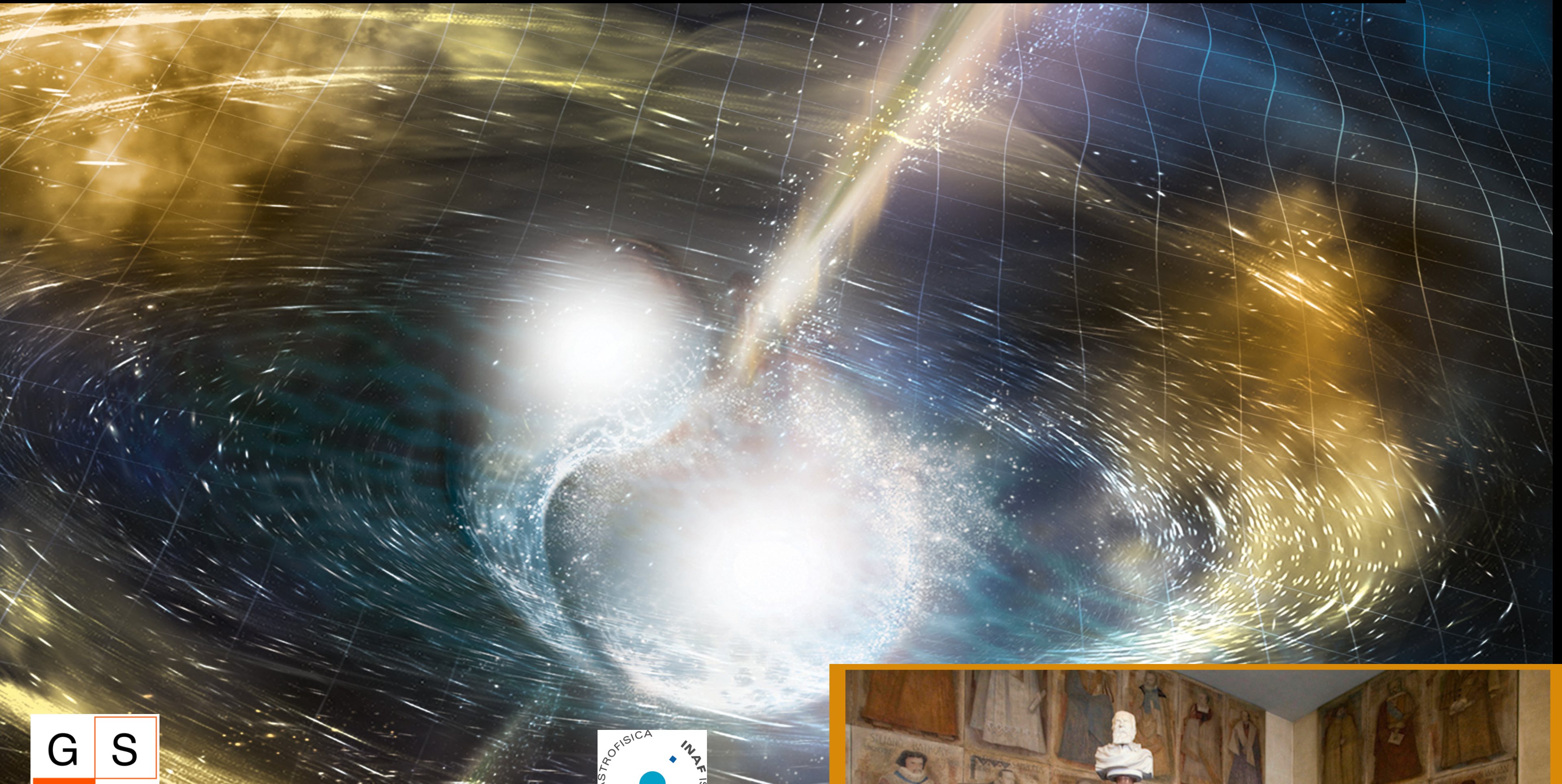
Multimessenger signatures for sources of Gravitational Waves



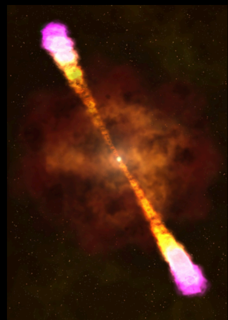
M. Branchesi
Gran Sasso Science Institute
INFN/LNGS and INAF

Chair of Galileo, from which, according to tradition, he gave lectures - Credits: Univ. of Padova - M. Pistore

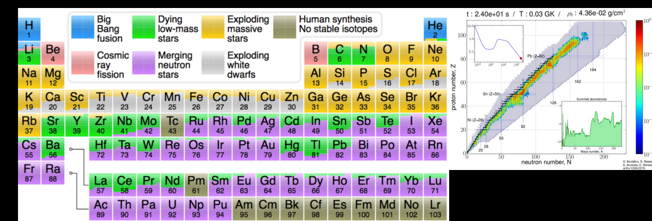
XIX International Workshop on Neutrino Telescopes

Radioactively powered transients

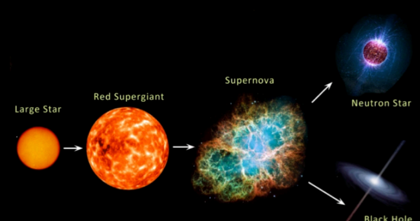
Relativistic astrophysics



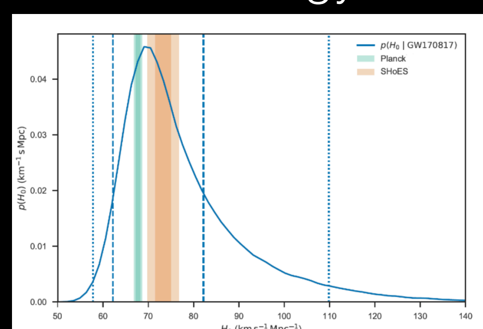
Nucleosynthesis and enrichment of the Universe



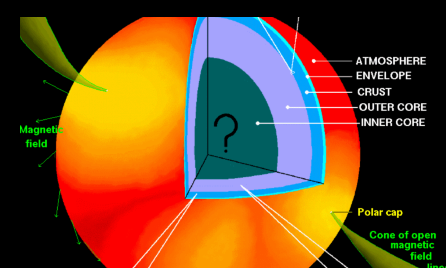
Compact object formation and evolution

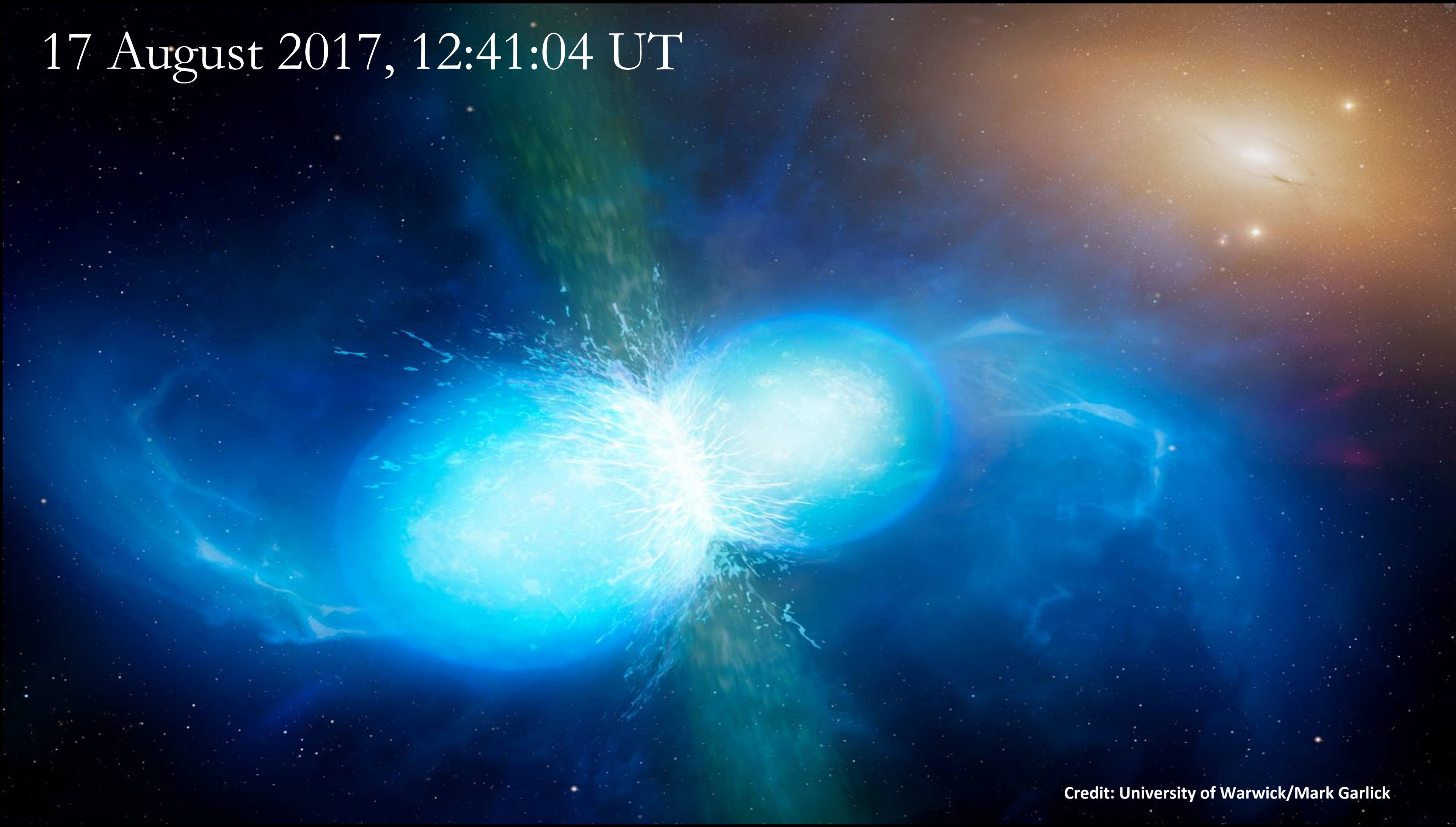


Cosmology



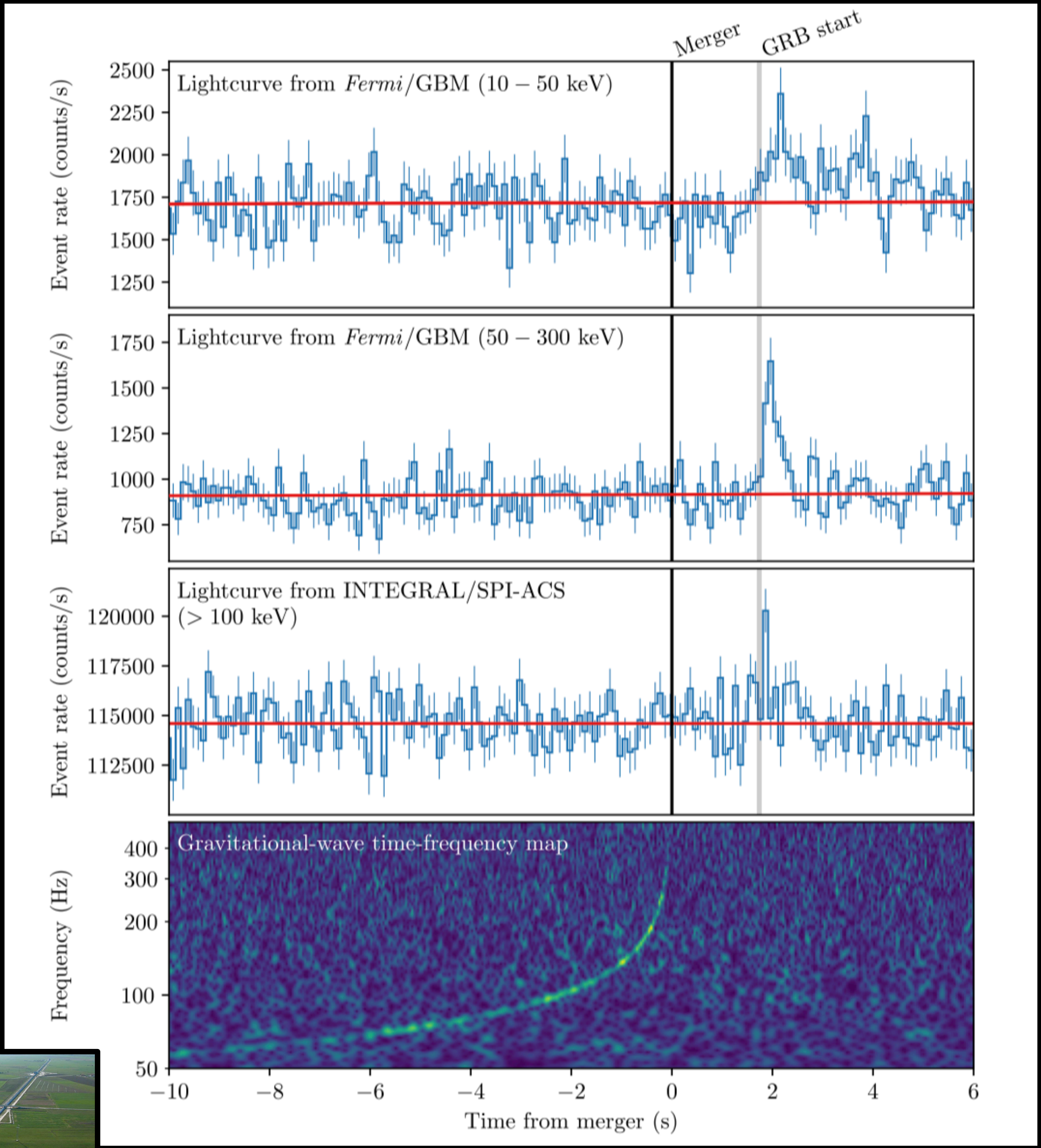
Nuclear matter physics



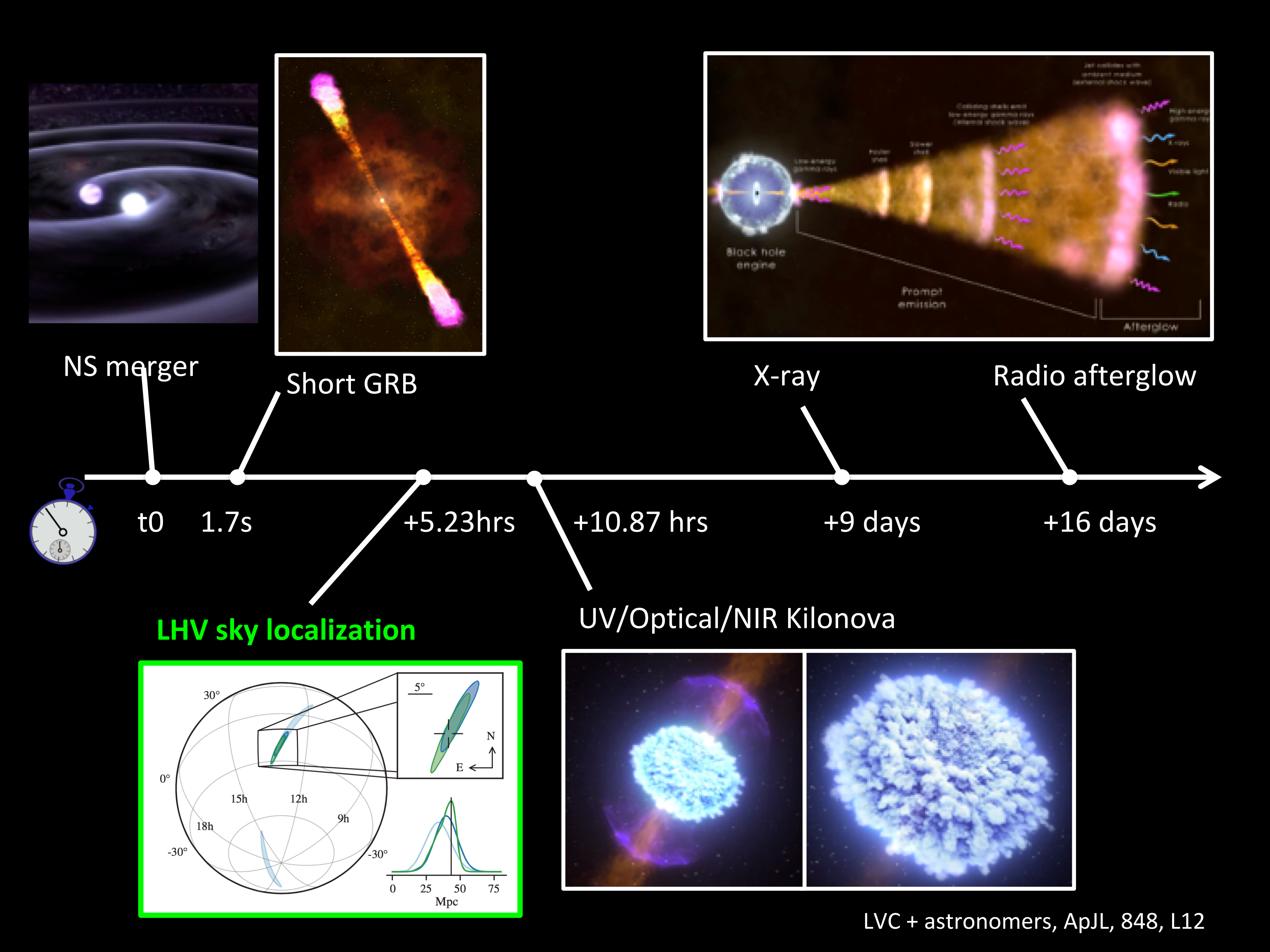

17 August 2017, 12:41:04 UT
Credit: University of Warwick/Mark Garlick


Fermi Space Telescope



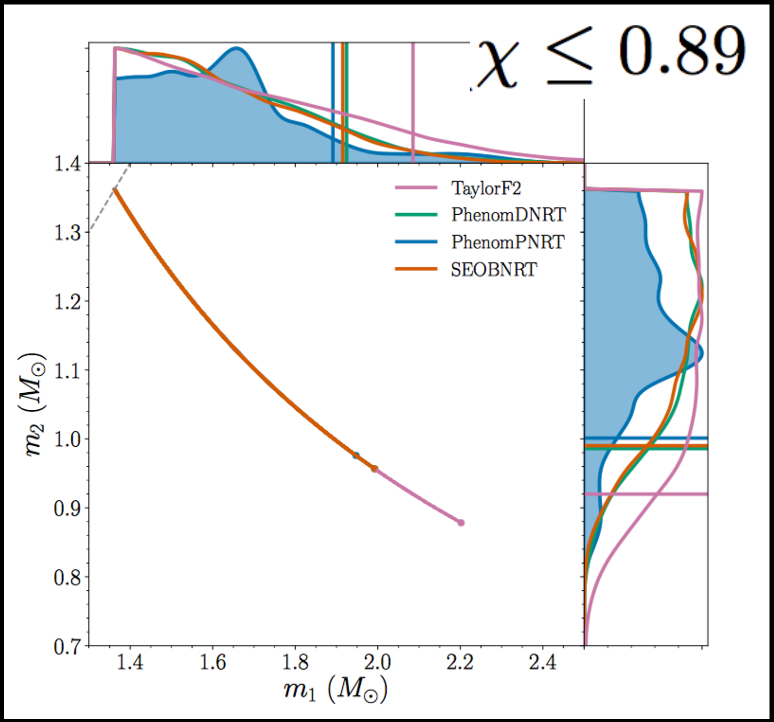


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from Fermi/GBM (50 – 300 keV)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

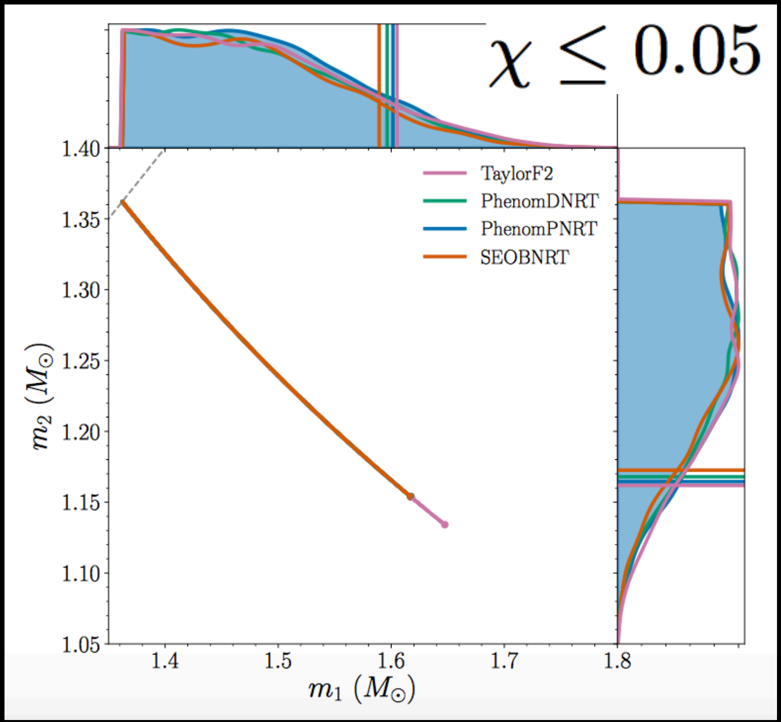
GW170817


NS merger
Short GRB
X-ray
Radio afterglow
Black hole engine
Prompt emission
Afterglow
t0
1.7s
+5.23hrs
+10.87 hrs
+9 days
+16 days
LHV sky localization
30°
0°
-30°
15h
12h
9h
18h
-30°
5°
N
E
0
25
50
75
Mpc
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**

  1.16 – 1.60 Mo low spin

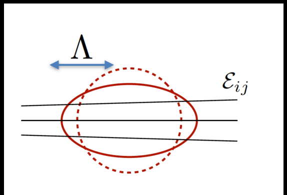
Masses are consistent with the masses of all known neutron stars!

