Title: Data analysis overview for IMR waveforms

Date: Nov 05, 2009 01:40 PM

URL: http://pirsa.org/09110032

Abstract: I present an overview of how inspiral-merger-ringdown (IMR) waveforms are currently being used within LIGO and Virgo search efforts. I'll discuss search strategies from the two major astrophysics working groups within t he LIGO/Virgo collaboration searching for transient gravitational-wave signals - the Compact Binary Coalescence group and the Burst Group.

For masses where the inspiral, merger and ring-down phases are prominent in the LIGO/Virgo band both working groups have developed pipelines that are sensitive to these systems and are now trying to work together to make a joint statement about LIGO and Virgo's sensitivity to IMR systems.

LIGO DCC # **G0900654**

LIGO / Virgo searches for binary inspiral. Past, present, and future.

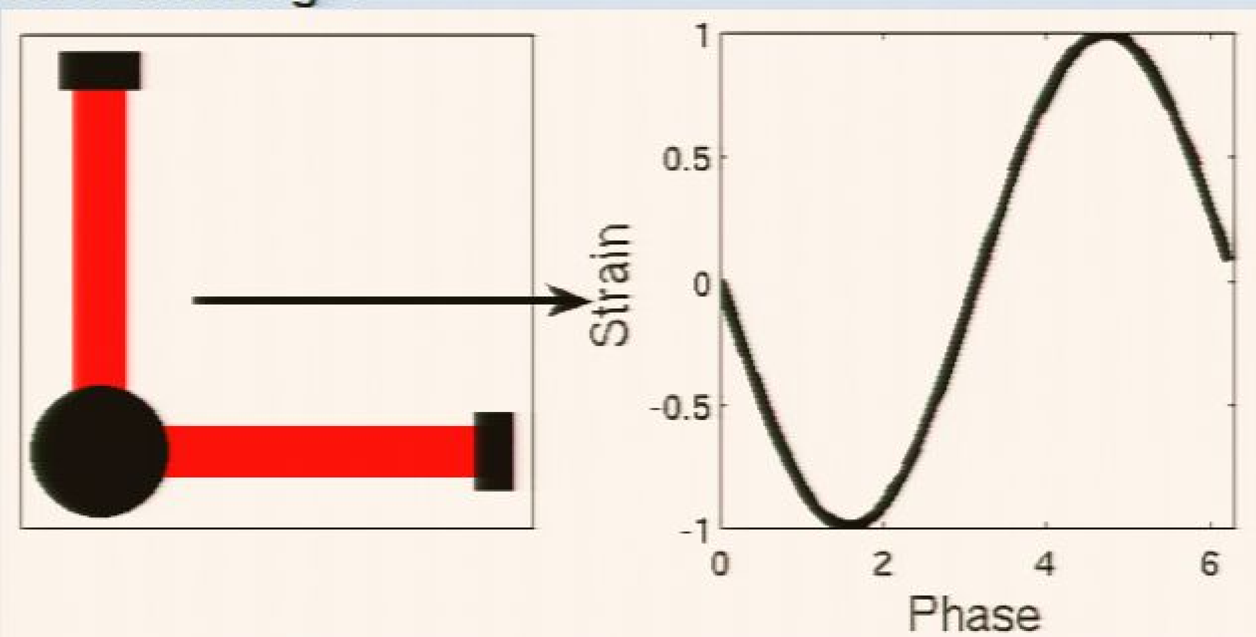
Chad Hanna - *California Institute of Technology*
on behalf of the LIGO Scientific Collaboration and Virgo Collaboration

Perimeter Institute for Theoretical Physics
Waterloo, Ontario - Nov 5, 2009

What is LIGO, Virgo? How do they work. What is data analysis?

Loosely defined, gravitational-wave data analysis is the procedure of detecting and estimating the parameters of gravitational wave signals. Some day, when we have signals, we'll call it Astronomy.

I will be referring to the analysis of LASER interferometric detectors like LIGO and Virgo.



Exaggerated for effect:

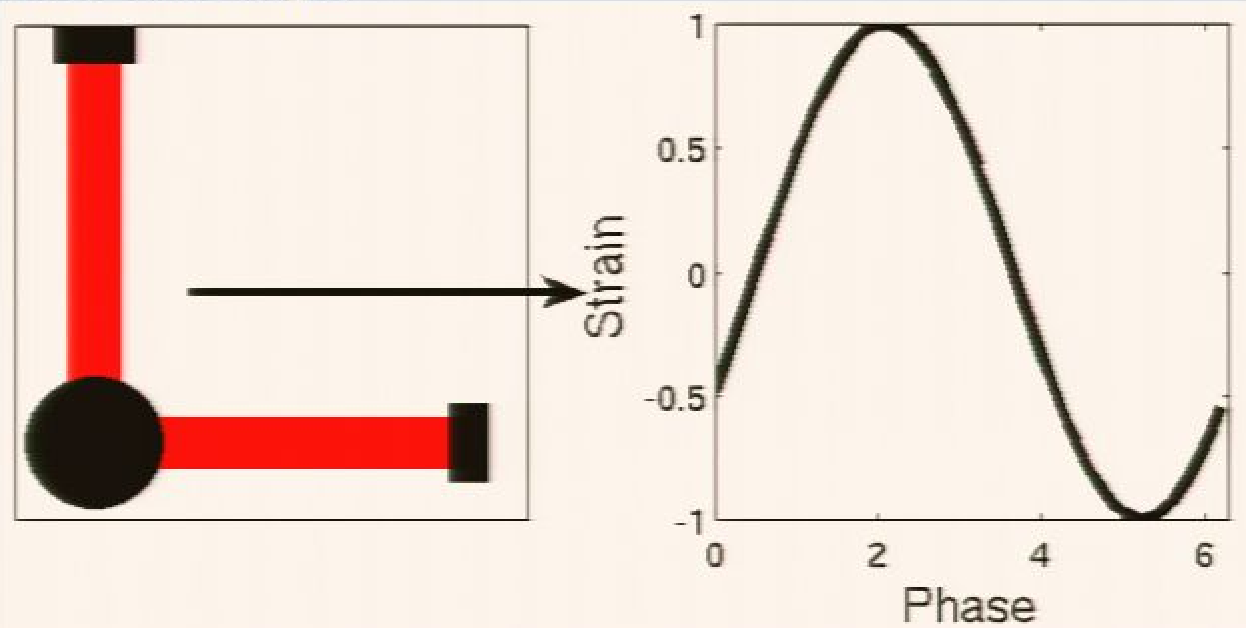
Gravitational waves can cause the relative distance in two arms of a laser interferometer to change.

The signal required to keep the interferometer "locked" during this can be calibrated to be proportional to the amplitude of the passing GW

What is LIGO, Virgo? How do they work. What is data analysis?

Loosely defined, gravitational-wave data analysis is the procedure of detecting and estimating the parameters of gravitational wave signals. Some day, when we have signals, we'll call it Astronomy.

I will be referring to the analysis of LASER interferometric detectors like LIGO and Virgo.



Exaggerated for effect:

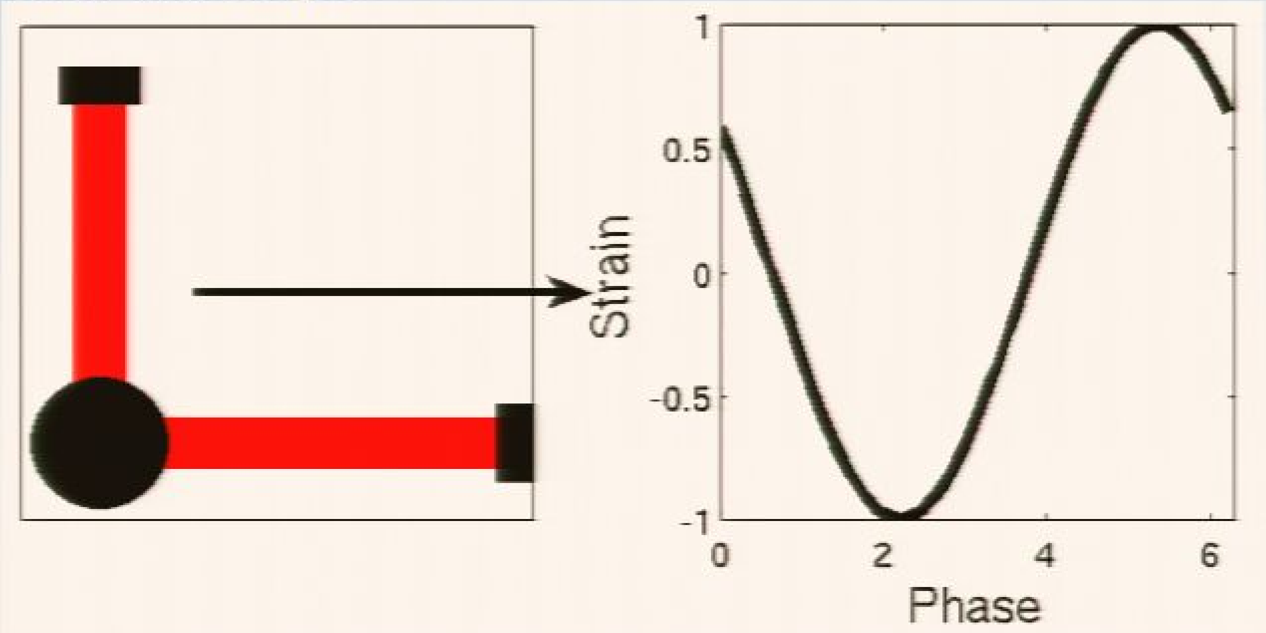
Gravitational waves can cause the relative distance in two arms of a laser interferometer to change.

The signal required to keep the interferometer "locked" during this can be calibrated to be proportional to the amplitude of the passing GW

What is LIGO, Virgo? How do they work. What is data analysis?

Loosely defined, gravitational-wave data analysis is the procedure of detecting and estimating the parameters of gravitational wave signals. Some day, when we have signals, we'll call it Astronomy.

I will be referring to the analysis of LASER interferometric detectors like LIGO and Virgo.



Exaggerated for effect:

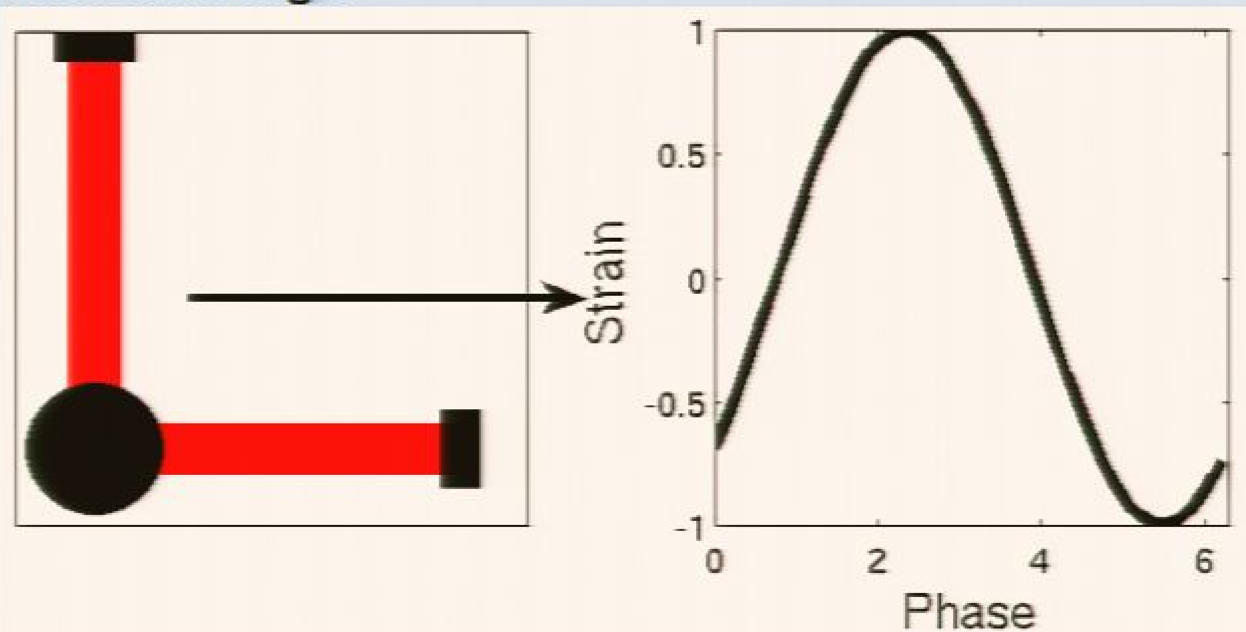
Gravitational waves can cause the relative distance in two arms of a laser interferometer to change.

