Searching for Binary Neutron Star Coalescences in LIGO

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For the LIGO Scientific and Virgo Collaborations

Probing Neutron Stars with Gravitational Waves
PSU - June 19, 2009

LIGO-G0900546

Binary Systems

PSR1913+16 Hulse-Taylor

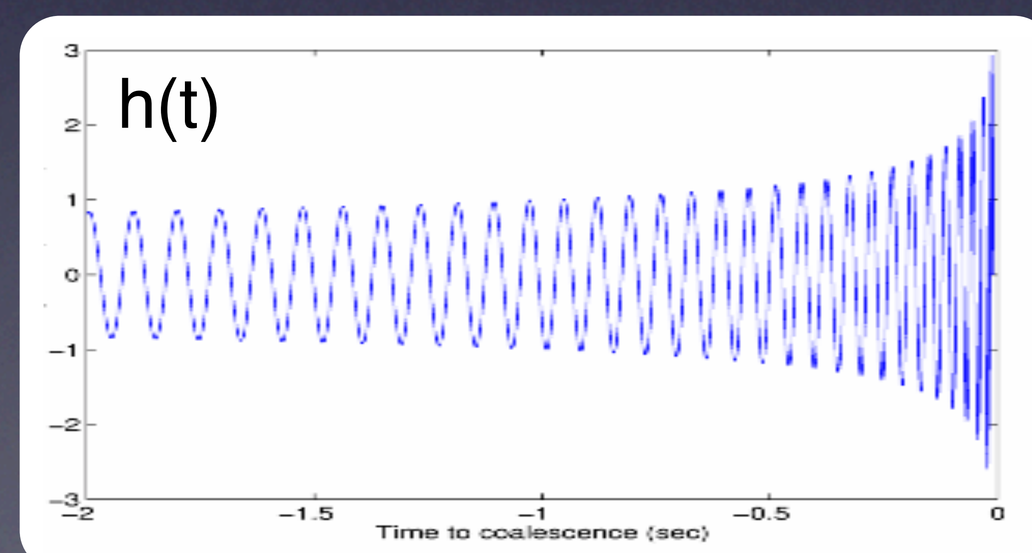
Neutron Star Binary System

- separated by 10^6 miles
- $m_1 = 1.4M_\odot$ $m_2 = 1.36M_\odot$ $\varepsilon = 0.617$

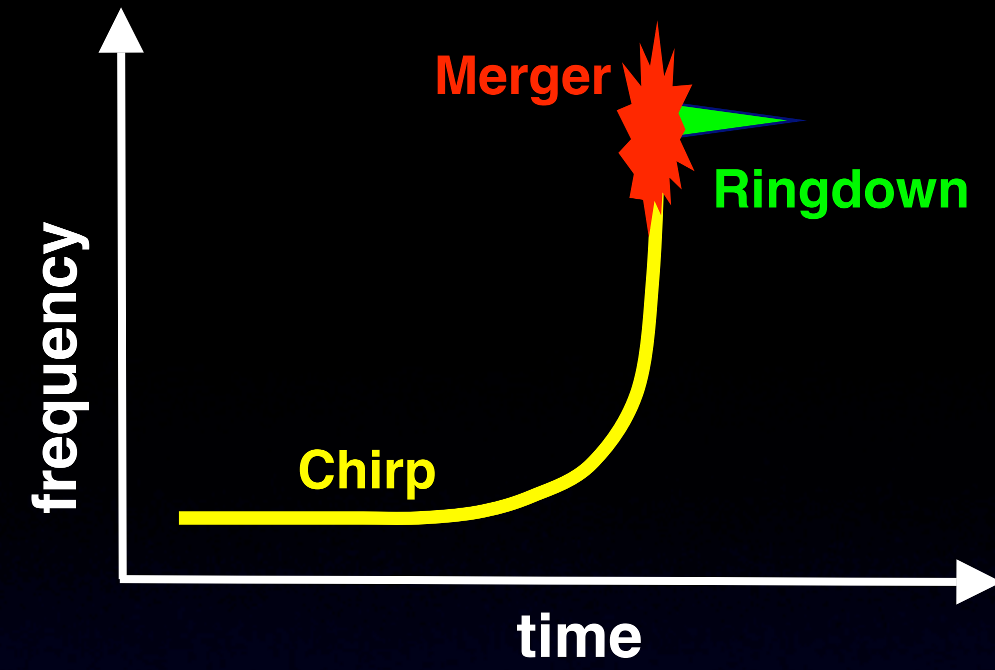
Exact match to general relativity

- spiral in by 3 mm/orbit
- shortening of orbital period
- indirect evidence for gravitational waves

- Gravitational waves carry away energy and angular momentum. Orbit will continue decay
- In ~300 million years, the "inspiral" will accelerate, and the neutron stars coalesce
- Gravitational wave emission will be strongest near the end



Compact Binary Coalescences



Credits : WUGRAV group, University of Washington; Damir Buskulic

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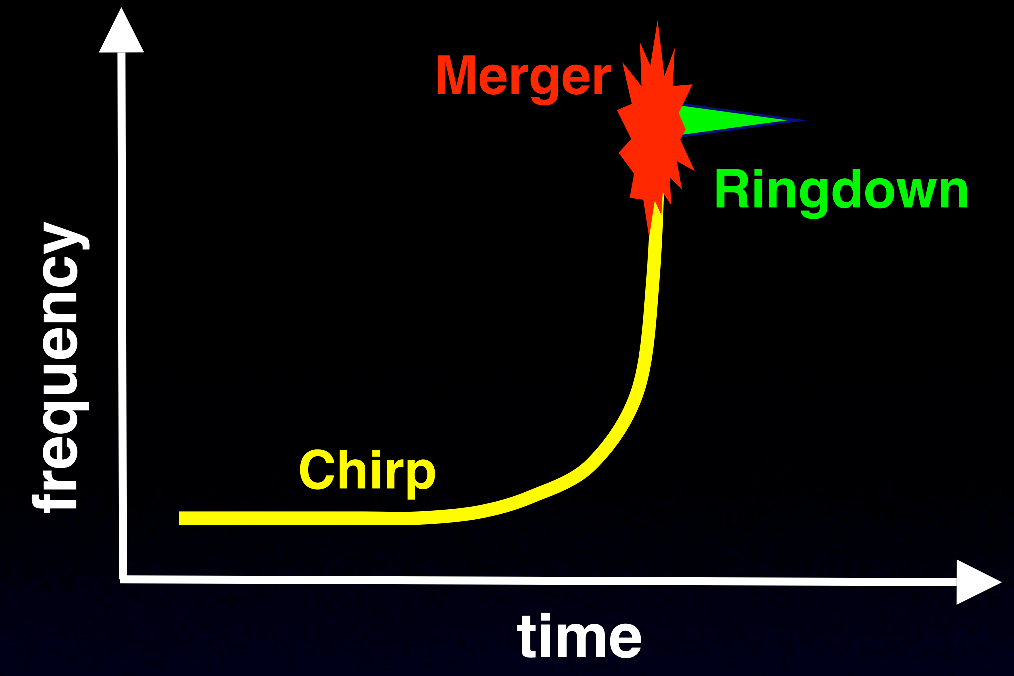

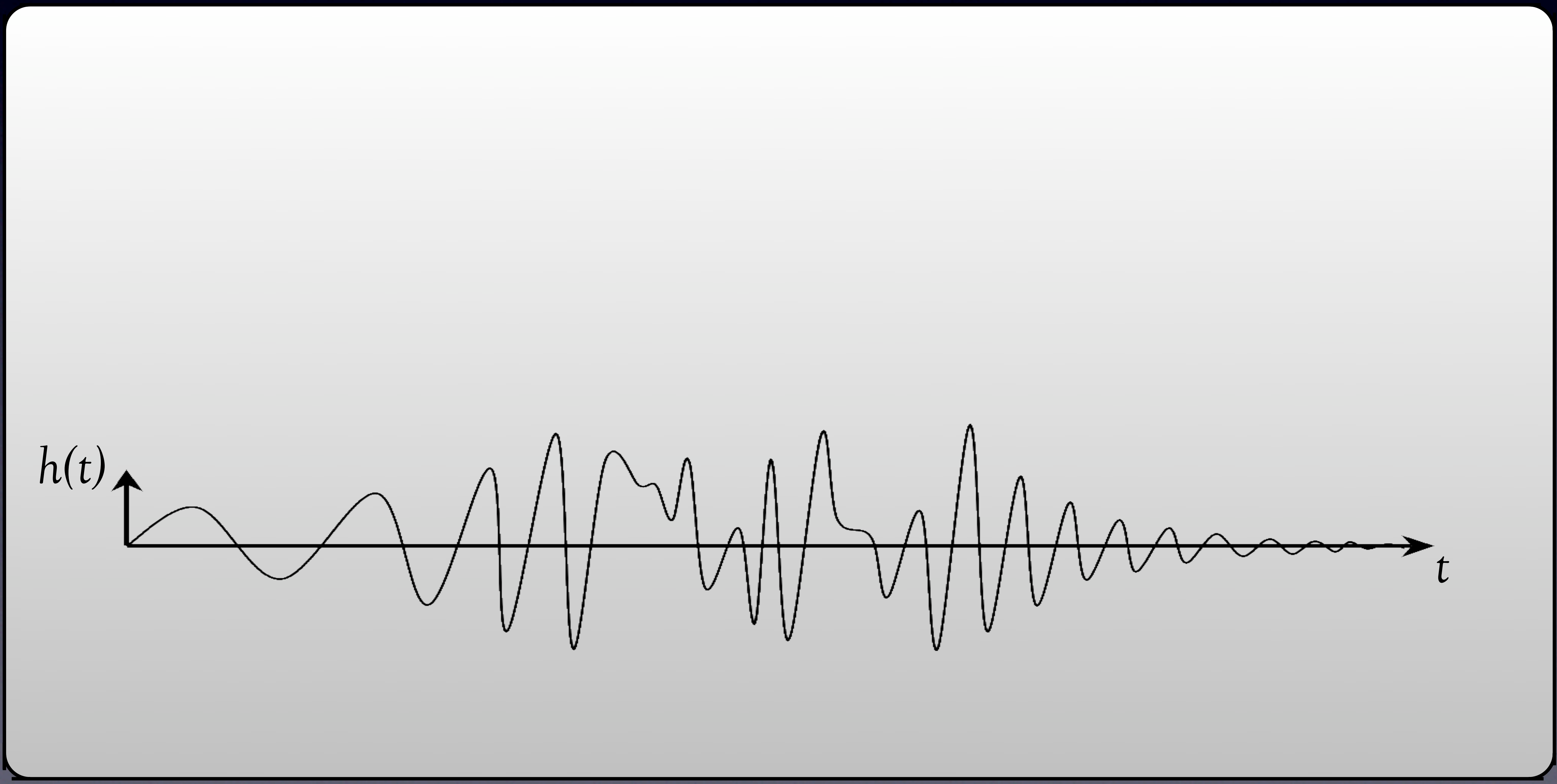

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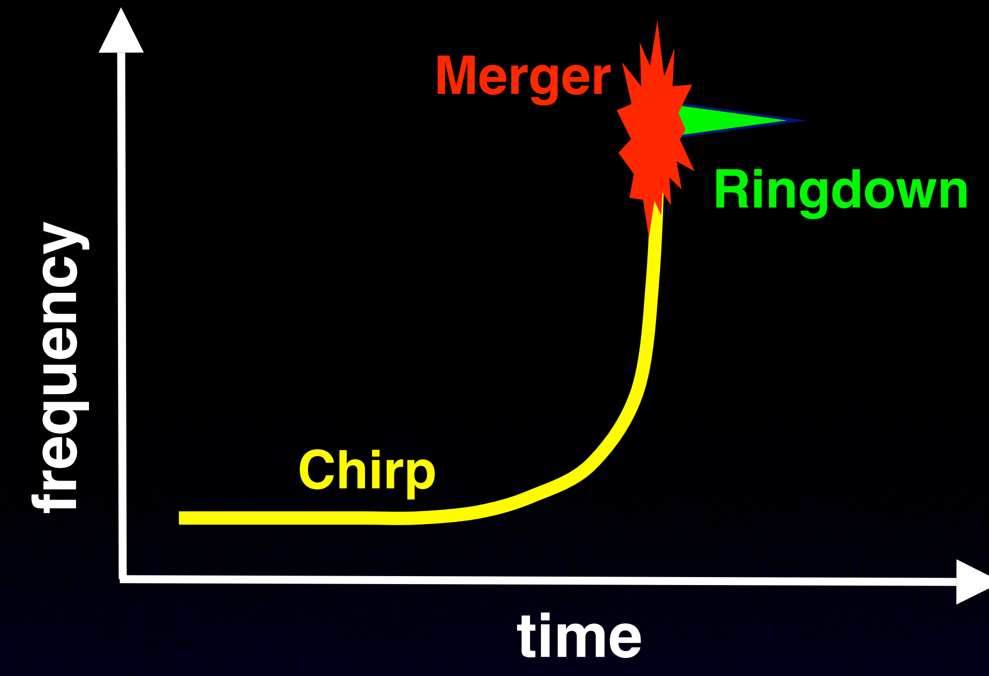

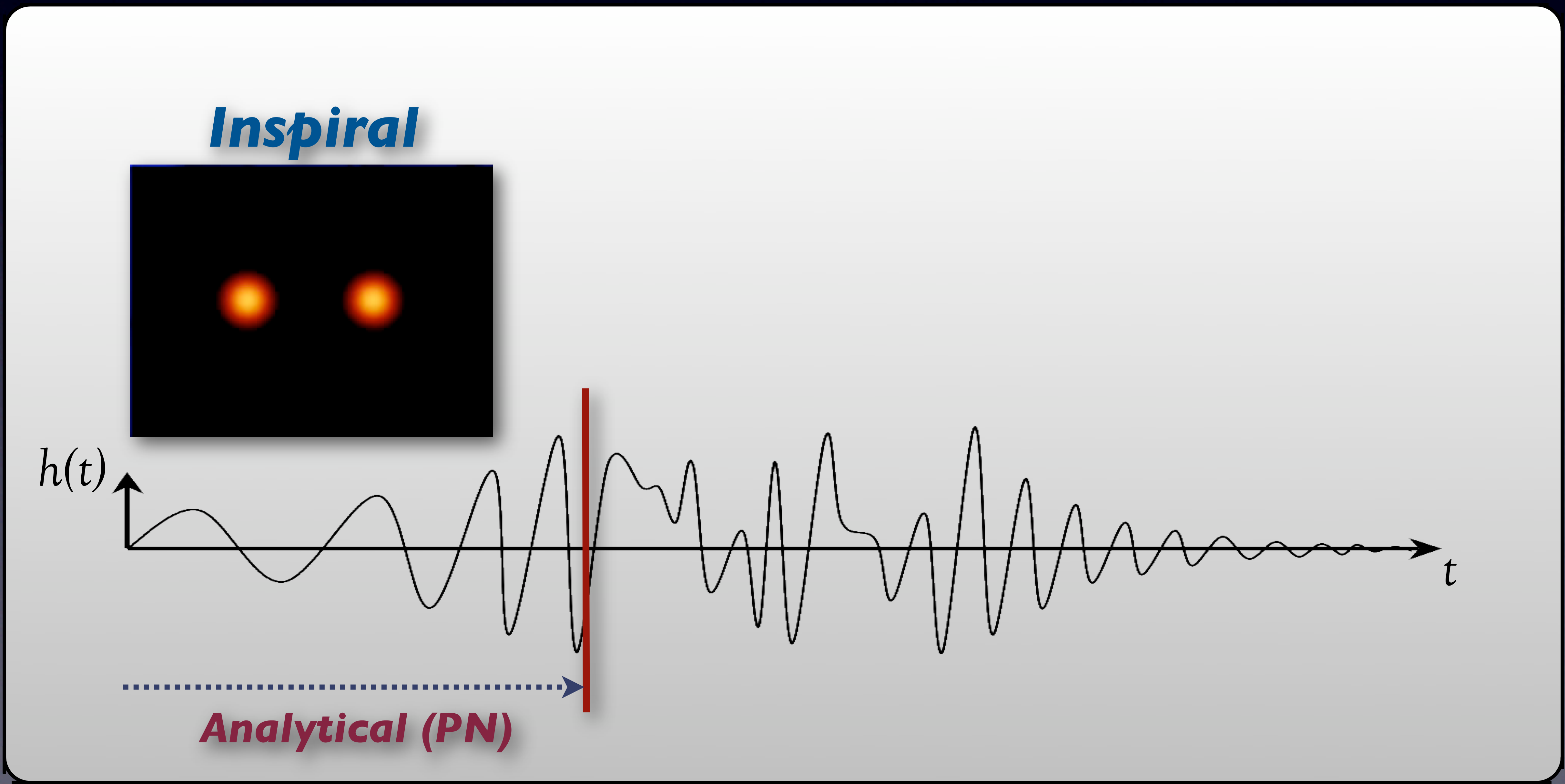

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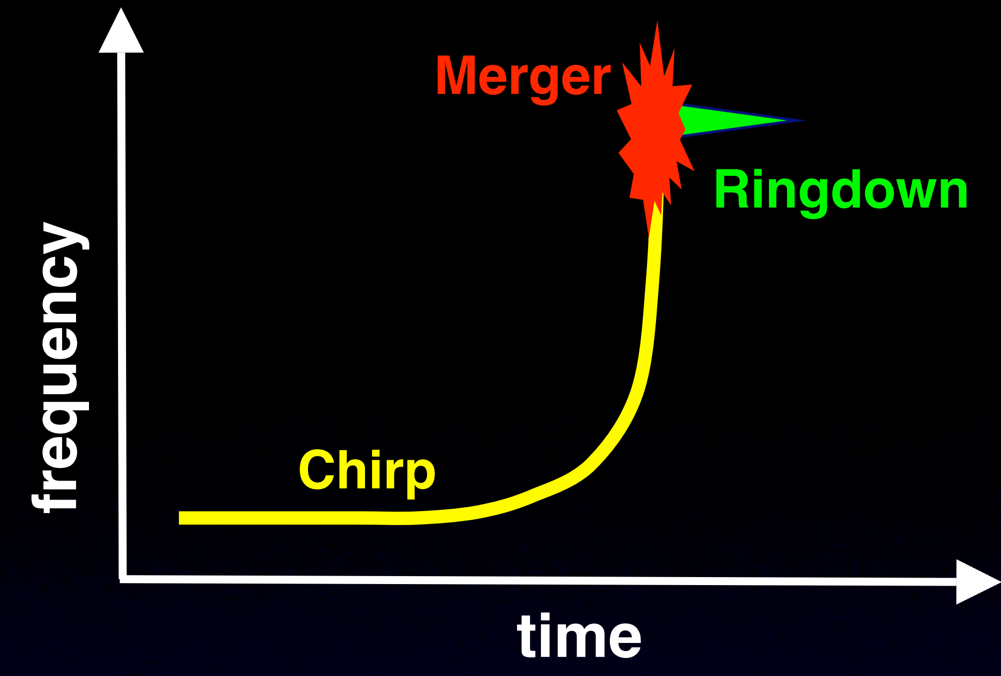

