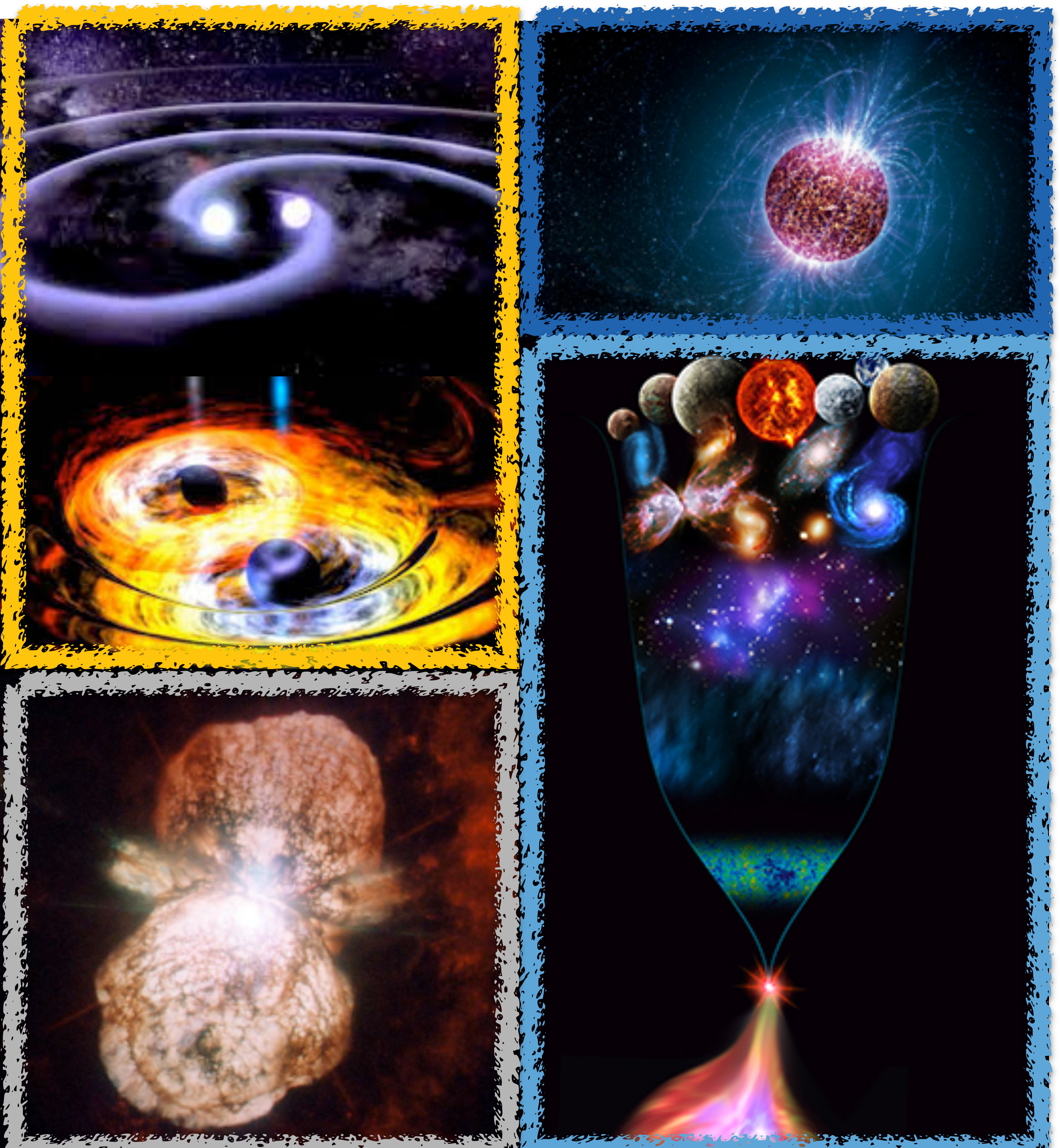
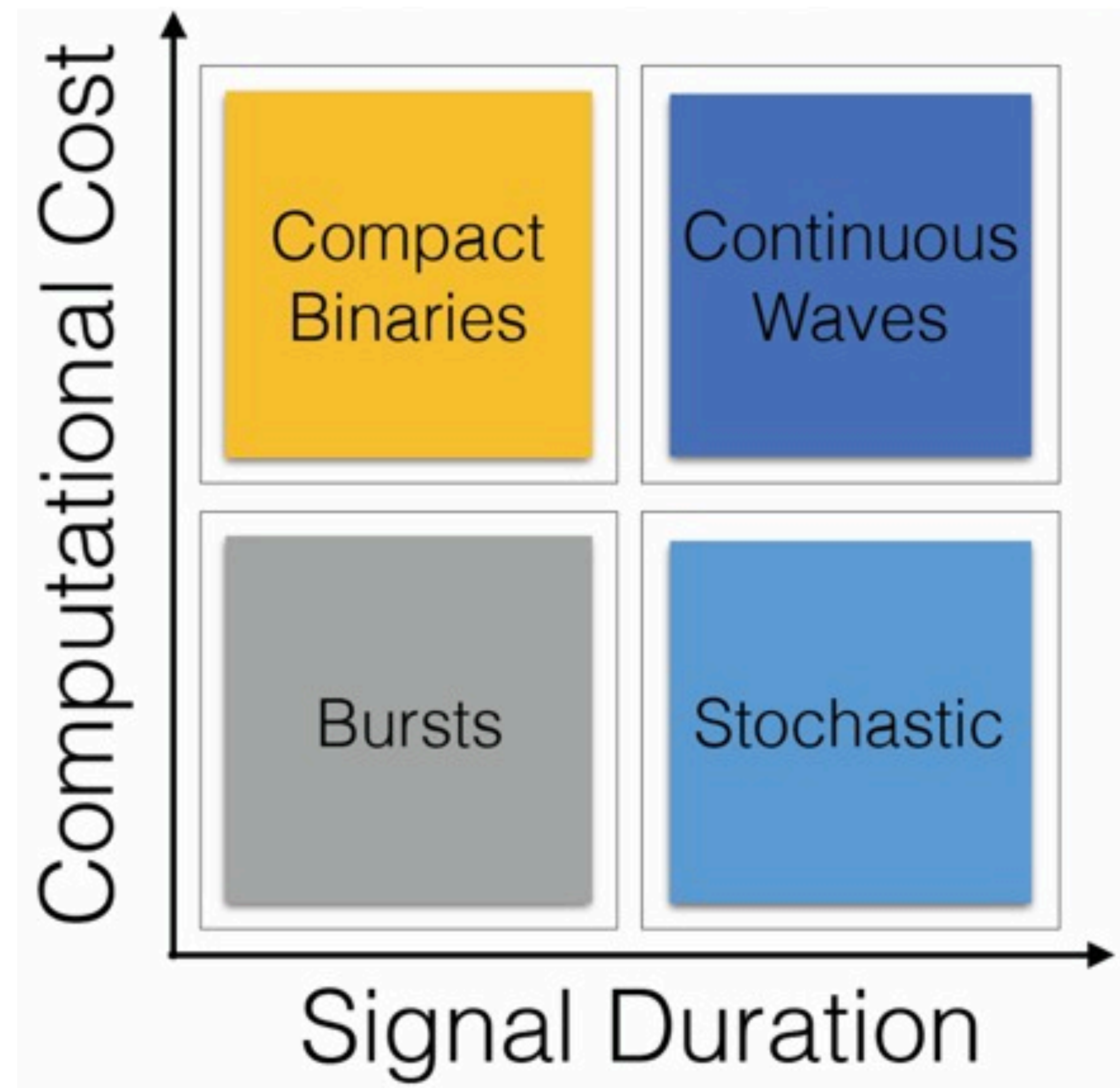
Searching for Gravitational Waves in LIGO Data

Lecture 3

Astrophysical Sources of Gravitational Radiation



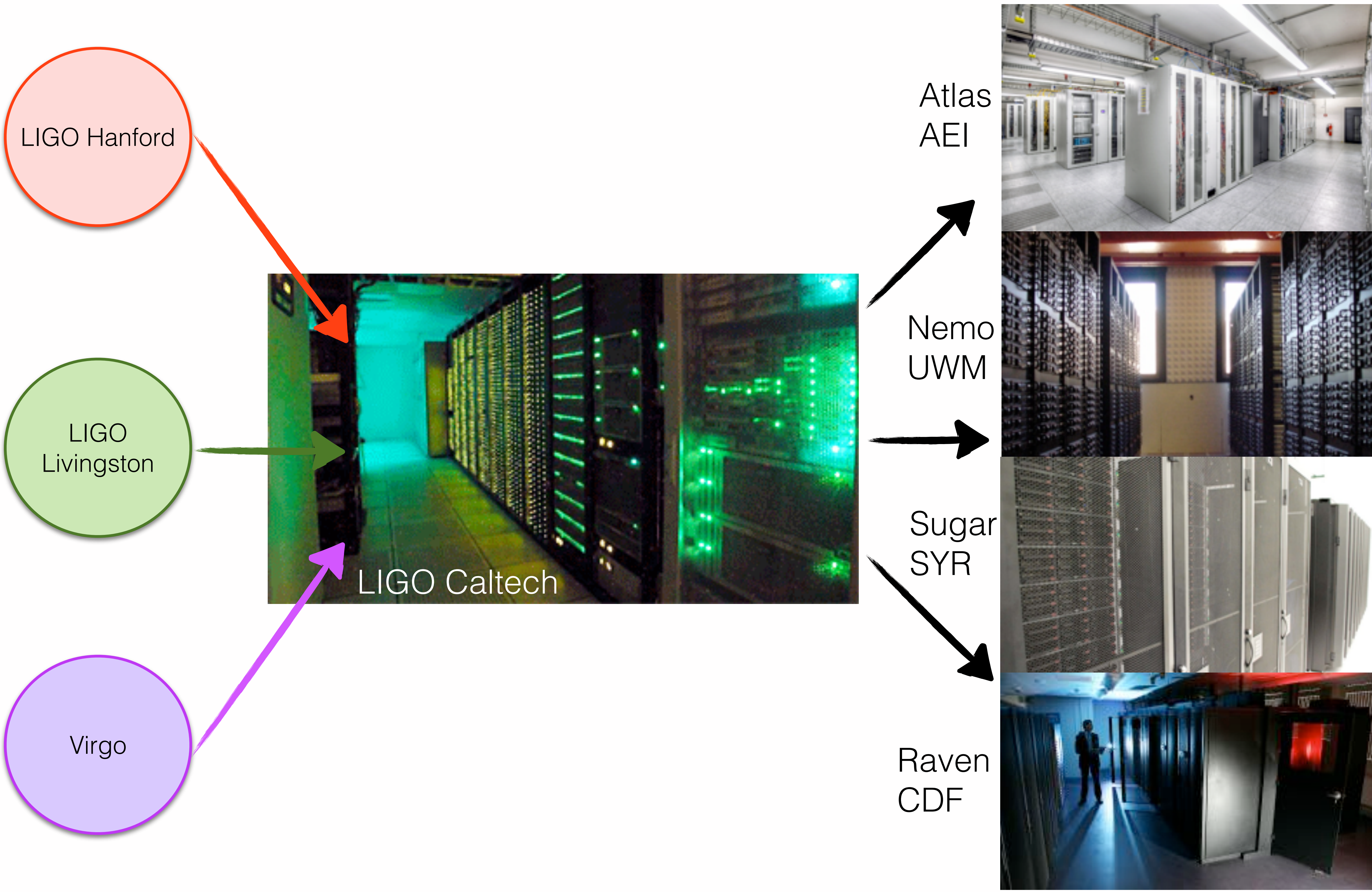


Main LIGO-Virgo Searches

1. Gravitational Wave Transients Searches
   1.1 Compact Binary Coalescences
   1.2 Generic Transients
   ...

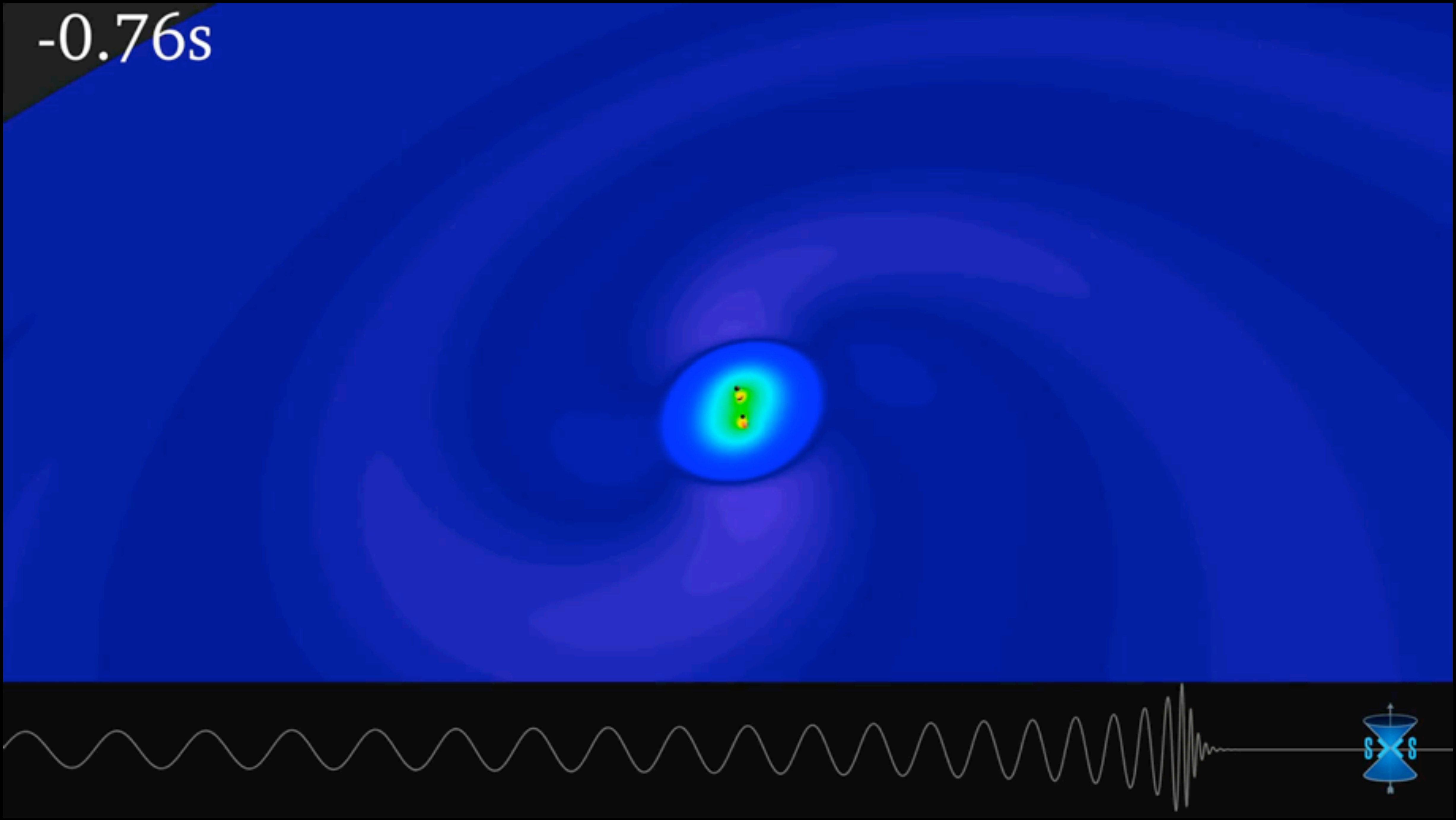
2. Persistent Gravitational Wave Searches
   2.1 Stochastic Background
   2.2 Spinning Neutron Stars
   ...

