EM Followup Activities in Korea

Hyung Mok Lee (KASI), Myungshin Im (Seoul National Univerity)
on behalf of the KU EM Followup Team

Korean/Uzbekistan Group

- Korean group together with Uzbek astronomers (KU Group) signed an MoU with LIGO/Virgo for EM followup observations in April 2014
- KU group composed of SNU and KASI actively participated the observational campaigns using several optical telescopes
- It is now expanding to include more people and telescopes, including radio telescopes

Memorandum of Understanding between

KU and LIGO and VIRGO

regarding follow-up observations of gravitational wave event candidates

April 5, 2014

Full name of the partner project: Korea-Uzbekistan Consortium (KU)

Abbreviated name: KU

Project web site (if available): N/A

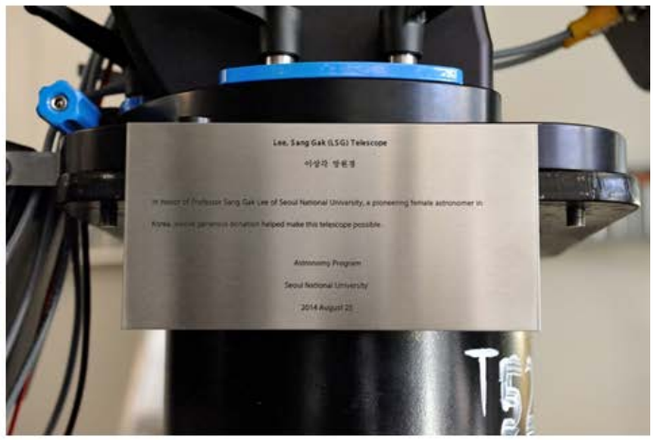
Name, institution, email and title[1] of the leader(s) (who will sign the MOU):
Prof. Myungshin Im, Seoul National University, myungshin.im@gmail.com
Prof. Hyung Mok Lee, Seoul National University, hmlee@astro.snu.ac.kr

Name, institution, email, and phone numbers of the liaison with LVC:
Prof. Hyung Mok Lee, Seoul National University, hmlee@astro.snu.ac.kr, +8

List of associated members (name, institution and email):
Hyung Mok Lee (Seoul National University) hmlee@astro.snu.ac.kr
Myungshin Im (Seoul National University) myungshin.im@gmail.com
Myung Gyoon Lee (Seoul National University) mglee@astro.snu.ac.kr
Jong-Hak Woo (Seoul National University) woo@astro.snu.ac.kr
Masateru Ishiguro (Seoul National University) ishiguro@astro.snu.ac.kr
Jongchul Chae (Seoul National University) chae@astro.snu.ac.kr
Sung-Chul Yoon (Seoul National University) astroyoon@gmail.com
Yongsun Park (Seoul National University) yspark@astro.snu.ac.kr
Sascha Trippe (Seoul National University) trippe@astro.snu.ac.kr
Hyun-Il Sung (Korea Astronomy and Space Science Institute) hisung@kasi.r
Shuhrat Ehgamberdiev (Ulugh Beg Astronomical Institute, Uzbekistan) shuh
Soojong Pak (Kyung Hee University) soojong@khu.ac.kr

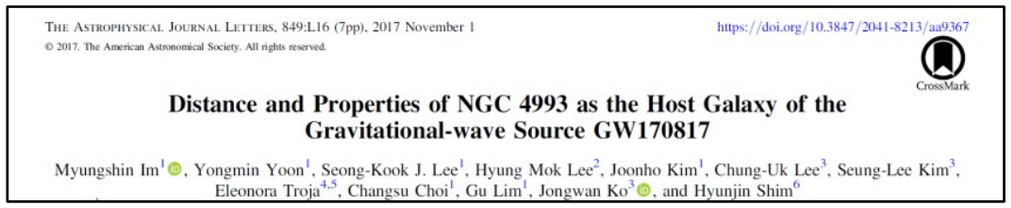
Facilities used for GW170817 Followup Campaign

- KMTNet
  - Three telescopes at Chile (CTIO), Australia (SAO) and South Africa (SAAO)
  - 1.6 m, 2x2 degree FOV
  - BVRI Filters
  - Mostly dedicated for the microlensing survey, but demonstrated its capability in time-of-opportunity observations.
- LSGT (이상각 망원경)
  - 0.5 m, *u,v,r,i,z* filters
  - Located in Australia
- Other i-Telescopes



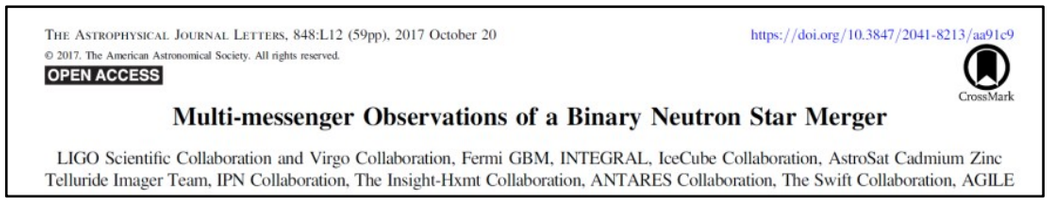
GW170817
Publications

- **EM counterpart discovery: Together with LVC+EM Followup partners**
- **Early emission characteristics (optical/NIR, imaging/spectroscopy – Constraints on models): Together with NASA X-ray group**
- **Host galaxy: KU group**
- Late-time emission study
- Cosmological application:
- GW detection strategy


The Astrophysical Journal Letters, 849:L16 (7pp), 2017 November 1 https://doi.org/10.3847/2041-8213/aa9367

Distance and Properties of NGC 4993 as the Host Galaxy of the Gravitational-wave Source GW170817

Myungshin Im[1], Yongmin Yoon[1], Seong-Kook J. Lee[1], Hyung Mok Lee[2], Joonho Kim[1], Chung-Uk Lee[3], Seung-Lee Kim[3], Eleonora Troja[4,5], Changsu Choi[1], Gu Lim[1], Jongwan Ko[3], and Hyunjin Shim[6]


The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

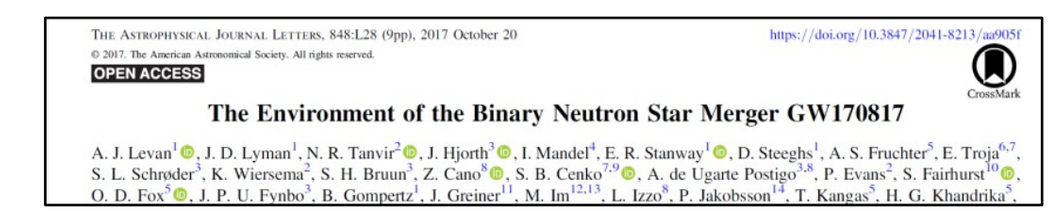
Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE


LETTER
doi:10.1038/nature24290

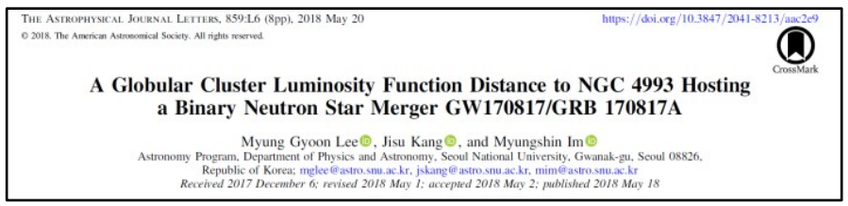
The X-ray counterpart to the gravitational-wave event GW170817

E. Troja[1,2], L. Piro[3], H. van Eerten[4], R. T. Wollaeger[5], M. Im[6], O. D. Fox[7], N. R. Butler[8], S. B. Cenko[2,9], T. Sakamoto[10], C. L. Fryer[5], R. Ricci[11], A. Lien[2,12], R. E. Ryan Jr[7], O. Korobkin[5], S.–K. Lee[6], J. M. Burgess[13], W. H. Lee[14], A. M. Watson[14], C. Choi[6], S. Covino[15], P. D'Avanzo[15], C. J. Fontes[5], J. Becerra González[16,17], H. G. Khandrika[1], J. Kim[6], S.–L. Kim[18], C.–U. Lee[18], H. M. Lee[19], A. Kutyrev[1,2], G. Lim[6], R. Sánchez–Ramírez[3], S. Veilleux[1,9], M. H. Wieringa[20] & Y. Yoon[6]


The Astrophysical Journal Letters, 848:L28 (9pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa905f

The Environment of the Binary Neutron Star Merger GW170817

A. J. Levan[1], J. D. Lyman[1], N. R. Tanvir[2], J. Hjorth[3], I. Mandel[4], E. R. Stanway[1], D. Steeghs[1], A. S. Fruchter[5], E. Troja[6,7], S. L. Schrøder[3], K. Wiersema[2], S. H. Bruun[3], Z. Cano[8], S. B. Cenko[7,9], A. de Ugarte Postigo[3,8], P. Evans[2], S. Fairhurst[10], O. D. Fox[5], J. P. U. Fynbo[3], B. Gompertz[1], J. Greiner[11], M. Im[12,13], L. Izzo[8], P. Jakobsson[14], T. Kangas[5], H. G. Khandrika[5],