The signal required to keep the interferometer "locked" during this can be calibrated to be proportional to the amplitude of the passing GW

What is LIGO, Virgo? How do they work.
What is data analysis?

Loosely defined, gravitational-wave data analysis is the procedure of detecting and estimating the parameters of gravitational wave signals. Some day, when we have signals, we'll call it Astronomy.

I will be referring to the analysis of LASER interferometric detectors like LIGO and Virgo.



Exaggerated for effect:

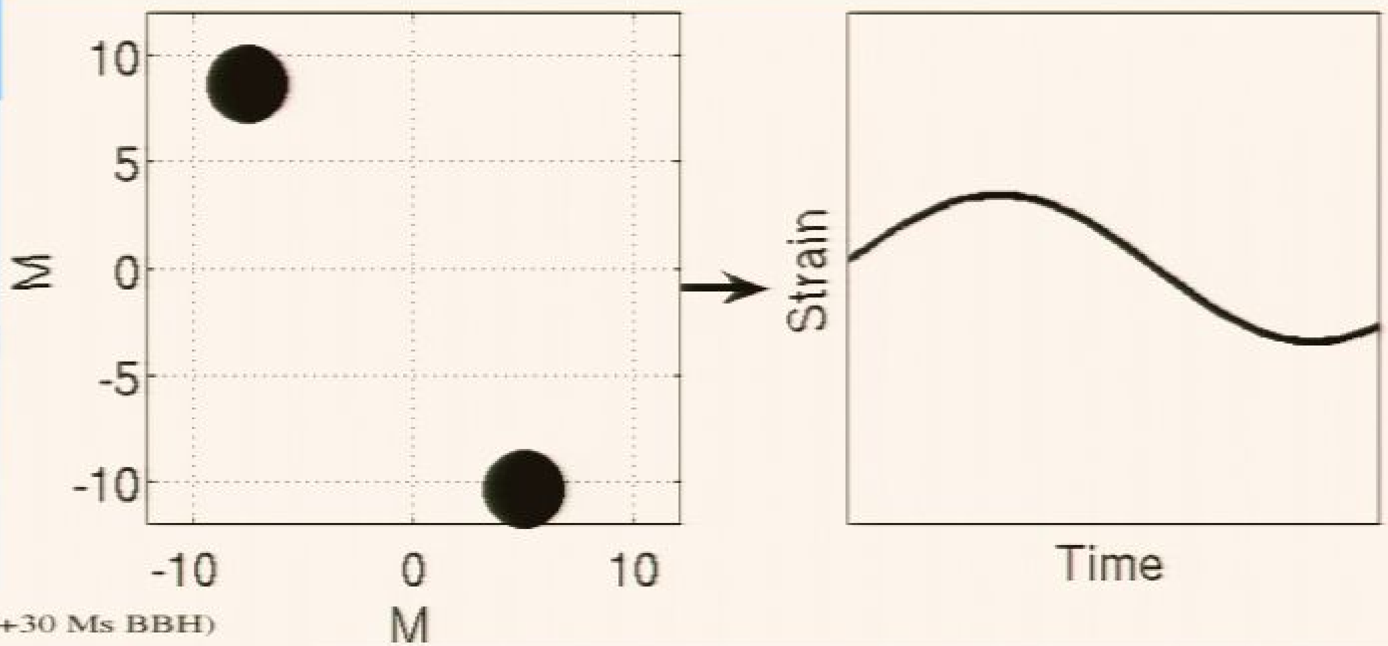
Gravitational waves can cause the relative distance in two arms of a laser interferometer to change.

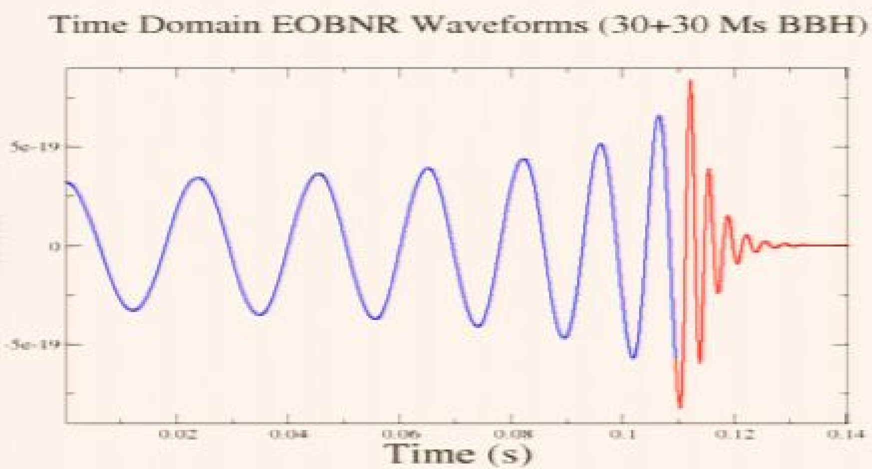
The signal required to keep the interferometer "locked" during this can be calibrated to be proportional to the amplitude of the passing GW

Compact Binary Coalescence, a promising source.

Gravity theory has driven searches for these sources and continues to do so.
What science have we done with these sources, and what will we do?

I. PN theory describes the beginning phase of coalescence, the inspiral. We have and will continue to exploit PN models for GW analysis. I'll talk about what has been done so far





II. Numerical Relativists are regularly evolving compact systems beyond inspiral. I'll discuss how the LVC collaboration includes NR.

III. What does the future hold? Speculation about the coming decade... What ideas will inform experiment in 10 years?

OUTLINE

1. Immediate goals of the LVC collaboration
   a) where we are
   b) what we can do with what we have

2. Where we are starting to go, the next couple of years
   a) Going beyond the inspiral, using numerical relativity

3. Advanced detectors – 10 years down the road
   a) What do we expect to find?
   b) What we can do with it
   c) What we need to know to get the most out of our signals

Compact Binary Coalescence searches

Immediate goal of the LVC collaboration: *To detect gravitational waves!*

Gravitational waves have been indirectly observed in binary pulsar systems that lose orbital energy at a rate predicted by GR.

These sources have too low of a frequency for ground based detectors to measure the signal

Double NS systems and systems with other compact objects (such as black holes) can be relevant to LIGO / Virgo if they have evolved to tighter orbits such that the orbital period is tens of milliseconds

The existence of binary pulsars at lower frequency and population synthesis models suggest that higher frequency compact binary systems exist.

We expect NS-NS systems and systems involving stellar mass black holes to exist from binary stellar evolution. Heaver systems involving intermediate mass black holes may also exist but often require more exotic formation scenarios

BOTTOM LINE: Compact binaries are known to be great GW sources...

Compact Binary Coalescence searches

What can we do in the mean time?:

1. Constrain merger rates

Even without detections we can constrain models for binary coalescence rates.

This in turn can constrain tunable parameters in population synthesis models, etc.

2. Provide additional information about some EM events

GRB 070201 had an overlap an location error box in Andromeda. LIGO was able to exclude the progenitor as compact binary coalescence in Andromeda to high confidence

Compact Binary Coalescence searches

Constraining merger rates

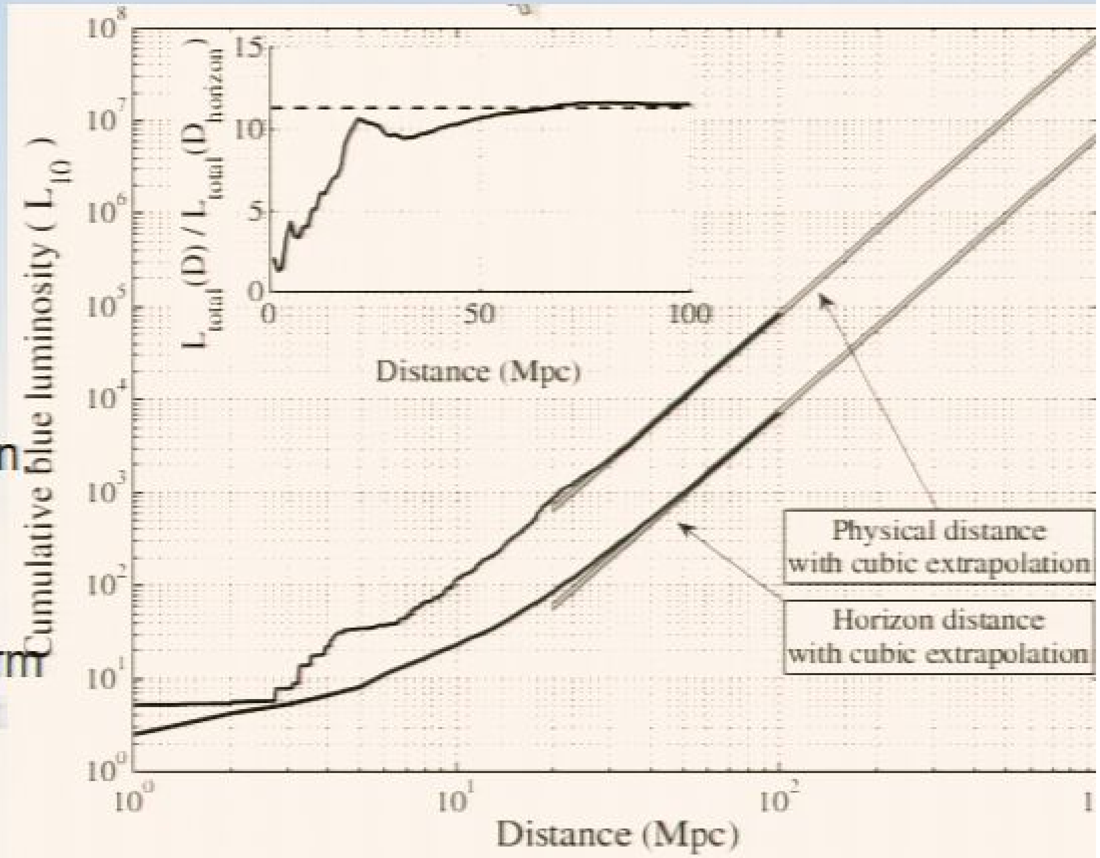
Goal: state 90% confidence upper bound on the merger rate of compact binaries in the nearby universe as a function of mass from direct measurement of GWs.

Rates have sometimes been quoted as mergers/yr/(N_{MWEG})

This rate gives is normalized to galaxies like the Milkyway. Since LIGO/Virgo is sensitive beyond our galaxy we can detect signals from many galaxies.

