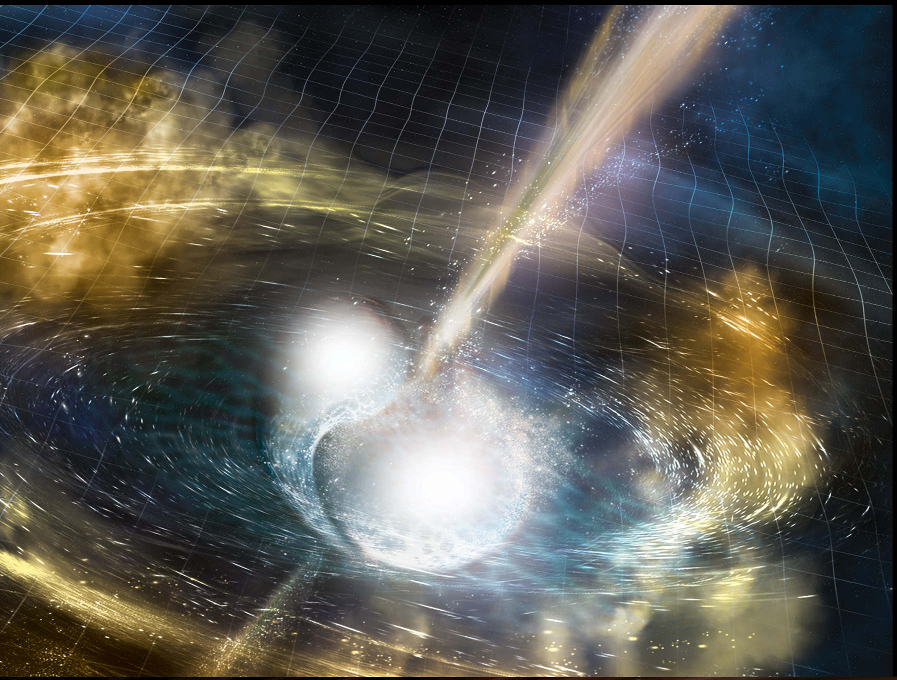
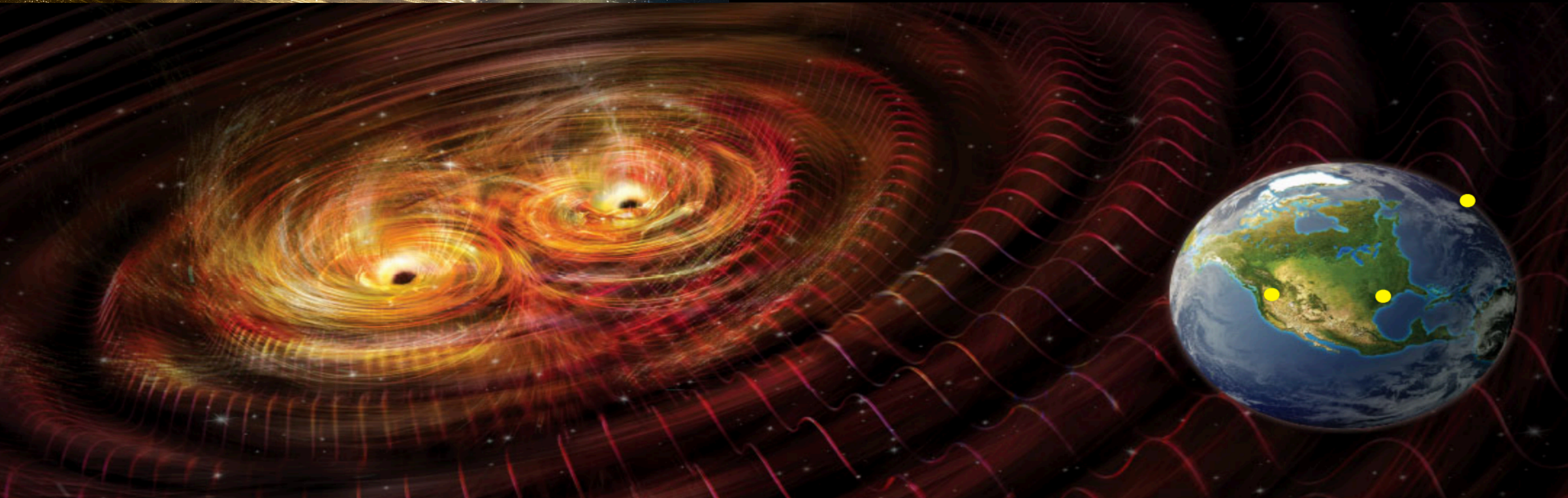
# Multi-messenger astrophysics

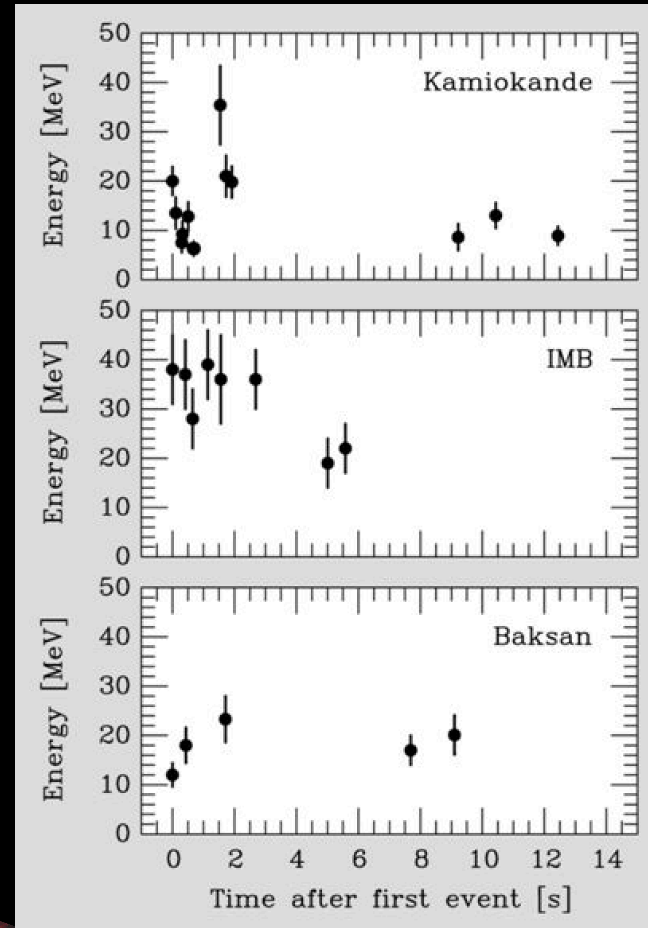


GSSI

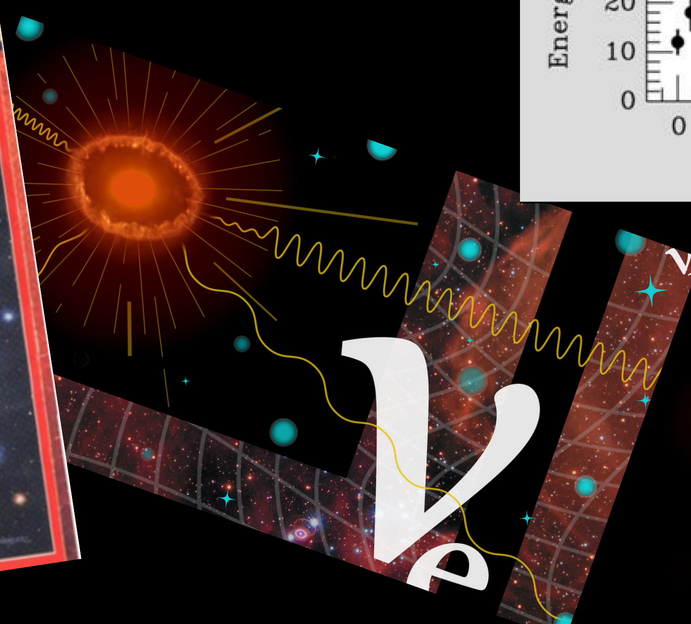
***M. Branchesi***
***Gran Sasso Science Institute***
***INFN/LNGS and INAF***



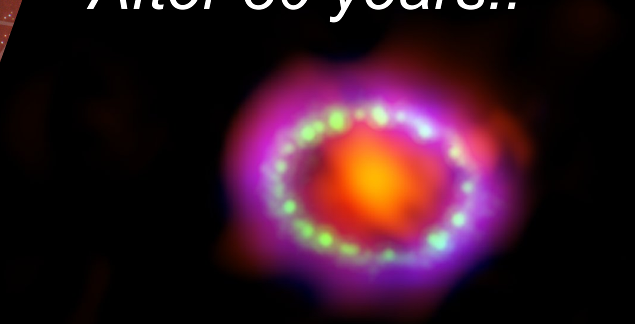
# SN1987A



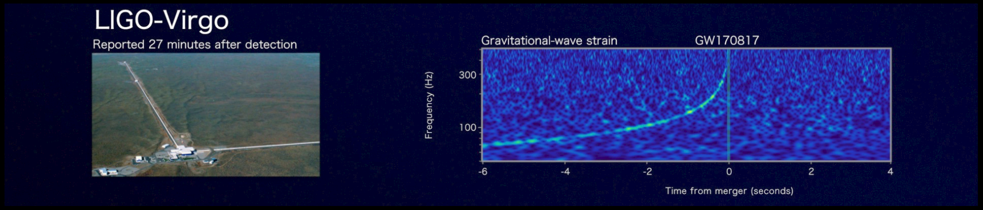




*After 30 years..*

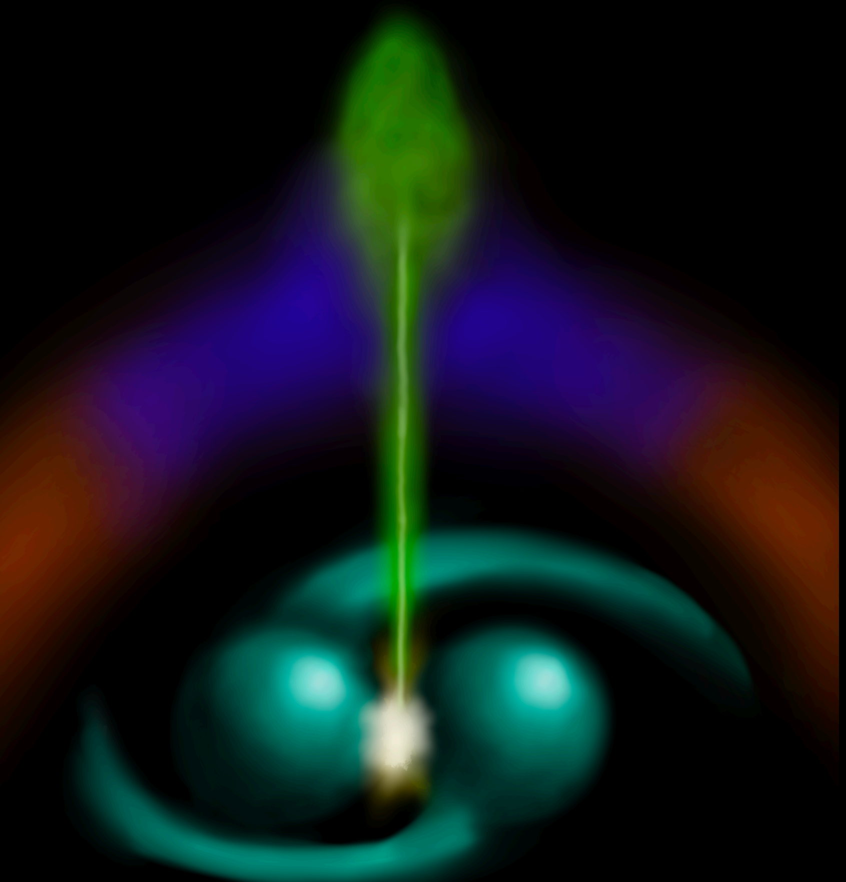


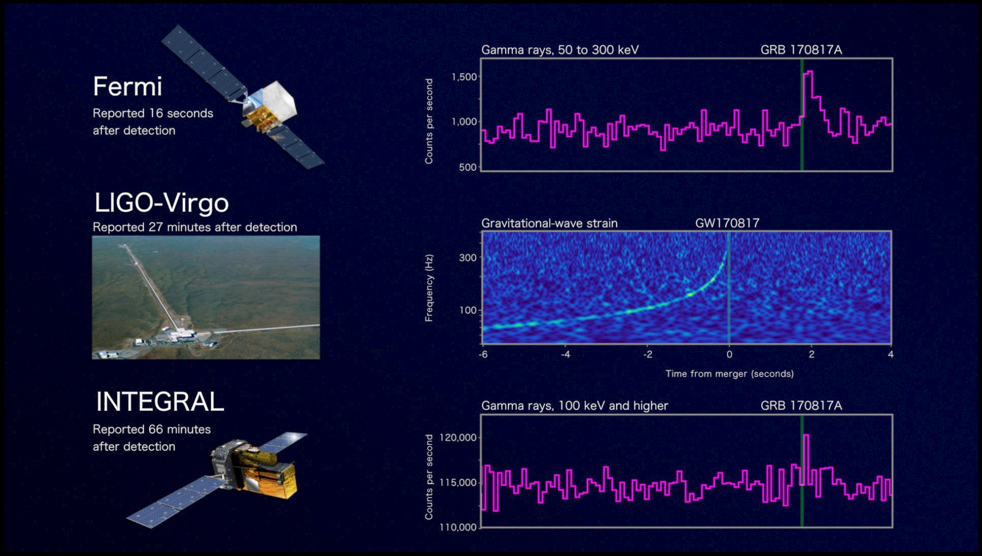
# GW 170817



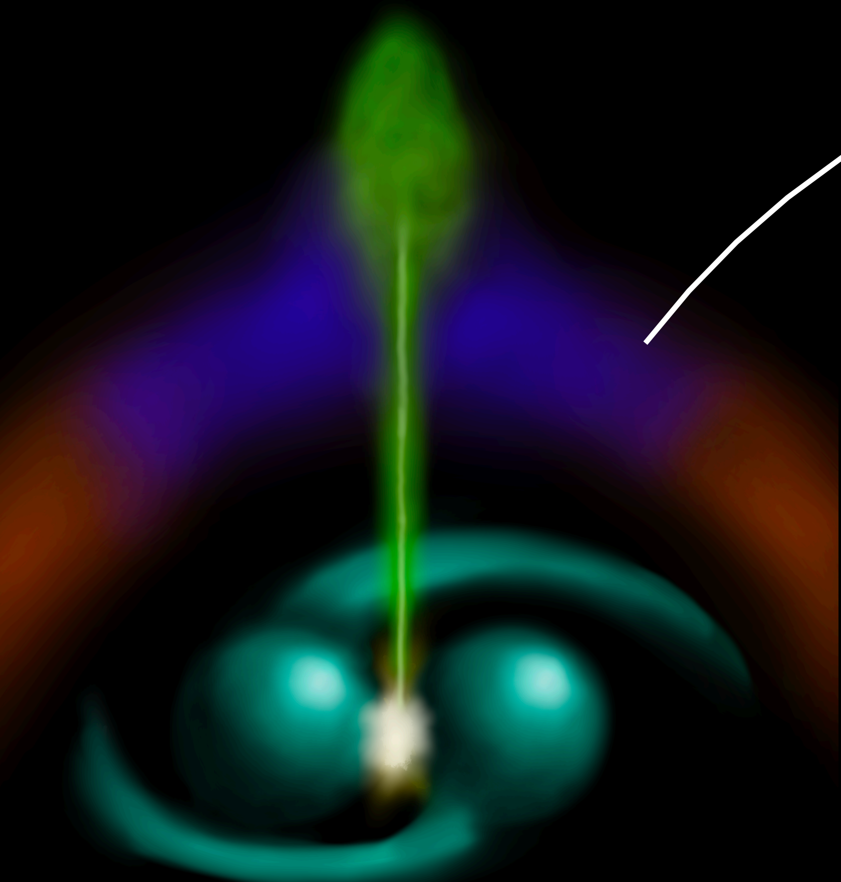

Credits: Ronchini

# The case of GW 170817



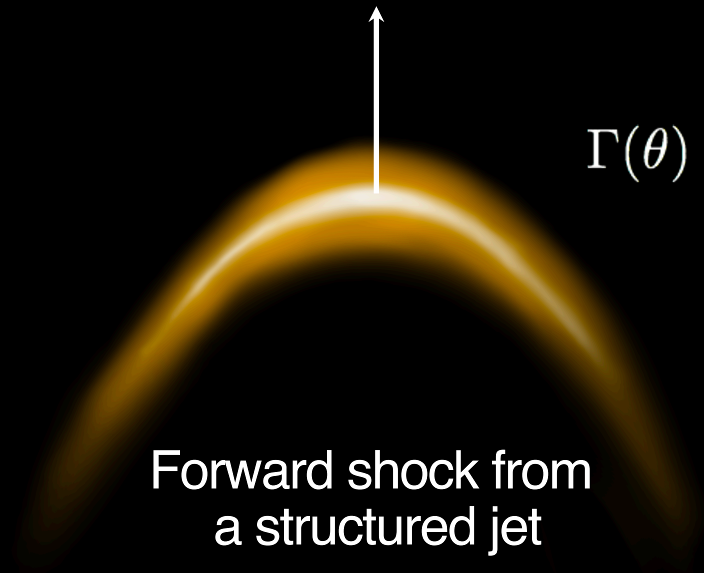


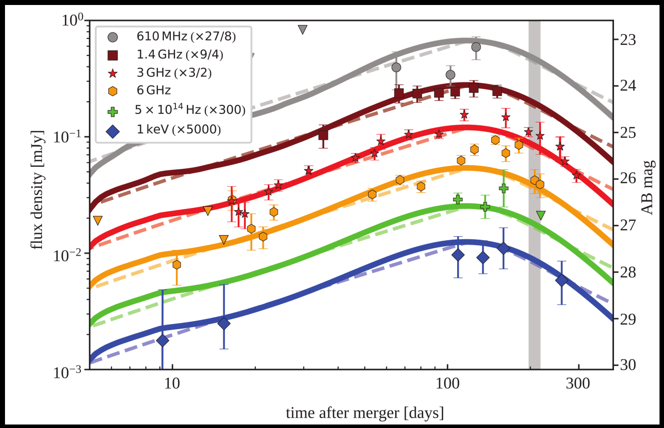
# GW 170817




Credits: Ronchini

# GW 170817



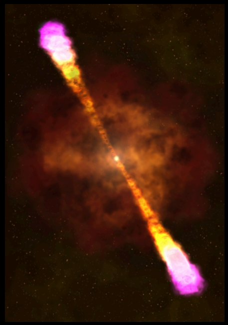




From Ghirlanda et al. 2019

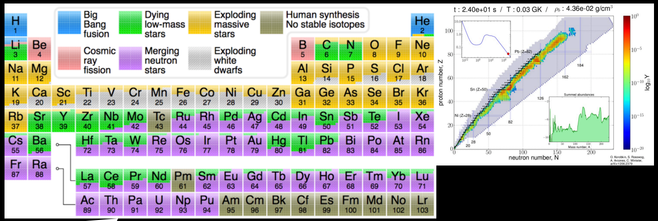
Credits: Ronchini

# Radioactively powered transients

## Relativistic astrophysics

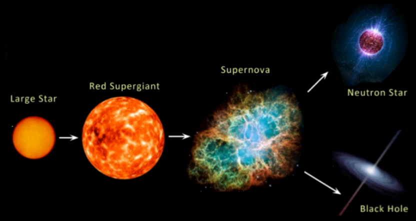


## Nucleosynthesis and enrichment of the Universe

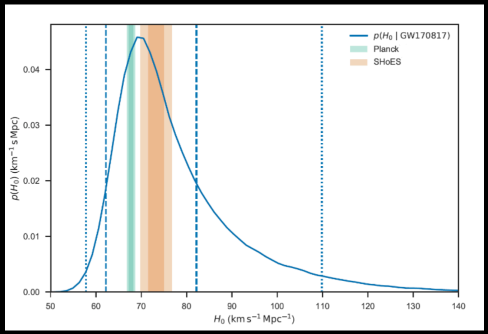




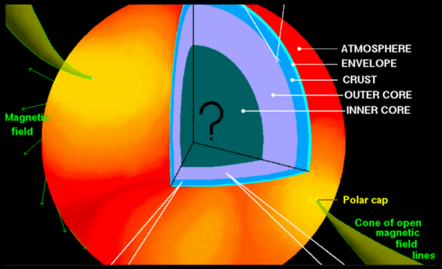
## Compact object formation and evolution



