



다중신호천문학 (Multi-Messenger Astronomy)

임명신(서울대학교)

천문학과 노벨상 연구주제

1. 밤하늘에 빛나는 것은 무엇?
2. 우주의 과거, 현재, 미래
3. 우주의 탐구의 기술

밤하늘에 빛나는 것은?

2019

외계행성
켈로즈(스위스)
마요르(스위스)

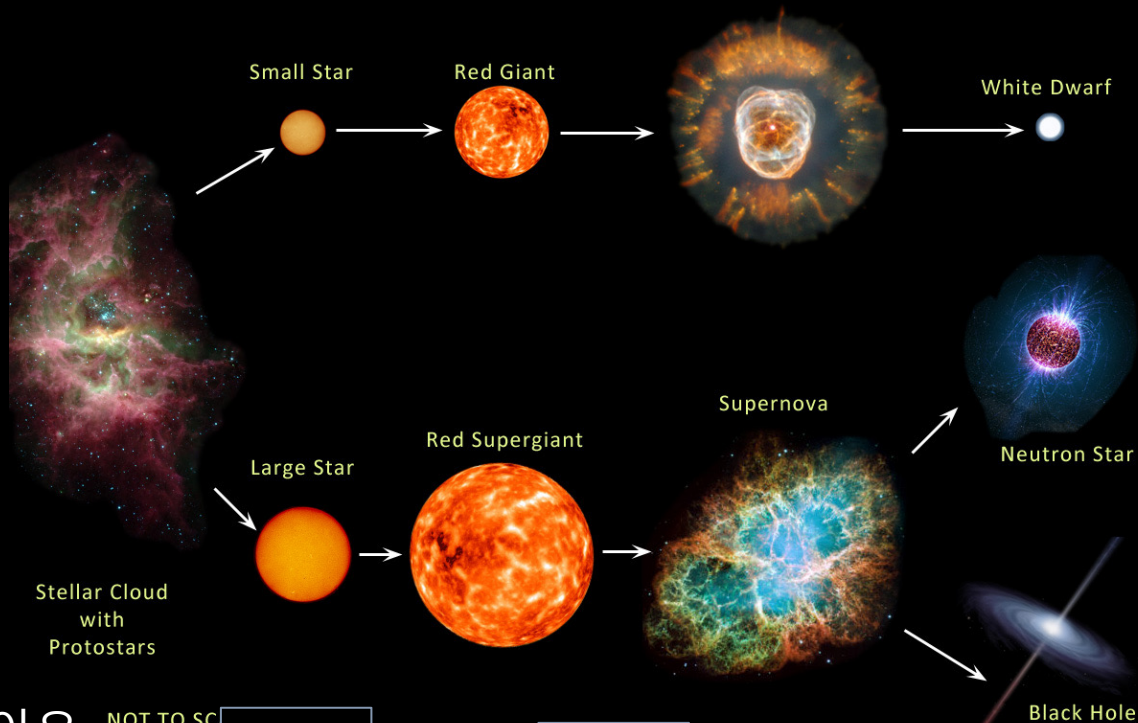
2022

우리은하 거대블랙홀
게츠(미국)
겐젤(독일)

별의 탄생
(성간운)

1967

별이 빛나는 이유
-베테(독일)



별의 죽음

백색왜성

중성자별

블랙홀

1983

원소 형성(별)
-파울러(영국)

1983

별의 죽음
찬드라세카
(인도)

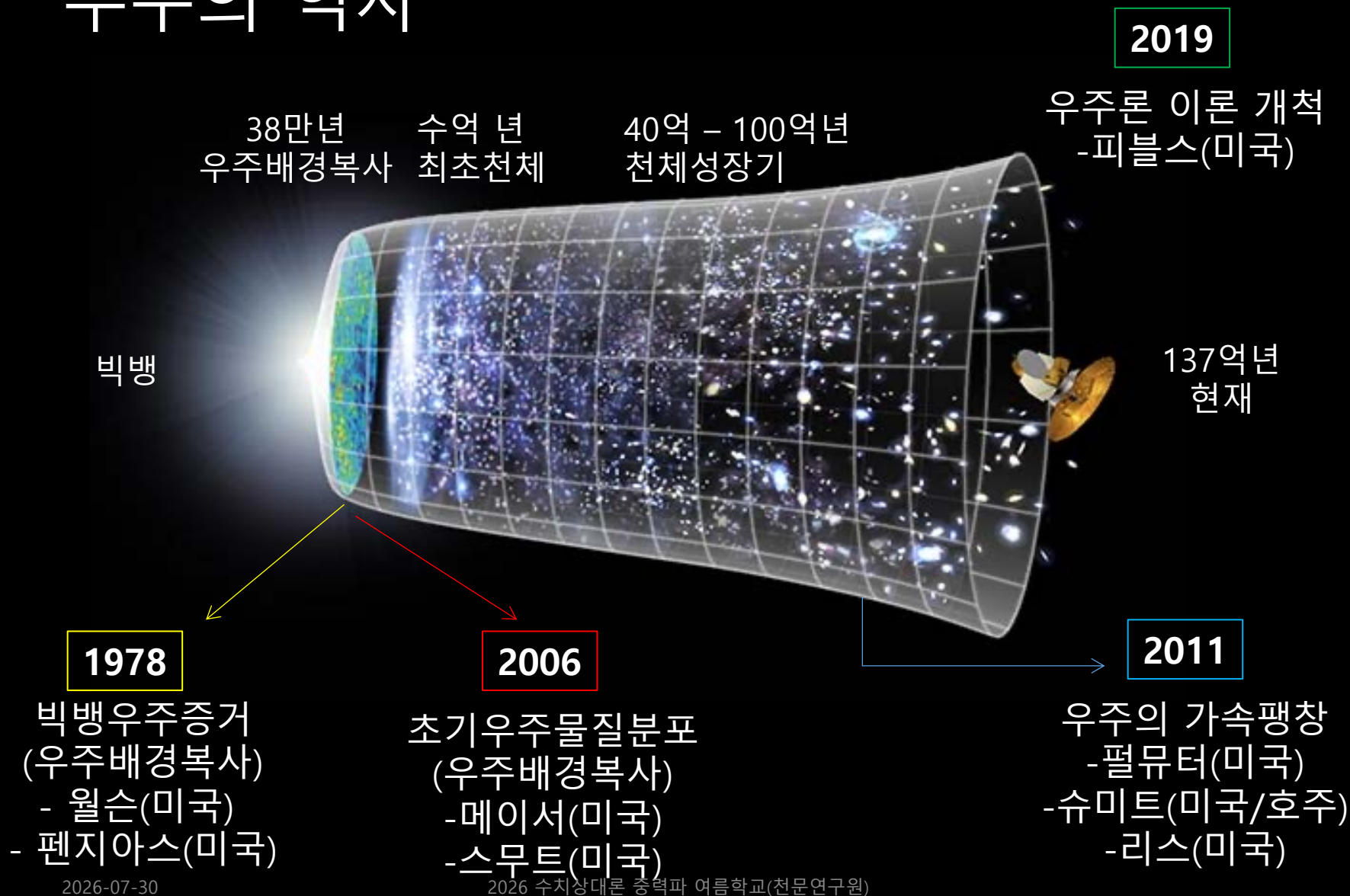
1974

펄서발견
(중성자별)
-라일(영국)
-휴잇(영국)

2002

블랙홀 존재증거
자코니(이태리)

우주의 역사



우주를 보는 새로운 창



빛(전자기파)

빛이 아닌 것

중성미자

중력파

2002

우주 중성미자연구
- 데이비스(미국)
- 코시바(미국)

1993

중력파 증거제시
- 헐시(미국)
- 테일러(미국)

2002

X-선 천문학
- 자코니(이태리)

1974

전파간섭계관측
- 라일리(영국)

2015

우주 중성미자연구
- 카지타(일본)
- 맥도널드(미국)

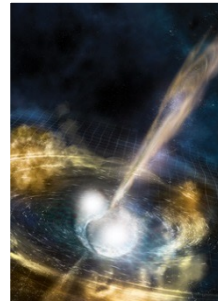
2017

우주 중력파 검출
- 바이스(미국)
- 쏜(미국)
- 베리시(미국)

다중신호천문학: 우주에서 오는 여러가지 신호를 이용하여 천체현상 연구



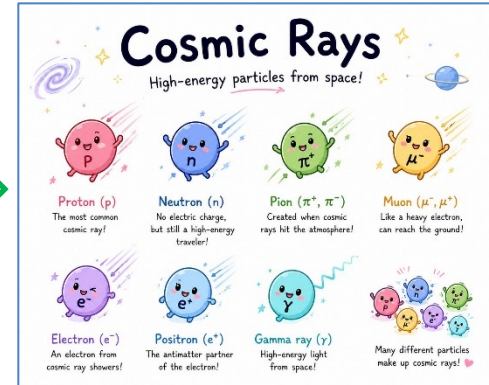
빛(전자기파)



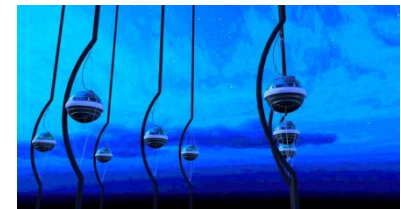
중력파
(GW)



우주선



뉴트리노 (Neutrino)



다파장 천문학
(빛 - EM: Electromagnetic Wave Signals)

2026-07-30

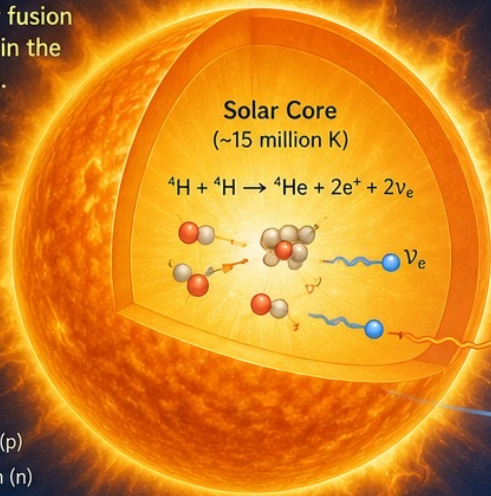
2026 수치상대론 중력파 여름학교(천문
연구원)

다중신호천문학 역사 1: Solar Neutrino

1967 The Solar Neutrino Discovery

The first detection of neutrinos from the Sun – a new messenger from the Universe

Neutrinos are produced in nuclear fusion reactions in the solar core.



Why neutrinos are special

Photons (light)

- Interact frequently with matter
- Take ~100,000 years to escape from the Sun

Neutrinos

- Interact extremely weakly with matter
- Escape the Sun almost immediately (~8 minutes)

Photons (diffuse for ~100,000 years)

Neutrinos (travel directly ~8 minutes)

Neutrinos travel across space and reach the Earth in ~8 minutes, unaffected by matter.



Impact: Birth of Neutrino Astronomy and Multi-Messenger Astronomy



Direct probe of the solar core

Neutrinos revealed information from the Sun's interior.



Neutrinos escape immediately

They carry messages from the core in real time.



Birth of neutrino astronomy

The Universe can be studied with particles, not just light.

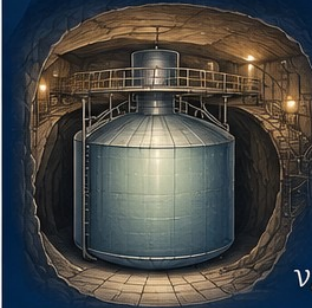


Foundation of multi-messenger astronomy

Different messengers reveal different physics.

Homestake Experiment

Lead, South Dakota, USA



Raymond Davis Jr. and collaborators used a tank of ~380,000 liters of cleaning fluid (perchloroethylene) to detect neutrinos via the reaction



They observed a few ${}^{37}\text{Ar}$ atoms per day – proof that neutrinos from the Sun exist!



The 1967 solar neutrino discovery opened a new window on the Universe, leading to the modern era of multi-messenger astronomy.

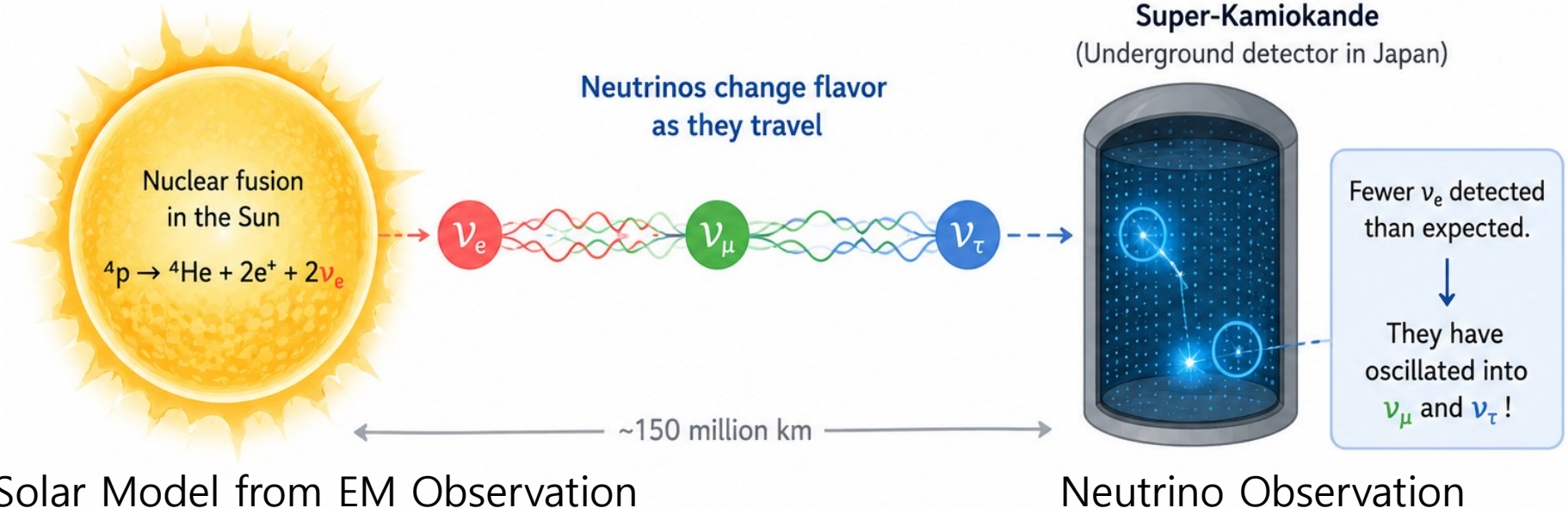
Neutrino Oscillation Discovery

Kajita and McDonald (Neutrino Observatories)

Sudbury Neutron Observatory (Canada)

Super-Kamiokande

(Underground detector in Japan)



What this means



Neutrinos have **mass**.



Neutrinos oscillate:

$$\nu_e \rightleftharpoons \nu_\mu \rightleftharpoons \nu_\tau$$



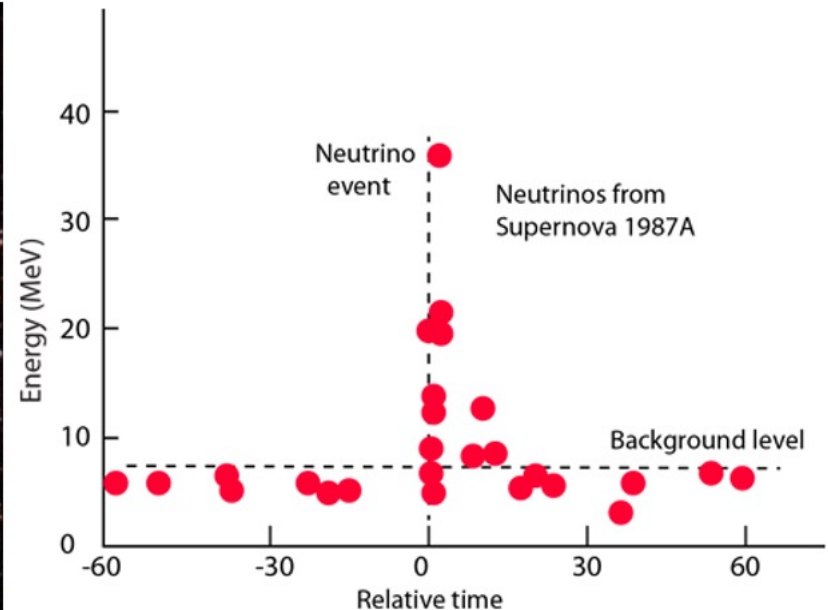
A major breakthrough in particle physics and astrophysics.



Nobel Prize in Physics 2015 to Takaaki Kajita and Arthur B. McDonald.

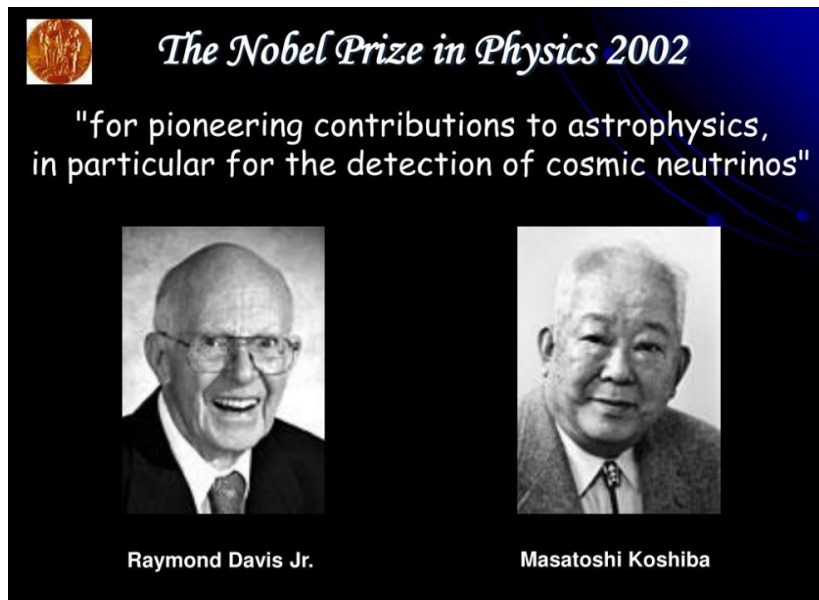
다중신호 천문학 역사 2: 초신성 Neutrino

- 1987년 대마젤란 은하에서 SN 1987A 발생
- 그와 동시에 지상 중성미자 천문대에서 중성미자 신호 포착
- 중성미자와 빛 신호 도달 지구 도달 시간 차이로부터 중성미자 질량이 $m_\nu < 12 \text{ eV}$ 임을 보임



Two Nobel Prizes for Neutrino MMA

Nobel Prize in Physics 2015



1967 Neutrino Discovery

1987 SN 1987A



© Nobel Prize Outreach. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2



© Nobel Prize Outreach. Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino Oscillation

- Related: 1967 Nobel prize for Hans Bethe

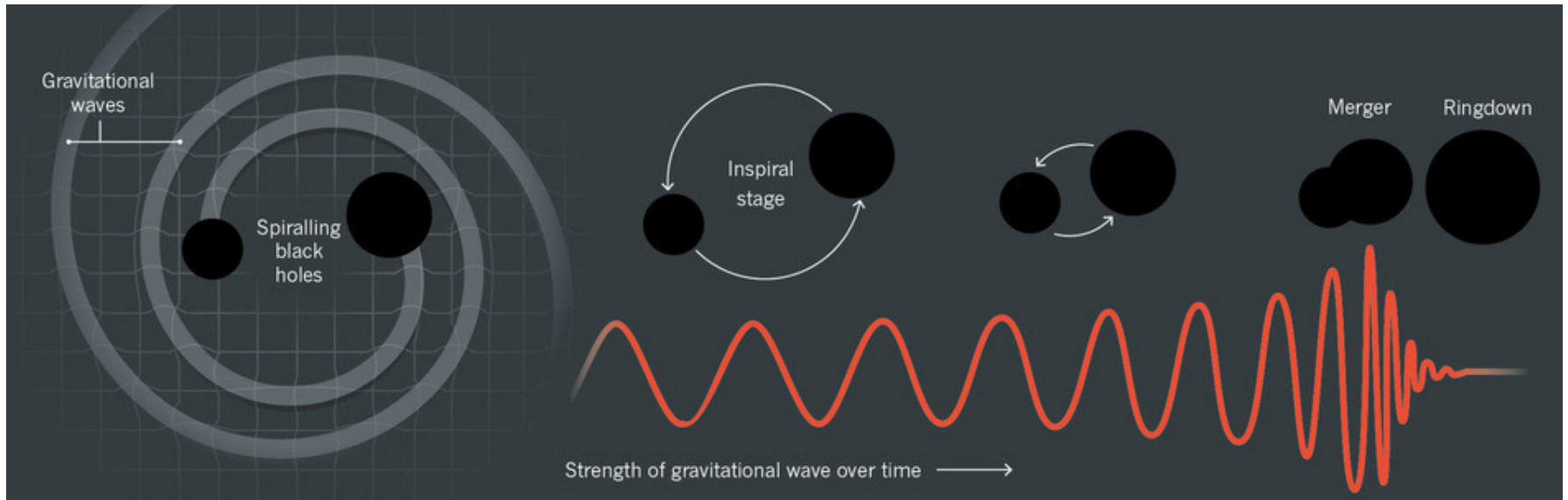
초신성 SN 1987A 사건 이후...

- 당분간 다중신호천문학 연구가 잠잠...
- 새로운 중력파 및 뉴트리노 천문대 건설에 시간 소요



중력파(Gravitational Wave)

- Ripples in the fabric of space-time due to massive accelerating objects
- Predicted at 1916 (General Relativity)



By Lucy Reading-Ikkanda

LIGO 및 Virgo 중력파 검출기



LIGO 중력파 검출기(Hanford, WA)



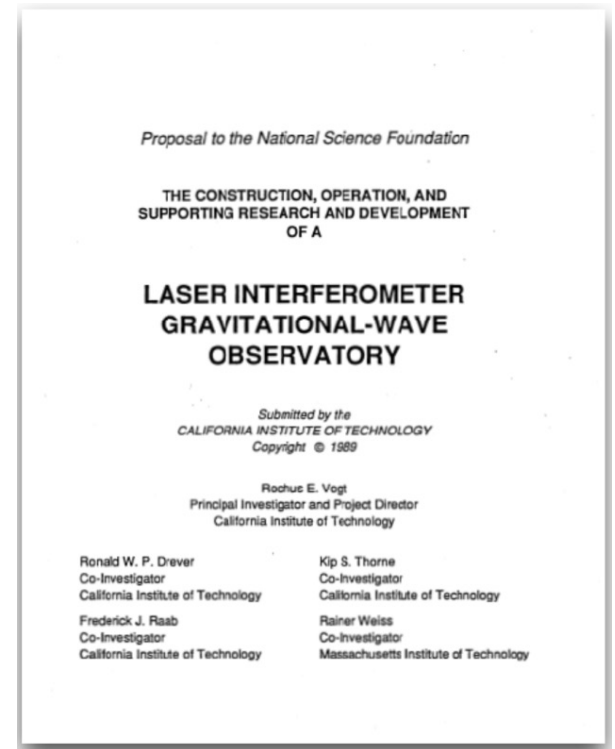
Virgo(비르고) 중력파 검출기(Italy)



LIGO 중력파 검출기(Livingston, LA)

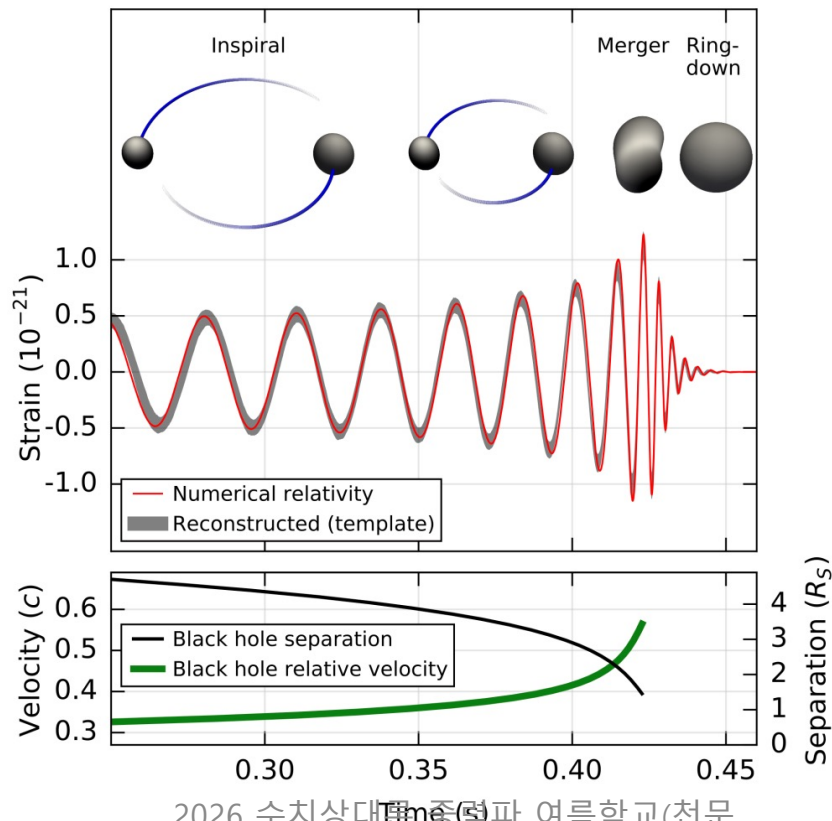
LIGO 연표

- 1967: 기본 디자인 구상(Rainer Weiss)
- 1968 – 1980: 연구그룹 결성(Kip Thorne, Ron Driver)
- 1980: Prototype 제작 연구비 지원(NSF)
- 1990: LIGO 프로젝트 승인(NSF)
- 1994: 건설시작(Barry Barish 등)
- 2002: 중력파 관측시작
- 2015: 중력파 최초 검출



The era of GW astronomy has arrived at 2015!

- BH-BH merger



GW 150914

[LIGO'S **GRAVITATIONAL-WAVE** DETECTIONS]

[**GW150914**]

DISCOVERED:

14.09.2015

1.3 BILLION
LIGHT-YEARS
AWAY

62 SOLAR
MASSES

366 KILOMETRES IN
DIAMETER

[**GW151226**]

DISCOVERED:

26.12.2015

1.4 BILLION
LIGHT-YEARS
AWAY

21 SOLAR
MASSES

124 KILOMETRES IN
DIAMETER

[**GW170104**]

DISCOVERED:

04.01.2017

3 BILLION
LIGHT-YEARS
AWAY

49 SOLAR
MASSES

289 KILOMETRES IN
DIAMETER

1 BILLION
LIGHT YEARS

2 BILLION
LIGHT YEARS

3 BILLION
LIGHT YEARS

4 BILLION
LIGHT YEARS

YOU ARE
HERE

DID YOU KNOW ?

THE SOLAR MASS IS
A STANDARD UNIT OF MASS
IN ASTRONOMY
IT IS EQUAL TO
THE MASS OF THE SUN
EQUAL TO APPROXIMATELY
 1.99×10^{30} KG

2026-07-30

2026 수치상대론 중력과 여름학(전국
연구원)

LIGO

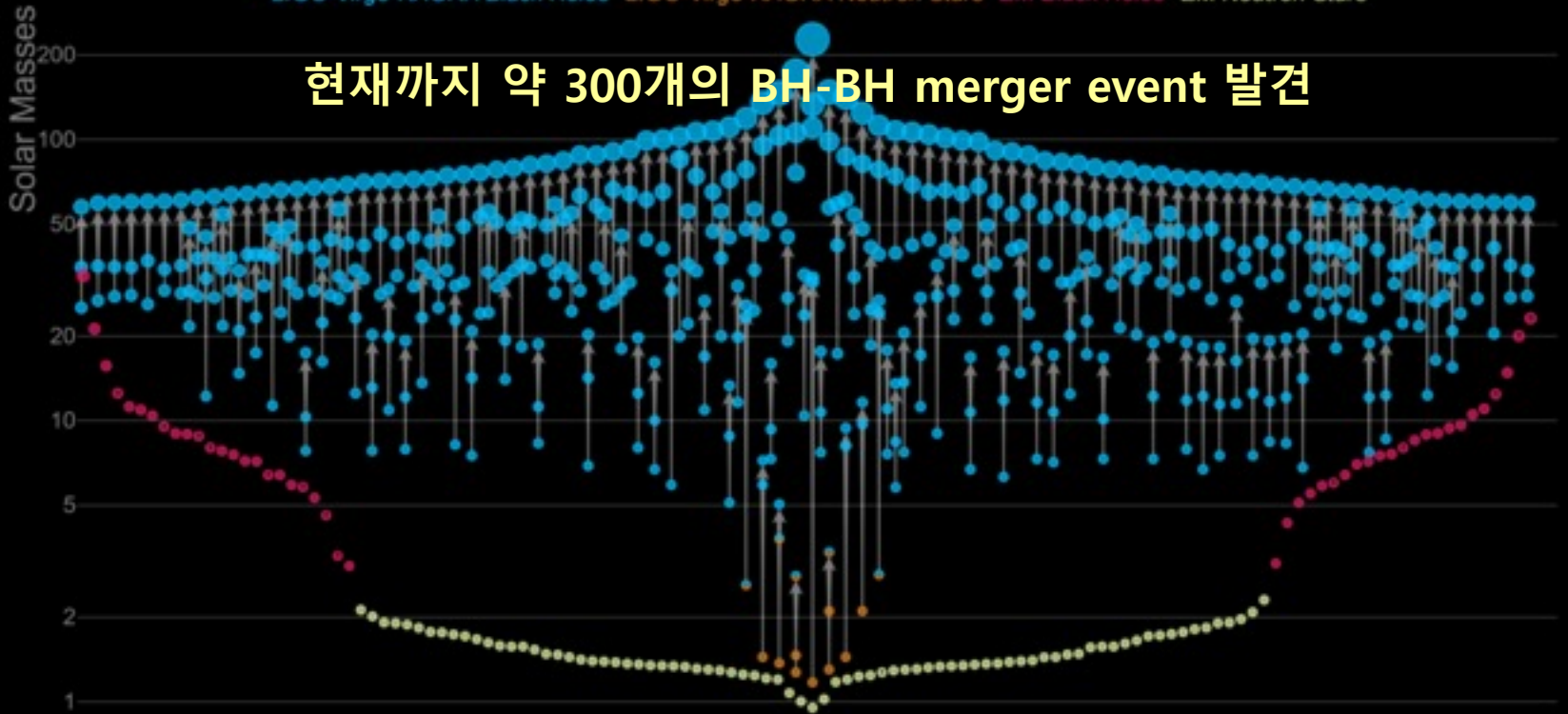
Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

현재까지 약 300개의 BH-BH merger event 발견



Run	Dates	Duration (months)	Detections
O1	September 18, 2015 to January 12, 2016	3	3
O2	November 30, 2016 to August 25, 2017	9	8
O3	April 1, 2019 to March 26, 2020	11	79
			Candidates
O4	May 24, 2023 to March 19, 2025	23	200

GW150914

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

PRL 116, 061102 (2016)



week ending
12 FEBRUARY 2016



Observation of Gravitational Waves from a Binary Black Hole Merger

우주에서 발생한 중력과 최초 검출

B.P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015, at 09:50:45 UTC, the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.2^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties are in 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

태양질량 30배 블랙홀이 충돌 빛을 내지 않음 → 천문학자 심심

Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

중력파만으로 알 수 있는 것, 알 수 없는 것?

GW only

Mass of GW emitting object

Rough location and distance

Other physical properties (orbits, etc)

GW speed

GW + EM

Precise location*

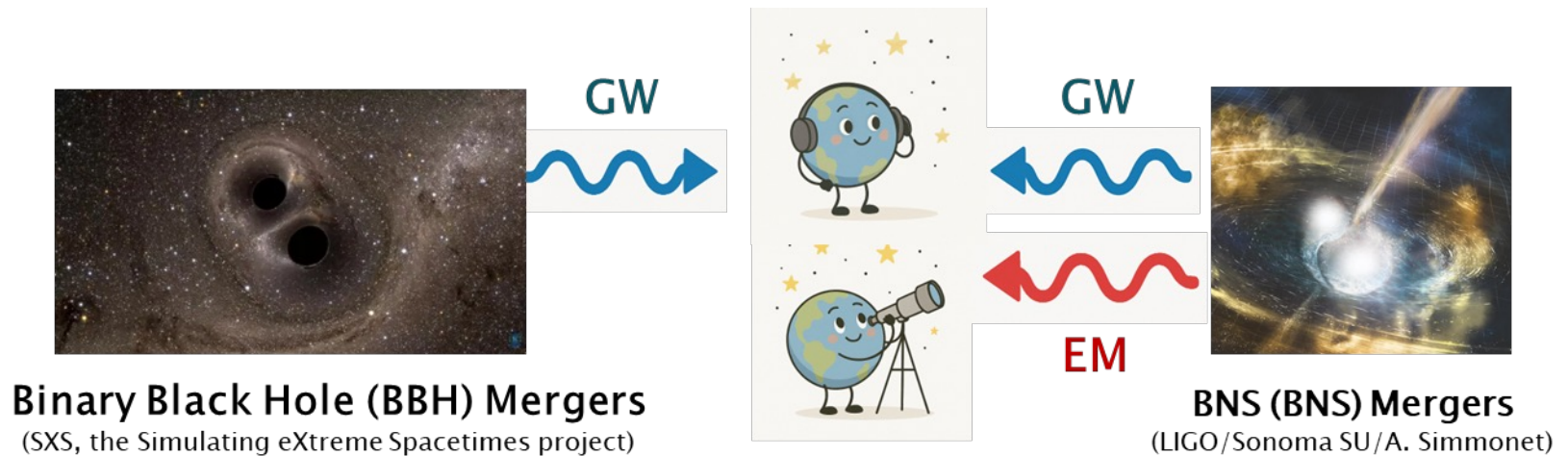
Radial velocity of GW

Phenomena associated with GW (e.g., Kilonova)

Cosmological application (e.g., Hubble constant, etc)

Speed of GW*

Multi-Messenger Astronomy (MMA) with GW and Electromagnetic Wave (EM) Signals



- GW observation alone is powerful
- But, with EM observation, GW observation can be even more powerful ➔ Multi-Messenger Astronomy (MMA)

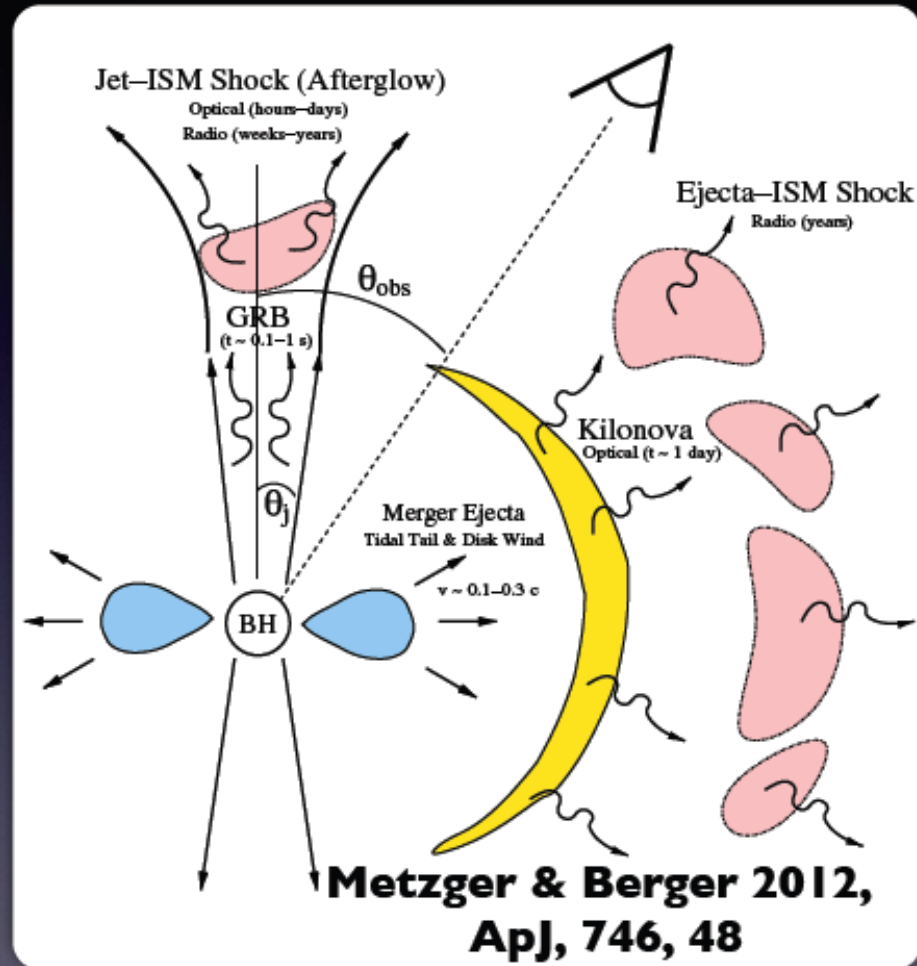
EM signature from NS-NS merger

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

GRB



Kilonova



WHY MULTIMESSENGER ASTRONOMY MATTERS

Gravitational Waves (GW) + Electromagnetic (EM) = Deeper Understanding of the Universe

1. DETECTION OF GW EVENT

Compact object merger
(e.g., binary neutron star)

EM OBSERVATIONS

Wide-field telescopes scan
rapidly across the sky

GW Observatories
(LIGO, Virgo, KAGRA)

EM Observatories
(e.g., 7DT, Rubin, Swift, Fermi,
X-ray, Radio, IR telescopes)

2. PRECISE LOCALIZATION

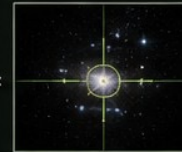
GW + EM localizations $\Rightarrow$ < 1 arcsecond accuracy



GW Localization
(~ 100 – 1000 deg 2)



EM Localization
(arcmin–arcsec)



Final Localization
(< 1 arcsecond)

3. HOST GALAXY & ENVIRONMENT

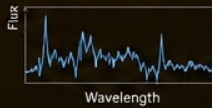
Pinpointed location identifies the
host galaxy and local environment

- Galaxy type & mass
- Metallicity
- Star formation rate
- Local density

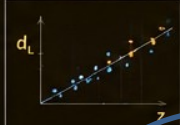
Reveals where GW events
occur in the universe

4A. REDSHIFT & COSMOGRAPHY

Host galaxy or kilonova gives redshift (z)



z measurement
GW gives luminosity distance (d_L)
 $H_0, \Omega_m, w_0, w_a \dots$
Probes the expansion history
and nature of dark energy



4B. KILONOVAE: THE FACTORY OF HEAVY ELEMENTS

EM counterpart (kilonova) reveals
physics and nucleosynthesis



- Ejecta mass & velocity
- Composition (r-process)
- Opacity & temperature
- Energy source (radioactive decay, dynamical ejecta, disk wind)

$\Rightarrow$ Heavy element production rate
such as gold, platinum, uranium

4C. COSMIC CHEMICAL EVOLUTION

From KNe rate & yields $\Rightarrow$ build the history
of heavy elements in the Universe

Au Pt U Eu Th ...



KNe rate
over cosmic time



Total r-process
production



Enrichment of
galaxies & ISM



Planet formation
& habitability

5. PHYSICS OF COMPACT MERGERS

GW provides masses, spins,
tidal deformabilities



- Equation of state (EOS) of
neutron-star matter
- Maximum neutron-star mass
- Nature of matter at nuclear
densities

6. SHORT GRB & JET PHYSICS

Tests models of short GRBs
and relativistic jets



- Jet launching mechanism
- Jet structure & viewing angle
- Prompt & afterglow emission
- Connection between BNS
mergers and short GRBs

7. STELLAR POPULATIONS & STELLAR EVOLUTION

Host galaxies & KNe tell the story
of stellar birth and death



- Ages & metallicities
- Star formation history
- Binary fraction
- How massive stars evolve
and end their lives

8. FUNDAMENTAL PHYSICS

Extreme environments
as natural laboratories



- Tests of General Relativity
- Lorentz invariance tests
- Speed of GW vs light
- Exotic compact objects?
- Neutrino physics

9. NEUTRINO EMISSION (Future)

Neutrinos carry away $\sim 10\%$
of the energy



- Constrains total energy
- Ejecta composition
- Dense matter EOS
- Multi-messenger synergy

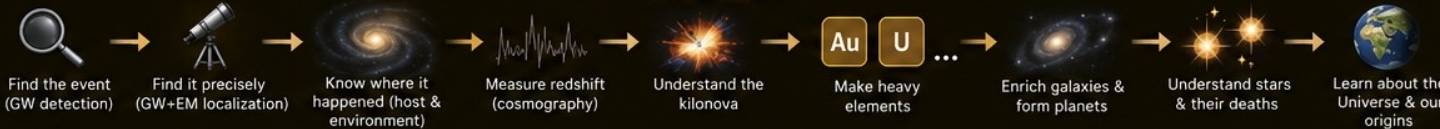
10. TRANSIENT ASTROPHYSICS

Part of the broader transient
universe



- Population rates
- Connections to other transients
- Unified view of explosive
phenomena

THE BIG PICTURE



MULTIMESSENGER ASTRONOMY

CONNECTS THE VERY SMALL
TO THE COSMIC SCALE

From neutron stars to nuclei,
from galaxies to planets,
from the Big Bang to life.

Where did the GW event happen?

GW localization is uncertain, but EM observations pinpoint the source.

