MultiMessanger Astronomy and Gravitational Waves

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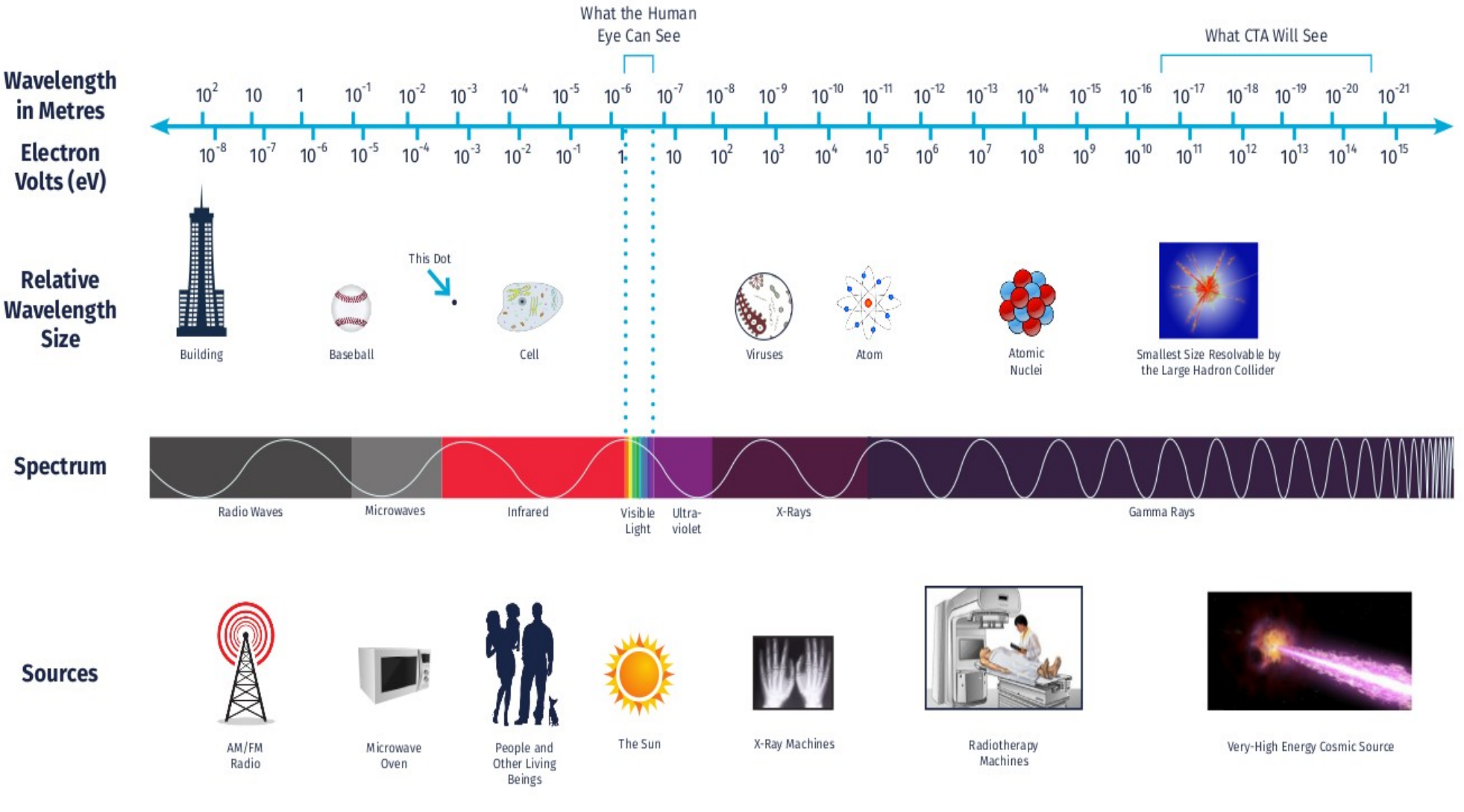
cherenkov telescope array

The Electromagnetic Spectrum

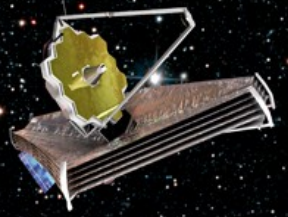


→ ESA'S FLEET ACROSS THE SPECTRUM

esa

Thanks to cutting edge technology, astronomy is unveiling a new world around us. With ESA's fleet of spacecraft, we can explore the full spectrum of light and probe the fundamental physics that underlies our entire Universe. From cool and dusty star formation revealed only at infrared wavelengths, to hot and violent high-energy phenomena, ESA missions are charting our cosmos and even looking back to the dawn of time to discover more about our place in space.

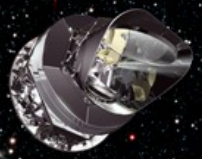
jwst
Observing the first light



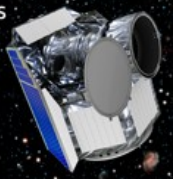
gaia
Surveying a billion stars

herschel
Unveiling the cool and dusty Universe

planck
Looking back at the dawn of time



cheops
Sizing and first characterisation of exoplanets

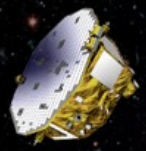


euclid
Exploring the dark Universe

hst
Expanding the frontiers of the visible Universe

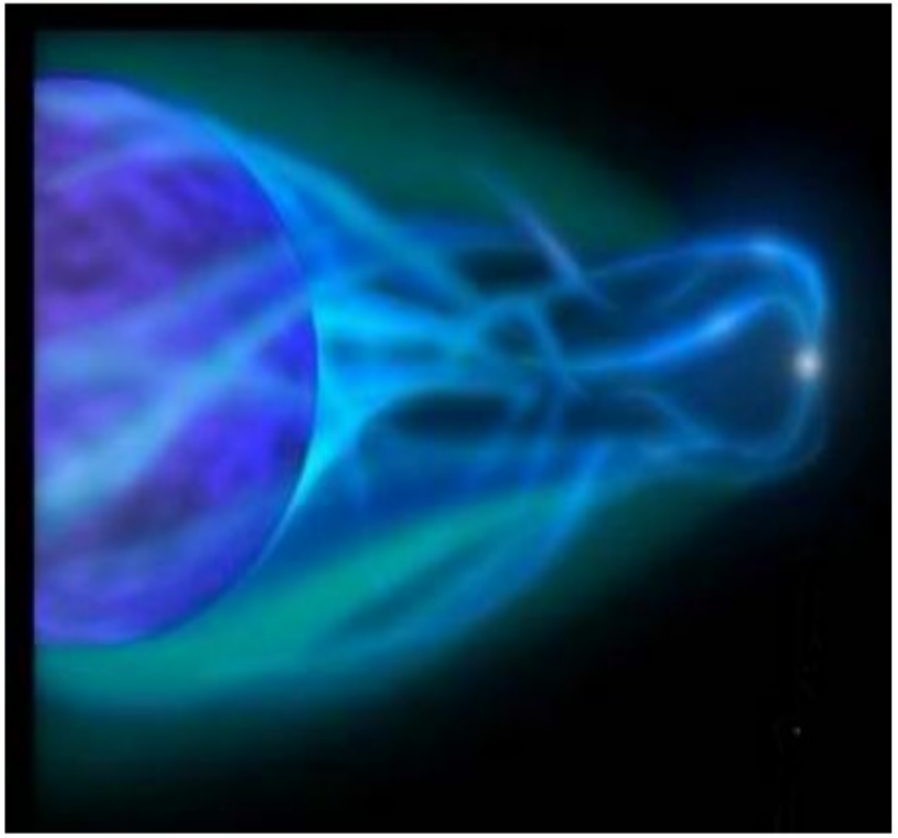
xmm-newton
Seeing deeply into the hot and violent Universe

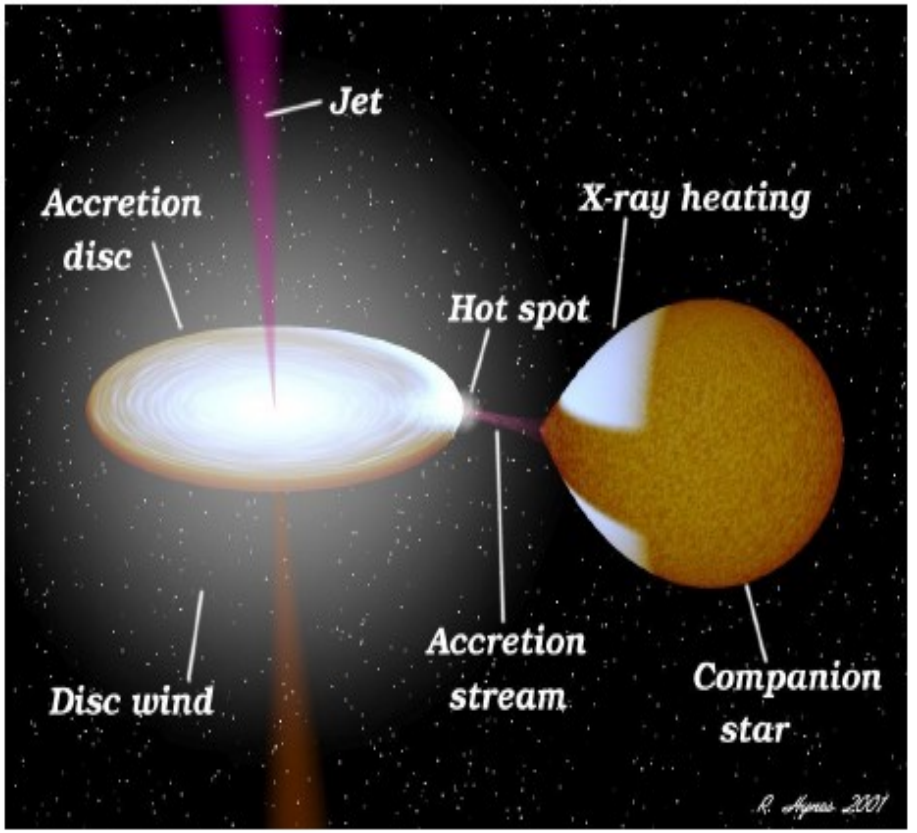
lisa pathfinder
Testing the technology for gravitational wave detection



integral
Seeking out the extremes of the Universe

Sistemi binari X e γ





Astrofisica 'multi-messaggera'

→ *Radiazione elettromagnetica*

→ *Neutrini*

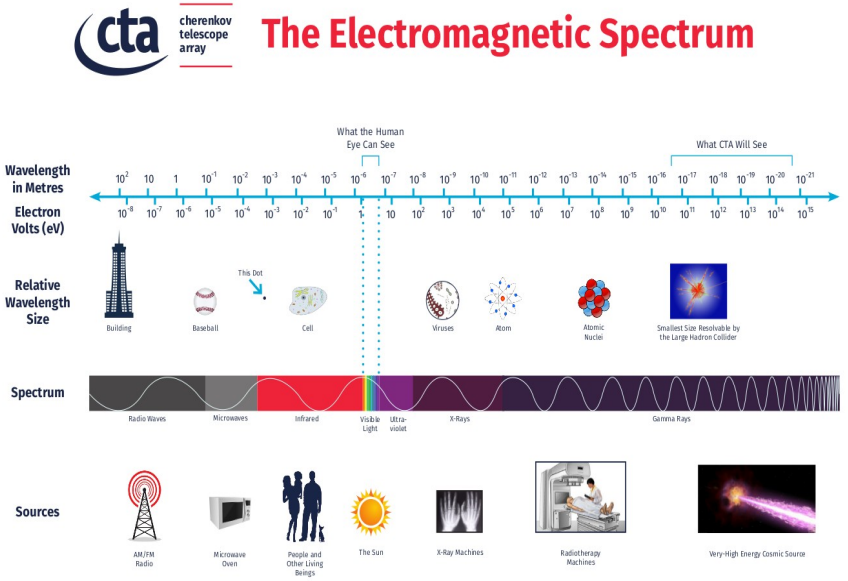
→ *Onde gravitazionali*

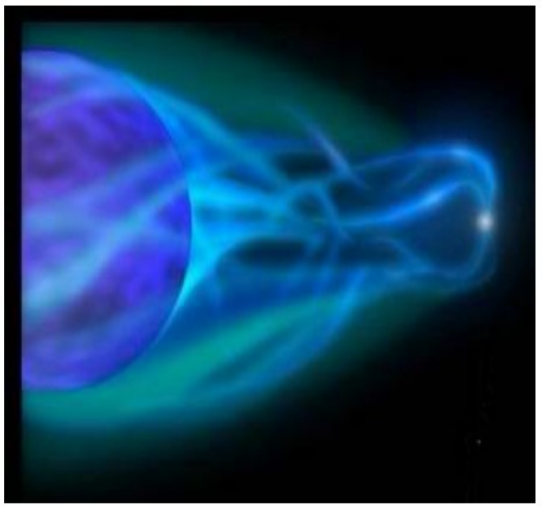
Astrofisica 'multi-messaggera'

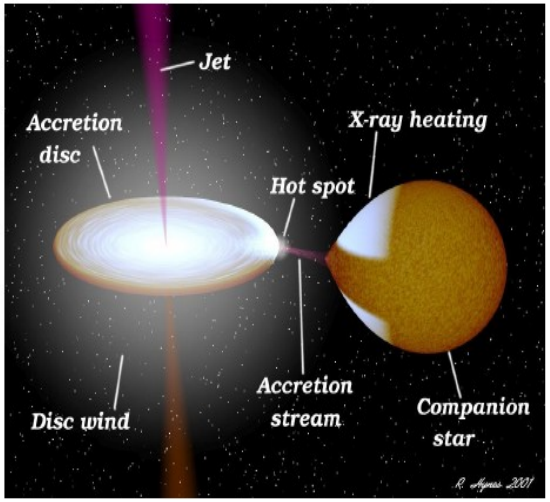
→ ***Radiazione elettromagnetica (e.g. James Webb)***

