Title: Searches for compact binary inspirals using hybrid waveforms

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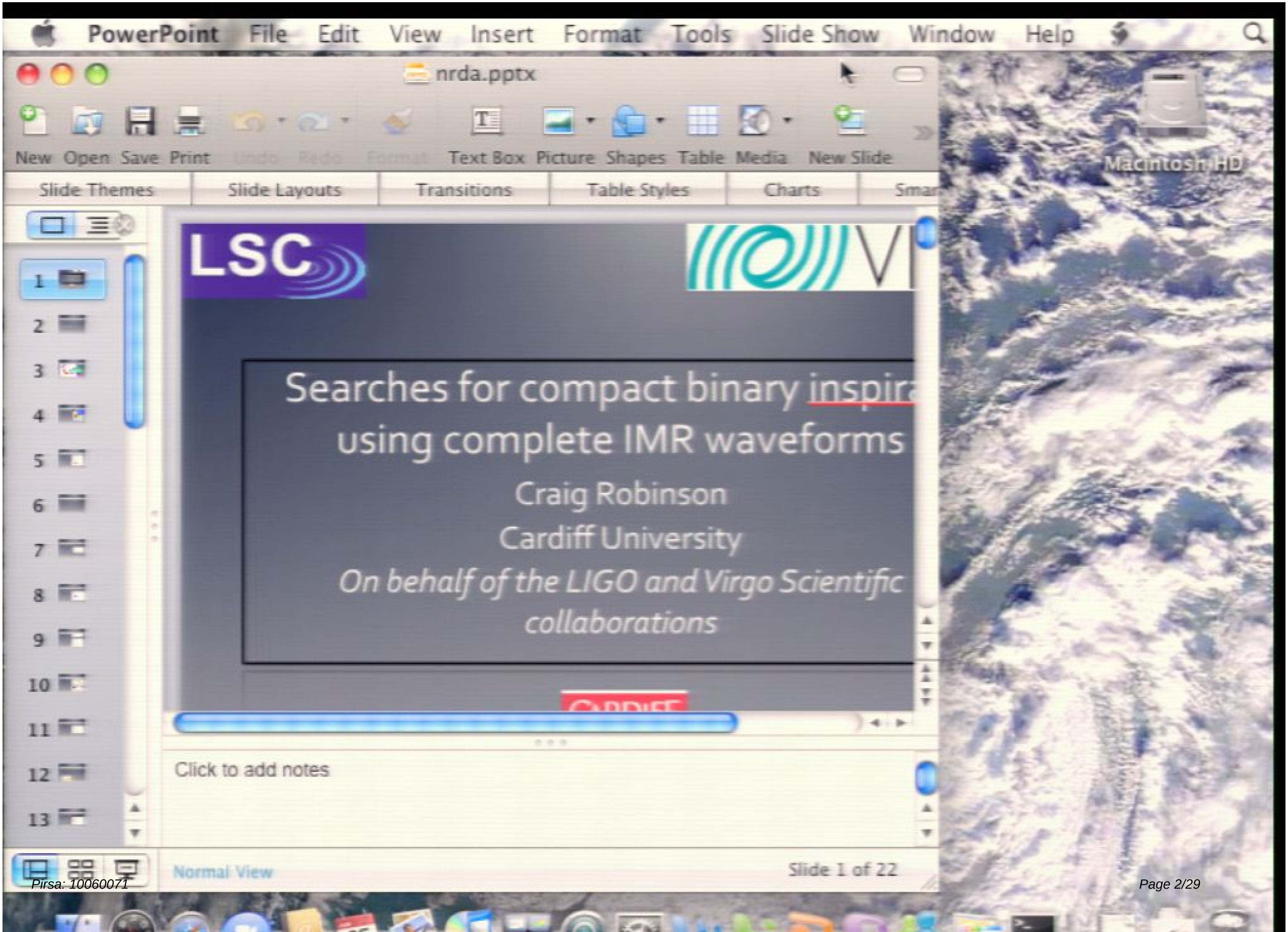
Abstract: TBA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Searches for compact binary inspira
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Craig Robinson
Cardiff University
On behalf of the LIGO and Virgo Scientific
collaborations
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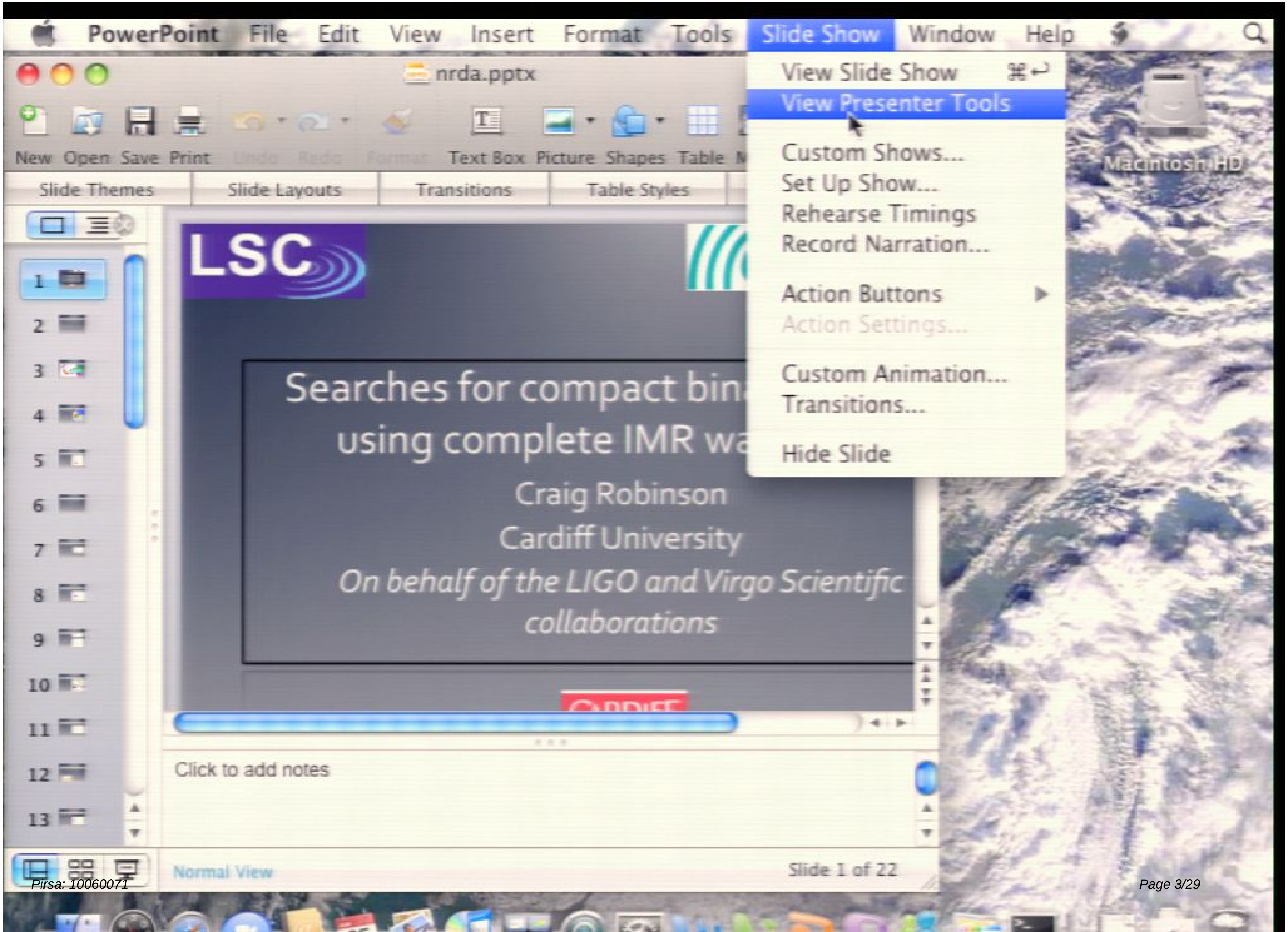
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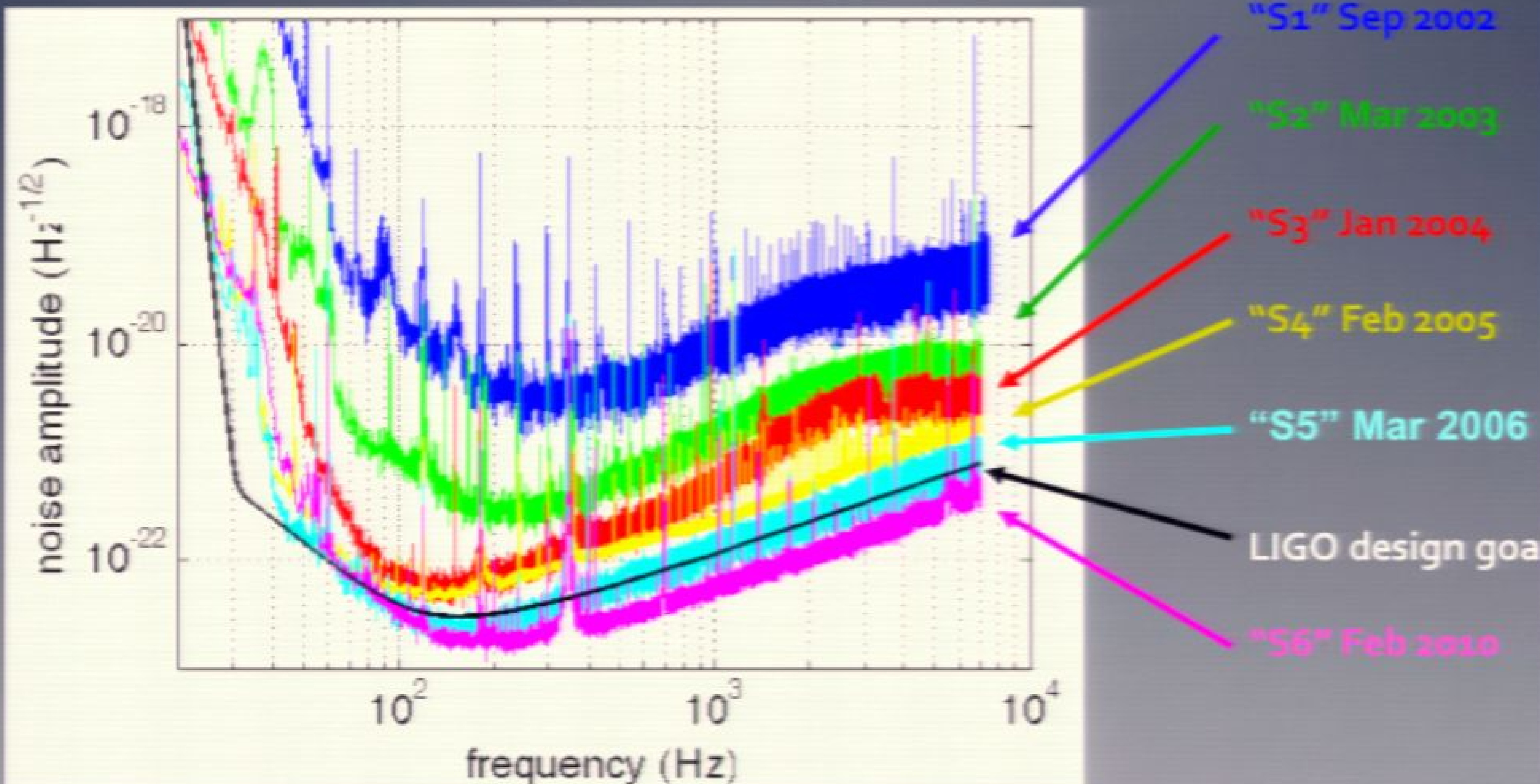
Searches for compact binary inspirals using complete IMR waveforms

