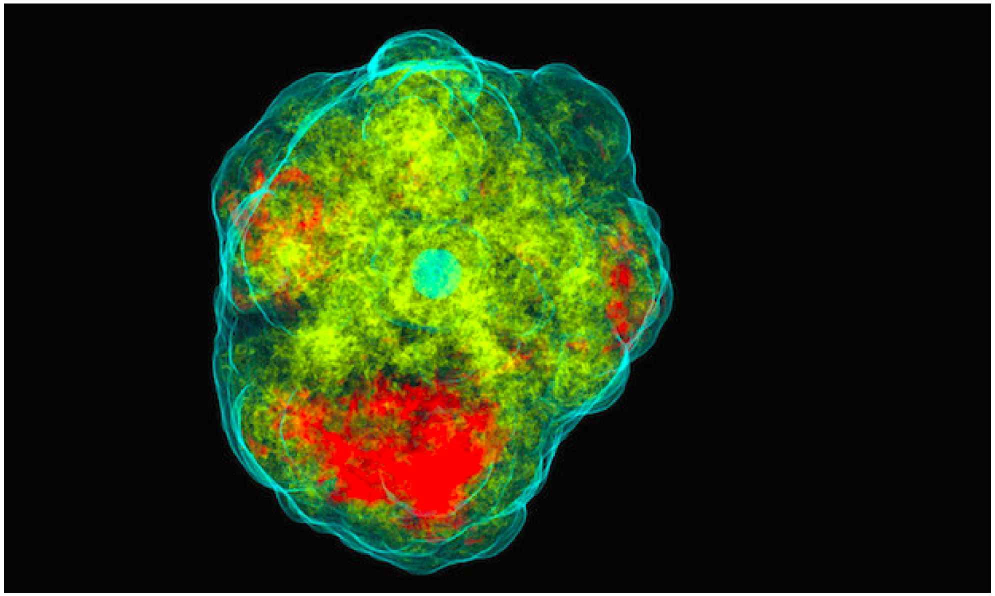
Gravitational wave burst searches



Marie Anne Bizouard

Laboratoire de l'Accélérateur Linéaire

CNRS/IN2P3 & Université Paris Sud

for the LLIGO and Virgo collaboration

Gravitational waves - Ecole de Physique des Houches – Session CX

July 2nd-27th, 2018

Outline of the lecture

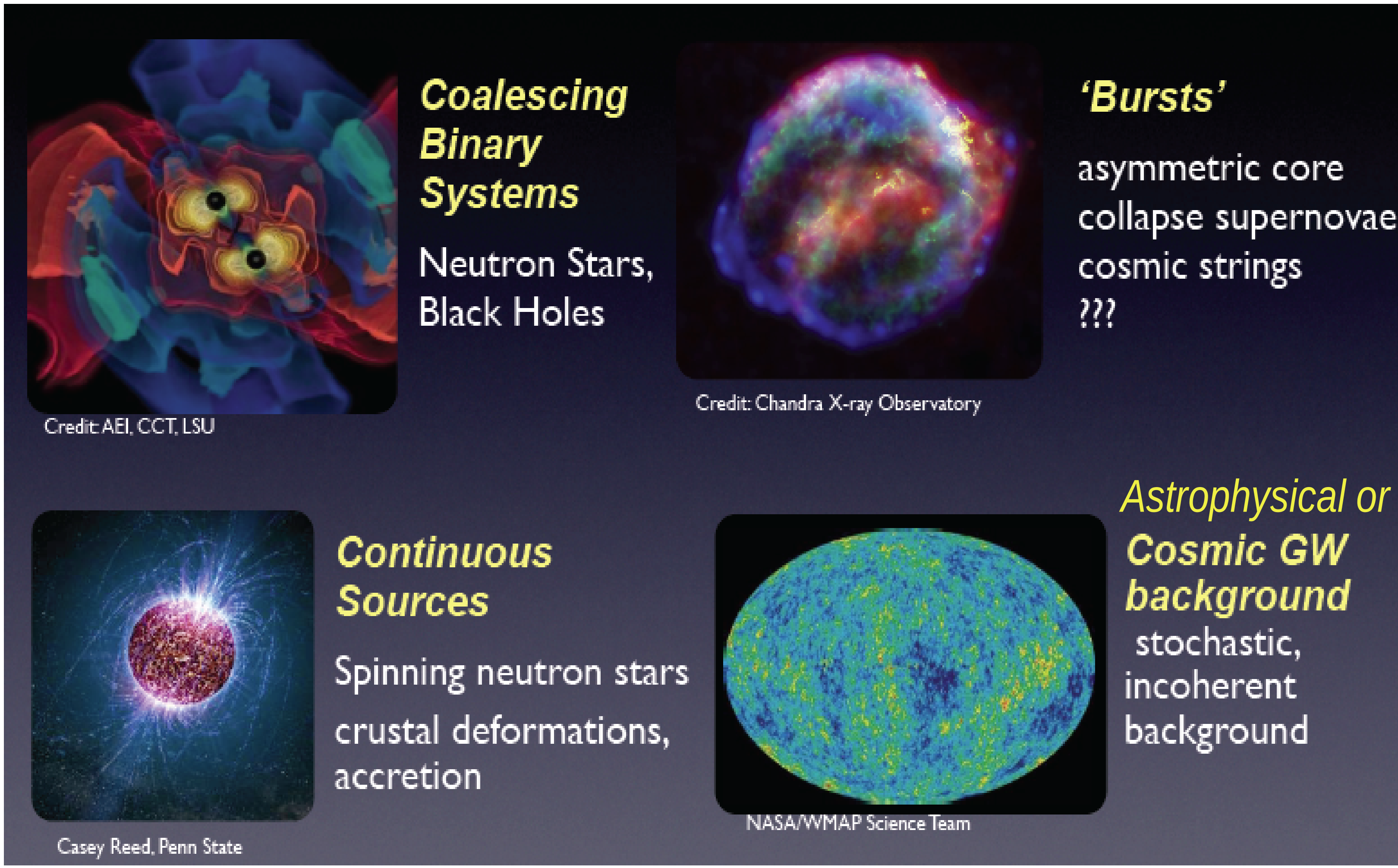
- Part I
  - Iconic burst GW source : CCSN
  - Burst waveform models.
- Part II
  - The detection problem.
  - The techniques to mine the data in the context of Burst GW searches.
  - Significance estimation.
- Part III
  - Building a coherent un-modelled search.
  - Signal reconstruction.
  - Real data challenges.

GW sources zoology

Known waveforms ⟷ Unknown waveforms

Short duration (~1s)

Long duration (∞)



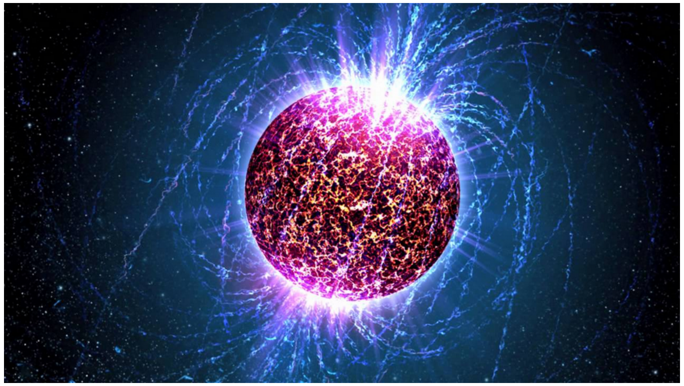
What are GW bursts ?

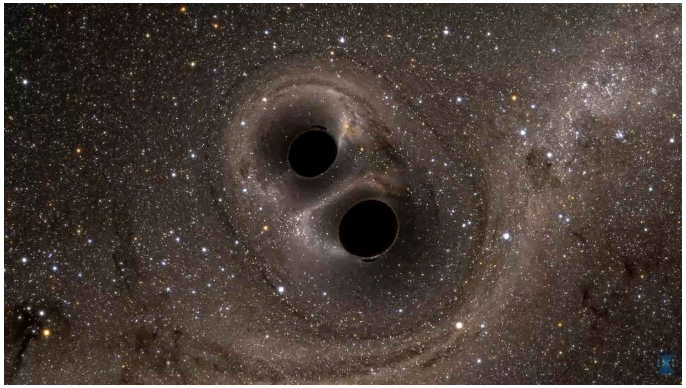
- Historically, transient signal whose waveforms are not accurately known or very complex such that templated searches are not affordable.

  Not totally true :

  - Cosmic string → templates do exist
  - Compact Binary mergers → templates do exist

- Transient : duration typically < 1s but some GW signals duration O (100s)



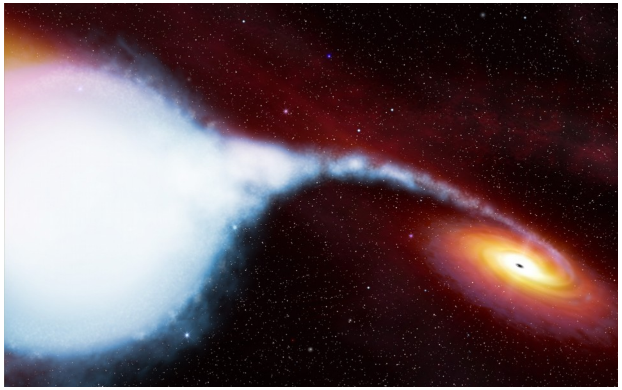


- Astrophysical GW sources : neutron star and black holes → core collapse supernova, black hole merger, fallback accretion onto a neutron star, neutron star instabilities (post-merger), magnetar flares, …

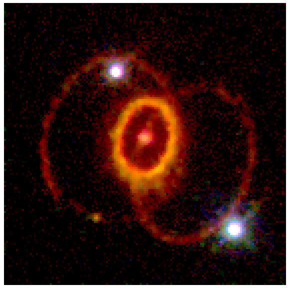
- Many GW sources are emitting photons and neutrinos → multi-messengers.

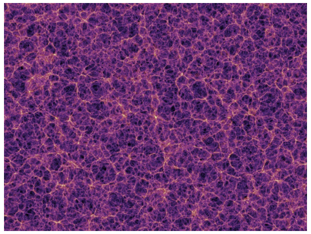
Burst sources

- Astrophysical sources :
  - Core collapse supernova.
  - Neutron star instabilities (rotation, bar modes,…).
  - Fallback accretion onto a neutron star.
  - Non axisymetric deformation in magnetars.
  - Pulsar glitches.
  - Neutron star post-mergers.
  - Black hole accretion disk fragmentation.
  - ...
- Cosmological sources :
  - Cosmic strings.



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





… and the unexpected.

GWs are bringing unique information about the onset of the explosion mechanisms and NS structure and nuclear physics and exotic theories, etc.

Supernova !

Supernova sources mentioned as burst source in Kip Thorne 80' review.

Rev. Mod. Phys. 52 (1980)

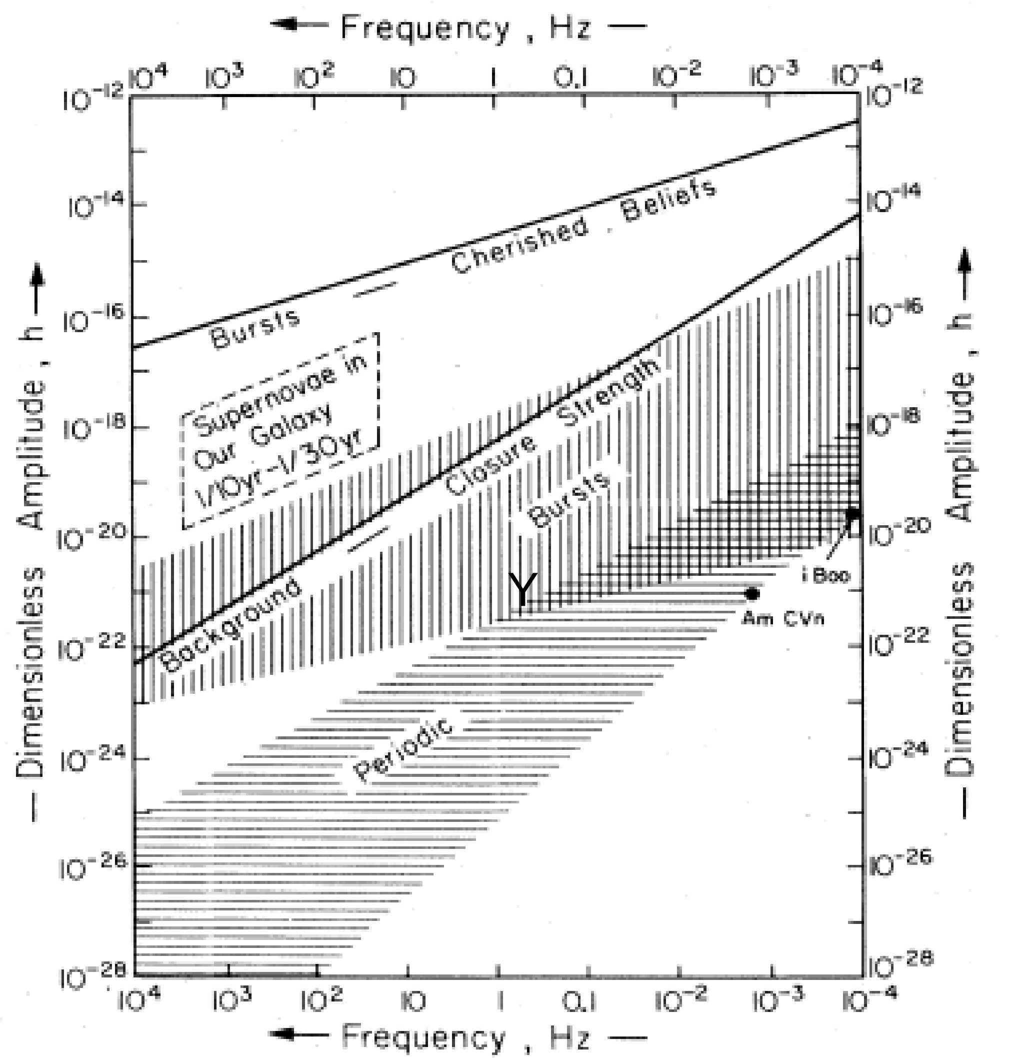


FIG. 3. Estimates of the strengths of the gravitational waves that bathe the Earth. See text for explanation of the lines and hatched regions.

The iconic Burst GW source : CCSN

- The early ages :
  - Observations examples : Crab Nebula explosion in 1054, Tycho Brahe's nova in 1572, Andromeda Nebula in 1885 …
  - 1934 : Baade & Zwicky papers : introduce the term « super-nova » to distinguish these observations from standard novae + link them with cosmic rays + neutron star hypothesis (remember neutron discovery by Chadwick in 1932 …).

PNAS papers
http://www.pnas.org/content/pnas/20/5/254.full.pdf

ON SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Common Novae.—The extensive investigations of extragalactic systems during recent years have brought to light the remarkable fact that there exist two well-defined types of new stars or novae which might be distinguished as *common novae* and *super-novae*. No intermediate objects have so far been observed.

These values correspond to a loss of mass

$$\Delta M = E_T/c^2, \quad \Delta M_1 = 1.37 \times 10^{34} \text{ gr.}, \quad \Delta M_2 = 3.32 \times 10^{30} \text{ gr.} \quad (16)$$

In reality the mass radiated away may be several times this amount, and it therefore becomes evident that *the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass.*

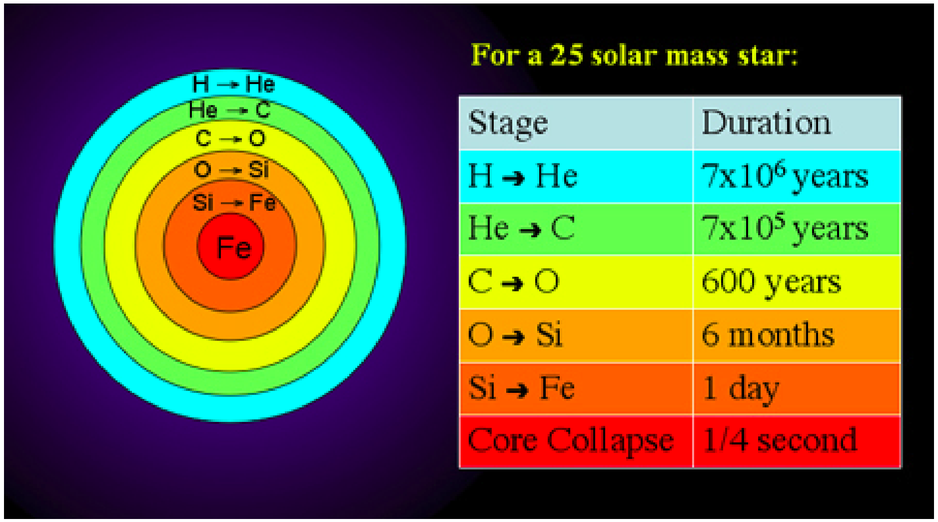
The iconic Burst GW source : CCSN

- The explosion mechanisms :

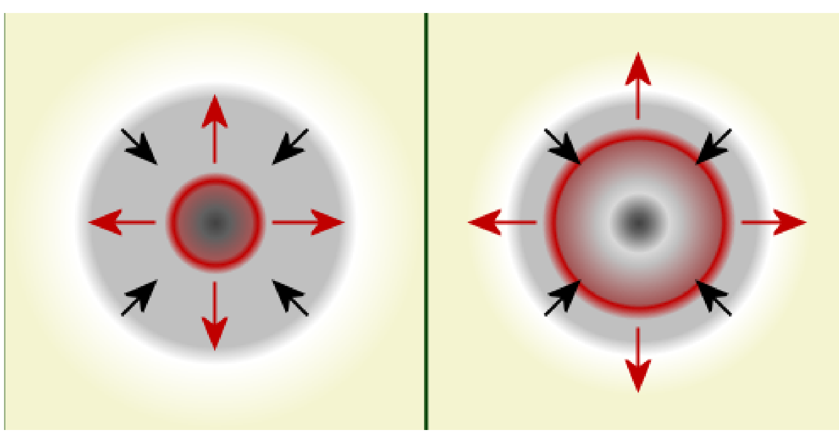
	Type I	Type Ib/Ic & type II
Progenitors	White dwarfs	Massive stars
Explosion mechanism	Matter/gas falls onto a 'dead' white dwarf raising its mass until the Chandrasekhar limit. → triggers runaway nuclear fusion explosion that destroys the star.	The core runs out of fuel to power its nuclear fusion reactions and collapses in on itself. → release gravitational potential energy in a form that blows away the star's outer layers.

OK but how ?

The fate of a massive star



Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second



- Elements undergo fusion forming heavier and heavier elements until iron is formed.
- When all fusion reactions are over, if the mass reaches the Chandrasekhar limit, gravity starts to win over all other forces : start of the collapse.
- Temperature increases, high energy photons are emitted and break iron nuclei into Helium.
- The core has continued to contract and gravity forces are no more compensated by the electron degeneracy pressure.
- Under pressure : $p + e^- \rightarrow n + \nu_{e.}$ Lots of energy is carried away by $\nu_{e.}$
- When the core reaches nuclear density, the collapse is stopped and a shock wave is bouncing infalling matter outwards.
- At some point nuclear reactions will slow down the matter and the shock is stalled.

The iconic Burst GW source : CCSN

- 1965 : Colgate & White seminal paper
  - White had demonstrated with first numerical simulation that the shock wave was not strong enough to trigger the explosion.
  - Role of neutrinos :

ApJ, 1966

THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

- 1973 : Neutral current discovery at CERN :
  - Wilson : elastic scattering of neutrinos on nuclei allows neutrino transport through dense matter with time scale larger than the last stage of collapse (requires density larger than 10^{12} g cm^{-3}).
  - → 99 % of the gravitational binding energy released (10^{53} erg) is carried away by neutrinos.

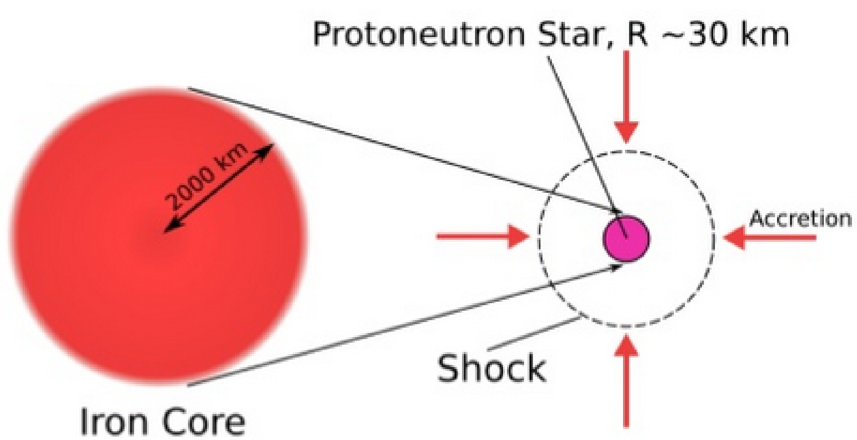
The iconic Burst GW source : CCSN

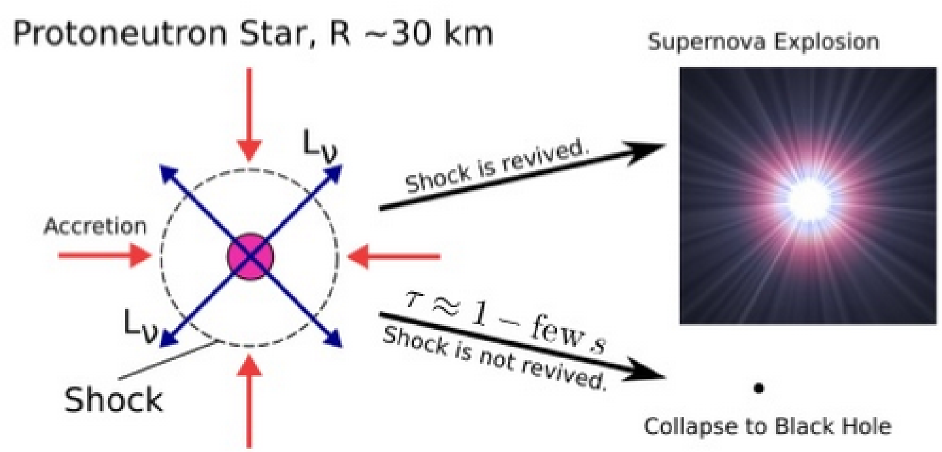
<u>Core bounce</u>

- Nuclear equation of state stiffens → rebound of the inner core ("core bounce").
- A hydrodynamic shock wave is launched at the outer edge of the inner core and propagates outward in mass and radius, slamming into the still infalling outer core.

<u>After core bounce</u>

- The shock quickly loses energy (dissociation of heavy elements + neutrino losses) and stalls.
- Without shock revival, black-hole (BH) formation is inevitable and even with a successful explosion, a BH may still form via fall-back accretion.





Figures credit : Christian Ott

The iconic Burst GW source : CCSN

- The explosion mechanism current paradigm : neutrino-driven delayed explosion (Wilson 82', Bethe&Wilson 85')

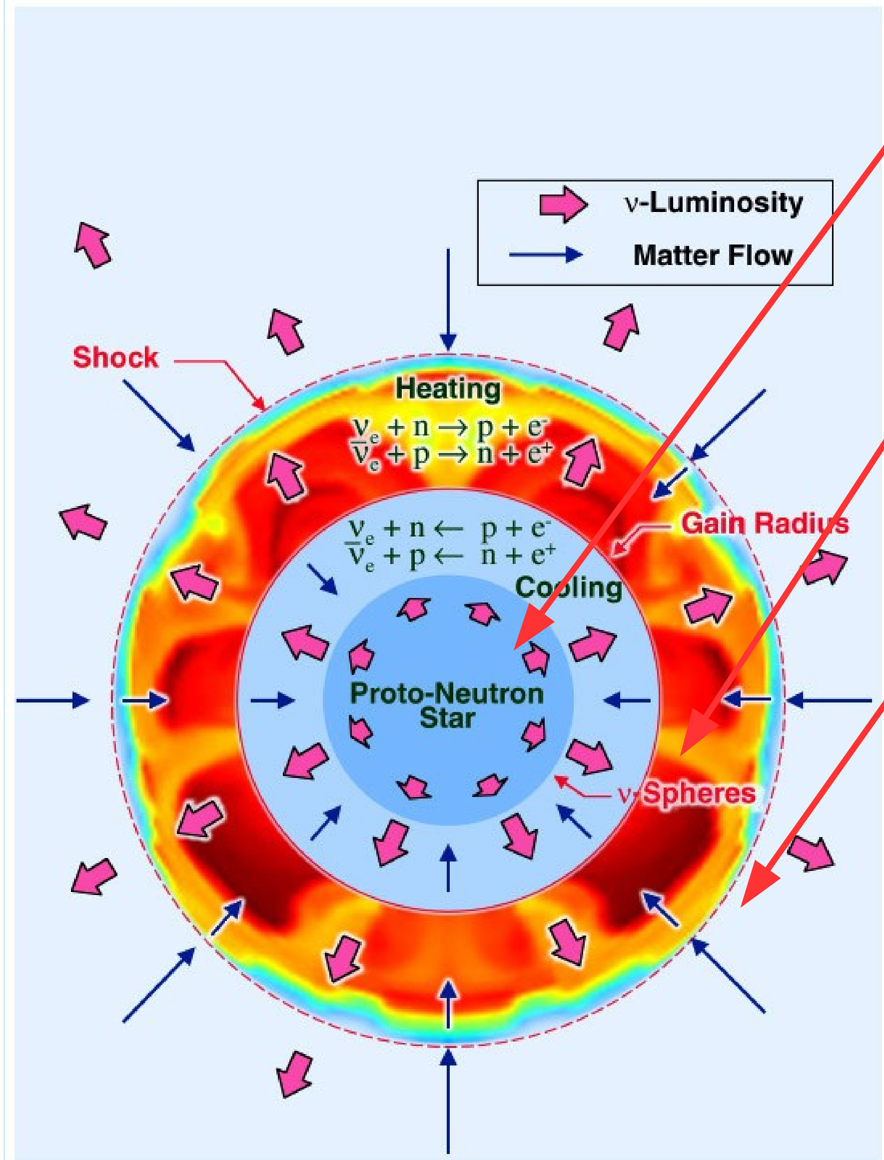


Figure credit : A. Mezzacappa

1. Trapped neutrinos diffuse out ($\tau_{\nu\text{-diff}} >> 1$) of the opaque PNS

2. Neutrinos heat matter in semi-transparant ($\tau_{\nu\text{-diff}} \sim 1$) post-shock region and drive convective flow in hot bubble region between gain radius and shock

3. Neutrinos stream freely ($\tau_{\nu\text{-diff}} << 1$) through transparent stellar envelope.

Additional key ingredients for explosion :

- Nuclear burning.
- Standing accretion shock instability (SASI) is an instability of the shock wave itself. SASI aids the explosion and determines the asphericity.

The iconic Burst GW source : CCSN

- Other mechanism :
  - Magneto-rotational (MHD) mechanism requires a rapid progenitor rotation.
  - Magneto-rotational mechanism can lead to explosion, if enough rotational energy, that develops jet.

- Which mechanisms are at play ?
  - Gravitational wave signatures are different for rotating core collapse and neutrino-driven supernova explosion.
  - Could also be a mixture of both mechanisms.

The iconic Burst GW source : CCSN

- And what about gravitational waves ?
- 50 - 70' : semi-analytical / quantitative gravitational radiation estimate for rotating core collapse and bounce, PNS oscillations, and non axisymetric deformations.
- 80' : the first simulations.

