Extracting Supernova Information from a LIGO Detection

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Goal: Supernova Astronomy with Gravitational Waves

- The physics involved in core-collapse supernovae remains largely uncertain
  - » Progenitor structure and rotation, equation of state
- Simulations generally do not incorporate all known physics
  - » General relativity, neutrinos, convective motion, non-axisymmetric motion
- Gravitational waves carry information about the dynamics of the core which is mostly hidden
- Question: What supernova physics could be learned from a gravitational wave detection?

Maximum Entropy

- Problem: the detection process modifies the signal from its initial form $\mathbf{h}_i$

$$\boldsymbol{d} = \boldsymbol{R}\boldsymbol{h}_i + \boldsymbol{n}$$

  - Detector response R includes projection onto the beam pattern as well as unequal response to various frequencies (strain $\rightarrow$ AS_Q)
- Solution: maximum entropy – Bayesian approach to deconvolution used in radio astronomy
  - Minimize the function

$$F(\boldsymbol{h}|\boldsymbol{d}, \boldsymbol{N}, \boldsymbol{m}) = 1/2\,\chi^2(\boldsymbol{h}|\boldsymbol{d}) - \alpha\, S(\boldsymbol{h}, \boldsymbol{m})$$

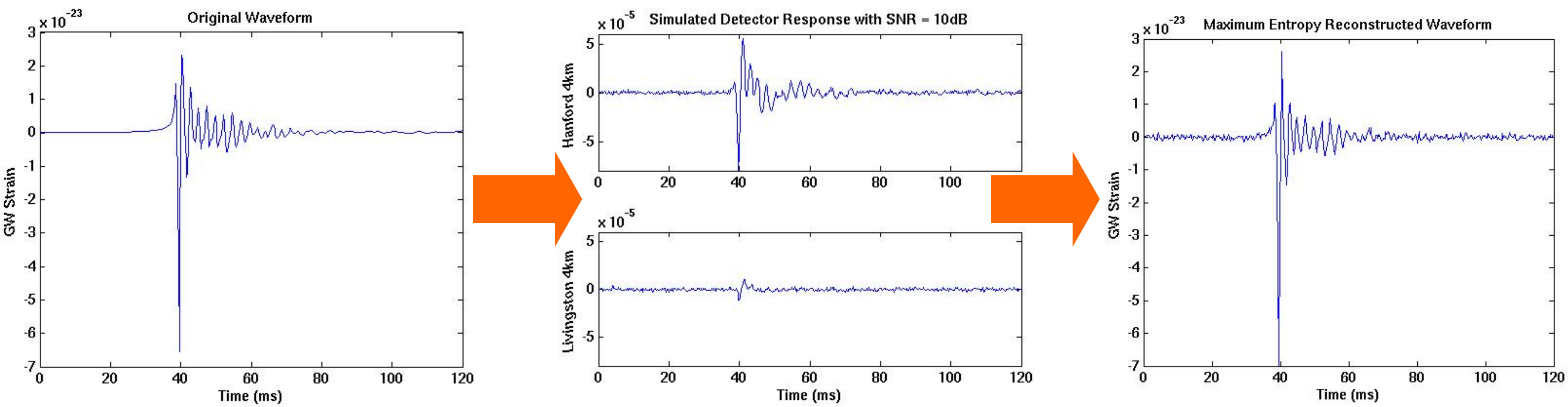
where

$$\chi^2(\boldsymbol{h}|\boldsymbol{N}, \boldsymbol{d}) = (\boldsymbol{R}\boldsymbol{h} - \boldsymbol{d})^T \boldsymbol{N}^{-1} (\boldsymbol{R}\boldsymbol{h} - \boldsymbol{d})$$

is the usual misfit statistic with **N** the noise covariance

Maximum Entropy Cont.

- Minimize $F(\mathbf{h}|\mathbf{d},\mathbf{N},\mathbf{m}) = 1/2\,\chi^2(\mathbf{h}|\mathbf{d}) - \alpha\, S(\mathbf{h},\mathbf{m})$
  - S(**h**,**m**) is the Shannon information entropy that ensures the reconstructed signal **h** is close to the model **m**. We set **m** equal to the rms of the signal.
  - α is a Lagrange parameter that balances being faithful to the signal (minimizing χ^2) and avoiding overfitting (maximizing entropy)
- Example:



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Waveforms: Ott et.al.(2004)

- 2D core-collapse simulations restricted to the iron core
- Realistic equation of state (EOS) and stellar progenitors with 11, 15, 20 and 25 $M_{\odot}$
- General relativity and Neutrinos neglected
- Some models with progenitors evolved incorporating magnetic effects and rotational transport.
- Progenitor rotation controlled with two parameters: fractional rotational energy β and differential rotation scale A (the distance from the rotational axis where rotation rate drops to half that at the center)

$$\beta = \frac{E_{rot}}{|E_{grav}|} \qquad \Omega(r) = \Omega_0 \left[1 + \left(\frac{r}{A} \right)^2 \right]^{-1}$$

