An MeV Lookout for Gravitational Wave Sources

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MeV Astronomy: Unlocking the Multi-Messenger Universe

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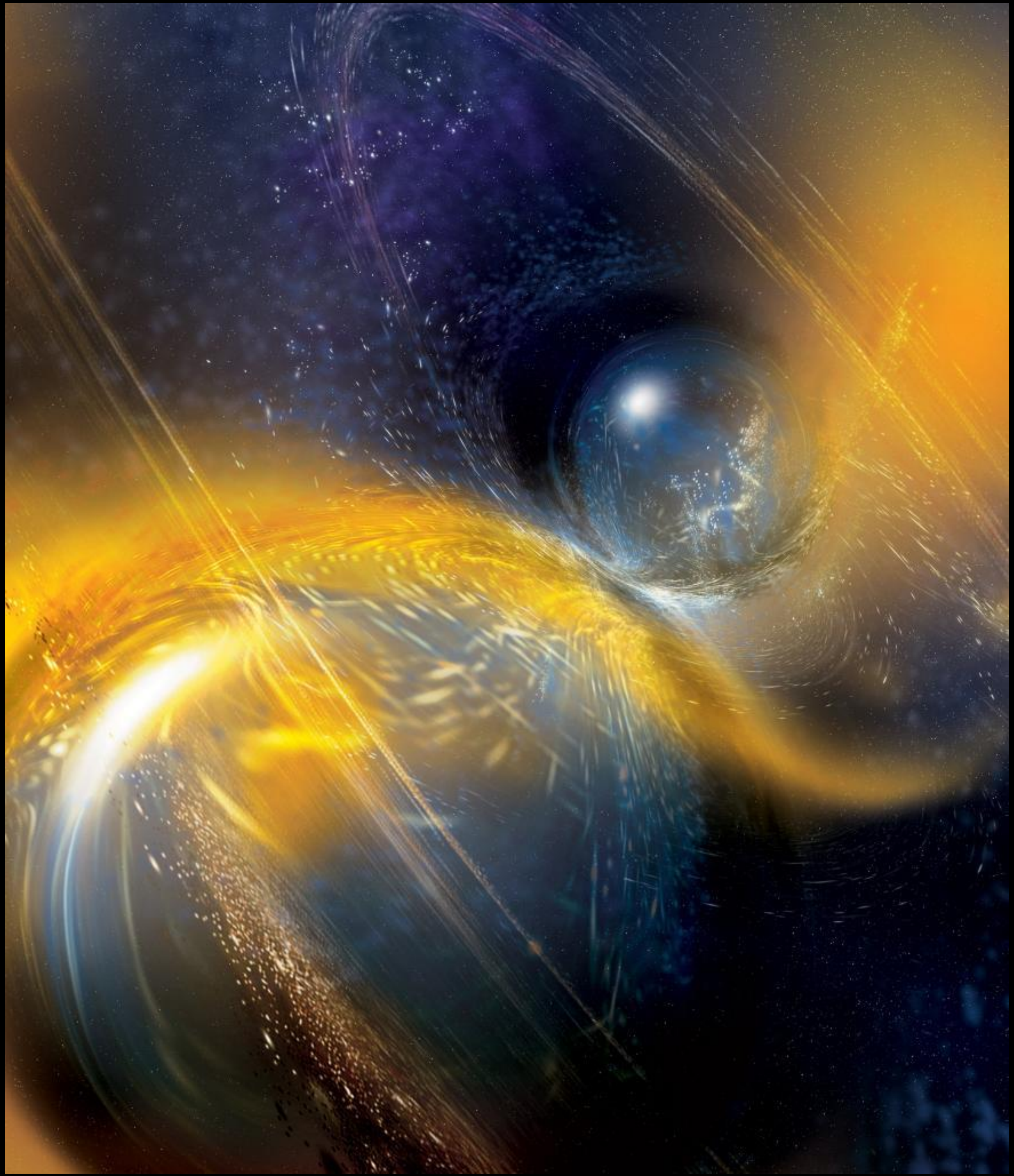
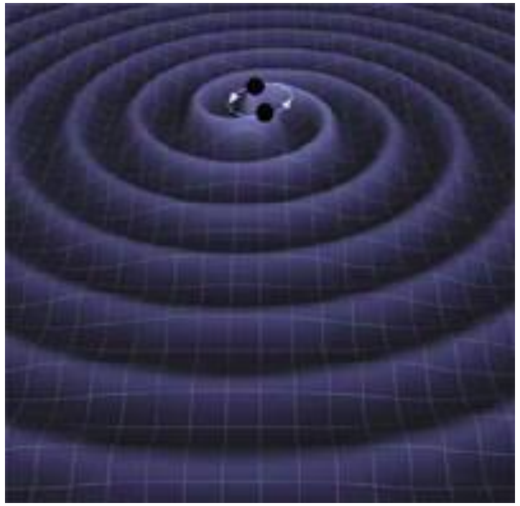
LIGO-G2002138-v1



Gravitational Wave Physics and Astronomy

- **Gravitational waves can be emitted by astrophysical systems with rapidly changing mass distribution**
  - Compact binary system: orbit, inspiral and merger (Black holes and/or neutron stars)
  - Core collapse of a massive star (supernova engine)
  - Non-axisymmetric spinning neutron stars
  - Cosmic strings, early universe physics, …



