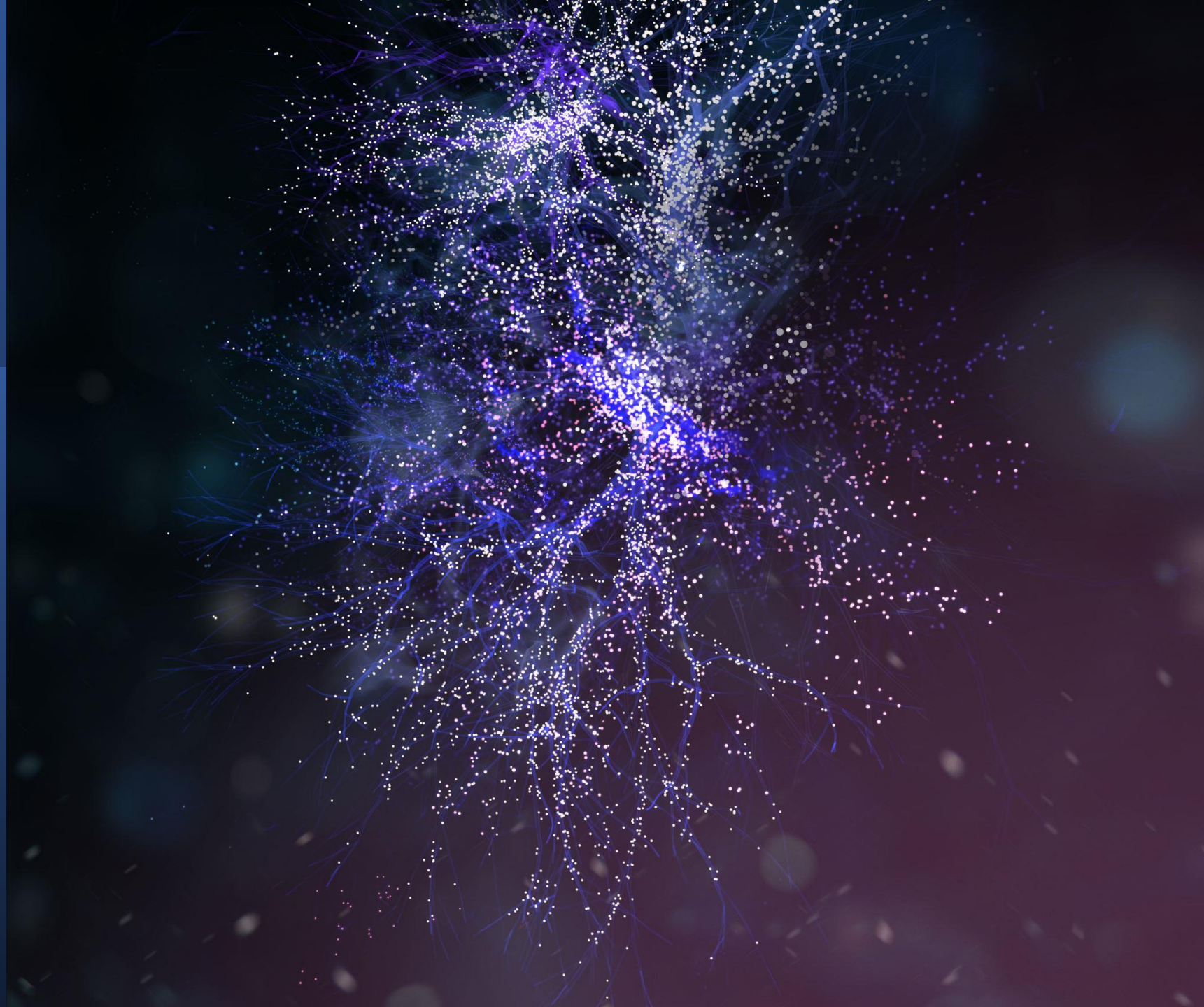
Marco Drago

La Sapienza Rome University

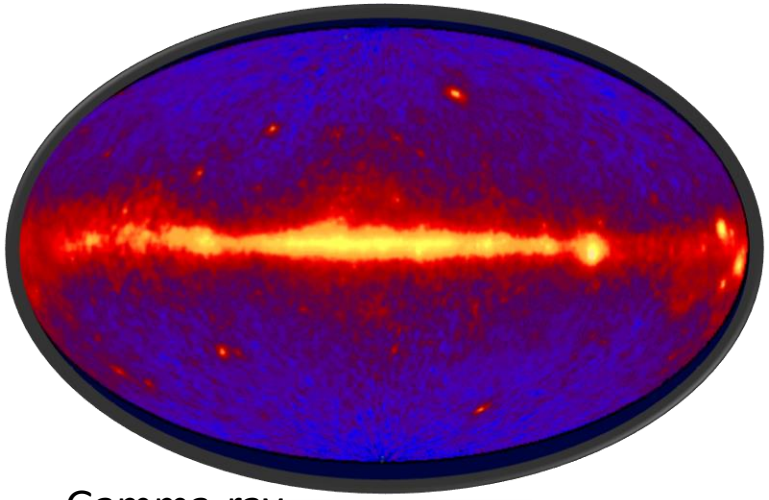
INFN Roma

Surfing the Universe

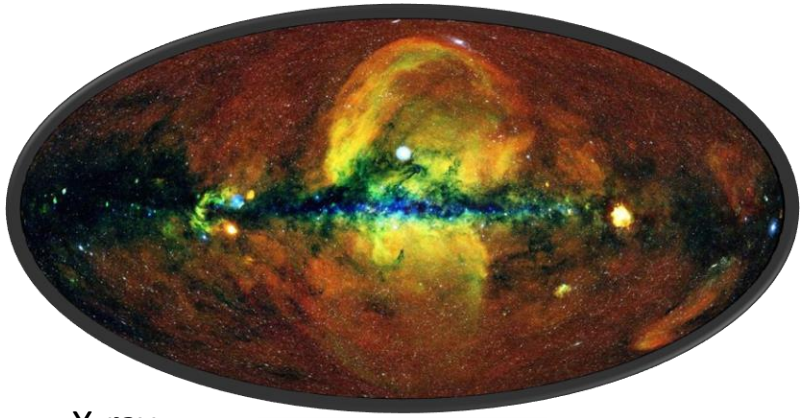
Starting the Multi-Messenger Era



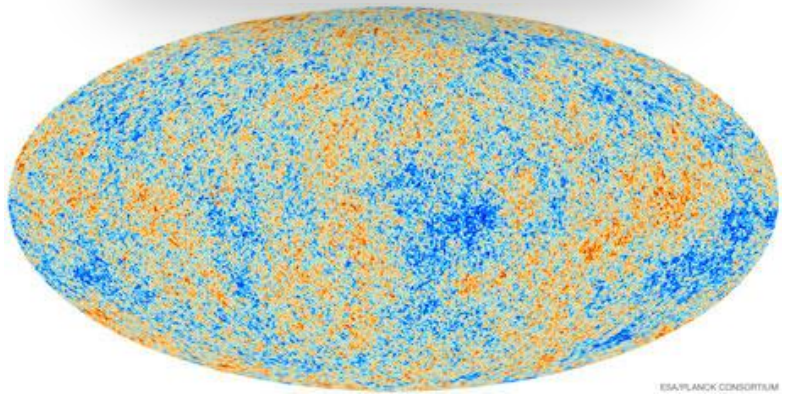
Why?



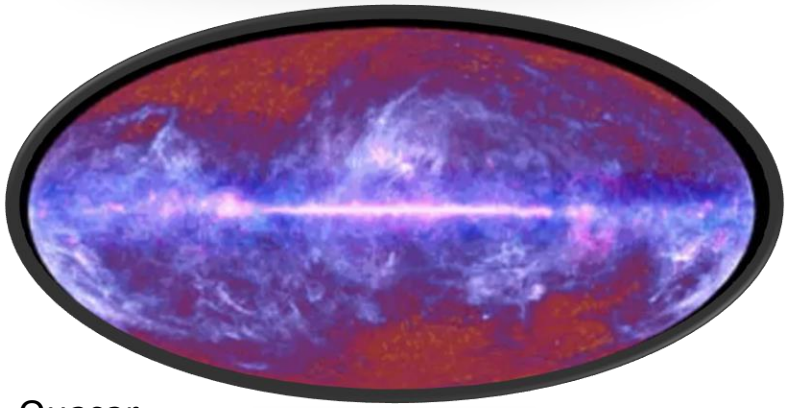
Gamma-ray



X-ray



Microwave



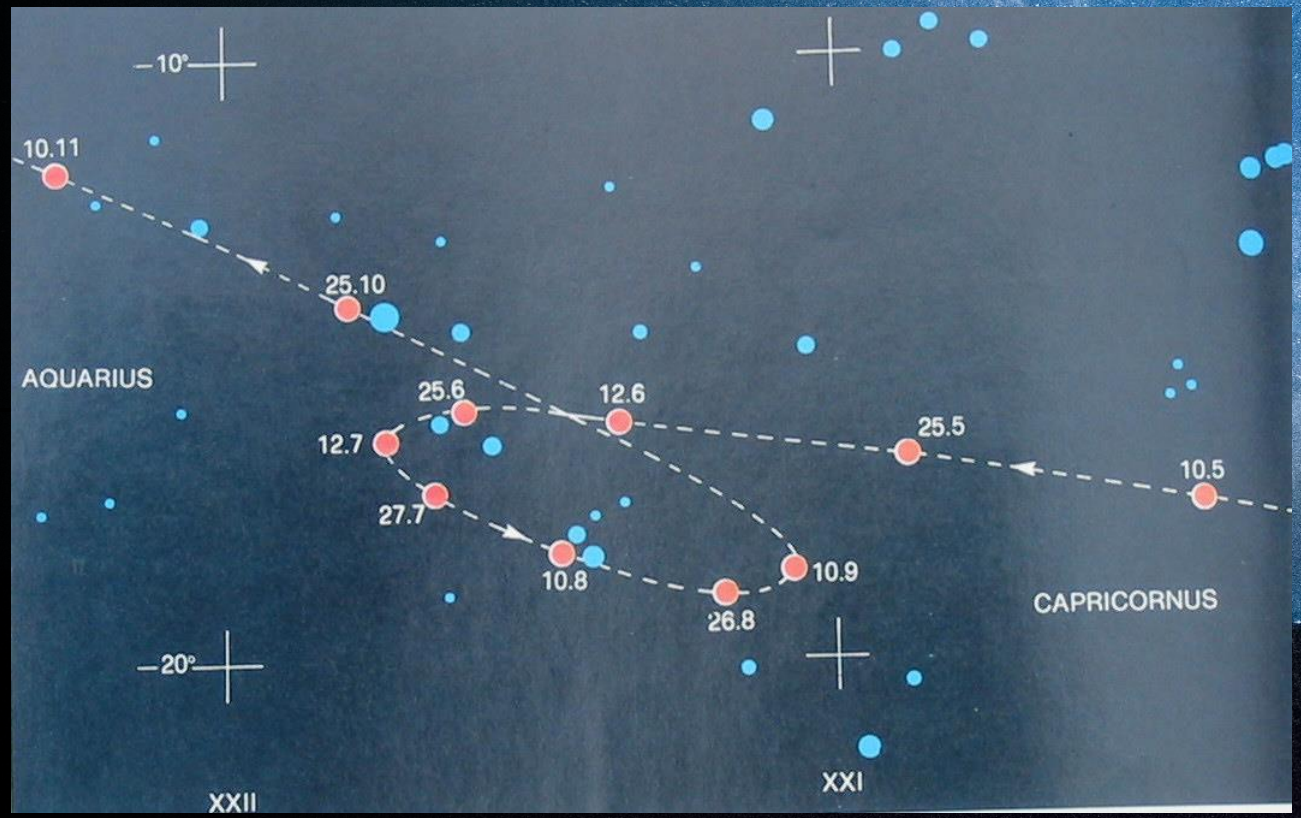
Quasar

Who?

Photons

The beginning of Astronomy

The beginning of Astronomy



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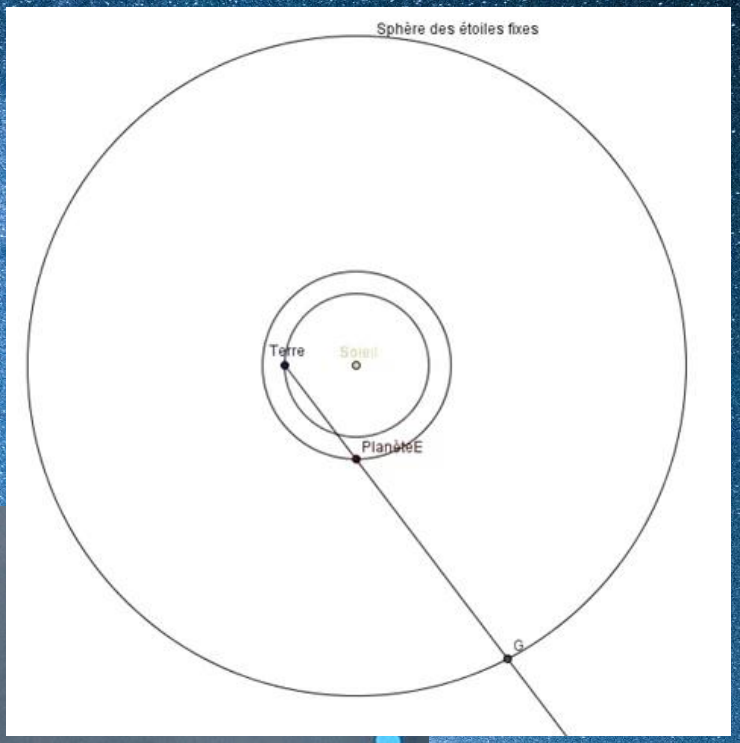
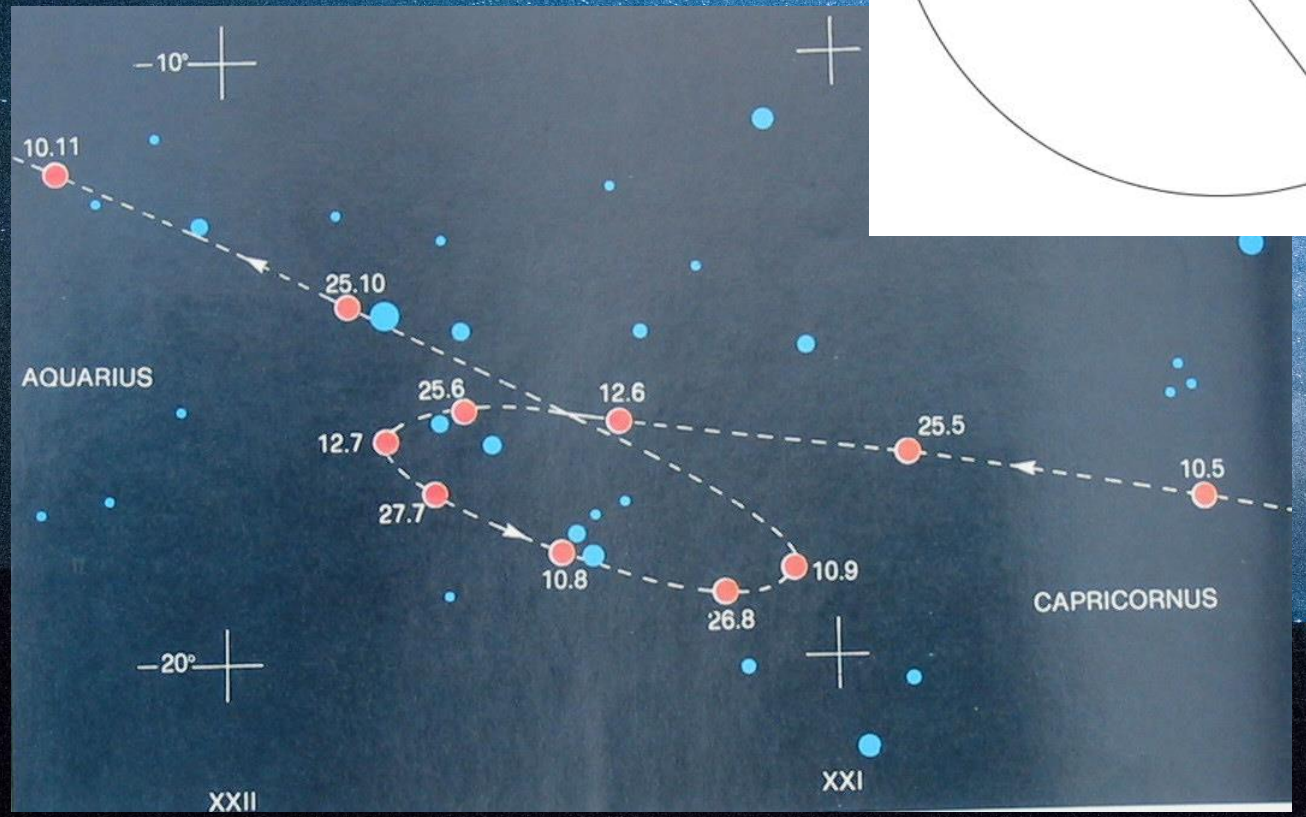

Sphère des étoiles fixes
Terre
Soleil
Planète
G


−10°
10.11
25.10
AQUARIUS
25.6
12.6
12.7
25.5
10.5
27.7
10.8
10.9
26.8
CAPRICORNUS
−20°
XXII
XXI

1600: has the brilliant idea of looking the sky with a telescope

Galileo breakthrough

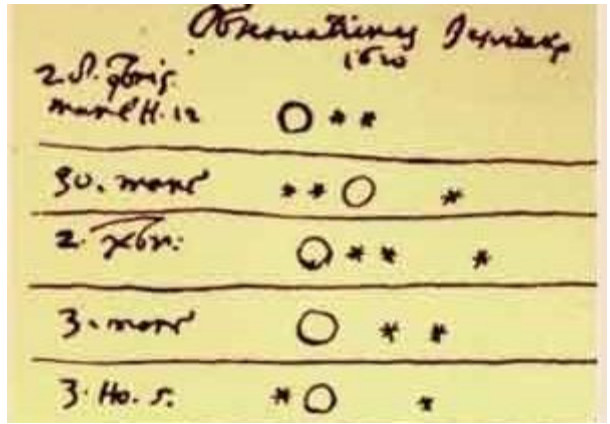
1600: has the brilliant idea of looking the sky with a telescope

