GW data analysis – A primer (1)

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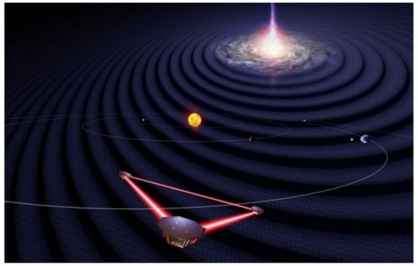
Pulsar timing array

LISA space mission



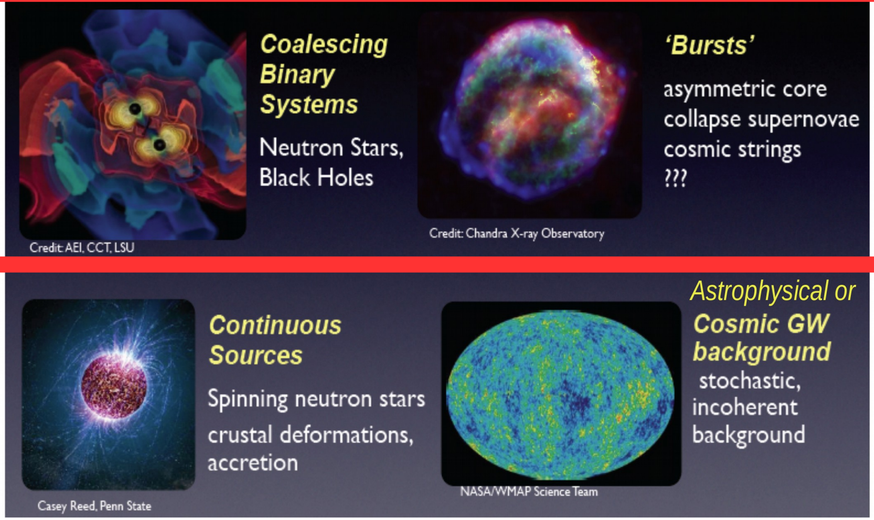
Ground-based detectors

Known waveform

Unknown waveform

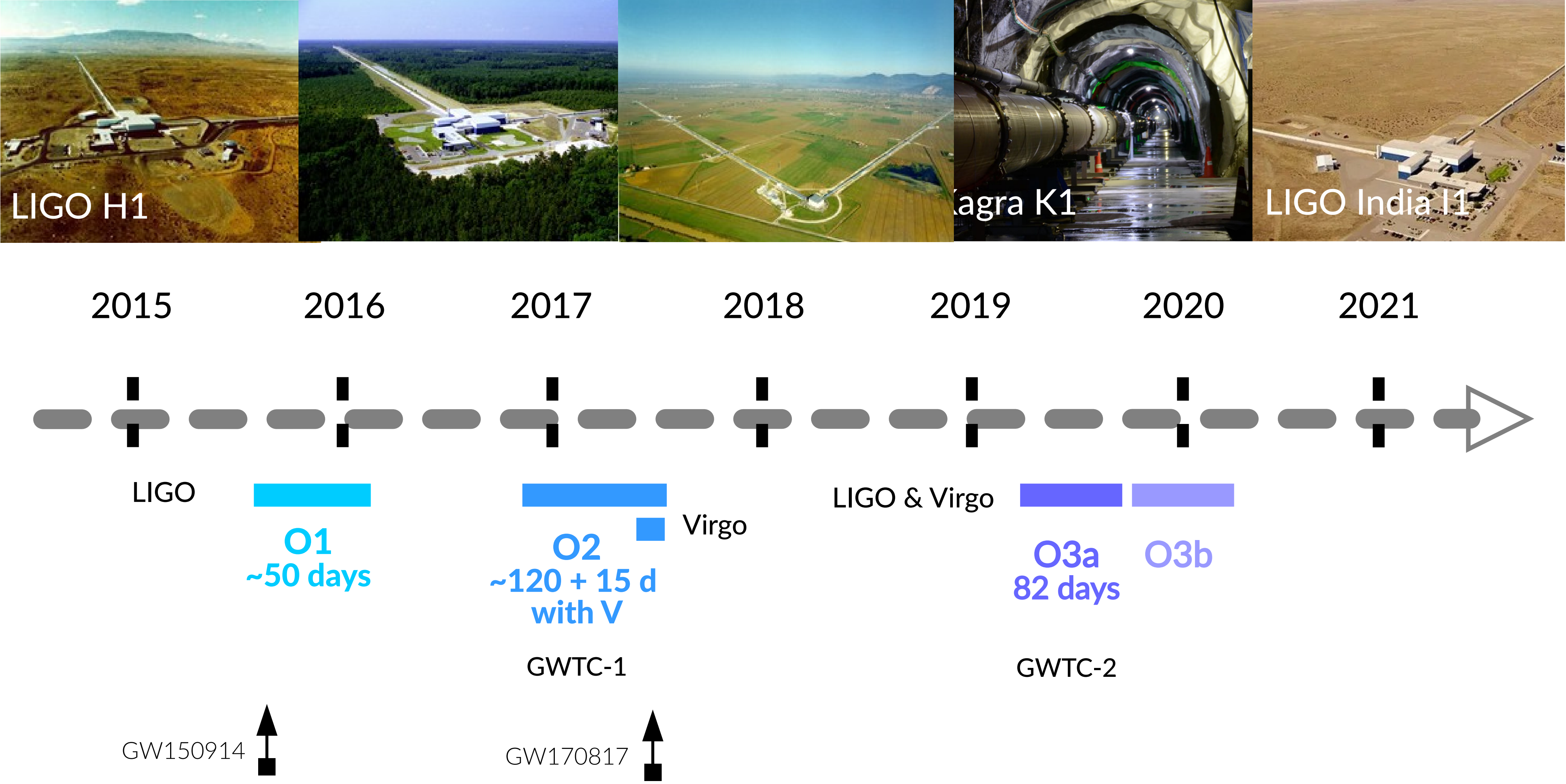
Transient
Short duration

Permanent
Long duration



Outline – Part 1

- General statement and main concepts
  - Observation model (signal and noise) – Likelihood
  - Detection theory – Optimal statistics
- From general principles to transient searches
  - Compact binary coalescences – Part 1 (Detection)
    - Expected gravitational-wave signal – Waveform models
    - Search implementation : matched filtering
    - Observing with multiple detectors
    - Background estimation and significance assessment
    - Pipeline and software packages
    - Exercises !


LIGO H1
Kagra K1
LIGO India I1
2015
2016
2017
2018
2019
2020
2021
LIGO
O1
~50 days
O2
~120 + 15 d
with V
Virgo
GWTC-1
LIGO & Virgo
O3a
82 days
O3b
GWTC-2
GW150914
GW170817

Jun 7 2021

Needle in the haystack

- We are looking for weak signals in noisy data
- Few numbers for compact binaries
  - The observing run O3a lasted 6 months, ~ 1.5 x 10^7 seconds.
  - 40 events were found, each lasting < ~5 seconds in the detector band
  - All but ~ 10^{-6} of the data contained nothing but noise...
  - ... and probably loads of undetectable signals from the distant universe.
- Search pipelines must find the **~ 10^{-6} of the data** containing a detectable signal
  - Can't skimp on the detection software! It must be close to "optimal" – the best that can be achieved in the presence of unavoidable noise.

Observation equation?

data = function(signal, noise)

Detector transfer function
and noise coupling

Recap – Gravitational waves

Outward propagating wave in z-direction

$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)}$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{h}(t) = h_+(t)\boldsymbol{\epsilon}^+ + h_\times(t)\boldsymbol{\epsilon}^\times$$

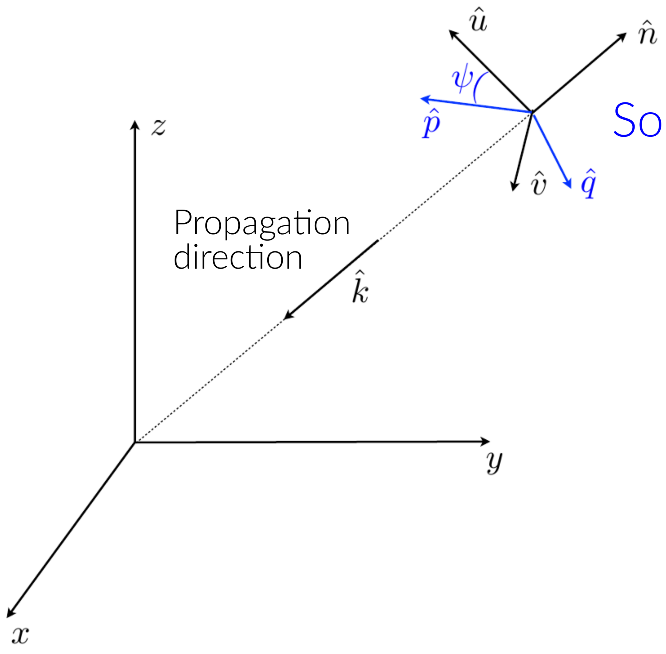
Polarization tensors

$$\epsilon^+ = \hat{p} \otimes \hat{p} - \hat{q} \otimes \hat{q}$$

$$\epsilon^\times = \hat{p} \otimes \hat{q} + \hat{q} \otimes \hat{p}$$

$\hat{p}, \hat{q}$ Preferred basis in source frame

Recap – Reference frames



$$\mathbf{h}(t) = h_+(t)\boldsymbol{\epsilon}_+ + h_\times(t)\boldsymbol{\epsilon}_\times$$

$$\mathbf{e}^+ = \hat{u} \otimes \hat{u} - \hat{v} \otimes \hat{v}$$
$$\mathbf{e}^\times = \hat{u} \otimes \hat{v} + \hat{v} \otimes \hat{u}$$

$$\begin{aligned}
\boldsymbol{\epsilon}^+ &= \hat{p} \otimes \hat{p} - \hat{q} \otimes \hat{q} \\
&= \cos 2\psi\, \mathbf{e}^+ - \sin 2\psi\, \mathbf{e}^\times
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\epsilon}^\times &= \hat{p} \otimes \hat{q} + \hat{q} \otimes \hat{p} \\
&= \sin 2\psi\, \mathbf{e}^+ + \cos 2\psi\, \mathbf{e}^\times
\end{aligned}$$

Cornish, arXiv: 0910.4372

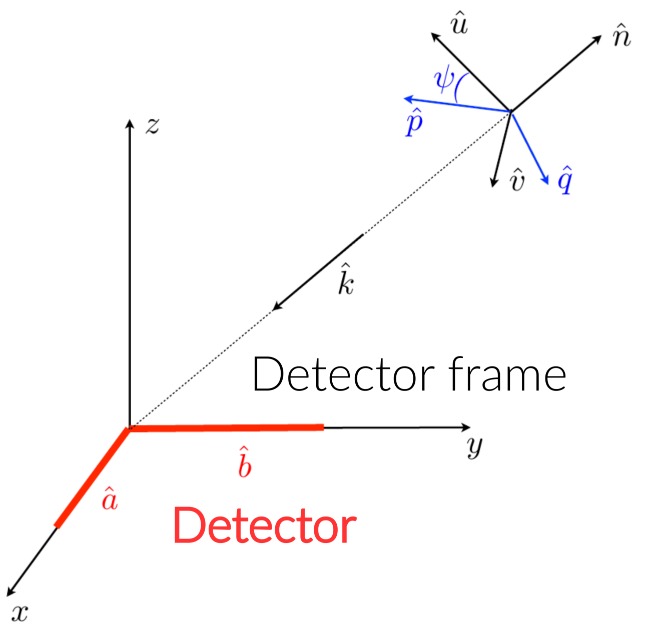
Detector response

θ, ϕ Source direction in the sky

$\hat{n} = \sin\theta\cos\phi\,\hat{x} + \sin\theta\sin\phi\,\hat{y} + \cos\theta\,\hat{z}$

$\hat{u} = \cos\theta\cos\phi\,\hat{x} + \cos\theta\sin\phi\,\hat{y} - \sin\theta\,\hat{z}$

$\hat{v} = \sin\phi\,\hat{x} - \cos\phi\,\hat{y}$



Time of flight difference along 2 directions **a** and **b**

$$\underbrace{h(t)}_{\text{Detector response}} \equiv \frac{\Delta T(t)}{2L} \approx \underbrace{\frac{1}{2}\left[\hat{a}\otimes\hat{a} - \hat{b}\otimes\hat{b}\right]}_{\text{Detector tensor}} : \mathbf{h}(t)$$

$$(\hat{a}\otimes\hat{a}) : \mathbf{e}^{+} = \cos^2\theta\cos^2\phi - \sin^2\phi$$

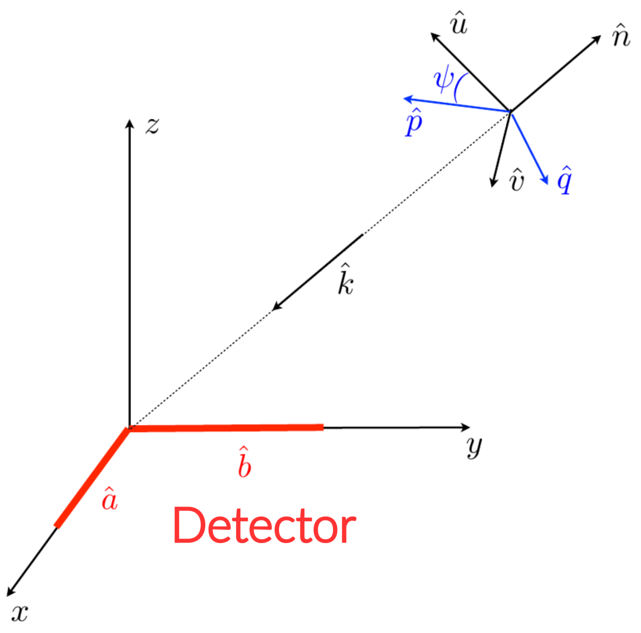
$$(\hat{a}\otimes\hat{a}) : \mathbf{e}^{\times} = \cos\theta\sin 2\phi$$

$$(\hat{b}\otimes\hat{b}) : \mathbf{e}^{+} = \cos^2\theta\sin^2\phi - \cos^2\phi$$

