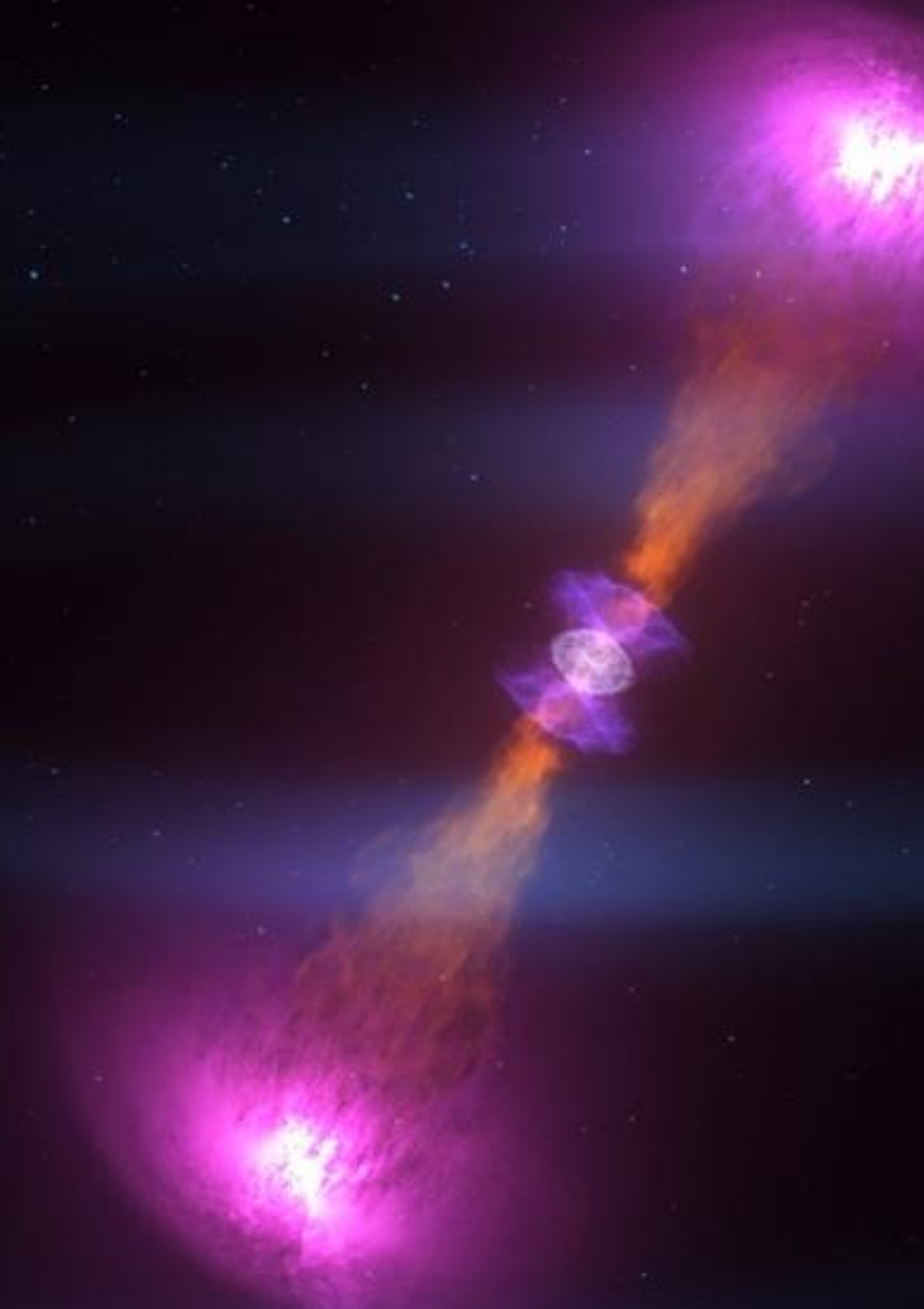


Astronomia Multimessaggero

La nuova frontiera nello studio dell'Universo

M. Razzano
Università di Pisa & INFN-Pisa

Incontri di Fisica dell'Area Pontecorvo
10 ottobre 2018

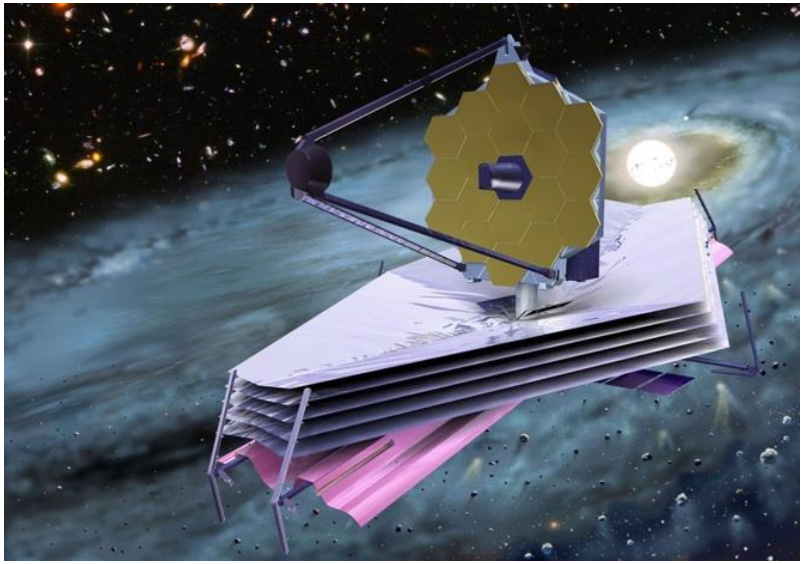
Present and future optical telescopes

Telescopio Galileo
(Asiago, 1.8 m)

Hubble Space
Telescope (2.4 m)

Keck Observatory
(Mauna Kea, 2x10m)

Present and future optical telescopes



2021 -
James Webb Space Telescope
(8 m)

2024 -
European Extremely Large Telescope
(39 m)

*

Beyond optical

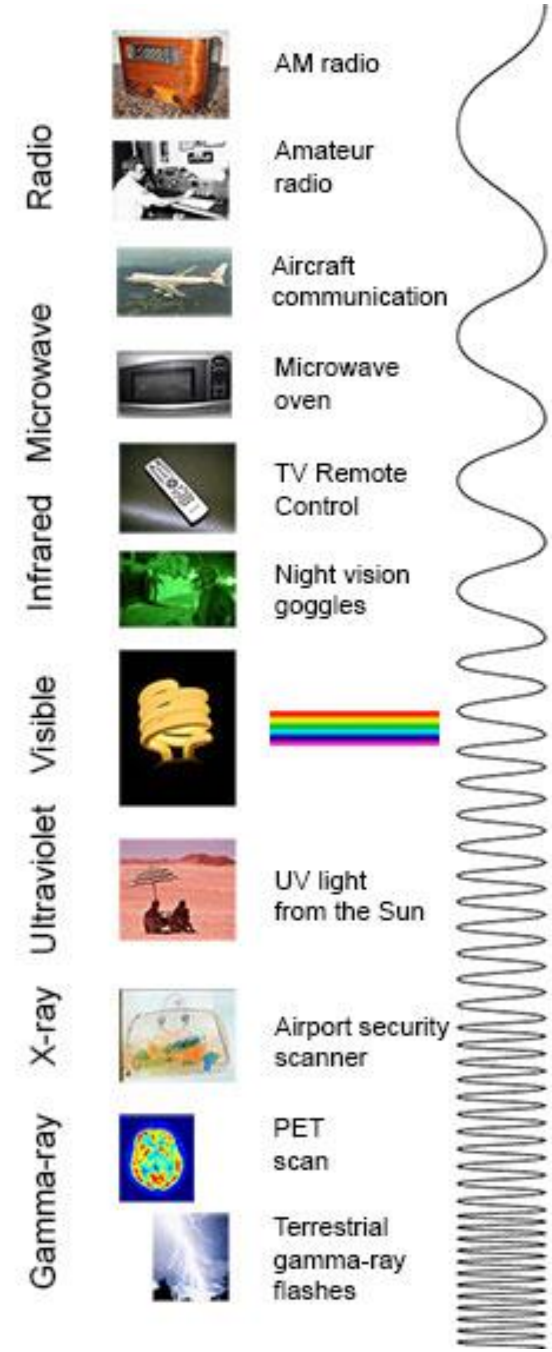
1930's - Radioastronomy
K. Jansky (Milky Way)

1830's → 1950's+ Infrared astronomy
W. Herschel et al. (Moon, stars, etc)

1940's - Ultraviolet astronomy
Rockets, satellites (Sun, stars)

1940's - 1960's – X-ray astronomy
Rockets,satellites (Sun, Scorpius X-1)

1960's Gamma-ray astronomy
Rockets,satellites (Diffuse, Sun)



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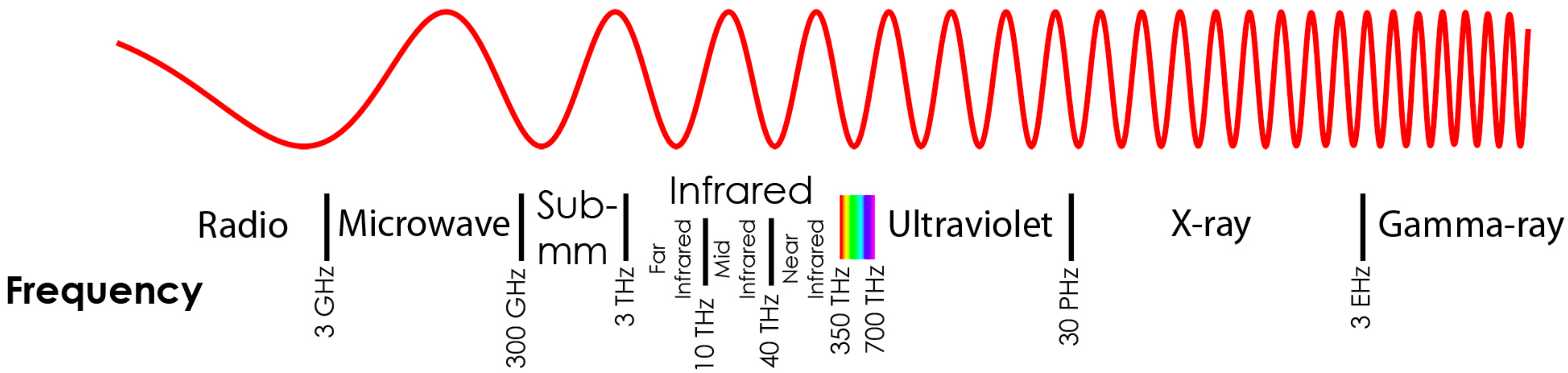
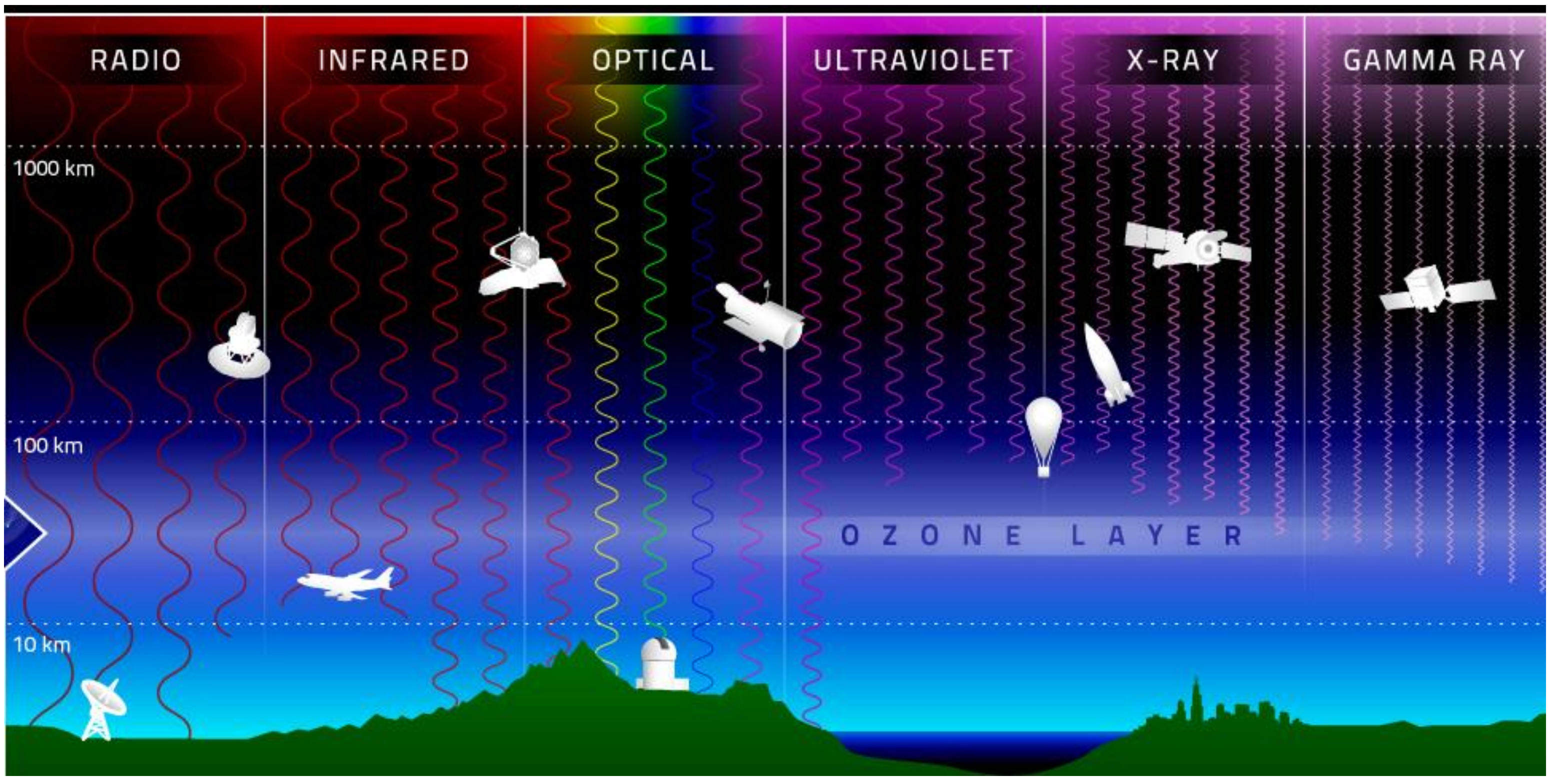
Multiwavelength astrophysics





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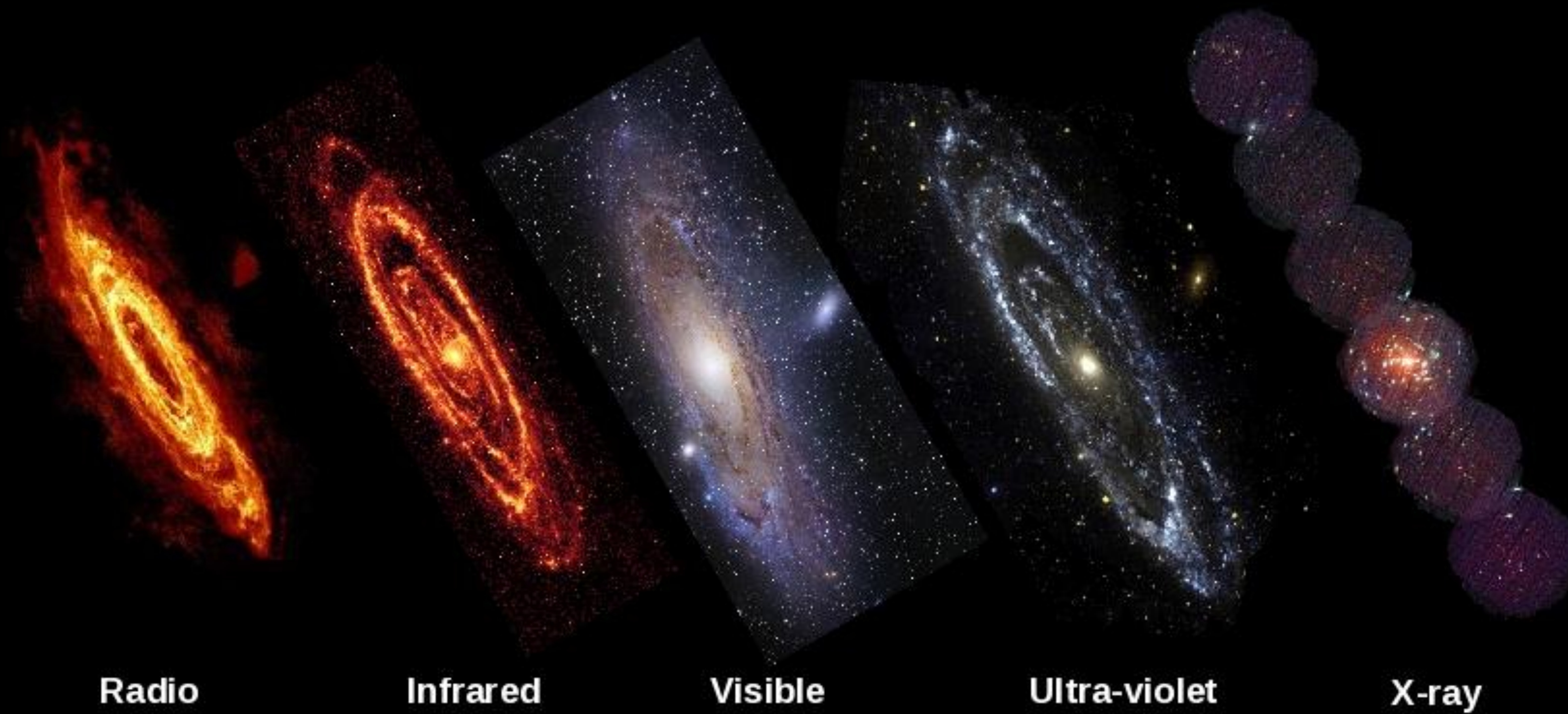
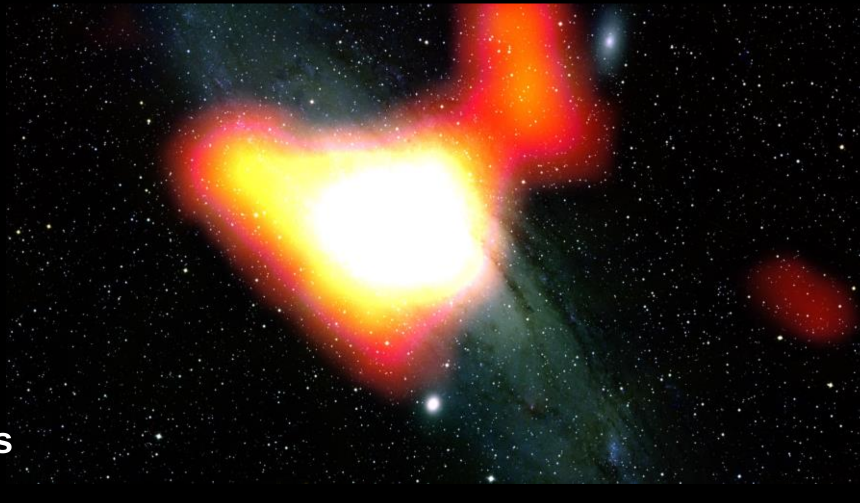
NGC 224 (Andromeda Galaxy)

