# GECKO

# Follow-up Observation of GW 190425 and Identification of KN with Gemini

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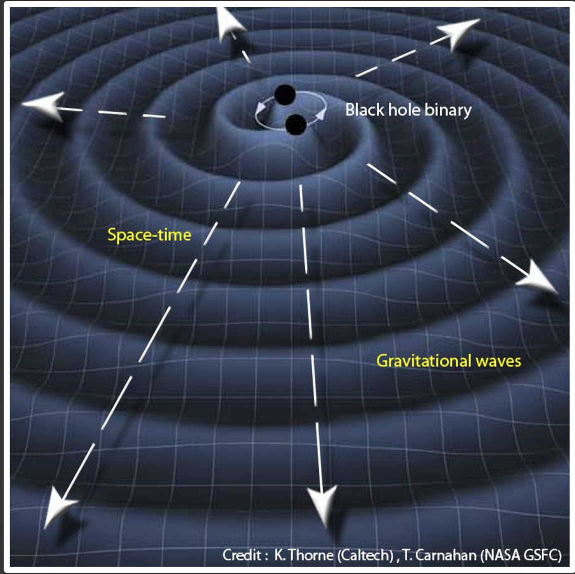
22.07.28 11:50-12:05+5

Gemini Science Meeting 2022

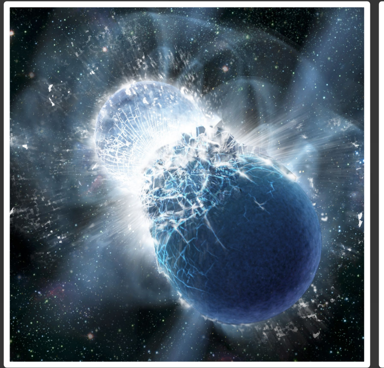
GW Universe

## Gravitational Wave (GW)




## Compact Binary Coalescence (CBC)

BNS merger



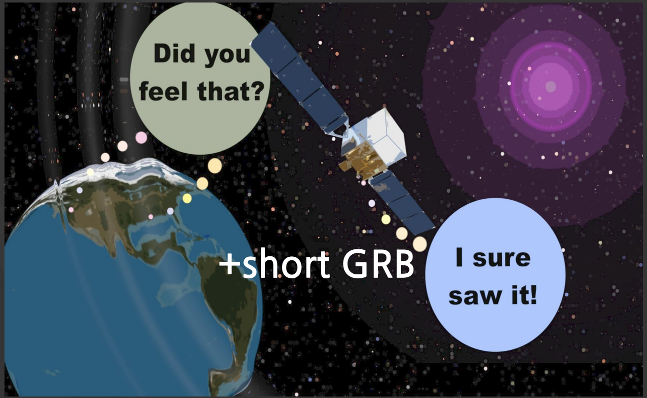
BHNS merger

**Kilonovae (KNe) → ElectroMagnetic wave (EM)**

## GW EM counterparts from BNS(BHNS) merger

# GW170817 : The first BNS merger

| GW | EM | | | Host galaxy |
|---|---|---|---|---|
| | γ-ray | Optical/NIR | Radio | NGC 4993 |






Coulter+17

**A new era of GW *Multi-Messenger Astronomy***

# GW EM Counterpart

- The exact position of GW source
  - Link between of BNS merger, short GRB, kilonova, and GW
  - Constraint on the kilonova models
- GW Host galaxy
  - The environment of BNS merger
- **GW standard siren**
  - GW luminosity distance + host galaxy redshift

**The Nature of the GW Source**

# Things to do in the future 🤔

1. **There is only 'one' GW EM counterpart**
   ⇒ More GW EM counterparts are essential for statistical approach

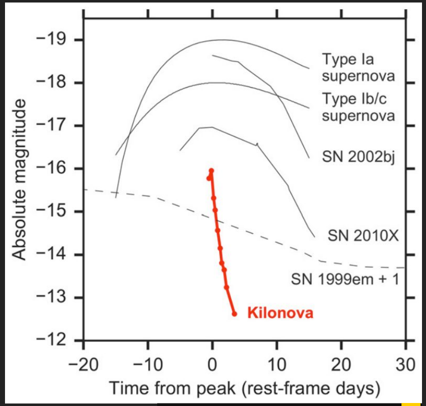
2. **Degeneracy betw. GW luminosity distance & inclination of the GW source**
   ⇒ KN/short GRB can constrain the inclination

3. **The fastest early detection is still +11 hours**
   → Early emission has crucial information for its nature

