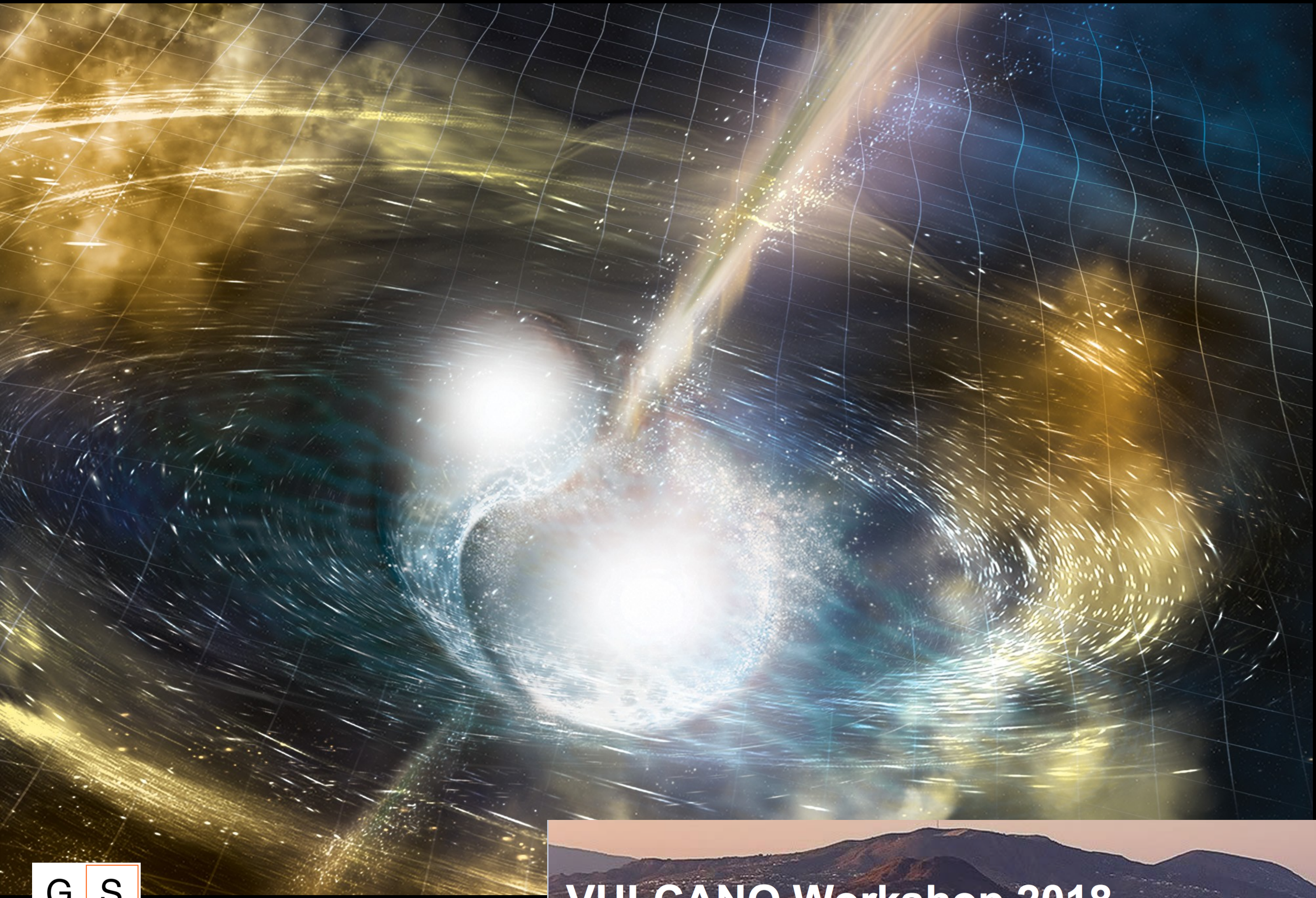
Multimessenger Astrophysics: the new era of GWs



M. Branchesi
GSSI/INFN LNGS

Challenges and successes of multi-messenger searches including GWs

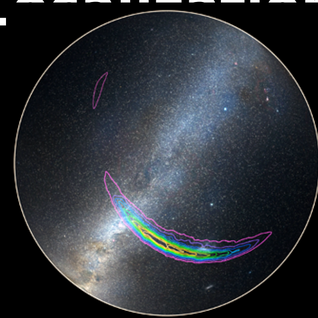
O1 and O2 low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alerts

LSC VIRGO

GW candidates **Sky Localization** **EM facilities**

LIGO-H LIGO-L

Virgo

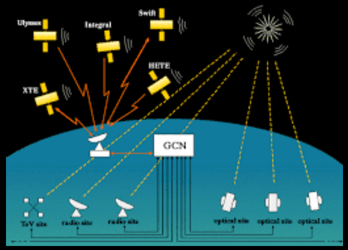


Event validation

Low-latency search
to identify the GW-candidates

Software to

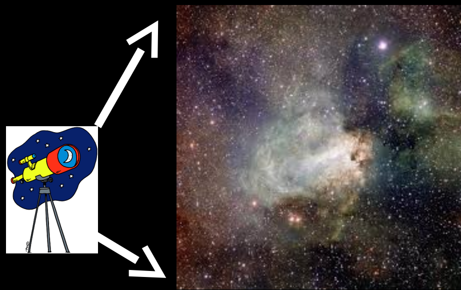
- select statistically significant triggers wrt background
- check detector sanity and data quality
- determine source localization



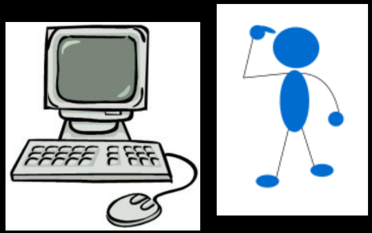
→ **a few min** → **30 min**

Parameter estimation codes → **Hours,days** → **GW candidate updates**

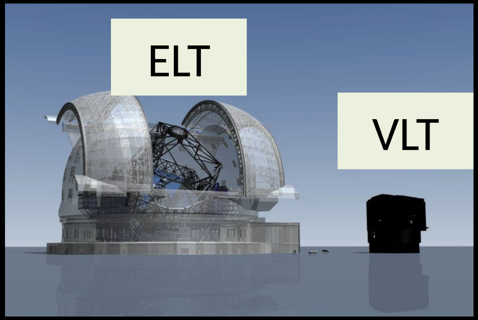
Hunt the elusive EM-counterpart!



Wide-field telescope
FOV >1 sq.degree



“Fast” and “smart” software to select a sample of candidate counterparts



Larger telescope to **characterize** the candidate nature

The EM Counterpart!

to cover hundreds/thousands of square degrees

to remove transients contaminants

To obtain observational time for the characterization

GCN Alerts contents to support observing startegy

Event **time** and **probability sky localizatiom map**

highly significant FAR = 1/100 yr

significant

low significance FAR = 1/yr

FAR = 1/month

FAR = Rate of noise events louder than the candidate event

Candidates to be observed selected based on the observer's choice of FAR threshold

Sky map + basic source classification

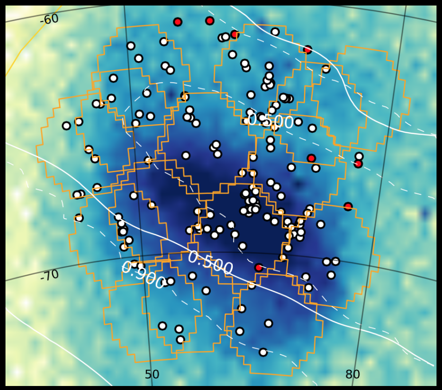
Credit: G. Greco, https://github.com/ggreco77/GWsky

To decide the search type

DES, Annis et al. 2016, ApJL

Burst ⟹ failed-SNe

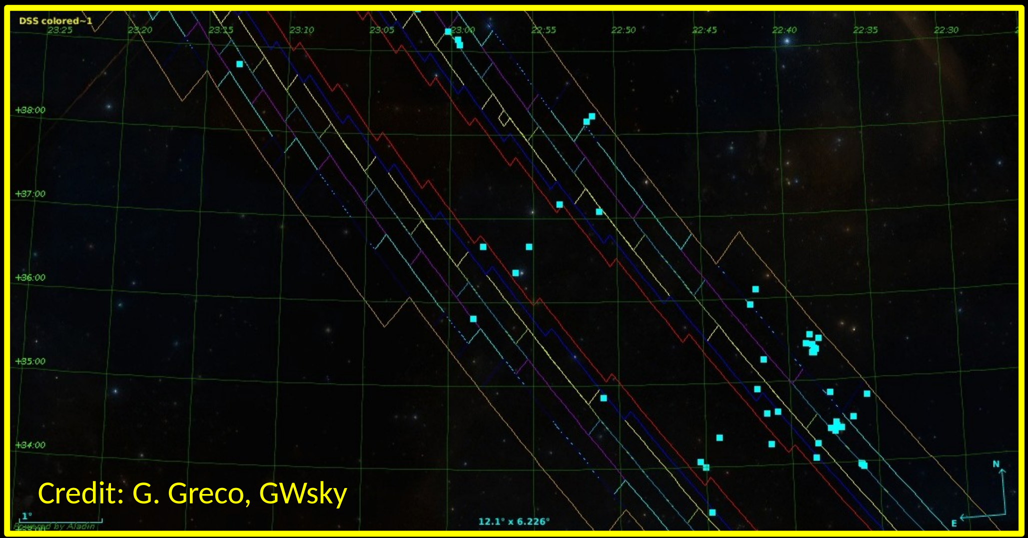
Search for missing supergiants in the LMC



Sky map + source classification + **distance (for binary systems)**

3D sky maps with direction-dependent distance

(Singer et al. 2016, ApJL 829, L15)



Targeting ranked galaxies

(Small FoV instruments)

"EM bright" indicators:

Probability of **presence of a NS** in the binary (object m<2.8 solar mass)

Probability of **presence of any NS tidally disrupted mass left outside the BH**

(Foucart 2012, PhRvD, Pannarale & Ohme, 2014, ApJ*)*

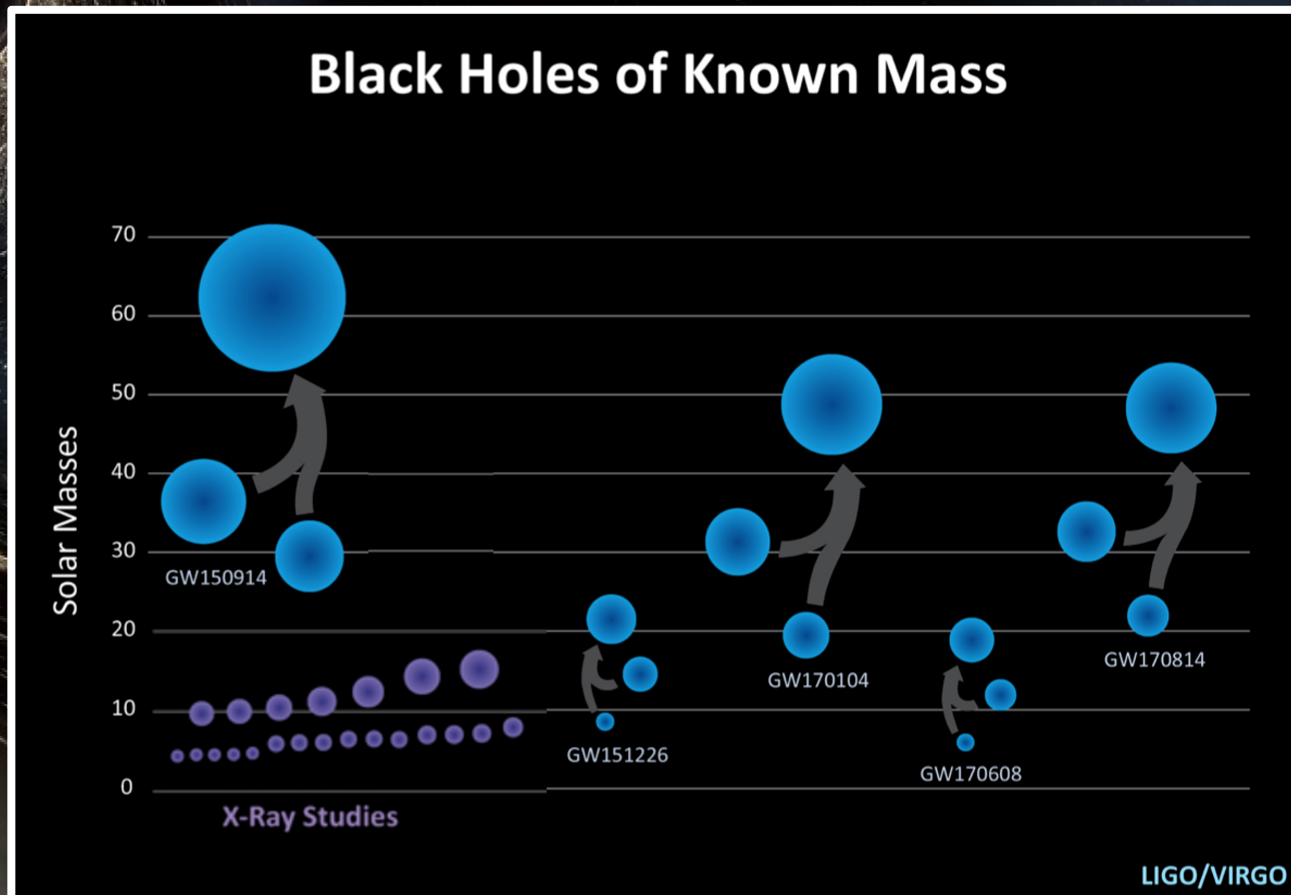
2015 September 14: GW150914

2015 December 26: GW151226

2017 January 04: GW170104

2017 June 06:GW170608

2017 August 14: GW170814



Credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

EM signal, host galaxy?

