

# Optical Follow-up Observations of the Gravitational Wave Source - Host Galaxy Properties -

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# GW170817: NS-NS merger

## Multi-Messenger Astronomy

- 2017-08-17 GW event marked the start of MMA using GW and EMW signals
- 3700 (39@Korea, 45 countries, 900+ institutions, 80 facilities ), 59 page ApJL paper

2017-08-17 12:41:04 UTC  
라이고 및 비르고 중력파 신호 포착

+2초 후  
페르미 및 INTEGRAL 감마선 신호 포착

+약 11시간 후  
칠레 천문대 망원경들이  
가시광선 신호 포착

+약 21시간 후  
국내연구진 호주 이상각망원경으로  
추적관측시작. 이후 약 4주간 추적관측  
(KMTNet, BOOTES-5망원경 등)

+약 9일 후  
찬드라 우주망원경  
X-선 신호 포착

+약 16일 후  
지상 전파망원경  
전파 신호 포착

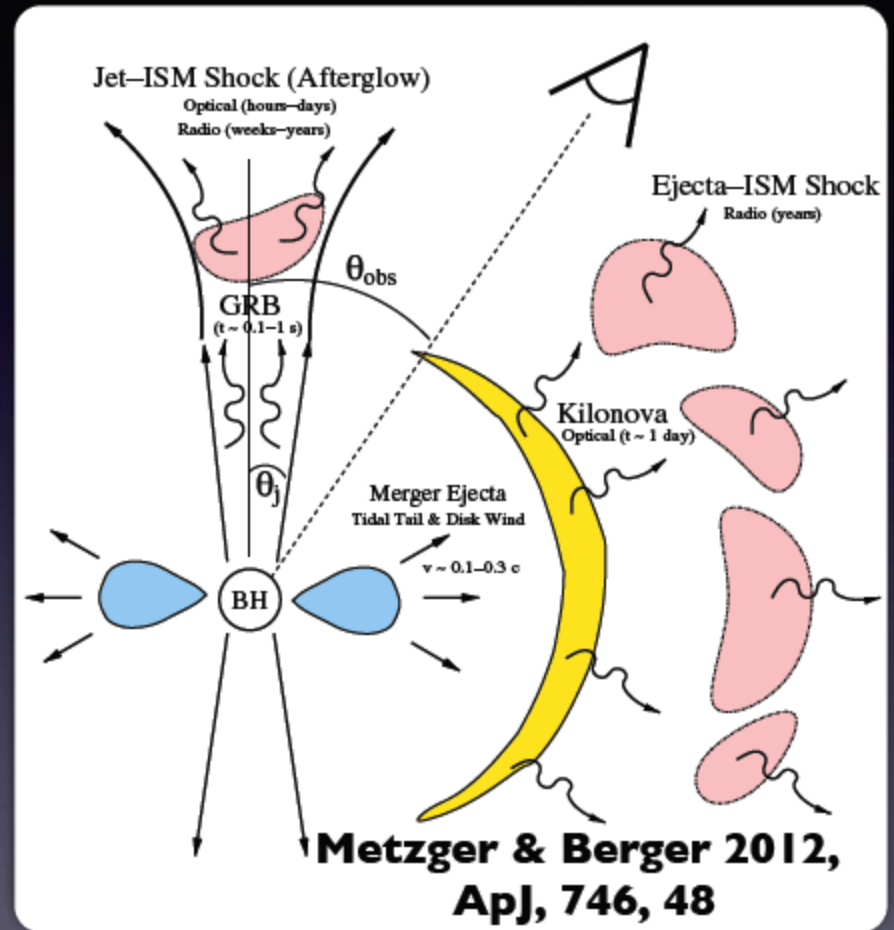
KMTNet(서울대/한국천문연구원)

그림출처: LIGO, NASA, 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley,  
서울대/한국천문연구원/임명신, NSF/Sonoma 주립대/A. Simonnet, NRAO

# EM signature from NS-NS merger

- On-axis short GRB
- Off-axis radio emission
- Radioactive emission
  - kilonova
  - macronova
  - mini SN

Short GRB ( $< 2\text{sec}$ ): NS merger  
Long GRB ( $> 2\text{sec}$ ): massive star




# Three questions

- Binary neutron star merger → short GRB-like event?
- EM counterpart = Kilonova? – Blue or red? Brightness?
- **Environment of NS merger? Host galaxy property**

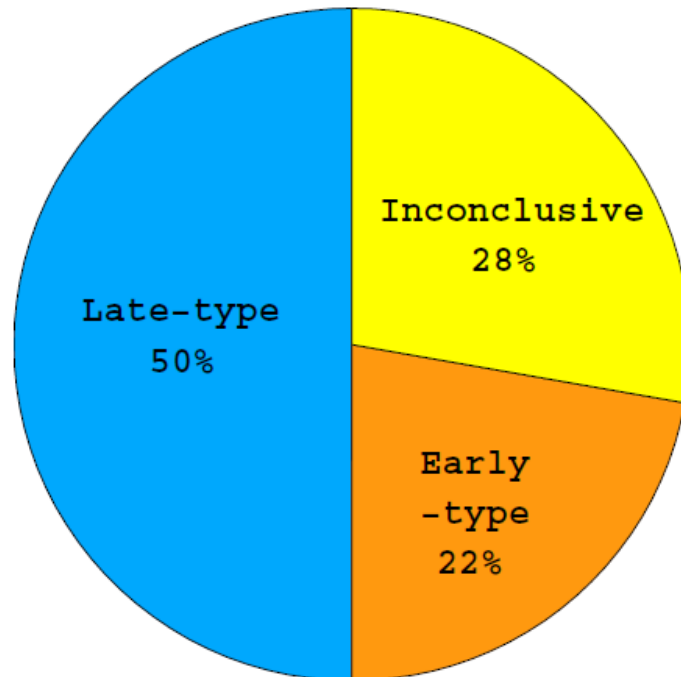


# What we learn?

- 
- Short GRB connection
  - Binary Neutron Star (BNS) merger timescale: short ( $< 3$  Gyr) or long ( $\gg 10$  Gyr) (e.g., O'Shaughnessy & Kim 2010)
  - Natal kicks: 5-500 km/sec (e.g. Fryer & Kalogera 1997)  
 $100\text{km/sec} \times 1 \text{ Gyr} = \sim 100 \text{ kpc}$

