Incorporating Numerical Relativity Waveforms into Gravitational Wave Data Analysis
⌊ LIGO-G080073-00-Z ⌋

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Outline

NR and GWDA to meet each other!

Numerical Relativity

- Enormous progress in the last few years - **2005 Breaktrough**
- Several NR groups worldwide with stable, accurate codes - already producing results and **waveforms** for BBH coalescence
- NR is able to simulate some of the most promising **sources** of gravitational radiation

Gravitational Wave Data Analysis

- LIGO has completed 5 science runs - producing large amounts of **data** and more to come in the future (advLIGO, Virgo, GEO600)
- **Detection** in the future seems plausible - no direct observations yet
- Clever **data analysis strategies** play a fundamental role

Multipole expansion of the wave (I)

- Output of NR $\longrightarrow$ full spacetime of a binary black hole system $\rightarrow \Psi_4$
- Required by GWDA $\longrightarrow$ strain $h(t)$ as measured by a detector far away

Different methods to extract h from a numerical evolution:

Ψ_4 complex scalar, related to h: $\Psi_4 = \ddot{h} = \ddot{h}_+ - i\ddot{h}_\times$

Zerilli function: spacetime as perturbation of Schwarzschild

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- Data calculated in a numerical simulation contains **complex** quantities over the whole sphere

$$\boxed{\Psi_4 = \Psi_4(\theta, \phi)}$$

- In the detectors, the signal from a binary produces a **real** strain

$$\boxed{h(t) = F_+ h_+(t) + F_\times h_\times(t)}$$

$F_+, F_\times$ are the *antenna pattern* functions of the detector

Multipole expansion of the wave (II)

- A suitable way to make interchange of data manageable is to decompose the data over a sphere into **modes**

- $h_+ - ih_\times$ can be decomposed into modes using **spin weighted spherical harmonics** ${}^{-s}Y_{\ell m}$ of weight -2

  - $h_+ - ih_\times = \frac{M}{r} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} H_{\ell m}(t)\ {}^{-2}Y_{\ell m}(\iota, \phi)\,.$

    where $MH_{\ell m} = \oint\ {}^{-2}Y^{\star}_{\ell m}(\iota, \phi)(rh_+ - irh_\times)\, d\Omega.$

- Define $h_+^{(\ell m)}$ and $h_\times^{(\ell m)} \Longrightarrow rh_+^{(\ell m)}(t) - irh_\times^{(\ell m)}(t) \equiv MH_{\ell m}(t)\,.$

(Waveform reconstruction $\longrightarrow h_+ - ih_\times = \sum_{\ell m} {}^{-2}Y_{\ell m}(\iota, \phi)\left[h_+^{(\ell m)} - ih_\times^{(\ell m)}\right].$

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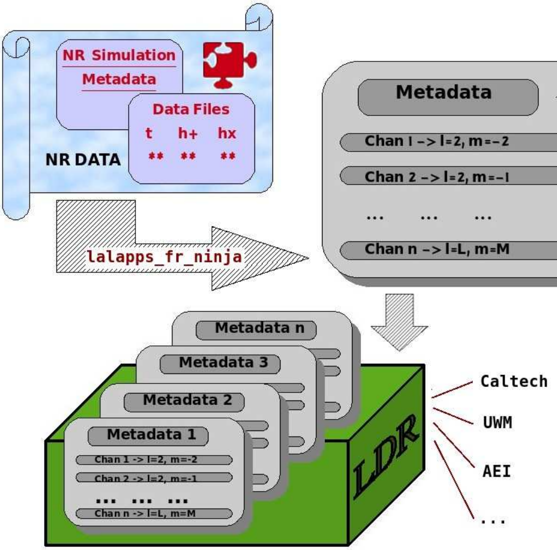
$\longrightarrow$ and incorporated to LAL with data analysis purposes in order to test the quality of the LSC searches

Incorporating NR data into the LSC infrastructure



First step:
→ Convert NR data from **ascii** to **FRAMES**

So that data in frames can be accessed and shared among the LSC via the **LSC Data Replicator**

Using NR frames to test the LSC searches

- Conversion of NR data from ascii to frames is just the **first step**
- Ideally, a library of different NR frames corresponding to various runs (for several mass ratios, spin configurations, etc) will be put together
- That NR data can then be used for data analysis
- Just to cite a straightforward example:

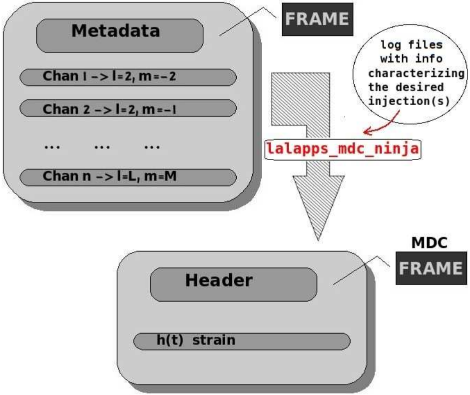
Numerical data can be injected into the detector data stream in order to check the performance of the current LSC searches

NR waveforms accounting for the whole coalescence process are of particular relevance for

INSPIRAL & **BURST**

searches

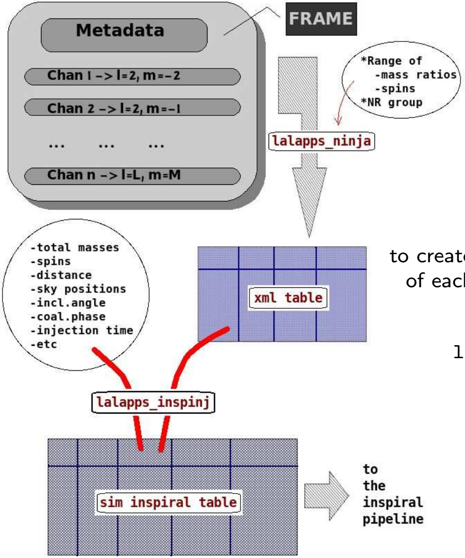
NR data within the BURST infrastructure



The burst group uses MDC frames for its injections

`lalapps_mdc_ninja` takes the NR frames plus details on the injections to compute h(t) and store it in a MDC frame that can be then used for burst searches

NR data within the INSPIRAL pipeline



The inspiral group uses a sim inspiral table to specify the parameters for its injections

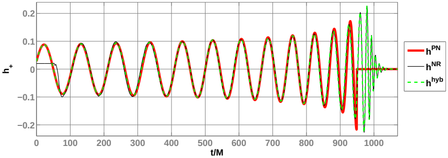
lalapps_ninja takes the NR frames plus a range of
- mass ratios
- spins

to create a xml table containing the location of each NR waveform that will be injected.

lalapps_inspinj takes this xml table plus the rest of the relevant parameters for the injection and creates a complete sim insp table, that then is passed to the inspiral pipeline

Versatility of the `ninja` codes

The `ninja` codes read data from ascii files.
This means one can use them to import *any* kind of data into the frame format.
In particular this includes the hybrid/phenomenological PN-NR waveforms



Phenomenological template family for black-hole coalescence waveforms.
P. Ajith *et al.* Class.Quant.Grav.24:S689-S700,2007

Matched post-Newtonian and numerical relativity waveforms

$$h^{\rm hyb}_{+,\times}(t,\boldsymbol{\nu}) \equiv \begin{cases} h^{\rm PN}_{+,\times}(t,\boldsymbol{\mu}_0) & \text{if } t < t_1 \\ a_0\,\tau\,h^{\rm NR}_{+,\times}(t,\boldsymbol{\nu}) + (1-\tau)\,h^{\rm PN}_{+,\times}(t,\boldsymbol{\mu}_0) & \text{if } t_1 \le t < t_2 \\ a_0\,h^{\rm NR}_{+,\times}(t,\boldsymbol{\nu}) & \text{if } t_2 \le t \end{cases}$$

Best matched TaylorT1 3.5PN with AEI-CCT equal-mass ($\eta = 0.25$) NR waves

The NINJA Project

The **N**umerical **INJ**ection **A**nalysis Project is an open collaboration aiming at testing the efficiency of various data analysis pipelines to numerical relativity waveforms buried in simulated Gaussian noise.

Goals and Guidelines:

- Promote concrete and effective interaction between numerical relativists and data analysts
- NR groups will provide waveforms, which will only be used within the scope of this collaboration
- NR data in gravitational wave frame format will be released containing simulated injections generated from the NR waveforms embedded in coloured Gaussian noise.
- Data analysts will employ the standard search pipelines to analyse the data
- A paper will be published reporting the results of this analysis

http://www.gravity.phy.syr.edu/dokuwiki/doku.php?id=ninja:home

Summary and Future work

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- Code to allow for injections of numerical data written (GPL)
- Sanity check performed and validity of the method tested
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Future work

- NINJA collaboration to kick off
- Will test the performance of the current LSC searches
- Work in progress, join the team and stay tuned!

  → "Data formats for numerical relativity waves". ArXiv:0709.0093 [gr-qc]

  → http://www.gravity.phy.syr.edu/dokuwiki/doku.php?id=ninja:home