Chirplets pour la détection des ondes gravitationnelles

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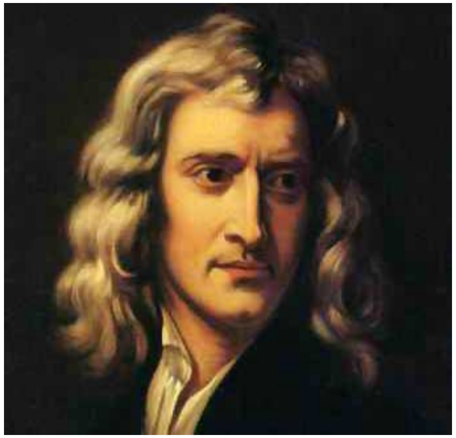
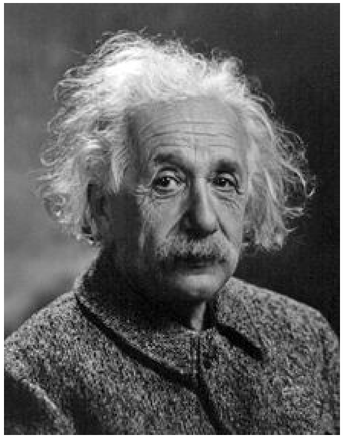
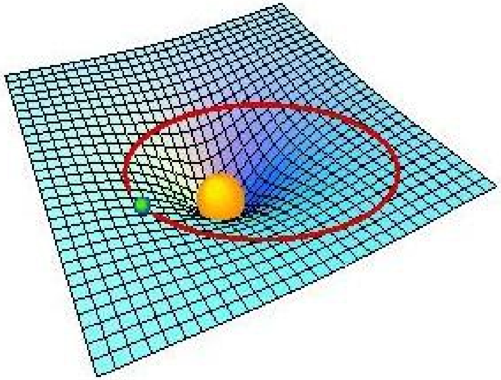
Outline

- Direct detection of GW with large-scale interferometers
- Data analysis techniques for searching for GW transients
  - Non-Gaussian background, estimation and rejection
  - Multi-detector network
- Chirplets

From Newton to Einstein

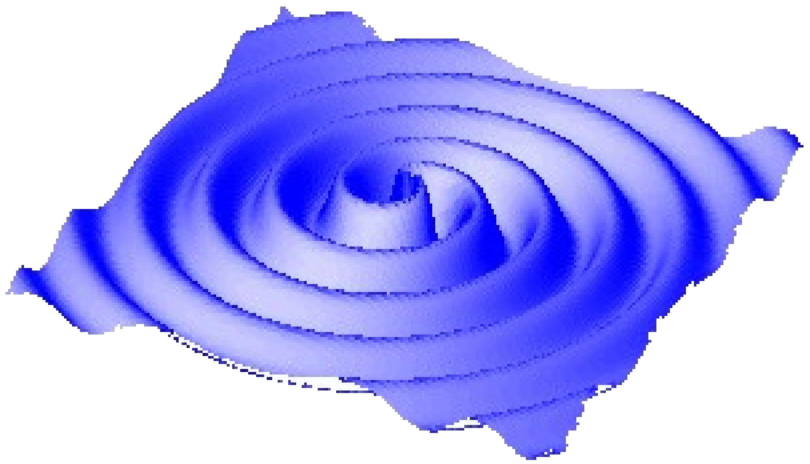


- Newton describes gravity as an **action at a distance** emanating from massive objects
- **Instantaneous** propagation of information
  - Violates special relativity
  - Information cannot propagate faster than light
- **General relativity**
  - Spacetime is a deformable and dynamic object
  - Gravity describes as a geometrical effect coming from spacetime curvature
  - Spacetime dynamics = Einstein's equations

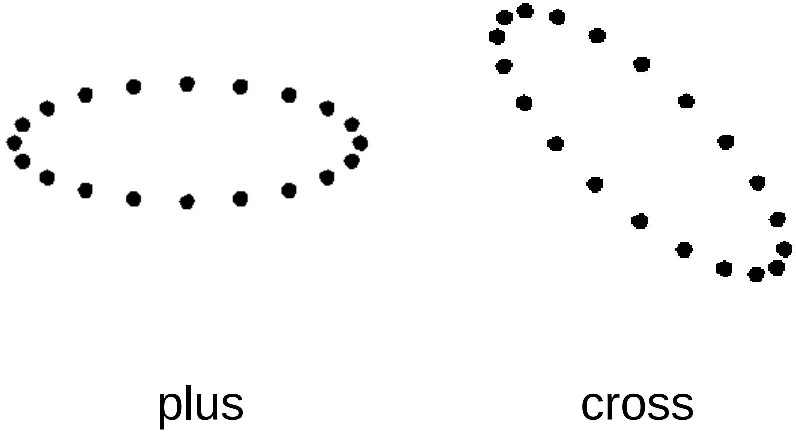
“spacetime tells matter how to move;
matter tells spacetime how to curve”

Gravitational waves GW

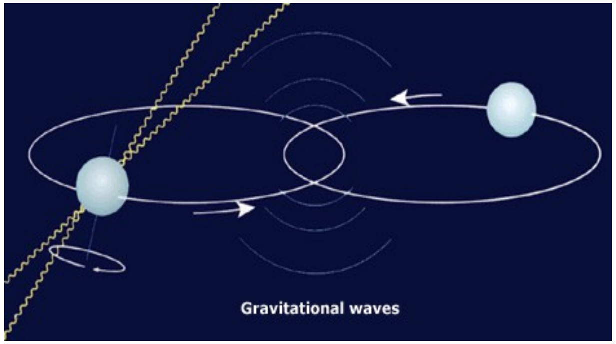
- Propagating distorsions of space-time metric
  - Predicted by General Relativity
  - Propagate at the speed of light
  - Transverse and quadrupolar (in far field)
  - Two polarizations (+ and x)
  - Dimensionless strain amplitude *h*



- Sources of GW
  - Produced by accelerated mass
  - Rapid changes in shape and orientation of massive objects
  - Large mass and density, relativistic motion → astrophysical sources

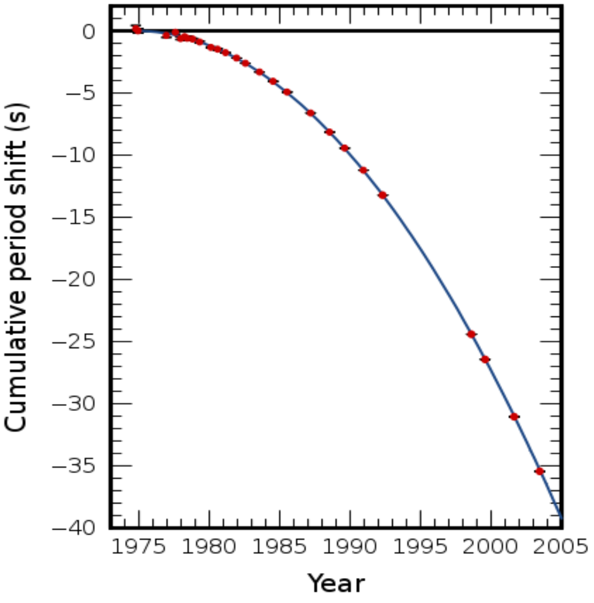


Indirect evidence



- Binary pulsar PSR B1913+16
  - Orbital decay → energy loss due to GW
  - In agreement with GR to ~0.2 %
  - Hulse & Taylor's Nobel prize

Binary orbit will continue to decay
over 300 millions years until coalescence



- GWs from binary systems
  - Estimate with quadrupole formula

$$h \sim G/c^4\,\ddot{Q}/d$$

  - For a binary close to coalescence

$$h_{expect} \propto MR^2 f^2/d \approx 10^{-21}$$

R=20 km, M=1.4 M_{sun}, f=400 Hz, d=15 Mpc

Direct detection of GW

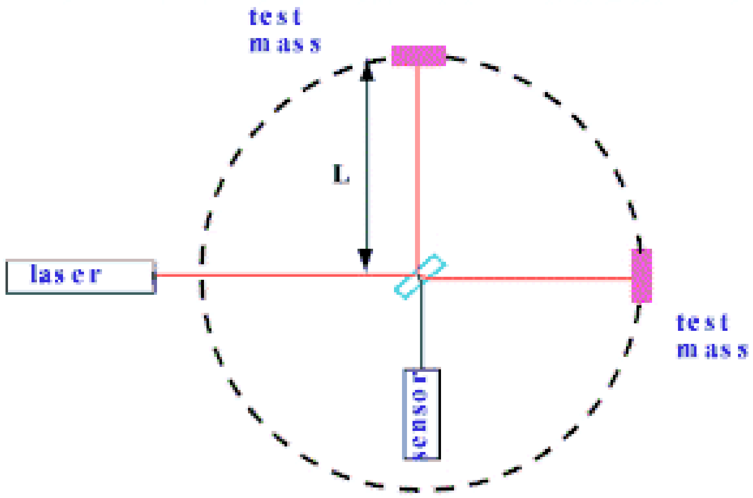
- Michelson interferometer
  - test mass displacement due to GW → phase shift measurement

$$h(t) = \frac{\delta L(t)}{L} \propto \delta\Phi(t)$$

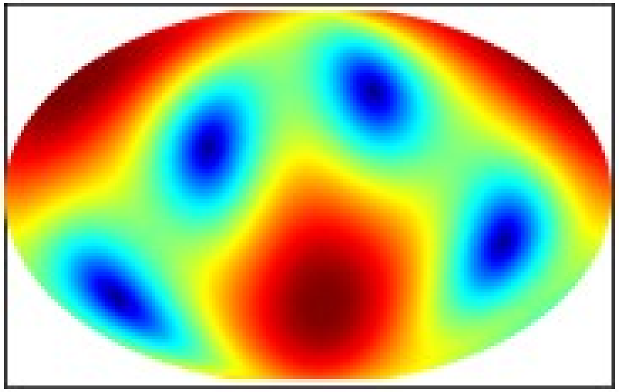
- Sees mixture of both polarizations

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

- Large aperture: not directional
  - more like a ear than an eye!
  - 1D time series (not a 2D image)