The Astrophysical Journal Letters, 859:L6 (8pp), 2018 May 20 https://doi.org/10.3847/2041-8213/aac2e9

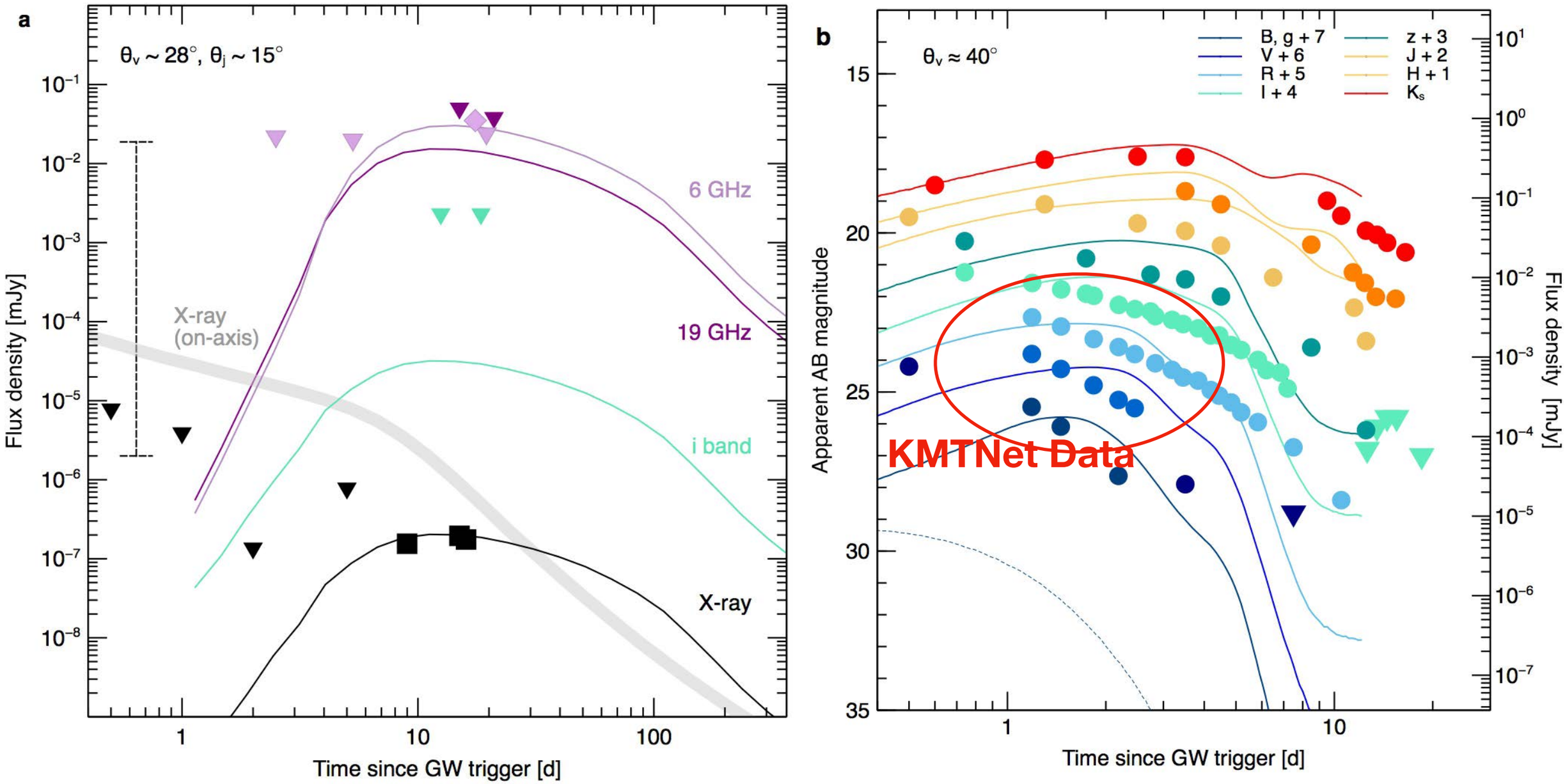
A Globular Cluster Luminosity Function Distance to NGC 4993 Hosting a Binary Neutron Star Merger GW170817/GRB 170817A

Myung Gyoon Lee, Jisu Kang, and Myungshin Im
Astronomy Program, Department of Physics and Astronomy, Seoul National University, Gwanak-gu, Seoul 08826, Republic of Korea; mglee@astro.snu.ac.kr, jskang@astro.snu.ac.kr, mim@astro.snu.ac.kr
Received 2017 December 6; revised 2018 May 1; accepted 2018 May 2; published 2018 May 18

The optical afterglow of the short gamma-ray burst associated with GW 170817

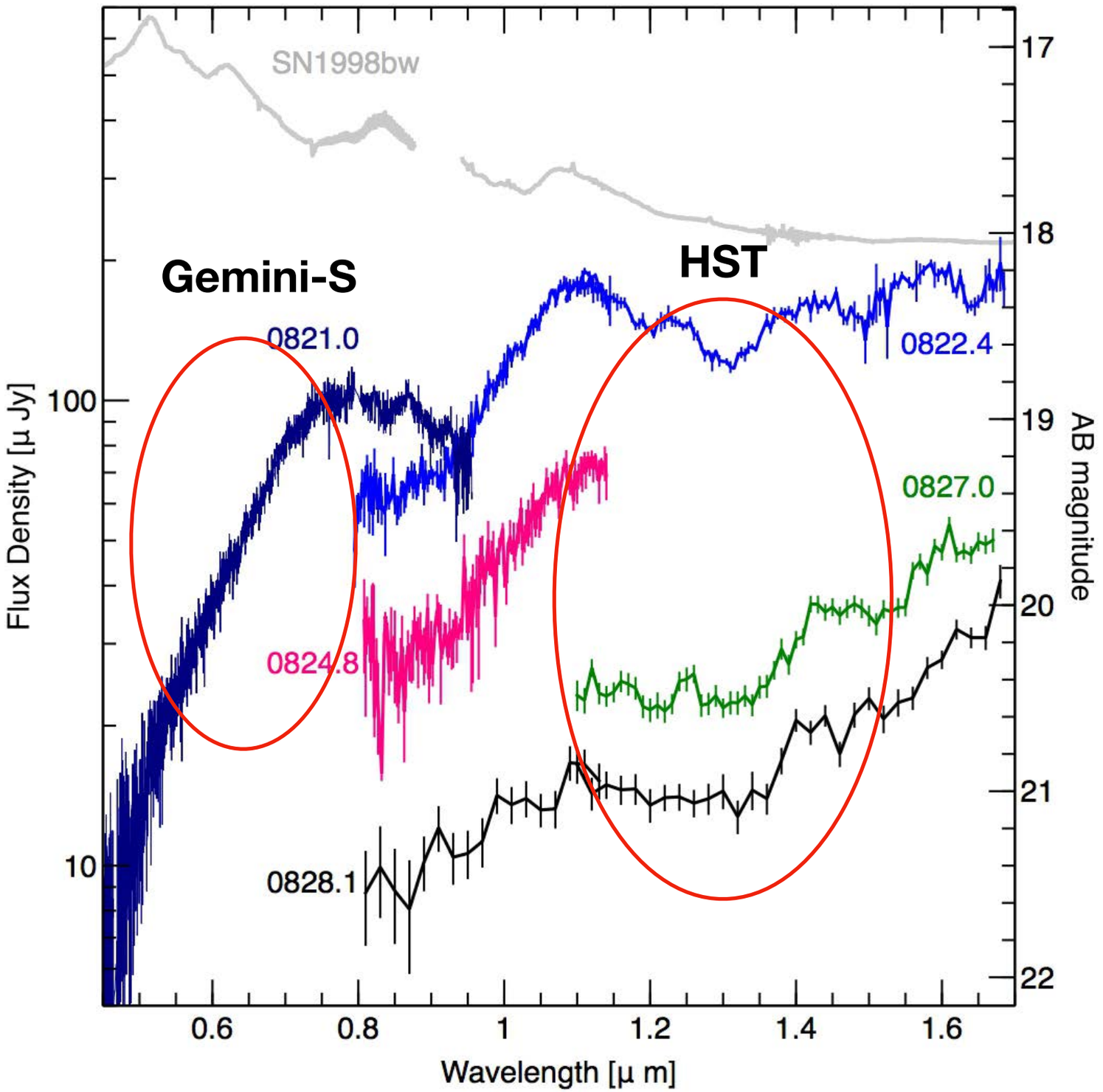
J. D. Lyman[1], G. P. Lamb[2], A. J. Levan[1], I. Mandel[3], N. R. Tanvir[4], S. Kobayashi[2], B. Gompertz[1], J. Hjorth[5], A. S. Fruchter[6], T. Kangas[6], D. Steeghs[1], I. A. Steele[2], Z. Cano[7], P. Evans[4], J.P.U. Fynbo[5], C. Gall[5], M. Im[8], L. Izzo[7], P. Jakobsson[9], Milvang-Jensen, B.[5], P. O'Brien[4], J.P. Osborne[4],