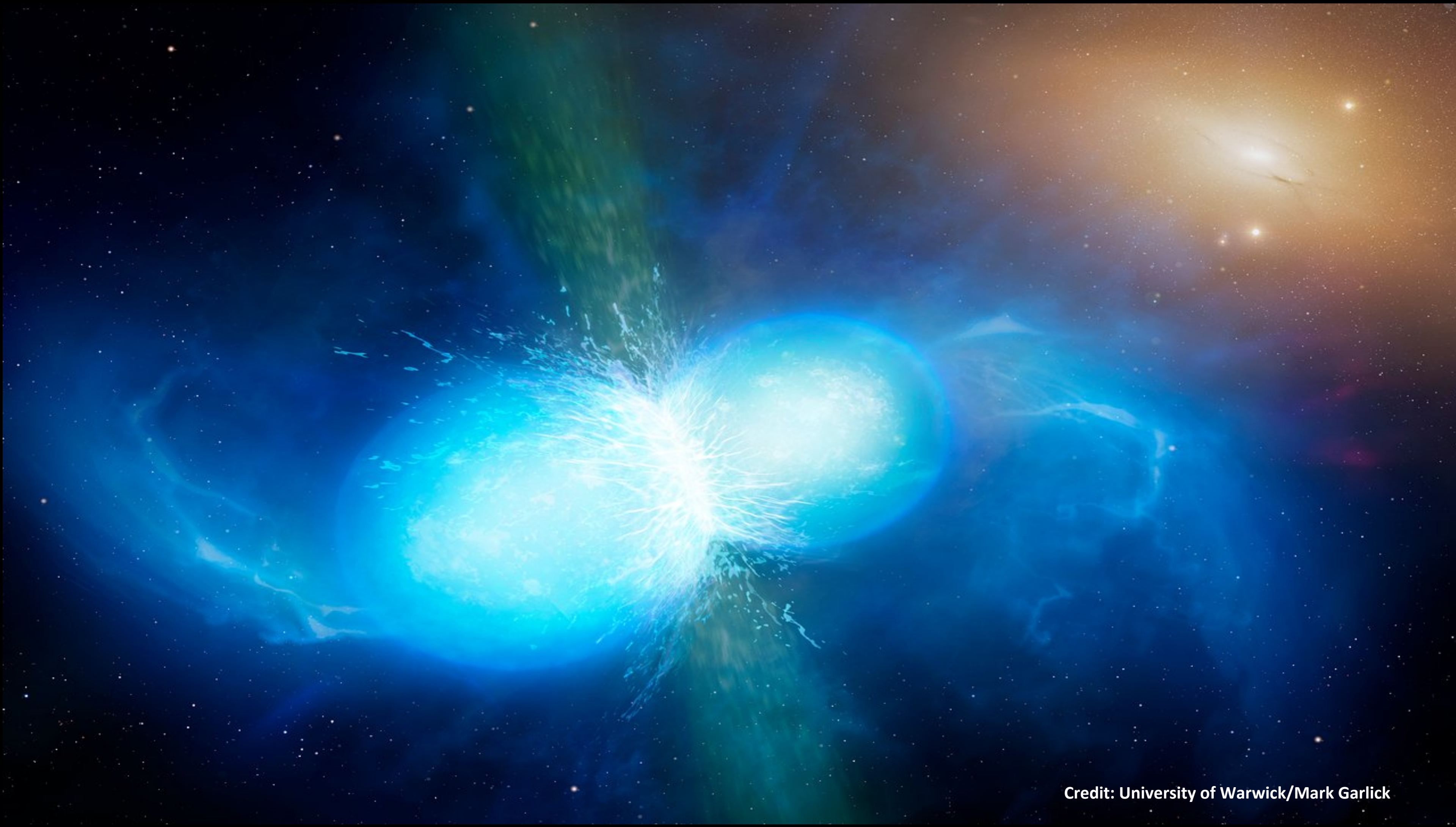

## Cosmology

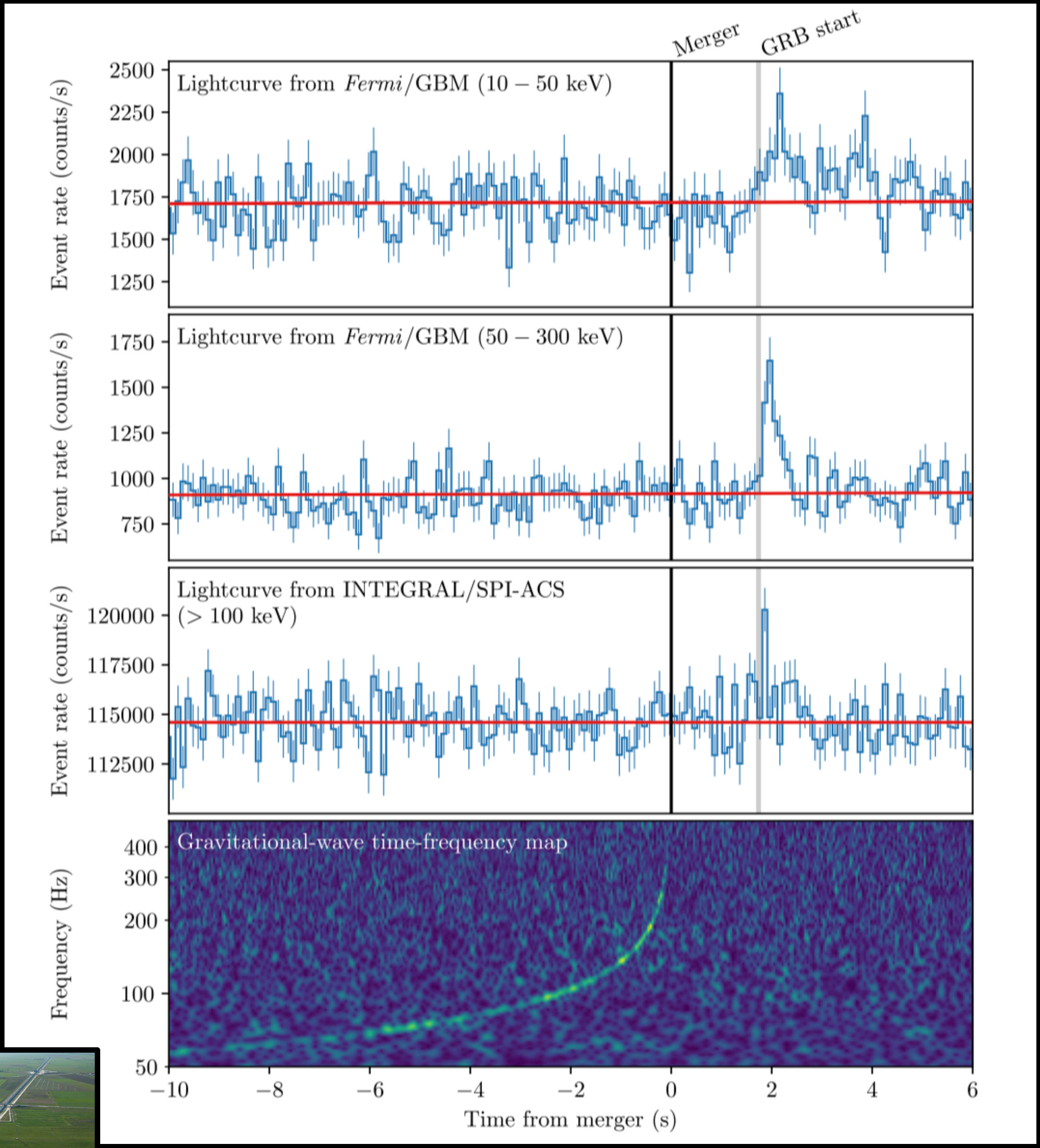



## Nuclear matter physics



# 17 August 2017, 12:41:04 UT

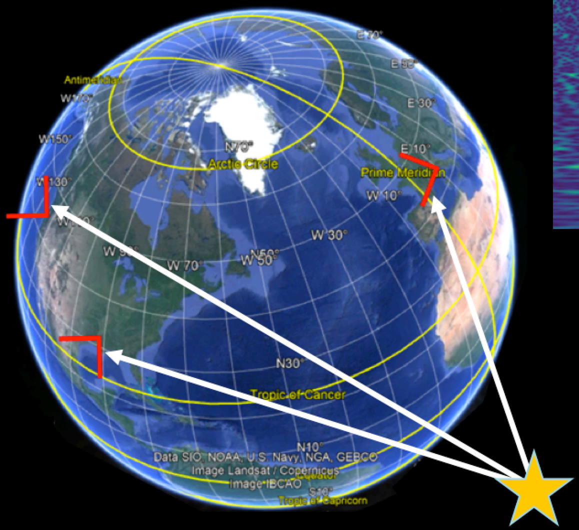


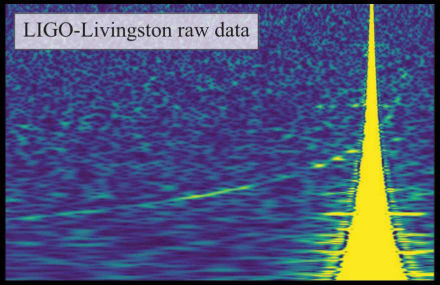




GW170817

Abbott et al. 2017, PhRvL, 119

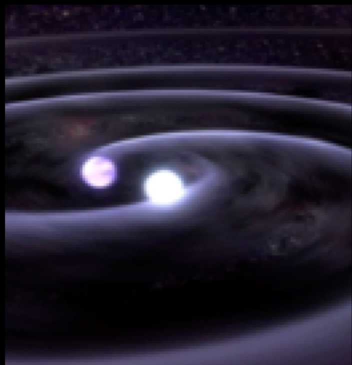
17 August 2017,  12:41:04 UT

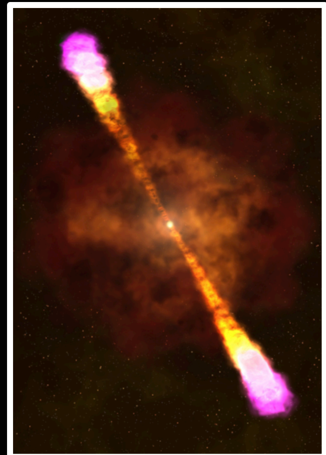


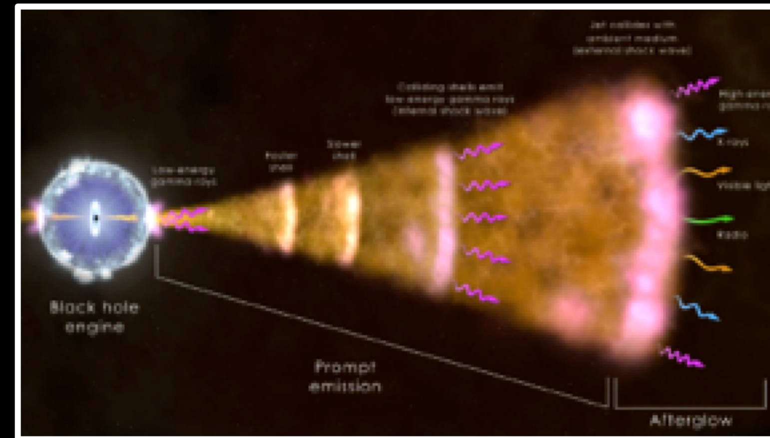




→ 17:54:51


Credit: LIGO/Virgo/NASA/Leo Singer








NS merger

Short GRB

X-ray

Radio afterglow

t0

1.7s

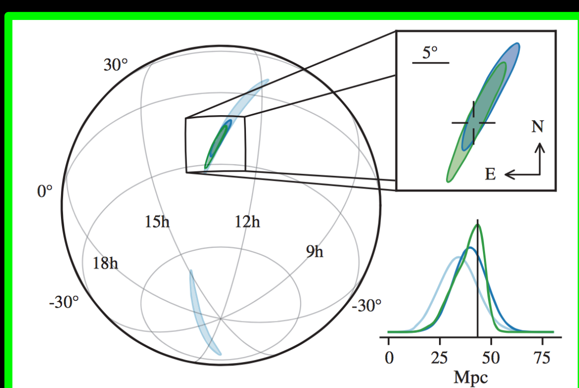
+5.23hrs

+10.87 hrs

+9 days

+16 days

**LHV sky localization**

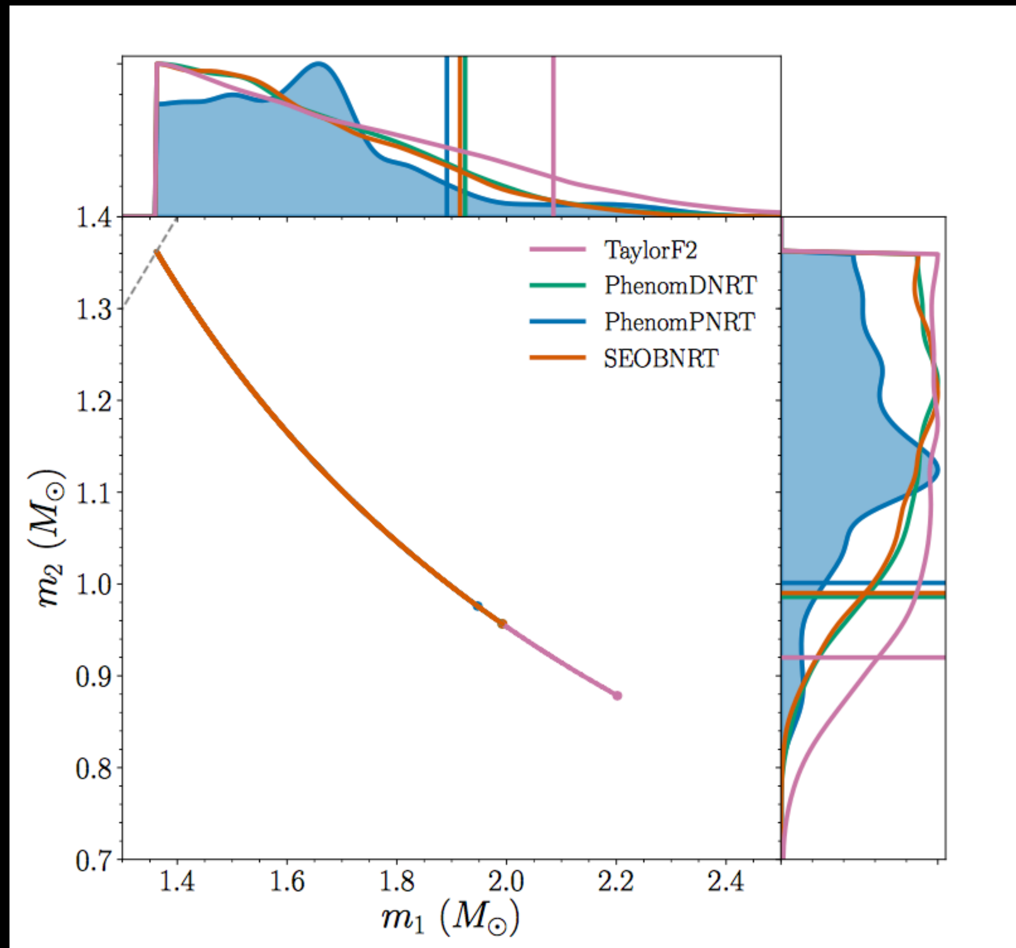



UV/Optical/NIR Kilonova

LVC + astronomers, ApJL, 848, L12

# *GW observables*

# GW170817: PARAMETERS OF THE SOURCE




23 < $f$ /$Hz$ < 2048

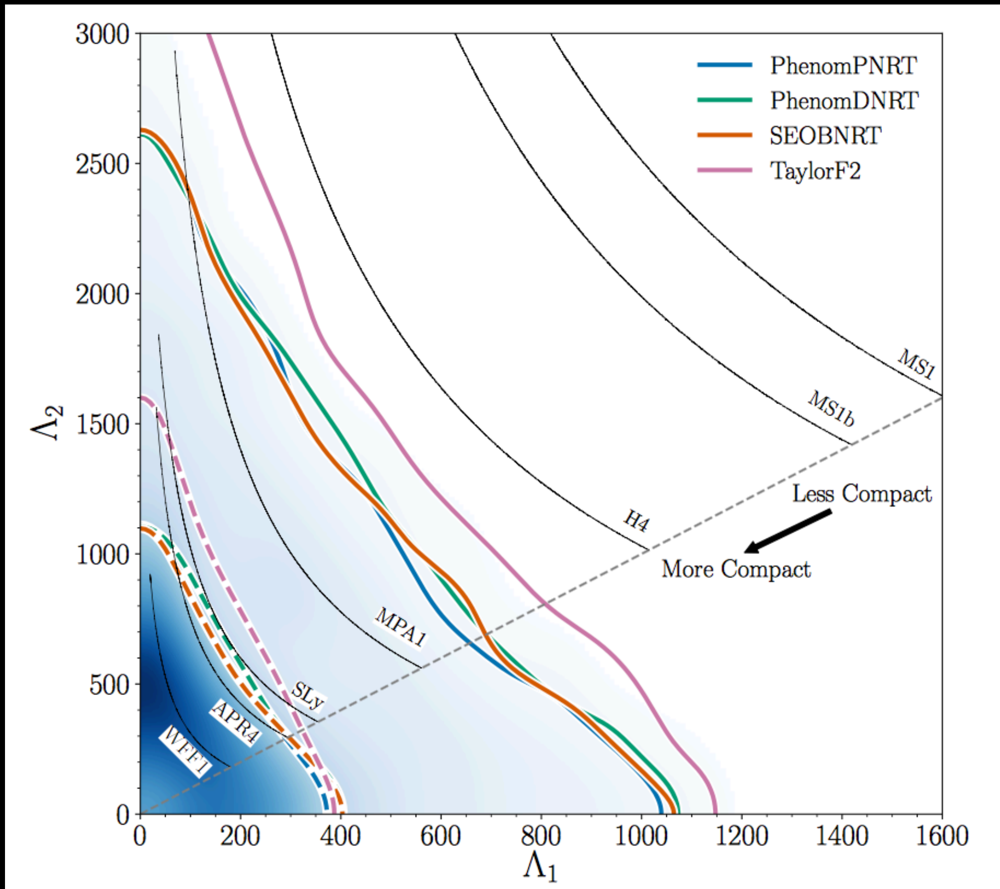
Analysis uses source location from EM

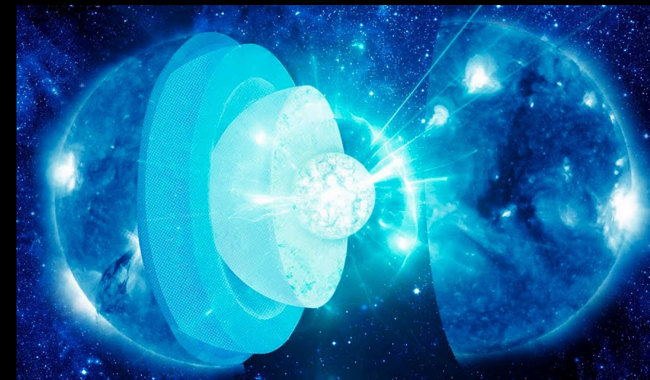
- **Mass range 1.0 – 1.89 Mo**

**Masses are consistent with the masses of all known neutron stars!**

Abbott et al. 2018, arXiv1805.11579

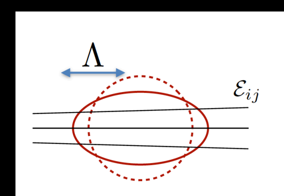
# NS LABORATORY FOR STUDYING SUPER-DENSE MATTER



TIDAL DEFORMABILITY

