Searching gravitational wave burst signals

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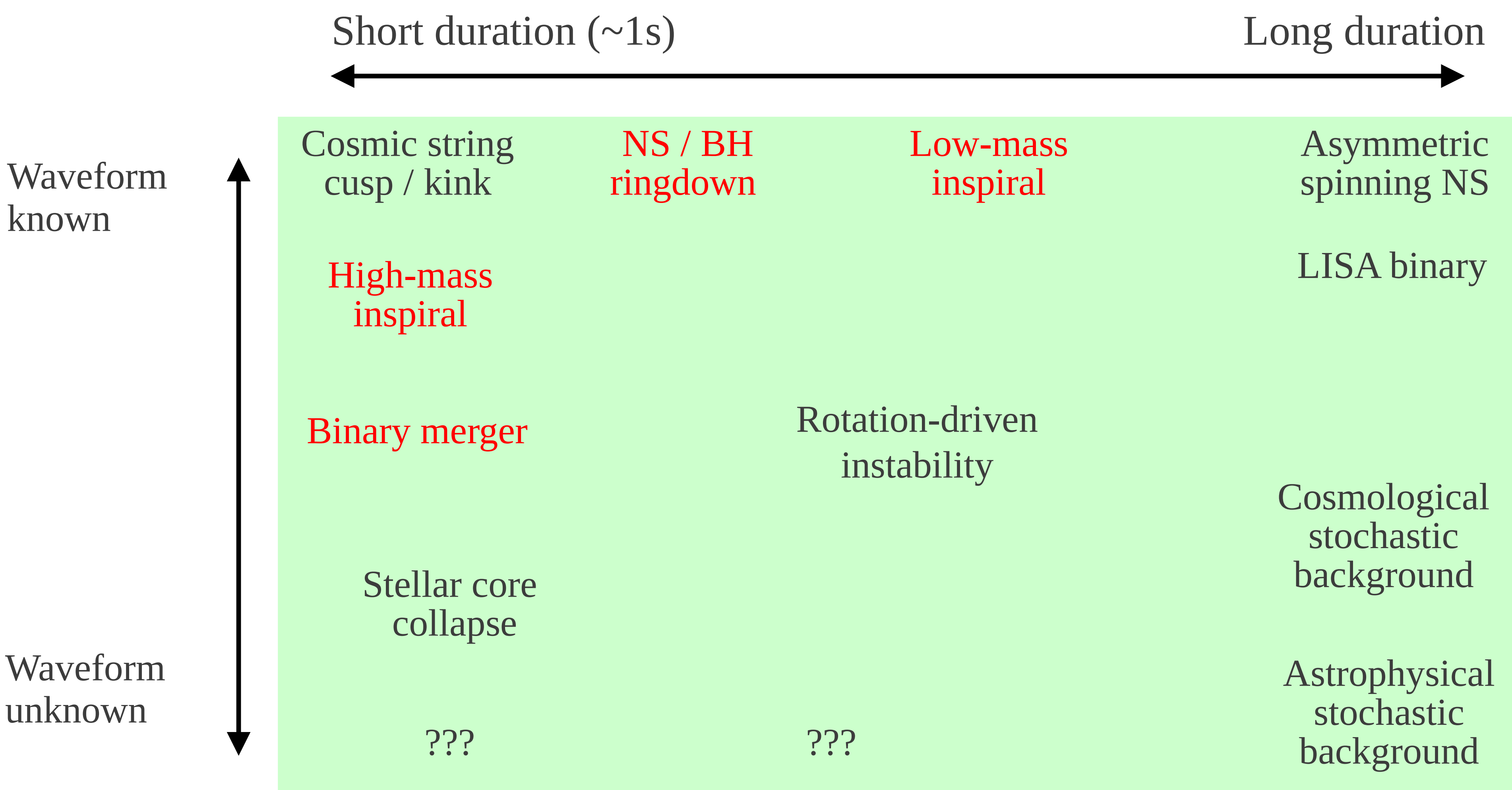
Outline

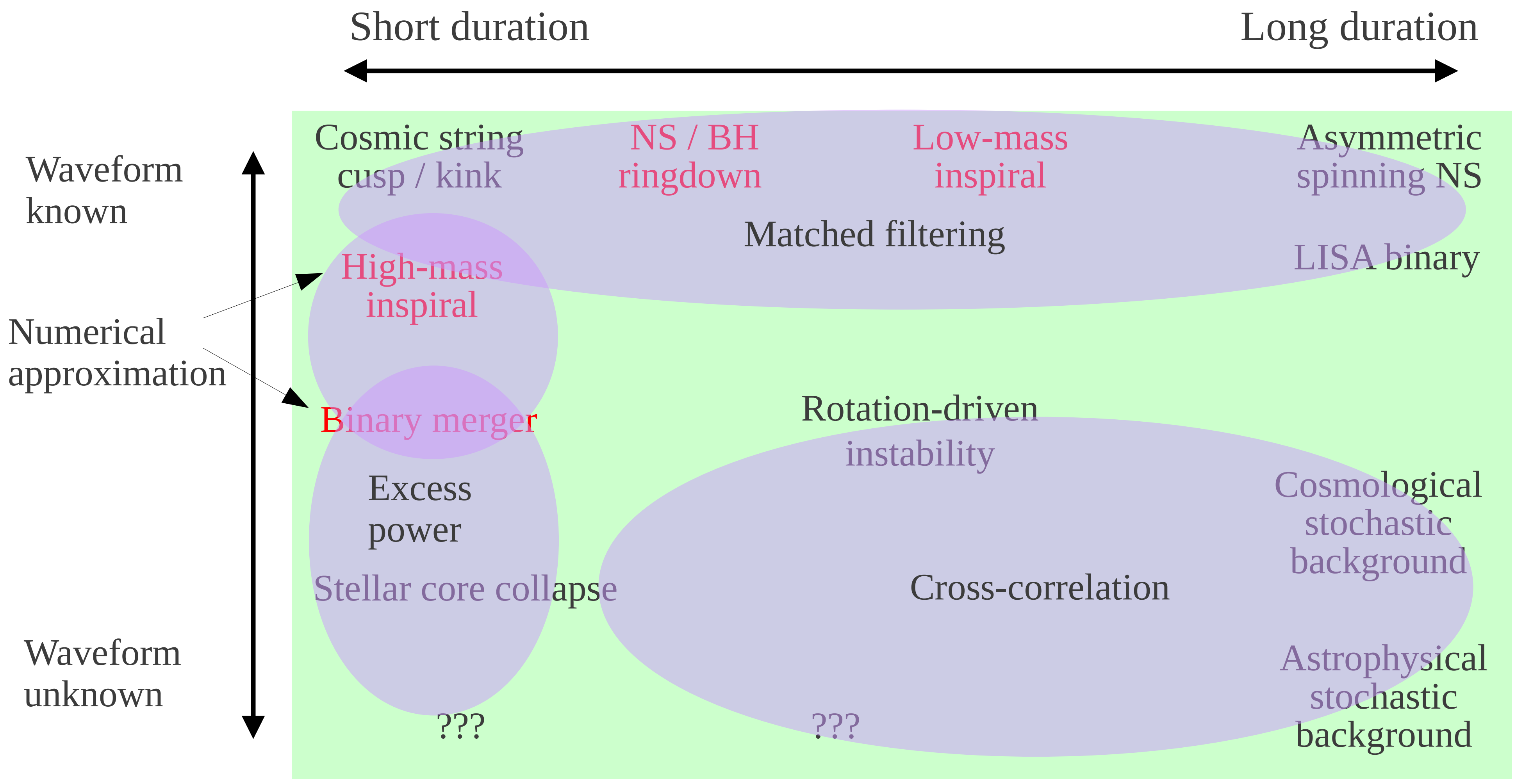
1. Sources and challenges
   - Astrophysical sources: waveform, rate and sensitivity
   - Gravitational wave detector's data characteristics
   - Challenges - what matters?
2. Techniques
   - From all-sky/all-time to triggered searches
   - Data processing pipelines
   - Confidence assessment
   - Dealing with non-Gaussian data
3. LIGO-Virgo search results

GW searches zoology



CBC searches: transient signal searches for LIGO-Virgo!

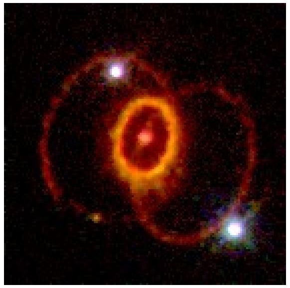
Methods summary



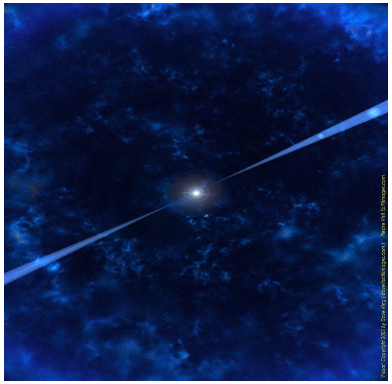
GW transient sources

- To emit GW a source must be compact, relativistic and asymmetric
- Astrophysical sources
  - Stellar core collapse
  - Black holes
  - Neutron star instabilities

  } associated with other messengers: (photons/neutrinos) GRB, SGR, pulsar glitches, supernova, ….

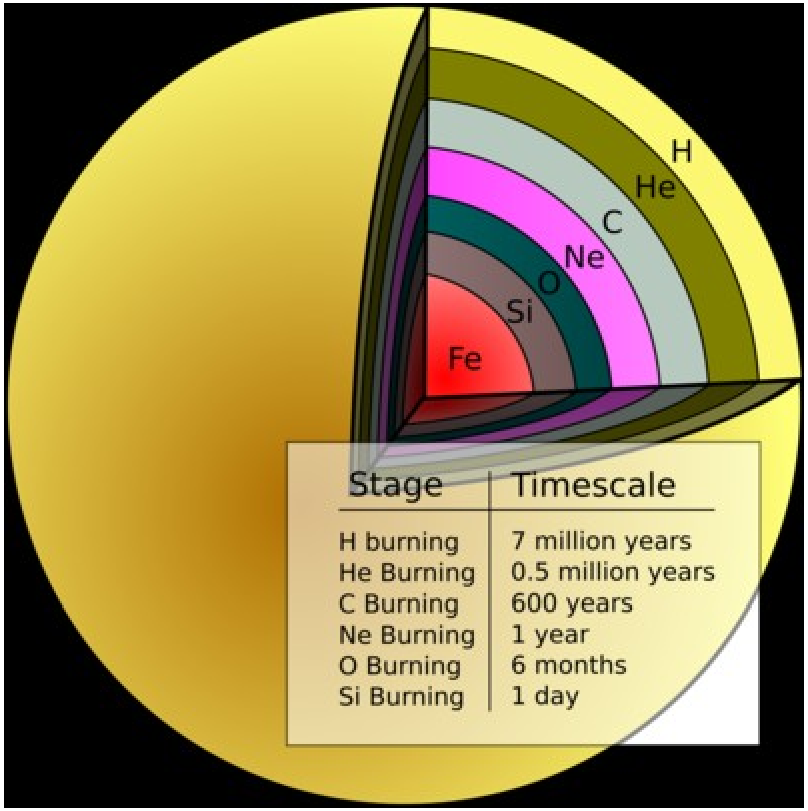


- Exotic objects: cosmic (super-)string, …
- Which information matters?
  - Astrophysical events rate
  - Signal waveform
  - Background / signal disentanglement
  - Other messenger association?

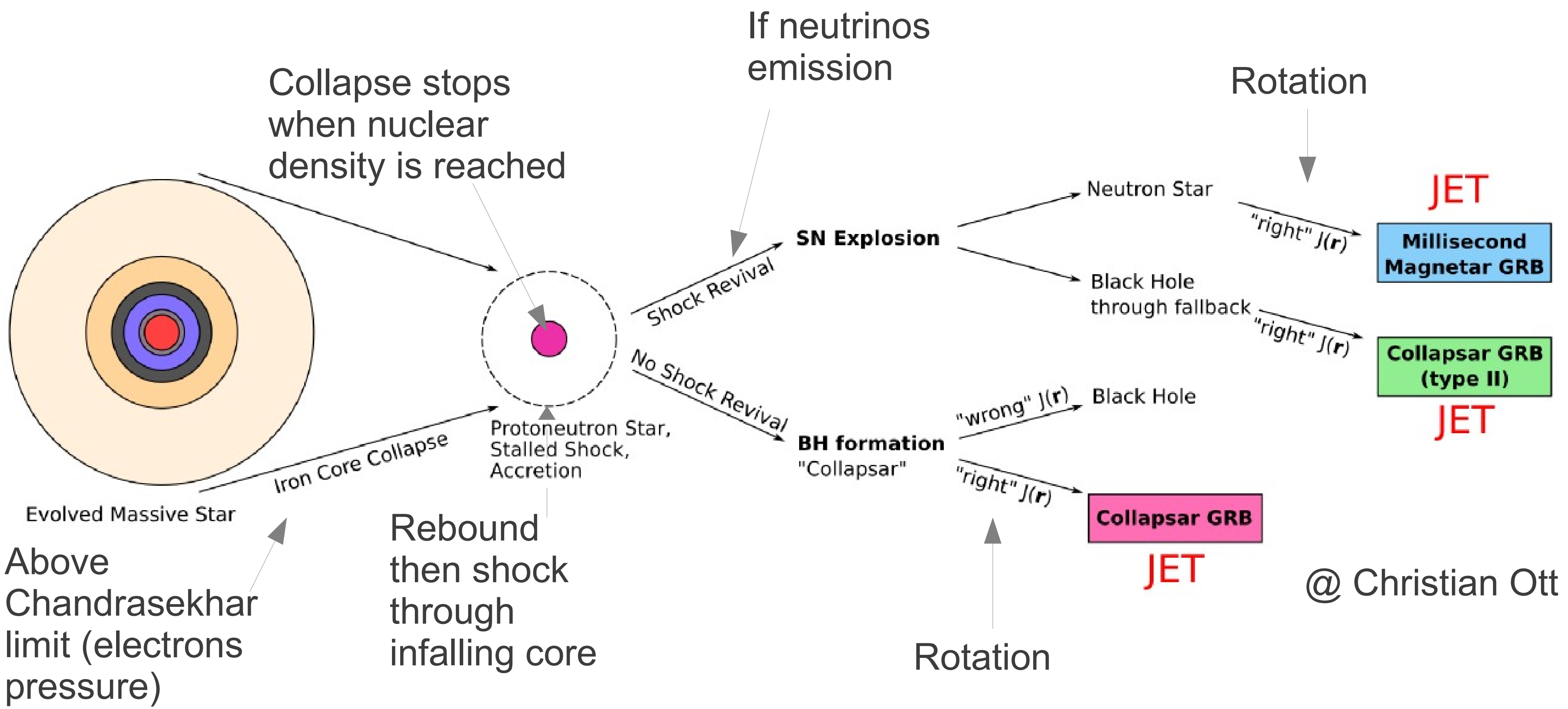


Stellar core collapse

- Stars spend most of their lives burning hydrogen.
- Helium settles in the core and will burn when temperatures increase sufficiently
- For massive stars $(M > 8 - 10 M_{\odot})$ the process continues through Carbon, Oxygen, … up to Iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron core builds up in center of star.



Stellar core collapse in a nutshell



Supernova classification & rate

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	$\sim 100 \times$ Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total $\sim$ 5600 as of 2011 (Asiago SN Catalogue)			

1 SNu = 1 SN per century and per 10^{10} $L_{sun,B}$

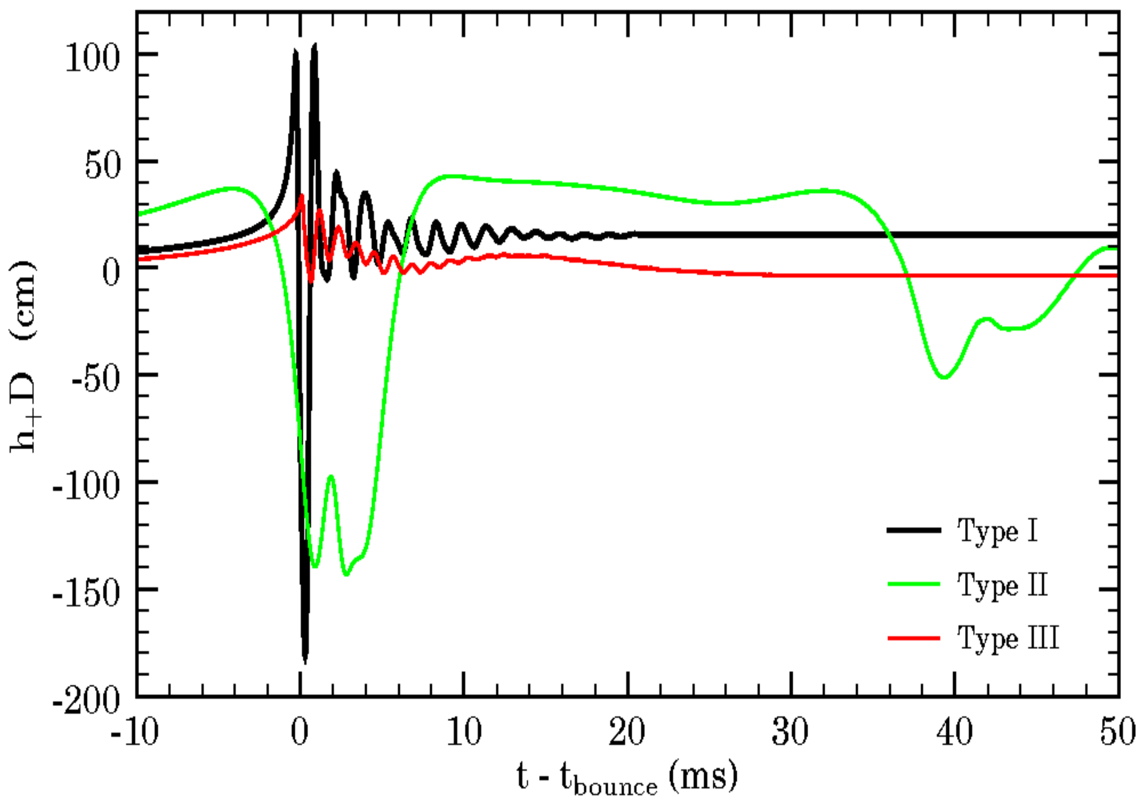
[G. Raffelt arXiv:1201.1637]

Core collapse waveforms

- Simulations include different mechanisms to explain the explosion and sphericity breaking (how to light a supernova?):
  - Neutrino heating to revive the shock + convection and hydrodynamic instabilities (i.e. SASI) to break sphericity
  - Acoustic mechanism
  - Magneto-hydro-dynamic mechanism
- ~10 groups have simulation codes
- Completeness of simulations:
  - Full GR with MHD vs approximations
  - Neutrino-matter coupling
  - Realistic equation of state of nuclear matter
  - 3D vs 2D
  - Electron capture

Core collapse waveforms

- Core bounce GW signature: historically focused first attention



Requires rotation + gravity + stiffening EOS

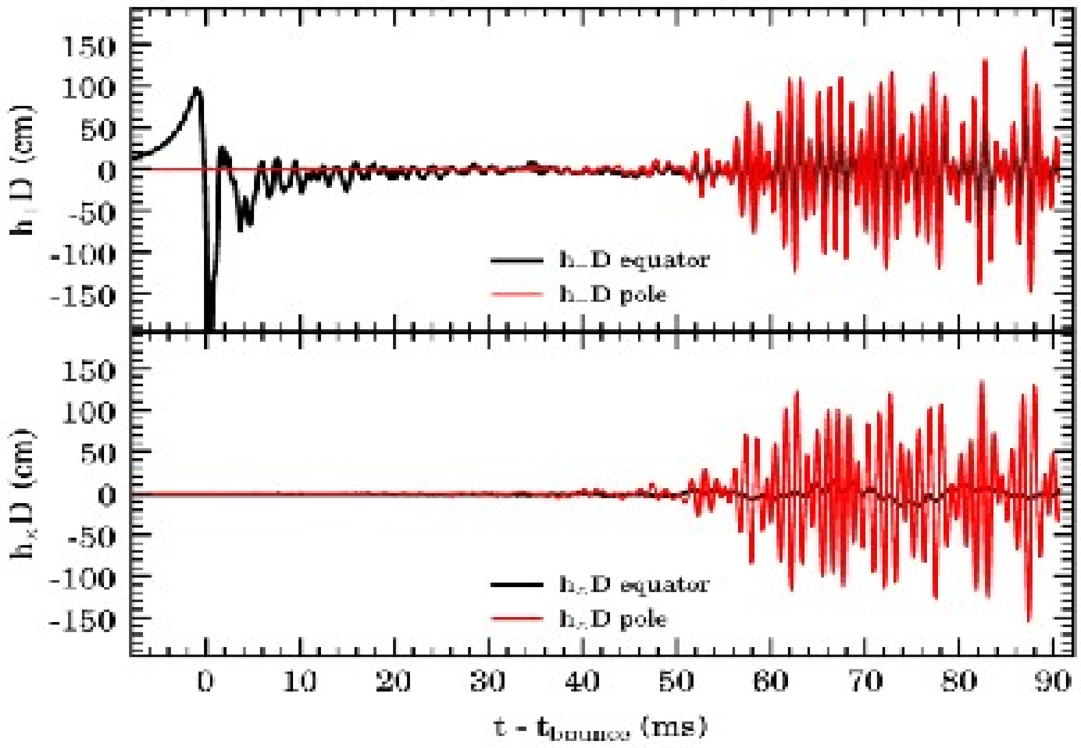
Axi-symmetric: only h+

3 types of waveforms

[Dimmelmeier+ '08, Scheidegger+ '10, Ott+ '12, Kuroda+ '13]

Core collapse waveforms

- Post bounce phenomena: instabilities development in the proto-neutron star.



