A Grand Tour of Gravitational Wave Signals and Detection Methods

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Itinerary

- **Preparing for the trip:**
  Brief review of gravitational waves and detectors
- **Mapping the territory:**
  An overview of gravitational wave signals
- **Driving directions:**
  Signal detection methods
- **Road hazards:**
  Data analysis challenges
- **The road ahead**

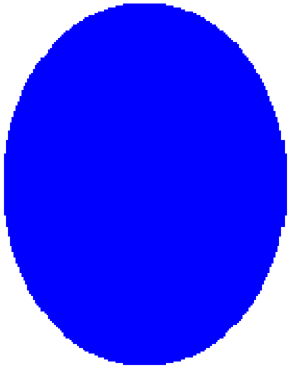
Gravitational Waves

Emitted by a massive object, or group of objects, whose shape or orientation changes rapidly with time

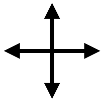
Changes the geometry of space in a time-varying way

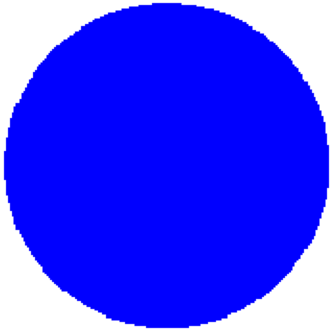
Strength and polarization depend on direction relative to source

Can be a linear combination of polarization components

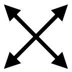


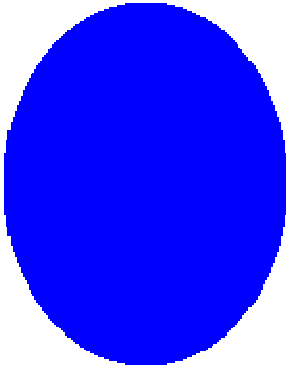
“Plus” polarization



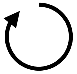


“Cross” polarization





Circular polarization



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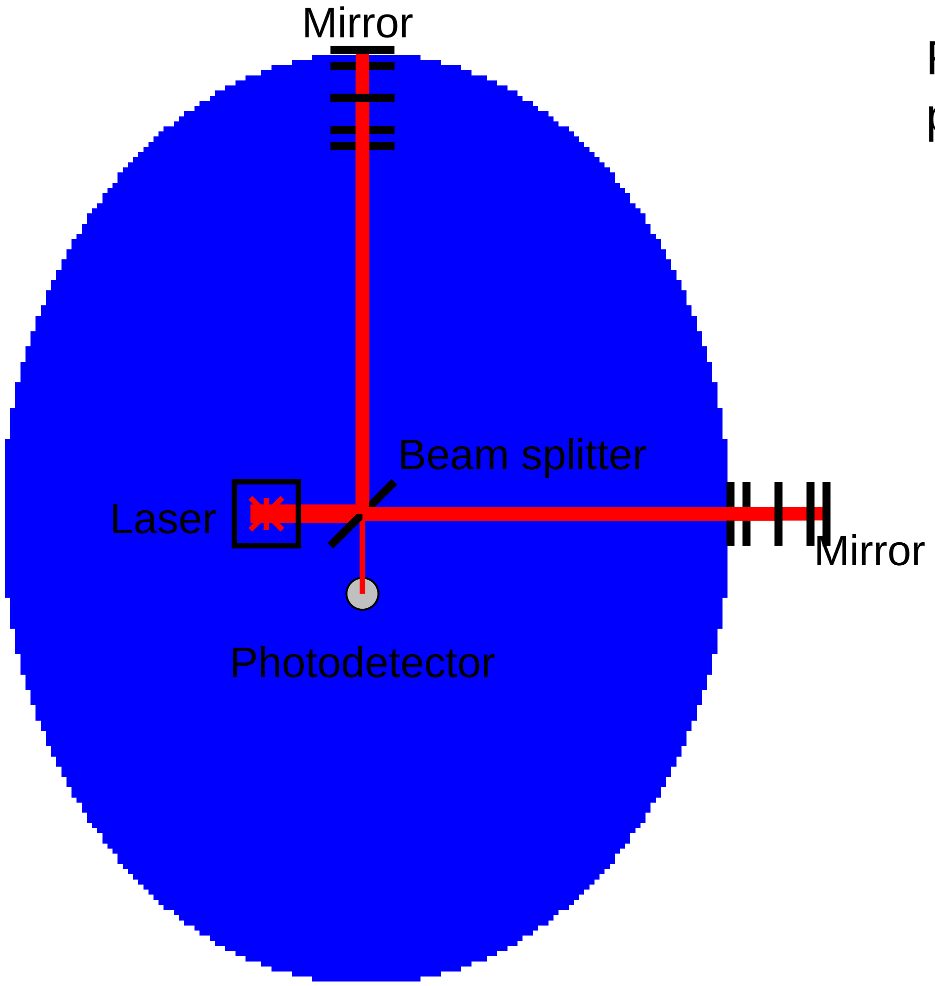
Laser Interferometers

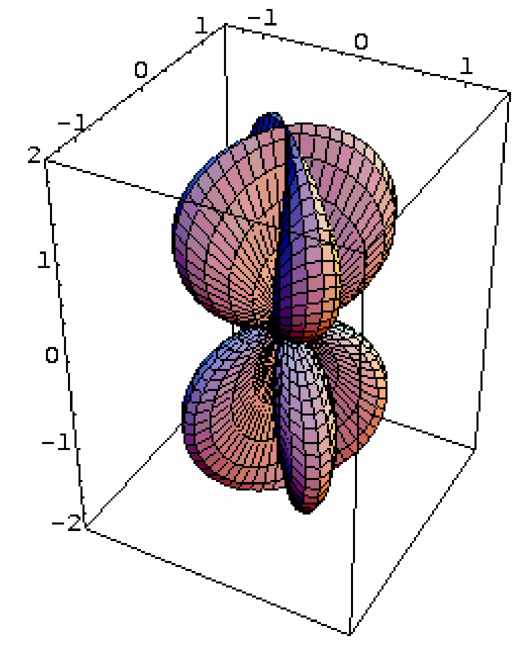
Measure *difference* in arm lengths to a fraction of a wavelength

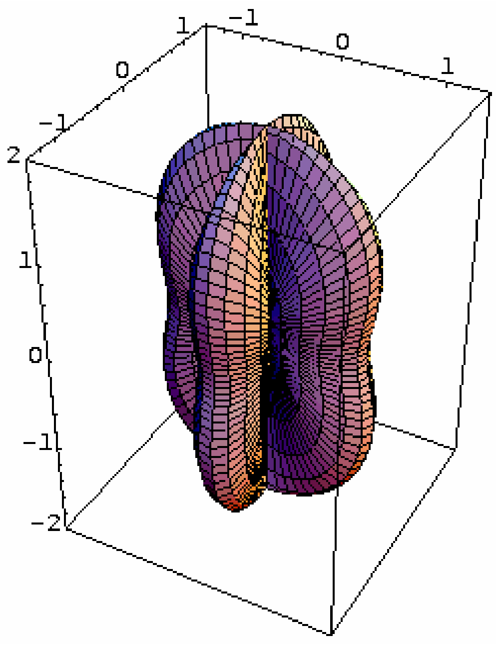


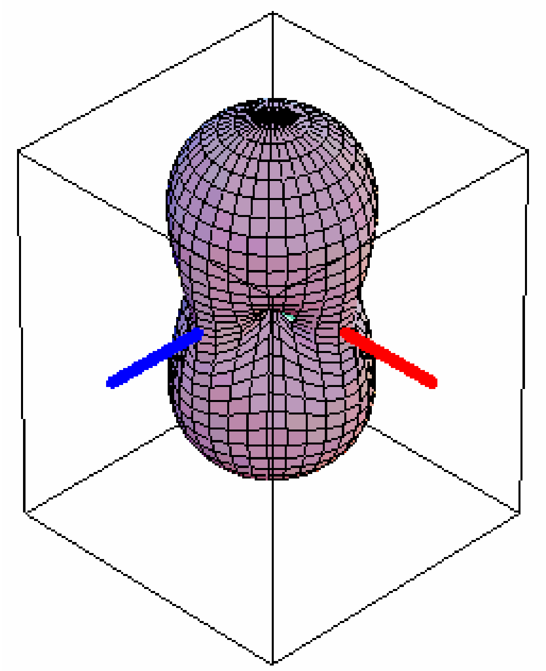
Responds to one polarization component

Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

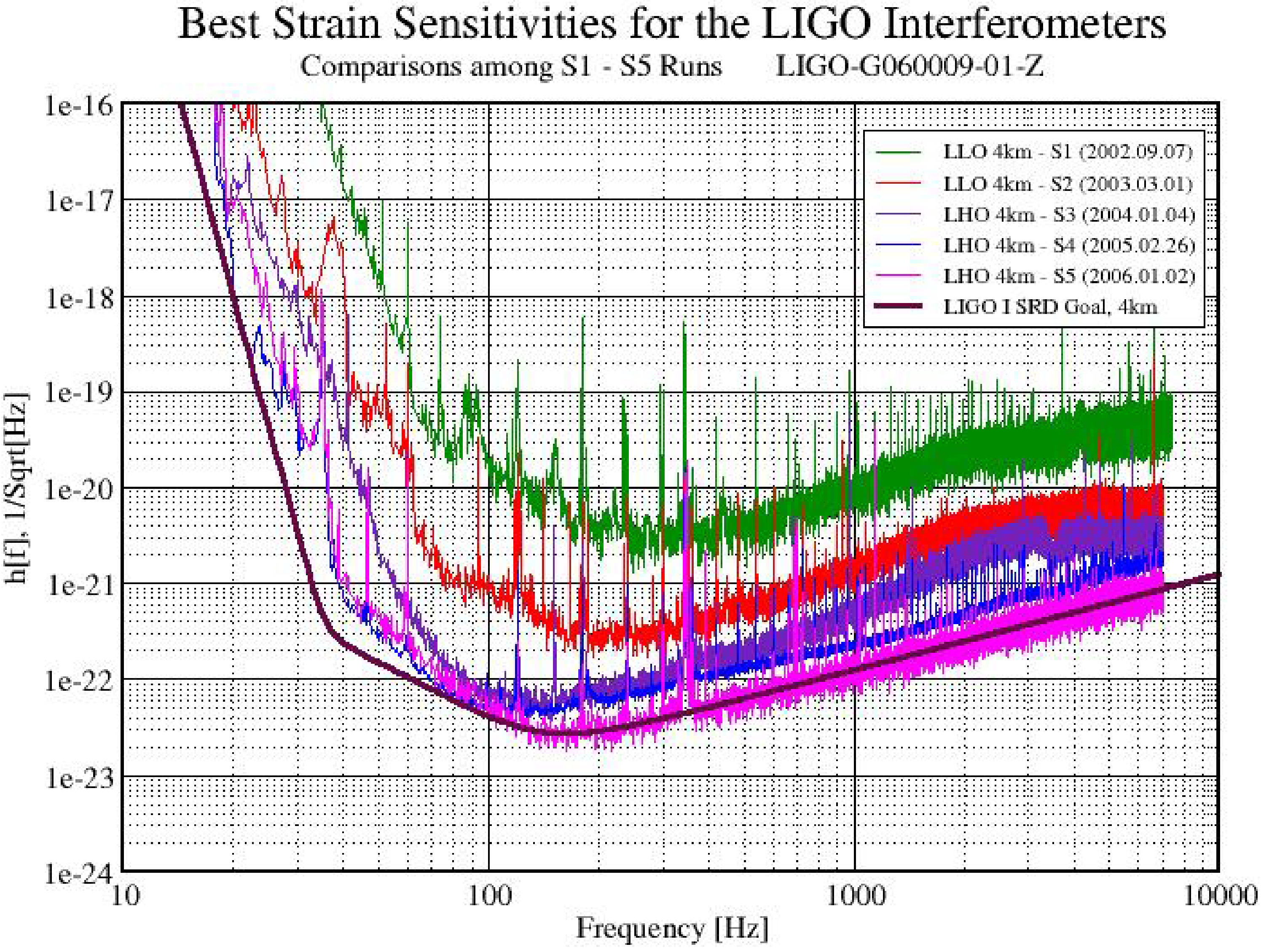

“×” polarization


“+” polarization


RMS sensitivity

A broad antenna pattern
⇒ **More like a microphone than a telescope**

LIGO Sensitivity, Science Runs S1 through S5



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The Gravitational Wave Signal Tableau