	GW150409	GW151226	LVT151012	GW170104	GW170608
D_L/Mpc	420[+150-180]	440[+180-190]	1000[+500-500]	880[+450-390]	340[+140-140]
Sky loc/deg²	230 (HL)	850 (HL)	1600 (HL)	1200 (HL)	860 (HL)

Abbott et al. 2016,PhysRevX,6; Abbott et al.2017,PhysRevL,118; Abbott et al. ApJL, 2017, 851

Sky localizations

90% credible areas of about

1200 deg² GW170104

230 deg² GW150914

1600 deg² LVT15012

850 deg² GW151226

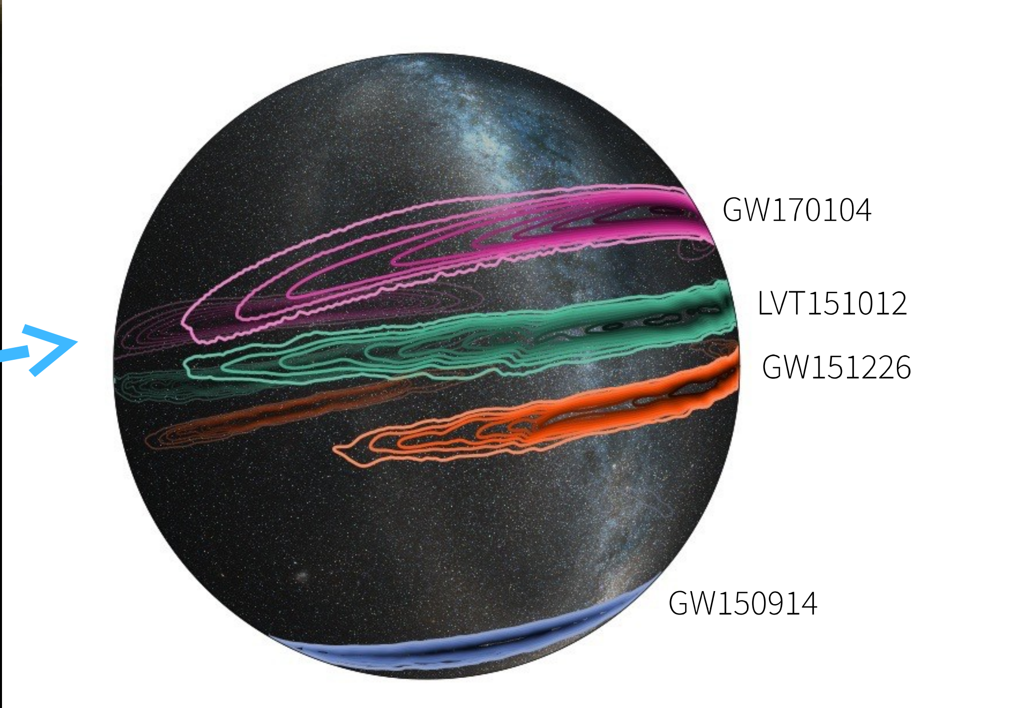
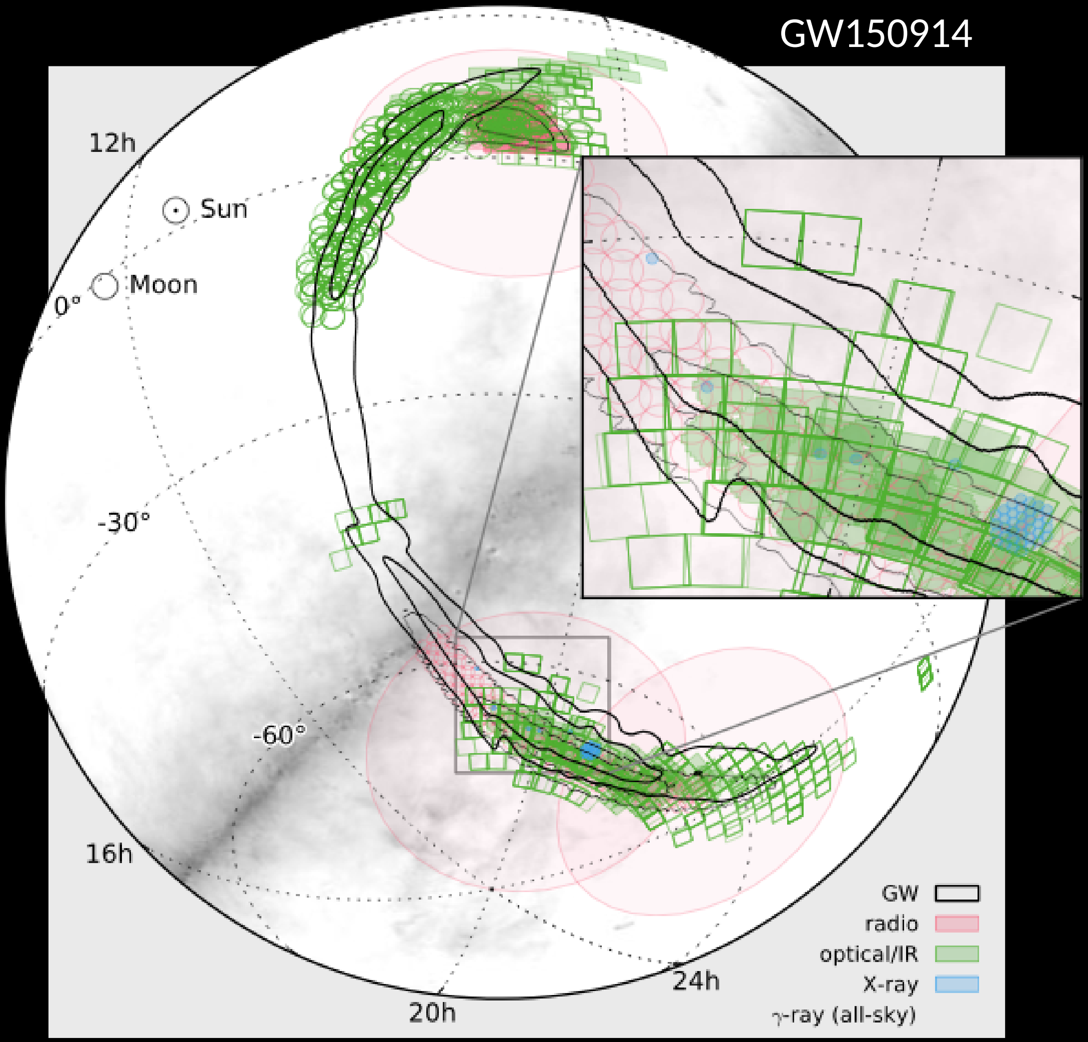


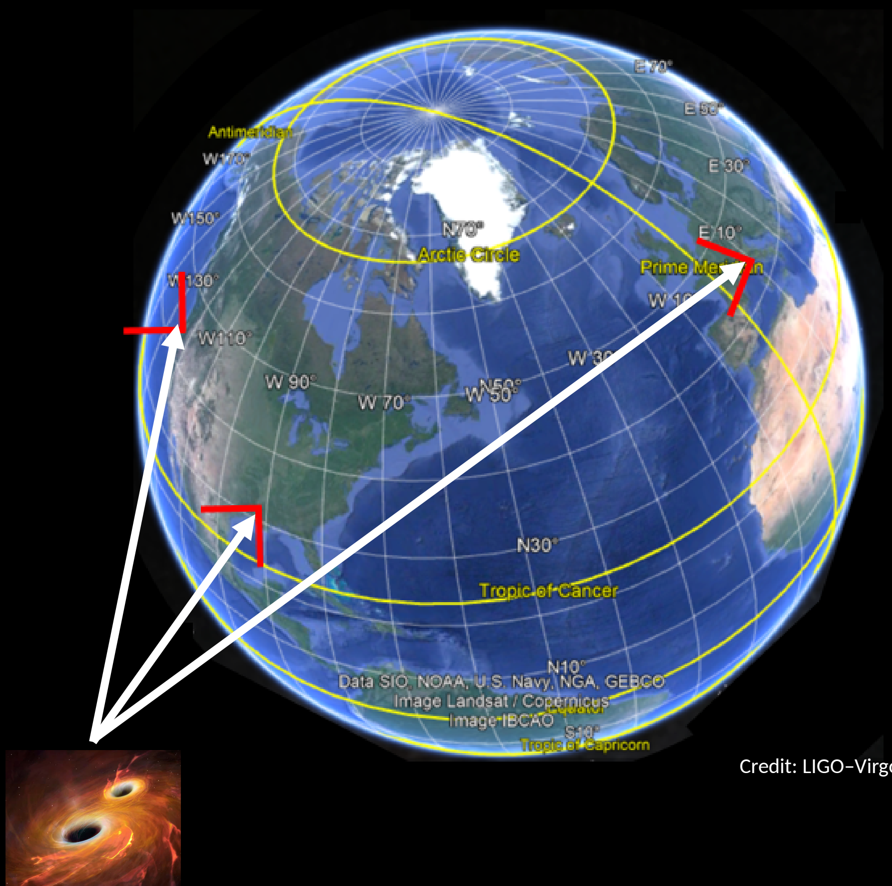
Image credit: LIGO/L. Singer/A. Mellinger