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$




From only GWs we cannot say both components of the binary were NS

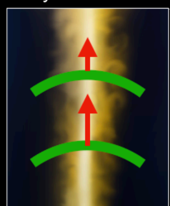
# *EM non-thermal emission*

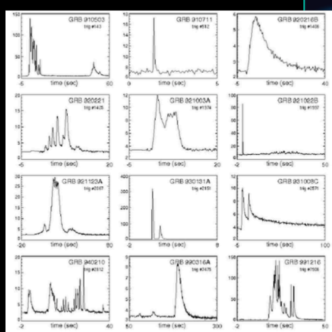
# *Short Gamma Ray Burst*

Prompt emission phase:

Energy range: keV-MeV

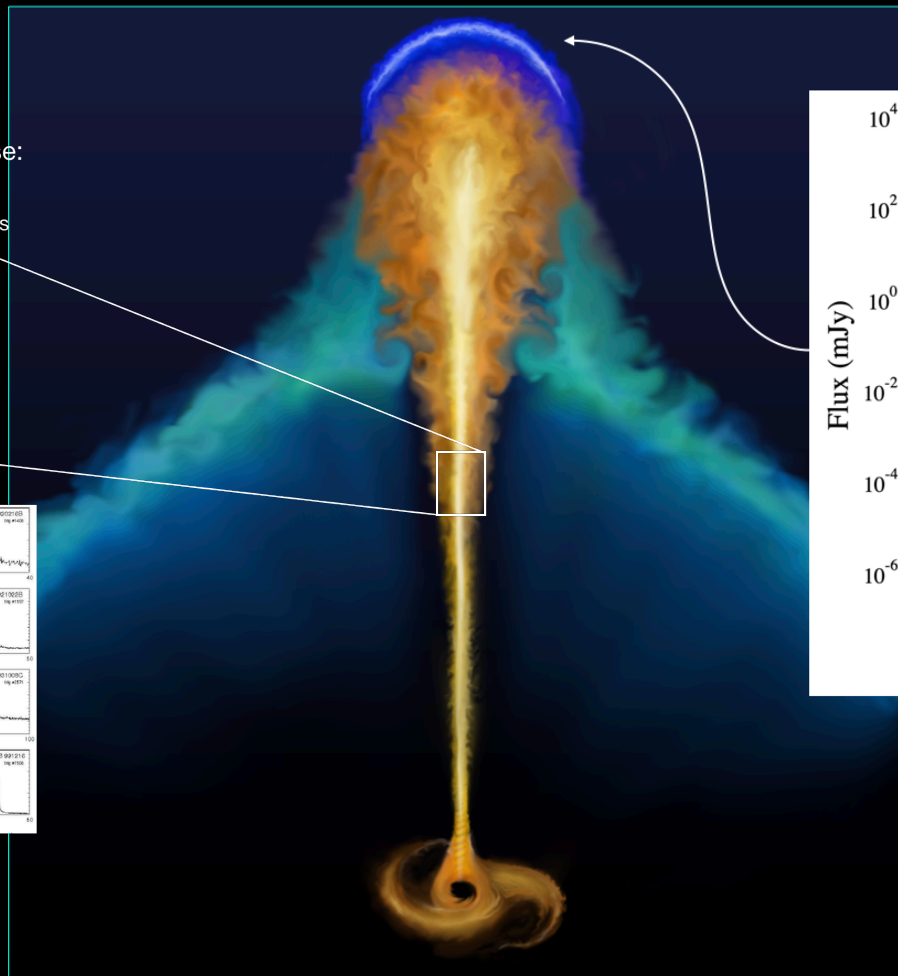
Variability time-scales: ms-s



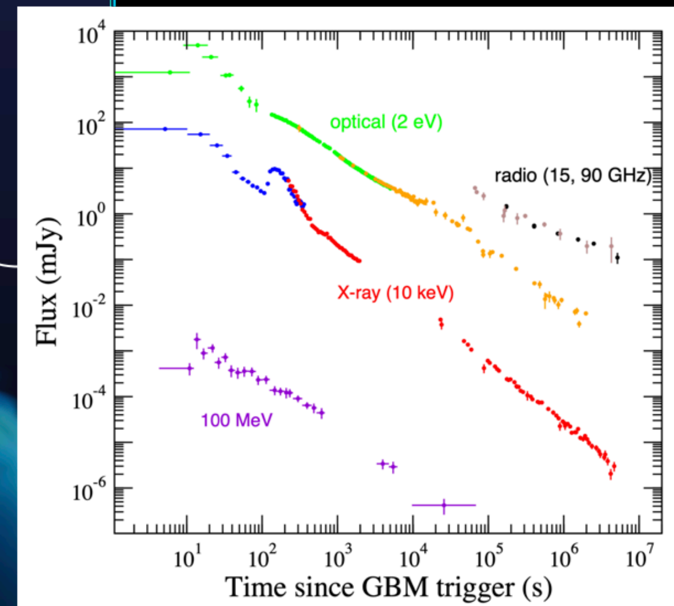


Shemi & Piran (1990)

Rees & Meszaros (1994)



Afterglow phase




From Panaitescu et al (2013)

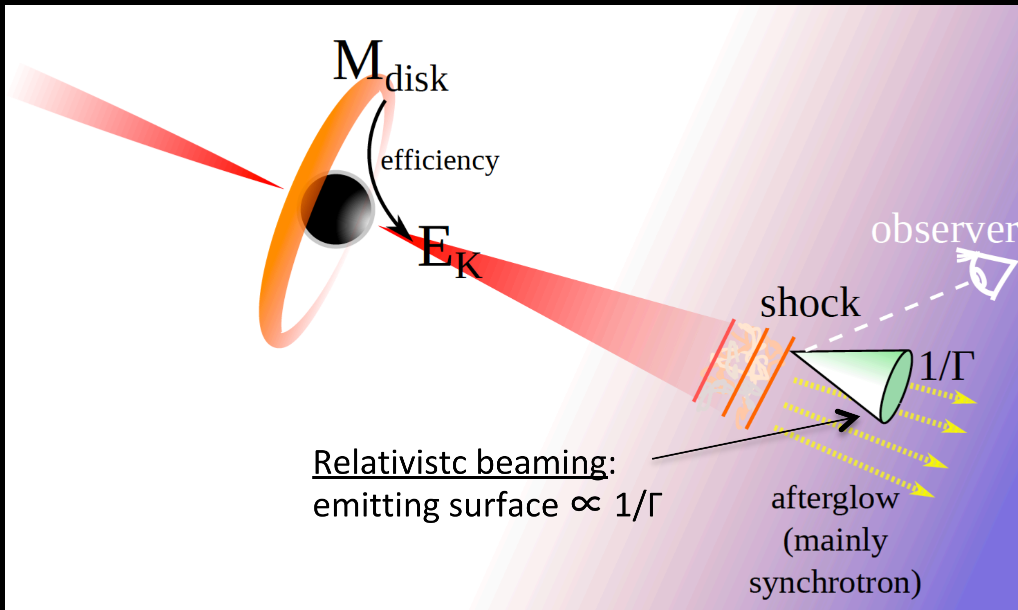
**Prompt emission**

**ϒ-ray** within seconds

**Afterglow emission**

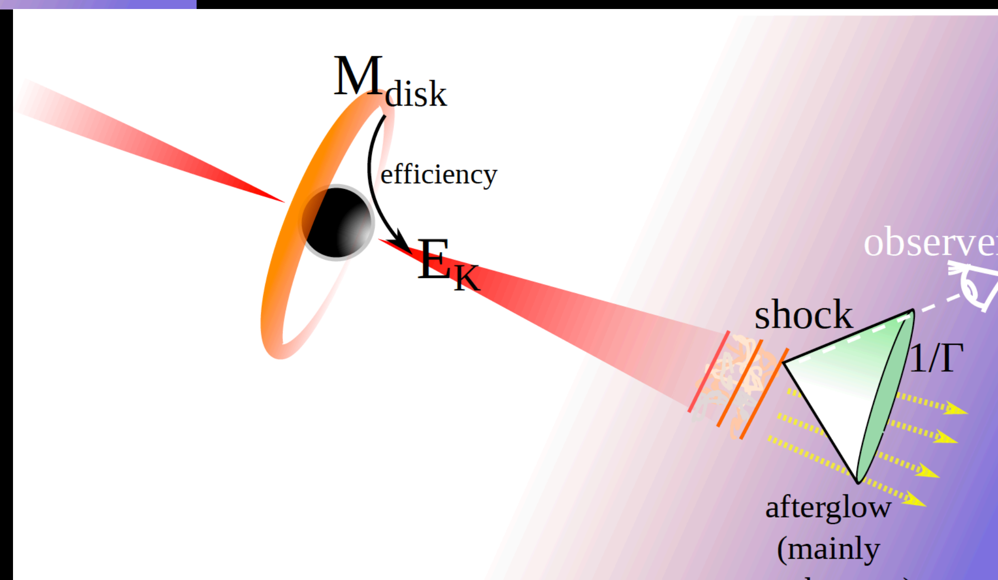
**Optical, X-ray, radio**

hours, days, months




EM emission detectable also by off-axis observers

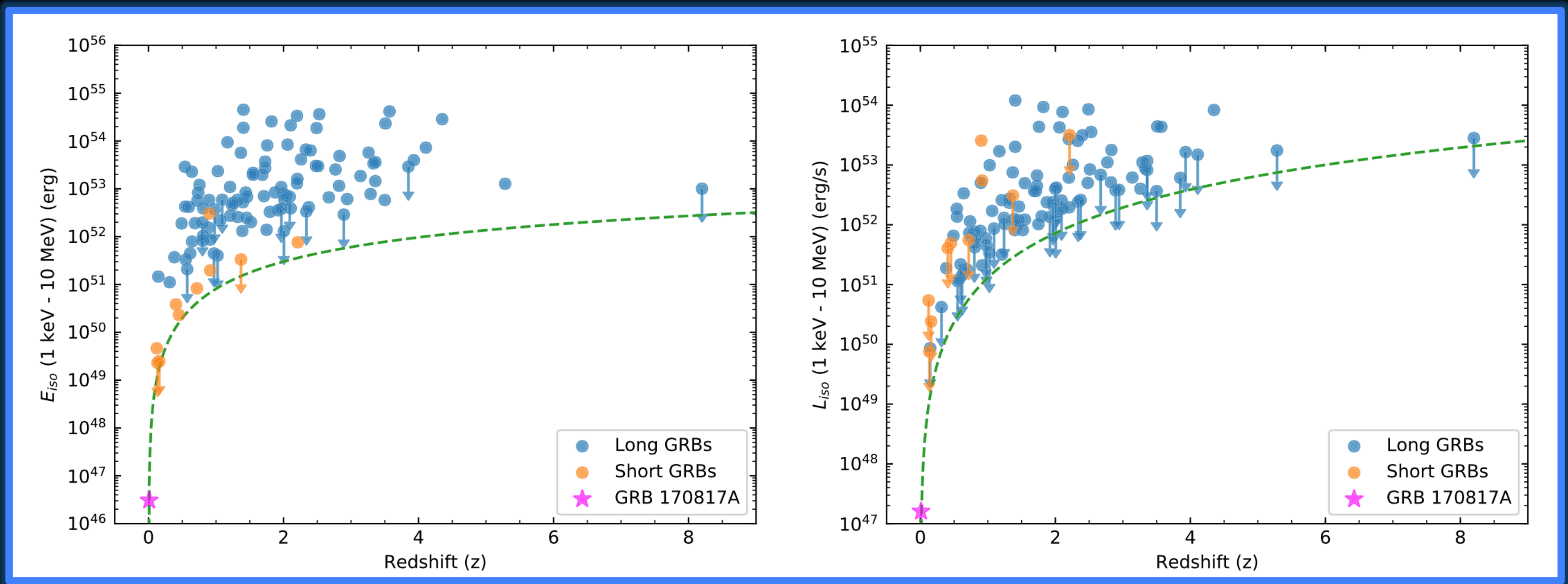
Early EM emission detectable only by on-axis observers




**Credit: Salafia**

# GRB 170817A

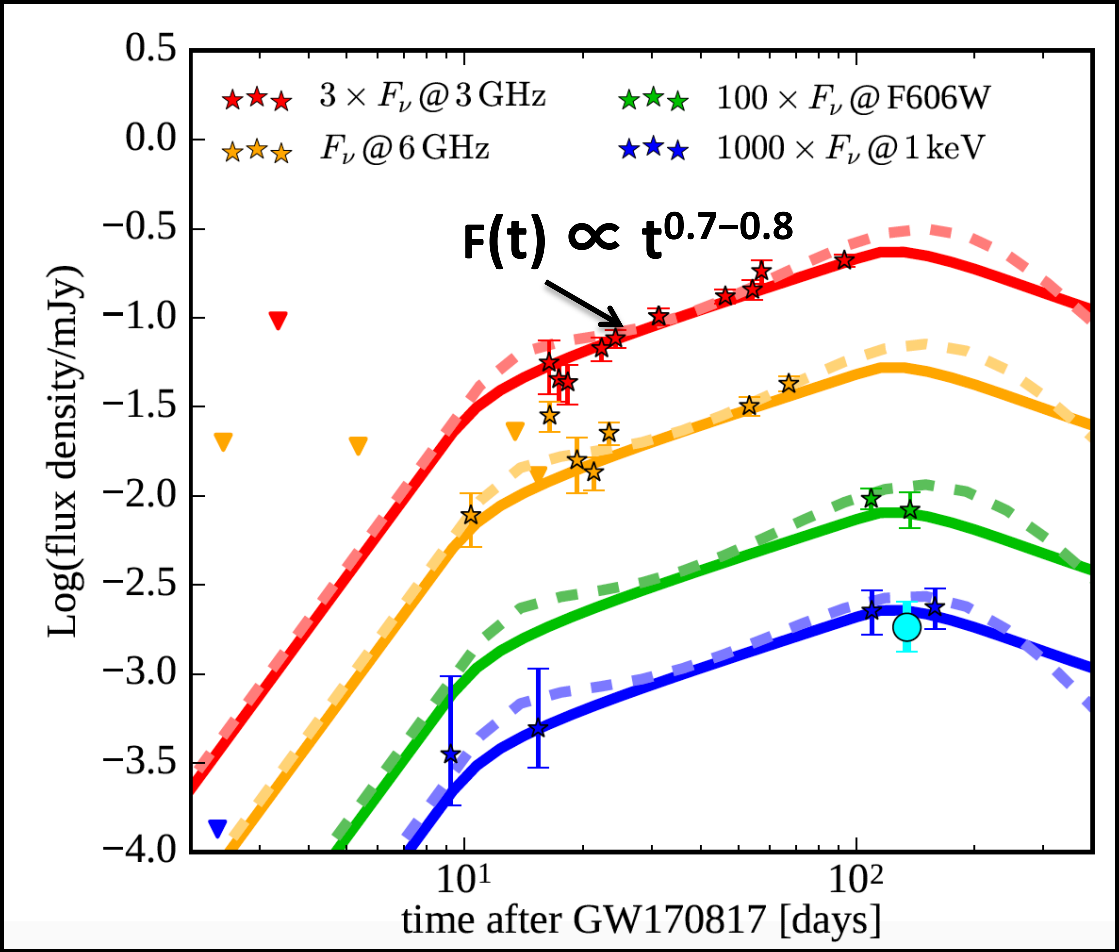
- 100 times closer than typical GRBs observed by Fermi-GBM
- it is also "subluminous" compared to the population of long/short GRBs
- $10^2 – 10^6$ less energetic than other short GRBs




Abbott et al. 2017, APJL, 848, L13

First short GRB viewed off-axis?