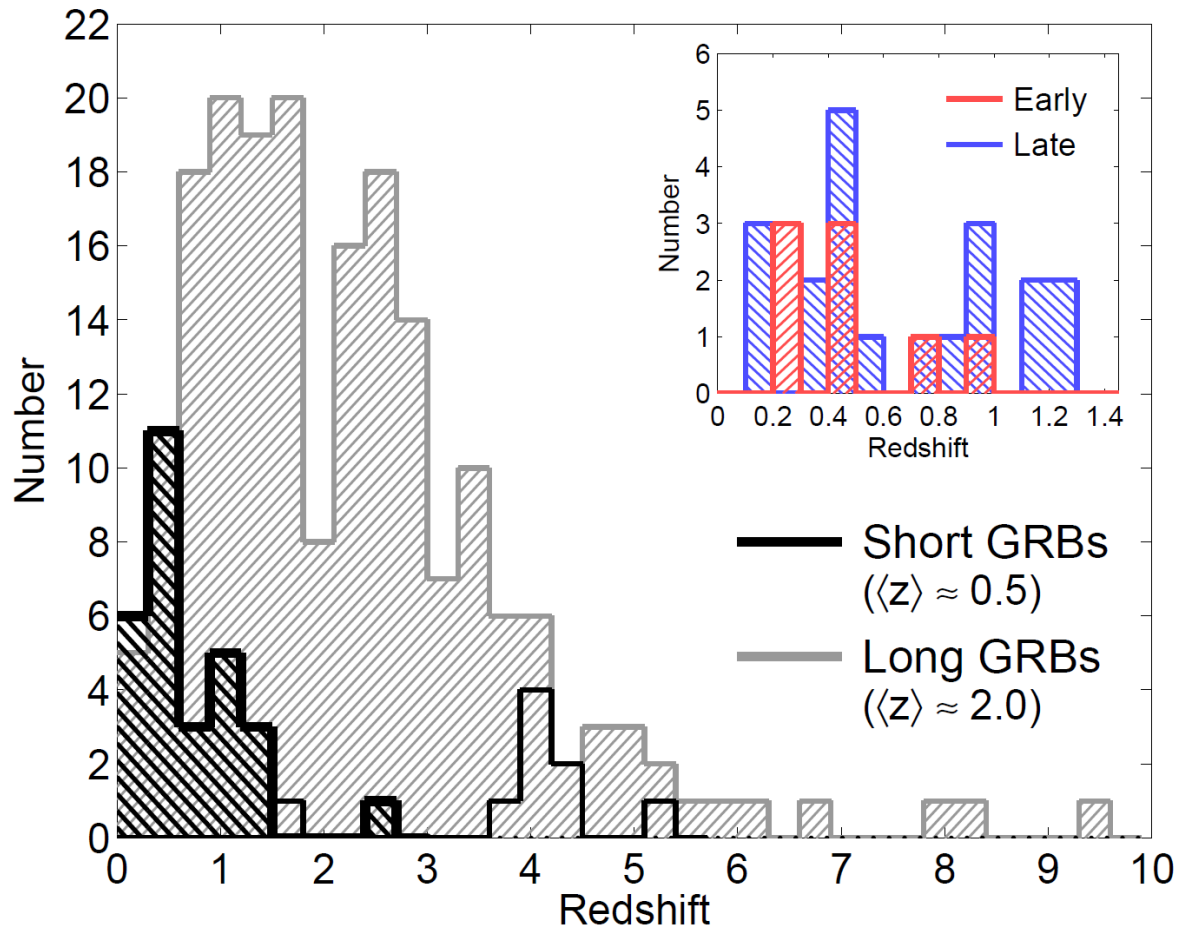
# Short GRB host galaxy: type

Sub-arcsec loc. + XRT  
Host-less Assigned  
Sample: 36



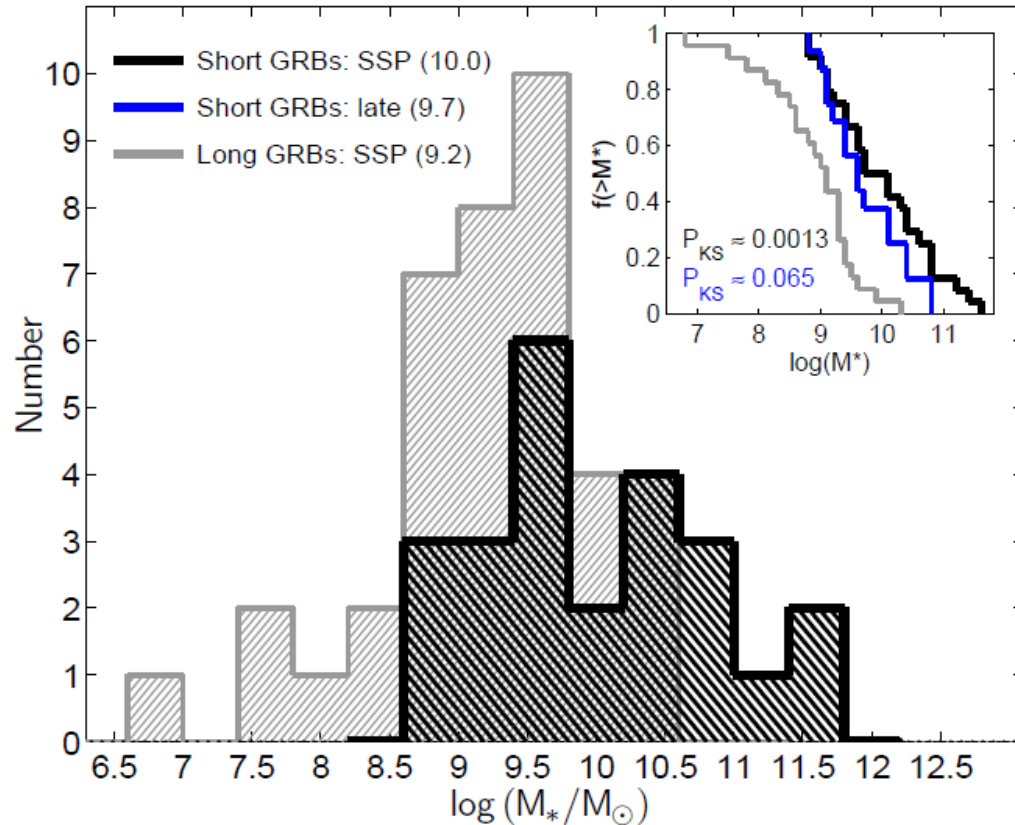
Fong et al. (2013), Berger (2013)

# Short GRB host galaxy: redshift



Berger (2013)