We no longer use N_{MWEG} as the normalization. Instead we use L_{10} (10^{10} suns in blue light)

It is important to normalize things this way nearby where the galaxy density is not uniform. As our range improves it is less relevant and we can simply use volume (e.g. Mpc^3)



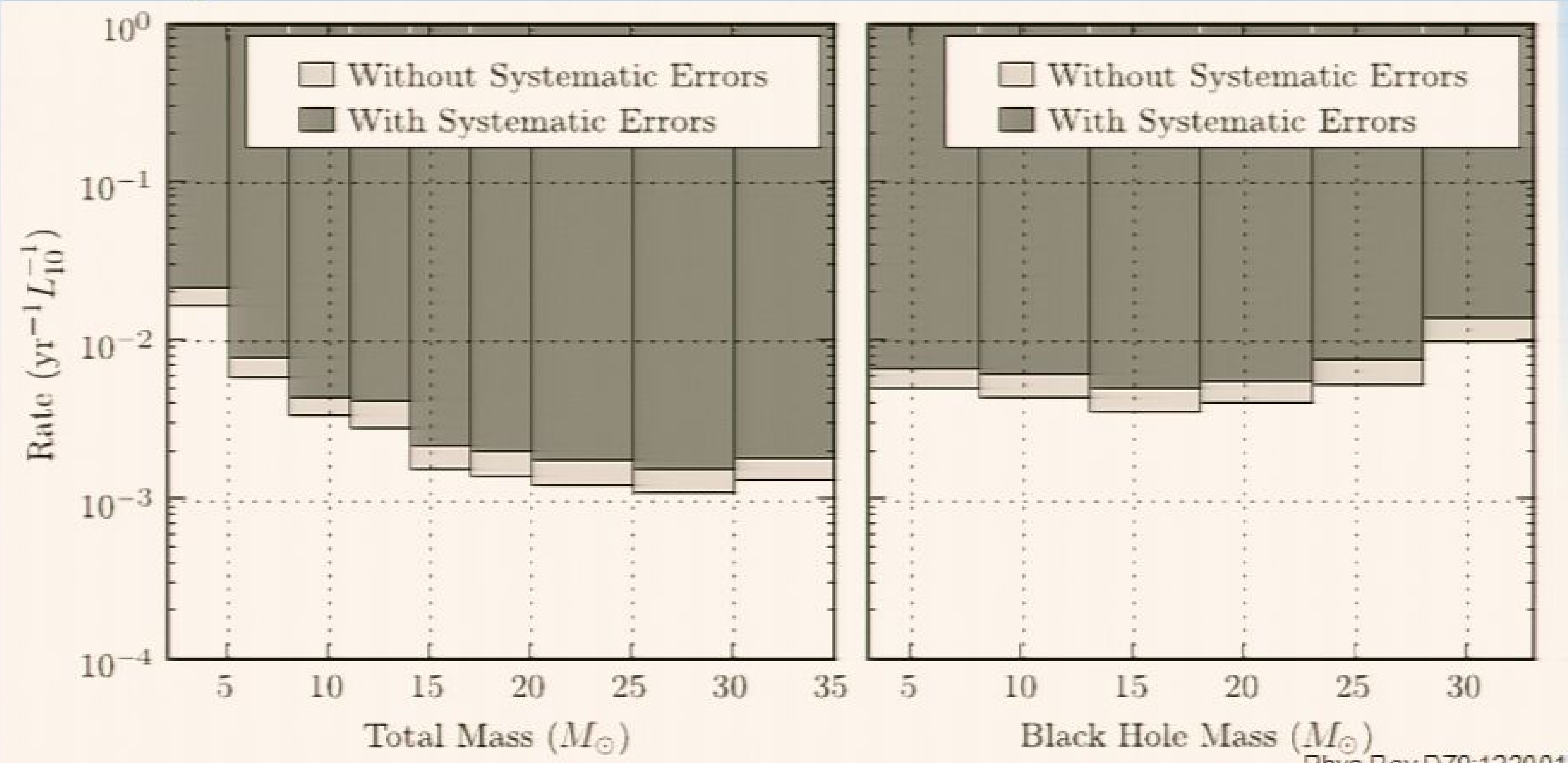
The Astrophysical Journal, 675:1459-1467, 2008

Chad Hanna 7

Compact Binary Coalescence searches

Constraining merger rates

Goal: state 90% confidence upper bound on the merger rate of compact binaries in the nearby universe as a function of mass from direct measurement of GWs.

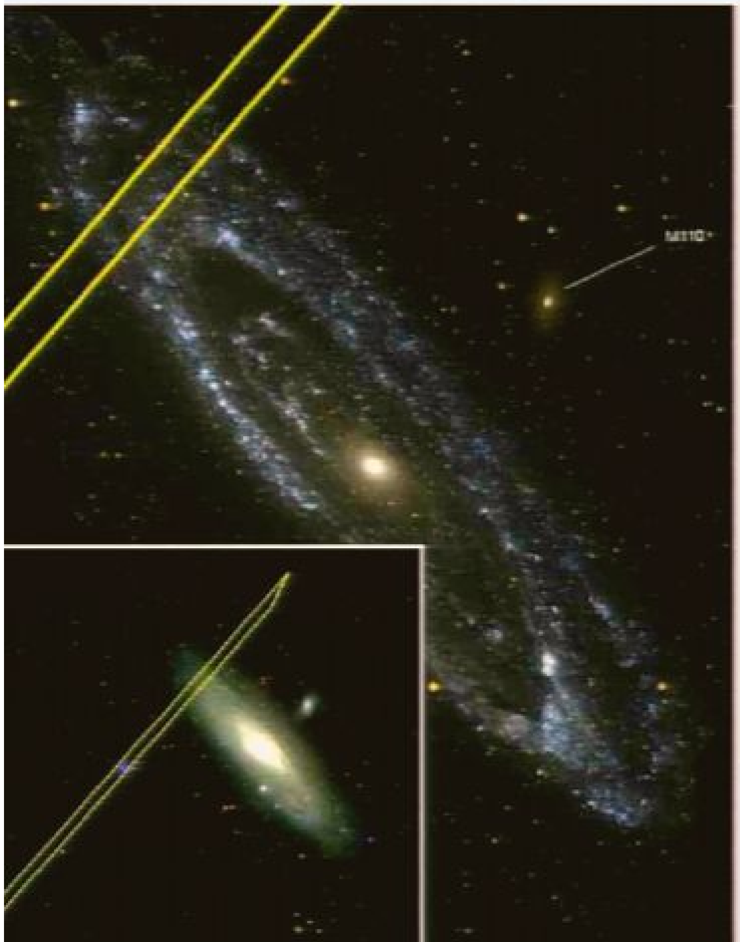


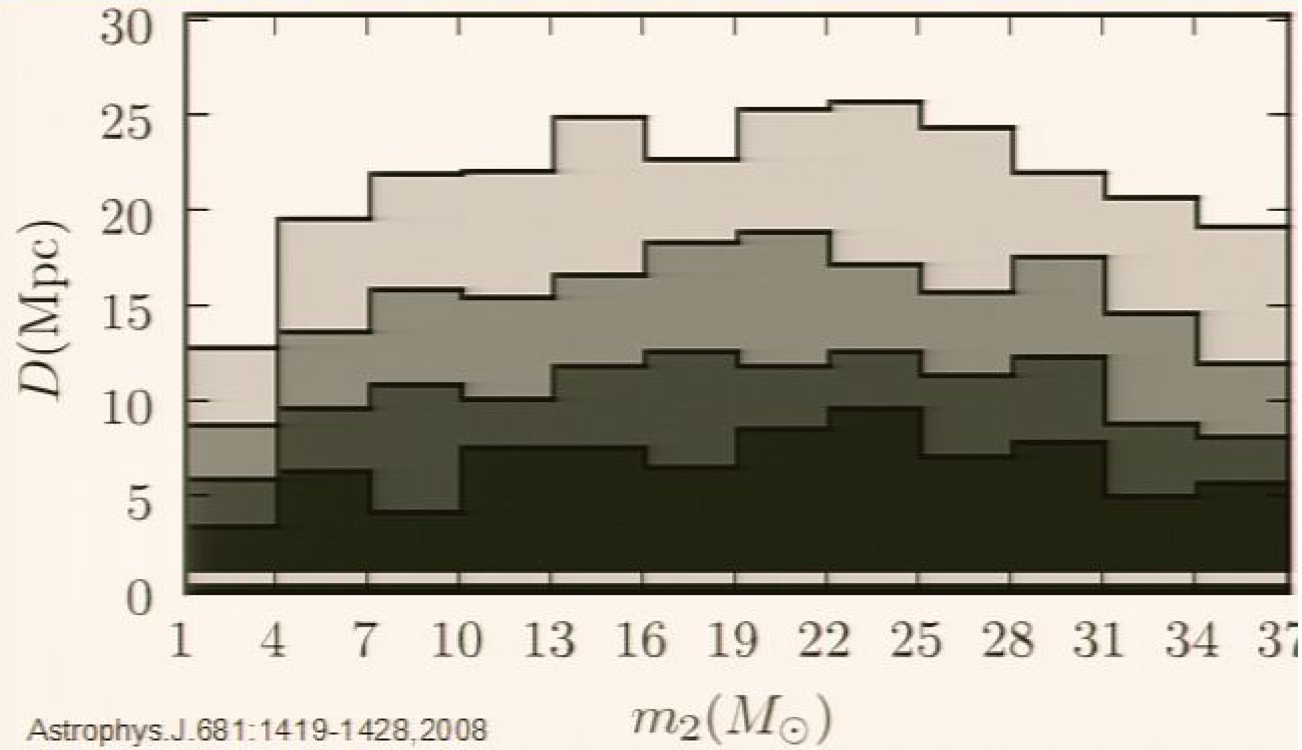
Phys.Rev.D79:122001,2009

Compact Binary Coalescence searches

Providing information about EM events

This is open ended, but we have an example GRB070201





Astrophys.J.681:1419-1428,2008

GRB070201 had an error box overlapping Andromeda. LIGO observations excluded that it's progenitor was a compact merger to greater than 99%

Compact Binary Coalescence searches, next step

Going Beyond the inspiral phase

The results shown on the previous slides made use of filtering the data for the inspiral only part of the waveform. For low mass systems this is okay.

Last Stable Orbit for a Schwarzschild Black Hole = 6M
In GW frequency that corresponds to ~ 4400 Hz (M_{sun} / M)

For heavier systems the Merger and ring down phase are in LIGO / Virgo's sensitive band. A 30 solar mass binary has the 6M radius at LIGO's most sensitive spot (~150Hz).

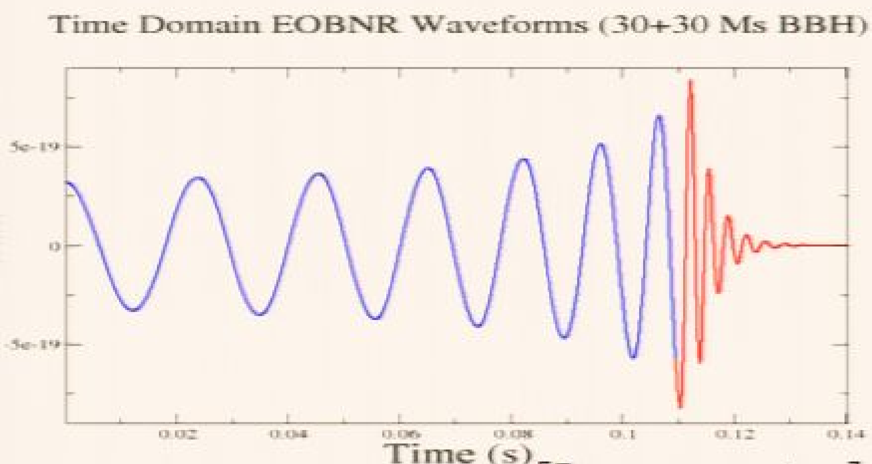
Searching for heavy systems is less founded than searching for stellar mass objects, but it is also more rewarding because they often require more exotic situations than simple stellar evolution to form.

What has the *LVC* been up to with NR inspired waveforms ?