→ *Neutrini*

→ *Onde gravitazionali*





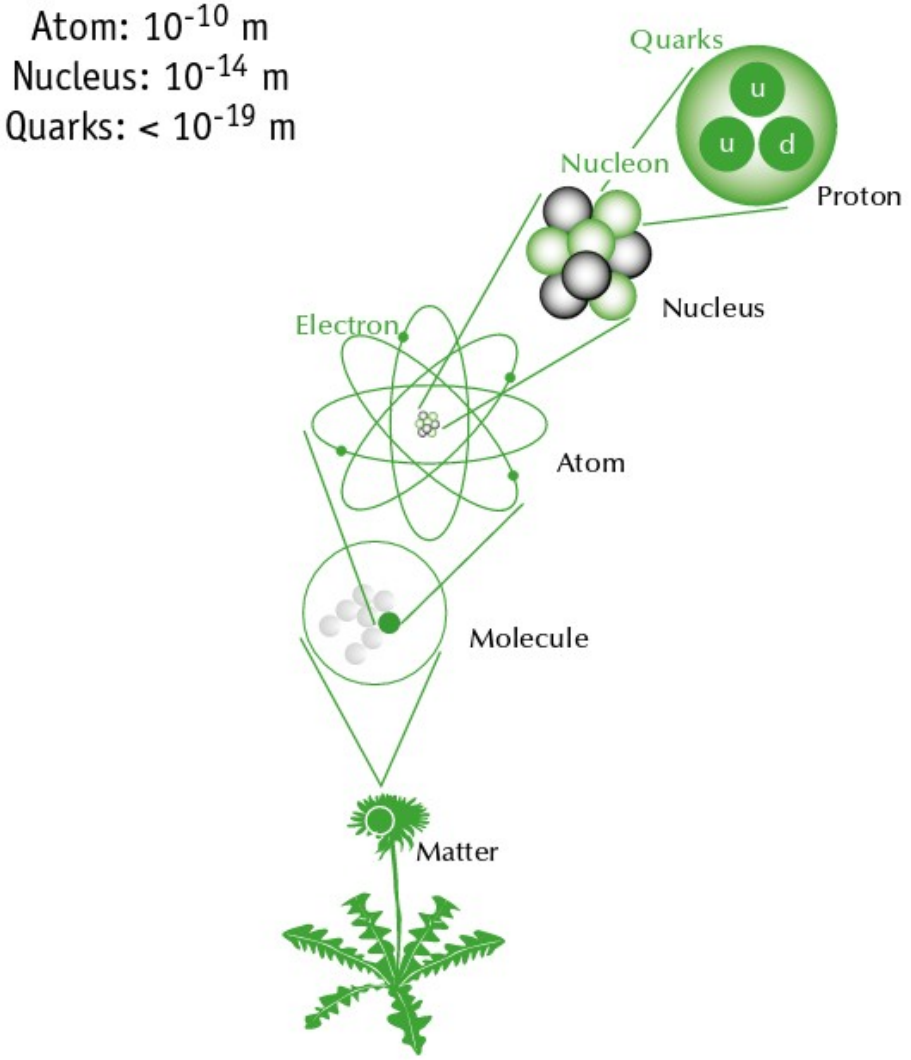


Astrofisica 'multi-messaggera'

→ *Radiazione elettromagnetica*

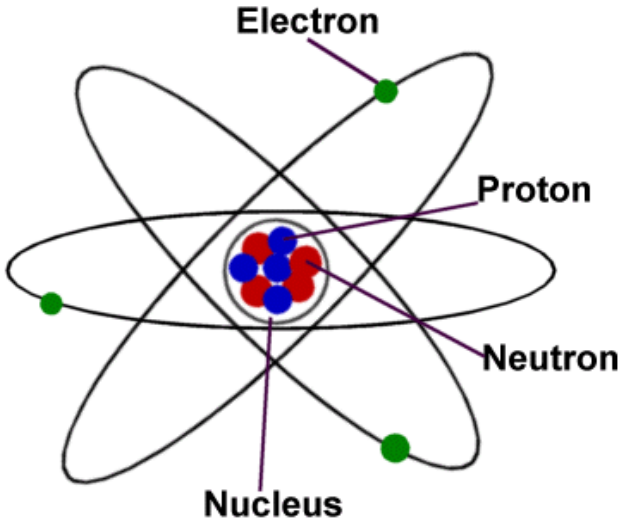
→ ***Neutrini***

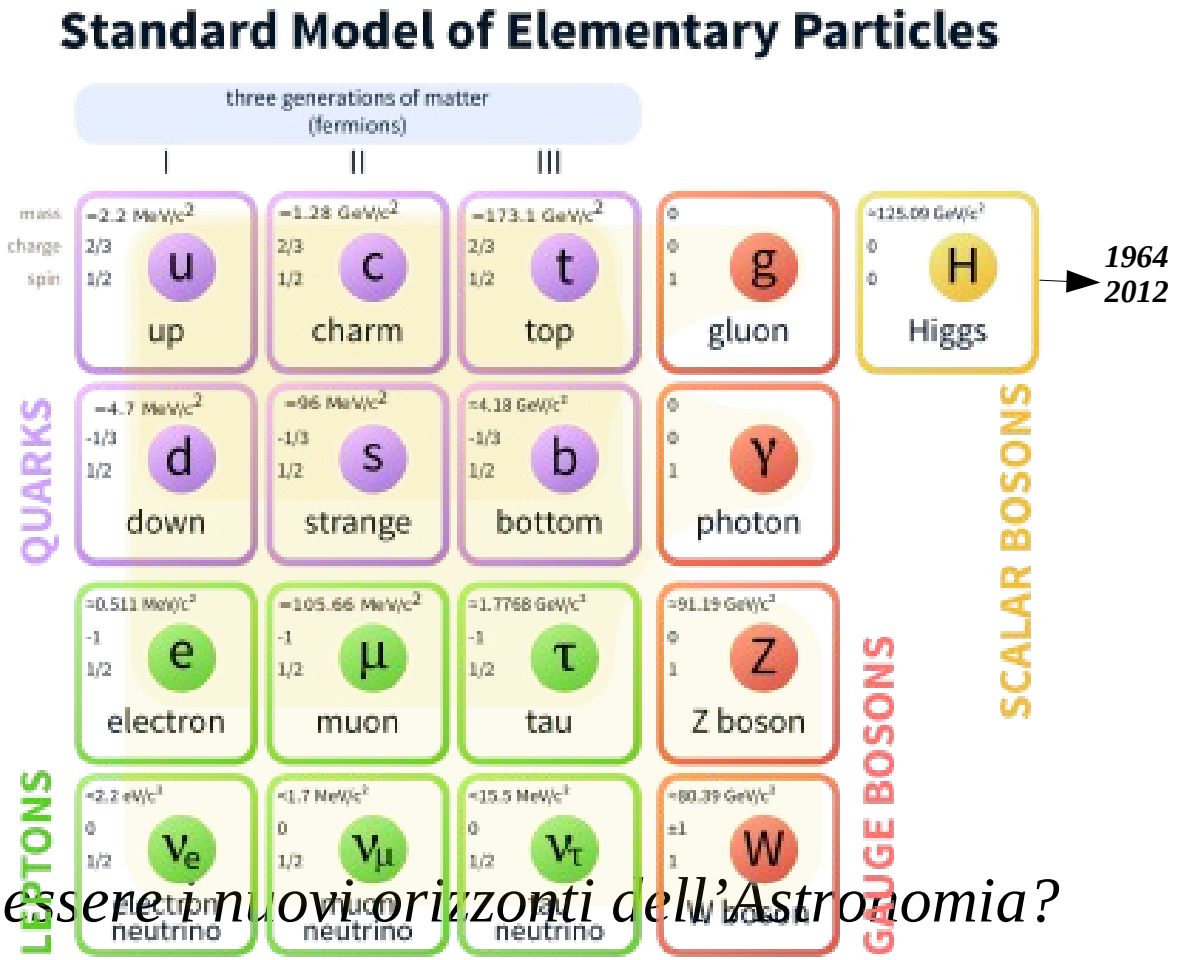
→ *Onde gravitazionali*



Neutrini I

particella subatomica elementare di massa piccolissima e carica elettrica nulla.





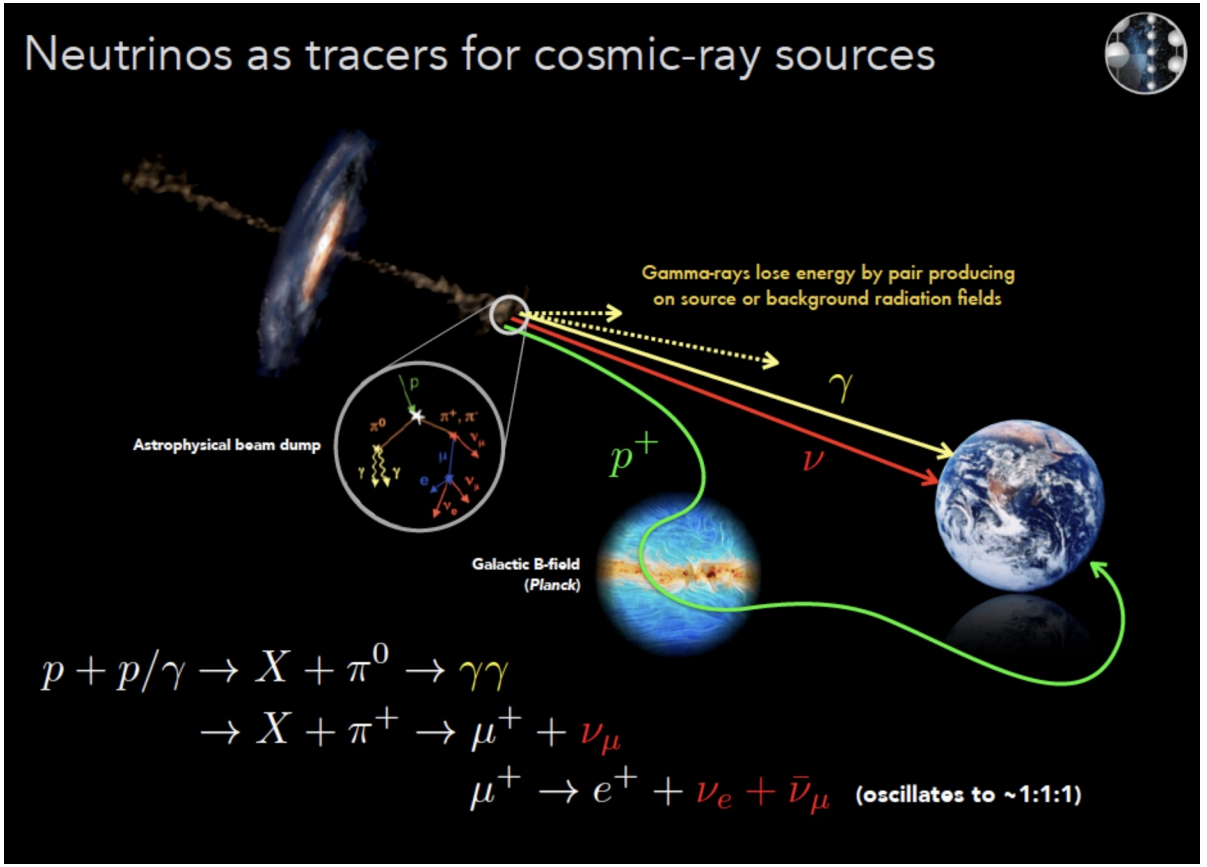
Perchè i neutrini dovrebbero essere i nuovi orizzonti dell'Astronomia?