Multi-wavelength light curves



NASA/Korean group, Nature 2017

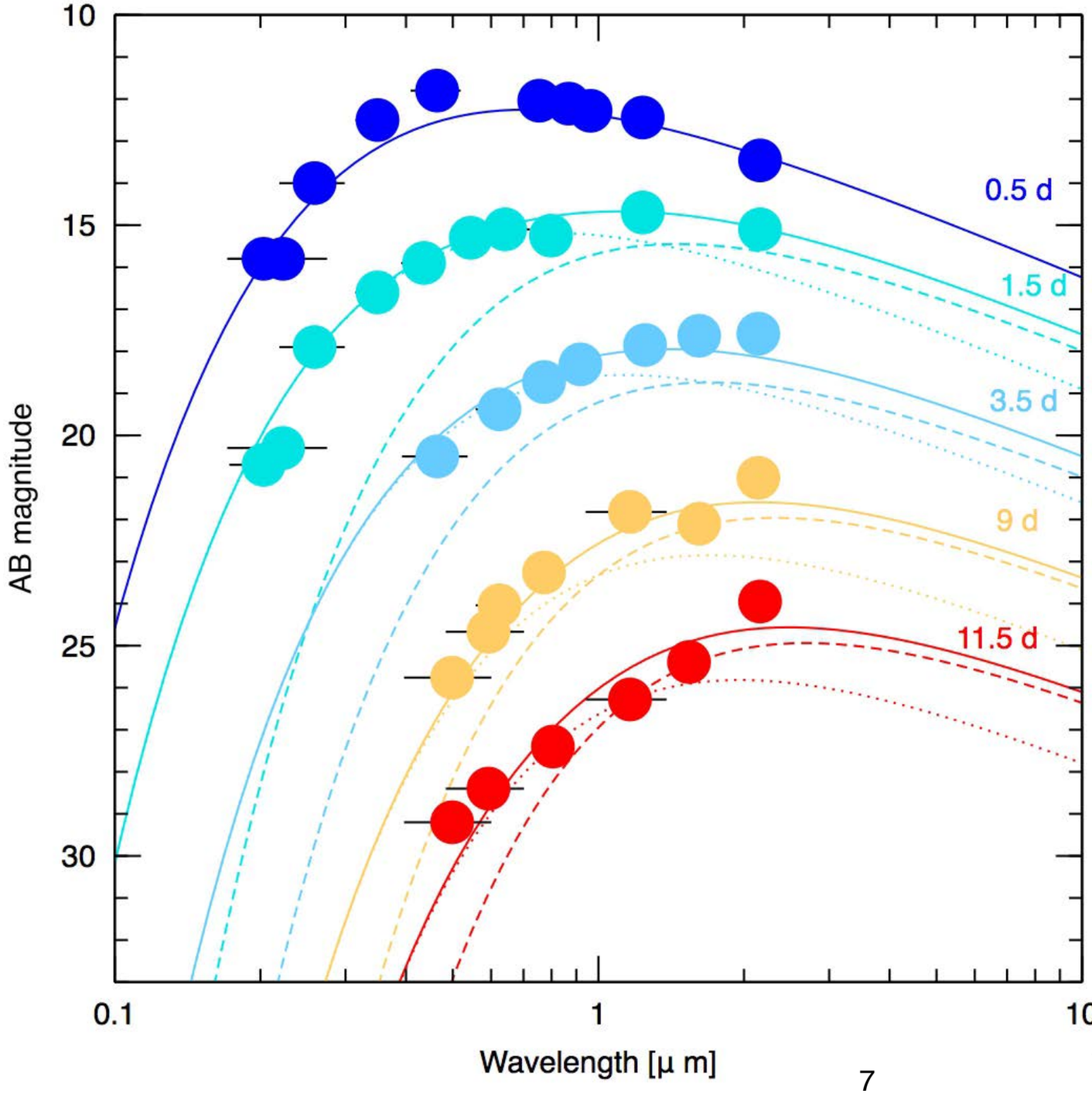
Optical and NIR spectra



- T+3.5d, by 8m Gemini telescope
- Featureless spectra with rapid turnover at <0.75 micron
- Becomes redder with time
- Consistent with the ejection of high velocity, neutron rich material during a NS merge

Nature 2017

Spectral Energy Distribution of the Optical/Infrared Counterpart



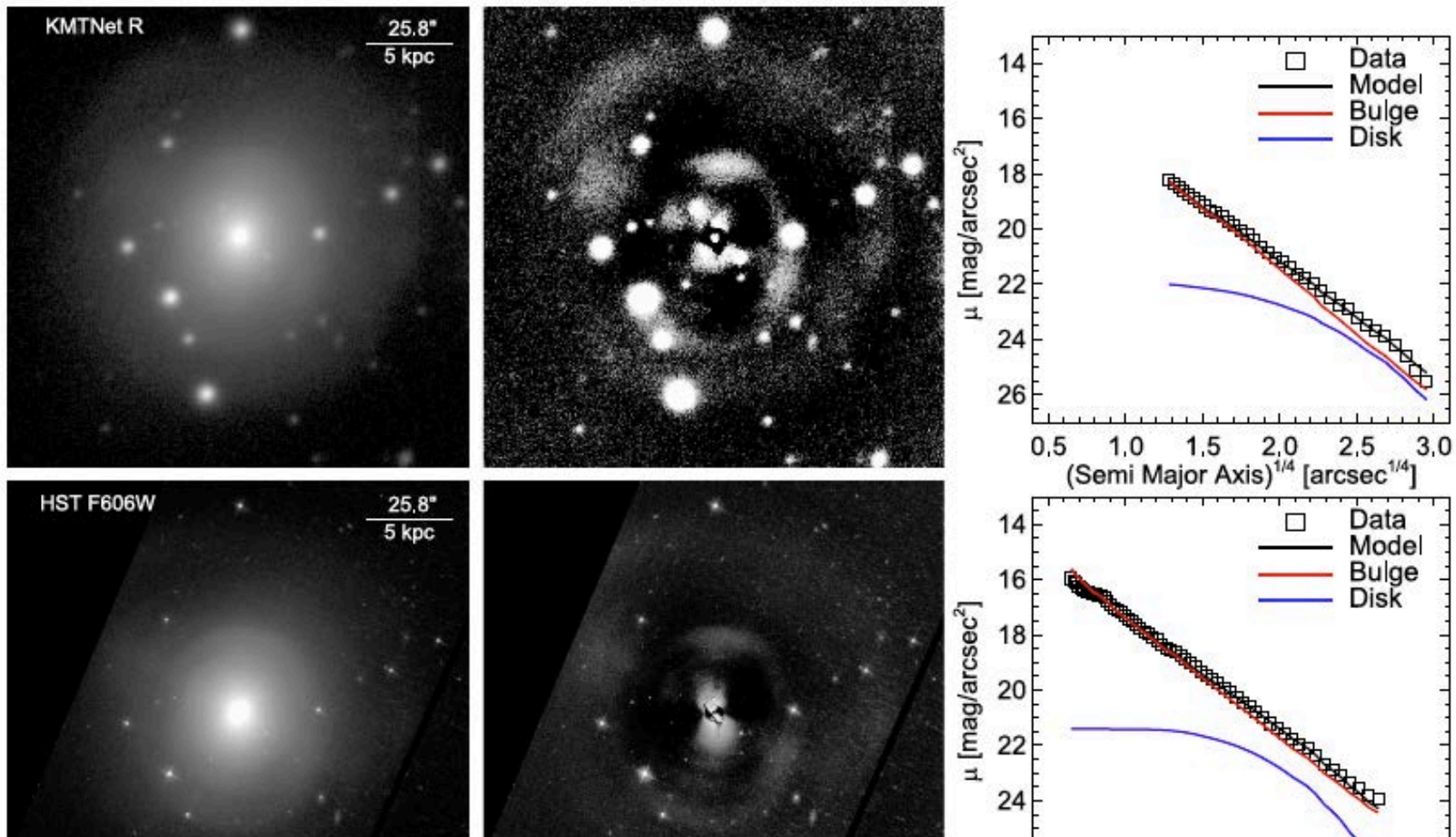
- Broadband optical/ near-infrared data well fitted to single or two component black body.

