VESF school 2013

# Searching for compact binary coalescence signals

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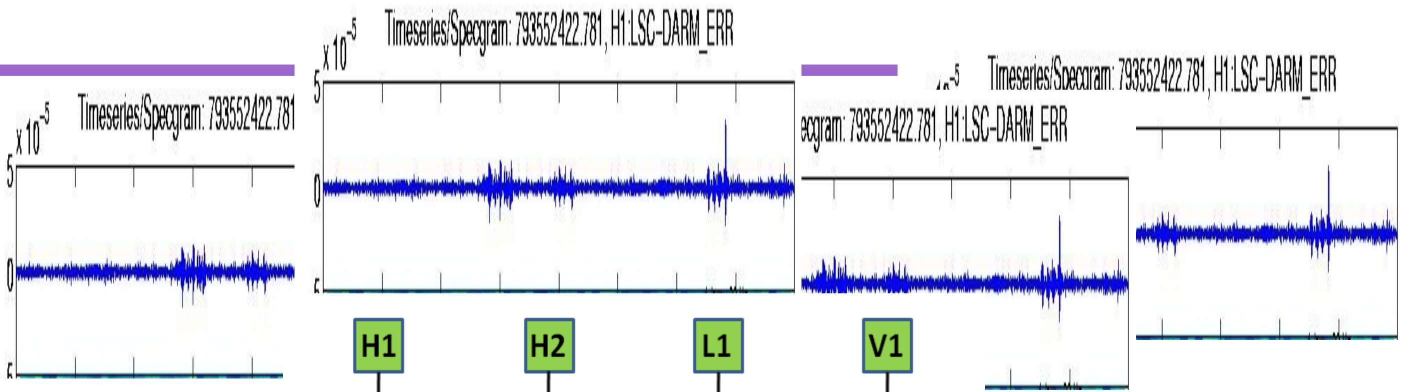
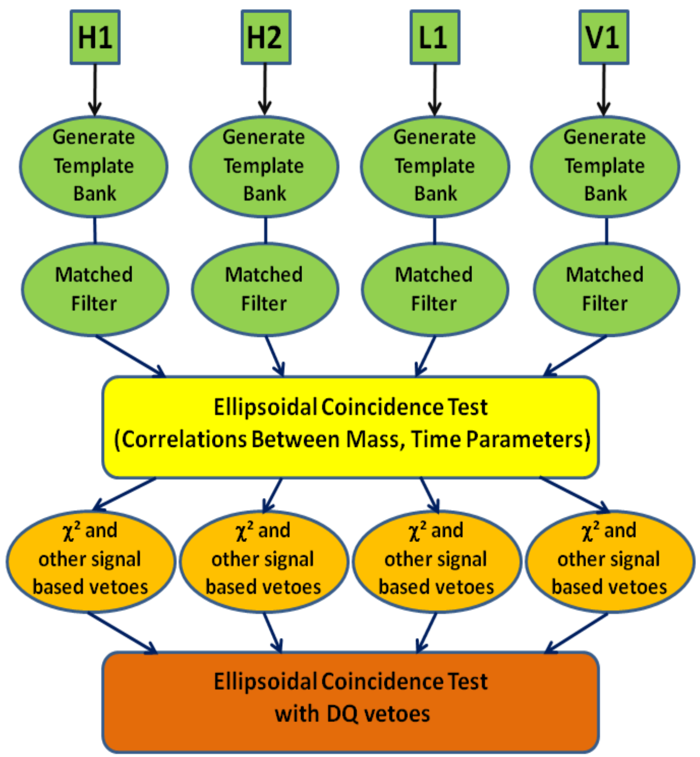
VESF
School on gravitational waves, neutrino and multi-wavelength EM observations:
The new frontier of Astronomy

# Outline

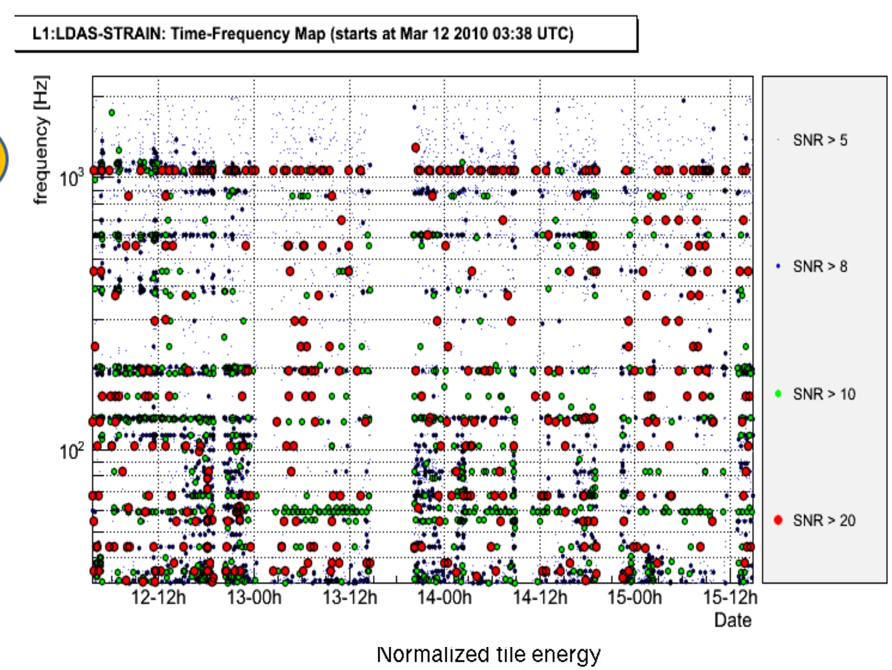
- Chapter 1: Data analysis
  - Overview of GW searches
  - Methods/techniques
  - Challenges with real data
  - Source parameter inference
- Chapter 2: Results
  - CBC search results with LIGO-Virgo
  - Detection scenarios with advanced detectors

# Data analysis overview



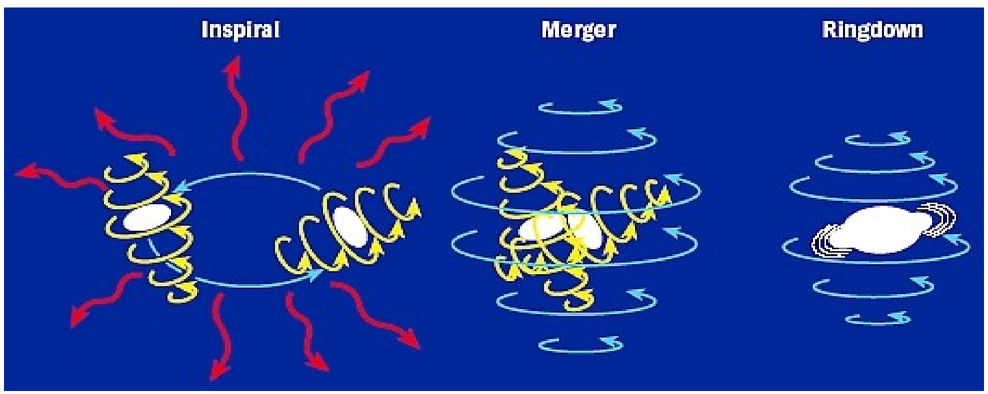



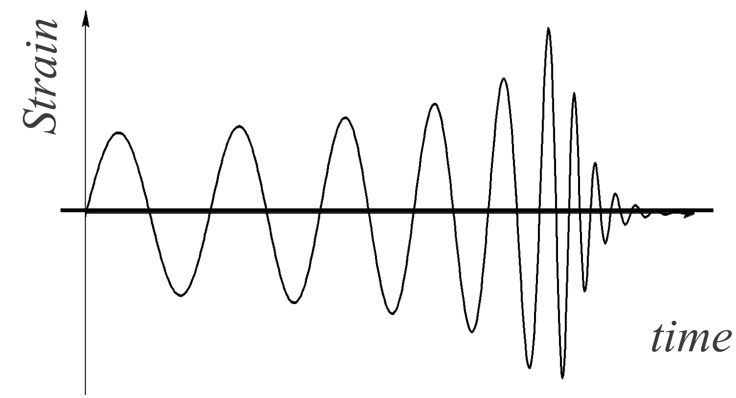

Prototype of an all-sky/all-time CBC search



# Let's start with the beginning: Sources

- Compact binary systems: Neutron stars (NS) and/or black holes (BH)
- What can LIGO-Virgo detect? The last minutes of the coalescence, the merger and the ring-down for a certain regime of masses [1 $M_\odot$ – 400 $M_\odot$]




- Rate:

| Source | $R_{low}$ | $R_{re}$ | $R_{high}$ | $R_{max}$ |
|---|---|---|---|---|
| NS-NS ($Mpc^{-3}$ $Myr^{-1}$) | 0.01 [1] | 1 [1] | 10 [1] | 50 [16] |
| NS-BH ($Mpc^{-3}$ $Myr^{-1}$) | $6 \times 10^{-4}$ [18] | 0.03 [18] | 1 [18] | |
| BH-BH ($Mpc^{-3}$ $Myr^{-1}$) | $1 \times 10^{-4}$ [14] | 0.005 [14] | 0.3 [14] | |

| IFO | Source[a] | $N_{low}$ $yr^{-1}$ | $N_{re}$ $yr^{-1}$ | $N_{high}$ $yr^{-1}$ | $N_{max}$ $yr^{-1}$ |
|---|---|---|---|---|---|
| | NS-NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS-BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| Initial | BH-BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |

Assume LIGO Sensitivity and SNR>8

# GW searches zoology

Short duration (~1s) — Long duration

Waveform known

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

High-mass inspiral

LISA binary

Binary merger

Rotation-driven instability

Cosmological stochastic background

Stellar core collapse

Waveform unknown

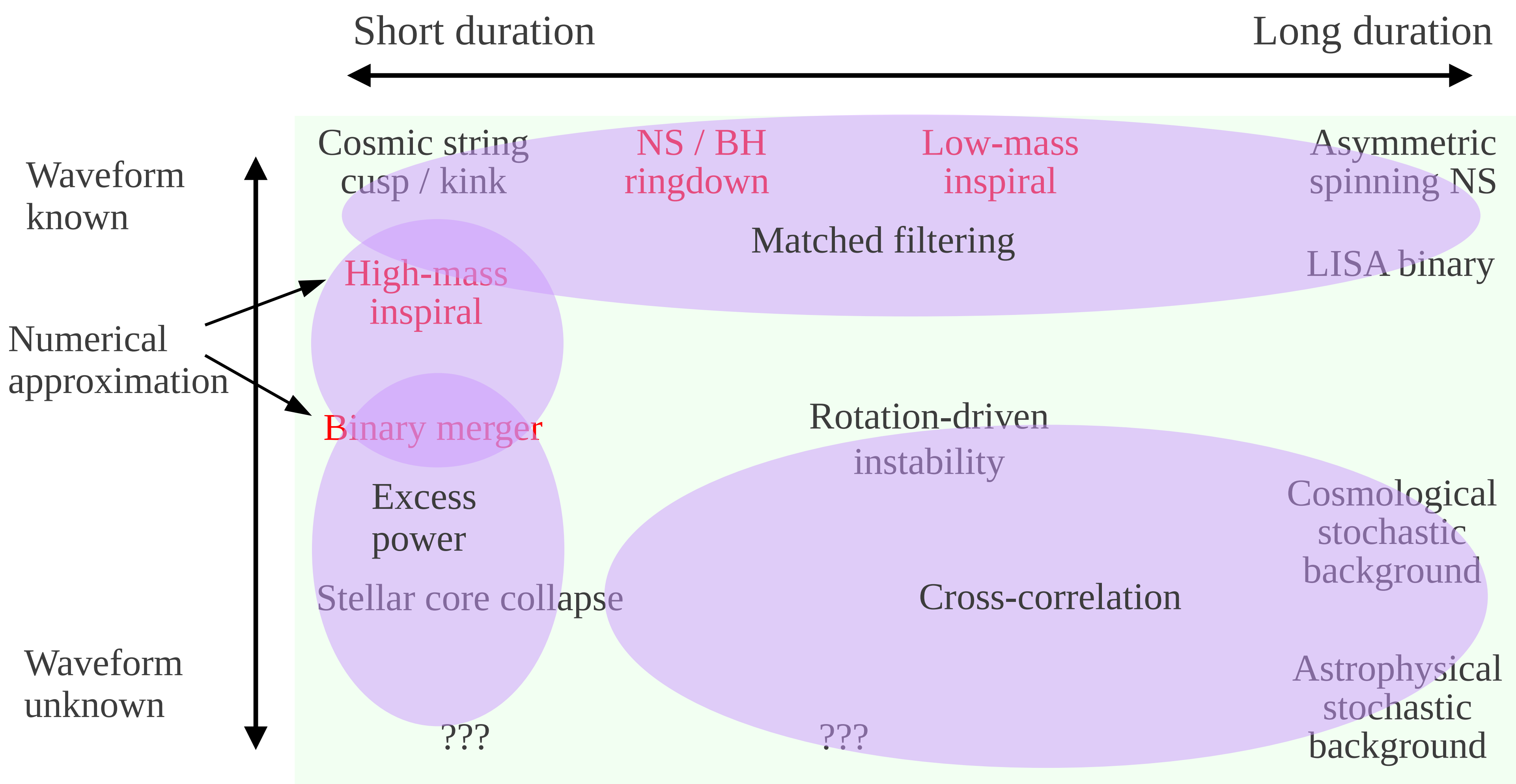
Astrophysical stochastic background

???

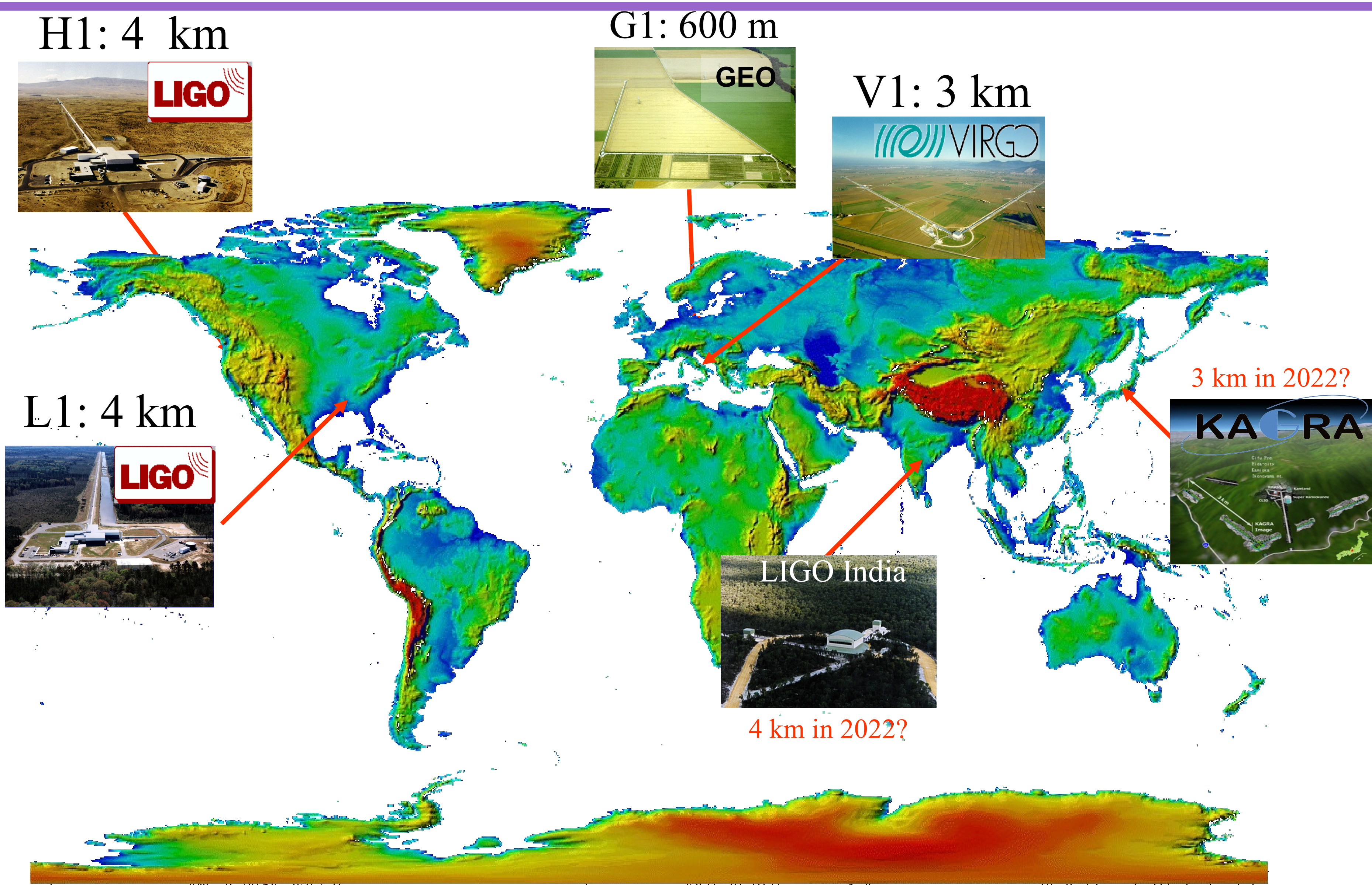
???

CBC searches: transient signal searches for LIGO-Virgo!

# Methods summary

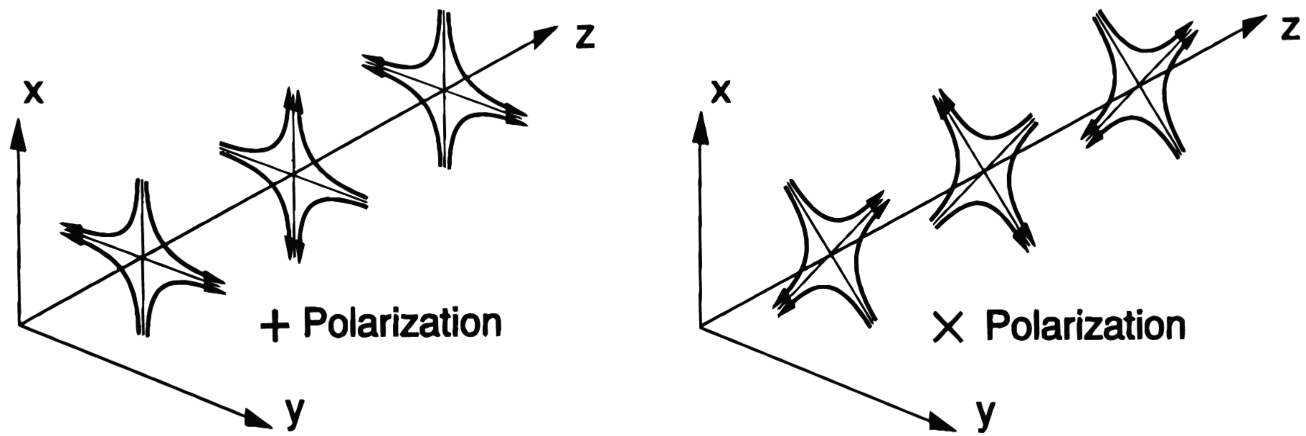


# Network of ground based detectors



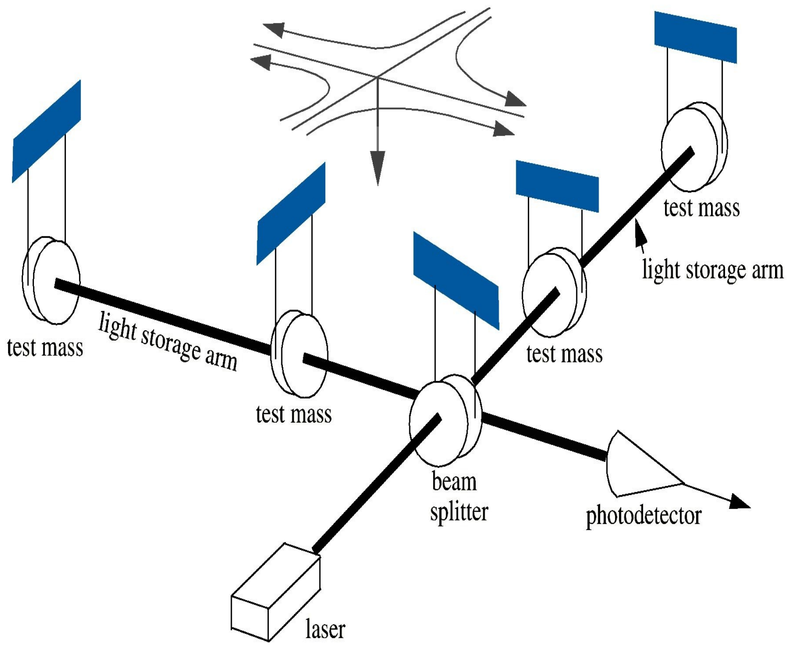
# GW: what they are

- 2 polarizations




- Linear combination of + and x polarizations. Can be linear, circular or elliptical polarized.
- For instance a CBC wave is circularly polarized if traveling face on. In the other cases, it will be elliptically polarized.

