Searches for gravitational-wave transients

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Outline

What and why? — Sources of GW transients

Sensitivity estimates

How? — Data analysis methods for searching GW transients

- Wavelets
- Data quality
- Multi-detector coherent analysis
- Significance and background estimation

Selected results from “all-sky searches”

Conclusions

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Sensitivity estimates

<u>How?</u> Data analysis methods for searching GW transients

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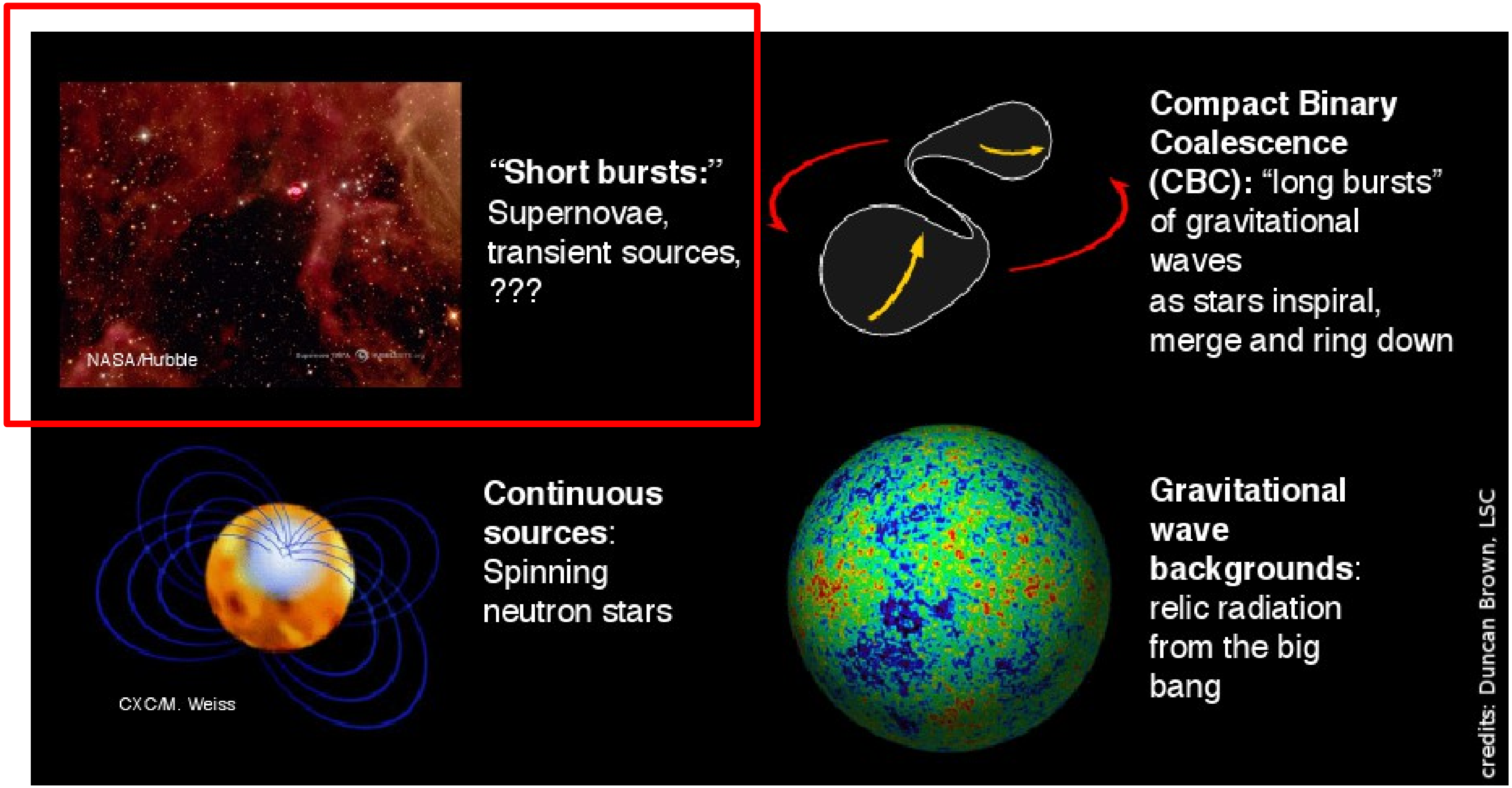
Sources of gravitational waves

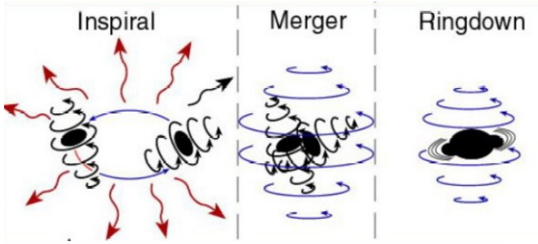
We will be interested in unmodelled GW transients in this presentation