The imperfect moon

Galileo breakthrough

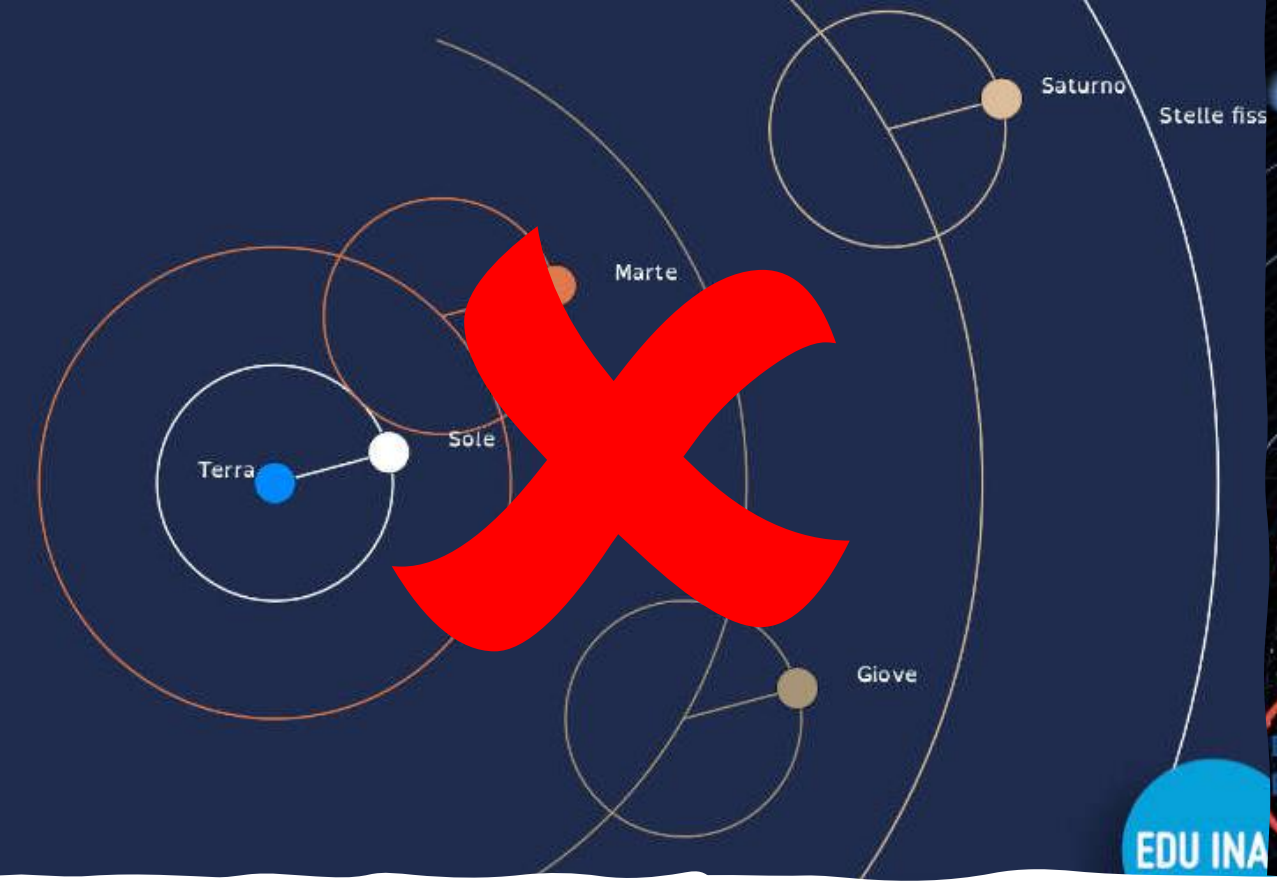
1600: has the brilliant idea of looking the sky with a telescope

The imperfect moon



Jupiter satellites

Galileo breakthrough



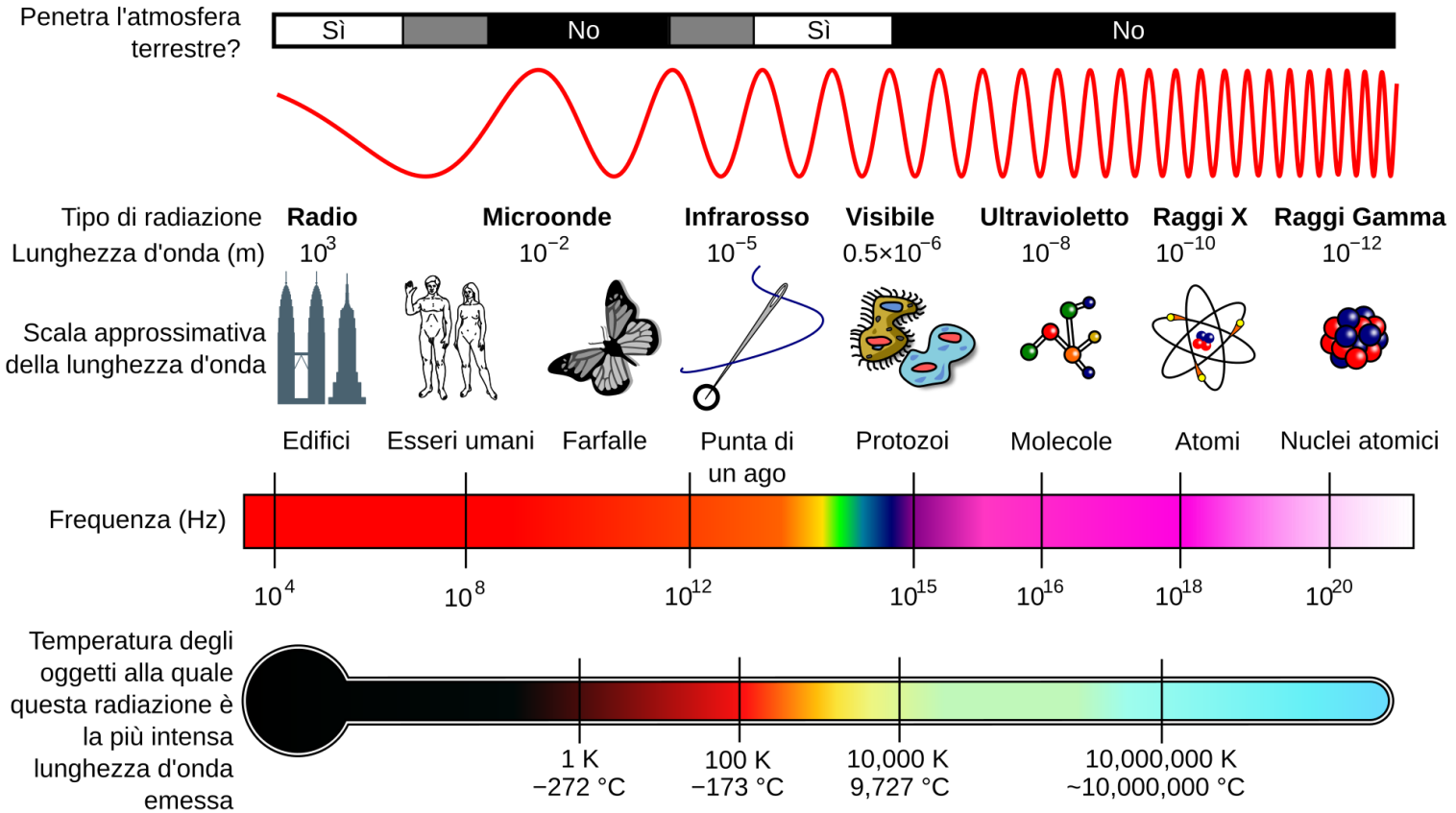
News view on the universe

What are we looking for?

Pink Floyd: The Dark Side of the Moon

What are we looking for?

Electromagnetic spectrum



Seeing the invisible


X-Ray, Uhuru


Radioastronomy, Very Large Array, New Mexico

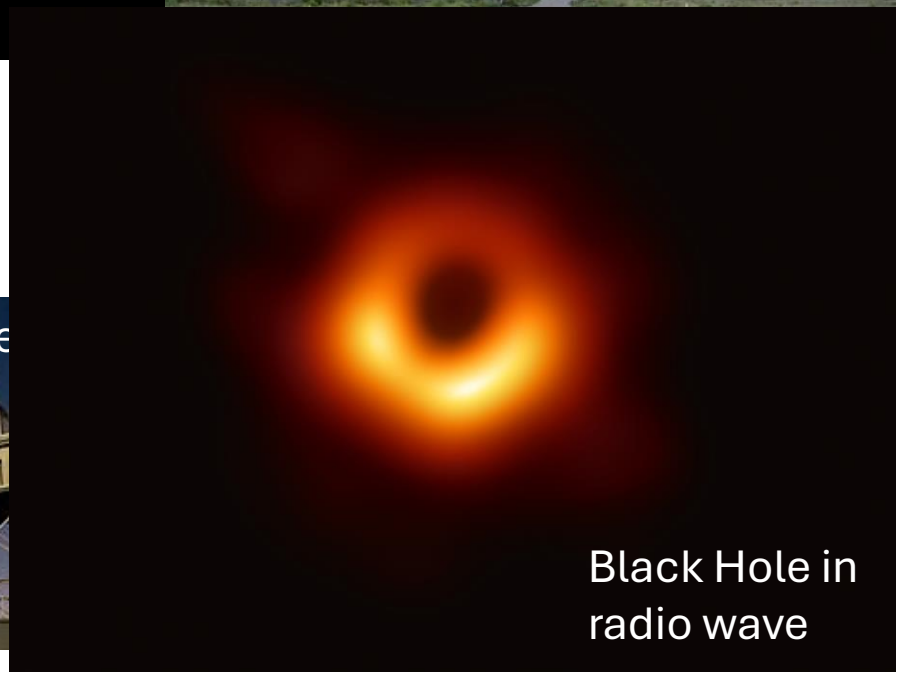

Cherenkov, CTA, La Palma, Cile

Seeing the invisible

Black Hole in visible light

X-Ray, Uhuru

Chere



Black Hole in radio wave

Neutrino

Neutrino

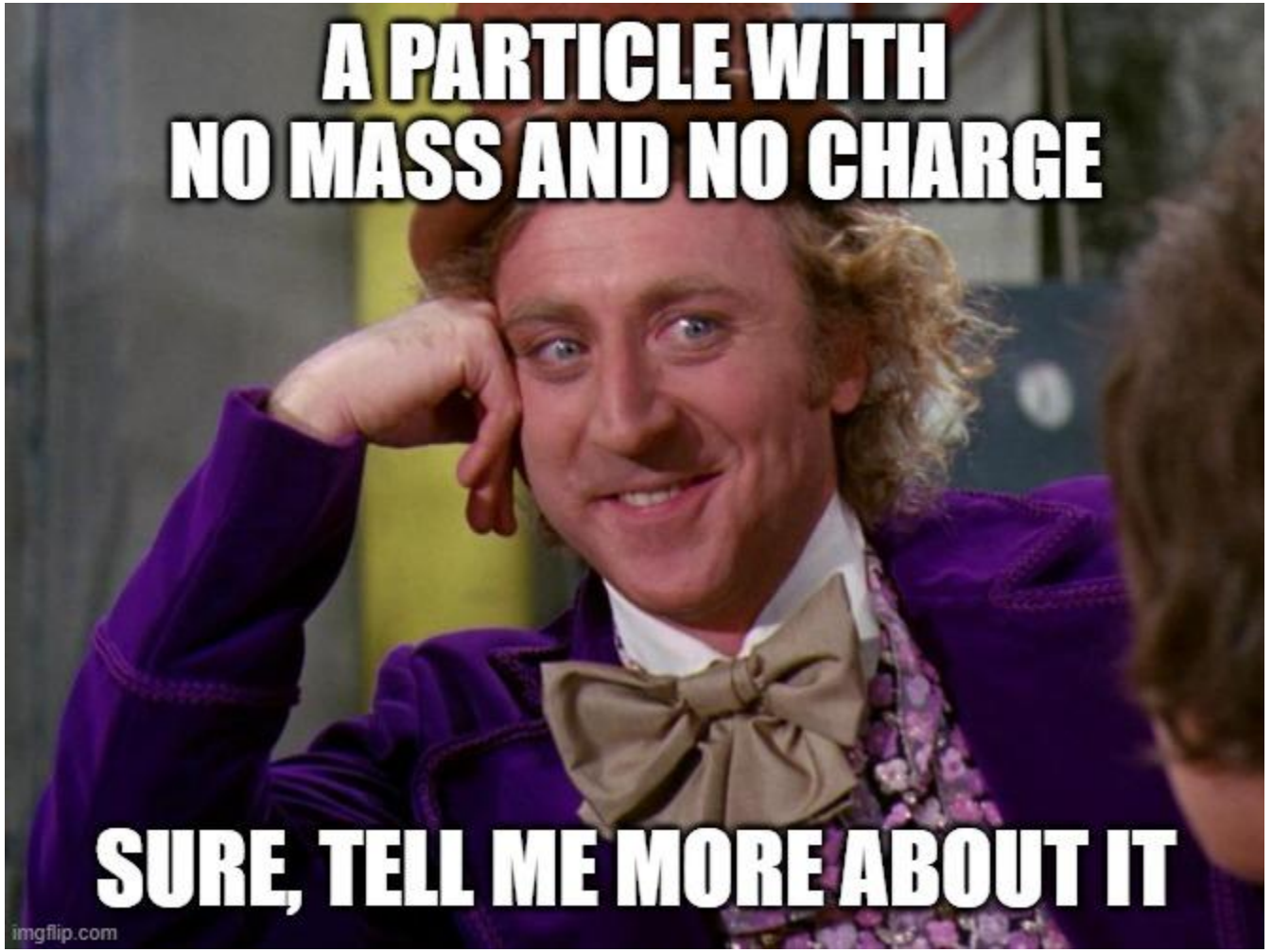
- Postulated from B-decay

$$p \rightarrow n + e^{+} + \nu_e$$

Neutrino

- Postulated from B-decay

$$p \rightarrow n + e^{+} + \nu_e$$

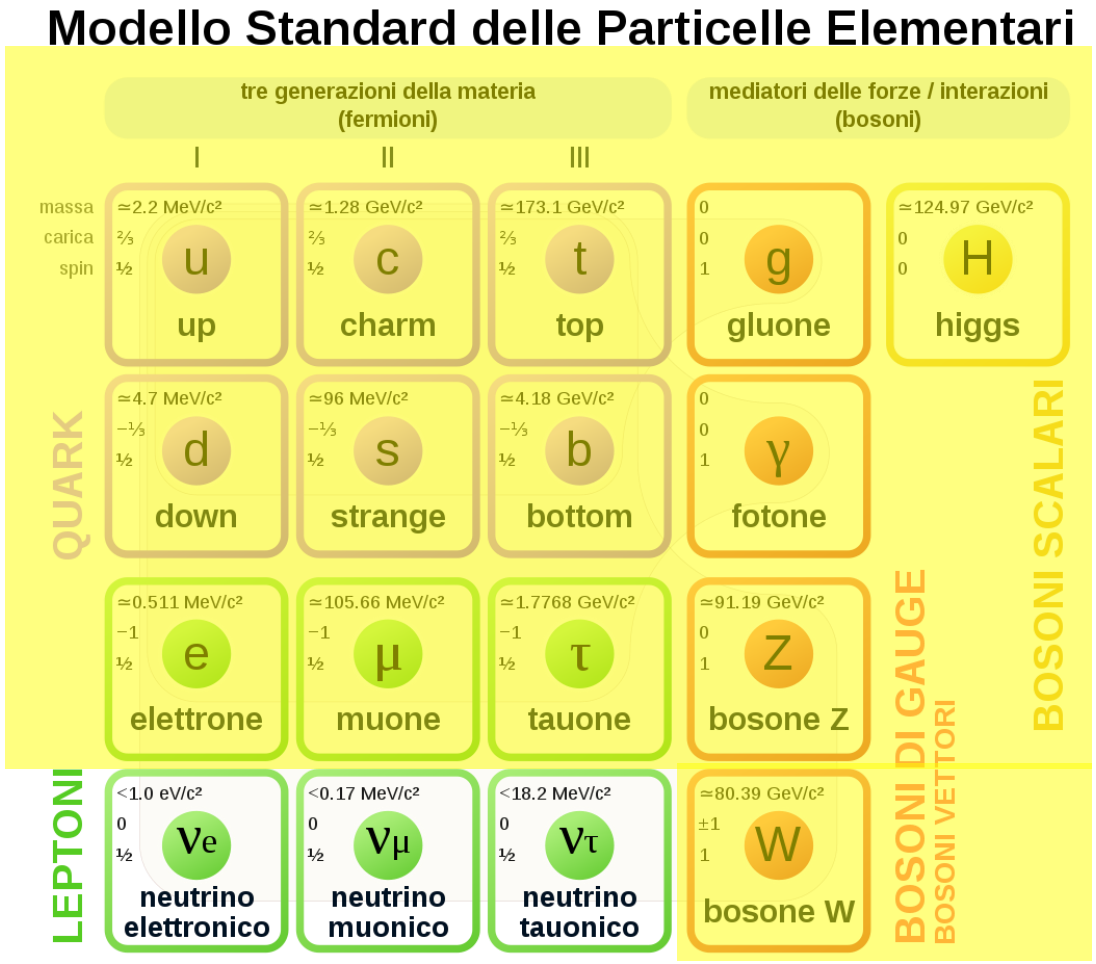


Neutrino

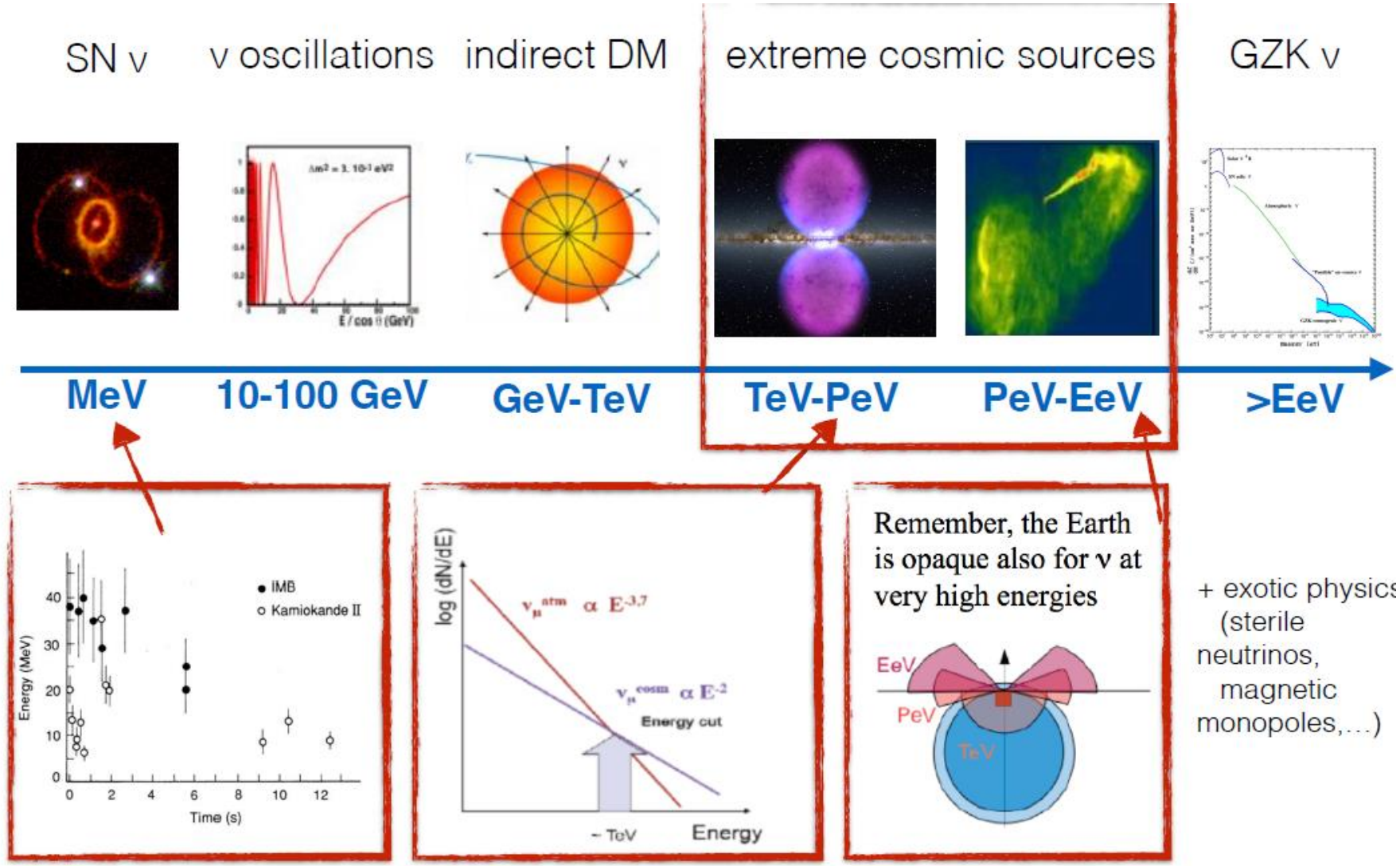
- Postulated from B-decay

$$p \rightarrow n + e^{+} + \nu_e$$

- Still open questions:
  - Oscillations and standard model?
  - Fermi or Maiorana Neutrino?



