Gravitational wave astronomy:

State of the art and perspectives for RICOCHET

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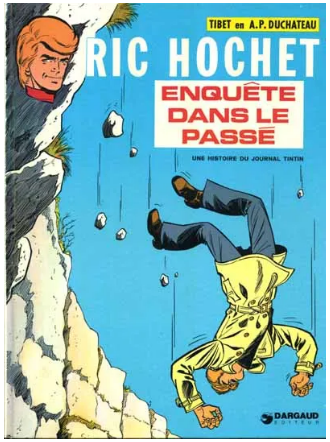
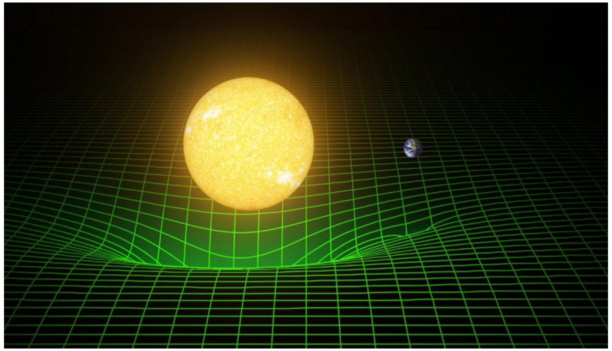
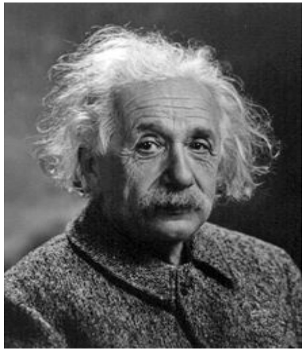
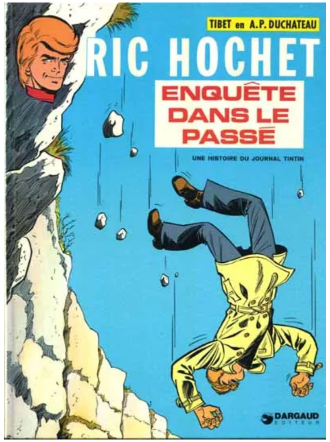


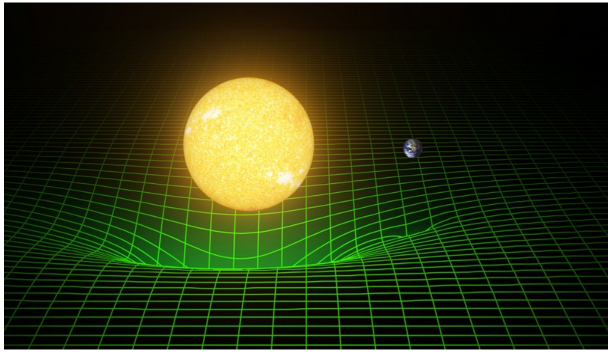




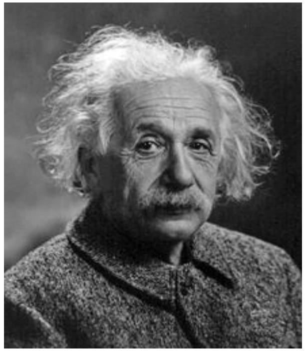
Space-time is dynamic and deformable

Gravity is connected to space-time curvature



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



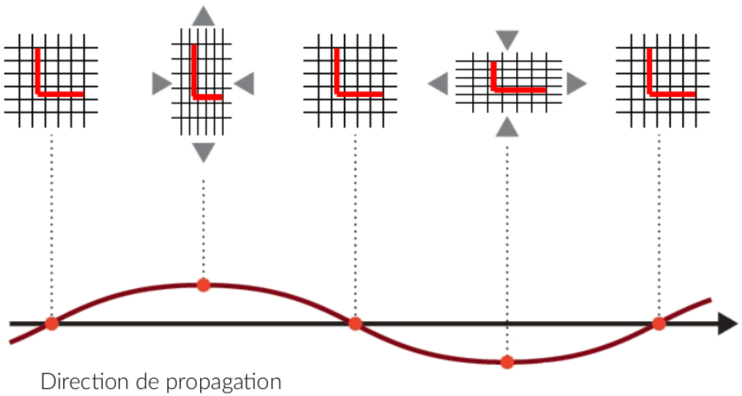


$$\Box \bar{h}_{ab} = 0$$

wave equation

Small perturbation of the background metric

$$g_{ab} = \eta_{ab} + h_{ab}$$



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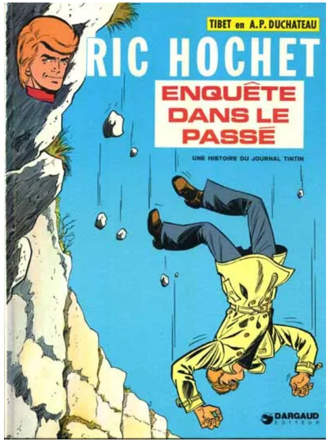
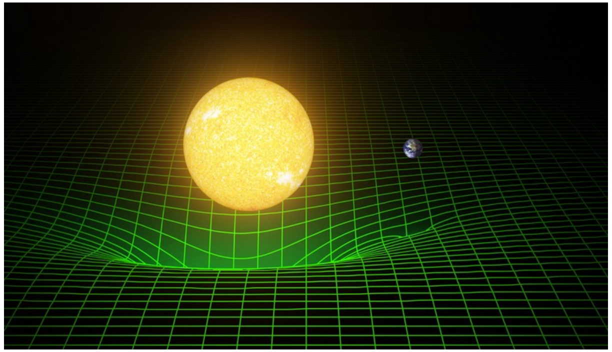
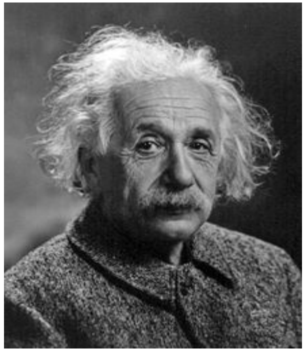






Space-time is dynamic and deformable

Gravity is connected to space-time curvature

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

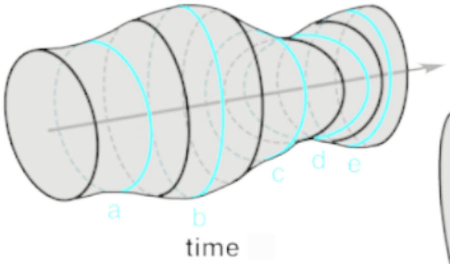
$$\Box \bar{h}_{ab} = 0$$

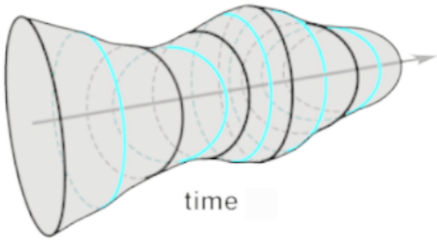
wave equation

Small perturbation of the background metric

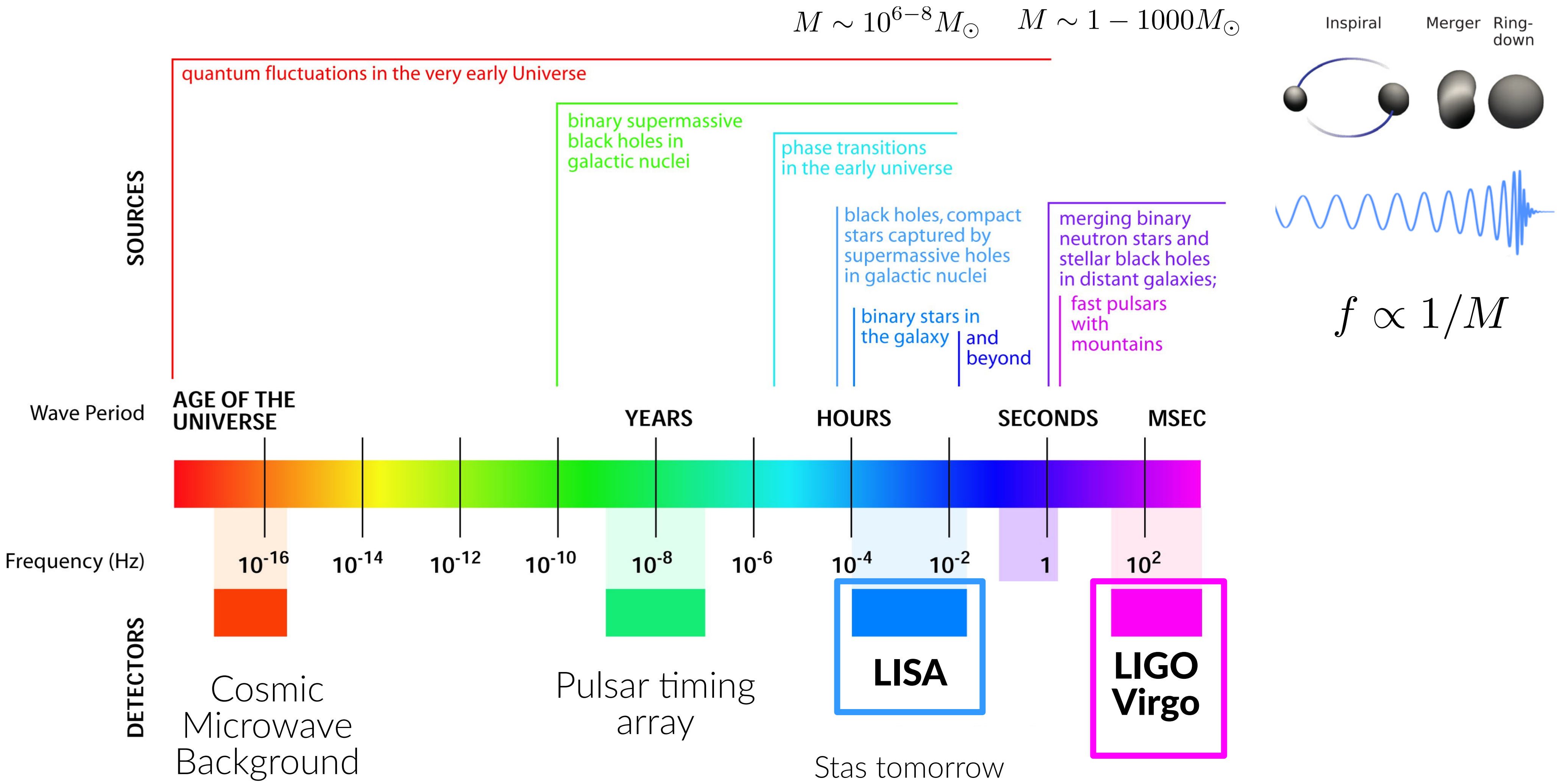
$$g_{ab} = \eta_{ab} + h_{ab}$$

General relativity predicts two GW polarizations





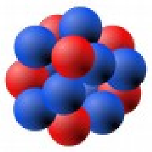
GW190412 – N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes project
https://www.youtube.com/watch?v=5AkT4bPk-00


$M \sim 10^{6-8} M_\odot$
$M \sim 1 - 1000 M_\odot$
Inspiral
Merger
Ring-down
$f \propto 1/M$
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
Cosmic Microwave Background
Pulsar timing array
LISA
LIGO Virgo
Stas tomorrow

$$h = \frac{\delta \ell}{L} \sim 10^{-21}$$

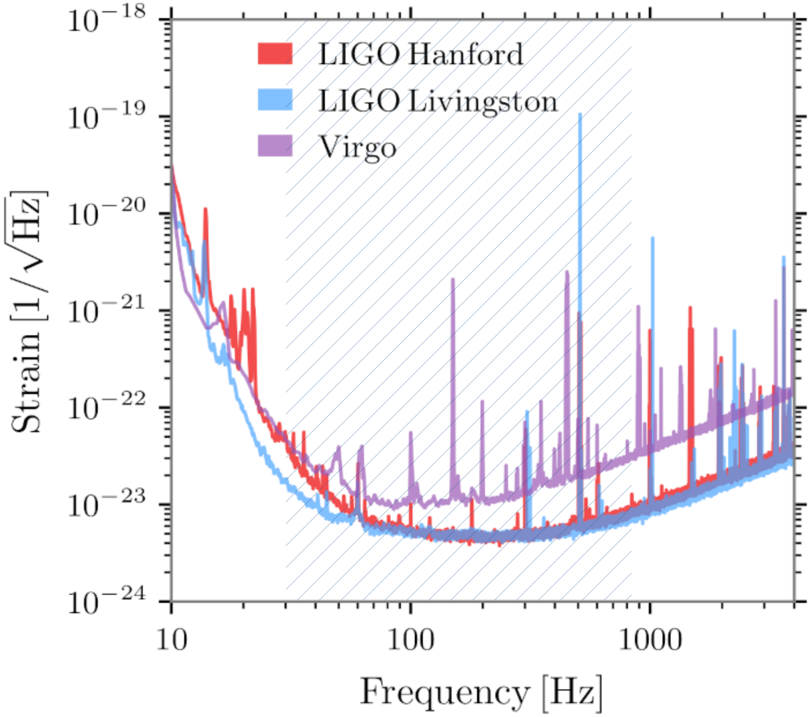
$$\delta \ell \sim 10^{-18} m$$

$$L = O(1)\mathrm{km}$$



Radius of atomic nuclei $10^{-15} m$ (x 1000)