Gravitational Radiation from Collapsing Rotating Stellar Cores

E. Müller

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-8046 Garching bei München, Federal Republic of Germany

Received August 6, 1981; accepted February 2, 1982

Summary. The gravitational radiation produced by the axisymmetric, Newtonian collapse models of rotating stellar cores examined by Müller and Hillebrandt (1981) is considered within a post-Newtonian multipole formalism. Waveforms and energy losses of the two lowest order multipoles together with the energy spectrum of the quadrupole radiation are calculated. The results indicate that the gravitational wave signals from supernovae are weaker than earlier, less sophisticated collapse calculations sug-

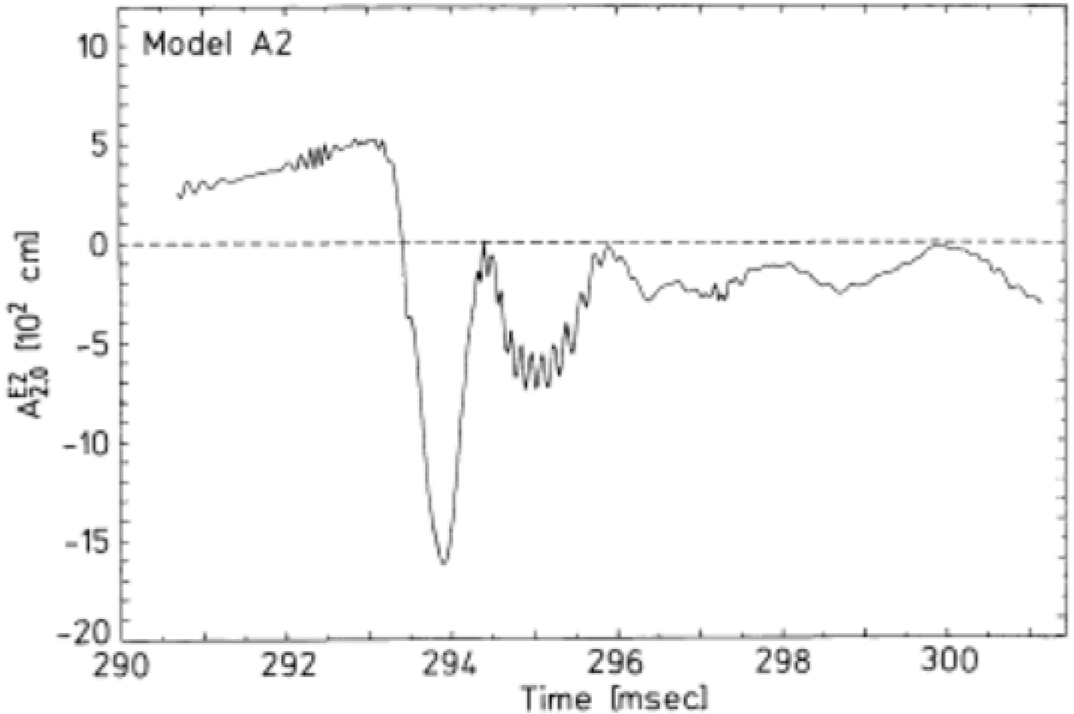
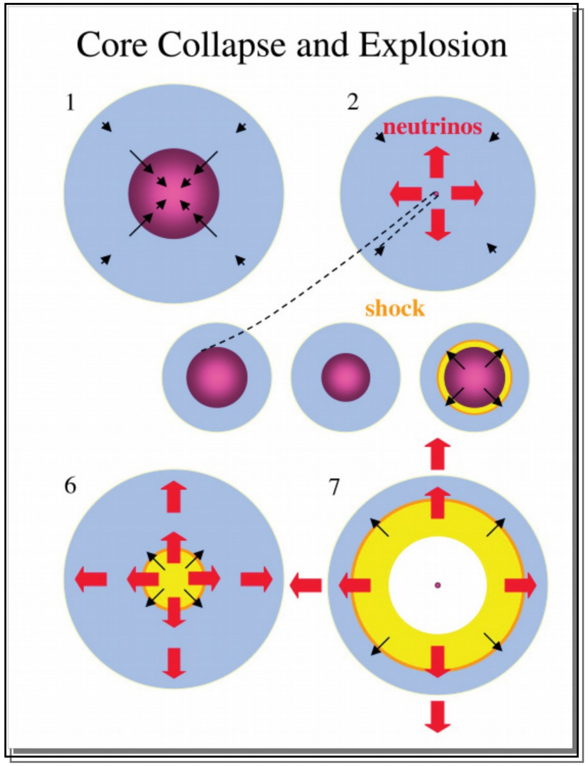


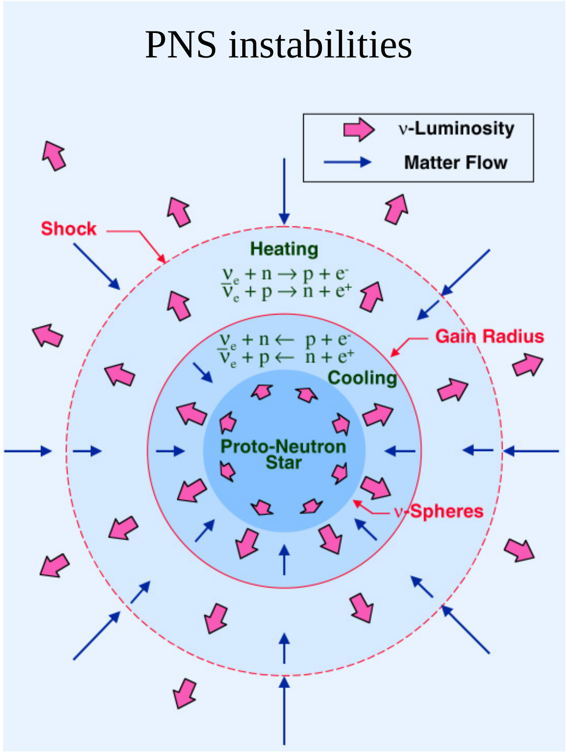
Fig. 1a. Quadrupole waveform for model A2

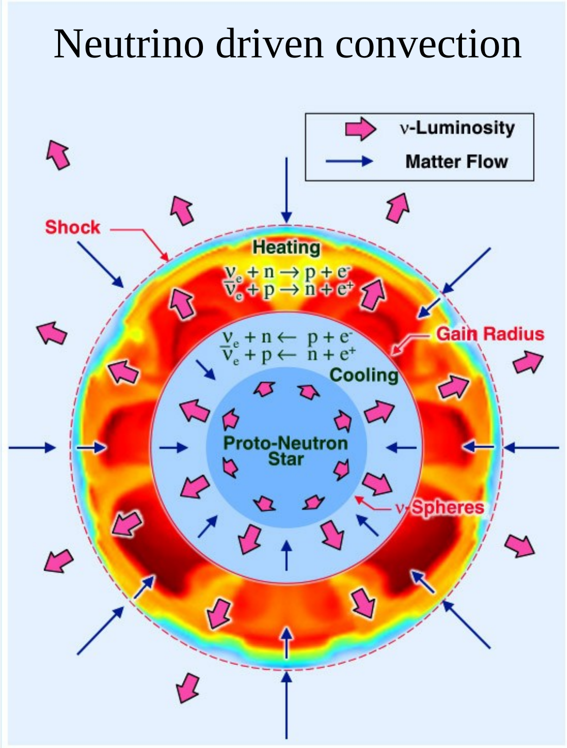
The iconic Burst GW source : CCSN

- GW emission mechanisms : rotating collapse and bounce, non axisymmetric rotational instabilities, postbounce convective overturn/standing accretion shock instability (SASI) and PNS pulsations.

- Neutrinos emission : A large correlation between neutrinos and GW time evolution signals is expected because of SASI (sloshing).







The iconic Burst GW source : CCSN

P. Cerda-Duran et al, Astrophys.J. 779 (2013) L18

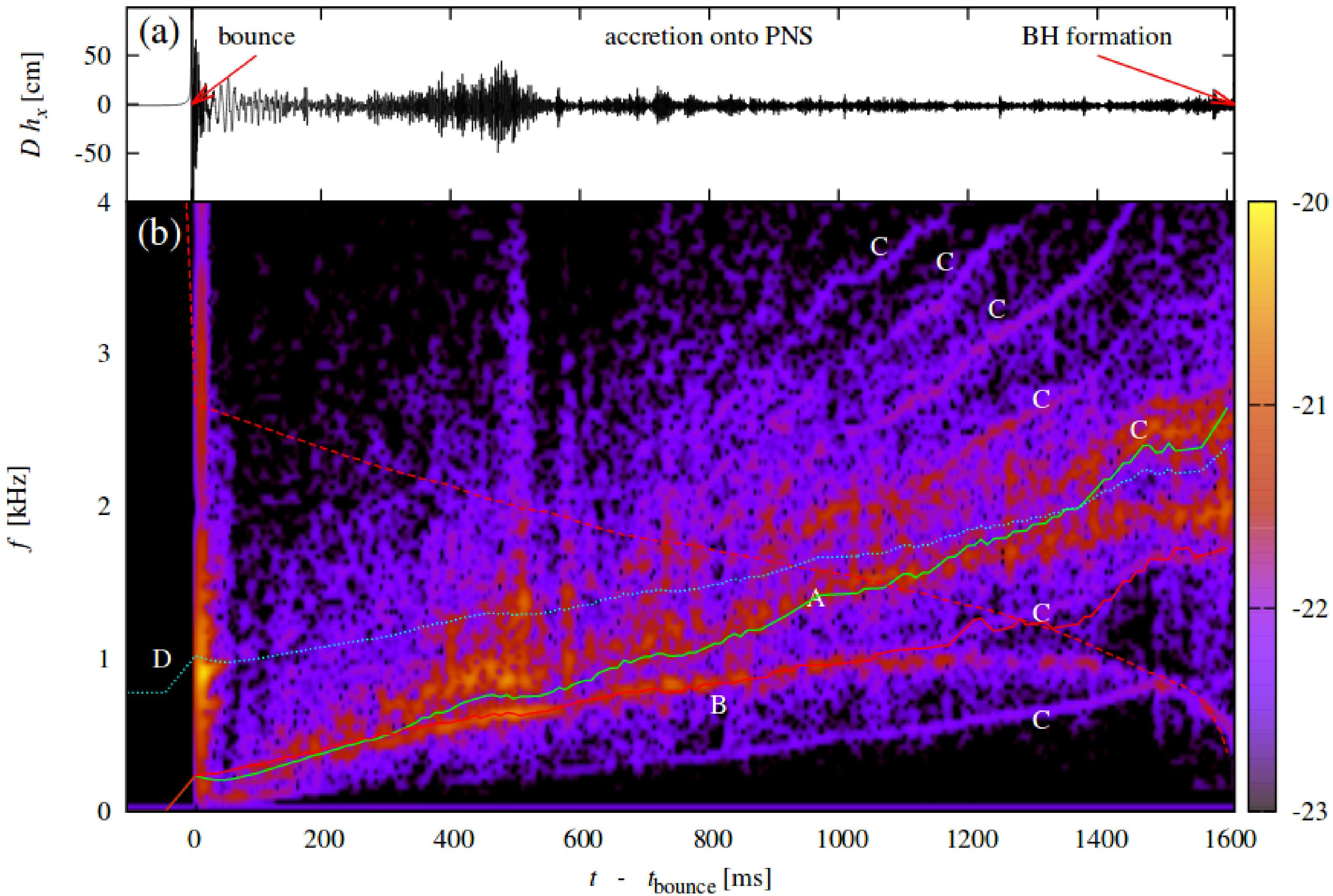
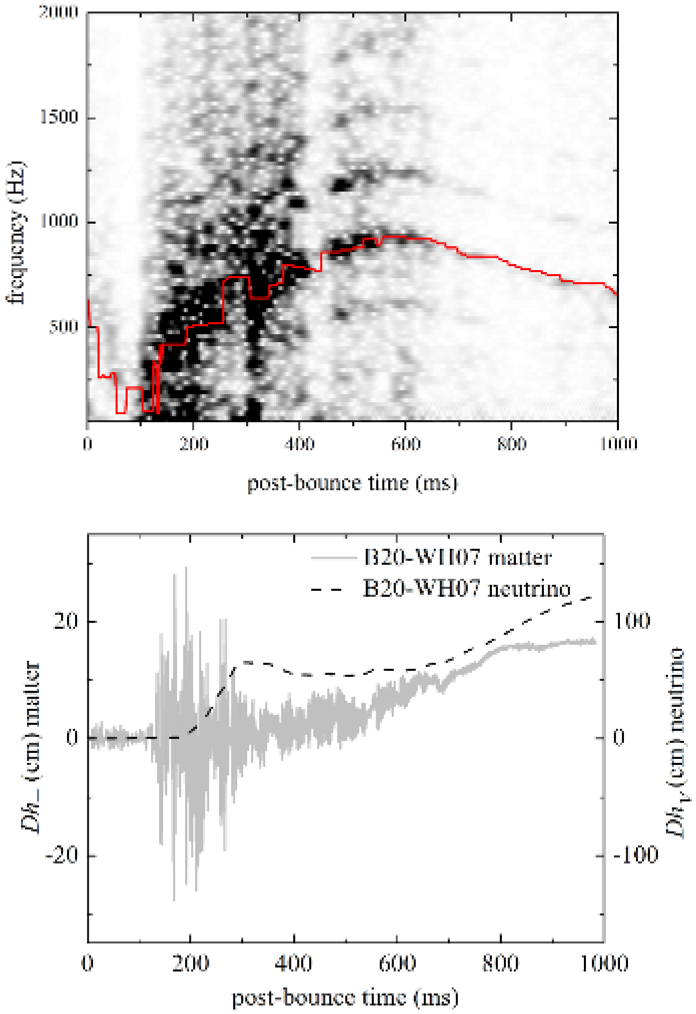


FIG. 3.— Waveform (a) and spectrogram (b) of the characteristic gravitational wave signal for the *fiducial model* at $D = 100$ kpc. We overplot estimates for the frequency evolution of g-modes at the surface of the PNS (solid-green line), g-modes in the cold inner core (solid-red line), quasi-radial mode (dashed-red line) and f-mode (dotted-blue line). Capital letters point to features described in the main text.

The iconic Burst GW source : CCSN

Yakunin et al, Phys.Rev. D92 (2015) no.8, 084040



Morozova et al, Astrophys.J. 861 (2018) no.1, 10

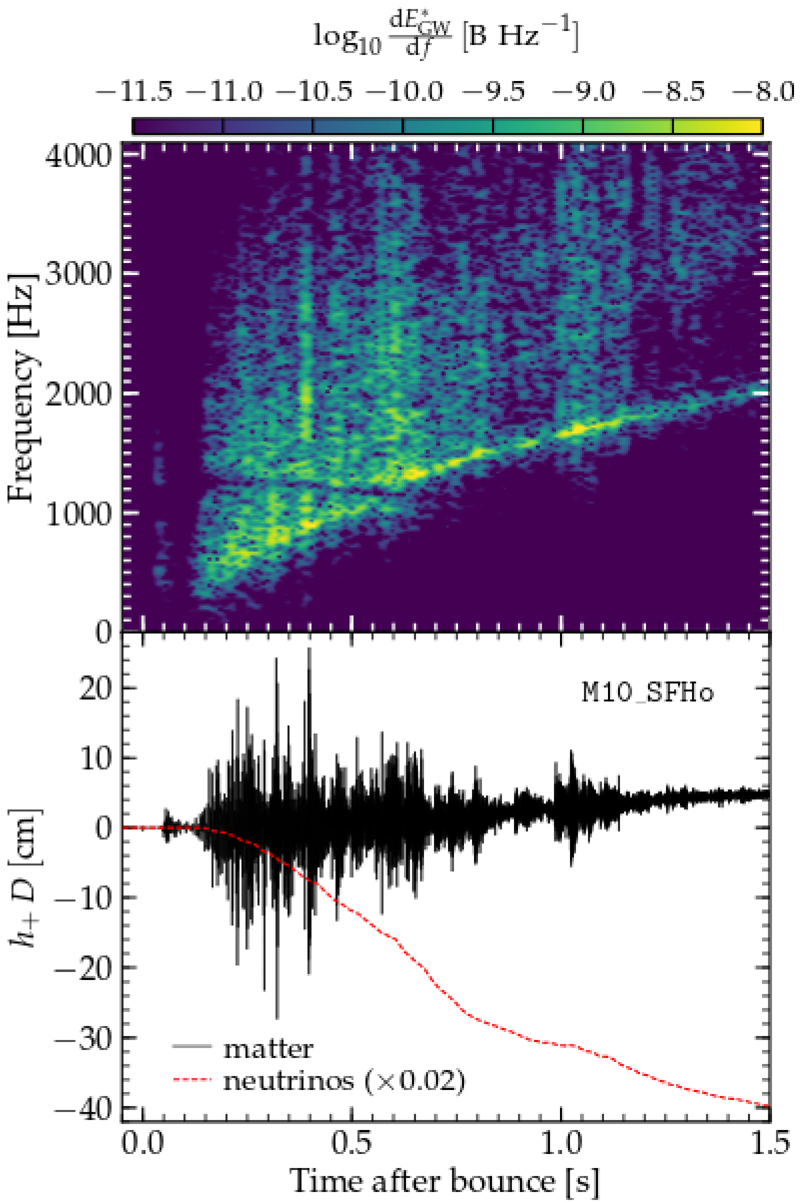
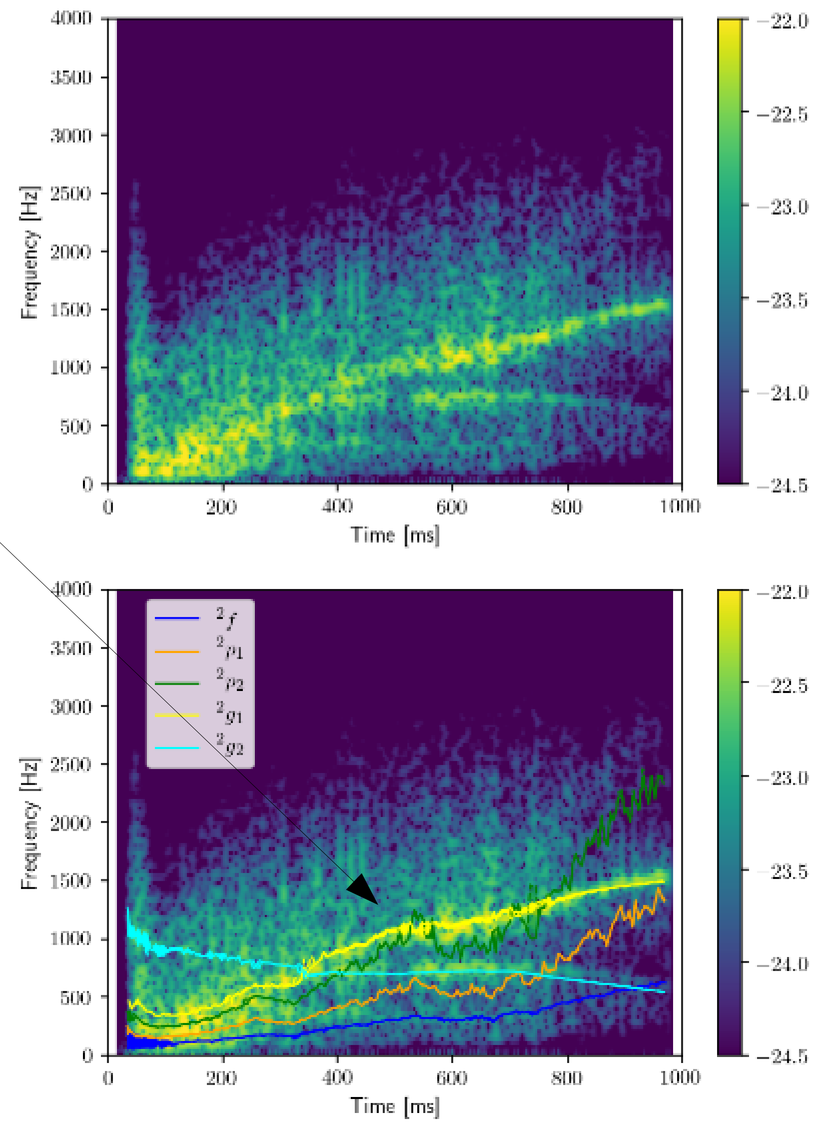


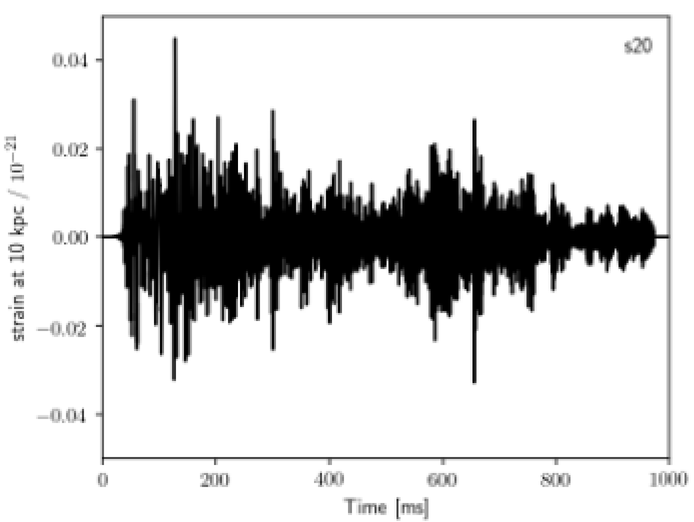
Figure 1. Spectrogram (top) and the corresponding waveform (bottom) of the GW signal from the model M10_SFHo.

The iconic Burst GW source : CCSN

Asteroseismology of core-collapse supernovae :

Eigen modes identification for a post bounce Oscillation of the PNS : f- g- p- modes

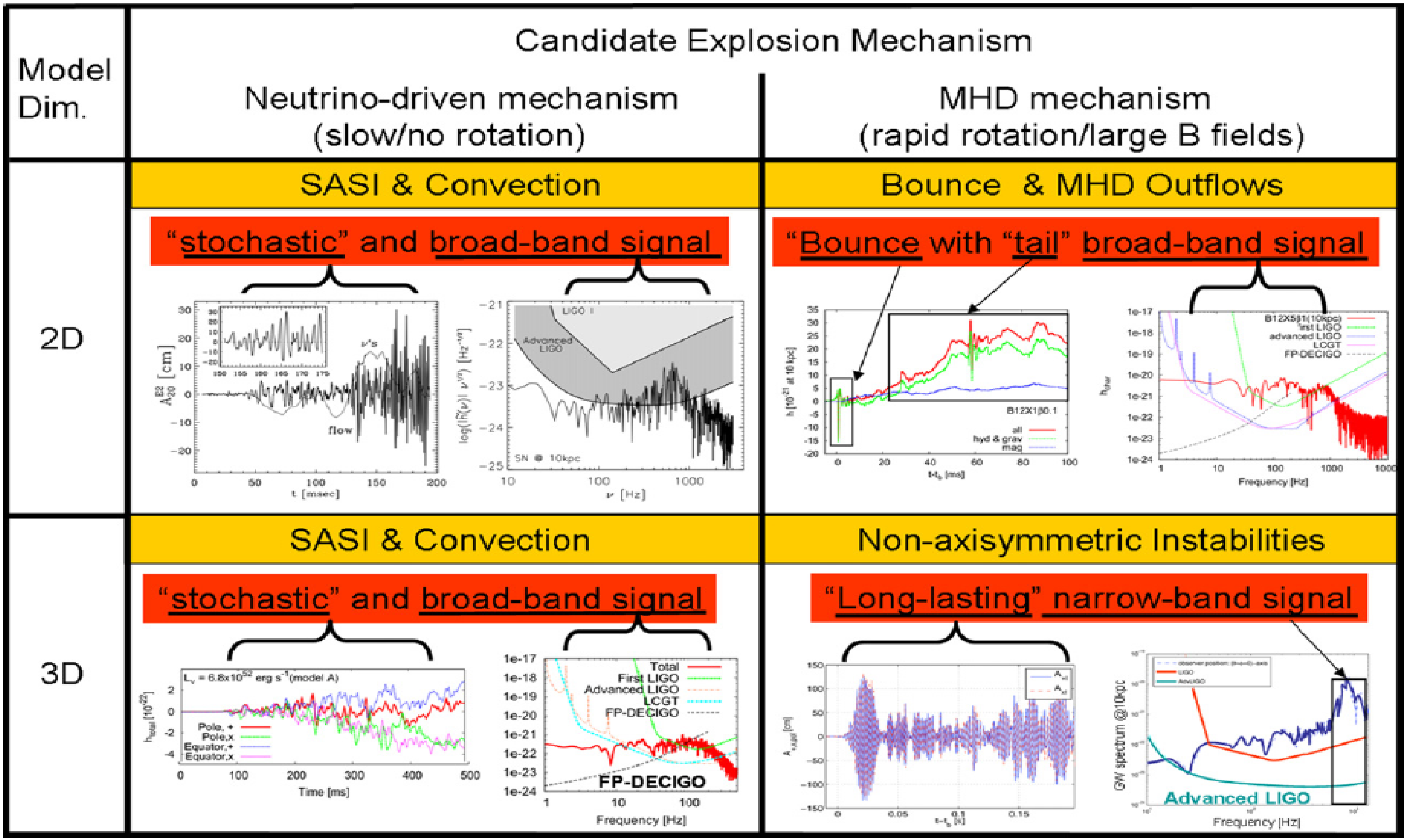




Torres-Forne et al, arXiv:1806.11366

The iconic Burst GW source : CCSN

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



What does it mean for DA ?

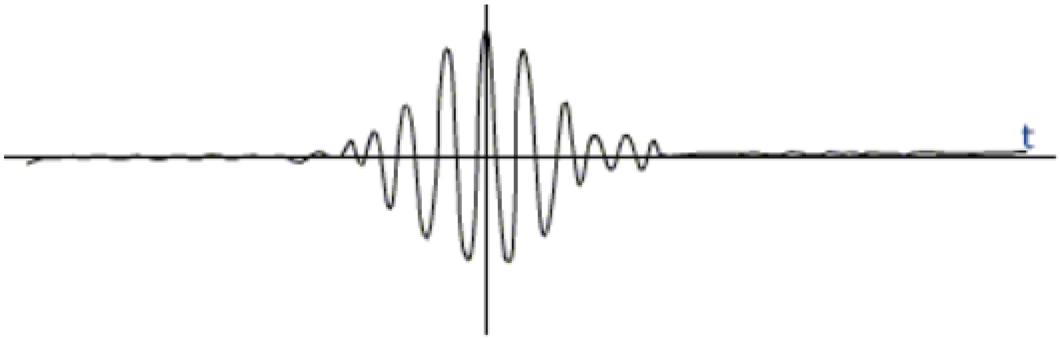
- Models :
  - CCSN GW emission/waveform simulations is still a very active domain.
  - There is still no complete code that includes all key ingredients : 3D, GR, realistic EOS, neutrino transport, nuclear physics, etc …
  - (Complete) numerical simulations require huge computing power.
  - The progenitors input data is still an uncertain domain.

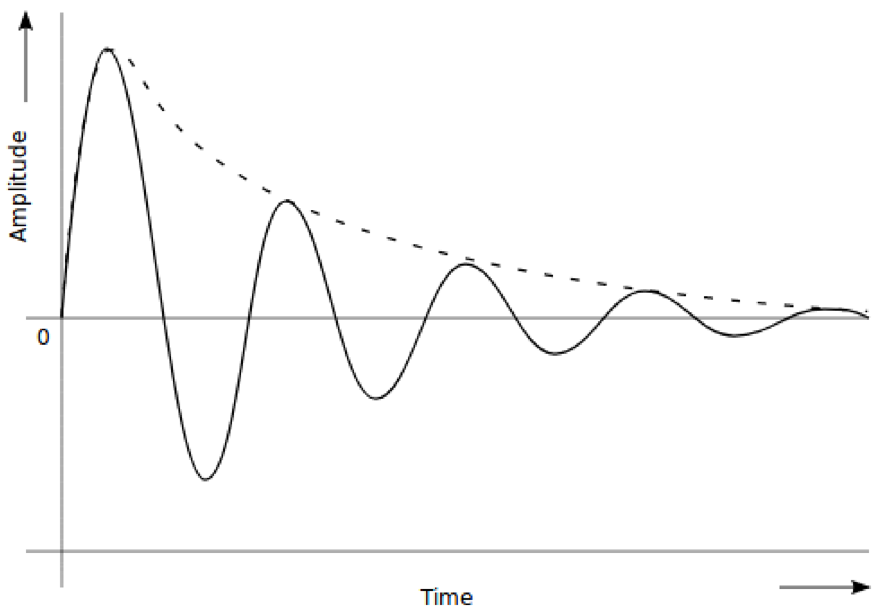
  ⇒ Use the models but dont trust them !

