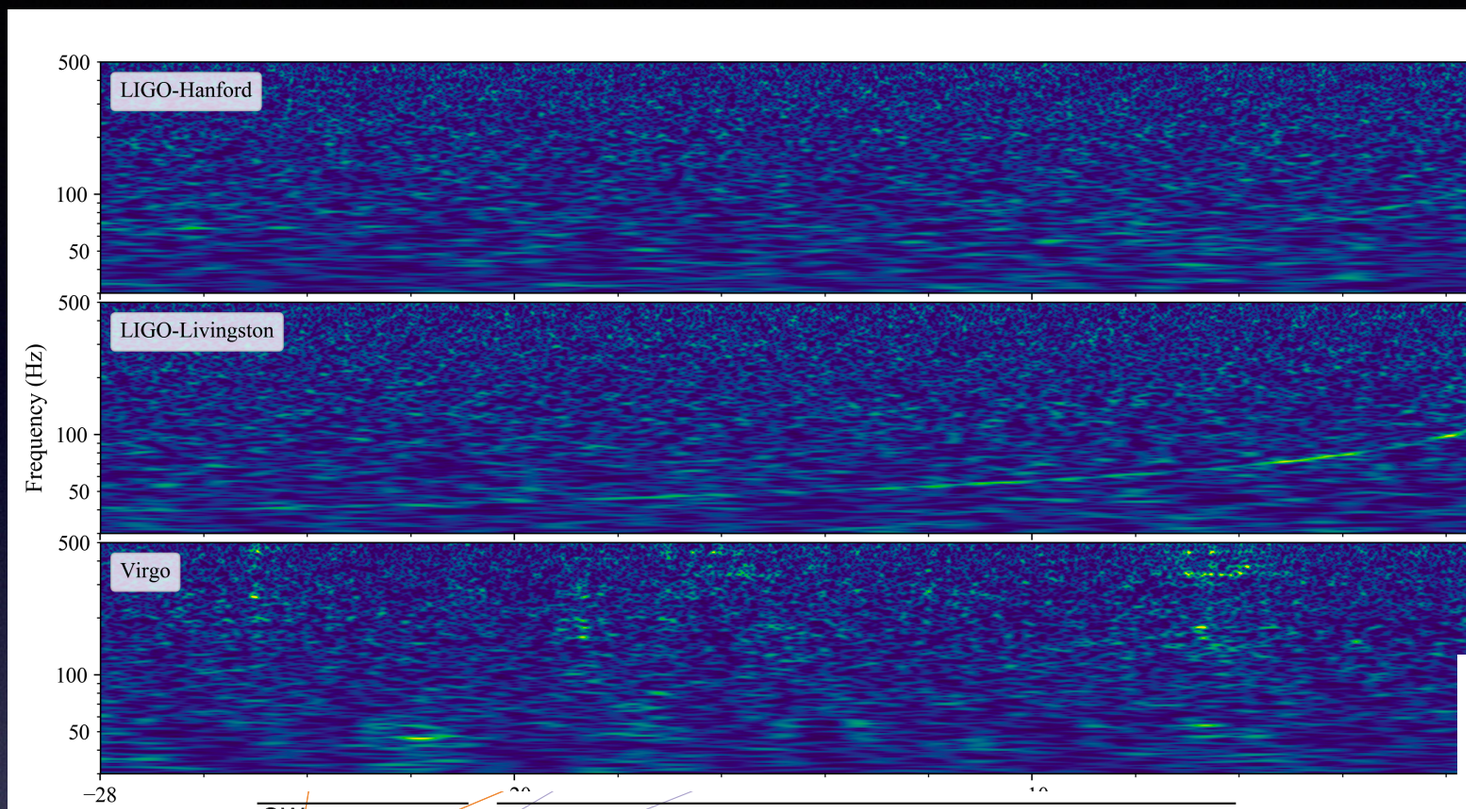
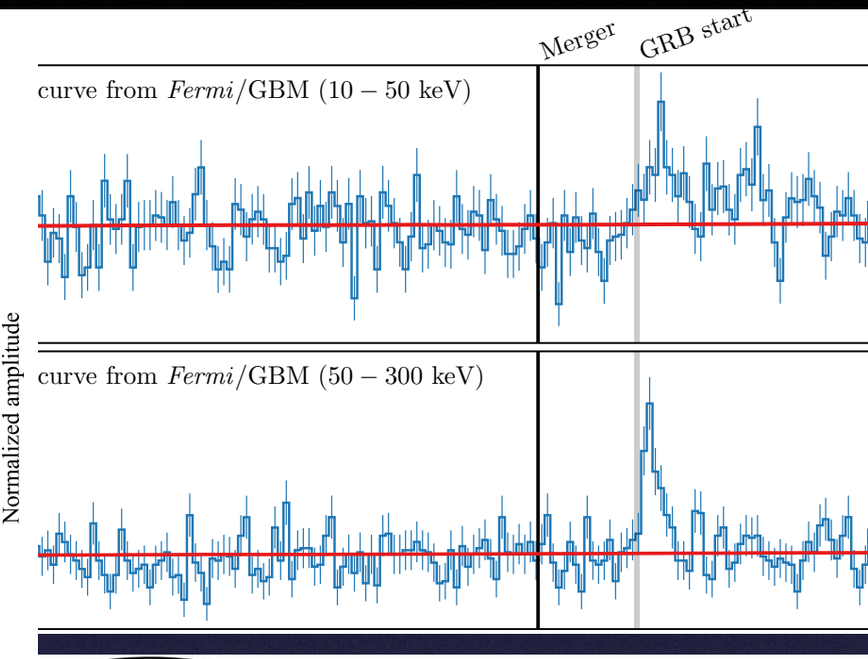
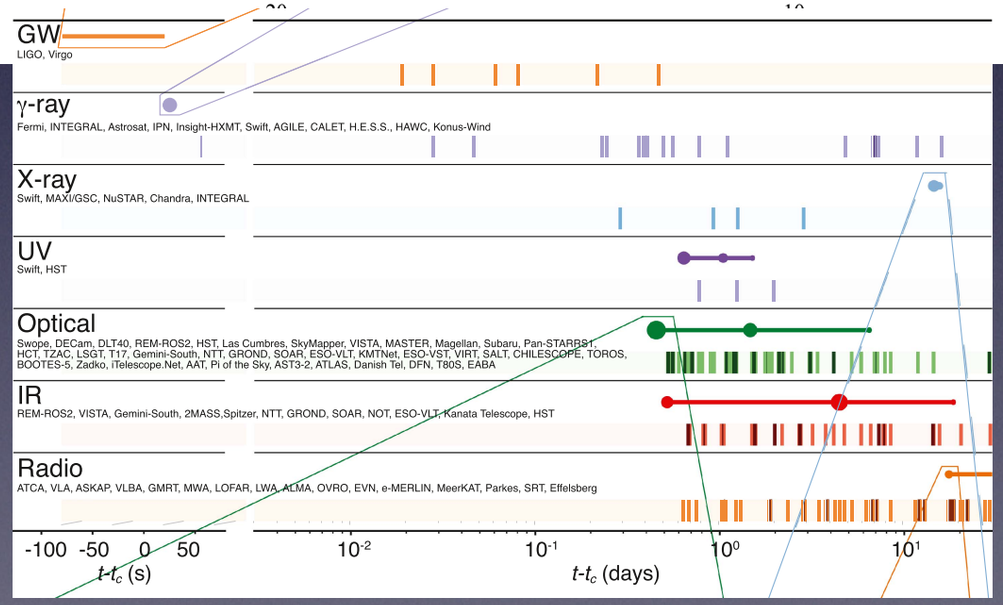
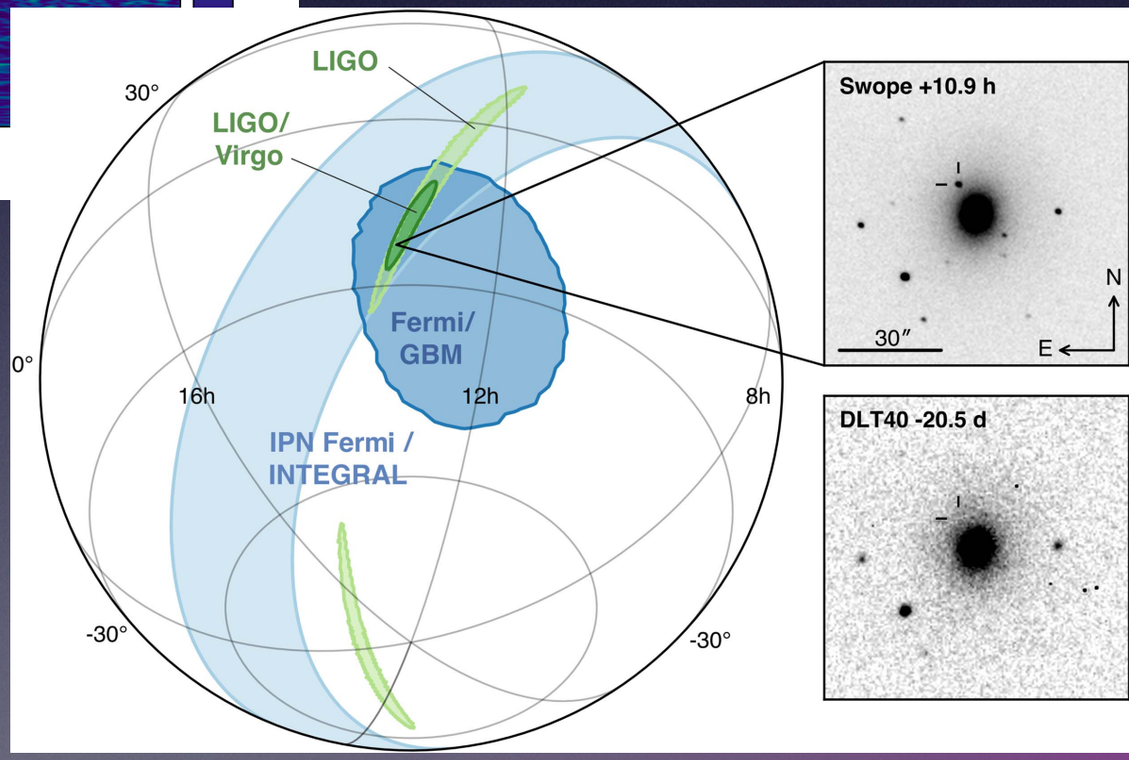
Multi-Messenger Observations of a Binary Neutron Star Merger









NORTHWESTERN UNIVERSITY

Vicky Kalogera

for the LIGO-Virgo Collaborations

CIERA

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
Whitman College
American University
University of the West of Scotland
UWS
Texas Tech University
Tsinghua University
Rochester Institute of Technology
Leland Stanford Junior University
Max Planck Institute for Gravitational Physics
Albert Einstein Institute
University of Strathclyde
Michigan
PAH
CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique theo
Università degli Studi del Sannio
Massachusetts Institute of Technology
NASA
Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
The University of Chicago
Montana State University
ACU
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The University of Adelaide
Australia
Southern University
Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
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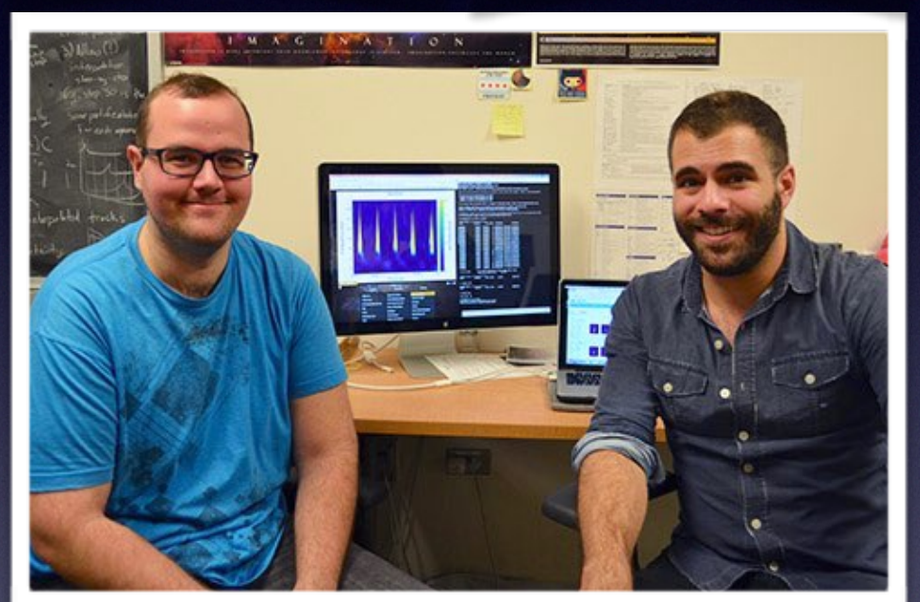
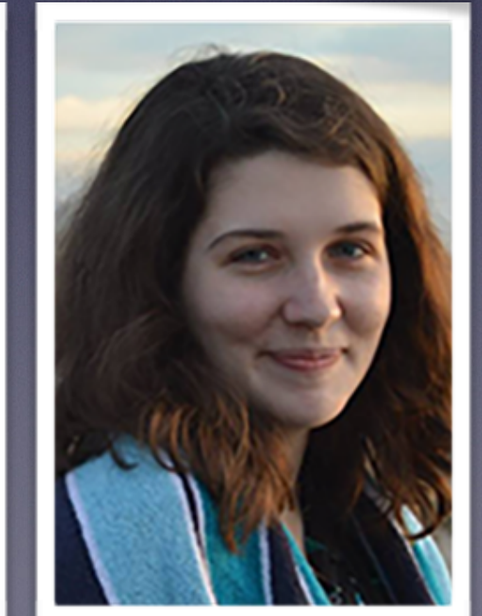
University of Wisconsin
UWMilwaukee
Universität Hamburg
Syracuse University
Suos Cultores Scientia Coronat
Founded AD 1870
Cardiff University
Prifysgol Caerdydd
Northwestern
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU
Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Penn State
1855
Hobart and William Smith Colleges
Science & Technology Facilities Council
Rutherford Appleton Laboratory

GW - EM @ Northwestern





C I E R A

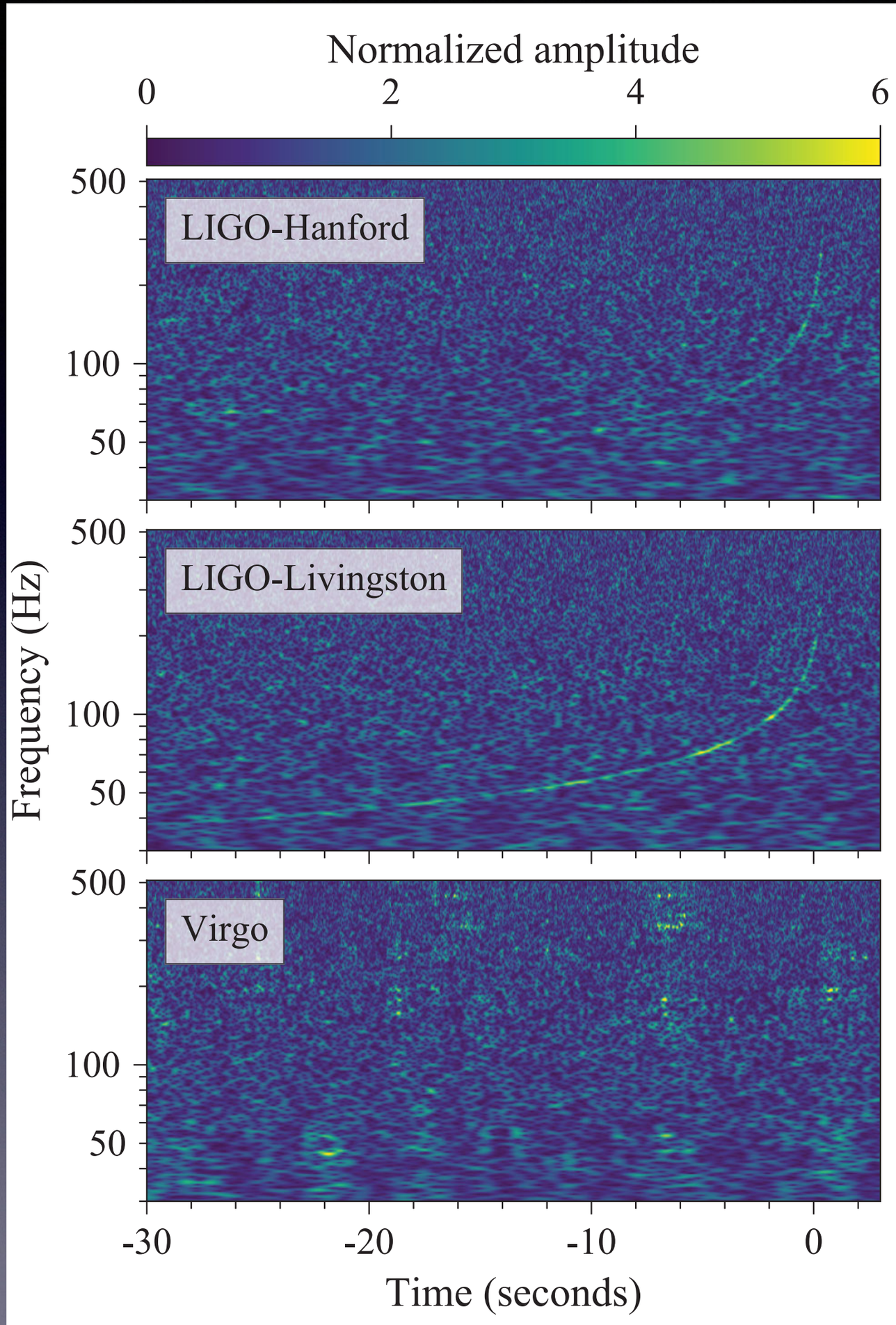
LSC VIRGO + EM Partners

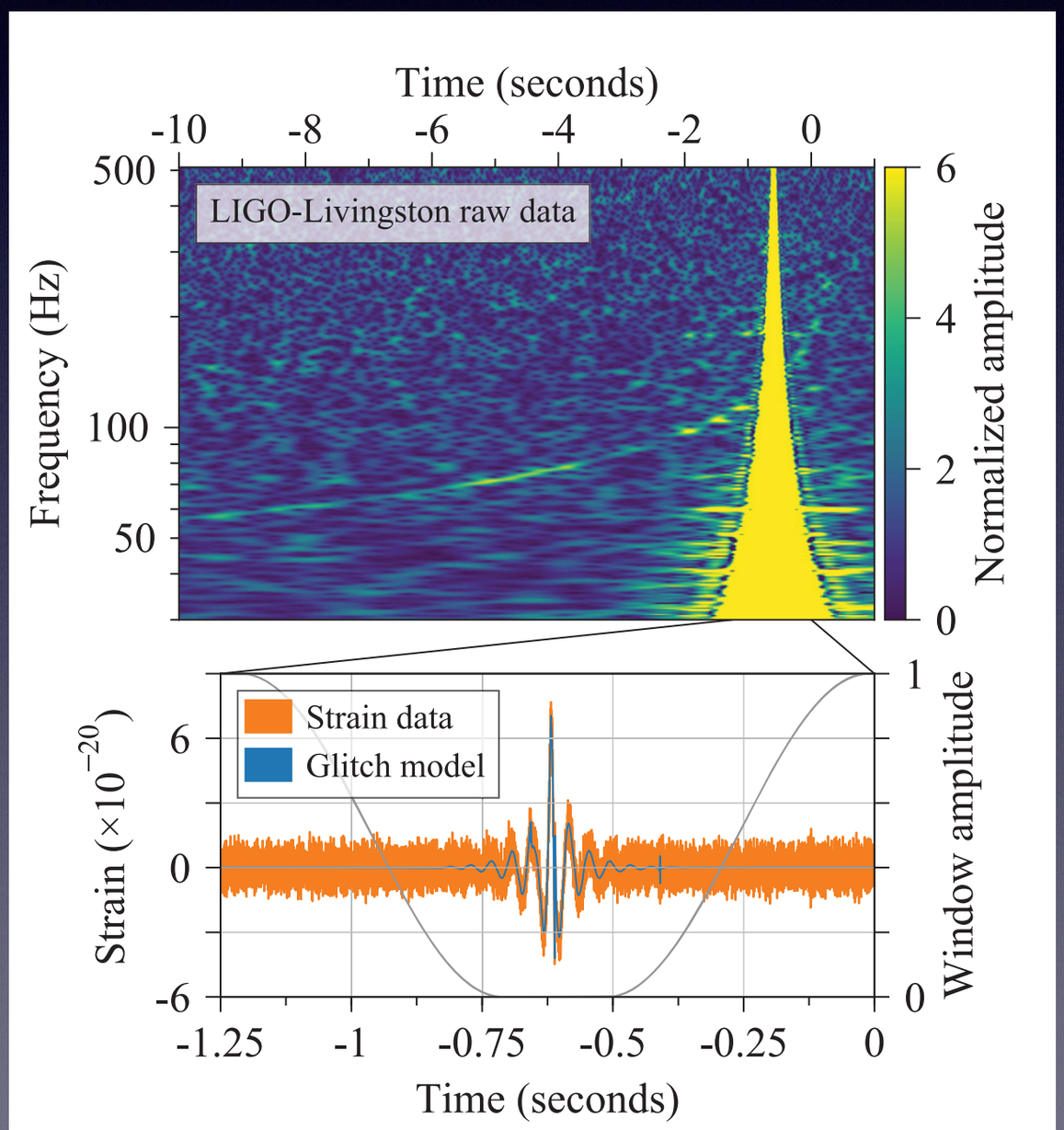
- GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
  — PRL 119, 161101 [2017]
- Multi-messenger Observations of a Binary Neutron Star Merger
  — ApJL 848, L12 [2017]
- Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A
  — ApJL 848, L13 [2017]
- A Gravitational-Wave Standard Siren Measurement of the Hubble Constant
  — Nature, published, [2017]
- Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817
  — accepted ApJL [2017]
- On the Progenitor of Binary Neutron Star Merger GW170817
  — accepted ApJL [2017]
- GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences — submitted PRL
- Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory — submitted ApJL