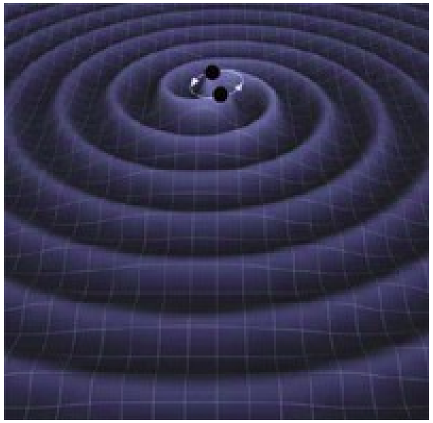


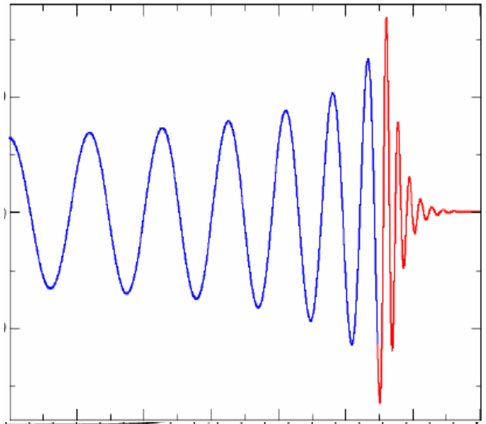
Sources of GW transients

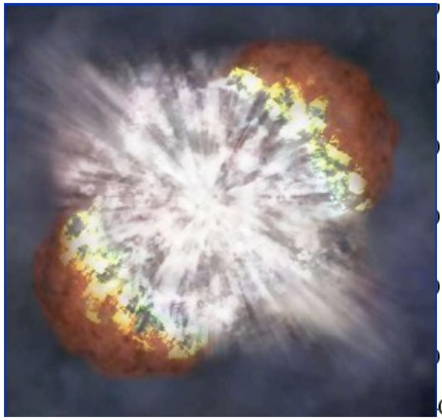
- Catastrophic astrophysical events

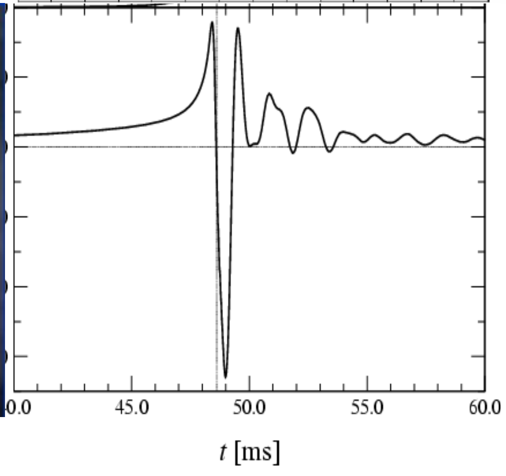
  the “violent Universe”
- Efficient production of GWs
  - ✓ Large masses and densities → compact objects, neutron star NS or black hole BH
  - ✓ Relativistic bulk motion → collapse or merger
  - ✓ Some degree of asymmetry
- Binary mergers
- Supernova core collapse
  - ✓ numerical simulations. no comprehensive view of the collapse.
- … and others (e.g. star quakes, cosmic strings, etc)











Science from GW transients

- Gravitational wave physics
  - ✓ Existence and property (e.g., speed, polarization)
- Physics of compact objects
  - ✓ Equation of state of dense matter
- Relativistic dynamics
  - ✓ Gravitation in strong field regime, $v/c \sim 1$
- New insights on high-energy astrophysics
  - ✓ Gamma-ray bursts
  - ✓ Soft-gamma repeaters

...

Characterization of GW transients (1)

- **Unmodelled bursts**
  - Short duration (<1 s), no precise waveform, few cycles
- RMS amplitude

$$h_{rss}^2 = \int dt\, h_+^2(t) + h_\times^2(t)$$

- Signal-to-noise ratio

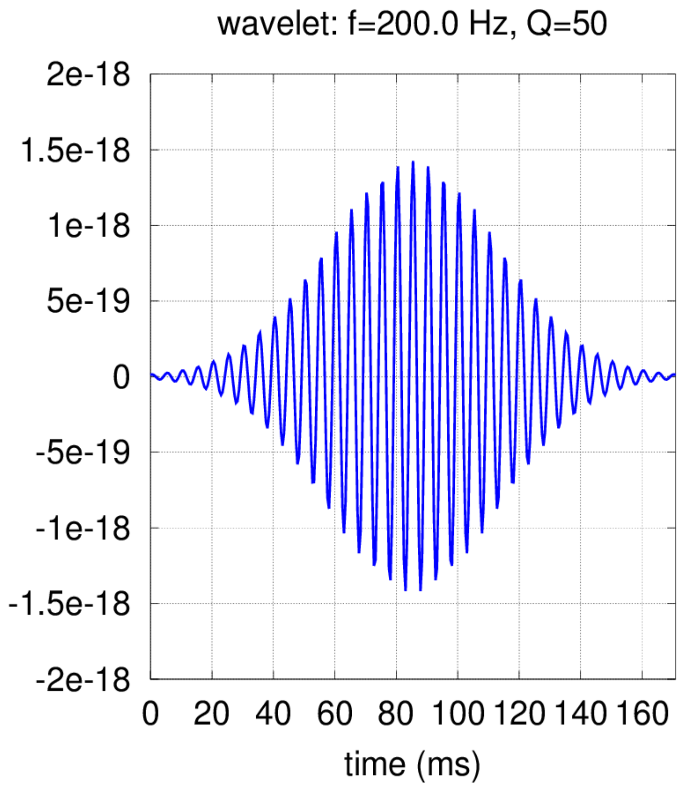
$$h = F_+ h_+ + F_\times h_\times$$

$$\rho^2 = \int df\, \frac{|H(f)|^2}{S(f)}$$

- Monochromatic GW signal

$$\rho^2 \propto \frac{h_{rss}^2}{S(f_0)}$$

GW polarization determines the remaining O(1) factor



$$h_{rss} = 4 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

Sutton, arXiv:1304.0210

Characterization of GW transients (2)

- **Unmodelled bursts**
  - Short duration (<1 s), no precise waveform, few cycles
- GW radiated energy

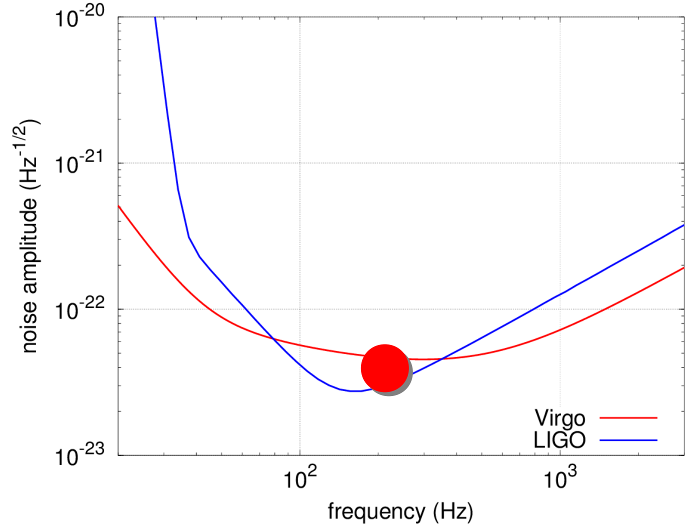
$$E_{GW} = \frac{1}{16\pi}\frac{c^3}{G} D_L^2 \iint d\Omega dt \, \dot{h}_+^2 + \dot{h}_\times^2$$

- Monochromatic GW signal

$$E_{GW} \approx 2\pi^2 \frac{c^3}{G} D_L^2 \, f_0^2 S(f_0)\rho^2$$

Energy units

1 erg (CGS units) = 10^{-7} J (KMS units)
M_{sun} c^2 = 1.8 x 10^{47} J = 1.8 x 10^{54} erg