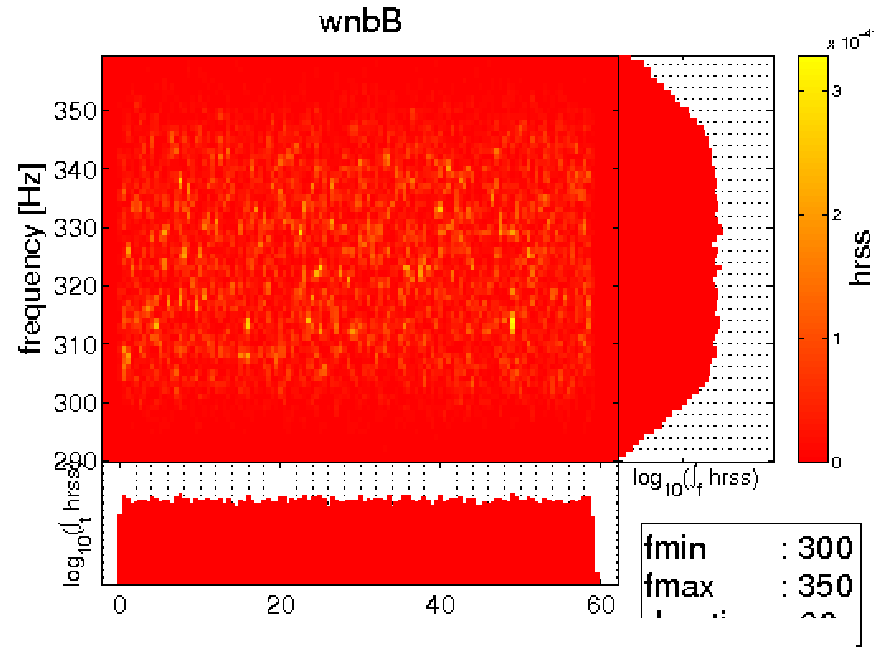
- GW search in GW detectors data :
  - Rather huge parameter space (low and high frequency components)
  - Seems that lots of gravitational radiation is due to matter convection/SASI → stochastic nature of the signal.

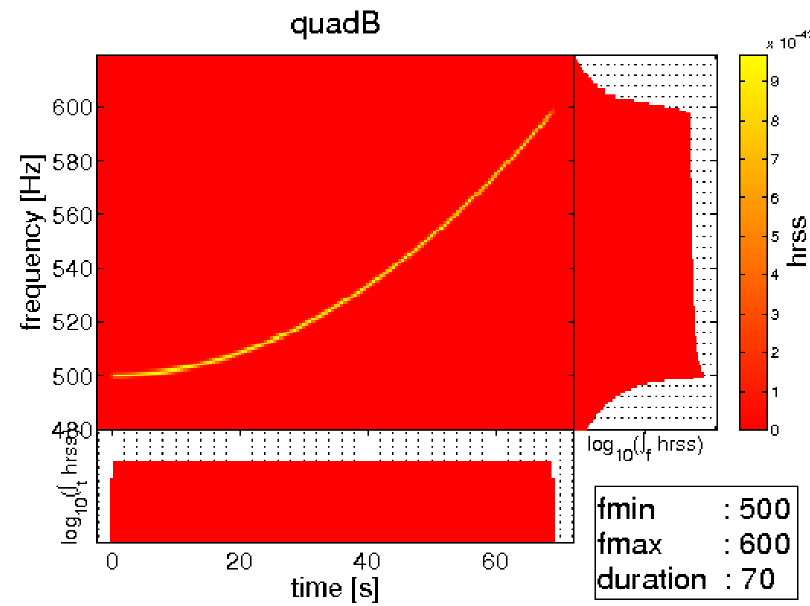
  ⇒ Use ad-hoc models

Ad-hoc models used in Burst searches

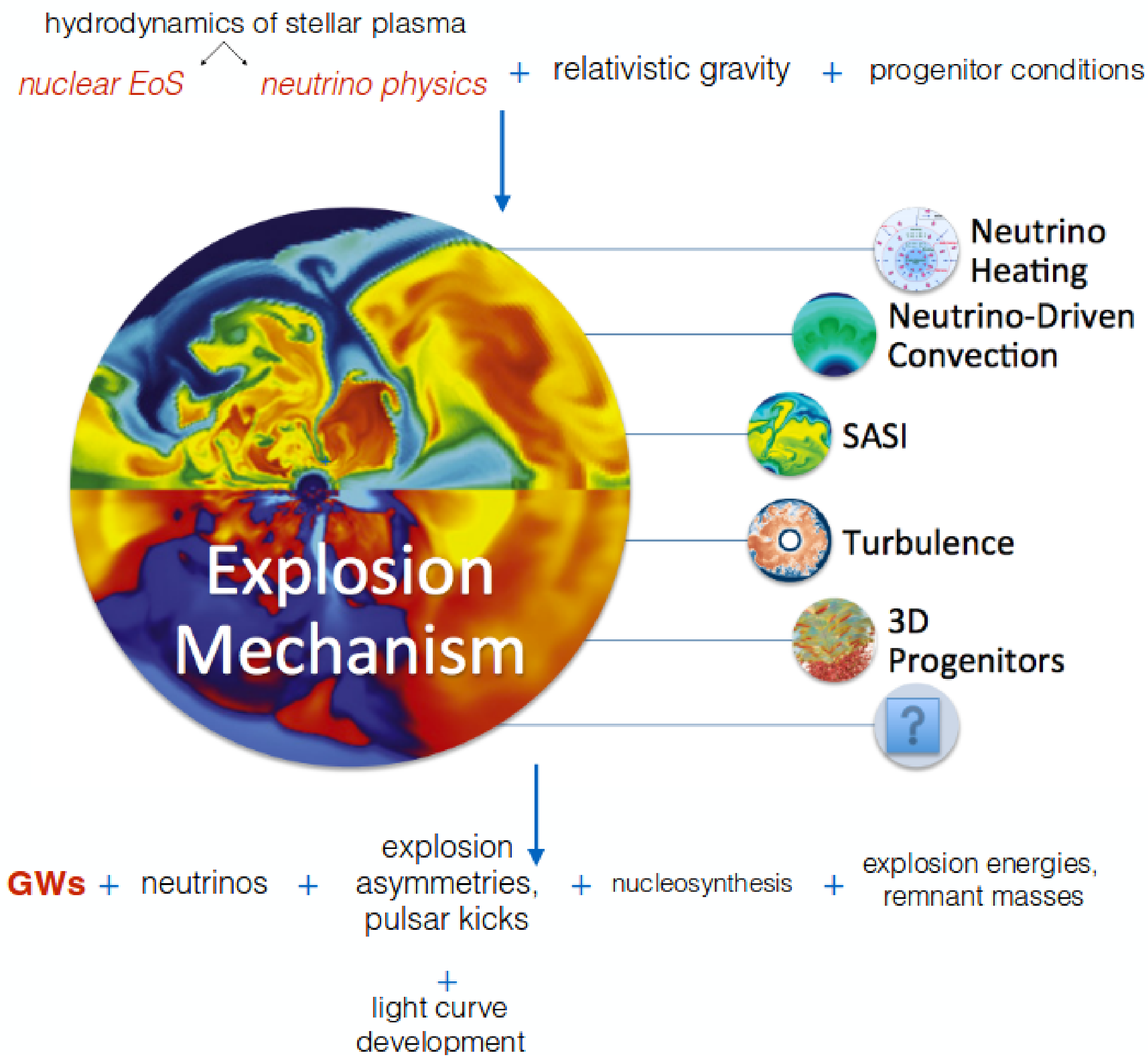








What could we learn from CCSN GWs ?



What can we learn from CCSN GW signatures?

Find explosion mechanism

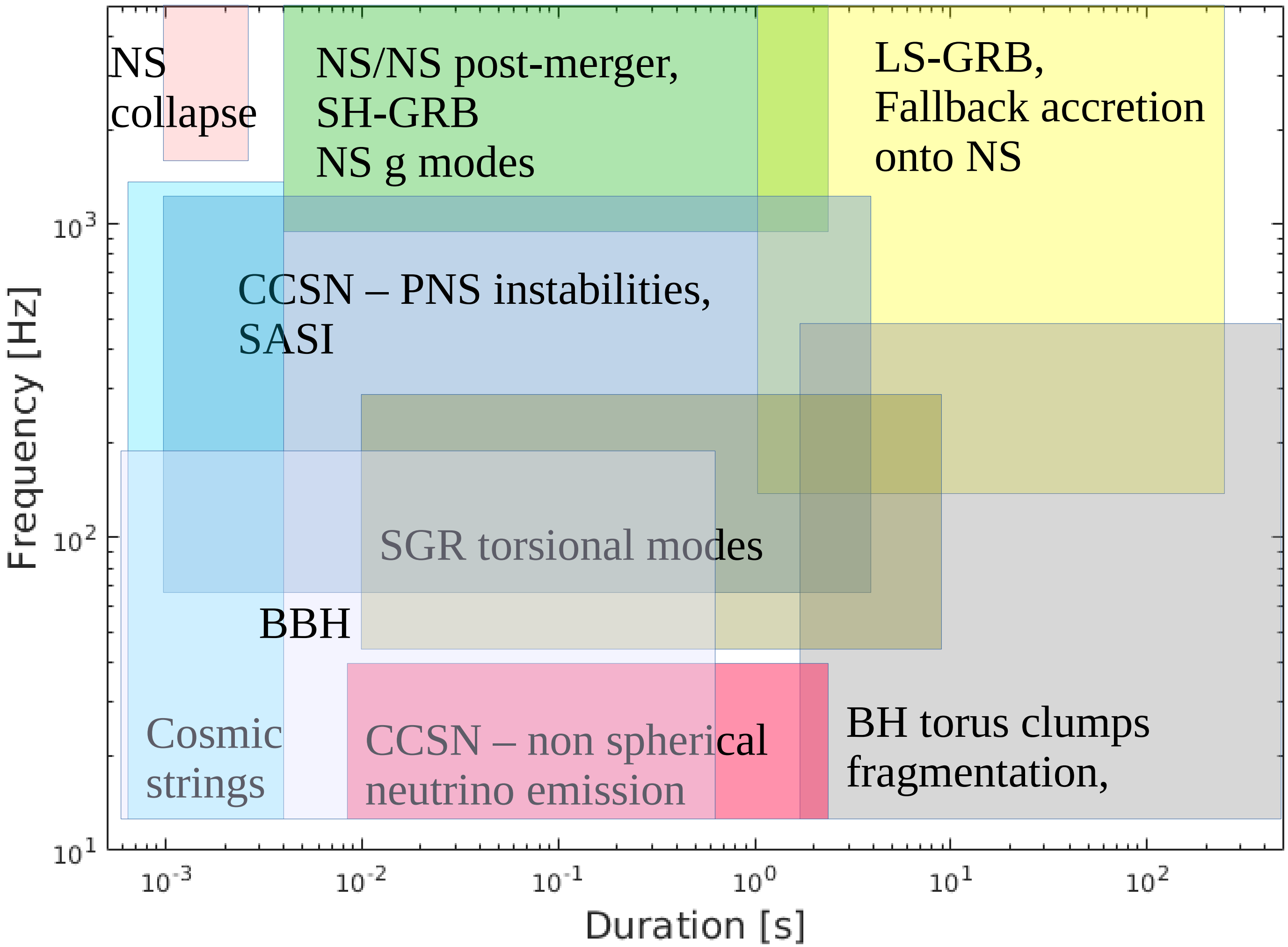
- Nuclear Equation of State,
- evolution of ProtoNeutron Star,
- asymmetry of explosion
- Set *upper limits on energy emitted by supernova*
- Measure angular momentum and rotational rate of ProtoNeutron Star
- Spot formation of Black Hole at its birth

Credit : T. Mezzacappa

The unknowns in CCSN

- Neutrino-driven explosion mechanism.
- Impact of the progenitors' parameters (mass, spin, composition, …).
- Role of magnetic fields.
- Role of hydrodynamics.
- ...

Burst search parameter space



Notations and conventions

- Assumptions :
  - Signal and noise adds linearly.

$$x(t) = n(t) + h(t)$$
$$h(t) = F_+ \times h_+(t) + F_\times \times h_\times(t)$$

« t » is the time in each detector that needs to be shifted of $\frac{\hat{\Omega}_0.\vec{d}}{c}$ to take into account the source sky position.

  - Noise and signals are uncorrelated.

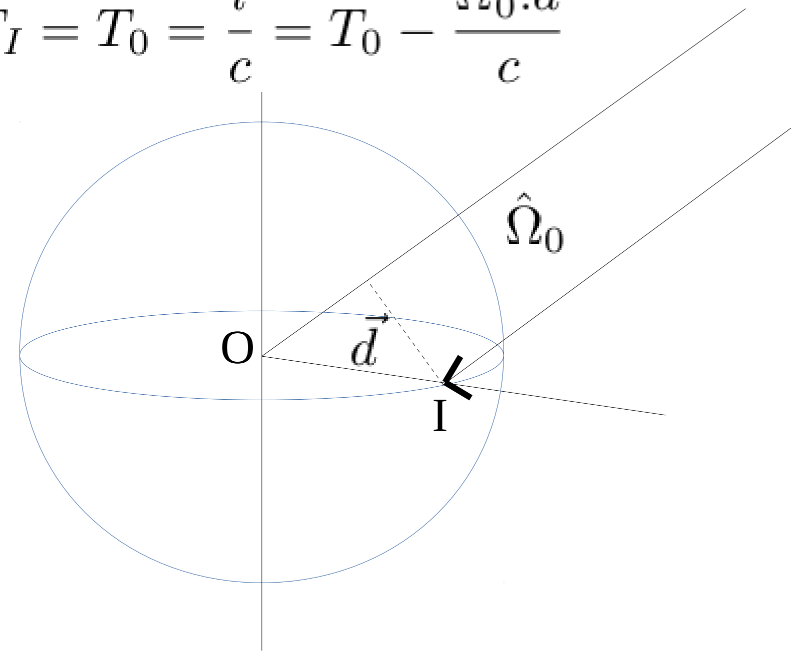
Correlation of 2 functions :

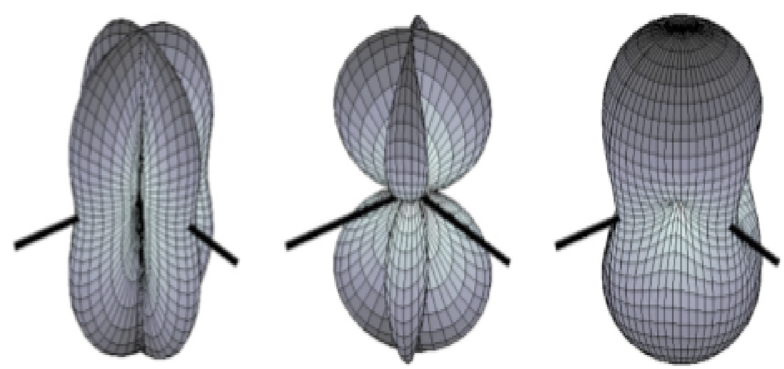
$$x \otimes k(t) = \int_{-\infty}^{+\infty} x(\tau)k(t+\tau)d\tau$$

$$< n \otimes h >= 0$$

<...> means the average over several noise realizations.

$$T_I = T_0 = \frac{l}{c} = T_0 - \frac{\hat{\Omega}_0.\vec{d}}{c}$$





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

Excess power

- Let's consider an « energy positive » signal, uncorrelated with the noise $< n \otimes h >= 0$
  <...> means the average over several noise realizations. To compute the « energy » of the data we compute its auto-correlation :

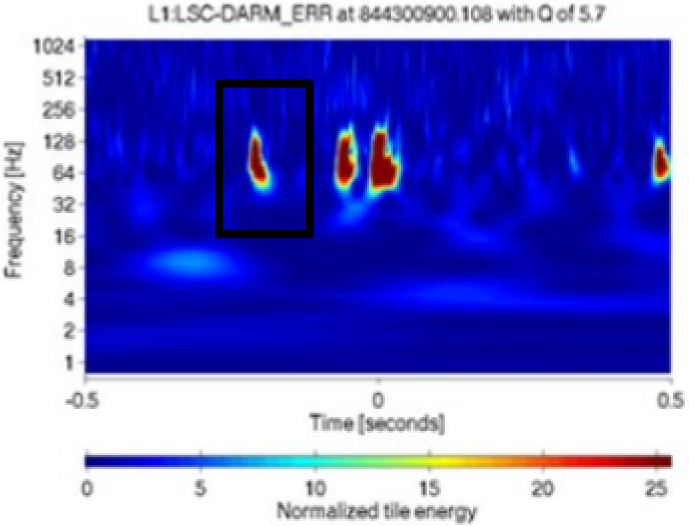
$$< x \otimes x >=< n \otimes n > + \underbrace{< h \otimes h >}_{>0} + 2 \underbrace{< n \otimes h >}_{=0}$$

$< n \otimes h >= 0$

In presence of a GW signal, $< x \otimes x >$ is showing an « excess of energy ».

Pb : so do noise non stationarity features (glitches) !

A solution : multi-detector searches …



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:

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

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

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

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

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

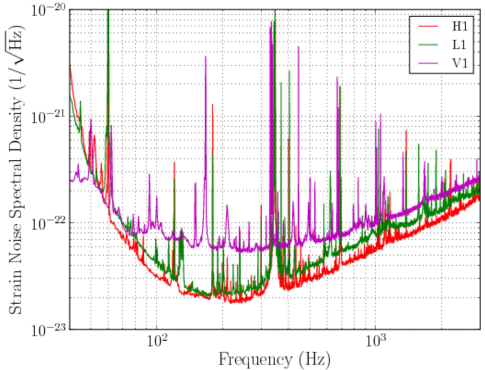
$$S \approx \lim_{T\to\infty} \frac{1}{T}|\tilde{x}_T(f)|^2$$

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

Whitened data : $$w[i] = \frac{\tilde{x}[i]}{\sqrt{S}}$$

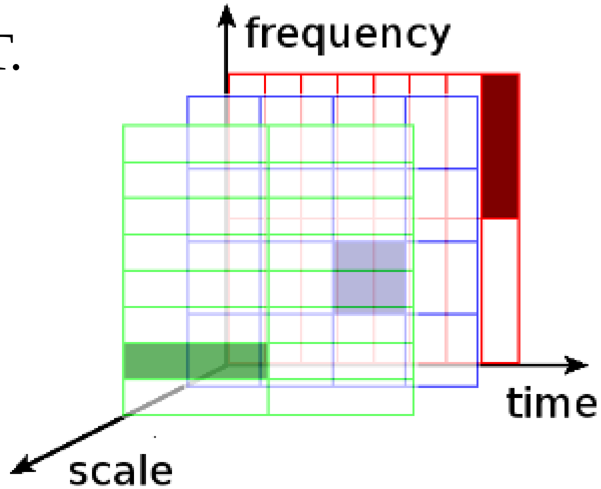


Time-frequency transforms

- Idea : the signal power is well localized in a compact frequency-time box. A GW signal will generate an excess of power regardless of the waveform

- Time-frequency transforms : spectrogram, Gabor, WignerVille, wavelet, …

  The wavelet transform is a kind of generalization of the FT.

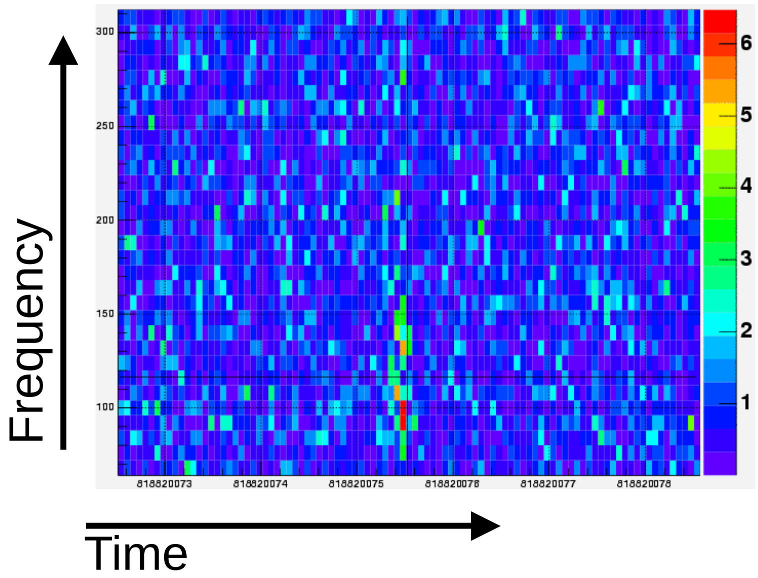


$$F(a,b) = \int_{-\infty}^{\infty} f(x)\, \psi^*_{(a,b)}(x)\, \mathrm{d}x$$

  Exemple with a « scaling » function :

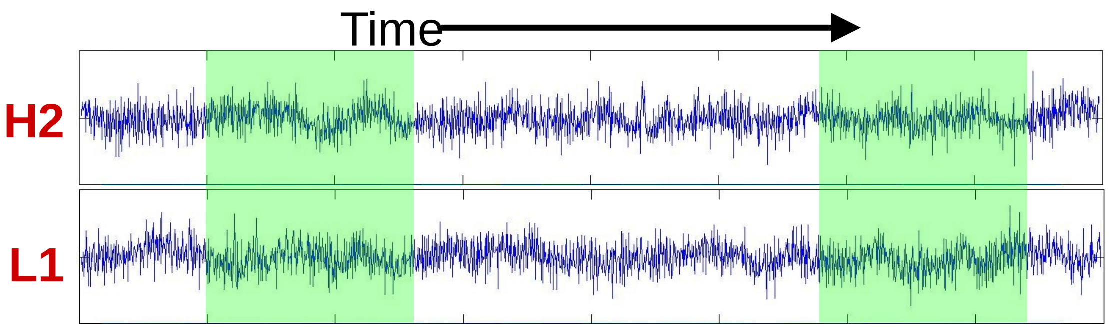
$$\left[W_\psi f\right](a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} \overline{\psi\left(\frac{x-b}{a}\right)} f(x) dx$$

- Look for « hot » pixels.



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 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

Multi-detector coherent searches

- Let's assume we know the source sky position Ω
- For each data sample, assuming we know the detectors' PSD, one has

$$\begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+/\sigma_1 \\ \vdots \\ F_N^+/\sigma_N \end{bmatrix} h^+ + \begin{bmatrix} F_1^\times/\sigma_1 \\ \vdots \\ F_N^\times/\sigma_N \end{bmatrix} h^\times + \begin{bmatrix} n_1 \\ \vdots \\ n_N \end{bmatrix}$$

$$\begin{aligned} \mathbf{x} &= \mathbf{F}^+ h^+ + \mathbf{F}^\times h^\times + \mathbf{n} \\ &= \xi + \mathbf{n} \end{aligned}$$

Data here are now whitened !

where σ_i are the detectors' noise standard deviations.

- Treat h_+ and h_x as free parameters to be fit to the data.
  - A solution for 3 detectors is derived in Gursel & Tinto paper (1989).
  - Other solution is to maximise a likelihood function (Flannagan & Hughes 1998).

Multi-detector coherent searches

- We want to define a rule that allows to distinguish between the 2 following hypotheses :
  - Ho (null hypothesis) : data contains only noise.
  - H1 (alternative hypothesis) : data contains noise and signal.
- Under each hypothesis, the data x is a realization of a stochastic process described by a probability $p(x|H_0)$ or $p(x|H_1)$.
- One way to distinguish both hypotheses is to define the likelihood ratio :

$$\Lambda(\mathbf{x}) = \frac{p(\mathbf{x}|H_1)}{p(\mathbf{x}|H_0)}$$

For a Gaussian noise model,

$$p(\mathbf{x}|H_0) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i}} \exp\left(-\frac{x_i^2}{2\sigma_i^2}\right)$$

$$p(\mathbf{x}|H_1) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i}} \exp\left(-\frac{(x_i - \xi_i)^2}{2\sigma_i^2}\right)$$

$$\xi_i = F_i^+ h^+ + F_i^\times h^\times$$

Coherent searches

- Advantages :
  - The global sensitivity is not limited by the least sensitive pipeline.
  - Null stream and network correlation coefficient can be constructed to distinguish genuine GW signals from the environmental and instrumental artifacts.
  - Source coordinates can be reconstructed.
- Pipeline exemple : coherent Wave Burst (cWB)
  - Initially developed to detect short unmodelled transient.
  - Has discovered first GW150914 (very efficient for high mass BBH mergers).
  - Has become a multi-source search pipeline.

Multi-detector coherent searches

- Let's take the logarithm of the likelihood ratio

$$\mathcal{L} = -ln\Lambda(x) = \sum_{i=1}^{N} \frac{(x_i - \xi_i)^2}{2\sigma_i^2} - \frac{x_i^2}{2\sigma_i^2}$$
$$= \sum_{i=1}^{N} \frac{\xi_i^2}{2\sigma_i^2} - \frac{x_i \xi_i}{\sigma_i^2}$$

- Note, that we can re-write the log likelihood in a more compact way :

$$2\mathcal{L} = \mathbf{x}\xi^T + \xi\mathbf{x}^T - \xi\xi^T$$

Matched filter of x with « template » ξ=Fh

- By minimizing L one can approximate a solution for $h_{+,x}$:

$$\left.\frac{\partial \mathcal{L}}{\partial h}\right|_{h=\hat{h}} = 0 \qquad \boxed{\hat{\mathbf{h}}_{+,\times} = (\mathbf{F}_{+,\times}\mathbf{F}^{\mathbf{T}}_{+,\times})^{-1}\mathbf{F}^{\mathbf{T}}_{+,\times}\mathbf{x}}$$

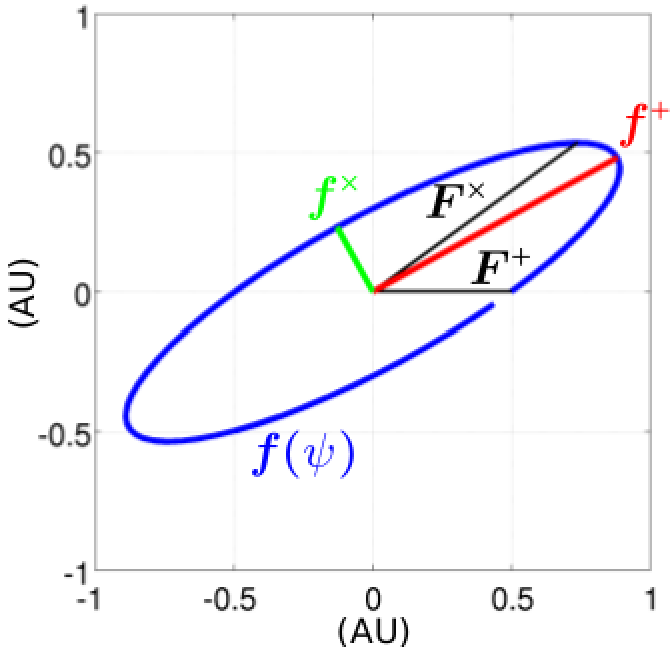
- In practise that does not converge well because $(\mathbf{F}_{+,\times}\mathbf{F}^{\mathbf{T}}_{+,\times})$ tends to be singular.