$$(\hat{b}\otimes\hat{b}) : \mathbf{e}^{\times} = -\cos\theta\sin 2\phi$$

Antenna patterns

θ, ϕ Source direction in the sky

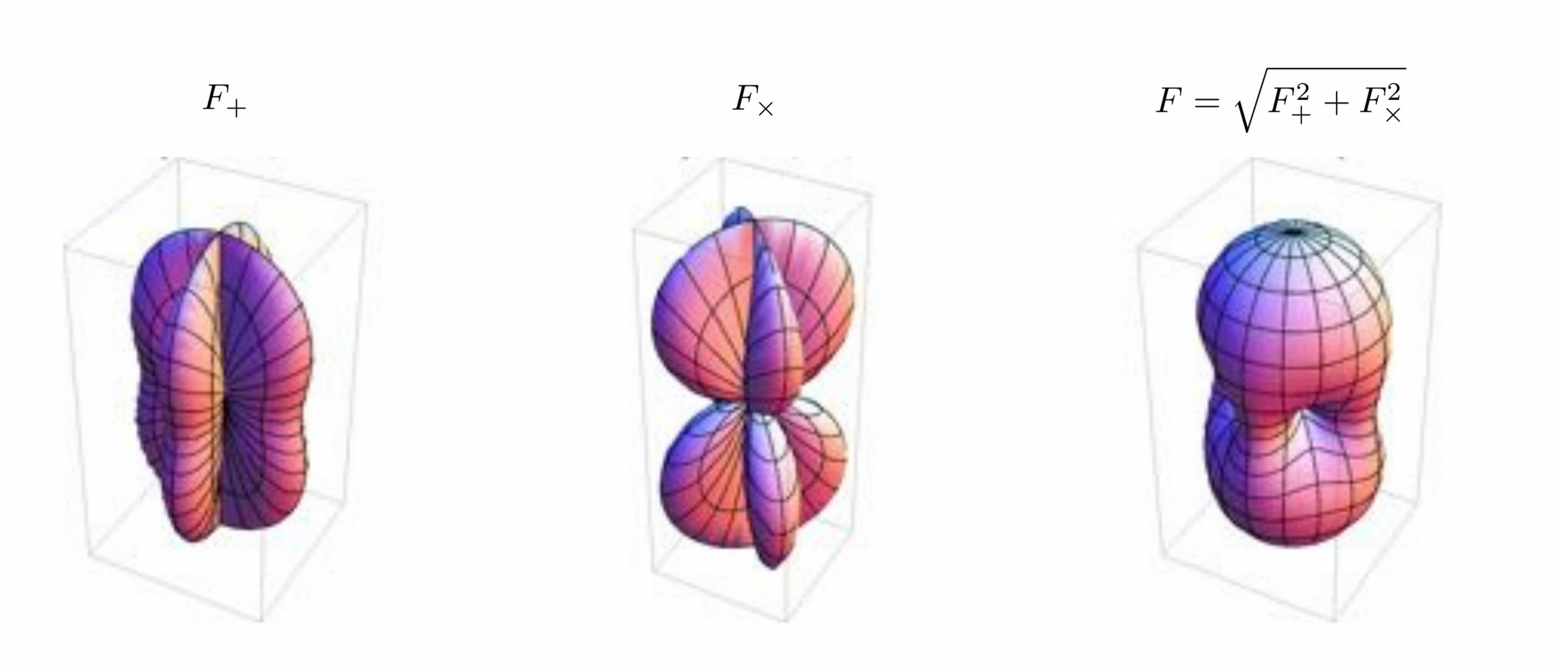


$$h(t) = F^{+} h_{+}(t) + F^{\times} h_{\times}(t)$$

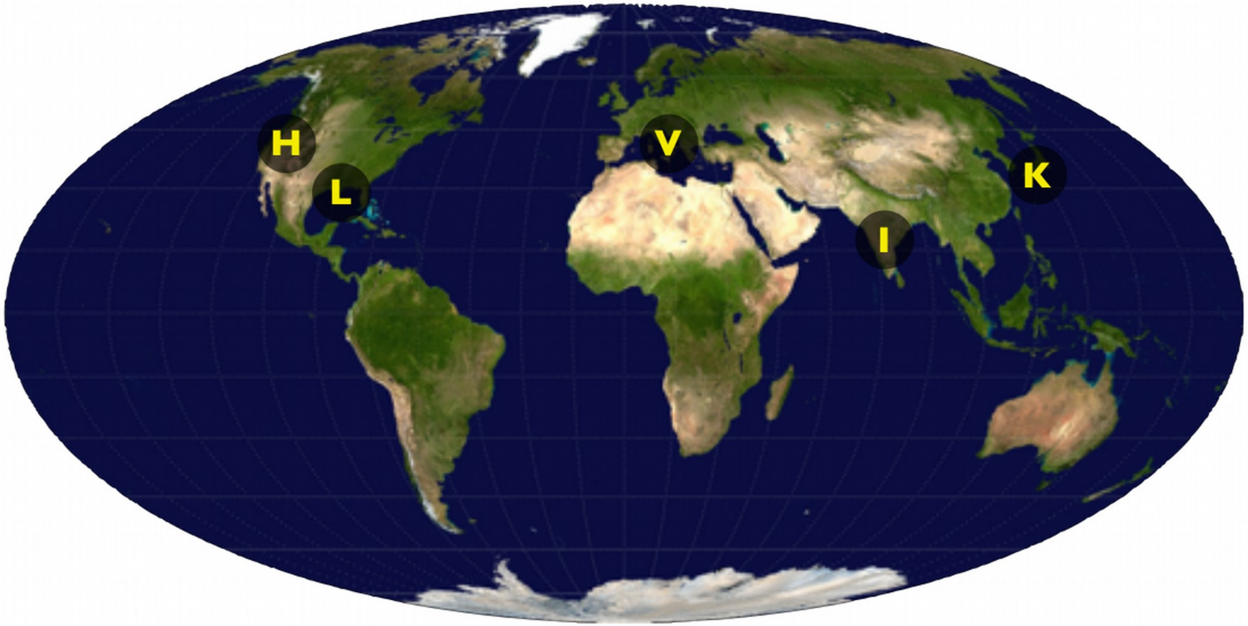
$$\begin{aligned} F^{+} &= \frac{1}{2}(\hat{a} \otimes \hat{a} - \hat{b} \otimes \hat{b}) : \epsilon^{+} \\ &= \frac{1}{2}(1 + \cos^2 \theta) \cos(2\phi) \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi \end{aligned}$$

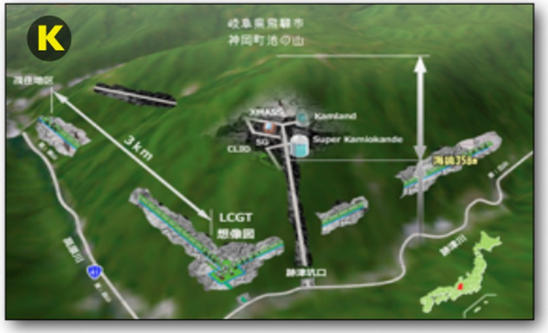
$$\begin{aligned} F^{\times} &= \frac{1}{2}(\hat{a} \otimes \hat{a} - \hat{b} \otimes \hat{b}) : \epsilon^{\times} \\ &= \frac{1}{2}(1 + \cos^2 \theta) \cos(2\phi) \sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi \end{aligned}$$

Antenna patterns



Terrestrial Network





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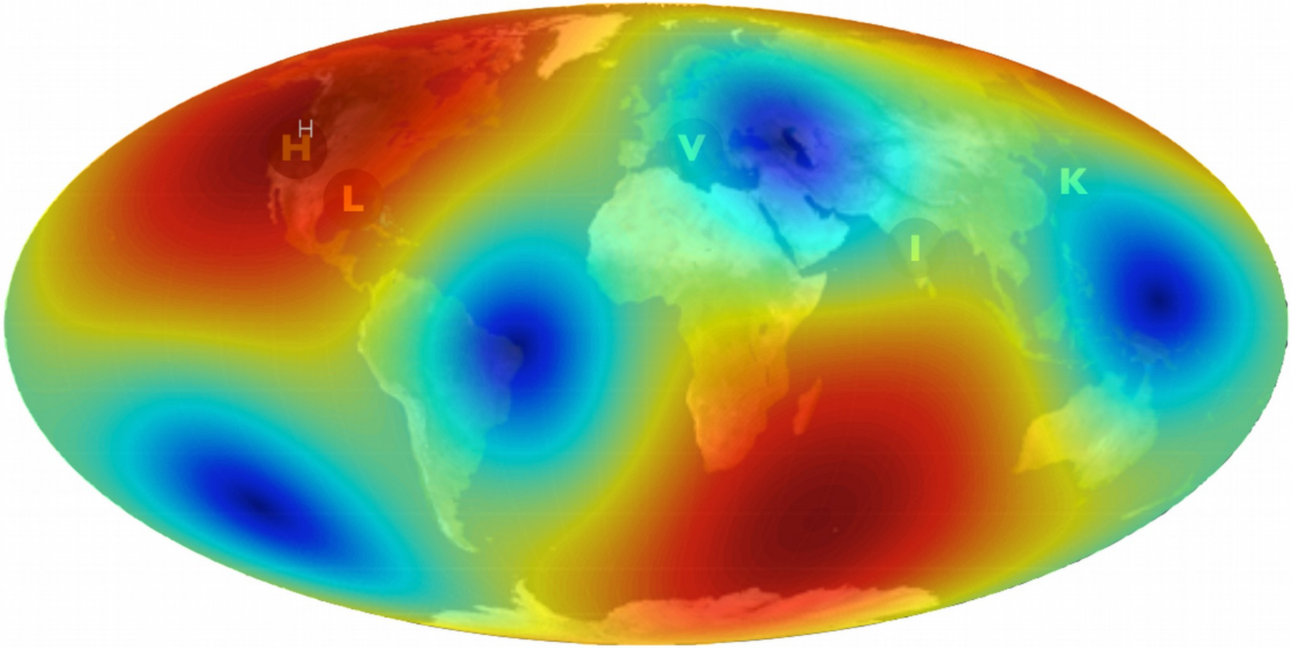
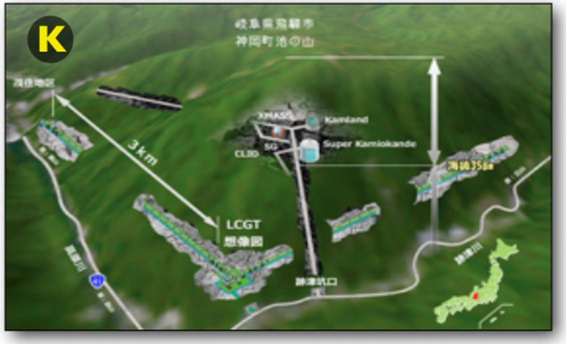
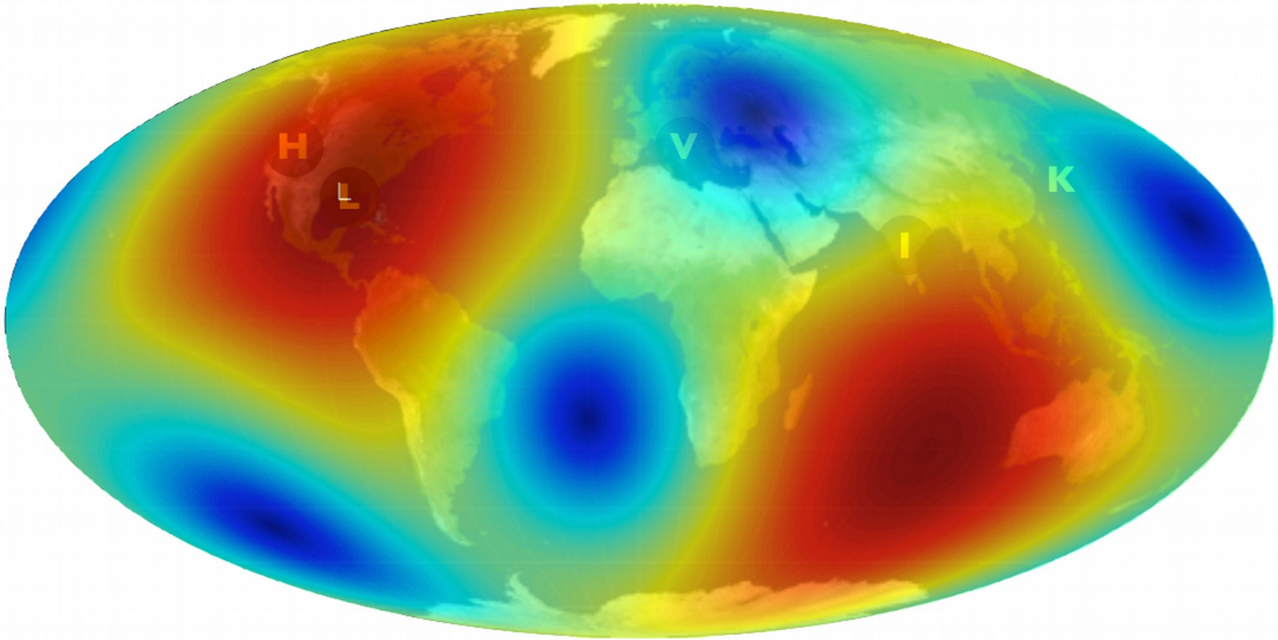
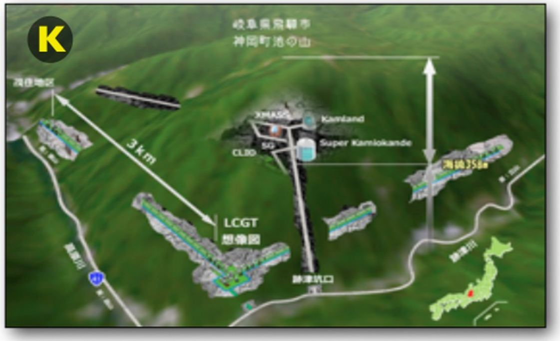