1. GW DETECTION

LIGO–Virgo–KAGRA detect a compact object merger



GW LOCALIZATION

Large uncertainty area

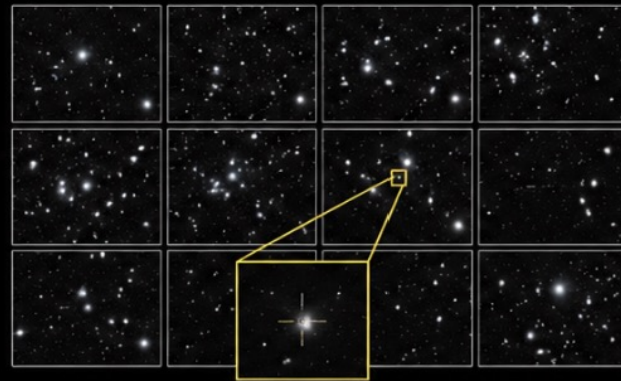
Typical 90% credible region
~ 10 – 1000 deg²



Many galaxies in the area
No unique host identification

2. EM FOLLOW-UP OBSERVATIONS

Telescopes scan the GW error region in X-ray, optical, infrared, radio



LOOKING FOR EM COUNTERPARTS



Kilonova
(optical/IR)



Short GRB
(gamma-ray)



Afterglow
(radio)

3. PINPOINTED LOCATION

EM counterpart identifies the exact position with < 1 arcsecond accuracy



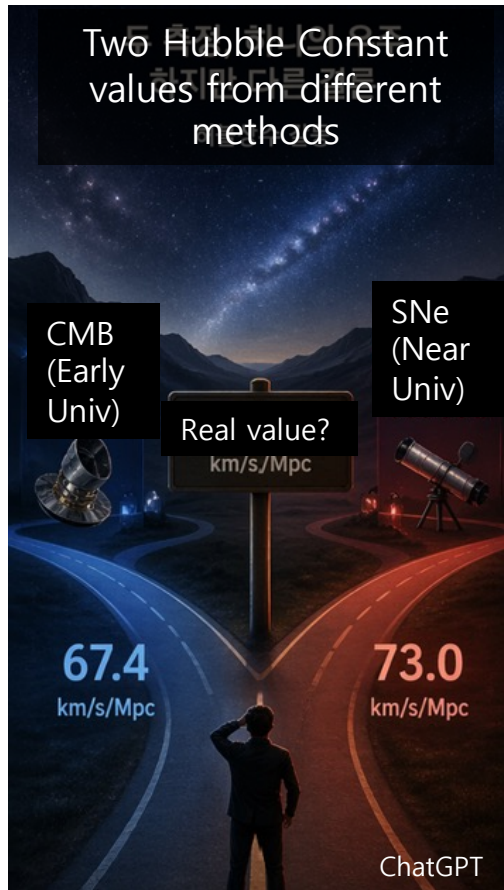
Accurate position ⇒ Host galaxy and local environment

- ✓ Galaxy type, mass, metallicity
- ✓ Star formation rate
- ✓ Local density, environment

- With EM observation, we get the exact location, host galaxy, and redshift of the event

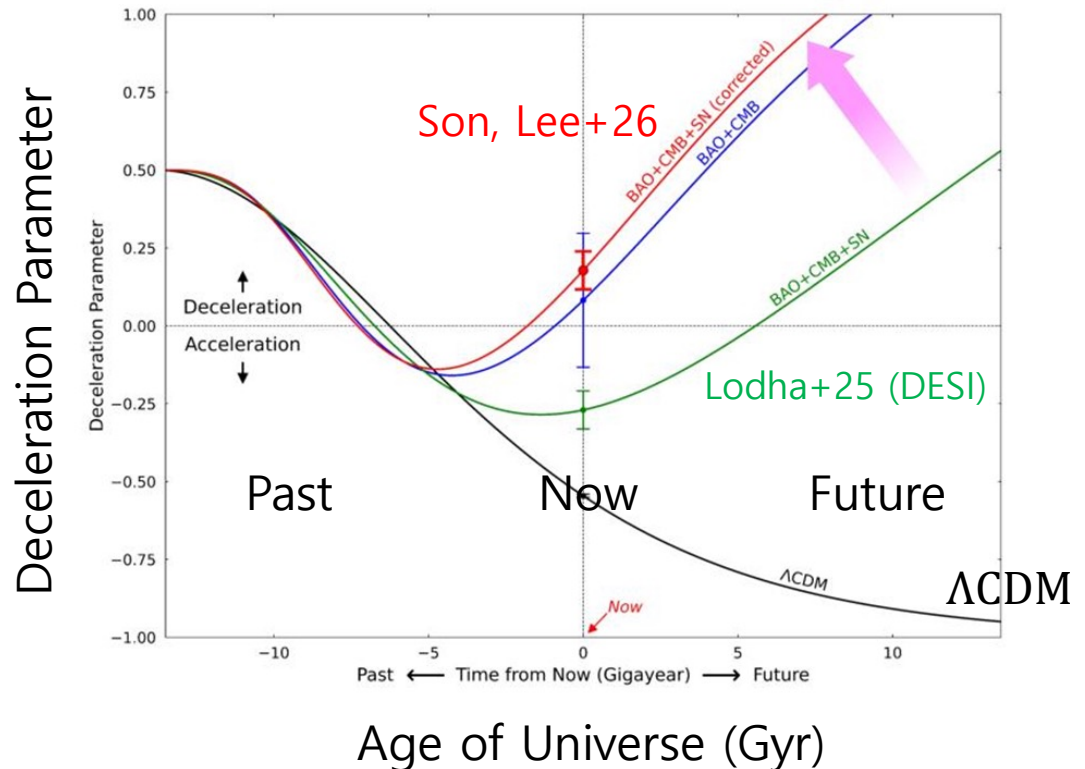
Tensions in Cosmology: Independent method is needed

Hubble Tension



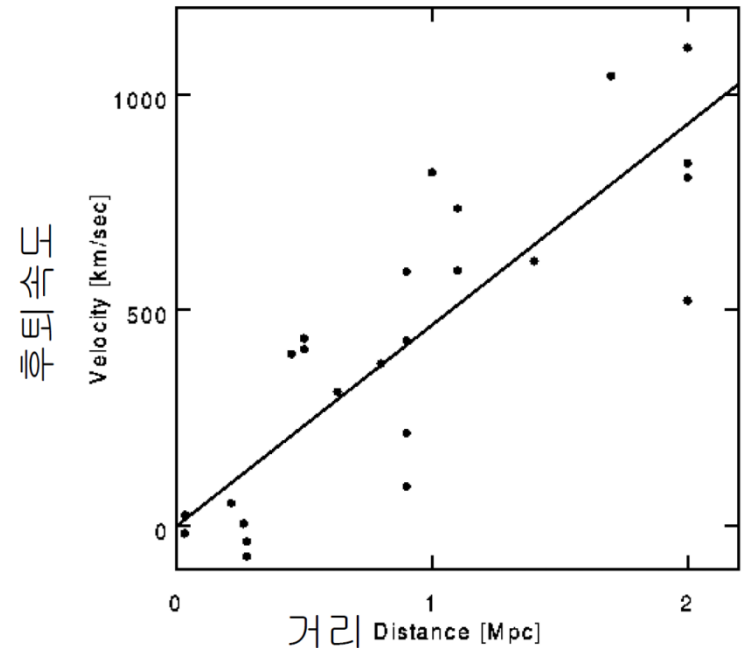
Dark Energy Tension:

- Is Dark Energy evolving?
- Universe still accelerating or decelerating?



우주론 연구: 허블상수

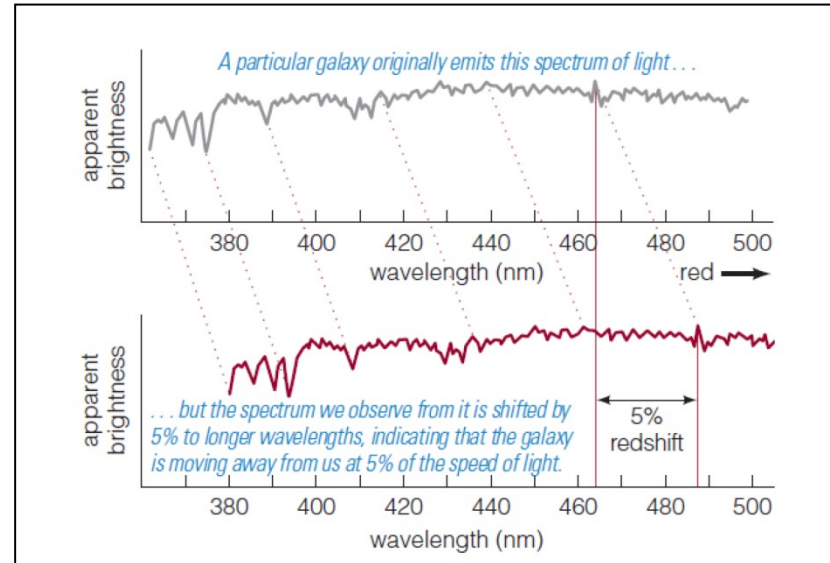
- $V = H_0 \times D$
- V: 후퇴속도
- D: 거리
- H_0 : 허블상수



후퇴속도와 거리

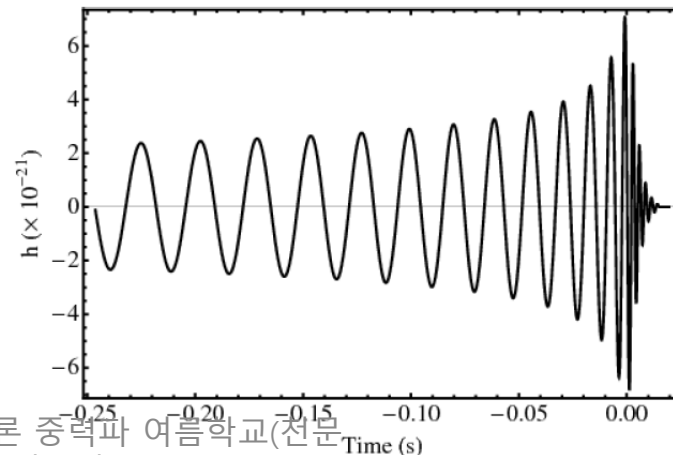
후퇴속도: 은하 스펙트럼 관측

$$V = \frac{(\lambda - \lambda_0)}{\lambda_0} c$$



거리: 중력파 관측

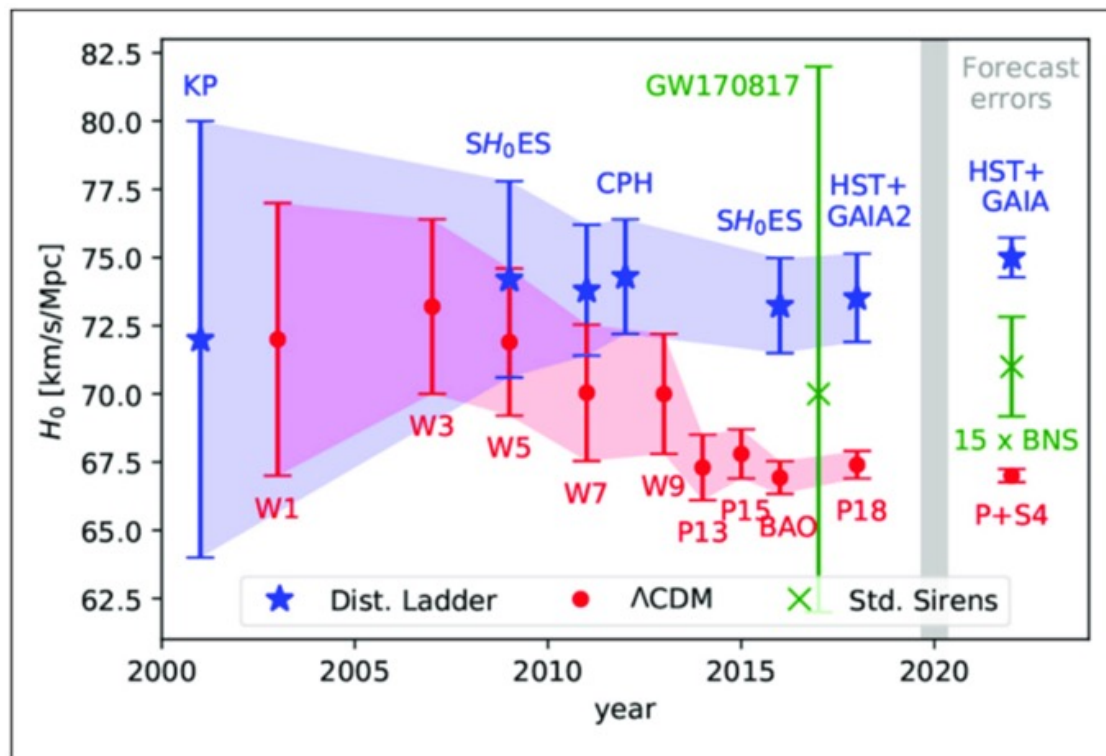
$$h_{\times} = \frac{4}{d_L} \left(\frac{G M_c}{c^2} \right)^{\frac{5}{3}} \left(\frac{\pi f}{c} \right)^{\frac{2}{3}} \cos \iota \sin[\Phi(t)]$$



GW MMA can solve the tensions by providing a robust, independent method

- GW: Distance
- Optical counterpart + Host: Redshift

} Hubble Constant
Dark Energy



Ezquiaga & Zumalacarregui (2018)

2018년 4월29일 뉴스

“3억5천만원 상당 금괴가”..
인천공항 쓰레기통서 발견

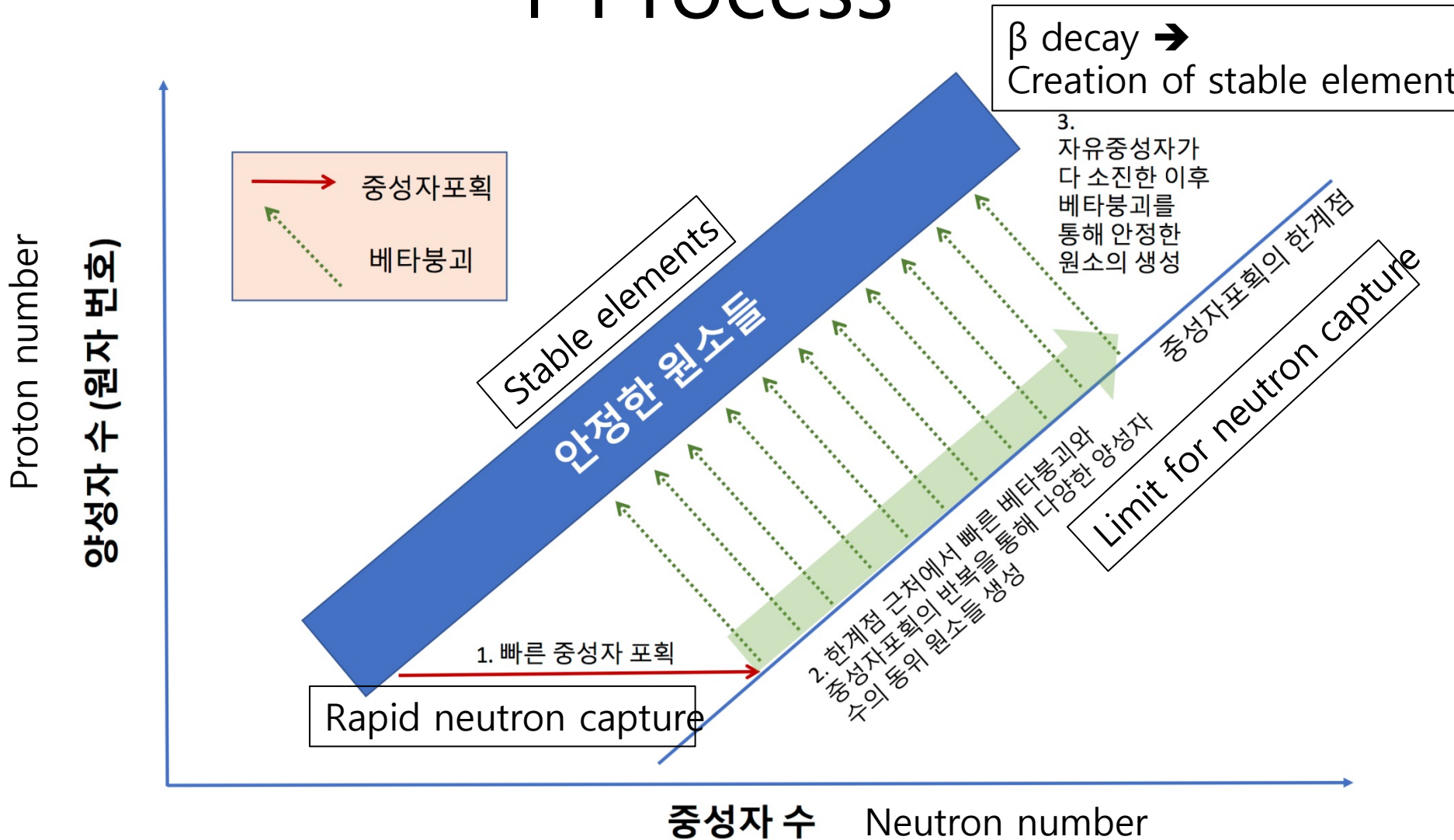


어디서 왔을까?

Where did the gold f (heavy elements more massive than Fe) come from?

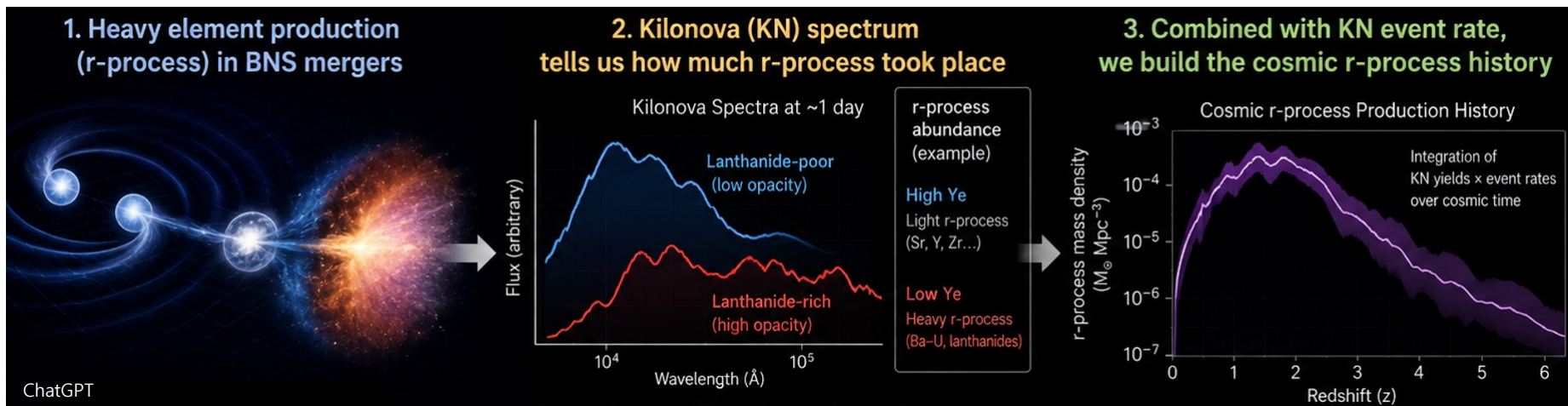


r-Process



Kilonovae (KNe) as the factory of heavy elements

- Heavy element production (r-process) from neutron rich materials in BNS
- KNe spectrum tells us how much r-process took place
- With the KNe event rate, one can understand the cosmic heavy element production history



(Kasen '17; Tanaka+'18; Vieira+'23, Tak+'23, '24; ...)

AI-produced

금 공장은 어디에?



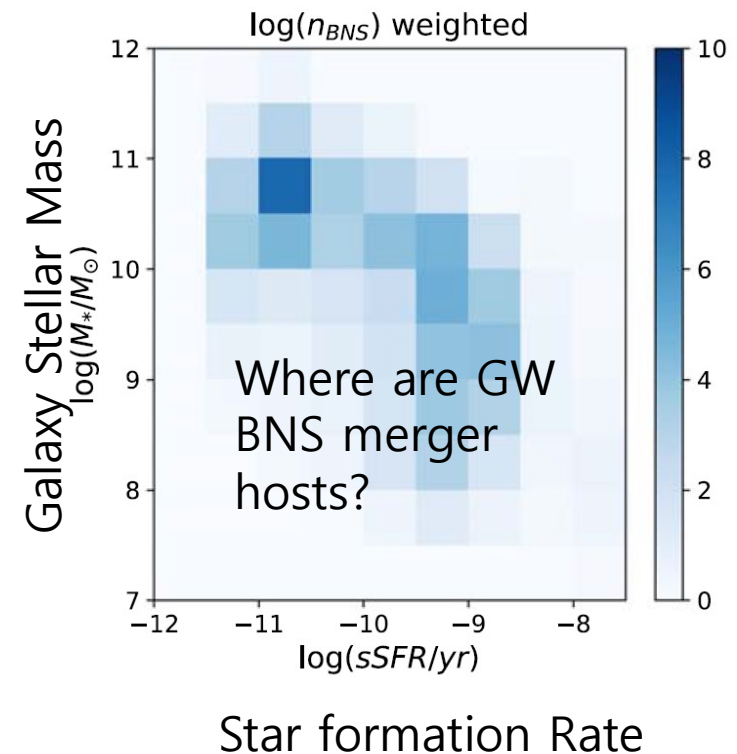
Environment of BNS merger:
Knowing their environment makes us easier to find
them and understand their evolutionary path



In what environment do BNS mergers occur?

- Massive and star-forming galaxies?
- Outskirts or inner region?
- Can simulations explain BNS merger locations?

Jeong+Im24



Why Multi-messenger Astronomy Matters for Short GRBs

Gravitational waves reveal the true origin of short gamma-ray bursts

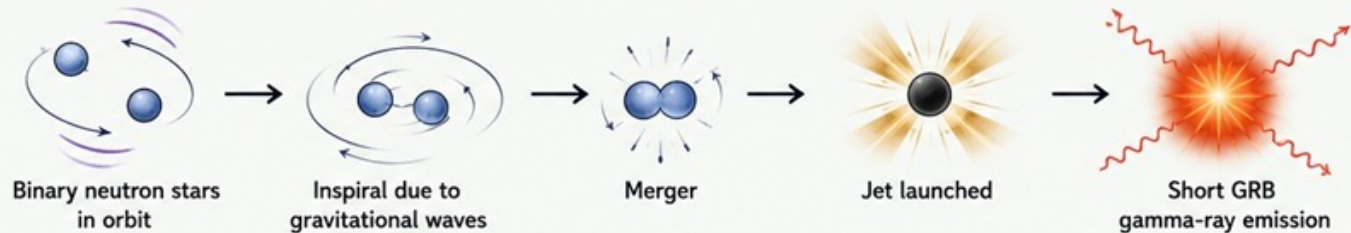
1 What is a short GRB?

- Brief flashes of gamma rays lasting < 2 seconds
- Occur in distant galaxies
- Long-standing **mystery**: What produces them?



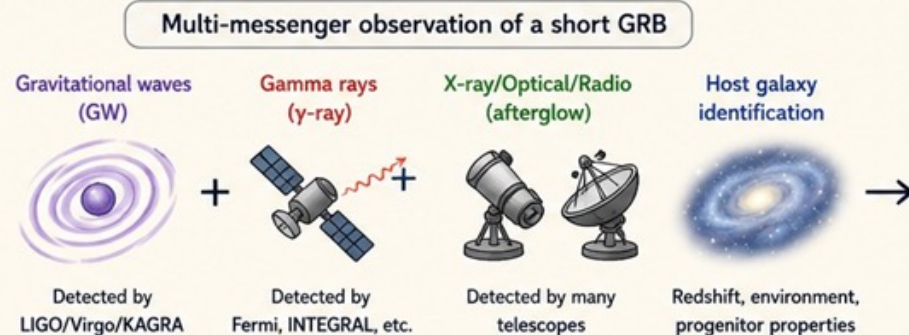
2 Postulated progenitor

The leading model:
Merger of a binary neutron star (BNS) system



3 How GW observation reveals the true origin

- Gravitational waves are emitted during the inspiral and merger.
- GW detectors (LIGO, Virgo, KAGRA) can detect this signal.
- Detecting GWs from a short GRB proves that the **progenitor is a binary neutron star merger**.

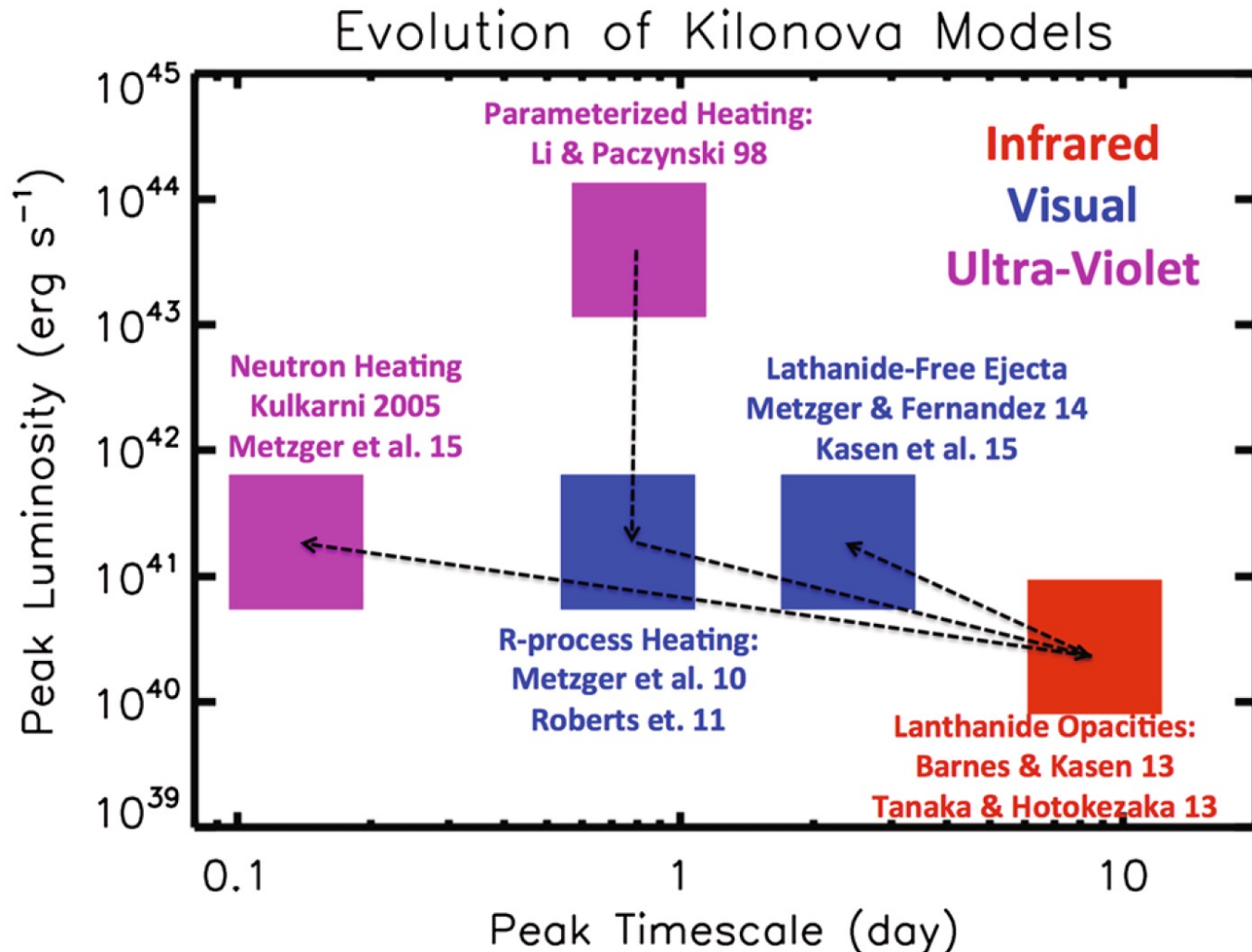


Conclusion

GW detection + EM counterpart confirms that short GRBs are produced by **binary neutron star mergers**.

★ Multi-messenger astronomy provides the definitive answer: Short GRBs come from binary neutron star mergers.

What is the nature of Kilonova?

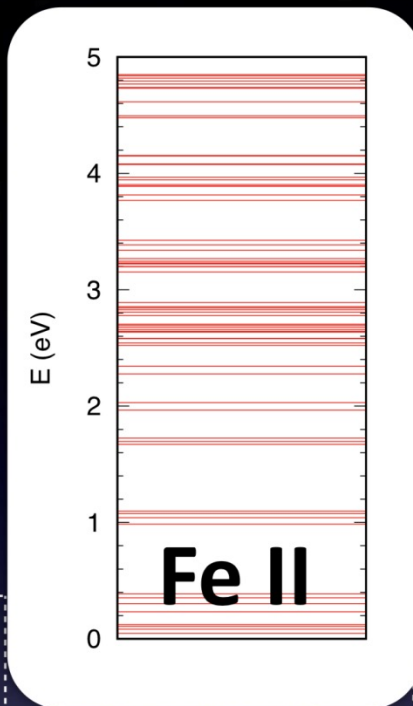
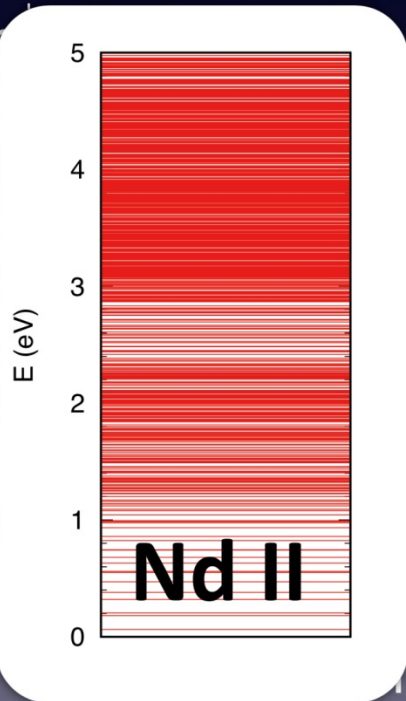


open s shell
($l=1$)

Slide from M. Tanaka

open p-shell
($l=2$)

open d-shell
($l=3$)



1 H																	2 He			
3 Li	4 Be															6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg															14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr			
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe			
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	
87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	
107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo									

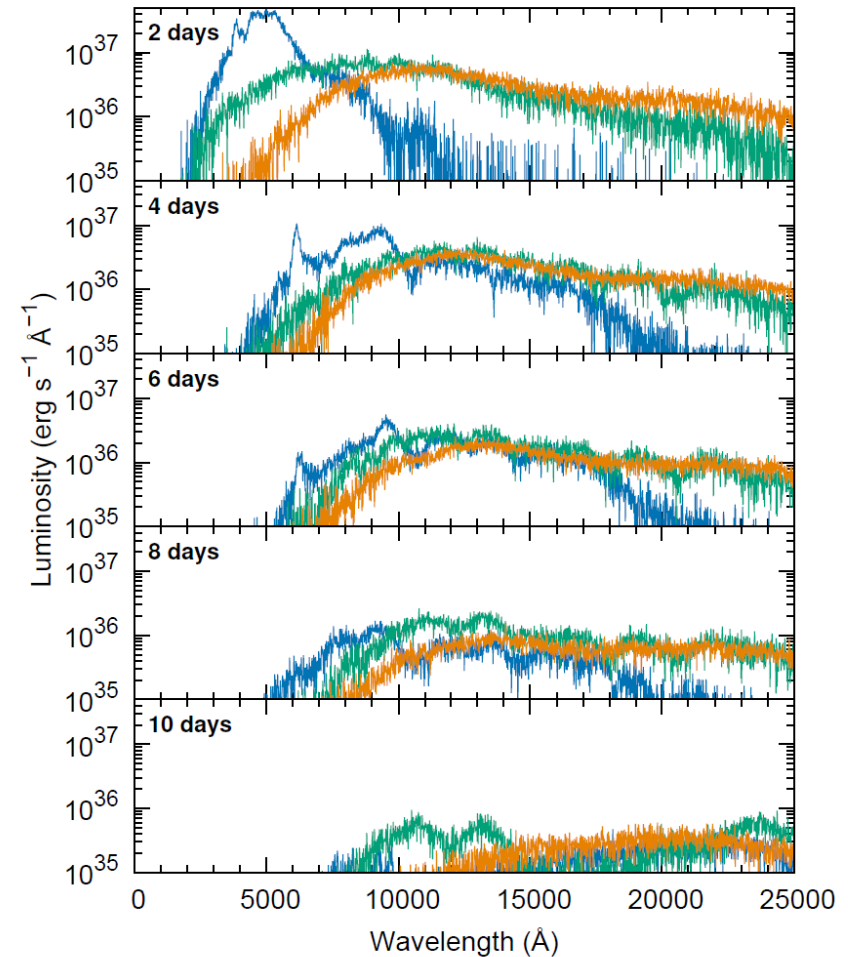
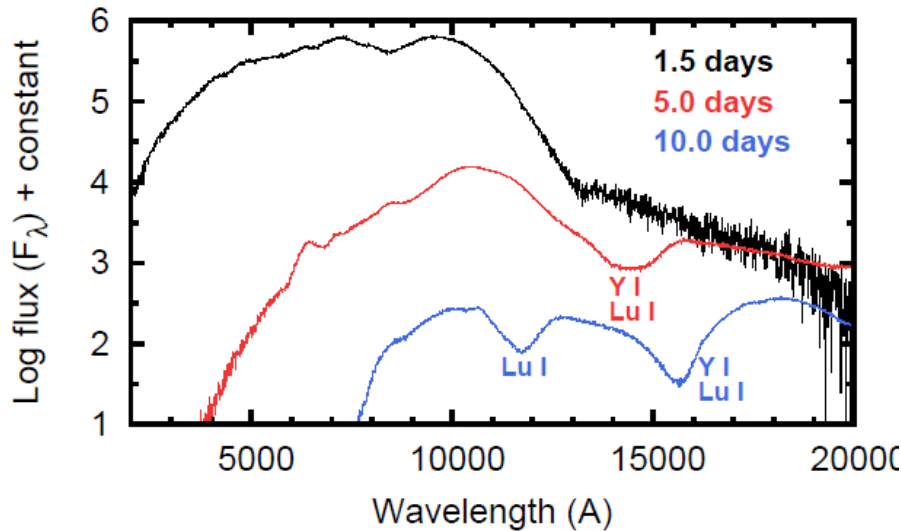
open d-shell
(l=3)

open p-shell
(l=2)

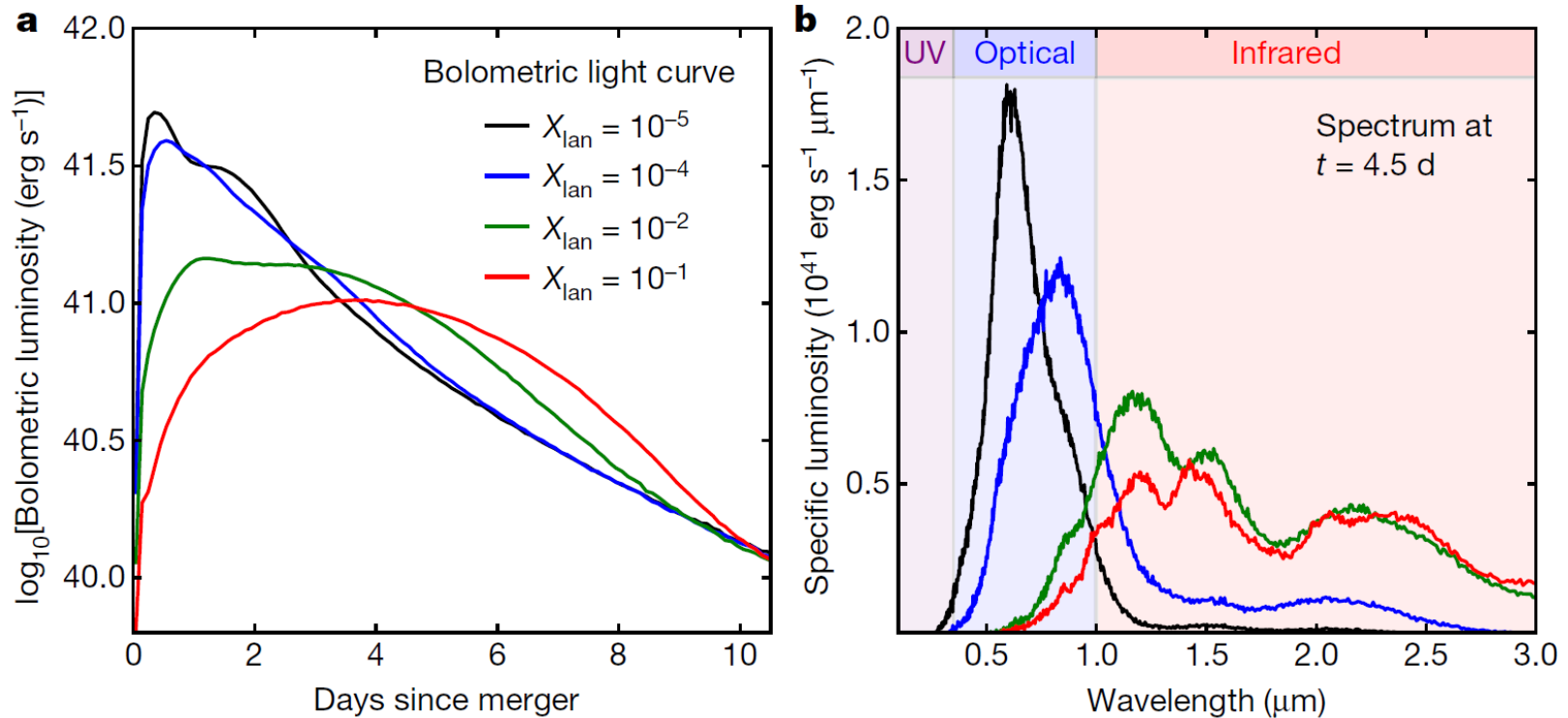
open f shell
(l=4)

Expected Spectrum of Kilonova

- Very red, due to high opacity of r-process heavy elements
- Or blue in the beginning, red later
- Peak at $\sim 1 \mu\text{m}$ (red spectrum)
- $\sim$ BB radiation with $T \sim 2500 \text{ K}$



Kilonova: Blue or Red?



X_{lan} : Lanthanide fraction

NS-NS merger

- Factory for heavy elements (Au, etc)
- Laboratory for matter in extreme condition (Eq. of state)
- Kilonova: understanding stellar evolution
- BH creation channel?
- Cosmological application (GW distance + redshift)



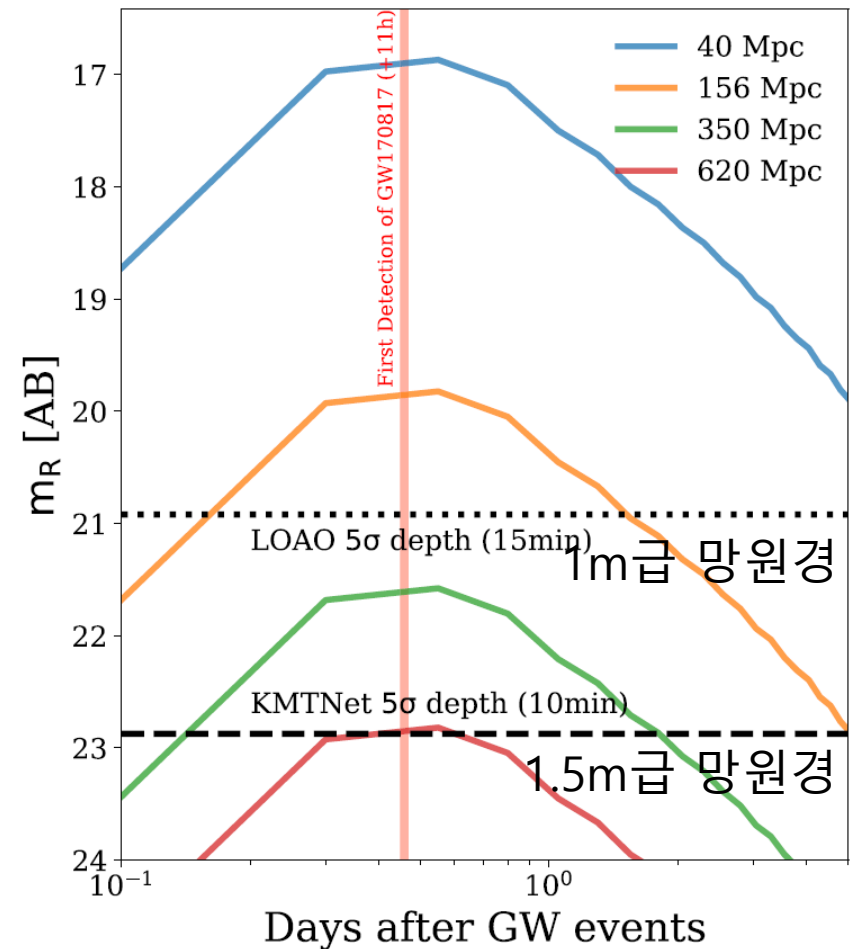
Dana Berry/SkyWorks Digital, Inc.

To do MMA, what do we need?

- Network of telescopes around the world and space!
- Field of view?
- Size of telescope?