# Short GRB host galaxy: mass

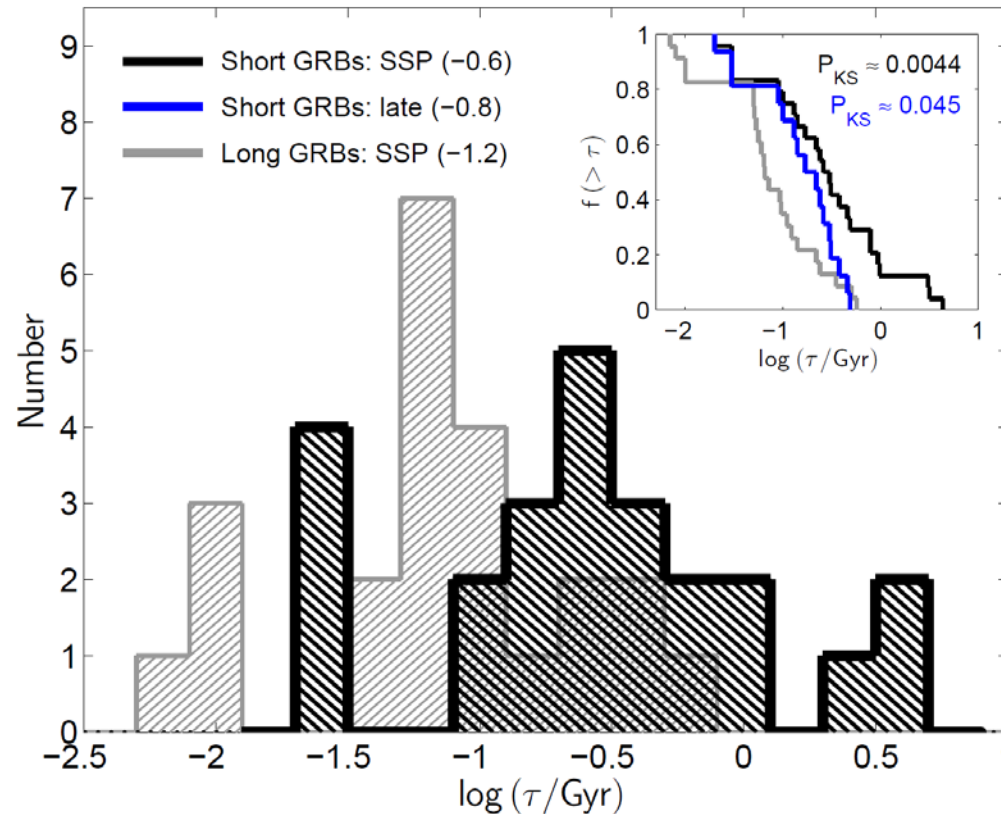


Liebler & Berger (2010)

- **Median stellar mass:  $\sim 10^{10} M_\odot$**



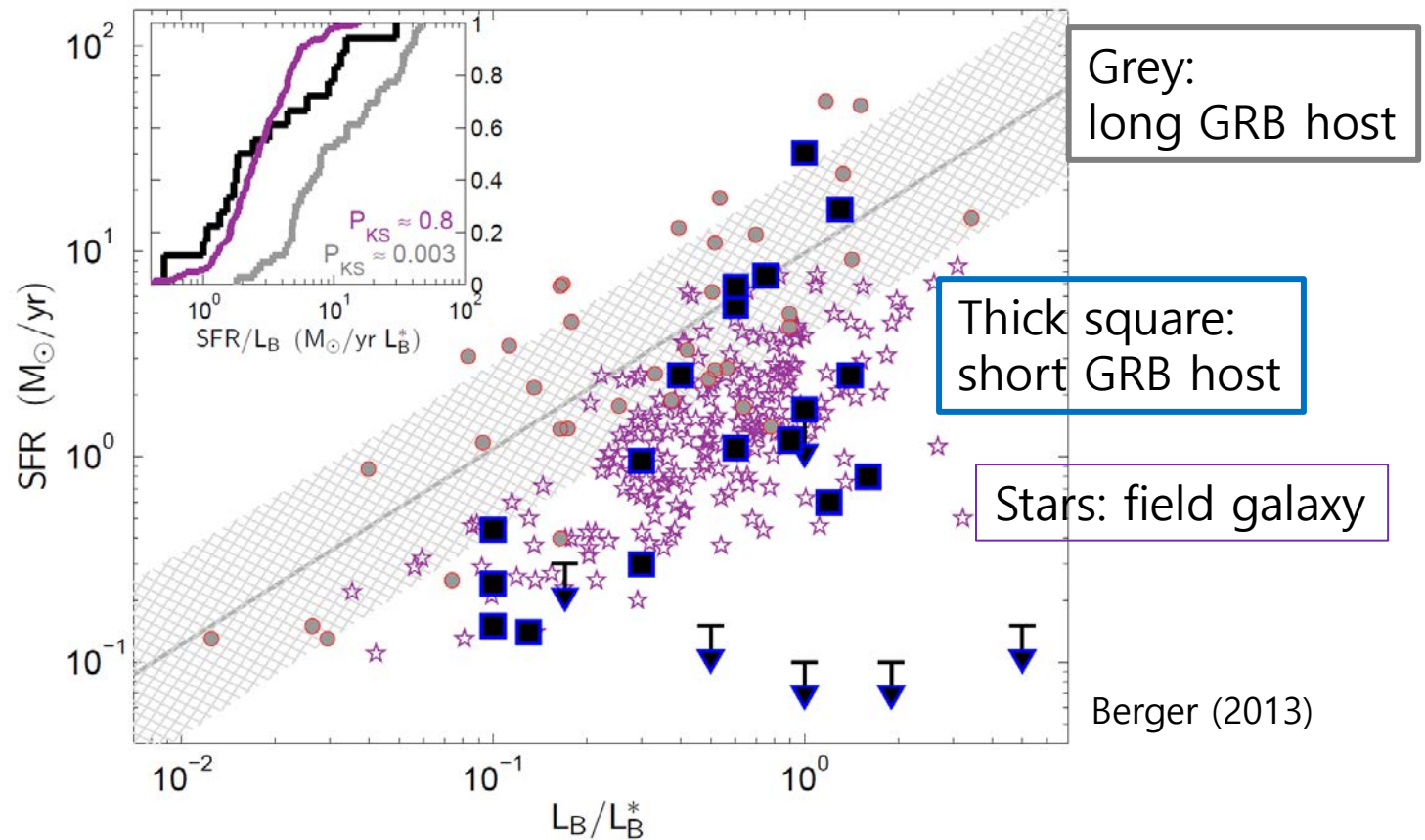
# Short GRB host galaxy: age



Liebler & Berger (2010)

- **Median age:  $\sim 0.3$  Gyr**

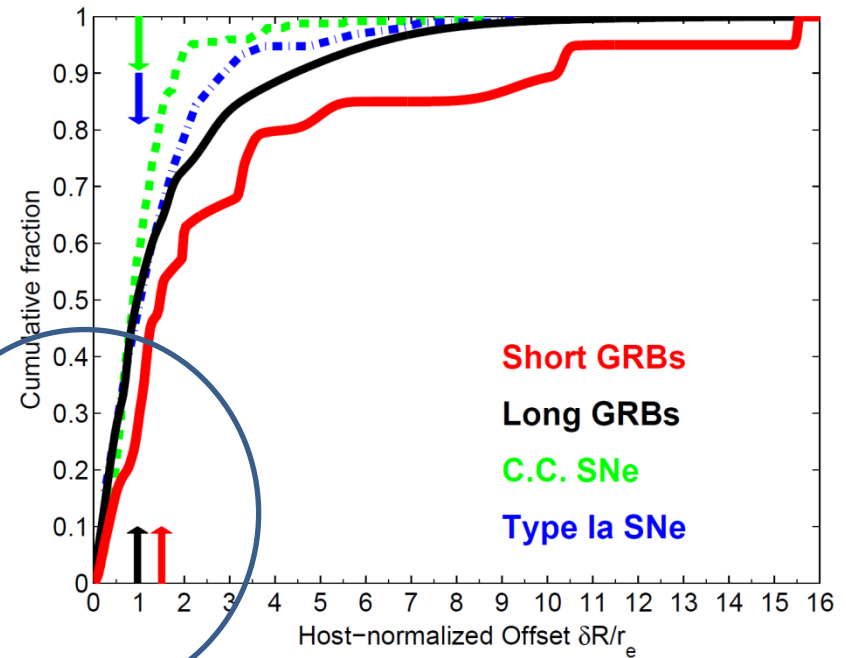
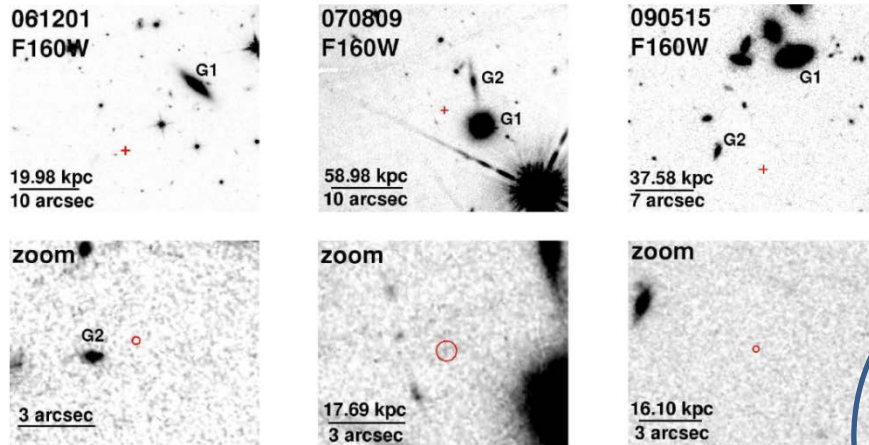
# Short GRB host galaxy: SFR