Nature article by NASA/Korean group

Properties of the Host Galaxy: NGC 4993

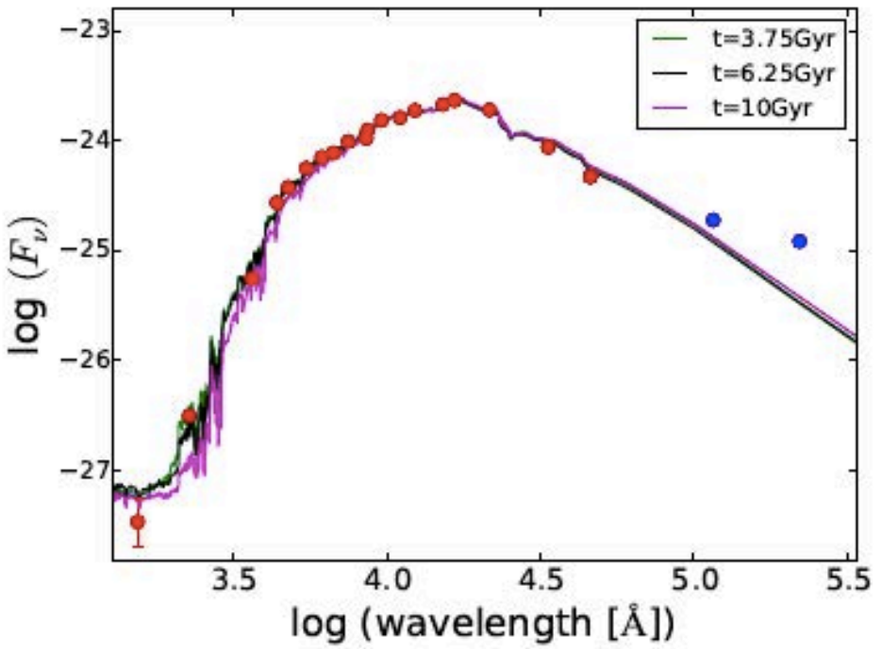
Im et al. 2017, ApJL

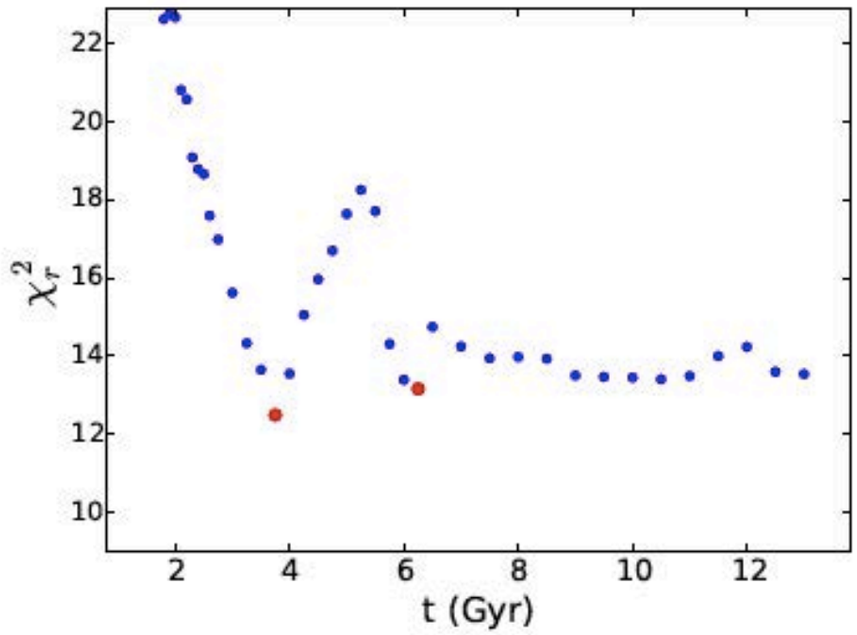
- High contrast images were constructed by stacking many images taken by KMTNet at B, V, R, and I
- Images taken by HST/ACS (F606W) and 2MASS (J, H, Ks) are publicly available
  - 2-dimensional surface brightness fitting to bulge + disk
  - Other models such as single Sersic or double Sersic also fits the surface brightness well.



SED fitting

- Photometric data are available at many filter bands: GALEX NUV & FUV, u,g,r,i,z (LSGT), B,V,R,I (KMTNet), F606W (HST), J, H, Ks (2MASS), W1, W2, W3, W4 (WISE)
- SED fitting provides the star formation history
  - The age is not well constrained, but could be 3-6 Gyrs
  - Age can be as old as 10 Gyr
  - Origin of the NS binaries?