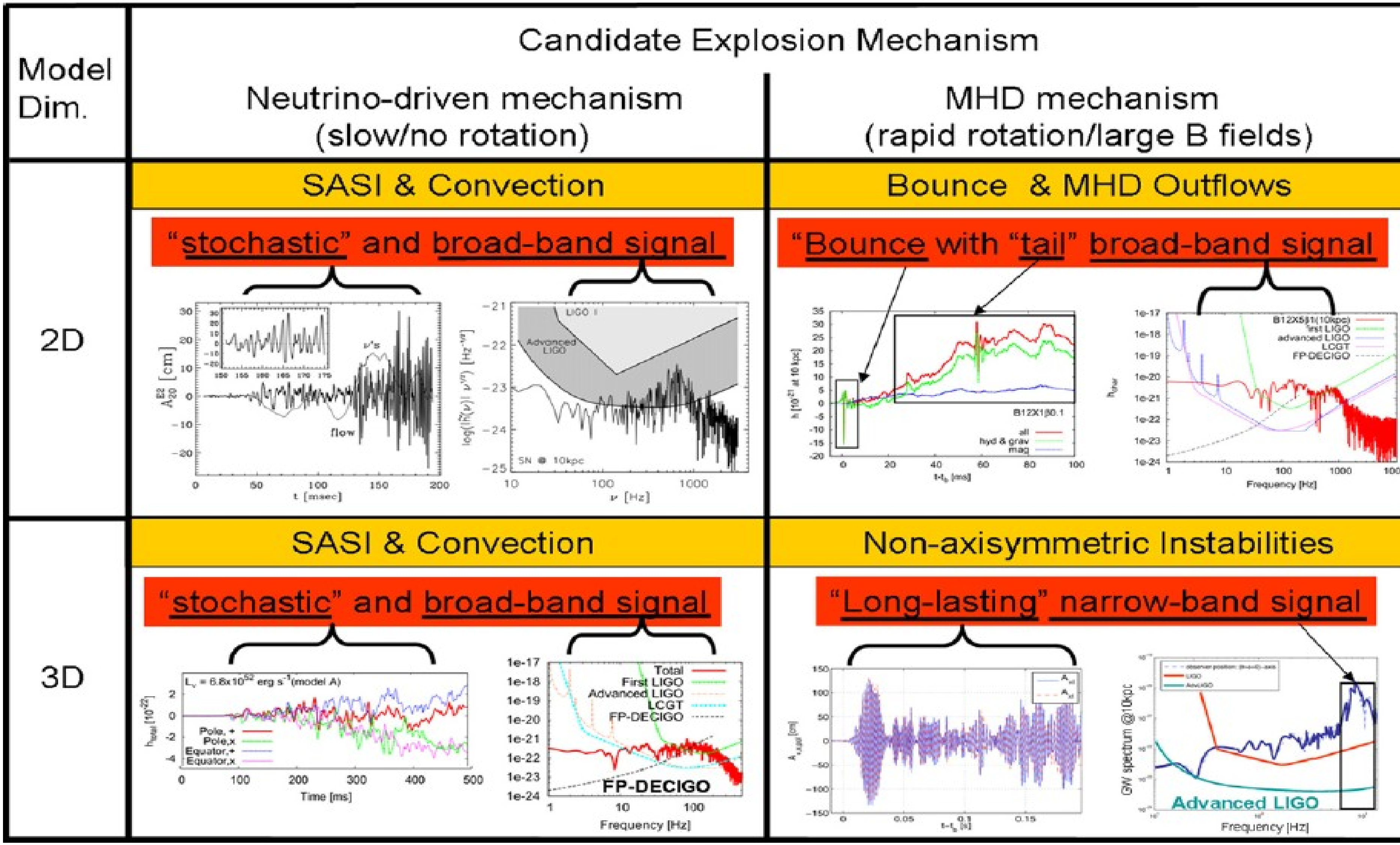
Post bounce convection

2D and 3D simulations difference

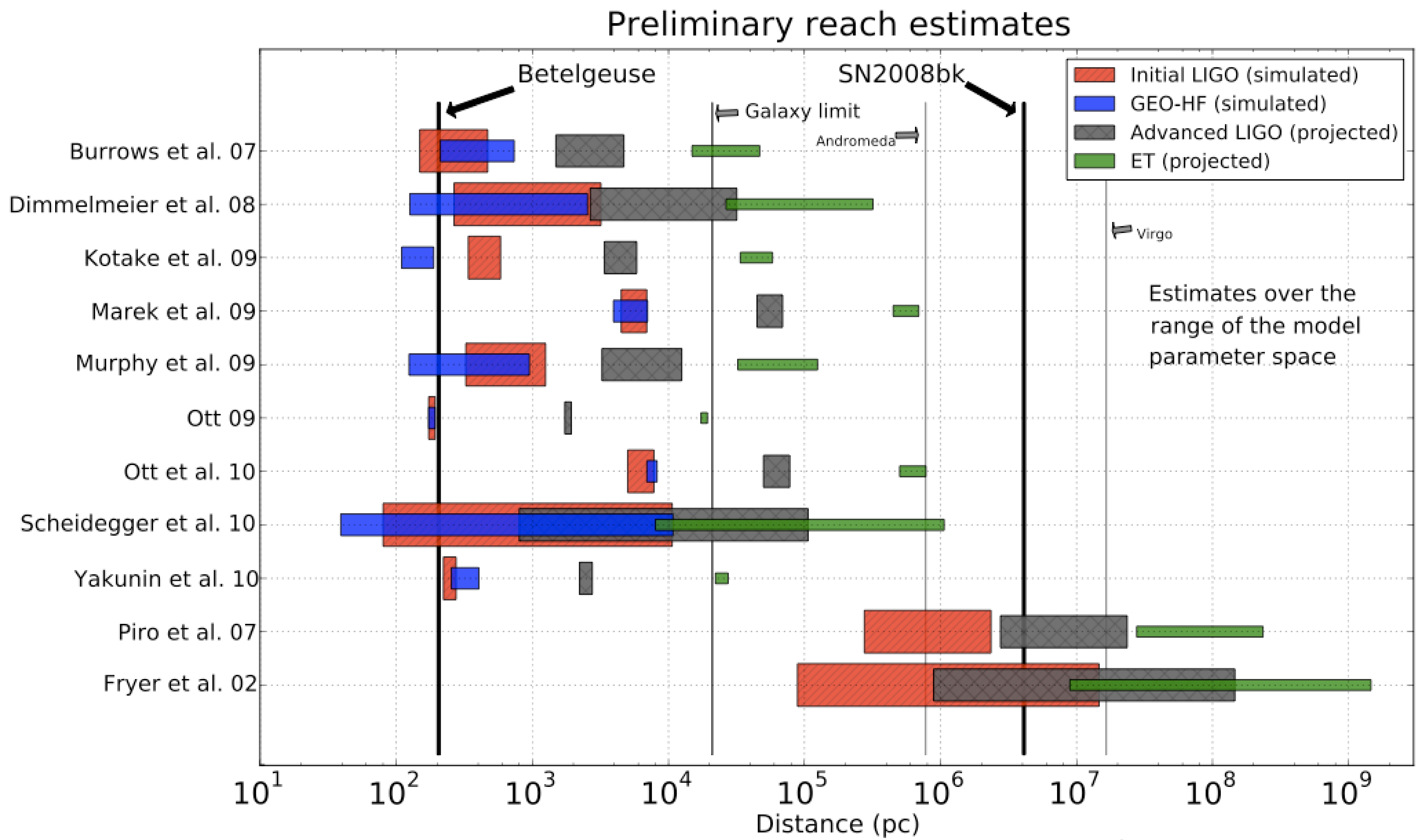
Waveform: stochastic nature

CCSN: post-bounce waveform summary

[Kotake C.R. Physique 14 (2013) 318-351]



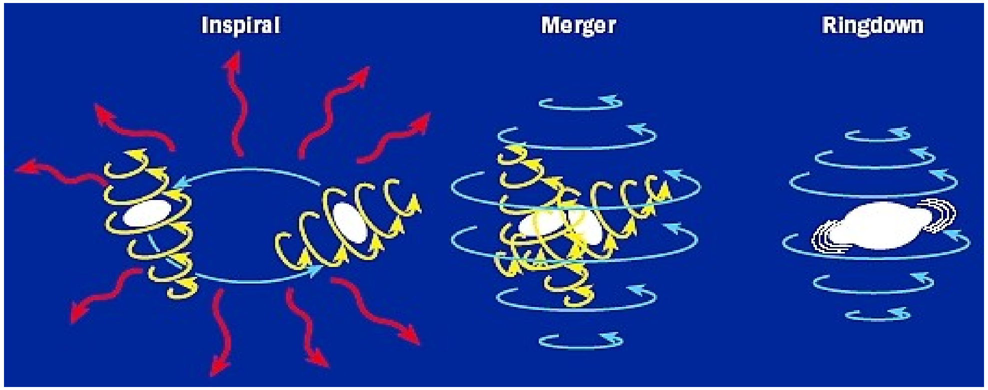
Core collapse supernova: how far can we go?

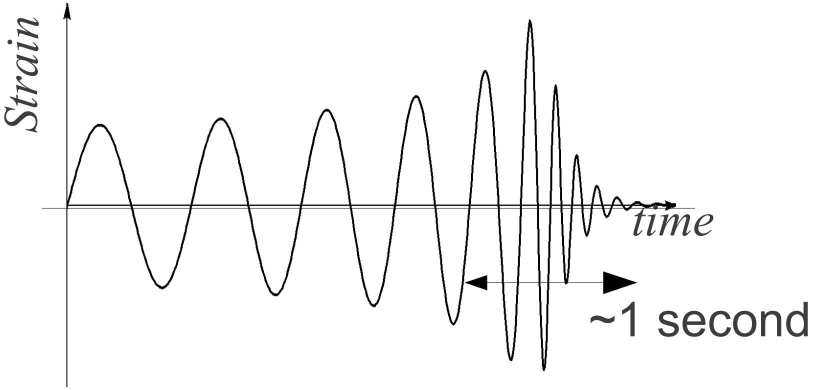


@ Peter Kalmus

Compact binary mergers

- 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⊙ – 400 M⊙]





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

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

→ For BNS waveforms are inside LIGO/Virgo band → up to several minutes

→ BBH merges inside LIGO/Virgo band

→ M_{tot}>100 M⊙ : only merger+ring-down ~ 1 second → burst transient!

Compact binary coalescence waveforms (up to ISCO)

Well described in Post Newtonian expansions $h(f) = C f^{-7/6} e^{-i\Psi(f)}$

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

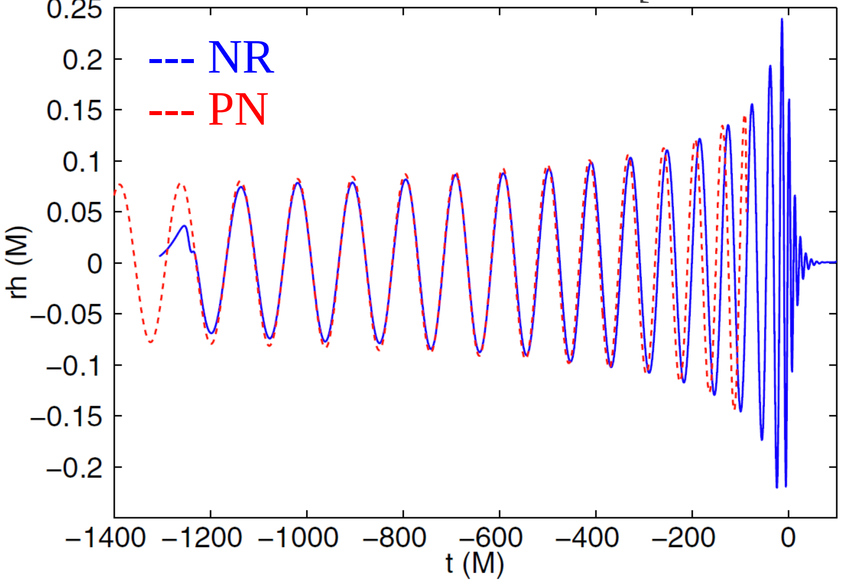
$$v = (\pi M f)^{1/3}$$

- Model complete (include also spin-orbit (1.5 PN) and spin-spin (2PN) effects
- Waveforms stop at ISCO.
- OK for low mass CBC → template matched filtering search for the inspiral phase

Binary black hole mergers

- System of interest for a burst GW search:
  - Stellar mass black holes (<10 $M_\odot$): observed!
  - Intermediate mass black holes (10 $M_\odot$ < M < 10^6 $M_\odot$): more hypothetical. Early universe seeds for super massive BHs (observed). Present universe formation in globular cluster by capture in hyperbolic orbits, 3 bodies interactions, young star clusters core collapse. IMBH could play a role in ultra-luminous X-ray sources.
- Transient GW searches focus on merger + ring-down phases

[ArXiv:0612024]



Do not need accurate waveforms, but benchmark/ efficiency computation is making use of complete waveforms provided by Numerical Relativity Calculations matched with PN waveforms.

Compact binary merger event rate

- Distance range: 10-10 BBH with advanced detectors: ~1 Gpc
- Rate: uncertain, but consider as one of the most promising sources in advanced detectors era.

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})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

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

LIGO-Virgo sensitivity and SNR>8

Advanced LIGO-Virgo sensitivity and SNR>8

Neutron star instabilities

- Supernova remnants or accreting white dwarf collapse → very rapidly rotating NS will develop non axisymetric dynamical instabilities
- The physics of NS is far from being simple. Many parameters play a role on the NS stability: equation of state for high density matter, matter superfluidity / superconducting, presence of proton, strange quarks, …)
- Pulsation normal modes: f and r modes are the most promising modes for GW emission ?
  - f-mode: fundamental (acoustic) pressure mode of the star (2-4 kHz). Rotation change frequencies. GW emission damps f-modes within ~ a tenth of a second.
  - r-modes: inertial modes due to rotation (Coriolis force). Lots of work around because have been thought to lead to high amplitude GW emission (GW radiation was thought to increase the amplitude of the mode)
  - bar mode instabilities occur when rotational kinetic ratio exceeds β=0.27
  - w-modes: pure GR effects (7 kHz) damped in a fraction of millisecond.
- GW Amplitude ? Last predictions are quite pessimistic.
- Rate? Very unclear. The fraction of very rapidly NS after a SN is not known (10^{-6} /yr/galaxy ?)

Black hole ringdown

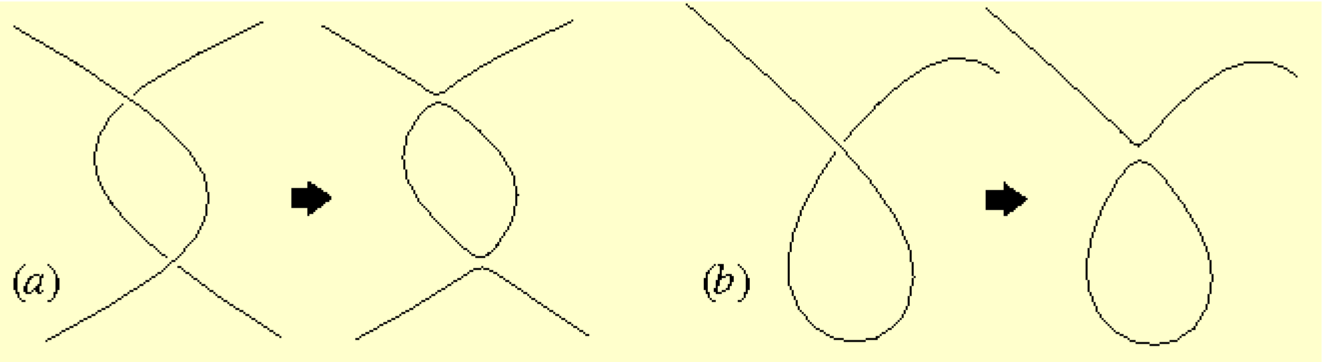
- A BH that is distorted from its stationary Kerr configuration will radiate GW that drive it back to the stationary state (hair loss theorem)
- A BH formed in core collapse will certainly be distorted: if large amounts of matter accrete onto it, it will continually driven into new states of distortion.
- Waveform (perturbation theory): Quasi-normal mode $e^{-t/\tau}\sin(2\pi f t)$
- BH spectroscopy: deduce the BH parameters (mass M, spin a) from QNM parameters (f, τ).

$$2\pi f = \frac{1}{M}\left[1 - 0.63\left(1 - \frac{a}{M}\right)^{0.3}\right] \qquad \tau = \frac{4}{2\pi f\left(1 - \frac{a}{M}\right)^{0.45}}$$

- GW amplitude: $h \approx 5.10^{-22}\left(\frac{E}{10^{-3} M_{\otimes} c^2}\right)^{1/2}\left(\frac{1kHz}{f}\right)^{1/2}\left(\frac{15Mpc}{r}\right)$

Cosmic strings (cosmological source)

- 1-D topological defects introduced by U(1) symmetry breaking occurring just after the inflation (Kibble mechanism 70's).
- Predictions of quantum field theory and string theories (M-theory is the unified theory for all fundamental interactions including gravity).
  - Super-strings are the basic constituents of matter.
  - Both cosmic strings and super-strings are expected to loose energy through GW emission.
- Expected to form a network that evolves with the expansion:
  - Strings stretch and auto/inter-commute
  - Inter-commute (exchange of partners): form kinks that emit (weak) GW burst
  - Auto-commute: oscillating loops with cusps (points reaching speed-of-light velocity emitting strong GW burst) occurrence at each oscillation. All loop energy released through GW.



Cosmic strings

- Cusps waveforms: $\tilde{h}(f) = A|f|^{-4/3}$ → matched filtering!
- Parameters:
  - GW amplitude depends on string tension (Gμ) and size L = εΓGμt. Γ~50, t is the cosmic time → ε is the free parameter. For super-strings: reconnection probability (p<1).
- Existing cosmological/experimental search constrains
  - CMB data (WMAP/Planck Gμ < 3.7/1.5 x 10^{-6})
  - Pulsar timing (stochastic background) : best limit for the large loop size scenario
  - GW stochastic background search
- GW cosmic string cusps search: competitive for small loop size

Multi-messenger searches – what for?

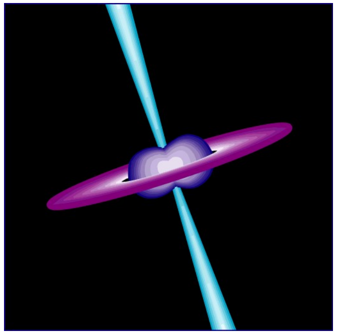
- 2 modes: EM events "triggered" GW searches & GW transient EM follow-ups
- Triggered searches: one knows time, position (sometimes distance) and some info about the putative GW signal to search → tune an "all-sky/all-time" generic unmodelled burst search. What do we gain?
  - Background reduction (parameter space reduction) → tackle weaker GW signals.
  - Combined information may infer astrophysical information about the source
  - Non detection GW results may rule out models
- EM follow-ups: prompt (<1mn) GW searches to identify possible GW candidates and reconstruct their sky position to send alerts for EM transient follow-ups that would be missed

→ Lecture by E. Chassande-Mottin

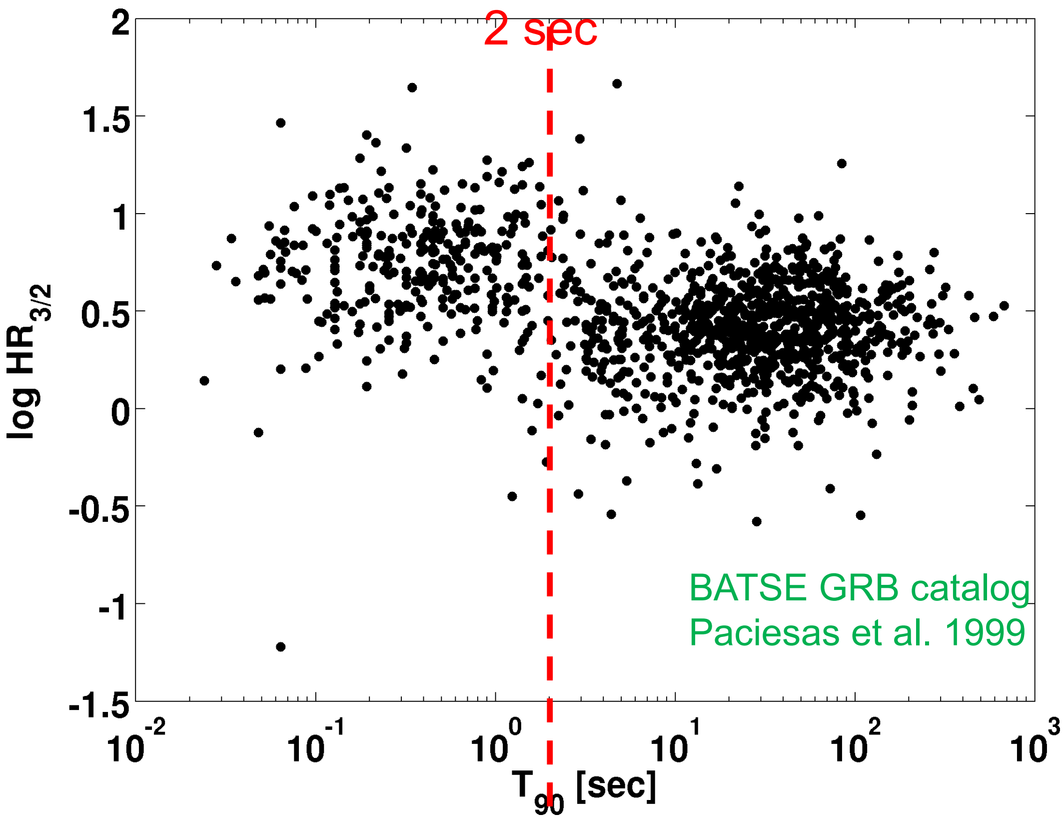
Transient GW events & "electro-magnetic" transients

GRBs

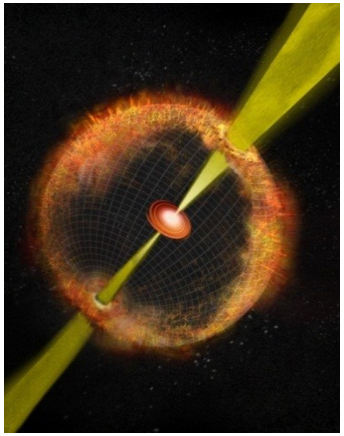
Short - Hard GRBs



NS-NS merger



Long - Soft GRBs



Most thought to be from binary mergers involving a neutron star

Some from giant flares from soft gamma repeaters (magnetars)

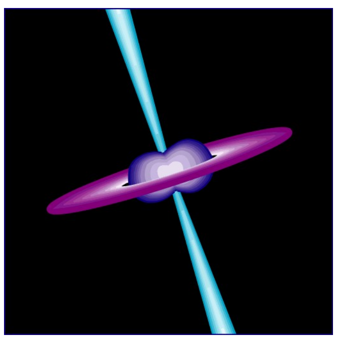
Most thought to be from the collapse of high-mass stars with rapidly rotating cores