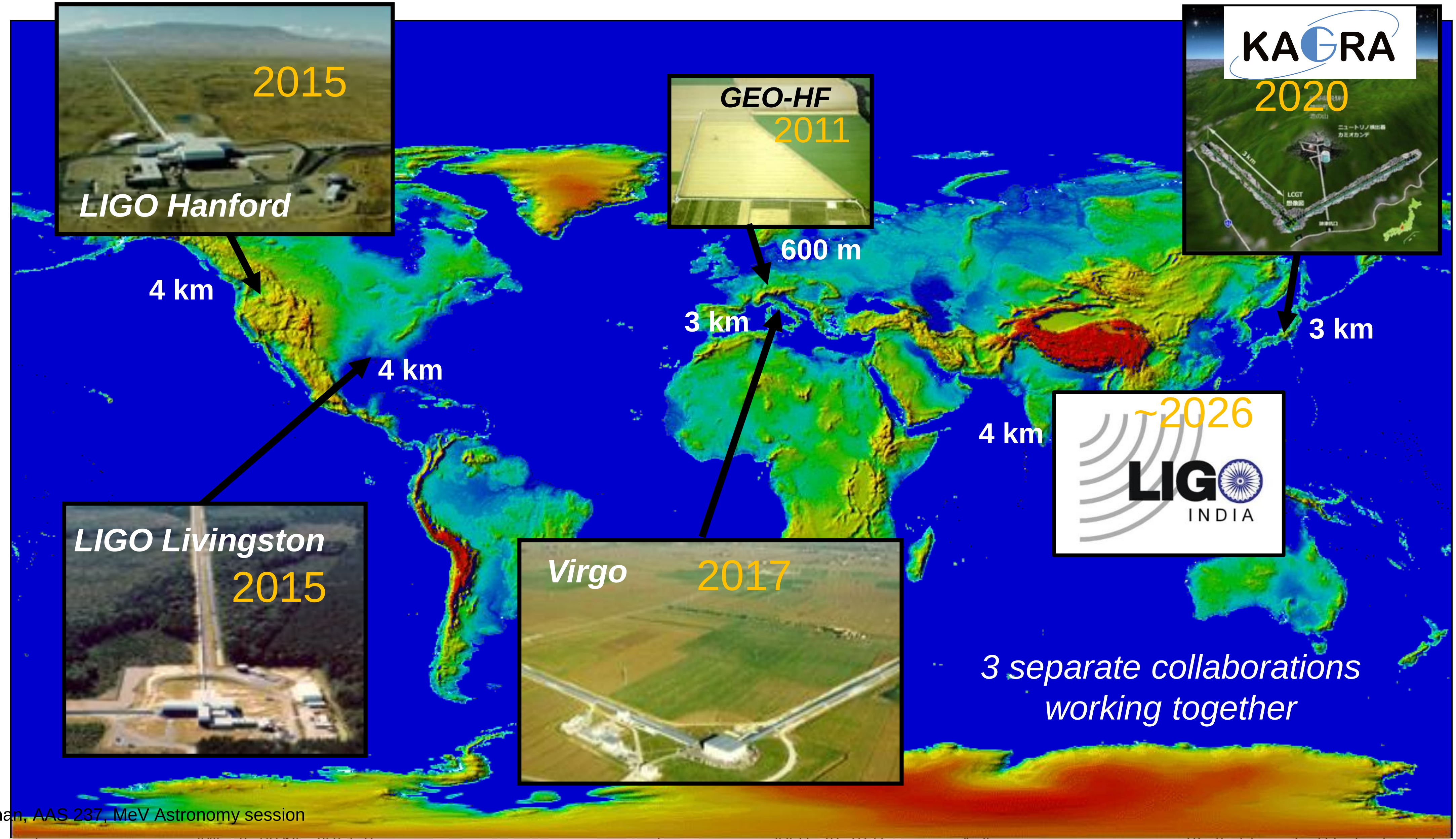
T. Carnahan/NASA GSFC/LIGO

- **Gravitational waves come directly from the central engine**
  - Not obscured or scattered by material
  - ➔ Complement ‘traditional’ astronomy observations of photons from photosphere, outflows, circumburst medium, shocks, …

Bill Saxton, NRAO/AUI/NSF

GWs are challenging to detect, but we *are* detecting them...

Building a network of Advanced GW detectors



LIGO Scientific Collaboration

\+ VIRGO

\+ KAGRA

GW170817: a binary neutron star merger!

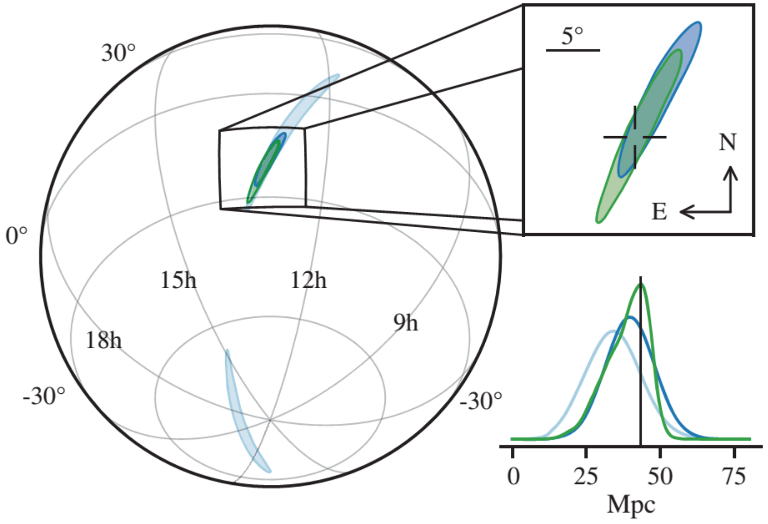
LIGO-Virgo Trigger G298048

Initially found in the GW data using a template with typical neutron star masses

And coincident (within ~2 sec) with a short gamma-ray burst detected by the GBM instrument on NASA's Fermi satellite!

Visible in LIGO spectrograms!

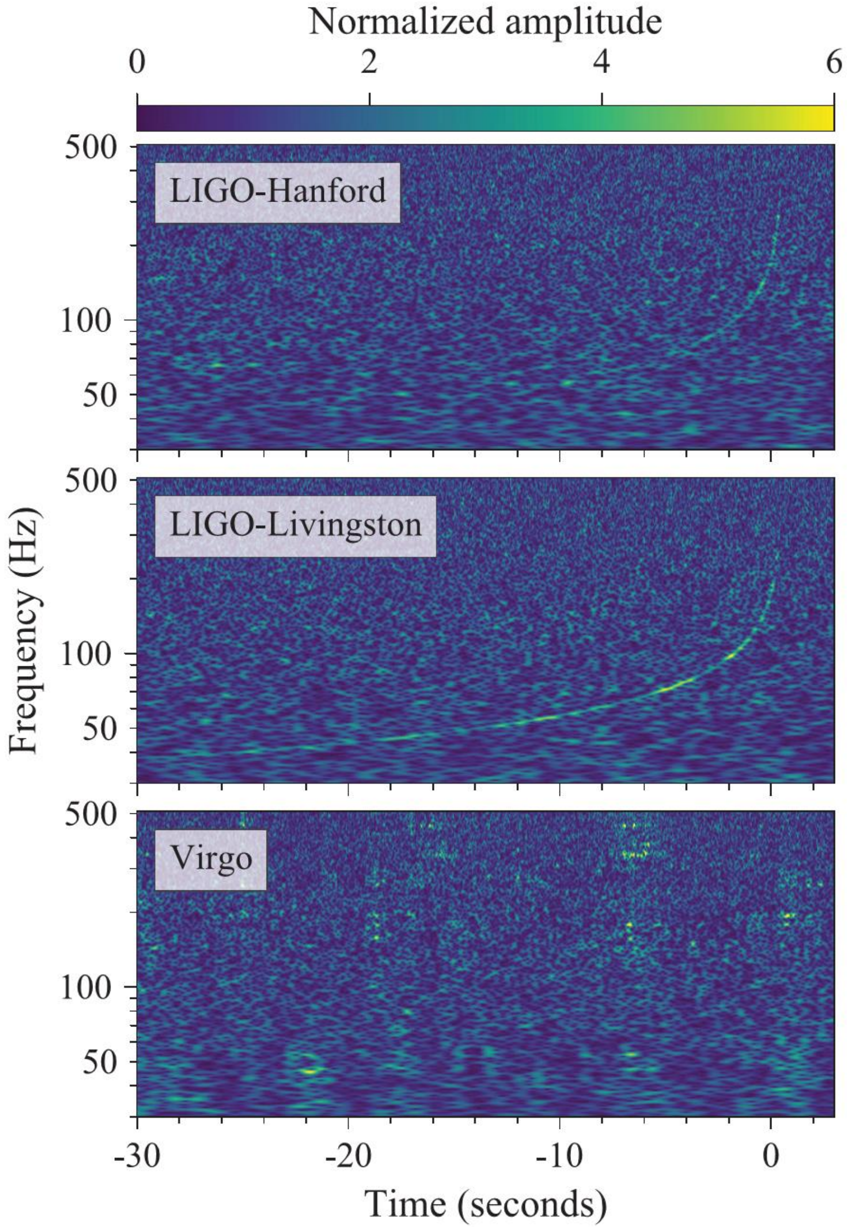
Localized rather well, by GW standards



To an area of ~31 deg^2
(after working around a glitch in the LIGO-Livingston data),
ultimately to ~16 deg^2

➔ Optical astronomers found the counterpart in NGC 4993 !