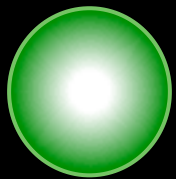
*After 150 days from the BNS merger…*



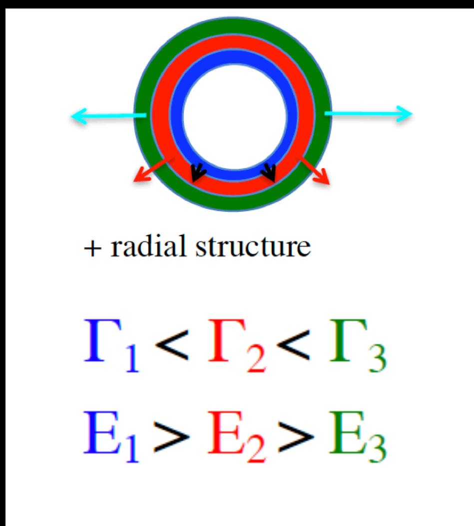

*..achromatic flux–rise until ~ 150 days!*

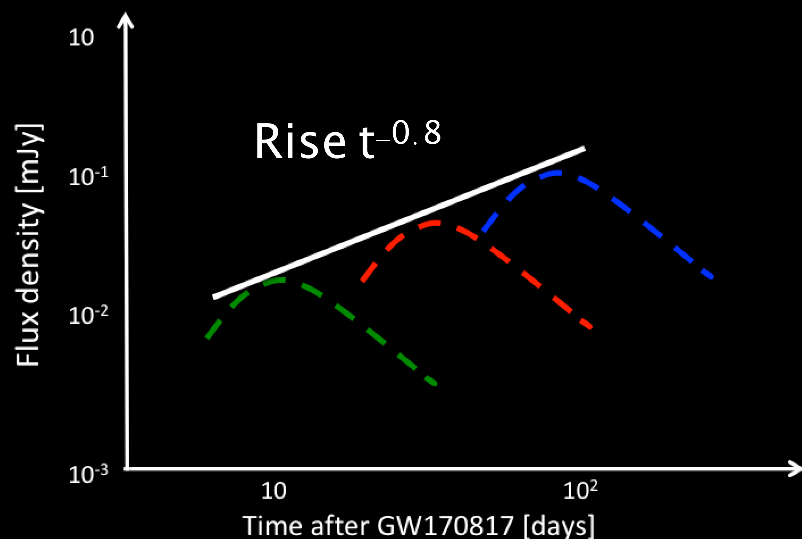
D'Avanzo et al. 2017, A&A

# RADIAL or ANGULAR STRUCTURE?

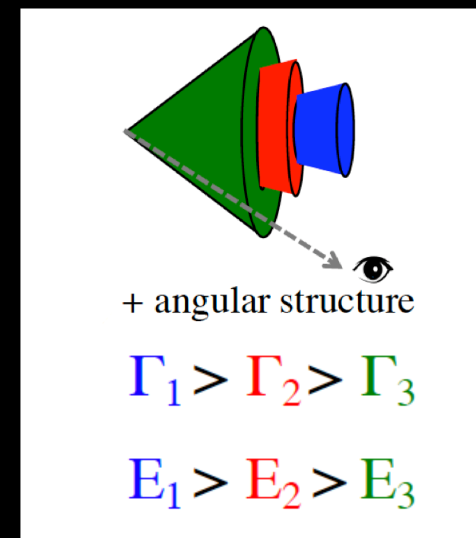


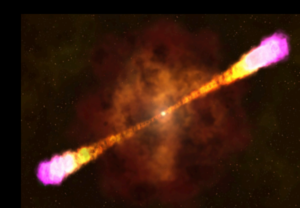
Mildly relativistic isotropic outflow (choked jet)



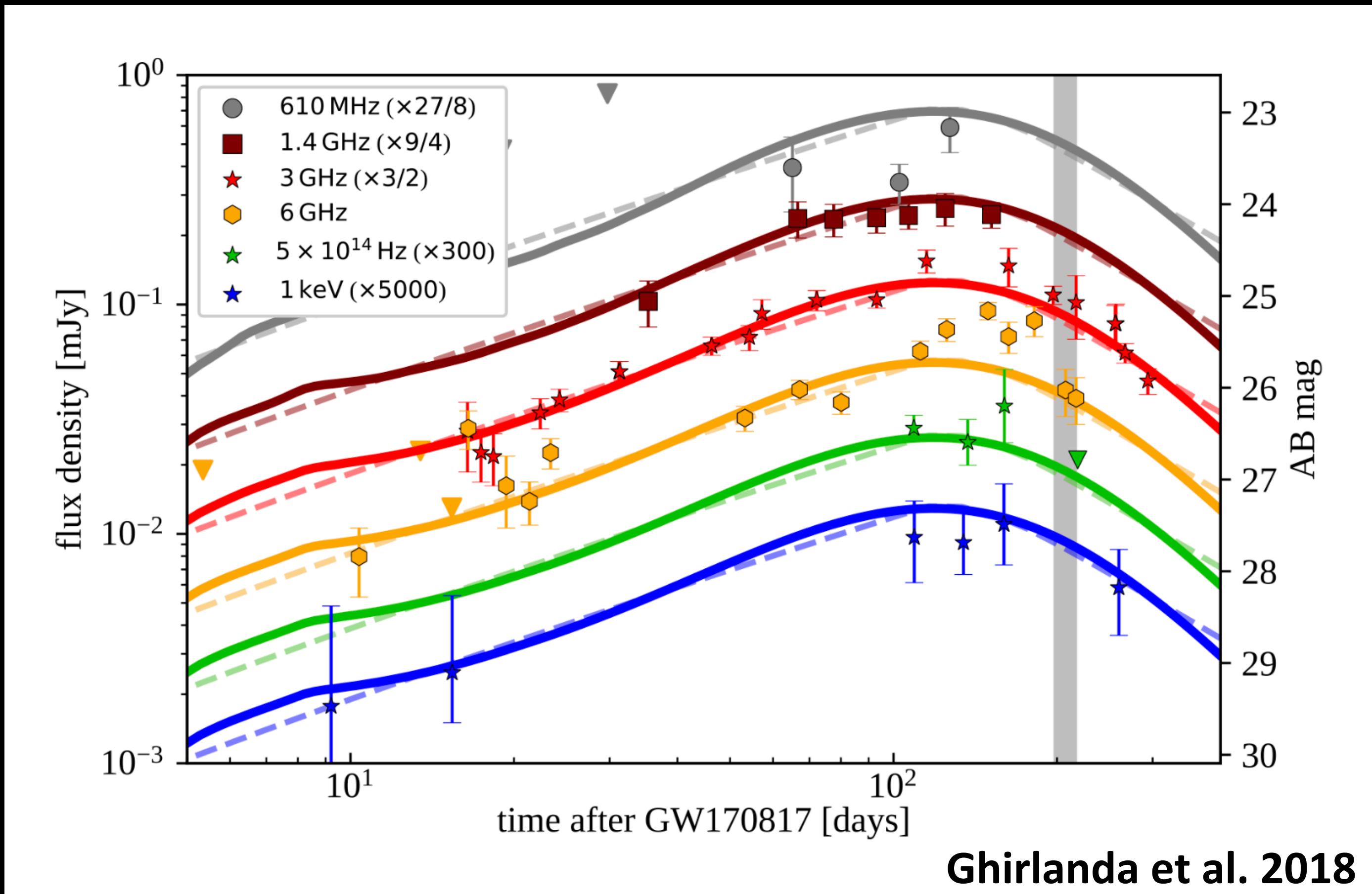

Structured Jet (successful) off-axis jet

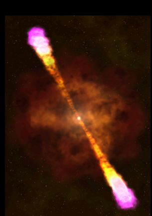


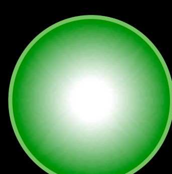
[see e.g. Rossi et al. 2002, Zhang et al. 2002, Ramirez-Ruiz et al. 2002, Nakar & Piran 2018, Lazzati et al. 2018, Gottlieb et al. 2018, Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017, Ghirlanda et al. 2019]

# *After 150 days from the BNS merger…decaying phase!*



Solid lines



Dashed lines

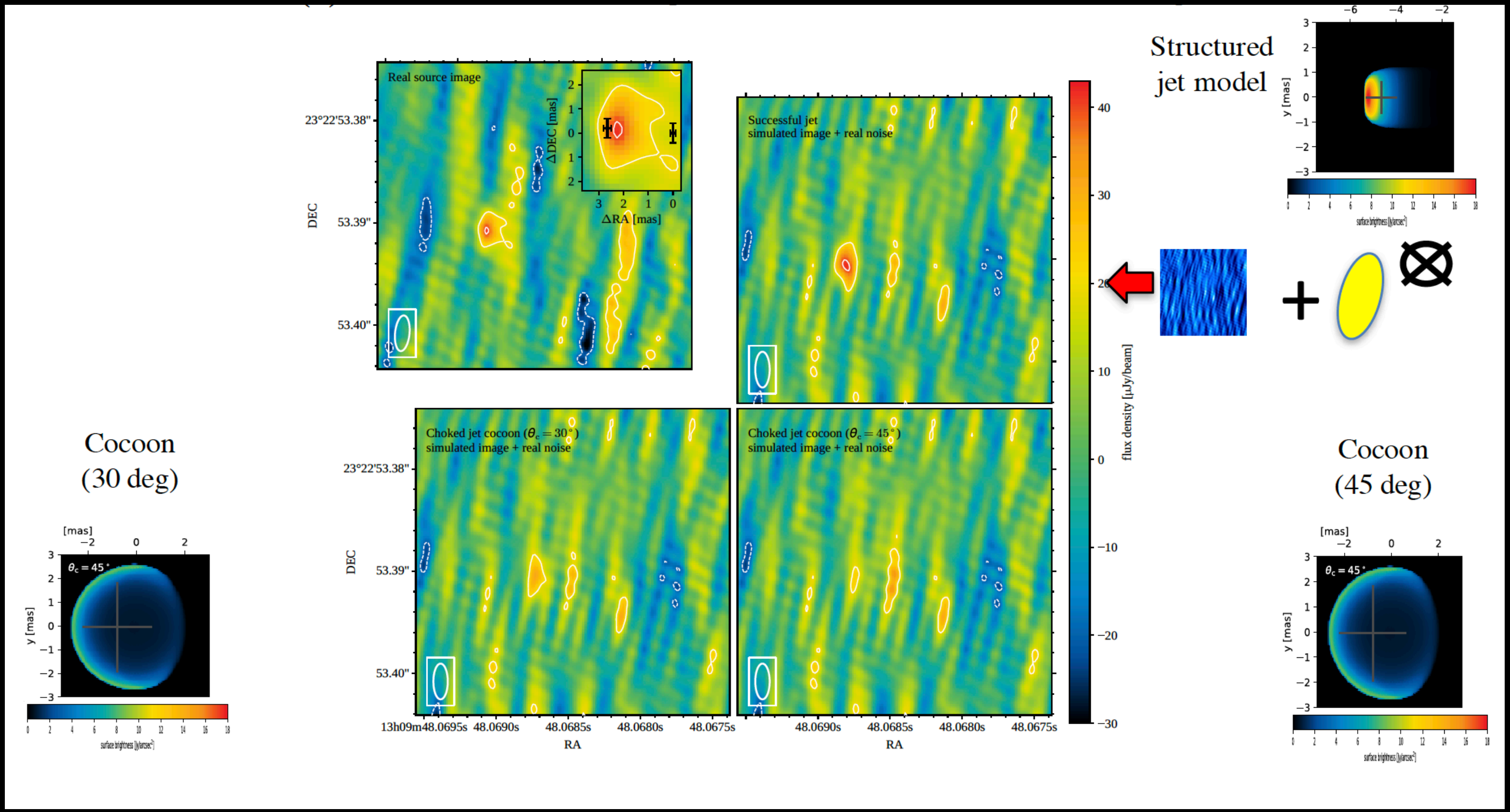
***MULTI-WAVELENGTH LIGHT CURVES CANNOT DISENTANGLE THE TWO SCENARIOS!***

[Margutti, et al. 2018, Troja, et al. 2018, D'Avanzo et al. 2018, Dobie et al. 2018, Alexander et al. 2018, Mooley et al. 2018, Ghirlanda et al. 2019]

# SIZE CONSTRAINTS


*Observations 207.4 days after BNS merger by global VLBI network of 33 radio telescopes over five continents constrain SOURCE SIZE < 2 mas*

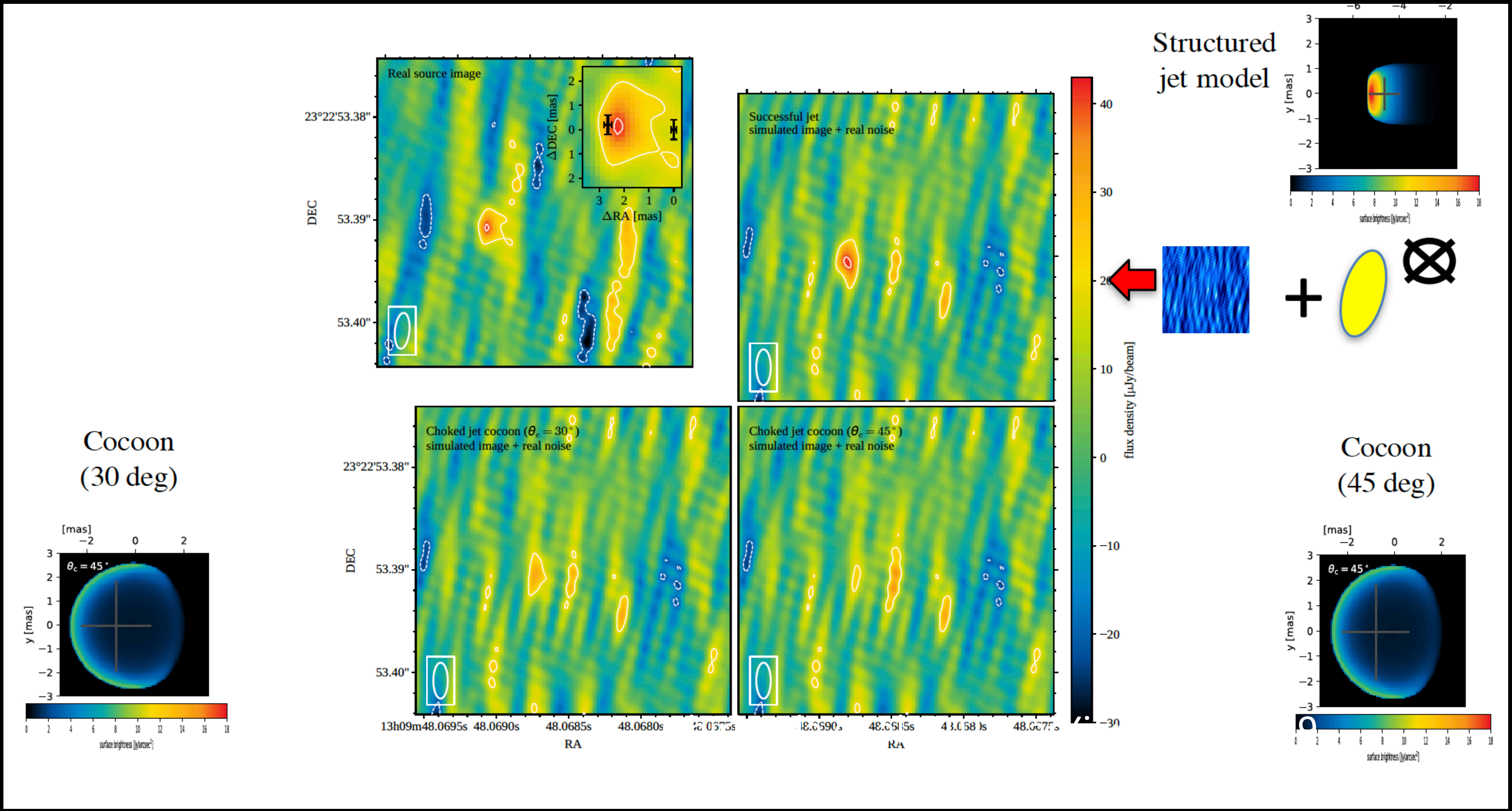
Ghirlanda et al. 2019, Science

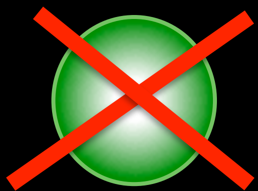



See also Mooley, Deller, Gottlieb et al. 2018

# SIZE CONSTRAINTS

Ghirlanda et al. 2019, Science



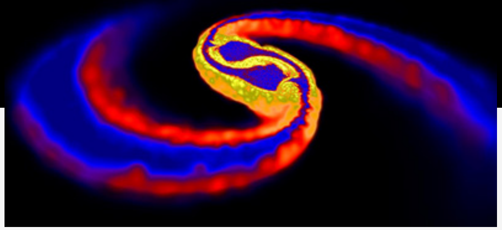
Ruled out nearly isotropic, mildly relativistic outflow , which predicts proper motion close to zero and size > 3 mas after 6 months of expansion

