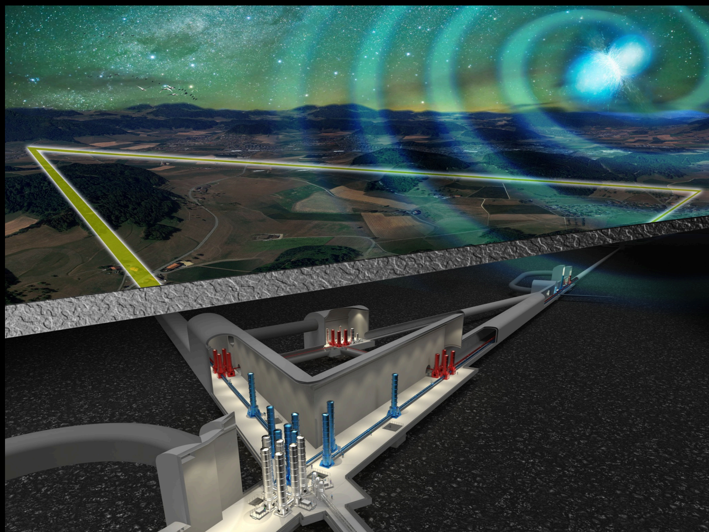
Gravitational-wave Astronomy



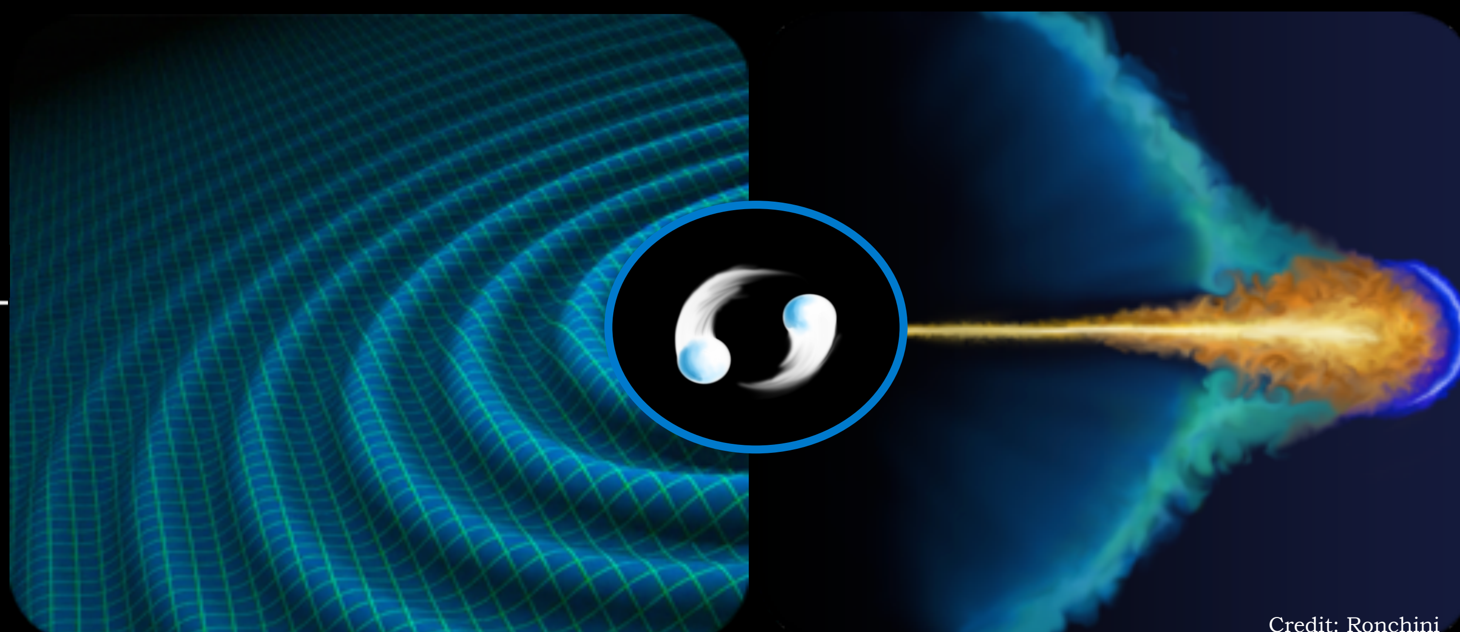
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare

ISTITUTO NAZIONALE DI ASTROFISICA
INAF

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

GSSI GW team



Credit: Ronchini

A new window into the Universe

Earth

Credit: LIGO–Virgo

KAGRA, Japan

O1

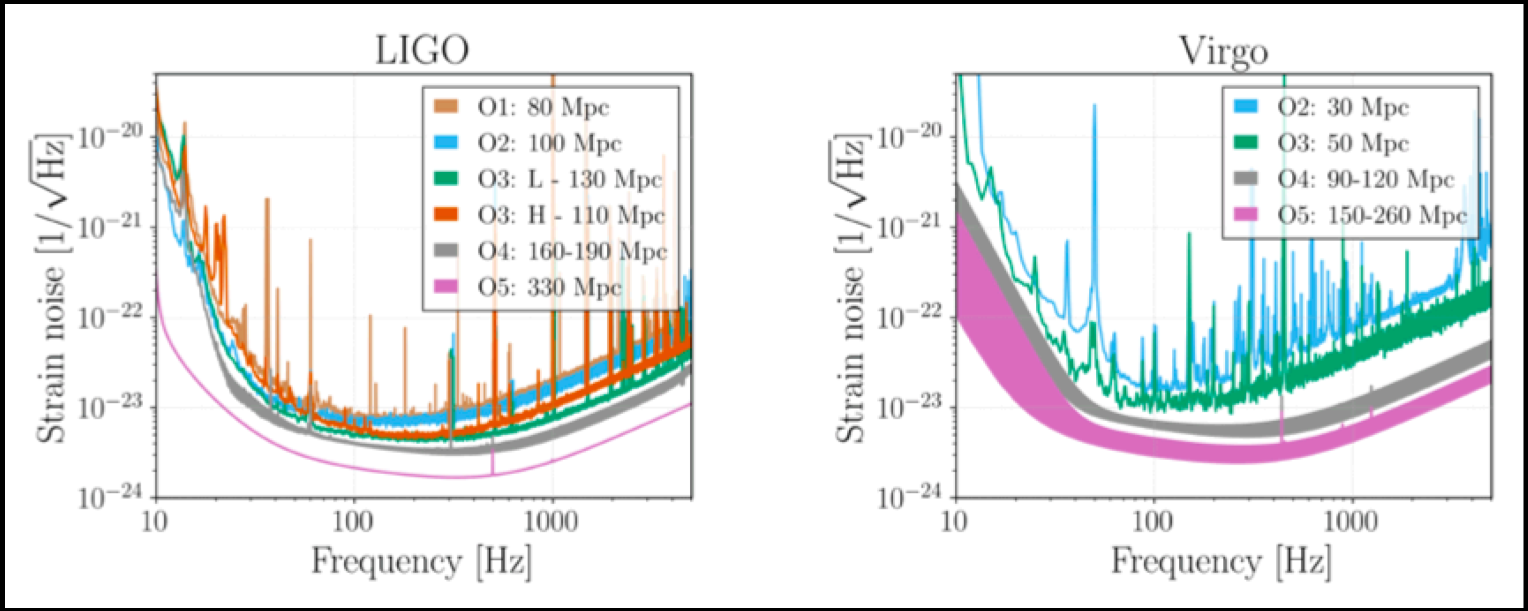
Sep ‘15 - Jan ‘16

O2

Nov ‘16 - Aug ‘17

O3

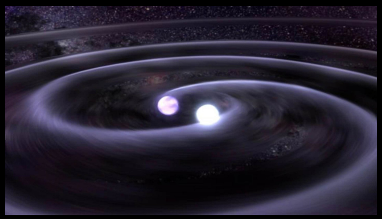
Apr ‘19 - Mar ‘20



Abbott et al. 2020, LRR

GW SOURCES DETECTABLE BY LIGO, Virgo and KAGRA

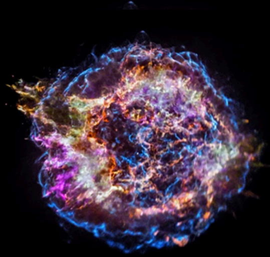
Binaries of compact objects

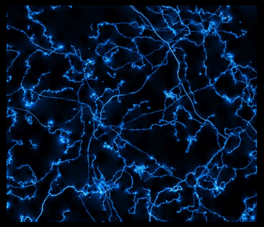


1–170 Myr^{-1}
per Milky Way equivalent galaxy

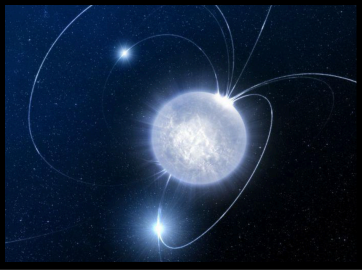
2 per century in
a Milky Way equivalent galaxy

Short-duration busrts

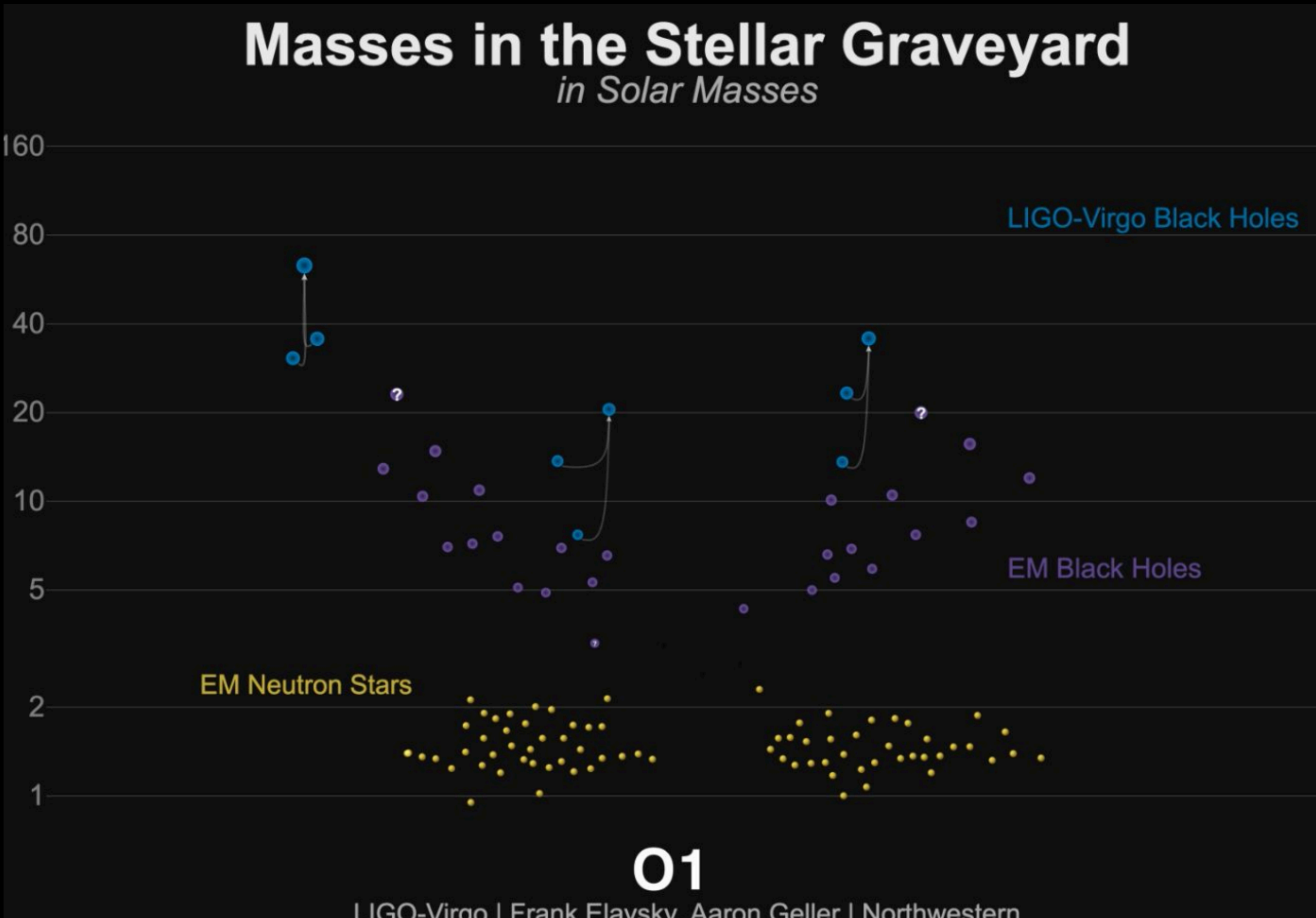




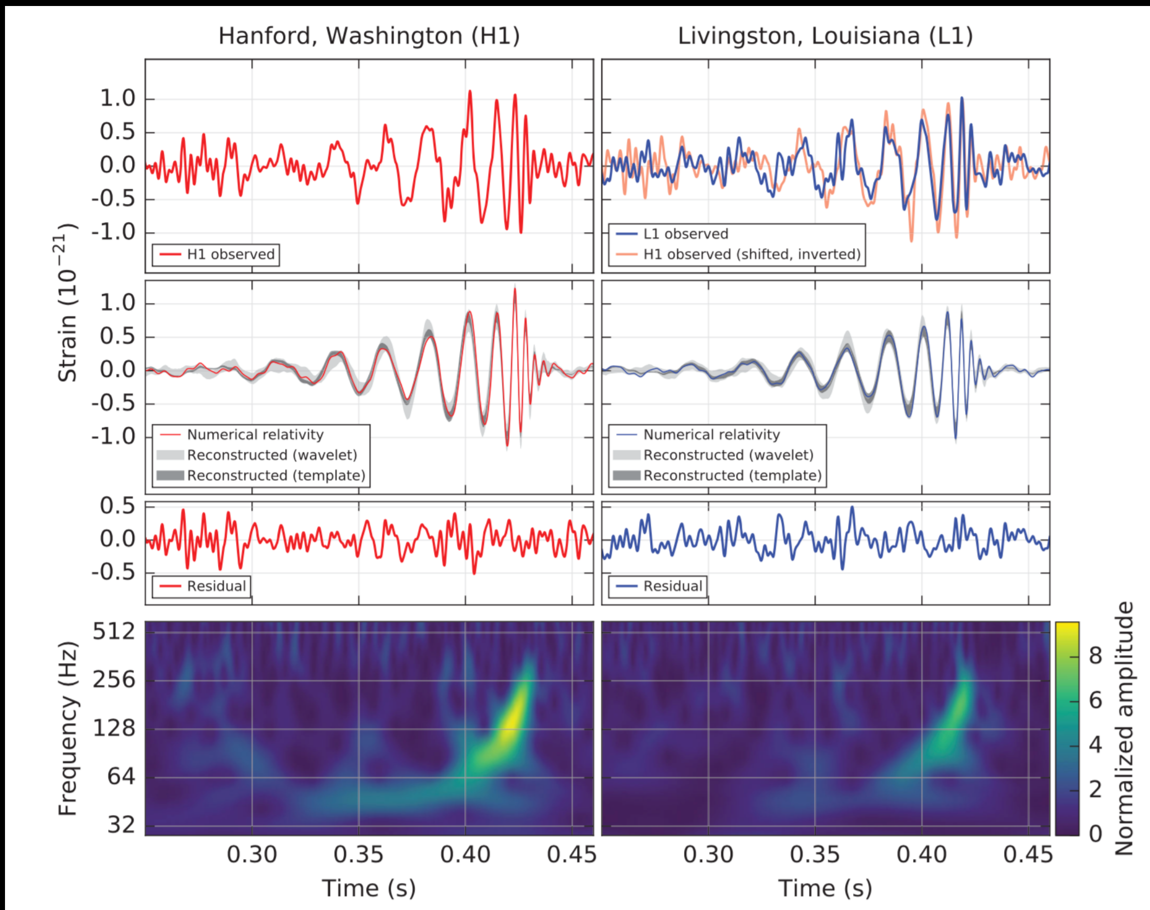
Continuos signals



Stochastic background


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
O1
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Observations of gravitational waves from a binary black- hole merger