Data Centers for Searches

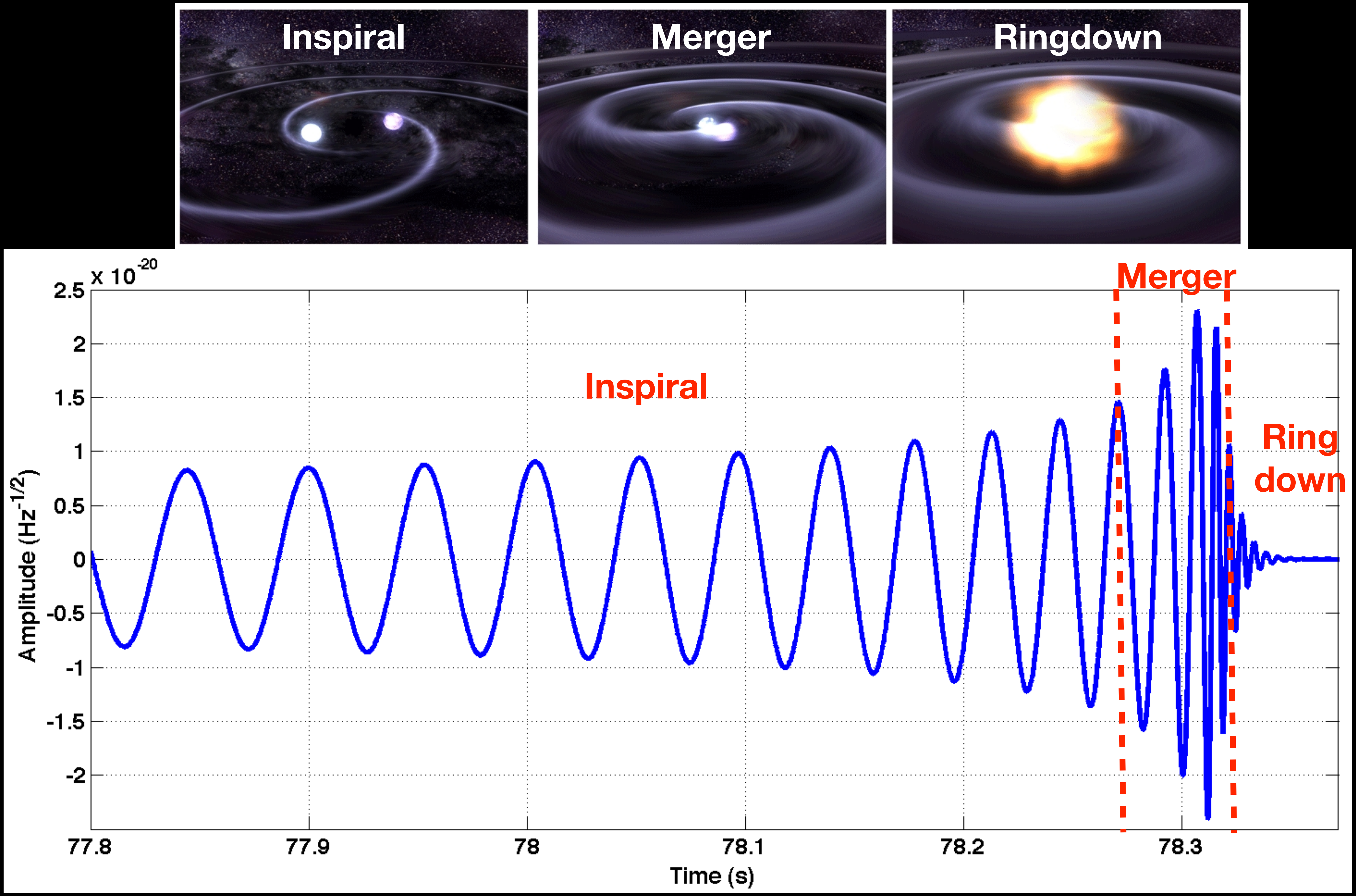


1.1 Compact Binary Coalescences

Dynamical Spacetime

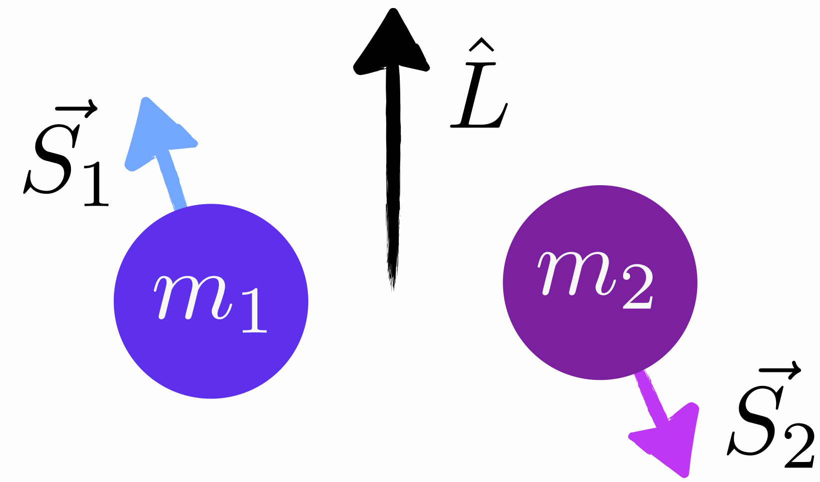


Courtesy: SXS Collaboration

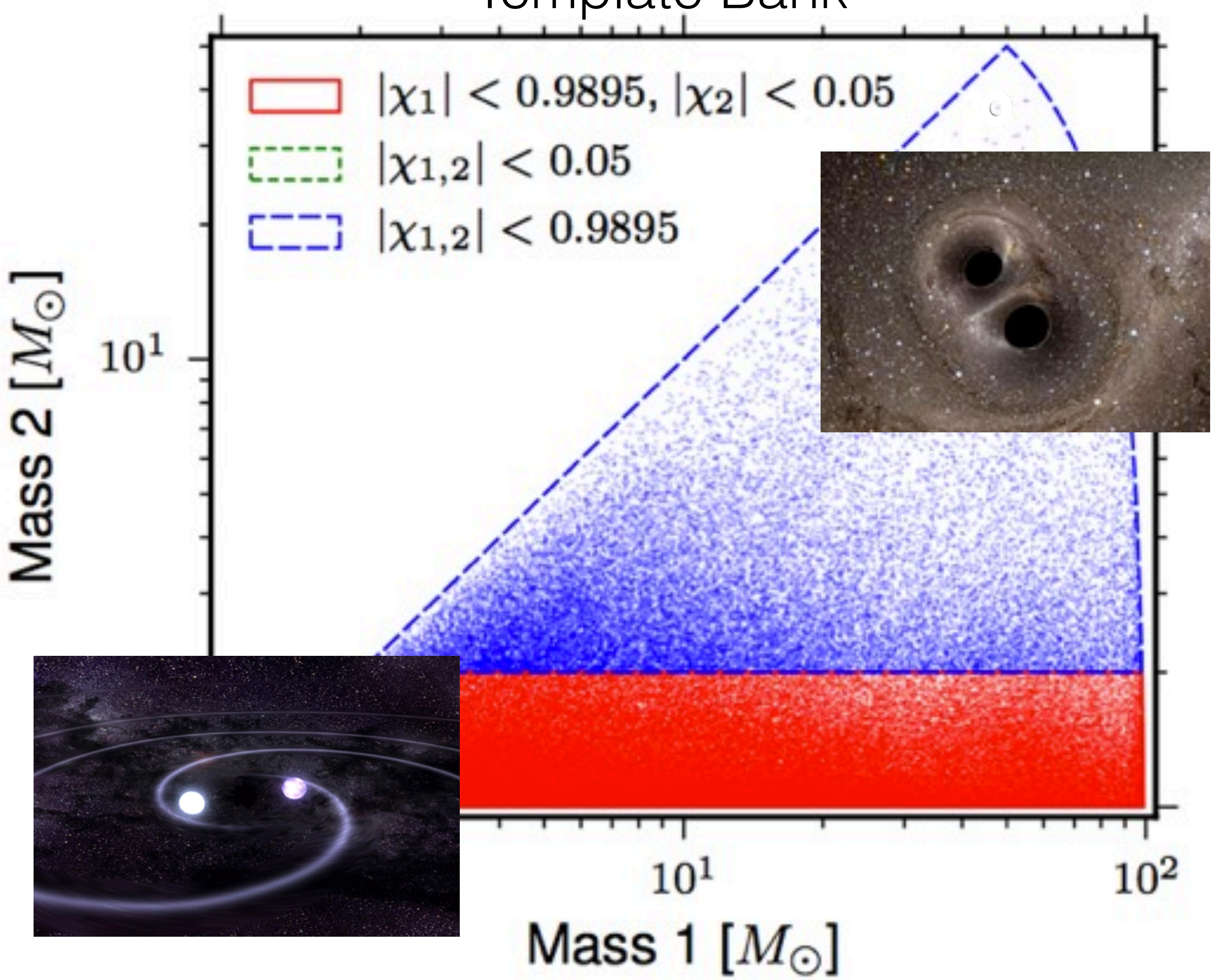

Inspiral
Merger
Ringdown
x 10^-20
Amplitude (Hz^-1/2)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
77.8
77.9
78
78.1
78.2
78.3
Time (s)
Inspiral
Merger
Ring
down

Matched-Filter Searches

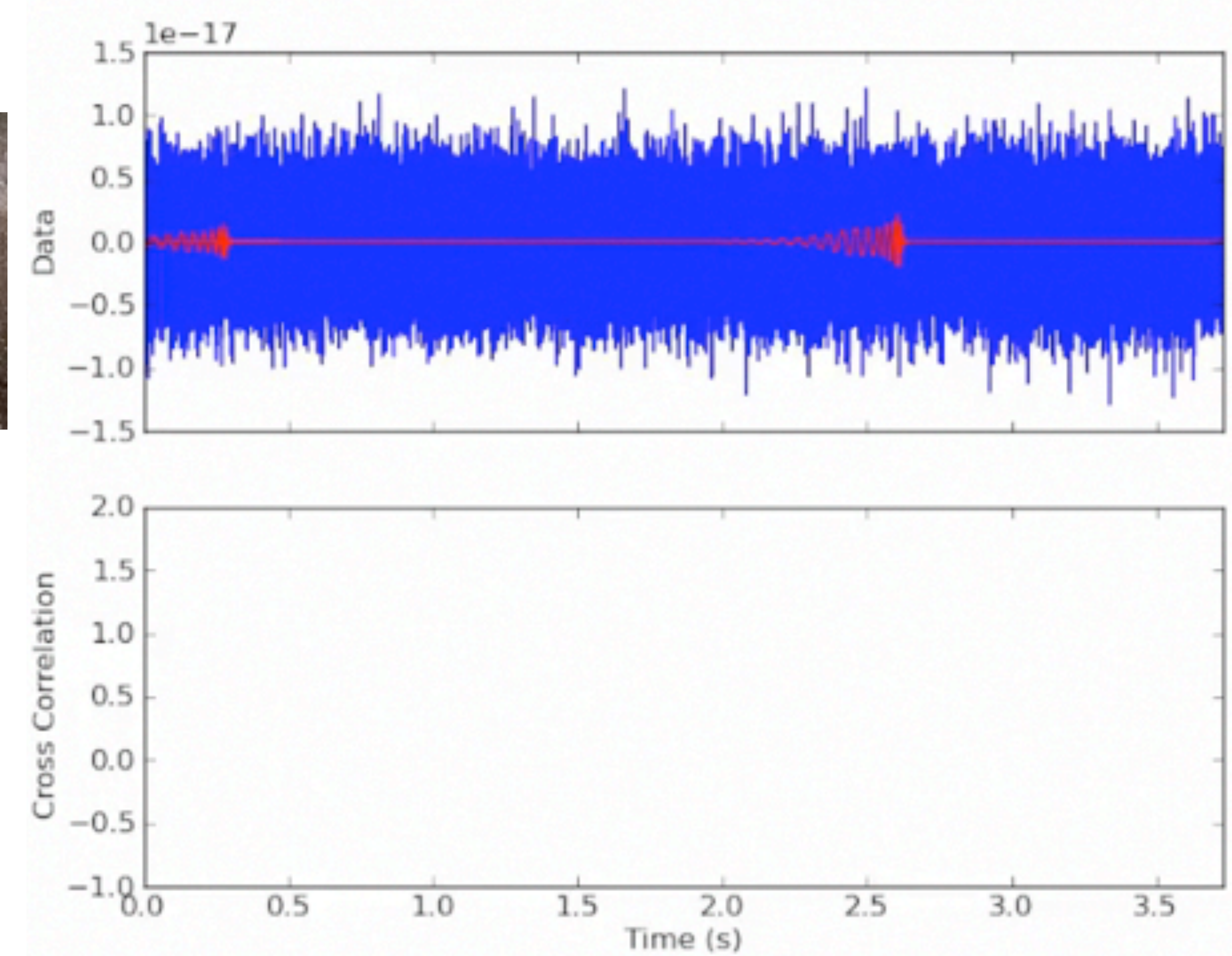
$$\chi_{1,2} \propto \vec{S_{1,2}} \cdot \hat{L}$$



Template Bank



Matched-filter signal-to-noise ratio



Formal Definition of Matched Filter

Cross-correlate data with template, weighted by detector noise:

$$Z(t) = A \int_{\infty}^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)e^{2\pi i f t}}{S_n(f)} df$$

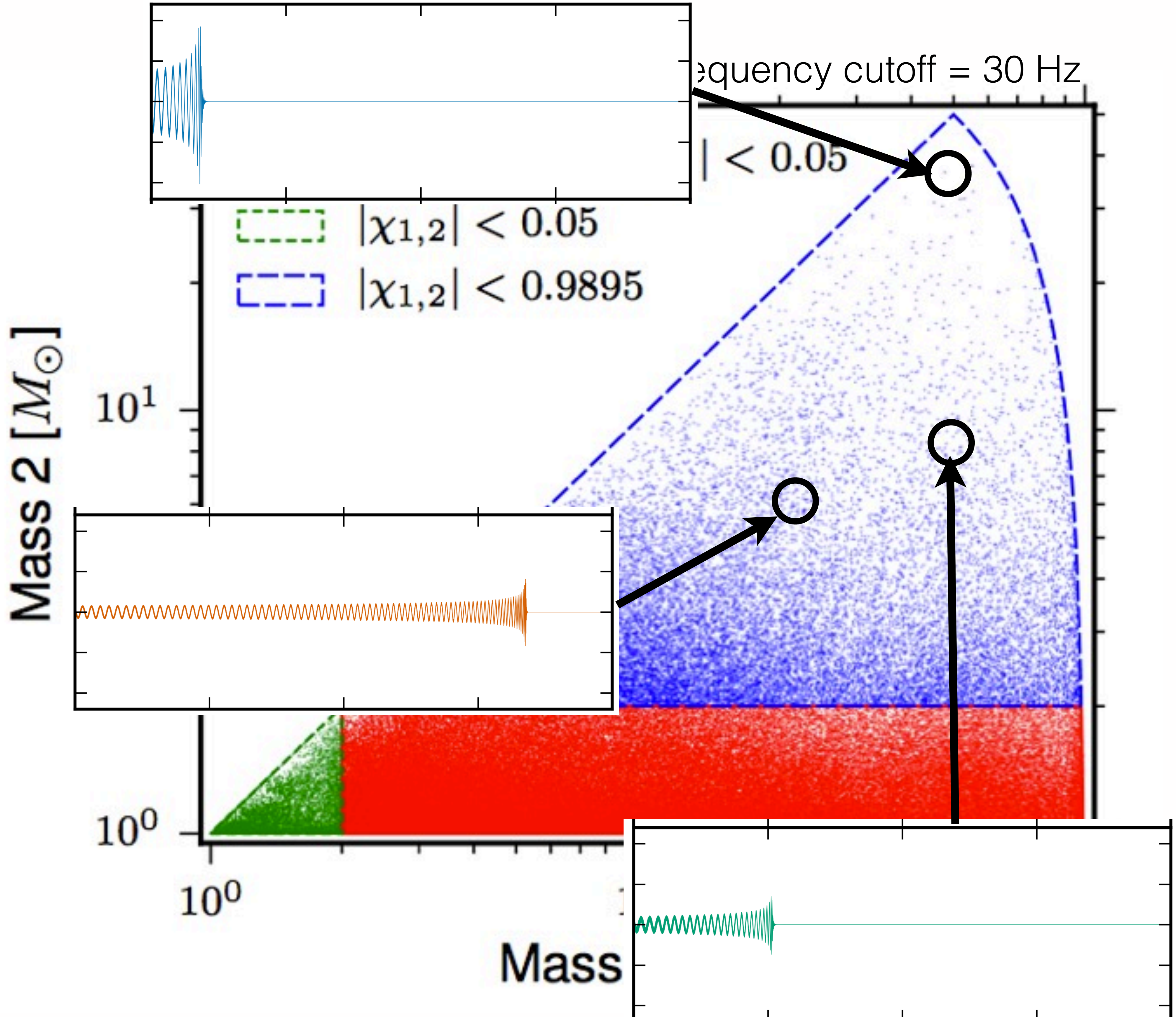
Cross-correlate template with template, weighted by detector noise:

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

Normalize output of optimal filter:

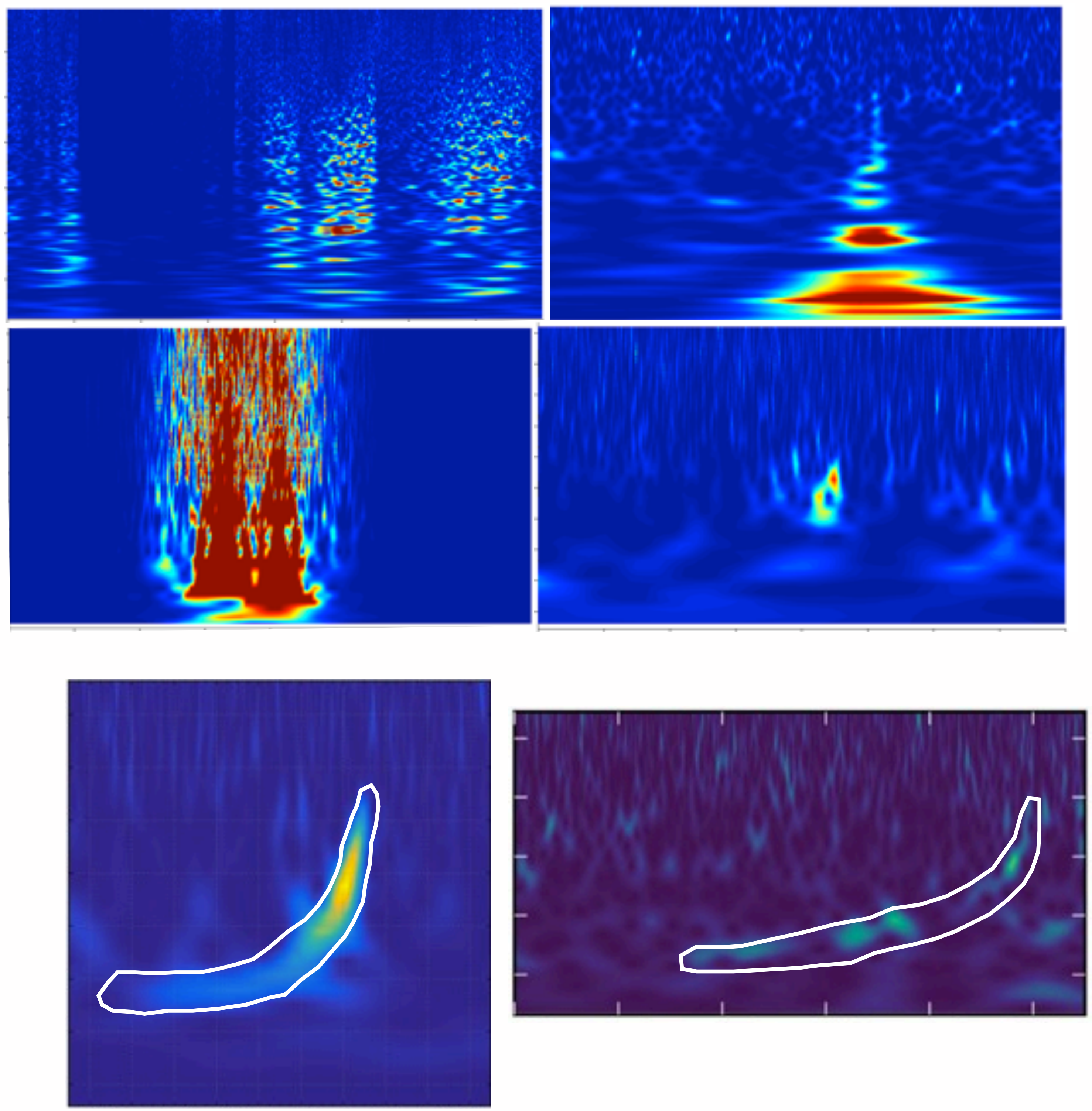
$$\rho(t) = \frac{|Z(t)|}{\sigma}$$

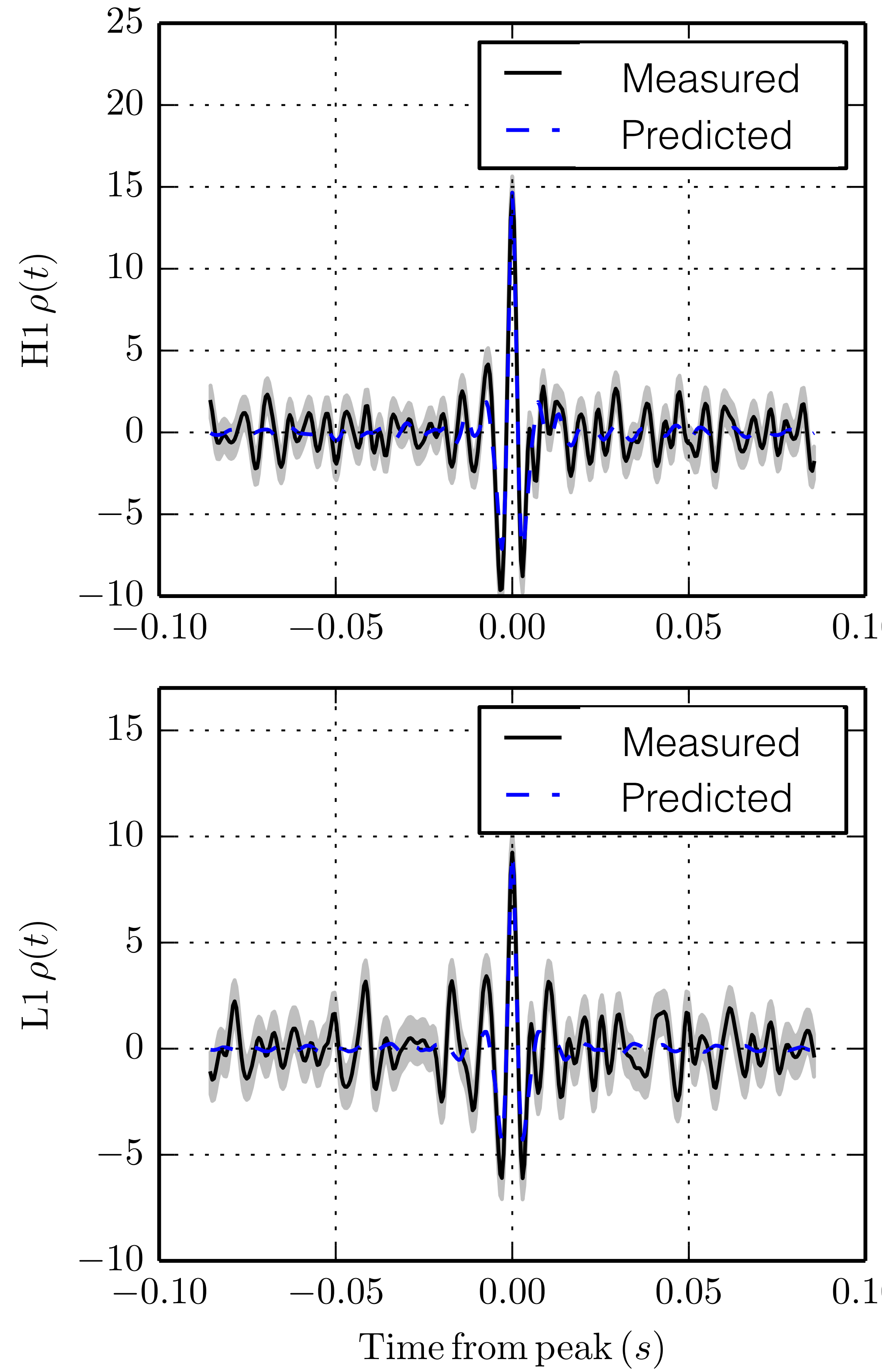
The O1 UberBank



Signal-based Vetoes

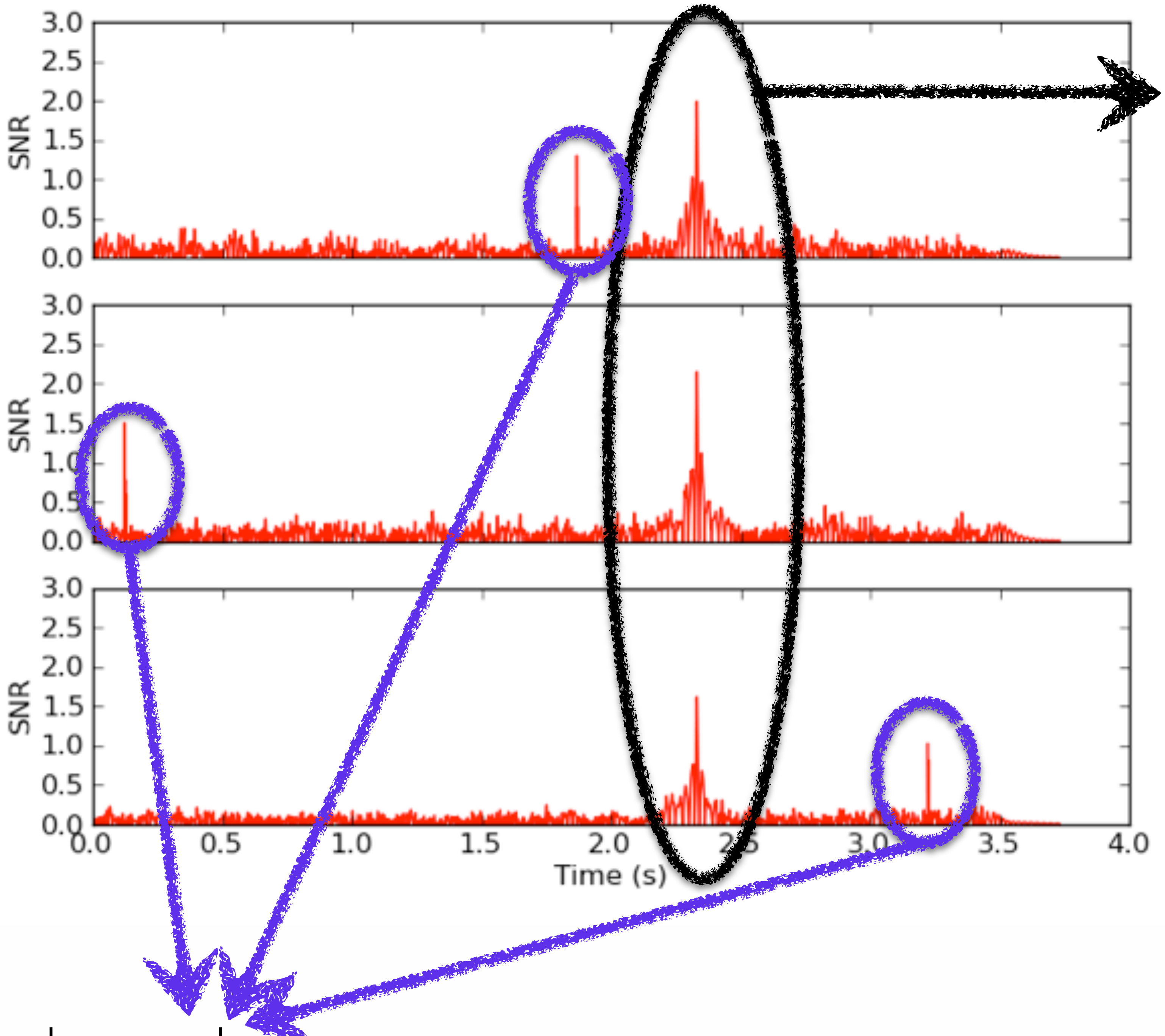
Time-frequency Spectrograms:
Glitches versus Signals





Messick, et al, arXiv 1604.04324

Coincident Triggers



Coincident GW candidate

Background noise model

Likelihood-based ranking statistic

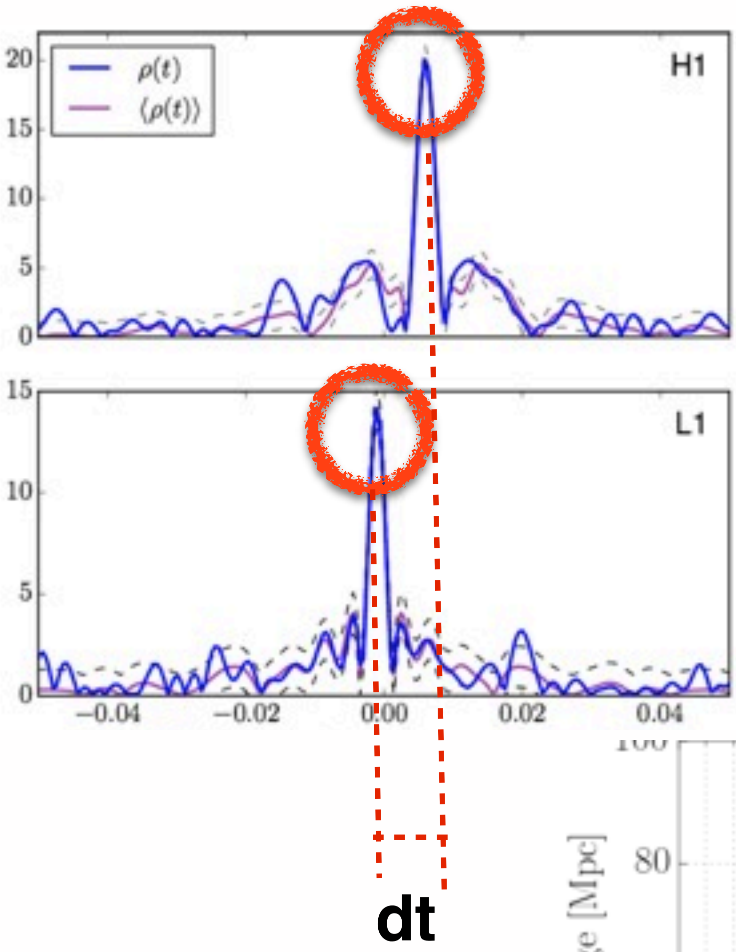
$$\mathcal{L} = \frac{P\left(d_{\mathrm{H}}, d_{\mathrm{L}} | \mathrm{signal}\right)}{P\left(d_{\mathrm{H}} | \mathrm{noise}\right) P\left(d_{\mathrm{L}} | \mathrm{noise}\right)}$$

Numerator: semi-analytic signal model

Denominator: background noise model

Likelihood Parameters

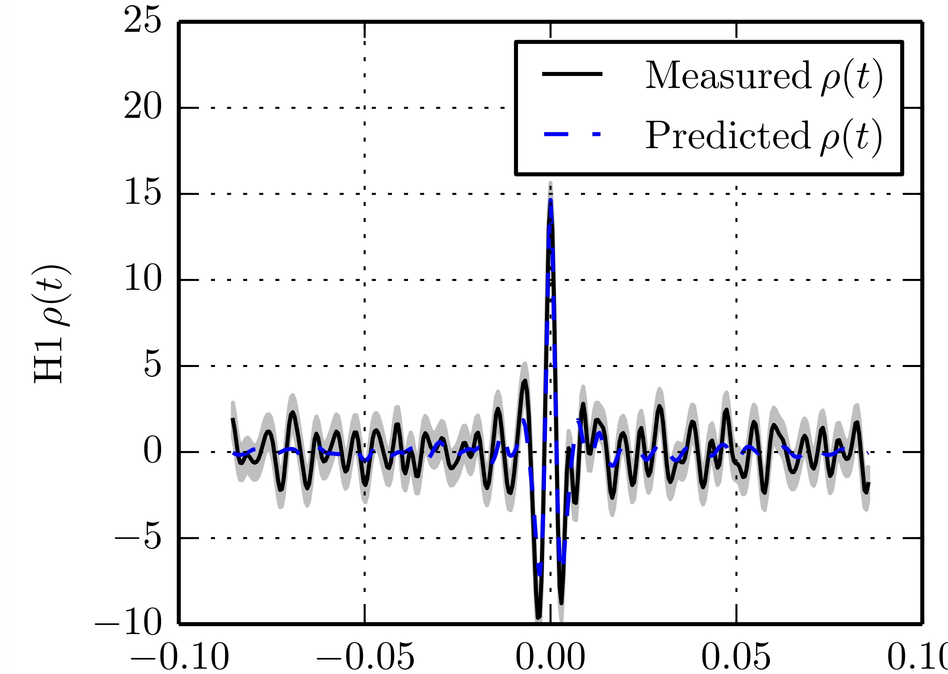
Signal-to-noise ratio



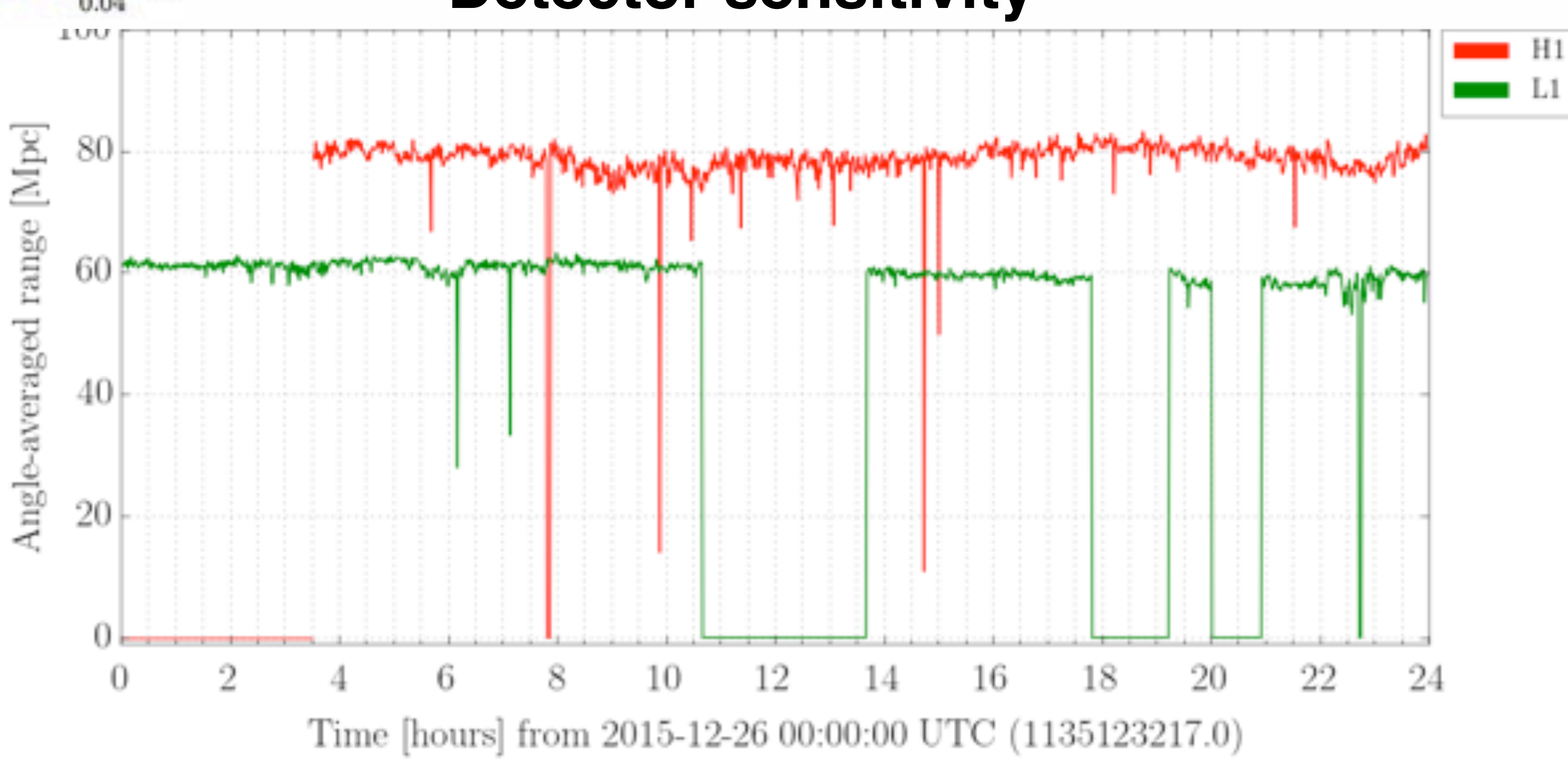
A multivariate ranking statistic

$$\mathcal{L} = \frac{P\left(d_{\mathrm{H}}, d_{\mathrm{L}} | \mathrm{signal}\right)}{P\left(d_{\mathrm{H}} | \mathrm{noise}\right) P\left(d_{\mathrm{L}} | \mathrm{noise}\right)}$$