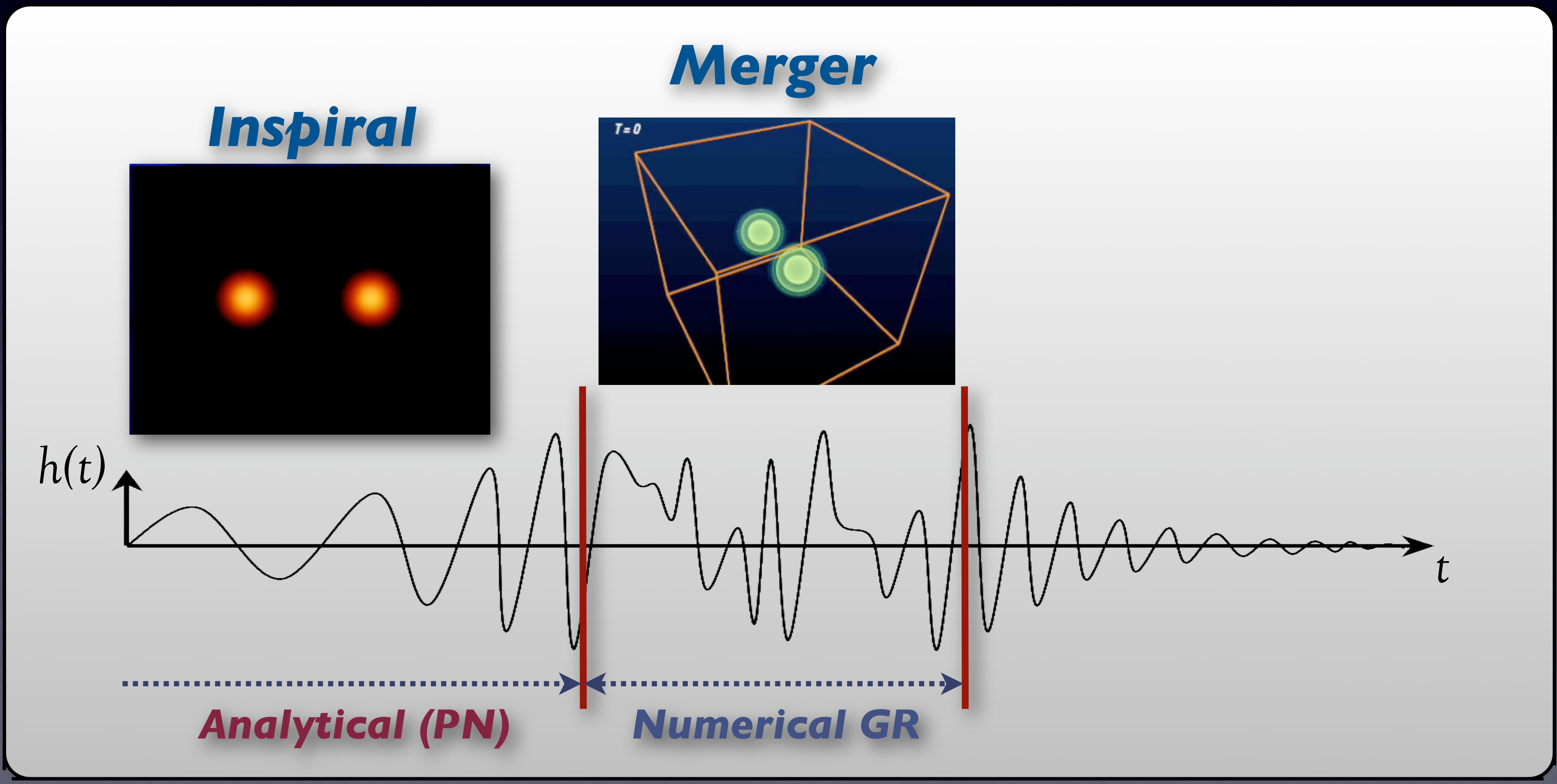

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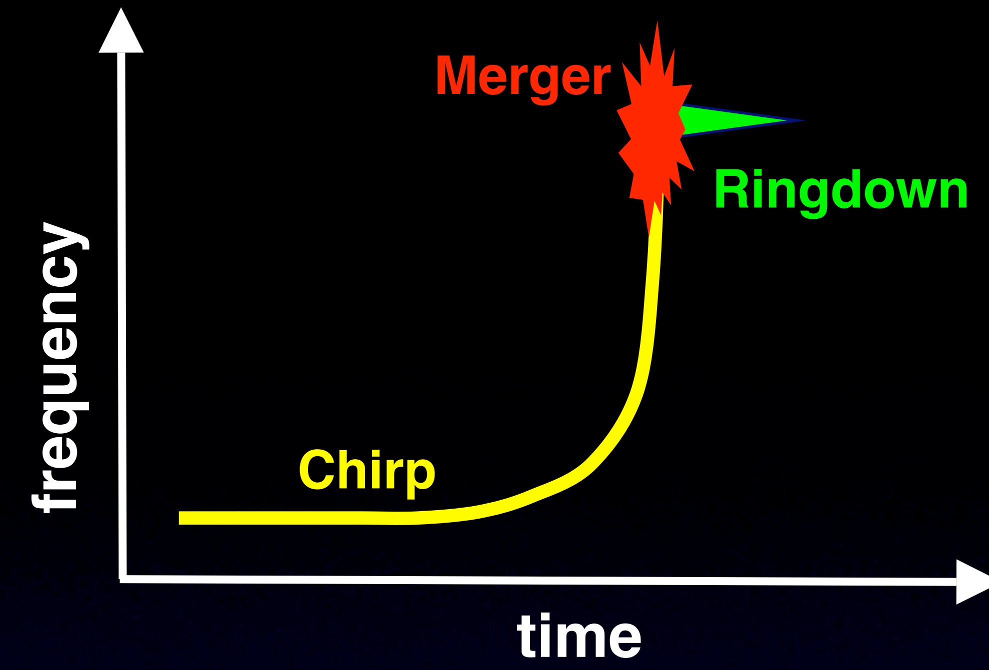
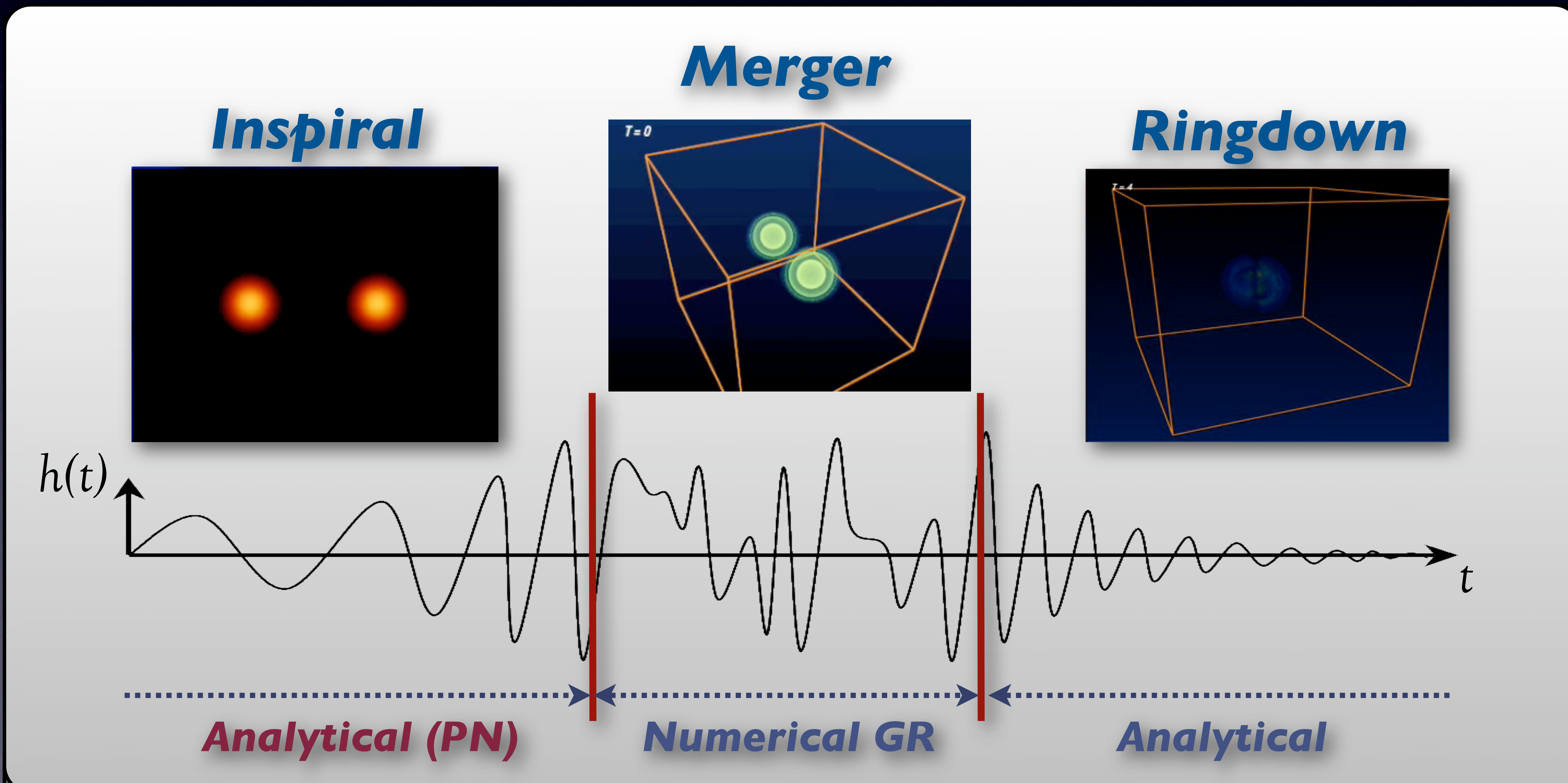
Compact Binary Coalescences





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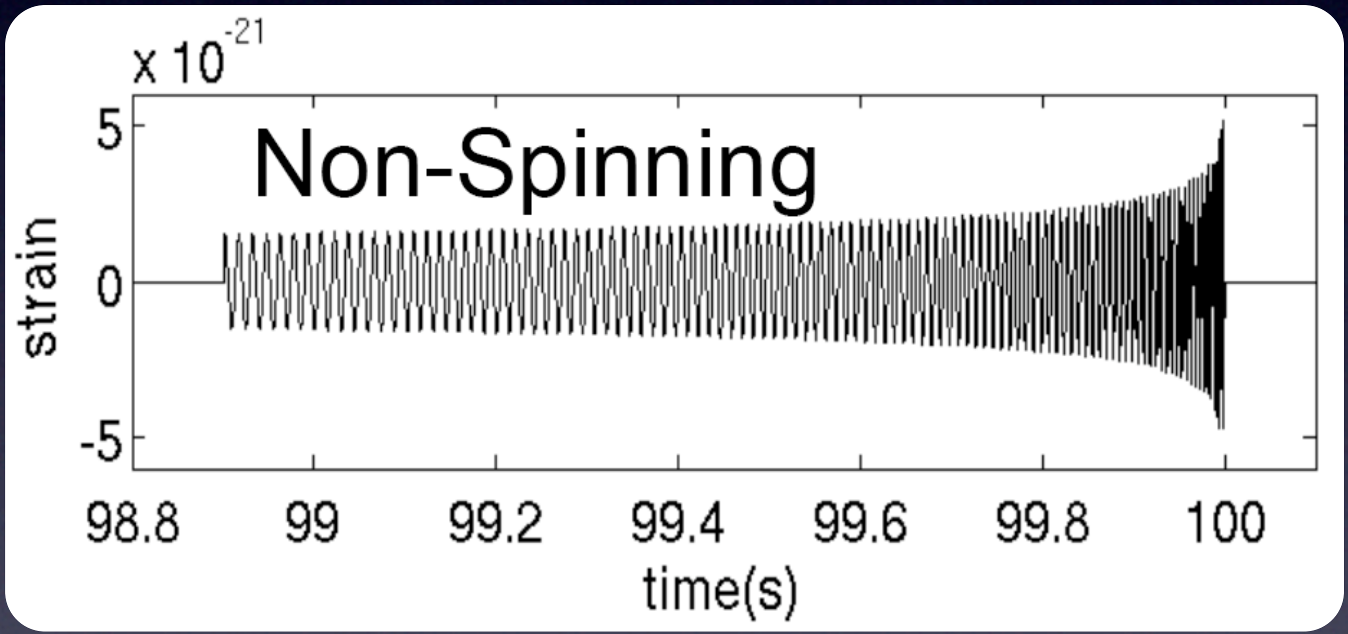
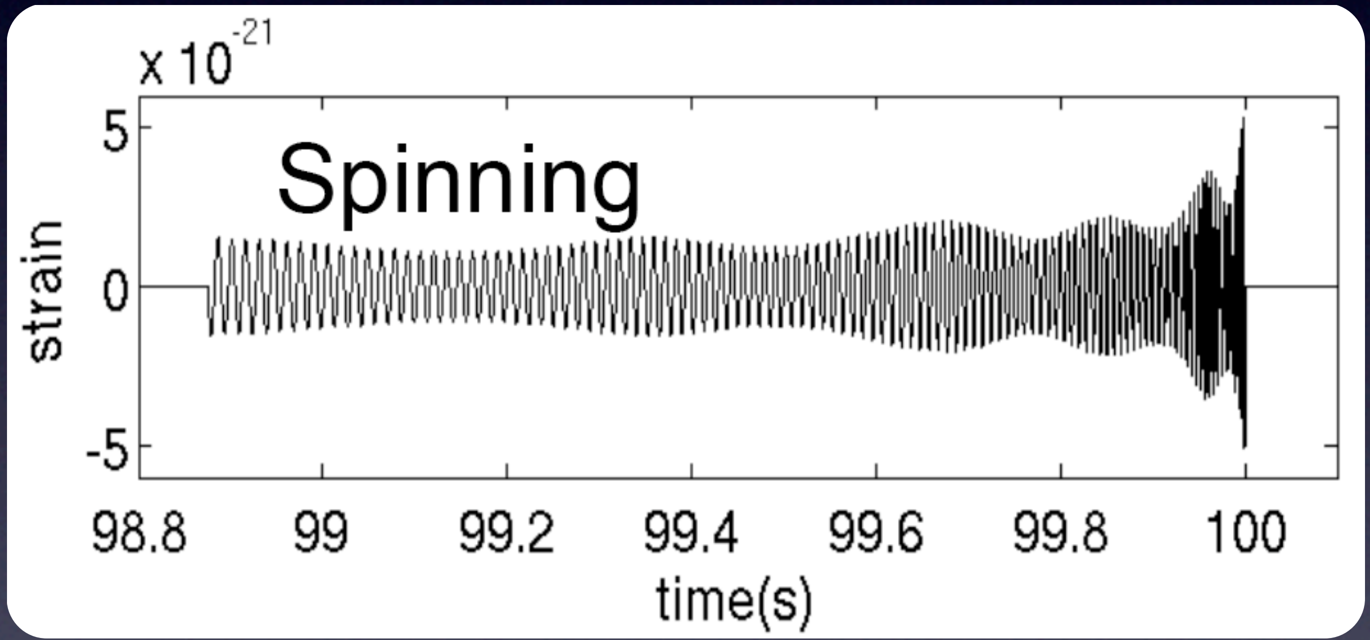
Compact Binary Coalescence Searches

Templated search: cross-correlate data with thousands of templates (matched filtering)

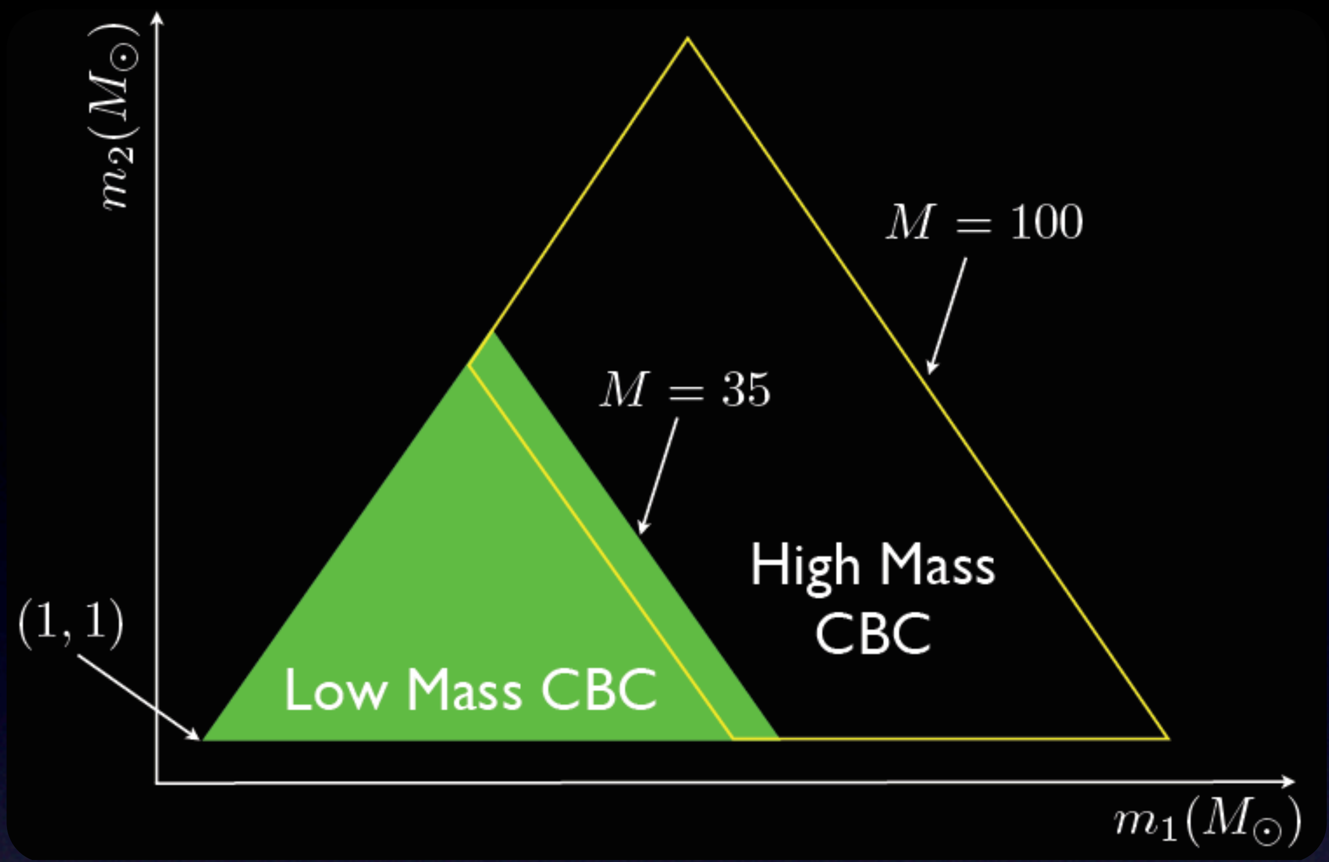




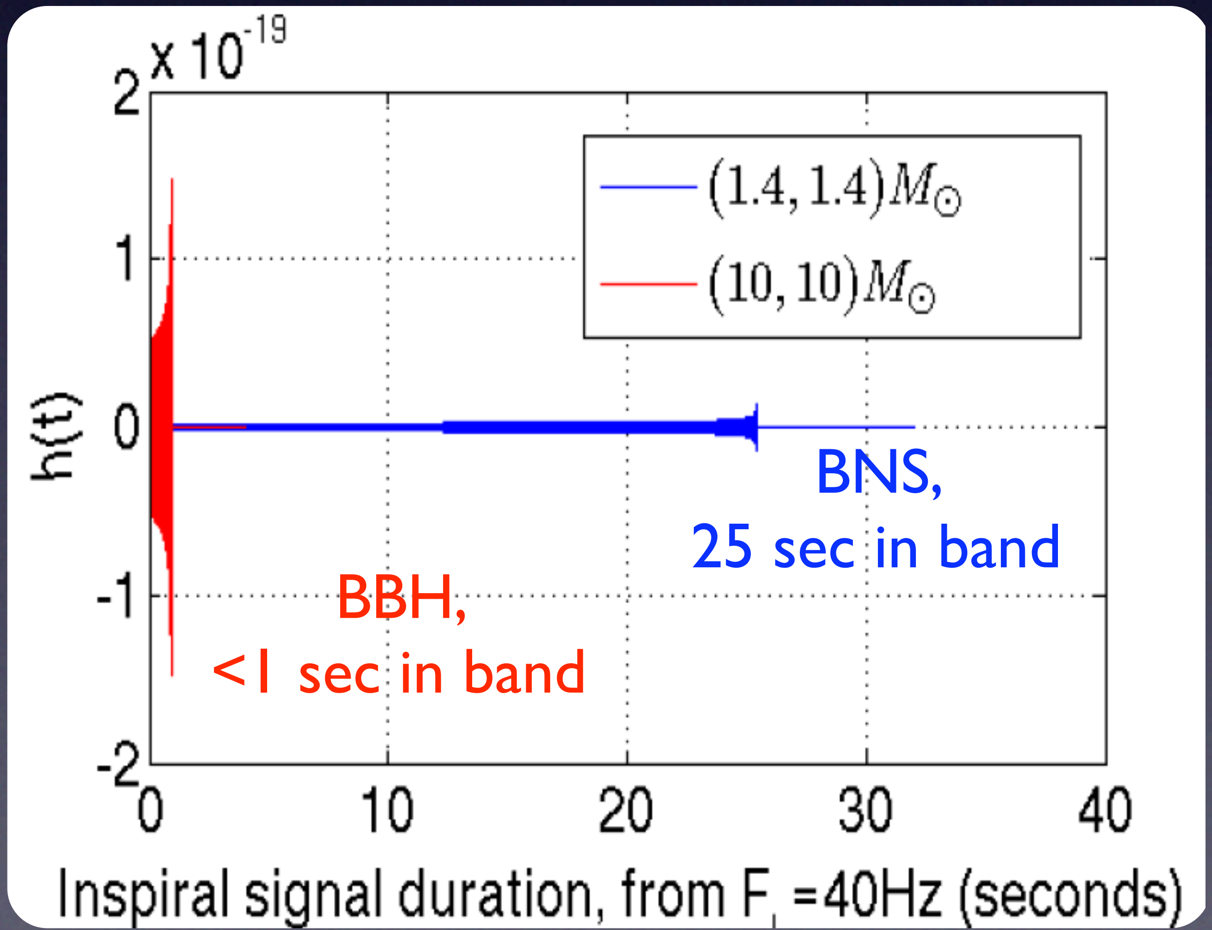
Inspiral chirp: amplitude and duration depend on the masses and spins.