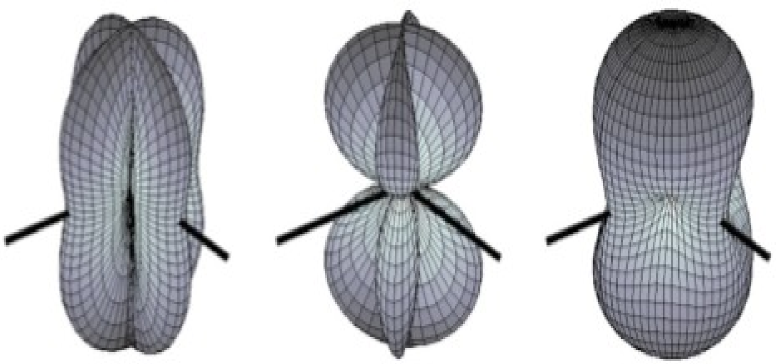
# Response of a GW interferometer




How to detect the path of a GW?
→ GW induces a differential change of the arms' length
→ light phase shift measurement

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

- Directional detector
- Directional sensitivity depends on polarization in a certain (+,×) basis



$F_+$ $\quad F_\times$ $\quad \sqrt{F_+^2 + F_\times^2}$

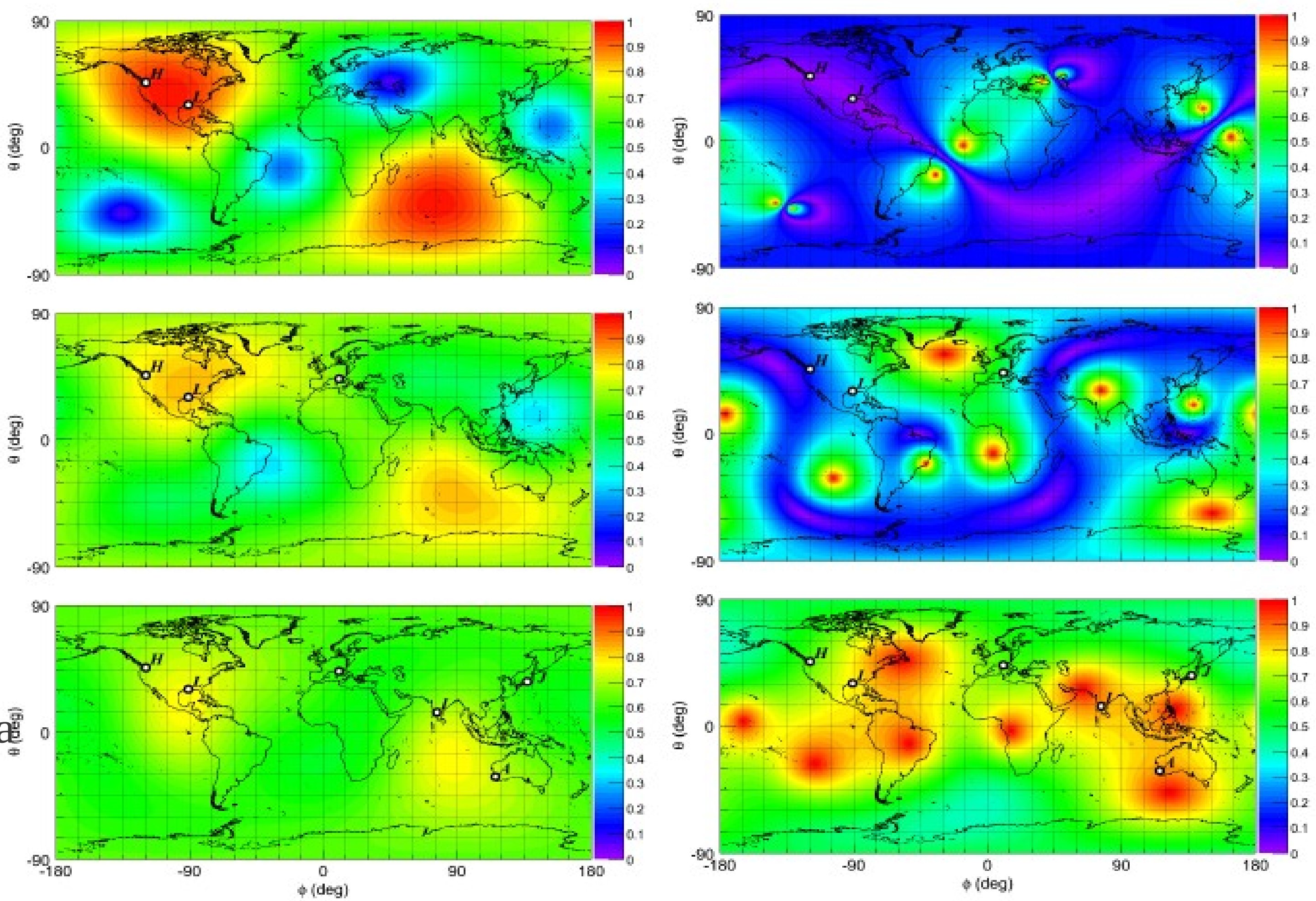
# Network sky coverage

Antenna factor coverage — Alignment factor

LIGO Hanford & LIGO Livingston

LIGO Hanford & LIGO Livingston & Virgo

6 detectors (US, Europe, Japan, India, Australia)



# Gravitational wave data

- GW detectors' readout system provides at any instant an estimate of strain: a quantity that is sensitive to arms' length difference: $h \sim \Delta L/L$

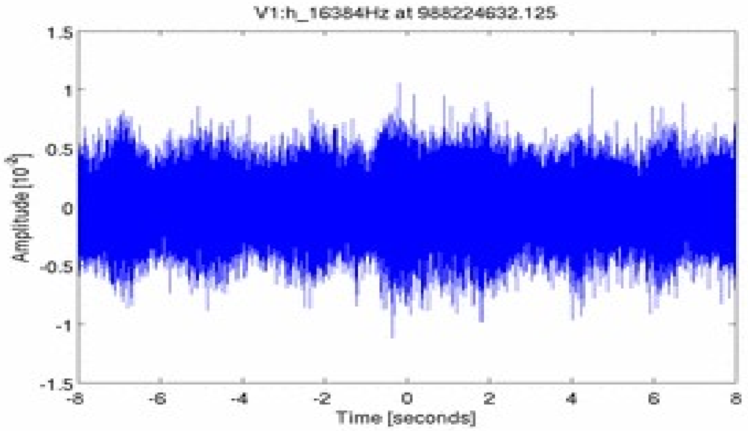
→ Digitized discrete time series: raw(t) (sampled at 16384 Hz or 20000 Hz) and synchronized with GPS clocks.

→ Calibration of raw(t): apply a frequency dependent factor [in reality this is a bit more complicated ...]

→ h(t) time series that is detector noise plus all hypothetical GW signals

$$h(t) = n(t) + GW(t)$$

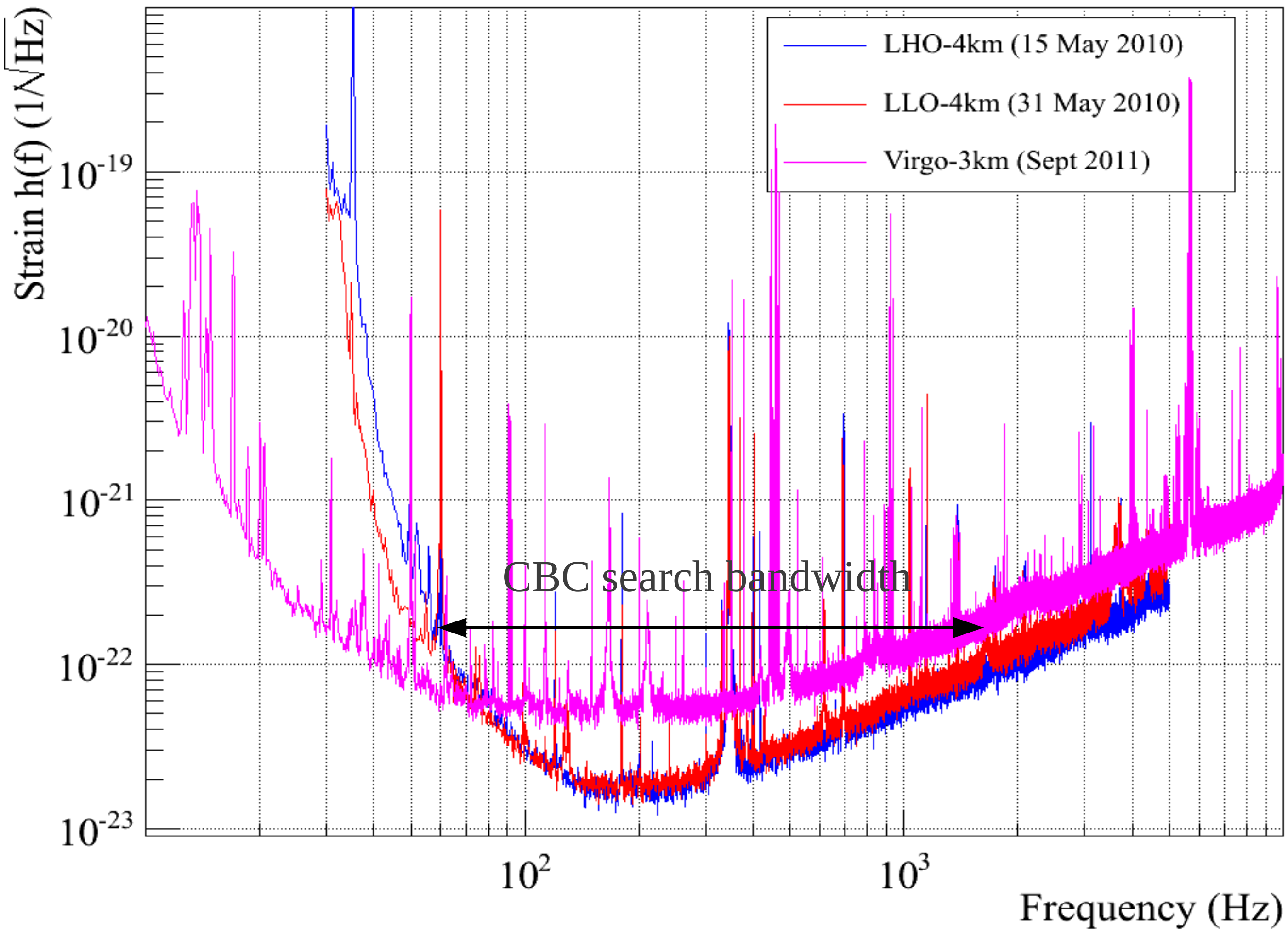
Question: nature of the noise?




- Detector monitoring: ~1000 auxiliary channels recorded at different sampling rate (environment/control monitoring)

→ detector characterization effort to disentangle genuine GW signal from noise

# GW detectors sensitivities

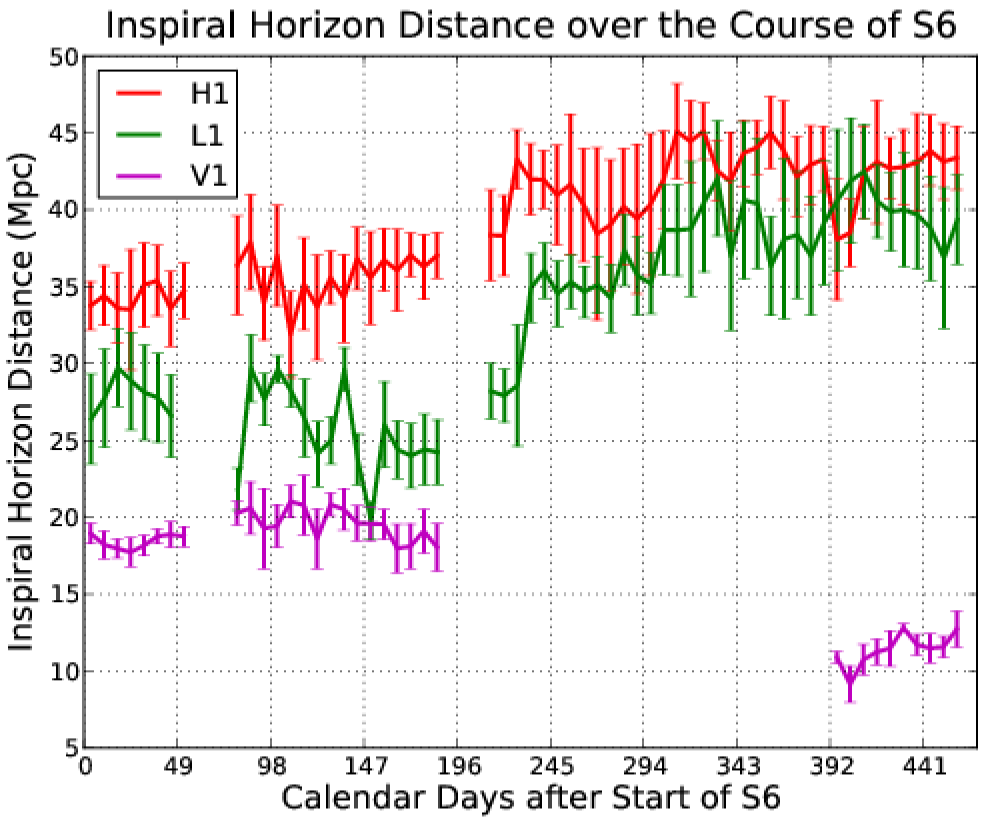



- Best noise spectrum achieved by LIGO Hanford, LIGO Livingston and Virgo
- Non white, non smooth … and non stationary ...

# CBC horizon distance

Another way to represent the sensitivity: distance at which an optimally oriented and located BNS (equal mass) system is detected with SNR=8

$$D = \frac{1}{8}\left(\frac{5\pi}{24c^3}\right)^{1/2}(G\mathcal{M})^{5/6}\pi^{-7/6}\sqrt{4\int_{f_{low}}^{f_{high}}\frac{f^{-7/3}}{S_n(f)}df}$$



# Frequency and time domain GW data representations

Fourier transform:

$$\tilde{x}(f) = \int_{-\infty}^{\infty} dt\, x(t) e^{-i2\pi f t}$$

$$x(t) = \int_{-\infty}^{\infty} df\, \tilde{x}(f) e^{i2\pi f t}$$

Time series $x_j$ with N samples at times $t_j = t_0 + j \times \Delta t$

→ Discrete Fourier transform:

$$\tilde{x}_k := \sum_{j=0}^{N-1} x_j\, e^{-i2\pi jk/N}$$

$$\Delta f = \frac{f_{sampling}}{N}$$

$$x_j = \frac{1}{N} \sum_{k=-N/2}^{N/2-1} \tilde{x}_k\, e^{i2\pi jk/N}$$

- Efficient algorithm to compute discrete Fourier transform: Fast Fourier Transform (FFT)

# Power Spectral Density (PSD) estimation

PSD = Fourier transform of the auto-correlation function of the data

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x(t)x(t+\tau)dt\; e^{-2\pi i f\tau}d\tau = \tilde{x}(f)\tilde{x}^*(f) = |\tilde{x}(f)|^2$$

Wiener-Khinchin theorem

When data has infinite extend in time domain, PSD estimate

$$\lim_{T\to\infty}\frac{1}{T}|\tilde{x}_T(f)|^2$$

In reality: finite amount of data → true PSD is convolved with the Fejèr kernel (Fourier transform of a square function)→ bias of estimators

Estimators:
Simplest estimator (periodogram): FFT the data → square each frequency component.

Averaged periodogram: to reduce variance of periodograms

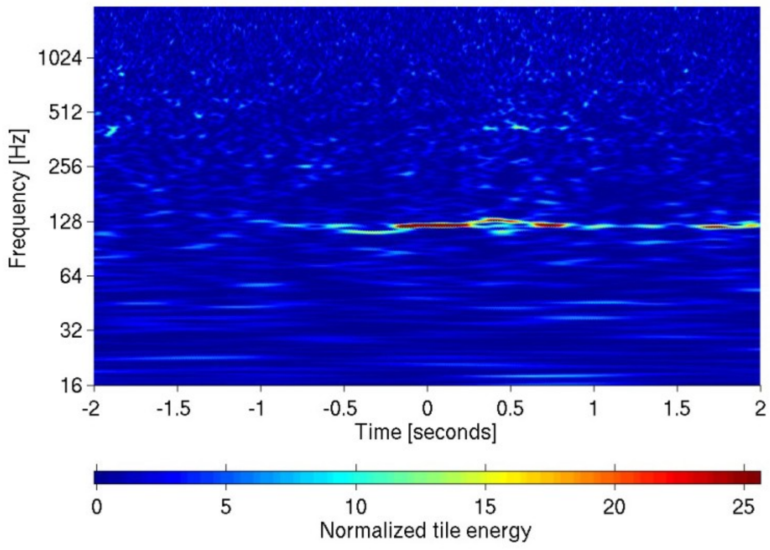
Windowed data periodogram: to reduce spectral leakage (data are not periodic!). Tapered window

Welch approach: average of periodograms computed over overlapping windowed data segments

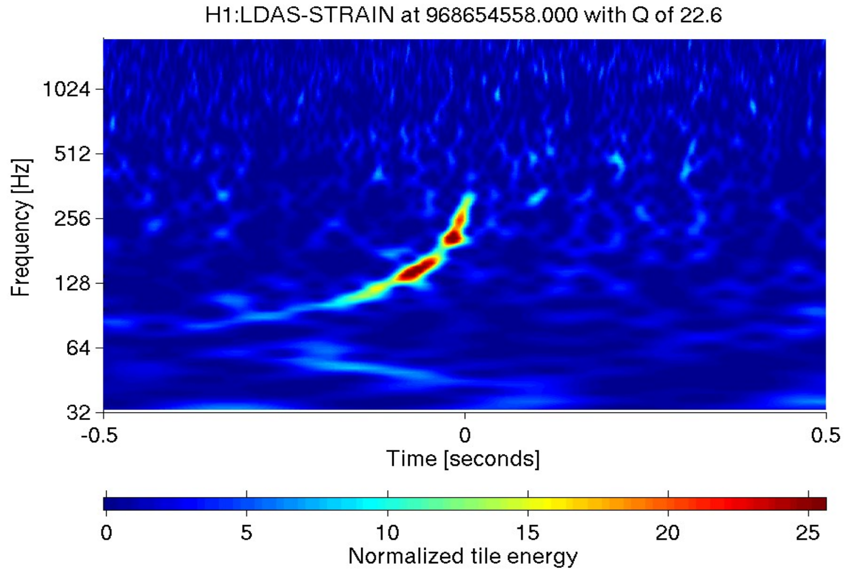
# Time frequency representation

- Transient signal → localized in time and frequency
- Many time frequency transforms (spectrogram, WignerVille, Wavelet, …).
- Massive use of time-frequency map for (un-modelled) searches and detector characterization

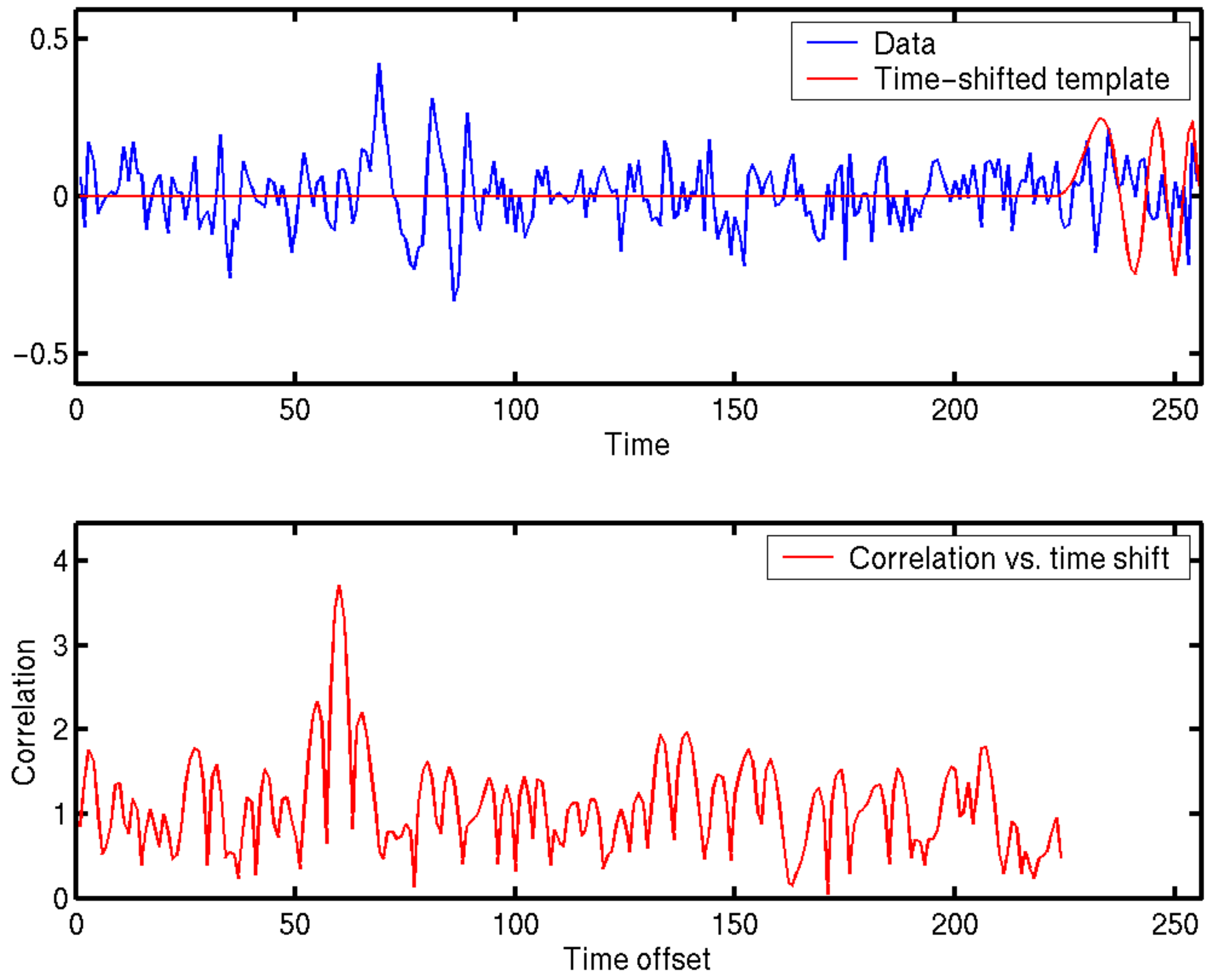
An “helicopter” event




An fake GW signal



# CBC pipeline processing core: match filtering



# Matched filtering

Matched filter is the optimal filter to maximize the SNR in presence of additive noise. Detector's output is:

$$x(t) = n(t) + h(t)$$

To extract $h(t)$ one filters $x(t)$. The simplest linear filter is correlation

$$\mathcal{C}(t) = \int x(t')k(t - t')dt'$$

$k(t)$ is the impulse response function of the filter $(x(t) = \delta(t)$
$\Rightarrow \mathcal{C}(t) = k(t))$

$$\mathcal{C}(t) = \int \tilde{x}(f)\tilde{k}^*(f)e^{2\pi i f t}df$$

which is just the inverse Fourier transform of $\tilde{x}(f)\tilde{k}^*(f)$

# Matched filtering

Now we need to find $k(t)$ that maximizes the signal-to-noise ratio (SNR),

$$x(t) = n(t) + h(t) \Rightarrow \mathcal{C}(t) = \mathcal{N}(t) + \mathcal{H}(t)$$

$$\rho(t) = \frac{\mathcal{C}(t)}{\sqrt{\overline{\mathcal{N}^2(t)}}}$$

$$\overline{\mathcal{N}^2(t)} = \int df |\tilde{k}(f)|^2 S_n(f)$$

In absence of noise, one can show that $\rho(t)$ is bounded,

$$\rho^2(t) <= \int df \frac{|\tilde{h}(f)|^2}{S_n(f)}$$

$\rho(t)$ is maximal when $\tilde{k}(f) \propto \frac{\tilde{h}^*(f)}{S_n(f)}$

$$\mathcal{C}(t) = 4 \int_0^\infty \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

