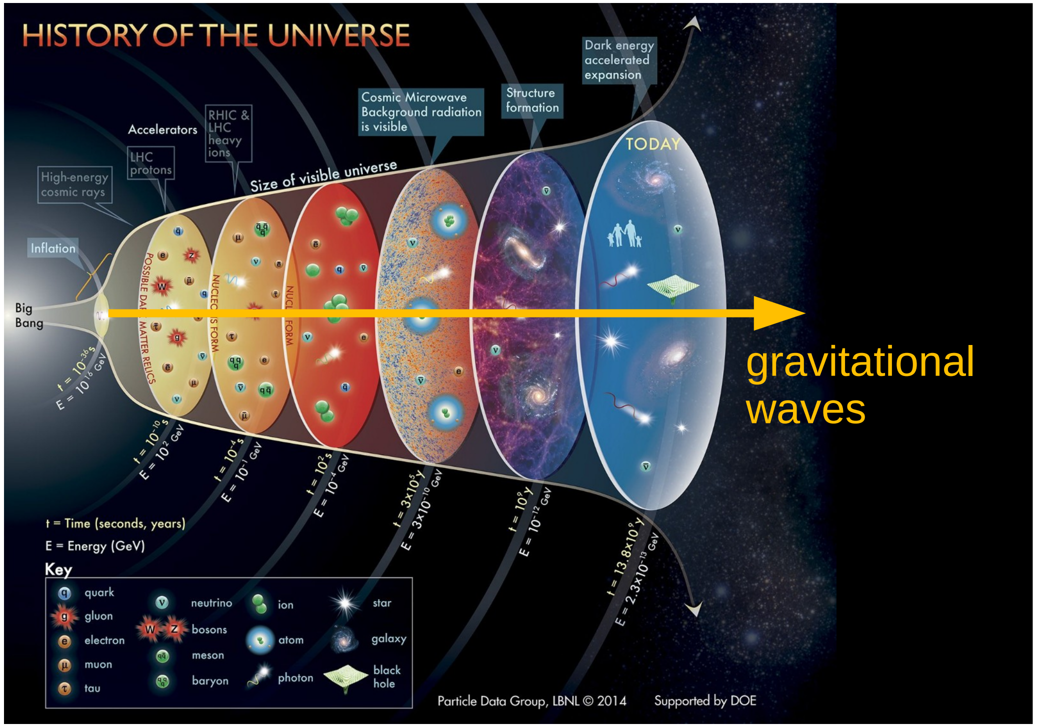
Gravitational wave physics

what we know and what we want to know



Valerie Domcke
CERN

Academic training lectures
April 2024

Outline

1) What we know

- Motivation
- What is a GW?
- LIGO: signal & detection
- LIGO: some highlights

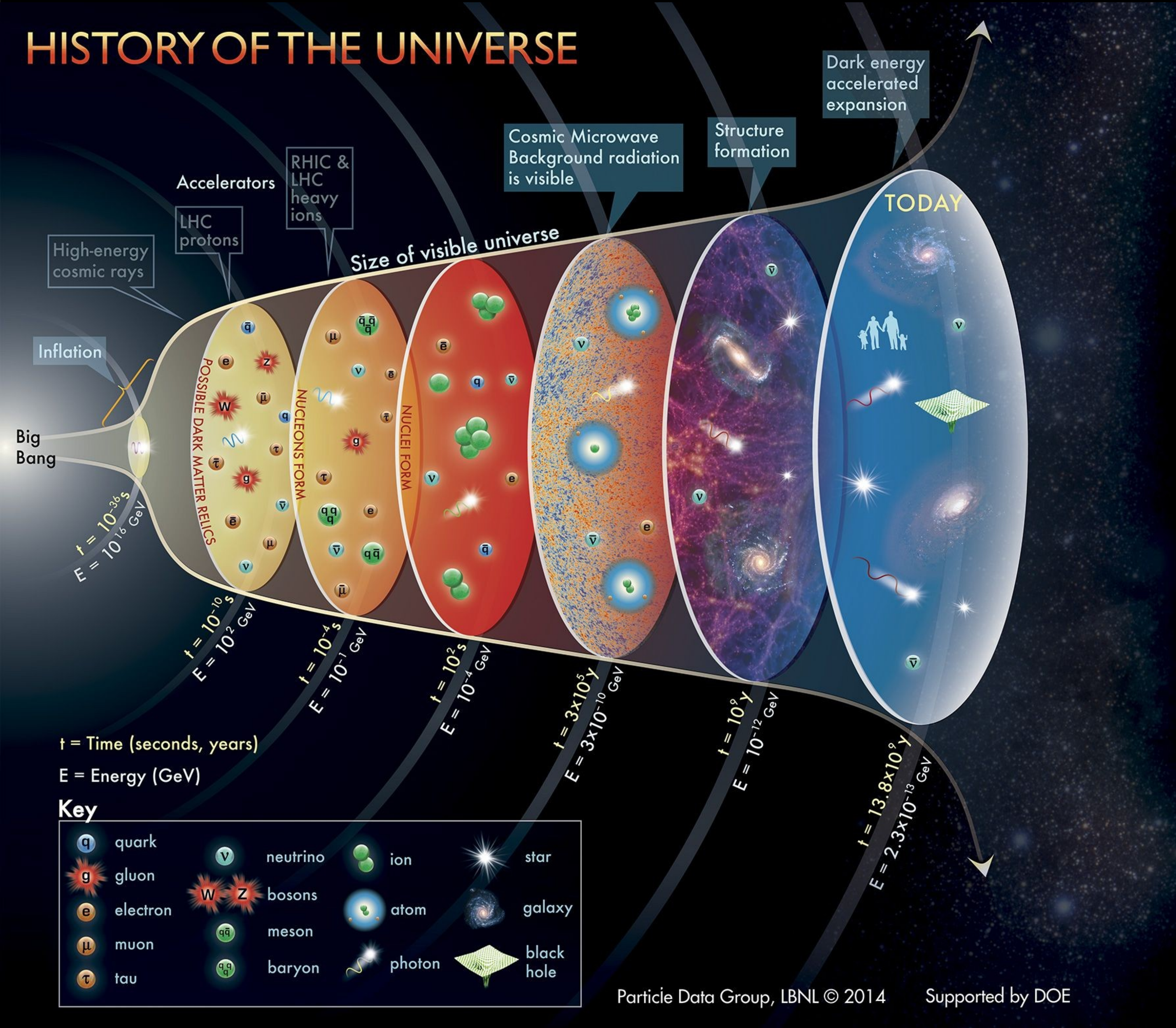
Literature:
- M. Maggiore, GWs, Vol I
- C. Caprini, D. Figueroa, Cosmological backgrounds of GWs, arxiv: 1801.04268