Virgo

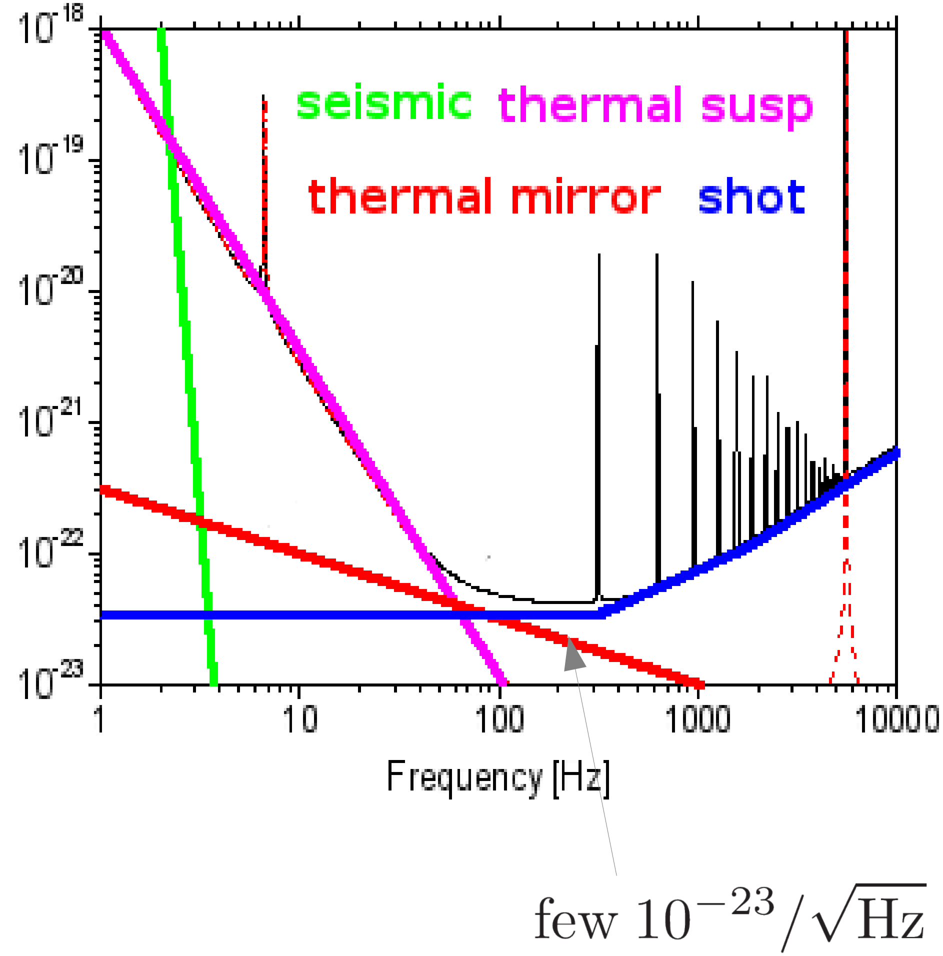


$(F_+^2 + F_\times^2)^{1/2}$

Sensitivity of interferometric GW detectors

- High-precision metrology
- Measurement limitations
  - Fundamental sensing and displacement noises
  - “Technical” noises (controls, electronics, acoustic, etc.)

  $$h_{noise} \approx 10^{-21}$$
- Observable freq. band
  - From few 10 Hz to few kHz