# Matched filter : summary

FFT of data

Template can be generated in frequency domain using stationary phase approximation

$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

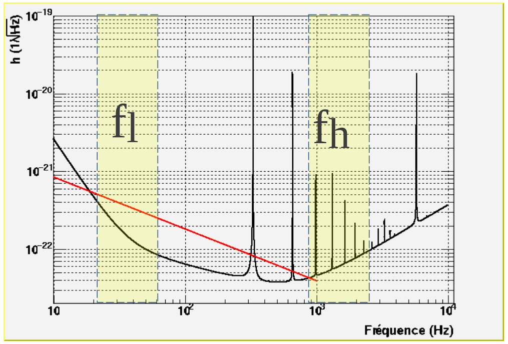
Noise power spectral density (in this case this is the two-sided Power spectrum)

- Phase coherence is more important than amplitude matching
- Need to build a bank of template that will cover the full parameter space

→ Filter over the full template bank

→ Threshold on C(t) → trigger generation

- SNR is simply: $$\rho^2(t) = \int_{-\infty}^{\infty} df \frac{|\tilde{h}(f)|^2}{S_n(f)}$$



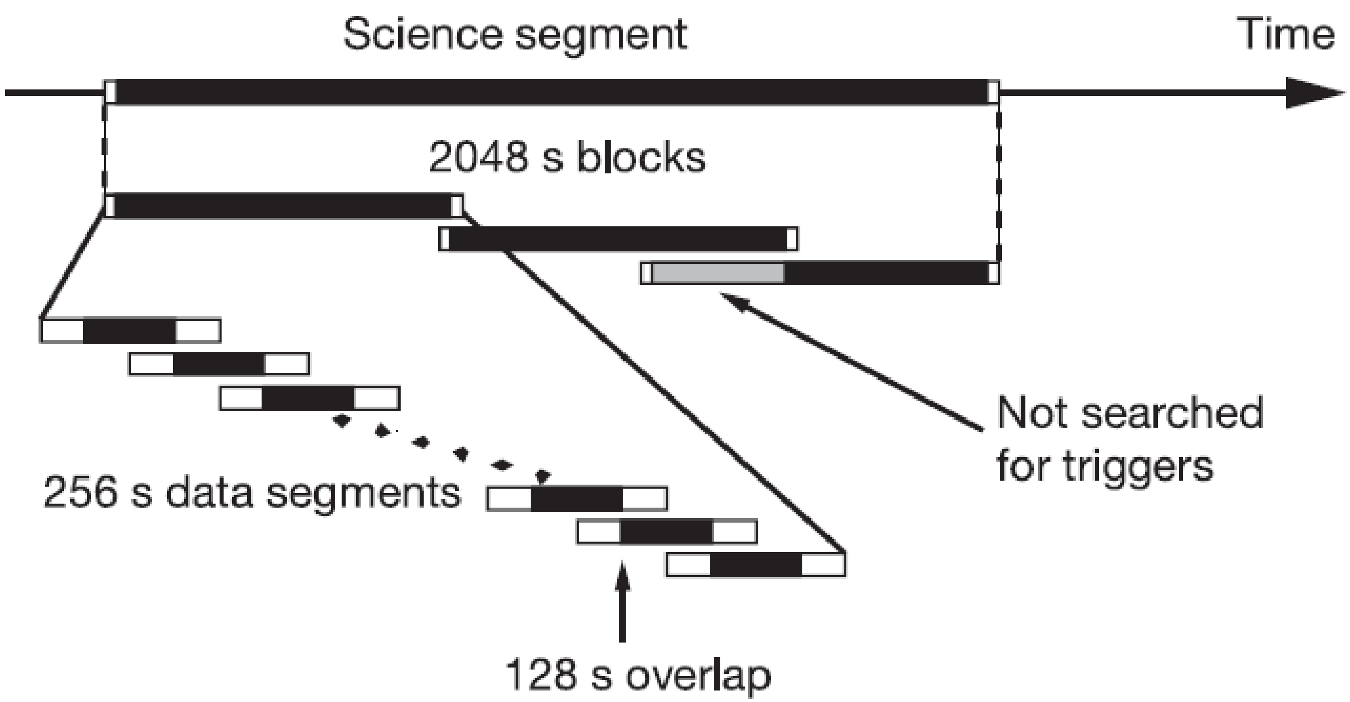

In practise, integrals computed over [$f_l$, $f_h$]

$f_l$: after “seismic wall”

$f_h$: when signal stops and/or $f_{sampling}$

# Searching a full data set: example

- Analyse “good” segments of data
- Fourier inverse over overlapping segments of 256 s (avoid wrap around problems)
- PSD computed over longer segments (2048 s)



# Source parameters vs signal parameters

- Inspiral source parameters
  - Masses $(m_1, m_2)$
  - Spins $(\vec{S_1}, \vec{S_2})$ → negligible for low mass $(M_{tot} < 10 M_{\odot})$
  - Coalescence time $(t_c)$
  - Orbital phase at coalescence $(\phi_c)$ → maximizing analytically (2 quadratures filtering)
  - Inclination of orbital plane $(\iota)$
  - Sky location $(RA, \delta)$
  - Distance $(d)$

  (inclination, sky location, distance) → affects amplitude only
  - Eccentricity → negligible for standard formation scenario
- Intrinsic parameters: masses, spins and coalescence time

  → 2+2*3 = 8 unknown parameters

  → Templates bank is going to be huge!

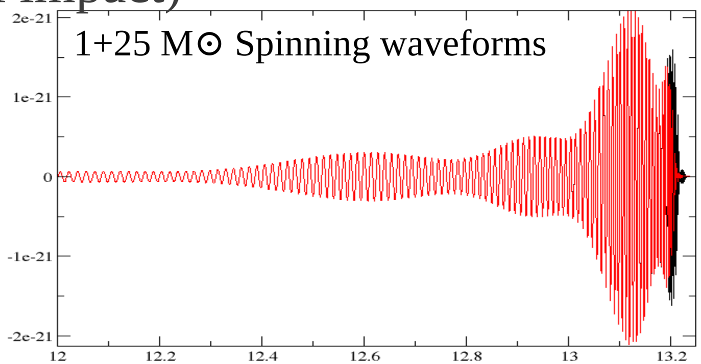
  → search split in 2 ≠ mass regimes (≠ approximations, ≠ physics, spins effects)

# Compact binary spins

- Observations:
  - NS are found weakly spinning.
  - Stellar mass BH spins are almost maximal.
- Spin orientation and precession:
  - For isolated compact binary it is likely that spins are nearly aligned to the orbital angular momentum (tilt angle depends on SN kicks distribution)
  - For dynamically formed CB: no a priori spins alignment. If mis-aligned → spin-orbit & spin-spin couplings will cause the spins to precess around the total angular momentum.

    → maximal effects expected on the phase evolution.

    → face-on (minimal impact) vs edge-on (maximal impact)



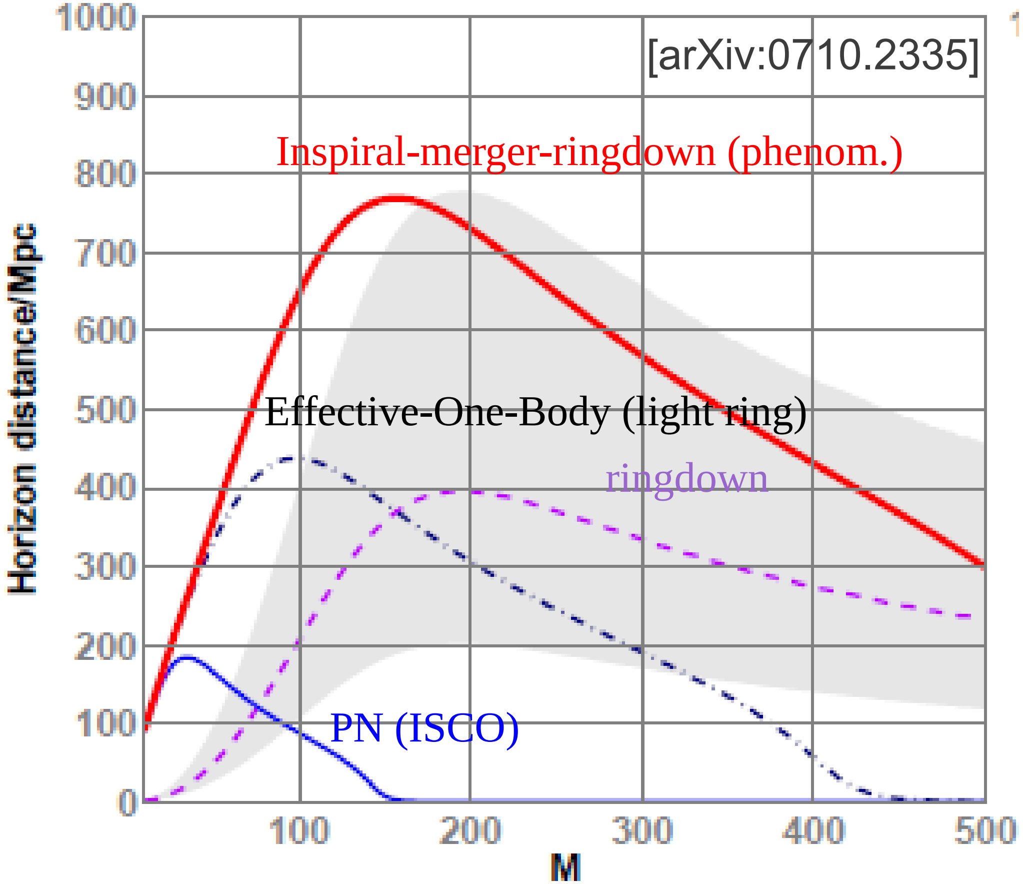
# Waveforms zoology

- Which mass regime (low mass, high mass, mass ratio)?
- Can we neglect the spins?

| | Approximations | Spins |
|---|---|---|
| Low mass $(M_{tot} < 12M_{\odot})$ | BNS case<br>SNR dominated by the inspiral phase. Waveforms accurate until PN approx. breaks | For initial detectors: spin could be neglected. Advanced LIGO/Virgo: spin 0.015 - 0.1 → 3%-25% mismatch. Aligned spins is still OK? |
| High mass $(M_{tot} > 12M_{\odot})$ | For masses higher than 50 Msun, merger and ring-down contribute dominantly → need full waveform inspiral + merger + ring-down (IMR)<br>Use of NR waveforms for merger. | BH spins is likely maximal<br>Spin precession effects can be large. Spins cannot be neglected for Advanced LIGO/Virgo |

# Template parameter space: masses

Initial LIGO




The more massive the system the lower the GW frequency at merger

$$f_{\rm ISCO} \sim \frac{4\rm kHz}{M_{tot}} \qquad f_{\rm merger} \sim \frac{15\rm kHz}{M_{tot}}$$

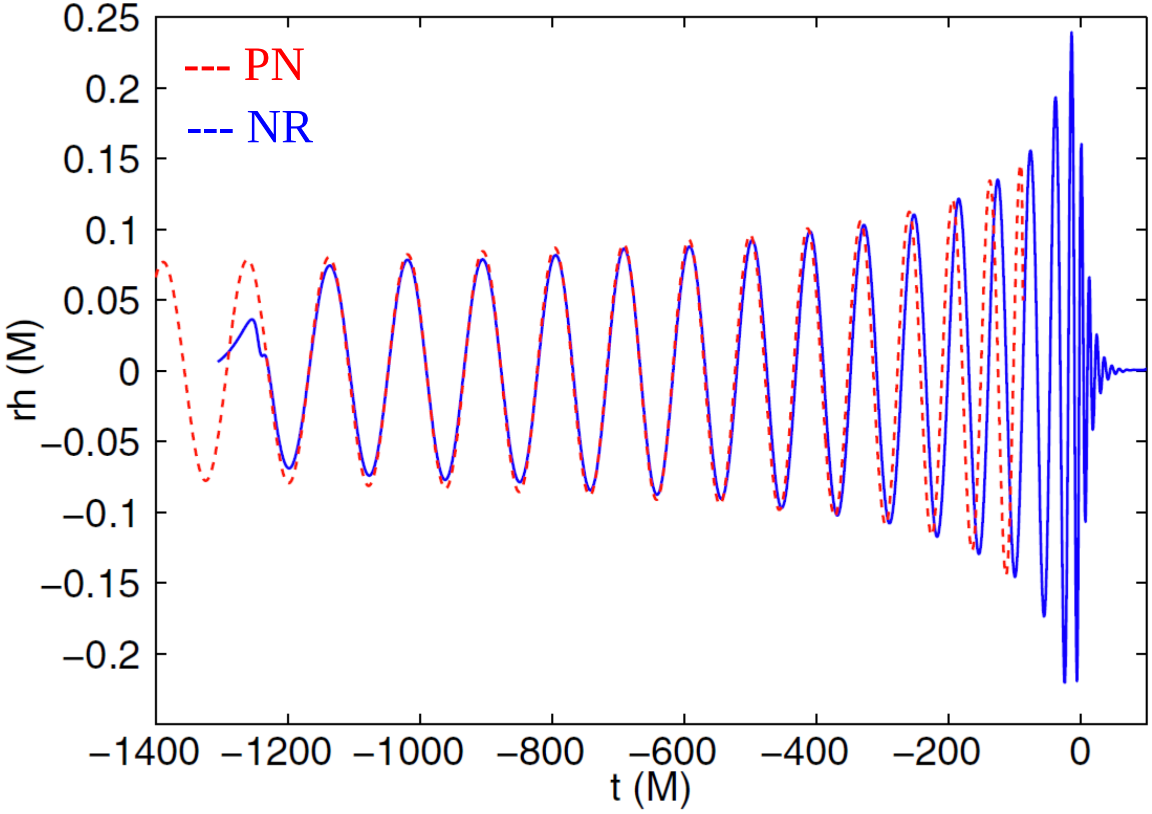
→ For BNS waveforms are inside LIGO/Virgo band
→ BBH merge inside LIGO/Virgo band
→ Mtot>100 Msun : only merger+ring-down

# Numerical relativity breakthrough to describe the full inspiral + merger+ring-down waveforms

It's now possible to accurately calculate final stages of inspiral, merger and ring-down.

→ can construct "hybrid" waveforms:

[ArXiv:0612024]



# Detection vs parameter estimation

- Complete description of the signal requires to explore the full parameter space: masses (2 dof) + spins (6 dof) + NR inputs
- Template search --> computationally limited
- Spinning waveforms have degeneracies

→ for detection:

  - A small inefficiency with 2dof template bank is acceptable
  - Use spinning waveforms to estimate the loss of efficiency for spinning CBC

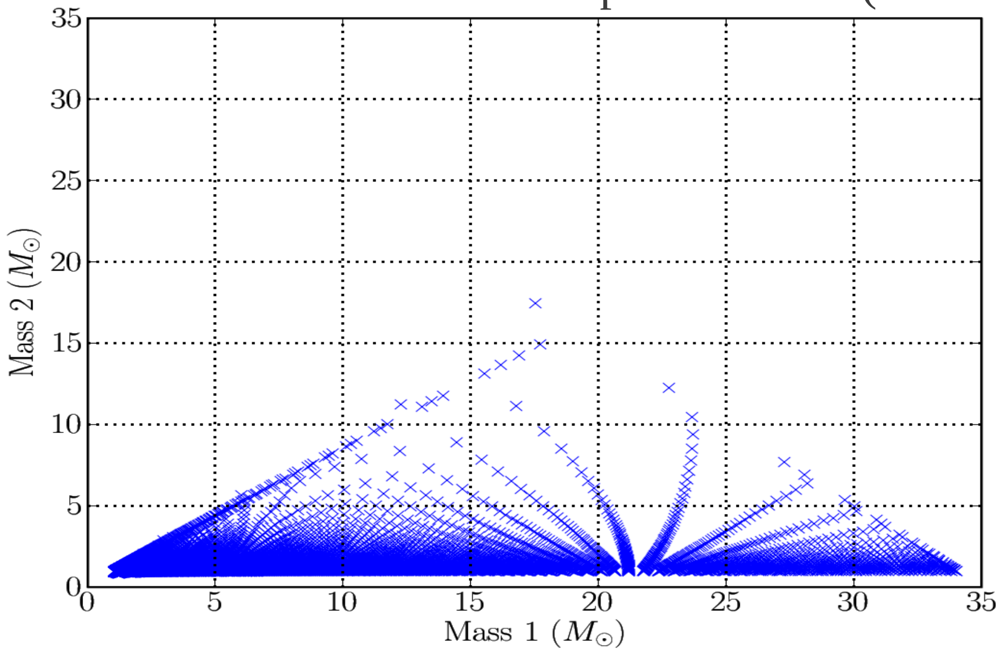
→ for GW candidate parameter estimation, use the most complete waveforms (up to 15 parameters to estimate)

# Template bank construction

- Goal: pave the mass parameter space with waveform such that any (m1,m2) system can be detected with a minimal loss of efficiency
- Distance between 2 neighboring templates:
  - Compute the match filtering M of T1 and T2: 1-M gives the loss of SNR.
  - Define an acceptable minimal match.
  - Several algorithms (metric based, stochastic, hash cell, …) have been developed.

Adapted for D>2 (mass+spin)

Example: low mass CBC search
2 parameters $m_1$ & $m_2$



# Waveforms template

- Restricted waveforms with 3.5 PN corrections: $h(f) = C f^{-7/6} e^{-i\Psi(f)}$

$$\begin{aligned}\Psi(f;M,\eta) &= 2\pi f t_C - 2\phi_C - \pi/4 \\ &+ \pi\left[\frac{38\,645}{756} - \frac{65}{9}\eta\right]\left[1 + 3\ln\left(\frac{v}{v_0}\right)\right] + \left\{\frac{11\,583\,231\,236\,531}{4\,694\,215\,680} - \frac{640}{3}\pi^2 - \frac{6\,848}{21}(\gamma + \ln(4\,v))\right. \\ &+ \left.\left(-\frac{15\,335\,597\,827}{3\,048\,192} + \frac{2\,255}{12}\pi^2\right)\eta + \frac{76\,055}{1\,728}\eta^2 - \frac{127\,825}{1\,296}\eta^3\right\}v^6 \\ &+ \pi\left[\frac{77\,096\,675}{254\,016} + \frac{378\,515}{1\,512}\eta - \frac{74\,045}{756}\eta^2\right]v^7\Big\},\end{aligned}$$

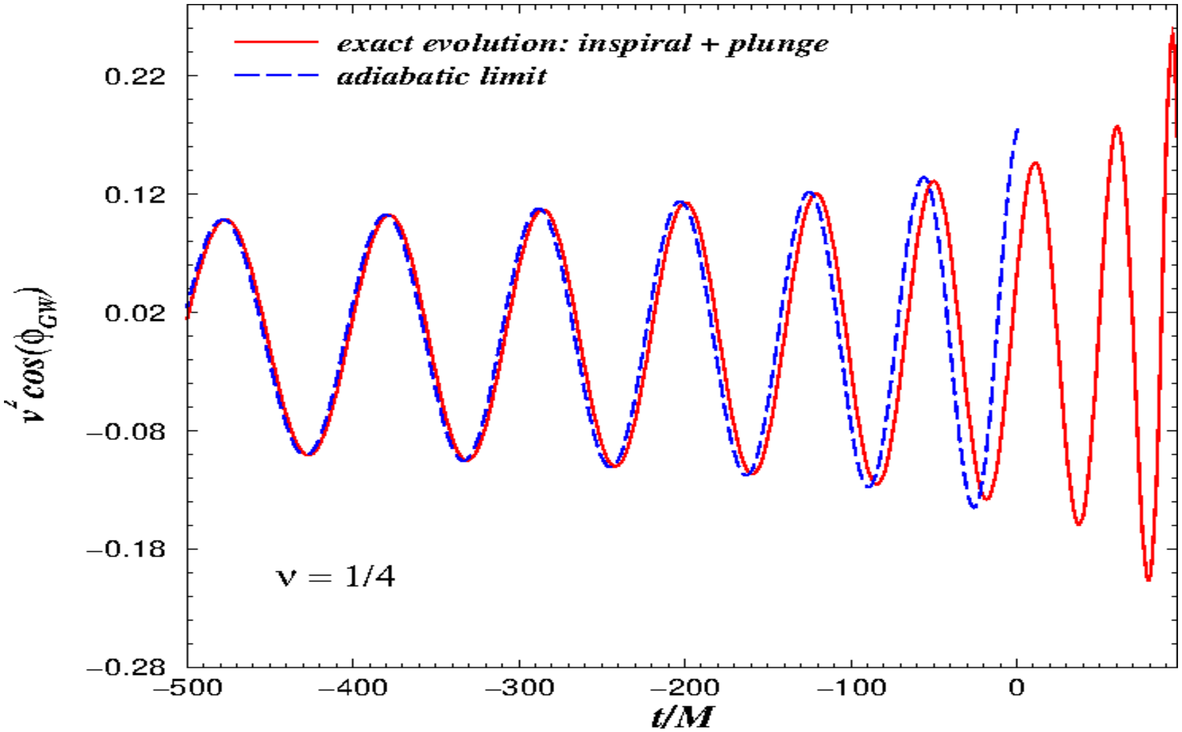
$$v = (\pi M f)^{1/3}$$

- Model complete (include also spin-orbit (1.5 PN) and spin-spin (2PN) effects
- Waveforms stop at ISCO.
- OK for low mass CBC

# Waveforms template

- Restricted waveforms with 3.5 PN corrections.
- Effective One Body approach (EOB): describe in a non perturbative way the transition from the adiabatic inspiral to the unstable plunge.