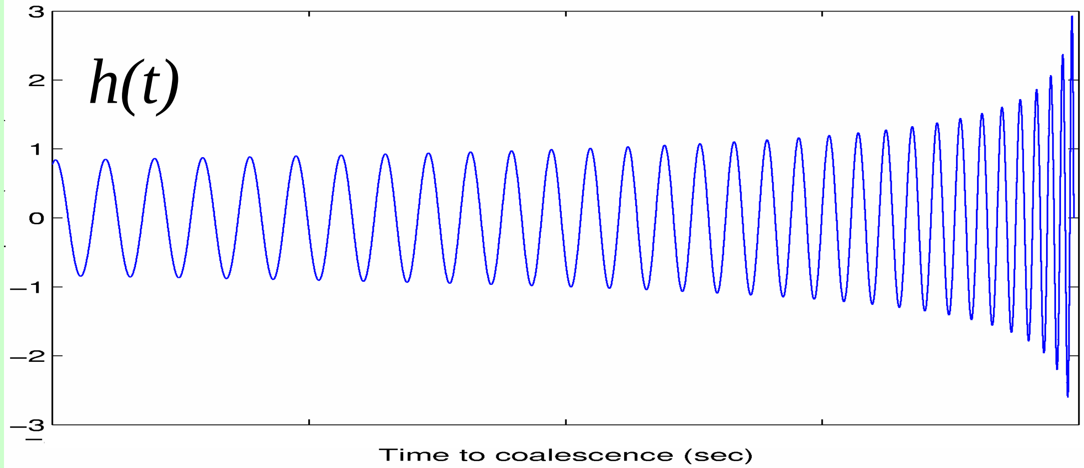
Short duration ⟷ Long duration

Waveform known

Waveform unknown

Low-mass inspiral

High-mass inspiral



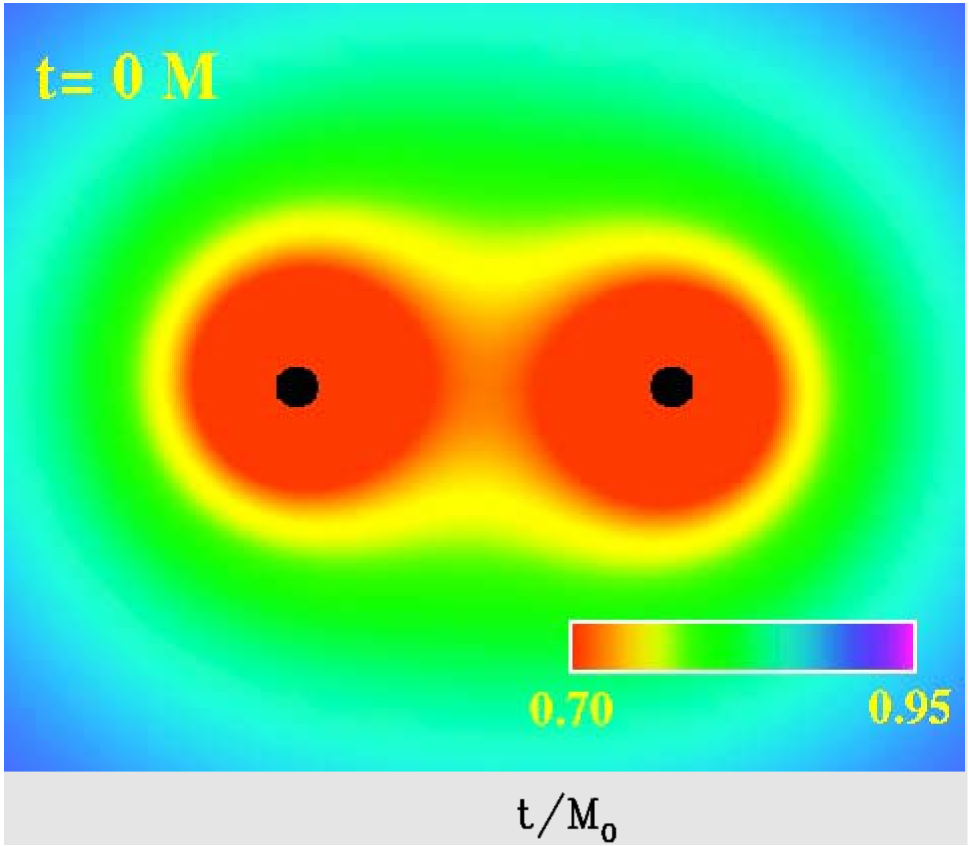
Binary merger

Recent Progress in Simulating Binary Mergers

Frans Pretorius, PRL 95, 121101 (2005)

Succeeded in evolving system through orbit, merger, and ringdown

Movies at http://astrogravs.gsfc.nasa.gov/conf/numrel2005/



α : “lapse function” used in simulation

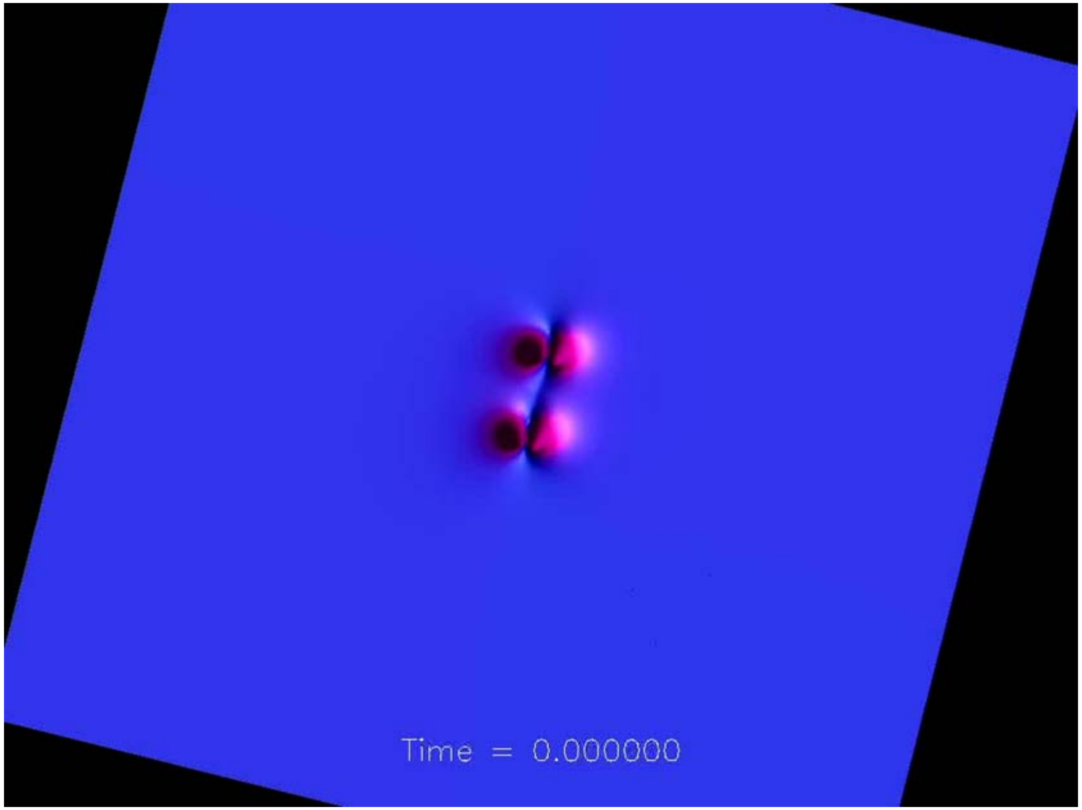
Ψ_4 : second time derivative of GW strain

Recent Progress in Simulating Binary Mergers

Campanelli, Lousto, Marronetti, & Zlochower, PRL 96, 111101 (2006)

Different numerical techniques compared to Pretorius

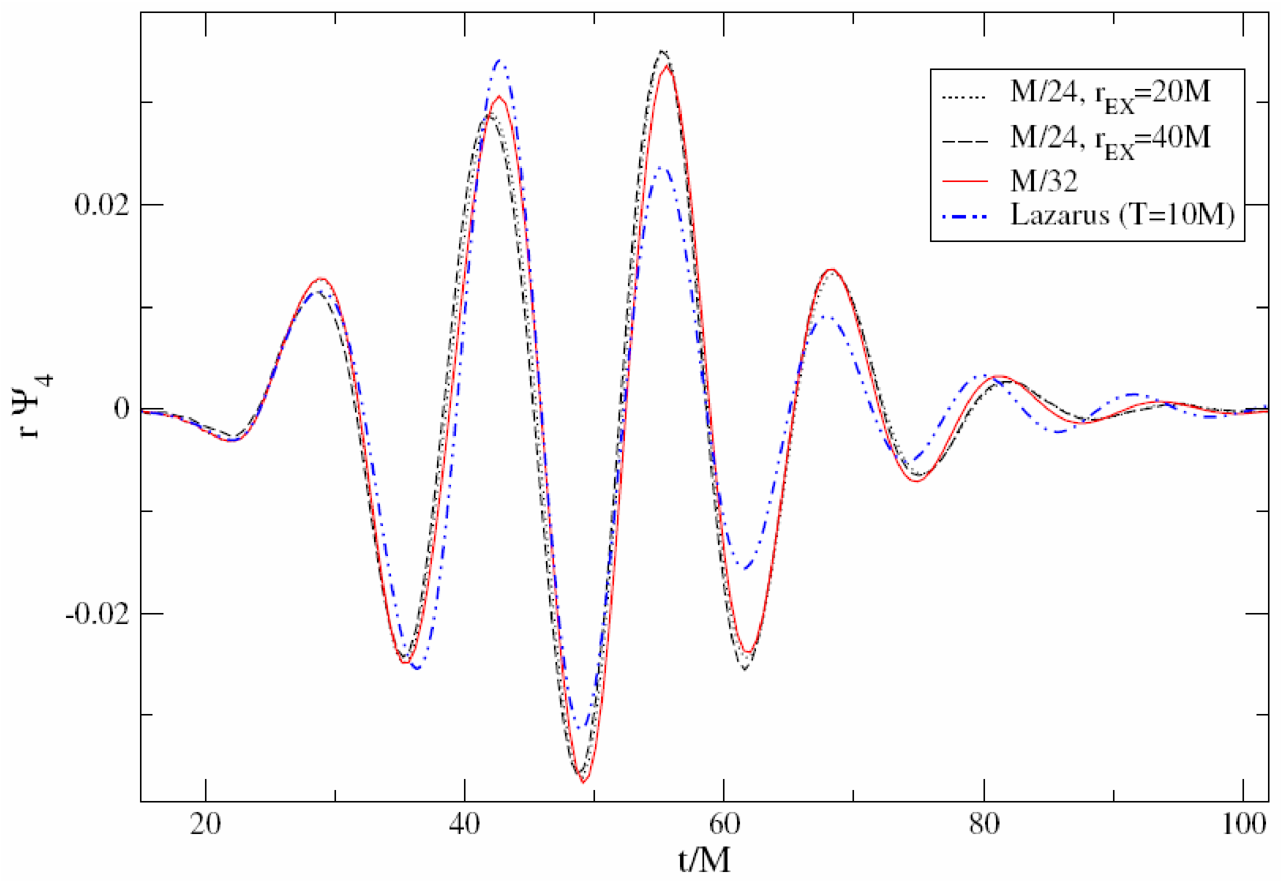
Movie at http://www.aip.org/mgr/png/images/bhmergermovie.mpg



Recent Progress in Simulating Binary Mergers

Baker, Centrella, Choi, Koppitz, & van Meter, PRL 96, 111102 (2006)

Similar approach and results to Campanelli et al.