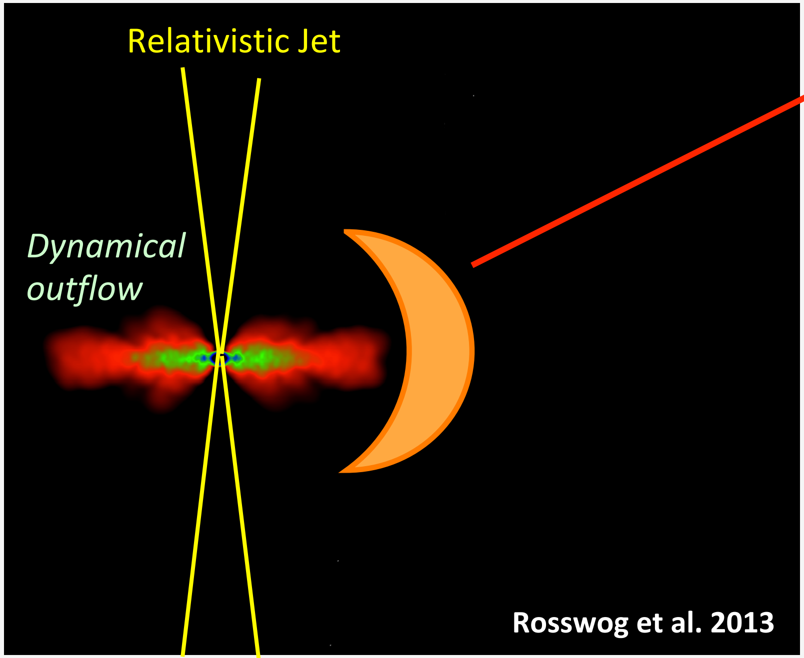
Ghirlanda et al. 2019, Science

*A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!*

# *Thermal-emission*

# Kilonova






## Tidal-tail ejecta → r-process

Neutron capture rate much faster than decay, special conditions: T > $10^9$ K, high neutron density $10^{22}$ $cm^{-3}$

↓

**nucleosynthesis of heavy nuclei**

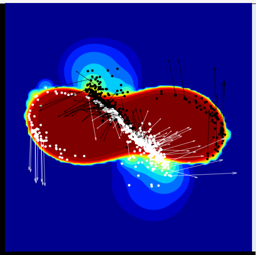
↓

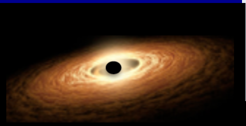
radioactive decay of heavy elements

↓

**Power short lived RED-IR signal (days)**

**Li & Paczynski 1998; Kulkarni 2005 Metzger et al. 2010; Tanaka et al. 2014; Barnes & Kasen 2013**



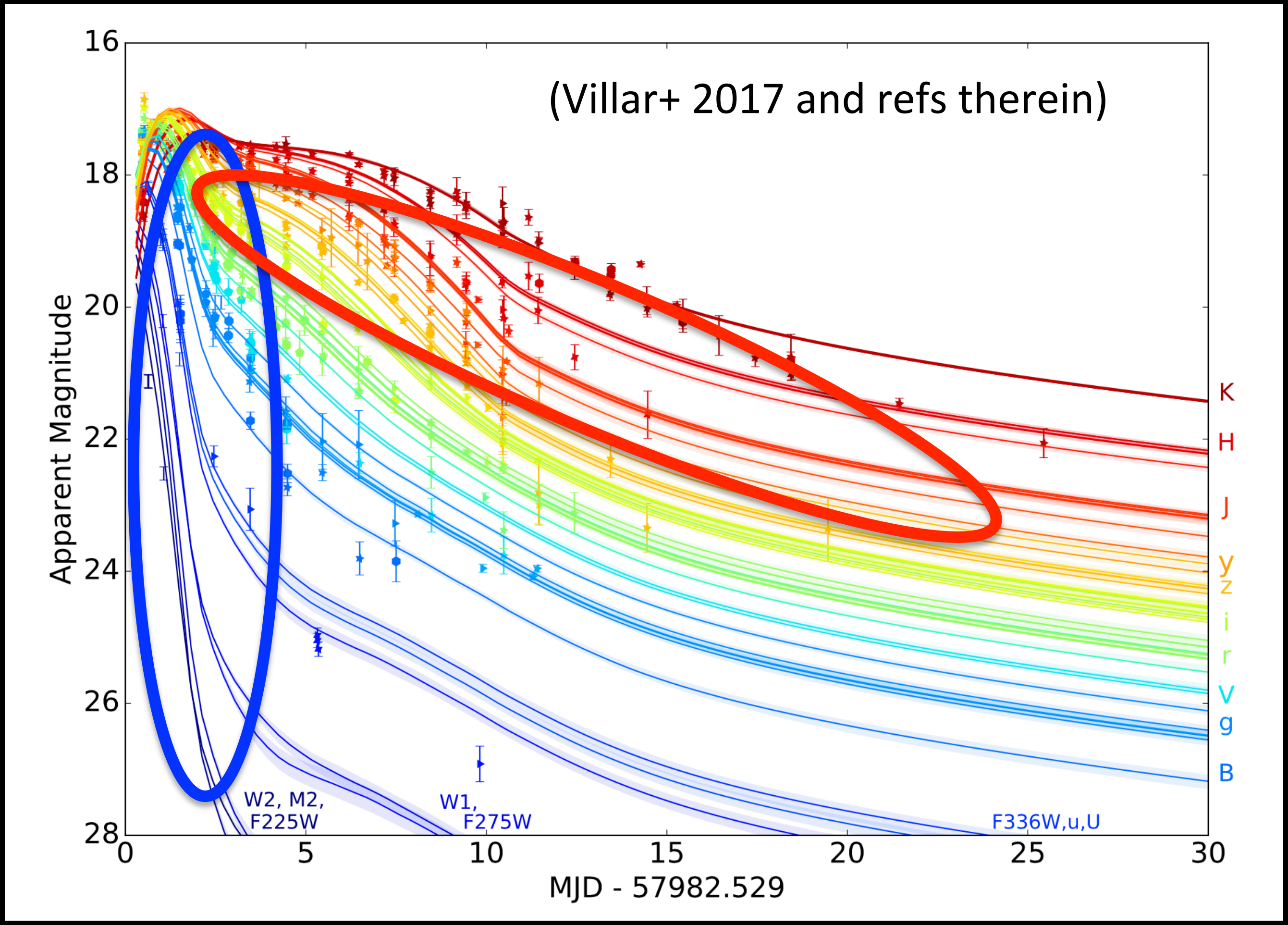


## Shock-heated ejecta, accretion disc wind outflow, secular ejecta

- Weak interactions: neutrino absorption, electron/positron capture
- Higher electron fraction, no nucleosynthesis of heavier element
- Lower opacity
- brief (~ 2 day) **blue optical transient**

**Kasen et al. 2015, Perego et al. 2014, Wanajo et al. 2010**

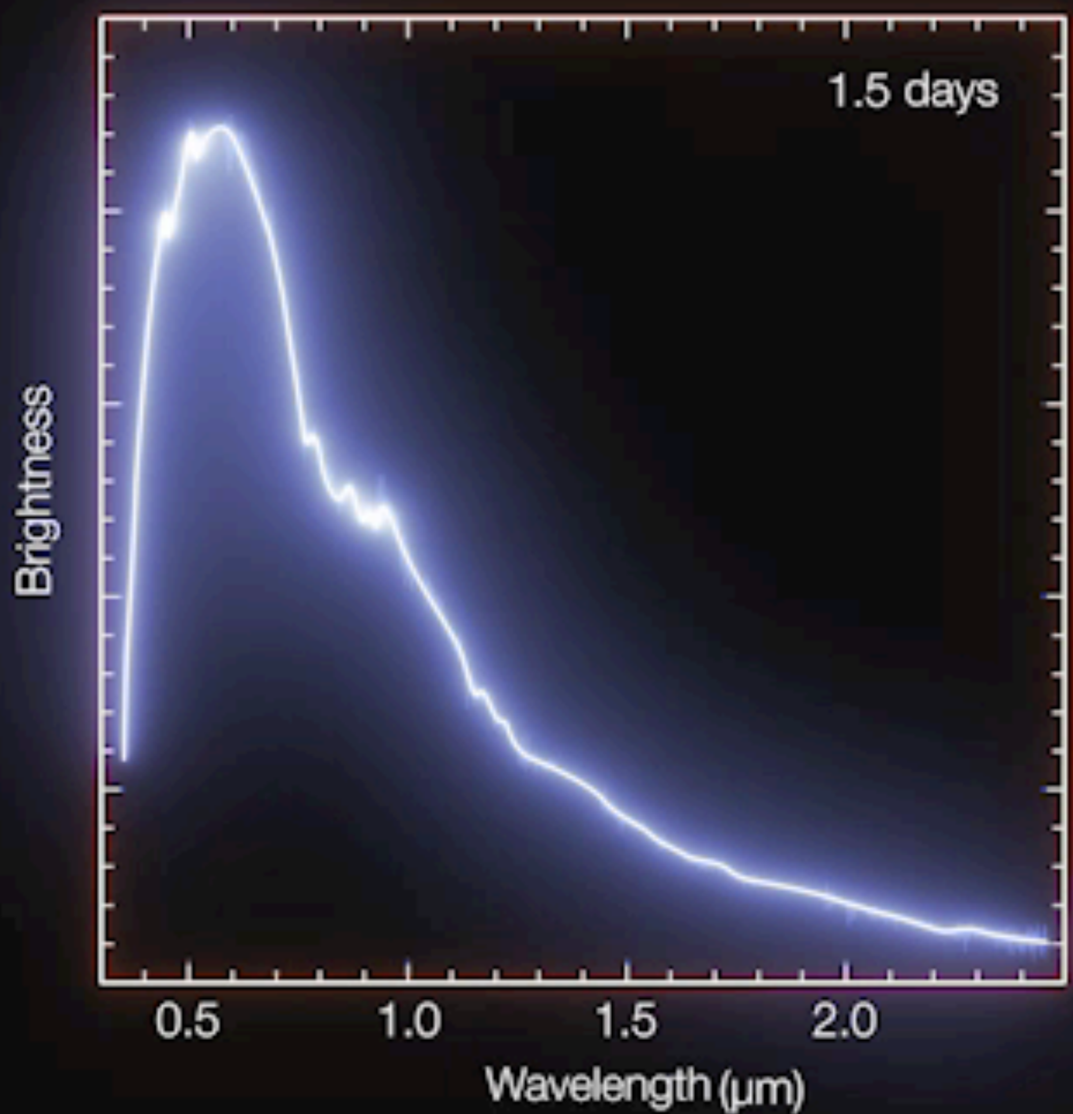
# UV/Optical/NIR Light Curves




Extremely well characterized photometry of a Kilonova:

*thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!*

ESO-VLT/X-Shooter




**First spectral identification of the kilonova emission**

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

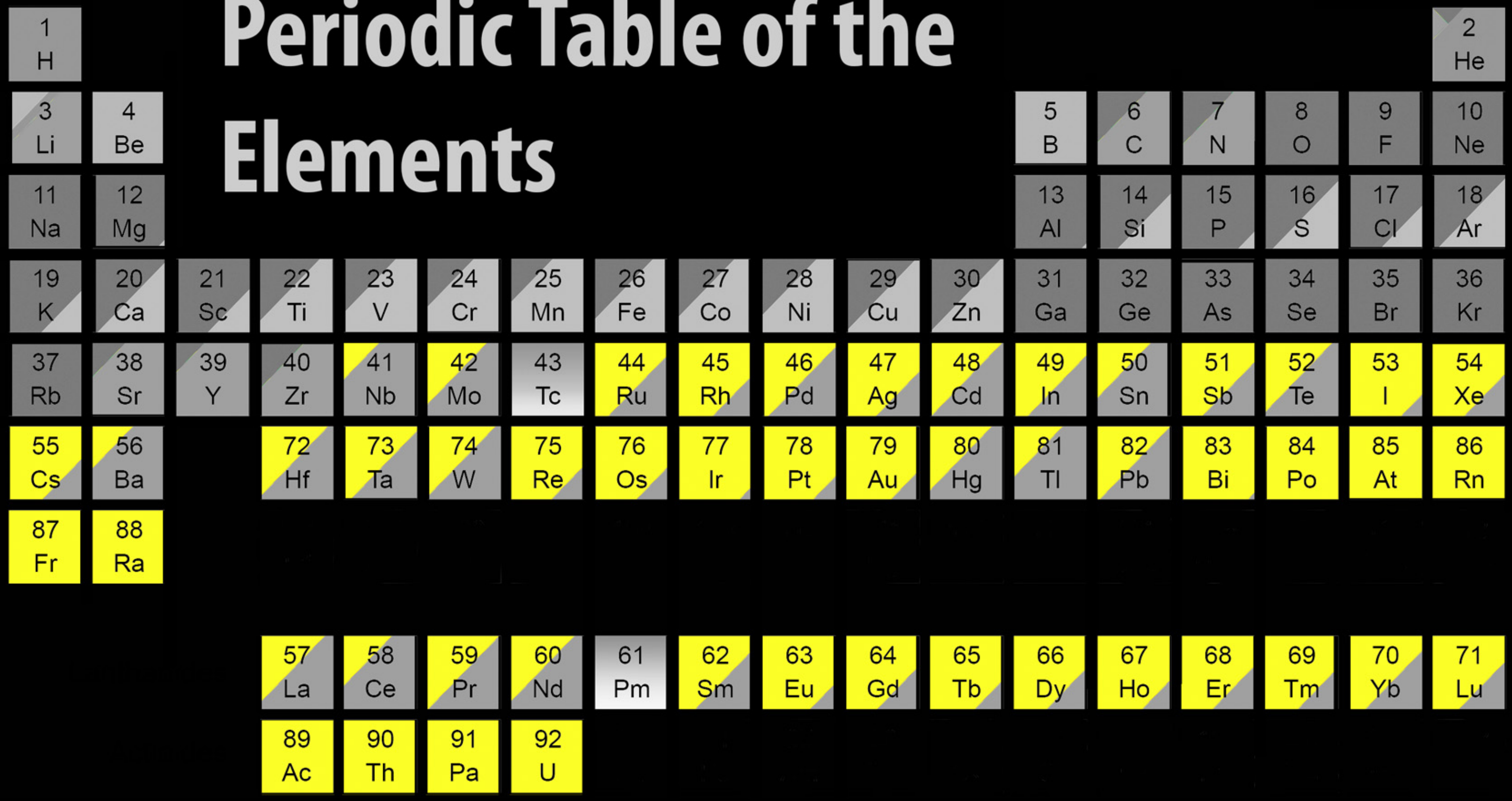
(Pian et al. 2017, Smartt et al. 2017)

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

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

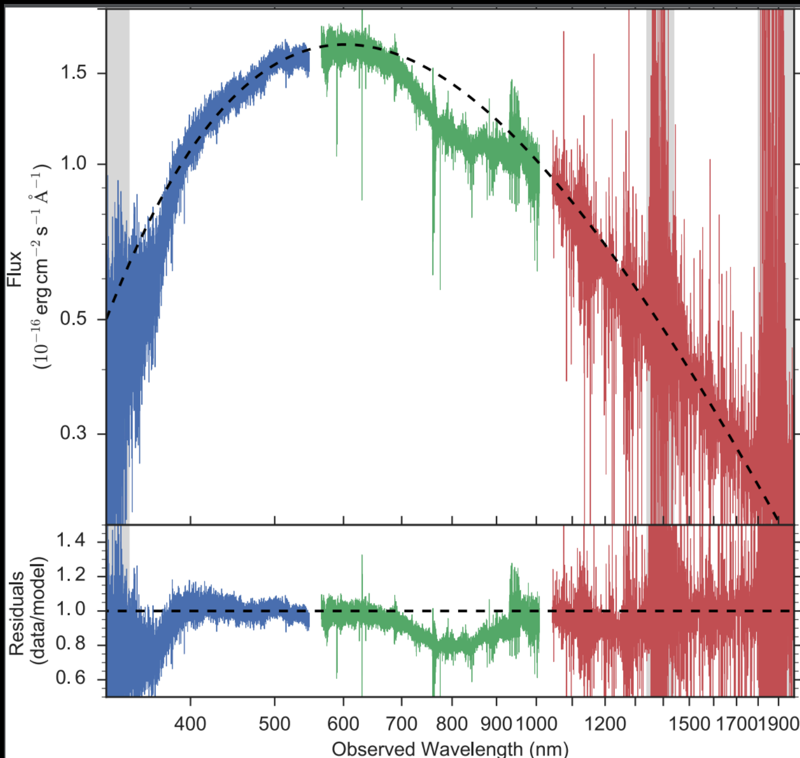
Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