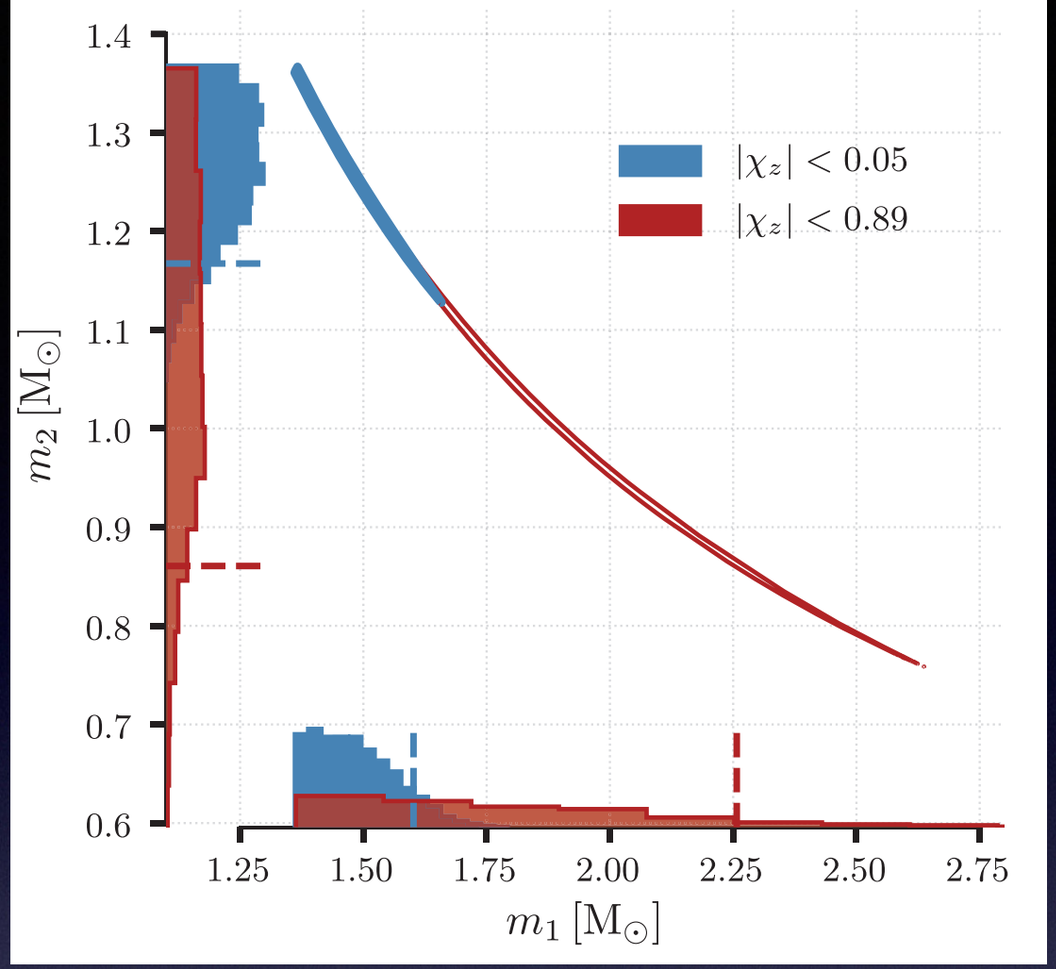
GW paper, the LVC, PRL, 2017

Network SNR > 32+

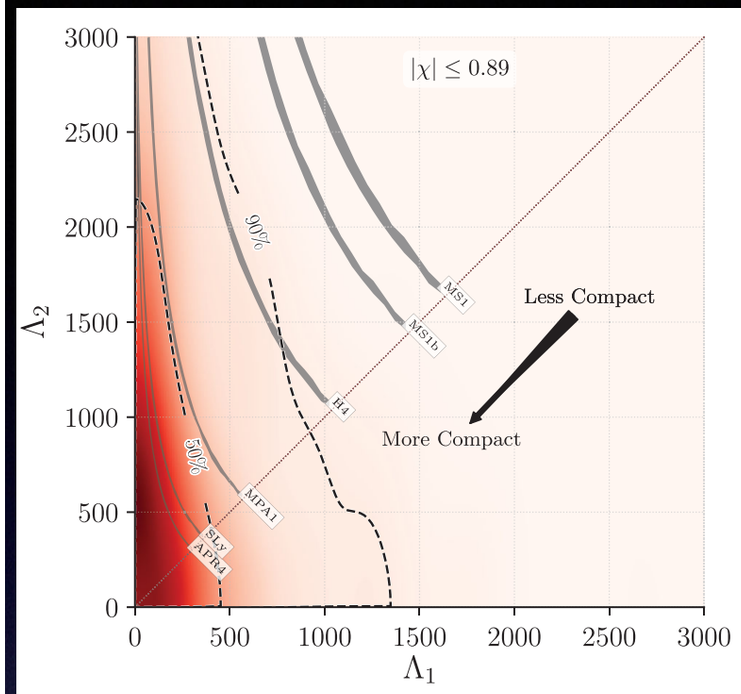
FAR < 1/80,000 yr







GW paper, the LVC, PRL, 2017



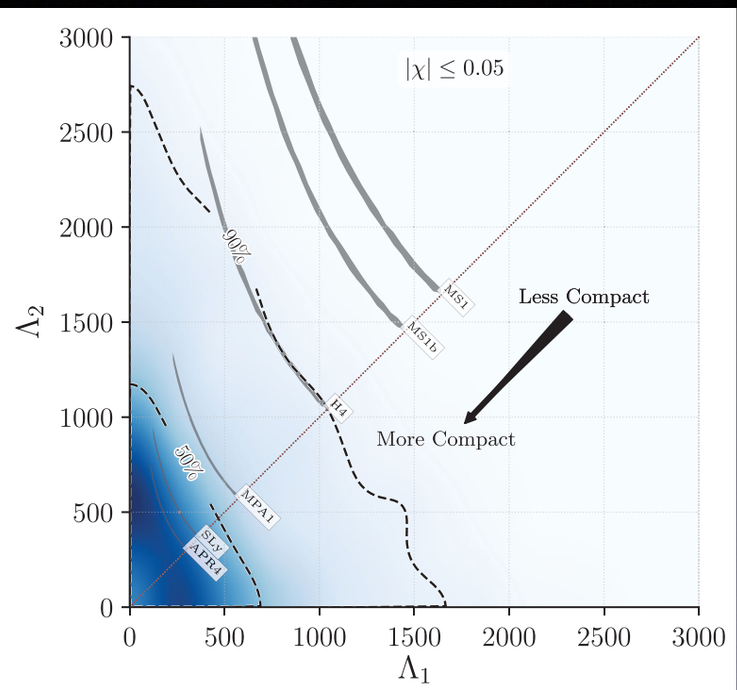
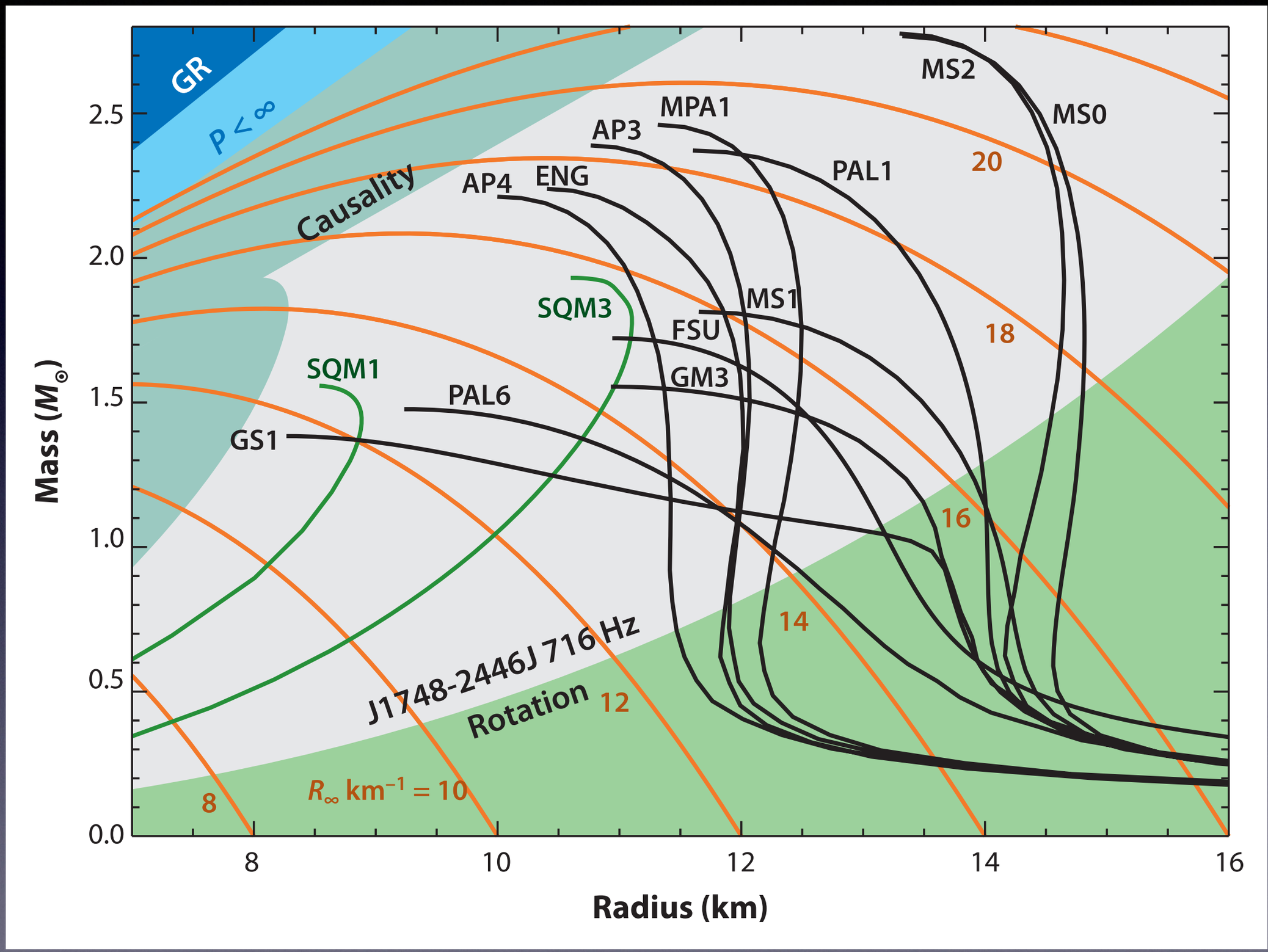


TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

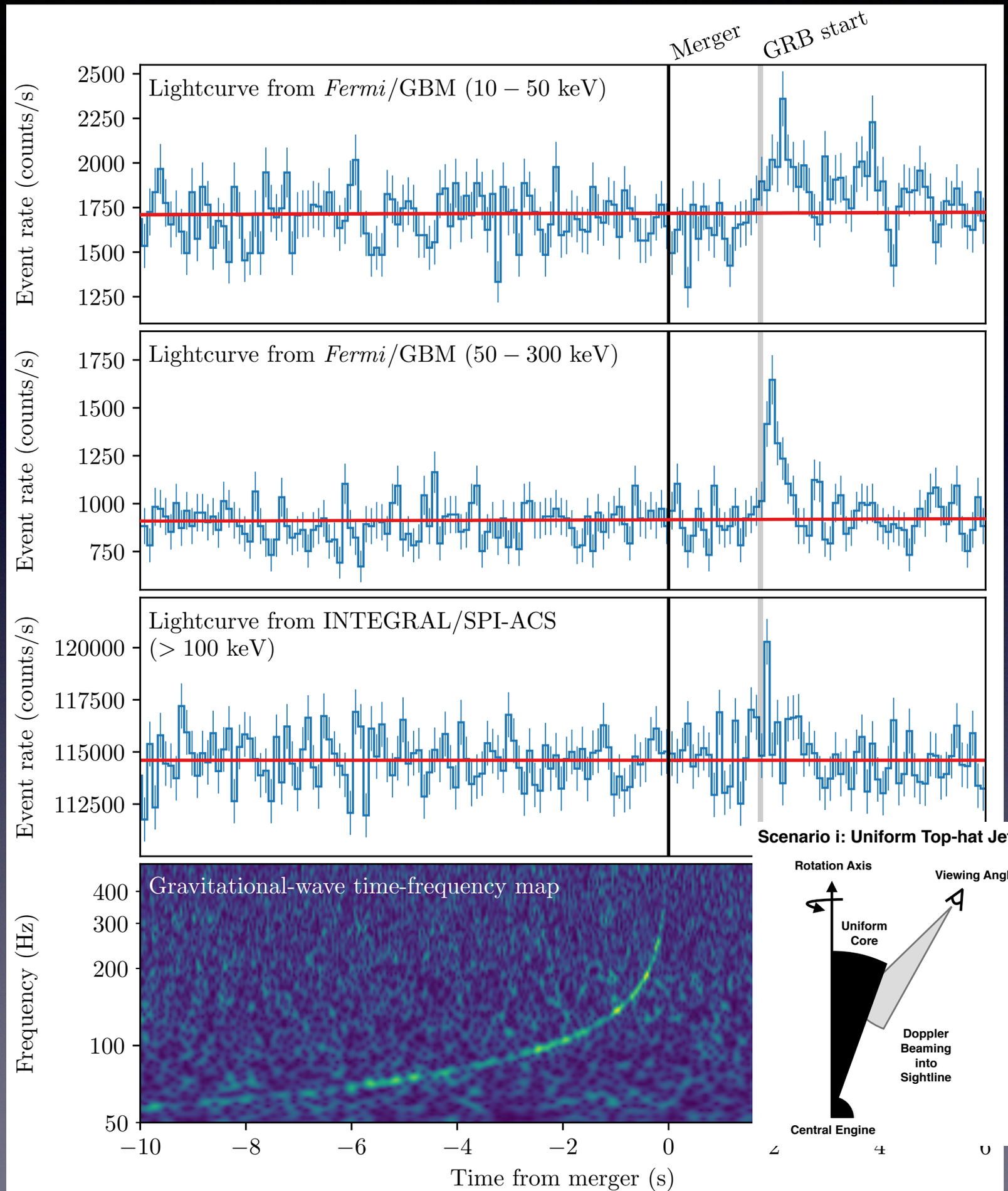
Lattimer review 2012

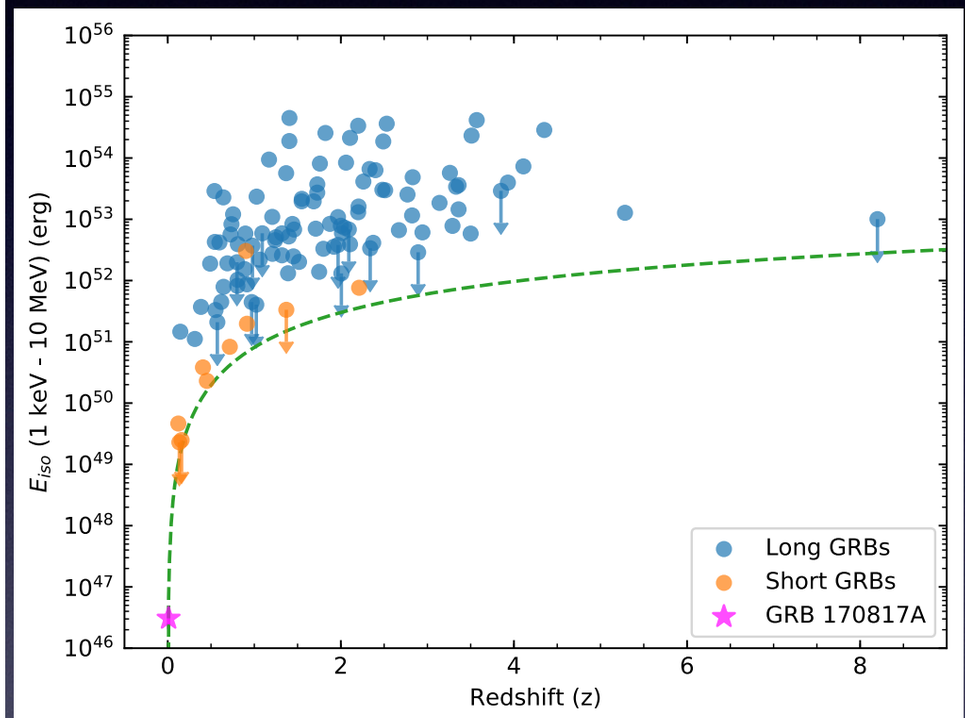


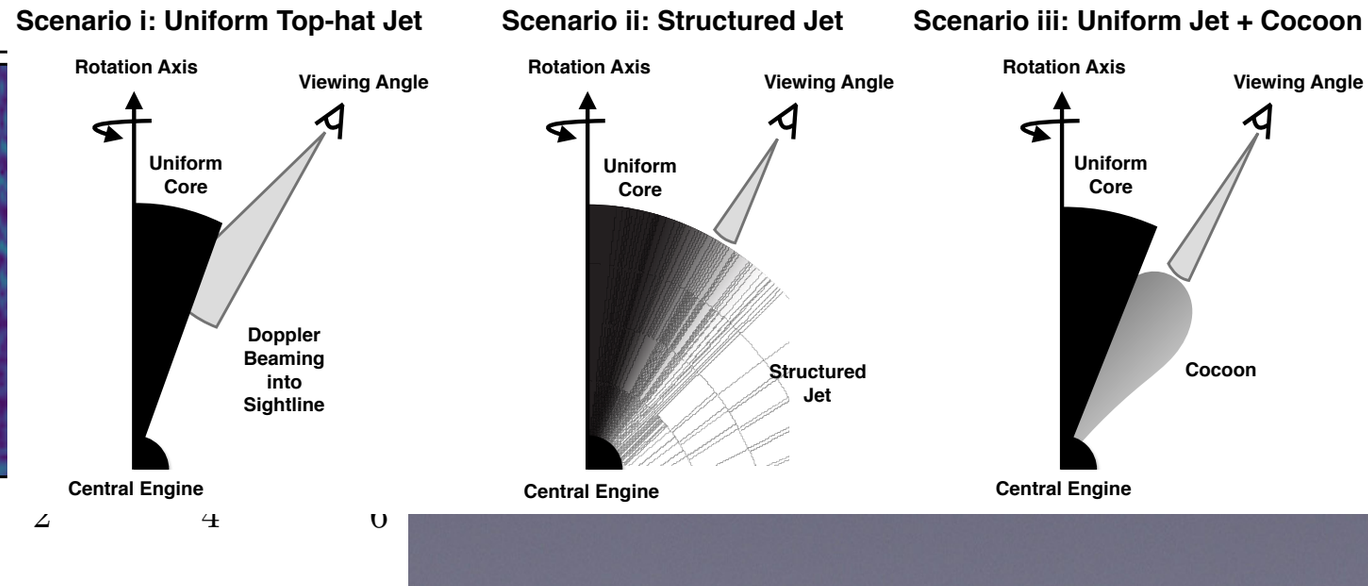
GW+GRB paper,
LVC+Fermi+INTEGRAL teams,
ApJ Letters, 2017