Sensitivities during O3
2019-2020

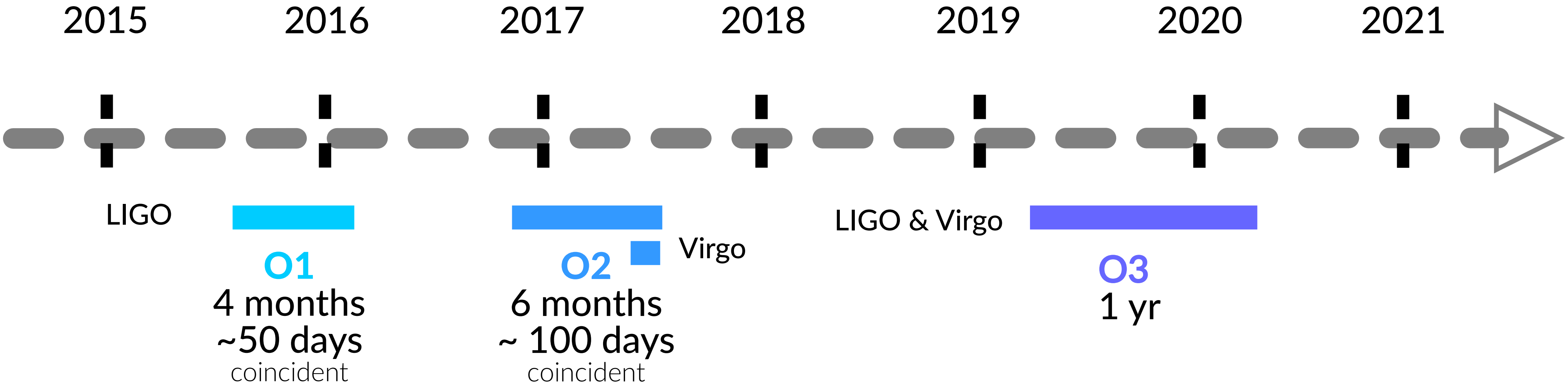


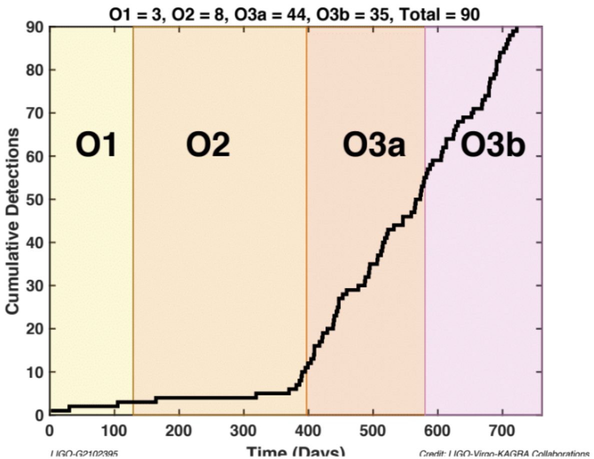
Distance range to
binary neutron stars
(averaged over sky position and inclination)

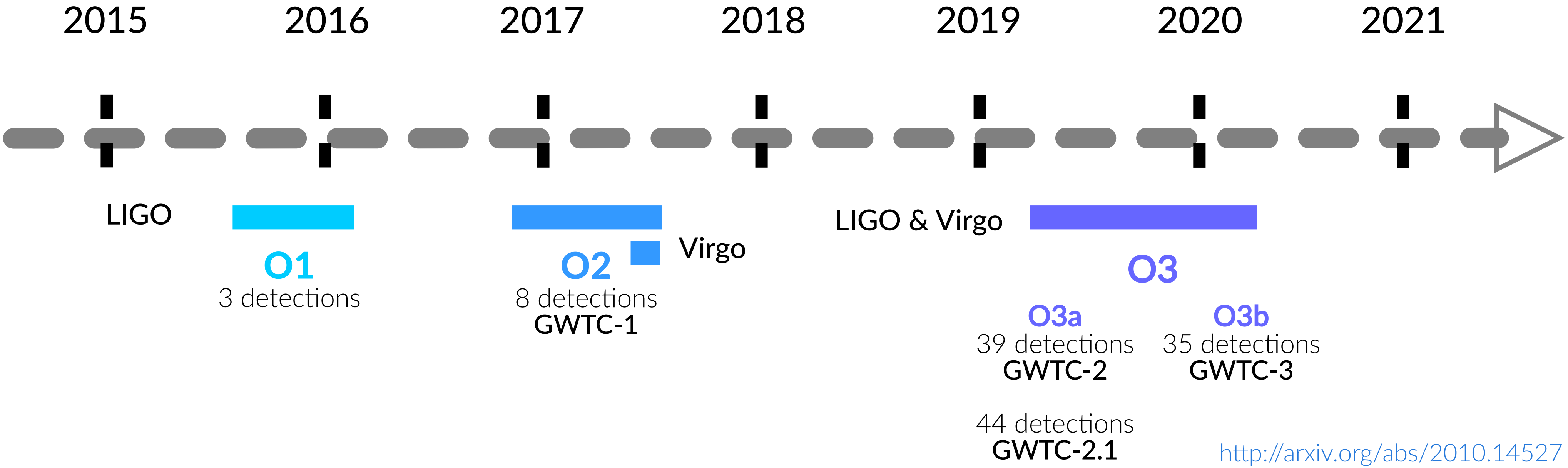
L1: 135 Mpc
H1: 115 Mpc
V1: 50 Mpc

1 parsec = 3.26 ly
= 31 x 10^{12} km


LIGO Handford H1
LIGO Livingston L1
Virgo V1


2015
2016
2017
2018
2019
2020
2021
LIGO
O1
4 months
~50 days
coincident
O2
6 months
~ 100 days
coincident
Virgo
LIGO & Virgo
O3
1 yr



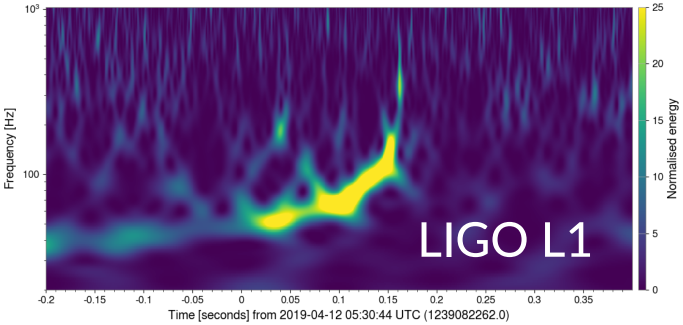


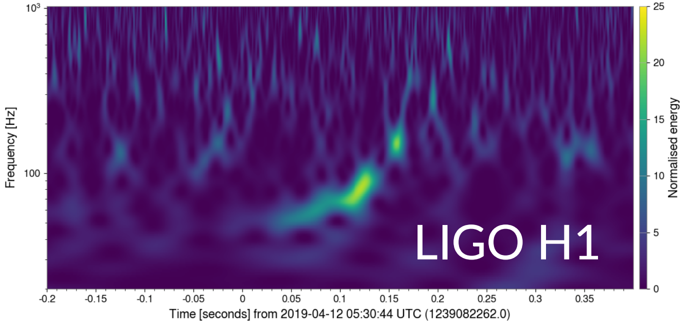
http://arxiv.org/abs/2010.14527
http://arxiv.org/abs/2108.01045
http://arxiv.org/abs/2111.03606

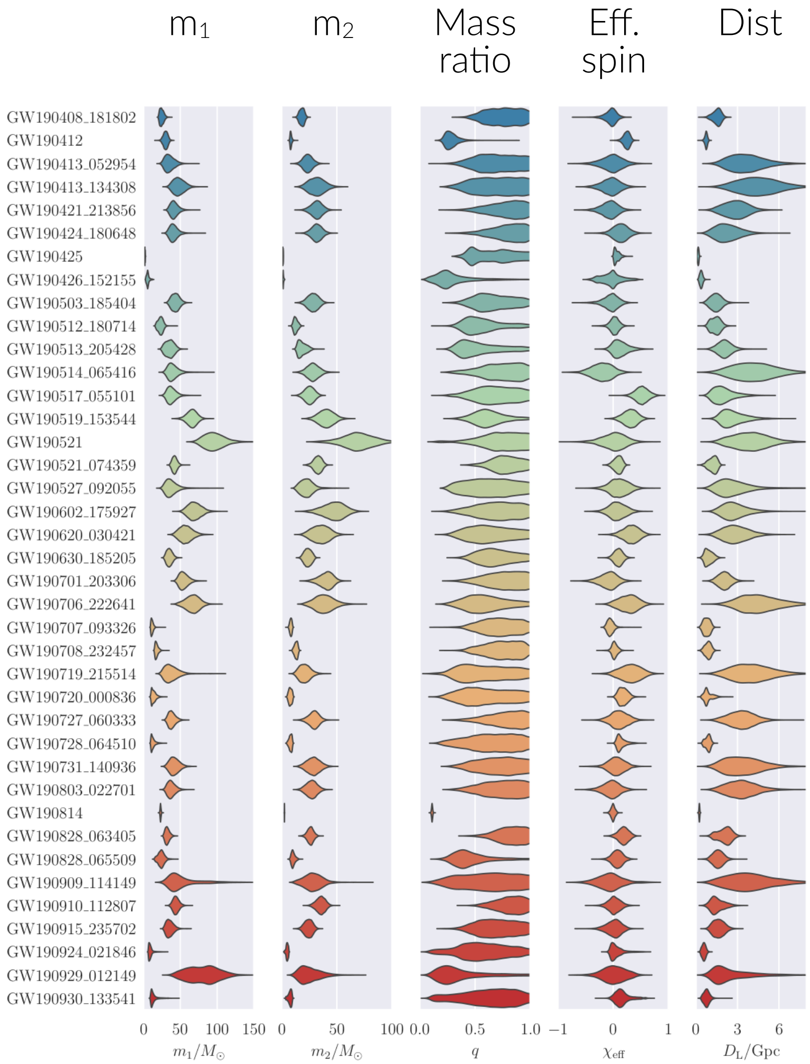
What did we detect?

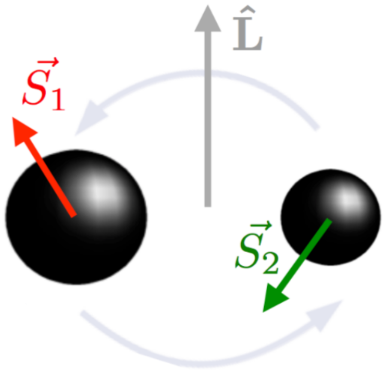
GWTC 2

- A large and unexpected population of “heavy” **binary black holes**









https://arxiv.org/abs/2010.14527

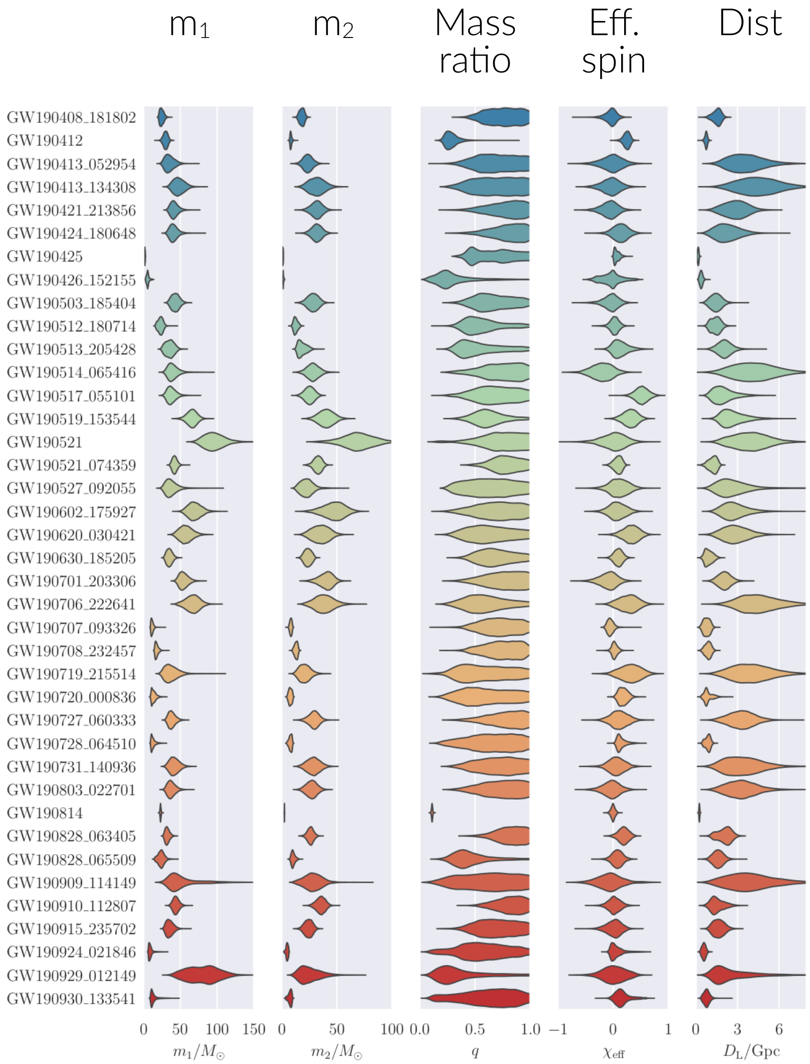
What did we detect?