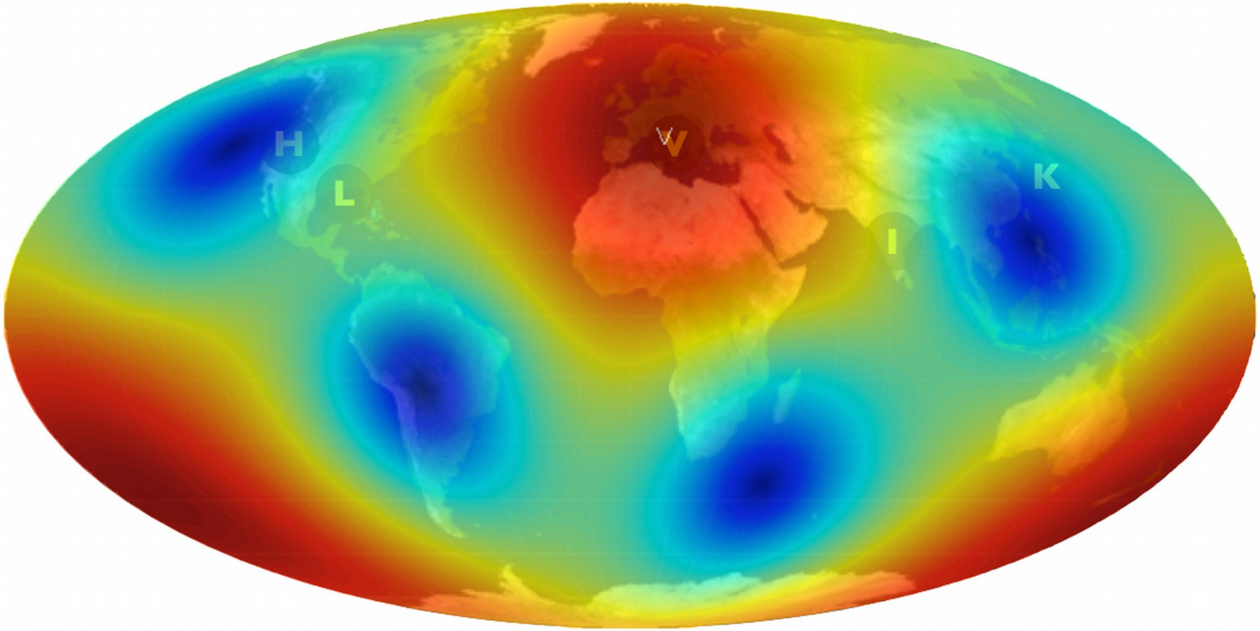


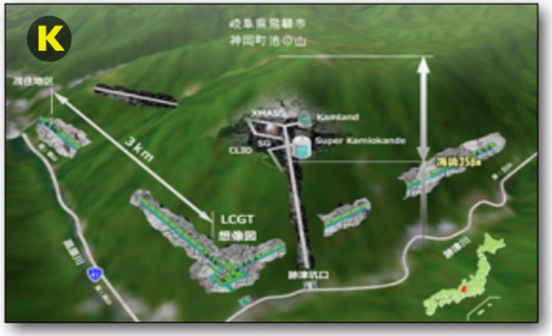
Terrestrial Network



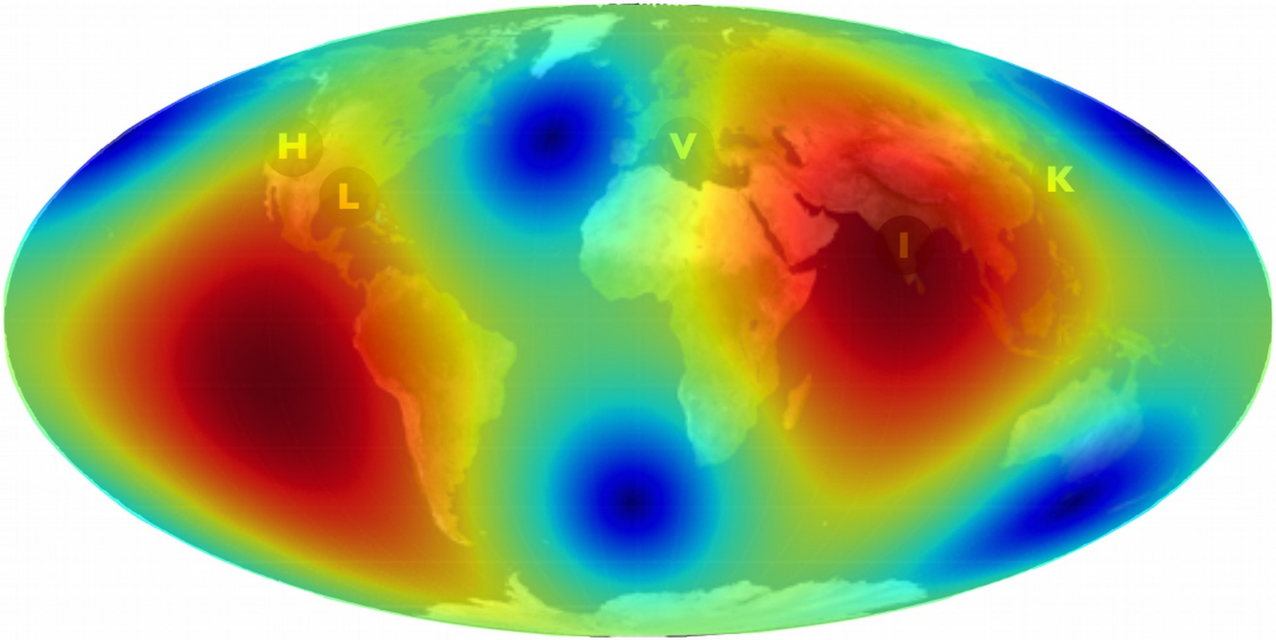


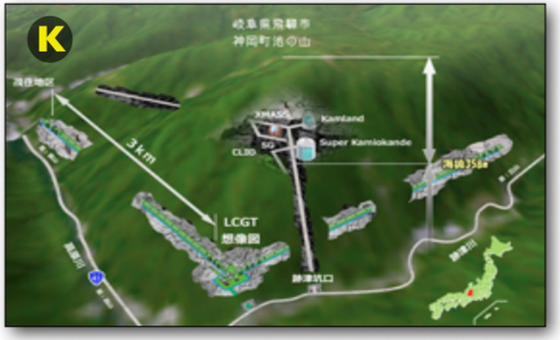
Terrestrial Network



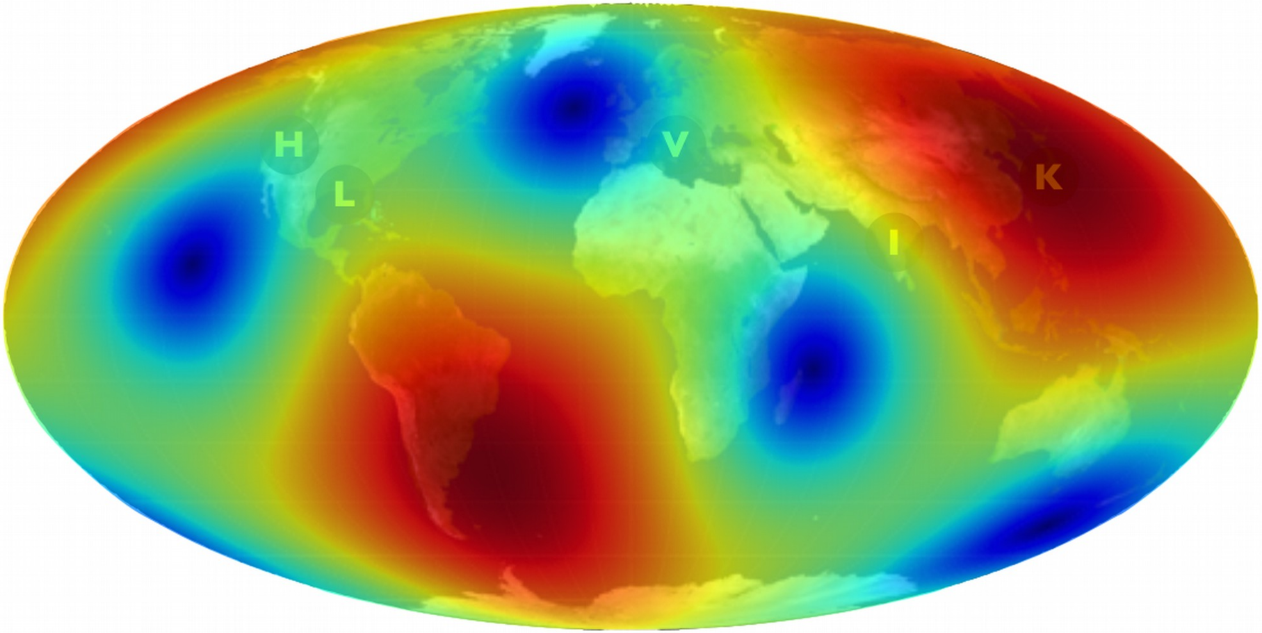


Terrestrial Network

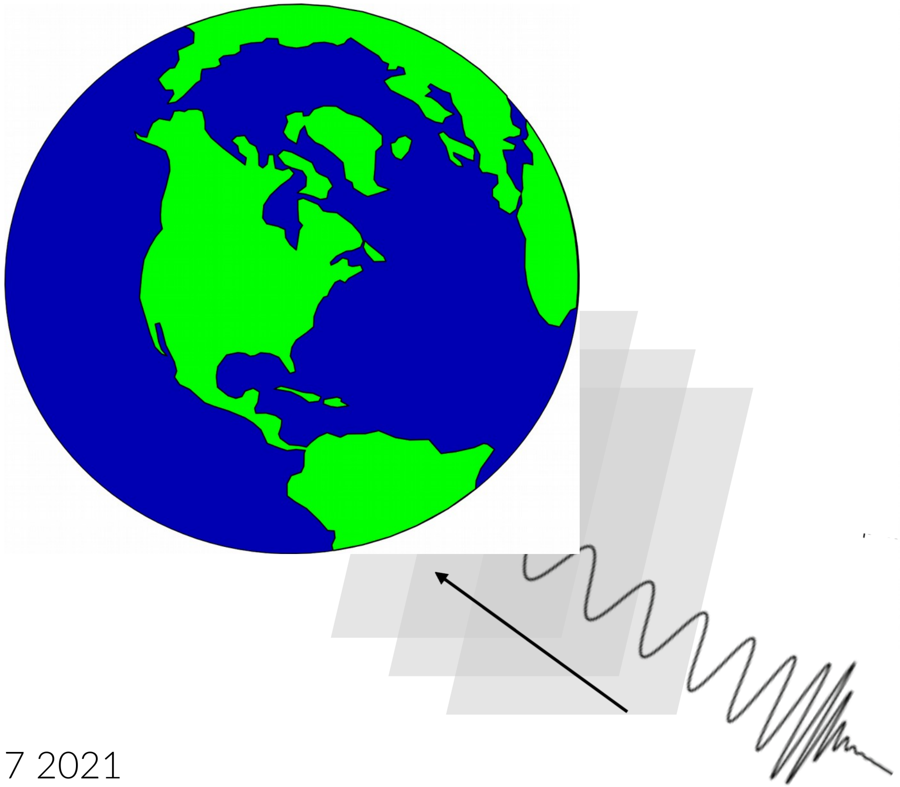


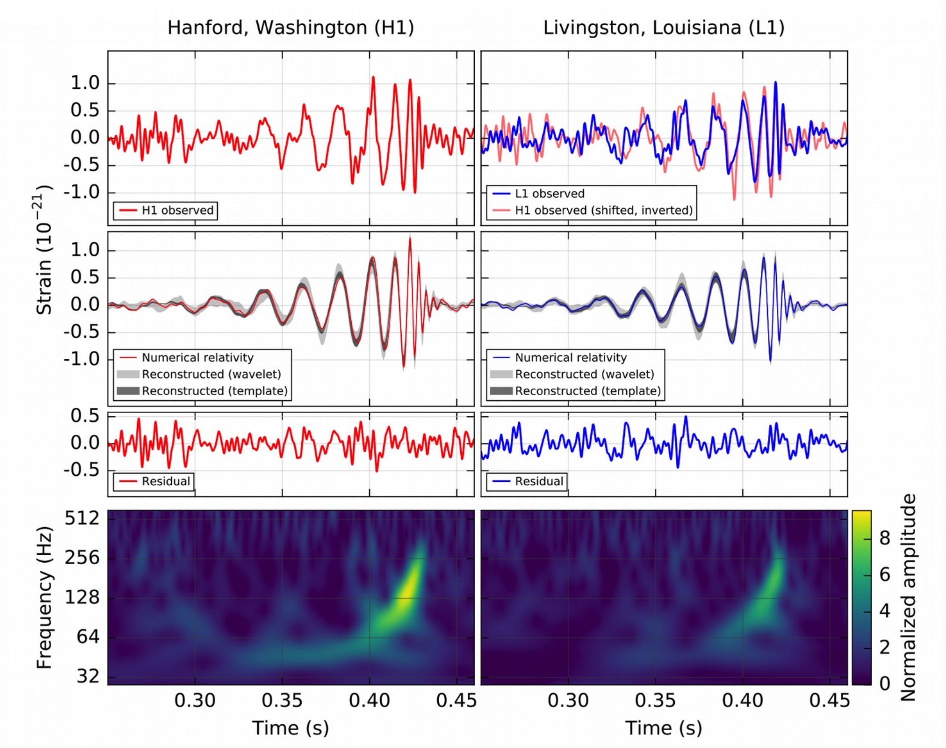


Terrestrial Network



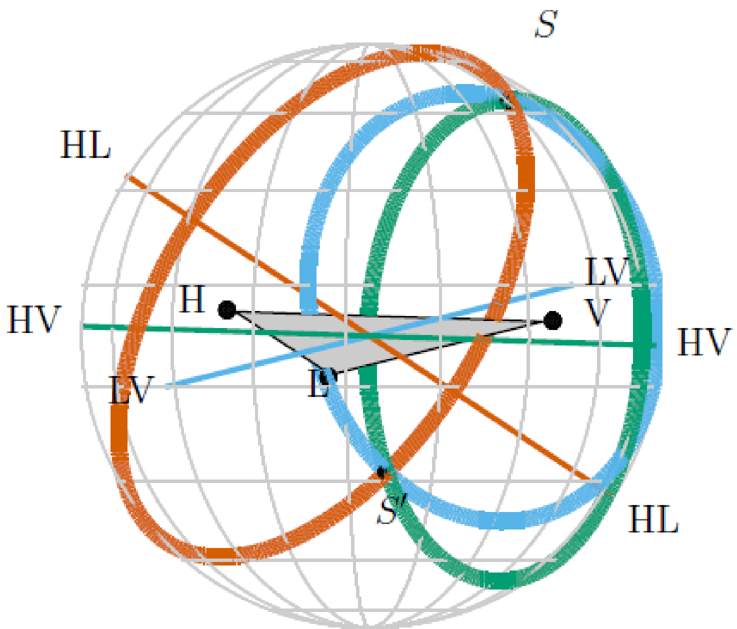
Propagation time delays

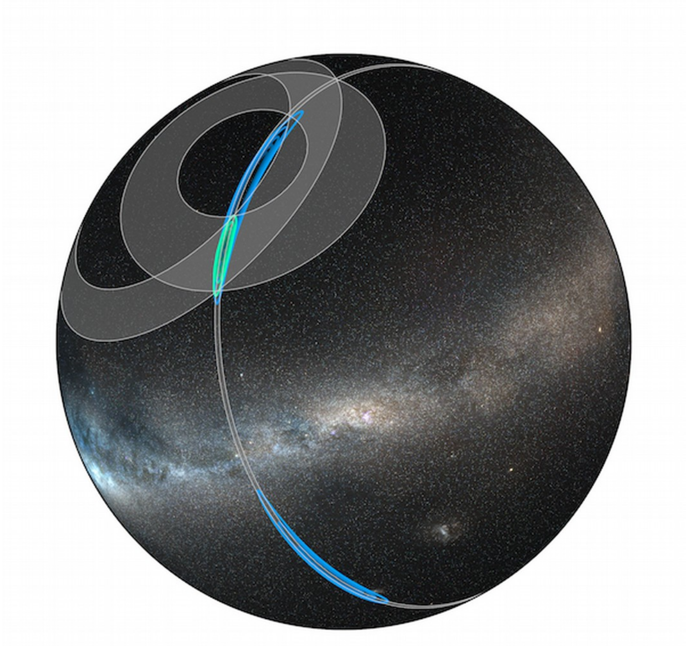




Time delay ~ 7 ms
Phase shift ~ 2.9 rad

Time delays allows triangulation





Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

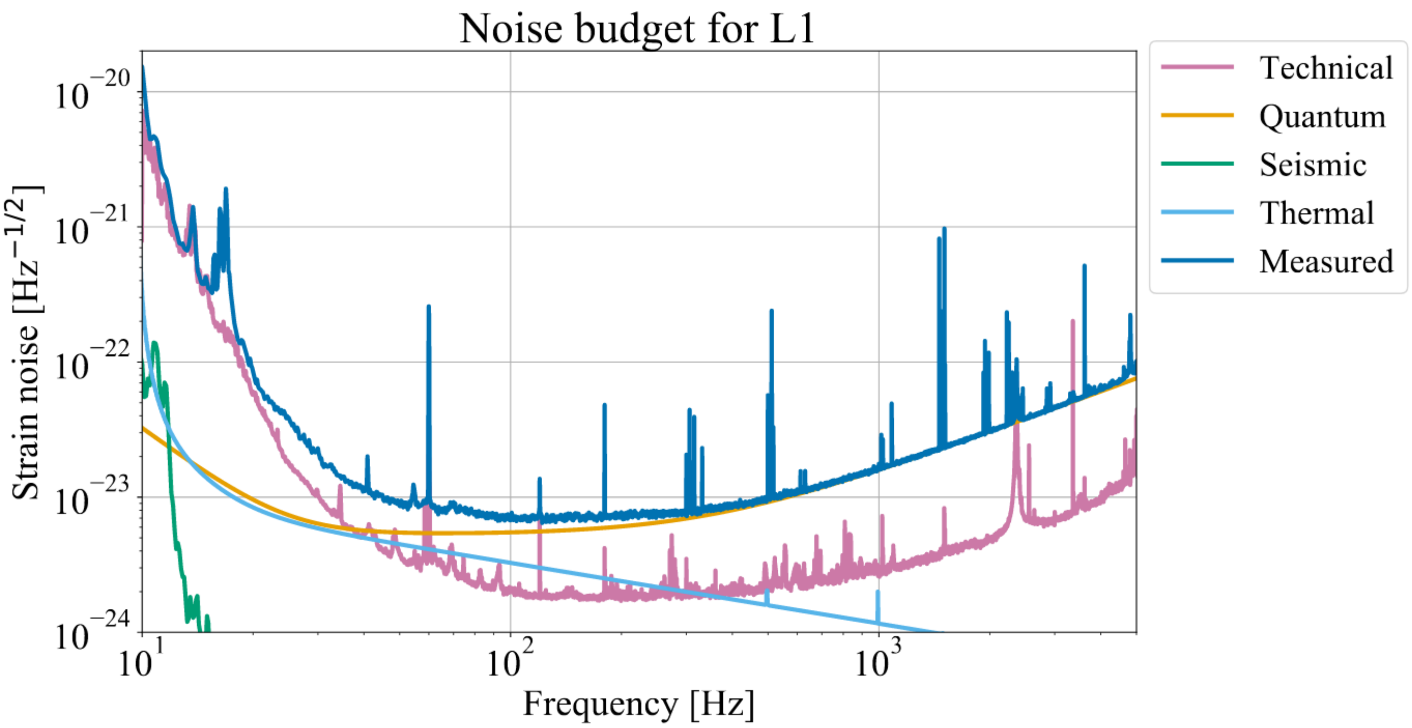
Observation equation (signal part)

data = function(signal, noise)

$$h_{\mathrm{signal}}(t) = F_+ h_+(t-\tau) + F_\times h_\times(t-\tau)$$

$F_+, F_\times, \tau$ depends on sky position θ, ϕ and polarization angle ψ

Observation equation (noise part)