Craig Robinson
Cardiff University
On behalf of the LIGO and Virgo Scientific collaborations

Outline

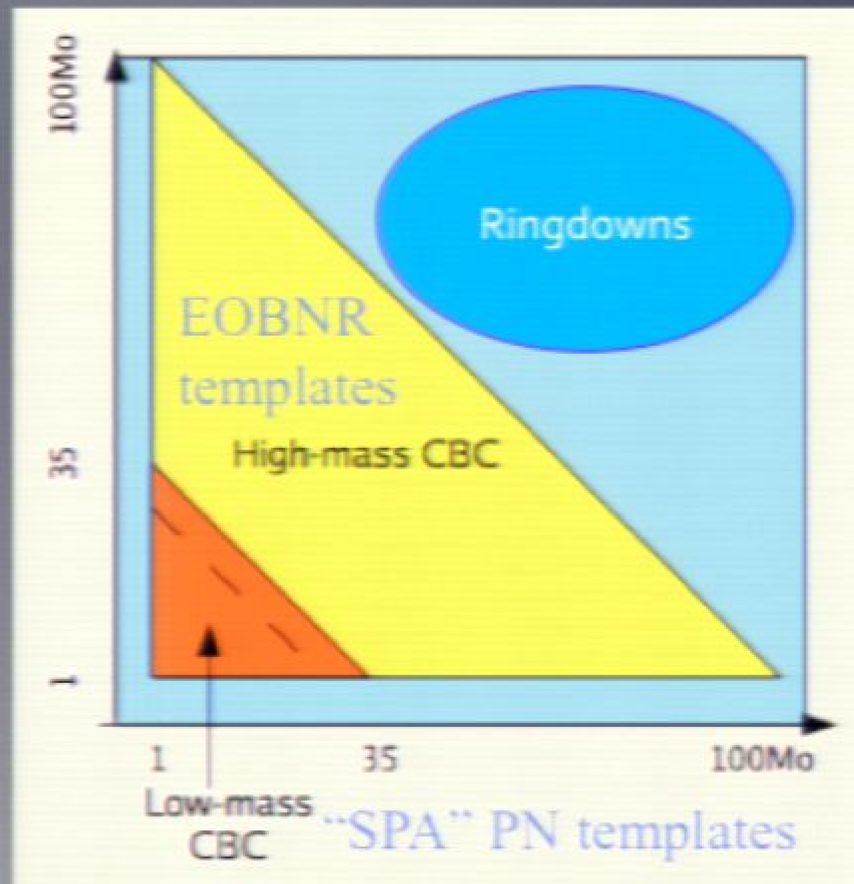
- Searches for inspiralling compact binaries
- Previous approaches to searches for high mass systems and their drawbacks
- The use of NR waveforms in GW searches
- Ongoing searches for compact binaries using templates inspired by NR waveforms
- Ongoing efforts to pull together burst and inspiral efforts
- Status and future work