temporal & spatial

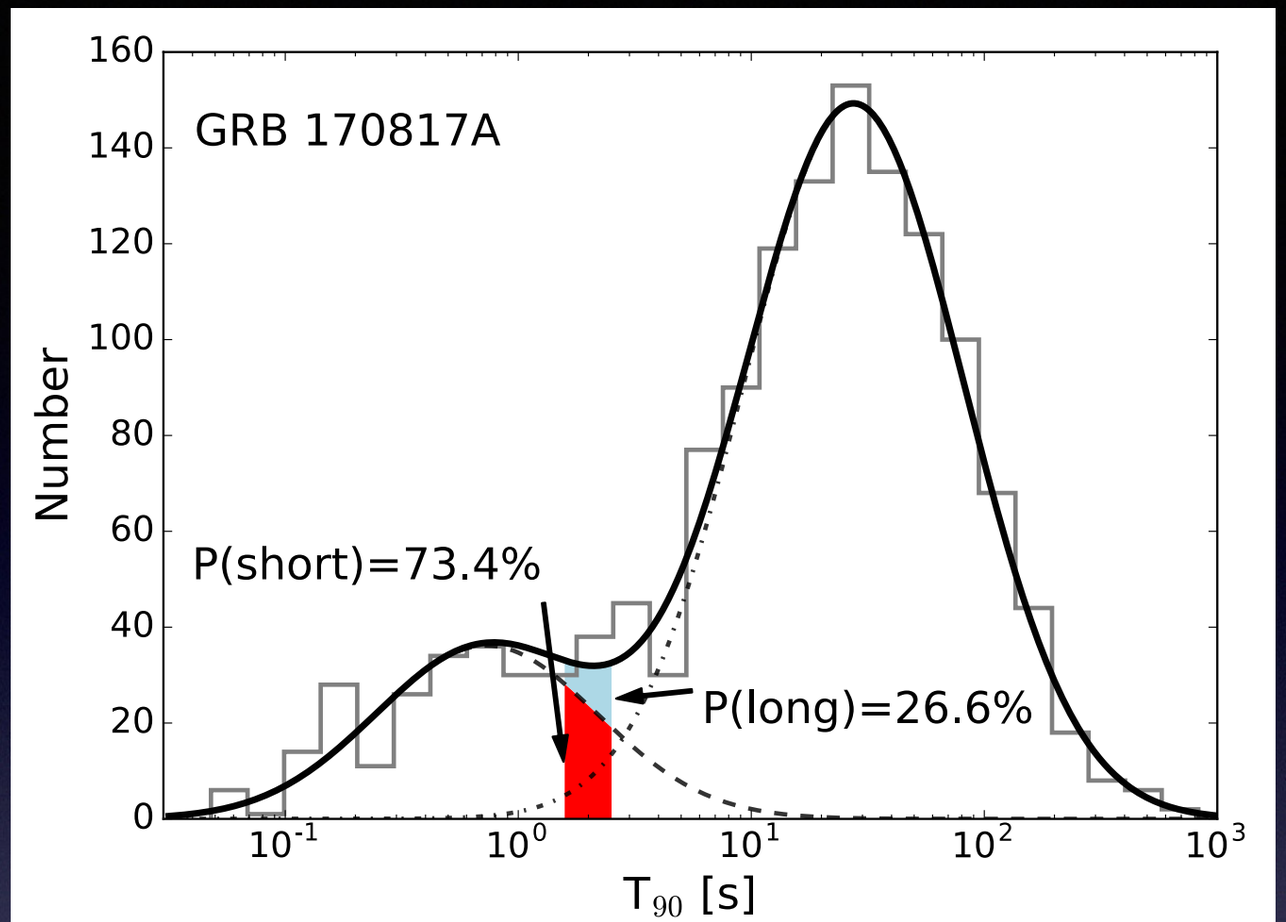
chance coincidence: ~5 x 10^-8

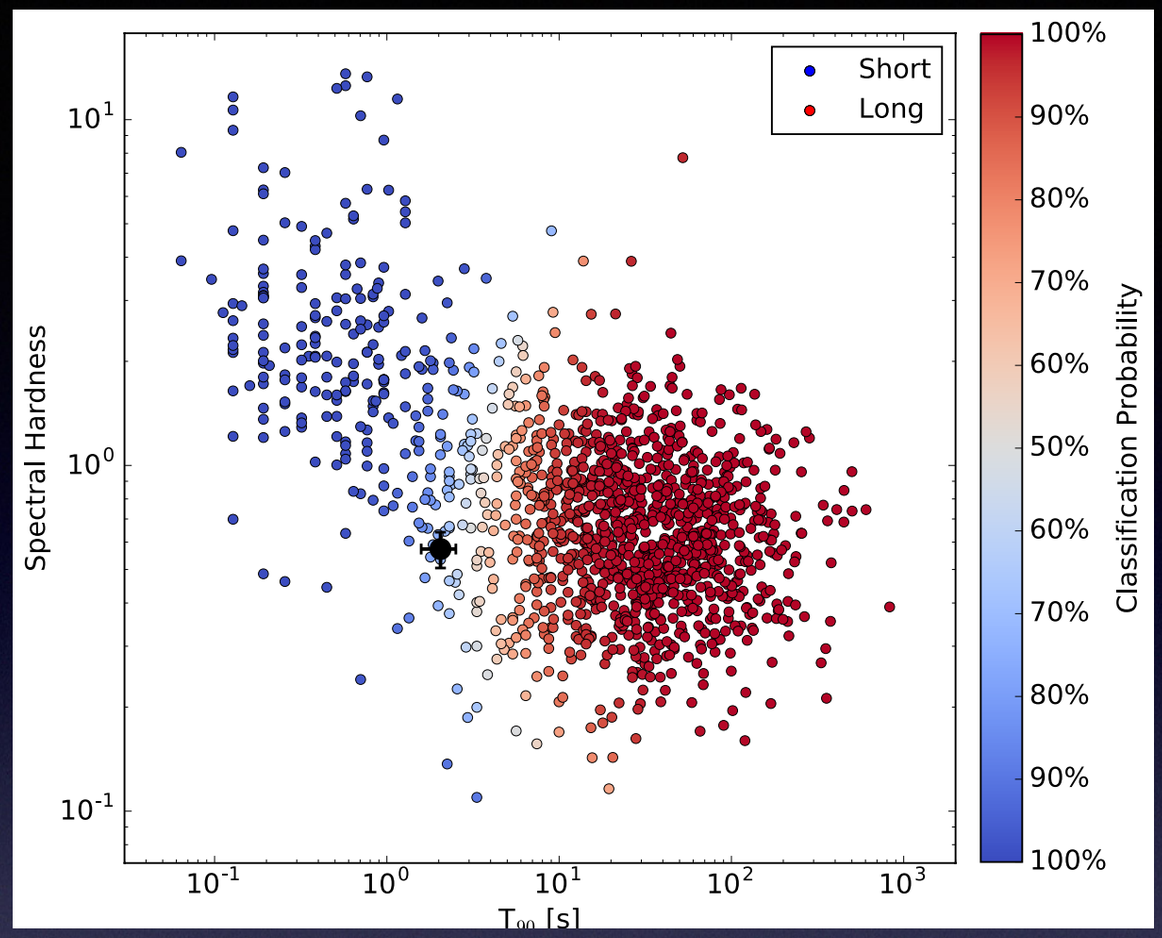


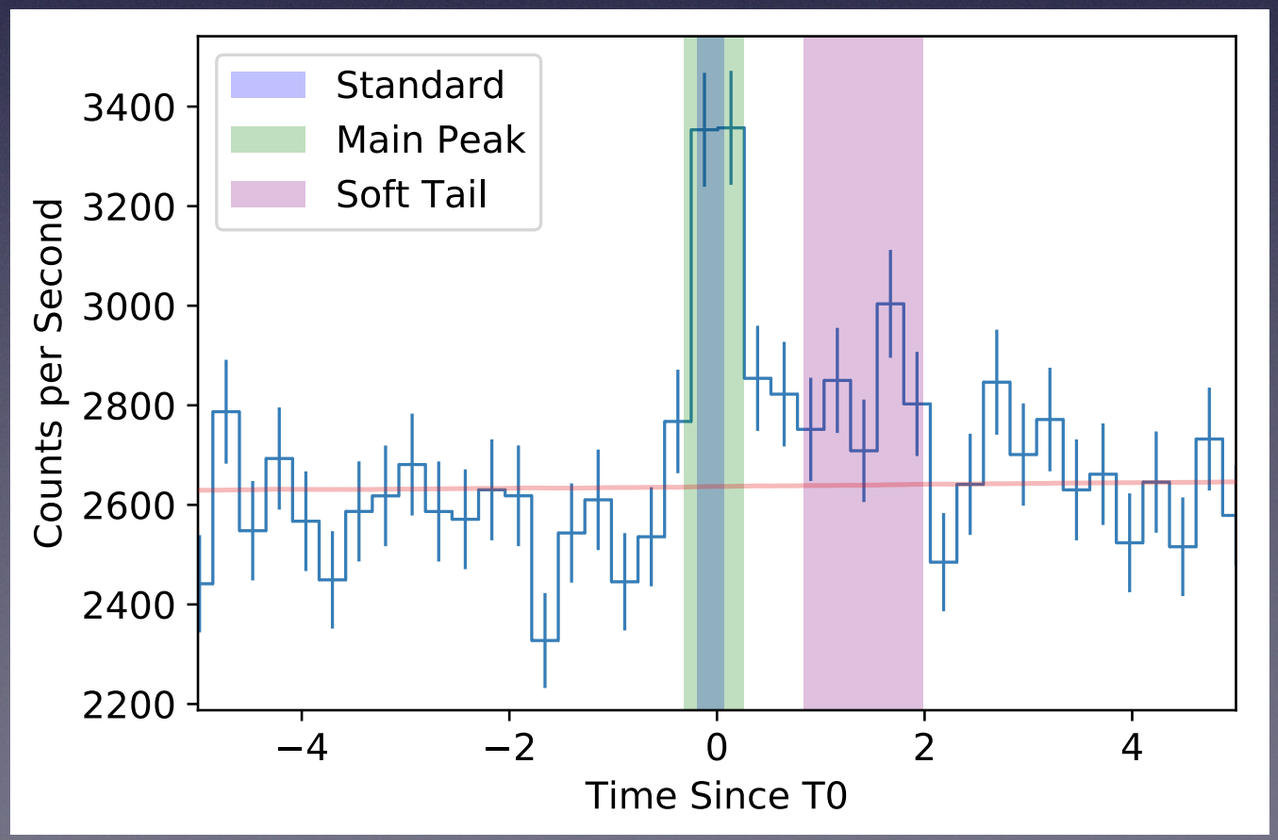




Fermi-GBM paper, Fermi-GBM, ApJ Letters, 2017

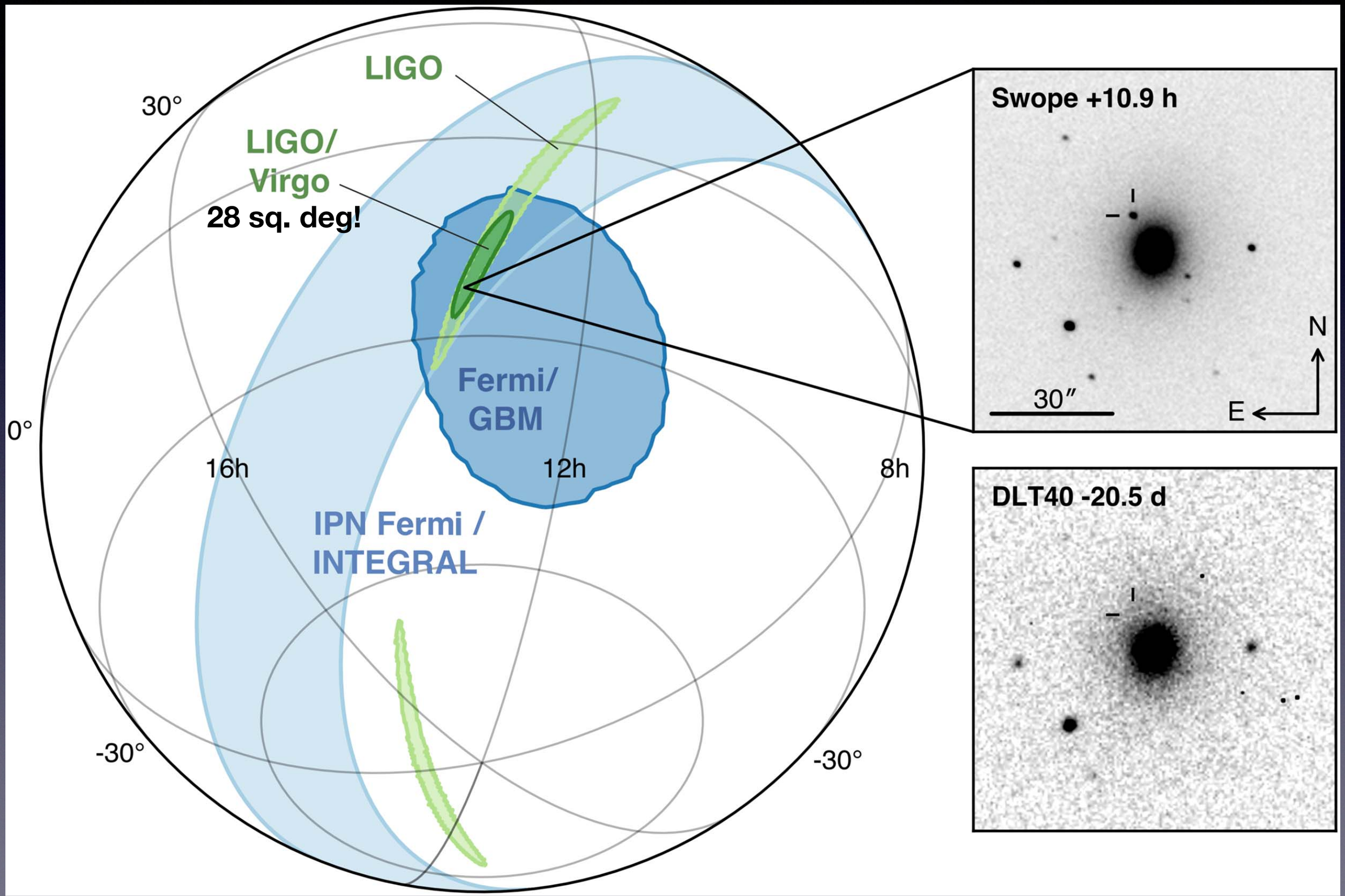


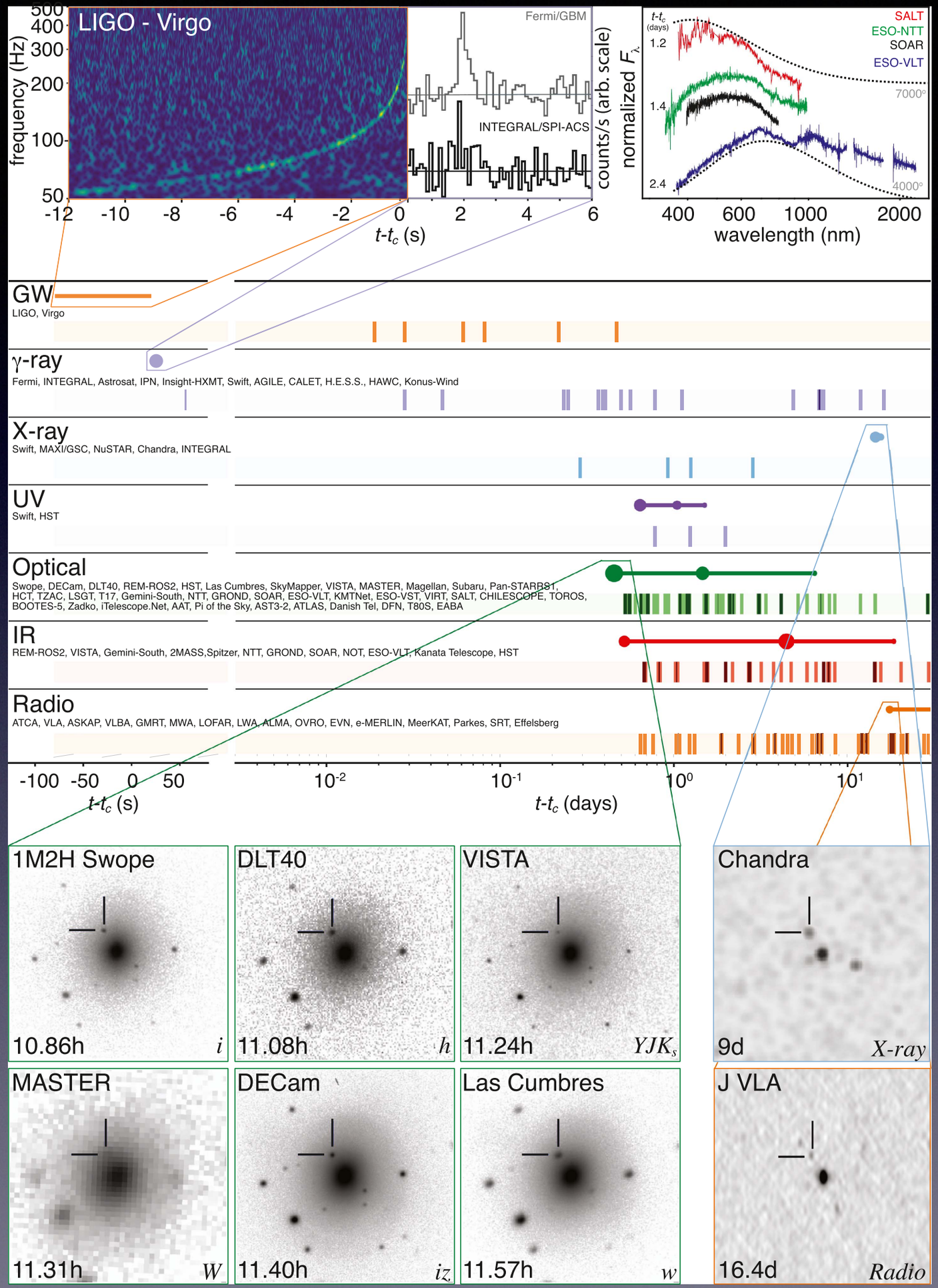




Not a “vanilla” short GRB

Multi-Messenger Astronomy paper, LVC+All EM teams, ApJ Letters, 2017





Multi-Messenger Astronomy paper,

LVC+All EM teams, ApJ Letters, 2017

3,500+ authors