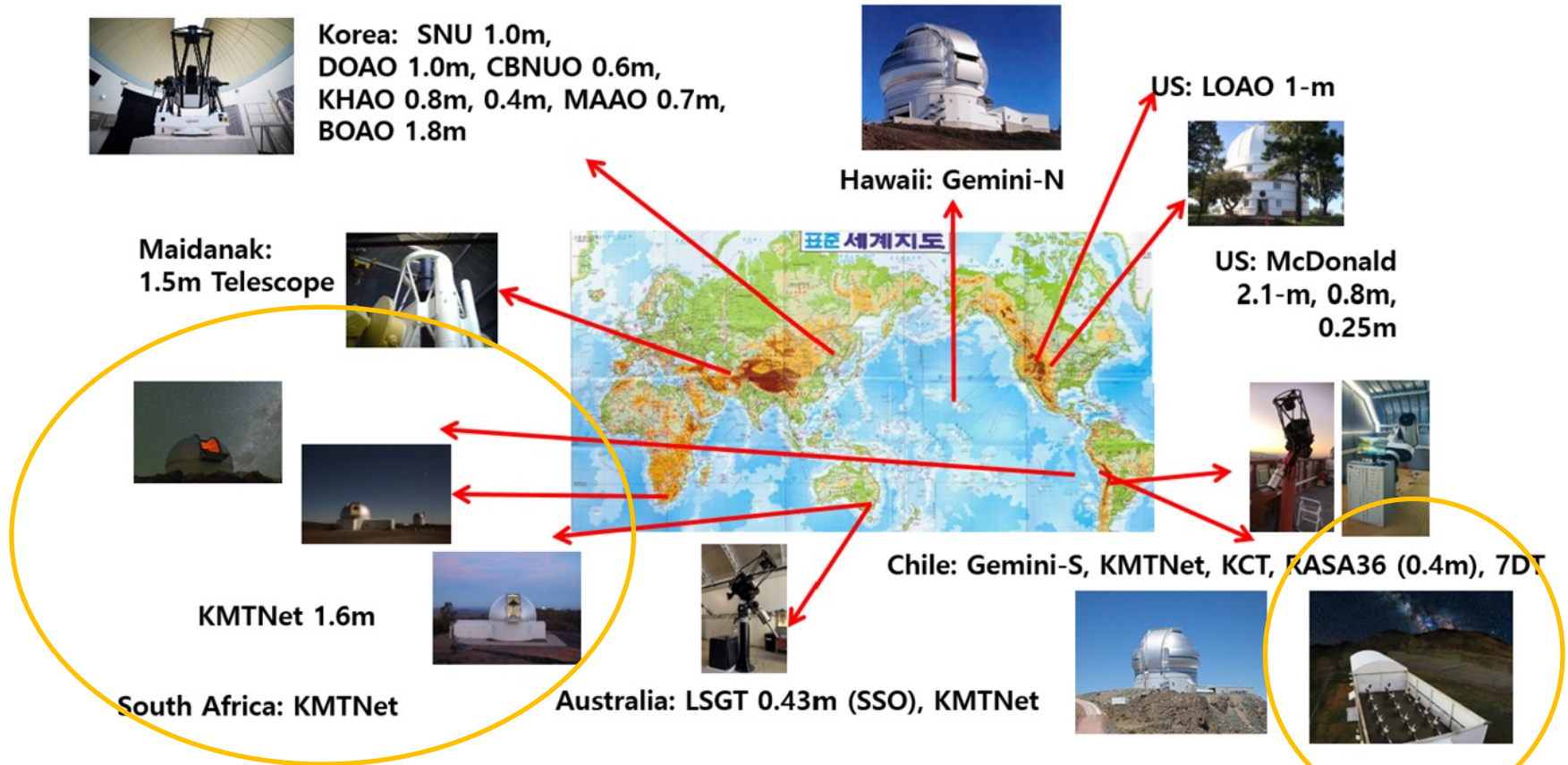
Kilonova at < 500 Mpc can be detected with many existing facilities

- $D < 150$ Mpc: 0.5 m
 - $D < 300$ Mpc: 1 m
 - $D < 500$ Mpc: 1.5 m
-
- 날씨, 기상, 노출시간 등에 영향





GW EM Counterpart Korean Observatory (GECKO)



- Wide-field telescopes + narrow-field telescopes
- Imaging telescopes + spectrophotometry telescopes

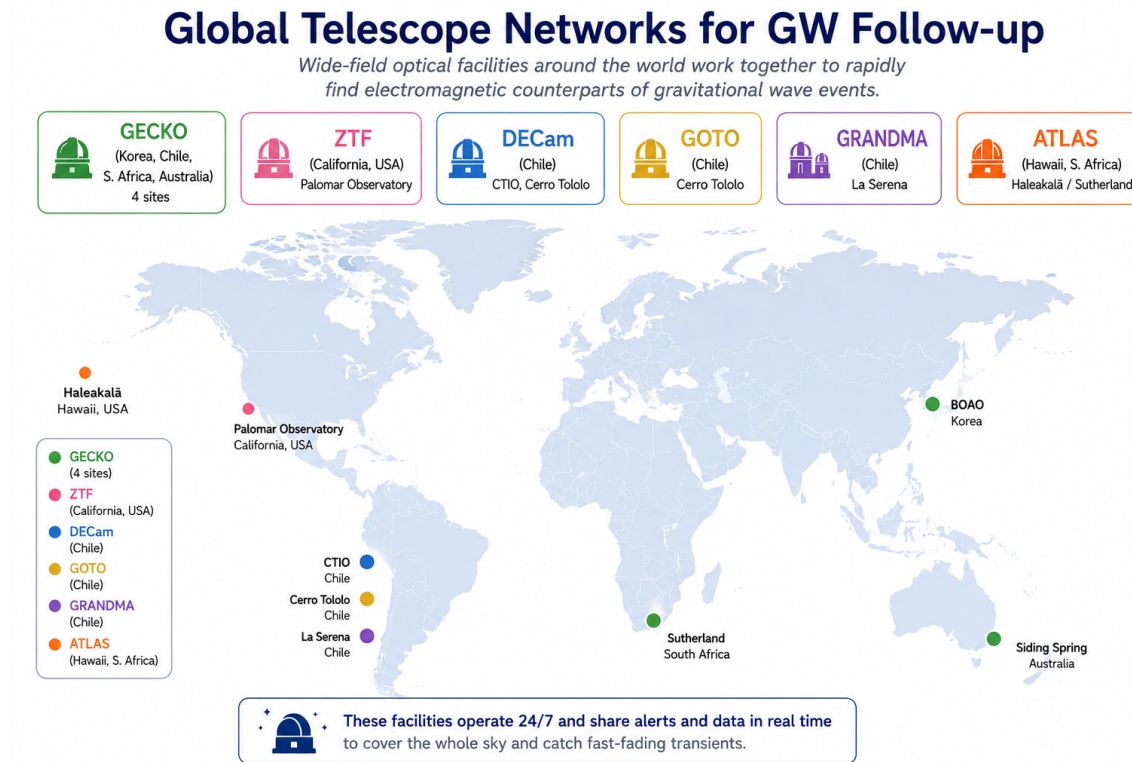


2026-07-30

2026 수치상대론 중력파 여름학교(천문
연구원)

There are also many other telescope networks

- ATLAS
- DECam
- GOTO
- GRANDMA
- J-GEM
- SAGUARO
- WINTER
- ZTF
-





Korea Microlensing Telescope Network (KMTNet)

- Three 1.6m telescopes at southern hemisphere
- FOV: 4 deg²
- Limiting mag: 23 AB mag (5- σ) in 6 min
- 24 hr/day coverage
- 100 deg² in a few hrs

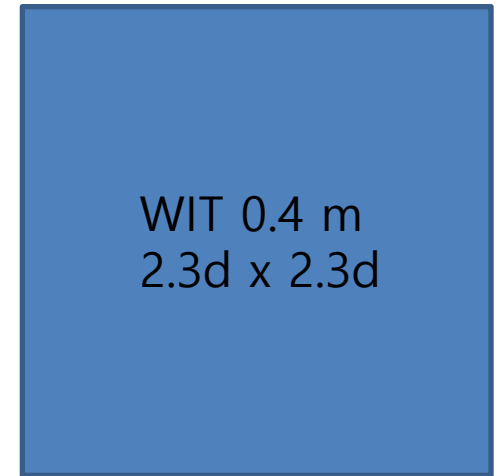
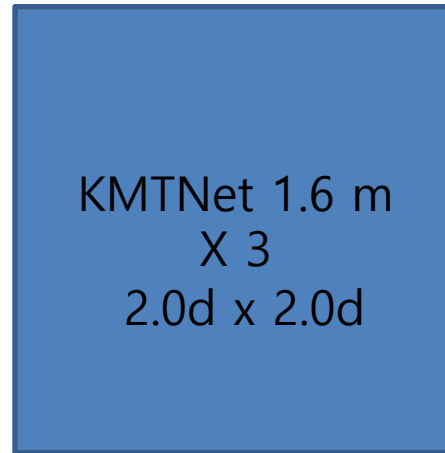


FOV of GECKO Telescopes

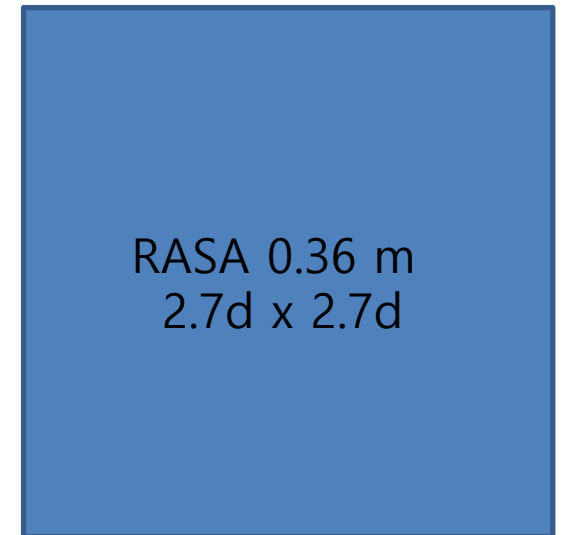
■ HST for comparison

Narrow-field

- SAO 1 m: 21' x 21'
- KHAO 0.8 m: 23' x 23'
- KHAO 0.4 m: 21' x 16'
- DOAO 1 m: 13' x 13'
- LSGT 0.4 m: 16' x 16'
- LOAO 1 m: 28' x 28'
- KCT 0.4 m: 24' x 18'



CBNUO 0.6 m
1.2d x 1.2d

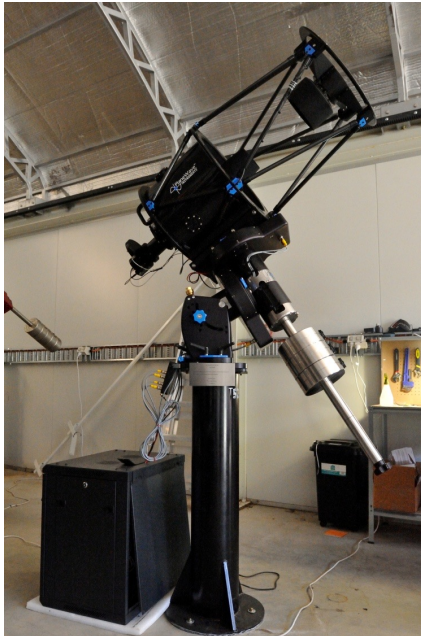


Wide-field



Observing strategy

- Targeted observation of nearby galaxies with ~ 10 narrow-field telescopes (e.g., LSGT), IMSNG
- Wide field imaging with a 0.25m telescope WIT-0 (FOV $\sim 5.5 \text{ deg}^2$)



Lee Sang Gak Telescope
(LSGT; 이상각 망원경)



Wide-field Imaging Telescope-0 (WIT-0)

Event Rate (2013 prediction)

Aasi, J. et al. 2013, arXiv:1304.0670v1

Epoch	Estimated Run Duration	$E_{\text{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg ²	20 deg ²
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

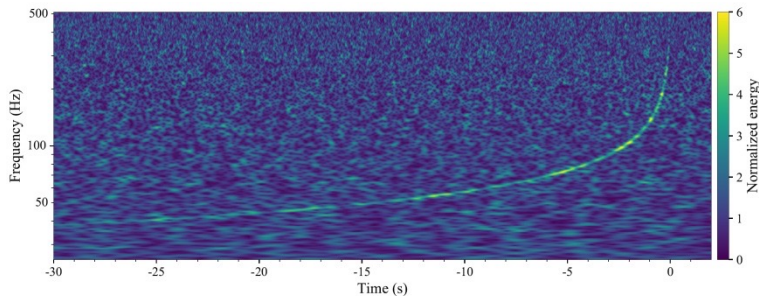
Epoch	Number of BNS Detection	
2015	0.03	
2016-2017	0.3	O2: 2016.11.30-2017.8.25
2017-2018	2	O3: 2018, Fall (9 months)
2019	6	

- Sooner or later, there will be a BNS merger event detection

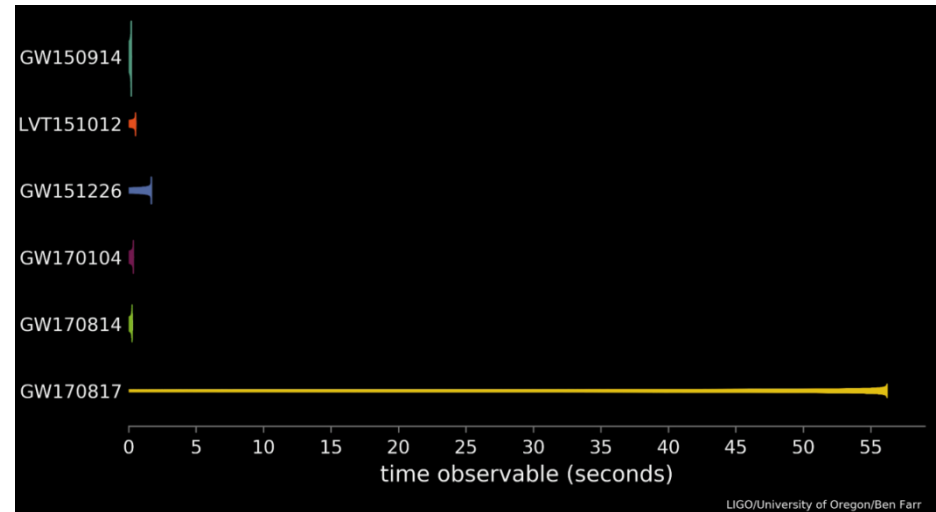


GW170817 detection

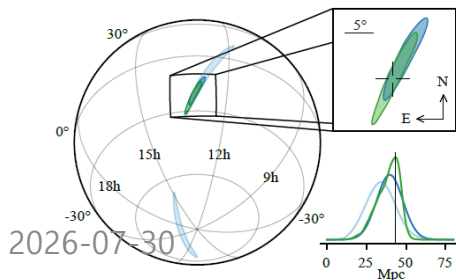
- 2017.08.17 21:41:04(KST) 라이고와 비르고 중력파 신호 관측
- 중성자별 선회단계에서 방출된 중력파의 최초 검출로 약 100초 지속
- 질량: 태양질량의 (1.36~1.60) 와 (1.17~1.36) 배. 총 질량은 ~2.74배
- 거리: ~40 Mpc(~1억3천만 광년), 천구상의 영역: 28 deg^2 이내
- 신호대잡음비(SNR): 32.4, 가짜 신호일 확률: 8만년당 하나 이하
- PRL(2017) 게재(한국중력파연구협력단 14명을 포함, 1100여명)



시간에 따른 주파수 변화



LIGO/University of Oregon/Ben Farr

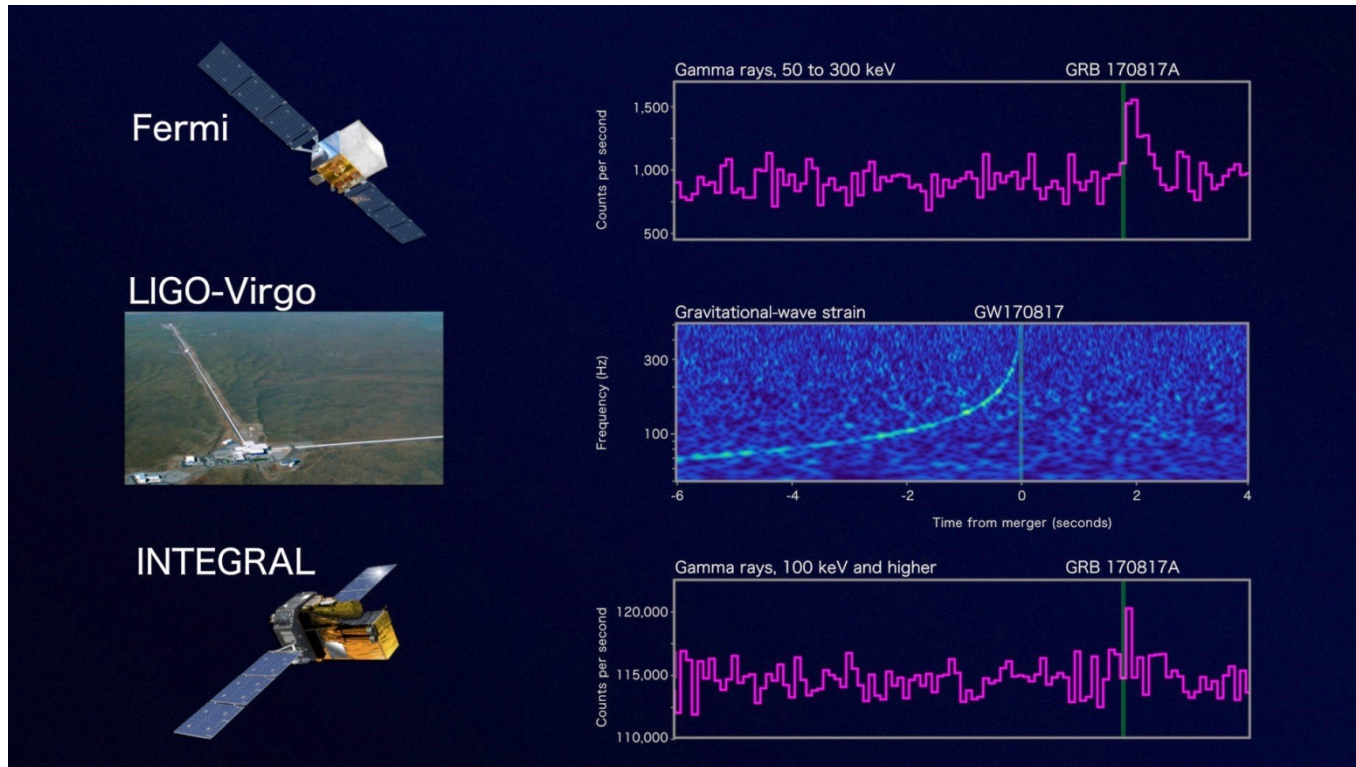


2026-07-30

중력파 파형 비교: 블랙홀 vs 중성자별
중력파원의 위치
2026 수치상대론 중력파 여름학교(전통)
그림출처: LIGO(라이고 협력단)

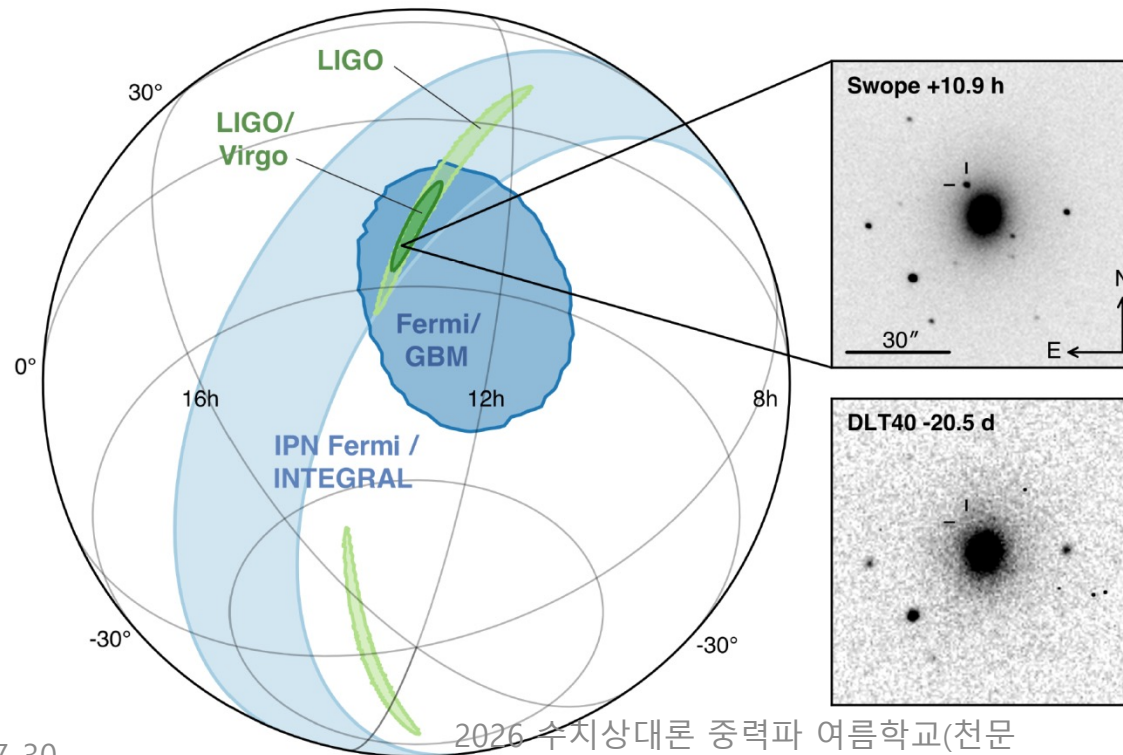
Short GRB detection (Fermi/INTEGRAL)

- Weak GRB 2 sec after GW detection, duration ~ 2 sec
- 10000x weak



Optical counterpart discovery

- 8 telescopes in Chile spotted GW counterpart at 11 hours after GW detection
- NGC 4993 at ~ 40 Mpc (RA:13h09m47s, Dec:-23d23m02s)



"MMA paper"
LIGO, Virgo,
Partner Astronomy Groups
2017, ApJL

Facilities for EM Follow-up

Korea:

SNUO 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**

Our first observation

- GW event 2hrs after SSO visibility
- No alert to KMTNet-SAAO/CTIO
- Observation started at SSO (LSGT, iTelescope), after discoveries at Chile telescopes



8월17일 초저녁
은하수 위치

NGC 4993

E

W

sasse



First Korean Observation

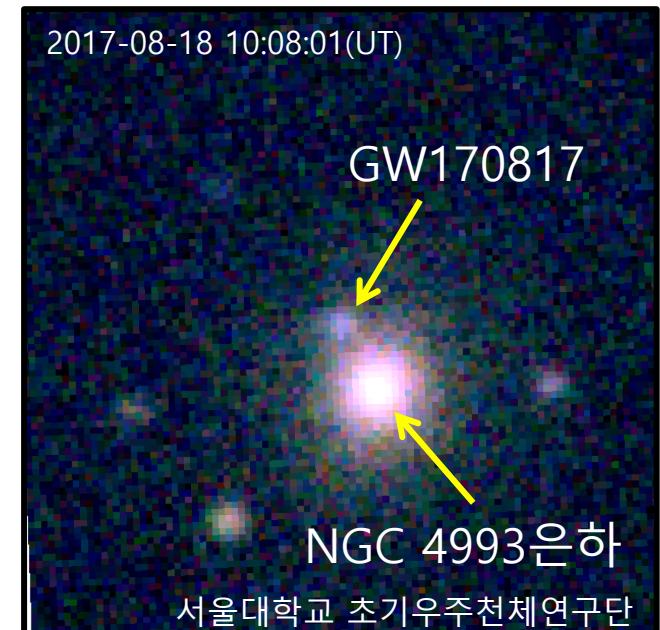
- At 2017-8-18, about 21 hours after the GW detection, the GW EM counterpart was detected by LSGT (0.43m telescope!)



이상각 망원경(호주 사이딩 스피링 천문대)

2026-07-30

2026 수치상대론 중력파 여름학교(천문
연구원)

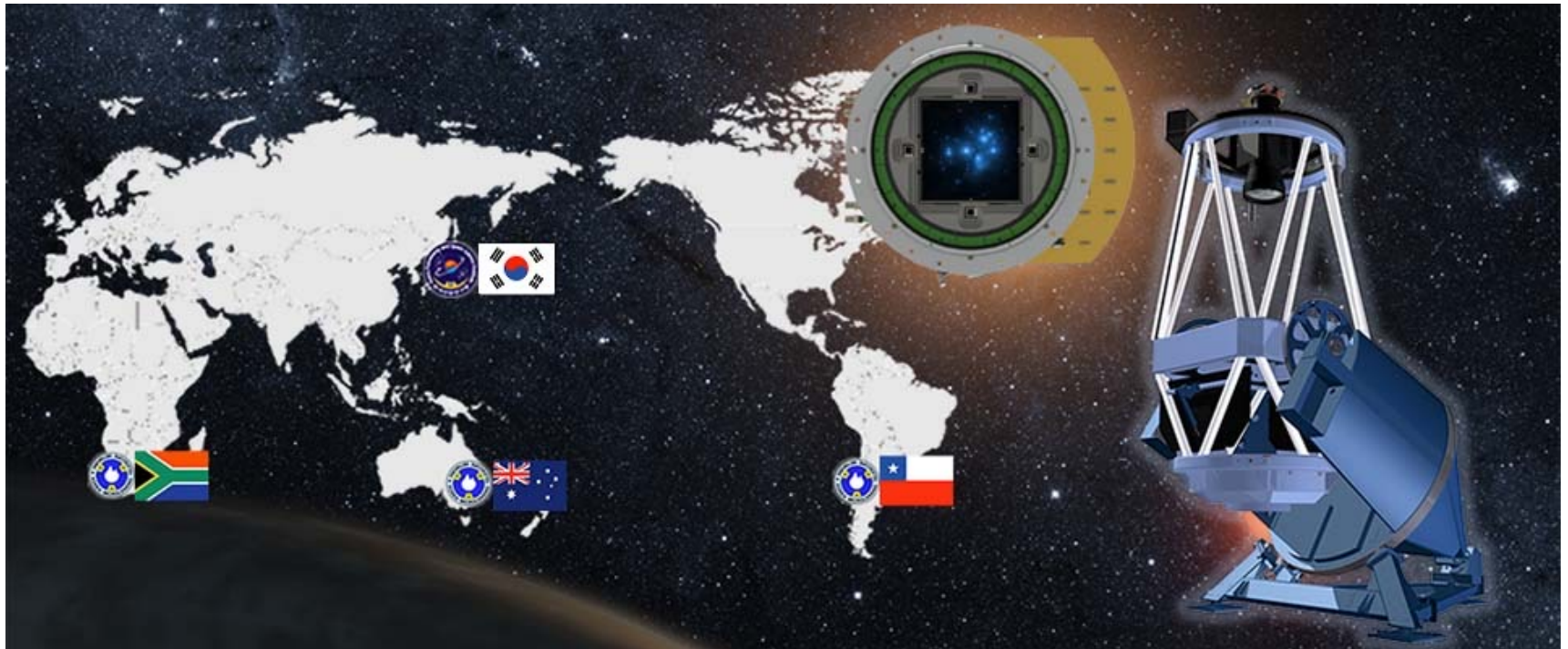


이상각 망원경이 포착한
GW170817의 가시광선 신호
(사이딩 스프링 천문대)

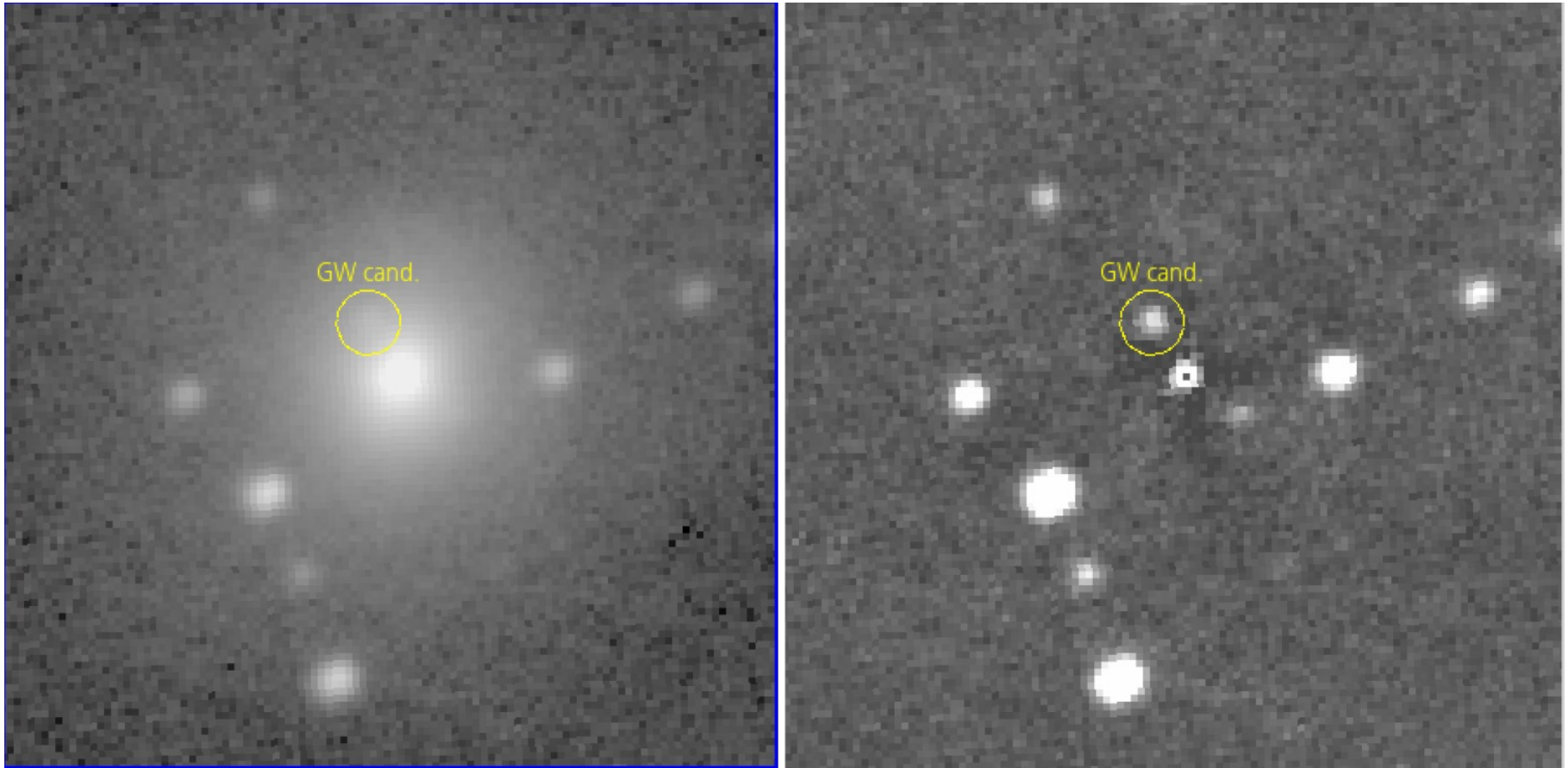


KMTNet Follow-up Observation

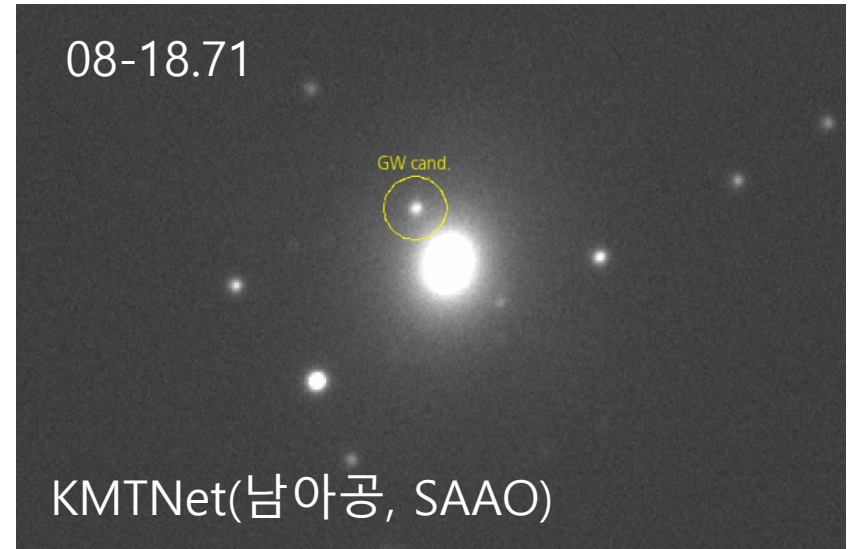
- Korea Microlensing Telescope Network: Three 1.6m telescopes at Southern Hemisphere (exoplanet microlensing)
- KMTNet SAO telescope started the observation at about 28 hours after the GW detection
- Observations continued till Sept. 9 (B,V,R,I)



Host galaxy subtraction (T31, R-band, 08-19.36)



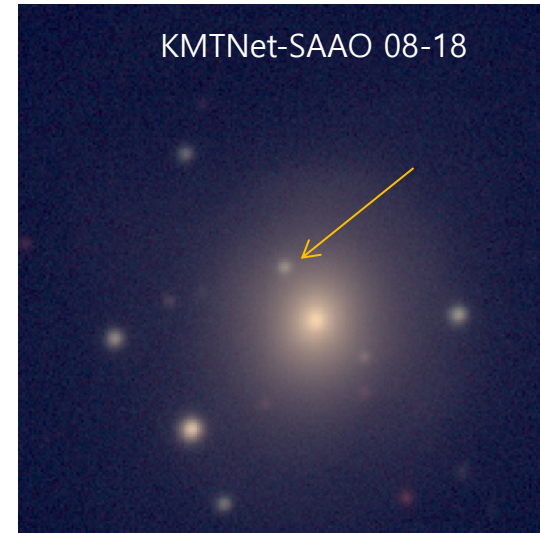
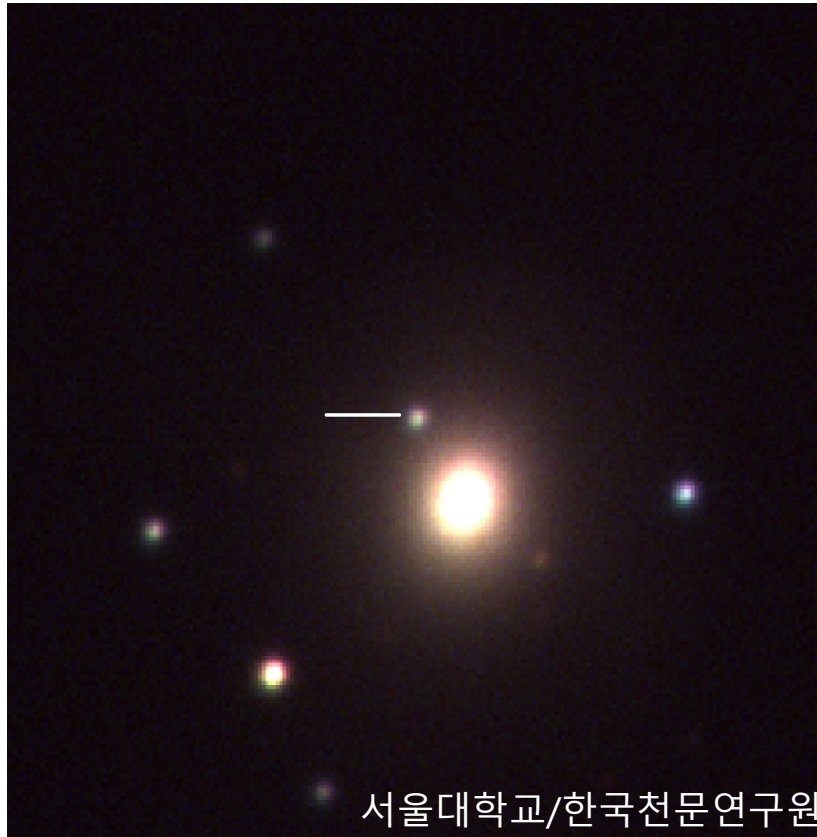
GW 170817 Optical Counterpart (B-band)



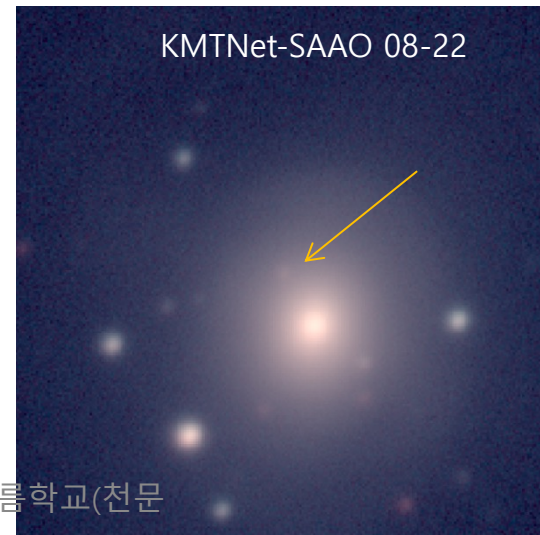


KMTNet image of GW170817

Evolution of optical counterpart



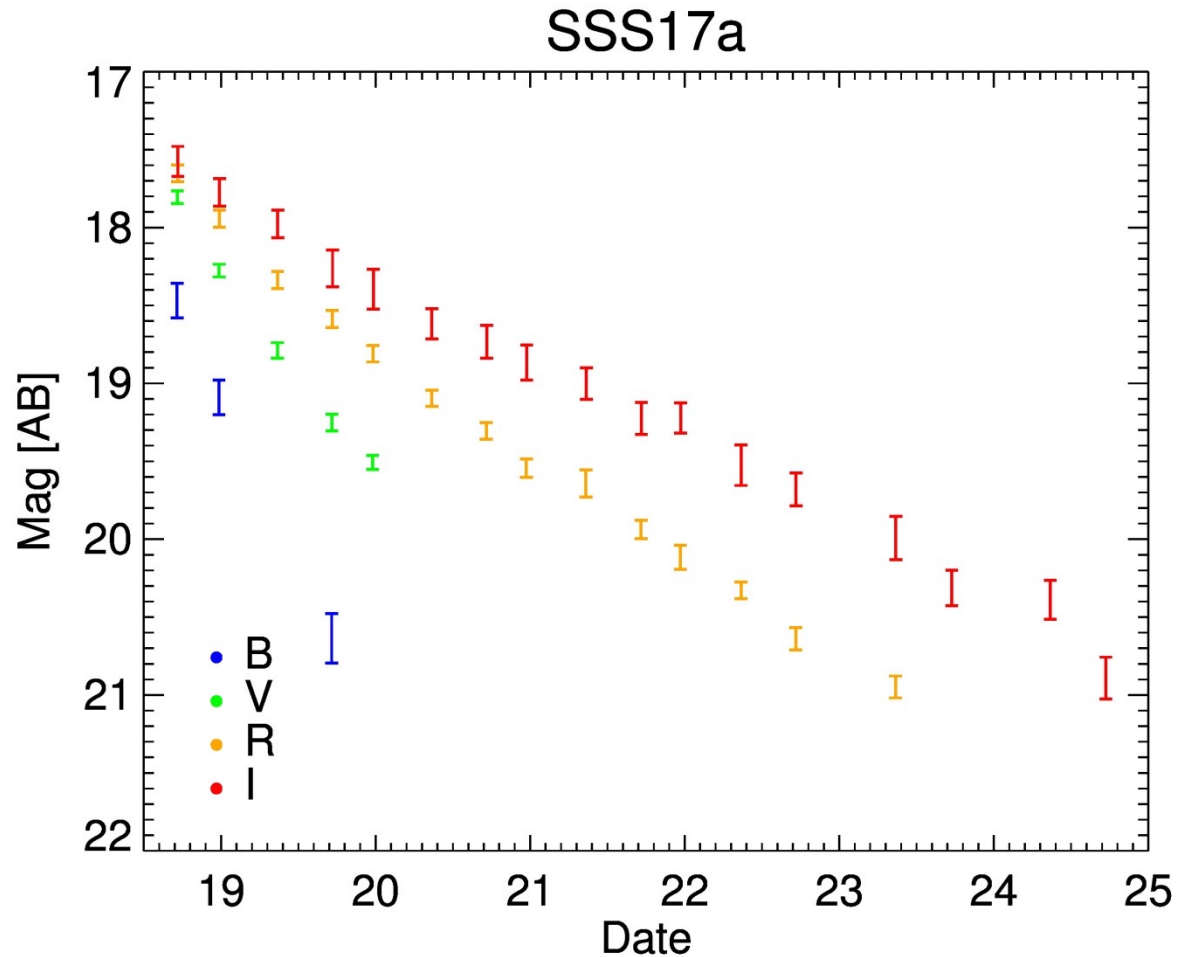
Early
Bright
+
Blue



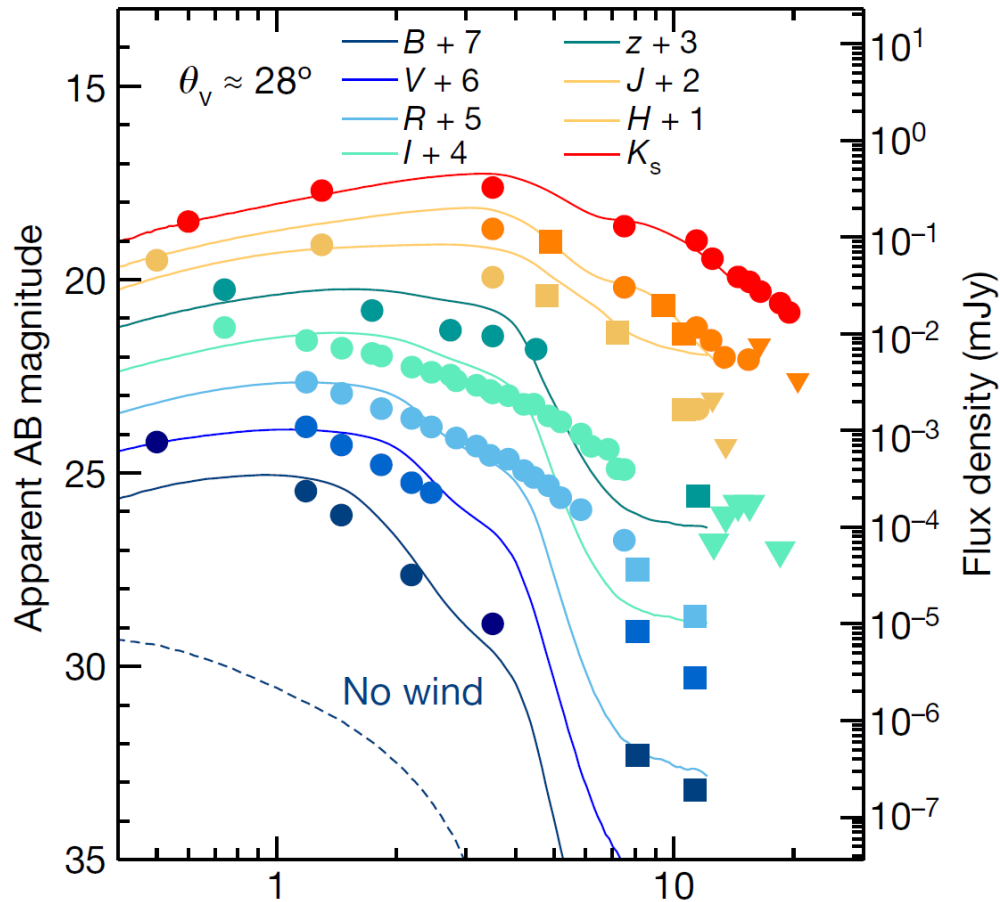
Later
Faint
+
Red

KMTNet light curve of GW170817

(J Kim, SL Kim, CU Lee)



Comparison with Kilonova model



- $M_{ej} \sim 0.01 \text{ Msun}$
- Wind model

➡ Kilonova!

Troja et al. (2017)

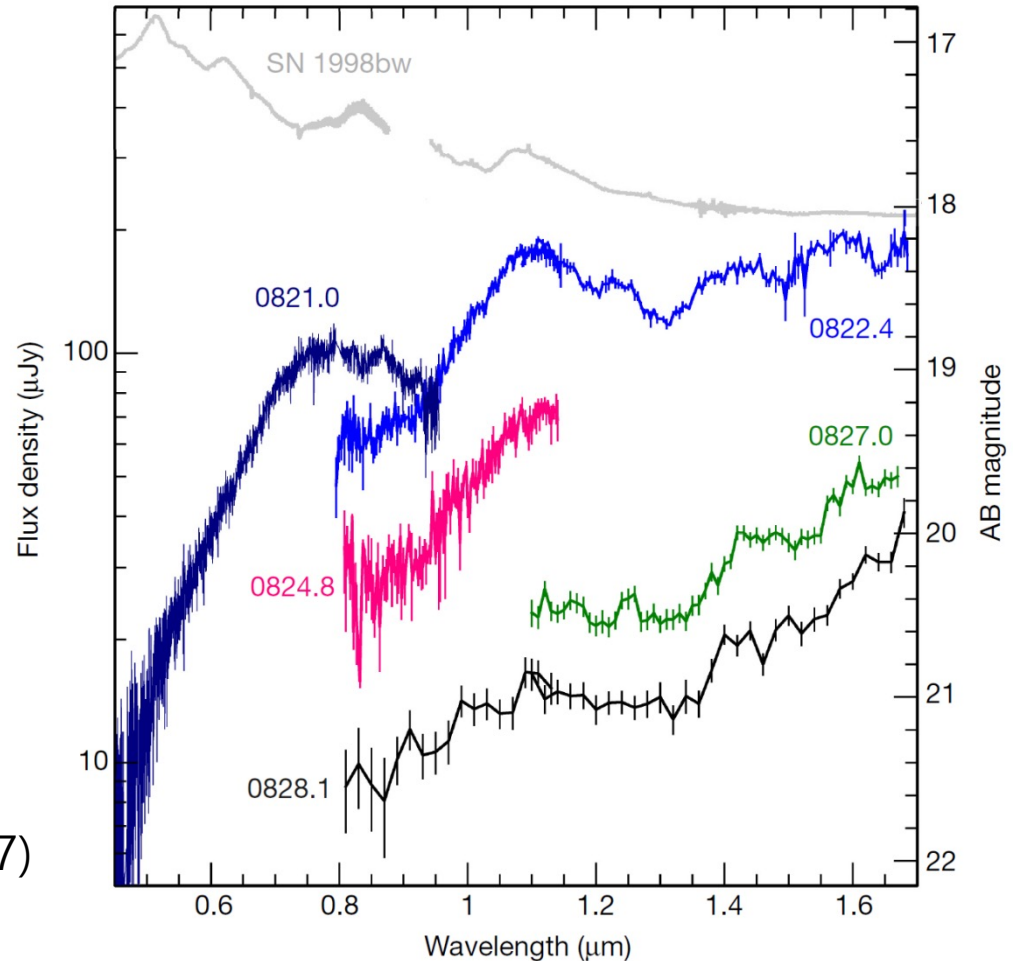
Spectral evolution

- Gemini spectra at +3 days
- Spectral features → very different from SNe
- Similar to kilonova predictions



Kilonova!