D_{eff} = effective distance, depends on the physical distance r and on orientation of the binary system; $D_{eff}>r$

Templates



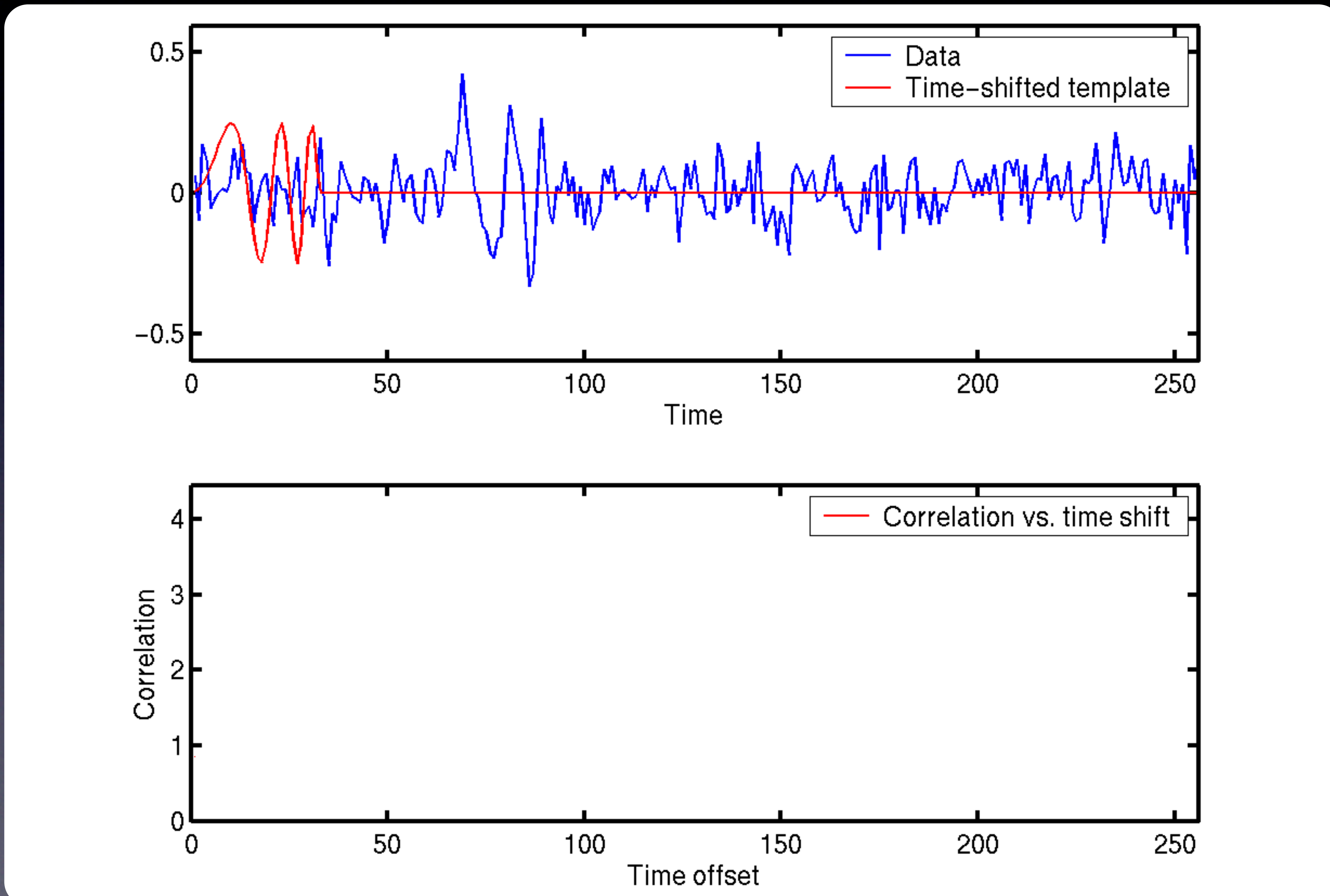
In-band signal duration depends on total mass



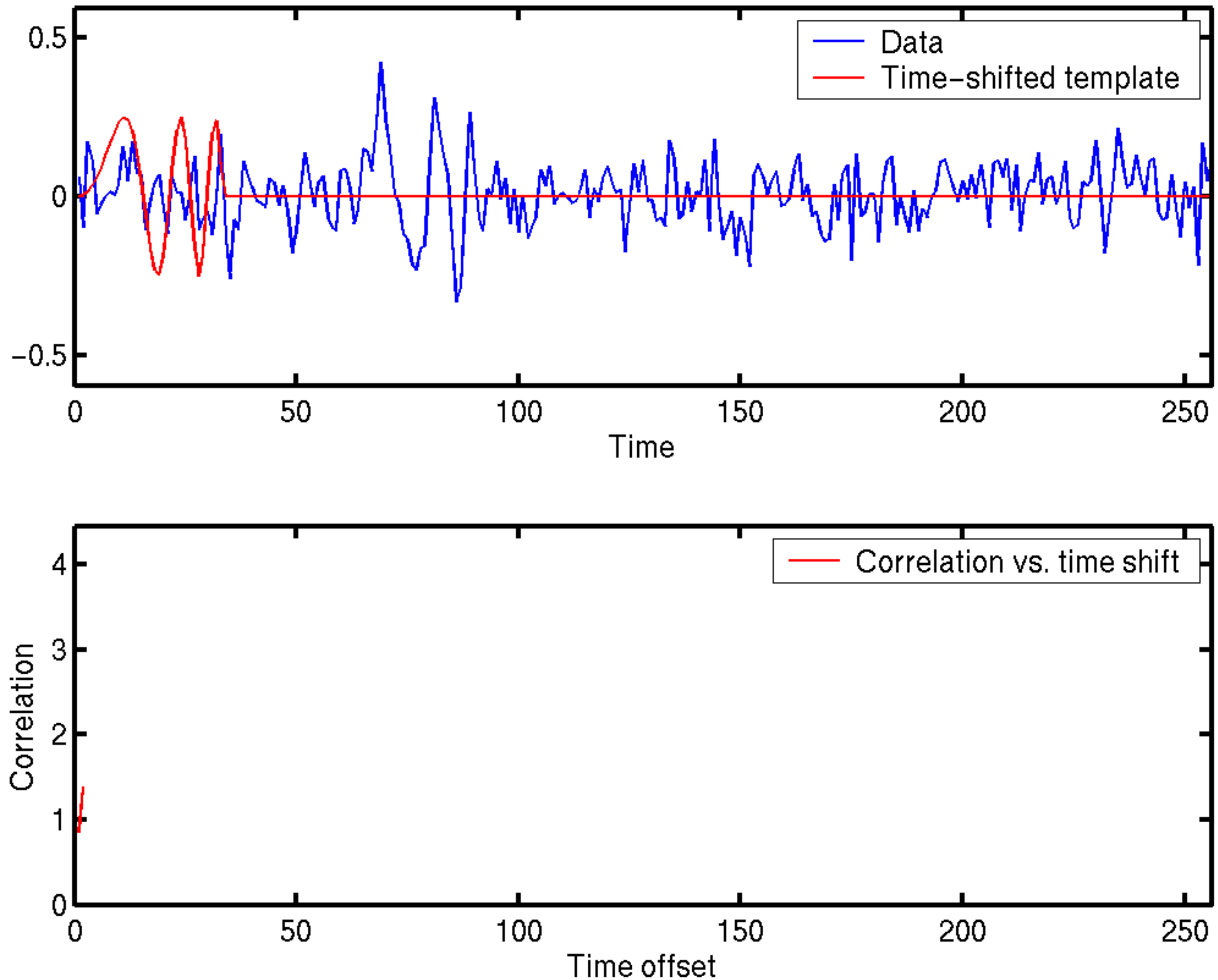
waveforms from **non-spinning** compact binaries, calculated in frequency domain with stationary-phase approximation (SPA)

Newtonian order in amplitude, second PN in phase, extended until the Schwarzchild innermost stable circular orbit (ISCO)

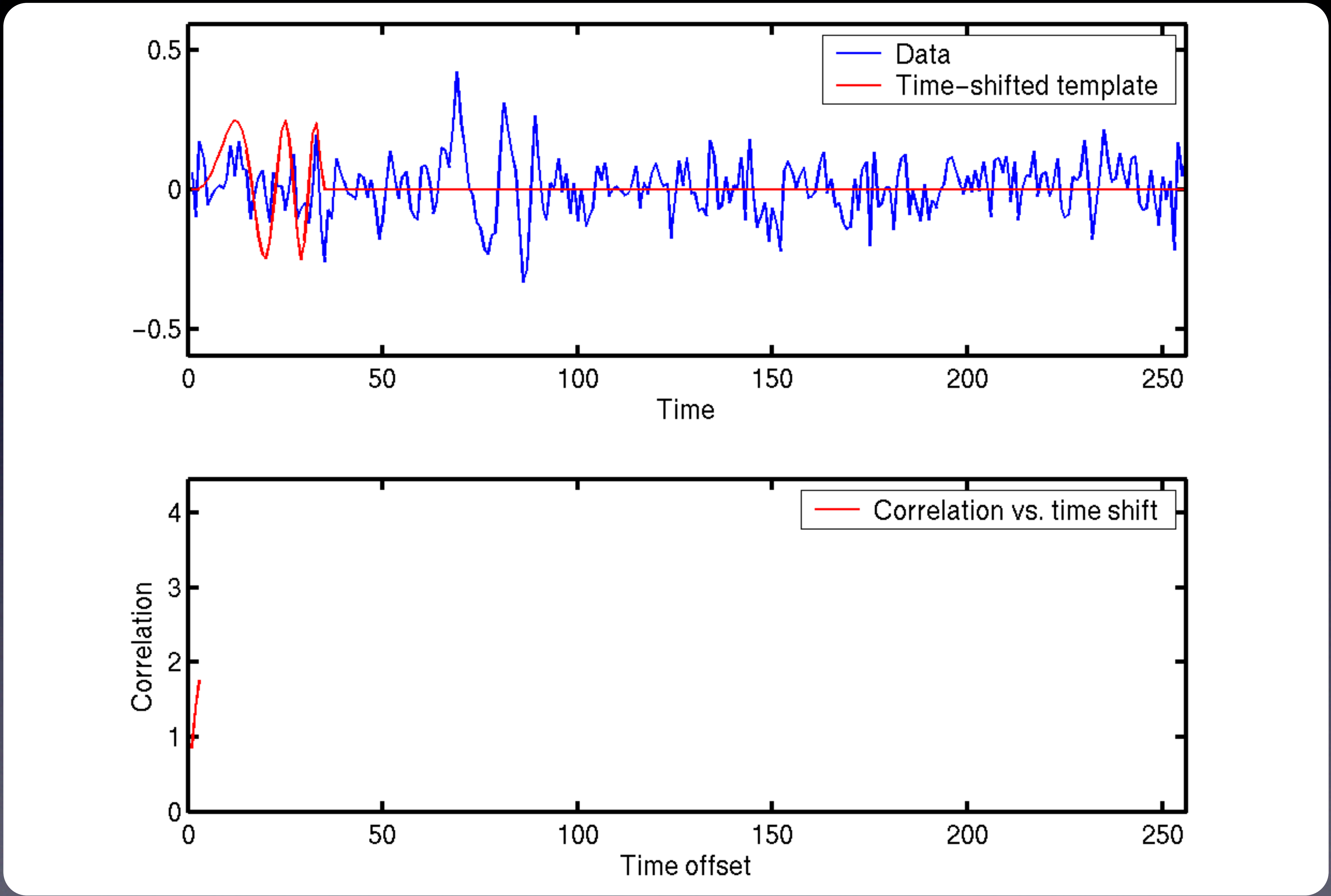
Finding "Triggers"



Finding "Triggers"



Finding "Triggers"



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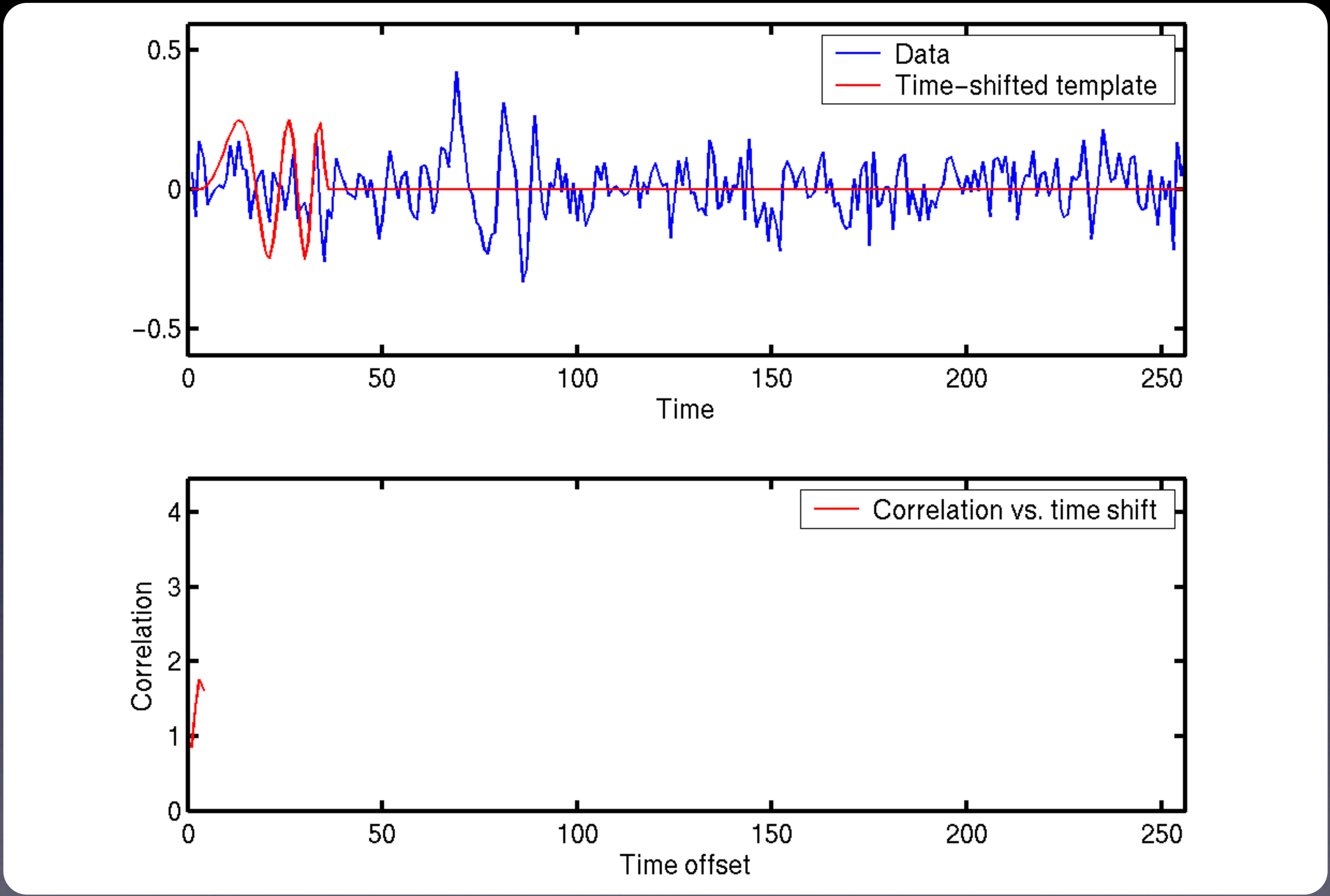
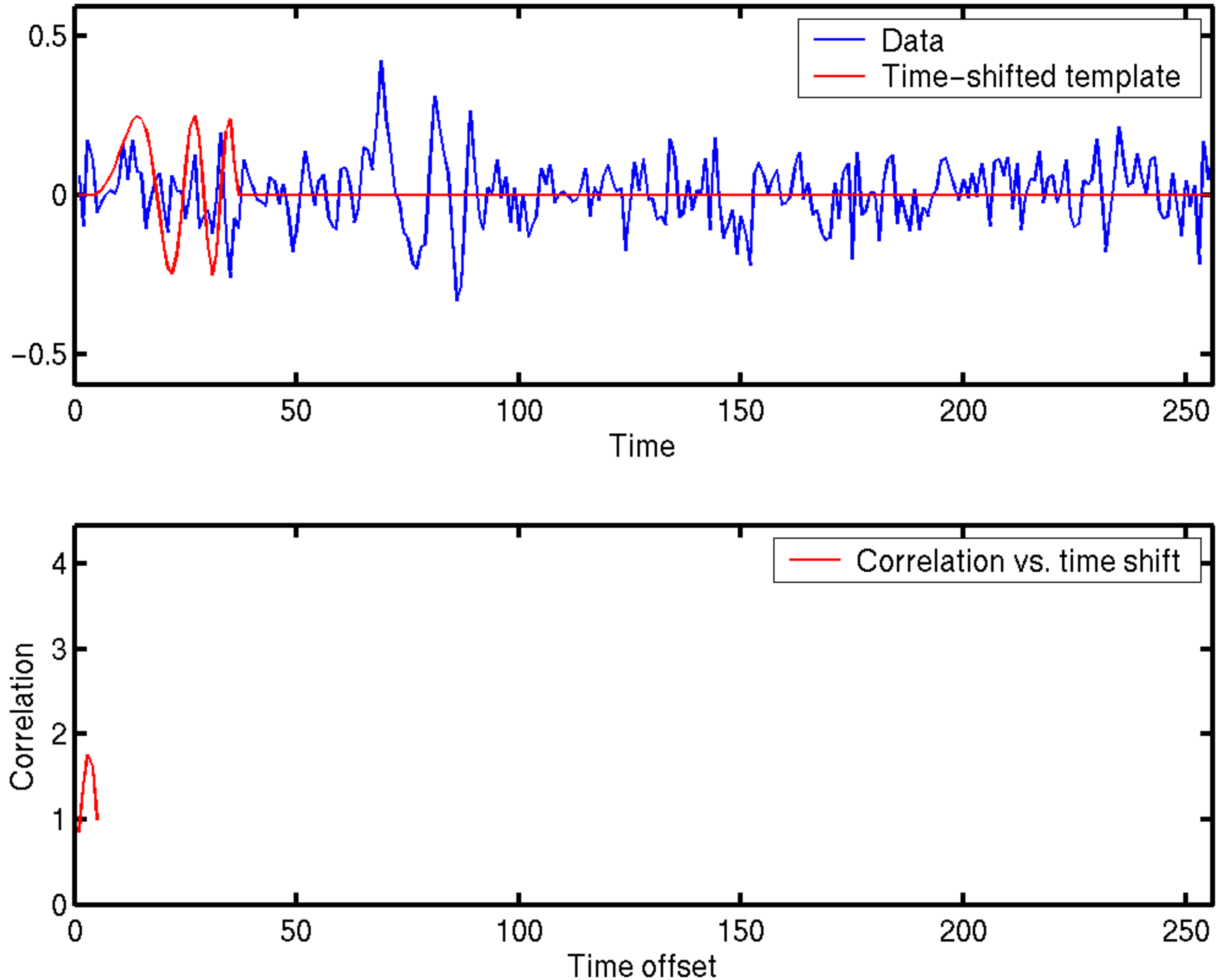


Finding "Triggers"