Science Runs



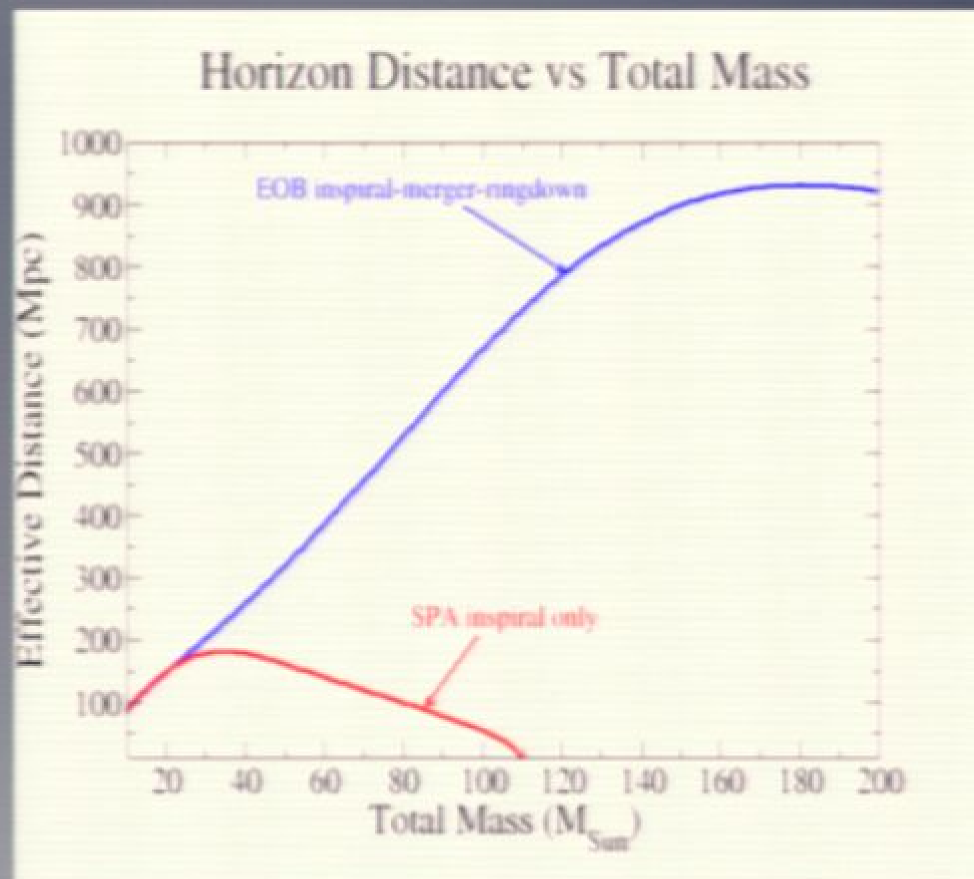
CBC searches

- The main searches performed by the CBC group:
  - Low mass search
    - Uses *TaylorF2* inspiral templates
  - High mass search
    - Uses EOBNR inspiral-merger-ringdown templates
  - Ringdown search



High Mass Binary Inspirals

- BH-BH and BH-NS binaries
- Total mass (25 – 100) $M_\odot$ with component masses (1 – 99) $M_\odot$
- Rate of BH-BH and BH-NS merger is very uncertain, could be ~ 0.01 – 1 $MWEG^{-1} Myr^{-1}$
- (10+10) $M_\odot$ BH binaries are detectable out to ~ 125 Mpc
- Higher mass binaries are detectable even further
- Merger and ringdown occur in the sensitive band of LIGO



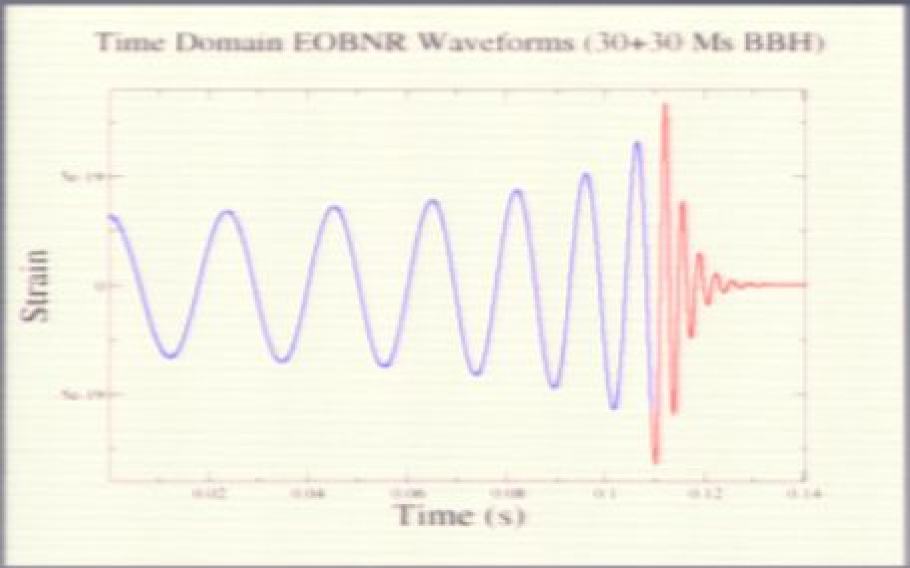
Plot created using Initial LIGO design PSD

Prior approaches to such searches

- In terms of CBC searches, several approaches were used:
  - Searches using inspiral-only PN approximants as templates
    - Good for low-mass searches e.g. binary neutron stars
    - Different PN approximants behave differently at late-stage inspiral – moreover, merger and ringdown were effectively ignored
  - Searches using phenomenological templates
    - E.g. BCV templates *(Buonanno et al, Phys.Rev.D67:024016,2003)*
    - Encapsulates differences between different PN approximants
    - But raises difficulties in interpretation of results
    - Still no inclusion of merger and ringdown
  - Searches for black hole ringdowns
    - Ringdown search performed up to very high masses (~ 500 $M_{\odot}$)
    - But ringdown only search ignores extra SNR and information provided by inspiral
  - Also burst searches
  - Searches tested using injections of inspiral-only signals