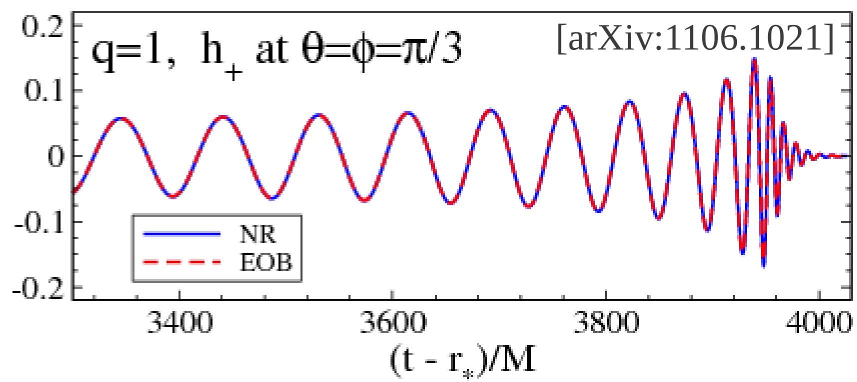
[arXiv:0001013v2]



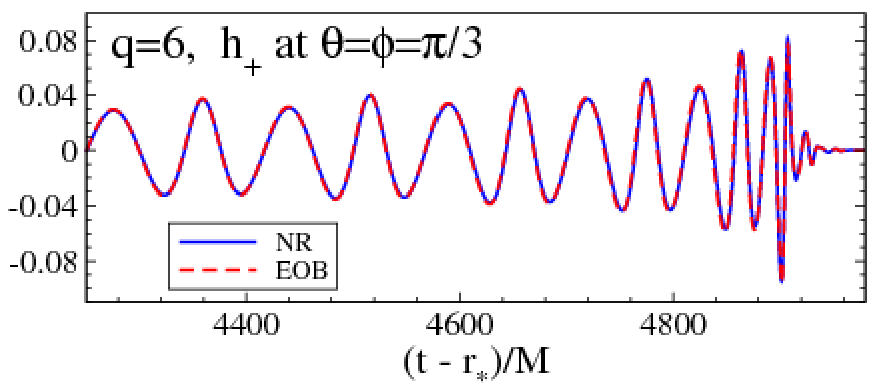
# Waveforms template

- Restricted waveforms with 3.5 PN corrections.
- Effective One Body approach (EOB): describe in a non perturbative way the transition from the adiabatic inspiral to the unstable plunge.
- EOB matched with NR (EOBNR): mismatch with NR < 0.2%

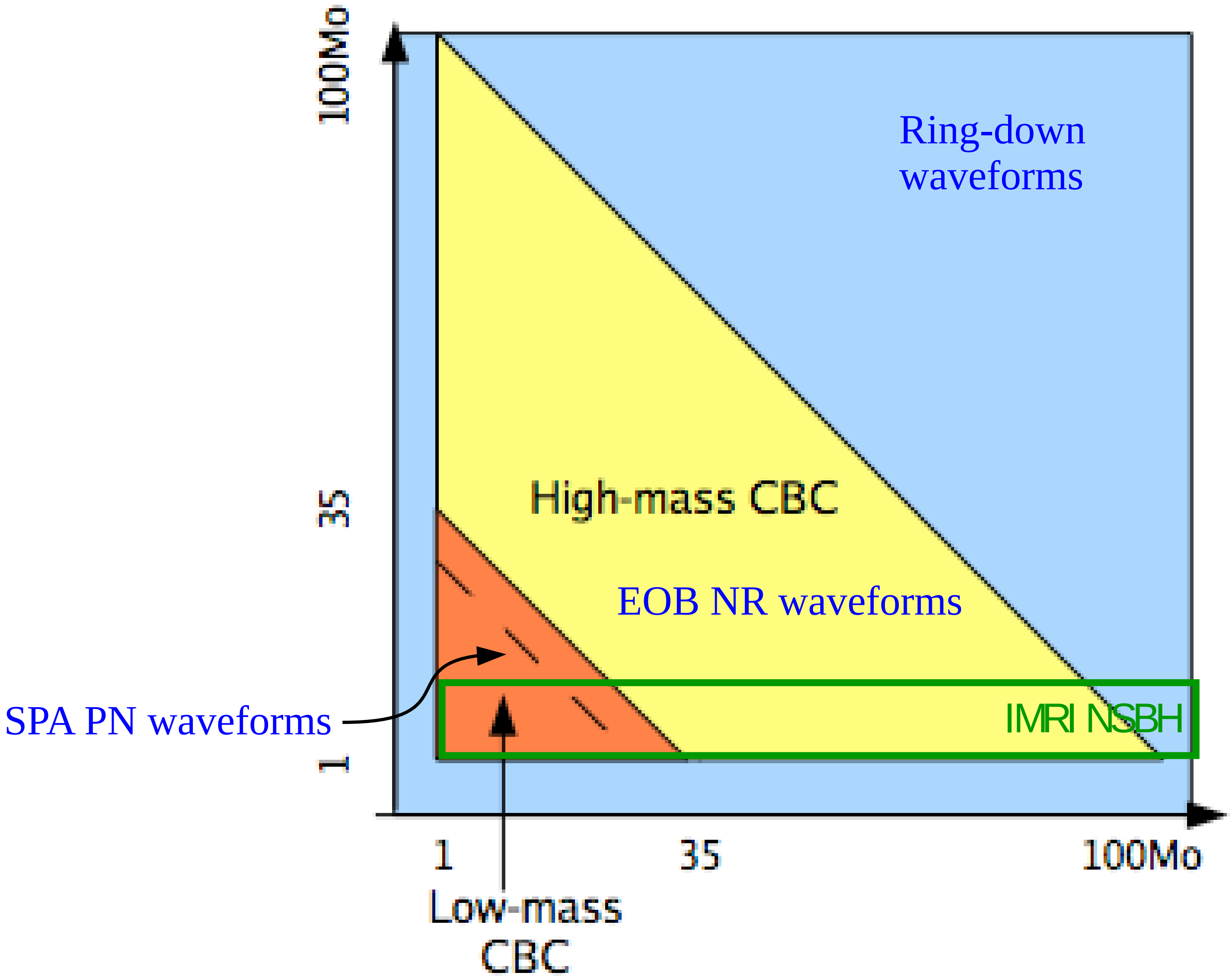
q=1 → equal mass




q=6 → mass ratio 1:6

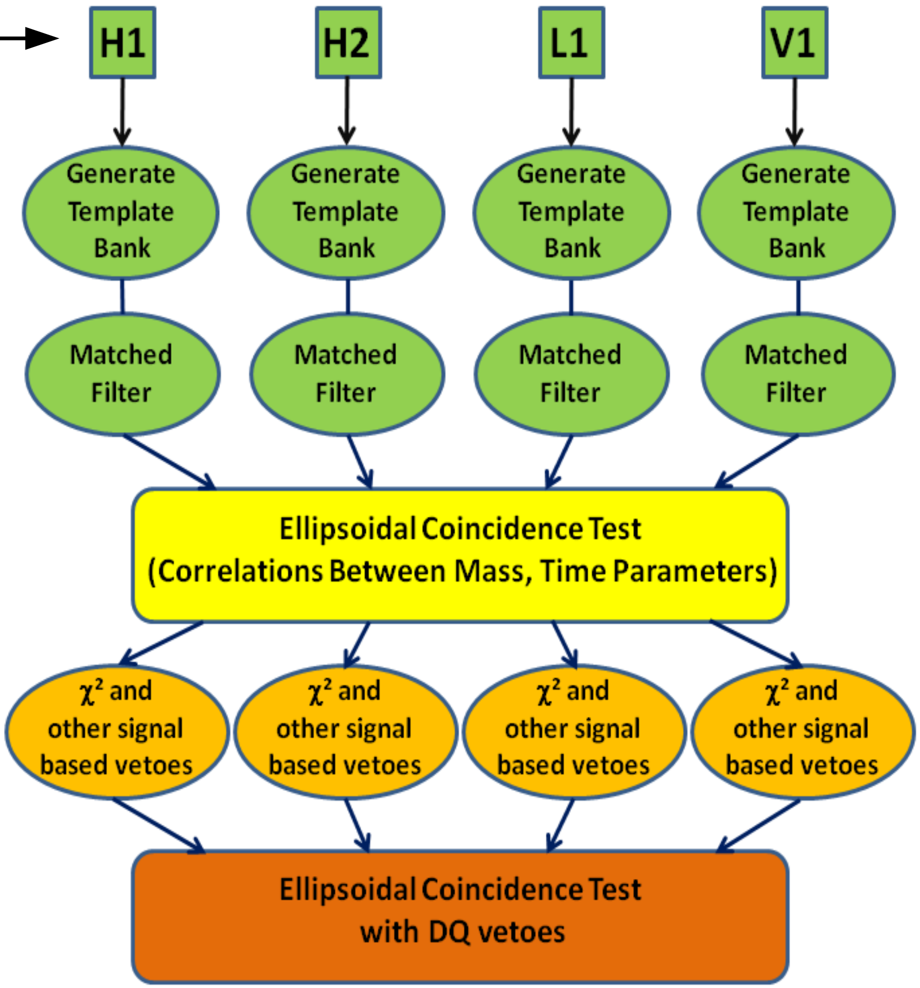


# Parameter space: masses



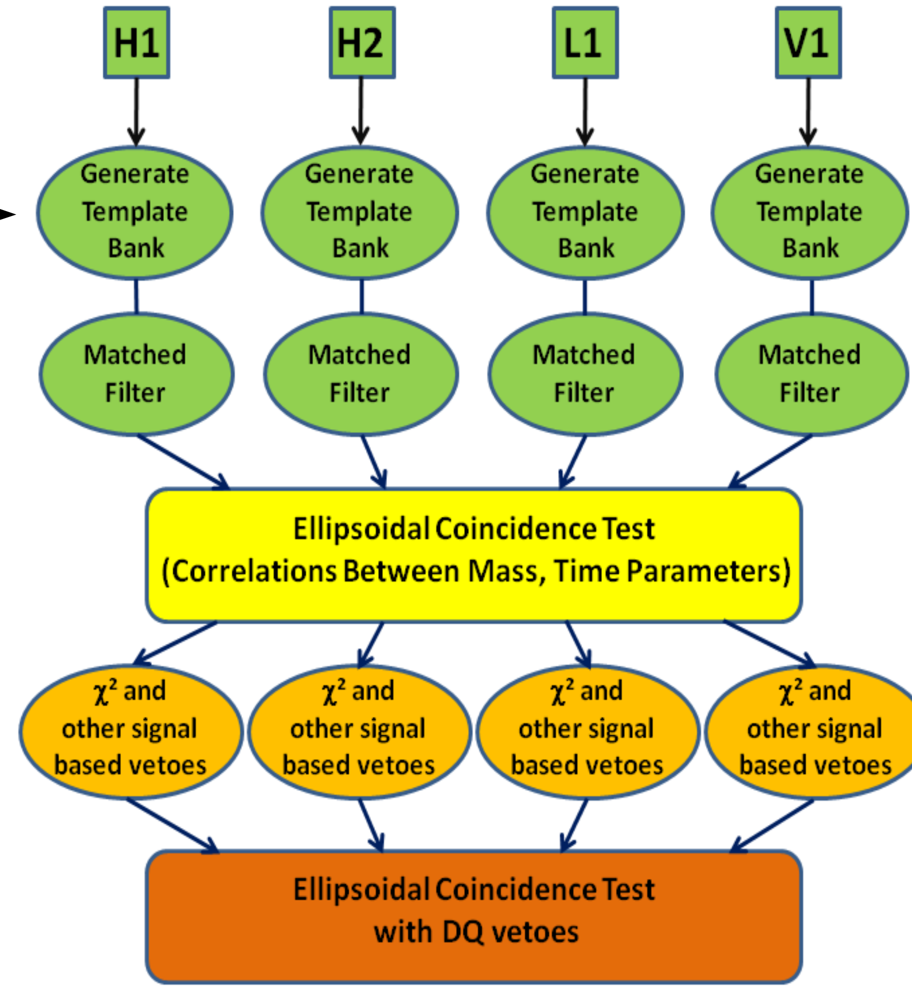
# Search pipeline example: low mass CBC search (2 parameters)

Coincidence analysis: each IFO data Stream will be processed separately



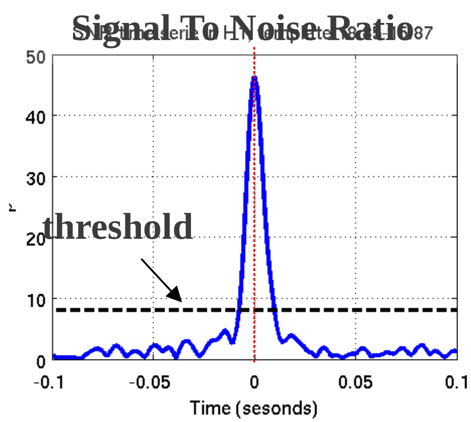
# Search pipeline example: low mass CBC search (2 parameters)

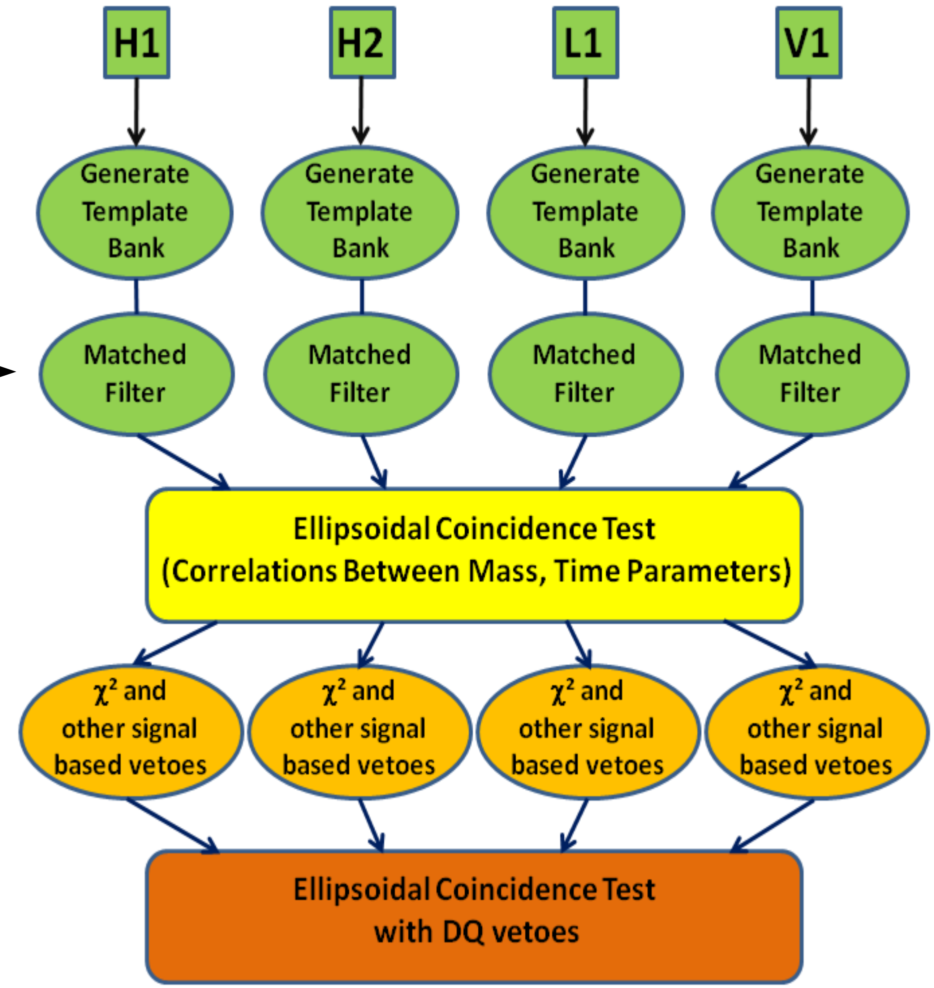
PN restricted waveforms (2 parameters)
Template number & placement depends on the PSD



# Search pipeline example: low mass CBC search (2 parameters)

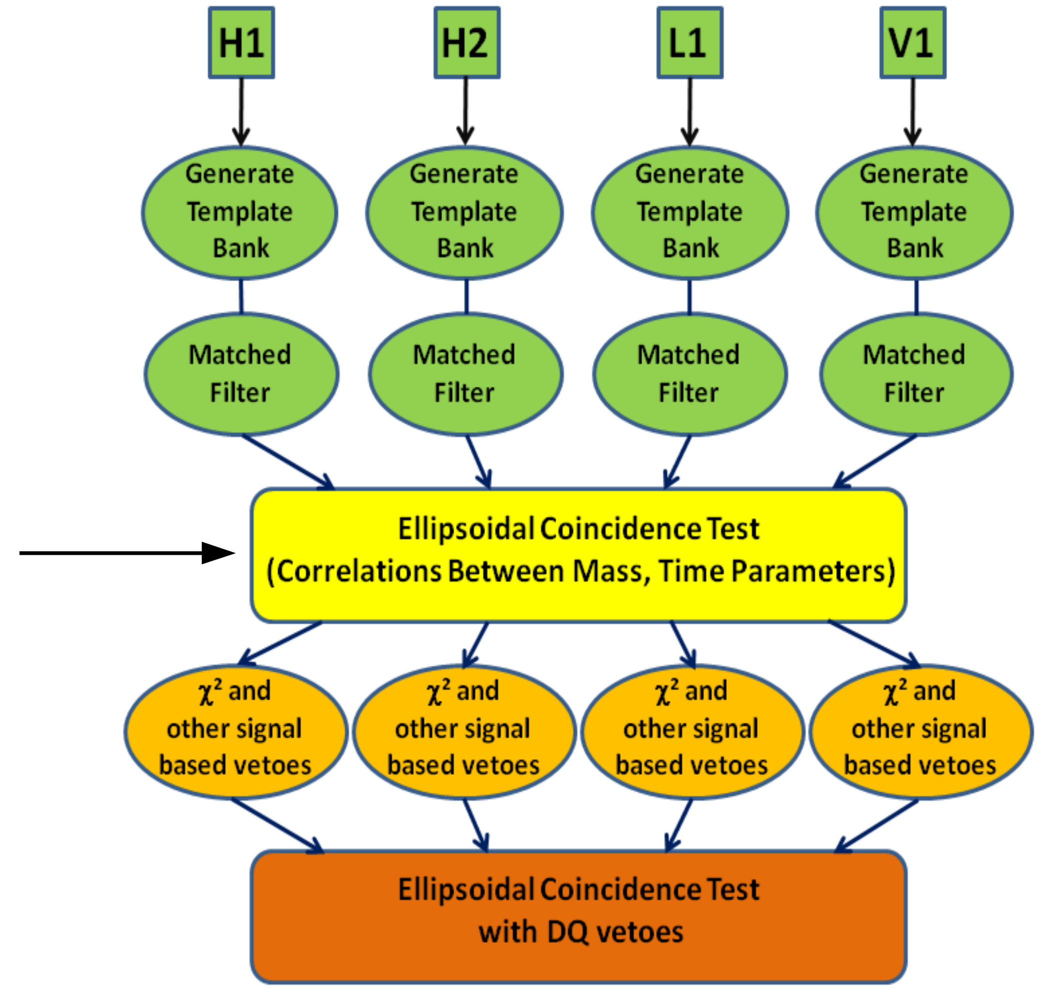
Match filter and threshold → “triggers”



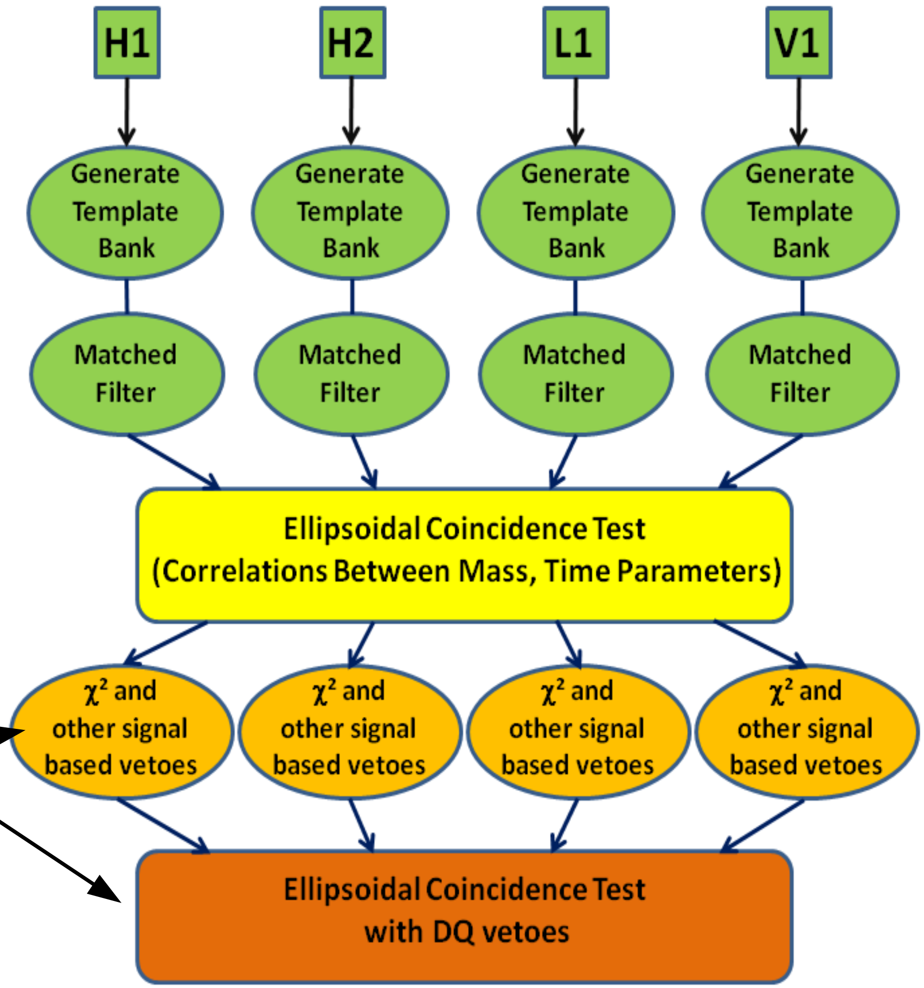



# Search pipeline example: low mass CBC search (2 parameters)

Coincidence between 2, 3 or 4 detectors (time & mass space coincidence)
→ false alarm rate reduced
→ time offset triggers to increase the effective livetime of the search for an accurate background estimation