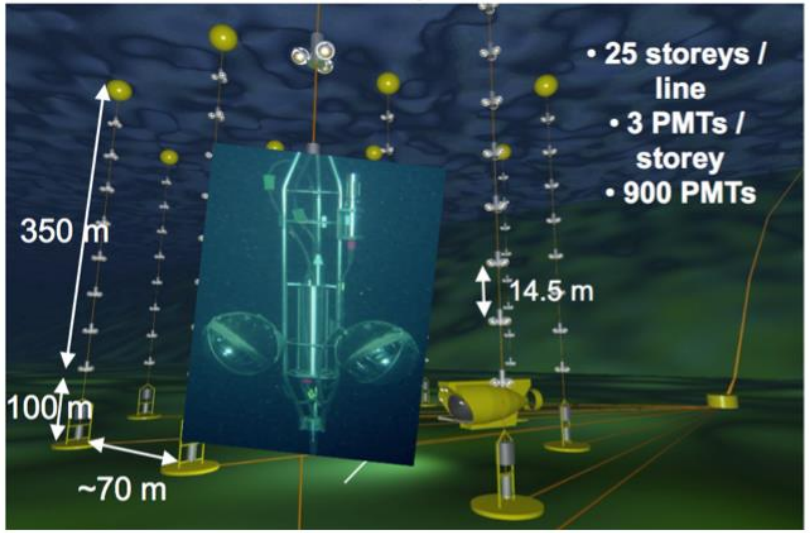
Scientific program of high neutrino telescope



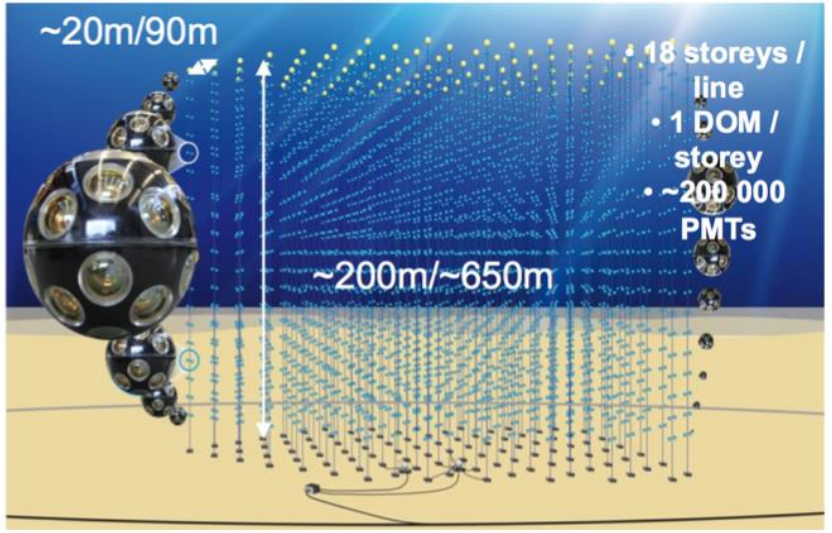
Credits: Silvia Celli

Neutrino telescope around the world

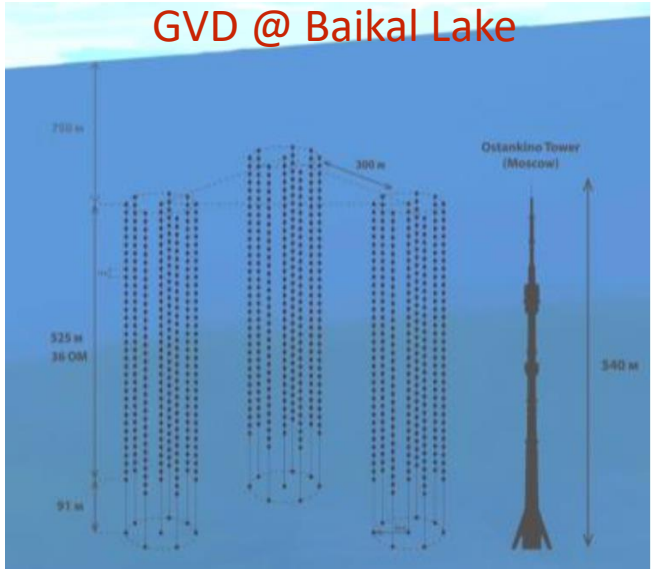
ANTARES



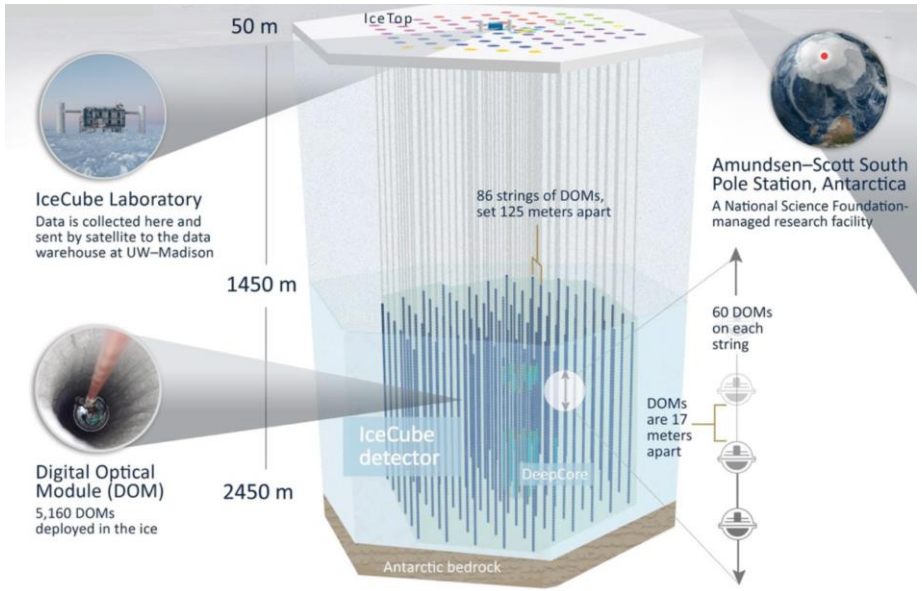
KM3NeT



GVD @ Baikal Lake



IceCube @ South Pole



Credits: Silvia Celli

Km3Net

Credits: Silvia Celli

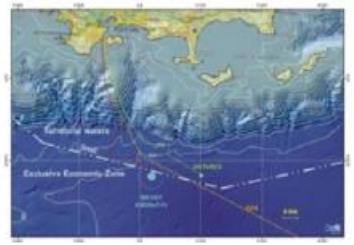
ARCA (1 GTon)

Astroparticle Research
with Cosmics in the Abyss

3500 m depth,
offshore Sicily

ORCA (6 MTon)

Oscillation Research
with Cosmics in the Abyss



2500 m depth,
offshore Toulon

Km3Net

Credits: Silvia Celli

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Astroparticle Research with Cosmics in the Abyss

3500 m depth, offshore Sicily

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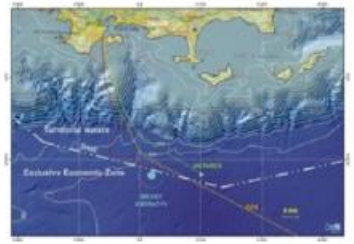
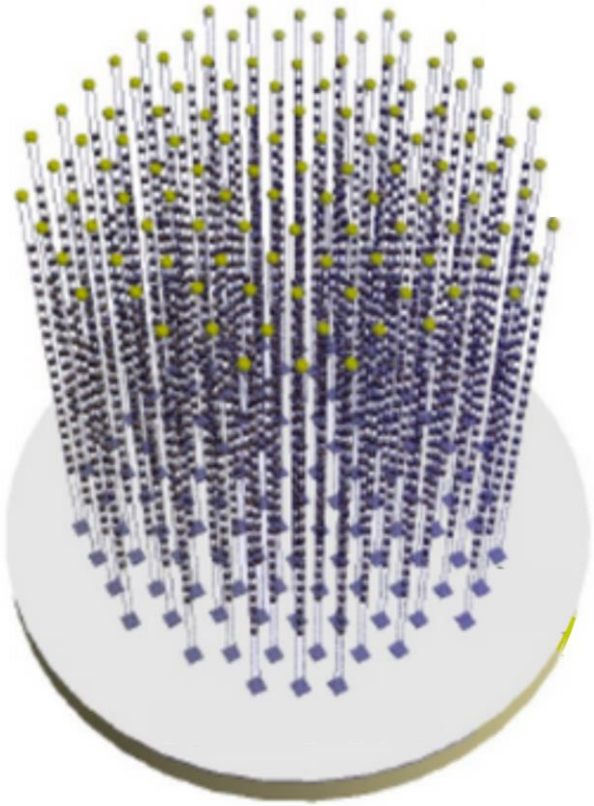


2500 m depth, offshore Toulon

ORCA/ARCA ~20/90 m



BUILDING BLOCK

115 DUs

Km3Net

Credits: Silvia Celli

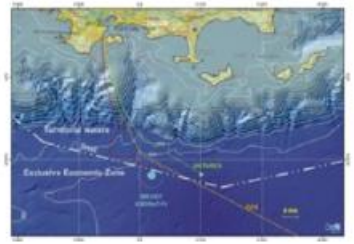
ARCA (1 GTon)

Astroparticle Research with Cosmics in the Abyss

3500 m depth, offshore Sicily

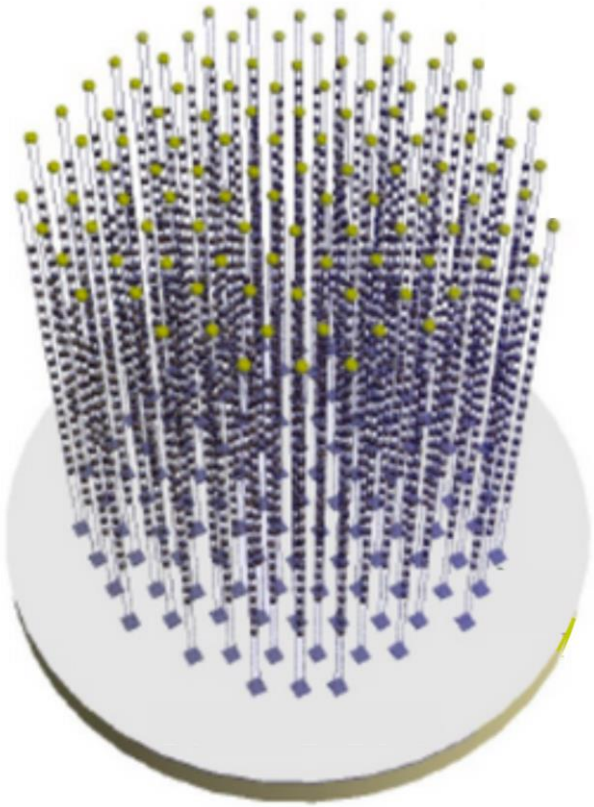
ORCA (6 MTon)

Oscillation Research with Cosmics in the Abyss



2500 m depth, offshore Toulon

ORCA/ARCA ~20/90 m



BUILDING BLOCK

115 DUs

ORCA/ARCA ~200/700 m

18 DOMs/DU

Km3Net

Credits: Silvia Celli

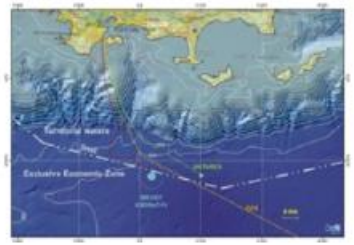
ARCA (1 GTon)

Astroparticle Research with Cosmics in the Abyss

3500 m depth, offshore Sicily

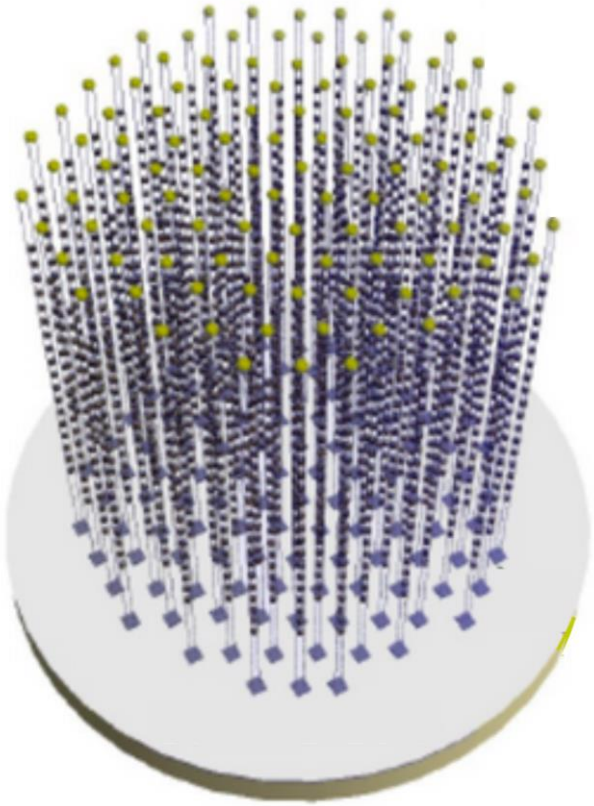
ORCA (6 MTon)

Oscillation Research with Cosmics in the Abyss



2500 m depth, offshore Toulon

ORCA/ARCA ~20/90 m



BUILDING BLOCK

115 DUs

ORCA/ARCA ~200/700 m

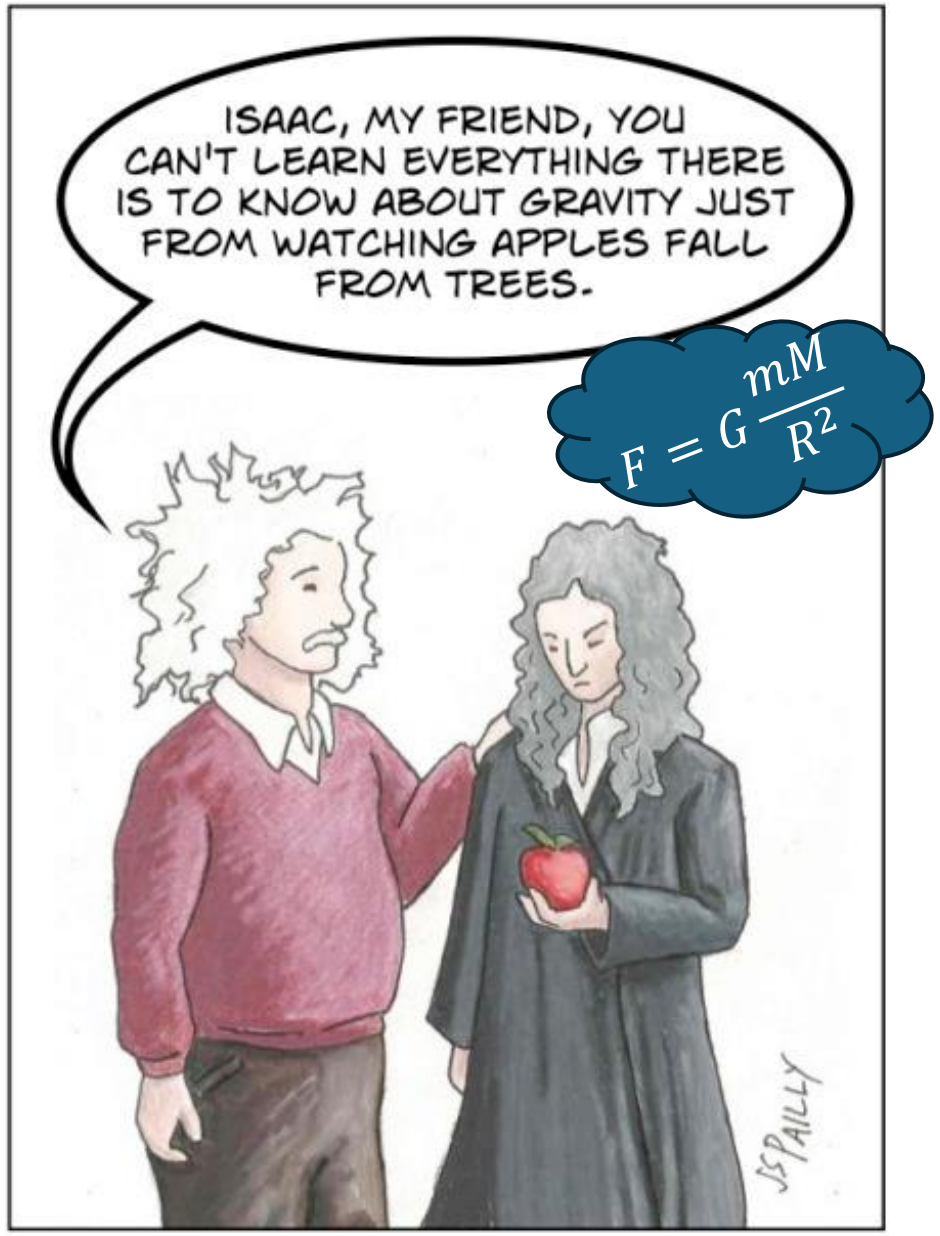
18 DOMs/DU

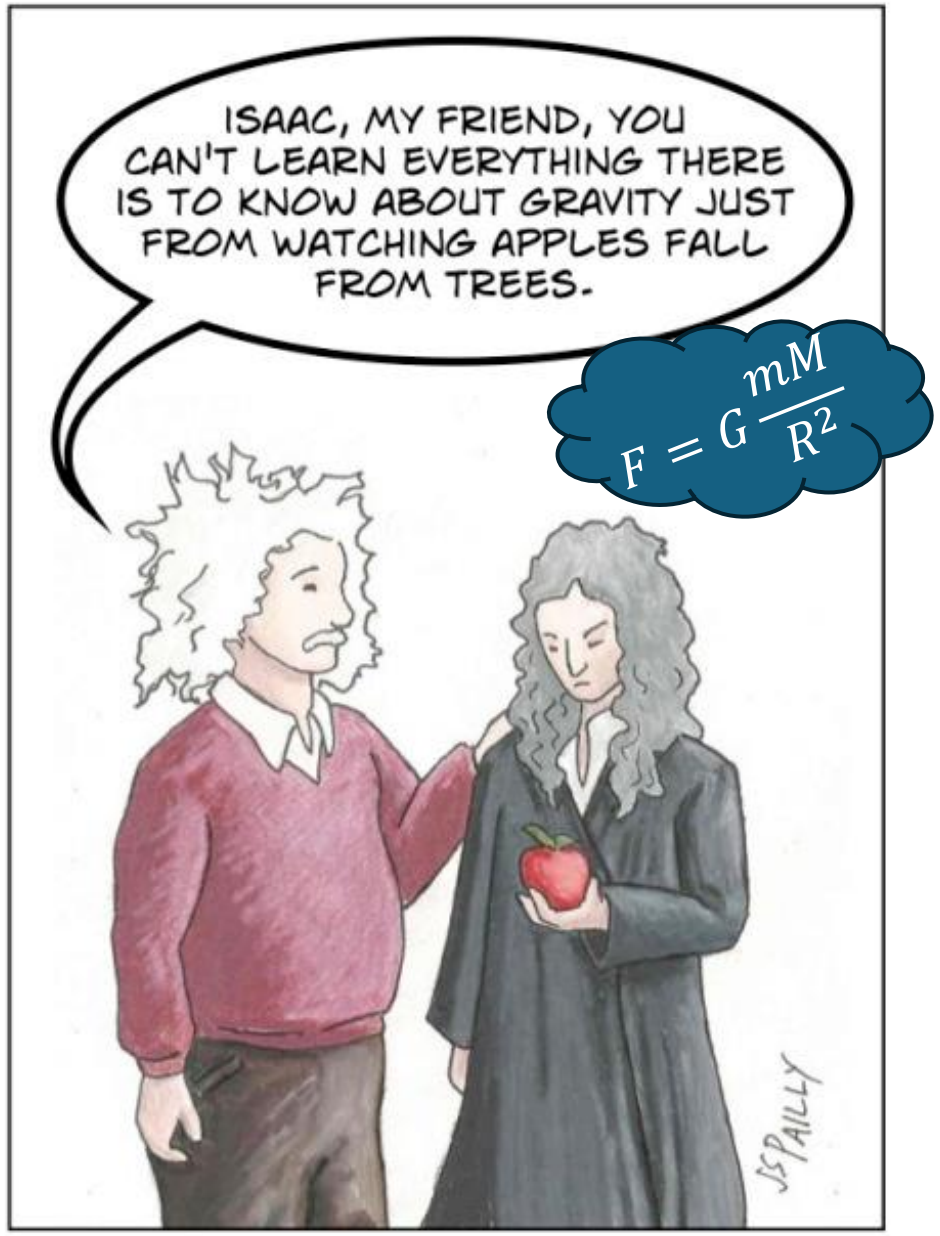
DOM

DOM: **17'' glass sphere containing: 31x3'' PMTs LED and Piezo Front end electronics**