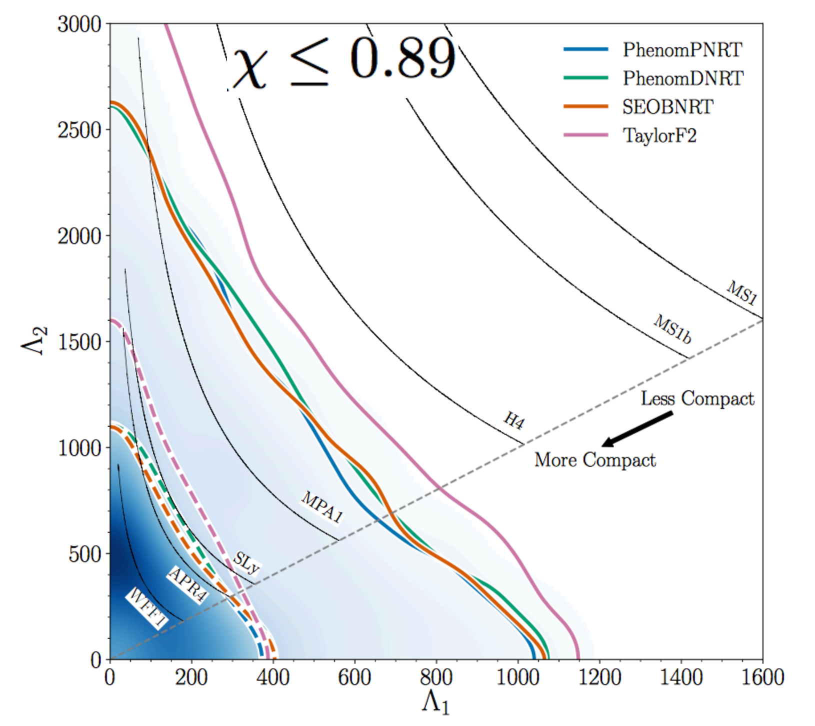
Abbott et al. 2018, arXiv1805.11579

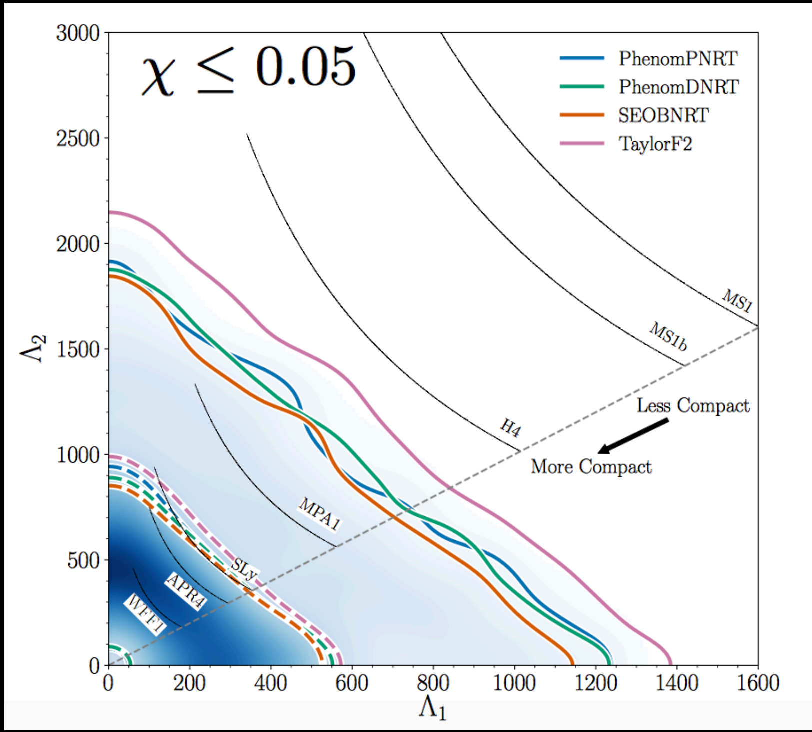
NS LABORATORY FOR STUDYING SUPER-DENSE MATTER

TIDAL DEFORMABILITY

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

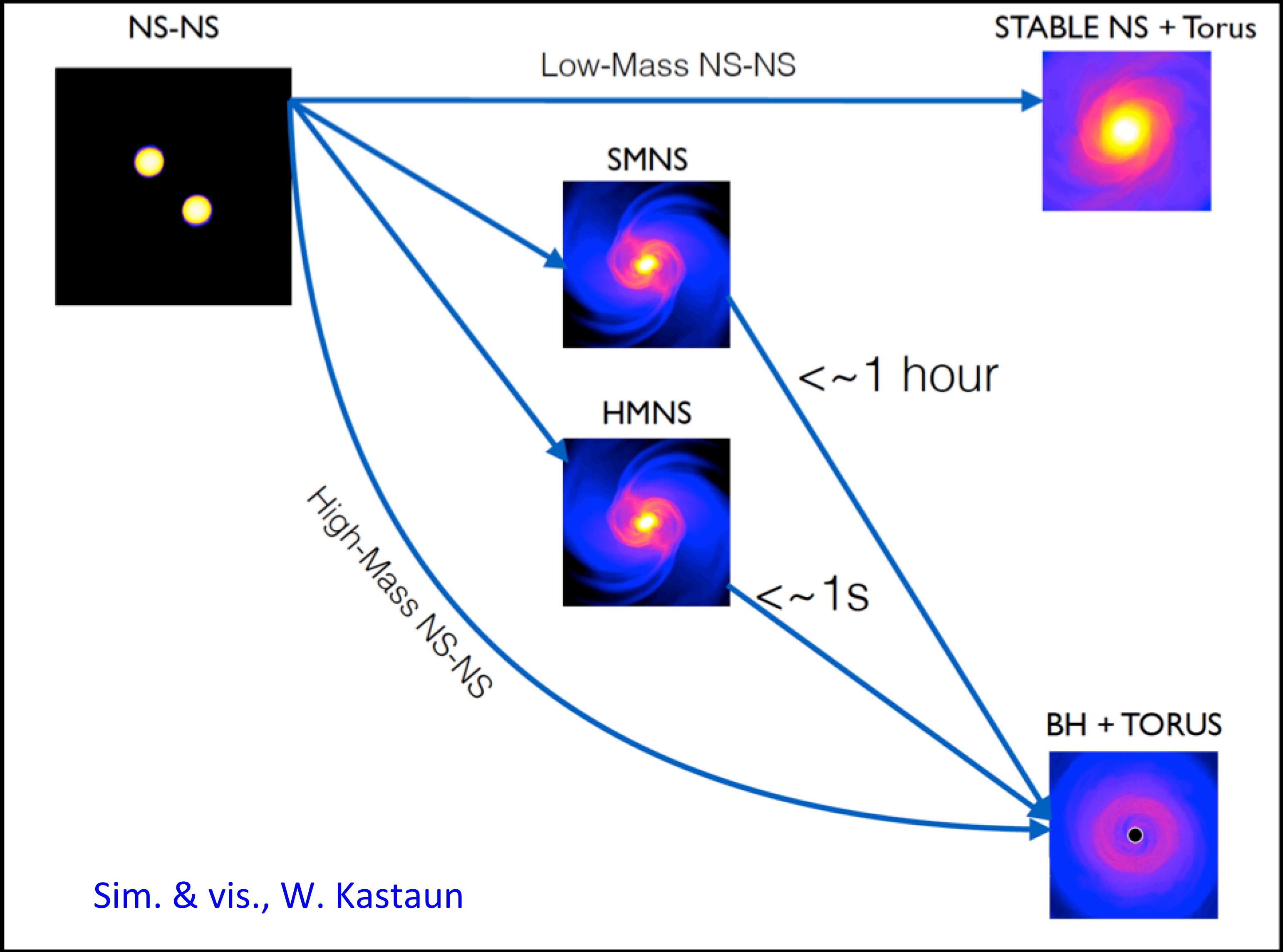






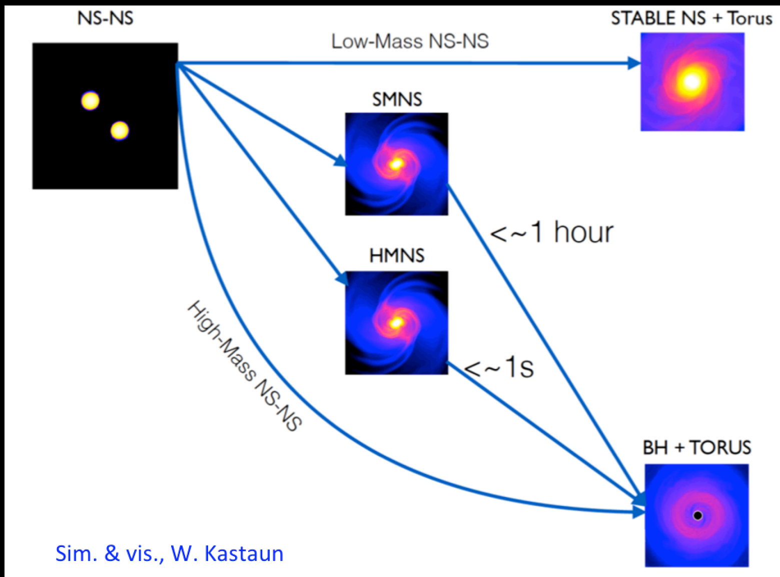
From only GWs we cannot say both components of the binary were NS

Post merger remnant?



Post merger remnant?

Abbott et al. 2017, ApJL,851



GW search:

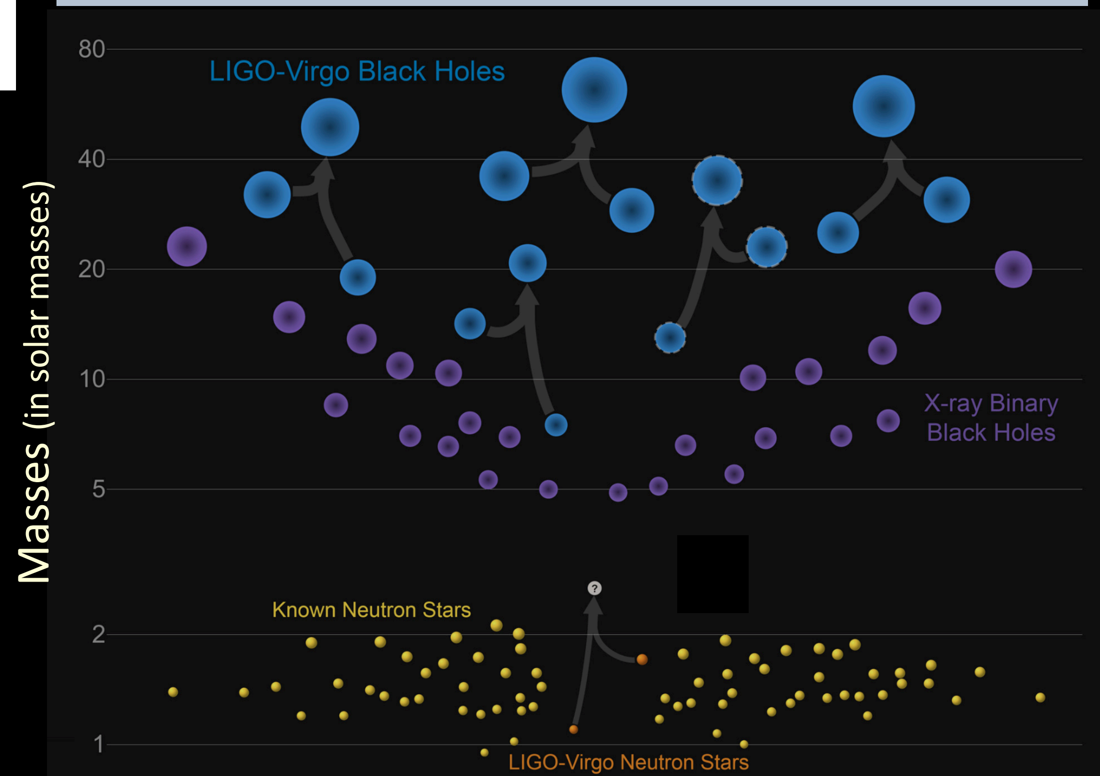
- **ringdown of BH** around 6 kHz

  → 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

Heaviest NS
or lightest BH known?



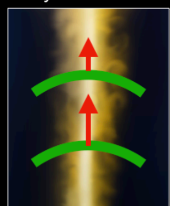
EM non-thermal emission

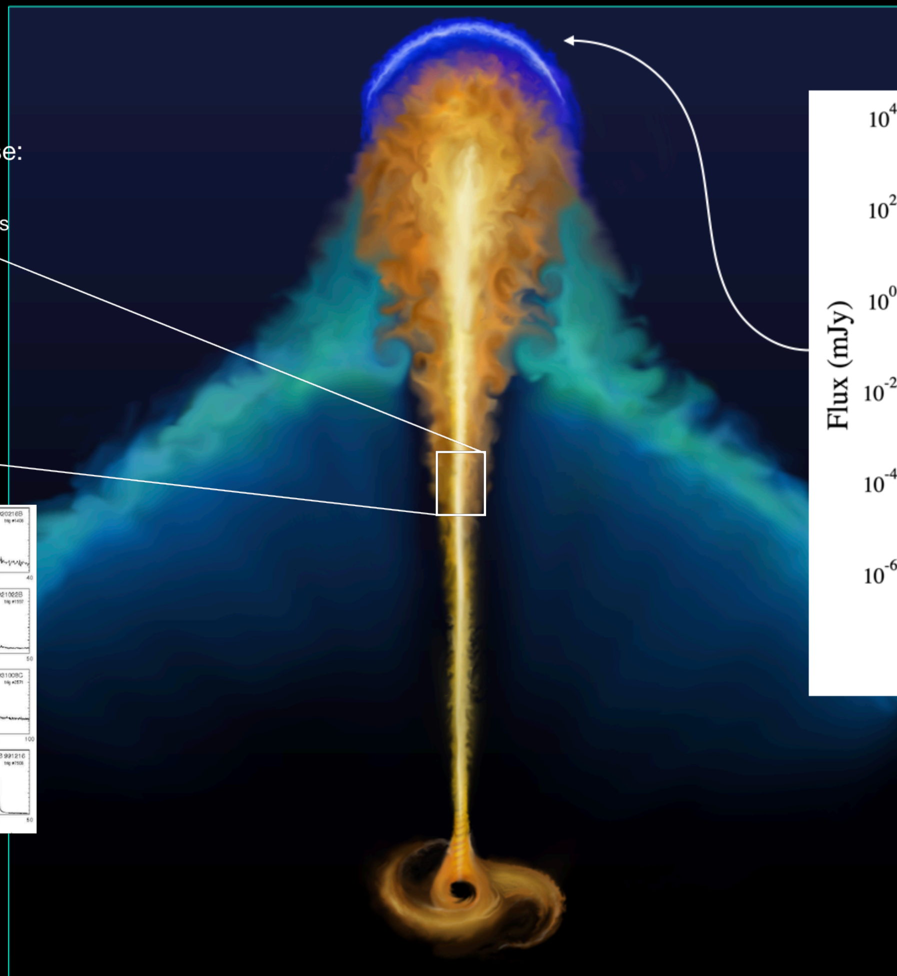
Short Gamma Ray Burst

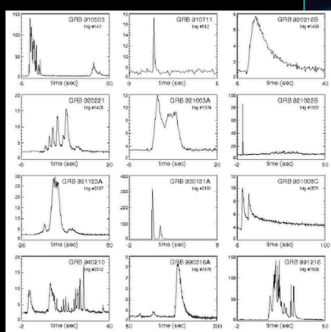
Prompt emission phase:

Energy range: keV-MeV

Variability time-scales: ms-s



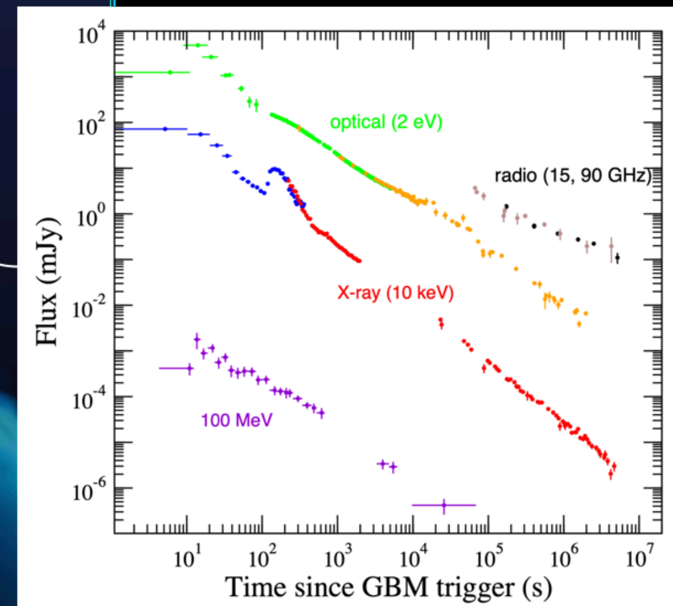




Shemi & Piran (1990)

Rees & Meszaros (1994)

Afterglow phase



From Panaitescu et al (2013)

Prompt emission

ϒ-ray within seconds

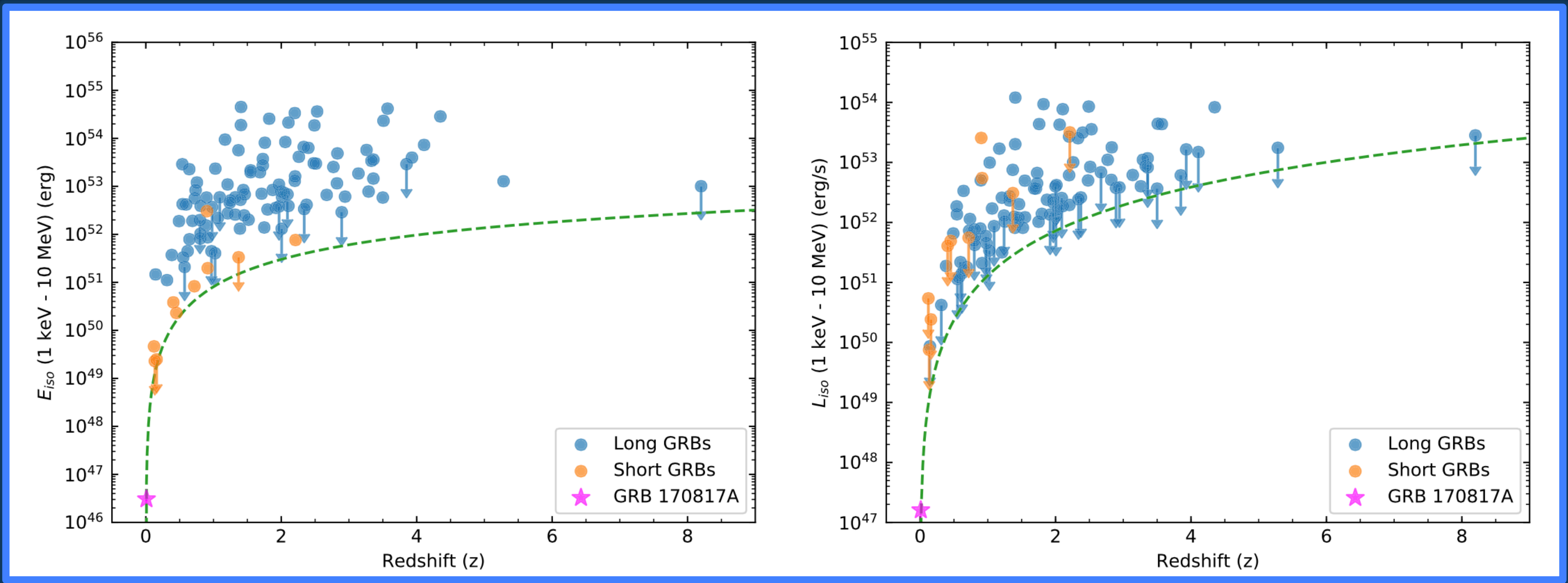
Afterglow emission

Optical, X-ray, radio

hours, days, months

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



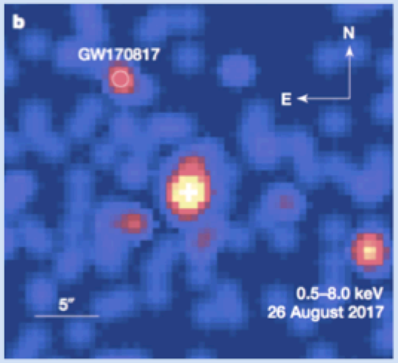
Abbott et al. 2017, APJL, 848, L13

Intrinsically sub-luminous event

or a classical short GRB viewed off-axis?

X-ray and radio emissions 9 and 16 days after the merger

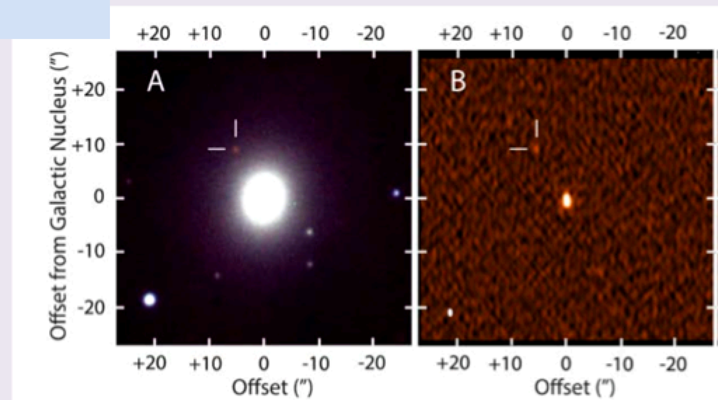
Chandra observation



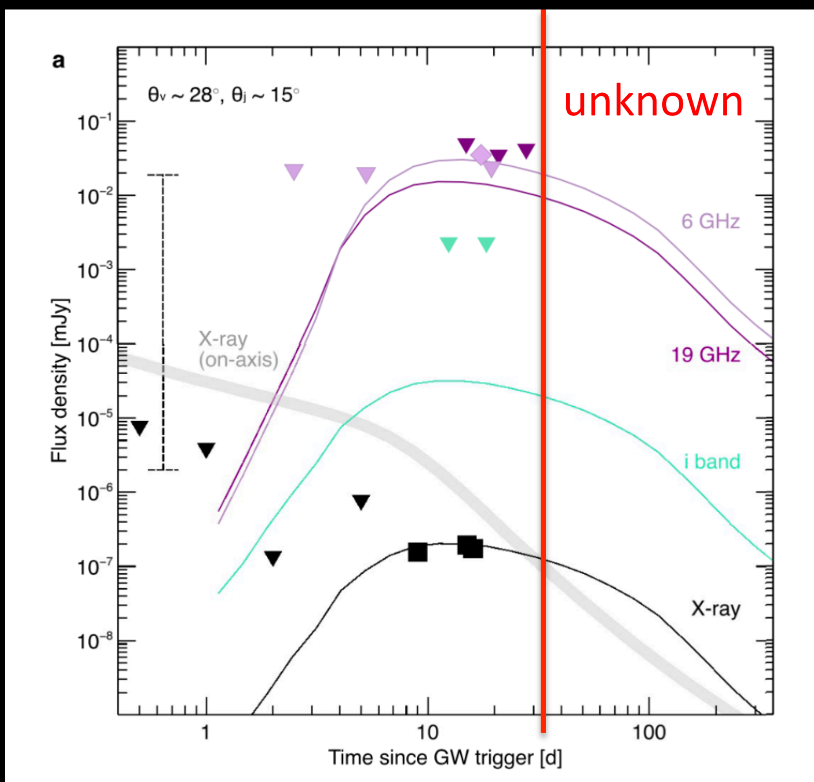
"..Our observations are instead consistent with the onset of an off axis afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections."