2) Current frontier

- GW background
- Pulsar timing arrays
- BSM searches with GWS

3) What we want to know

- Going to space & underground
- New opportunities at new frequencies



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
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$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
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$t = 10^{9}$ y
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$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
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electron
muon
tau
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bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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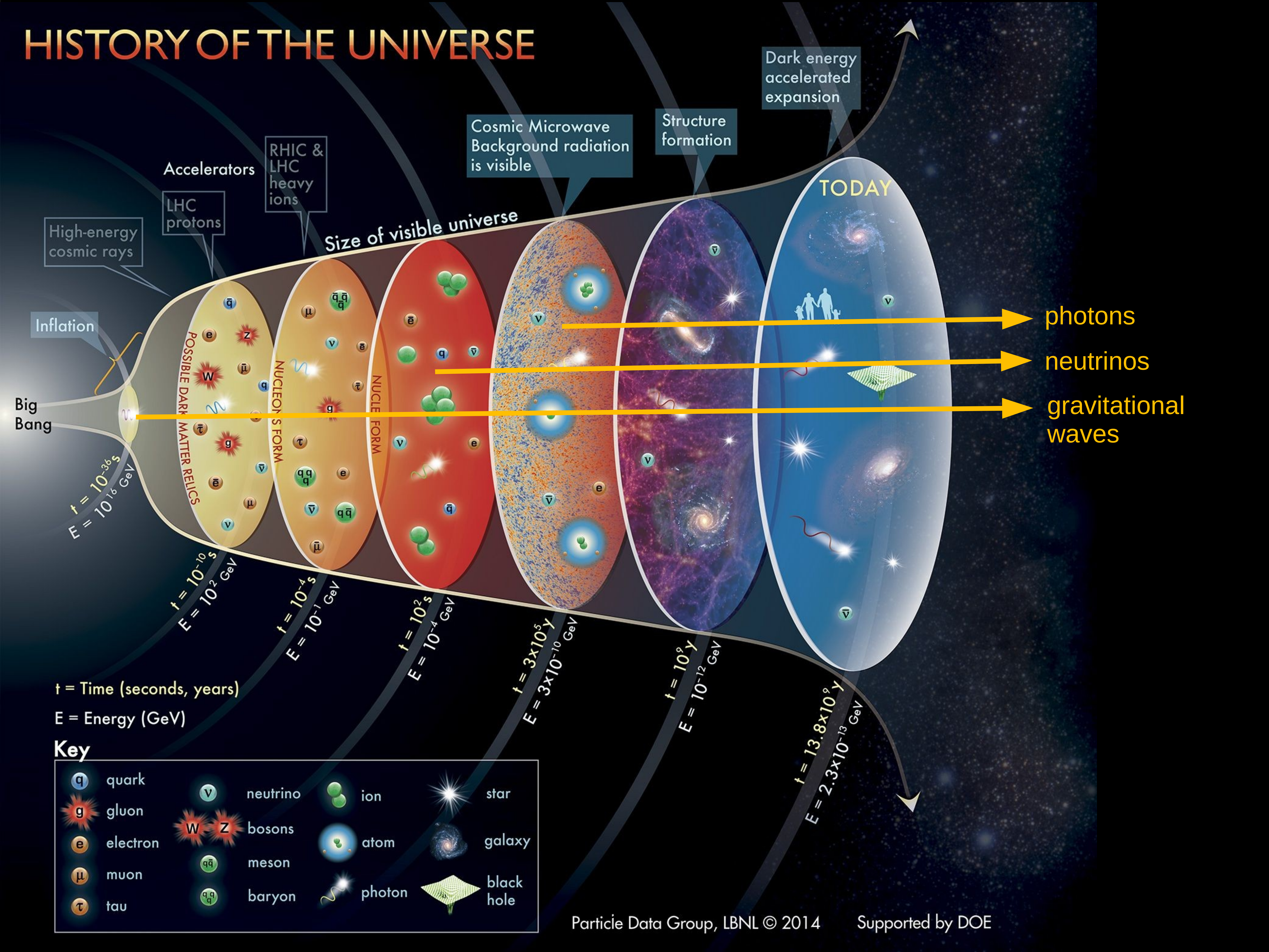
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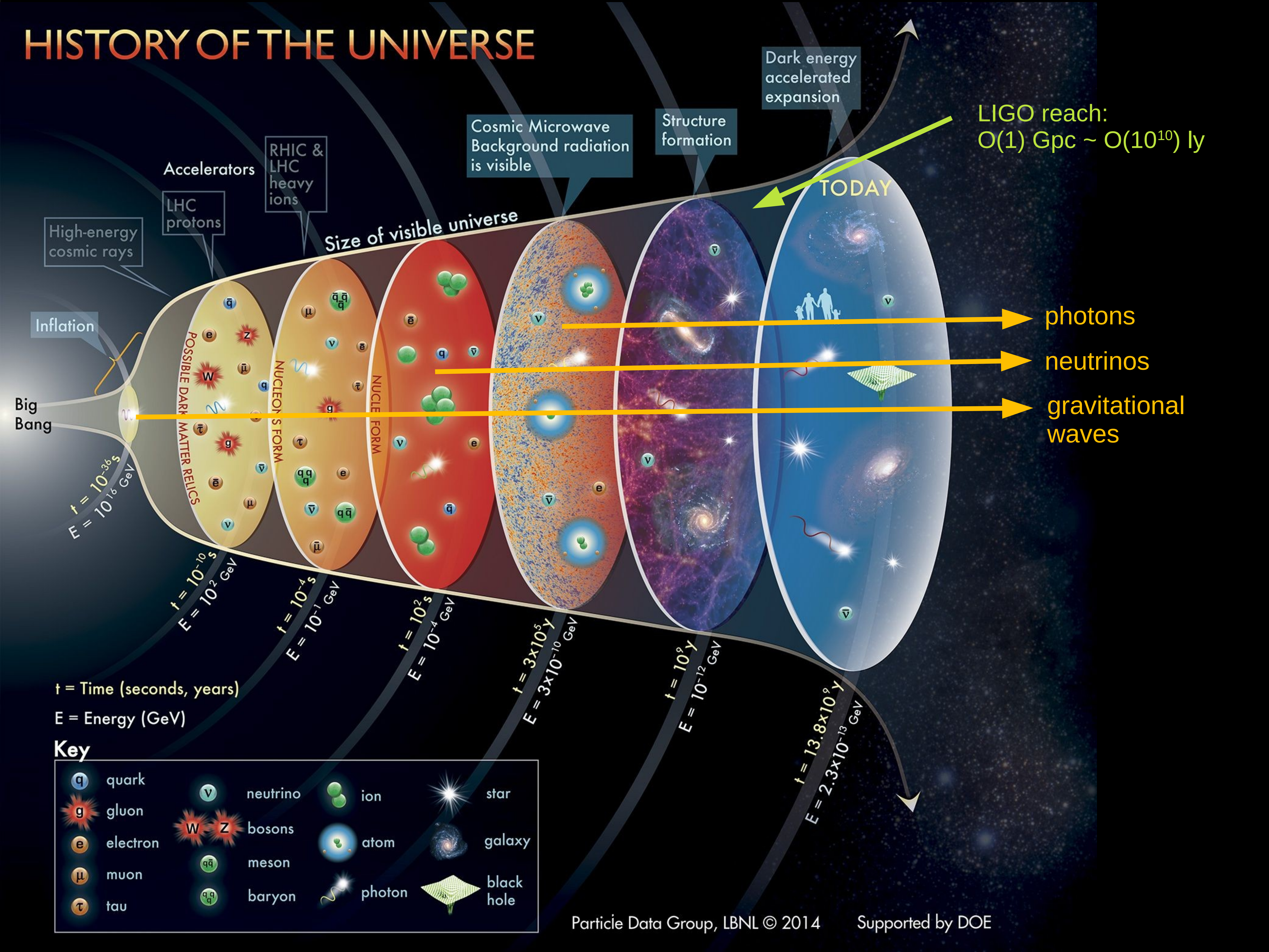

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O(1) Gpc ~ O(10^{10}) ly
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What is a GW ?

