THE NINJA PROJECT

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for the NINJA project

NRDA 2008 Conference, Syracuse NY

August 13, 2008

LIGO-G080564-00-Z

NINJA:
the Numerical INJection Analysis project

- Goal: to study the sensitivity of data analysis pipelines to binary black hole numerical relativity waveforms buried in simulated Gaussian noise

- First step towards incorporation of numerical relativity waveforms in gravitational wave data analysis

- Open to all interested numerical relativity and data analysis groups
  - 10 NR groups contributed waveform of their choice
  - Waveforms were added to simulated, colored Gaussian noise
  - 9 DA teams analyzed the data with various methods
  - 65 participants, from 23 institutions

AEI-Golm: N. Dorband, S. Husa, B. Krishnan, D. Pollney, C. Reisswig, L. Rezzolla, L. Santamaria, J. Seiler, J. Whelan

Birmingham: B. Aylott, J. Veitch, A. Vecchio

Caltech: M. Boyle, L. Buchman, T. Chu, K. Matthews, H. Pfeiffer, M. Scheel

Cambridge: O. Rinne

Cardiff: S. Fairhurst, B. Farr, B. Sathyaprakash

Carleton: Christensen

Cork: M. Hannam

Cornell: L. Kidder

FAU: P. Marronetti, W. Tichy

Goddard: J. Camp, B. Kelly, A. Stroeer

INFN/Caltech: S. Chatterji

INFN/Urbino: G. Guidi, A. Vicere'

Jena: B. Brugmann, U. Sperhake

LSU: P. Diener, E. Schnetter

Northwestern: V. Kalogera , I. Mandel, V. Raymond , M. van der Sluys

Princeton: F. Pretorius

PSU/GT: F. Herrman, I. Hinder, P. Laguna, D. Shoemaker

RIT: M. Campanelli, J. Faber, C. Lousto, H. Nakano, Y. Zlochower

Syracuse: D. Brown, L. Pekowsky

UIUC: Z. Etienne, Y.T. Liu, S. Shapiro

UMass Amherst: L. Cadonati, M. Dias, S. Mohapatra

U. Maryland: A. Buonanno, E. Ochsner, Y. Pan

UWM: P. Brady, L. Goggin, A. Mercer, R. Vaulin

NINJA-A

Goals for the first run:

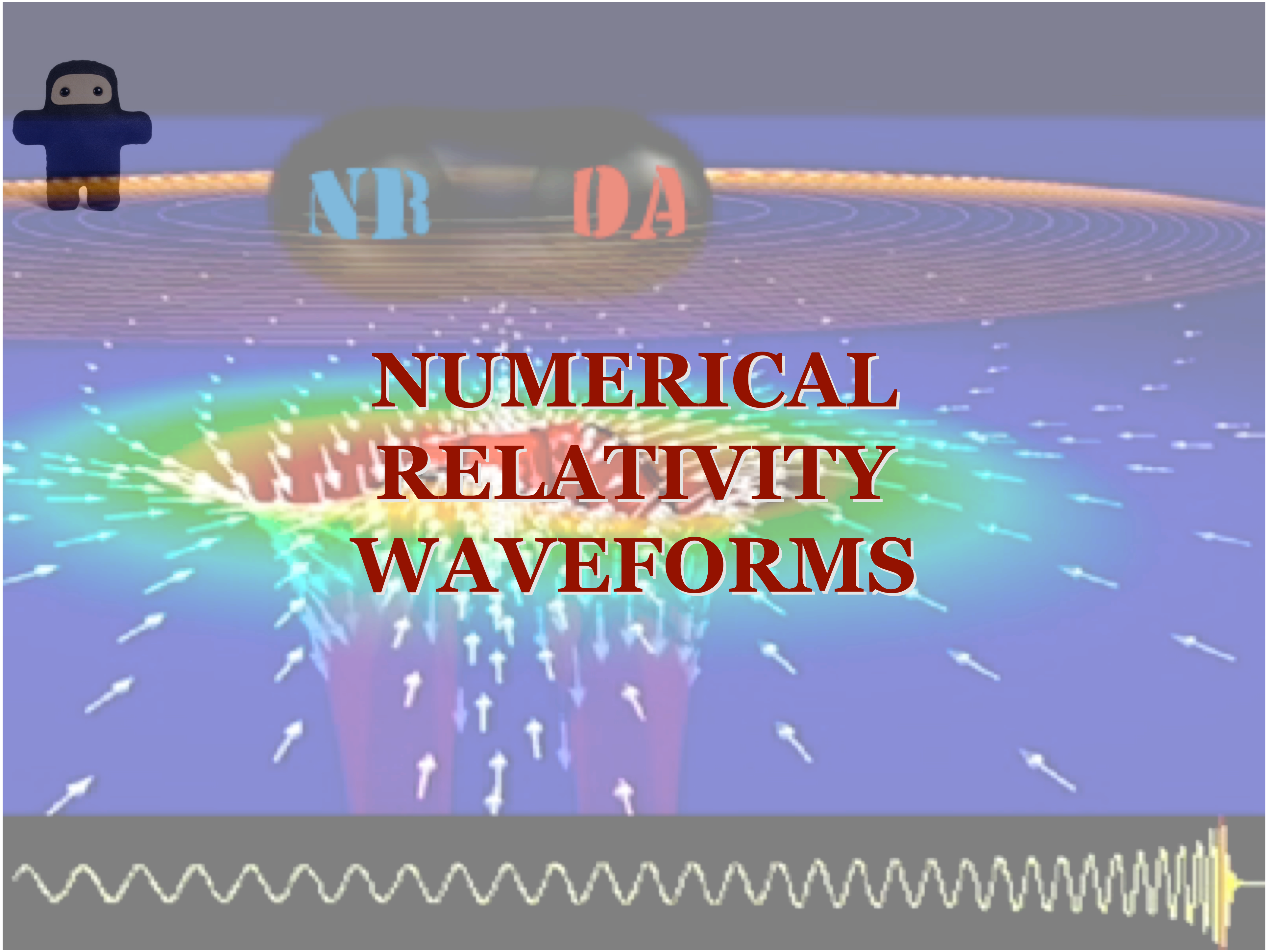
- Bring together the two communities
- Each NR group chooses which waveforms to share
- Each DA group chooses how to do analysis and which results
- Learn what are the issues and understand how to address them next time (NINJA-B)
- Target: CQG publication by the fall

Planned schedule, from the NINJA kickoff teleconference April 3, 2008

- Submission of waveforms: April 30
- 1 page writeup describing waveform: May 16
- Creating noisy data with signals: May 16
- 2 page writeup of analysis results: July 18
- Final paper editing and discussions in July
- Presentations and discussion of future prospects (NRDA meeting in Syracuse): August 11-14

We are about 1-month behind schedule: we identified some issues with the simulated data, which require a rerun

NUMERICAL RELATIVITY WAVEFORMS



Waveform exchange - arXiv:0709.0093

Format based on standard mode decomposition of the two polarizations $h_{+,\times}^{(lm)}(t)$

Choice of waveform left to each NR group:

- Up to 2 waveforms per code
- Or a maximum of 5 for a single 1-parameter family

Sample waveform file

```
# numerical waveform from ....
# equal mass, non spinning, 5 orbits, l=m=2
# time          hplus          hcross
0.000000e+00 1.138725e-02 -8.319811e-04
2.000000e-01 1.138725e-02 -1.247969e-03
4.000000e-01 1.138726e-02 -1.663954e-03
6.000000e-01 1.138727e-02 -2.079936e-03
8.000000e-01 1.138728e-02 -2.495913e-03
1.000000e-00 1.138728e-02 -2.911884e-03
1.200000e+00 1.138729e-02 -3.327850e-03
1.400000e+00 1.138730e-02 -3.743807e-03
1.600000e+00 1.138731e-02 -4.159757e-03
1.800000e+00 1.138733e-02 -4.575696e-03
2.000000e+00 1.138734e-02 -4.991627e-03
```

Sample metadata file

```
[metadata]
simulation-details = NRfile.dat
nr-group = friendlyNRgroup
email = myemail@somewhere.edu
mass-ratio = 1.0
spin1x = 0.0
spin1y = 0.0
spin1z = 0.5
spin2x = 0.0
spin2y = 0.8
spin2z = 0.0
freqStart22 = 0.1

[ht-data]
2,2  = example1_22.dat
2,1  = example1_21.dat
2,0  = example1_20.dat
2,-1 = example1_2-1.dat
2,-2 = example1_2-2.dat
```

Waveforms: 10 NR groups

1. AEI-CCT [Dorband, Husa, Pollney, Reisswig, Rezzolla, Seller]
   - Equal-mass, spinning binaries
   - The spin is (anti-)aligned with the orbital angular momentum
   - one spin fixed at 0.6, the other varies from -0.6…0.6.

2. BAM_FAU [Marronetti, Tichy]
   - Equal mass, spinning binaries
   - Spin magnitude a/m=0.75, randomly aligned
   - $S_1/M_1^2 = (-0.63,-0.22,0.32)$, $S_2/M_2^2 = (-0.52,-0.54,0.03)$)

3. BAM_HHB [Hannam, Husa, Brugmann]
   - Equal mass, spinning binaries [arXiv:0712.3787]
   - the two BH have same spin, parallel to total angular momentum
   - $S_i/M_i^2=(0,0.25,0.50,0.75,0.85)$

Waveforms: 10 NR groups

4. Caltech/Cornell [Boyle, Buchman, Chu, Kidder, Matthews, Pfeiffer, Rinne, Scheel]
   - Equal mass, non-spinning [arXiv:0710.0158]
   - initial eccentricity 5×10^{-5}
   - 16 orbits + merger + ringdown

5. GSFC [Kelly]
   1. 4:1 mass ratio, non-spinning [arXiv:0706.3732 [gr-qc]].
   2. 3:1 mass ratio, with spins in the plane, initially aligned with the smaller hole's tangential velocity. [arXiv:0802.0416 [astro-ph]]

6. LEAN [Sperhake]
   1. 4:1 mass ratio, non-spinning, 10 orbits [arXiv:0711.1097]
   2. Equal mass, spinning S_i/M_i^2=0.926, 3 orbits [arXiv:0709.2160]

Waveforms: 10 NR groups

7. Princeton [Pretorius]
   - equal-mass non-spinning mergers; generalized harmonic coordinates code
     1. Cook-Pfeiffer “d=19” initial data
     2. “zoom-whirl” type orbit ending in merger.

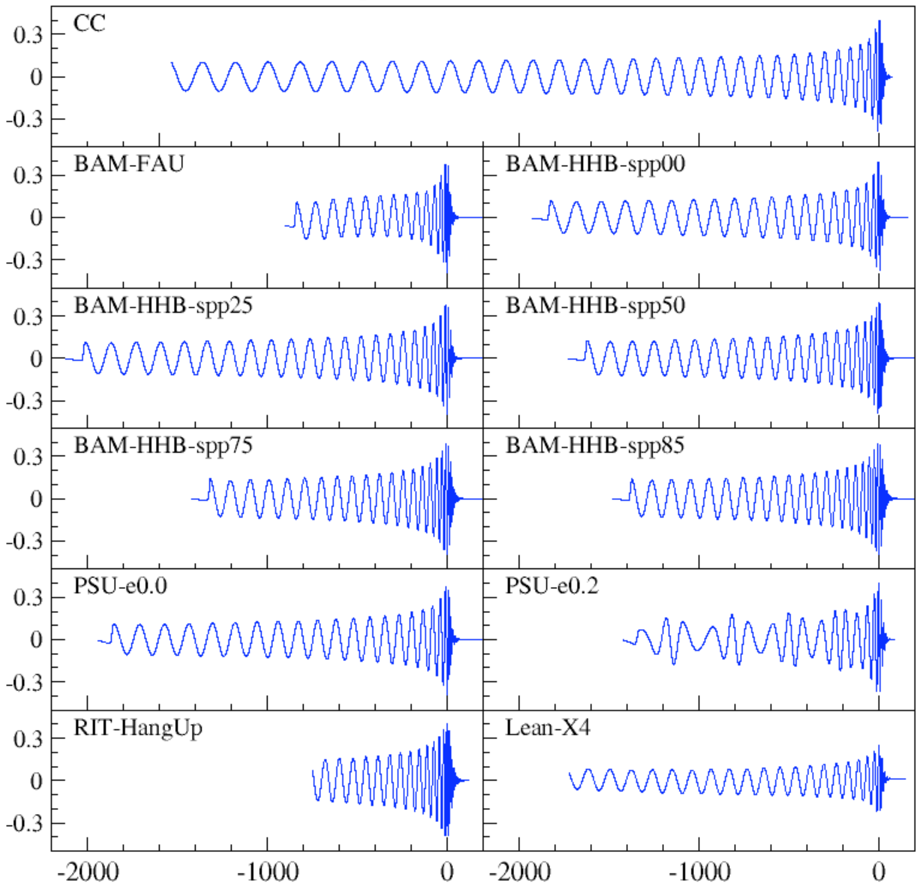
8. PSU [Herrmann, Hinder, Laguna, Shoemaker]
   1. Equal mass, circular inspiral [arXiv:0710.5167].
   2. Equal mass, eccentric inspiral e=0.2

9. RIT [Campanelli, Lousto, Faber, Nakano, Zlochower]
   - Equal mass, spinning
   - spins aligned with the orbital angular momentum [arXiv:0803.0351]