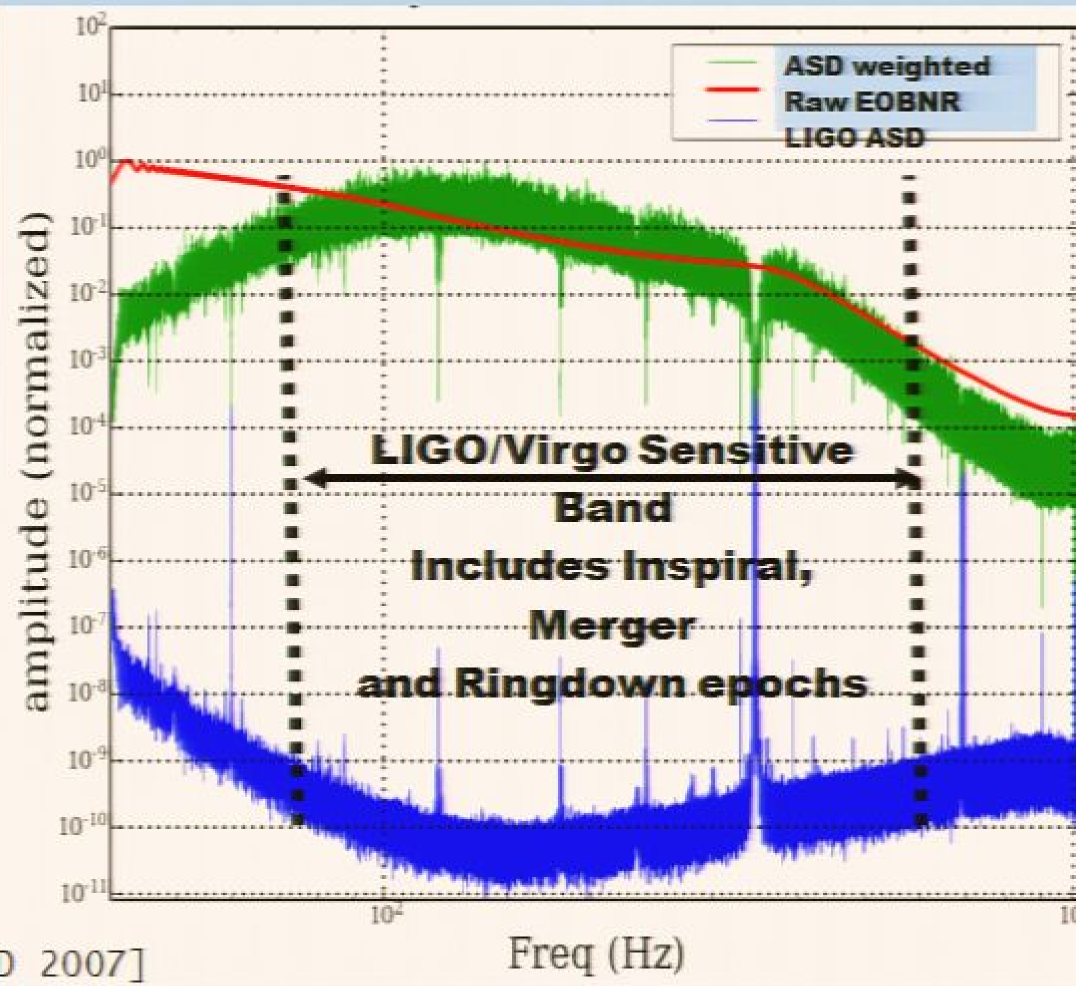
:earch 1-99 component M25-100 ,o **total M**o

lost of the mass space produces vaveforms with inspiral, merger ınd ringdown in band.

his means that it is critical to have good model of the complete vaveform that includes NR



[Buonanno et al, PRD 2007]



LSC VIRGO

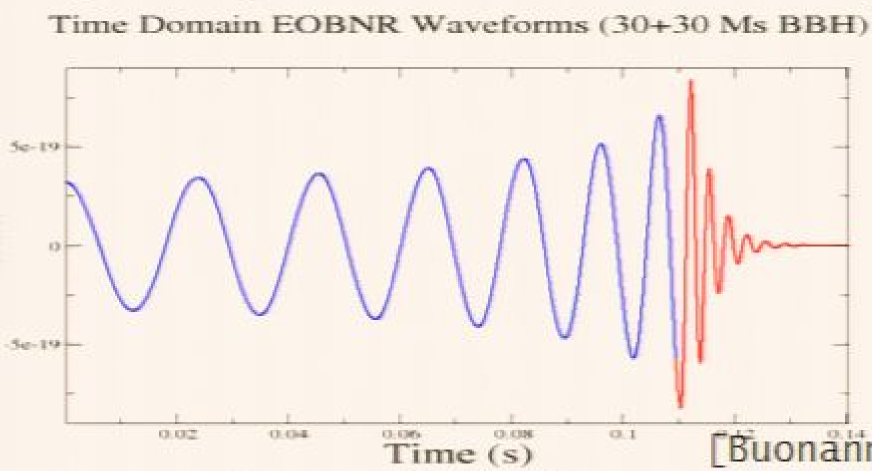
Chad Hanna 11

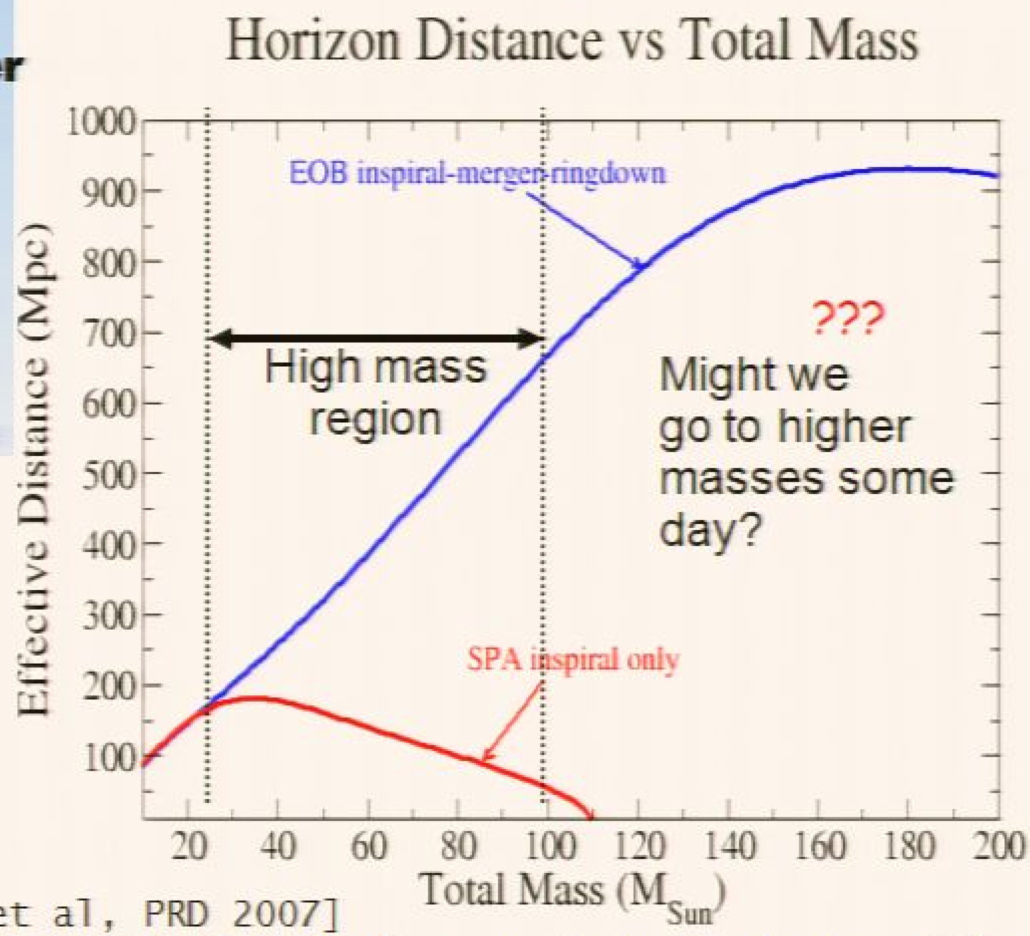
What has the LVC been up to with NR inspired waveforms ?

earch 1-99 component M25-100 ,o **total M**o **in S5 and S6 ongoing**

/e filter with EOB waveforms and eed about ~2000 waveforms to cover he space with sufficient accuracy.

'he EOB waveforms are tuned to IASA-Goddard NR in mass ratios of :1 – 1:4, but have been extended nalytically to the entire mass range





[Buonanno et al, PRD 2007]

nanno and Damour 99,00; Damour, Jaranowski and Schafer 00; Damour, Sathyaprakash and Iyer 9

What has the LVC been up to with NR inspired waveforms ?

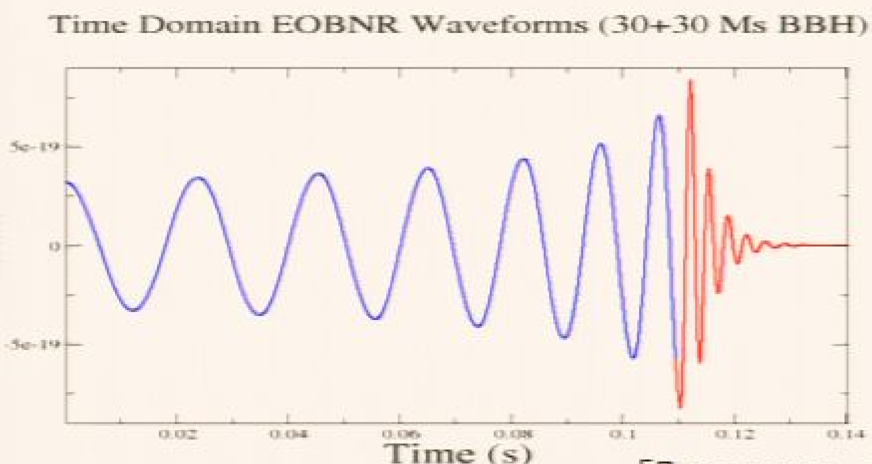
"High Mass Group"

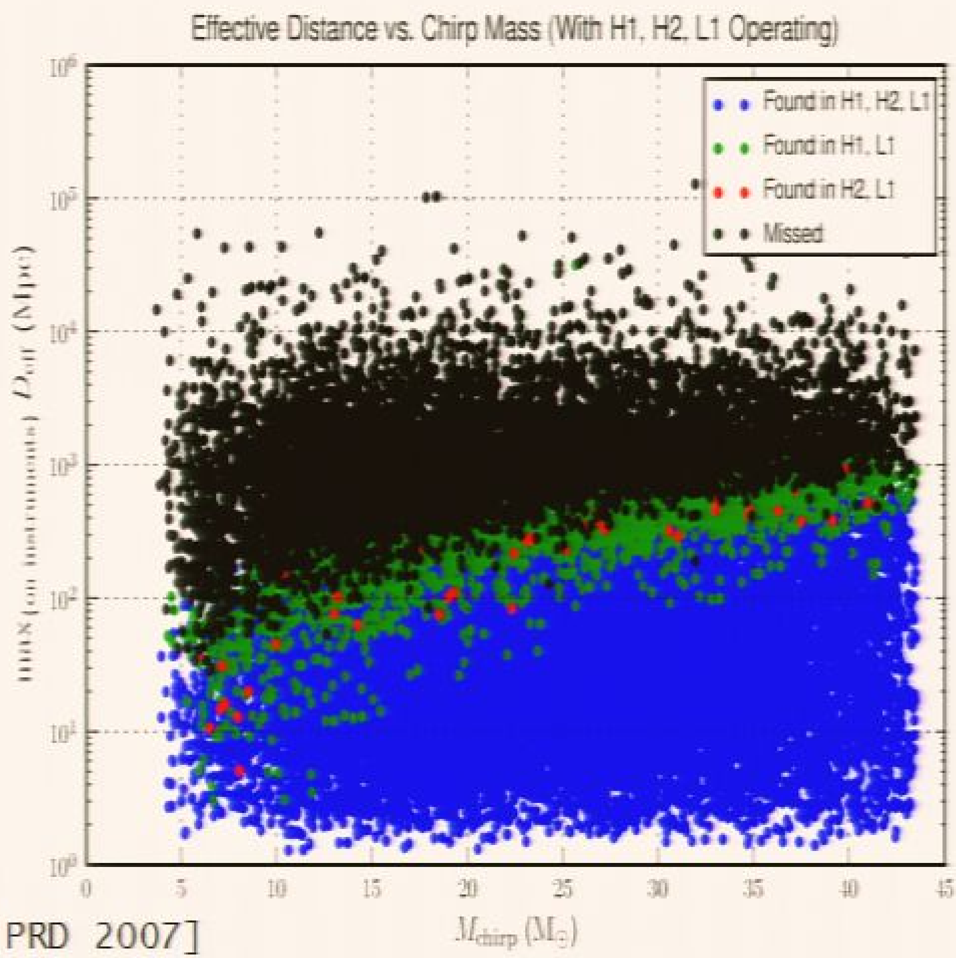
earch 1-99 component M25-100 ,o total Mo in S5 ongoing

FILTERING

hese EOB + NR waveforms are alled EOBNR on the remaining lides

ALSE ALARM RATE IS NOT TAKEN NTO ACCOUNT HERE. We have plans o constrain the rate of such systems n the absence of a detection.