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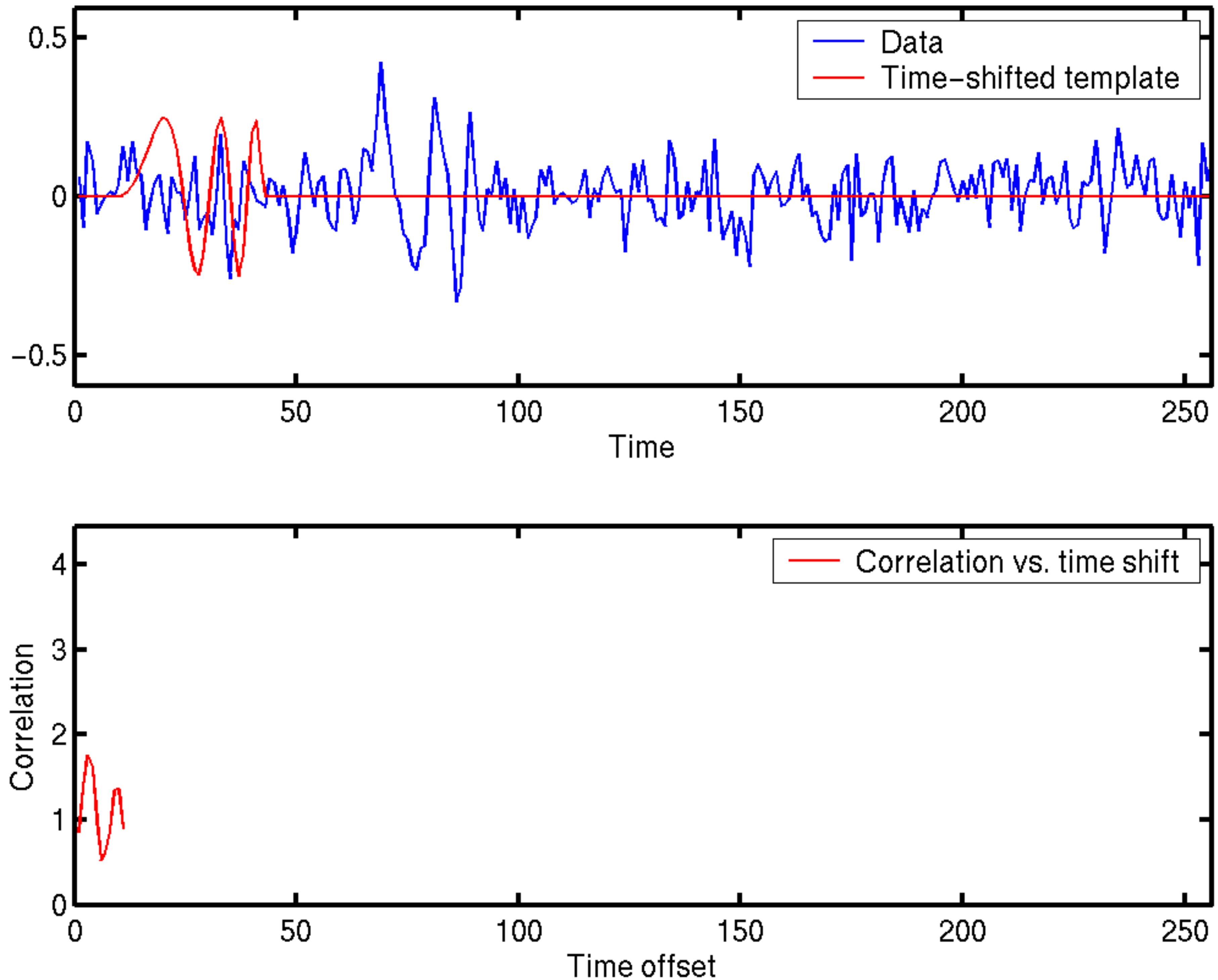

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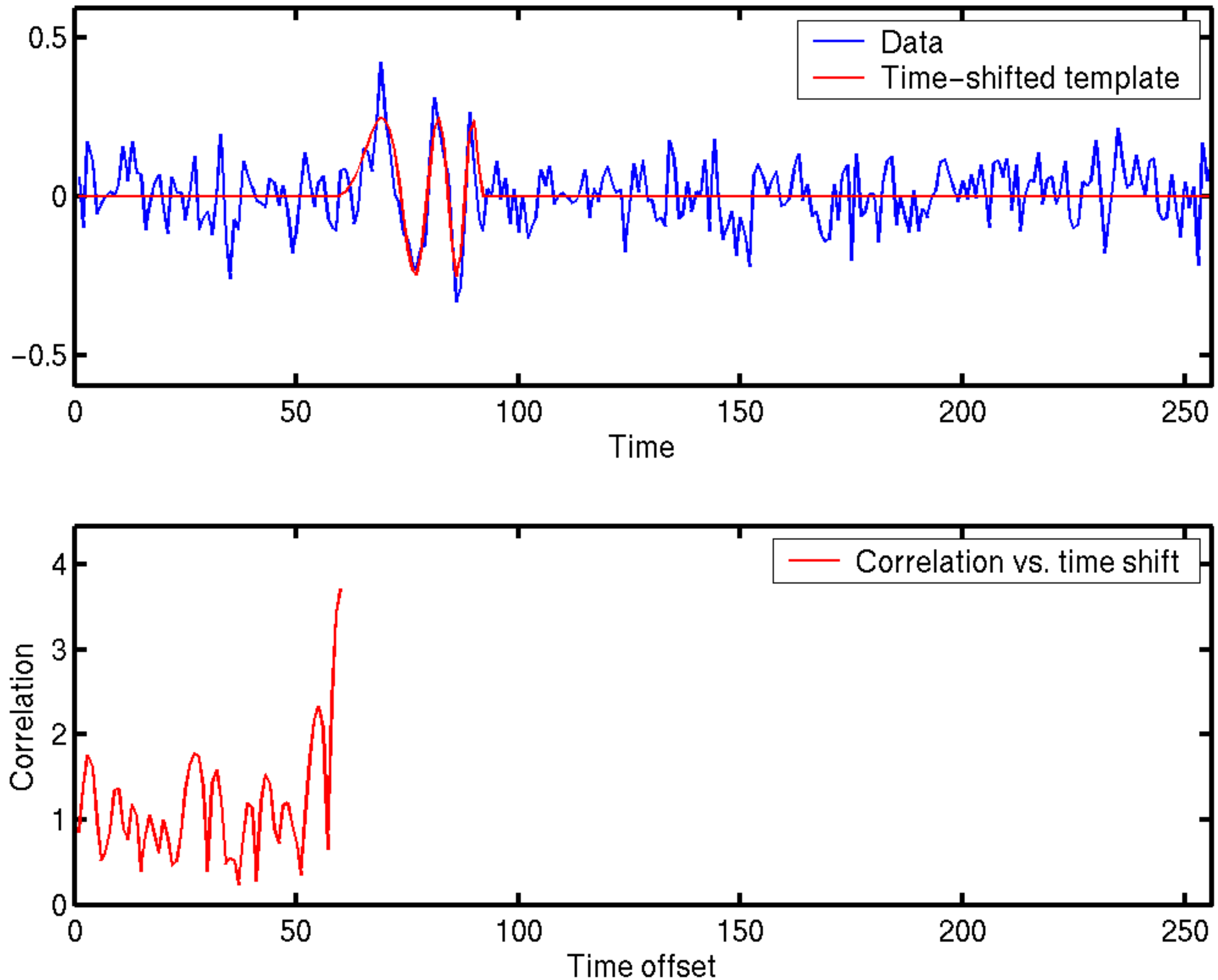
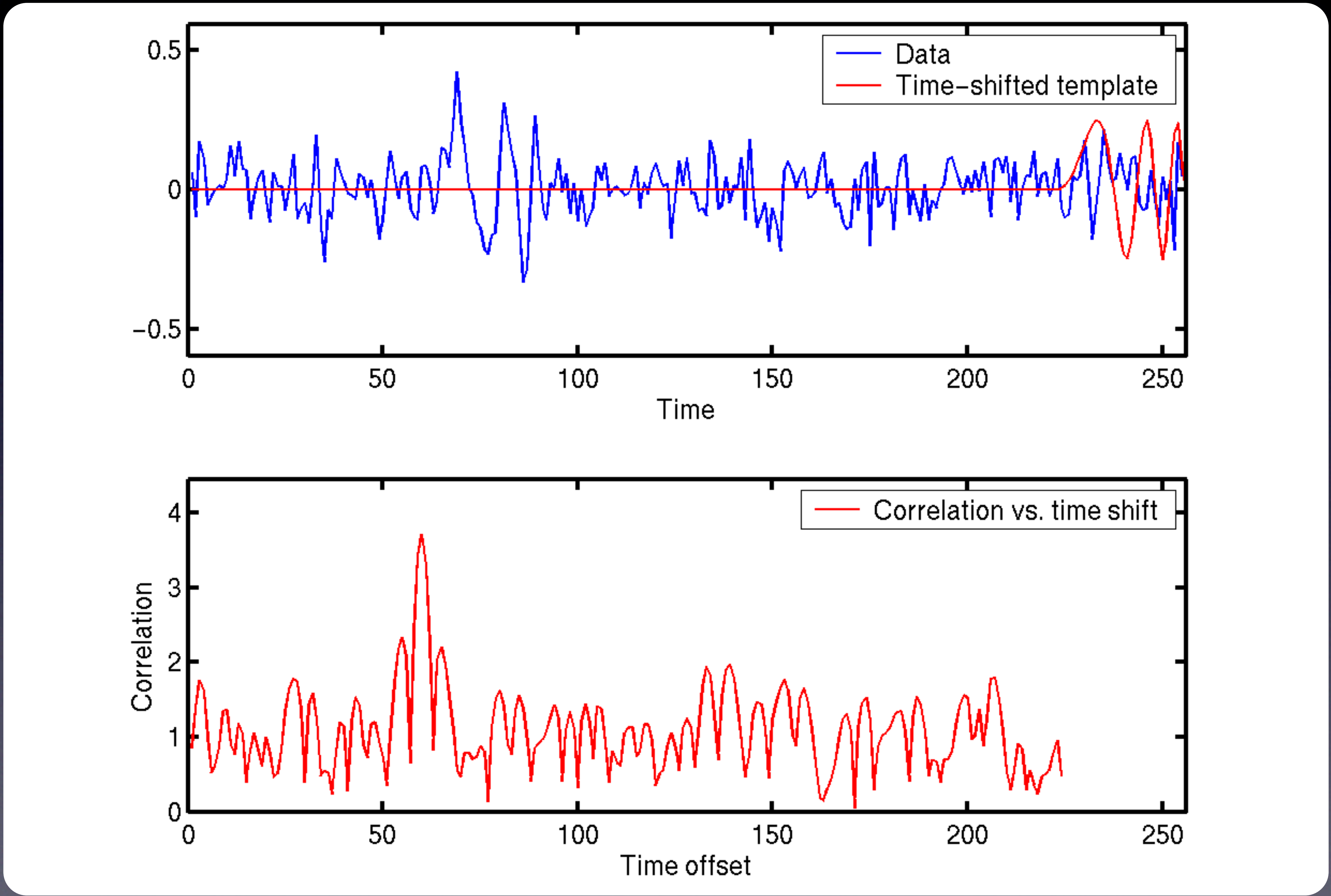


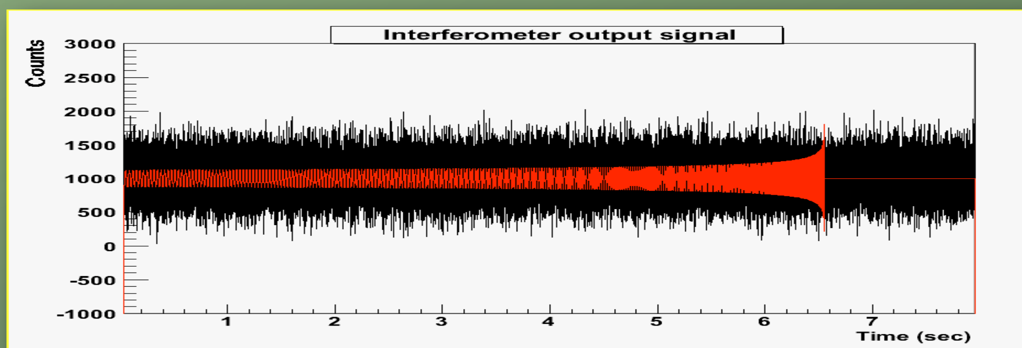
Finding "Triggers"



Matched Filtering

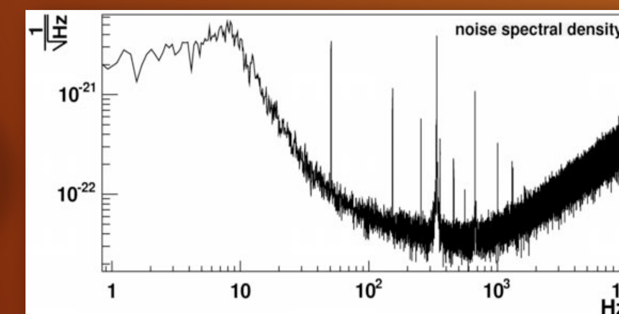
Data

$$\tilde{d}(f) = \tilde{n}(f) + \tilde{s}(f)$$

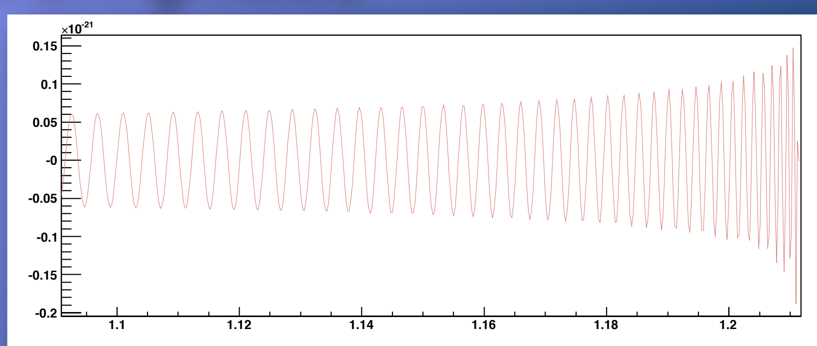


Noise spectral density

$$S_n(f)$$



Template $\tilde{h}(f)$



$$z = \langle d|h \rangle = 4 \int_0^\infty \frac{\tilde{d}(f)^* \tilde{h}(f)}{S_n(f)} df$$

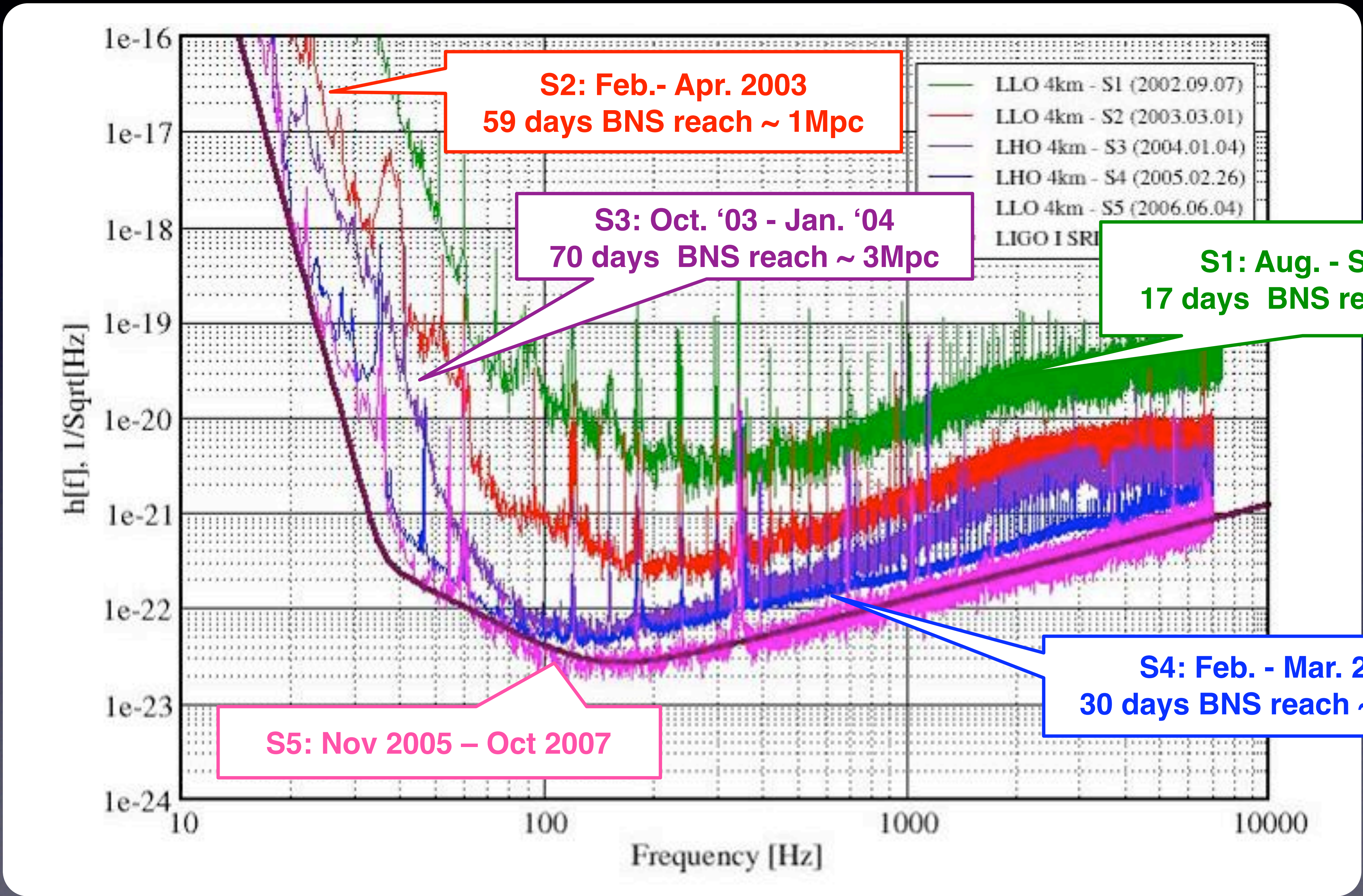
Template normalization:

$$\sigma^2 = \langle h|h \rangle = 4 \int_0^\infty \frac{\tilde{h}(f)^* \tilde{h}(f)}{S_n(f)} df$$