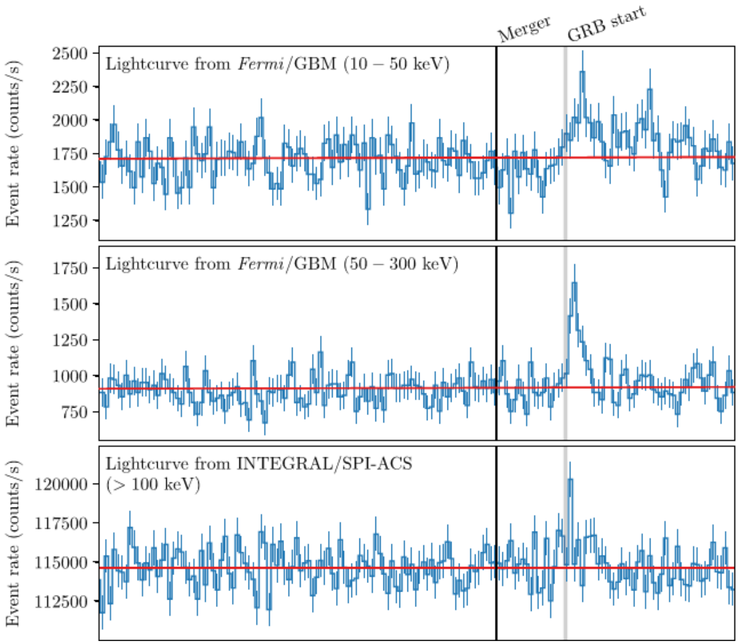
[Abbott+++ 2017, ApJL 848, L12, and many other papers]



[Abbott et al. 2017, PRL 119, 161101]

Emergence of GRB 170817A / AT2017gfo EM signatures

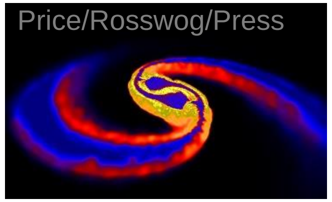
Gamma-Ray Burst



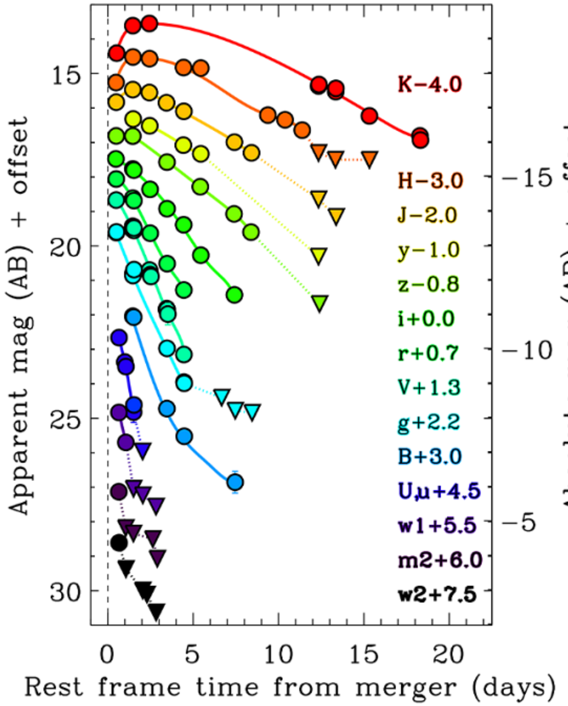
[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

Pretty typical observed properties, but very dim (i.e., low E_{iso}) considering how close it was

Kilonova

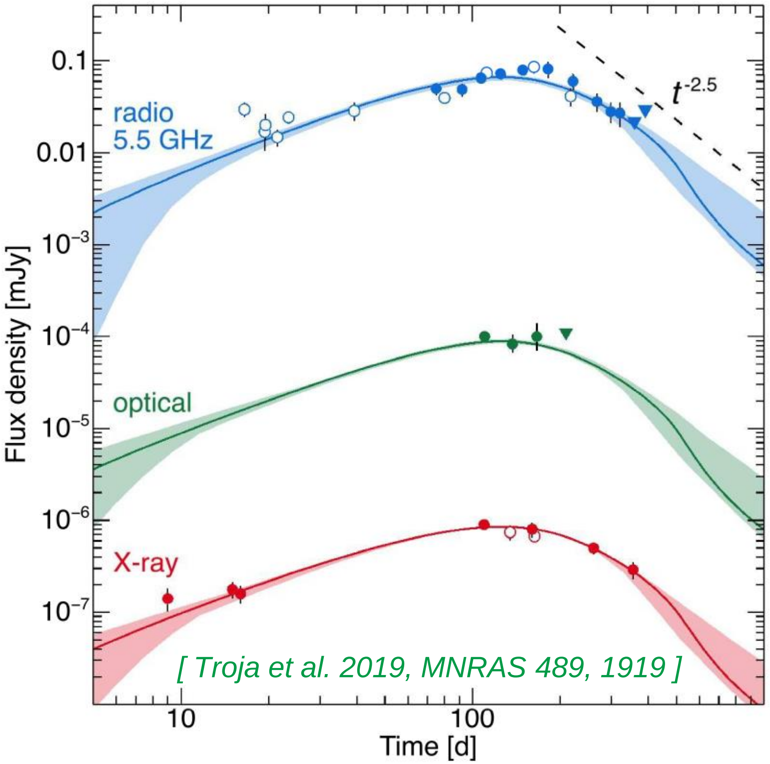


Thermal emission from ejected material, heated by decay of *r*-process elements formed in event



[Drout et al. 2017, Science 10.1126/science.aaq0049]

Afterglow



[Troja et al. 2019, MNRAS 489, 1919]

Slow onset and rise, constant spectral index completes picture of a successful jet off-axis by around ~20°

Off-axis jet + kilonova picture

A few percent of the original mass is ejected outward at a few tenths of the speed of light !

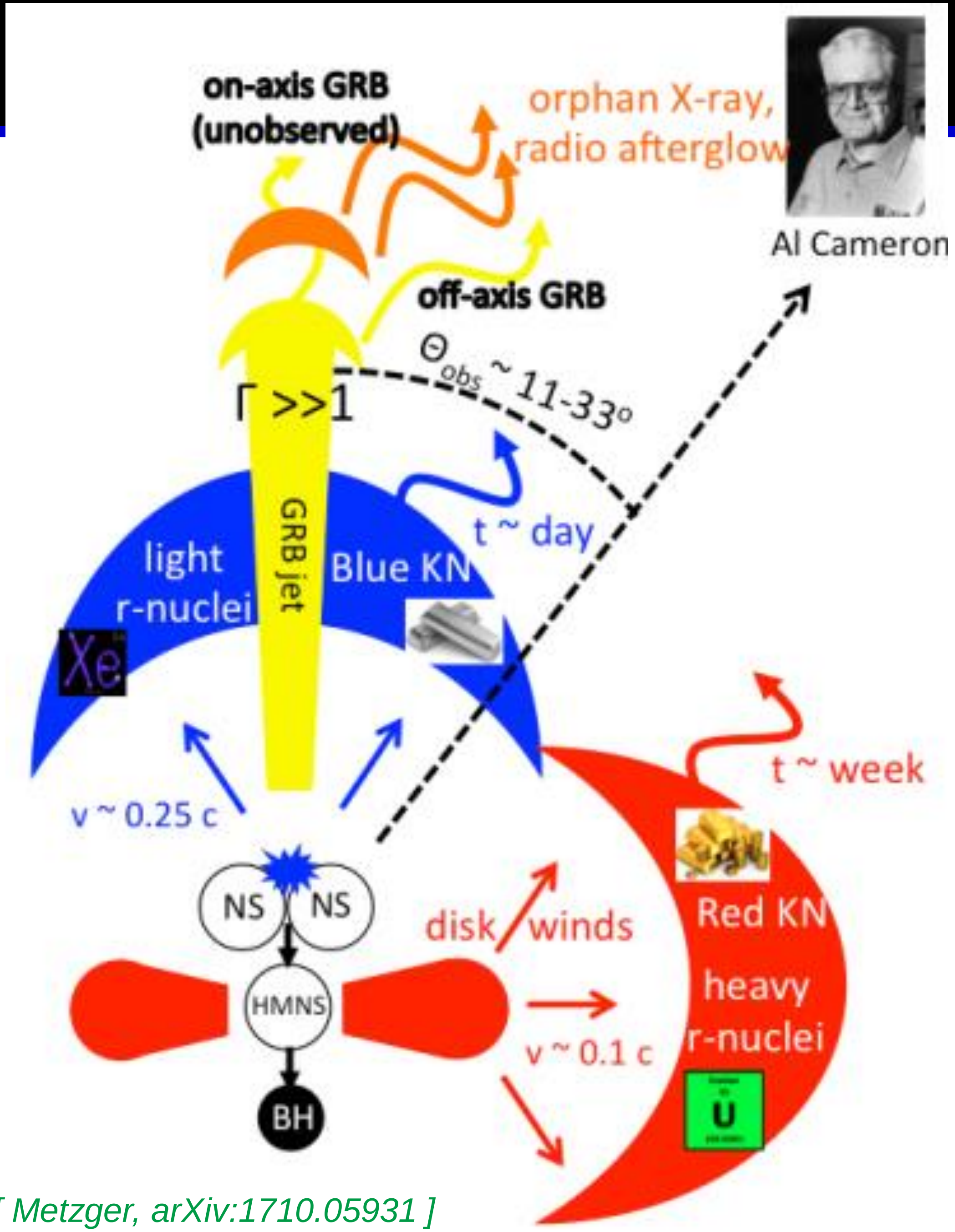
The heavy elements formed in this ejecta depend on the degree of neutron richness