Gravitational Waves

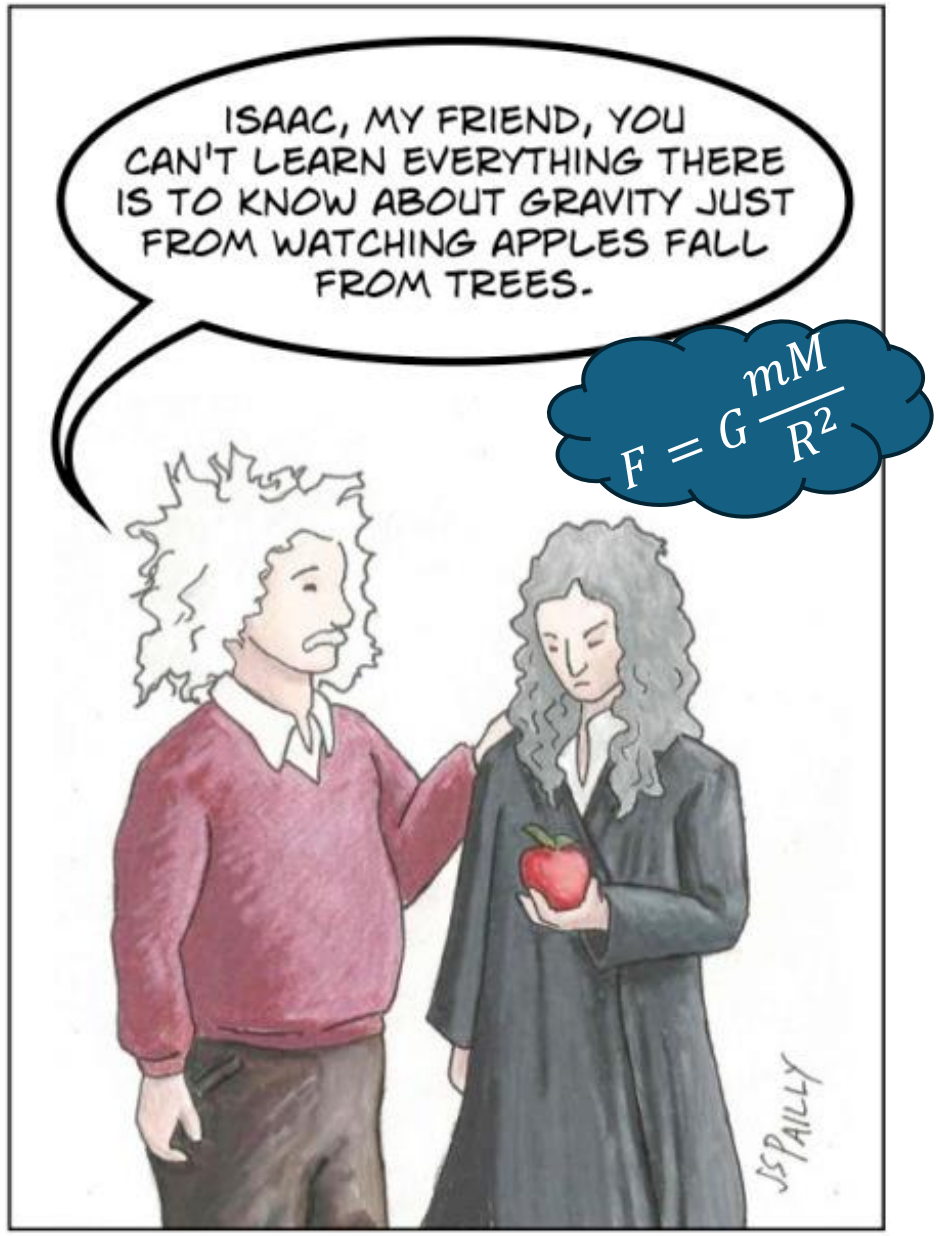
A new way to Gravity





A new way to Gravity

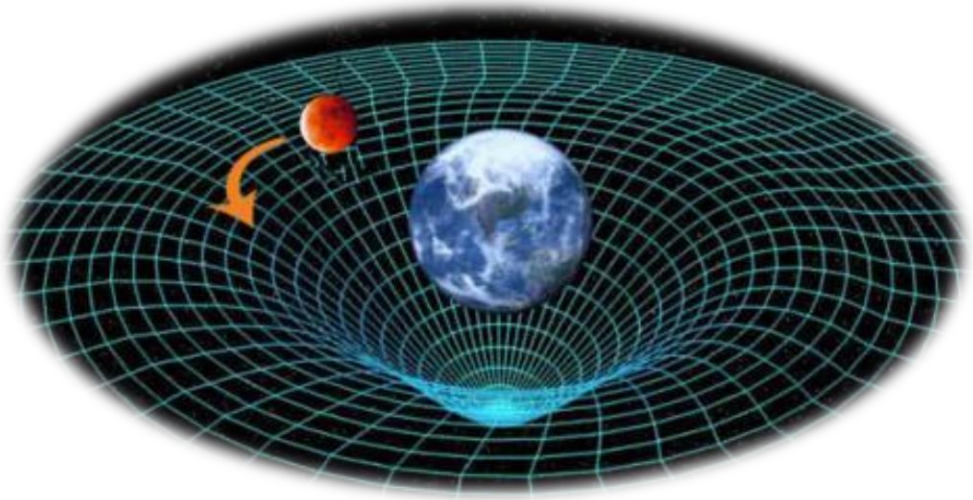
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$



A new way to Gravity

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

Masses distort space
Trajectories follows space deformation



Solving Einstein Equations

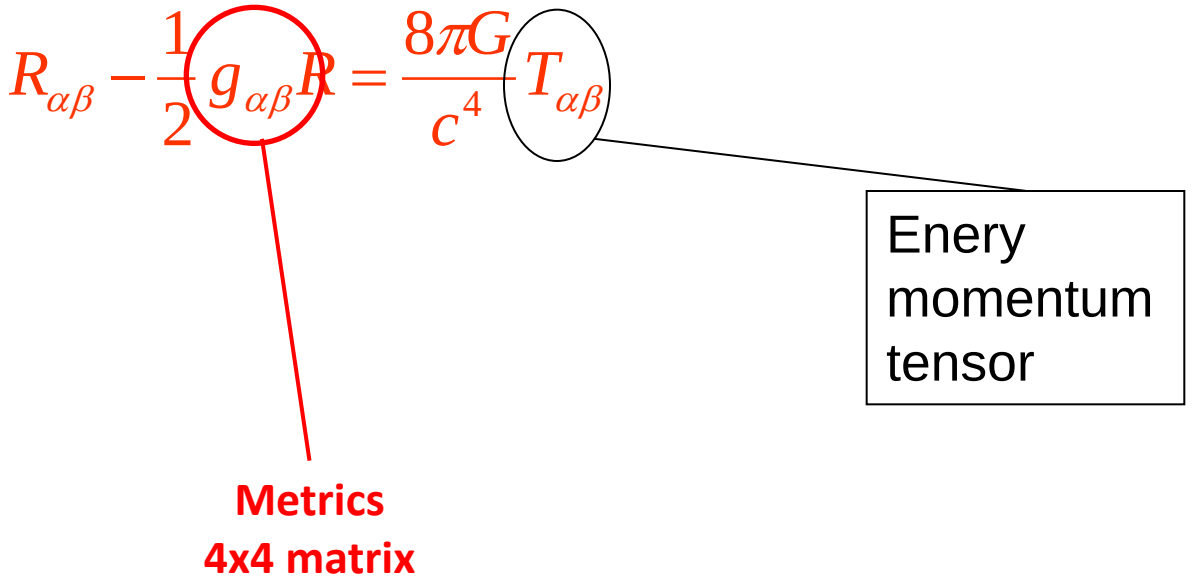
$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Solving Einstein Equations

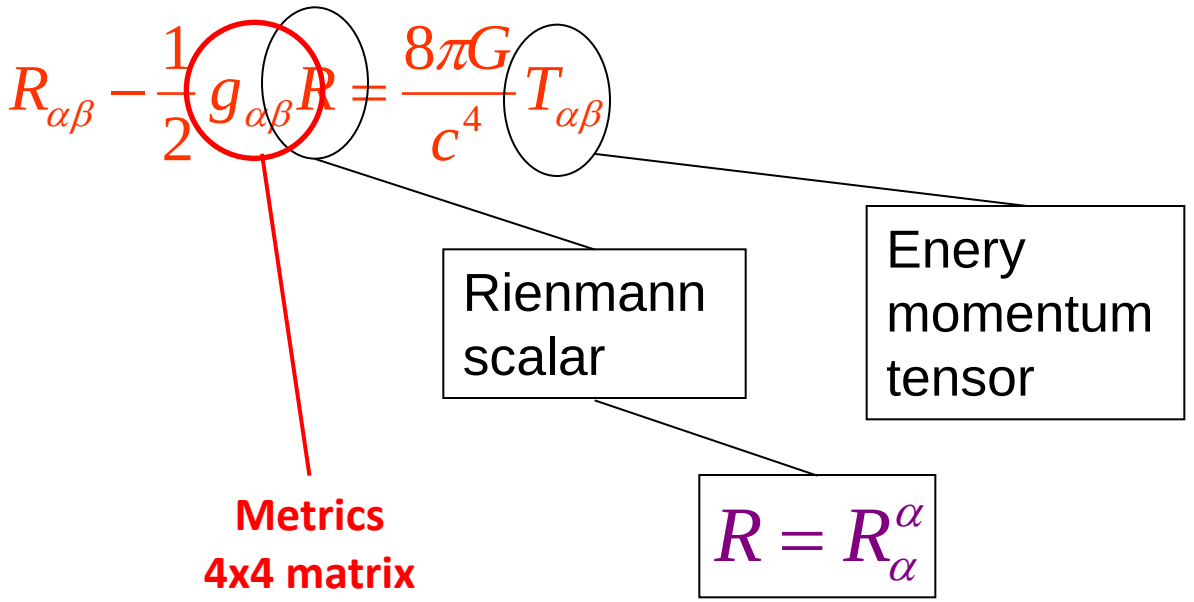
$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Metrics
4x4 matrix