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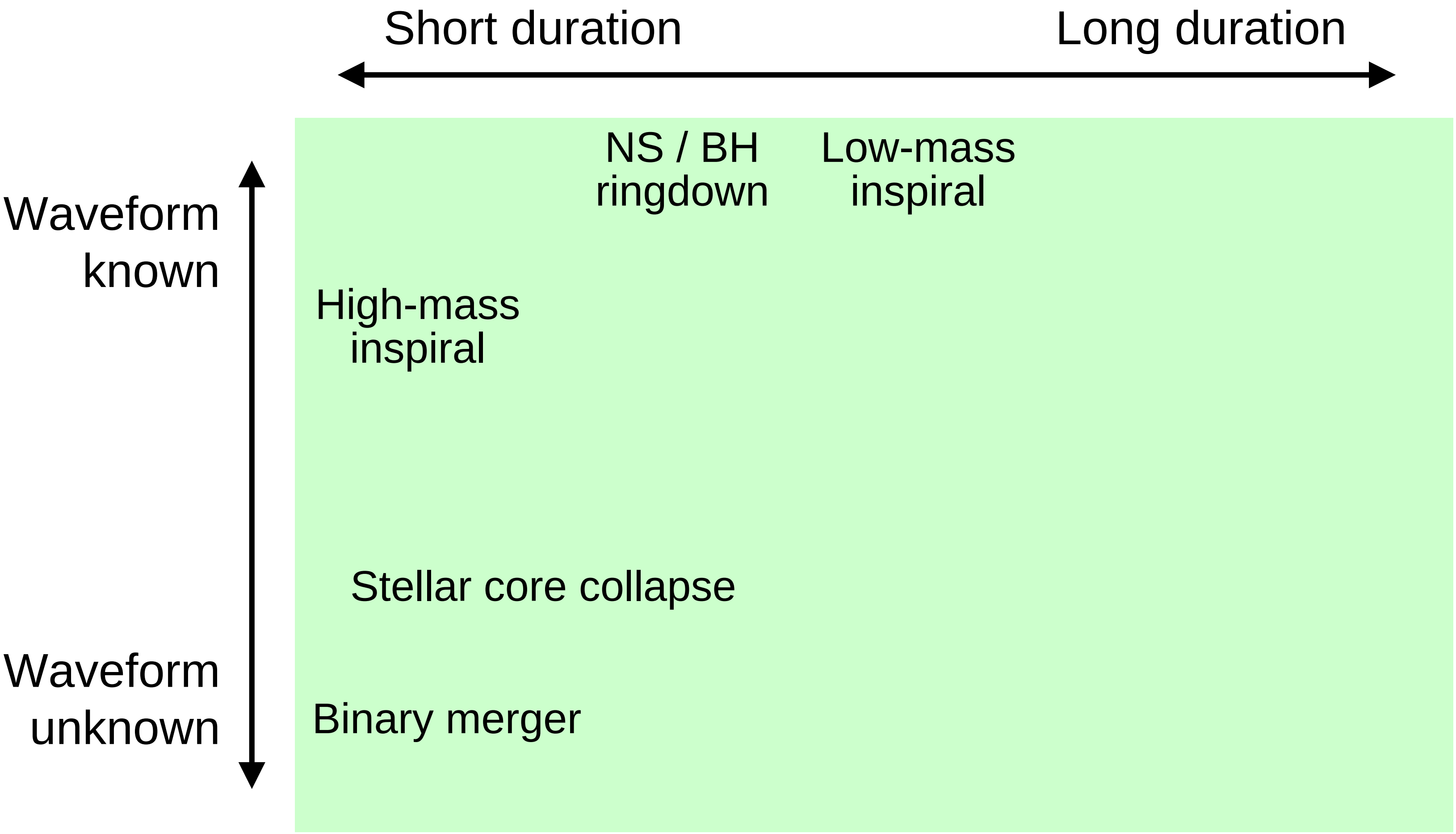

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NS / BH ringdown

Low-mass inspiral

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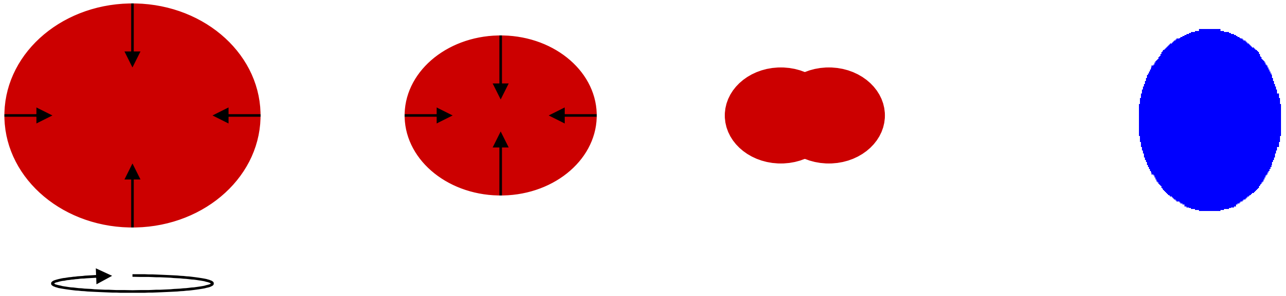
Stellar core collapse

Binary merger

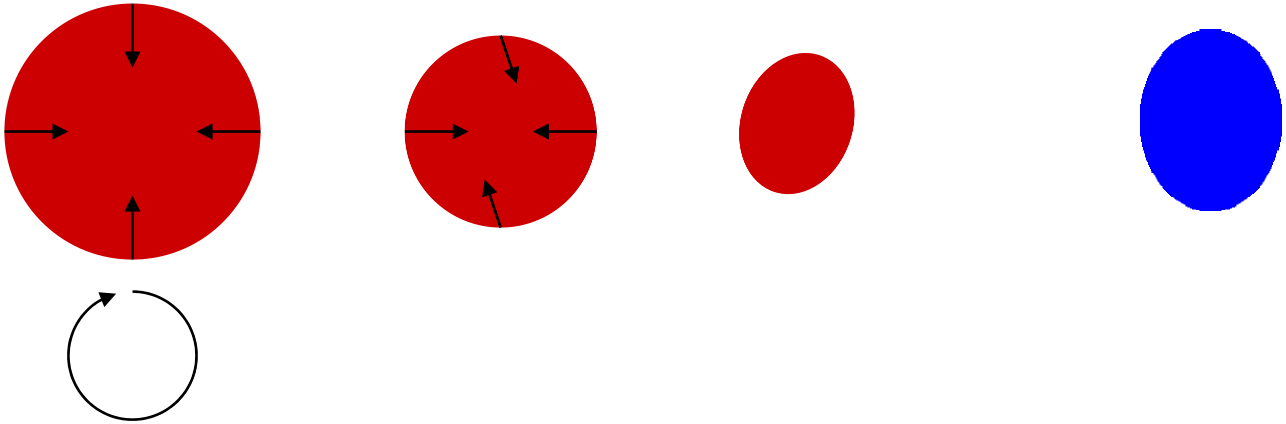
Gravitational Wave Emission from Stellar Core Collapse

Gravitational wave emission requires an aspherical collapse

Centrifugal forces from rotation can lead to a pole-equator difference

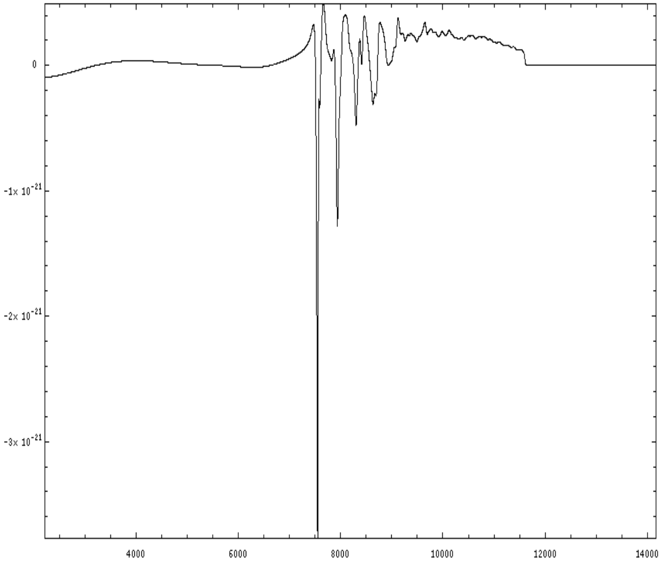


Rotational instability can break axisymmetry spontaneously

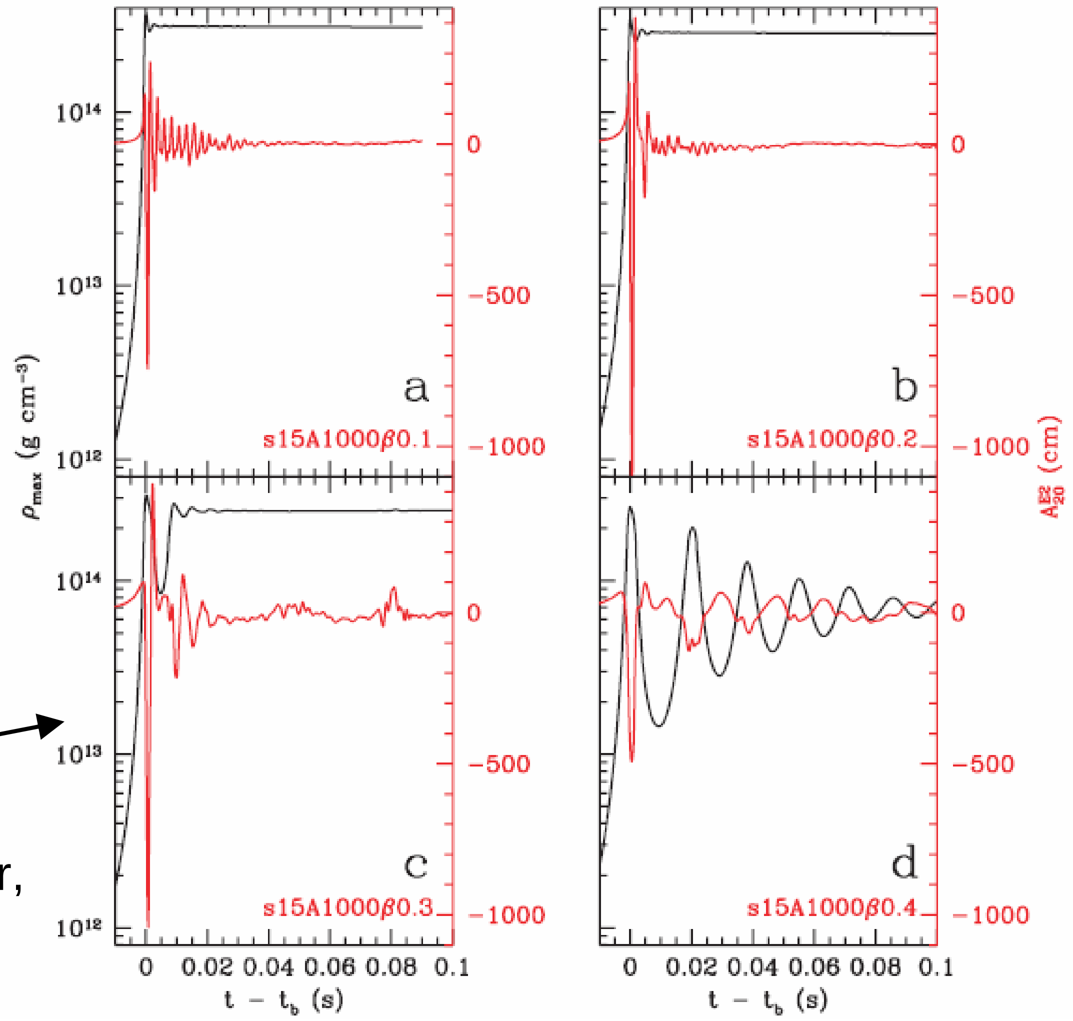


In-falling material can drive oscillation modes of core

Axisymmetric Simulations of Stellar Core Collapse



Zwerger and Müller, Astron. Astrophys. **320**, 209 (1997)