Troja et al. (2017)





Kilonova nature + X-ray detection

- X-ray counterpart → Connection with short GRB
- Optical observation → Kilonova nature
- Troja et al. 2017, Nature(총저자 34명, 임명신, 이형목, 김승리, 이충욱 등 서울대학교, 천문연구원 등 국내연구진 9명 참여, 주요저자: 임명신, 이성국)

LETTER

doi:10.1038/nature24290

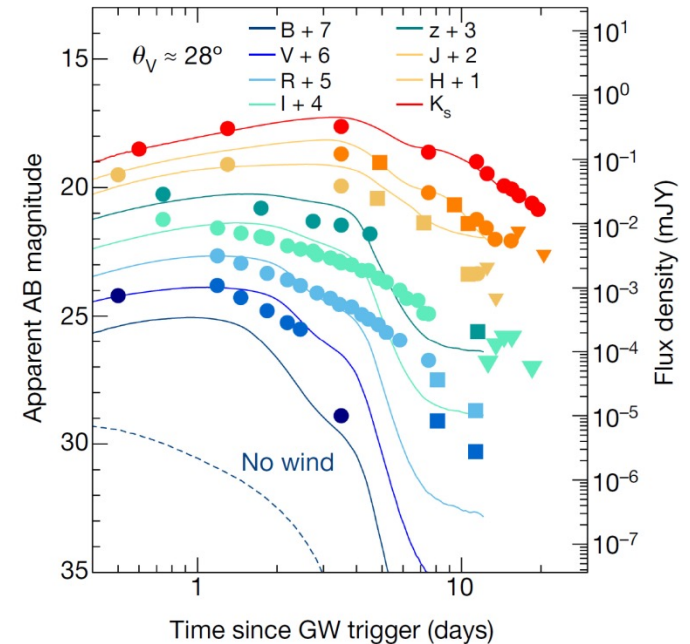
The X-ray counterpart to the gravitational-wave event GW170817

E. Troja^{1,2}, L. Piro³, H. van Eerten⁴, R. T. Wollaeger⁵, M. Im⁶, O. D. Fox⁷, N. R. Butler⁸, S. B. Cenko^{2,9}, T. Sakamoto¹⁰, C. L. Fryer⁵, R. Ricci¹¹, A. Lien^{2,12}, R. E. Ryan Jr⁷, O. Korobkin⁵, S.-K. Lee⁶, J. M. Burgess¹³, W. H. Lee¹⁴, A. M. Watson¹⁴, C. Choi⁶, S. Covino¹⁵, P. D'Avanzo¹⁵, C. J. Fontes⁵, J. Becerra González^{16,17}, H. G. Khandrika⁷, J. Kim⁶, S.-L. Kim¹⁸, C.-U. Lee¹⁸, H. M. Lee¹⁹, A. Kutryk^{1,2}, G. Lim⁶, R. Sánchez-Ramírez³, S. Veilleux^{1,9}, M. H. Wieringa²⁰ & Y. Yoon⁶

A long-standing paradigm in astrophysics is that collisions—or mergers—of two neutron stars form highly relativistic and collimated outflows (jets) that power γ -ray bursts of short (less than 2 seconds) duration^{1–3}. The observational support for this model, however, is only indirect^{4,5}. A hitherto outstanding prediction is that gravitational-wave events from such mergers should be associated with γ -ray bursts, and that a majority of these bursts should be seen off-axis, that is, they should point away from Earth^{6,7}. Here we report the discovery observations of the X-ray counterpart associated with the gravitational-wave event GW170817. Although the electromagnetic counterpart at optical and infrared frequencies

On 17 August 2017 at 12:41:04 Universal Time (UT; hereafter T_0), the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detected a gravitational-wave transient from the merger of two neutron stars at a distance¹² of 40 ± 8 Mpc. Approximately two seconds later, a weak γ -ray burst (GRB) of short duration (< 2 s) was observed by the Fermi Gamma-ray Space Telescope¹³ and INTEGRAL¹⁴. The low luminosity of this γ -ray transient was unusual compared to the population of short GRBs at cosmological distances¹⁵, and its physical connection with the gravitational-wave event remained unclear.

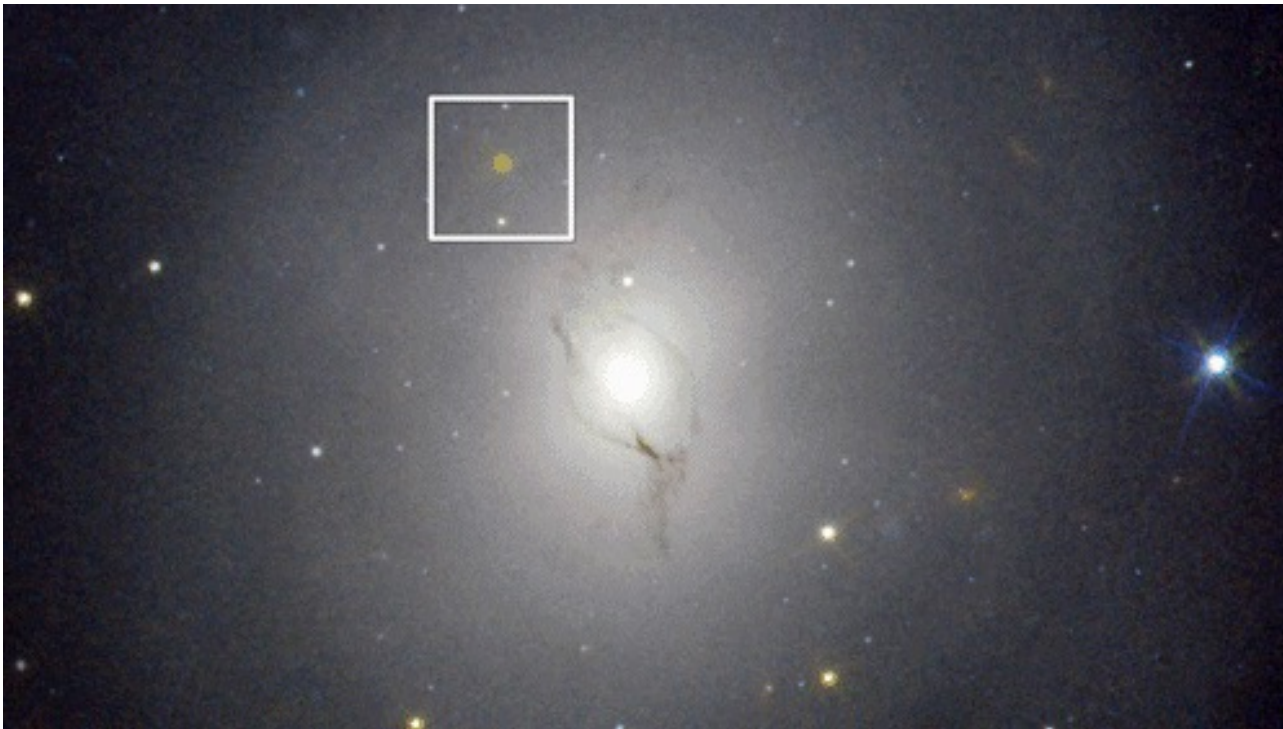
A vigorous observing campaign targeted the localization region of the gravitational-wave transient, and rapidly identified a source of



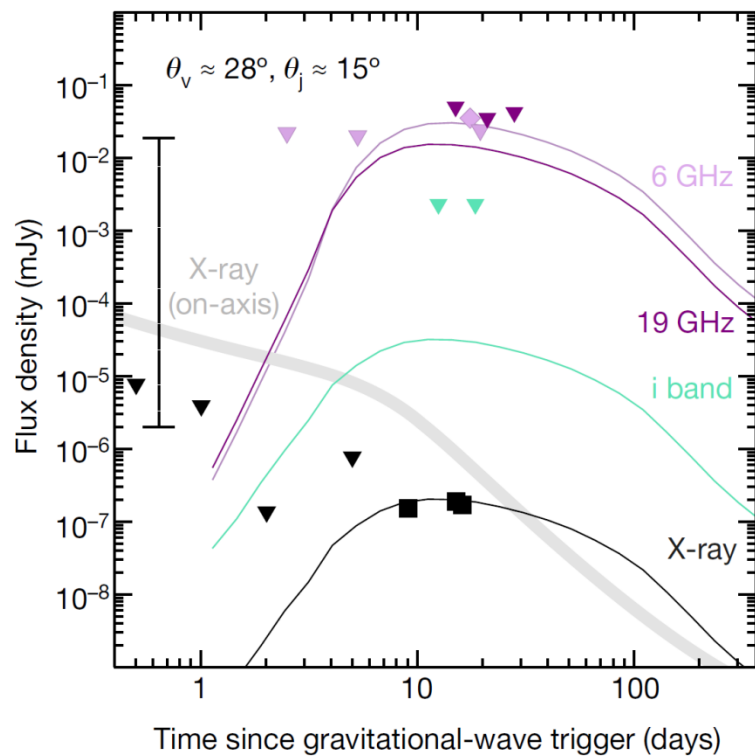


X-ray detection

- Chandra X-ray observation detection 9 days after GW detection

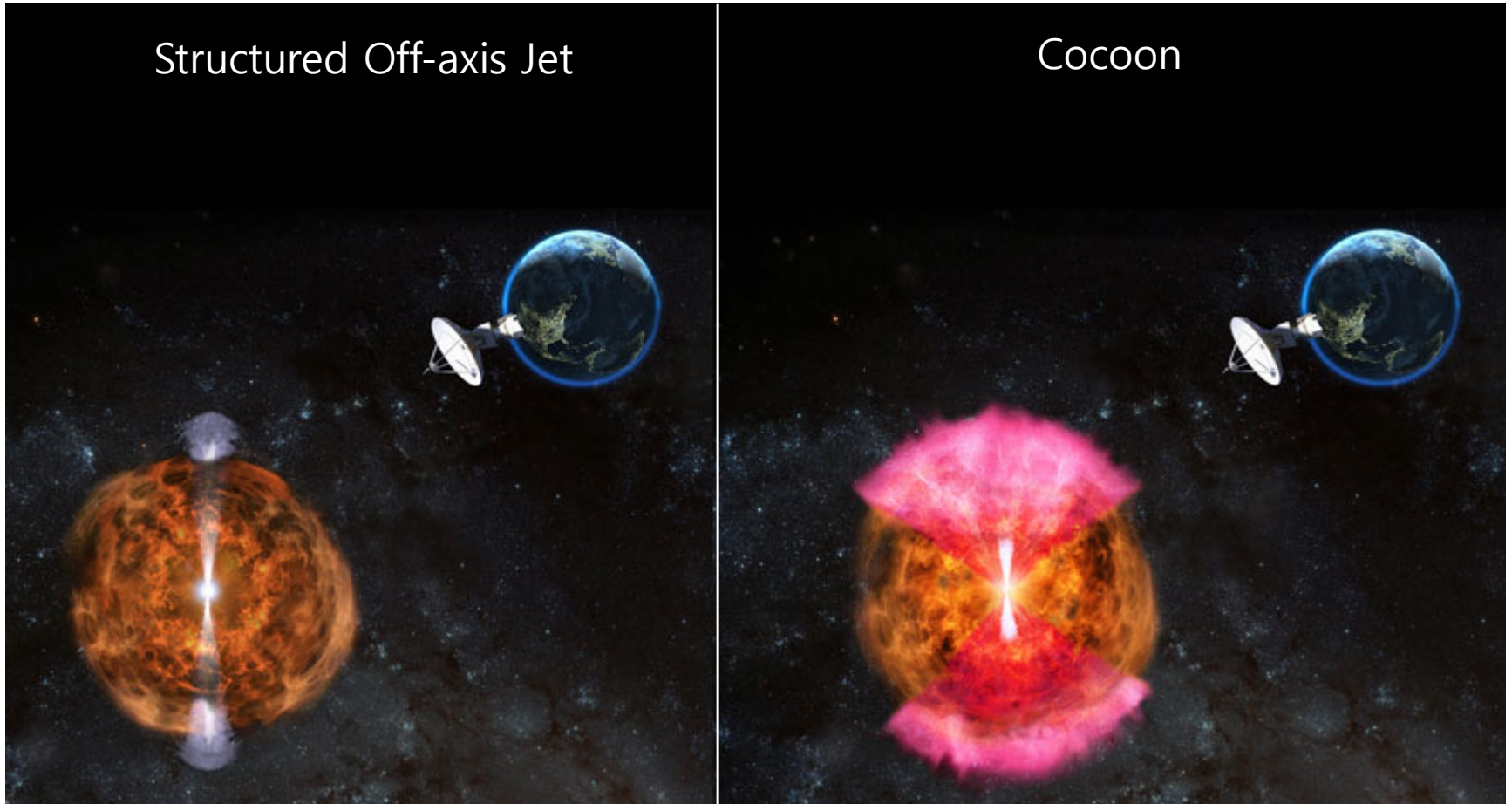


Weak gamma-ray emission + Delayed X-ray/radio emission



- Weak GRB by x10000
- 9 days, 16 days delay until X-ray/radio onset

Off-axis jet or Cocoon model?

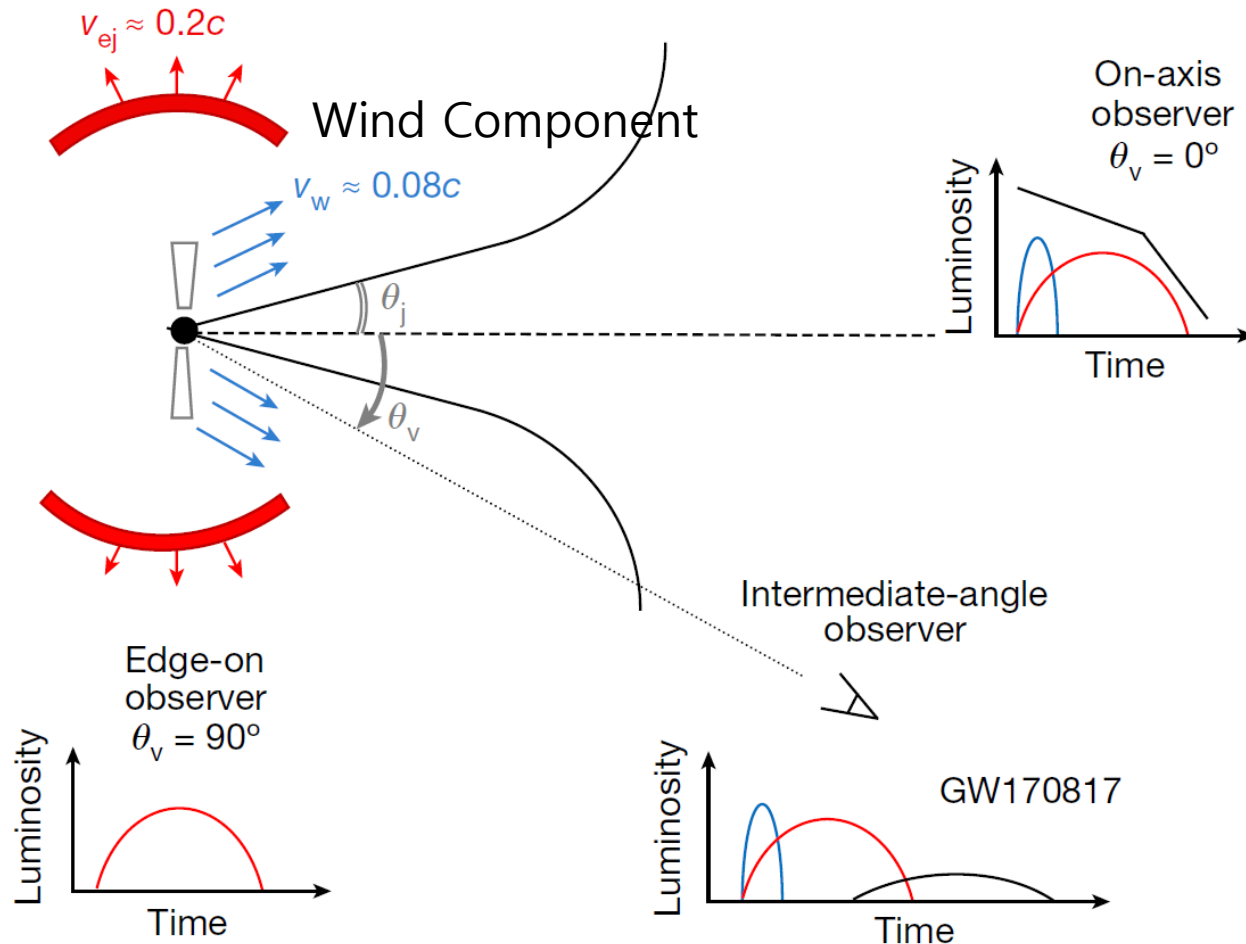


Credit: NRAO/AUI/NSF/D. Berry

GW170817 model 1

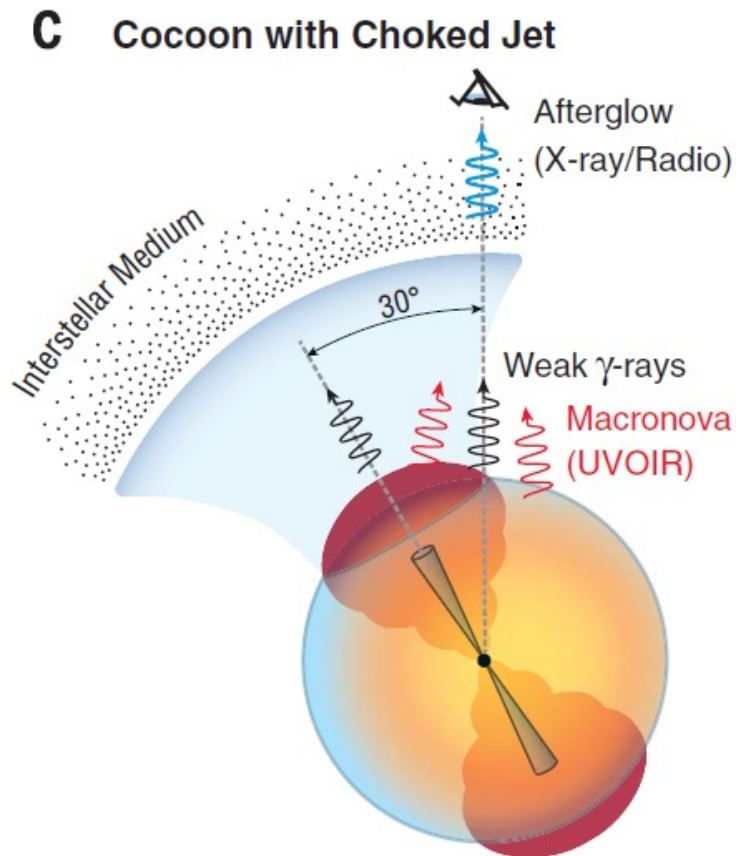
Off-axis short GRB

Ejecta Component



GW170817 model 2

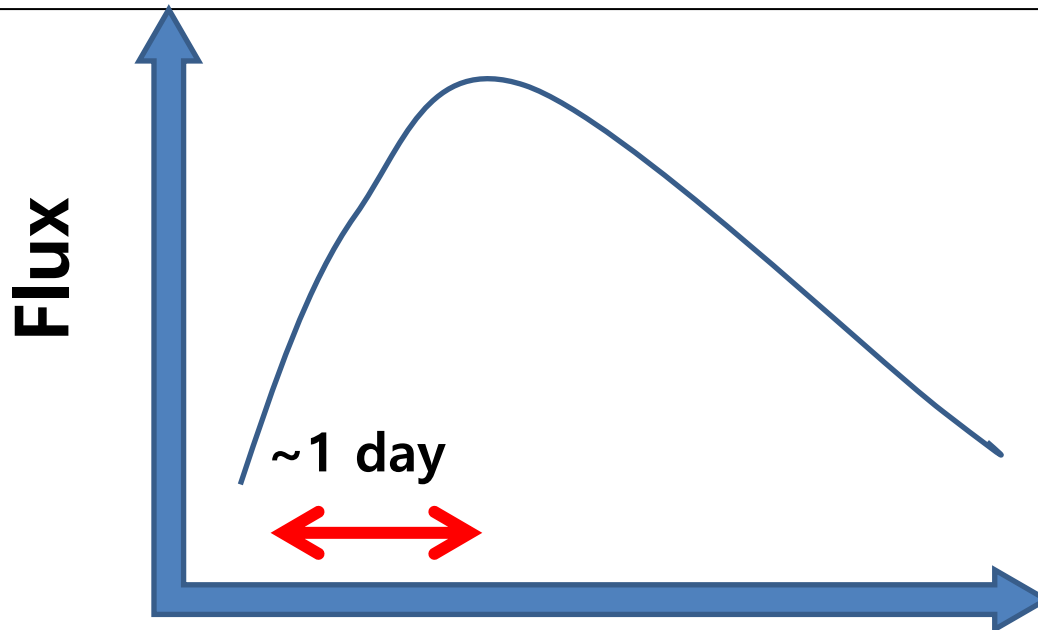
Cocoon model



Radioactive emission

- ~1 day rise time (thermalize + go through expanding ejecta)

$$t_{\text{rise}} \approx 1.6 \text{ day} \left(\frac{M}{10^{-2} M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2} \left(\frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2}$$



Timescale for t_{peak}

$$\tau \simeq \rho \kappa R = \frac{3M\kappa}{4\pi R^2} \simeq 70 \left(\frac{M}{10^{-2}M_{\odot}} \right) \left(\frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}} \right) \left(\frac{v}{0.1c} \right)^{-2} \left(\frac{t}{1 \text{ day}} \right)^{-2}$$

$$t_{\text{diff}} \simeq \frac{R}{c} \tau = \frac{3M\kappa}{4\pi c R} = \frac{3M\kappa}{4\pi c v t},$$

$$t_{\text{peak}} \equiv \left(\frac{3M\kappa}{4\pi \beta v c} \right)^{1/2} \approx 1.6 \text{ d} \left(\frac{M}{10^{-2}M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2} \left(\frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2},$$

Merger ejecta with

M: total mass, v: expansion velocity, $R = v \cdot t$: radius after t

κ : opacity (cross section per unit mass) $1 - 100 \text{ g cm}^{-2}$

β : density profile factor (~ 3)

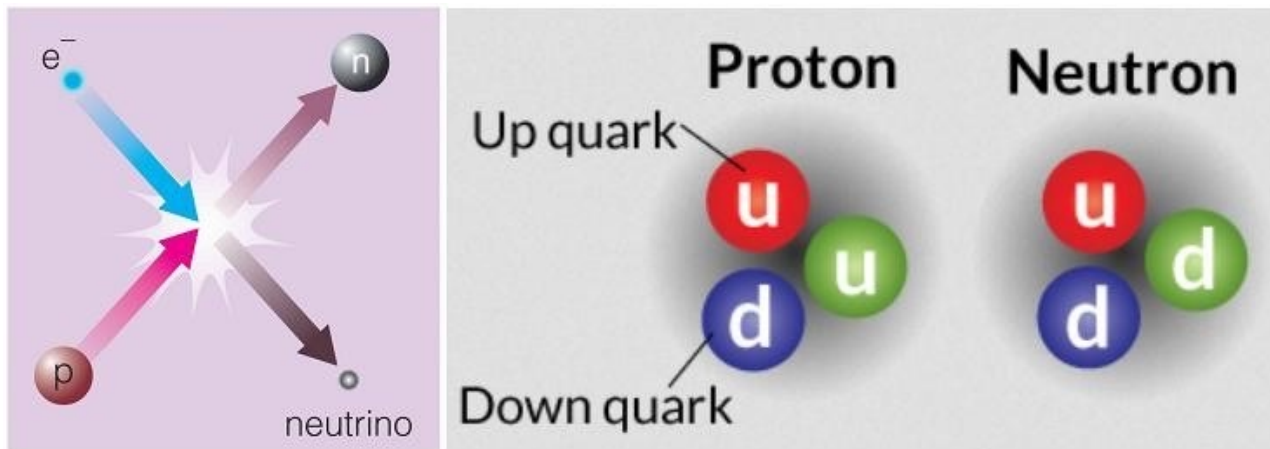
Shock-cooling

- Almost instantaneous



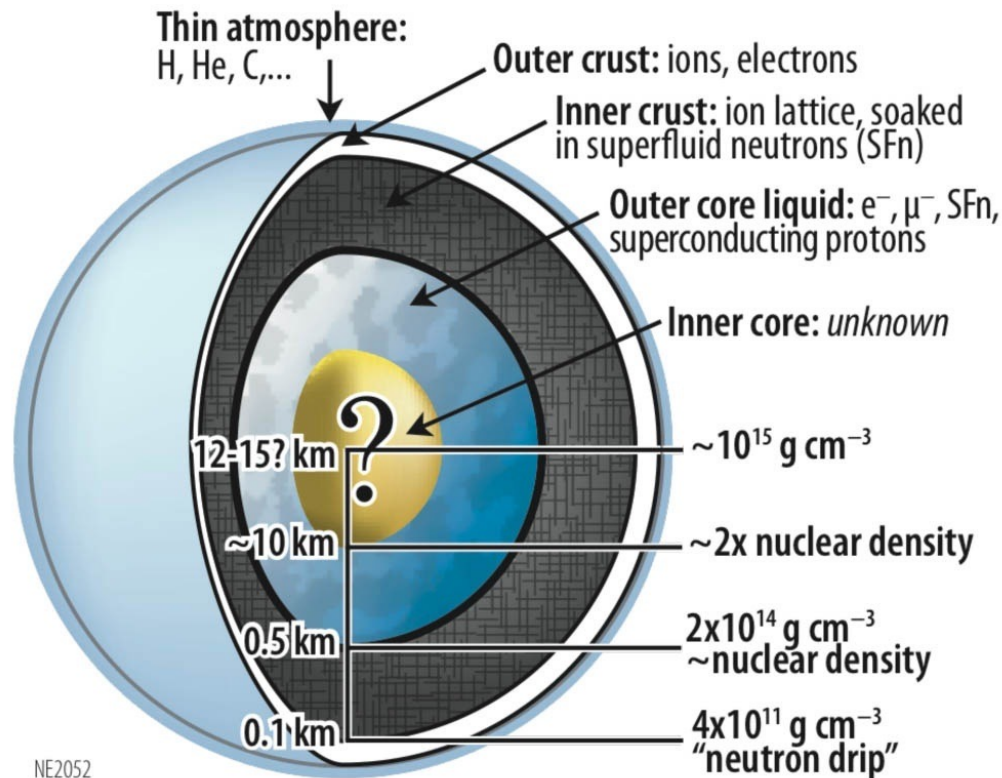
Neutron star formation

- Collapse of the iron core → neutron star
- Inverse Beta decay → neutrinos!



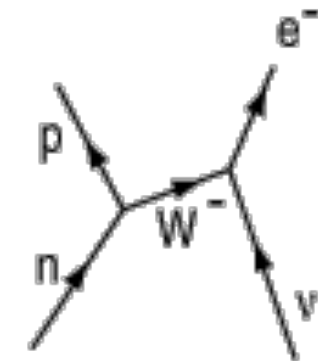
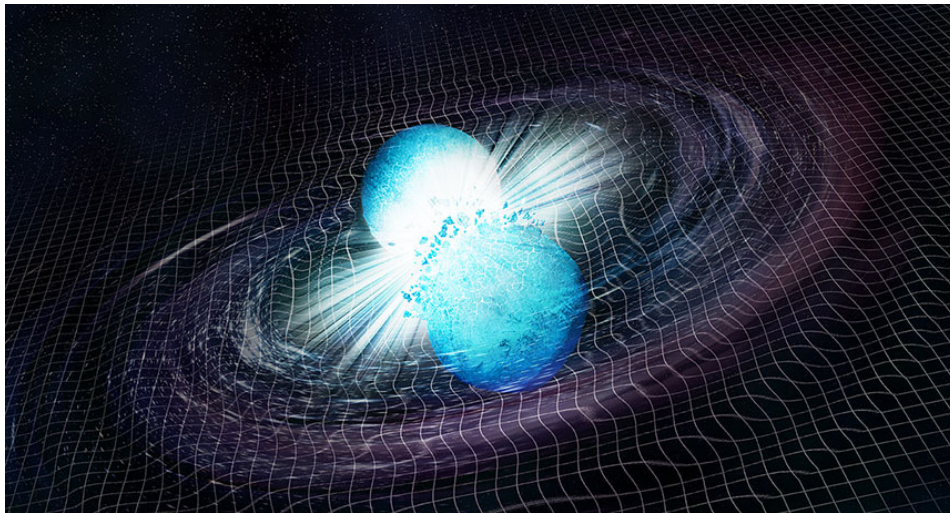
Inside neutron star

- Neutron : Proton ratio = 5:4 ?
- Anyway, still a lot of protons/electrons inside



When two NSs collide

- A lot of neutrino irradiation occur
- If NS is long-lived and ejecta are subject to intense neutrino radiation, then neutrinos interact with neutrons and convert them to protons and electrons

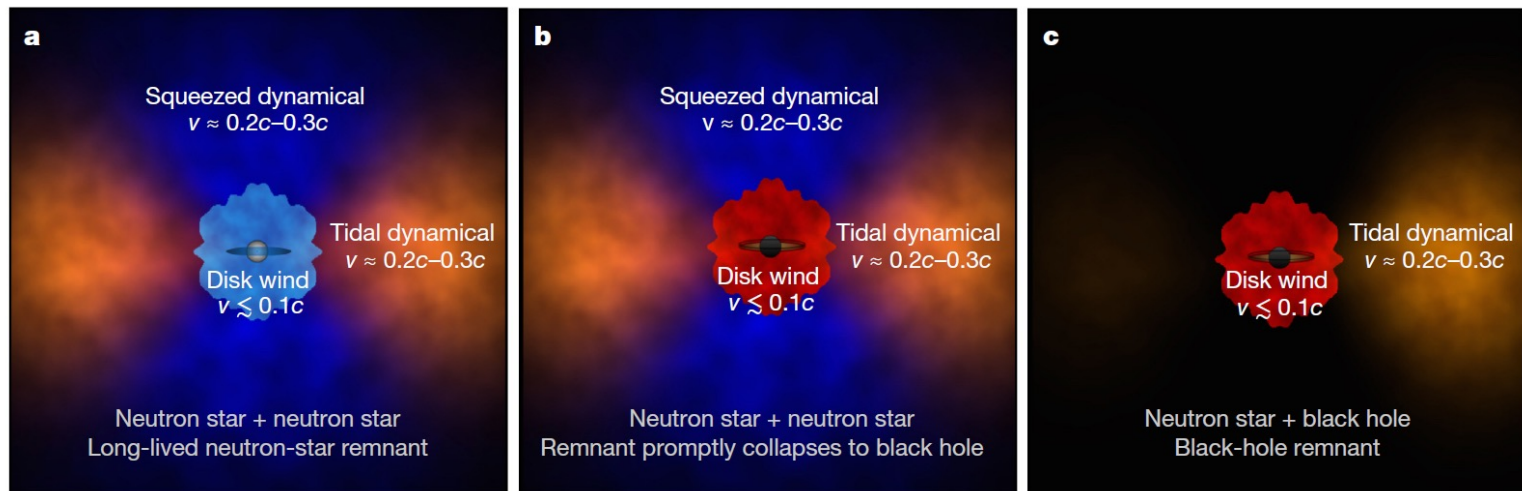


Neutrino interacts
with neutron

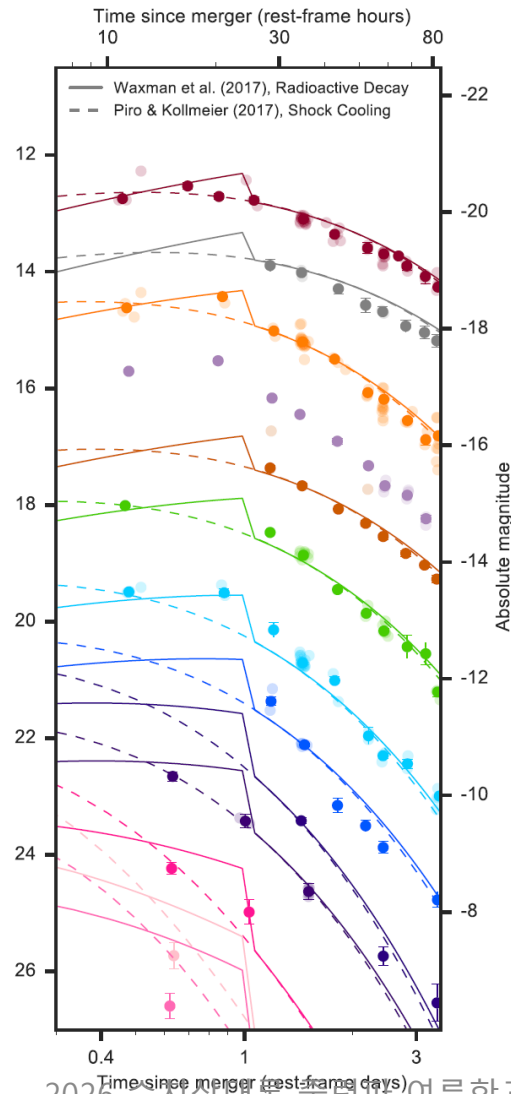
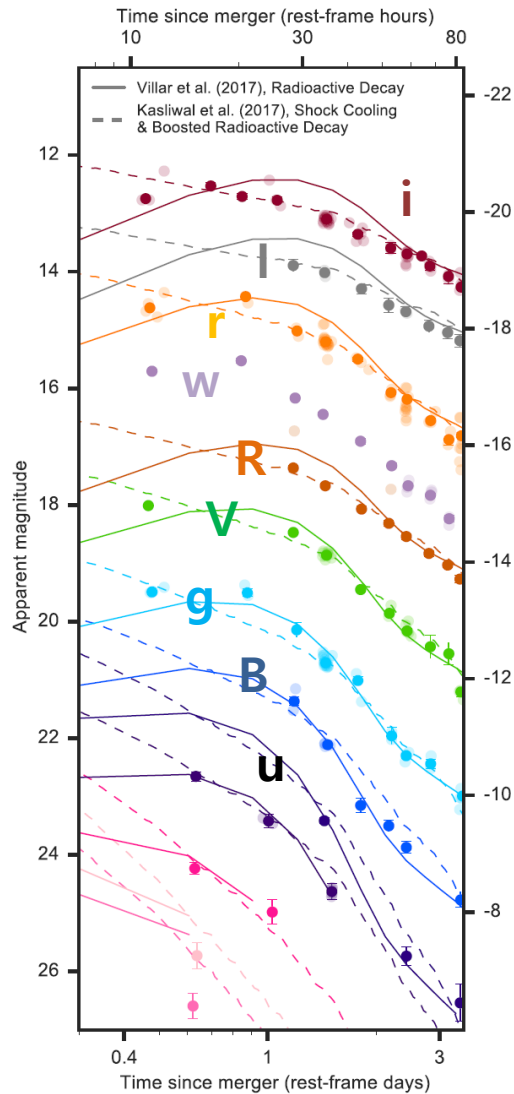


When two NSs collide

- Then, the newly made neutrinos reduce the number of neutrons necessary for r-process to occur: this happens in the wind component
- Less production of lanthanides $\rightarrow$ blue kilonova



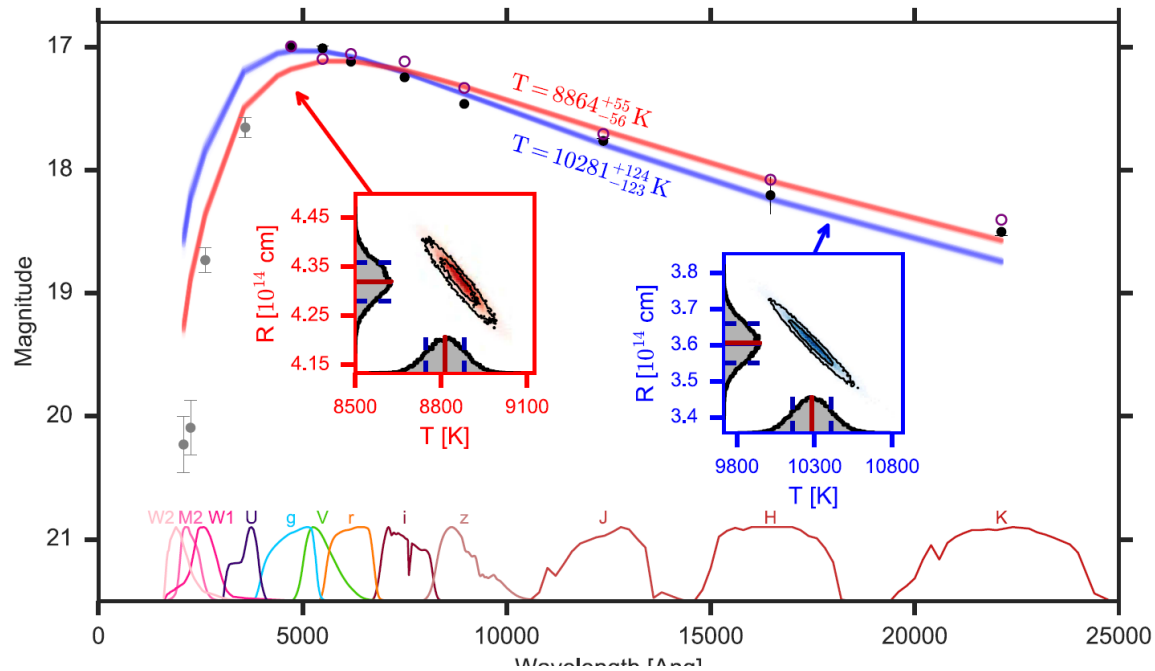
Comparison with data



Radioactive decay models
- Slowly rising curve
at $t < 1\text{day}$

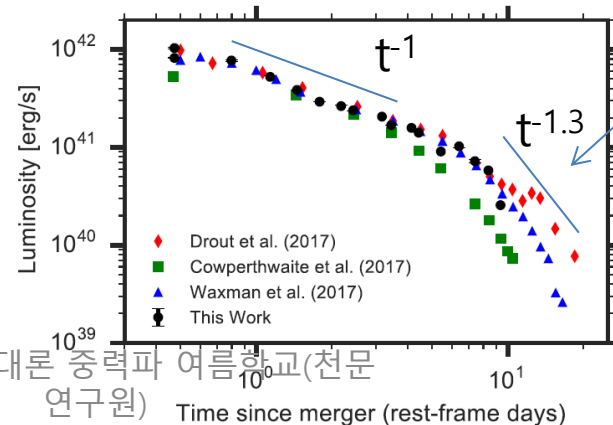
Shock-heated models
- Steadily decaying curve
at $t < 1\text{day}$

BB-fitting + Bolometric luminosity



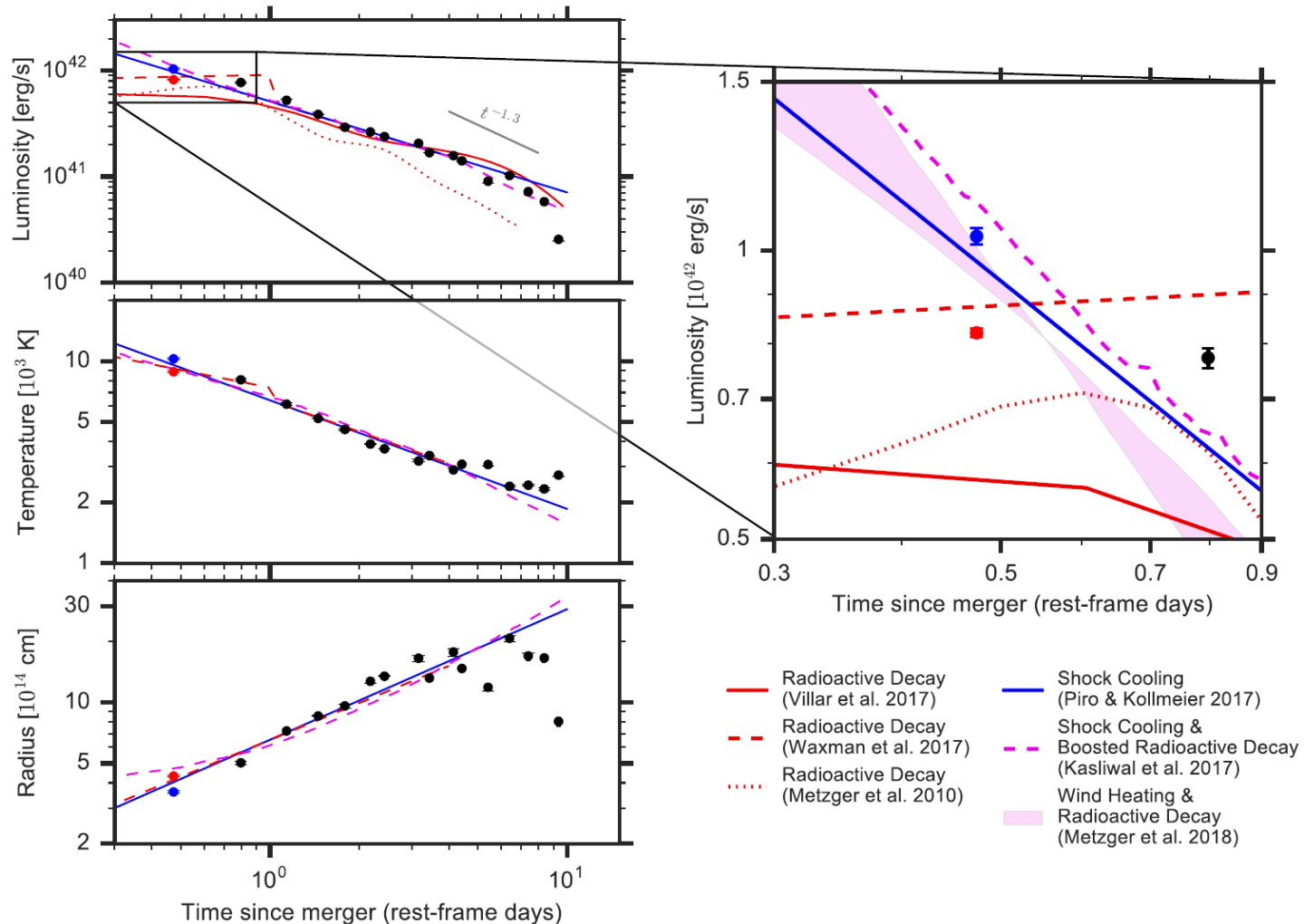
$$E = \sigma T^4$$

$$L \sim R^2 T^4$$



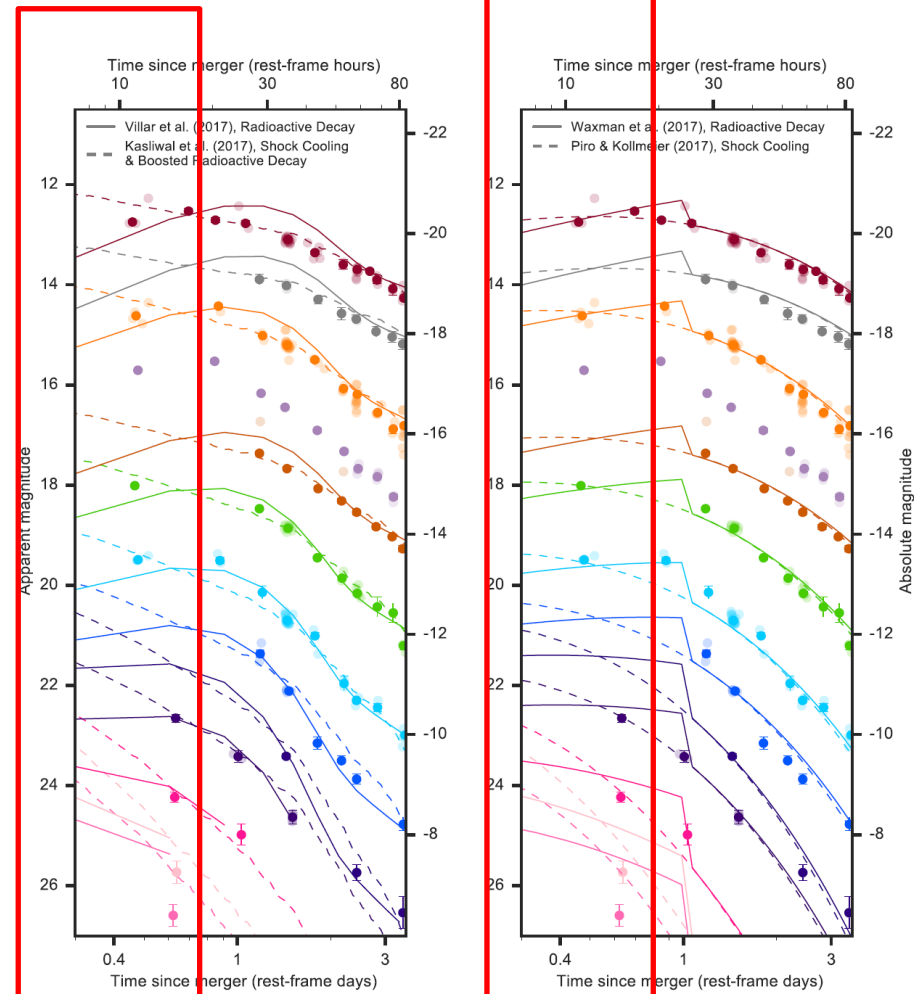
~ radioactive heating rate

Constraints from bolometric luminosity curve: Ambiguous due to lack of early UV points



