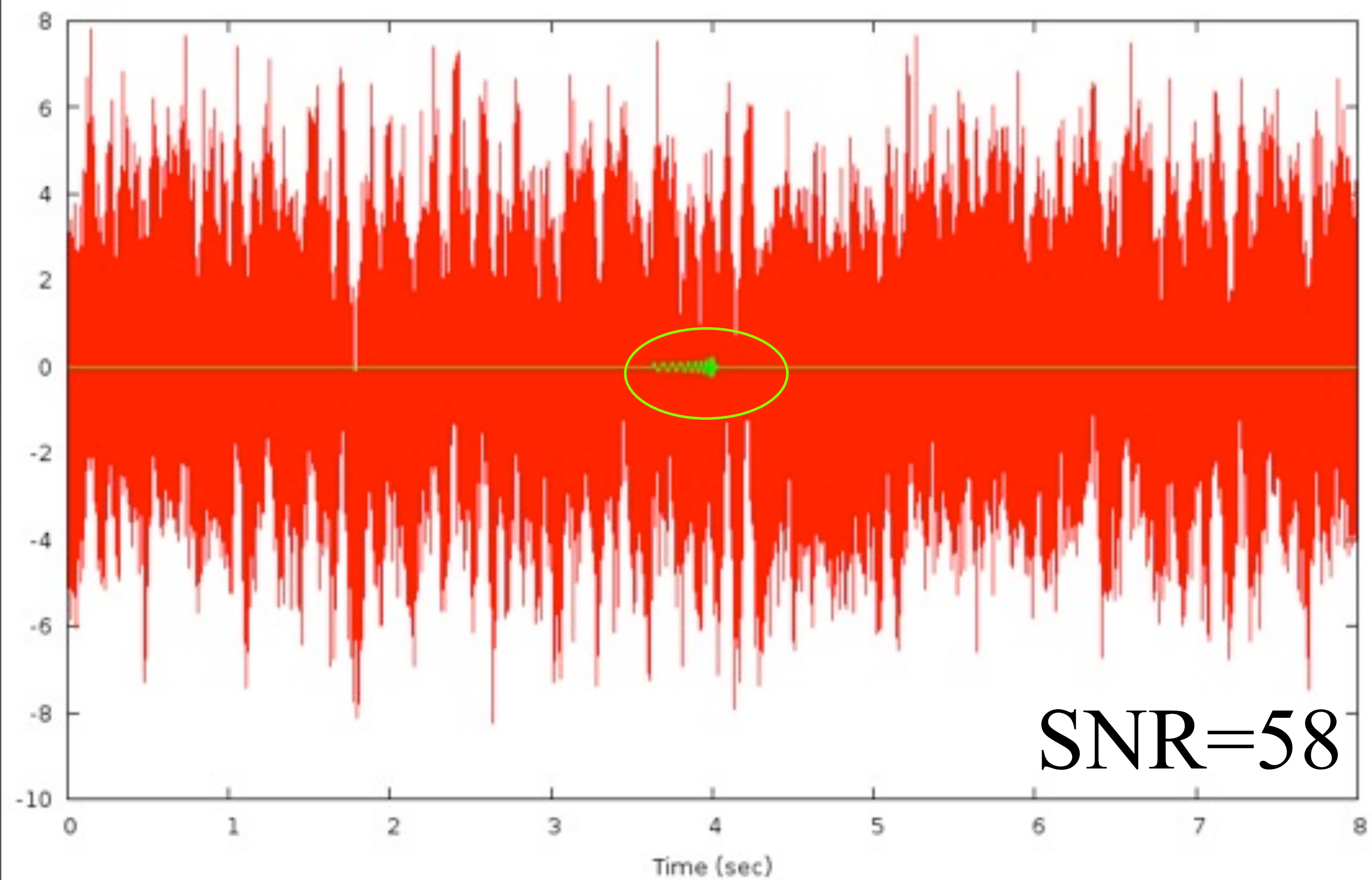
For NS-NS
Initial LIGO reach ~ 10 Mpc
AdvLIGO reach ~ 300 Mpc

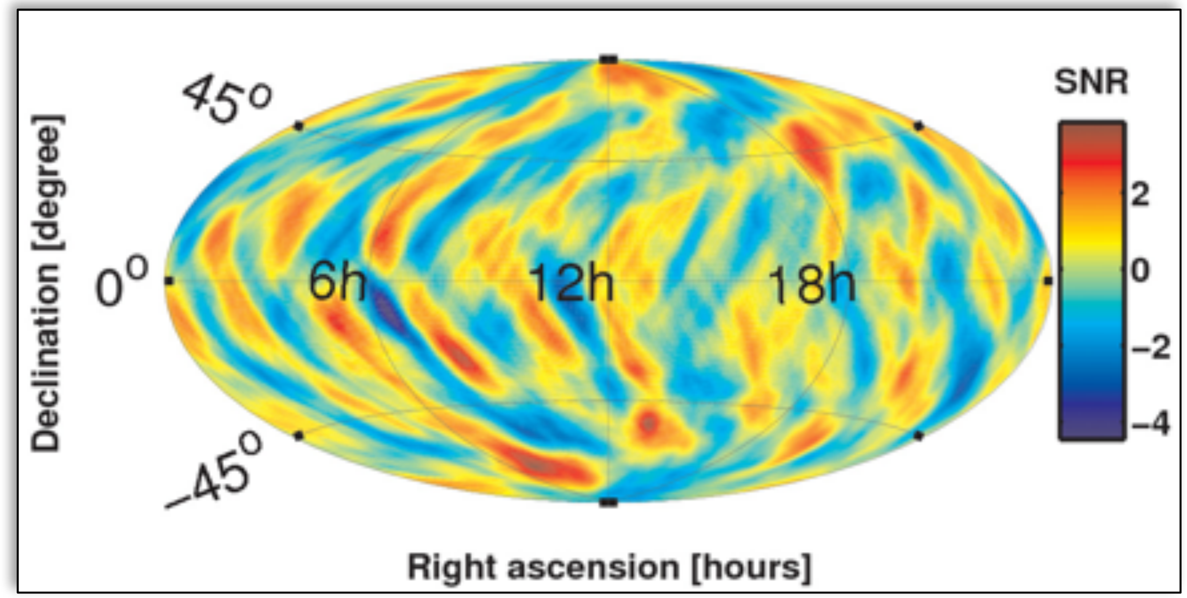
note: Virgo cluster is 16 Mpc away
1 Mpc = 3×10^{22} meters

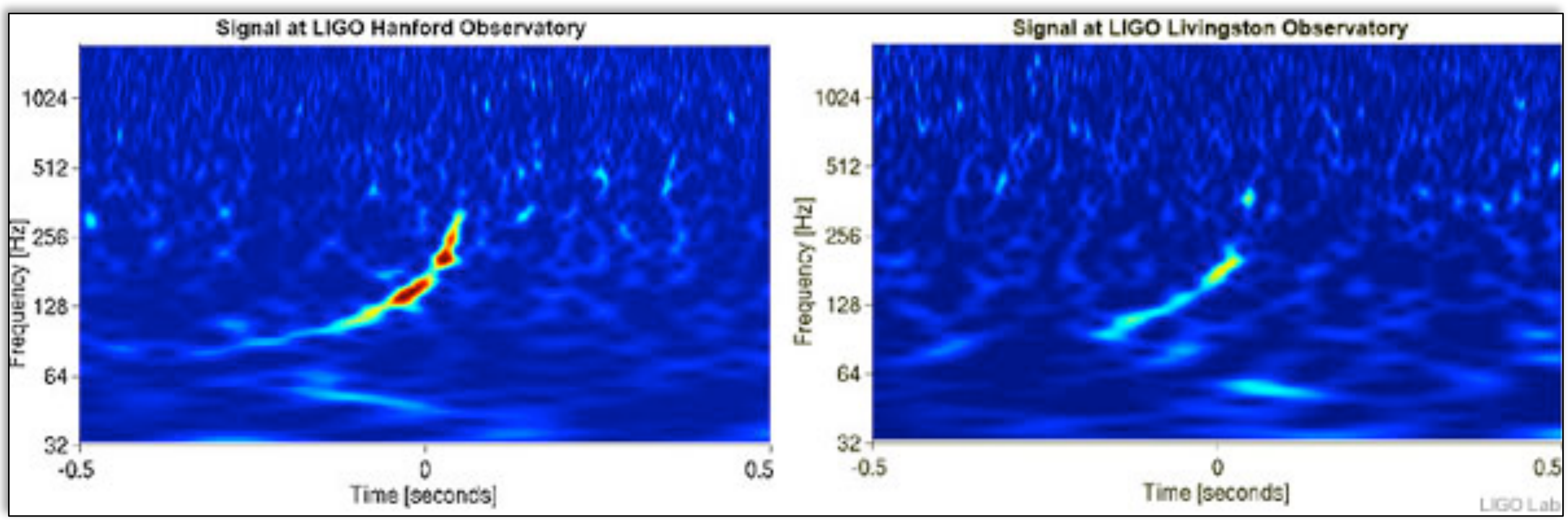
The Gravitational Wave Spectrum



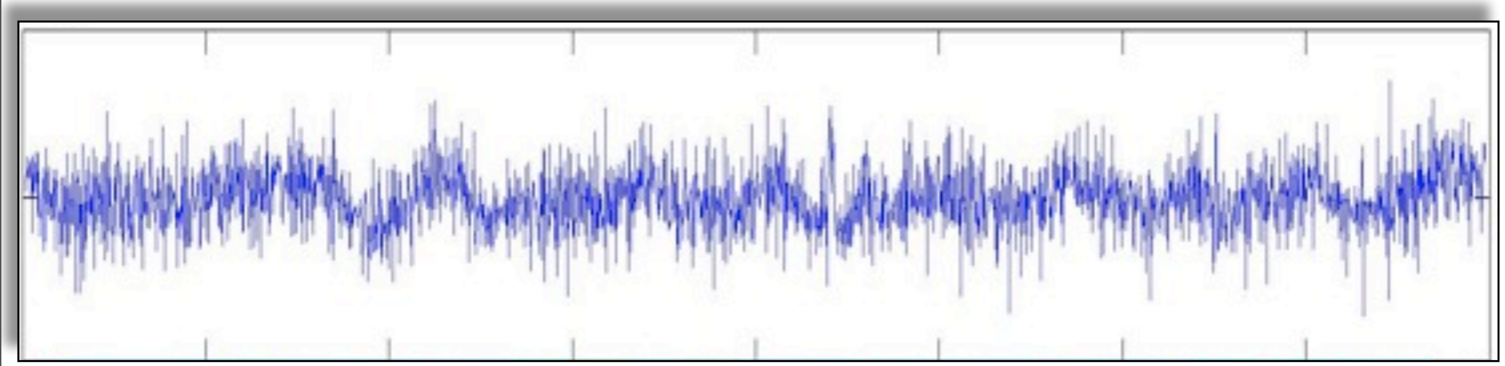
The Data Analysis Challenge

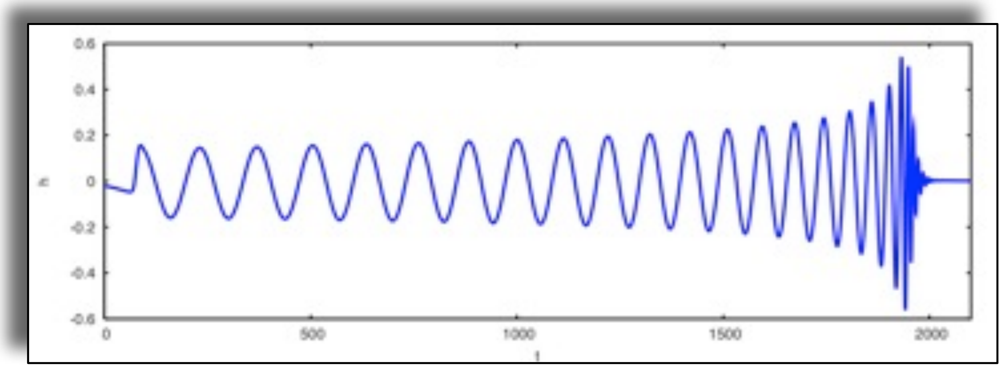






Optimal Matched Filtering



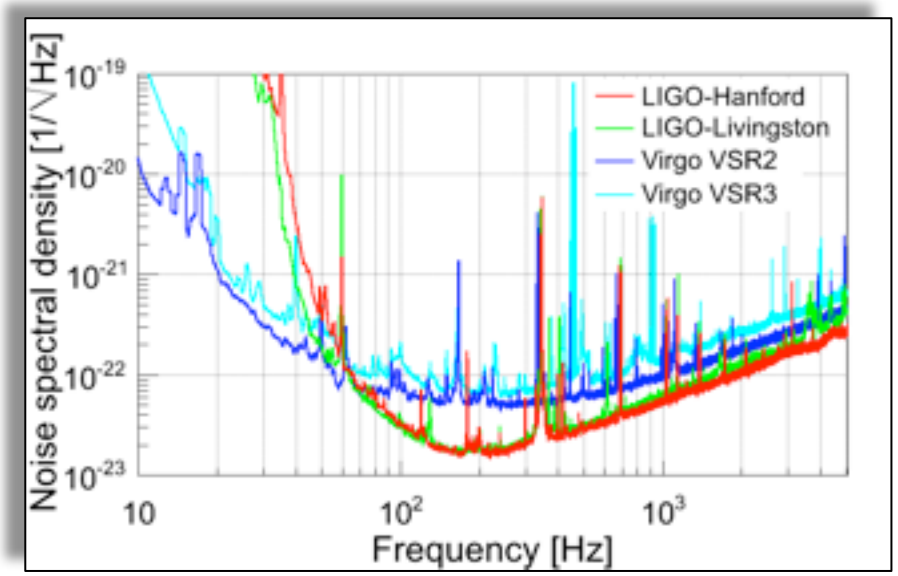


Data $\frac{\delta L}{L}$

Template prediction of h(t)