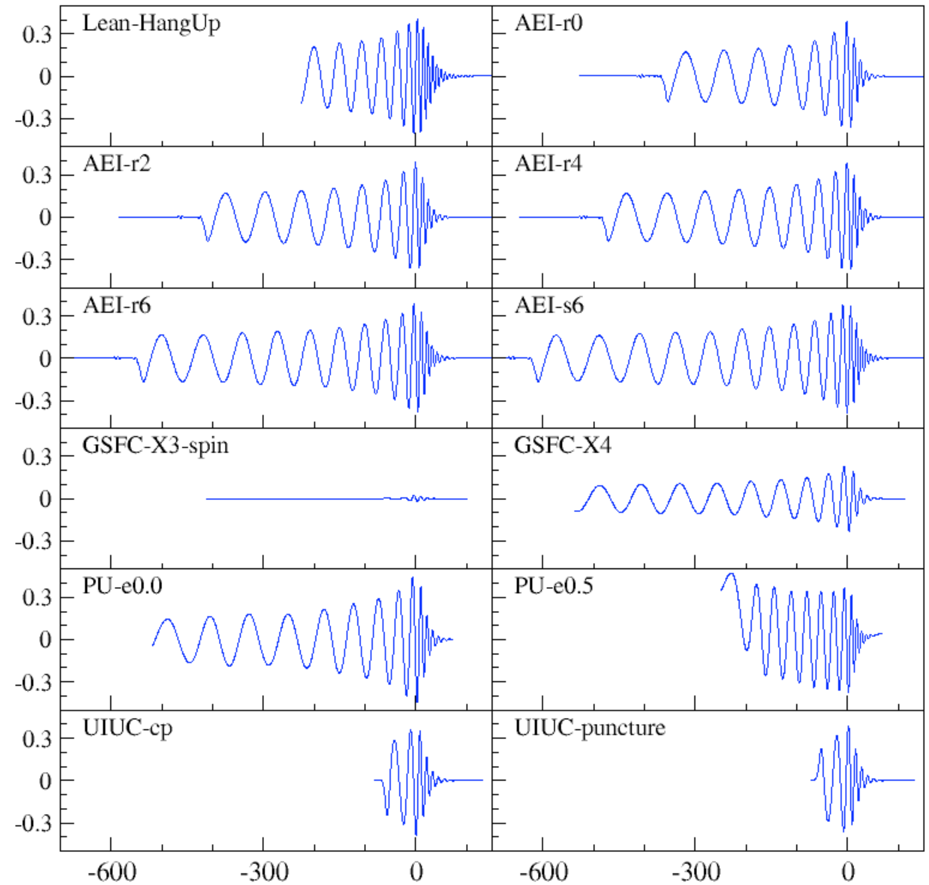
10. UUIC [Etienne, Liu, Shapiro]
    Equal mass, non-spinning (same initial M Ω)
    1. moving puncture initial data
    2. Cook-Pfeiffer irrotational initial data

Plots of h_+ l=2 m=2

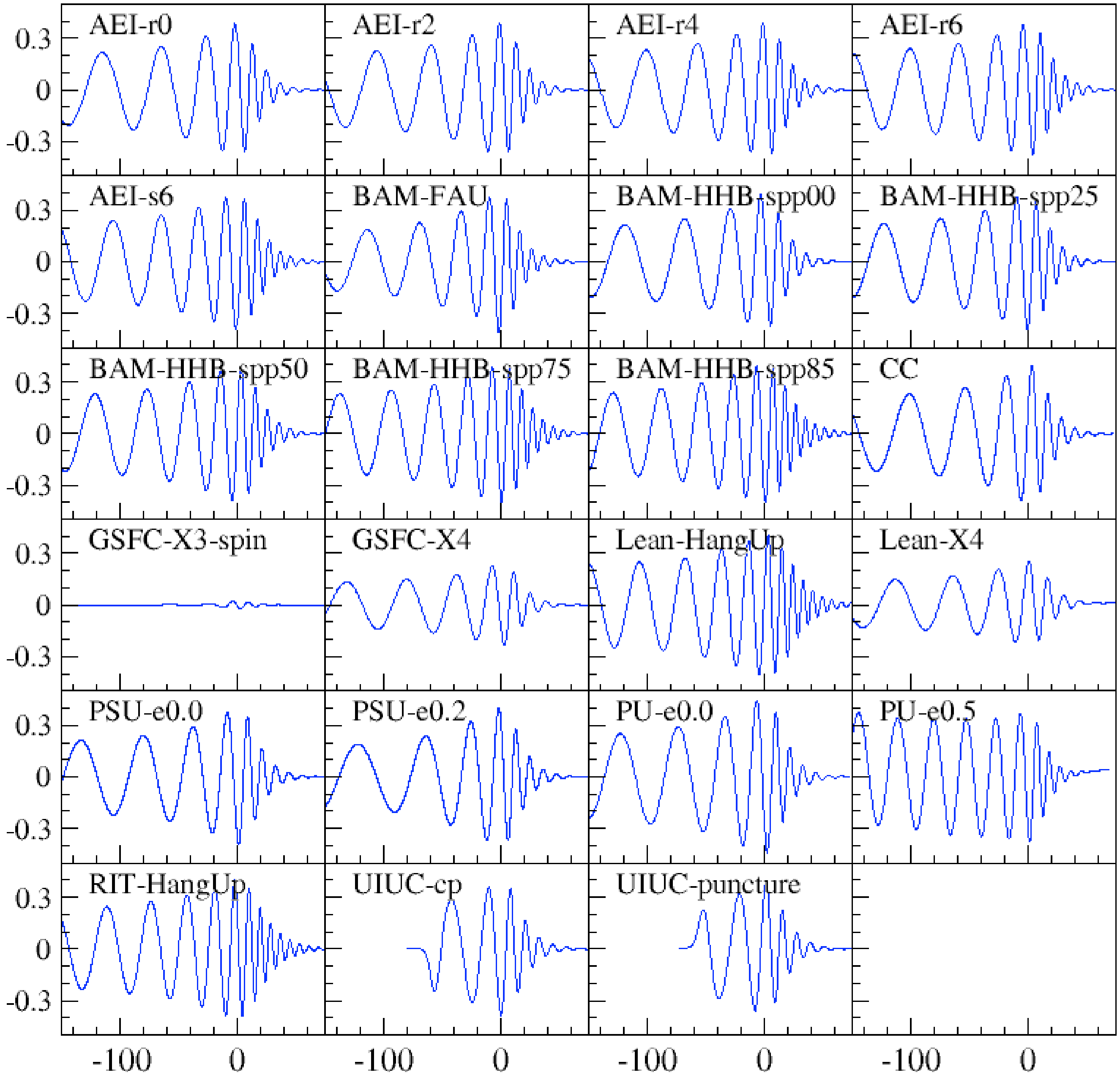
Re_h22 - long waveforms



Re_h22 - short waveforms



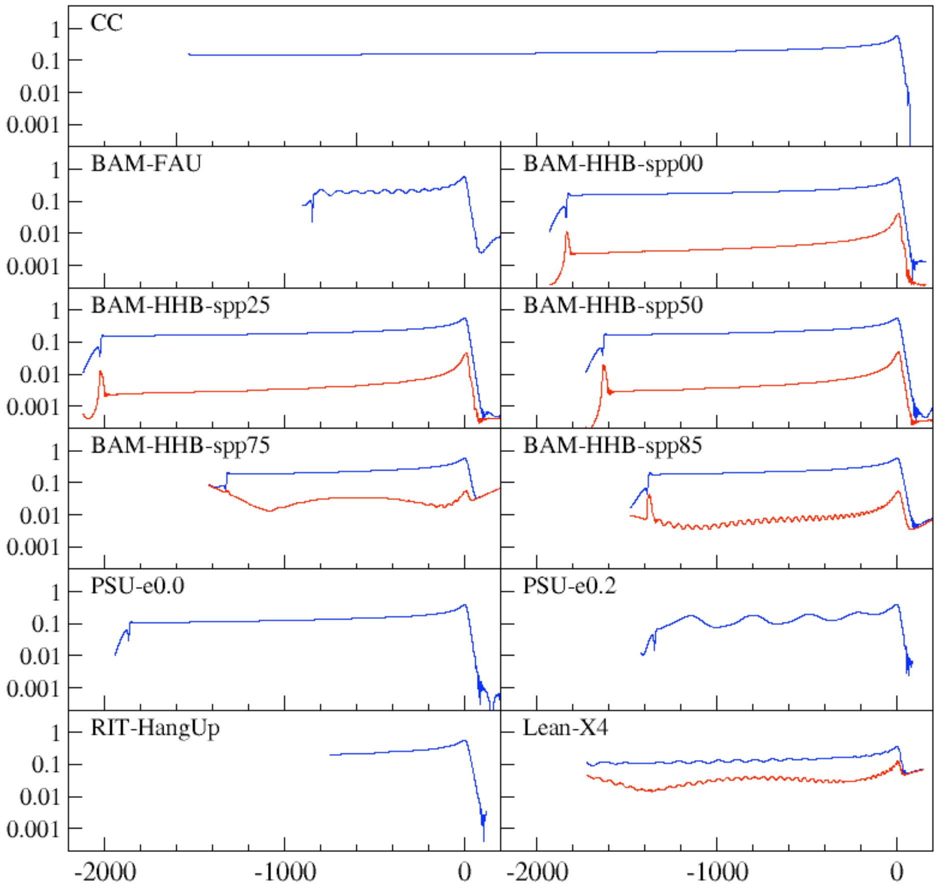
Re_h22 - merger



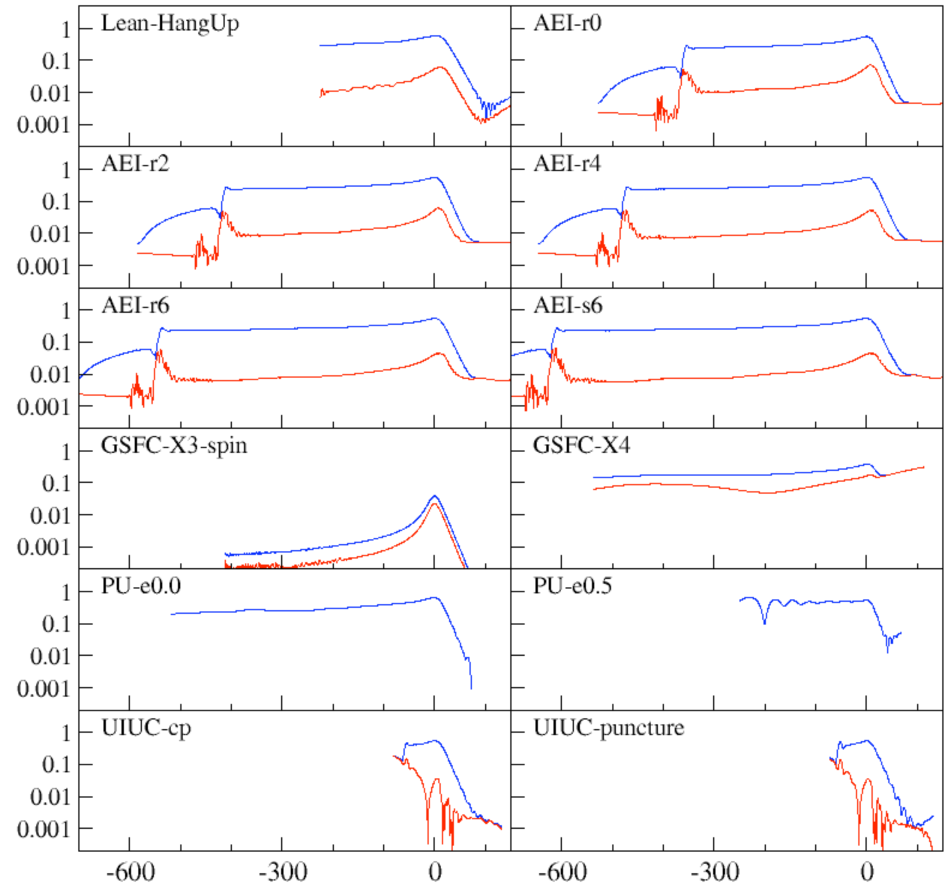
$$\sqrt{\sum_{l,m} (h_{+}^{lm})^2 + (h_{\times}^{lm})^2}$$

Red: removed l=2, m=±2

SumAllModes - long waveforms

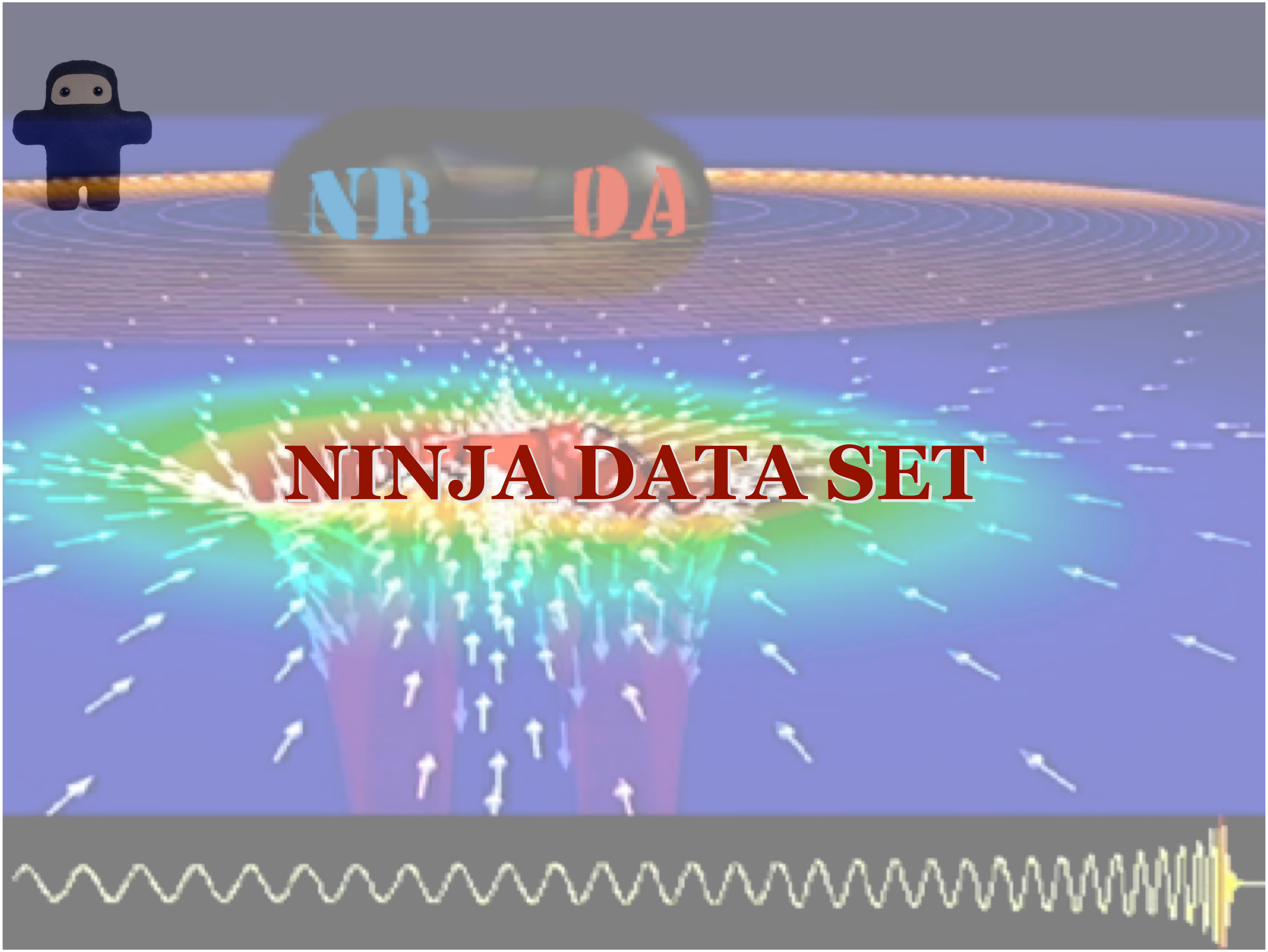


SumAllModes - short waveforms



Under consideration for NINJA-B:

- How many modes are needed for complicated waveforms?
  - A fixed l cutoff?
  - Upload modes with minimum % fraction of total energy?
  - Impact on the total systematics, function of mass/noise curve
- Hybrid with PN to avoid abrupt startup?
- Coordination of waveforms, for comparisons/systematical studies?