Counterpart search



Abbott et al. 2016, ApJL, 826, 13
Abbott et al. 2016, ApJS, 225, 8

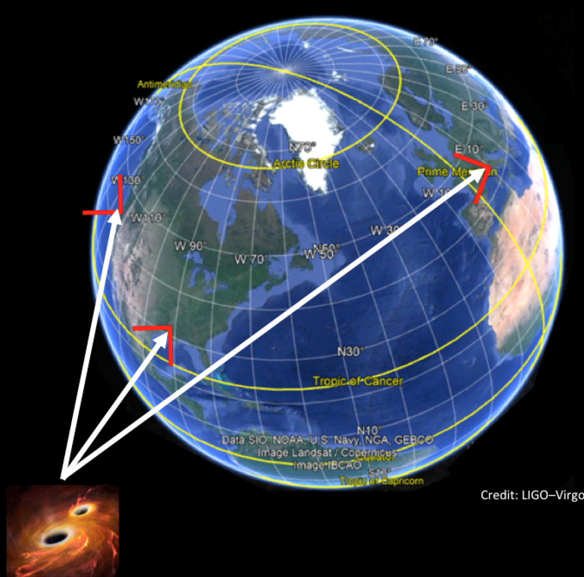
2017 August 14, 10:30:43 UT



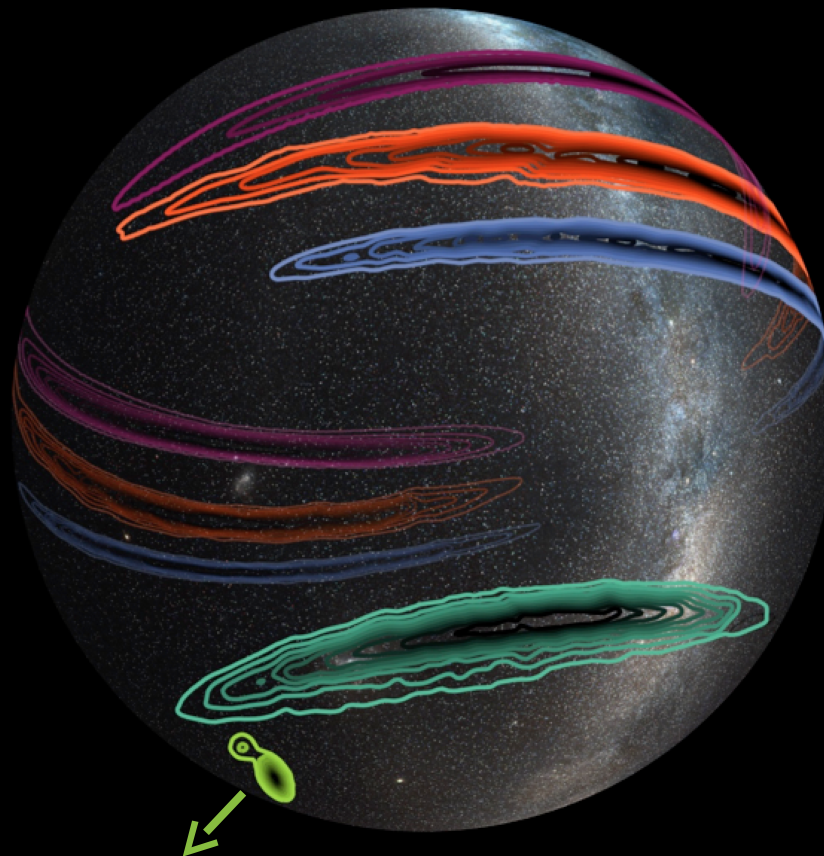
Credit: LIGO–Virgo

Virgo observed its first
BBH coalescence
,GW170814

2017 August 14



Credit: LIGO–Virgo

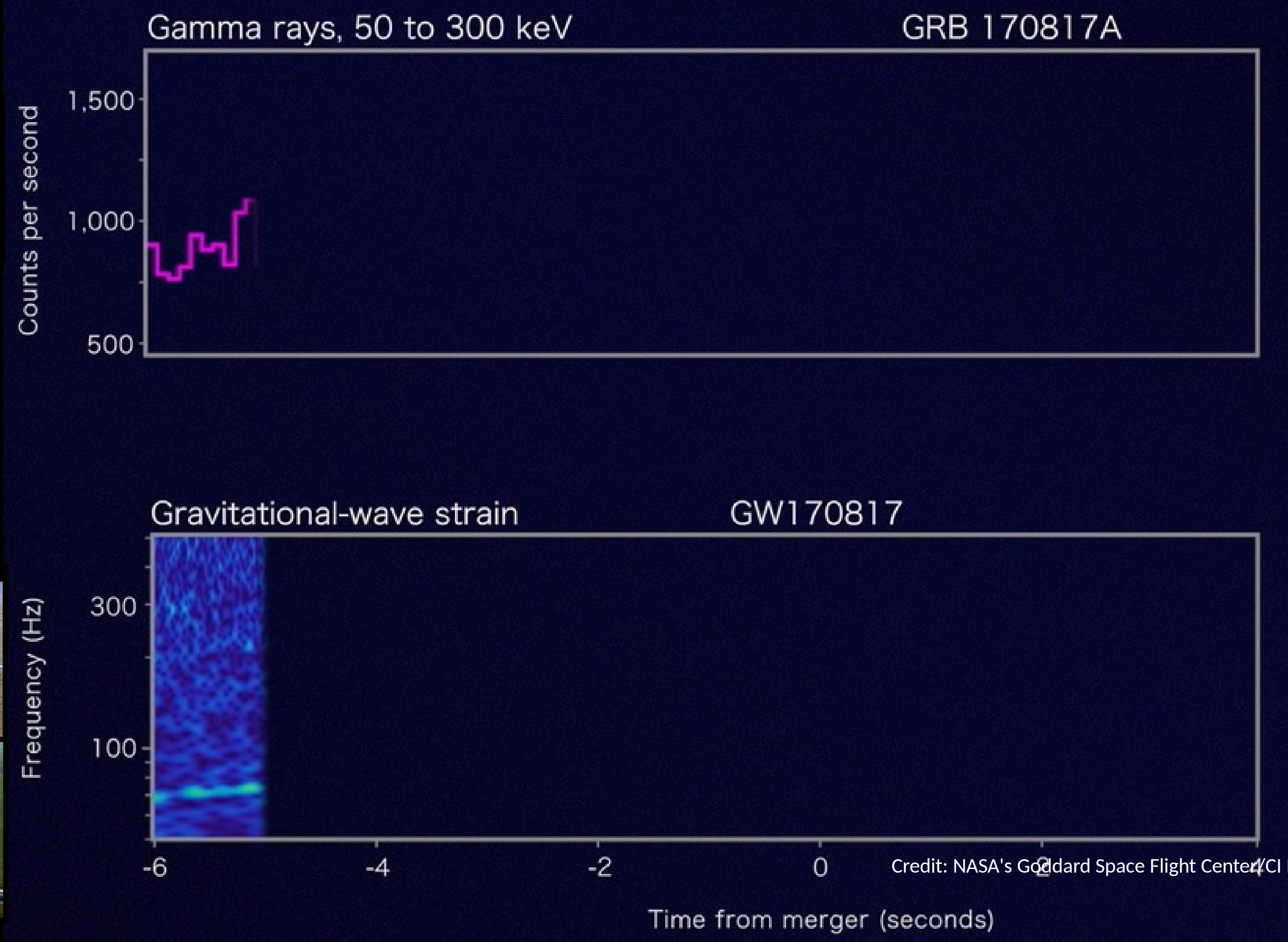


GW17081
4

Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

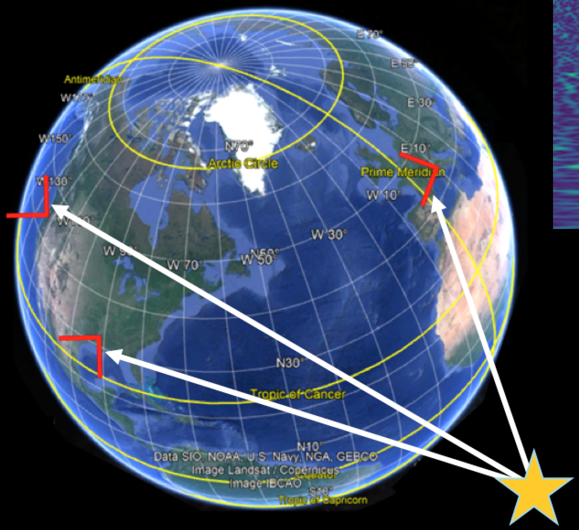
2017 August 2017, 12:41:04 UT

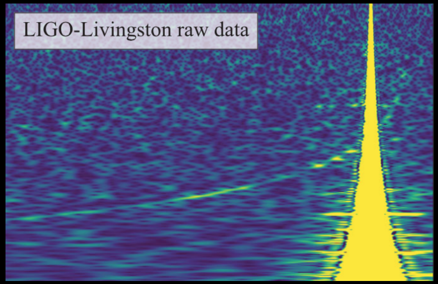
Credit: University of Warwick/Mark Garlick