Im et al. 2017, ApJL

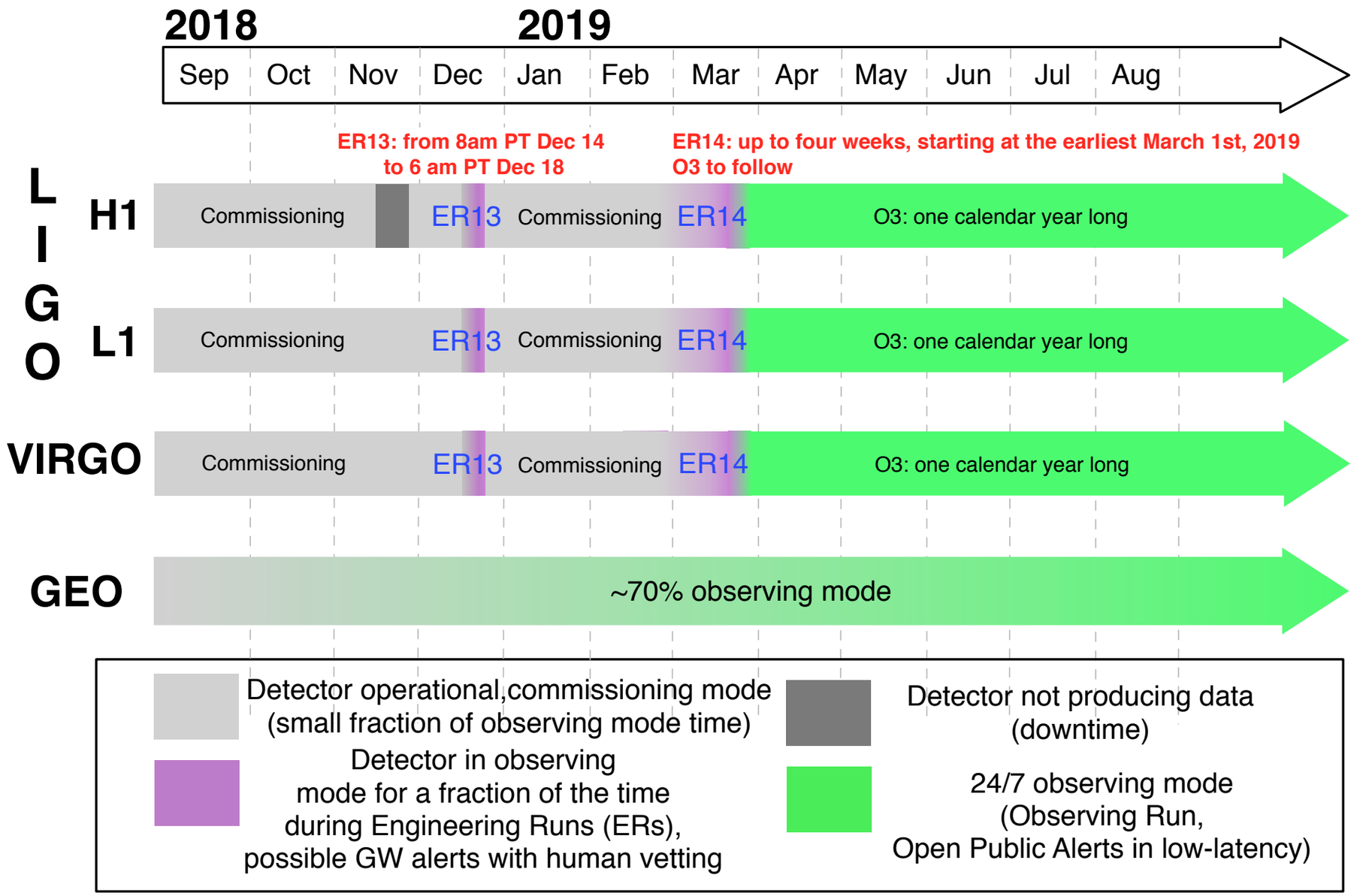
Outlook for O3

LIGO-G1801056

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

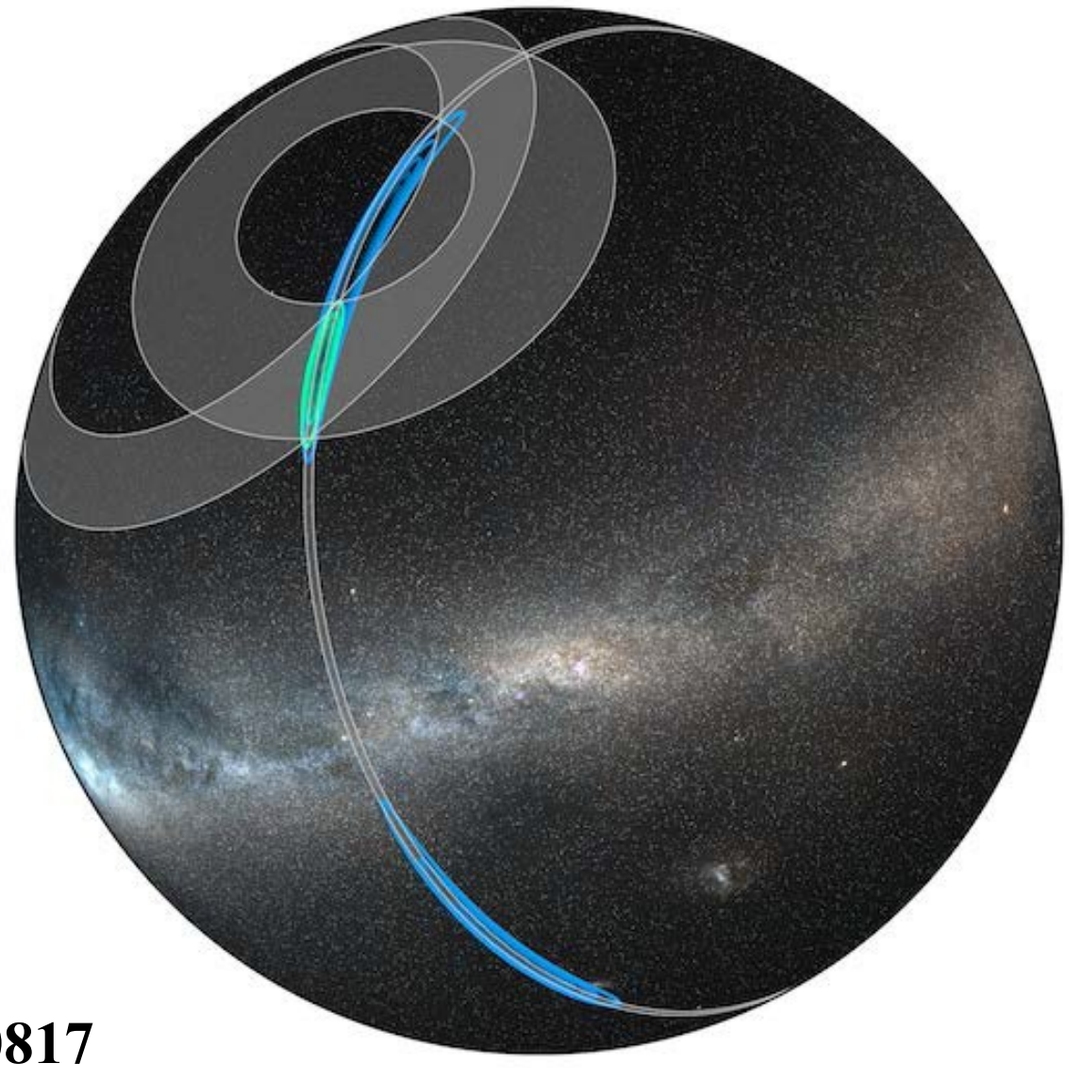
(Public document G1801056-v4, based on G1800889-v7)



https://www.ligo.org/scientists/GWEMalerts.php

What is expected in O3 + ER

- **Event rate**
- **Localization**
- **Alert content**



GW170817

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

Event rate (BNS)

Living Reviews in Relativity (in press)

Epoch			2015–2016	2016–2017	2018–2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40–60	60–75	75–90	105	105
		Virgo	—	20–40	40–50	40–70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40–80	80–120	120–170	190	190
		Virgo	—	20–65	65–85	65–115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60–80	60–100	—	—	—
		Virgo	—	25–30	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.05–1	0.2–4.5	1–50	4–80	11–180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	<1	1–5	1–4	3–7	23–30
		20 deg^2	<1	7–14	12–21	14–22	65–73
	median/deg^2		460–530	230–320	120–180	110–180	9–12
Searched area	% within	5 deg^2	4–6	15–21	20–26	23–29	62–67
		20 deg^2	14–17	33–41	42–50	44–52	87–90

post-GW170817:
$R_{BNS} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6}$ Mpc^{-3}yr^{-1}

Phys. Rev. Lett. 119, 16110

2018 Amsterdam Townhall meeting Dent, Pankow, et al.

Event rate (NSBH)

7

BNS/NSBH rate distributions at **end of O1**

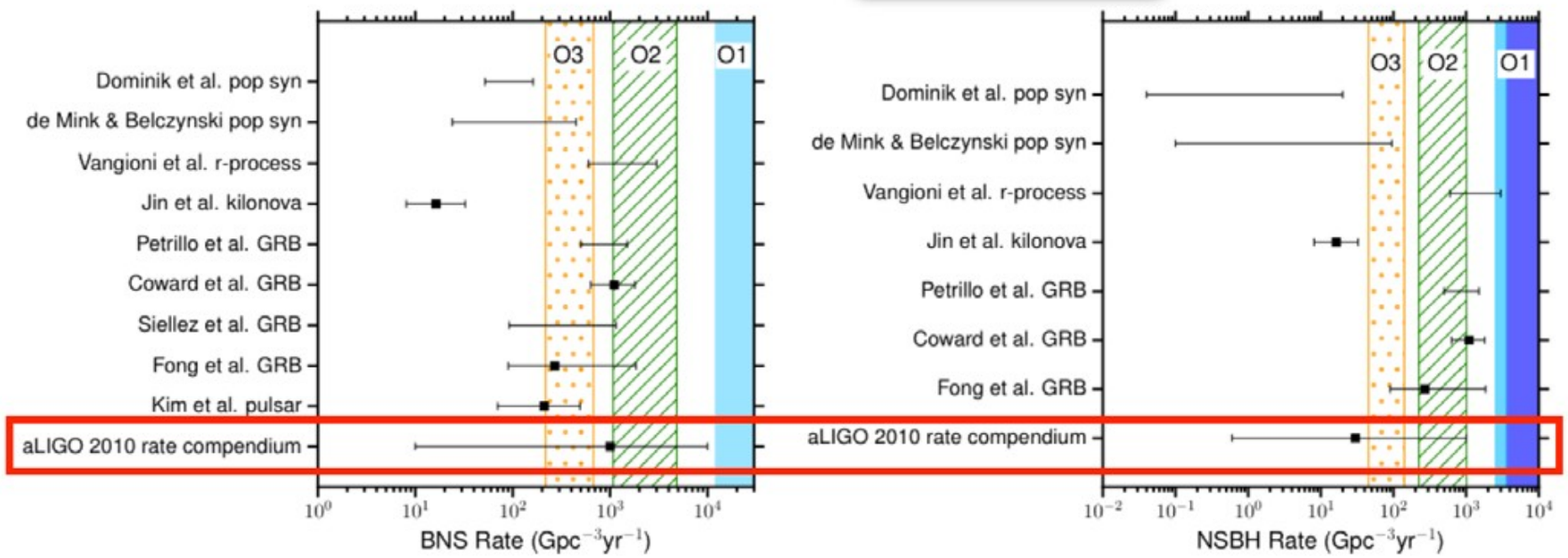


TABLE IV: Compact binary coalescence rates per Mpc^3 per Myr.[a]

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$	$R_{\rm max}$
NS-NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS-BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

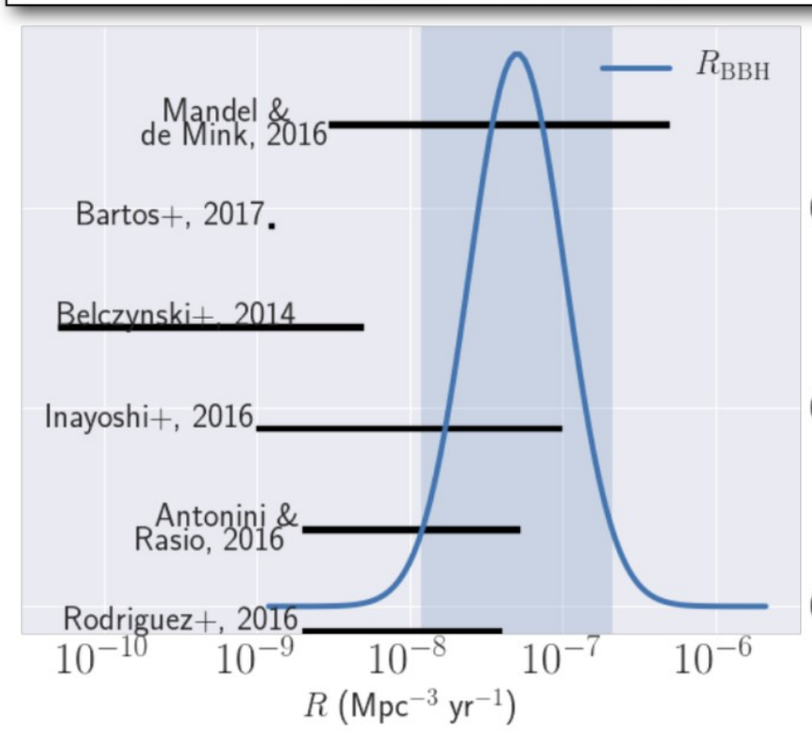
Class. Quantum Grav. 27 (2010) 173001

2018 Amsterdam Townhall meeting Dent, Pankow, et al.

Very small!