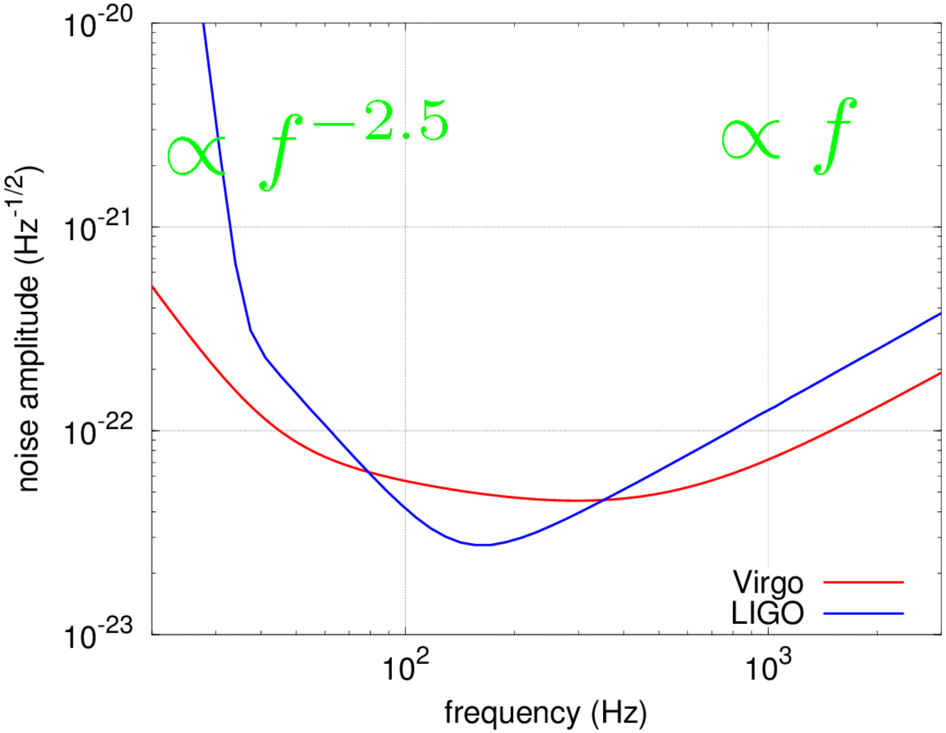


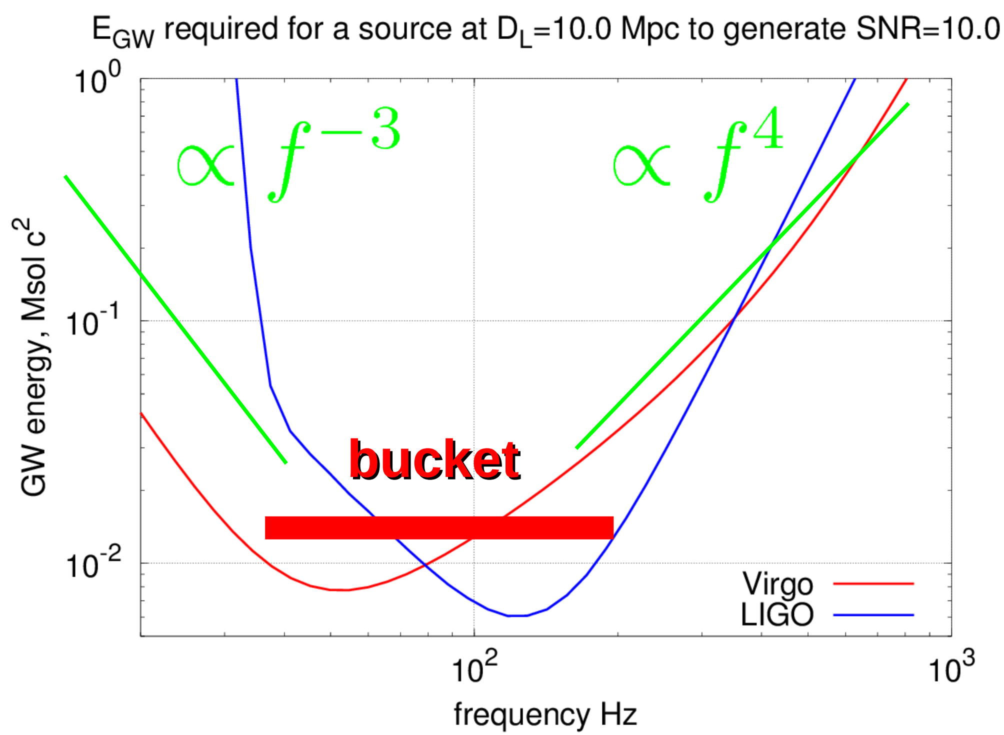
$$D_L = 10 \text{ Mpc} \quad \rho = 10$$
$$f_0 = 200 \text{ Hz}$$
$$S(f_0) \approx 4 \times 10^{-23} \text{Hz}^{-1/2}$$
$$E_{GW} \approx 5 \times 10^{45} \text{J}$$
$$\sim 5 \times 10^{52} \text{erg}$$
$$\sim 2 \times 10^{-2} M_\odot c^2$$

Sutton, arXiv:1304.0210

Sensitivity estimate for GW transients

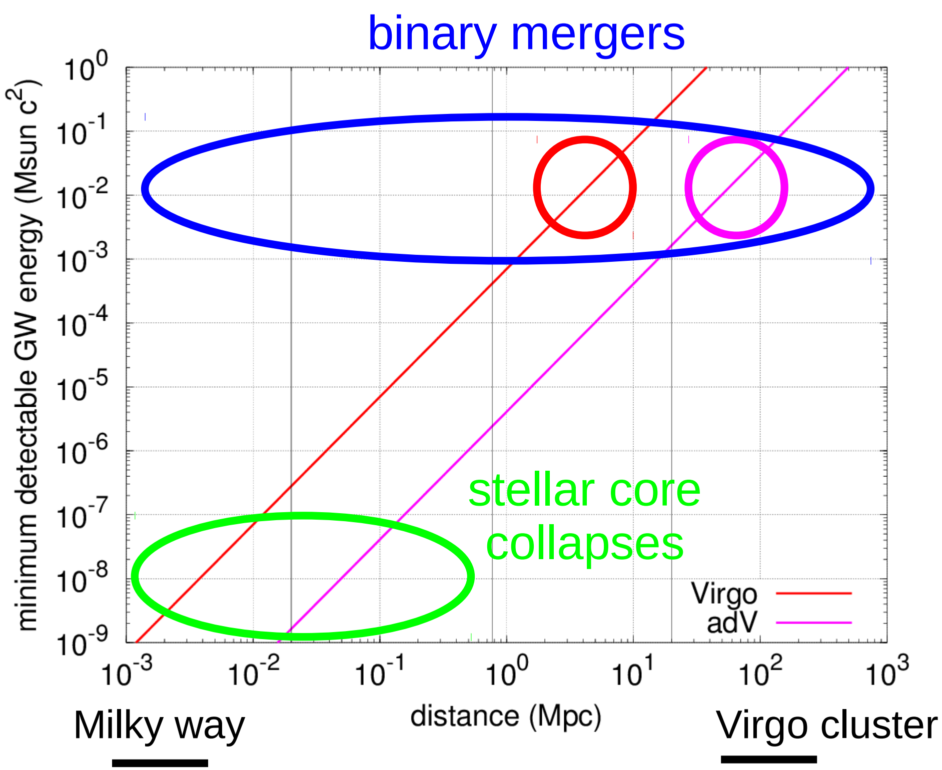
$$E_{GW} \approx \frac{2\pi^2 c^3}{G} D_L^2 f_0^2 S(f_0) \rho^2$$