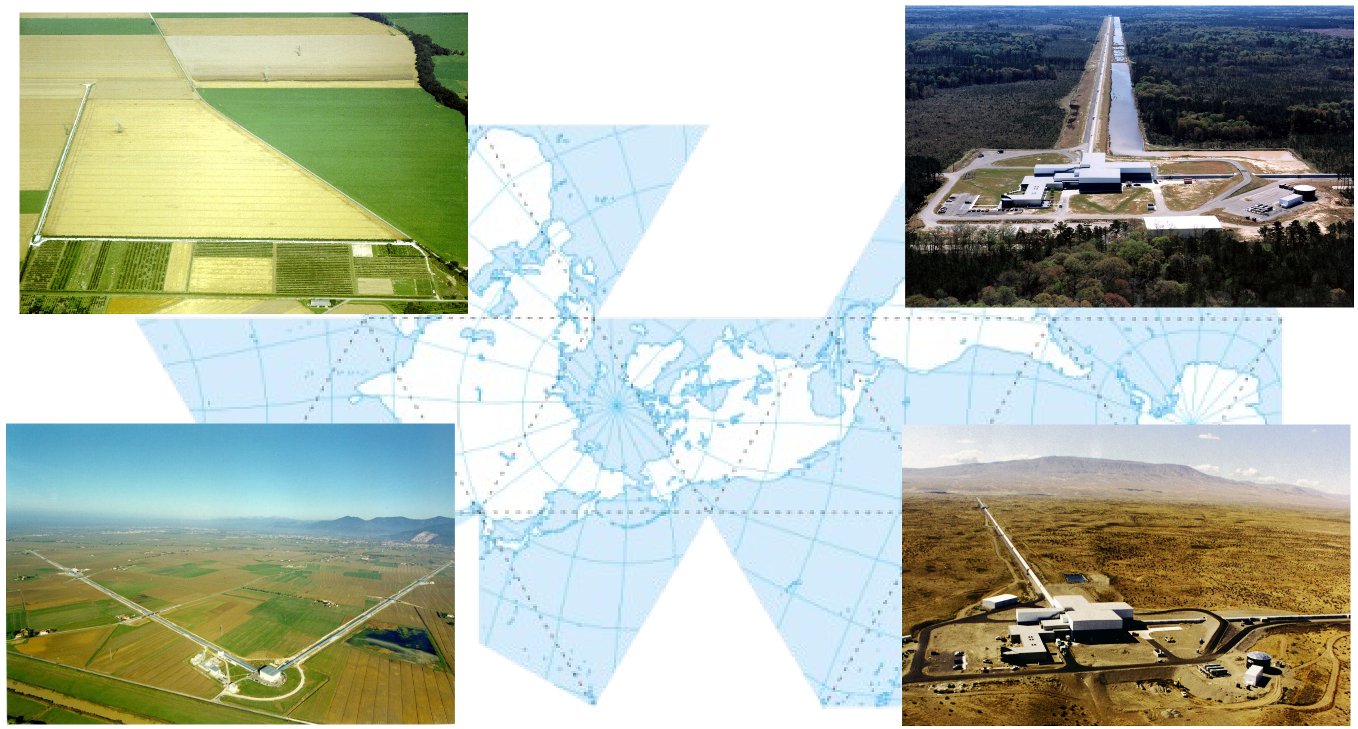


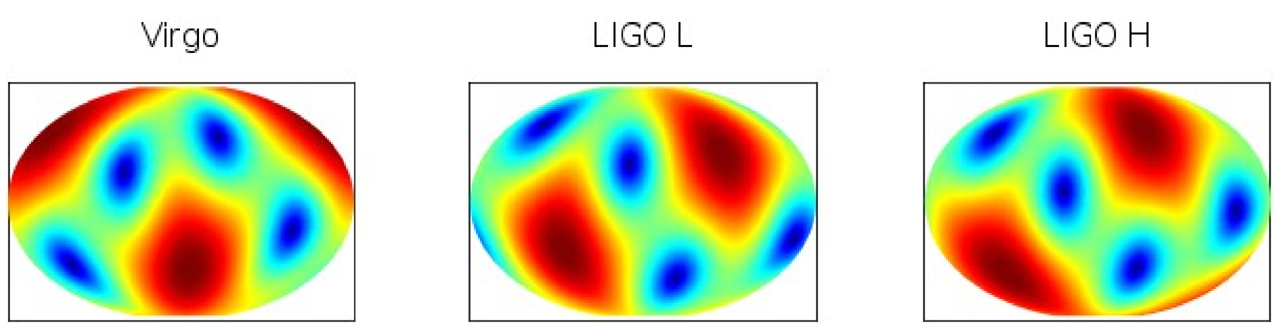
Worldwide network of GW detectors

GEO 600
Germany

Virgo
Italy

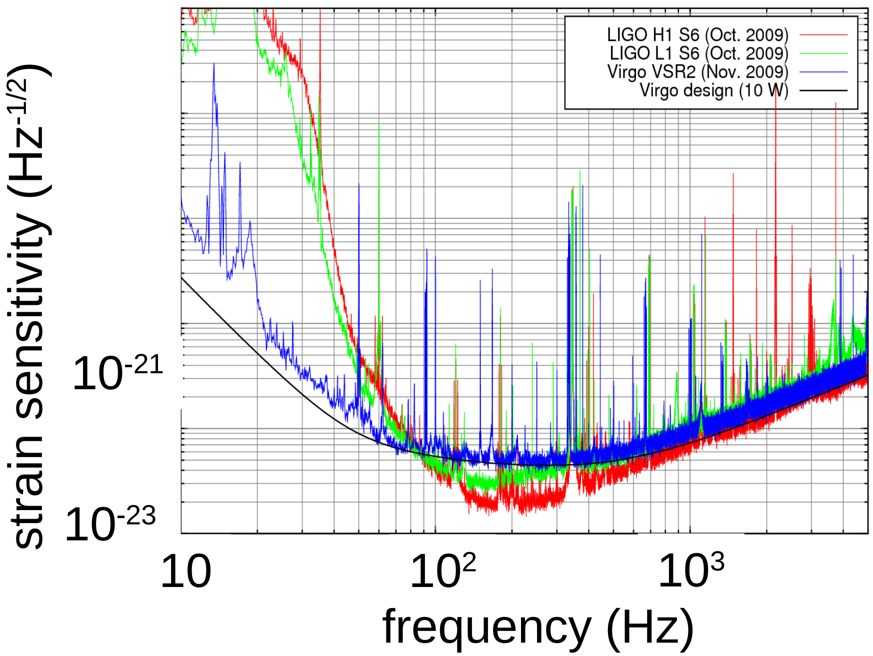
LIGO
US

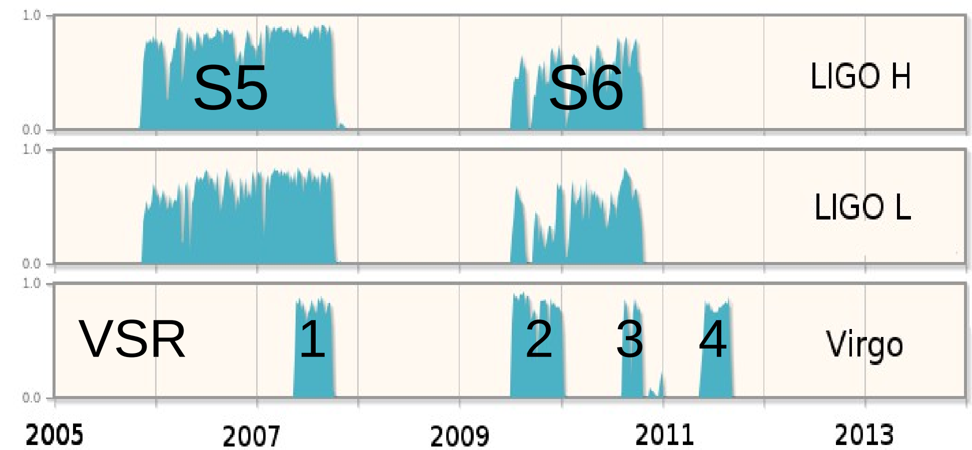




Since 2007, partnership and data exchange agreement

Achieved sensitivity and data takings





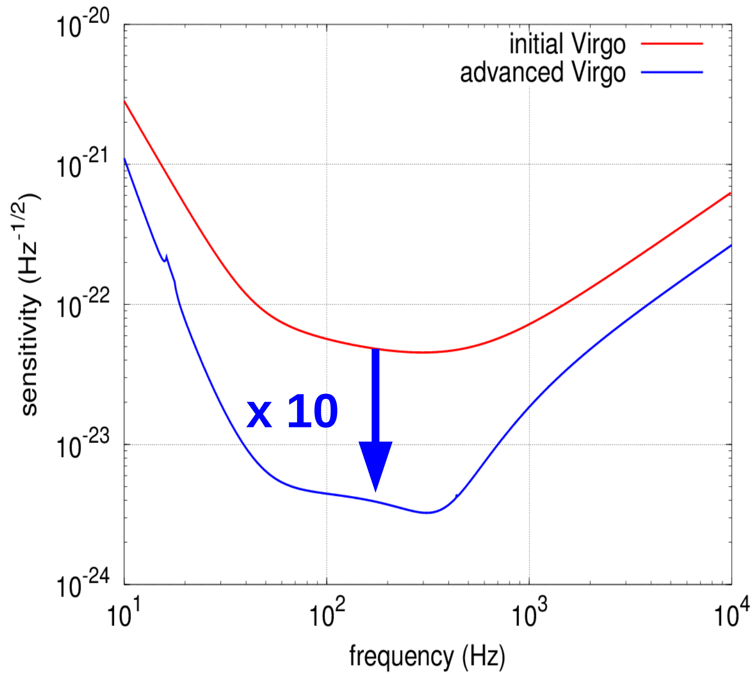
Reached design sensitivity

Detectability horizon to coalescing neutron-star binaries (BNS) is ~ 20 – 40 Mpc

3 joint LIGO – Virgo science runs

~2 yrs total

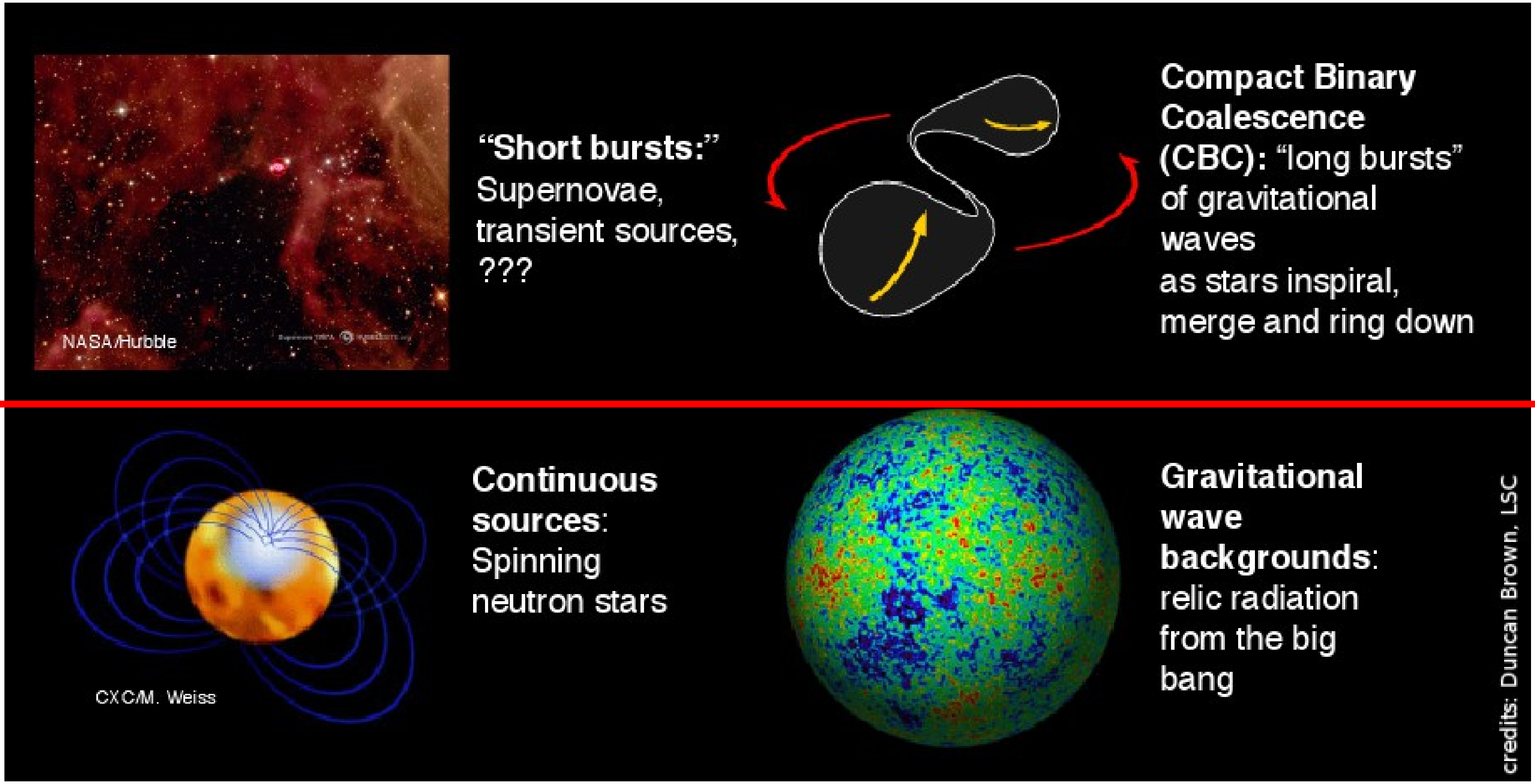
What's next?



- Horizon of initial detectors too small
- Advanced detector: sensitivity x 10
  - Use same vacuum enclosure
  - Upgrade instrumentation
  - BNS out to 140 Mpc
- → x 1000 more events
  - Few 10^{th} of BNS/year
- Advanced Virgo approved
  - Installation under way
  - First science data 2016
  - Similar upgrade for LIGO
  - Kagra (Japan), LIGO India

Sources of gravitational waves

We will be interested in transient sources in this presentation

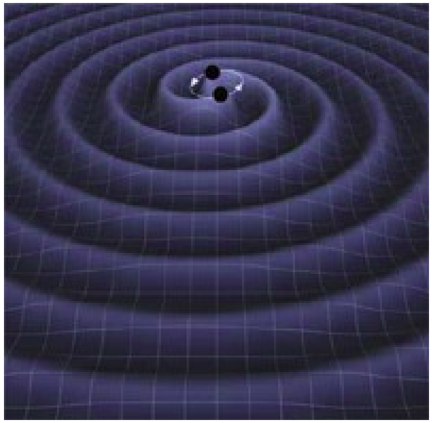


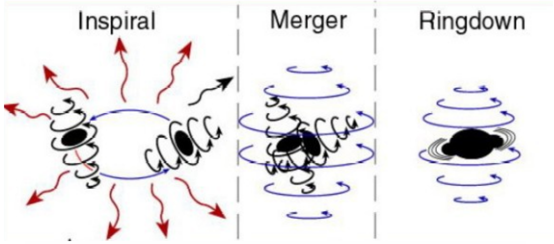
Sources of gravitational wave transients

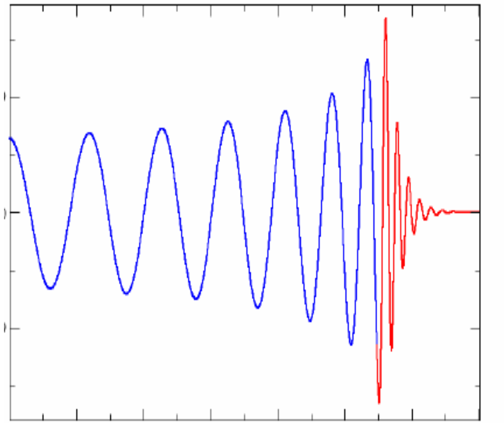
- Catastrophic astrophysical events

  the "violent Universe"
- Efficient production of GWs
  - compact objects: neutron stars (NS)

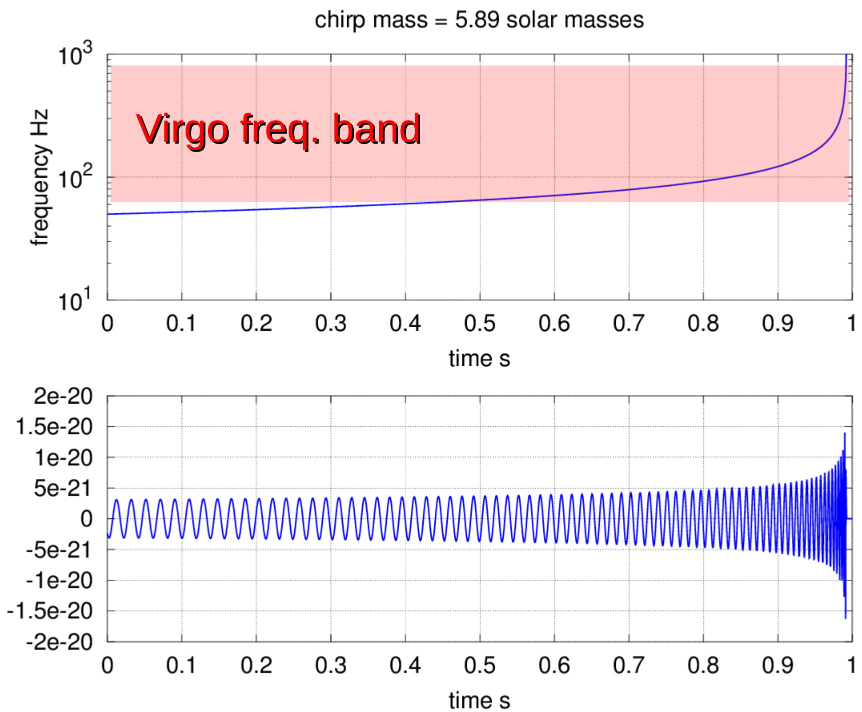
    or black holes (BH)
  - bulk motion at relativistic velocities
  - Some degree of asymmetry
- Binary mergers (BNS, BH-NS, BBH)
  - Frequency modulated, chirp-like signals
  - GW phase ~ 2 x orbital phase
  - Orbital phase obtained by post-Newtonian expansions. Phase evolution is power law.
  - Numerical relativity required in the final merger part