**Rapid identification is the keys to the success of MMA**

# Obstacles for Rapid Follow-up

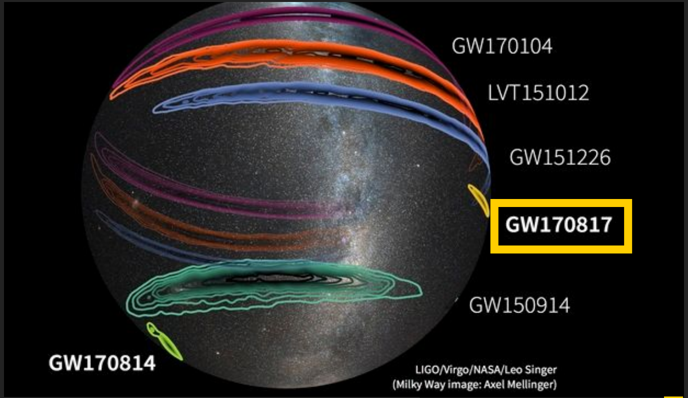
## Faint & Fast decay of Kilonova




Arcavi+17

- Fainter than SN (few mags)
- Δm/day > 0.5

## Poor skymap localization




Singer+16

Optimal **facilities and observing strategy** are essential

# Gravitational wave Electromagnetic wave Counterpart Korean Observatory (GECKO)

**Uzbekistan**
Maidanak 1.5-m

**KOREA**
SAO 1.0-m
KHAO 0.76-m
SOAO 0.6-m
DOAO 1.0-m

**US**
LOAO 1.0-m

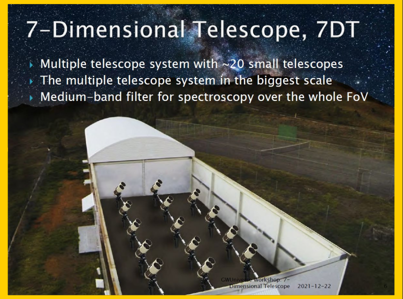
McDonald 2.1-m, 0.8-m, 0.25-m

**Chile**
KCT 0.36-m
RASA 0.36-m

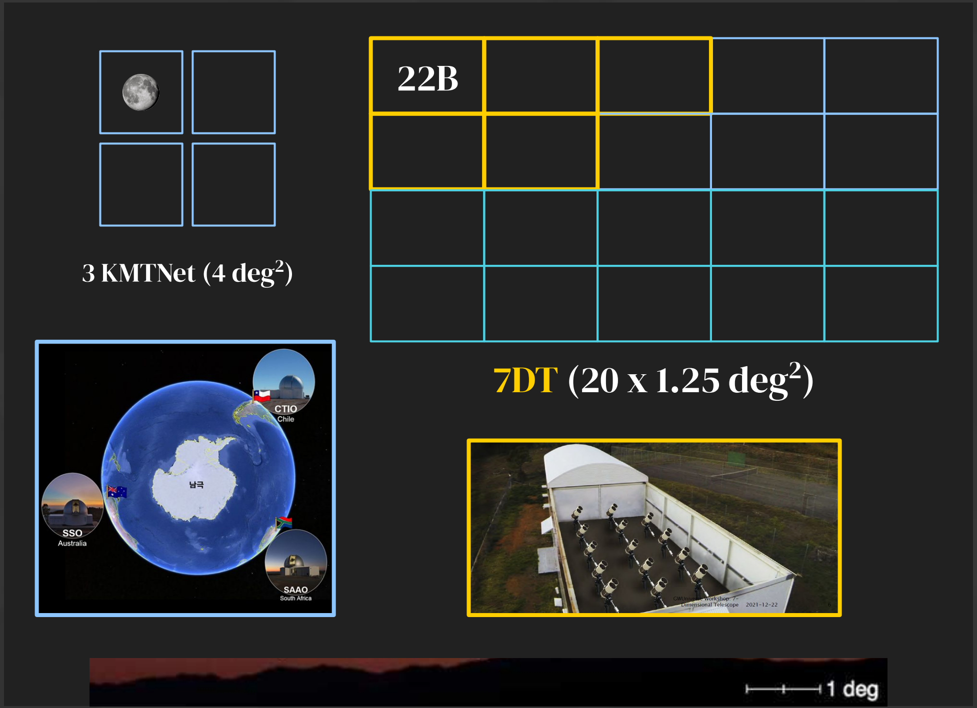
**Three KMTNet 1.6-m**
- SAAO
- SSO
- CTIO