Neutrini II

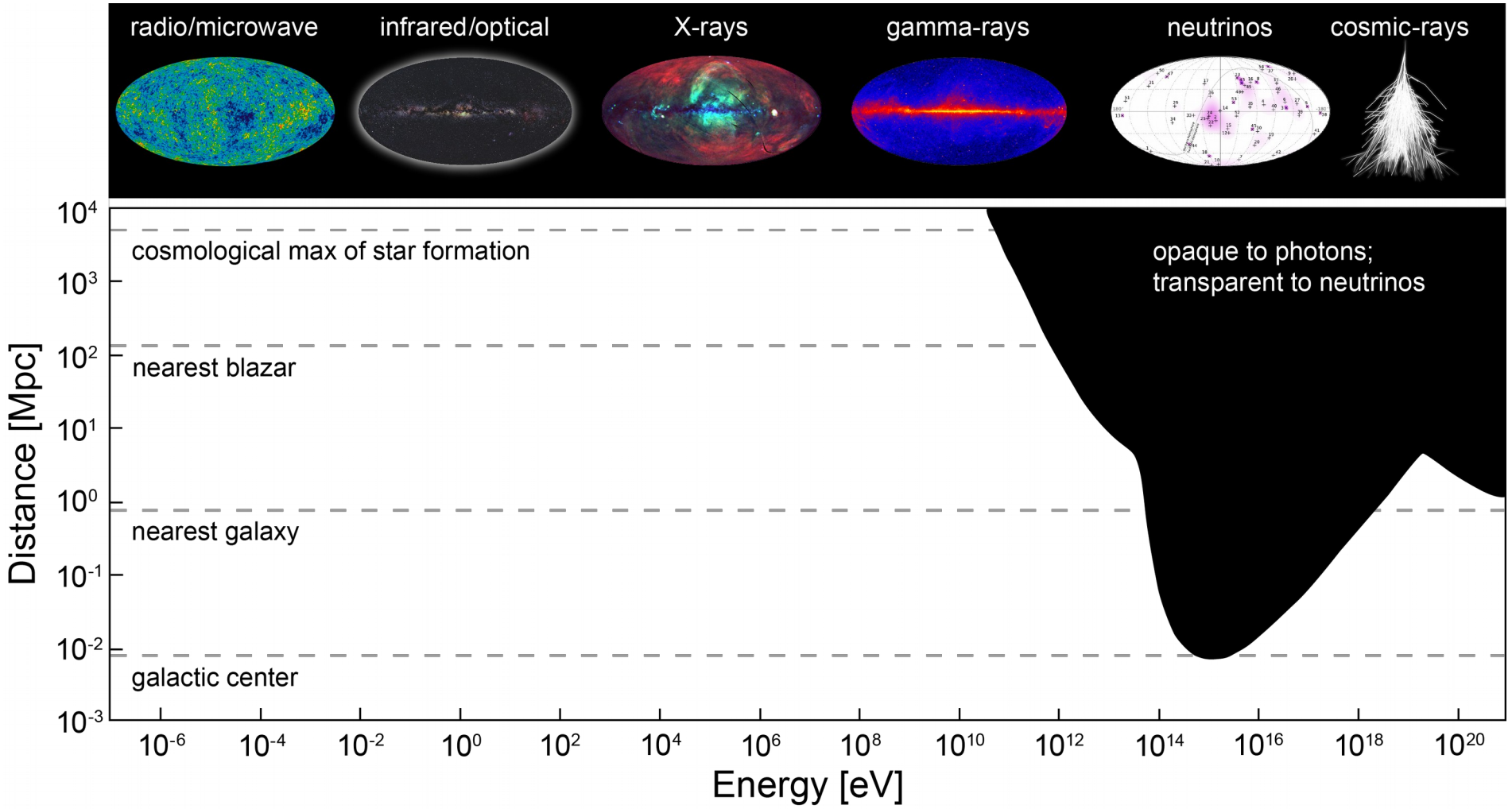
Mare di neutrini da raggi cosmici (particelle cariche estremamente energetiche) sull'atmosfera terrestre.

Da sorgente non-terrestre:

* *Sole*
* *SN1987A*
* *TXS 0506+056 (IceCUBE Science 2018)*
  ν @ 290 TeV + fotoni da radio a 175 GeV



Per avere un neutrino a quella energia, serve un protone estremamente energetico: i ***blazar*** *riescono ad accelerarli, sono* ***sorgenti di raggi cosmici***


radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
cosmological max of star formation
nearest blazar
nearest galaxy
galactic center
opaque to photons;
transparent to neutrinos
Distance [Mpc]
Energy [eV]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-6
10^-4
10^-2
10^0
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20

Onde gravitazionali I

Perturbazioni dello spazio-tempo previste nell'ambito della teoria della ***relatività generale***.

[Fisica classica (Newton, fine 1600)

La fisica del quotidiano (v <<<<<< c)

Il tempo è assoluto

Relatività ristretta (Einstein, 1905)

v ~ c (1%, ...)

La velocità della luce è assoluta (finita) → dilatazione del tempo ($T=\gamma T_0$)

Relatività generale (Einstein, 1915)

Relatività ristretta + Gravità → Relatività generale

Distorsione dello spazio-tempo (inclusa la luce!) da oggetti massicci

??

La fisica classica è ancora valida!]

Onde gravitazionali II

Perturbazioni dello spazio-tempo previste nell'ambito della teoria della relatività generale (increspature di 1/1000 di protone che viaggiano a c).

*Cercate per 50 anni, viste direttamente nel **2015:***

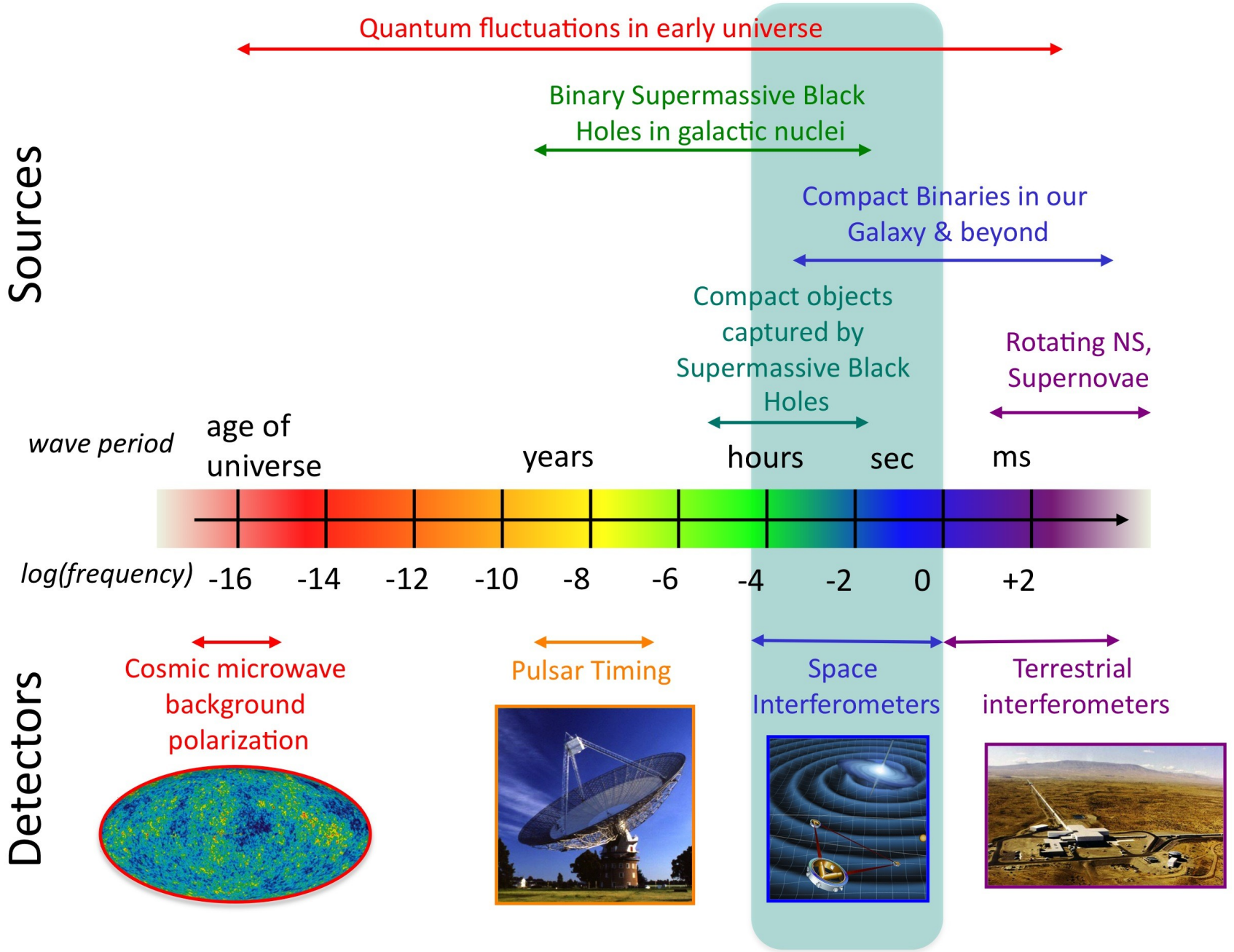
- *LIGO: **due buchi neri** 36 + 29 (=65) masse solari → 62 masse solari*
  La massa mancante (3 masse solari) si è sprigionata in onde gravitazionali: energia più intensa di tutte le stelle messe insieme … al buio. La Terra si è espansa e contratta di uno spazio ~ dimensione di un atomo

- *Altri eventi BN + BN*

- *LIGO + VIRGO: Il 17 agosto **2017** (GW170817): **SN + SN** (circa 1 massa solare) 200 strumenti da Terra e Spazio entro poche ore si sono girati a guardare*