SNR

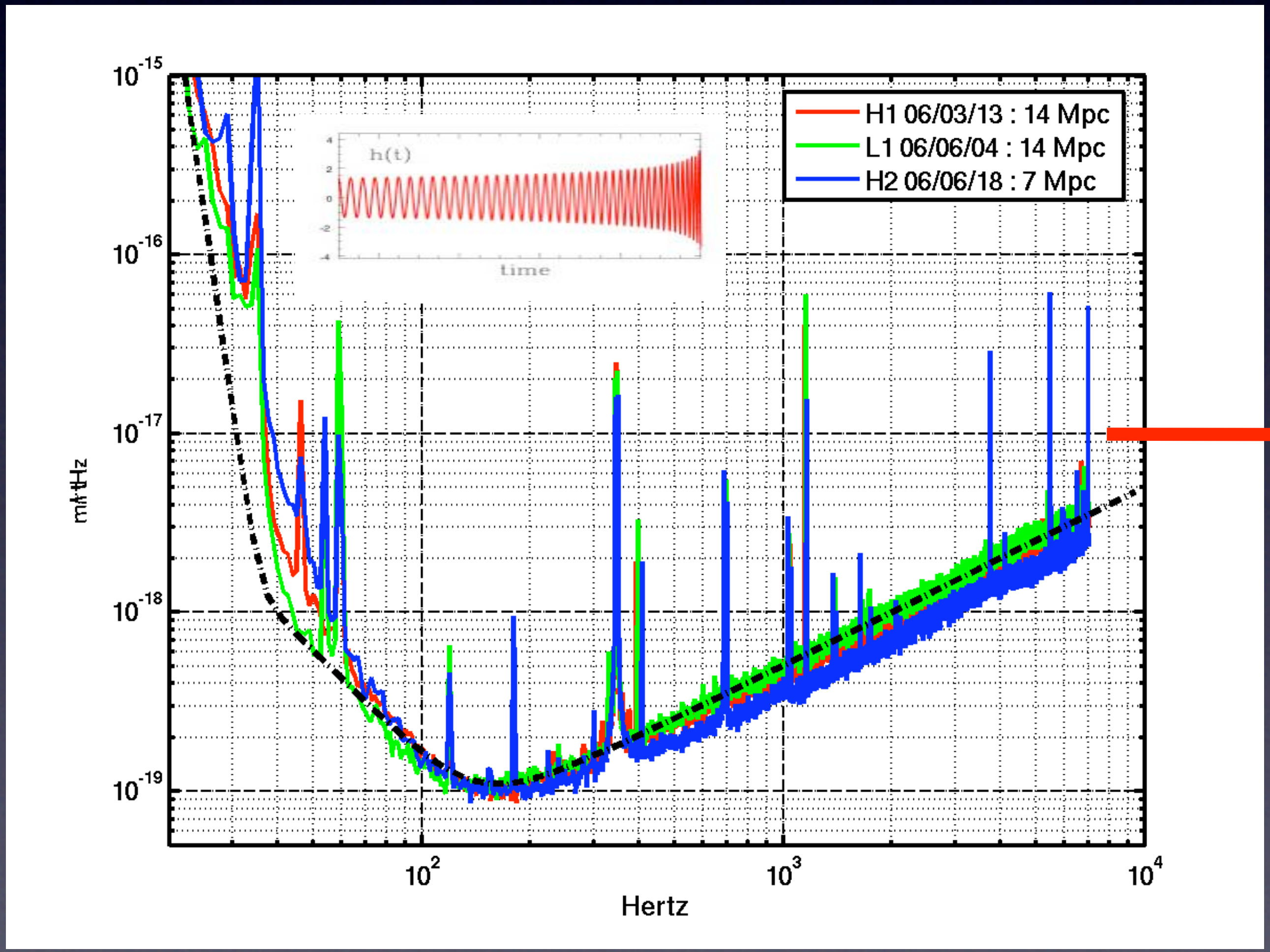
$$\rho = \frac{|z|}{\sigma}$$

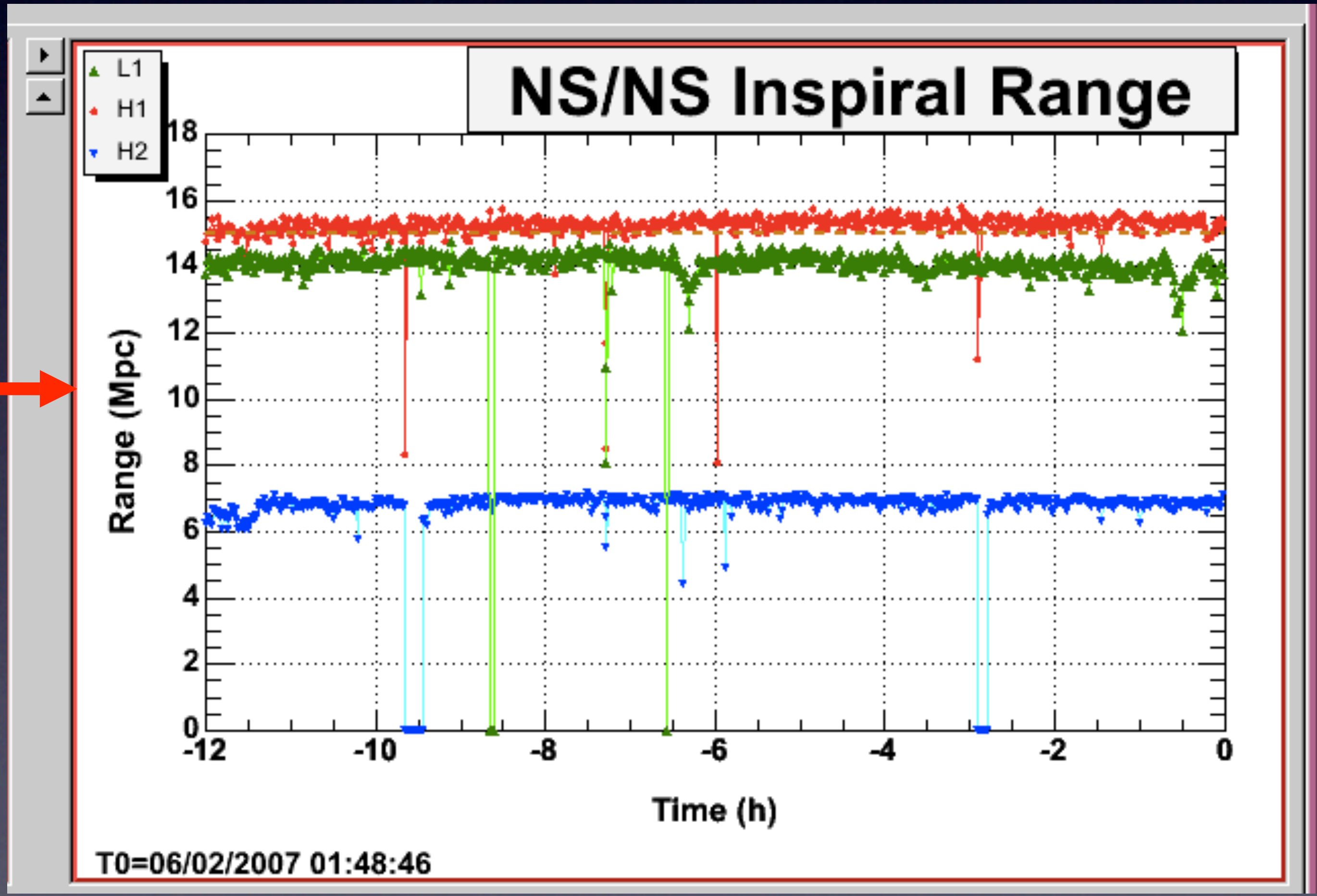
LIGO Noise Evolution



Binary Neutron Stars (BNS): a Measure of Performance

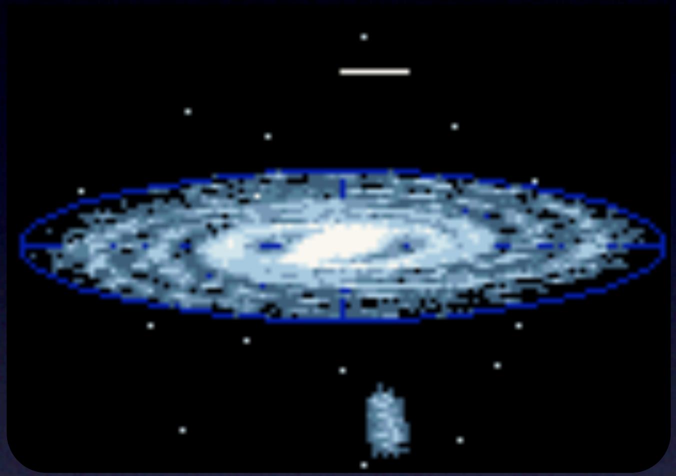
The inspiral waveform for BNS is known analytically (post-Newtonian approximations). We can translate strain amplitude into (effective) distance.





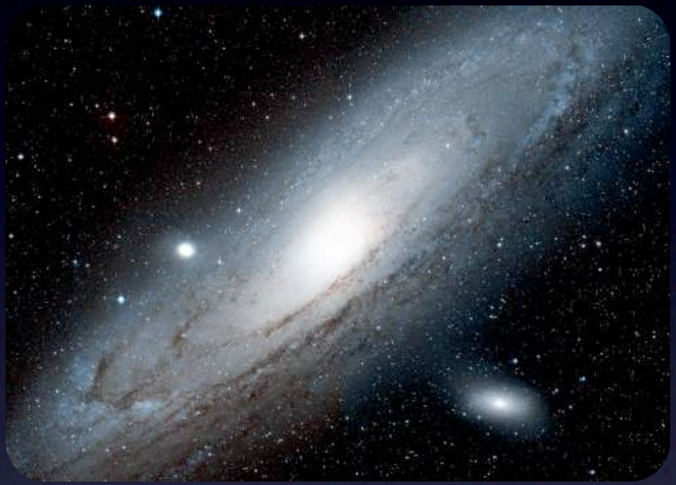
Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization
Predicted rate for S5: 1/3 years (most optimistic), 1/100 years (most likely)

Reach for Binary Neutron Stars



Milky Way
(8.5 kpc)

Sept 2002
[~1 galaxy]



Andromeda
(700 kpc)

March 2003
[~2 galaxies]

Virgo Cluster
(15 Mpc)

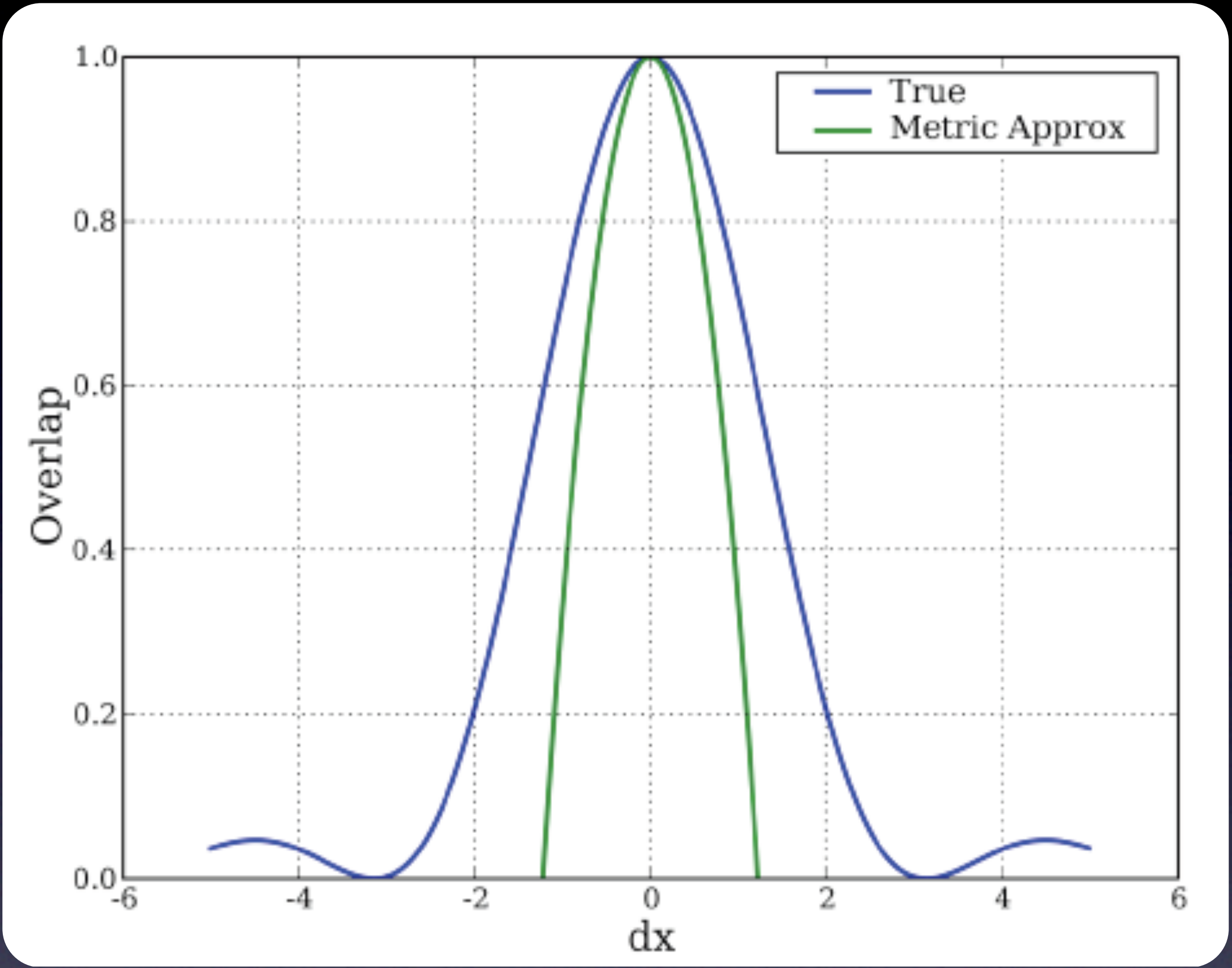
2005-2007
[~10^3 galaxies]

1 light year = 9.5×10^{12} km
1 pc = 30.8×10^{12} km = 3.26 light years

Challenges:

1. Need to search over a wide parameter space
   - Binary components mass from 1 to 20 $M_\odot$
   - Cover spin space
   - Search 1 year of data (~ 20TB)
2. Detector data is non-gaussian
   - false alarms

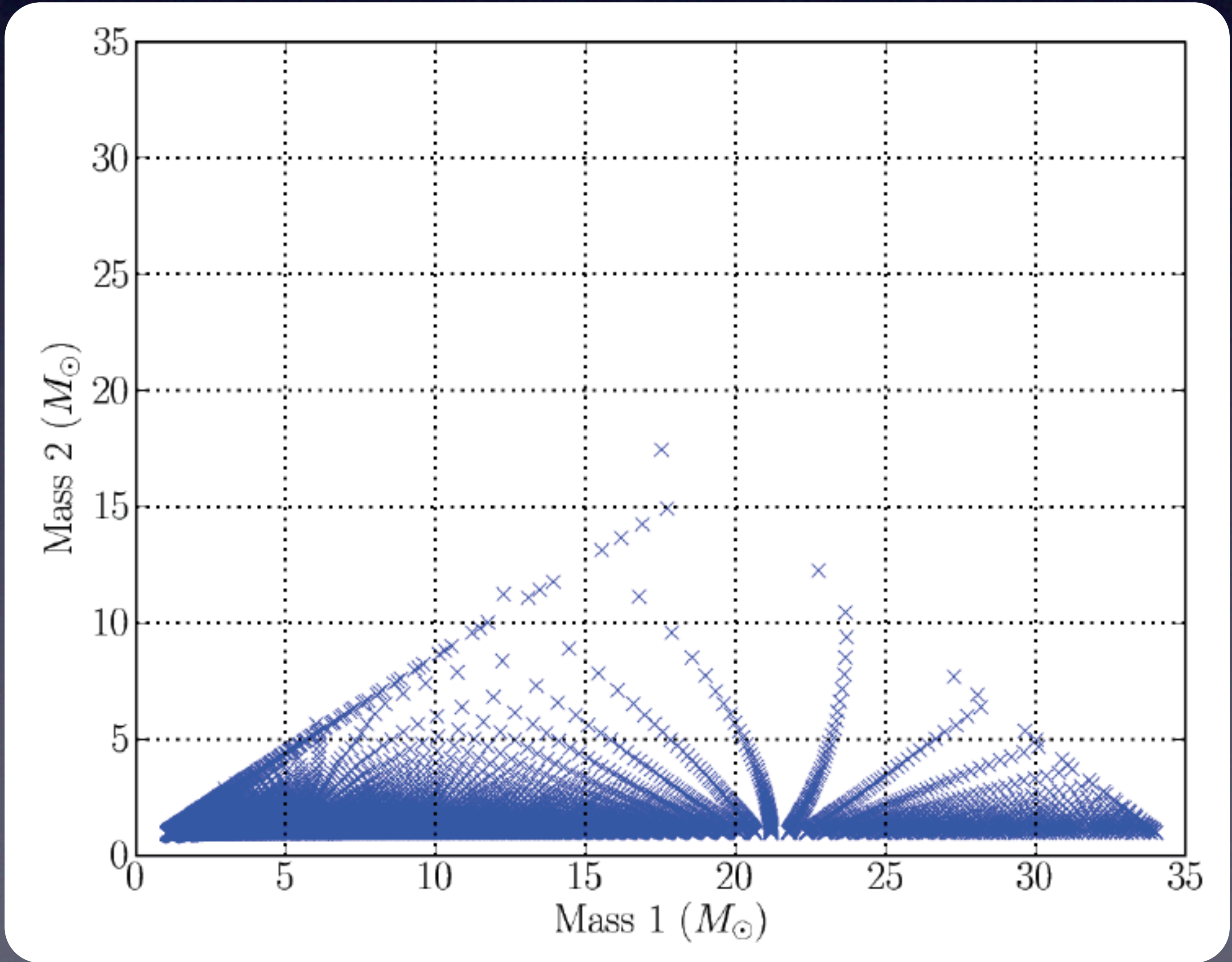
Searching the Parameter Space



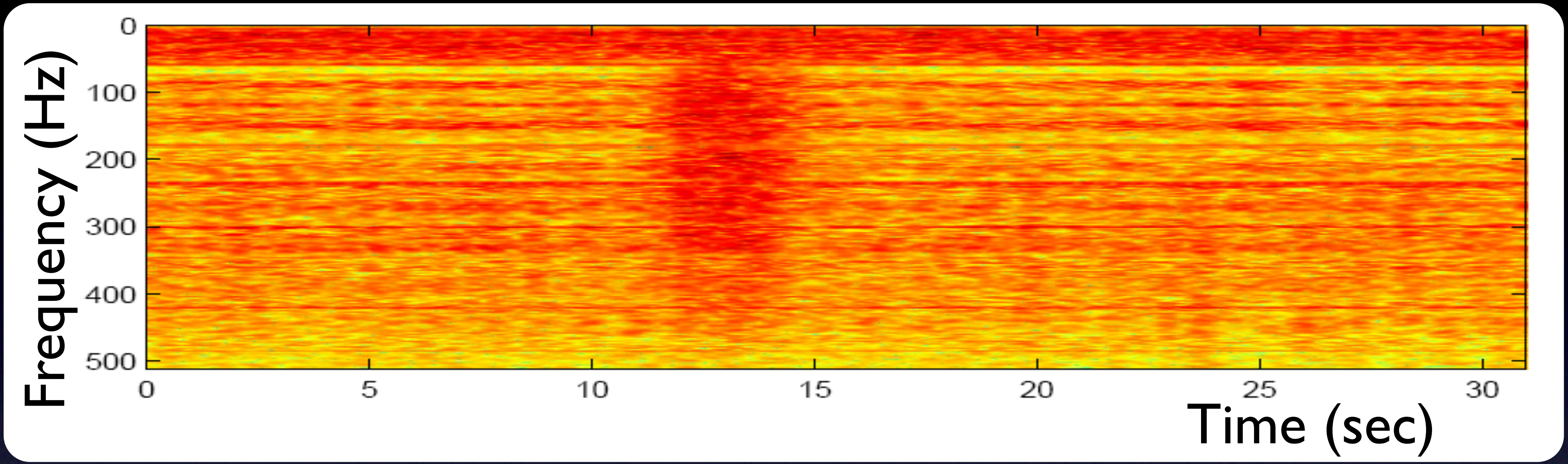
Define a metric
on the parameter space

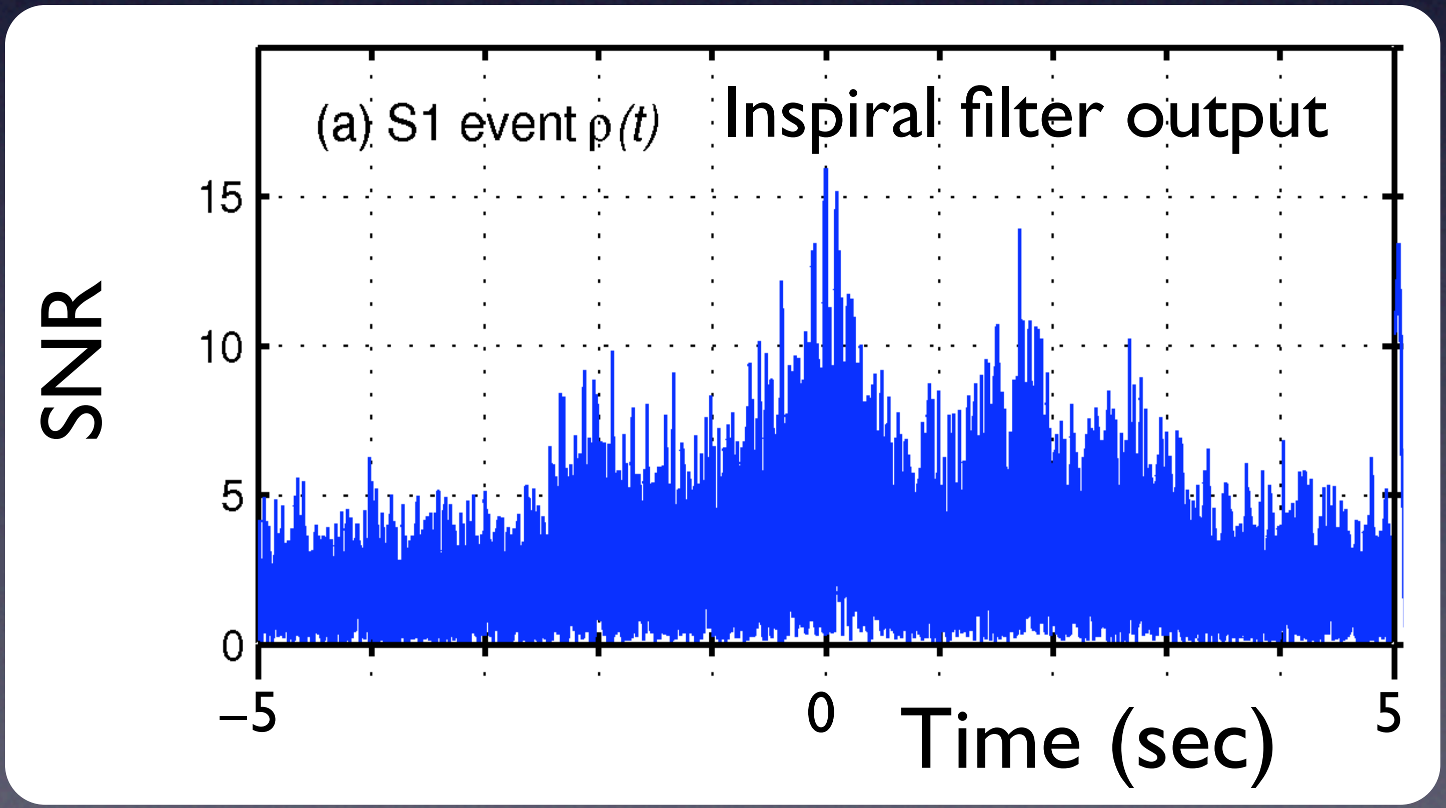
$$\frac{< h(\mathbf{x})|h(\mathbf{x}+\mathbf{dx}) >}{|h(\mathbf{x})||h(\mathbf{x}+\mathbf{dx})|} = 1 - g_{ab}(\mathbf{x})dx^a dx^b$$