Ott, Burrows, Livne, and Walder, ApJ **600**, 834 (2004)

Core Oscillations & Acoustic Waves in Stellar Core Collapse

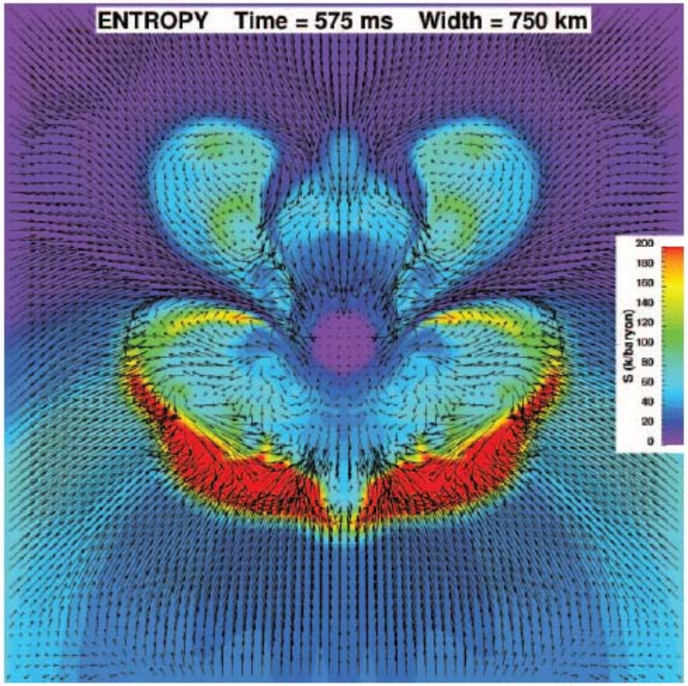
Burrows, Livne, Dessart, Ott, and Murphy, ApJ 640, 878 (2006)

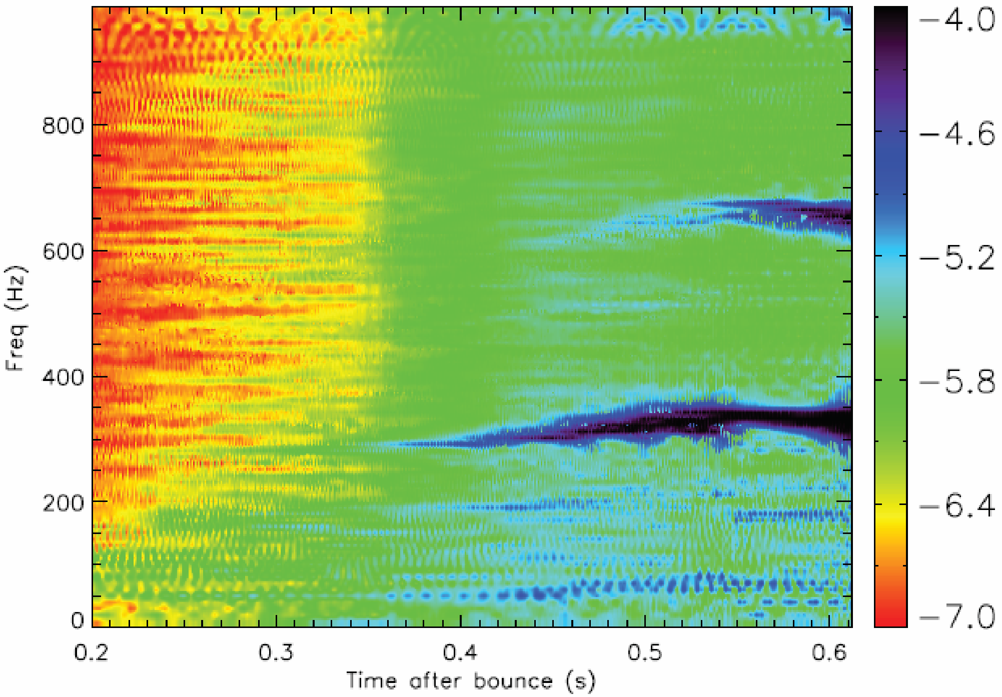
Also: http://www.nsf.gov/news/news_summ.jsp?cntn_id=105798&org=NSF

Axisymmetric simulation with non-rotating progenitor

Observe that in-falling material eventually drives oscillations of the core

Acoustic waves carry energy to outer mantle, driving explosion

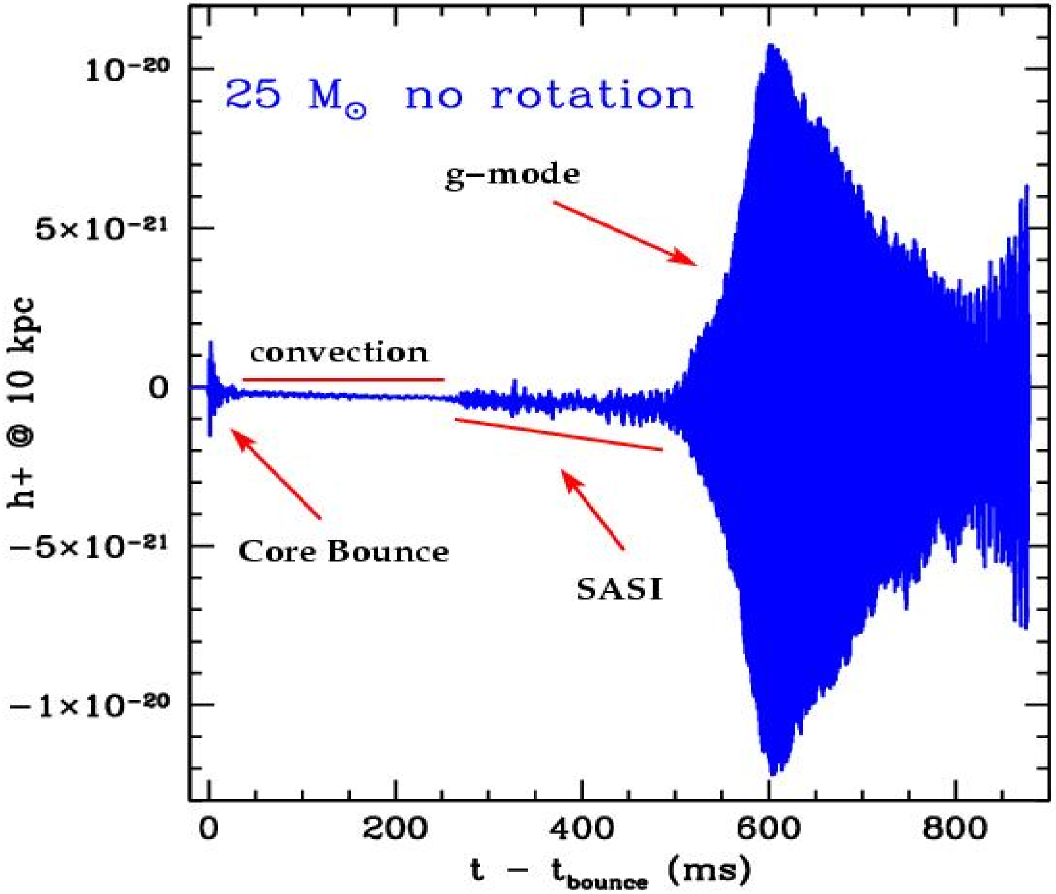




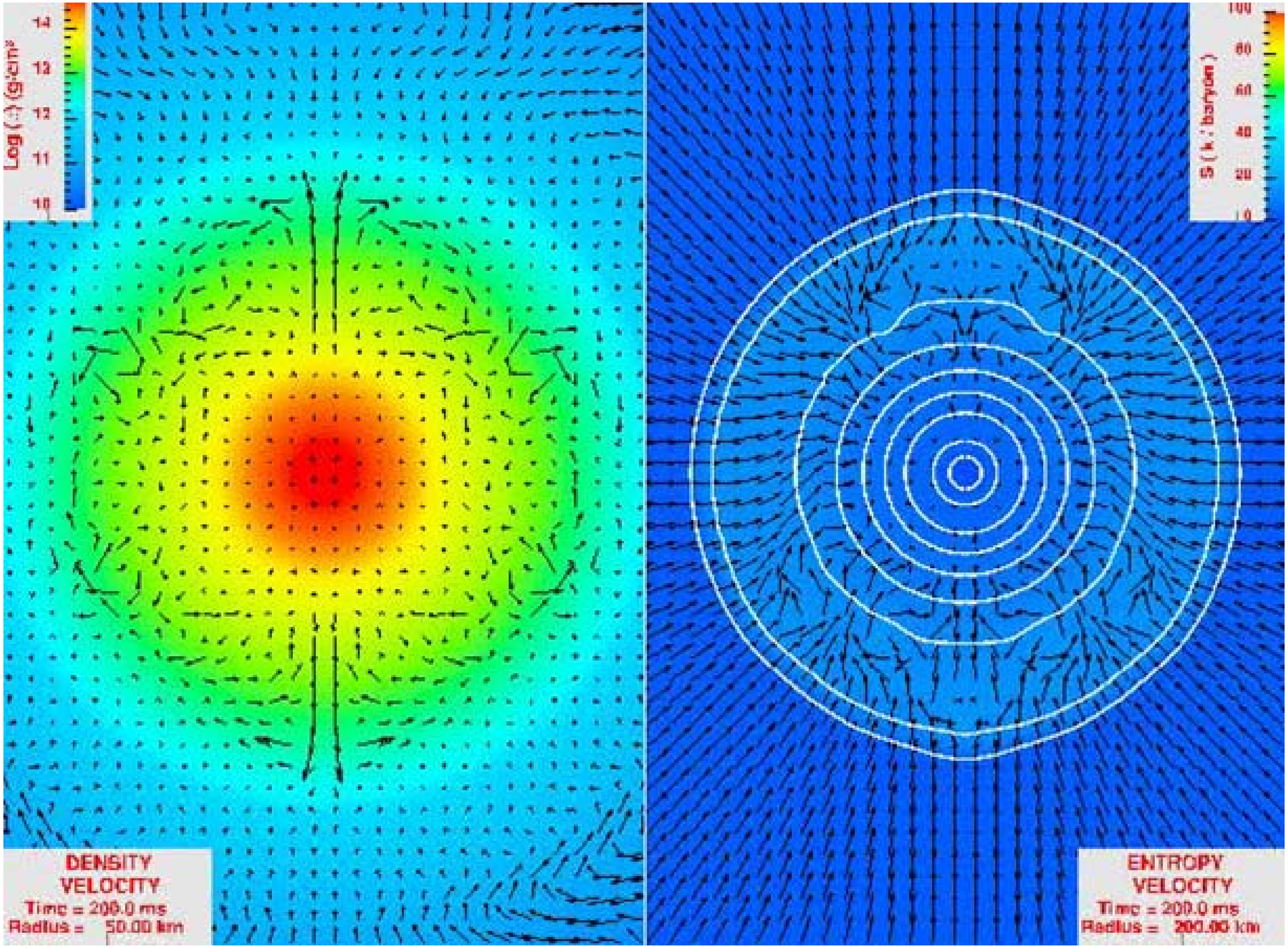
Gravitational Waves from Ott et al. Simulation

PowerPoint slides and movies posted at
http://zenith.as.arizona.edu/~burrows/briley/

Suggests that total power radiated in gravitational waves can be huge!