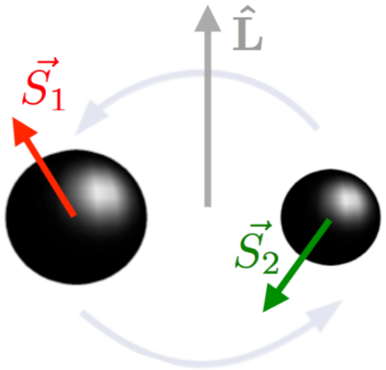
GWTC 2

- A large and unexpected population of “heavy” **binary black holes**
  - Raises many questions

    How do they form?
    In what environment?
    Is their a single formation channel?

  - Some of the detected binaries are **incompatible** with the current understanding of black hole formation from massive stars





https://arxiv.org/abs/2010.14527

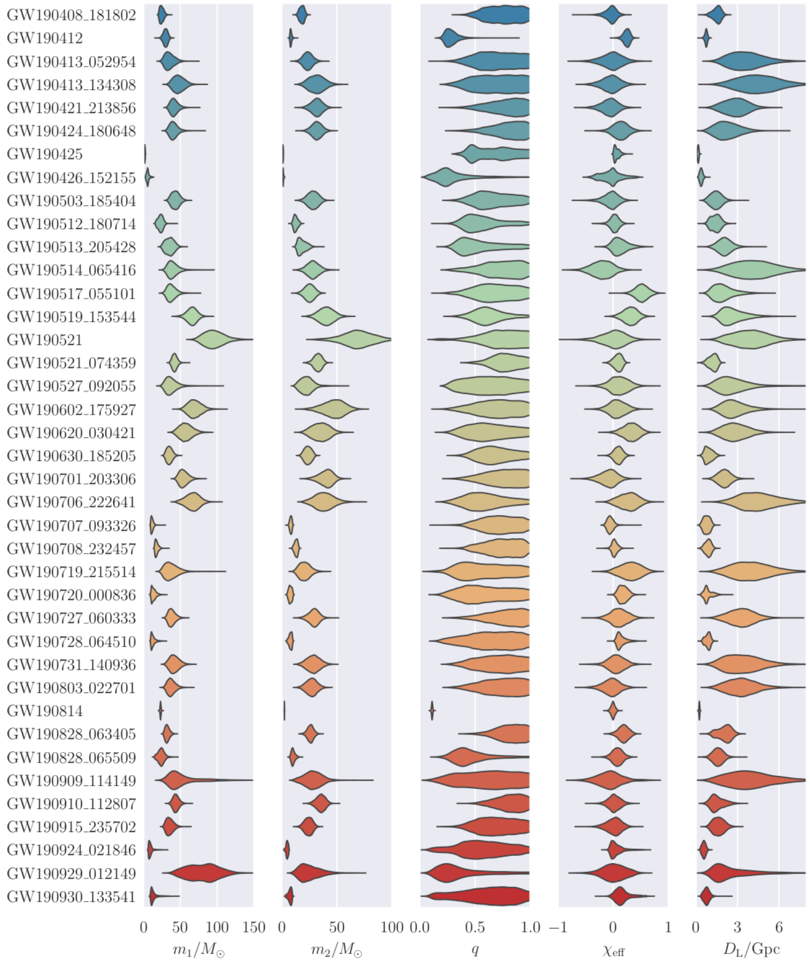
What did we detect?

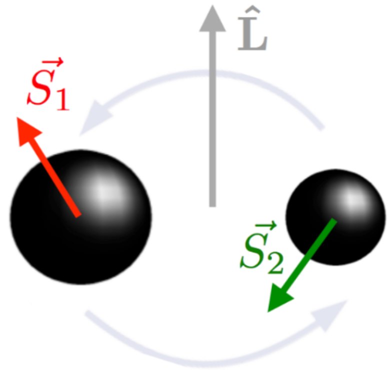
GWTC 2

- Other types of binary systems
  - Binary neutron stars
  - Possible mixed black hole and neutron star binaries

Black holes from stellar core collapses are expected to be > 3 M_{sun}

m$_1$ m$_2$ Mass ratio Eff. spin Dist





https://arxiv.org/abs/2010.14527

What else and for science?

- A pletora of searches and analyses
  - Tests of general relativity
  - Compact star population studies
  - Inference on cosmological parameters
  - GW lensing
  - Subsolar black holes searches
  - Unmodelled searches of short / long signals
  - Search for continuous signals from pulsars
  - Dark matter searches: boson clouds around black holes
  - Background anisotropies
  - Cosmic strings and other topological defects

- Astrophysics of compact stars
  - How many black holes in the Universe?
  - How do they form?
  - What are their properties?
- Fundamental physics
  - Is gravitation describe by the general theory of relativity?
- Cosmology
  - How fast the Universe is expanding?

gw-openscience.org

- Full data set and related products freely distributed
  - ✓ 220+ papers contributed by groups around the globe
- Analysis software packages
- Documentation, usage recommendations
- Training through workshops and online course

NEW

GW Open Data Workshop

May 23 - 25, 2022

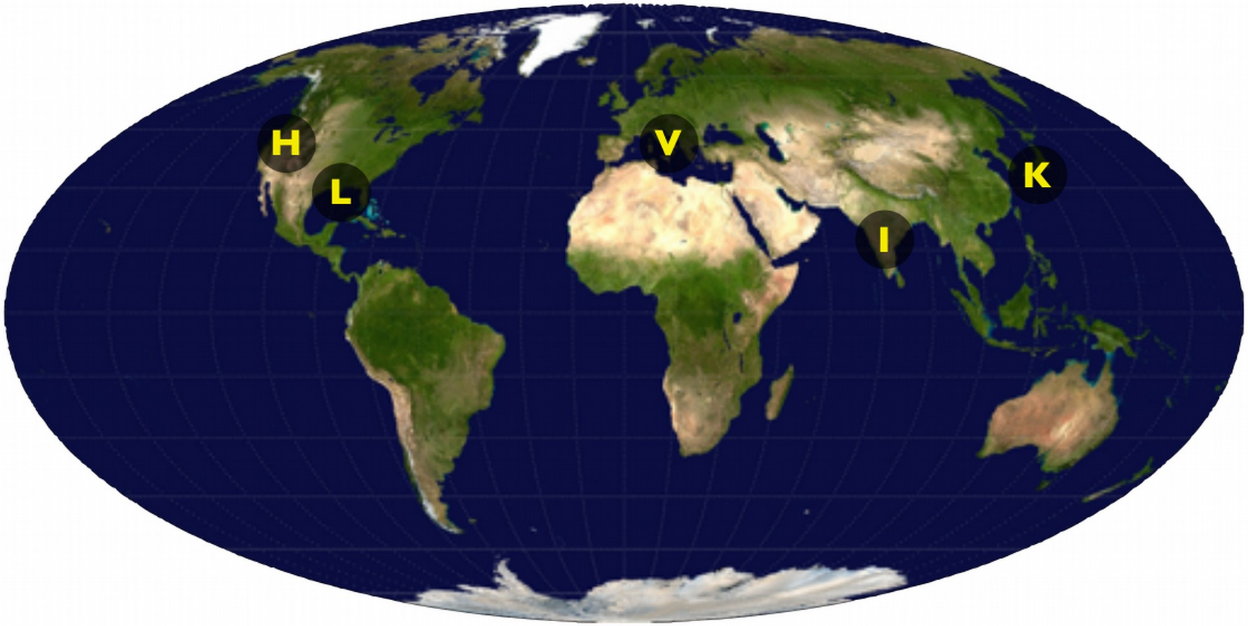
https://www.gw-openscience.org/odw/odw2022/

Distributed workshop with a worldwide network of study hubs

To join Paris' hub: https://forms.gle/XXwMvRNCNVAzXHh88

What’s next?

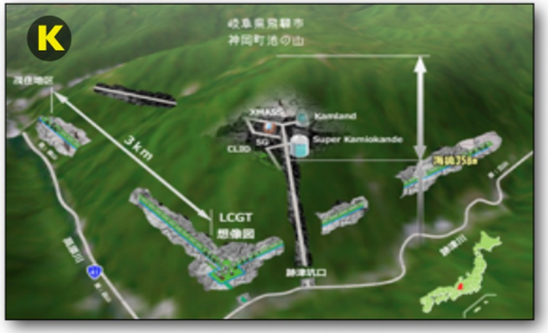

H


H
L
V
K
I

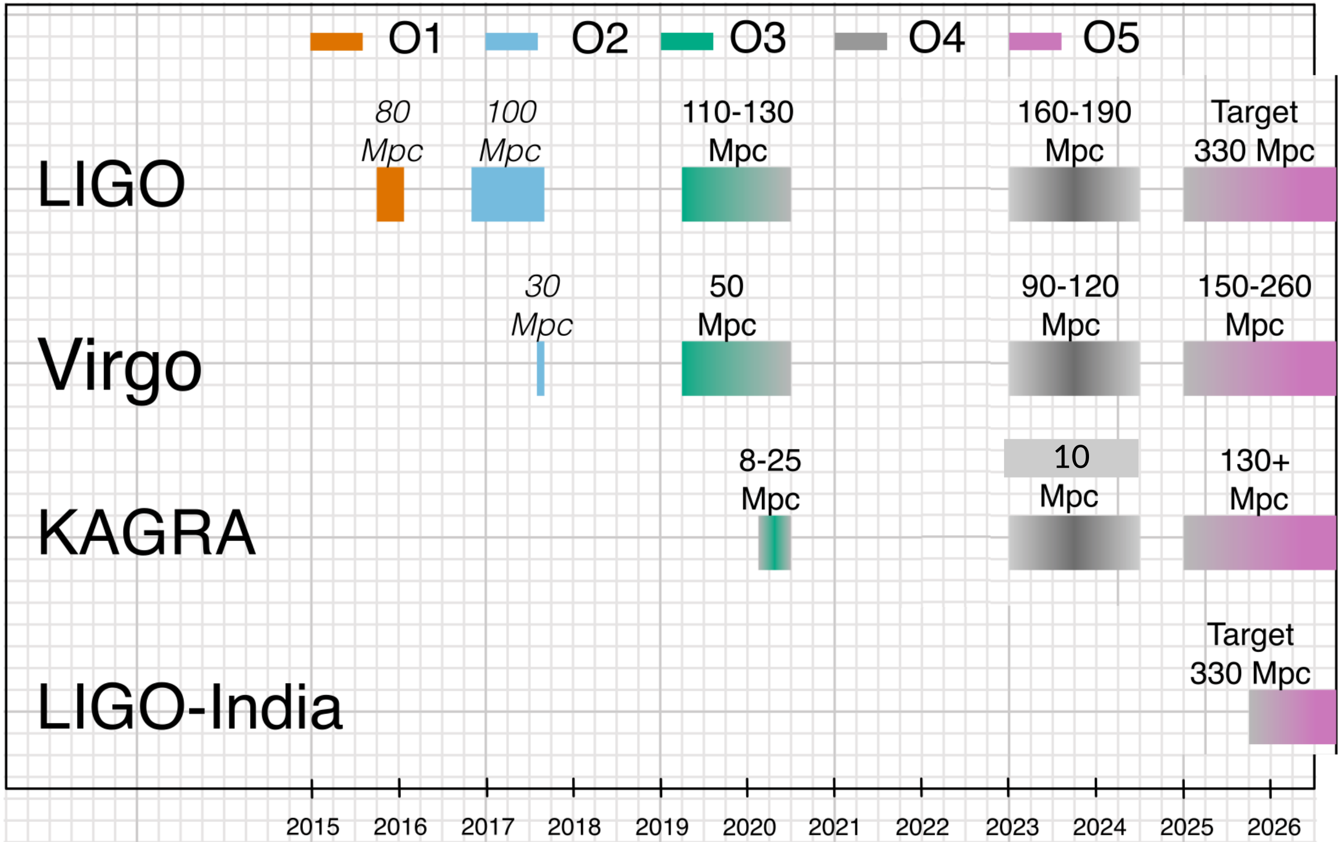

L


V


I


K
岐阜県飛騨市
神岡町池の山
XMASS
Kamland
Super Kamiokande
CLIO
3 km
LCGT
想像図

What’s next?