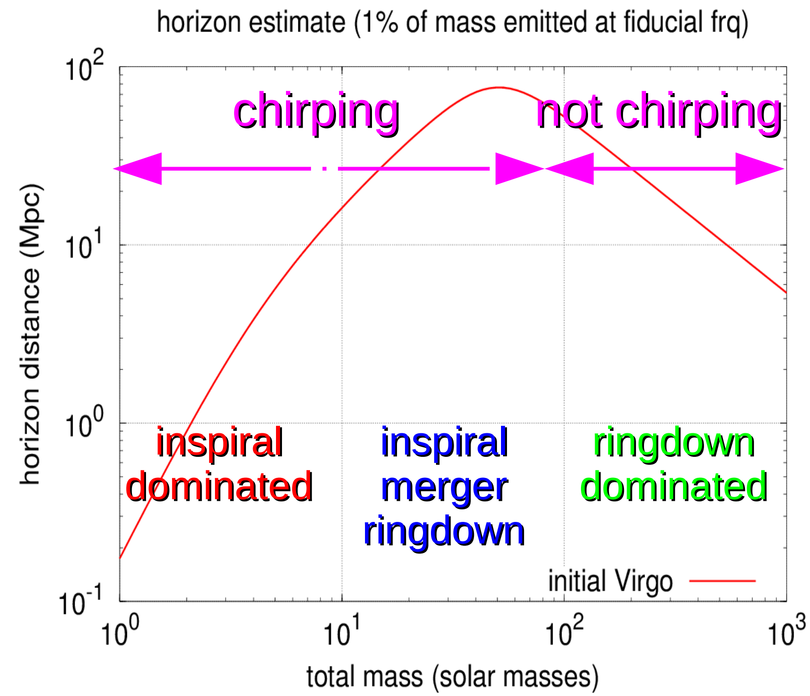


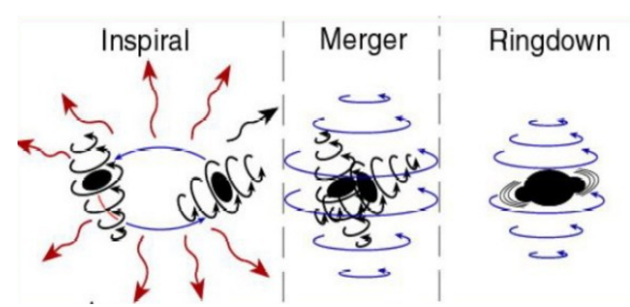




More on GW chirp from inspiralling binaries





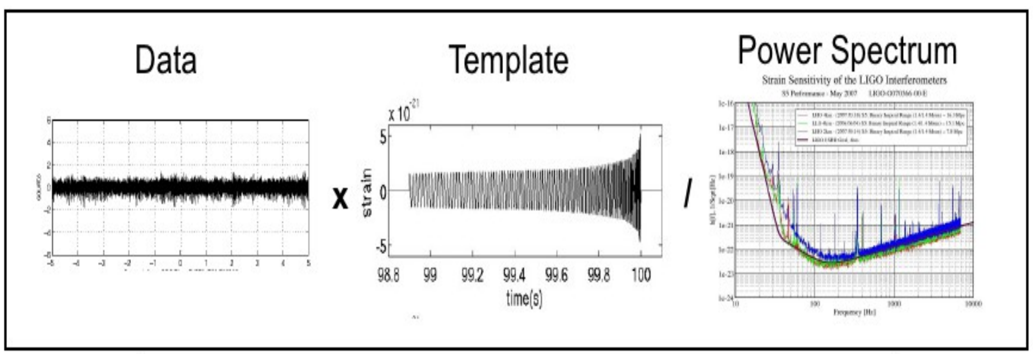


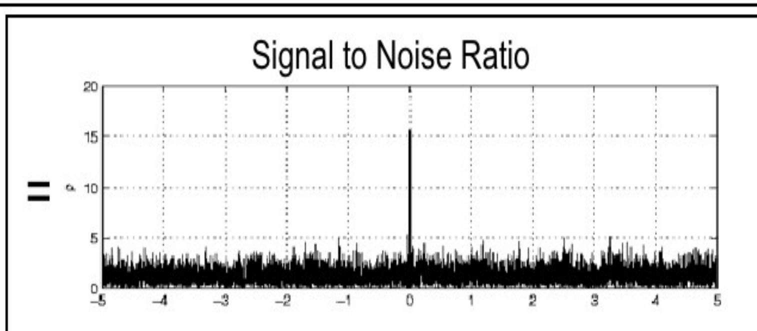
- Characterized by the two component masses + binary orientation
- More complete models includes spins as well

Searches for GW transients

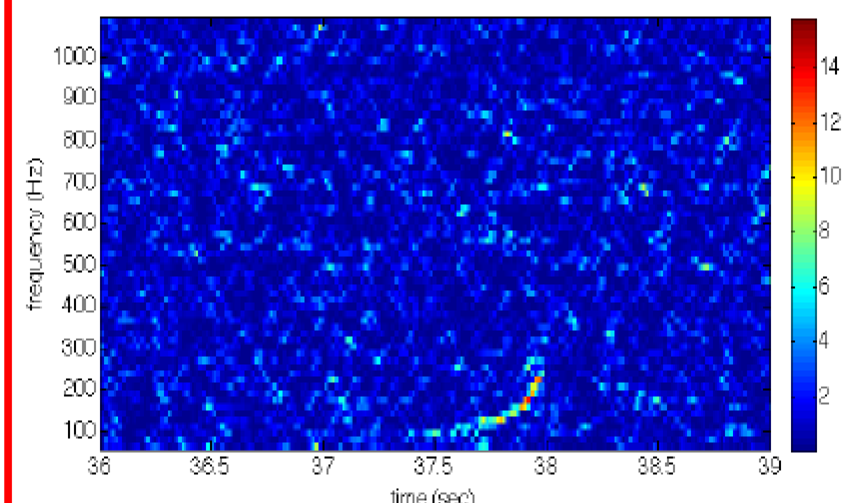
Time series analysis
rare transients with low signal to noise ratio

Expected signal is **known**
(inspiralling binaries)
Matched filtering

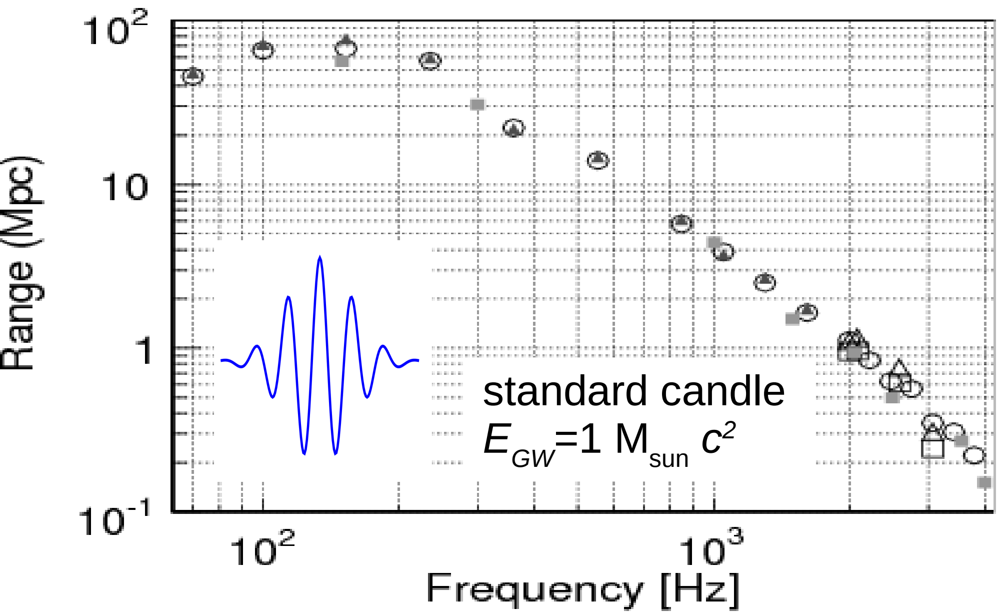




Expected signal is **unknown**
Excess in time-frequency maps
(wavelets)



Selection of results



$$\text{Range} \sim \sqrt{E_{GW}}$$

detectable GW energy at a given distance

10 kpc: E_{GW}= 3 x 10^{-8} M_{sun} c^2
(comparable to CC SN)

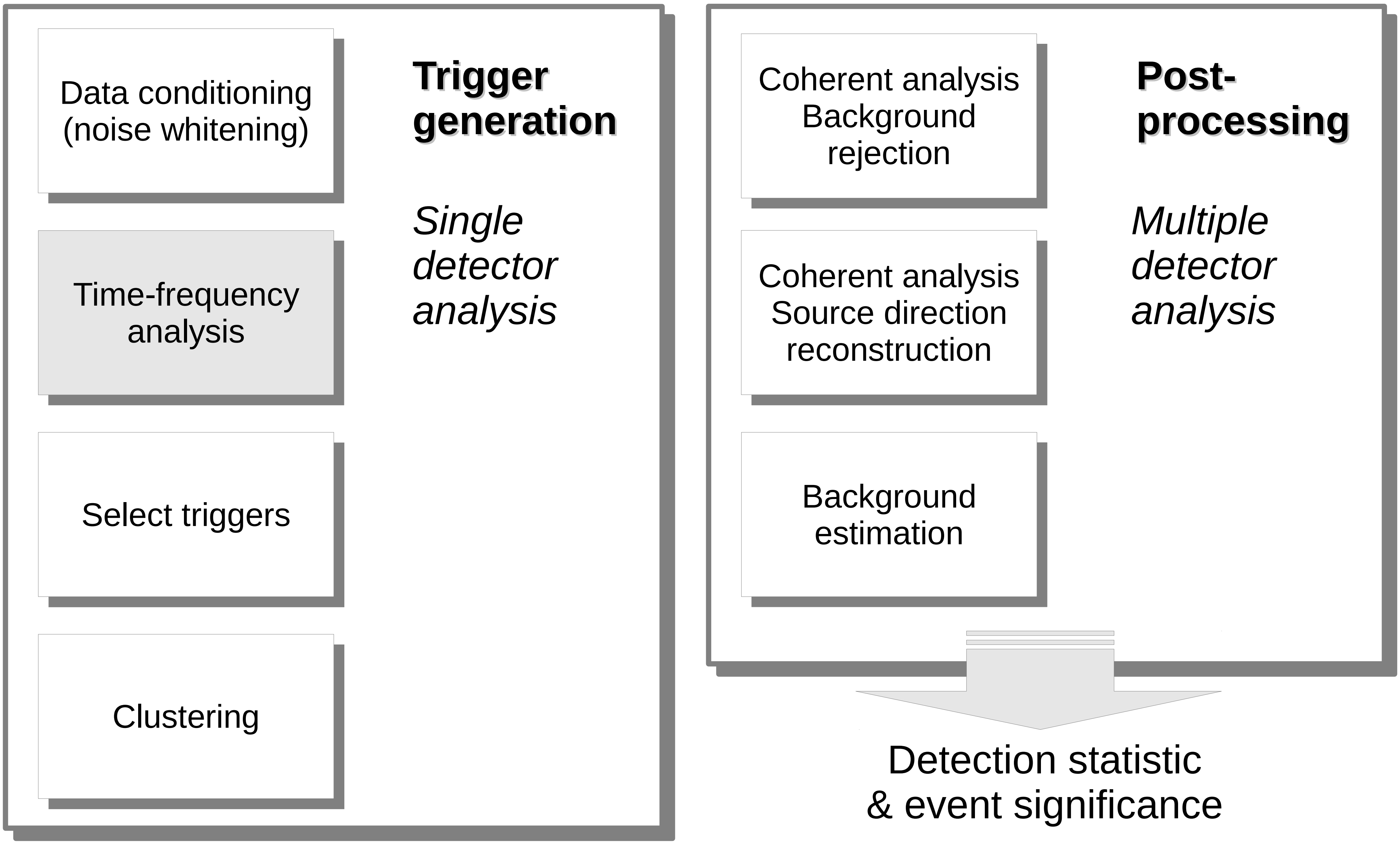
15 Mpc: E_{GW}= 10^{-1} M_{sun} c^2
(comparable to black-hole binary merger)

- Latest “all-sky” burst search
  - S5-VSR1 & S6-VSR 2/3: 2 yrs observation total
  - Transients (< 1s) in 64 Hz– 5 kHz
  - Search with coherent WaveBurst
  - **No GW candidate event**
  - Upper-limits on the rate of bursts estimated using generic waveforms
- Blind injections
  - Fake signals secretly added to the data to test the detector and analysis
  - Last test: event (inspiral) **successfully recovered** as a detection candidate with FAR < 1/7000 y (> 4 sigma)