Signal-based veto



Detector sensitivity

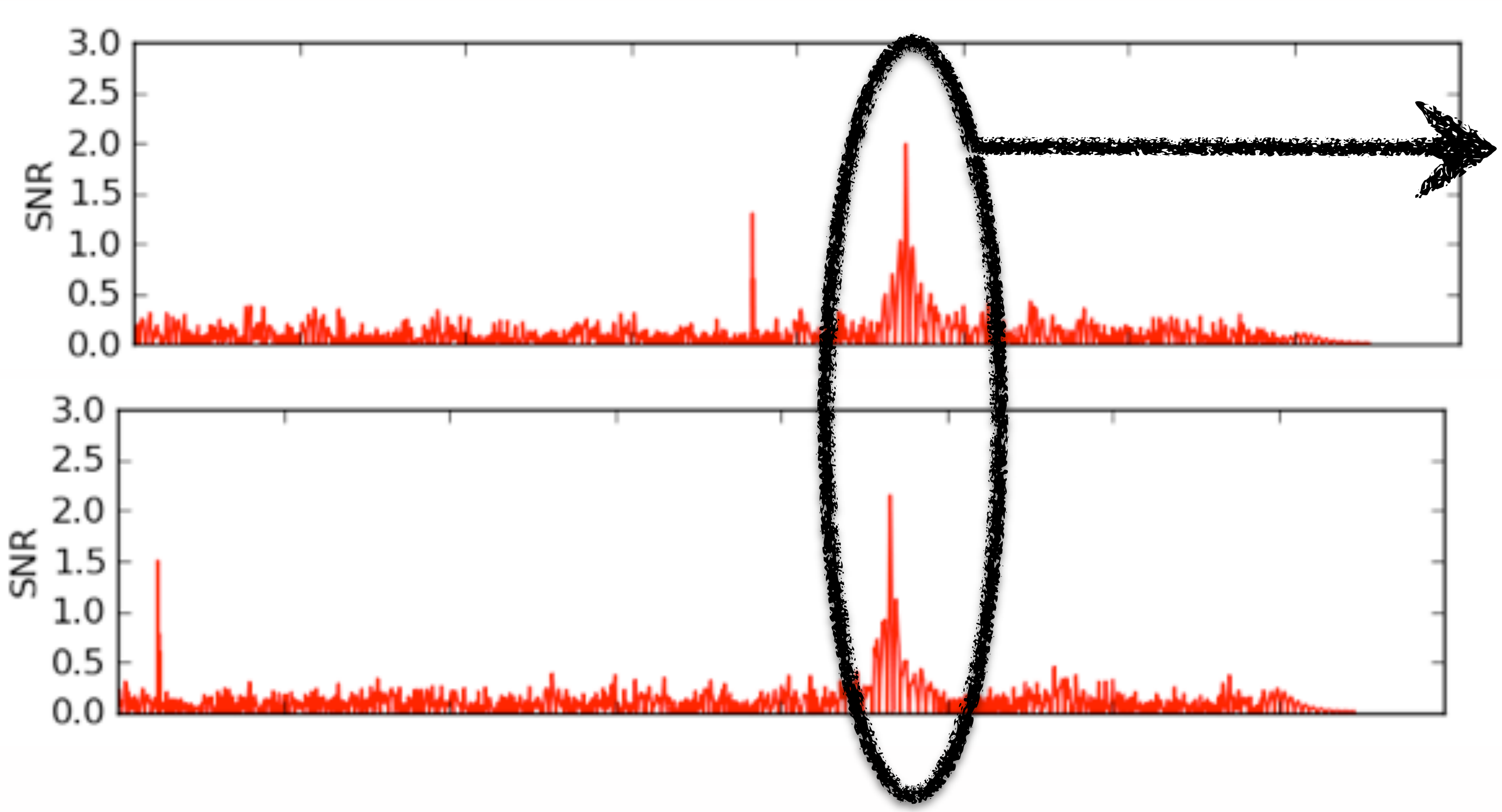


Estimating the Background

Two Methods

1. Time-shift
2. Non-coincident Triggers

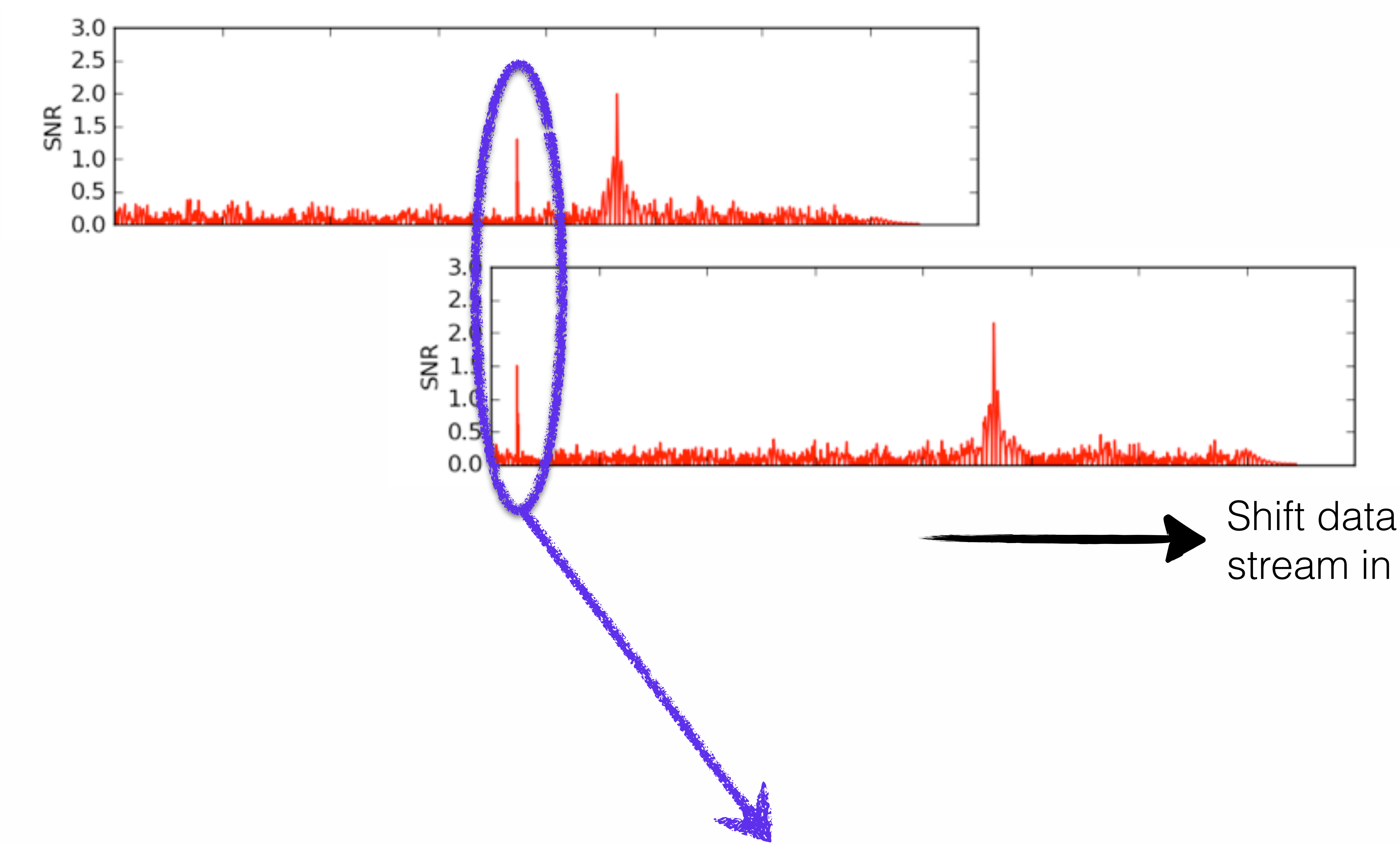
The Time-shift Method



Coincident GW candidate

Determine the rate by which detector noise produces an event with a detection statistic value equal to or higher than the candidate event.