Einstein's equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

curved space-time
described by metric $g_{\mu\nu}$

energy momentum tensor of
matter / energy content

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$\Longrightarrow$

space time metric determines trajectories of all objects

$\Longleftarrow$

massive objects curve space time

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→

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←

massive objects curve space time

small perturbation around background metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1$

$$(\partial_t^2 - \partial_{\vec{x}}^2) h_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

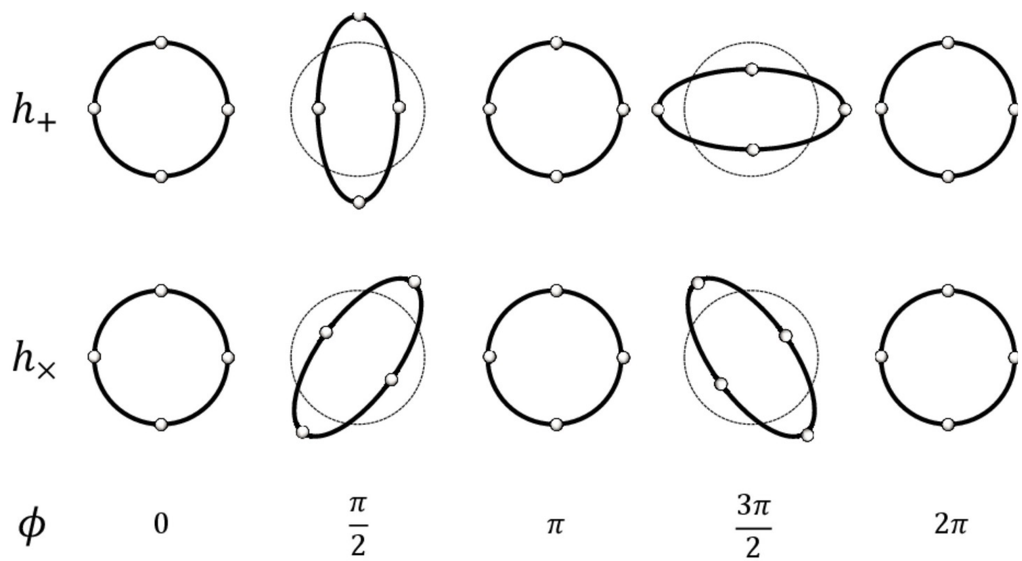
propagation of GW in vacuum

source term of GWs

For experts:
SVT decomposition,
tensor component
on both sides

What does a GW look like?

GW coming out of the plane, effect on test masses :



⟶ transverse, two polarizations, massless

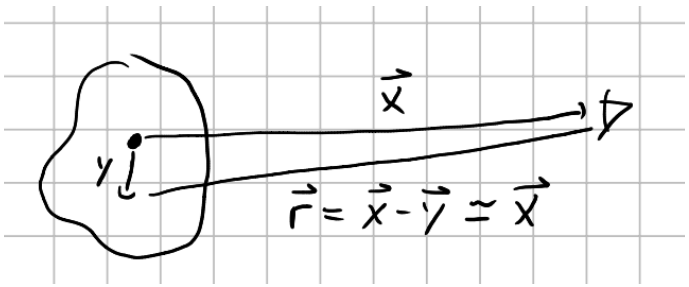
$$\mathrm{h}_{ij} = \left(h_+ e^+_{ij} + h_\times e^\times_{ij}\right) \cos[\omega(t-z)]\,, \qquad \mathrm{e}^+_{ij} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}\,, \quad e^\times_{ij} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

How are GWs sourced ?

$$(\partial_t^2 - \partial_{\vec{x}}^2) h_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

far field regime, like in electrodynamics:

$$\longrightarrow \quad h_{ij}(t, \vec{x}) = \frac{4G}{c^4} \frac{1}{r} \int d^3y \, T_{\mu\nu}(t - \frac{r}{c}, y)$$



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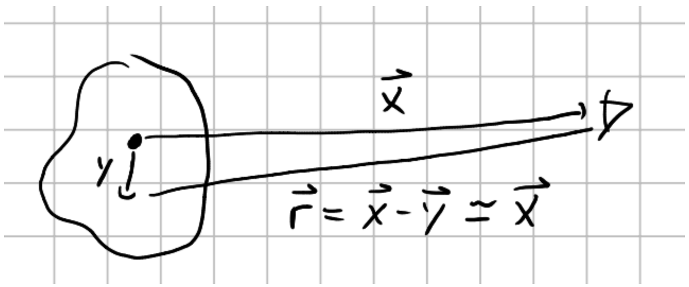

re-write integral, take tensor component:

$$\longrightarrow \qquad h_{ij}(t, \vec{x}) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t - r/c)$$

amplitude drops as 1/distance

second time derivative of quadrupole moment

$$I_{ij} = \int d^3 y \, (y_i y_j - \frac{1}{3} y^2 \delta_{ij}) \rho(\vec{y})$$

$$\rho = T_{00} = \text{energy density}$$

- need a moving object
- need a quadrupole moment

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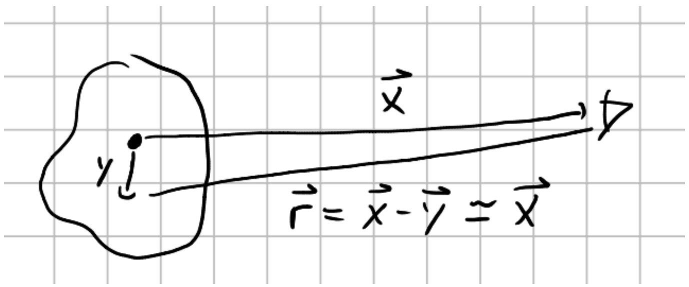

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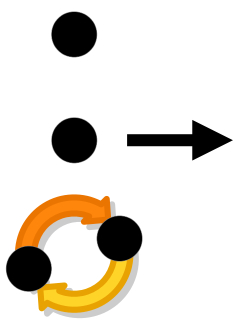