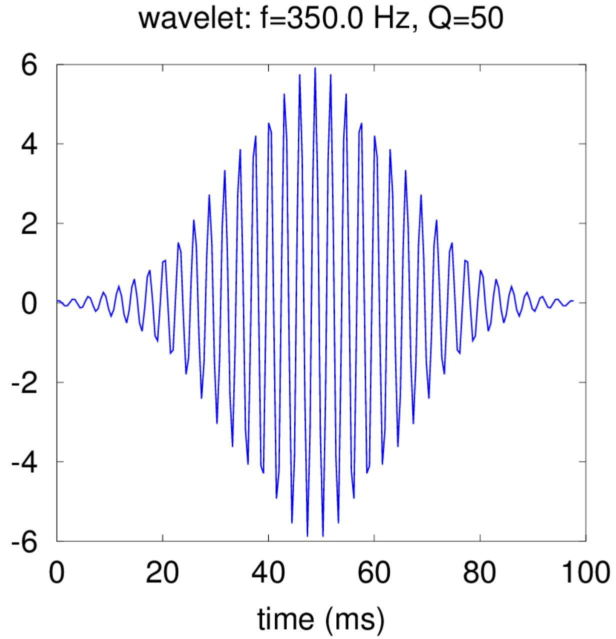
Full story: arXiv:1111.7314

http://www.ligo.org/science/GW100916

Basics about GW burst searches



Morlet/sine-Gaussian wavelets



$$\psi(\tau+t) = A\exp\left(-\frac{(2\pi f)^2}{Q^2}\right)\exp(2\pi i f\tau)$$

- Overcomplete wavelet families that minimize SNR loss

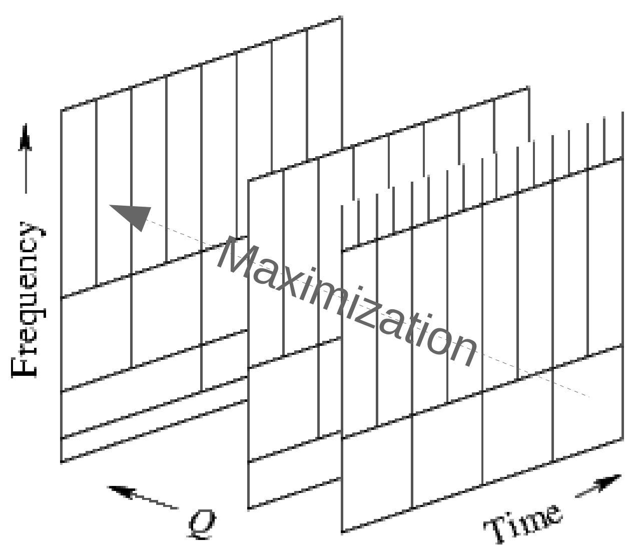
$$\mu = 1 - \int d\tau\, \psi(\tau;p)\psi(\tau;p+\delta p)$$

2nd order approx., metric in wavelet space

$$\mu = \frac{4\pi^2 f^2}{Q^2}\delta t^2 + \frac{2+Q^2}{4f^2}\delta f^2 + \frac{\delta Q^2}{2Q^2} - \frac{\delta f\,\delta Q}{Qf}$$

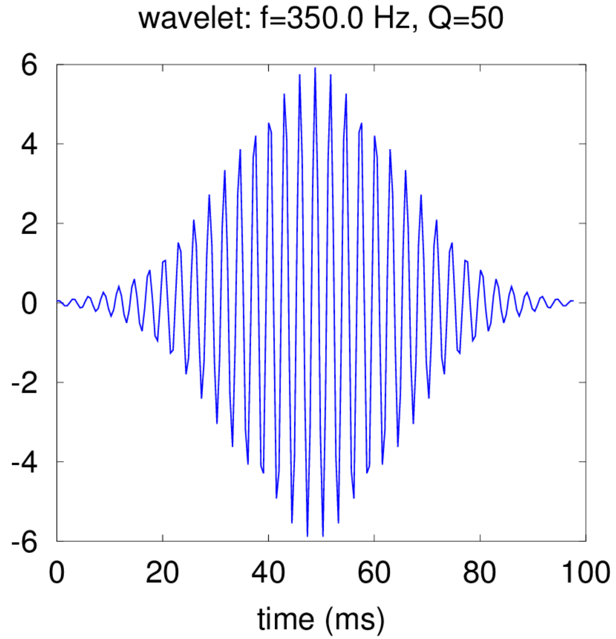
Multiresolution! Wavelet transform

Logaritmic sampling in Q



Find best matching wavelets at each t,f location

Morlet/sine-Gaussian wavelets



$$\psi(\tau + t) = A \exp\left(-\frac{(2\pi f)^2}{Q^2}\right) \exp(2\pi i f \tau)$$

- Overcomplete wavelet families that minimize SNR loss

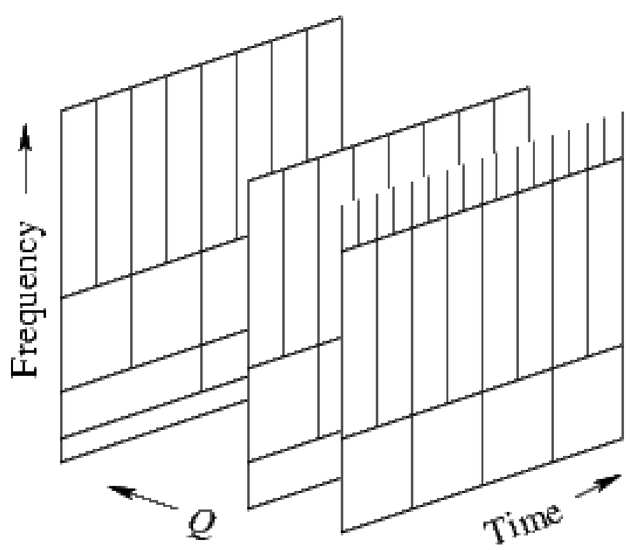
$$\mu = 1 - \int d\tau \, \psi(\tau; p)\psi(\tau; p + \delta p)$$

2nd order approx., metric in wavelet space

$$\mu = \frac{4\pi^2 f^2}{Q^2}\delta t^2 + \frac{2 + Q^2}{4 f^2}\delta f^2 + \frac{\delta Q^2}{2Q^2} - \frac{\delta f \delta Q}{Q f}$$

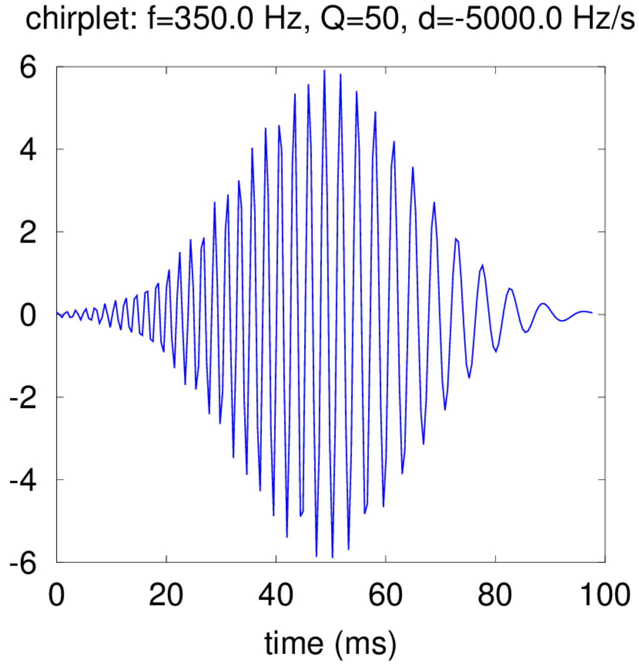
Multiresolution! Wavelet transform

Logaritmic sampling in Q



Cst frequency/stationary wavelets poorly adapted to chirping signals

Chirplets (1)

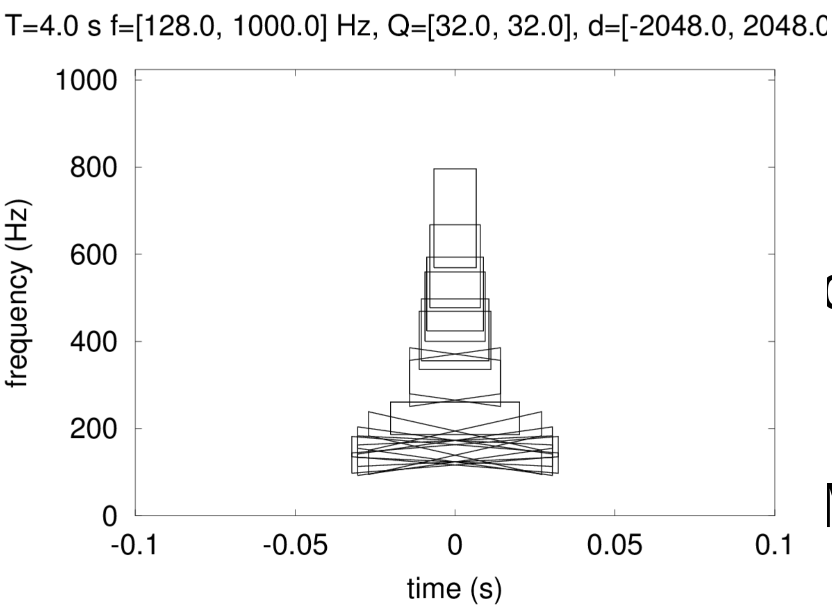


$$\psi(\tau + t) = A \exp\left(-\frac{(2\pi f)^2}{Q^2}\right) \exp(2\pi i [f\tau + d/2\, \tau^2])$$

- Metric in chirplet space

$$\mu = \frac{Q^4 d^2 + 16\pi^2 f^4}{4Q^2 f^2}\delta t^2 + \frac{2+Q^2}{4f^2}\delta f^2 + \frac{\delta Q^2}{2Q^2} + \frac{Q^4}{128\pi^2 f^4}\delta d^2 - \frac{Q^2 d}{2f^2}\delta t \delta f - \frac{\delta f \delta Q}{Qf}$$

$$\delta d \propto (f/Q)^2$$



- # of chirplets required for full coverage

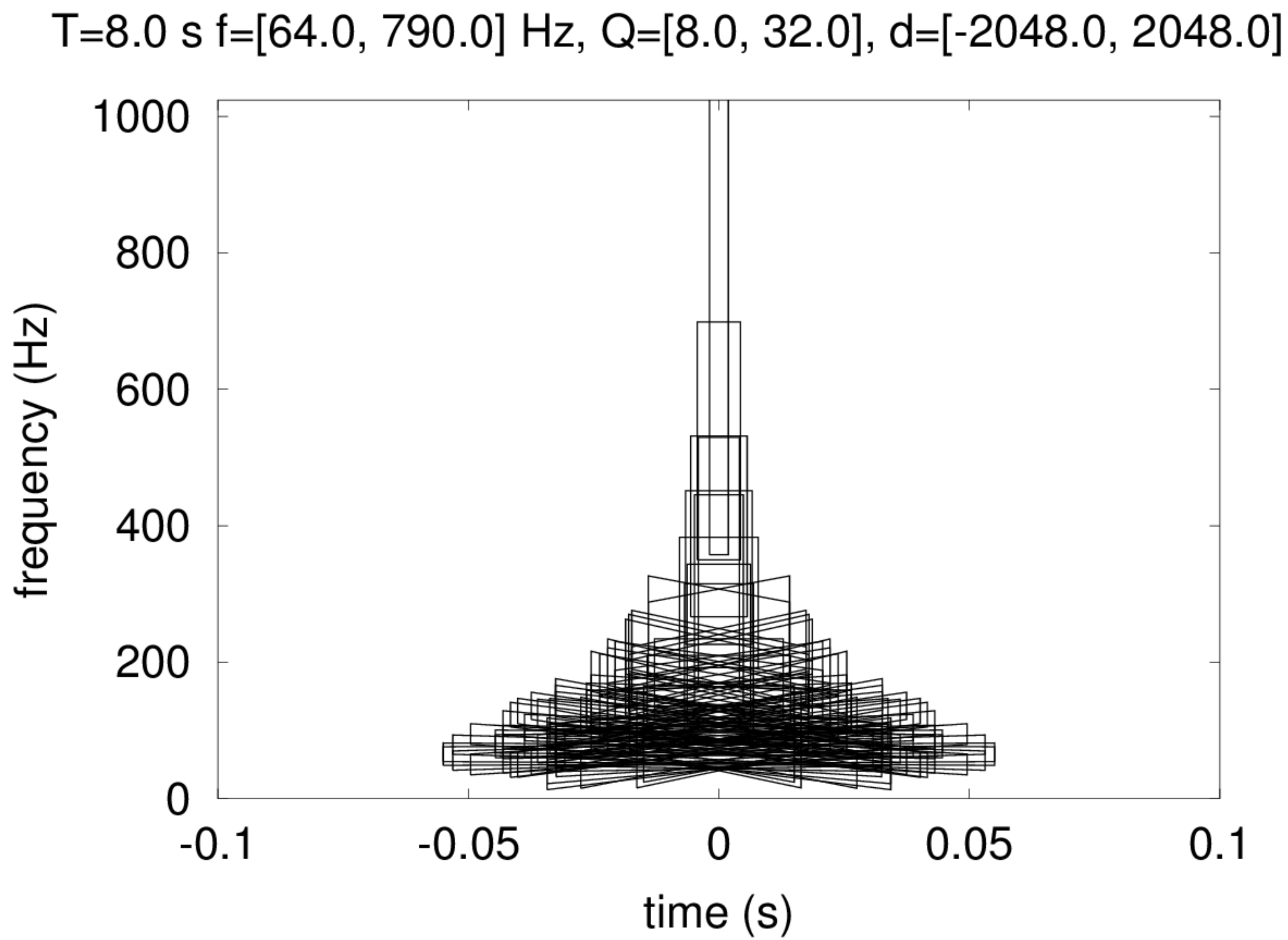
$$\mathcal{N} \propto Q_{max}^3 d_{max} / f_{min}^2$$