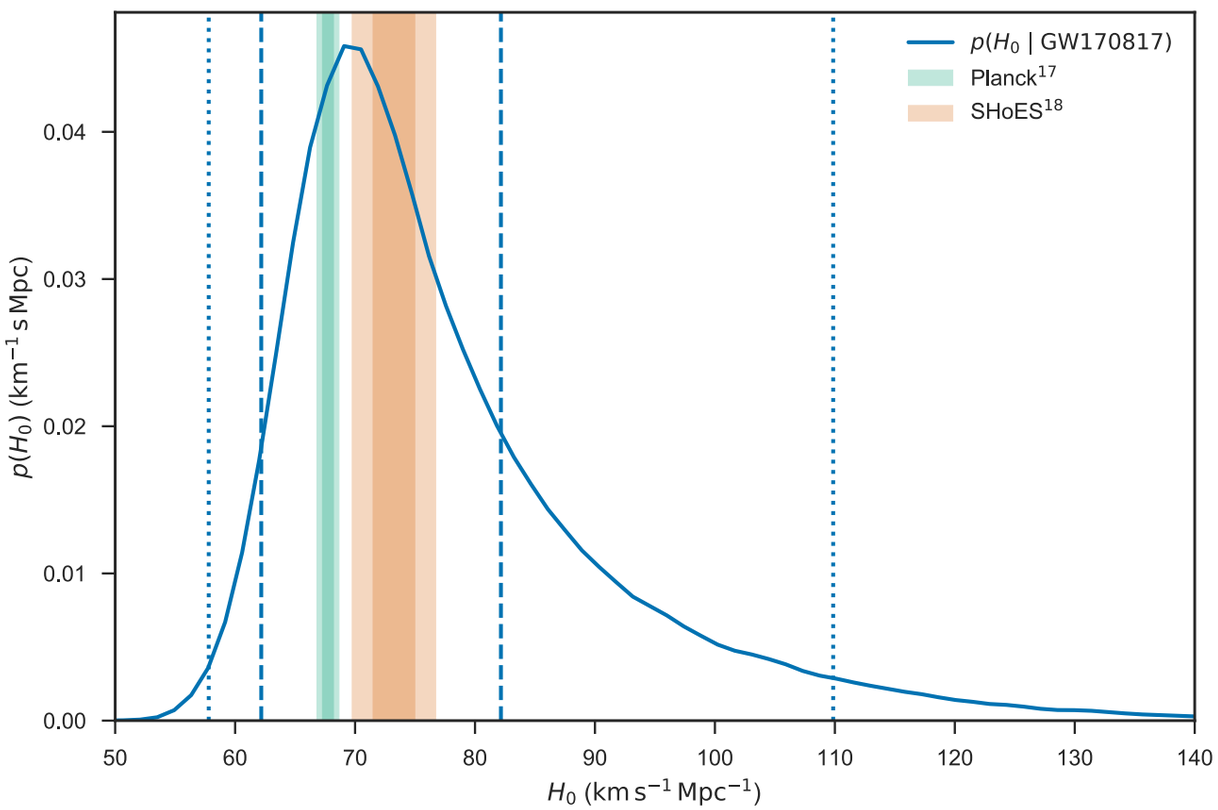
950+ institutions

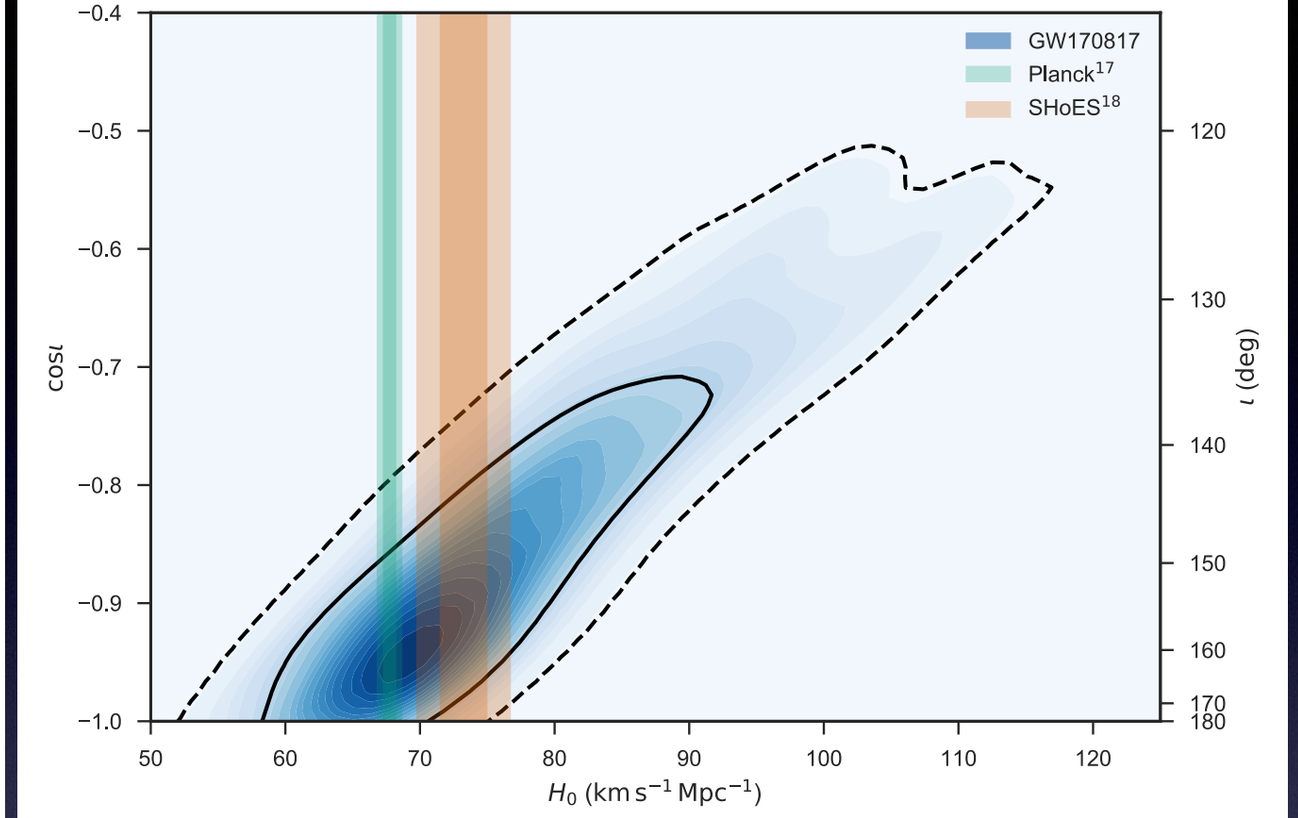
59 research teams

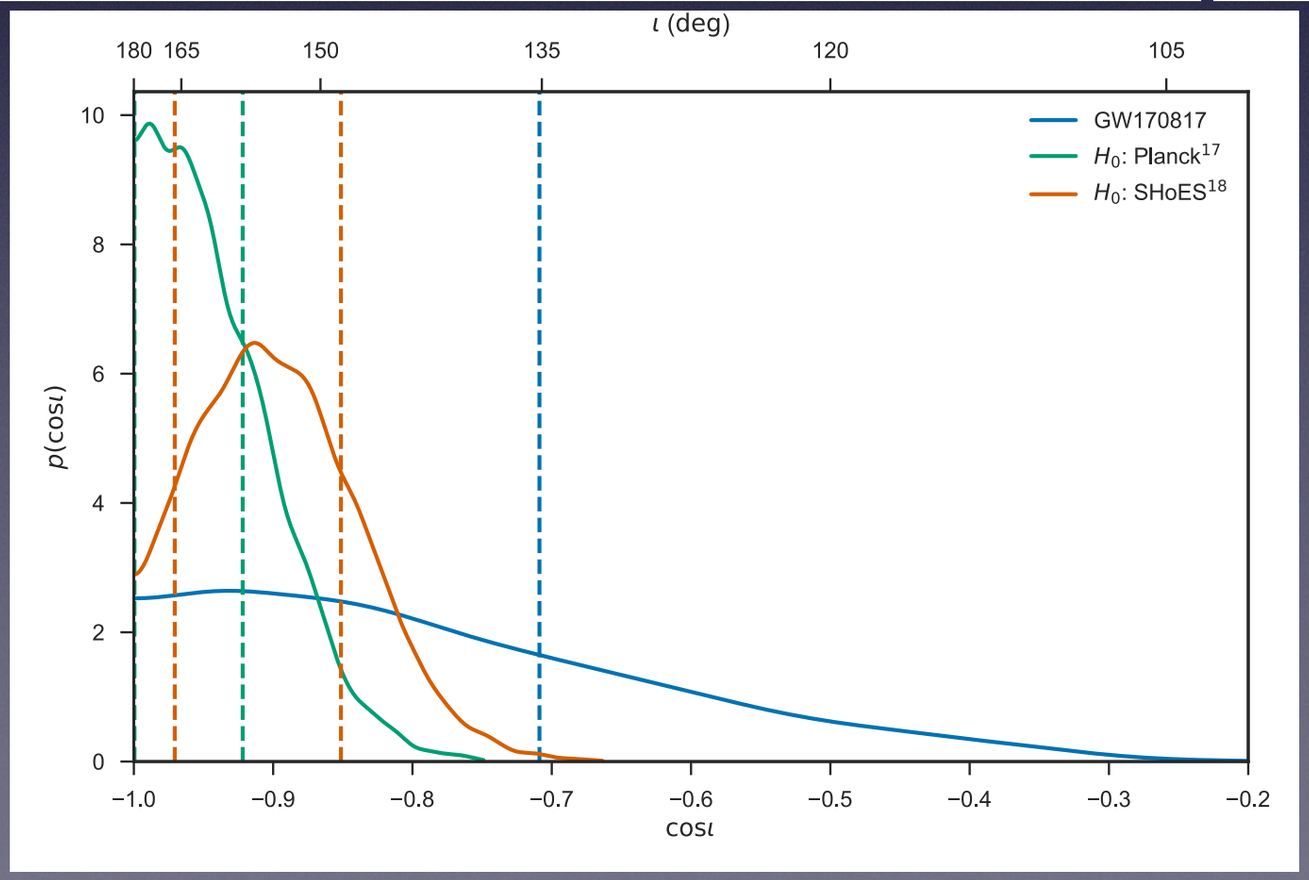
59-page ApJL, 24 pages of authors

paper-writing team of 11

H0 paper, LVC + 6 EM host-galaxy co-discovery teams, Nature, 2017

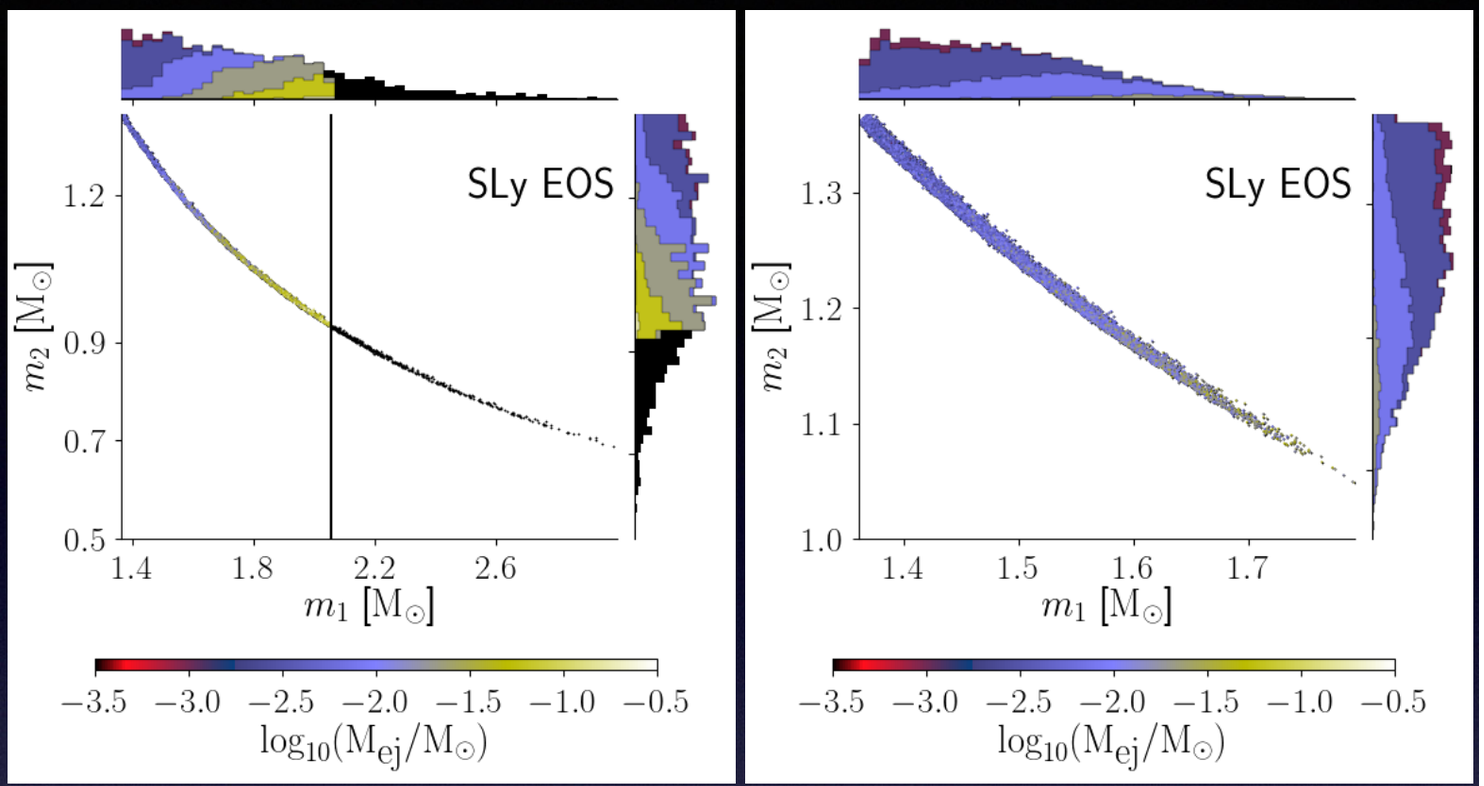


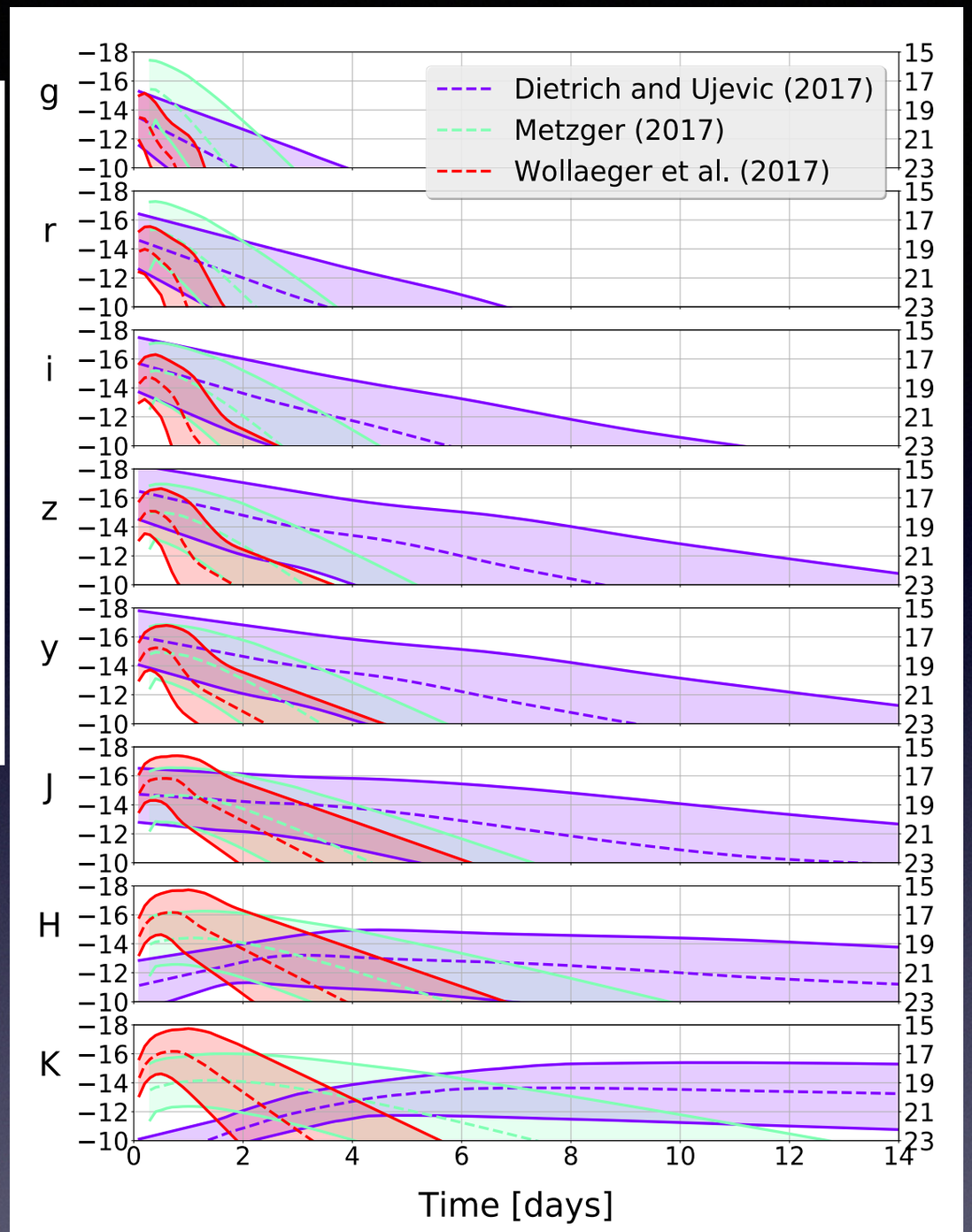


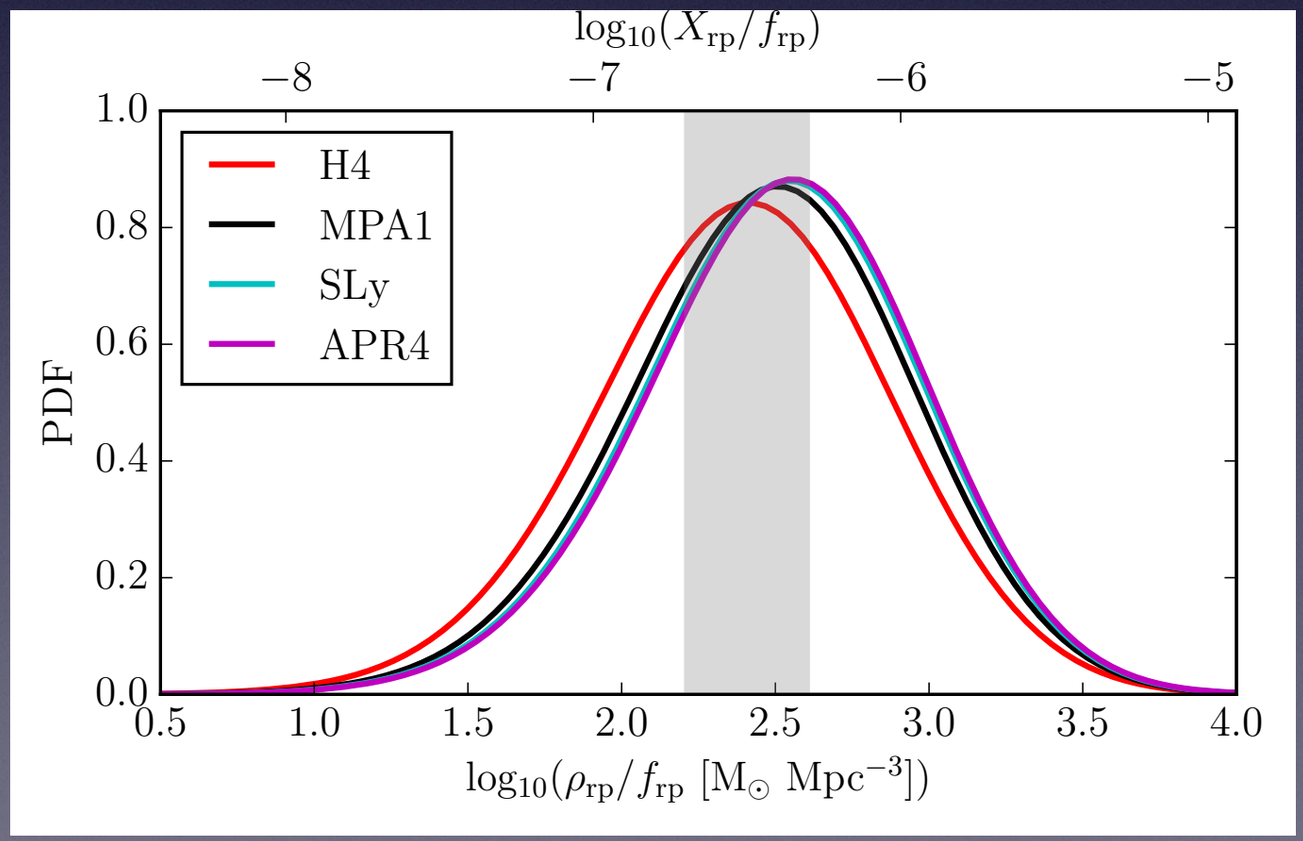


$$70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Kilonova paper, LVC, ApJ Letters, 2017