With different resulting opacities:

→ "Blue" (lanthanide-poor, less opaque, faster fading)

and

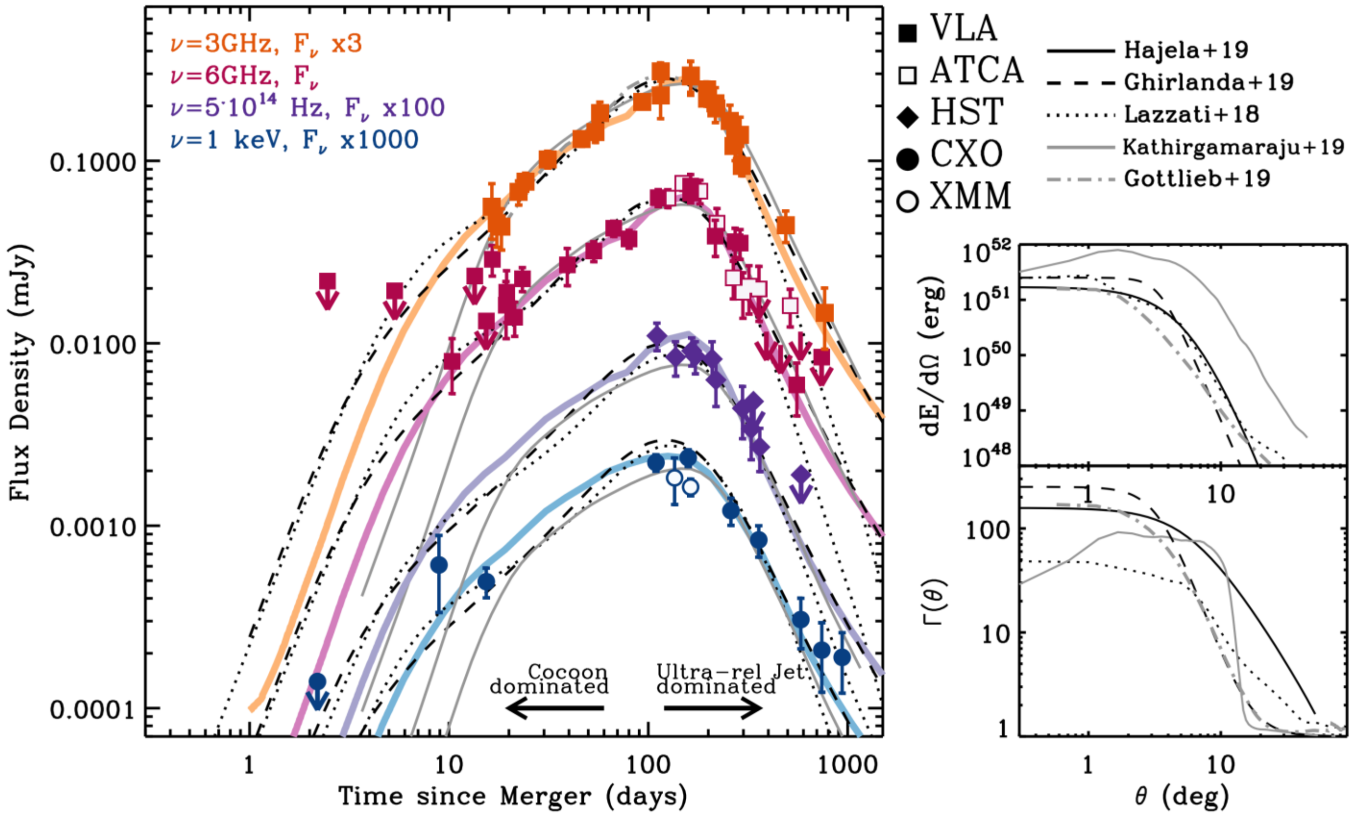
→ "Red" (lanthanide-rich, more opaque, slower fading)



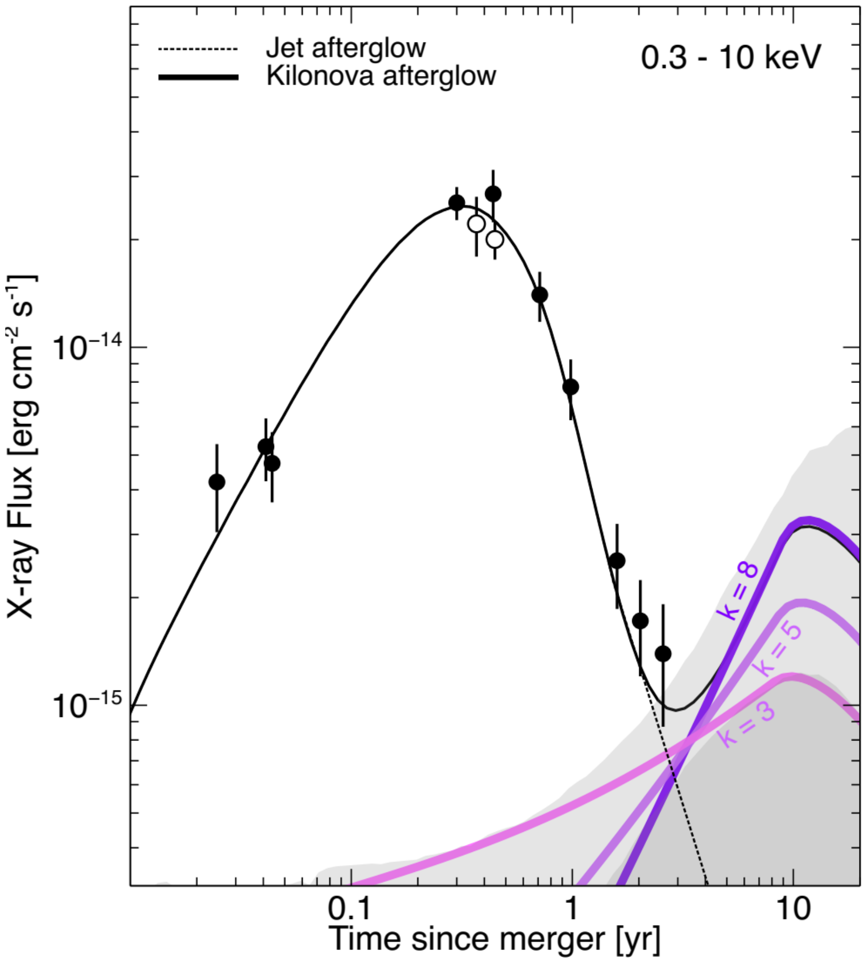
[Metzger, arXiv:1710.05931]

Some recent summaries of the afterglow...

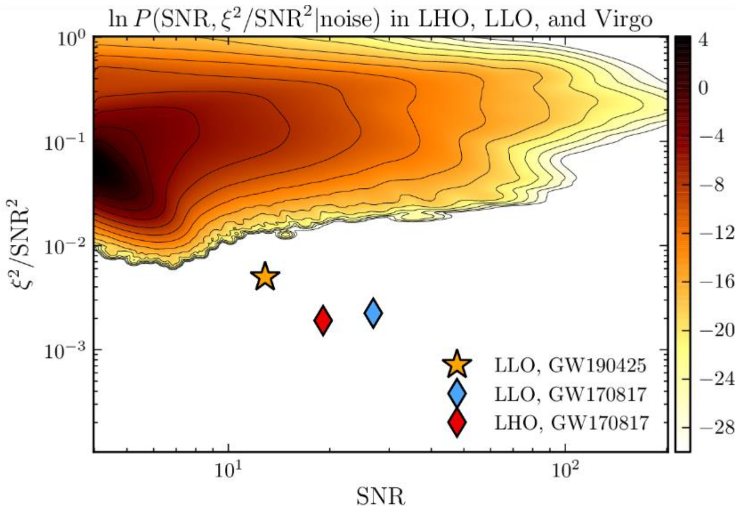
[Margutti & Chornock, arXiv:2012.04810]



[Troja et al. 2020, MNRAS 498]



More multi-messenger events, please!