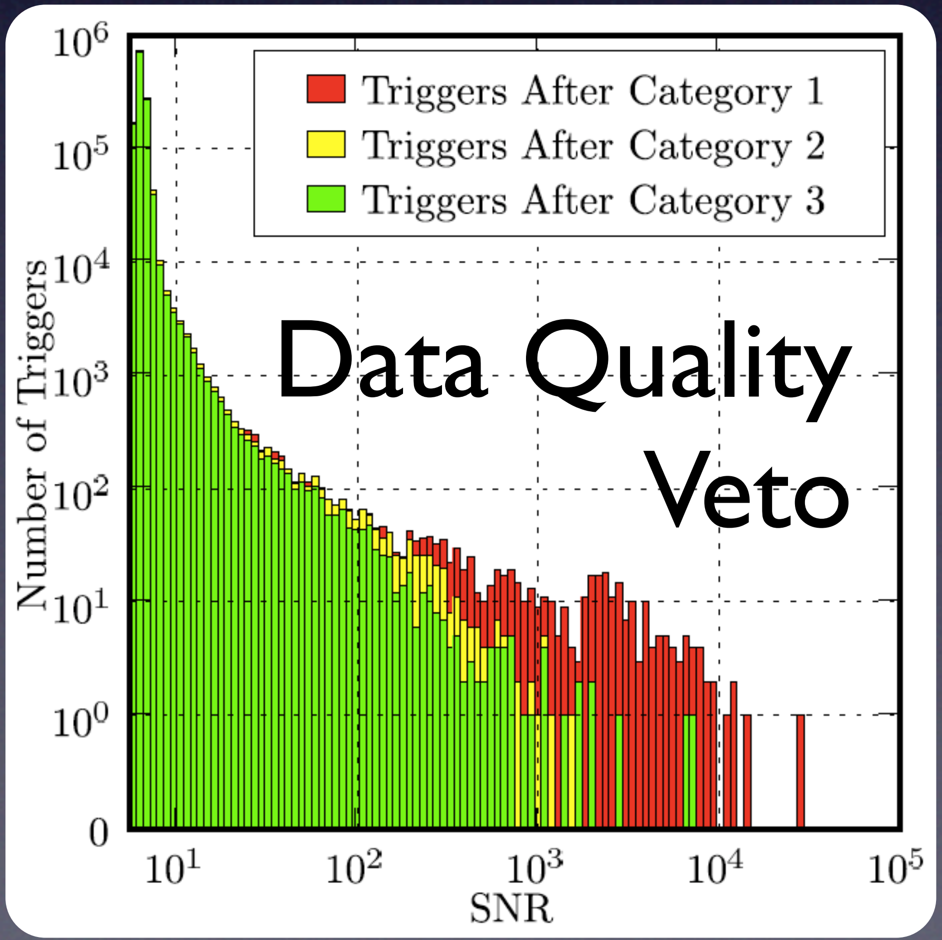
Place a grid of templates such that no more than 3% of the signal is lost



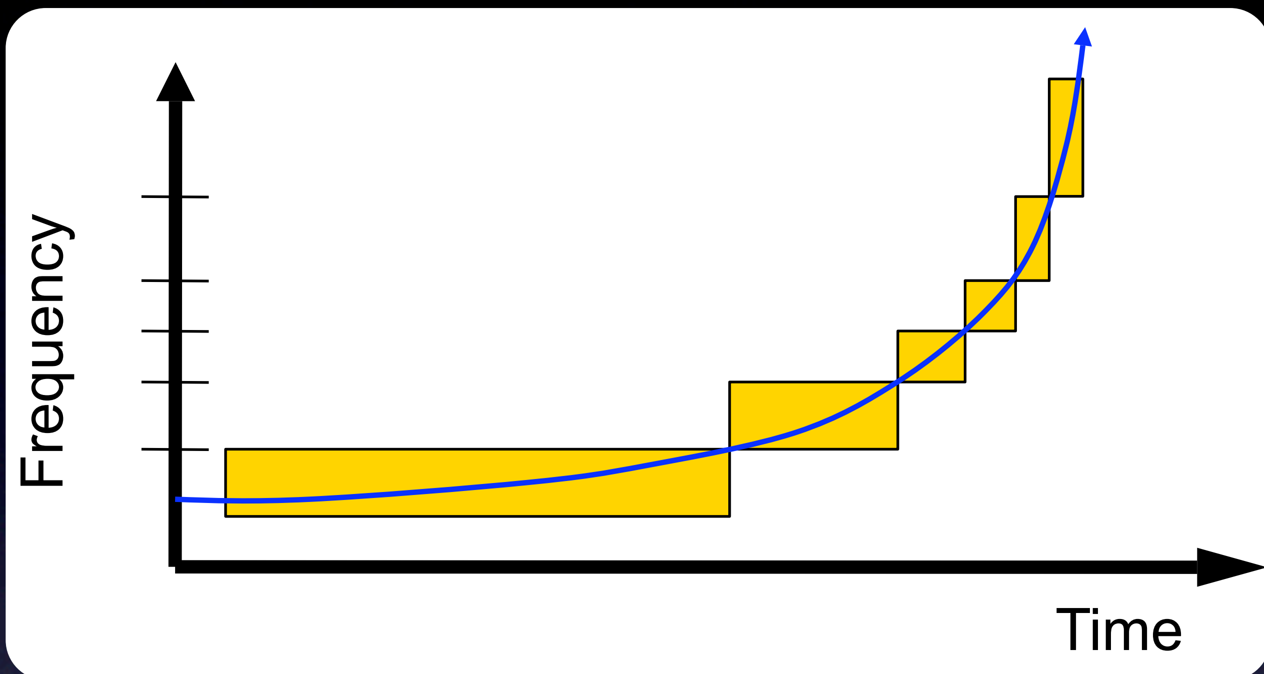
Dealing with Non-Stationary Noise







χ^2 test and effective SNR

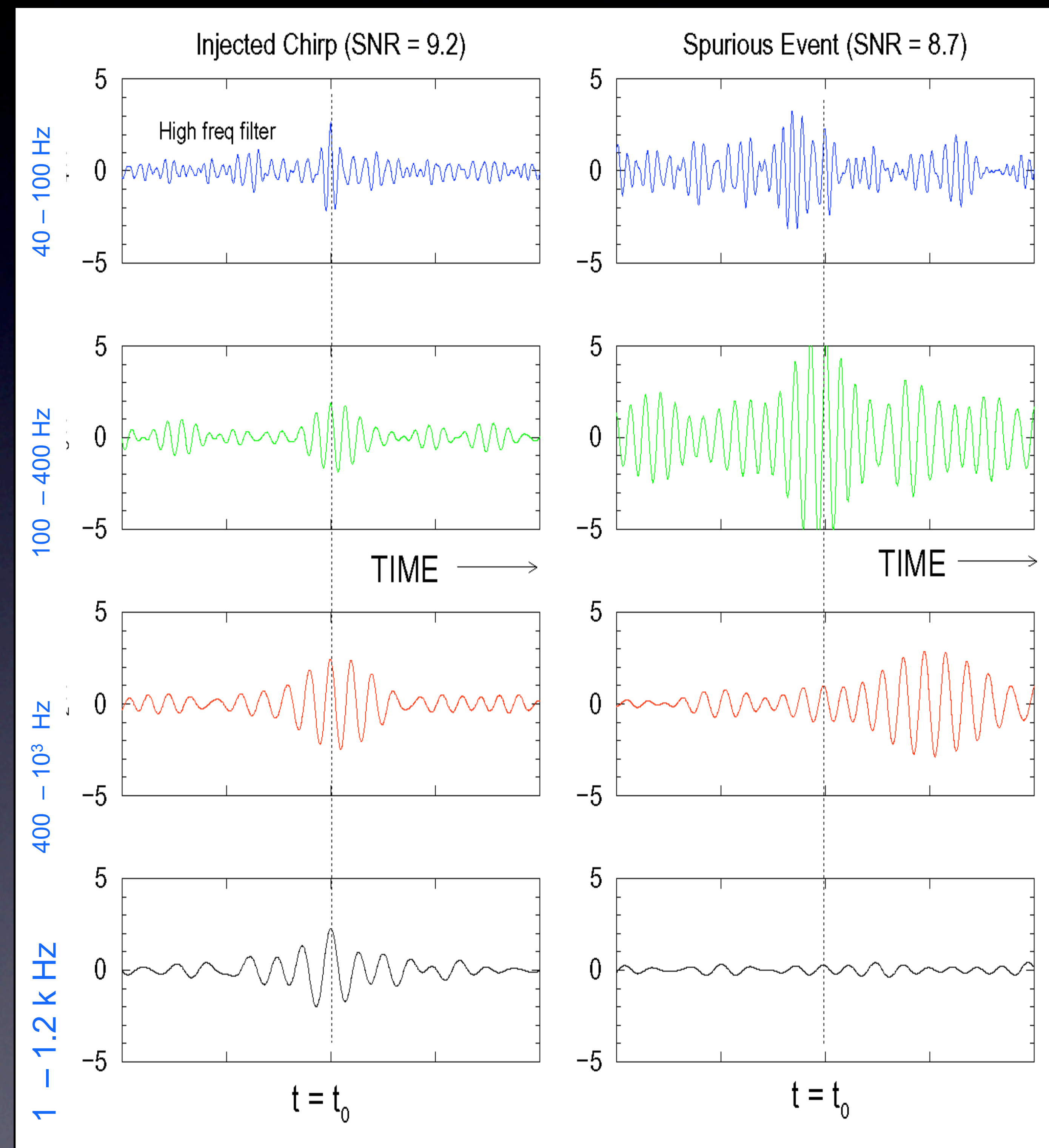


Divide template into p bands,

compute $z_l(t)$ in each band

$$\chi^2(t) = p \sum_{l=1}^{p} \left\| z_l(t) - z(t)/p \right\|^2$$

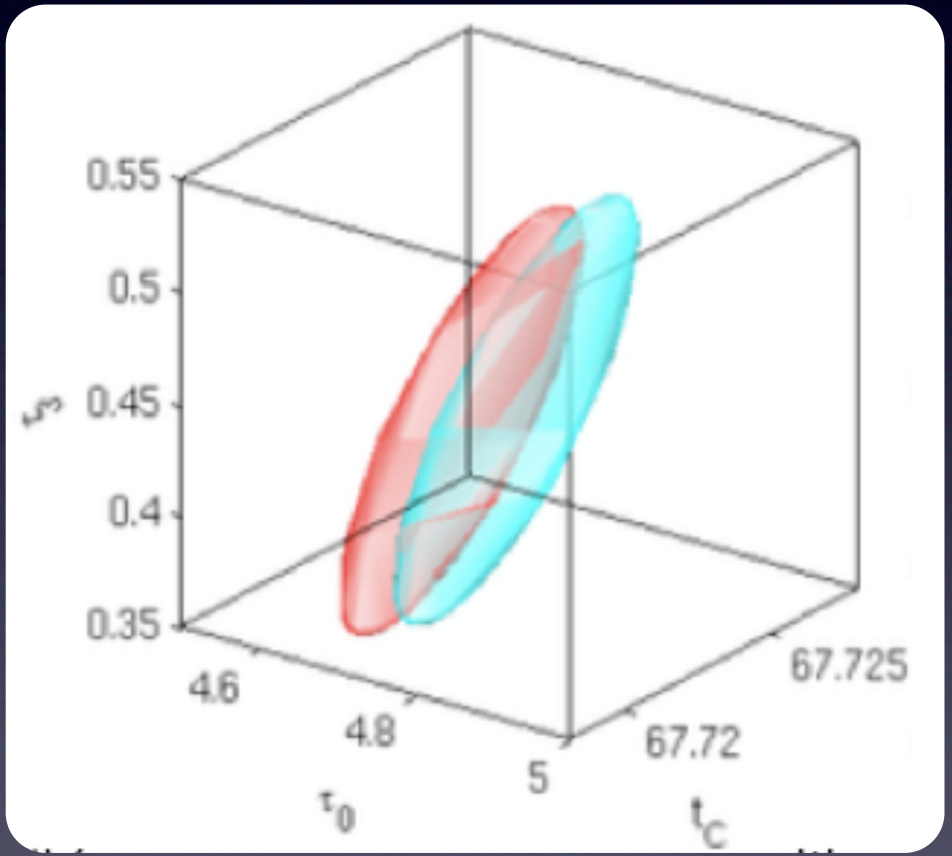
$$\rho_{\rm eff}^2 = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{2p-2}\right)\left(1+\frac{\rho^2}{250}\right)}},$$



Coincidence

Require at least two detectors, "similar" parameters (according to the template metric)

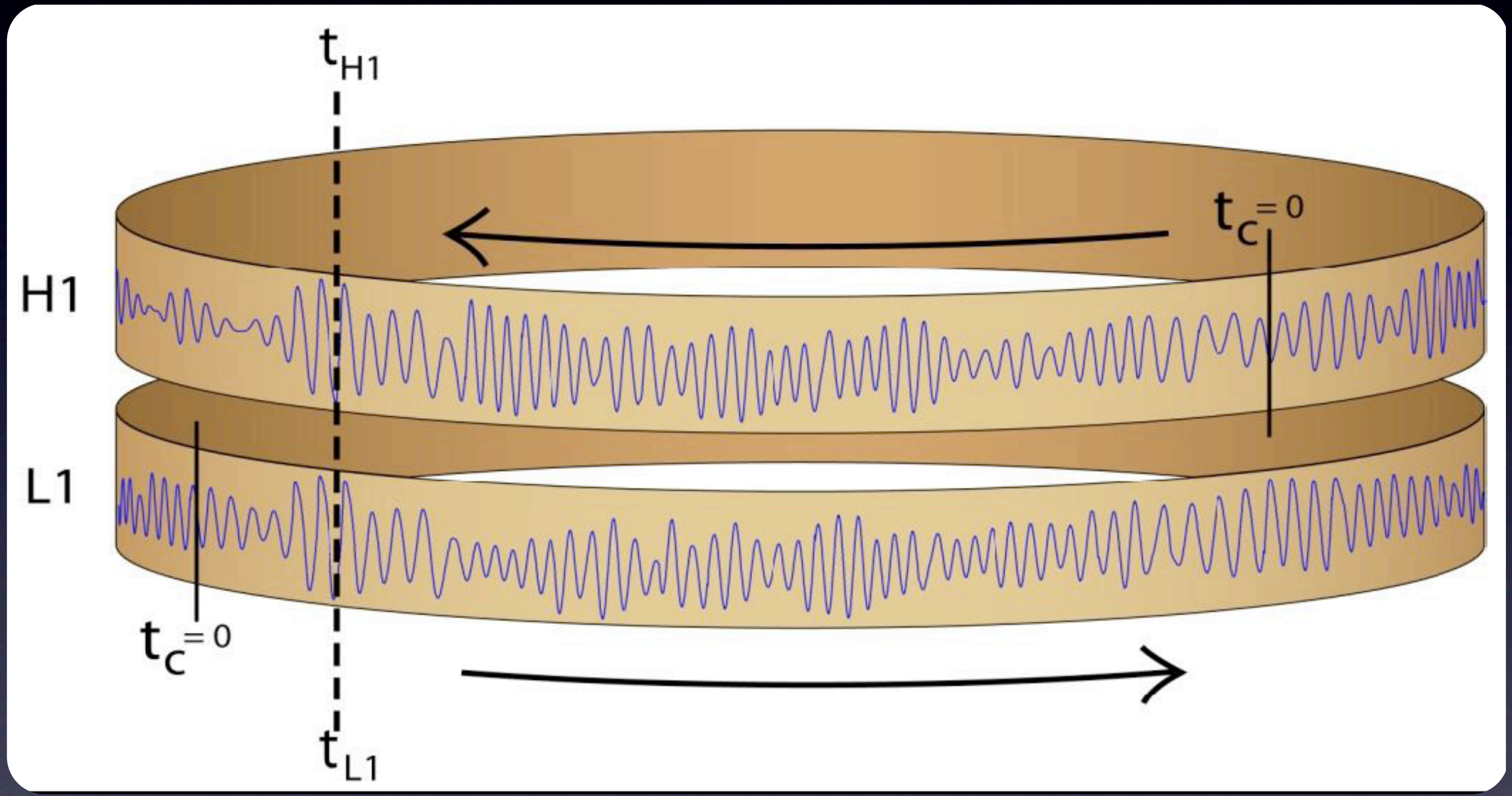
- Reduce false alarms due to environmental/detector noise
- Naturally account for correlations between parameters by using metric to determine coincidence window



$$\rho_c^2 = \sum_{i=1}^{N} \rho_{\mathrm{eff},i}^2$$

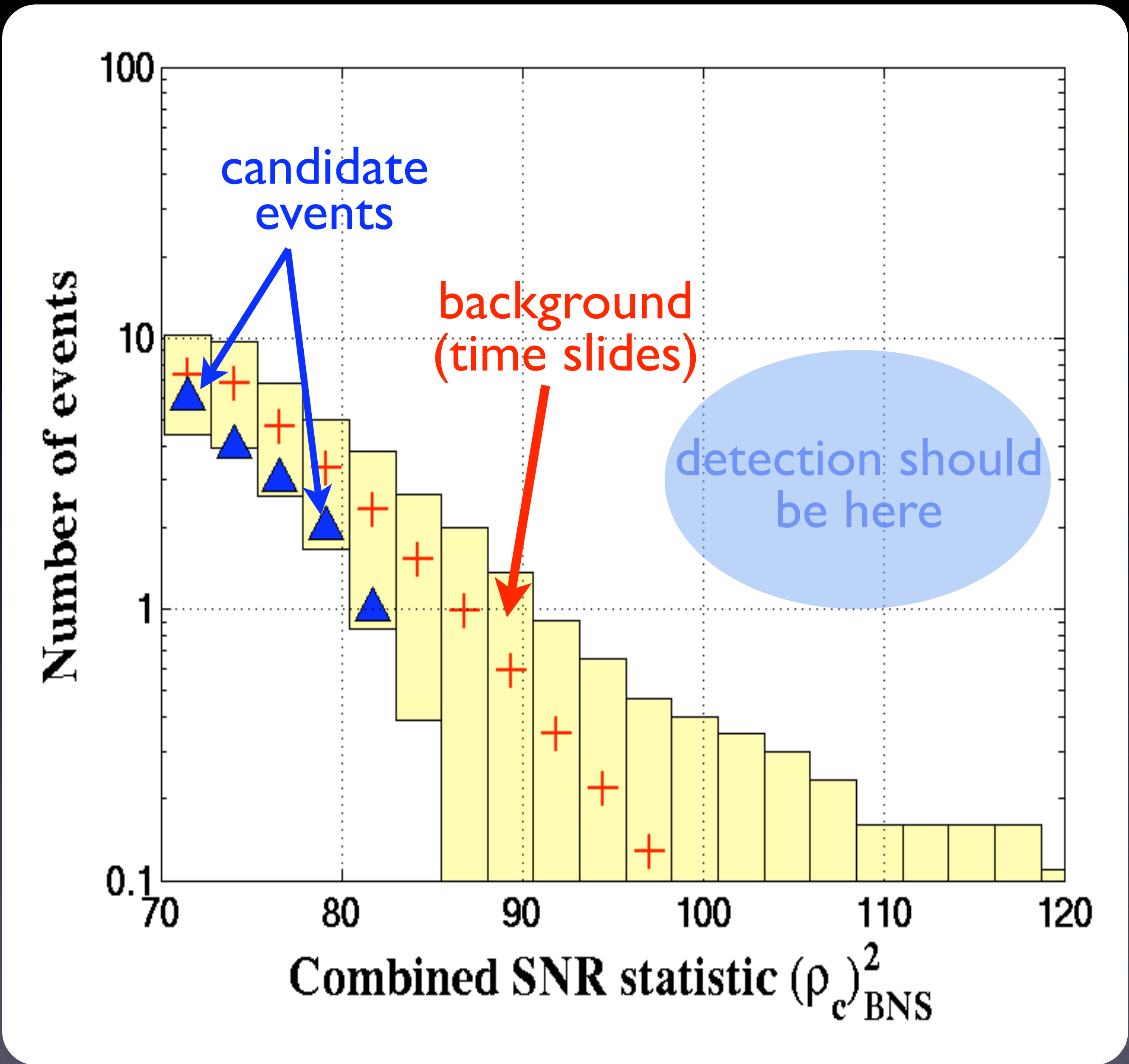
$$\tau_0 = \frac{5}{256\pi f_L \eta}(\pi M f_L)^{-5/3}, \quad \tau_3 = \frac{1}{8 f_L \eta}(\pi M f_L)^{-2/3}$$