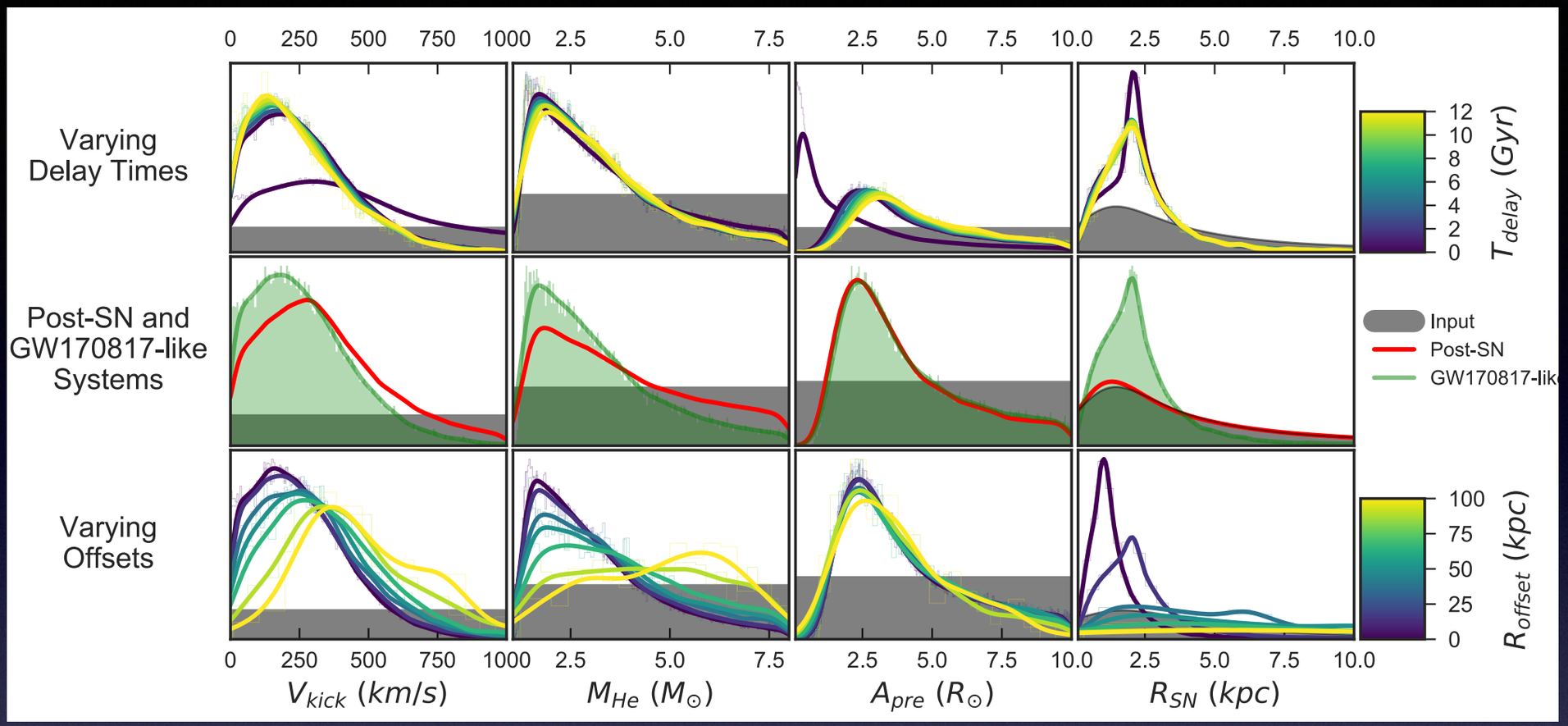


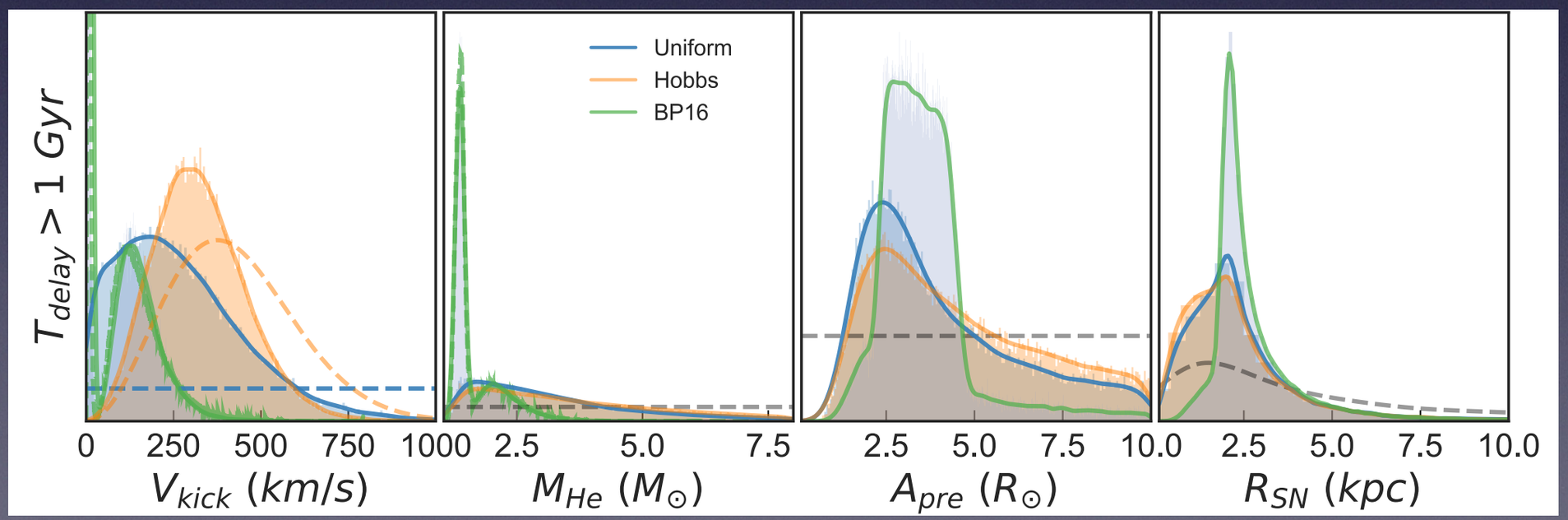




if >~10% of the matter dynamically ejected is converted to r-process elements, GW170817-like BNS mergers could fully account for the amount of r-process material observed in the Milky Way

Progenitor paper, LVC, ApJ Letters, 2017





Progenitor Constraints:

— dominated by requirement that post-SN binary remains bound

— insensitive to star-formation history, as long as stellar ages are older than 1 Gyr

@90% — SN V_kick < 550 km/s

— CM V_sys < 400 km/s

GW170817: EM follow-up across *nine* orders of magnitude in λ

Slide by:
Wen-fai Fong
Raffaella Margutti

GW170817: EM follow-up across *nine* orders of magnitude in λ

What? Kilonova, Host galaxy
Probes: Lanthanide-free and rich ejecta, Parent stellar population

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Wen-fai Fong
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GW170817: EM follow-up across *nine* orders of magnitude in λ

λ

X-ray | **UV/Optical** | **Near-IR** | **Radio**

What? Kilonova, Host galaxy
Probes: Lanthanide-free and rich ejecta, Parent stellar population

What? Off-axis afterglow
Probes: Relativistic outflow (collimation, kinetic energy, particle density)

Slide by:
Wen-fai Fong
Raffaella Margutti

Discovery of the optical counterpart

Waiting for the sun to set…

Photo credit: W. Fong

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Raffaella Margutti

Discovery of the optical counterpart

Waiting for the sun to set...

Photo credit: W. Fong

1st announcements
@ approx. 12 hr:
Swope, DECam, DLT40, VISTA,
MASTER, Las Cumbres
(Coulter et al., Soares-Santos et al., Valenti et al.,
Tanvir et al., Lipunov et al., Arcavi et al. 2017)
c.f. LIGO Scientific & Virgo Collaboration et al. 2017 ; ApJL, 848, L12

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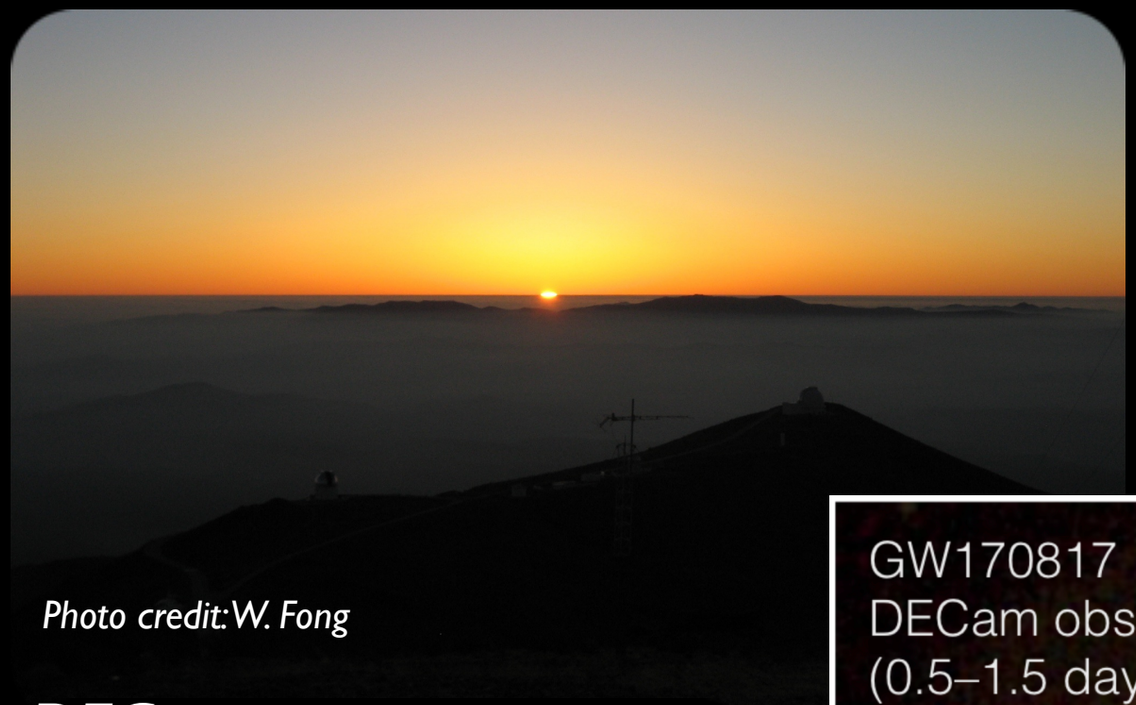

Photo credit: W. Fong

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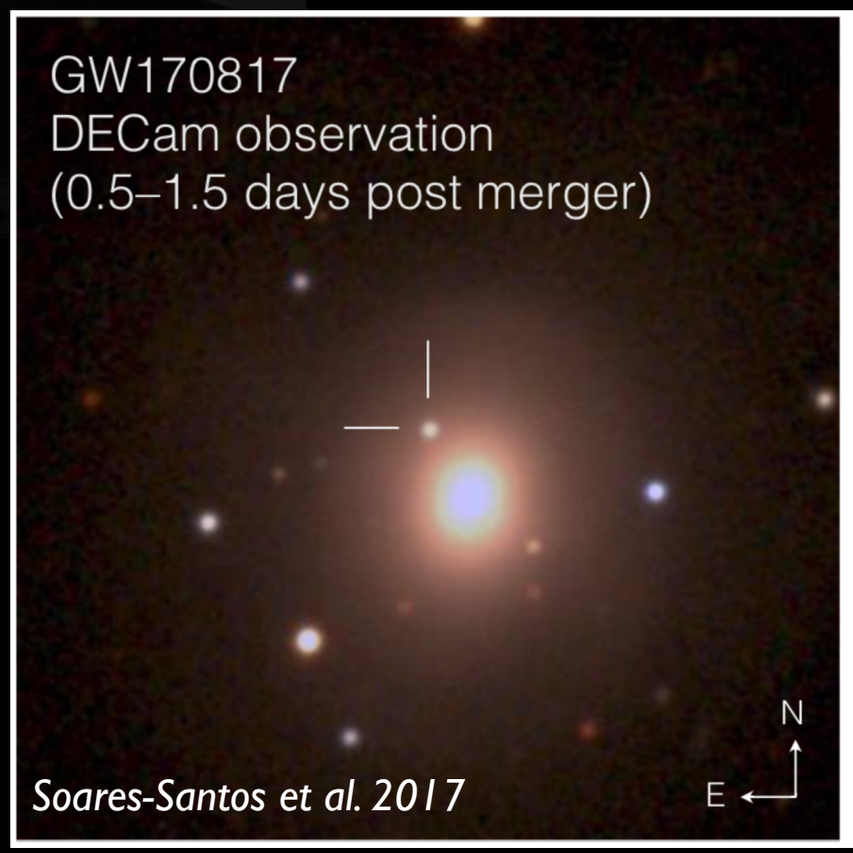
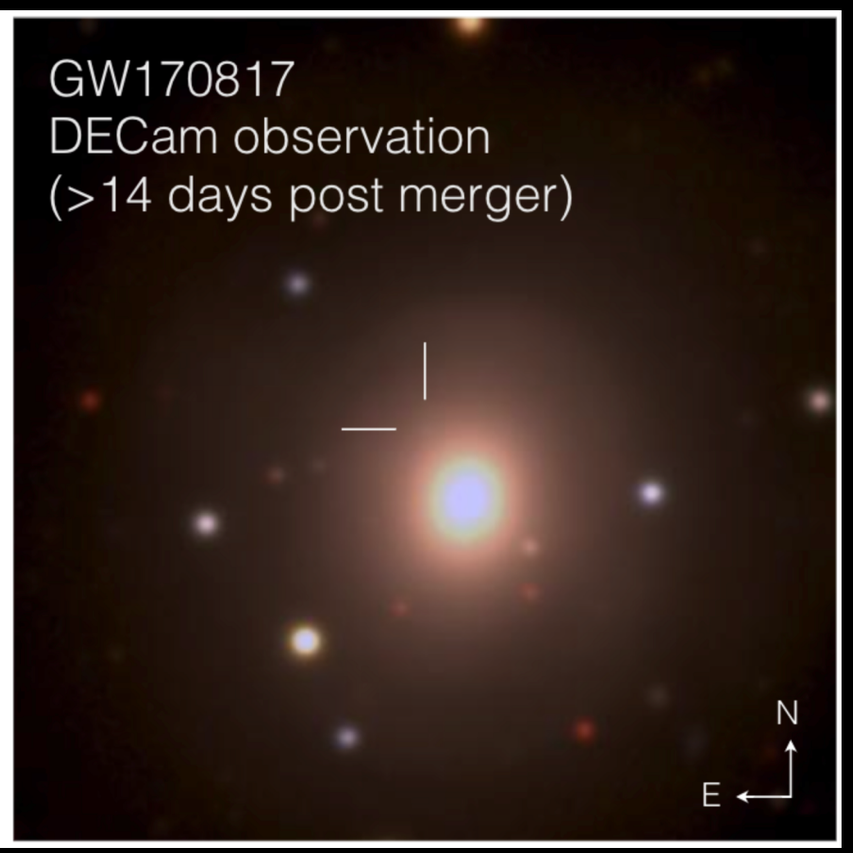
c.f. LIGO Scientific & Virgo Collaboration et al. 2017 ; ApJL, 848, L12

DECam:
3 sq. deg. on a 4-meter



Soares-Santos et al. 2017



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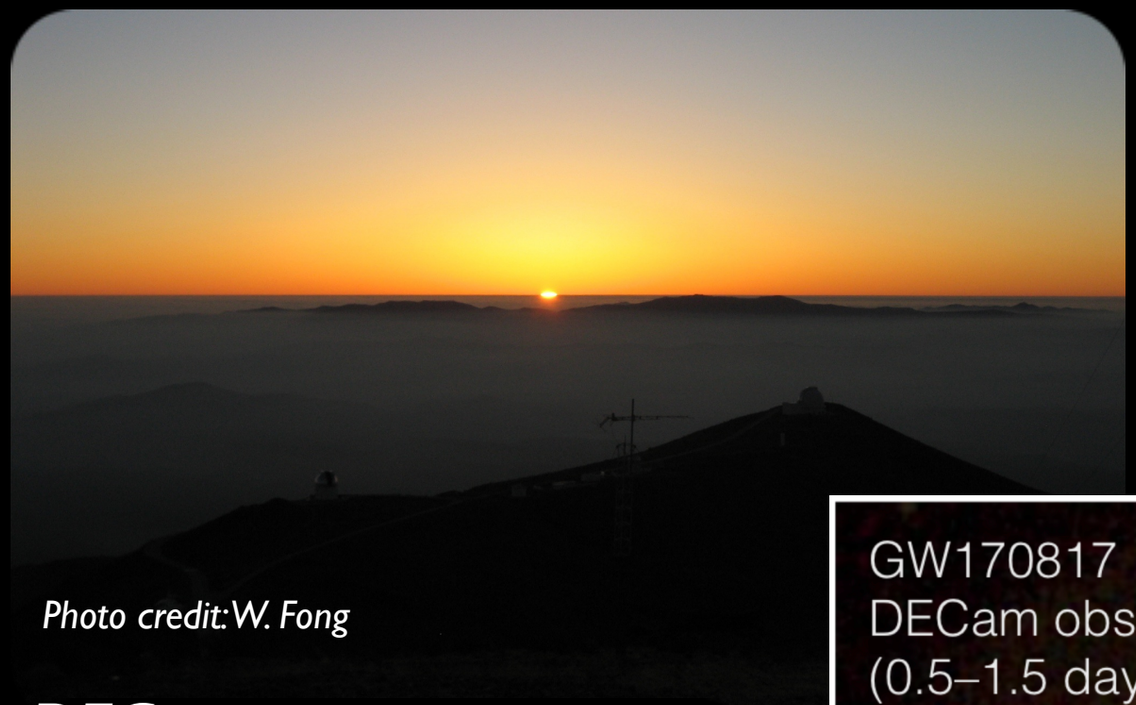

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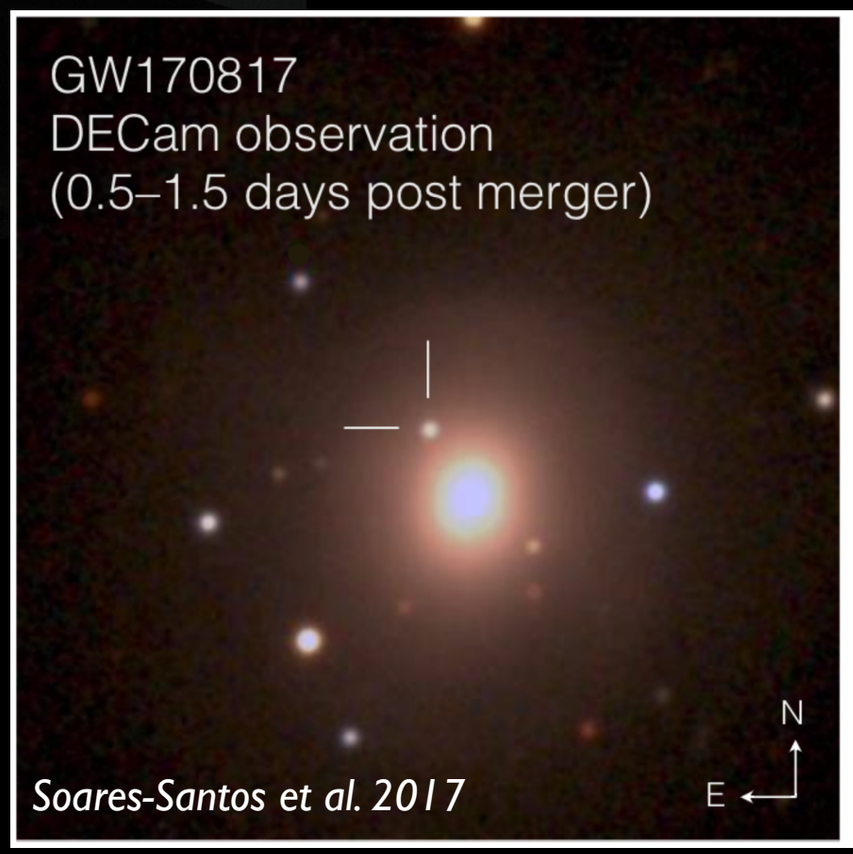
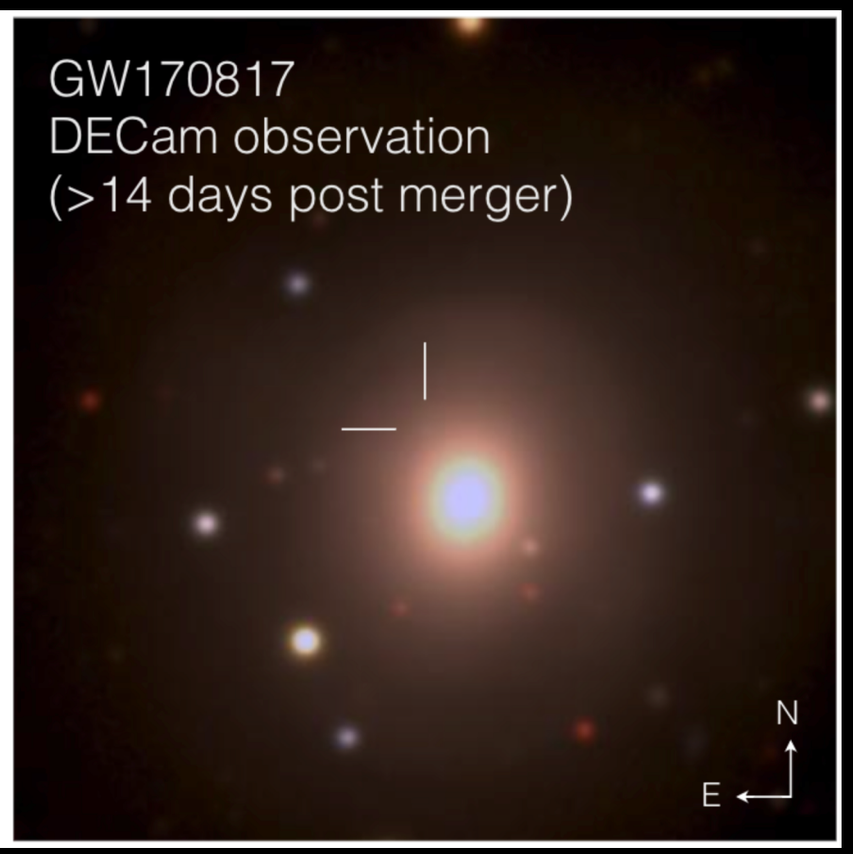


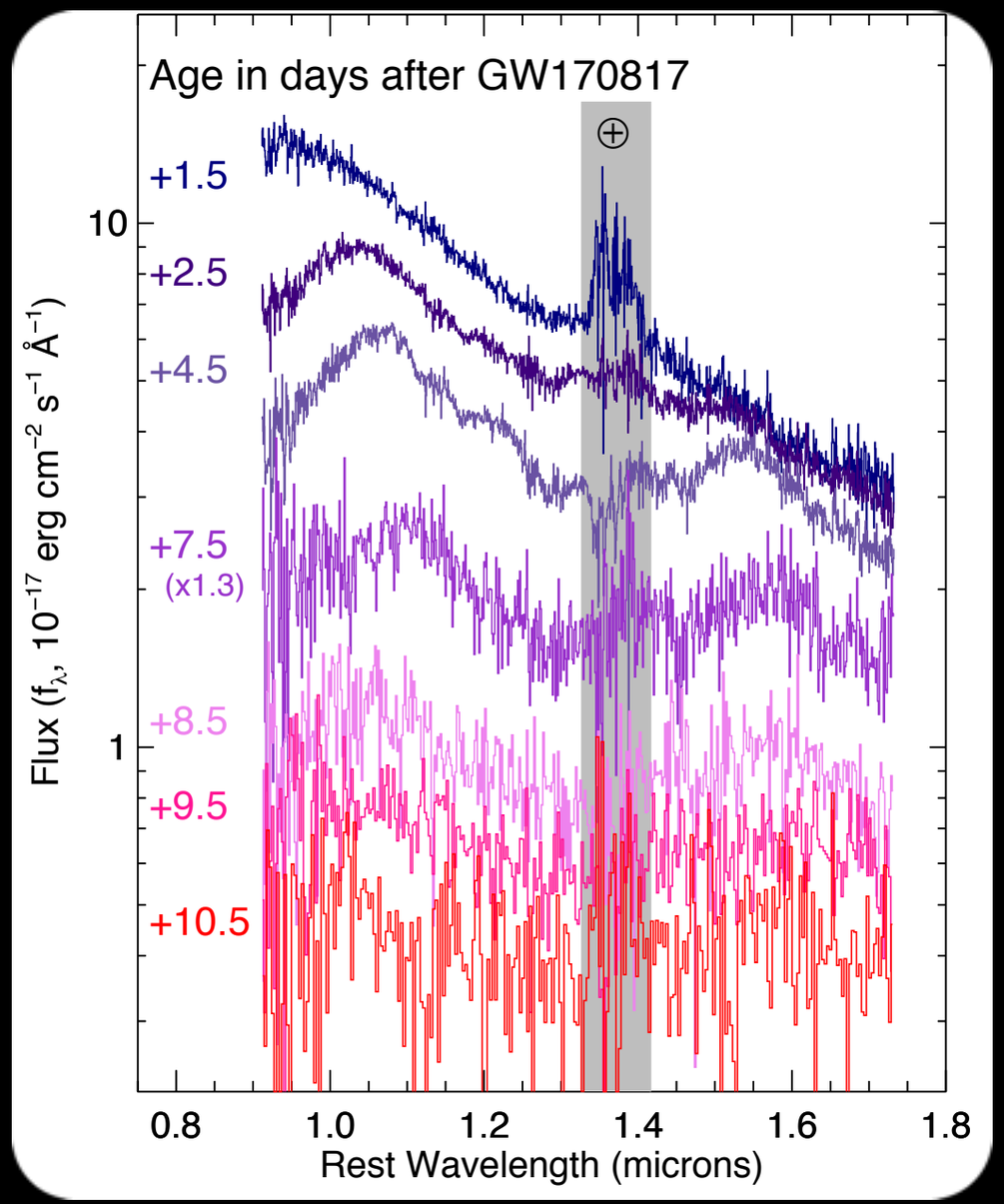
Soares-Santos et al. 2017



Public, archival Hubble Space Telescope imaging in April 2016 confirmed NO SOURCE at location to deep limits!