Observation equation (noise part)

data = function(signal, noise)

The noise that affects the measurement combines linearly

data = signal + noise

Observation equation (noise part)

Noise components that can be modelled are Gaussian

$$p(n_i) \propto \mathcal{N}(0, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp - \frac{n_i^2}{2\sigma^2}$$

$$p(n) = \frac{1}{(2\pi)^{N/2}\sigma^N} \exp - \sum_i \frac{n_i^2}{2\sigma^2}$$

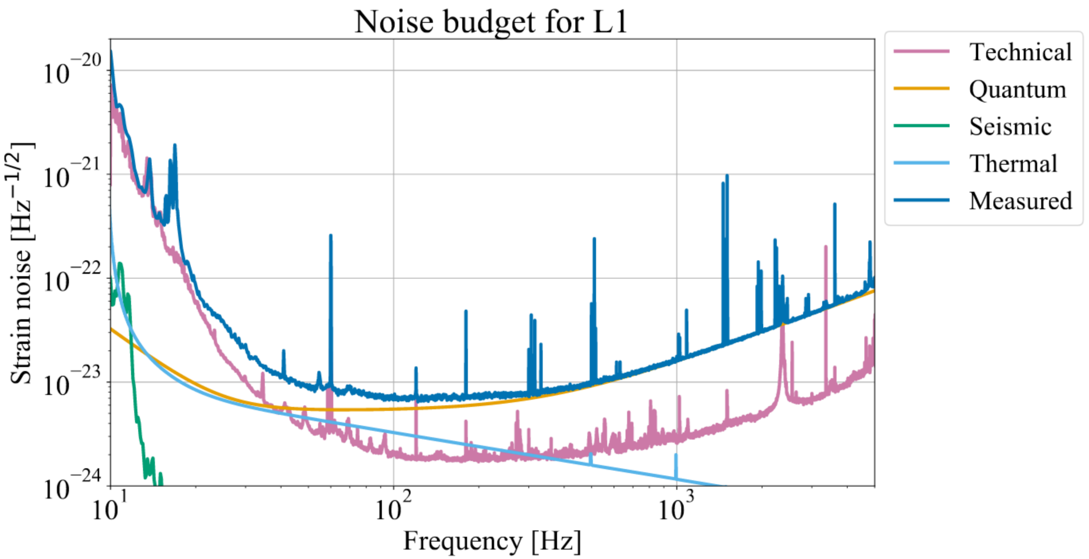
Observation equation (noise part)

- **Gaussian and correlated**

  Multi-variate Gaussian variable

$$p(n) \propto \mathcal{N}(0, C) = \frac{\exp -\frac{1}{2} n_i C^{-1}_{ij} n_j}{\sqrt{|2\pi\, C|}}$$

- **Correlated and stationary**
  - Can be described by a **spectrum**
  - Results in noise “color”



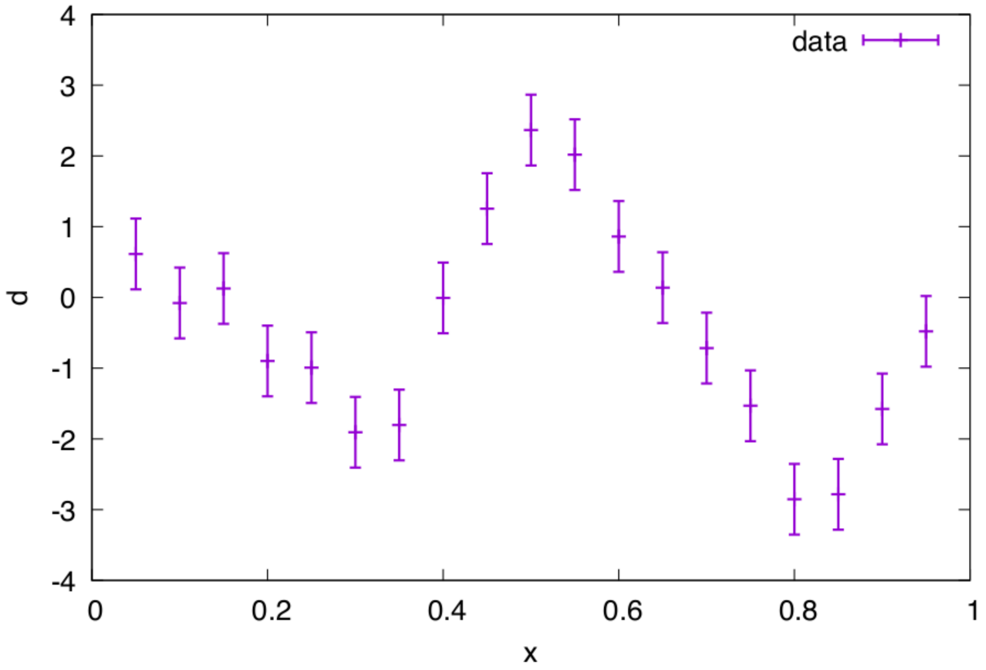
Time	$\leftrightarrow$	Frequency
Correlation	$\leftrightarrow$	Power spectral density
C		$S_{\text{noise}}(f)$

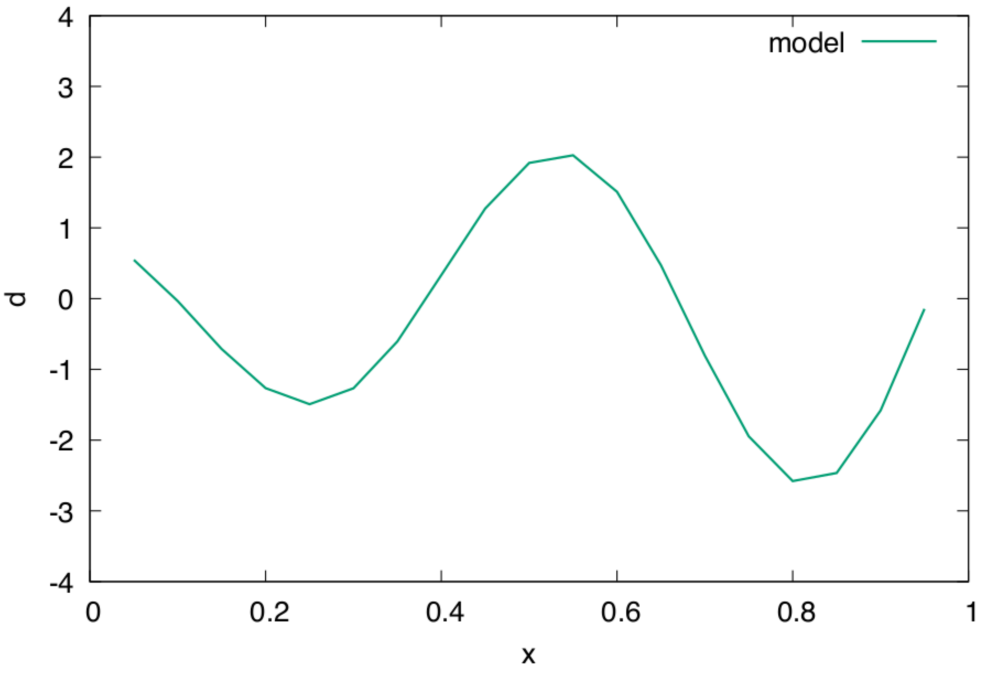
Jun 7 2021

Observation equation

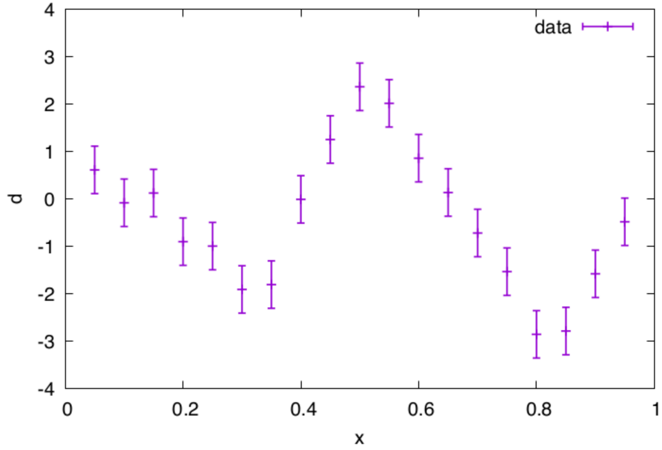
$$d = h + n$$

signal h





$$d = h + n \quad \Rightarrow \quad d - h = n$$



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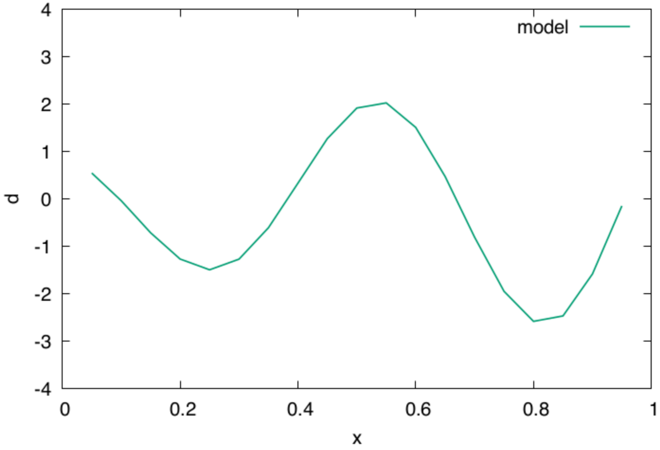

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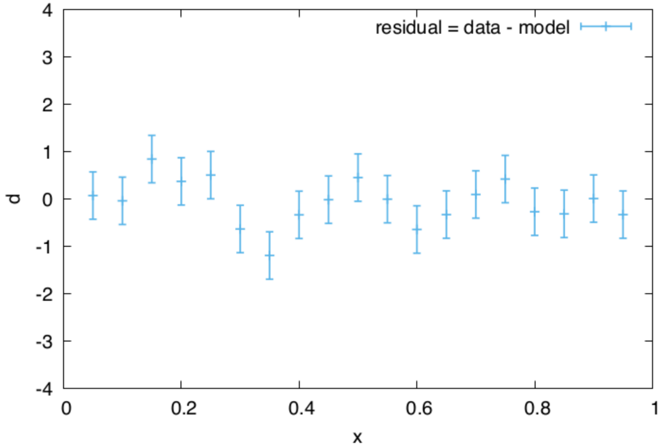
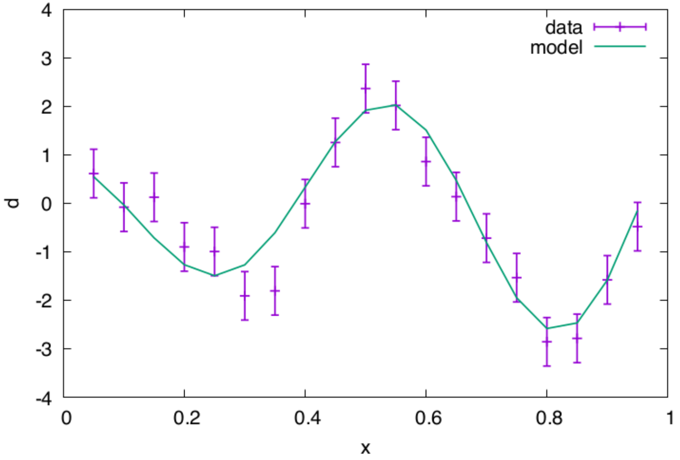
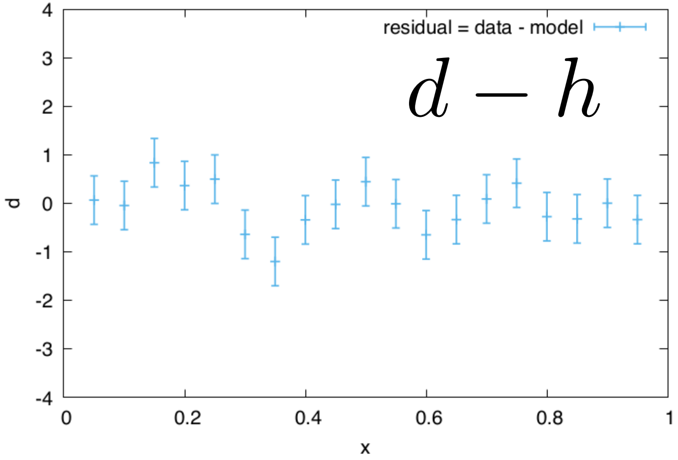


residual

Statistical modelling (1 detector)





Likelihood $p(d|h) \propto \mathcal{N}(h, C) = \dfrac{\exp -\frac{1}{2}(d_i - h_i)C^{-1}_{ij}(d_j - h_j)}{\sqrt{|2\pi\, C|}}$

Encapsulates everything: Gaussian, correlated, additive

Statistical modelling (multiple detectors)

Detector *k* response : $h^{(k)}$ (includes antenna pattern and time delay)

Likelihood (single det) : $$p(d^{(k)}|h^{(k)}) = \frac{\exp -\frac{1}{2}(d_i^{(k)} - h_i^{(k)}) C_{(k)}^{-1}{}_{ij} (d_j^{(k)} - h_j^{(k)})}{\sqrt{|2\pi\, C_{(k)}|}}$$

Likelihood (multi det) : $$p(\{d^{(k)}\}|h) = \prod_k p(d^{(k)}|h^{(k)})$$ Assuming detector noises are independent

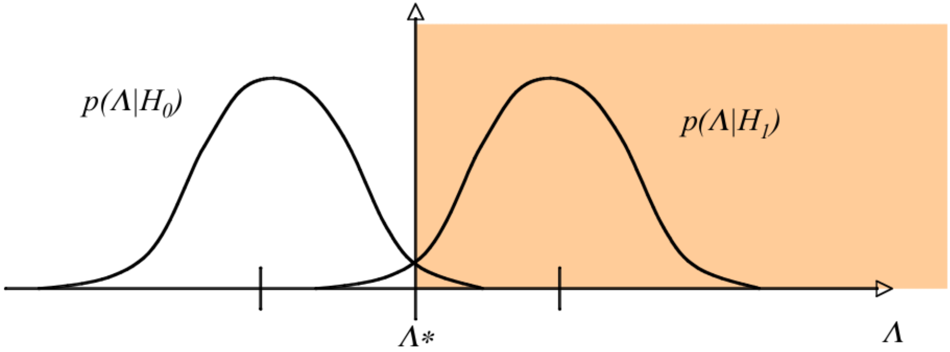
Allows the data from all detectors to be analyzed jointly (coherently)
Proper “triangulation” for source sky localization

Detection – Optimal statistics

Hypothesis testing – (H1) $d = h + n$ **vs** (H0) $d = n$ (h=0)

Likelihood ratio statistic

$$\Lambda = \frac{p(d|h)}{p(d|h=0)} \lessgtr \text{threshold}$$



Maximize detection prob at a given false alarm prob

Estimation – Maximum likelihood

Find h that maximizes: $$p(d|h) = \frac{\exp -\frac{1}{2}(d_i - h_i)C^{-1}_{ij}(d_j - h_j)}{\sqrt{|2\pi\, C|}}$$

Maximize the likelihood amounts to minimize residual norm

$$\chi^2 = (d_i - h_i)C^{-1}_{ij}(d_j - h_j) = \langle d - h | d - h \rangle$$

where we used a freq-weighted scalar product

$$\langle a|b\rangle = a_i\; C^{-1}_{ij}\; b_j = \int \frac{\hat{a}(f)\hat{b}^*(f)}{S_{\rm noise}(f)}\mathrm{d}f$$