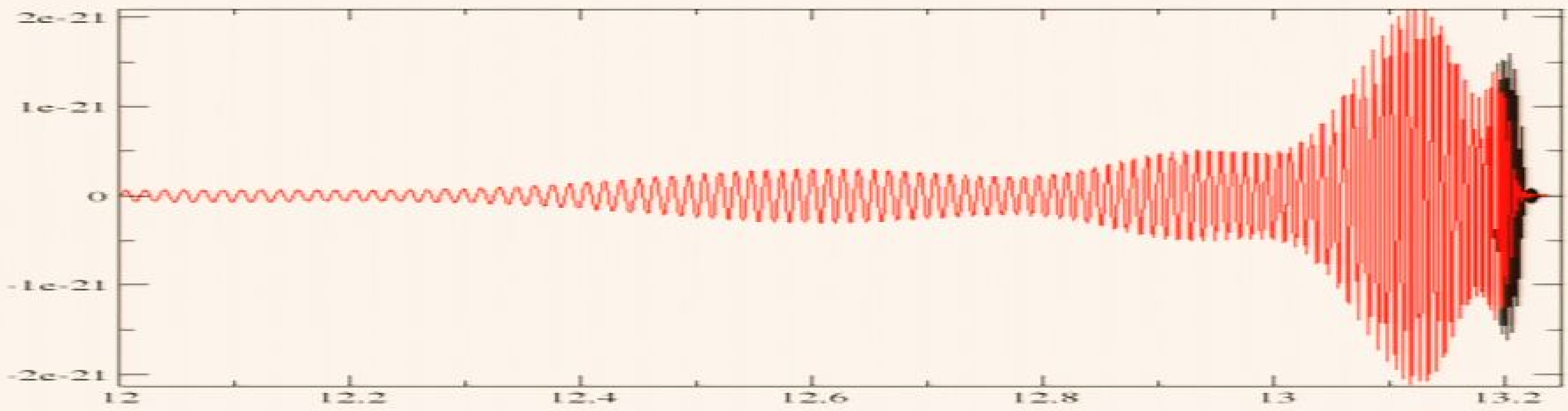


[Buonanno et al, PRD 2007]

What has the *LVC* been up to with NR inspired waveforms ?

WHAT WE *NEED* FROM NR / GR THEORY

1. Increasingly asymmetric mass ratios and more orbits if possible
2. Spin.
3. Matter.



What about the next decade?

Within five or six years advanced LIGO and Virgo will be operating at a sensitivity of about 10 times more than present detectors

We can do science without detections, but let's face it we stand to learn far more from what we *can see* than what we *cannot*.

There are many, speculative sources that might show up as signals in this detector era. And there are many theories (also sometimes speculative) that can be constrained by not observing certain phenomena.

But there is one class of sources where it is *likely not just possible* to have tens of signals in the first year of advanced detector running.

QUESTION: HOW CAN WE EXTRACT THE MOST PHYSICS FROM BINARY MERGERS?

What about the next decade?

Within five or six years advanced LIGO and Virgo will be operating

We may hope to detect about 40 events per year above SNR 8.

The Astrophysical Journal, 675:1459Y1467, 2008

We expect the sources to be uniformly distributed in space. The number of events should go up as the cube of our range. Another way of putting this is that the probability of getting an event above a certain SNR is inversely proportional to the SNR cubed at constant sensitivity.

$$P(SNR > x) \propto (SNR)^{-3}$$

That means if we get about 32 events above SNR 8 we only expect 4 above SNR 16 and nothing above SNR ~30.

Question: If we detect for one year and get our 40 detections making all the world happy that we found gravitational waves, what can we do the next year assuming the same sort of numbers to get the best physics out?

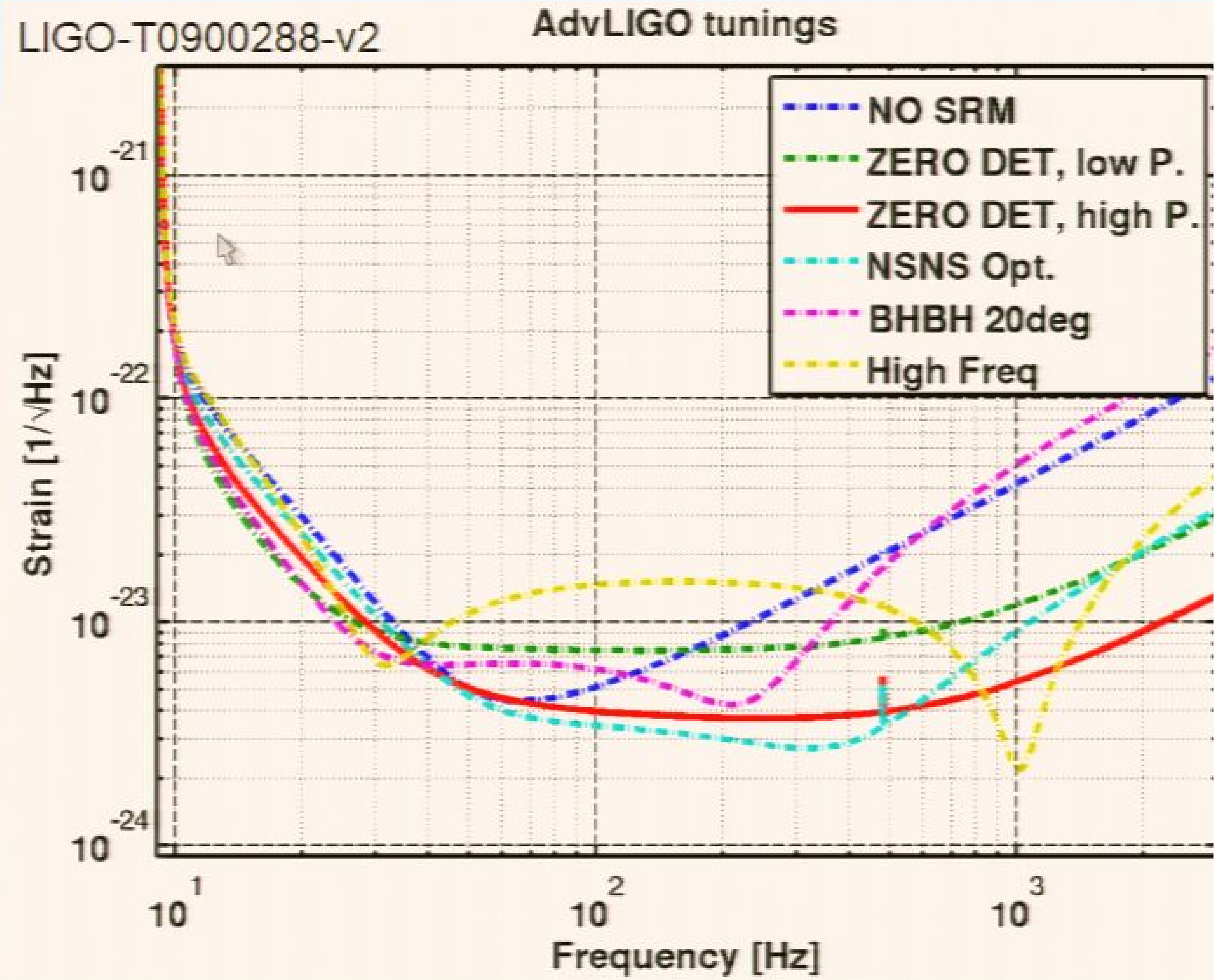
What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

It is possible to tune GW detectors to a narrow band mode. But not without effort. One has to pick in advance what the interesting frequency is.

Assuming another year like the first one do we try narrow band tuning?

What do we gain? Probing neutron star EOS? Magnetic fields? Deviation from GR? Do we expect these effects to show up at any particular frequency given the systems we observe from the previous year?



What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

We will only have a limited observation time and modest signals. Advanced LIGO/Virgo will not be easy!

To extract information about new physics we really need to know where to look.

Those interested in Neutron Star physics have been thinking about this and are making proposals.

What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

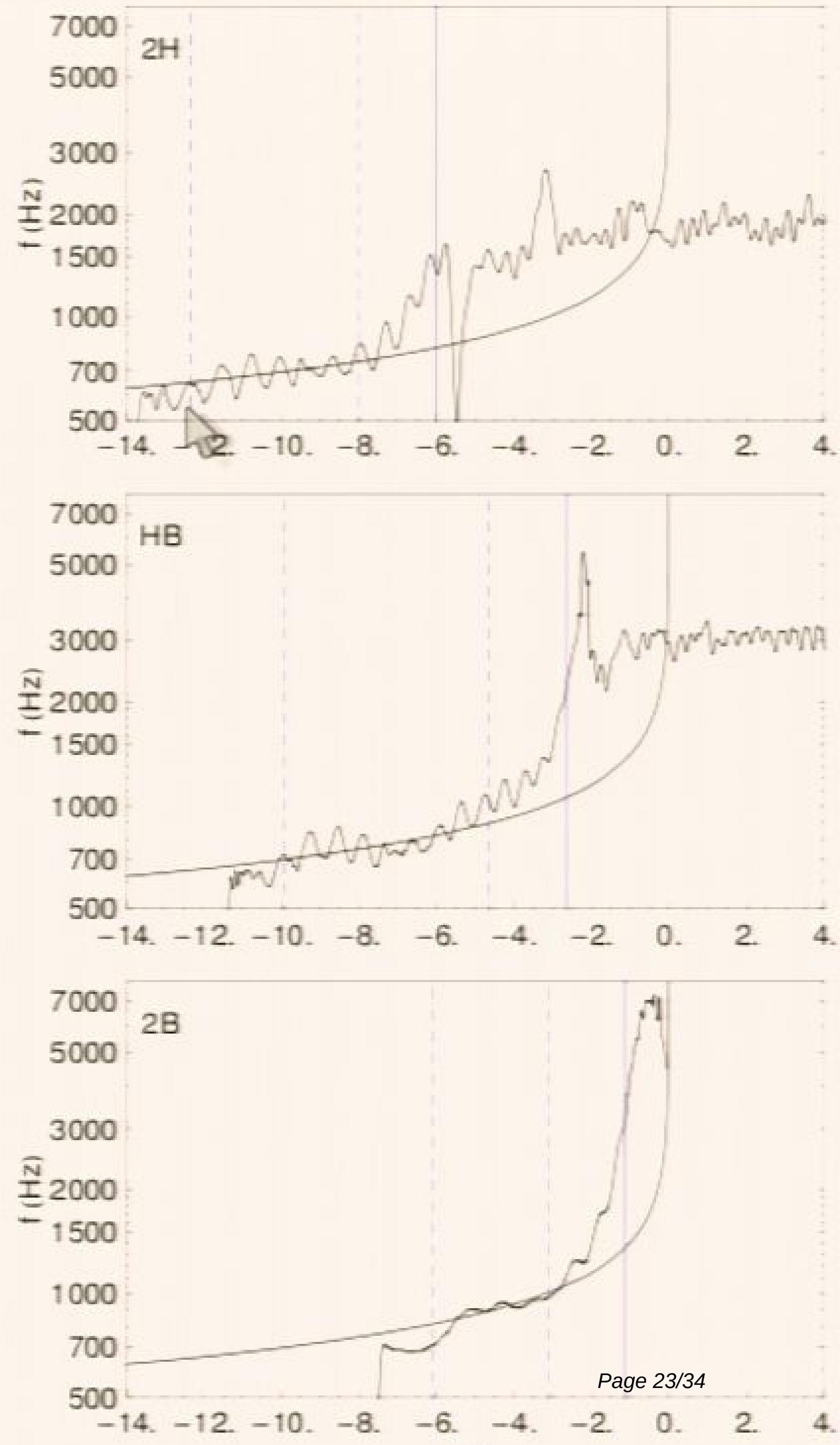
Probing NS equations of state

The time-frequency evolution of the binary signal, the “chirp” is modified by having compact objects that are not point particles.

The EOS of the neutron star which will determine its radius and other properties can be probed by studying the deviations in NS-NS or NS-BH mergers.

The effects occur at high frequency (~1KHz)

That means that detecting these effects may be easier with different detector configurations



C Markakis et al 2009 J. Phys.: Conf. Ser. 189 012024

What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

A Challenge: What else can we learn from binary mergers in the advanced detector era?

(matter in strong gravity, alternative theories...)

What will we need to do to maximize our knowledge (a different detector configuration?)

Thanks for your time, any questions?