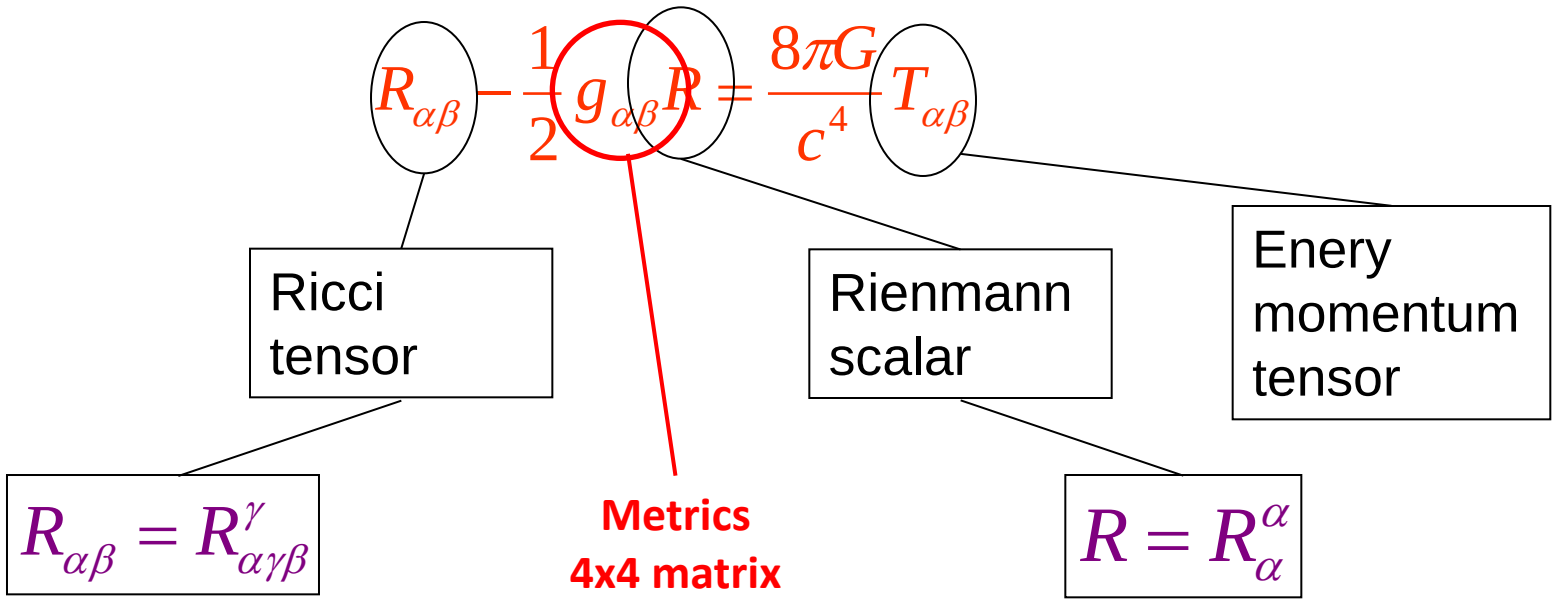
Solving Einstein Equations



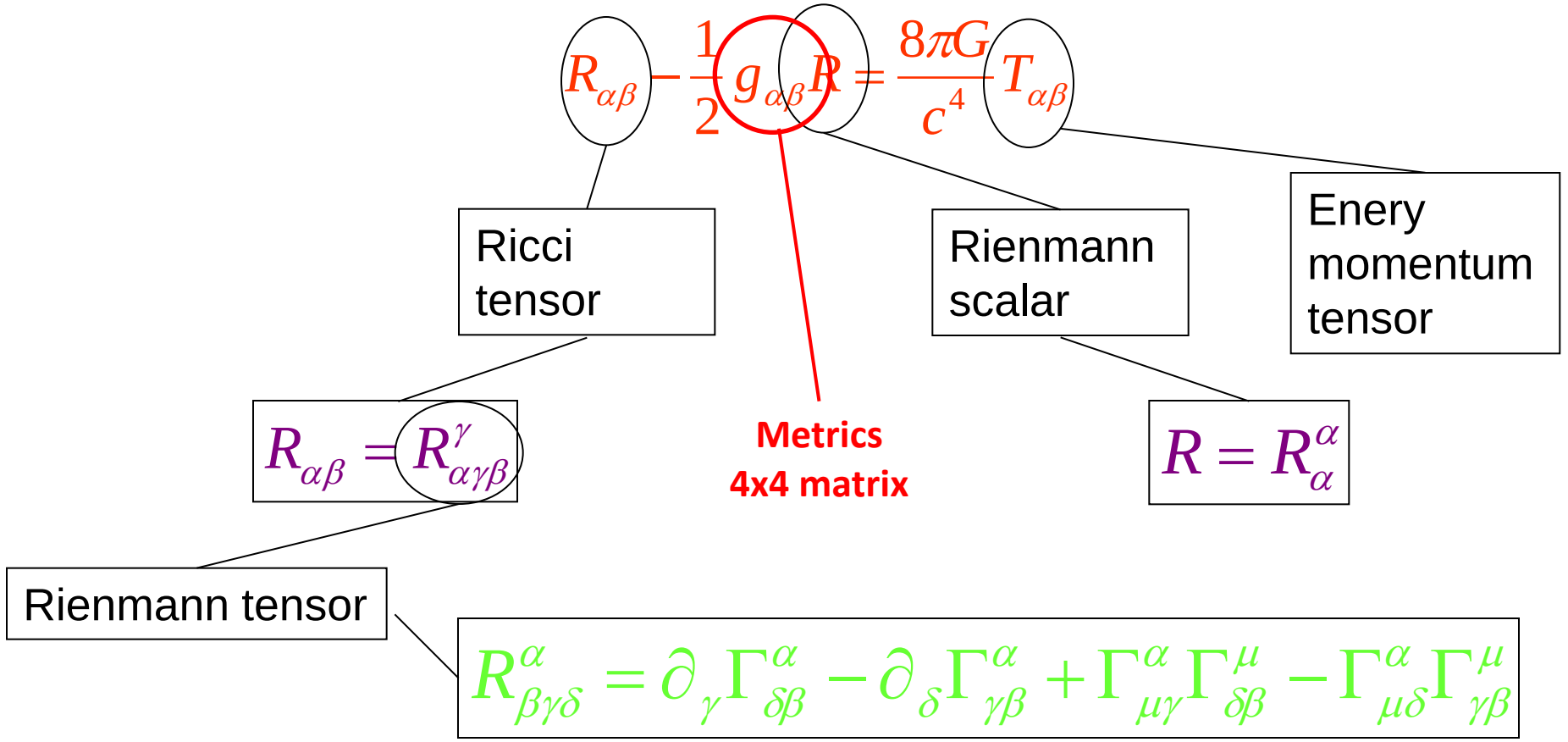
Solving Einstein Equations



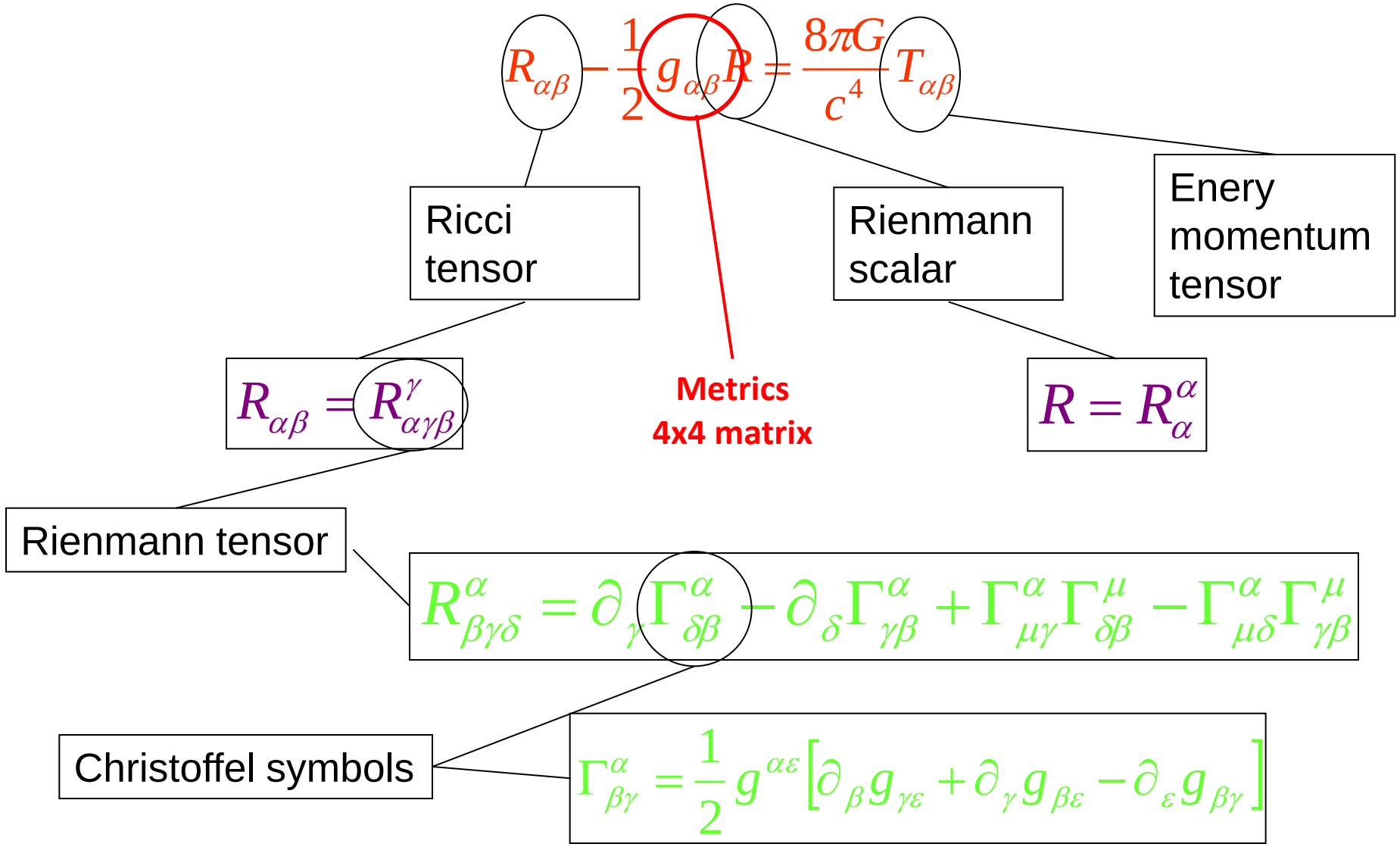
Solving Einstein Equations



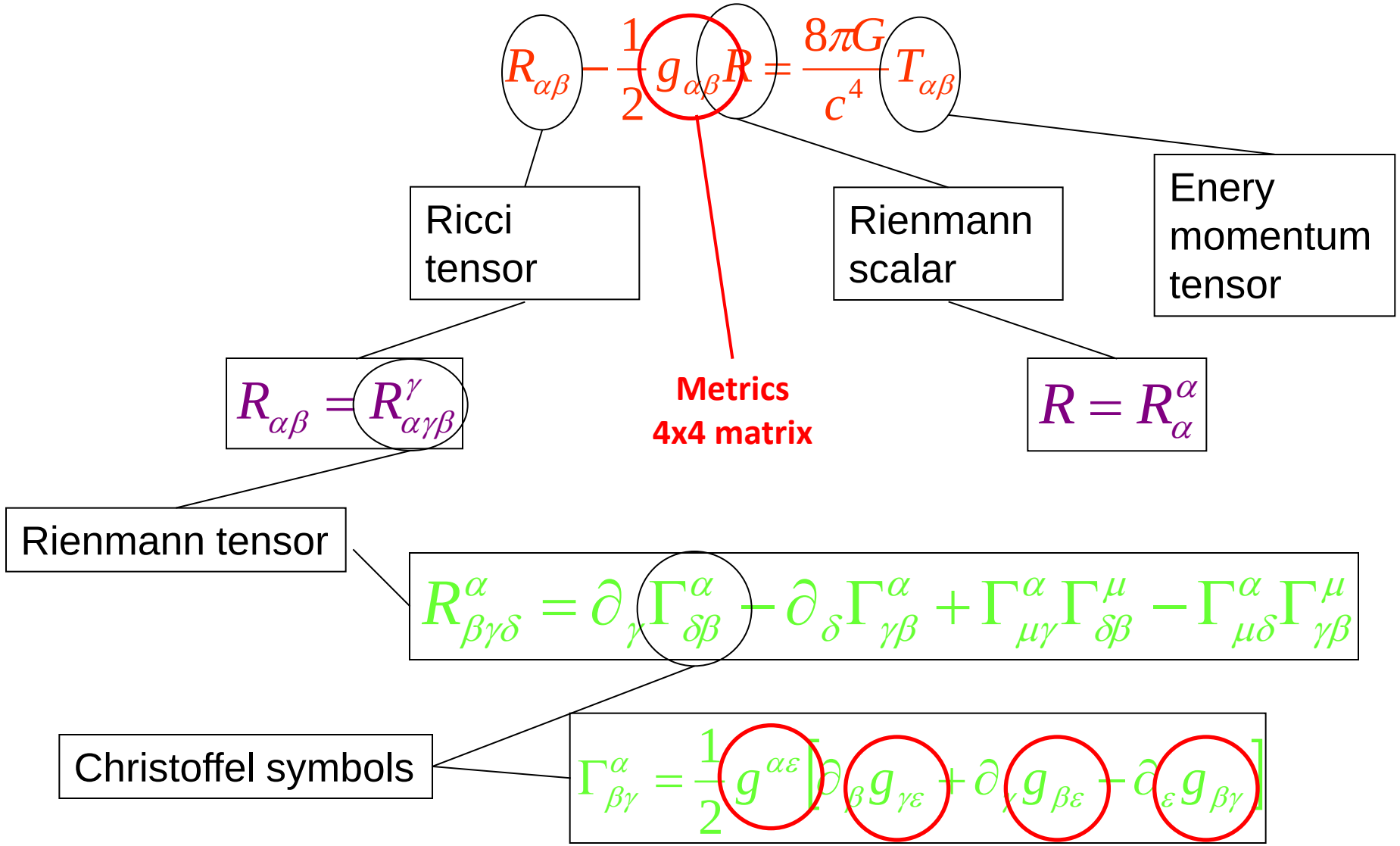
Solving Einstein Equations



Solving Einstein Equations



Solving Einstein Equations



Solving Einstein Equations

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

Ricci tensor

Rienmann scalar

Enery momentum tensor

$$R_{\alpha\beta} = R^{\gamma}_{\alpha\gamma\beta}$$

Metrics
4x4 matrix

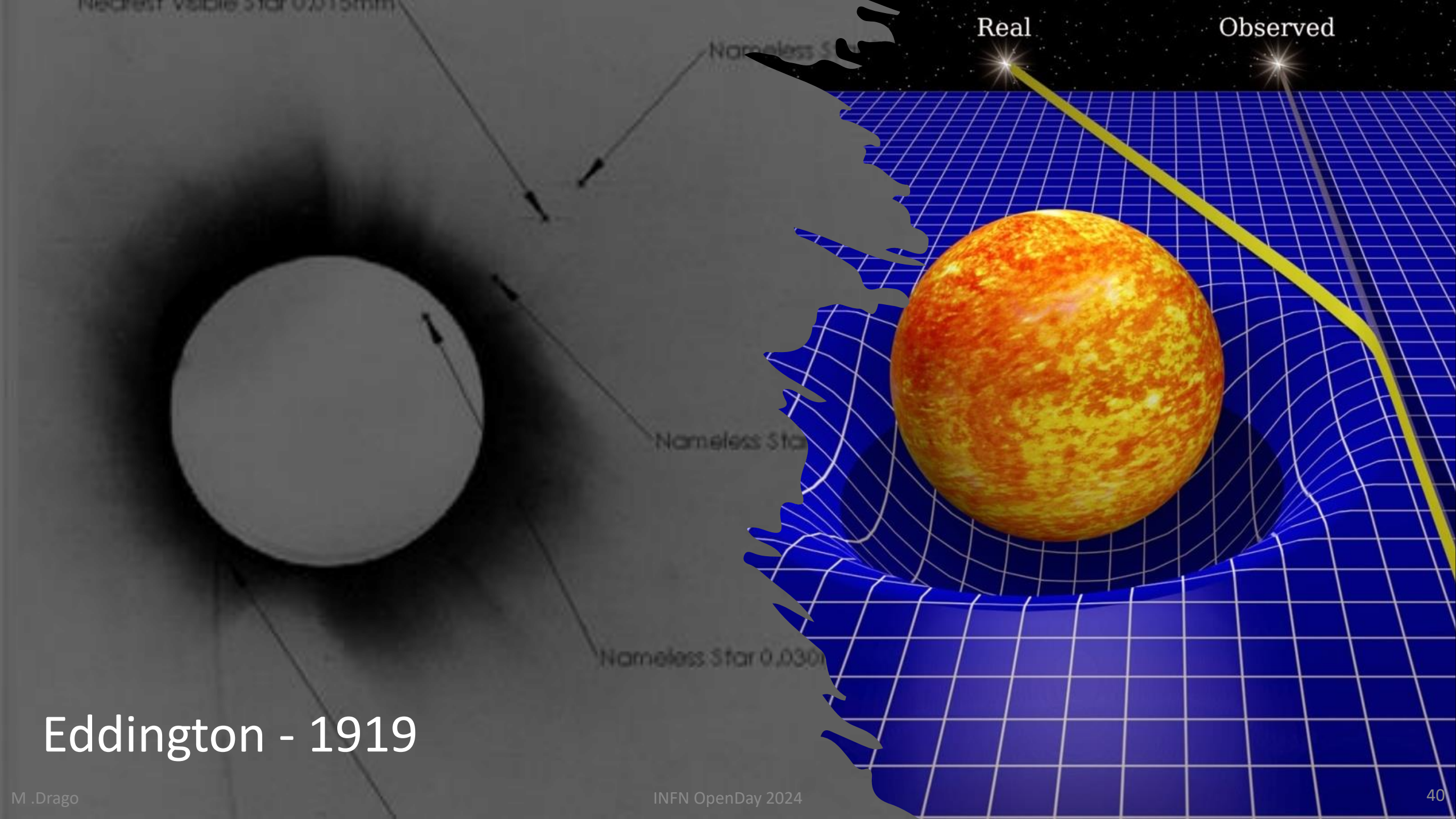
$$R = R^{\alpha}_{\alpha}$$

Rienmann tensor

$$R^{\alpha}_{\beta\gamma\delta} = \partial_{\gamma}\Gamma^{\alpha}_{\delta\beta} - \partial_{\delta}\Gamma^{\alpha}_{\gamma\beta} + \Gamma^{\alpha}_{\mu\gamma}\Gamma^{\mu}_{\delta\beta} - \Gamma^{\alpha}_{\mu\delta}\Gamma^{\mu}_{\gamma\beta}$$

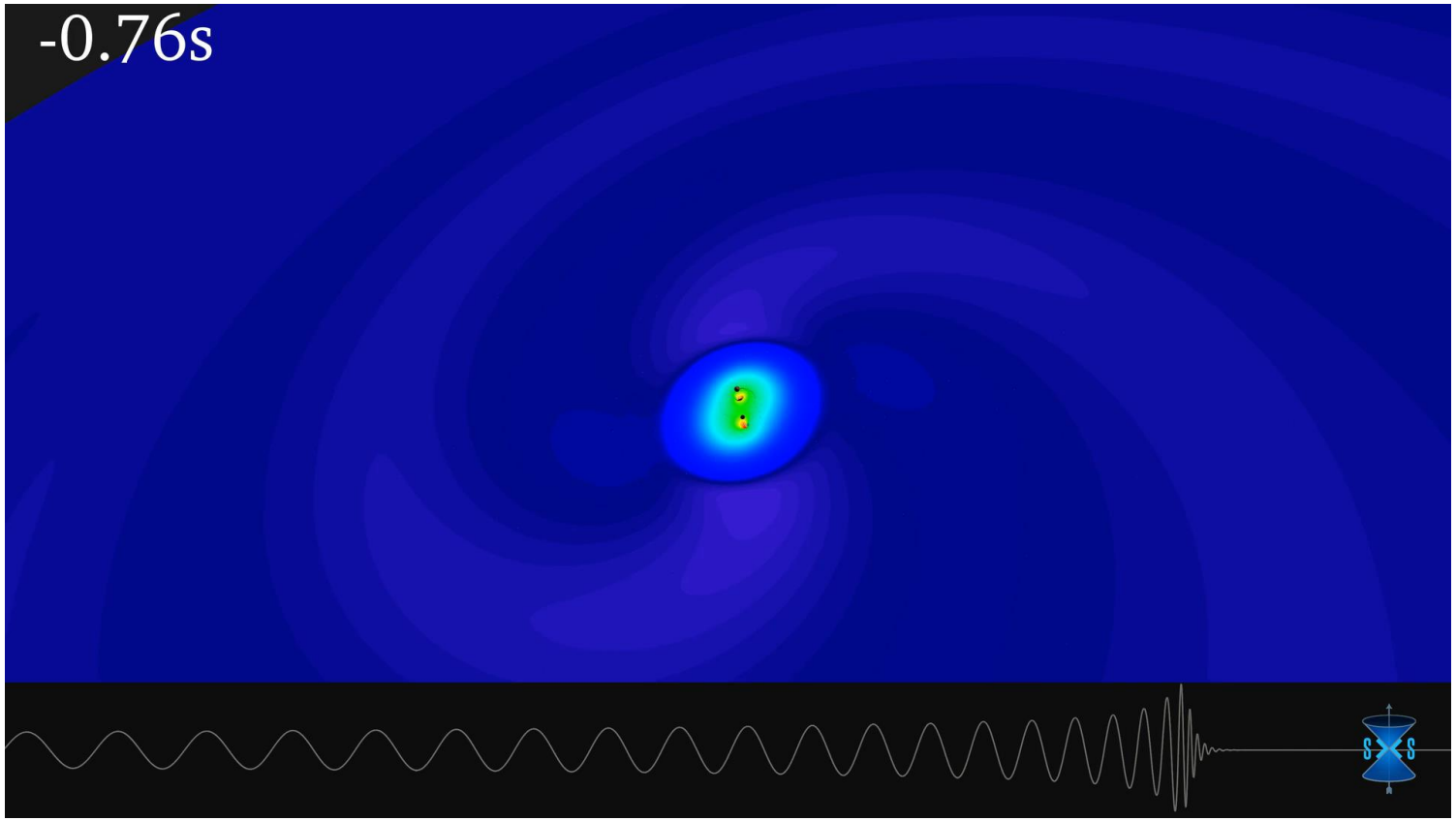
Christoffel symbols

$$\Gamma^{\alpha}_{\beta\gamma} = \frac{1}{2} g^{\alpha\varepsilon} \left[\partial_{\beta} g_{\gamma\varepsilon} + \partial_{\gamma} g_{\beta\varepsilon} - \partial_{\varepsilon} g_{\beta\gamma} \right]$$

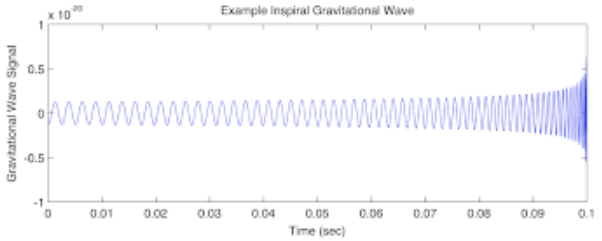


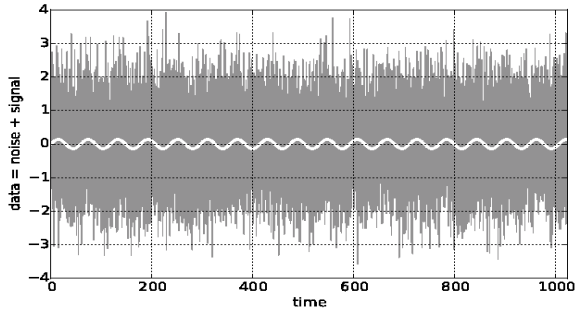
Eddington - 1919

The most known signal

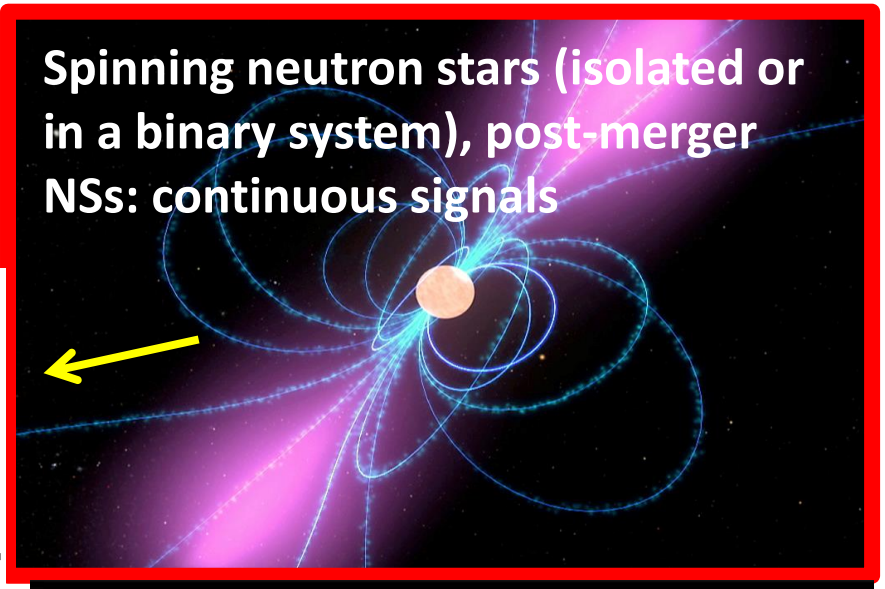


Coalescing binaries:
NS-NS, BH-BH, NS-BH

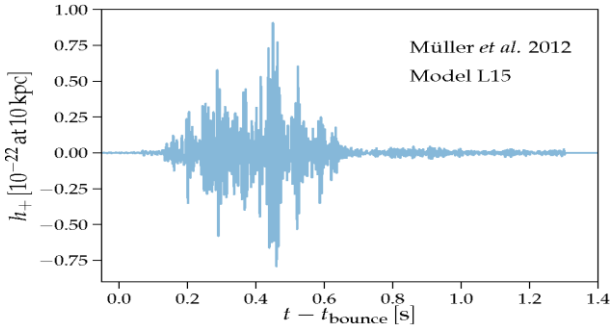


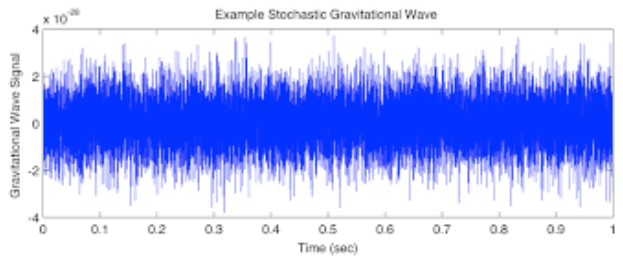


Spinning neutron stars (isolated or in a binary system), post-merger NSs: continuous signals