[Abbott et al., ApJL 892, L3]

From the O3 observing run, only one binary neutron star event has been confirmed (so far): GW190425

- LIGO-Hanford wasn't taking data at the time
- Offline analysis: S/N ratio 12.9 in LIGO-Livingston, ~2.5 in Virgo (GW170817 was twice as strong, and captured by LHV network)

No conclusive EM counterpart was found

- It wasn't for lack of trying! Over 100 GCN Circulars were issued
- Many optical transient candidates were followed up further, determined to be unrelated
  [e.g. Hosseinzadeh+, ApJL, 880, L4; Lundquist+, ApJL, 881, L26; Coughliin+, ApJL, 885, L19; Antier+, MNRAS, 492, 3904]
- Pozanenko et al. reported a weak GRB detected by INTEGRAL SPI-ACS
  - Two pulses, ~0.5 and ~5.9 s after the merger time *[Astronomy Letters, 45, 710; arXiv:1912.13112]*
  - But this has not been generally received as strong evidence, without an optical/UV/IR counterpart too

Challenges:

- The sky area was ~10,000 square degrees
- The distance to the source was 160 ± 70 Mpc
- Higher mass, prompt collapse to a black hole leaves less (and less irradiated) ejecta for a kilonova
  ➔ intrinsically redder and fainter than GW170817 *[Foley et al., MNRAS, 494, 190; arXiv:2002.00956]*

How can we gain in multi-messenger detection rate?

(Here, focusing on prompt emission)

Improve burst sensitivity for short GRBs

Dependent on distance, highly dependent on off-axis observing angle and Γ of jet

Fermi-GBM found GRB 170817A, but it was only a factor of ~2 above detection threshold

Improve localization of short GRBs

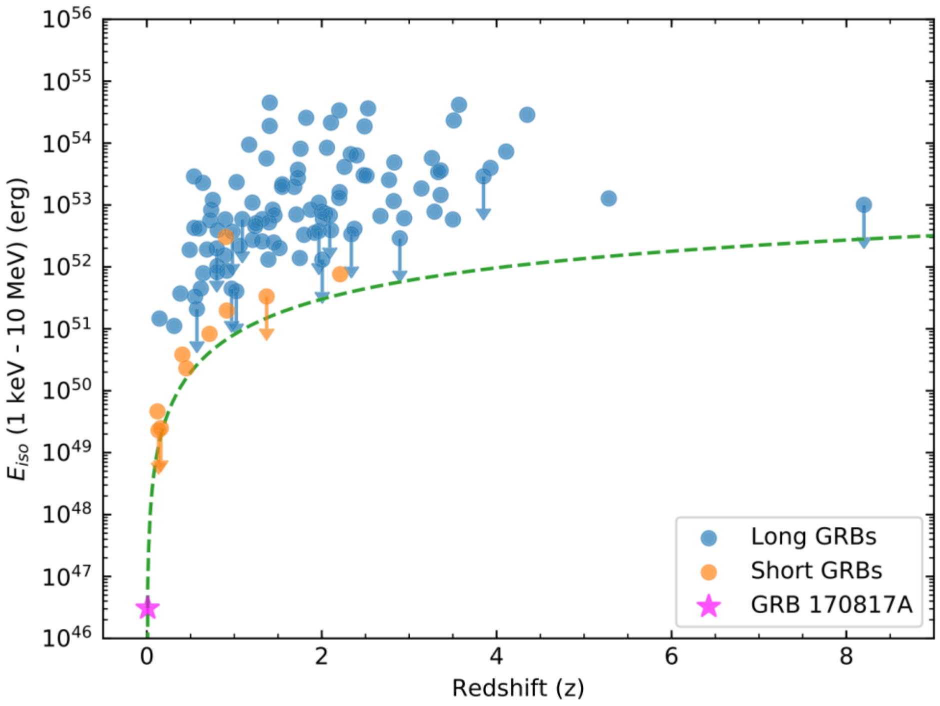
Enables identification of weaker joint events from the GW and EM data

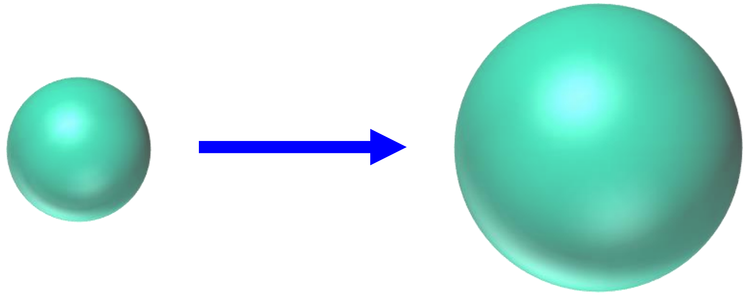
Improve sensitivity (range) of GW detectors

More events and candidates

Higher S/N for a subset of candidates
➔ better localization and estimation of astrophysical source parameters

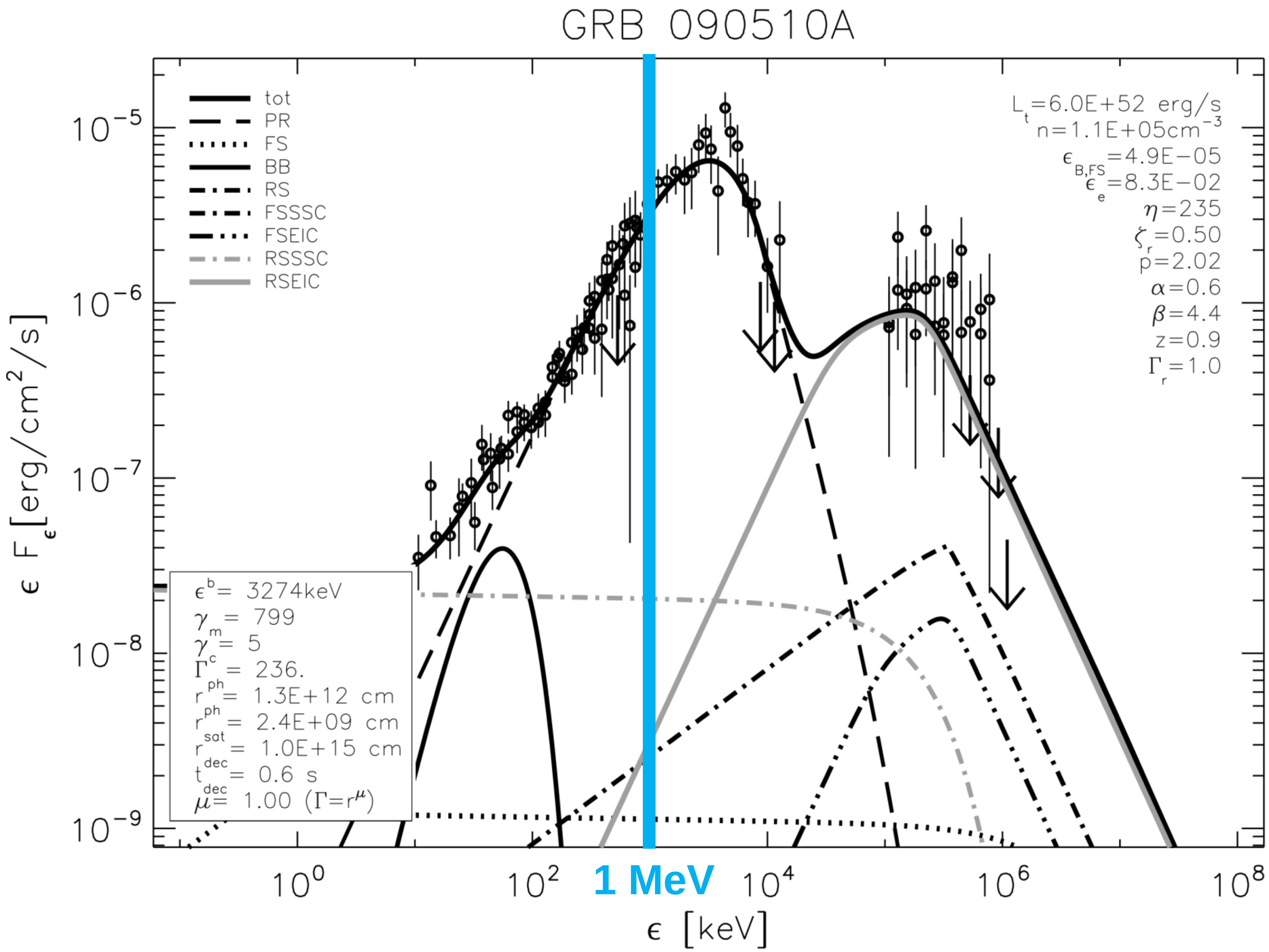
[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]