Credit: NASA's Goddard Space Flight Center/CI Lab

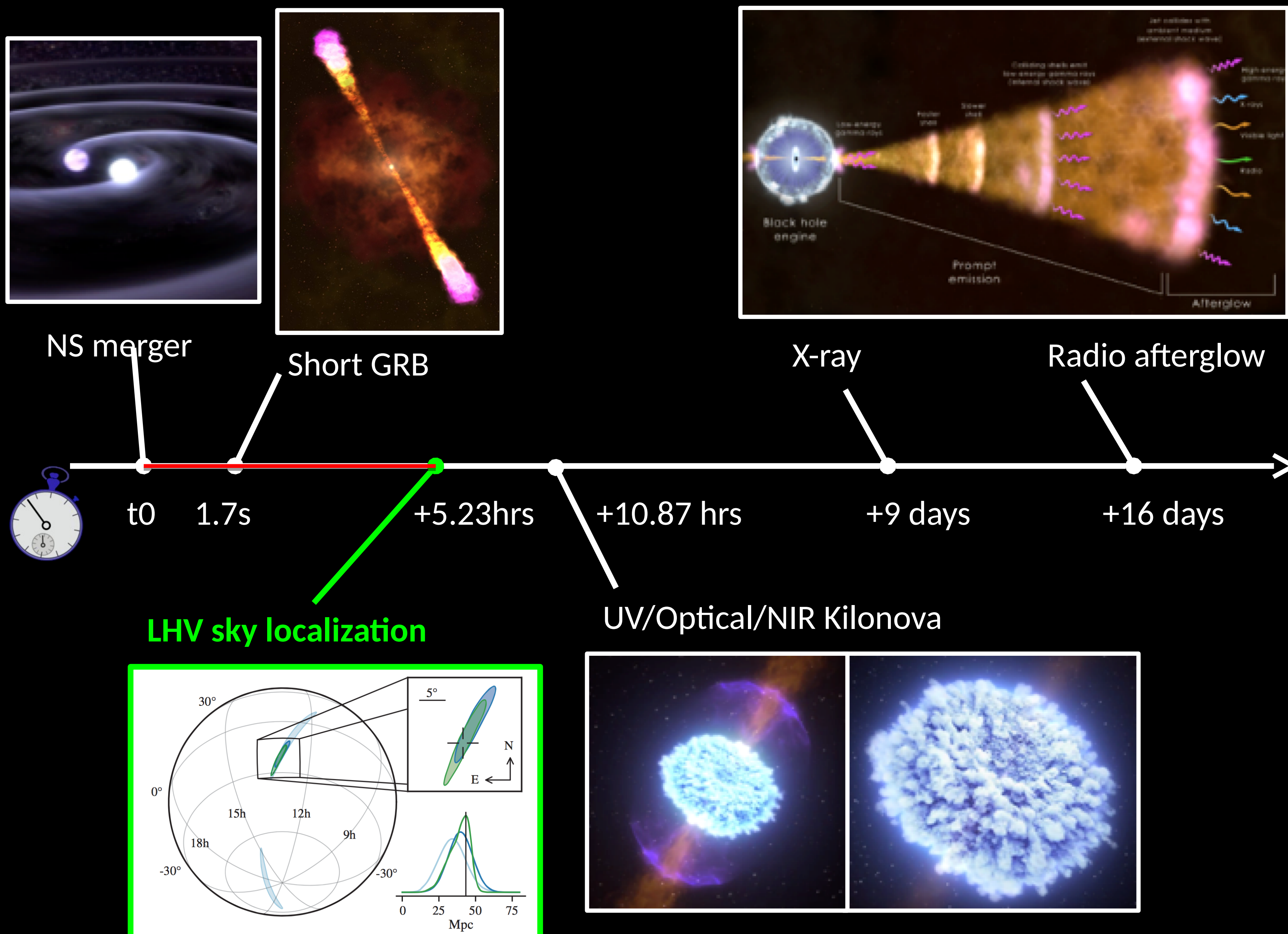
17 August 2017, 12:41:04 UT





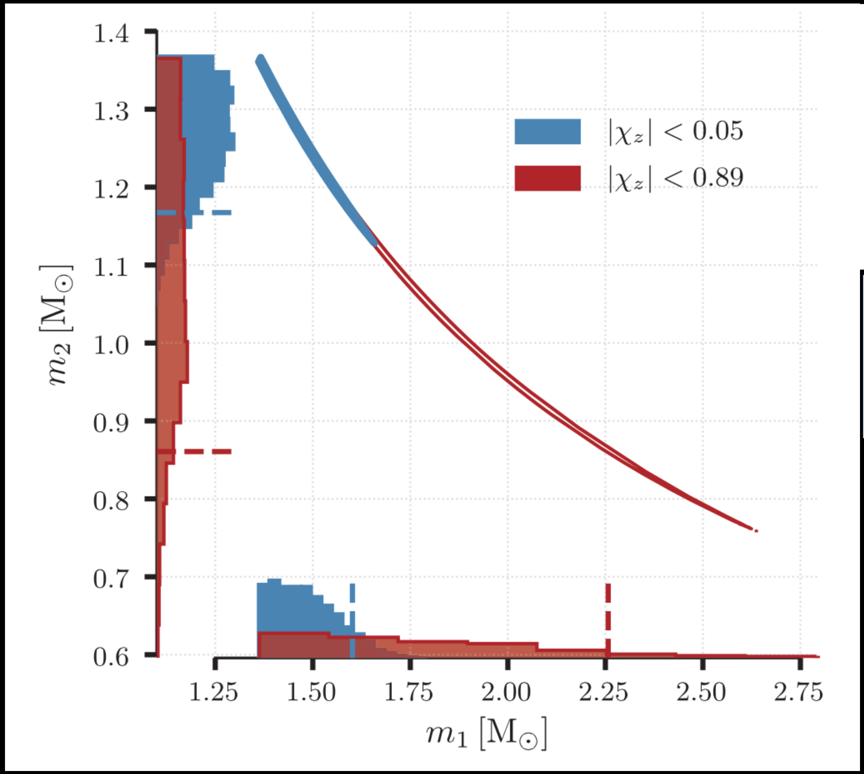
17:54:51

Credit: LIGO/Virgo/NASA/Leo Singer



LVC + astronomers, ApJL, 848, L12

GW170817: PARAMETERS OF THE SOURCE



Mass range **0.86 – 2.26 Mo**

1.17 – 1.60 Mo low spin

Mass ratio **m1/m2 = 0.4 -1**

m1/m2 = 0.7- 1 Mo low spin

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

GW luminosity distance **40 (+8-18)** Mpc

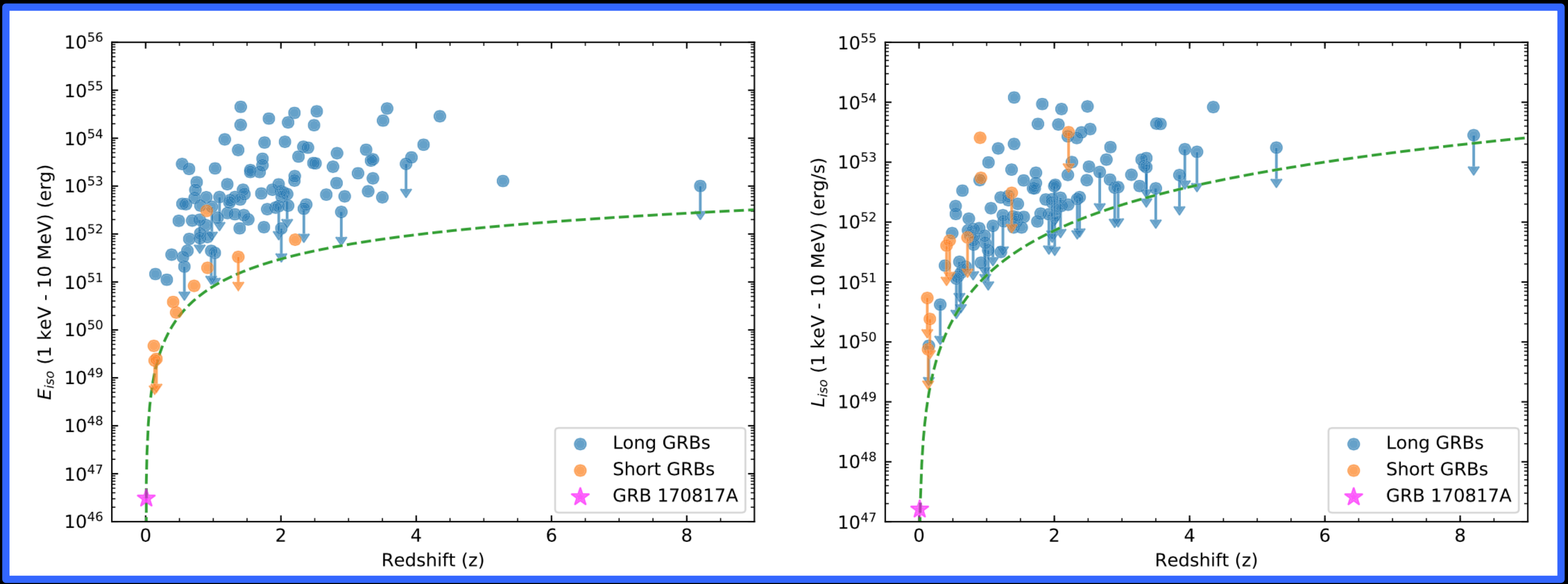
Viewing angle Θ < 55°

NGC4993 redshift (Ho=67.9) ⊟ Θ < 28°

Abbott et al. 2017, Physical Review Letters, 119, 161101

GRB 170817A

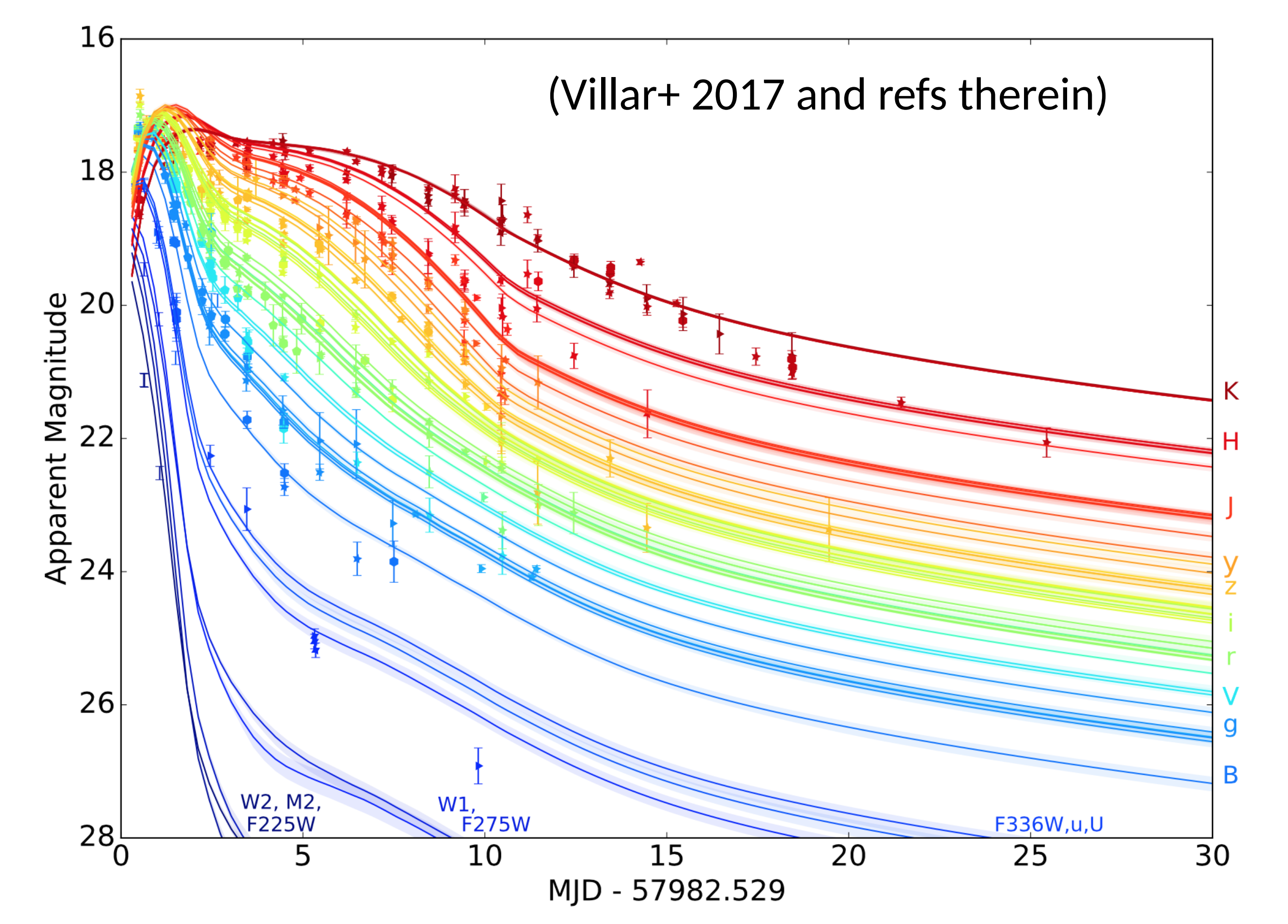
- 100 times closer than typical GRBs observed by Fermi-GBM
- it is also "subluminous" compared to the population of long/short GRBs
- 10^2 – 10^6 less energetic than other short GRBs



Abbott et al. 2017, APJL, 848, L13

Intrinsecally sub-luminous event
or a classical short GRBs viewed off-axis?

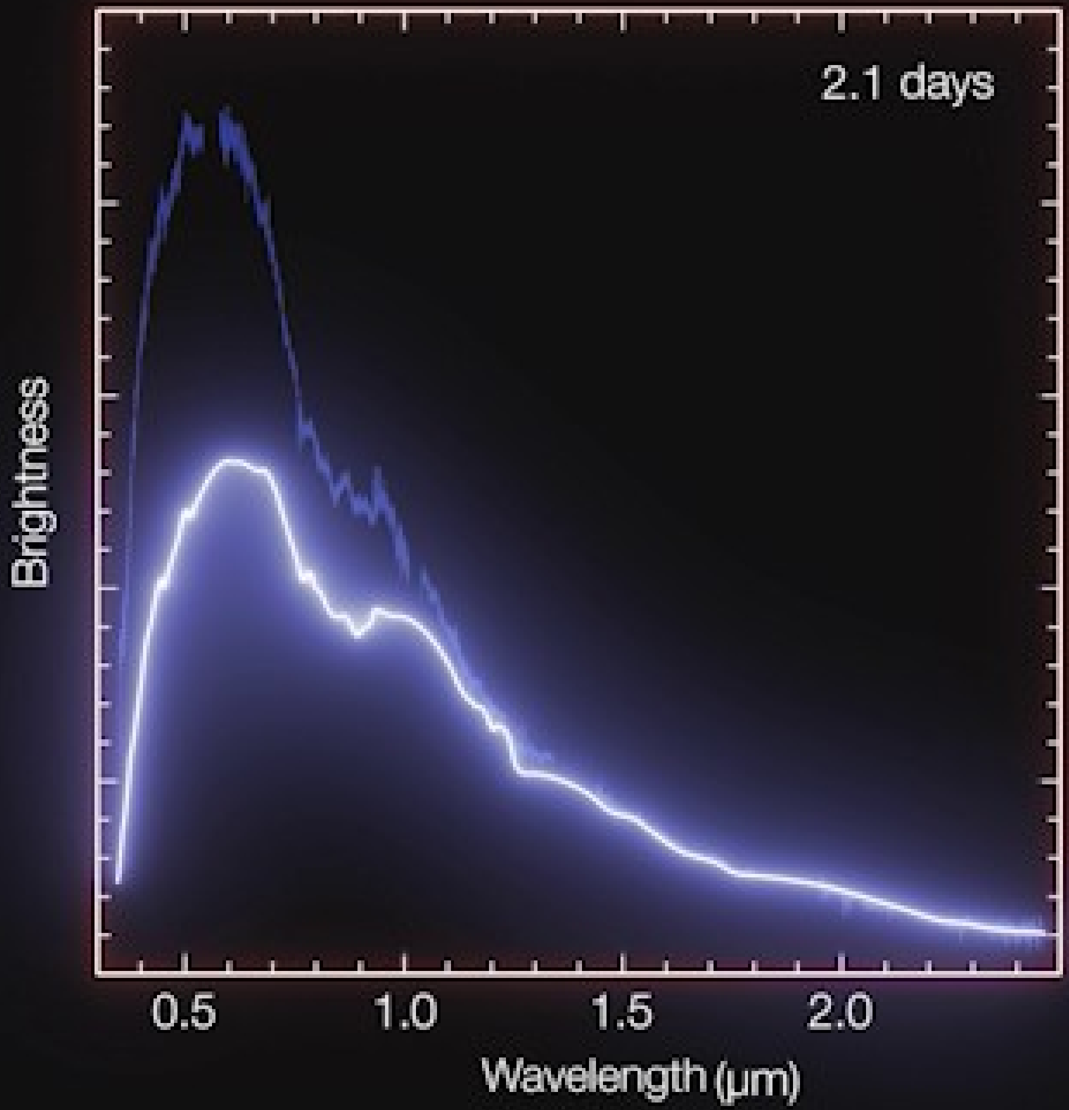
UV/Optical/NIR Light Curves



Extremely well characterized photometry of a Kilonova:

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

ESO-VLT/X-Shooter

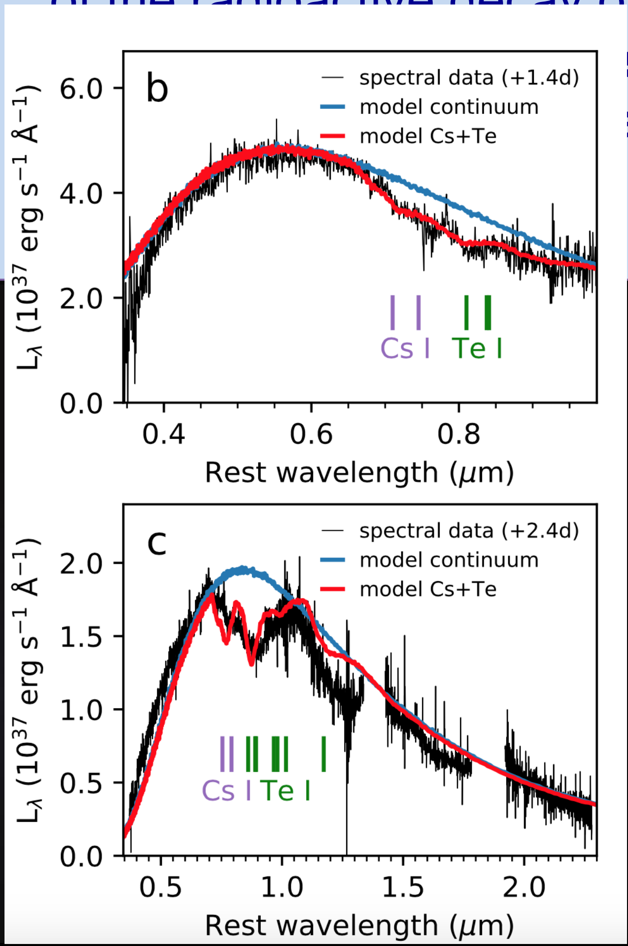


Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

First spectral identification of the kilonova emission

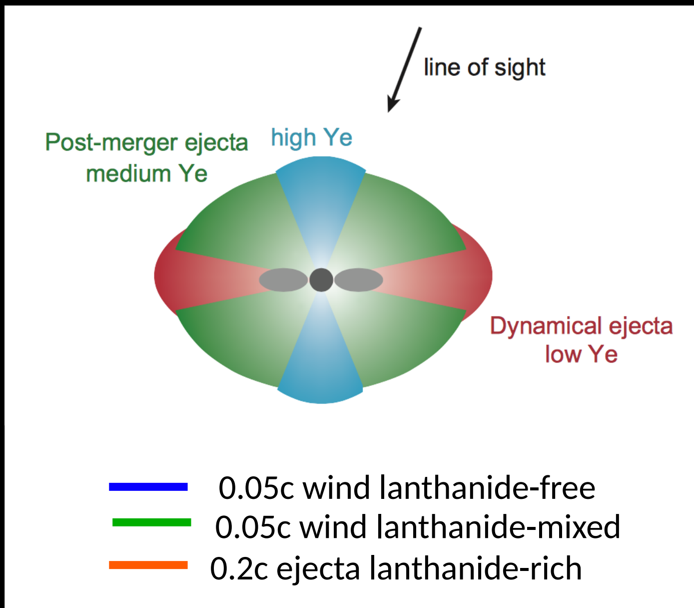
Possible signatures of Cesium and Tellurium