Supernovae seen in some cases

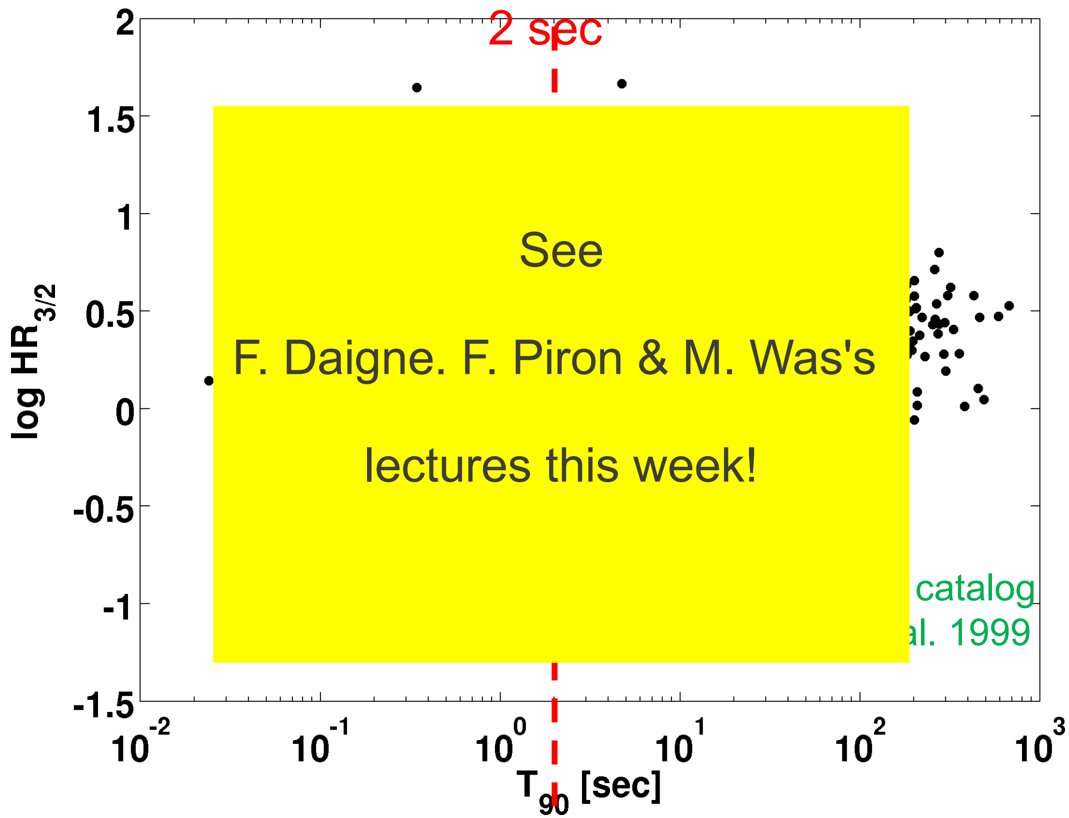
Transient GW events & "electro-magnetic" transients

GRBs

Short - Hard GRBs



NS-NS merger



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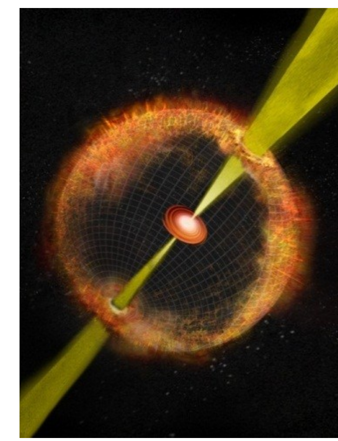

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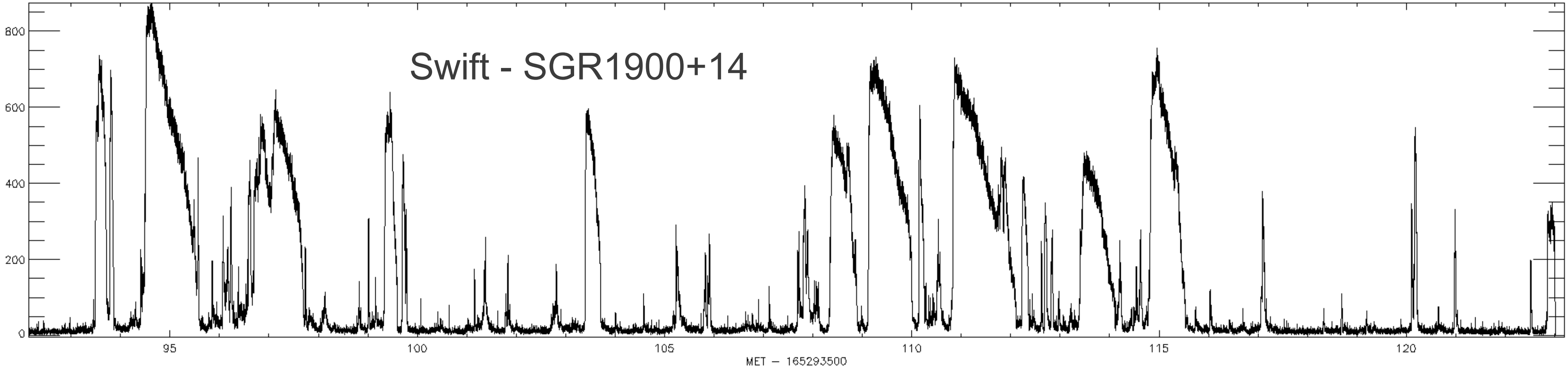
Transient GW events & “electro-magnetic” transients

Magnetar flares: Soft Gamma Ray Repeaters (SGRs) & anomalous X-ray pulsars (AXPs) are believed to be magnetars (NS with $B>10^{15}$ G):

- Occasionally emit flares of soft gamma-rays $E_{EM}=10^{42}$ erg.
- Some SGRs produce giant flare with energy up to 10^{46} erg (burst <0.2 s)
- Giant flare could be related to cracking of the crust (star quake). Possible excitation of vibrational modes (quasi-periodic oscillations seen in X-ray detectors)

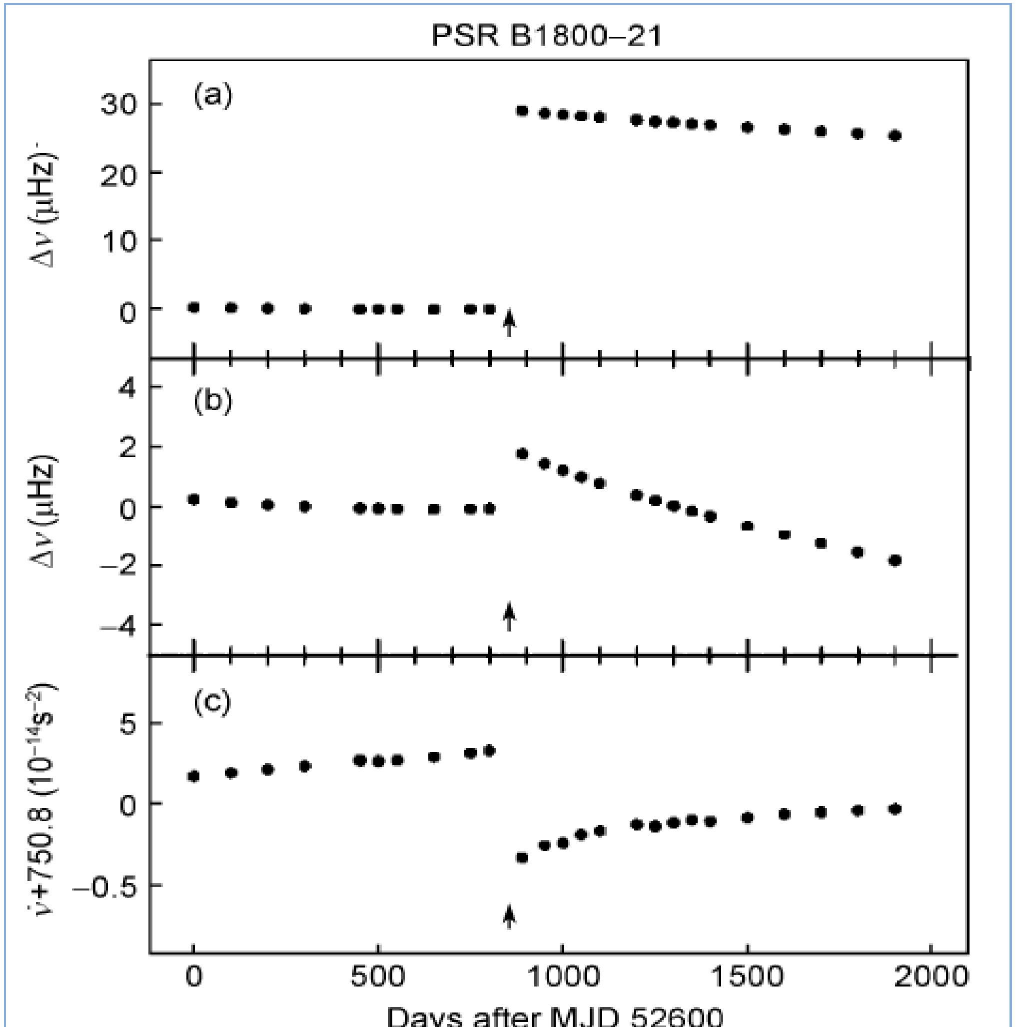
→ may excite non-radial oscillation modes that couple to GW emission.

40 bursts in 30 s



Transient GW events & “electro-magnetic” transients

Pulsar glitches: frequency glitch observed in some young pulsars.



The mechanism is not clear but some scenario has been proposed:

- crust craking (star quake)

- superfluid-crust interaction

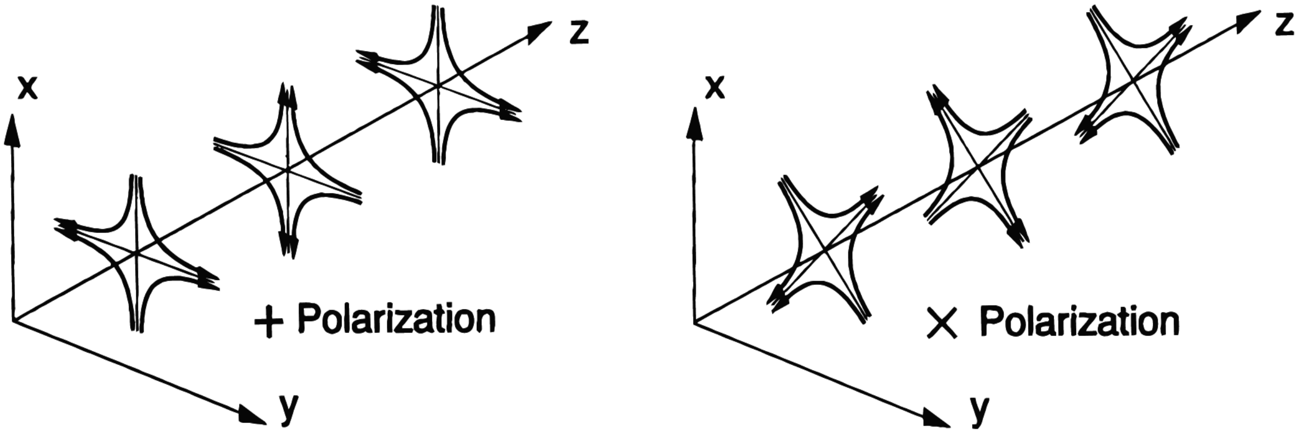
→ normal mode of the NS excitation that couples with GW emission.

→ GW search assuming damped normal mode waveforms

GW transient search challenges

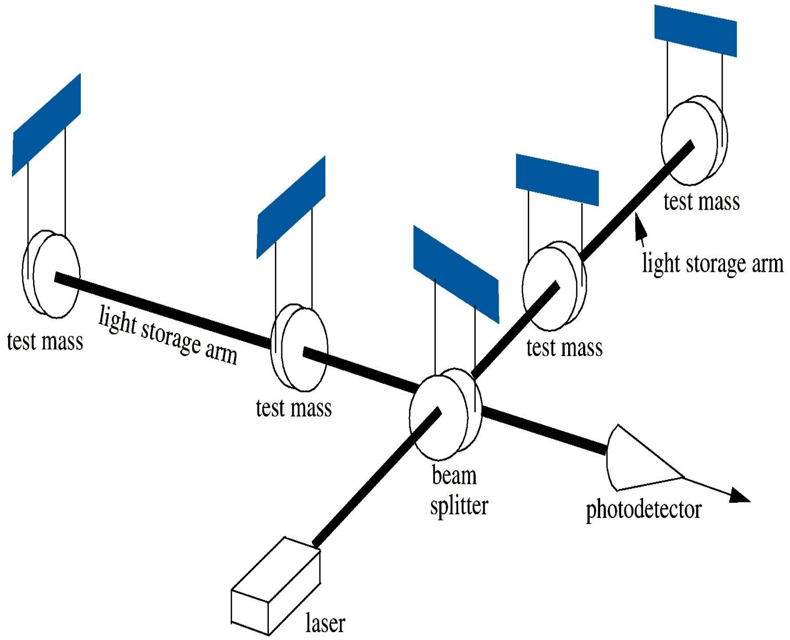
GW: what they are

- 2 polarizations



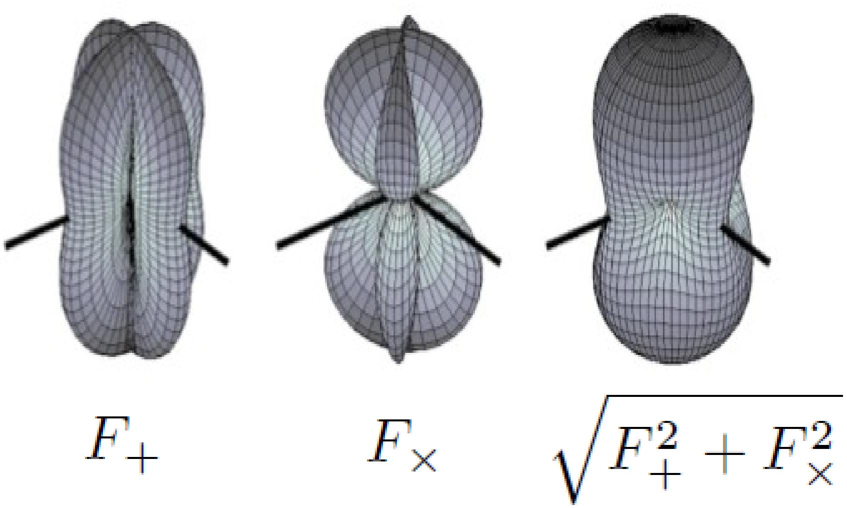
- Linear combination of + and x polarizations. Can be linear, circular or elliptical polarized.
- For instance a compact binary coalescence wave is circularly polarized if traveling face on. In the other cases, it will be elliptically polarized.

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

Gravitational wave data

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

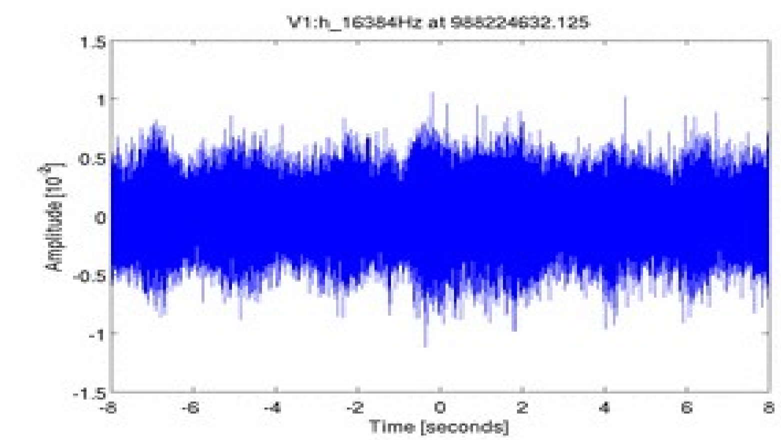
  → Digitized discrete time series: raw(t) (sampled at 16384 Hz or 20000 Hz) and synchronized with GPS clocks.

  → 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

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

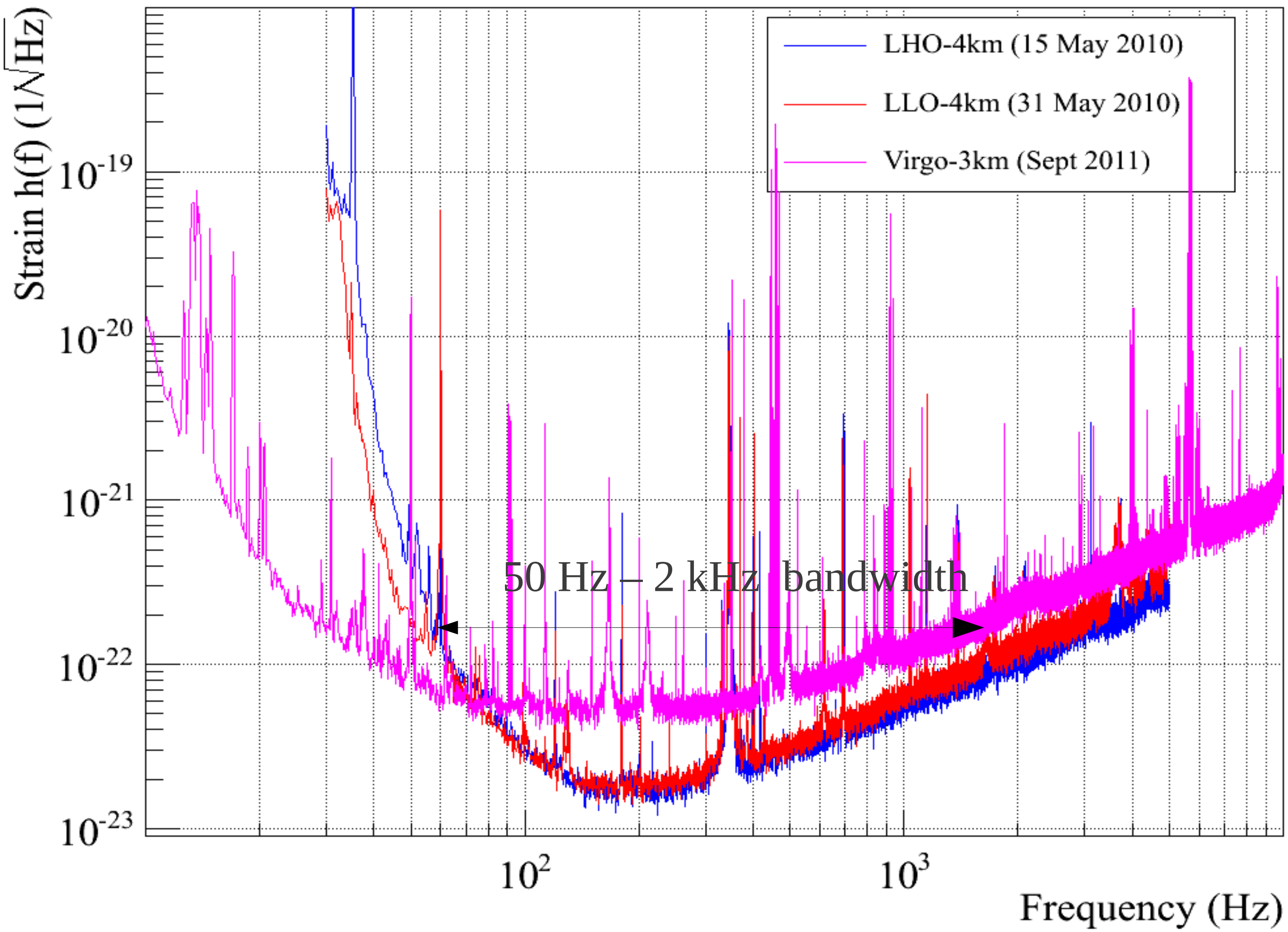
Question: nature of the noise?



- 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 ...

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

Challenges of GW transient searches

- Search of low SNR, short duration & rare events in non Gaussian data → background events rejection techniques (data quality vetoes, signal based vetoes, …)
- Almost no accurate waveforms → need of generic search
- Estimation of the significance of the selected events → background event rate estimation (need a network of detectors)
- Estimation of the source sky location
- Identification of the source (CCSN, etc)

How to characterize a burst signal?