compared to # of wavelets

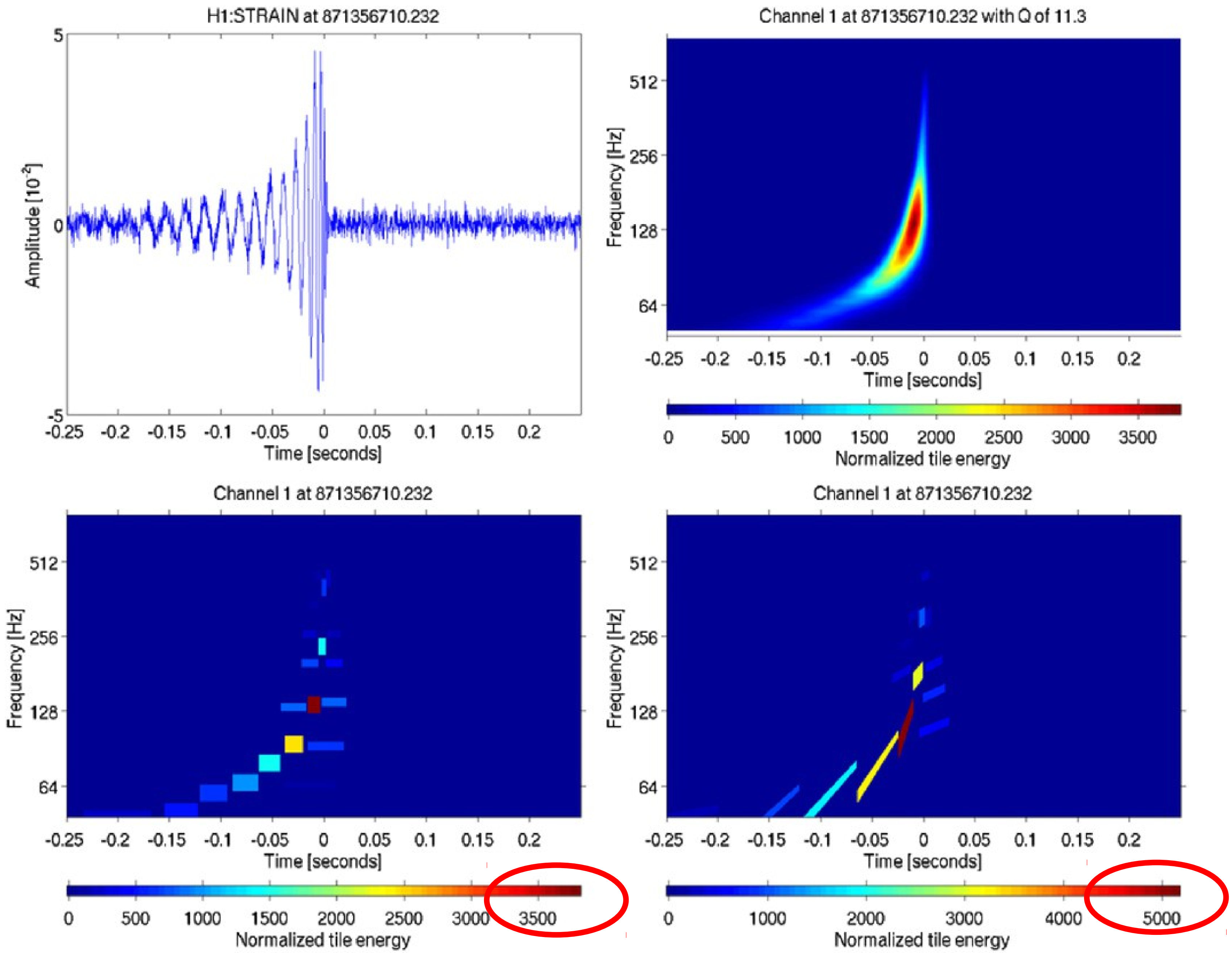
$$\mathcal{N} \propto f_{max} \log Q_{max}$$

Much broader signal space!

Chirplets (2)



T=8.0 s f=[64.0, 790.0] Hz, Q=[8.0, 32.0], d=[-2048.0, 2048.0]
1000
800
600
400
200
0
frequency (Hz)
-0.1
-0.05
0
0.05
0.1
time (s)



wavelets

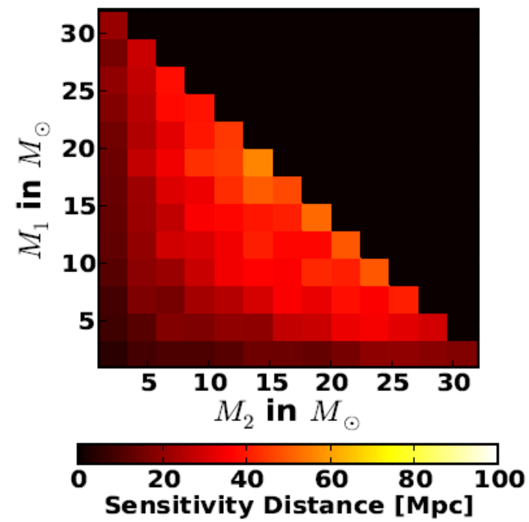
chirplets

Performance studies (1)

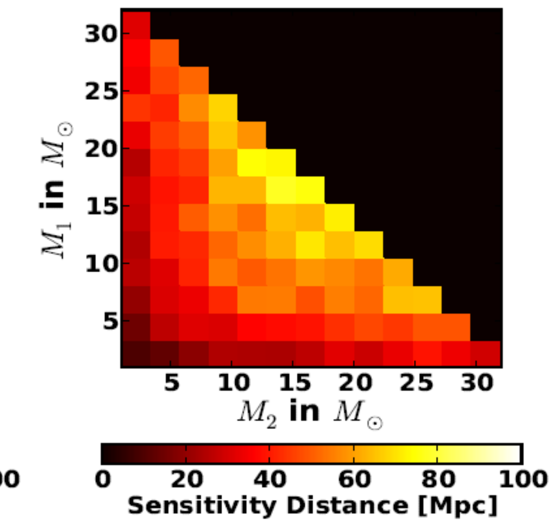
Monte-Carlo to evaluate the detectability of inspiralling binary chirp with chirplets

Improvement for low-mass BBH horizon x ~1.5 – event rate x 3

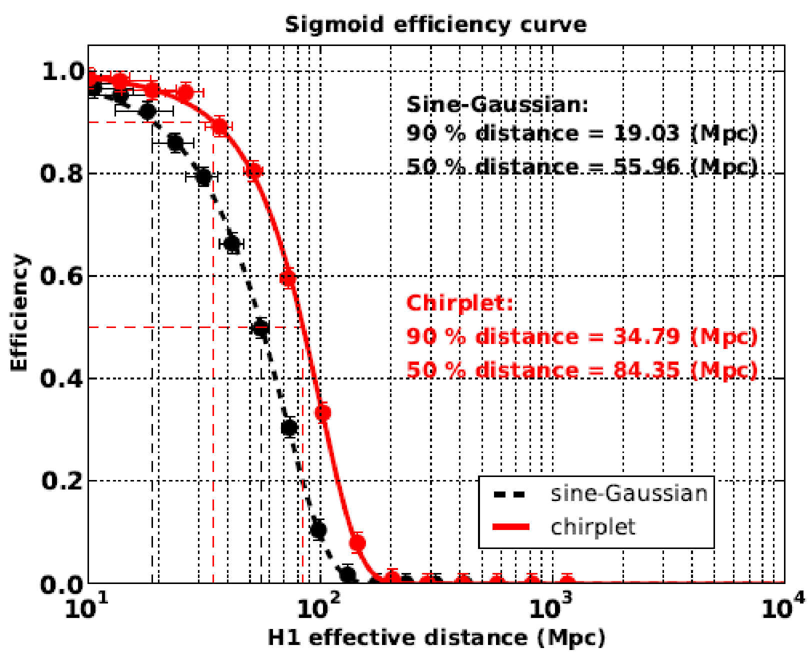
wavelets vs chirplets



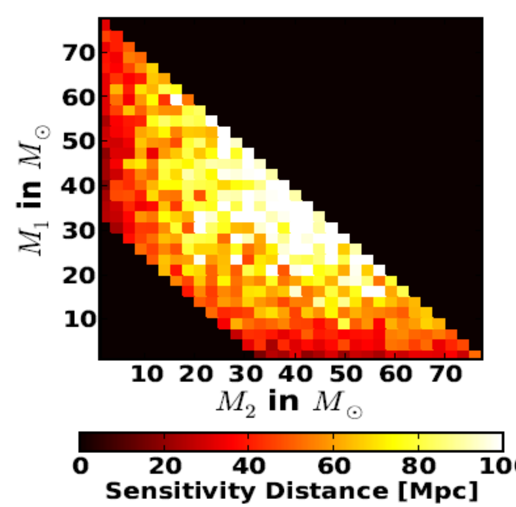
(a) Sine-Gaussians on 4-35 $M_\odot$.



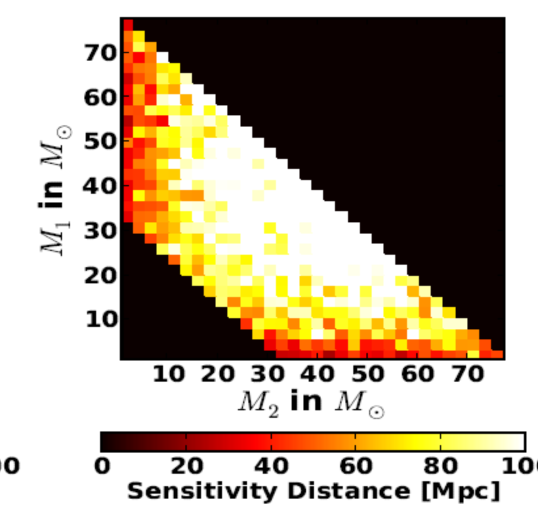
(b) Chirplets on 4-35 $M_\odot$.



(a) Efficiency curves for set 4-35 $M_\odot$.