Gravitational Waves from Burrows et al. Simulation



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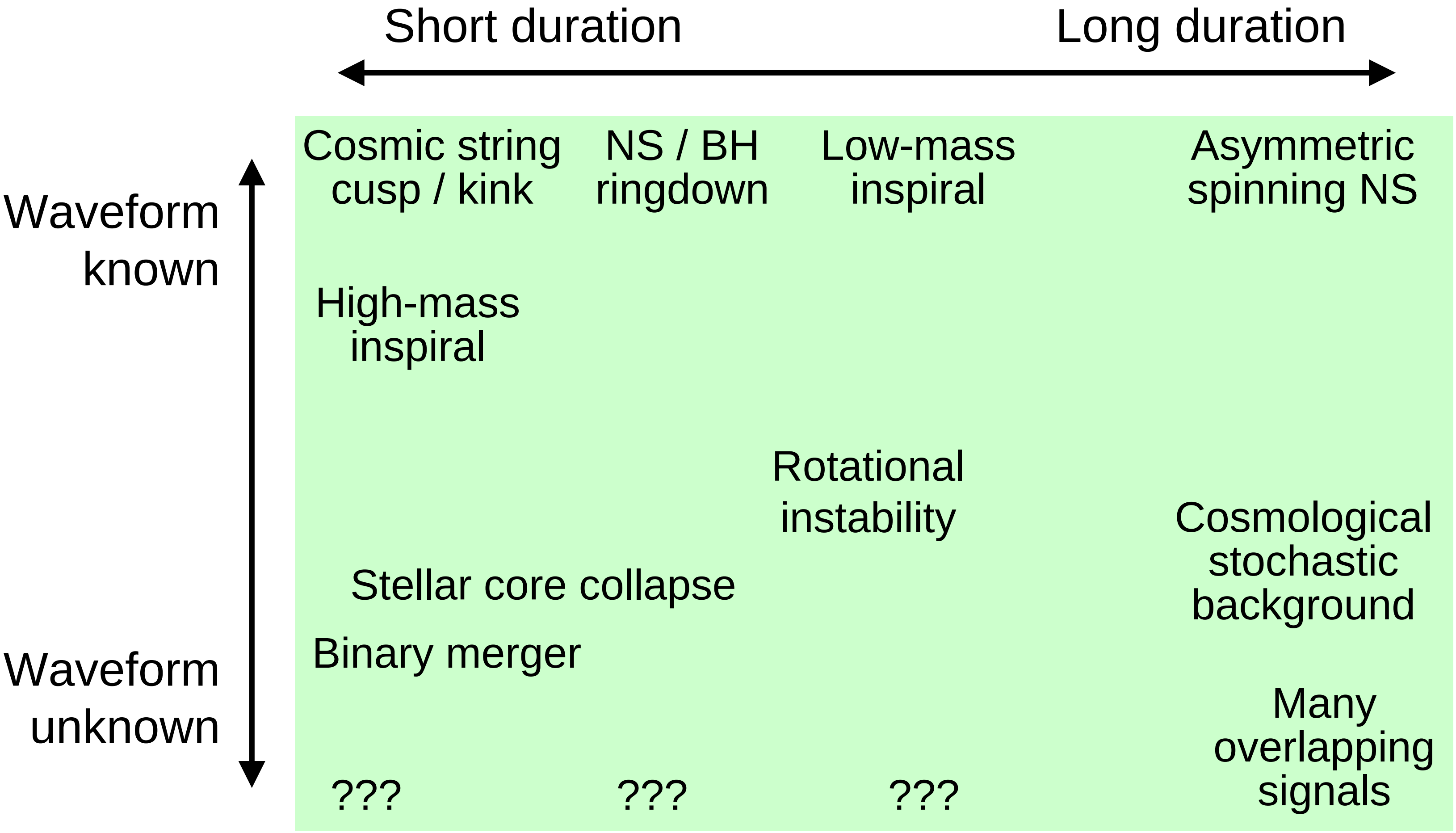

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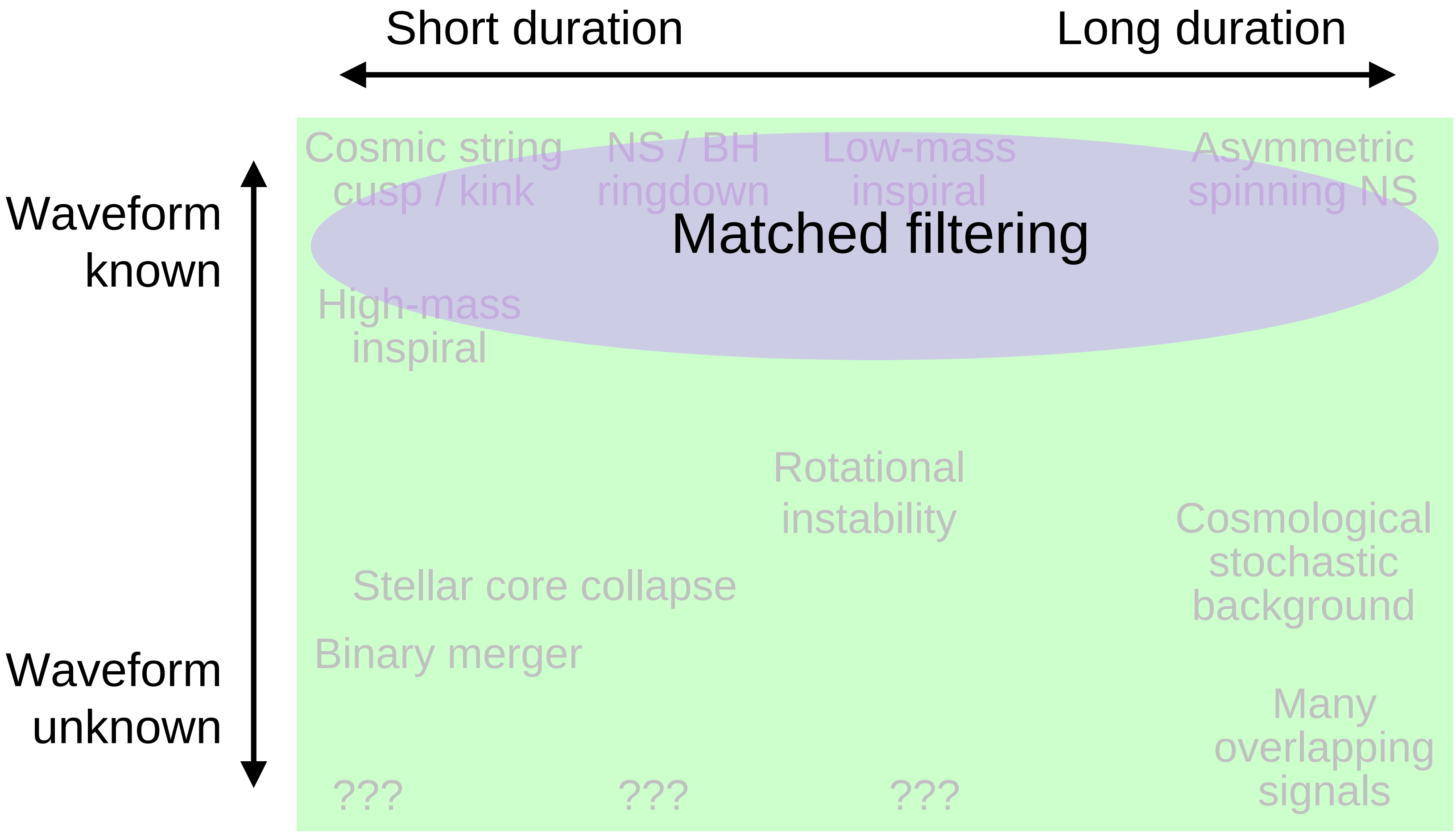
Signal Detection Methods



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

Matched filtering

High-mass inspiral

Rotational instability

Cosmological stochastic background

Stellar core collapse

Binary merger

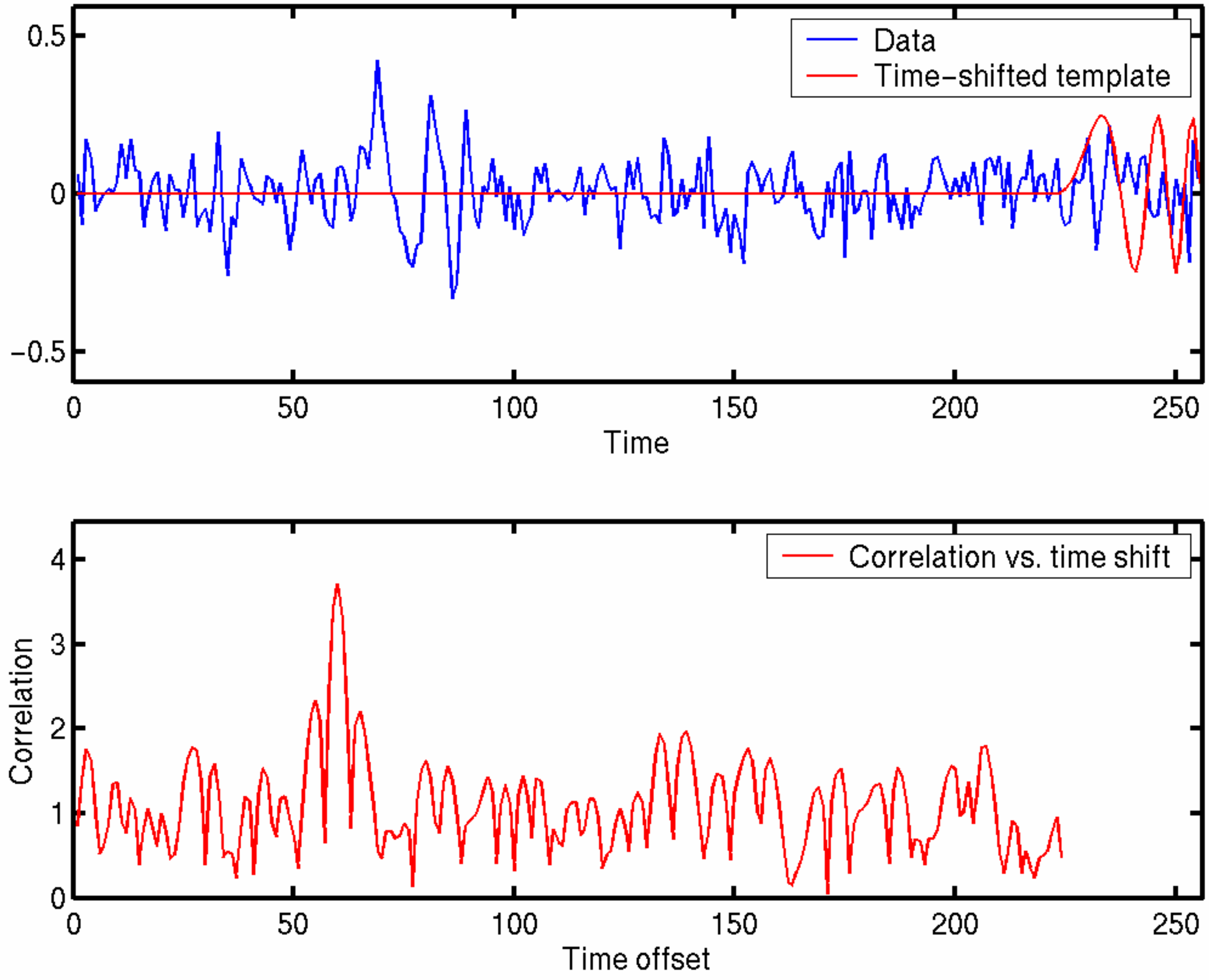
Many overlapping signals

???