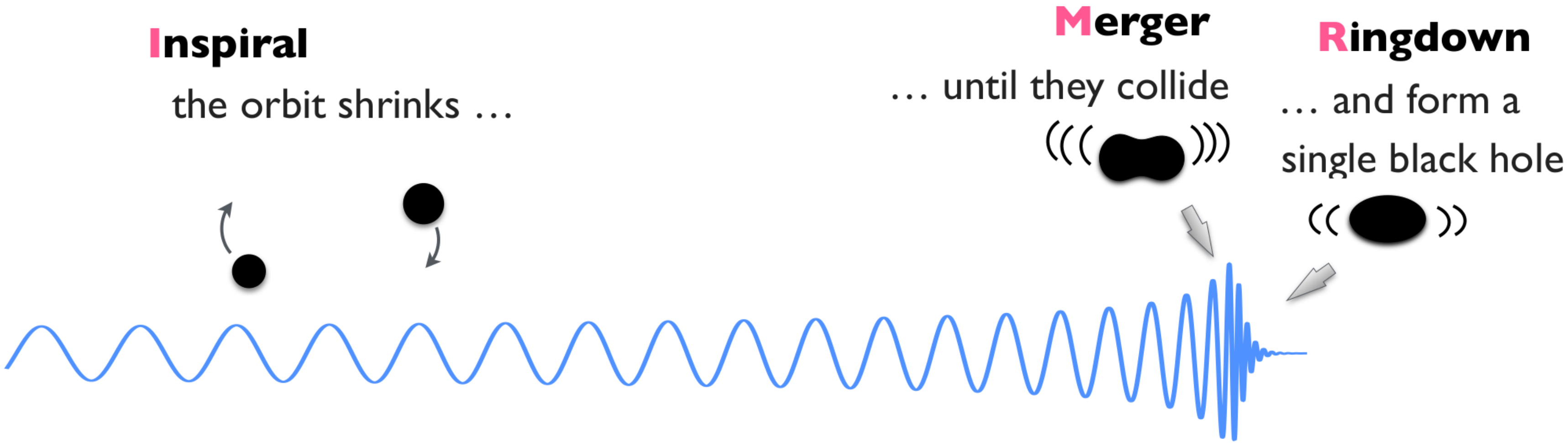
Key question: Do we know anything about the signal?

- Completely known
  - Compact binary coalescence → matched filtering
- Partially known
  - “Unmodelled” transients → time-frequency searches
- Unknown or completely random
  - Stochastic background → cross-correlation

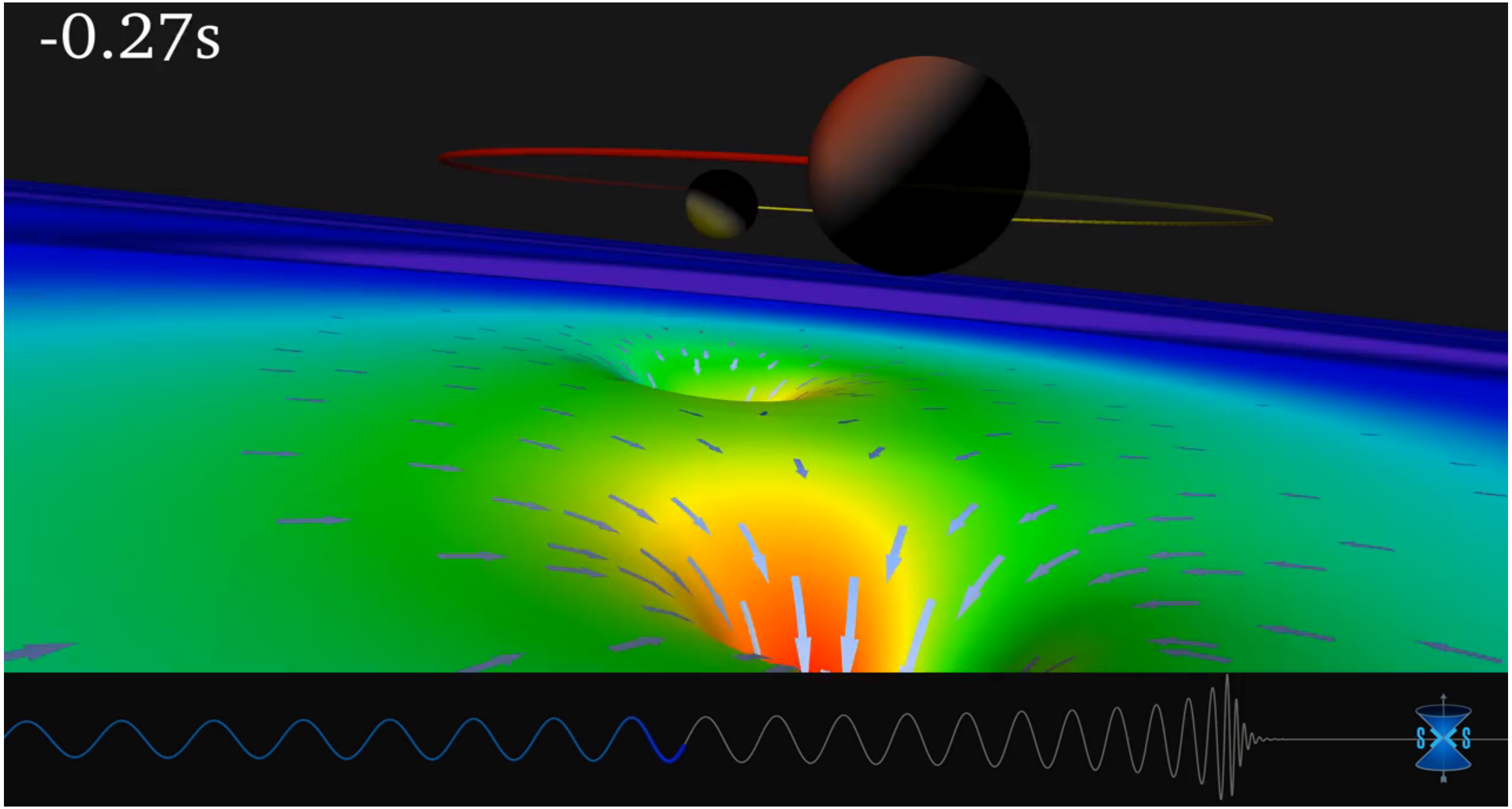
Other important questions

- Is the stationary assumption for the noise really valid?
- Is the Gaussian assumption for the noise really valid?

Compact binary coalescences – Detection



Compact stars : Neutron star or black holes or more exotic objects (boson stars, gravastars, ...)


-0.27s

Orbital dynamics and gravitational radiation

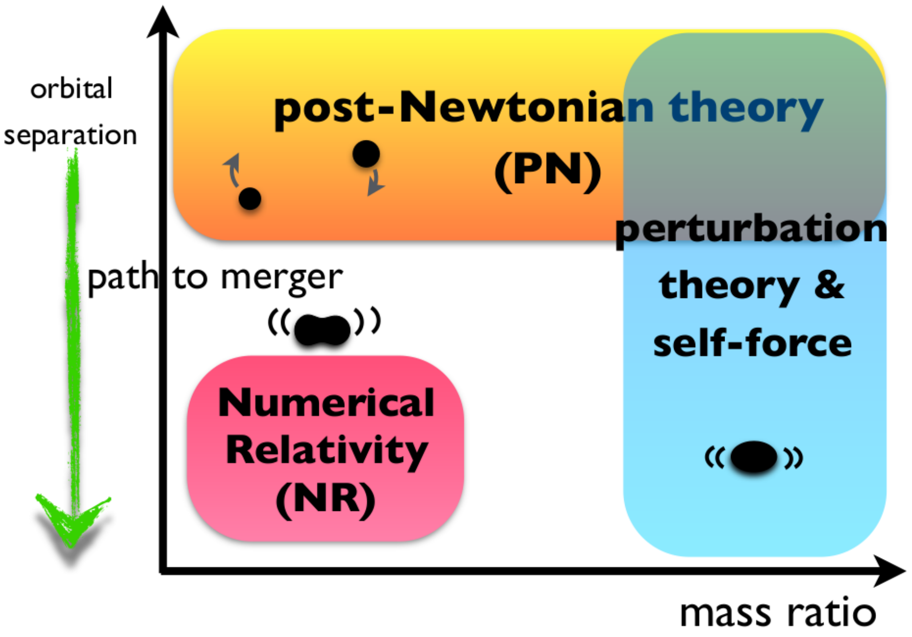
- In the inspiral phase, the orbits are quasi-Keplerian
  - The energy loss due to GW emission is small enough that the orbits nearly close on themselves
  - Adiabatic sequence of quasi-circular orbits

    which ends at the “Innermost Stable Circular Orbit” (ISCO), at twice the Schwarzchild radius.
- GW frequency is twice the orbital frequency

Inspiral-merger-ringdown waveform

- The exact resolution of the two-body problem is hard in general relativity
  - Analytic approximations
  - Numerical relativity
- Major families
  - Phenomenological ansatz
  - Effective one-body approximation
  - Surrogate numerical relativity (for large masses and large q)

Note: very active developments on calculation techniques borrowed from quantum physics "scattering amplitudes"



Credits: G Pratten/P Schmidt

Inspiral-merger-ringdown waveform

Orbital energy

$$E = -\frac{\nu M v^2}{2}\left\{1 + \left(-\frac{9+\nu}{12}\right)v^2 + \left(\frac{-81+57\nu-\nu^2}{24}\right)v^4 + \left(-\frac{675}{64} + \left[\frac{34445}{576} - \frac{205\pi^2}{96}\right]\nu - \frac{155}{96}\nu^2 - \frac{35}{5184}\nu^3\right)v^6 + \mathcal{O}(v^8)\right\}$$

Energy loss due to GW radiation

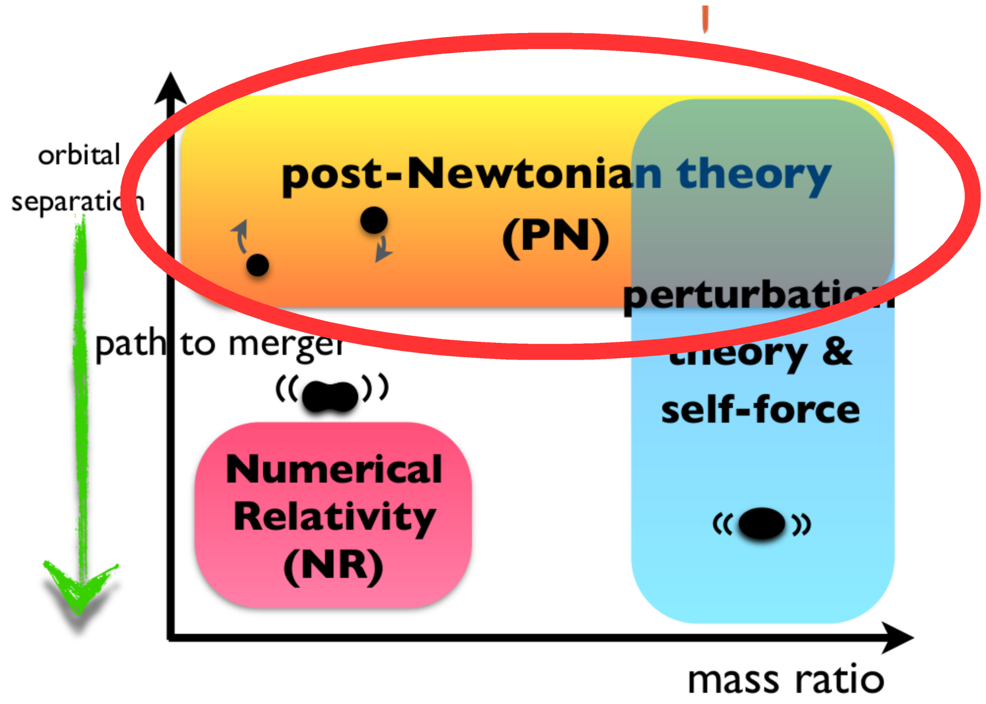
$$\mathcal{F} = \frac{32\nu^2 v^{10}}{5}\left\{1 - \left(\frac{1247}{336} + \frac{35}{12}\nu\right)v^2 + 4\pi v^3 + \left(-\frac{44711}{9072} + \frac{9271}{504}\nu + \frac{65}{18}\nu^2\right)v^5\right.$$

Resolve eqs of motion: $\dfrac{dv}{dt} = \dfrac{-\mathcal{F}(v)}{E'(v)}$

Deduce orbital phase and polar waveform $\dfrac{d\varphi(t)}{dt} = \dfrac{v^3}{M}$

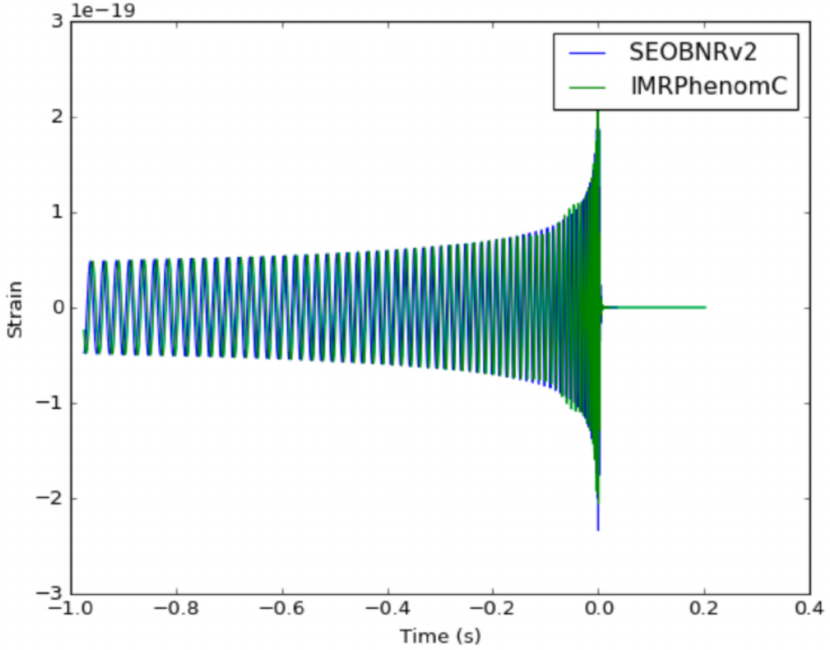
$$h_+ = \frac{2\nu M}{D}v^2(1+\cos^2\iota)\cos[2\varphi(t)]$$

$$h_\times = \frac{4\nu M}{D}v^2\cos\iota\,\sin[2\varphi(t)]$$

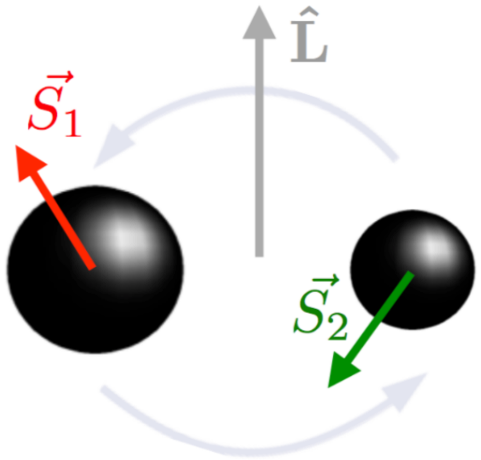


Differences between waveform families

- There are small differences between waveform approximants
  - Can help to estimate the “systematic error” wrt the “true” GR waveform