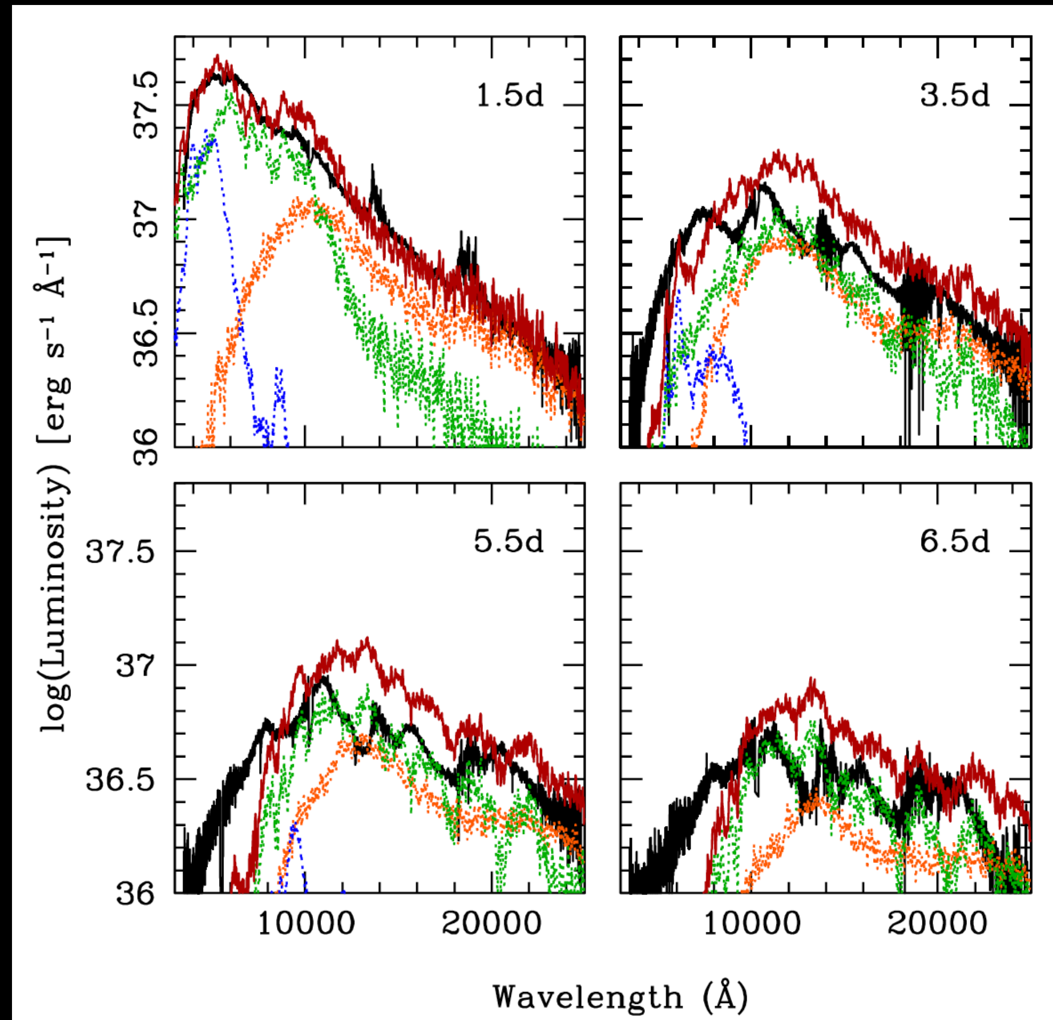
- the data revealed signatures of the radioactive decay of
- sis
- avy
- the



Smartt et al. 2017, Nature

Multi-component kilonova emission (Pian et al. 2017, Nature,551, 57)





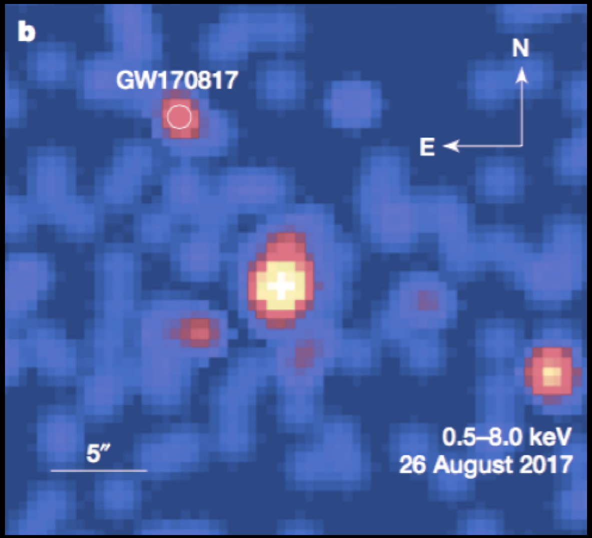
Best fit requires three components

ejected mass ~ 0.03 – 0.05 $M_\odot$

At present models are not able to reproduce consistently all the observed spectral features

X-ray and radio emissions

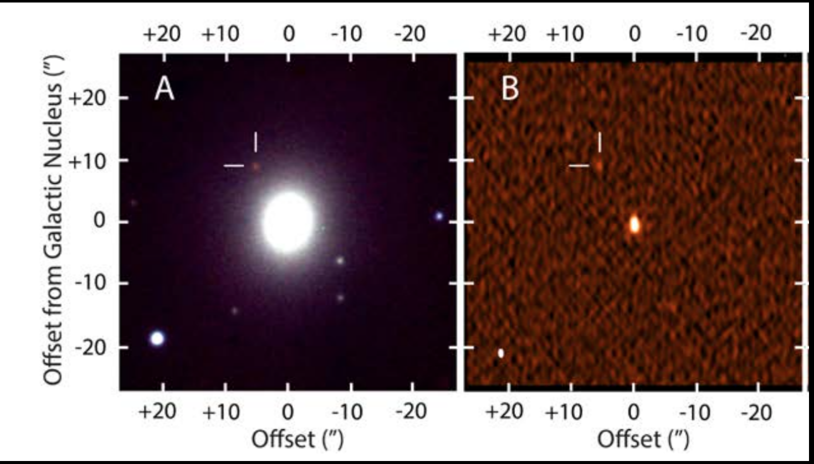
Chandra observation



Troja, et al. Nature 2017

"..Our observations are instead consistent with the onset of an off axis afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections."

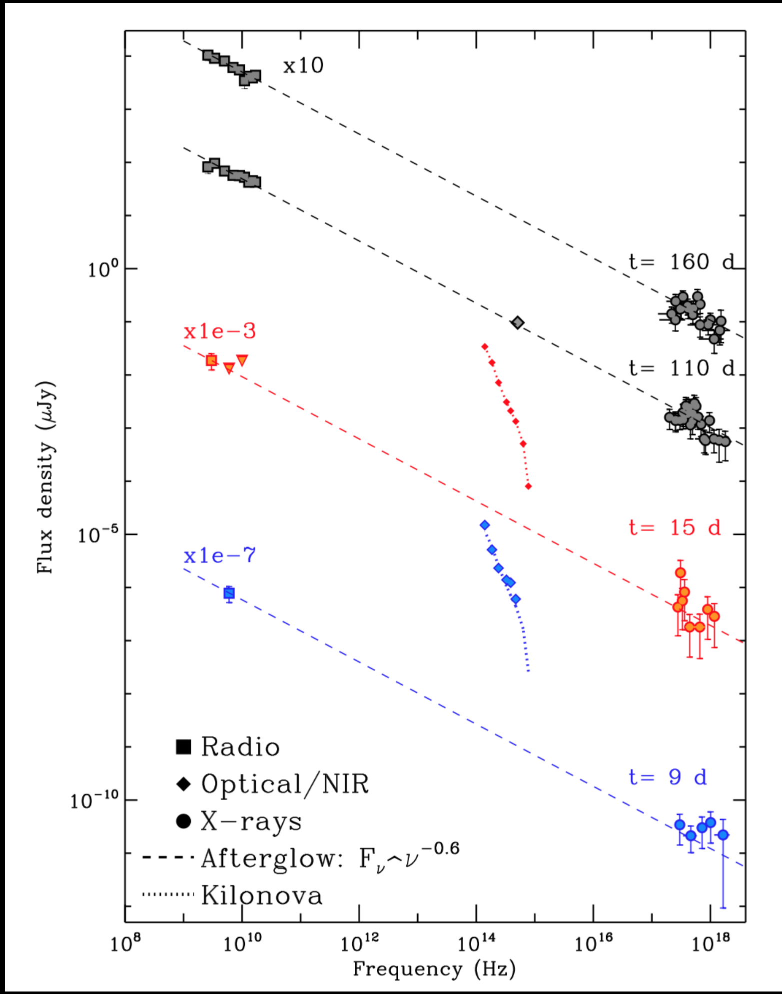
VLA observation



Hallinan et al. Science, 2017

First GRB observed off-axis?

After 100 days from the BNS merger…

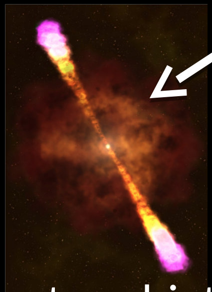


Margutti et al. 2018, ApJL

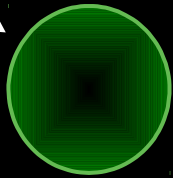
Power-law spectrum extending for eight orders of magnitude in frequency

Non-thermal synchrotron emission radiation from **mildly relativistic ejecta with Γ ~ 3 – 10**

What is the nature of the mildly relativistic ejecta?

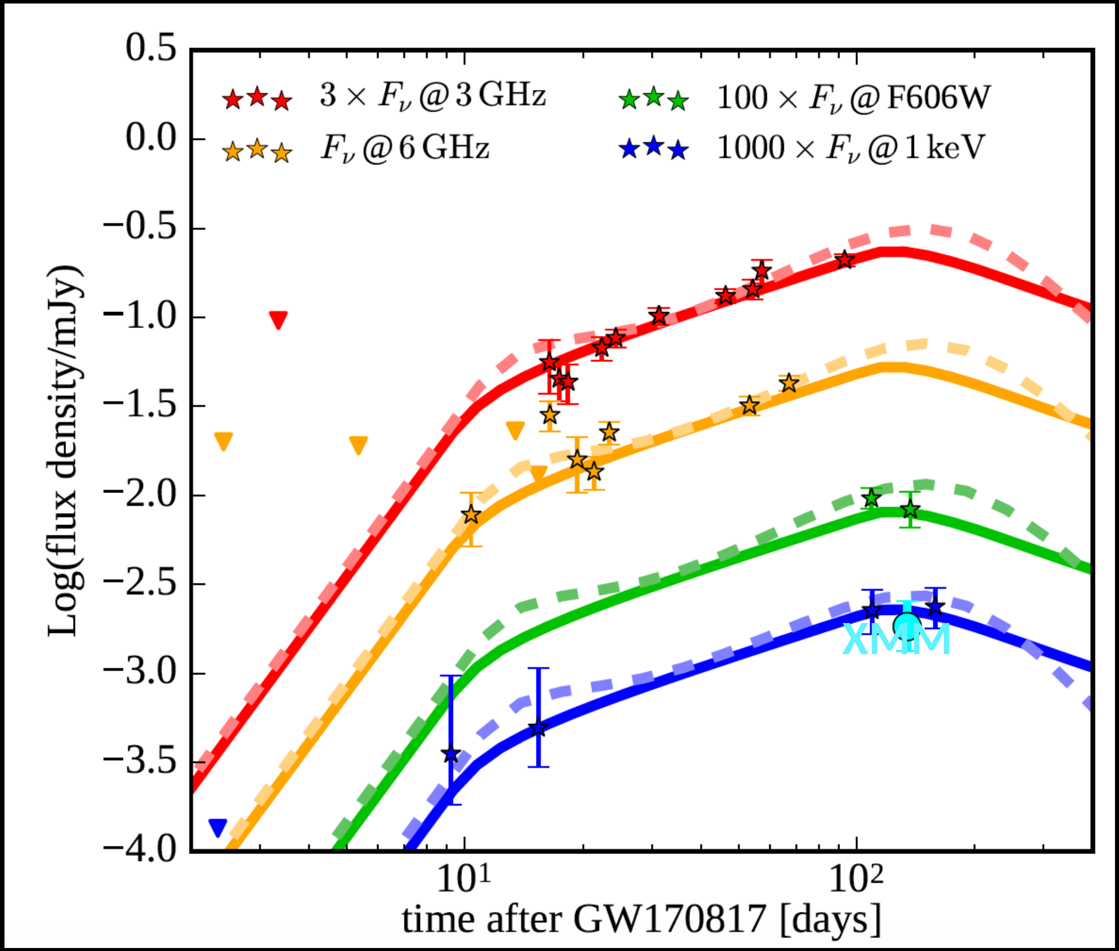


Structured-jet viewed off-axis
(e.g Margutti et al. 2018, D'Avanzo et al. 2018)

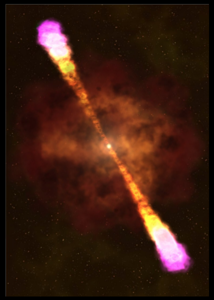


Isotropic fireball: choked jet or jet-less
(e.g. Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017)

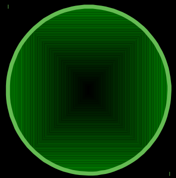
Flattening of light curves….