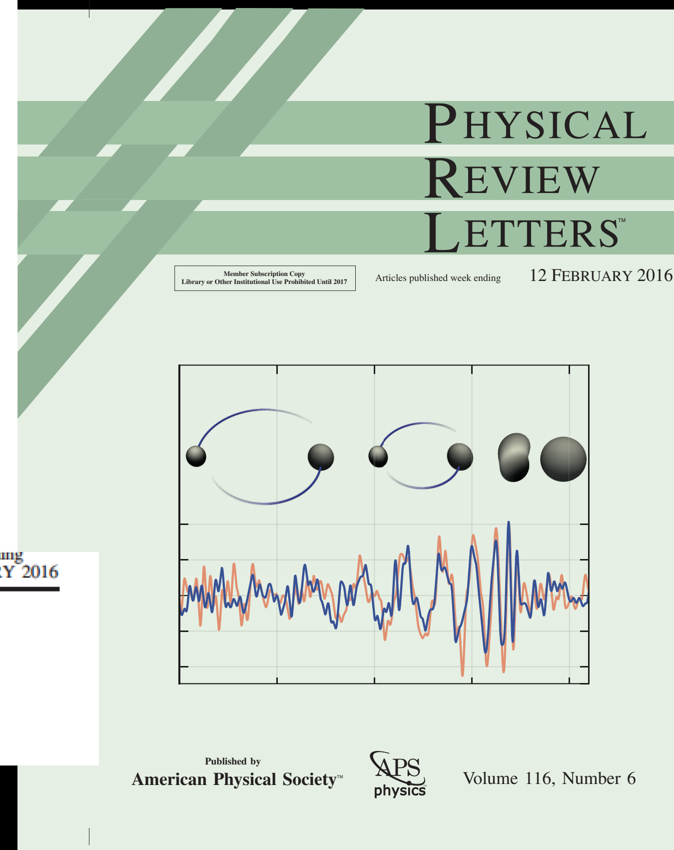
GW150914

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

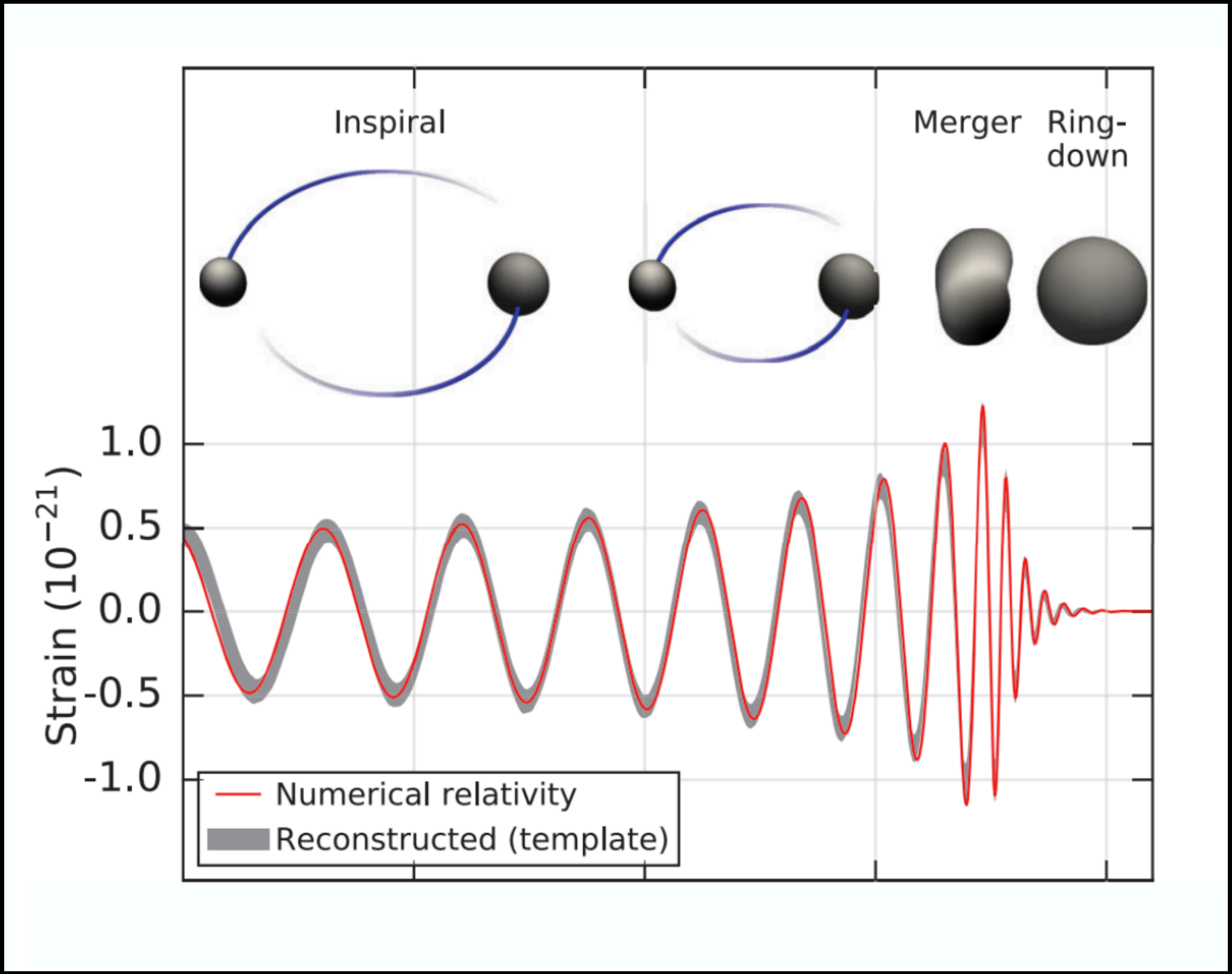
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



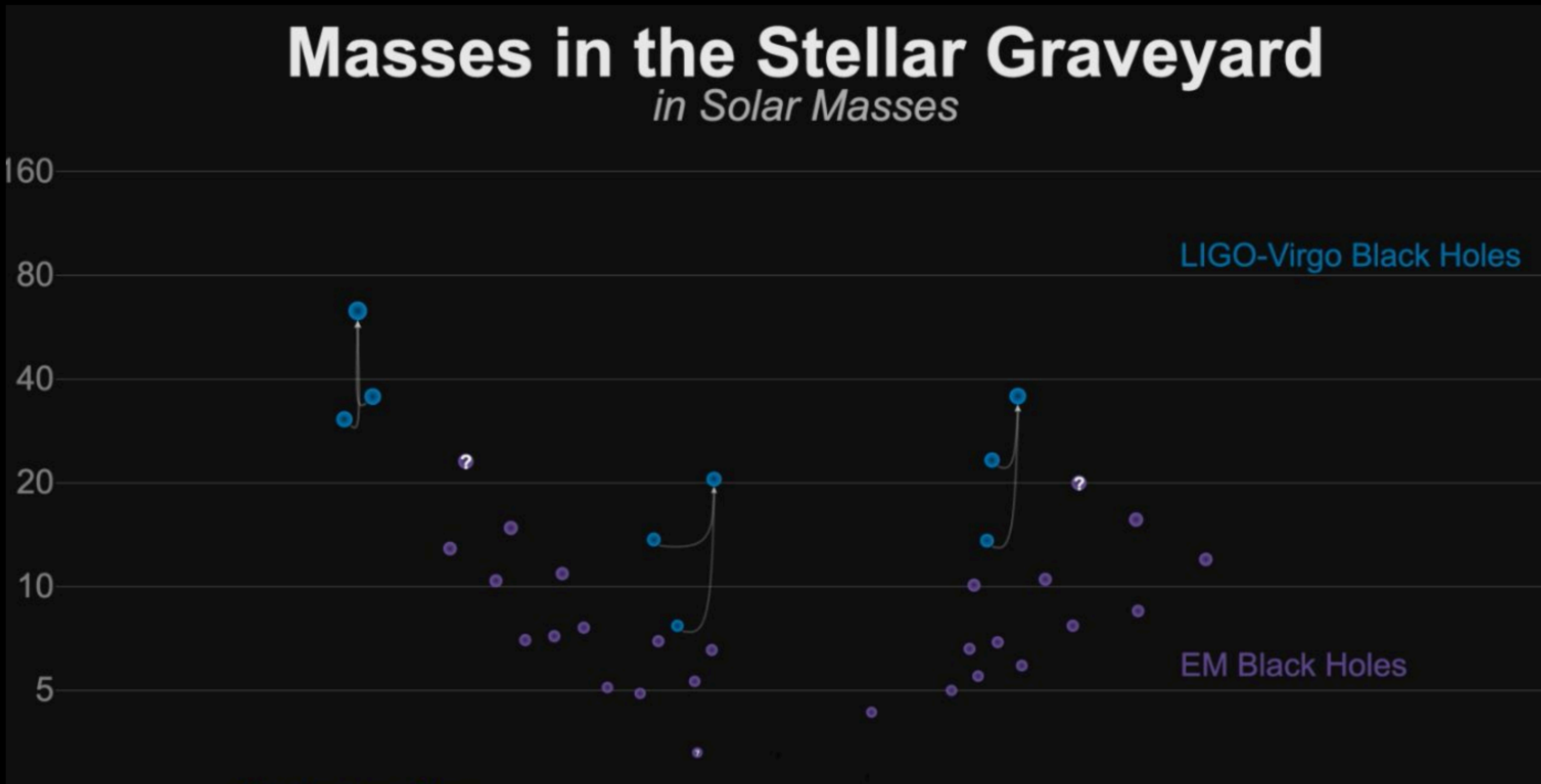
Source modelling



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp mass drive the early inspiral

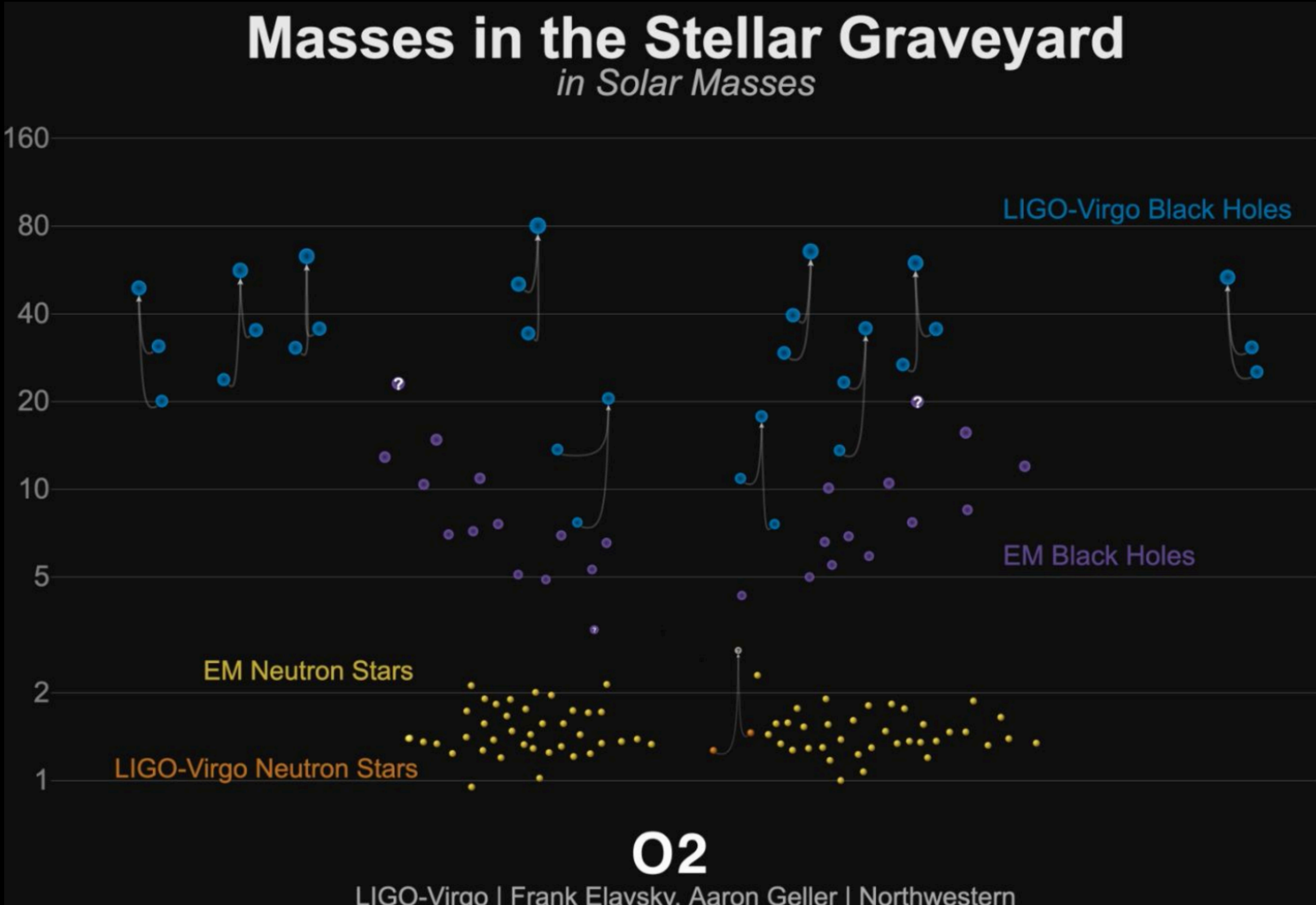
Late inspiral and merger
→ individual masses



GW OBSERVATIONS

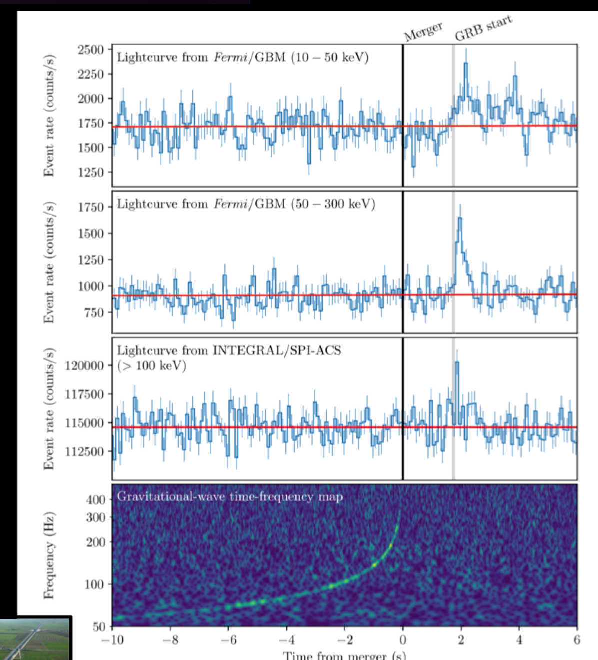
- Binary stellar-mass black holes (BBHs) exist;
- BBHs can inspiral and merge within the age of the Universe;
- Heavy stellar-mass black holes (with mass >20 $M_{\odot}$) exist

(LVC 2018 ApJL, 818)



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
O2
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

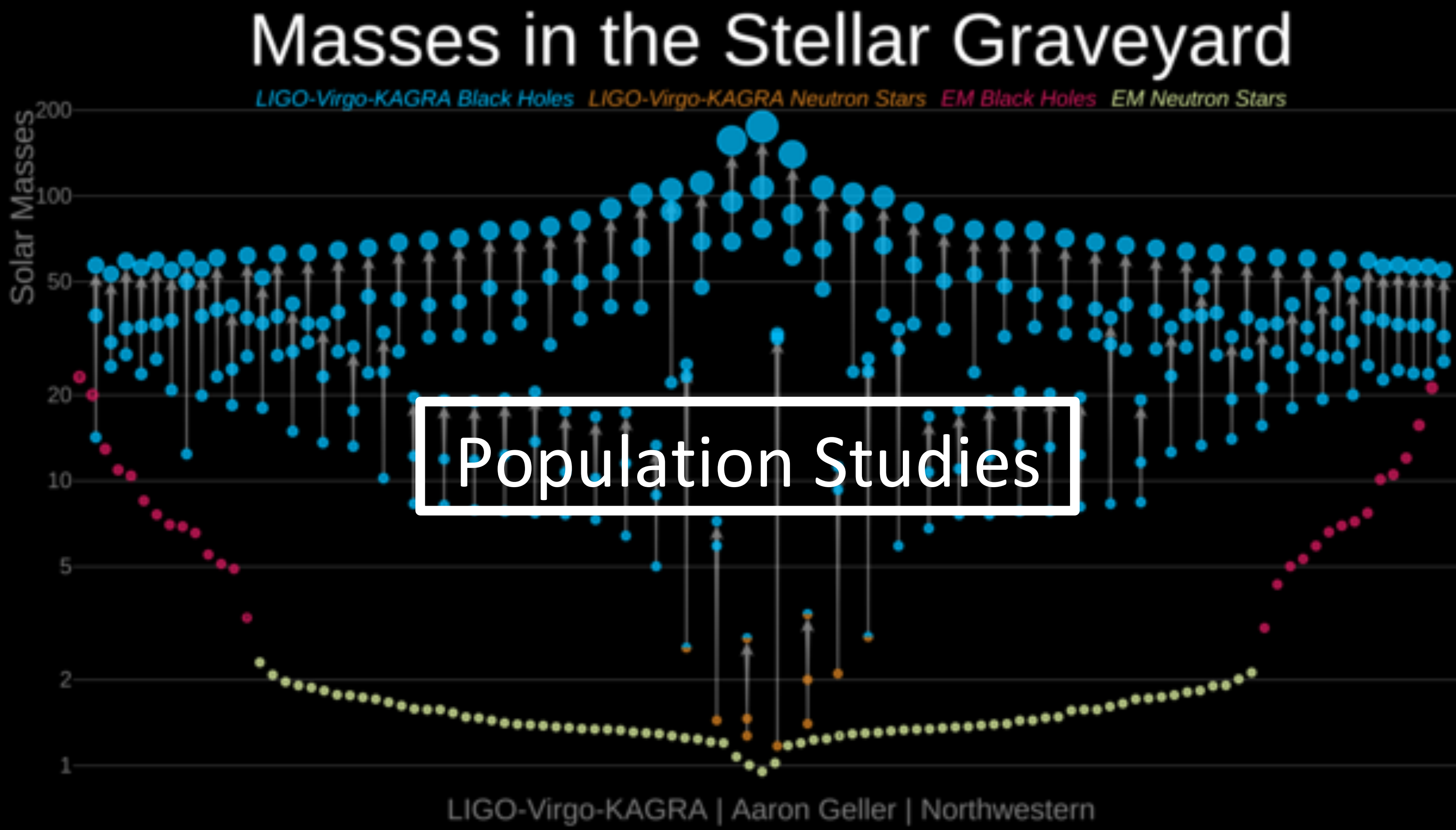
GW170817



GW170817

Abbott et al. 2017, PhRvL, 119

O1+O2+O3



Population Studies

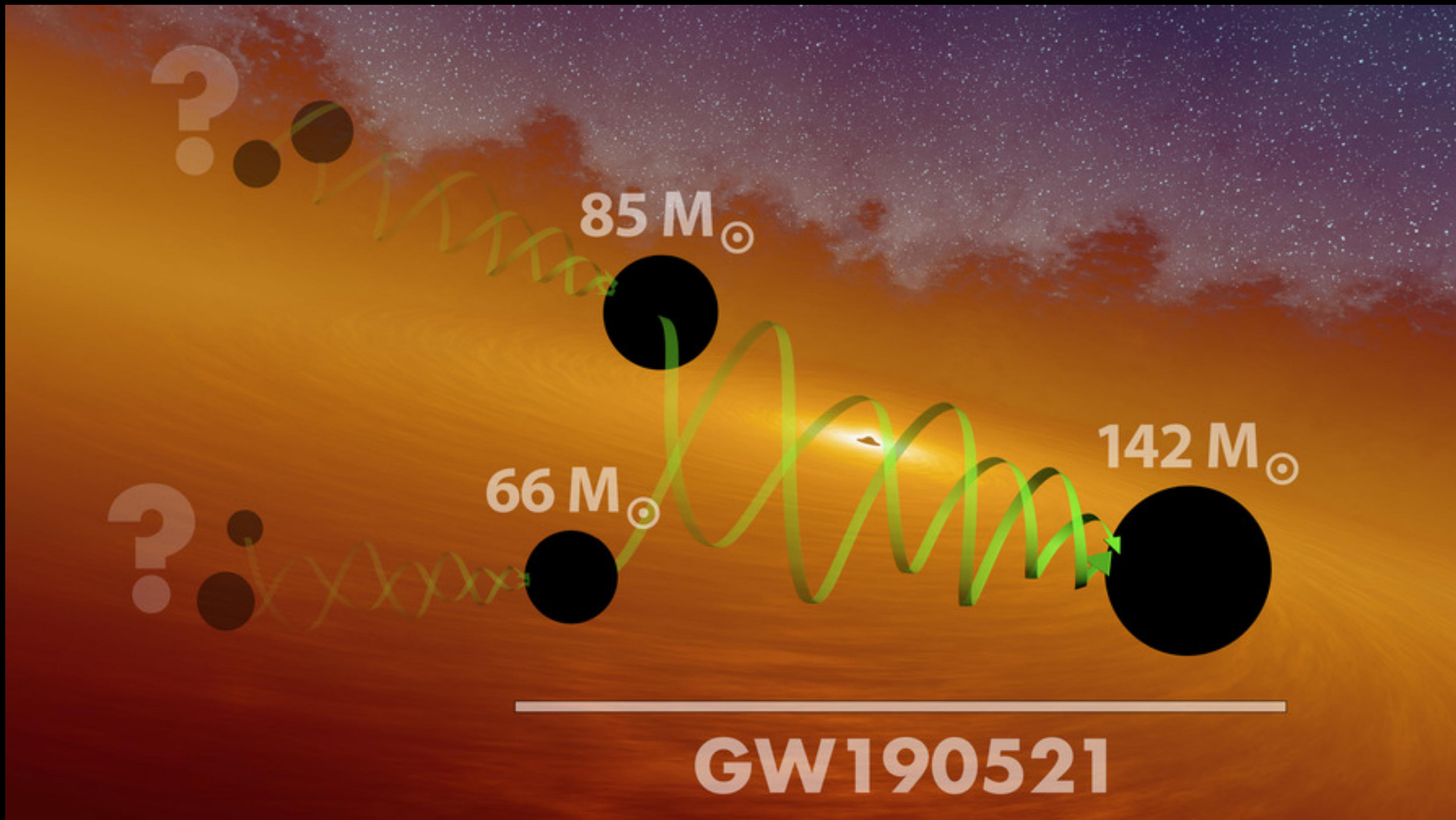
90 GW EVENTS!