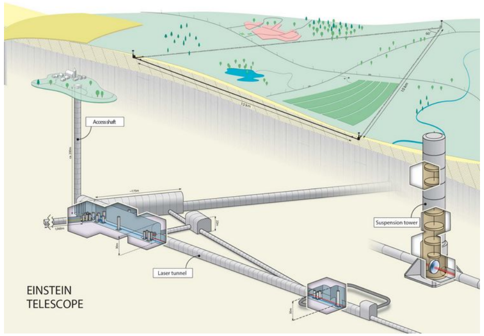
Post-O5 (2028)

Pre-design and plan in progress

[submit Jun 22]

Einstein tel (2035)

ESFRI roadmap



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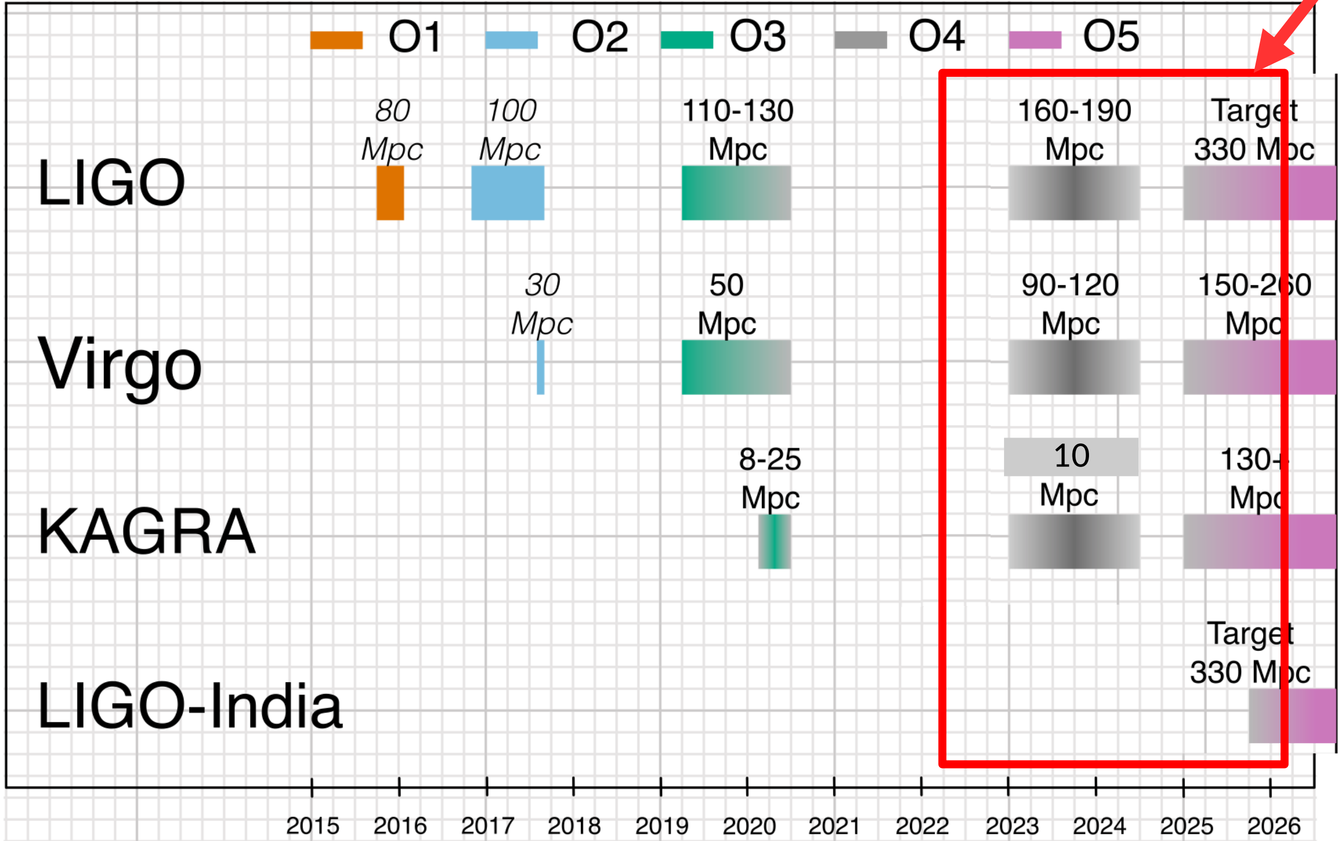

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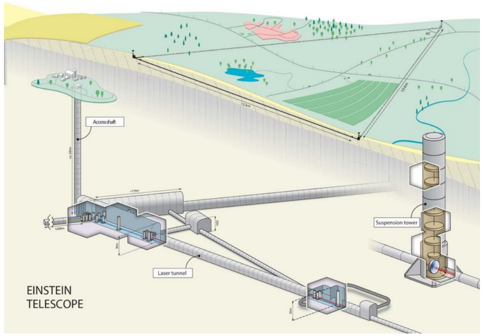


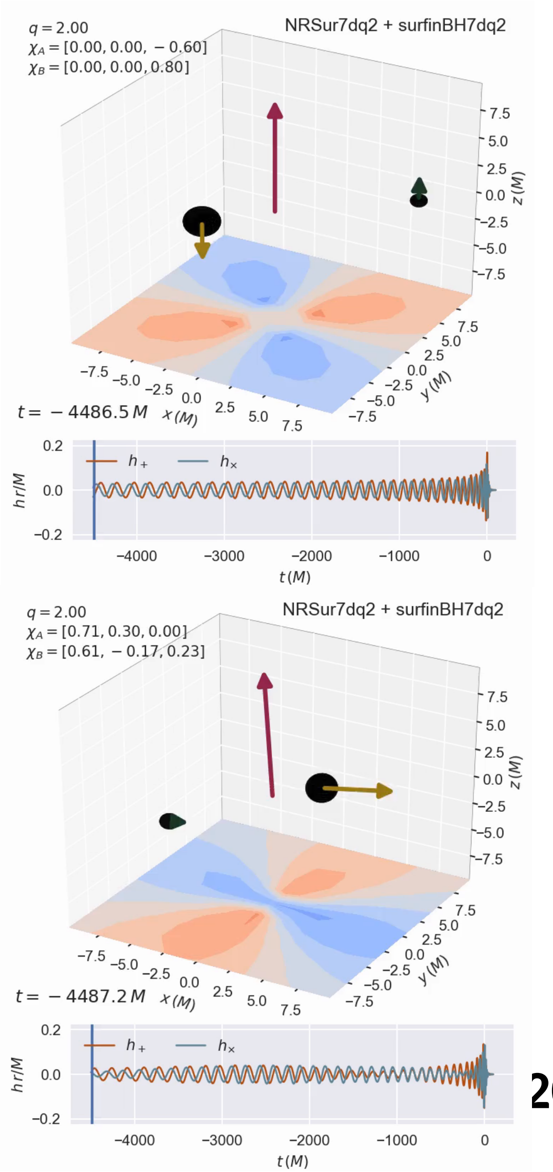

C’est bien beau tout ça,
mais on en a quoi
à carrer de ses trous noirs ?
It’s the **polarization**, stupid!

GW polarization (1)

- In GR, two polarizations h_+ and h_x
  - Intrinsically, GW are a **bivariate signal**

    Note: more polarizations predicted in alternative theories of gravity
- **Polarization carries physical information**
  - For compact binary mergers, wave polarization is related to the inclination of the orbital plane
  - Change of polarization → change of orientation
    Smoking gun for **orbital precession**
  - Polarized chirp = "AM-FM-PM" signal

    → Cyril's presentation



https://vijayvarma392.github.io

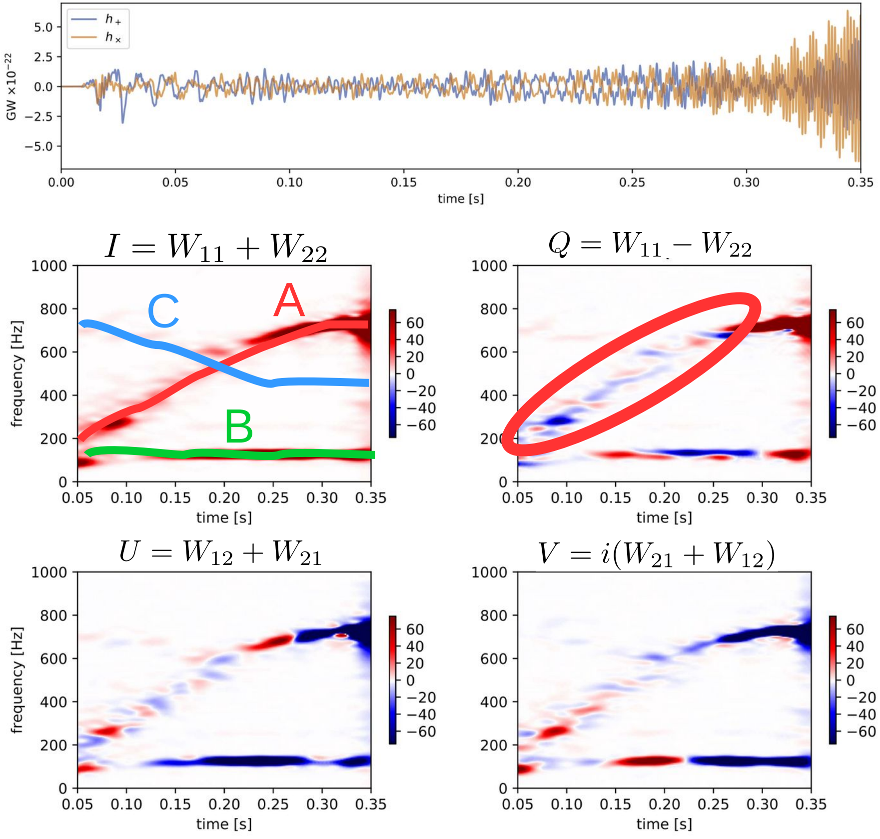
$1 + W_{22}$

GW polarization (2)

- GW polarization carries physical information
  - Diagnose the **complex GW signature from supernova core collapse**
  - Interpret the modes during the dynamical phases of the collapse
    1) Prompt post-bounce convection
    2) Quiescence
    3) Standing accretion shock instability
  - During 1) and 2), mode A → proto neutron-star *g*-mode oscillation

    Random polarization typical of buoyancy driven convection

Simulated GW from supernova core collapse



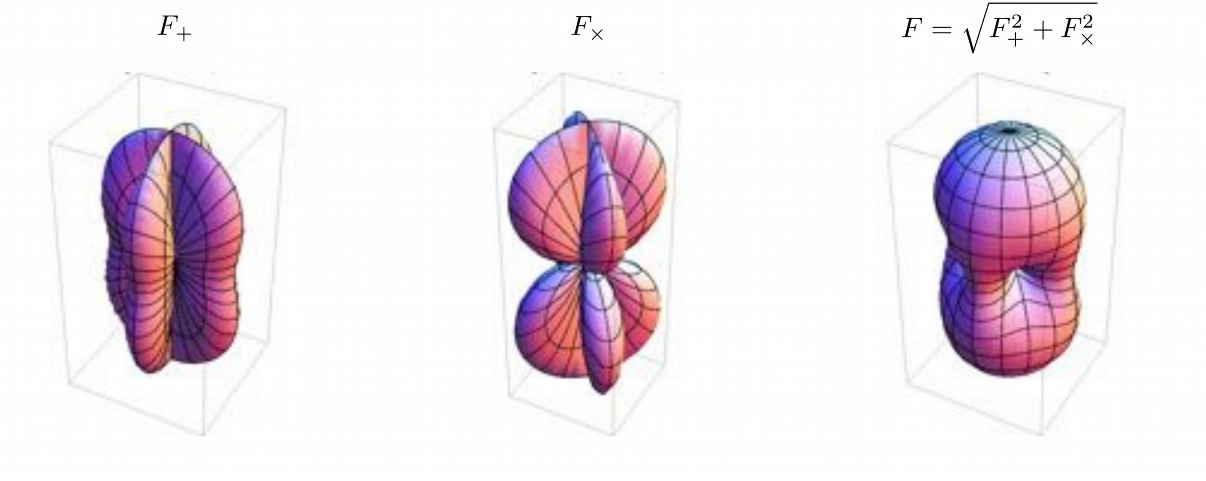
$$W_{ij}(f,t) = s_i(f,t)s_j^*(f,t),$$

Kawahara et al, 2018
https://arxiv.org/abs/1810.00334

Polarization reconstruction from global detector network (1)