Dashed lines



Solid lines

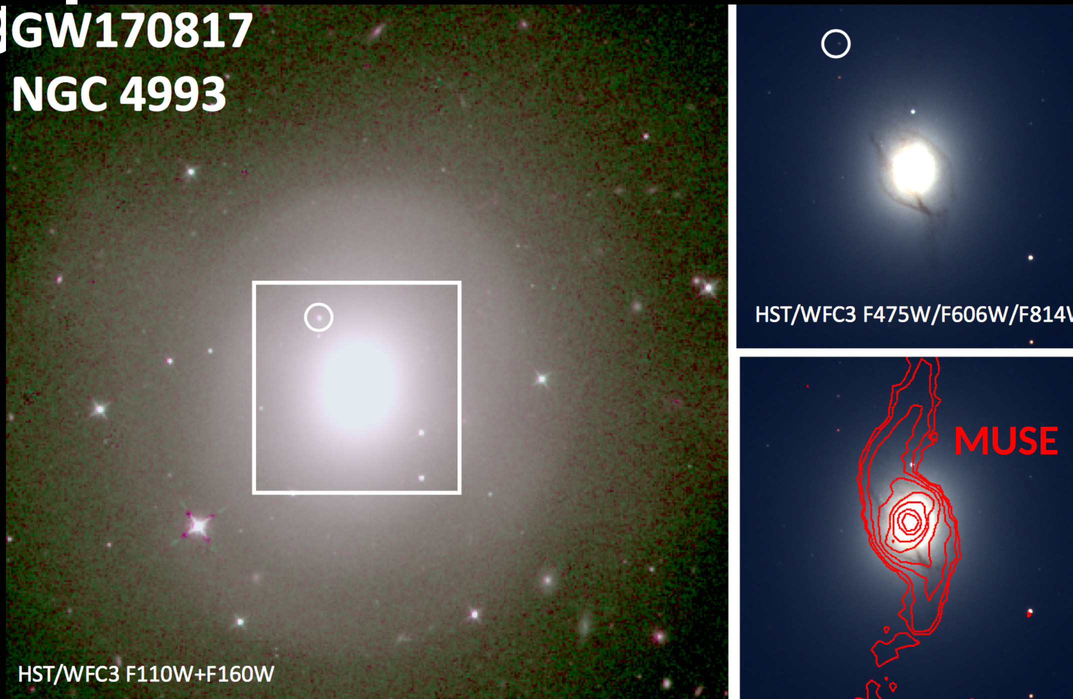


D'Avanzo et al. 2017, A&A accepted

See Troja's talk!

Polarimetry?
Rate GW/GRB 170817-like association?

NGC4993 Host g



Levan et al. 2017, ApJL, 848

log(M*/Msol) ~10.65
Median age ~ 11.2 Gyr
SFR ~ 0.01 Msol yr^{-1}

Blanchard et al. 2017

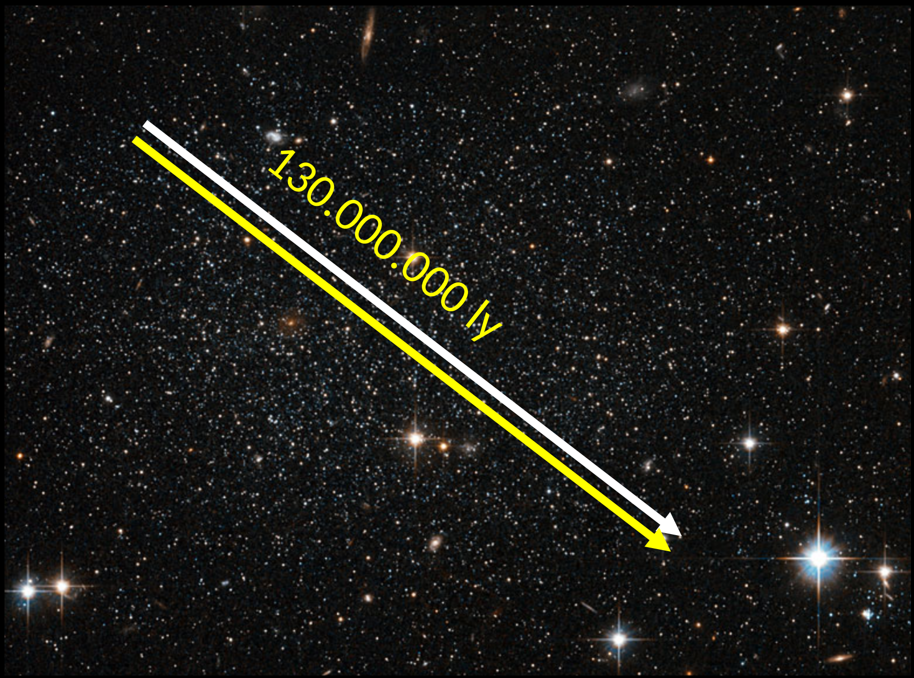
S0 galaxy at z = 0.009783

- Face-on spiral shells and edge-on spiral features → **recent (< 1 Gyr) galaxy merger**
- HST imaging → **no globular or young stellar clusters**
- **Old population** in the vicinity of GW source
- Age and offset from the galaxy center → **small natal kick velocity**

(Levan et al. 2017; Pan et al. 2017; Kasliwal et al. 2017; Im et al. 2017)

Multimessenger science

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



1.7 s delay and 40 Mpc distance
→ difference speed of gravity
and speed of light between
-3×10^{-15} and $+7 \times 10^{-16}$

GWs propagate at the speed of light!

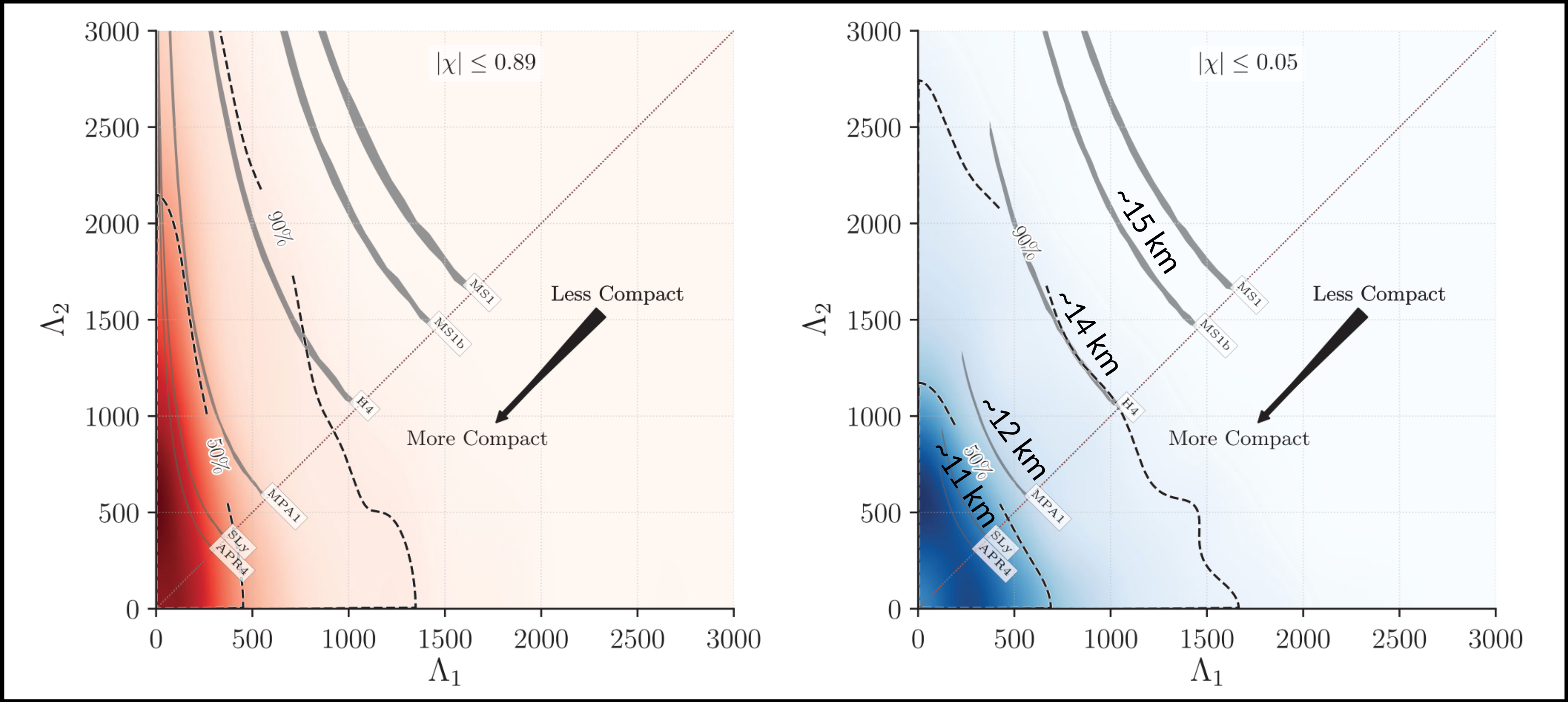
LVC 2017, APJL, 848, L13

Consequences of multi-messenger detection of GW170817 for cosmology

Constraint on the speed of GWs ruled out many classes of modified gravity models

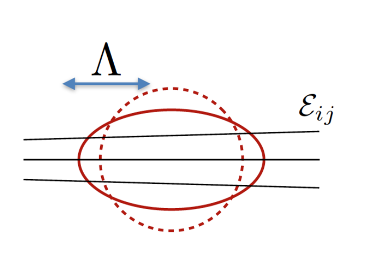
(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. ’17, Creminelli & Vernizzi ’17)

NS LABORATORY FOR STUDYING SUPER-DENSE MATTER



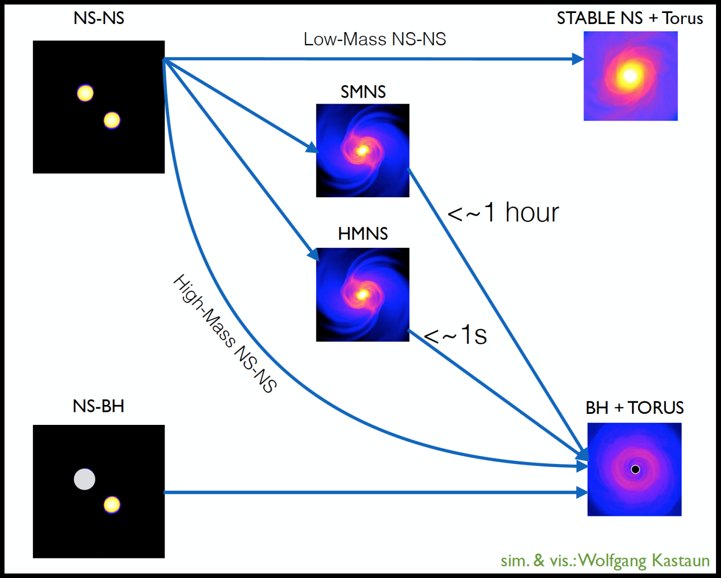
TIDAL DEFORMABILITY

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



- ⇒ Ejected, disk mass ⇒ EM emission

Post merger remnant?