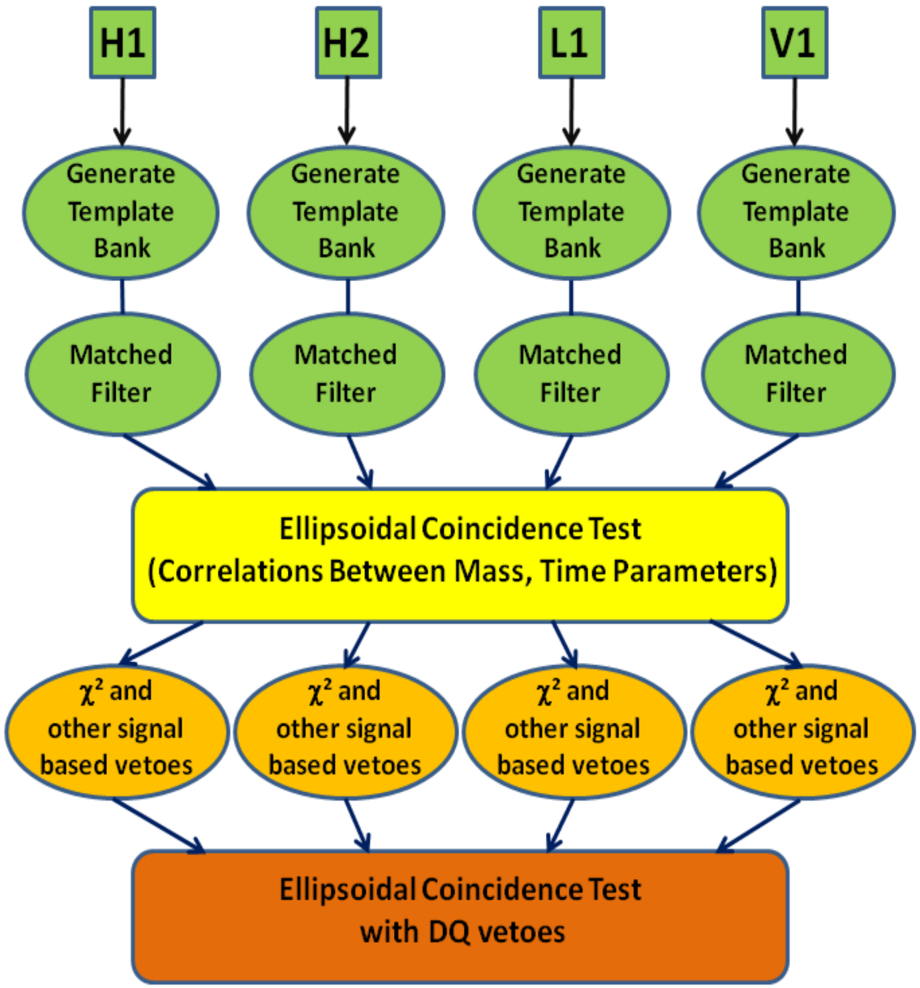
# Search pipeline example: low mass CBC search (2 parameters)




Eliminate non Gaussian “features” of the data: vetoes

- Signal based vetoes: waveform consistency tests
- Instrumental vetoes (Data Quality information to eliminate poor quality periods or identified “glitches” that mimic a CBC signal)

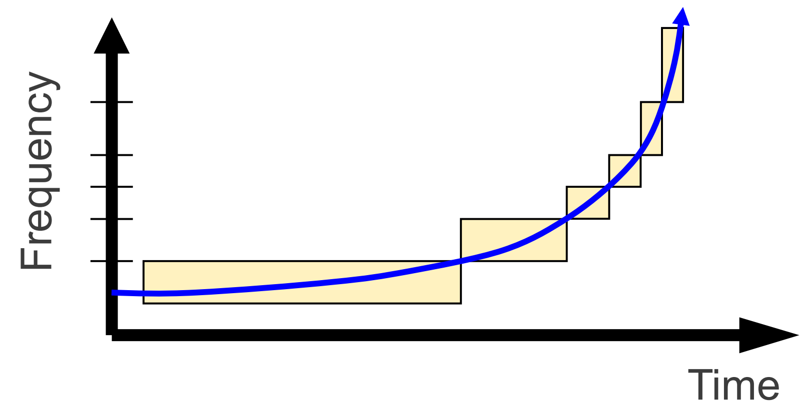
# Search pipeline example: low mass CBC search (2 parameters)




- Remaining coincident triggers are ranked according to a detection statistic (ex: combined SNR, weighted likelihood, …)
- Outstanding triggers (low p-value) are studied individually

# Waveform consistency tests: $\chi^2$ test

- Divide the “selected” template into p parts
- The frequency intervals are chosen so that for a true signal, the SNR is uniformly shared among the frequency bands.

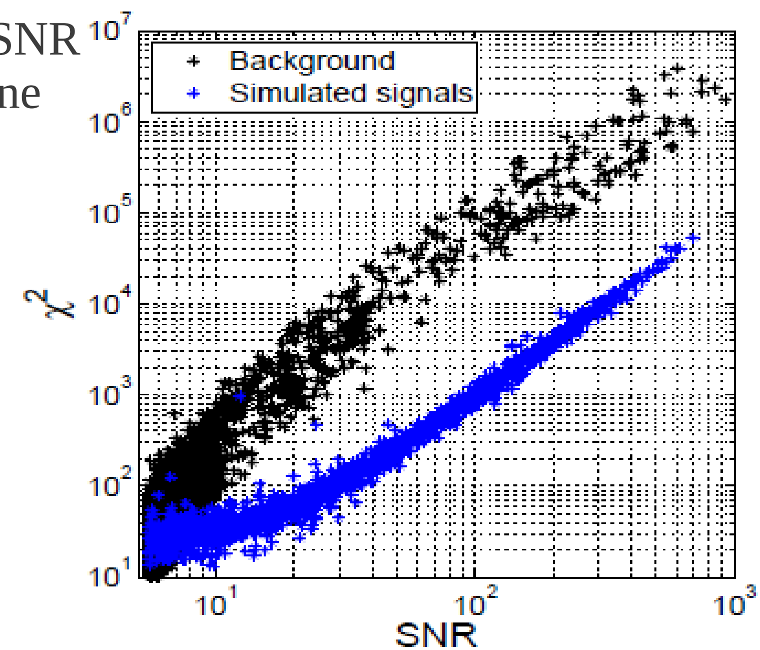



$$\chi^2(t) = p \sum_{j=1}^{p} |\rho_j - \frac{\rho}{p}|^2$$

- For a stationary and Gaussian noise $\chi^2$ has an expectation value: $< \chi^2 > = p - 1$

- In practise $\chi^2$ values are larger than expected for large SNR (discrete template banks effect) → cut in (SNR, $\chi^2$) plane

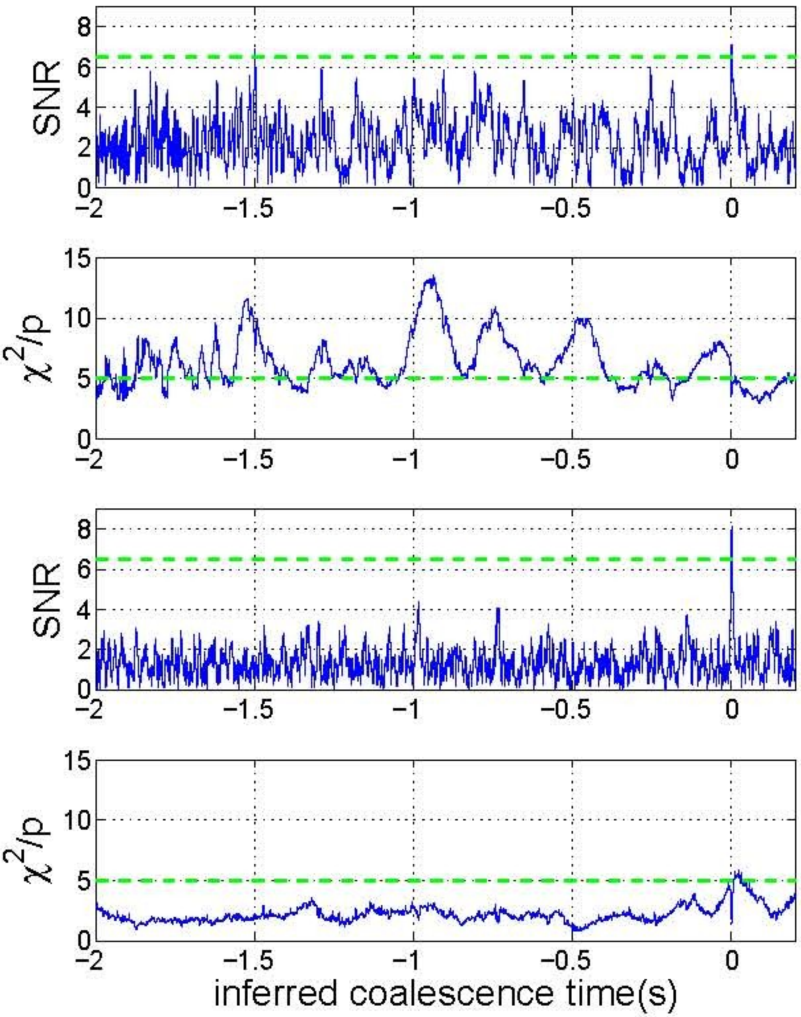
- Weighted SNR




$$\rho_{\text{new}} = \begin{cases} \rho, & \chi^2 \le n_{\text{dof}} \\ \dfrac{\rho}{\left[\left(1 + \frac{\chi^2}{n_{dof}}^{4/3}\right)/2\right]^{1/4}}, & \chi^2 > n_{\text{dof}} \end{cases}$$

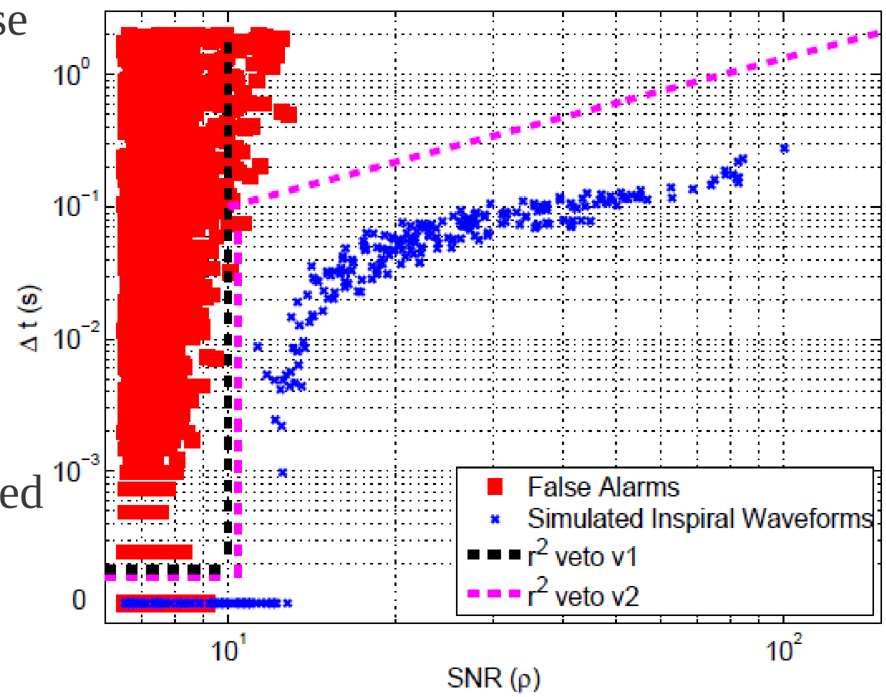
# Waveform consistency tests: $r^2$ test

- Use as discriminating variable the time spent by $\chi^2(t)$ above some threshold in some time window prior to the measured coalescence time.




Non gaussian noise

CBC signal injected
In Gaussian noise

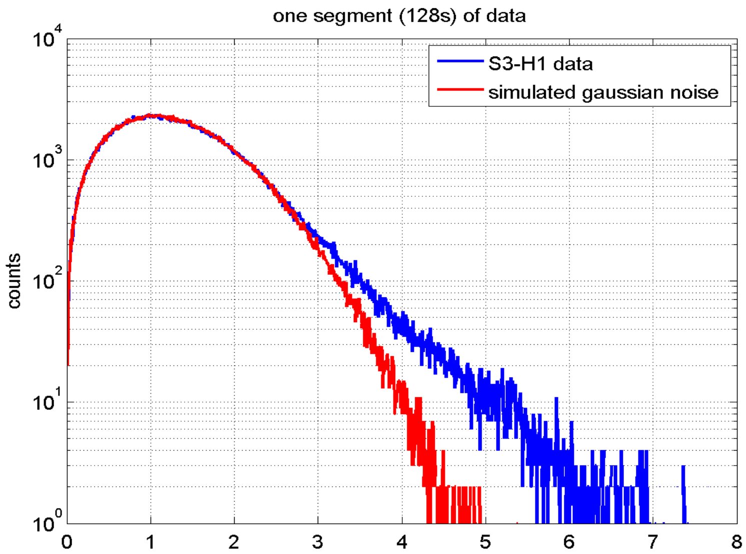


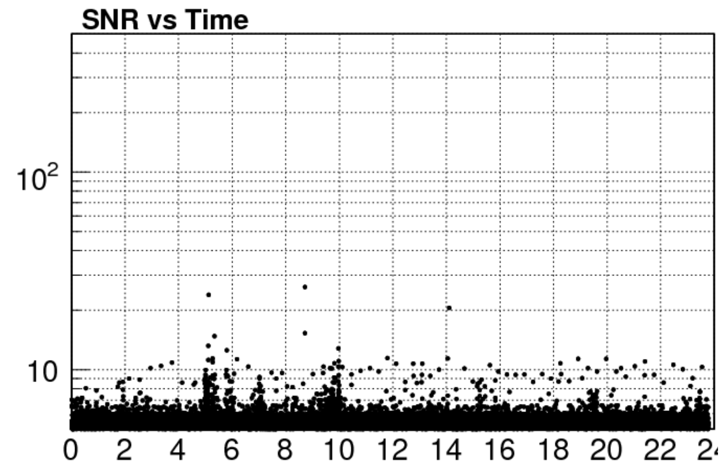
# Gaining confidence in a signal candidate

- How do we know whether a signal in the data is a real GW?
  - Consistency with a source model (see previous examples)
  - Define a performant ranking statistic
  - Estimate p-value (coincidence/consistency in multiple detectors)
  - Absence of instrumental problems at the time of the signal
  - Validation of instrument response (candidate follow-up)
  - Association with a known astrophysical object (parameter estimation)

# Coincidence/consistency tests – background estimation

- Single detectors output is not Gaussian (long tails)

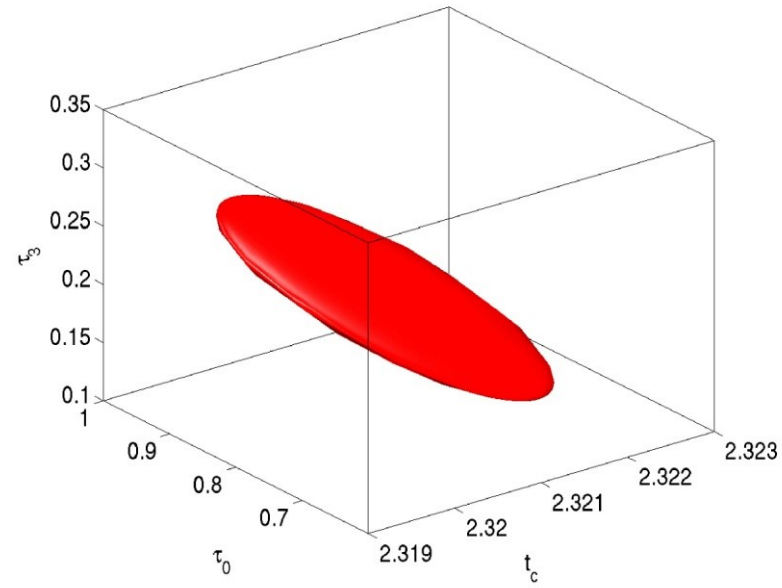



- Signals should arrive at consistent times:
  - LIGO Hanford vs Livingston: ± 10 ms
  - LIGO vs Virgo: ± 27 ms
- Signals should have consistent properties:
  - Same or similar template in all detectors
  - Consistent frequency, amplitude, ...

# Coincidence/consistency tests – background estimation

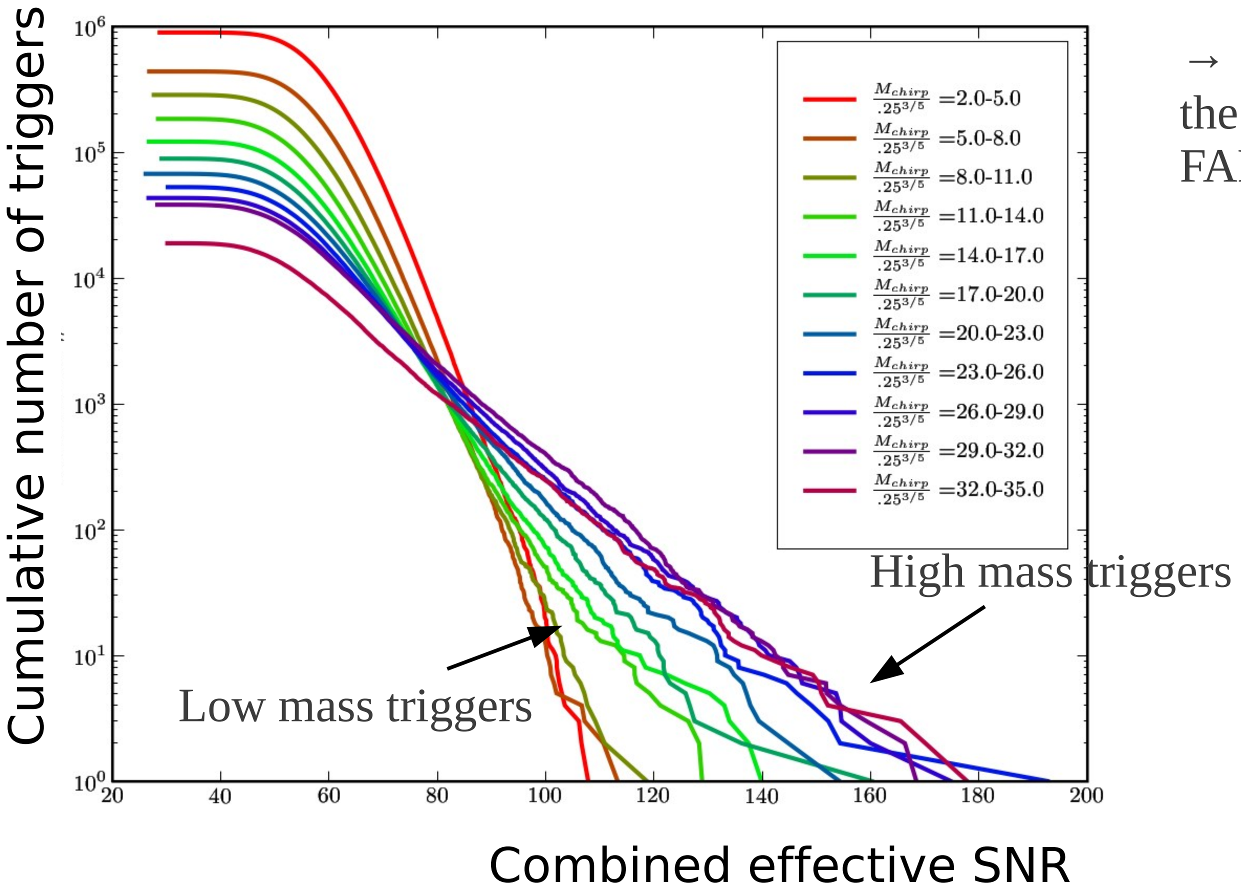
- CBC search asks for coincidence in at least 2 detectors
  - time coincidence
  - Mass coincidence (M and η)
- Use ellipsoids in the parameter space
  - To take into account correlation between parameters and parameters accuracy
  - Ellipsoids built using parameter space metric
  - One “distance” parameter to tune




→ background reduction : ~ factor 10

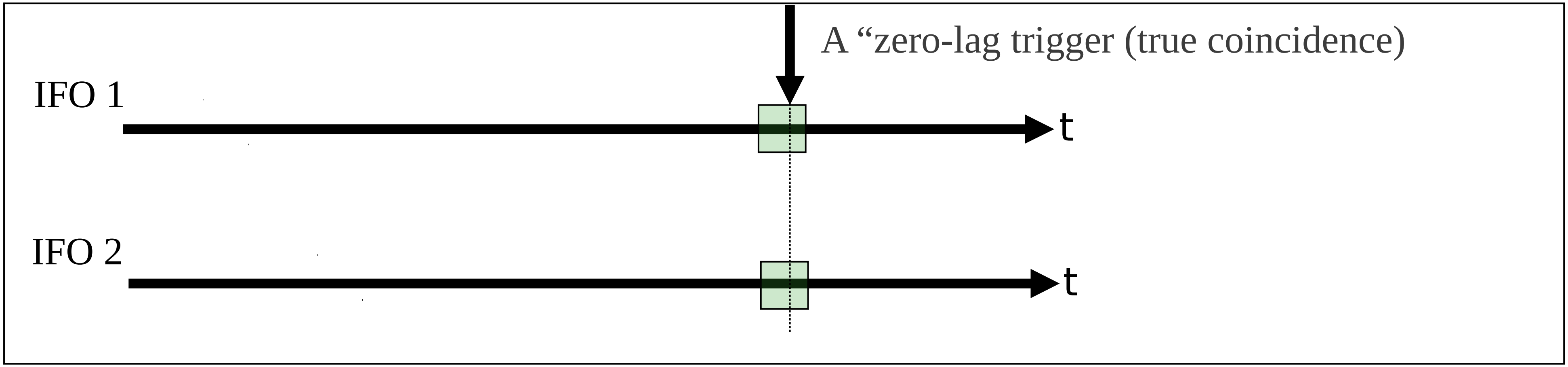
# Background estimation

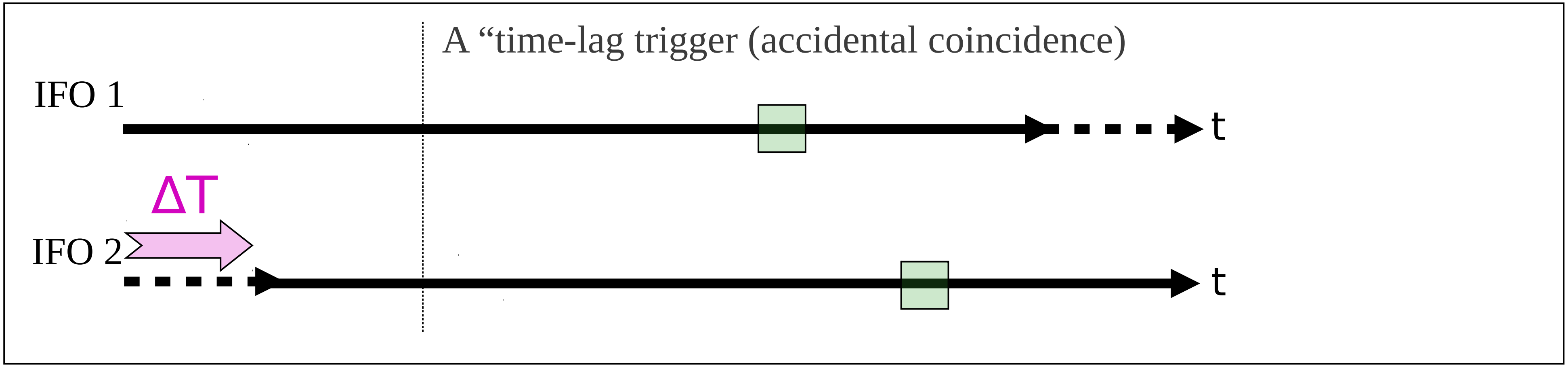
- Mass dependence of the FAR: high mass templates that have less cycles brings loudest SNR triggers.