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

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



Array of linear “antennas”

$\rightarrow$ array processing (radar) …

… with differences:

- Irregular array geometry
- Unknown and non-monochromatic signal

Polarization reconstruction from global detector network (2)

Log-likelihood:

$$\mathcal{L}(h) = d^T h - \frac{1}{2} h^T h$$

Write $h = F\mathfrak{h}$ with

$$F = \begin{bmatrix} F_+ & F_\times \end{bmatrix} \qquad \mathfrak{h} = \begin{bmatrix} h_+ \\ h_\times \end{bmatrix}$$

Maximize $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\mathfrak{h}} = 0$ and find

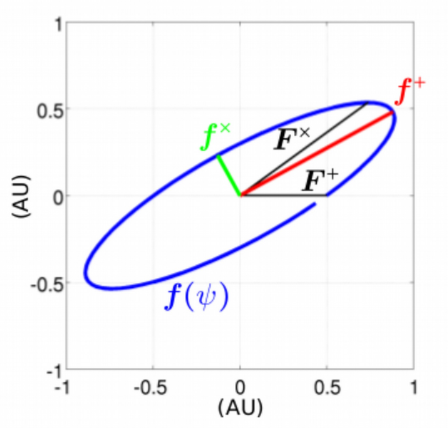
$$\mathfrak{h}^* = (FF^T)^{-1} F^T d$$

- Generalized likelihood ratio test
- Regularized when antenna pattern F is degenerate

$$\mathcal{L}(F\mathfrak{h}^*) = (d^T f_+)^2 + \boxed{(d^T f_\times)^2}$$

Set to 0 or downweighted when F is singular

Left-singular vectors of F



- Compute $\mathcal{L}$ over the full sky and obtain a likelihood map

- Could instead regularize by requiring a specific polarization for $\mathfrak{h}$

→ Cyril's contributions

Open questions for RICOCHET

- Modelling of AM-FM-PM signals
  - Fast astrophysical template generation
- Polarimetric processing of gravitational wave data
  - Generic tools for polarization-based analysis / filtering
  - Noise rejection based on polarization requirement?
- Polarization reconstruction from data
  - Polarization priors for regularization?

- The future of GW astronomy is a promising playground for RICOCHET
  – More and better detectors = more sources and better reconstruction of polarizations

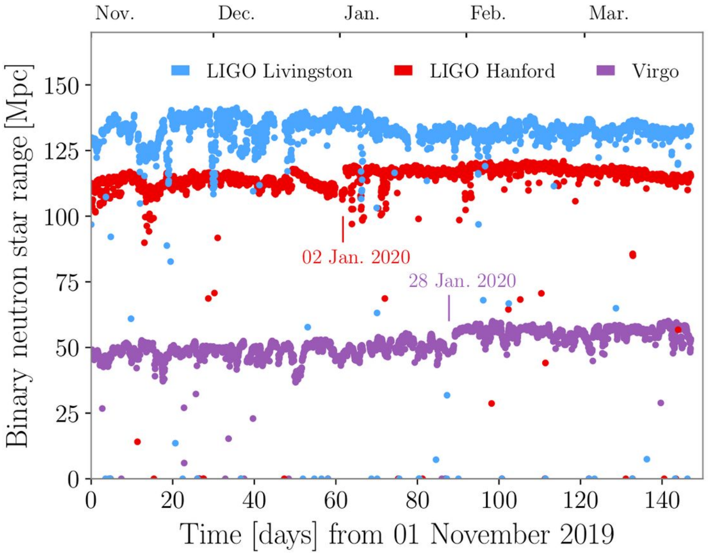
… and fun area for data science in general

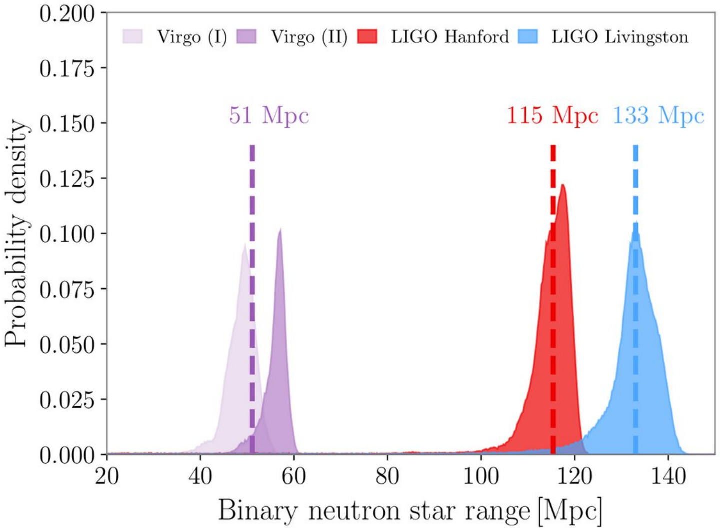
Online seminar on Apr 6 at 16:00 on the lesson learned from Kaggle challenge by Chris Messenger [ask me for the Zoom link!]


LIGO Handford H1


LIGO Livingston L1


Virgo V1


Nov.
Dec.
Jan.
Feb.
Mar.
LIGO Livingston
LIGO Hanford
Virgo
02 Jan. 2020
28 Jan. 2020
Binary neutron star range [Mpc]
Time [days] from 01 November 2019


Virgo (I)
Virgo (II)
LIGO Hanford
LIGO Livingston
51 Mpc
115 Mpc
133 Mpc
Probability density
Binary neutron star range [Mpc]

Observation equation?

data = function(signal, noise)

Detector transfer function
and noise coupling

Recap – Gravitational waves

Outward propagating wave in z-direction

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

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

Polarization tensors

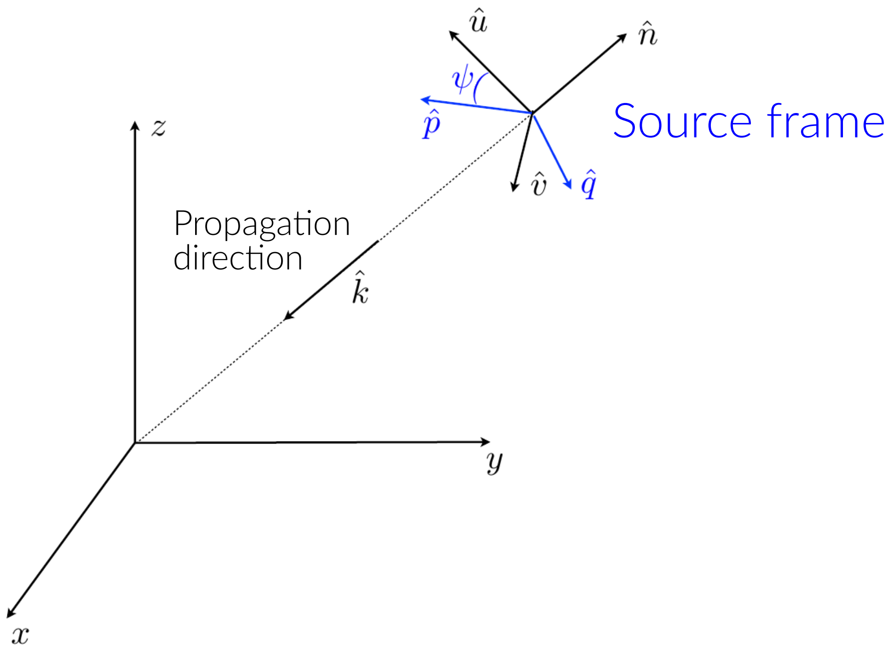
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

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

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

Recap – Reference frames



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

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

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

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

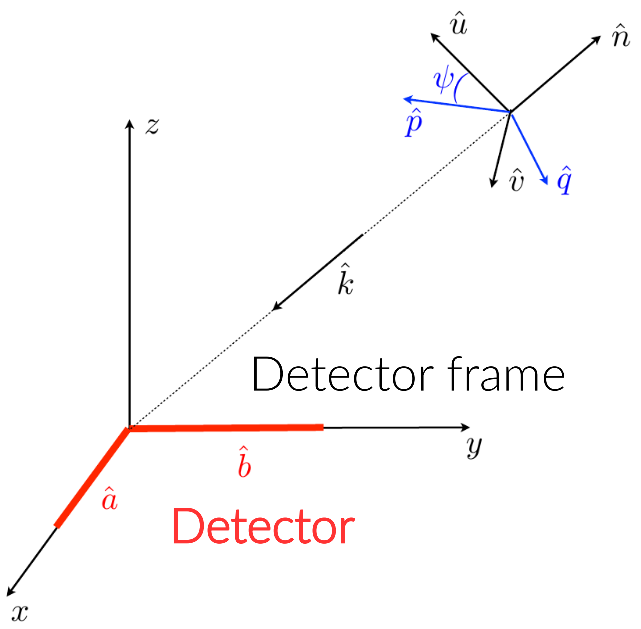
Cornish, arXiv: 0910.4372

Detector response

θ, ϕ Source direction in the sky

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

Radiation frame



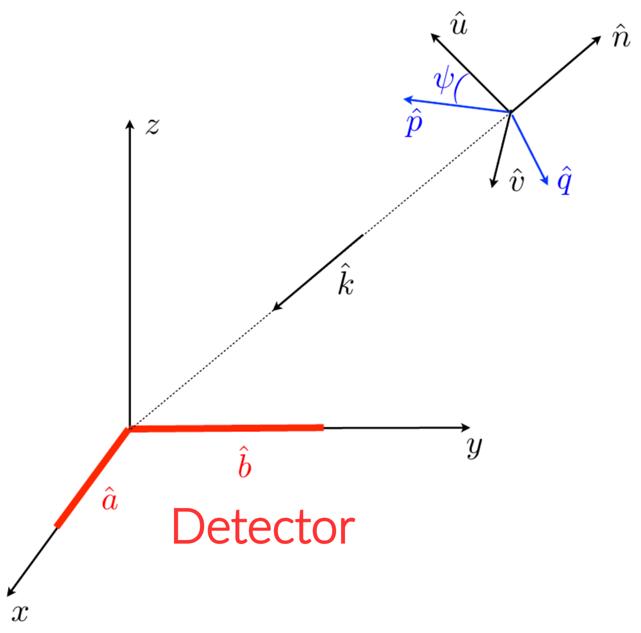
Time of flight difference along 2 directions a and b

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

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

Antenna patterns

θ, ϕ Source direction in the sky



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

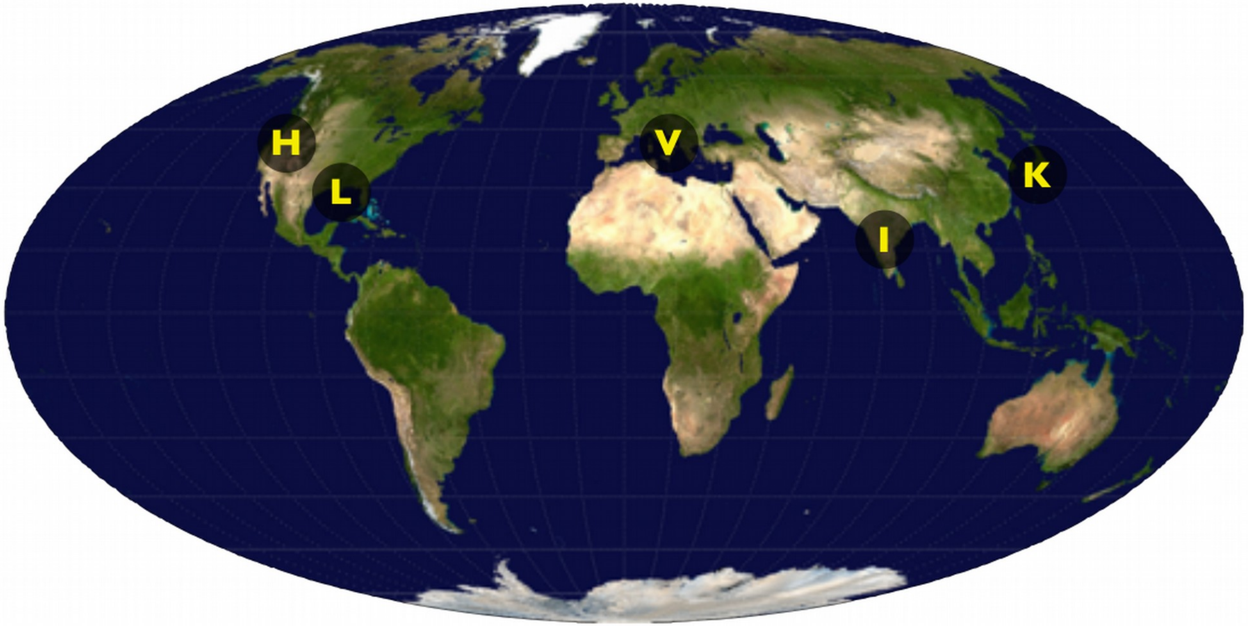
$$\begin{aligned} F^+ &= \frac{1}{2}(\hat{a}\otimes\hat{a} - \hat{b}\otimes\hat{b}) : \epsilon^+ \\ &= \frac{1}{2}(1+\cos^2\theta)\cos(2\phi)\cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi \end{aligned}$$