What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

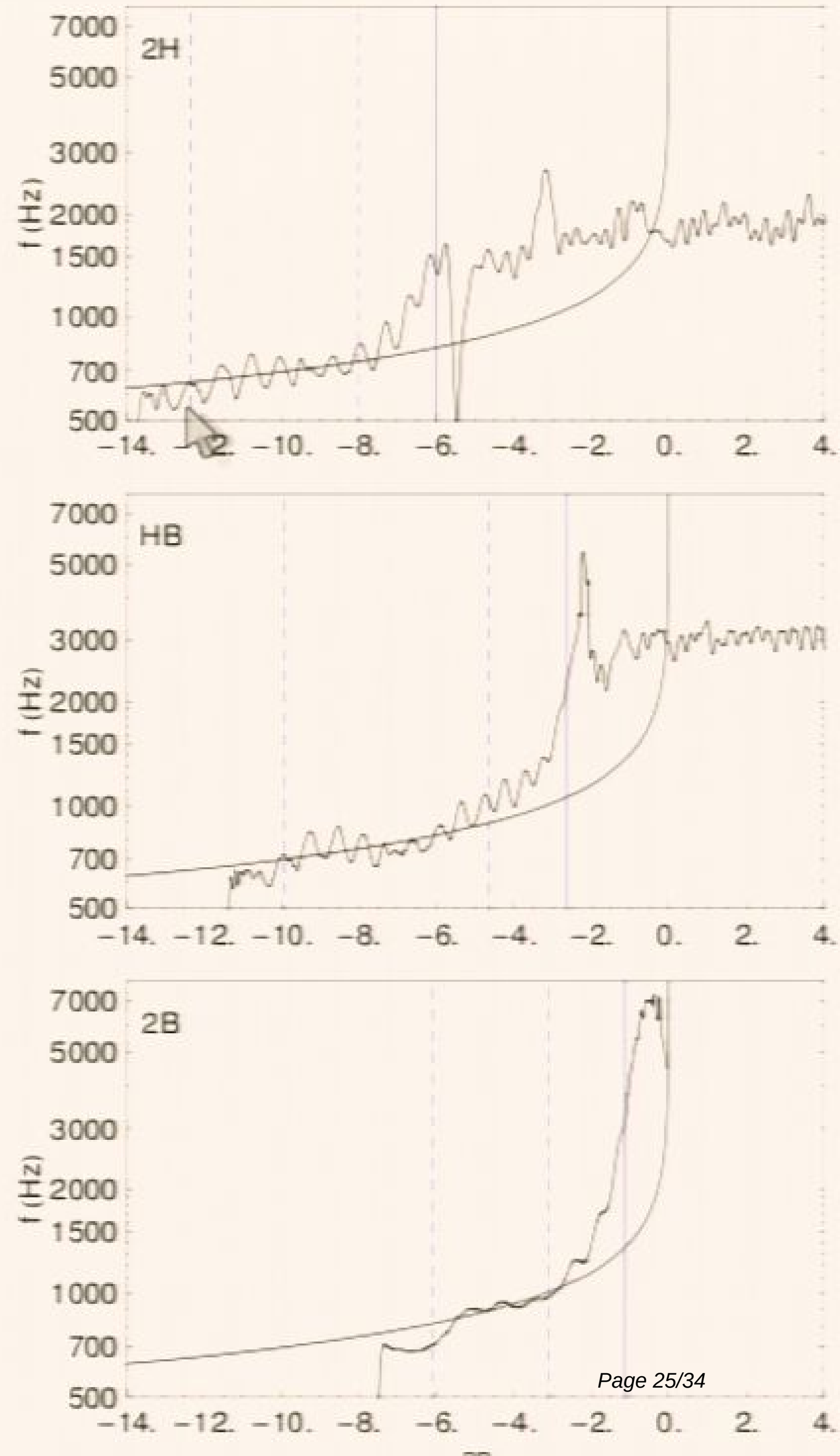
Probing NS equations of state

The time-frequency evolution of the binary signal, the “chirp” is modified by having compact objects that are not point particles.

The EOS of the neutron star which will determine its radius and other properties can be probed by studying the deviations in NS-NS or NS-BH mergers.

The effects occur at high frequency (~1KHz)

That means that detecting these effects may be easier with different detector configurations



C Markakis et al 2009 J. Phys.: Conf. Ser. 189 012024

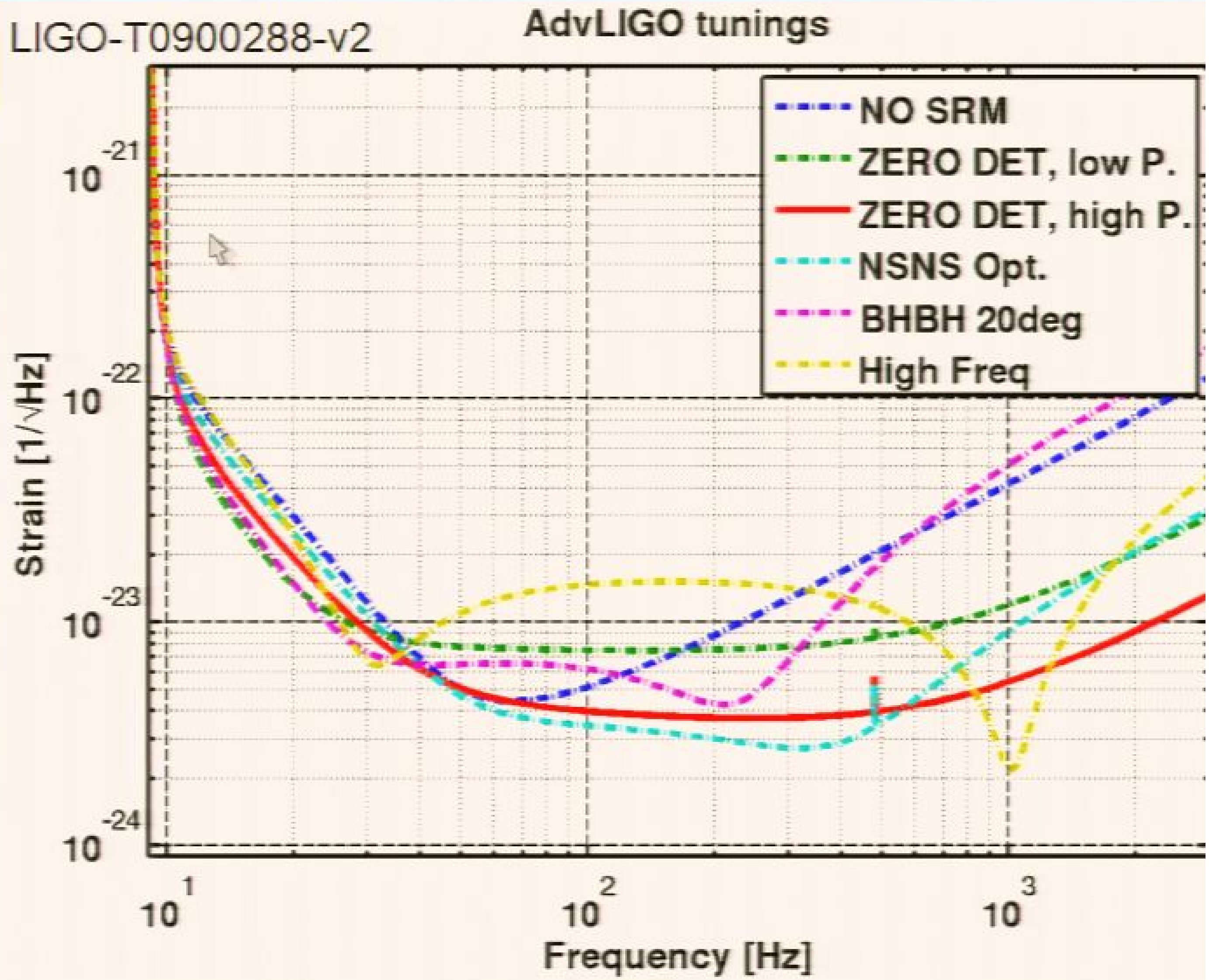
What about the next decade?

A GLIMPSE INTO THE POSSIBILITIES

It is possible to tune GW detectors to a narrow band mode. But not without effort. One has to pick in advance what the interesting frequency is.

Assuming another year like the first one do we try narrow band tuning?

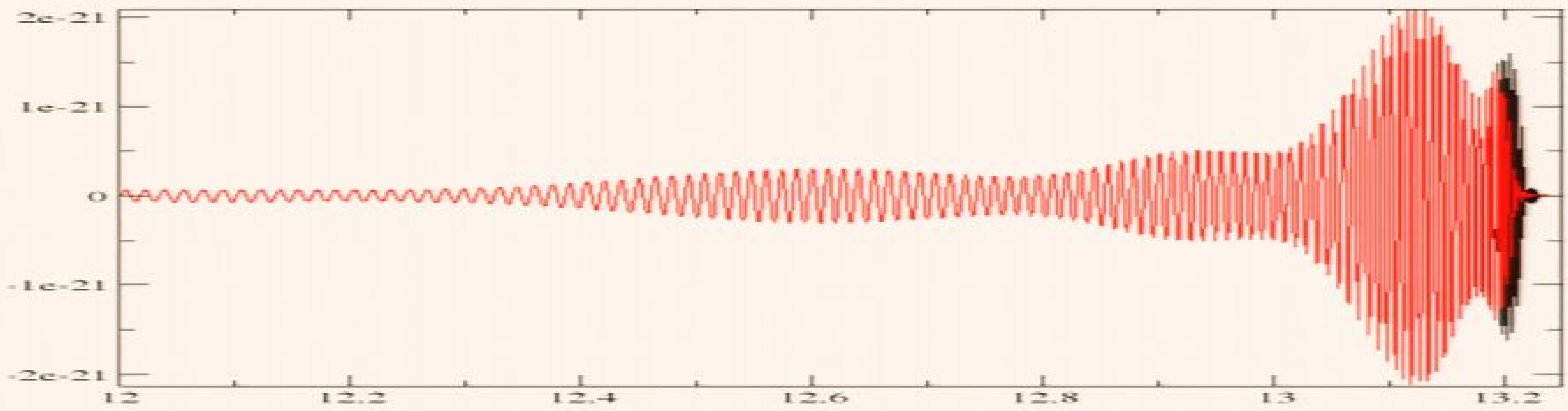
What do we gain? Probing neutron star EOS? Magnetic fields? Deviation from GR? Do we expect these effects to show up at any particular frequency given the systems we observe from the previous year?



What has the *LVC* been up to with NR inspired waveforms ?

WHAT WE *NEED* FROM NR / GR THEORY

1. Increasingly asymmetric mass ratios and more orbits if possible
2. Spin.
3. Matter.



What has the LVC been up to with NR inspired waveforms ?

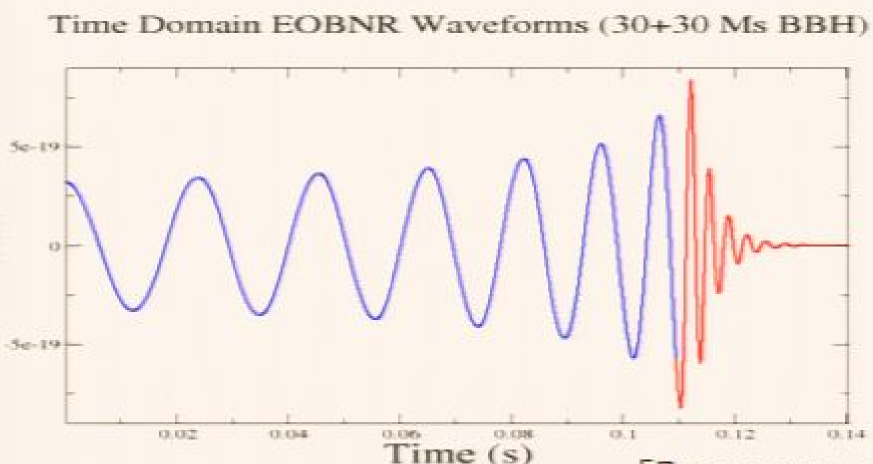
"High Mass Group"