Use of NR simulations for searches

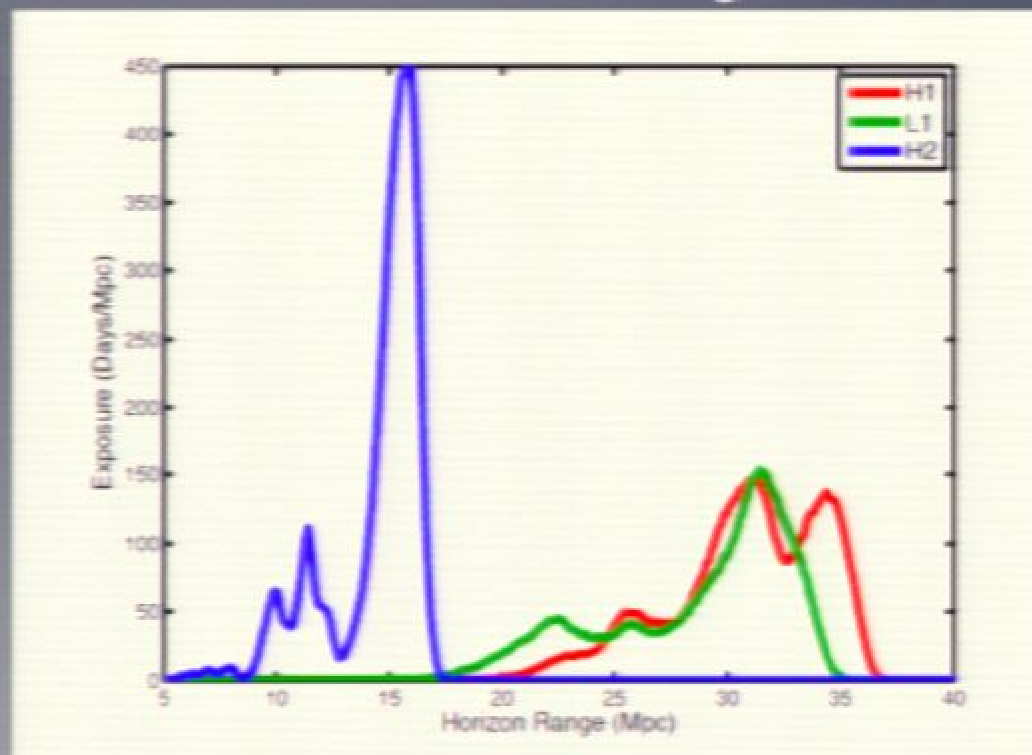
- Allows new template/injection families to be developed
  - Calibrated to NR simulations
  - Also include merger/ringdown
- Inject NR waveforms into data to test search pipelines
  - *NINJA project – see talk by M. Boyle*



LIGO S5 High-mass search

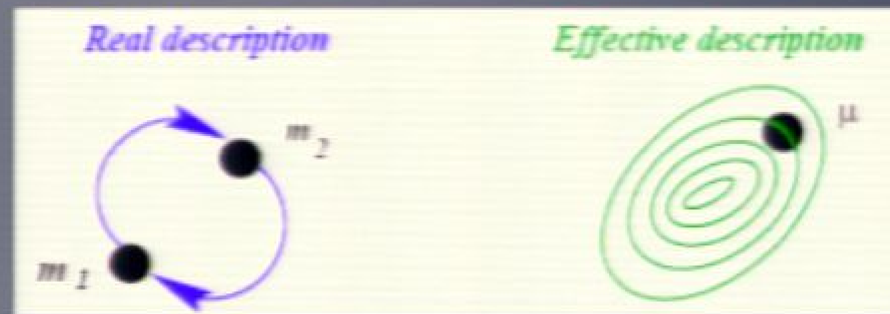
- First search to use templates incorporating inspiral-merger-ringdown
- LIGO S5 data taken from Nov 2005 – Nov 2007
- 3 detectors operating at initial LIGO design sensitivity
- Over a year of triple coincident data

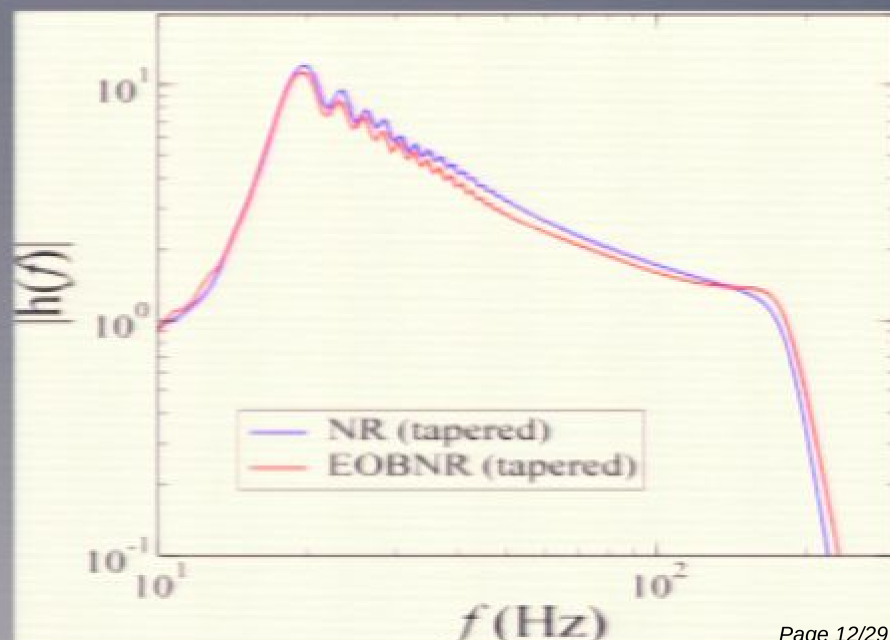
NS-NS Horizon Range



Search template – EOB inspiral-merger-ringdown model

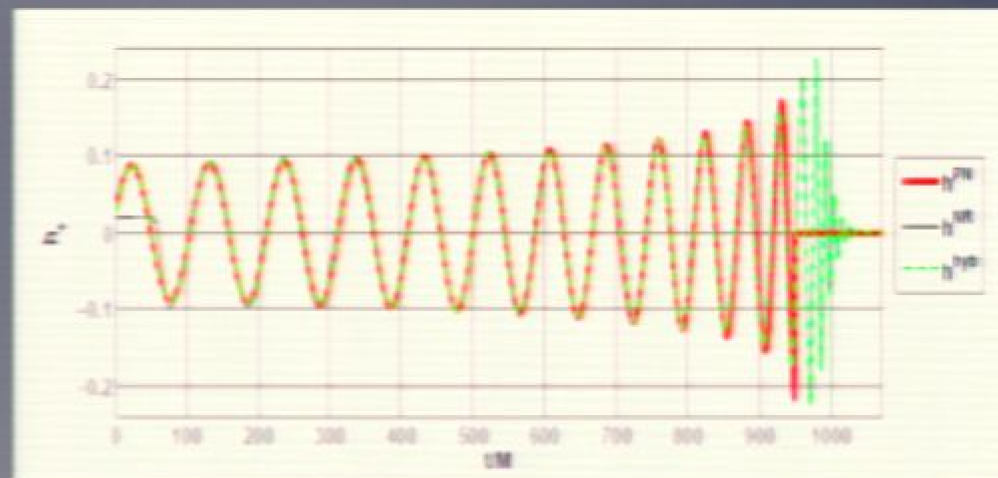
- The effective-one-body (EOB) approach uses a re-summed Hamiltonian of the binary dynamics during inspiral up to the light ring
- The EOB inspiral-plunge waveform is computed along the trajectory provided by the EOB Hamiltonian
- The EOB merger-ringdown waveform is a superposition of quasi-normal modes smoothly attached near the light ring
- The model was calibrated to NR waveforms with mass ratios 1:1 - 4:1 from the NASA-Goddard group
- Based on *Buonanno et al, PRD 2007*