Median SFR  $\sim$  **1  $M_\odot/\text{yr}$  (short GRB)** vs 10  $M_\odot/\text{yr}$  (long GRB)

# Short GRB location

Berger (2013)



- 25% at  $< R_{\text{eff}}$  (Fong & Berger 2013)  
Natal kick?

# Facilities for EM follow-up

**Korea:**

**SNUO 1.0m, 0.6m, SOAO 0.6m,  
BOAO 1.8m, DOAO 1.0m**

**Maidanak:**

**1.5m Telescope**

**US: LOAO 1-m**



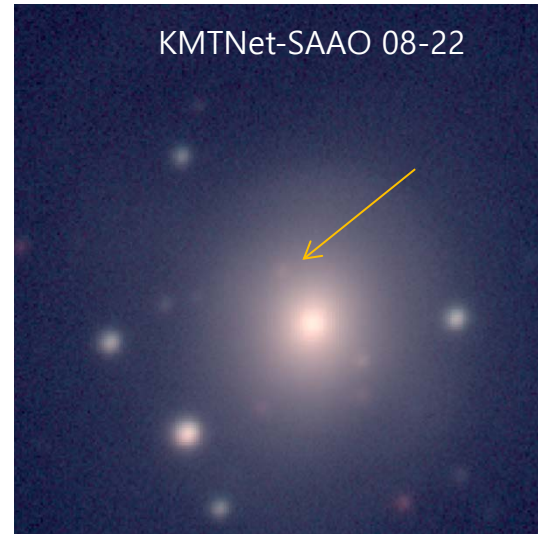
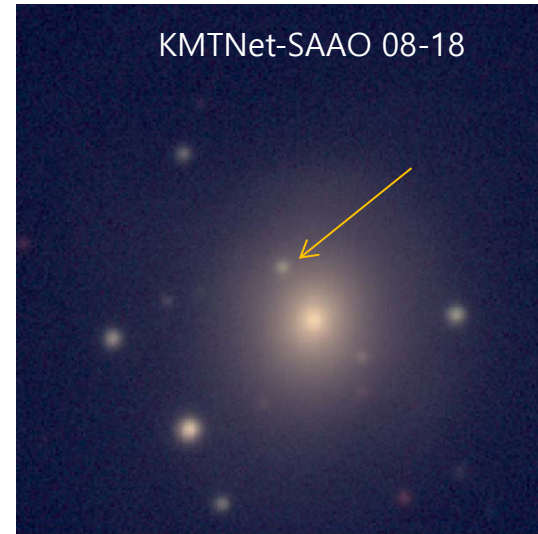
**KMTNet 1.6m  
Telescopes**