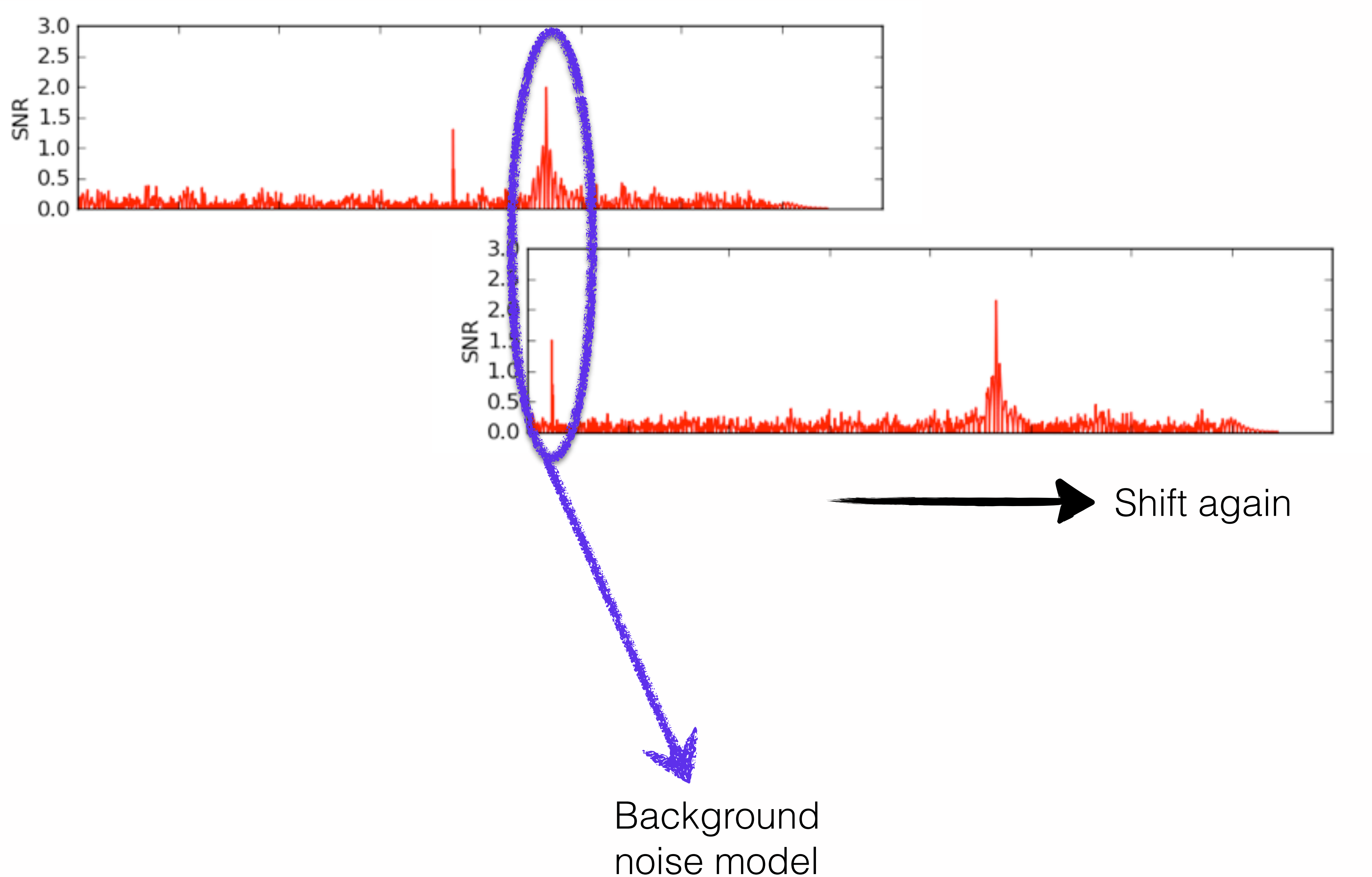
The Time-shift Method



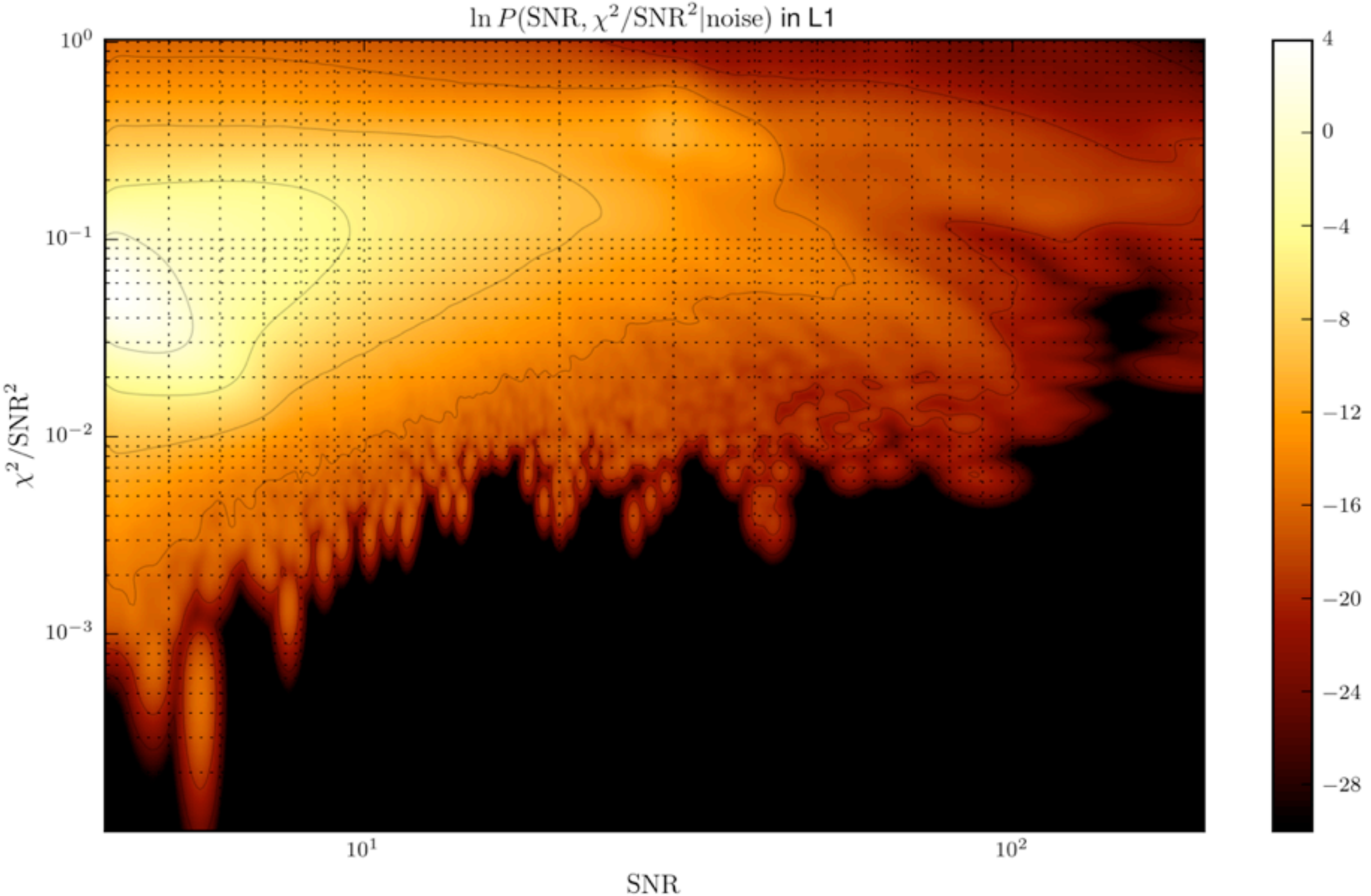
Shift data
stream in time

Background
noise model

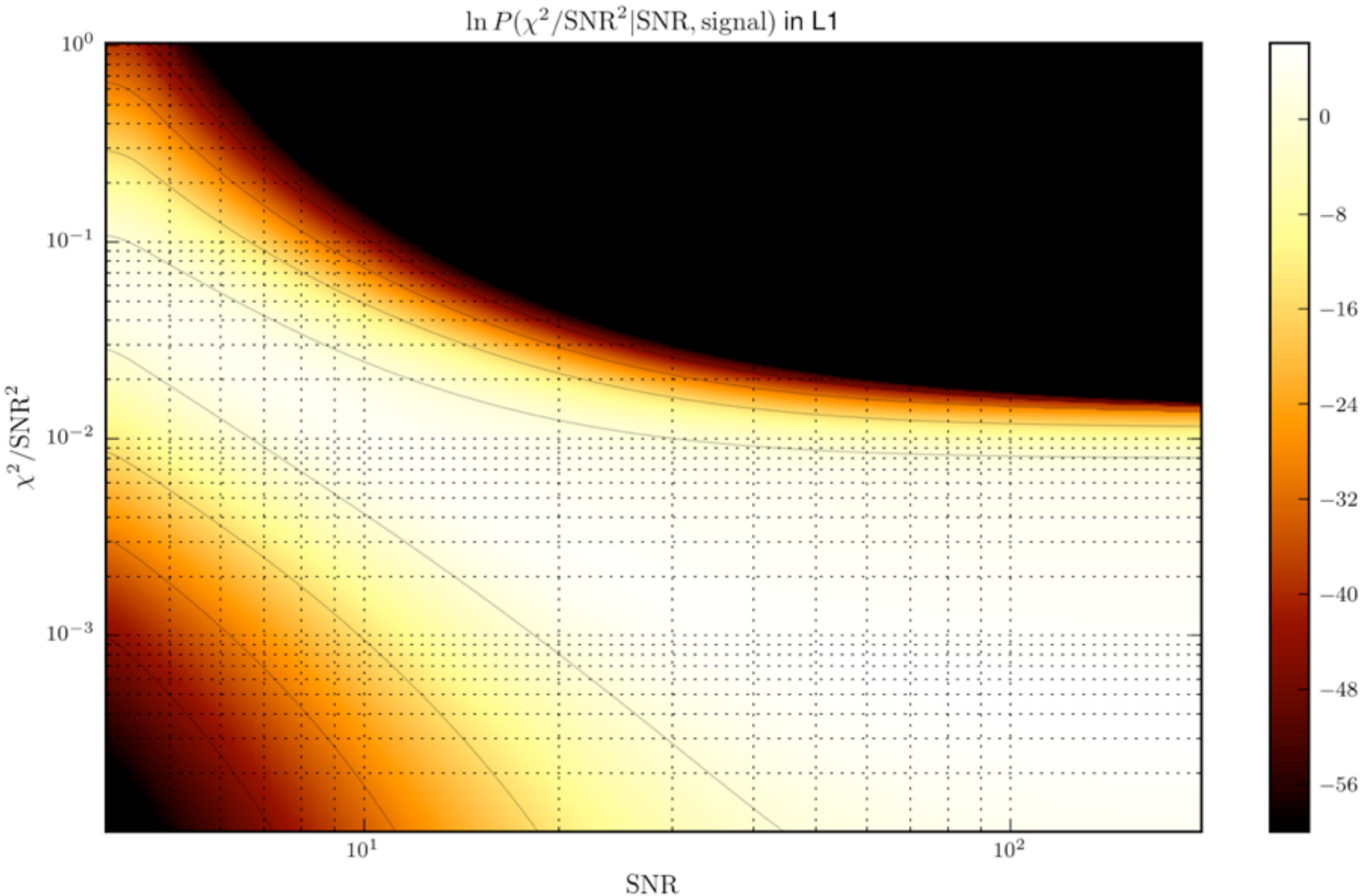
The Time-shift Method



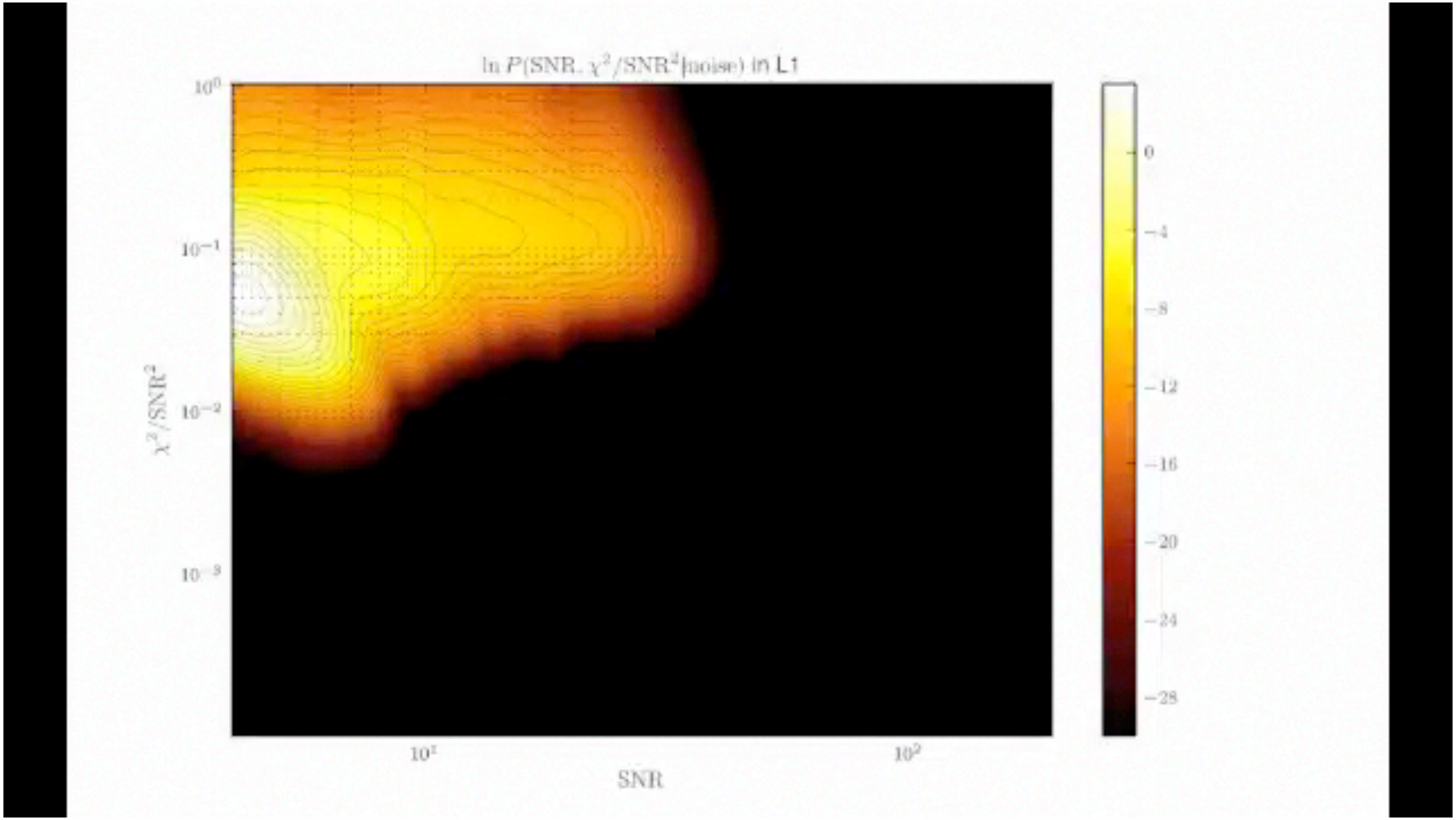
Background Noise Model



Signal Model



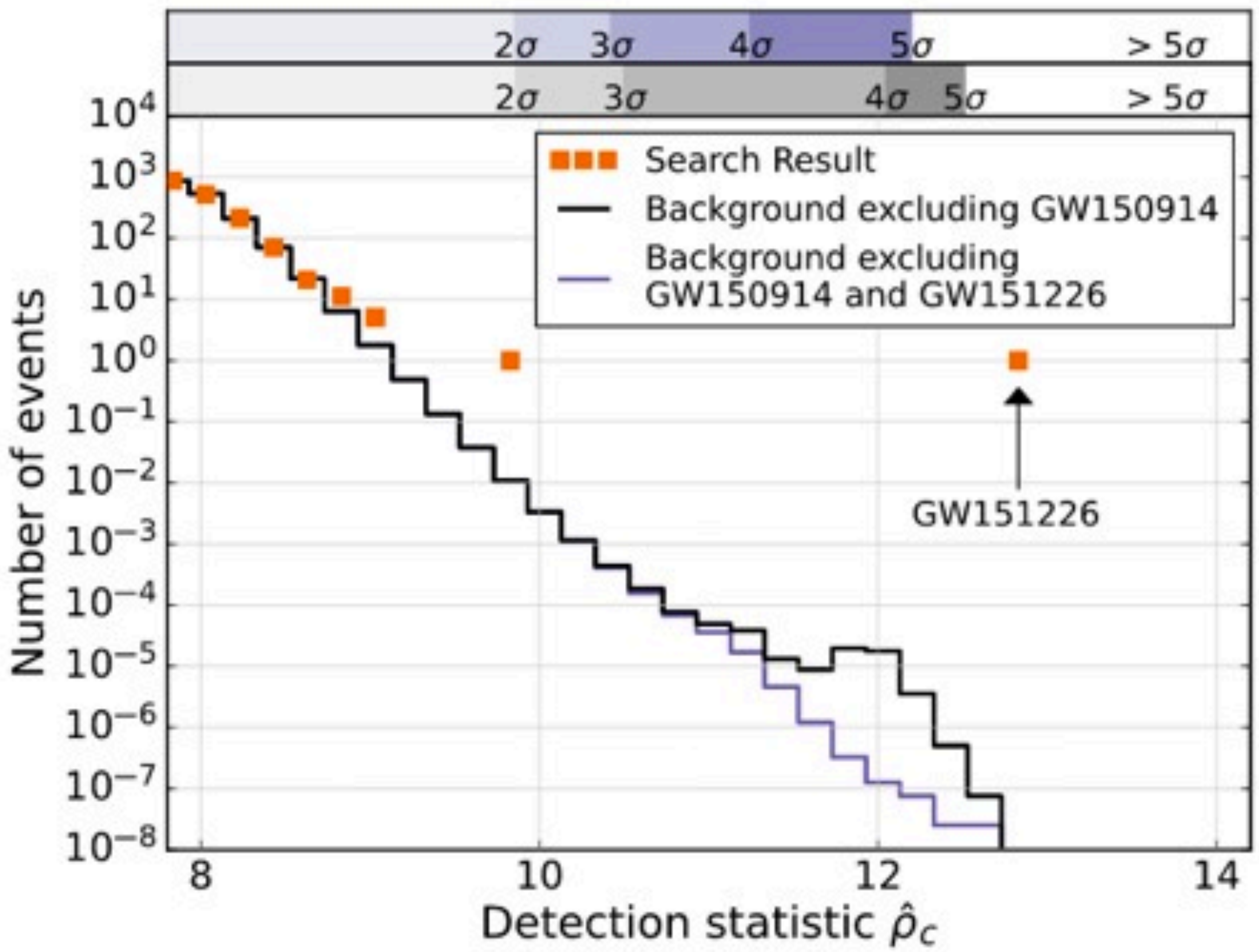
Evolution of Noise Model with Mass



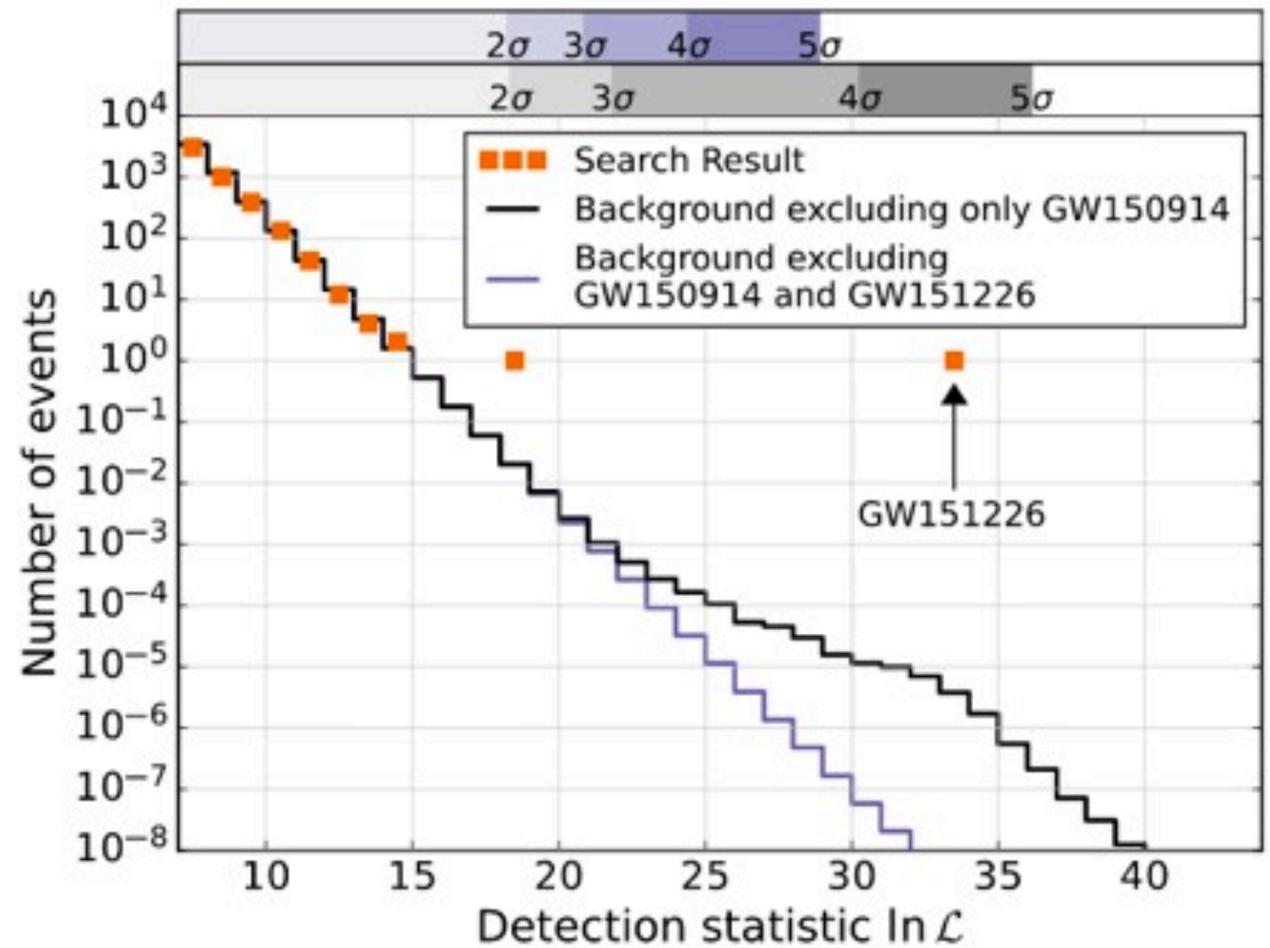
The search background is calculated separately for each mass and chi bin.

The Problem with the Timeshift Method

Timeshift Method



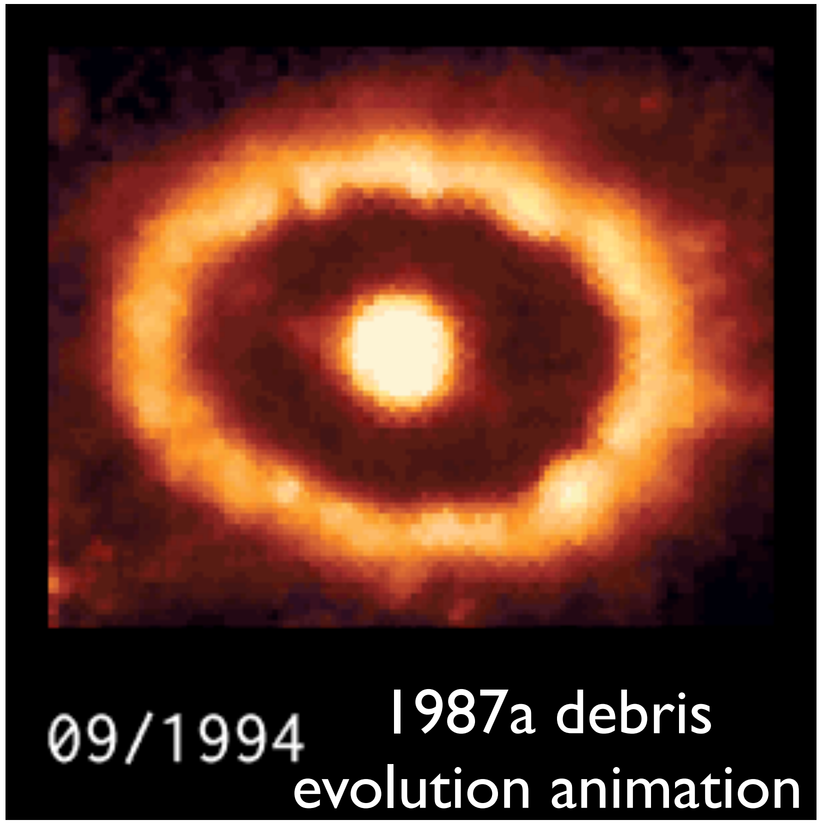
GstLAL Background Modeling Method

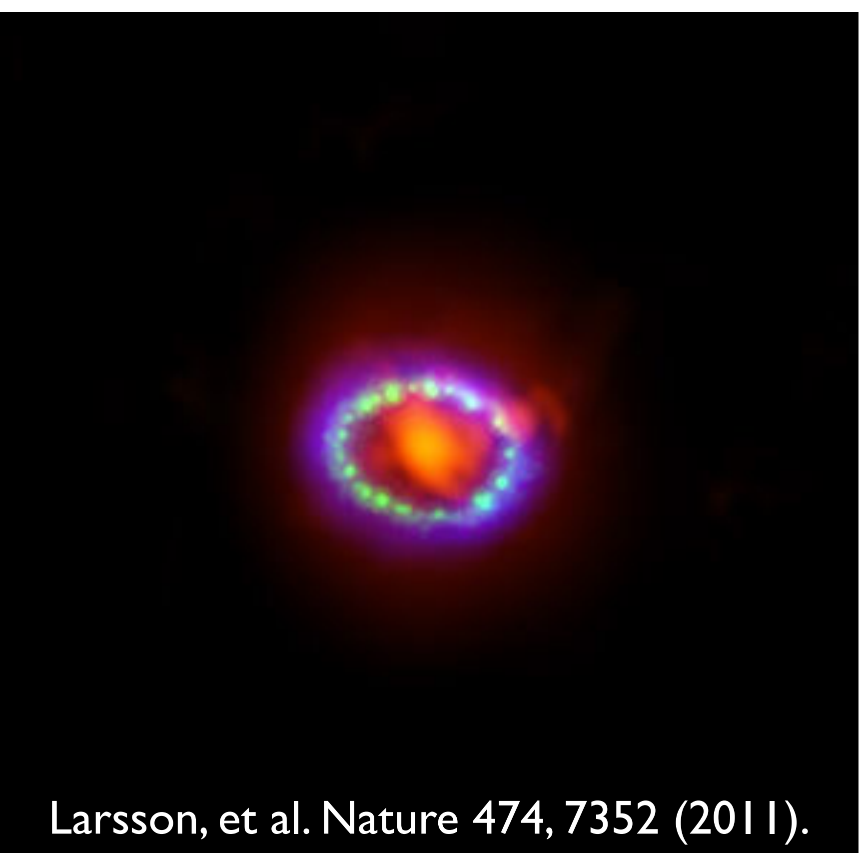


For a strong signal, the timeshift method is very unlikely to ever produce a timeshift coincidence at the same level of significance or higher.

1.2 Generic Transients

Burst Sources of Gravitational Waves





Transient GW astronomy using minimal assumptions. Sources could include:

- core collapse SN
- merger phase of binary compact objects
- NS instabilities
- accretion disk instabilities
- fall back accretion, cosmic string cusps/kinks
- unexpected...

Burst Search Method

Coherent excess power search in different detectors.

Require coincidence but do not enforce any particular time-frequency or phase evolution.

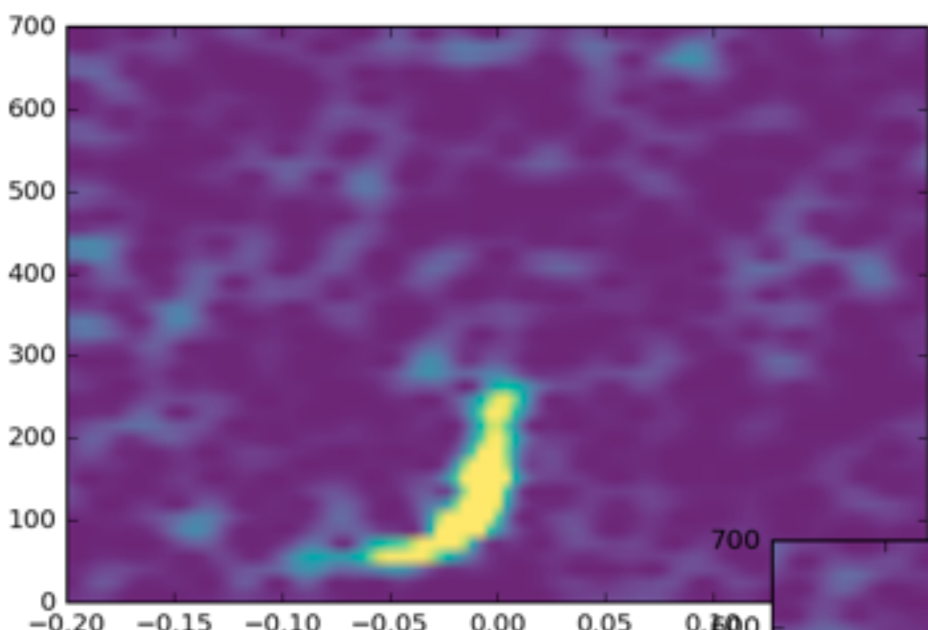
Search in time windows covering 10 ms-1000s.

Search in frequency bands covering 20Hz-5000Hz.