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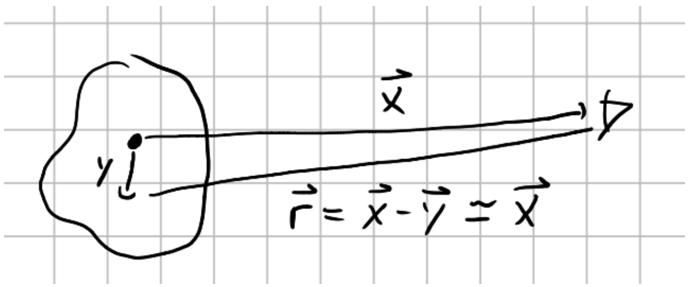

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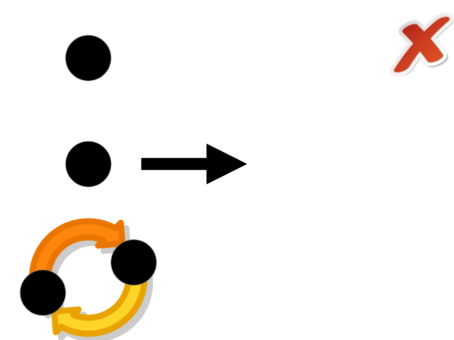

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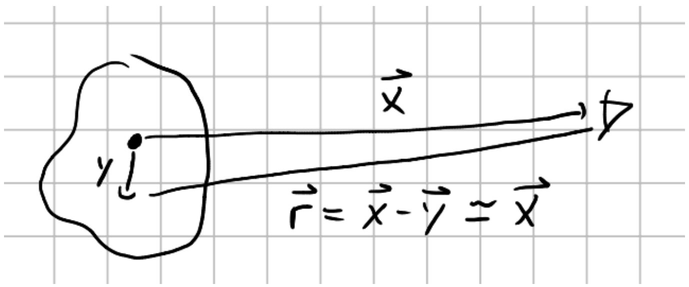

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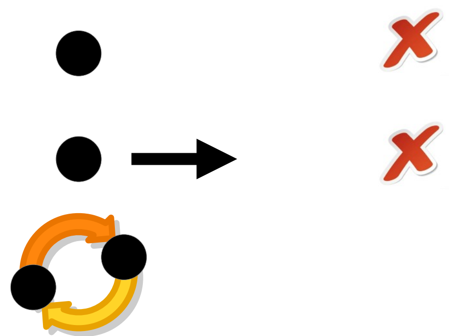

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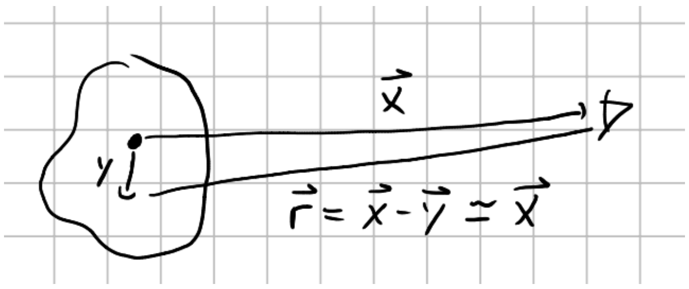

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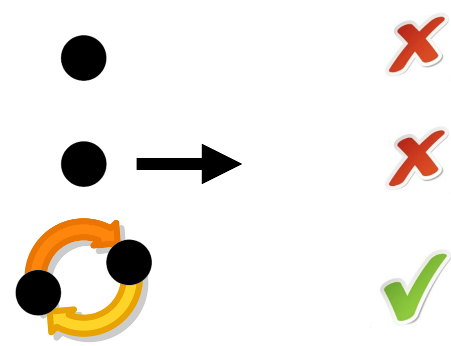
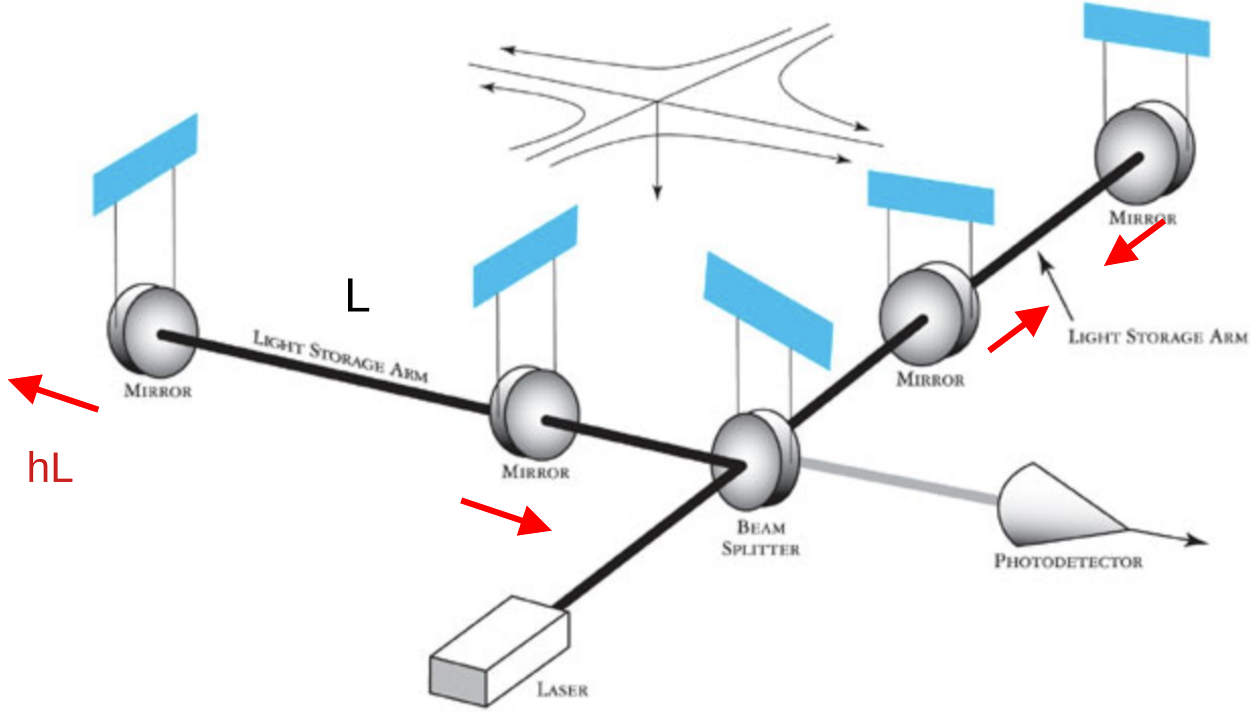
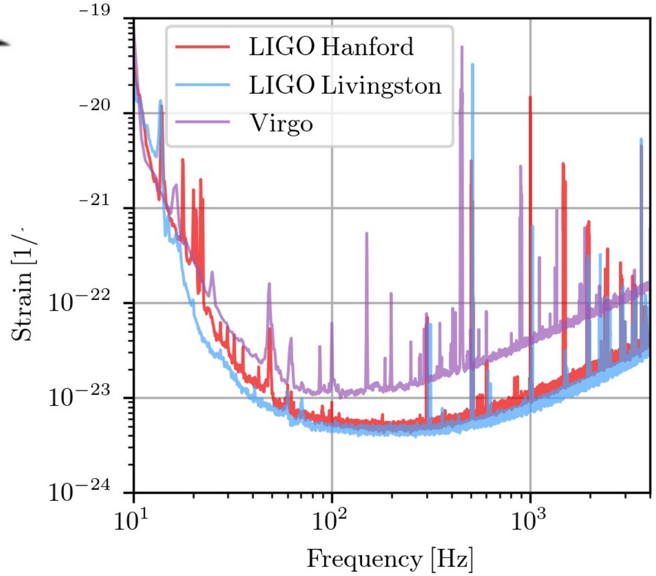