Multi-detector coherent searches

- <u>Dominant polarization frame formalism:</u>

$$\mathbf{x} = \mathbf{F}^{+}h^{+} + \mathbf{F}^{\times}h^{\times} + \mathbf{n}$$
$$= \xi + \mathbf{n}$$

- The 2 N-dim vectors $\mathbf{F}_{+}$, $\mathbf{F}_{x}$ define a plane (aka « detector plane »).
- We will orthonormalize them using the property that the detectors' response is invariant under a rotation along the z axis (in the source wave frame). It actually corresponds to fixing the polarization reference $\Psi=\Psi_{DP}$.
- Network response function : $\mathbf{f}(\psi) = \mathbf{F}^{+}h^{+} + \mathbf{F}^{\times}h^{\times}$
- Let's maximize f(Ψ) for all linearly polarized signals : $(h^{+}, h^{\times}) \propto (cos2\psi, sin2\psi)$



Multi-detector coherent searches

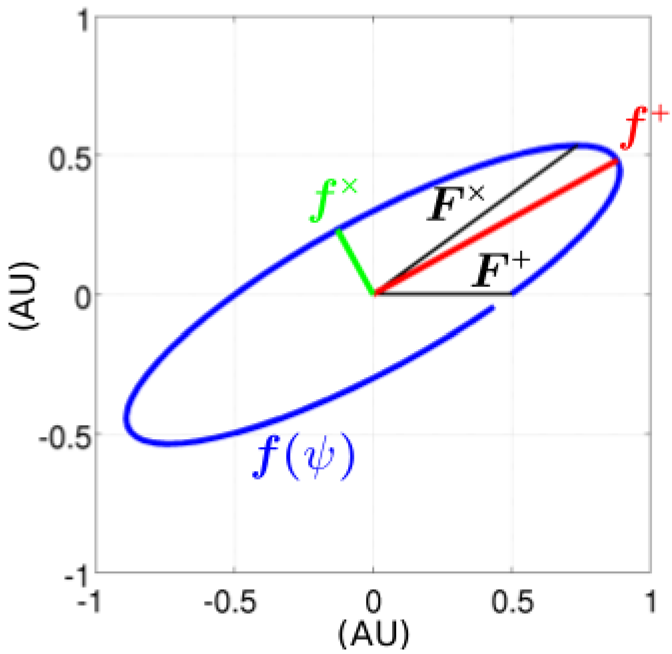
$$
\begin{aligned}
M = |\mathbf{f}(\psi)|^2 &= |\mathbf{F}^+ cos2\psi + \mathbf{F}^\times sin2\psi|^2 \\
&= |\mathbf{F}^+|^2 cos^2 2\psi + |\mathbf{F}^\times|^2 sin^2 2\psi + 2\mathbf{F}^+.\mathbf{F}^\times sin2\psi cos2\psi \\
&= |\mathbf{F}^+|^2 \frac{1 + cos4\psi}{2} + |\mathbf{F}^\times|^2 \frac{1 - cos4\psi}{2} + \mathbf{F}^+.\mathbf{F}^\times sin4\psi
\end{aligned}
$$

$$
0 = \frac{\partial M}{\partial \psi} = -2(|\mathbf{F}^+|^2 - |\mathbf{F}^\times|^2) sin4\psi + 4\mathbf{F}^+\mathbf{F}^\times cos4\psi
$$

$$
\psi_{DP} = \frac{1}{4} arctan(\frac{2\mathbf{F}^\times.\mathbf{F}^+}{|\mathbf{F}^+|^2 - |\mathbf{F}^\times|^2})
$$

$$
\boxed{
\begin{aligned}
\mathbf{f}^+ &= \mathbf{F}^+ cos2\psi_{DP} + \mathbf{F}^\times sin2\psi_{DP} \\
\mathbf{f}^\times &= -\mathbf{F}^+ sin2\psi_{DP} + \mathbf{F}^\times cos2\psi_{DP}
\end{aligned}
}
$$

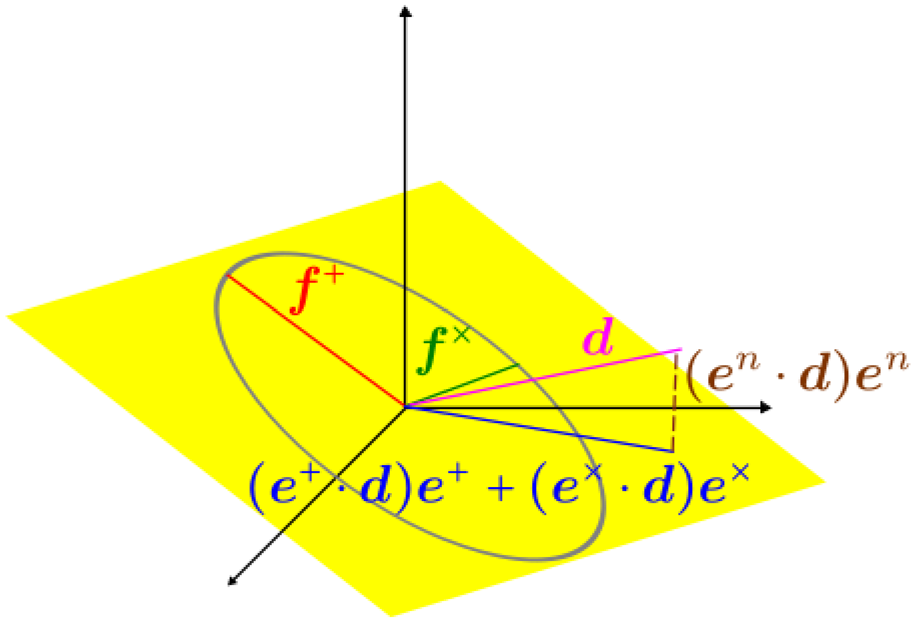
$$
\begin{aligned}
\mathbf{e}^+ &= \mathbf{f}^+/|\mathbf{f}^+| \\
\mathbf{e}^\times &= \mathbf{f}^\times/|\mathbf{f}^\times|
\end{aligned}
$$



Multi-detector coherent searches

- <u>Null stream construction :</u>
- Goal : reject suprious events
- Principle : Signal is correlated across the network in a particular way dictated by the $\mathbf{f}_+$ and $\mathbf{f}_x$ vectors. Noise is uncorrelated.
- Data vectors that contain signal should only deviate from the ($\mathbf{f}_+$, $\mathbf{f}_x$) plane by a little.

  ⇒ data vectors whose projection onto the orthogonal direction (*null space*) is large are likely to be glitches.
- Null space : $\boldsymbol{e}^n = \boldsymbol{e}^+ \wedge \boldsymbol{e}^\times$
- Null energy : $E_n = |\boldsymbol{e}^n \cdot \boldsymbol{d}|^2$
- For Gaussian noise, E_n is χ2 distributed



Multi-detector coherent searches

- Likelihood ratio in the DPF becomes :

$$\begin{aligned}\mathcal{L} &= \sum_{i=1}^{N} \frac{\xi_i^2}{2\sigma_i^2} - \frac{x_i \xi_i}{\sigma_i^2} \\ &= \frac{1}{2}(\mathbf{f}^+ h^+ + \mathbf{f}^\times h^\times)^2 - \mathbf{x}.(\mathbf{f}^+ h^+ + \mathbf{f}^\times h^\times) \\ &= \frac{1}{2}|\mathbf{f}^+|^2 {h^+}^2 - \mathbf{x}.\mathbf{f}^+ h^+ + \mathcal{L}_\times\end{aligned}$$

- Estimators of signal polarization are thus solution of :

$$\begin{aligned}\mathbf{x}.\mathbf{f}^+ &= \frac{1}{2}|\mathbf{f}^+|^{\mathbf{2}}\mathbf{h}^+ \\ \mathbf{x}.\mathbf{f}^\times &= \frac{1}{2}|\mathbf{f}^\times|^{\mathbf{2}}\mathbf{h}^\times\end{aligned}$$

- 2 aligned detectors : twice the same equation

  → the network is sensitive to only 1 polarization.

  → the other polarization just adds noise.

Multi-detector coherent searches

- Likelihood regulators :
  - Instead of solving each polarization, solve the detector response ξ_i. But this is actually equivalent to have h_x=0.
  - CWB regulator : add a dummy detector

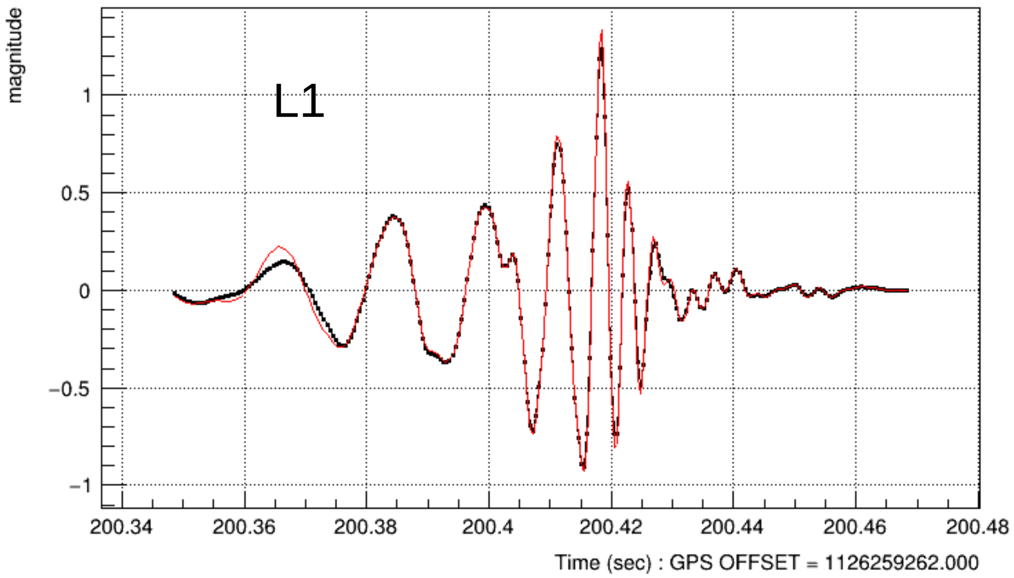
$$|\mathbf{f}'_\times|^2 = |\mathbf{f}_\times|^2 + \delta$$

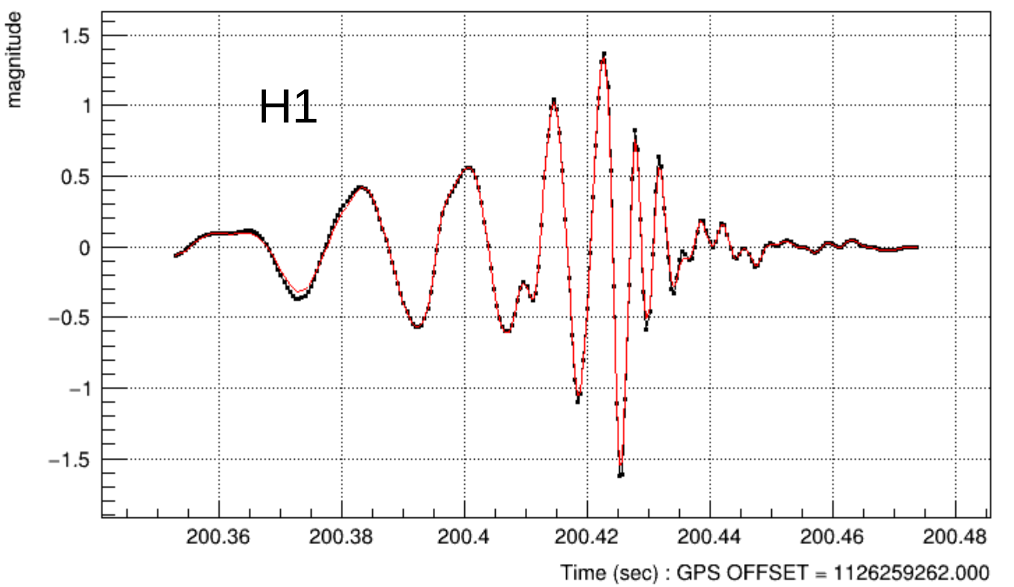
$$\begin{aligned} f^+_{N+1} &= 0 \\ f^\times_{N+1} &= \sqrt{\delta} \\ x_{N+1} &= 0 \\ \mathbf{f}^+ . \mathbf{f}^\times &= 0 \end{aligned}$$

  - Depending on δ different statistic can be defined
    - δ=0 : standard likelihood.
    - δ=∞ : hard constraint likelihood.

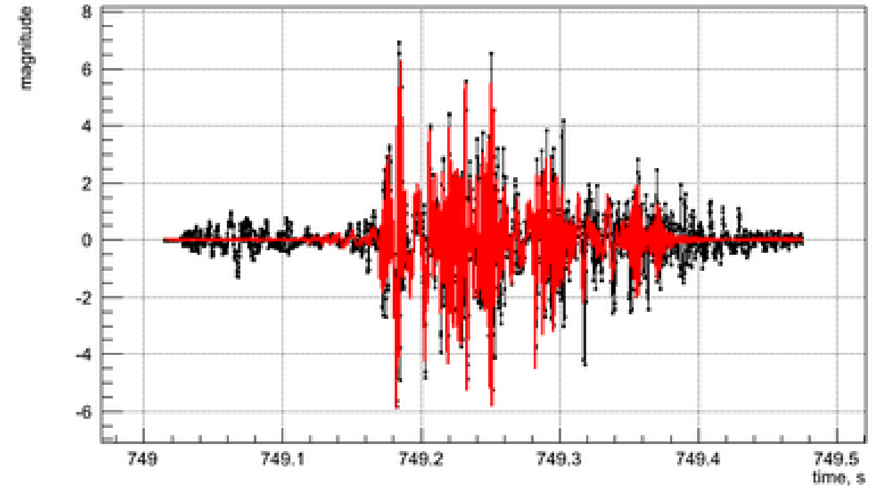
Example of waveform reconstruction with cWB

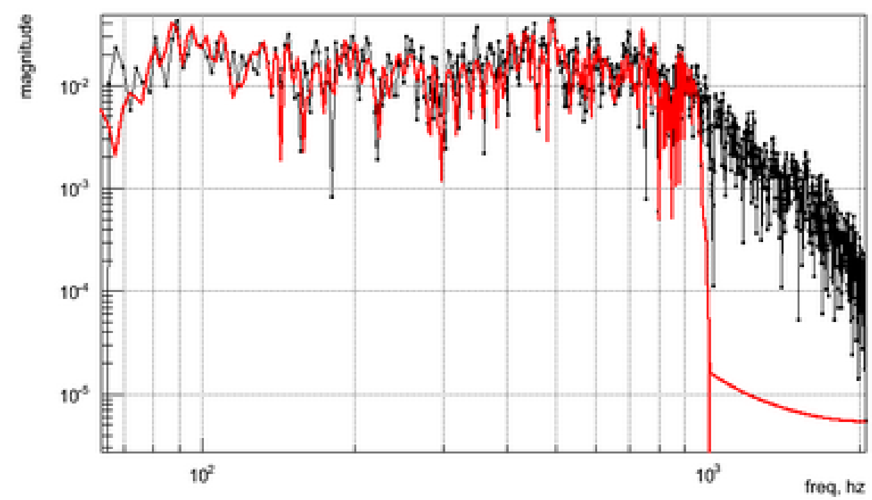
BBH event like G150914 (simulation)





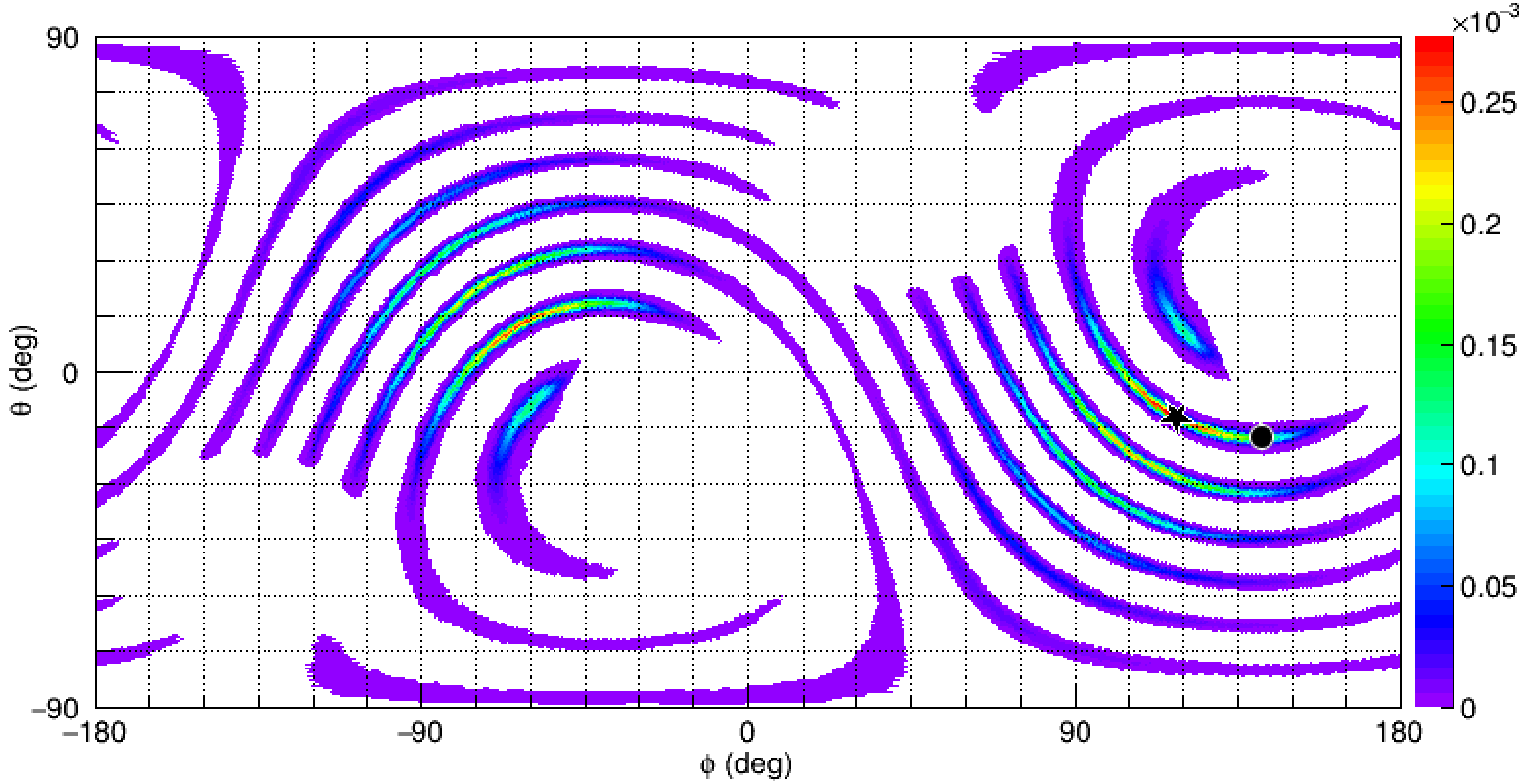
More complex waveform : CCSN
Yakunin et al (neutrino driven SASI
mechnism simulation)





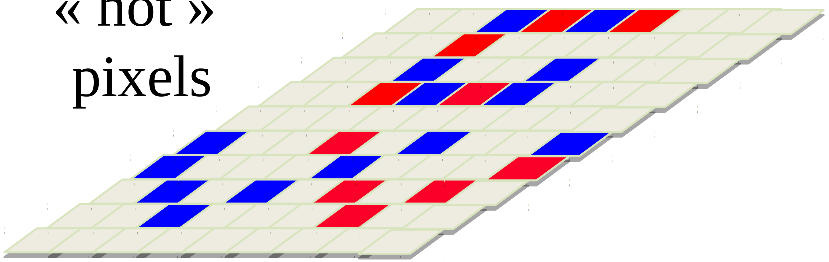
Sky localization

- Likelihood function depends on Ω through the antenna functions and through the arrival time delay between detectors.
- Brute force method : repeat the procedure over a grid of Ω covering the entire sky. Provides « likelihood » map



cWB time-frequency transform

« hot »
pixels



- x(t) → w(t,f)
- Wilson-Daubechies-Meyer transform : modification of the Meyer wavelet Φ

$$\tilde{x}(\omega, t) = \int \mathrm{e}^{-\mathrm{i}\omega\tau} \phi(\tau - t) x(\tau) \mathrm{d}\tau$$

$$g_{n0}(t) = \phi(t - nT)$$

$$g_{nm}(t) = \sqrt{2}\ (-1)^{mn} cos(2\pi mt/T)\phi(t - nT/2)\ ,\ \ m + n = 2k\ \ ,\ m > 0$$

$$g_{nm}(t) = \sqrt{2}\ sin(2\pi mt/T)\phi(t - nT/2)\ ,\ \ m + n = 2k + 1\ \ ,\ m > 0$$

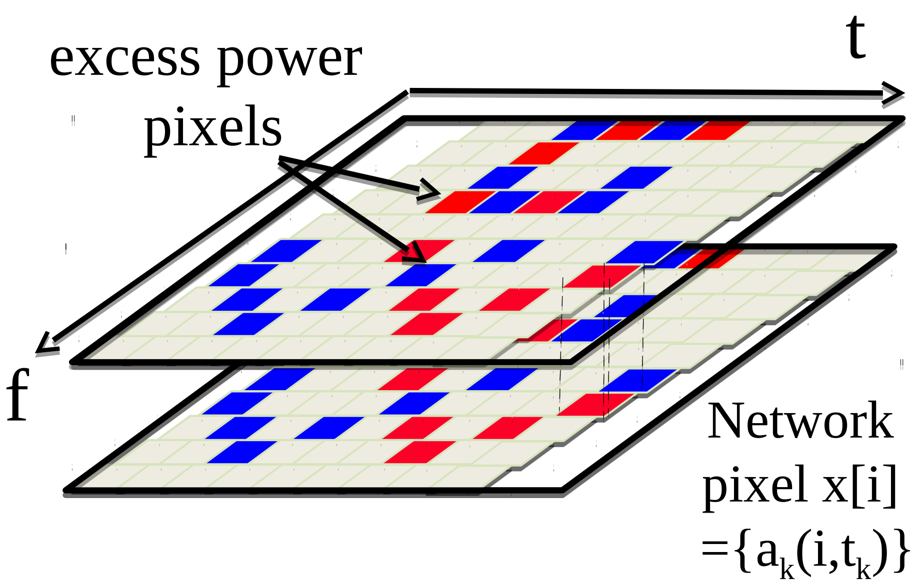
$$\tilde{\phi}(\omega) = \frac{1}{\sqrt{\Delta\Omega}} \quad , \quad |\omega| < A$$

$$\tilde{\phi}(\omega) = \frac{1}{\sqrt{\Delta\Omega}} cos\left[\nu_n\left(\frac{|\omega| - A}{B}\right)\frac{\pi}{2}\right] \quad , \quad A \leq |\omega| < A + B\ ,$$

where A and B are two positive parameters

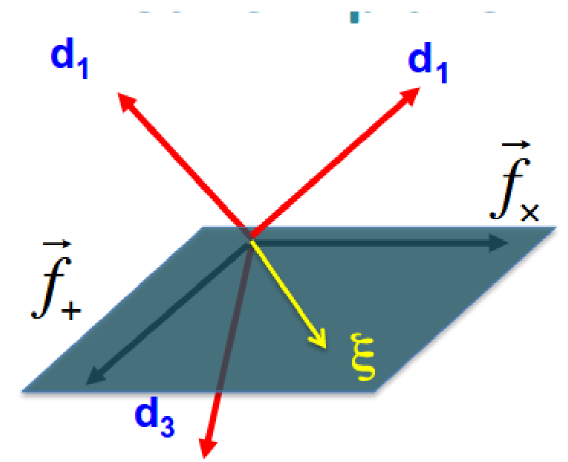
$$2A + B = \Delta\Omega\ ,$$

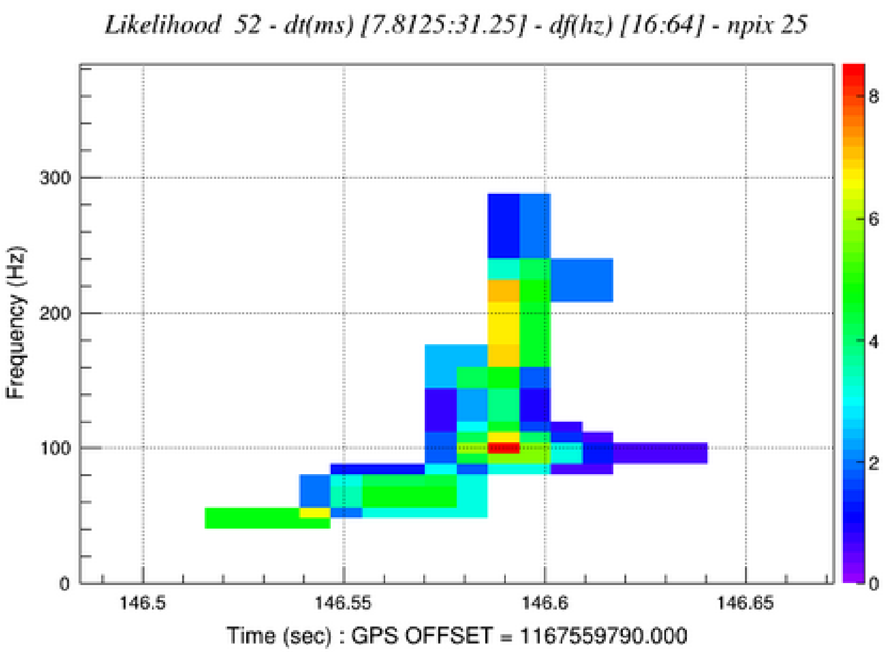
CWB detection ranking statistic



- x[i] → w[i,j]
- Define the coherent energy E_c and the incoherent energy E_i.

f_+ & f_x defines the « dominant polarization frame »





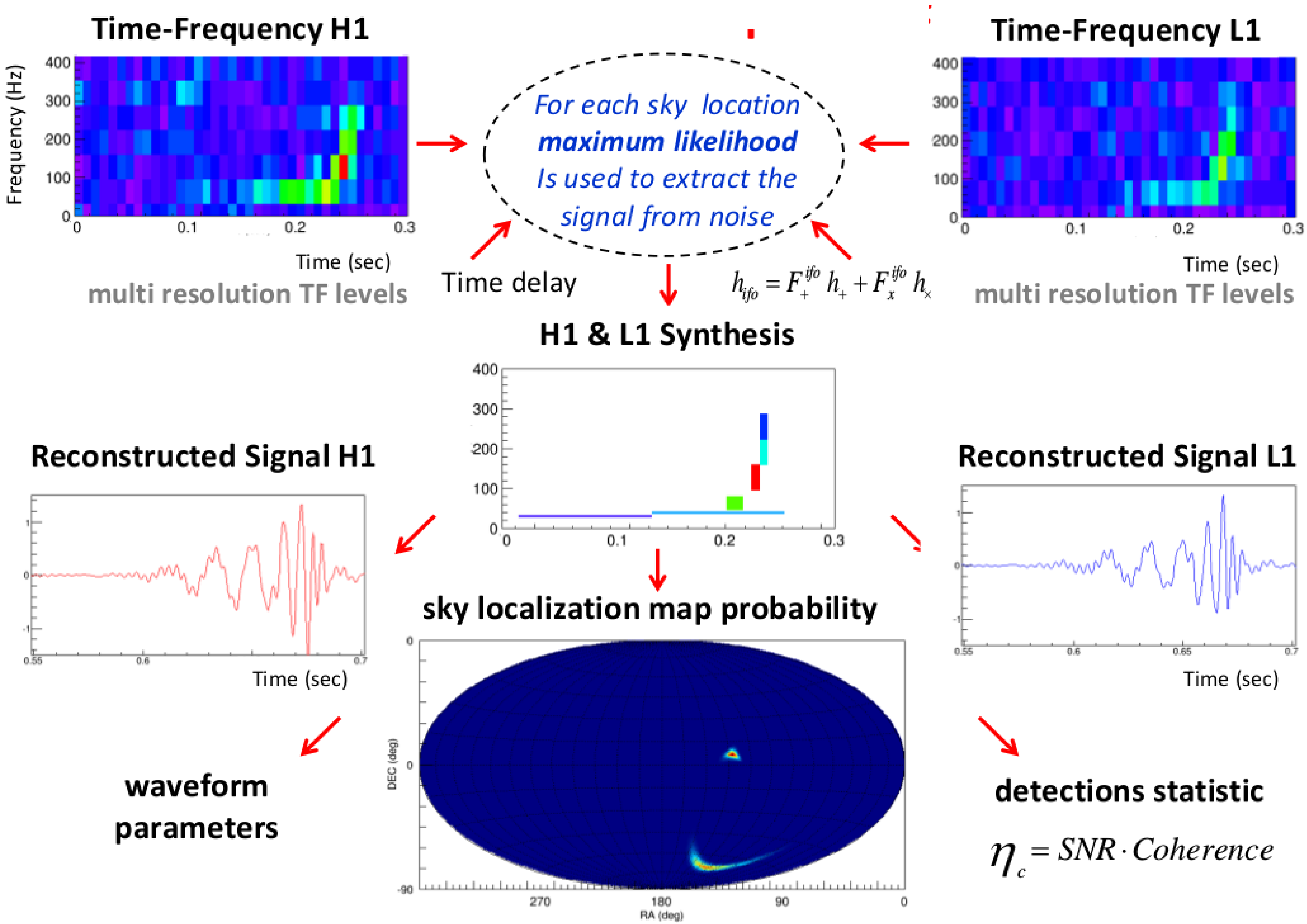
$$E_i = \Sigma_{i \in cluster} \Sigma_n x_n[i] P_{nn}[i] x_n[i]$$