Spectrum of short GRB prompt emission

Spectrum of an on-axis short GRB peaks around ~1 MeV !

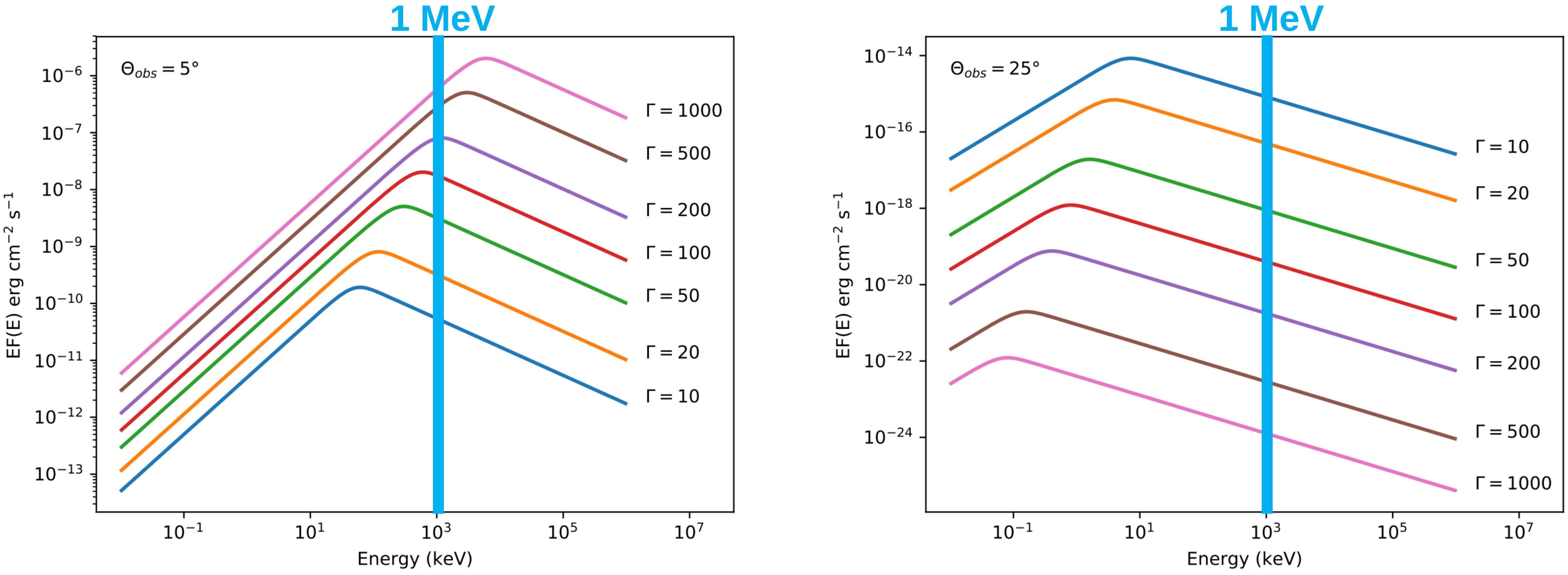


[Veres, Zhang & Meszaros 2013, ApJ 764, 94]

Spectrum modeling for off-axis viewing angles

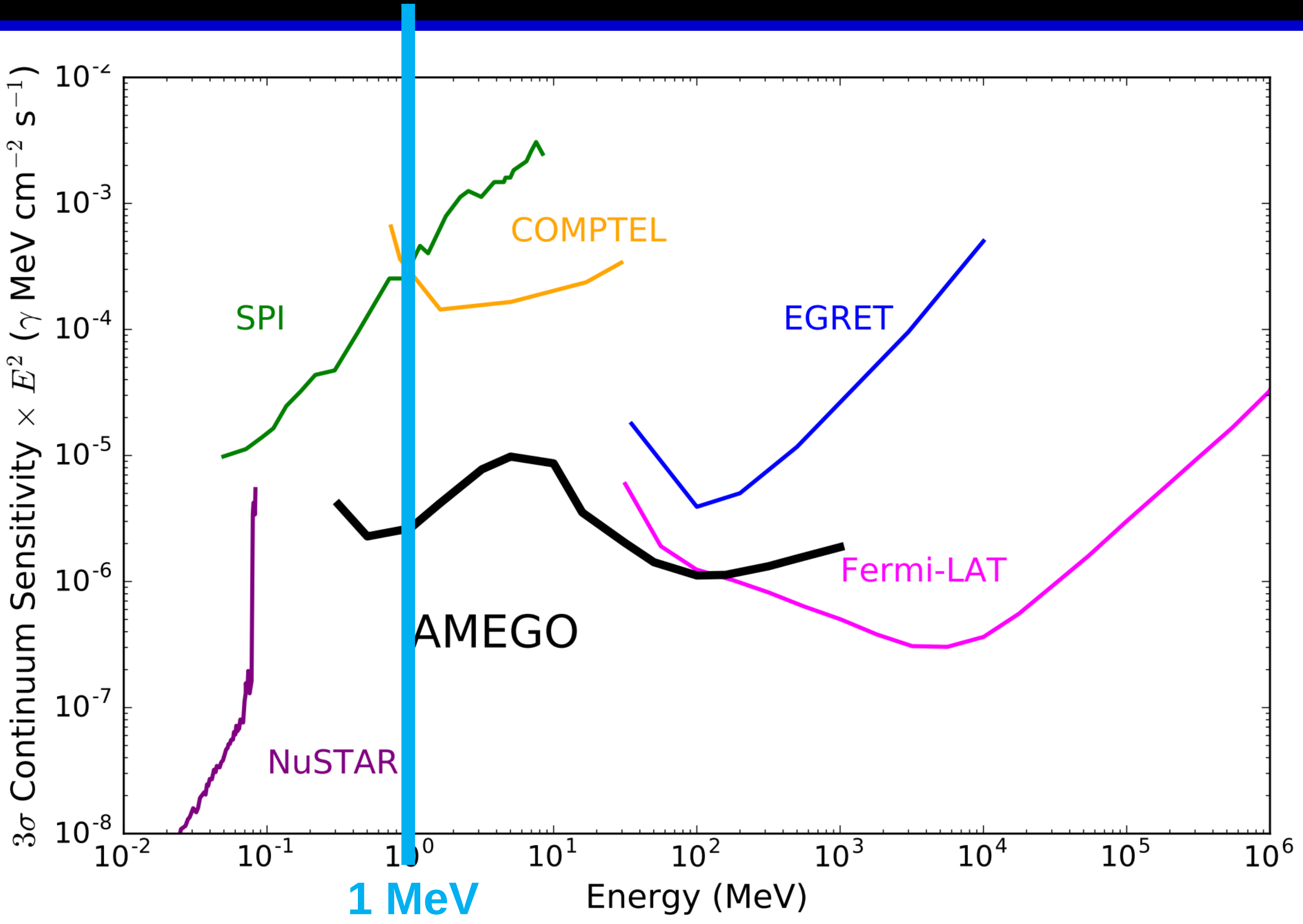
Off-axis: peak shifts to lower energy, depending on jet/cocoon structure and Γ

e.g. from a very recent preprint I happened to see, using a top-hat jet model:



[Farinelli et al., arXiv:2101.02984]

Having a sensitive MeV observatory would be great!