LVK arXiv:2111.03606

GW190521

The birth of a intermediate massive black-hole!

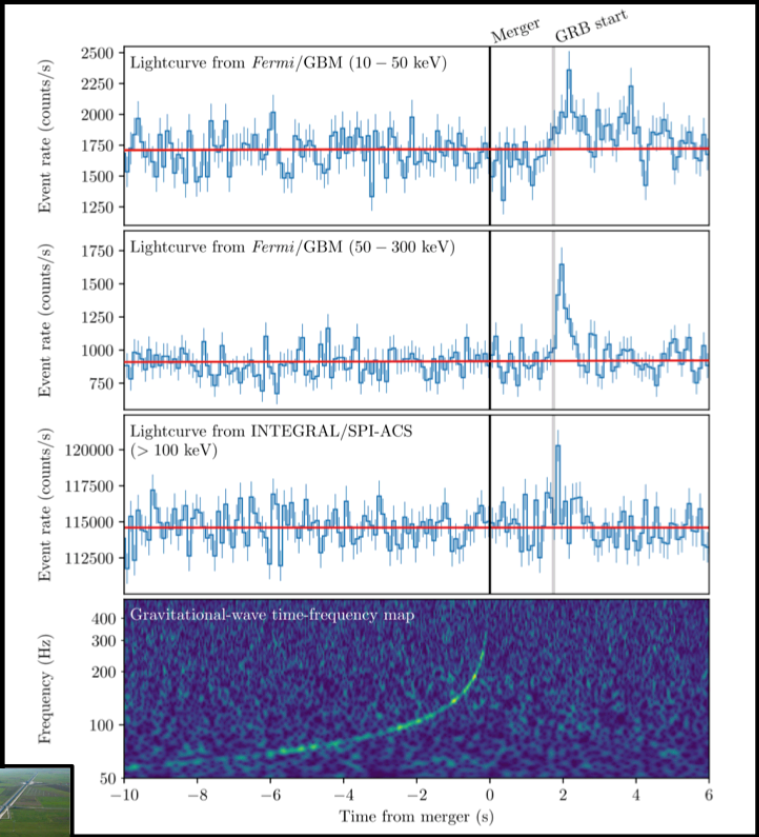
Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)



credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Abbott et al 2020, PRL, 125
Abbott et al 2020, APJL, 900

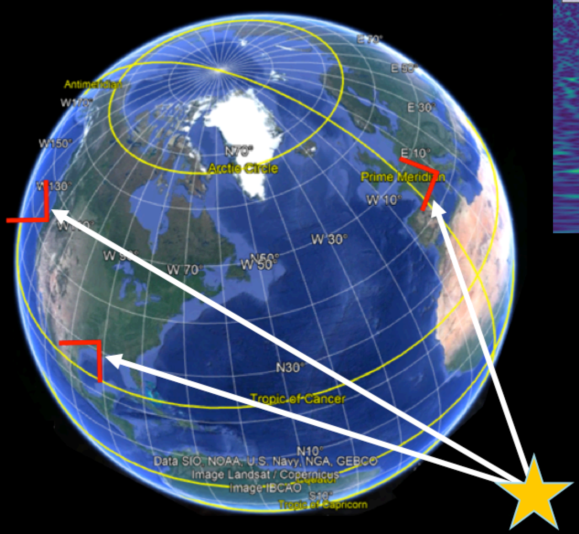
GW170817

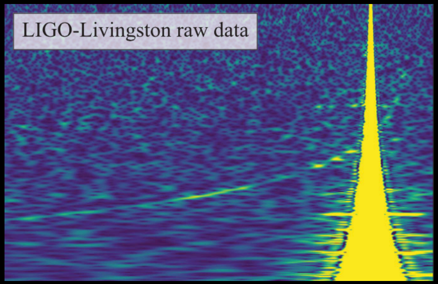


GW170817

Abbott et al. 2017, PhRvL, 119

17 August 2017, 12:41:04 UT

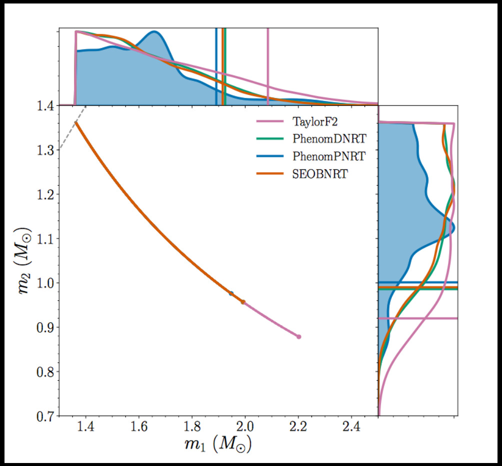




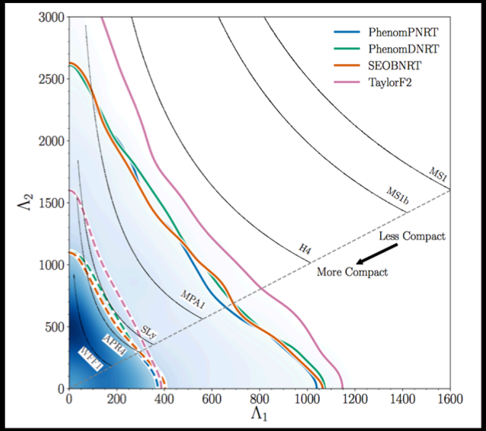
→ 17:54:51

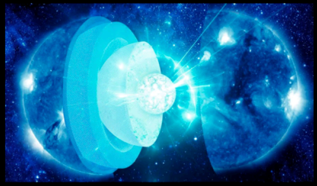
Credit: LIGO/Virgo/NASA/Leo Singer

GW 170817



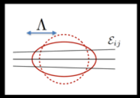
Masses are consistent with the masses of all known neutron stars!

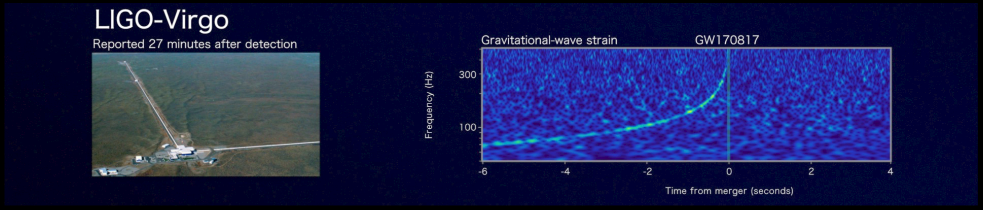




TIDAL DEFORMABILITY

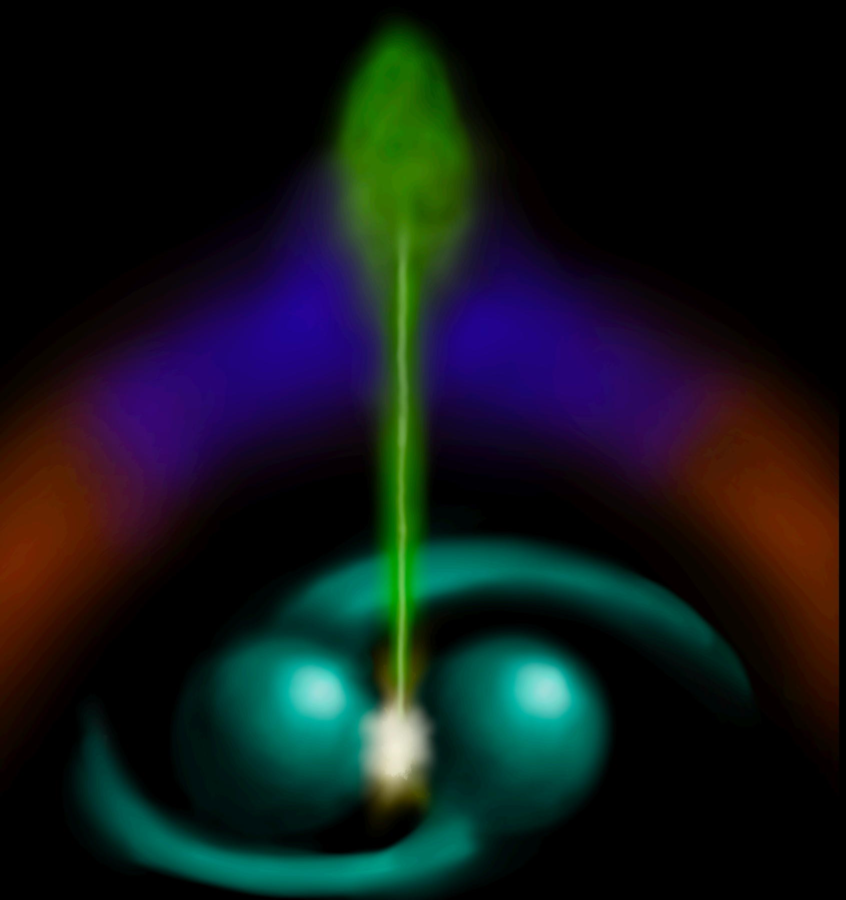
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

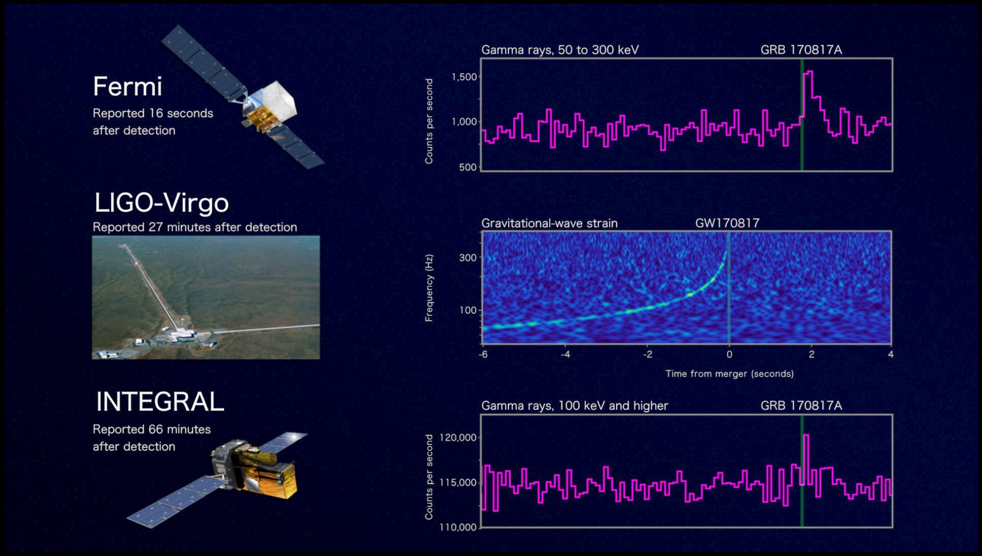




Credits: Ronchini

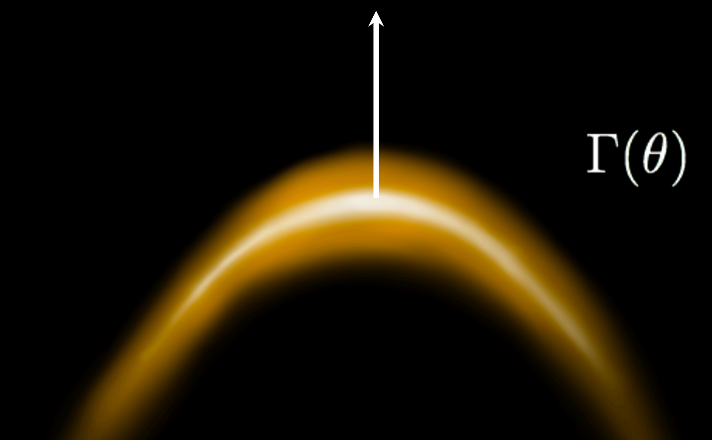
GW 170817



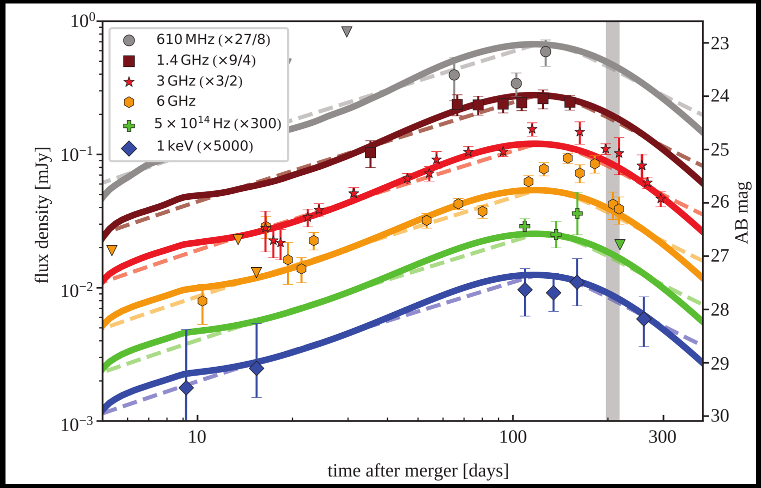


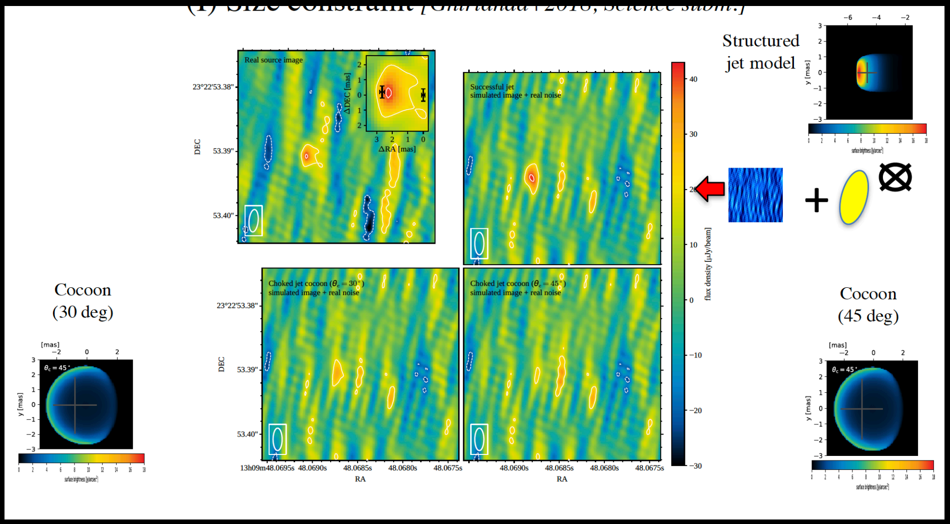
Fermi
Reported 16 seconds after detection
LIGO-Virgo
Reported 27 minutes after detection
INTEGRAL
Reported 66 minutes after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000