$$< s, h >= 4Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df$$

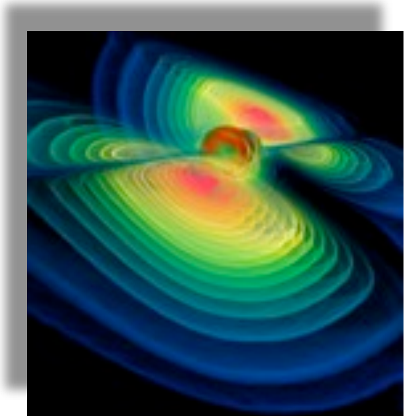
Noise Power Spectral Density



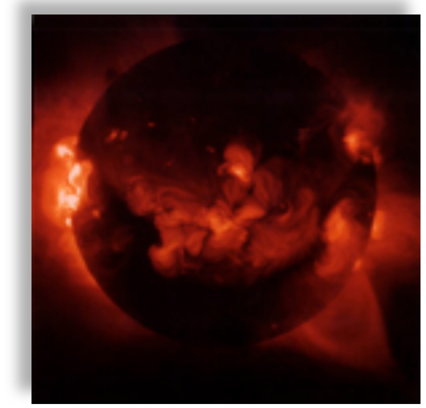
$$\mu(s,h) = \max_\lambda \frac{< s, h >}{\sqrt{< s, s >< h, h >}}$$

Look for maxima of $\mu(s, h)$
above some threshold

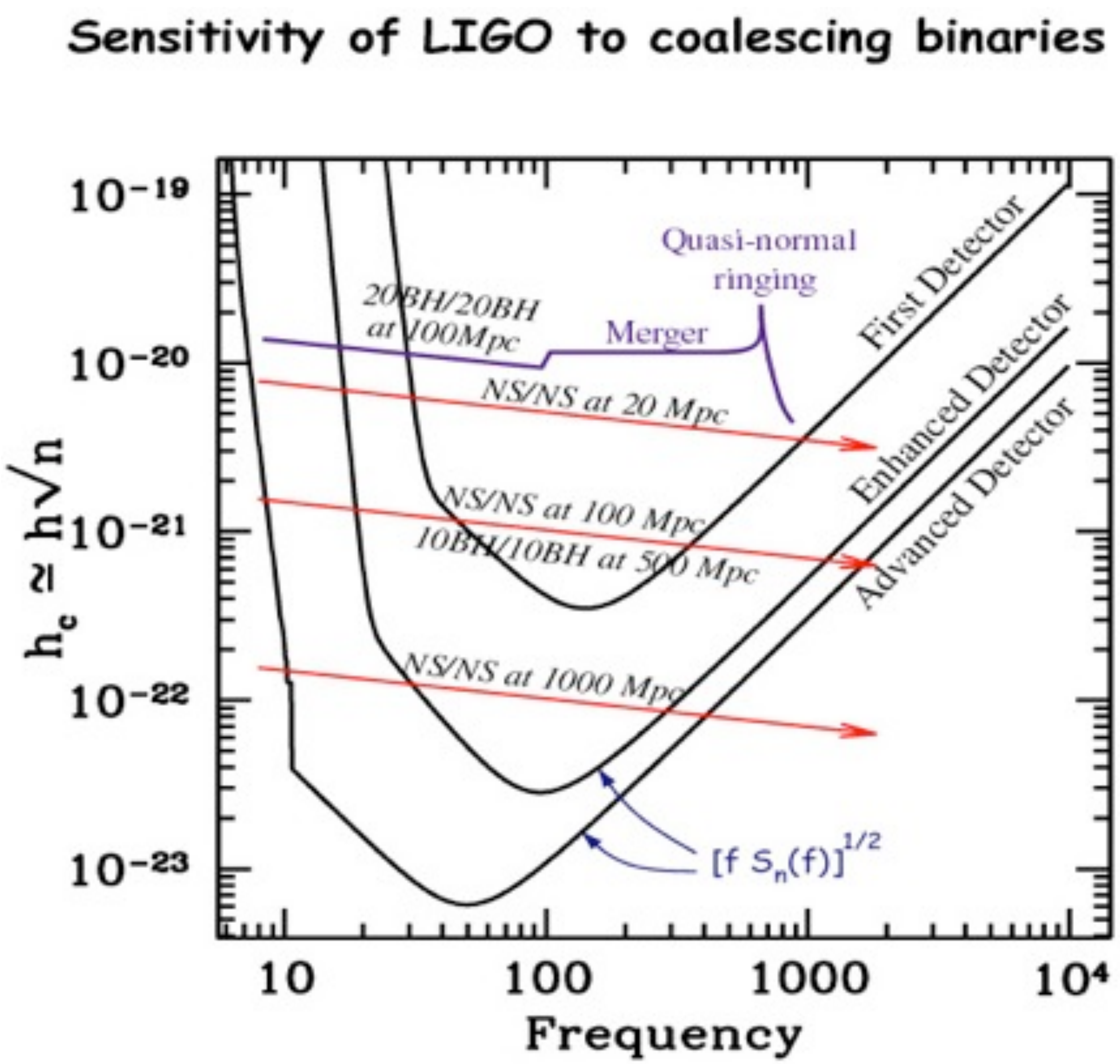
Black Holes Collisions



In a few seconds, a BH collision emits as much energy in gravitational radiation as a star does in light during its entire life!



BBH Initial LIGO: < .1/year
Advanced LIGO: > 10/year
BBH Signal lasts milli-seconds
Waveforms necessary for detection



increasing total mass ↖
increasing distance away from earth ↓

BBHs require solving: $G_{\mu\nu} = 8\pi\, T_{\mu\nu}$ Numerical Relativity

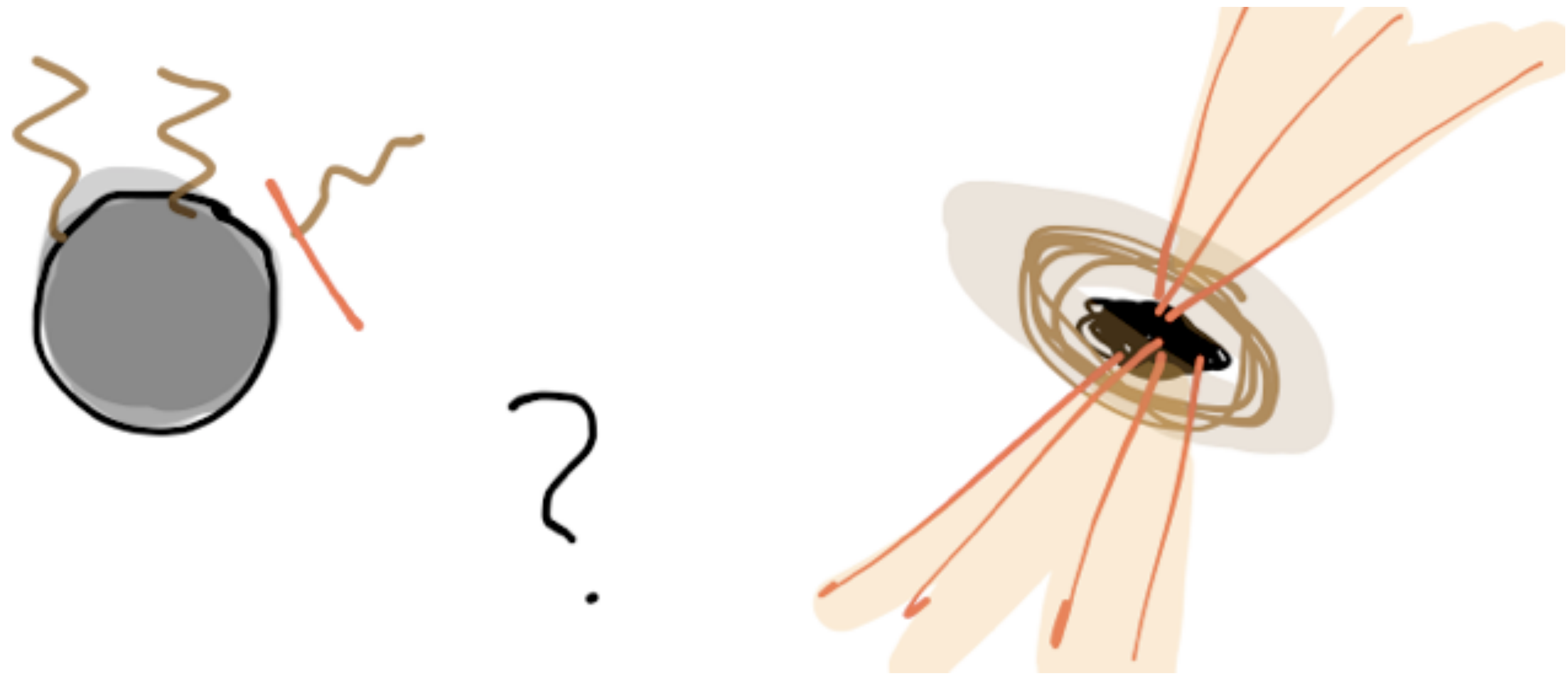
The First Crisp Definition of Numerical Relativity

MISNER summarized the discussion of this session: "First we assume that you have a computing machine better than anything we have now, and many programmers and a lot of money, and you want to look at a nice pretty solution of the Einstein equations. The computer wants to know from you what are the values of $g_{\mu\nu}$ and $\frac{\partial g_{\mu\nu}}{\partial t}$ at some initial surface, say at t = 0. Now, if you don't watch out when you specify these initial conditions, then either the programmer will shoot himself or the machine will blow up. In order to avoid this calamity you must make sure that the initial conditions which you prescribe are in accord with certain differential equations in their dependence on x, y, z at the initial time. These are what are called the "constraints." They are the equations analogous to but much more com-

GR 1: Conference on the role of gravitation in physics
University of North Carolina, Chapel Hill [January 18-23, 1957]

The Two-Body Problem in General Relativity

Shapiro and Teukolsky 1985
"... the Holy Grail of numerical relativity: a code that simultaneously avoids singularities, handles black holes, maintains high accuracy, and runs forever."



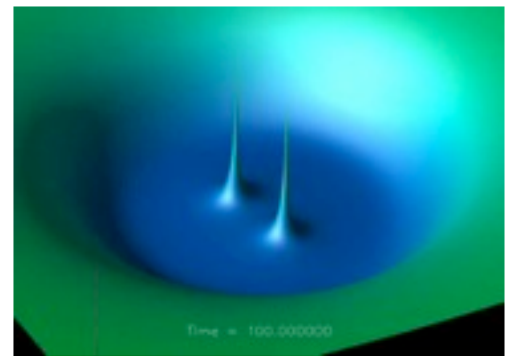
- Simple? It is pure curvature, no messy neutron stars.
- Black Holes are complicated - there is a physical singularity!
- Black Holes are simple - described by mass and spin (and charge)!
- It took over 20 years to successfully orbit, merge and ringdown two black holes.