NR
DA
NINJA DATA SET

Data Generation - guidelines

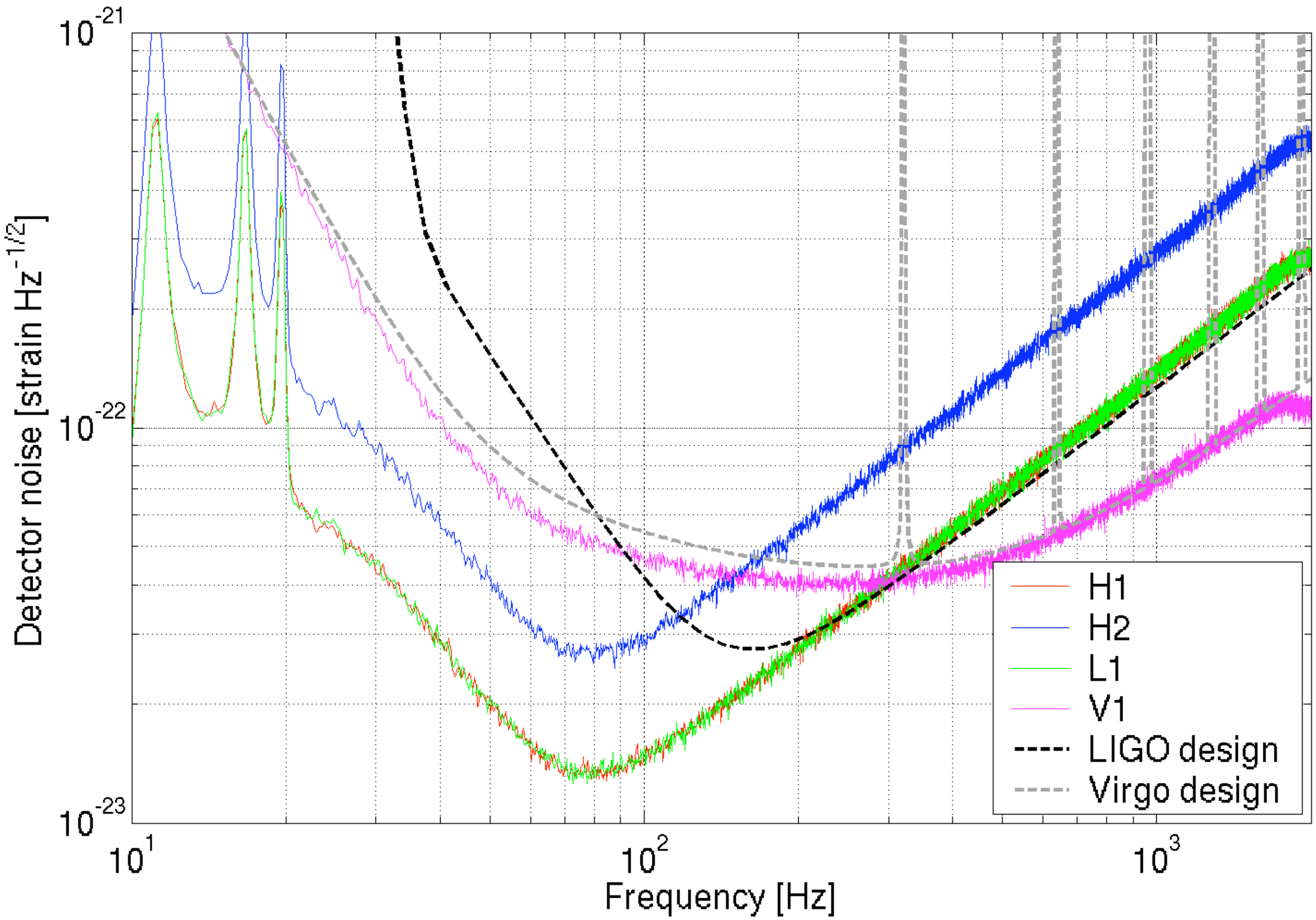
- Submitted ascii waveform files are converted to binary "frame files" (one for each simulation); metadata is contained in the file itself
- A set of signal parameters will be generated with appropriate distributions for mass, spins, sky position, orientation and coalescence time.
- The submitted NR waveforms will be used to generate signals as received by the detectors and added to appropriately colored Gaussian noise
- Available waveforms from different NR groups will be fairly represented.
- The noisy data, along with the parameters of the injections, will be released to all participants.

The signals:

- Total mass: 25-350 $M_{\odot}$
- Gaussian noise corresponding to the 3 LIGO and the Virgo detectors at initial design sensitivity
- Total of ~100 signals in ~1 day of data
- Optimal SNR: ~5-30.
- Starting frequency needs to be sufficiently small (~30 Hz) for a waveform to be injected.

An issue with the first release…

The simulated “LIGO” noise is not what it is supposed to be:



So:

No 4-detector coincidence analyses with this set
These are not “LIGO” detectors, we’ll call them D1, D2,D3

Moreover:

An SNR cut was applied to the injection:

- Draw position, mass, then compute expected SNR based on the theoretical noise curve.
- If SNR<5, inject a string of zeros (rather than re-drawing the parameters)

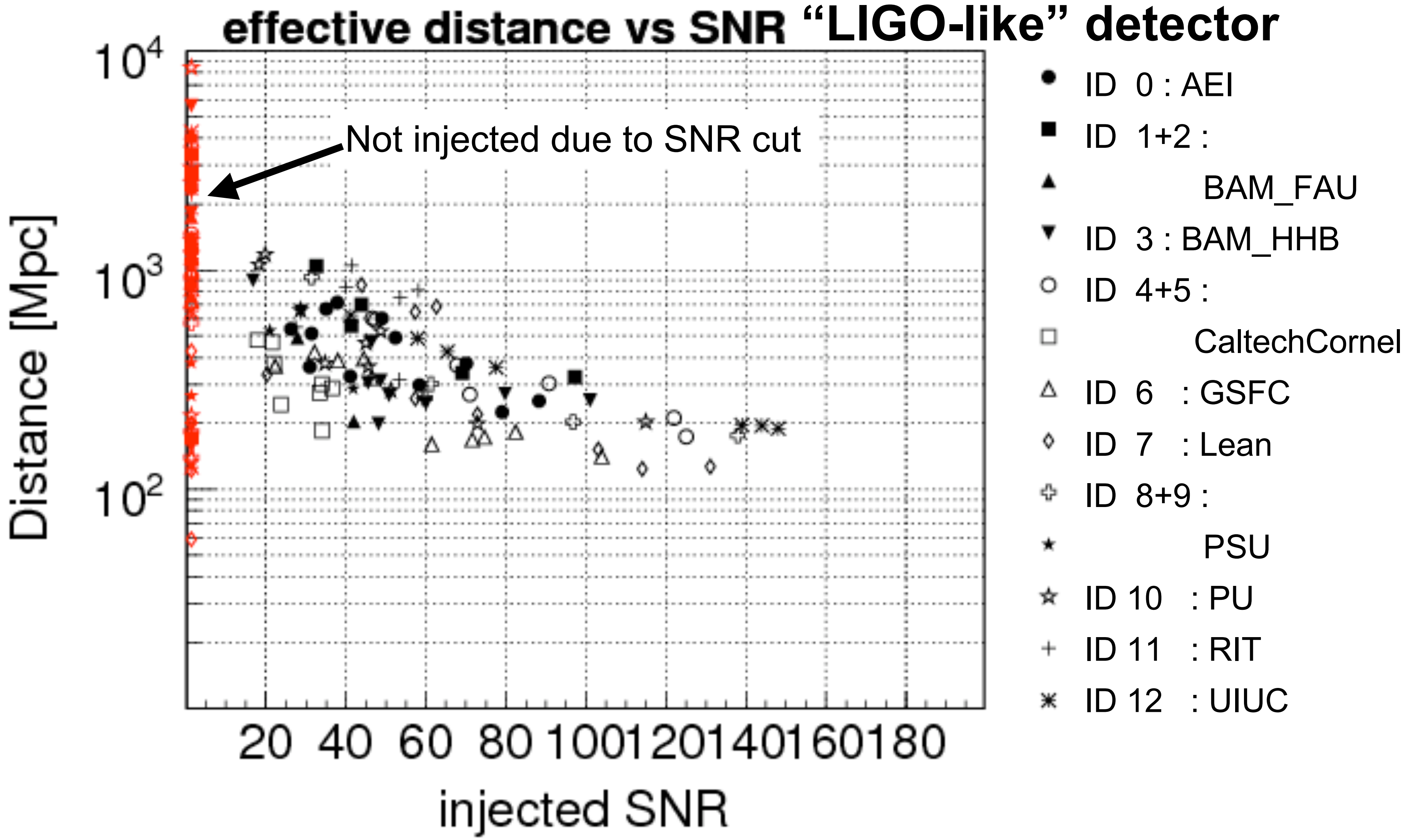
⇒ Fewer injections than the 160 planned; "which ones" depends on the detector

- Since the simulated noise was lower than the LIGO design curve used in this cut, "good" injections at low SNR were lost

  ⇒ Only loud injections present in "LIGO-like" data (SNR>15)