[AMEGO Decadal RFI Response from https://asd.gsfc.nasa.gov/amego/]

Near-term improvements to GW detectors: the **A+** upgrade

Addresses quantum and thermal noise effects that limit LIGO sensitivity

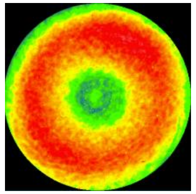
* There is also an Advanced Virgo Plus upgrade project

Major funding has been awarded by NSF, UK Research & Innovation / STFC, and the Australian Research Council

Major areas of improvement:

Add long “filter cavities” to provide frequency-dependent squeezing, reducing quantum noise at <u>both</u> high and low frequencies

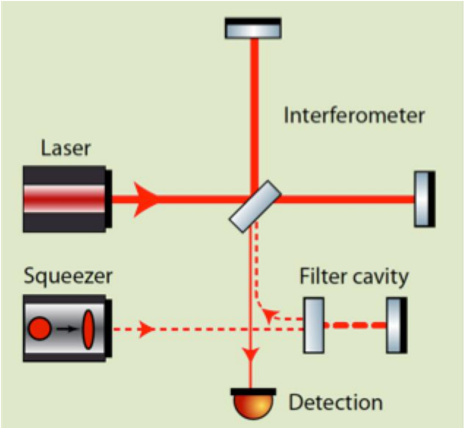
Improve mirror coatings on the large test masses to reduce thermal noise



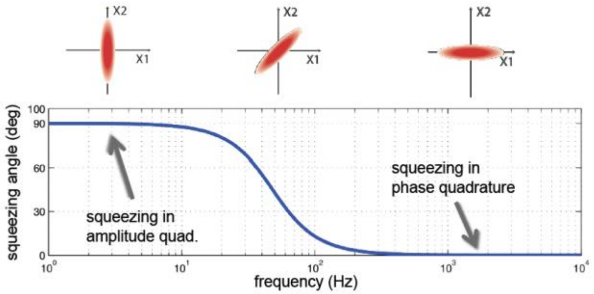
LIGO Lab/ G. Billingsley

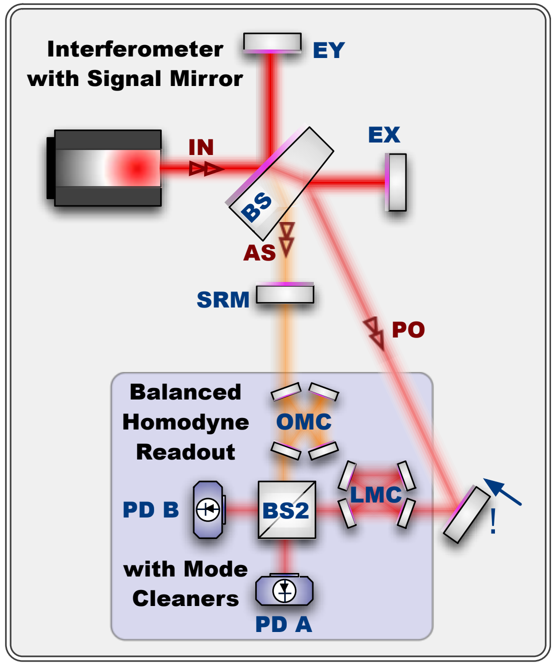
New optical components to reduce losses at high laser power

Balanced homodyne readout



[Evans et al., PRD 88, 022002; Isogai et al.]





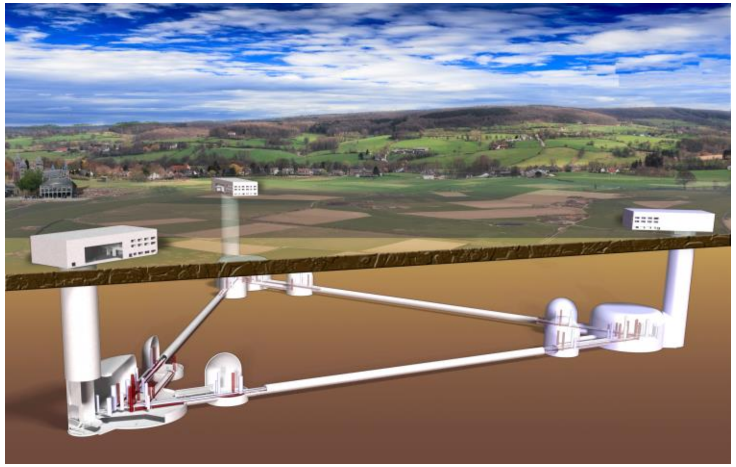
[Fritschel, Evans and Frolov, Optics Express 22, 4224]

Full realization of A+ improvements (~2026) will increase the rate of GW events by a factor of ~5 overall

LIGO-India will start up as an A+ detector

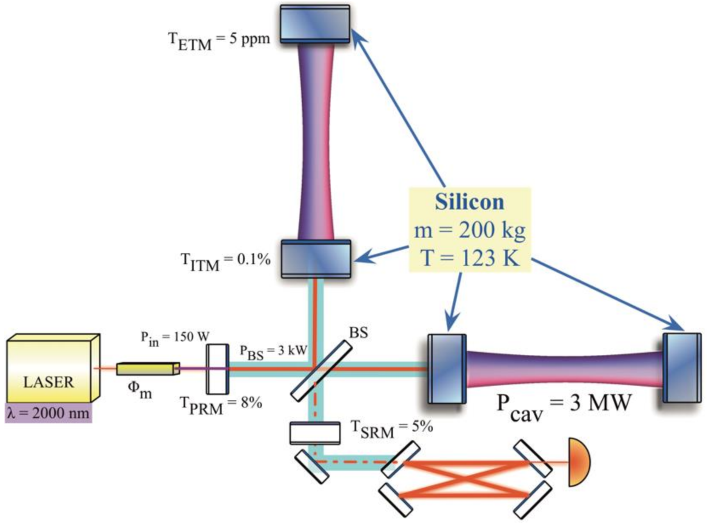
Longer-term: third-generation GW detectors

Being pursued as a globally coordinated effort under the auspices of a subcommittee of the Gravitational Wave International Committee, GWIC 3G (https://gwic.ligo.org/3Gsubcomm/)