GW search:

- **ringdown of BH** around 6 kHz

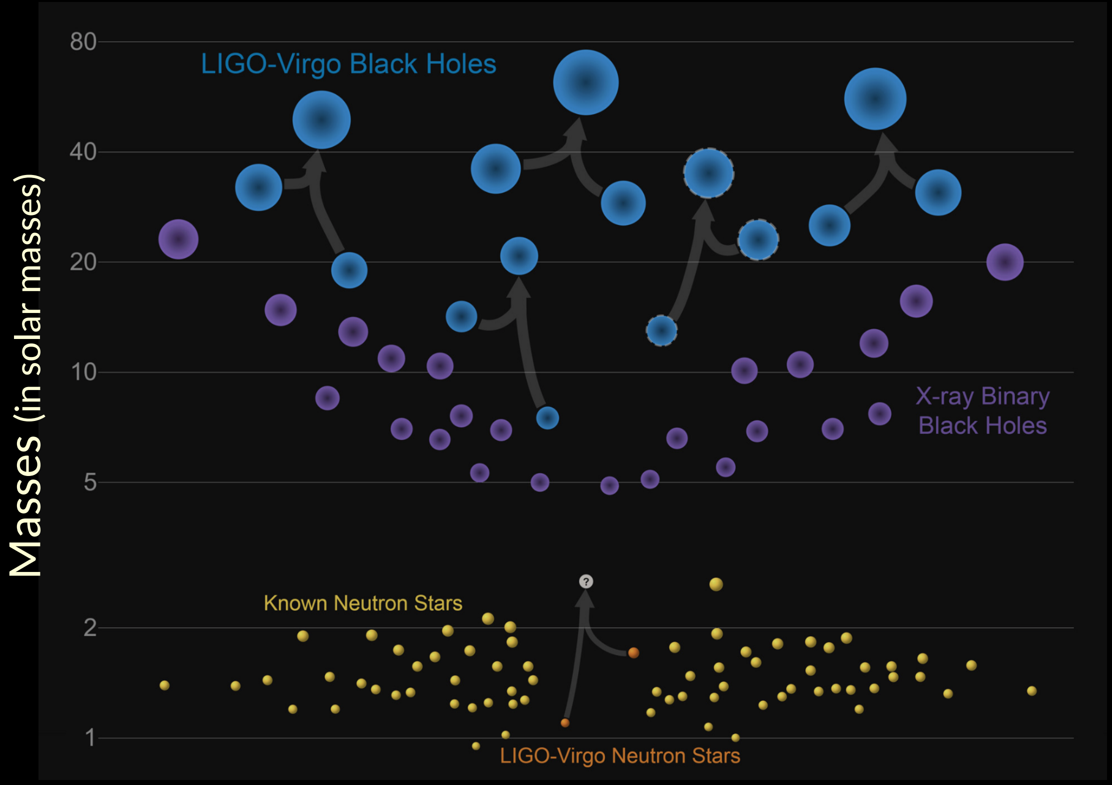
  ▭ LIGO/Virgo response strongly reduced

- **short (tens of ms) and intermediate duration (≤ 500 s) GW signals** up to 4 kHz

  ▭ no evidence of postmerger signals, but it cannot rule out short- or long-lived NS

Haviest NS

or lightest BH known?

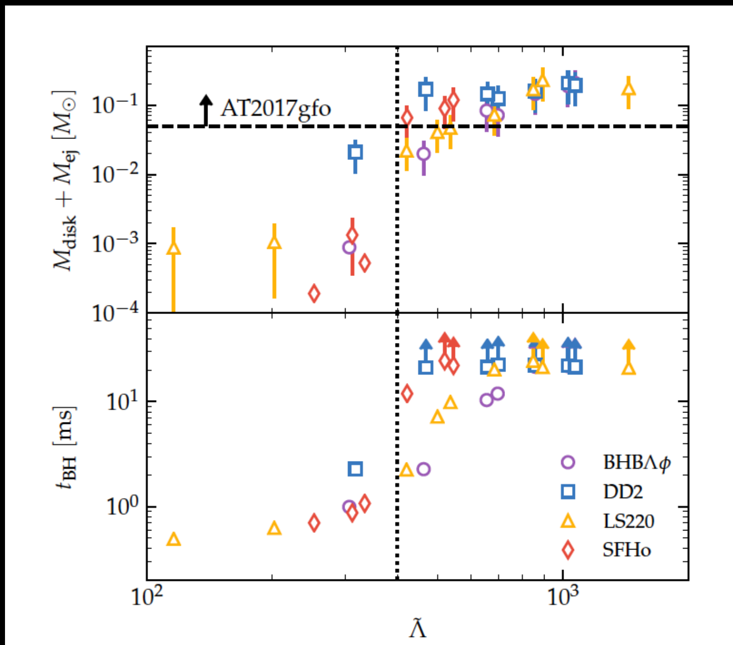


Remnant

▭ EM emission

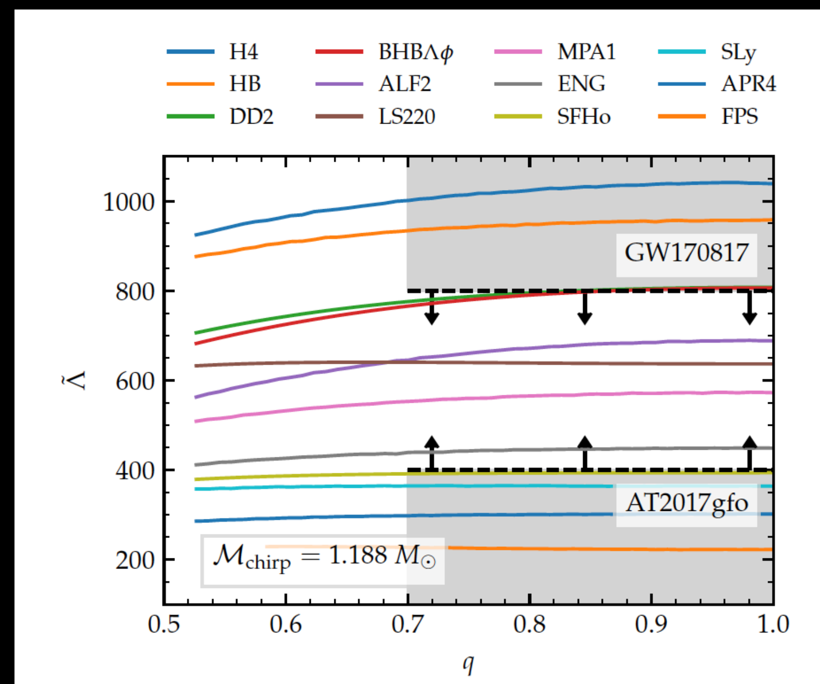
Multimessenger constraints on nuclear EOS

Simulations in NR



EM observations ⟹ Mej,tot > 0.05Mo
suggests a lower limit Λ > 400

EM observations
exclude
very soft EOS!



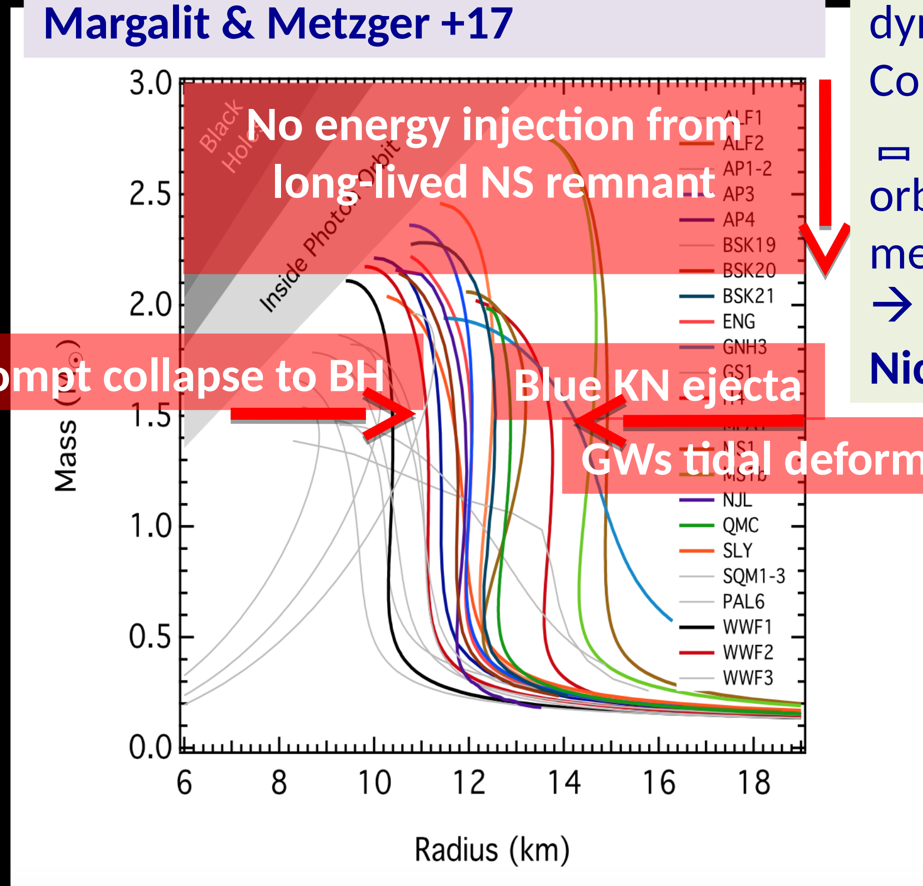
Radice, Perego, Zappa 2017

EM constraints on the type of remnant and multi-messenger constraints on radii and maximum mass of NSs

High ejecta mass
0.03 - 0.05 $M_\odot$
⇒ delayed/no collapse
GW Mtot < $M_{threshold}$
Bauswein+17

No extended high-energy emission, moderate kinetic energy for kilonova and off-axis jet, GW mass of the binary
Margalit & Metzger +17

Blue component ejecta 0.2-0.3 c
→ shock-heated dynamical ejecta
Compact NS
⇒ closer binary, higher orbital velocity at merger
→ stronger shock
Nicholl+ 17



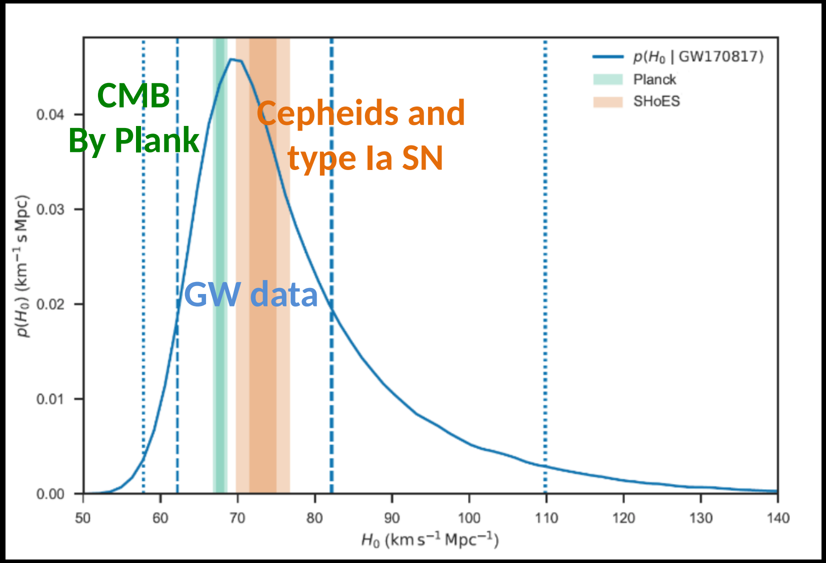
No energy injection from long-lived NS remnant

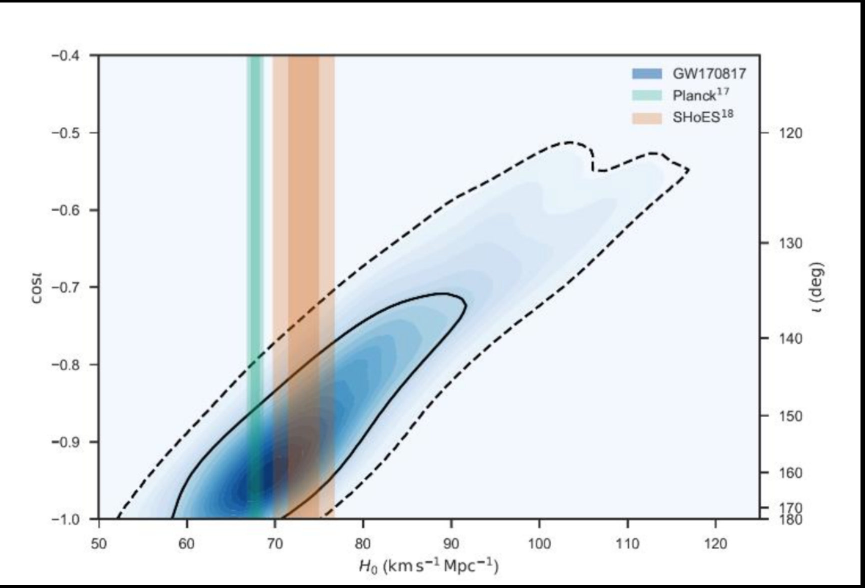
No prompt collapse to BH

Blue KN ejecta

GWs tidal deformability (LVC 17)