Implications

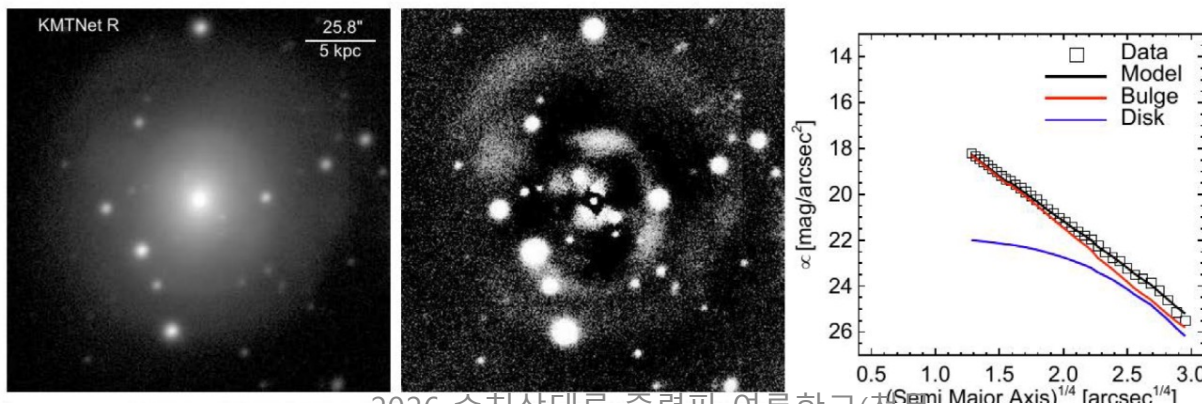
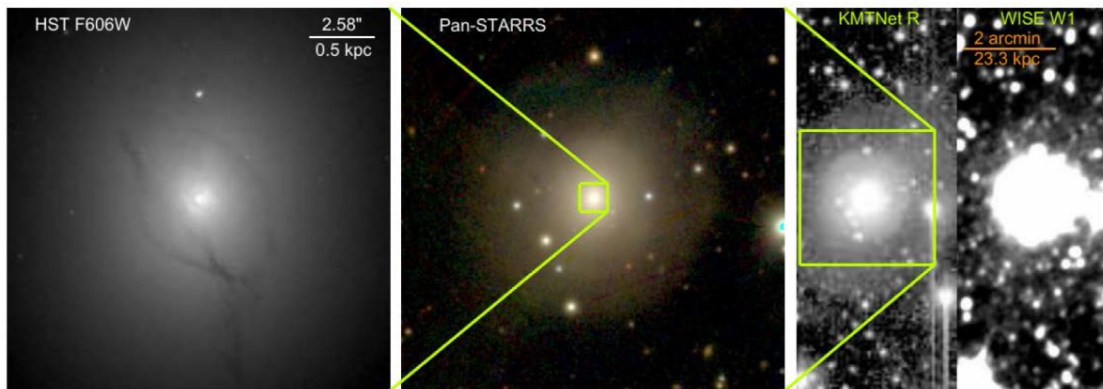
- GW170817: unclear which model is correct
- Early optical signal → Important test of the kilonova emission mechanism





GW170817 host galaxy

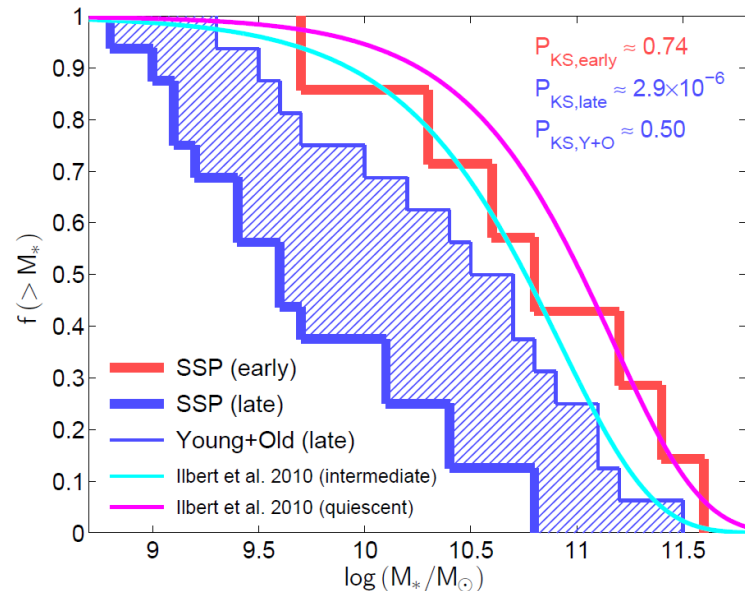
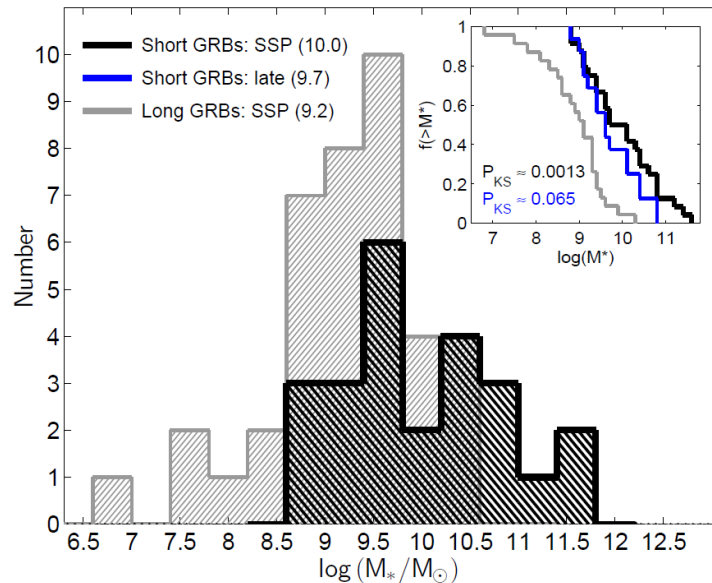
- KMTNet, LSGT, HST
- Distance and properties of NGC 4993 as host galaxy of a gravitational wave source, GW 170817", 2017, **ApJL**, (총저자 12명, 임명신, 윤용민, 이성국, 이형목, 김준호, 이충욱(천문연), 김승리(천문연), E. Troja(NASA/Goddard,U Maryland), 최창수, 임구, 고종완, 심현진)



Im et al. (2017)
ApJL in press
(Oct. 3, submitted
Oct. 13, accepted)

NS-NS Merger Host Galaxy

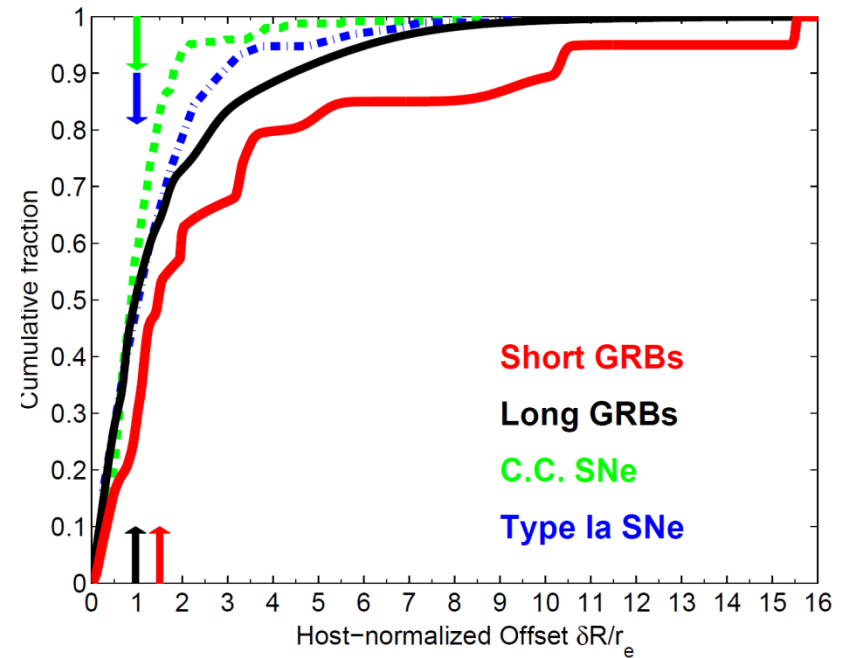
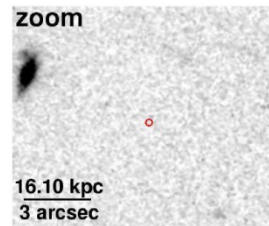
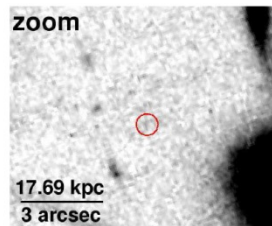
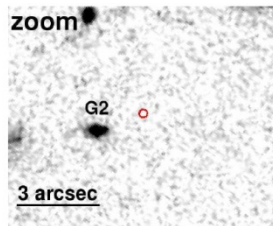
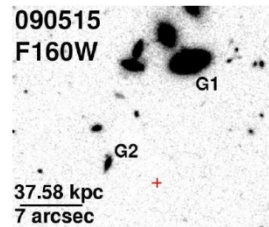
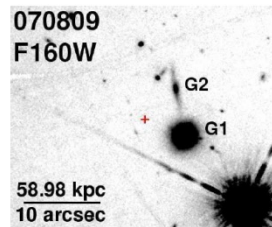
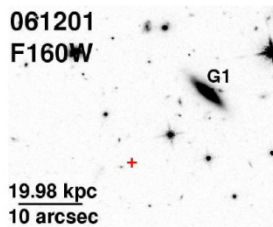
- It should have properties similar to short GRB host galaxy
- $M_* \sim 10^{8.5-11.8} M_\odot$
- $10 \text{ Myr} < \text{Age} < 5 \text{ Gyr}$
- $0 < SFR \left(\frac{M_\odot}{\text{yr}} \right) < 10$



Berger (2013) and references therein
2026 우리대학은 중학의 이름학교(인문
연구원)

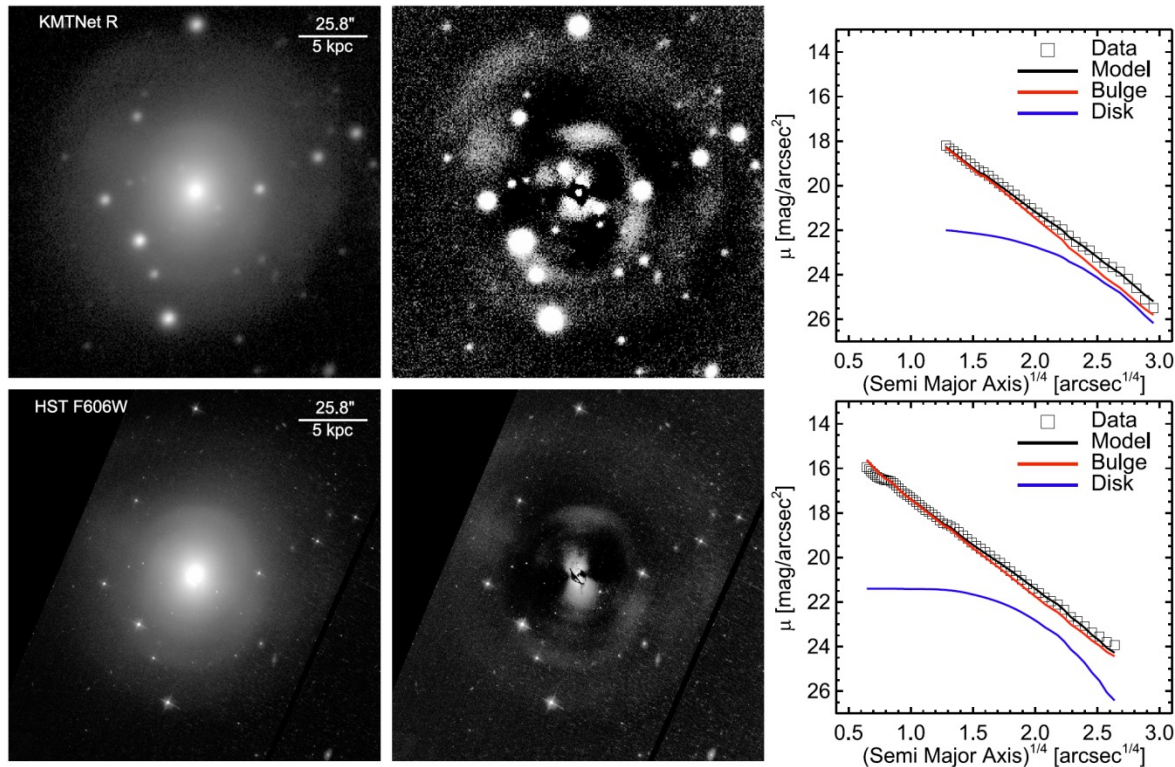
Short GRB location

Berger (2013)



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

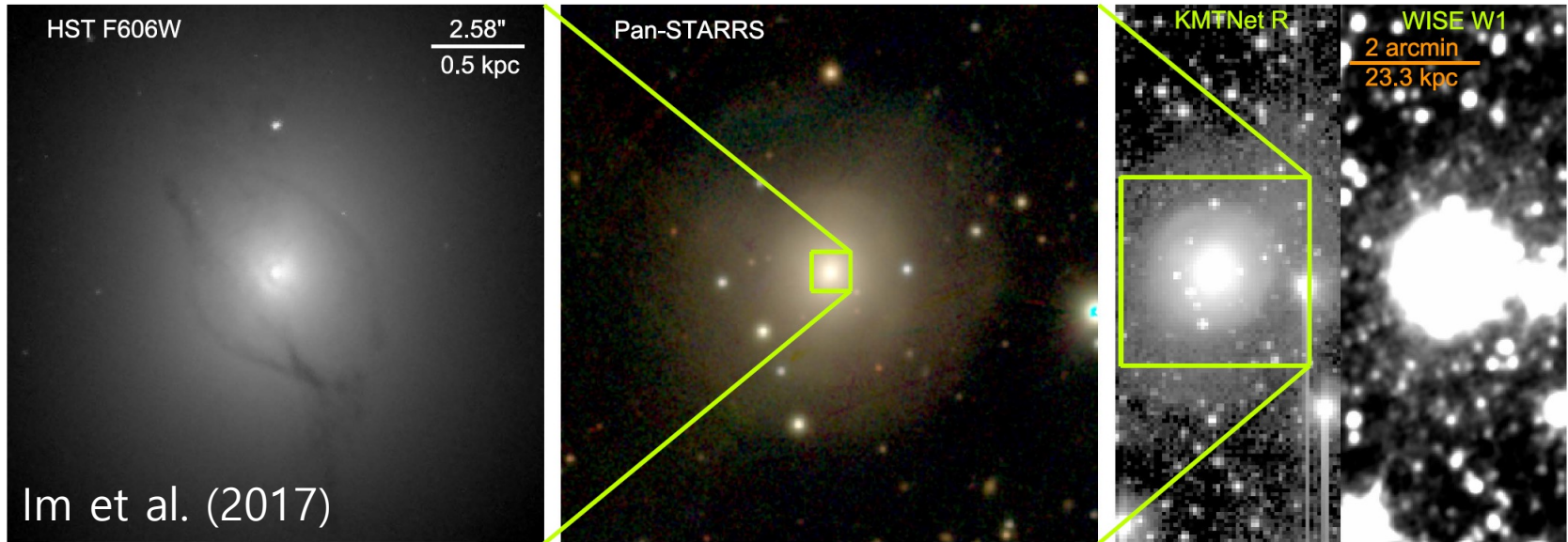
NGC 4993 is $\sim E$ (Y Yoon)



Im et al. (2017)

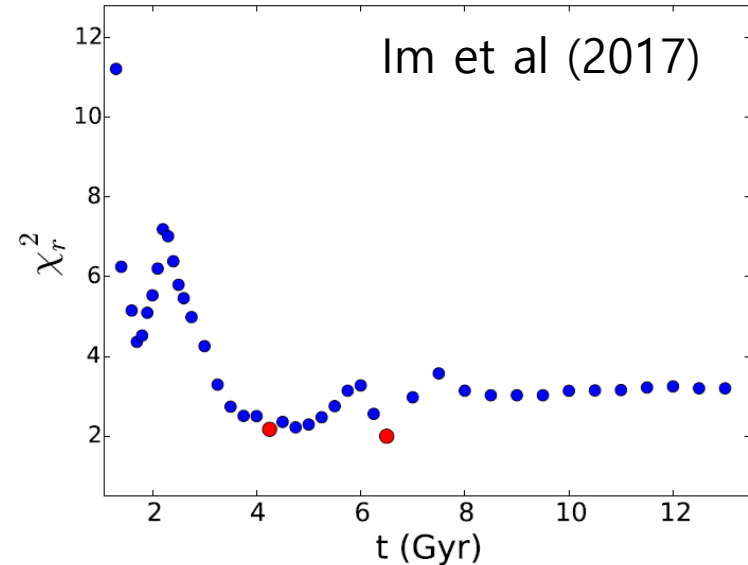
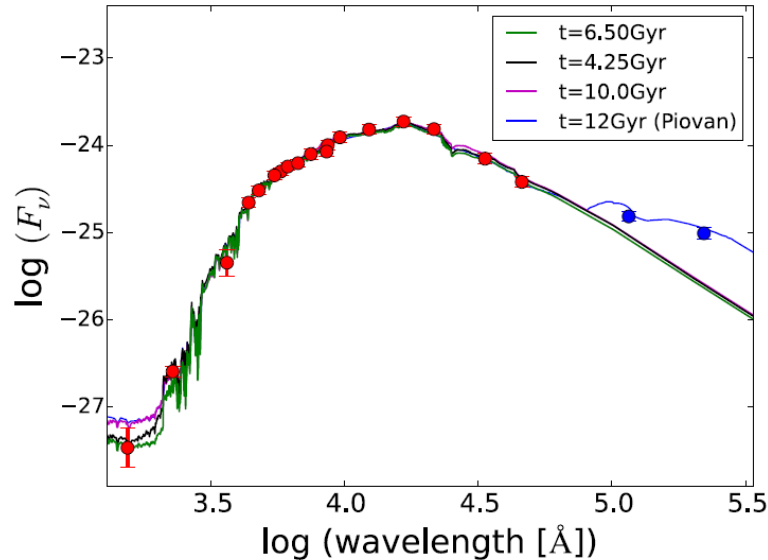
- Galfit SB fitting
- Sersic index $n = 3-4$, $B/T = 0.7 - 1.0$
- $R_{\text{eff}} = 10'' - 15''$ (2-3 kpc)

Disturbed morphology



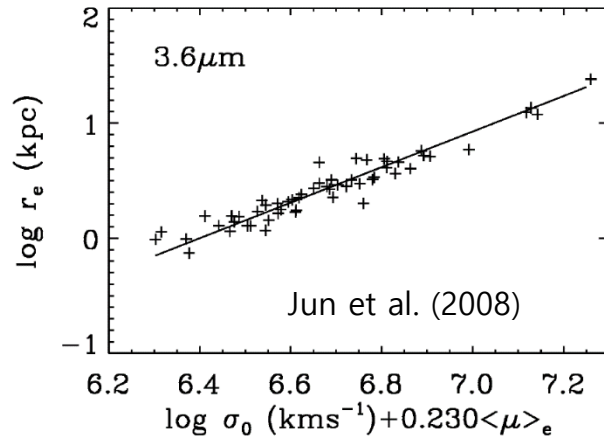
- Dust lane and tidal shell suggest NGC 4993 has undergone merger activities

NGC 4993 stellar population (SK Lee)



- SED-fitting with SK-Lee's code (Chabrier (2003) IMF)
- $M^* = 0.3 - 1.2 \times 10^{11} \text{ Msun}$
- Age: $> 2 \text{ Gyr}$
- No SF
- $E(B-V) = 0.00 - 0.07$

FP distance to NGC 4993



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

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

FP Distance to NGC 4993

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

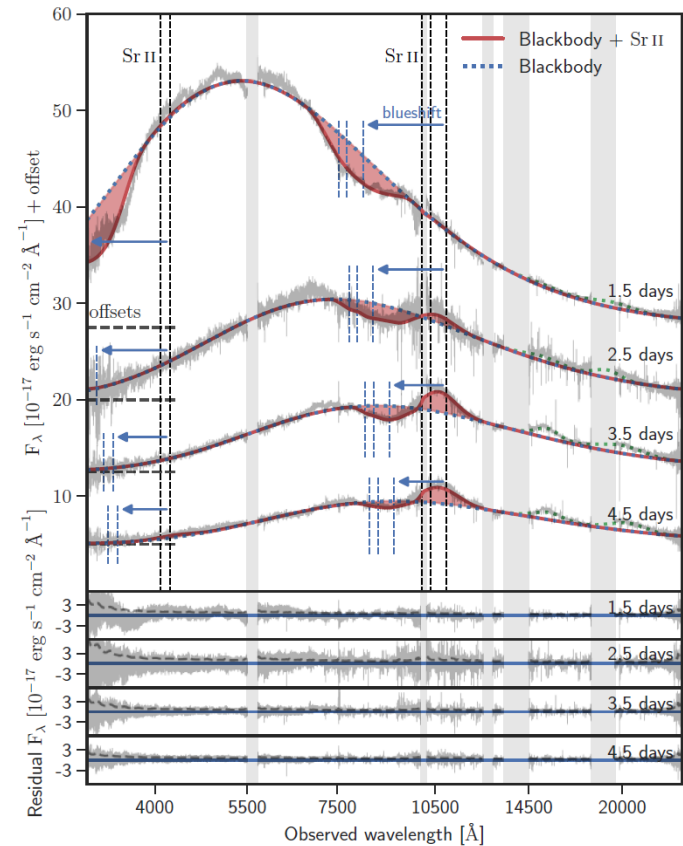
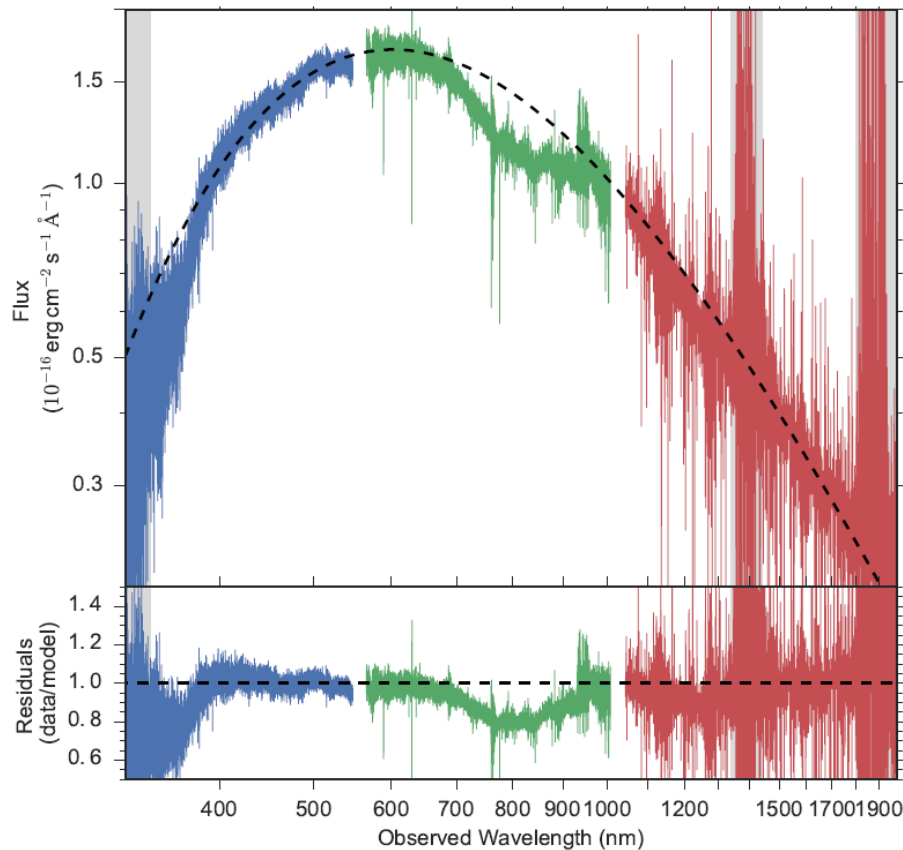
17 FP parameter sets

$$\rightarrow D_A = 37.7 \pm 8.7 \text{ Mpc},$$

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

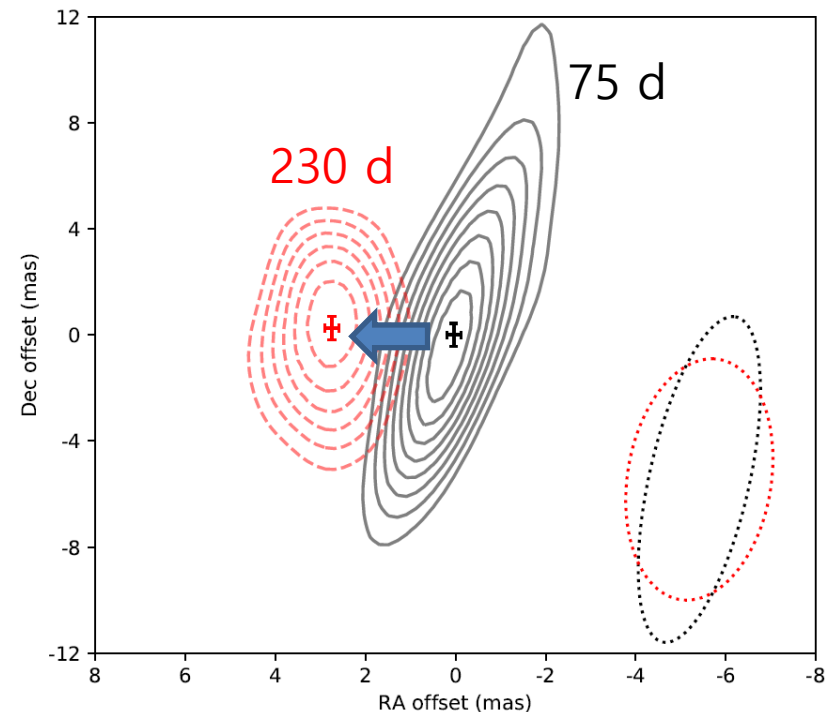
Im et al. (2017)

Detection of Sr in AT2017gfo Spectrum (Watson+19)



Relativistic Jet Detection (Mooley+18)

- VLBA 관측을 통해 $t = 75$ day, 230 day에 Jet 이동 포착
- Apparent velocity = $4.1 c$
- Superluminal motion can fixed the observer's viewing angle



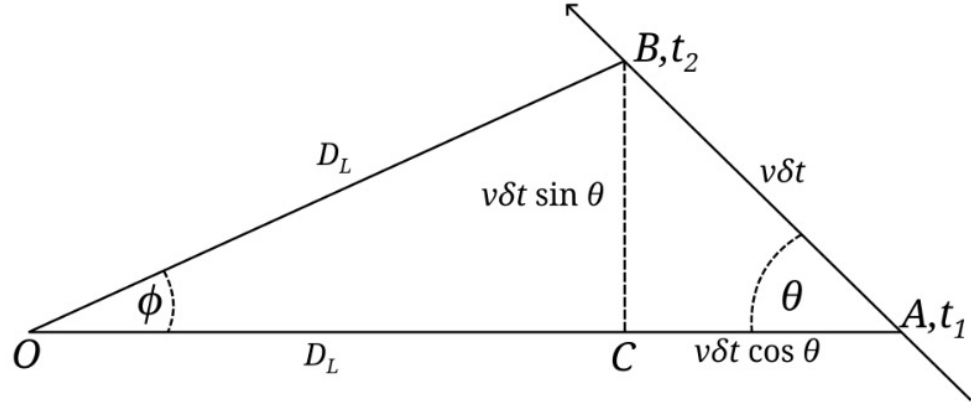
Superluminal Motion

$$AB = v \delta t$$

$$AC = v \delta t \cos \theta$$

$$BC = v \delta t \sin \theta$$

$$t_2 - t_1 = \delta t$$



$$t'_1 = t_1 + \frac{D_L + v \delta t \cos \theta}{c}$$

$$t'_2 = t_2 + \frac{D_L}{c}$$

$$\delta t' = t'_2 - t'_1 = t_2 - t_1 - \frac{v \delta t \cos \theta}{c} = \delta t - \frac{v \delta t \cos \theta}{c} = \delta t(1 - \beta \cos \theta)$$

, where $\beta = v/c$

$$\delta t = \frac{\delta t'}{1 - \beta \cos \theta}$$

$$BC = D_L \sin \phi \approx \phi D_L = v \delta t \sin \theta \Rightarrow \phi D_L = v \sin \theta \frac{\delta t'}{1 - \beta \cos \theta}$$

$$\text{Apparent transverse velocity along } CB, v_T = \frac{\phi D_L}{\delta t'} = \frac{v \sin \theta}{1 - \beta \cos \theta}$$

$$\beta_T = \frac{v_T}{c} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}.$$

Implication for cosmological application

- GW distance relation with GW strain amplitude (h)

$$h \propto \frac{1}{D_L} \times f(\iota),$$

- D_L = luminosity distance
- ι = binary inclination angle

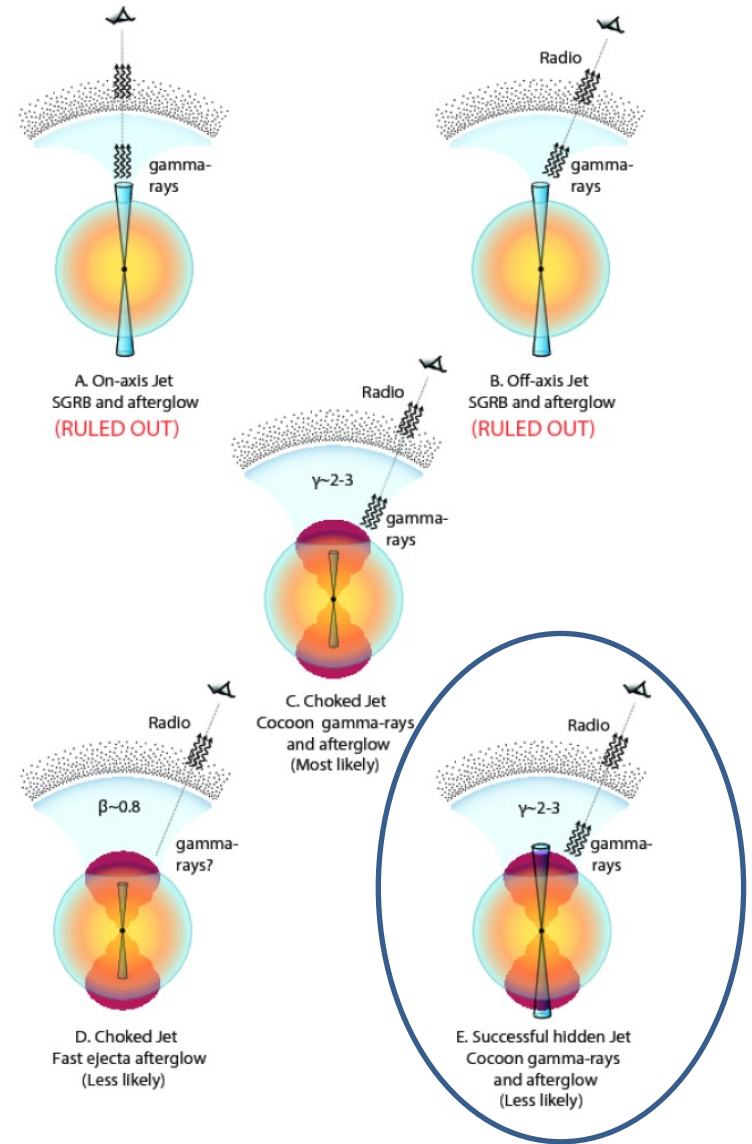
- Superluminal motion of relativistic jet ~ observer viewing angle of $\theta_{\text{obs}} \approx 20^\circ$

➔ Vast improvement in distance measurement!
(Hotokezaka+19)

- $\delta H_0 \sim 15\% \rightarrow 7\%$

Other implication

- Existence of relativistic jet $\rightarrow$ no failed jet in cocoon model
- Structured jet model is favored



Mooley+17



Worldwide effort

- 중력파 천문대 3대, 지상 천문관측시설 70개, 우주망원경 7대
- 45개국 900여 기관, 50여 개 연구그룹, 3500여 명의 과학자들 참여
- 10월16일 76편의 논문 동시공개(한국연구진 7편, www.kilonovae.org)



2026-07-30

2026 수리상대론 중력파 여름학교(천문연구원)
출처: 서울대학교 초기우주천체연구단 및 LIGO-Virgo

Multi-Messenger Astronomy (다중신호 천문학)

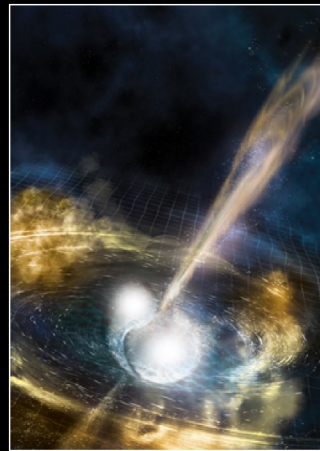
- 중력파 + 빛(전자기파) + 입자와 같이 다양한 관측방법을 사용하여 우주를 관측하는 새로운 연구방법



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



+2초 후
페르미 및 INTEGRAL 감마선 신호 포착



KMTNet(서울대/한국천문연구원)



+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

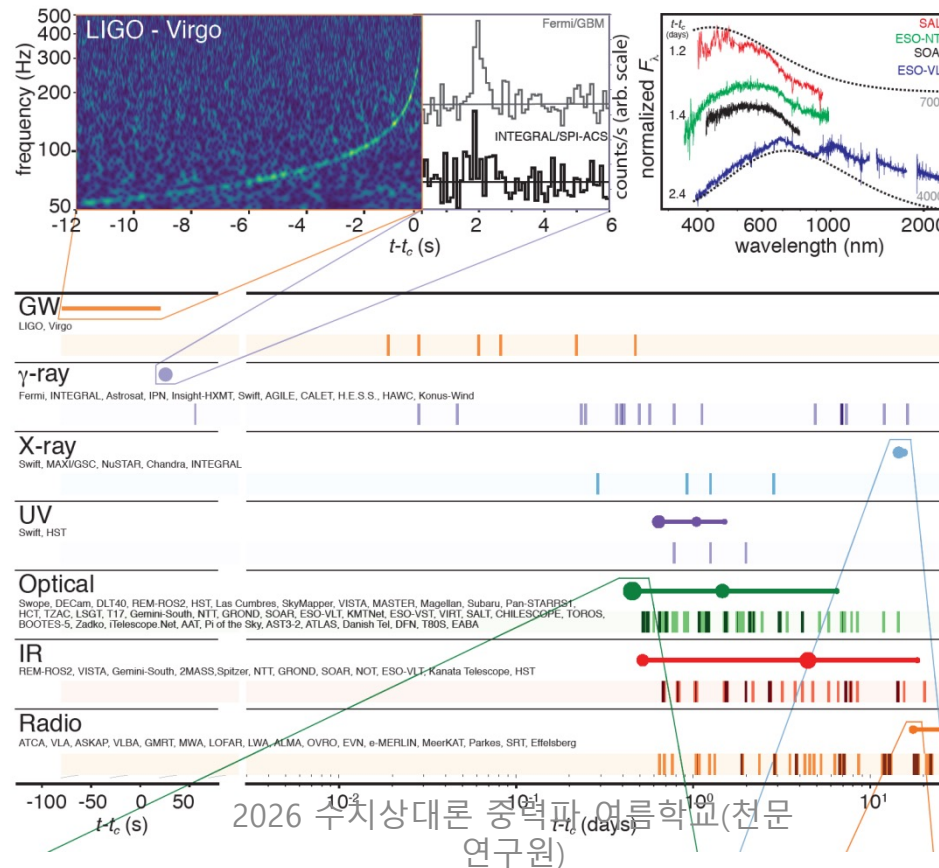


+약 16일 후
지상 전파망원경
전파 신호 포착



Multi-Messenger Astronomy Paper (MMA paper, ApJL)

- 중력파, 전자기파에서 GW170817의 연구가 어떻게 진행되었는지 기술
- 종합적인 연구결과 요약
- 총저자 3700여명(한국중력파연구협력단, 천문연구원, 서울대학교 초기우주천체연구단, 성균관대학교 등 39명 포함)
- 총59페이지(저자리스트:24페이지, Acknowledgement: 7페이지, Table: 17페이지)



"MMA paper"
LIGO, Virgo,
Partner Astronomy Groups
2017, ApJL
(Oct. 3, submitted,
Oct. 7, accepted)



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 Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAVITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, IAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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Table 1

A Partial Summary of Photometric Observations up to 2017 September 5 UTC with at Most Three Observations per Filter per Telescope/Group, i.e., the Earliest, the Peak, and the Latest in Each Case

Telescope/Instrument	UT Date	Band	References
DFN/–	2017 Aug 17 12:41:04	visible	Hancock et al. (2017),
MASTER/–	2017 Aug 17 17:06:47	Clear	Lipunov et al. (2017a, 2017b)
PioftheSky/PioftheSkyNorth	2017 Aug 17 21:46:28	visible wide band	Cwiek et al. (2017); Batsch et al. (2017); Zadrozny et al. (2017)
MASTER/–	2017 Aug 17 22:54:18	Visible	Lipunov et al. (2017b, 2017a)
Swope/DirectCCD	2017 Aug 17 23:33:17	i	Coulter et al. (2017a, 2017b, 2017)
PROMPT5(DLT40)/–	2017 Aug 17 23:49:00	r	Yang et al. (2017a), Valenti et al. (submitted)
VISTA/VIRCAM	2017 Aug 17 23:55:00	K	Tanvir & Levan (2017)
LasCumbres1-m/Sinistro	2017 Aug 18 09:43:11	r	Arcavi et al. (2017e)
T17/–	2017 Aug 18 09:47:13	g	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
SkyMapper/–	2017 Aug 18 09:50:00	v	...
T17/–	2017 Aug 18 09:56:46	r	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
SkyMapper/–	2017 Aug 18 10:01:00	i	Wolf et al. (2017),
SkyMapper/–	2017 Aug 18 10:03:00	r	Wolf et al. (2017),
SkyMapper/–	2017 Aug 18 10:05:00	g	Wolf et al. (2017),
T17/–	2017 Aug 18 10:06:18	i	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
SkyMapper/–	2017 Aug 18 10:07:00	v	Wolf et al. (2017),
LSGT/SNUCAM-II	2017 Aug 18 10:08:01	m425	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
SkyMapper/–	2017 Aug 18 10:09:00	u	Wolf et al. (2017),
LSGT/SNUCAM-II	2017 Aug 18 10:12:48	m475	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
LSGT/SNUCAM-II	2017 Aug 18 10:15:16	m525	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
T17/–	2017 Aug 18 10:15:49	z	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
LSGT/SNUCAM-II	2017 Aug 18 10:21:14	m575	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
LSGT/SNUCAM-II	2017 Aug 18 10:22:33	m625	Im et al. (2017a, 2017b), Im et al. (2017, in preparation)
AST3-2/wide-fieldcamera	2017 Aug 18 13:11:49	g	Hu et al. (2017),
Swift/UVOT	2017 Aug 18 13:30:00	uvm2	Cenko et al. (2017); Evans et al. (2017b)
Swift/UVOT	2017 Aug 18 13:37:00	uvw1	Cenko et al. (2017); Evans et al. (2017b)