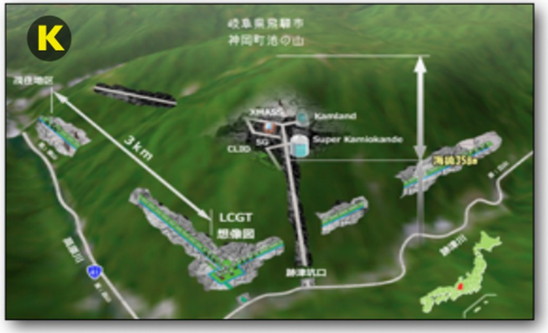
$$\begin{aligned} F^\times &= \frac{1}{2}(\hat{a}\otimes\hat{a} - \hat{b}\otimes\hat{b}) : \epsilon^\times \\ &= \frac{1}{2}(1+\cos^2\theta)\cos(2\phi)\sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi \end{aligned}$$

Antenna patterns

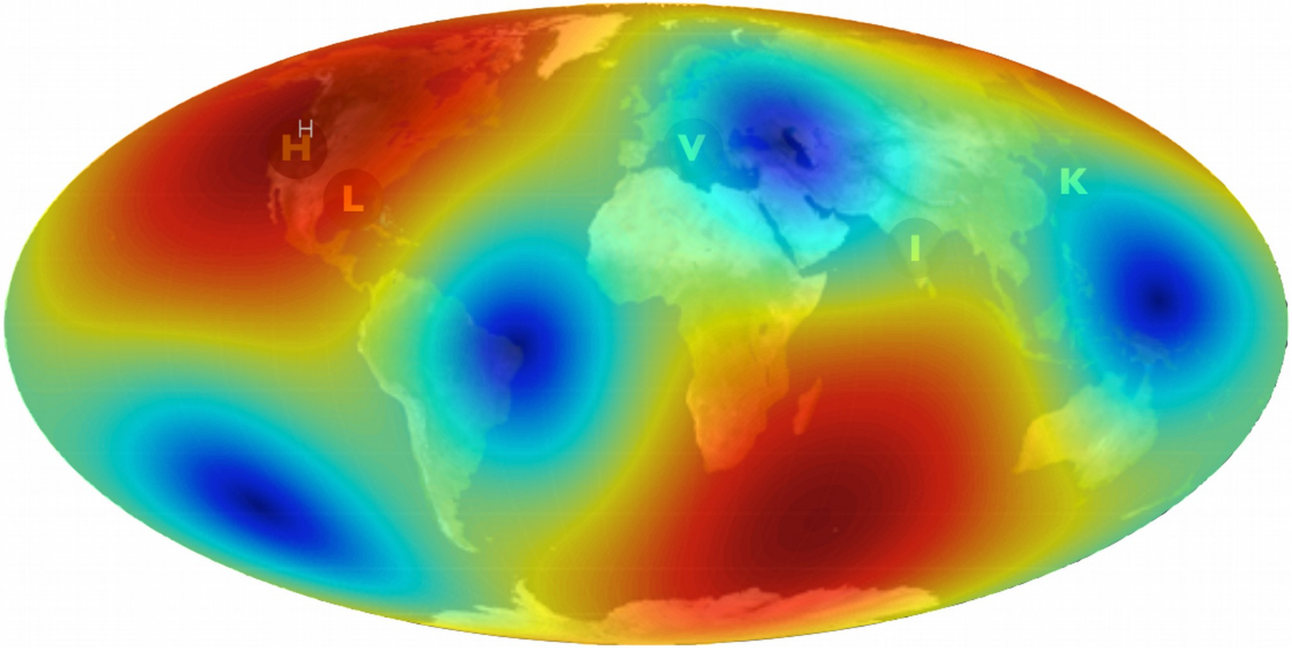
F_+ $\quad$ $F_\times$ $\quad$ $F = \sqrt{F_+^2 + F_\times^2}$