GRAVITATIONAL-WAVE COSMOLOGY





$v_H = H_0 d$ Combining the distance

measured from GWs $d = 43.8^{+2.9}_{-6.9}$ Mpc

and NGC4993 recession velocity

$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

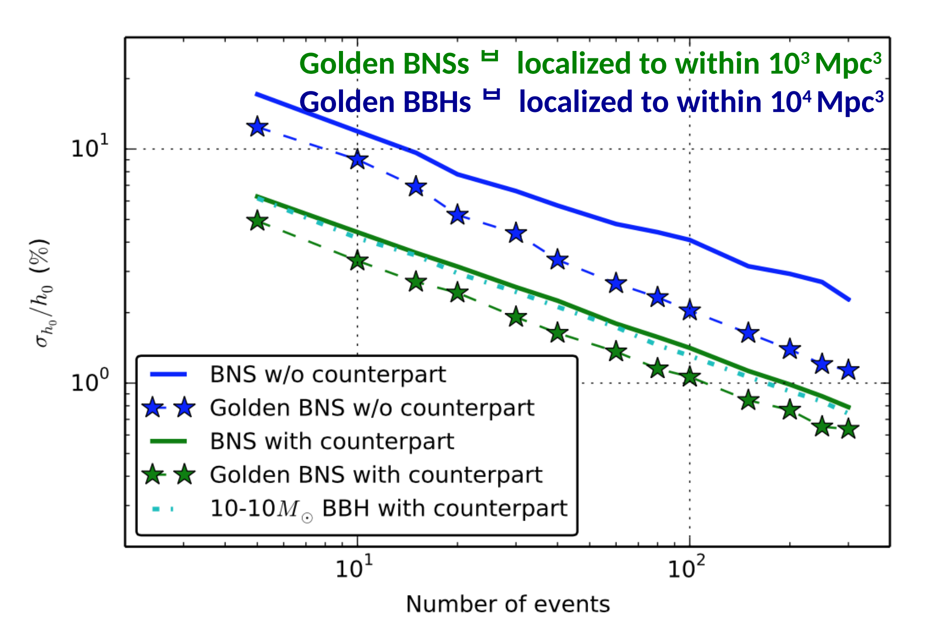
Abbott et al. 2017, Nature, 551, 85A

Era of precision GW-cosmology

- **BNS standard sirens with EM** measurement of the redshift

- **Only BNS GW detections → statistical case**, using cross-correlation with potential host galaxies within the localization volumes

Chen+ 2017, arXiv:1712.06531



~ 10/60/200 BNS with EM counterpart → H0 constrained to 4/2/1%

~ 100 detections of BNS (~ 30 golden events) → H0 constrained to 4 %

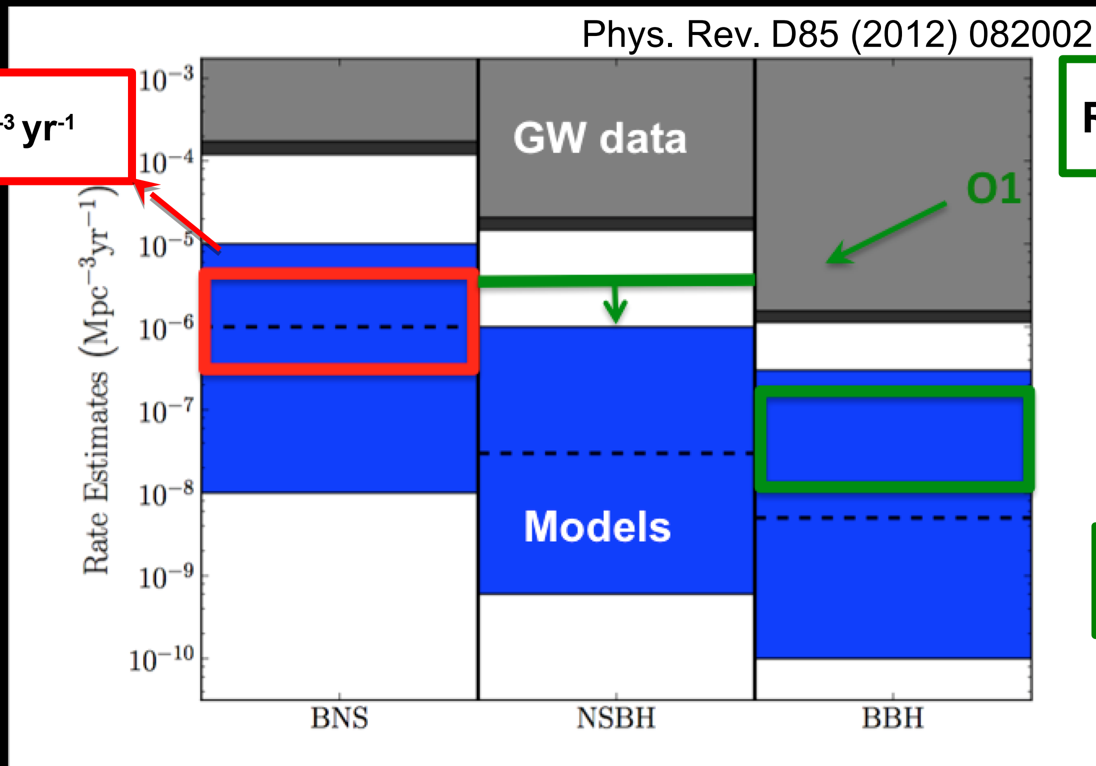
To improve H0 estimate:

- Using **inclination information from kilonova / afterglow models**
- Break the degeneracy inclination/distance with **preicise measure of the host galaxy distance** (e.g. Surface brightness fluctuation → distance error less then 5%, **Cantiello+ 2017**)

Astrophysical rate

R_{BNS}=320-4740 Gpc^{-3} yr^{-1}

LVC 2017 PhRvL,119



R_{NSBH} <3600 Gpc^{-3} yr^{-1}

LVC 2016 ApJL,1832

R_{BBH}=12-213 Gpc^{-3} yr^{-1}

Expected detection rate for O3

NS-NS	NS-BH	BH-BH
9^{+19}_{-7}	1^{+28}_{-1}	35^{+78}_{-26}

LIGO BNS range 120 Mpc
Virgo BNS range 65 Mpc

Credit: C.Pankow for LVC, MIT and Amsterdam Town Hall Meetings

From Next run: the LIGO and Virgo collaboration will release **open public alerts (OPAs)** for all event candidates in which we have a reasonable confidence and we consider to likely to be real

Goals of OPA

- *To maximize the science the entire scientific community can do with the GW detections*

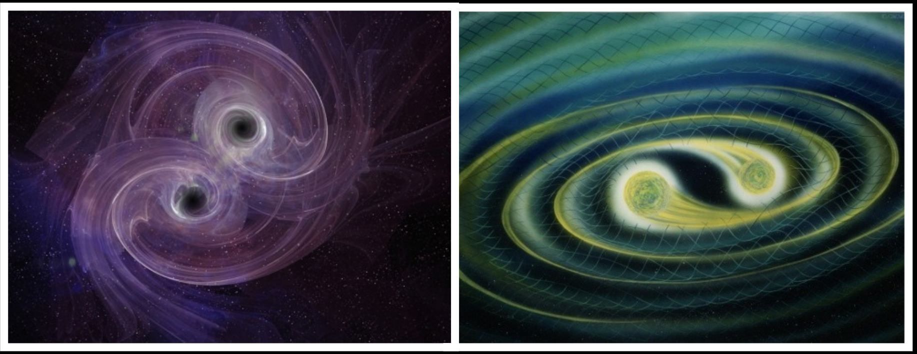
→ *To minimize the chance of missing EM/neutrino counterparts*

The alerts will look a lot like events in O1 and O2, except that they will all be instantly public

LVC will issue automated preliminary alerts, prior to vetting, with minimal latency

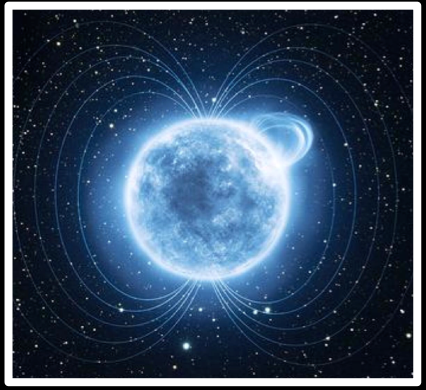
This is only the birth of GW astronomy…….

Coalescence of binary system of neutron stars and/or stellar-mass black-hole



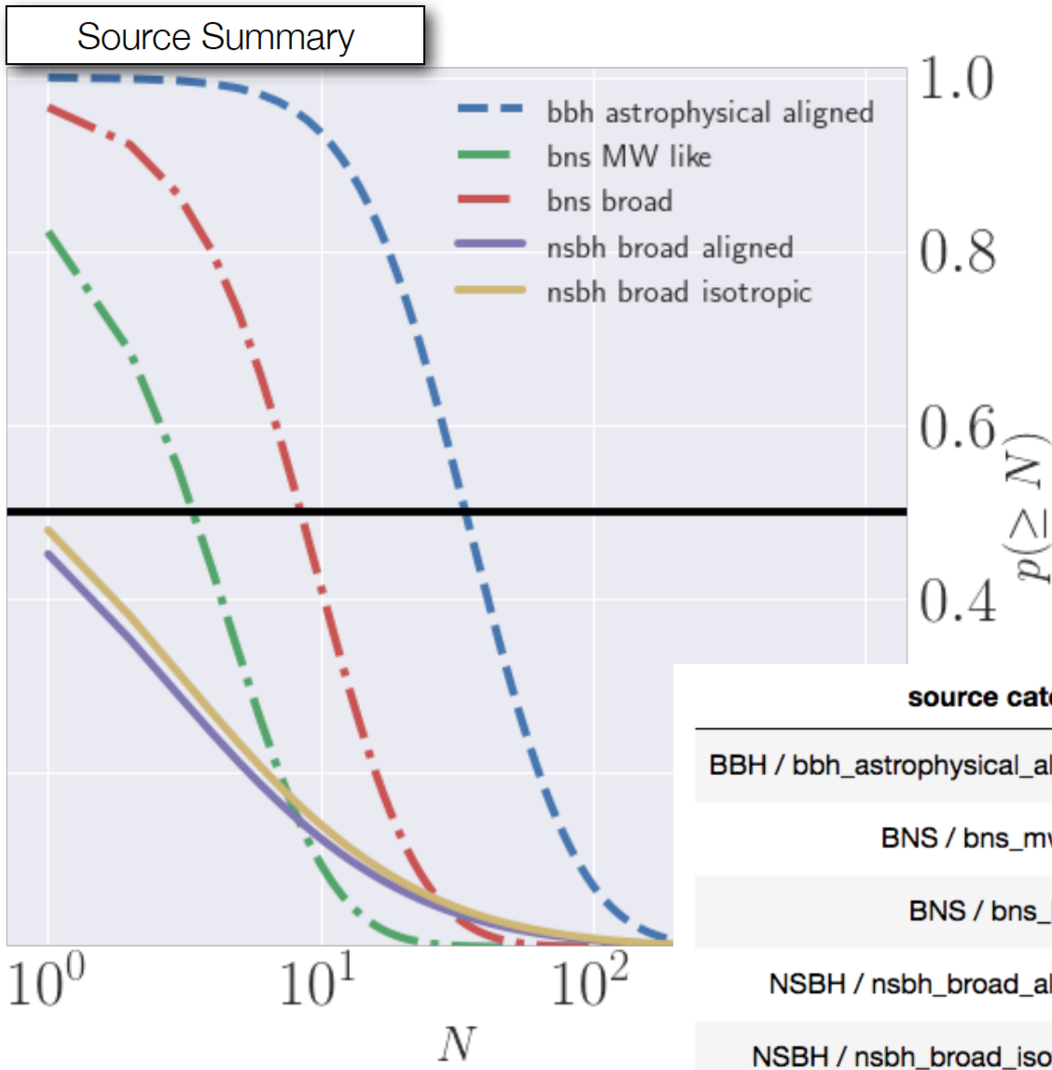
Core-collapse of massive stars

Isolated neutron-star



Unexpected….

EXTRA



Assumptions:
$\rho_{net} > 12$
T_{obs}: 1 yr with 50% duty cycle

source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	35^{+78}_{-26}
BNS / bns_mw_like	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	4.9×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Credit: C.Pankow for LVC, MIT and Amsterdam Town Hall Meetings