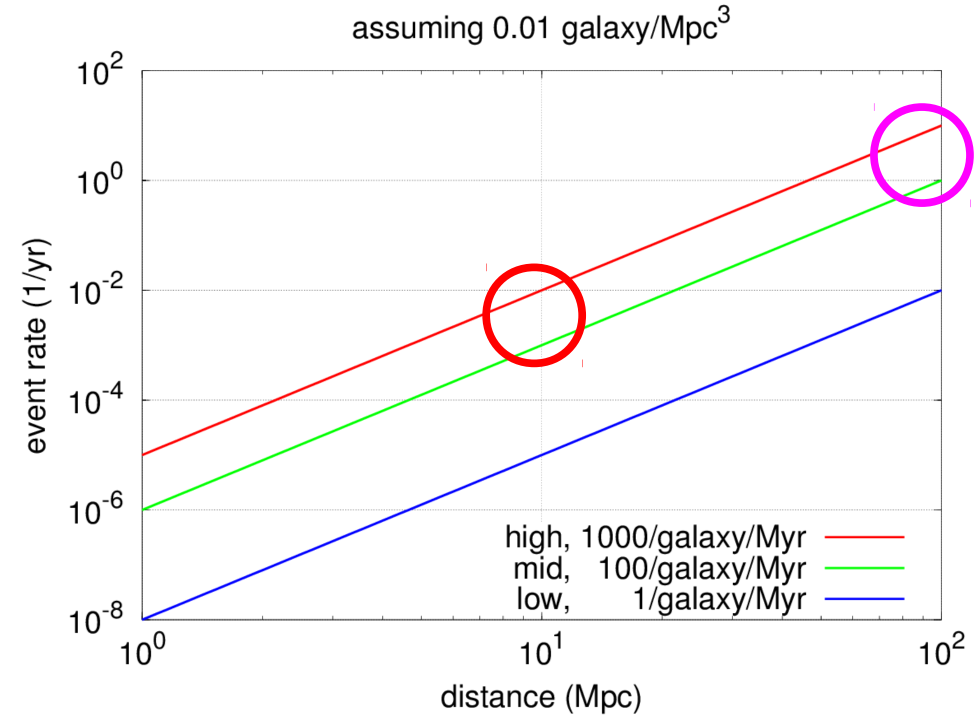




At D_L = *10* Mpc, minimum detectable GW energy for SNR=10
is $E_{GW} = 10^{-2} M_{sun} c^2$ for initial detectors

Sensitivity estimate for GW transients





Assuming $E_{GW}=10^{-2}\ M_{sun}\ c^2$ emitted in the bucket

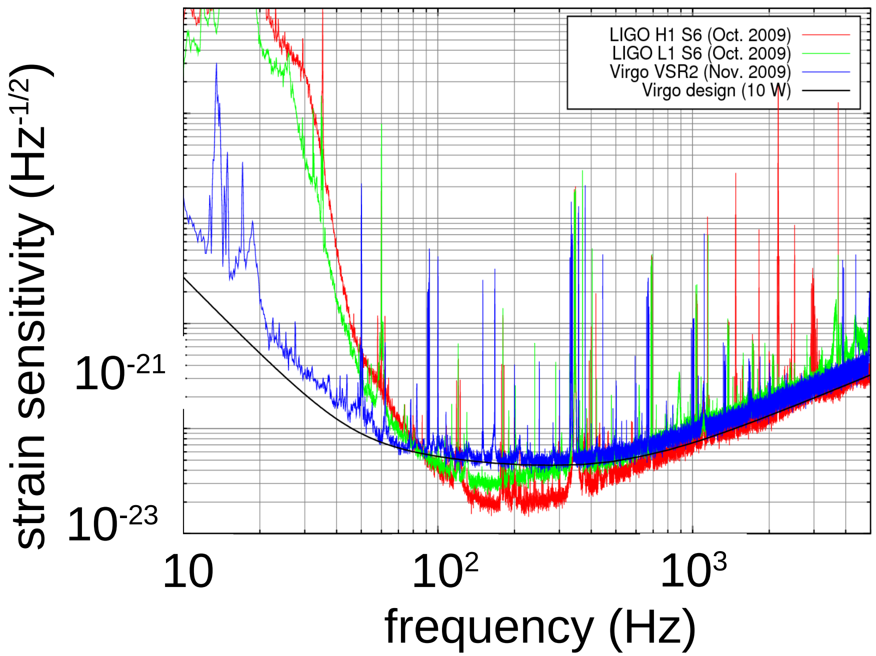
- Horizon ~ 10 Mpc, initial detectors
- Horizon ~ 100 Mpc, advanced detectors
  O(1) to O(10) BNS events/year