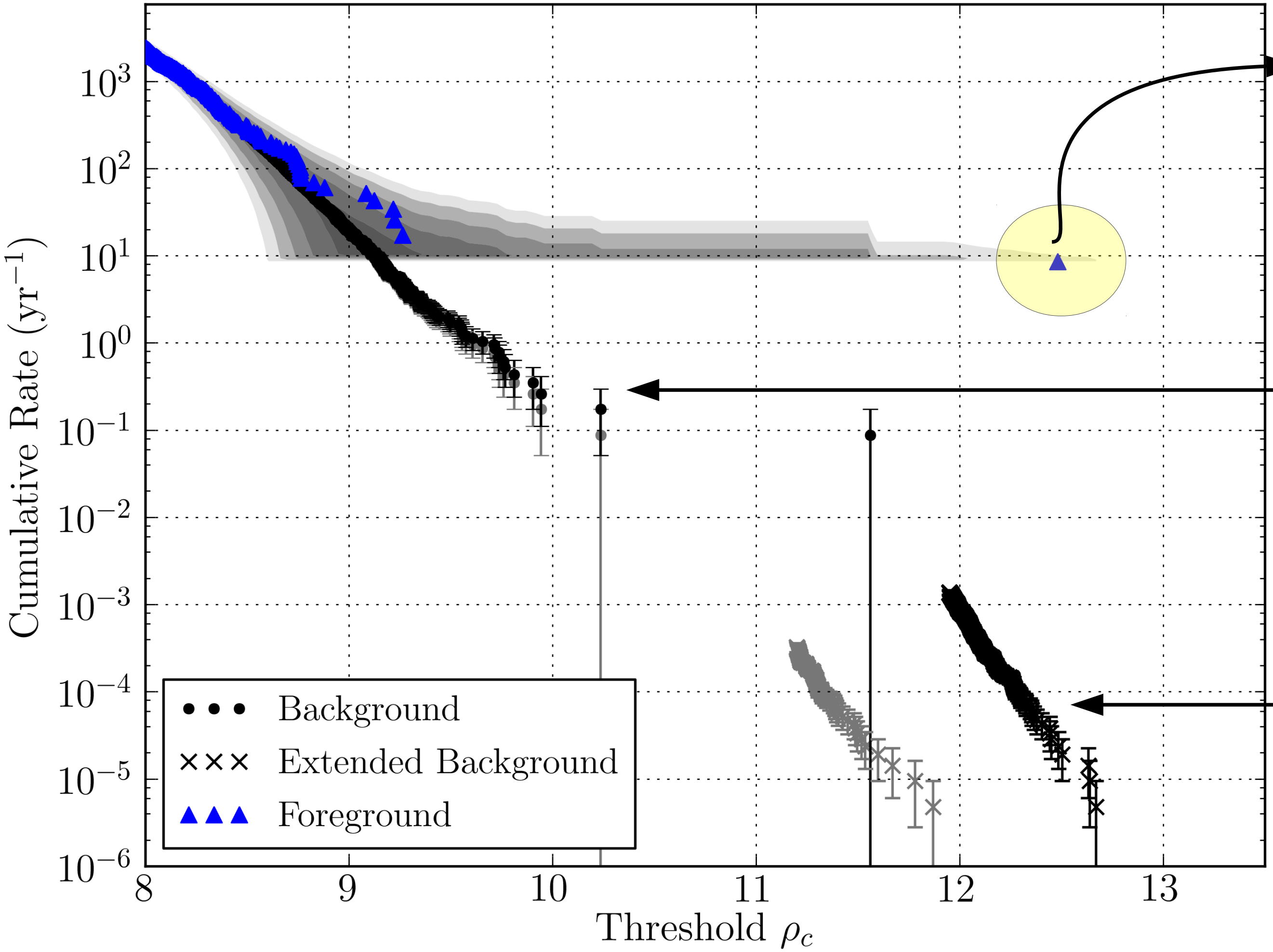

→ define several mass regimes to define the FAR and the ranking statistic based on FAR.

# Background estimation



# Example (low mass LIGO-Virgo):




Loudest event (fake signal) significance: 1 in 7000 years

p-value: 7 $10^{-5}$ ↔ “3.8 sigma”

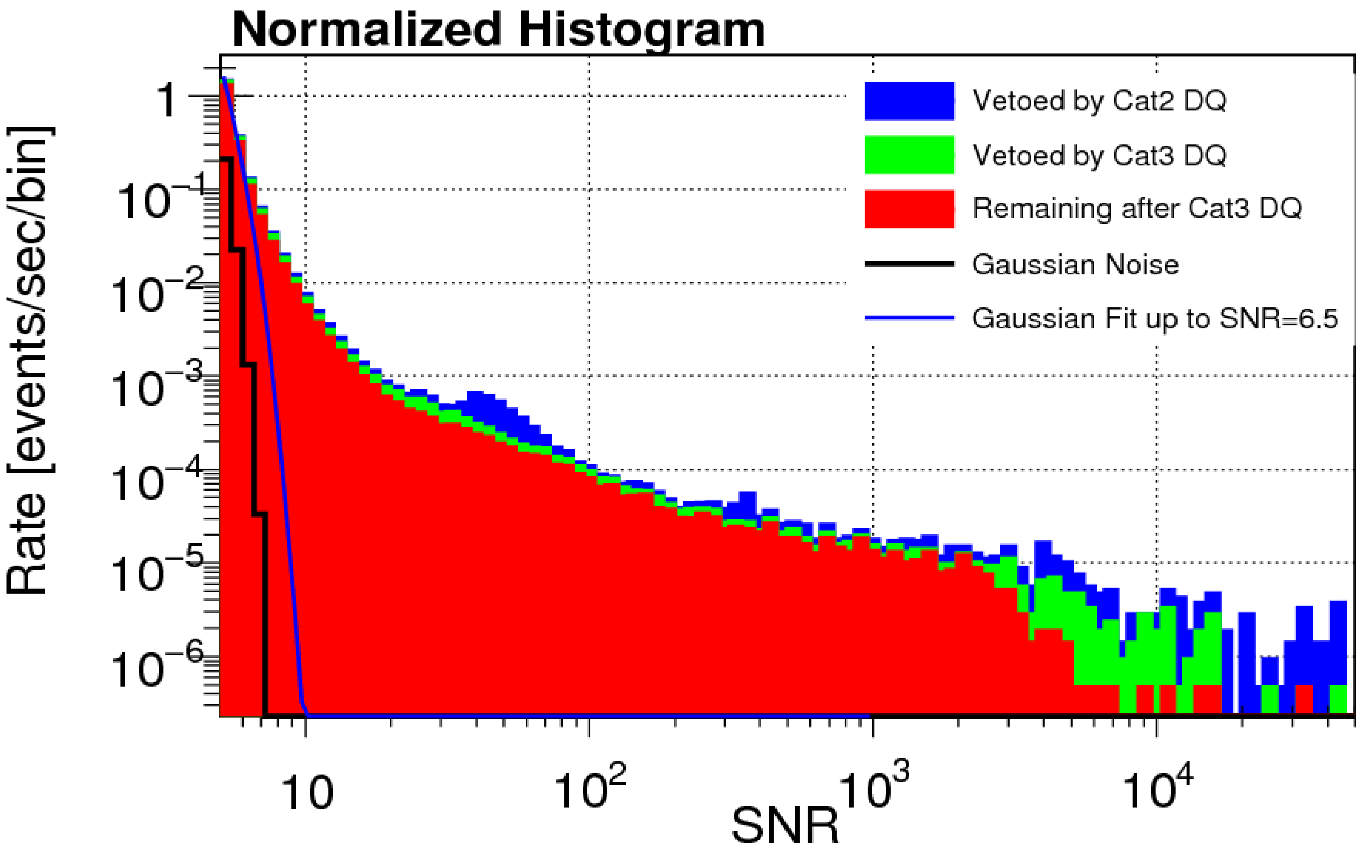
100 time shifts

40,000 time shifts

# Data quality/instrumental vetoes

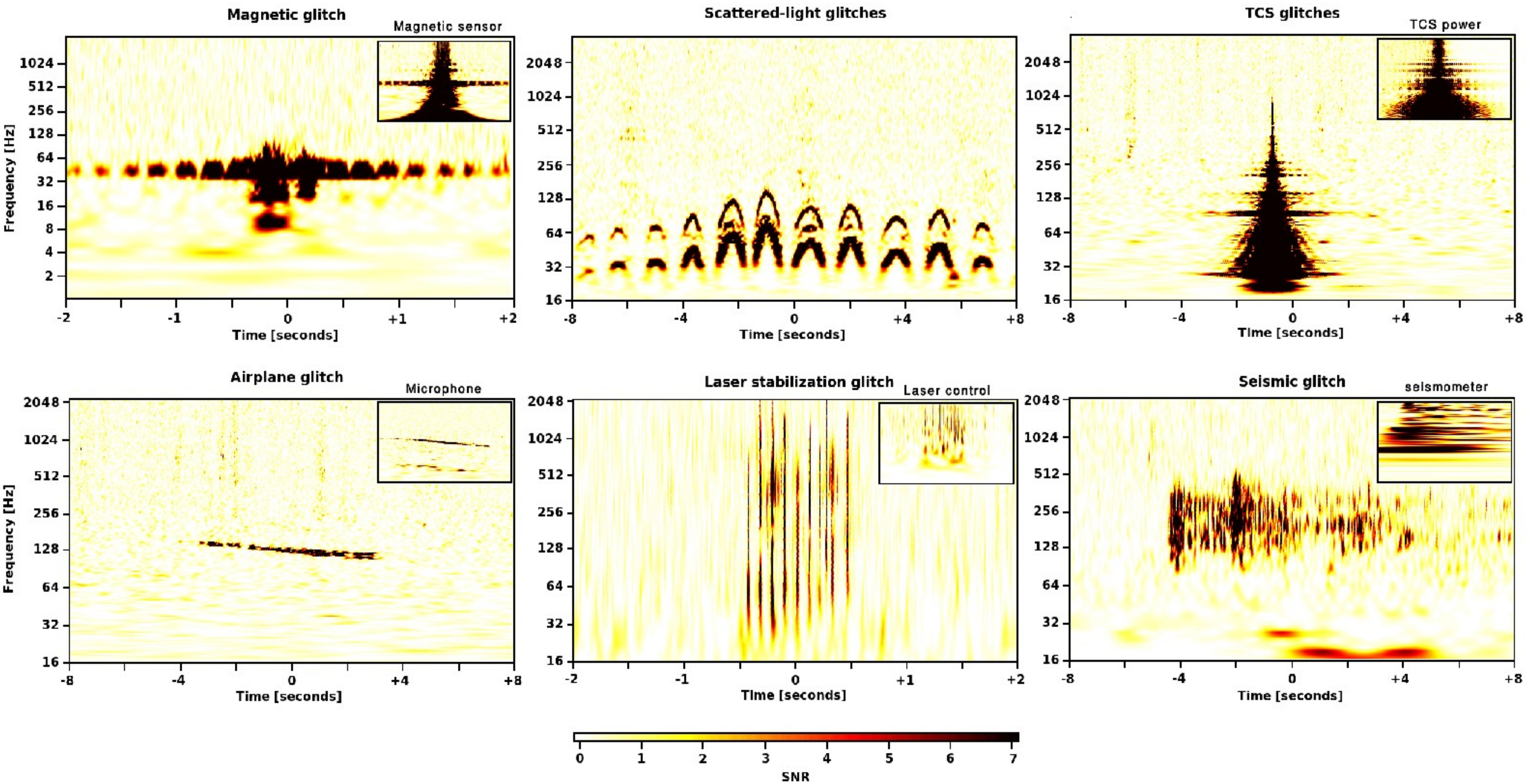
- Minimal data quality cuts: ask for periods when IFOs are “locked” and in “Science”. No ADC saturation …

→ not enough to suppress all noise transients




S6C LIGO Livingston
Omega triggers

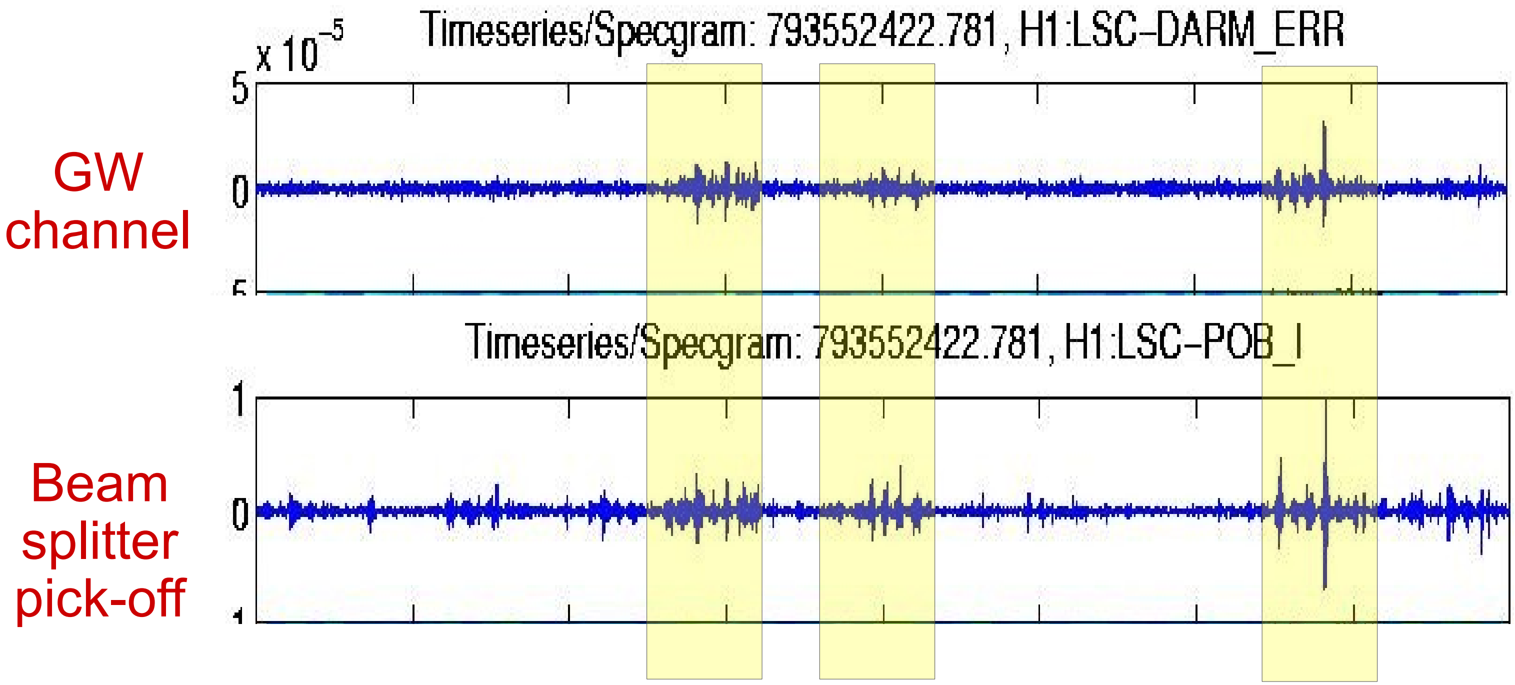
# Data quality/instrumental vetoes




Virgo VSR2-3

# Data quality/instrumental vetoes

- Instrumental vetoes based IFO slow monitoring (low power, electronic failure, etc)
- Instrumental vetoes based on statistical properties of coincidence between the GW channel and auxiliary channels



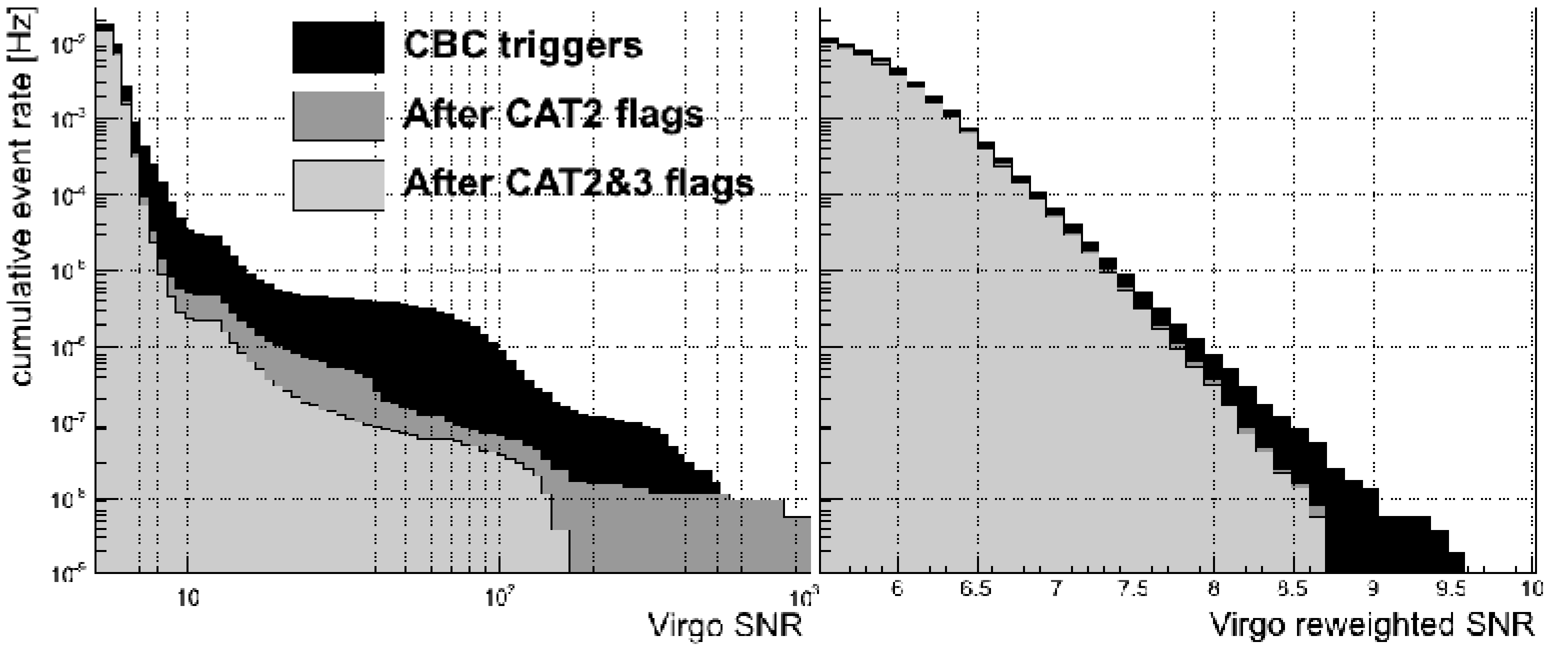

Virgo VSR2-3

# Data quality/instrumental vetoes

- Statistical properties:
  - Efficiency (ε): eliminate false triggers, especially those with high SNR. Fraction of triggers which are flagged
  - Use percentage (UP): veto segments should always eliminate at least 1 trigger. Fraction of vetoes used to veto at least 1 trigger.
  - Dead time (dt): fraction of science time that is vetoed
  - Safety: vetoes should never suppress a real GW events. This is checked using hardware injected signals (force/current applied to a mirror to produce a differential motion equivalent to the effect of a GW)
- Auxiliary channels are “selected” according to several criteria:
  - High ε/dt, high UP, safety OK
- According to their statitical properties, vetoes belongs to different categories (CAT1, 2, 3)

Virgo VSR2-3

# Data quality/instrumental vetoes

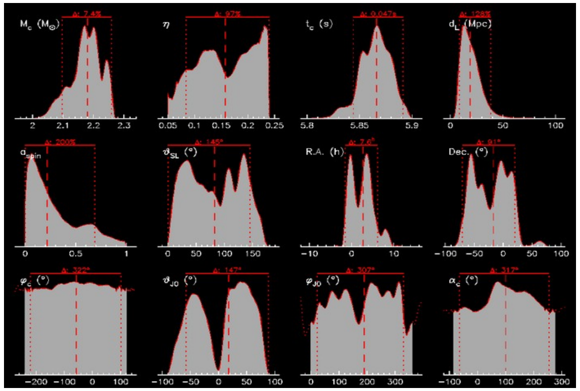



CBC low mass search: Virgo vetoes eliminate a fraction of the loudest coincident triggers