First clear support for heavy element nucleosynthesis in a neutron star merger

Near-IR spectroscopy from Gemini-South (8-m) exhibits rapid and blue-to-red evolution



Chornock, Berger, Kasen et al. 2017

Slide by: Wen-fai Fong, Raffaella Margutti

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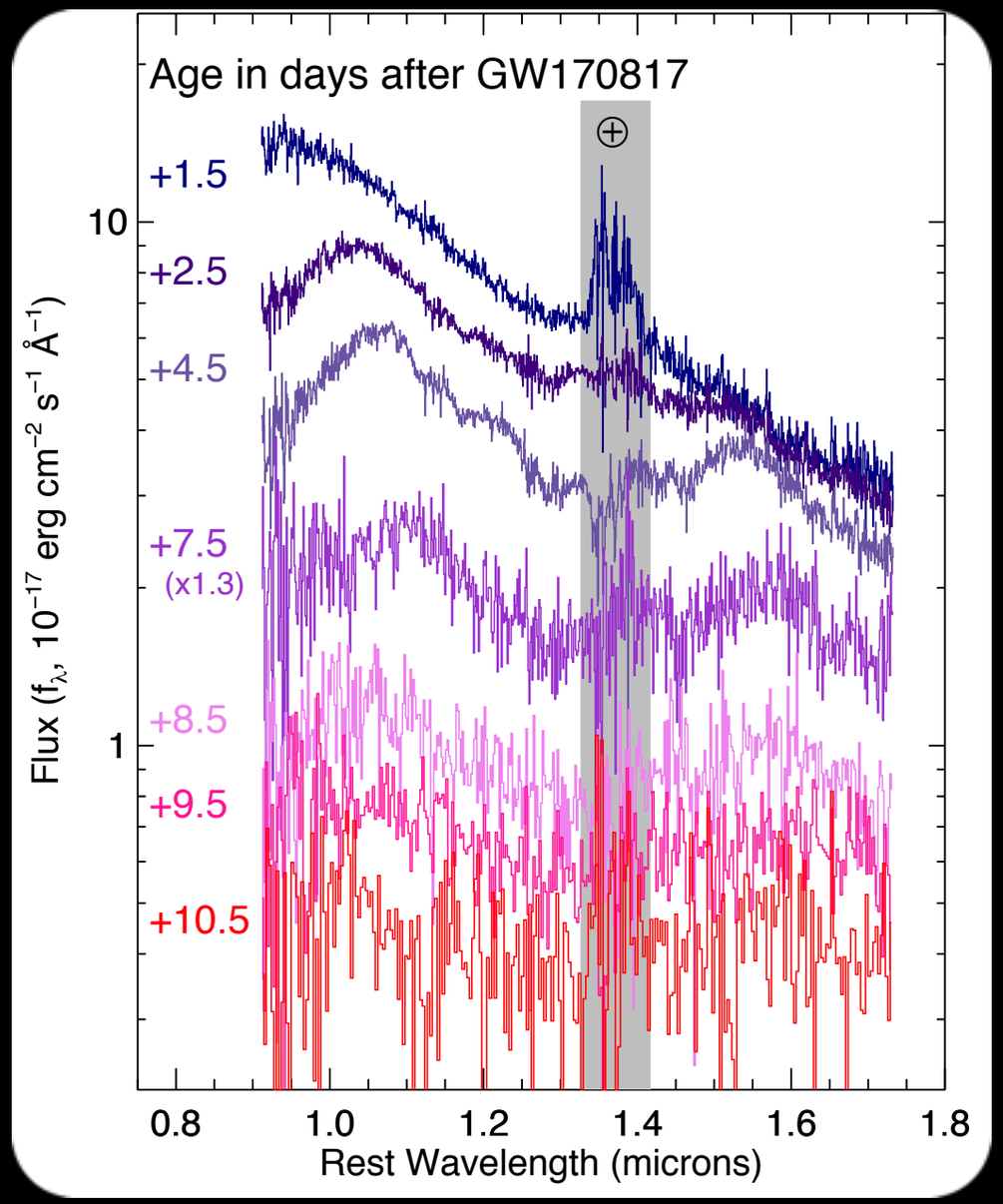

Chornock, Berger, Kasen et al. 2017

Together with light curves (Cowperthwaite et al. 2017) and UV/optical spectroscopy (Nicholl et al. 2017), the observations require two components:

i) Blue, lanthanide-free, fast: $M_{ej} = 0.01\ M_{sol}$
$v_{ej} = 0.3c$

ii) Red, lanthanide-rich, slow: $M_{ej} = 0.04\ M_{sol}$
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Slide by: Wen-fai Fong, Raffaella Margutti

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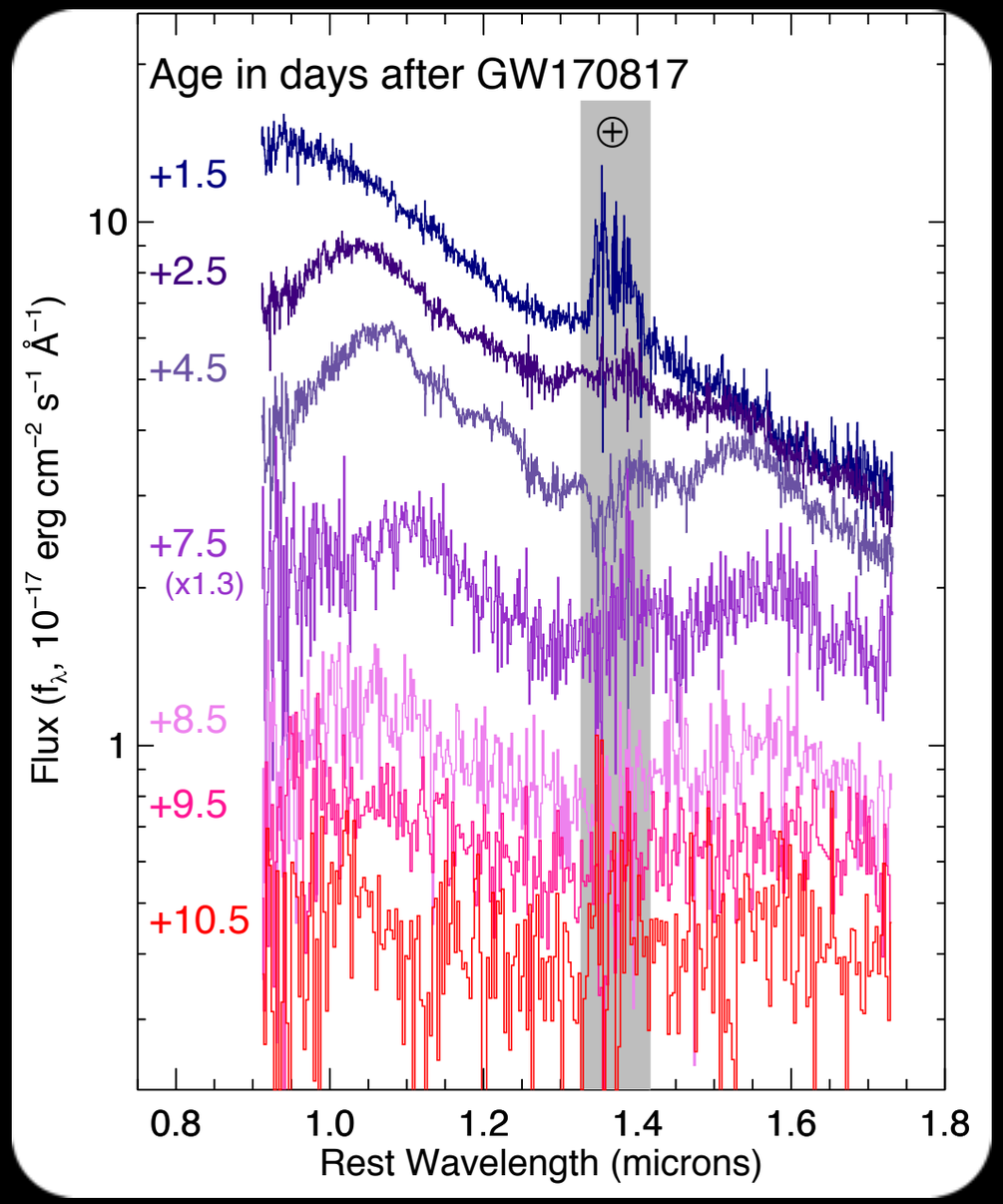

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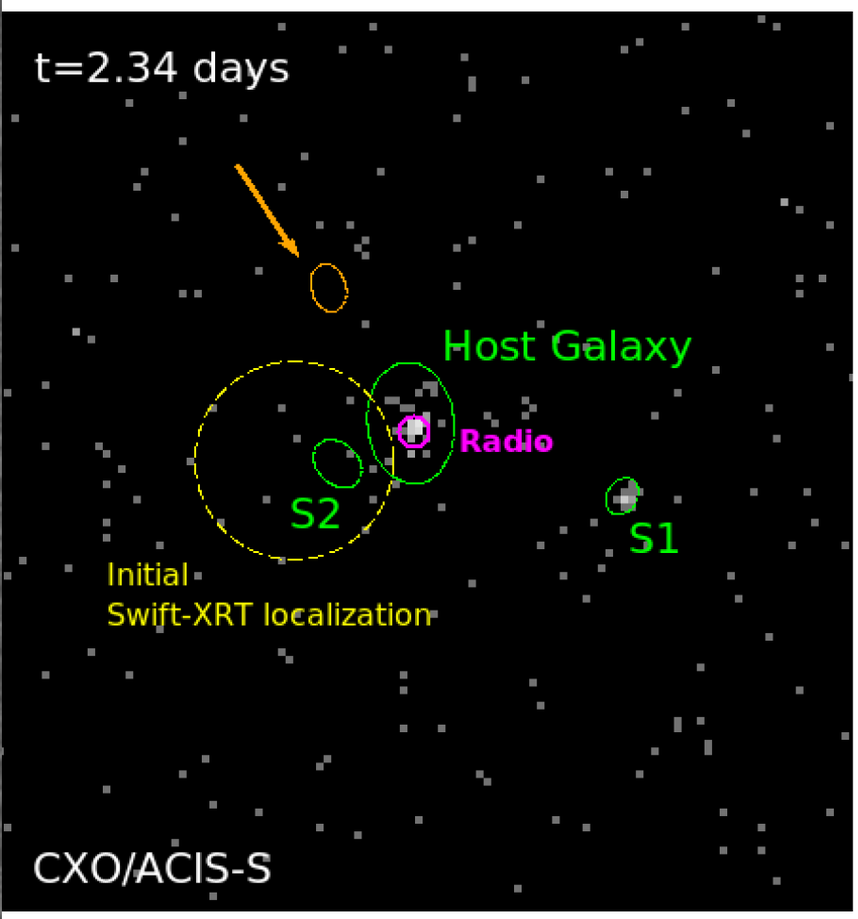
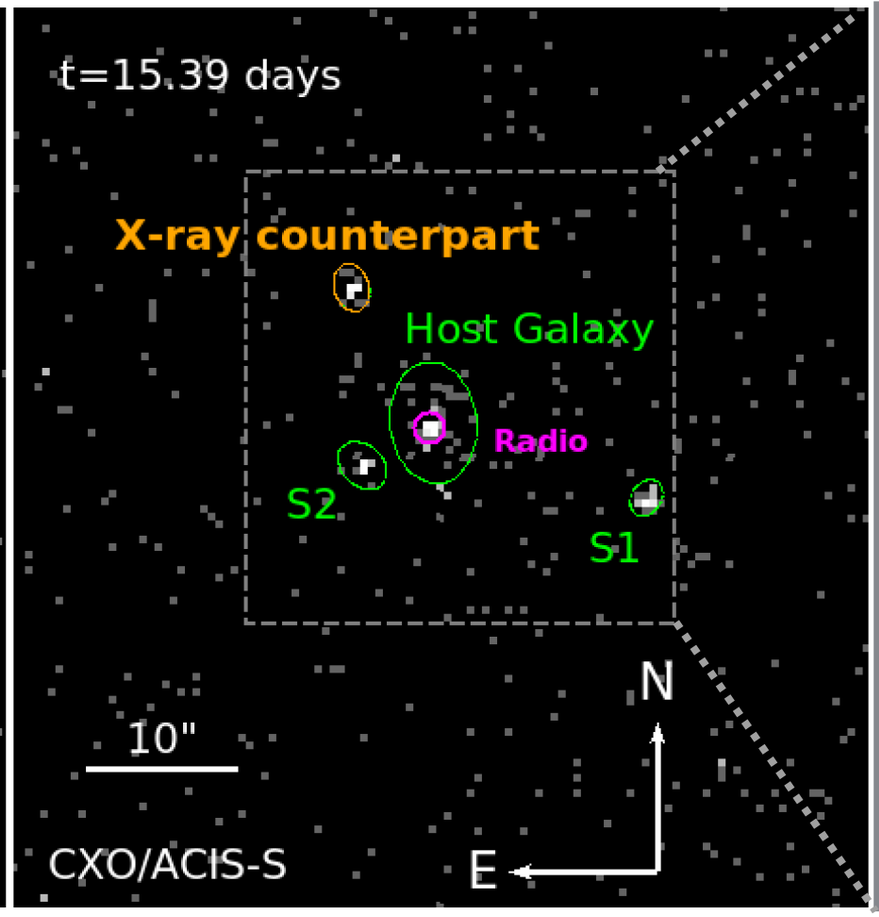
Broad agreement with the literature:
Arcavi et al. 2017 (Las Cumbres)
Drout et al. (Swope, Magellan)
Evans et al. 2017 (Swift)
Kasliwal et al. (Gemini, HST, ground-based)
Smartt et al. (PanSTARRs, GROND, ATLAS)
Troja et al. 2017 (Gemini, HST)
LIGO/Virgo collab. et al. (GW)
AND MORE!

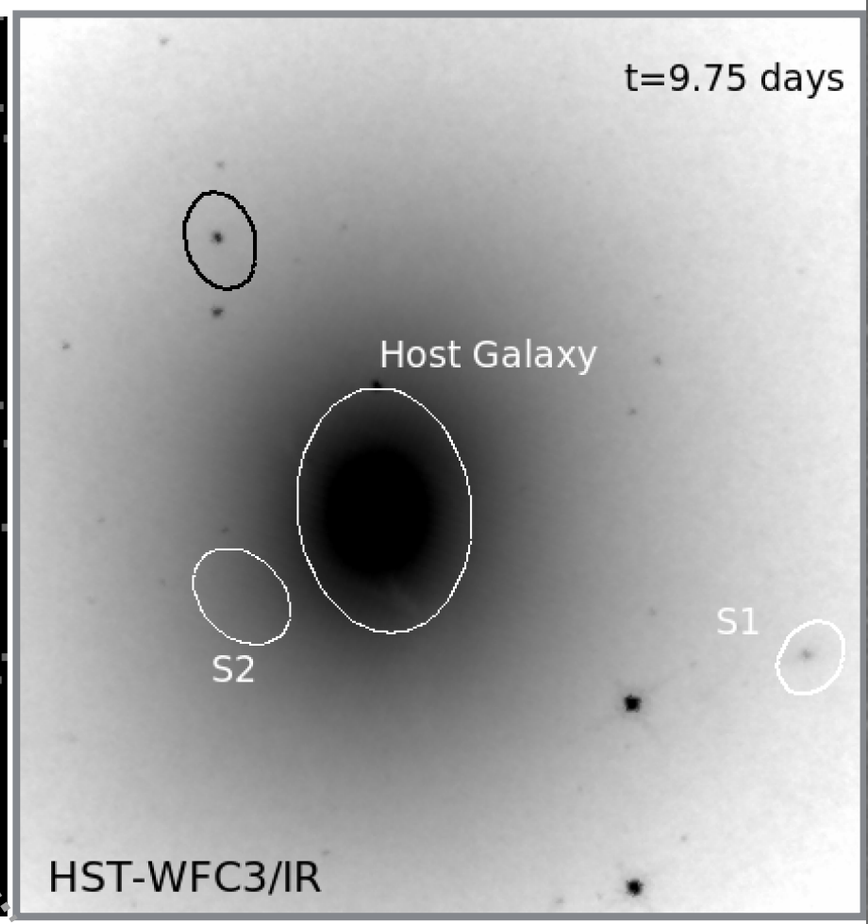
Slide by: Wen-fai Fong, Raffaella Margutti

X-rays from GW170817 (Chandra)

A **NEW** source appears at the location of the optical counterpart!!!