Binary Black Hole Problem “Solved”

FIRST ORBIT by Bruegmann, Tichy and Jansen
Phys.Rev.Lett. 92 (2004) 211101

2005 Pretorius
Binary inspiral and merger

Phys.Rev.Lett. 95 (2005) 121101



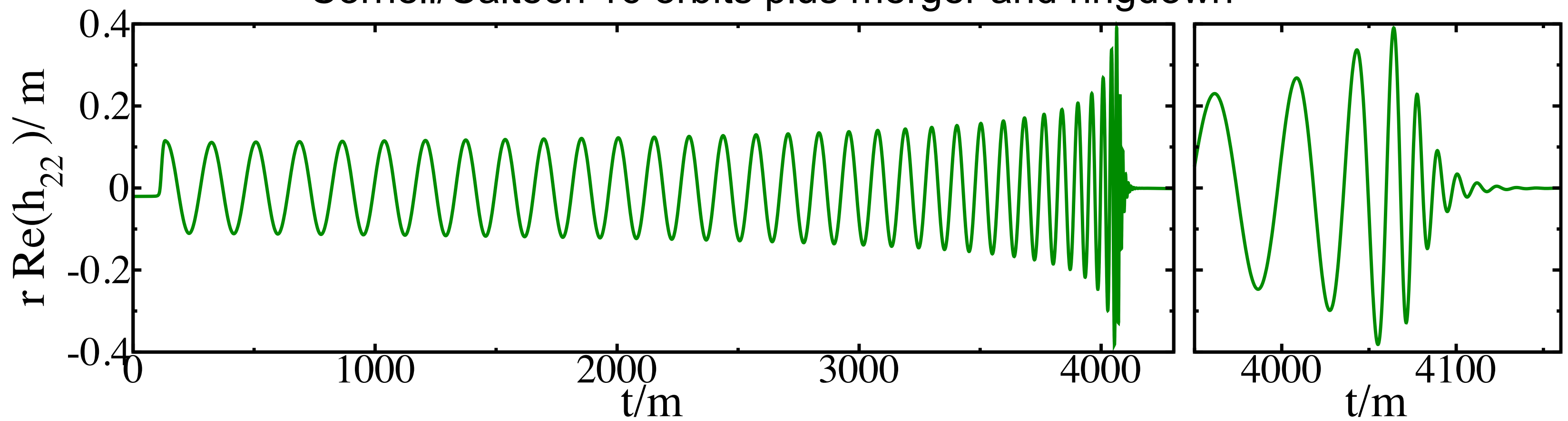
2006 RIT and NASA
Moving Punctures Method

Campanelli, Lousto, Zlochower
Phys.Rev.Lett. 96 (2006) 111101

Baker, Centrella, Choi, Koppitz, van Meter
Phys.Rev.Lett. 96 (2006) 111102

Ian Hinder and Frank Herrmann, PSU

Cornell/Caltech 16 orbits plus merger and ringdown



Courtesy Lee Lindblow

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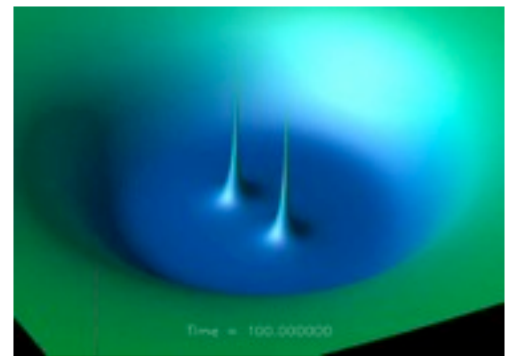

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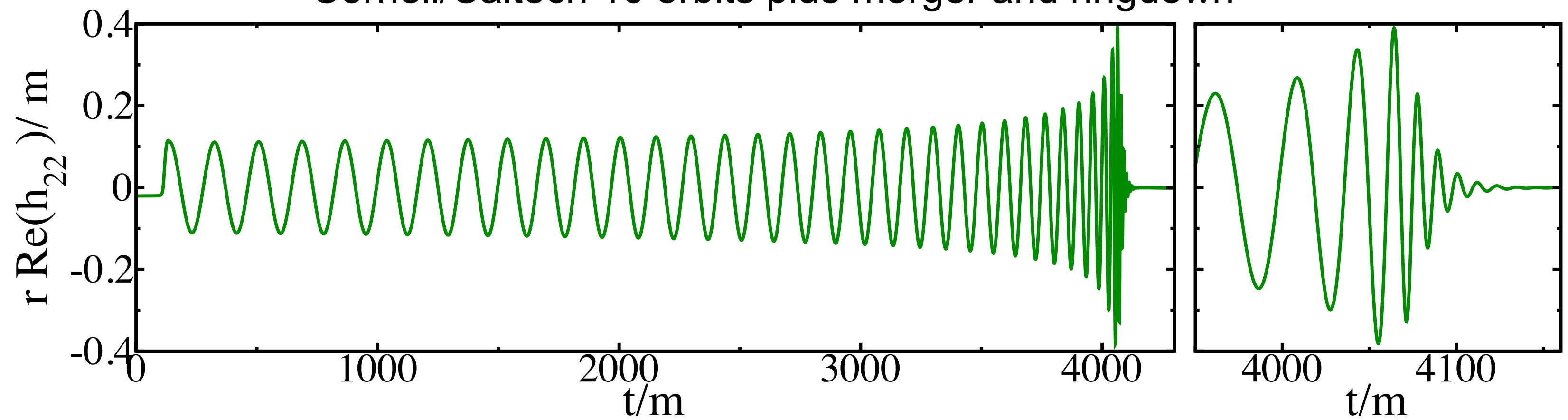
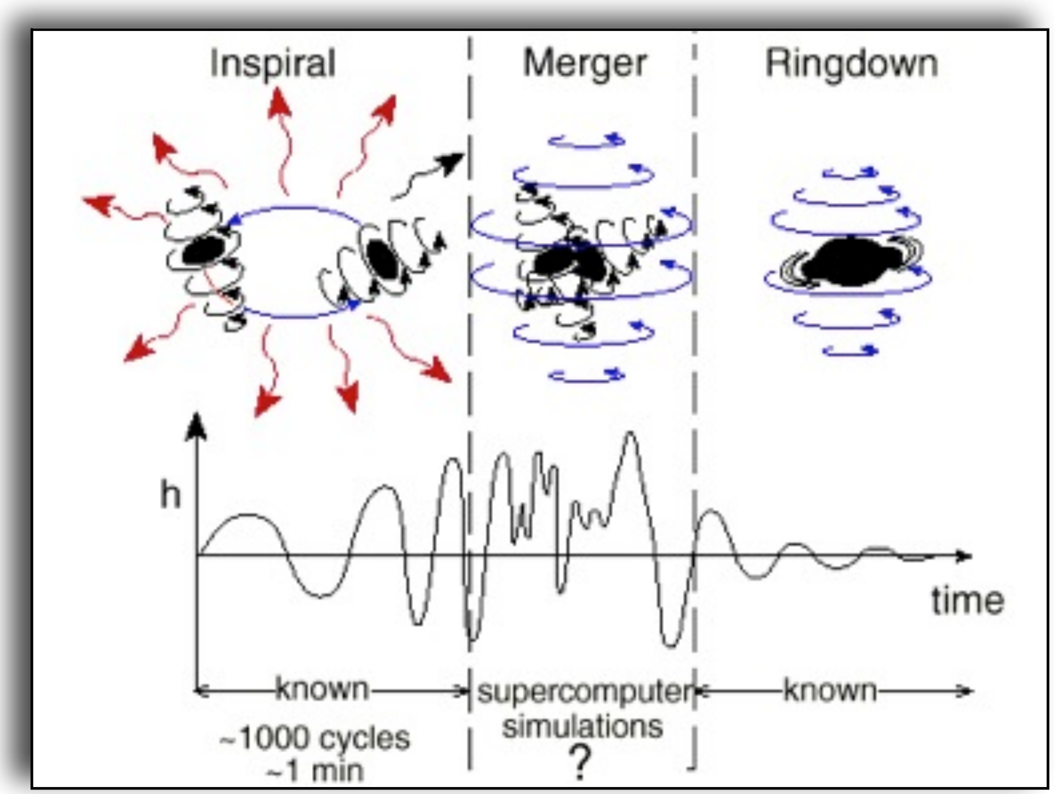


Courtesy Lee Lindblow

What made it possible?



Why did it take so long?

We did not have the appropriate package of Mathematical Tools (e.g. Gauges, Formulations) and Computational Infrastructure (e.g. Adaptive Mesh Refinements, Hardware, etc.)

Holy Grail Obtained!

Fundamental Gravitational Physics Explored

Orbital Hang Ups

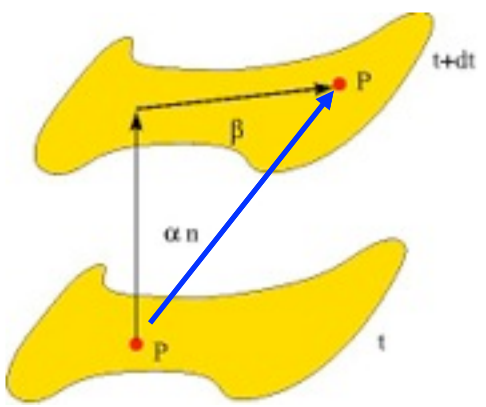
Gravitational Recoil

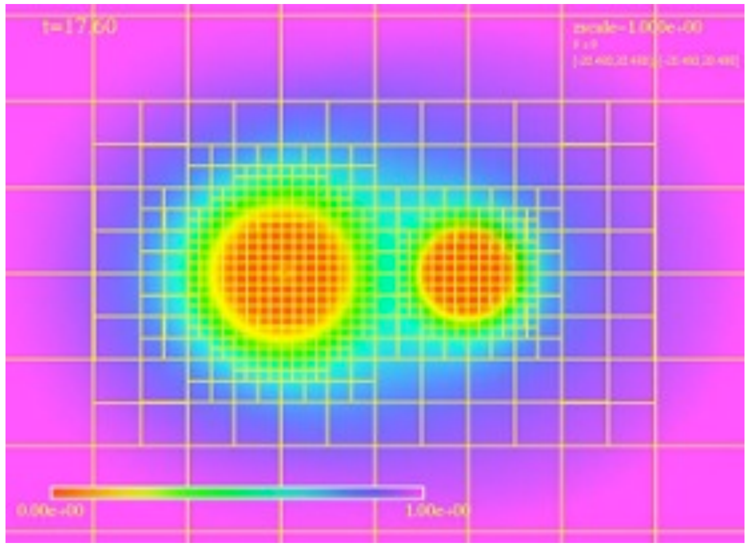
Black Hole Remnant

Black Hole Triplets

Extreme Orbits

Gravitational Wave

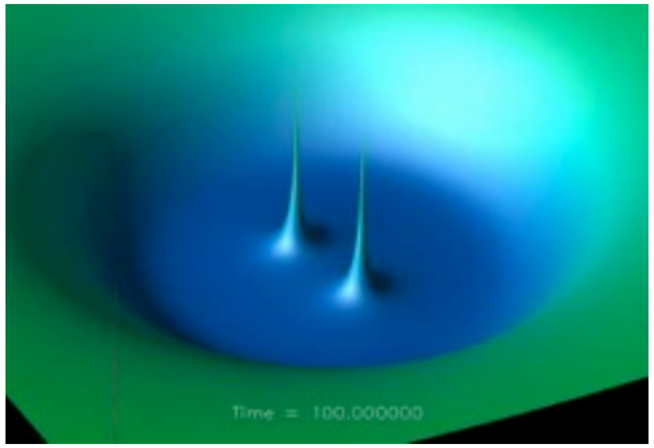




Dale Choi (NASA-GSFC)

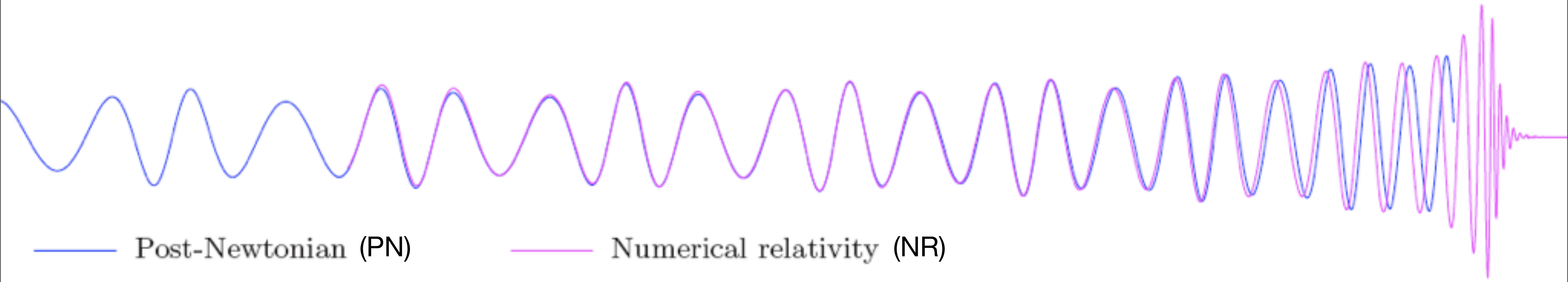
Where are we now? Challenges?