# Parameter estimation

- Parameters error estimate: Fisher matrix method
- We have a model → Bayesian approach provides well understood PDFs and degeneracies as a function of SNR (posterior distribution combines the information in the data with the prior information).
- The posterior distribution of a set of parameters $\vec{\theta}$ given a model H is given by Bayes' theorem:

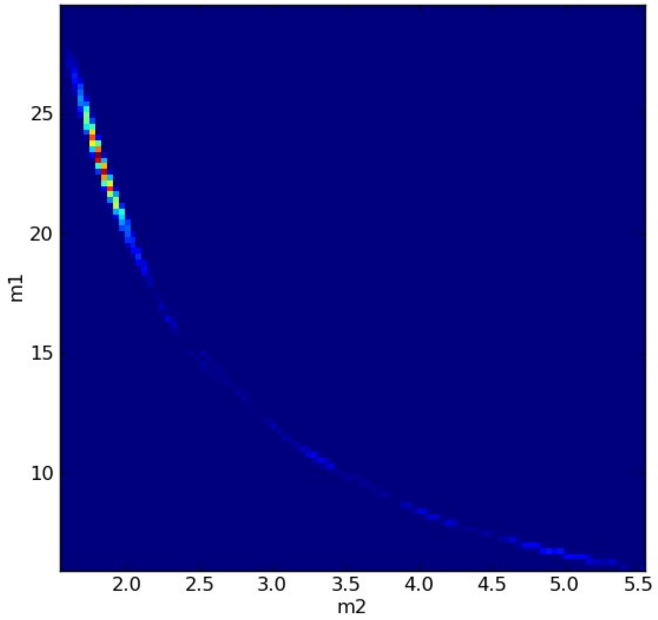
$$p(\vec{\theta}|\{d\}, H) = \frac{p(\vec{\theta}|H)p(\{d\}|\vec{\theta}, H)}{P(\{d\}|H)}$$

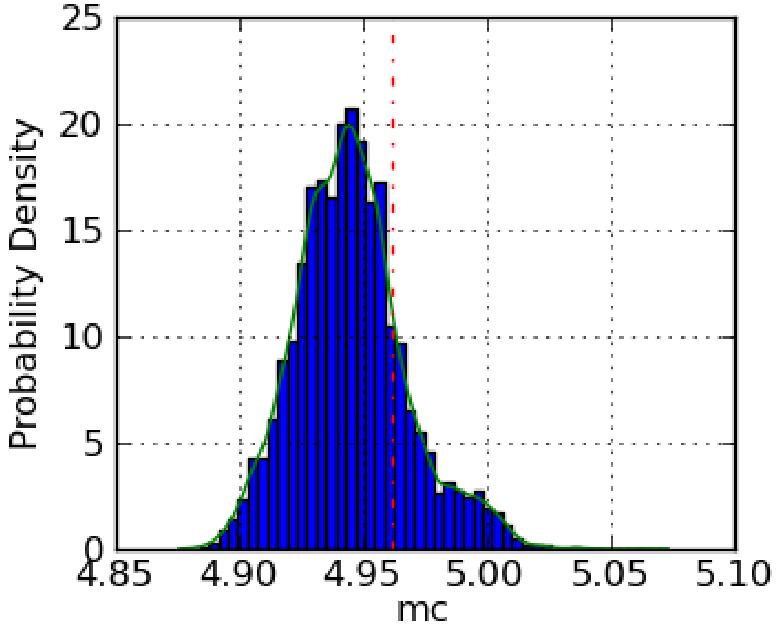


- MCMC are rather computationally slow but accurate. Present implementations include fulling precessing spinning waveforms (15 parameters).

# Example: mass estimation

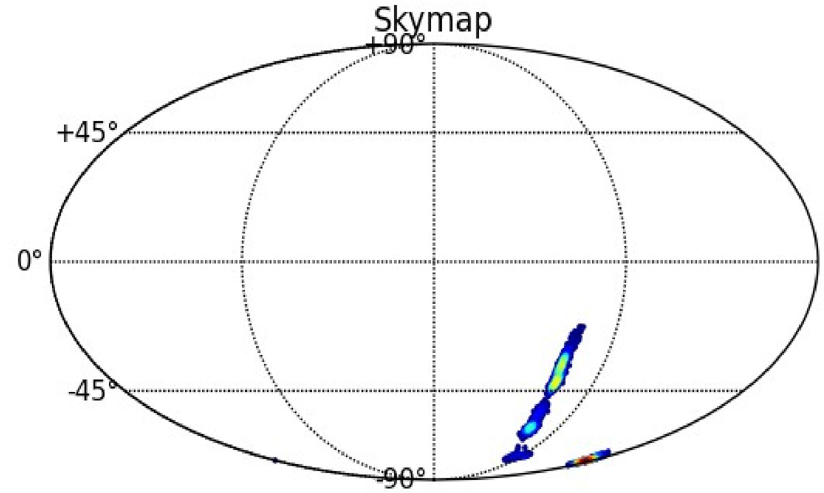
- NS-BH inspiral signal injected into LIGO & Virgo
- Parameters extracted via a Bayesian MCMC including the effects of spins
- Masses are reconstructed correctly but the chirp mass is better reconstructed since it governs the phase evolution of the waveform.

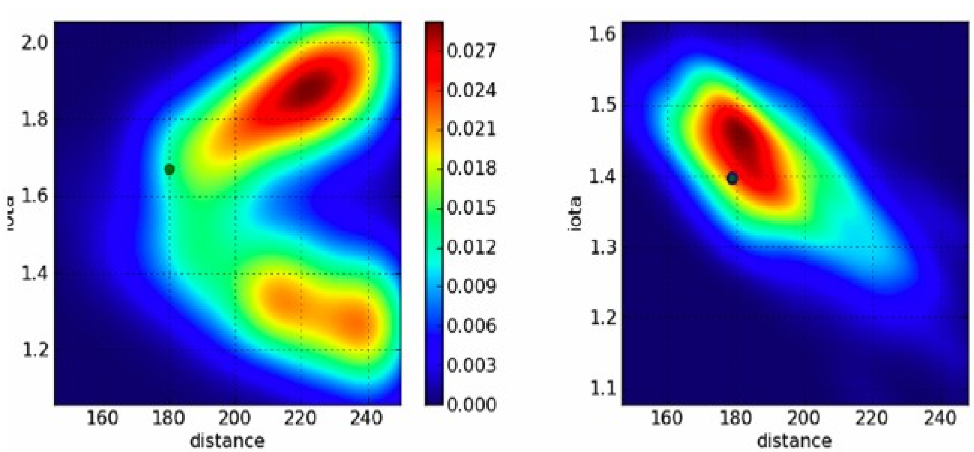


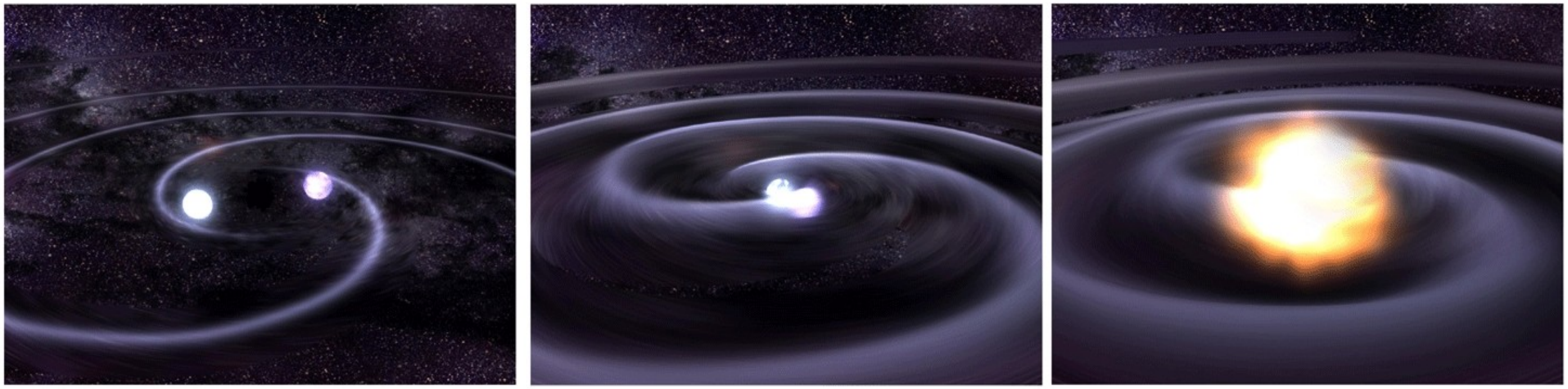
# Example: sky location & distance estimation

- Sky location is reconstructed but nowhere near as well as can be done with EM telescopes.
- Luminosity distance can be extracted from the amplitude of one knows the inclination angle ι.
- The 2 polarizations of the waveform depend on the inclination angle differently, so they can be disentangled if we have 3 or more detectors, oriented differently.
- CBC are standard sirens to get luminosity distance → measure Hubble constant (with 10% accuracy)

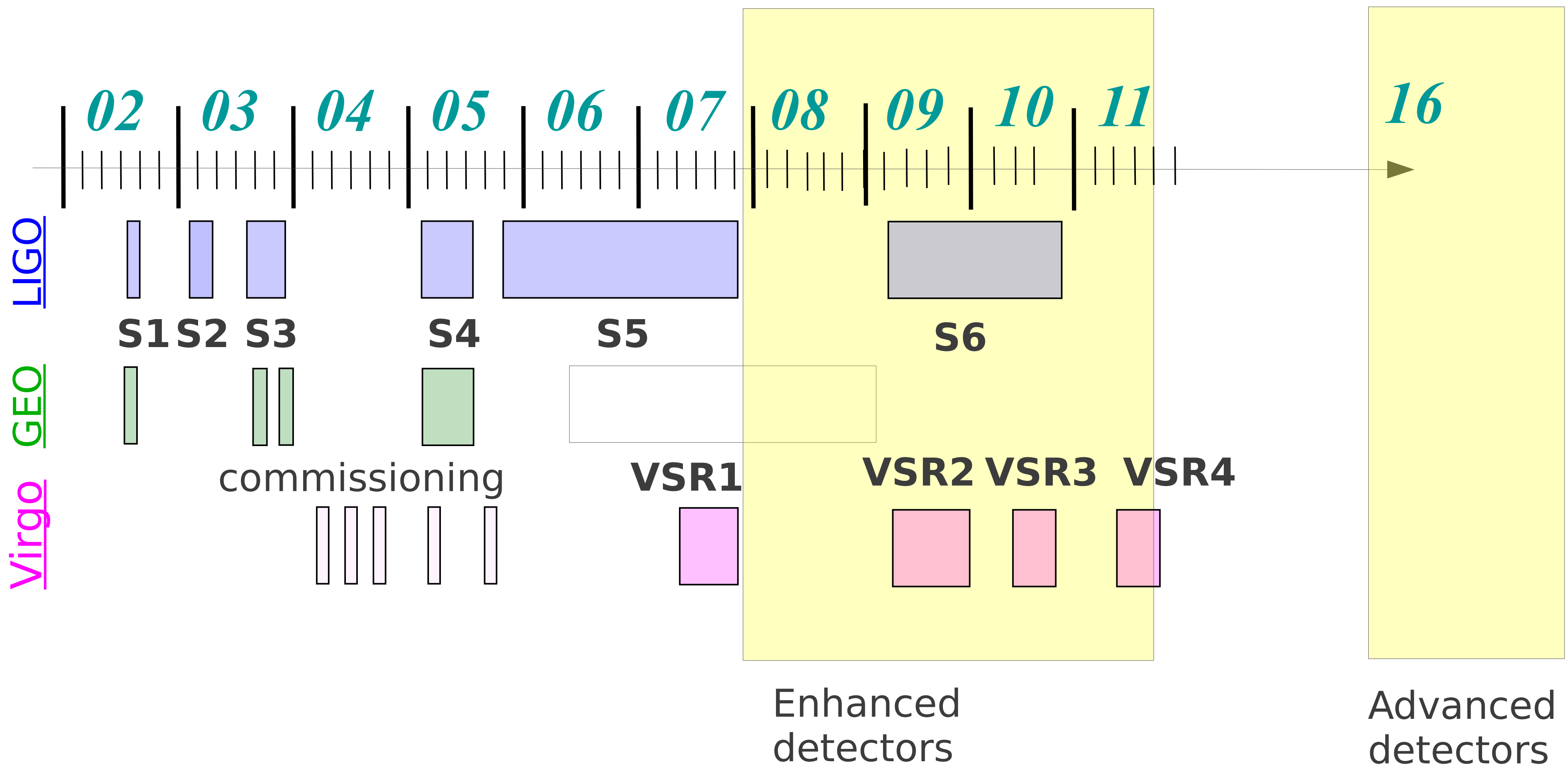


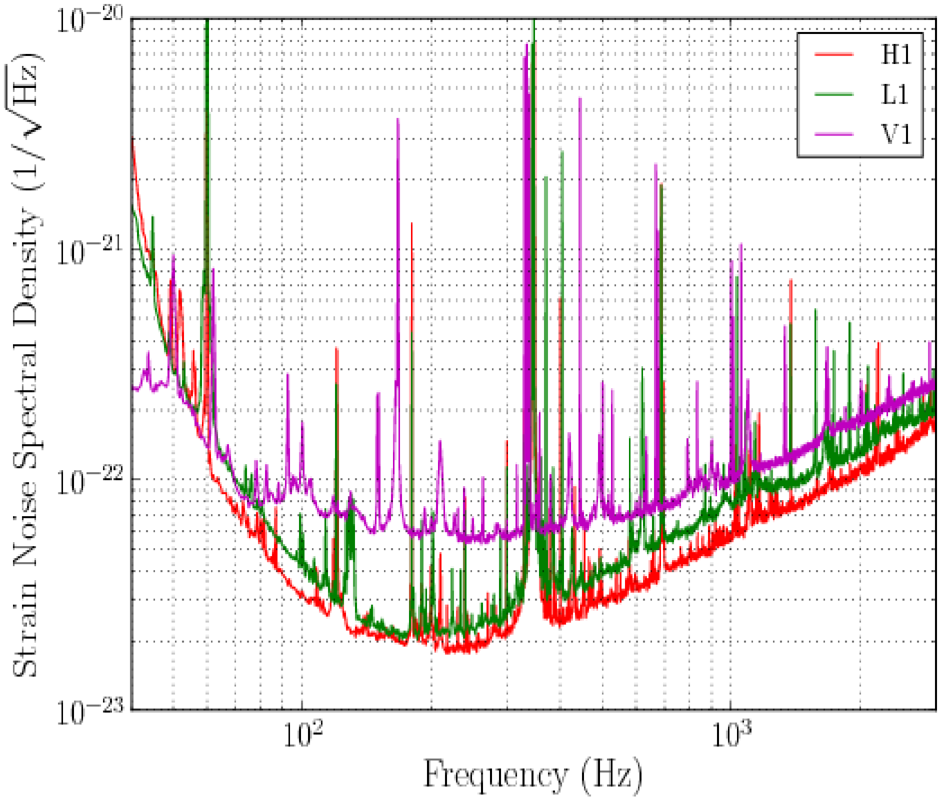
# Results

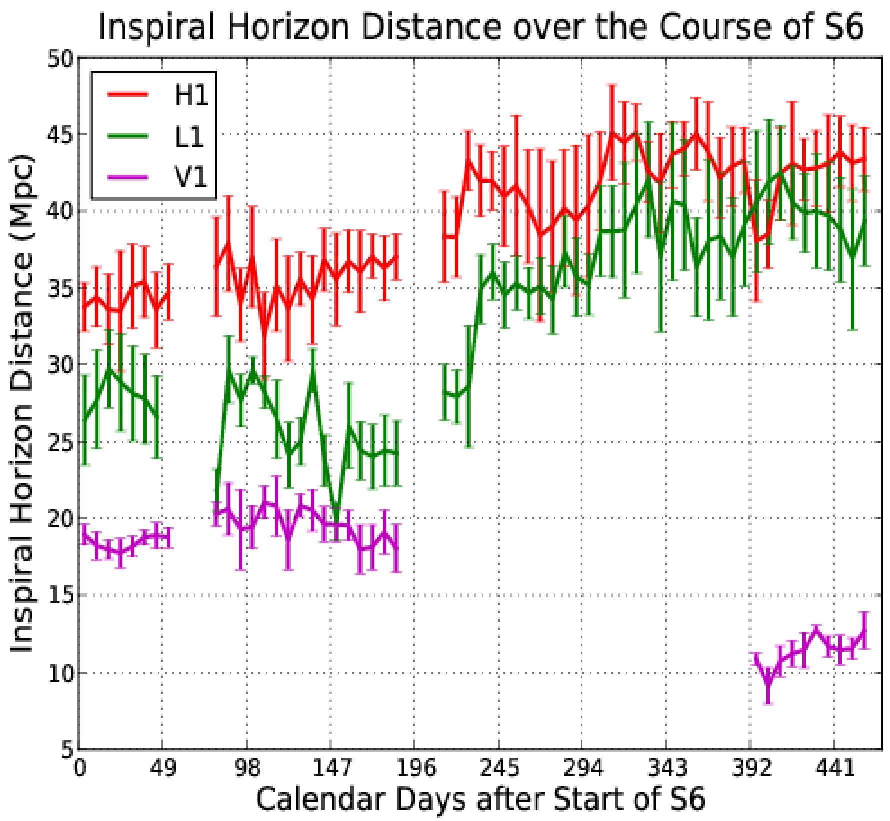


# LIGO – Virgo Runs



# S6/VSR2-3 LIGO Virgo sensitivities



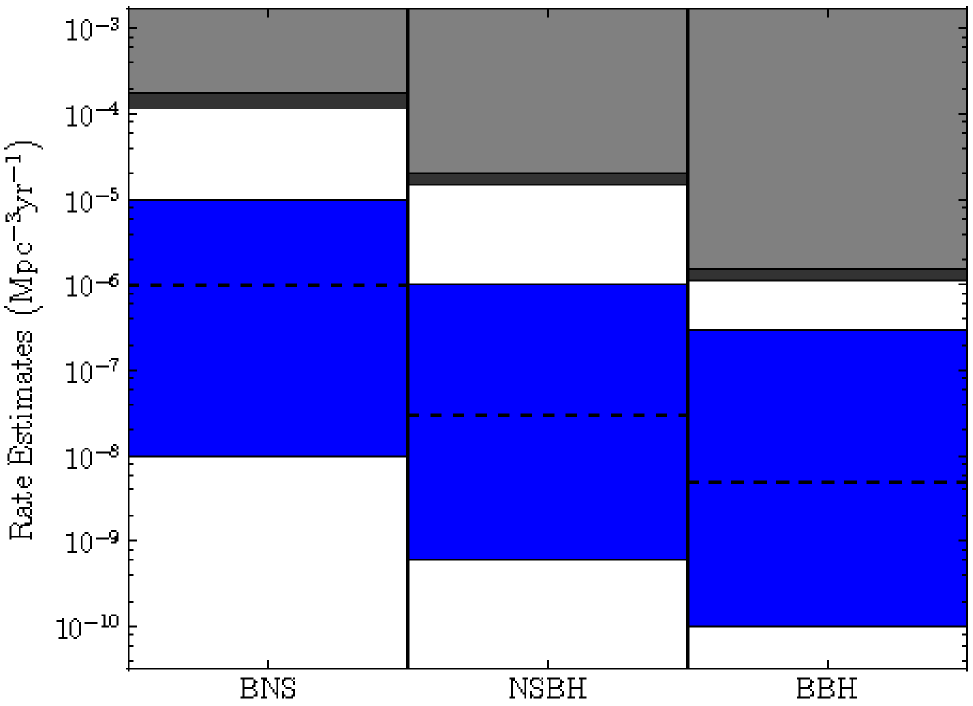
# S6/VSR2-3 low mass CBC search

Phys. Rev. D 85, 082002 (2012)

- Search for 2-25$M_\odot$ total mass CBC
- PN restricted waveforms
- No evidence for a GW signal
- 90% upper limits on the events rate

NSNS: 1.3 x $10^{-4}$ $Mpc^{-3}$ $yr^{-1}$
NSBH: 3.1 x $10^{-5}$ $Mpc^{-3}$ $yr^{-1}$
BHBH: 6.4 x $10^{-6}$ $Mpc^{-3}$ $yr^{-1}$

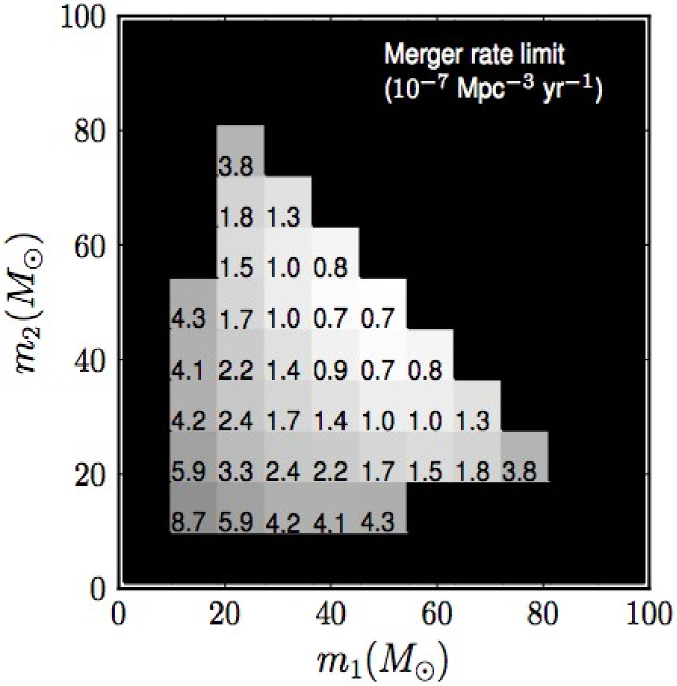
Still 2 orders of magnitude above "realistic" rate