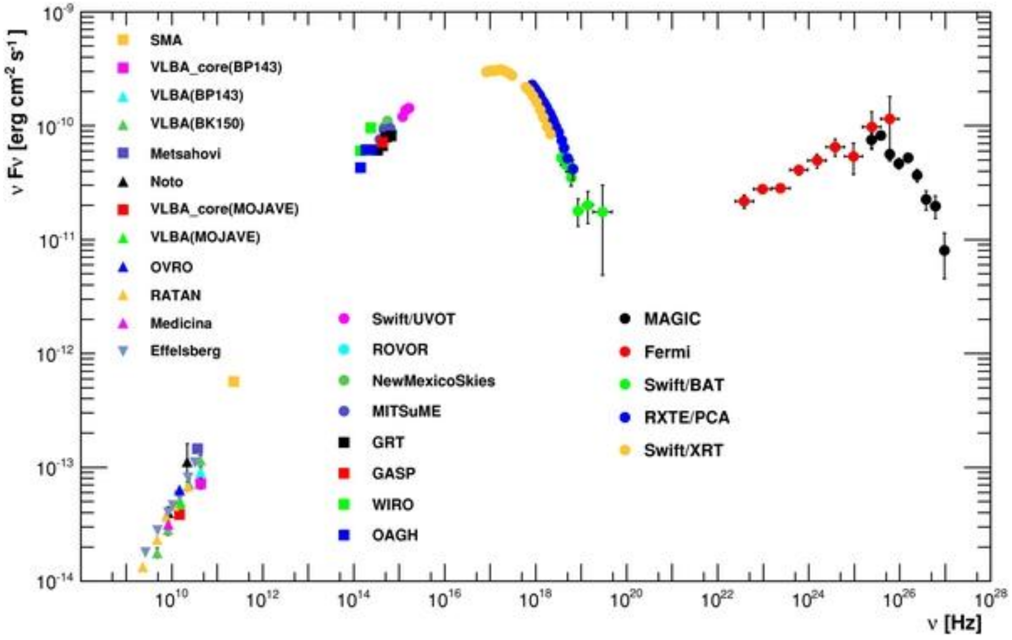


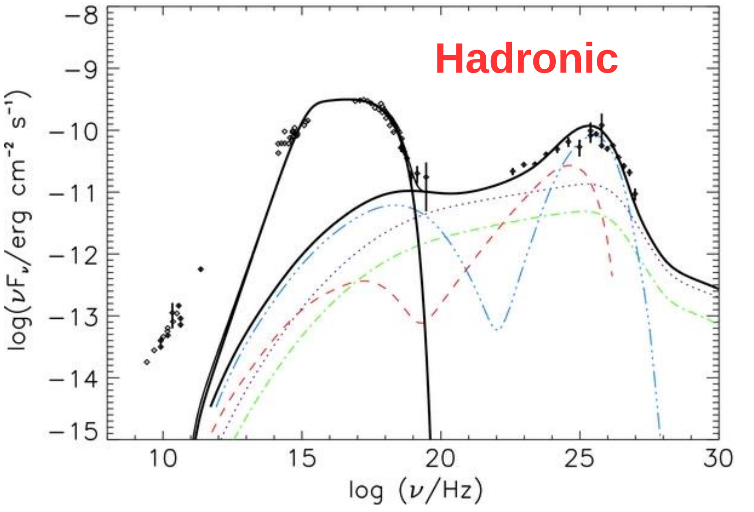

Gamma rays

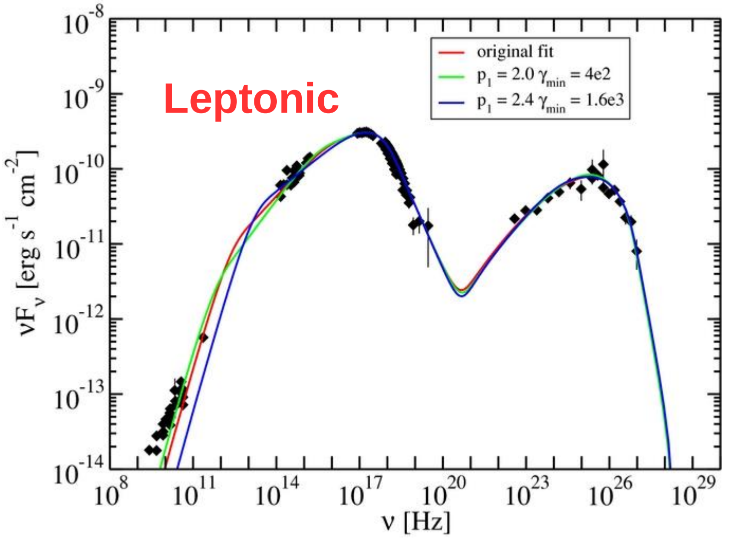
What do we learn?

Case study

Emission processes in Active Galactic Nuclei (blazar)
Here Markarian 421







Abdo et al. 2011, ApJ, 736,131

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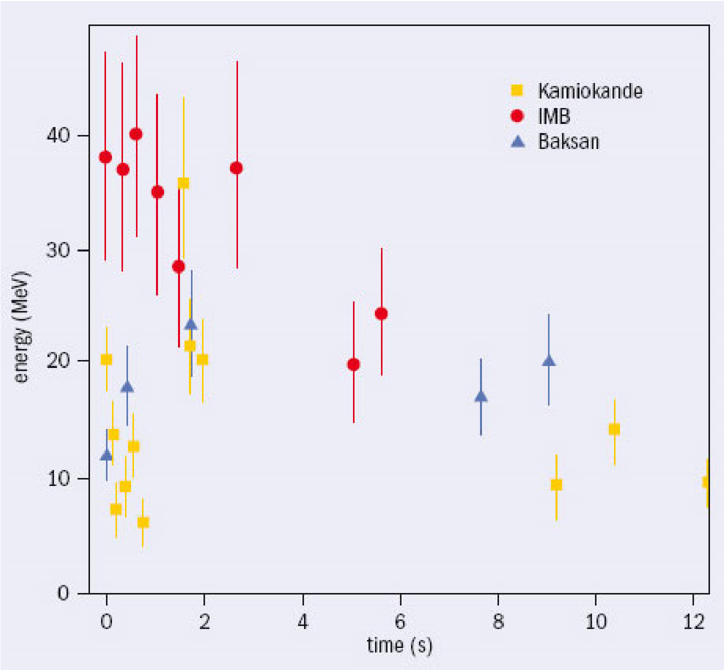
SN 1987A in Large Magellanic Cloud

Feb 23/24, 1987

Jan 20, 2017



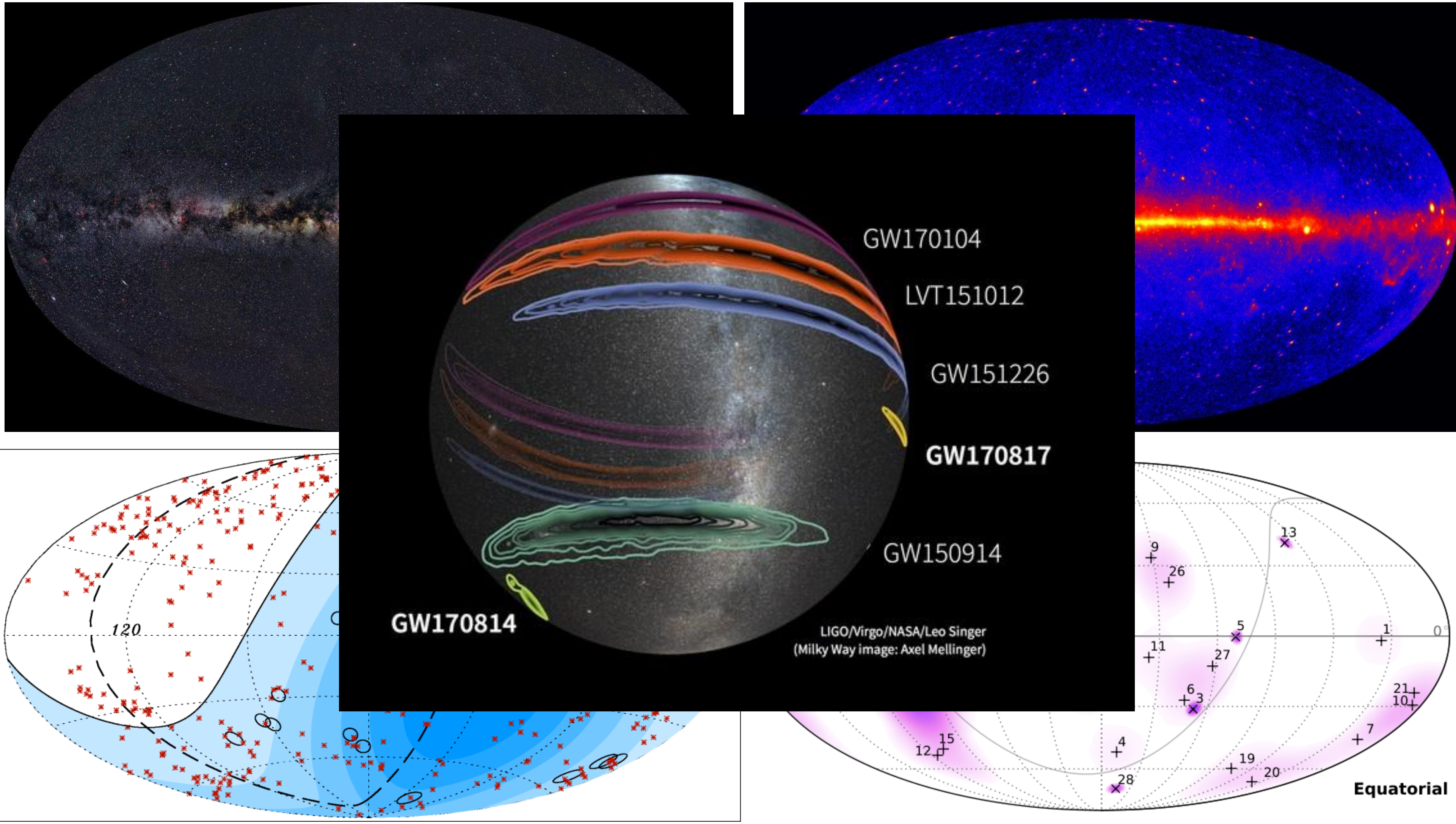
- **T-3h**
- Kamiokande II (Japan)
- Irvine-Michigan-Brookhaven (USA)
- Baksan (Russia)

*

The multimessenger sky today

Optical (APOD)

Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

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Why the multimessenger astronomy?

- Providing a deeper insight into the most extreme events in the Universe

- Exploring the nature of their progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)

- Accessing complementary information:
  - EM → emission processes, acceleration mechanisms, environment
  - GW → mass distribution
  - Neutrinos → nuclear processes, etc.

- How? Rely on precise (arcmin/arcsecond) localization
  - Identify an EM counterpart
  - Pinpoint host galaxy of a merger

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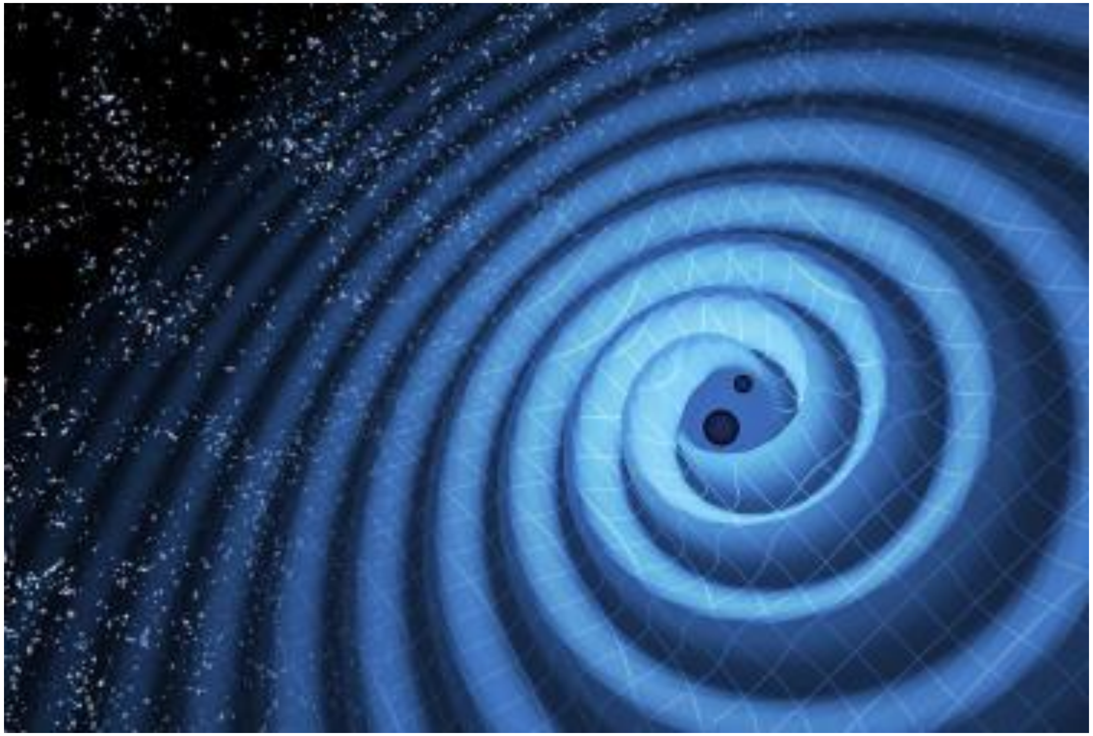
Gravitational waves, the new "messengers"

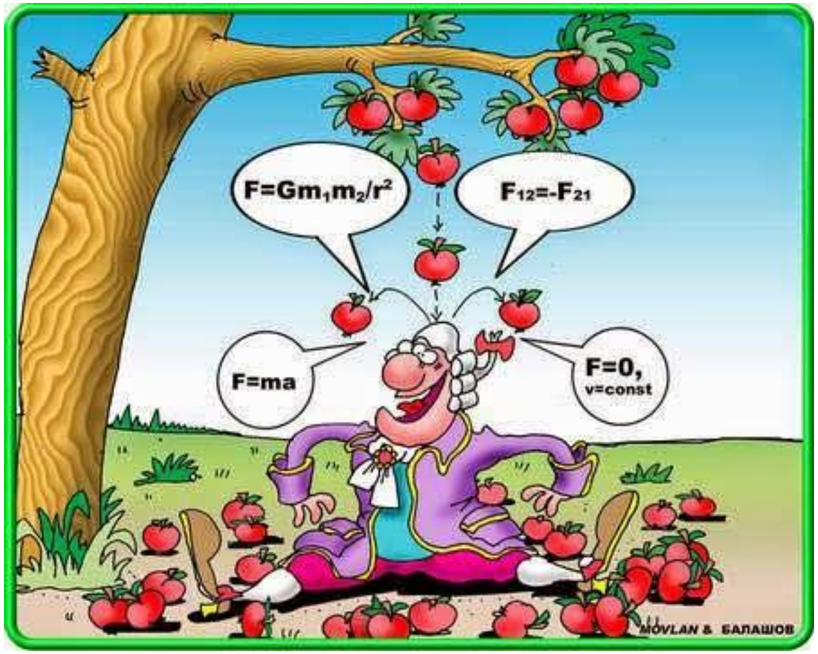


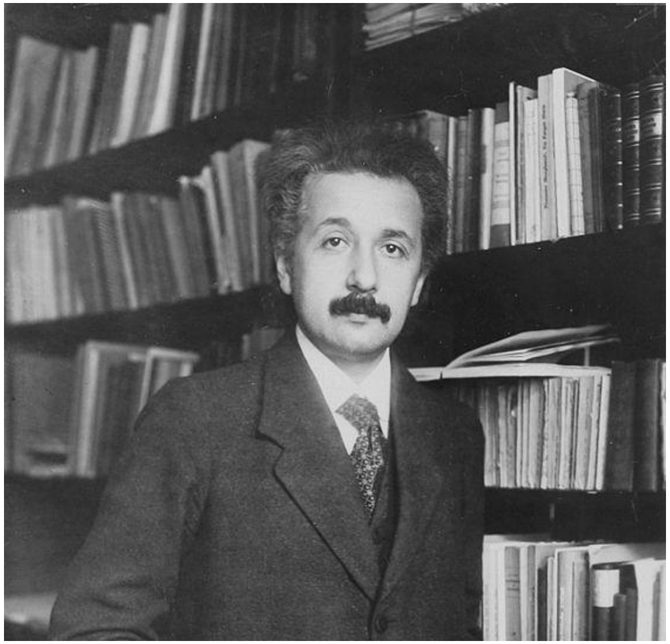
- Ripples in spacetime
- Traveling as speed of light

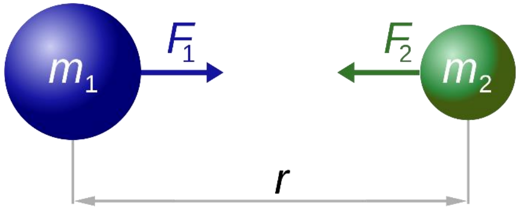
- Large masses/violent phenomena
- e.g
  - Merging black holes or neutron stars
  - Supernova
  - Rotating neutron stars