- Multiple codes and approaches: Ensuring that results are right!
- Checks with post-Newtonian calculations have been carried out.
- Covering more of the parameter space (masses, spins)
- New methods to tackle more extreme mass ratios (beyond 1:10) and spins (beyond 0.9)
- Most of current BH codes need to improve their scaling



F. Pretorius, PRL 95, 121101 (2005). M. Campanelli et al PRL 96, 111101 (2006). J. G. Baker et al PRL 96, 111102 (2006). F. Herrmann et al CQG. (2007). J. G. Baker et al., APJ. 653, L93 (2006). J. A. Gonzalez et al PRL 98, 091101 (2007). F. Herrmannet al, APJ. 661, 430 (2007). M. Koppitz et al., PRL 99, 041102 (2007). M. Campanelli,et al APJ J. 659, L5 (2007). J. A. Gonzalez, et al PRL 98, 231101 (2007). W. Tichy and P. Marronetti, PRL. D 76, 061502 (2007). M. Campanelli, et al PRL 98, 231102 (2007). J. G. Baker et al., APJ. 668, 1140 (2007). F. Herrmann,et al PRD 76, 084032 (2007). B. Bruegmann, et al PRD 77, 124047 (2008). D. Pollney et al., PRD 76, 124002 (2007). C. O. Lousto and Y. Zlochower, PRD 77, 044028 (2008). J. G. Baker et al., APJ. 682, L29 (2008). S. Dain, C. O. Lousto, and Y. Zlochower, PRD 78, 024039 (2008). J. Healy et al PRL102, 041101 (2009). J. A. Gonzalez, U. Sperhake, and B. Bruegmann, PRD 79, 124006 (2009), T. Chu et al arXiv.org:0909.1313 (2009). D. Pollney, et al arXiv.org:0910.3803 (2009). M. Hannam et al PRD 78, 104007 (2008). J. G. Baker et al PRL 99, 181101 (2007). M. Hannamet al PRD 77, 044020 (2008). M. Boyle et al.PRD 76, 124038 (2007). M. Campanell et al PRD79, 084010 (2009). M. Boyle et al., PRD 78, 104020 (2008). I. Hinder, F. Herrmann, P. Laguna, and D. Shoemaker, arXiv.org:0806.1037. Lousto and Zlochower arXiv:1009.0292.

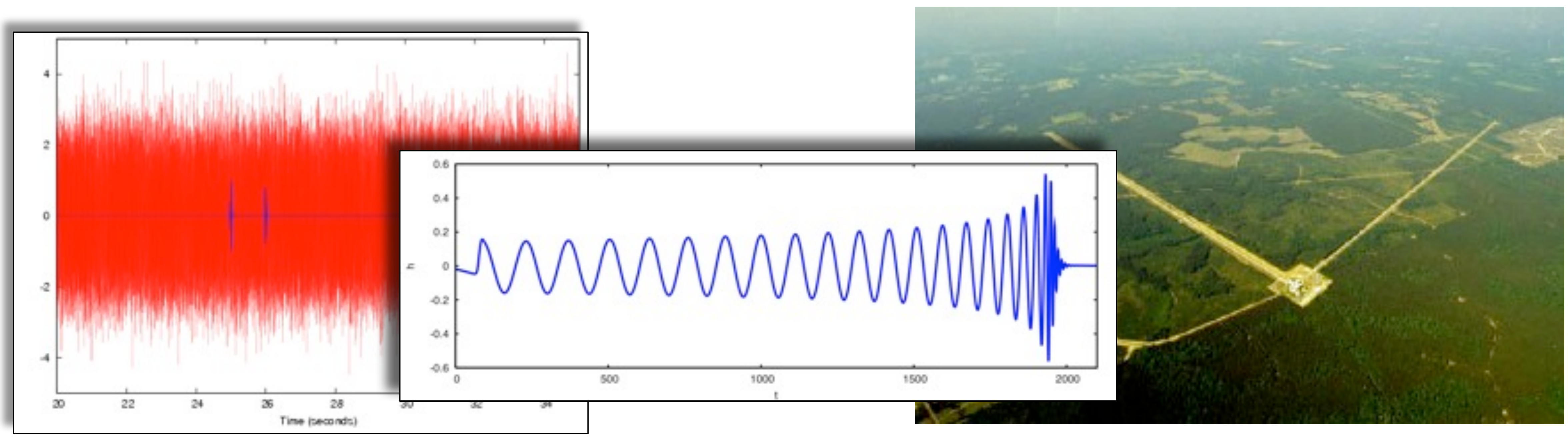
Historical Perspective on NR and GWs



- LIGO/Virgo target source is NS-NS inspiral
- PN adequate for both detection and characterization of signal for current generations of detectors
- Until 2005, no BBH solution through BH merger existed
- Approximations developed
    - Effective One Body Model (Buonanno & Damour PRD 59 1999)
    - Lazarus (Baker et al PRD 65 2002)
- Template banks built of equal-mass, non-spinning inspiral using PN
- NR groups quickly start probing the physical parameter space

How can GW capitalize on NR success?

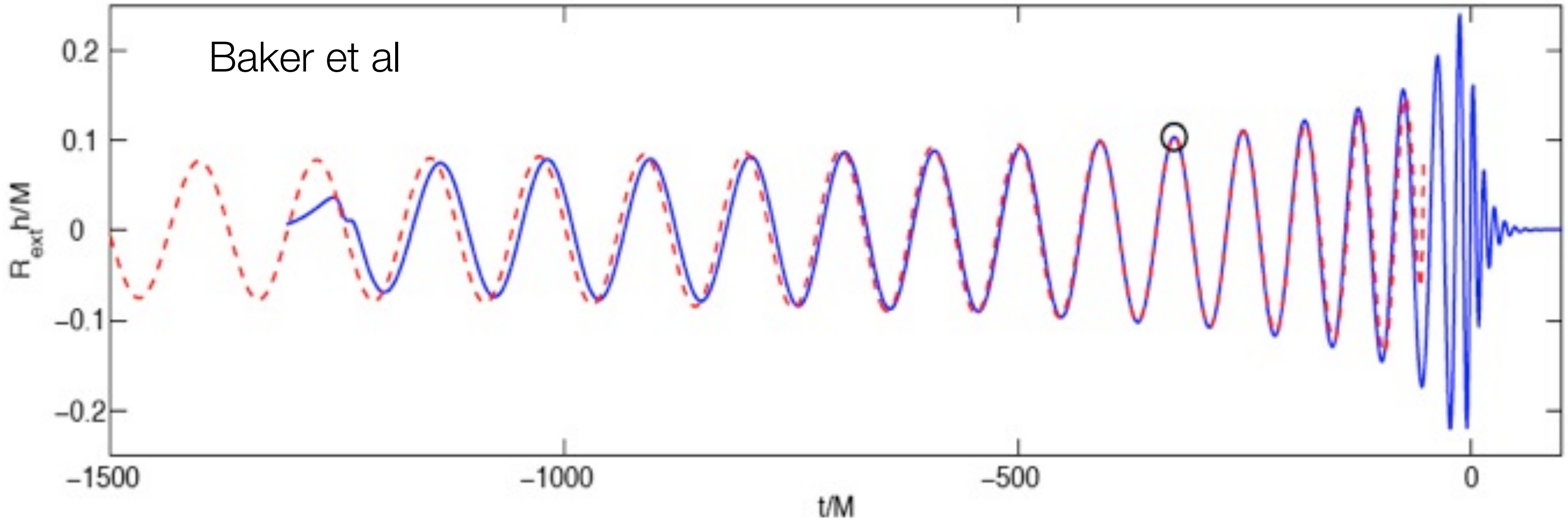
- What physics is encoded in the NR waveforms? The Unexpected? nonlinearities?
- Do we know enough to detect? Can we differentiate the system parameters?



OUR UNDERSTANDING OF
GRAVITY CHALLENGED in 2015

Testing PN

Equal-mass, non-spinning comparisons agree up to 2-3 orbits before merger.



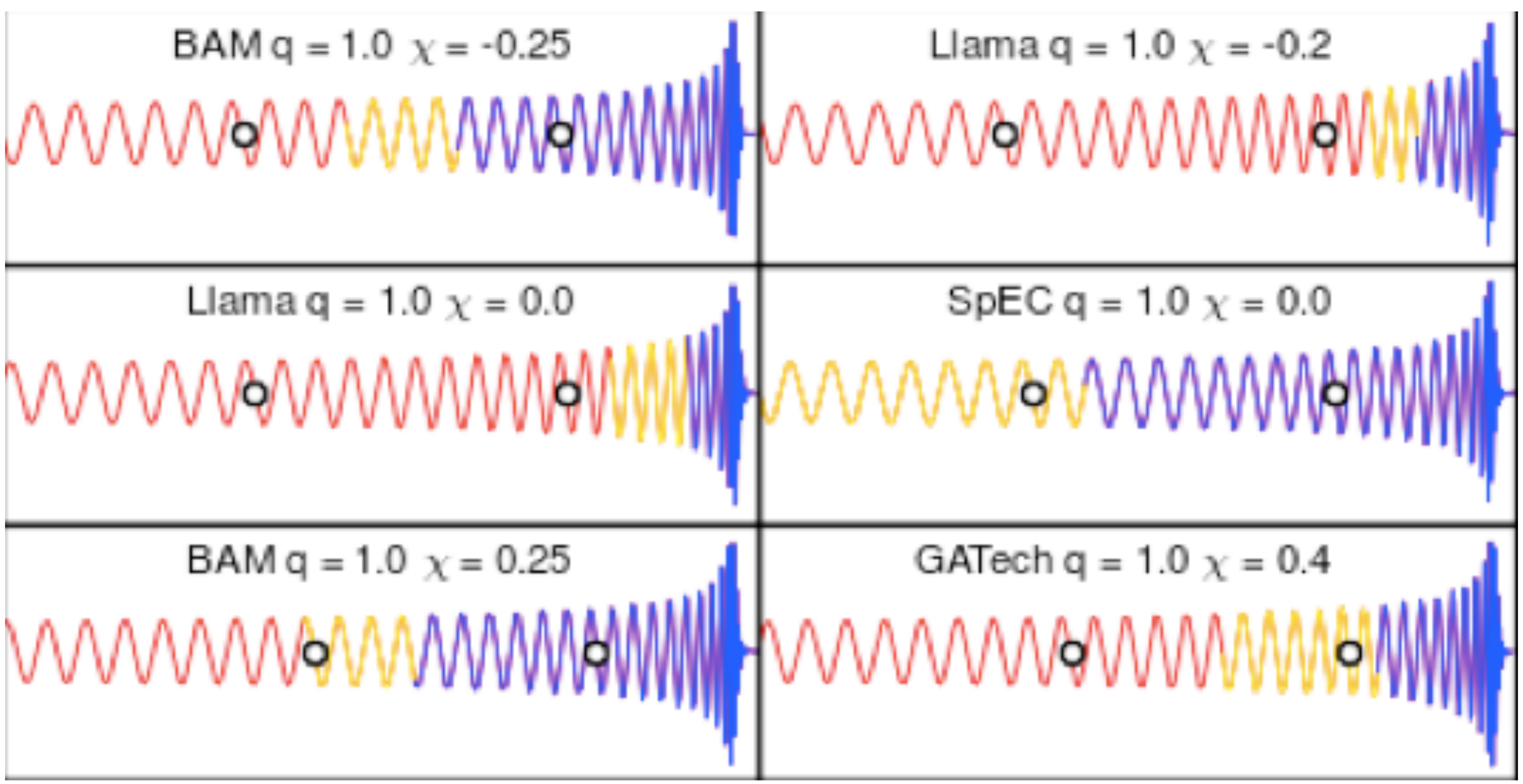
- Equal-mass nonspinning
  - Baker et al PRL 99, 181101 (2007)
  - Boyle et al PRD 76 (2007) - Finds < 0.05 radians over 30 cycles for 3.5 PN order.
  - Pan et al PRD 77 (2008).
- Non-precessing, spinning, unequal mass (less agreement)
  - Hannam et al 2007, 2008
  - Santamaria et al 2010
- Eccentric, Hinder et al 2010 (less agreement)