Margutti, Berger, Fong et al. 2017

Host-Galaxy properties (AGN):

Blanchard, Berger, Fong et al. 2017

Fong, Berger, Blanchard et al. 2017

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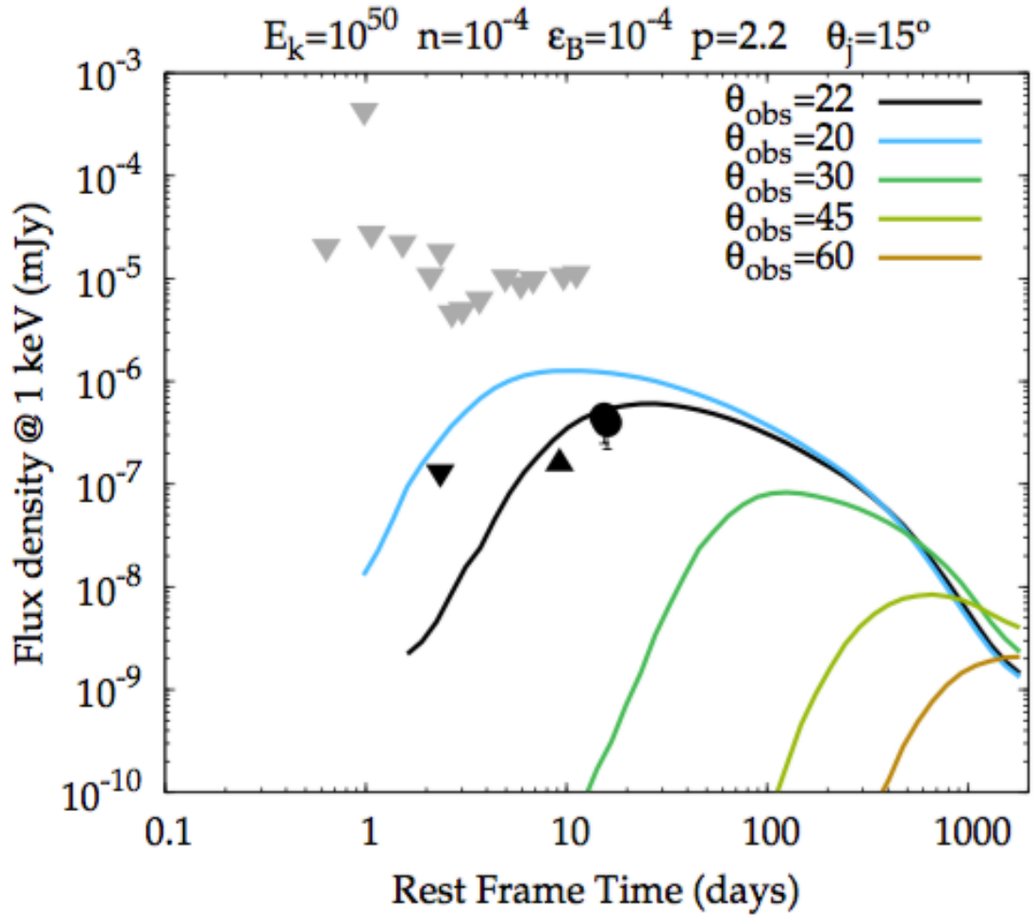
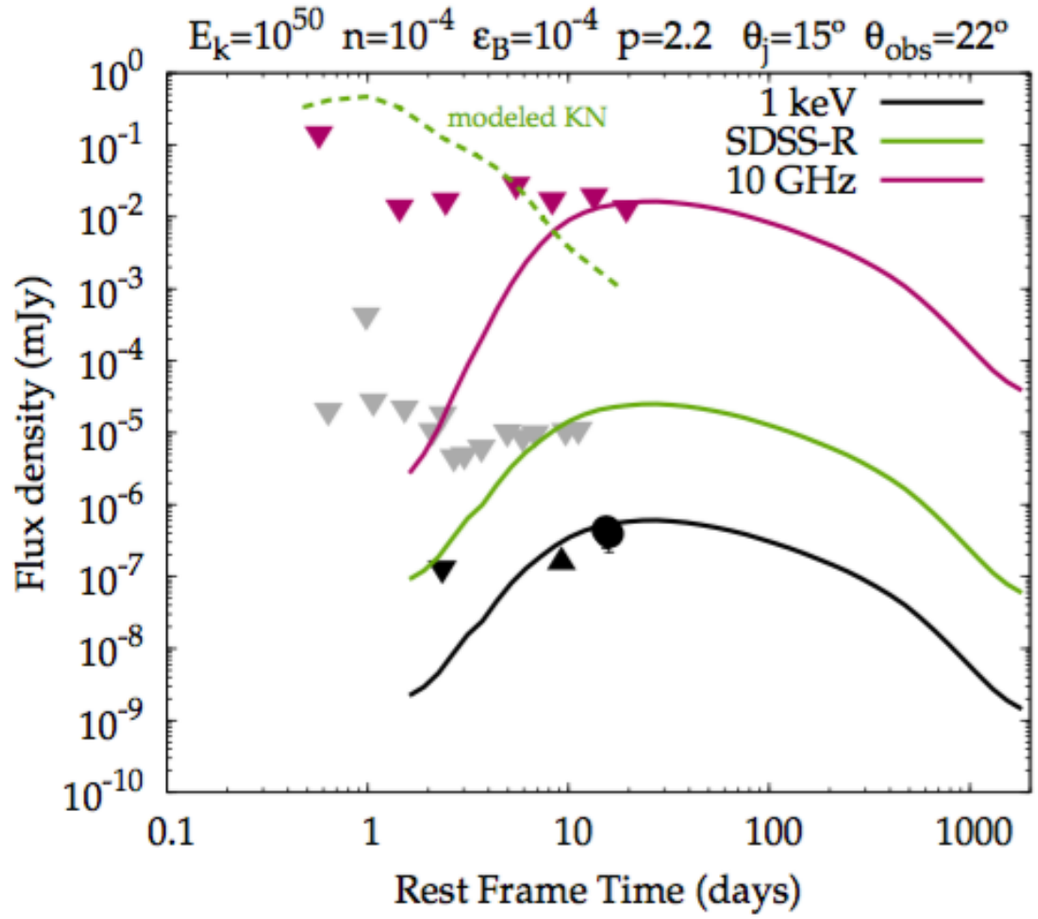
Raffaella Margutti

X-rays (Chandra) + our Radio (VLA, ALMA)





Margutti, Berger, Fong et al. 2017

Alexander, Berger, Fong et al. 2017

$n \sim 10^{-2}$ - 10^{-4} cm^{-3}

$Ek=10^{48}$-$3x10^{50}$ erg

Theta_obs=25-50 deg

Best Fitting Model Parameters

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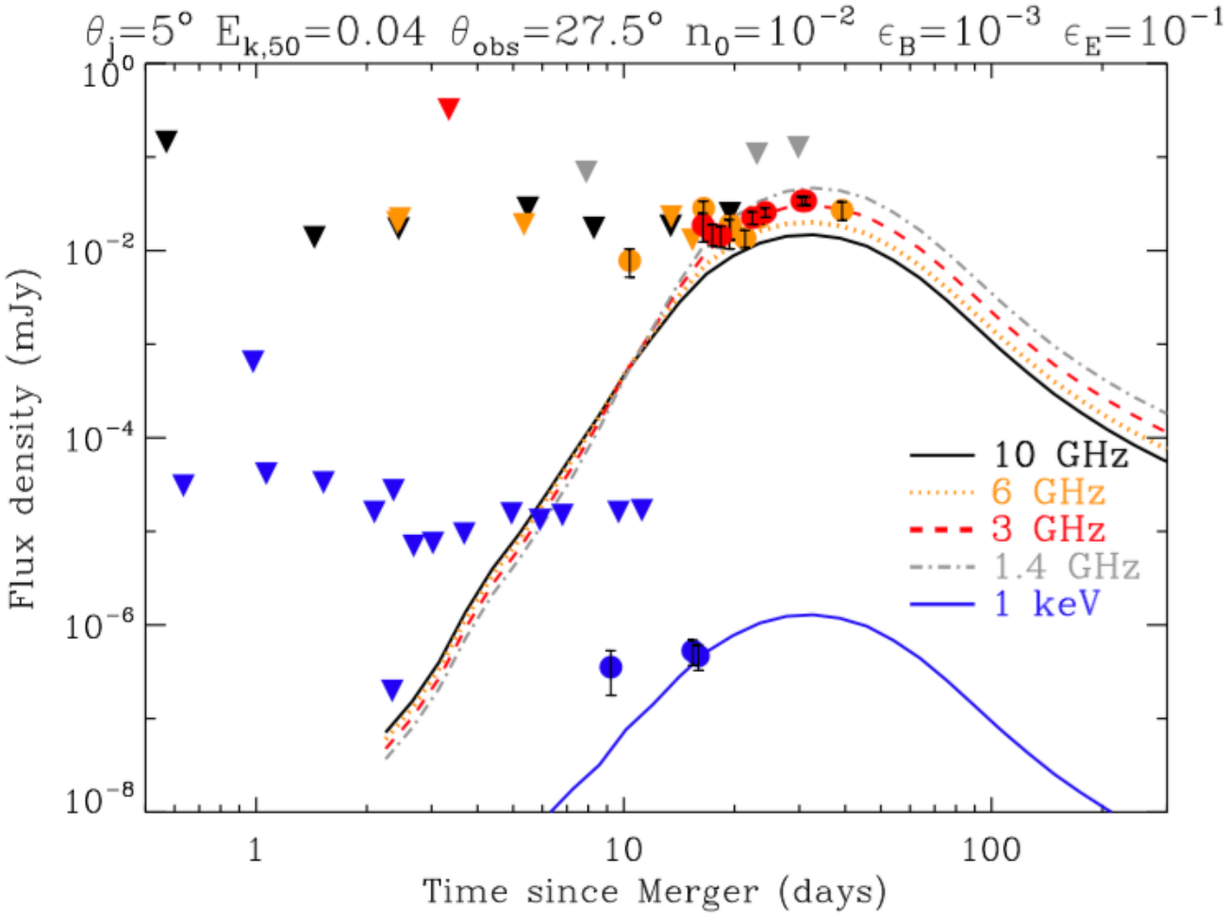
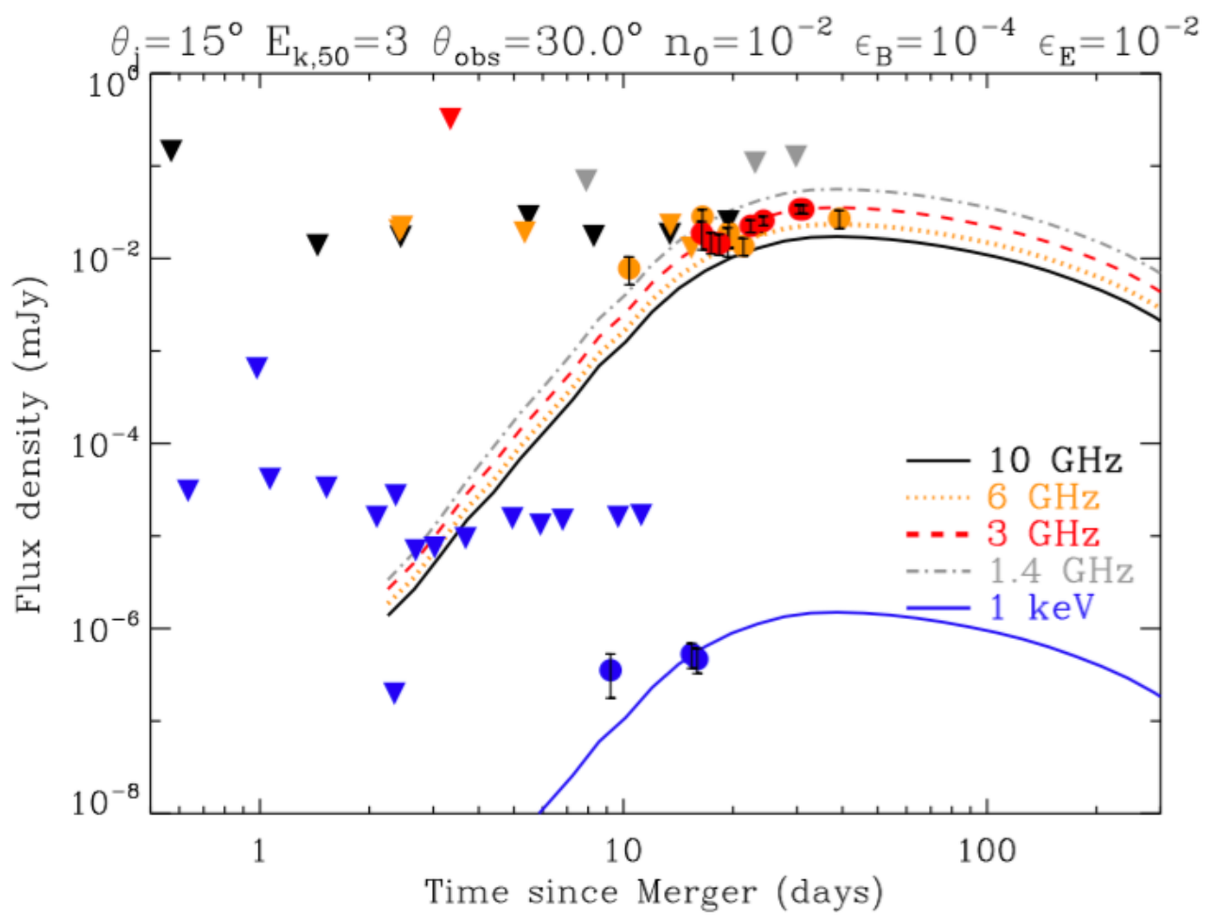
X-rays + Radio
(entire data set at t<40 days)





Guidorzi, Margutti, Scolnic et al. 2017

$n \sim 10^{-2}$ - 10^{-4} cm^{-3}

$Ek = 10^{48}$-3×10^{50} erg

Theta_obs=25-50 deg

Broad agreement with results from:
Haggard et al. 2017
Troja et al. 2017

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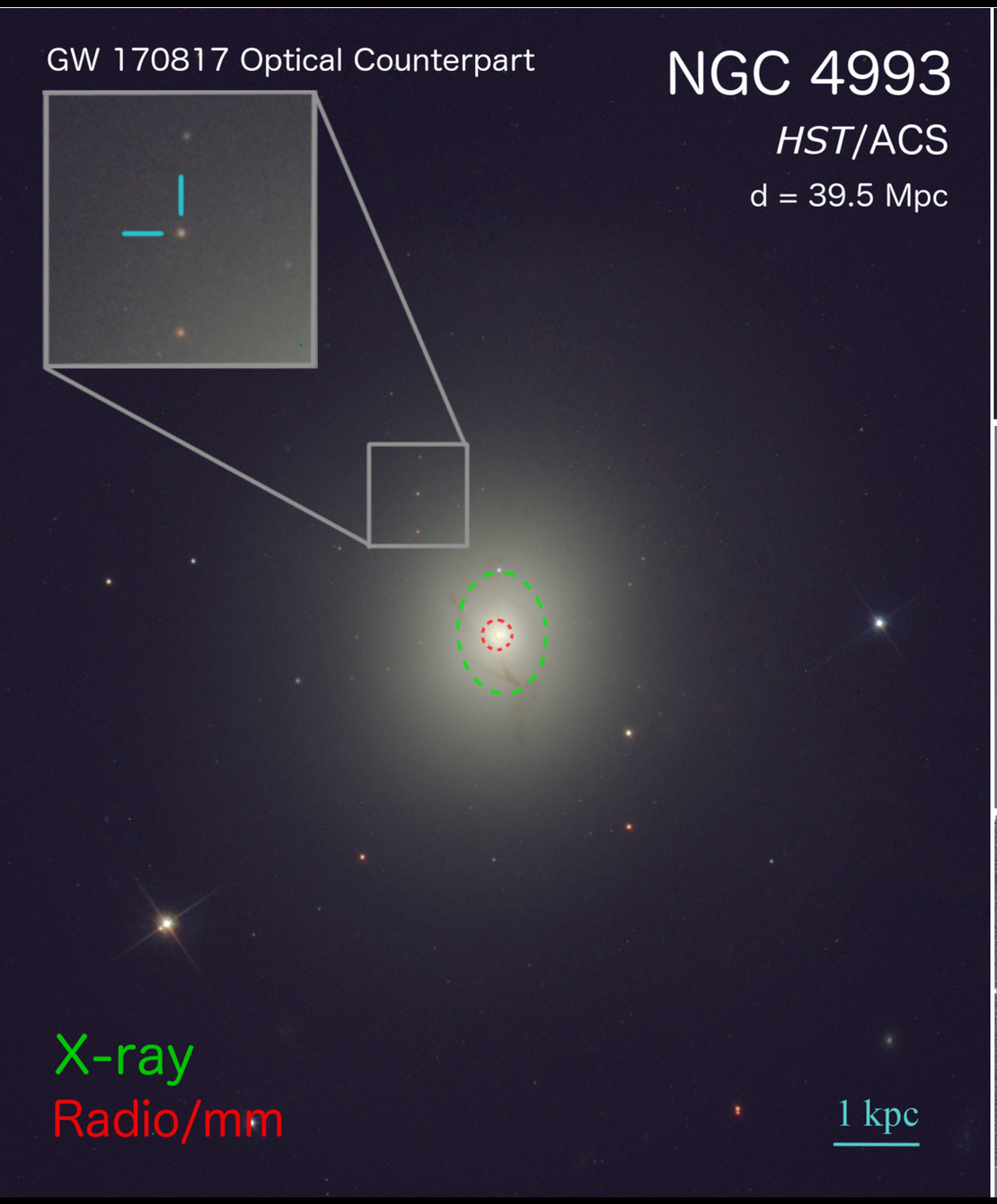
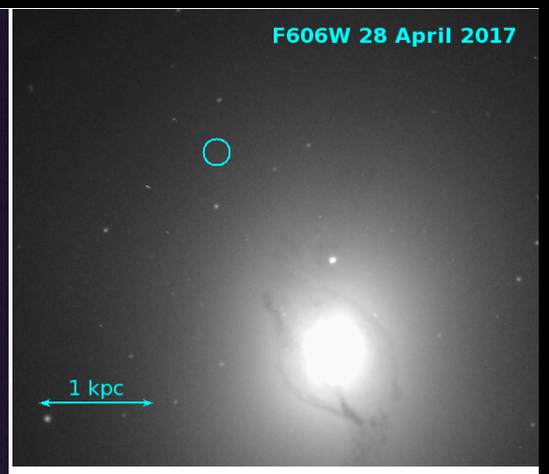
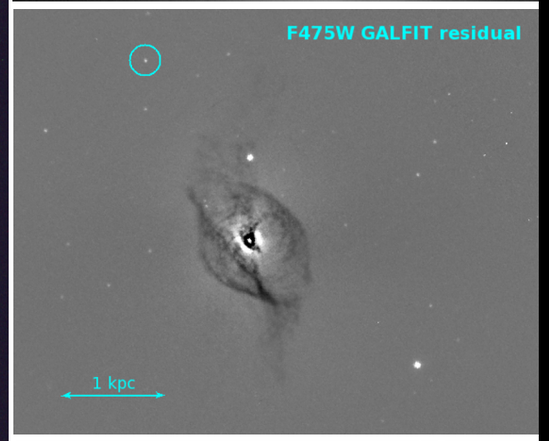
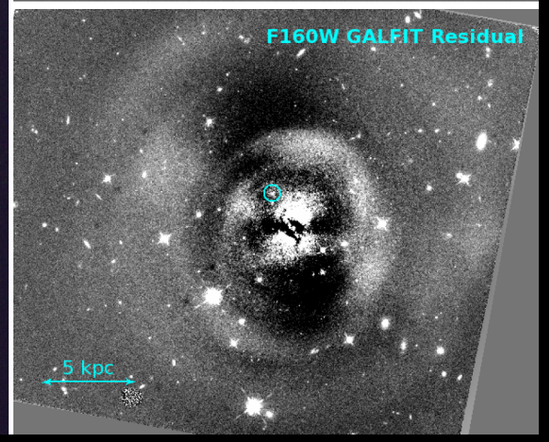
Host galaxy: a nearby S0/Elliptical









Blanchard, Berger, Fong et al. 2017

Pre-explosion:
No source to MV>-7.2 mag
(median of GCLF in ellipticals)