???

???

Illustration of Matched Filtering



Optimal Matched Filtering for Short Signals

Data

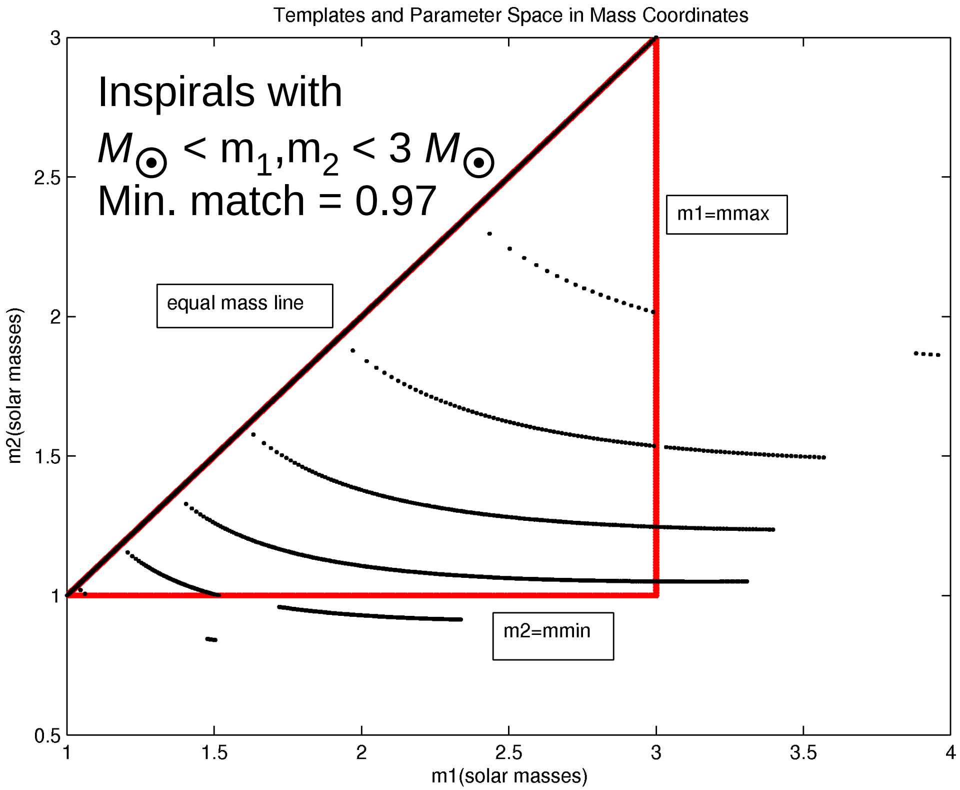
Template

$$z(t) = 4\int_{0}^{\infty} \frac{\tilde{s}(f)\;\tilde{h}^{*}(f)}{S_n(f)}\; e^{2\pi i f t}\, df$$

Noise power spectral density

Look for maxima of $|z(t)|$ above some threshold ➔ trigger

Use a bank of templates to cover parameter space of target signals



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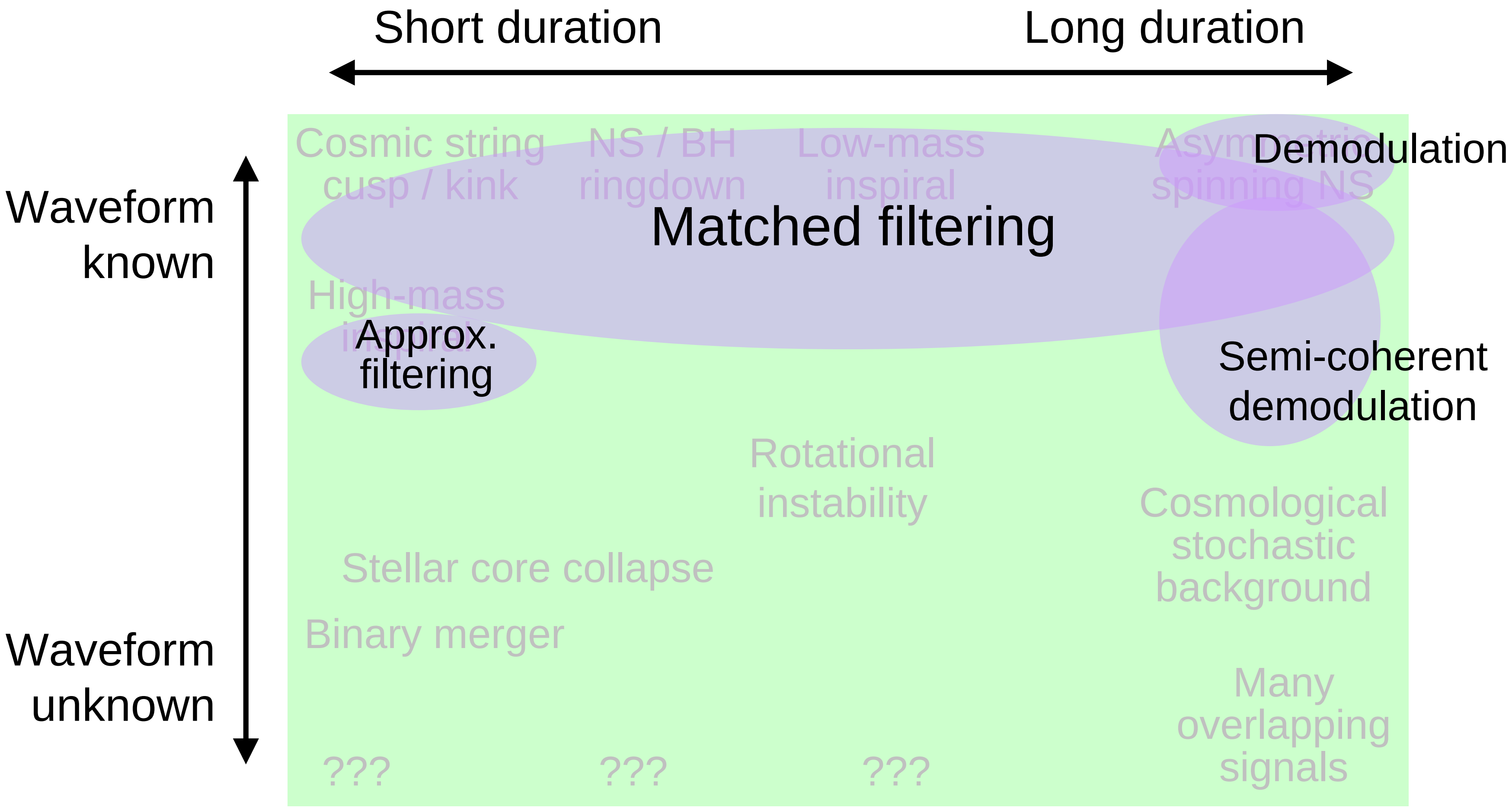
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Demodulation / Matched Filtering for Continuous-Wave Signals

Even a “continuous” gravitational wave is not received as a monochromatic signal

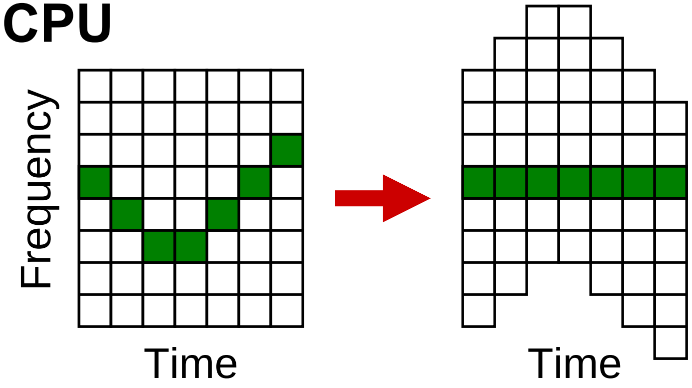
- Doppler shift due to Earth’s orbit and rotation
- Antenna pattern depends on sidereal time of day
- Intrinsic frequency of source may be changing
- Source in binary system exhibits additional Doppler shift