→ ***era multi-messaggera***

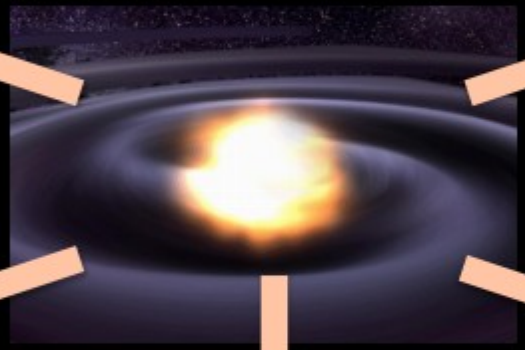
The Gravitational Wave Spectrum

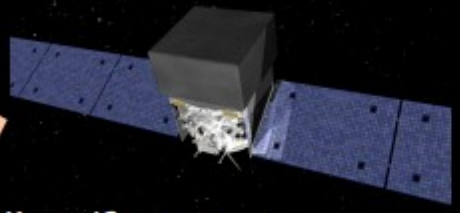


Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

Binary Neutron Star Merger

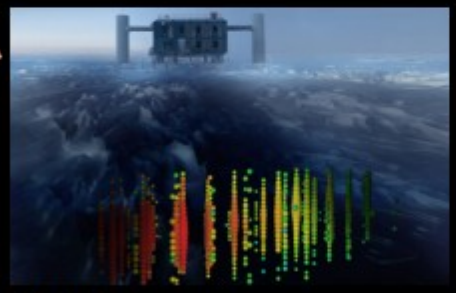




X-rays/Gamma-rays

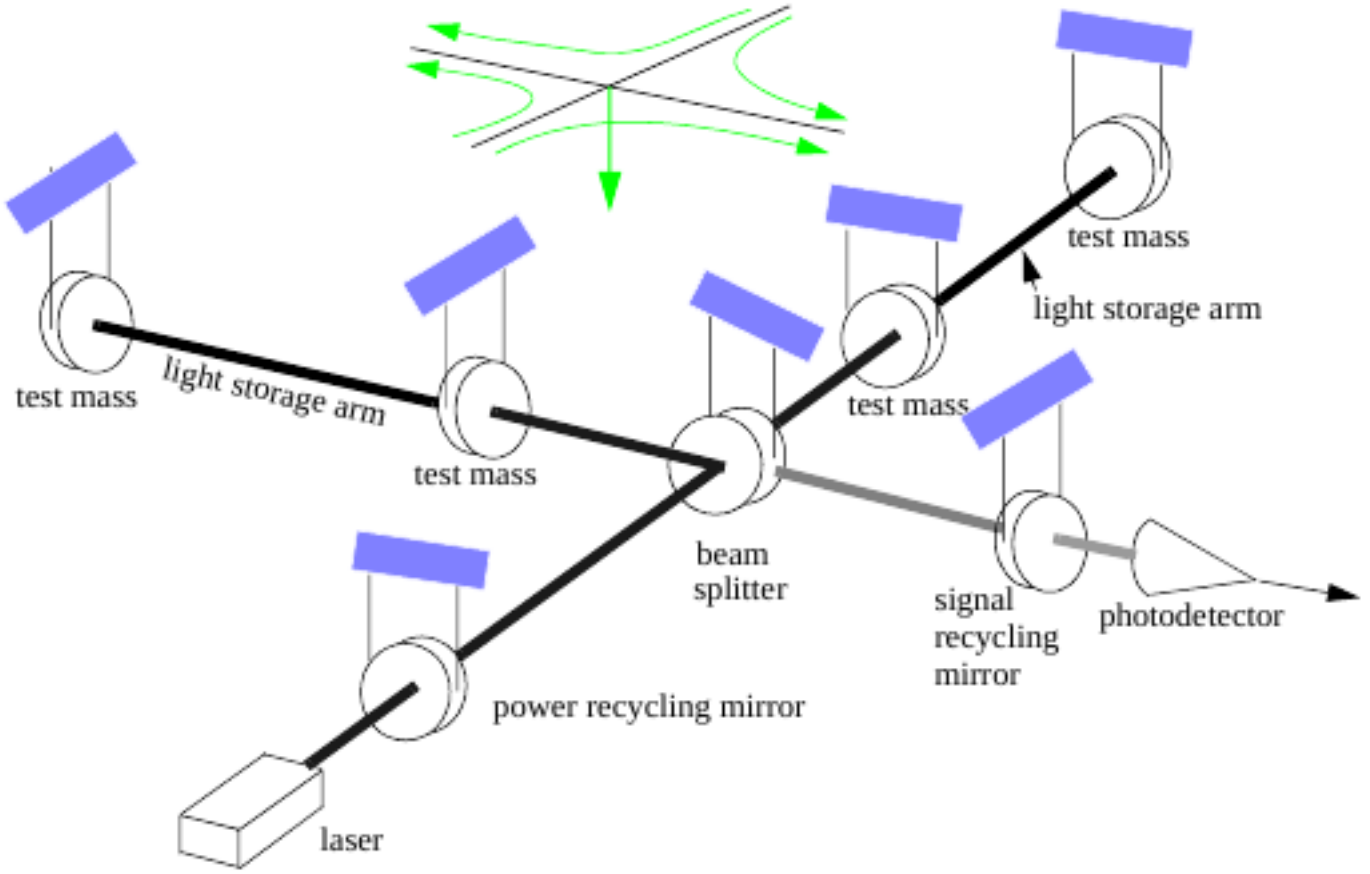
Visible/Infrared Light

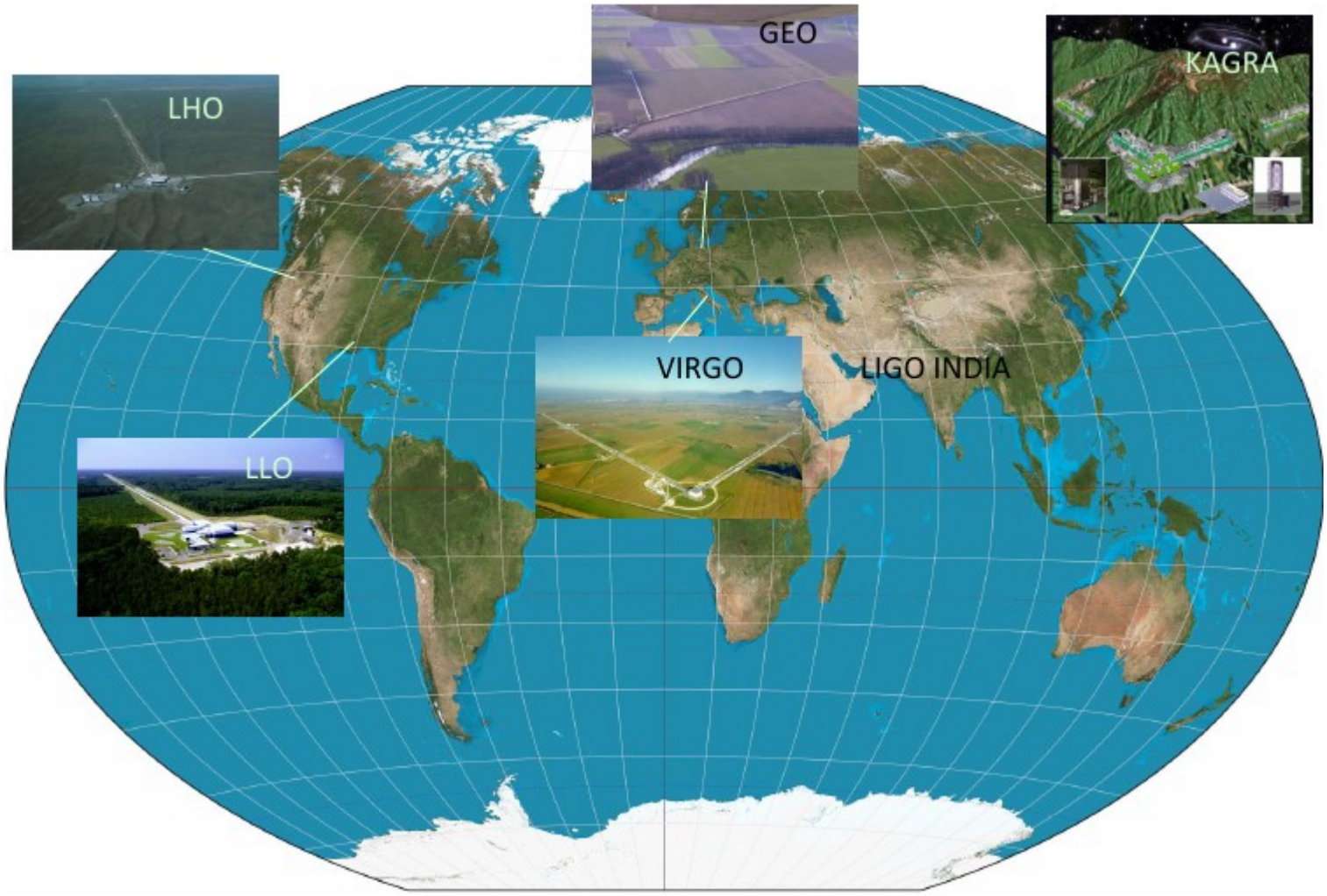
Radio Waves



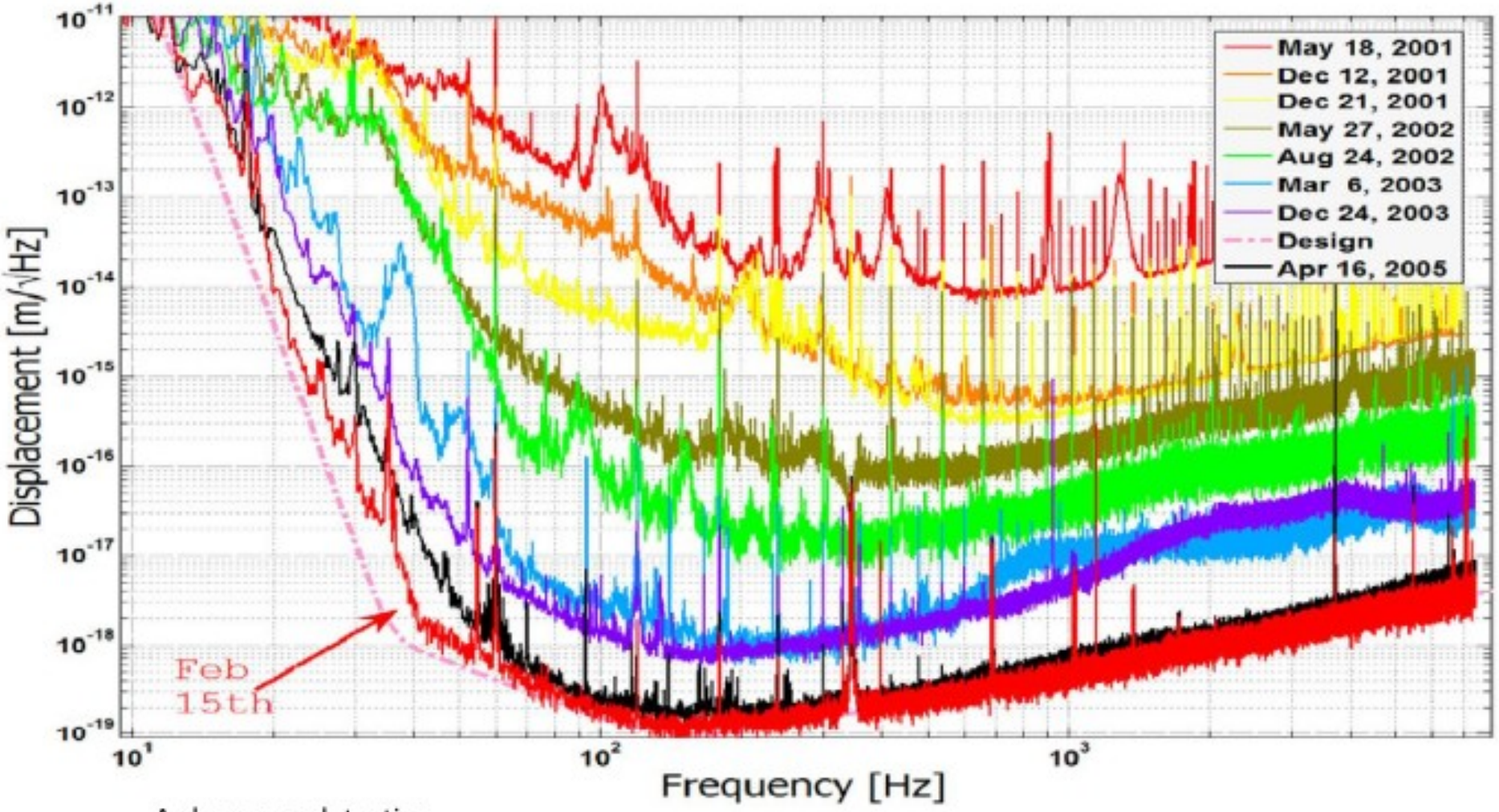
Neutrinos

Advanced LIGO Fabry-Perot Michelson Interferometer Schematic

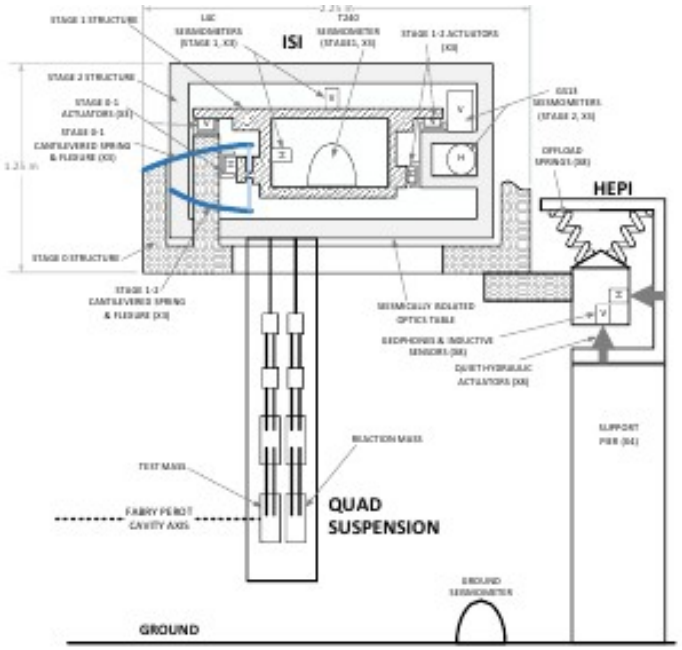


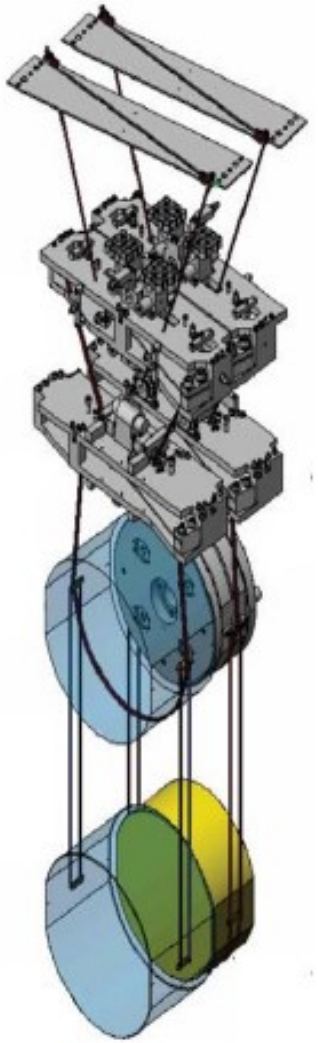

LHO
GEO
KAGRA
VIRGO
LIGO INDIA
LLO

Evolution of the initial detector 2001 - 2006