GW 170817



Forward shock from
a structured jet

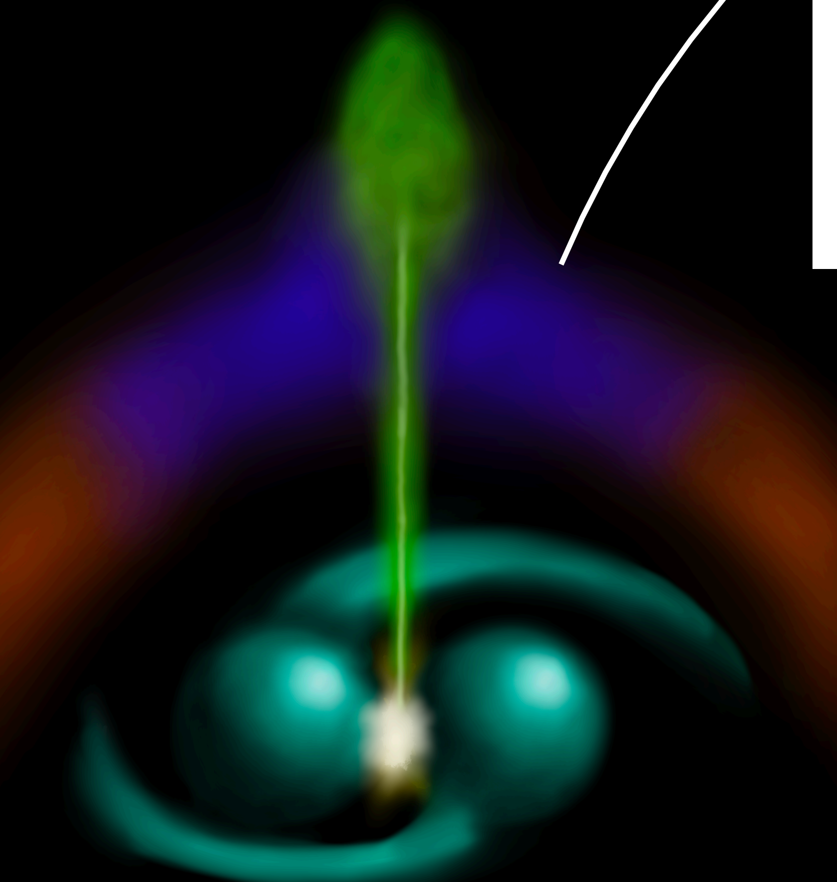


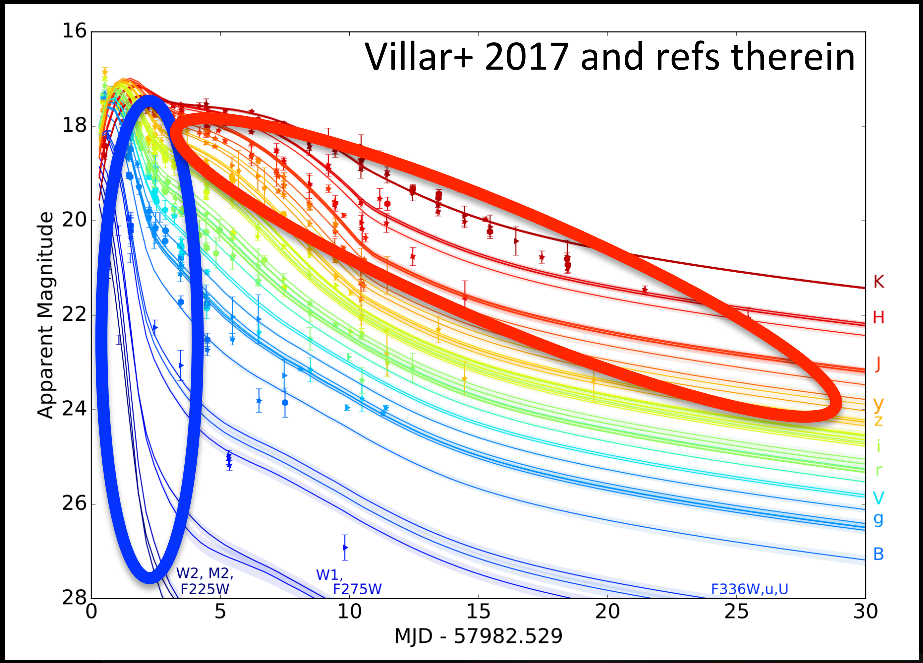


From Ghirlanda et al. 2019

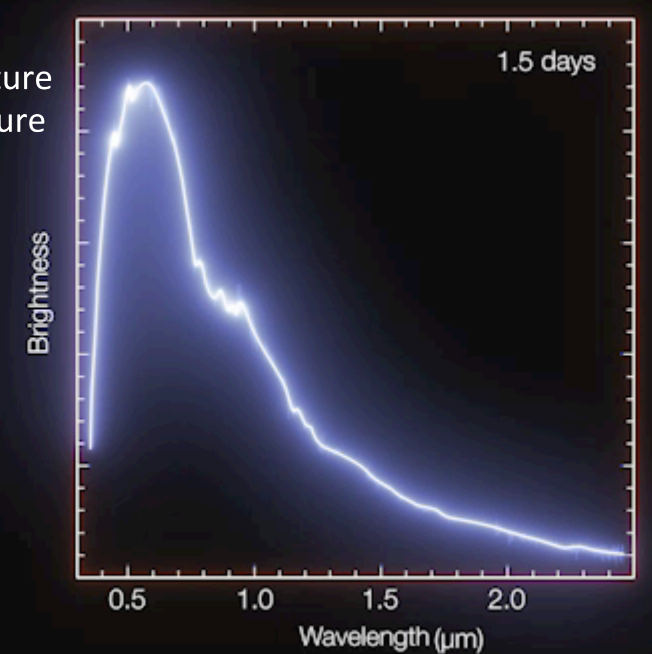
Credits: Ronchini

GW 170817



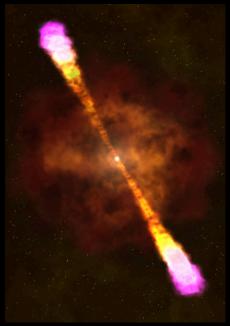


Pian et al. 2017 Nature
Smartt et 2017 Nature

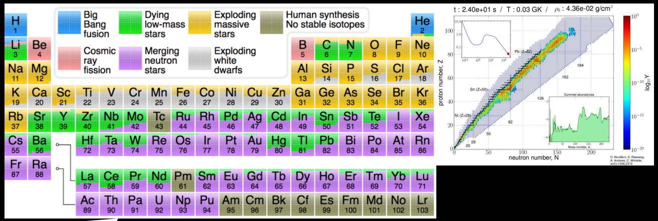


Radioactively powered transients

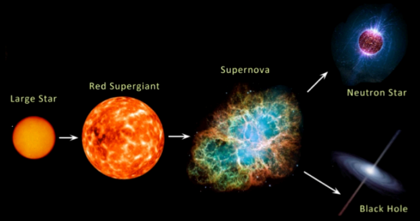
Relativistic astrophysics



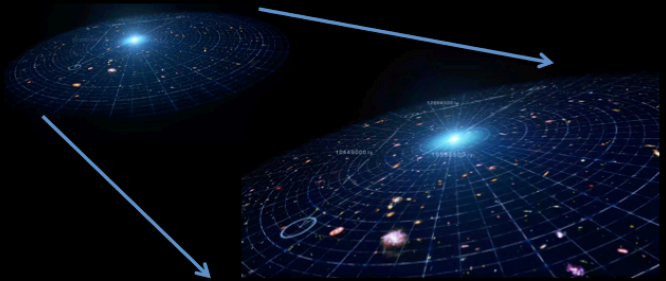
Nucleosynthesis and enrichment of the Universe



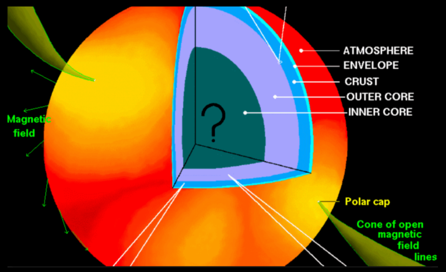
Compact object formation and evolution



Cosmology



Nuclear matter physics



How was that possible?

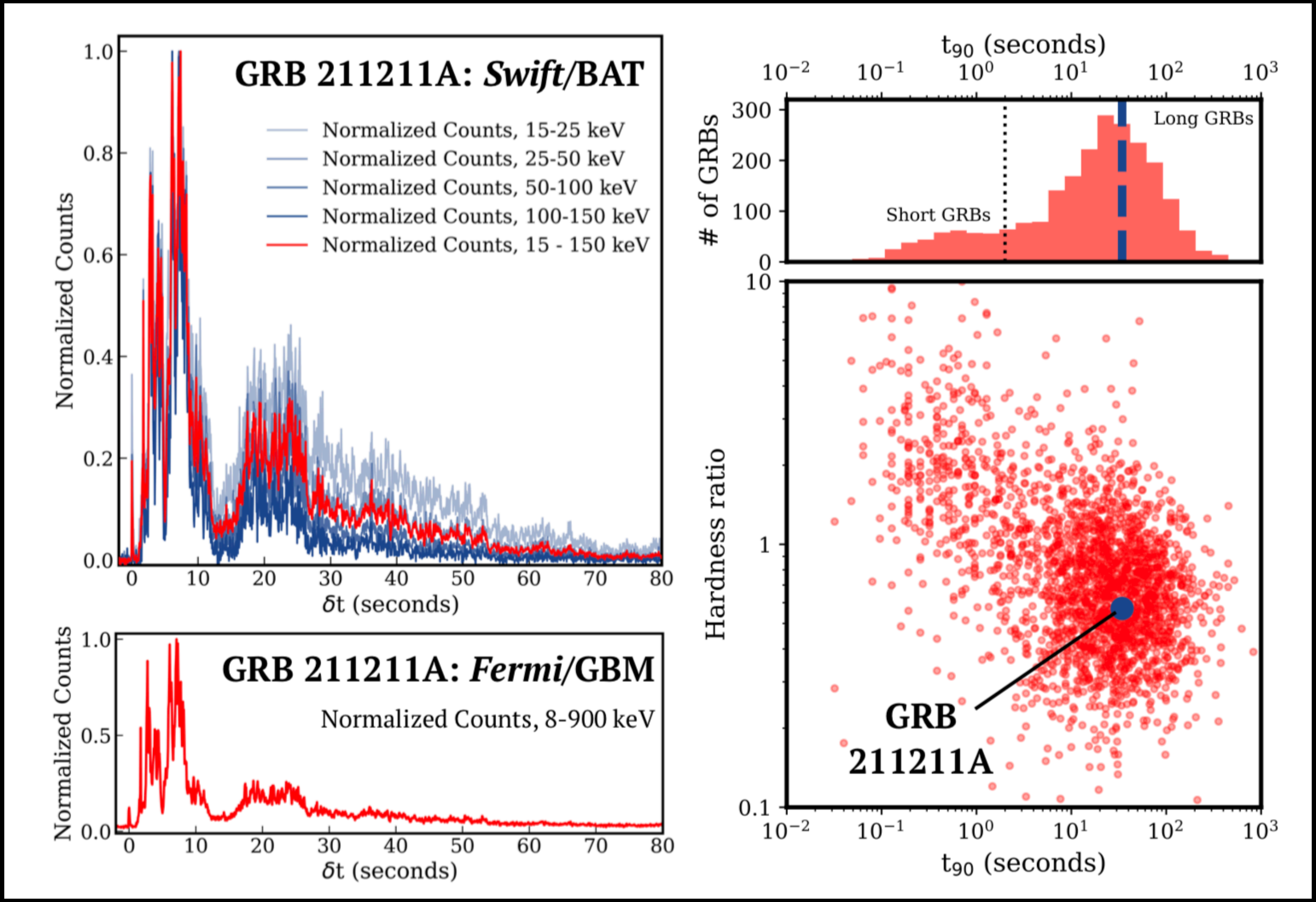
What happened after GW17017?

LIGO, Virgo and KAGRA O1+O2+O3 runs

90 GW CANDIDATE EVENTS!

LVK arXiv:2111.03606

GRB 211211A: long GRB/KILONOVA

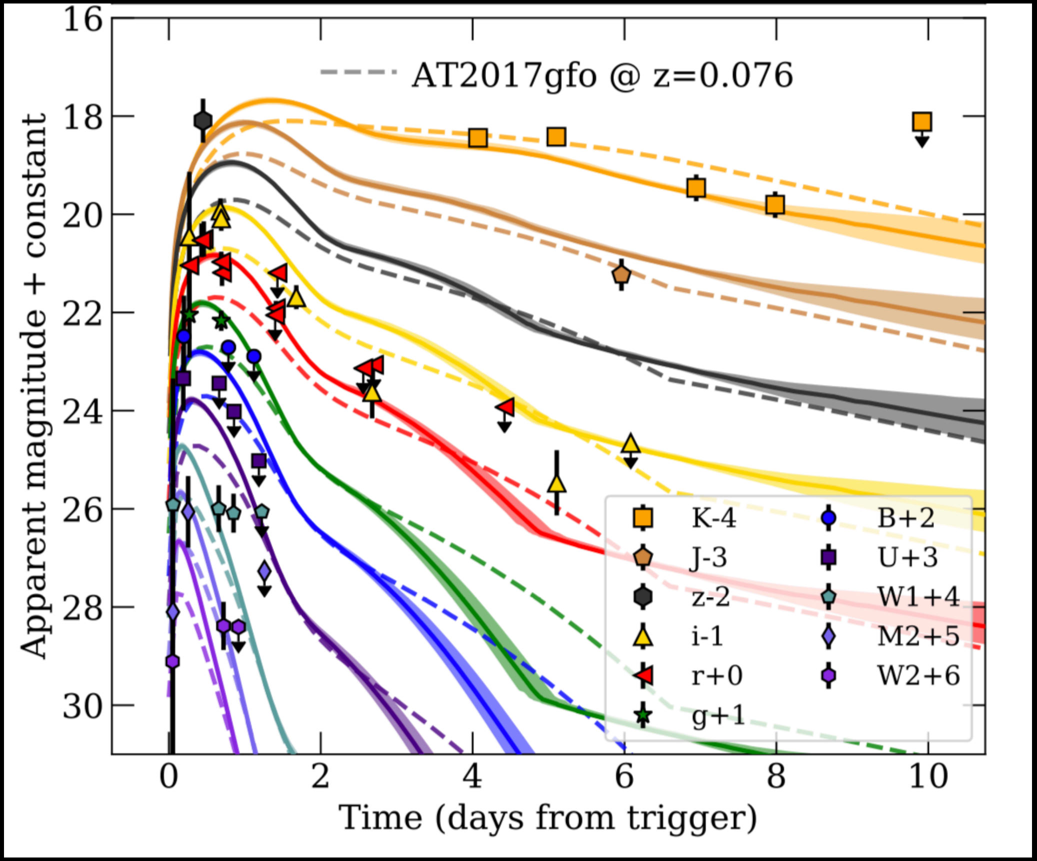


Minute-duration GRB, prompt and bright spikes last more than 12 s

Nearby GRB at 350 Mpc and 7.9 kpc from the galaxy center

Rastinejad, J. C. et al. arXiv:2204.10864

GRB 211211A: long GRB/KILONOVA



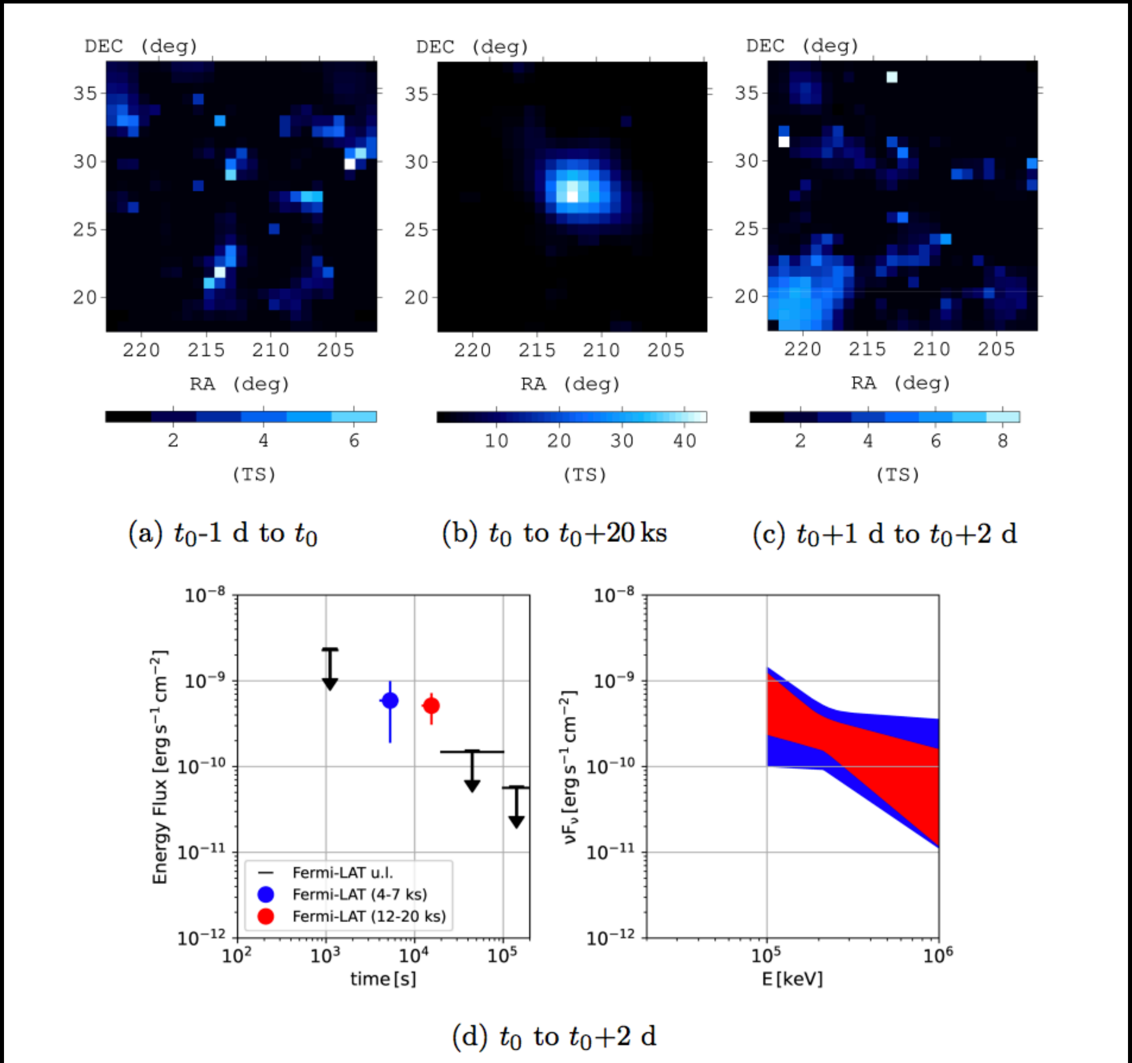
Rastinejad, J. C. et al. arXiv:2204.10864