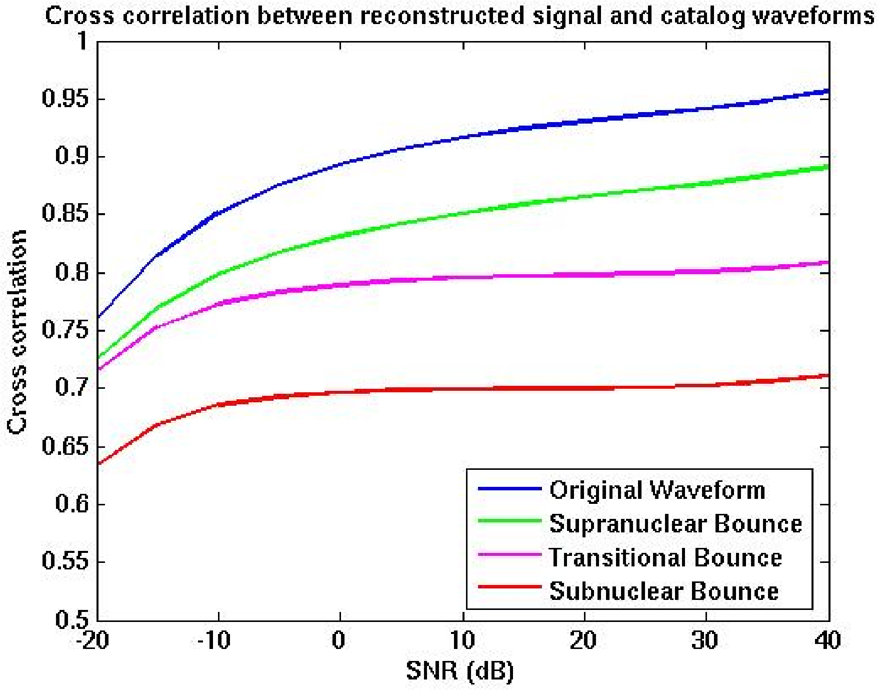
  - Low β (zero to a few tenths of a percent): Progenitor rotates slowly. Bounce at **supranuclear** densities. Rapid core bounce and ringdown.
  - Higher β: Progenitor rotates more rapidly. Collapse halted by centrifugal forces at **subnuclear** densities. Core bounces multiple times
  - Small A: Greater amount of differential rotation so the central core rotates more rapidly. Transition from supranuclear to subnuclear bounce occurs for smaller value of β

Simulated Detection

- Start with Ott et.al. waveform from model having $15M_{\odot}$ progenitor with β = 0.1% and A = 1000km
- Project onto H1 and L1 beam patterns as if signal coming from intersection of prime meridian and equator
- Convolve with H1 and L1 impulse responses calculated from calibration info at GPS time 754566613 (during S3)
- Add white noise of varying amplitude to simulate observations with different SNRs
- Recover initial signal via maximum entropy

Extracting Bounce Type

- Calculated maximum cross correlation between recovered signal and all waveforms in catalogue
- Maximum cross correlation between recovered signal and original waveform (blue line)
- Plot at right shows highest cross correlations between recovered signal and a waveform of each type.
- Recovered signal has most in common with waveform of same bounce type (supranuclear bounce)



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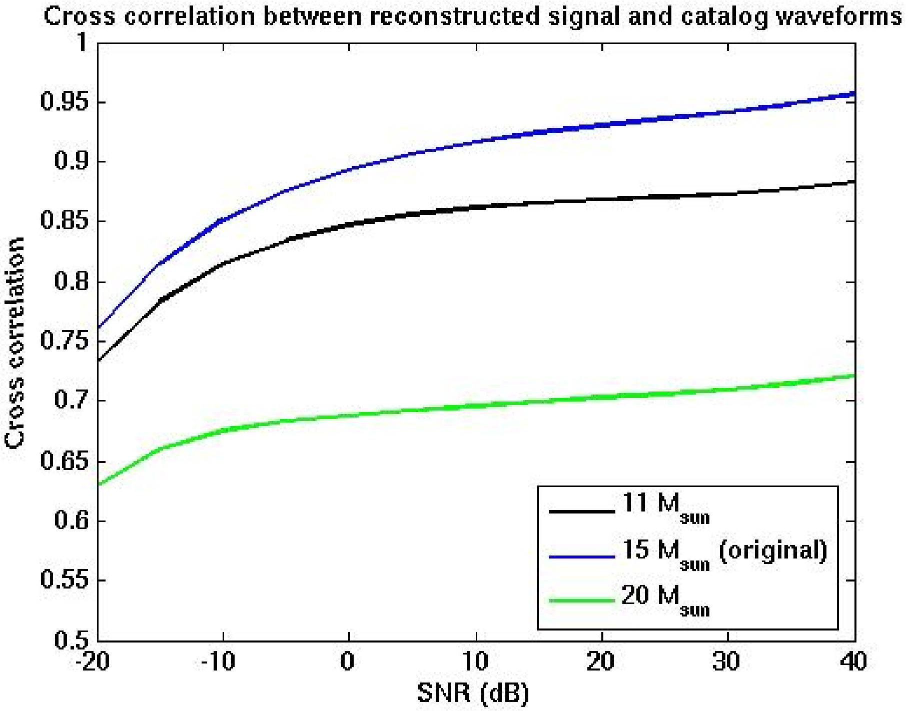
Extracting Mass