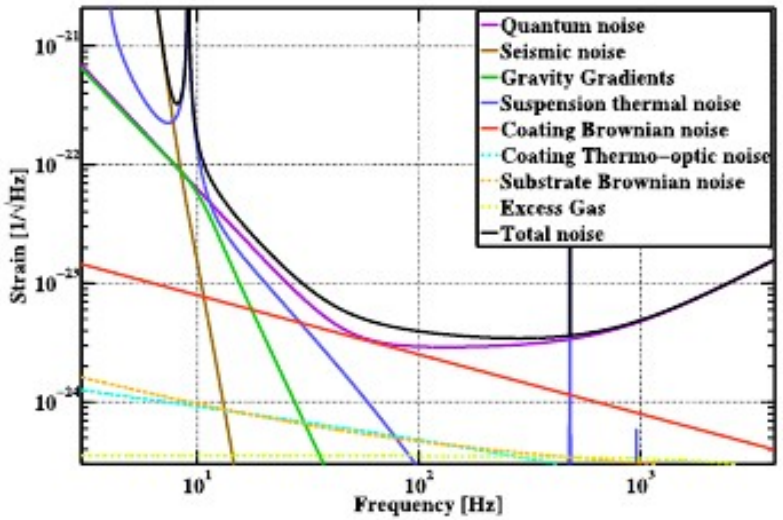


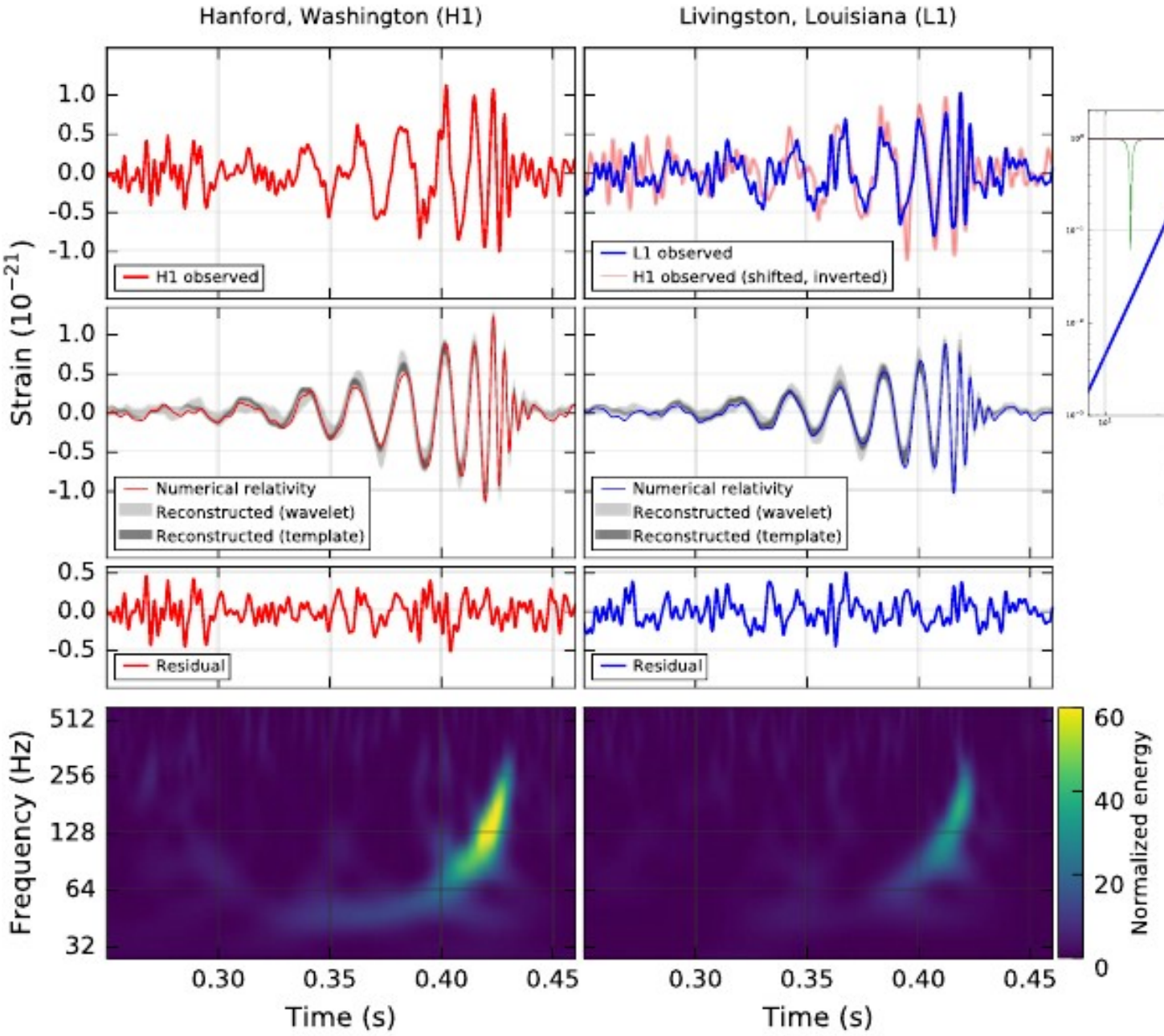
A clean non-detection

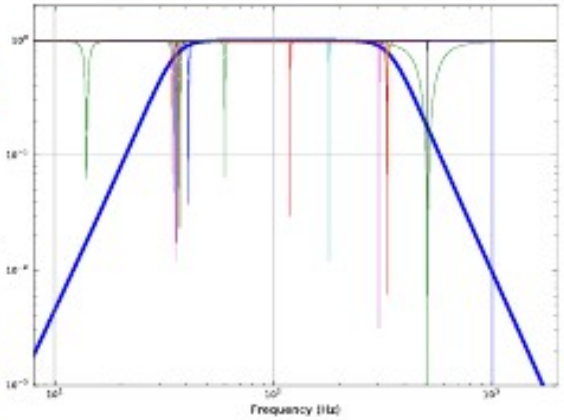




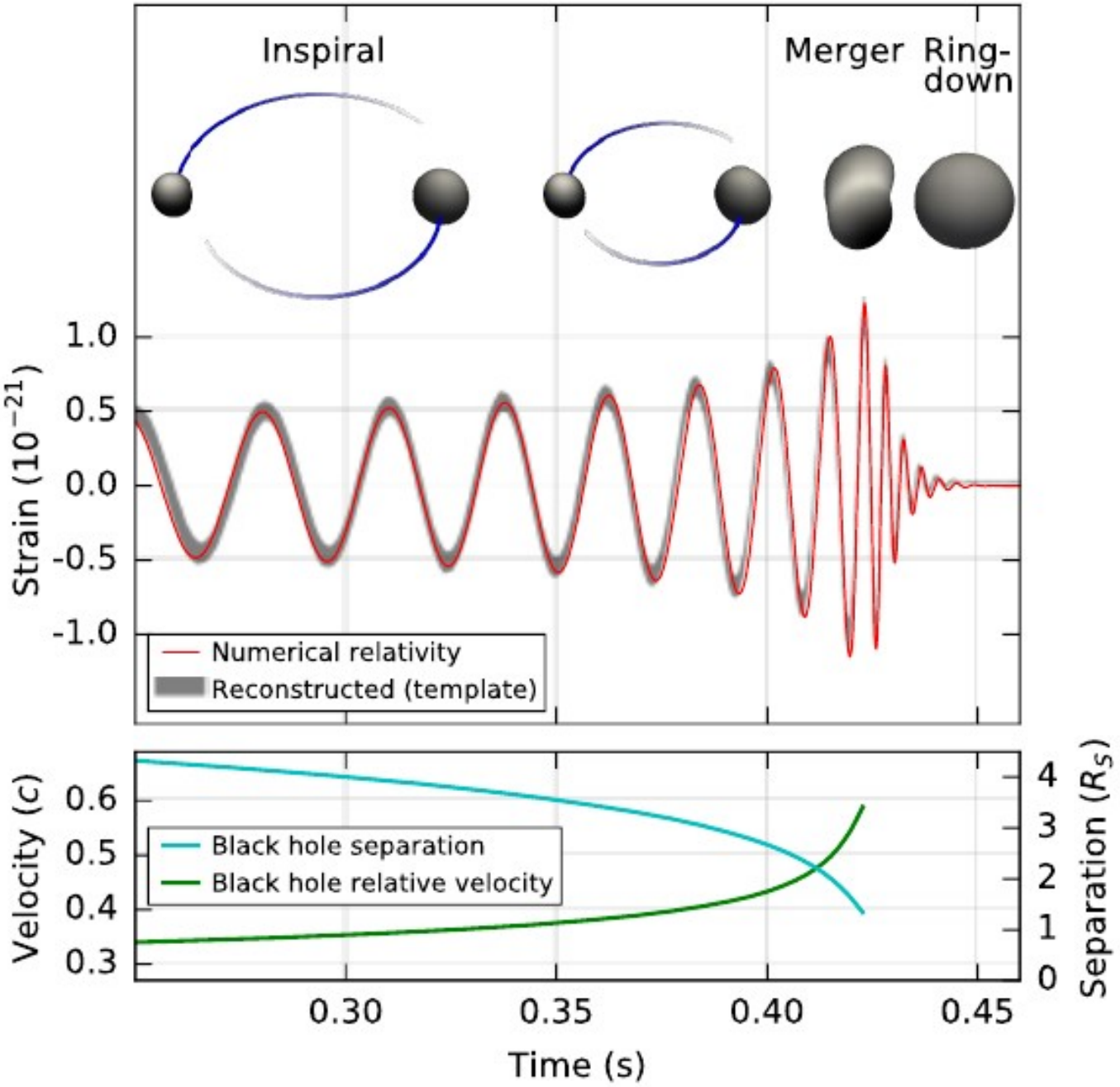
Advanced LIGO design noise budget



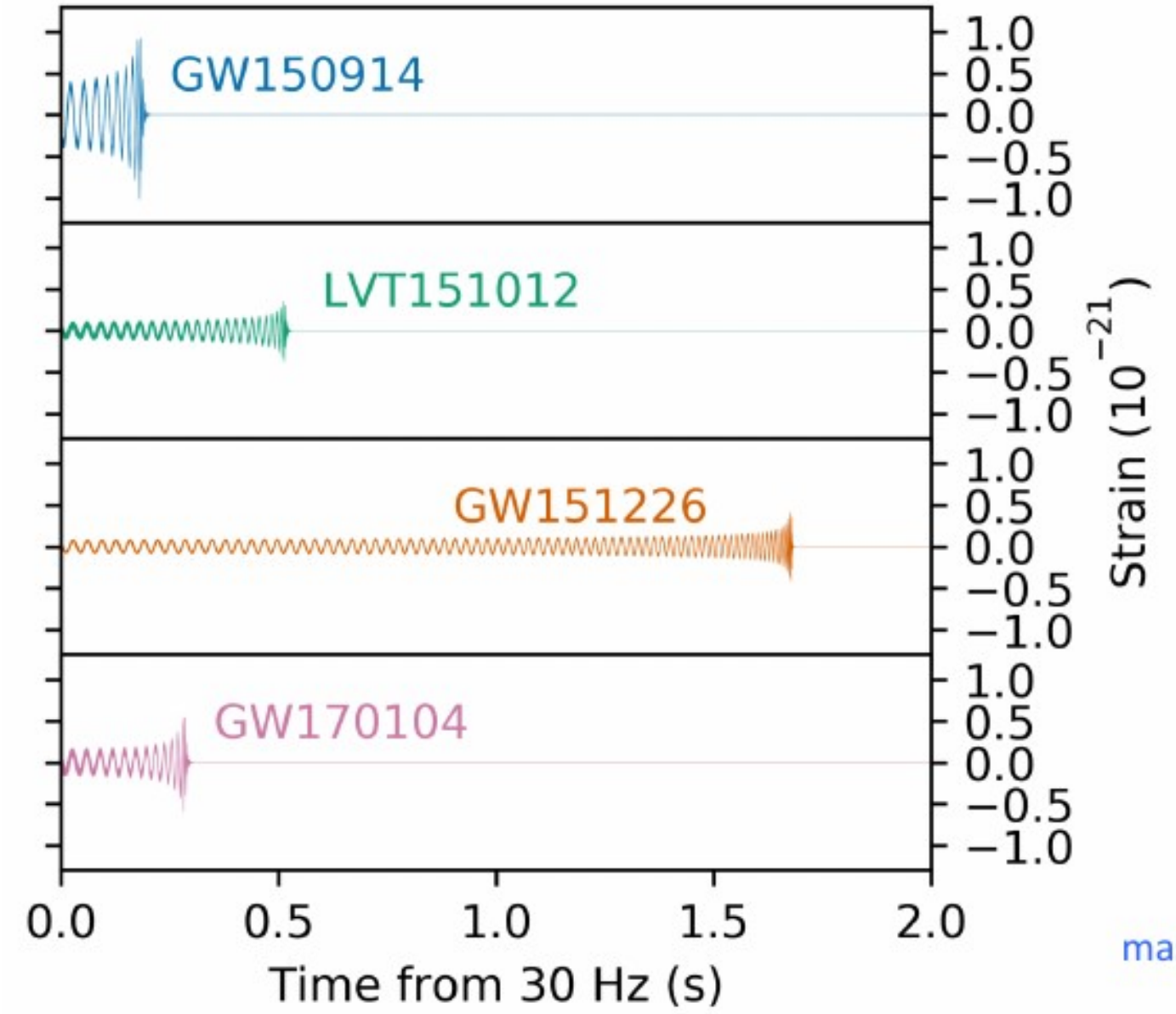




Simple high-low pass filter with notches


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

Results of O1 and O2 run announced June 1, 2017



m1=36, m2= 29, Δm=3

if at 1 au

$h \sim 10^{-6}$

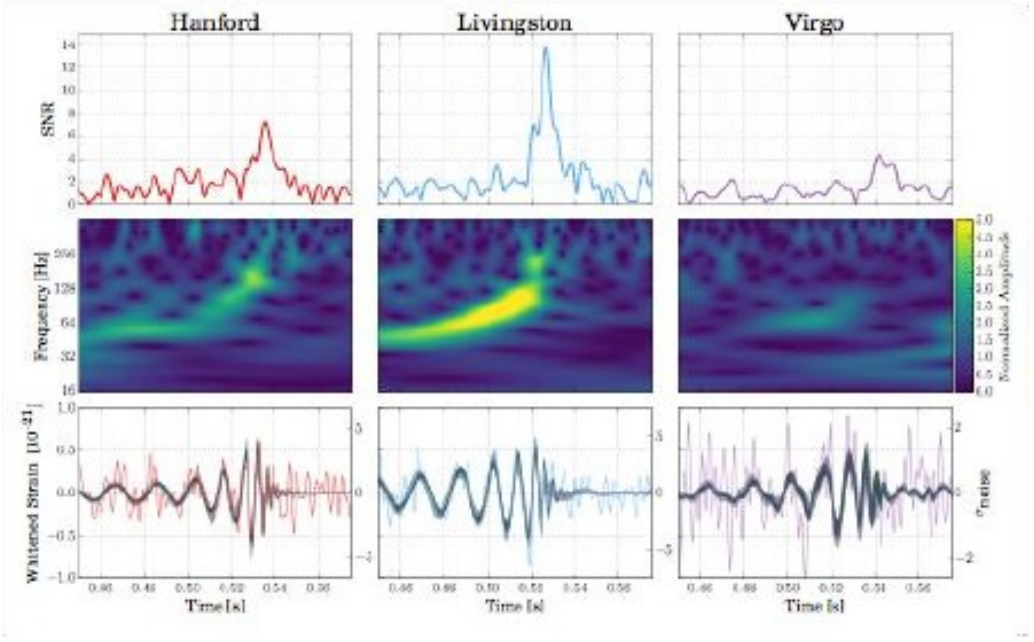
$I_g \sim 10^{25}$ w/m^2

m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

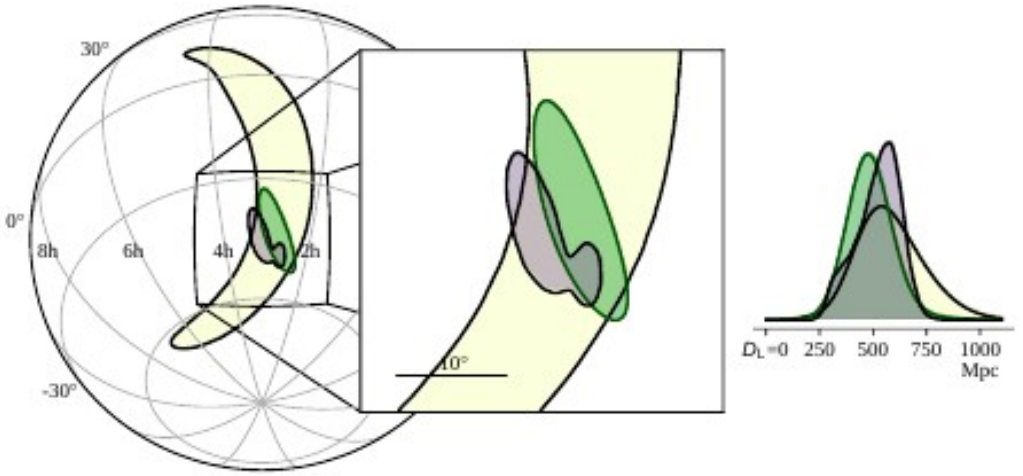
m1=31, m2= 19, Δm=2

masses in source frame

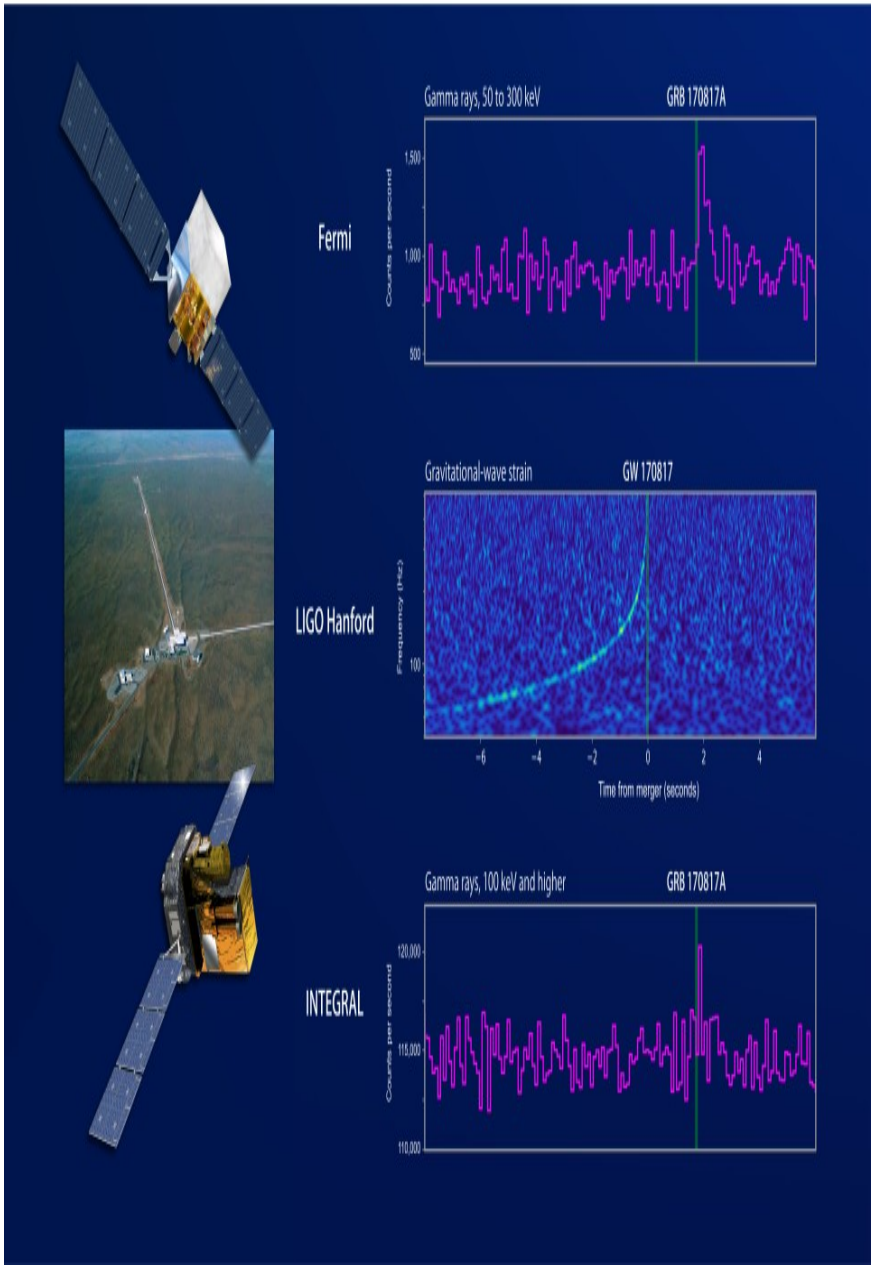