Troja, et al. Nature 2017

VLA observation

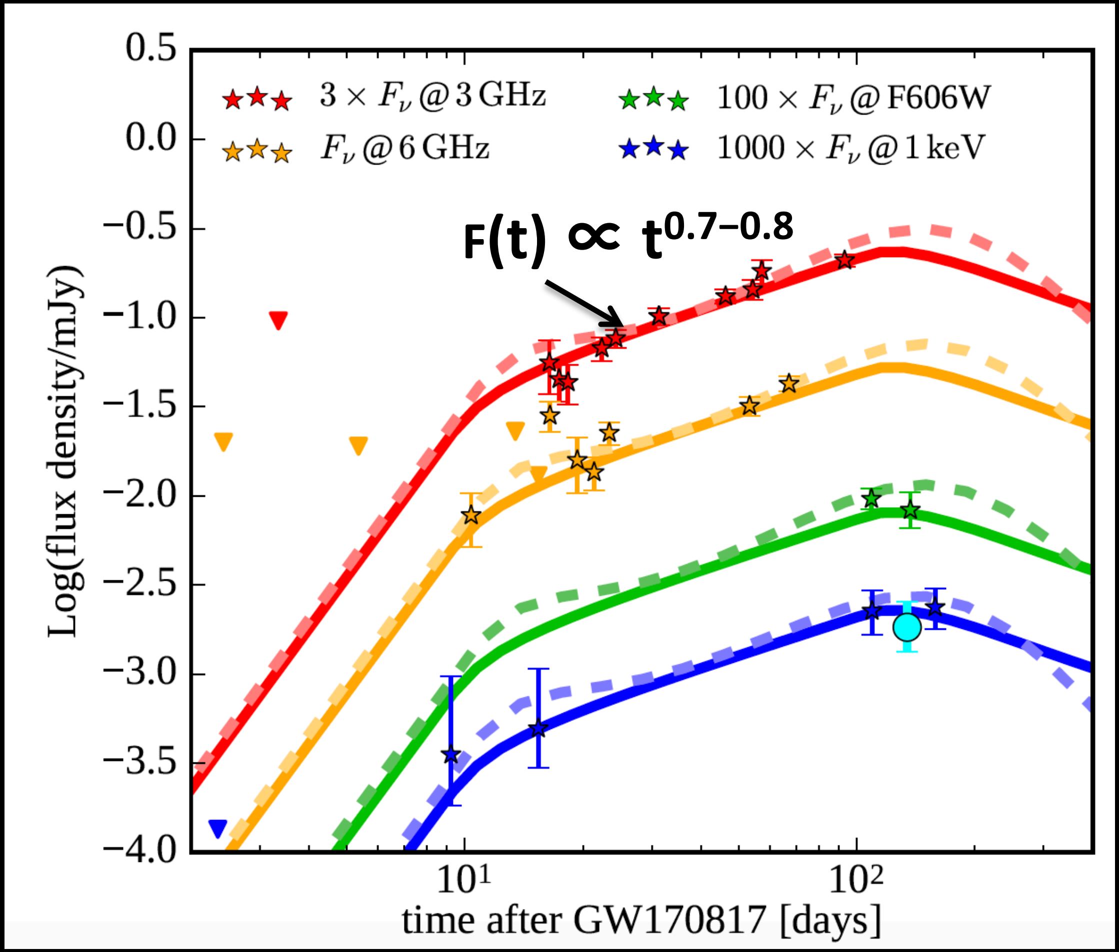


Hallinan et al. Science, 2017



First GRB observed off-axis?

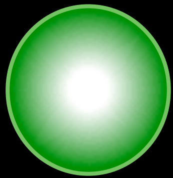
After 150 days from the BNS merger…



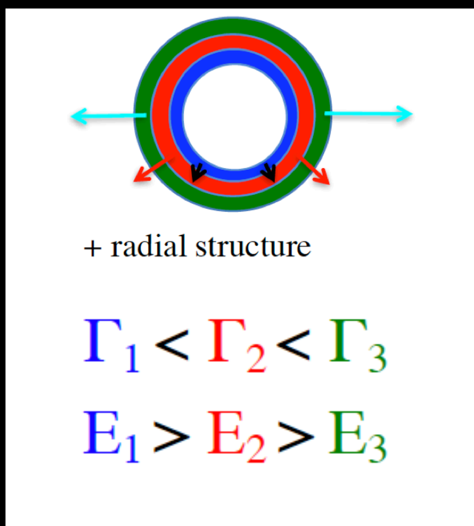
D'Avanzo et al. 2017, A&A

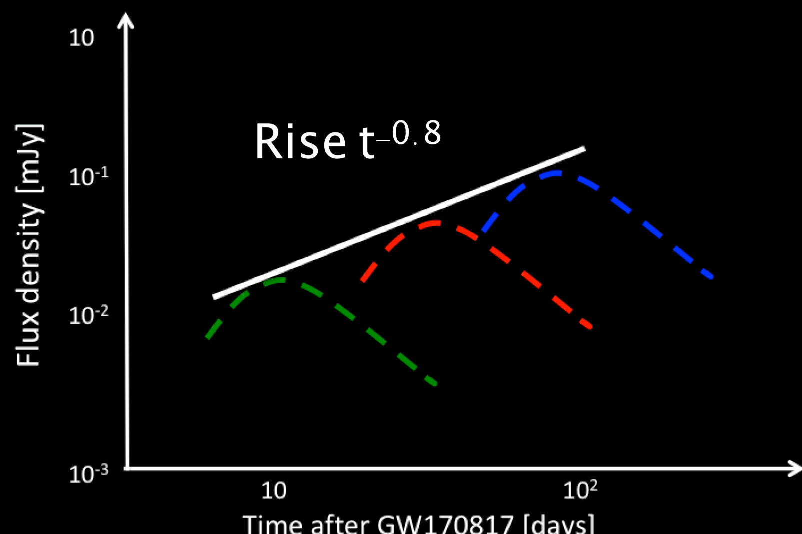
..unexpected slow achromatic flux–rise until ~ 150 days!

RADIAL or ANGULAR STRUCTURE?

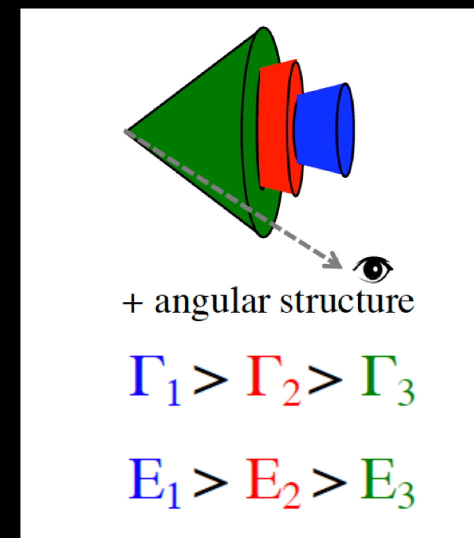


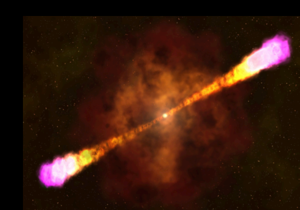
Mildly relativistic isotropic outflow (choked jet)





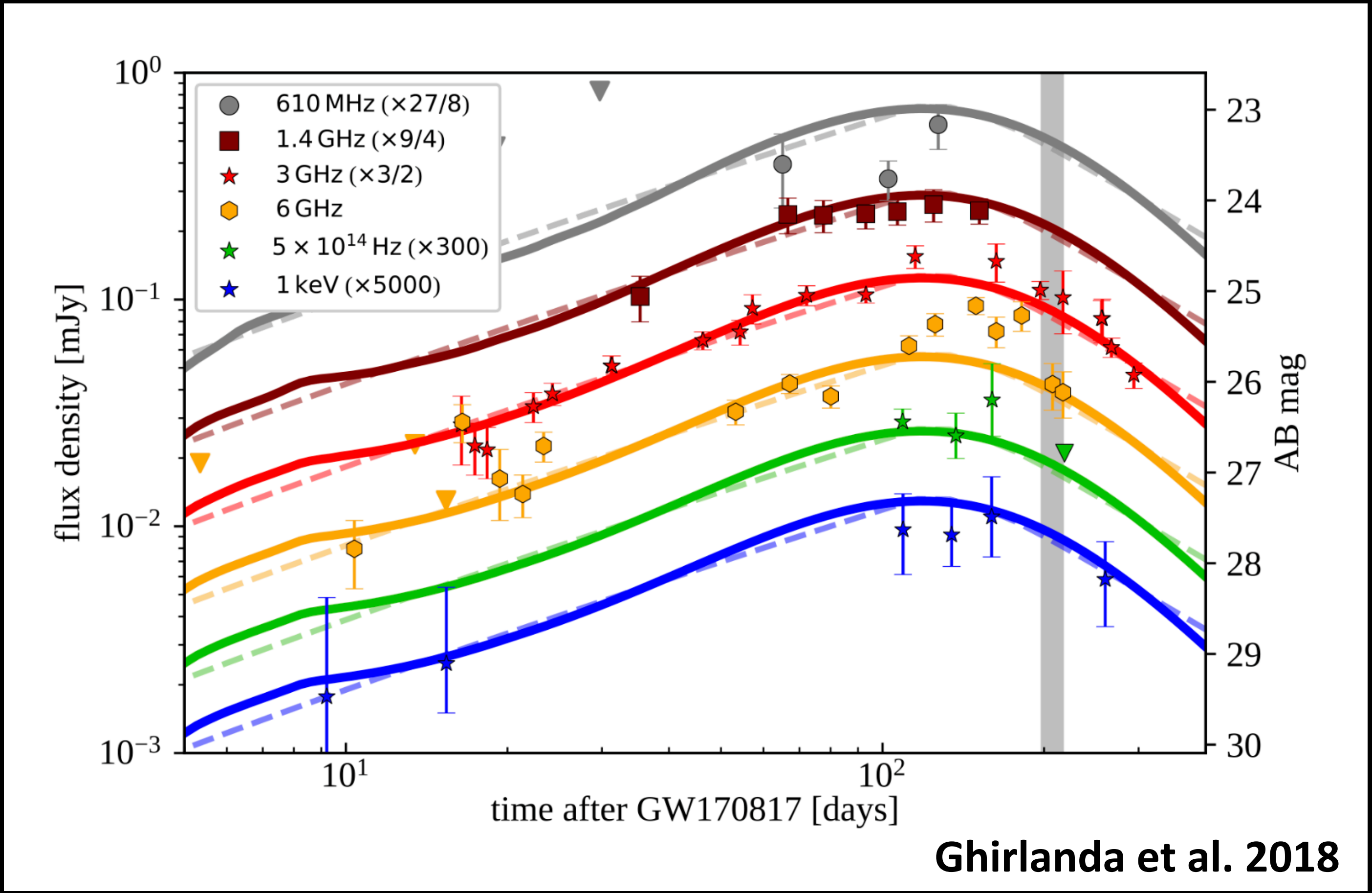
Structured Jet (successful) off-axis jet

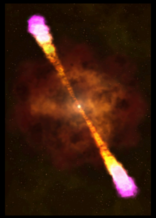




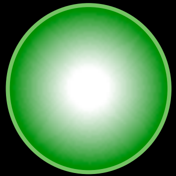
[see e.g. Rossi et al. 2002, Zhang et al. 2002, Ramirez-Ruiz et al. 2002, Nakar & Piran 2018, Lazzati et al. 2018, Gottlieb et al. 2018, Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017, Ghirlanda et al. 2019]

After 150 days from the BNS merger…decaying phase!





Solid lines

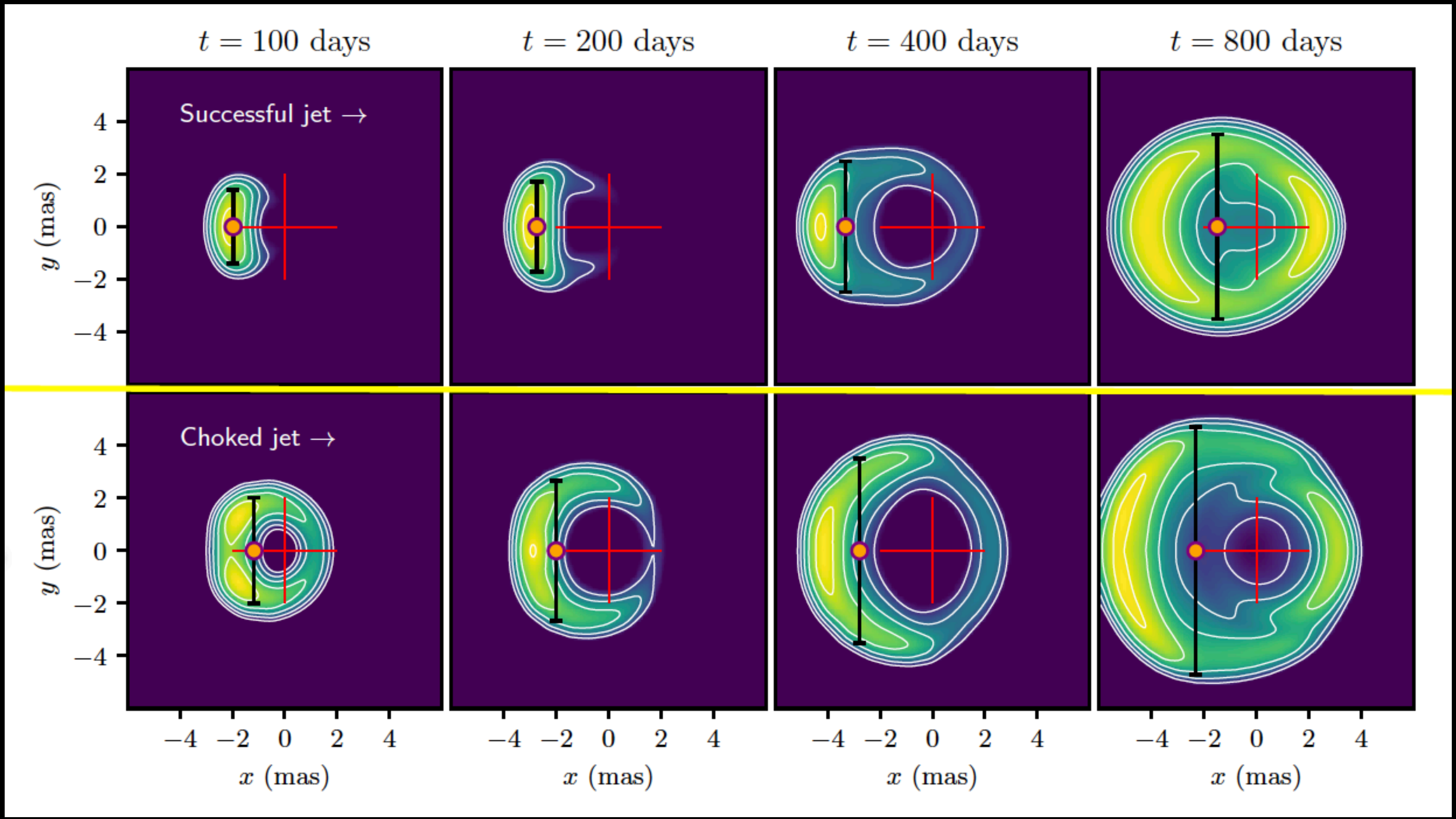


Dashed lines

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]

RADIO HIGH RESOLUTION IMAGING



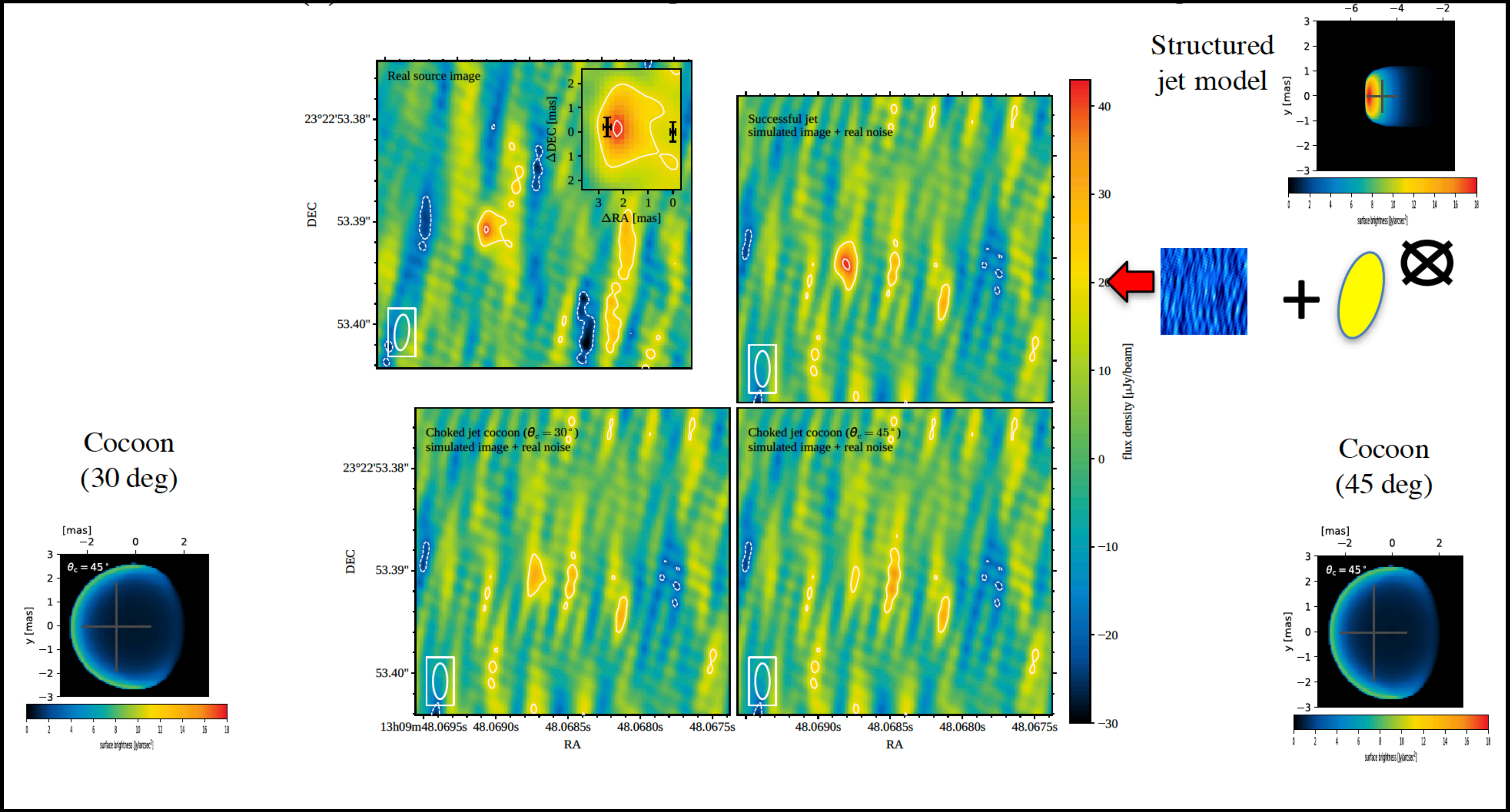
At the same epoch: structured jet has LARGER DISPLACEMENT and SMALLER SIZE than isotropic midly relativistic outflow!