10% of the local long GRB population could arise from mergers

GW170817-like events are within reach

See also Xiao, S. et al. and Troja et al. arXiv:2209.03363

GRB 211211A: GeV emission



(a) t_0-1 d to t_0

(b) t_0 to t_0+20 ks

(c) t_0+1 d to t_0+2 d

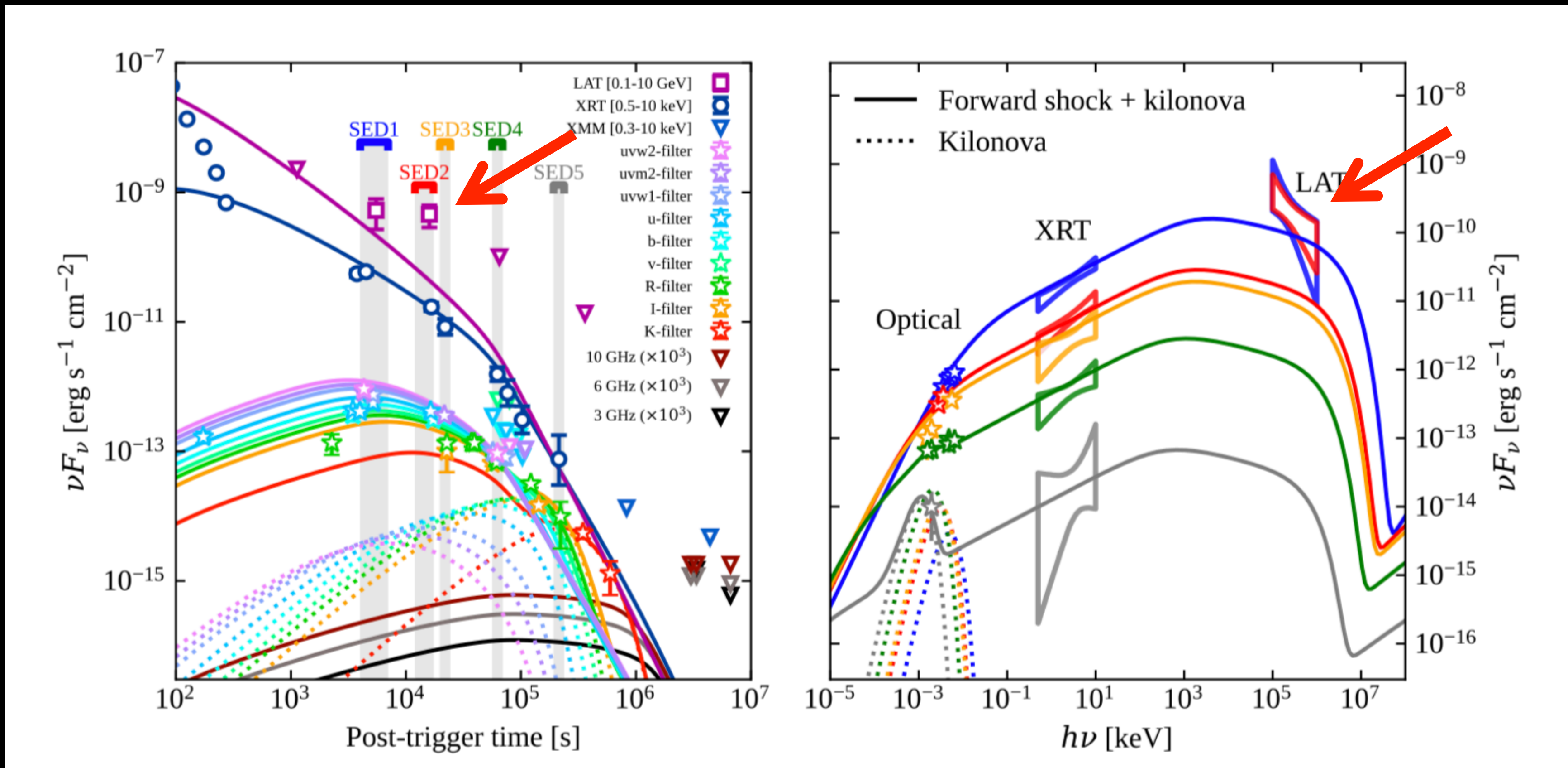
(d) t_0 to t_0+2 d

Discovery of a significant (>5σ) transient-like emission by Fermi/LAT

Photon energies 0.1-1 GeV

Mei et al. 2022, arXiv:2205.08566

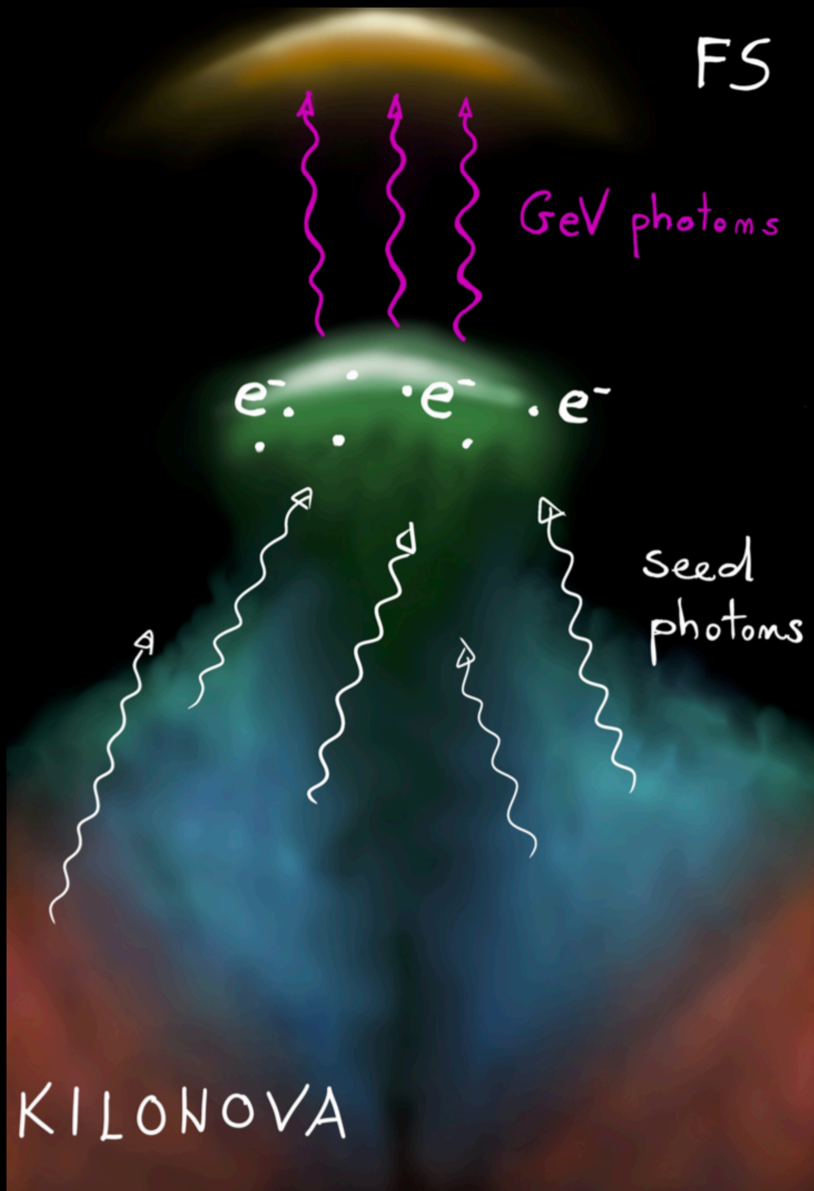
GRB 211211A: GeV excess



The GeV emision is in EXCESS with respect to synchrotron emission from standard forward shock of the relativisic jet explaining the afterglow emission in the other bands

Mei et al. 2022, arXiv:2205.08566

GEV emission from a compact binary merger



External Inverse Compton

kilonova → seed photons for the EIC

presence of a long-lived low power jet

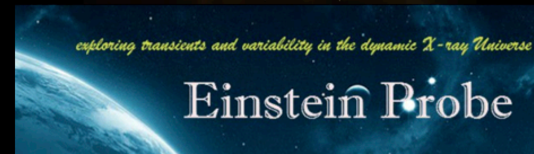
New counterpart for GW signals

To probe engine/jet and ejecta

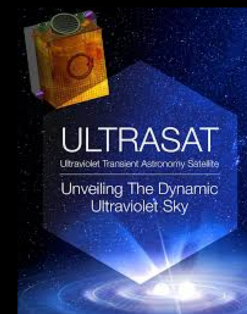
Mei et al. 2022, arXiv:2205.08566

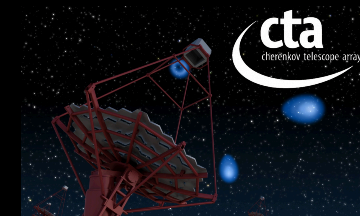
Next observing runs

SVOM



NEW OBSERVATORIES





Rubin Observatory

LIGO INDIA

NETWORK OF GW DETECTORS

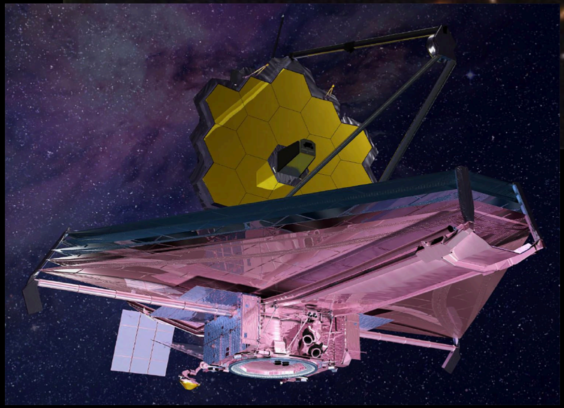
LOFAR

SKA SQUARE KILOMETRE ARRAY

IceCube GEN2

KM3NeT

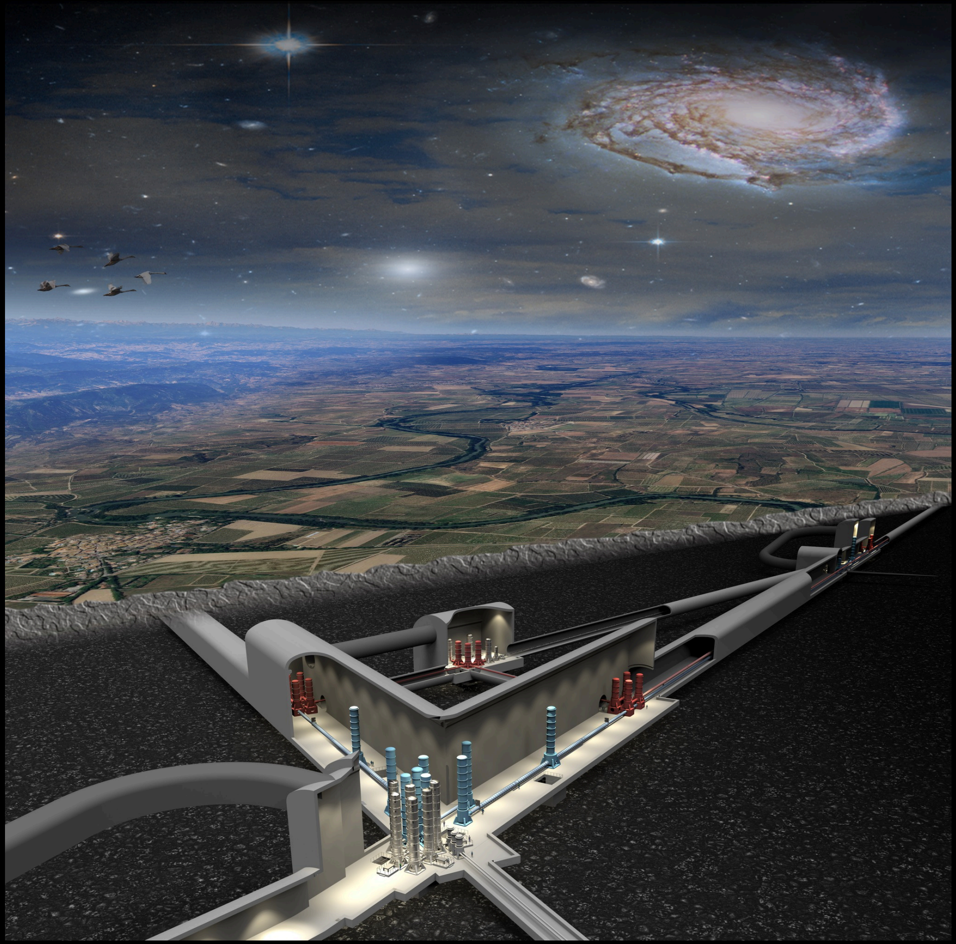
NEUTRINO DETECTORS


The future of GW and Multimessenger astronomy

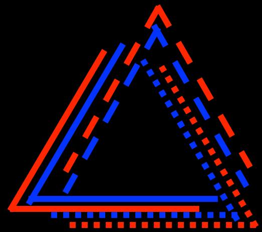
See GWIC roadmap, Bailes et al. 2021, Nature Reviews Physics