$$E_c = \Sigma_{i \in cluster} \Sigma_{n \neq m} x_n[i] P_{nm}[i] x_m[i]$$

$$c_c = E_c/(E_c + E_n)$$

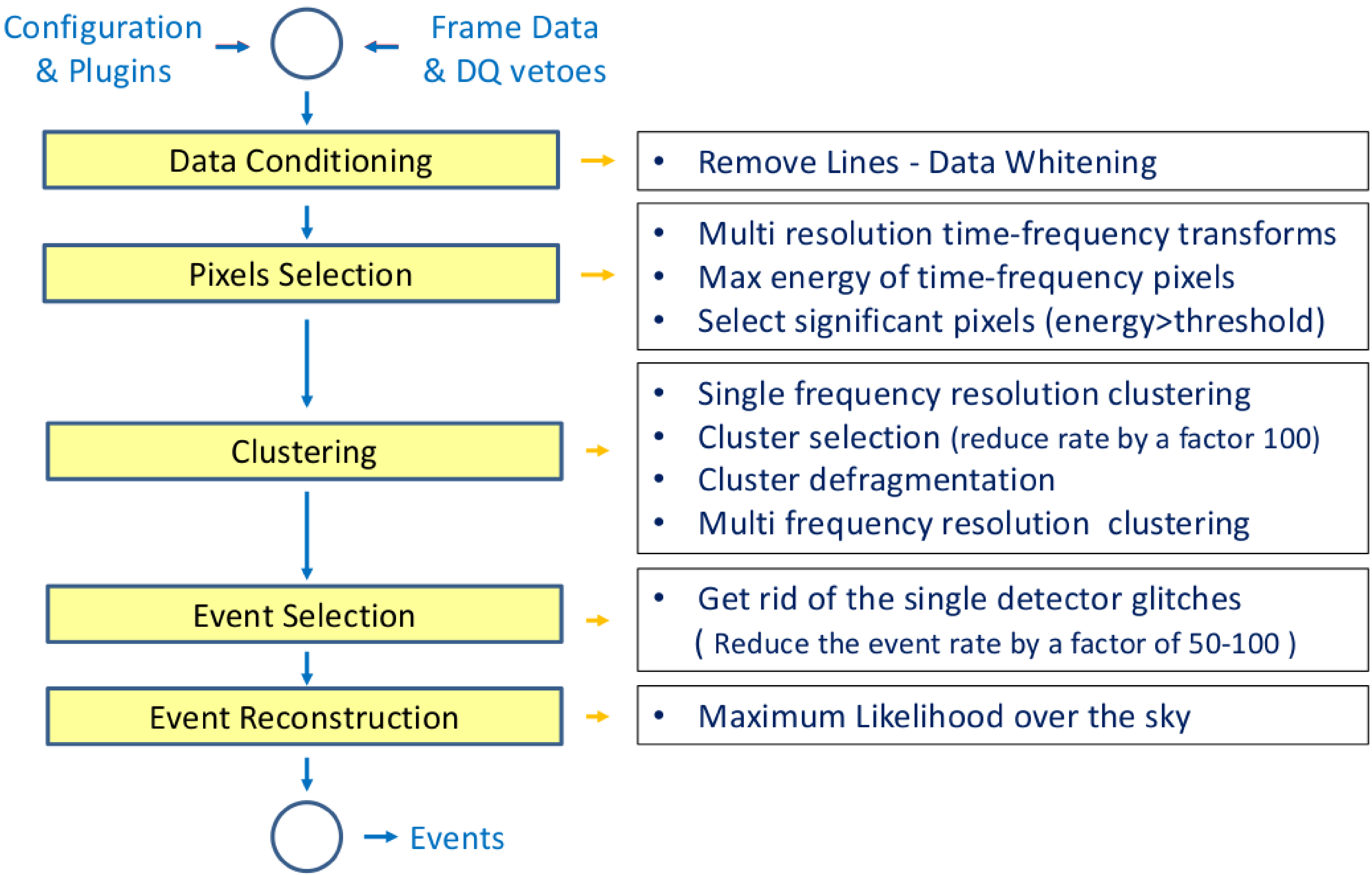
$$\eta_c = \sqrt{c_c E_c K/(K-1)}$$

The cWB pipeline

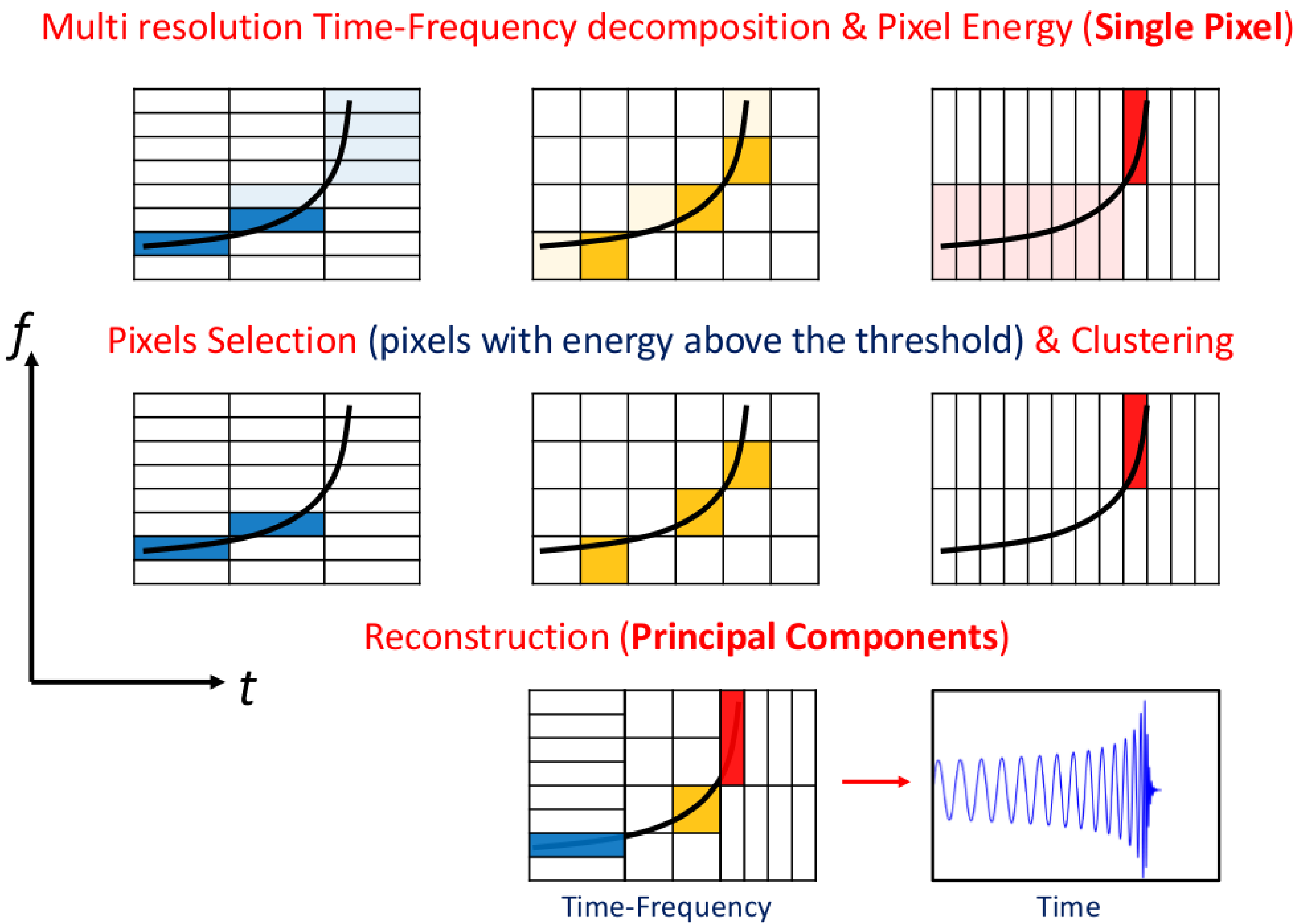


The sky location with highest probability is used to reconstruct signal & its detection statistic

The cWB pipeline



Pixels selection and reconstruction



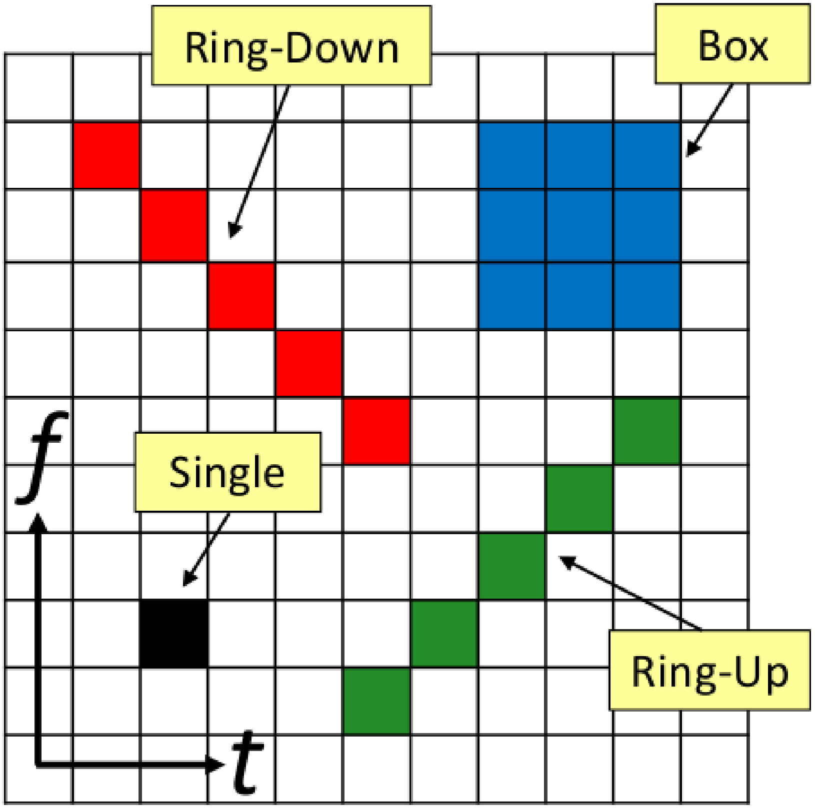
Wavelet packet / patterns

- **The basic idea is to take, instead of one basis wavelet function, a superimposition (*the packets*) of wavelet basis functions $\varphi_{ij}(t)$**

$$P(t) = \sum_{i,j \in TF} \alpha_{ij}\, \varphi_{ij}(t)$$

- **In Wavelet Packet Decomposition the coefficients α_{ij} are pre-defined. We select α_{ij} for a *TF-pattern* in such a way that :** $\langle x(t)|P(t)\rangle^2 = |A|^2 = E$

- **E is the total pattern energy and $A \cdot P(t)$ is the time domain waveform describing the pattern.**



TF-Patterns

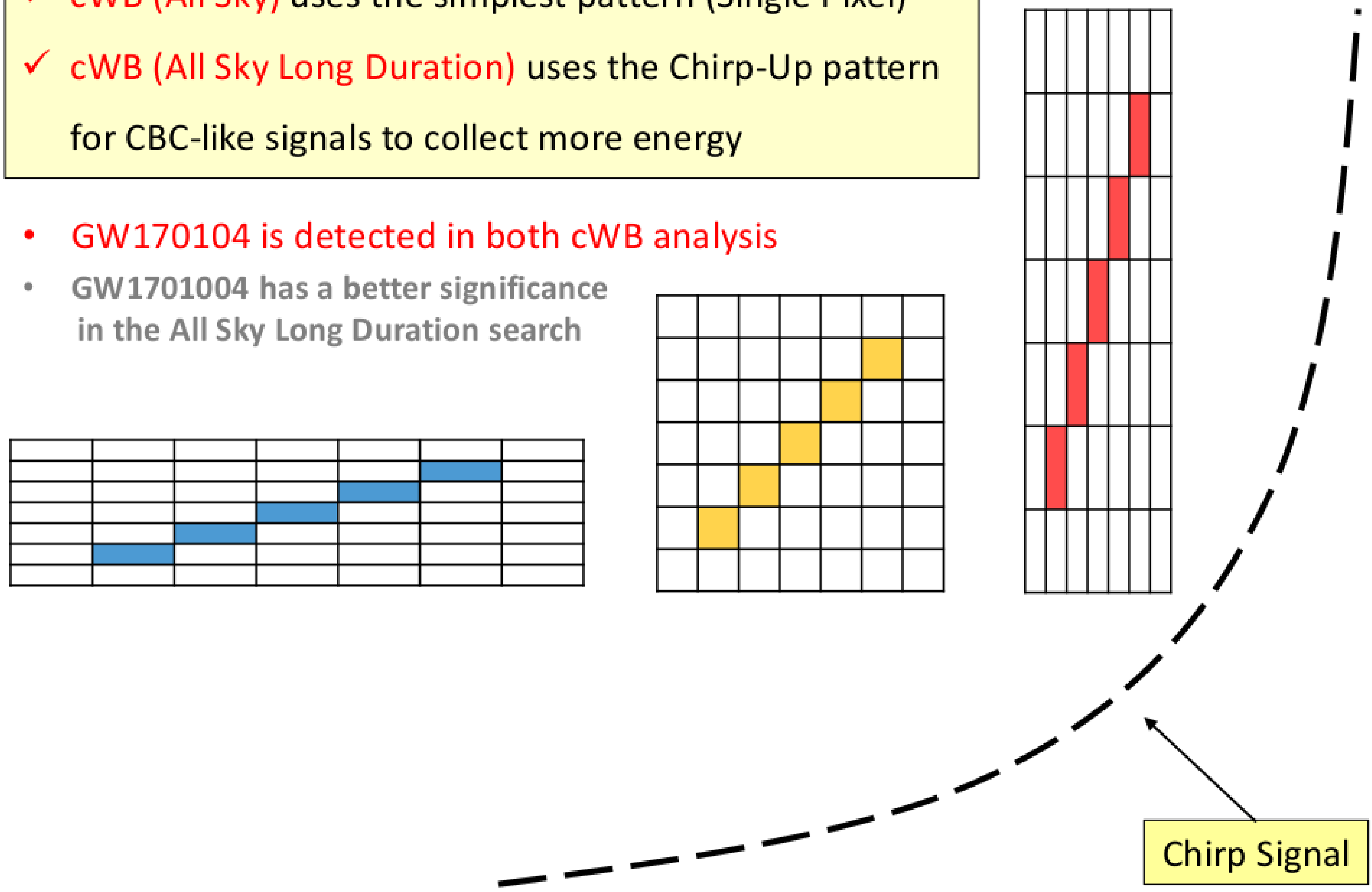
- **The new pixels selection and clustering is :**
  - **For each pixel we compute A_{ij}**
  - **Select pixels having $|A_{ij}|^2 > threshold$**

- **The waveform in time domain is reconstruted by Wavelet Packet using pixels from all resolutions**

cWB pattern for CBC like signals

- ✓ Different patterns can be used for pixel selection
- ✓ cWB (All Sky) uses the simplest pattern (Single Pixel)
- ✓ cWB (All Sky Long Duration) uses the Chirp-Up pattern for CBC-like signals to collect more energy

- GW170104 is detected in both cWB analysis
- GW1701004 has a better significance in the All Sky Long Duration search



cWB searches

off-line All-Sky transient searches with cWB in O2

All-Sky SHORT BURSTS

Low Frequency

Processing: single pixel, [16,1024] Hz

Bin.1: (polluted by known glitches) [32,996] Hz. Cuts: norm, netcc
Bin.2: (else, disjoint), [48,996] Hz
Cuts: norm, netcc, Qveto, Lveto

High Frequency

Processing: single pixel, [512,4096(?)] Hz

Single Bin(?): [896,4096(?)] Hz
Cuts: norm, netcc

All-Sky LONG BURSTS

Processing: single pixel, [16, 2048] Hz, down to 0.5Hz freq. resolution

Single Bin: [24, 2048] Hz
Cuts: netcc, duration (>1.5s)

All-Sky search for generic CBC transients without templates

IMBHB (total mass >~ 100 $M_\odot$)

Processing: same All-Sky-LF processed data

Single Bin: [24:256] Hz
Cuts: chirp-mass, norm, chi2, netcc, tailored Qveto, Lveto

Stellar Mass BBH (total mass ~< 100 $M_\odot$)

Processing: ramp-up, [16,1024] Hz

Single Bin: [48,996] Hz,
Cuts: chirp-mass, chi2, norm, netcc, Qveto, Lveto

eBBH

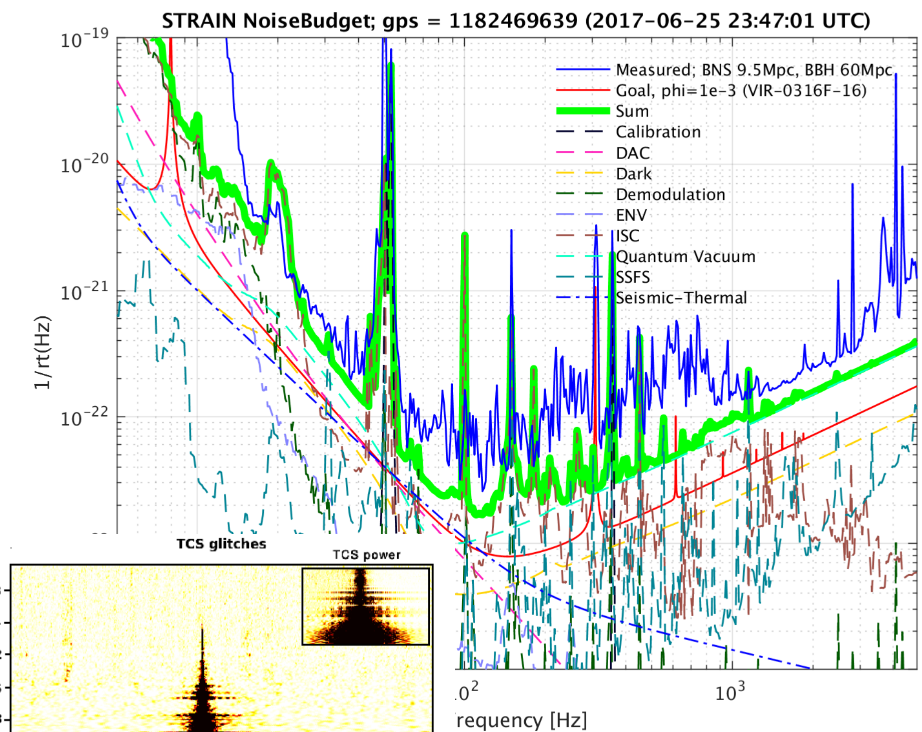
Followup analysis and interpretation comparing against pyCBC

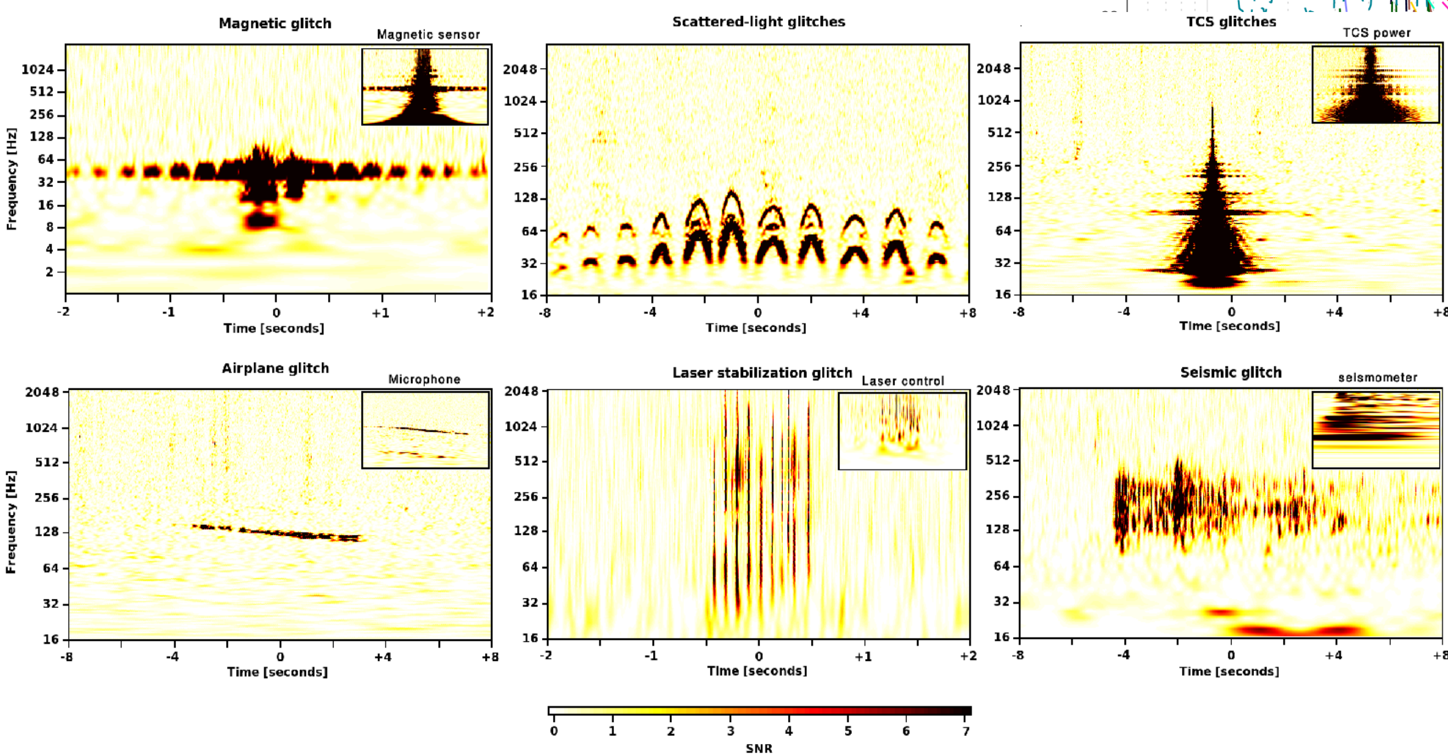
Burst search challenges

- Data are not stationary, nor Gaussian
- Many, many short duration glitches in each detector.

→ coincidence/coherence to reject many glitches.

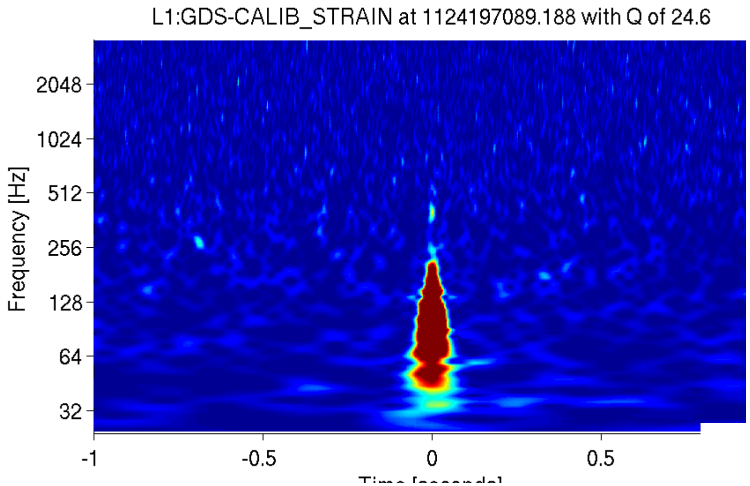
→ Background estimation needs to be robust.

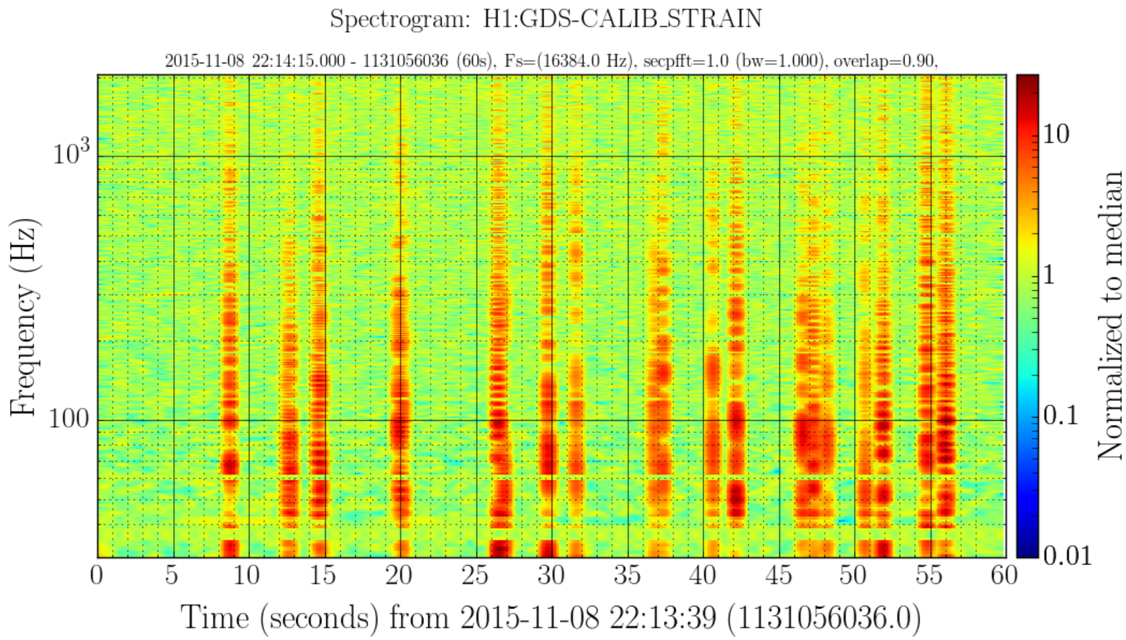


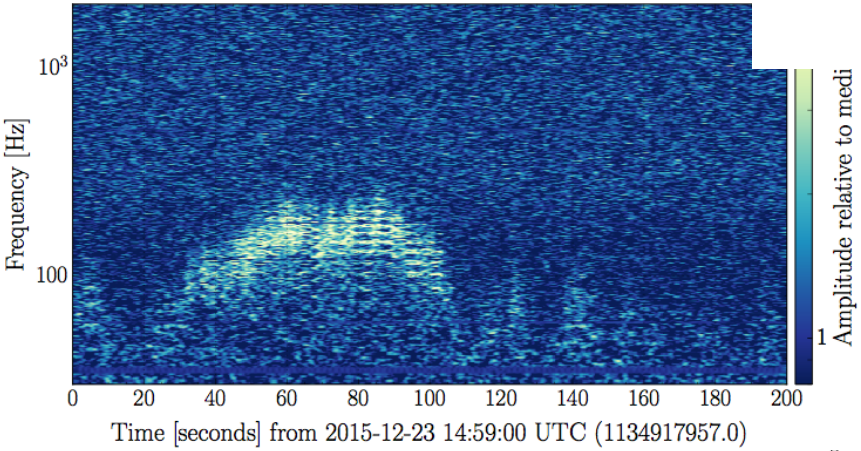


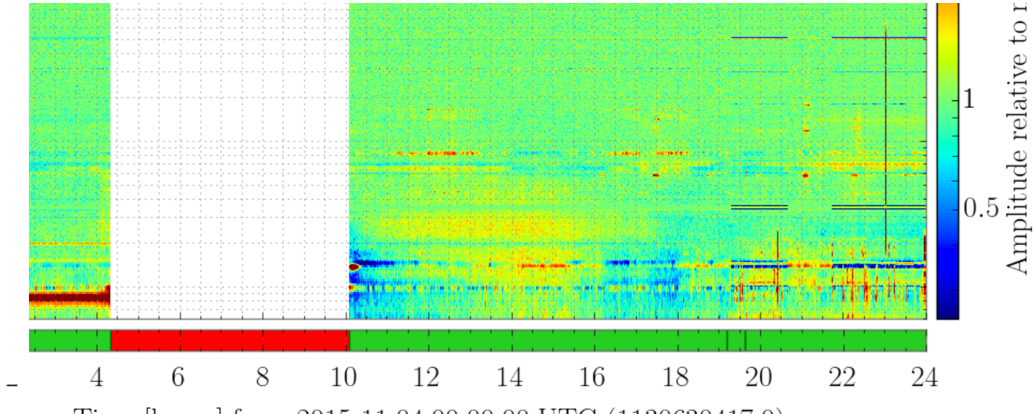
O1 data quality

- Many glitch sources (RF-modulation electronics fault, « blip » glitches, …) : either correlation in auxiliary channels → vetoes
- Spectral lines : wandering, 1Hz combs, breathing effects