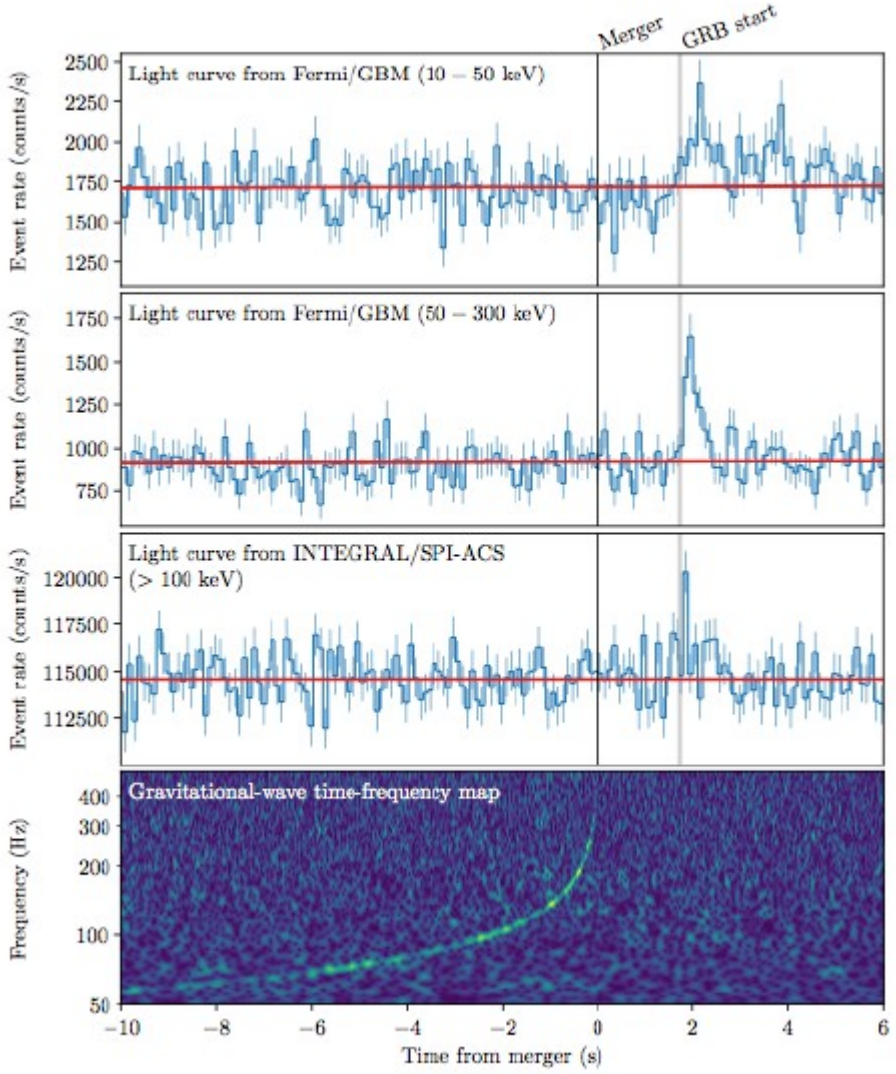
Triple coincidence
GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7



Localization on sky and distance

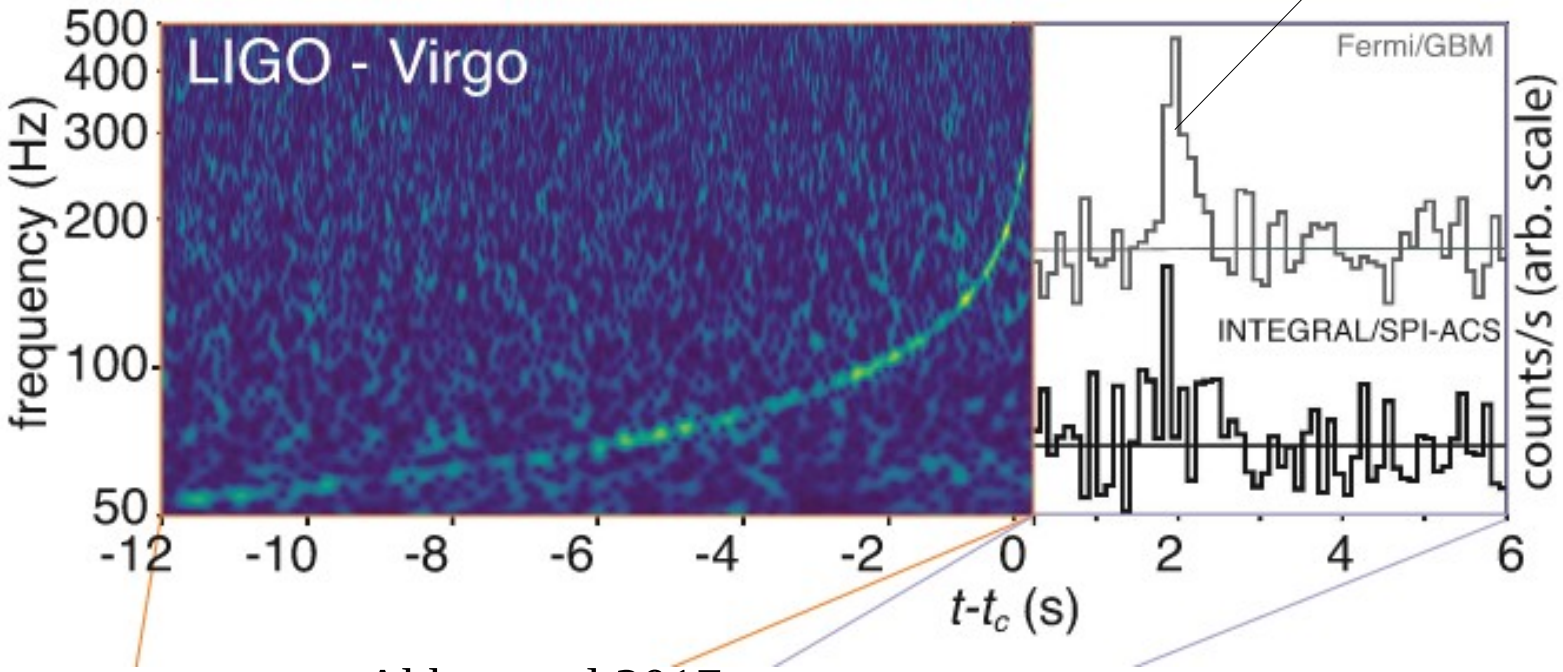

Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO Hanford
Gravitational-wave strain
GW 170817
Frequency (Hz)
100
−6
−4
−2
0
2
4
Time from merger (seconds)
INTEGRAL
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000


Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Light curve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Light curve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

Onde gravitazionali

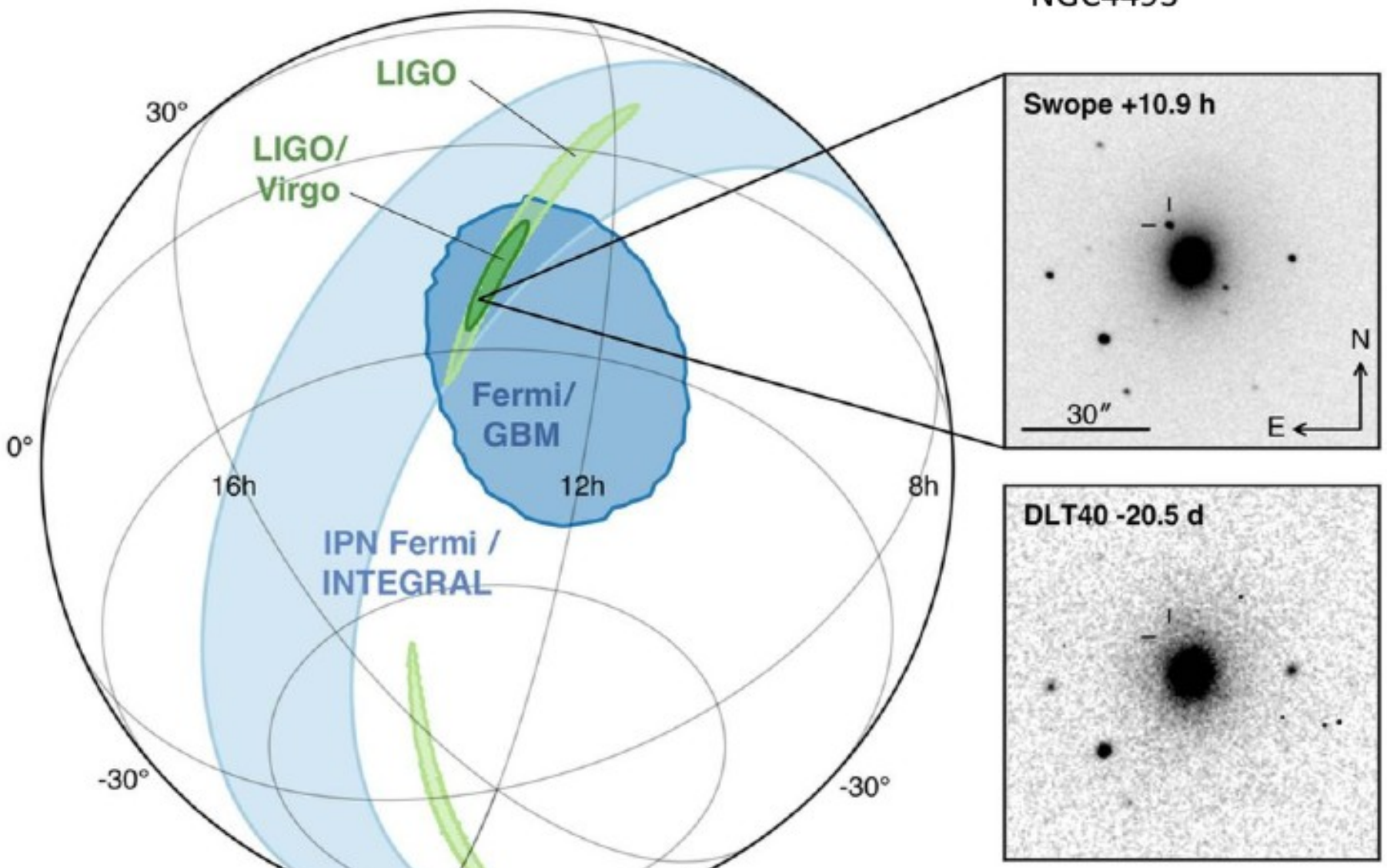
Lampo gamma corto!