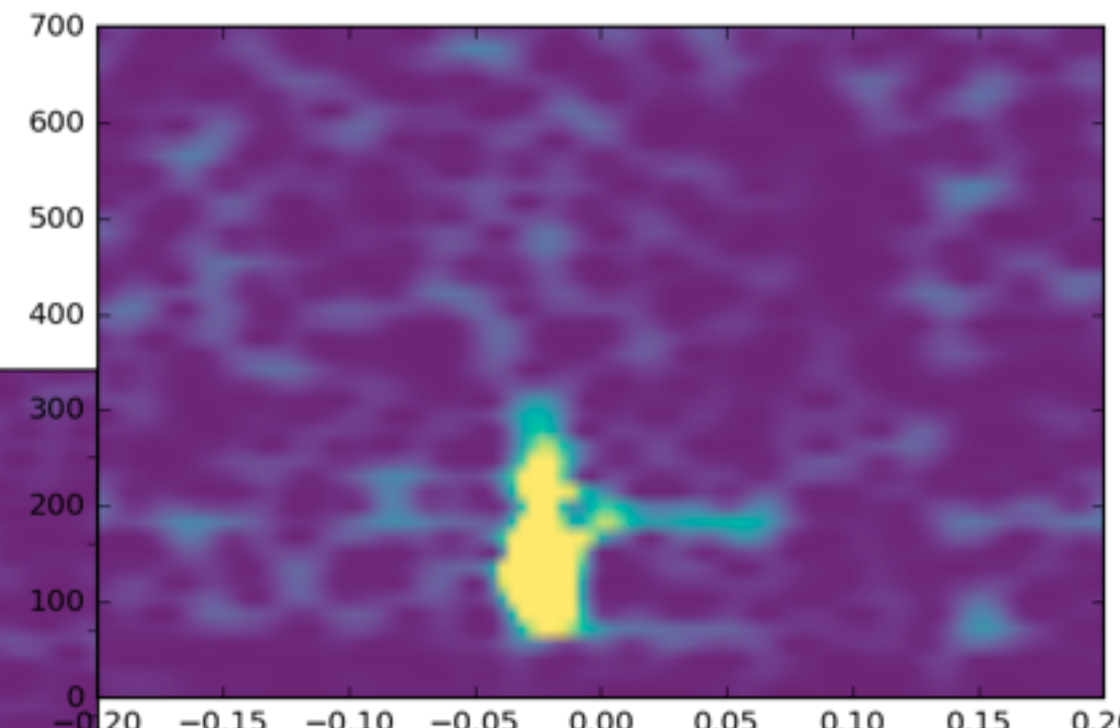
Burst Search Method

Some examples of excess power in the time-frequency domain:

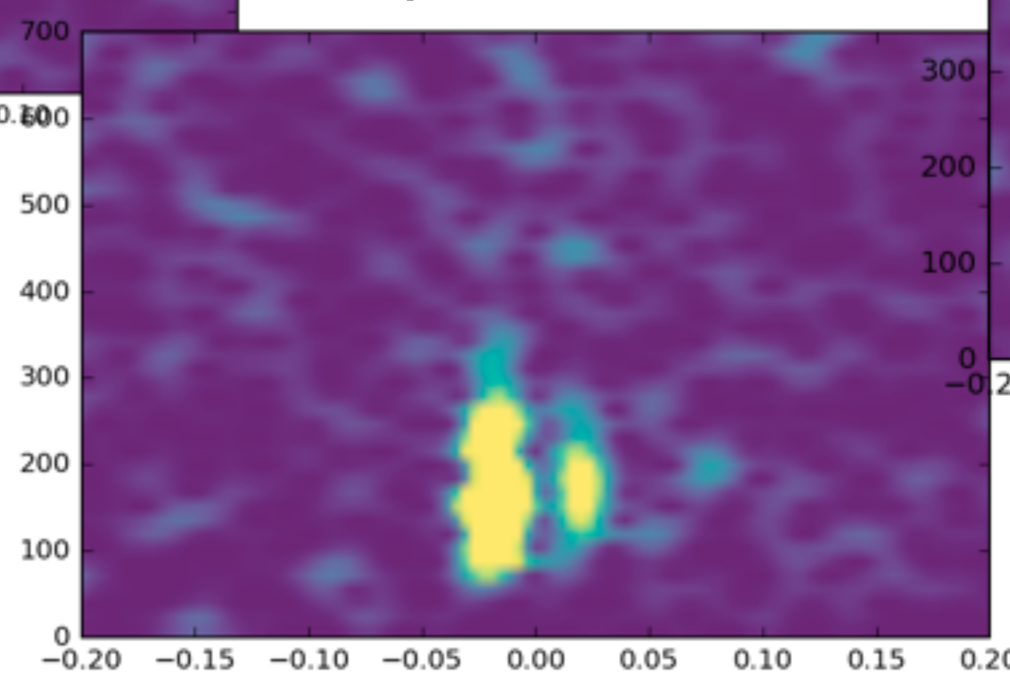
BBH



Cosmic String Cusp



Supernova



2.1 Stochastic Background

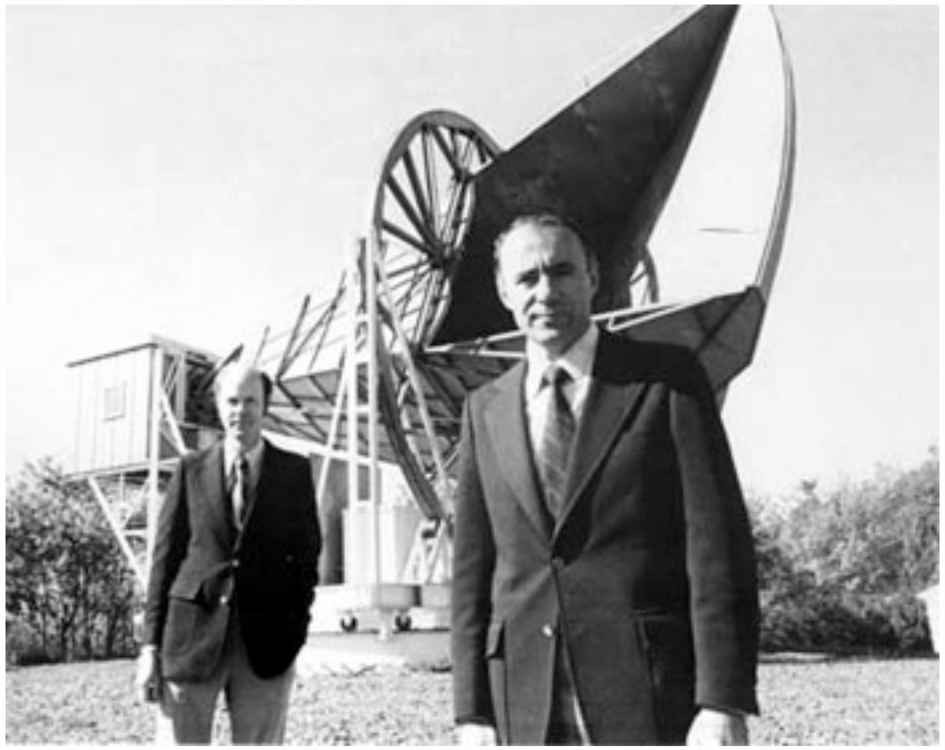
What is a stochastic background?

- Stochastic (random) background of gravitational radiation

- Can arise from superposition of large number of unresolved GW sources
  1. Cosmological origin
  2. Astrophysical origin

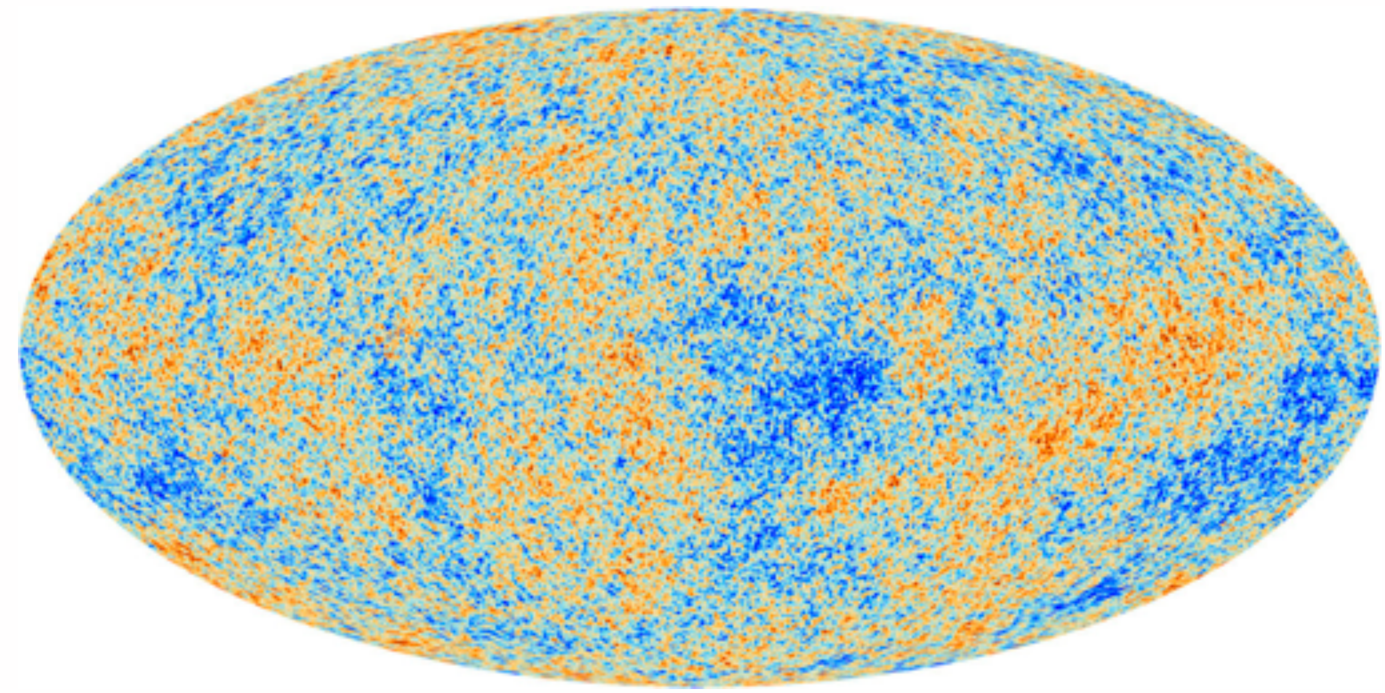
- Strength of background measured as gravitational wave energy density ρ_{GW}

Cosmic Microwave Background



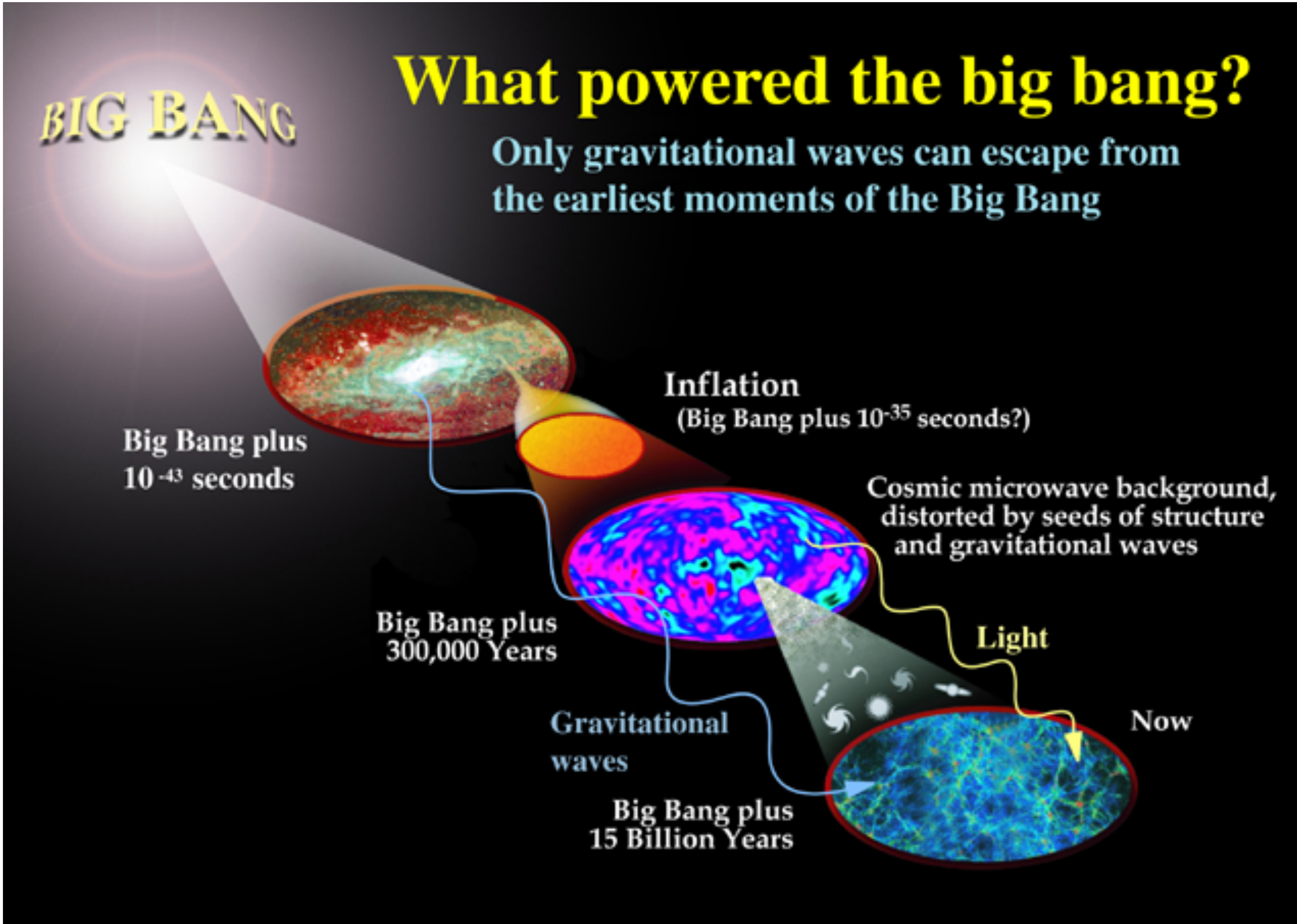
- 1965 - Penzias and Wilson accidently discovered Cosmic Microwave Background (CMB), leftover radiation from 380,000 years Big Bang

- 1978 - awarded Nobel prize

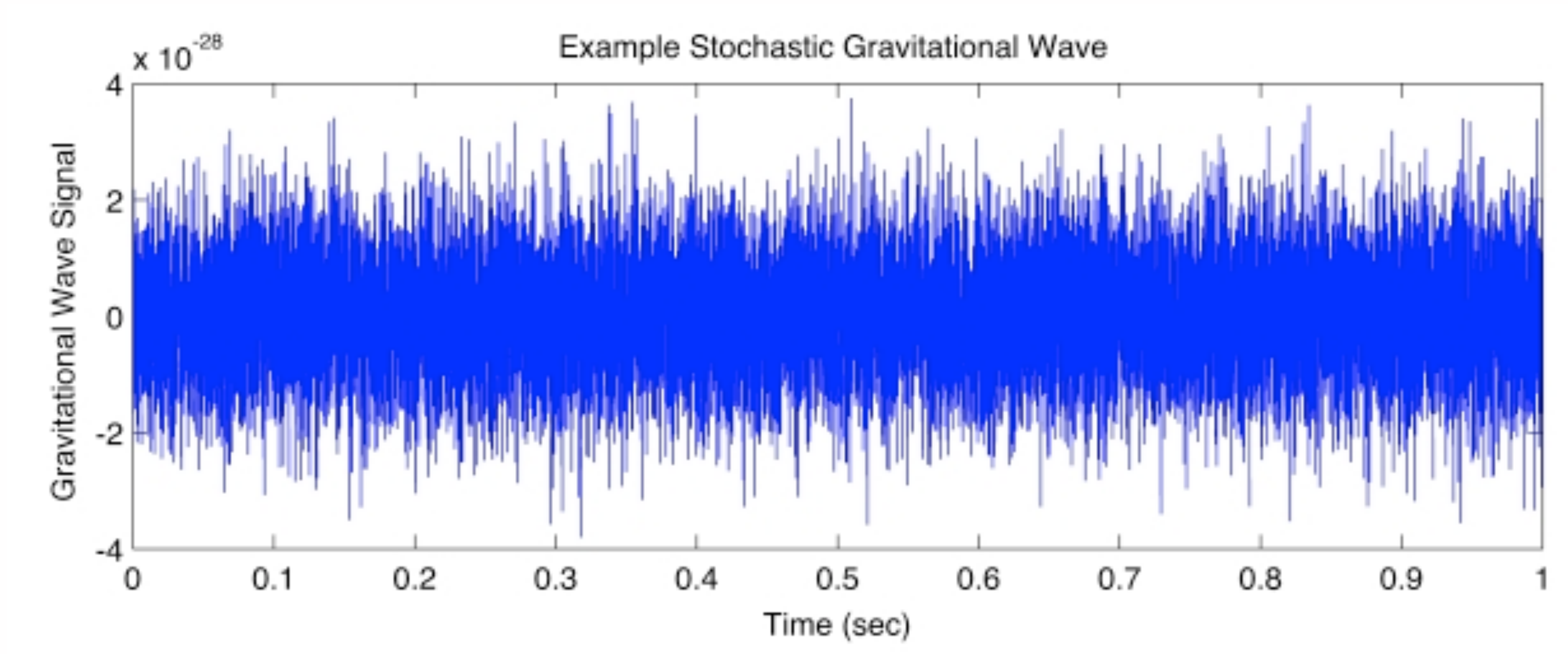


- CMB as seen by Planck, an ESA observatory
- Wavelengths of photons are greatly redshifted (1mm)
- Effective temperature ~ 2.7K
- Can be detected by far-infrared and radio telescopes

Cosmological Gravitational Wave Background



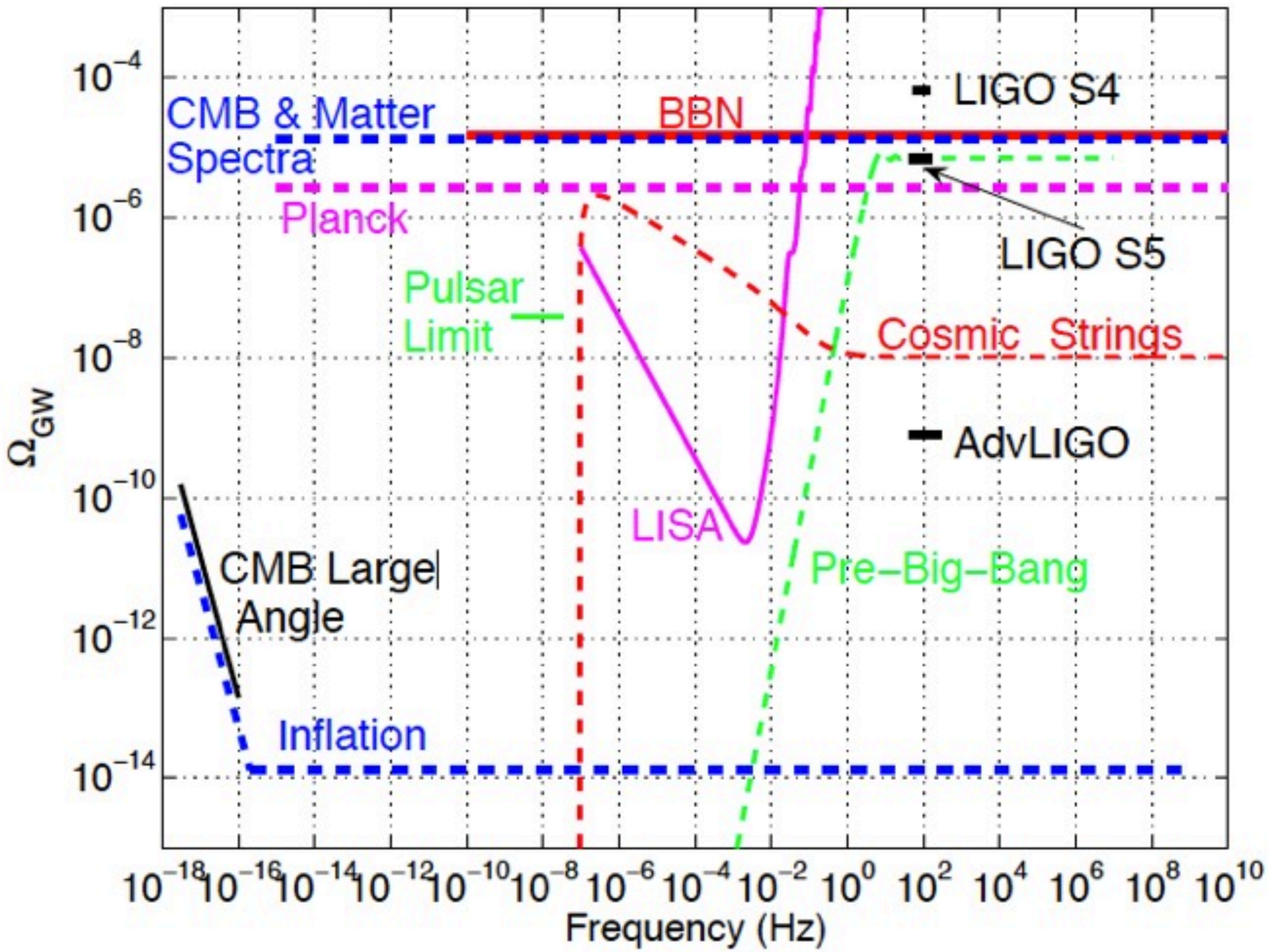
Cosmological Gravitational Wave Background