Numerical INJection Analysis Project (NINJA)

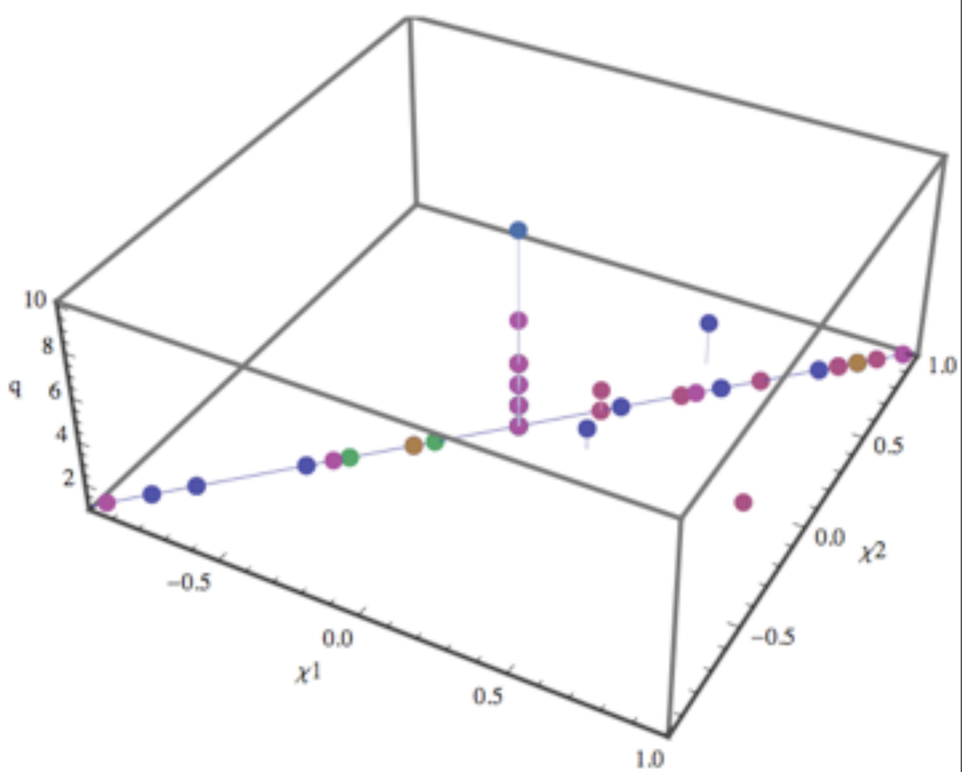
- Established in January 2008 at a KITP workshop to facilitate close ties between the numerical relativity and data analysis communities.
- Studied the response of gravitational-wave search schemes to waveforms calculated using numerical relativity.
- Open collaboration:
  - 10 numerical relativity groups submitted 23 waveforms produced by 9 independent codes of any BBH configuration
  - 9 data analysis groups added the NR waveforms to simulated, colored Gaussian noise and analyzed the results using burst detection, inspiral detection and parameter estimation
- NINJA-1 resulted in 2 publications with the full author list and 5 related publications (CQG 26 2009 165008)

NINJA-2 Improvements for better science

- Increase and verify quality of NR waveforms
- Produce long hybrid waveforms be stitching PN and NR
- Conduct extensive comparisons between codes, PN approximates and hybridization
- Systematic study of the aligned-spin parameter space: are we missing any signals?
- Real noise, for a realistic false alarm calculation (MOU with LVC)



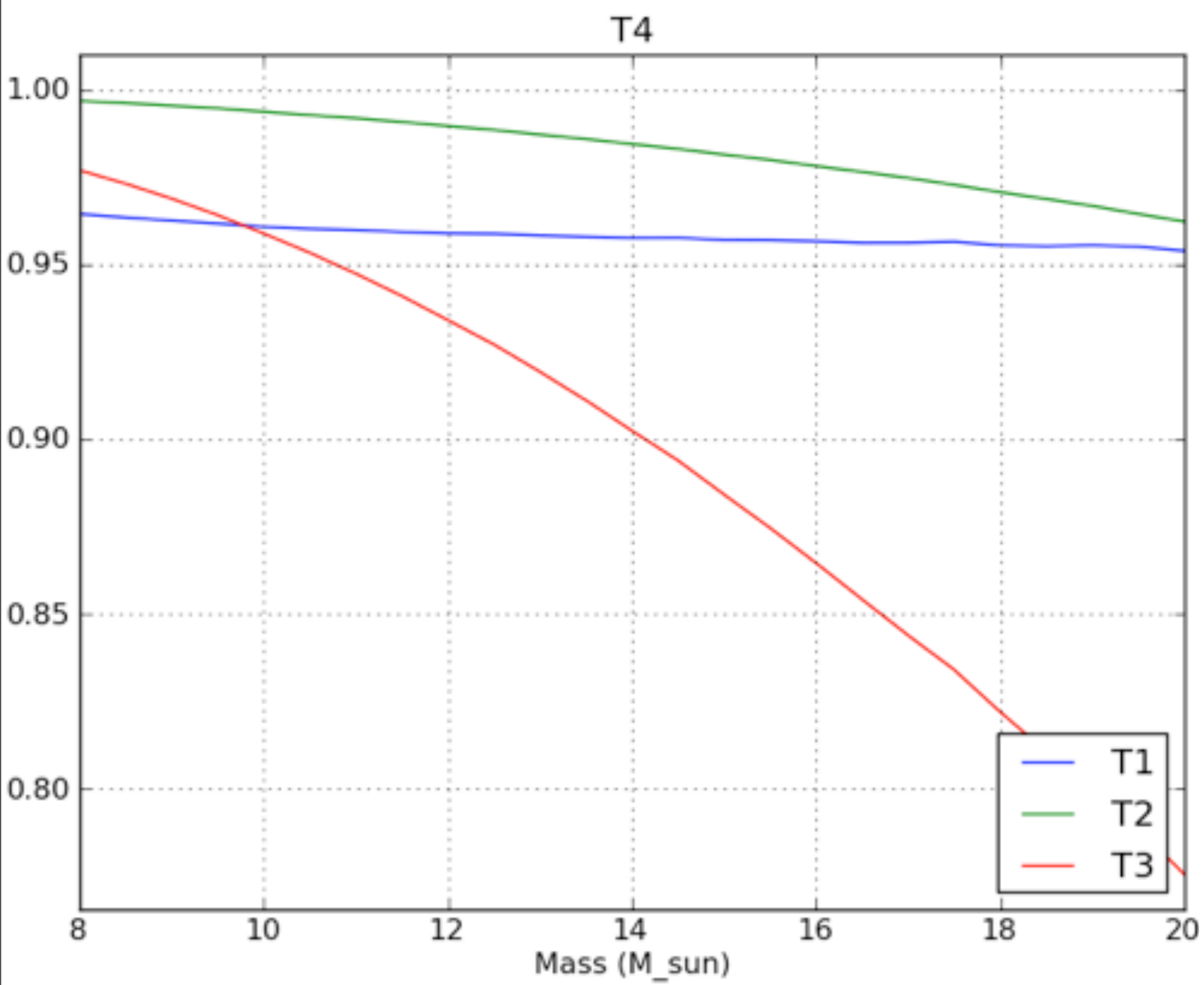
NINJA-2 waveform catalog

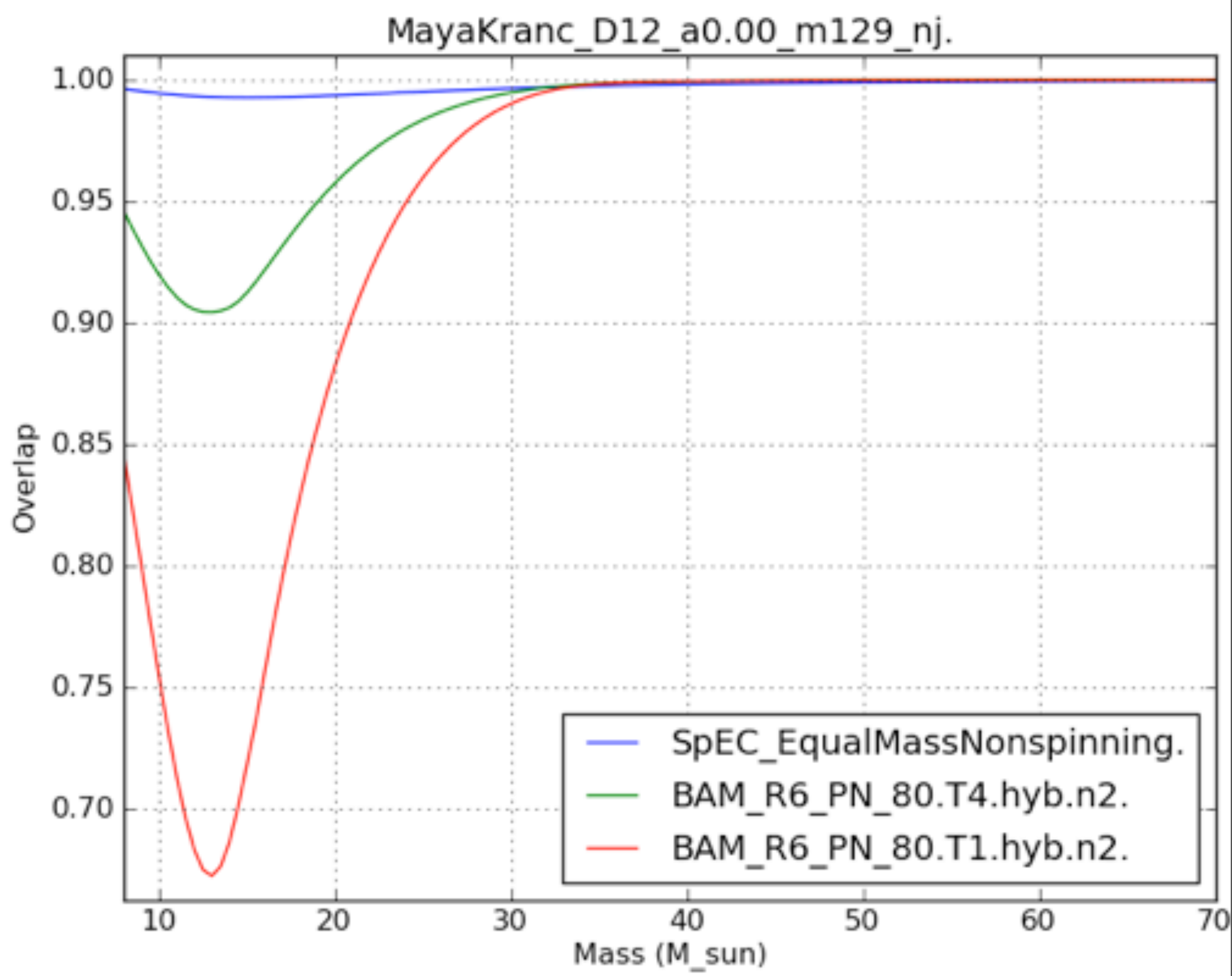


NINJA-2 Results

$$\langle h_1 | h_2 \rangle = 2 \int_{f_{\min}}^{f_{\max}} \frac{\tilde{h}_1 \tilde{h}_2^* + \tilde{h}_1^* \tilde{h}_2}{S_n}$$