[Gill & Granot 2018; Nakar+2018; Zrake+2018; Mooley+2018; Ghirlanda+2018]

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

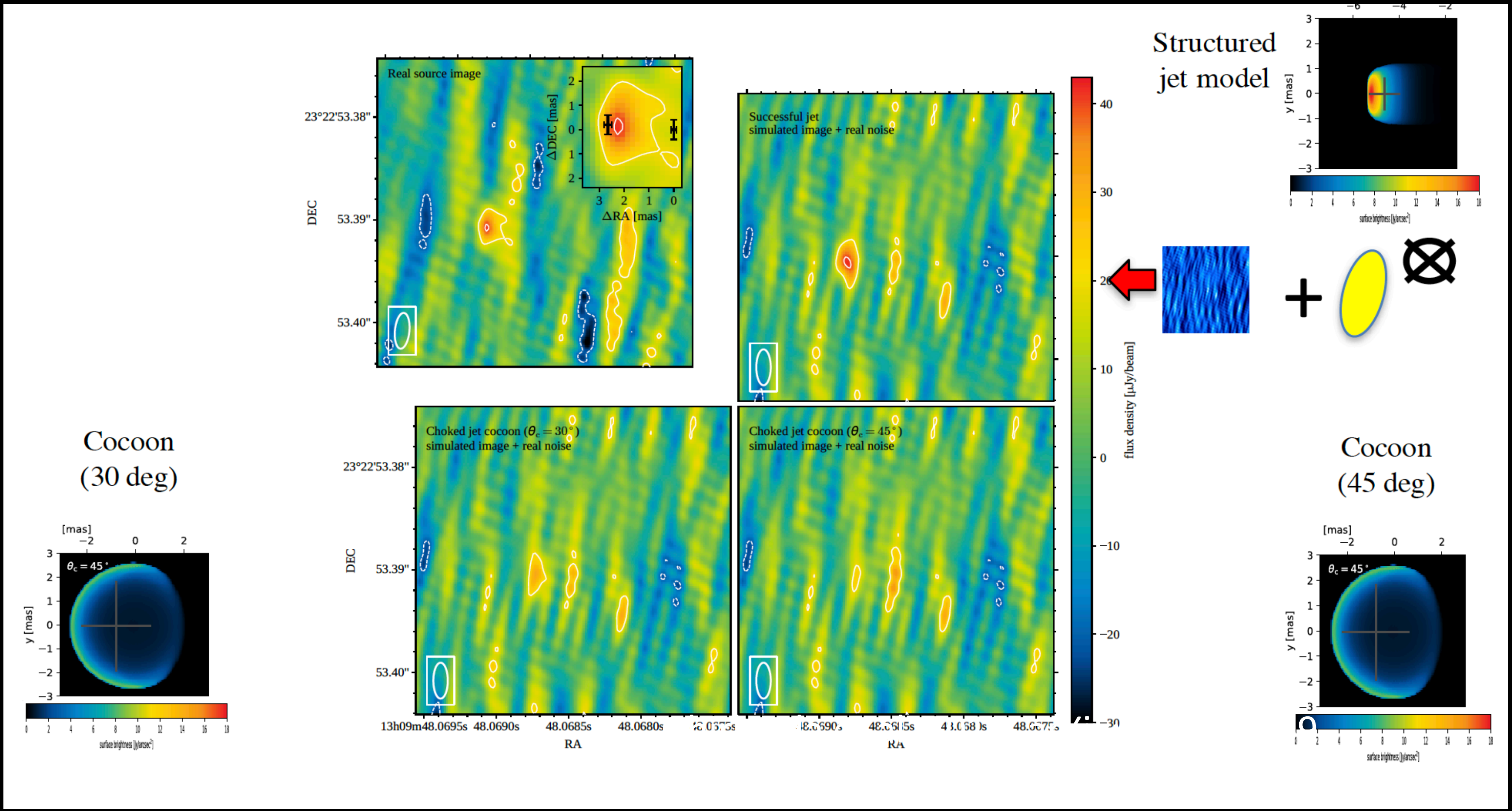
Ghirlanda et al. 2019, Science

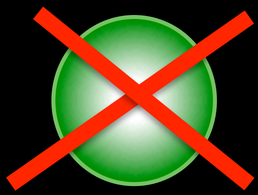


See also Mooley, Deller, Gottlieb et al. 2018

SIZE CONSTRAINTS

Ghirlanda et al. 2019, Science





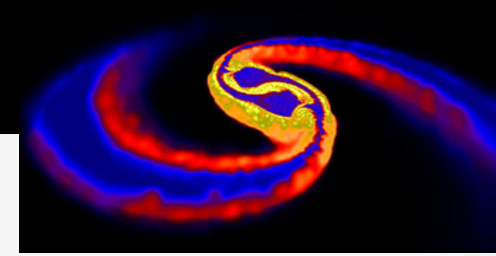
Ruled out nearly isotropic, mildly relativistic outflow , which predicts proper motion close to zero and size > 3 mas after 6 months of expansion

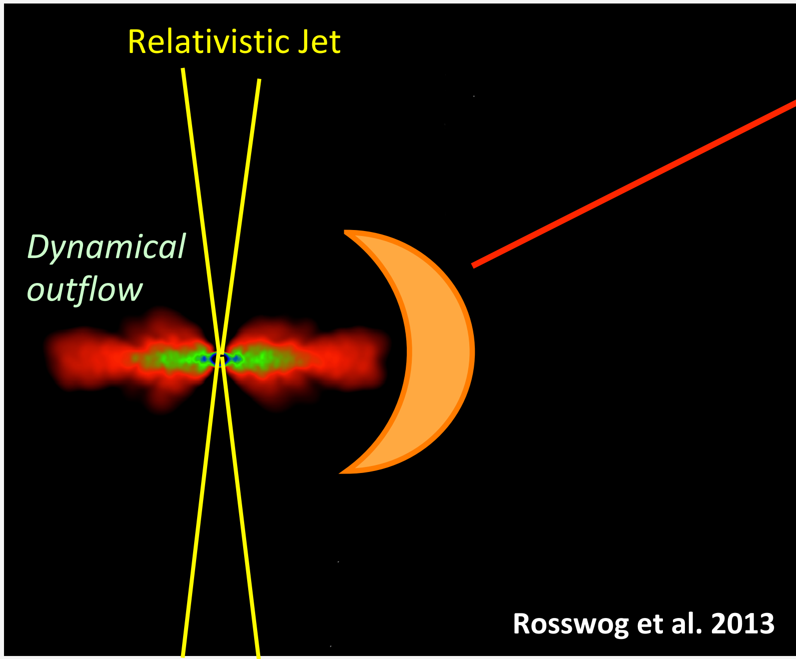
Ghirlanda et al. 2019, Science

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

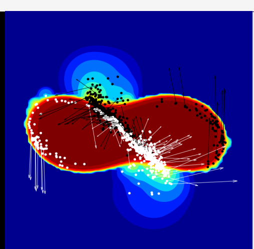
↓

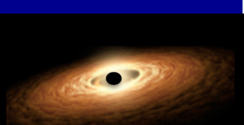
radioactive decay of heavy elements

↓

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

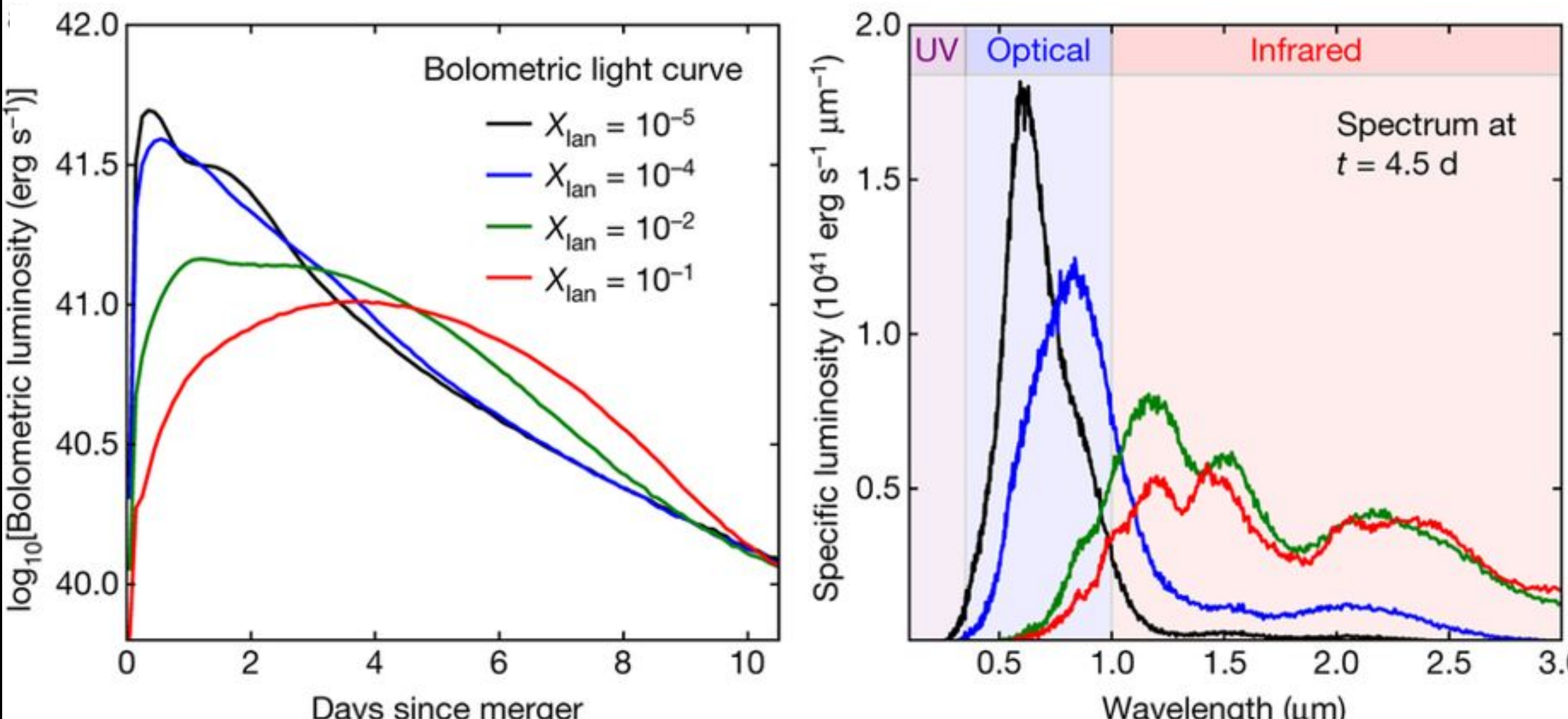
→ Lower opacity

→ brief (~ 2 day) **blue optical transient**

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

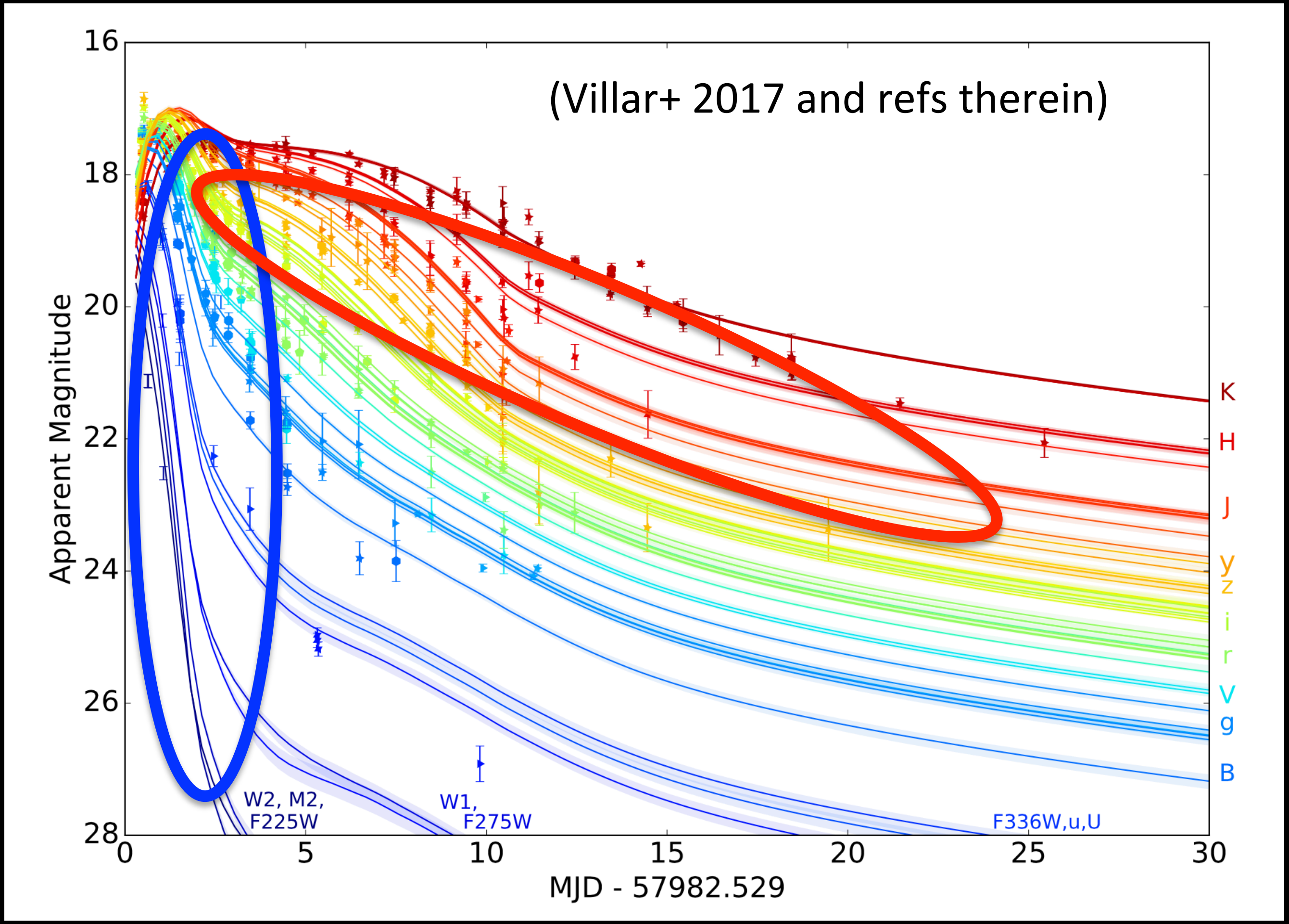
Observables: expectations

Kasen et al. 2017



Light curve shape (duration and peak luminosity) and spectarl shape are dramatically affected by lanthanides

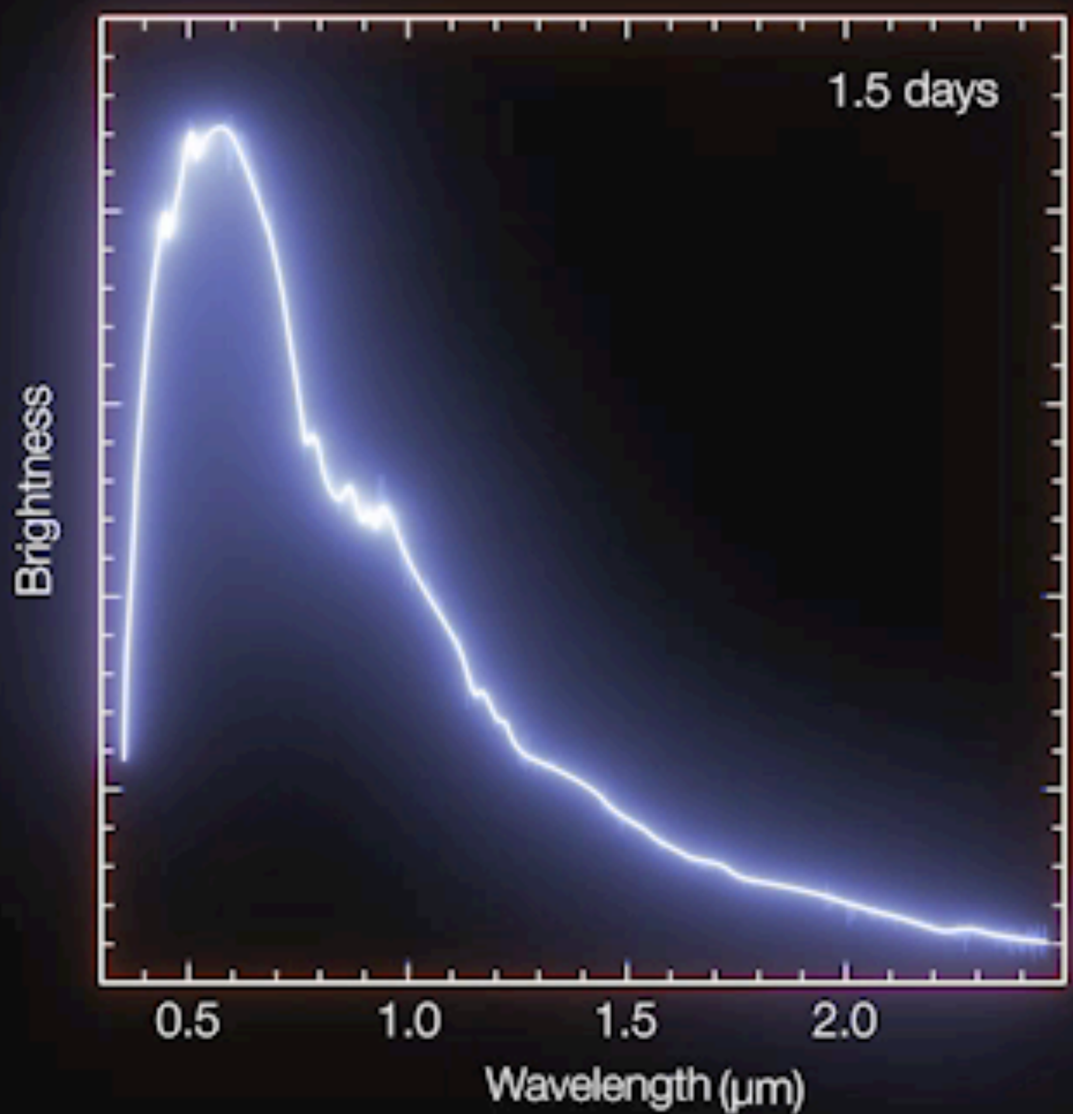
UV/Optical/NIR Light Curves



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)

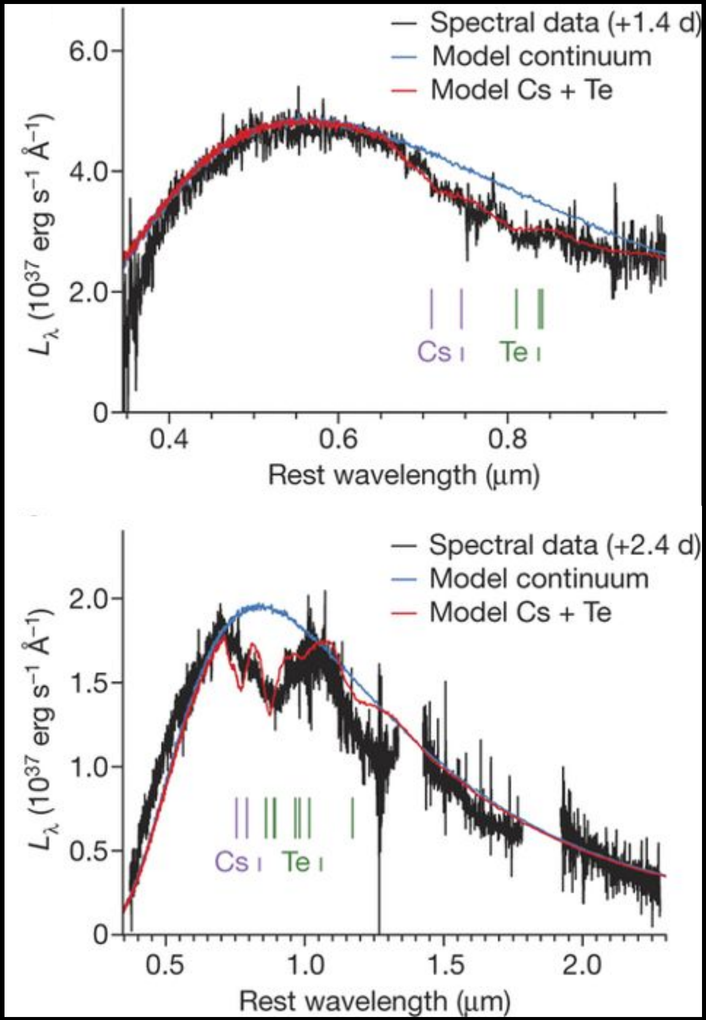
- BNS merger **site for heavy element production in the Universe!**

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

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

Nucleosynthesis

Smartt et al. 2017

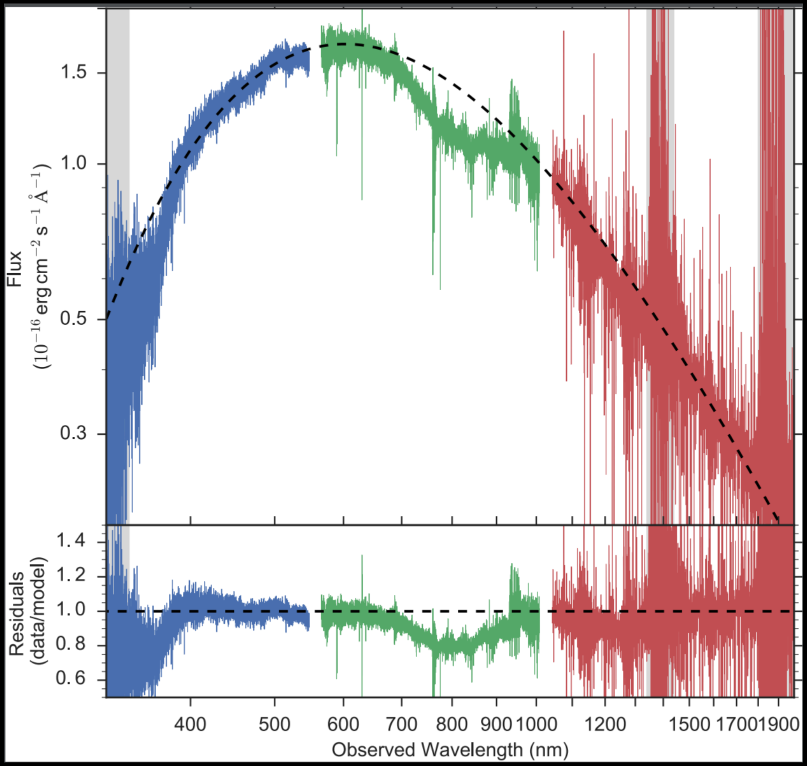


Attempt to identify elements

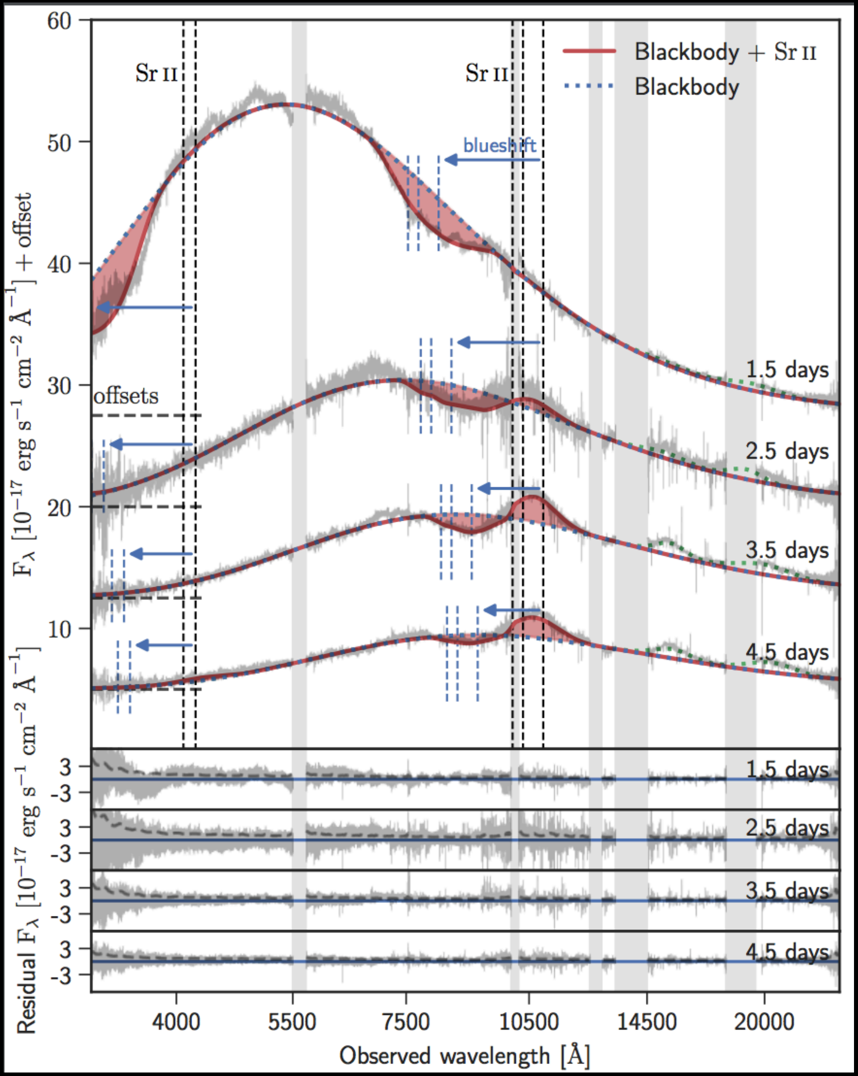
Spectral analysis hampered because of:

- heavy elements have forest of lines hence strong blending
- relativistic velocity makes for extremely broad lines (multi-components and different velocities)
- atomic data are incomplete and uncertain

A recent work…



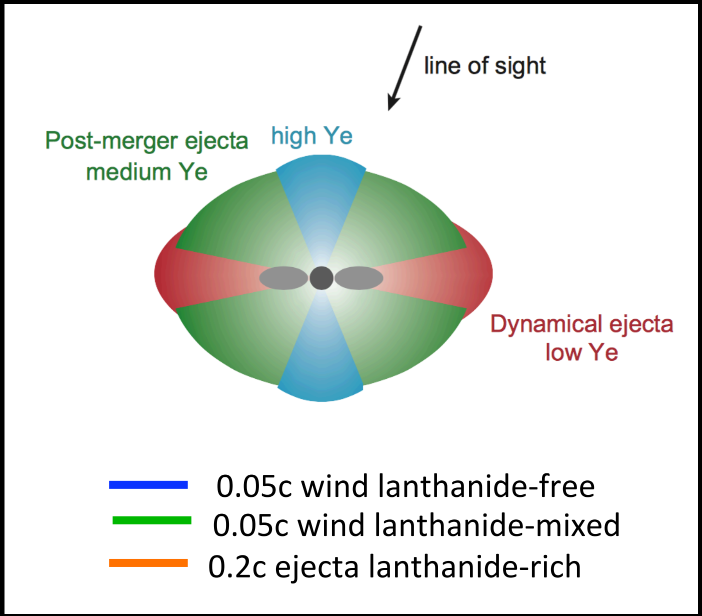
Watson, D. et al. accepted in Nature

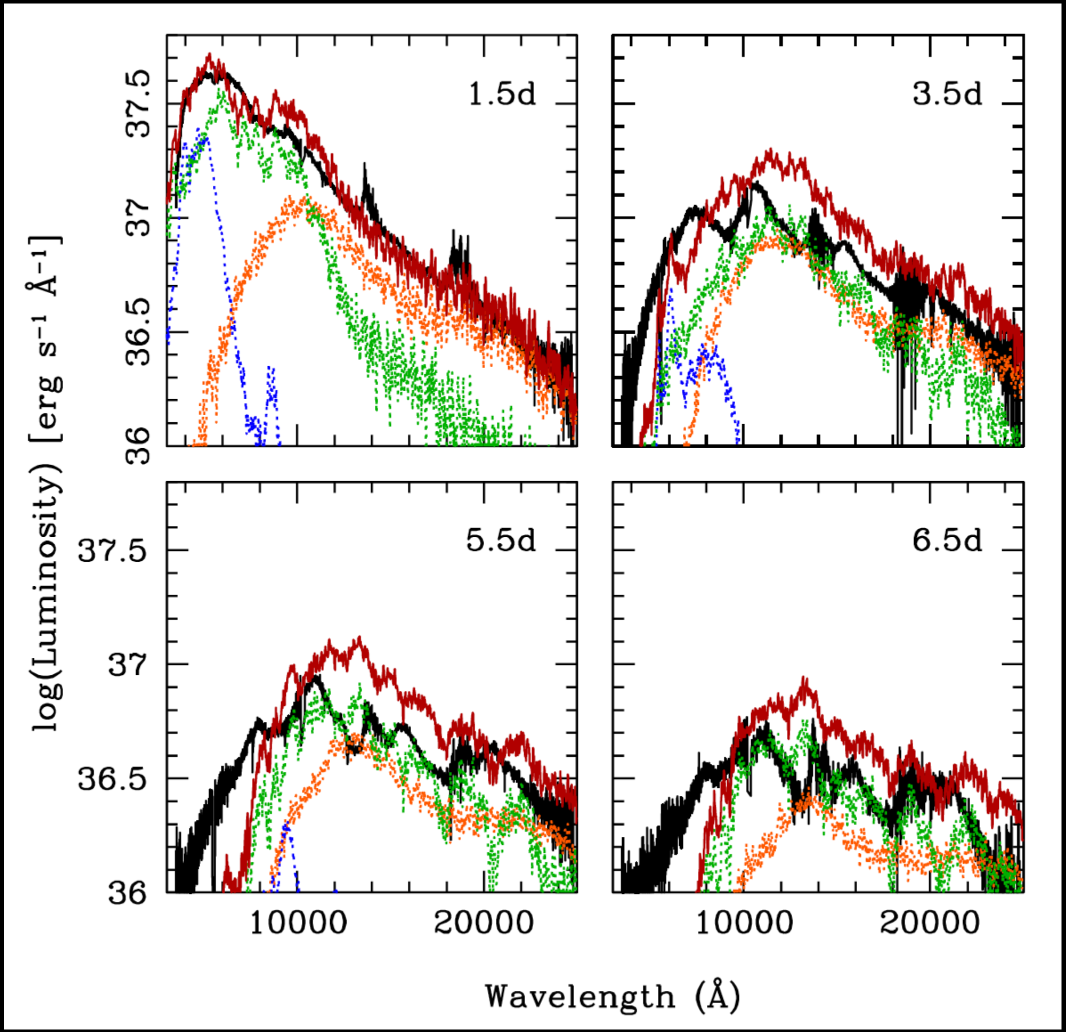


identification of the neutron-capture element **strontium**

See also Perego et al. 2020

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





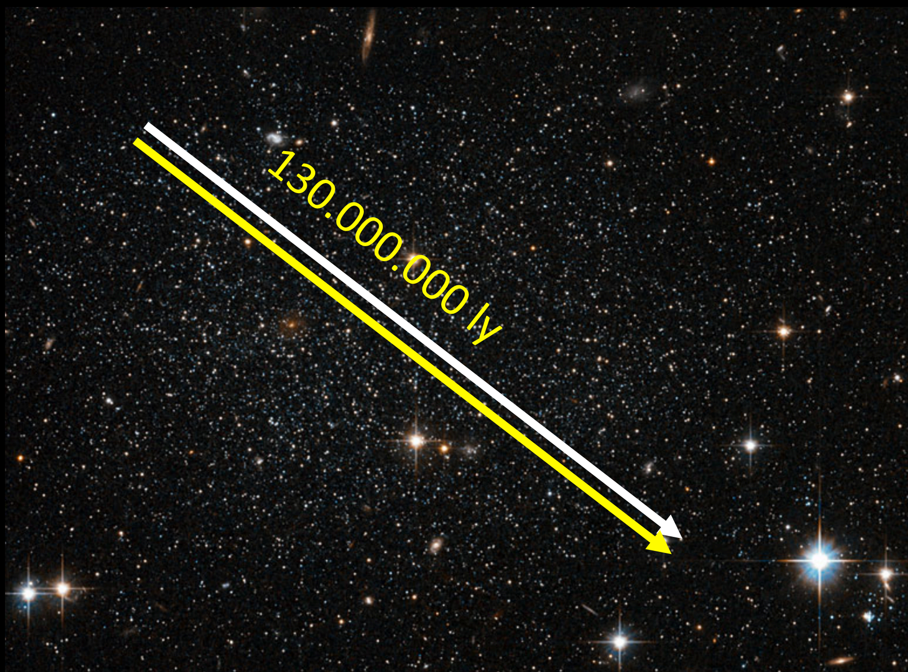
Best fit requires three components

ejected mass ~ 0.03 – 0.05 $M_\odot$

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

Multi-messenger studies

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



GRB/GW delay

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

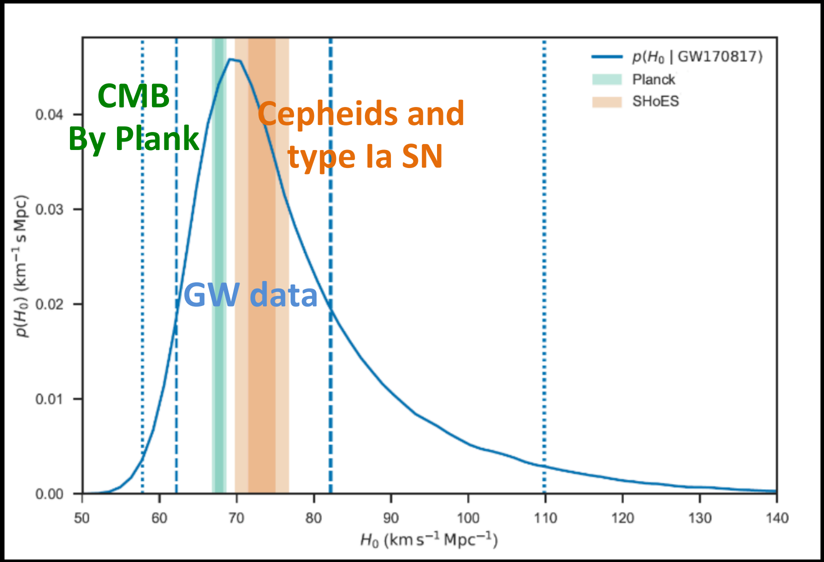
and 40 Mpc distance
→ difference speed of gravity and speed of light between

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

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



Recession velocity /redshift

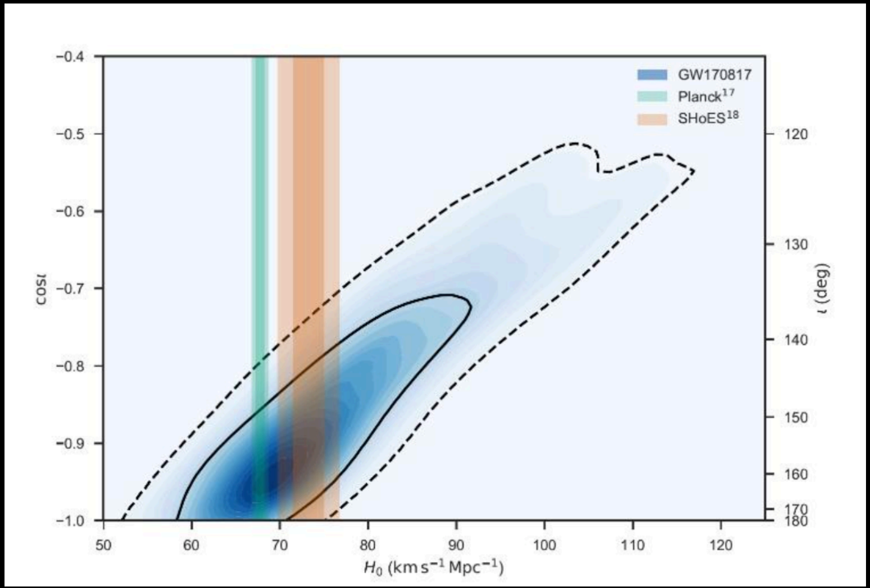
GW distance

$v_H = H_0 d$ Combining the distance

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

and NGC4993 recession velocity

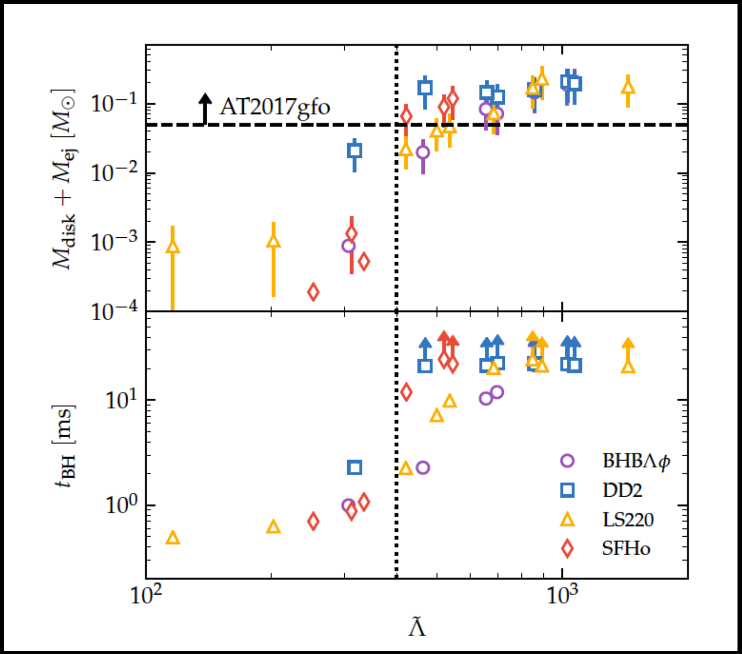
→ $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



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

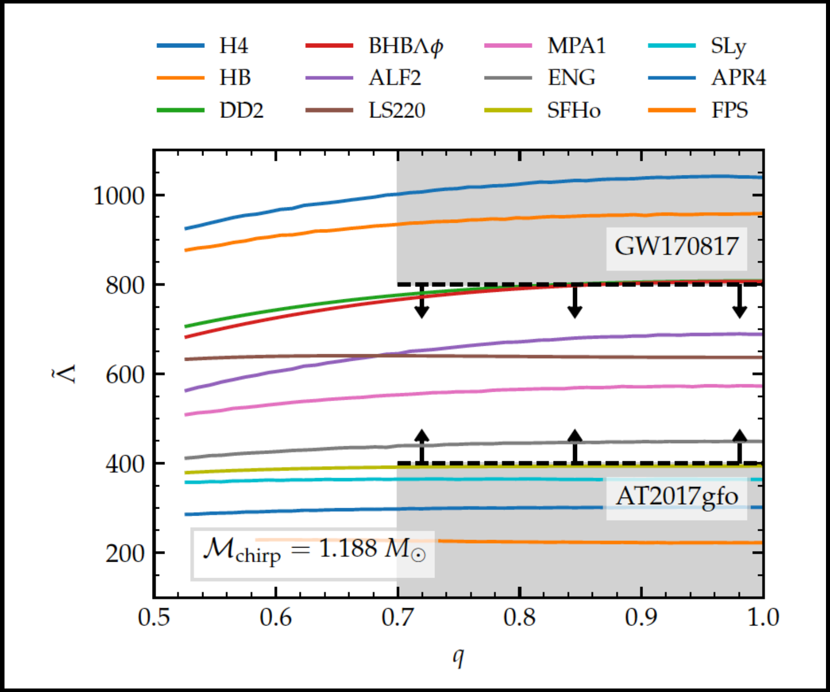
MULTIMESSENGER CONSTRAINTS ON NUCLEAR EOS

Simulations in NR



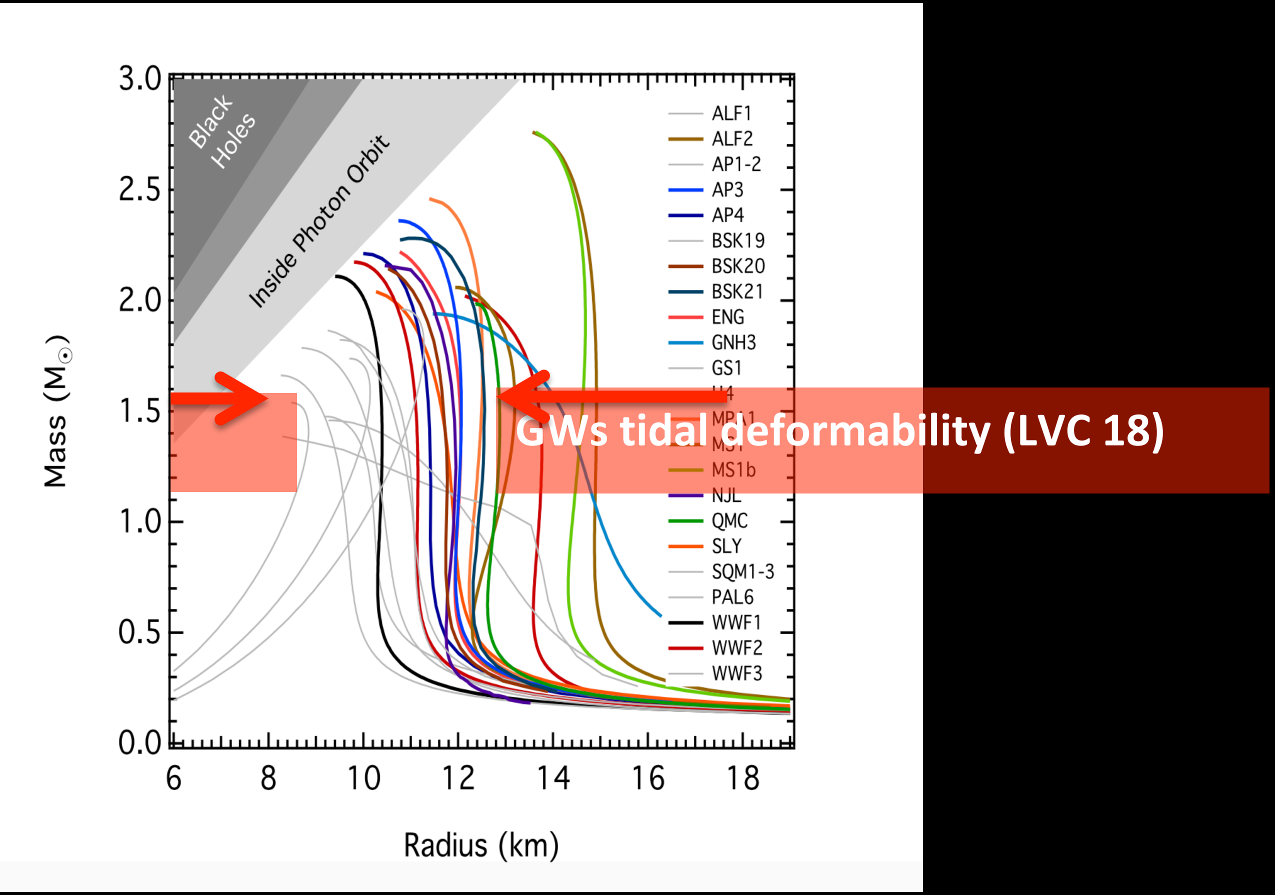
EM observations → Mej,tot > 0.05Mo suggests a lower limit Λ > 400

EM observations exclude very soft EOS!