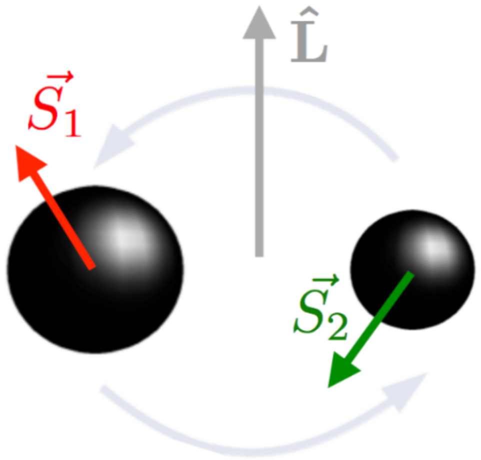


Waveform parameters



- Component masses: m_1, m_2
- Component spins: S_1, S_2 (2 x 3 params)
- Sky location: right ascension α, declination δ
- Luminosity distance: d_L
- Orbital plane orientation: inclination $\iota \cong \theta_{LN}$, polarization angle ψ
  - If component spins are not aligned with the orbital angular momentum L, the orbital plane will *precess* so the inclination angle is θ_{JN}
- At coalescence: phase φ_c , time t_c
- That's 15 parameters, for (adiabatically) quasi-circular orbits

Waveform parameters



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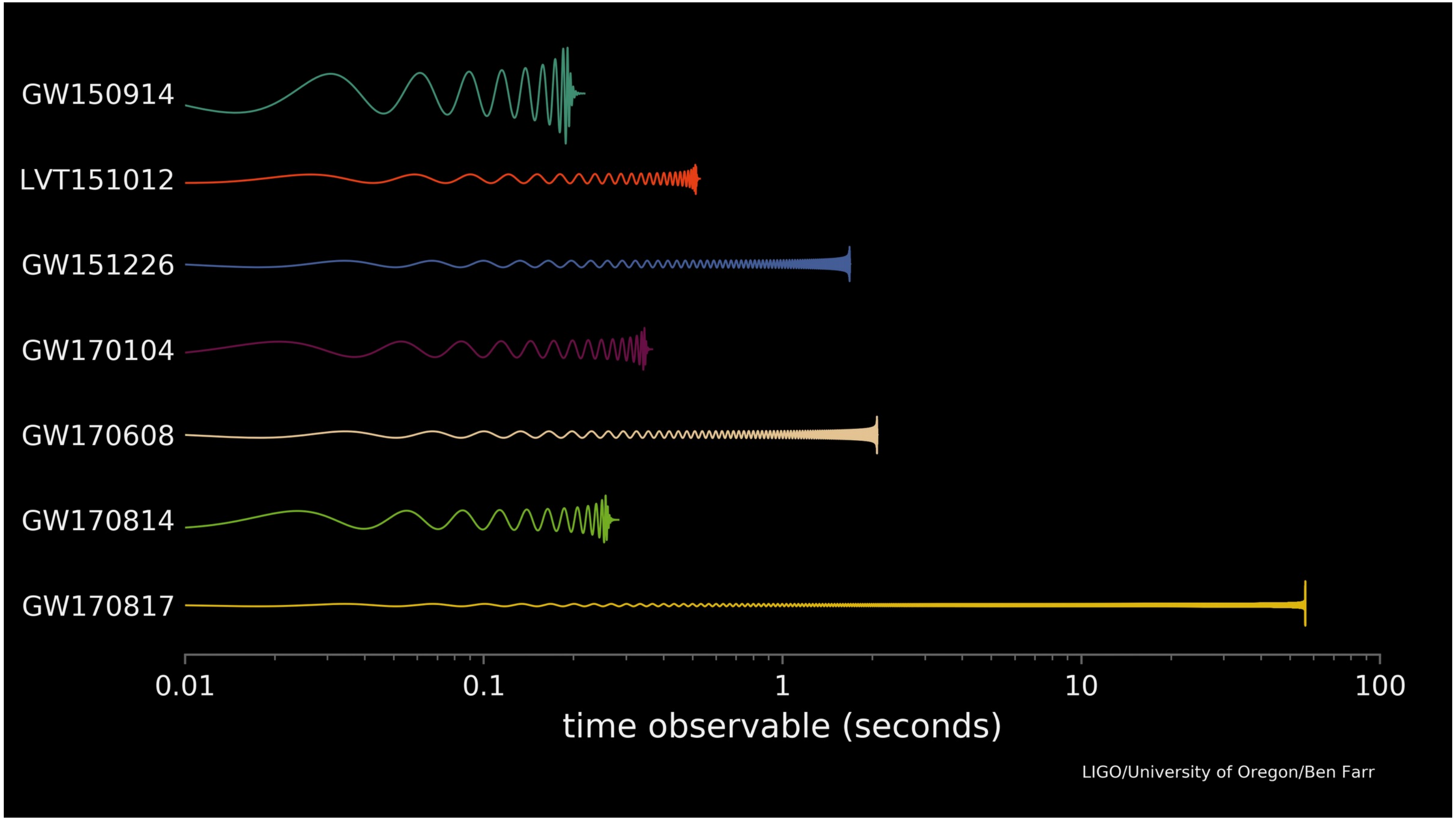
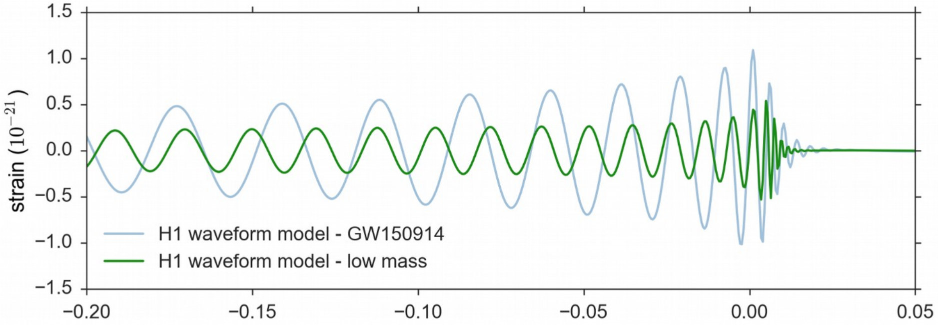
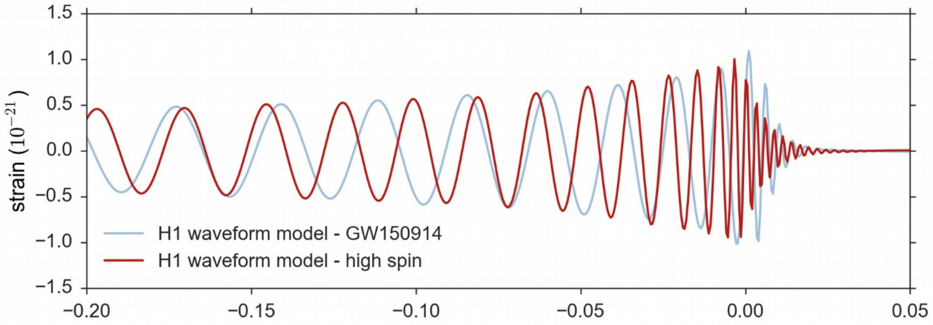
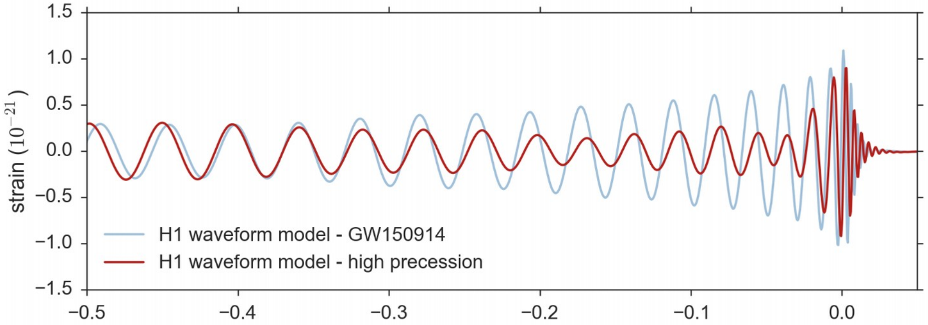
- That's 15 parameters, for (adiabatically) quasi-circular orbits
  - 8 intrinsic and 7 extrinsic

Waveform variability





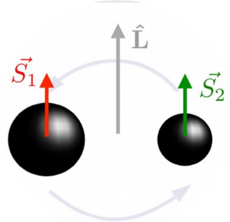




Varying the mass parameters

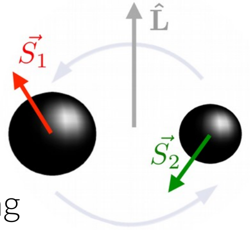
Effect: overall phase evolution, and final ringdown frequency – Chirp mass and mass ratio

Varying the spin amplitude



Effect: “orbital hang-up” – Effective spin

Varying the spin orientation



Effect: relativistic spin precession – Precessing spin

Post-Newtonian Expansion

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

0PN	$\frac{3}{128}\, u^{-5}$	Measure chirp mass
1PN	$\left(\frac{3715}{32256} + \eta \frac{55}{384}\right) \eta^{-2/5} u^{-3}$	Measure individual masses
1.5PN	$-\left(\frac{3\pi}{8} - \frac{1}{32}\left[113(1 \pm \sqrt{1-4\eta}) - 76\eta\right] \hat{L} \cdot \vec{\chi}_{1,2}\right) \eta^{-3/5}\, u^{-2}$	Measure spin combination
2PN	$\left(\frac{15293365}{21676032} + \frac{27145}{21504}\eta + \frac{3085}{3072}\eta^2 + \sigma(\hat{L} \cdot \vec{\chi}_{1,2},\, \vec{\chi_1} \cdot \vec{\chi_2},\, \chi_{1,2}^2)\right) \eta^{-4/5}\, u^{-1}$	Measure individual spins

Chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

Mass ratio: $q = \frac{m_1}{m_2}$

Effective spin:

$$\chi_{\text{eff}} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$

Matched filtering

Likelihood: $$p(d|\boldsymbol{\lambda}) \propto \exp -\frac{1}{2}\langle d - h(\boldsymbol{\lambda}) | d - h(\boldsymbol{\lambda})\rangle$$

Parameters: $\boldsymbol{\lambda} = \{m_1, m_2, \mathbf{S}_1, \mathbf{S}_2, \ldots\}$

Likelihood ratio: $$\Lambda(\boldsymbol{\lambda}) = \frac{p(d|h(\boldsymbol{\lambda}))}{p(d|h=0)} = e^{-\langle d|h\rangle + \frac{1}{2}\langle h|h\rangle}$$

Maximize over **λ**

Let's do over **amplitude** only for now

$$h(\boldsymbol{\lambda}) \equiv \rho\, h_{\mathrm{norm}}(\boldsymbol{\lambda})$$

Compute ρ such that $\partial\Lambda/d\rho = 0$
and replace in Λ

Matched filtering

Likelihood: $$p(d|\boldsymbol{\lambda}) \propto \exp -\frac{1}{2}\langle d - h(\boldsymbol{\lambda})|d - h(\boldsymbol{\lambda})\rangle$$

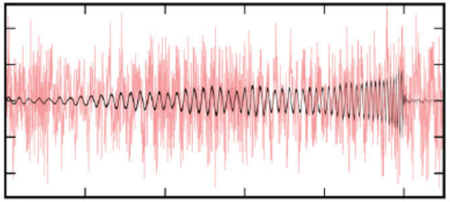
Parameters: $\boldsymbol{\lambda} = \{m_1, m_2, \mathbf{S}_1, \mathbf{S}_2, \ldots\}$

Likelihood ratio: $$\Lambda(\boldsymbol{\lambda}) = \frac{p(d|h(\boldsymbol{\lambda}))}{p(d|h=0)} = e^{-\langle d|h\rangle + \frac{1}{2}\langle h|h\rangle}$$

Generalized likelihood ratio: $$\rho(\boldsymbol{\lambda}) = \langle d|h_{\rm norm}(\boldsymbol{\lambda})\rangle = \int \frac{\hat{d}(f)\hat{h}^*_{\rm norm}(f;\boldsymbol{\lambda})}{S_{\rm noise}(f)}\mathrm{d}f$$

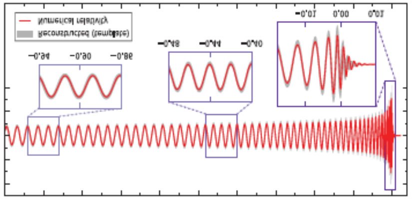
$$\rho(\boldsymbol{\lambda}) = \int \frac{\hat{d}(f)\hat{h}^*_{\mathrm{norm}}(f;\boldsymbol{\lambda})}{S_{\mathrm{noise}}(f)}\mathrm{d}f$$

Data



X

Waveform



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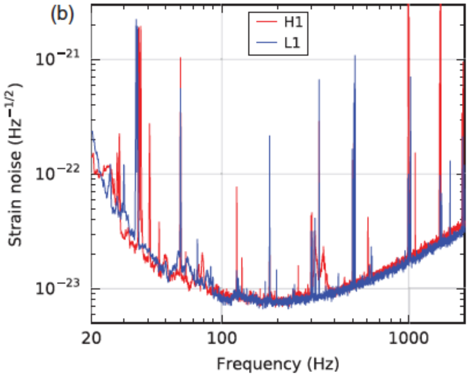
Sensitivity



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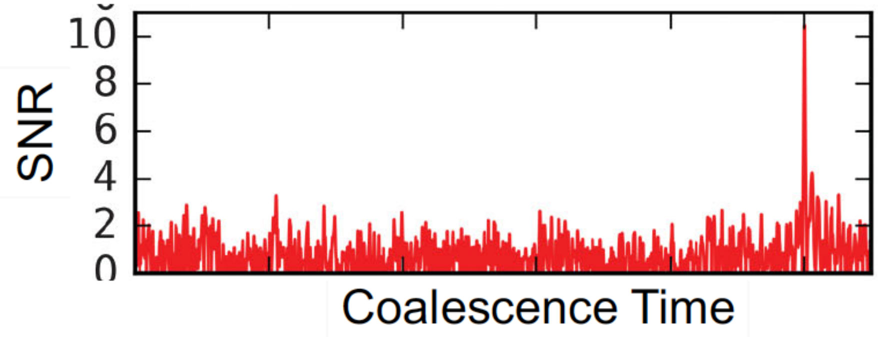
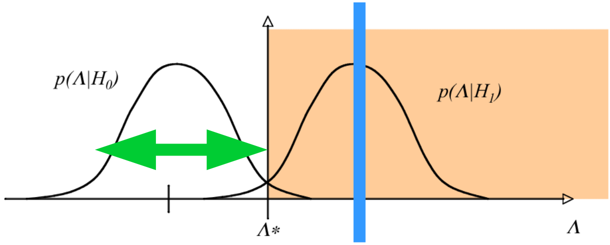


Signal-to-noise ratio SNR

Definition: $$\mathrm{SNR} = \frac{\text{Expected value if signal}}{\text{Std if no signal}}$$



Constrast between the two hypotheses

$$\mathrm{SNR} = \frac{E[\rho]}{\mathrm{var}[\rho_0]^{1/2}} = \langle h|h_{\mathrm{norm}}\rangle = \sqrt{\langle h|h\rangle}$$

$$\mathrm{SNR}^2 = \int \frac{|h(f)|^2}{S_{\mathrm{noise}}(f)}\mathrm{d}f$$

Figure-of-merit used to predict detectability – Typ. SNR > 7

Matched filtering (cont'd)