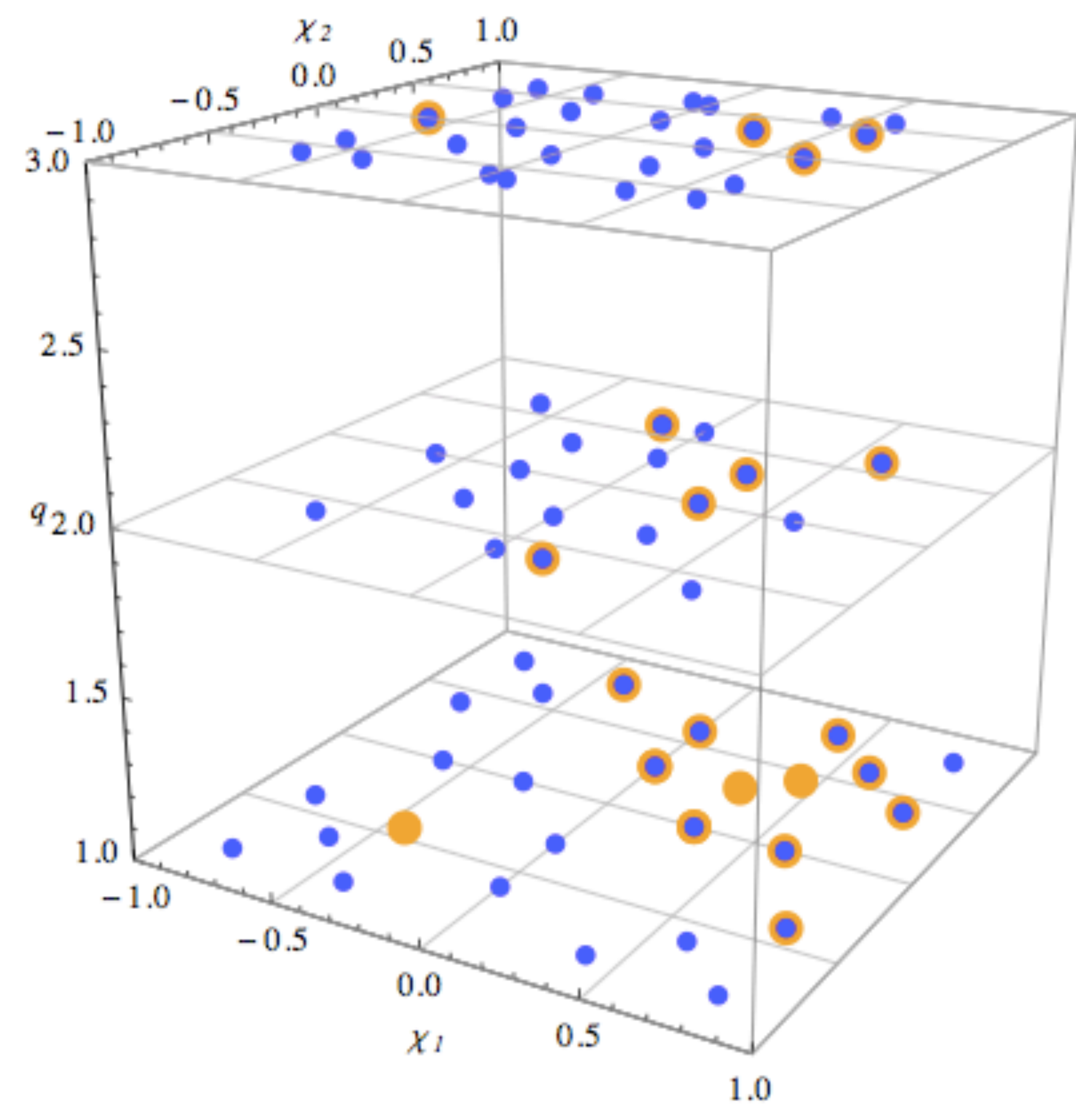
- NR codes/waveforms agree
- PN approximates differ and are the largest source of error
- This implies, we need longer NR waveforms (time!!)
- Need better coverage of parameter space
- CQG 29 (2012) & One in preparation
- Take home message was PN stitching will matter



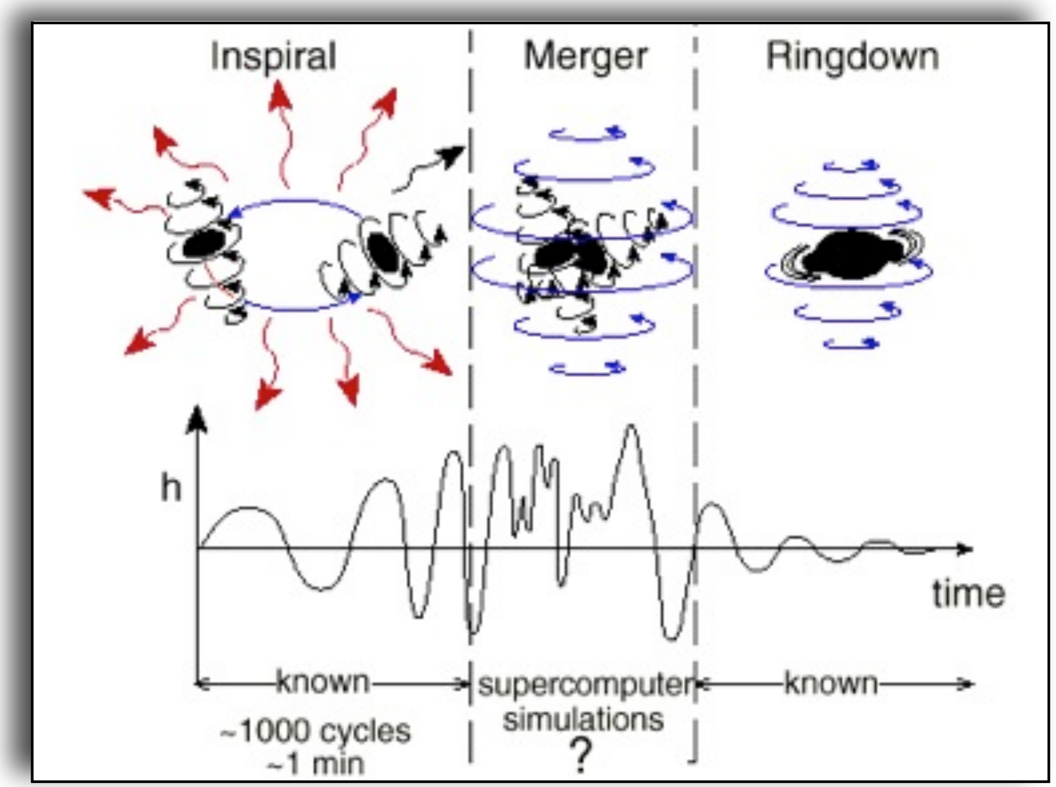


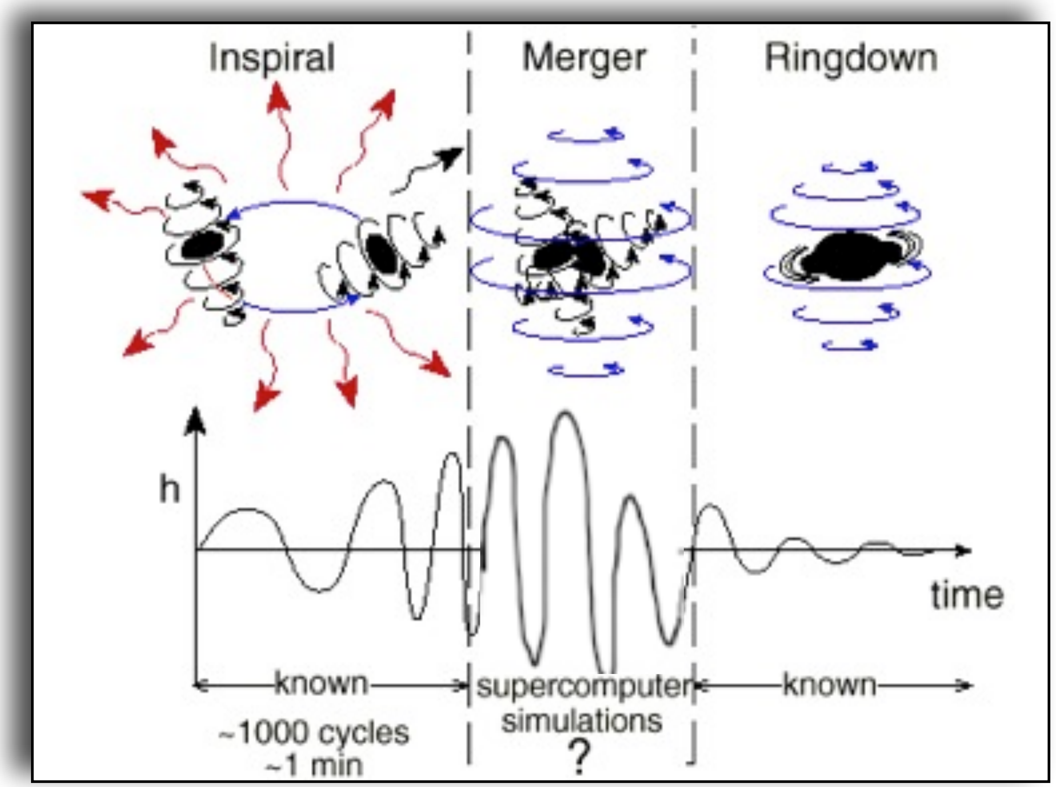
Numerical Relativity & Analytical Relativity (NRAR Collaboration)

- Goal is to compute the next generation template banks.
- Phenomenological waveform families are fit to NR waveforms produced by the community (Ajith et al arXiv.org:0704.376, Pan et al arXiv:0704.1964, Ajith 0710.2335, Buonanno et al 0706.3732, Damour et al 2008, Damour 2009, Buonanno et al 2009, NINJA 2009 and Samurai 2009, Santamaria & Ajith 2007)
- First paper is out (arXiv:1307.5307 Hinder et al for the NRAR collaboration)
- We learned that current template families will likely detect mergers of BBHs from non-precessing systems.



But ...



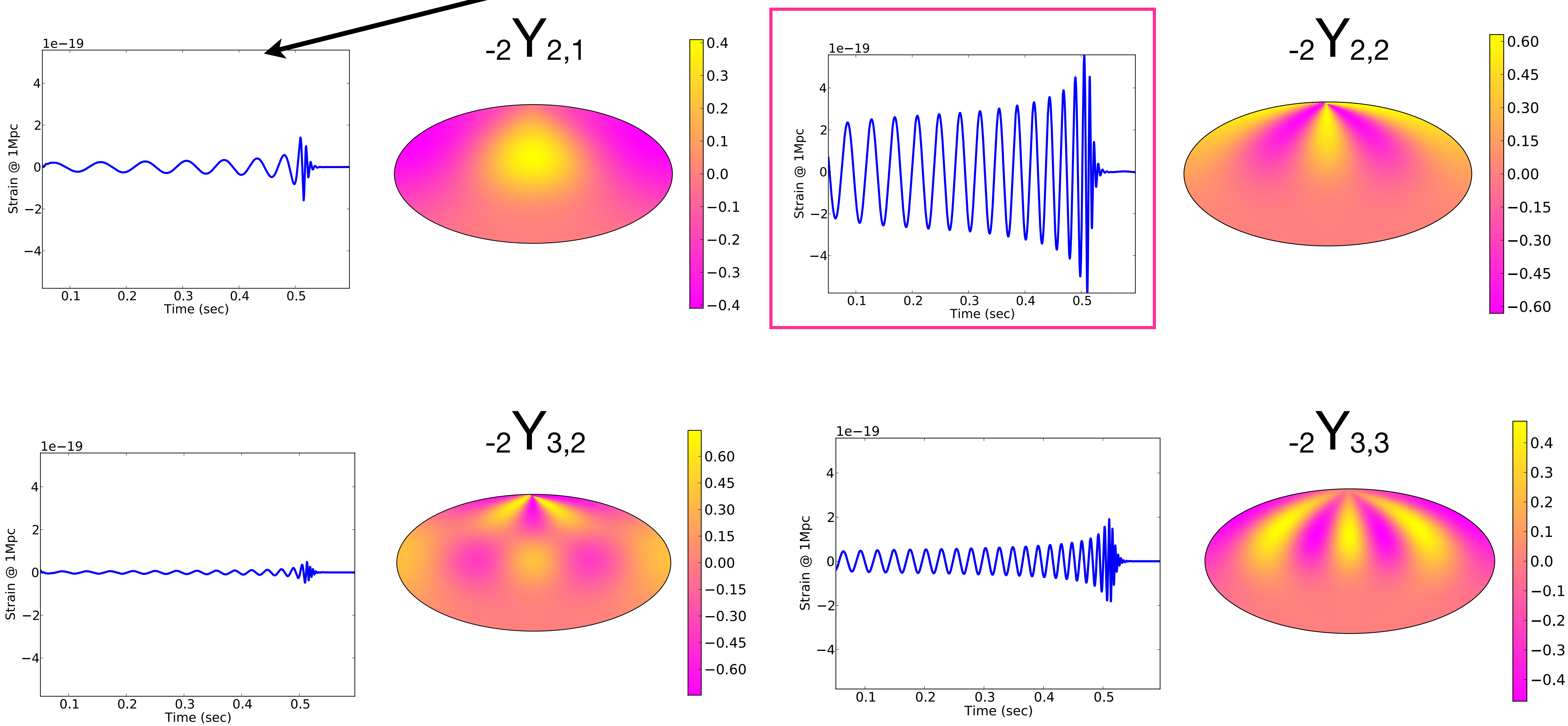


$$rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t)$$

Why not worry about this before? equal-mass, non-spinning or aligned spins radiate in 2,2 almost exclusively