	Unmodelled search	Modelled search
Assumptions:	Short (<1s) & narrowband. No precise waveform	Known waveforms. Template bank of waveforms.
Source strenght:	RMS amplitude: $h_{rss}^2 = \int dt\ h_+^2(t) + h_\times^2(t)$	Matched filtering SNR: $\rho^2(t) = \int_{-\infty}^{\infty} df \frac{\lvert\tilde{h}(f)\rvert^2}{S_n(f)}$
Search Sensitivity:	Radiated GW energy	Compact Binary Coalescence horizon:

$$E_{GW} = \frac{c^3}{16\pi G} T \int d\Omega < \dot{h}_+^2(t) + \dot{h}_\times^2(t) >$$

$$D_{horizon} = \frac{1}{8}(\frac{5\pi}{24c^3})^{1/2} G(\mathcal{M})^{5/6}\pi^{-7/6}\sqrt{4\int \frac{f^{-7/3}}{S_h(f)}df}$$

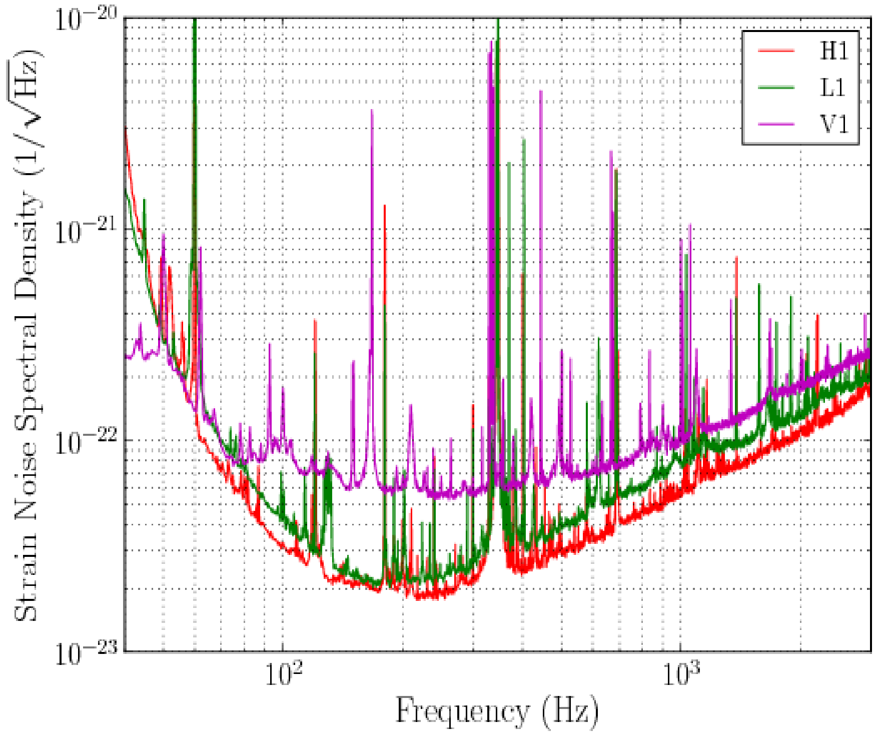
$$\text{Monochromatic signal} \rightarrow E_{GW} \sim \frac{\pi^2 c^3}{G} S(f_0) d_L^2 f_0^2 \rho^2$$

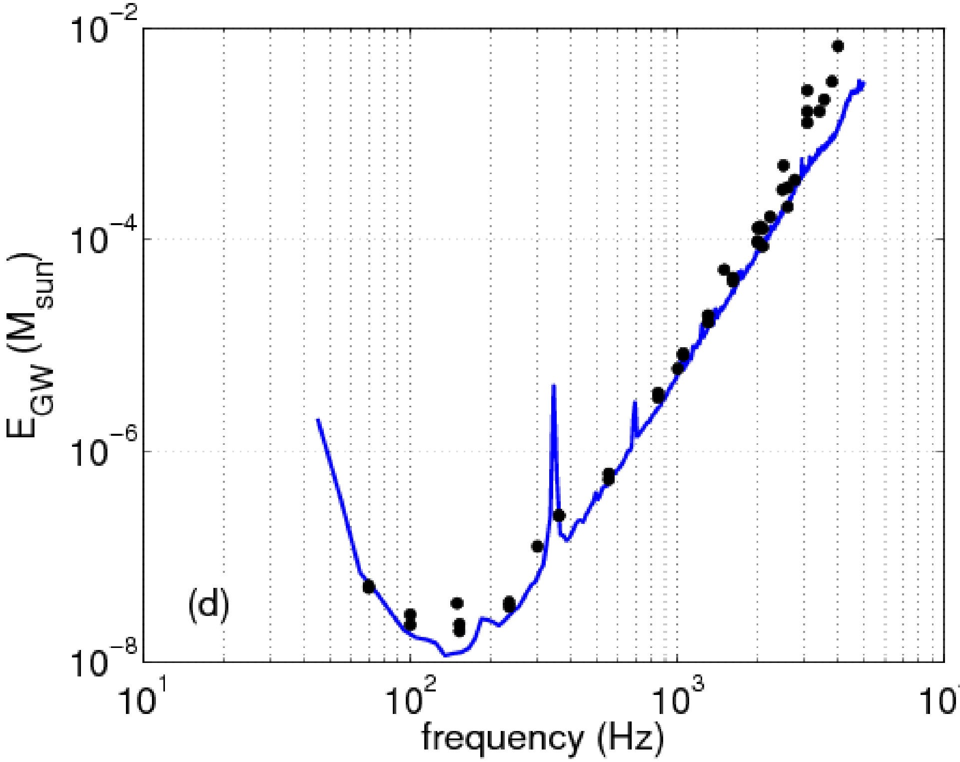
For initial LIGO-Virgo and $\rho \sim 10$ (SNR for $\sim 50\%$ efficiency)
$f_0 = 200$ Hz $\rightarrow S(f_0) \sim 4 \times 10^{-23} Hz^{-1/2}$
$E_{GW} = 10^{-8}\ \mathrm{M}_\odot c^2\ (10^{-2}\mathrm{M}_\odot c^2) \Rightarrow d_L = 10$ kpc (10 Mpc)

Typical SN GW emission

Un-modelled burst search sensitivity

[arXiv:1304.0210]



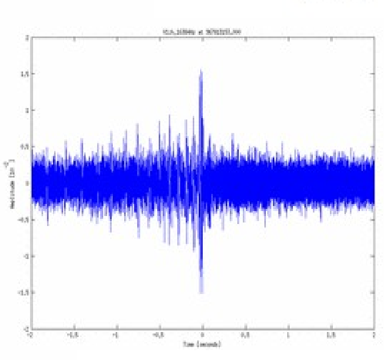


Not as sensitive as matched filtering, but not too bad (~ factor 2) when the signal is short

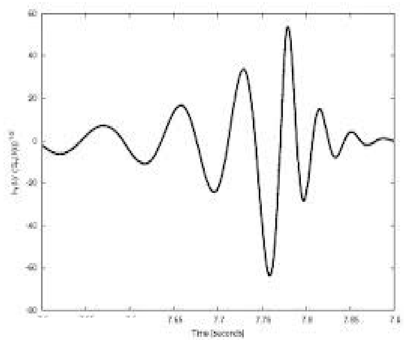
GW burst search: data processing

Waveform is known → matched filtering

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



x



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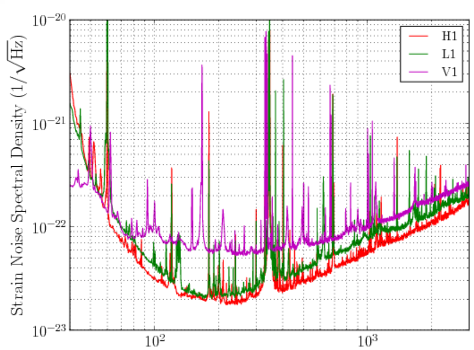

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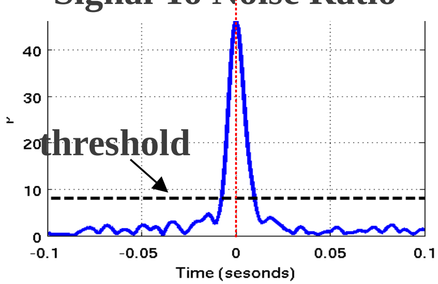
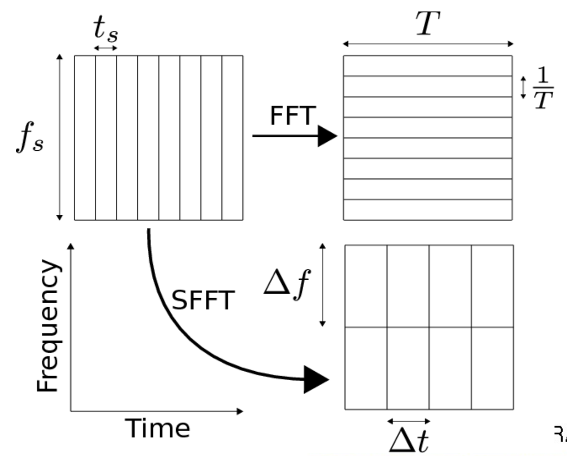
Signal To Noise Ratio

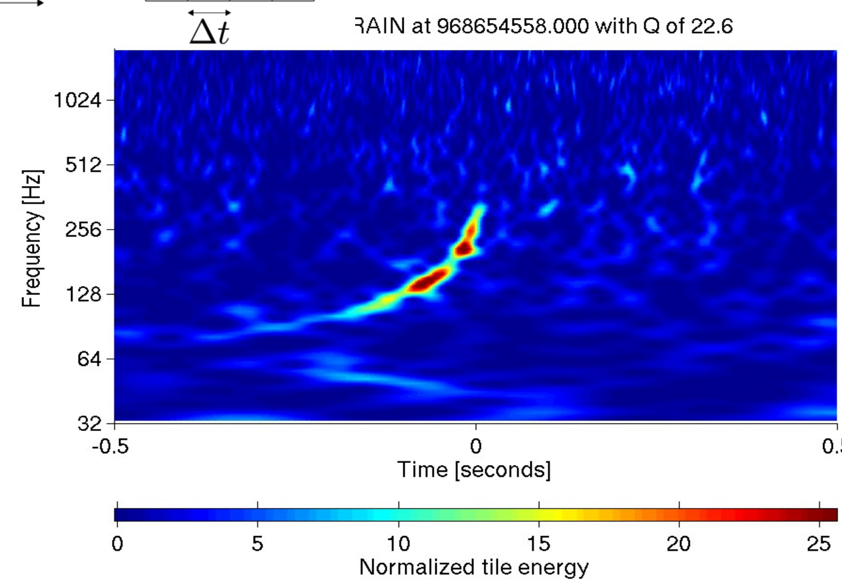


Unknown waveform → excess in time frequency maps

→ many time- frequency transforms (spectrogram, WignerVille, wavelet, ….)

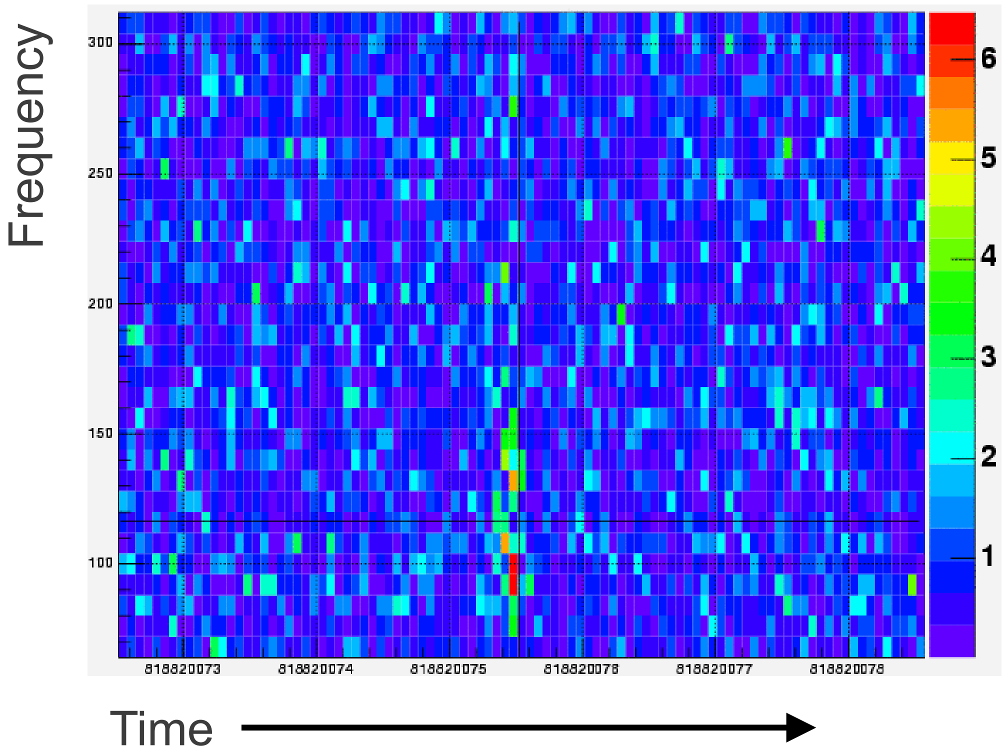


$$\sigma_t \sigma_f \geqslant \frac{1}{4\pi}$$



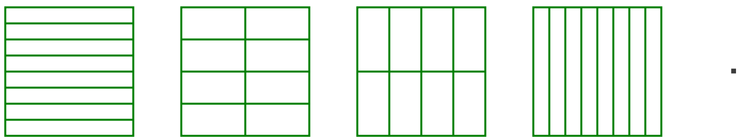
Excess power methods

- Decompose data stream into time-frequency pixels
  - Fourier components, wavelets, “Q transform”, etc.
  - Several implementations of this type of search
- Normalize relative to noise
  as a function of frequency
- Look for “hot” pixels
  or clusters of pixels



Waveburst

- Used in many LSC-Virgo burst searches
- Process all detectors' channels simultaneously: Wavelet decomposition from 64–2048 Hz
  - with 6 different resolutions from
    1/16 sec × 8 Hz to 1/512 sec × 256 Hz



    Pixel power thresholding → select "black pixels"

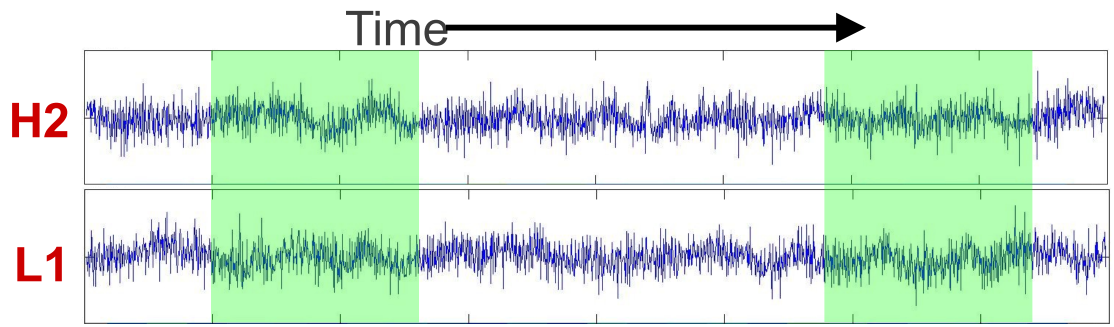
    Cross-stream pixel coincidence

    Clustering of coincident pixels to build up the event

    Signal parameter estimation: time, duration, frequency, amplitude

Cross-correlation methods

- Look for the same signal buried in 2 data streams: correlation



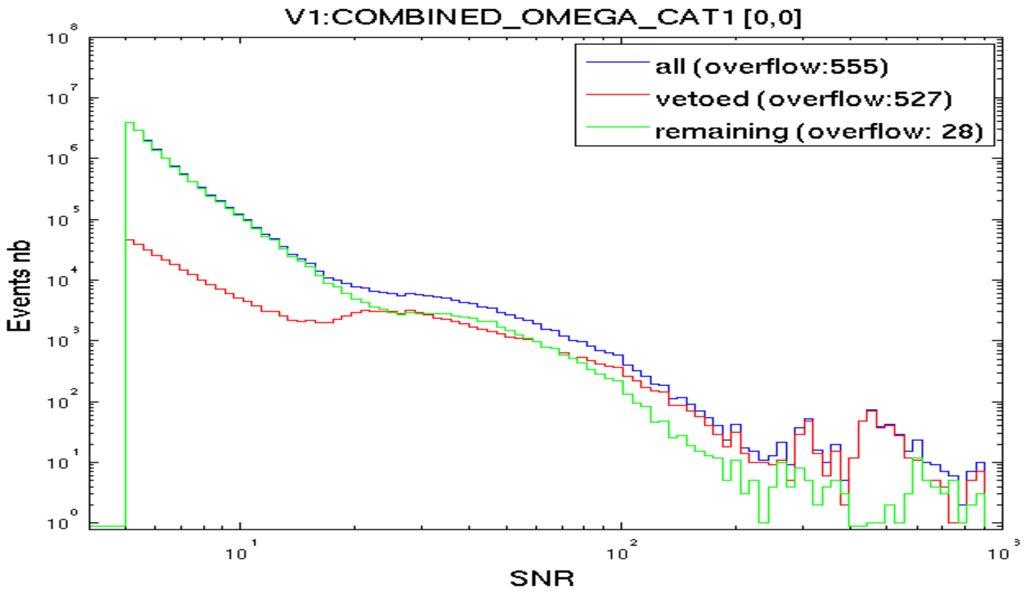
- Look for shape consistency regardless of the relative amplitude.
- Need to integrate over the targeted signal duration.
- Need to notch put common narrow spectral lines (violin resonances) that can generate spurious cross-correlation between detectors.

Adapted for long GW transients where “excess-power” methods break down

Event trigger generation: single detector case

1. Matched filtering or time-frequency multiresolution analysis
2. Threshold → tiles/pixels selection
3. TF pixel clusterisation → “triggers”
4. Define a statistic (SNR, likelihood, …) that gives a “weigh”/significance to each trigger.

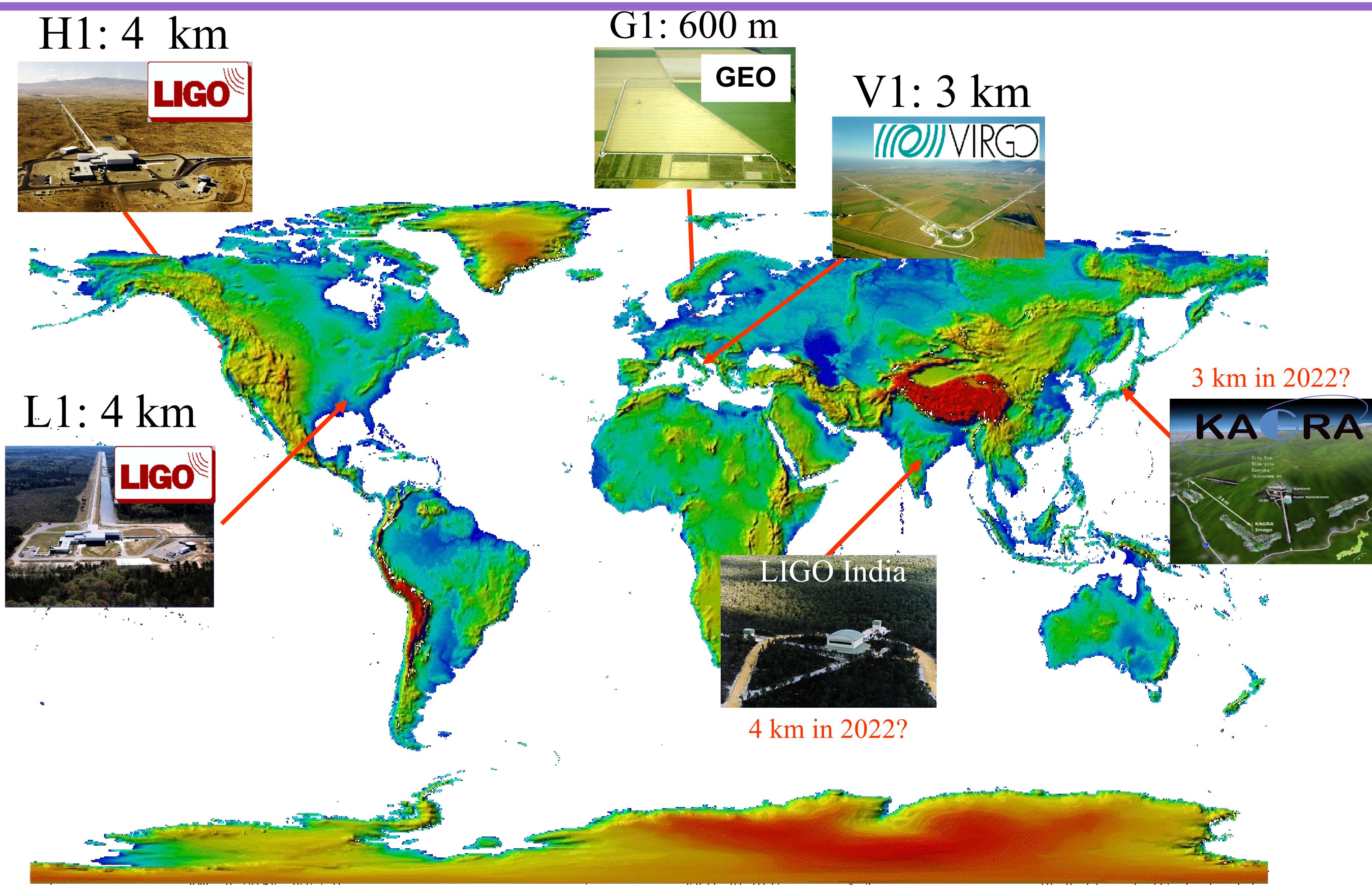
   → Triggers distribution is totally dominated by non Gaussian glitches present in all GW detectors data



How to improve the significance of the triggers?
How to gain confidence?

→ Use of data quality information
→ Use of signal waveform information
→ Use of external triggers
→ Use of a network of GW detectors

Network of ground based detectors



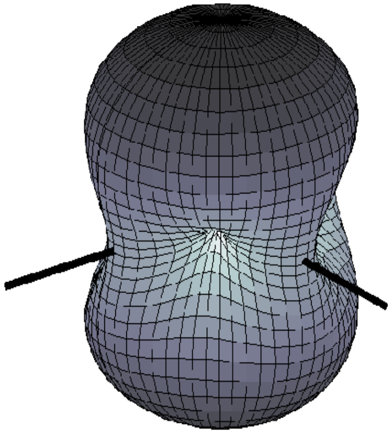
Multi-detectors search

- LIGO-Virgo network example:
  - H1L1: 10 ms
  - H1V1: 27 ms
  - L1V1: 16 ms
- Noise is mostly independent in each detector, but signal amplitude is modulated by each detector beam pattern functions.