# Periodic Table of the Elements

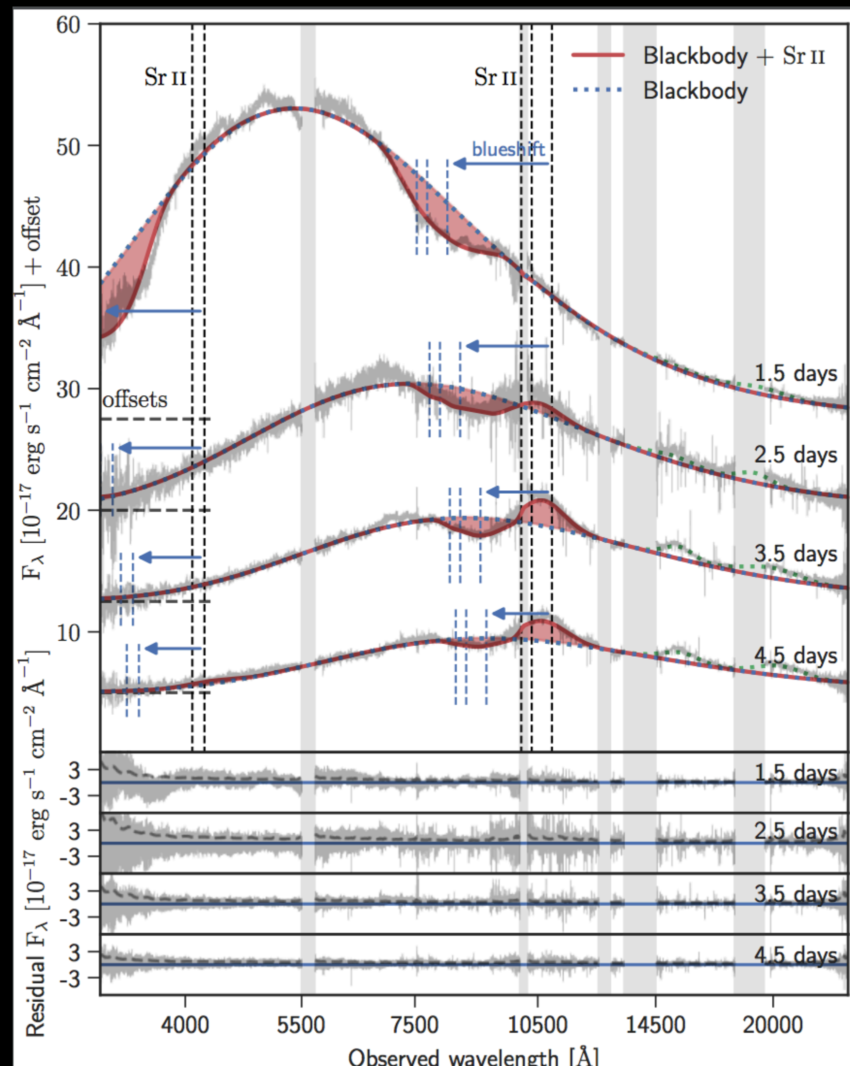



**Yellow: Formed by Merging Neutron Stars**

Credit:Jennifer Johnson/SDSS




Watson, D. et al. 2019 Nature

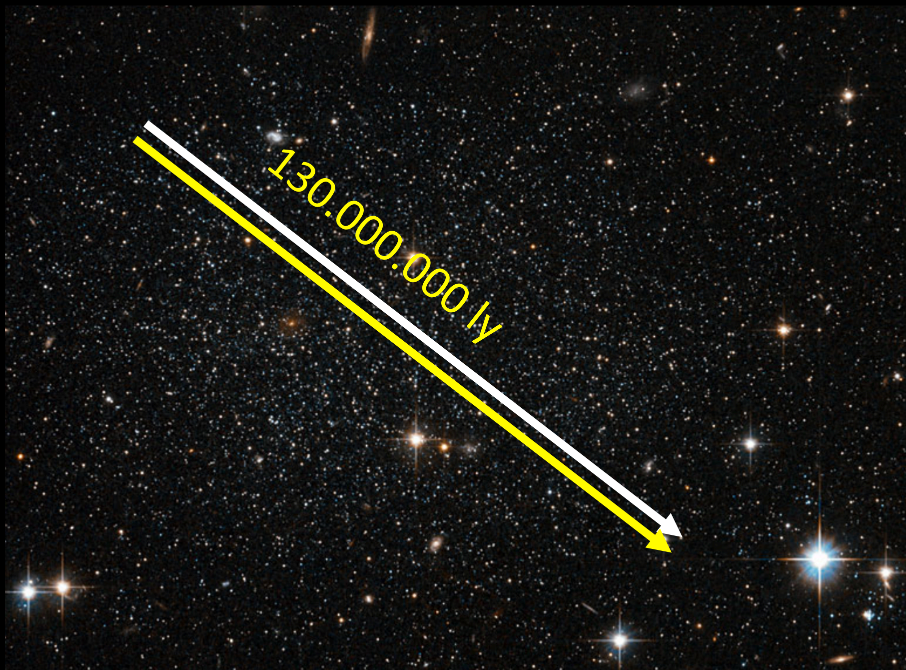



identification of the neutron-capture element **strontium**

See also Perego et al. 2021

*Multi-messenger studies*

# GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY




GRB/GW delay

$$\Delta t = (1.74 \pm 0.05)\, s$$

and 40 Mpc distance
→ difference speed of gravity and speed of light between

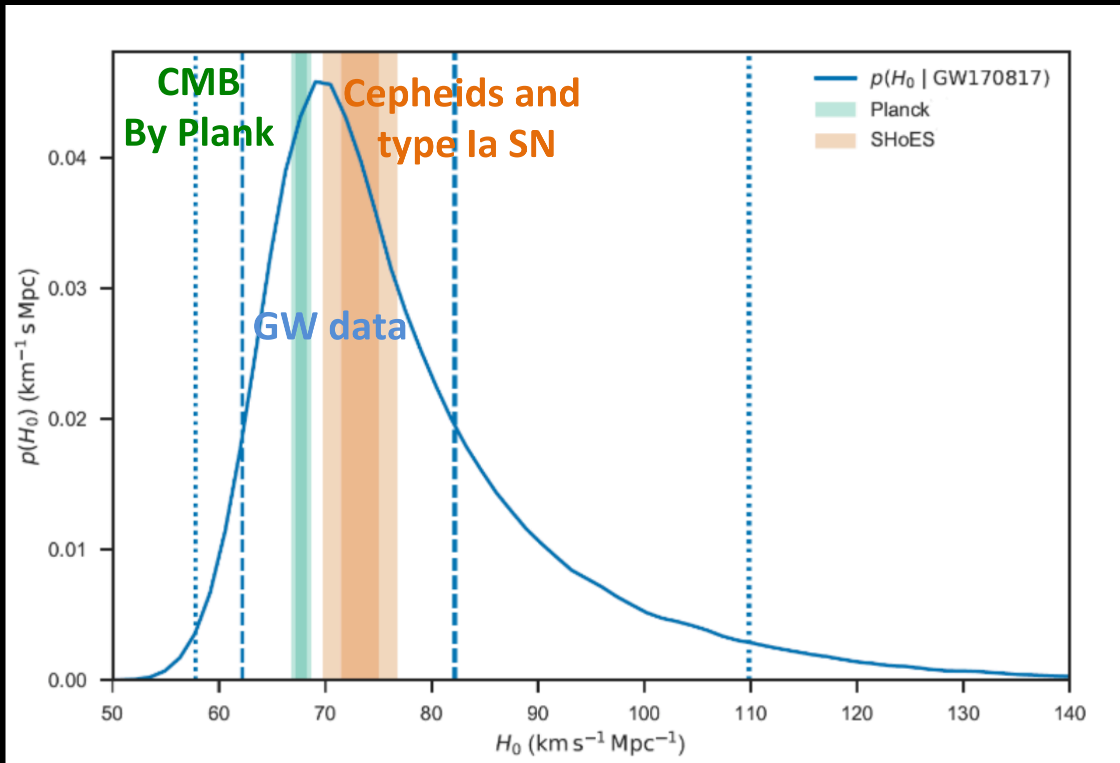
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

GWs propagate at the speed of light to within $1:10^{15}$!

LVC 2017, APJL, 848, L13

***Consequences of multi-messenger detection of GW170817 for cosmology →***
Constraint on the speed of GWs ruled out many classes of modified gravity models
(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. ’17, Creminelli & Vernizzi ’17)

# GRAVITATIONAL-WAVE COSMOLOGY:

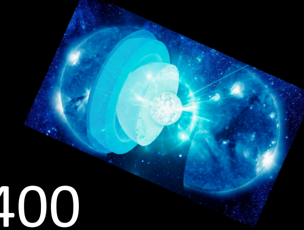



**Abbott et al. 2017, Nature, 551, 85A**

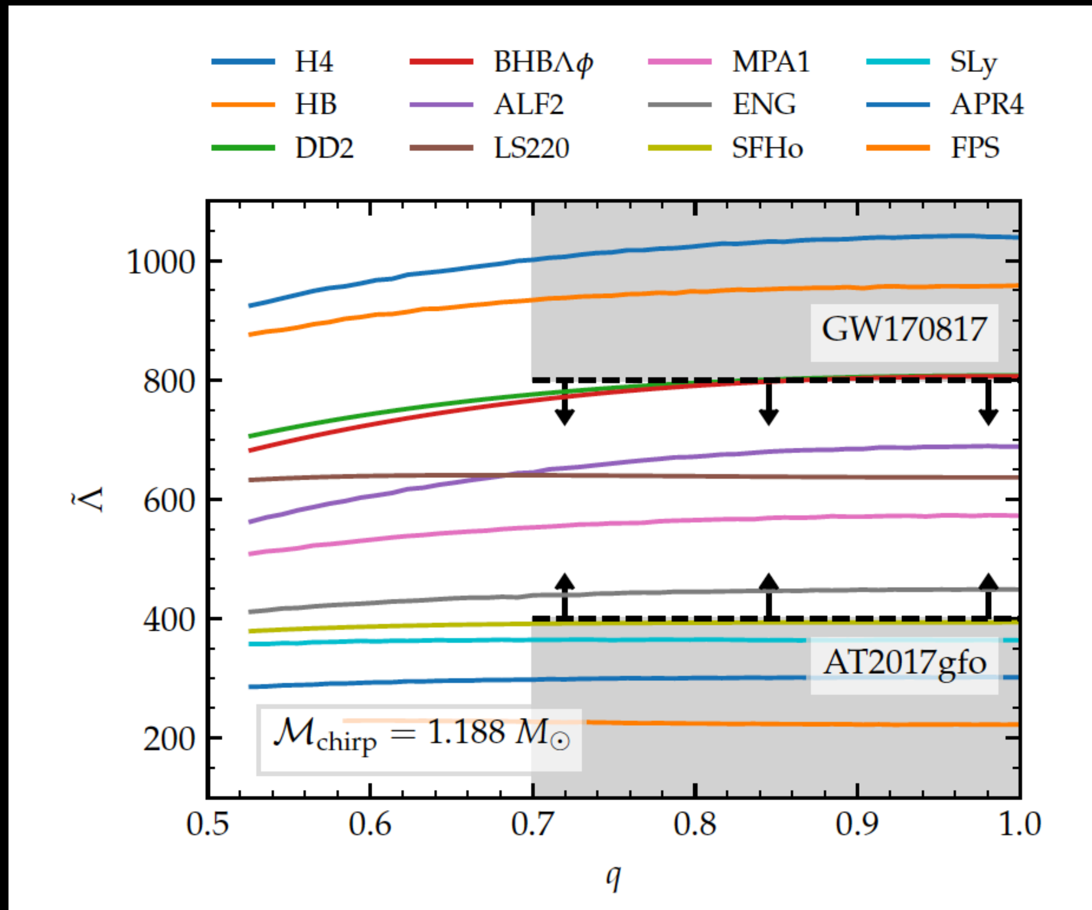
- Recession velocity /redshift
    - GW distance

→ HUBBLE COSTANT

# MULTIMESSENGER CONSTRAINTS ON NUCLEAR EOS



EM observations → Mej,tot > 0.05Mo → lower limit Λ > 400

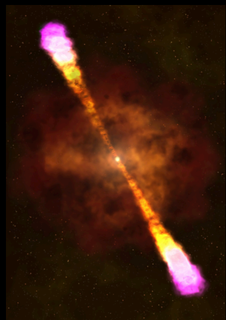



Radice, Perego, Zappa, Bernuzzi 2017

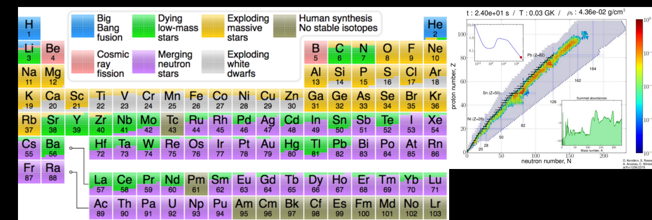
EM observations exclude very soft EOS!

## Radioactively powered transients

## Relativistic astrophysics

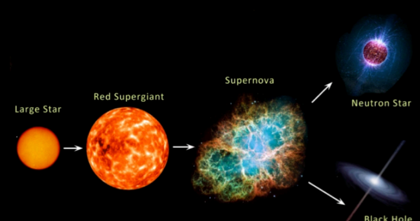


## Nucleosynthesis and enrichment of the Universe

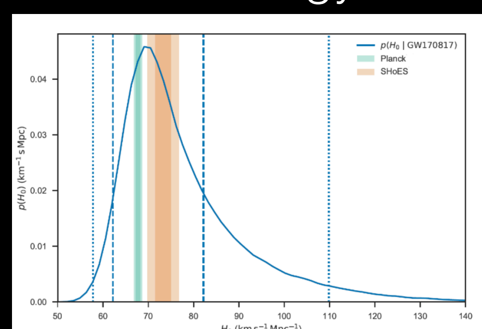




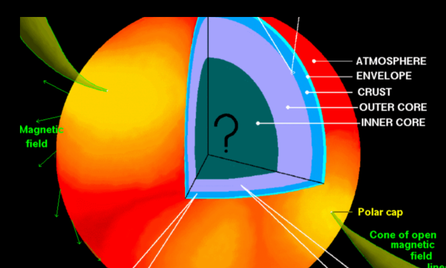
## Compact object formation and evolution




## Cosmology




## Nuclear matter physics

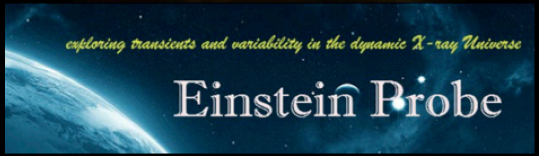


NO OTHER FIRM EM COUNTERPARTS: large sky-localization and fainter counterparts to be searched…

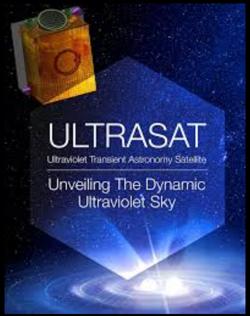




**NEW OBSERVATORIES**

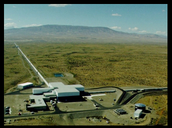









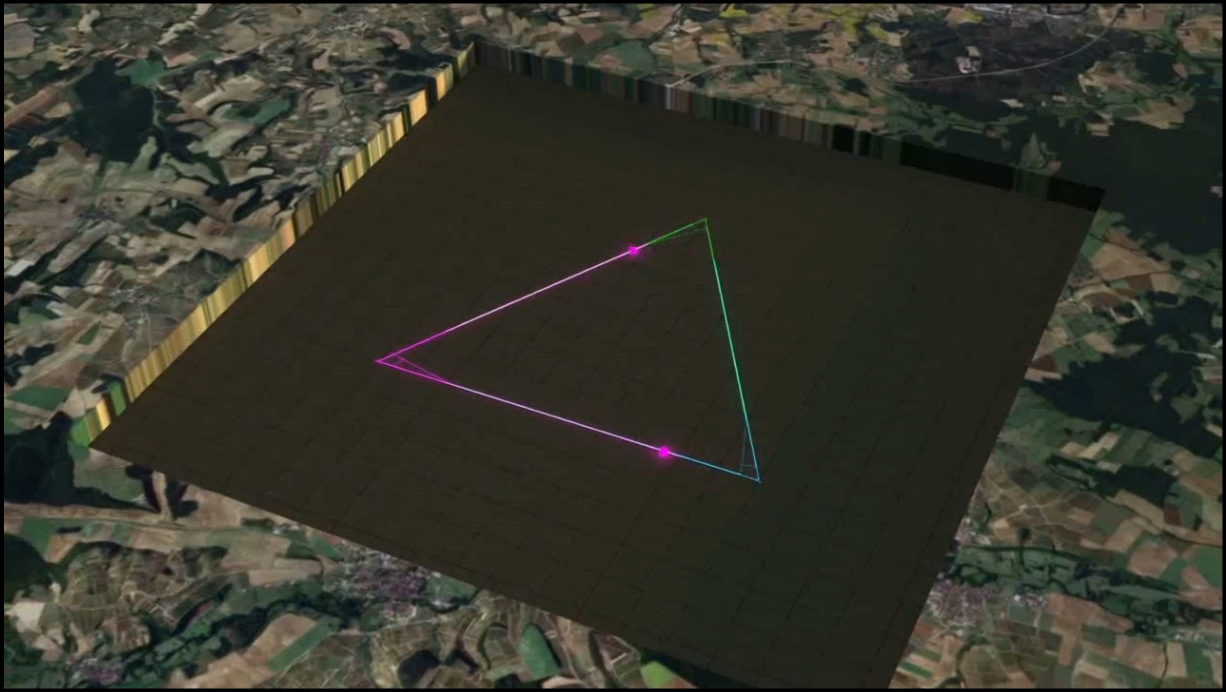
**NETWORK OF GW DETECTORS**



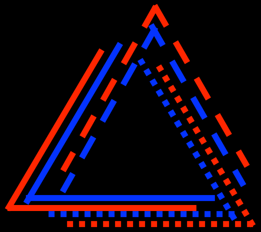
# The future of GW and Multimessenger astronomy