ET: the European 3G GW observatory concept

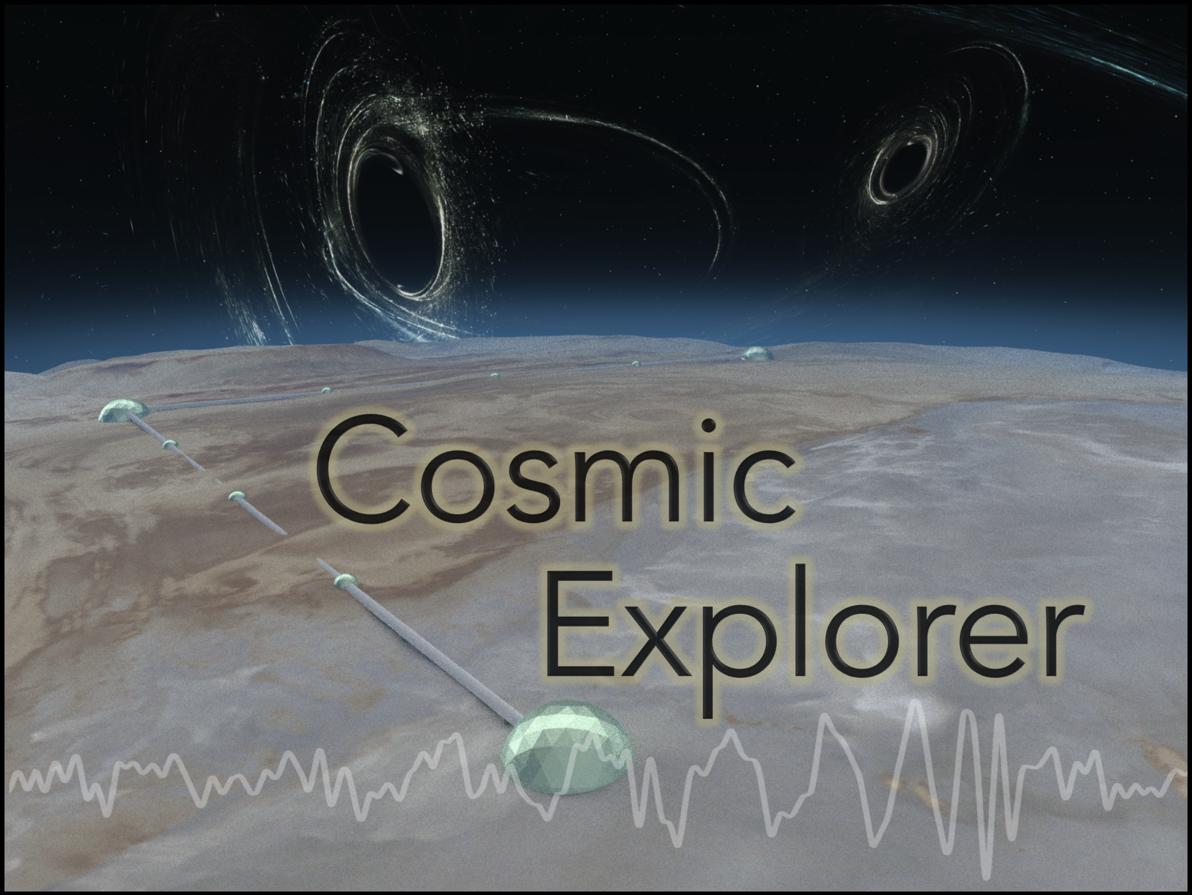


INCLUDED IN ESFRI ROADMAP in 2021

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

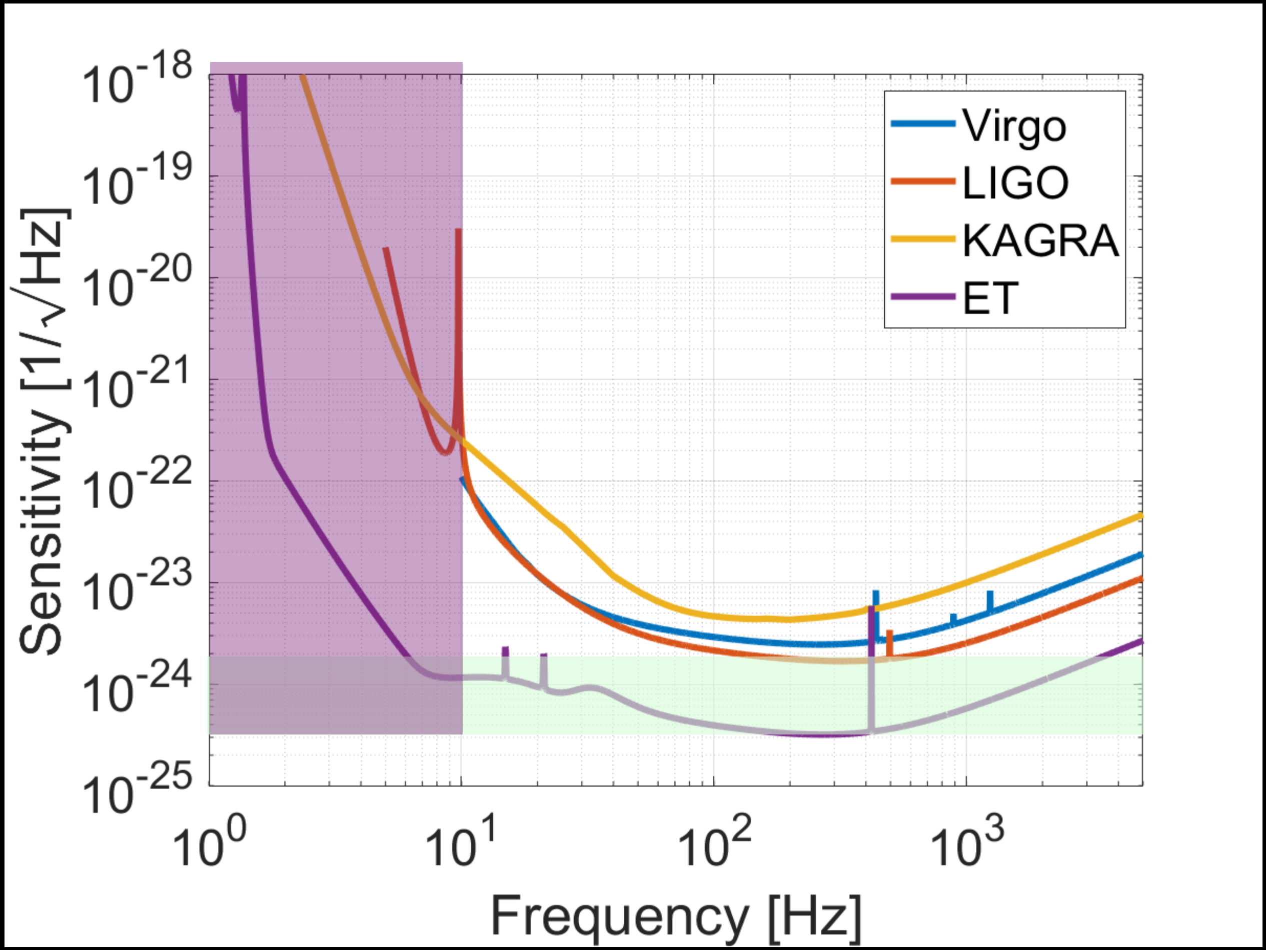


3G effort worldwide



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

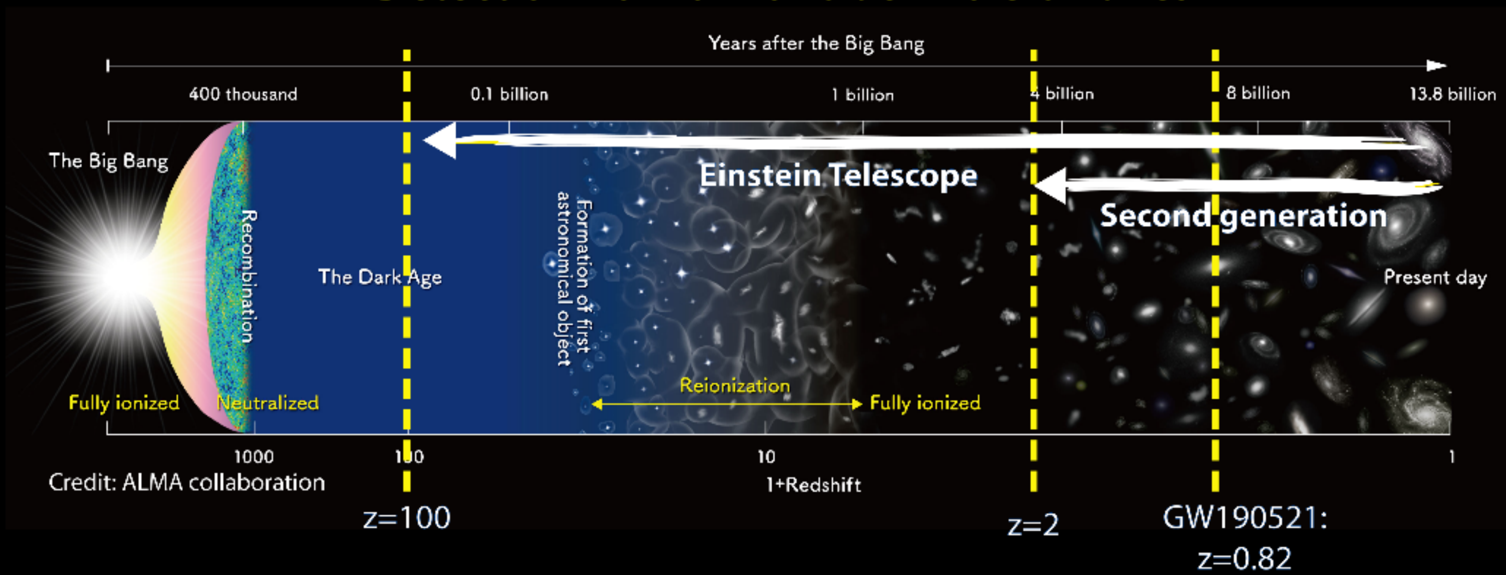
EXPECTED SENSITIVITY

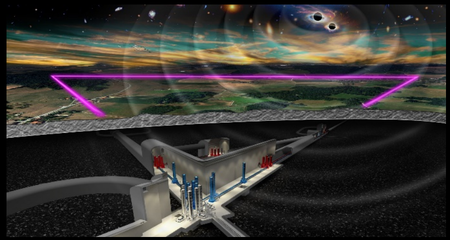


The ET sensitivity will make it possible:

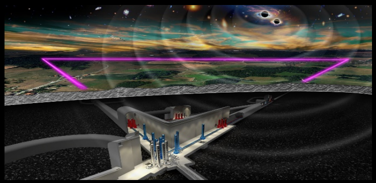
- Large distances back to the EARLY UNIVERSE

Detection horizon for black-hole binaries

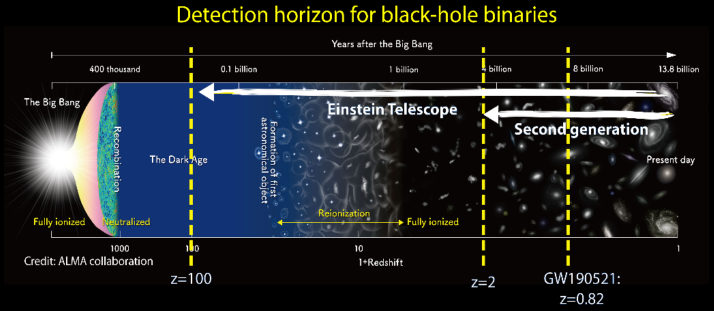




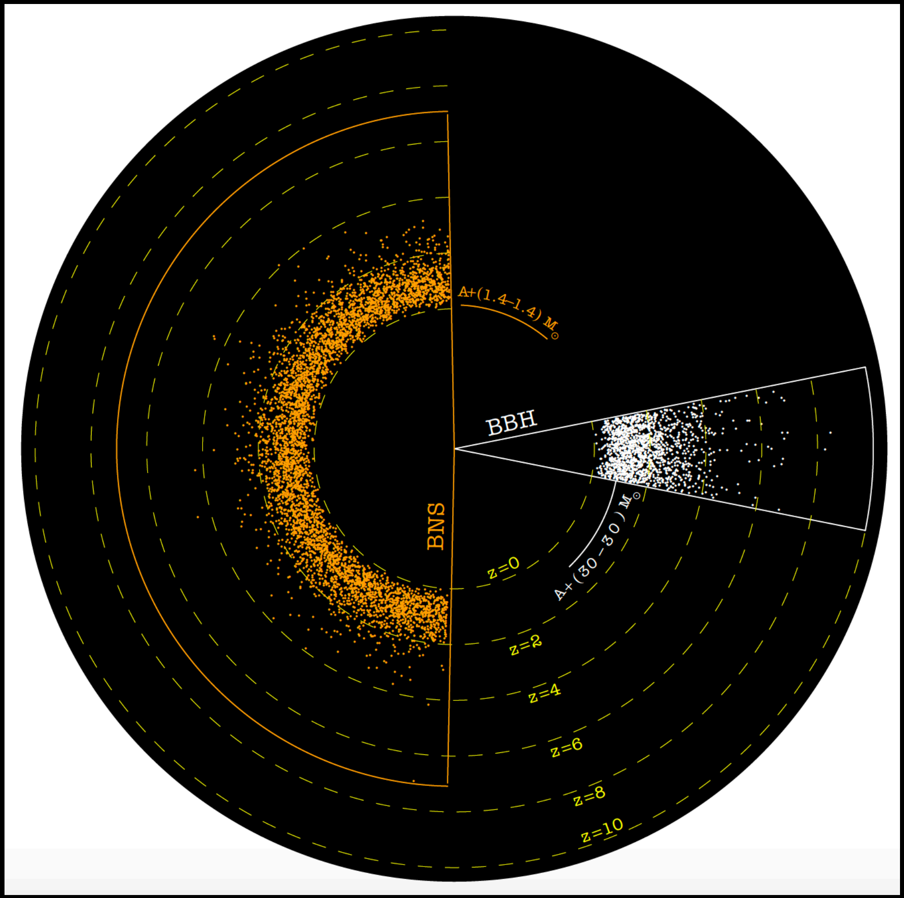
The ET sensitivity will make it possible:



- Large distances back to the EARLY UNIVERSE

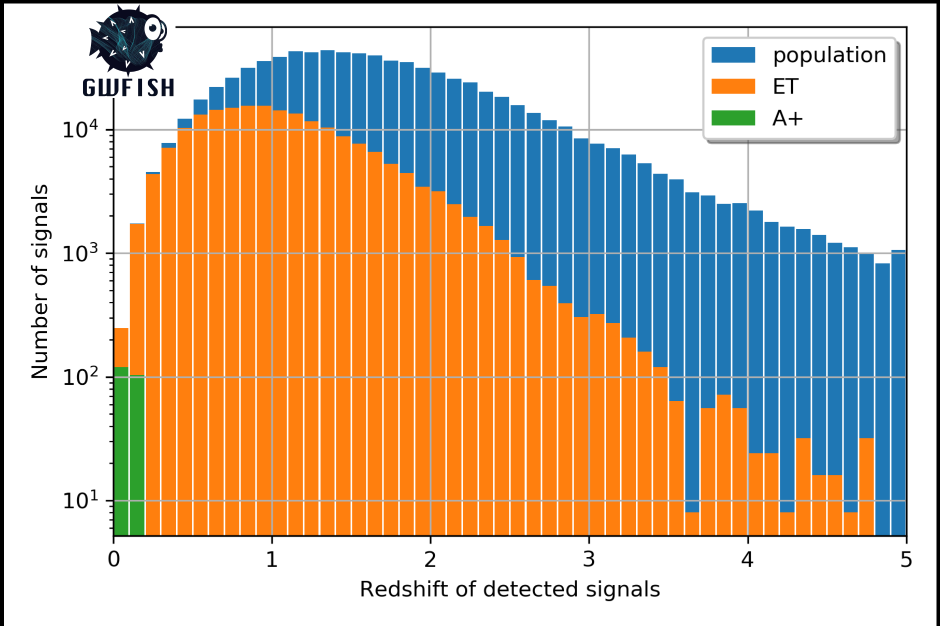


- POPULATION:
  increase number of detections

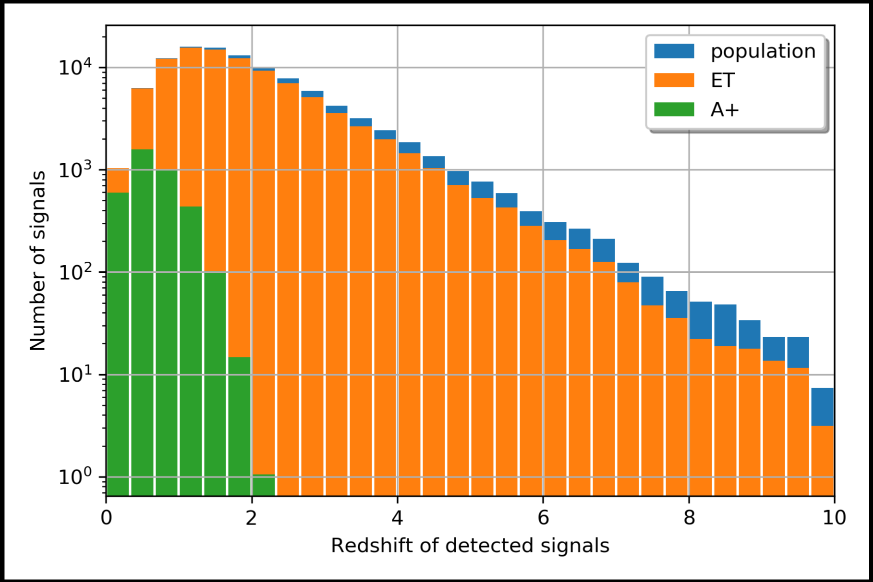


COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS



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

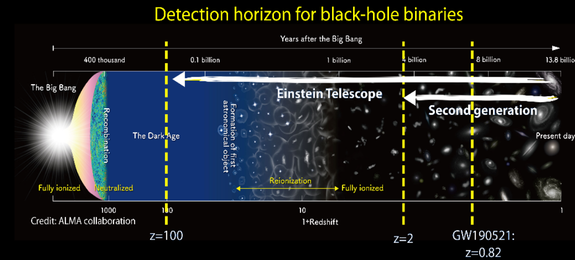
10^5 BNS detections per year

10^5 BBH detections per year

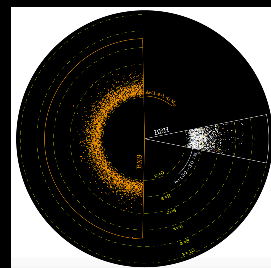
Harms et al. arXiv:2205.02499

The ET sensitivity will make it possible:

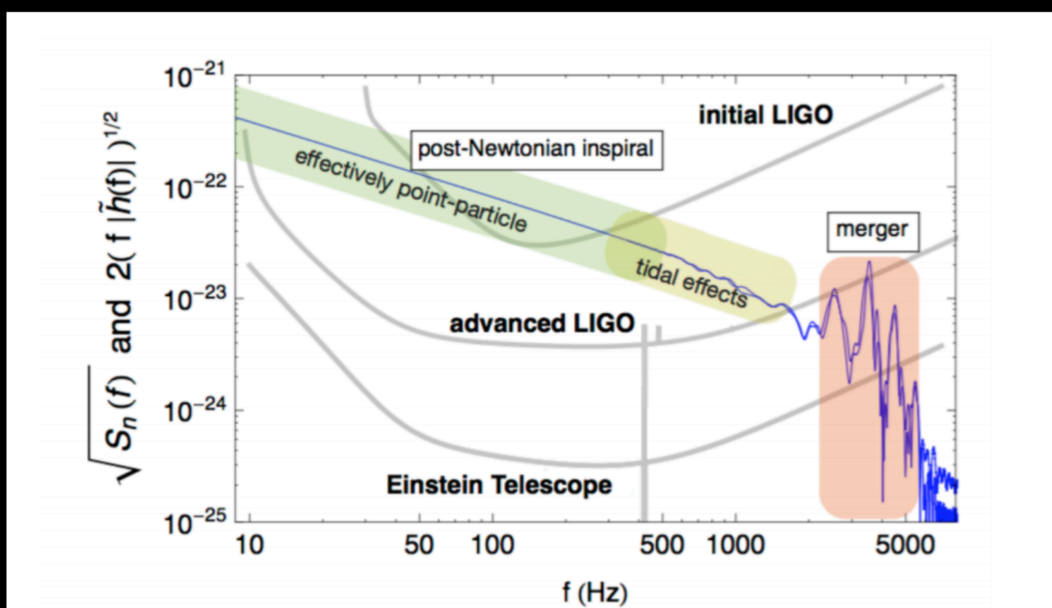
- EARLY UNIVERSE

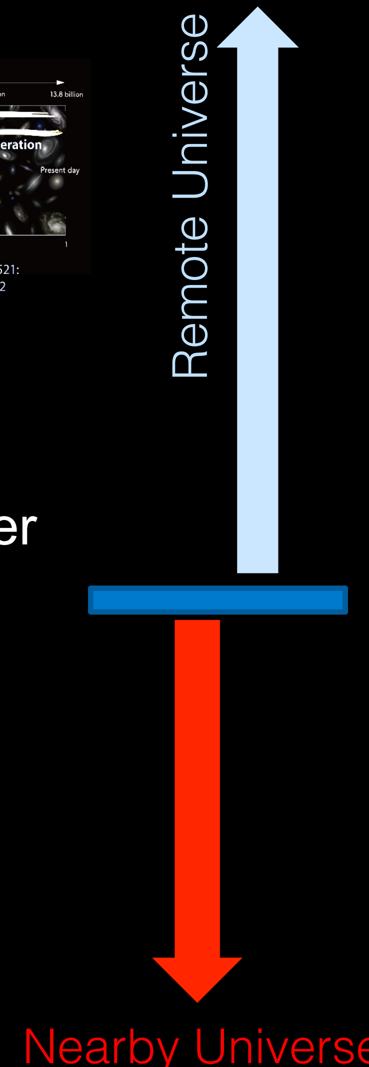


- POPULATION



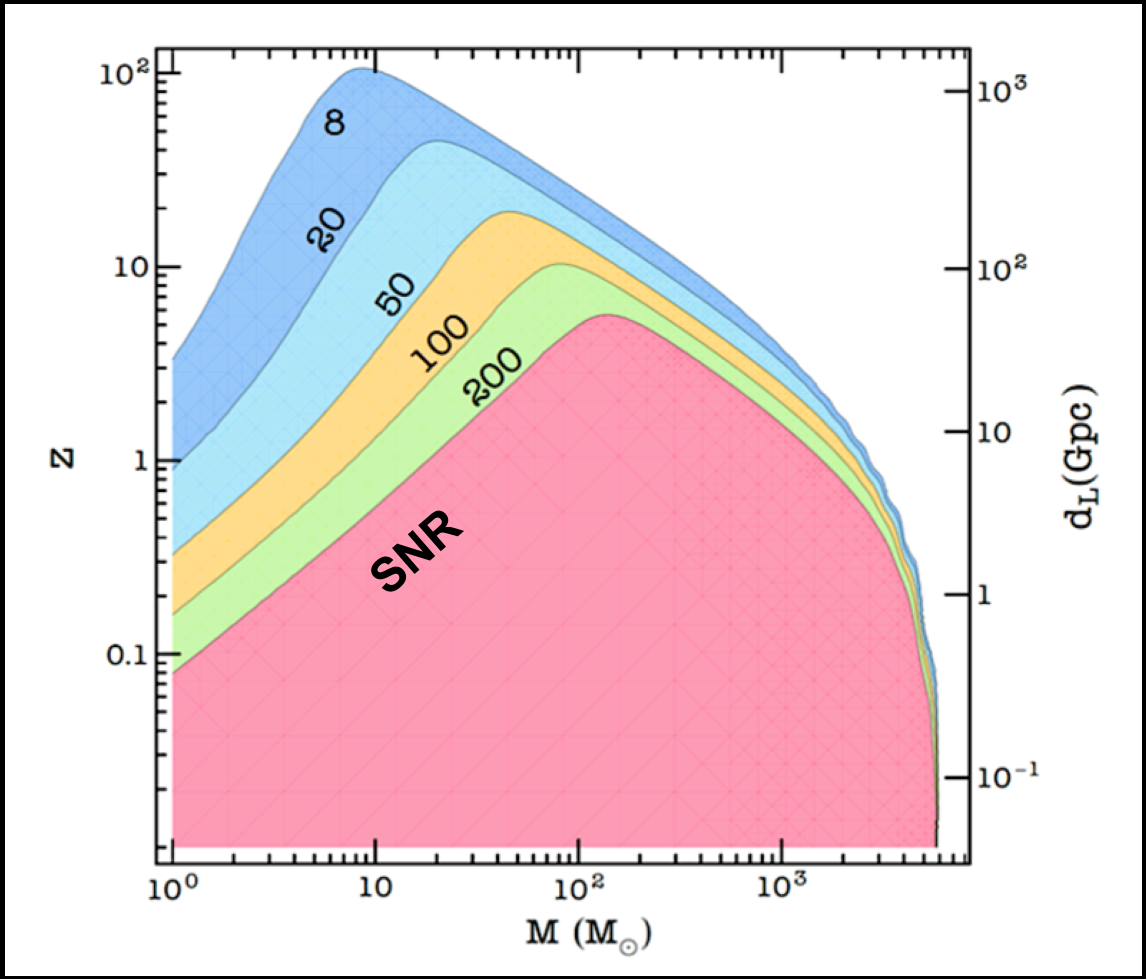
- PRECISION GW ASTRONOMY: exceptional parameter estimation accuracy for very high SNR events