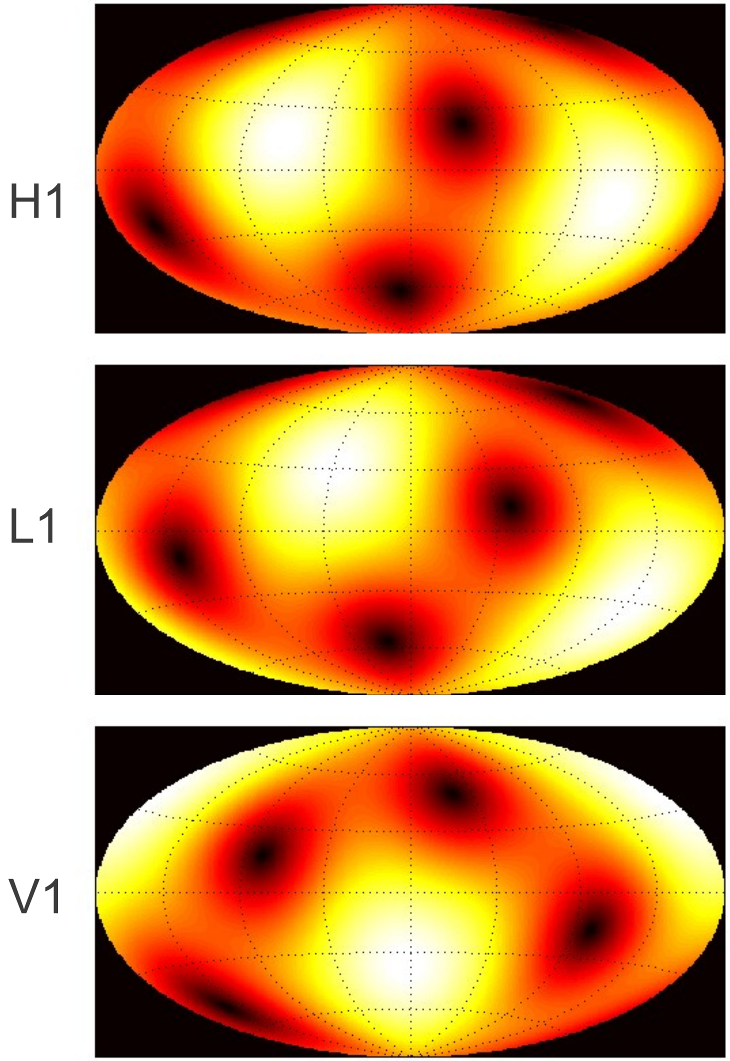
$$F_+ = \frac{1}{2}\left(1+\cos^2(\Theta)\right)\cos(2\Phi)\cos(2\Psi) - \cos(\Theta)\sin(2\Phi)\sin(2\Psi)$$

$$F_x = \frac{1}{2}\left(1+\cos^2(\Theta)\right)\cos(2\Phi)\sin(2\Psi) - \cos(\Theta)\sin(2\Phi)\cos(2\Psi)$$

Source polarization



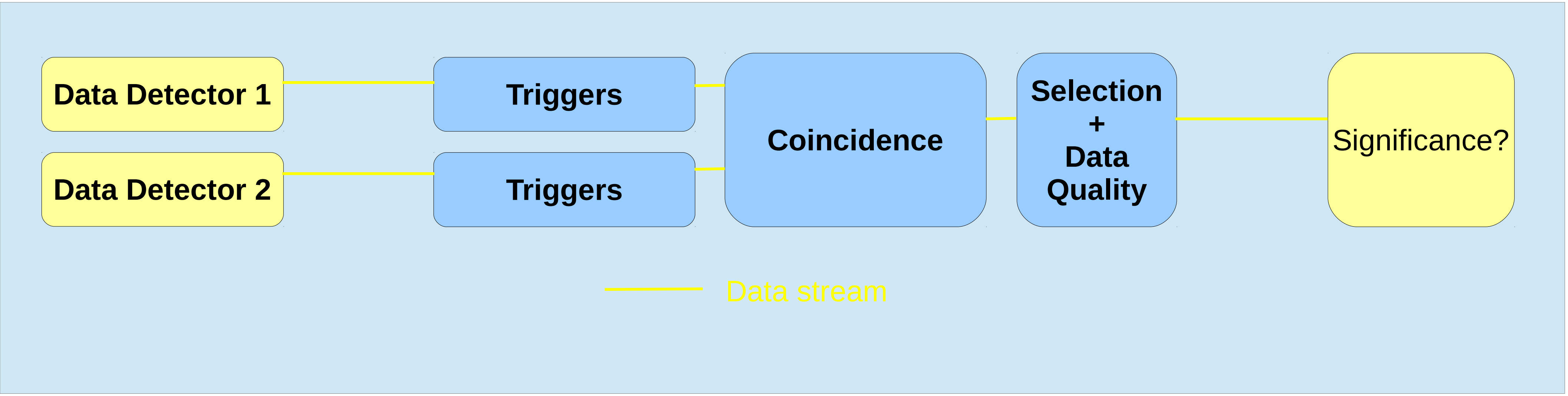
Multi-detectors search



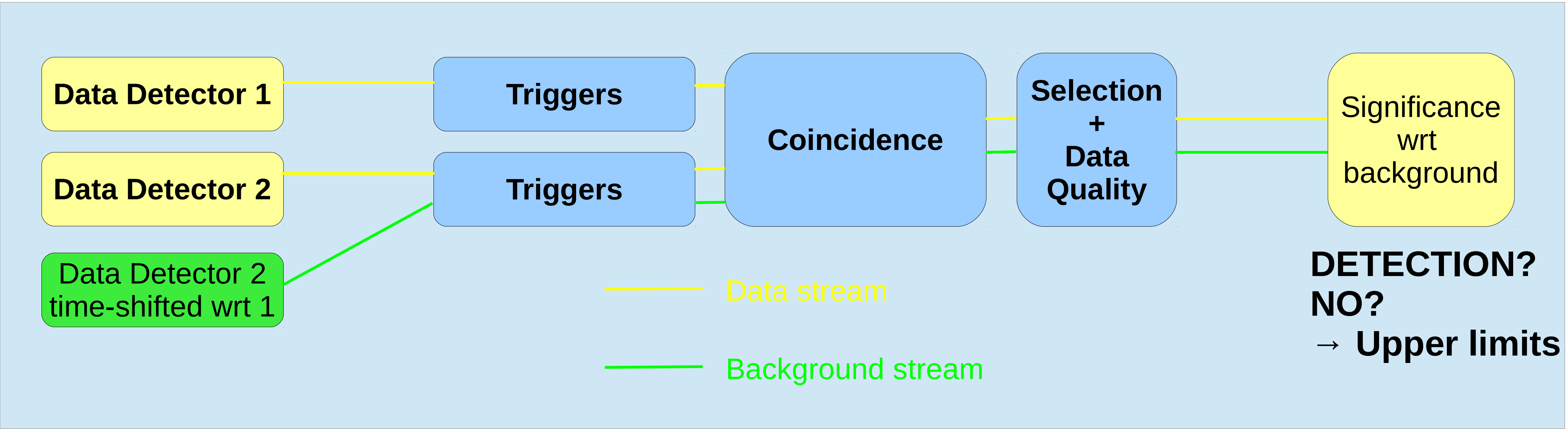
- Earth rotation allows to cover almost the full sky
- Effective experience livetime can be increased by time shifting one detector wrt others → improve the background estimation/significance of an event.

Coincident analysis

- Only time of signal parameters information used
- Different AND/OR combinations

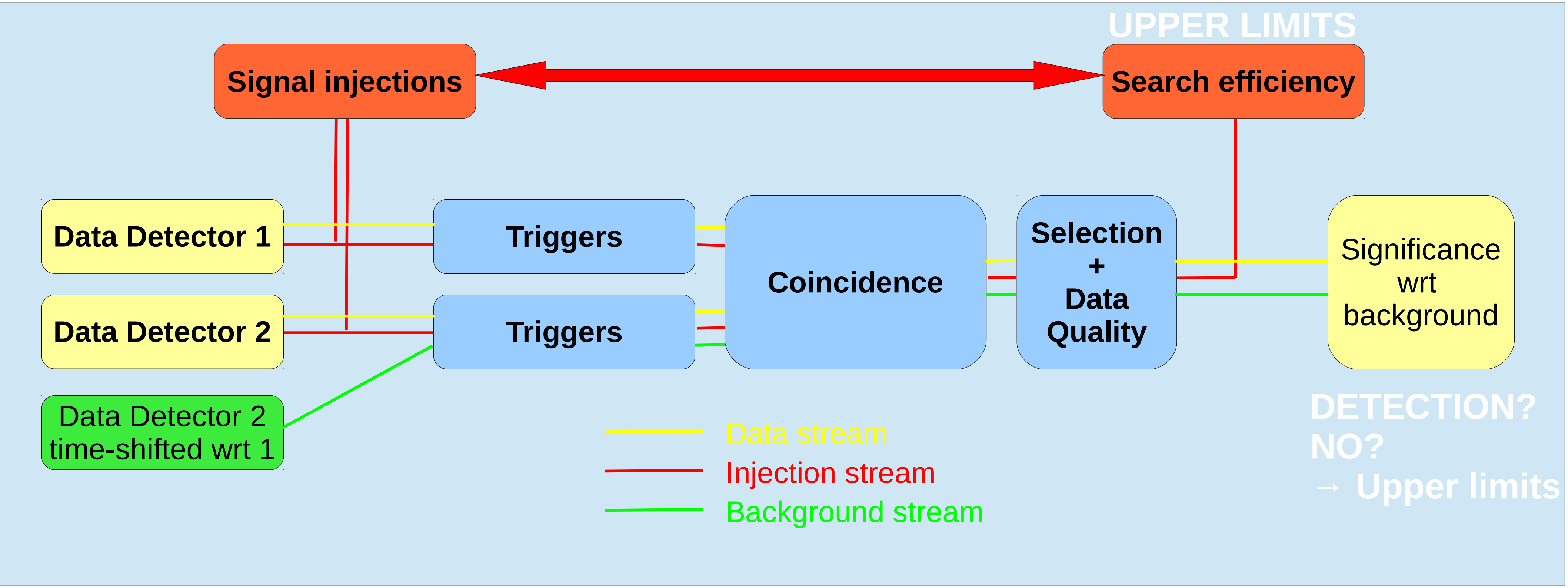


Coincident analysis



DETECTION?
NO?
→ Upper limits

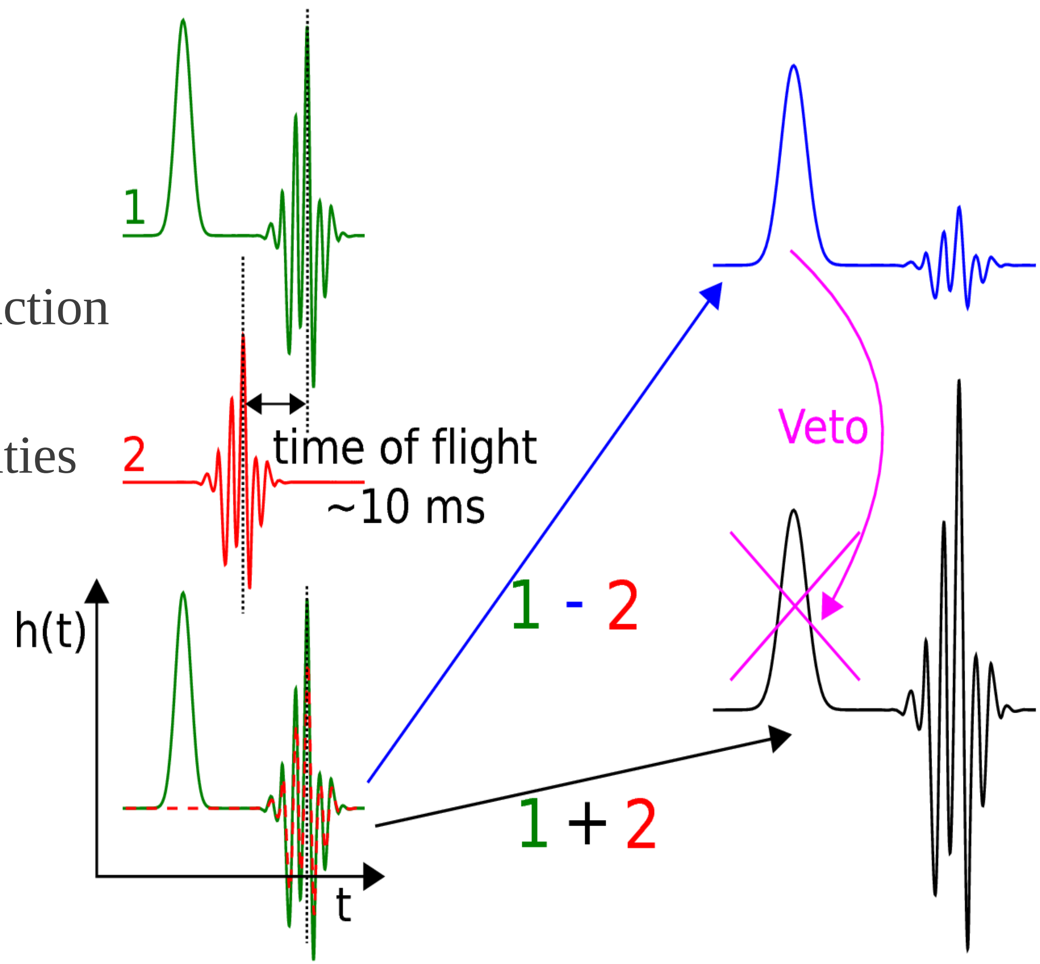
Coincident analysis



Coherent analysis

- Add coherently data stream to increase the total SNR
- For each source sky position
  - Compute the delay
  - Shift data
  - Take into account beam pattern function at instant t
  - Take into account detector sensitivities

→ CPU time consuming

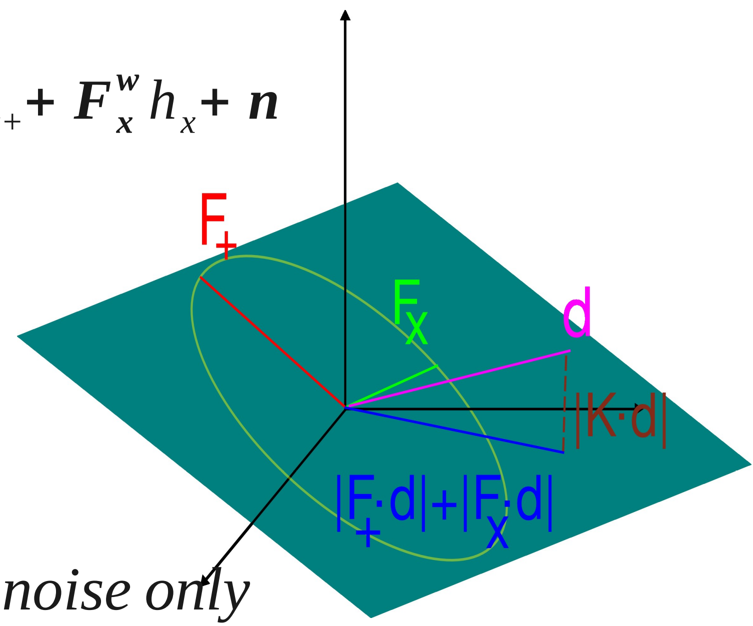


Coherent analysis formalism

- Null stream in N detectors → inverse problem is to find h_+ and h_X

$$\begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} F_i^+/\sigma_i \\ \vdots \\ F_N^+/\sigma_N \end{bmatrix} h_+ + \begin{bmatrix} F_i^x/\sigma_i \\ \vdots \\ F_N^x/\sigma_N \end{bmatrix} h_x + \begin{bmatrix} n_1 \\ \vdots \\ n_N \end{bmatrix} \quad \rightarrow \quad \boldsymbol{d} = \boldsymbol{F}_+^w h_+ + \boldsymbol{F}_x^w h_x + \boldsymbol{n}$$

Vector of whitened data time shifted at
a given time/frequency for a given sky position



$$E_{tot} = |d|^2 \quad \textit{Total energy}$$

$$E_{null} = E_{tot} - |\boldsymbol{F}_+^w \boldsymbol{d}|^2 - |\boldsymbol{F}_x^w \boldsymbol{d}|^2 = |\boldsymbol{K.d}|^2 \quad \textit{Null energy ie noise only}$$

$$E_{inc} = \sum_{\alpha=1}^{N} |K_\alpha d_\alpha|^2 \quad \textit{Incoherent energy ie contribution from each detector}$$

- Degeneracies: when F_+ and F_x are parallel or one is vanishing:
  - Sensitivity to only 1 polarization. Need to hard constraints (polarization, un-physical region suppression, ...)

Coherent waveburst

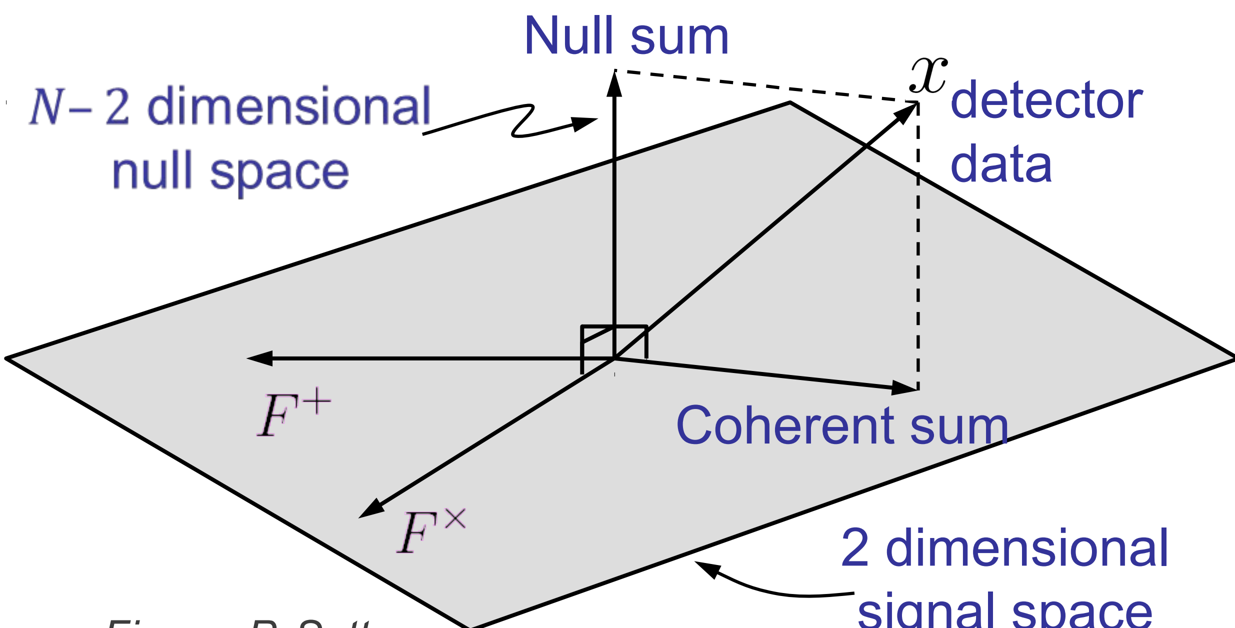


Figure: P. Sutton

Coherent sum:
Find linear combination of detector data that maximizes signal to noise ratio

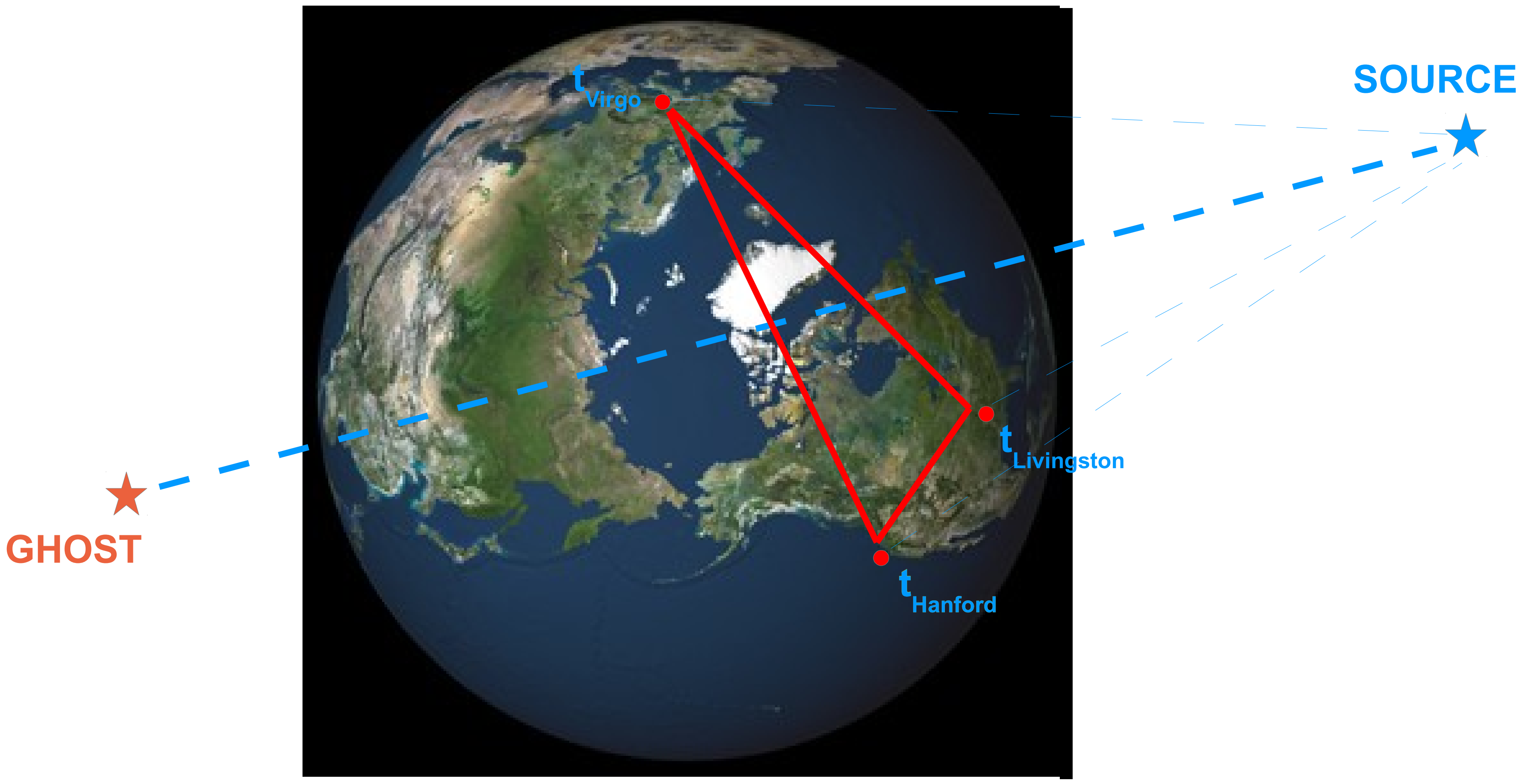
Null sum:
Linear combination of detector data that has no GW signal—provides consistency test