See GWIC roadmap, Bailes et al. 2021, Nature Reviews Physics

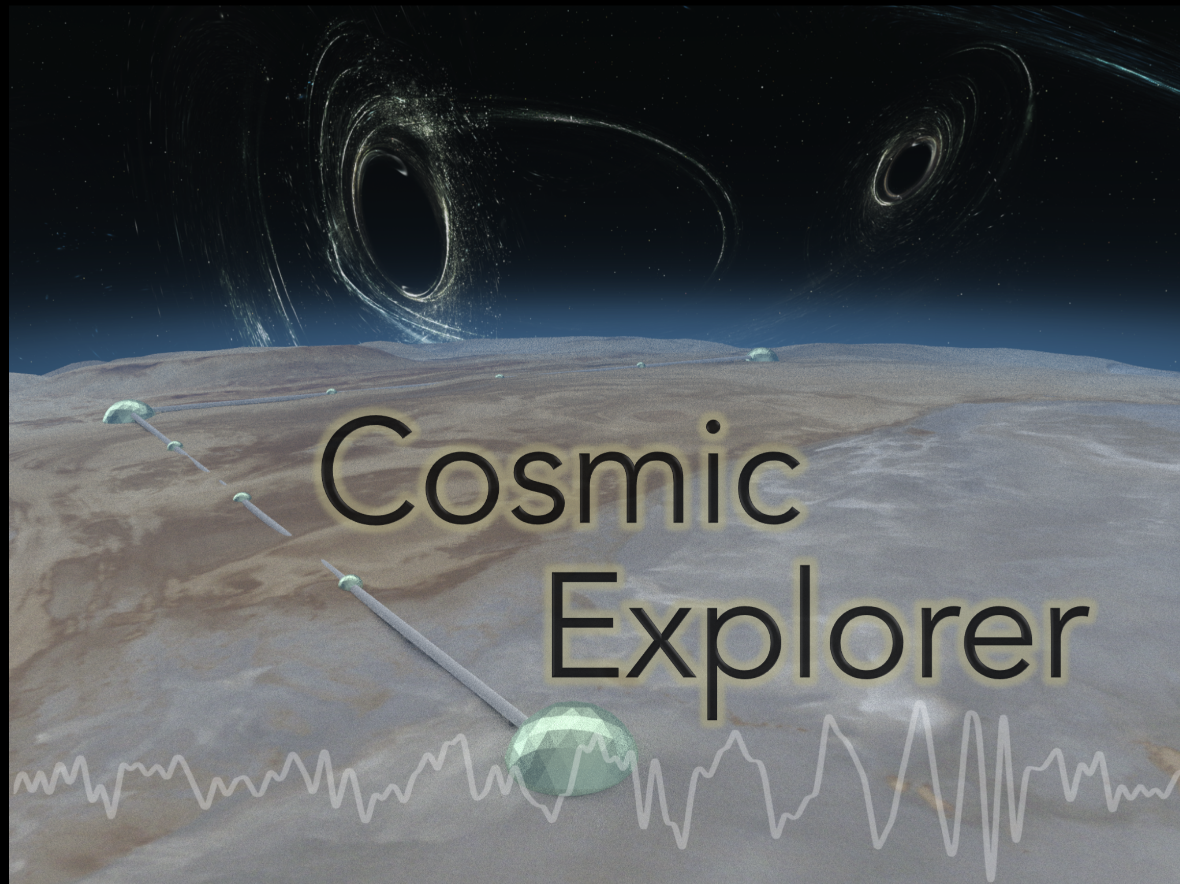
# ET: the European 3G GW observatory concept



Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...

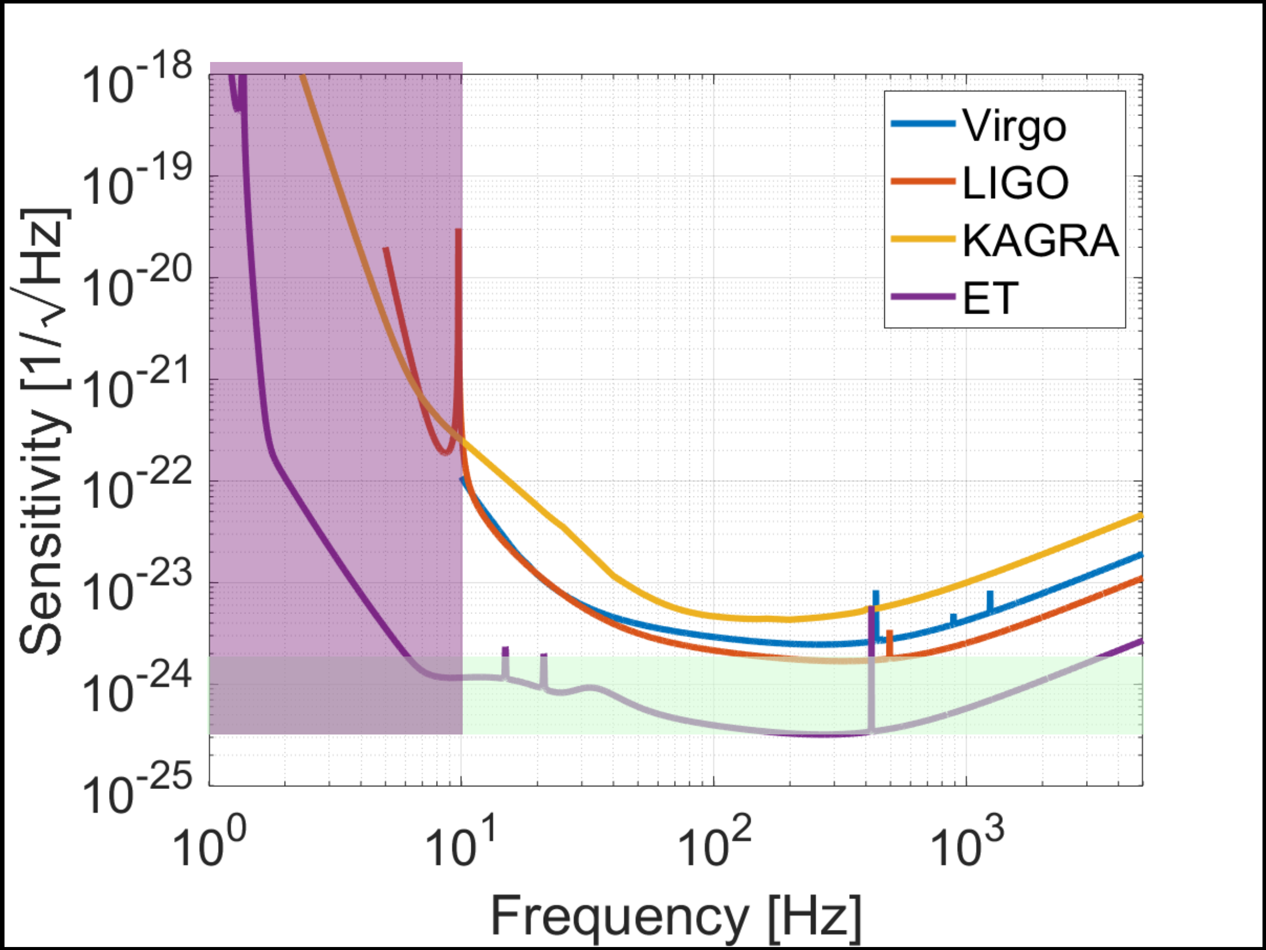


# Worldwide effort: Cosmic Explorer




Cosmic Explorer:  L shaped detectors, two sites
(40km, 20 km [option])

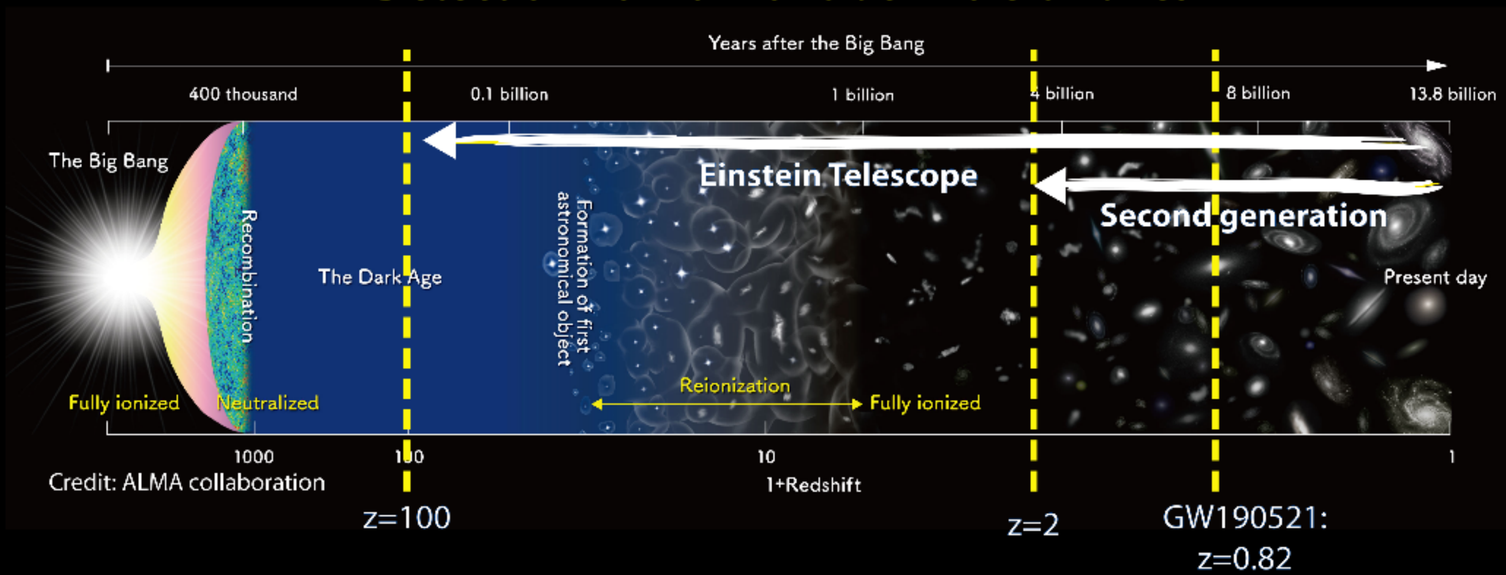
# EXPECTED SENSITIVITY

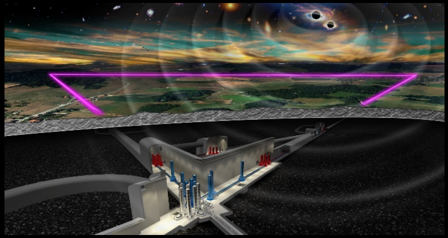


## The ET sensitivity will make it possible:

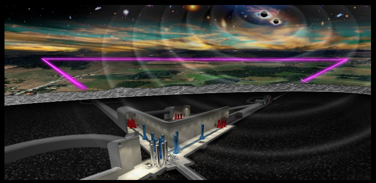
- Large distances back to the EARLY UNIVERSE

### Detection horizon for black-hole binaries

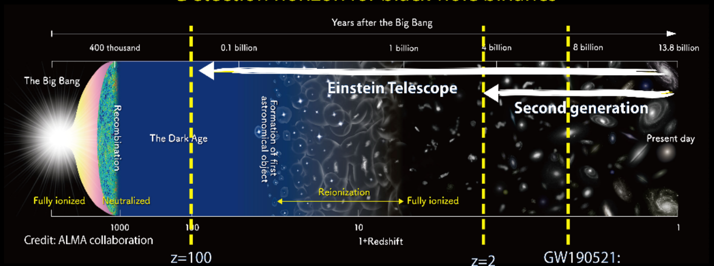


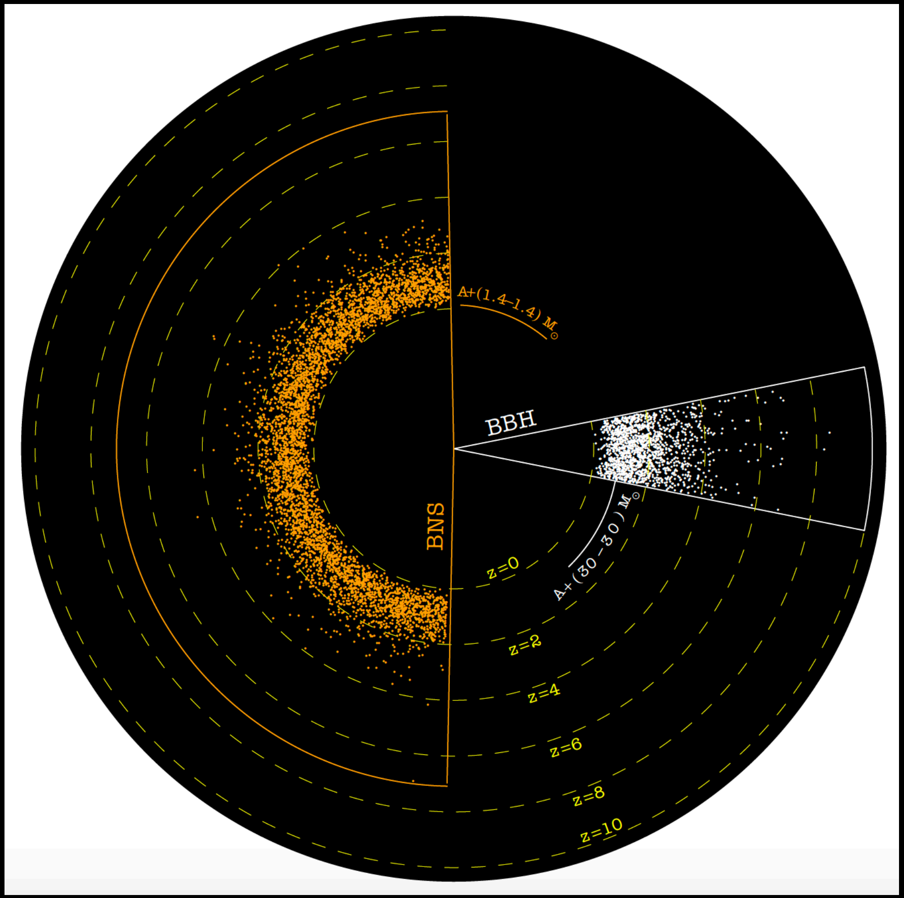
## The ET sensitivity will make it possible:



- Large distances back to the EARLY UNIVERSE

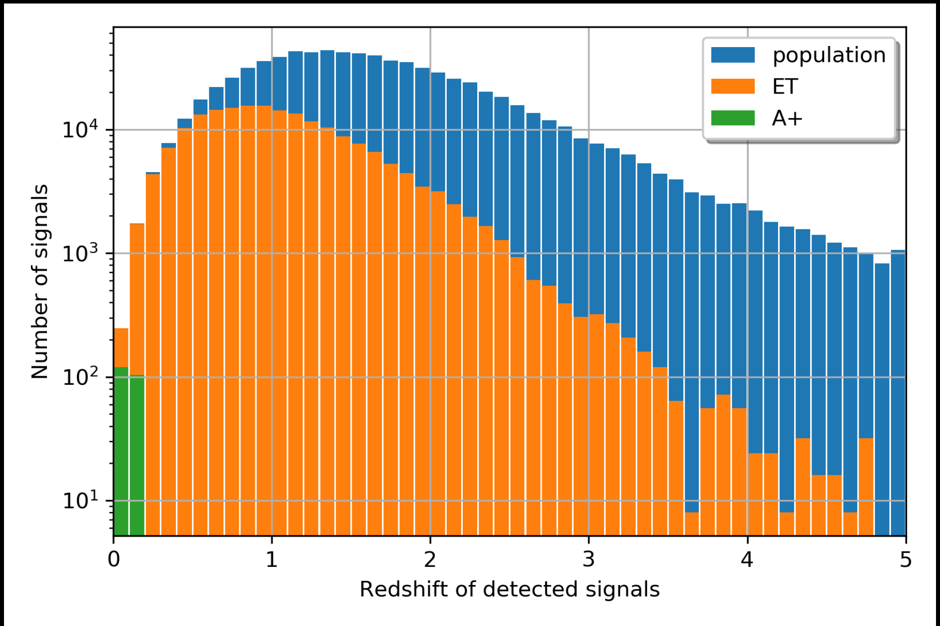



- POPULATION:
  increase number of detections

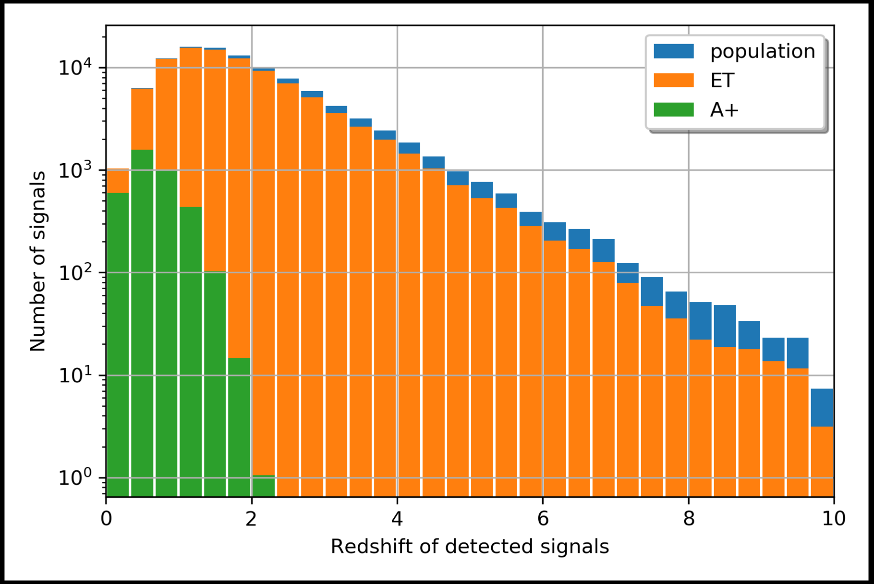


# COMPACT OBJECT BINARY POPULATIONS

## BINARY NEUTRON-STAR MERGERS



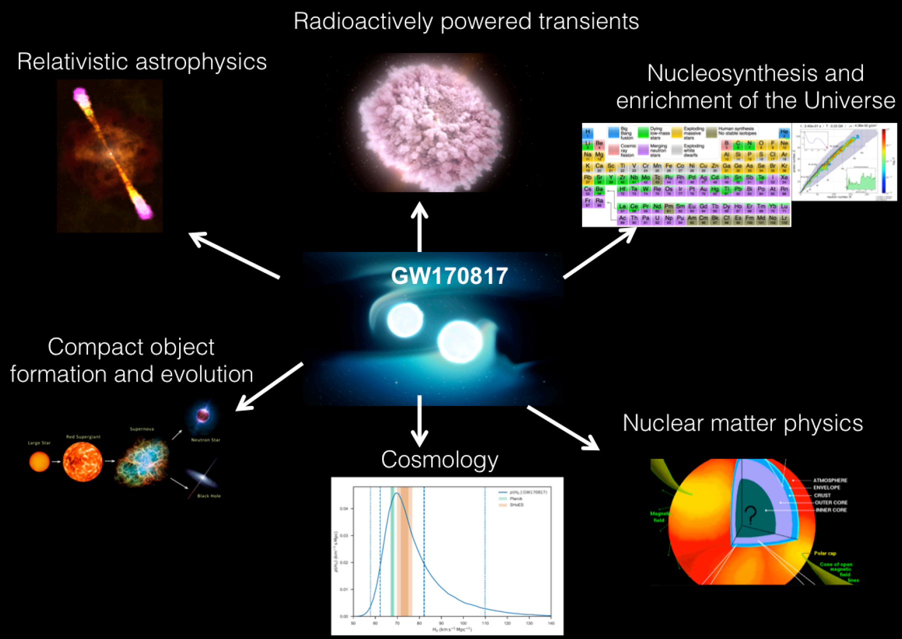

## BINARY BLACK-HOLE MERGERS




Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

$10^4$-$10^5$ BNS detections per year

$10^4$-$10^5$ BBH detections per year




**Kilonova/GW - EOS constraints**

**Kilonova/GW - Nucleosynthesis**

**GRBs – BNS/NSBH merger up to high z**

**Relativistic jet properties**

**Jet-less/jet GRBs**

**GRB/stable NS remnant**

**Link to Star Formation History**

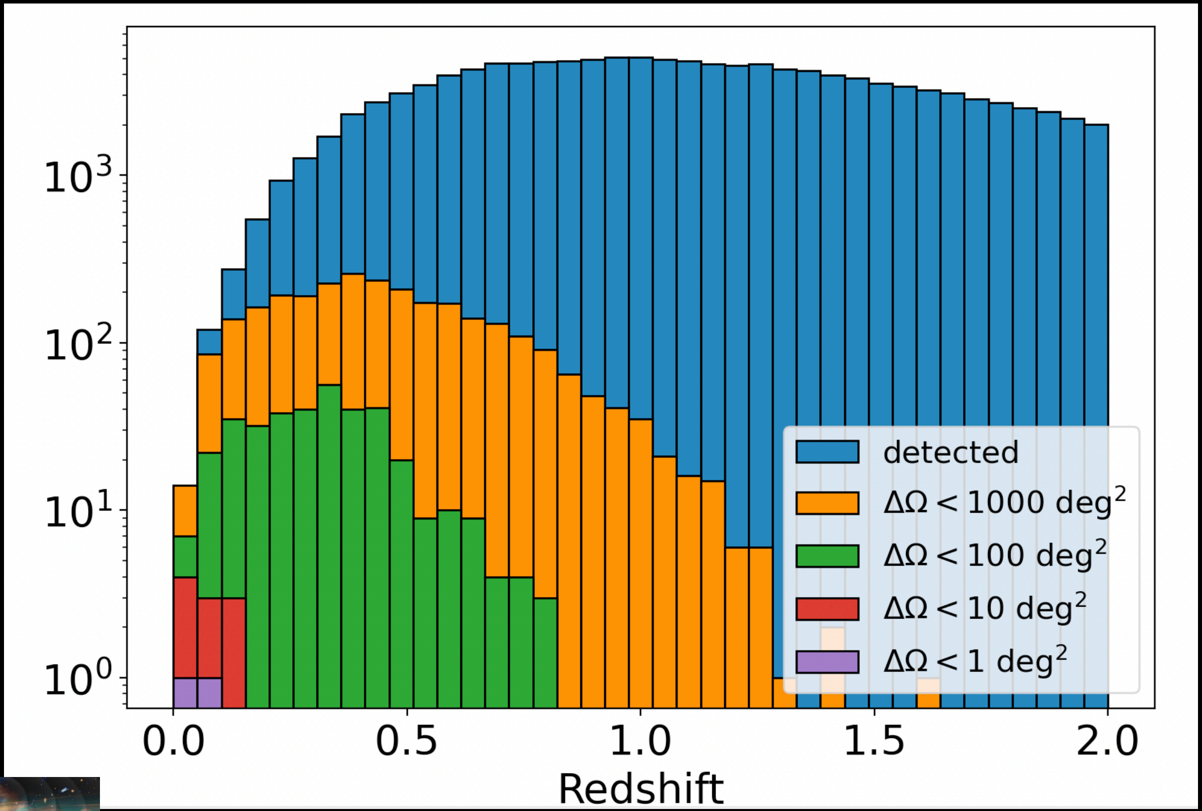
**Emission mechanism**

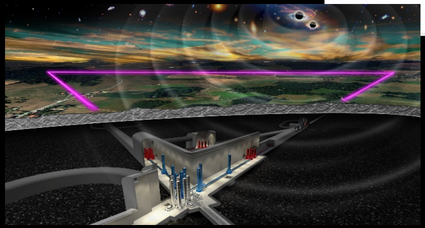
**Cosmology**

- Large increase of detection rate
  - population of BNS
  - detections along the cosmic history
- Better parameter estimation

- Higher chance to detect other sources and counterparts: core-collapse SN, new-born neutron stars, magnetars, FRBs, neutrinos

# ET sky-localization capabilities

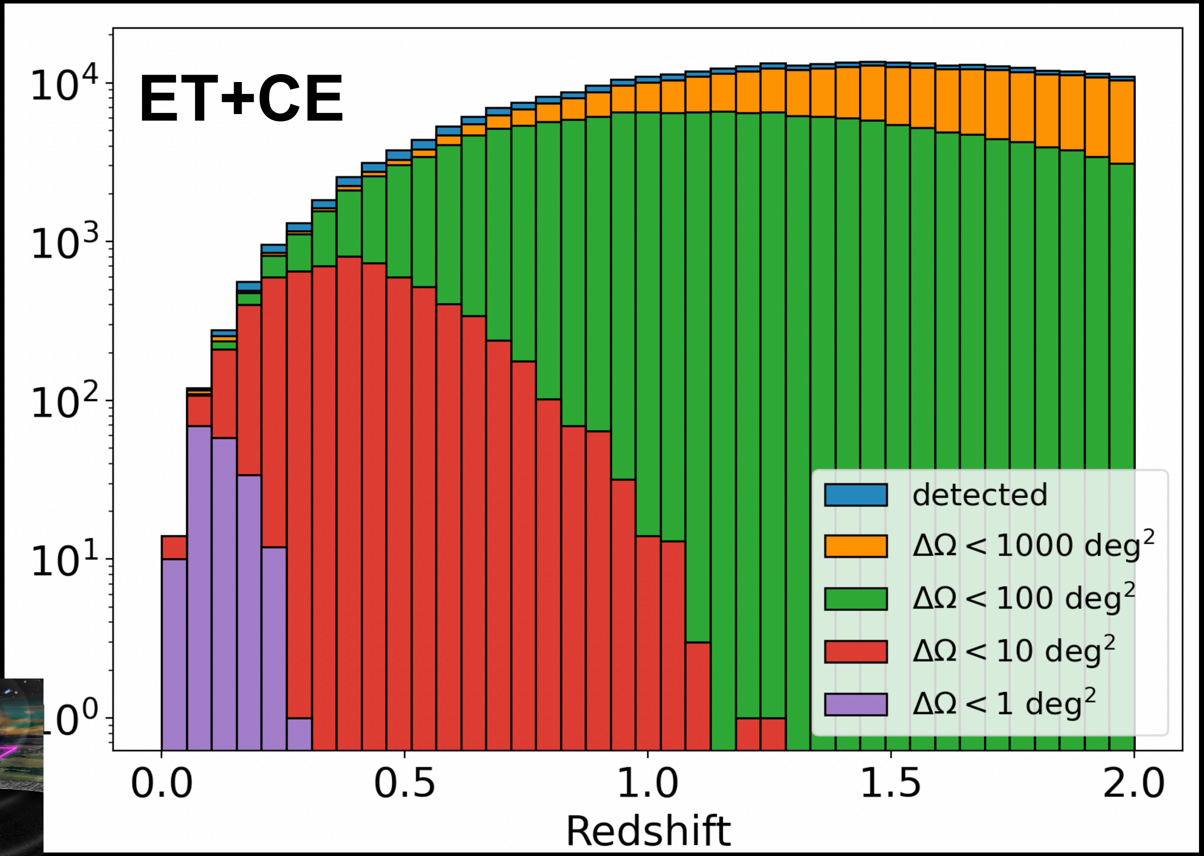


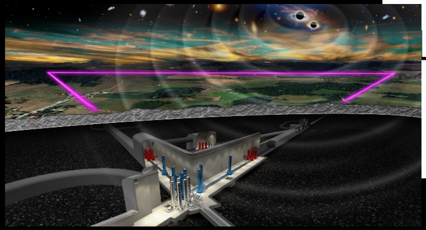



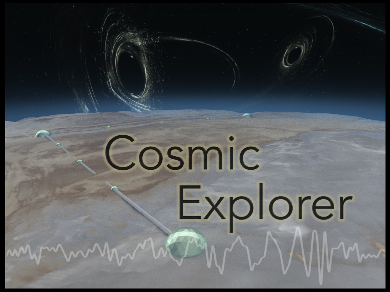
ET low frequency sensitivity make it possibile
To localize BNS!

- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

# Network sky-localization capabilities

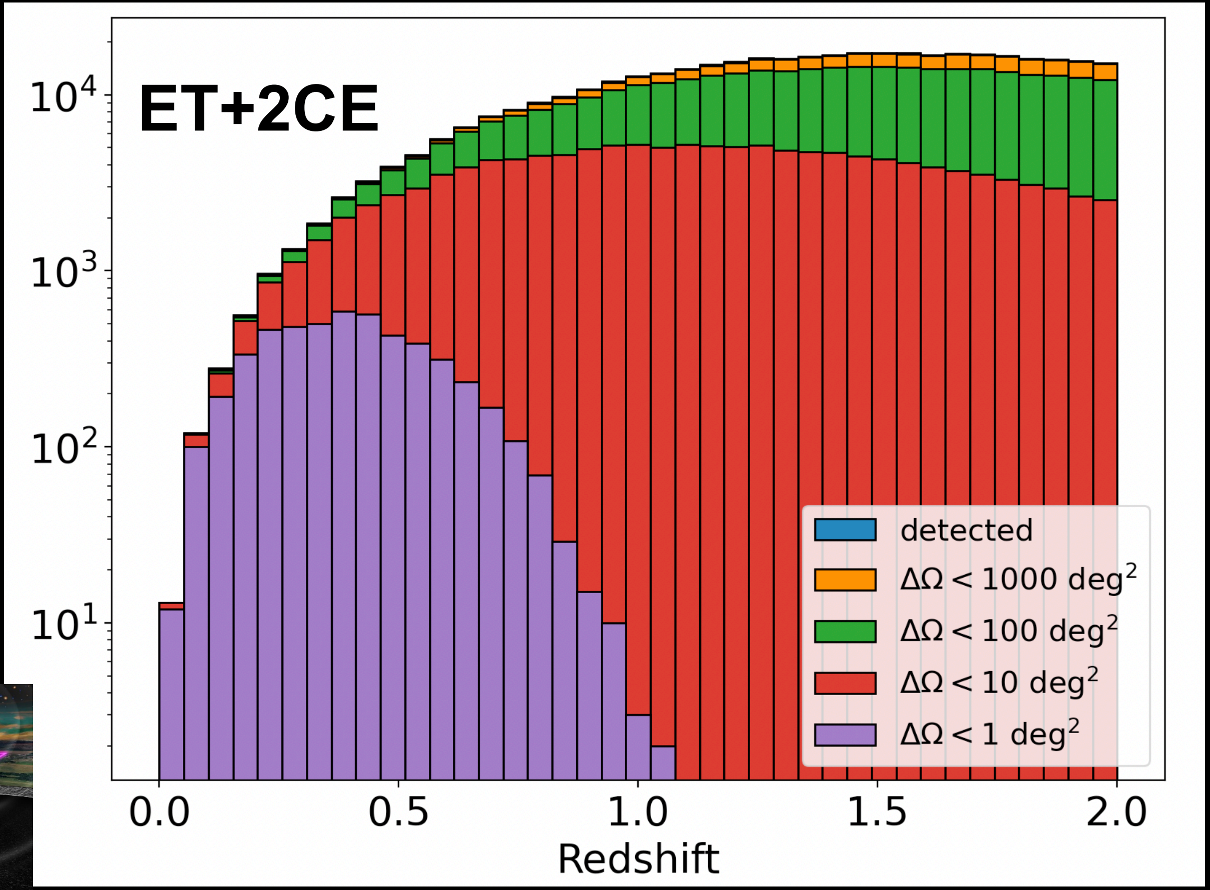


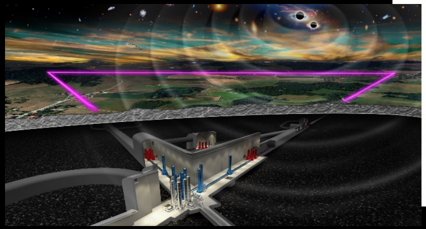



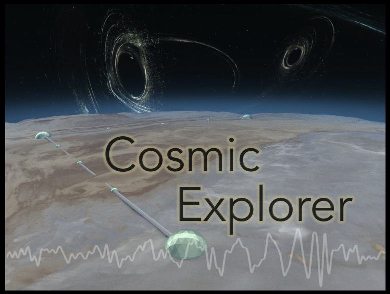



- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

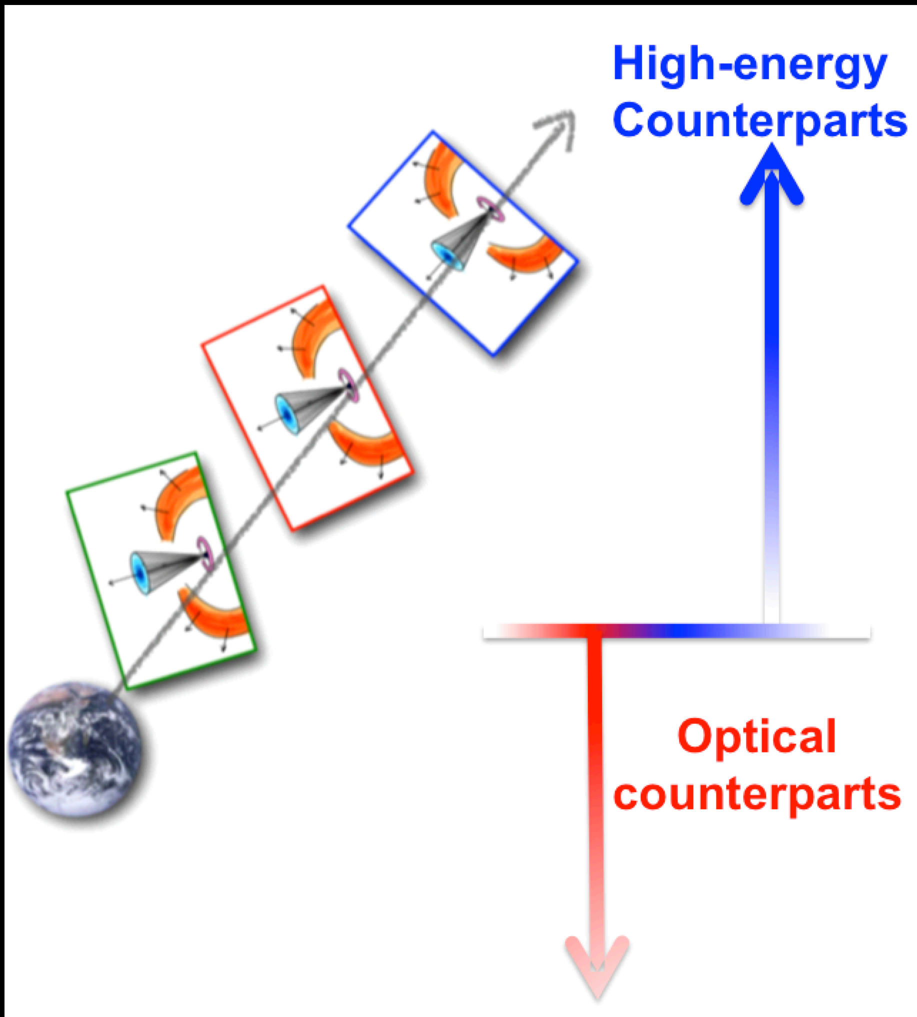
# Network sky-localization capabilities






- O(1000) detections per year with sky-localization (90% c.r.) < 1 sq. deg




RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS,
COSMOLOGY and MODIFIED GRAVITY

Credit: Ronchini

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE

*Hundreds of MM events per year!*

See Ronchini et al. 2022

Image credit: NASA Goddard Space Flight Center

# A REVOLUTION IN OUR KNOWLEDGE OF THE EARLY UNIVERSE, FUNDAMENTAL PHYSICS AND ASTROPHYSICS…