Radice, Perego, Zappa, Bernuzzi 2017

EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs



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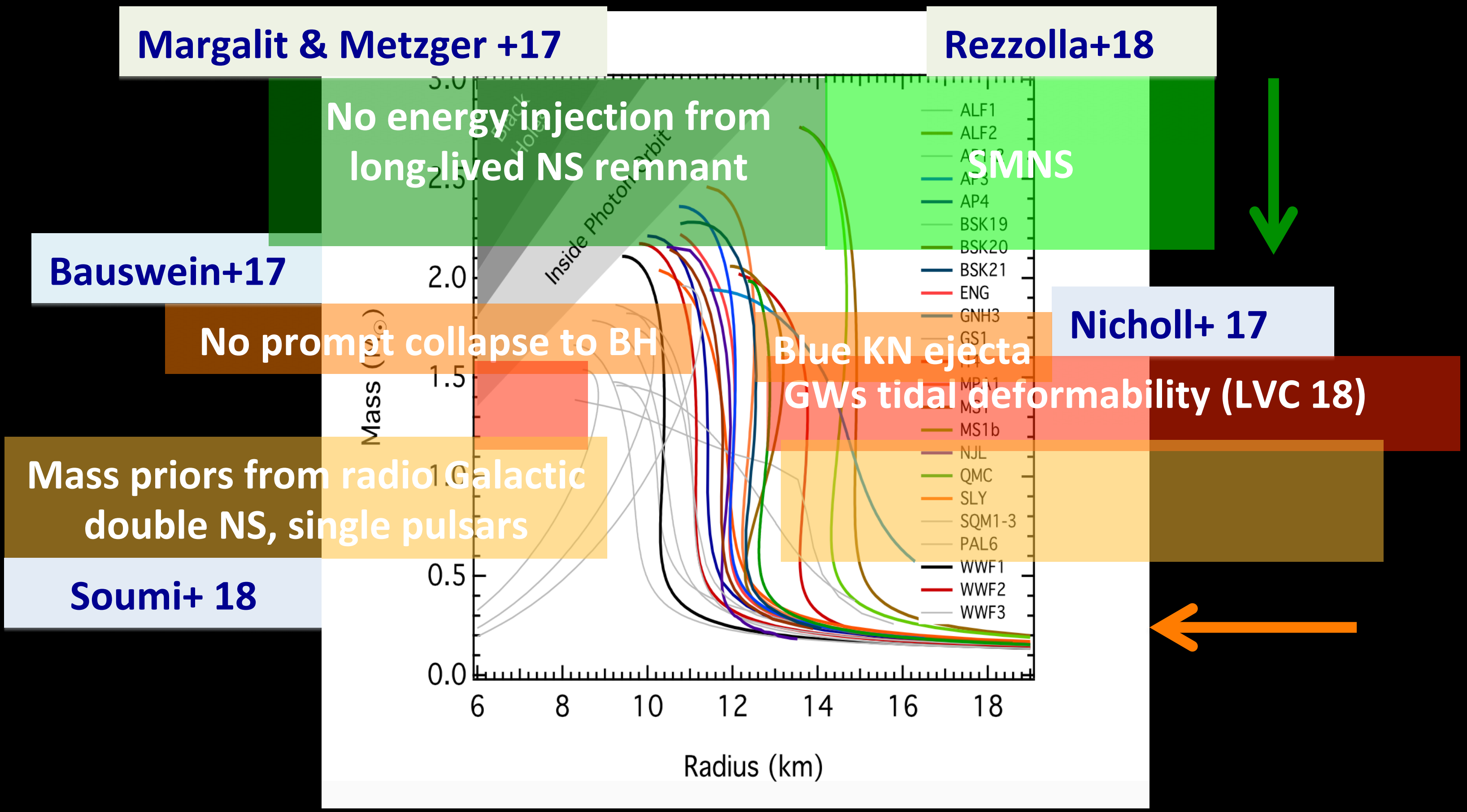
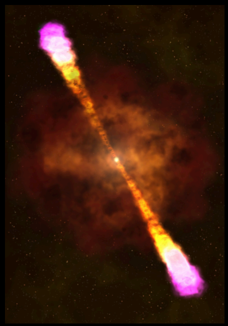
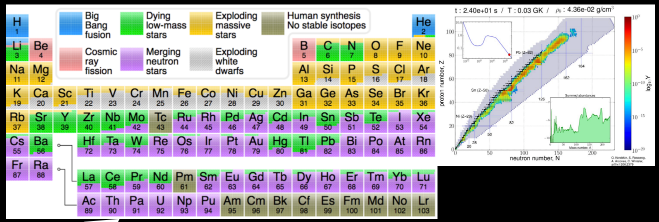


Radioactively powered transients

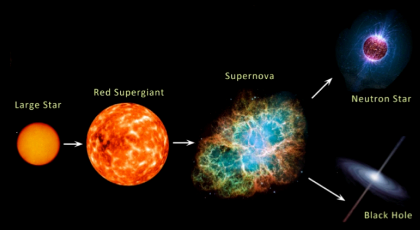
Relativistic astrophysics



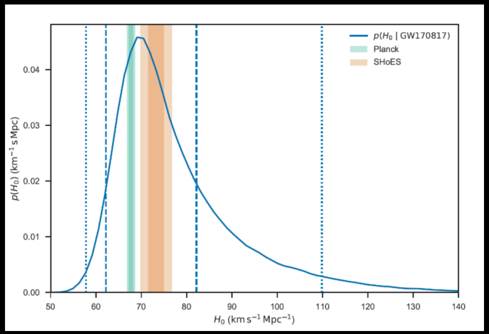
Nucleosynthesis and enrichment of the Universe



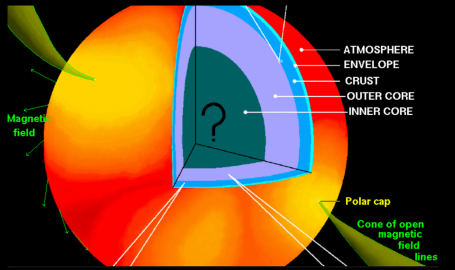
Compact object formation and evolution



Cosmology

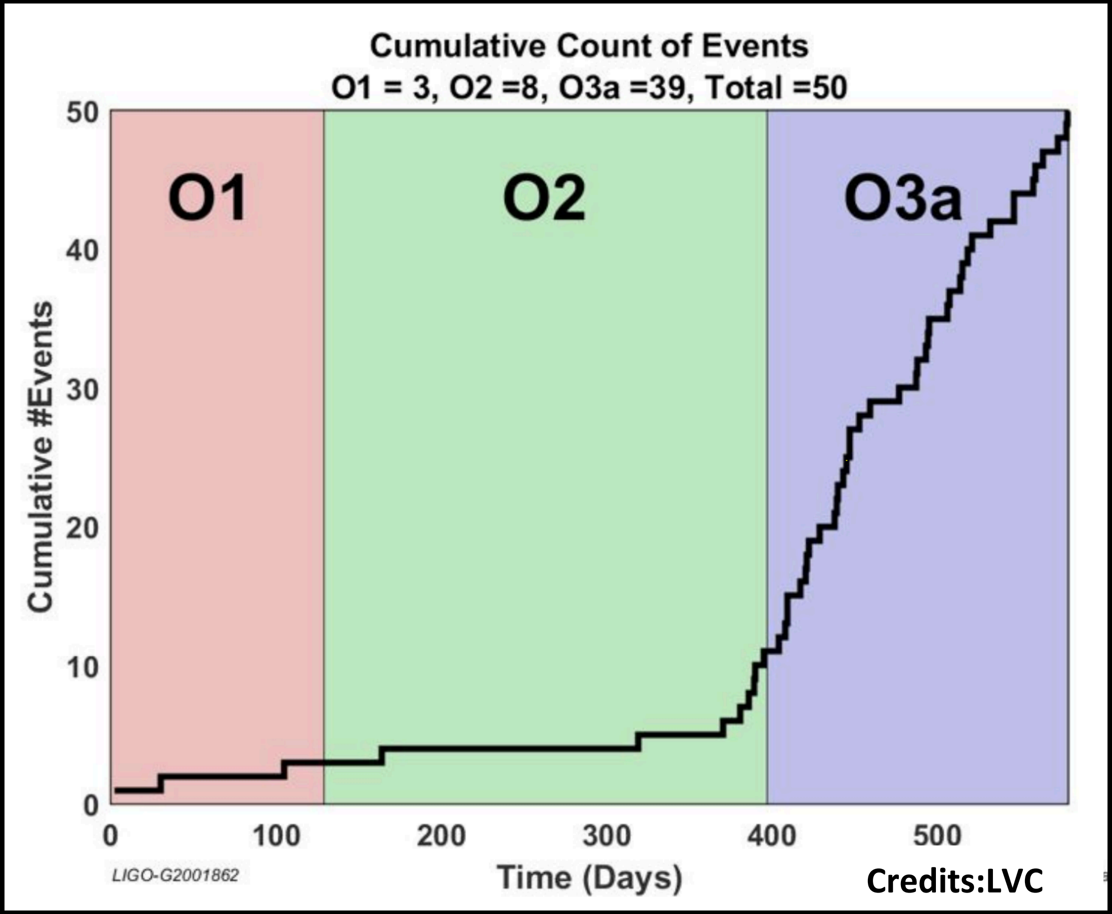


Nuclear matter physics



First run O1, second run O2,
and half of third run O3a

O3a Event Rate



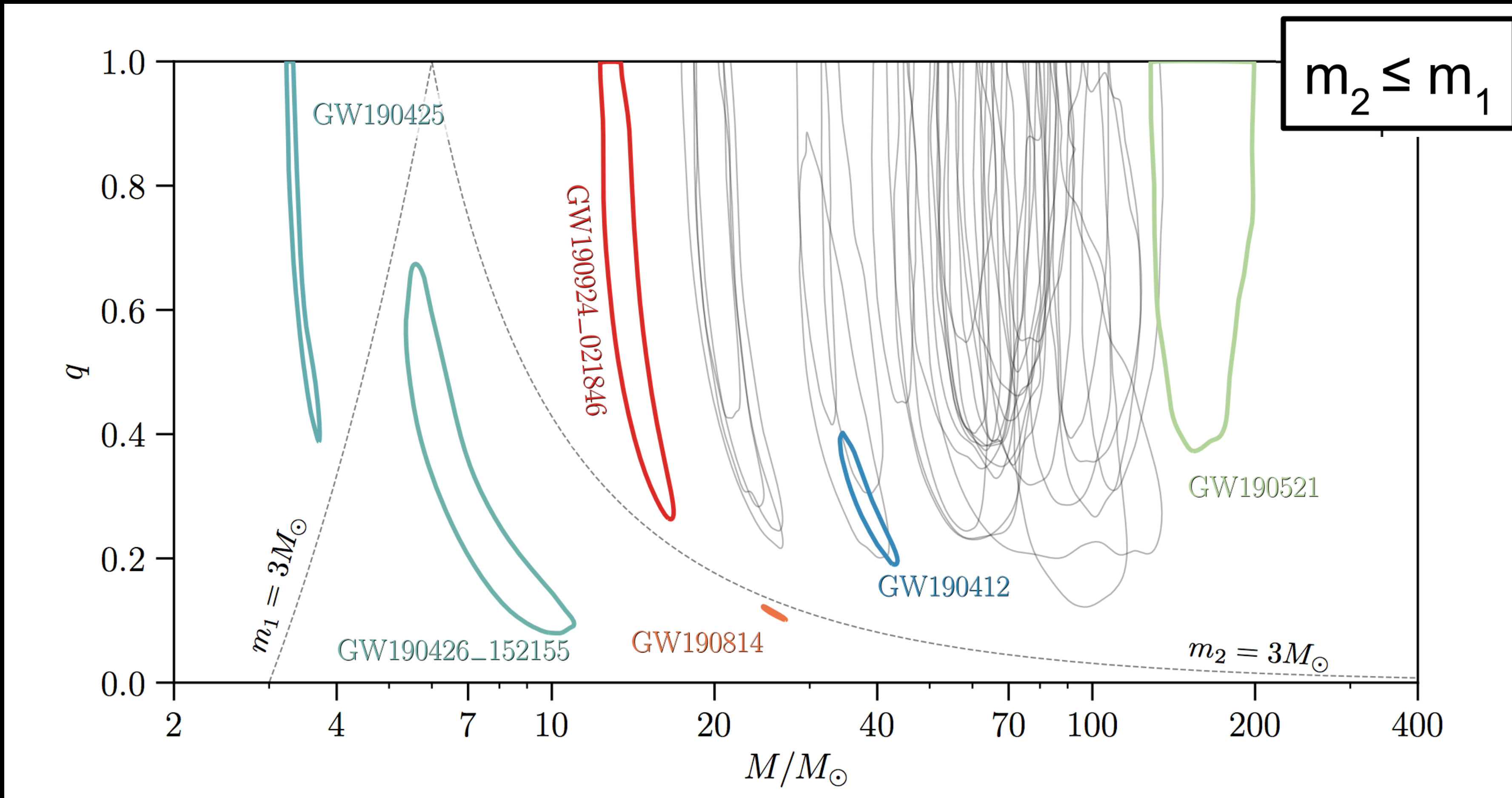
LVC Catalog paper, arXiv: 2010.14527

39 candidate GW events in ~26 weeks of O3a (FAR 2 per year → contamination fraction of less than 10%)

26 candidate events
low-latecy reported
in GCN alerts
+
13 candidate events
offline analysis

O1, O2, O3 → 50 candidate GW events

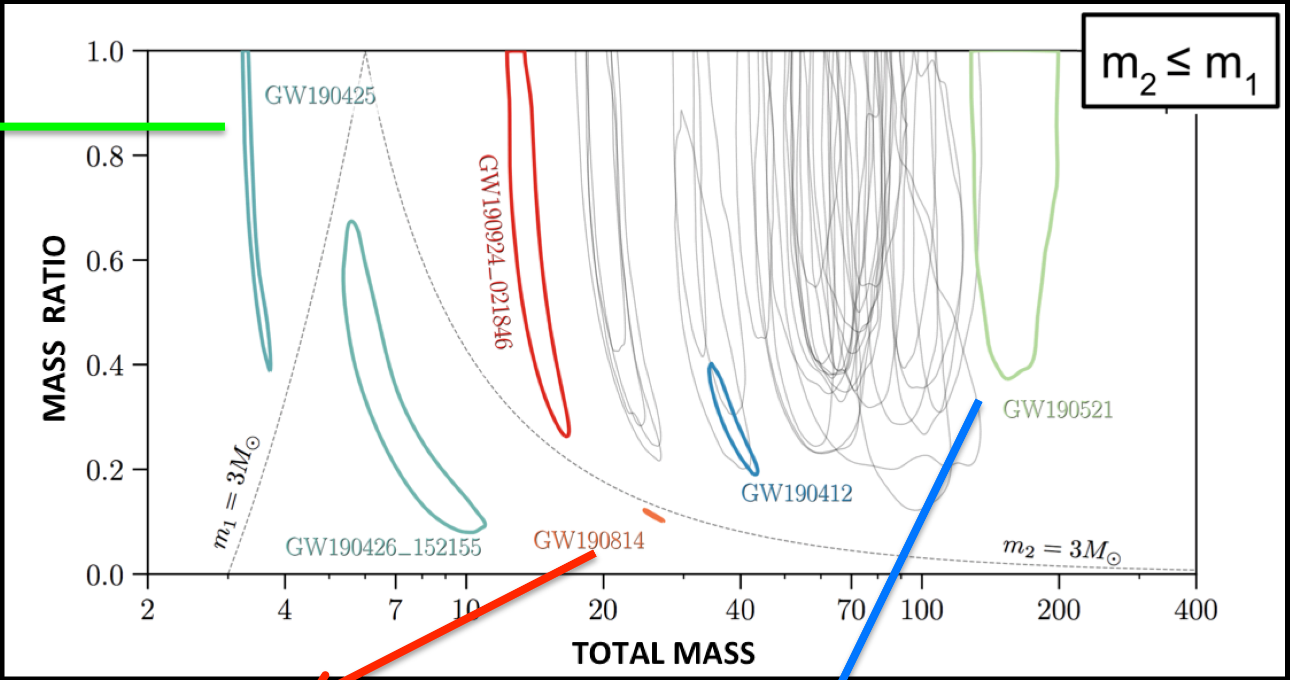
TOTAL MASS vs MASS RATIO



LVC Catalog paper, arXiv: 2010.14527

Notable candidate events

GW190425:
m1 and m2 < 3 Mo
Consistent with BNS

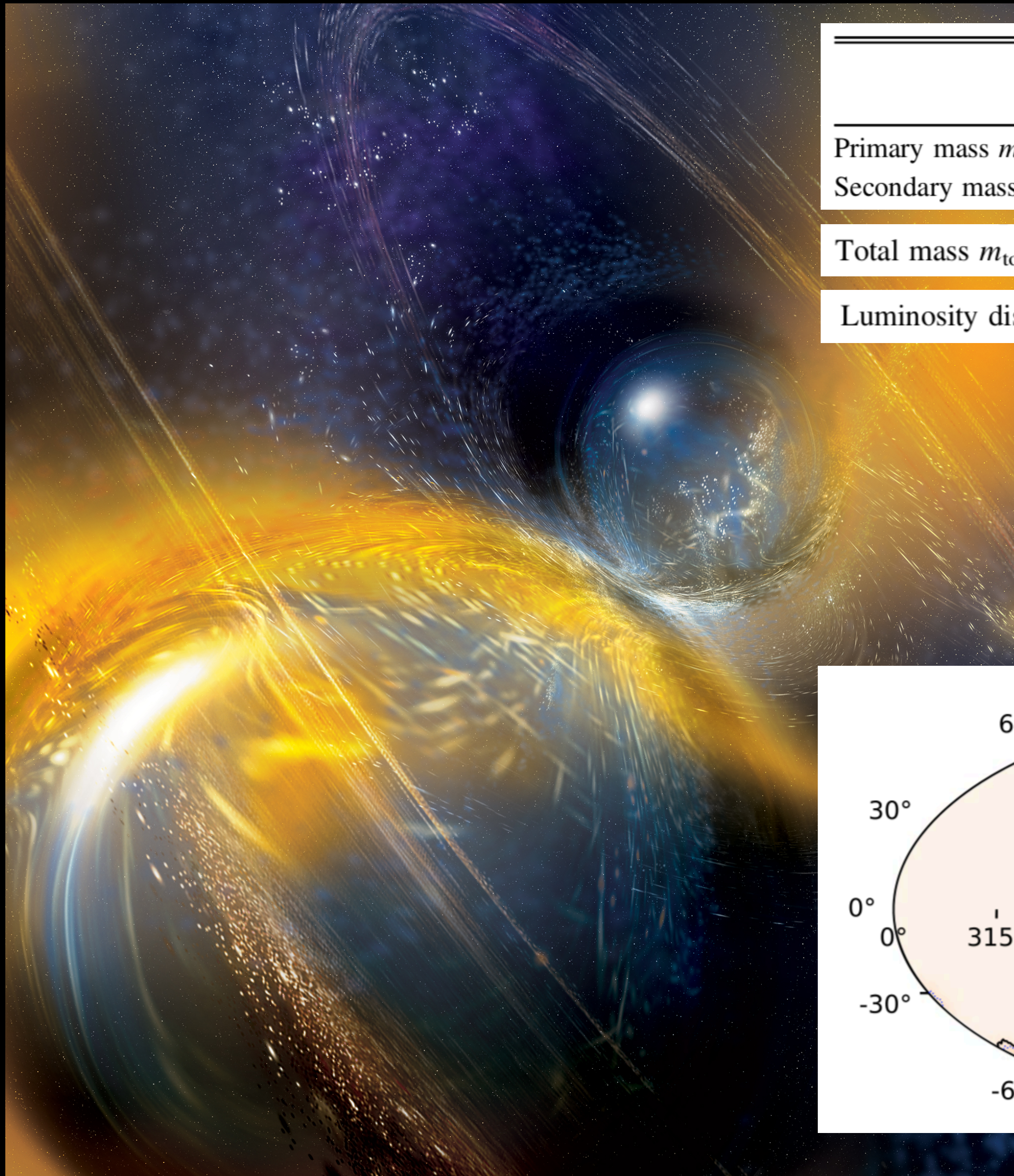


GW190814: m2 < 3Mo
NSBH or BBH?

GW190521:
most massive component BHs
→ intermediate massive BH

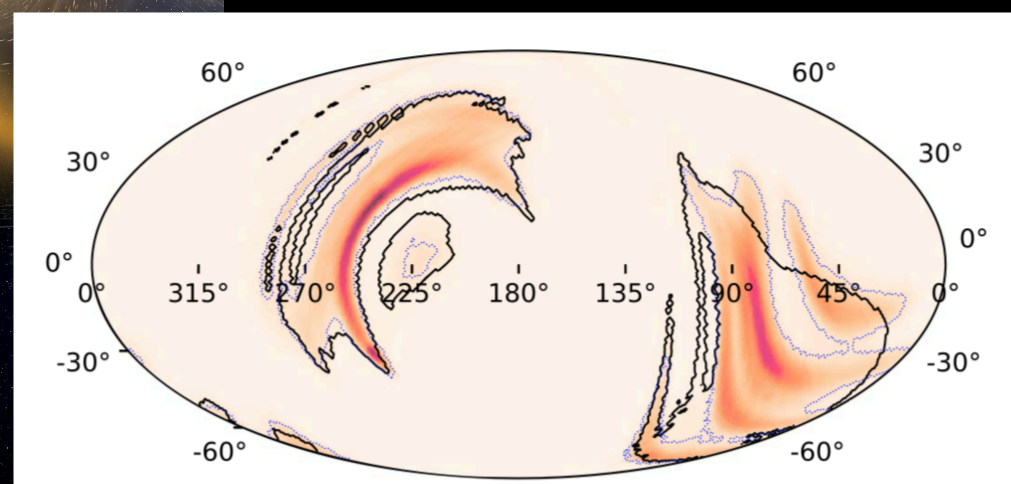
LVC Catalog paper, arXiv: 2010.14527

GW190425: another BNS detection!



	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}$ M$_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc

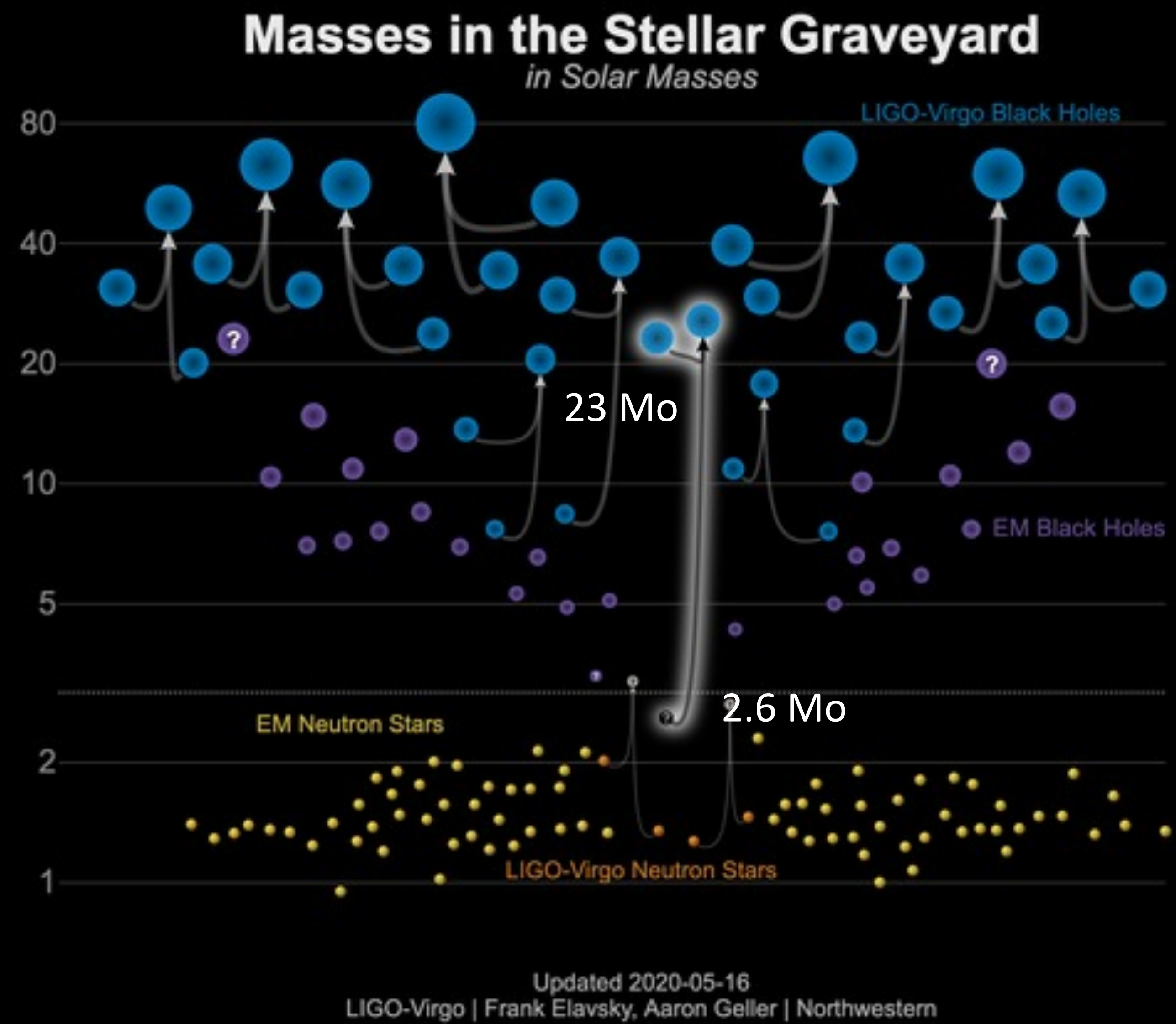
NO firm EM counterpart!