Treat this as a maximum likelihood problem

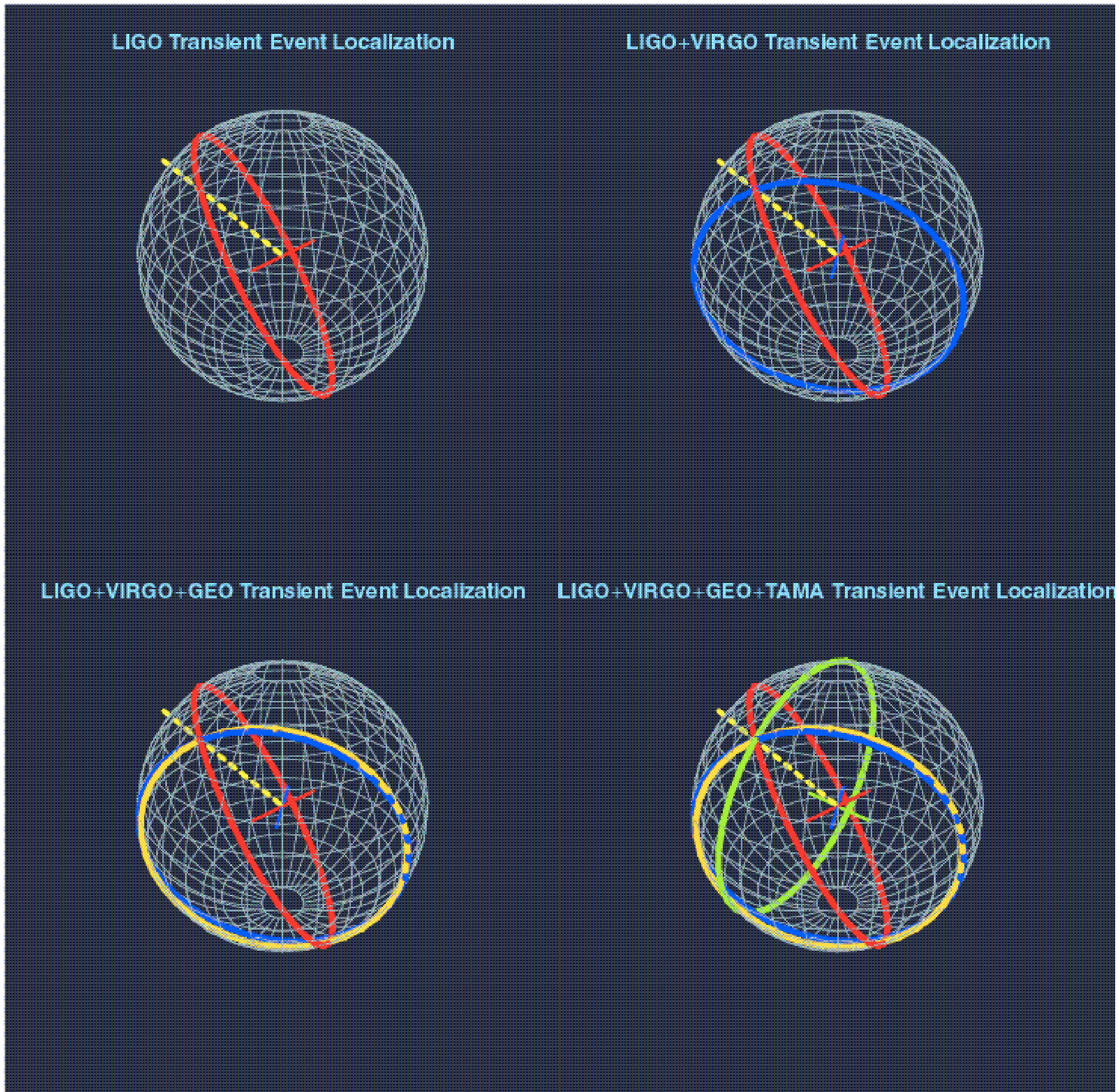
Consider all possible sky positions (arrival directions)

Find the sky position, $h_+(t)$ & $h_\times(t)$ with the greatest likelihood for producing the data that was recorded

Source sky localisation



Source sky localisation

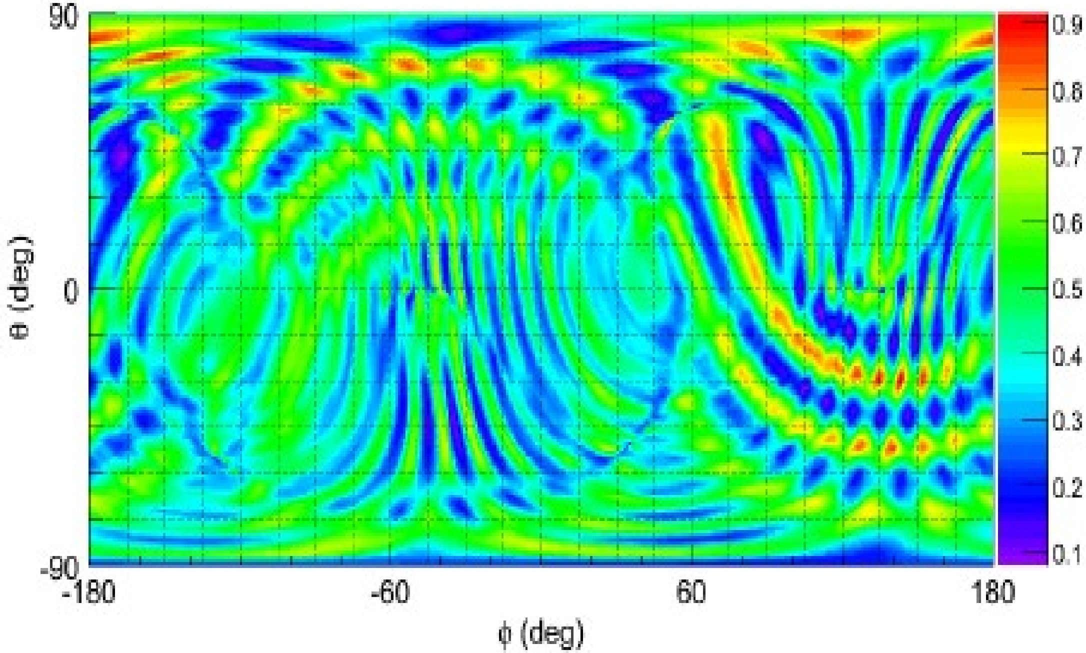


- 2 detectors → circle in sky
- Timing triangulation provides leading order estimates: error dominated by timing uncertainty: $\sigma_t \sim \frac{1}{2\pi\rho\sigma_f}$

  → tens of square degrees

  → better resolution at high frequency
- Coherent analysis inverse problem by-product

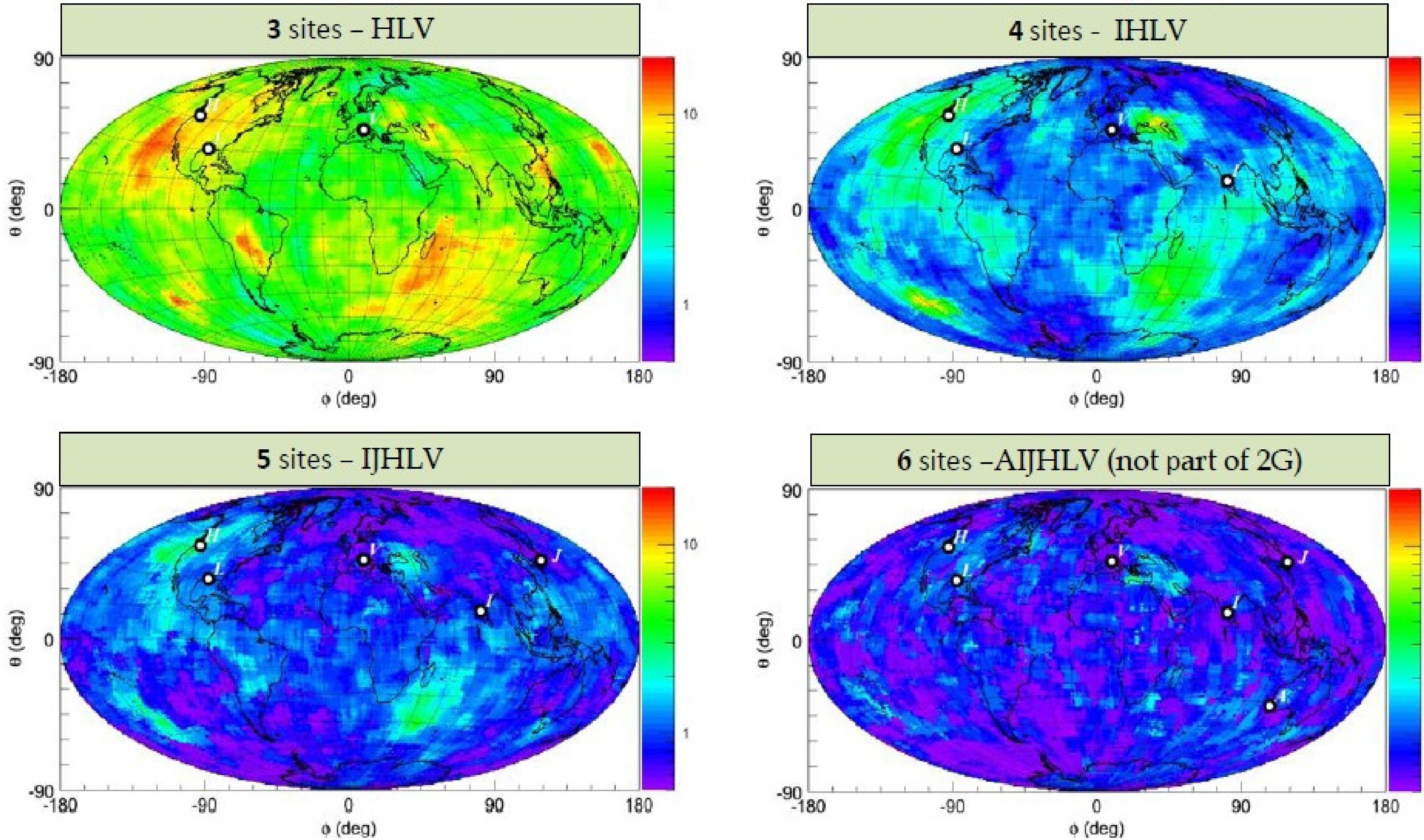
Coherent waveburst sky localization



- Provides most probable source sky location
- Error area: sum of discrete regions → can contain disjoint regions
- Performance: depends on many factors (signal strength, detectors, signal waveforms, ...)

Sky dependence

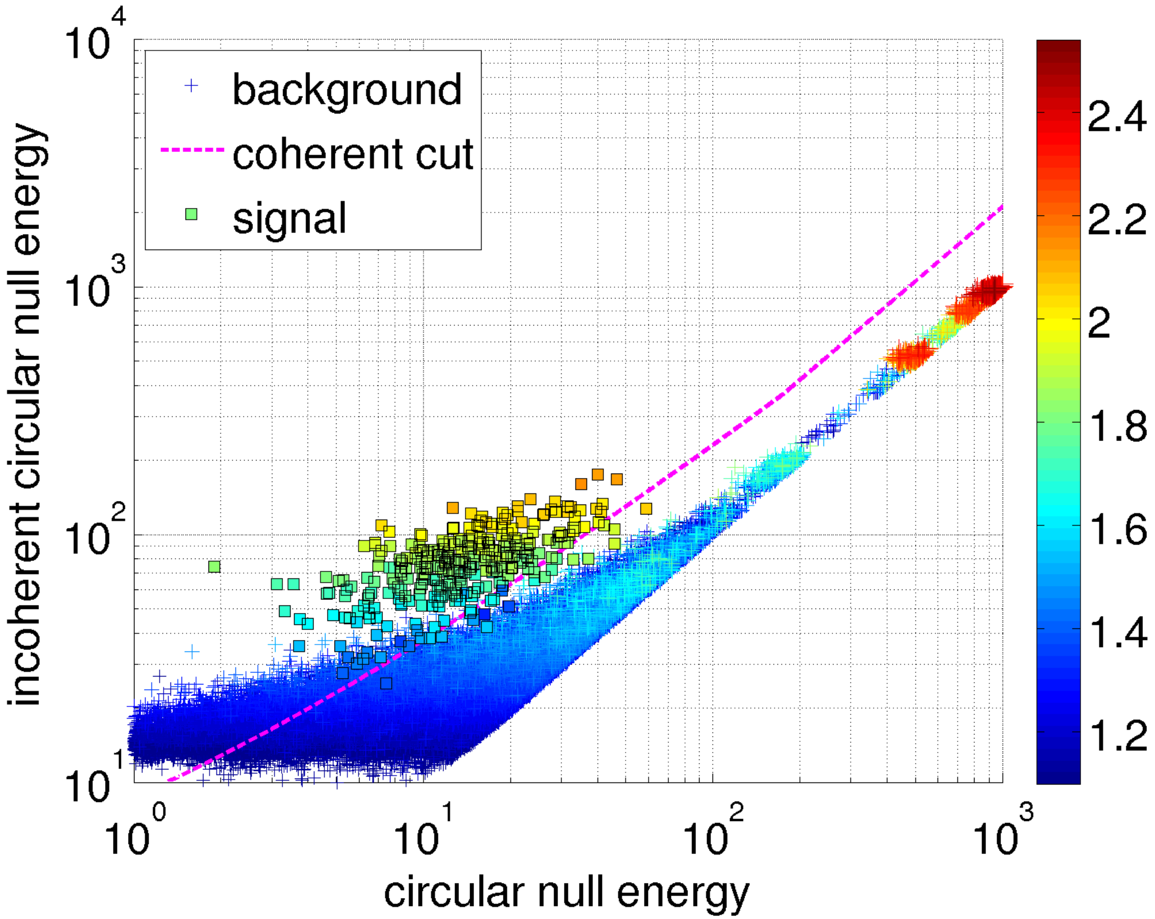
Median error angle (50% CL, SNR<30) for reconstruction of ad-hoc signals (extra slides)



@ M. Drago

Glitch rejection

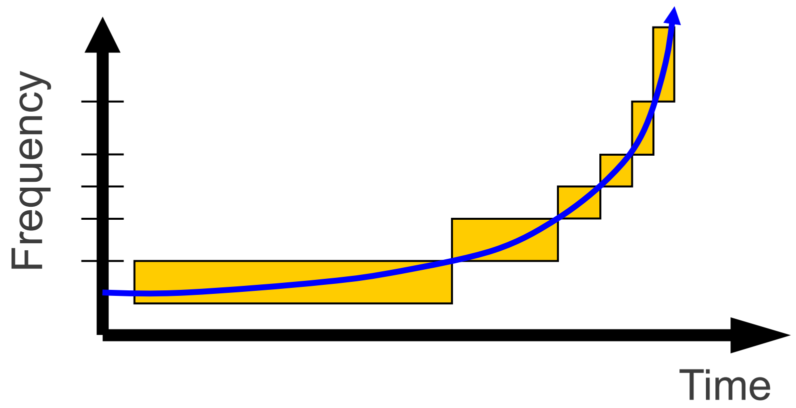
- Un-modelled burst search : coherent analysis: compare null and incoherent energy:
  - For a GW signal E_{inc}/E_{null} is large
  - For a glitch $E_{null}/E_{inc} \sim 1$



@ Xpipeline GRB search

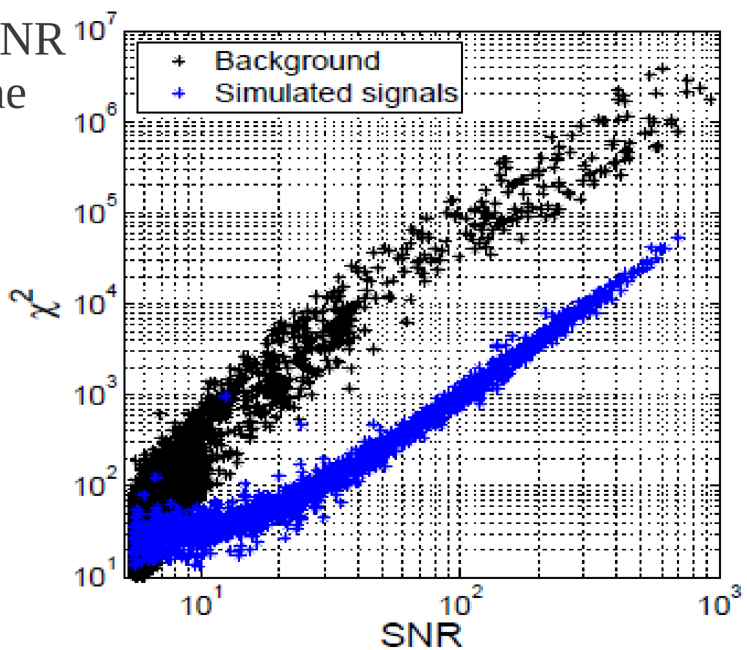
Another example of glitch rejection: waveform consistency χ^2 test for known waveform

- 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 χ^2 has an expectation value: $< \chi^2 >= p - 1$
- In practise χ^2 values are larger than expected for large SNR (discrete template banks effect) → cut in (SNR, χ^2) plane
- Weighted SNR

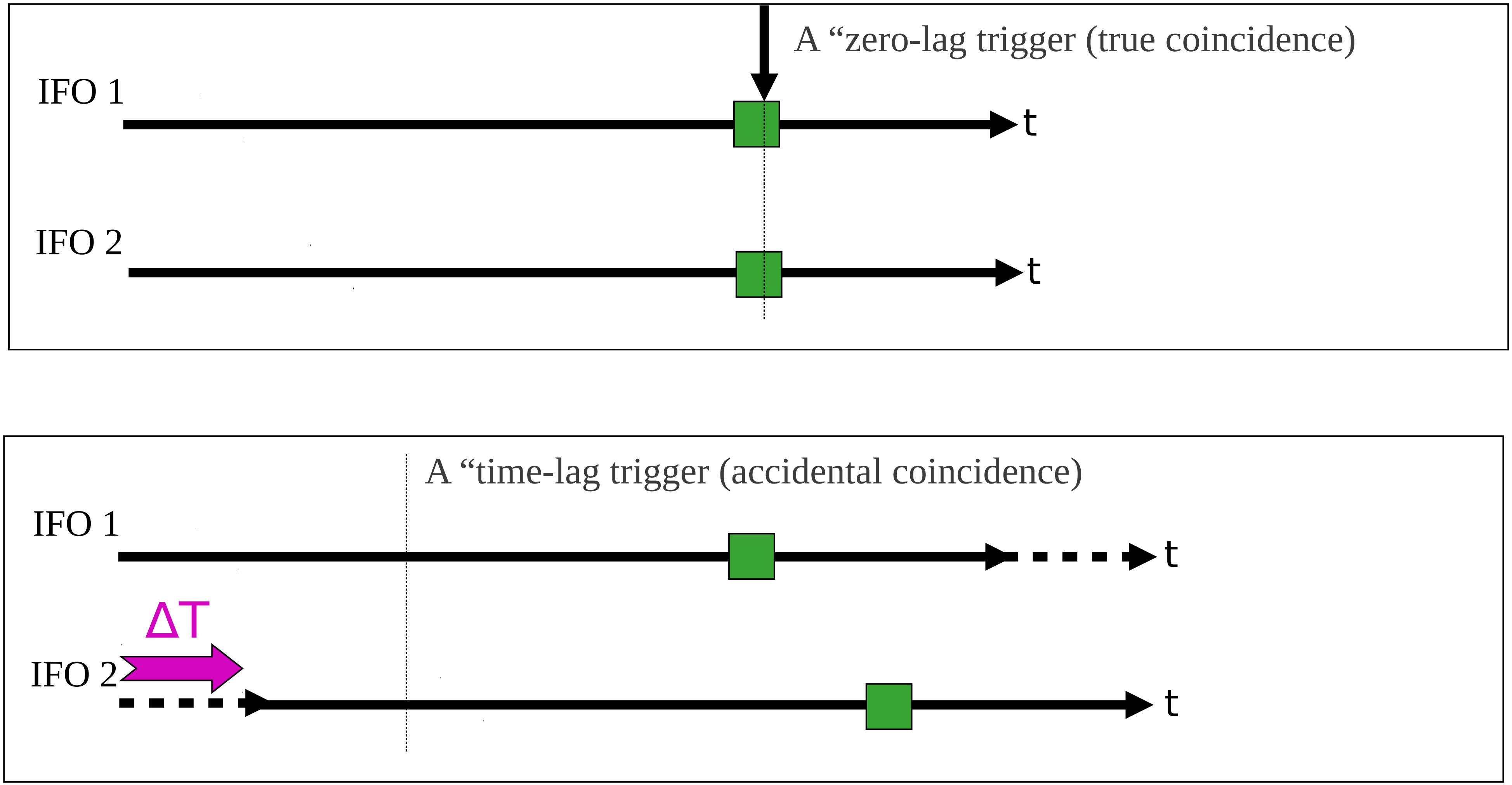


$$\rho_{\mathrm{new}} = \begin{cases} \rho, & \chi^2 \leq n_{\mathrm{dof}} \\ \frac{\rho}{\left[\left(1 + \frac{\chi^2}{n_{dof}}^{4/3}\right)/2\right]^{1/4}}, & \chi^2 > n_{\mathrm{dof}} \end{cases}$$