earch 1-99 component M25-100 ,o total Mo in S5 ongoing

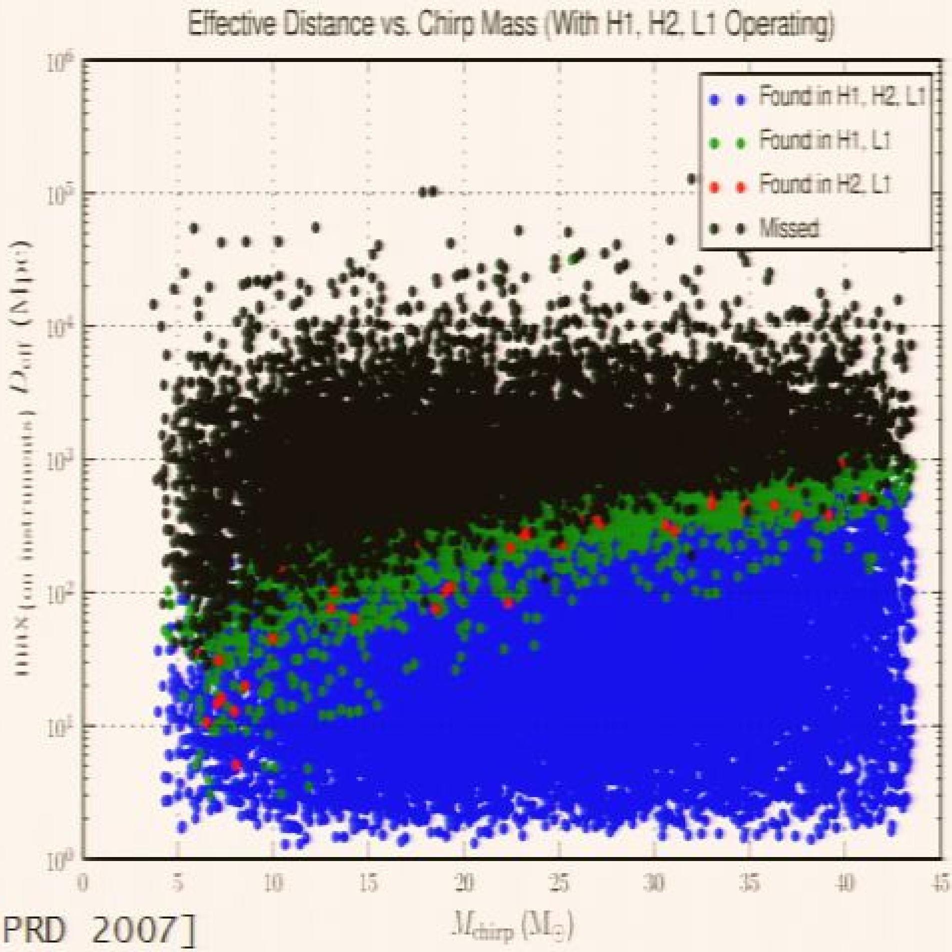
FILTERING

hese EOB + NR waveforms are alled EOBNR on the remaining lides

ALSE ALARM RATE IS NOT TAKEN NTO ACCOUNT HERE. We have plans o constrain the rate of such systems n the absence of a detection.



[Buonanno et al, PRD 2007]

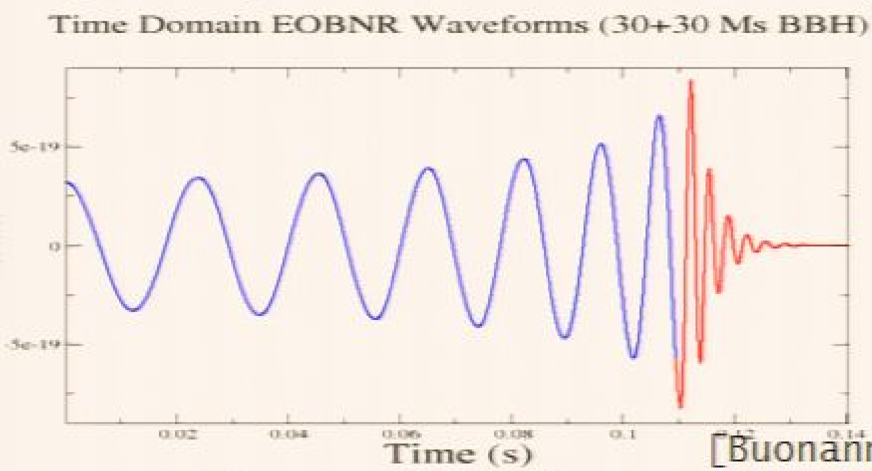


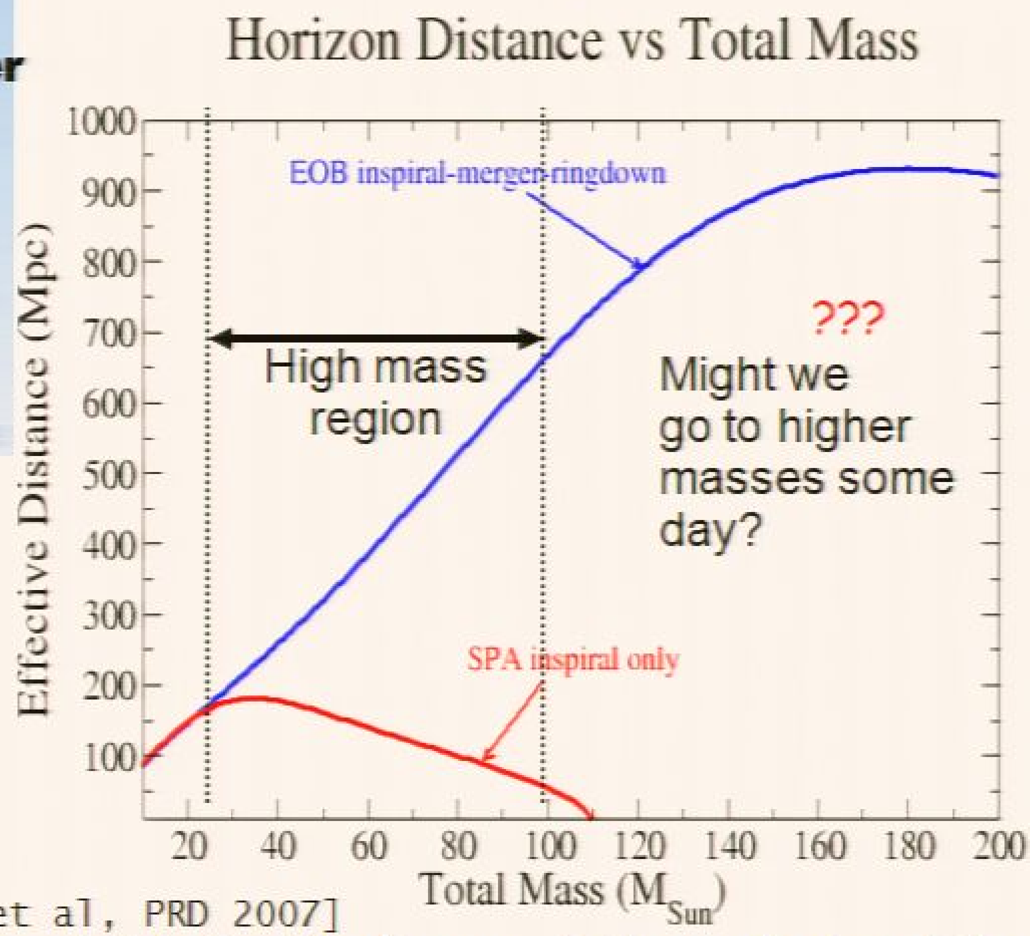
What has the LVC been up to with NR inspired waveforms ?

earch 1-99 component M25-100 ,o **total M**o **in S5 and S6 ongoing**

Ve filter with EOB waveforms and eed about ~2000 waveforms to cover he space with sufficient accuracy.

The EOB waveforms are tuned to IASA-Goddard NR in mass ratios of :1 – 1:4, but have been extended nalytically to the entire mass range





[Buonanno et al, PRD 2007]

nanno and Damour 99,00; Damour, Jaranowski and Schafer 00; Damour, Sathyaprakash and Iyer 9

Compact Binary Coalescence searches, next step

Going Beyond the inspiral phase

The results shown on the previous slides made use of filtering the data for the inspiral only part of the waveform. For low mass systems this is okay.

Last Stable Orbit for a Schwarzschild Black Hole = 6M
In GW frequency that corresponds to ~ 4400 Hz (M_{sun} / M)

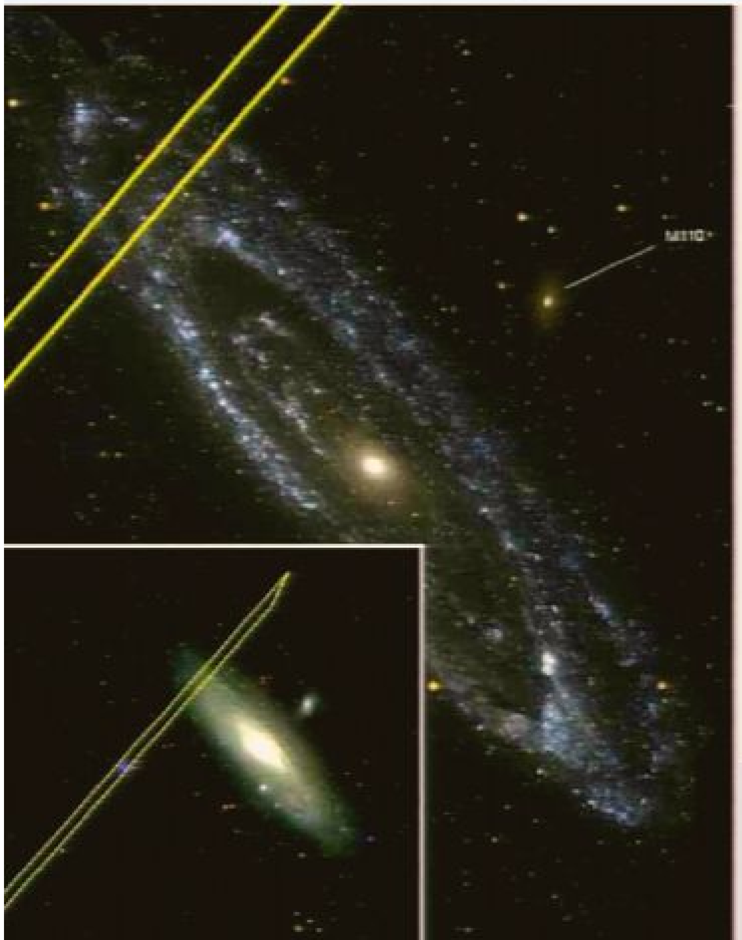
For heavier systems the Merger and ring down phase are in LIGO / Virgo's sensitive band. A 30 solar mass binary has the 6M radius at LIGO's most sensitive spot (~150Hz).

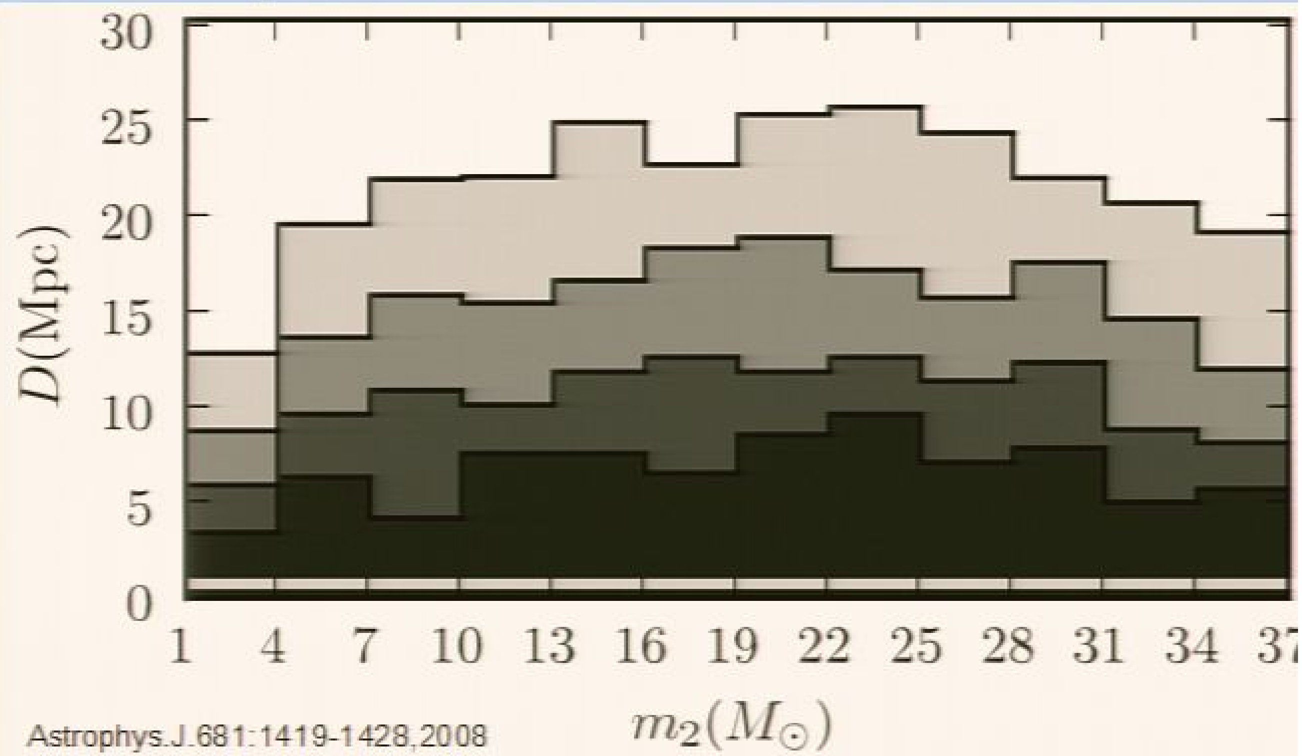
Searching for heavy systems is less founded than searching for stellar mass objects, but it is also more rewarding because they often require more exotic situations than simple stellar evolution to form.