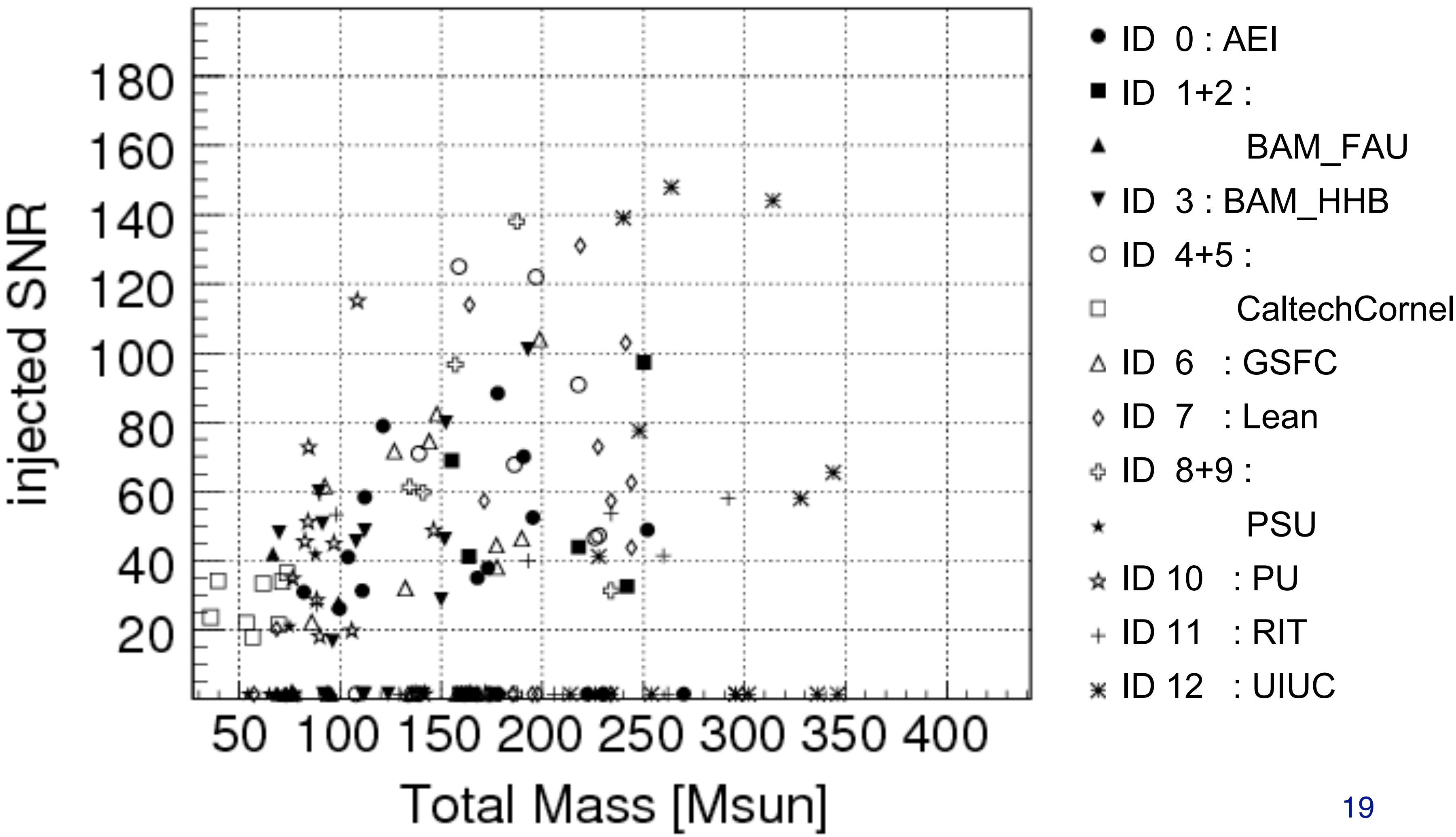
  ⇒ Most algorithms "find" them

“LIGO-like” detector

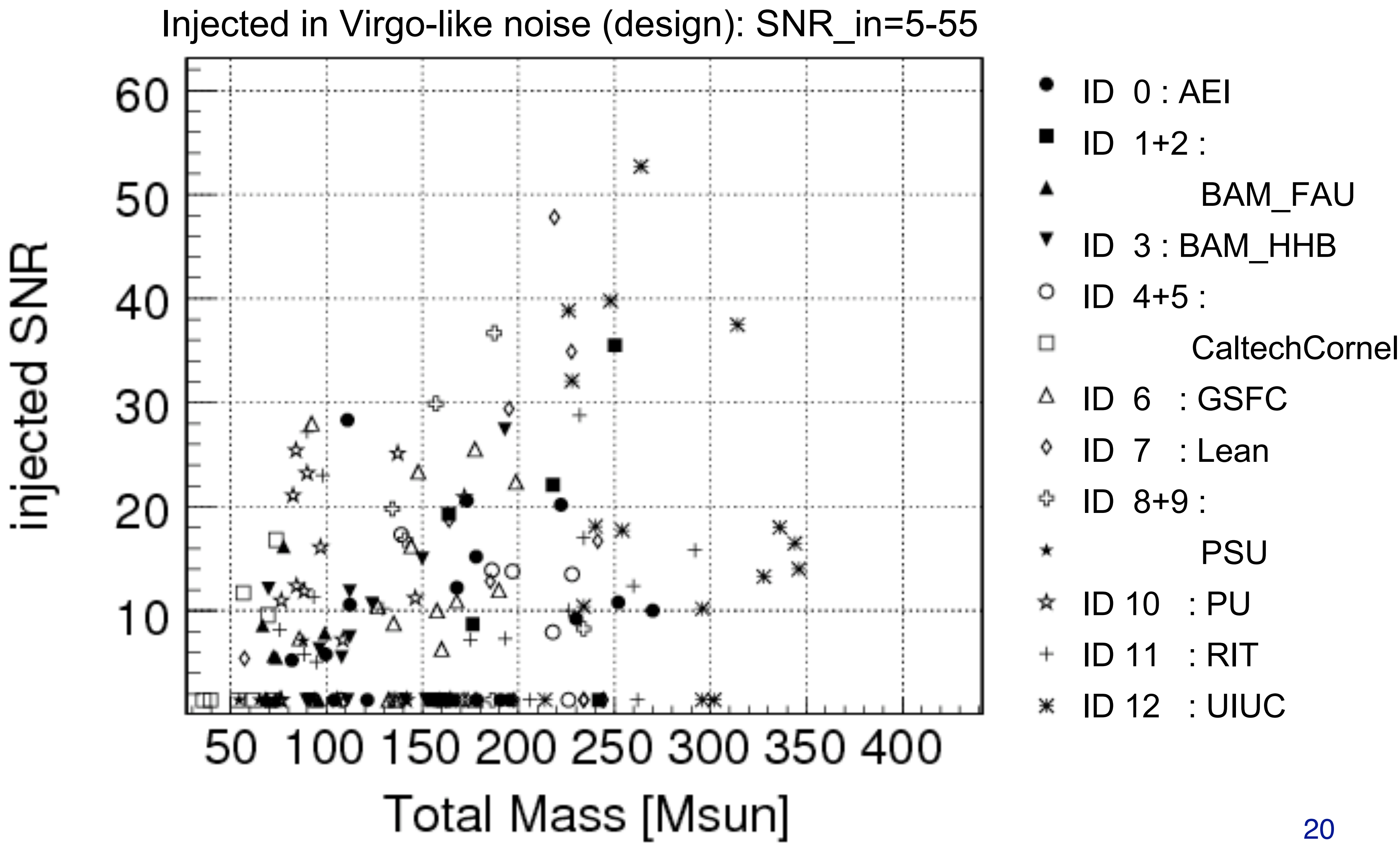


Injected SNR vs M_T

Injected in **wrong** LIGO-like noise: SNR_in=15-150



Injected SNR vs M_T



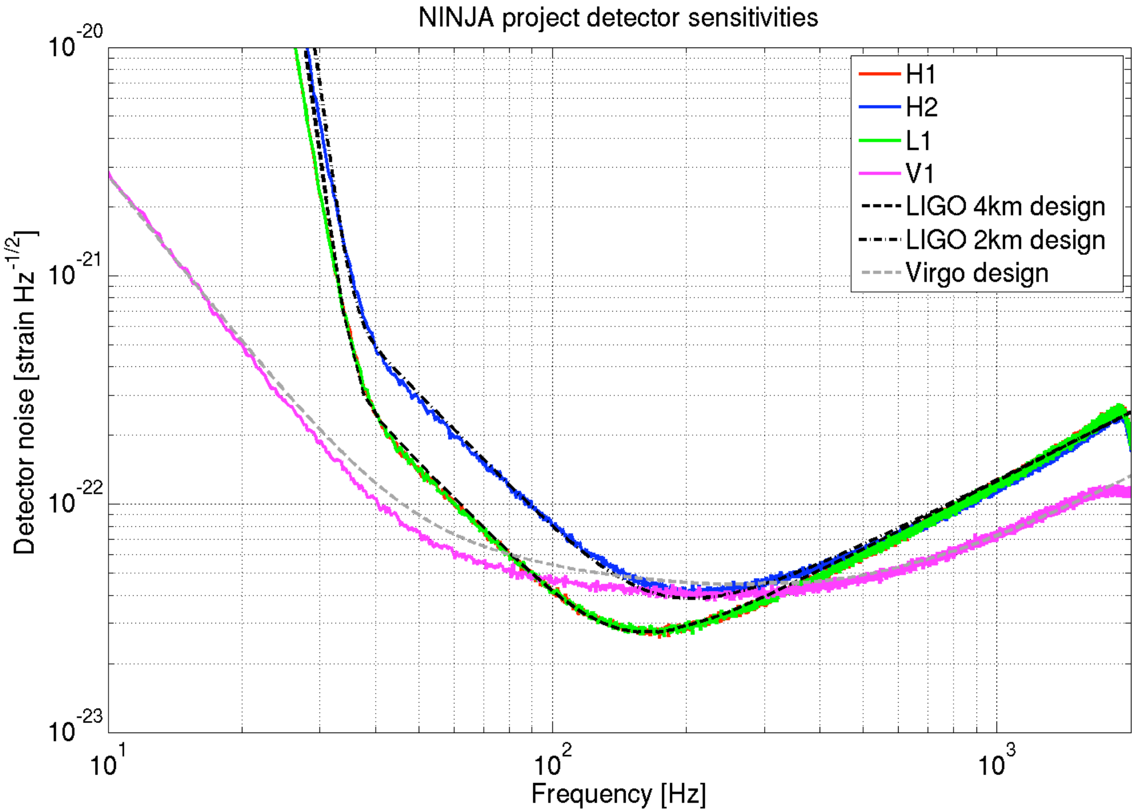
Timing

- Can we have a detector-independent definition of coalescence time?
- Is the waveform peak time sufficient?
- How do we quote the time delay between waveforms at different detectors with different noise?

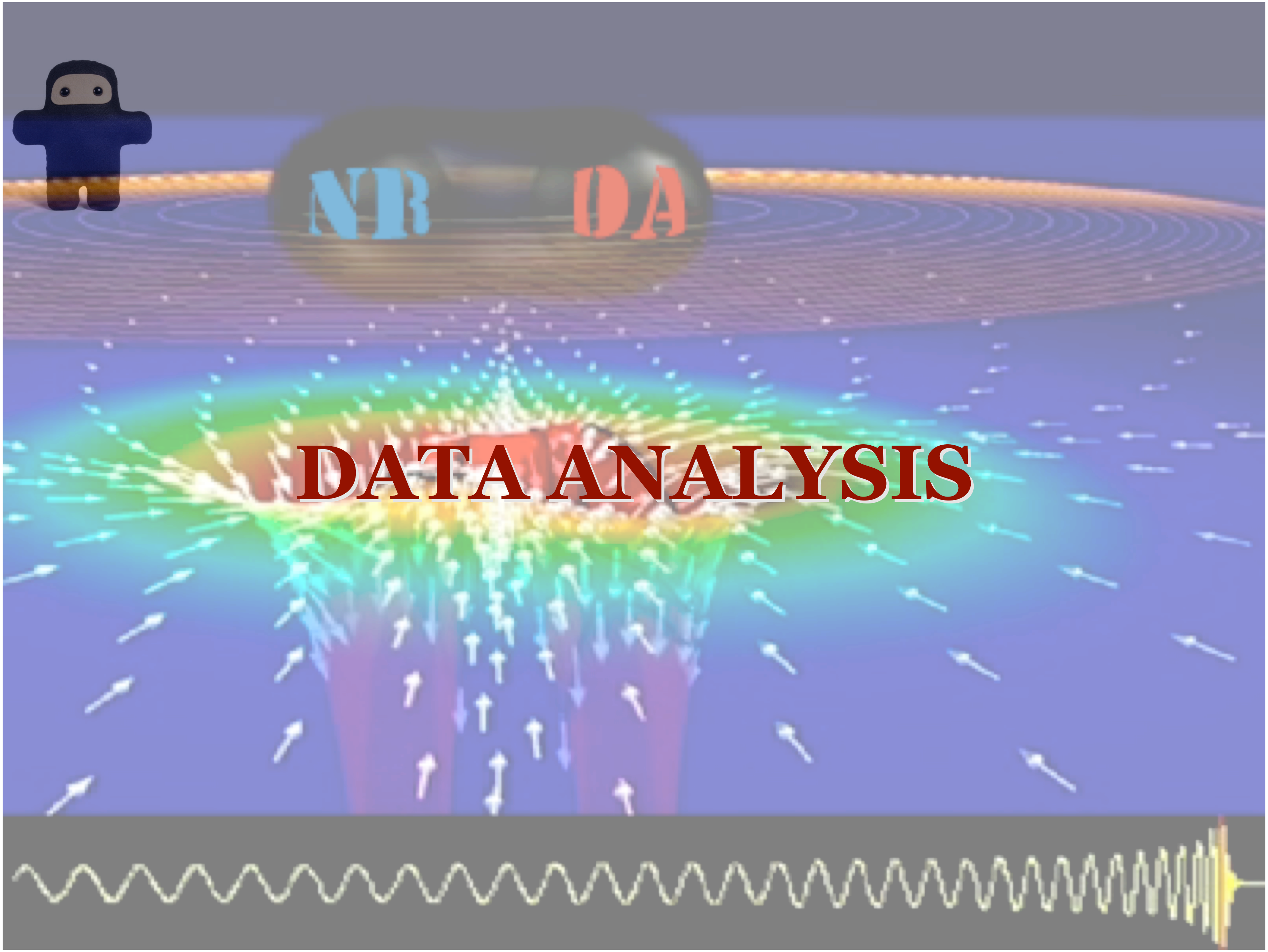
A new release is forthcoming

A new NINJA data set is in production, with the correct noise curves.

The new set will be used for the publication. Current set is still valid for discussion at this meeting, for 4 hypothetical detectors.



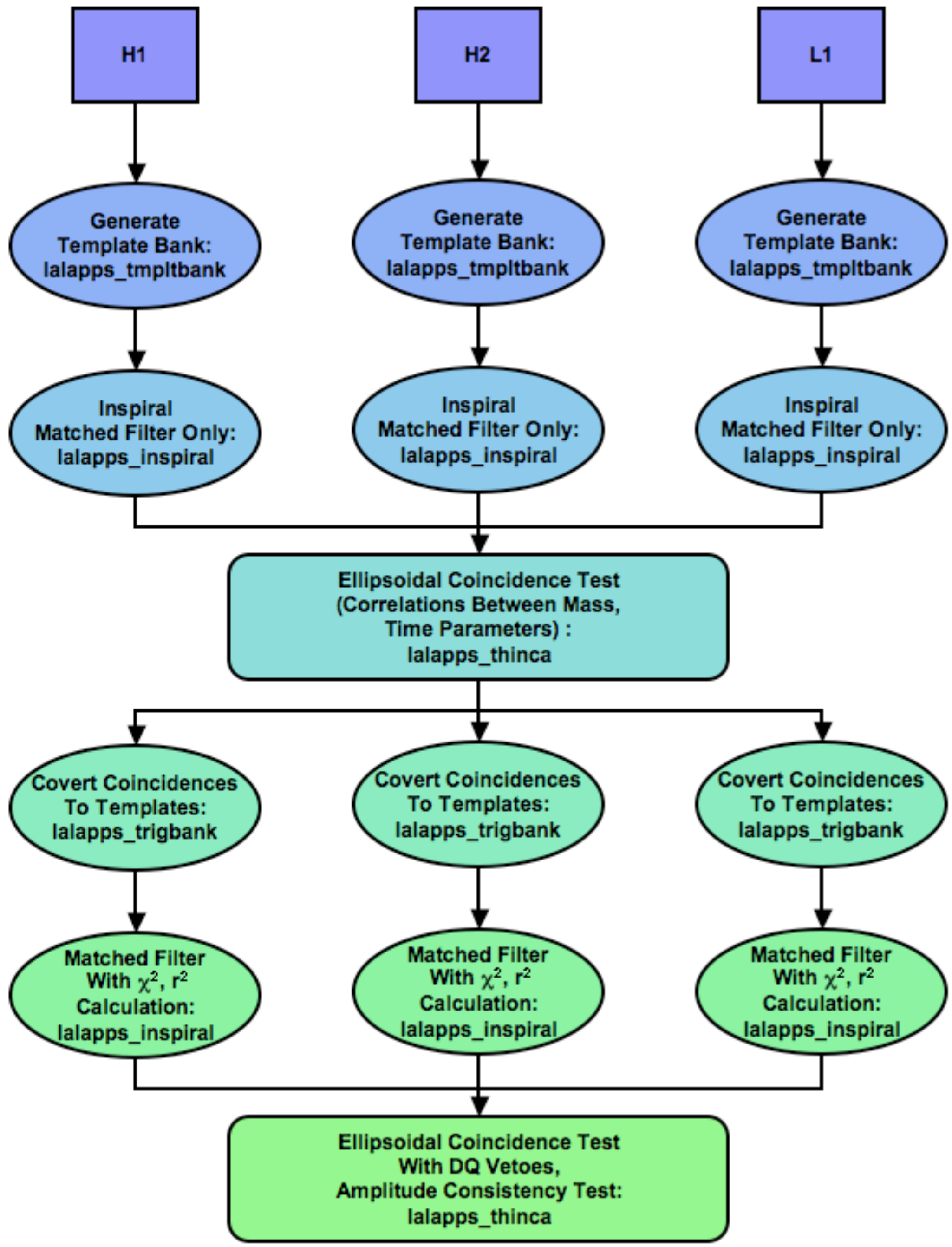
All results shown here are PRELIMINARY.
Analyses will be re-run shortly, on the new data set