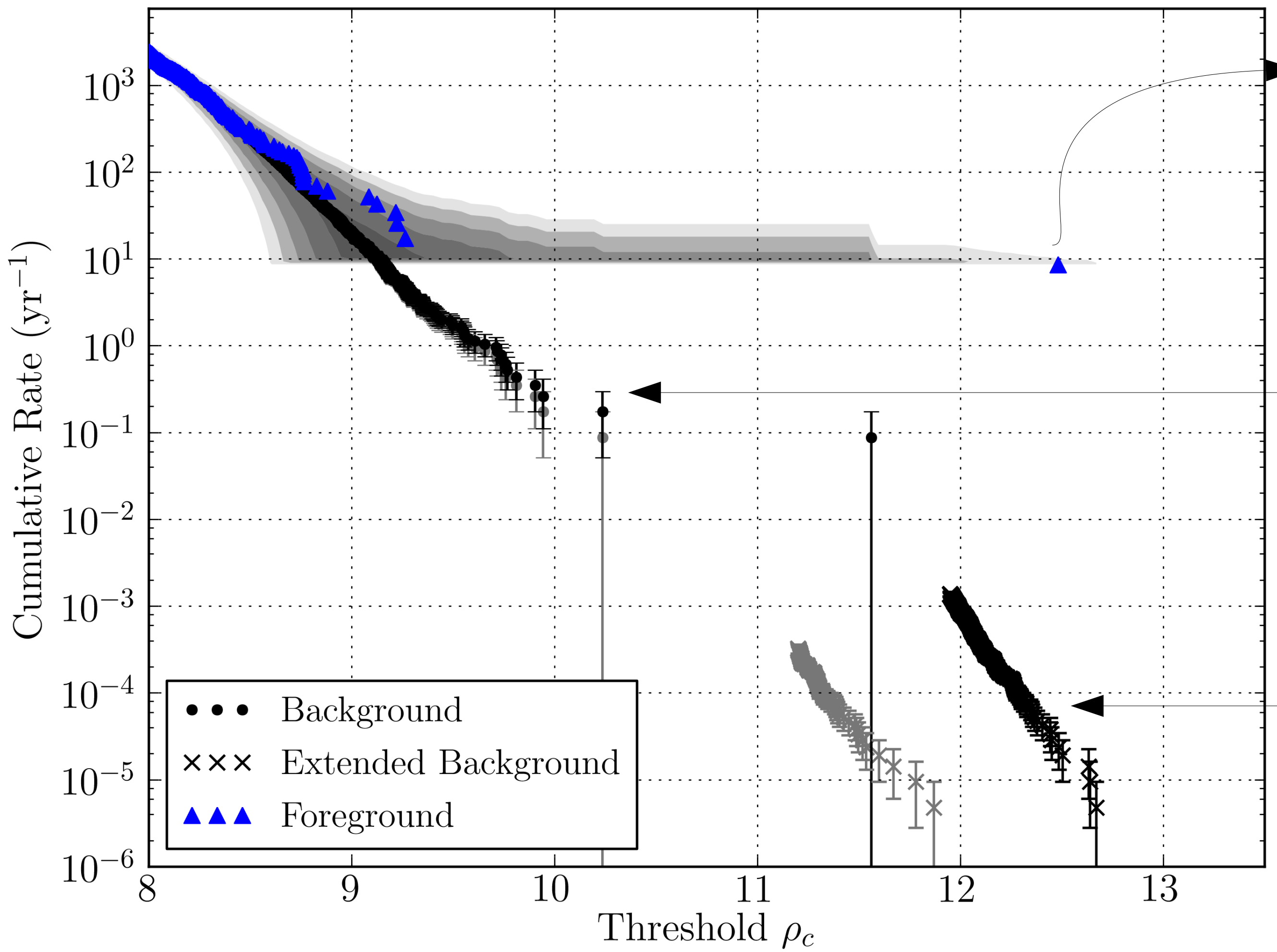
Gaining confidence in a signal candidate

- How do we know whether a signal in the data is a real GW?
  - Consistency with a source model (see previous examples)
  - Define a discriminating 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)

Background estimation



Example (low mass LIGO-Virgo) with a fake CBC event:



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

p-value: 7 10^{-5} ↔ "3.8 sigma"

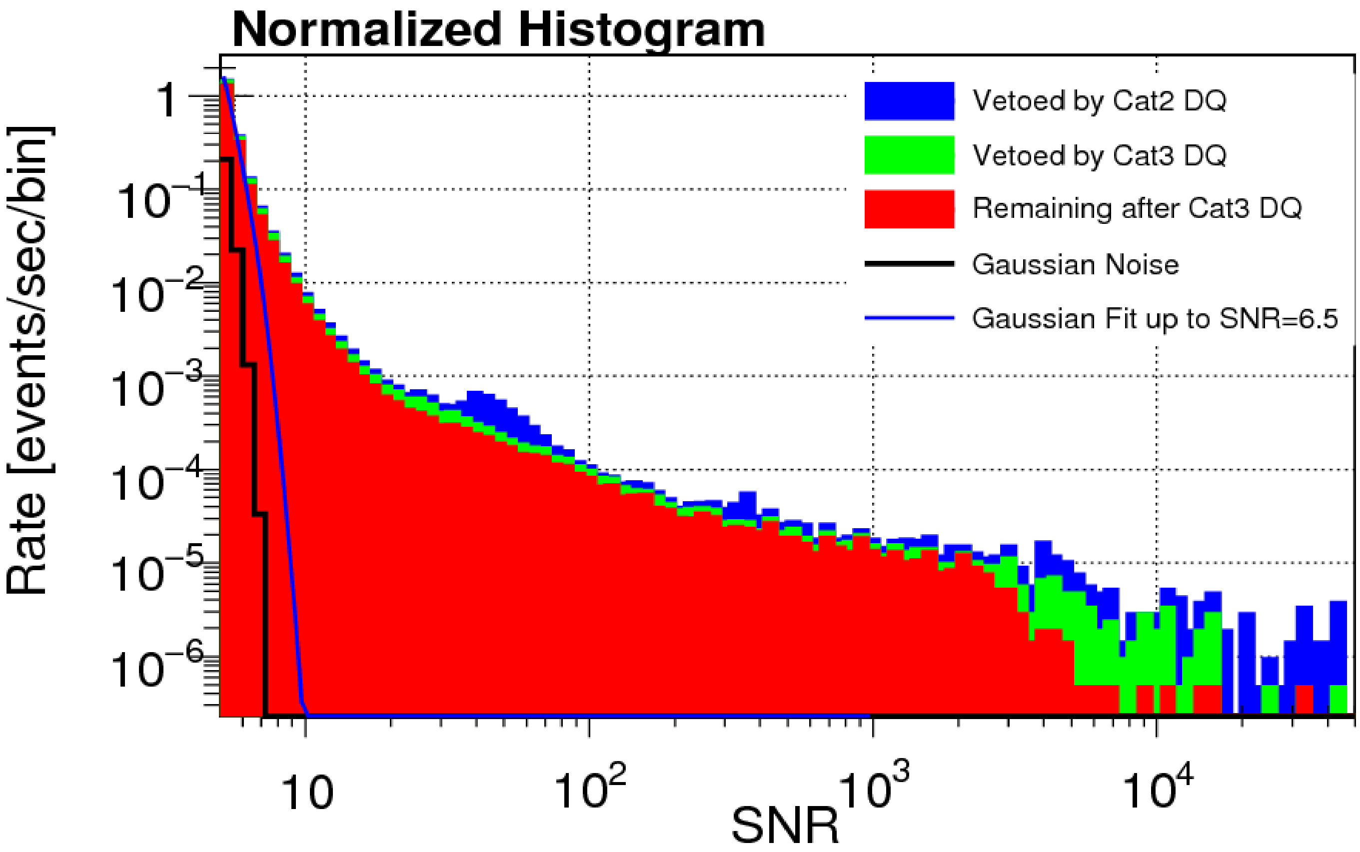
100 time shifts

40,000 time shifts

Data quality/instrumental vetoes

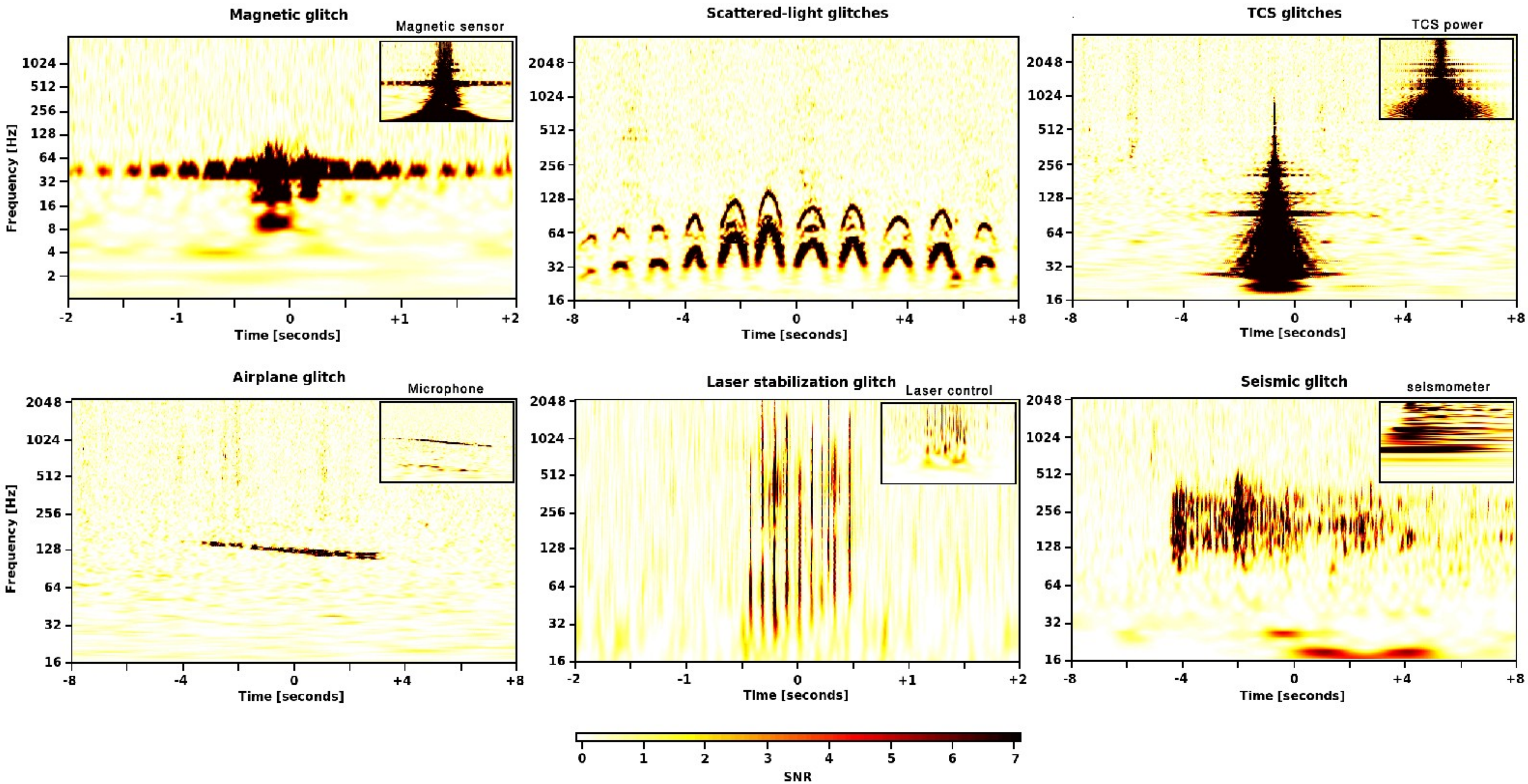
- Minimal data quality cuts: ask for periods when IFOs are “locked” and in “Science”. No ADC saturation …

→ not enough to suppress all noise transients



S6C LIGO Livingston Omega triggers

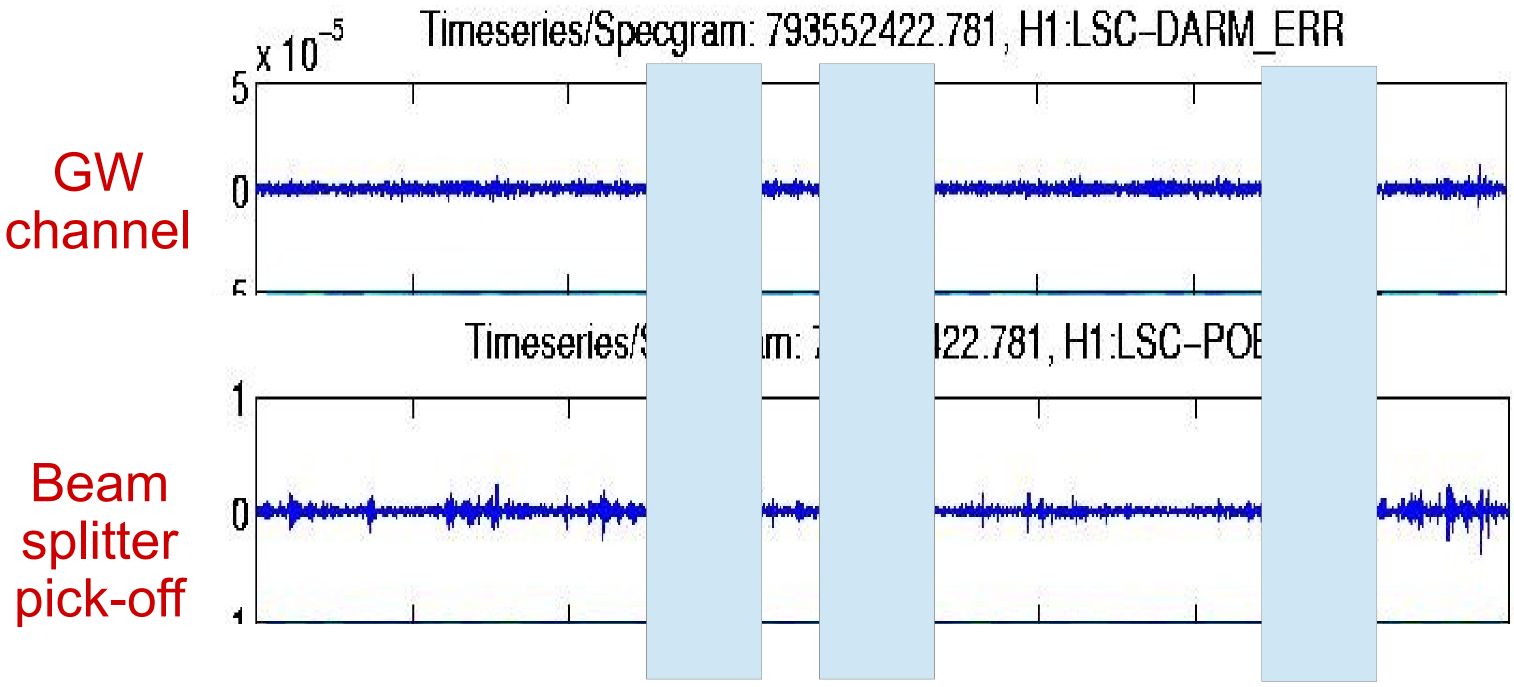
Data quality/instrumental vetoes



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



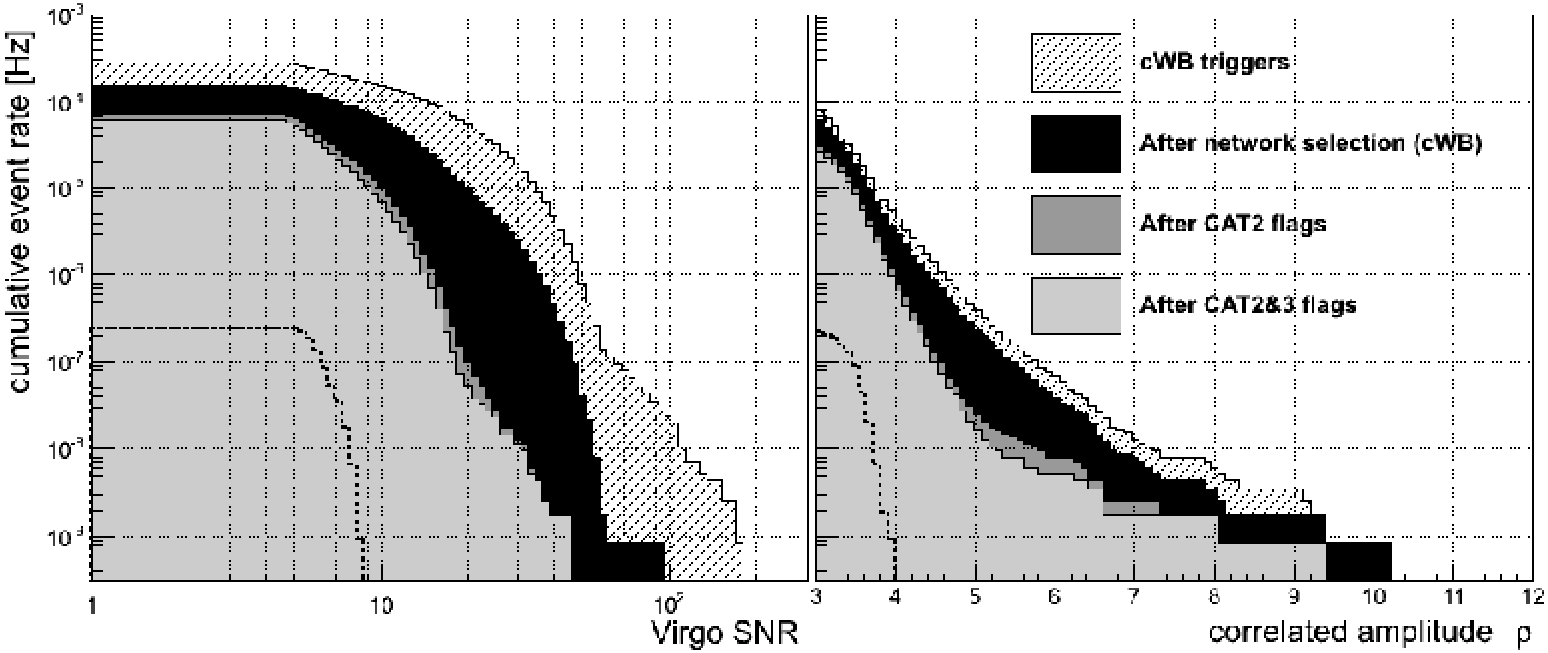
Virgo VSR2-3

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 statistical properties, vetoes belongs to different categories (CAT1, 2, 3)

Virgo VSR2-3

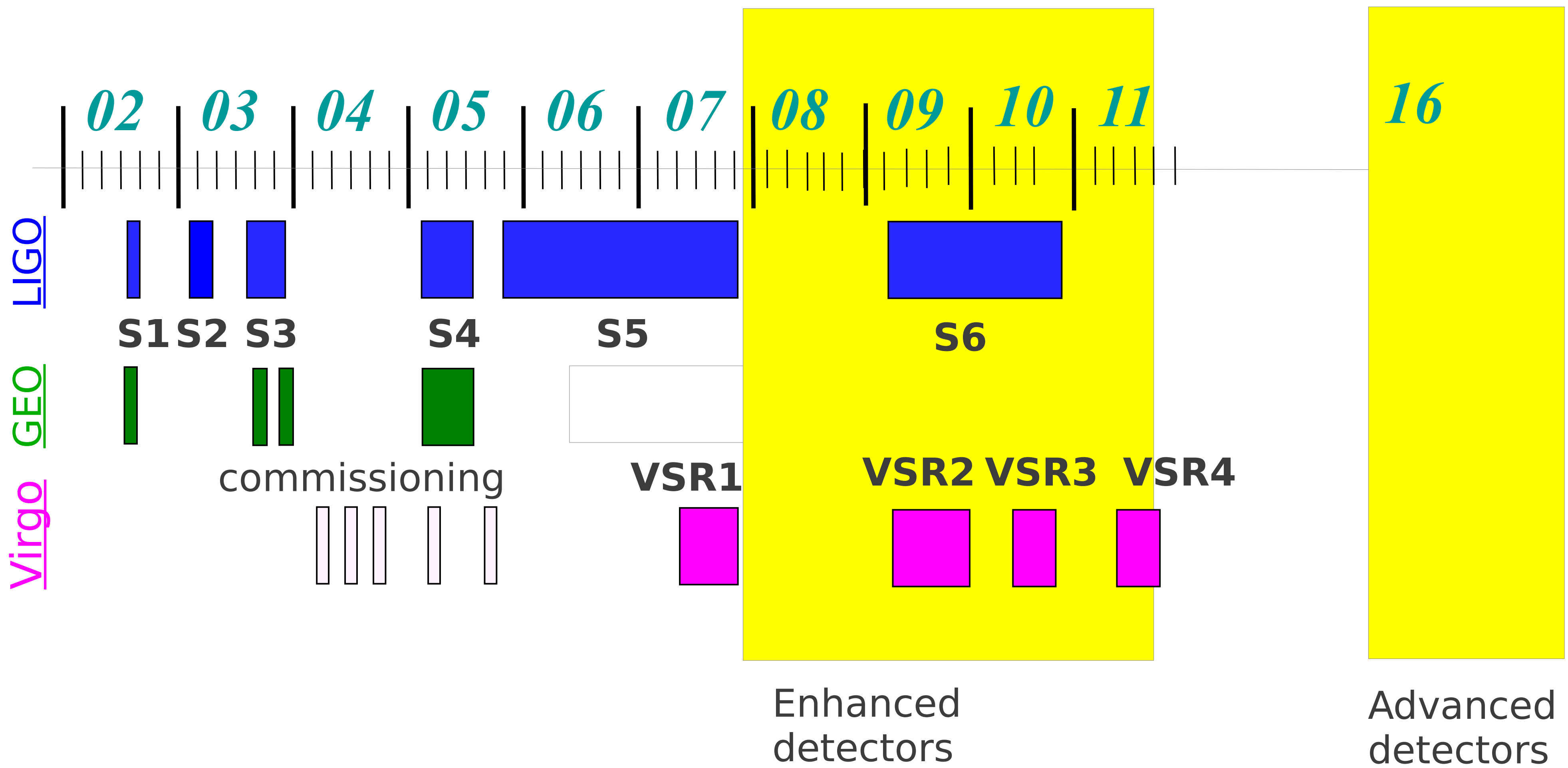
Data quality/instrumental vetoes



All-sky un-modelled burst search: Virgo vetoes eliminate a fraction of the loudest coincident triggers

Some LIGO-Virgo burst search results

LIGO – Virgo Runs



A variety of burst searches

- Multiple burst search methods approach in LSC-Virgo (stimulating concurrence, robustness, unknown targets, …)
- LSC-Virgo have published many burst searches:
  - All-sky searches (CCSN, BBH, unknown): all runs since 2003
  - Triggered searches:
    - GRB: 39 GRBs during S2/S3/S4, 137 during S5/VSR1, 150 during S6/VSR2+3, GRB 030329, GRB 070201, GRB 051103
    - Magnetar flare GW burst searches: SGR 1806–20 giant flare QPO search, SGR 1900+14 storm "stack" search. GW bursts from flares emitted by six different magnetars.
    - Bursts associated with Vela pulsar glitch, or high-energy neutrinos
  - Cosmic string cusps search during S4

No GW burst events found!