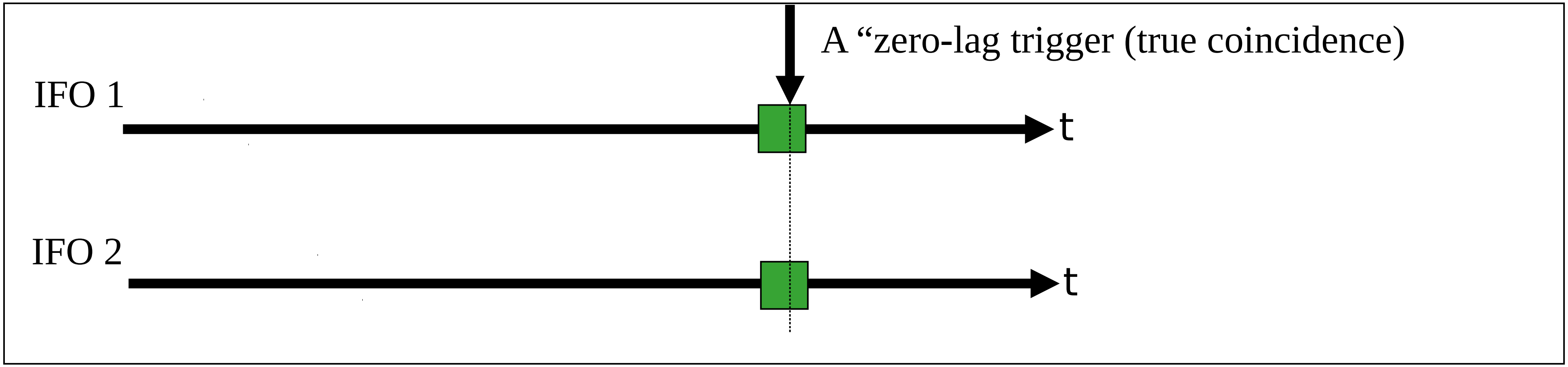


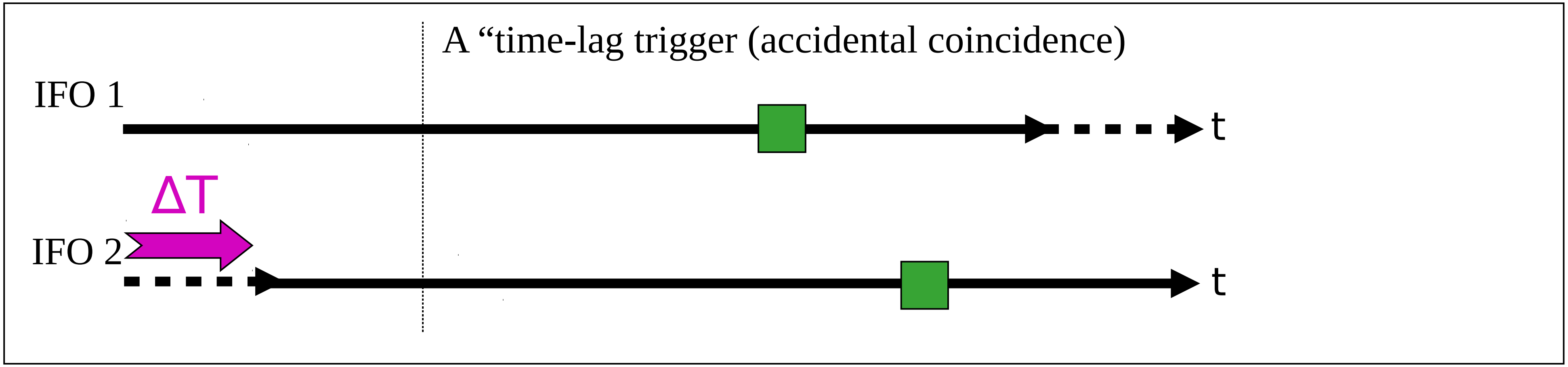






Background estimation





Glitch rejection : null stream method

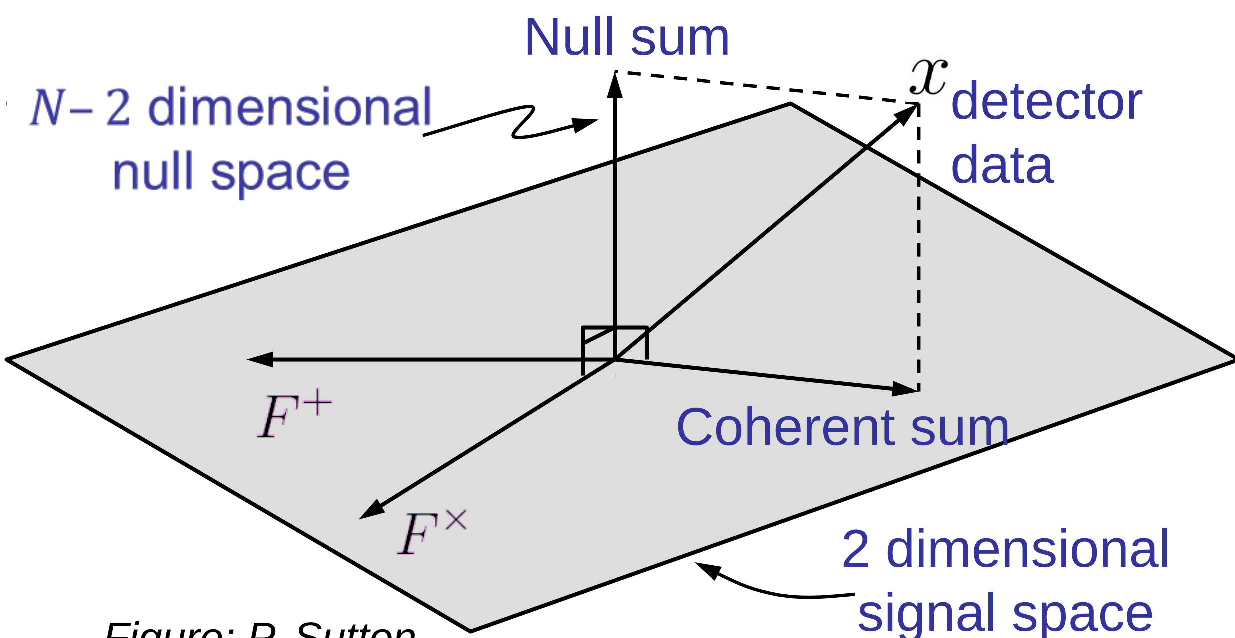


Figure: P. Sutton

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

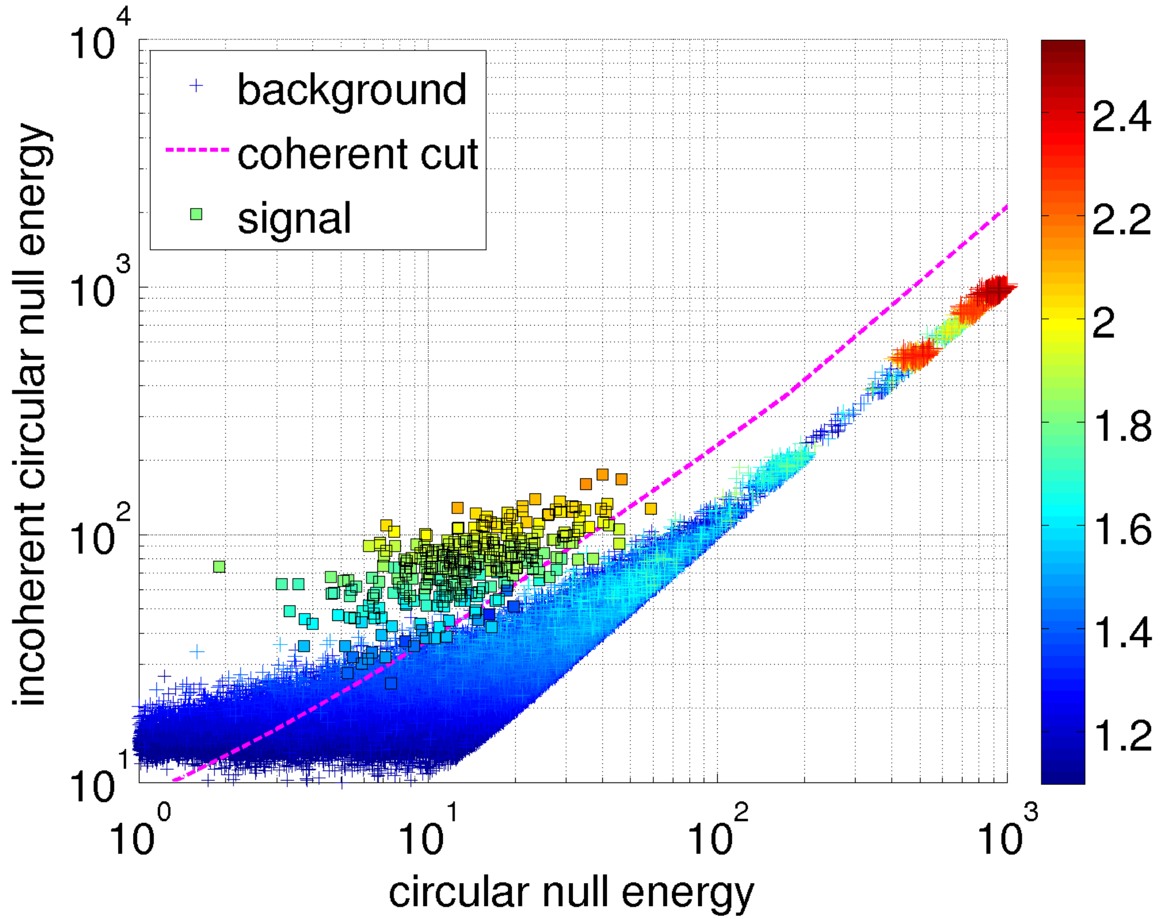
Consider all possible sky positions (arrival directions)

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

Glitch rejection : null stream method

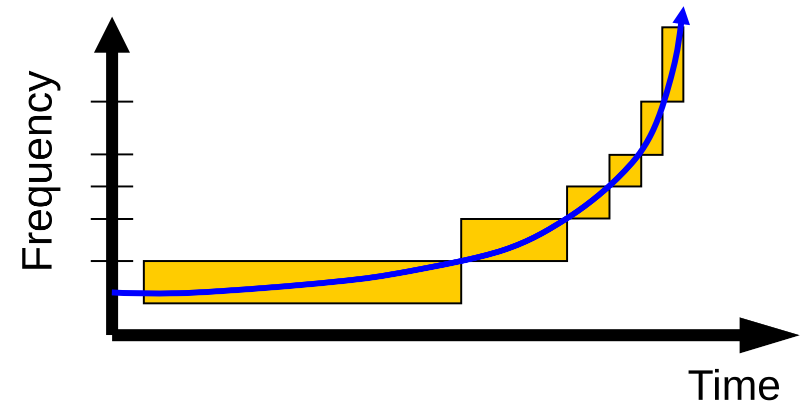
- Un-modelled burst search : coherent analysis: compare null and incoherent energy:
  - For a GW signal E_{inc}/E_{null} is large
  - For a glitch $E_{null}/E_{inc} \sim 1$

@ 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.

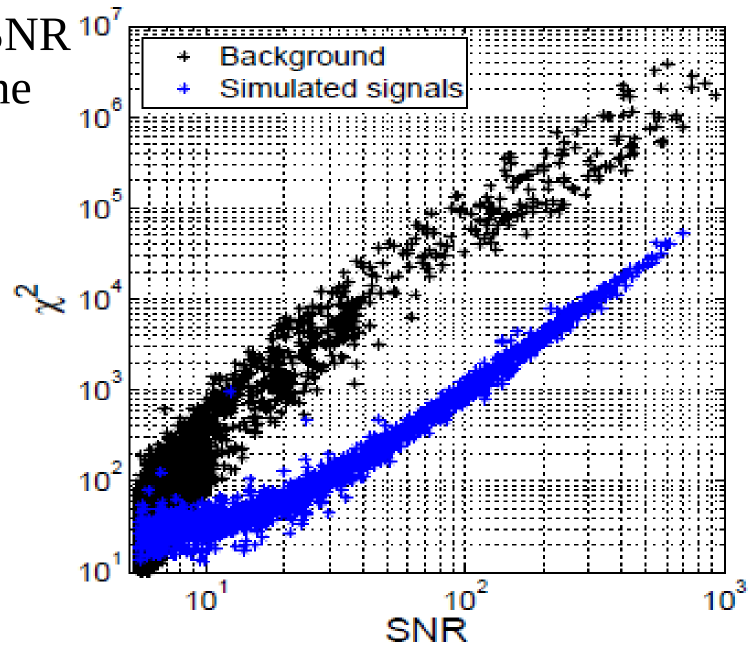


$$\chi^2(t) = p \sum_{j=1}^{p} |\rho_j - \frac{\rho}{p}|^2$$

- 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

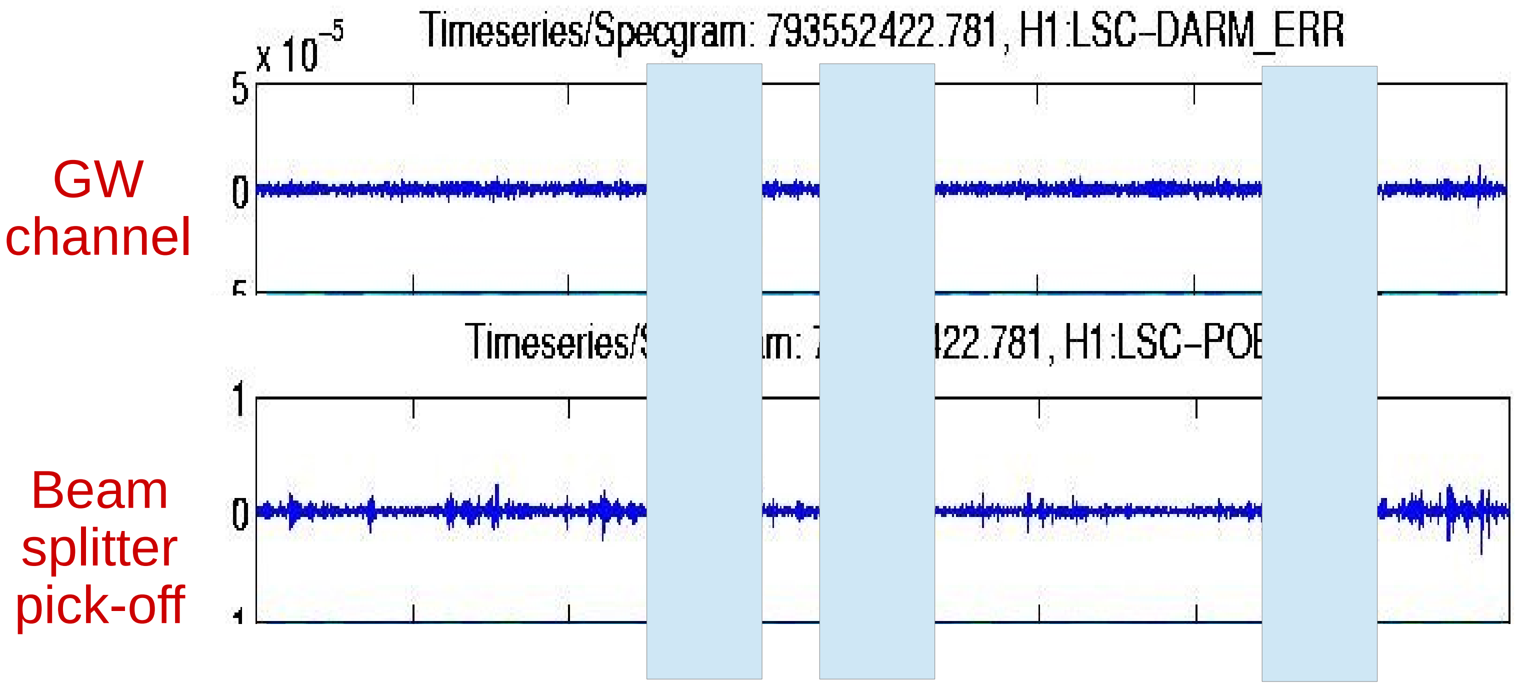
- Weighted SNR



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

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



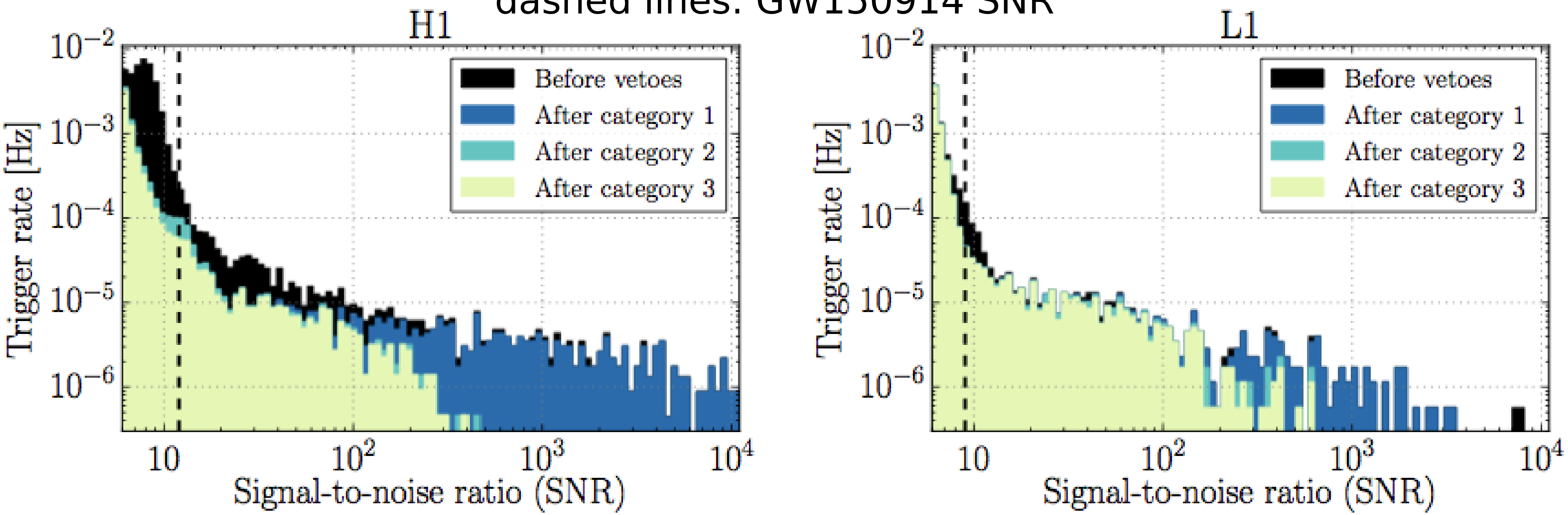
Virgo VSR2-3

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)

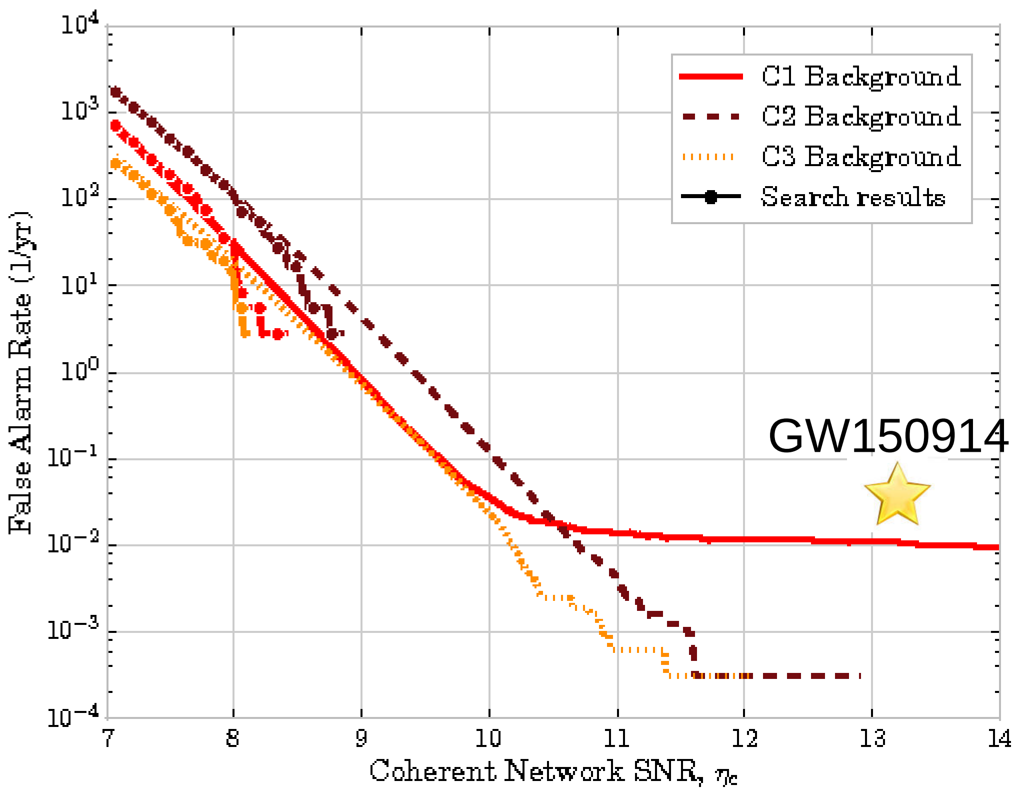
Data quality/instrumental vetoes

dashed lines: GW150914 SNR



Vetoes eliminate a large fraction of the loudest triggers.

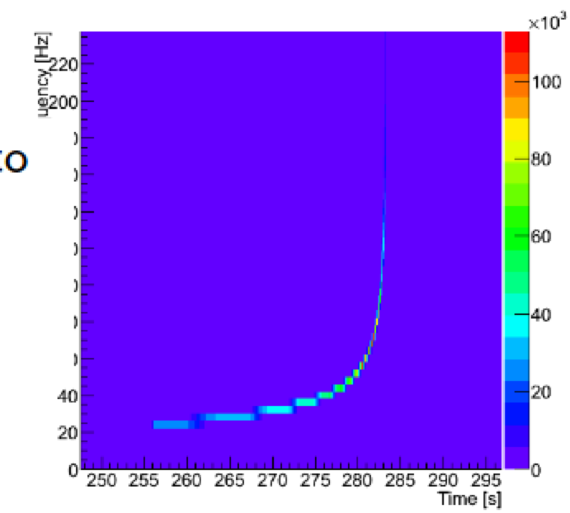
O1 : all-sky unmodelled searches

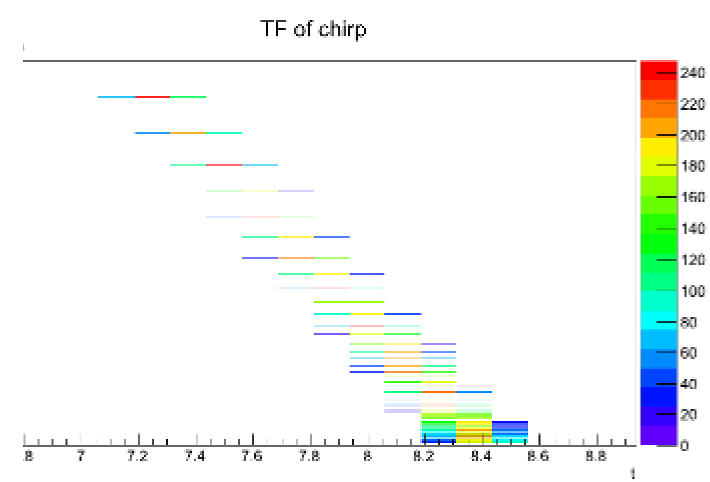


- 3 « bins » search to isolate known source of glitches and focuses on BBH signals
  - C1 : triggers that looks like « blip » glitches
  - C3 : triggers that chirps
  - C2 : remaining triggers
- « Chirping » bin : frequency evolution depends on the masses

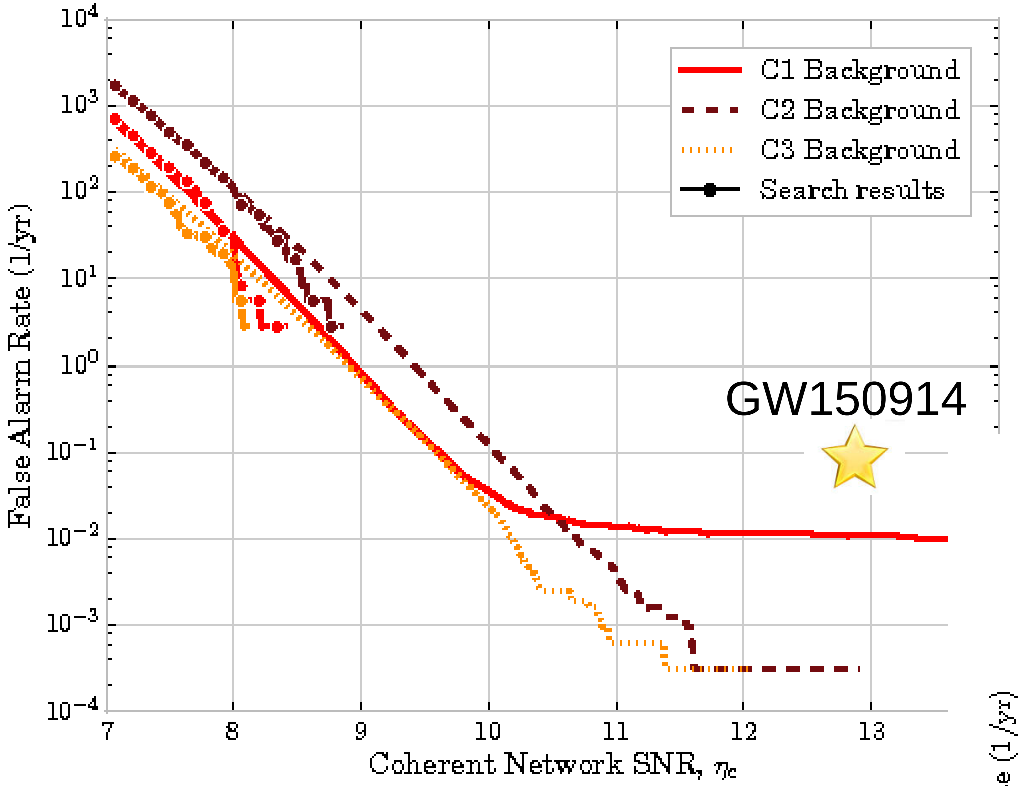
$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3}$$

Fitting a chirp signal is equivalent to fitting a line y=sl·x+C, y $\equiv (3/8)f^{-8/3}$, x≡t, sl $\equiv \frac{96}{5}\pi^{8/3}(\frac{GM_c}{c^3})^{5/3}$

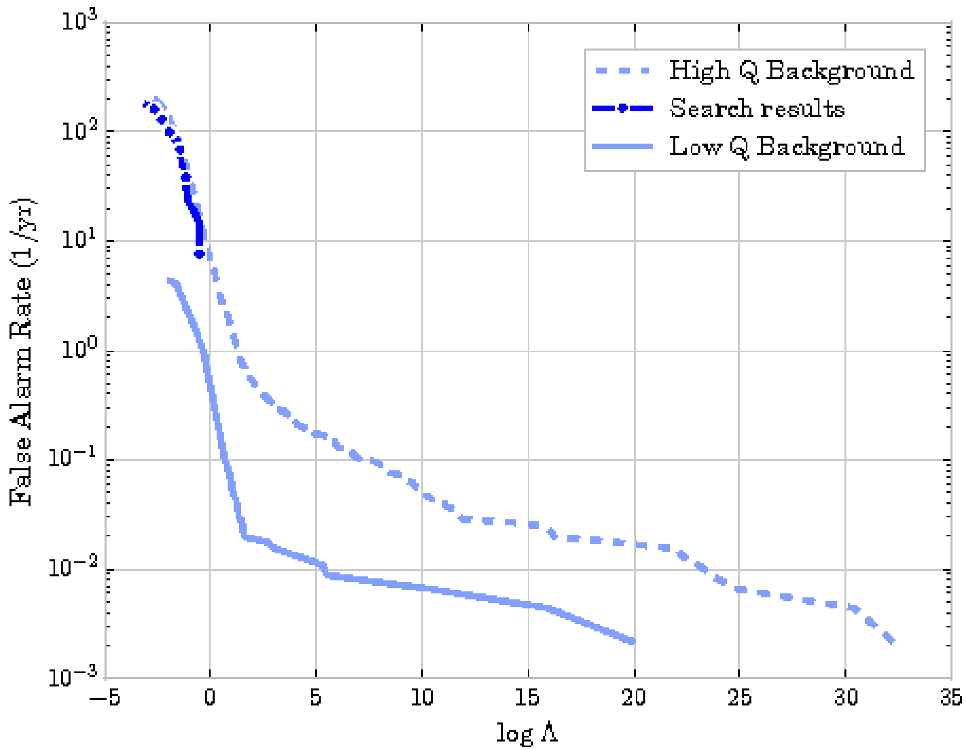




O1 : all-sky unmodelled searches



- Multi-pipeline searches
  - use different data mining techniques
  - increase confidence
  - more « eyes » looking at the data
- Drawback : trial factors !