Demodulation depends sensitively on source parameters

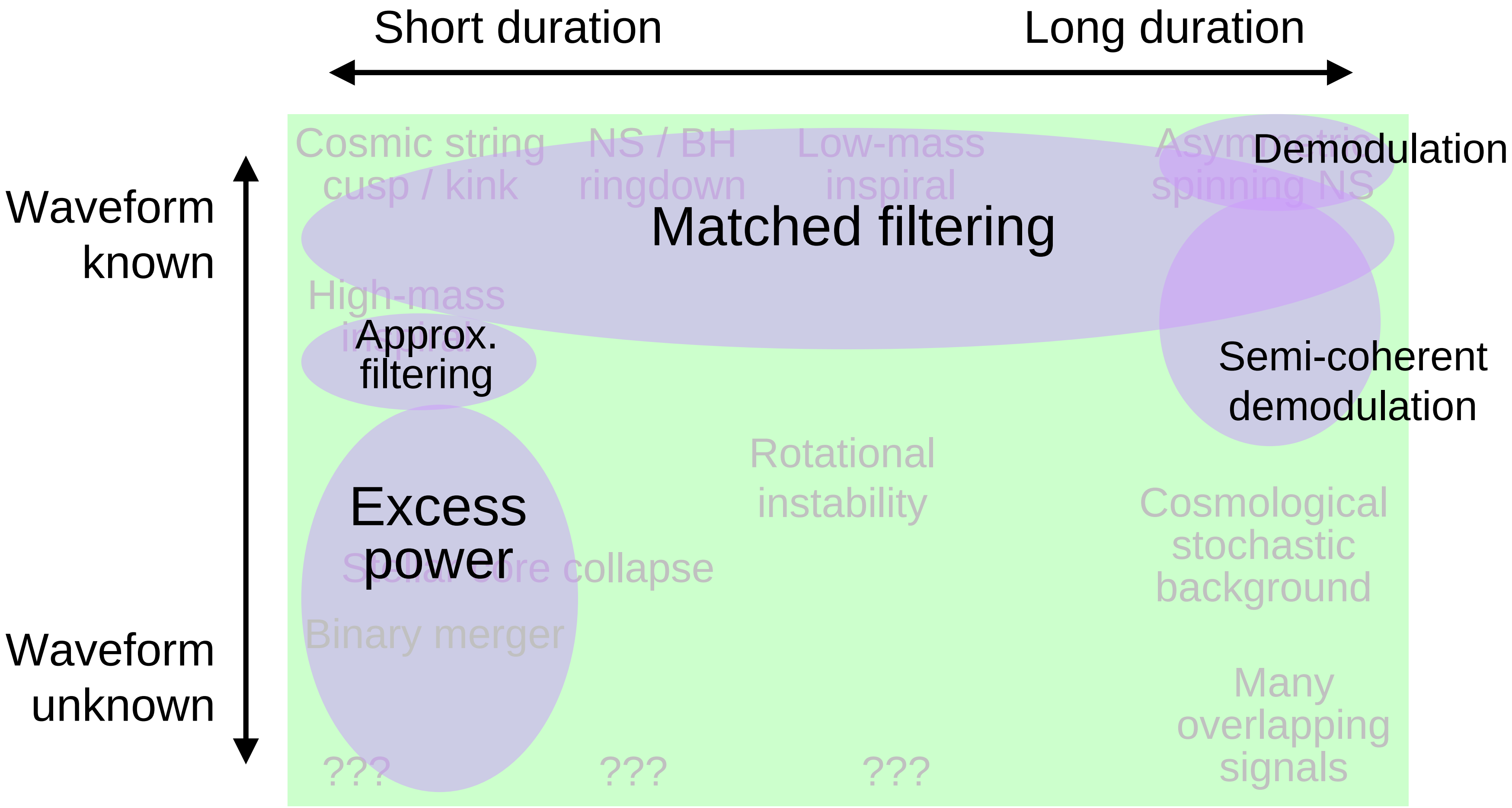
- Large-parameter-space searches are limited by computational power

Semi-coherent methods use less CPU

- Stack-slide, Hough transform, etc.
- Can be used as part of a hierarchical search



Signal Detection Methods



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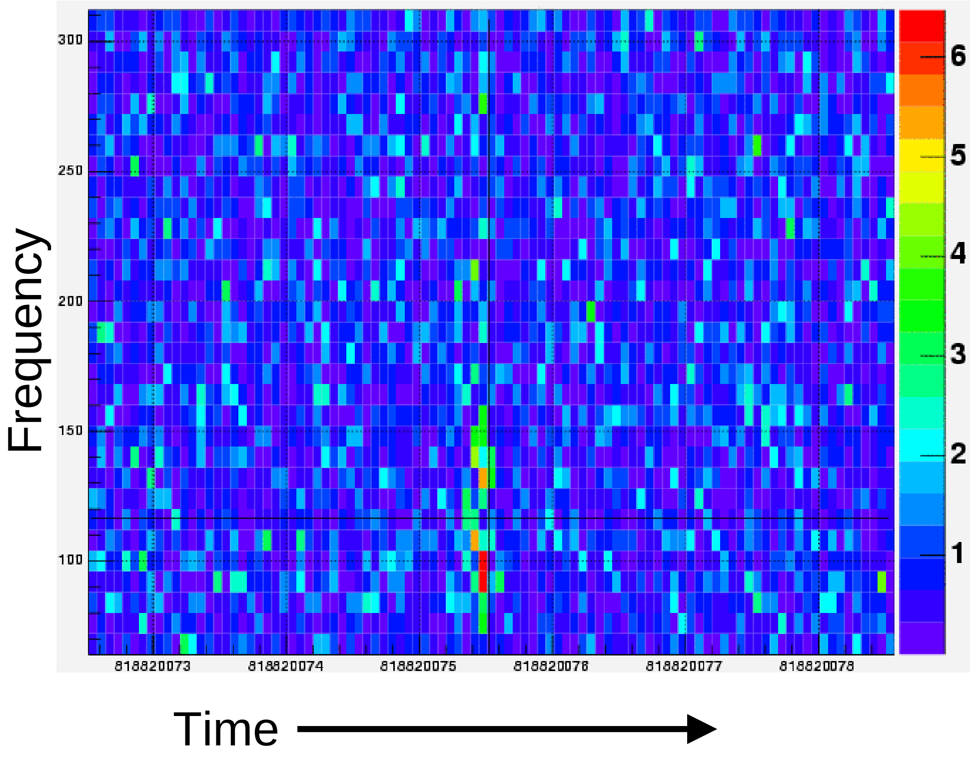
“Excess Power” Search Methods

Decompose data stream into time-frequency pixels

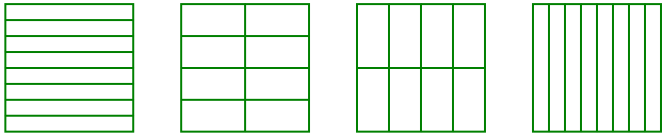
Fourier components, wavelets, “Q transform”, etc.

Normalize relative to noise as a function of frequency

Look for “hot” pixels or clusters of pixels



Can use multiple ($\Delta t, \Delta f$) pixel resolutions



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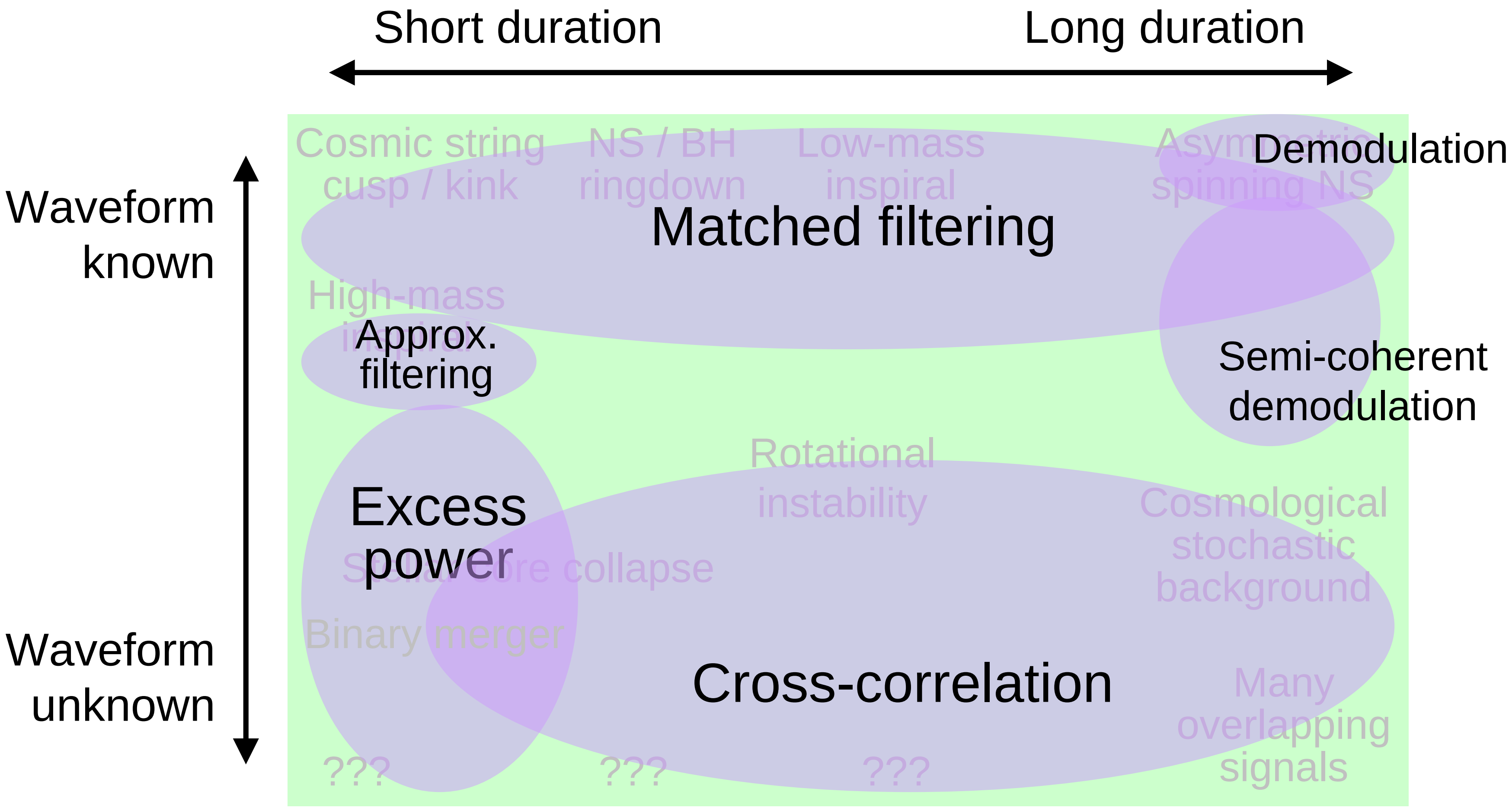
Signal Detection Methods



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Cross-correlation

Many overlapping signals

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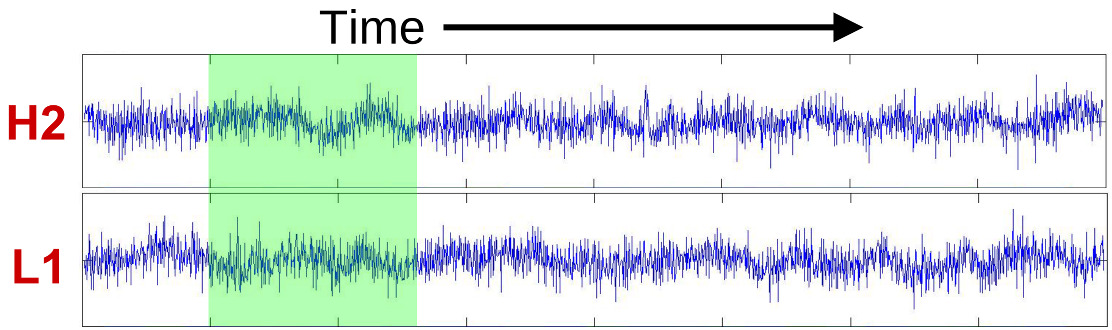
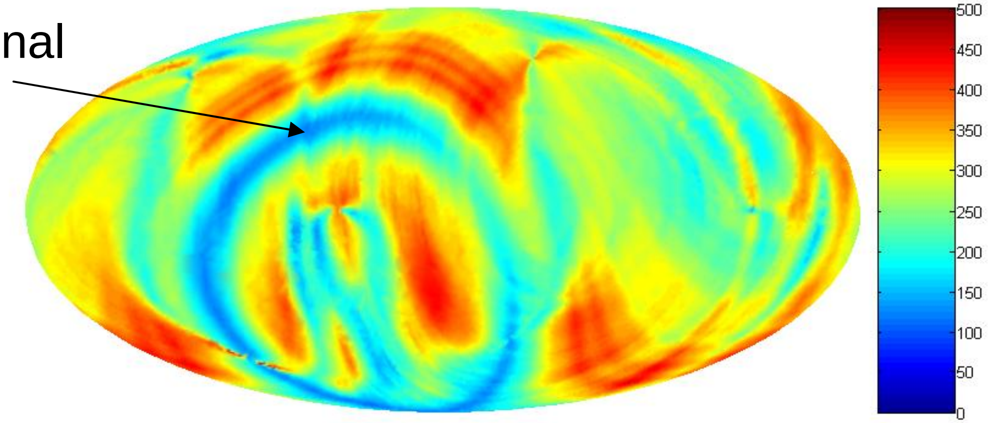
Cross-Correlation Methods