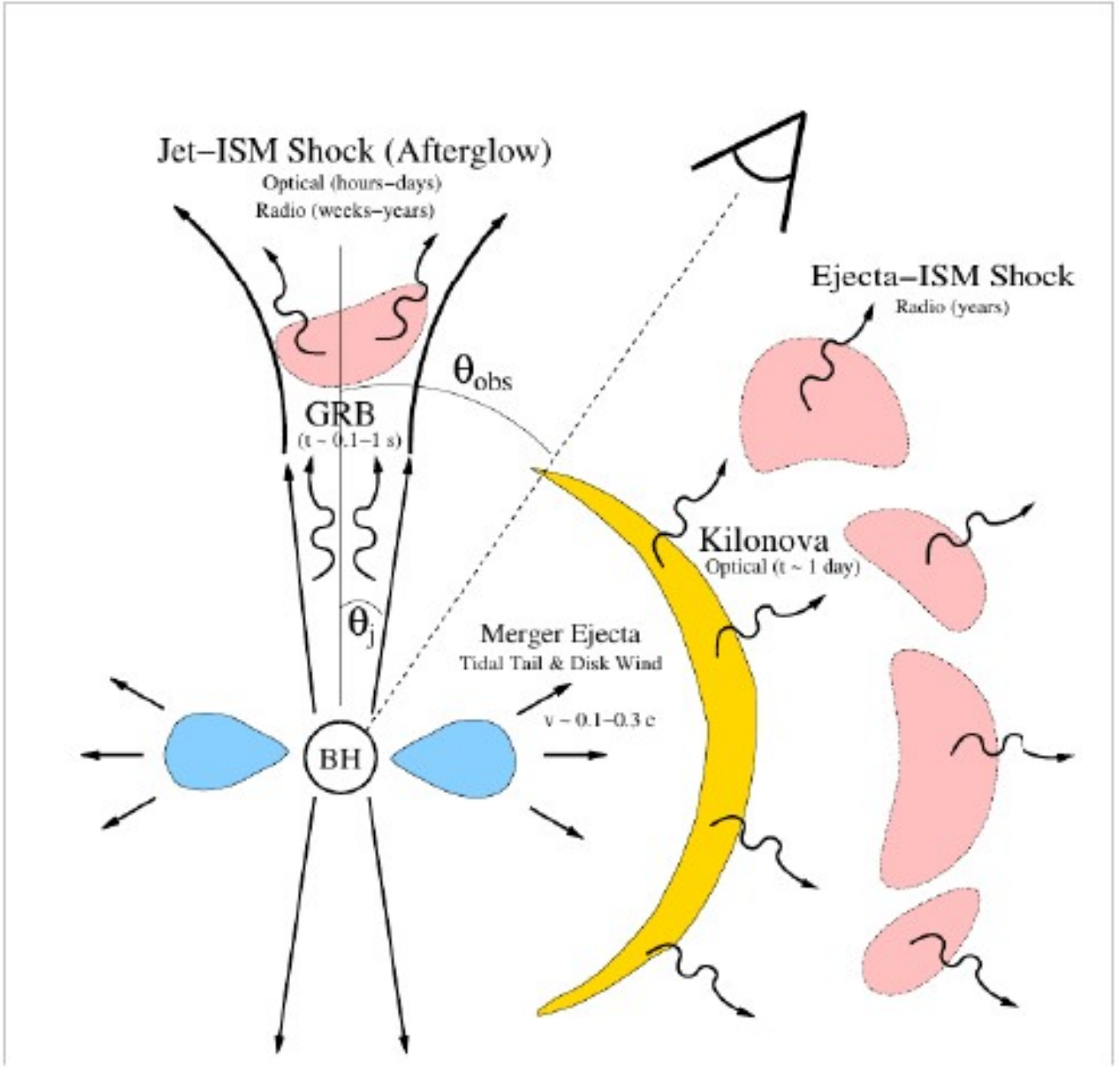
Doppia stella di neutroni



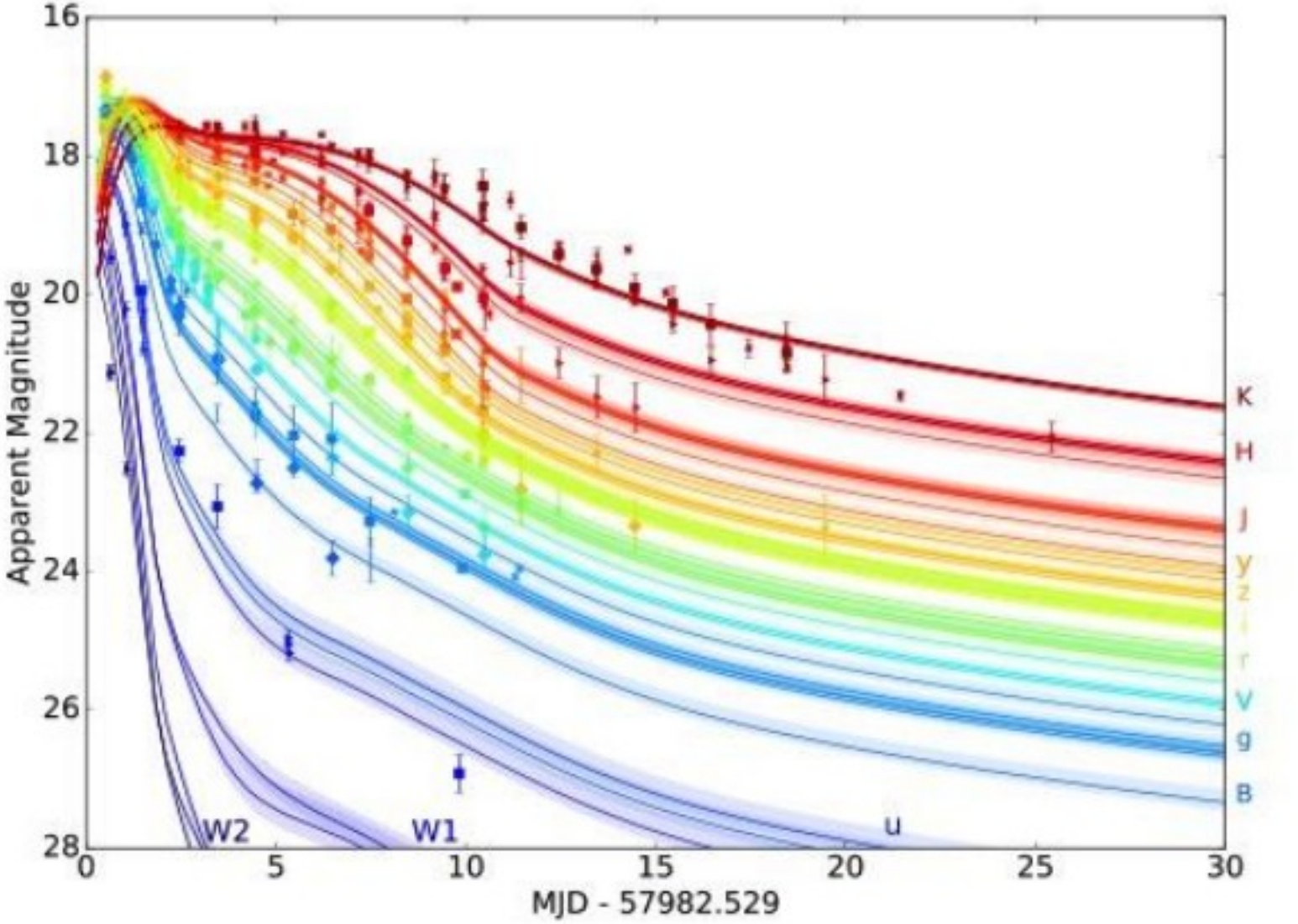
Abbot et al 2017 (il Mondo! Ottico, Radio, ...)

"For the first time, gravitational and electromagnetic waves from a single source have been observed. […] and mark a new era in multi-messenger"


NGC4493
LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
16h
12h
8h
-30°
Swope +10.9 h
N
E
30″
DLT40 -20.5 d

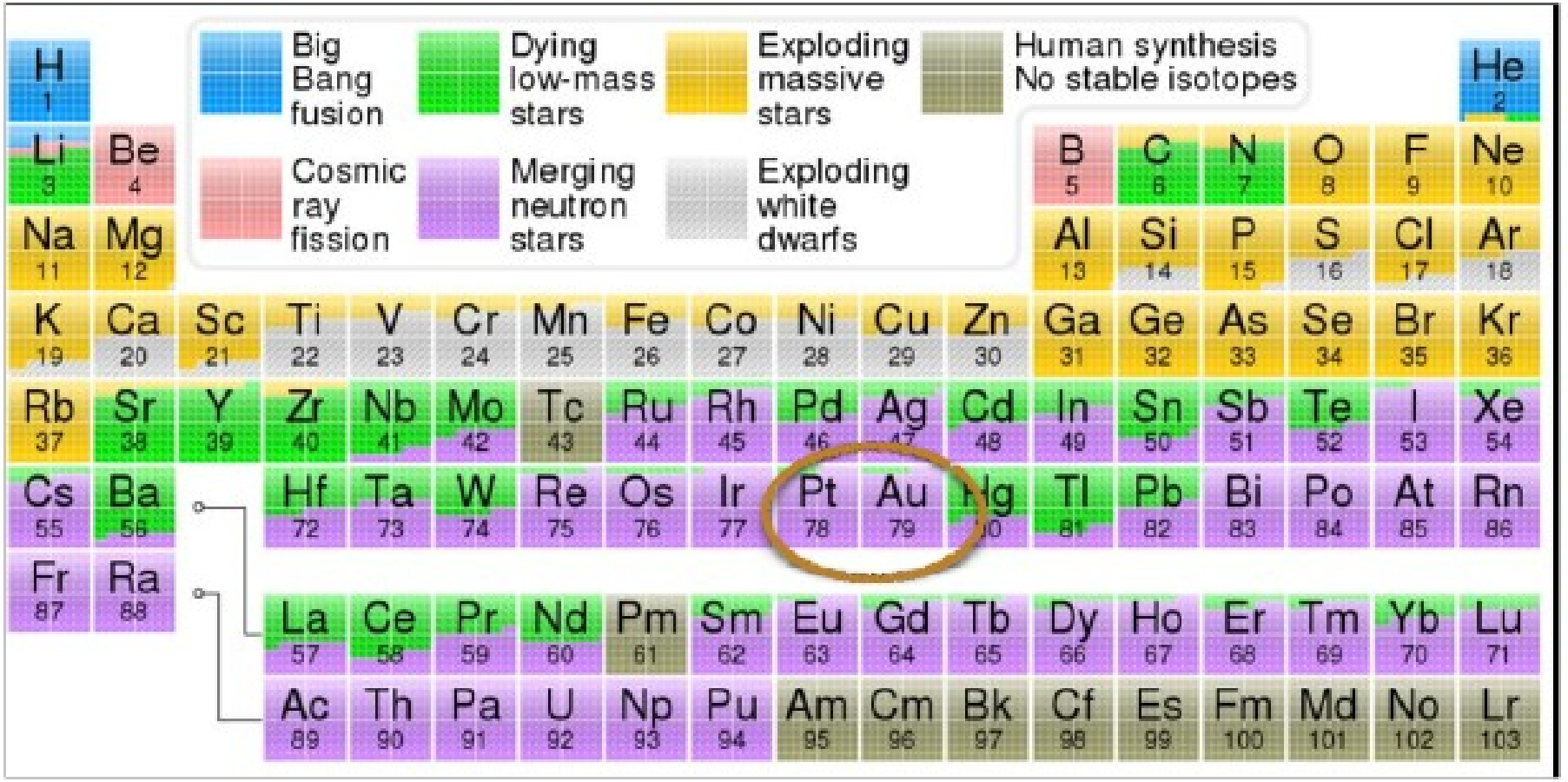

Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)
θobs
GRB
(t ~ 0.1–1 s)
θj
BH
Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c
Kilonova
Optical (t ~ 1 day)
Ejecta–ISM Shock
Radio (years)