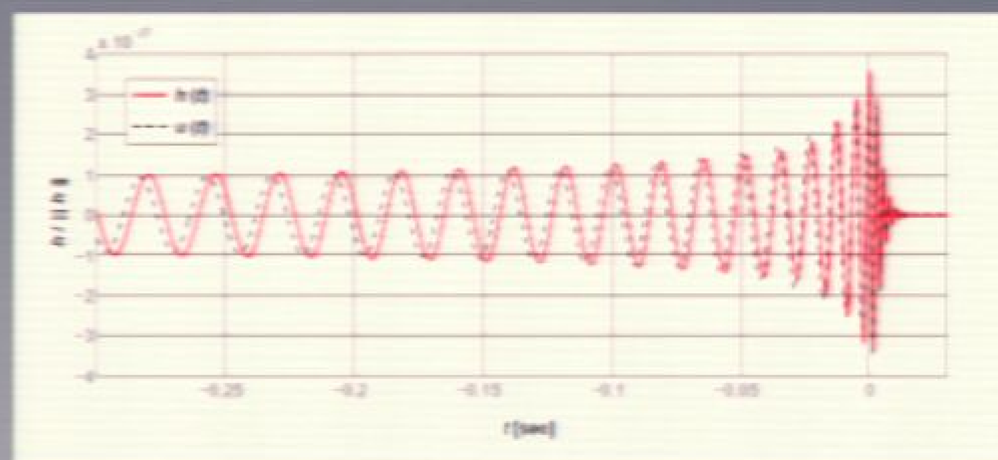




Injections – phenomenological IMR waveforms

- As detailed *in Ajith et al, PRD 2008*
- Hybrid waveforms are created by stitching PN waveforms to NR waveforms from the final few orbits
- Phenomenological waveforms are fit to the hybrid waveforms in the frequency domain
    - The inspiral waveform has the structure of stationary-phase approximation waveforms
    - The ringdown waveform decays as a Lorentzian
    - Undetermined coefficients are calibrated to match the hybrid waveforms
    - The waveforms are parameterized by the masses with no spurious degrees of freedom
    - The model was calibrated to AEI-Jena waveforms with mass ratios 1:1 – 4:1

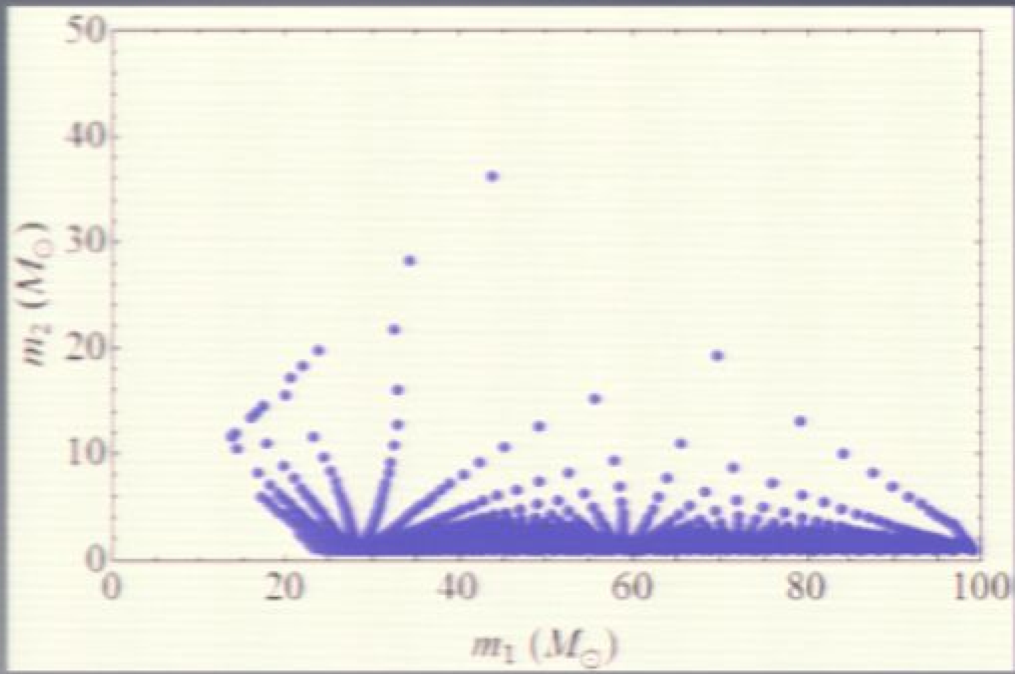




Matched filtering pipeline

- A matched filtering approach is used to find potential signals buried in noise
- A template bank is laid out to cover the mass range so that adjacent templates nominally have an overlap > 0.97
- The data are filtered against each template
- Any triggers are tested for coincidence with other detectors
- A second coincidence test is performed with signal-based vetoes such as χ^2 applied to significantly reduce triggers due to noise