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

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

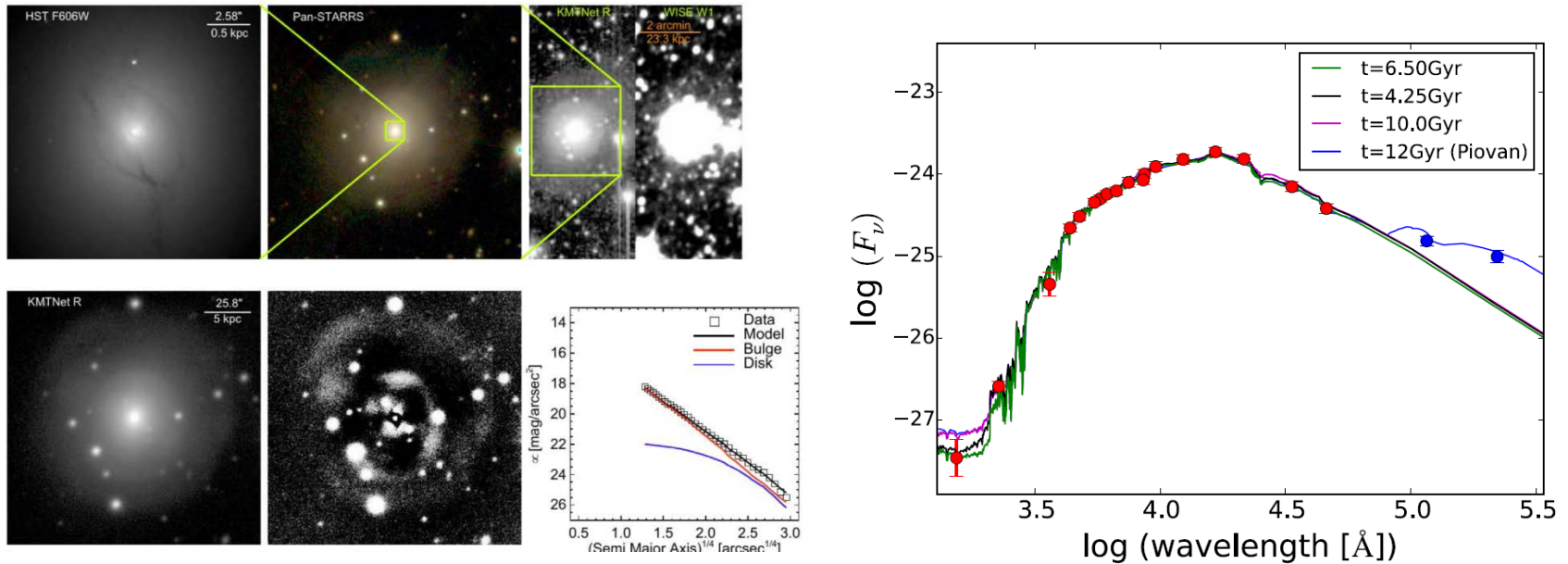
# KMTNet Image of GW170817

Host galaxy: NGC 4993@40Mpc



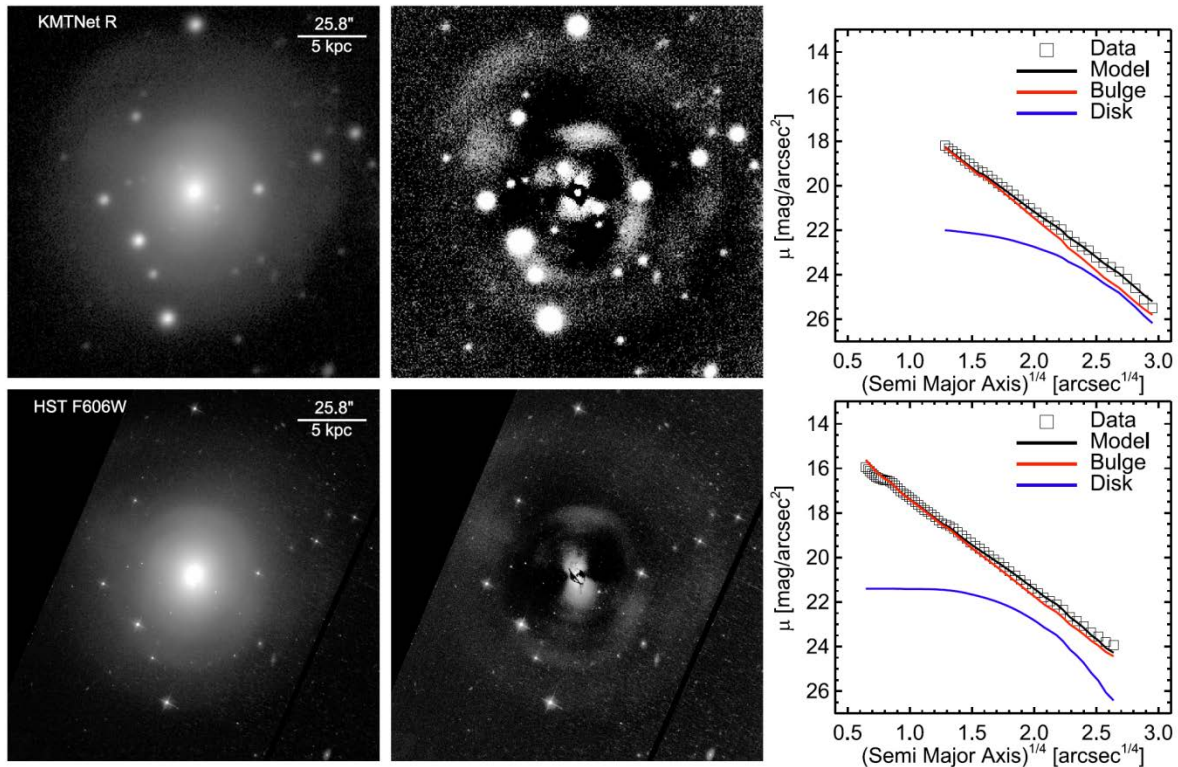
# GW170817 Environment

- Host galaxy: NGC 4993 at  $\sim 40$  Mpc
- KMTNet (BVRI), LSGT (u), HST data (F606W), 2MASS (JHK), WISE (W1,W2,W3,W4) GALEX (FUV, NUV)



Im, M., et al. (2017, ApJL) [Oct. 3, submitted, Oct. 13, accepted]

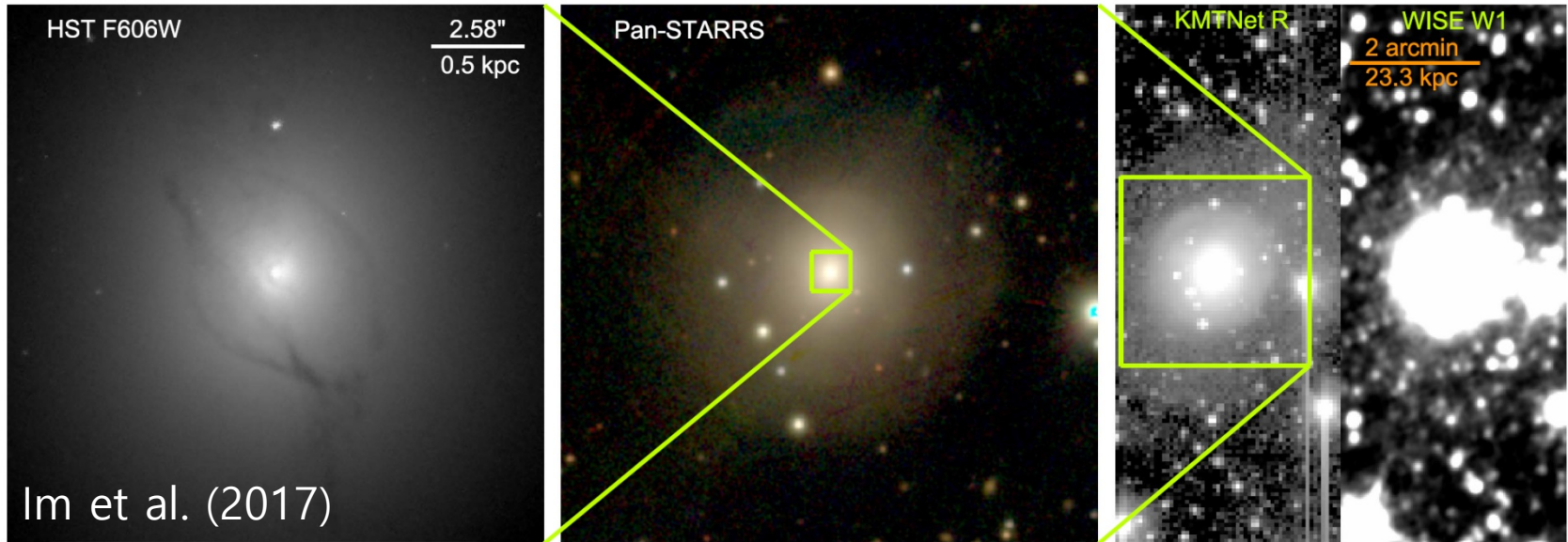
# NGC 4993 is $\sim E$ (Y Yoon)



Im et al. (2017)

- Galfit SB fitting
- Sersic index  $n = 3-4$ ,  $B/T = 0.7 - 1.0$
- $R_{\text{eff}} = 10'' - 15''$  (2-3 kpc)
- E rather than S0a