Maximize over **λ**: analytically over extrinsic params (d_L, φ_c, t_c)

$$z(\tau;\boldsymbol{\lambda}) = \int \frac{\hat{d}(f)\hat{h}^*_{\mathrm{norm}}(f;\boldsymbol{\lambda})}{S_{\mathrm{noise}}(f)} e^{2\pi i f \tau}\mathrm{d}f$$

$$\rho(\boldsymbol{\lambda}) = \max_{\tau} |z(\tau;\boldsymbol{\lambda})|$$

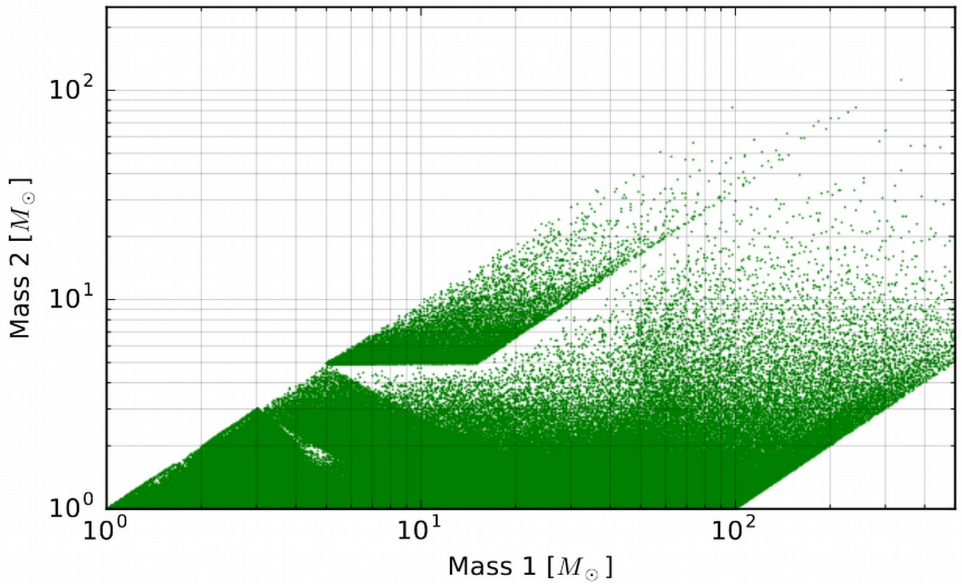
Can be computed with FFT

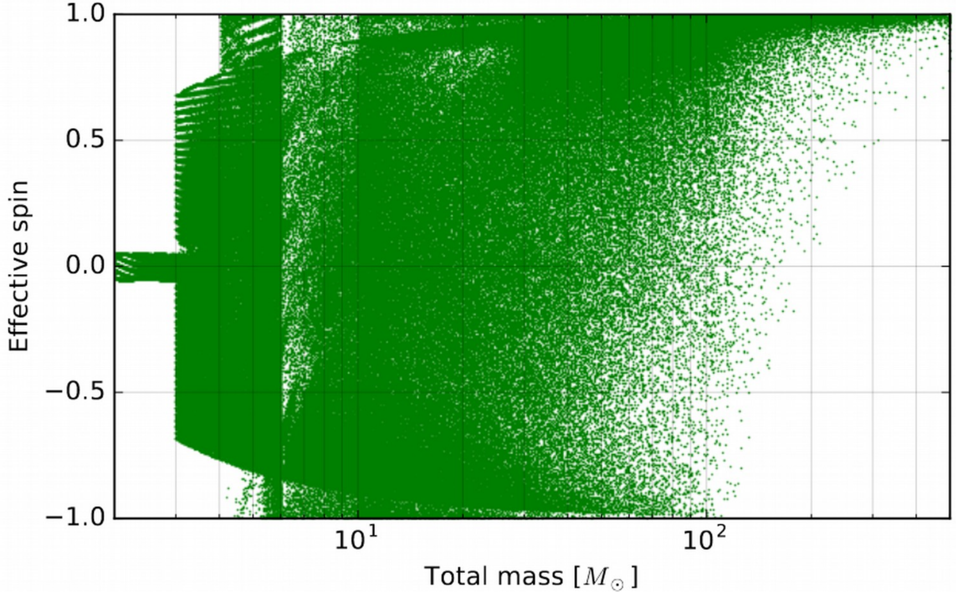
Maximize over **λ**: for the rest, use brute force "grid search"

Matched filtering (cont'd) – Grid search

Grid spacing ensures < 3 % of SNR loss (2 % in BBH region)

Correlation or match <h1|h2> between neighboring templates is > 97 %

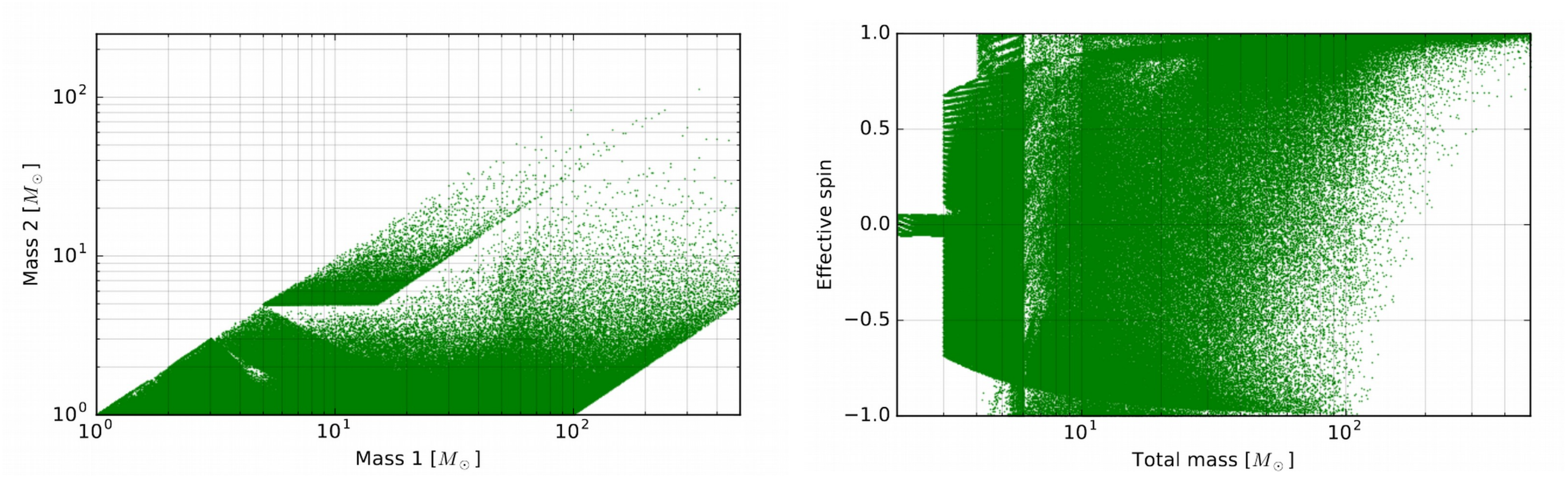




Template bank used for O2 searches : 400,000 waveforms

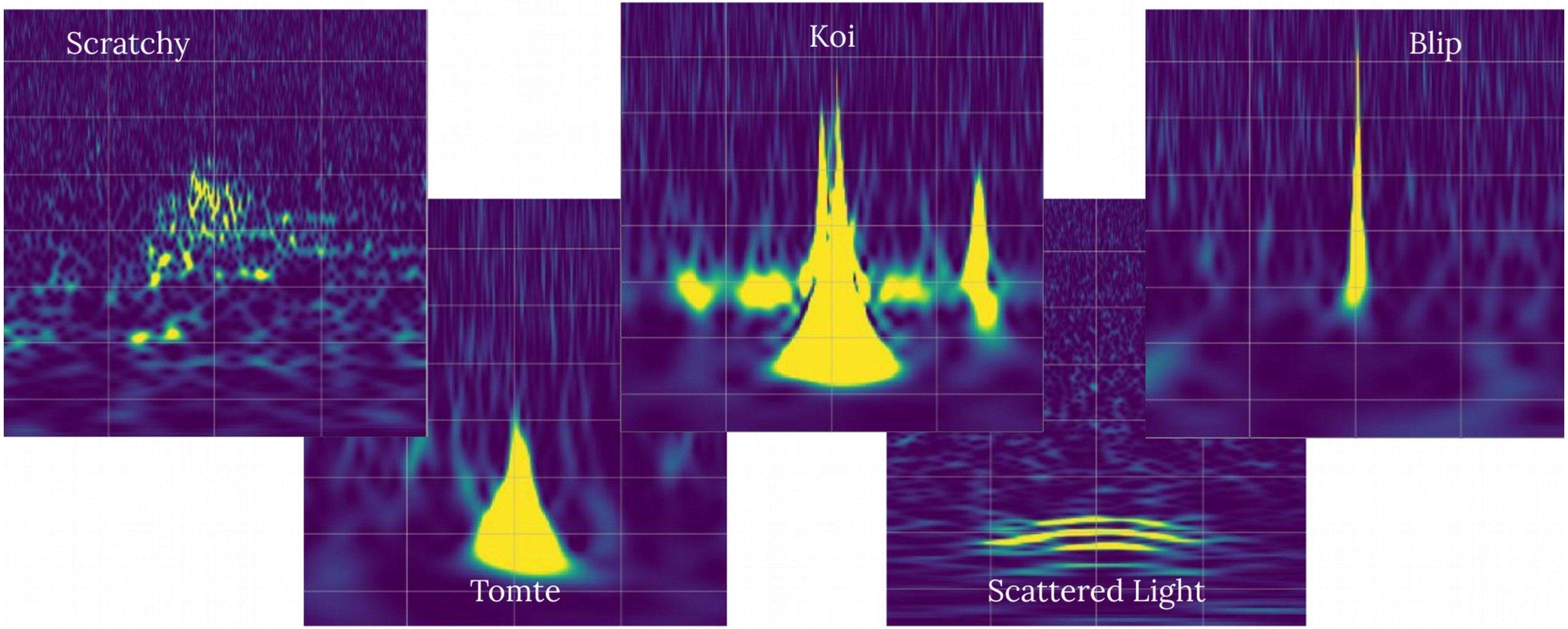
Dal Canton, Harry – arXiv:1705.01845

Matched filtering (cont'd) – Grid search



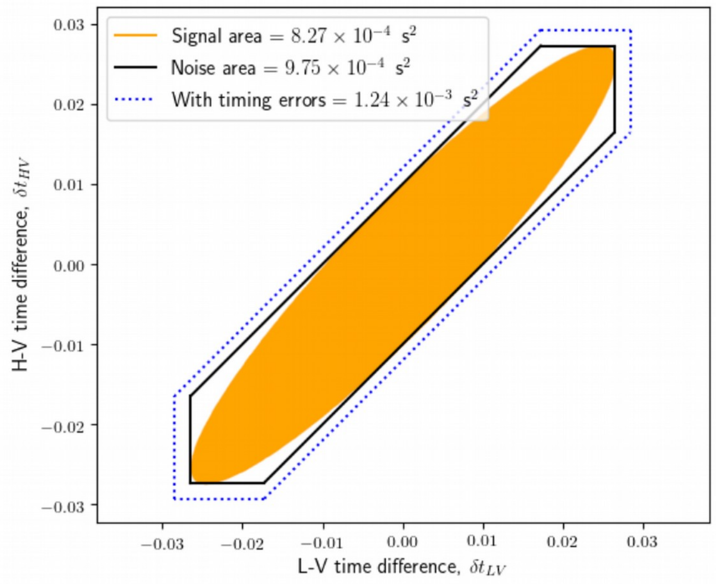
https://github.com/gwastro/pycbc-config/tree/master/O1/bank
https://github.com/gwastro/pycbc-config/tree/master/O2/bank
https://git.ligo.org/lscsoft/gstlal/-/tree/master/gstlal-inspiral/share/O3

Non-Gaussian/non-stationary noise artifacts



Noise mitigation and glitch rejection (1)

- Use **multiple detector data**
  - **Coincidence** in time and template parameters
  - Consistency in phase and SNR
  - Note: there are no fully coherent searches in production so far
- Use info from **environmental and detector monitoring channels**



arXiv:2002.08291

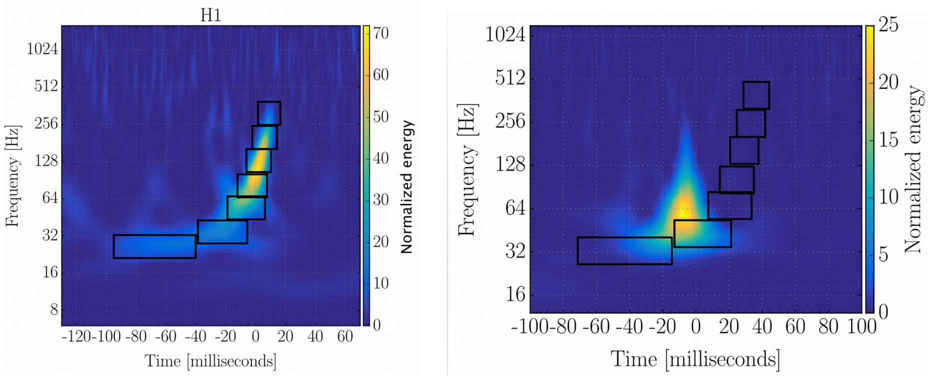
Noise mitigation and glitch rejection (2)

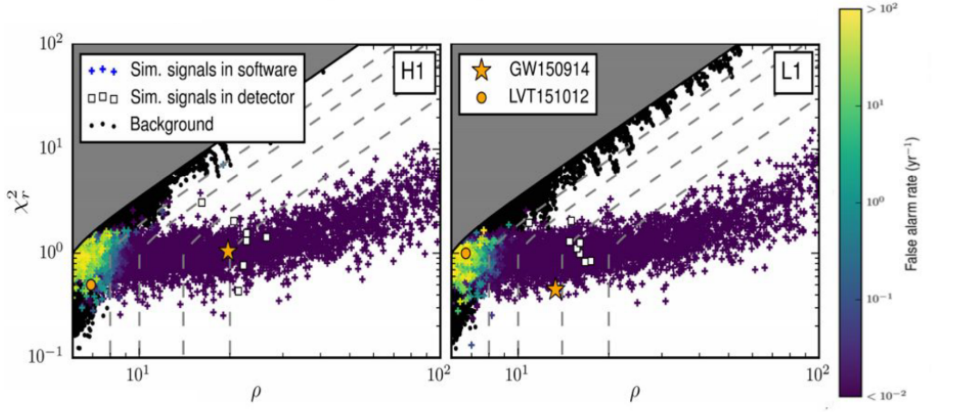
- χ^2 signal consistency test
  - Companion statistics that tests the spectral profile of triggers

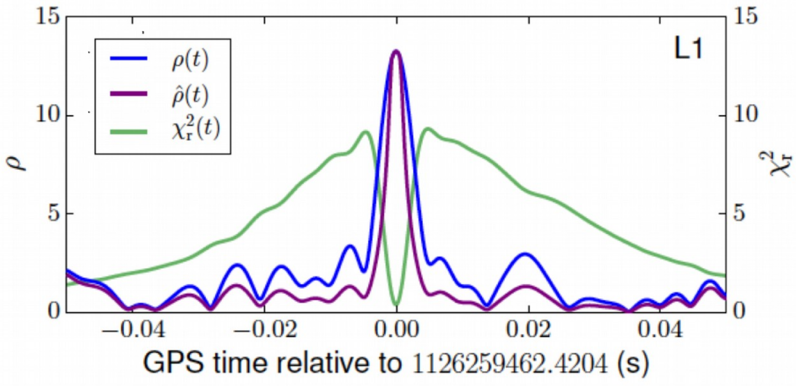
$$\chi^2 = \sum_{k \in \text{bins}} (\rho_k - \rho / N_{\text{bins}})^2 \qquad \rho = \sum_{k \in \text{bins}} \rho_k$$

  - Combine ρ and χ^2 statistics

$$\hat{\rho} = \begin{cases} \dfrac{\rho}{[(1+(\chi_r^2)^{p/2})/2]^{1/p}} & \text{for } \chi_r^2 > 1 \\ \rho & \text{for } \chi_r^2 \leq 1 \end{cases}$$