Papers from Korean group

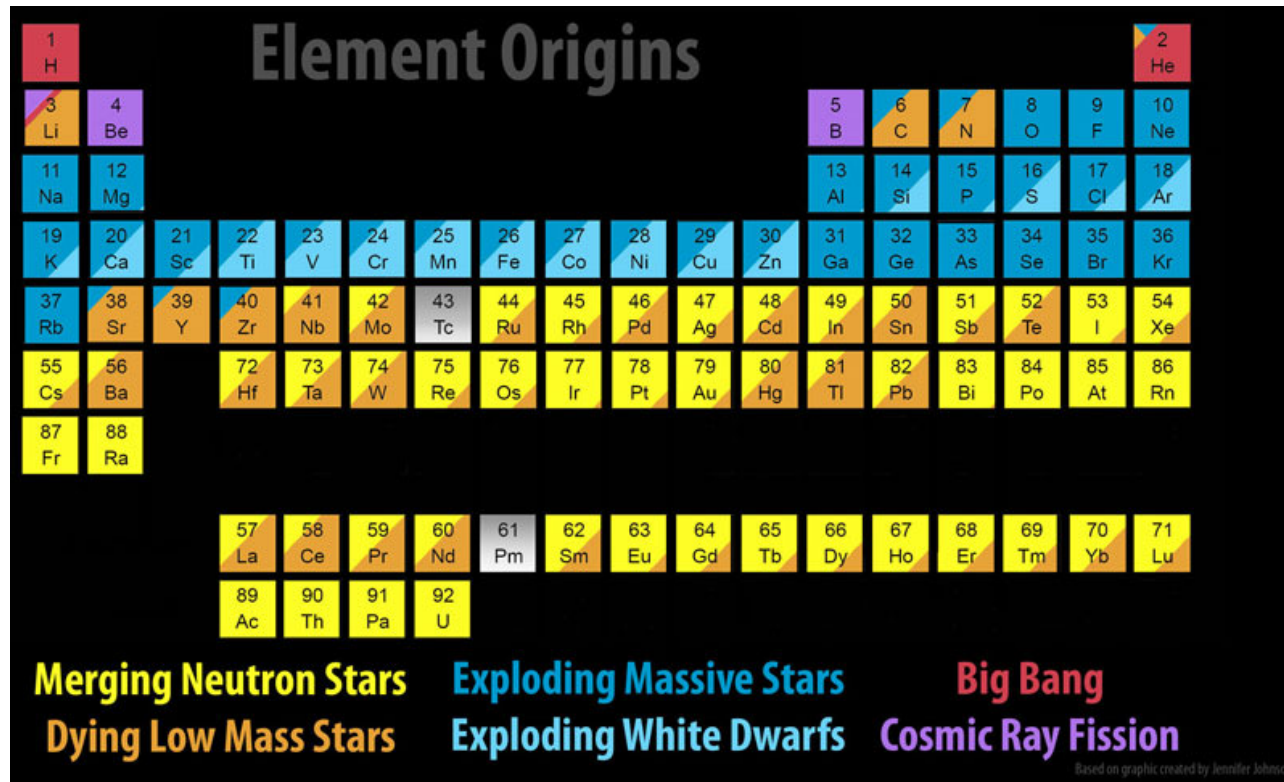
	논문제목	저자	발표학술지
1	The X-ray counterpart to the gravitational wave event GW 170817	E. Troja, L. Piro, H. van Eerten, R. T. Wollaeger, M. Im, et al. (총저자 34명, 국내 연구진 9명, 임명신, 김준호, 이형목, 김승리, 이충욱, 최창수, 이성국, 임구, 윤용민)	Nature(주요저자)
2	Distance and properties of NGC 4993 as the host galaxy of the gravitational wave source, GW170817	M. Im, Y. Yoon, S.-K. Lee, et al. (총저자 12명, 국내연구진 11명, 임명신, 윤용민, 이성국, 이형목, 이충욱, 김승리, 최창수, 김준호, 임구, 고종완, 심현진)	The Astrophysical Journal Letters(제1교신)
3	Multi-Messenger Observations of A Binary Neutron Star Merger	총저자 3500명 이상, 국내연구진 38명	The Astrophysical Journal Letters
4	The Environment of The Binary Neutron Star Merger GW 170817	Levan, A. et al. (총저자 38명, 국내연구진 1명)	The Astrophysical Journal Letters
5	GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral	총저자 1100여명, 국내연구진 14명*	The Physical Review Letters
6	A gravitational-wave standard siren measurement of the Hubble constant	총저자 1300여명, 국내연구진 14명*	Nature
7	Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A	총저자 1150여명, 국내연구진 14명*	The Astrophysical Journal Letters

* 이형목 (서울대 1명), 이현규 (한양대 1명), 이창환, 조희석, 김영민 (부산대 3명), 이형원, 김정초 (인제대 2명), 김정리 (천문연구원 1명), 강궁원, 배상욱 (한국과학기술정보연구원 2명), 오정근, 오상훈, 손재주, 김환선 (국가수리과학연구소

Important Results

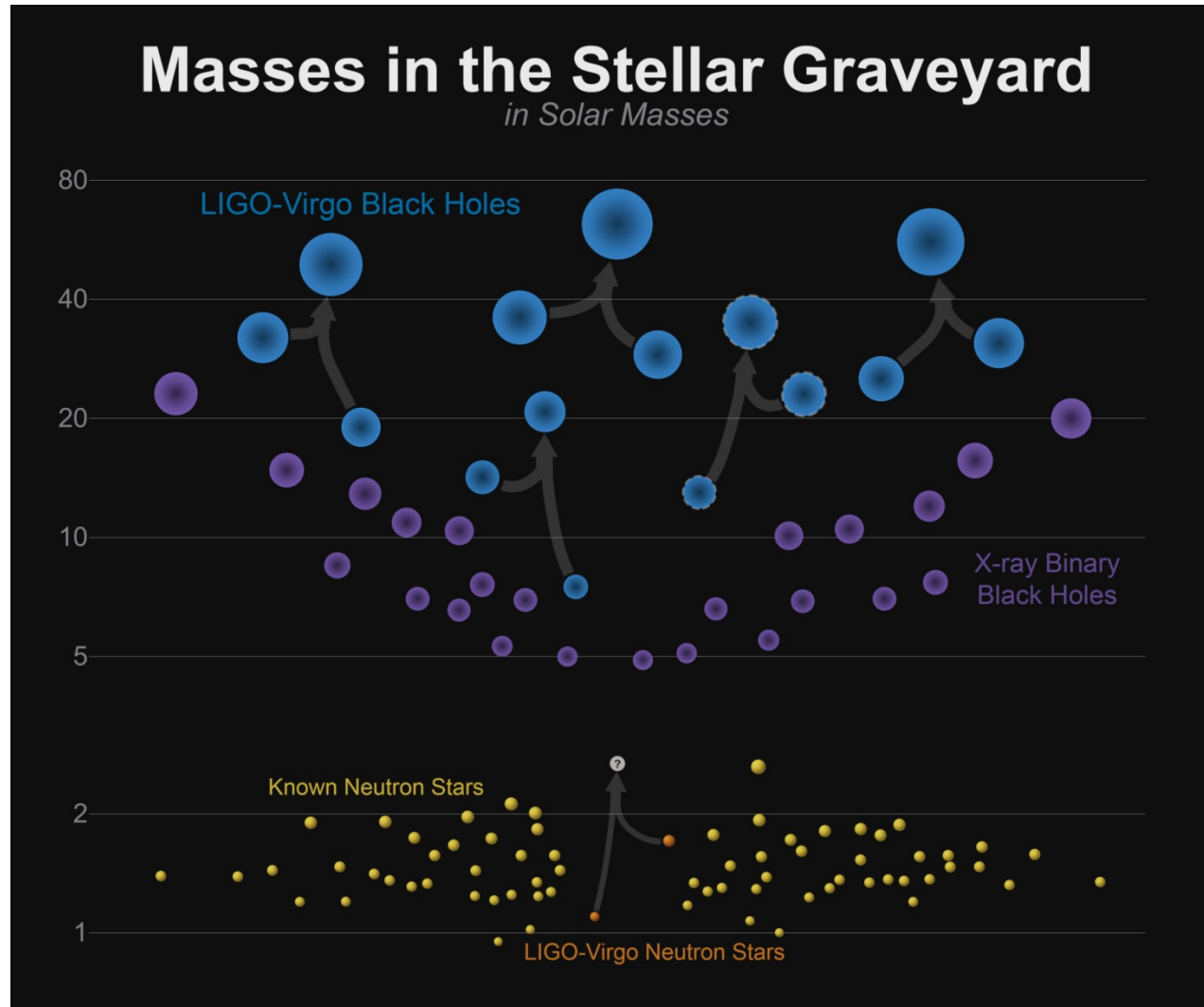
- **NS-NS merger proof**
 - mass from GW ($1.5 M_{\odot} + 1.25 M_{\odot} = 2.75 M_{\odot}$)
 - (off-axis?) short GRB signal as predicted
 - First convincing detection of kilonova (Korean team + world astronomers)
 - host galaxy consistent with NS-NS merger (Korean team + several other groups)
- **Cosmological application**
 - First application of H_0 measurement with GW + optical signal (Korean GWG + LIGO/Virgo)
- **Search strategy**
 - host galaxy property as a guide (Korean team + several other groups)

Implication: First secure identification of the factory of gold, platinum, uranium etc

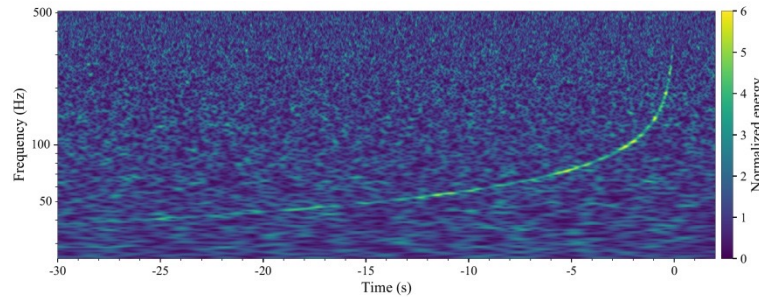


- Efficient neutron capture (r-process) leads to creation of these elements
- 200 earth mass gold, 500 earth mass platinum

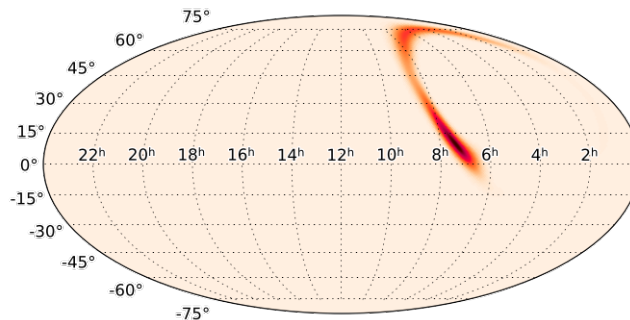
Result of NS-NS merger?



EM Follow-up procedure



중력파 검출 → 3개의 detector 신호로부터
위치, 거리 및 사건의 특성파악



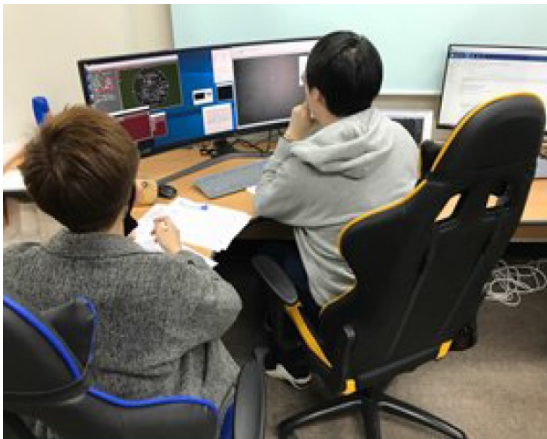
Localization map을 배포

GCN Circular 예시

```
////////////////////////////////////  
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.
```

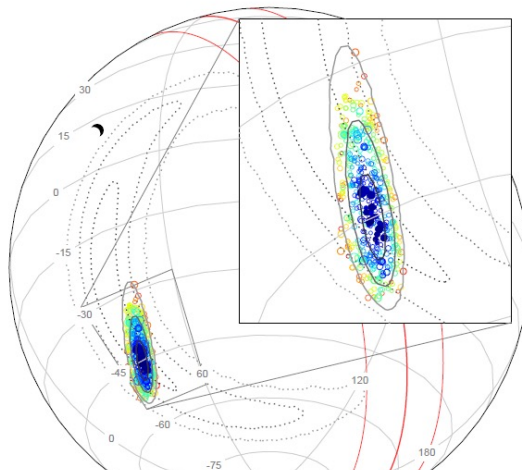

Alert system

- GW alert (e-mail: GCN circular) → observation
- Human alert to observatory
- Automatic follow-up observation
- How can we improve this system?
- Automatic initiation of the observation?



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
 - Improvement in the host galaxy candidate catalog
 - New distance (e.g., FP-based distance)



Arcavi et al. (2017)

관측요청: 메일, 전화, 메신저 등등

Korea:

SNUO 0.6m, SOAO 0.6m,

BOAO 1.8m, DOAO 1.0m

Maidanak:

1.5m Telescope

US: LOAO 1-m



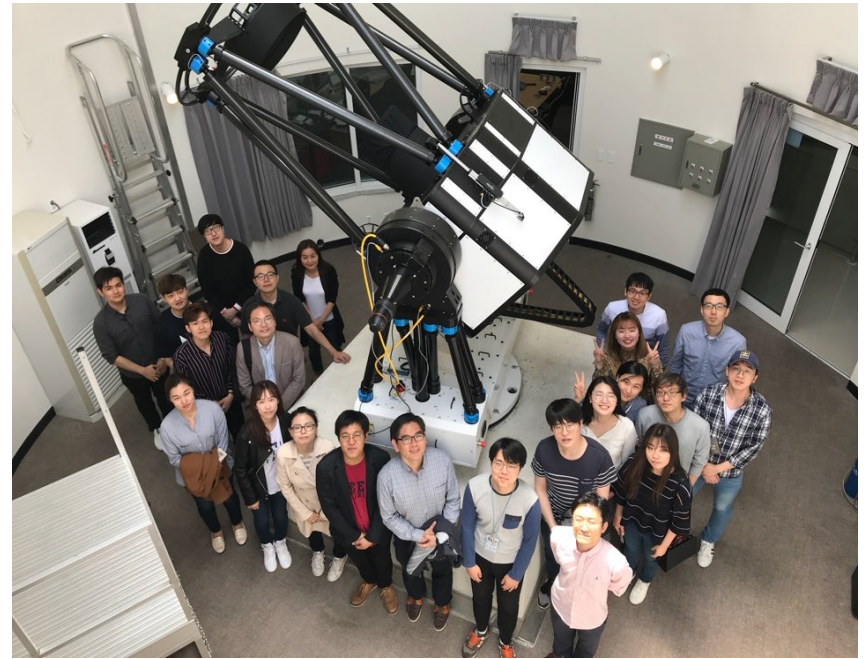
KMTNet 1.6m
Telescopes

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

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

SNU Astronomical Observatory (SAO) 1m Telescope

- 1m f/6 telescope
- Two Nasmyth ports
- Installation: 2018-03-27
- 4k x 4k imager (21.2' x 21.2')
- Long-slit spectrograph (R ~ 1000)
- Seeing: 1.0" – 2.5"



2018.5.15

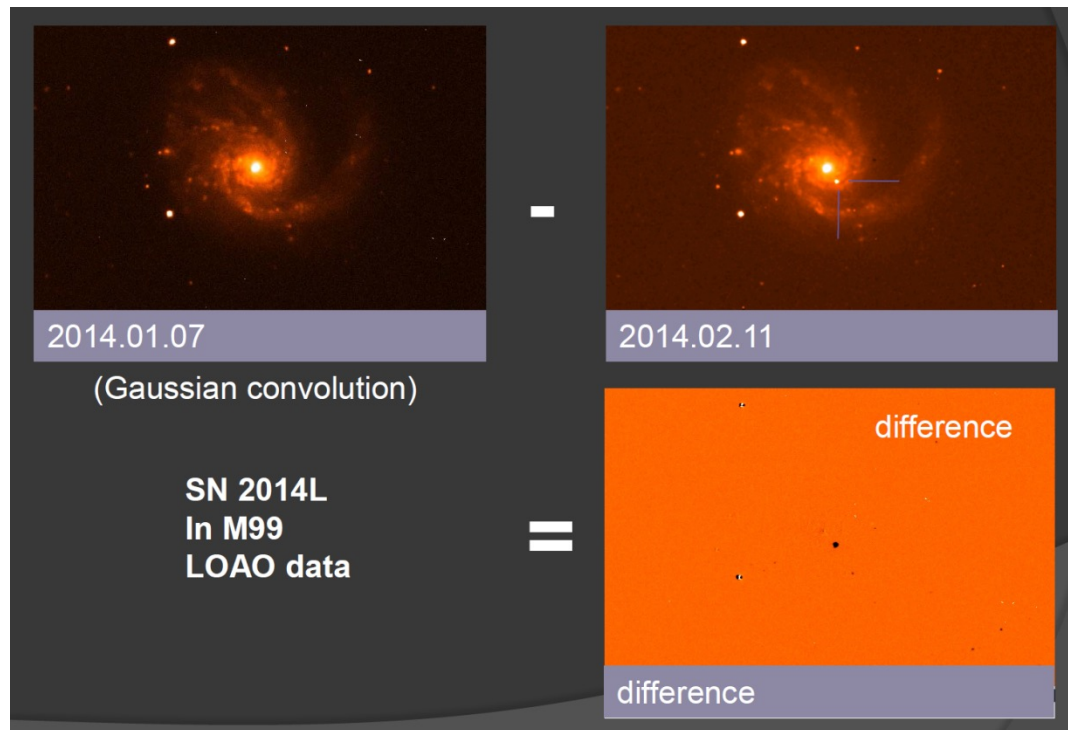
자료처리

Image reduction

- Bias/dark subtraction
- Flat-fielding
- Astrometry – 천체좌표 특정
- 빠른 자료처리를 위해 대부분의 과정을 자동화

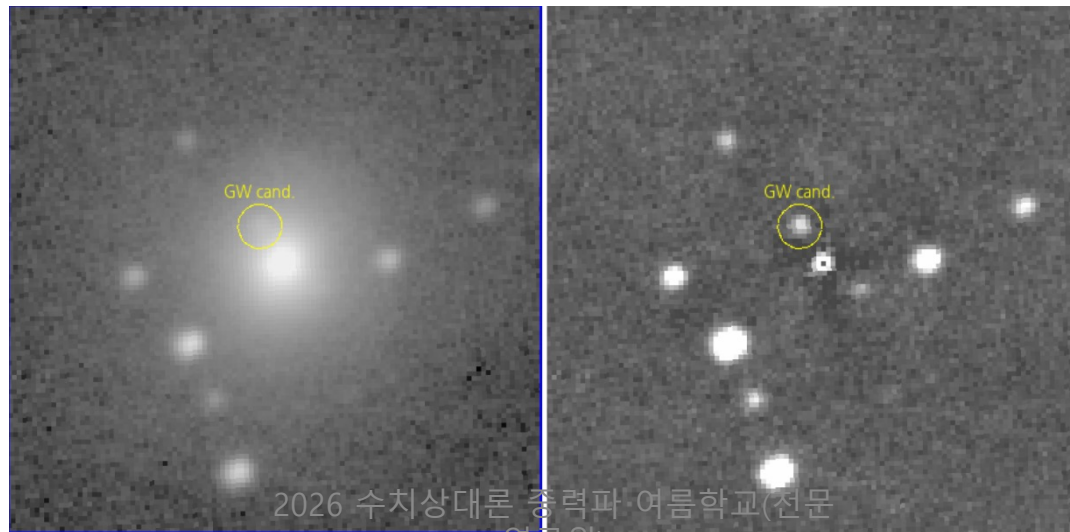
Transient identification

- Image subtraction
- Careful subtraction is often difficult
- Automatic classification



Photometry/spectral analysis

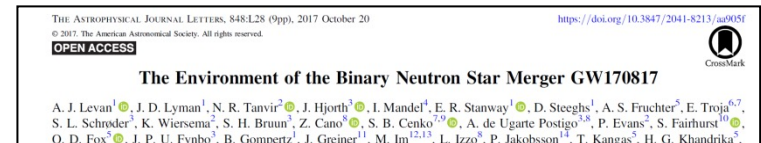
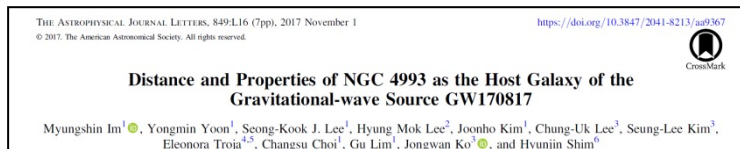
- Derivation of photometric zero-points
- Photometry
- Reduction of the spectra
- Classification of spectra → Kilonova?



주변천체의 밝기를
바탕으로
Transient의
밝기 결정

Scientific output

- GW170817: 7 papers from our EM follow-up observations (other groups ~10+ papers)
- EM counterpart discovery
- Early emission characteristics (optical/NIR, imaging/spectroscopy – Constraints on models)
- Host galaxy
- Late-time emission study
- Cosmological application
- GW detection strategy
- We need to be better prepared

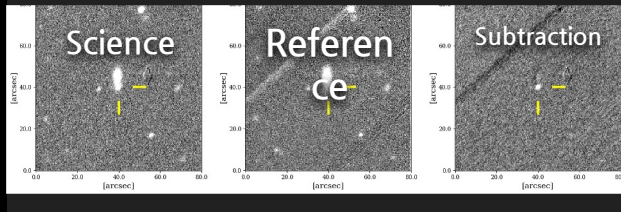


2019-04-01 O3 관측시즌 시작 GECKO 관측 불철주야 수행

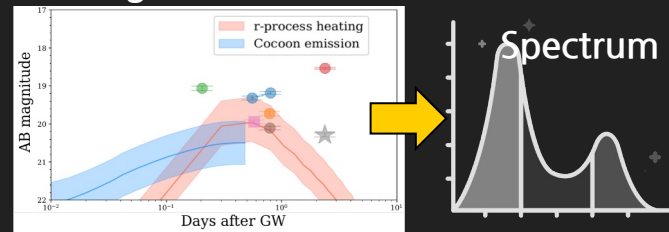
1. Automated system for GW signal



2. Transient search



3. Distinguish KN

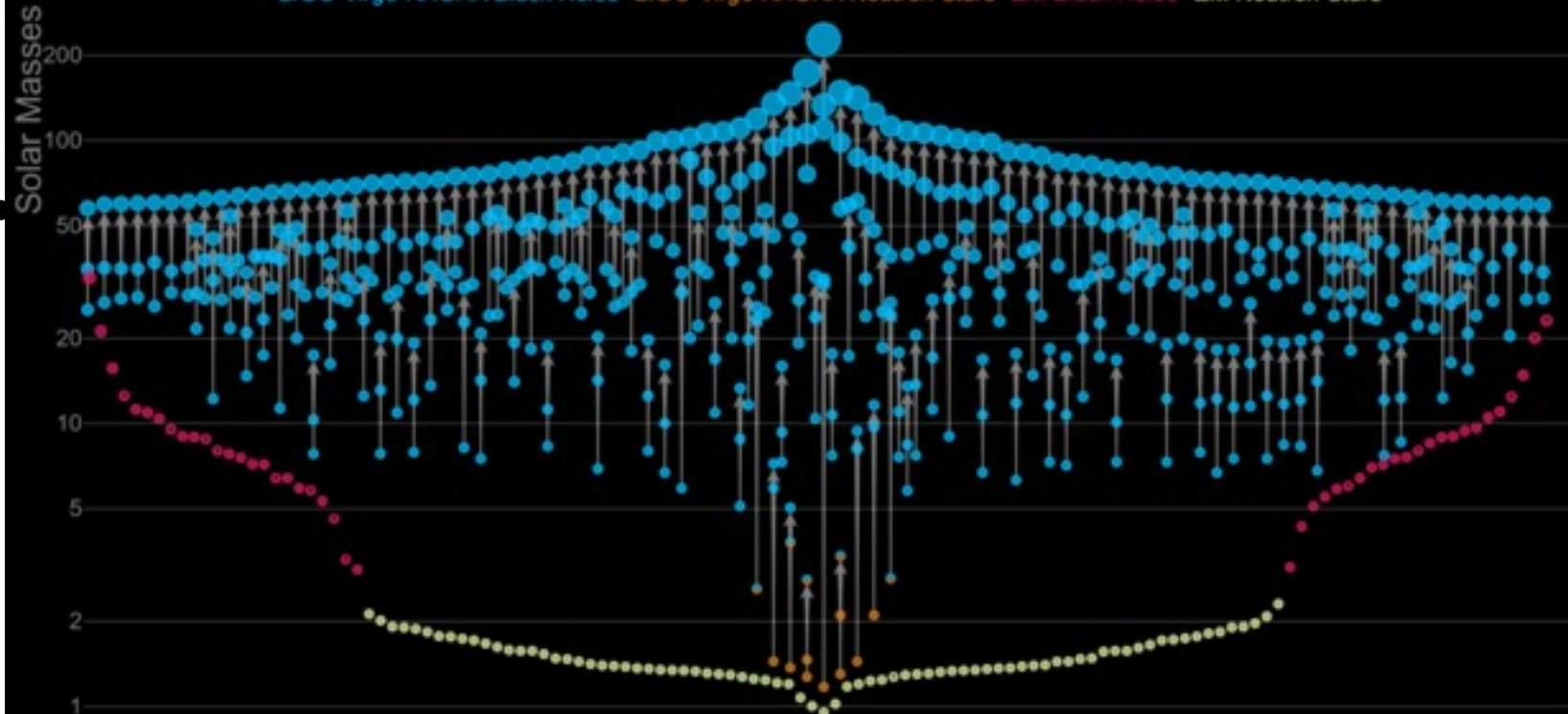


From presentation by G. Paek



Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

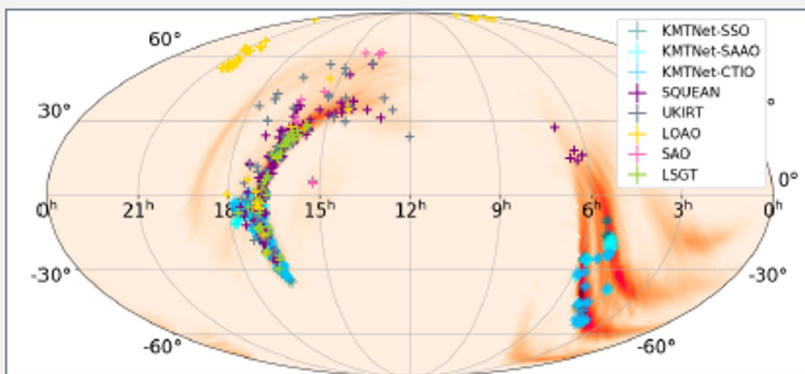


Run	Dates	Duration (months)	Detections
O1	September 18, 2015 to January 12, 2016	3	3
O2	November 30, 2016 to August 25, 2017	9	8
O3	April 1, 2019 to March 26, 2020	11	79
			Candidates
O4	May 24, 2023 to March 19, 2025	23	200

GW190425(중성자별 합병 BNS)



Observation result



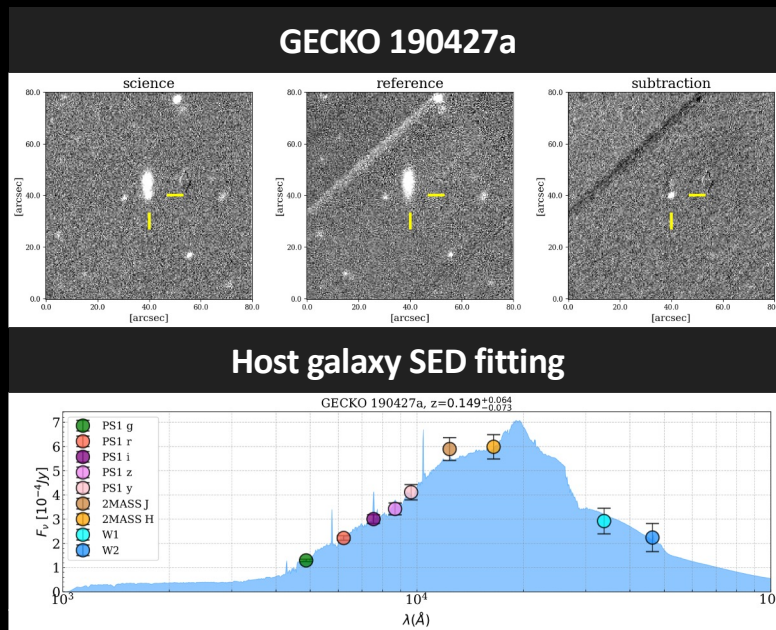
Observatory	Filter	Depth
SAO	R	19.50
LOAO	R	20.45
LSGT	R	19.76
SQUEAN	I	20.91
UKIRT	J, K	20.43
KMTNet	R	20.31

- Follow-up from 90 min to 6 days after trigger
- Covered 610/5419(~10%) kinds of host galaxy candidate
- Covered ~29% score
- **Find no EM counterpart to S190425z**

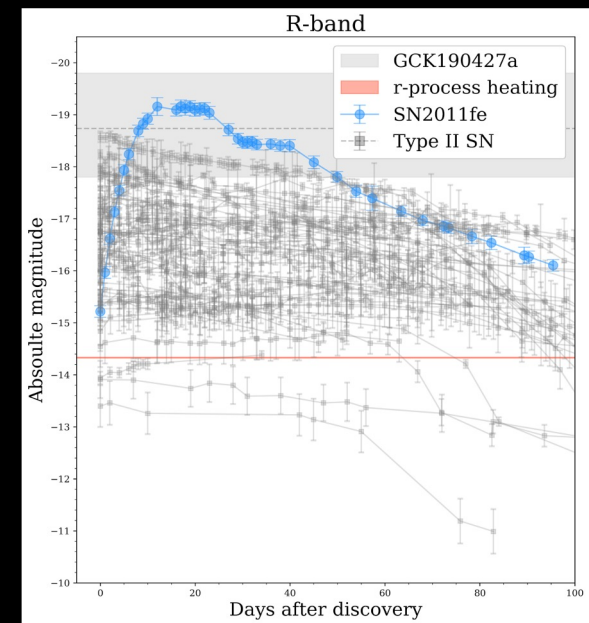
The first BNS merger event in O3 run

Trigger time	2019-04-25 09:40:17 UTC
Detectors	LIGO Livingston & Virgo (2 of 3)
FAR	~ 1/70,000 year
GW luminosity distance	156 ± 41 Mpc
90% confidence localization area	7461 deg ²

GW190425 - 중성자별 합병 사건 돌발천체(transient)

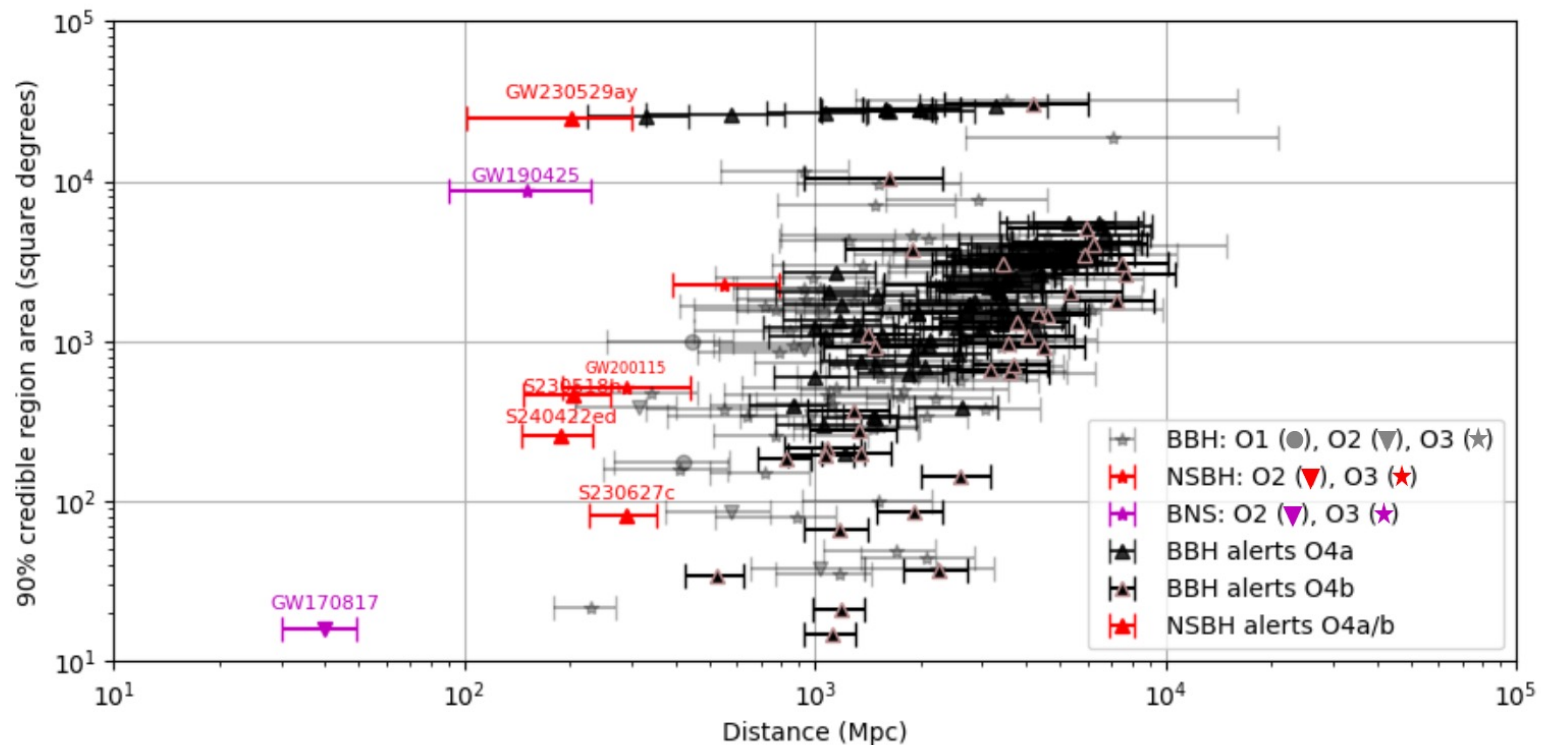


$z(\text{phot})=0.15$ ($D_L = 700$ Mpc)



O3 ('19 - '20) + O4('23 - '25)

- +1 BNS, ~6-7 NSBH, but no optical counterparts



Pillas+25

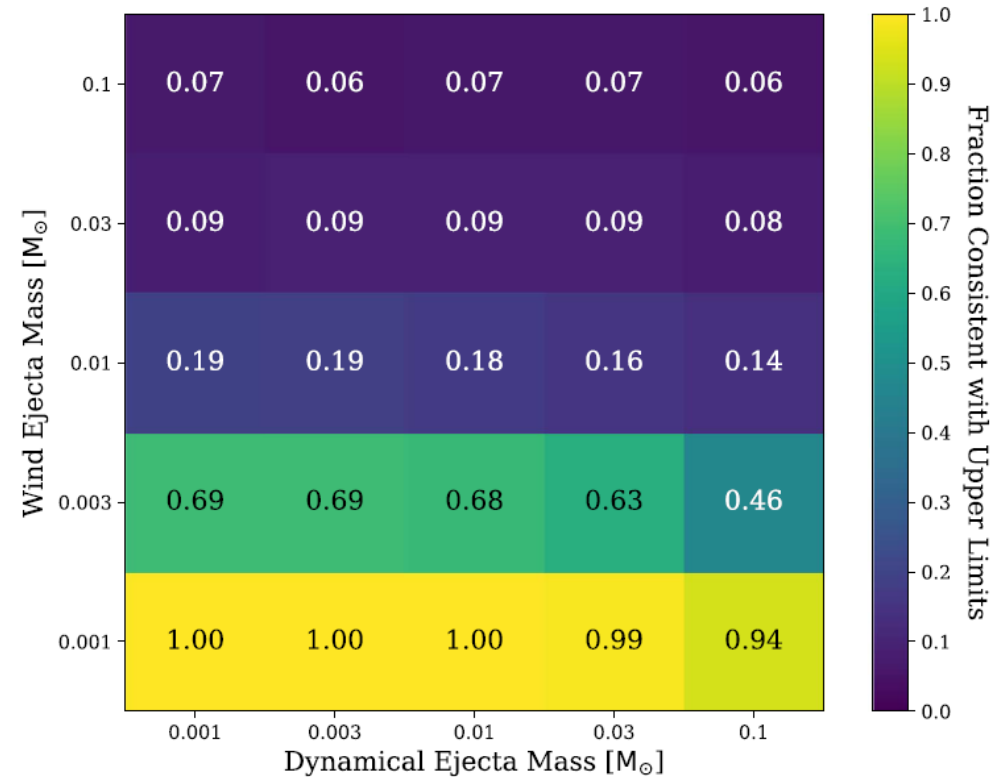
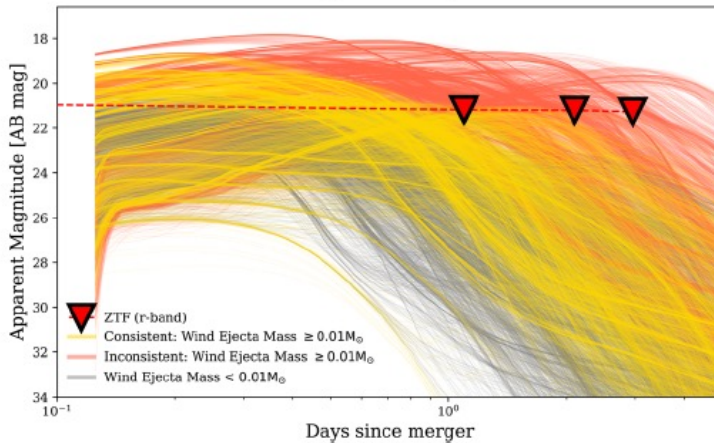
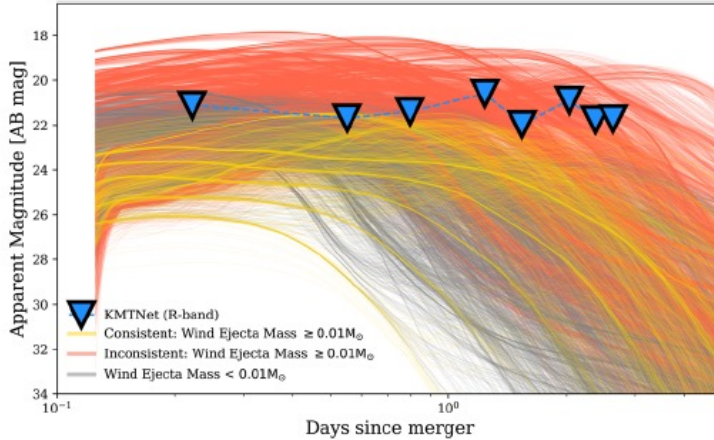
9 years since the first detection of optical counterpart of GW event, GW170817

- **2017-08-17 GW event marked the start of MMA using GW and EM signals**
- Many promises of MMA: kilonova, cosmology, heavy element production, compact merger environment, etc

The only GW event with EM counterpart ID so far



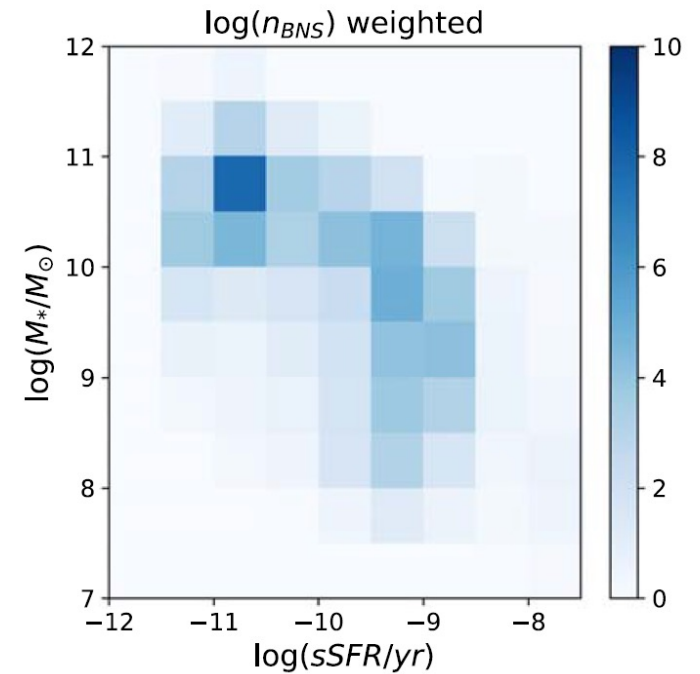
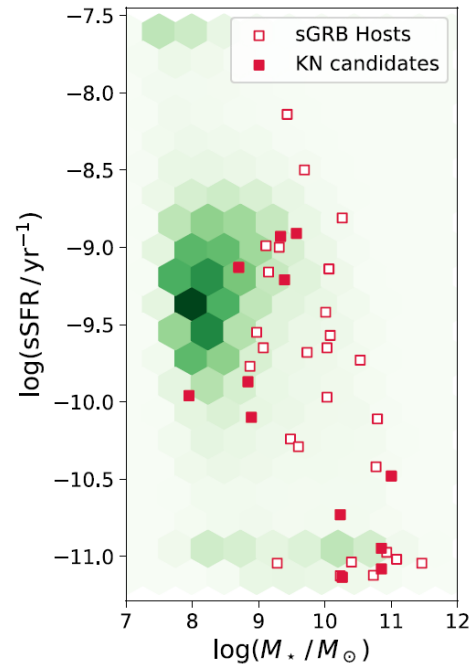
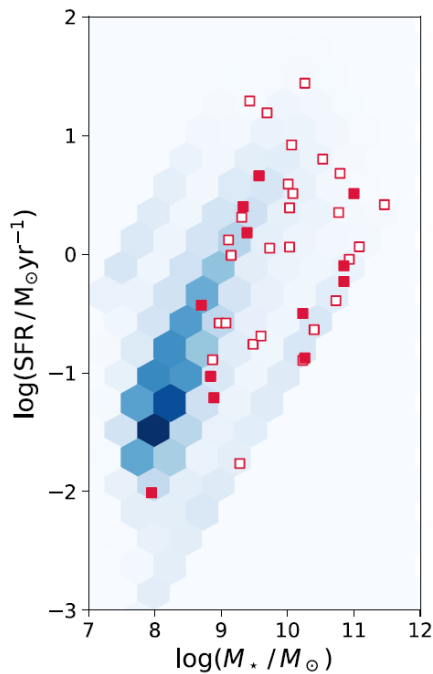
Non-detection도 괜찮아 다양한 KN model 검증



Paek+24, 25

Host galaxy studies

- Massive, star-forming galaxies?
- Outskirts or inner region?
- Can simulations explain BNS merger locations?