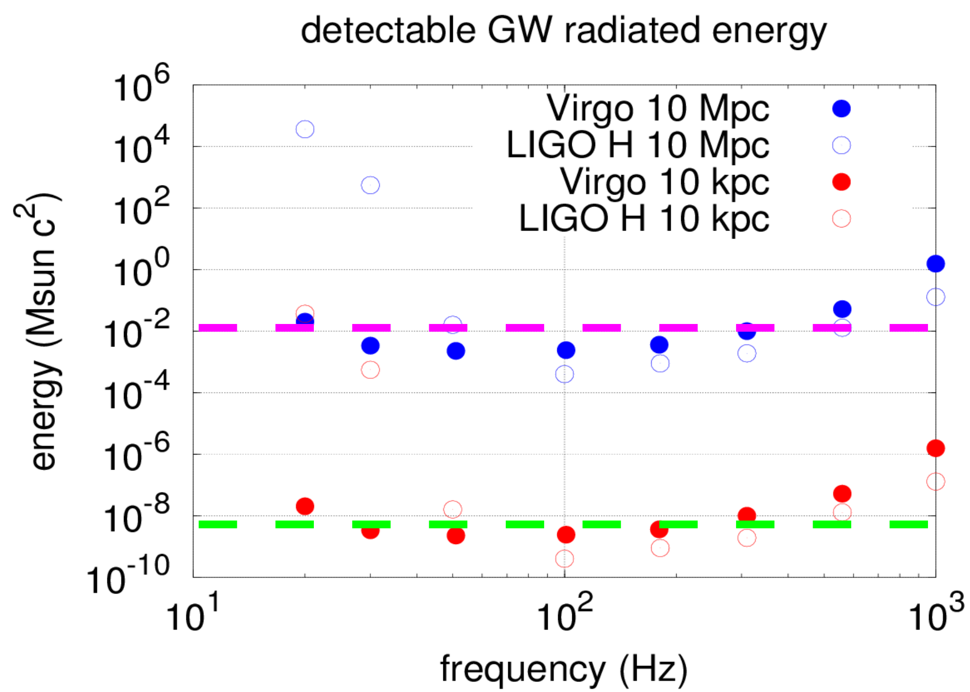
Typical event rates

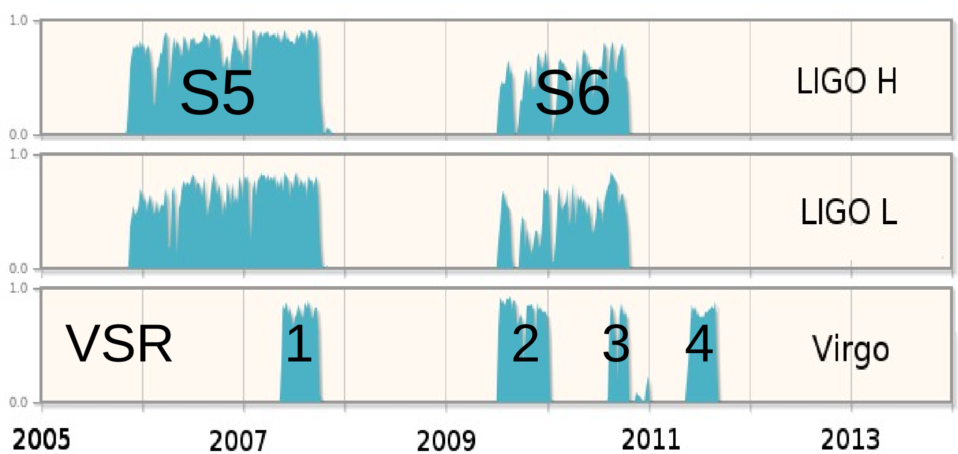
SN = 10,000 /galaxy/Myr

BNS=1 – 100 – 1000/galaxy/Myr

Achieved sensitivity and data takings





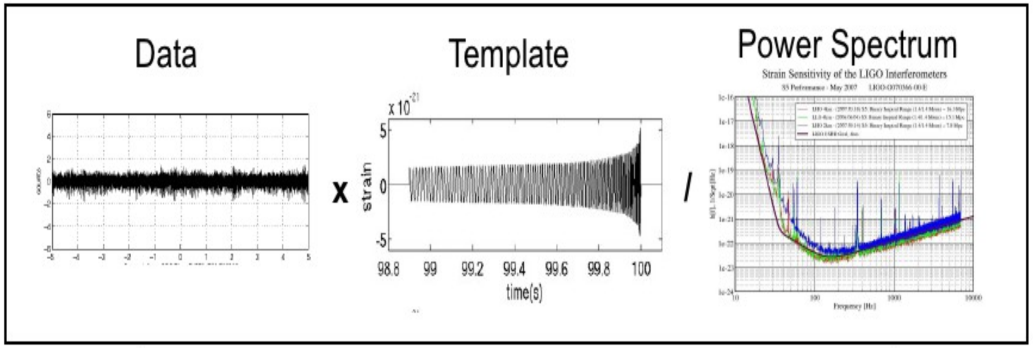


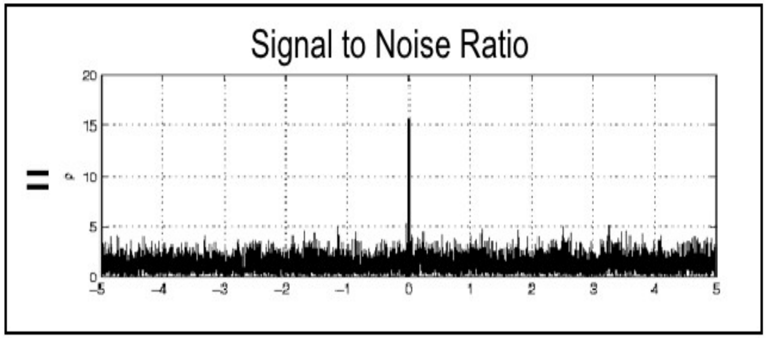
- 3 joint LIGO – Virgo science runs
  ~2 yrs total
- NS-NS = 1% total mass emitted in GW
  horizon is ~ 20 – 40 Mpc
- Core Collapse SN = 10^{-8} M c2
  galactic SN are observable

Searches for GW transients: basic ideas

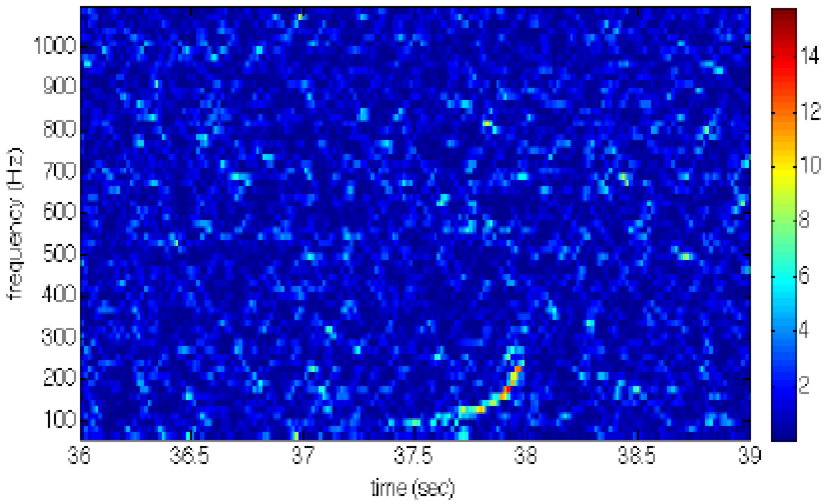
Time series analysis
rare transients with low signal to noise ratio