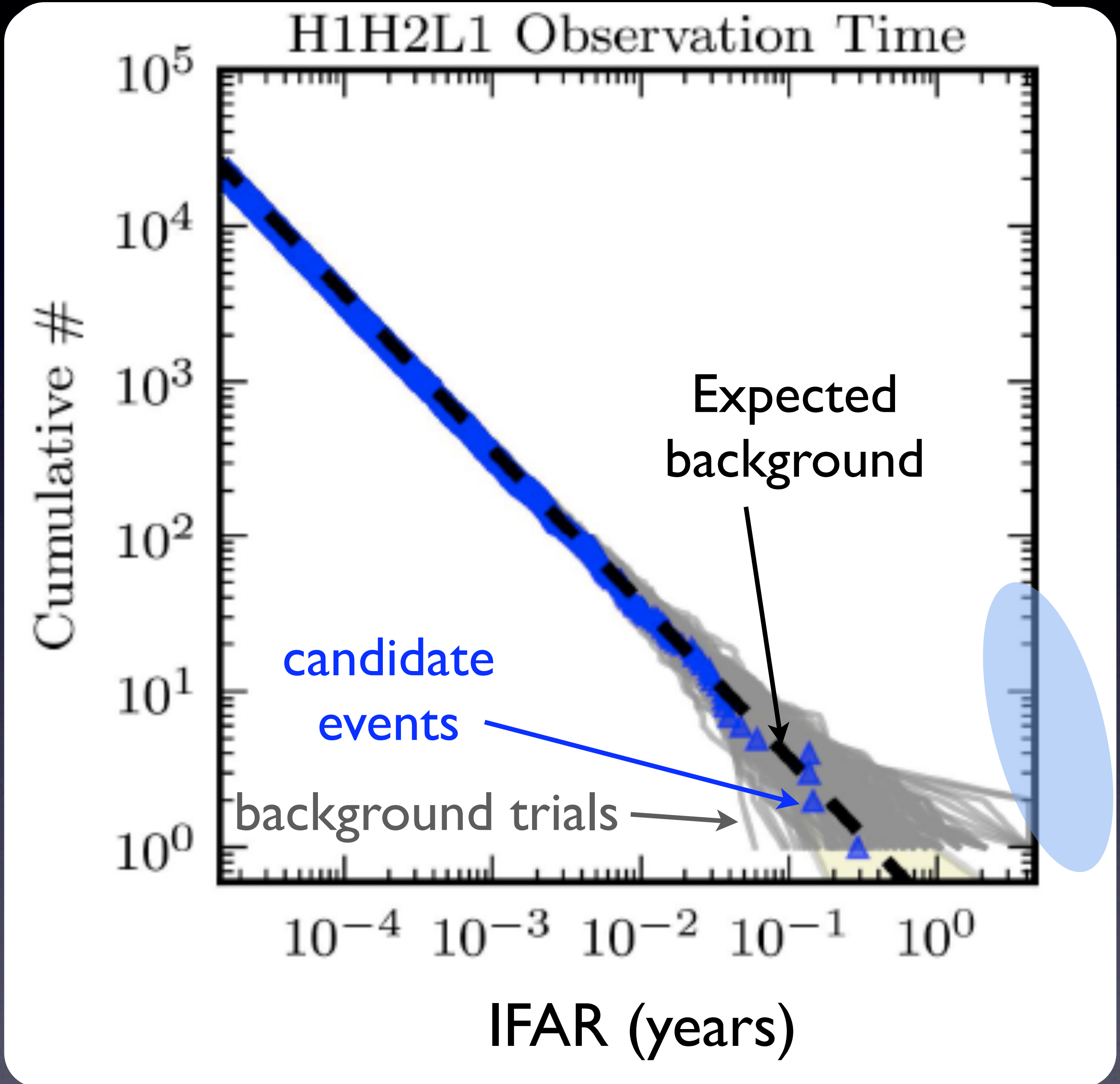
Background



time-slide data from different detectors 100 times,
to estimate false alarms / accidentals

Detection Statistics





S4 run -- PRD 77 (2008) 062002

S5 year 1 -- arXiv:0901.0302

Results

Analyzed data from first 18 months of S5 (arXiv:0901:0302, 0905:3710)

✴ **No GW candidates: set upper limits**

✴ Binary coalescence rate in a galaxy follows approximately the star formation rate, or blue light luminosity.
If NS is 1.35 $M_{\odot}$ and BH is 5.0 $M_{\odot}$, 90% CL upper limits are:

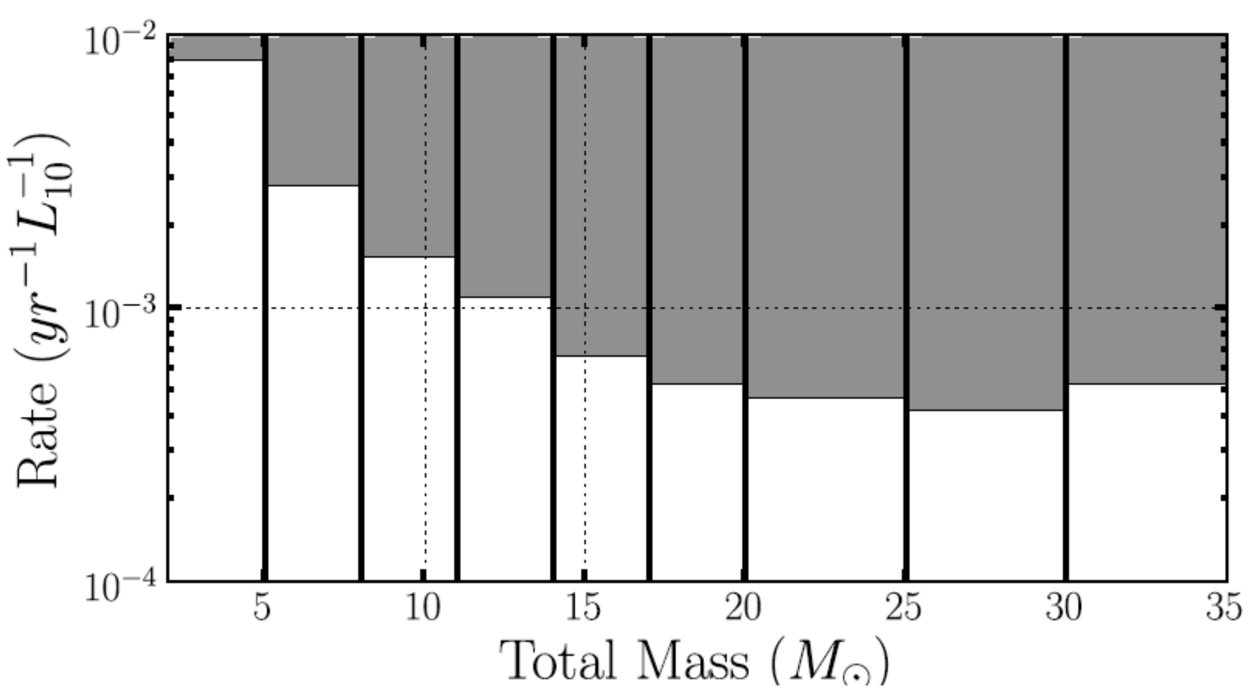
- BNS rate < 1.4 x 10^{-2} / L_{10} / year
- BBH rate < 7.3 x 10^{-4} / L_{10} / year
- BHNS rate < 3.6 x 10^{-3} / L_{10} / year

$L_{10} = 10^{10} L_{\odot,B}$
(Milky Way = 1.7 L_{10})

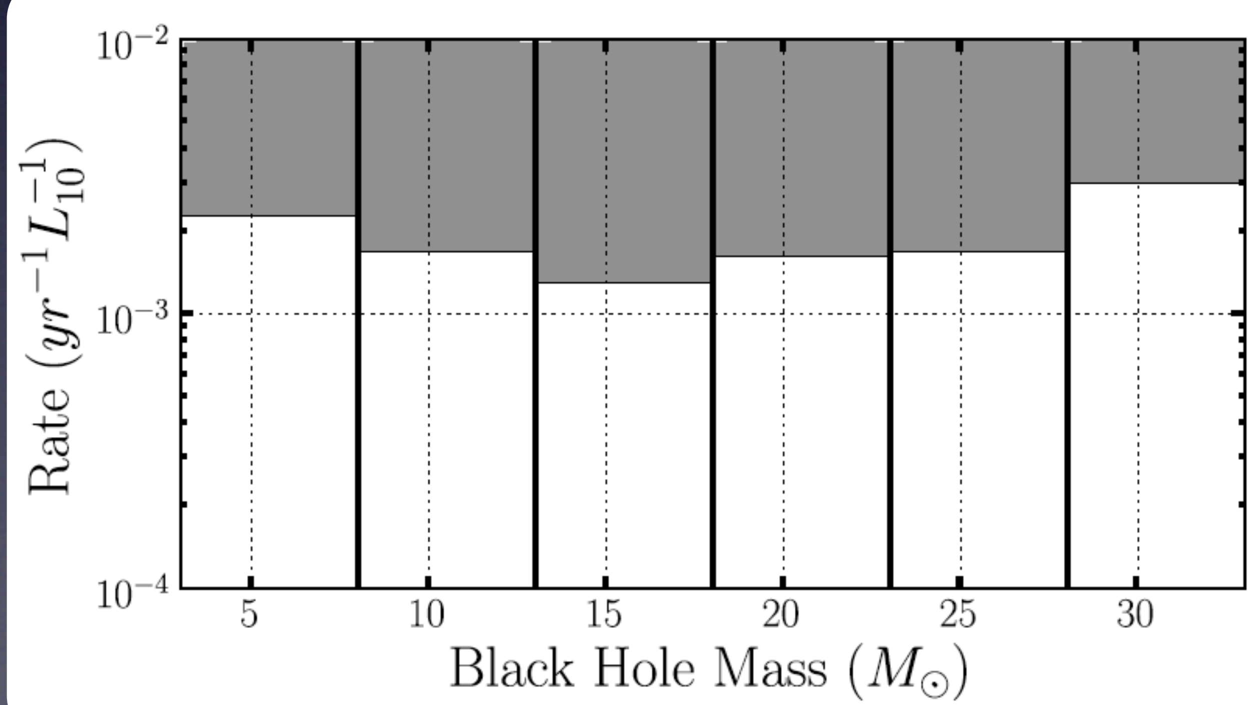
These results are 1 to 2 orders of magnitude above optimistic astrophysical predictions, ~3 orders of magnitude above best estimates.

Component Masses ($M_\odot$)	1.35/1.35	5.0/5.0	5.0/1.35
$D_{\rm horizon}$ (Mpc)	~ 30	~ 100	~ 60
Cumulative Luminosity (L_{10})	490	11000	2100
Non-spinning Upper Limit ($\mathrm{yr}^{-1} L_{10}^{-1}$)	1.4×10^{-2}	7.3×10^{-4}	3.6×10^{-3}
Spinning Upper Limit ($\mathrm{yr}^{-1} L_{10}^{-1}$)	–	9.0×10^{-4}	4.4×10^{-3}

$m_1 = m_2$



$m_1 = 1.35\ M_\odot$



$L_{10} = 10^{10}\ L_{\odot,B}$ (Milky Way = 1.7 L_{10})

arXiv:0905.3710

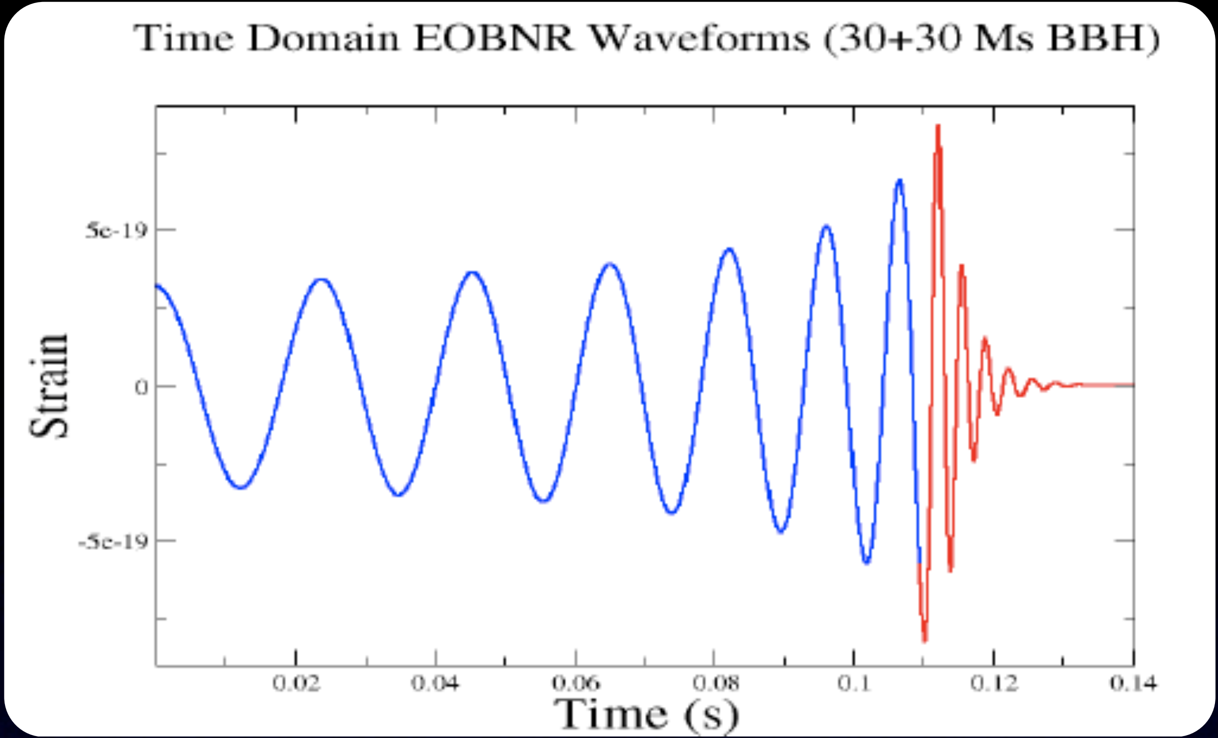
“High” mass

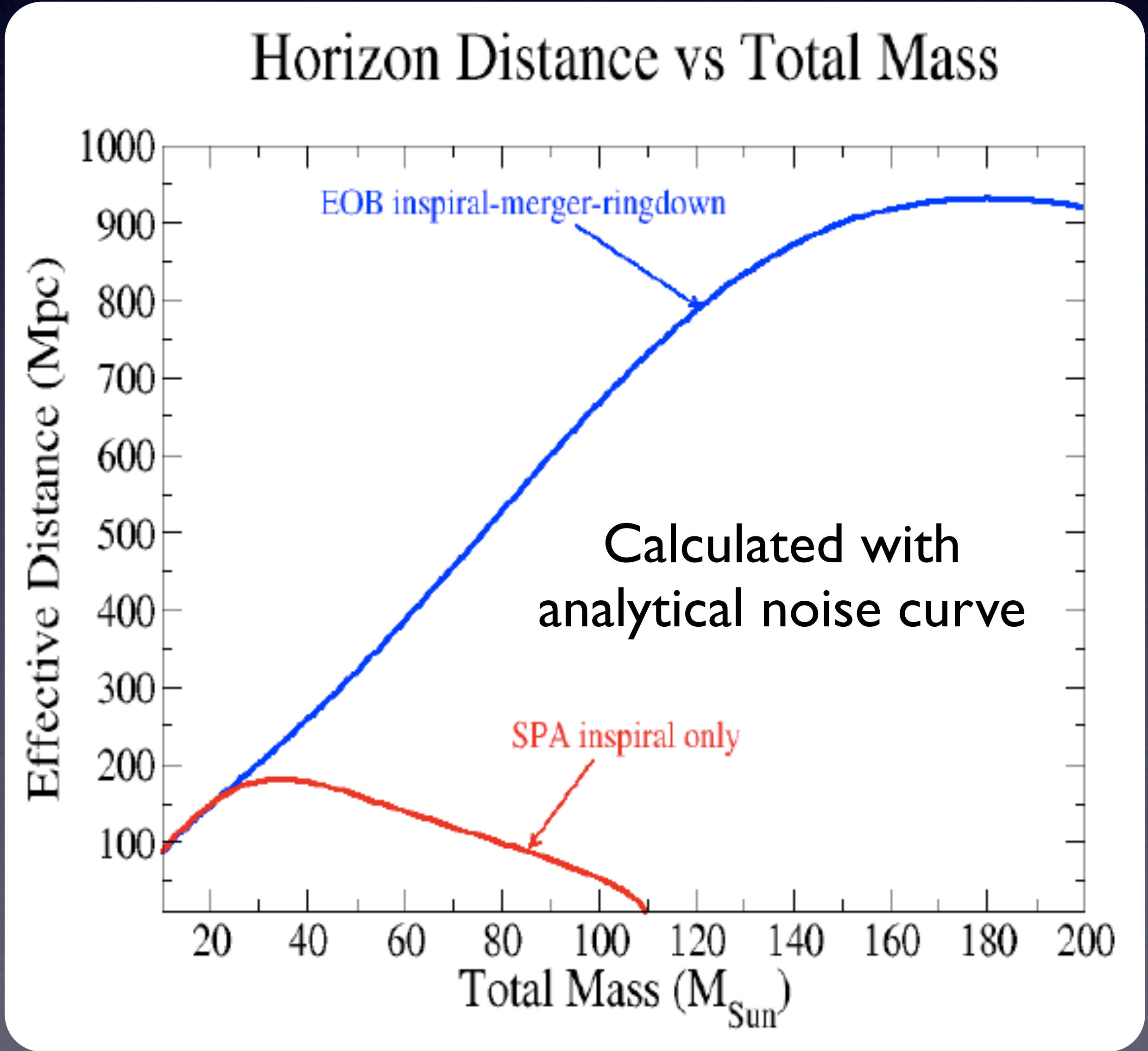
BH-BH and BH-NS

total mass (25-100) $M_\odot$

component mass (1-99) $M_\odot$

- Short signals: merger and ringdown in LIGO band.
- Rate uncertainty: ~0.01-1/MWEG/Myr
- Reach:
  - 10+10 $M_\odot$ detectable to ~125 Mpc (34,000 MWEG)
  - Higher mass detectable to hundreds of Mpc (~100,000s MWEG)





GRB 070201

(ApJ 2008, 681, 1419)