Jeong+Im24

Slide from 2014 spring KAS meeting

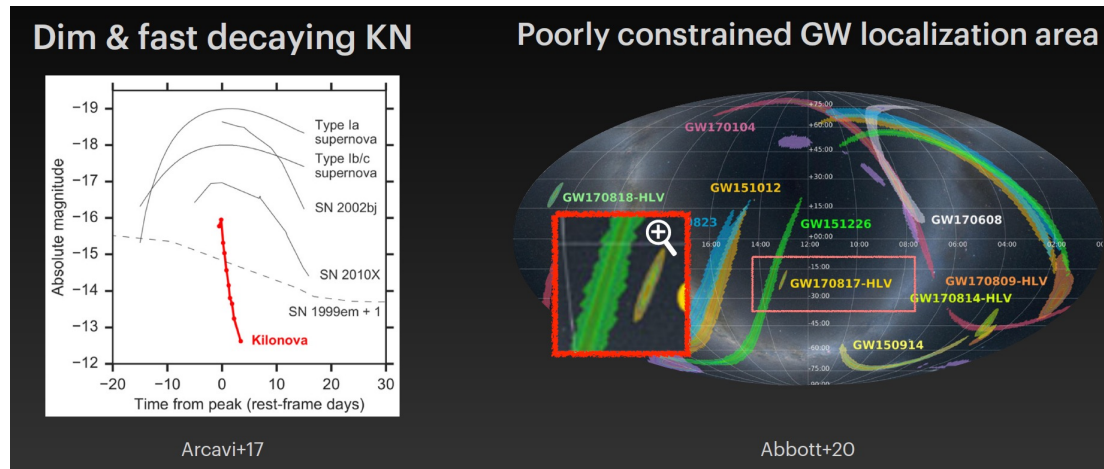
Summary

- GW detection in 2015-2019? **Yes, in 2015!**
- Positional accuracy, $\sim 1000 \text{ deg}^2$ (2015, $< 50 \text{ Mpc}$), $20 - 200 \text{ deg}^2$ (2016-2018, $< 100 \text{ Mpc}$), 20 deg^2 (2019+, $< 200 \text{ Mpc}$) **Yes, in 2017!**
- Expected brightness $z \sim 20.5$ AB mag at $D=100 \text{ Mpc}$ **Yes, in 2017!**
- Korea-Uzbek Consortium joined LIGO/VIRGO EM follow-up activity **Yes, but we can be more active**

- **The era of multi-messenger astronomy has arrived!**

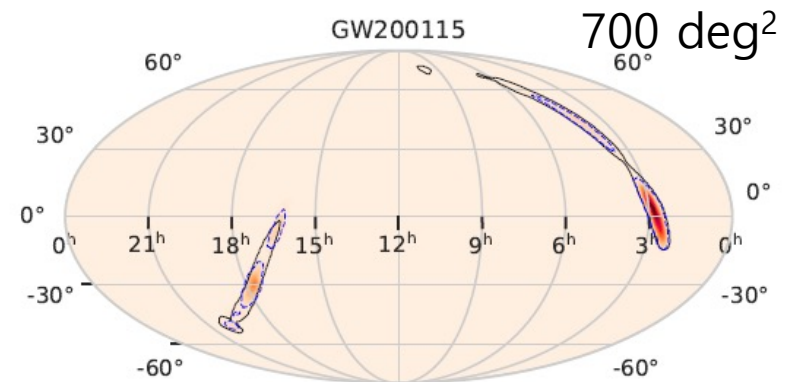
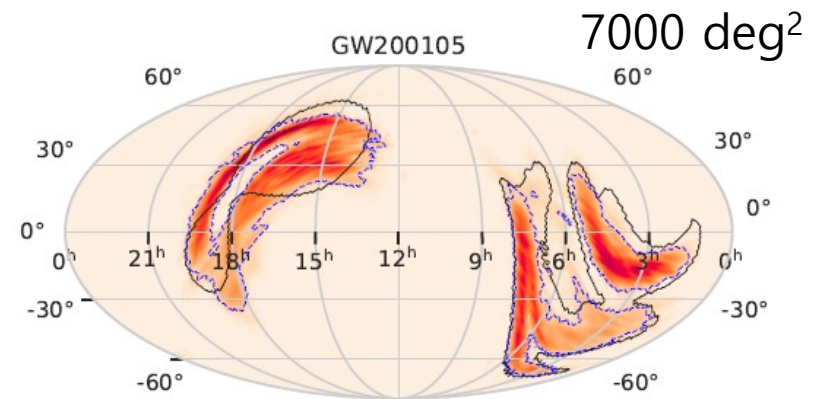
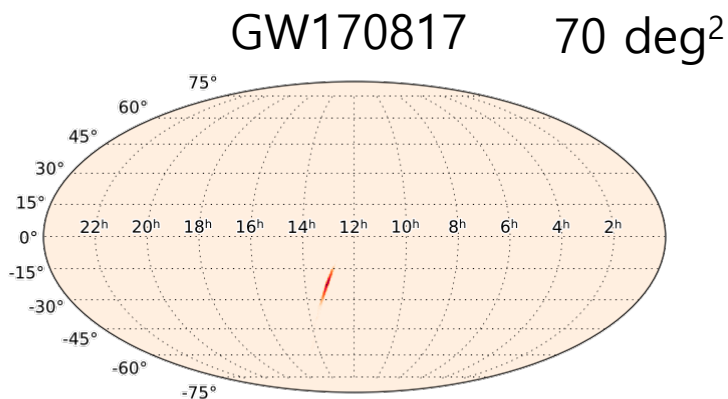
Challenges to Overcome for MMA

- Search area is **too wide** ($\sim 100 \text{ deg}^2$ or more)
- Kilonovae (Kne): **Faint, fast-decaying** transient ($> 20 \text{ mag}$)
: A KN needs to be found fast (first 1-2 days)
- **Too many other** transients ($10\text{-}100/\text{deg}^2$)



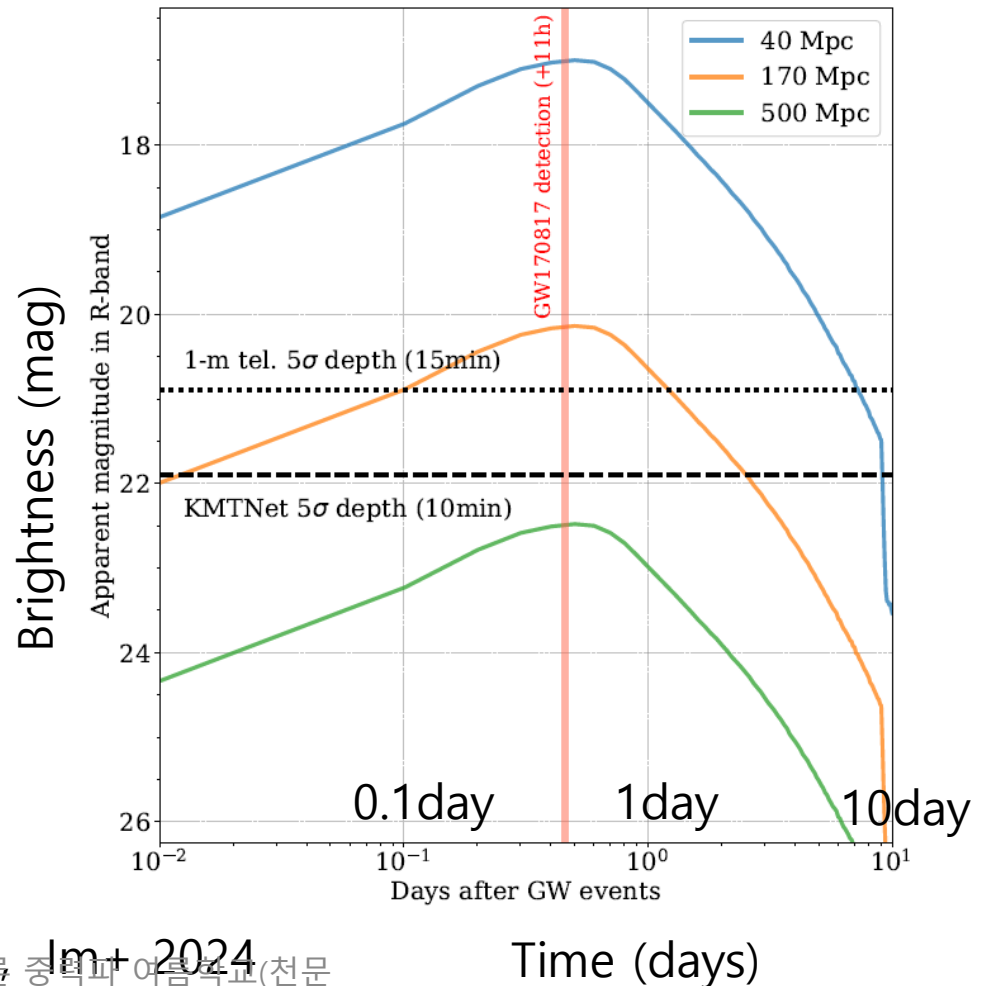
1. Localization area 10's to 1000's deg²

- GW localization area: too wide to cover
- JWST FoV: 10 arcmin²
- ~1/4 million JWST fields to cover 700 deg² (GW200115)



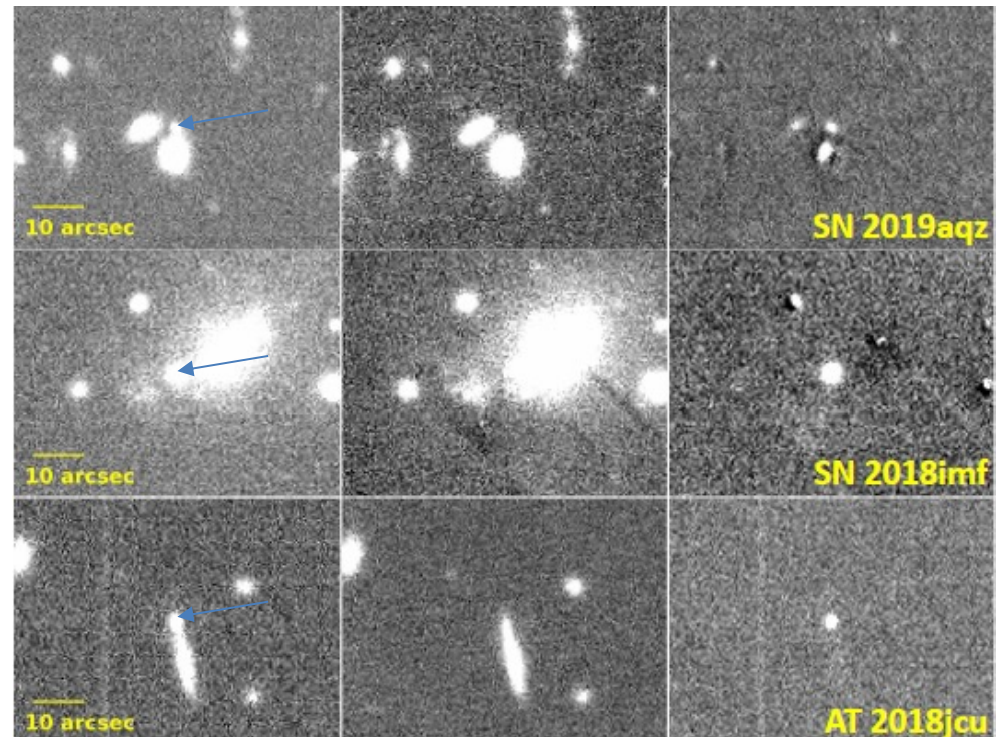
2. Kilonovae are faint and become fainter fast

- Peak luminosity R ~ -16 mag
 - Peak apparent mag: 17 – 22.5 mag
 - Becomes a few mag fainter in several days
- ➔ Rapid identification is essential



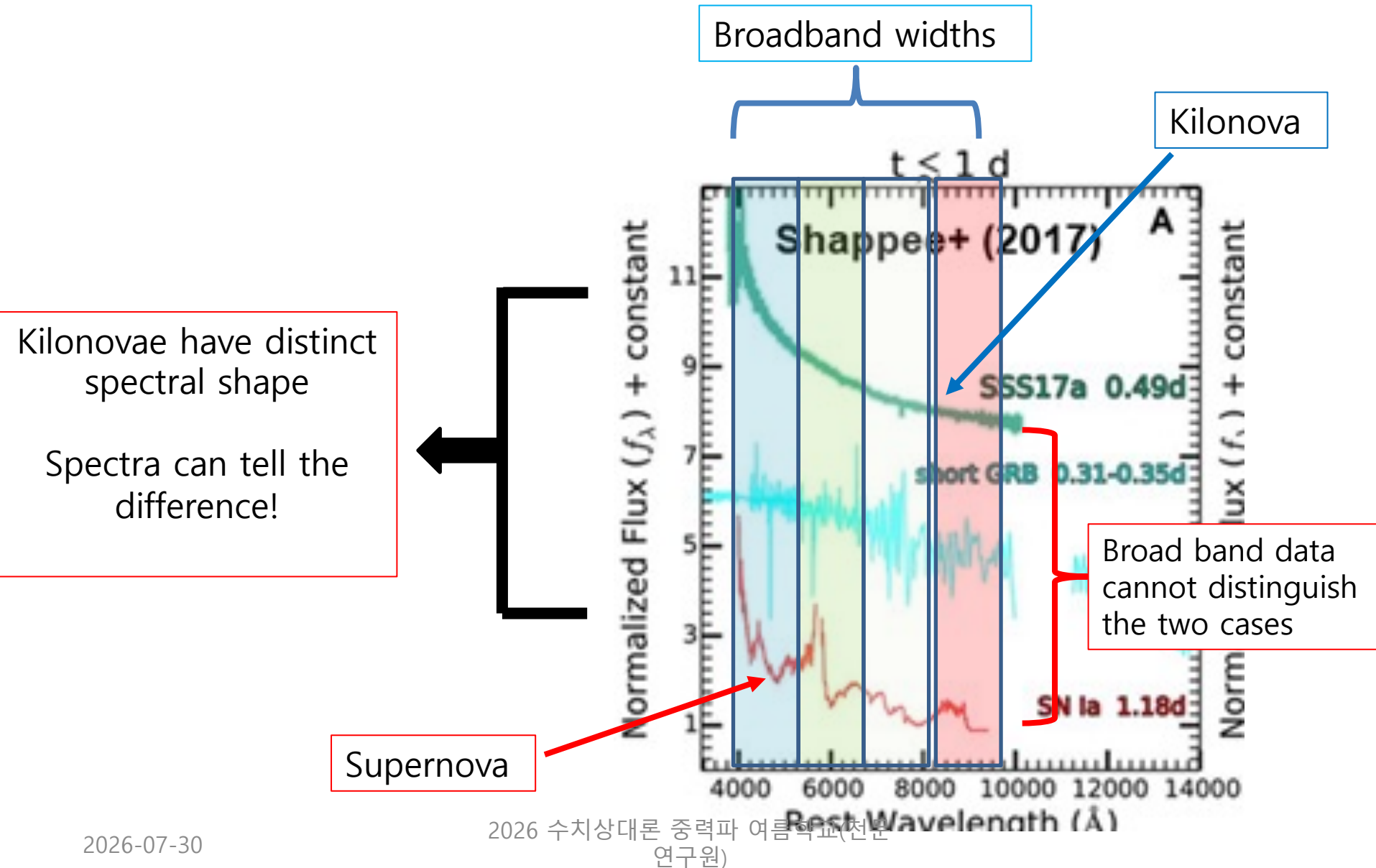
3. Many transients/fake signals in wide FOV

- Transients
100/10 deg²
(Kim+21)
- Variable sources
700/10 deg²
(Sesar+07)
- 100,000s artifacts



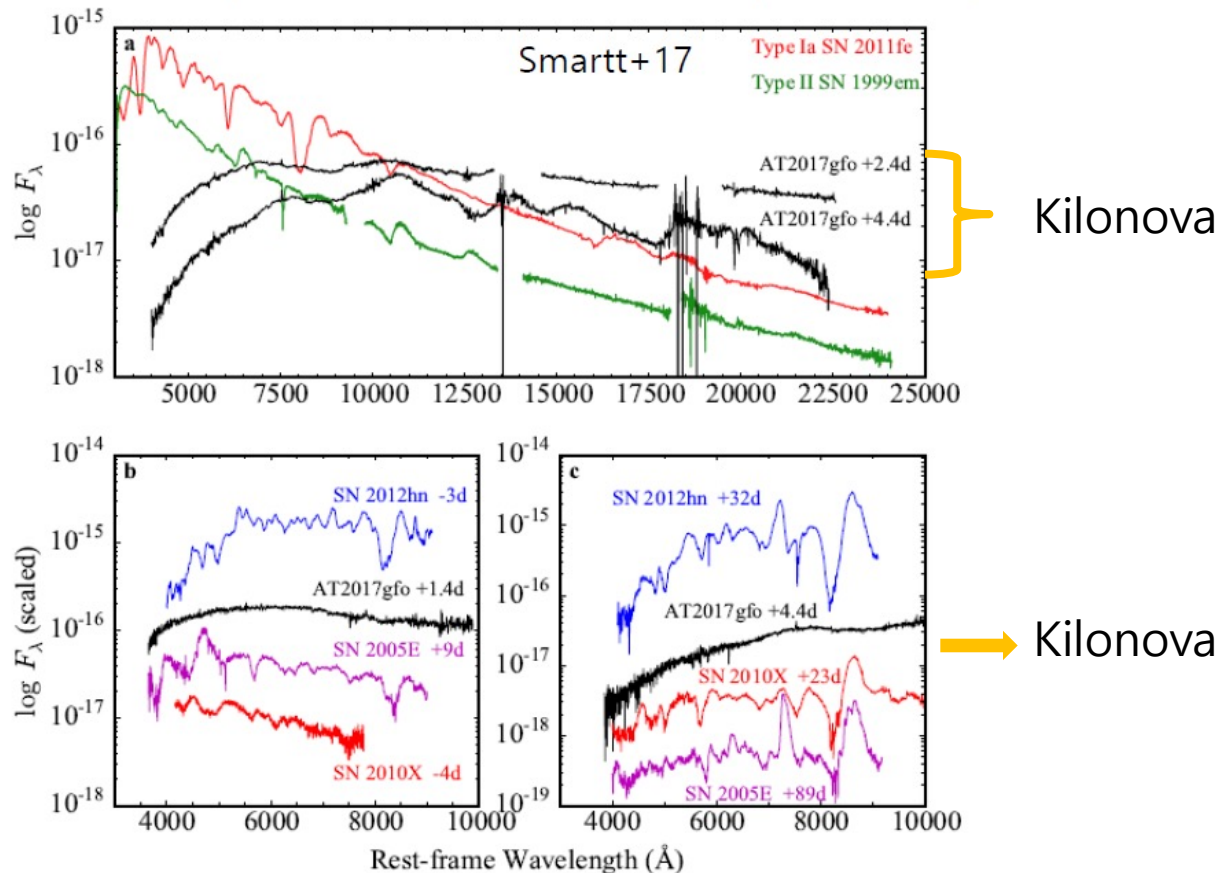
Need spectrum to select a kilonova

Spectrum: key to distinguish KNe from other transients



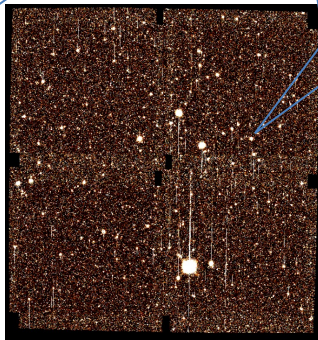
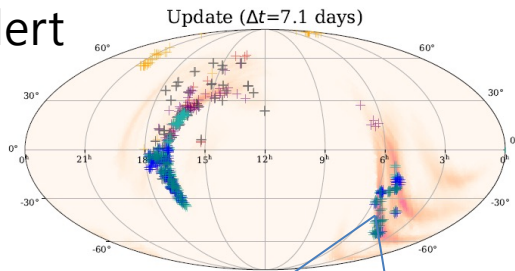
Spectrum can tell which transient is kilonova

Comparison of KN and SN spectra

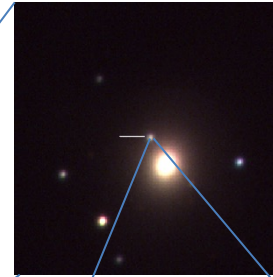


Search for KN

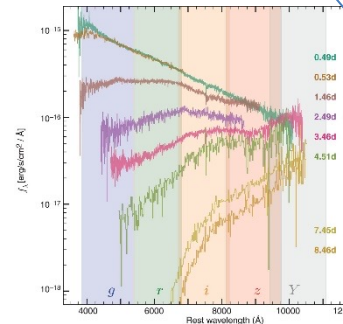
GW Alert



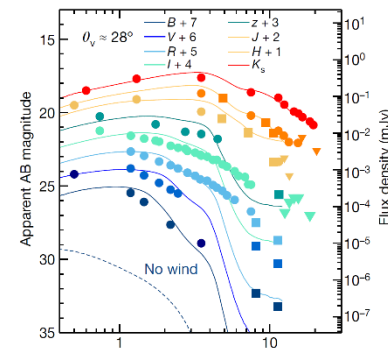
Imaging Observations
(~a few 100,000 sources per field)



Transient search



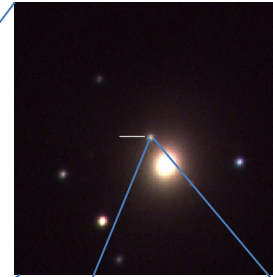
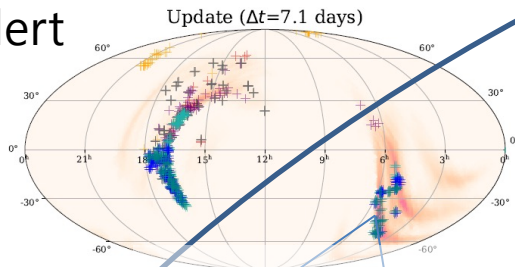
Spectroscopy and
KN identification



Time series
follow-up

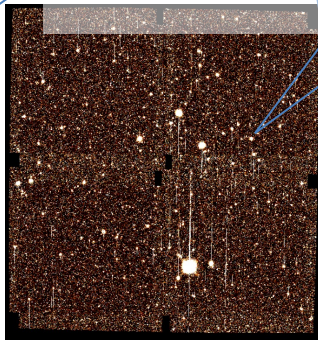
Search for KN

GW Alert

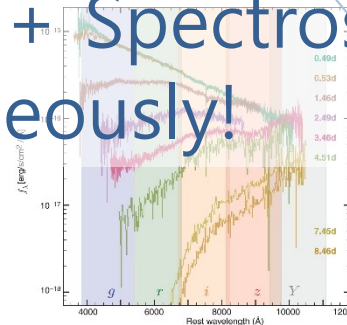


Transient search

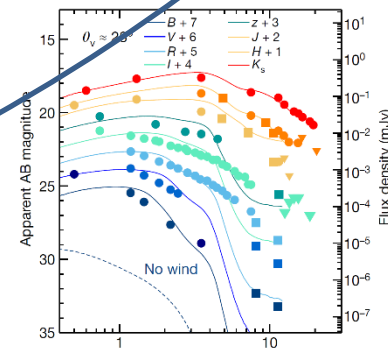
Let's do Imaging + Spectroscopy
Simultaneously!



Imaging Observations
(~a few 100,000 sources per field)



Spectroscopy and
KN identification



Time series
follow-up

7-Dimensional Telescope, 7DT

- ~20, 0.5m telescopes in Chile (El Sauce Observatory)
-
- Simultaneous imaging at 40 wavelengths (400 – 900 nm, 25nm resolution)
- Pixel scale 0.5", 1.25 - 25 deg² Field of view
- 7D = x,y,z (3) + time (1) + flux (1) + wavelength (1) + radial velocity (1)

7DT Components

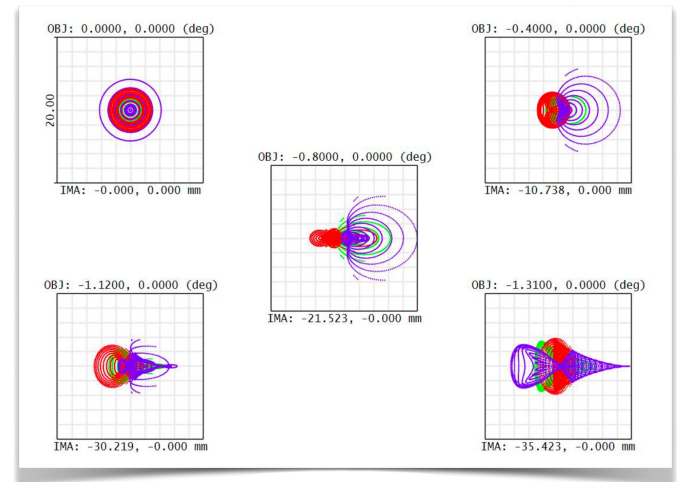
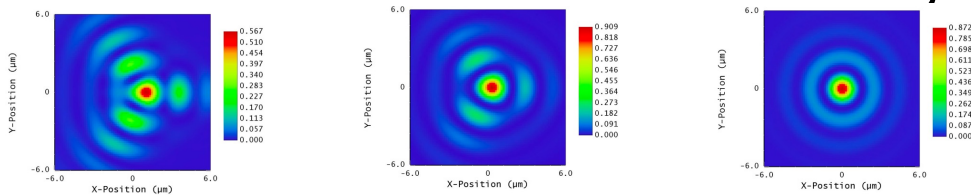
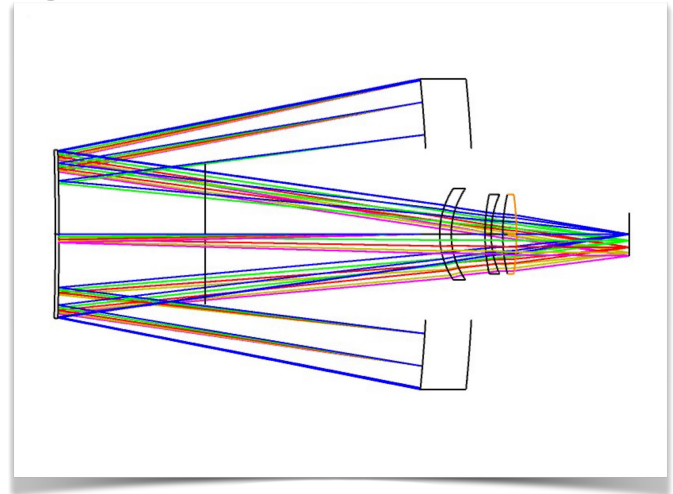
- 20, 0.5-m wide-field telescopes
- High precision telescope mount
- 60M pixel BI CMOS camera (3.76 micron)
- 40 medium-band + (3 – 5) broad band



Planewave DR500 telescope for 7DT

Telescope

- PlaneWave Delta-Rho 500 (DR500)
 - Corrected Dall-Kirkham Telescope
 - Optical performance
 - On-axis : 0.54"
 - Off-axis 30mm : 0.86"
 - Field diameter ~ 3 deg



Camera

- Moravian C3-61000Pro
 - Sony IMX455 CMOS sensor (pix size: $3.76\text{ }\mu\text{m}$)
 - 10k x 6k pixels = 60M pixels
 - 36mm x 24mm
 - 1.4 deg x 0.9 deg on DR500



Telescope site

- Chile, El Sauce Observatory (near CTIO/Cerro Pachon)
- Altitude: 1700 m
- 320 clear nights
- Median seeing $\sim 1.5''$
- Operated by ObsTech



Dome Construction Status

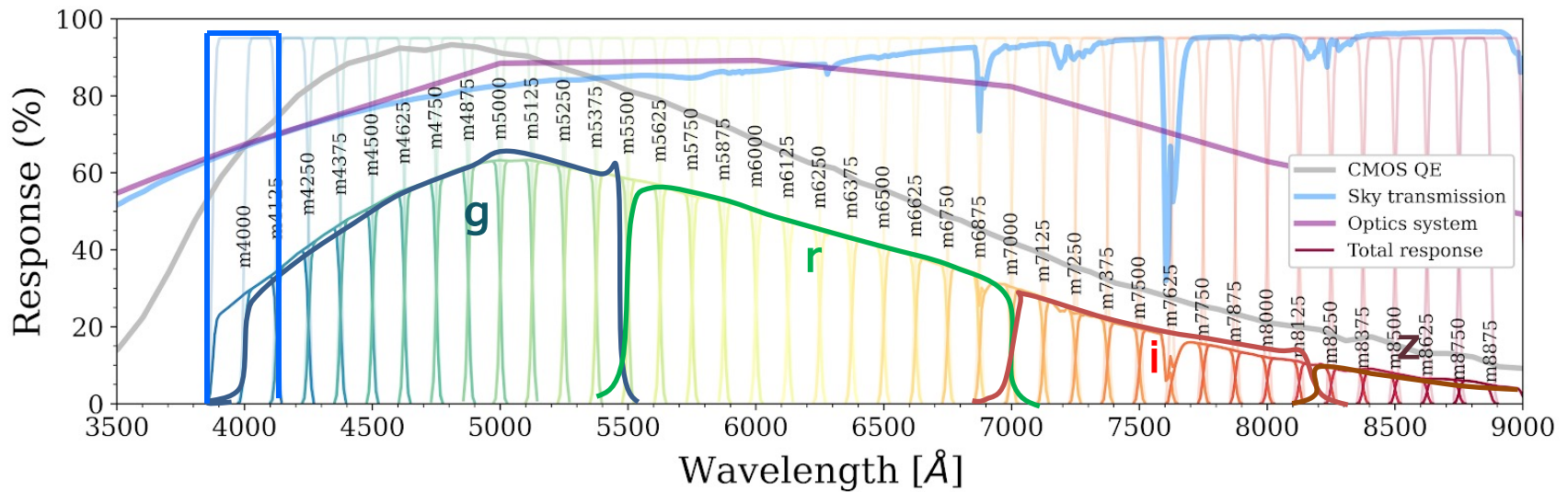


Dome completed in June, 2023
Telescope installation in mid July, 2023

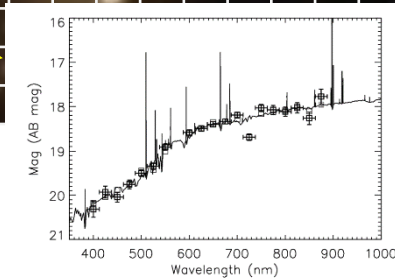
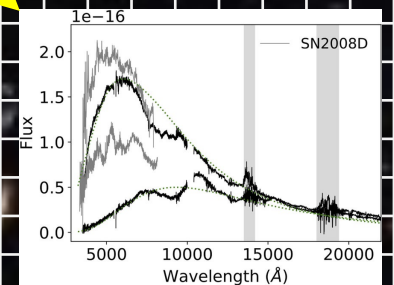
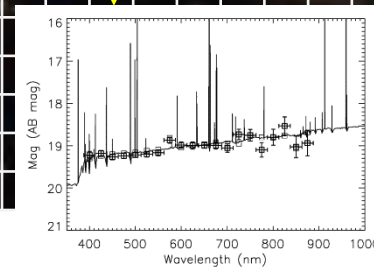
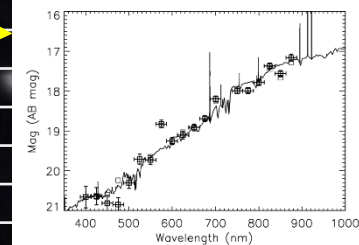
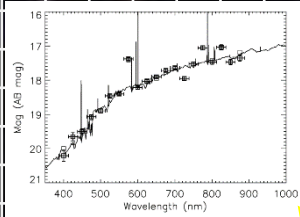
40 Medium-band Filters

- Width: 25nm (vs broad-band 150nm) at 400 – 900 nm
- Interval: 12.5nm
- $R \sim 40$ low resolution spectra → Good S/N with small telescopes
- Spectra for every pixel in the field of view (1.3 deg^2)

Medium-band vs Broad-band filters



Wide-field spectral mapping can identify KN fast

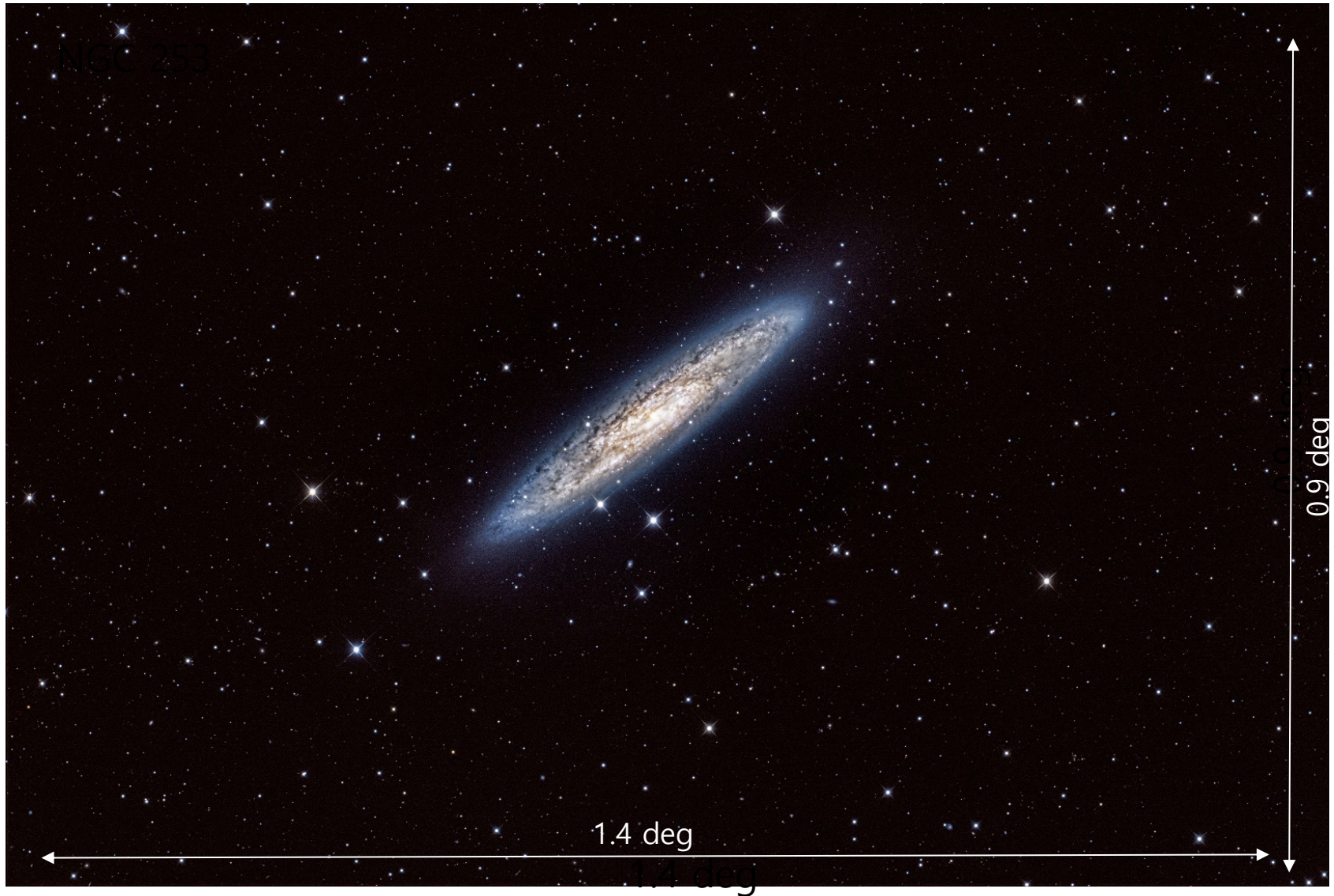


2025: Current Status

16 telescopes are in place
7-Dimensional Sky Survey (7DS) is ongoing

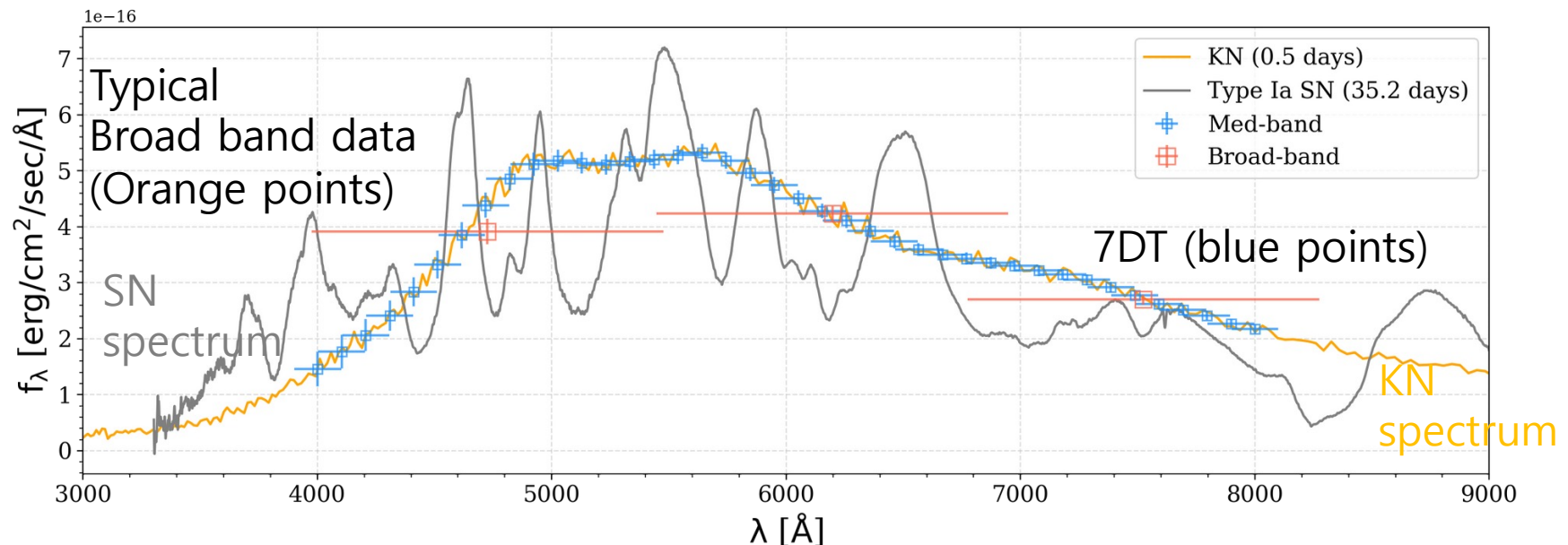


7DT First light image (2023-10-10)



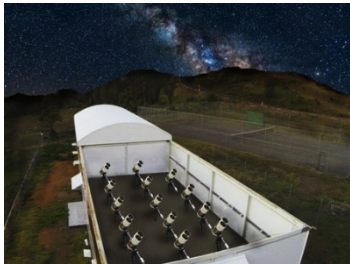
Kilonova vs Type Ia SN (G. Paek)

- With broad-band only (orange points): impossible to distinguish KNe from Type Ia SNe
- With 7DT (blue points): KN is easily distinguished from SNe



7DT, Three Observing Modes

1. Deep Observing Mode
Single filter + the same position
= 2.3m wide-field tel.

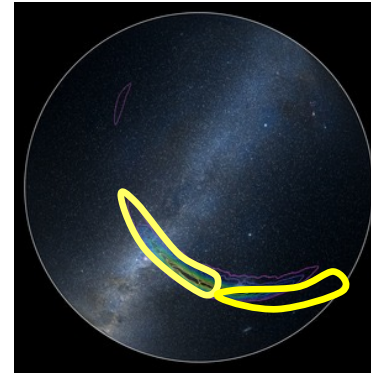


7DT



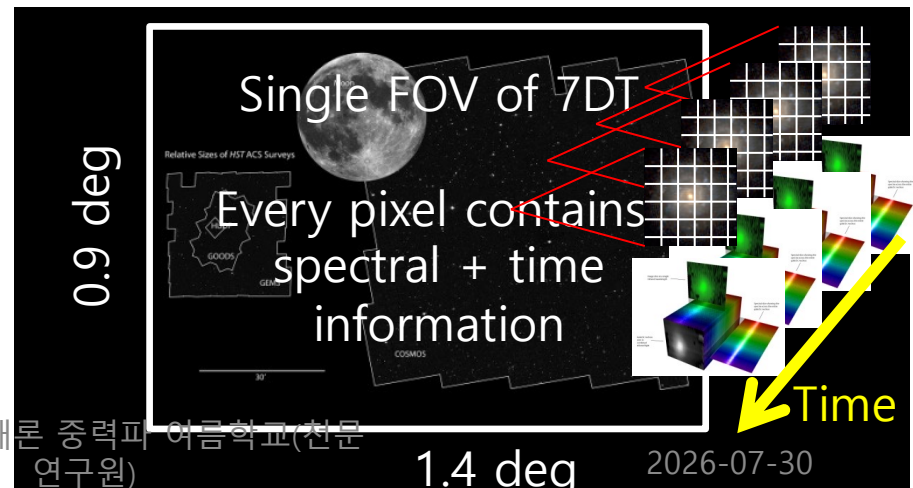
SDSS

2. Wide-field Mode
Single filter, different positions = 25deg^2



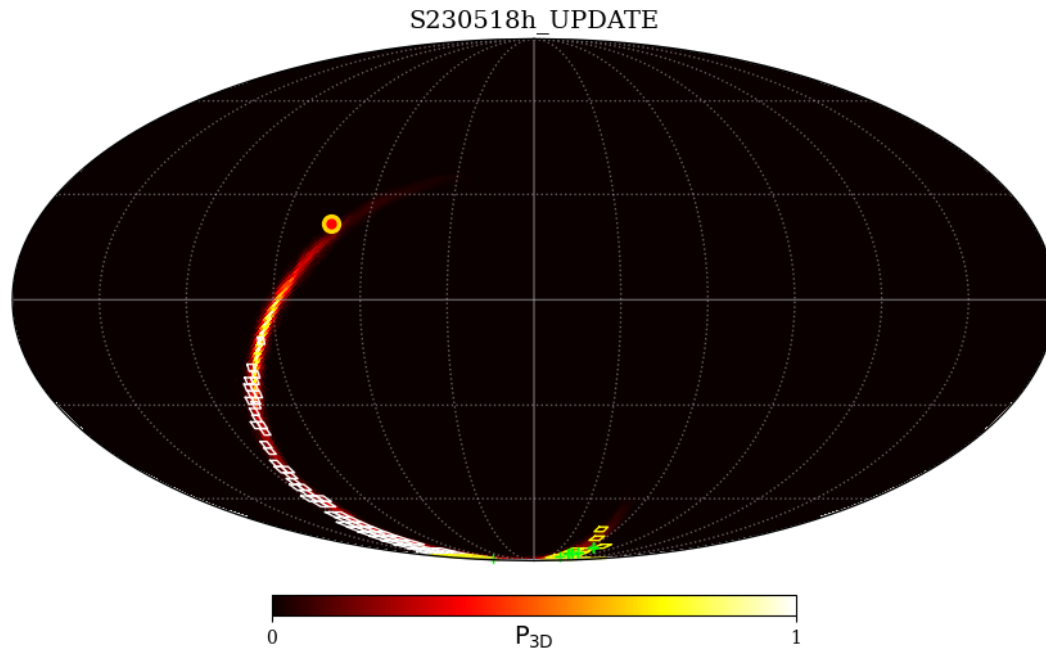
GW150914 can be covered with several observations

3. Spectroscopic Mode
Wide-field IFU-type observations



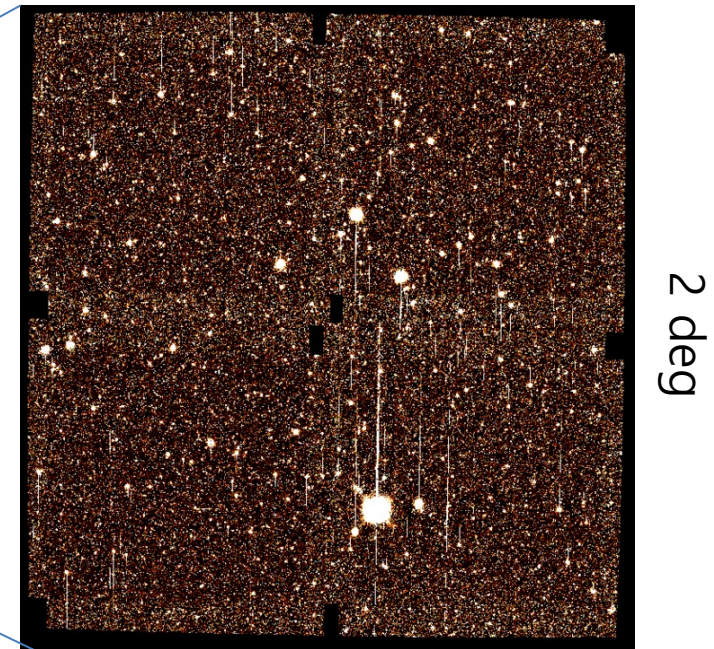
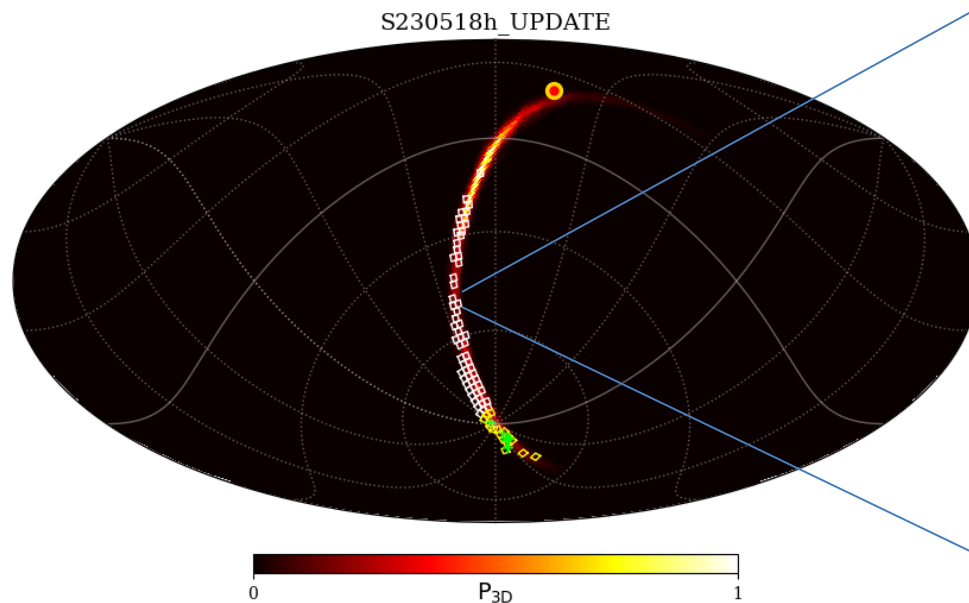
S230518h

- NS-BH merger event (2023-05-18 22:59:08 KST)
- No remnants expected → No EM Counterpart: Is this true?
- 90% Credible Region + Distance: 666 deg^2 , $278 \pm 68 \text{ Mpc}$ ($z \sim 0.065$)



GECKO Observation

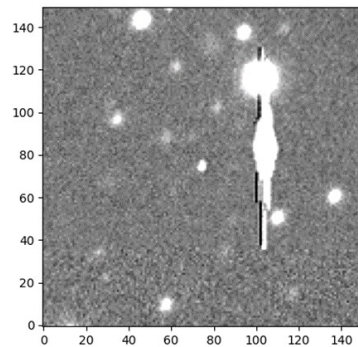
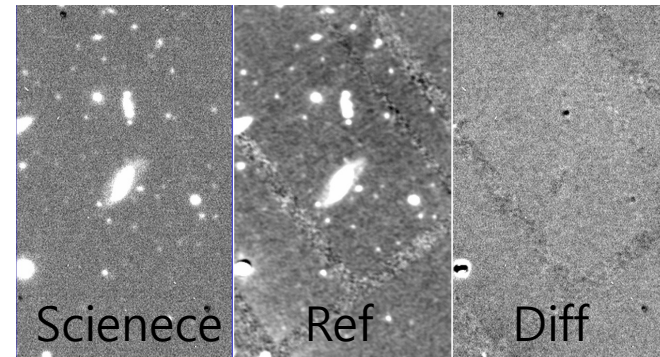
- Observation started at about 3+ hours after the alert
- Most of the observable regions covered by GECKO facilities
- 50% of the 90% credible area was covered



KMTNet image

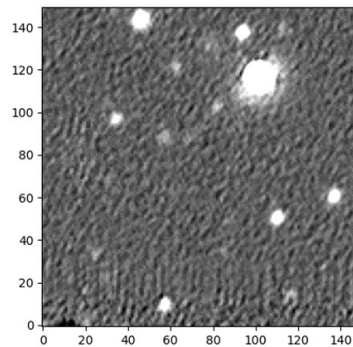
Transient Search

- Image subtraction + detecton: 5.3×10^6
- Initial flagging: 3.7×10^4
- AI real/bogus filtering: 2,690
- Filtering known stars (Gaia + VSX): 1,400
- Matching with GLADE+ galaxies: 153
- Total number: ?