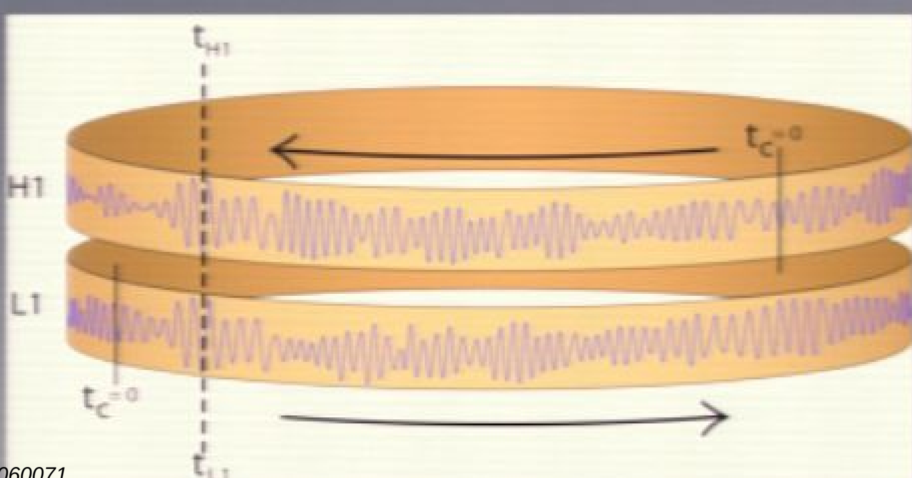
Template Bank in Mass Space



Typically ~2000 templates

Matched filtering pipeline

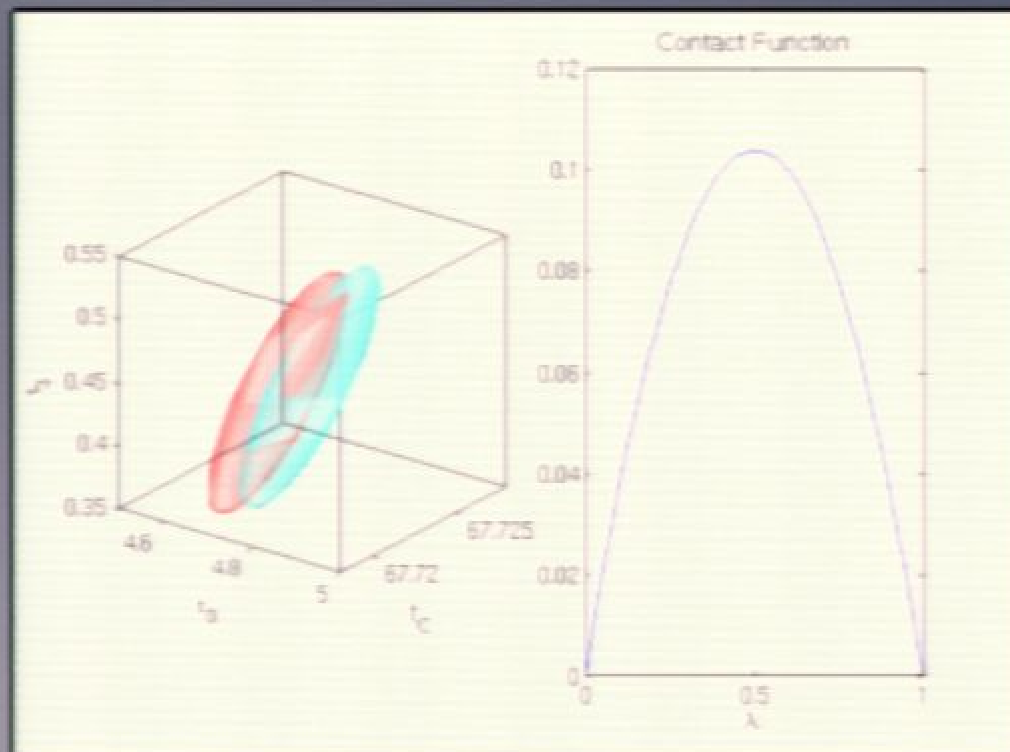
- Analysis split into chunks of approx 2 months duration
- The loudest coincident triggers in each chunk are subjected to further scrutiny
- Upper limit will be set on the rate of binary coalescences in this mass range (subject to various caveats…)



- Time slides are used to estimate the rate of background triggers
- Repeat the analysis, but slide the data from each site relative to one another
  - Any coincident events between sites must be accidental
- We also inject waveforms to test our efficiency at recovering signals
  - Inject EOBNR waveforms over full mass range
  - Inject phenomenological waveforms with mass ratios up to 10:1

Coincidence test

- Candidate events must be seen in at least 2 detectors
- Parameters in each detector must agree to within a certain tolerance for events to be considered coincident
- Coincidence windows on masses and coalescence time determined by parameter space metric



The chi-squared test

- Goodness-of-fit test between data and template
- Template split into 10 frequency bands containing equal 'power' By filtering against the data we get
  - $y_i = \langle x, u_i \rangle$, $z_i = \langle x, v_i \rangle$
- It is obvious that
  - $\frac{(y^2 + z^2)}{\sigma^2} = \rho^2$, $y = \Sigma y_i$, $z = \Sigma z_i$

The chi-squared test

- We construct the quantities
  - $\Delta y_i = y_i - y/p,$ $\Delta z_i = z_i - z/p$
    where p is the number of frequency bands
- Define the χ^2 statistic as:
  - $$\chi^2 = p \frac{\sum[(\Delta y_i^2 + \Delta z_i^2)]}{\sigma^2}$$

  For perfectly matched signal and template in absence of noise, χ^2 will be zero

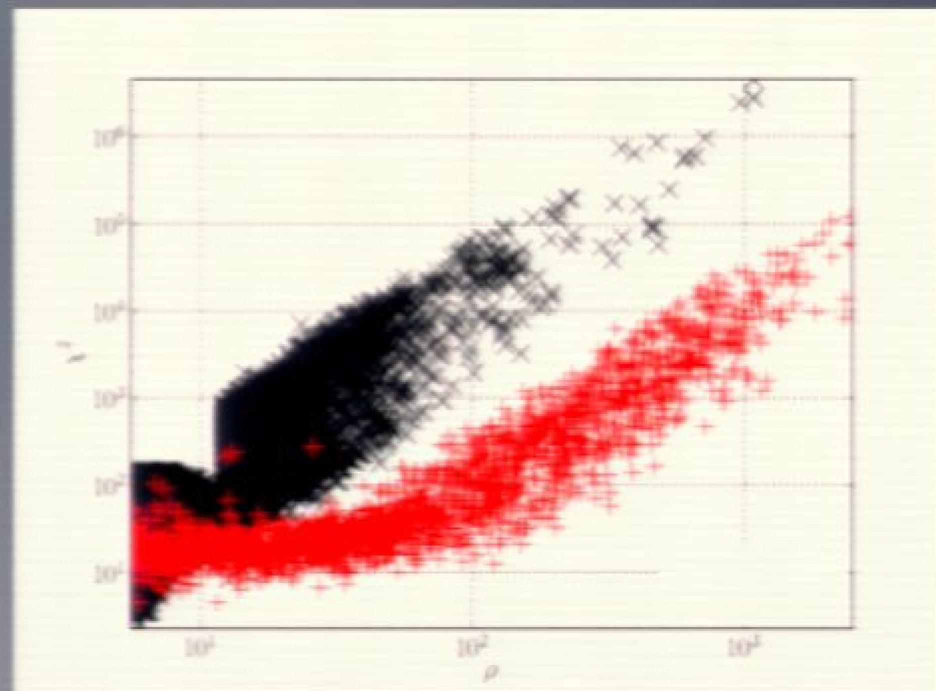
  For a signal in the presence of noise, χ^2 will have a low value

  For a high SNR glitch, χ^2 will take a high value
- In practice, we use the χ^2 value along with the SNR to create a new statistic, the effective SNR.