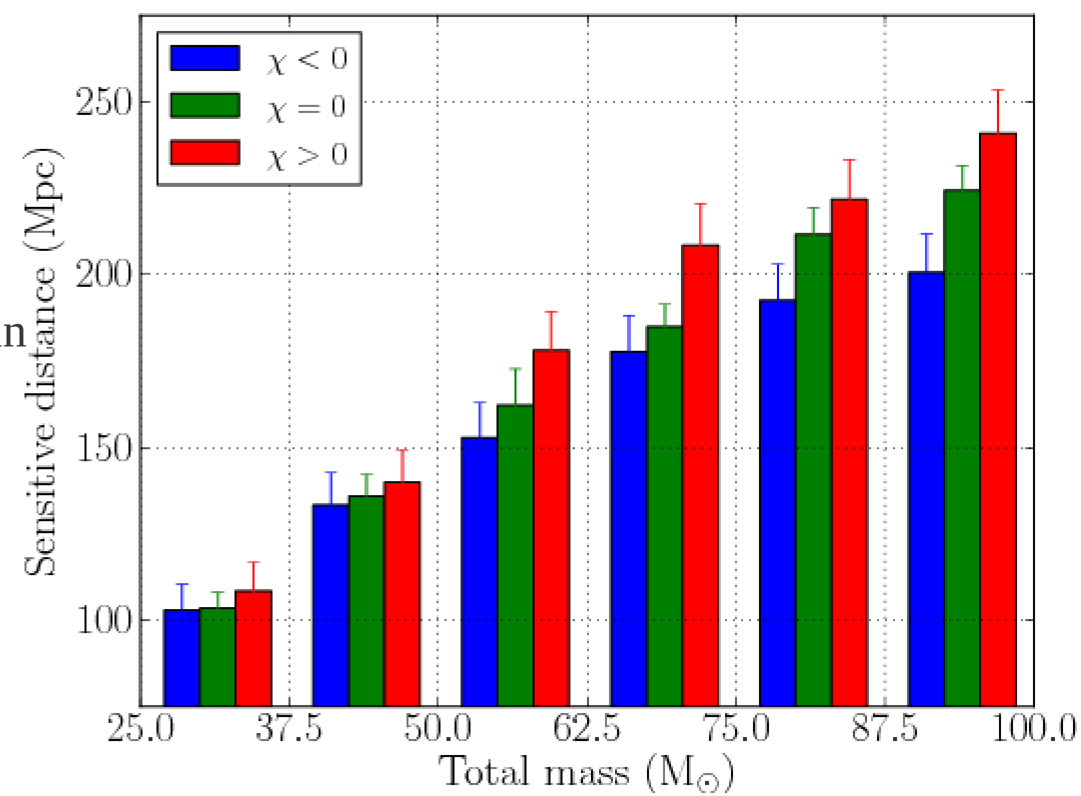
# S6/VSR2-3 high mass CBC search

Phys. Rev. D 87, 022002 (2013)

- EOBNR waveforms template (no spins)
- Maximum sensitive distance of the detectors over this period for a (20,20) $M_\odot$ coalescence was 300 Mpc
- 90% confidence level merger rate limit of 3.3 $10^{-7}$ $Mpc^{-3}$ $yr^{-1}$ for an equal mass 19-28 $M_\odot$




- Dependence of sensitivity wrt aligned spin Components
- Aligned spin values: −0.85≤χ≤0.85
- Mass ratio 1:4

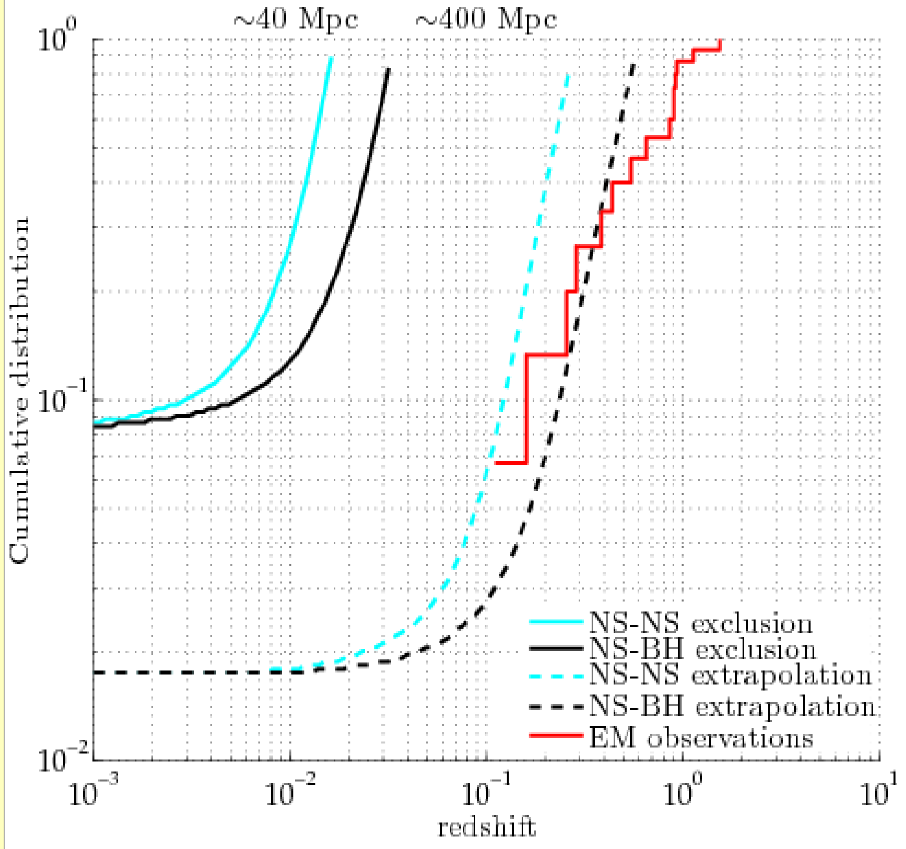


# GRBs

Astrophys. J. 760, 12 (2012)

- BNS and NSBH merger are suspected to be short GRB progenitors
- Study more than 300 (long & short) GRBs since 2003
- Short GRB search: coherent CBC triggered pipeline
- 2009-2010 results: exclusion distance of 16 Mpc for BNS and 28 Mpc for NSBH.
- Assuming all GRBs emit the same amount of energy, one can derive an exclusion limit on the cumulative number as a function of their redshift.

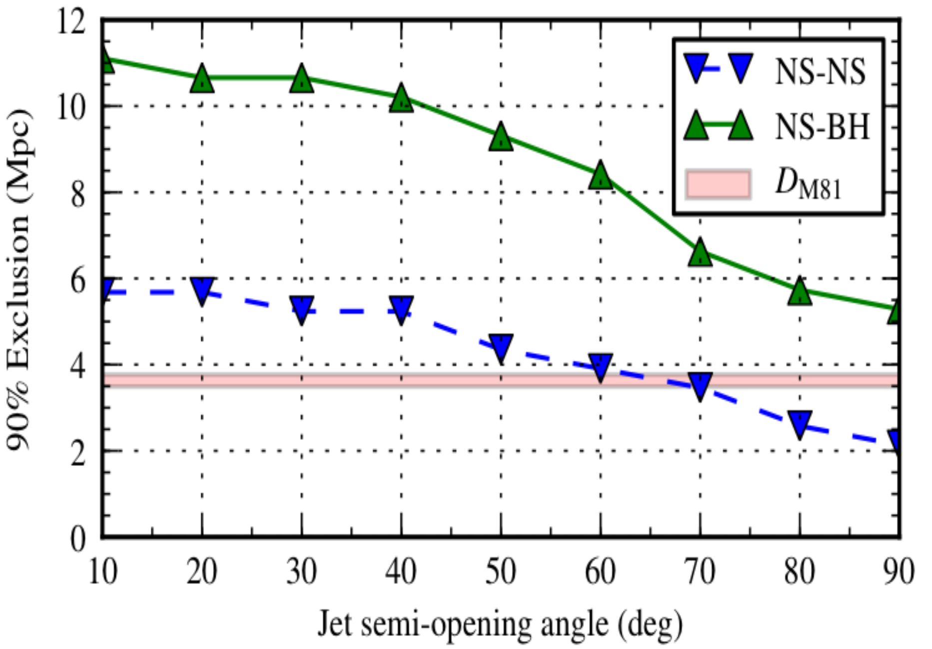
  → with advanced detectors, we will be sensitive to what EM observations say.



# GRB 051103

Astrophys. J. 755, 2 (2012)

- Short hard-γ spectrum GRB overlapping M81 (3.6 Mpc) observed few days before S5.
- Progenitors: NS-NS/BH or SGR giant flares
- CBC and burst searches: no evidence for a GW signal:
  -->Merger progenitor is excluded at 98% CL.
  -->SGR hypothesis can't be ruled out (weak GW emission).
- Given the importance of GRB/GW association, and the rather near possible host galaxy this is a significant non detection result

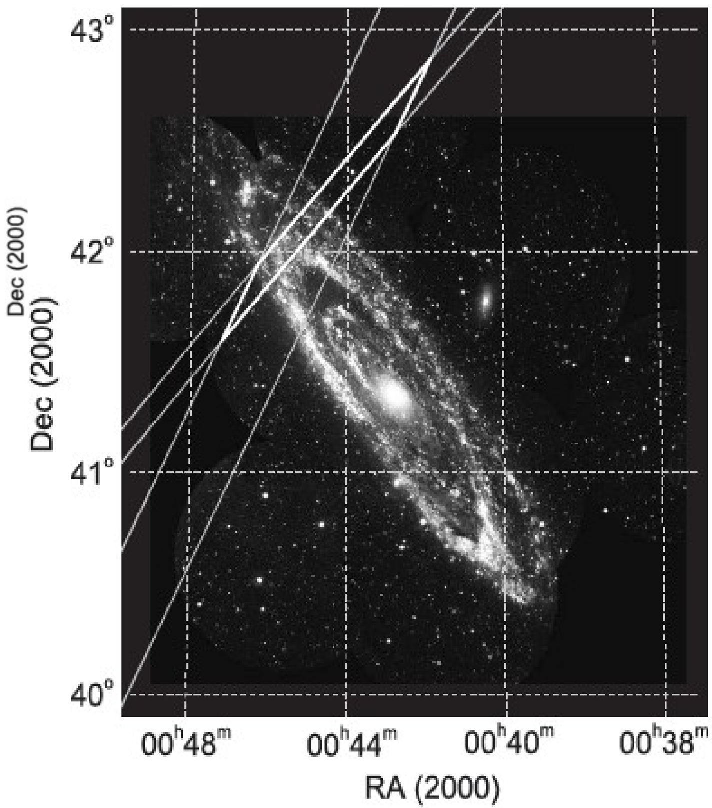


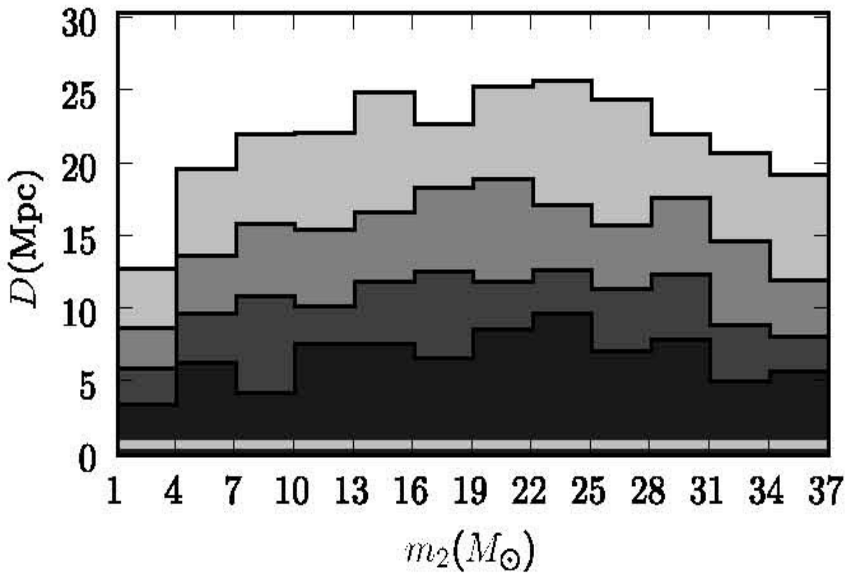
# GRB 071103

Ap.J. 681(2):1419–1430 (2008)

- Short GRB whose error box overlapped spiral arm of M31 (770 kpc away)
- LIGO hanford H1 (4km) & H2 (2km) were operating and sensitive up to 35 Mpc and 15 Mpc.

- Null results. Exclude CBC progenitor in M31 as source with 99% confidence
- Can't exclude SGR in M31



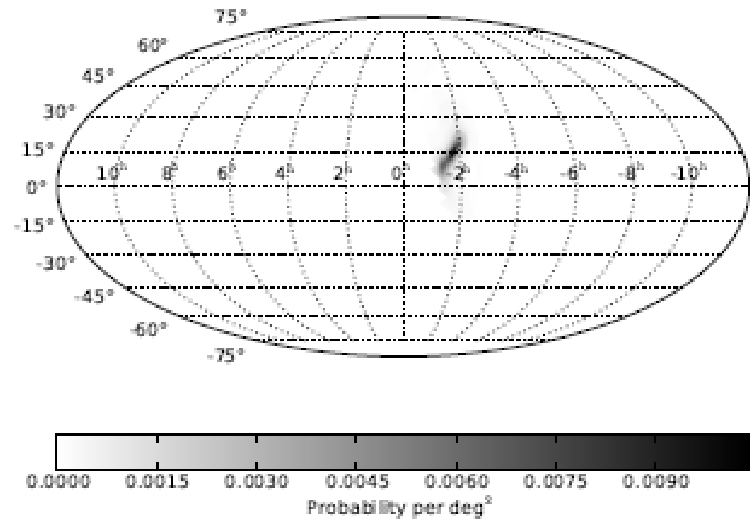



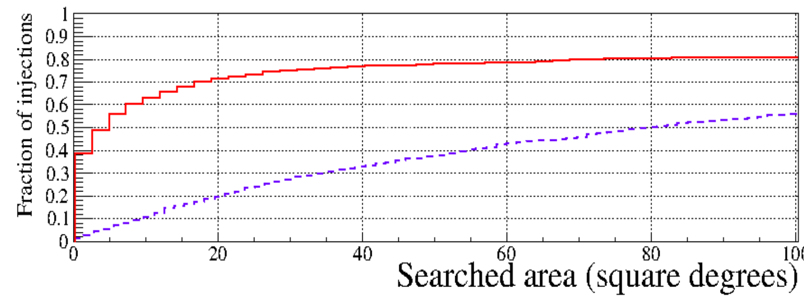
# Low latency CBC searches

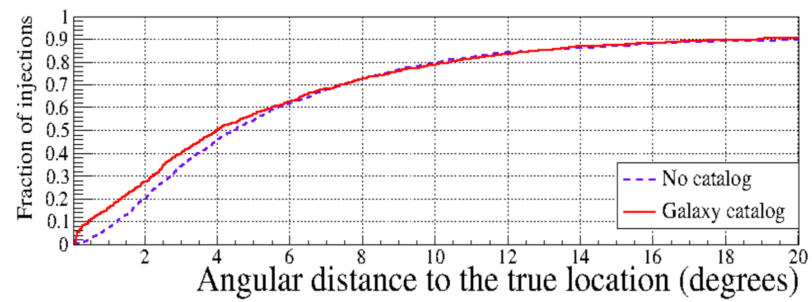
A & A 541, A155 (2012)

- Low latency search pipeline development (Goal: send alerts to telescopes within few minutes. GW inspiral signal may be detected first)
- Low mass search (1-35 $M_{\odot}$), including source sky position estimation.
- Search prototype tested at the end of S6/VSR3 with alerts sent to telescopes.
- 3 events have been selected. 1 has been followed-up by our telescope partners (FAR: 1/6.4 days)

- Latency: ~minutes
- Sky location: not so great (tens of deg$^2$).
  - Using catalogues of galaxies help (but no galaxy complete catalogues for advanced detectors horizon distances)
  - Including spins may improve the accuracy



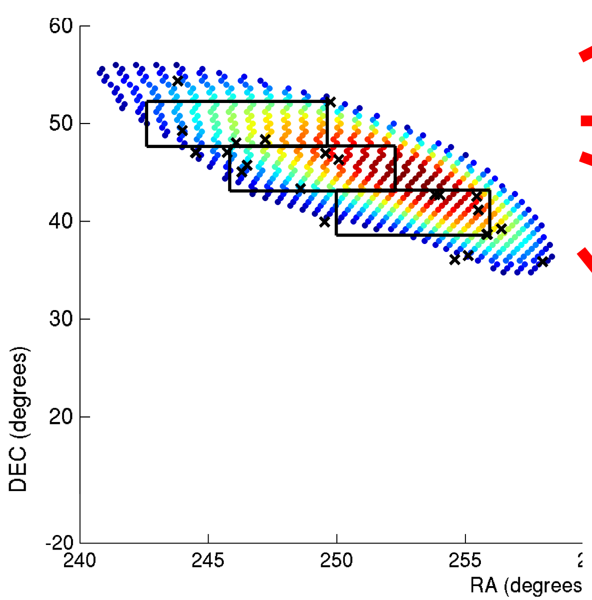



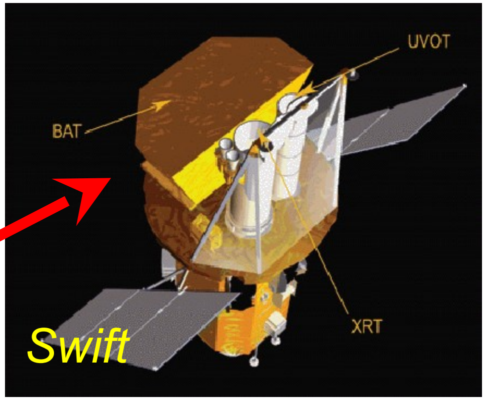



# Electromagnetic follow-ups to GW triggers (“LOOC-UP”)

Analyze GW data promply to identify possible event candidates and reconstruct their apparent sky position → send alerts to telescopes

Try to capture an EM transient that would otherwise have been missed!
First test during S6/VSR3 runs



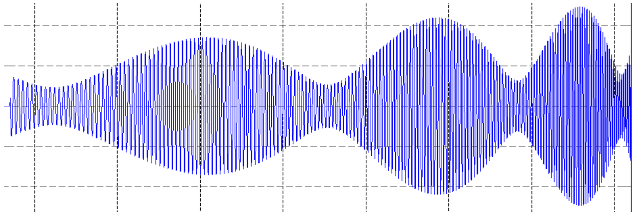





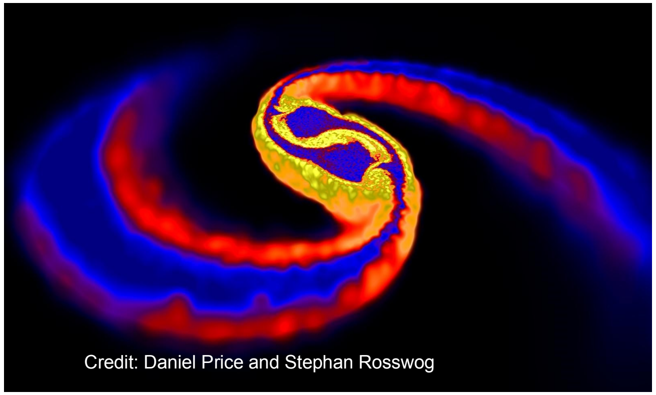

Other telescopes...

# Preparation for advanced detectors

- Low latency searches: streaming mode, sky location (parameter estimation) and candidate significance estimation is less than a few minutes to send alerts.



- Pipeline developments
- Waveforms:
  - Template placement algorithms for spinning waveforms
  - Phenomenological spinning IMR waveforms gain study
- Long term projects (after discovery): astrophysics with BH and NS
  - Test of GR (measure deviation to GR)
  - Tidal disruption of NS near merger
  - EOS study
  -



Credit: Daniel Price and Stephan Rosswog

# Bright future with advanced LIGO and advanced Virgo

Expected rate with 10 times more sensitive detectors

| IFO | Source[a] | $\dot{N}_{\rm low}$ $\rm yr^{-1}$ | $\dot{N}_{\rm re}$ $\rm yr^{-1}$ | $\dot{N}_{\rm high}$ $\rm yr^{-1}$ | $\dot{N}_{\rm max}$ $\rm yr^{-1}$ |
|---|---|---|---|---|---|
| Initial | NS-NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS-BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| | BH-BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | $< 0.001^b$ | $0.01^c$ |
| | IMBH-IMBH | | | $10^{-4\,d}$ | $10^{-3\,e}$ |
| Advanced | NS-NS | 0.4 | 40 | 400 | 1000 |
| | NS-BH | 0.2 | 10 | 300 | |
| | BH-BH | 0.4 | 20 | 1000 | |
| | IMRI into IMBH | | | $10^b$ | $300^c$ |
| | IMBH-IMBH | | | $0.1^d$ | $1^e$ |

Promising … but when?

# Bright future with advanced LIGO and advanced Virgo

- 2015: A 3 month run with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range). Virgo in commissioning at $\sim$20 Mpc with a chance to join the run.
- 2016-17: A 6 month run with H1L1 at 80 – 120 Mpc and Virgo at 20 – 60 Mpc.
- 2017-18: A 9 month run with H1L1 at 120 – 170 Mpc and Virgo at 60 – 85 Mpc.
- 2019+: Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.
- 2022+: Four-detector H1L1V1+LIGO-India network at full sensitivity (aLIGO at 200 Mpc, AdV at 130 Mpc).

# Bright future with advanced LIGO and advanced Virgo

| Epoch | Estimated Run Duration | Burst Range (Mpc) LIGO | Burst Range (Mpc) Virgo | BNS Range (Mpc) LIGO | BNS Range (Mpc) Virgo | Number of BNS Detections | % BNS Localized within 5 $deg^2$ | % BNS Localized within 20 $deg^2$ |
|---|---|---|---|---|---|---|---|---|
| 2015 | 3 months | 40 – 60 | — | 40 – 80 | — | 0.0004 - 3 | - | - |
| 2016–17 | 6 months | 60 – 75 | 20 – 40 | 80 – 120 | 20 – 60 | 0.006 - 20 | 2 | 5-12 |
| 2017–18 | 9 months | 75 – 90 | 40 – 50 | 120 – 170 | 60 – 85 | 0.04 - 100 | 1-2 | 10-12 |
| 2019+ | (per year) | 105 | 40 – 70 | 200 | 65 – 130 | 0.2 - 200 | 3-8 | 8-28 |
| 2022+ (India) | (per year) | 105 | 80 | 200 | 130 | 0.4 - 400 | 17 | 48 |

First discovery in 2016?

Need to be lucky for
EM follow-up ?