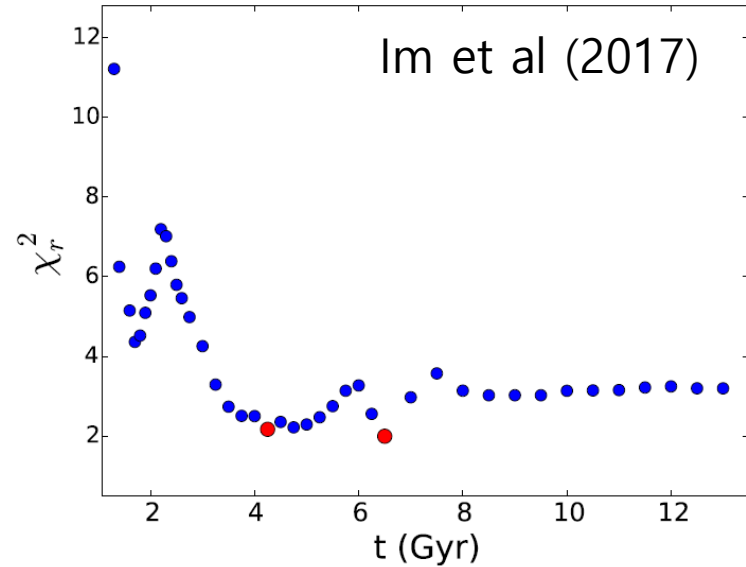
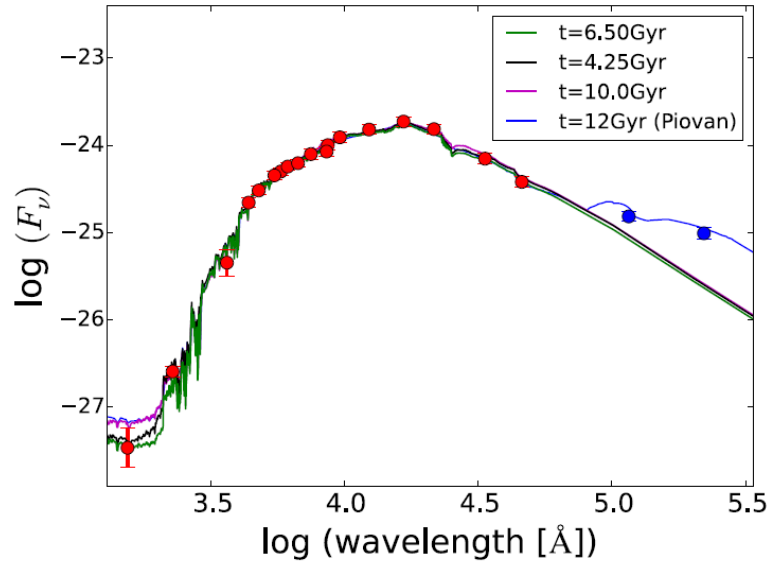
# Disturbed morphology



- Dust lane and tidal shell suggest NGC 4993 has undergone merger activities

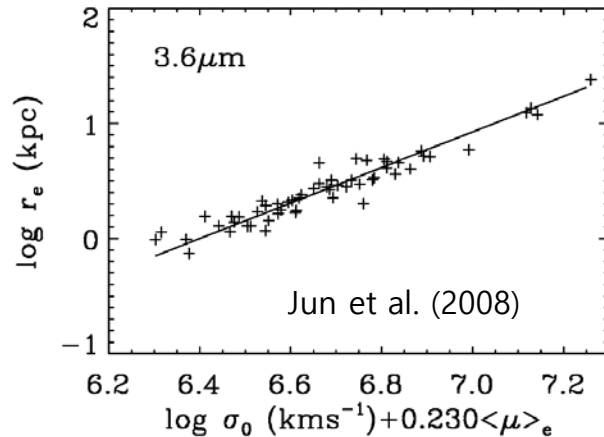


# NGC 4993 stellar population (SK Lee)



- SED-fitting with SK-Lee's code (Chabrier (2003) IMF)
- $M^* = 0.3 - 1.2 \times 10^{11} M_\odot$
- Age:  $> 3$  Gyr
- No SF
- $E(B-V) = 0.00 - 0.07$

# FP distance to NGC 4993



$$\log r_e = a \log \sigma_0 + b \log \langle I \rangle_e + c.$$

$\sigma \approx 180 \text{ km/sec}$  (Carter et al. 1988; Beuing et al. 2002; Wegner et al. 2003; Ogandao et al. 2008)

FP Distance to NGC 4993

Filter	Distance (Mpc)	Mean Distance (Mpc)
<i>B</i>	31.7 <sup>a</sup> , 34.7 <sup>b</sup> , 36.4 <sup>c</sup> , 41.7 <sup>d</sup>	36.1 (4.2)
<i>V</i>	31.8 <sup>a</sup> , 33.0 <sup>e</sup> , 32.3 <sup>f</sup> , 41.8 <sup>d</sup>	34.7 (4.7)
<i>R</i>	36.2 <sup>a</sup> , 41.3 <sup>d</sup>	38.8 (3.6)
<i>I</i>	36.9 <sup>a</sup> , 44.6 <sup>g</sup> , 46.9 <sup>d</sup>	42.8 (5.2)
<i>J</i>	38.8 <sup>a</sup>	38.8
<i>H</i>	39.6 <sup>a</sup>	39.6
<i>K</i>	44.1 <sup>a</sup> , 28.4 <sup>h</sup>	36.3 (11.1)
Average	37.7 (5.3)	38.2 (2.7)

17 FP parameter sets

→  $D_A = 37.7 \pm 8.7 \text{ Mpc}$ ,




→ or  $D_L = 38.4 \pm 8.9 \text{ Mpc}$

# NGC 4993 summary

- E with  $M^* \sim 10^{10-11} M_{\odot}$
- Old ( $t > 3$  Gyr)
- No or little SFR ( $< 0.1 M_{\odot}/\text{yr}$ )
- $R_{\text{eff}} \sim 2-3$  kpc ( $10'' - 15''$ )
- $D_L \sim 38.4 \pm 8.9$  Mpc
- NS merger occurred at  $R = 10.23'' \pm 0.08''$  (25% occurred at  $R < R_{\text{eff}}$  for short GRB)

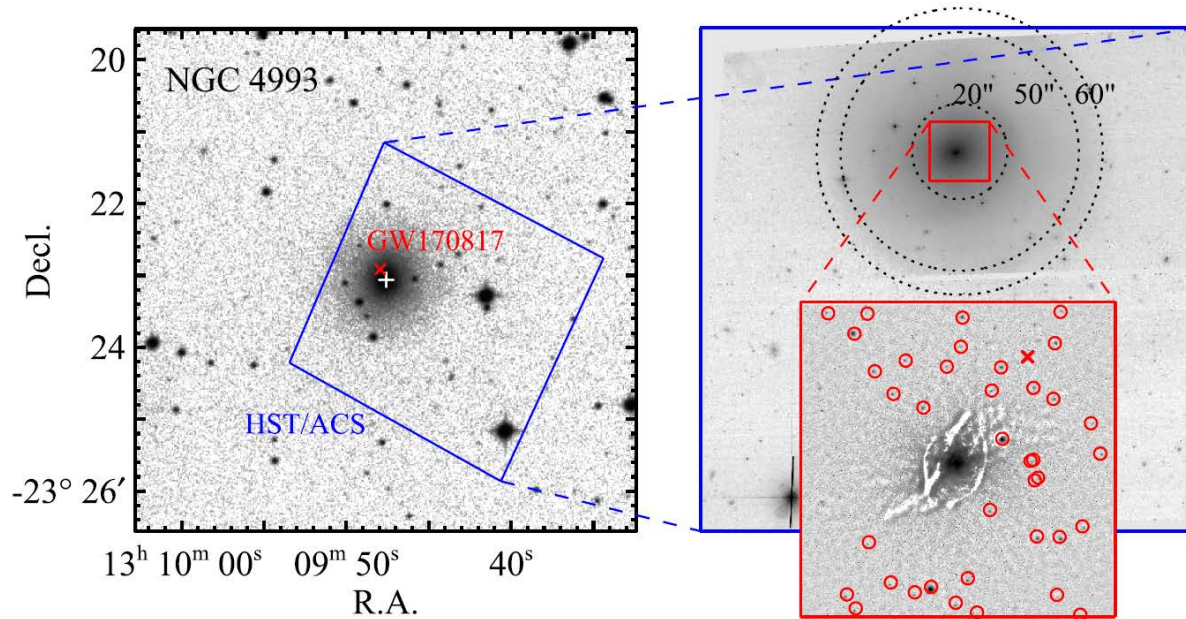


# A Globular Cluster Luminosity Function Distance to NGC 4993 Hosting a Binary Neutron Star Merger GW170817/GRB 170817A

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Astronomy Program, Department of Physics and Astronomy, Seoul National University, Gwanak-gu, Seoul 08826, Republic of Korea; [mglee@astro.snu.ac.kr](mailto:mglee@astro.snu.ac.kr), [jskang@astro.snu.ac.kr](mailto:jskang@astro.snu.ac.kr), [mim@astro.snu.ac.kr](mailto:mim@astro.snu.ac.kr)