*

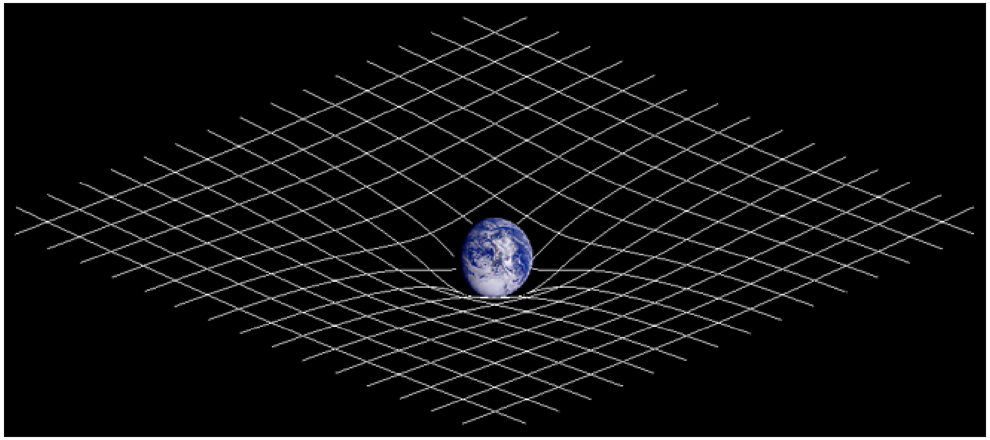
GWs and Einstein's theories of gravity







$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



1686 **1915**

*

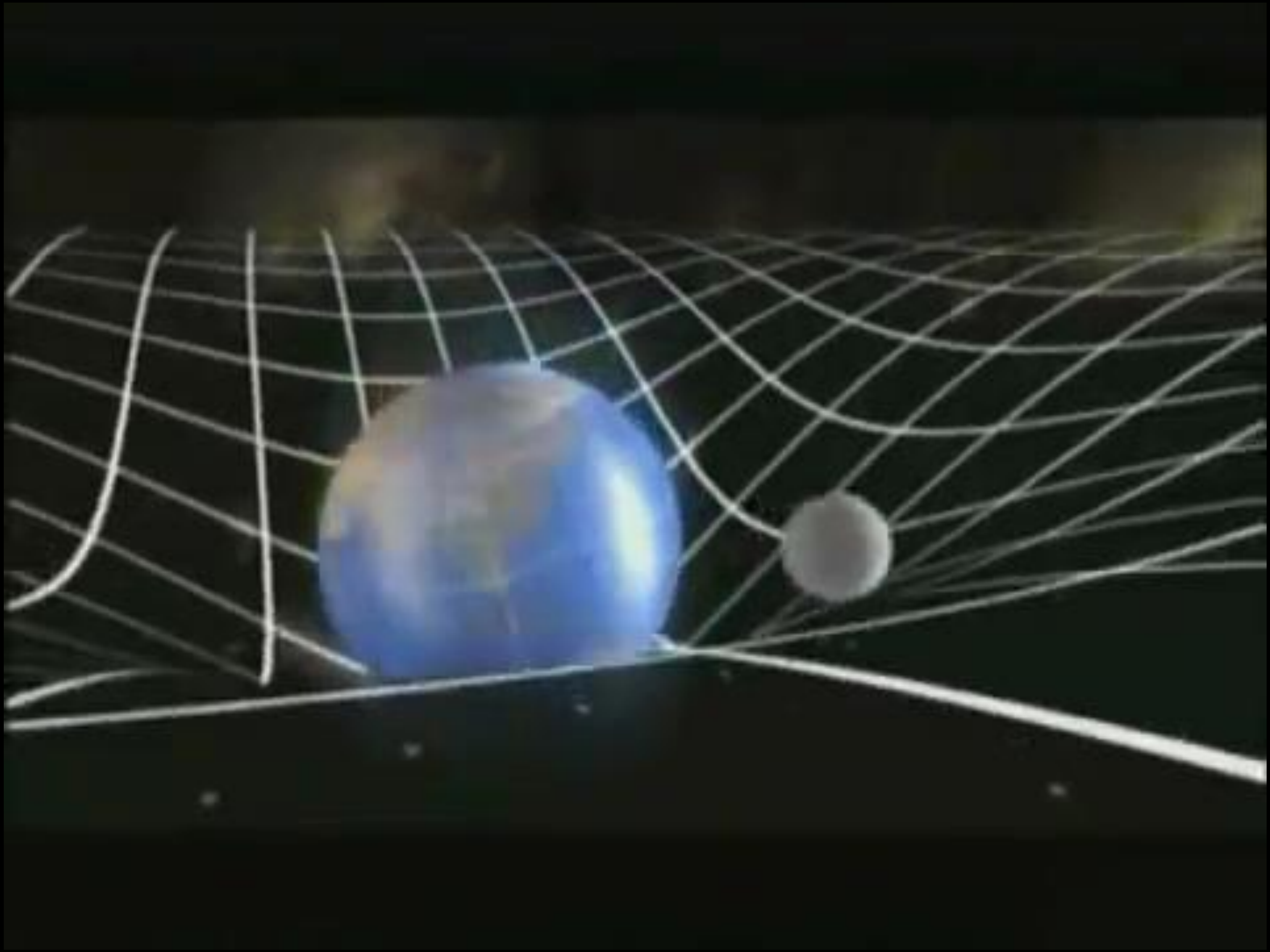
Einstein's field equations

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

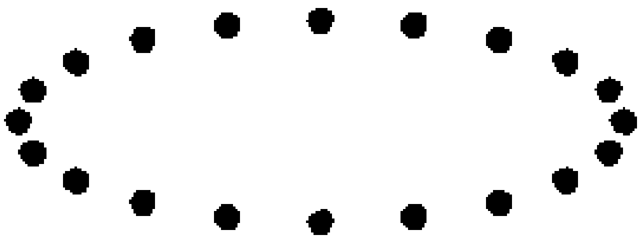
"Mass tells space-time how to curve,
and space-time tells mass how to move"
(J. Wheeler)

*

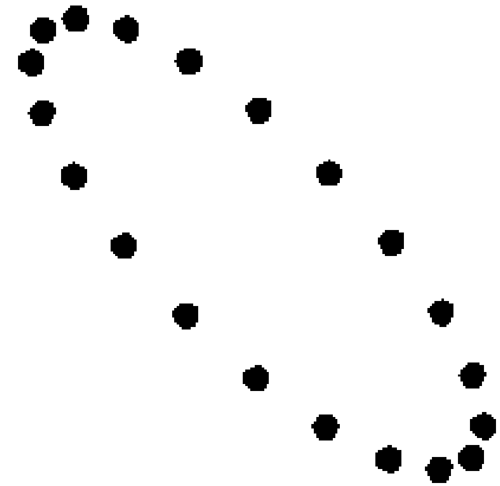
The curved spacetime



The effects of Gravitational Waves



polarization “+”

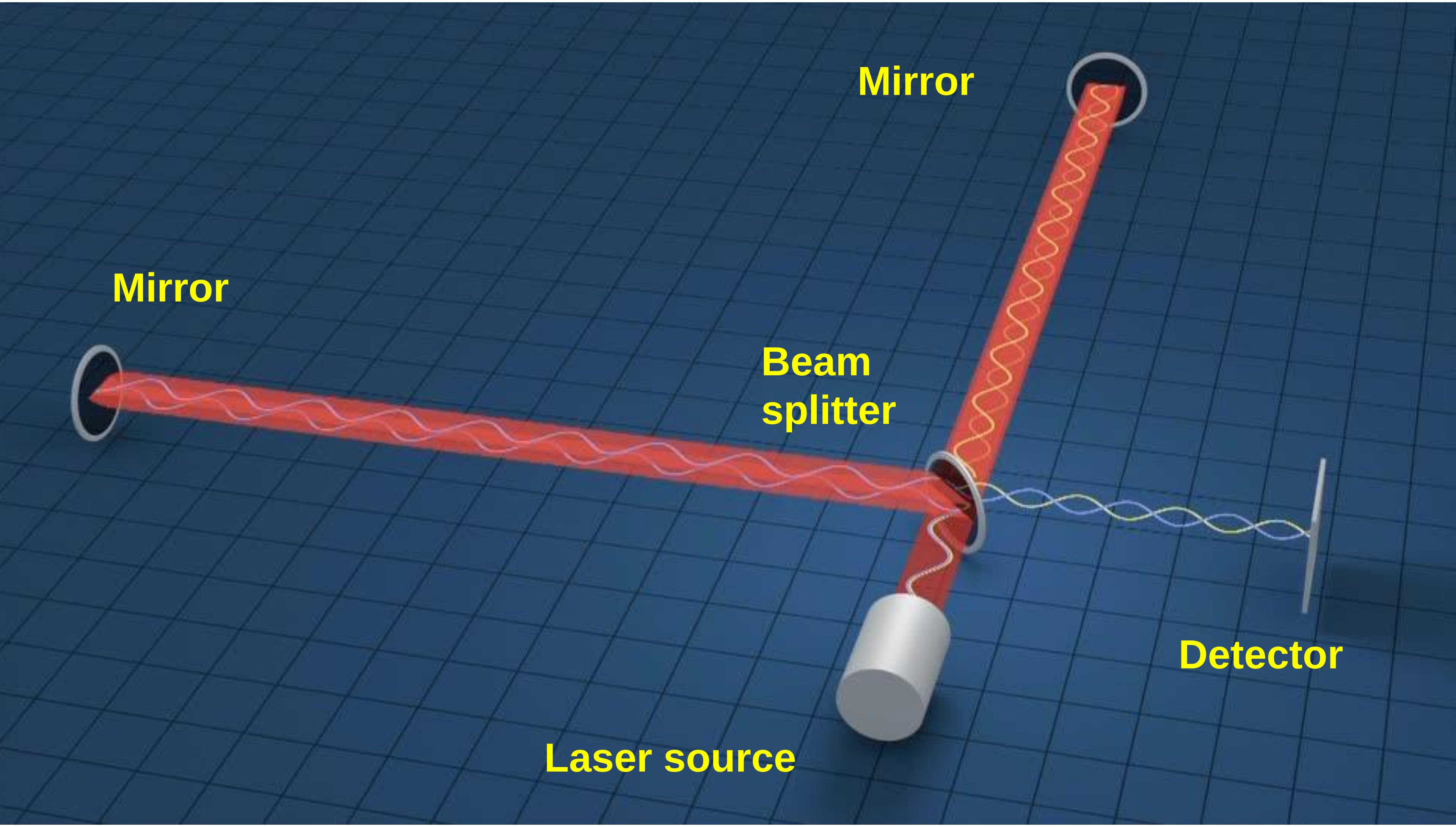


polarization “x”

Typically, differential displacement $\Delta L/L \approx 10^{-21}$

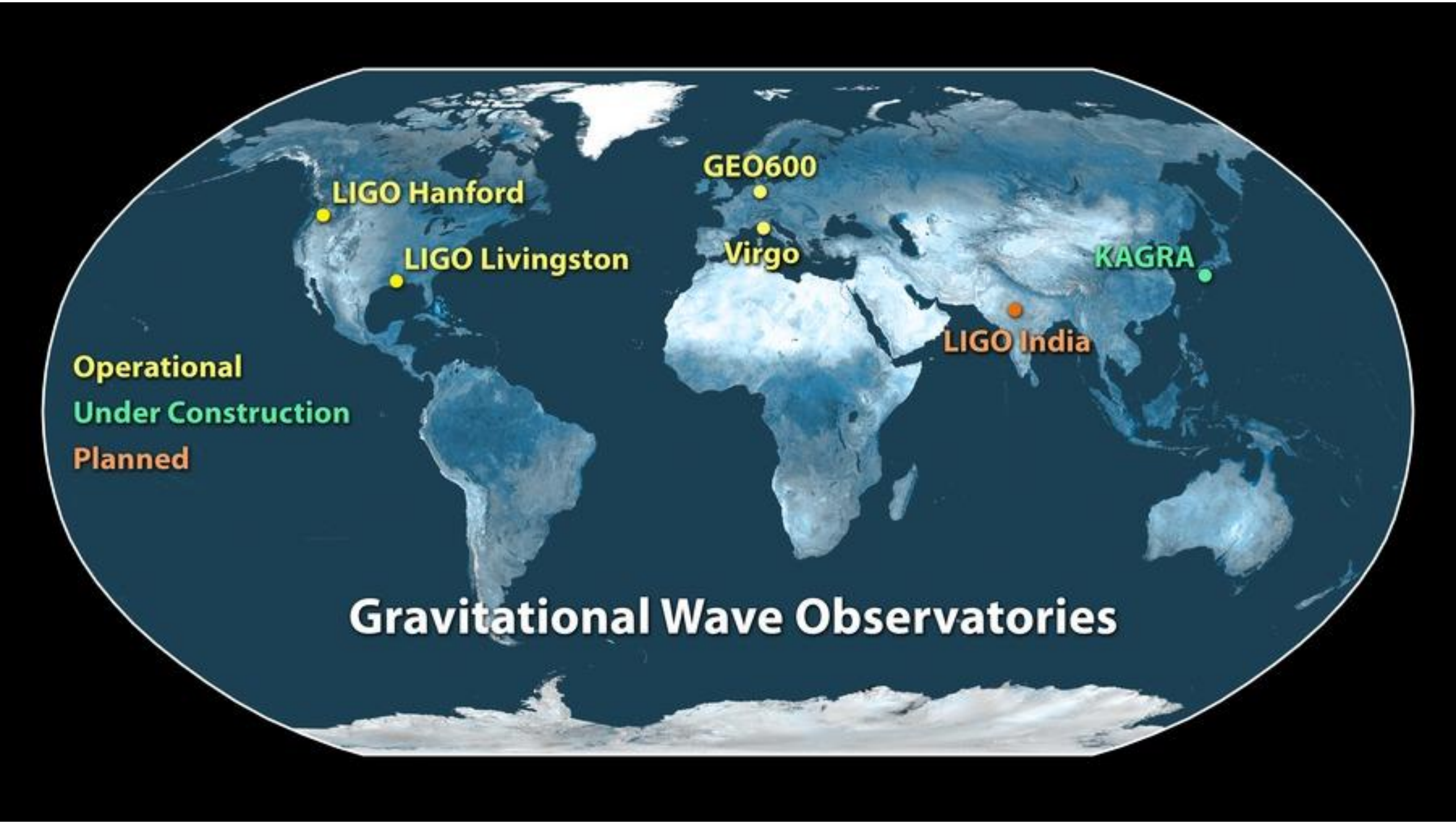
For values in the order of 1 km, this results in $\Delta L \approx 10^{-18}$ m !

Detecting Gravitational Waves



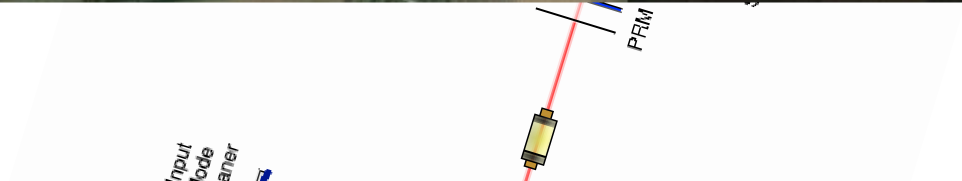
0

A global network



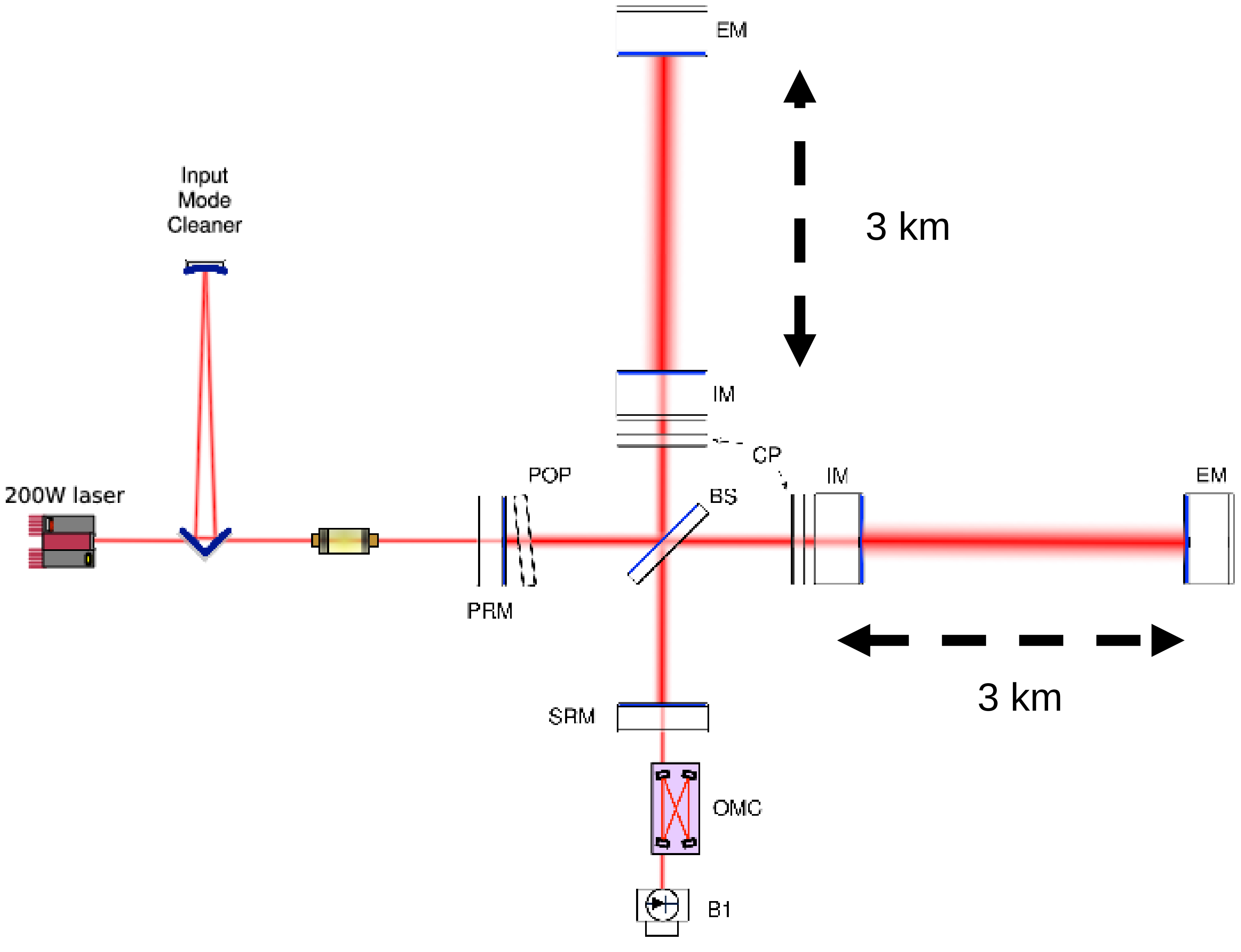
The Virgo interferometer

The Virgo interferometer

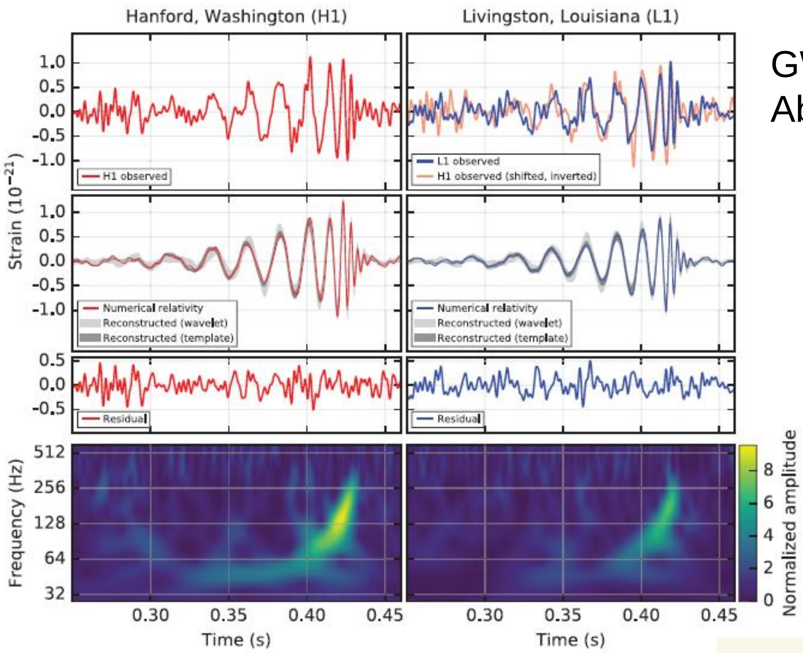


Advanced Virgo

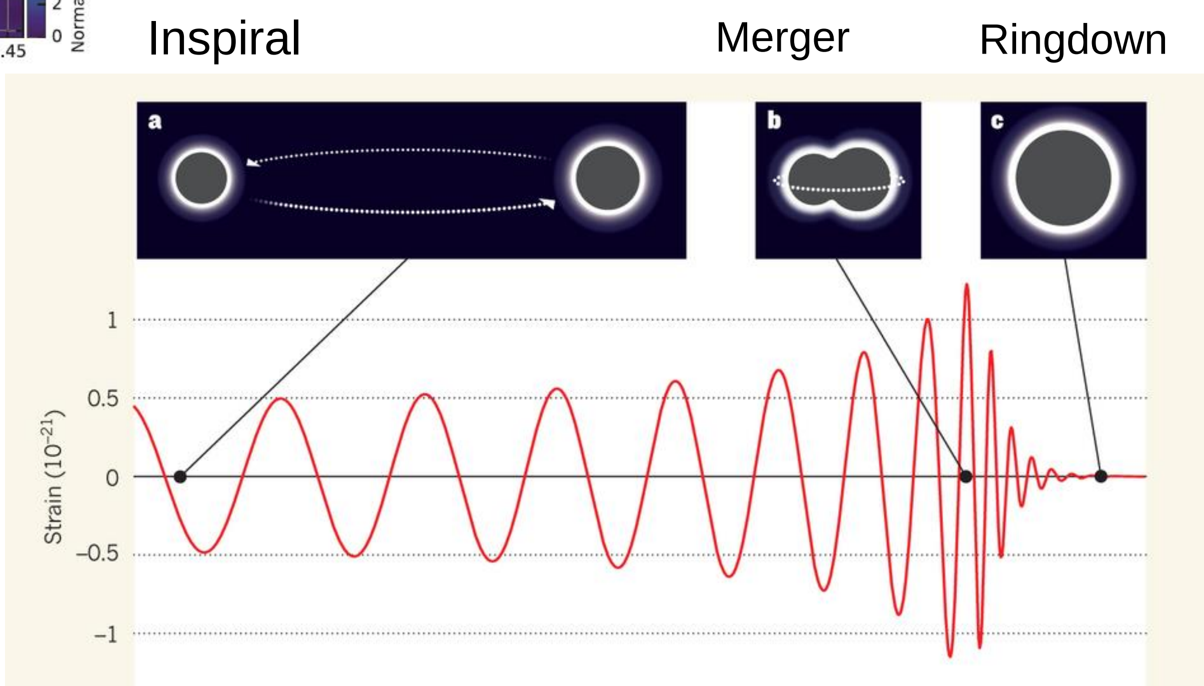
Advanced Virgo



The first detections



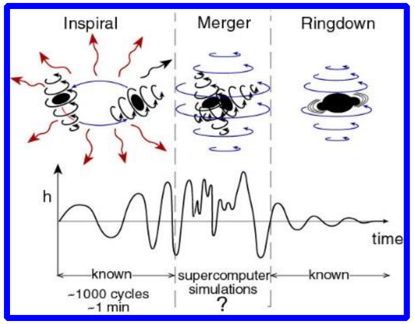
GW15109
Abbott+16, PRL116,6



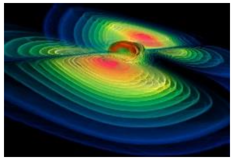
Expected (multimessengers) sources by Advanced LIGO/Virgo