NR DA
DATA ANALYSIS

Analysis - the guidelines

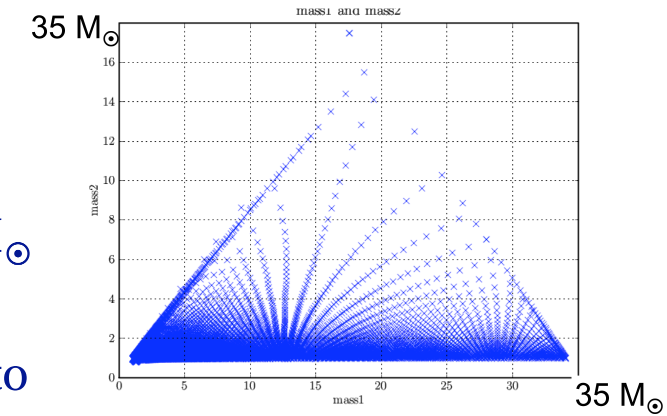
- Data analysis is to be performed on the injections embedded in simulated detector noise
- Different kinds of data analysis methods and pipelines are encouraged
- Data analysis groups should submit a 2-page writeup of results
- Some sugestions: ROC curves, found/missed plots for the injections, parameter estimation plots, etc.
- We would like to devise a figure of merit for comparison between data analysis pipelines, where appropriate

LSC inspiral pipeline



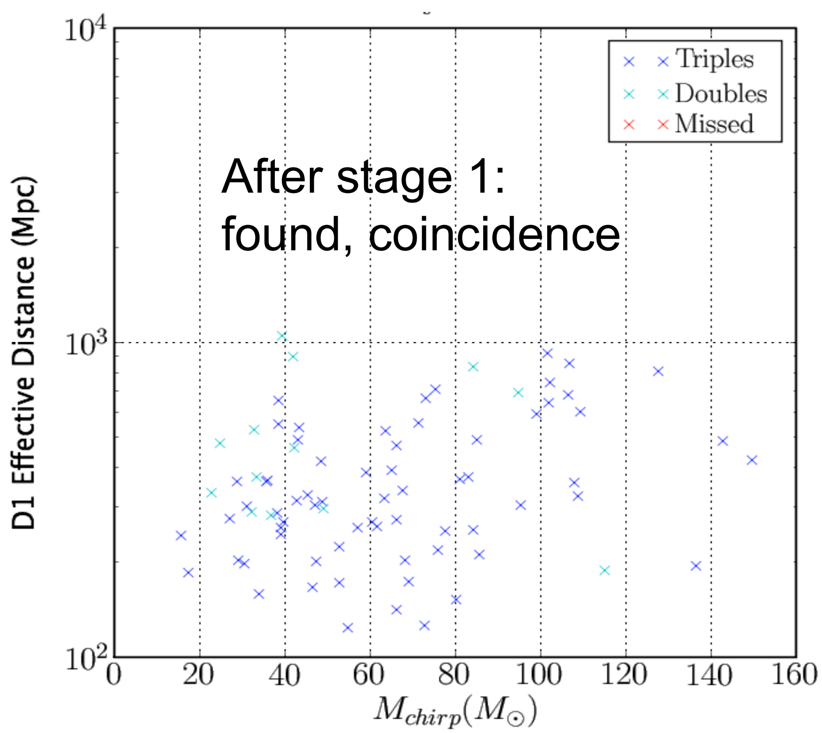
inspiral standard: 2pN TaylorF2 1-35 $M_\odot$

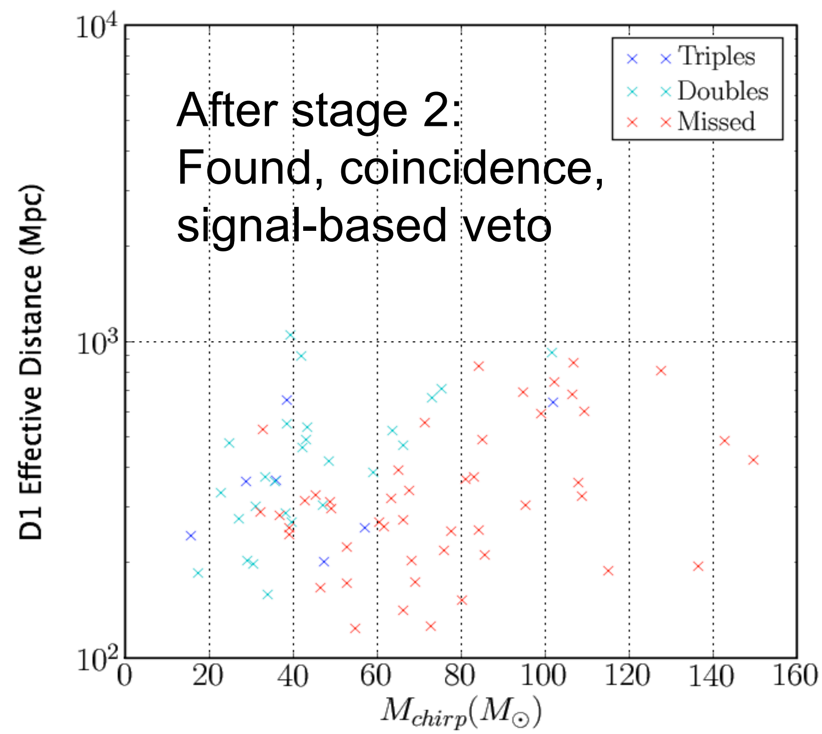
[UWM: Brady, Goggin, Mercer, Vaulin]



Standard Inspiral pipeline, 3 detectors (SNR_inj>15):

- TaylorF2 approximant at ISCO (r=6M) 1-35$M_\odot$
- All found after stage 1 (SNR>5.5, coincidence)
- Most high mass injections fail signal-based veto



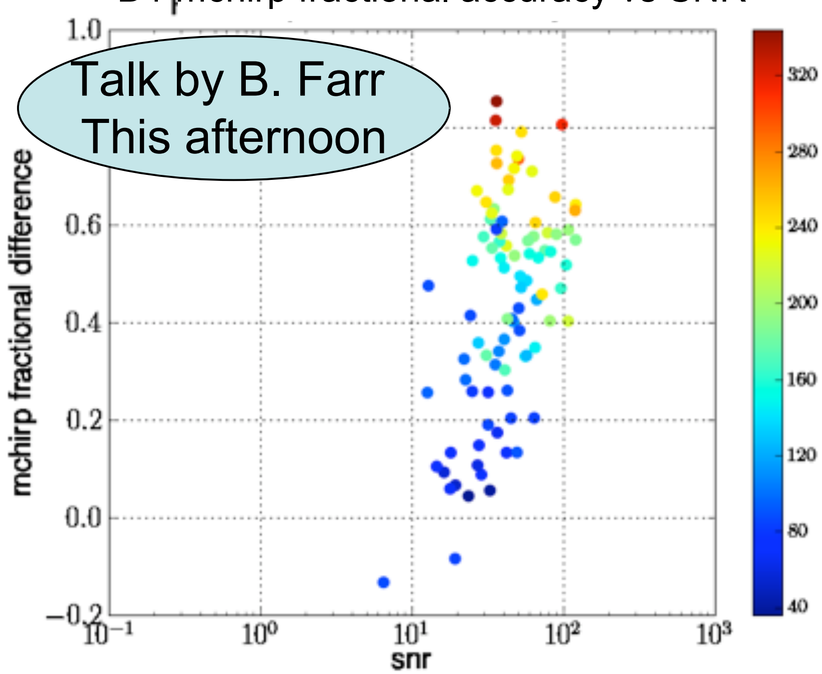


inspiral with TaylorF2 and EOB

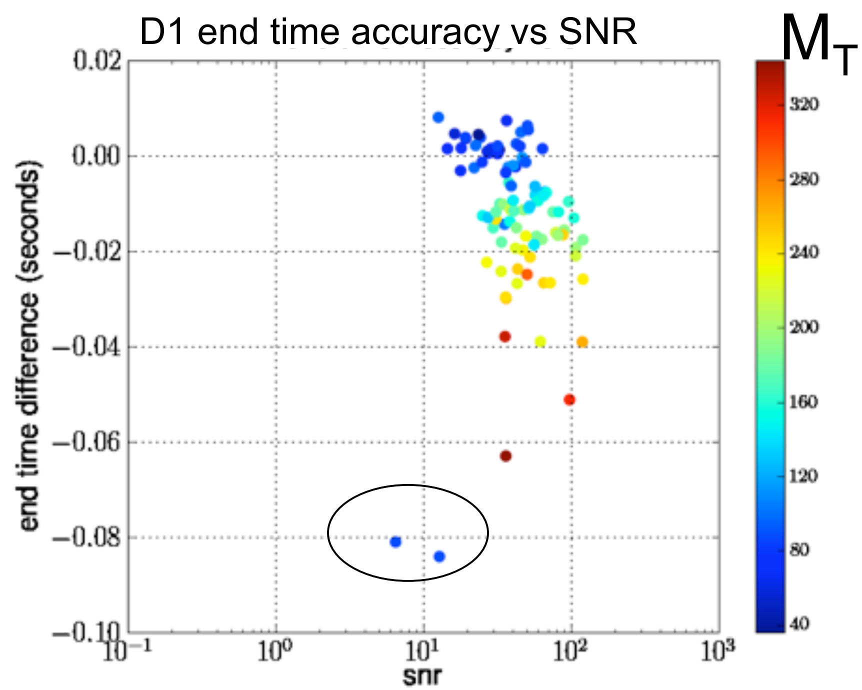
[Cardiff: Farr, Fairhurst, Sathyaprakash]

	Stage1/Stage2
• Standard Inspiral pipeline, 3 detectors (SNR_inj>15):	
– TaylorF2 approximant at ISCO (r=6M) 20-130$M_\odot$	73/72
– TaylorF2 approximant at ERD(*) 20-130$M_\odot$	93/92
– EOB approximant at light ring 20-100$M_\odot$	90/89

D1 mchirp fractional accuracy vs SNR



D1 end time accuracy vs SNR



(*) effective ringdown frequency, based on a study of Goddard waveforms

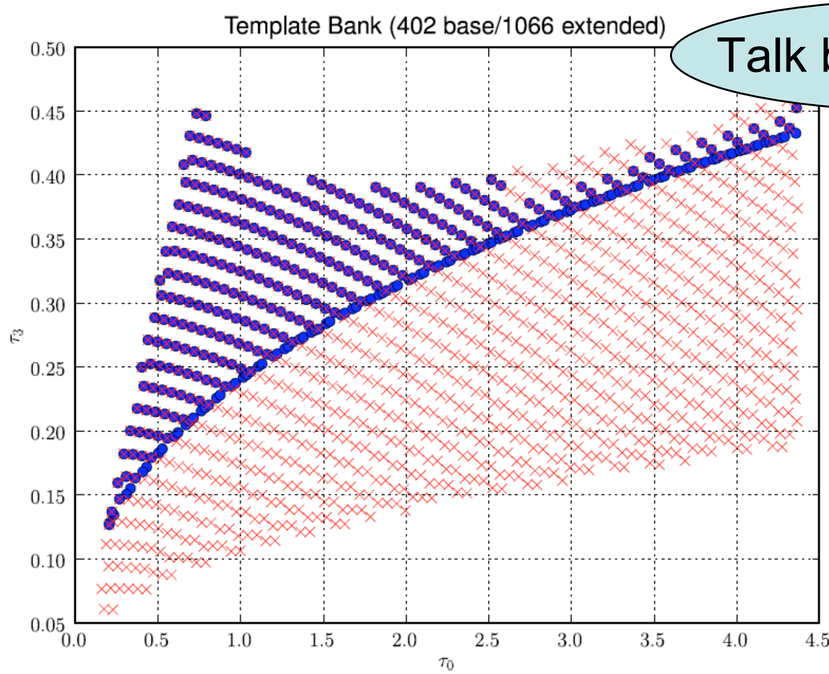
inspiral with extended TaylorF2

[Syracuse: Brown, Pekowsky]

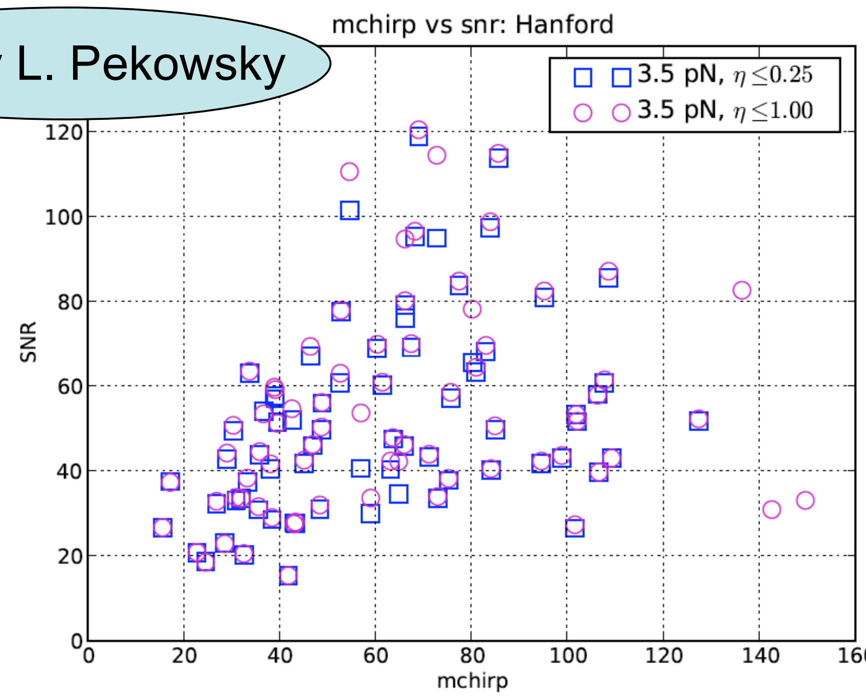
$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

- Standard Inspiral pipeline, 3 detectors (SNR_inj>15):
  - TaylorF2, 2.0PN, η≤0.25 at ISCO (r=6M) 20-80$M_\odot$
  - TaylorF2, 3.5PN, η≤0.25 at ERD(*) 20-80$M_\odot$
  - TaylorF2, 3.5PN, η≤1 at ERD(*) 20-80$M_\odot$