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

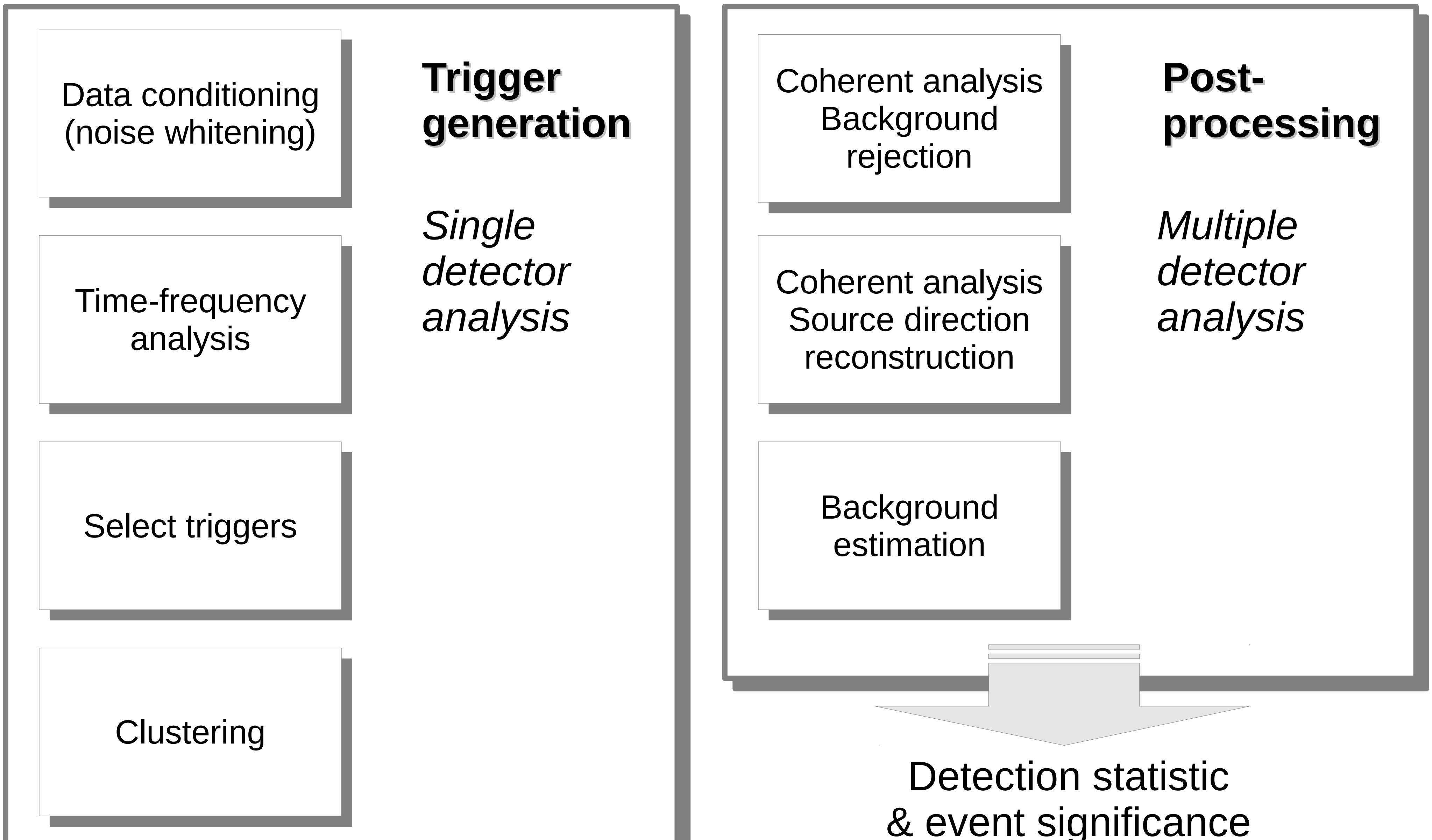




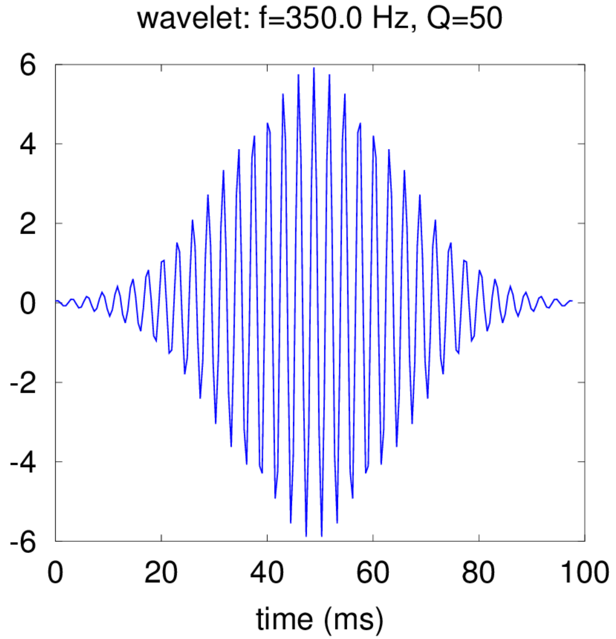
Expected signal is **unknown**
Excess in time-frequency maps
(wavelets)

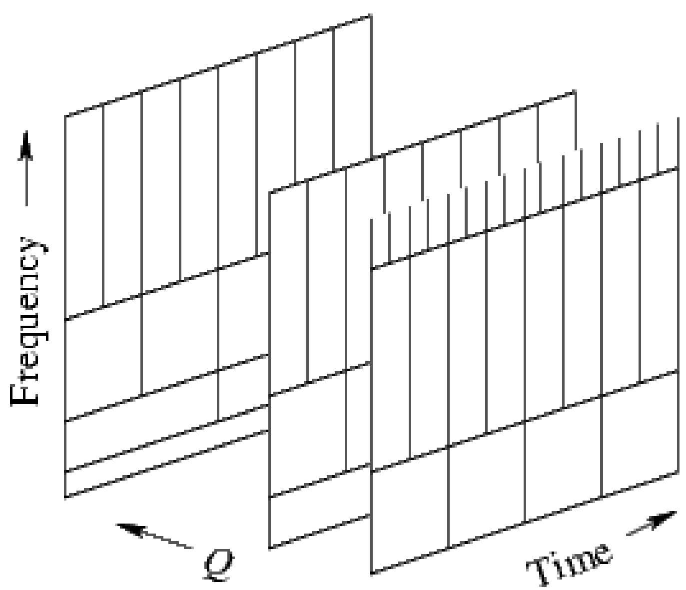


GW burst search pipeline



Event trigger generation





- Time-frequency multiresolution analysis from wavelet basis

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

$$T_{t,f,Q} = \langle x, \psi_{t,f,Q}\rangle$$

- Select significant wavelet coefficients
- Form time-frequency cluster *Ω*
- Likelihood statistics – Gaussian noise

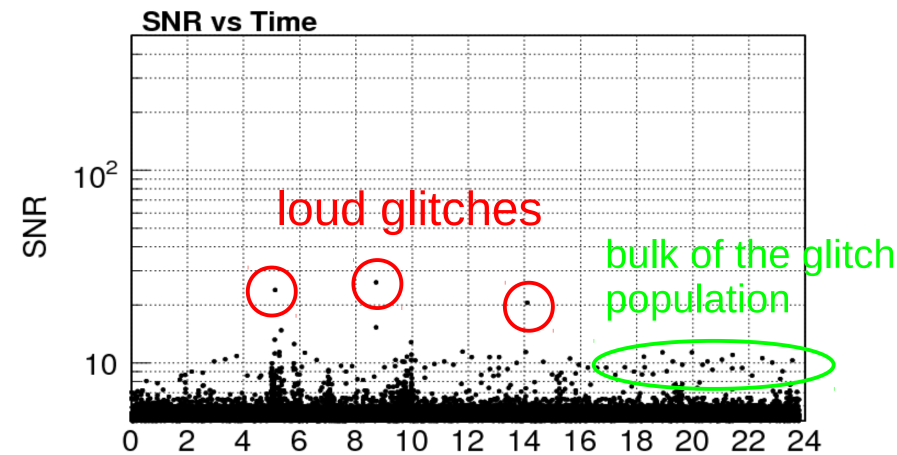
$$\mathcal{L}(h) = \frac{P(\{T\}_\Omega|h)}{P(\{T\}_\Omega|0)}$$