Event rate (BBH)

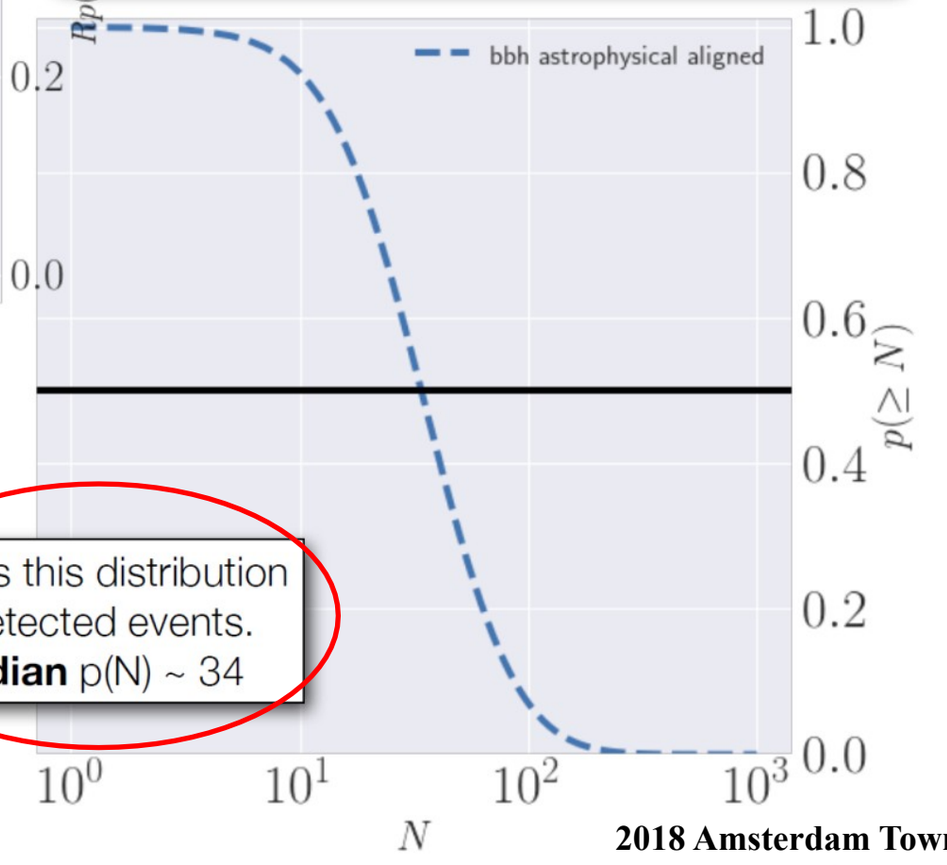
Binary Black Hole Rates
(post-GW170104)



This rate distribution…
R_{BBH} ~ 1.2 x 10^{-8} — 2.1 x 10^{-6} Mpc^{-3}yr^{-1}

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

log-uniform: $p(m_1) \sim m^{-1}$ $(5 < m_1 < 100\ M_\odot)$
…with O3 surveyed space-time volume:
VT_{BBH} ~ 7 x 10^8 Mpc^3 yr



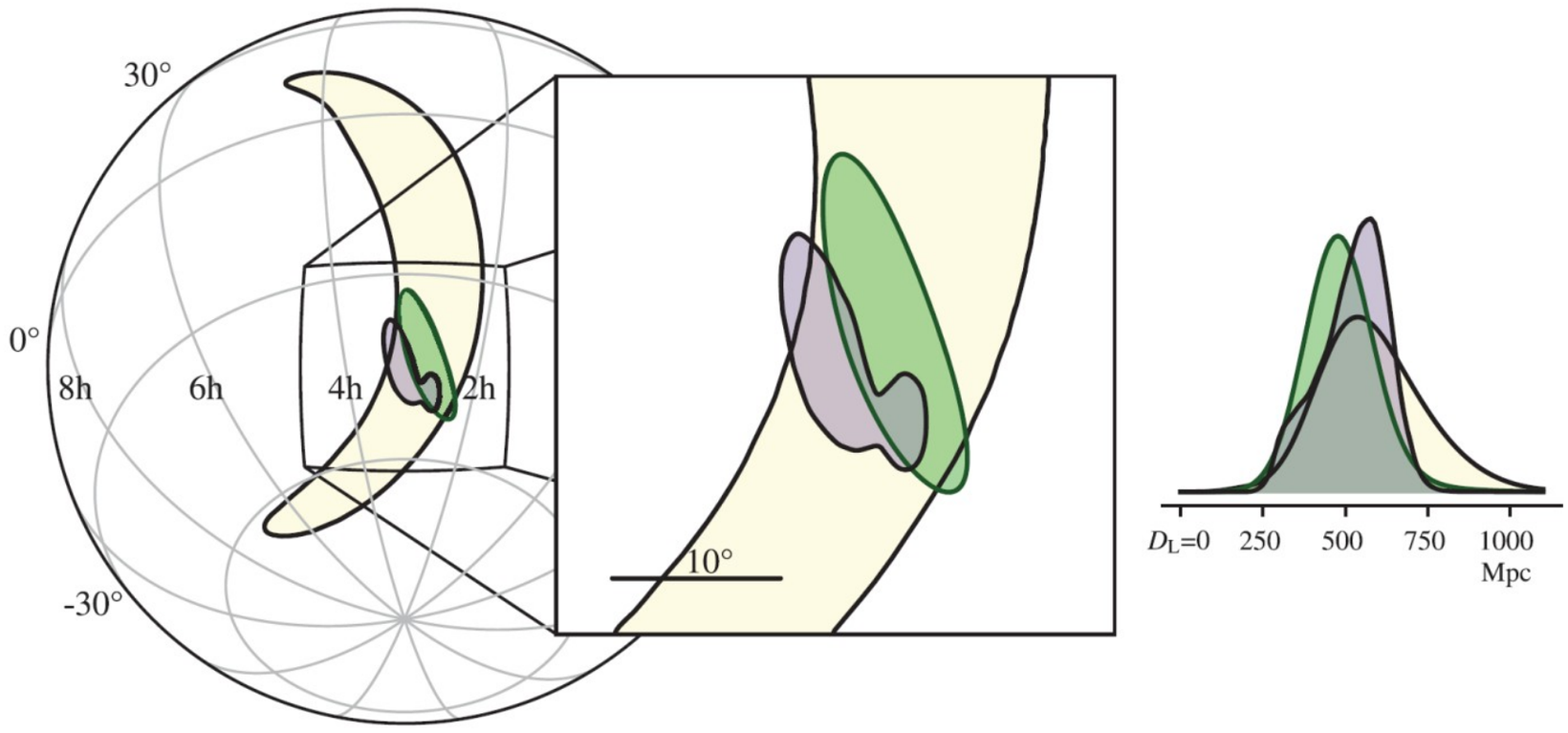
…gives this distribution of detected events.
median p(N) ~ 34

12

2018 Amsterdam Townhall meeting Dent, Pankow, et al.

Localization

- **Position uncertainty ~30 deg²**
- **Or ~30 galaxies to target for GW170817-like event**

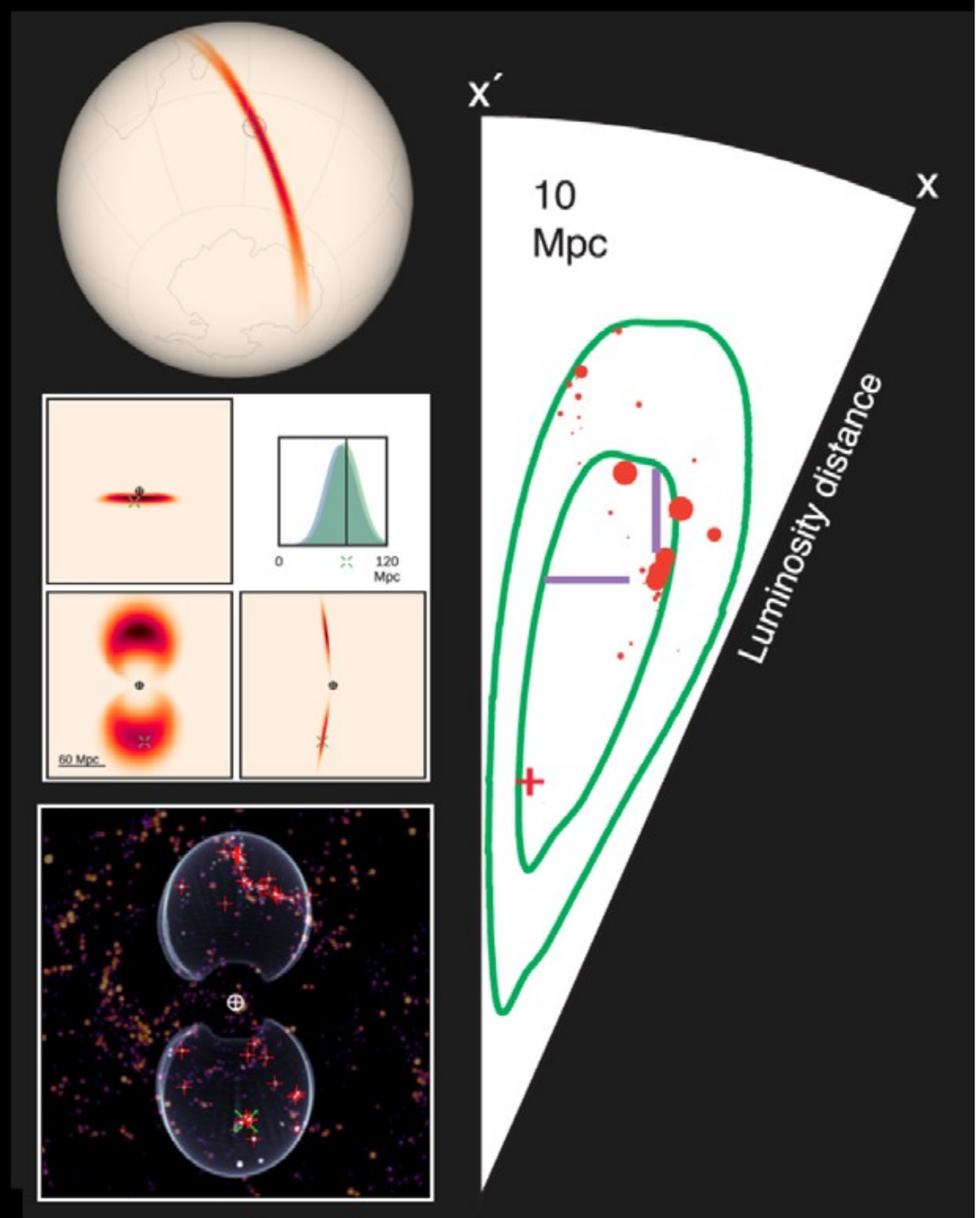


GW170814 (Abbott et al. 2017, PRL, 119, 141101)