Effective SNR

- Combination of SNR and chi-squared
- Better separates injected signals and time slides
- Given by:

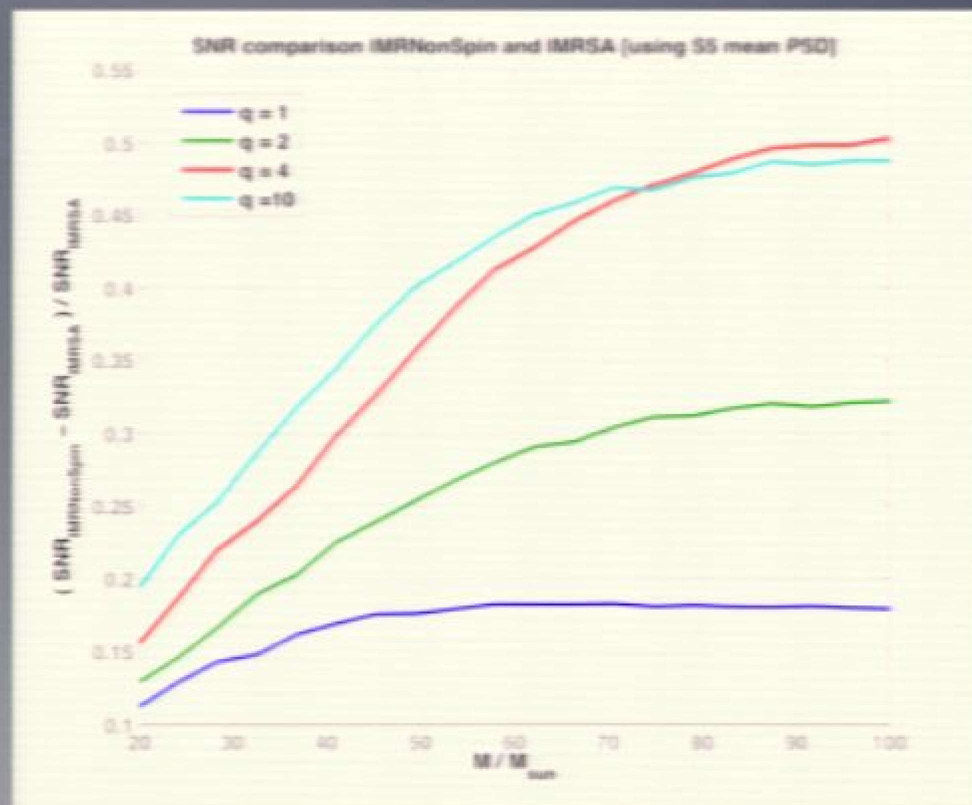
$$\rho_{eff}^2 = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{2p-2}\right)\left(1+\frac{\rho^2}{50}\right)}}$$



Parameter space broken up into mass bins – candidates ranked according to false alarm rate calculated from time slides

But wait…

- A lot of time has passed since 2007!
- More recent NR simulations have led to improved analytic waveforms
- Differences in SNR can be very significant – as much as 50%
- This must be borne in mind when interpreting the results

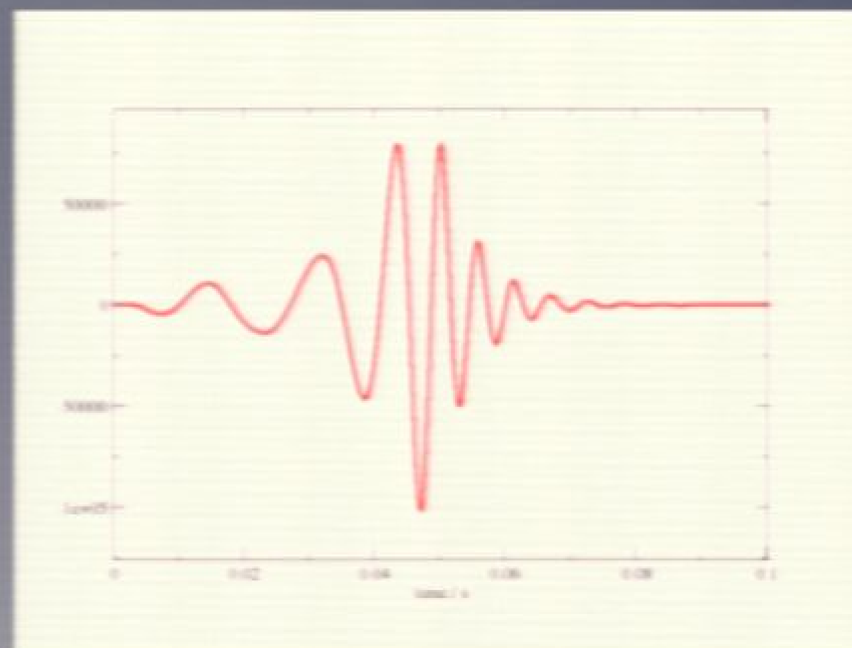


Future improvements

- LIGO S6 science run is ongoing – Virgo VSR2 took place during last half of 2009. Virgo VSR3 will commence soon
- Ranking candidate events using a multivariate classifier – has the potential to significantly improve the sensitivity of the search
- Improved EOB and phenomenological waveforms are now available – get these into the search
- IMR waveforms with spin effects and higher harmonics are becoming available/in development
- Improve template placement at higher masses
  - Current placement depends on the same metric as low mass search
  - In the future we will explore using a metric specifically for IMR waveforms

What about burst searches?

- As we go into the high mass regime, the signals are very short within the sensitive band
- One might expect that burst searches would perform well for such 'bursty' signals
- It may be that the lack of assumptions in a burst search allow them to better take into account effects such as spin



Whitened $50+50M_\odot$ template

The IMR group

- Pulling together CBC and burst group efforts
- Aim of comparing and contrasting different approaches assessing how best to combine approaches to aid detection confidence
- Much infrastructure has been developed to allow 'apples-to-apples' comparisons between burst (Omega, coherent Waveburst) and CBC (high mass, ringdown) pipelines
- All searches will participate in NINJA 2

Summary

- In the S5 run, we searched for BBH or BH-NS systems with total mass 25-100M☉ using inspiral-merger ringdown templates
  - The LIGO interferometers operated at design sensitivity providing over a year of triple-coincident data
  - The first search to use complete IMR templates
- We expect to have public results later this year
- In future we expect to make improvements to the search, including using a multivariate classifier to rank candidates, and using newer, improved waveforms as templates
- Efforts are underway to pull together burst and CBC efforts to search for high mass coalescing binaries
- NR has a significant contribution to make for such searches:
  - Informing the development of newer, better search templates/injections
  - Injecting numerical waveforms allows us to test pipelines and compare the performance of different approaches

Questions?

The IMR group

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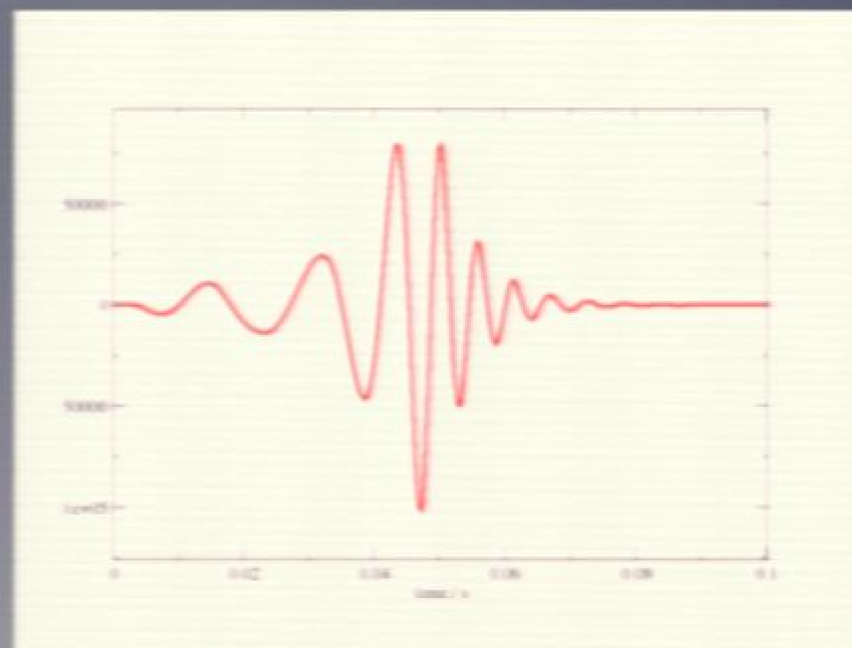