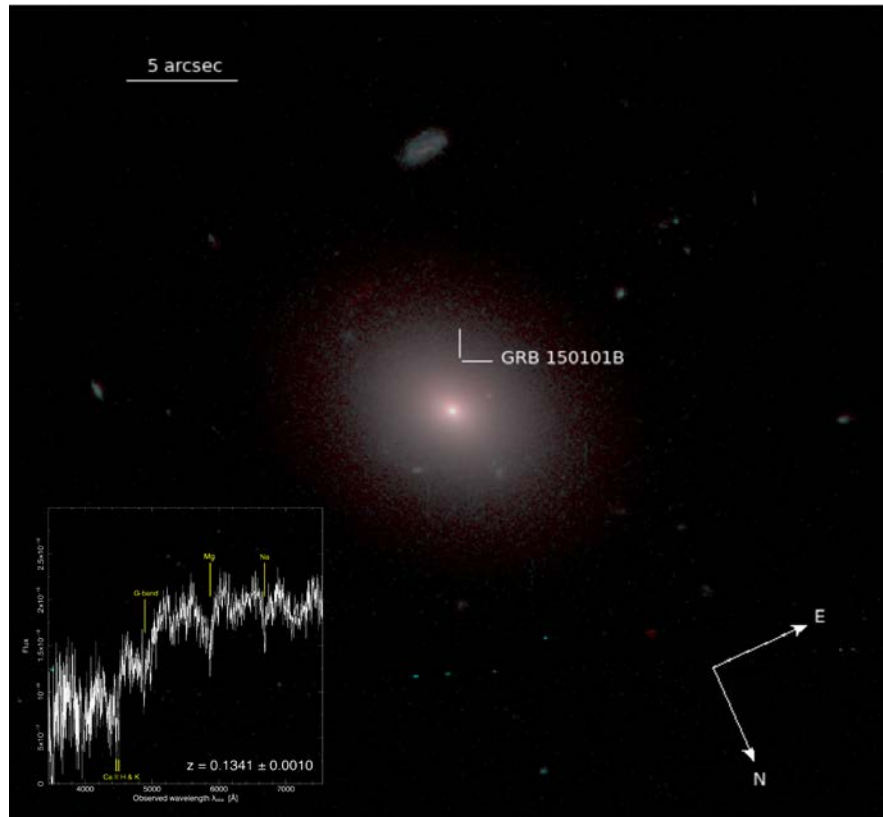
Received 2017 December 6; revised 2018 May 1; accepted 2018 May 2; published 2018 May 18



- GC-cluster LF based distance:  $41.65 \pm 3.00$  Mpc

Lee, M. G., Kang, J., & Im, M. (2018, ApJL)

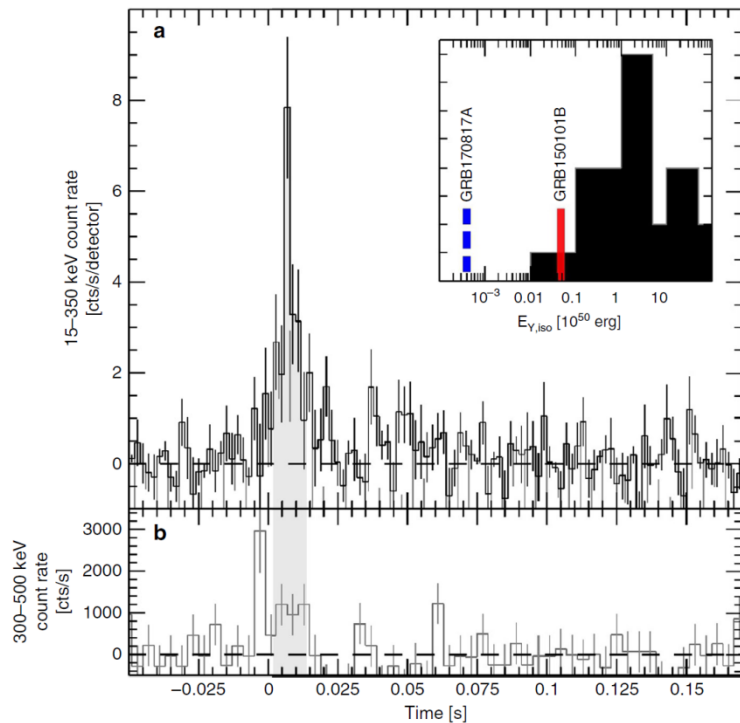
# GRB 150101B: Another blue kilonova?



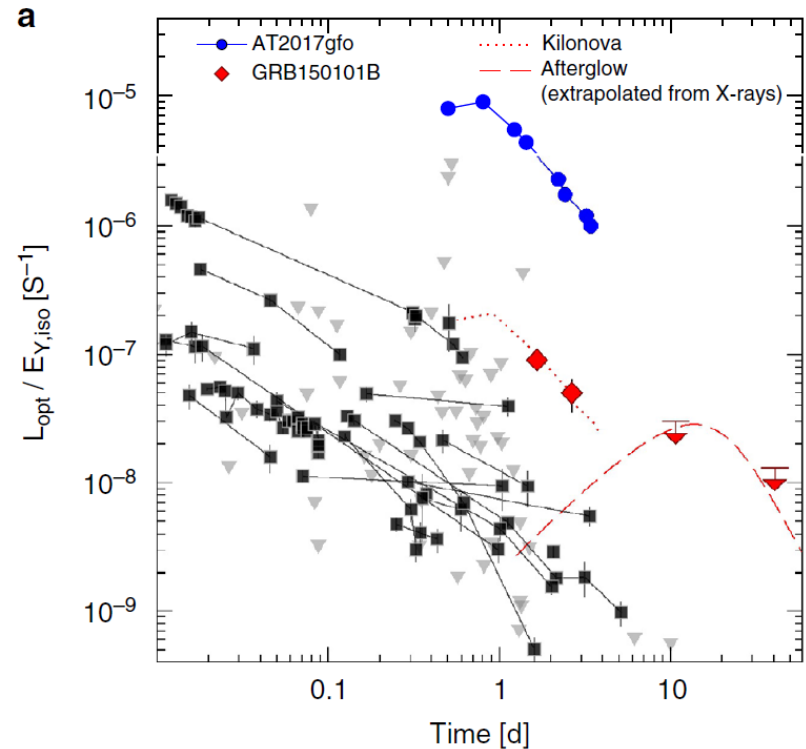
Short GRB at  $z=0.1343$

Troja, E., ..., Lee, SK, Yoon, Y, Im, M., ... et al. (2018, Nature Comm.)