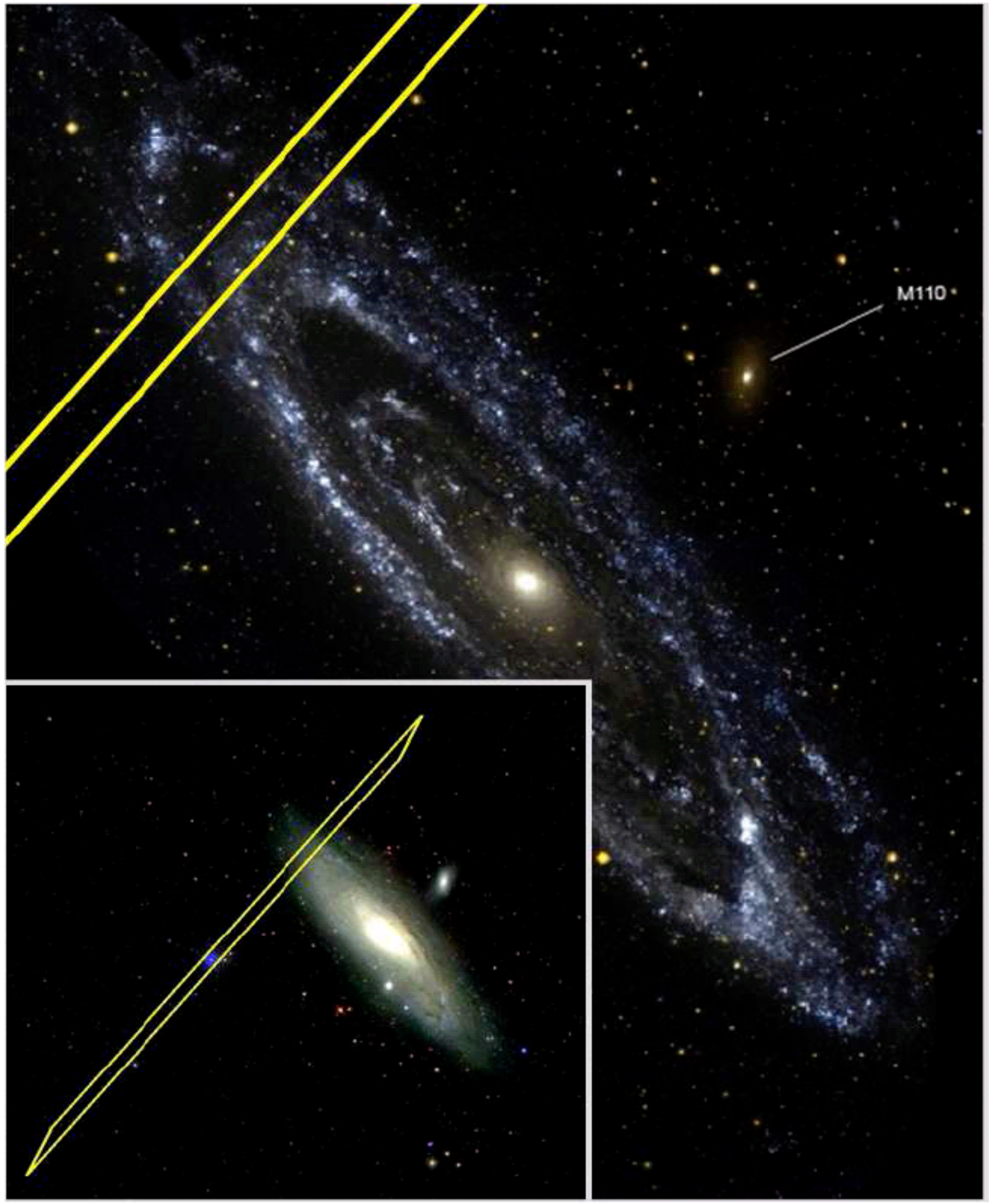


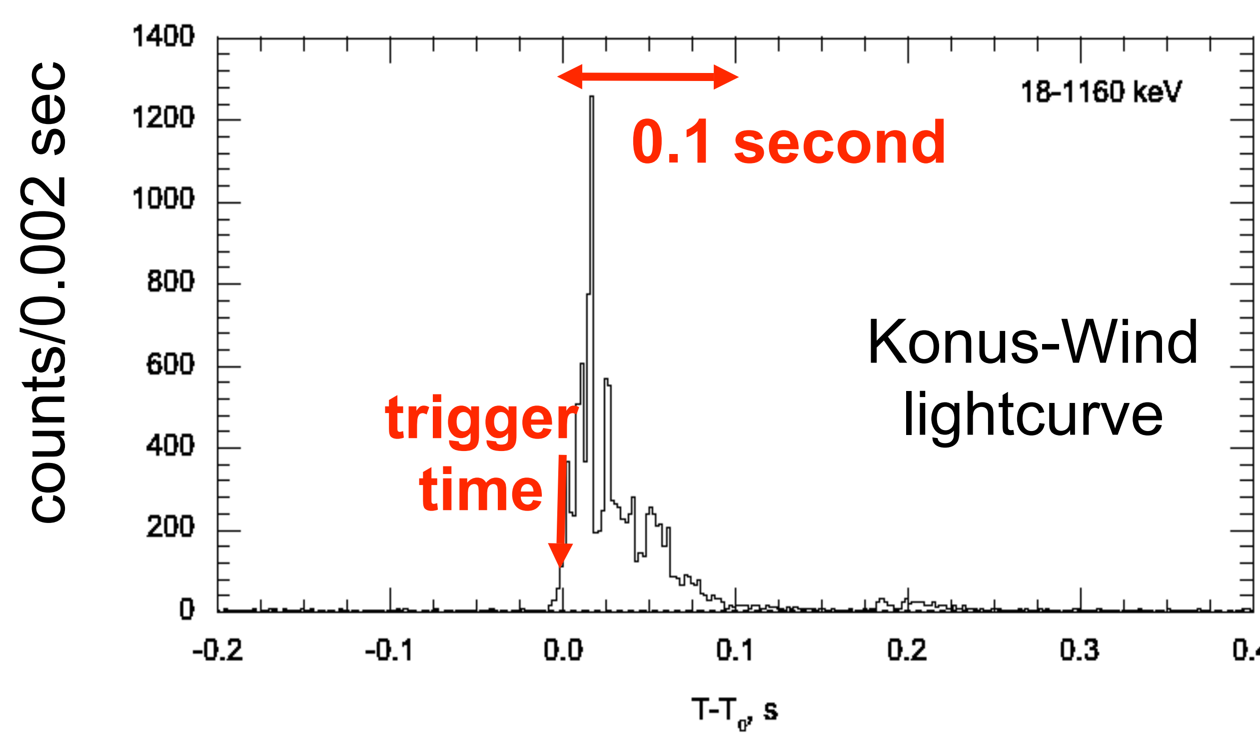
FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main fi gure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

"intense short hard GRB" (GCN 6088)

Duration ~0.15 seconds

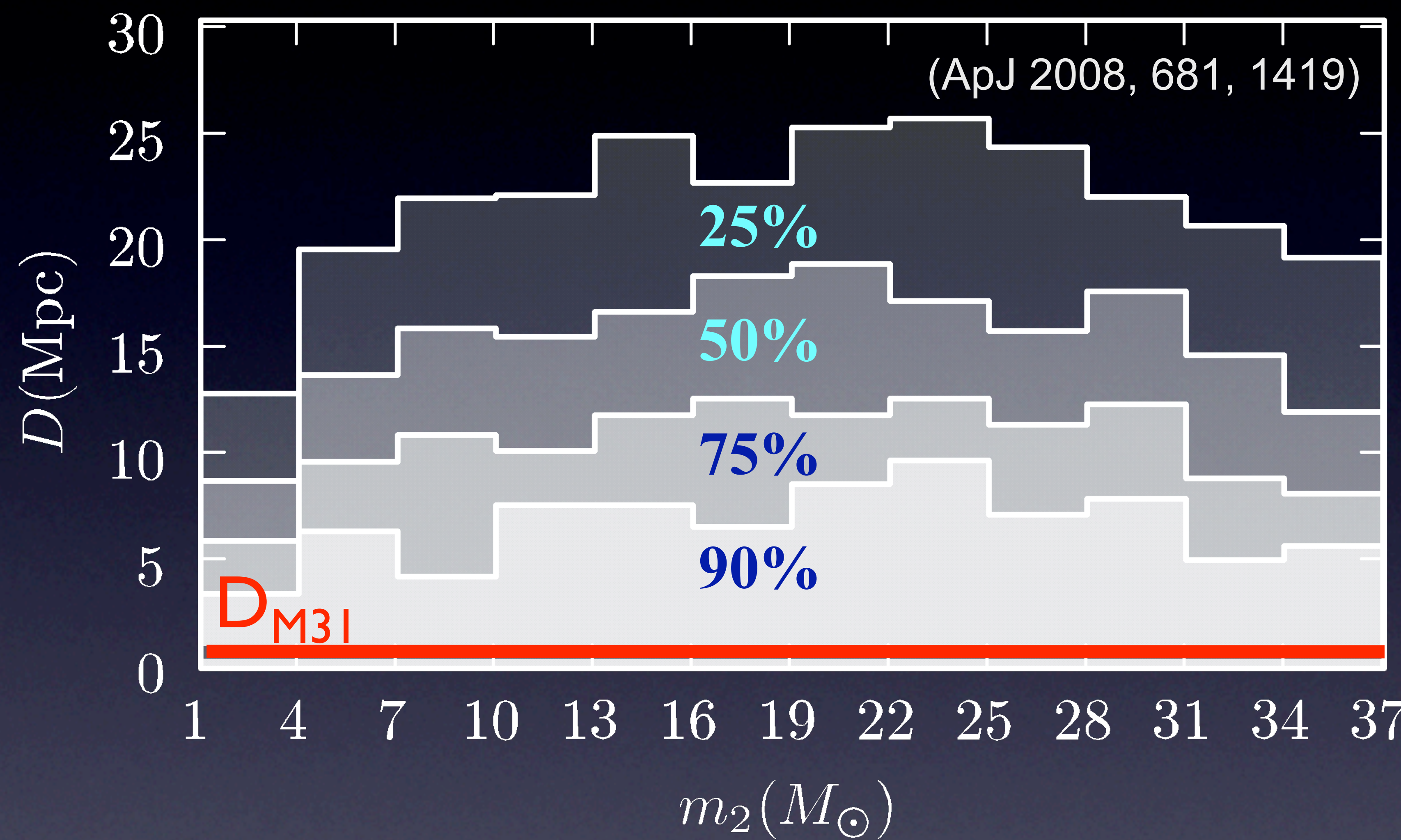
* short GRB whose position error box overlapped with spiral arms of Andromeda galaxy (M31)
* galaxy located at a distance of ~770 kpc
* at the time of GRB, LIGO S5 run was ongoing; the two Hanford interferometers were in science mode
* GRB sky position was not optimal

$$F_{RMS} = \sqrt{F_+^2 + F_\times^2}/\sqrt{2} = 0.304$$



Model Based Compact Binary Inspiral Search 070201

- Analyze 180 s around trigger.
- Few hours before/ after to understand background and detectability, with simulated inspirals
- calculation of probabilities takes into account different properties of inspiralling binary system, e.g. mass, spins, inclination, sky location



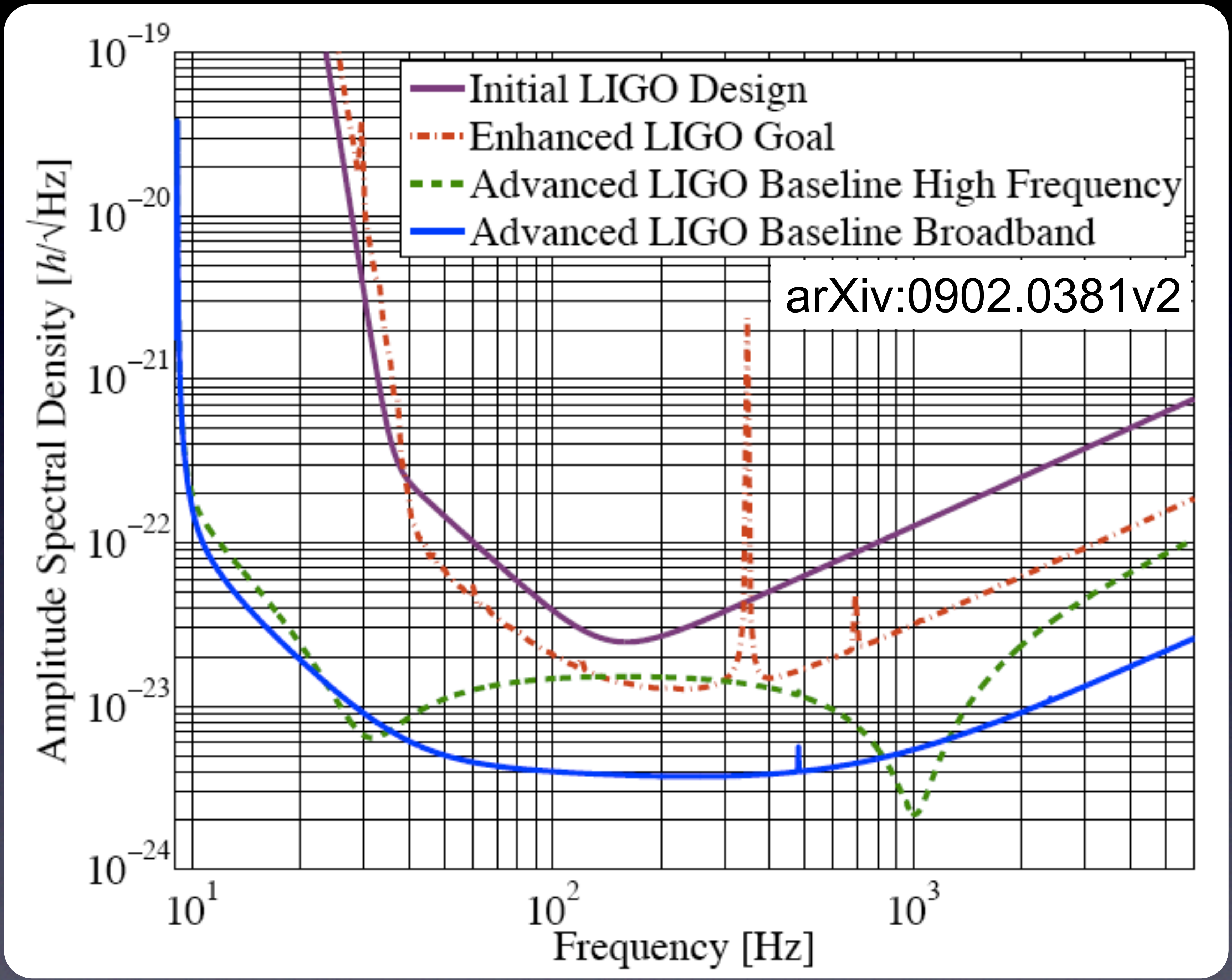
Exclude compact binary progenitor with:

$1\ M_\odot < m_1 < 3\ M_\odot$; $1\ M_\odot < m_2 < 40\ M_\odot$

D < 3.5 Mpc with 90% C.L.

Exclude CBC progenitor in M31 with > 99% C.L.

Advanced LIGO

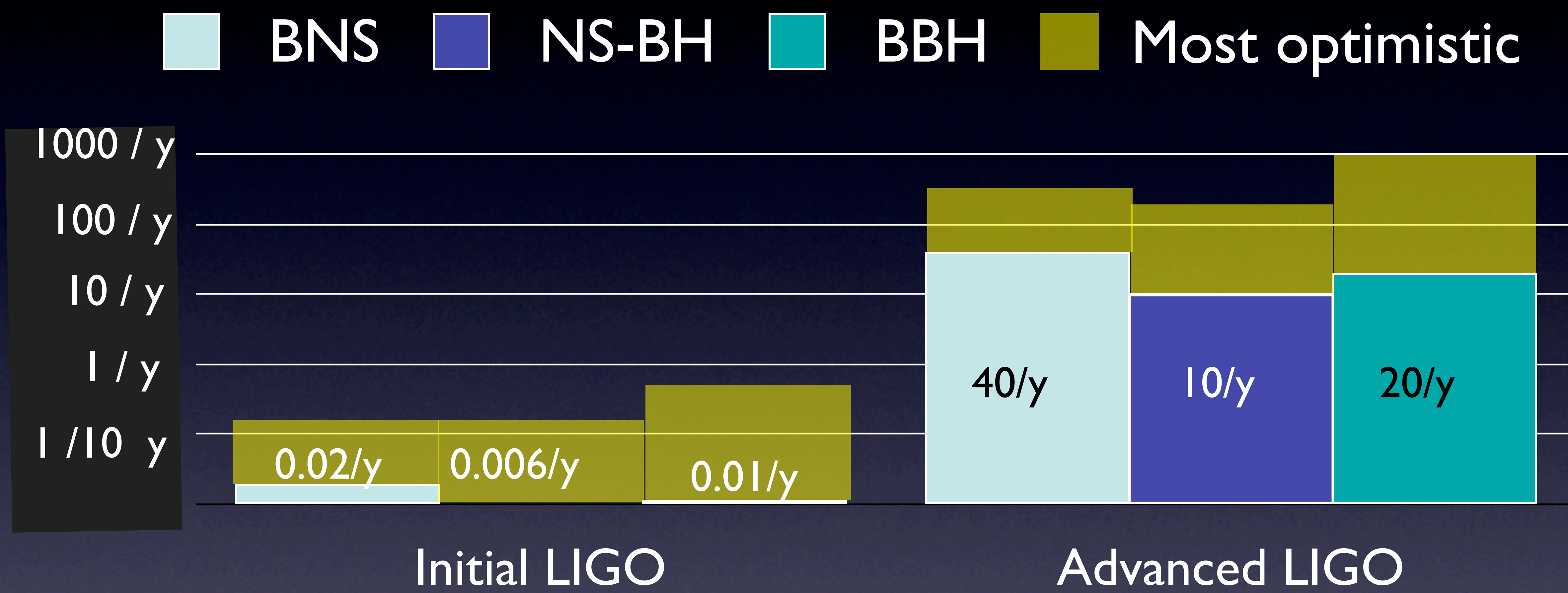


Factor of ~10 in amplitude sensitivity

Factor of ~1000 in volume

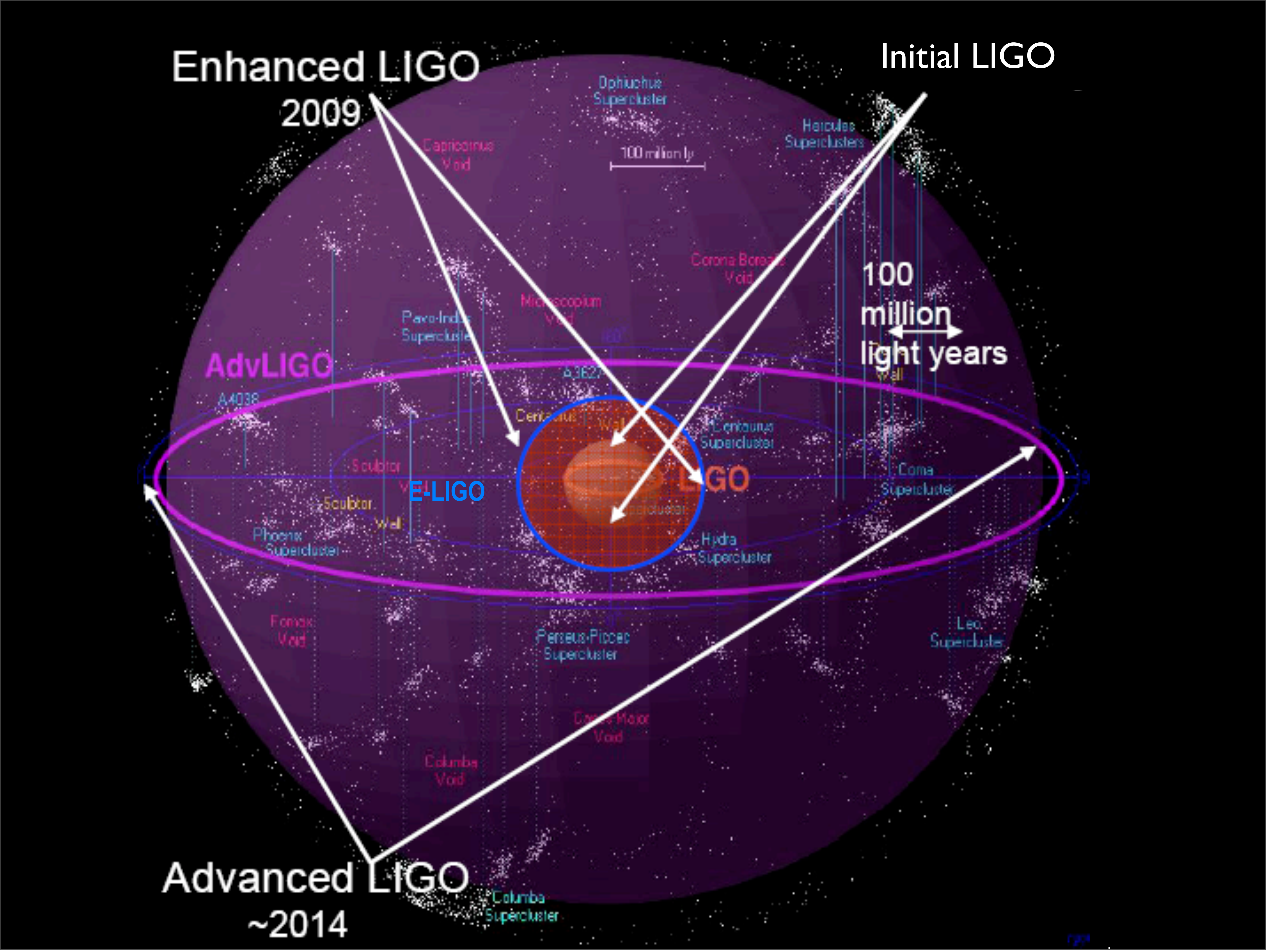
- Advanced LIGO is approved and funded; construction started
- Expect to be operational in 2014 or 2015

Science with Advanced LIGO



Binary neutron star mergers: from ~20 Mpc to ~350 Mpc

Binary black hole mergers: from ~100 Mpc to z=2



Enhanced LIGO
2009
Initial LIGO
Ophiuchus Supercluster
100 million ly
Hercules Superclusters
Capricornus Void
Corona Borealis Void
100 million light years
Pavo-Indus Supercluster
AdvLIGO
A4038
A3627
E-LIGO
Sculptor Void
Sculptor Wall
Phoenix Supercluster
Centaurus Supercluster
Coma Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Columba Void
Columba Supercluster
Advanced LIGO
~2014