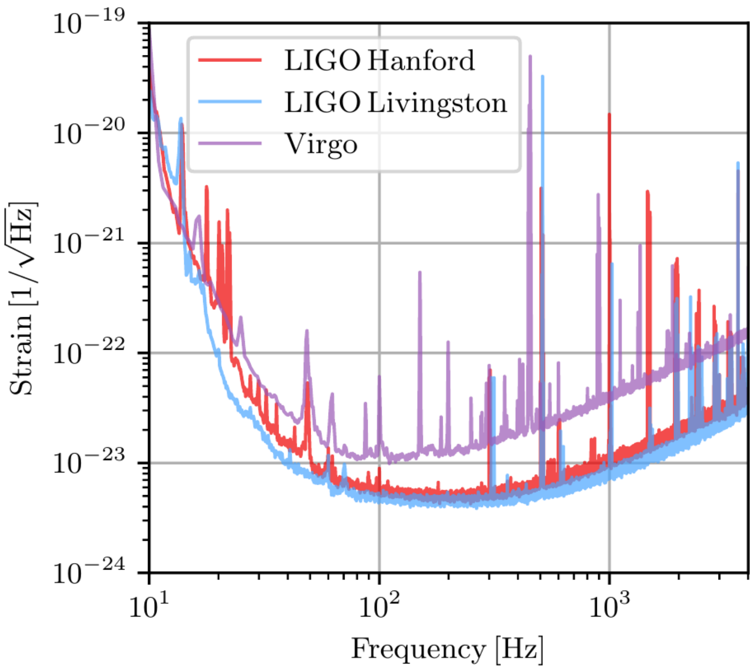


arXiv:1208.3491

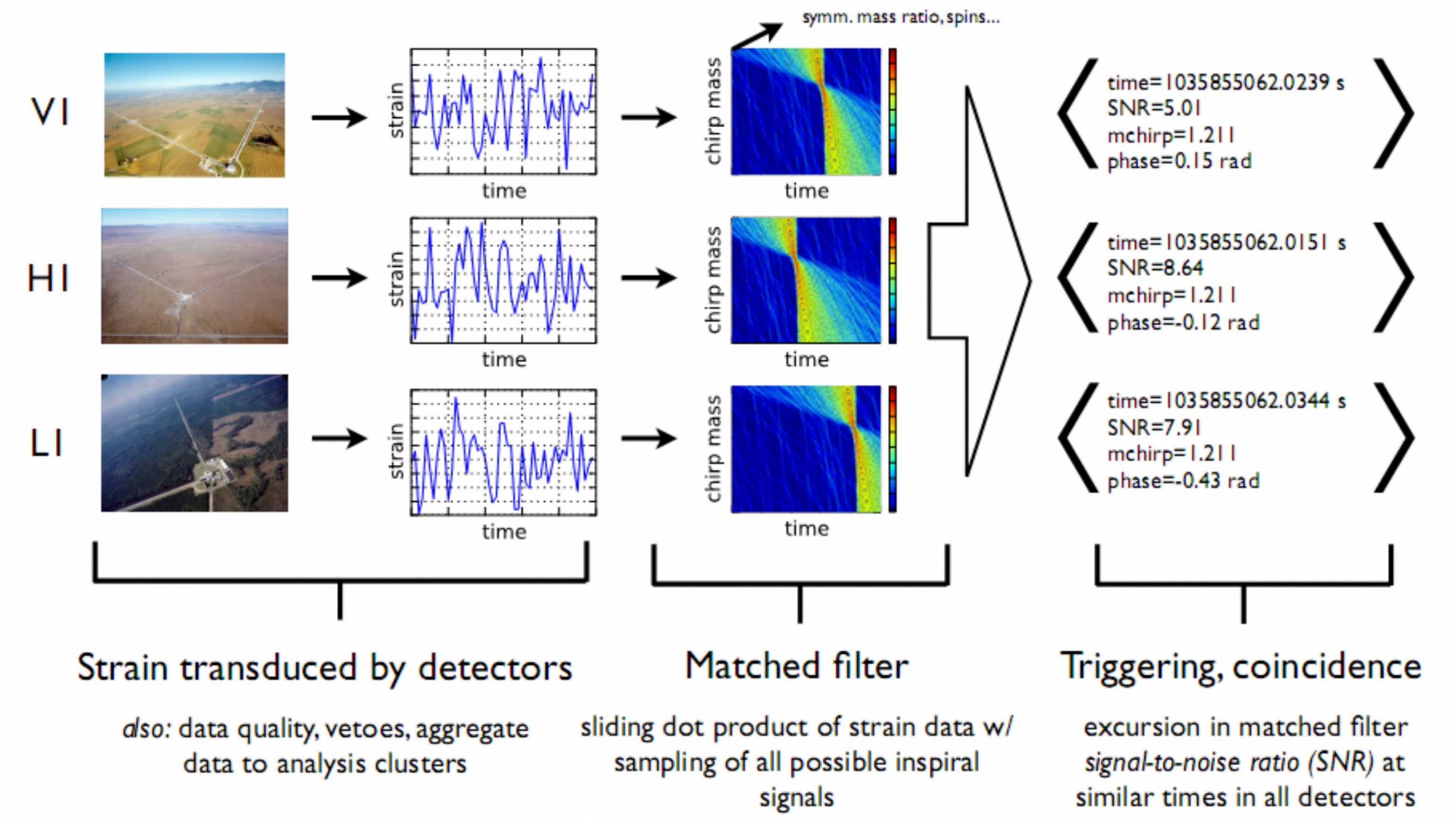
Matched filtering (cont'd) – Whitening

$$z(\tau;\boldsymbol{\lambda}) = \int \frac{\hat{d}(f)\hat{h}^*_{\mathrm{norm}}(f;\boldsymbol{\lambda})}{S_{\mathrm{noise}}(f)} e^{2\pi i f \tau}\,\mathrm{d}f$$

- Down-weighting noisy frequency regions (low-, high- and "lines")
- Filtering with $S_{\mathrm{noise}}^{-1/2}$ is known as "whitening"
- Requires regular estimates of noise PSD to adapt slow drift in the noise level



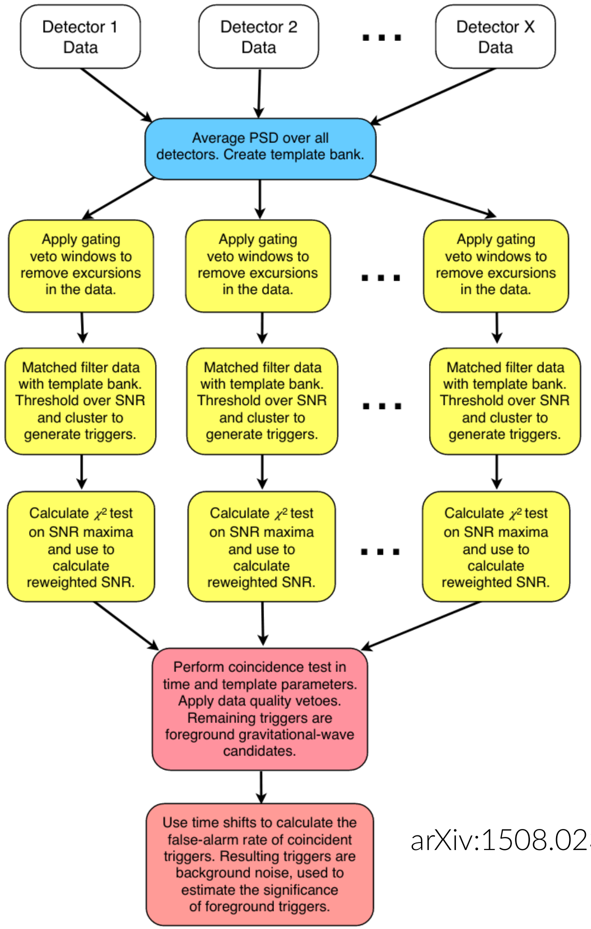
Workflows and pipelines



Workflows and pipelines

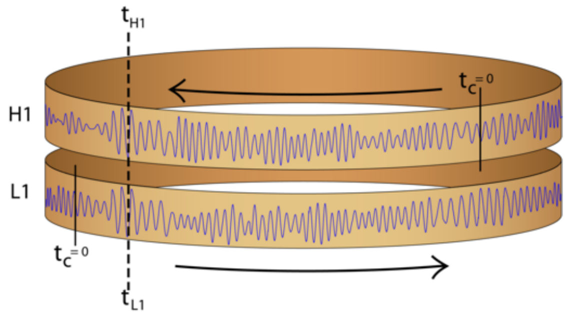
- GstLAL lscsoft.docs.ligo.org/gstlal
- PyCBC pycbc.org
- MBTA T. Adams et al. (2016)
- SPIIR Q. Chu (2017)
- IAS Venumadhav et al. (2020)

- Bulk of computing is **embarrassingly parallel**
- Run on dedicated **computer clusters** of CPU or GPU or on distributed computing infrastructures
- **Complex workflows** orchestrated using schedulers such as Condor or Pegasus



arXiv:1508.02357

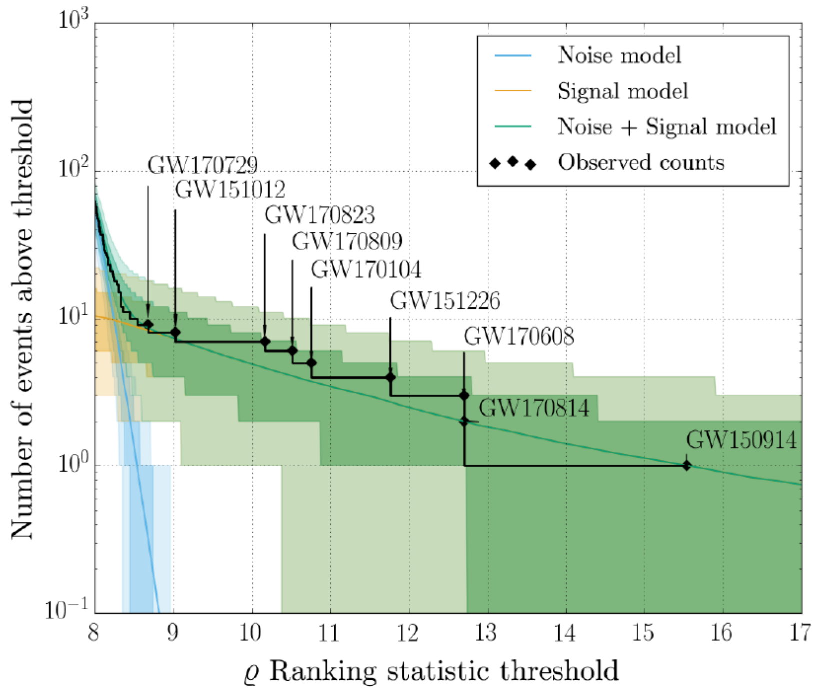
Event significance assessment

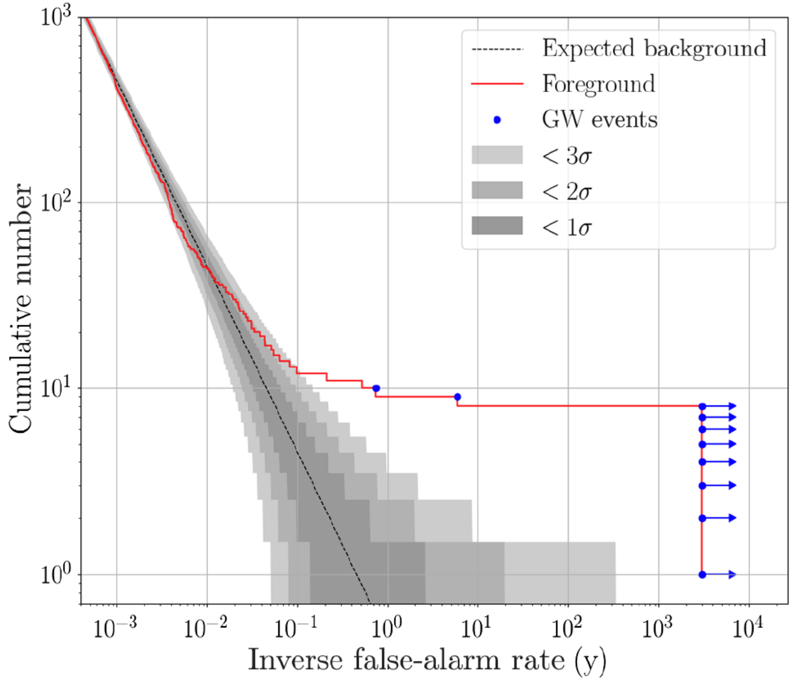


- Background **rate of accidental noise (glitch) coincidence** in two or more detectors
- Impossible to shield against GW – There are no “noise-only” data
- **Empirical estimate** using surrogate “noise only” data obtained by applying **non-physical time shifts**
  - Allows to generate **> 100,000 equivalent yr**!
- Coincidences in time shifted triggers = background
- Deduce event significance
  - **False alarm rate** = rate of background triggers ranked higher than the foreground

Background estimate

O2 science run



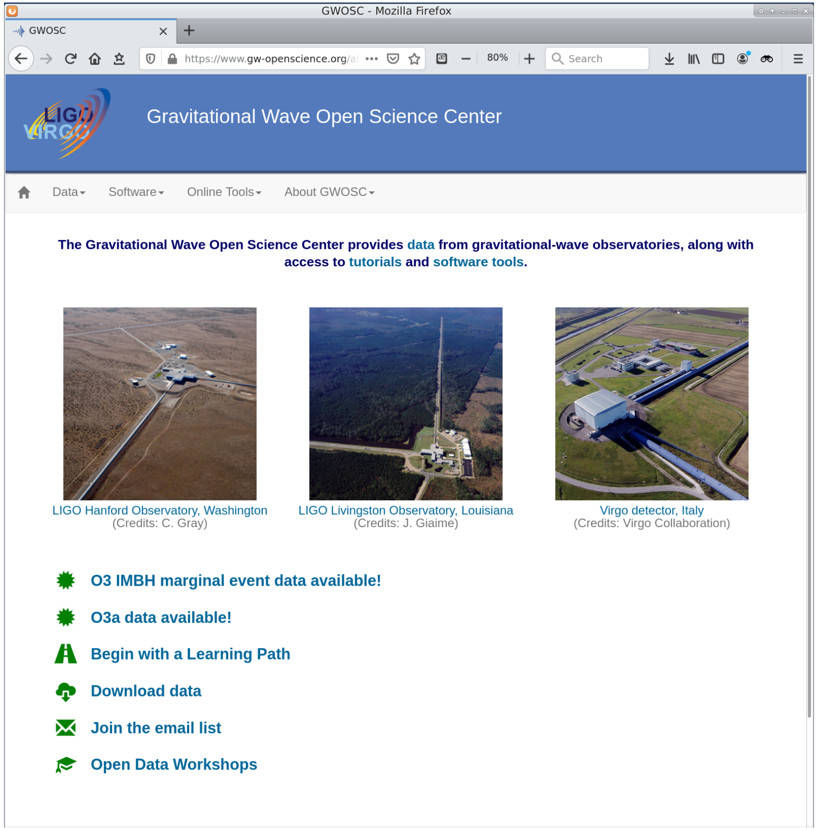


Conclusions

- Fundamentals of GW data analysis
  - Observation model (detector response and noise model)
  - Deduced the likelihood
- Compact binary coalescence searches
  - Application of detection statistics
  - Matched filtering and its practical implementation
  - Dealing with noise imperfections
- You will experiment with those concepts with the tutorials (kick-off at the project session today)

This presentation borrowed materials from other excellent lectures.
Thank you to Neil Cornish, Alan Weinstein and others!

gw-openscience.org



- Public release of GW data and event catalogs
  - **O3a data published on Apr 30 2021!** NEW!
- Documentation, usage recommendations
- Online training: video tutorials and Jupyter notebooks
  - https://gw-odw.thinkific.com NEW!
  - More than 500 registered participants – Join the club!

References

- Papers/Reviews
  - LIGO/Virgo, “A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals”, Class Quantum Grav 37, 055002 (2020)
- Books
  - Maggiore, “Gravitational Waves: Volume 1: Theory and Experiments”
  - Creighton & Anderson, “Gravitational-Wave Physics and Astronomy: An Introduction to Theory, Experiment and Data Analysis”