GW spectrum: $\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}f}$

Critical energy density of universe: $\rho_c = \frac{3c^2 H_0^2}{8\pi G}$

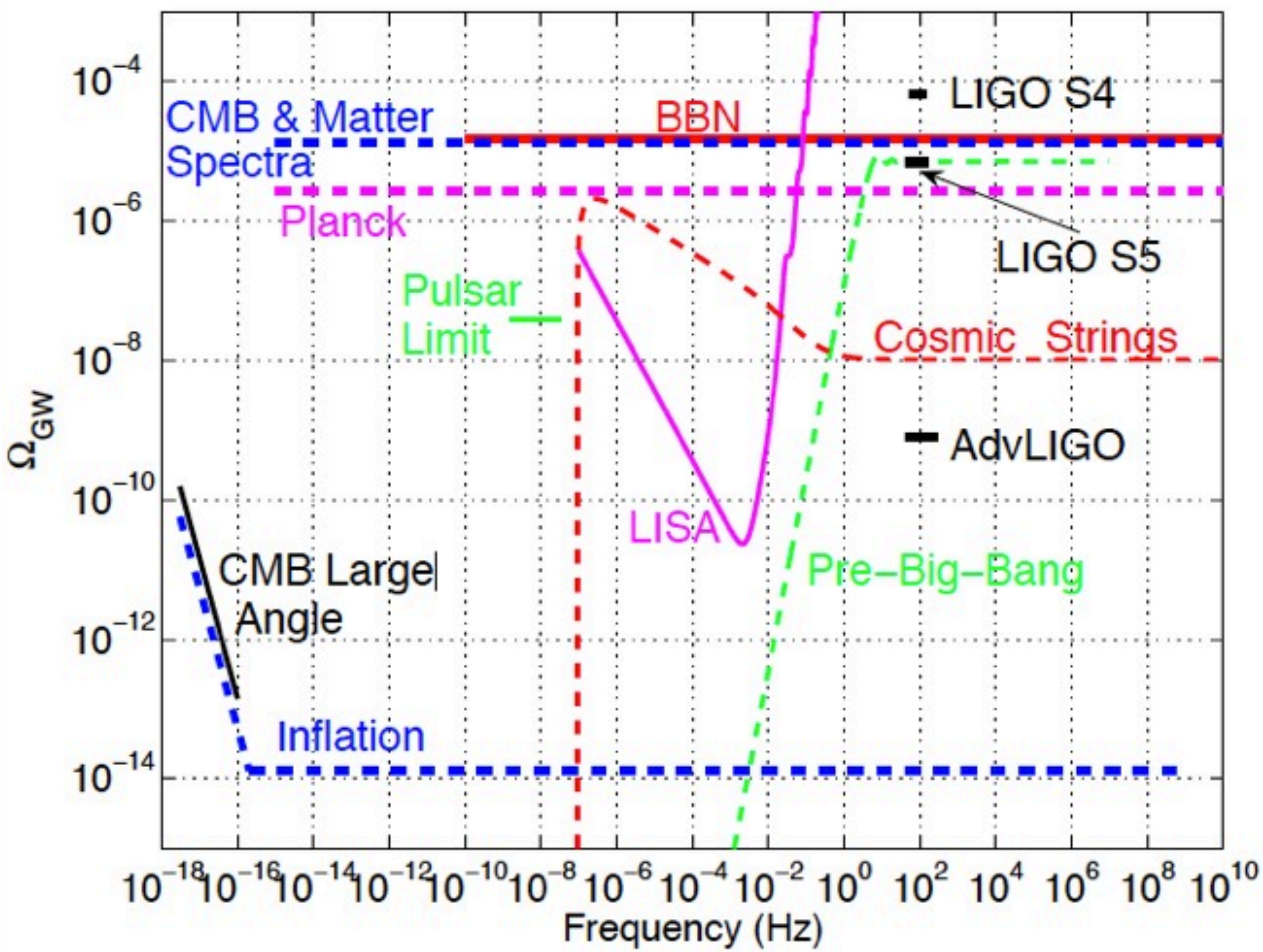
Cosmological Gravitational Wave Background



Big-Bang-Nucleosynthesis: abundances of light nuclei produced

Cosmic Microwave Background Measurements: structure of CMB and matter power spectra

Cosmological Gravitational Wave Background



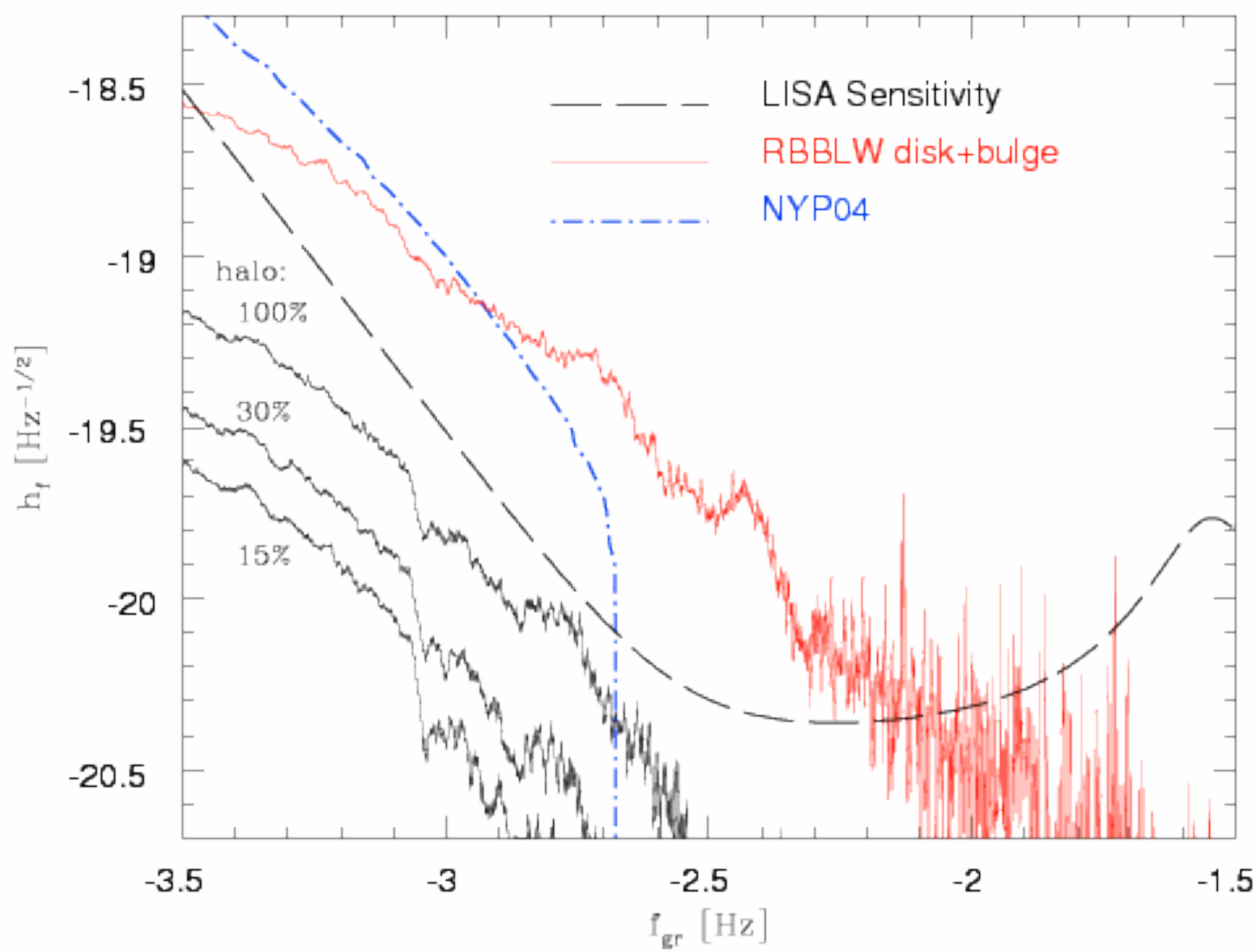
Inflation: measuring GWs can test for “stiffness” in early universe

Models of Cosmic Strings: topological defects in early universe

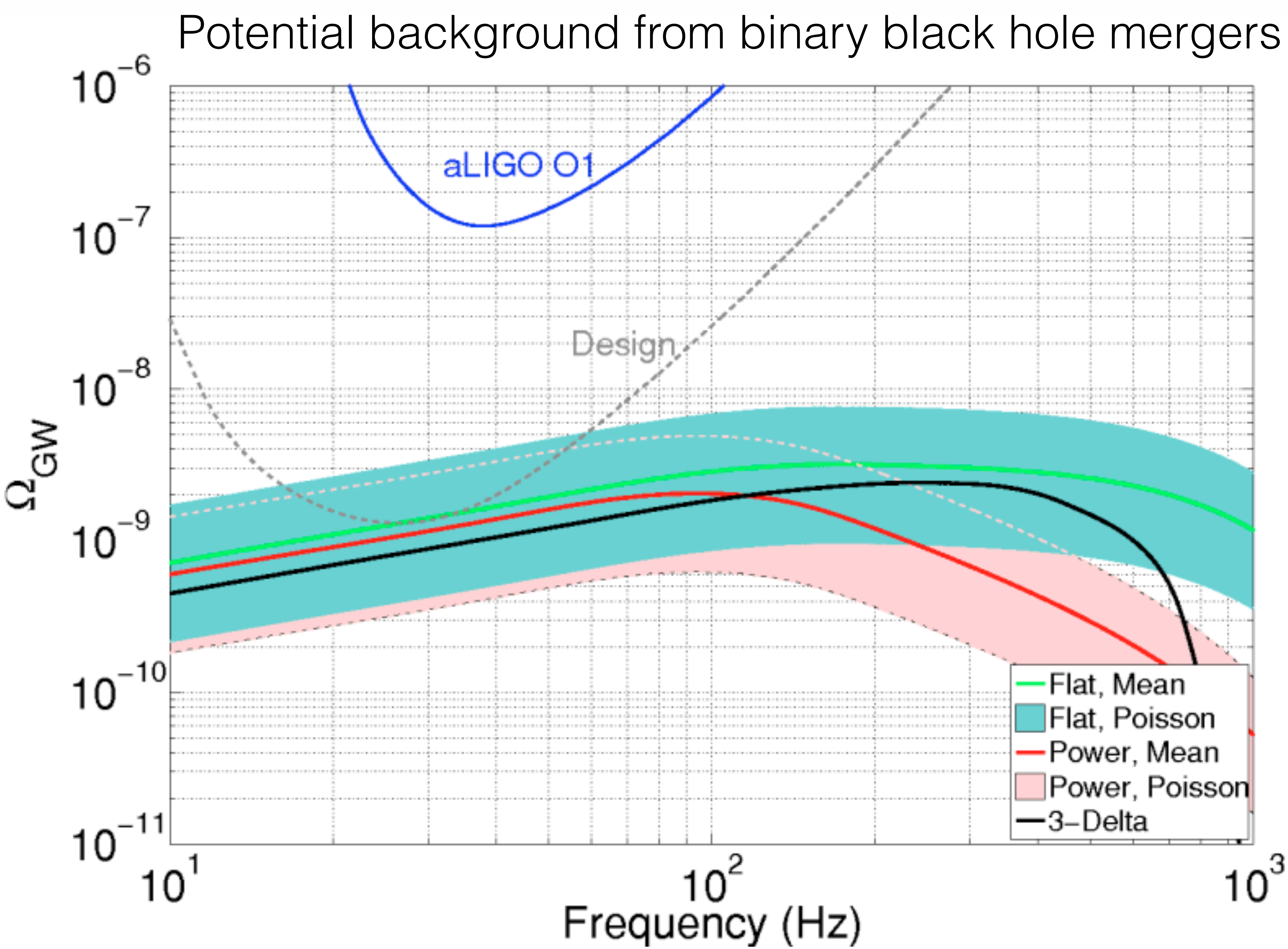
Astrophysical Gravitational Wave Backgrounds

- Produced by an extremely large number of weak, independent, and unresolved gravity-wave sources
  - Binary black holes and/or neutron stars
  - Supernovae
  - White dwarf binaries

For example, the expected contribution from double white dwarfs for LISA



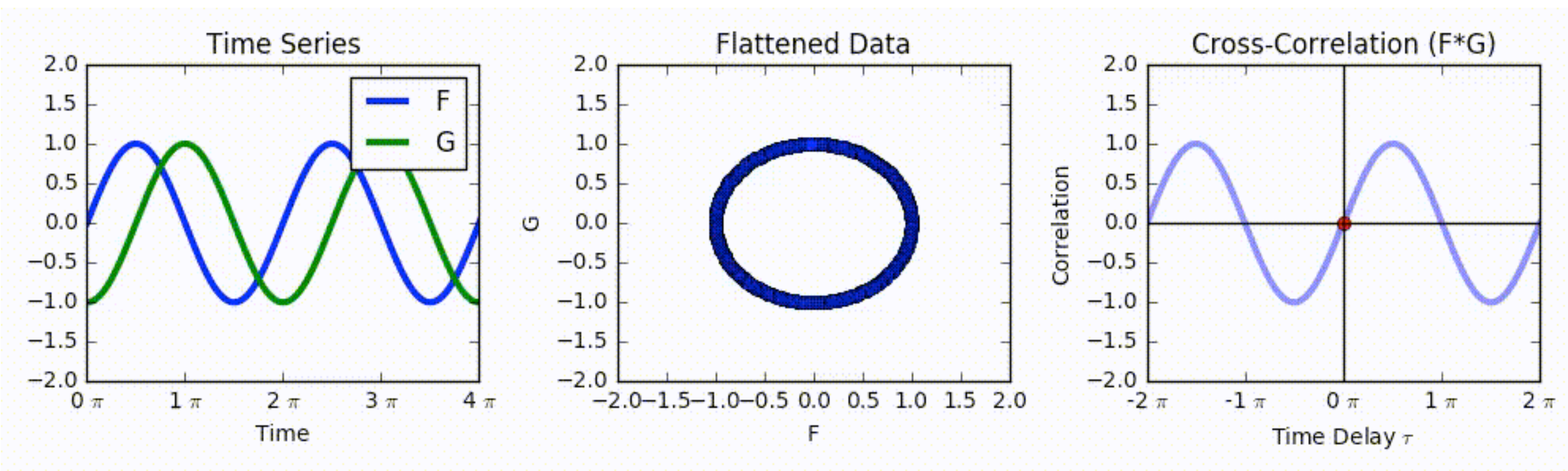
Astrophysical Gravitational Wave Backgrounds



Detecting Stochastic Backgrounds

Cross-correlation of two interferometers' data streams multiplied by a filter function:

$$Y = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df' \delta_T(f - f') \tilde{s}_1(f)^* \tilde{s}_2(f') \tilde{Q}(f')$$



Detecting Stochastic Backgrounds

The filter function has the form:

$$\tilde{Q}(f) = N \frac{\gamma(f)\Omega_{\mathrm{GW}}(f)H_0^2}{f^3 P_1(f) P_2(f)}$$

overlap reduction function: $\gamma(f)$

power law template for GW spectrum: $\Omega_{\mathrm{GW}}(f) = \Omega_\alpha \left(f/100\,\mathrm{Hz}\right)^\alpha$

present value of Hubble parameter: H_0

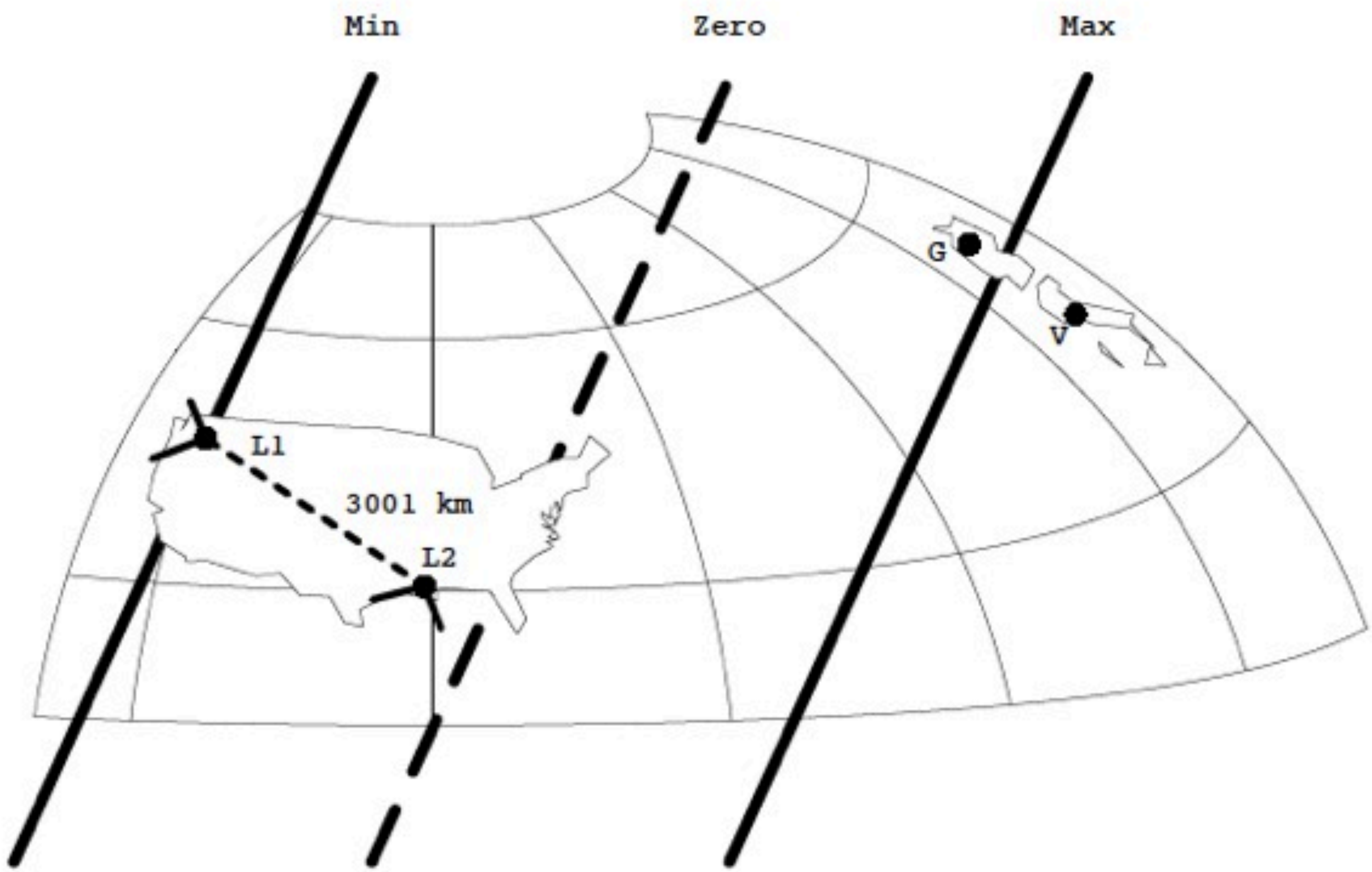
noise in detector 1: $P_1(f)$

noise in detector 2: $P_2(f)$

Purpose: Enhance SNR at frequencies where signal is strong and suppress SNR at frequencies where detector noise is large.