	Stage1/Stage2
TaylorF2, 2.0PN, η≤0.25 at ISCO (r=6M) 20-80$M_\odot$	72/71
TaylorF2, 3.5PN, η≤0.25 at ERD(*) 20-80$M_\odot$	85/85
TaylorF2, 3.5PN, η≤1 at ERD(*) 20-80$M_\odot$	91/88



Talk by L. Pekowsky



(*) effective ringdown frequency, based on a study of Caltech-Cornell waveforms

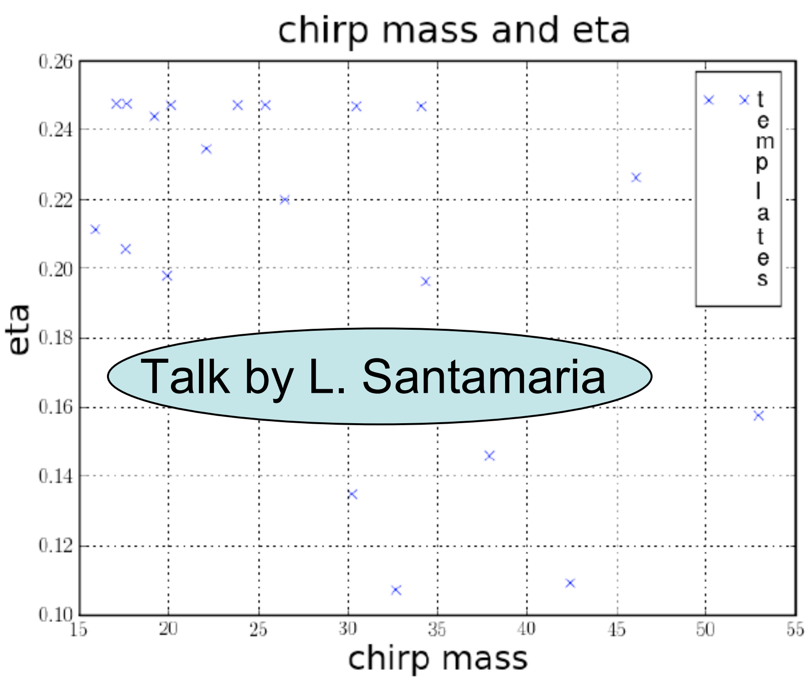
inspiral with phenomenological wf

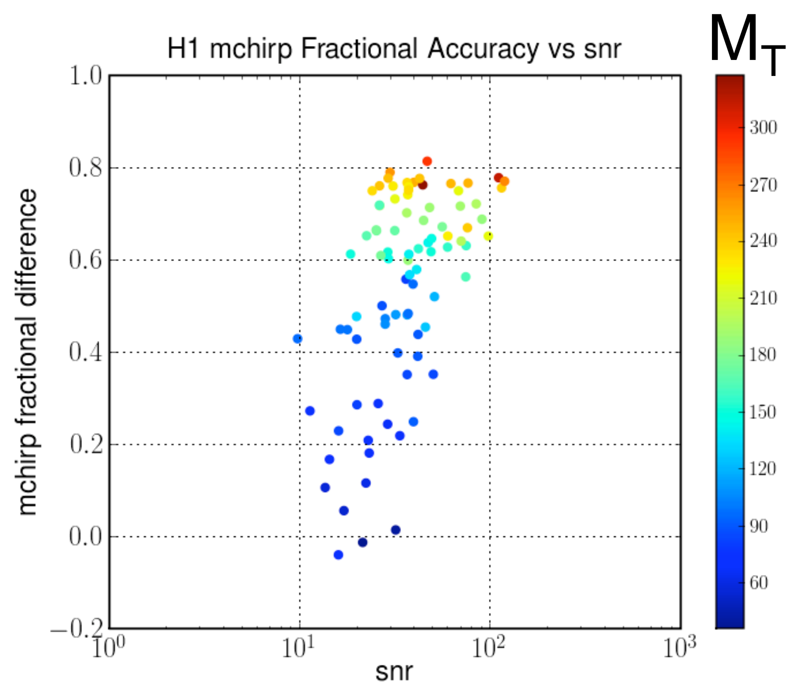
[AEI: Krishnan, Santamaria, Whelan]

- Standard Inspiral pipeline, 3 detectors
- phenomenological templates, hybrid match of PN and NR

  [Ajith et al. PRD 77,104017(2008); CQG 24, S689(2700)]

  - Non-spinning, 40-160$M_{\odot}$ (to be extended to 350 $M_{\odot}$), uses 2PN metric, waveforms truncated either at ISCO or at light ring
  - Coincidence needs tuning





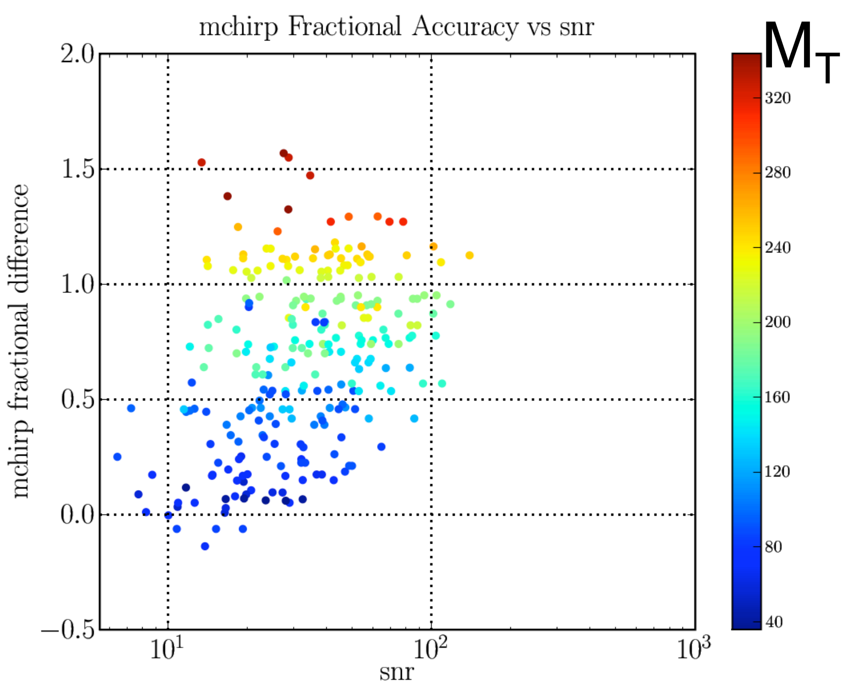
inspiral with EOBNR wf

[Maryland/Cardiff: Ochsner, Buonanno, Pan, Sathyaprakash]

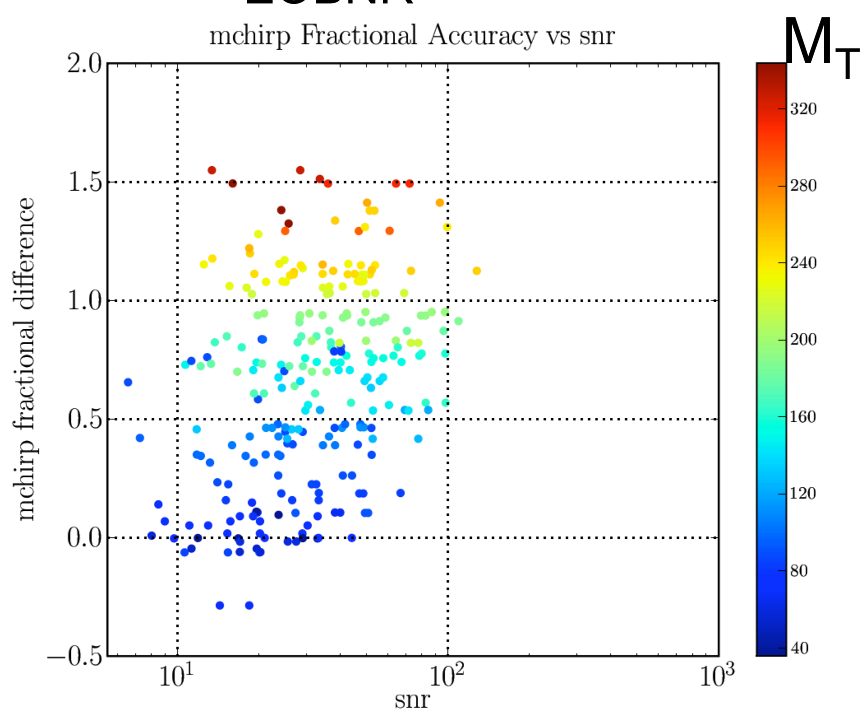
- Standard Inspiral pipeline, 3 detectors
- Templates: EOBNR: non-spinning EOB model calibrated to NR results, using Goddard BBH with mass ratio 1:1, 2:3, 1:2, 1:4
- Total mass: 20-70$M_\odot$

Talk by E. Ochsner

EOB model, terminated at light ring



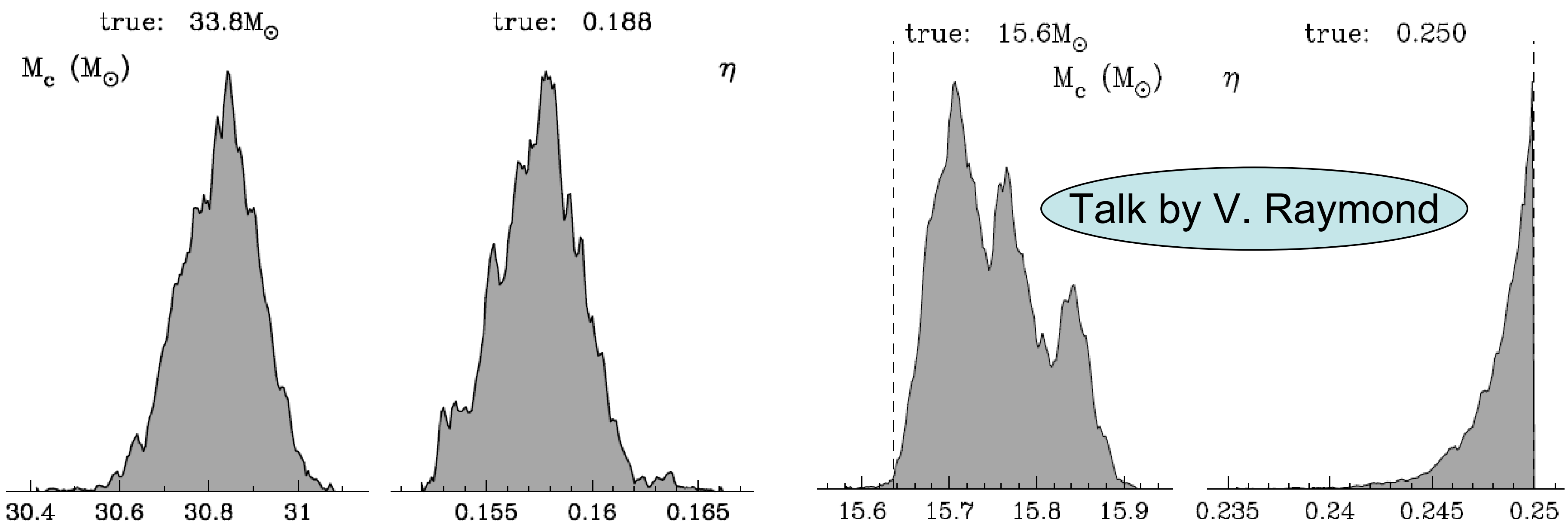
EOBNR



Parameter Estimation with MCMC

[NW: Mandel, van der Sluys, Raymond, Kalogera, Rover, Christensen]

- Markov-Chain Monte Carlo computes posterior PDF of unknown signal parameters, then search for set of parameters with best fit to data.
- Templates: restricted 1.5pN in phase, 0pN amplitude, only large body is spinning.
- Injections are detected, but, parameter estimation problematic at high mass: the code tries to match merger+ringdown with inspiral-only template



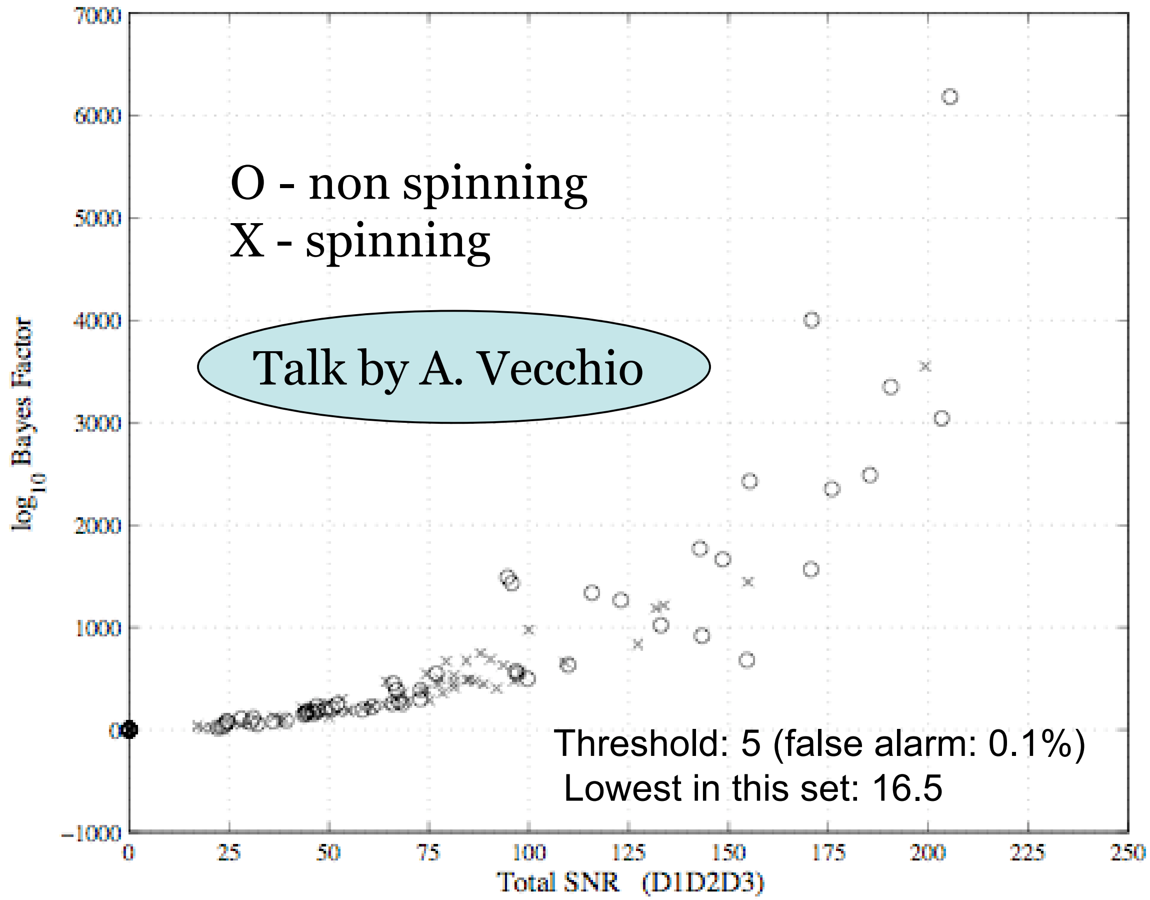
Bayesian model selection

[Birmingham: Aylott, Veitch, Vecchio]