# GRB 150101B properties: Similar to AT2017gfo (GW170817)

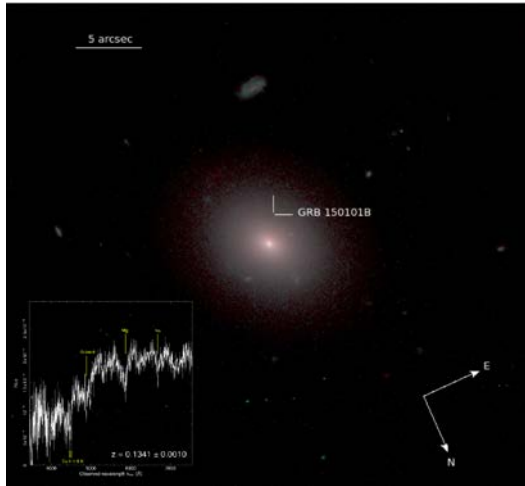


Short GRB ( $\sim 20$ ms) but weak

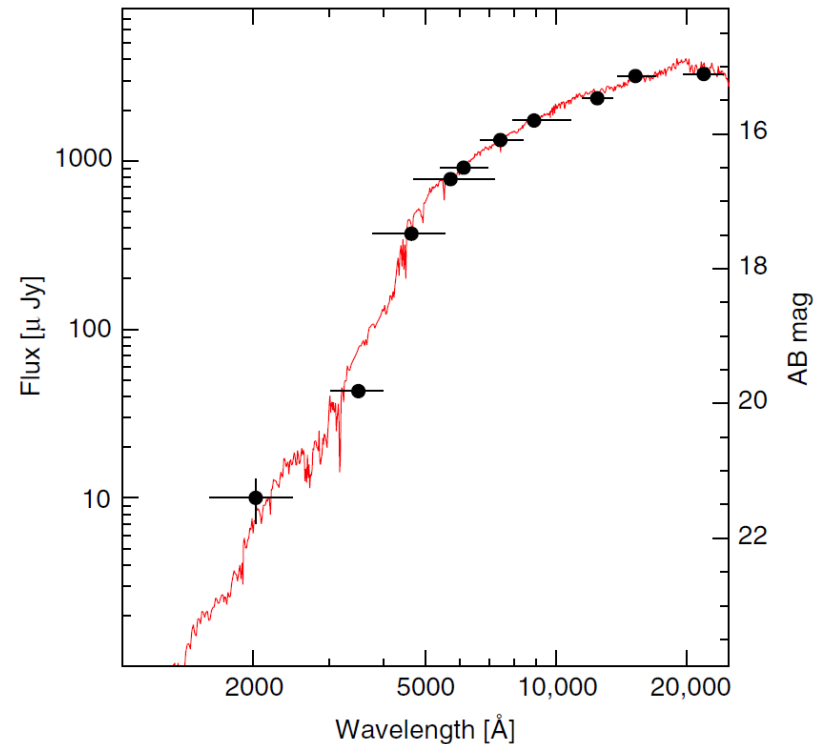


Relatively bright  
optical/X-ray counterpart

# GRB 150101B host galaxy



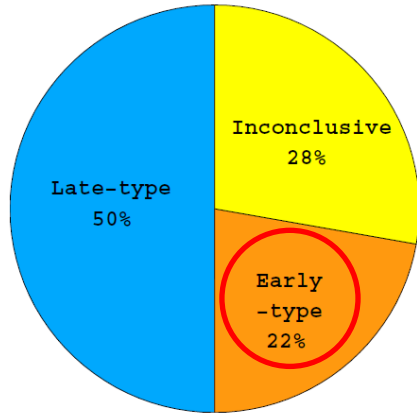
- Host galaxy: Early-type galaxy
- Age = 2 (+6, -1) Gyr
- $M_{\star} = 1.0 (+1, -0.2) \times 10^{11} M_{\odot}$
- $R_{\text{eff}} = 3.4''$  (8.1 kpc) –  $2''$  (6 kpc)
- GRB position ( $3''$ ) at  $R \sim R_{\text{eff}}$



**Host galaxy is another massive E,  
and sGRB location at  $r \sim r_{\text{eff}}$**

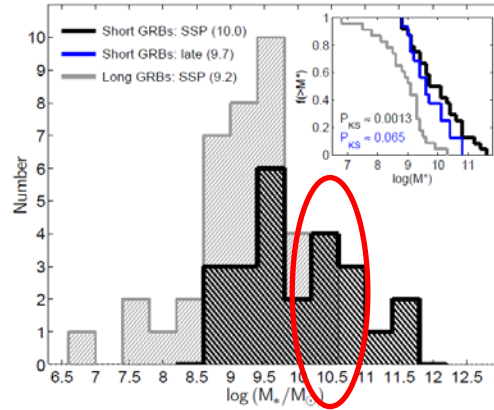
# GW170817, GRB150101B hosts

Sub-arcsec loc. + XRT  
Host-less Assigned  
Sample: 36



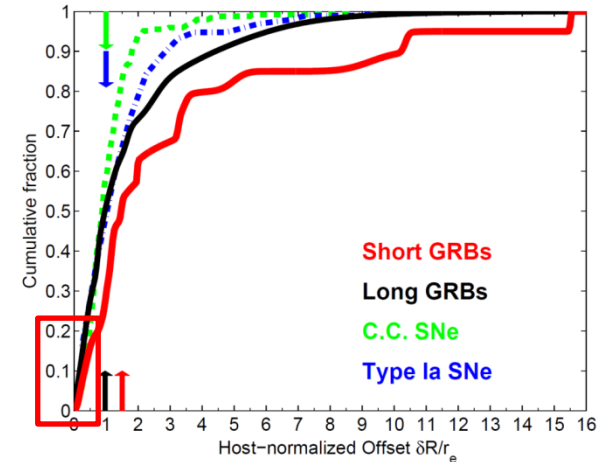
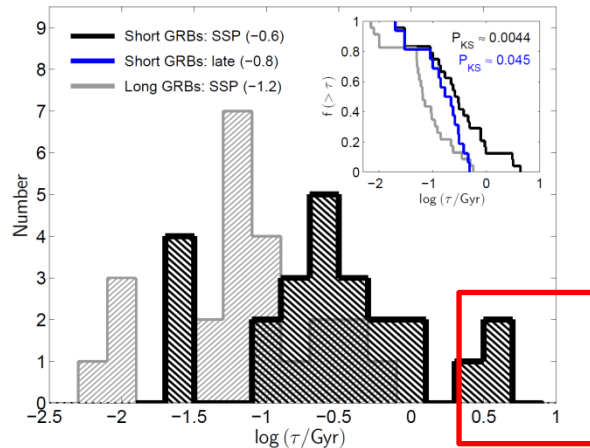
Morphology:  
E (22%)

Age: > 2 Gyr



Mass  $\sim 10^{11}$  Msun

Location:  
 $R < R_{\text{eff}}$  (25%)





# Discussion

- GRB/GW location is close to the center:  
**Natal kick may not be strong**
- Massive, E hosts: **NS merger may be more frequent in E galaxies (c.f. sGRB)**
- Old E hosts: **NS merger may happen at old age**

# Near future prospects

- **LIGO/Virgo O3 observation at Feb 2019, Engineering run, Dec 2018**
- BNS range: 120 Mpc (LIGO), 65 Mpc (Virgo)
- Burst of GW detections expected

## **Expected GW events in O3 run**

**7 BNS**

**32 BBH**