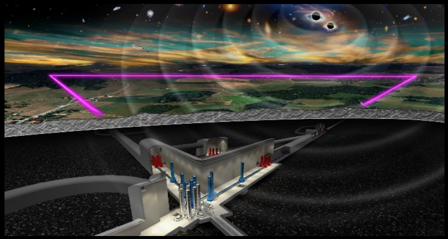




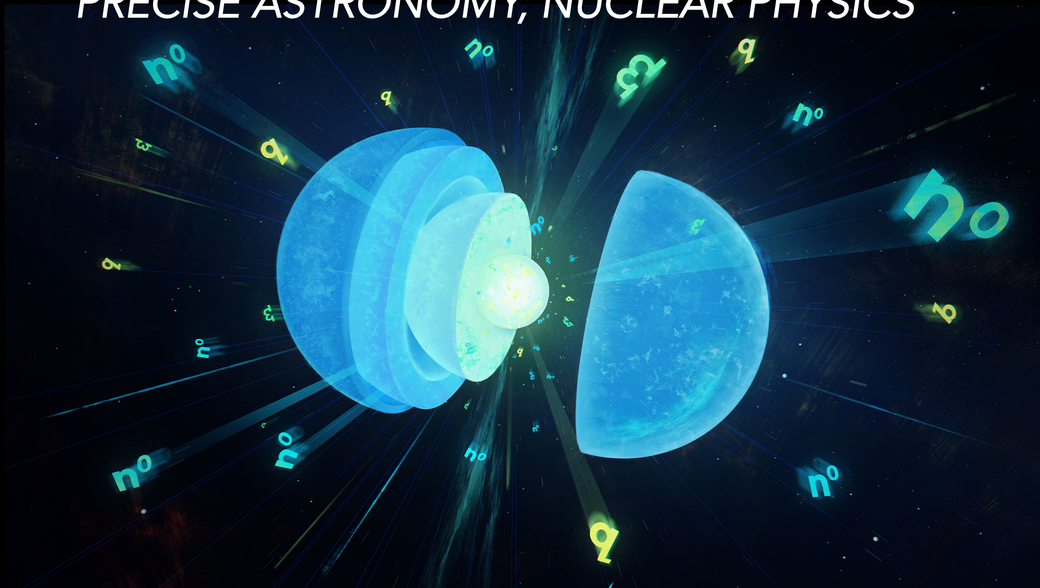
The ET wide frequency band will make it possible:

- Access UNEXPLORED MASS up to 10^3 Mo

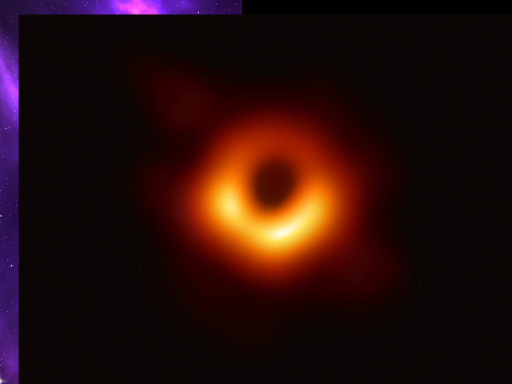




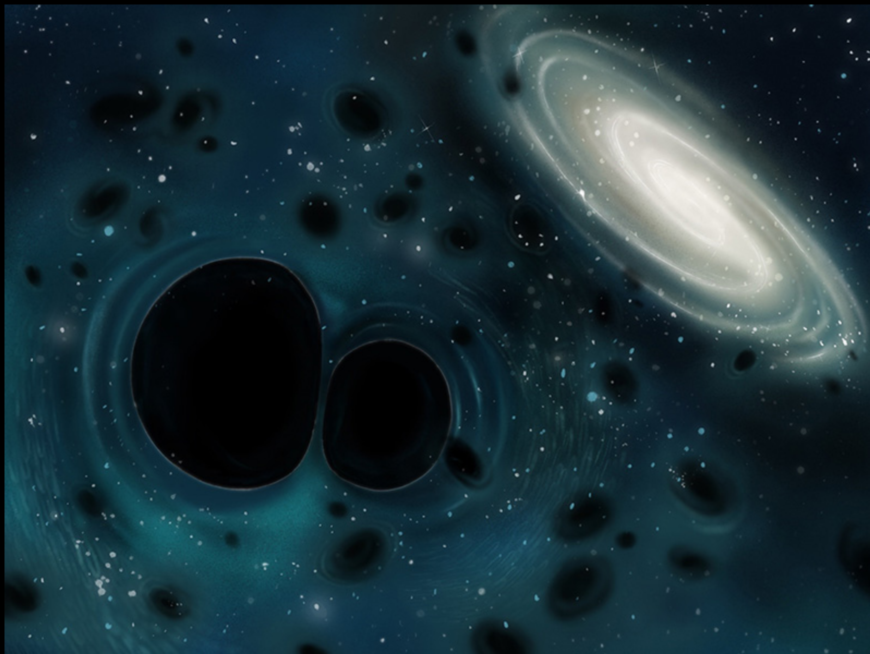
PRECISE ASTRONOMY, NUCLEAR PHYSICS



BLACK HOLES WITHH MASSES OF 100-10000 Mo

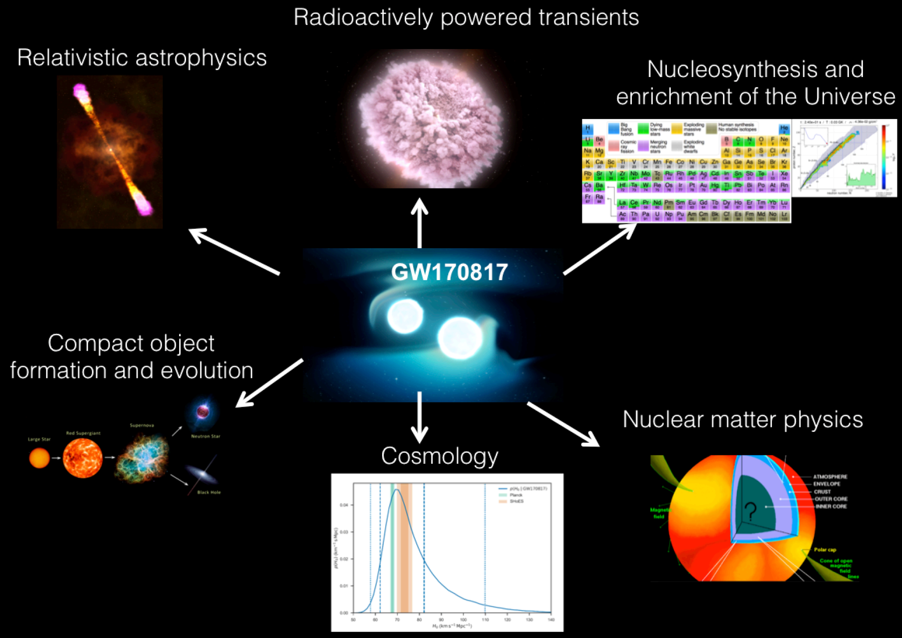


PRIMORDIAL BLACK-HOLES



UNIVERSE EXPANSION, DARK ENERGY, MODIFIED GRAVITY AT COSMOLOGICAL SCALE

Multi-messenger in the ET era



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

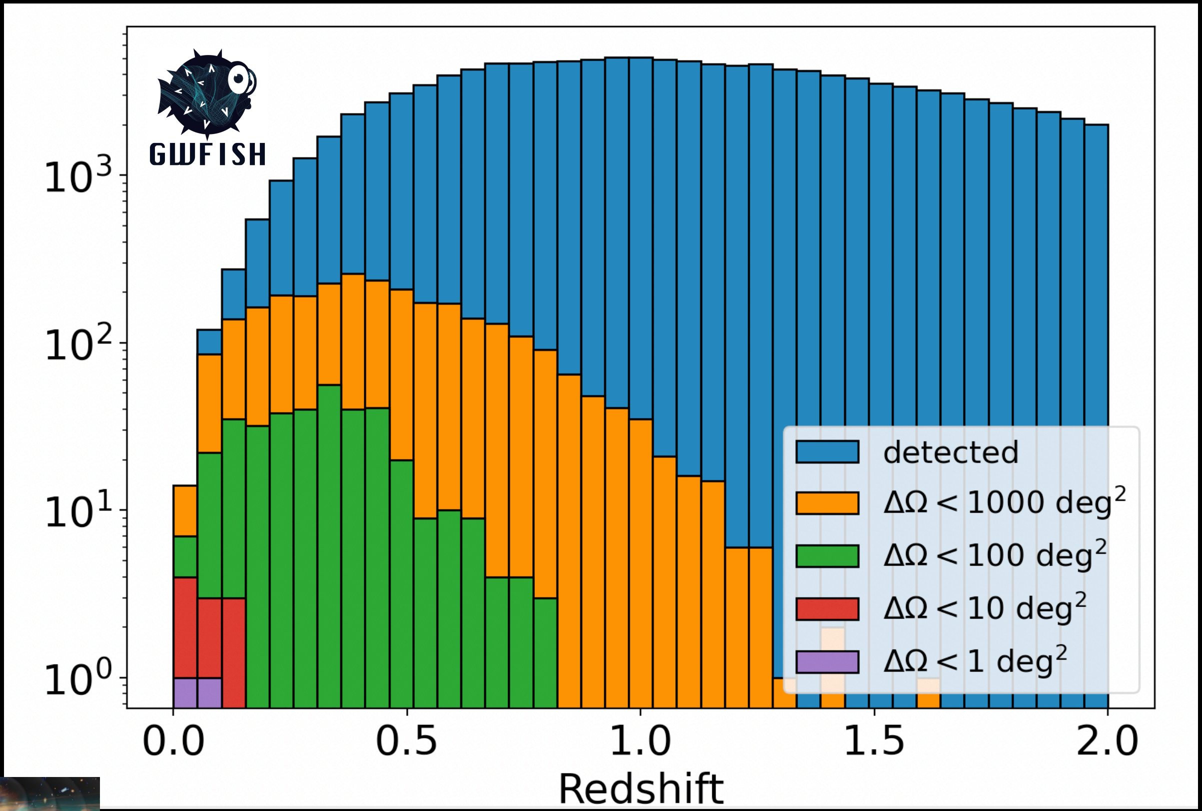
Emission mechanism

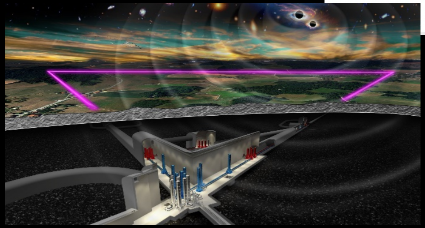
Cosmology

- Large increase of detection rate
  - population of BNS/NSBH
  - 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

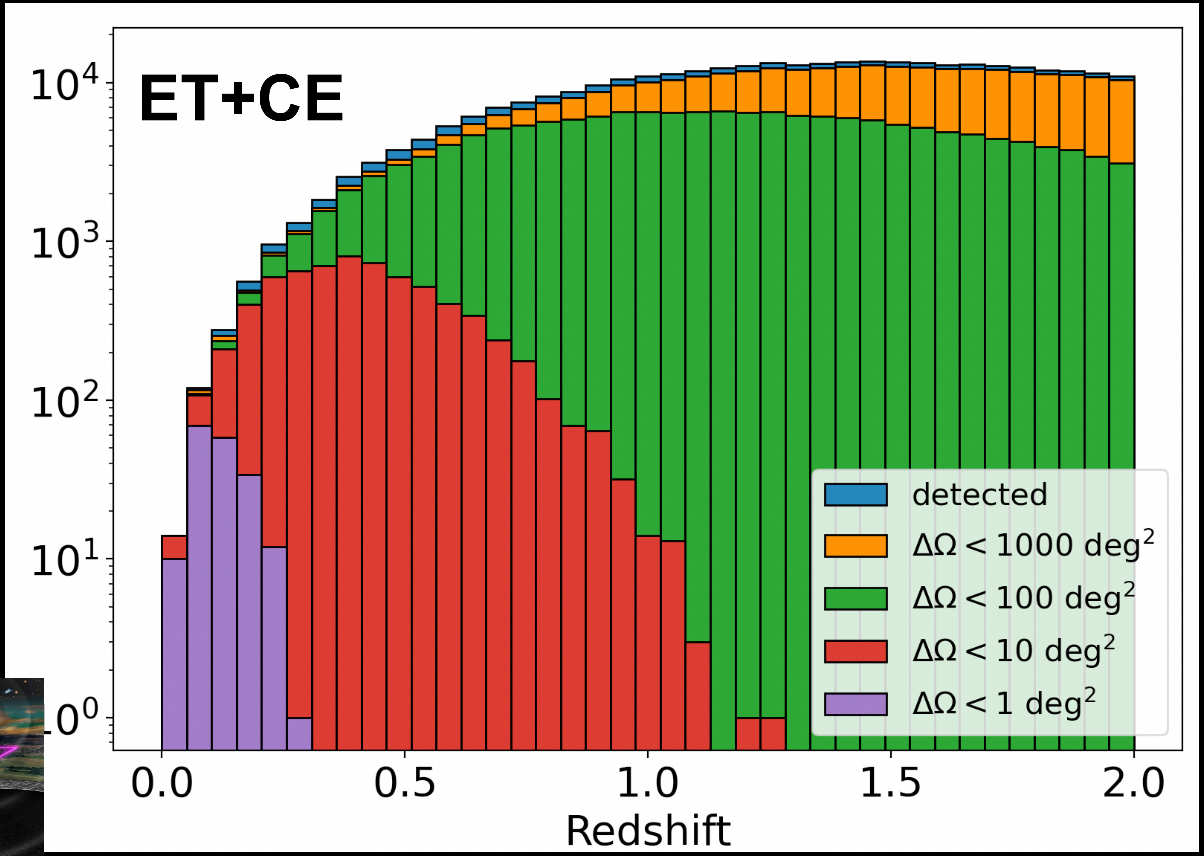


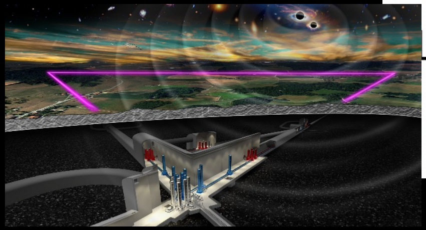


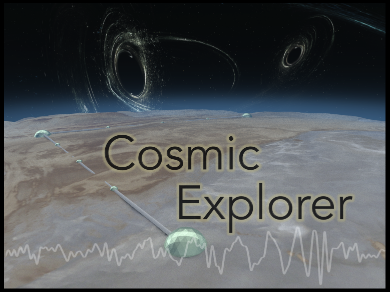
ET low frequency sensitivity make it possibile
To localize BNS!