(d) Sine-Gaussians on 35-80 $M_\odot$.



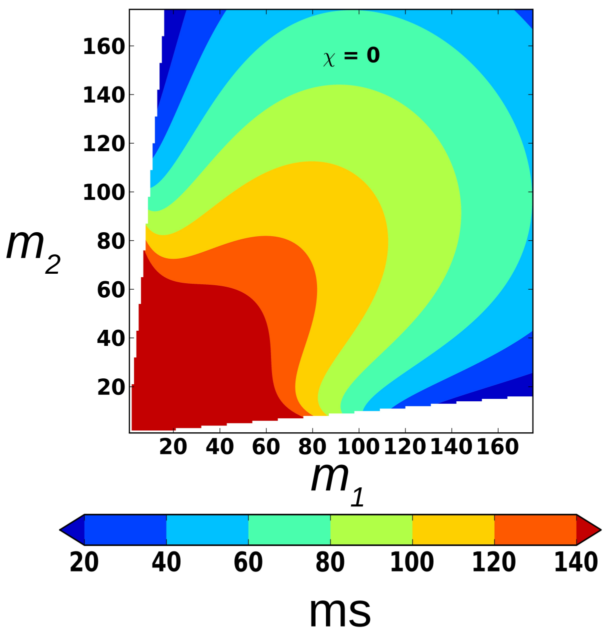
(e) Chirplets on 35-80 $M_\odot$.

Performance studies (2)

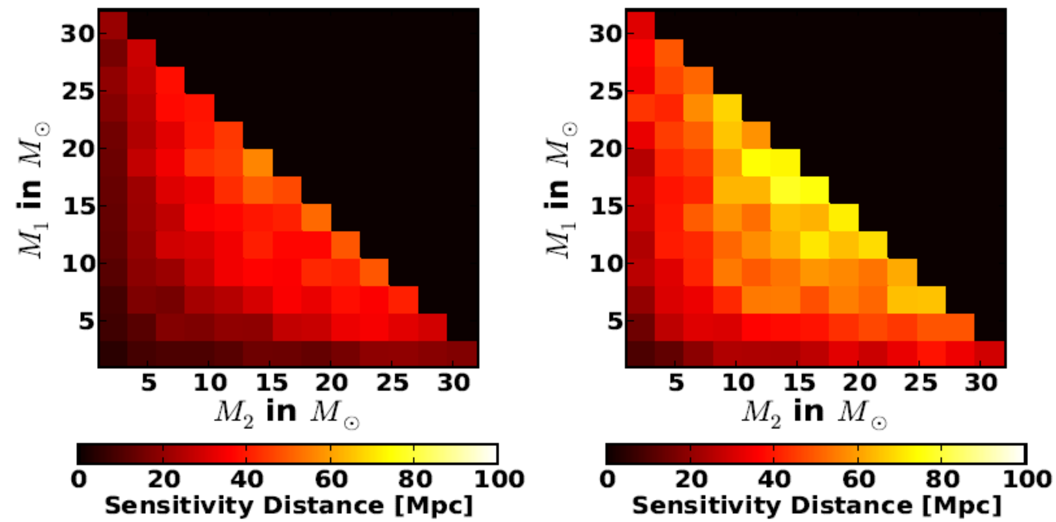
Monte-Carlo to evaluate the detectability of inspiralling binary chirp with chirplets

Improvement for low-mass BBH horizon x ~1.5 – event rate x 3

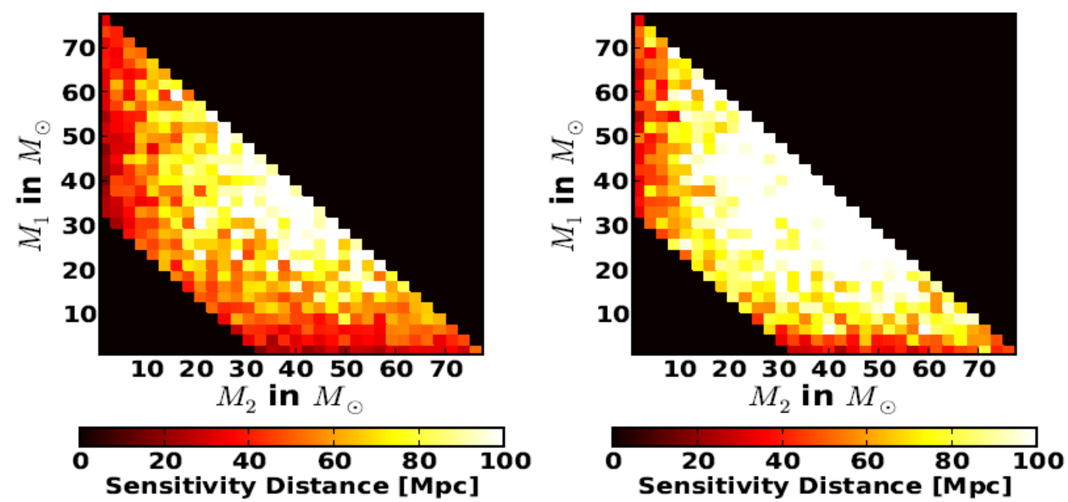
Equal-mass binaries have longer chirp time



wavelets vs chirplets



(a) Sine-Gaussians on 4-35 $M_\odot$. (b) Chirplets on 4-35 $M_\odot$.



(d) Sine-Gaussians on 35-80 $M_\odot$. (e) Chirplets on 35-80 $M_\odot$.

Basics about GW burst searches

Trigger generation

Single detector analysis

- Data conditioning (noise whitening)
- Time-frequency analysis
- Select triggers
- Clustering

Post-processing

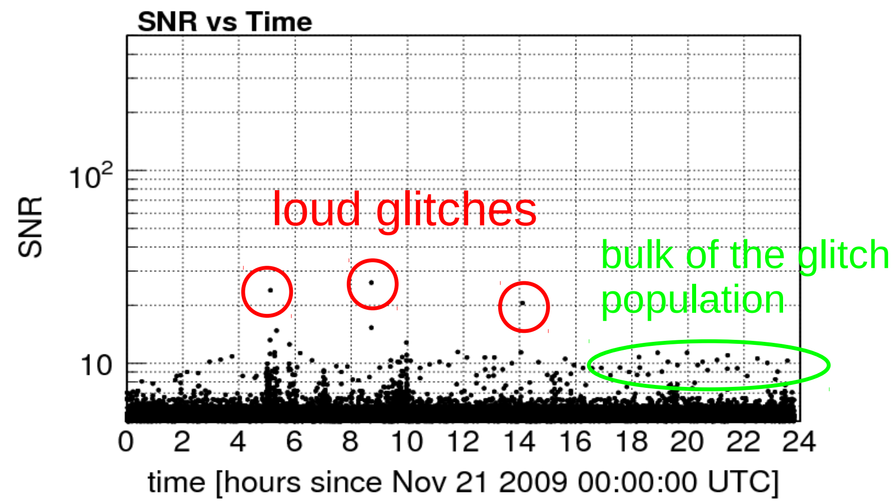
Multiple detector analysis

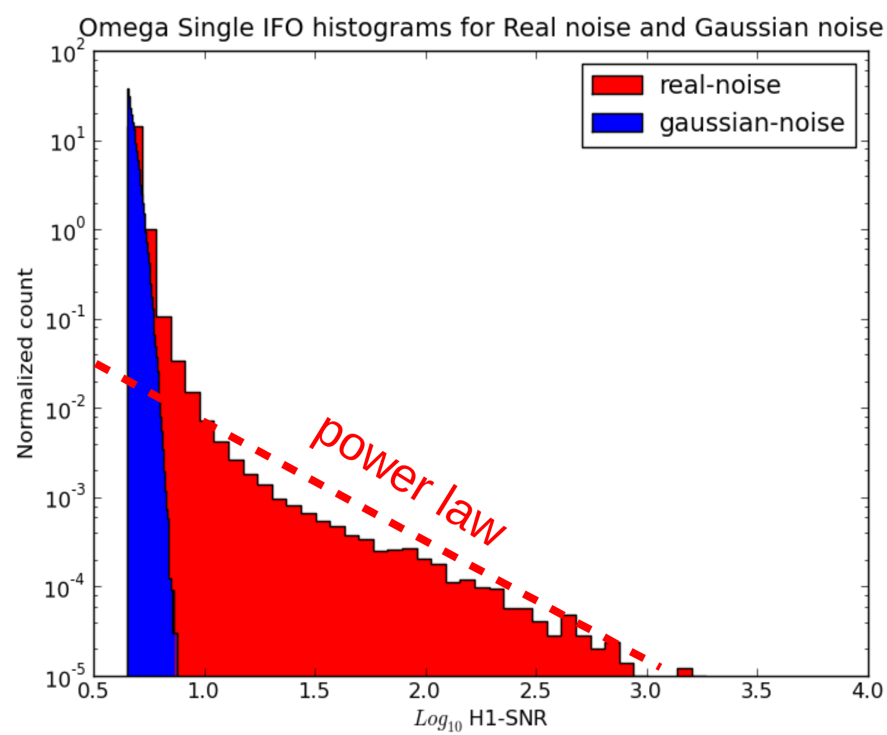
- Coherent analysis Background rejection
- Coherent analysis Source direction reconstruction
- Background estimation

Detection statistic
& event significance

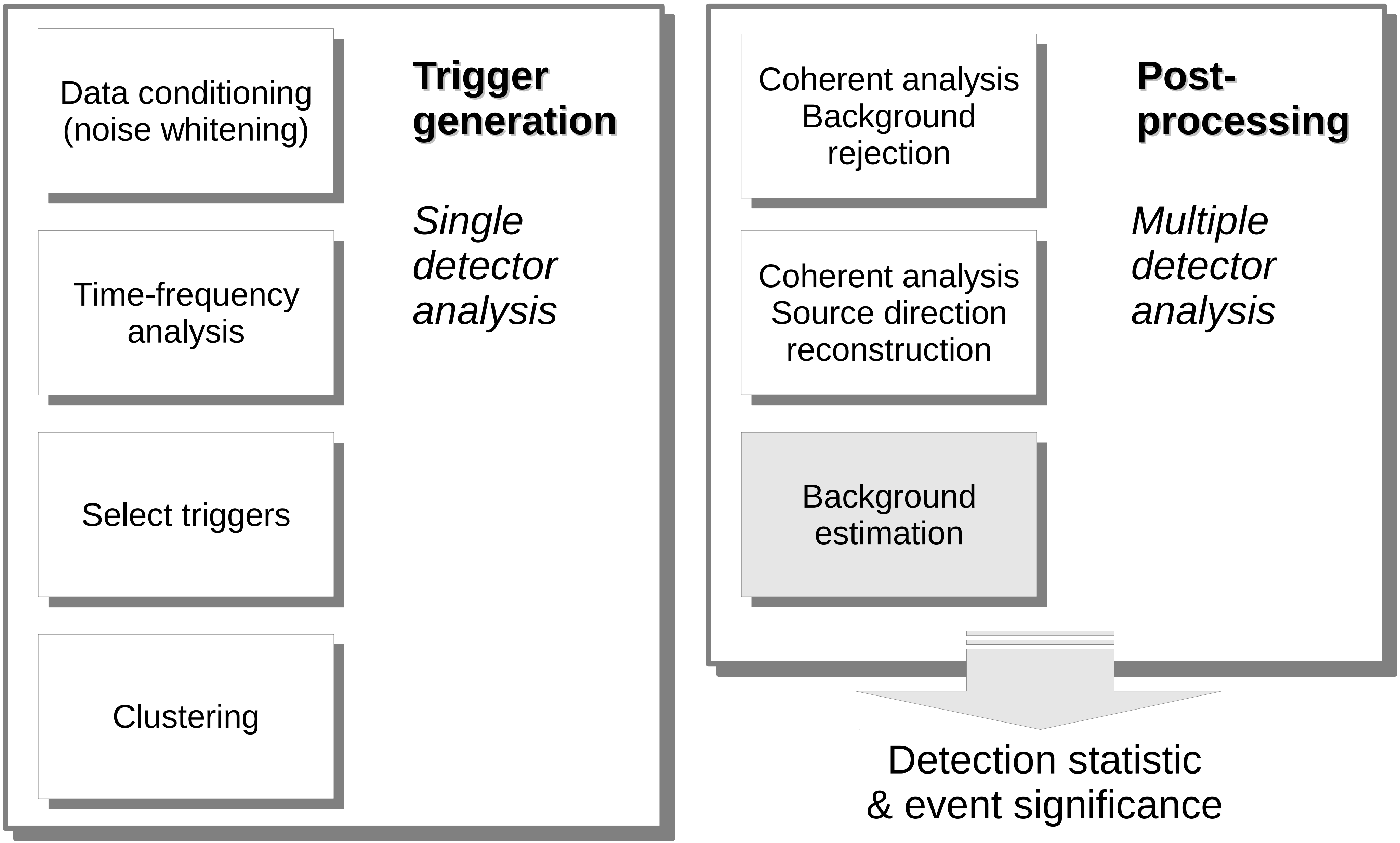
Dealing with real-world data (1)