Broad band kilonova spectra vs time

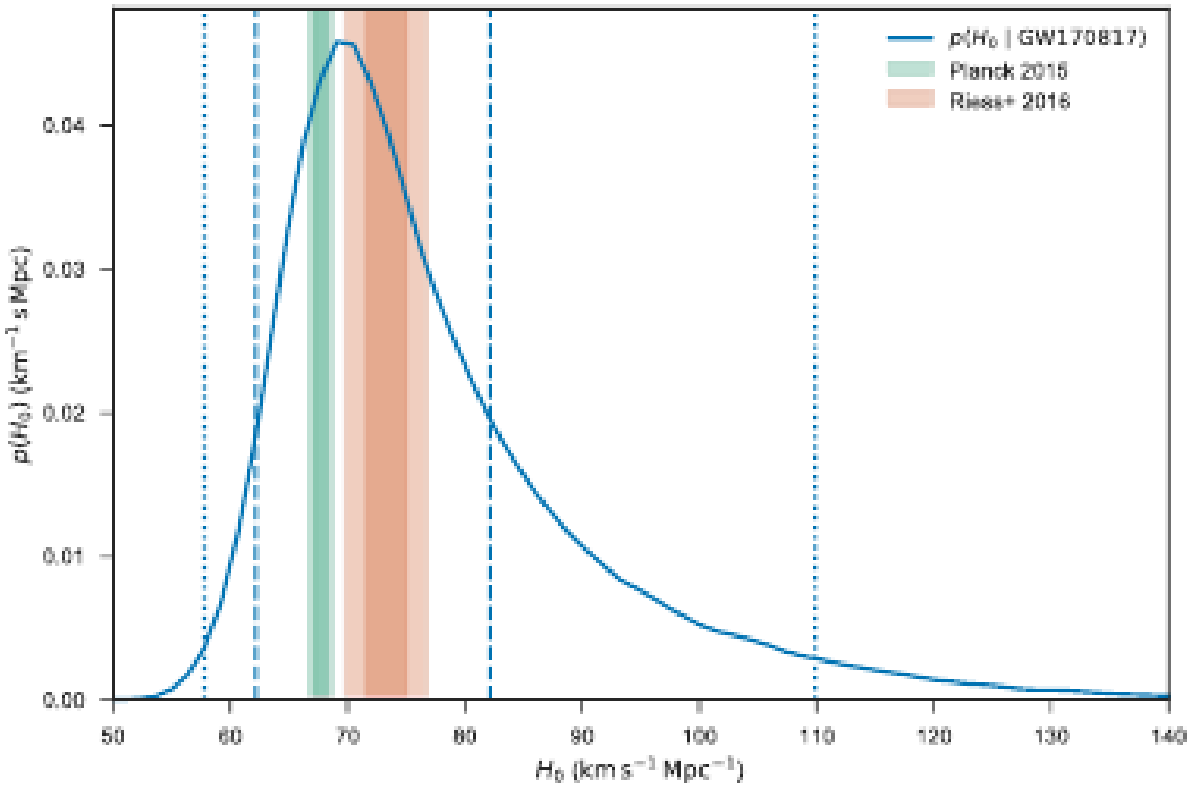


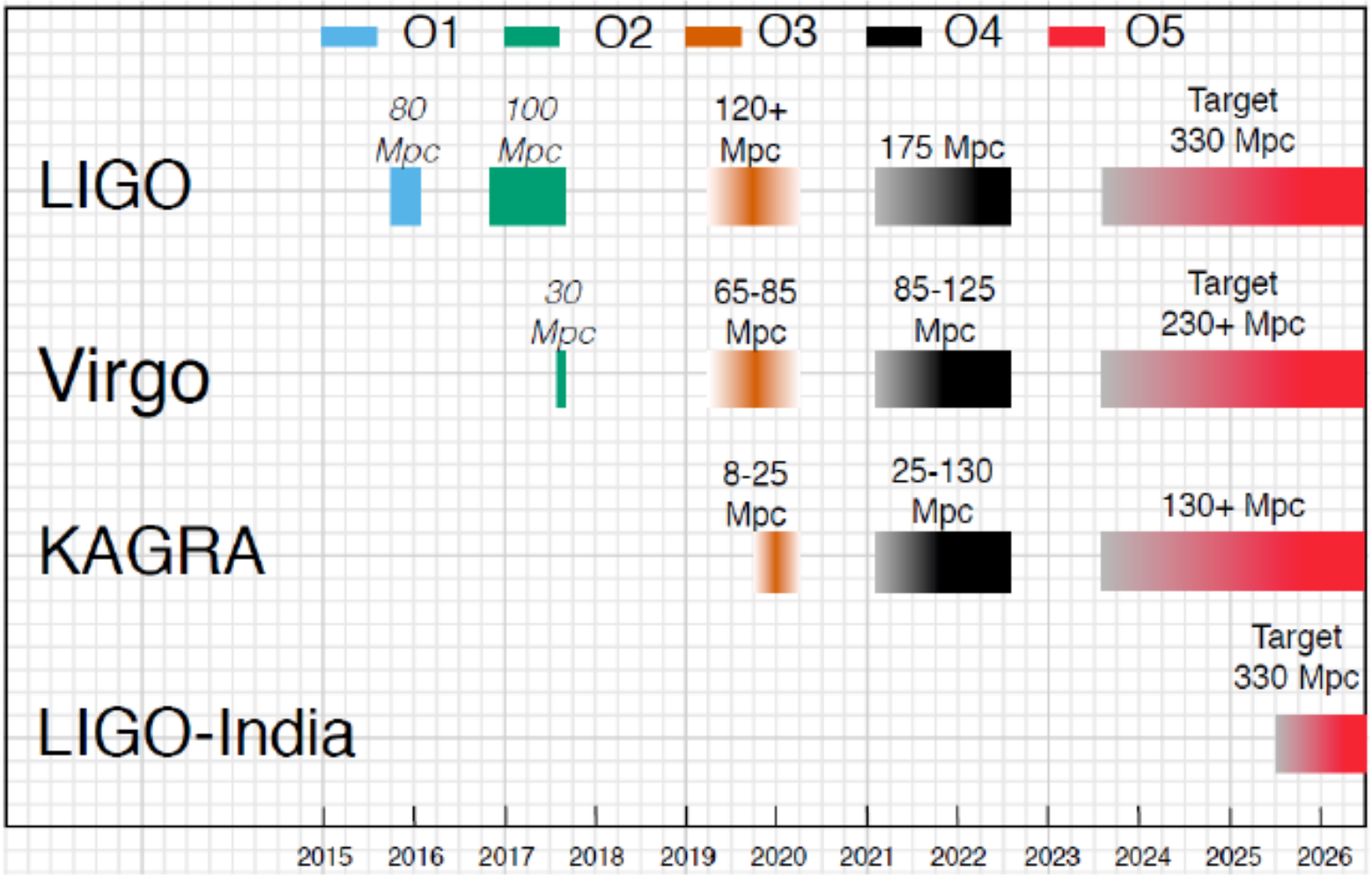
Villar et al arXiv astroph 1710.11576

Origin of the elements

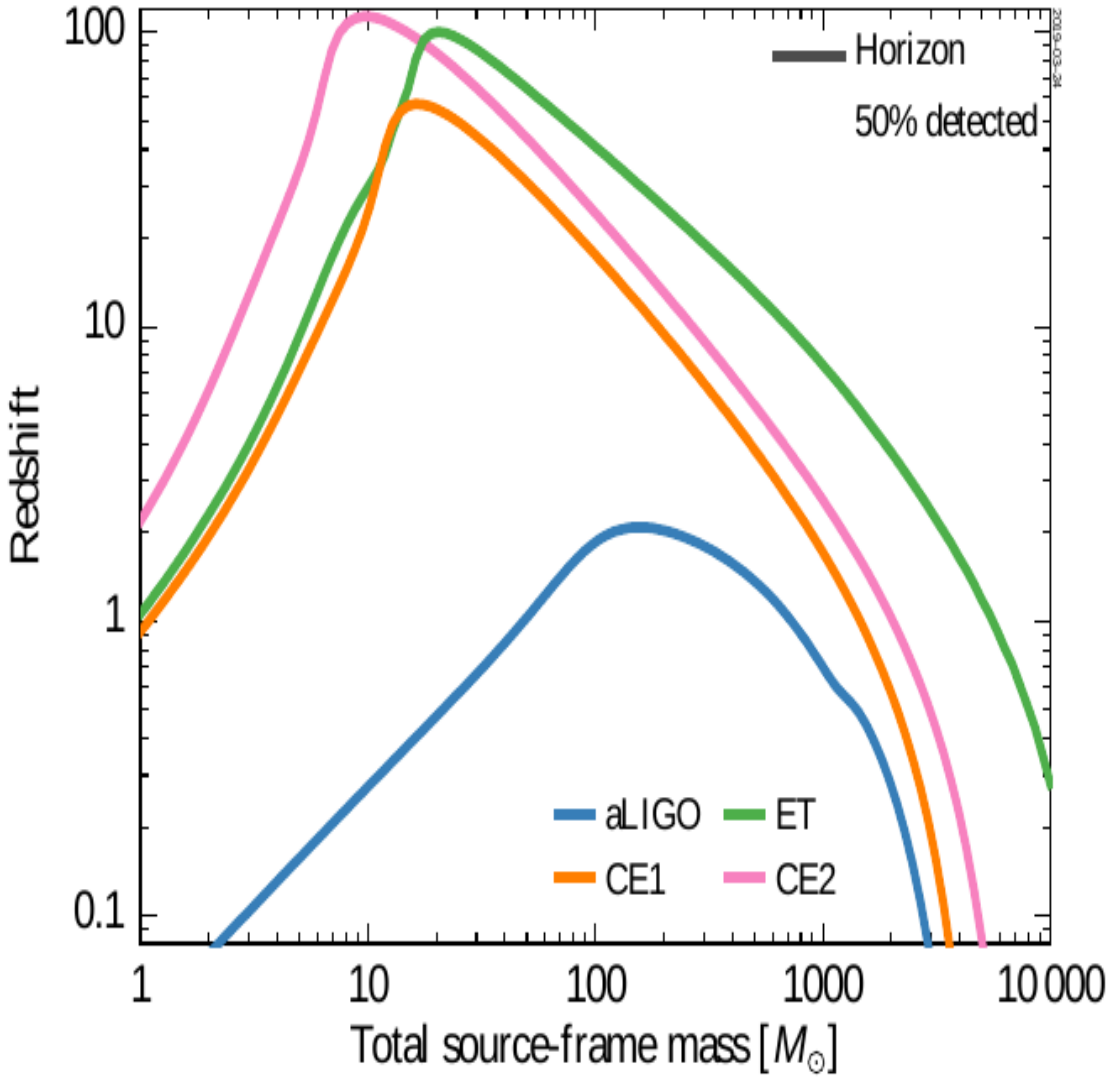


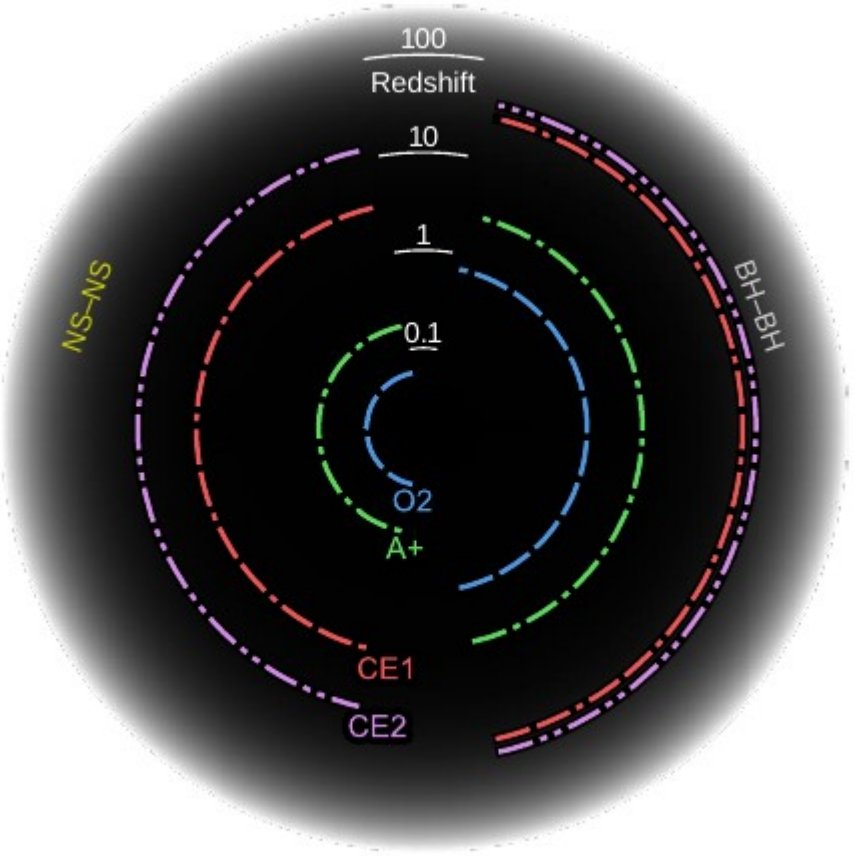
Hubble constant measurement: Galaxy z and distance from GW amplitude




O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
120+ Mpc
175 Mpc
Target 330 Mpc
Virgo
30 Mpc
65-85 Mpc
85-125 Mpc
Target 230+ Mpc
KAGRA
8-25 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

R. Flaminio


Horizon
50% detected
aLIGO
ET
CE1
CE2
Redshift
Total source-frame mass [$M_\odot$]
100
10
1
0.1
1
10
100
1000
10 000


100
Redshift
10
1
0.1
NS–NS
BH–BH
O2
A+
CE1
CE2

age of universe years hours minutes 1/10 to 1/1000 sec