Alert content: Localization

Localizations

- Gzip-compressed HEALPix images in FITS
- Sky probability sampled in equal-area pixels
- (CBC only) Distance: location, scale, and normalization of an r^2 weighted Gaussian conditional distance distribution
- New for O3:
  - error ellipses for well-localized events
  - multi-resolution HEALPix files for faster manipulation



Example of GCN Circular

```
//////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.
```

Near-future plan for EM Group

- **Papers from previous observations**
- **Facilities**
- **Human resources**
- **Analysis plan**
- **Scientific output (papers)**

17+ telescopes

Maidanak: 1.5m Telescope

Korea:
SAO 1.0m/0.6m, SOAO 0.6m,
BOAO 1.8m, DOAO 1.0m
KVN Radio Telescopes

US: LOAO 1-m

Hawaii:
Gemini-N
UKIRT

Gemini-S

KMTNet 1.6m Telescopes

Australia: 0.43m LSGT + iTelescope.Net (SSO)

US: McDonald 2.1-m, 0.8m, 0.25m

Human resources

- **SNU group – GW alert, observation with SNU-facilities, data analysis**

- **KASI group – Observation with KASI facilities (KMTNet, LOAO, SOAO, BOAO, KMTNet, KVN)**

- **Ewha group – Data analysis/Software development?**

- **International partners: McDonald, Maidanak**

  - **All groups will be involved in scientific analysis of the results**

Analysis

- **Alert system**
  GW alert → automatic observation
- **Target generator**
  Input: GW localization map + galaxy catalog
  Output: List of galaxy targets or tiling pattern of the observation
- **Image Processing**
  Basic reduction: bias/dark, flat-fielding + astrometry
- **Photometry/spectral analysis**
  Fast photometry calibration and photometry of interesting objects
- **Transient identification**
  Identification of new transients in the image

Observing strategy

- **Targeted observation** of host galaxy candidates with ~10 narrow-field telescopes (e.g., LSGT)
- **Wide field imaging** with a 0.25m telescope WIT in Texas **(FOV ~ 5.5 deg^2)**

Lee Sang Gak Telescope (LSGT; 이상각 망원경)

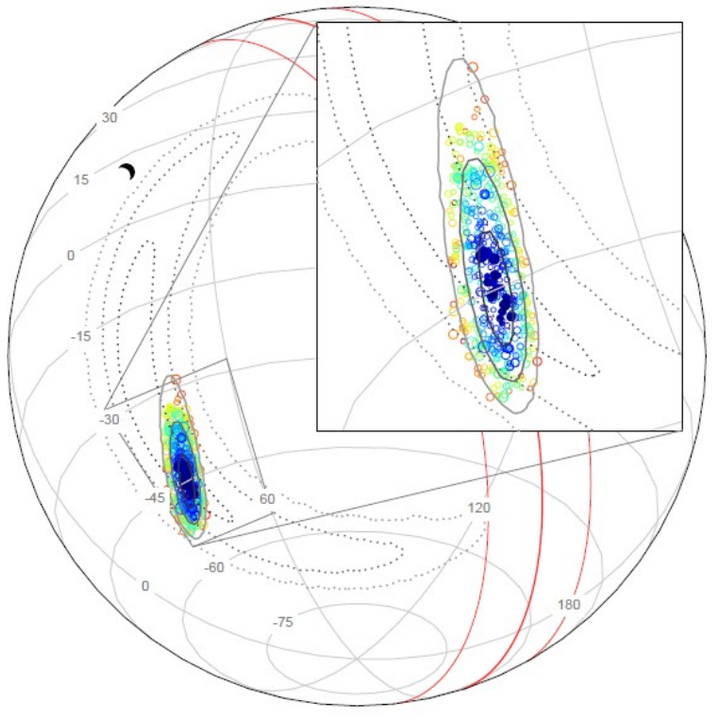
Wide-field Imaging Telescope (WIT)

Target generator

- **Input: GW localization map + galaxy catalog**
- **Output: List of galaxy targets or tiling pattern of the observation**

- **Currently, human-initiated search of galaxy database**

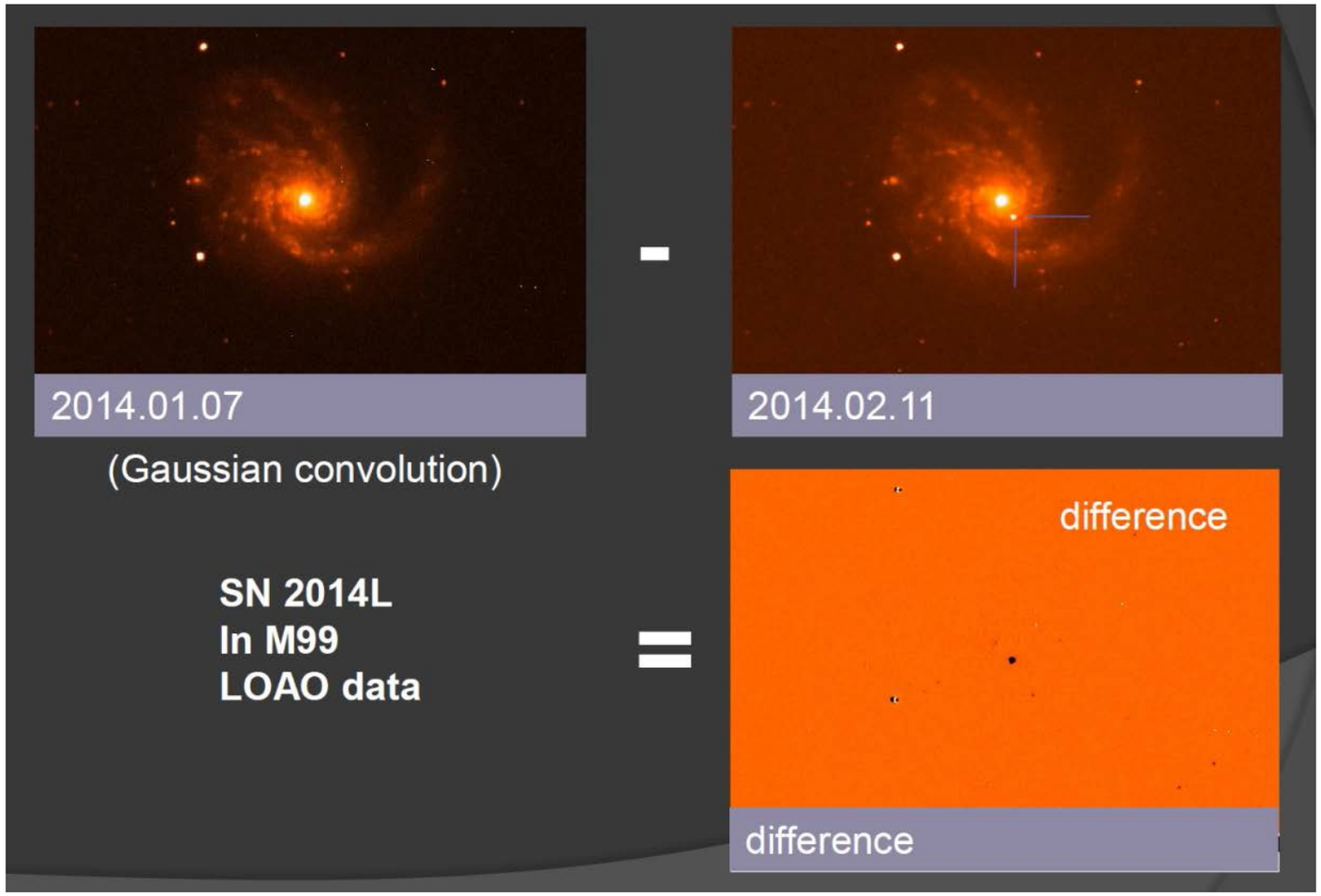
- **Automation of the procedure is desired**
- **Improvement in the host galaxy candidate catalog**
- **New distance (e.g., FP-based distance)**