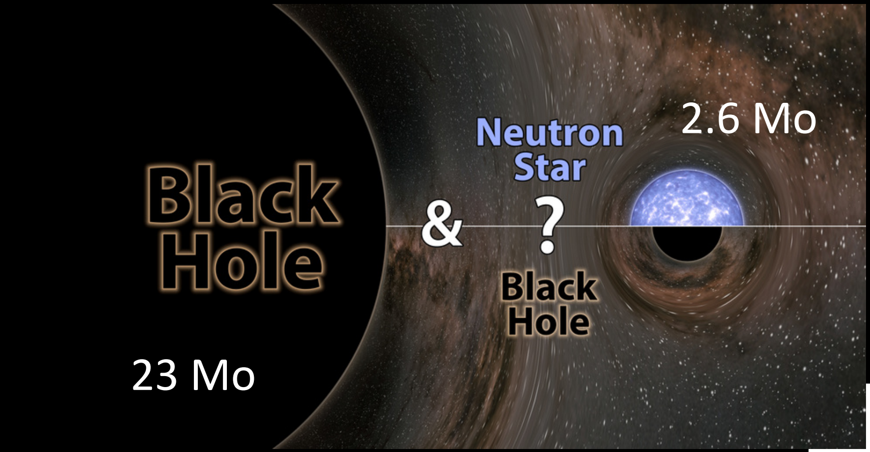
Sky localization of 8284 deg^2

Abbott et al. 2020, ApJL, 892

GW190814: FIRST NS-BH or low-mass BBH?



GW190814

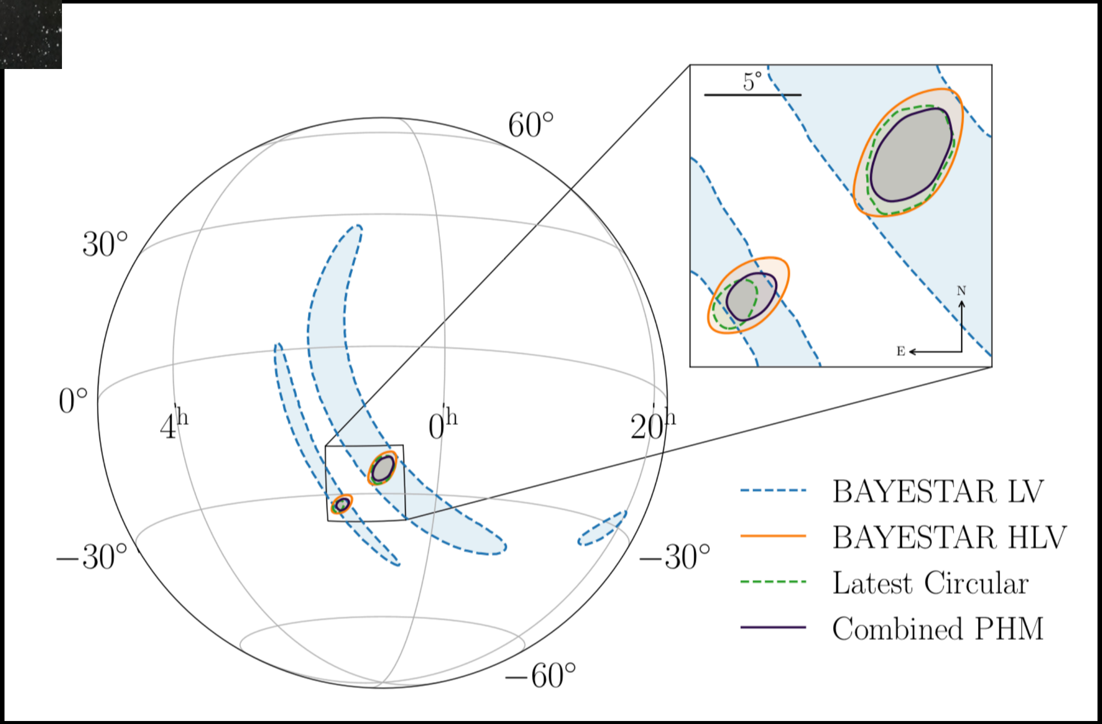


- NO evidence of measurable tidal effects in the GW signal
- NO EM counterpart

→ *Consistent with both BBH and NSBH scenarios*

→ *In the NSBH, observation results can be explained by the large mass ratio*

Abbott et al. 2020, ApJL, 896

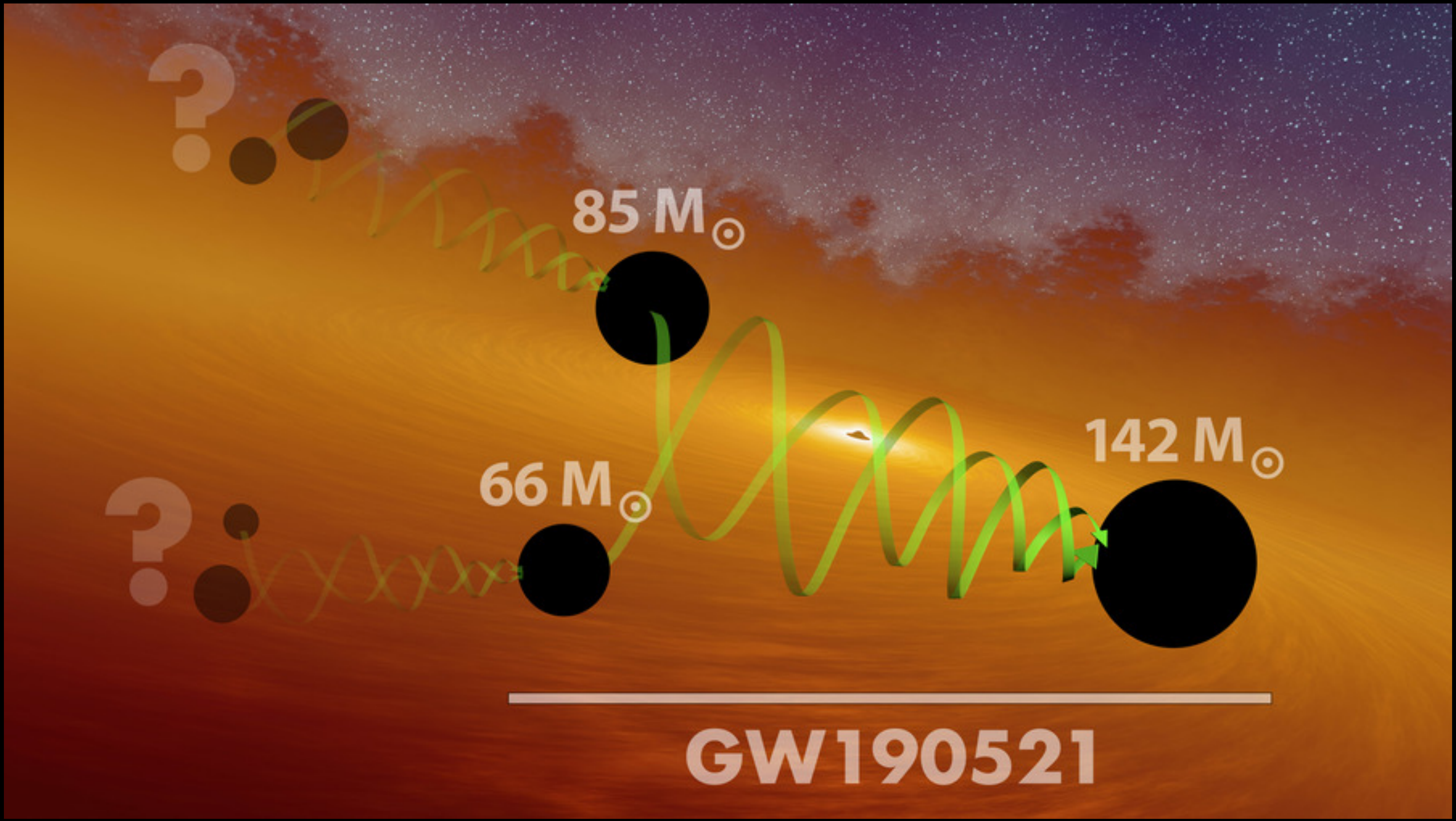


Sky localization of 18.5 deg^2

GW190521

The birth of a intermediate massive black-hole!

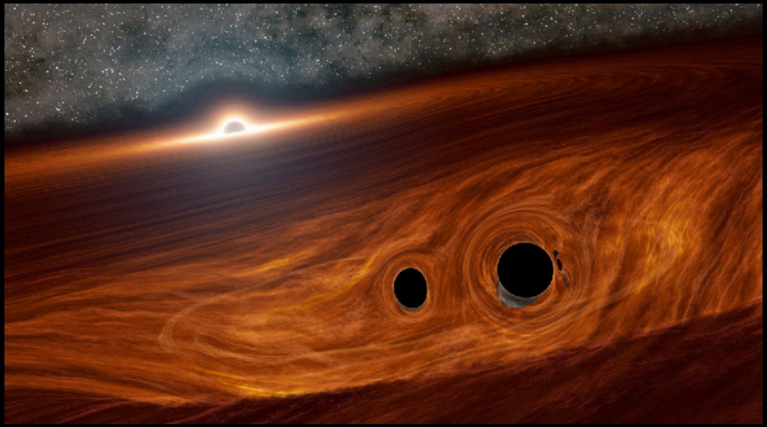
Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)



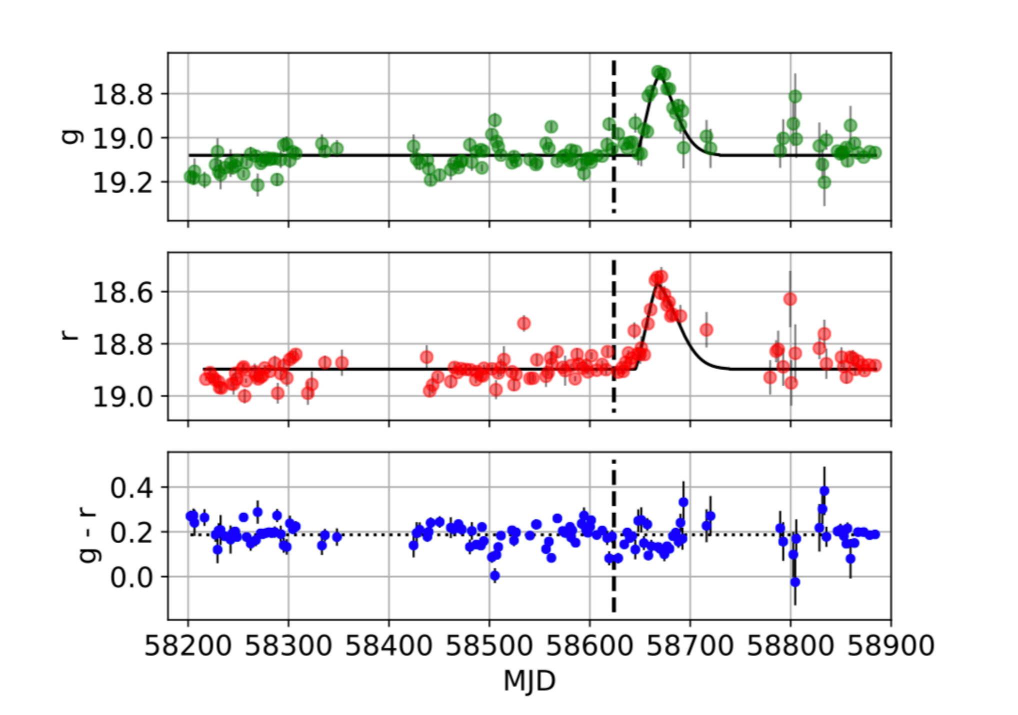
credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

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

BBH in the accretion disk of a supermassive black hole?



Caltech/R. Hurt (IPAC)



Graham et al 2020, PRL 124

ZTF detected a candidate counterpart(!?)

- EM flare close to AGN

~ 34 days after the GW event

- consistent with expectations for a kicked BBH merger in the accretion disk AGN
- 765 deg^2 localization area
- ZTF observed 48% of the 765 deg^2 (90% c.r.)

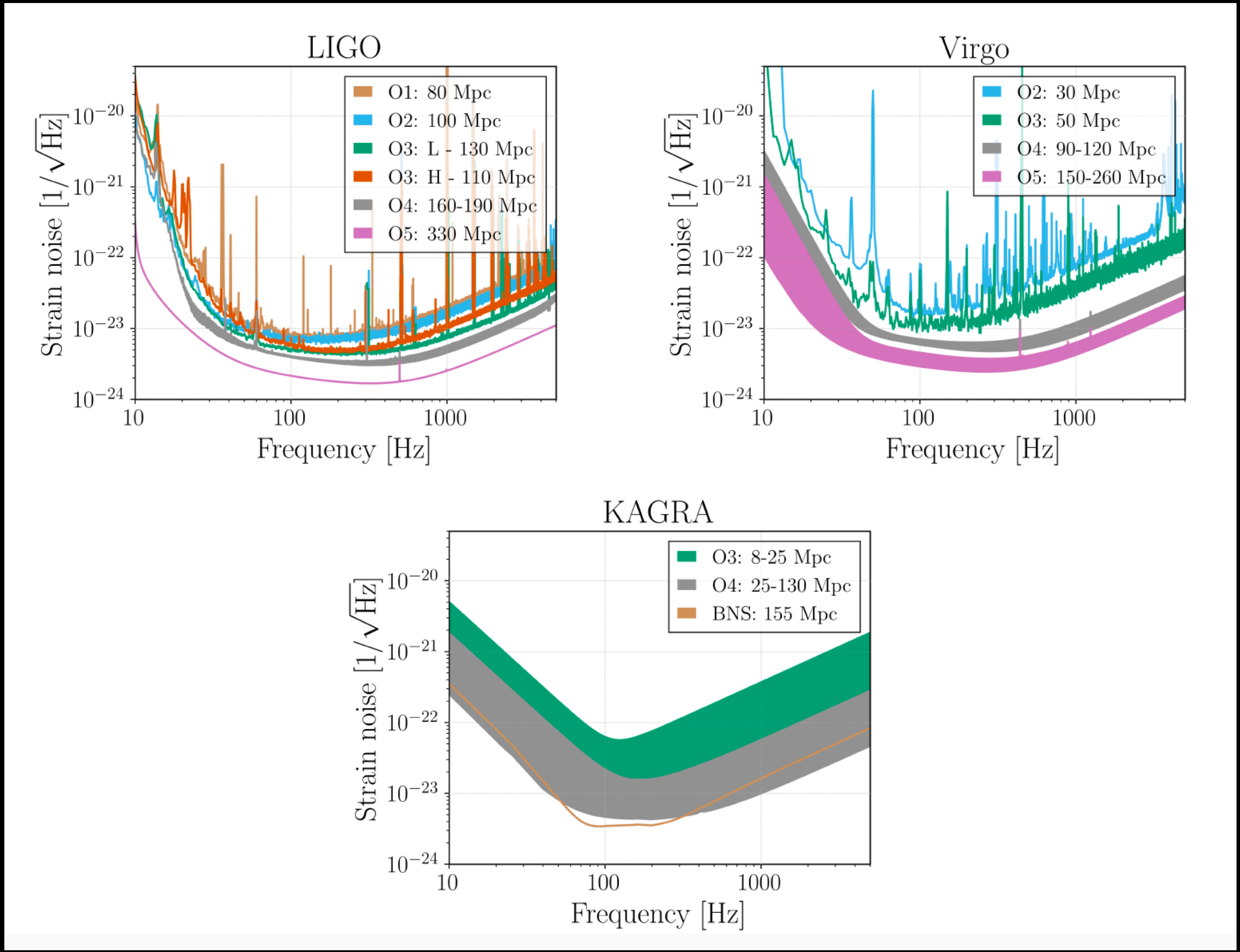
Next observating runs

A new window into the Universe

Credit: LIGO–Virgo

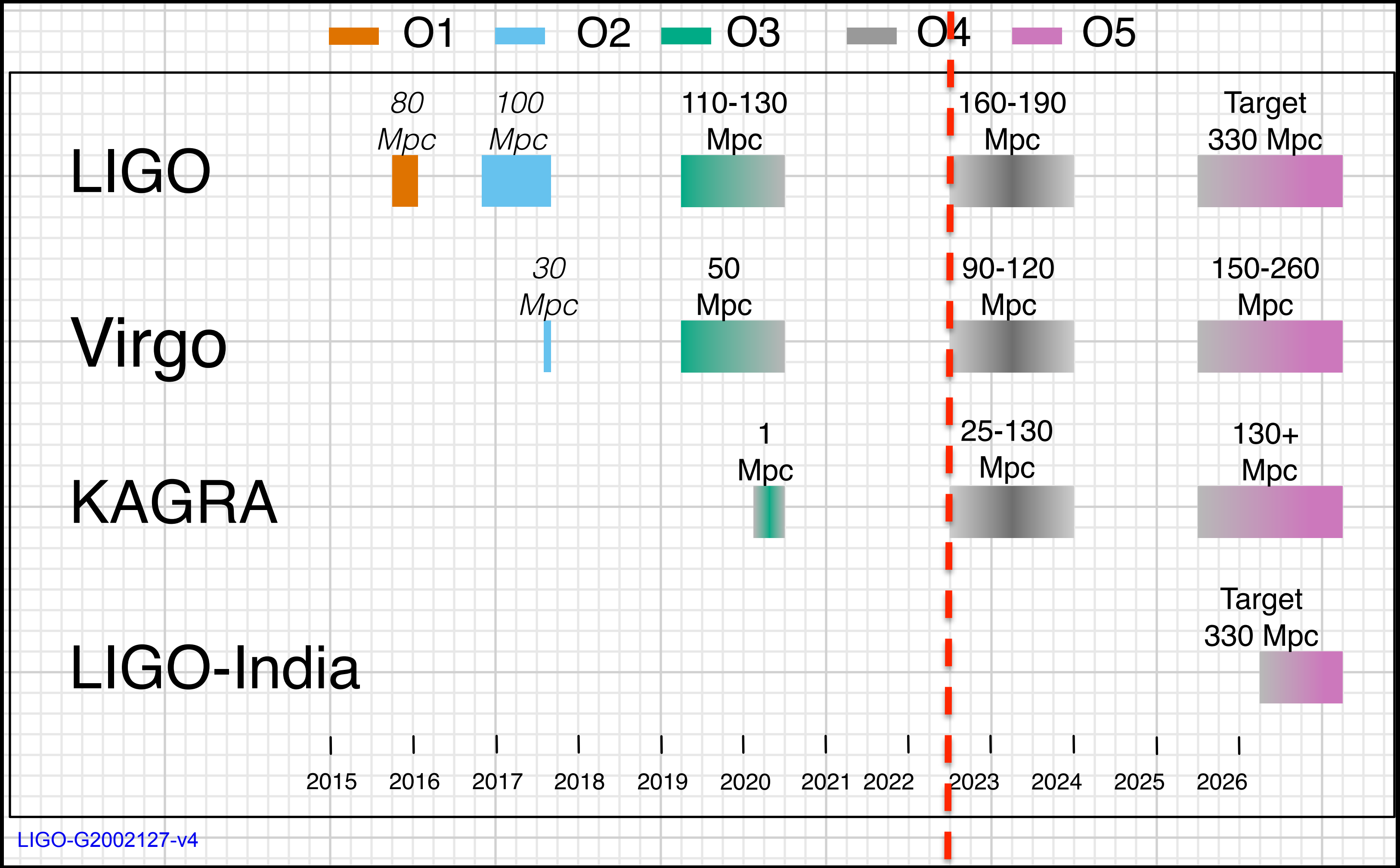
KAGRA, Japan

Strain sensitivities as a function of frequency



Abbott et al. 2020, LRR

Observing run timeline and BNS sensitivity evolution



Starting of 04 not before June 2022

LOCALIZATION: sky-area and volume

Abbott et al. 2020, LRR

		BNS	NS-BH	BBH
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

Detection: SNR > 4 in at least two detectors and network SNR > 12

EXPECTED NUMBER OF DETECTIONS FOR O3 and O4

detection counts per one-calendar-year observing run

Observation Run	Network	Expected BNS Detections
O3	HLV	1^{+12}_{-1}
O4	HLVK	10^{+52}_{-10}

Detection: SNR > 4 in
at least two detectors
and network SNR > 12
About FAR < 1/100 yr