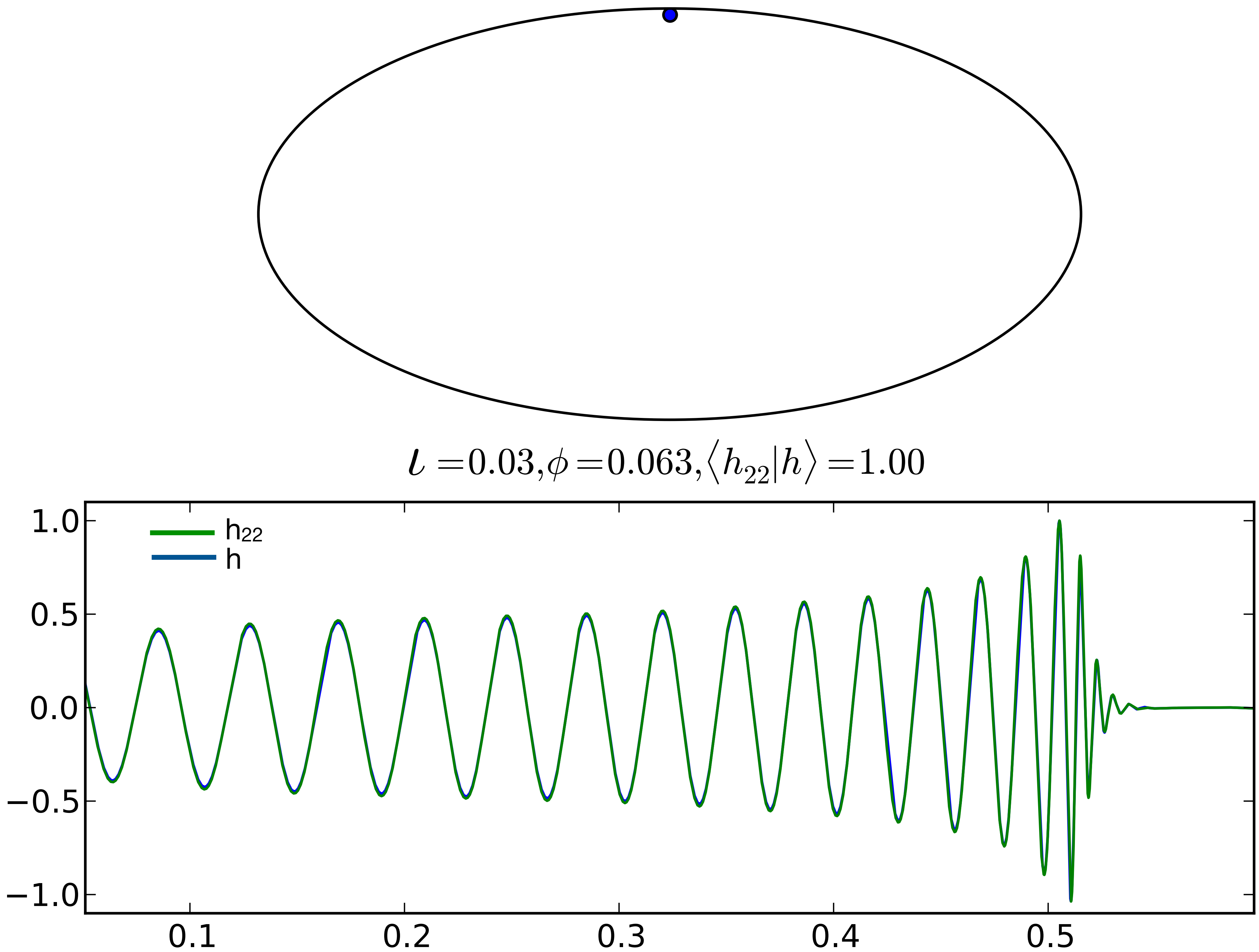
Gravitational Radiation decomposed into spherical harmonics

$$rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t)$$



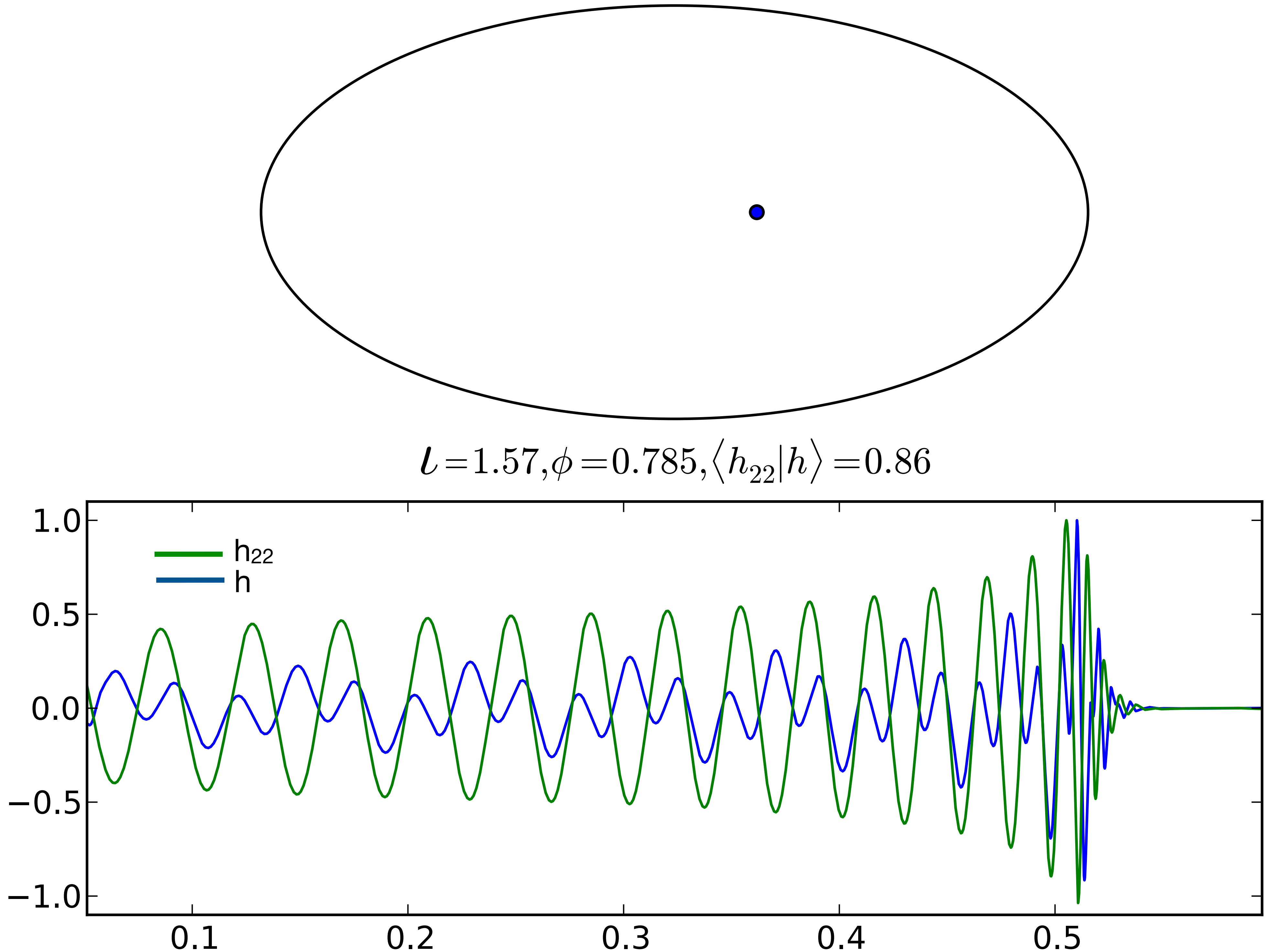
q=m_1/m_2=10, nonspinning

Some orientations match (2,2) well and look “simple”



q=10, nonspinning

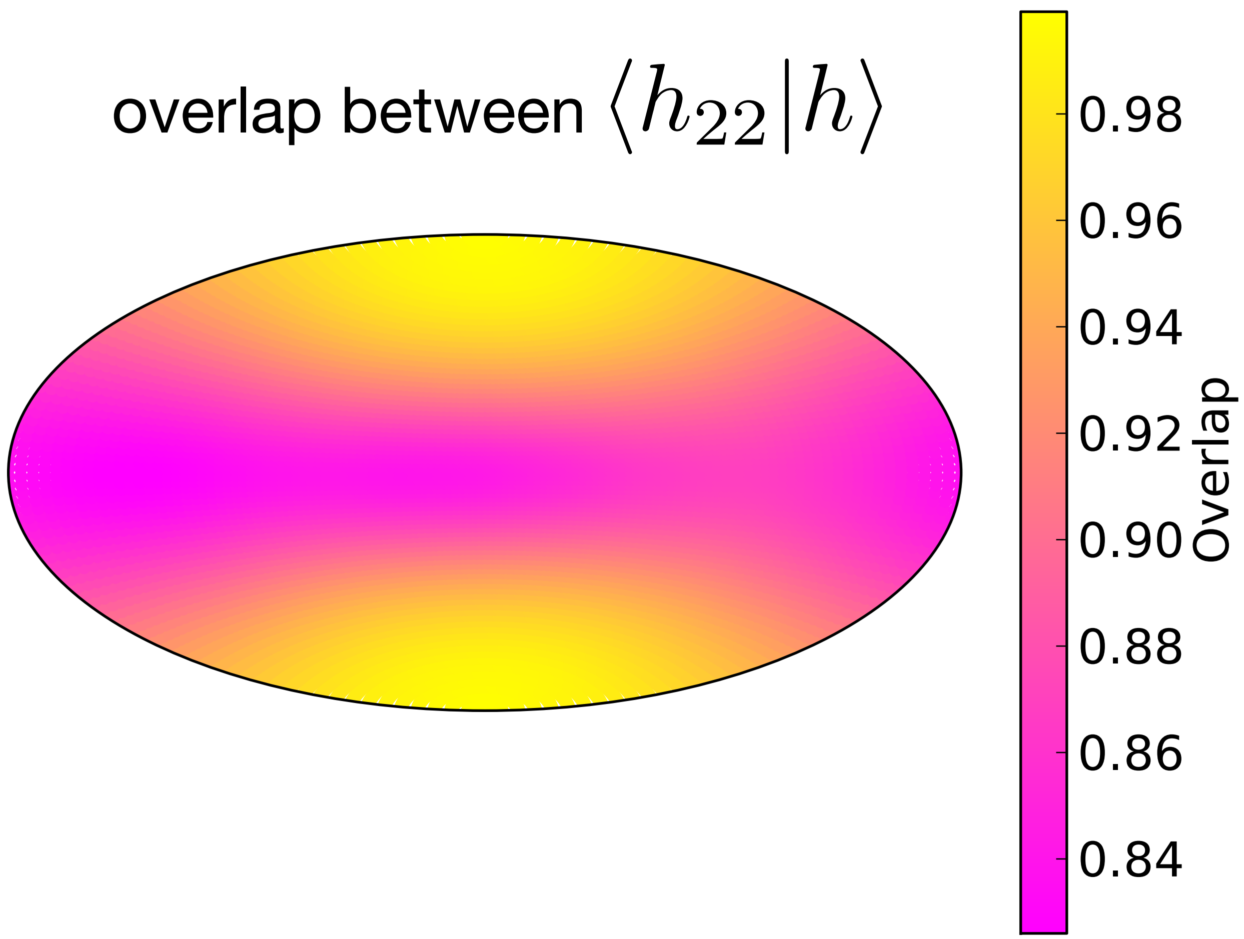
Some orientations ...