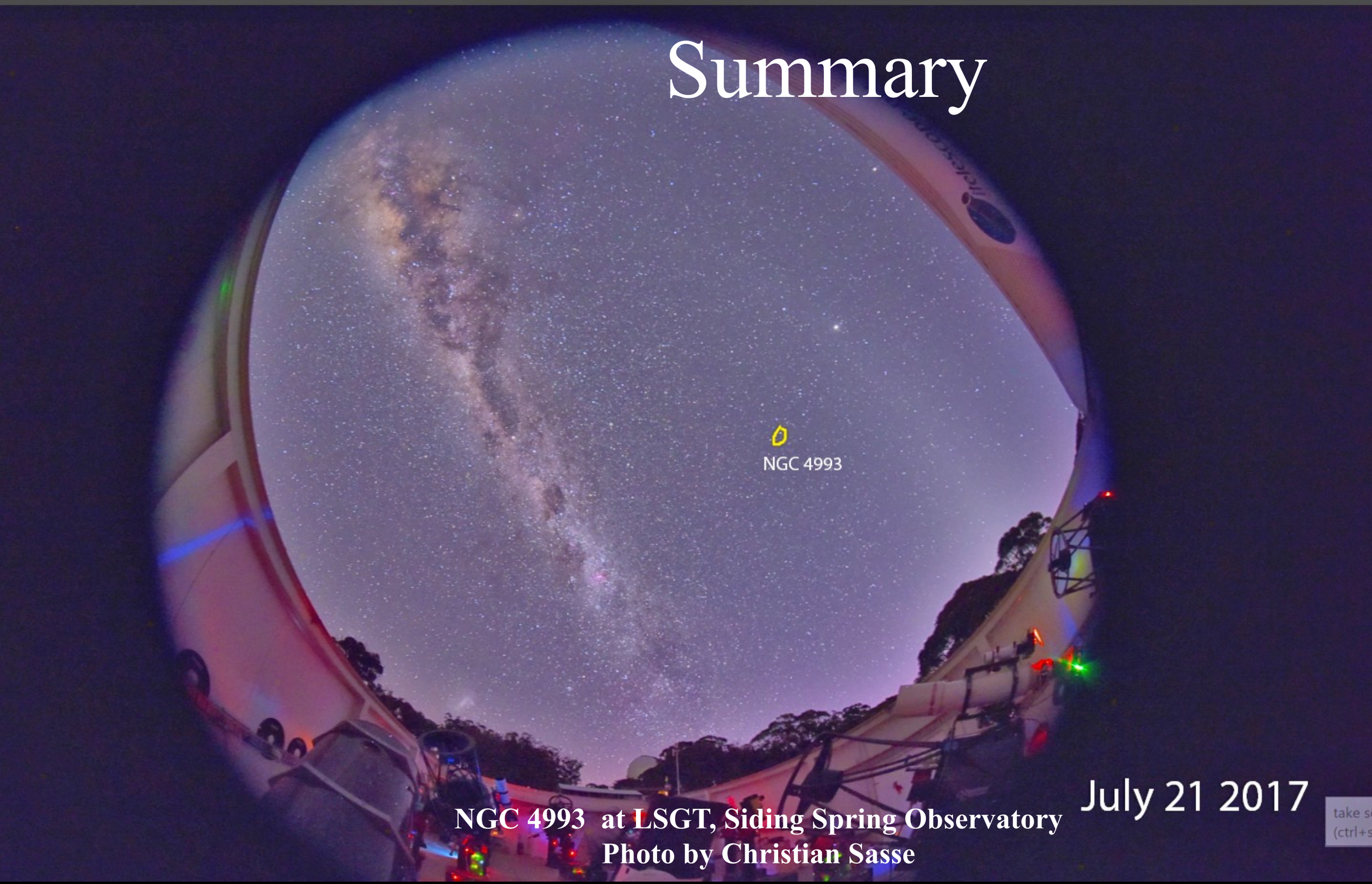
Arcavi et al. (2017)

Transient identification

- **Image subtraction**
- **Careful subtraction is often difficult**
- **No automatic identification is done with our script → needs improvement in this area**
- **Use of public archive images for subtraction or construction of the sky map**



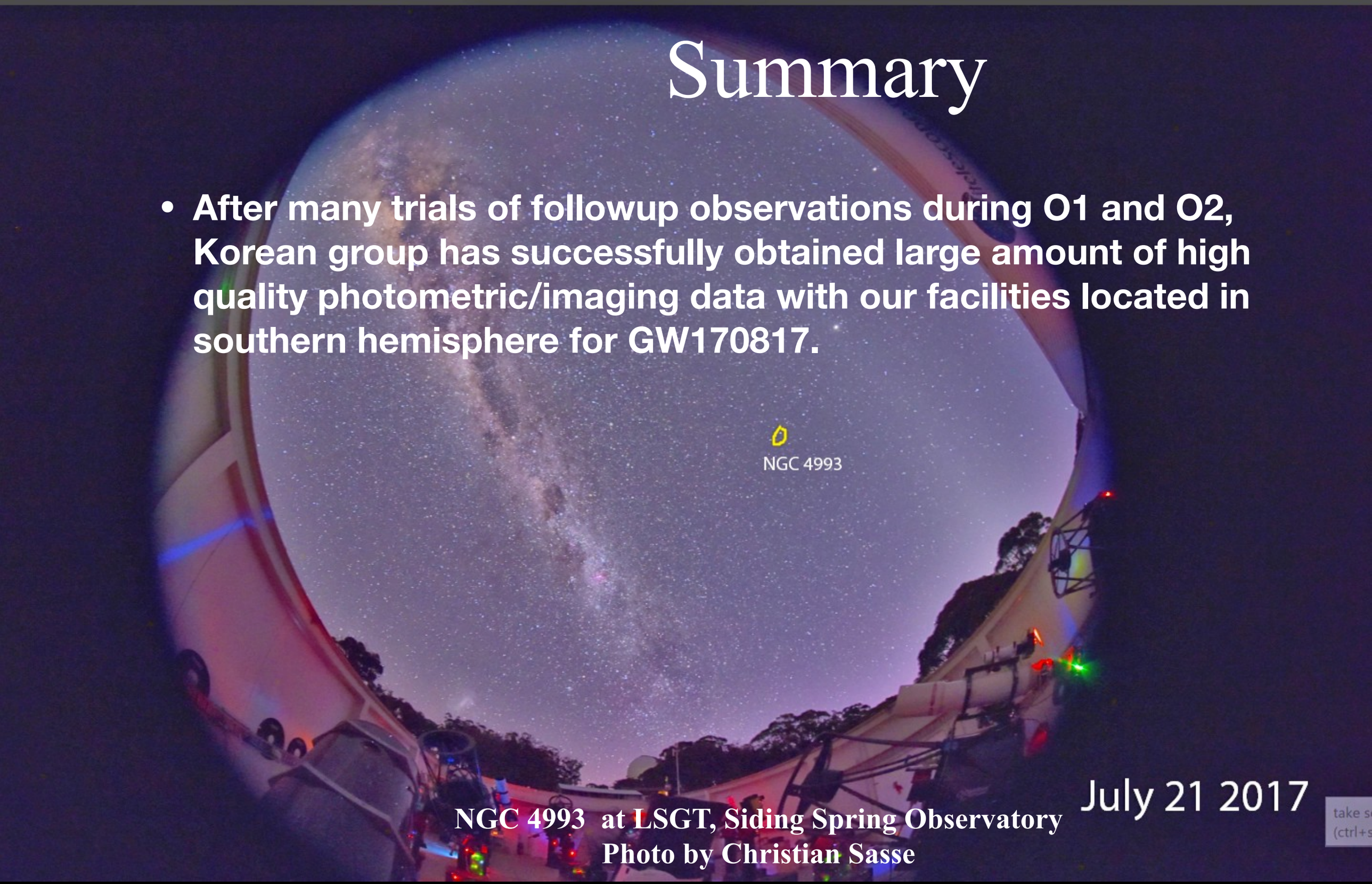
Summary



NGC 4993 at LSGT, Siding Spring Observatory
Photo by Christian Sasse

Summary

- **After many trials of followup observations during O1 and O2, Korean group has successfully obtained large amount of high quality photometric/imaging data with our facilities located in southern hemisphere for GW170817.**



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- **Our group is ready to actively take part in the EM followup campaign for O3 and beyond**

NGC 4993

July 21 2017

NGC 4993 at LSGT, Siding Spring Observatory
Photo by Christian Sasse

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- Available telescopes are located both norther and southern hemispheres at wide range of longitudes

NGC 4993

July 21 2017

NGC 4993 at LSGT, Siding Spring Observatory
Photo by Christian Sasse

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- Our group is ready to actively take part in the EM followup campaign for O3 and beyond
- Available telescopes are located both norther and southern hemispheres at wide range of longitudes
- Wavelength coverage also spans from near UV to mid-IR and radio

NGC 4993

July 21 2017

NGC 4993 at LSGT, Siding Spring Observatory
Photo by Christian Sasse