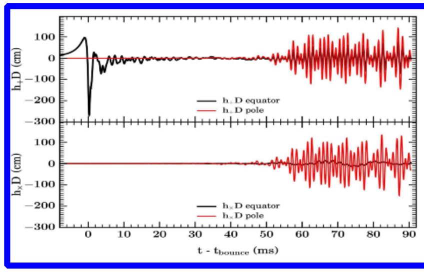
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$



- **Core-collapse of massive stars**
  - Uncertain waveforms
  - $E_{gw} \sim 10^{-8} – 10^{-4}\ Mc^2$

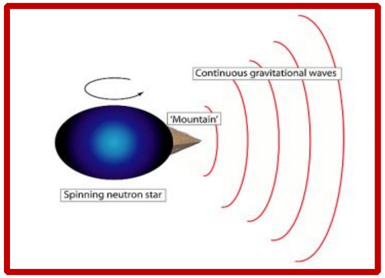




Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic



- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency

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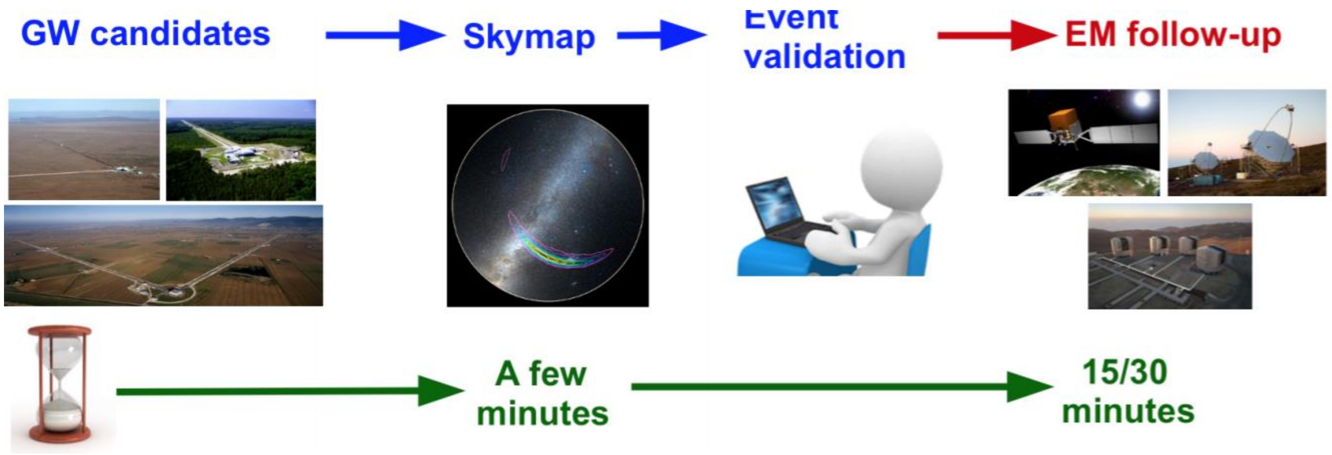
The follow-up strategy

- Advanced Era (2015-)
  - Detection from GW pipelines → quick meeting (follow-up "advocates"+experts)→Alert !
  - Alerts sent to astronomers via LVC GCN (covered by MoU, >90 teams, >200 instruments)
  - Broadband coverage (EM+neutrinos)



EM event	EM band	Timescale
Prompt emission	Gamma rays	<seconds
Afterglow	X-ray, optical, radio	Hours-days
Kilonova-macronova	Optical-near IR	Days-weeks
Radio blast wave	Radio	Months-years

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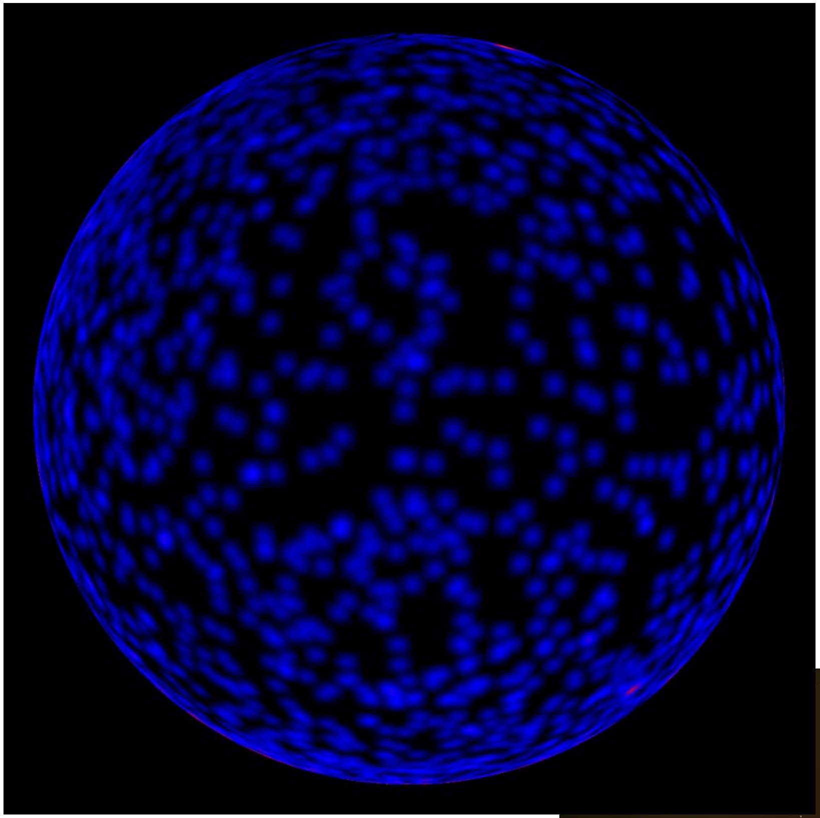
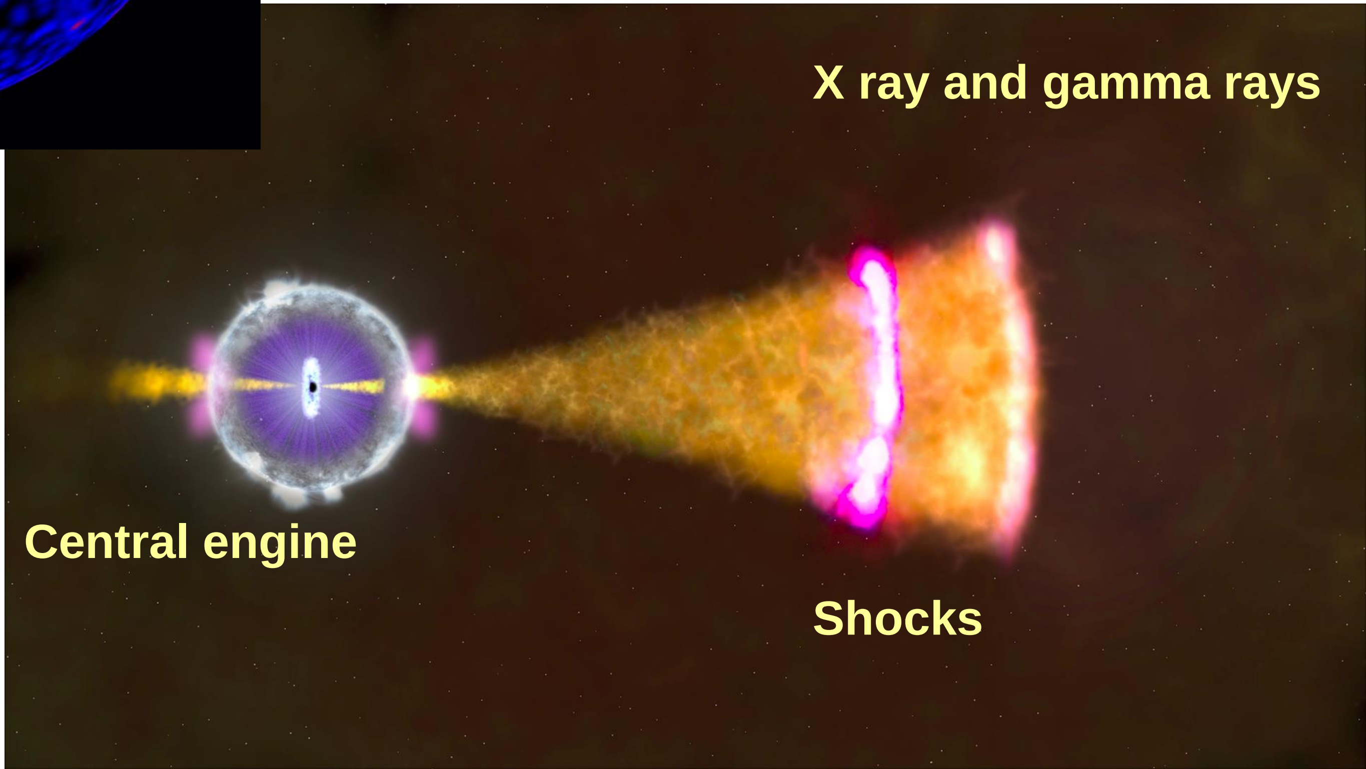


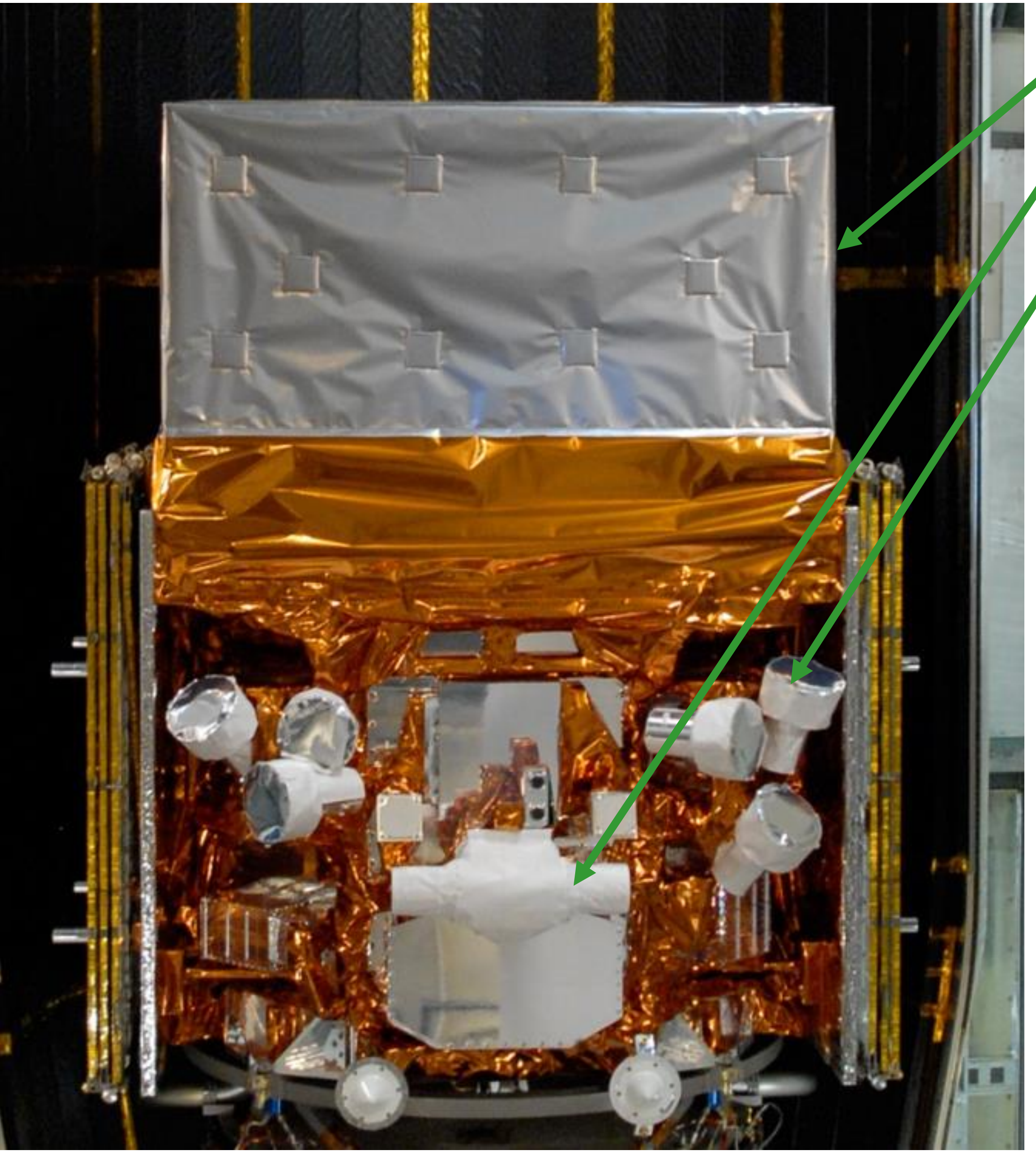
Multimessenger Science case: Gamma Ray Bursts

GRB130427A
(Fermi-LAT)



Credits: D. Darling (top), NASA (right)

The Fermi Observatory



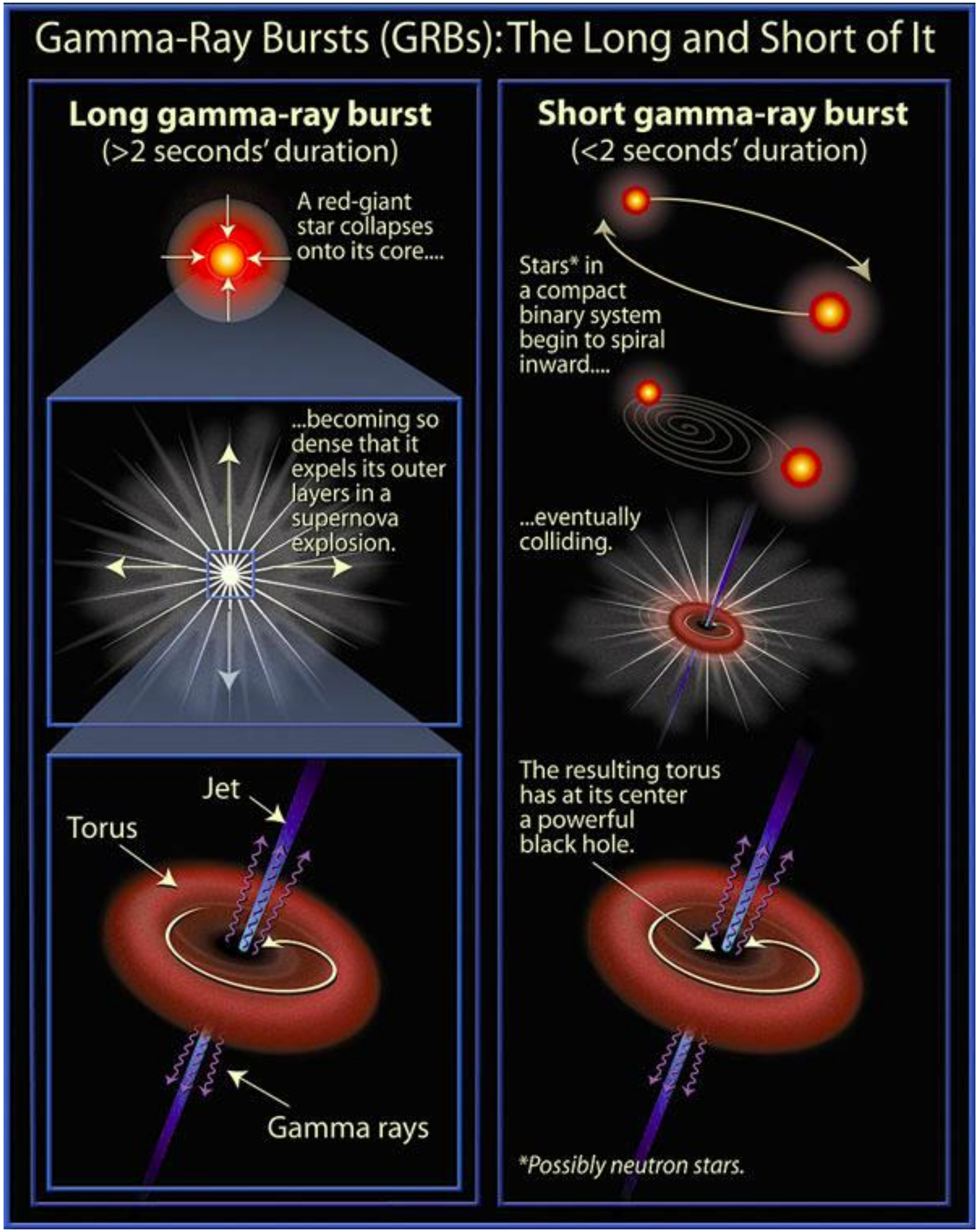
Large Area Telescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