Compact Binary Coalescence searches

Providing information about EM events

This is open ended, but we have an example GRB070201





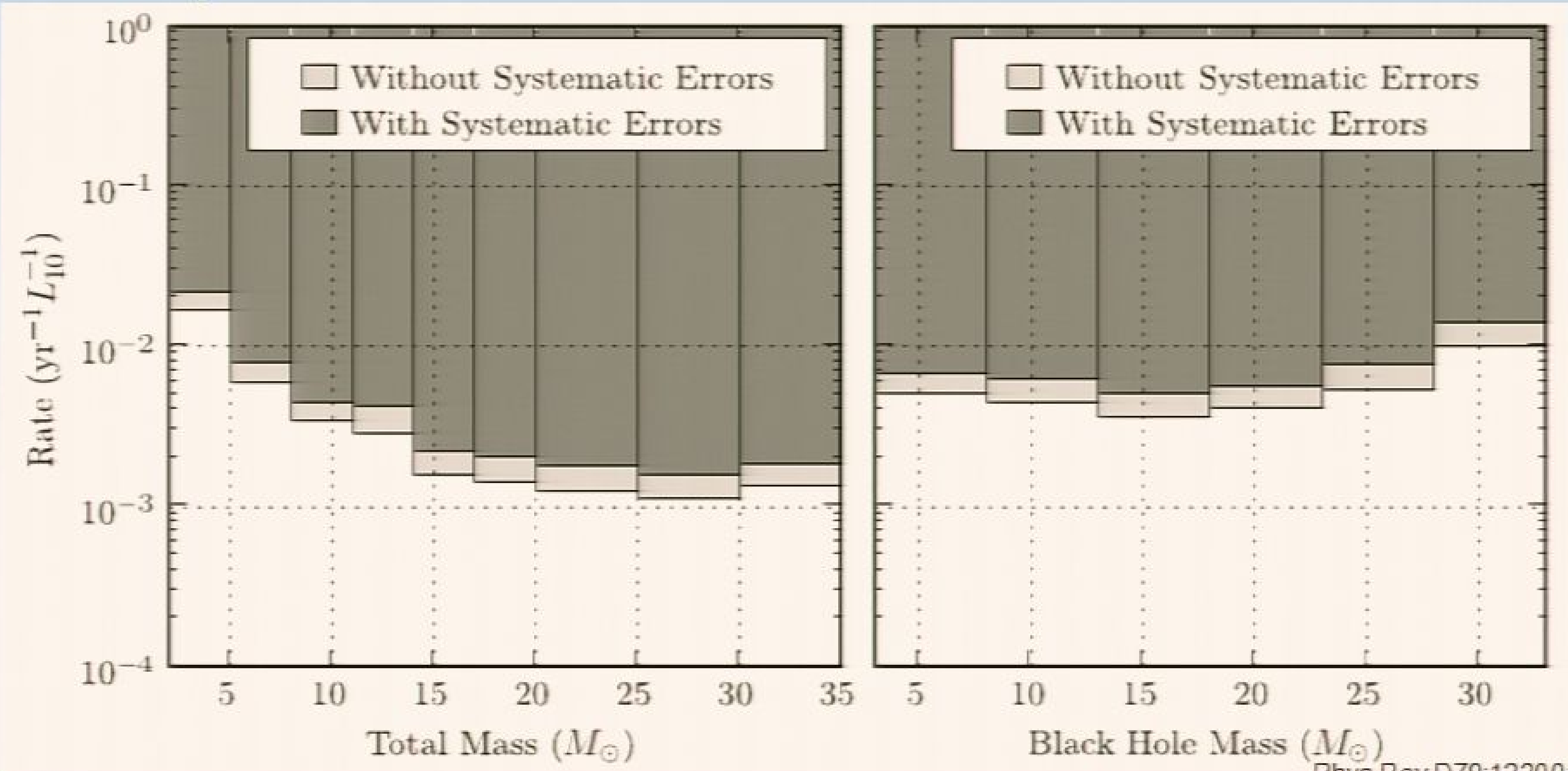
Astrophys.J.681:1419-1428,2008

GRB070201 had an error box overlapping Andromeda. LIGO observations excluded that it's progenitor was a compact merger to greater than 99%

Compact Binary Coalescence searches

Constraining merger rates

Goal: state 90% confidence upper bound on the merger rate of compact binaries in the nearby universe as a function of mass from direct measurement of GWs.

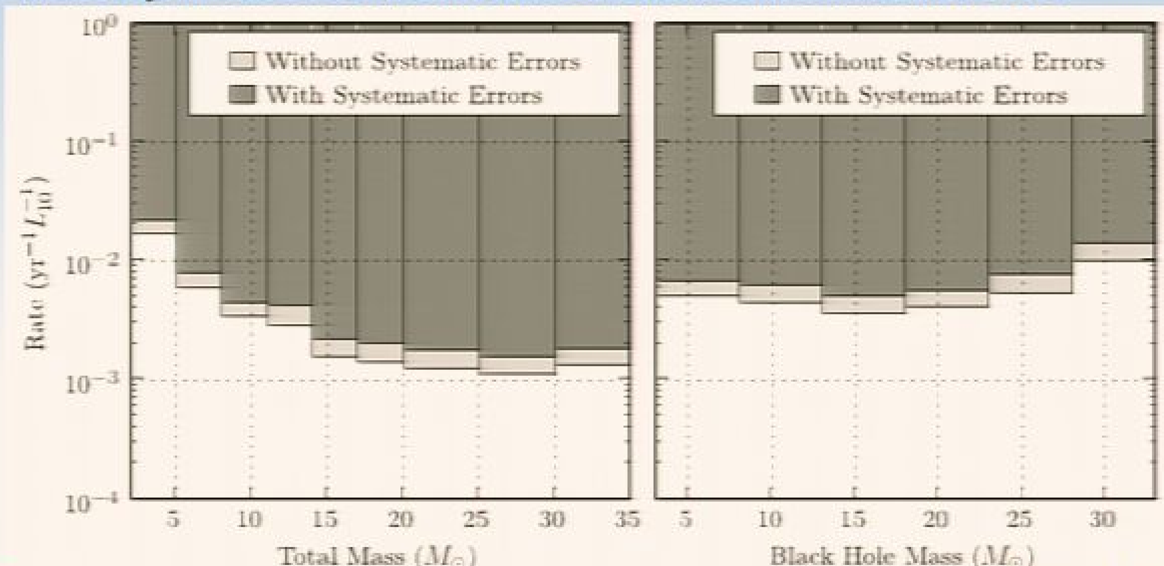


Phys.Rev.D79:122001,2009

Compact Binary Coalescence searches

Constraining merger rates

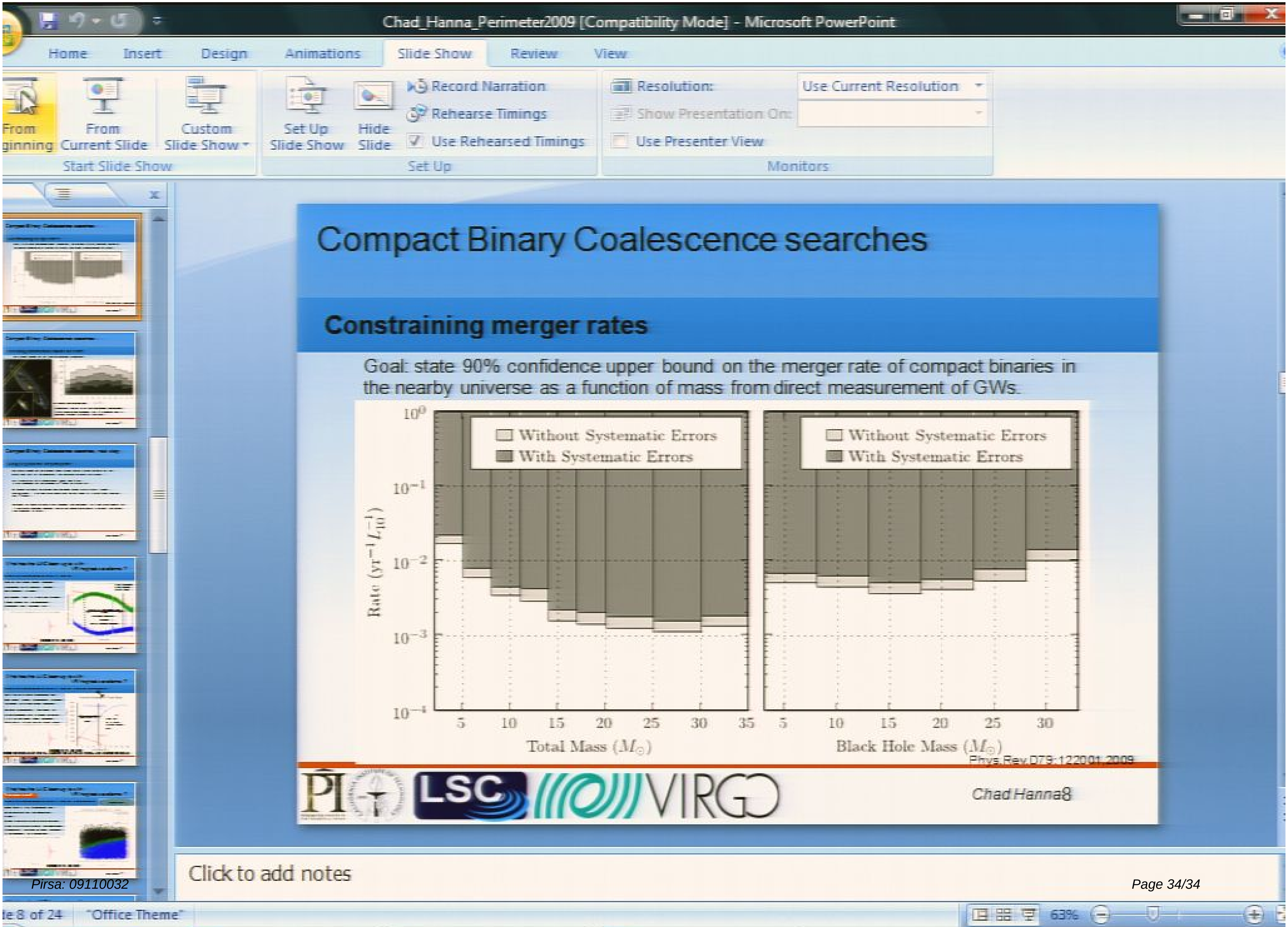
Goal: state 90% confidence upper bound on the merger rate of compact binaries in the nearby universe as a function of mass from direct measurement of GWs.



Phys.Rev.D79:122001,2009

Chad Hanna 8

Click to add notes


Chad_Hanna_Perimeter2009 [Compatibility Mode] - Microsoft PowerPoint
Compact Binary Coalescence searches
Constraining merger rates
Goal: state 90% confidence upper bound on the merger rate of compact binaries in the nearby universe as a function of mass from direct measurement of GWs.
Without Systematic Errors
With Systematic Errors
Rate $(yr^{-1}L_{10}^{-1})$
Total Mass $(M_\odot)$
Black Hole Mass $(M_\odot)$
Phys.Rev.D79:122001,2009
LSC
VIRGO
Chad Hanna 8
Click to add notes