- Non-stationary and non-Gaussian
  - zoo of instrumental glitches → background has heavy tails
- Data quality is a key issue
  - Veto known artifacts
  - Cross-correlation with >100 auxiliary channels
  - Trade-off: maximize “efficiency” (fraction of glitches that get vetoed) and minimize “dead time” (volume of vetoed data)
  - Safety checks with “hardware” injection of fake GW signals
  - 70 DQ flags, efficiency 90% for loud glitches





Basics about GW burst searches



Dealing with real-world data (2)

- Due to instrument complexity, comprehensive noise modelling is out of reach
- Background estimation is also a key issue: “time-slide” analysis
  - Exploit availability of multiple detectors
  - Apply *non-physical* (> 1 s) time-shifts to data stream and repeat analysis

    → Reference background distribution of noise-only events
  - Compare distribution of non time-shifted (“zero-lag”) events to reference to get confidence (probability of occurrence)
  - Limitation of the number of time-slides (1 s – 1 day)

Basics about GW burst searches

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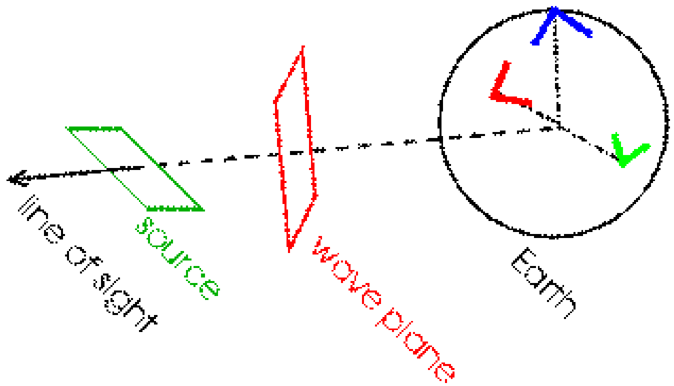
Post-processing

Multiple detector analysis

- Coherent analysis Background rejection
- Coherent analysis Source direction reconstruction
- Background estimation

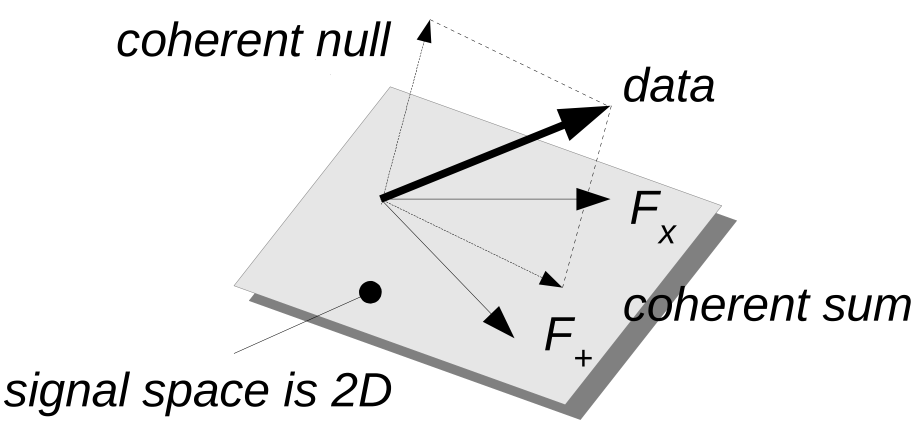
Detection statistic & event significance

Dealing with multiple GW detectors (1)



$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

data = *response* x *signal* + *noise*



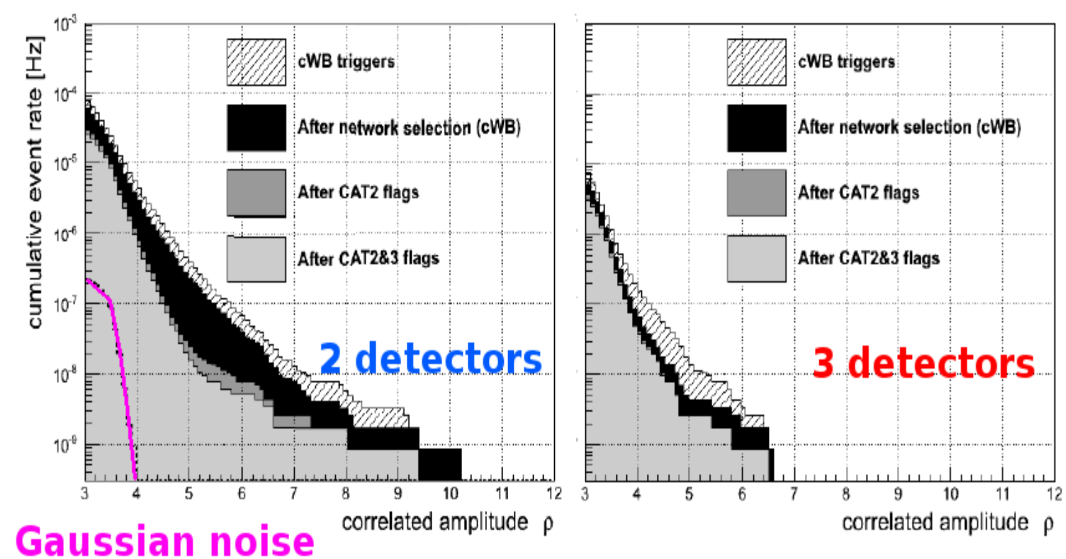
- Detector network

  detectors receive **the same polarizations** but **couple differently**

  GW is **coherent** as opposed to **glitches**

- Background rejection

  coherent sum vs coherent null ratio

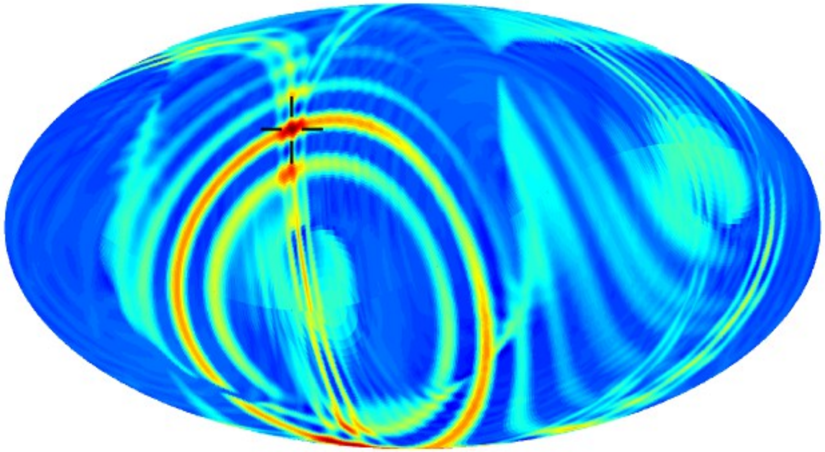


Dealing with multiple GW detectors (2)

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

data = *response* x *signal* + *noise*

Log probability distribution shows familiar rings, fringes etc.



For SNR 10 500 Hz SGQ5 over North Atlantic, into simulated HLV

- Source position reconstruction

  follow-up with other astronomical instruments such as telescopes, etc

  "triangulation"

- Array proc. for GW antenna

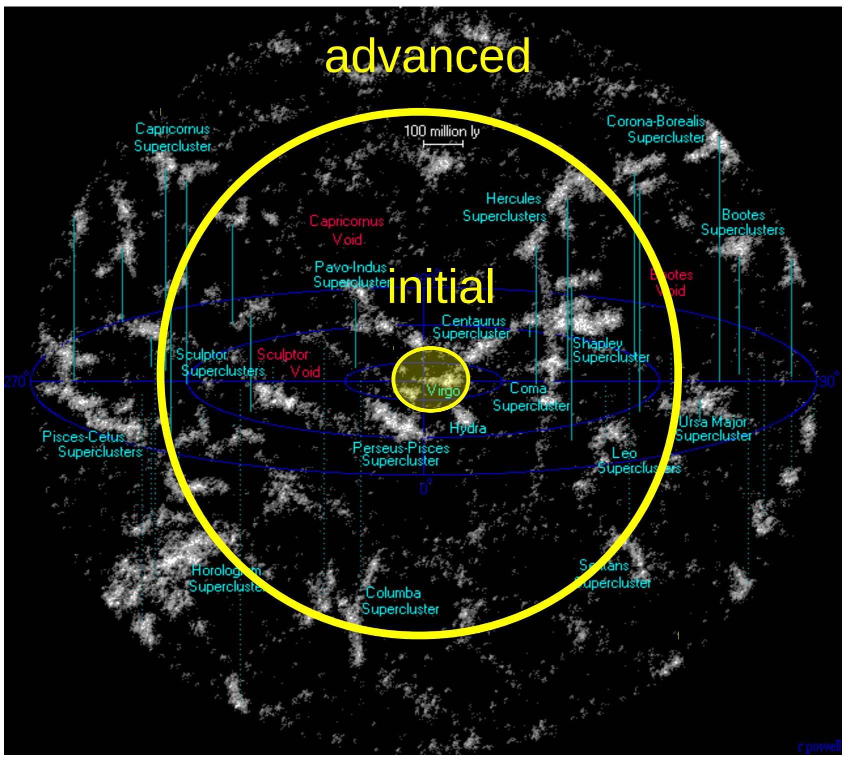
  solve inverse problem at each sky pixel

- Network is sparse and irregular

  degeneracies: F_+ and F_x can be //

  requires regulator

Outlook



- A new window on the Universe opens with GW observations
- We are prepared to detect a signal
  - We know how to deal with non-Gaussian tails
  - More improvements to come
- Chirplets can improve reach of GW burst searches
  - Orthogonal chirplet packet? (inversion)
  - Multiresolution: fast chirplet transform?
  - Clustering/chaining chirplets
- With the 2nd generation of instruments, the next decade will probably see the 1st direct detection of GW

Stay tuned!

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