Look for same signal buried in two data streams



Integrate over a time interval comparable to the target signal

Extensions to three or more detector sites being worked on

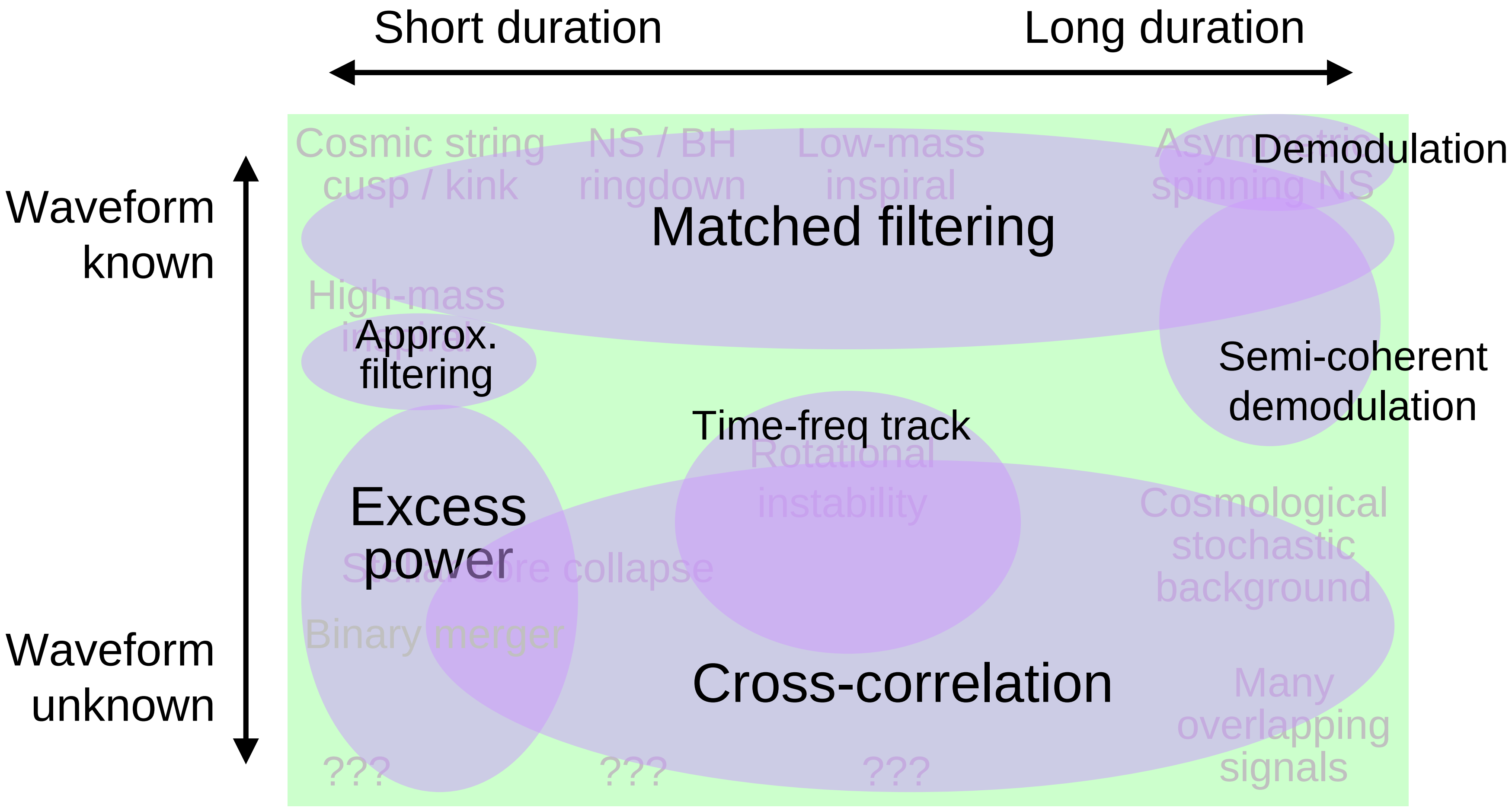


Simulated signal injected here

Inconsistent

Consistent

Signal Detection Methods



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Time-freq track

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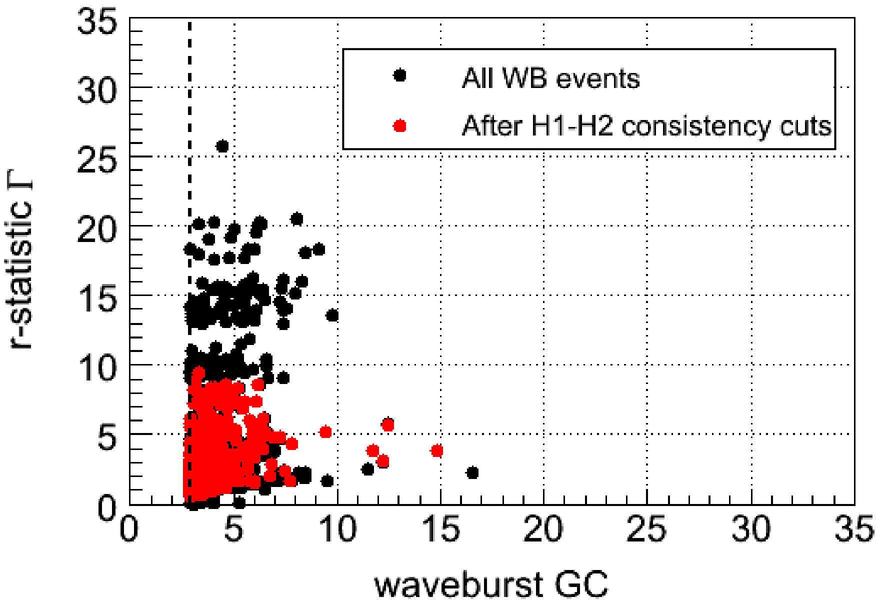
Variable Data Quality

Various environmental and instrumental conditions catalogued; can study relevance using *time-shifted* coincident triggers

Example from S4 all-sky burst search:

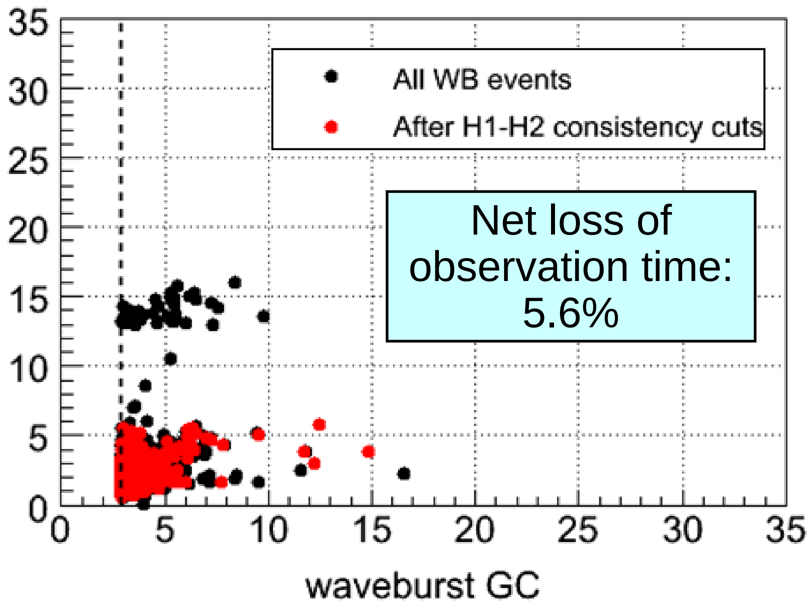
Minimal data quality cuts

Require locked interferometers
Omit hardware injections
Avoid times of ADC overflows



Additional data quality cuts

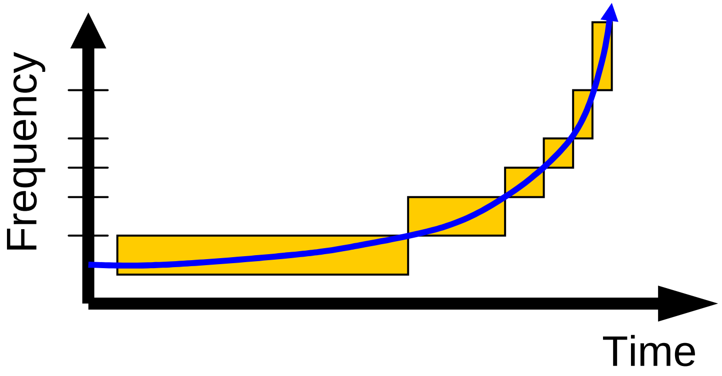
Avoid high seismic noise, wind, jet
Avoid calibration line drop-outs
Avoid times of “dips” in stored light
Omit last 30 sec of each lock



Net loss of observation time: 5.6%

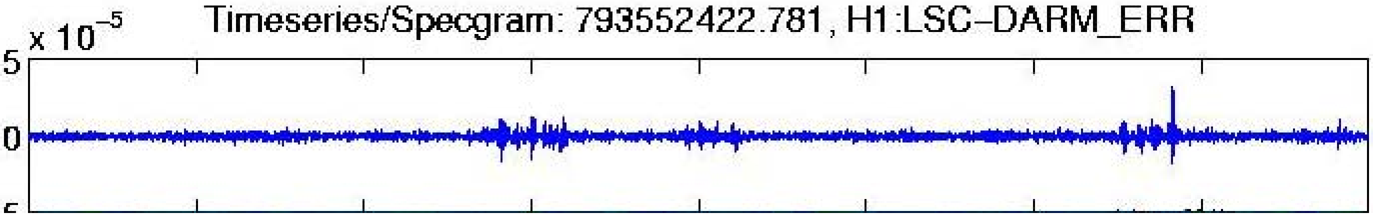
Non-Stationary Noise / Glitches

For inspirals: chi-squared test and other consistency tests

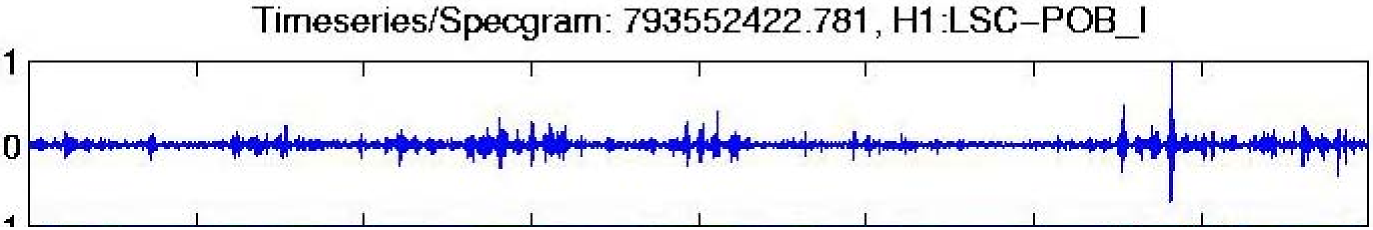


Auxiliary-channel vetoes

GW channel



Beam splitter pick-off



Most important: require consistent signals in multiple detectors!

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Are We There Yet?

Gravitational wave detectors are in an exploration phase

- Need to be open to all possible signals, known and unknown

General methods exist to search for all types of signals

- Different methods best for different types

The challenge is to get the most out of our data

- Current implementations vary in maturity level
- Implementation details are often the tricky part