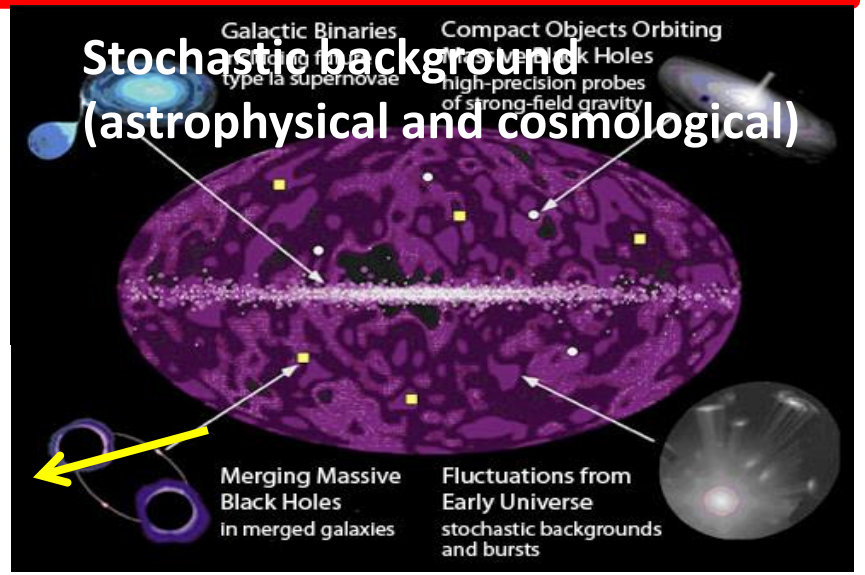


Star core-collapse, NS merger, NS oscillations (starquakes,…): burst signals

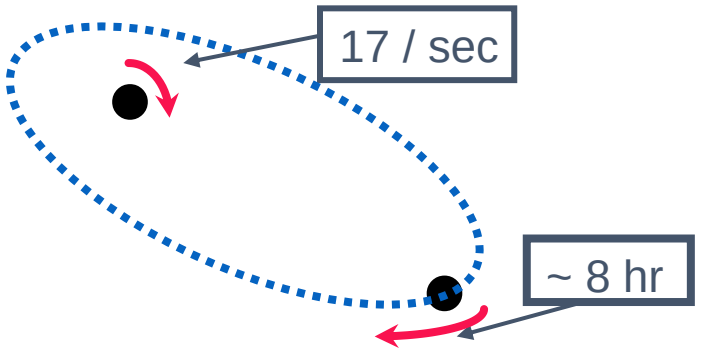


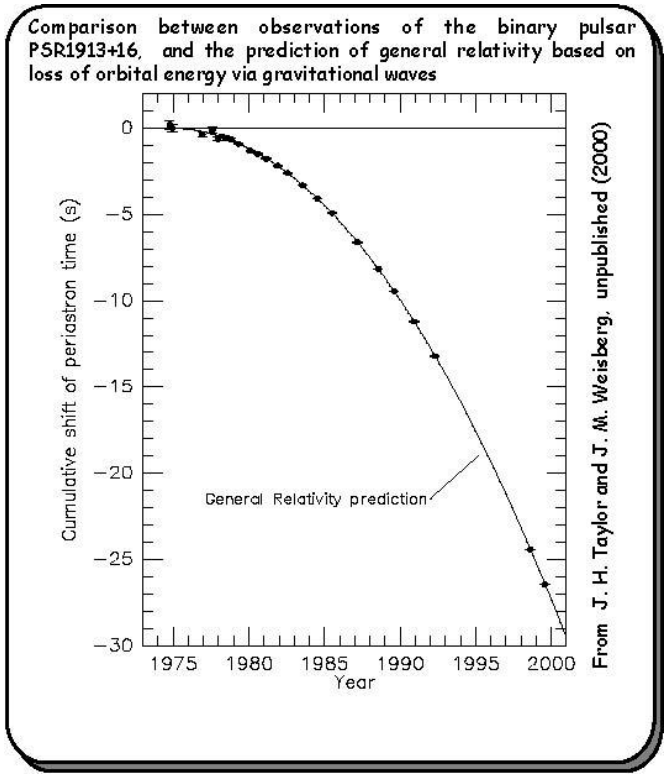


Stochastic background (astrophysical and cosmological)



Joseph Taylor Russell Hulse

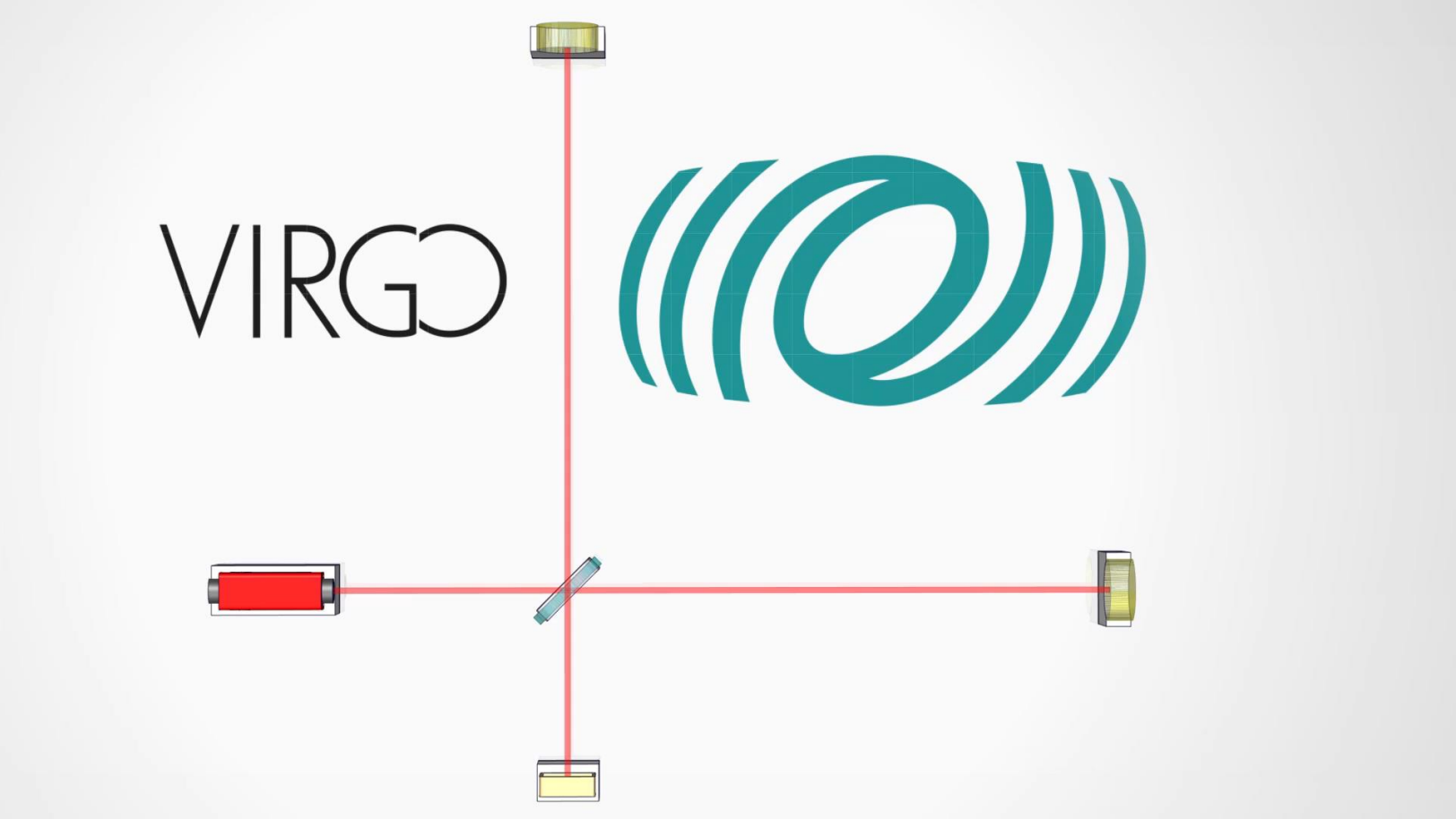


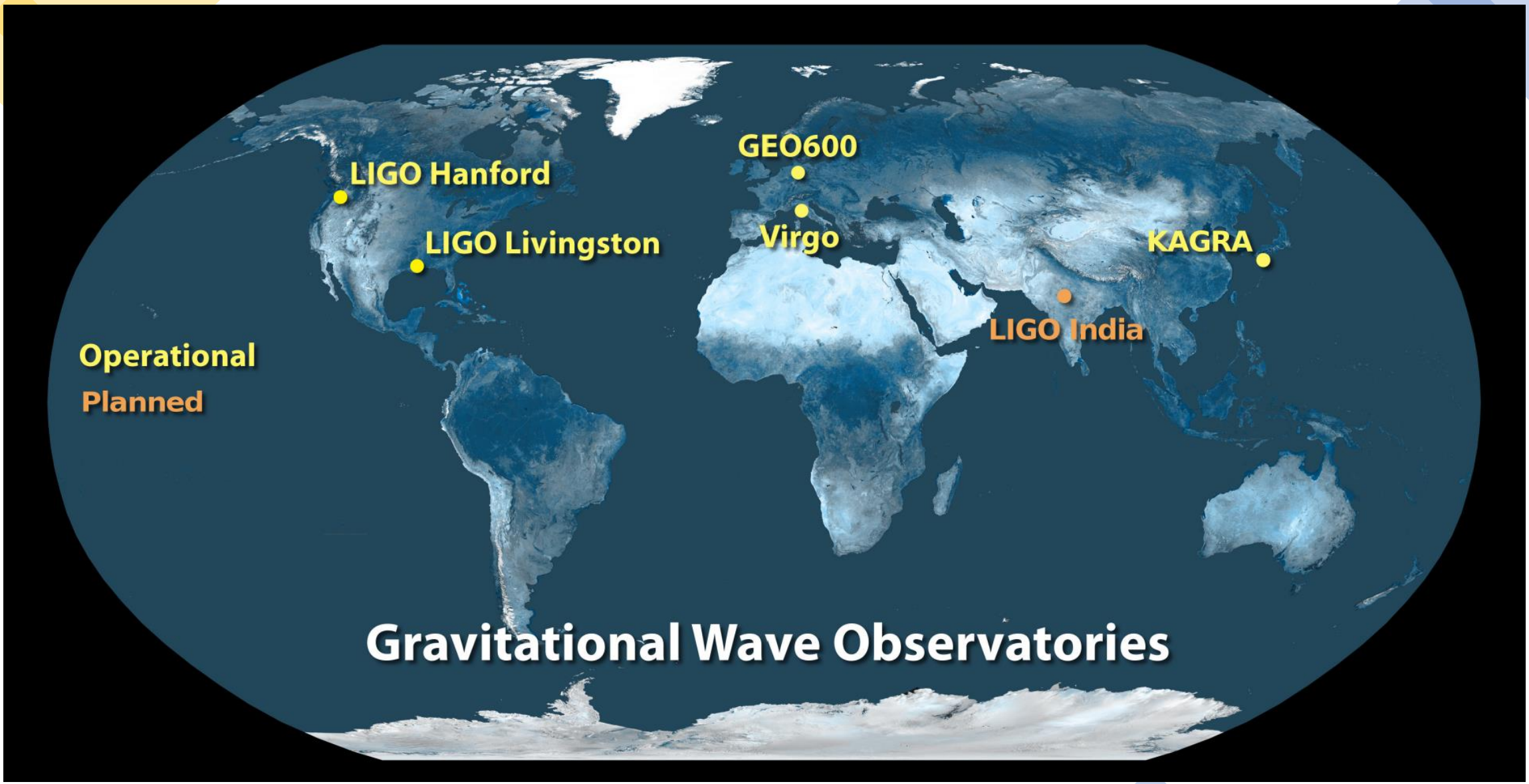


Existence proof: PSR 1913+16

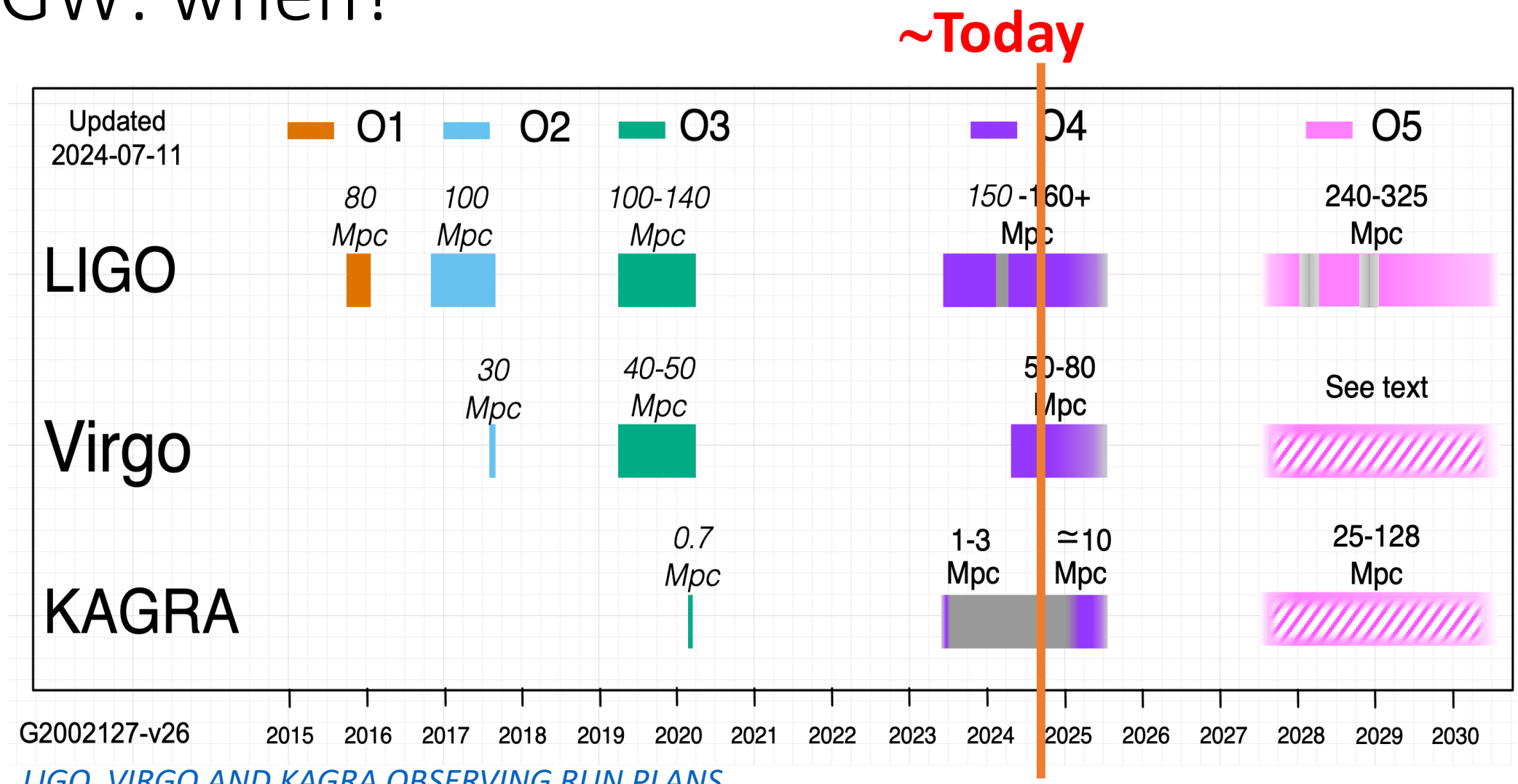
The effect of a Gravitational Wave

Interferometers




GEO600
LIGO Hanford
Virgo
LIGO Livingston
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories

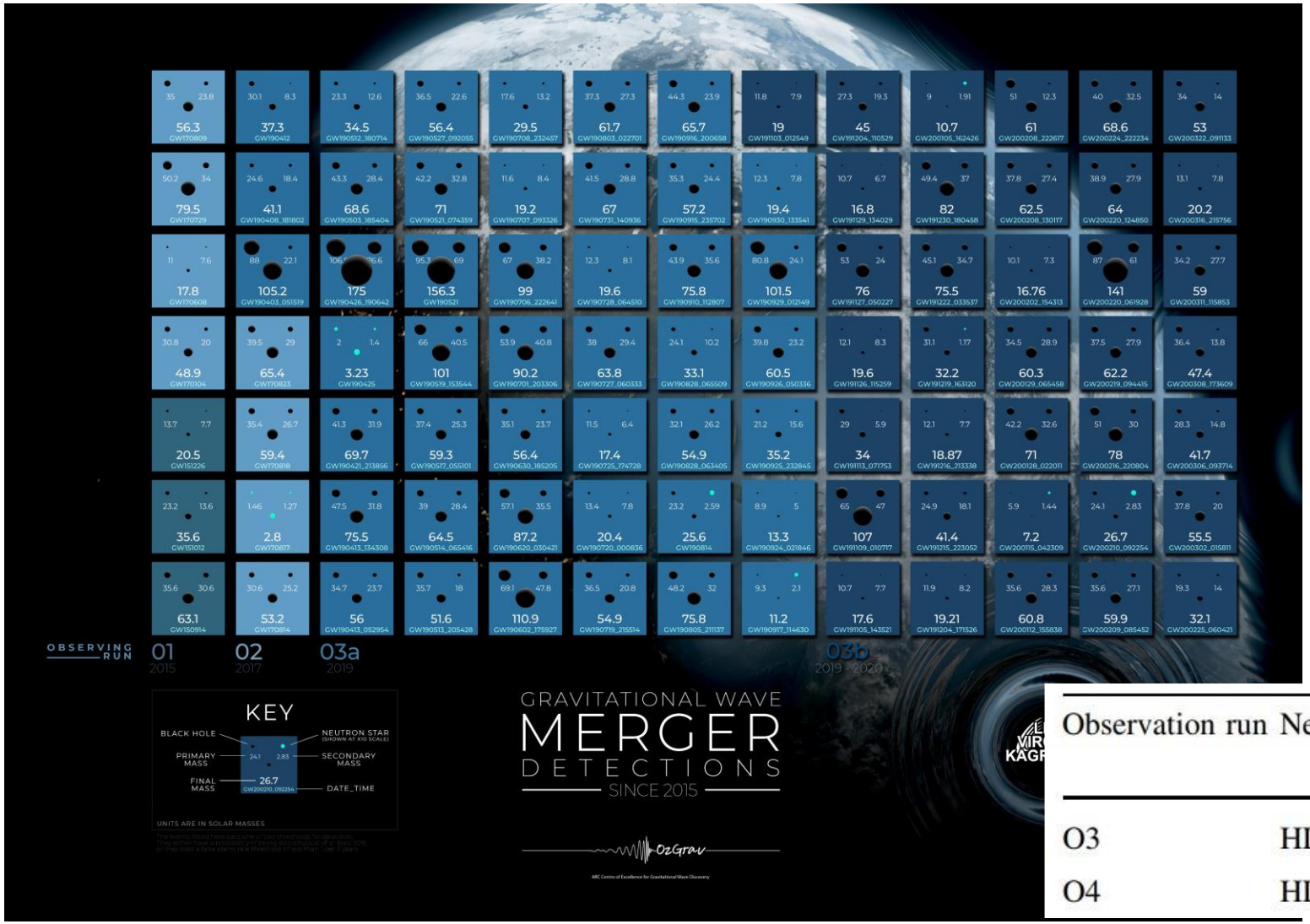
GW: when?



LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

GW: how many?