- Plot at right shows cross correlation between reconstructed signal and waveforms from models with progenitors that differ only by mass
- The reconstructed signal is most similar to the waveform with the same mass



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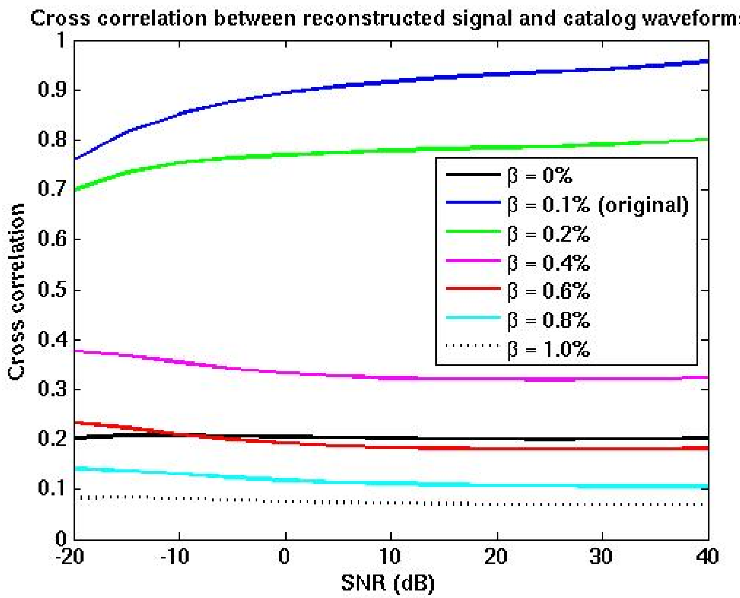
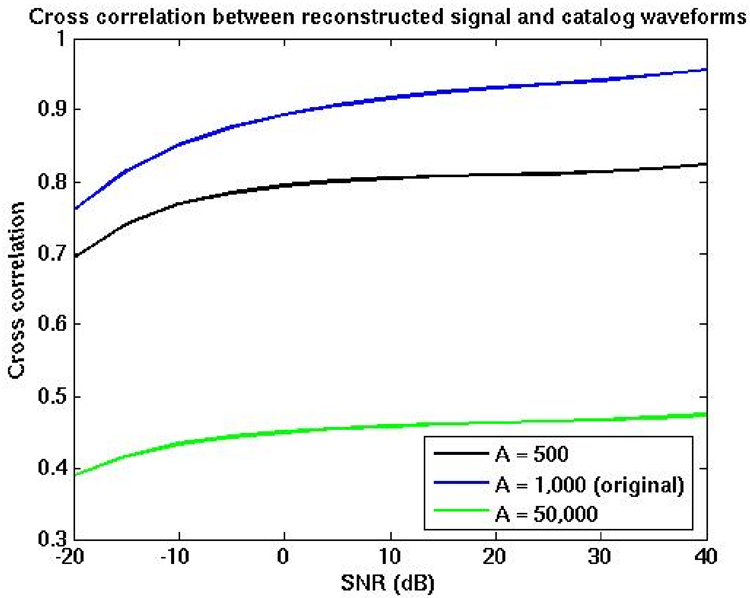
LIGO

Extracting Rotational Information





- Plots above show cross correlations between reconstructed signal and waveforms from models that differ only by fractional rotational energy β (left) and differential rotation scale A (right)
- Reconstructed signal most closely resembles waveforms from models with the same rotational parameters

Conclusions

- Maximum entropy successfully reconstructs signals from data.
- Reconstructed core-collapse supernova signals carry information about the physics of the supernova that produced them including bounce type, mass, and rotational parameters.
- Gravitational wave supernova astronomy can be realized!