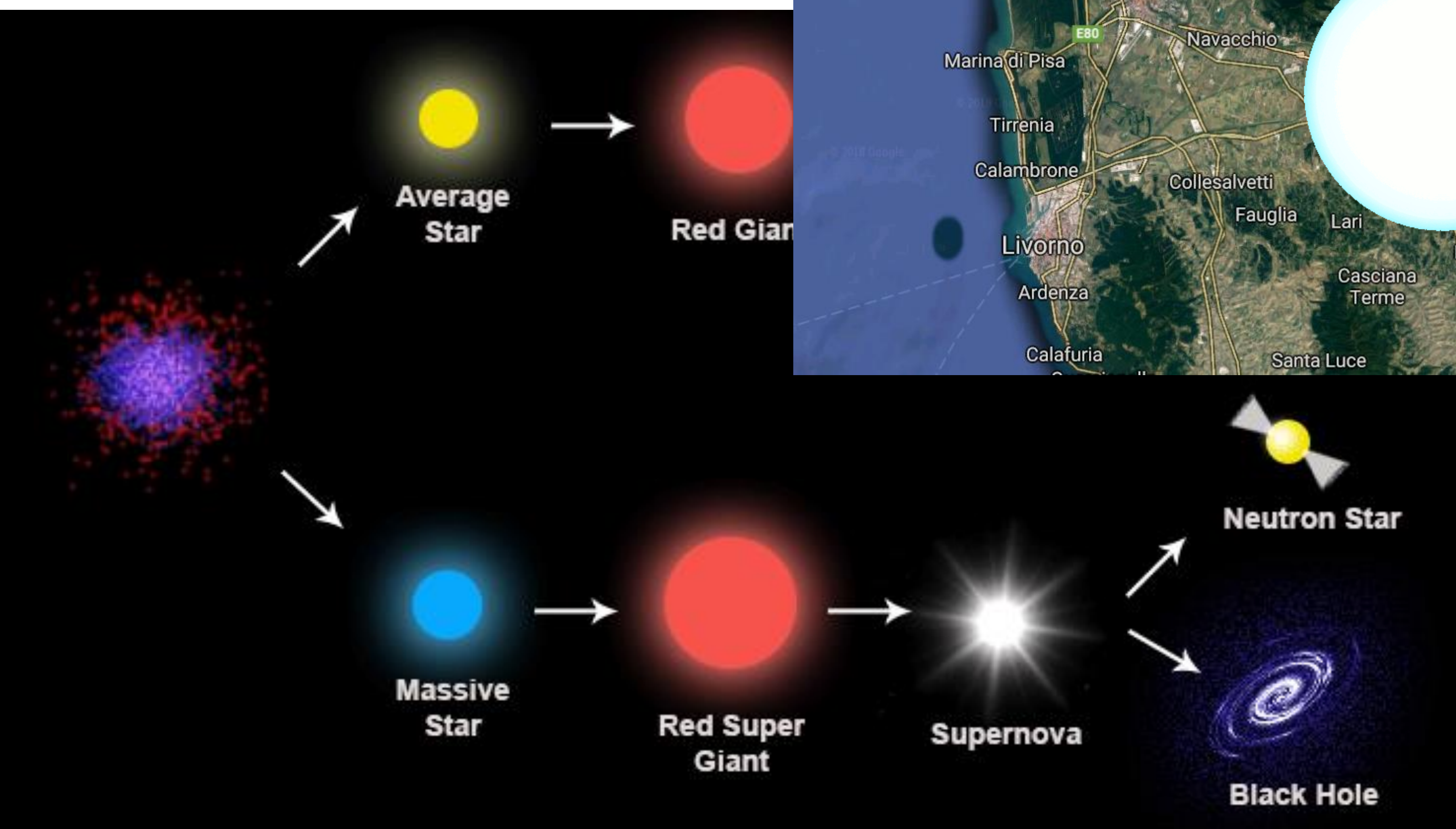
KEY FEATURES

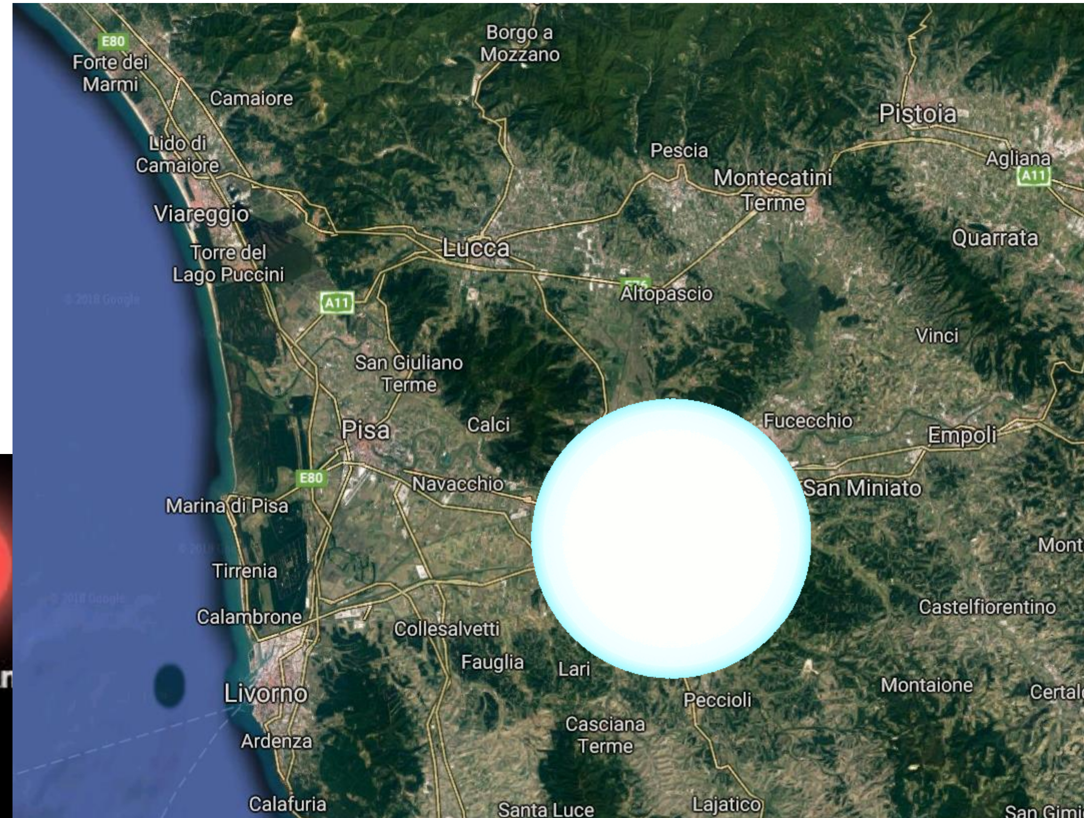
- Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!
- Large effective area
- Large leap in all key capabilities. Great discovery potential.

The origin of GRBs?

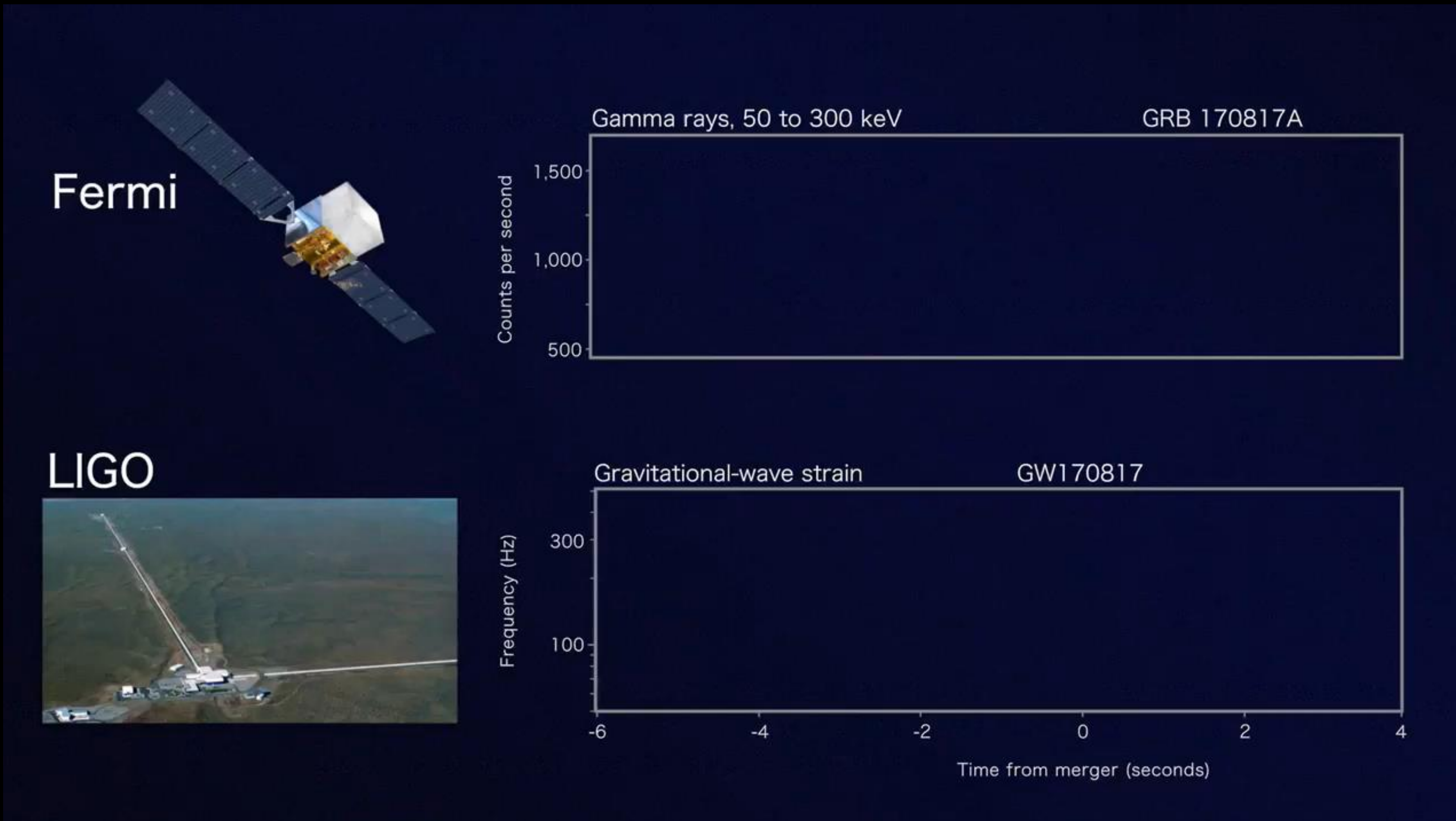


…what is a neutron star?



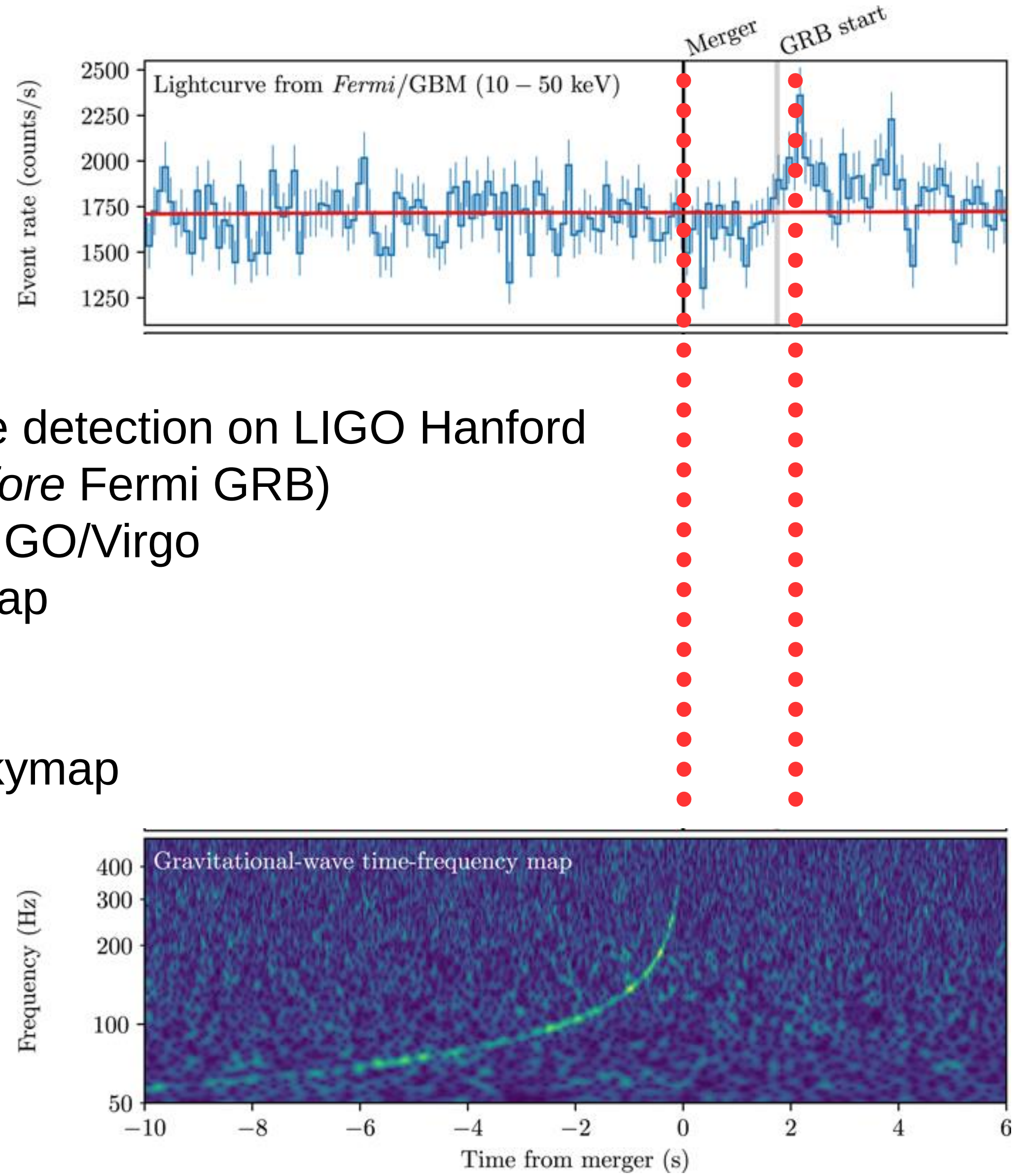


August 17, 2017



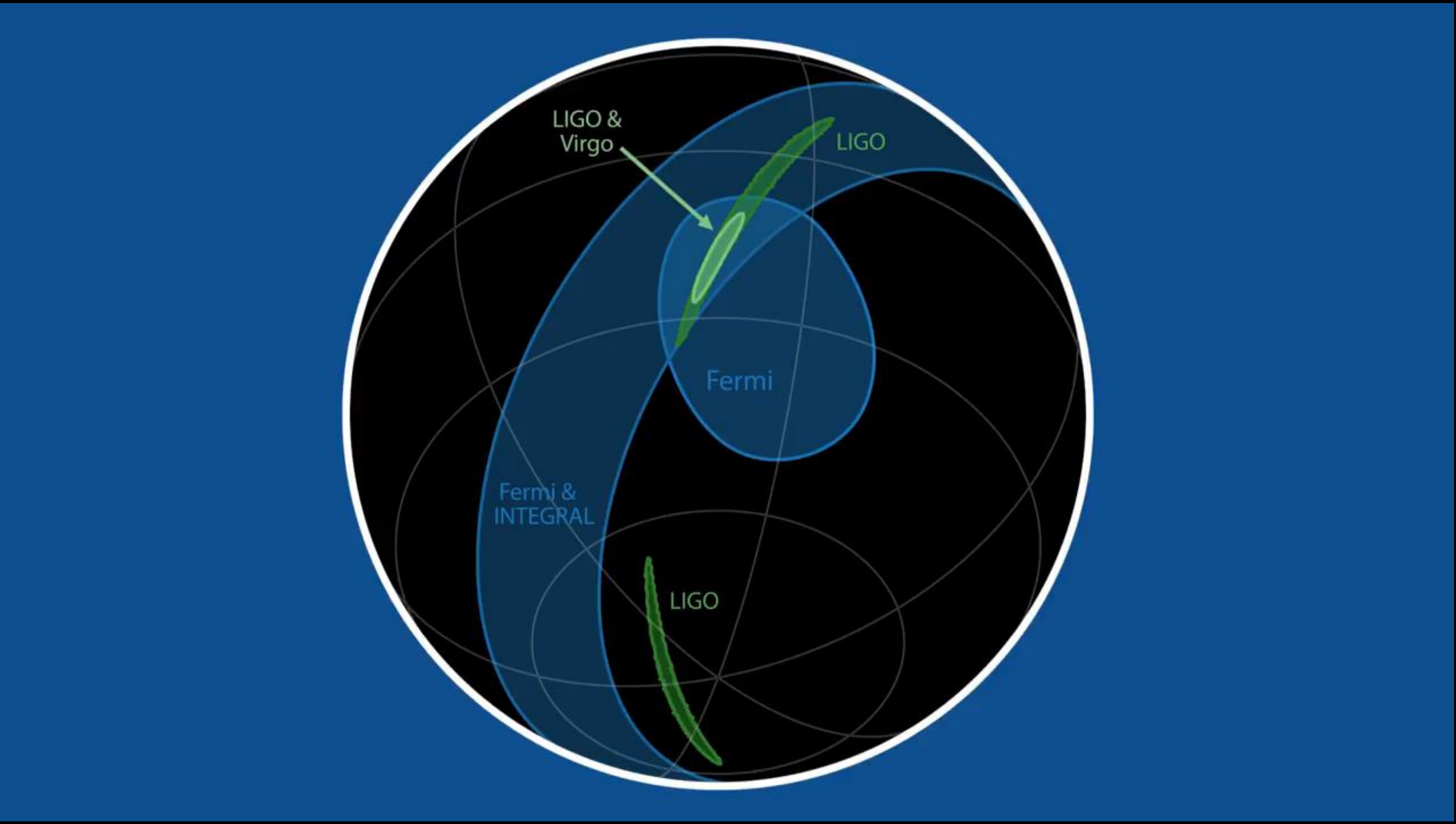
Timeline of the GW170817 discovery

- **12:41:06 UTC** : onboard *Fermi*-GBM trigger
- **12:14:20 UTC** : Automatic Fermi Gamma-ray Coordinates Network (GCN)
- **~12:47 UTC** : low-latency GW pipeline detection on LIGO Hanford
  - Detected time 12:41:04 (1.7 sec *before* Fermi GRB)
- **13:21:42 UTC** : First alert sent from LIGO/Virgo
- **17:54:51 UTC**: First LIGO-Virgo skymap
  - Error region ~31 deg^2
  - Distance 40 Mpc
- **23:54:40 UTC**: Refined LIGO-Virgo skymap