Investigate performance of different template families on detection confidence.
For now: TaylorF2
Plan: compare to EOB

Marginalized Bayes factor using uniform priors with:
M in 30-140 $M_{\odot}$
η in 0.1-0.25
D in 1-500 Mpc

3 detectors
30 Hz low freq cutoff



Sum in quadrature of SNR in D1, D2, D3

All signals detected, including signals outside prior range

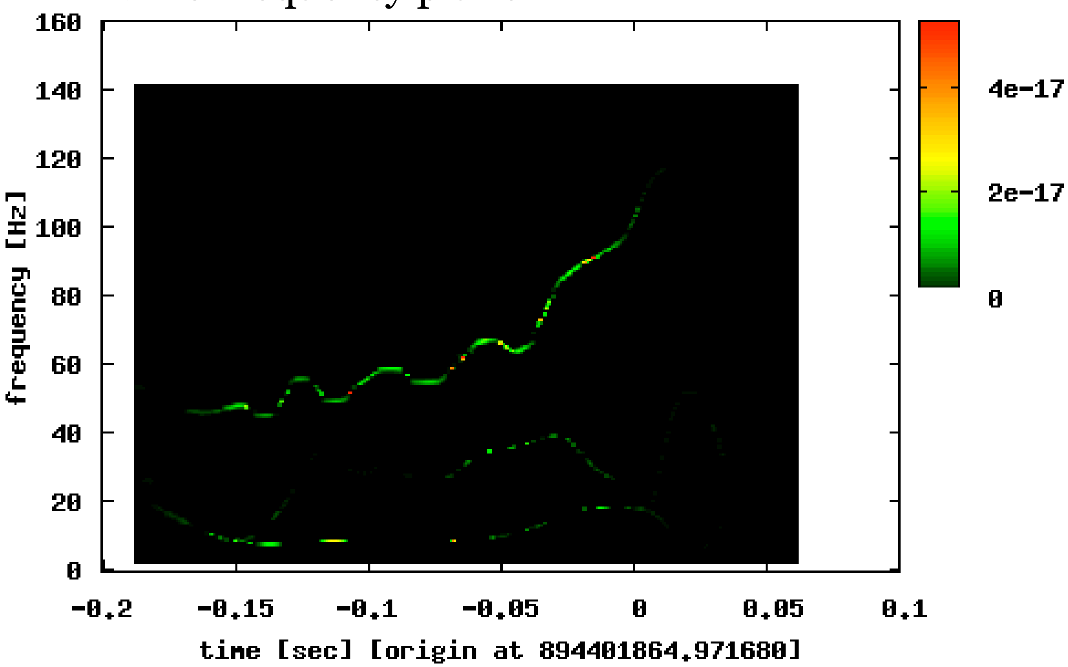
Adaptive search with HHT

[Goddard: Stroeer, Camp]

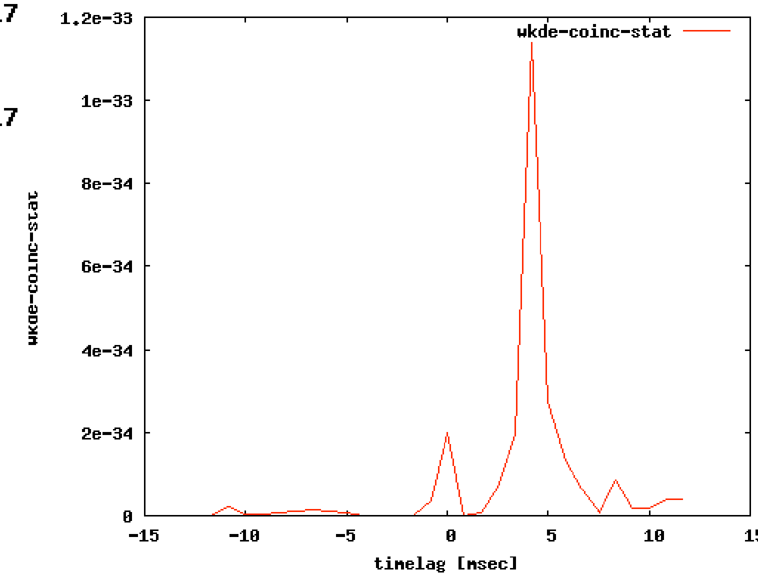
Talk by A. Stroeer

- New pipeline based on Hilbert Huang Transform
- template-free, non-parametric decomposition in different frequency scales found in the data, tracking instantaneous frequency and amplitudes.
- Detection based on the instantaneous power found in the data.

Richness of structure in the single-detector time-frequency plane

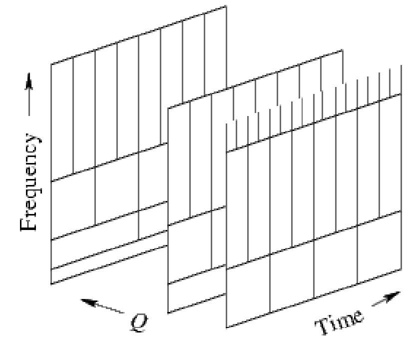


2-detector analysis: time-frequency maps overlapped at several time lags

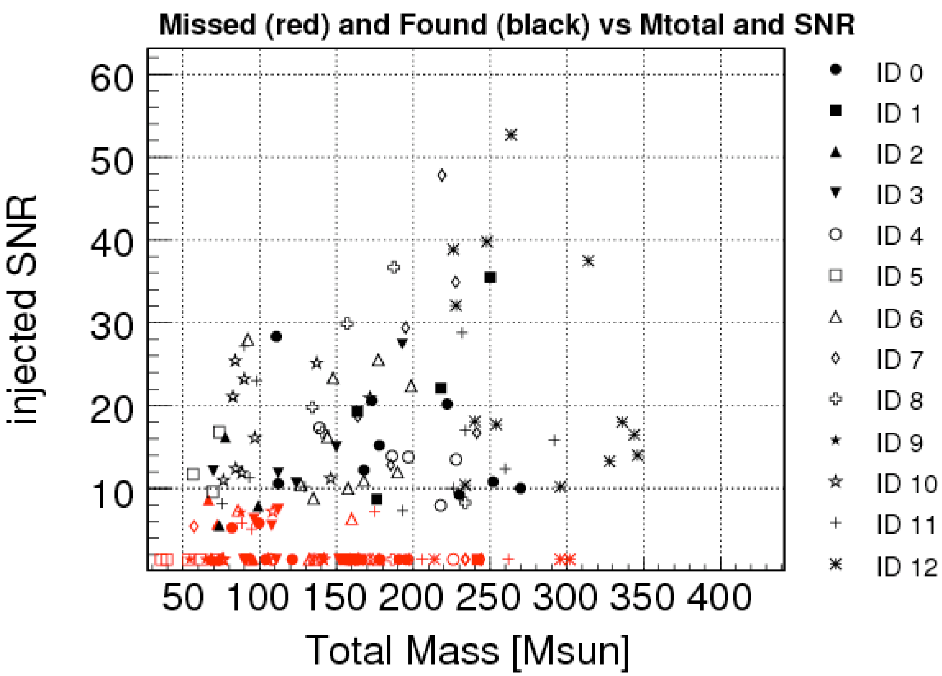


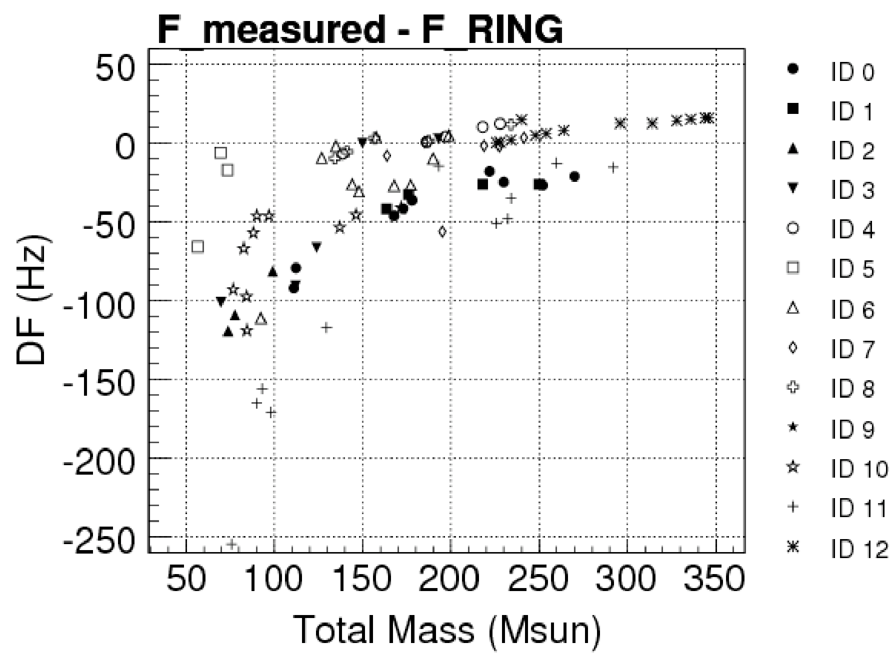
Burst search with Qpipeline

[UMass/Urbino: Cadonati, Chatterji, Guidi, Mohapatra, Vicere']



- Qpipeline: multiresolution, time-frequency search. Equivalent to matched filter search for sine-Gaussians in whitened data.
- Search: 48-2048 Hz; Threshold: SNR=5.5
- Here: single detector with low-SNR injections (D4)
- Plan on full coherent follow-up

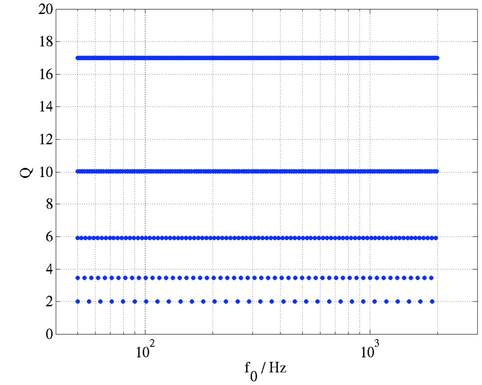


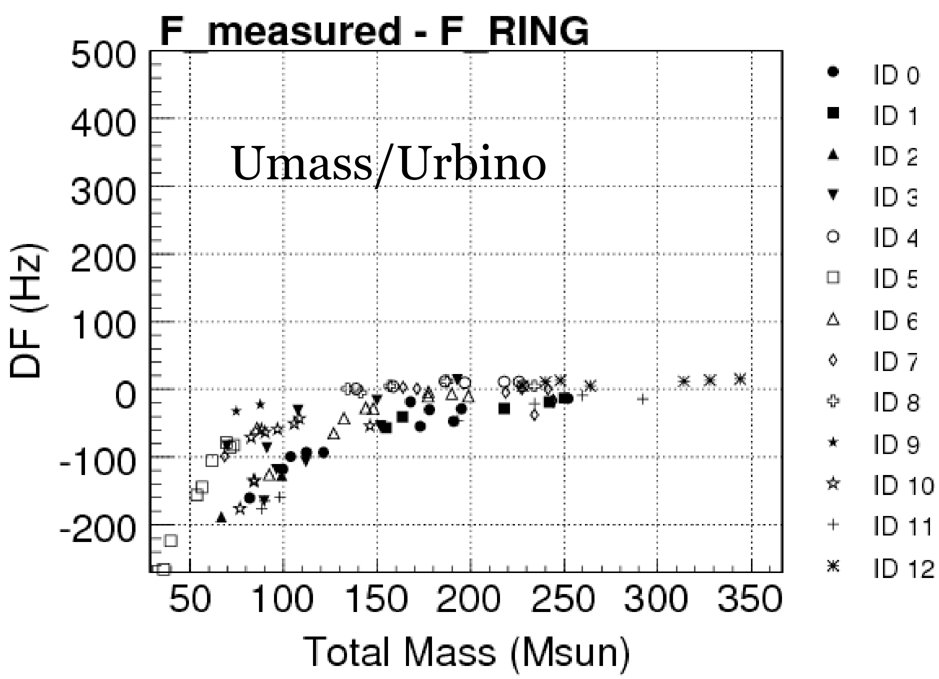


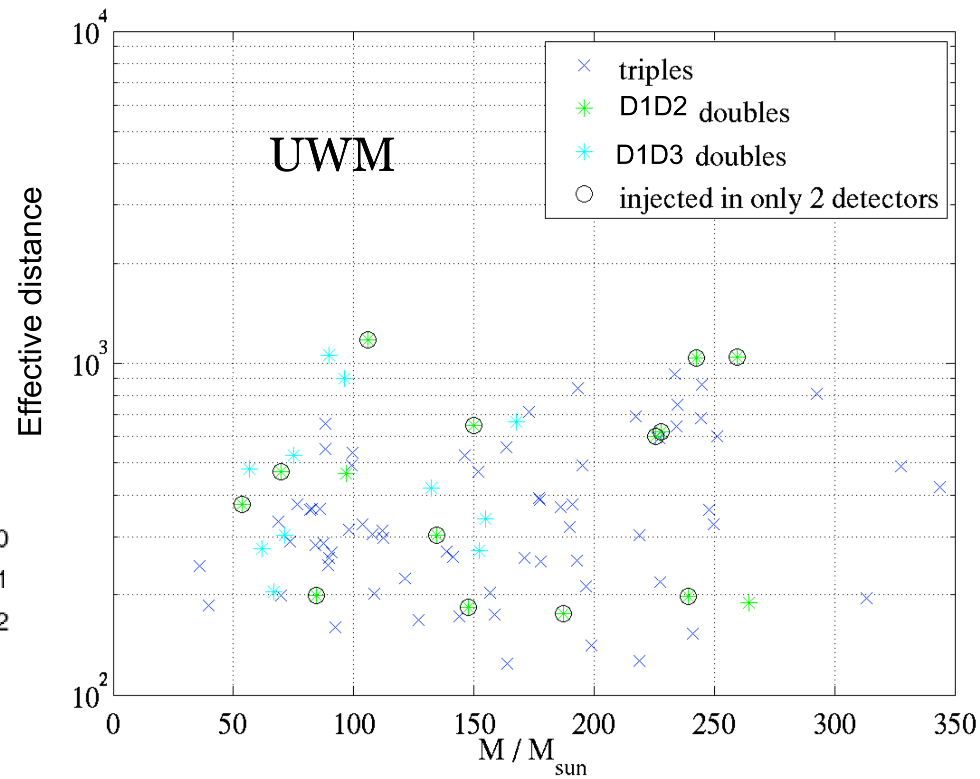
F_ring: ringdown frequency, estimated as in arXiv: 0712.354 and arXiv:0710.3345