KMTNet

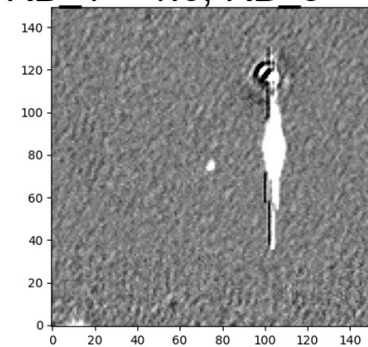
—



Reference

=

RB 1 = 1.0; RB 3 = 1.0



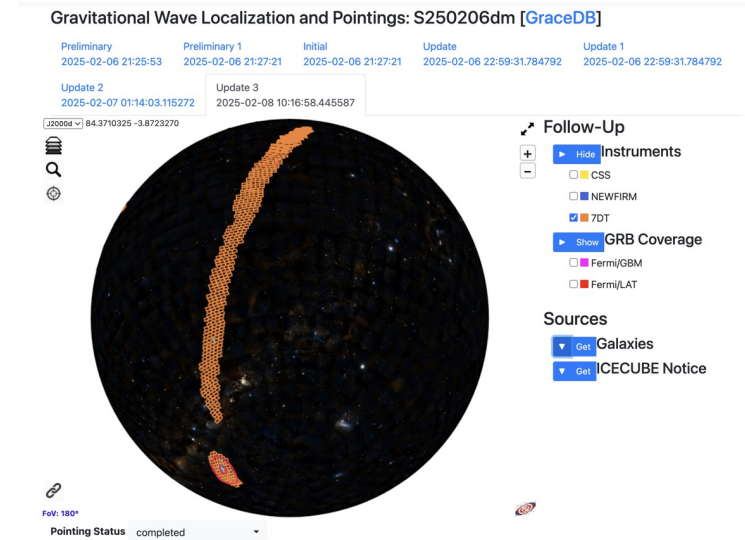
Subtrated image

GW follow-up observation by 7DT

2025-03-05

- 6 GW events have been observed

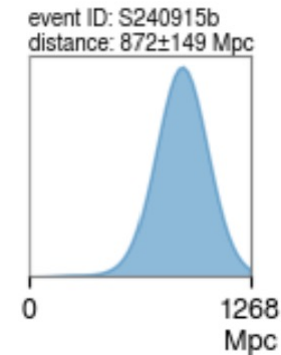
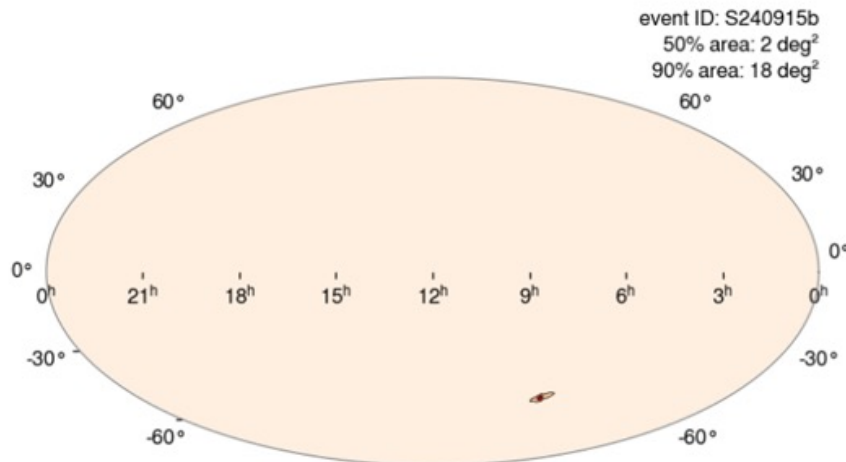
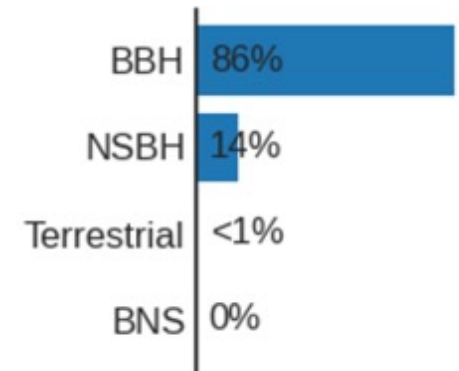
Event name	Observation coverage	Obsmode	Filter	Exptime
S240422ed	207 deg	Search	r	360s
S240422ed	7 deg	Spec		7200s
S240910ci	40 deg	Spec		600s
S240915b	35 deg	Spec		1800s
S240925n	25 deg	Spec		300s
S250206dm	590 deg	Search	g,r	600s
S250206dm	90 deg	Search	g	6000s



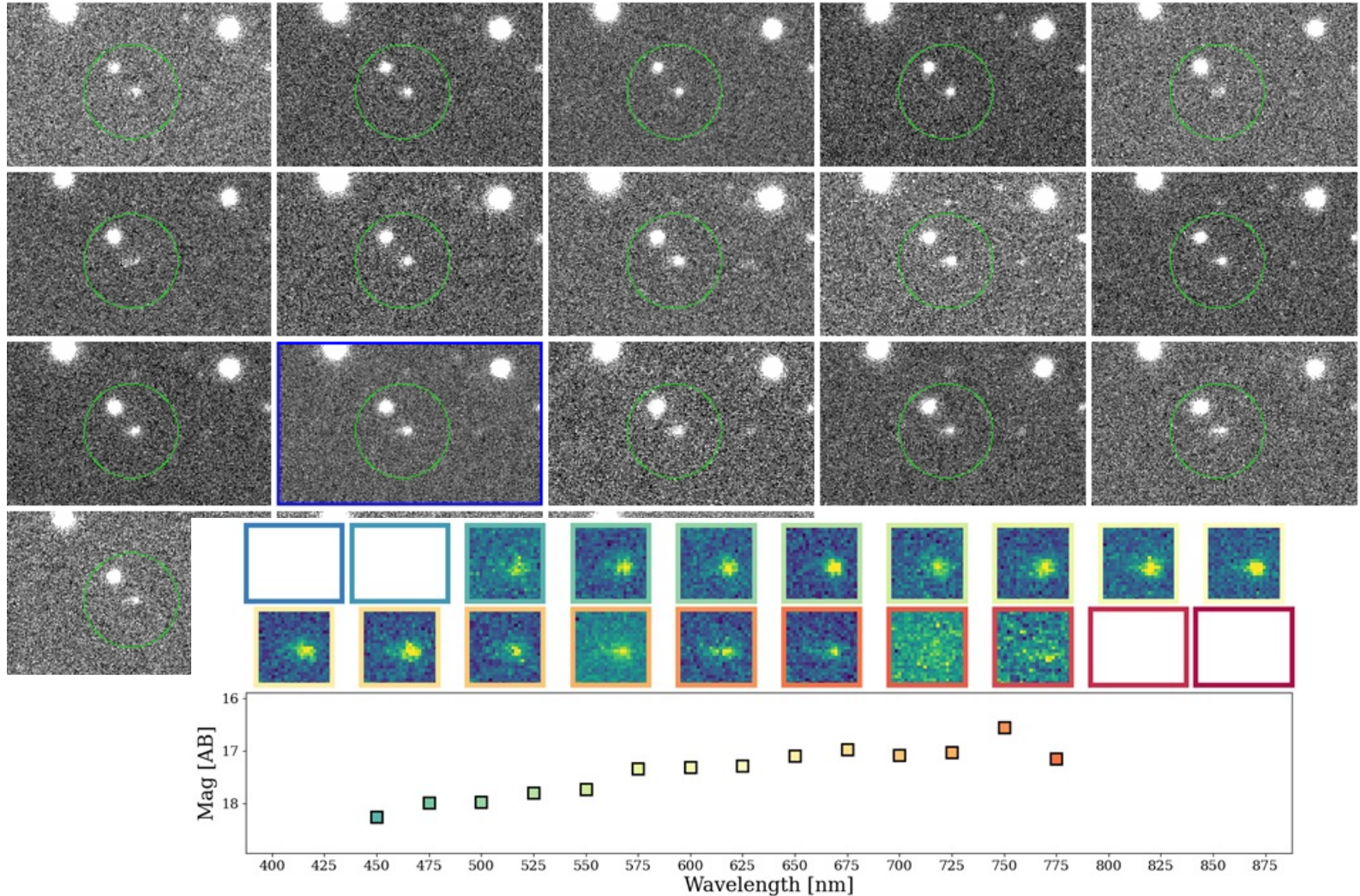
Example. 7DT observation on S250206dm ($\sim 590 \text{deg}^2$ covered)

S240915b

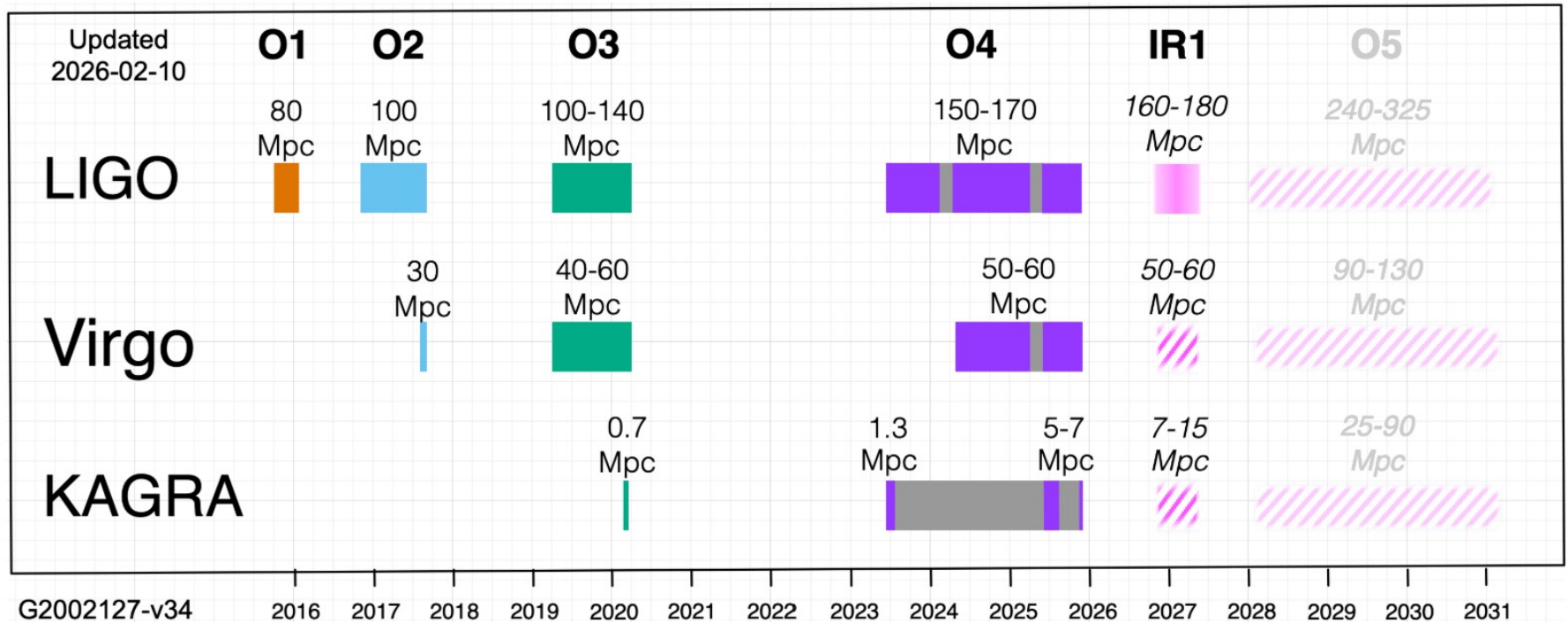
- Very well localized events and a possible NSBH (14%)
- FAR = 1/100 vrs



7DT image of GECKO24I



Near Future Prospects

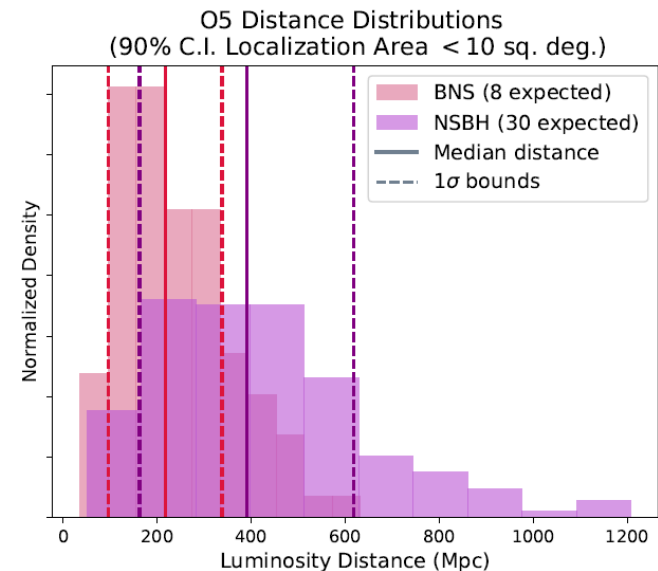


Forecast for O5

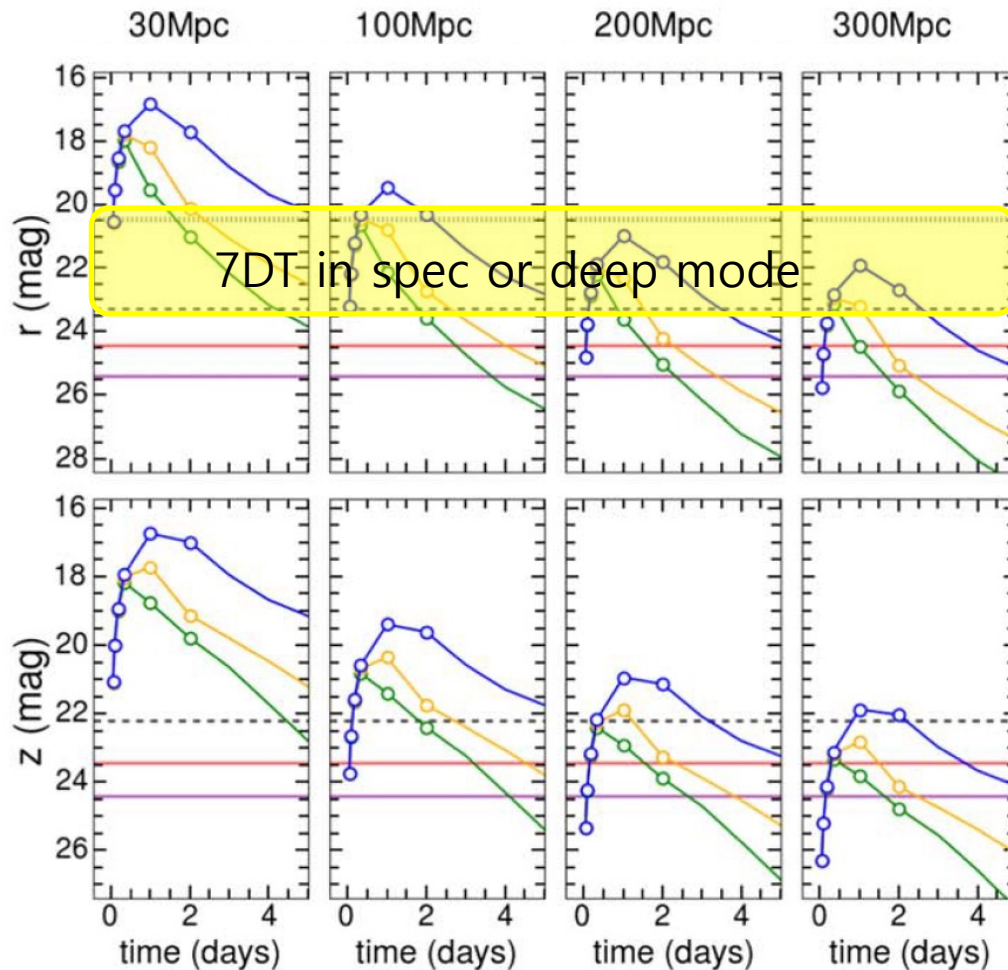
Andreoni+22, 24

	O5		
	Total	$20 < \Omega_{90\%} \leq 100$	$\Omega_{90\%} \leq 20$
NS-NS	190^{+410}_{-130}	22^{+49}_{-15}	$13^{+29}_{-9.1}$
NS-BH	360^{+360}_{-180}	45^{+45}_{-23}	23^{+23}_{-12}
BH-BH	480^{+280}_{-180}	104^{+61}_{-39}	70^{+41}_{-26}

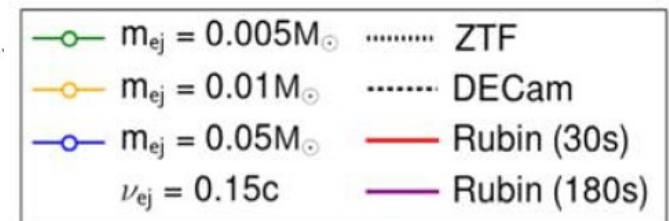
- 10 - 100 NS-involved events in O5
- Many at 300-400 Mpc



KNe in O5 & A+ will be distant (~ 300 Mpc) but catchable with existing facilities



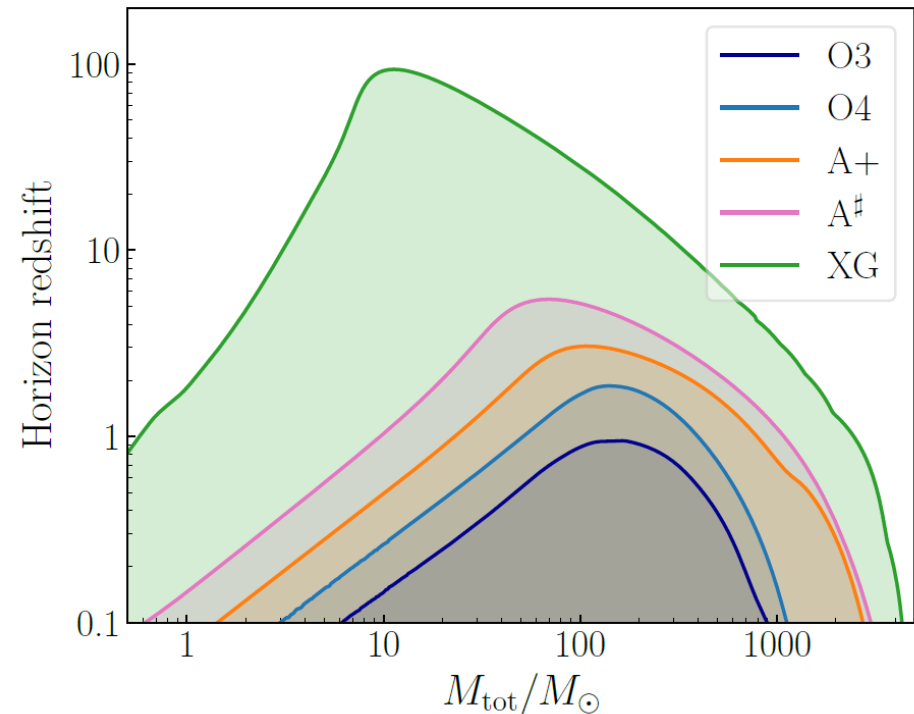
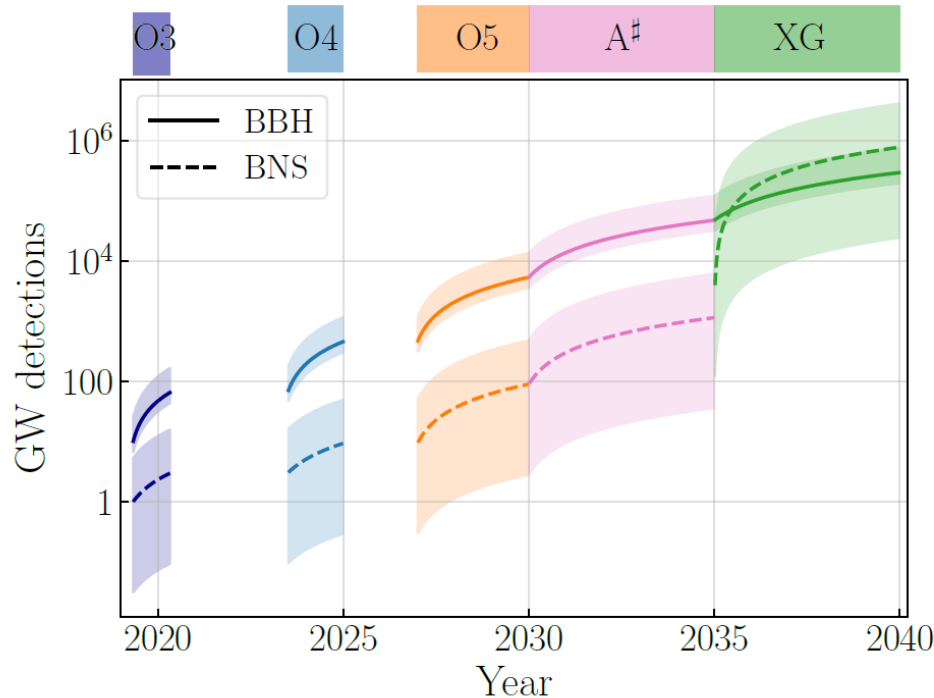
- 7DT can catch close KNe in spec-mode, distant ones in deep mode
- Large facilities (DECam, Rubin) will play important role



Andreoni+22

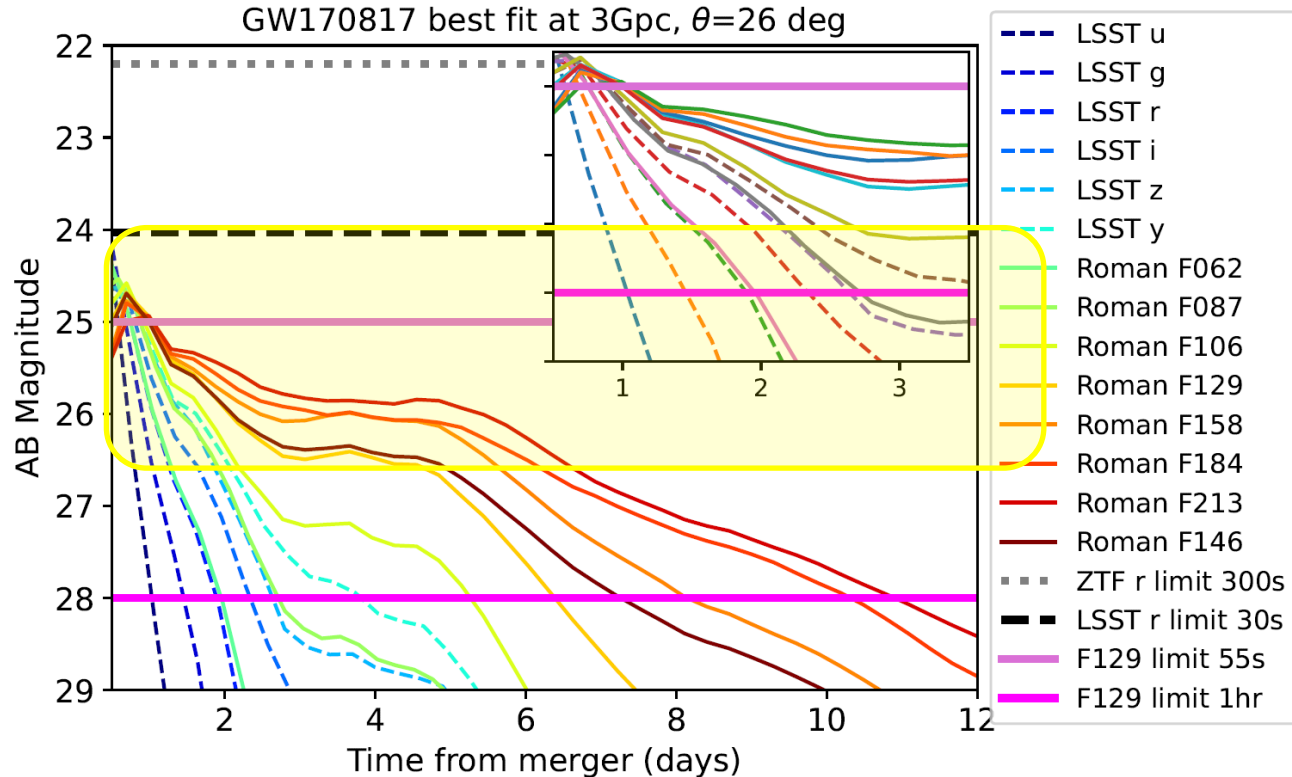
Distant Future Prediction

Chen+24



- Currently, BNS merger rate of 1/yr at $D < 200$ Mpc
- In future, 10^4 to 10^6 such events out to 10,000 Mpc

Kilonovae at $z=0.5$ (3 Gpc) are very faint:
about $r=25-26$ mag at peak



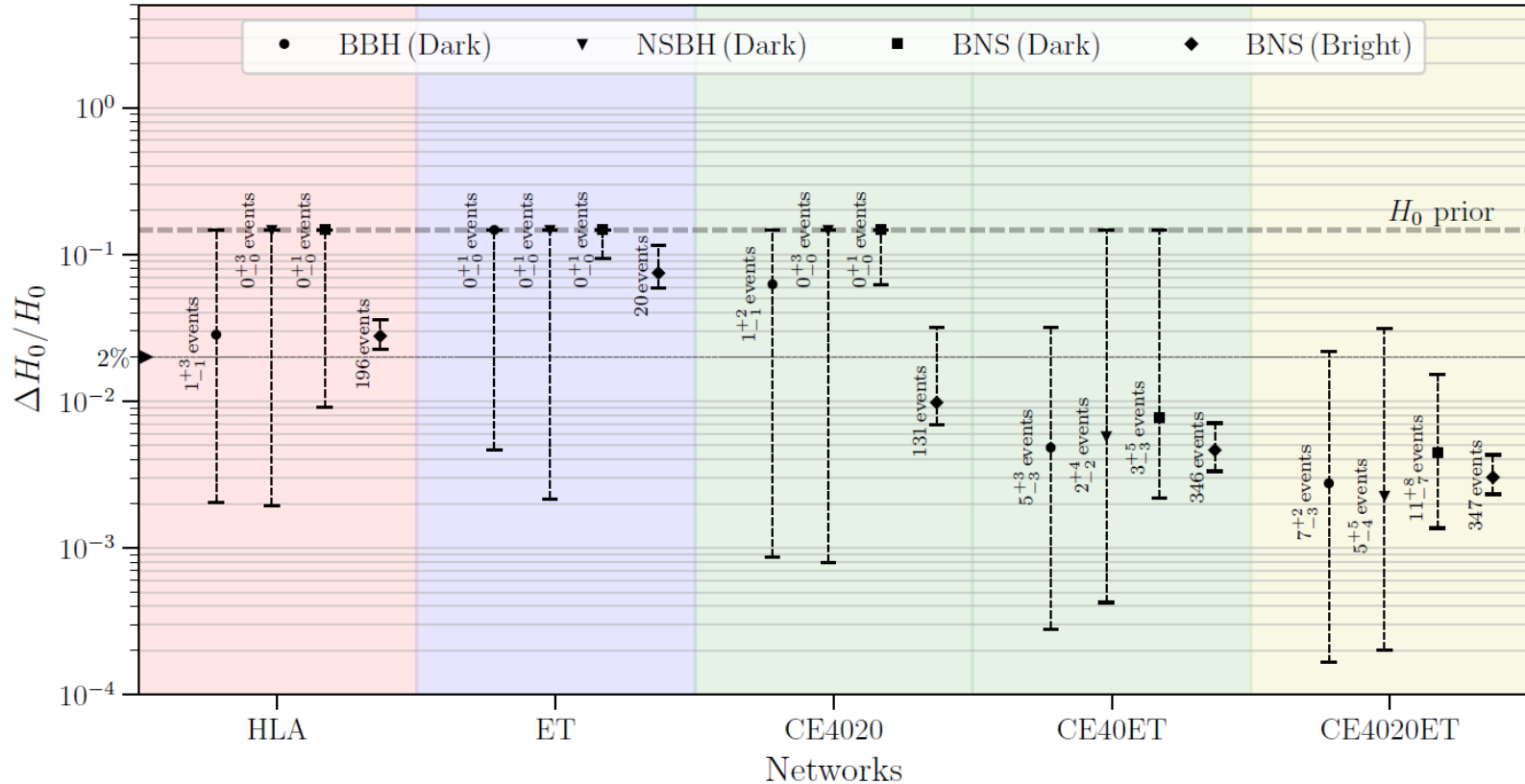
Rubin
(30s to 1hr)

- At $z=0.8$, 1 mag fainter → Rubin might be able to identify KN (but only Chilean sky)

Future Prediction for H0

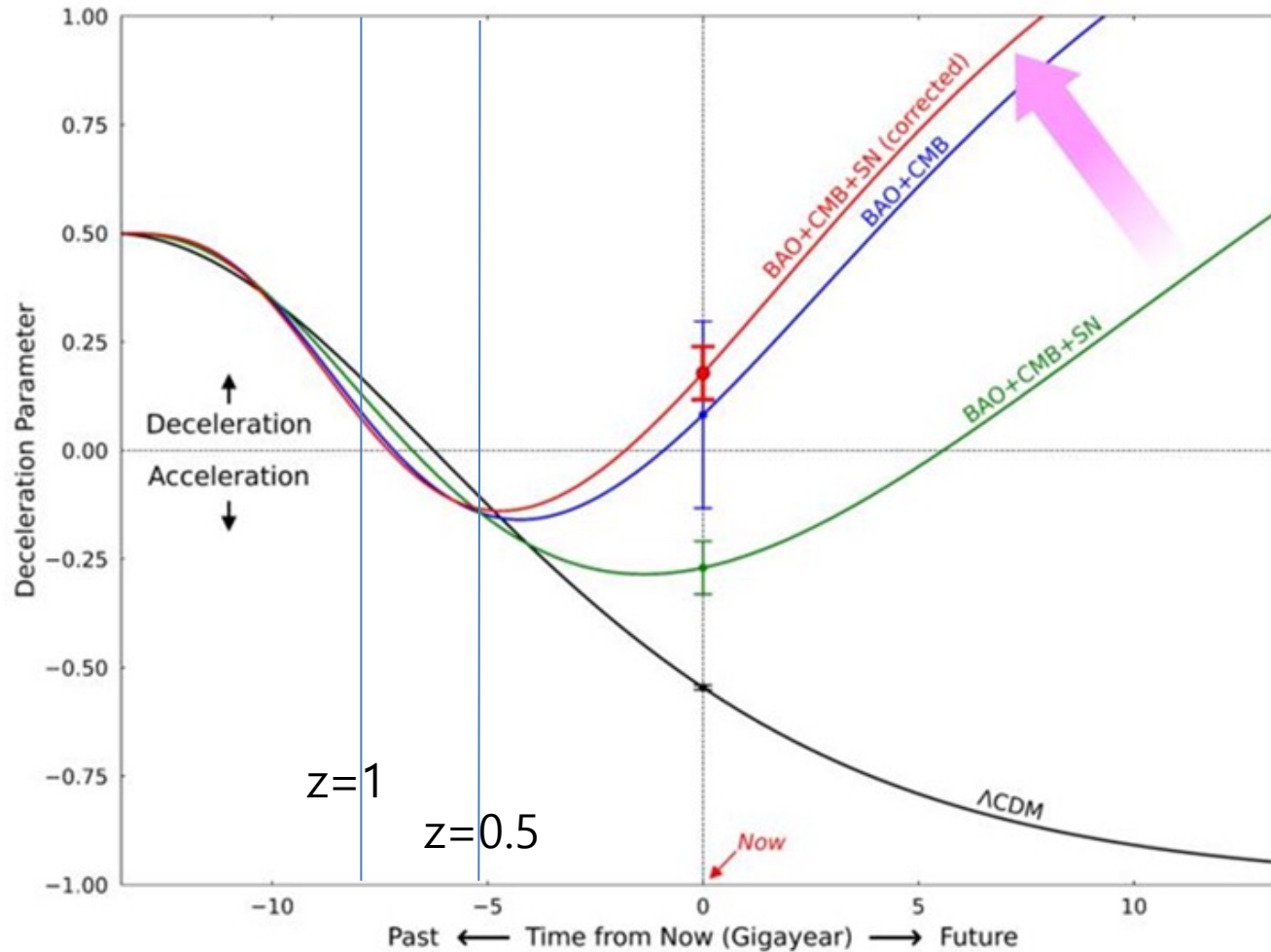
Chen+24

Gravitational – wave Standard Sirens

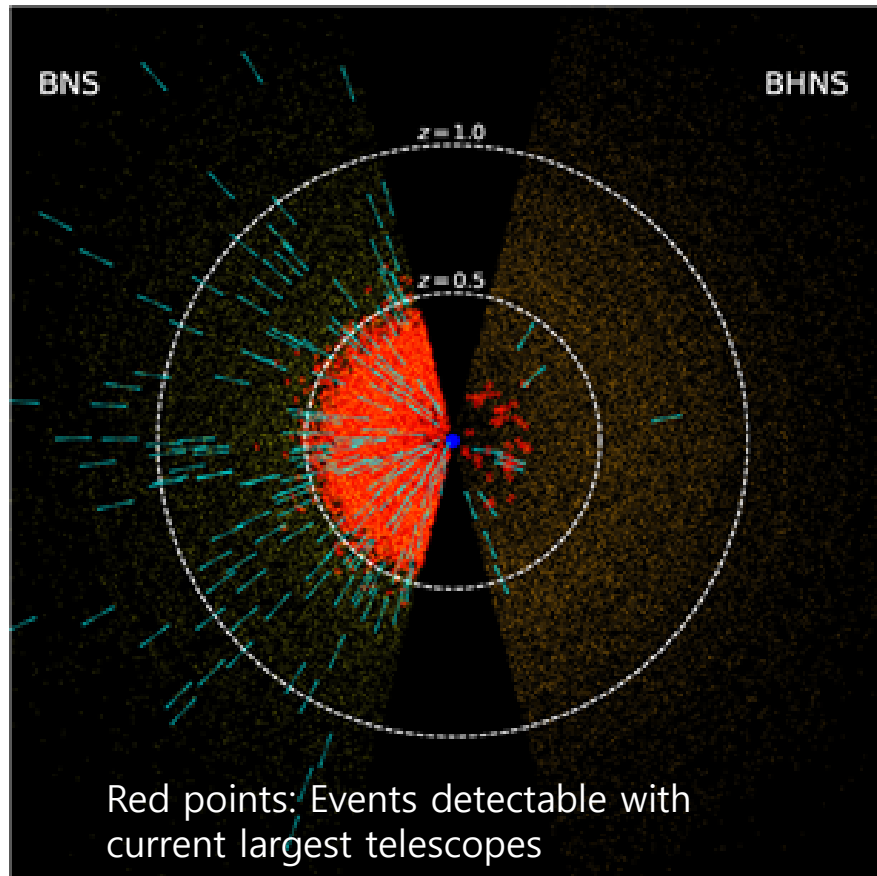


- < 1% accuracy for H0

Precision measurement is possible for Dark Energy ($\delta w_0 < \sim \%$, $\delta w_a < 10\%$) with tens of thousands of MMA events



In 3G GW detection era, the horizon distance will be limited by EM observations

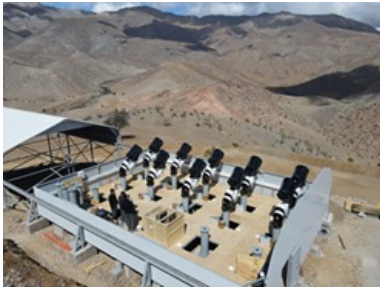


ET Blue Book

- Discovery: Wide-field, ground-based large telescopes
- Characterization: Space telescopes
- Too many events for existing optical facilities (1000s per year)
- Need more like Rubin, Roman, in future

What optical telescopes will be available in future?

Discovery



7DT, ZTF,



Rubin, DECam, VST, ...

Characterization



JWST, Roman, CSST...

Gemini, Subaru, VLT, ...

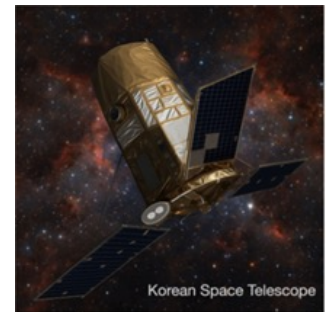


GMT, TMT, ELT

Future facilities?



ng7DT (planning)



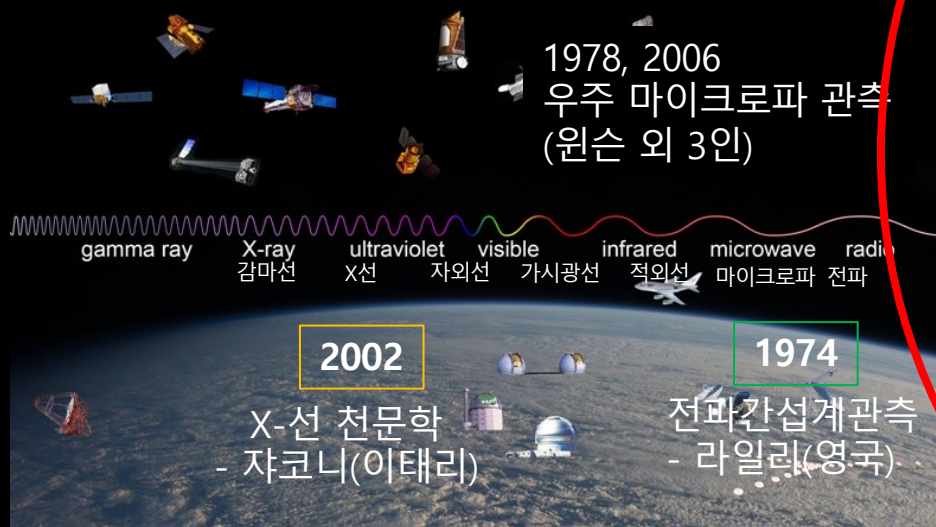
Korean Space Telescope (1.4m, planning)

다중신호 천문학

- GW170817: 중력파 다중신호 천문학의 잠재력을 제시(우주론, 고에너지 현상 규명, 중원소 생성 과정 규명)
- GECKO+7DT 등 우리나라도 다중신호천문학에서 활약할 기회 충분
- MMA 미래 전망은 장미빛? → 중력파 사건 대비 광학관측시설 성능 개선 필요

우주를 보는 새로운 창 다중신호천문학

빛(전자기파)



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- 쏜(미국)
- 베리시(미국)

- 새로운 우주를 연구 → 인류 지식 확장에 크게 기여