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

Network sky-localization capabilities



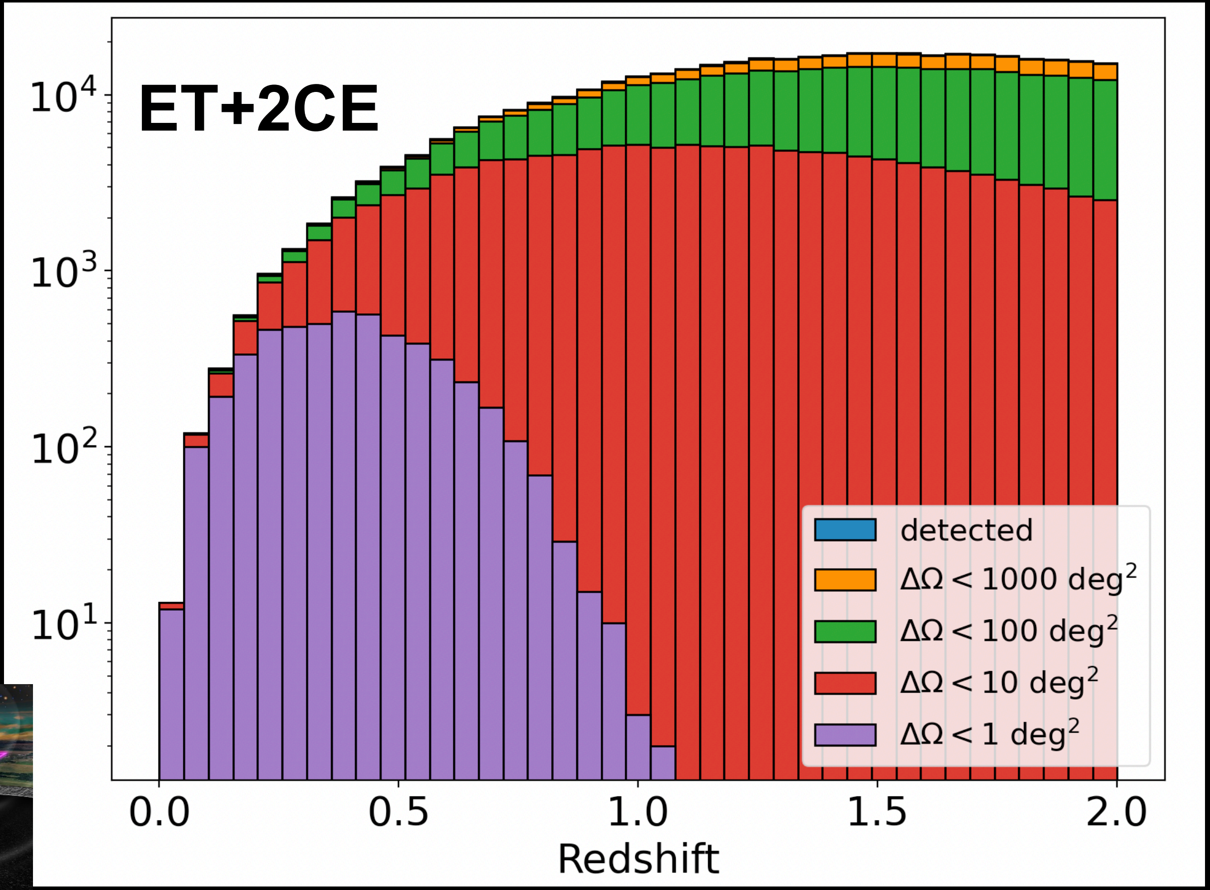


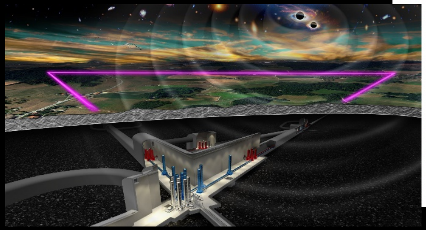


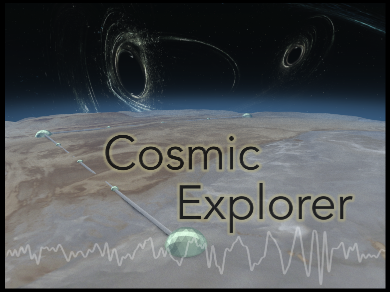
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Harms et al. arXiv:2205.02499, Ronchini et al. arXiv:2204.01746

Network sky-localization capabilities

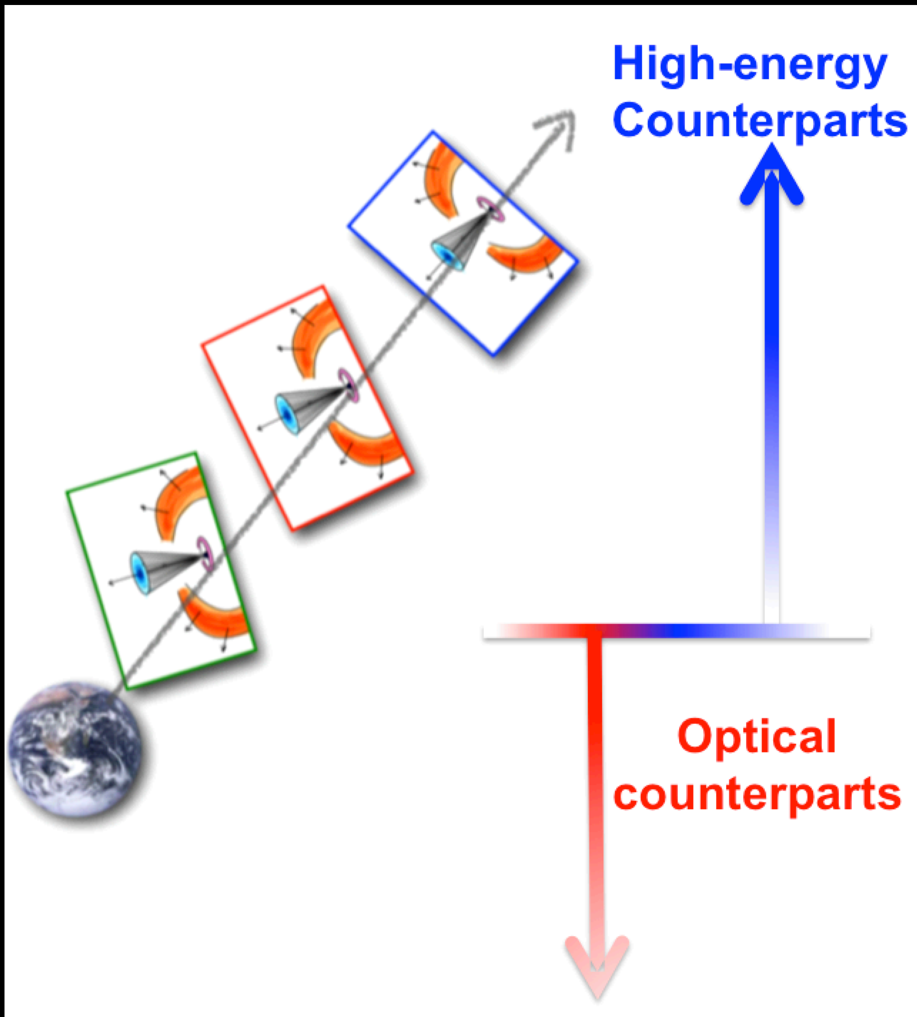






- O(1000) detections per year with sky-localization (90% c.r.) < 1 sq. deg

Harms et al. arXiv:2205.02499, Ronchini et al. arXiv:2204.01746



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

Credit: Ronchini

KILONOVA PHYSICS,
NUCLEOSYNTHESIS, NUCLEAR
PHYISCS and H0 ESTIMATE

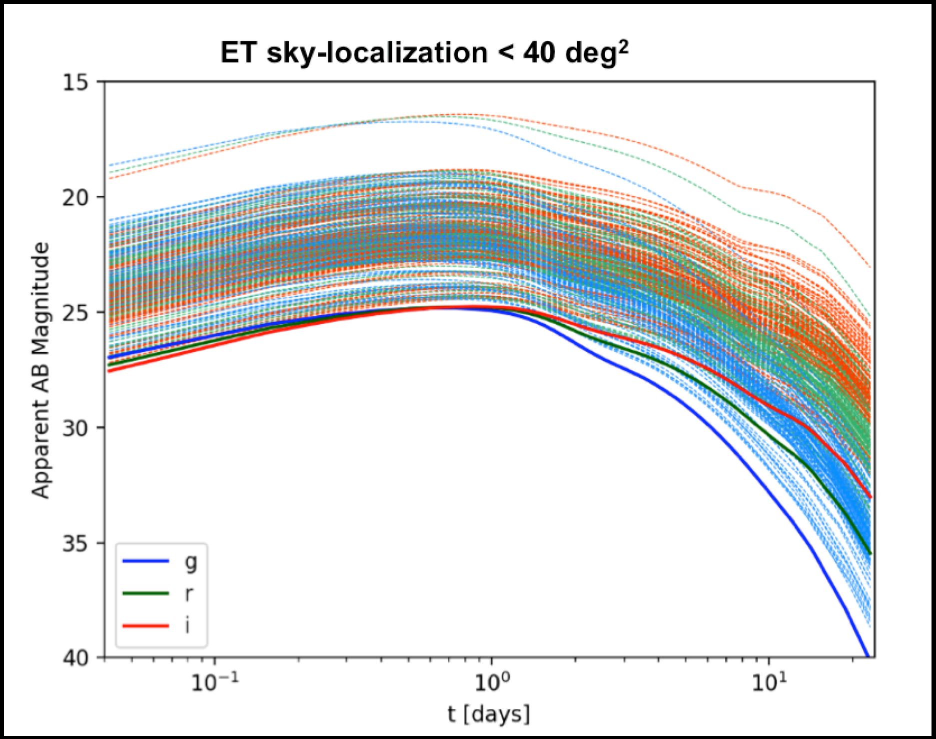
Hundred of MM events per year!

Image credit: NASA Goddard Space Flight Center

THERMAL EMISSION - KILONOVAE

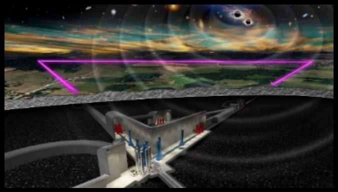
KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

ET+Vera Rubin synergy



VERA RUBIN OBSERVATORY ToO:

- three epochs of 600s observations in two filters
- detection efficiency is larger than 99% up to z=0.3



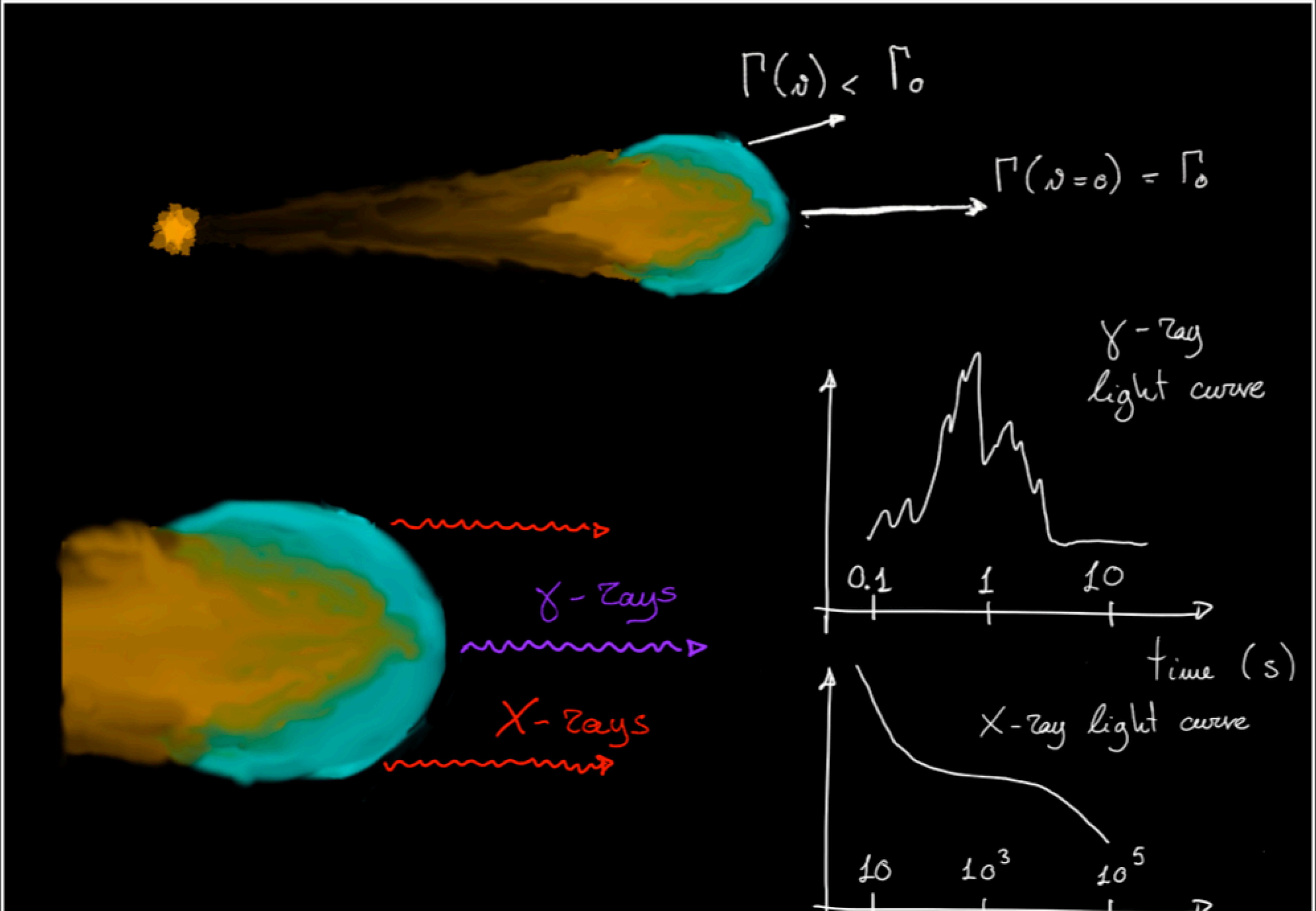
Around 40 joint ET/VRO per year with less than 10% of VRO telescope time

COSMOLOGY: Hubble constant measurement from GW standard sirens with percent precision!

HIGH-ENERGY

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

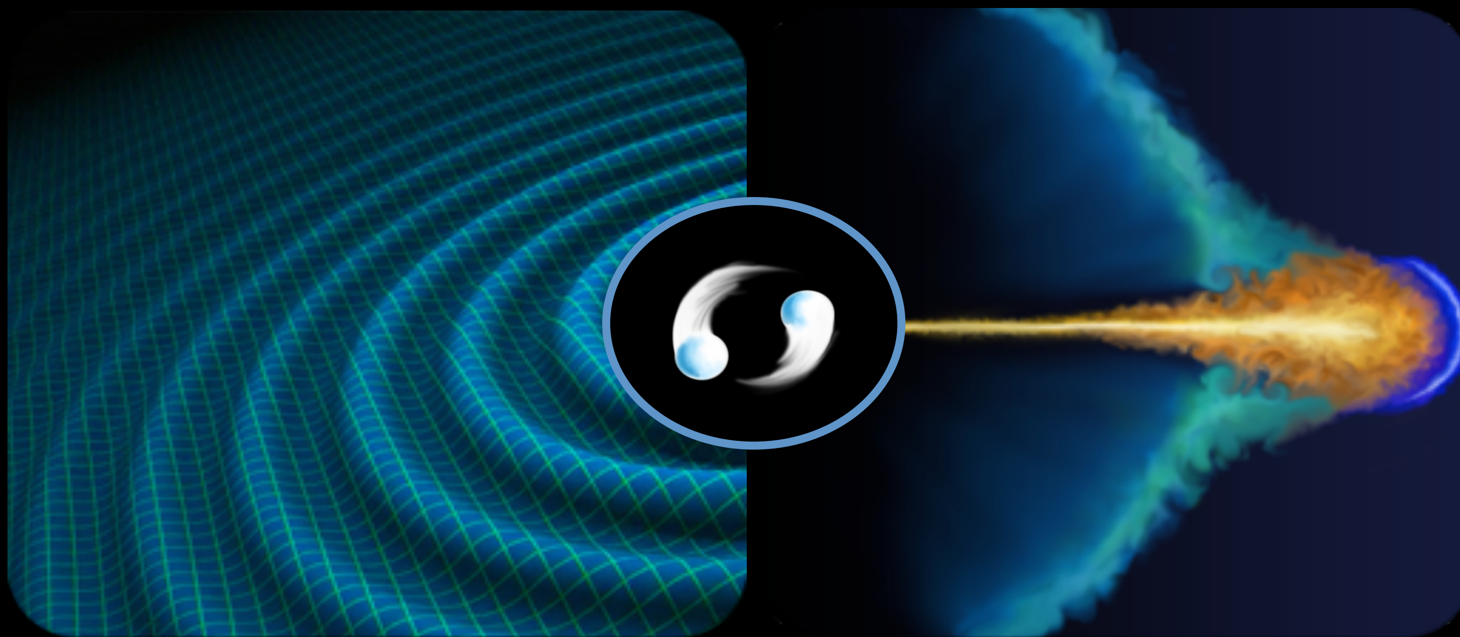
Prompt and afterglow emission from a structured jet



Credit: Ronchini/GSSI

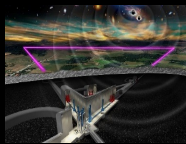
GW + γ-ray joint detections per year

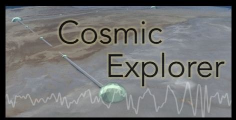
SURVEY MODE

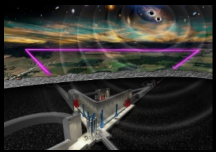


Almost all detected short GRB will have a GW counterpart

Depending on the satellites, we will have **tens to hunreds** of detections per year

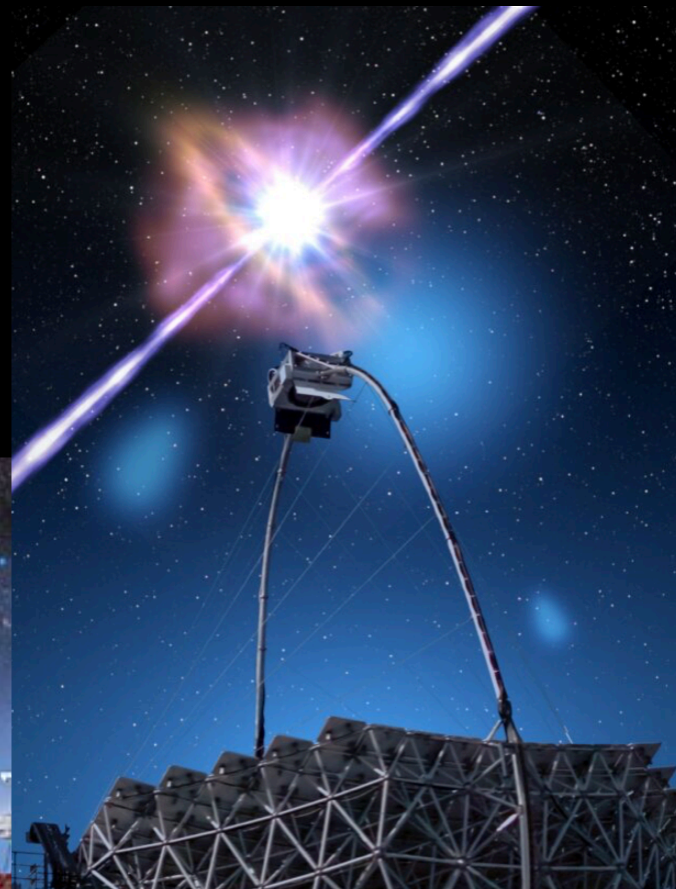


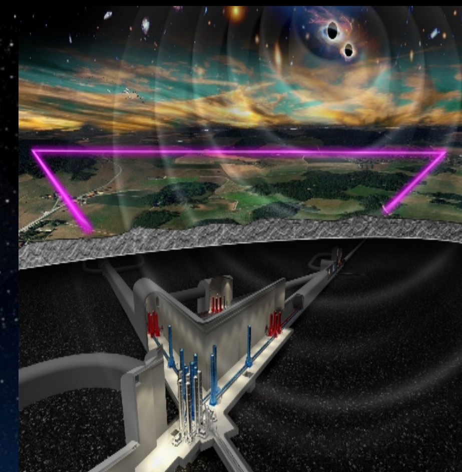




Ronchini, **MB**, **Oganesyan**, et al. **2022 A&A**

CTA and GW DETECTOR synergies





GRB 190114C (MAGIC)
GRB 180720B(HESS)
Afterglow VHE emission!

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

Thanks!

GSSI GW team

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A. Mei, S. Ronchini, G. Oganesyan,
B. E. Loffredo, N. Hazra et al.

AHEAD 2020
HIGH ENERGY ASTROPHYSICS

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