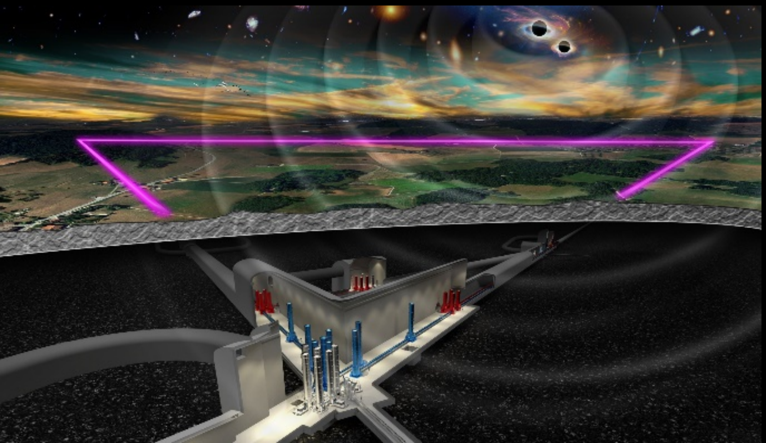
3G detector

The European 3G idea

EINSTEIN TELESCOPE

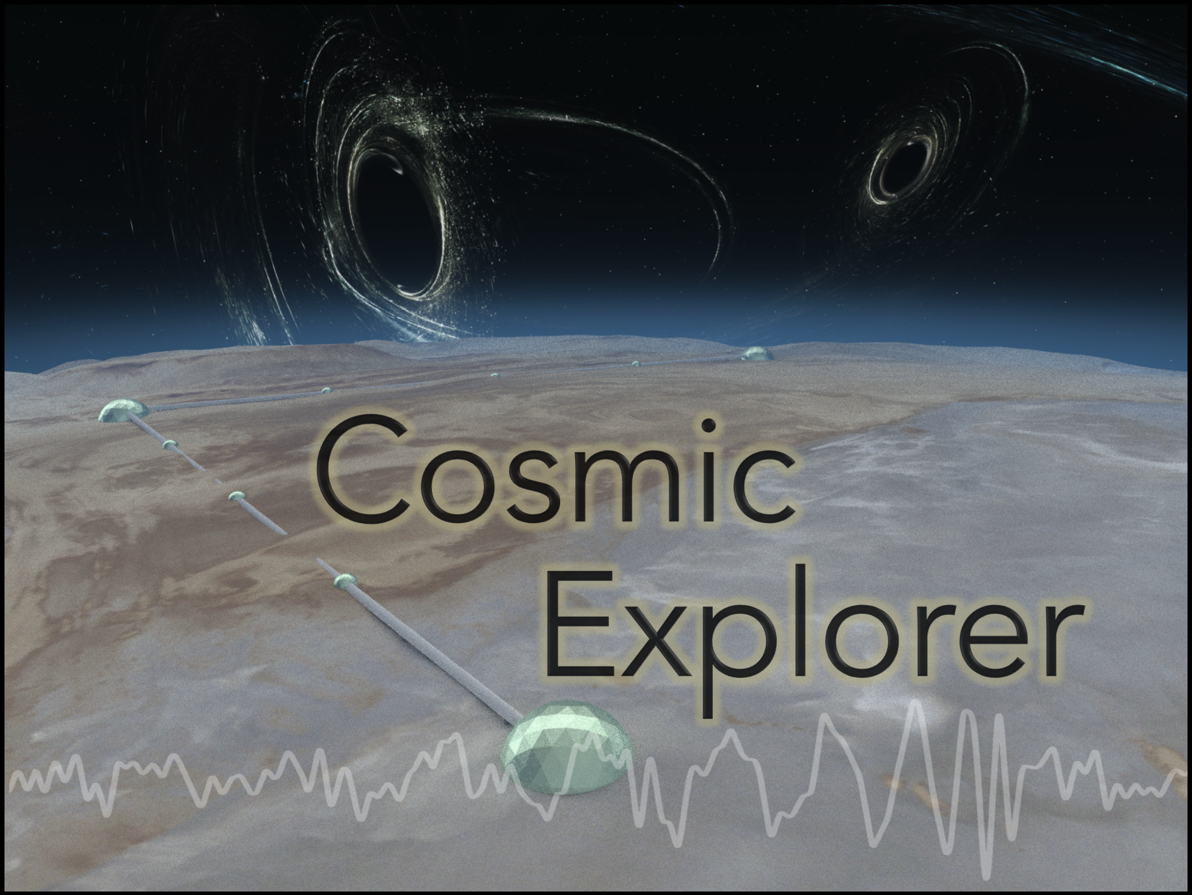
Europe we developed the idea of a 3G GW observatory

- Factor 10 better (x1000 Volume) than Advanced (2G) detectors
- Wide frequency, with special attention to low frequency (few HZ)
- Capable to work alone (but aiming to be in a 3G network)
- 50-years lifetime of the infrastructure

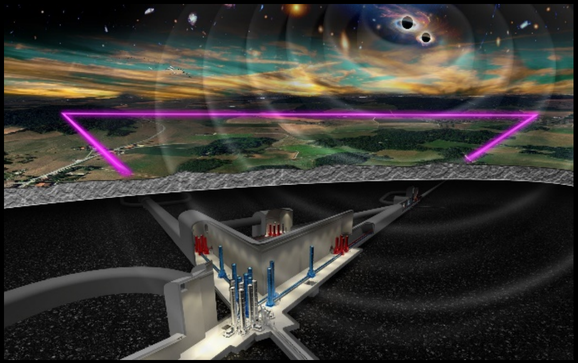


ESFRI proposal submitted in September

3G effort worldwide

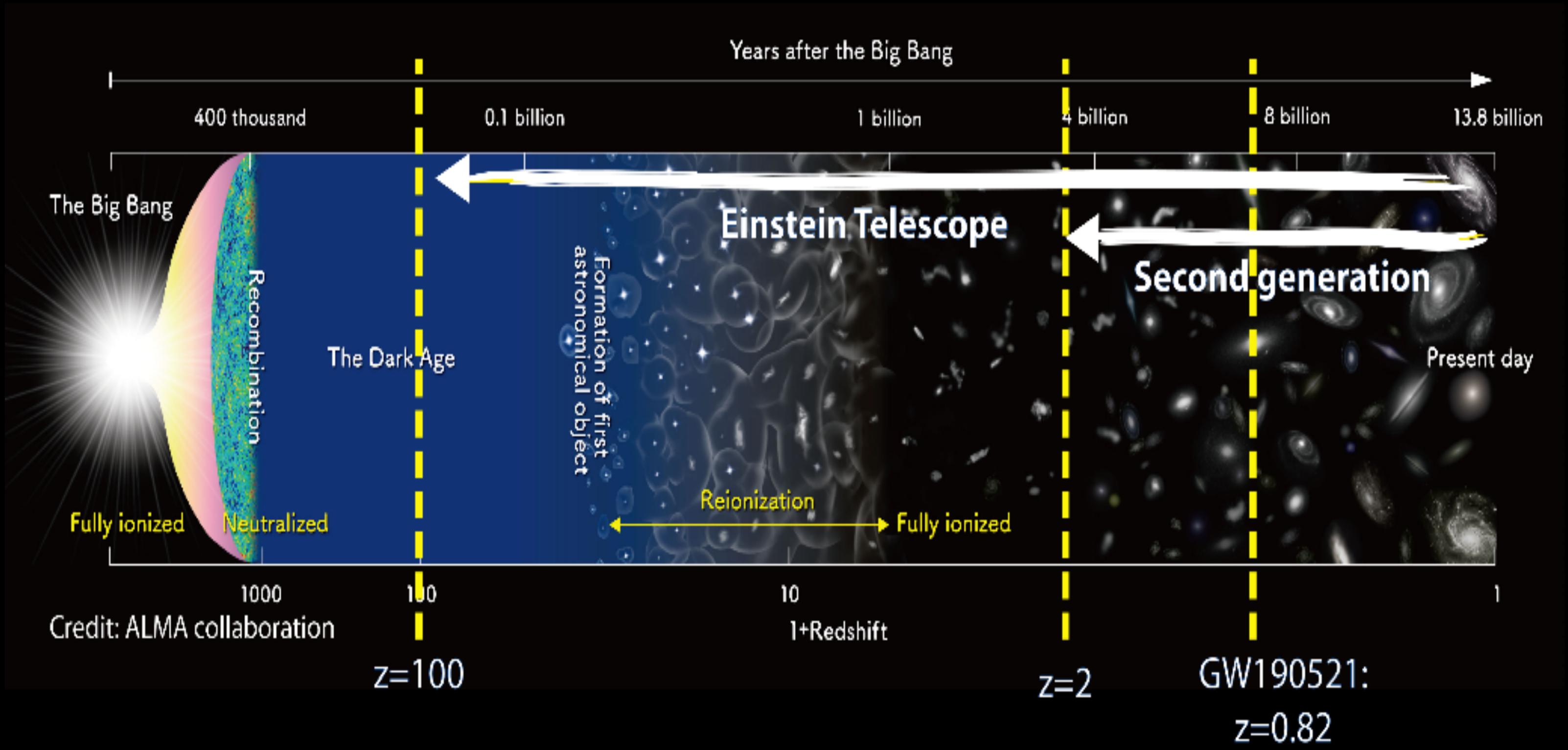


NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector



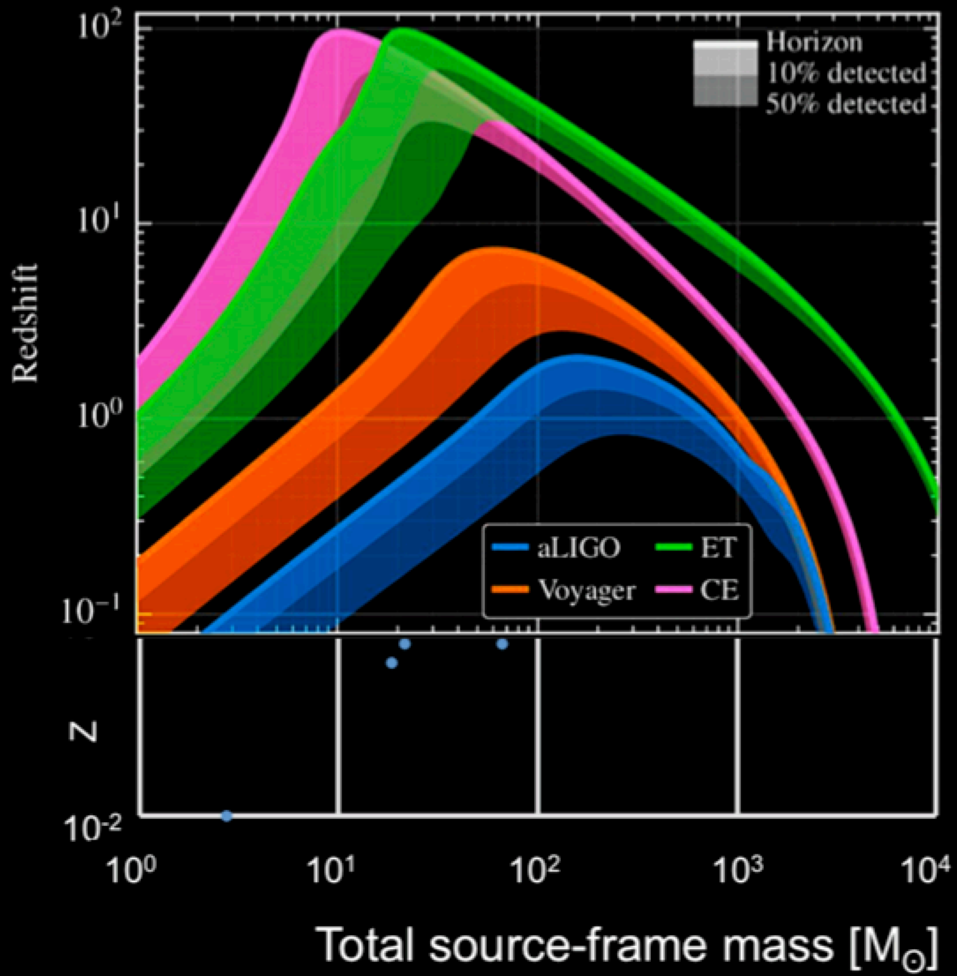
Einstein Telescope

Detection horizon for black-hole binaries



What ET and future EM observatories can do?

Binary systems of Compact Objects



- Study BNS/NSBH/BBH along the cosmic history
- Large increase of detatction rate
- Better parameter estimation

Kilonova/GW - EOS constrains

Kilonova/GW - Nucleosysthesis

GRBs – BNS/NSBH merger up to high z

Relativistic jet properties

Jet-less/jet GRBs

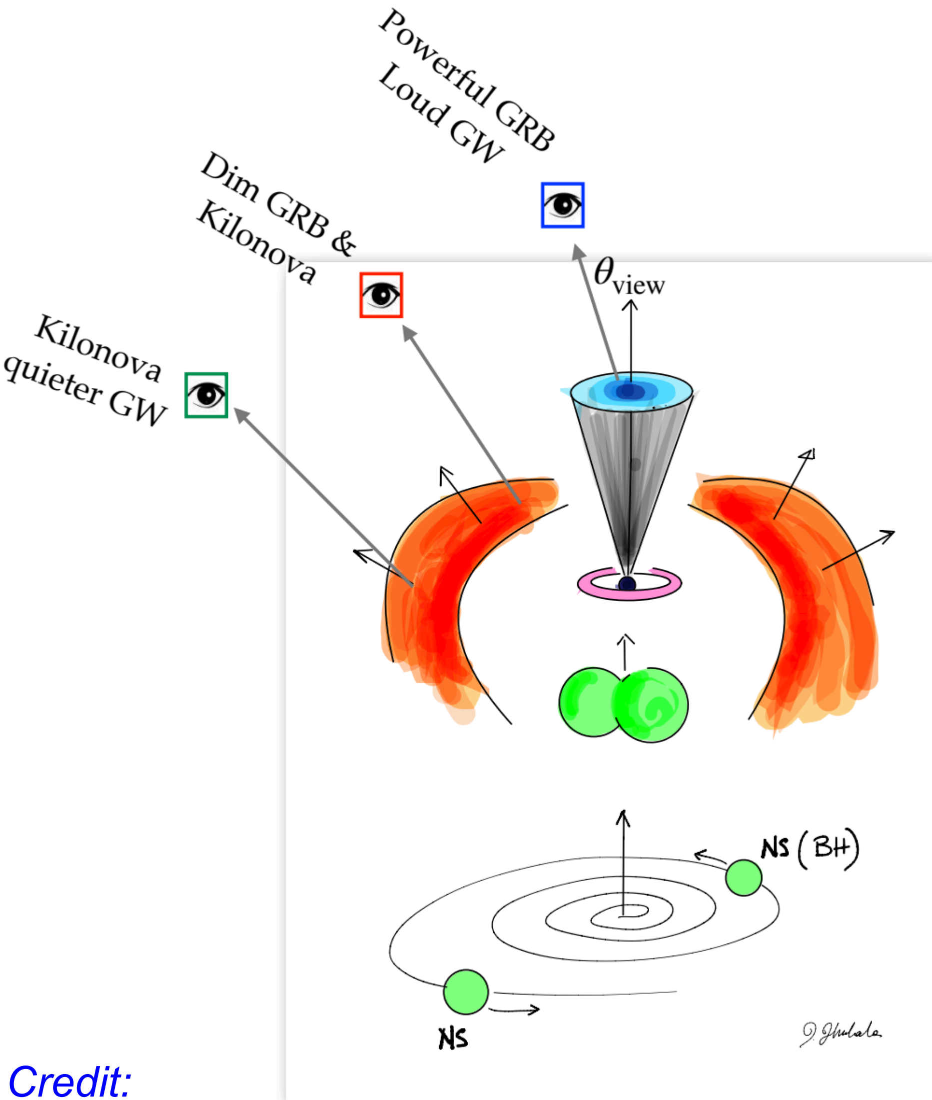
GRB/stable NS remnant

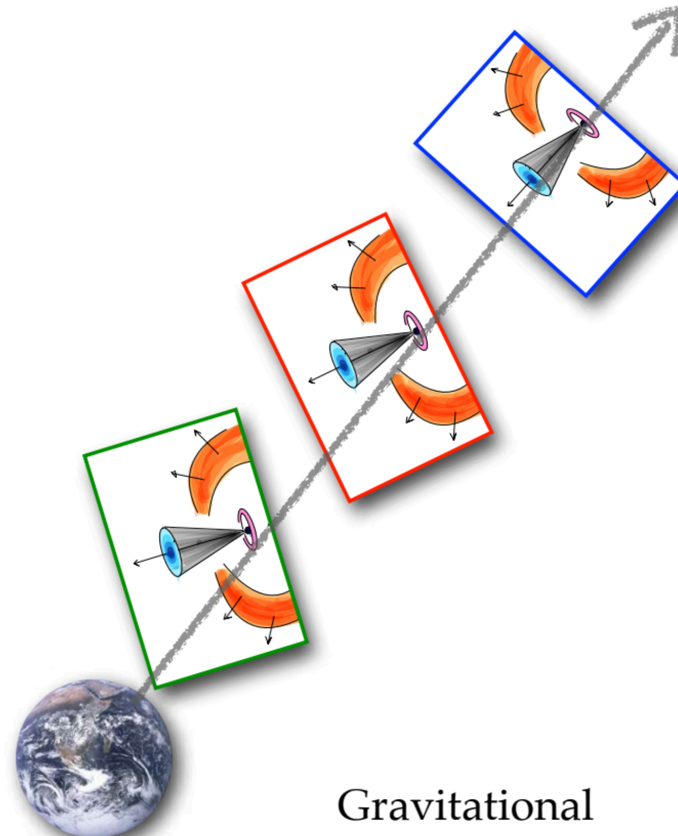
Link to Star Formation History

Emission mechanism

Cosmology

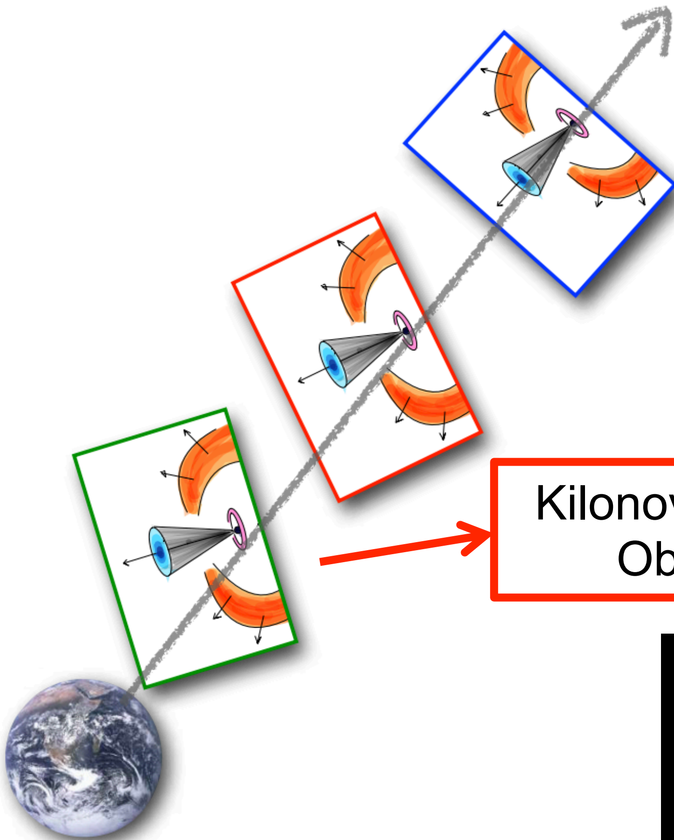
10^5 BBH detections per year
10^4 BNS detections per year





Gravitational
&
Electromagnetic
ranges

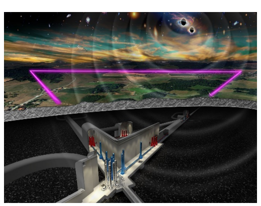
Credit: Ghirlanda



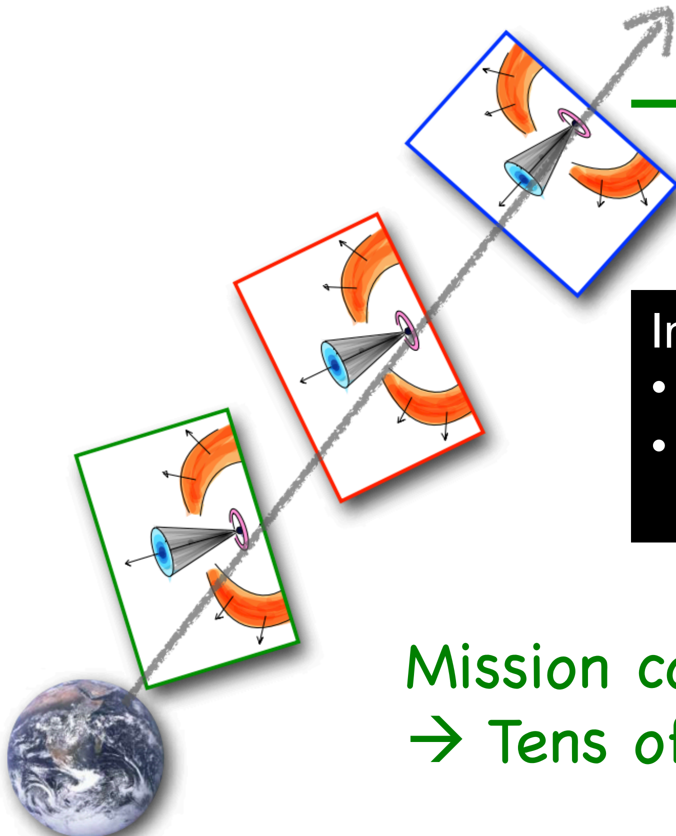
Kilonovae detectable by the Vera Rubin Observatory survey up to 1 Gpc

In this volume

- ET about 100 event per year have sky loc < 10 sq. degrees
- For ET+LVKI 10^3 per year have sky loc < 10 sq. degrees



A few tens of joint detections!



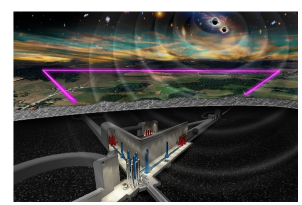
High-energy Kev-MeV GRB

In this volume

- ET poor sky localization
- For ET+CE order of 10^3 events per year with sky loc < 10 sq. degrees

Mission concept THESEUS (wide FoV)

→ Tens of joint detections!



Next decades multi-messenger observatories