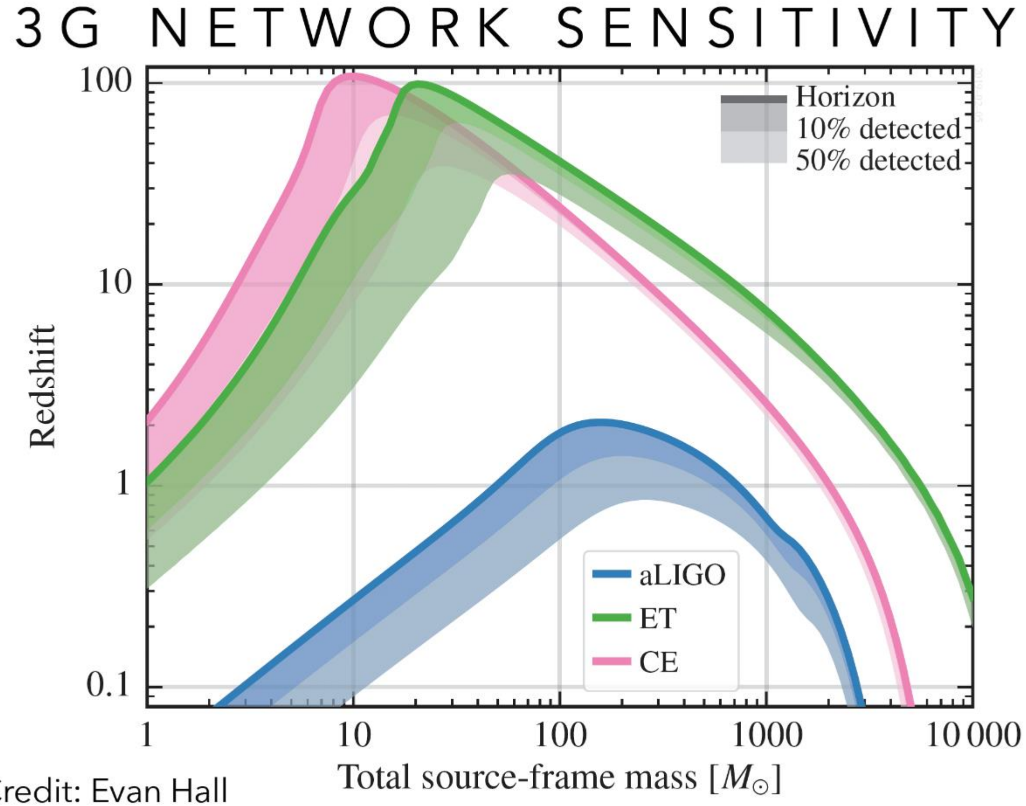
Einstein Telescope (European project)
https://www.et-gw.eu/

Underground 10 km triangular array of interferometers



Cosmic Explorer (U.S. project)
https://cosmicexplorer.org/

Surface detector with arms up to 40 km long, migrating to cryogenic silicon optics



Credit: Evan Hall

Could be operating in the 2030s

Degeneracies in GW170817 neutron star masses & spins

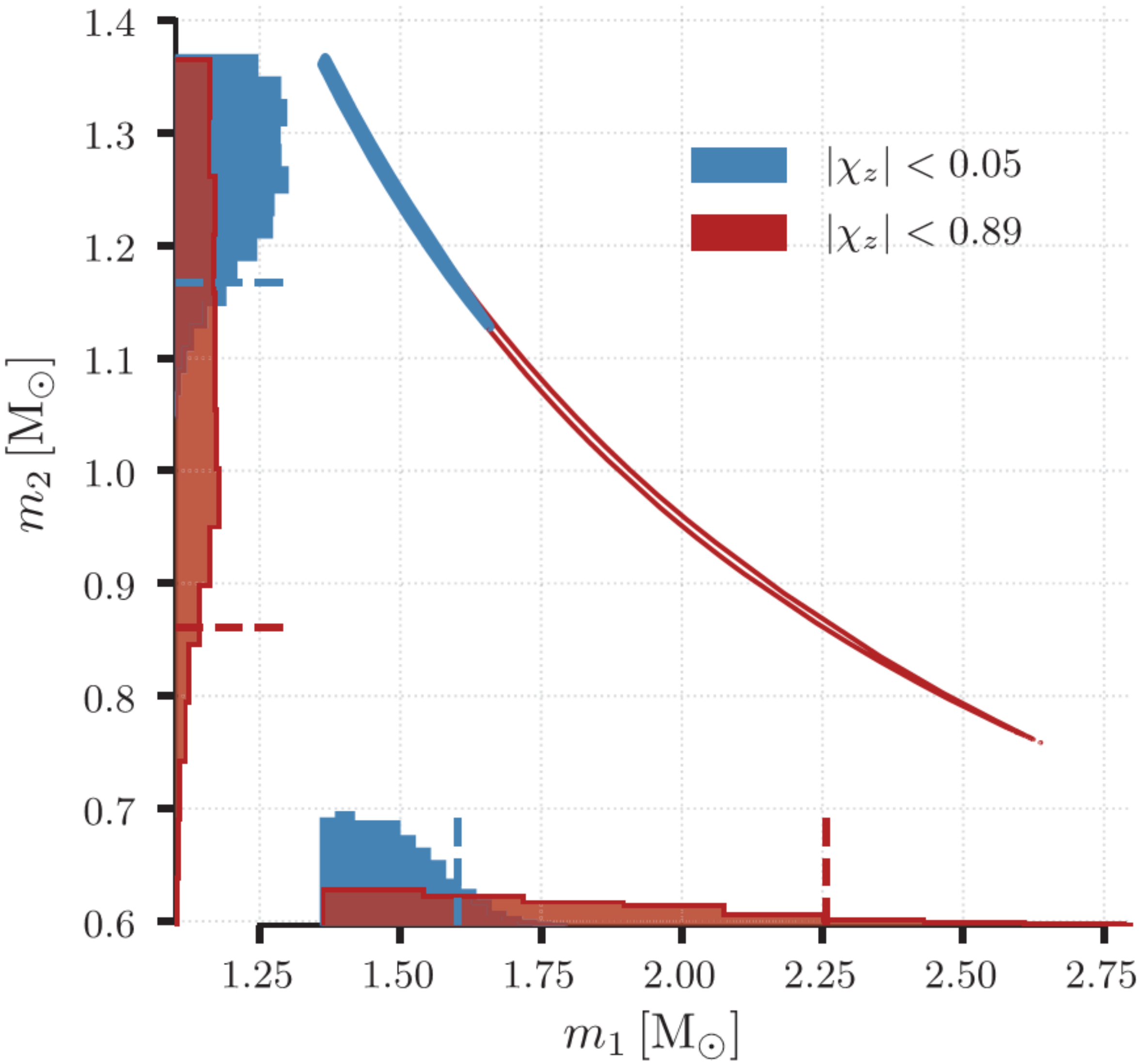
"Chirp mass" determined very precisely by the gravitational wave data:

$$M_{chirp} = 1.186 \pm 0.001\ \mathrm{M}_\odot$$

Component masses could be equal at $m_1 = m_2 = 1.36\ \mathrm{M}_\odot$, or could be unequal

Mass ratio and spins have similar influence on the waveform recorded by the GW detectors

Observations of EM emissions can break this degeneracy if reliable modeling can be done



[Abbott et al. 2017, PRL 119, 161101]

Binary merger astrophysics connections

Binary merger observables

GW signal properties:

- GW chirp mass
- GW amplitude
- GW polarization
- GW late inspiral phasing
- GW post-merger signal
- Reconstructed sky location

EM (and ν) observables:

Light curves: intensity and spectrum versus time

- Prompt emission (gamma-ray, X-ray, visible, radio?)
- Afterglow (X-ray, radio)
- Kilonova (UV, visible, IR)

- ➔ Precise sky location
- Neutrino (high-energy) in coincidence?

Astronomical context:

- Position inside or outside a galaxy
- Host galaxy redshift

Population statistics:

- Distribution of mass and spin parameters
- Population variation with distance

Source properties & astrophysics

Progenitor system parameters:

- True masses and spins
- Distance
- True sky location
- Orbit orientation
- Eccentricity of orbit

Neutron star astrophysics:

- NS equation of state: Determines size and deformability versus mass, and maximum mass

Merger outcomes:

- Jet / Outflow structure
- Circum-burst medium
- Post-merger system astrophysics: Mass ejection, fall-back accretion, nuclear physics

Cosmology:

- Cosmological expansion
- Galaxy population and structure; lensing

Binary system origin and evolution:

- Compact object formation channels
- Initial binary orbit (if initially a binary)
- Multi-body interactions during life

Fundamental physics:

- True theory of gravity
- Fundamental particles and fields

Summary

The binary merger GW170817 was a truly exceptional event

Upgrades to the GW detector network will enable catching more neutron star mergers — but the GRB and optical counterparts will generally be much fainter

A gamma-ray mission covering the MeV band can provide the sensitivity and directionality needed to detect and localize a larger set of short GRB counterparts, providing direct information and aiding further follow-up observations

Complementary energy, spectrum and timing information will help disentangle the astrophysical properties of individual events, and thereby improve understanding of the source population, cosmology and tests of fundamental physics

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard Space Flight Center) and T. Nielsen (Univ. of Hawaii)