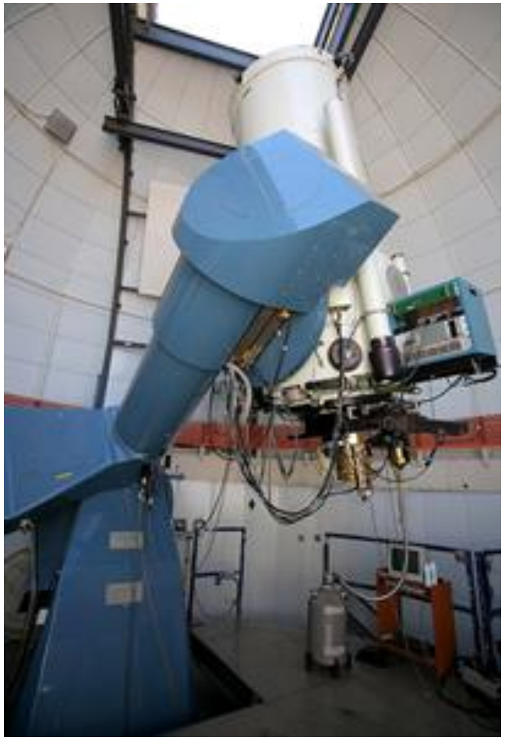


Abbott+17, ApJ 848,2

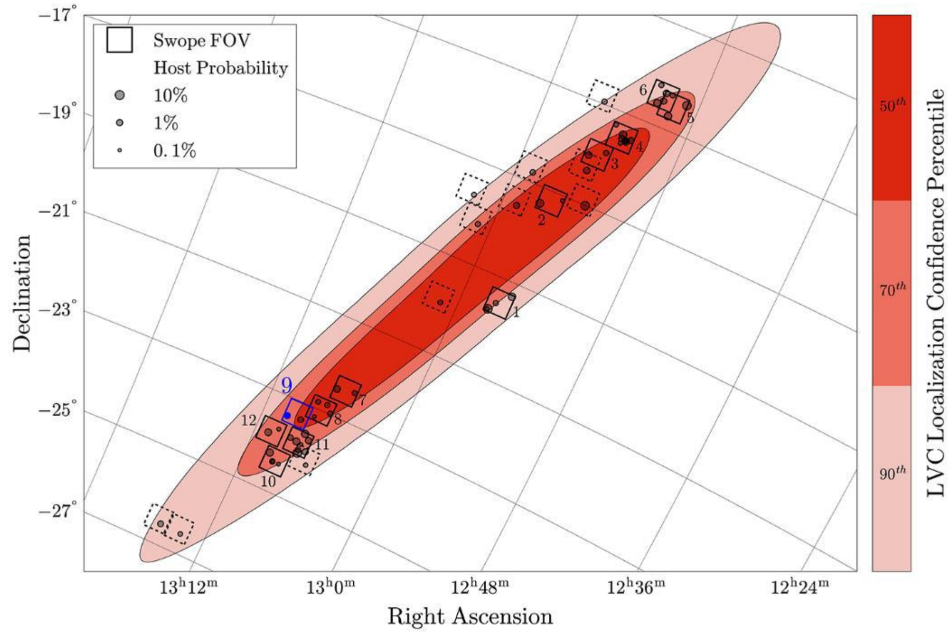
Sky localization



The optical transient

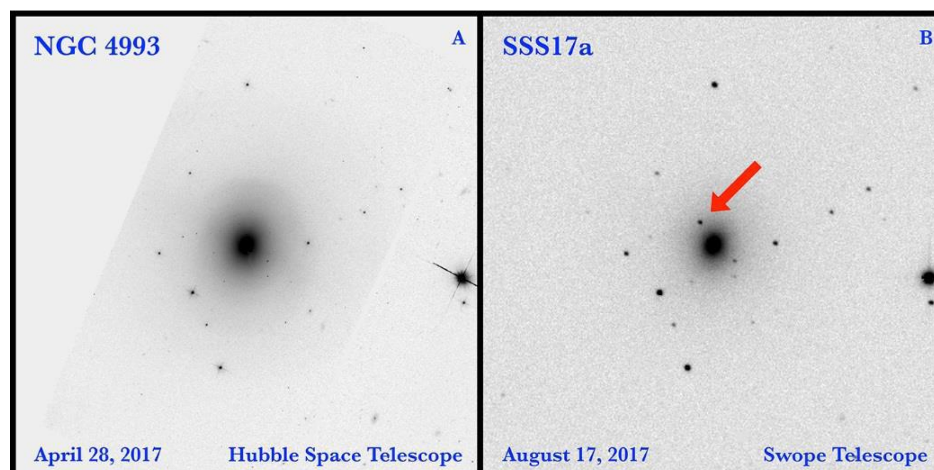


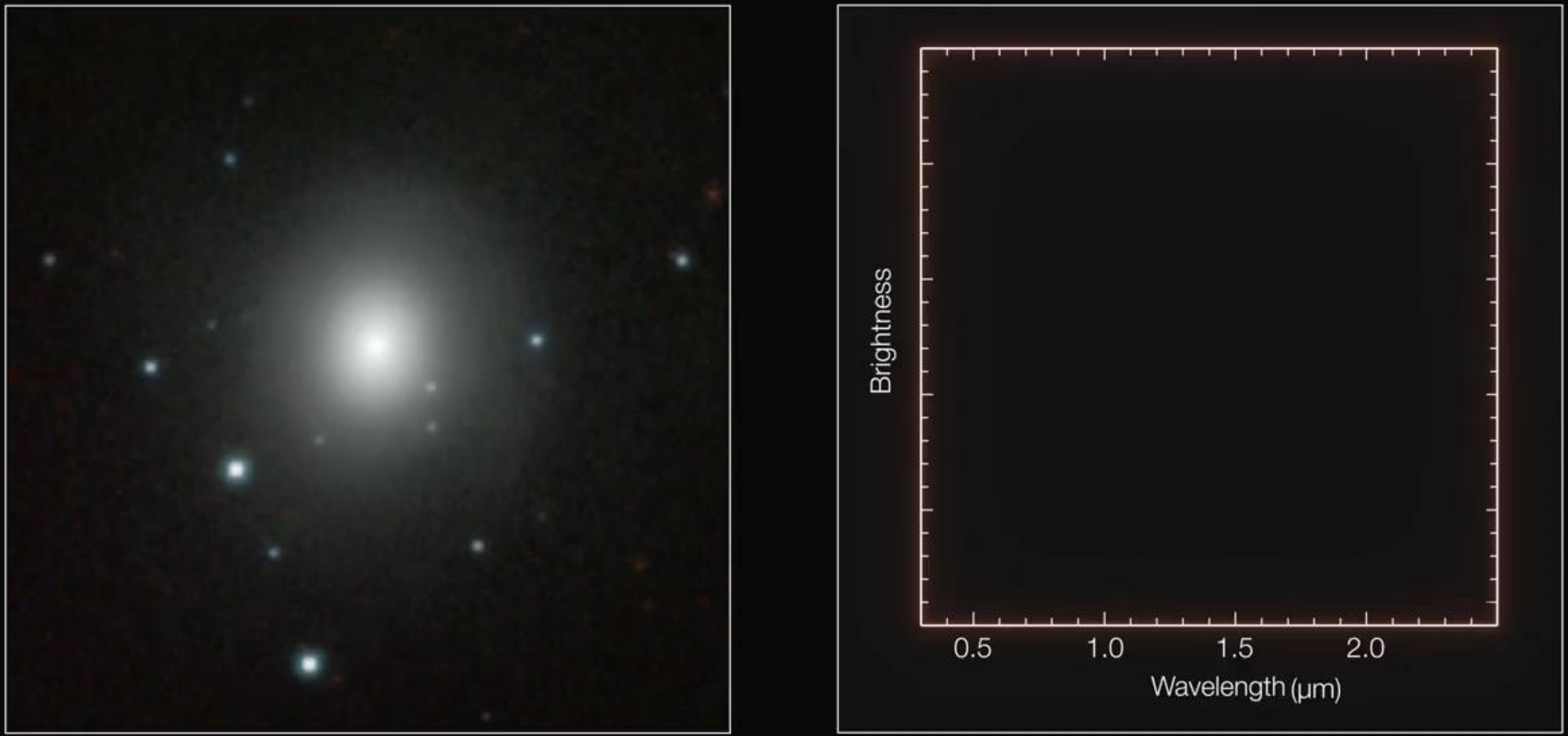
One-Meter, Two-Hemisphere (1M2H) team
1-m Swope telescope, Las Campanas (Chile)



- Observation at t_0+10.8 hr
- mag(i) ~17
- Names SSS17a
- later AT2017gfo
- ESO 508 cluster at 40 Mpc

- *(Coulter et al. 2017)*

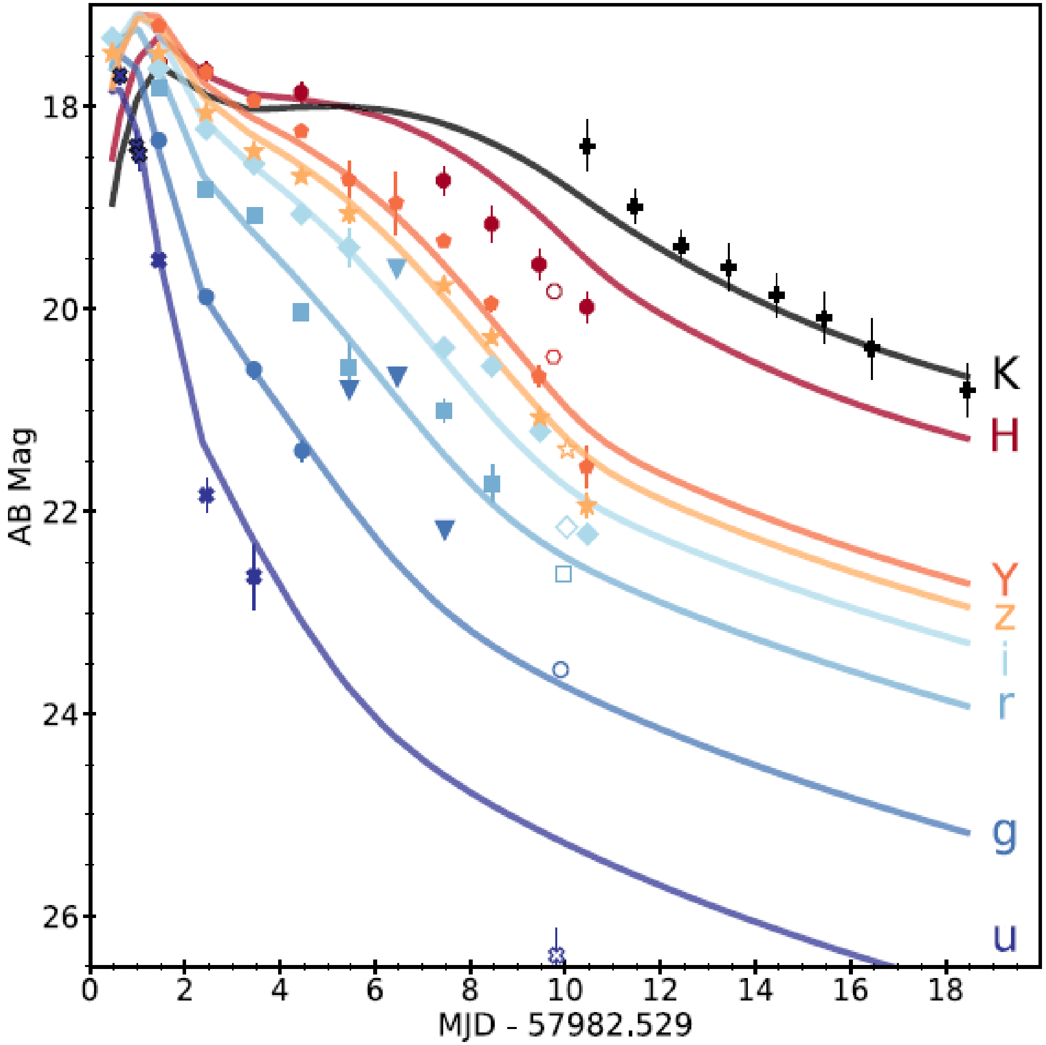




Time: -1225 days

Broadband follow-up: UV, optical, IR

Next days Follow-up observations to rule out chance coincidences
Photometry using DECam, HST, Gemini-south, Swift, from IR to UV



Cowperthwaite et al. 2017

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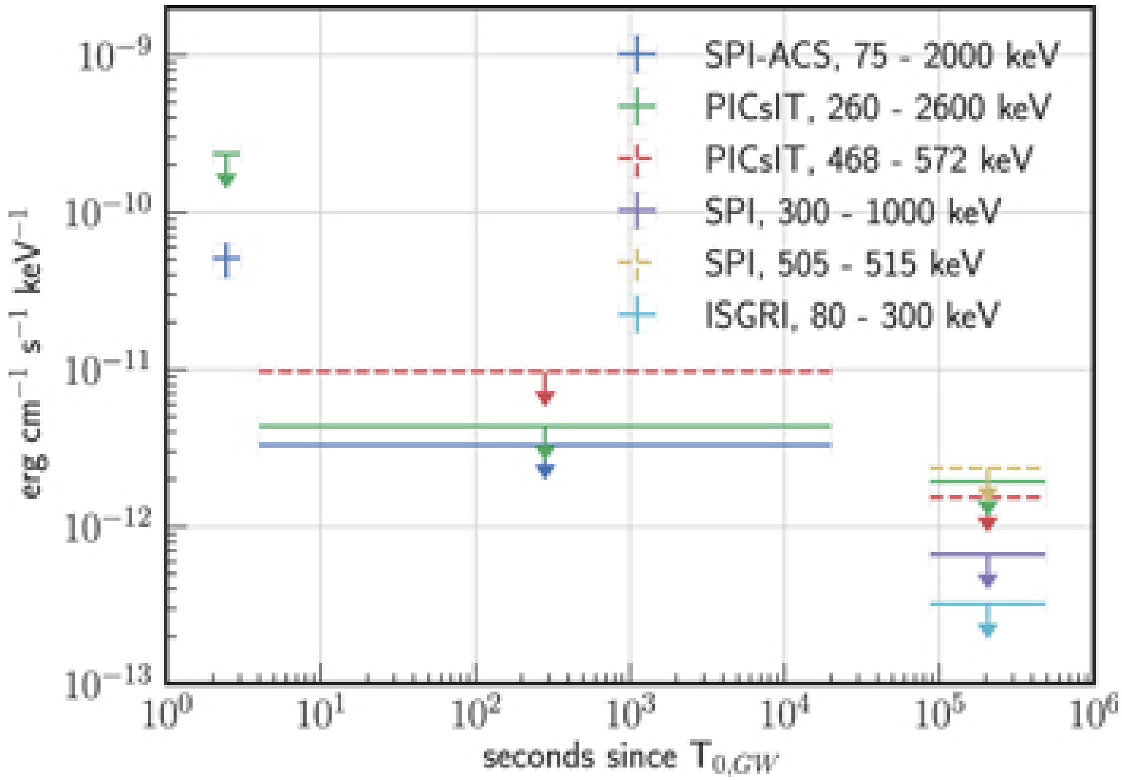
Broadband follow-up: gamma rays

Gamma rays probe highly relativistic processes

Many high-energy facilities online (IPN)

- Fermi GBM+Fermi LAT
- AGILE
- INTEGRAL
- HXMT
- CALET
- AstroSat
- HESS
- HAWC



INTEGRAL upper limits

(Savchenko et al, 2017)

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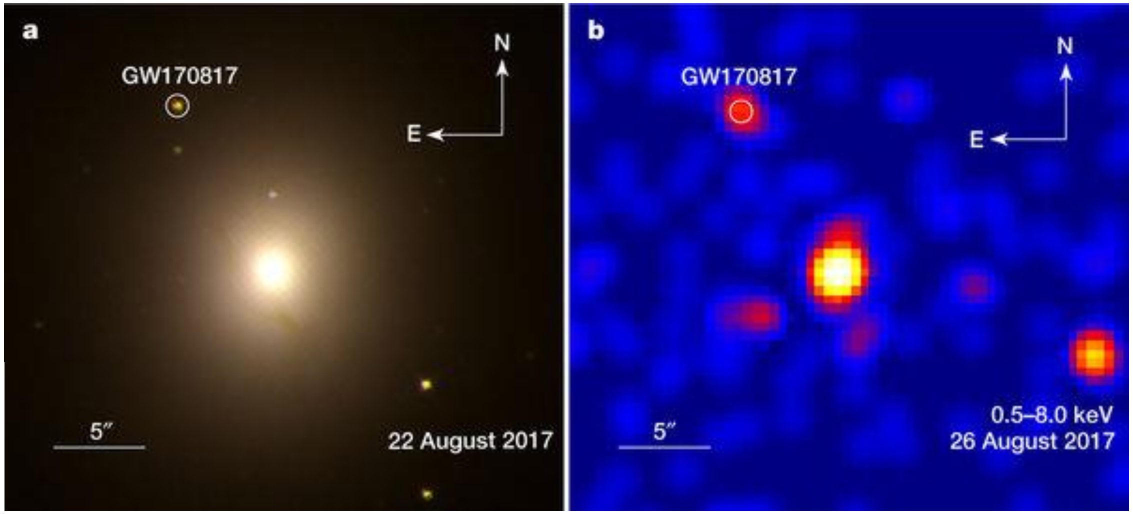
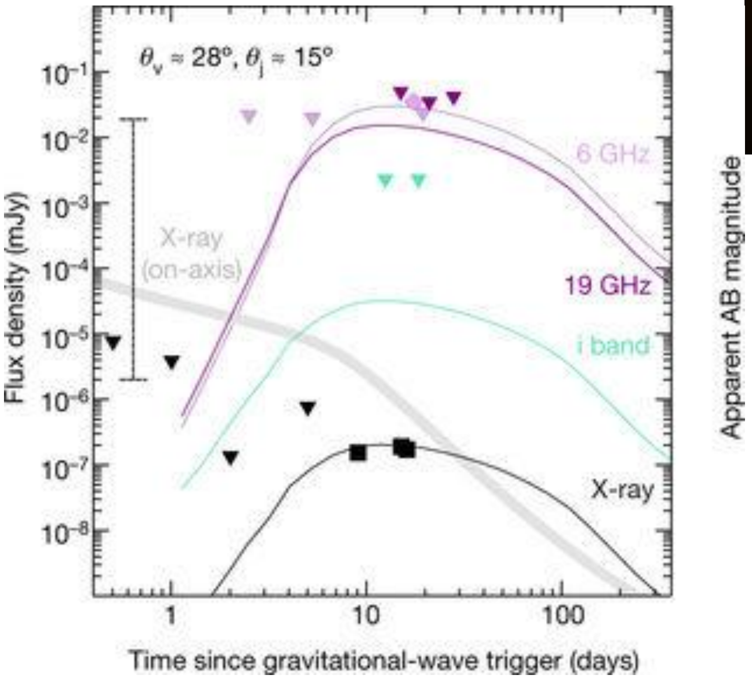
Broadband follow-up: X-rays

- No detections until t_0+9 days
- First detection by Chandra (Troja et al., 2017)
- Emission up to t0+15 days (occulted by Sun)