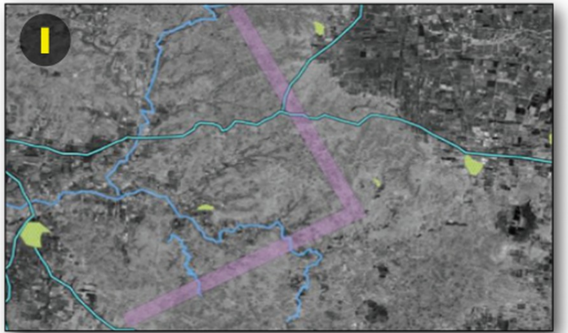
Terrestrial Network

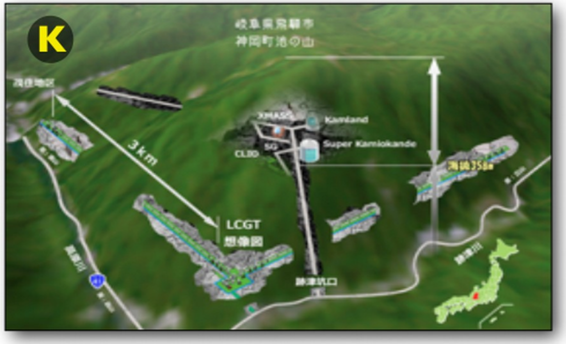




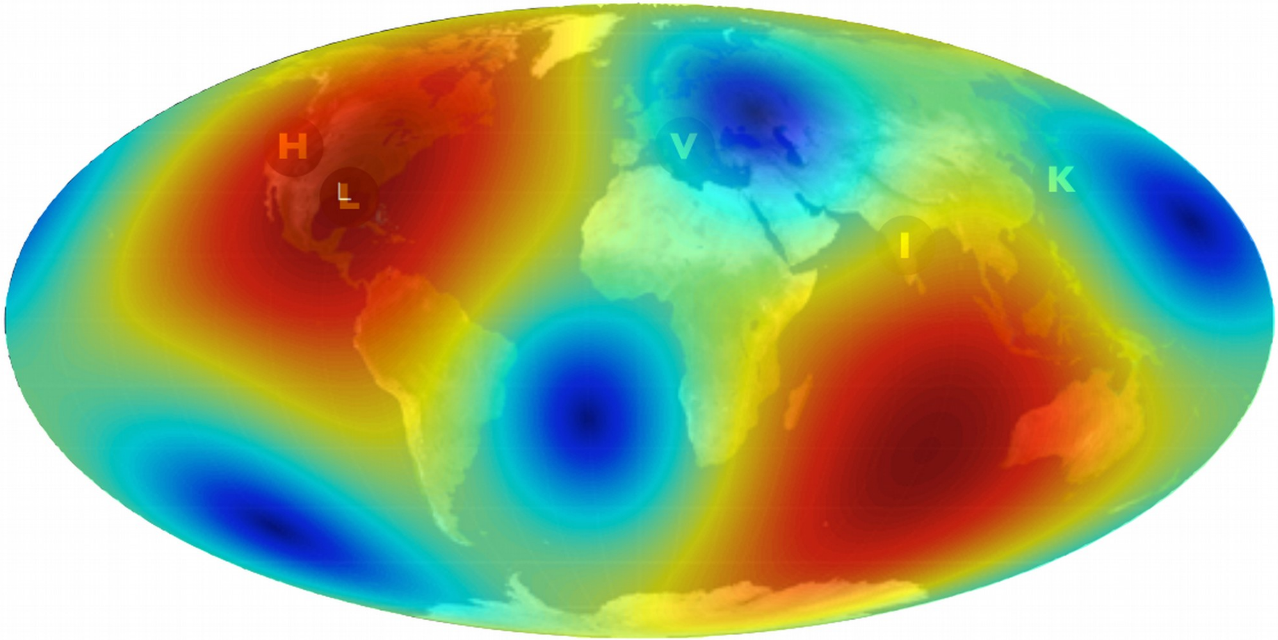
Terrestrial Network

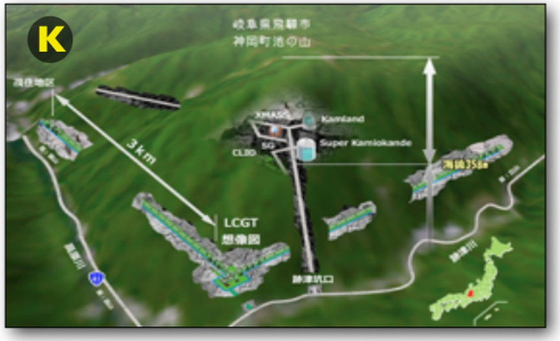




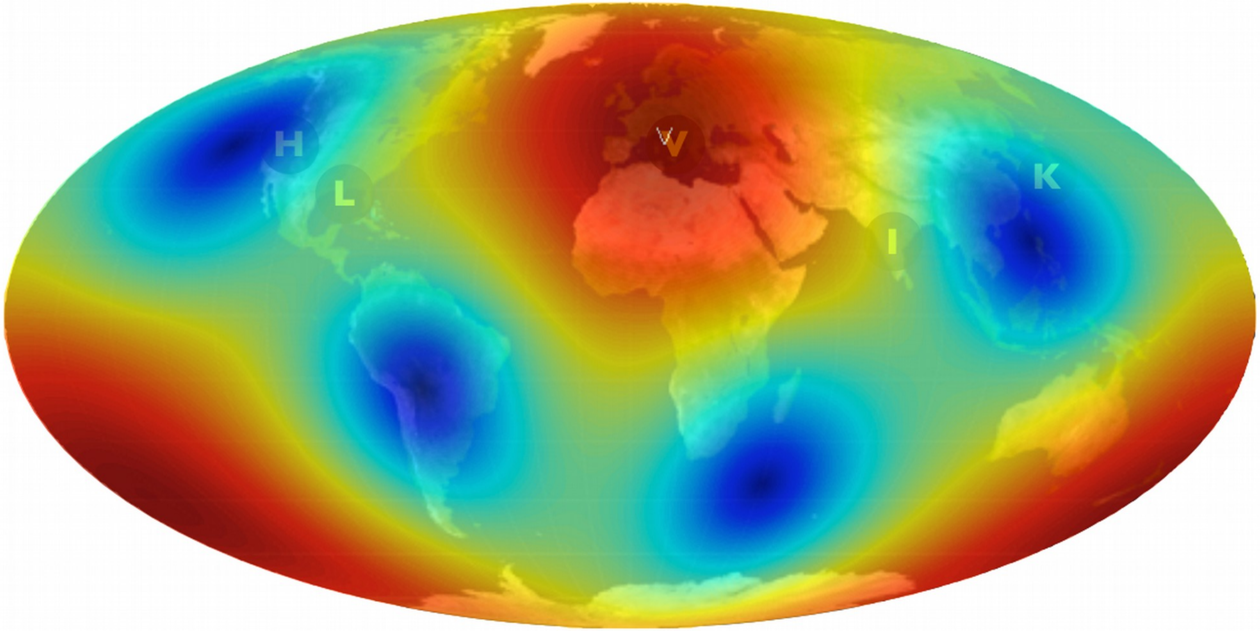


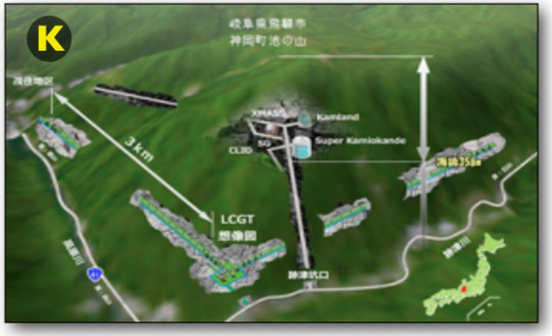
Terrestrial Network



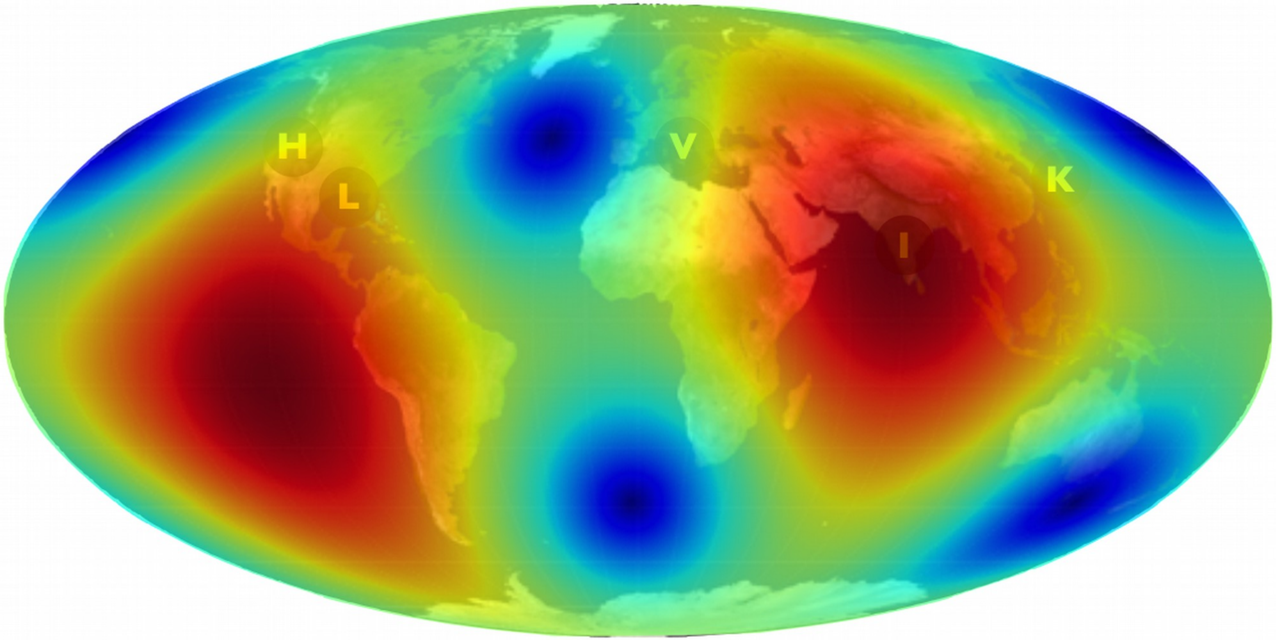


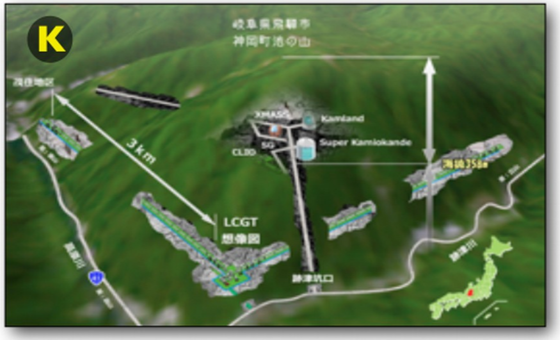
Terrestrial Network



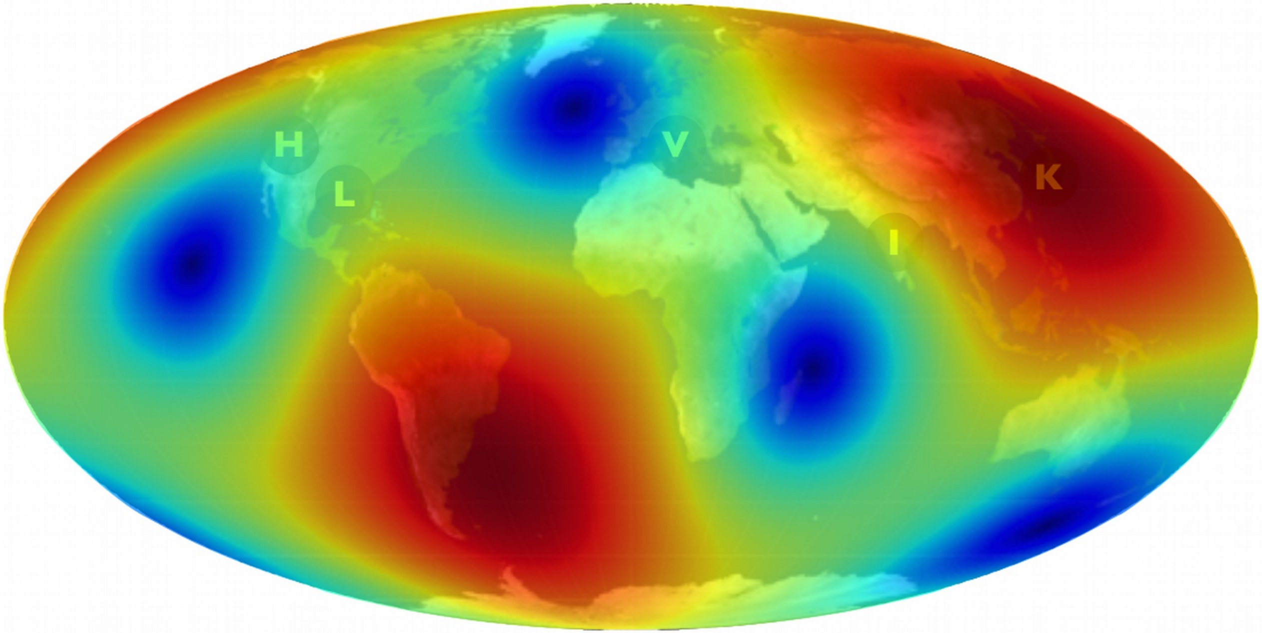


Terrestrial Network

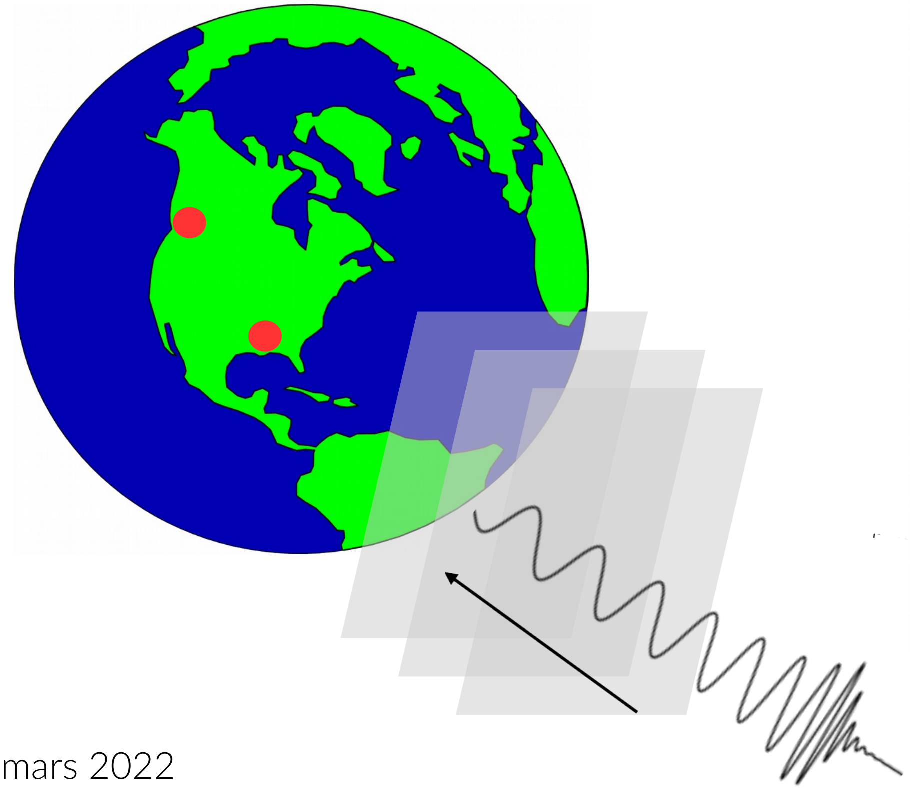


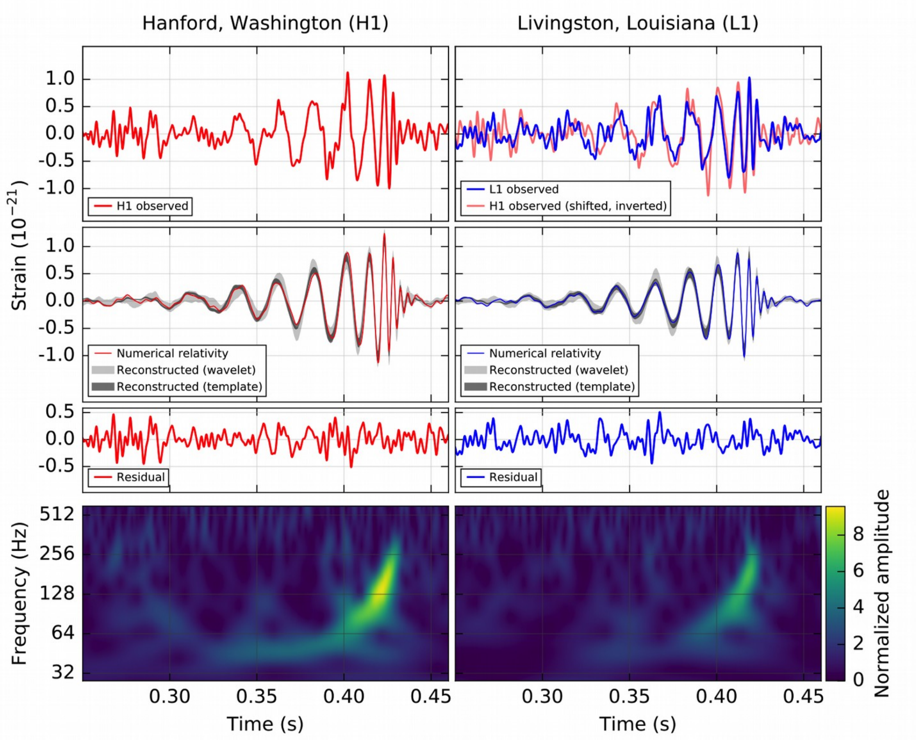


Terrestrial Network



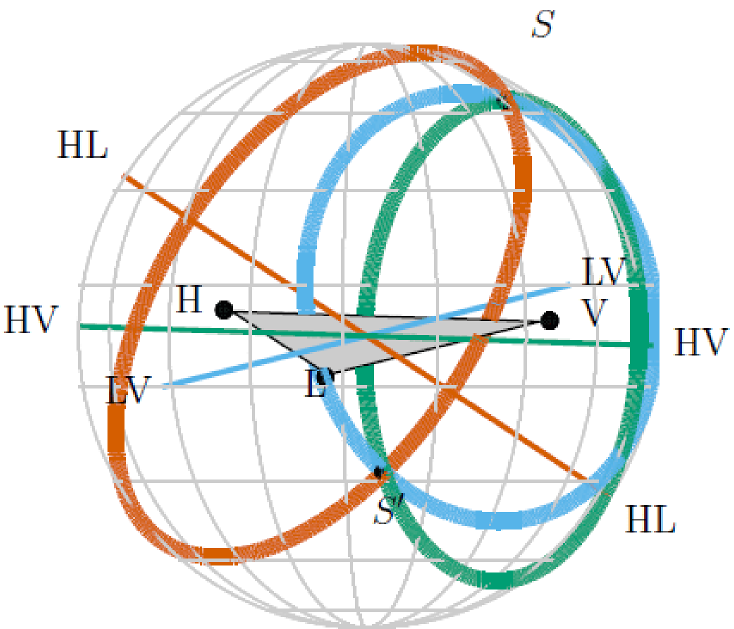
Propagation time delays

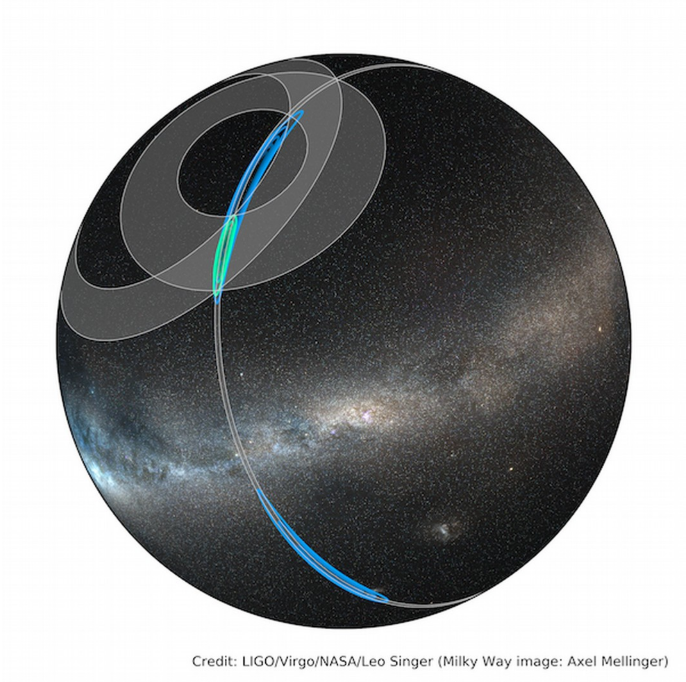




Time delay ~ 7 ms
Phase shift ~ 2.9 rad

Time delays allows triangulation





Observation equation (signal part)