Optical: Dust lanes

Near-IR: Concentric shells, clear merger history

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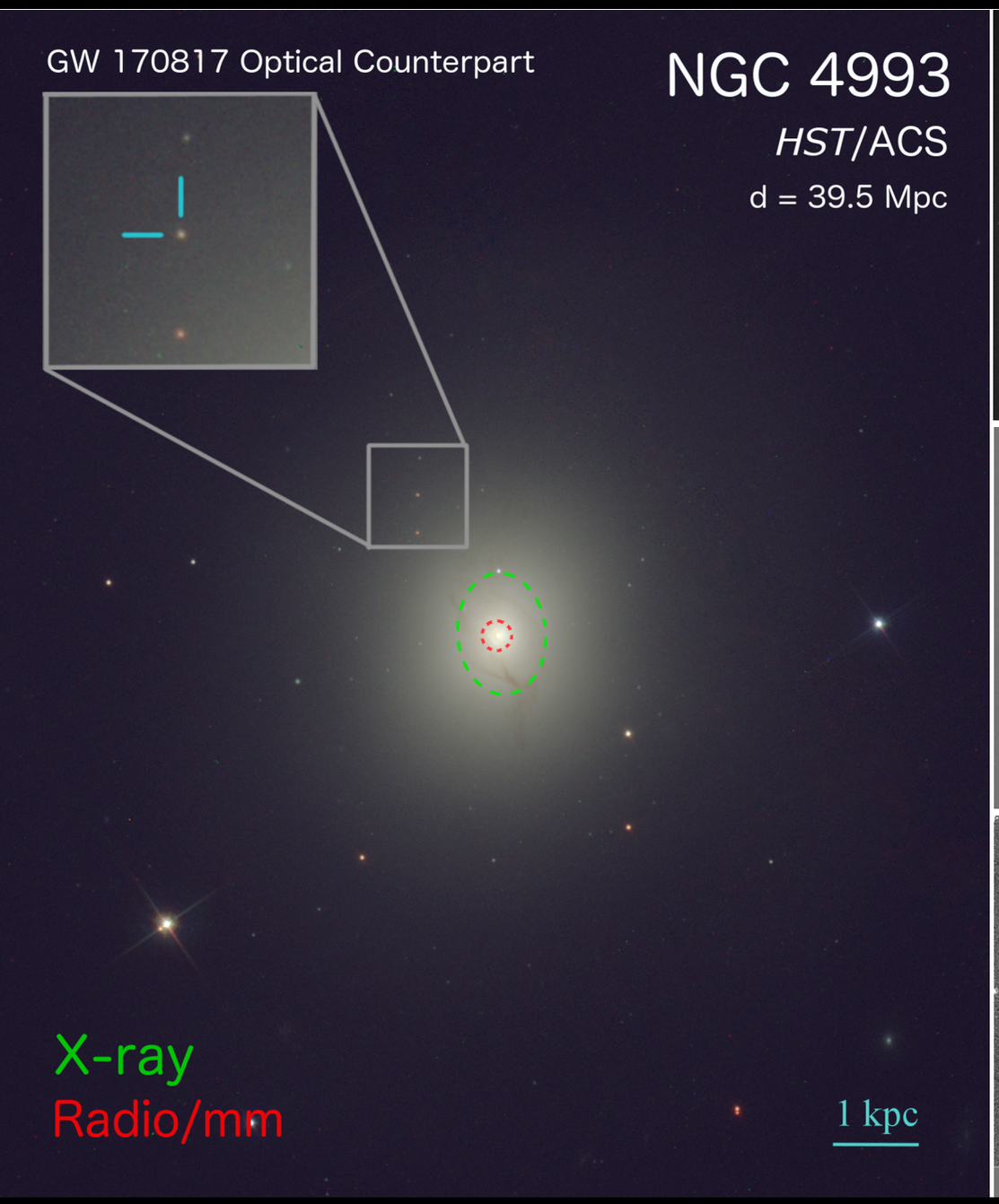
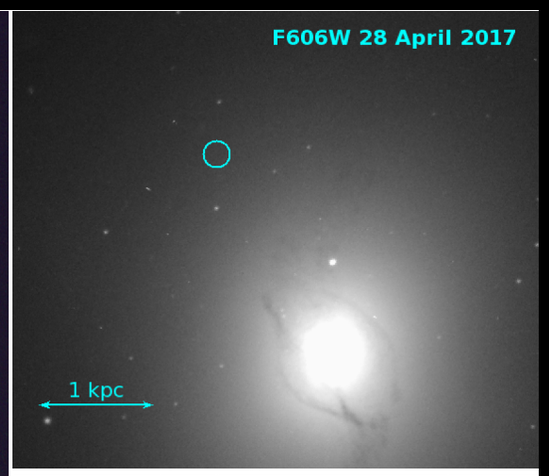
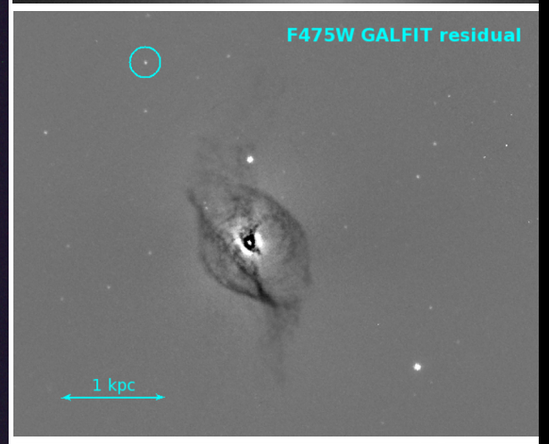
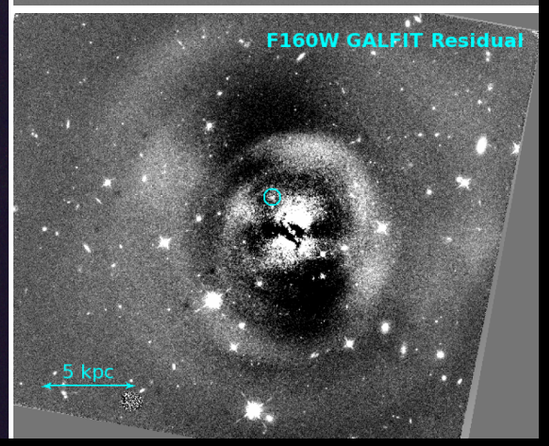
Raffaella Margutti

Host galaxy: a nearby S0/Elliptical









Blanchard, Berger, Fong et al. 2017

<u>Pre-explosion:</u>
No source to MV>-7.2 mag
(median of GCLF in ellipticals)

<u>Optical:</u> Dust lanes

<u>Near-IR:</u> Concentric shells, clear merger history

<u>Inferred properties:</u>
E/S0 morphology
$\log(M^*/M_{sol}) \sim 10.7$
age~11.2 Gyr
SFR~0.01 M_{sol} yr^{-1}
[Fe/H]~0.08

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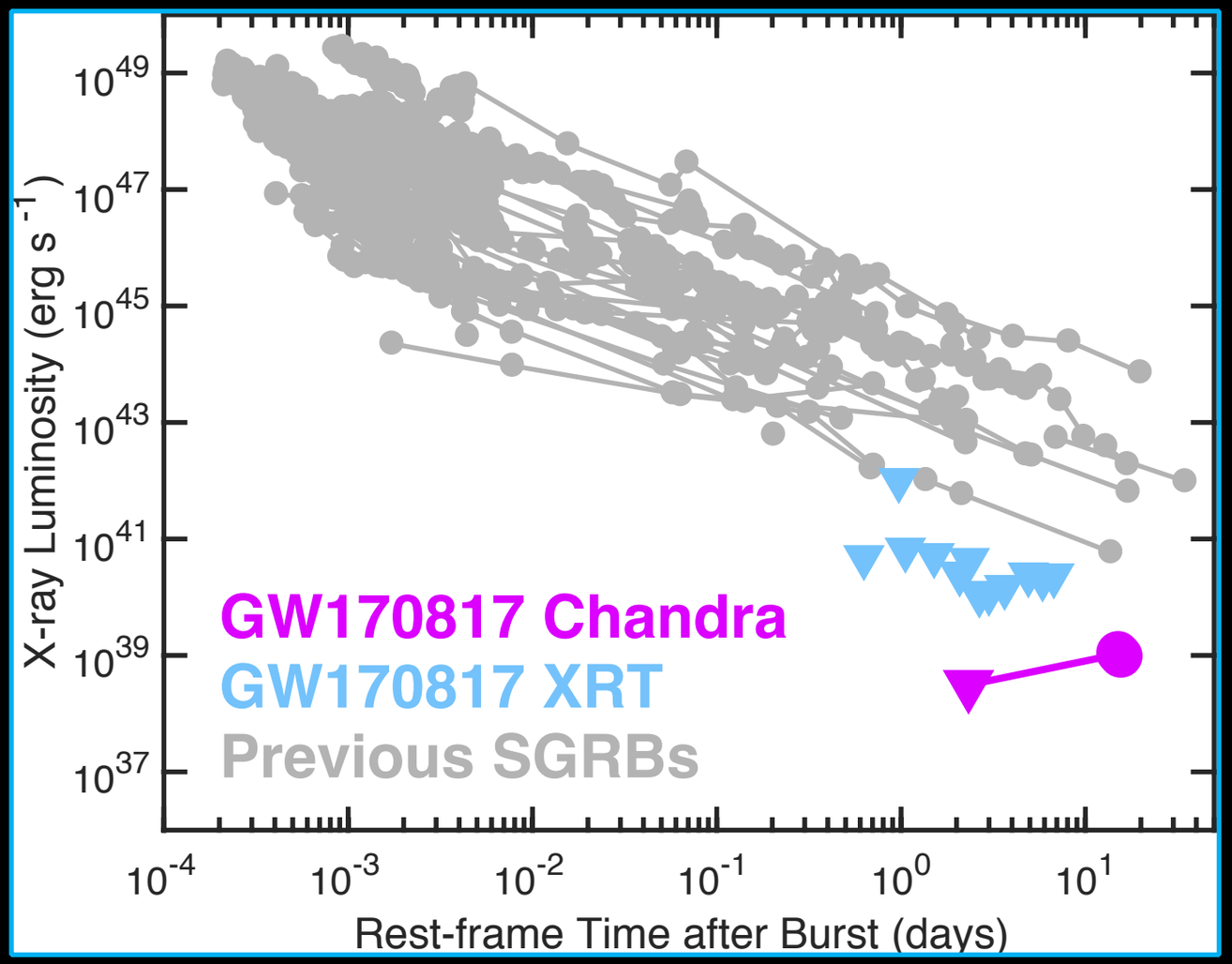
Raffaella Margutti

Broad agreement with literature *except* for age
(Kasliwal et al.; Levan et al.; Pan et al.; Troja et al. 2017)

Comparison to cosmological short GRBs

Under-luminous in X-rays + radio (off-axis)



Fong, Berger, Blanchard et al. 2017

(Other comparisons: Levan et al. 2017; Pan et al. 2017)

Slide by: Wen-fai Fong, Raffaella Margutti

Comparison to cosmological short GRBs

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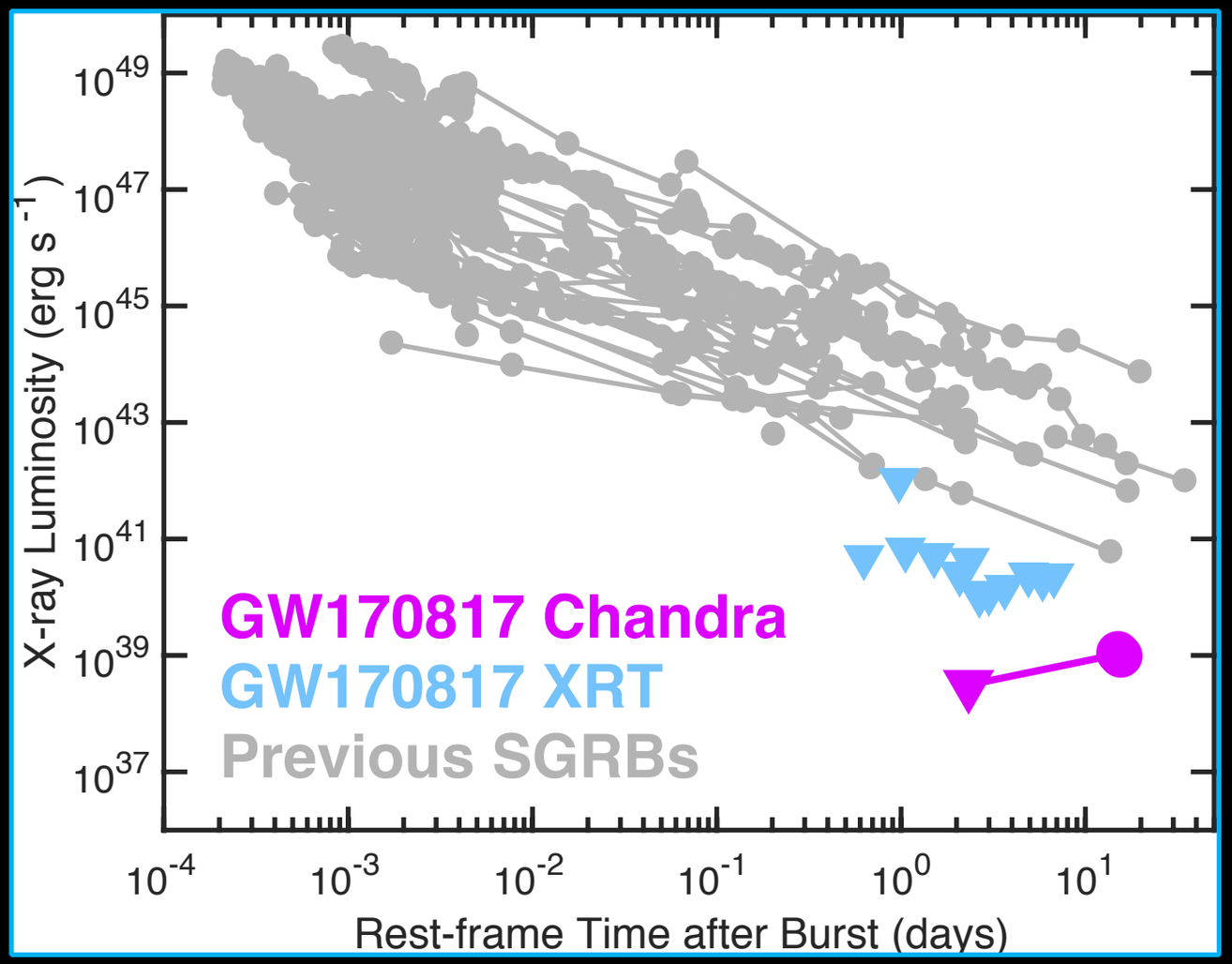
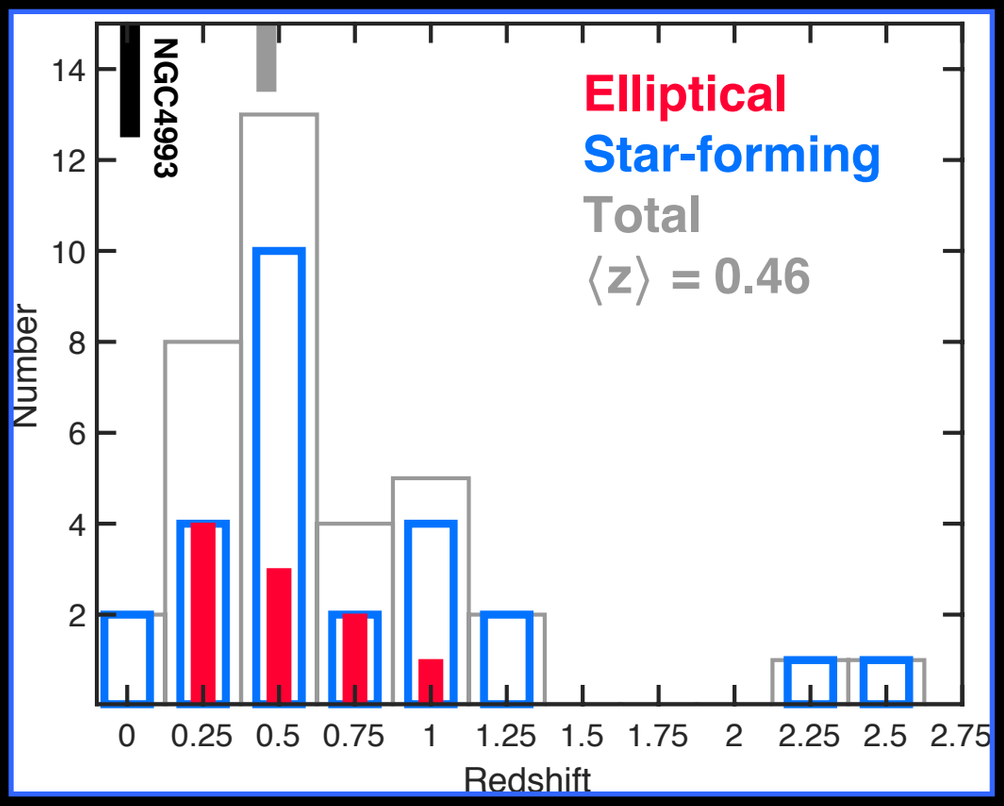


Fong, Berger, Blanchard et al. 2017

(Other comparisons: Levan et al. 2017; Pan et al. 2017)

Nearby!



Slide by: Wen-fai Fong, Raffaella Margutti

Comparison to cosmological short GRBs

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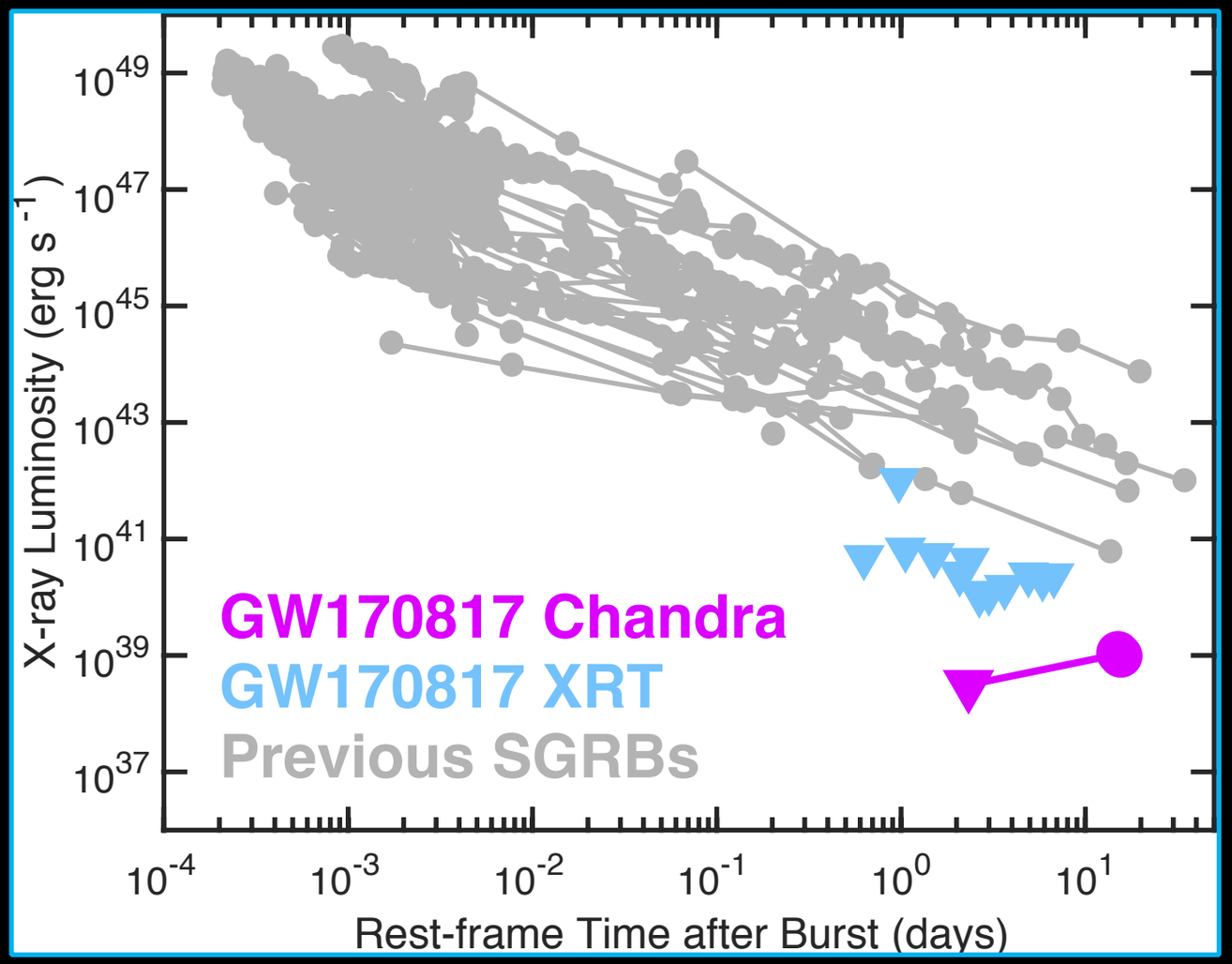

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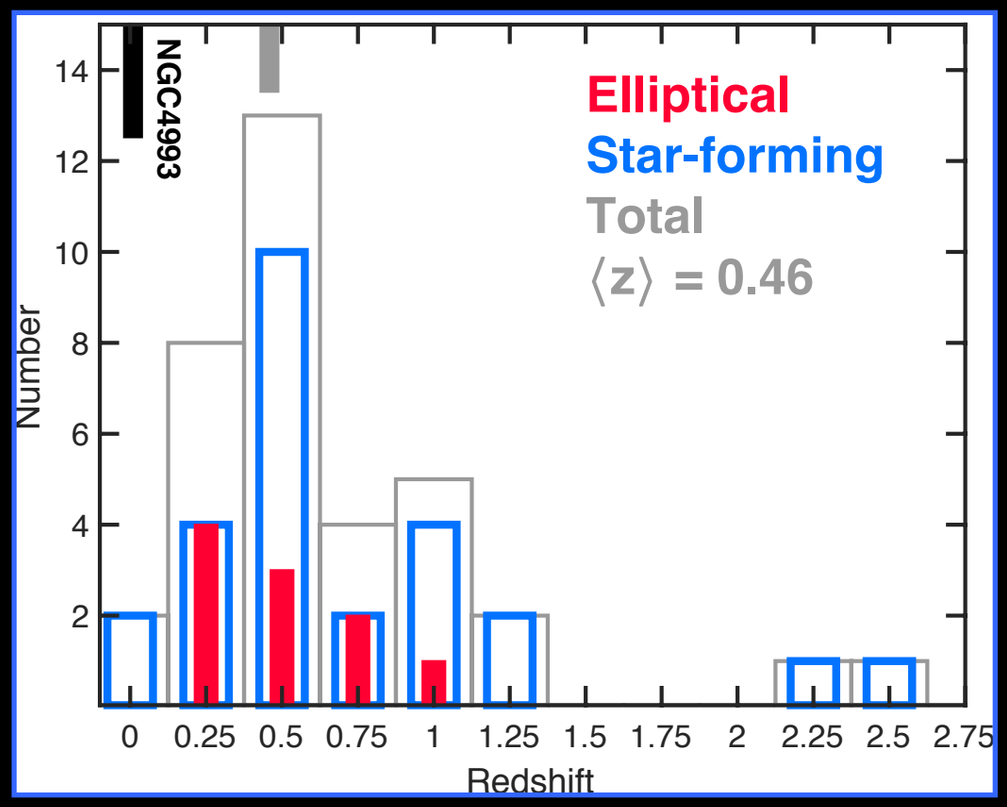

Rankings w.r.t. Short GRBs

Stellar Mass = 72%

B-band Luminosity = 94%

Age = 100%

SFR = 0%

Projected offset (kpc) = 24%

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