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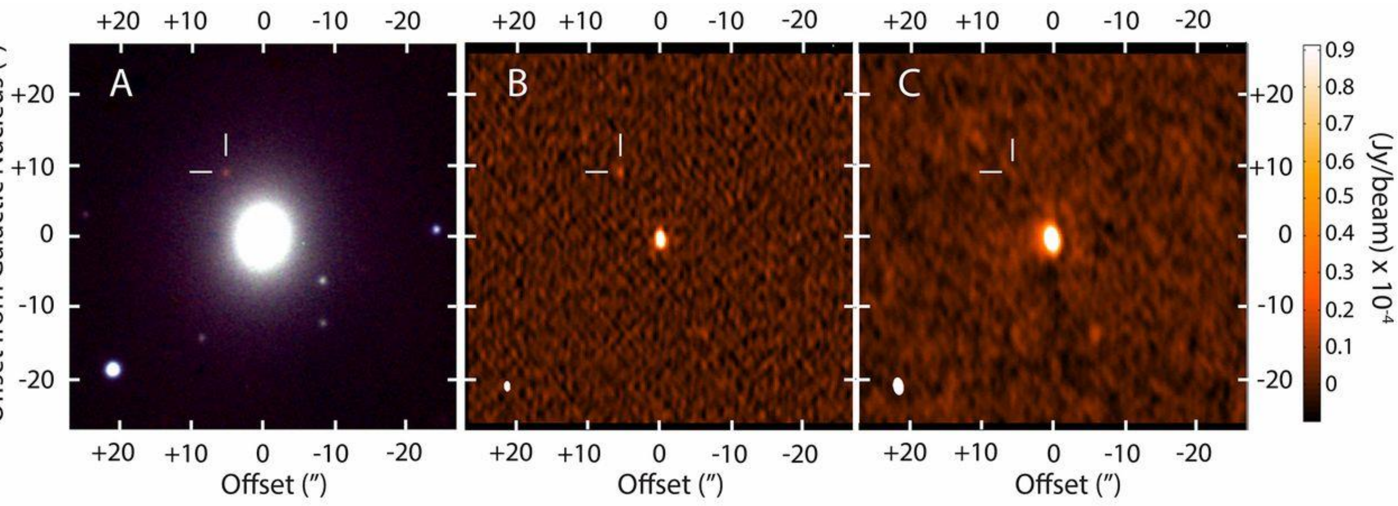
Broadband follow-up: radio

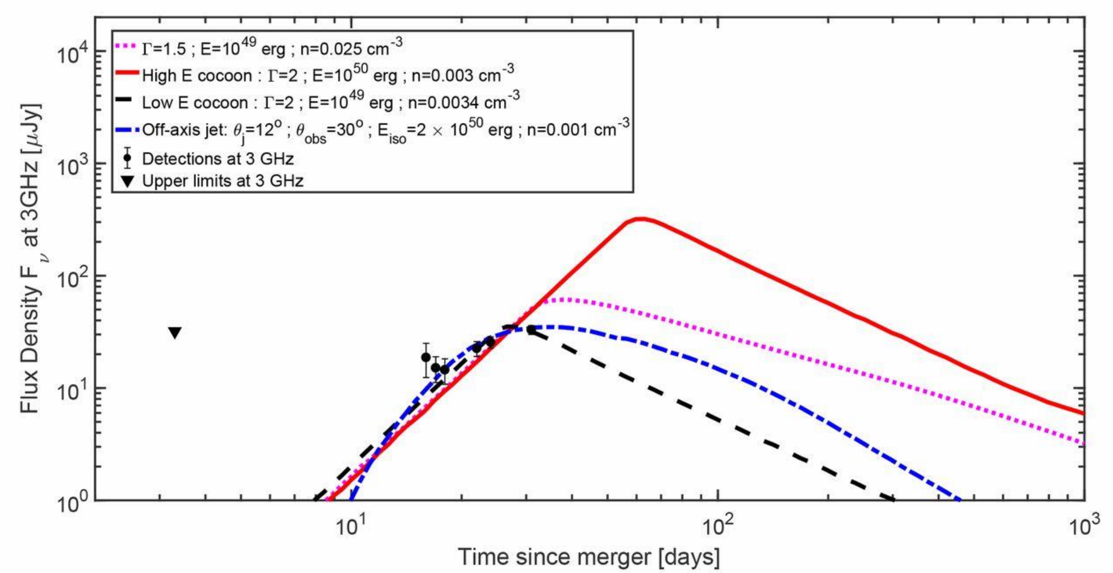
- First detection at t_0+16 days by VLA, confirmed by ATCA



6 GHz image
@VLA

Consistent with cocoon
or off-axis emission

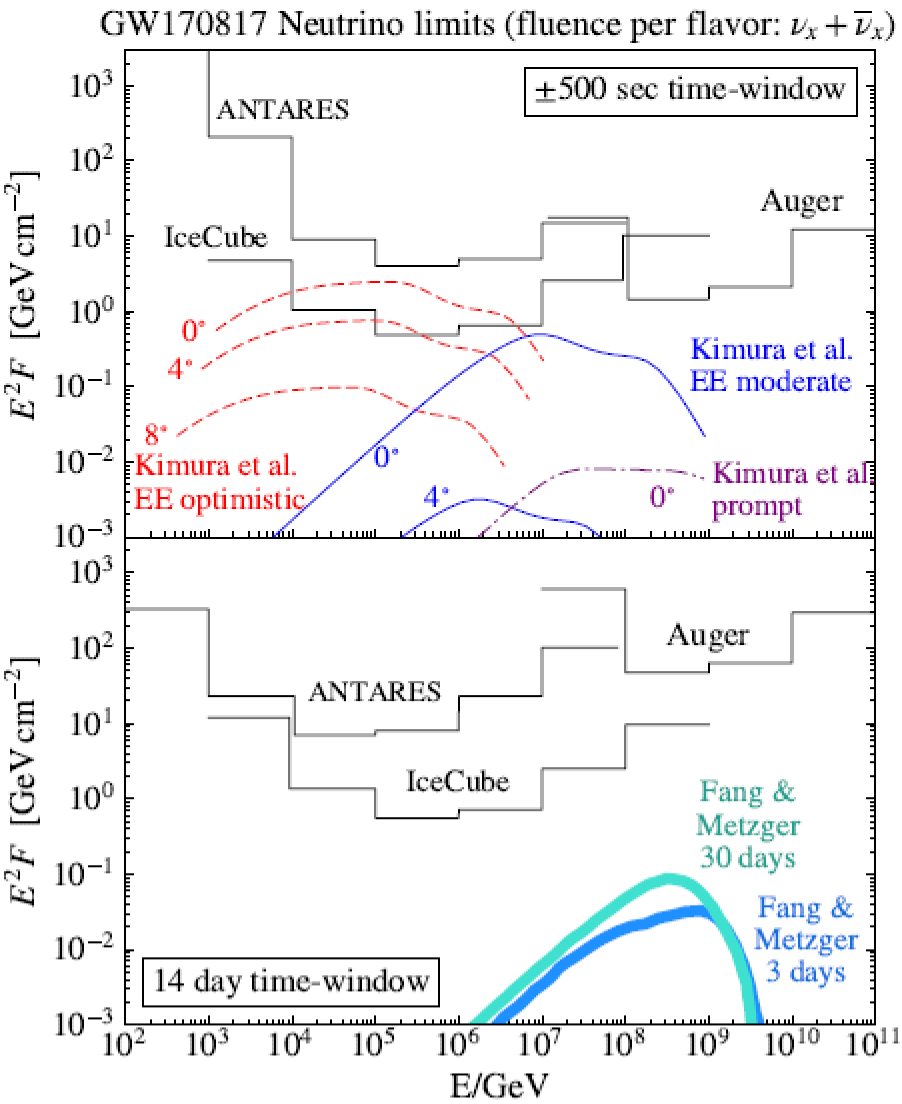
Hallinan et al 2017



Broadband follow-up: neutrinos

- Icecube
- ANTARES
- Pierre Auger Observatory

No detection
Upper limits computed



Albert et al 2017

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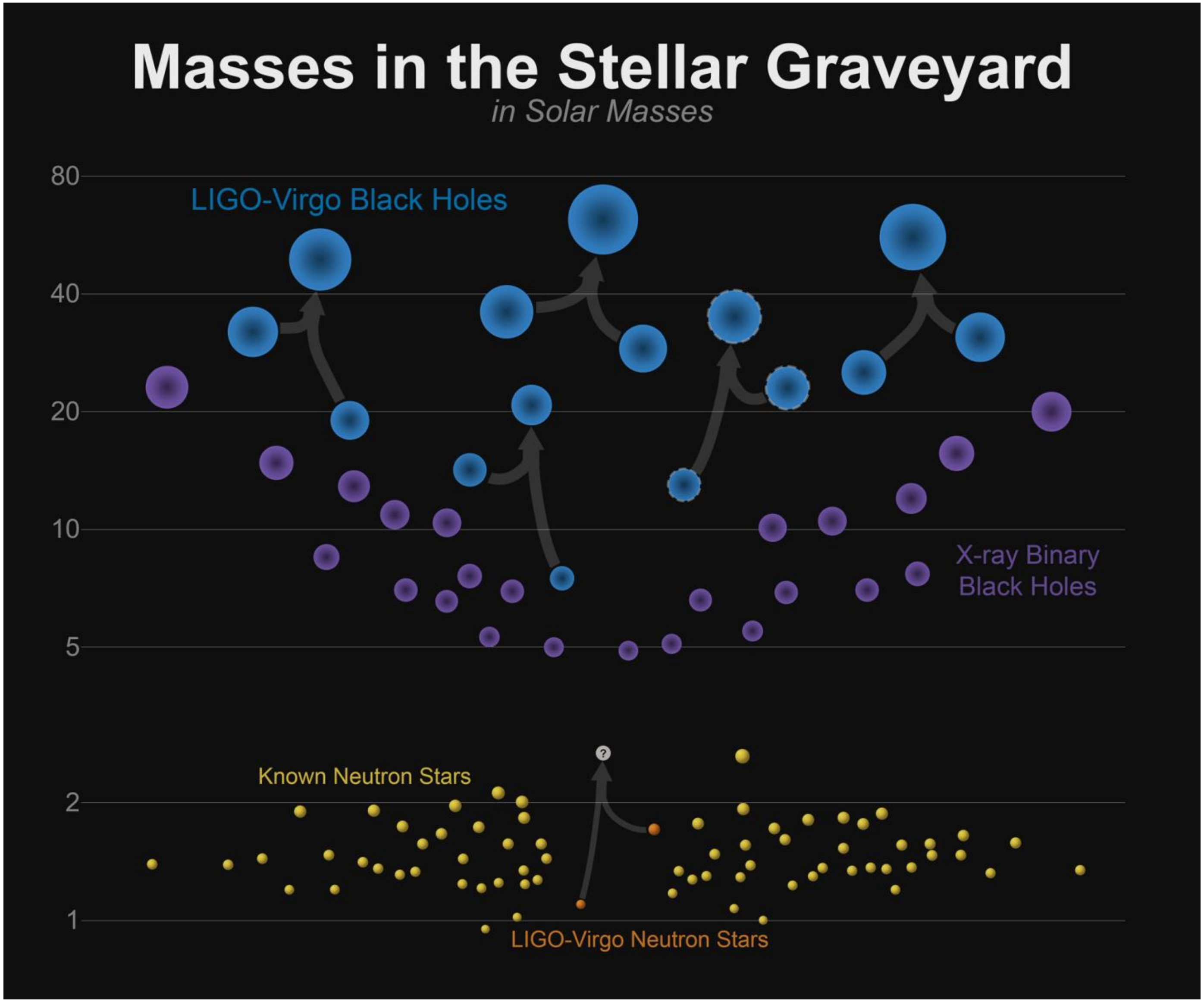
An global observing campaign

Lessons learned: NS physics

- NS masses and constraints on EoS
- Explored new mass range with GWs



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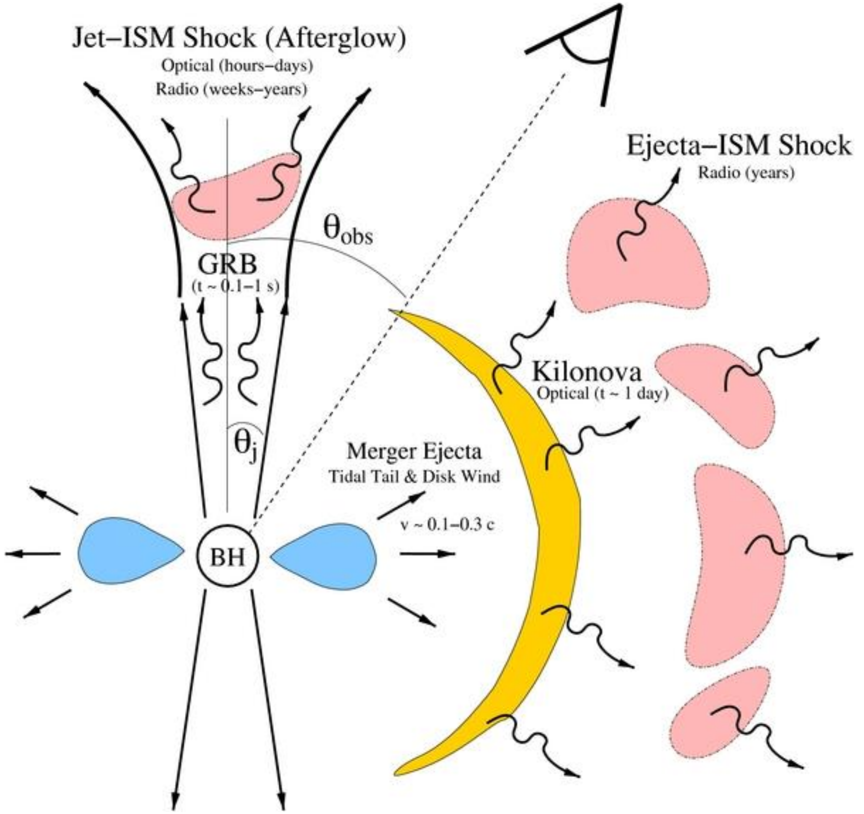
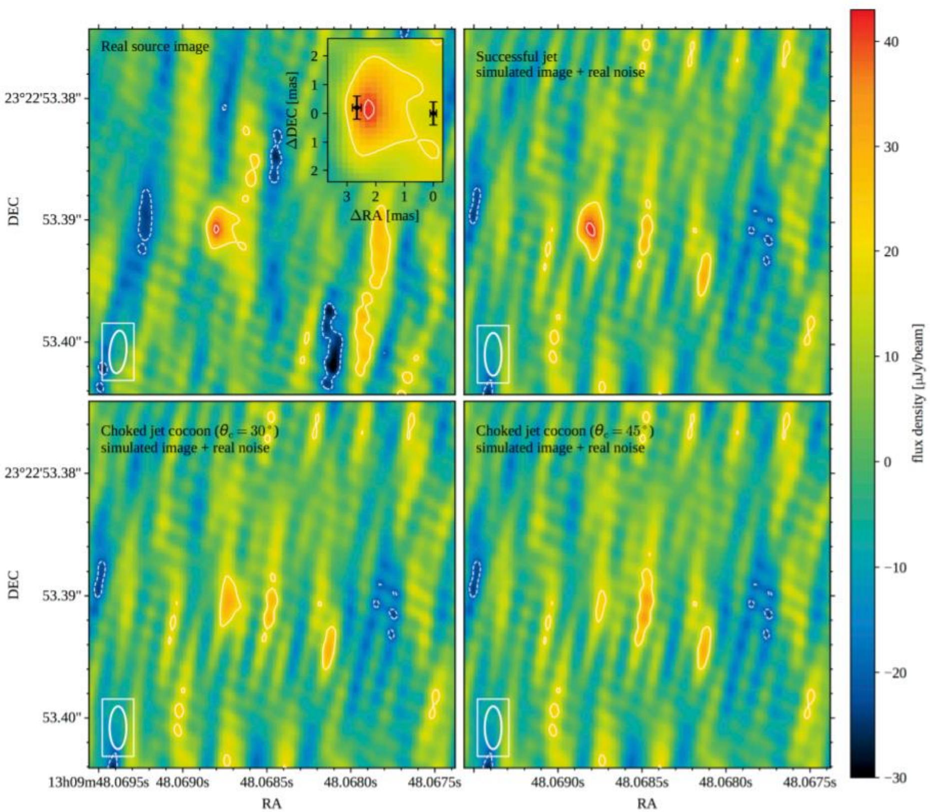
Lessons learned: GRB physics

- NS mergers – short GRBs association
  (Abbott et al. 2017, ApJ 848,13)
- GRB EM emission: few models, including
  1. Jet seen off-axis
  2. Structured core+outer cocoon
  3. Isotropic fireball
- VLBI radio imaging pointing toward (1)



Metzger & Berger 2012, ApJ,746,1



Ghirlanda et al. 2018, arxiv1808.00469

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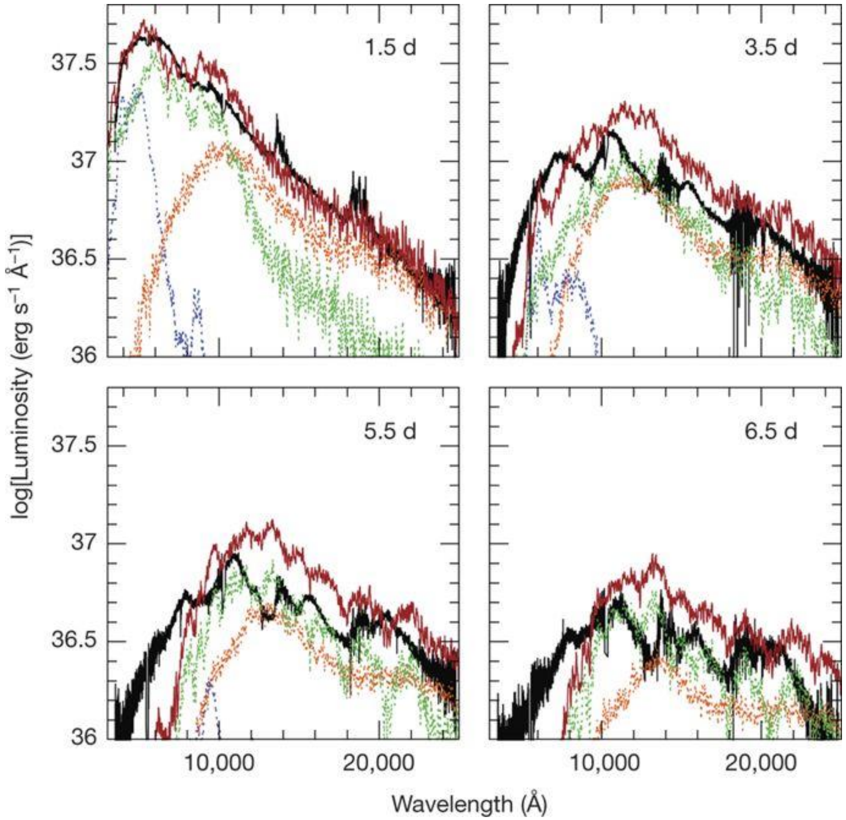
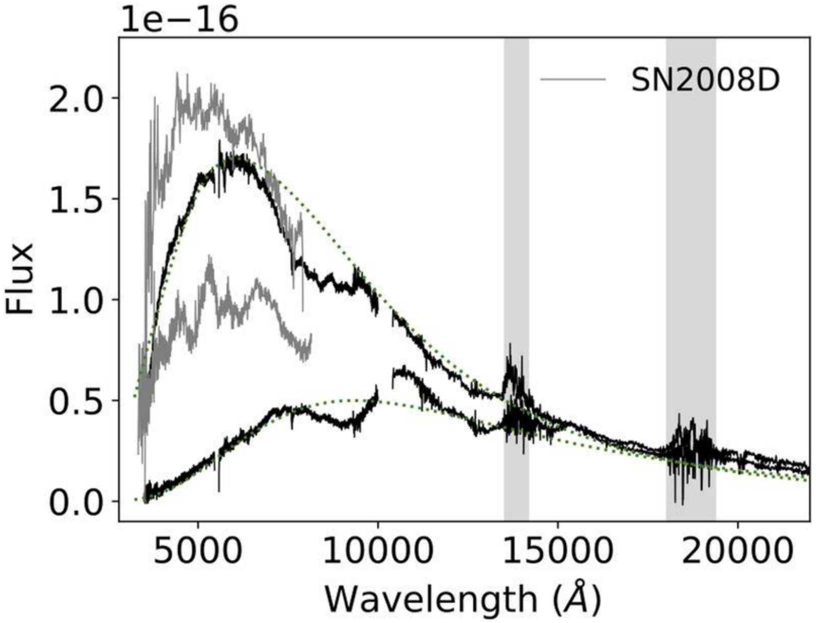
Lessons learned:
origin of heavy elements

- Confirmation of a kilonova transient(1/10 SN luminosity)
- Evidence of heavy element production via r-processes



1.5-3.5 d

2-5 d



Pian et al. 2017, Nature, 551,67

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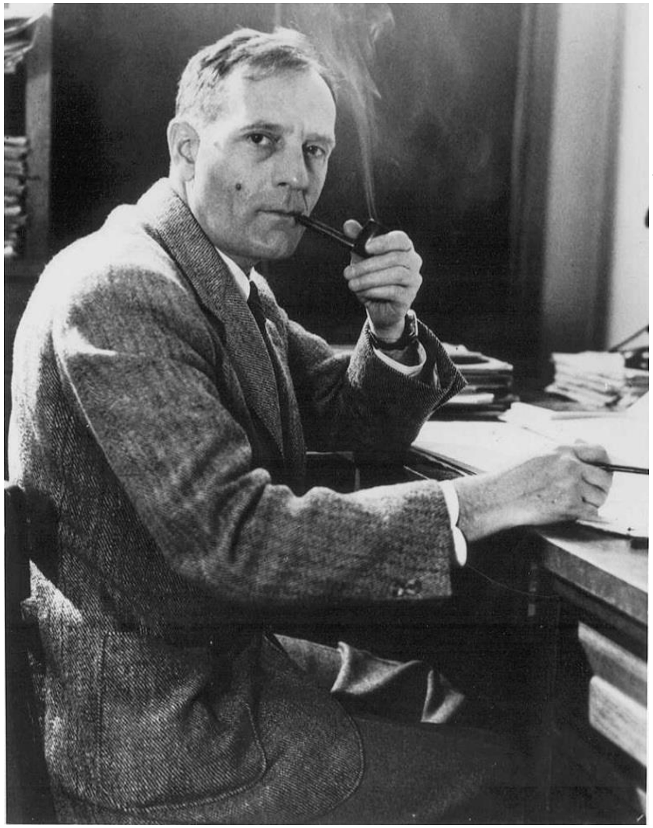
Lesson learned: cosmology



Velocity-Distance Relation among Extra-Galactic Nebulae.