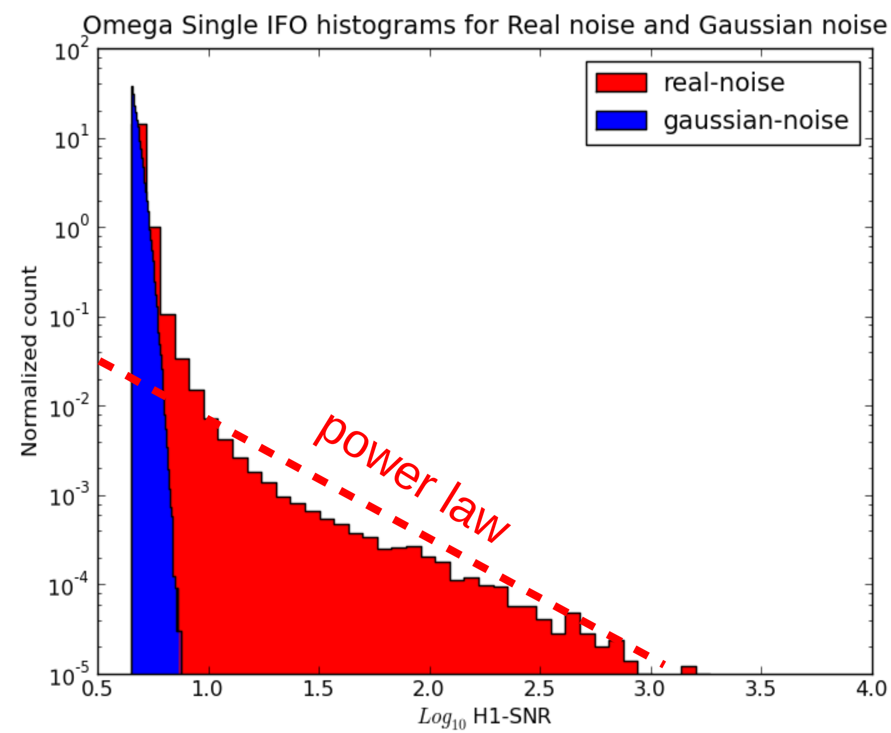
$$\log\mathcal{L}(h) = \sum_\Omega T^2_{t,f,Q} - (T_{t,f,Q} - h_{t,f,Q})^2$$

maximized over *h* $\longrightarrow$ $\log\mathcal{L}_{max} = \sum_\Omega T^2_{t,f,Q}$

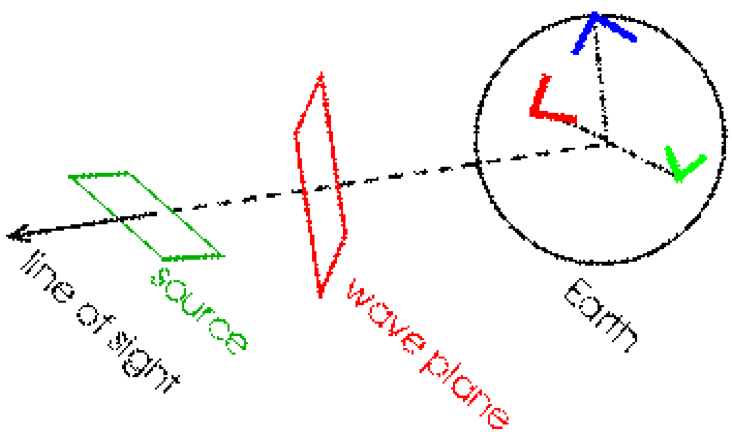
Dealing with real-world data

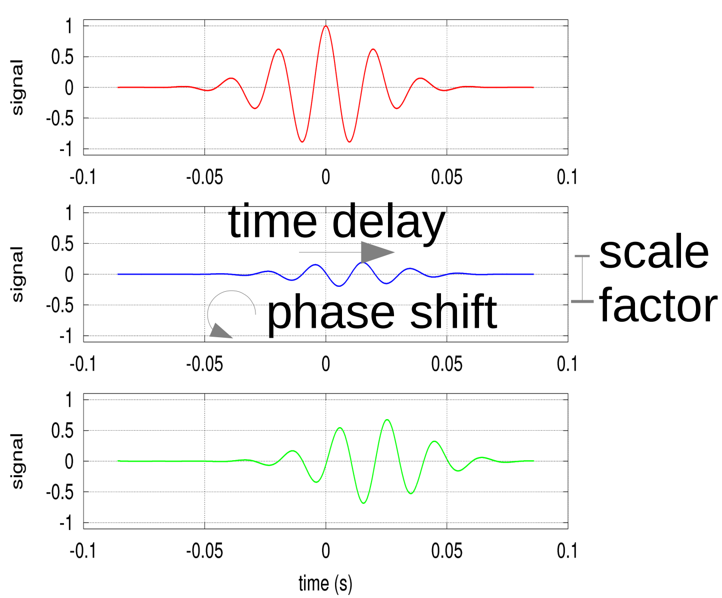
- Non-stationary and non-Gaussian
  - zoo of instrumental glitches → background has heavy tails
- Data quality is a key issue
  - Veto known artifacts
  - Cross-correlation with >100 auxiliary channels
  - Trade-off: maximize “efficiency” (fraction of glitches that get vetoed) and minimize “dead time”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





Worldwide network of GW detectors





- Response of detector network
  - Detectors receive the same wave...
  - … but the wave couples differently

$$s(t) = F_+ h_+(t-\tau) + F_\times h_\times(t-\tau)$$

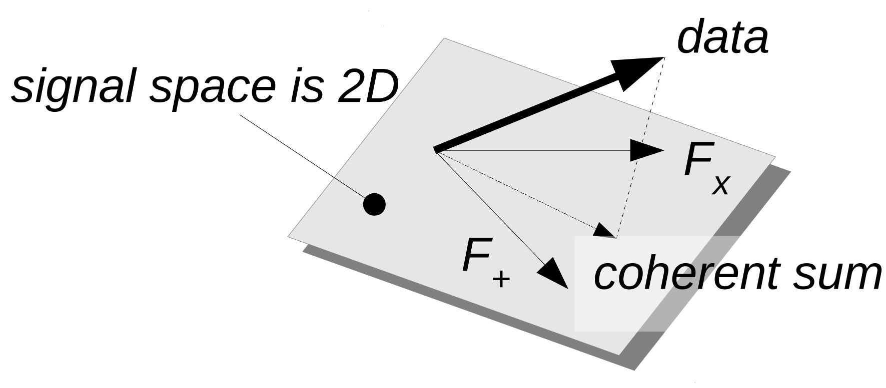
- Search for GW transients in multi-detector data
  - Sensitivity improvement
  - Source direction reconstruction by "triangulation" → point telescopes
  - Background rejection
  - Background estimation

Multiple detectors (1)

Coherent detection

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

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



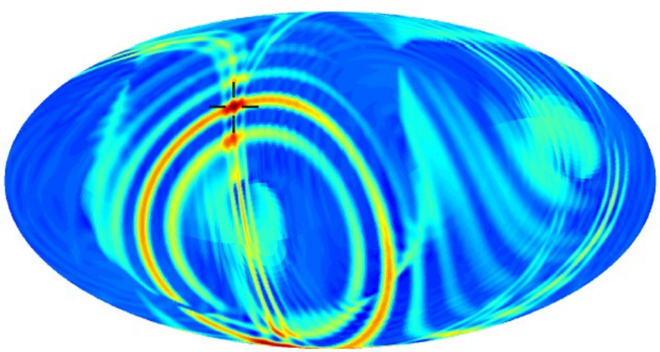
- Detection with multiple detectors
  - ✓ Inverse problem
  - ✓ “Coherent” likelihood statistics
    → Norm of projection onto GW plane
  - ✓ Projector: compensate time/phase shift + add
- Degeneracies
  - ✓ F_+ and F_x can be parallel or one of the vectors can vanish → regulator