Valerie Domcke - CERN

LIGO: laser interferometer GW observatory





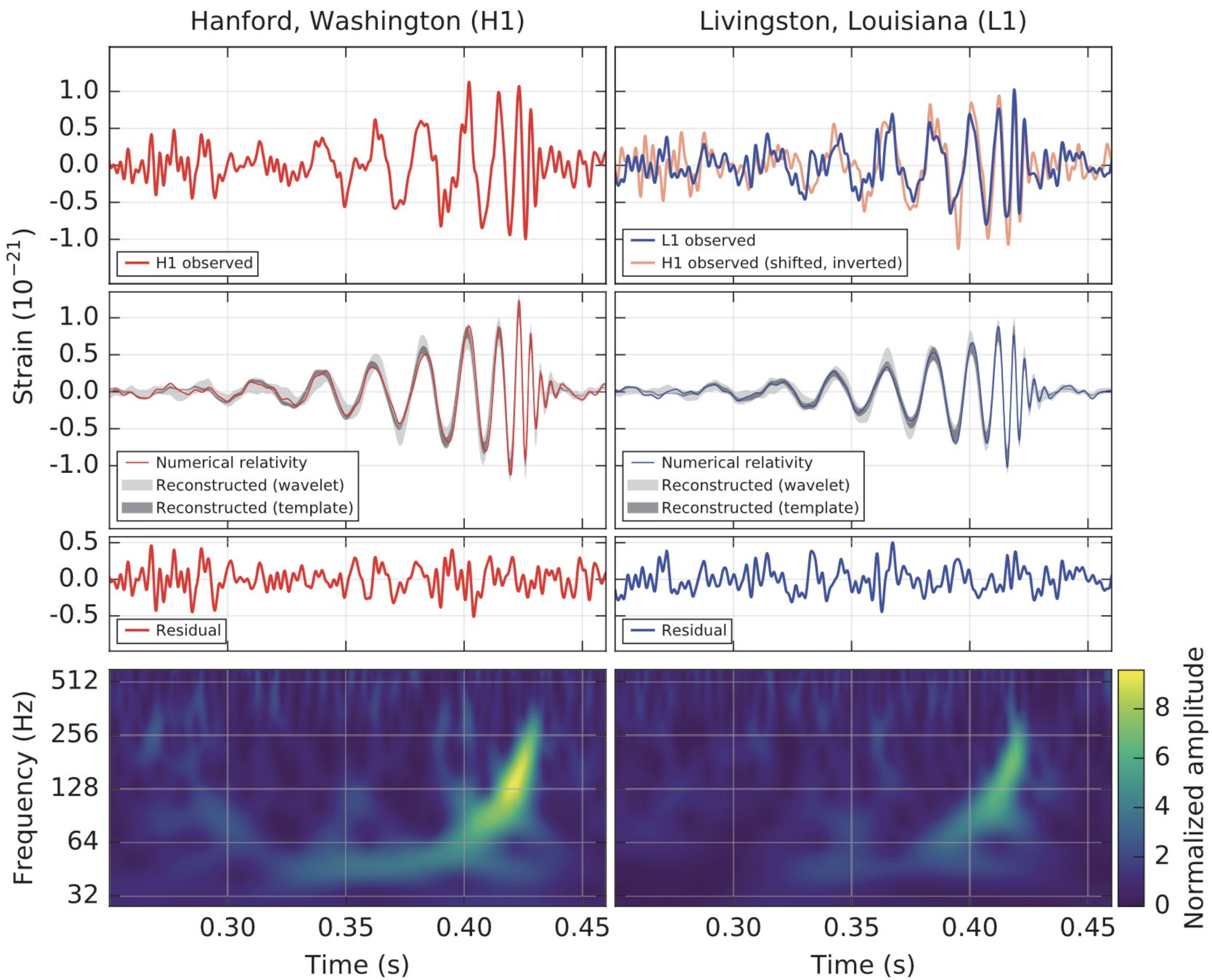
GW moves the mirrors, changing the relative light travel time in the two arms.

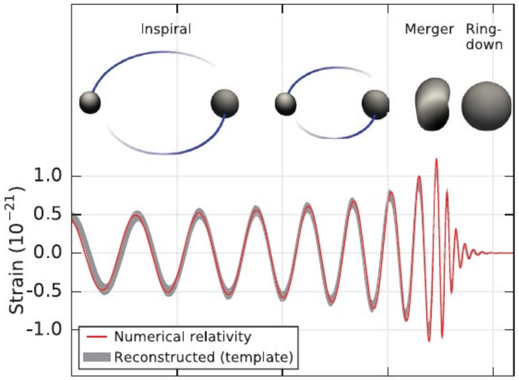
Resulting phase shift changes interferometer pattern