q=10, nonspinning

Higher Modes and Their Implications on Detection

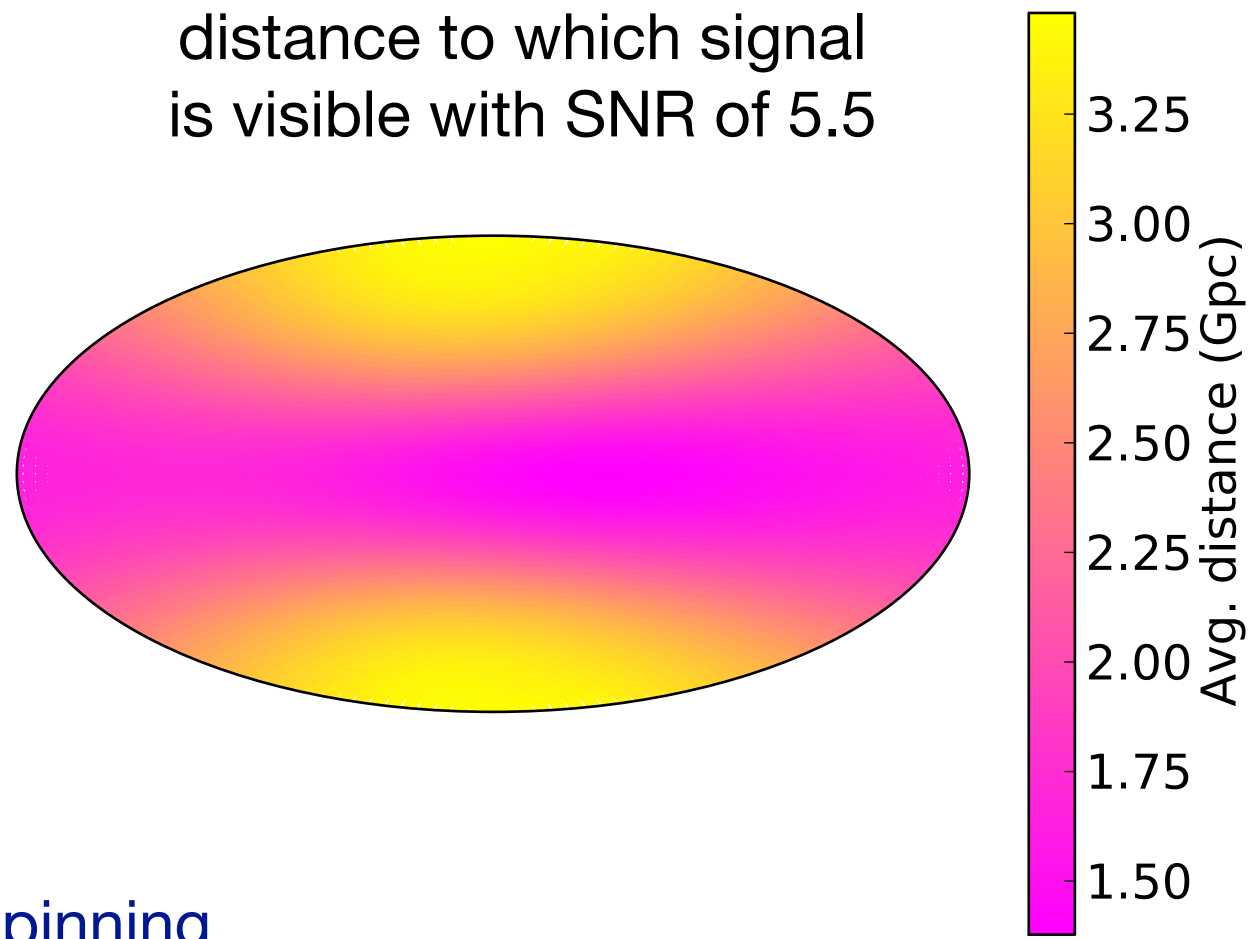
overlap between $\langle h_{22} | h \rangle$



Caveats:

- one detector
- template's parameters match the signal
- detector optimally oriented
- total mass set to $100M_{\odot}$

distance to which signal is visible with SNR of 5.5



q=10, nonspinning

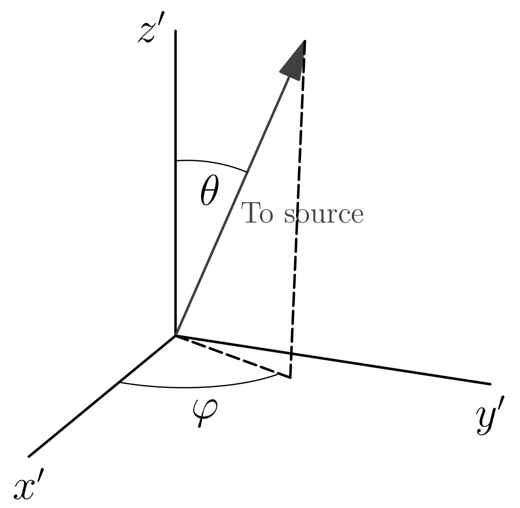
Integrate over detector sky to obtain Volume

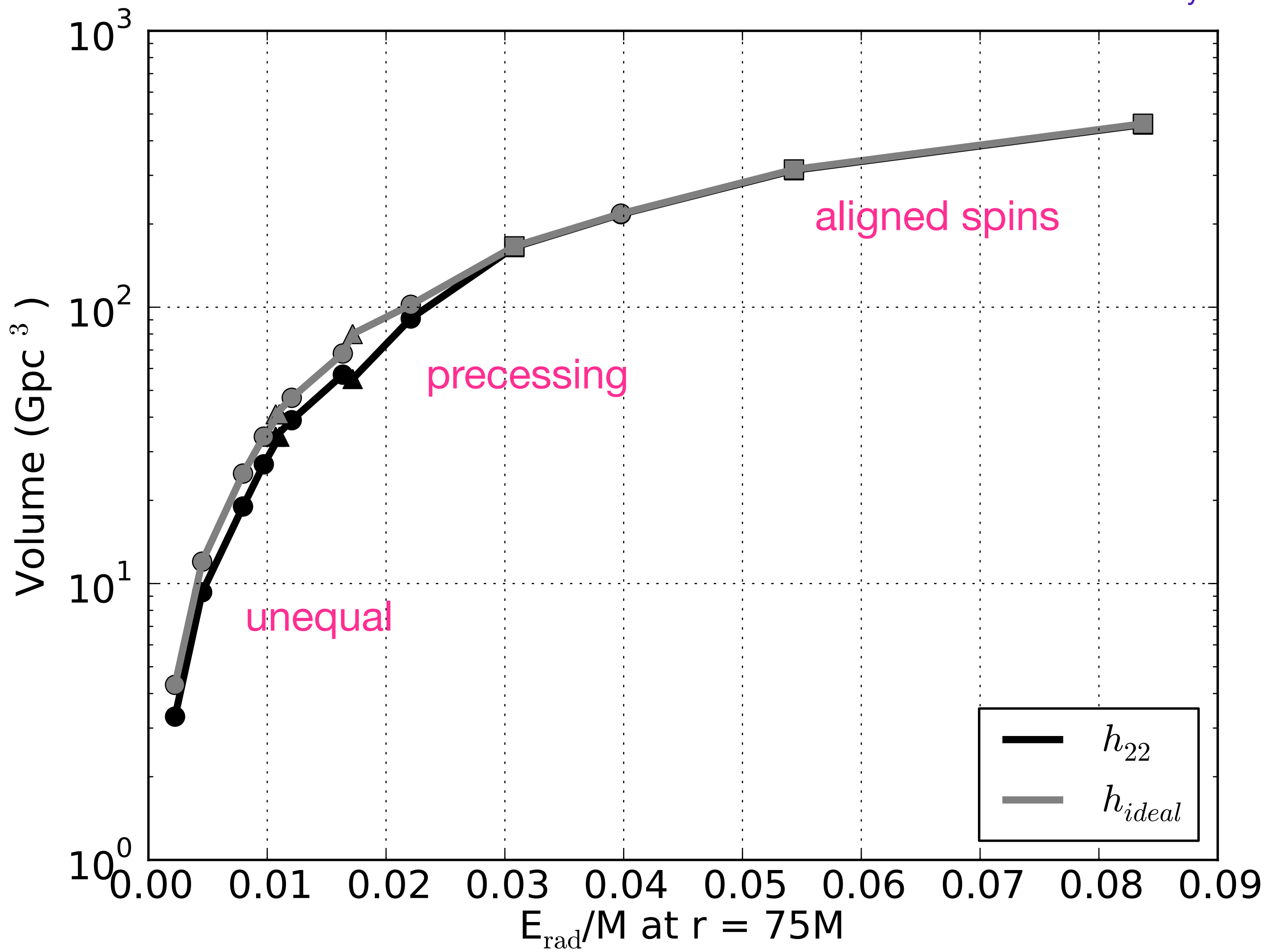
$q=m_1/m_2$	a	Volume using h_{22} (GPC^3)	Volume using h_{ideal} (GPC^3)
1	0	217	218
5	0	39	47
10	0	9.3	12
1	-0.4	165	166
1	0.8	458	461
4	0.6 (150º)	34	41
4	0.6 (90º)	55	80

Pekowsky et al PRD 87 084008 2013

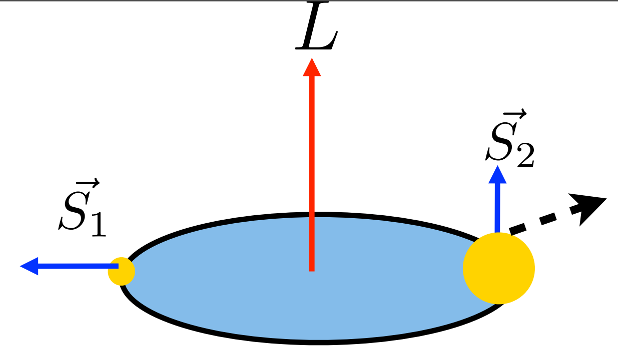
$$V = \frac{R^3}{3}\int_0^{2\pi} d\varphi \int_0^{\pi} \sin(\theta) d\theta \, F_0^3(\theta,\varphi)$$

$$R = \frac{1}{N}\sum_i^N \frac{\rho(s(\iota_i,\phi_i,\psi_i),h)}{5.5}$$





Precession complicates things



q	a	Volume using h_{22} (GPC^3)	Volume using h_{ideal} (GPC^3)	Volume using h_{2m} (GPC^3)
4	0.6 (150^o)	34.01	41	34.28
4	0.6 (90^o)	54.83	80	58.16

1) "How much could the search be improved by adding higher modes to templates?" (Pekowsky et al PRD 87 084008 2013)
2) "Which modes are most important for detection?" (Healy et al arXiv:1302.6953)
3) "Comparing gravitational waves from nonprecessing and precessing black hole binaries in the corotating frame" (Pekowsky et al arXiv:1304.3176)

Related papers: Schmidt et al PRD 84 2011
O'Shaugnessy et al PRD 84 2011
Boyle PRD 84 2011

What does this mean? We will still detect most precessing signals, however, the big question is will recover the parameters correctly? Second big question is, can we build good algorithms with 2 extra parameters?

Important Questions for NRDA

- Parameter space coverage - more precession, extreme spins and mass ratios
  - 171 generic runs Mroue et al arxiv:1304.6077 & my group has hundreds of NR waveforms (shorter)
  - extreme spins Lovelace et al CQG 29 2012 & extreme mass ratios (Manuela's talk)
  - but, the parameter space is huge! how well do we really have to cover it
- How long and accurate do NR waveforms be?
  - Ohme et al PRD 84 2011, MacDonald et al CQG 28 2011
- Can we use NR waveforms directly? Field et al PRL 106 2011, Canon et al PRD 83 2011
- Is it worth it to the DA community to add sky parameters to their search?
- We should not forget that future generations of detectors will be more accurate and demand and reveal more information about non-linear GR.

Conclusion

- Gravitational waves are the only way to map the warpage of spacetime near black holes
- Numerical Relativity allows us to predict the warpage from General Relativity
- Now, we are theoretically watching the dynamics of spacetime as black holes collide
- Results in implications for electromagnetic astrophysics and gravitational-wave astronomy
- Look to 2016-2020 for gravitational wave detection