Multiple detectors (2)
Source direction reconstruction

For a given source direction/orientation

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

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



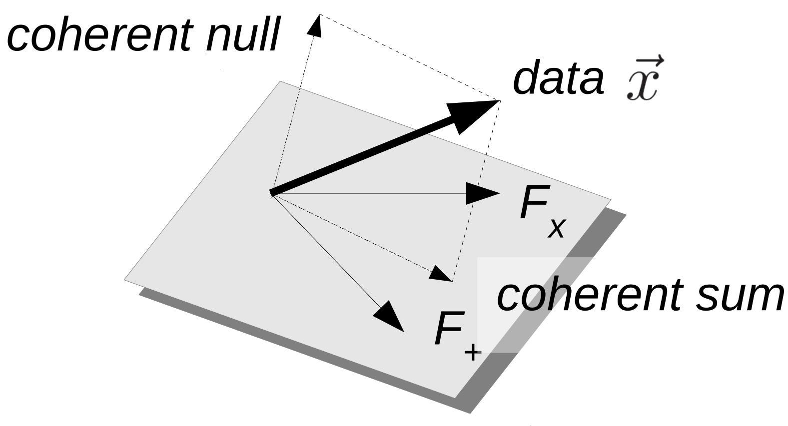
- Likelihood skymaps
  - Source direction is unknown a priori → solve inverse problem for all sky positions
- Angular resolution
  - Triangulation (timing-based reconstruction) provides leading order estimate
  - Timing uncertainty $\sigma_t \approx \dfrac{1}{2\pi\rho\sigma_f}$

    in the bucket, ~ 0.1 ms
  - Diffraction limit estimate

    1/100 time of flight ~ 4 degrees

    tens of square degrees
  - Better resolution for burst at higher frequencies

Multiple detectors (3)
Background rejection



Coherent null energy

$$E_{null} = P^{jk} x_j x_k^*$$

Incoherent null energy

$$I_{null} = P^{kk} |x_k|^2$$

- Glitch rejection
  - ✓ GW are coherent as opposed to glitches
- Null or noise space
  - ✓ Projector *P* onto null space: combining so that GW cancelled in the sum
- "Coherent veto"
  - ✓ Veto events with large null space component

For GW: on and off-diagonal terms cancel

$$E_{null} \ll I_{null}$$

For glitches: no cancellation

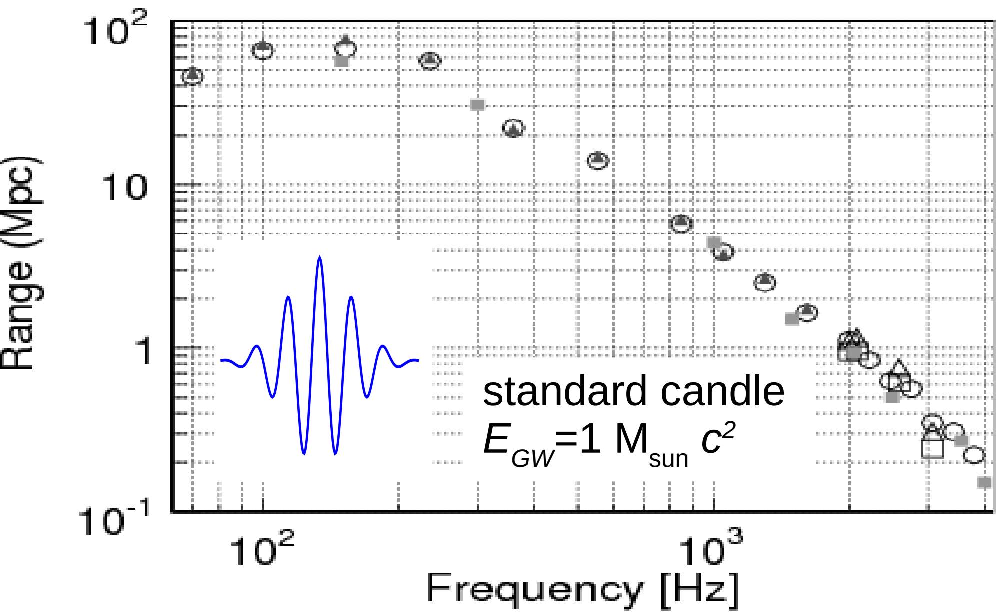
$$E_{null} \approx I_{null}$$

Multiple detectors (4)
Background estimation

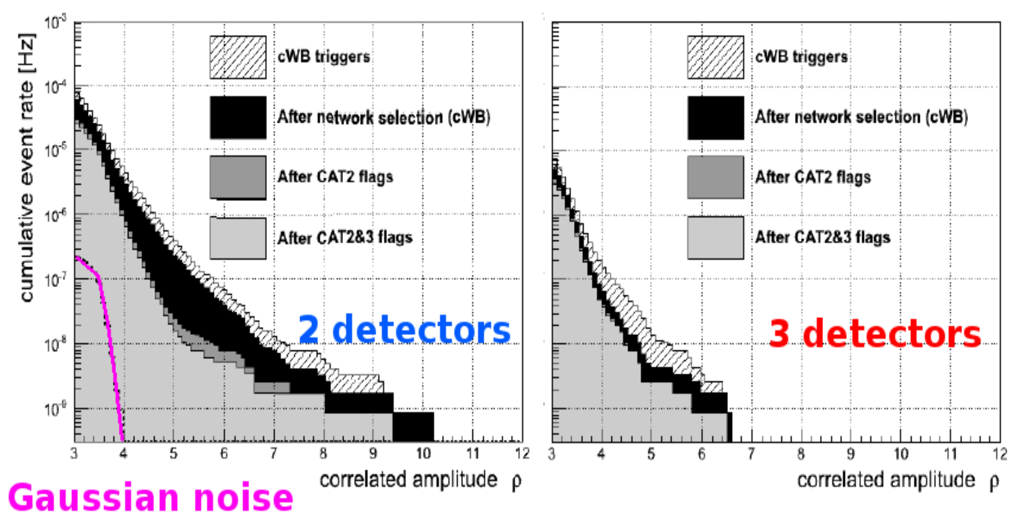
- Due to instrument complexity, comprehensive noise modelling is out of reach
- Background estimation is also a key issue: “time-slide” analysis
    - ✔ Exploit availability of multiple detectors
    - ✔ Apply *non-physical* (> 1 s) time-shifts to data stream and repeat analysis

      → 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)

Selection of results



- 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



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

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)

Many synergies with high-energy astrophysics