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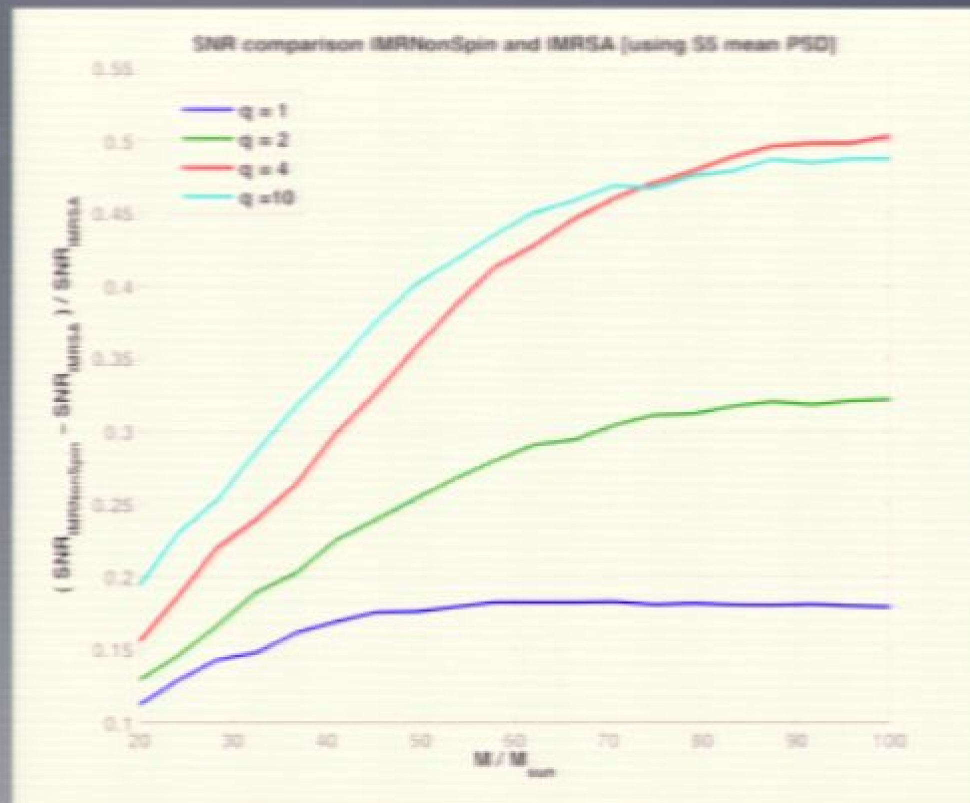

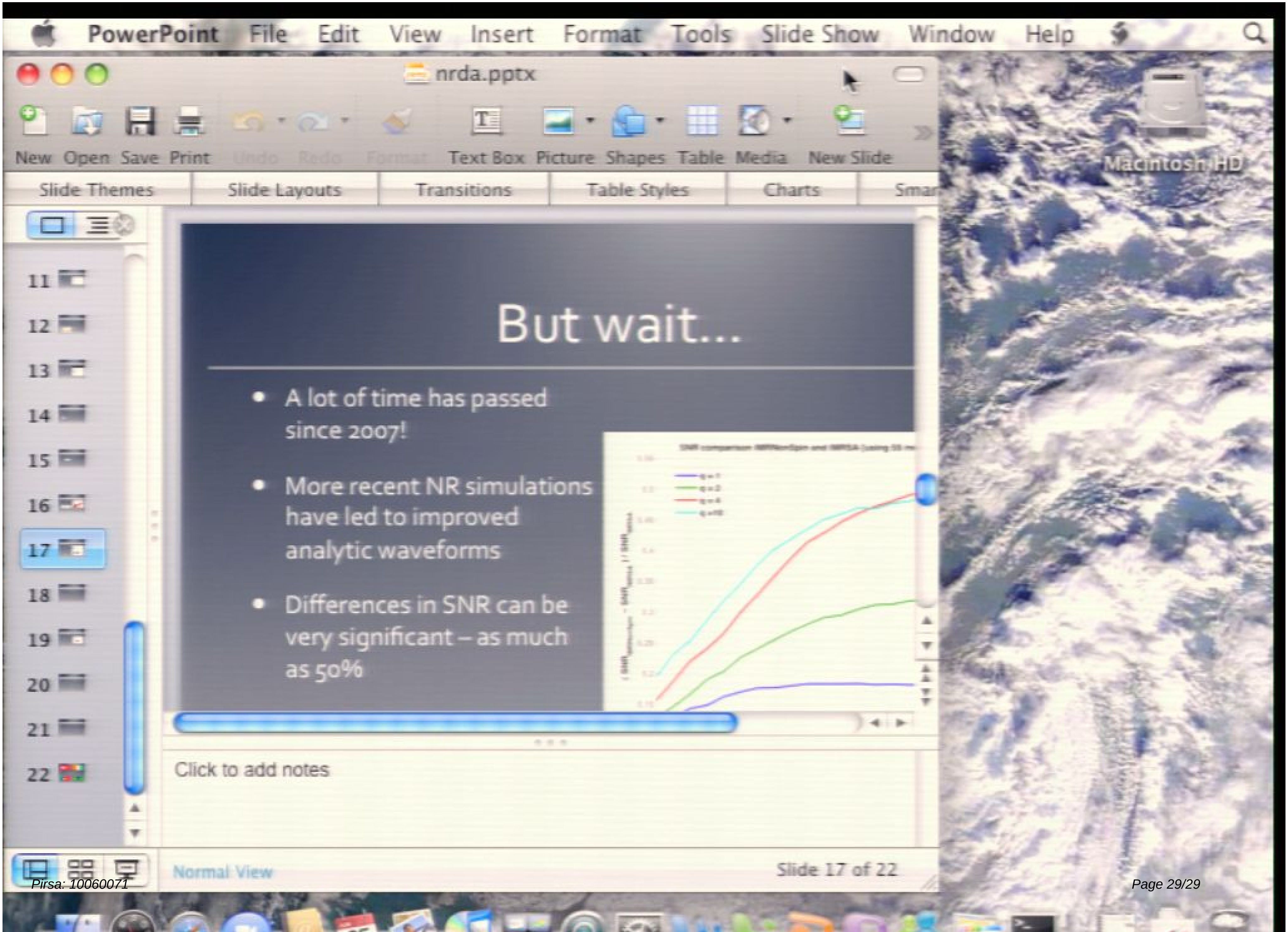
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