Overlap Reduction Function

Signal in two detectors will not be exactly the same because:
i) time delay between detectors
ii) non-alignment of detector

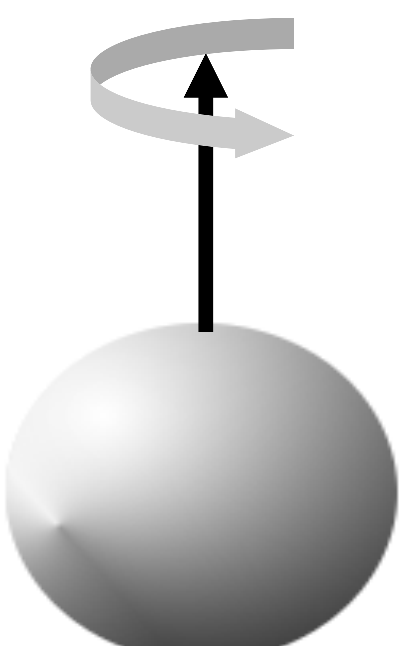


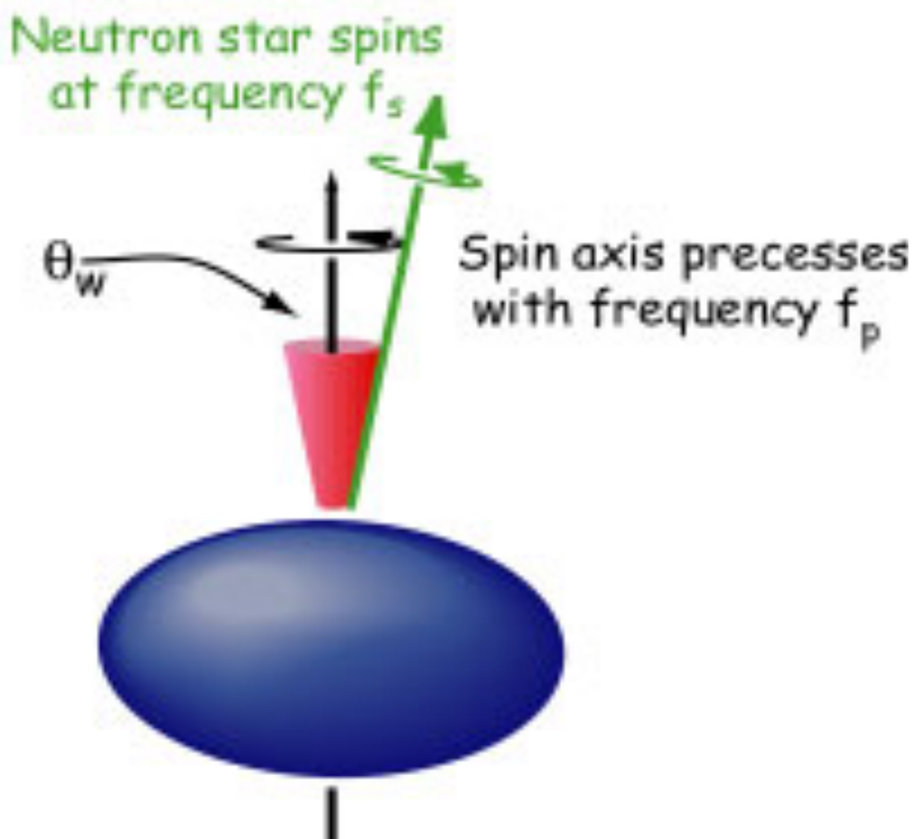
2.2 Spinning Neutron Stars

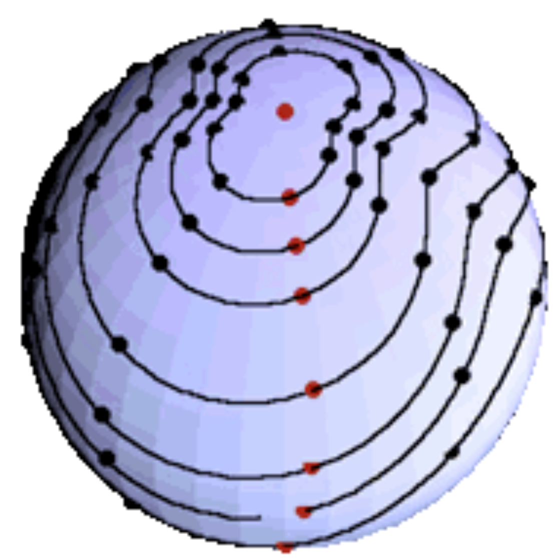
Continuous Gravitational Wave Searches

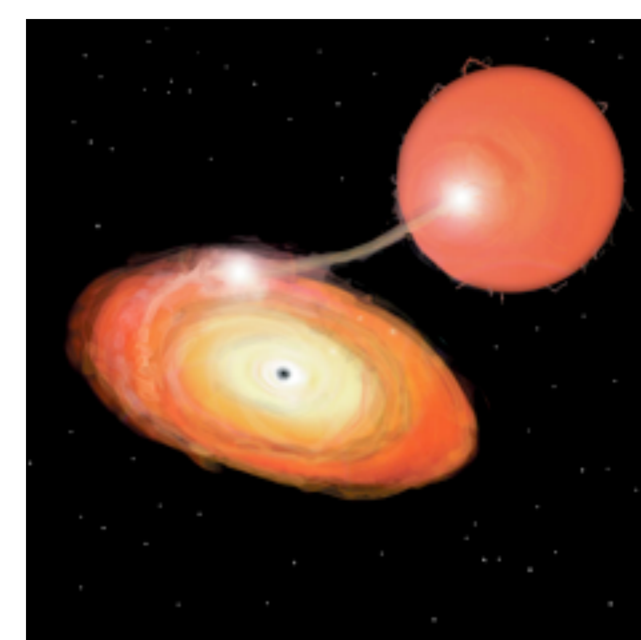
Non-axisymmetric rotating neutron stars;
asymmetry could arise from:

- equatorial ellipticity (mm-high mountain) $f_{\mathrm{GW}} = 2 f_{\mathrm{rot}}$
- free precession around rotation axis $f_{\mathrm{GW}} \sim f_{\mathrm{rot}} + f_{\mathrm{prec}}$
- excitation of long-lasting oscillations $f_{\mathrm{GW}} \sim 4/3 f_{\mathrm{rot}}$
- deformation due to matter accretion $f_{\mathrm{GW}} = 2 f_{\mathrm{rot}}$









Continuous Gravitational Wave Searches

Continuous signal with $h \propto \epsilon$ $\quad$ $\mathrm{SNR} \propto \frac{h}{\sqrt{S_n}}\sqrt{T}$

Equatorial ellipticity $\epsilon = \frac{I_{\mathrm{XX}} - I_{\mathrm{YY}}}{I_{\mathrm{ZZ}}}$

Maximum Deformations

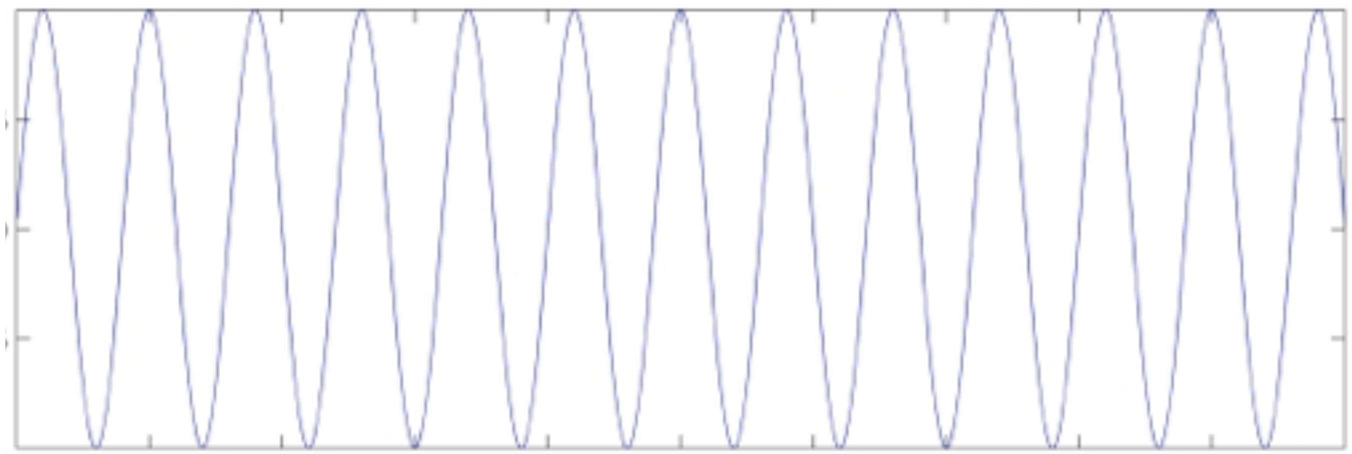
$\epsilon < 10^{-5}$ Normal Neutron Star

$\epsilon < 10^{-3}$ Hybrid Neutron Star

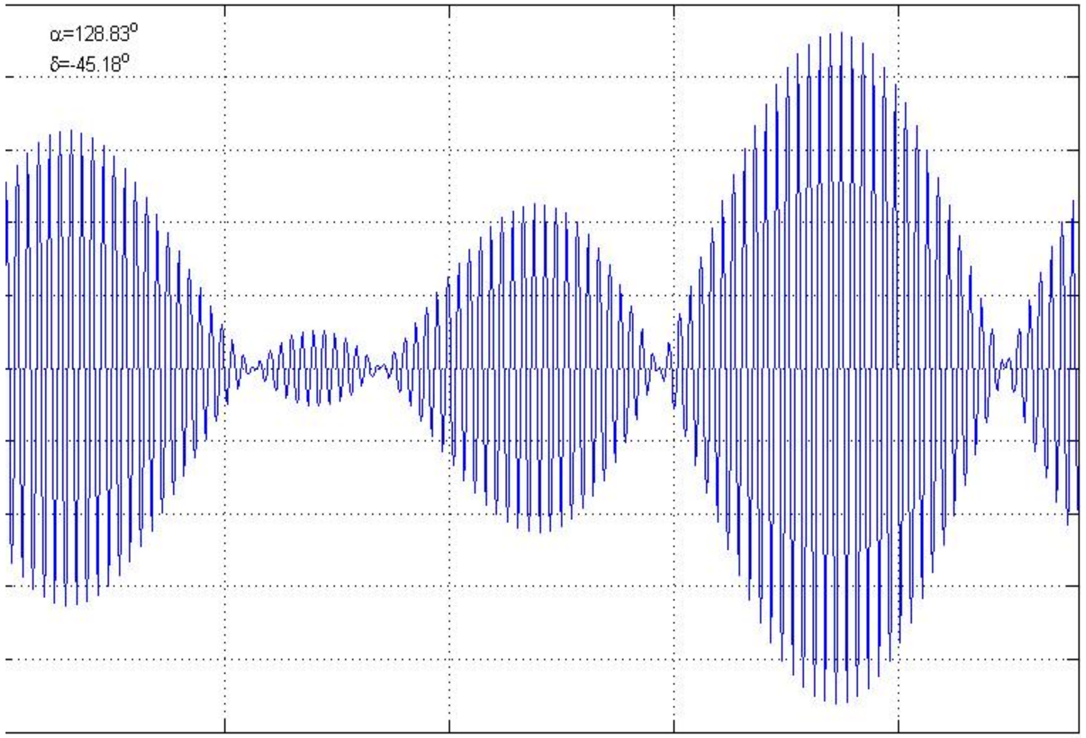
$\epsilon < 10^{-1}$ Extreme Quark Star

Complications with “Continuous” Waves

At the source



At the detector

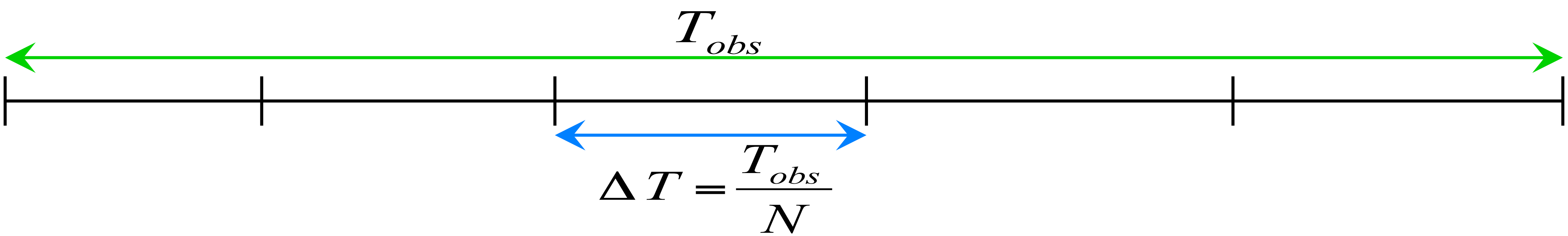


Nearly monochromatic, continuous signal but could have:

- relative velocity between source/detector (Doppler Effect)
- amplitude modulation due to antenna sensitivity of detector
- frequency and phase evolution

Blind Continuous Gravitational Wave Searches

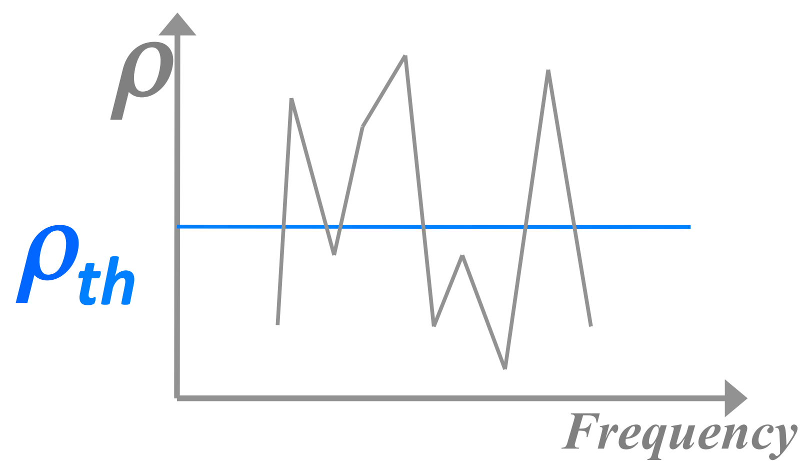
Break up data into segments and Fourier transform each segment:



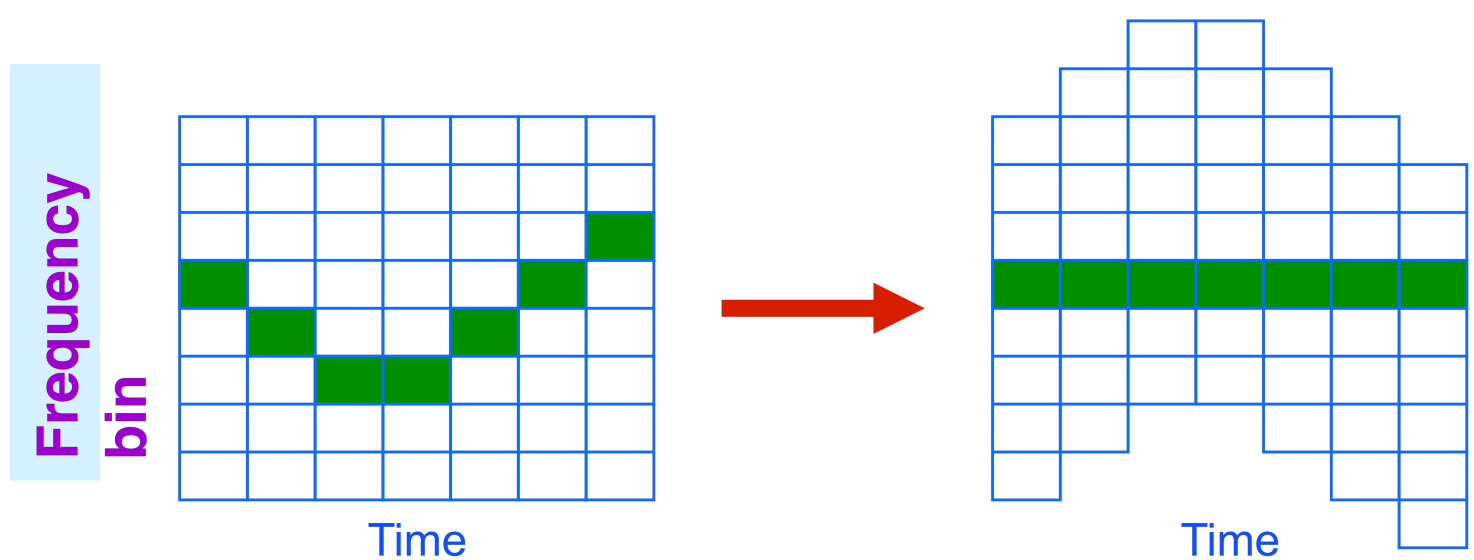
Search over parameter space of angles to source, spindown parameters, etc.

Blind Continuous Gravitational Wave Searches

Keep frequency-time bins where power exceeds a given threshold:



Use pattern recognition to see if some of the bins fall along a curve:



Einstein@home

https://einsteinathome.org

Einstein@Home uses your computer's idle time to search for weak astrophysical signals from spinning neutron stars (often called pulsars) using data from the LIGO gravitational-wave detectors, the Arecibo radio telescope, and the Fermi gamma-ray satellite.

Einstein@Home volunteers have already discovered about fifty new neutron stars, and we hope to find many more.