LIGOs first signal

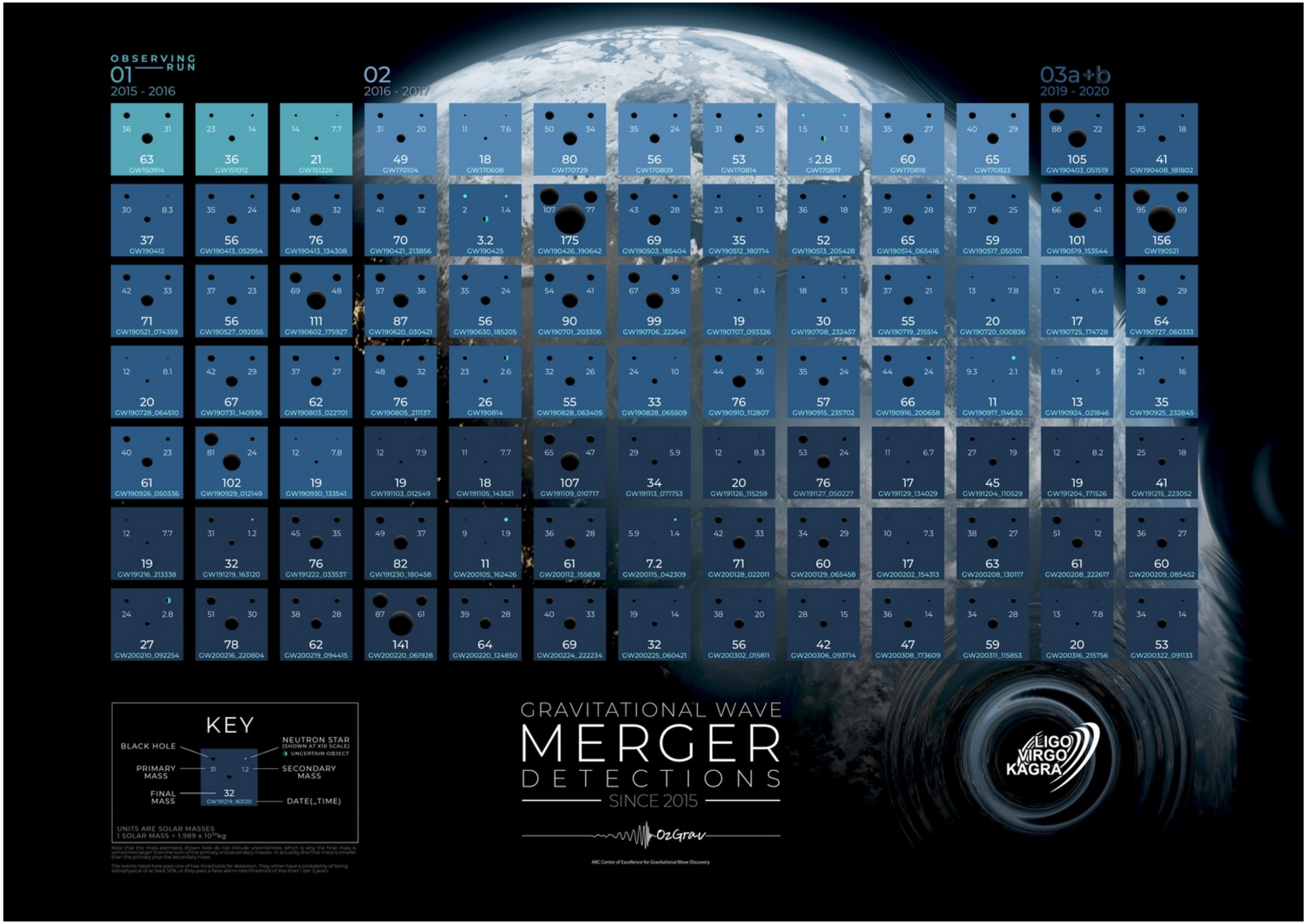
1602.03837

GW150914



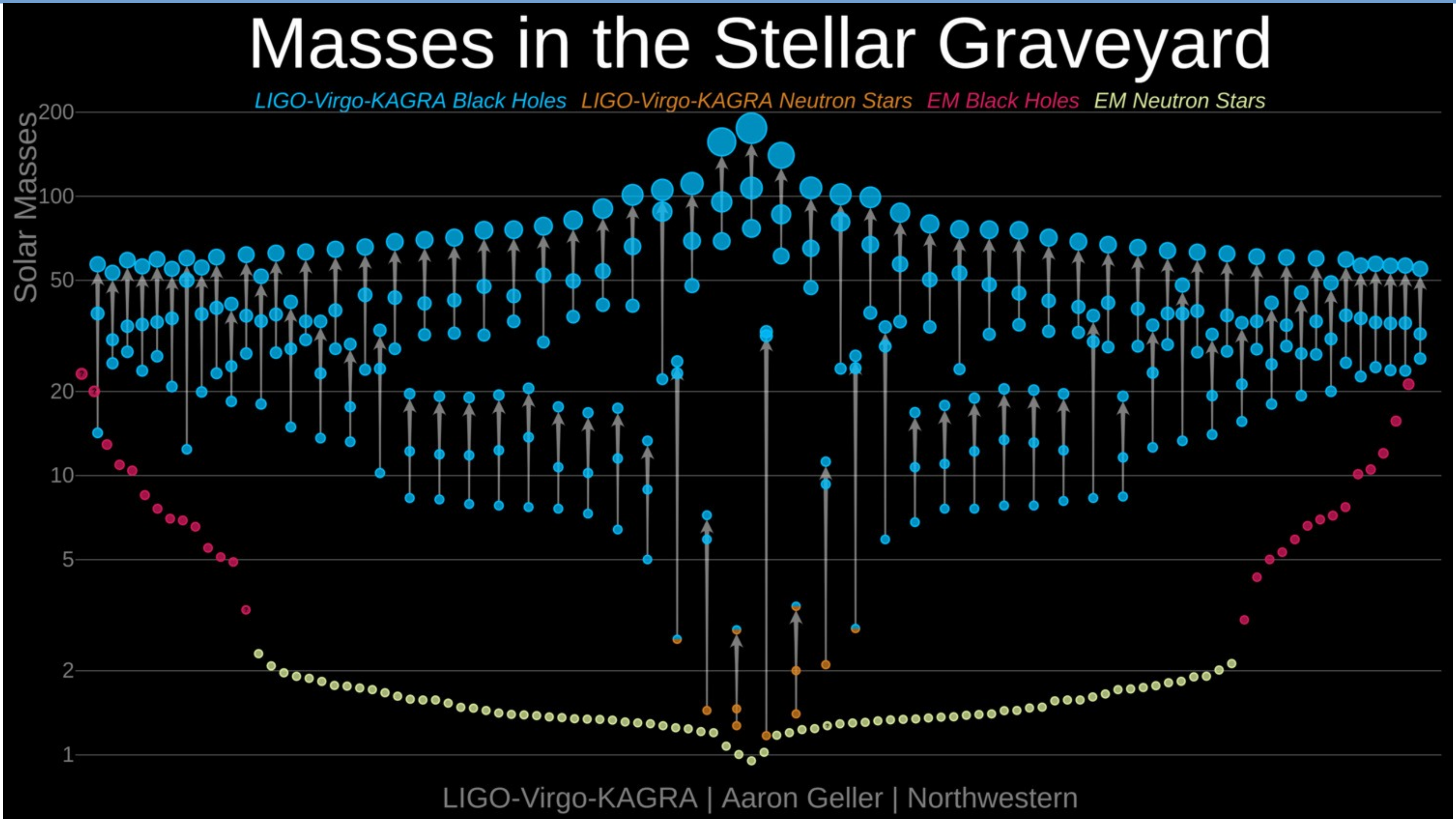


LVK catalogue, O1 - O3

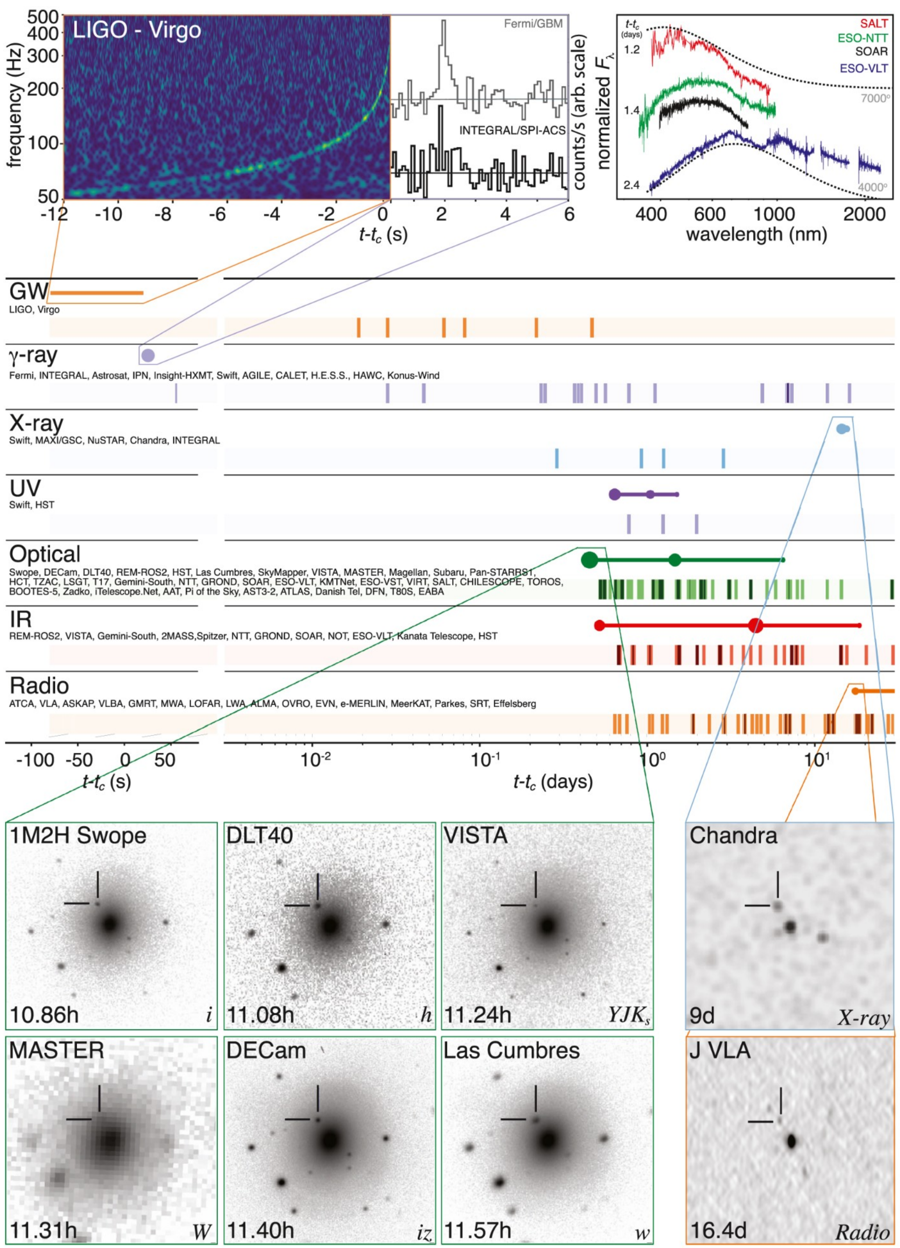


O4a : completed Feb `24, O4b: start 10/04/2024. Each one year of data taking

LVK catalogue O1 – O3, mass distribution



Tests of star formation and population models, search for primordial black holes



Stratta, Pannarale `22

GW170817, 1710.05832

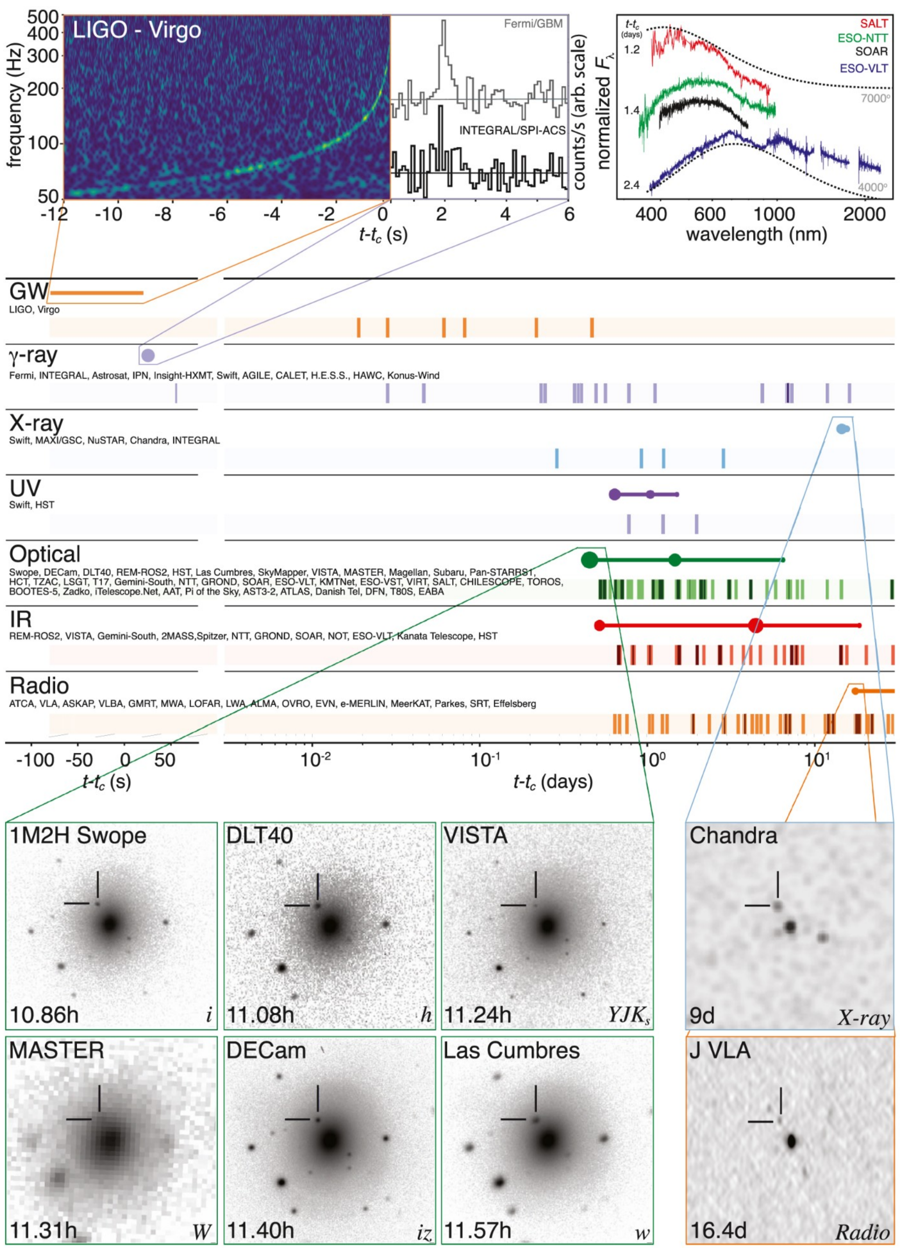
GW signal **and** optical counterpart

→ constrain speed of GWs (massive gravity) versus speed of light

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}.$$

B. P. Abbott et al 2017 ApJL 848 L13