ArXiv:2111.03606



Three scientific runs:

- O1: 3 GW
- O2: 8 GW
- O3: 79 GW

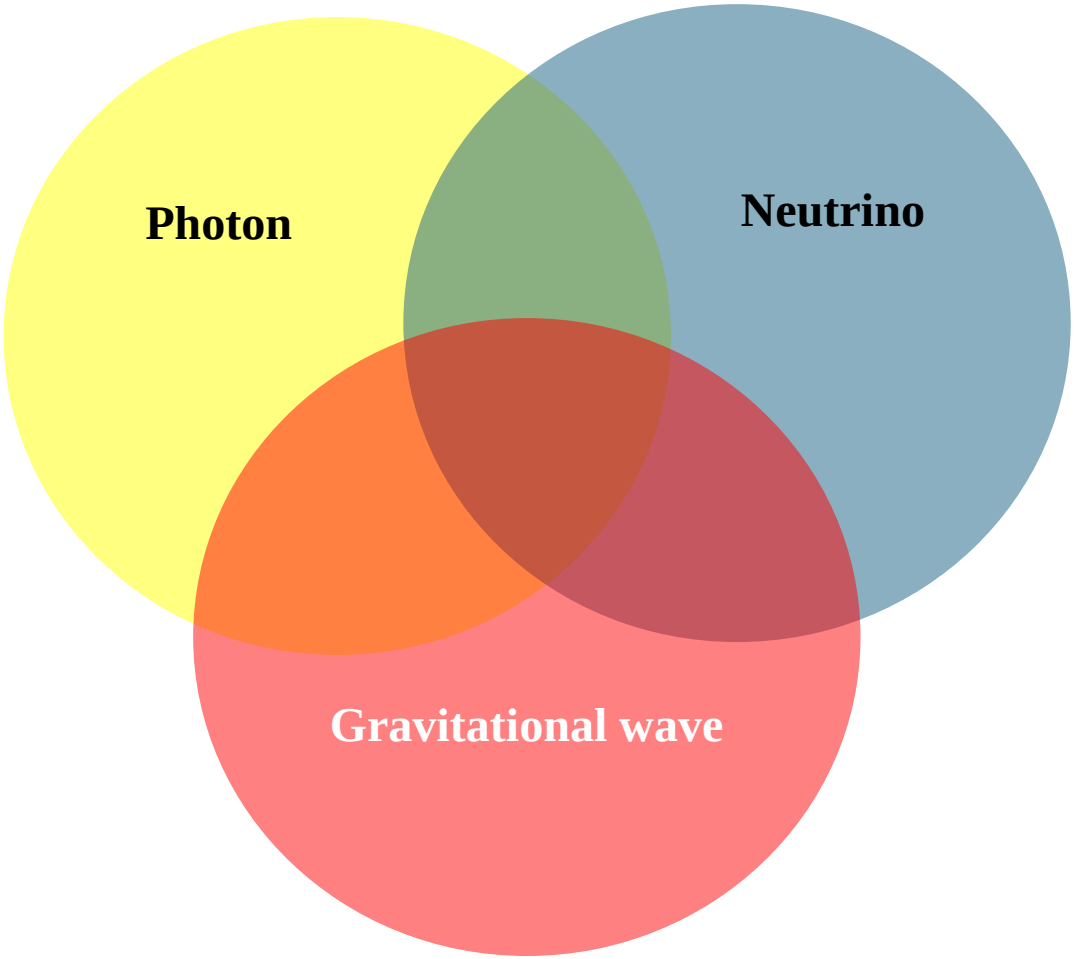
90 detections

Expected rate:

ArXiv:1304.0670

Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

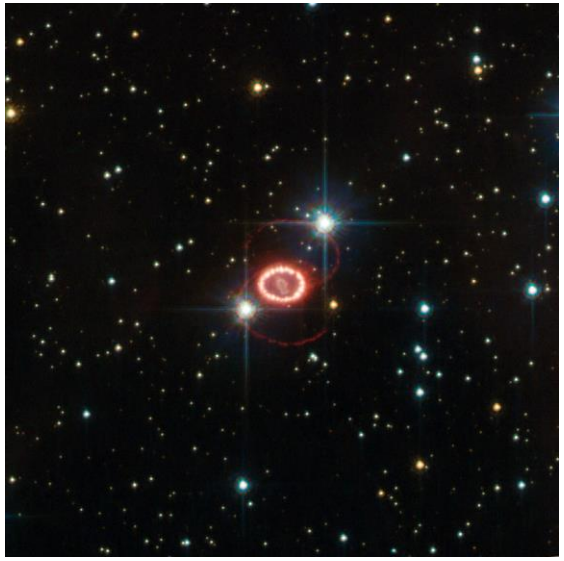
Multi-messenger discoveries



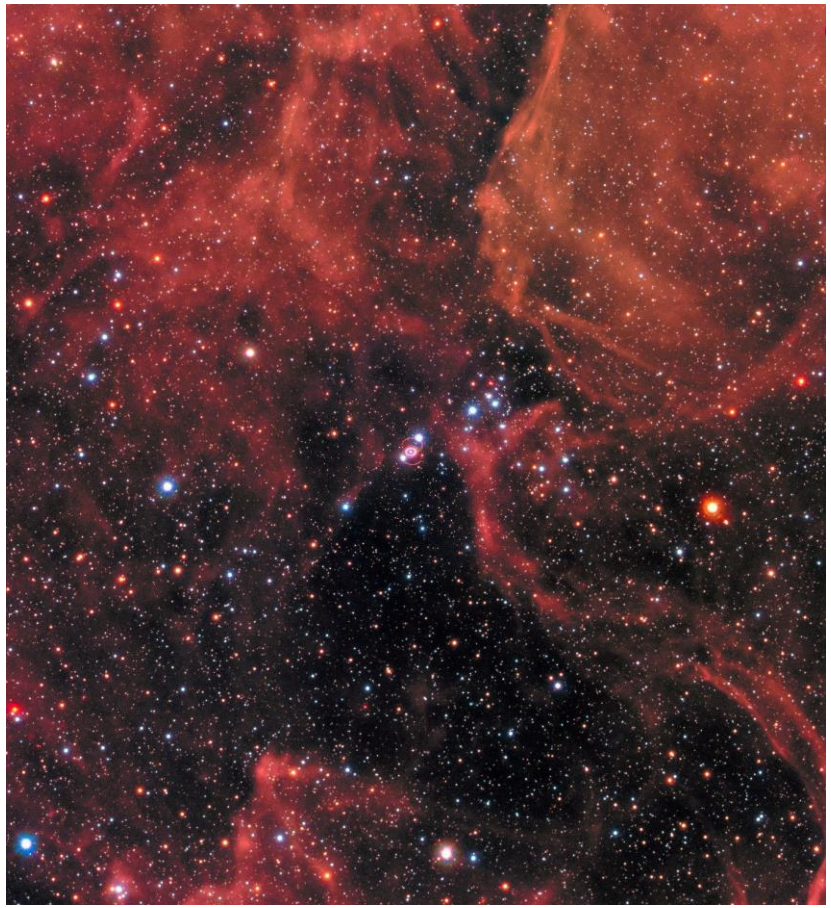
1987 supernova

- Probably the first multi-messenger detection
  - EM spectrum
  - Neutrino

  - No GW observed (Resonant bars)

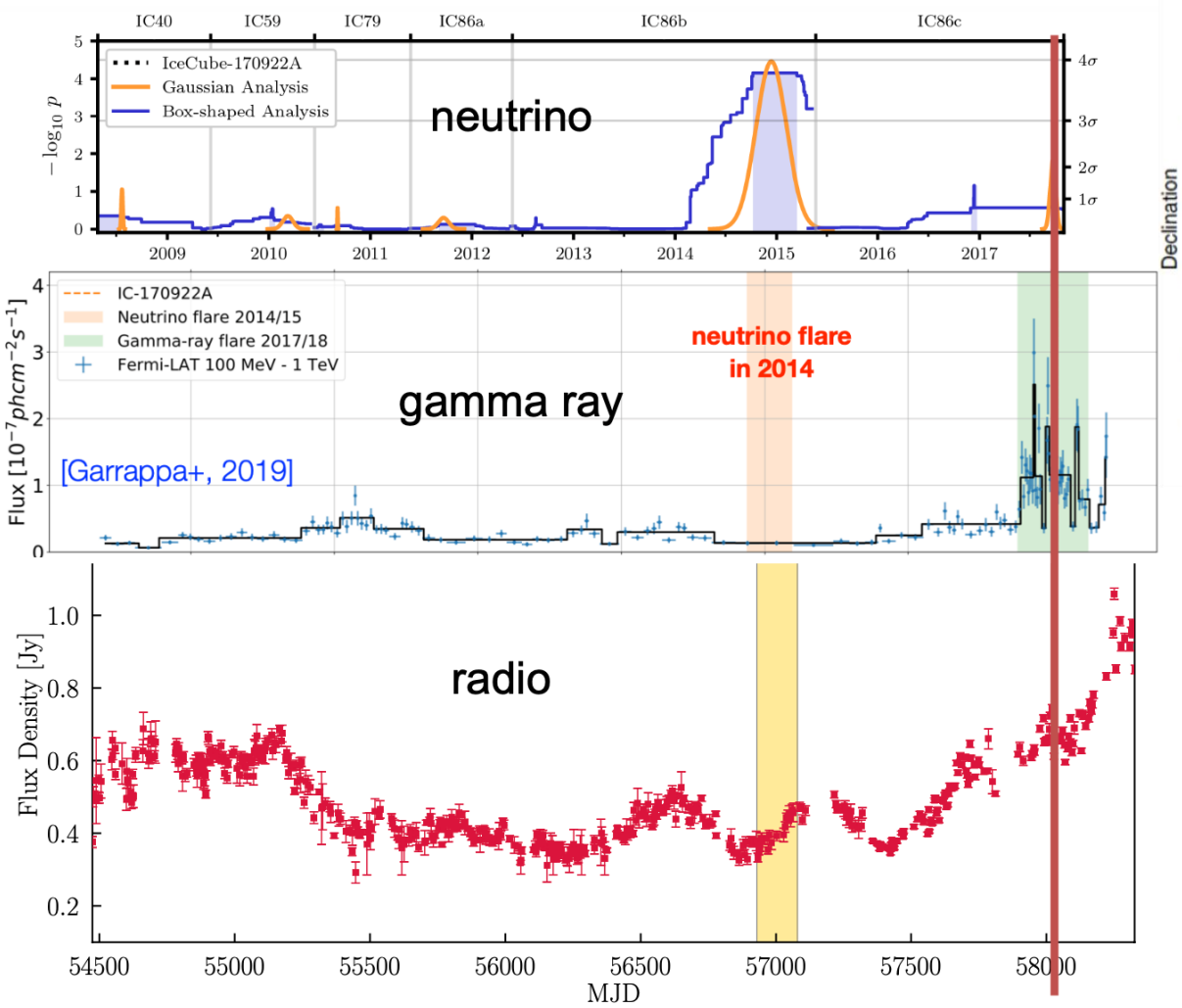


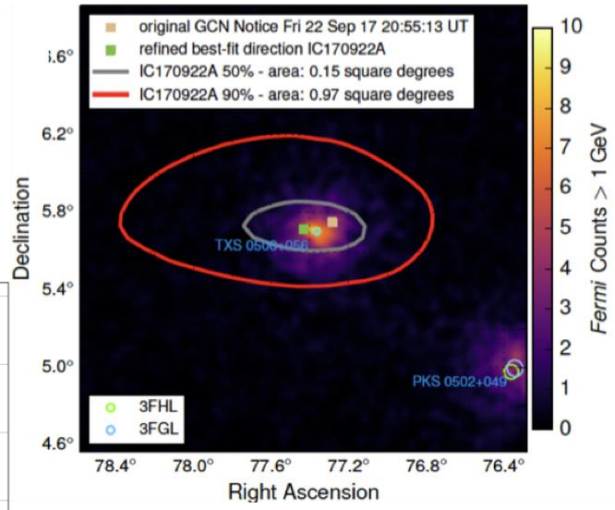
Credits: By NASA, ESA

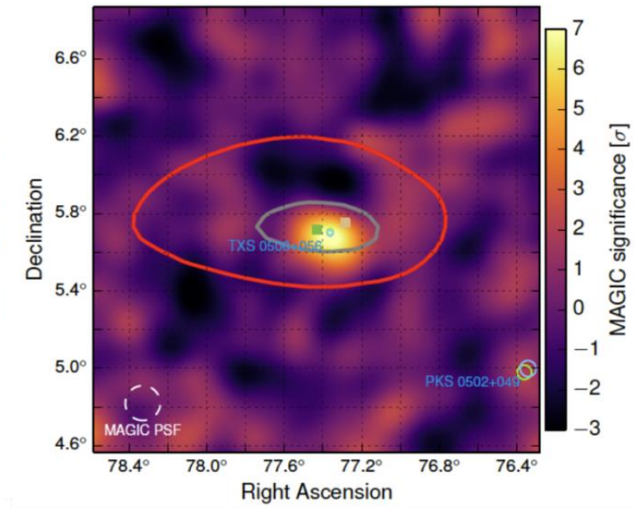


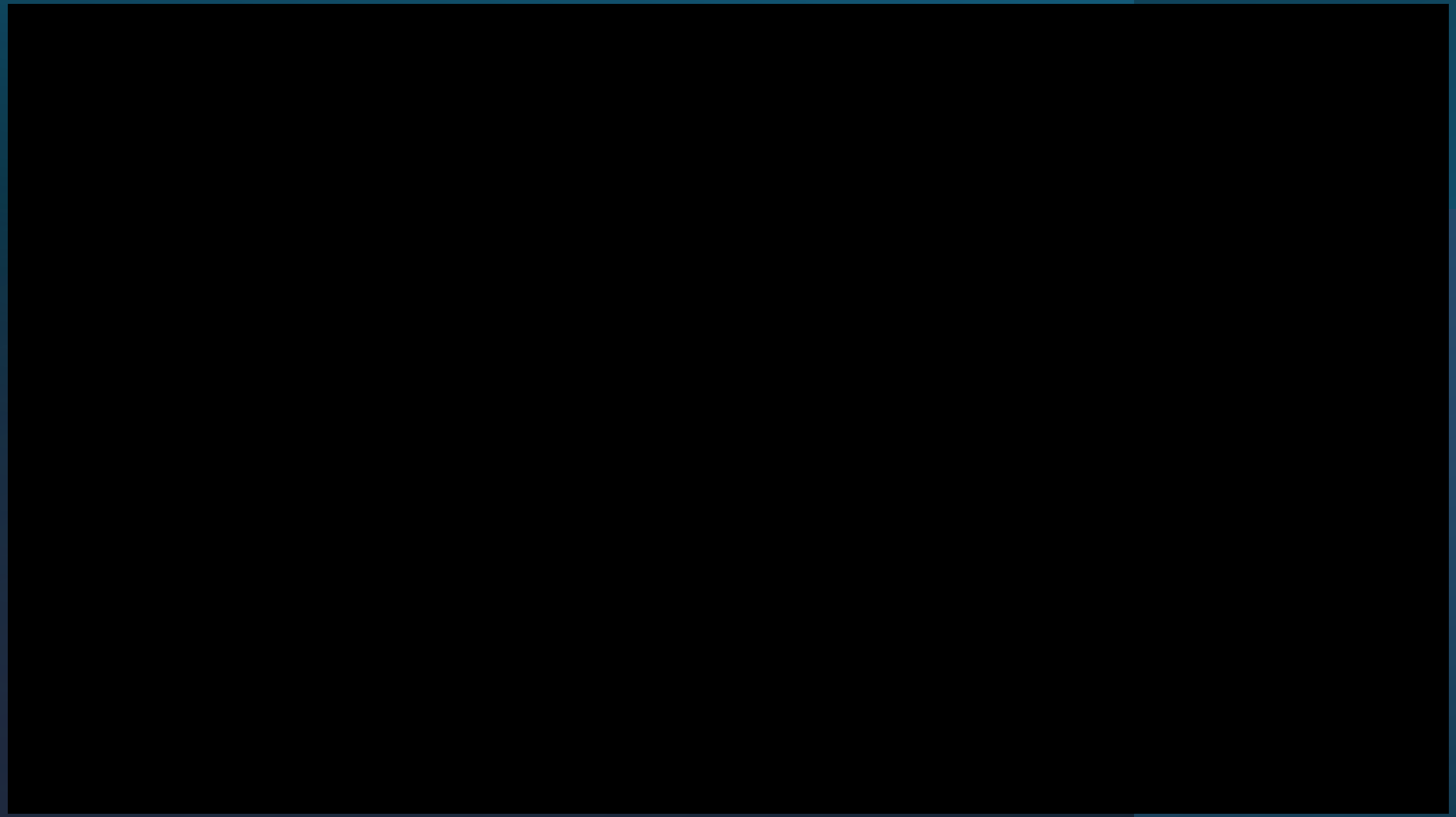
Credits: By NASA, ESA, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard-Smithsonian Center for Astrophysics)