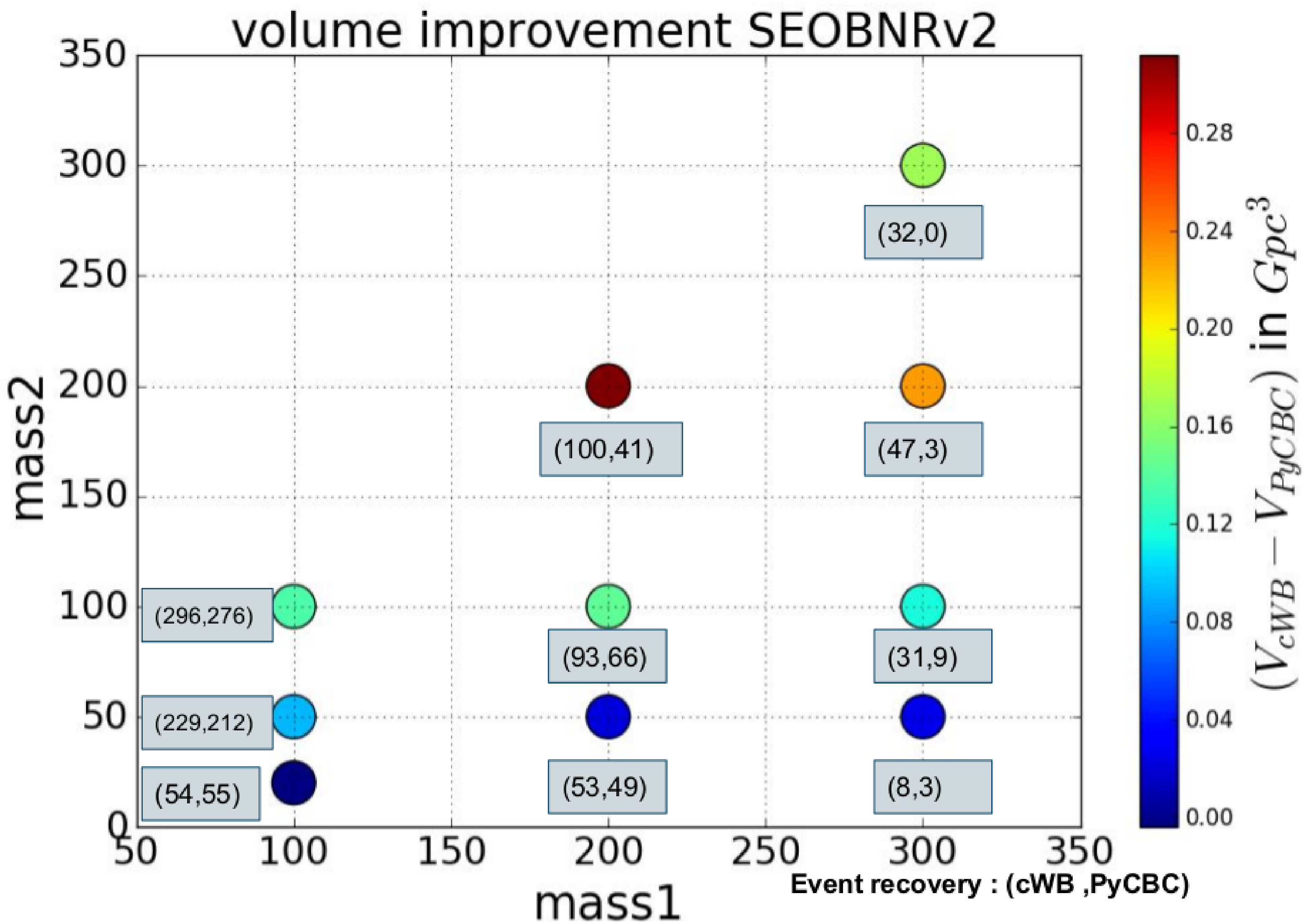


High mass BBH merger : cWB vs pycbc

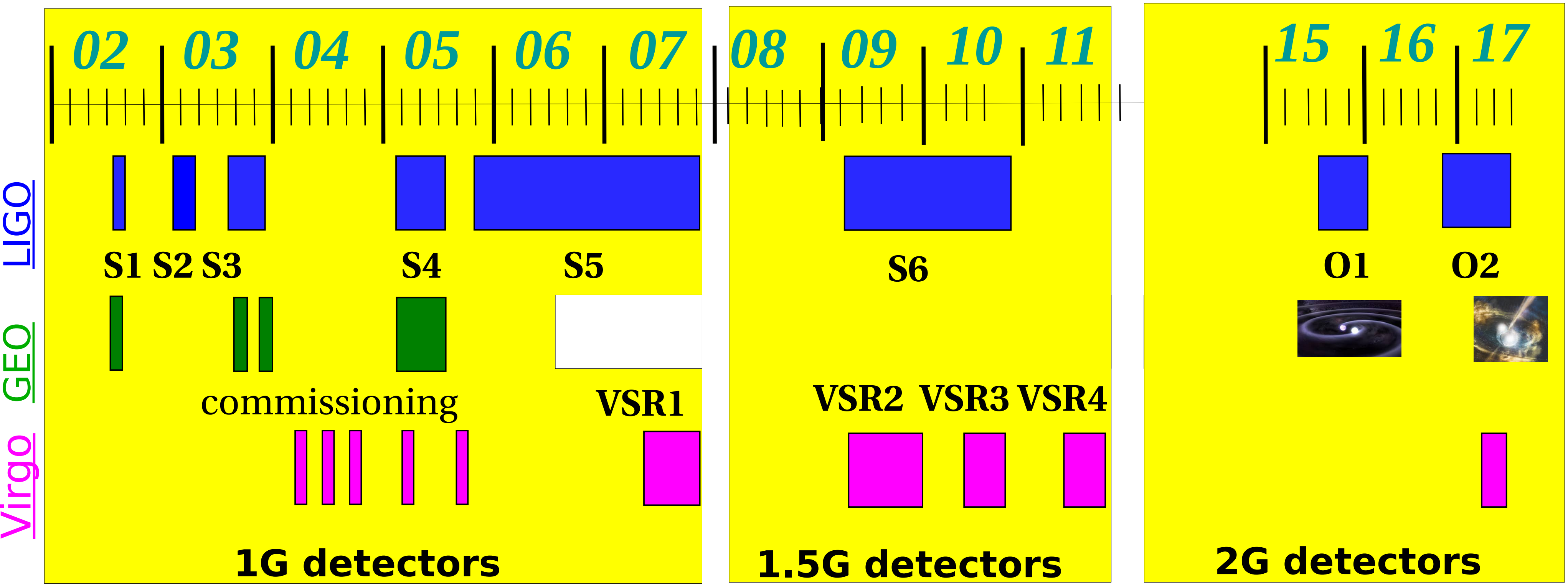
SEBNRv2 in cWB and PyCBC in chunk19

- Data ~ **5.19 days** and BKG data **116.8 Years**.

https://wiki.ligo.org/Bursts/Chunk19IMBHBcWBanalysis



A selection of Burst GW searches



2000

- Sensibility not high enough for detection
- First observation runs (upper limits)

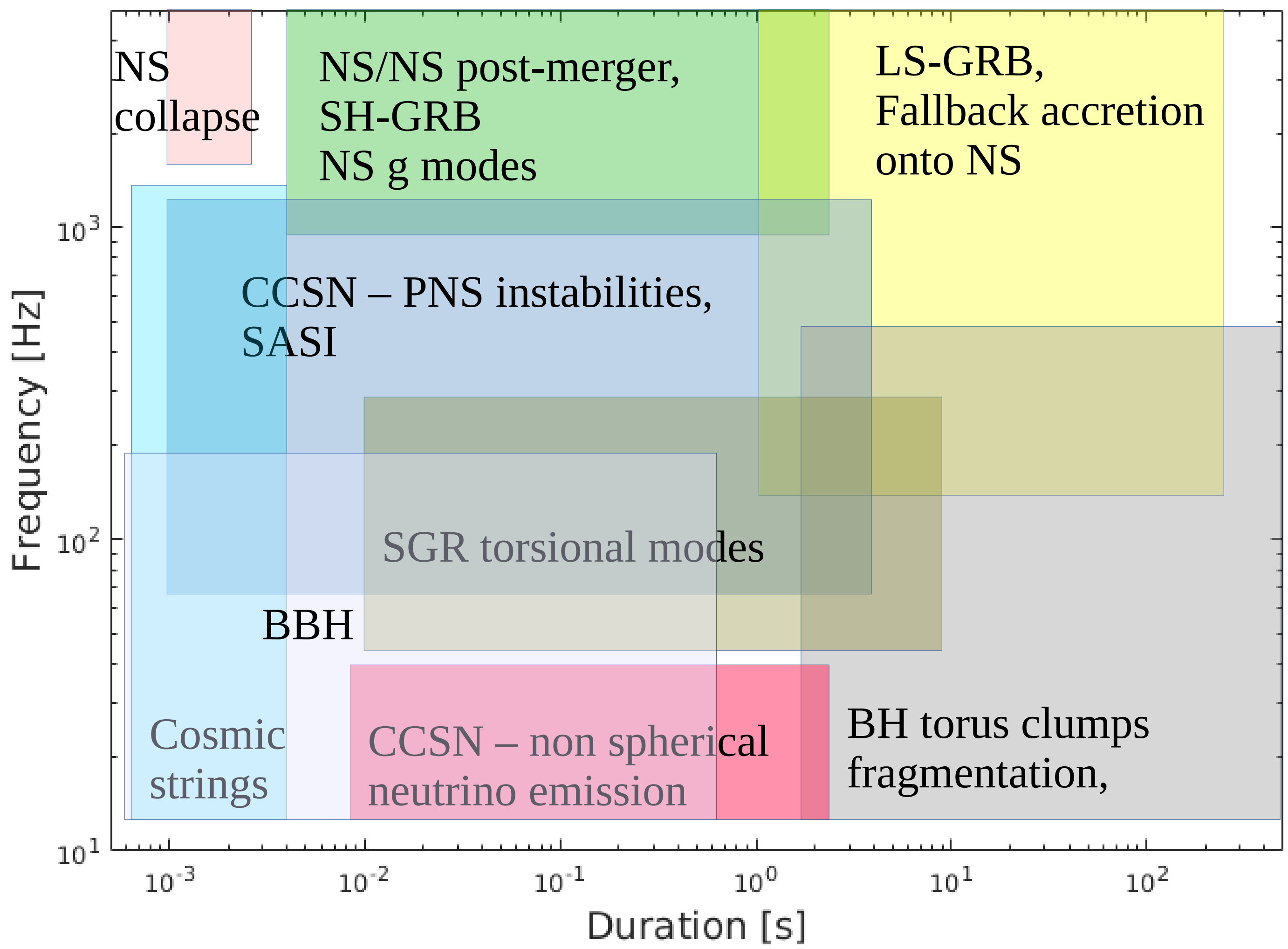
2010

- Begin GW networking
- Begin multi-messenger analysis

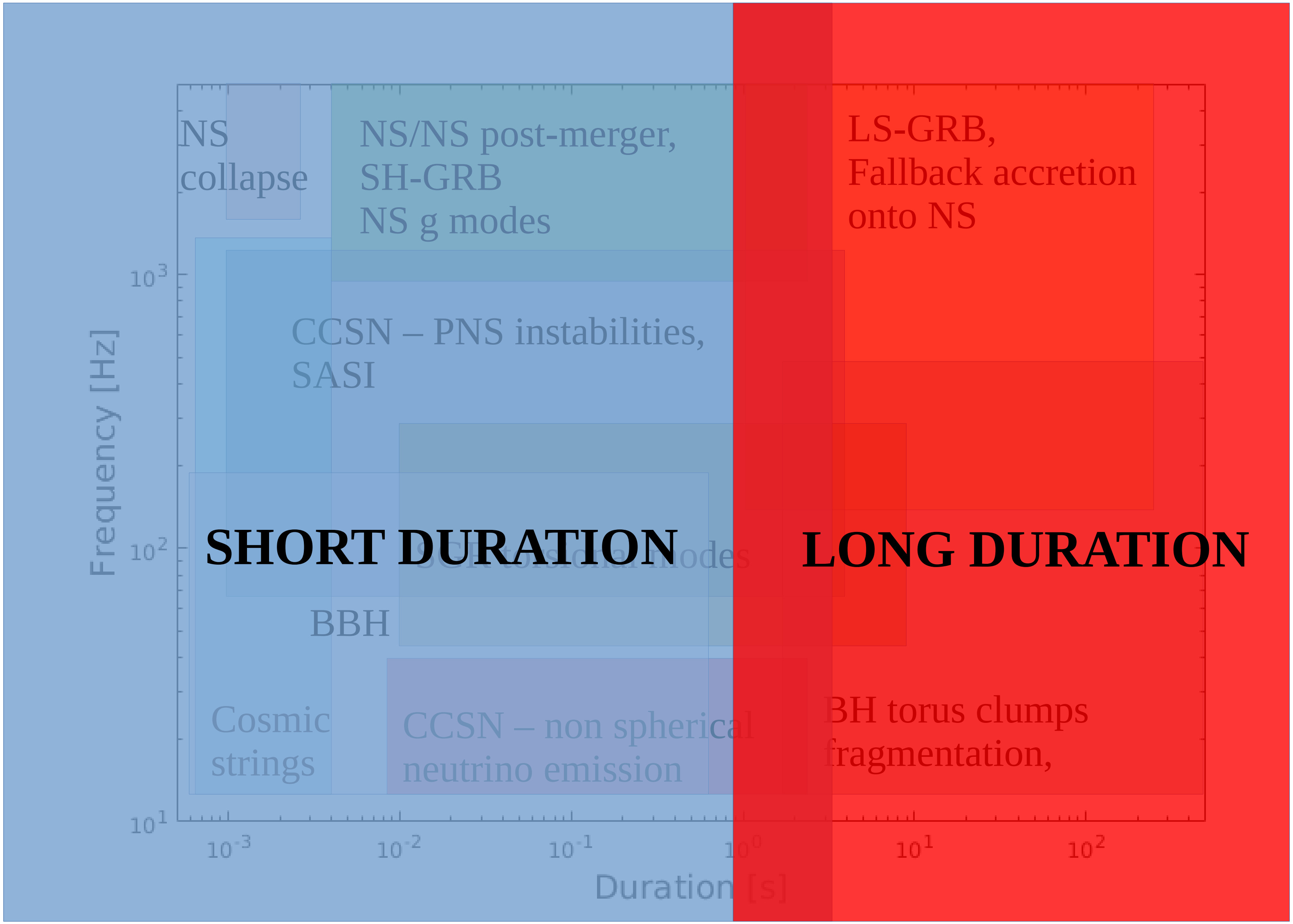
2015

- **Begin GW astronomy**

All-sky/all-time burst searches : generic searches

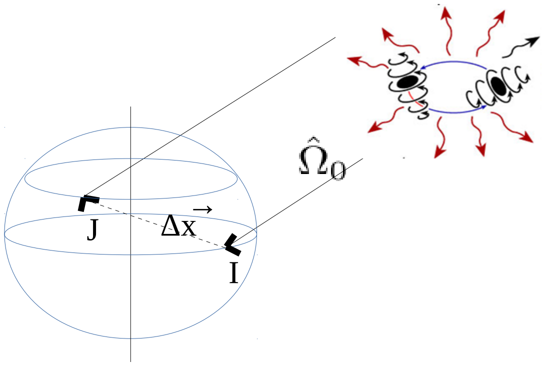


Burst searches : generic searches



2011: All-sky long transient search

- Development of a coherent cross-correlation pipeline in collaboration with the Stochastic Gravitational Wave Background group.
- For a pair of detectors: excess cross-power statistic for a point source:



$$\hat{Y}(t;f;\hat{\Omega}) \equiv 2\,\mathrm{Re}\left[\tilde{Q}_{IJ}(t;f;\hat{\Omega})\tilde{s}_I^*(t;f)\tilde{s}_J(t;f)\right]$$

Filter function:

$$\tilde{Q}_{IJ} = \frac{e^{2\pi i f\hat{\Omega}\cdot\Delta\vec{x}_{IJ}/c}}{\epsilon_{IJ}(t;\hat{\Omega})}$$

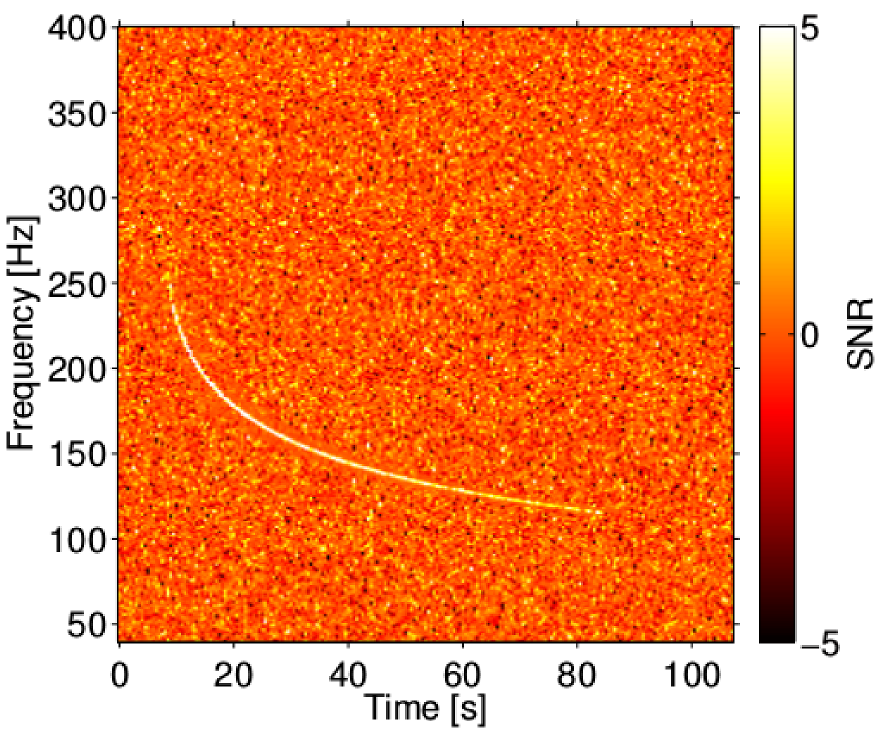
- Pixel SNR:

$$\mathrm{SNR}(t;f;\hat{\Omega}) \equiv \frac{\hat{Y}(t;f;\hat{\Omega})}{\hat{\sigma}_Y(t;f;\hat{\Omega})}$$

- Cluster SNR:

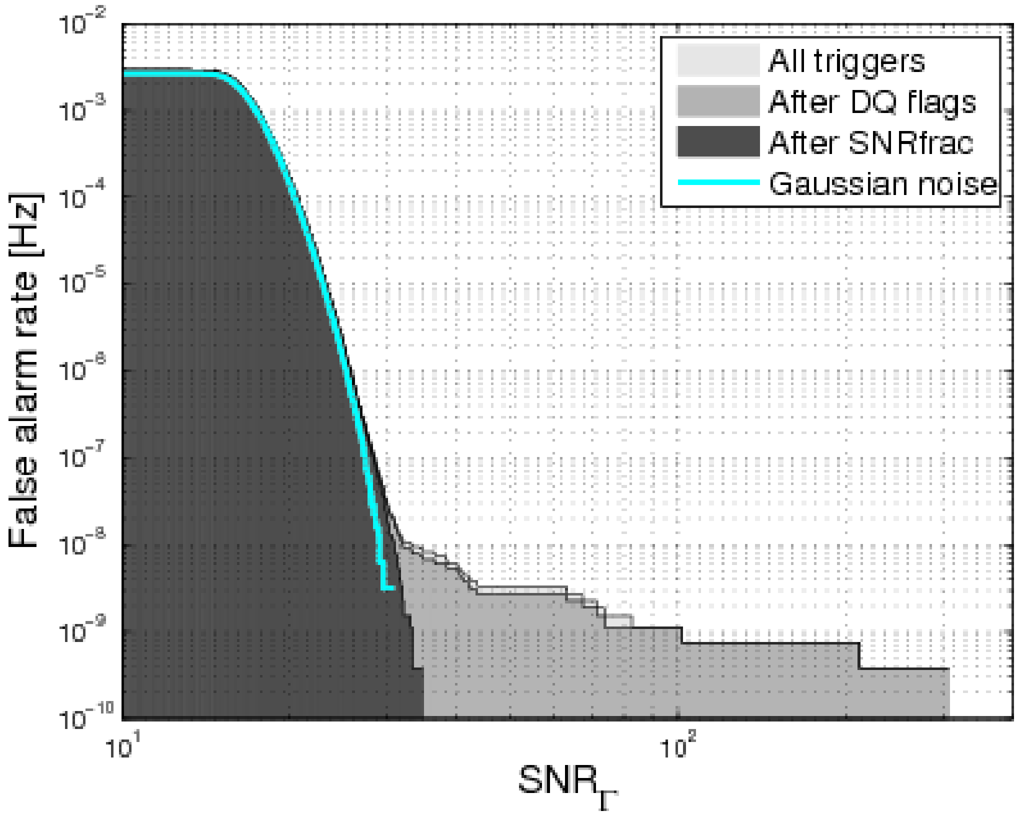
$$\mathrm{SNR}_\Gamma \equiv \frac{\sum_{(t;f)\in\Gamma}\hat{Y}(t;f;\hat{\Omega})\hat{\sigma}_Y^{-2}(t;f;\hat{\Omega})}{\left(\sum_{(t;f)\in\Gamma}\hat{\sigma}_Y^{-2}(t;f;\hat{\Omega})\right)^{1/2}}$$

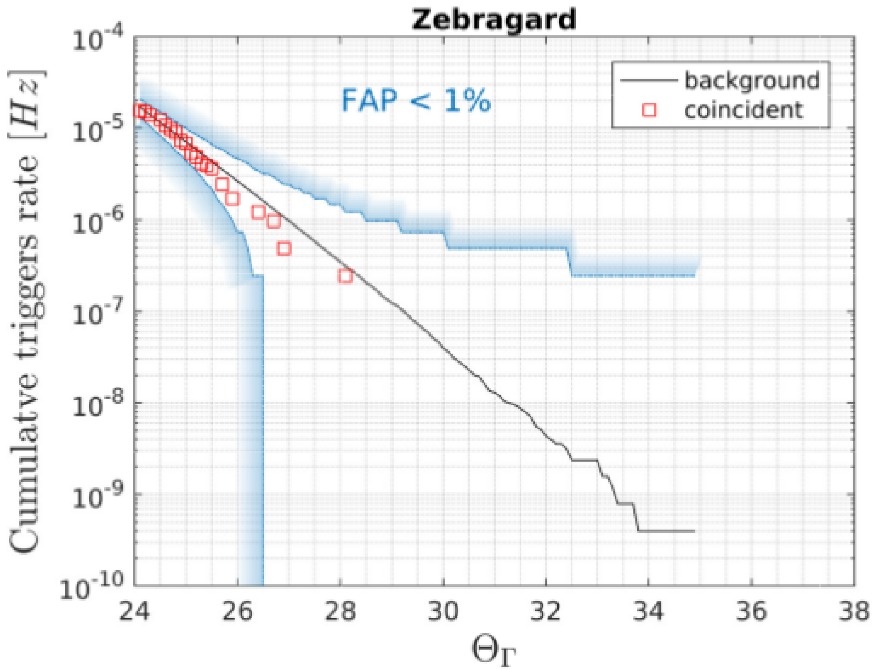
- All-sky → scan all possible **Ω**

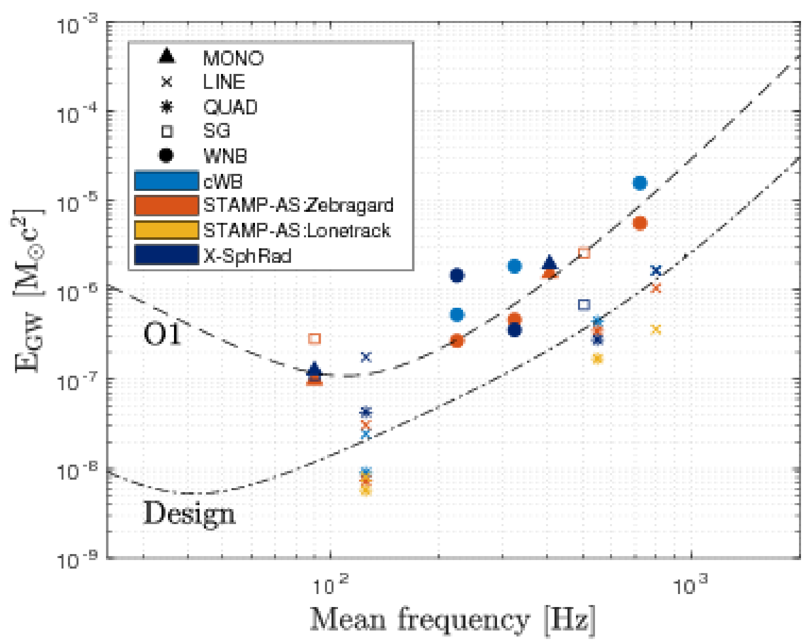


STAMP-AS

O1 : all-sky unmodelled searches : long transient

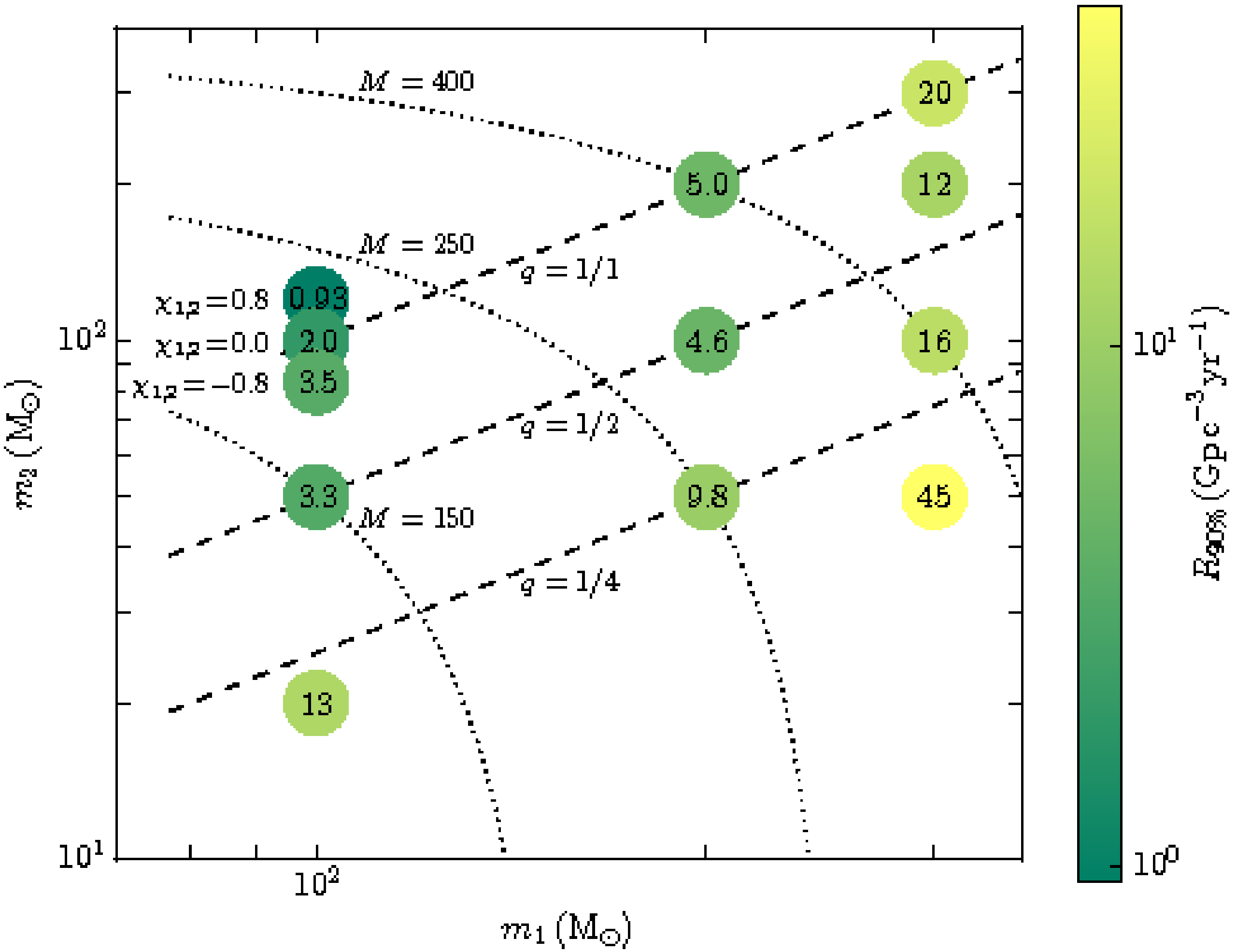






- After vetoes applied : background of the search is closed to a Gaussian distribution

O1 :Intermediate mass black hole mergers

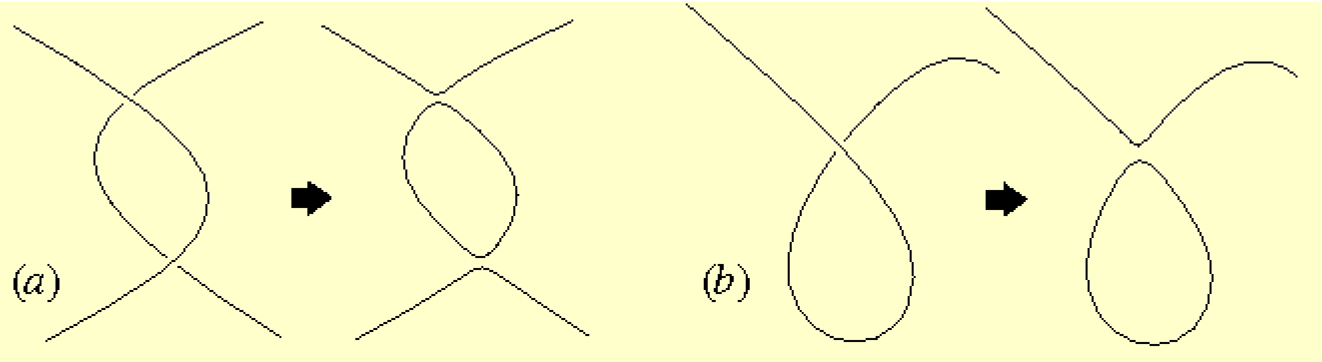


- Total mass : 100-600 Msun
- Only the 3 known BBH events found.
- Rate upper limit : Exemple for a 100+100 Msun system, no spins

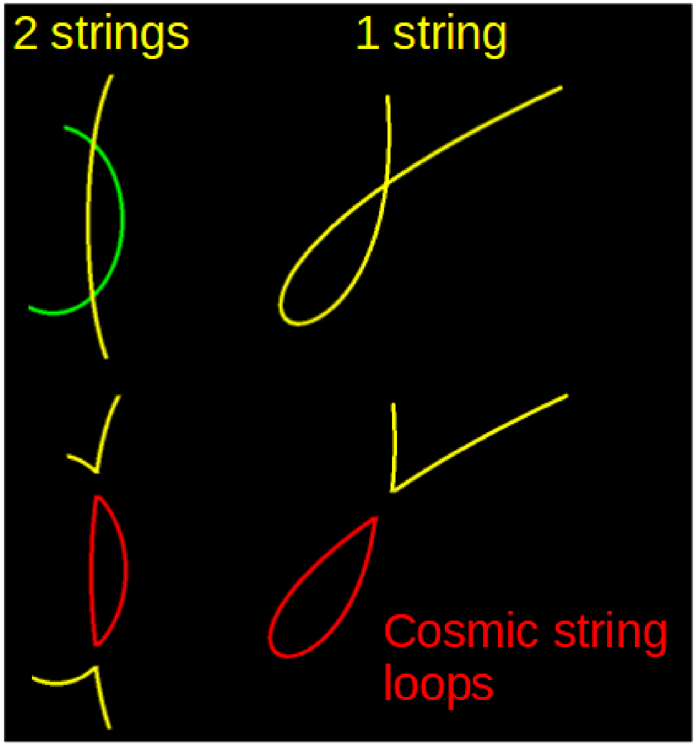
$$0.93\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Cosmic strings

- 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.