Ringdown matched filter

- UMass/Urbino [Cadonati, Chatterji, Guidi, Mohapatra, Vicere']:
  single-interferometer matched filter and event-by-event comparison with Burst, Inspiral trigger set (IBR analysis)
- UWM [Brady, Goggin, Mercer, Vaulin]:
  standard ringdown pipeline

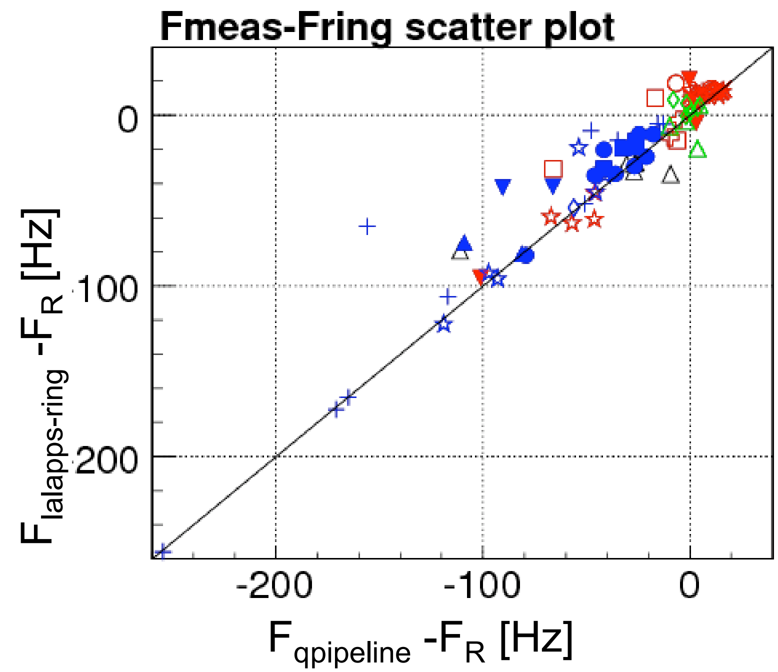




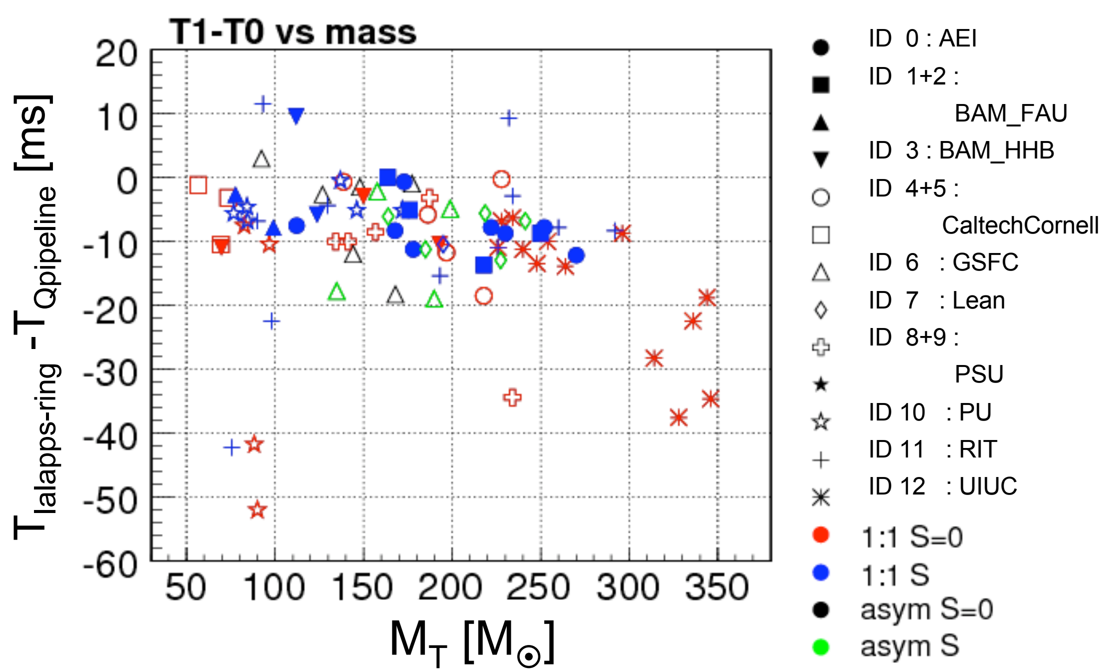


Burst-Ringdown

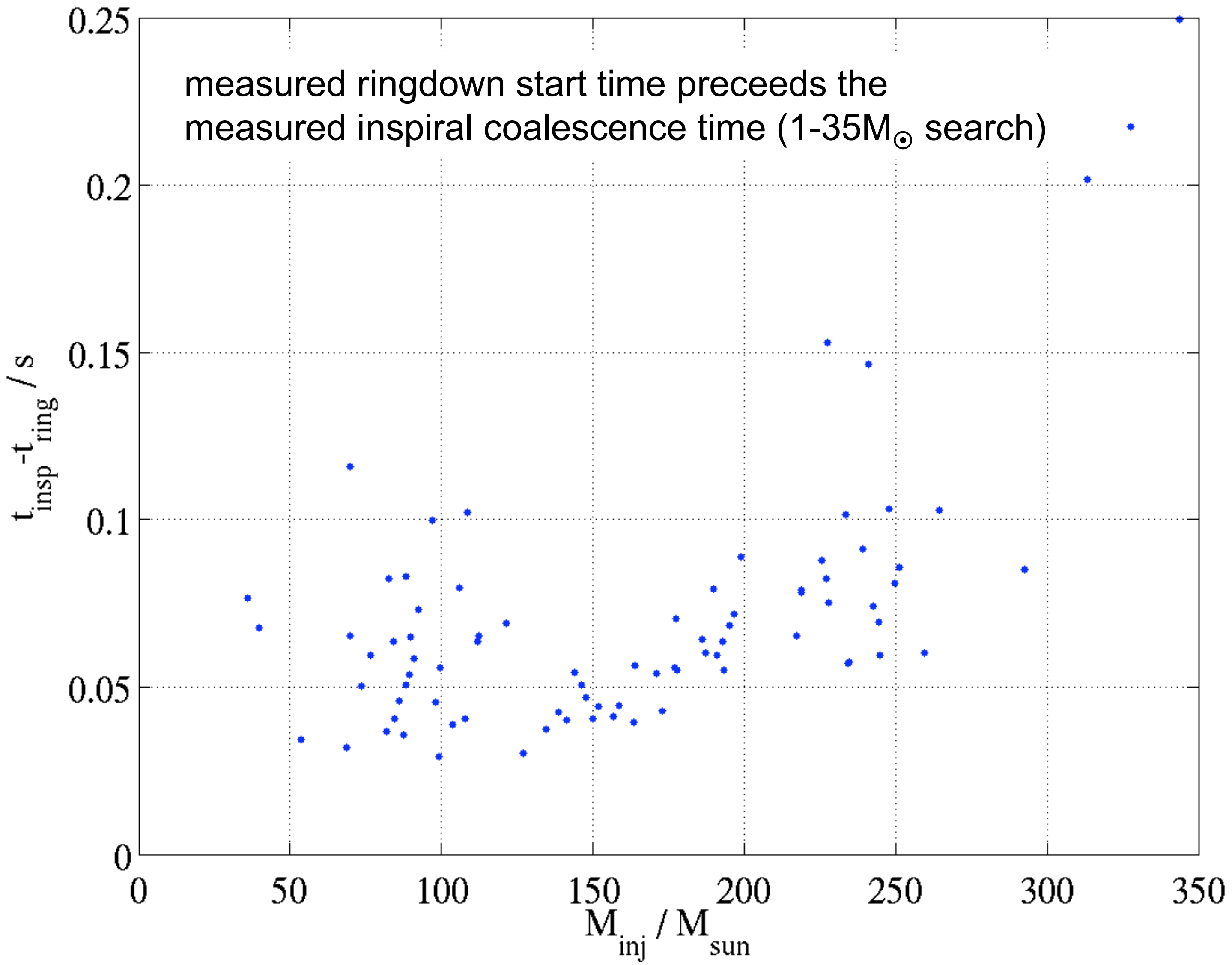
[UMass/Urbino]

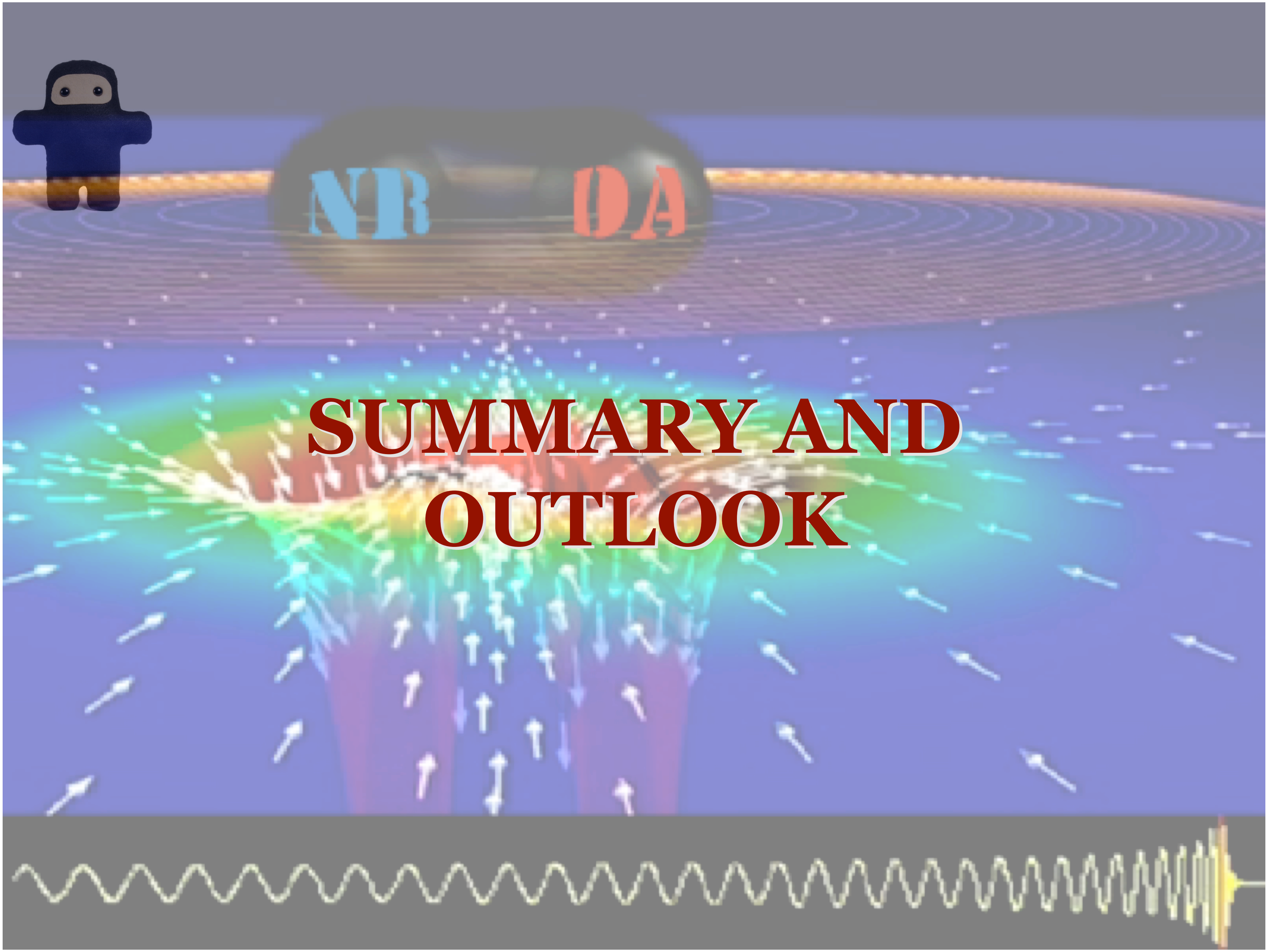


Burst and ringdow algorithms find injections with comparable SNR, frequencies (esp. at large mass).
Ringdown start time preceeds burst peak time.
Details are being explored.



Inspiral-Ringdown [UWM]




SUMMARY AND
OUTLOOK

NINJA-A

- NINJA success:
  - Unpreceeded level collaboration between the NR and DA communities
  - Produced a data set using information from 10 NR groups
  - Analysis by 9 teams through actual pipelines
- There were some glitches, but they have been identified and a new data set will be released soon. Meanwhile the machinery is oiled…

NINJA-A reloaded

A new data set (for final NINJA-A results and publication) will be released shortly with:

1. Correct LIGO noise curves
2. Same injection parameters as in results shown today
3. Remove the SNR cut: each signal is injected into *ALL* or *NONE* of the detectors.
4. Revisit timing of waveforms/time-delay between detectors.
5. Fix a couple of problem found in posted NR waveforms.

NINJA-B

- Consistent criteria for waveforms?
- Hybrid waveforms?
- A figure of merit to compare pipelines?
- Use Enhanced/Advanced detector noise?
- Quantitative statements on accuracy?
- ….