TXS 0506+056: a flaring blazar









Fermi

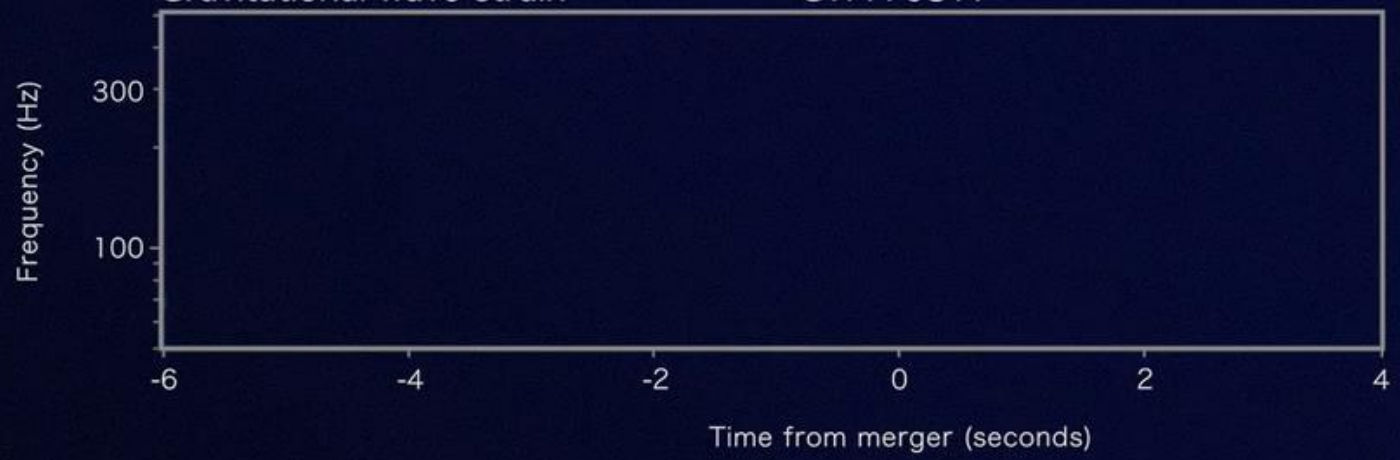
Gamma rays, 50 to 300 keV

GRB 170817A

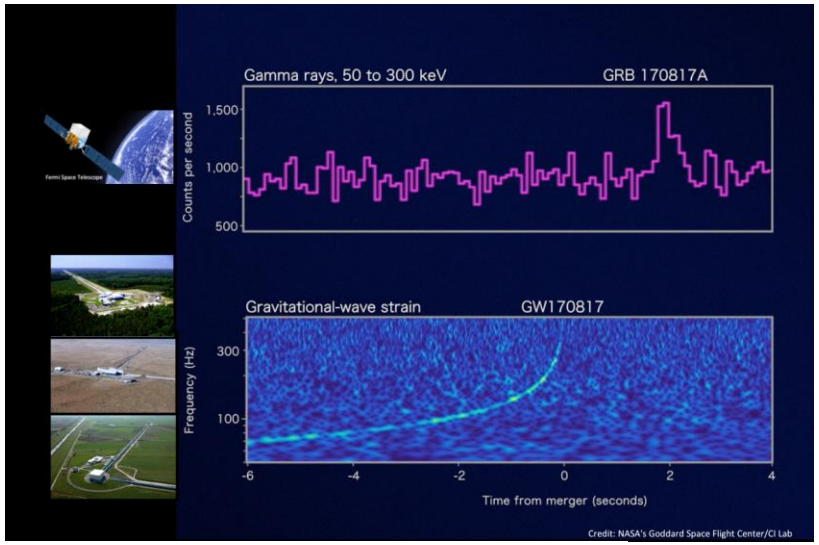
LIGO

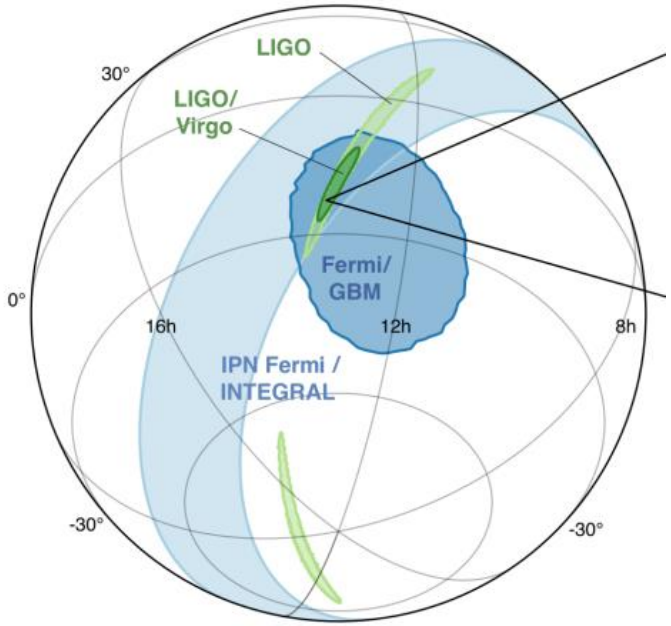
Gravitational-wave strain

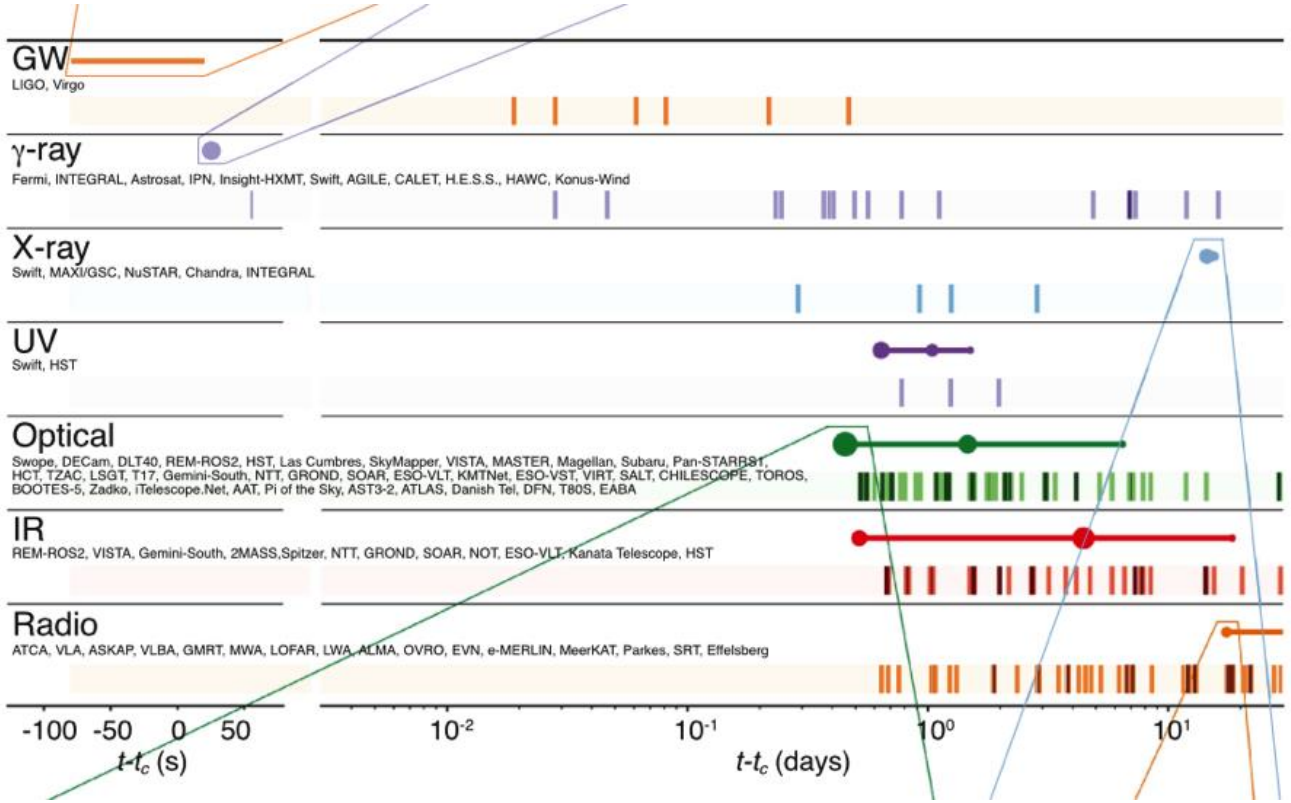
GW170817

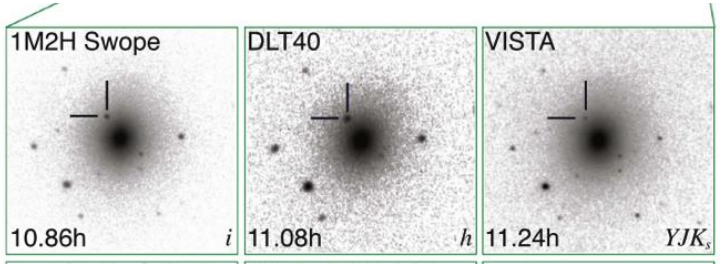


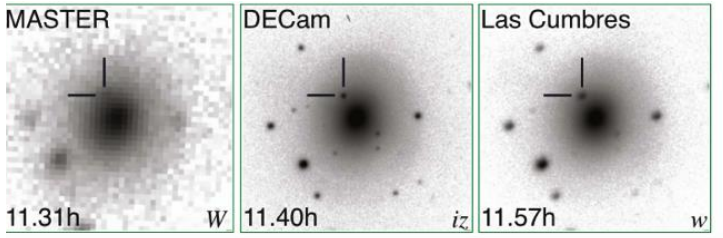
GW170817 & GRB170817A

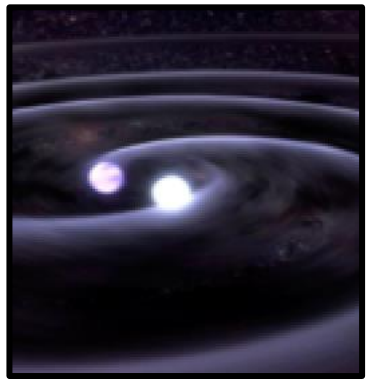




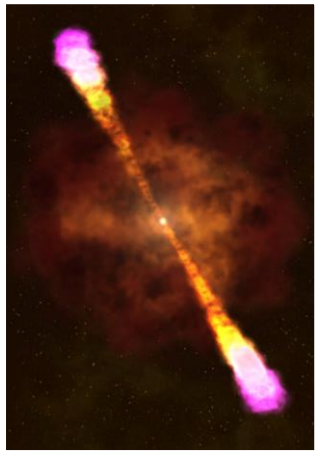




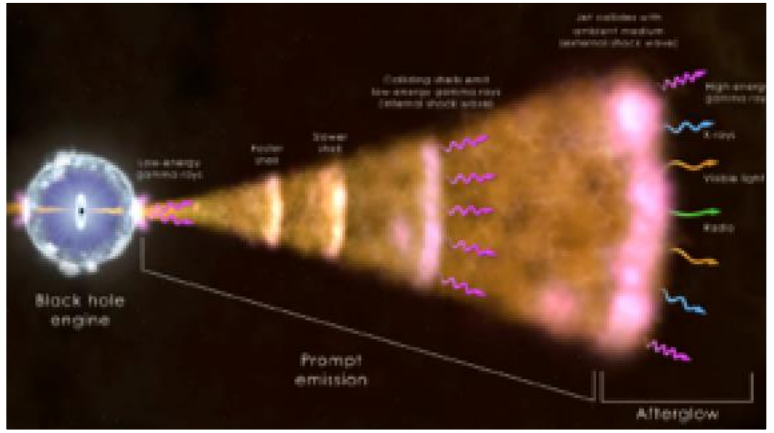




NS merger

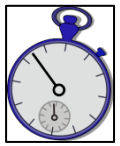


Short GRB



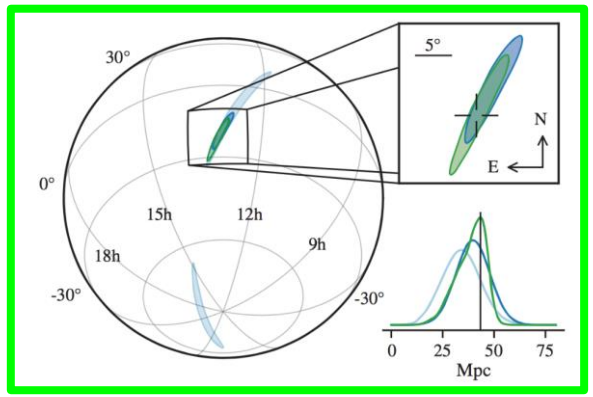
X-ray afterglow

Radio



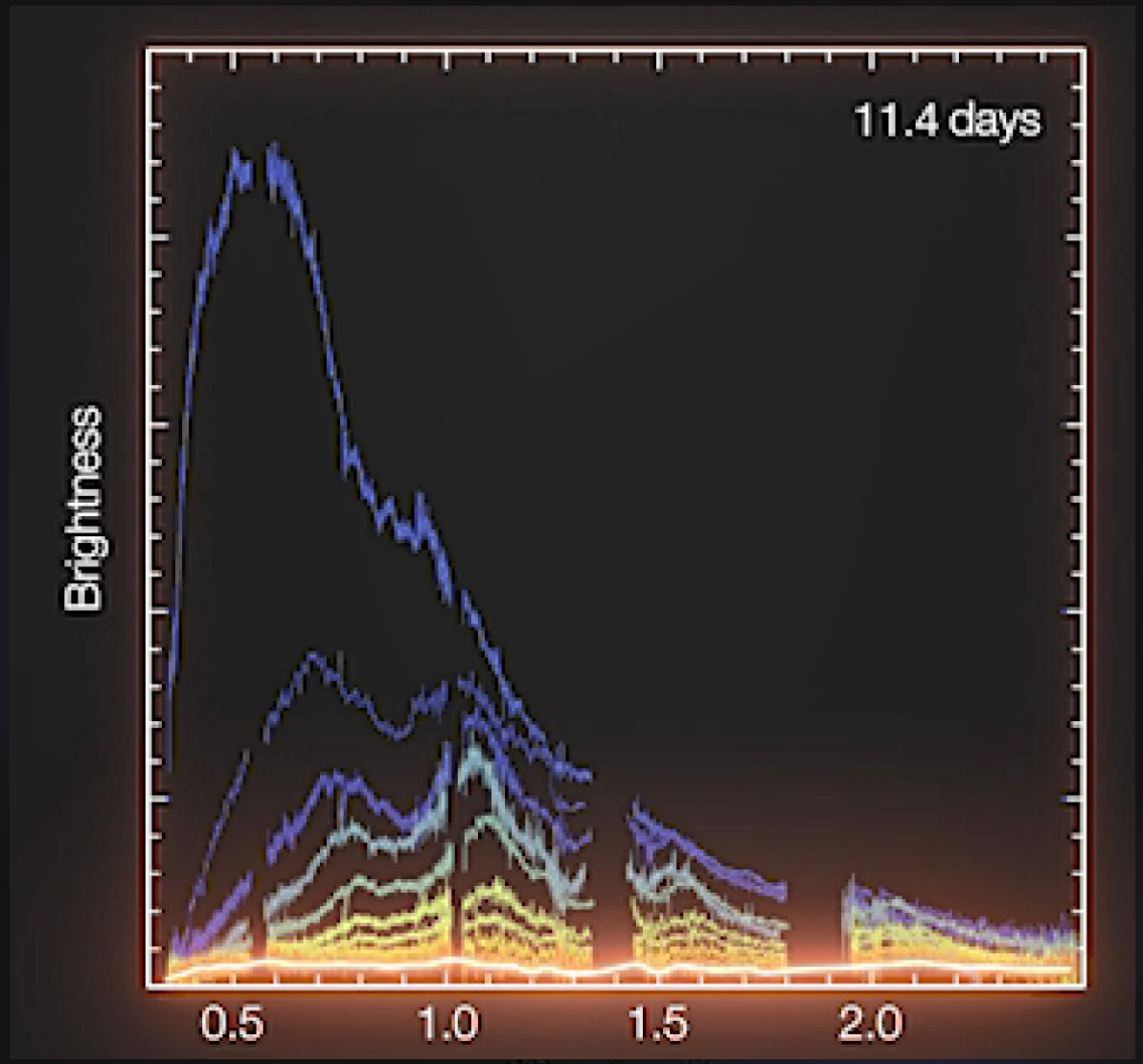
t0 1.7s +5.23hrs +10.87 hrs +9 days +16 days

LHV sky localization



Credits: M. Branchesi

LVC + astronomers, ApJL, 848, L12



EJECTED MASS $\sim 0.03 - 0.05\ M_{\odot}$

EXPANSION VELOCITY $\sim 0.1 - 0.3\ c$

First spectral identification of the kilonova emission

- the data revealed signatures of the radioactive decay of **r-process nucleosynthesis**

(Pian et al. 2017, Smartt et al. 2017)

- BNS merger **site for heavy element production in the Universe!**

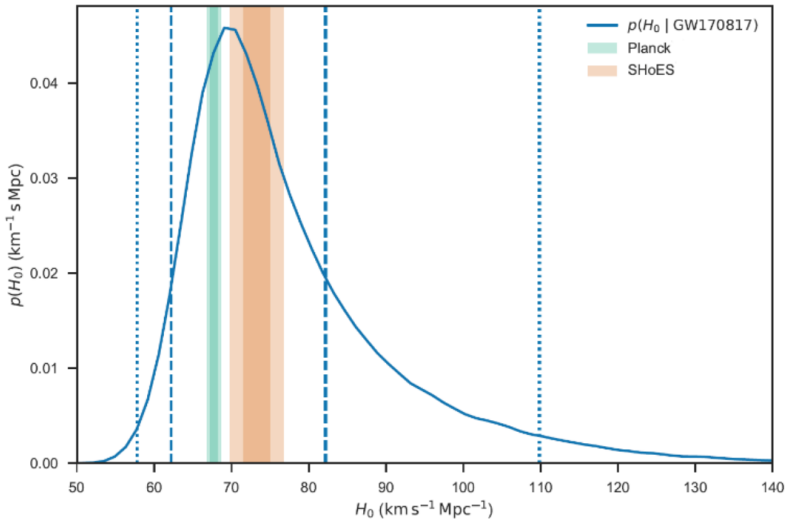
(Cote et al. 2018, Rosswog et al. 2017)

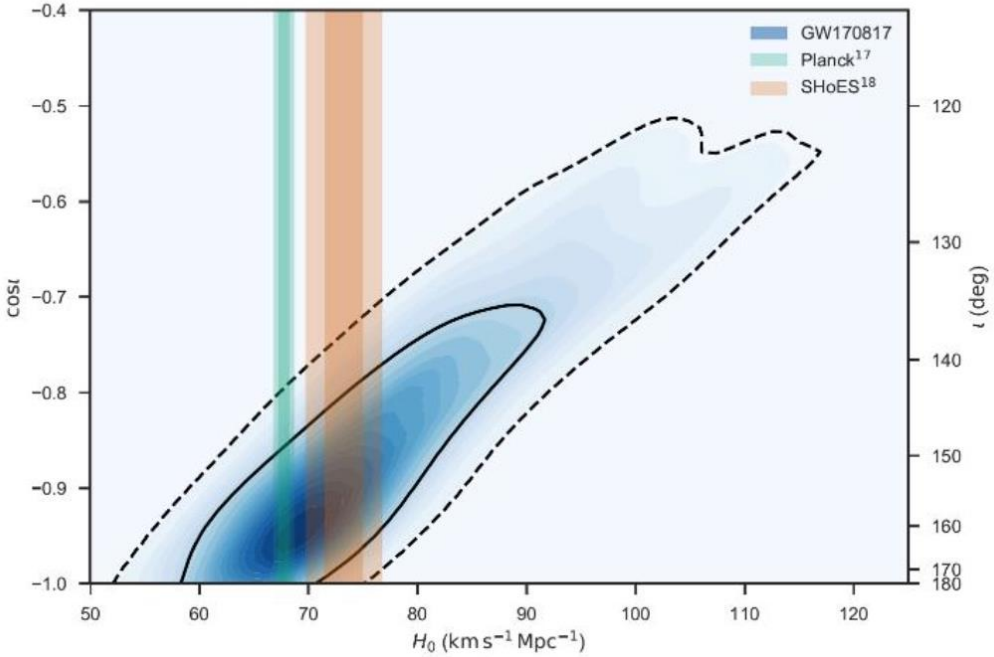
Credits: M. Branchesi

H_0 measurement

Combine distance from GW:

$$d = 43.8^{+2.9}_{-6.9}\ \text{Mpc}$$





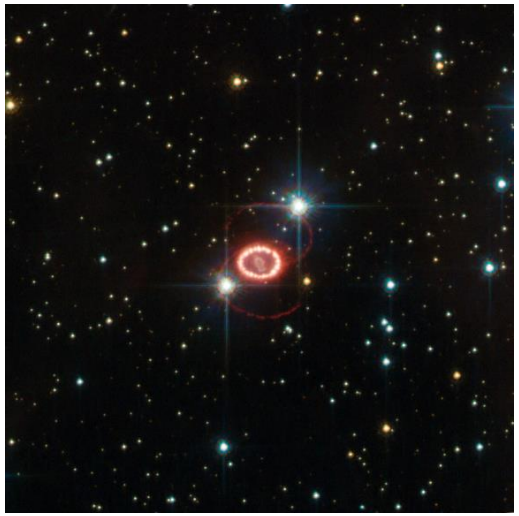
And NGC4993 recession velocity we have:

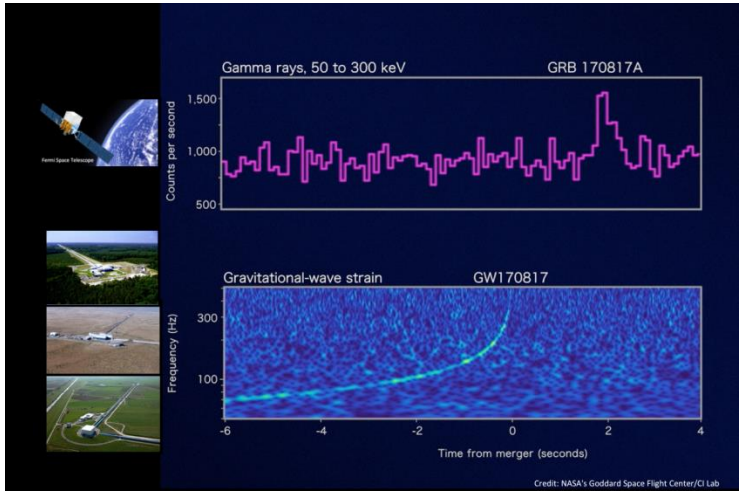
$$H_0 = 70^{+12.0}_{-8.0}\ \text{Mpc}$$

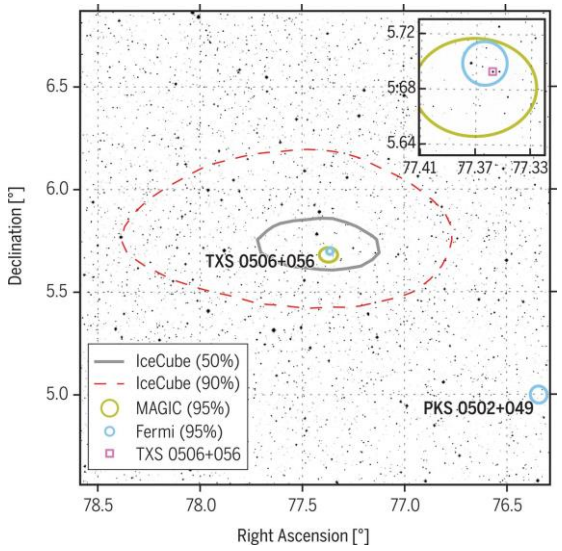
Abbott et al. 2017, Nature, 551, 85A

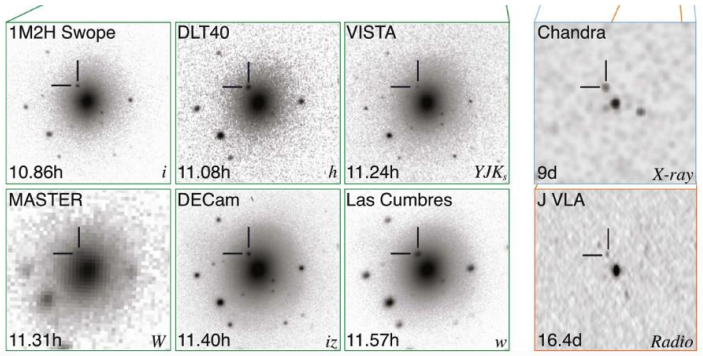
The END (?)

Sorgente	EM	GW	ν
Sun	✓		✓
Supernova 1987	✓		✓
BNS 170817	✓	✓	
TXS0506+056	✓		✓









- BNS new discoveries
  - Short GRB produced by BNS
  - GW velocity measurement
  - Heavy element production
  - H_0 measurement