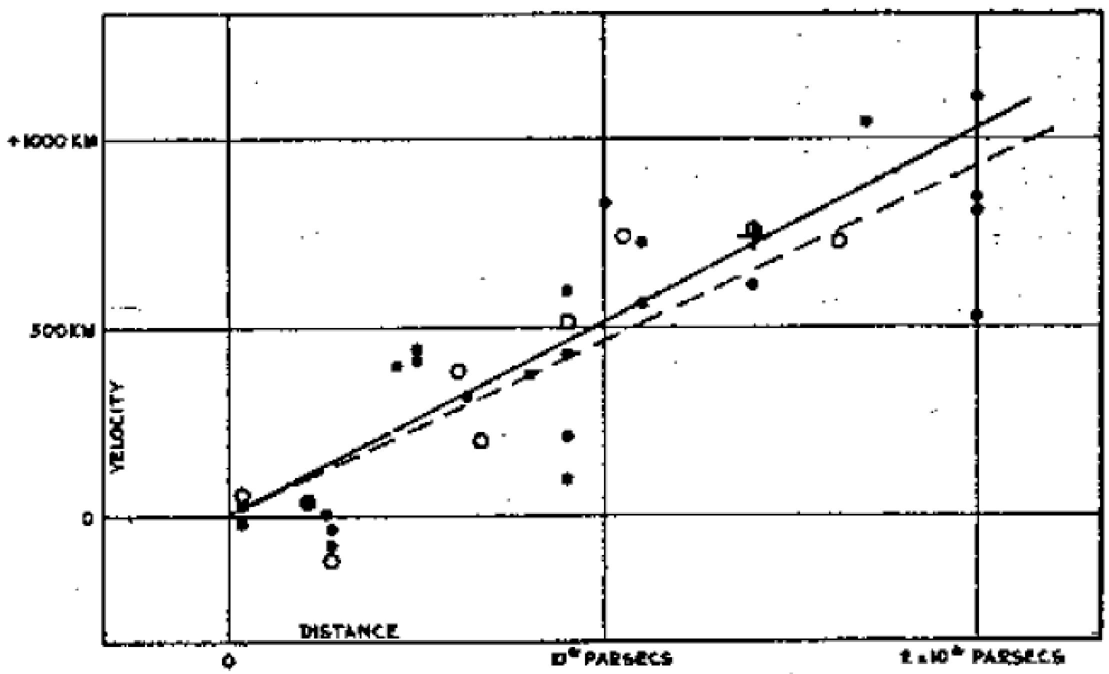


FIGURE 1

$$V = H_0 \; d$$

- Gravitational waves → d («standard syrens»)
- IF we know the galaxy counterpart → Redshift → V

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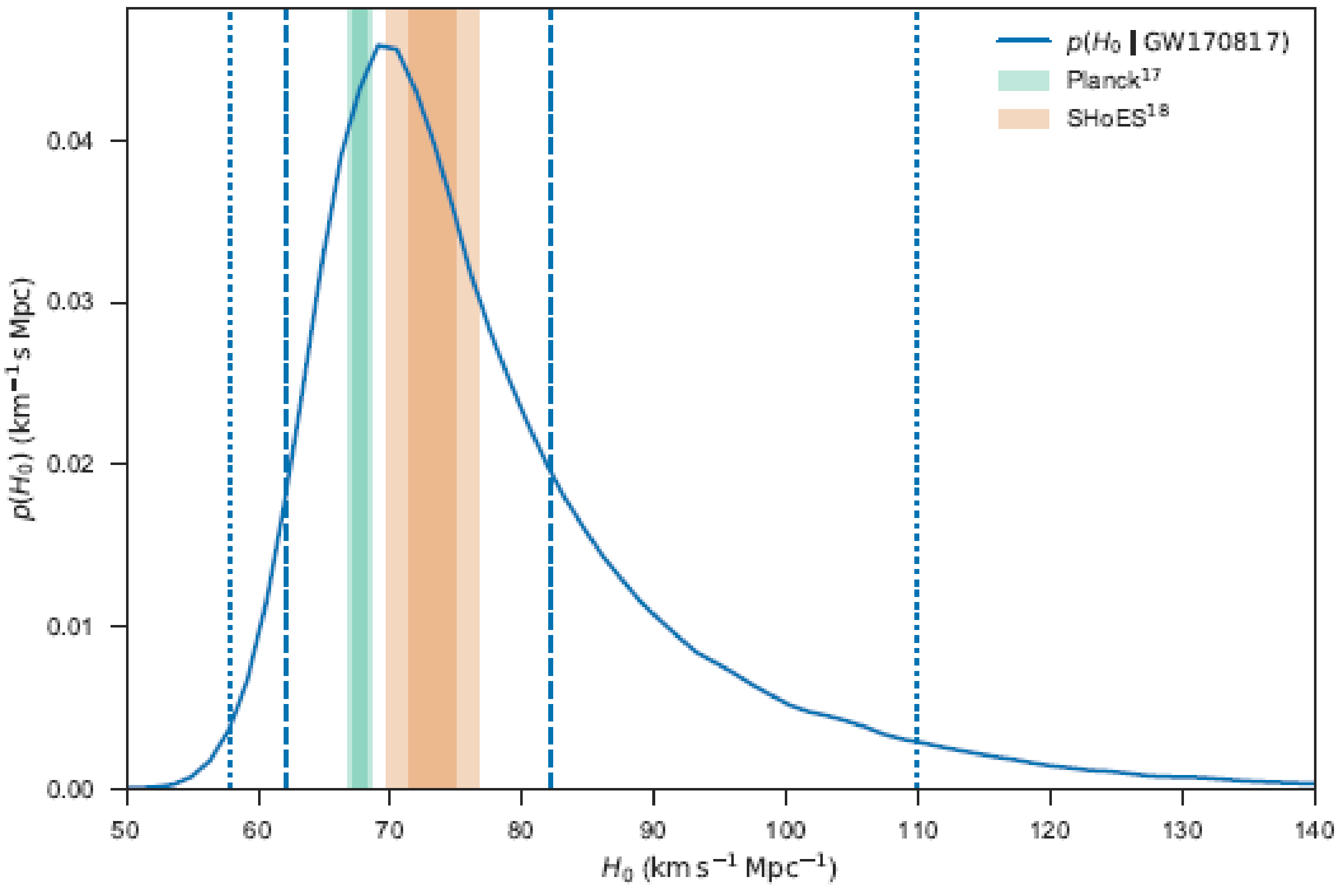
Multimessenger H_0



$H_0 = 70^{+12}_{-8}$ Km s^{-1} Mpc^{-1}

Abbott et al 2017, Nature, 551, 85

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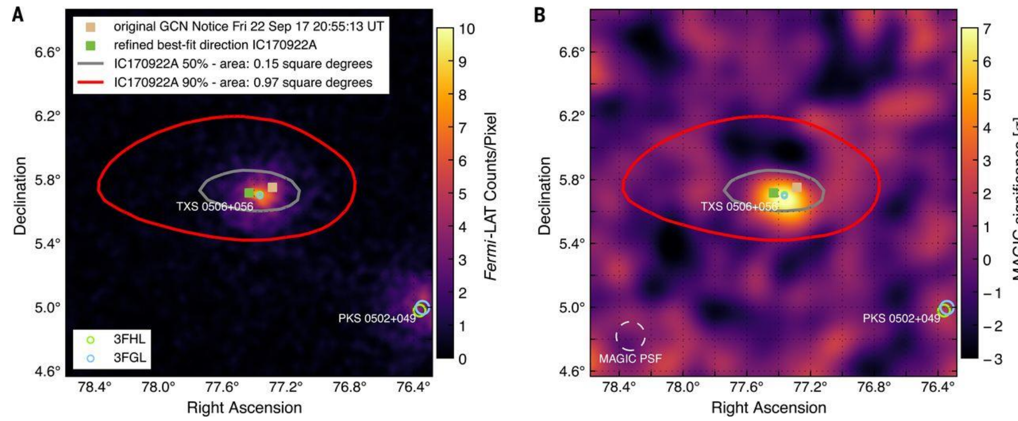
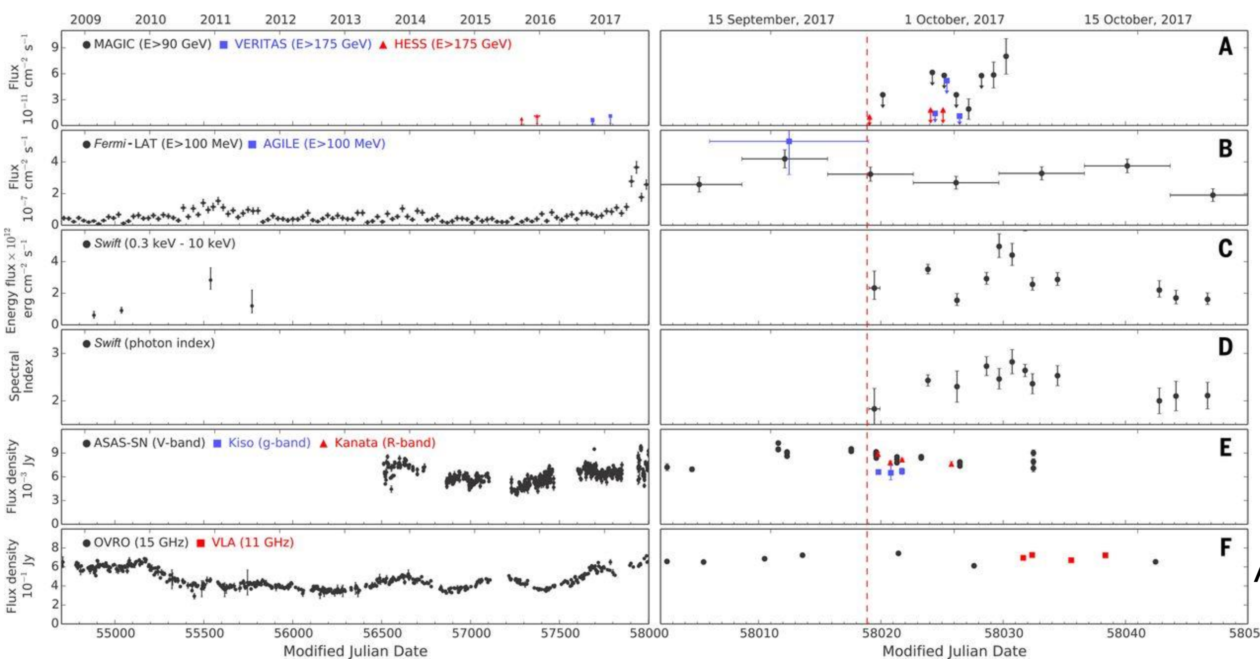
Multimessenger neutrino observations

- Sept 22, 2017: 290-TeV neutrino by IceCube
- Consistent with blazar TXS 0506+056 (3.7 billion light years)
- Flaring blazar seen by Fermi-LAT and MAGIC





Aartsen et al 2017, Science,361,178

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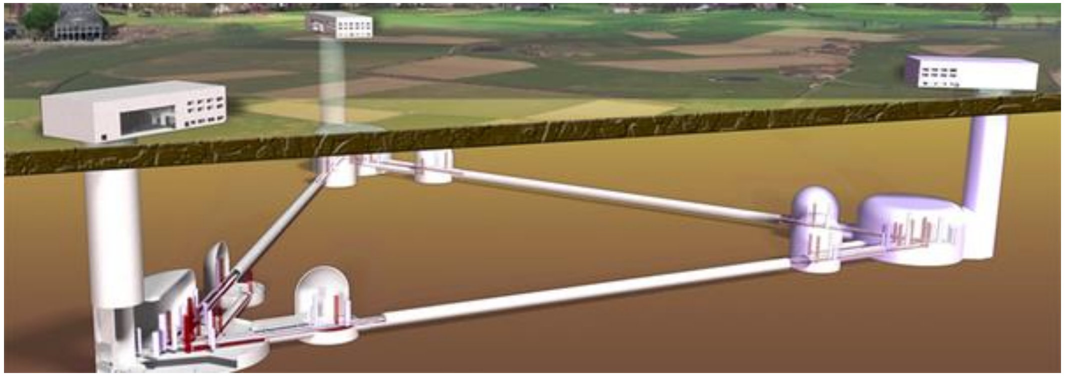
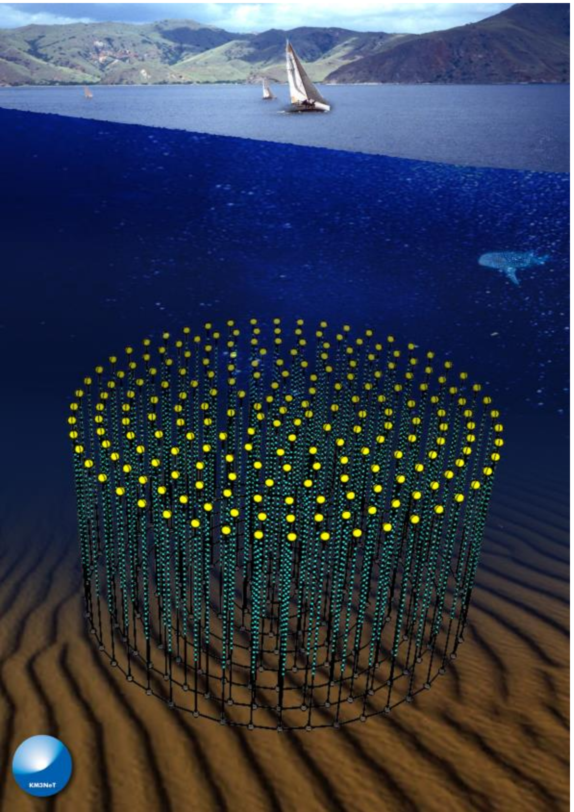
The future

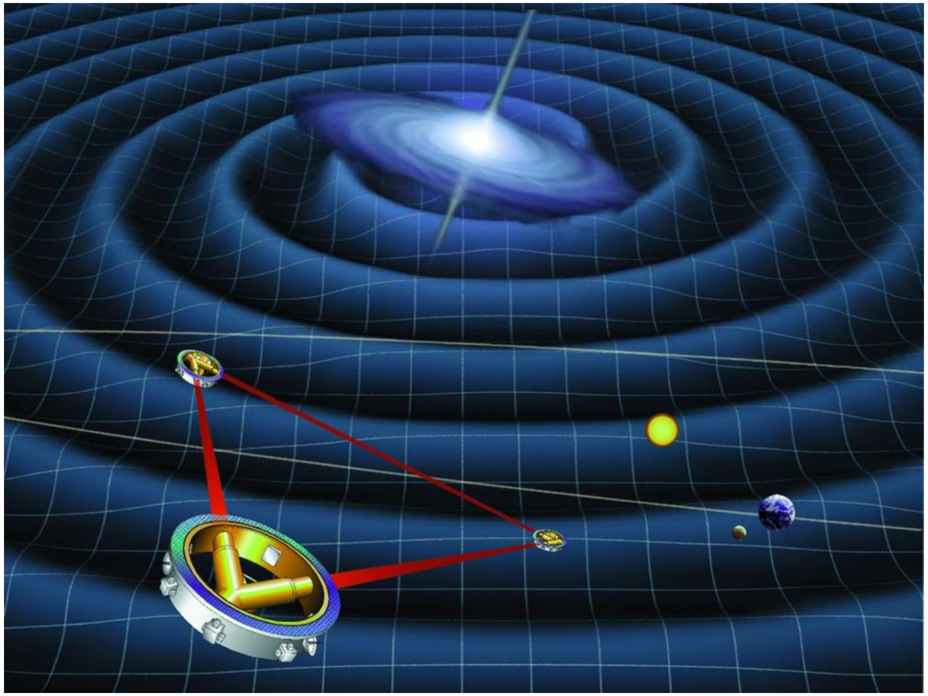


Einstein Telescope

Laser Interferometer
Space Antenna (LISA)



KM3NeT



New eyes on the Universe

- GW and photons provide complementary information
  - Multimessenger observations extremely promising
- Multimessenger approach is key to study the most extreme objects in the Universe
  - Natural laboratories to probe fundamental physics
  - Transients (e.g. GRBs)
  - Also, other sources (e.g. neutron stars)
- GW170817 provided a first successful multimessenger story
  - Great synergy and coverage
  - >70 teams involved, EM+neutrinos
  - Kilonova counterpart discovered
  - Astrophysics & fundamental physics
- Present & Future
  - Not just BBH: what about BH-NS systems?
  - ...and supernovae?
  - ...and the unexpected?
  - What about a photon-gravitational wave-neutrino triple?


Grazie per l’attenzione !