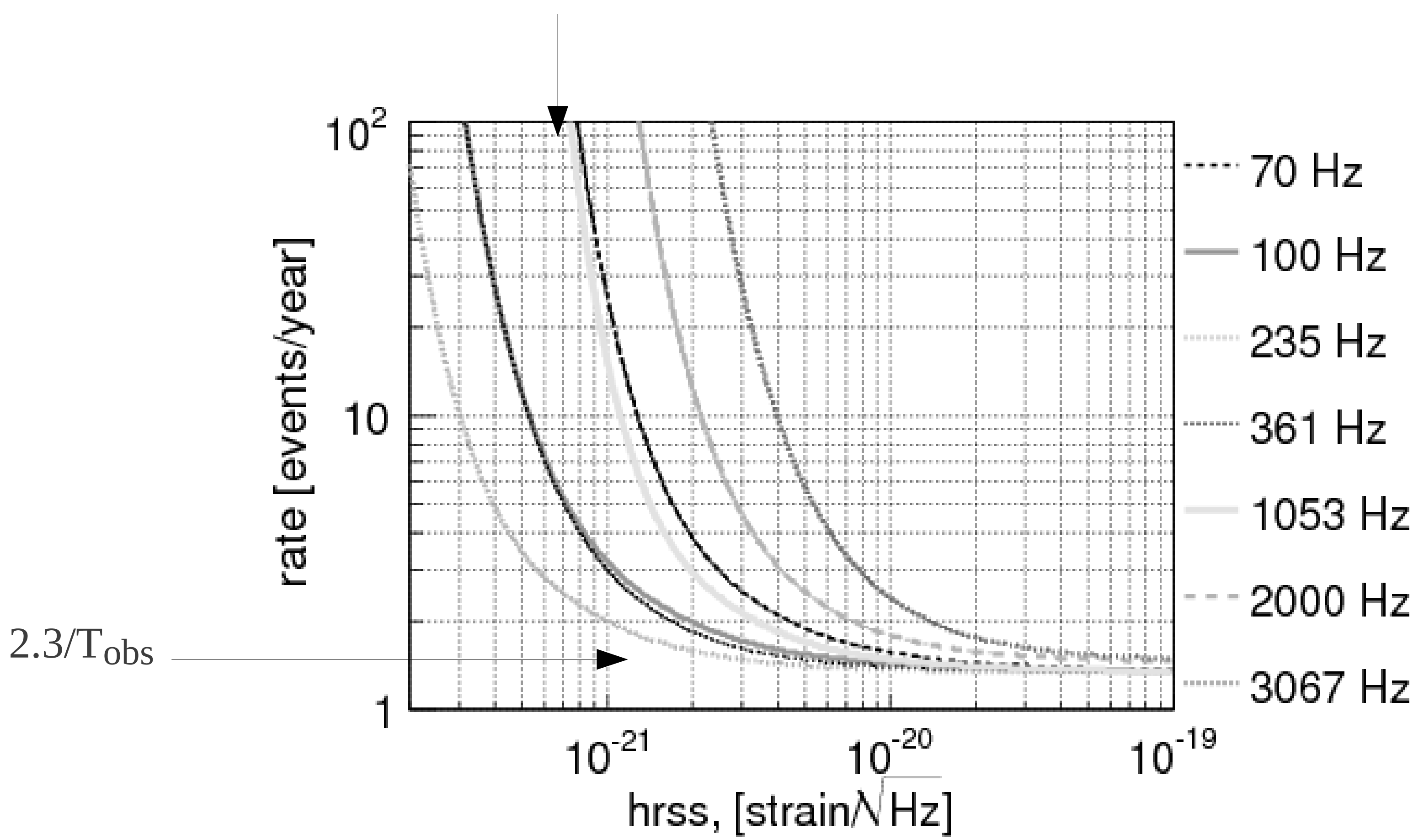
Generic burst all-sky search

- All LIGO and Virgo data sets have been searched since 2005 with at least 2 detectors.
  - Total livetime: 636 days
  - Coherent analysis
- Parameter space: 64-5000 Hz
- Background measured with artificial time shifts.
- No events survived selection cuts.
- Upper limits on burst rate vs amplitude for representative (ad-hoc) waveforms using injections.

Abadie et al., Phys. Rev. D in press, arXiv:1202.2788

Generic burst search sensitivity

- Search efficiency is determined for different monochromatic ad-hoc waveforms and different polarization hypothesis.
- Event rate upper limits are derived as function of the strength of the putative signal.

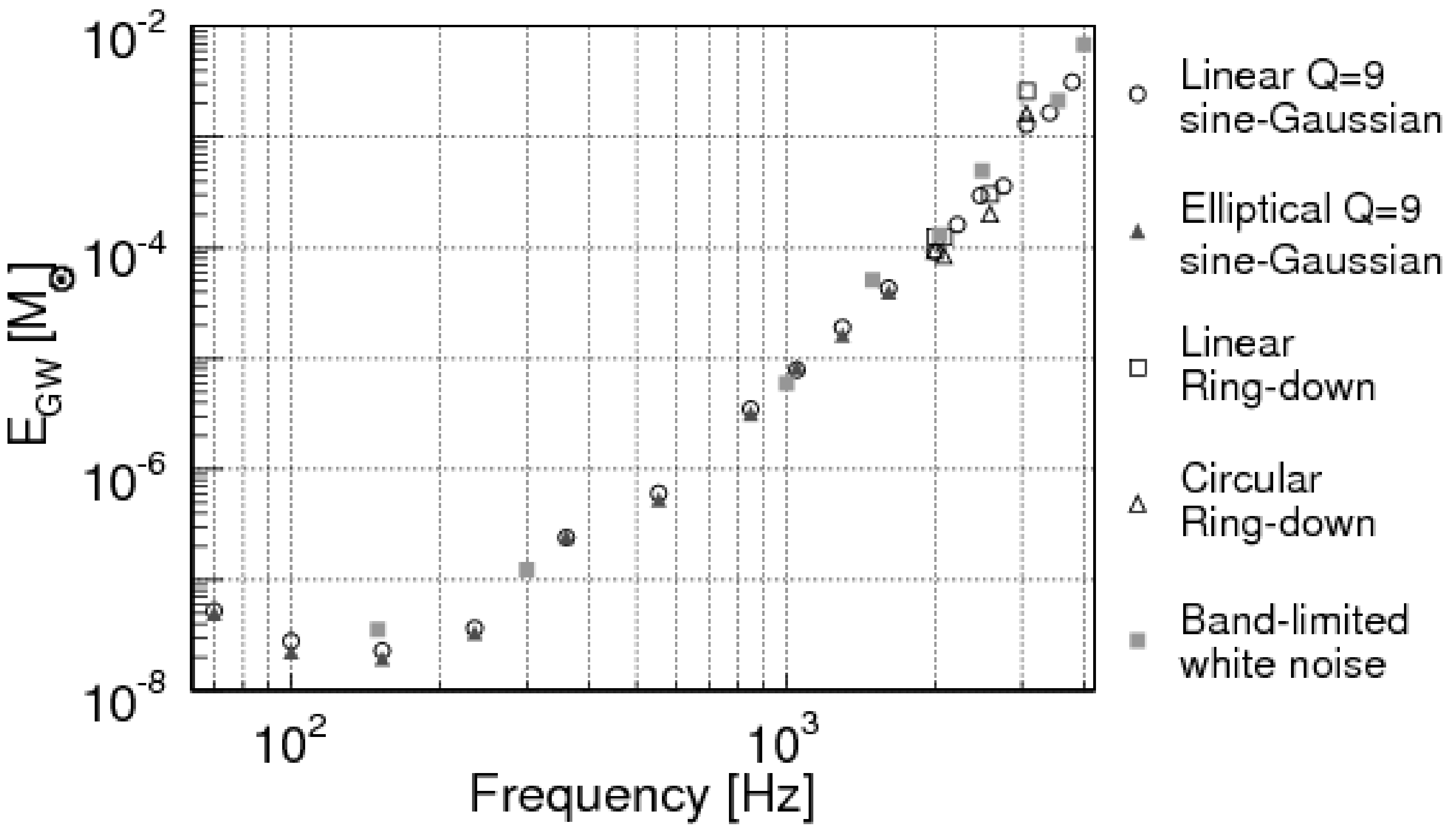


Search sensitivity in energy units

GW energy emission assuming a Galactic source (10 kpc) that could have been detected with 50% efficiency

$$E_{GW} = \frac{r^2 c^3}{4G}(2\pi f_0)^2 h_{rss}^2$$

d=10 kpc → E_{GW} ~10^{-8} M_{sun} c^2 → CCSN
d=15 Mpc → E_{GW} =10^{-1} M_{sun} c^2 → BBH



IMBH "burst" search

- S5/VSR1 data results (no detection) published. S6/VSR2-3 upper limits coming soon

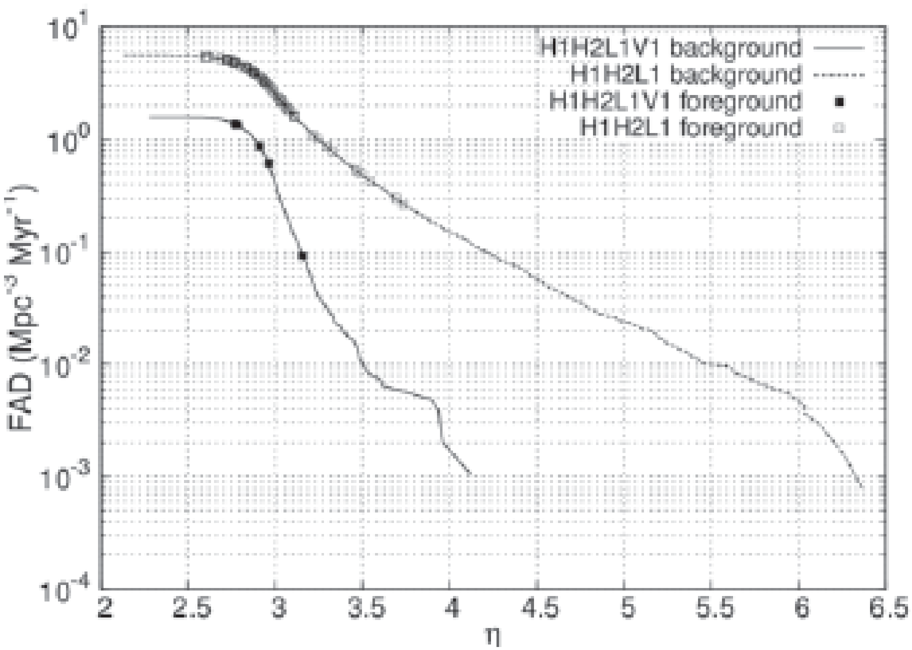
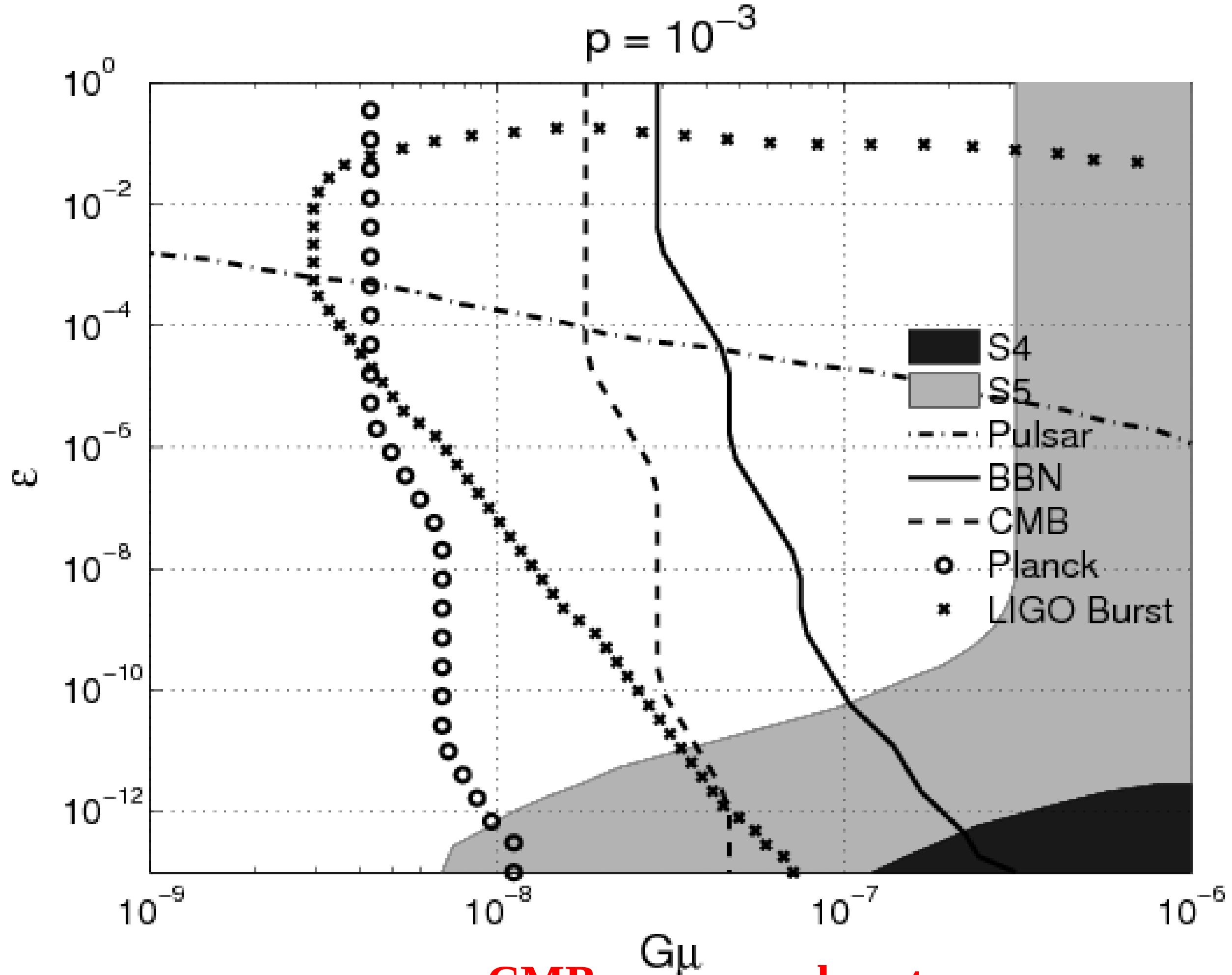


FIG. 1: False alarm density rate vs η for the background events (H1H2L1V1 - solid line, H1H2L1 - dashed line) and the foreground events (H1H2L1V1 - black squares, H1H2L1 - open squares).

- Specific upper limits using IMBH waveform models
- Mass range 100-450 M⊙ and mass ratio 4:1, non spinning
- Used EOBNR waveforms (with a posteriori corrections on efficiency)
- 90% upper limits on the effective range and rates.
- Most constraining ULs in the 88 M⊙+ 88 M⊙: 241/190 Mpc (depending on network) and 0.13 Mpc^{-3} and Myr^{-1}.

FAR FROM EXPECTED RATES OF ~ 10^{-5} Mpc^{-3} Myr^{-1}

Cosmic string cusps search



CMB **burst**

S4 (2004) LIGO only dataset
S5/VSR1-S6/VSR2-3 results coming soon

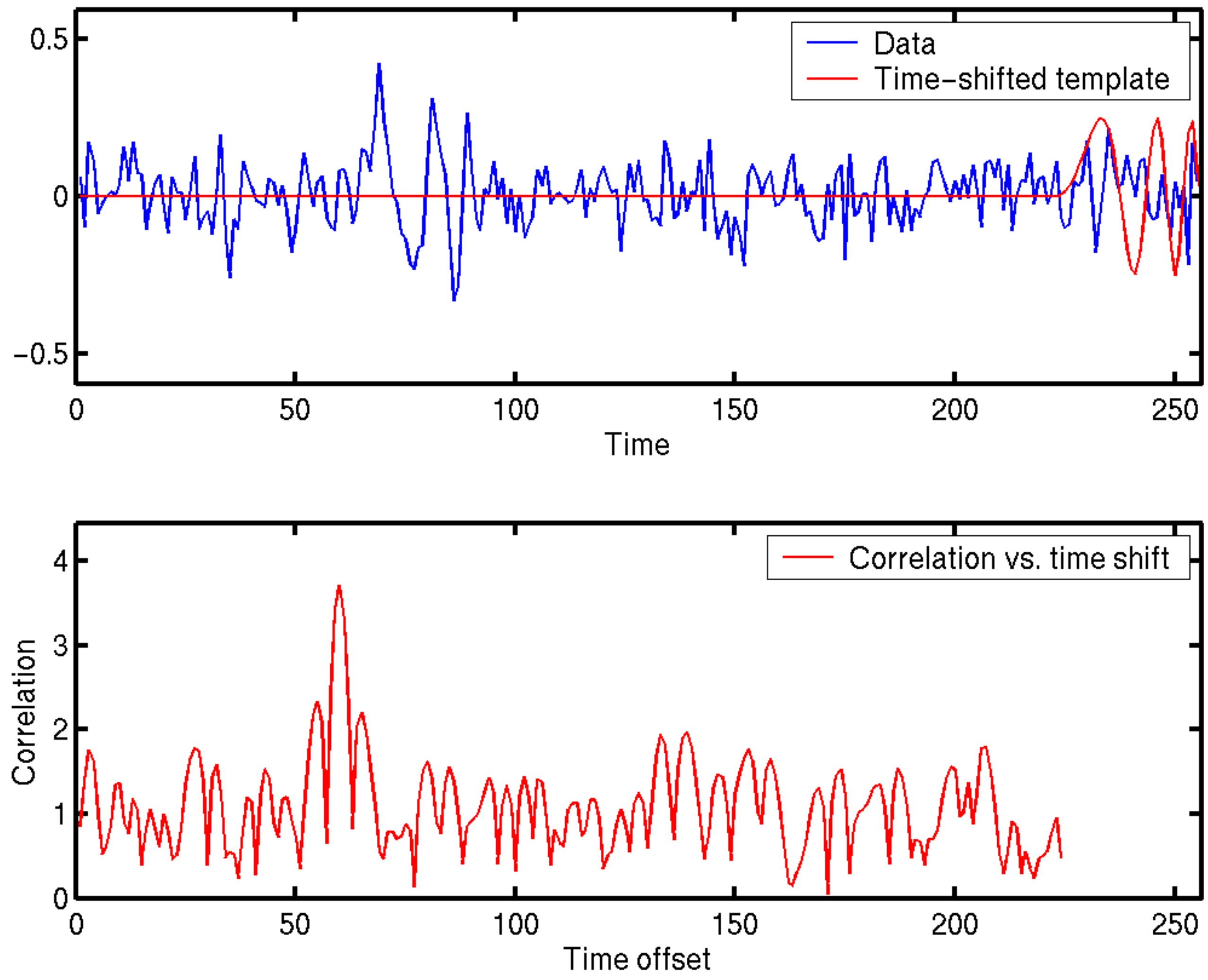
Best limits given by Planck, but independent and direct search

Conclusion/future

- ALIGO/AdV sensitivities should provide good surprises for burst searches (at least IMBH, CCSN range still limited to our galaxy).
- Low latency all-sky searches ready but will require data quality investigations to gain confidence in GW candidates before setting the GW alerts system.
- Triggered searches, EM follow-ups, GW-High Energy Neutrinos: listen to the next talks ...

Extra slides

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 $\tilde{k}(f) \propto \frac{\tilde{h}^*(f)}{S_n(f)}$

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

Bright future with advanced LIGO and advanced Virgo

Expected rate with 10 times more sensitive detectors

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

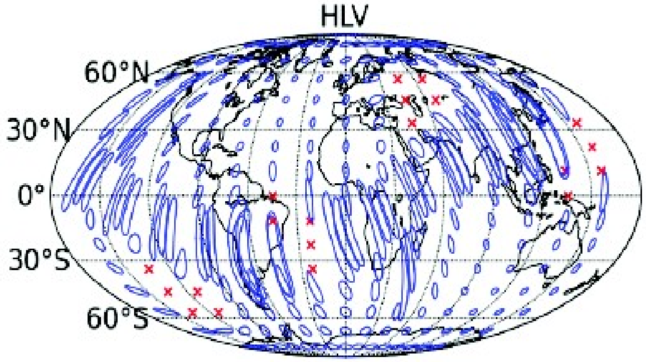
First discovery in 2016?

Need to be lucky for
EM follow-up ?

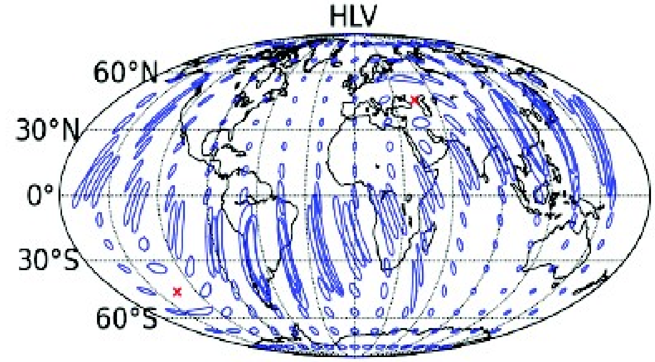
Advanced detector sky localization

BNS source @ 80 Mpc

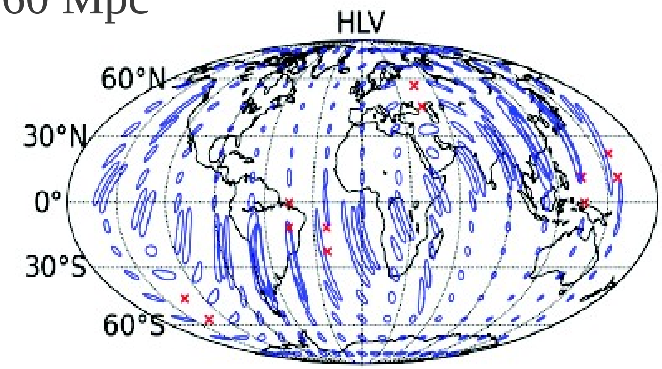
2016-2017 runs



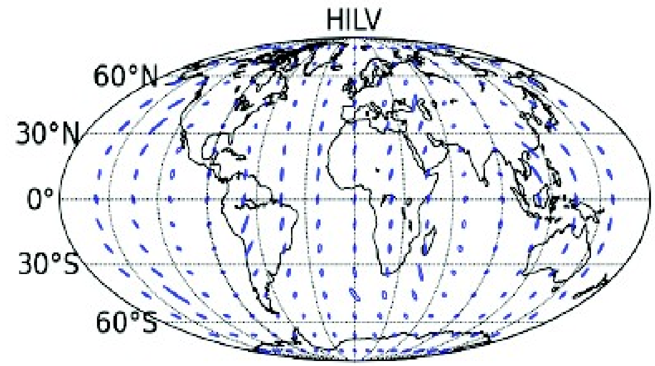
2018-2019 runs



BNS source @ 160 Mpc



2019+ runs



HLV + LIGO India 2022+