Neutron stars: testing GR



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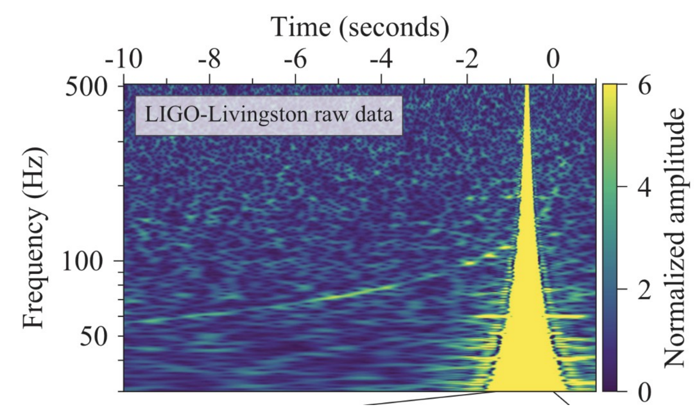
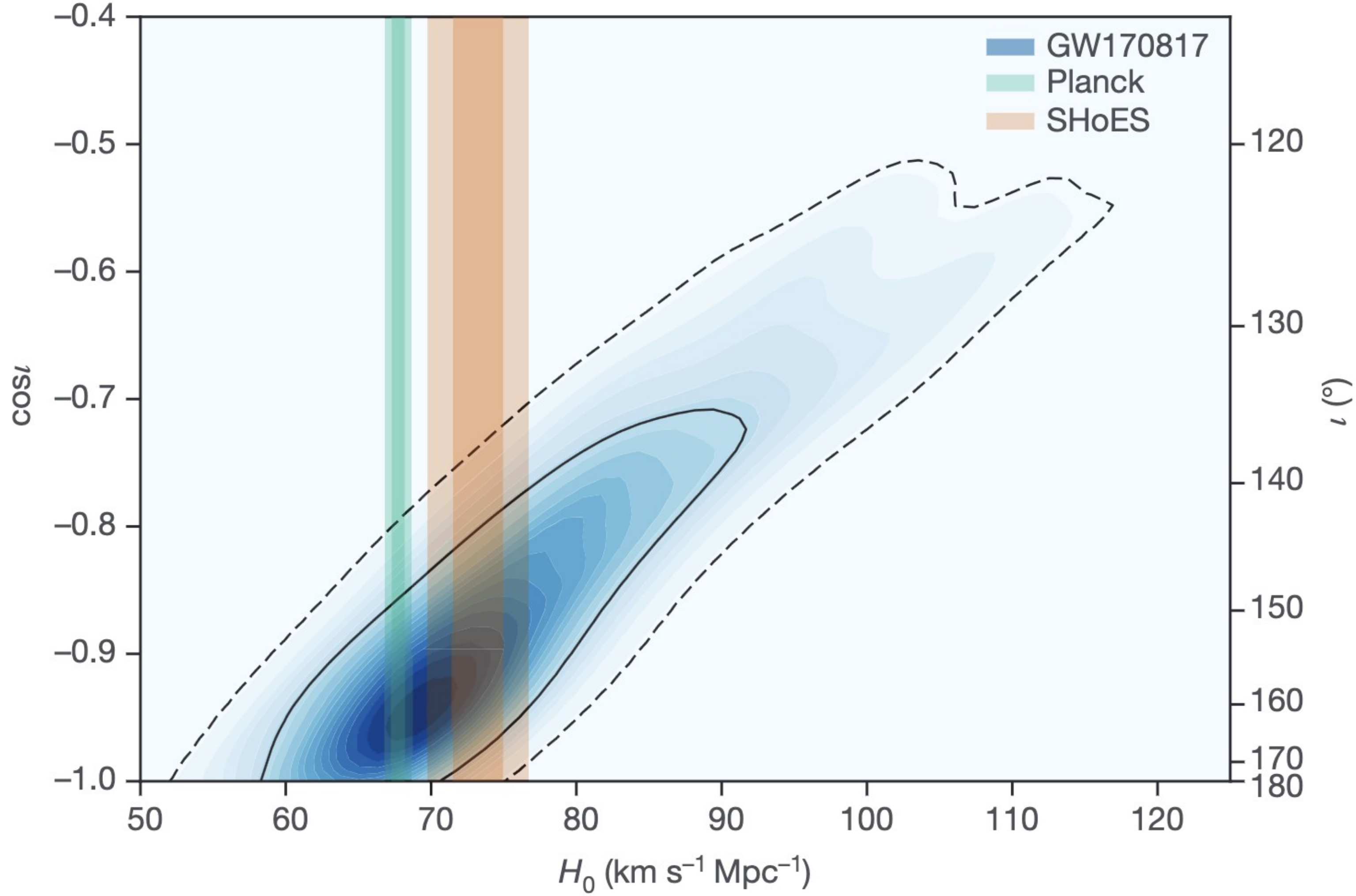


Neutron stars: testing ΛCDM

GW170817

LV Collaboration, Nature 551, 85–88 (2017)

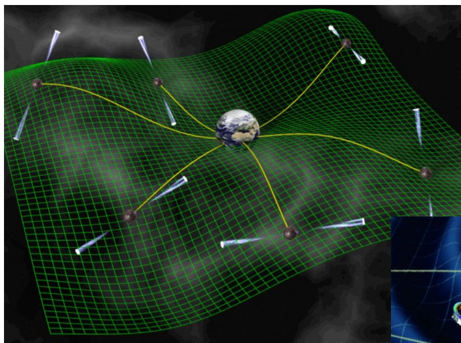


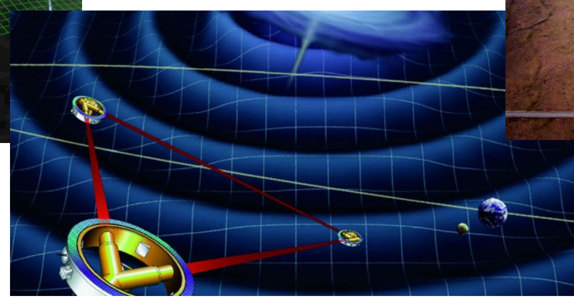
Independent measurement of recent expansion rate of the Universe (dark energy)

GW observatories : status and outlook

pulsar timing arrays

interferometers





LISA

LIGO

?

nHz mHz kHz

frequency

QCD PT EW PT GUT PT

$10^9 M_\odot - 10^6 M_\odot$ $10^6 M_\odot - 10 M_\odot$ $100 M_\odot - M_\odot$

mass (merging compact objects)
time (cosmological events)

To sum up

GWs are perturbations of the space time metric, sourced by

- violent (large acceleration)
- anisotropic (large quadrupole moment) motion
- with high mass / energy density (large quadrupole moment)

GWs deform length (and time), act as a force on free-falling objects

→ measured through extremely accurate relative length measurement (LIGO)

GW astronomy has provided tests of star formation, black hole properties, general relativity, our Standard Model of Cosmology, and many more.

Next lectures: pushing the boundaries in sensitivity and frequency, probes of physics beyond the Standard Model of Particle Physics.