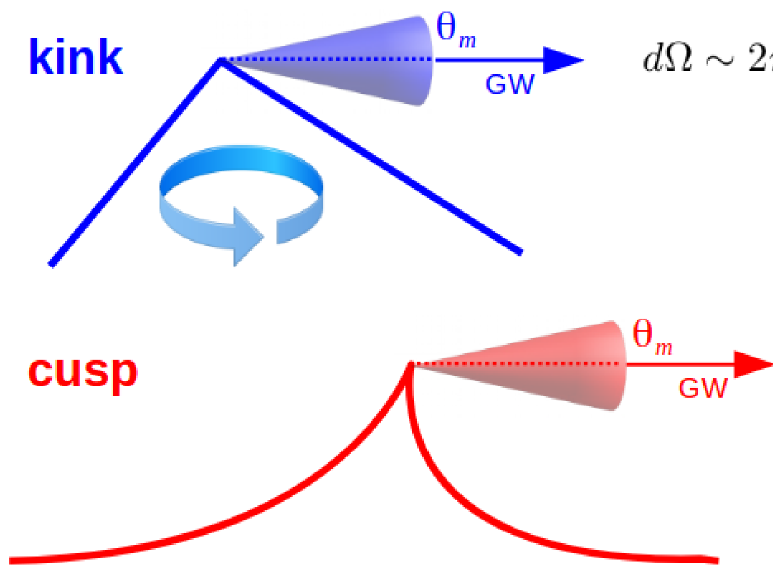


Cosmic strings



Loop formation
Loop oscillation → cusps and kinks

$$\theta_m(\ell, z, f) = (g_2 f(1+z)\ell)^{-1/3}$$
$$\theta_m < 1$$



$$d\Omega \sim 2\pi\theta_m$$

$$d\Omega \sim \pi\theta_m^2$$

GW waveform:

$$h(\ell, z, f) = A_q(\ell, z) f^{-q} \Theta(f_h - f)$$

$$A_q(\ell, z) = g_1 \frac{G\mu\ell^{2-q}}{(1+z)^{q-1} r(z)}$$

q = 4/3 for cusps, q = 5/3 for kinks

Cosmic strings

- Parameters:
  - String tension ($G\mu$)
  - Loop size at formation t (αt)
  - For super-strings: reconnection probability ($p<1$).
- Existing cosmological/experimental search constrains
  - CMB data (WMAP/Planck $G\mu < 3.7/1.5 \times 10^{-6}$)
  - 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. Unfortunately this is disfavored.

O1 : Cosmic strings search results

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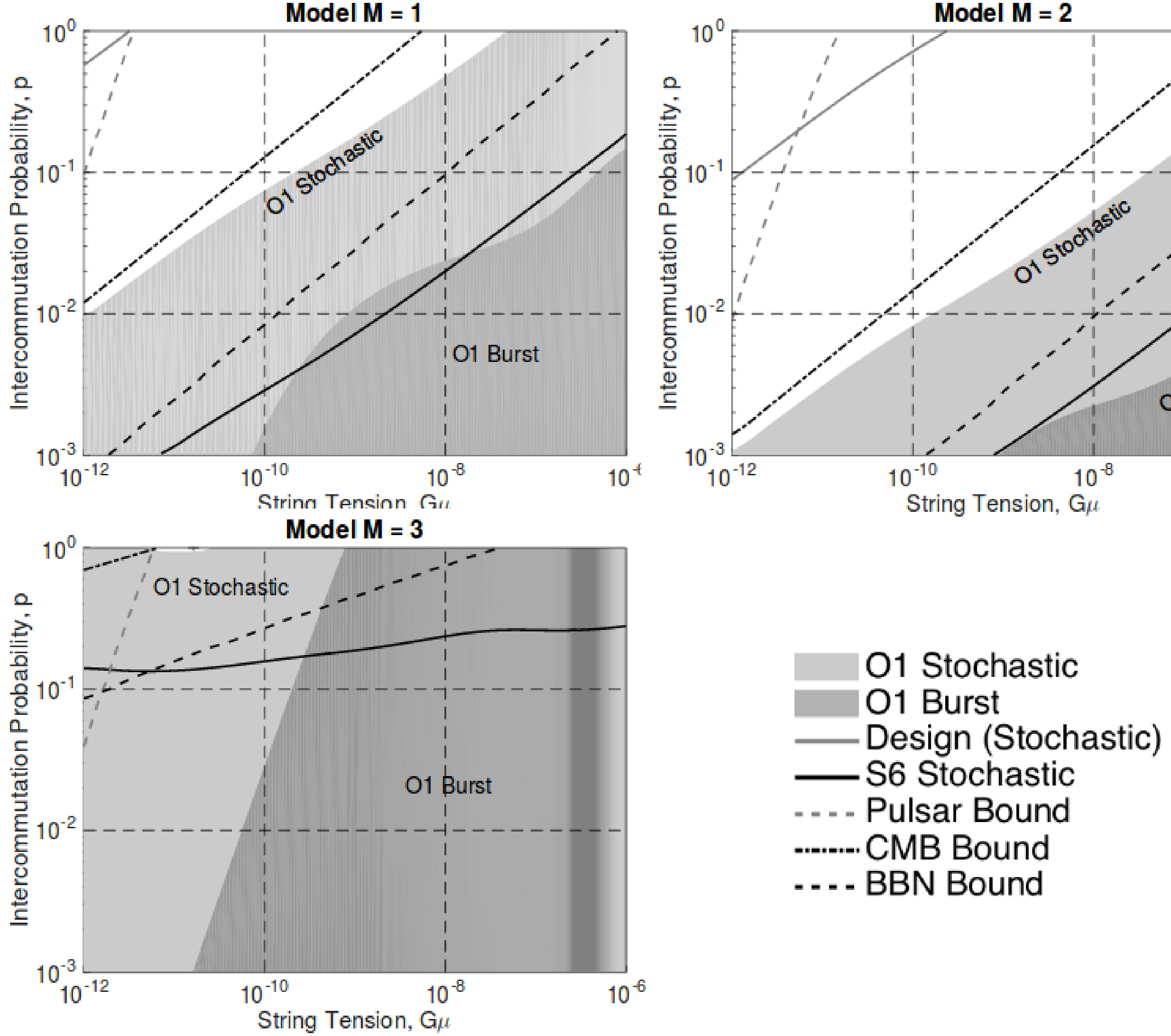


Model 1: original large loop distribution

All loops have same size at formation and they are large.

Model 2: large loop Nambu-Goto distribution of Blanco-Pillado et al.

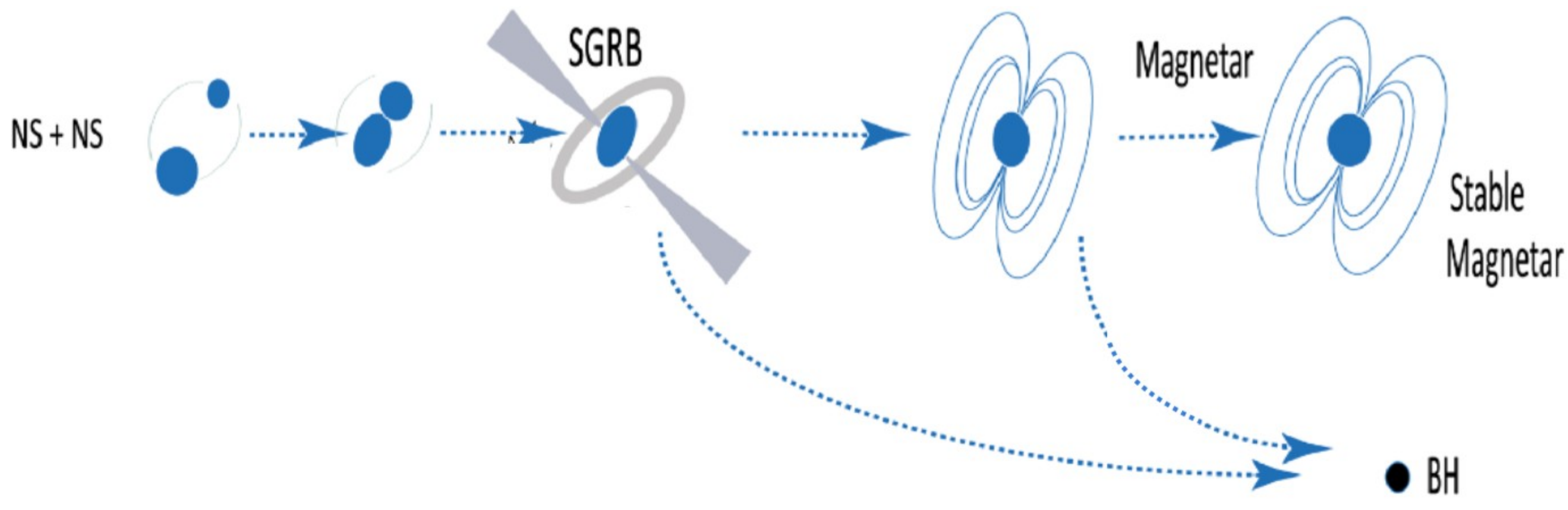
The loop production function can be determined from numerical simulations.

Model 3: large loop Nambu-Goto distribution of Ringeval et al.

As opposed to model 2, here the (different) numerical simulation is not used to determine the loop production function at time t, but rather the distribution of non-self intersecting loops at time t.

FIG. 6: 95% confidence exclusion regions are shown for three loop distribution models: $M = 1$ (top-left), $M = 2$ (top-right), and $M = 3$ (bottom-left). Shaded regions are excluded by the latest (O1) Advanced LIGO stochastic [31] and burst (presented here) measurements. We also show the bounds from the previous LIGO-Virgo stochastic measurement (S6) [63], from the indirect BBN and CMB bounds [27, 28], and from the PTA measurement (Pulsar) [29]. Also shown is the projected design sensitivity of the Advanced LIGO and Advanced Virgo experiments (Design, Stochastic) [64]. The excluded regions are below the respective curves.

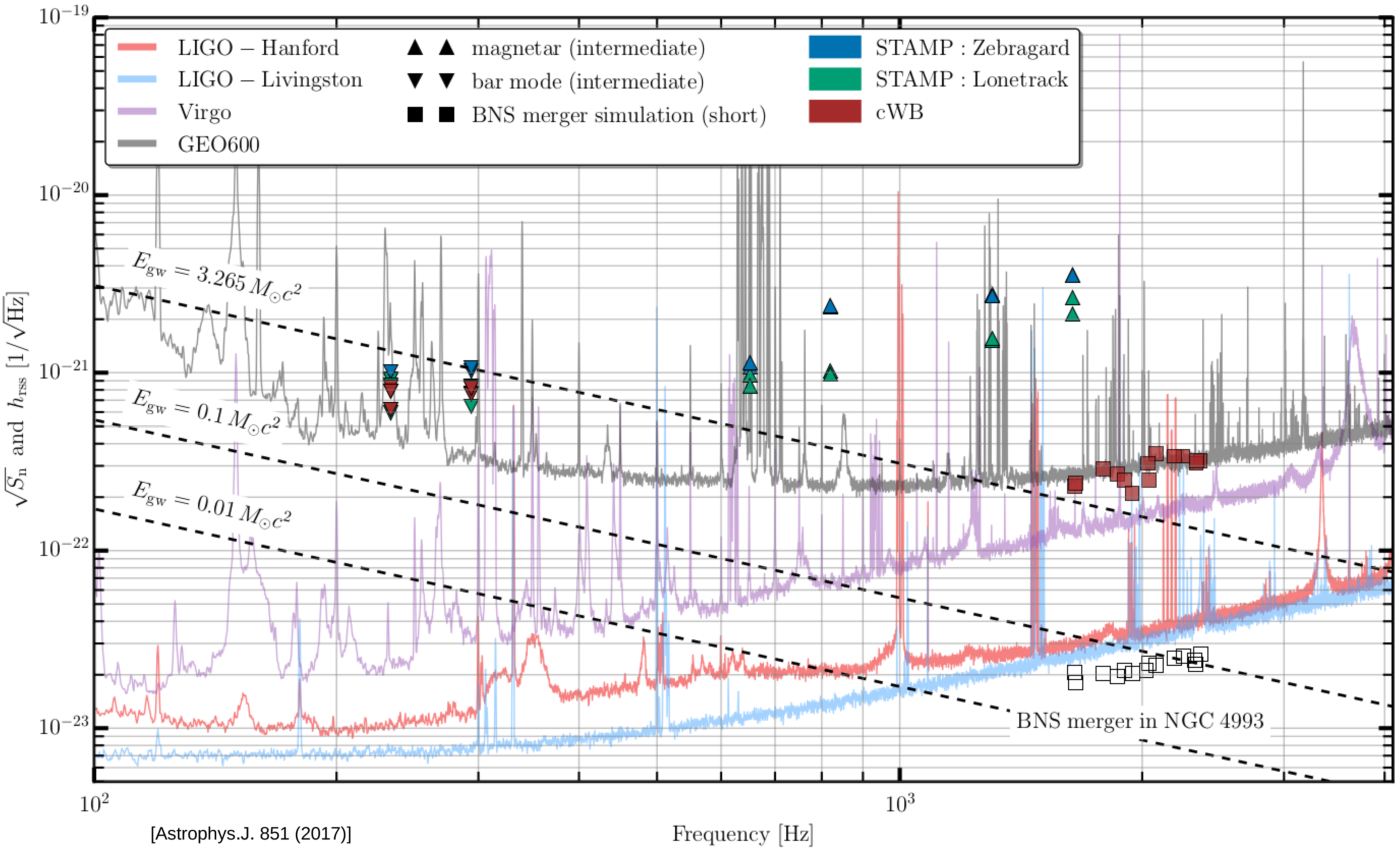
GW170817 : nature of the remnant



The outcome of the BNS can be :

- BH prompt formation, favored by soft EOS
- Hypermassive NS, that collapses to a BH in < 1s
- Supremassive NS, that collapses to a BH in 100-10000s (long-lived transient)
- Stable NS

GW170817 : nature of the remnant

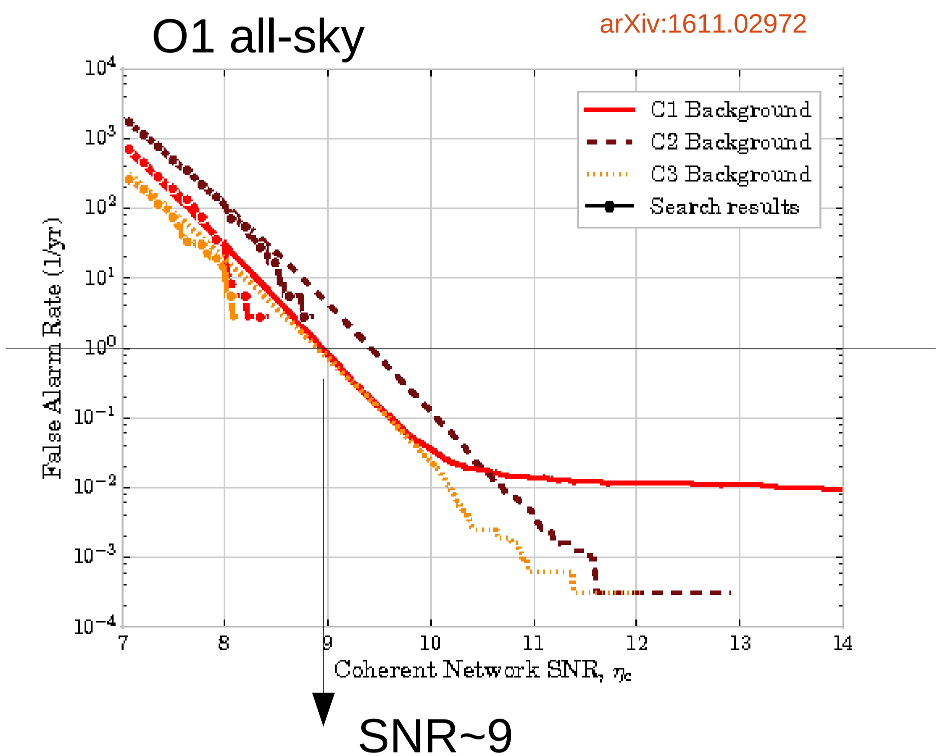


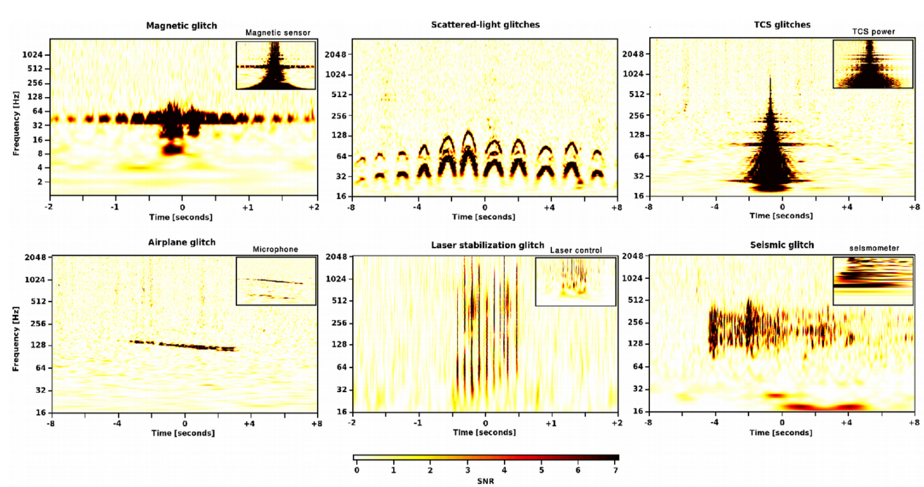
[Astrophys.J. 851 (2017)]

CCSN detection strategy

- Unmodelled burst (<1s) GW event searched at any time and any location in LIGO/Virgo (and soon KAGRA) data. Non Gaussian background does not allow to look for weak signals.

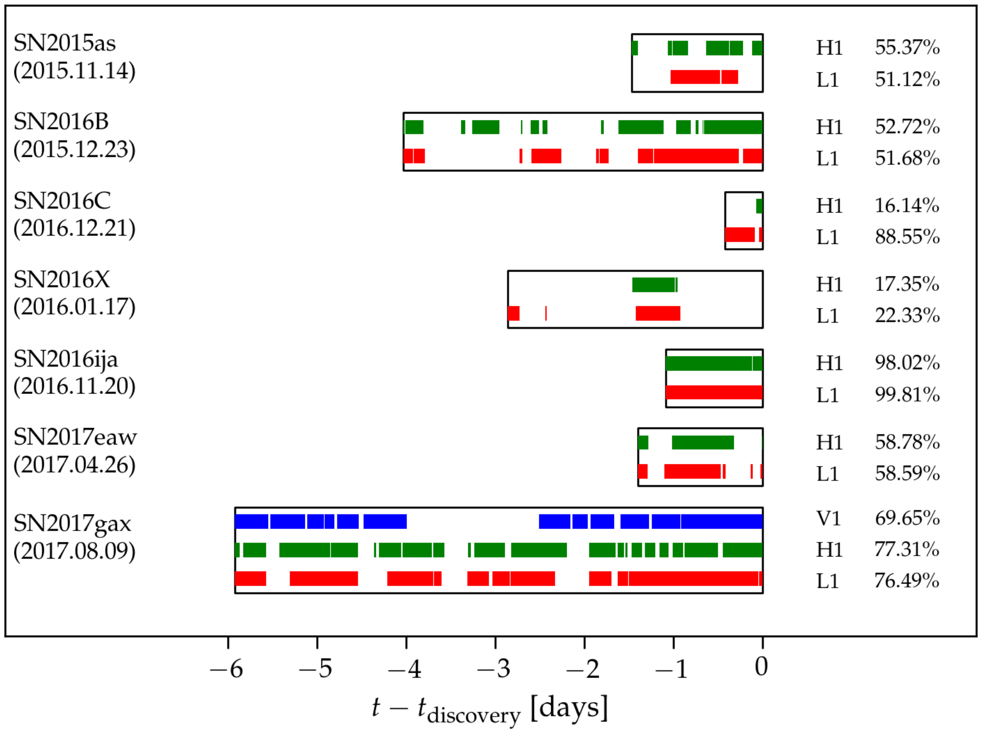
- Triggered search :
  - Neutrino trigger : ~10ms time precision for bounce occurrence time. Sky location ~ 5 deg².
  - Optical trigger : [hours – days] time precision. Sky location ~ arcminutes.





- If we have a precise time window (~1s precision) and the sky location, we can infer the signal below detection threshold.

Multi-messenger searches : CCSN



16 Mpc

19 Mpc

18 Mpc

20 Mpc

15 Mpc

5.9 Mpc

19.7 Mpc

Paper in preparation

- Consider all CCSN within 20 Mpc when at least 2 detectors are on.
- Models : « standard » + 2 extreme emission models (accretion disk around BH[1] and phenomenological long-lasting bar mode instabilities[2]).

[1] Piro & Pfahl Astrophys. J.658, 1173 (2007)

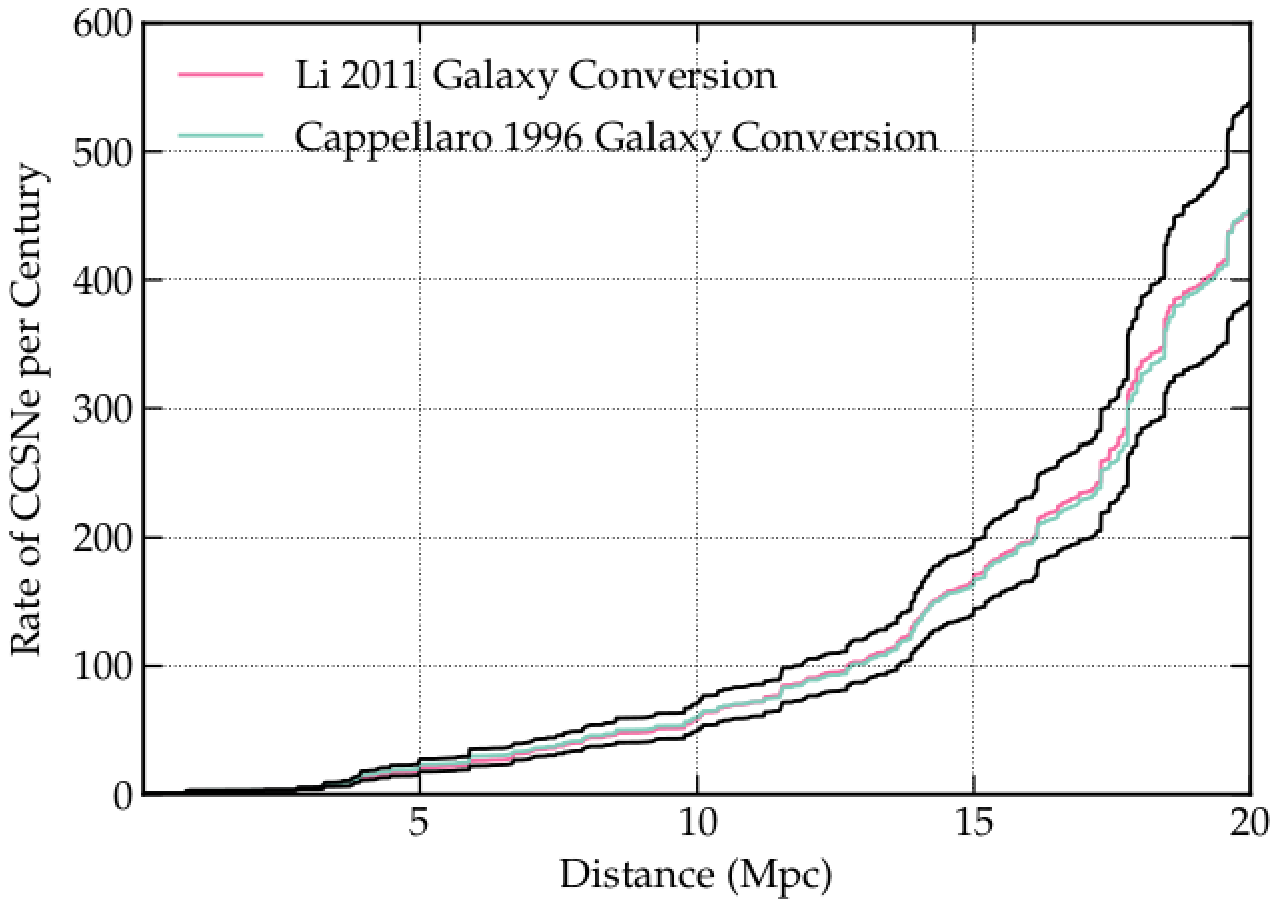
[2] Ott, Tech. Rep. LIGO-T1000553 (2010)

CCSN : how far can we detect ? How many ?

With advanced LIGO and advanced Virgo:

Distance: between 100 kpc (SASI and MHD) and 20 Mpc (extreme model like disk fragmentation and bar mode) [Gossan et al arxiv:1511.02836]

Rate [J. Gill et al]



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[2] Flanagan & Hughes, «Measuring gravitational waves from binary black hole coalescences: 2. The Waves' information and its extraction, with and without templates », Phys.Rev. D57 (1998) 4566-4587

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[6] C Ott, «The Gravitational Wave Signature of Core-Collapse Supernovae », Class.Quant.Grav. 26 (2009) 063001

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