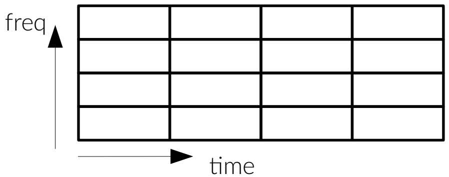
data = function(signal, noise)

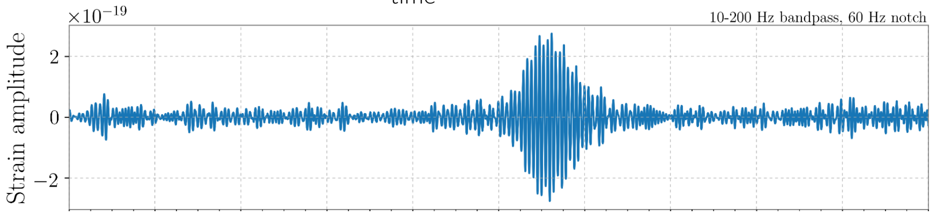
$$h_{\mathrm{signal}}(t) = F_+ h_+(t-\tau) + F_\times h_\times(t-\tau)$$

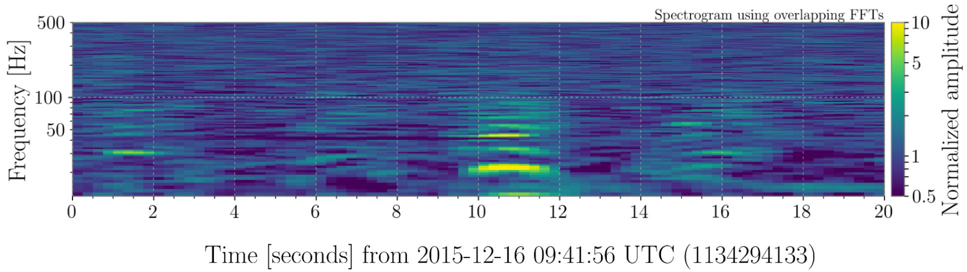
$F_+, F_\times, \tau$ depends on sky position θ, ϕ and polarization angle ψ

Time-frequency maps

Spectrogram or short-time Fourier transform

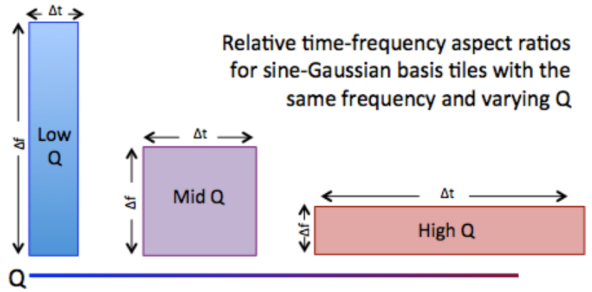


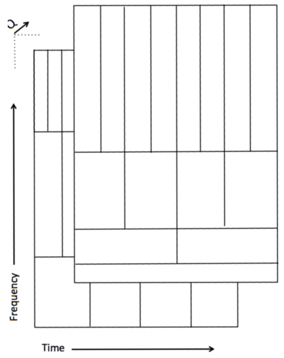


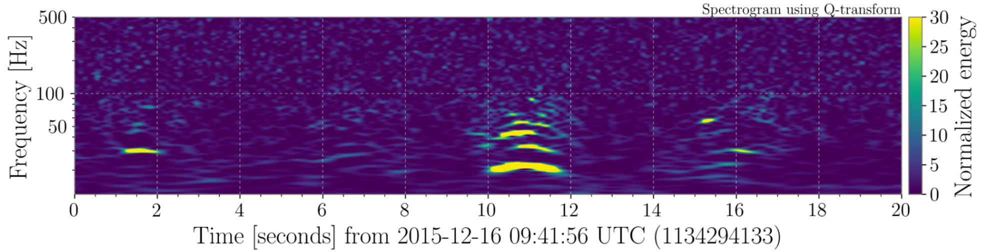


Q transform

S. Chatterji et al. CQG (2010)







Coherent WaveBurst (1)

$$\mathcal{L}(h) \equiv -\log \Lambda = \langle d|h\rangle - \frac{1}{2}\langle h|h\rangle$$

Using a vector-based formalism:

$$\mathcal{L}(h) = d^T h - \frac{1}{2} h^T h$$

Write $h = F\mathfrak{h}$ with

$$F = \begin{bmatrix} F_+ & F_\times \end{bmatrix} \qquad \mathfrak{h} = \begin{bmatrix} h_+ \\ h_\times \end{bmatrix}$$

Maximize $\frac{d\mathcal{L}}{d\mathfrak{h}} = 0$ and find

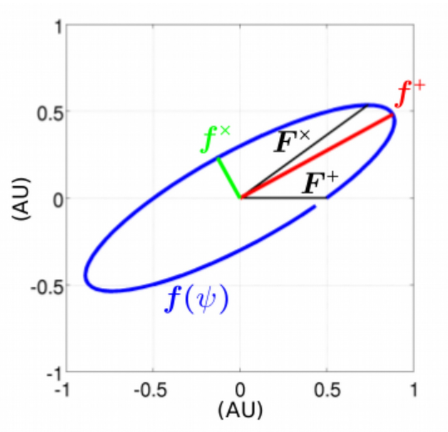
$$\mathfrak{h}^* = (FF^T)^{-1} F^T d$$

- **Generalized likelihood ratio test –** Maximize over h
- **Regularized when antenna pattern *F* is degenerate**

$$\mathcal{L}(F\mathfrak{h}^*) = (d^T f_+)^2 + (d^T f_\times)^2$$

Set to 0 or downweighted when F is singular

Left-singular vectors of F

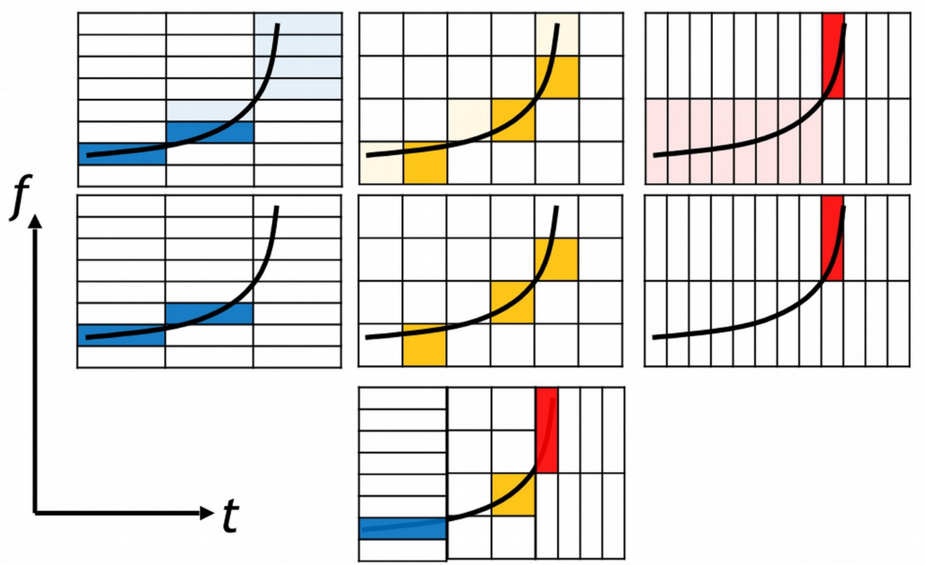


- **Compute $\mathcal{L}$ over the full sky and obtain a likelihood map**

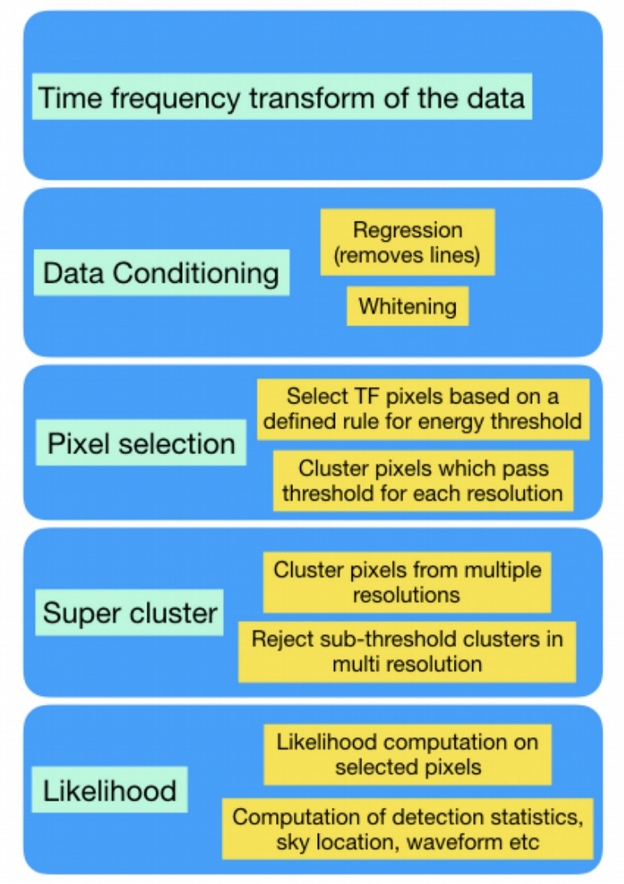
Coherent WaveBurst (2)

$$\mathcal{L}(F\mathfrak{h}^*) = (d^T f_+)^2 + (d^T f_\times)^2$$

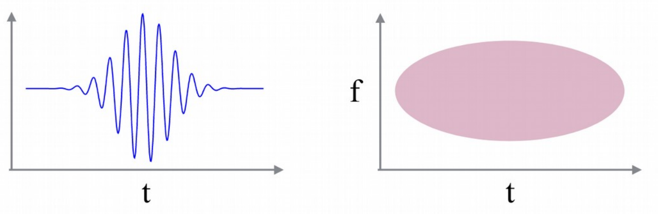
First project *d* onto a set of time-frequency bases and select bright pixels



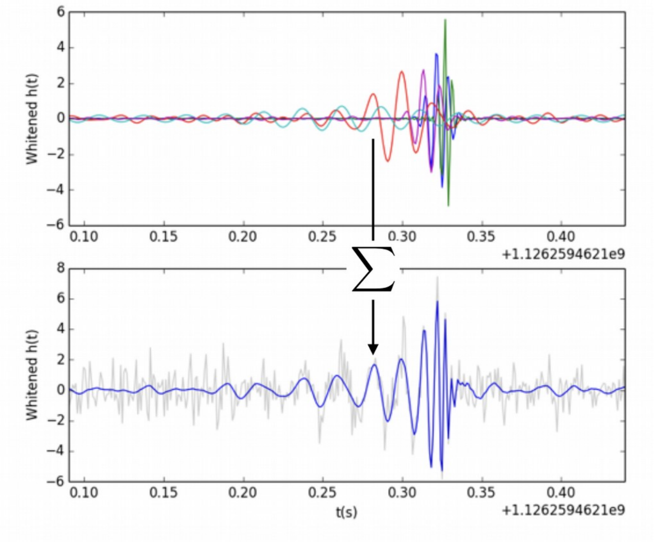
https://gwburst.gitlab.io/



Bayeswave



$$\Psi(t) = Ae^{-(t-t_0)^2/\tau^2}\cos(2\pi f_0(t-t_0)+\phi_0)$$



- **Three hypotheses**

  (1) signal + noise (2) glitch + noise (3) noise only
- **Signal and glitch waveform models**
  - Sum of Gabor wavelets $h = \sum_a^N \Psi(t;\theta_a)$
  - Signal: coherent model for all detectors
  - Glitch: incoherent (different wavelets for each detector)
- **Posterior on parameters obtained using a rever**
  - Include model order N
- **Hypothesis testing using Bayes factor**

https://git.ligo.org/lscsoft/bayeswave