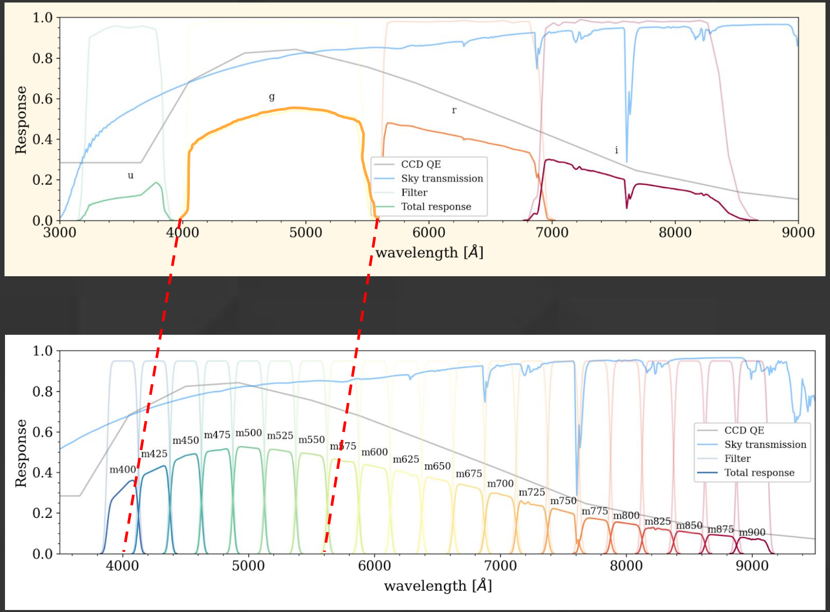
**Australia**
Siding Spring
LSGT 0.43-m

**ToO program**
Gemini-North &
Gemini-South,
UKIRT



# Gravitational wave Electromagnetic wave Counterpart Korean Observatory (GECKO)



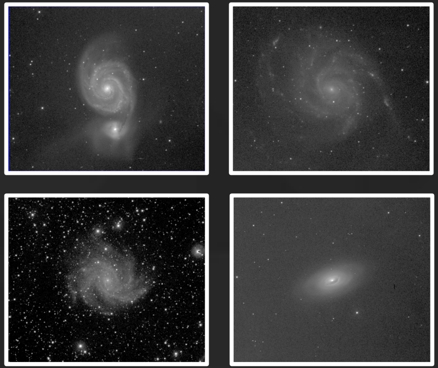



# Gravitational wave Electromagnetic wave Counterpart Korean Observatory (GECKO)


# Strategies to Find GW EM Counterparts

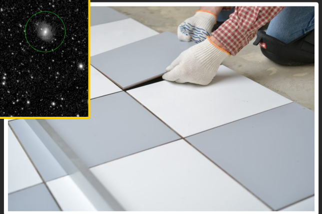
## 🎯Galaxy-targeted observation

- ❑ Prioritized GW host galaxy candidates
- ❑ **Narrow** field-of-view (FoV) tel.
  e.g. Most of 1-m telescopes



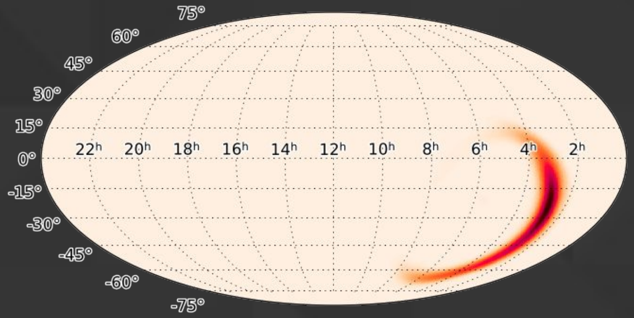

## 🪟Tiling observation

- ❑ Tiling the GW localization map
- ❑ **Wide** field-of-view (FoV) tel.
  e.g. 7DT, and KMTNet



# Galaxy-targeted observation

GW → Progenitor / Distance range / Localization → Galaxy catalog → Host galaxy candidates



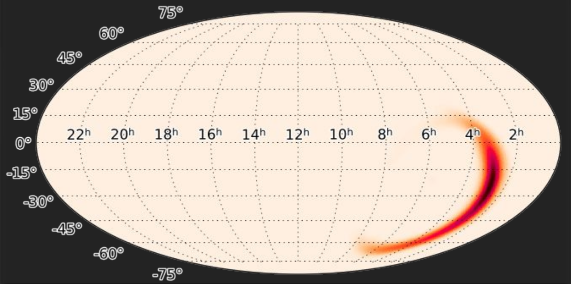

**G**alaxy
**L**ist for the
**A**dvanced
**D**etector
**E**ra

- 3,200,000 objects
- RA, Dec, Distance, Photometry (K-band, …)

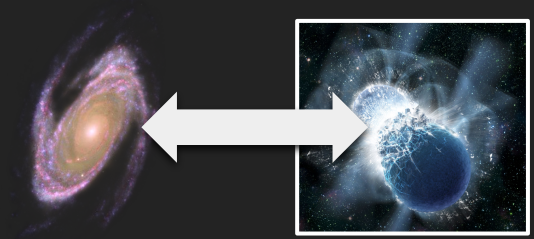
Dalya+18

# Galaxy-targeted observation : Prioritization

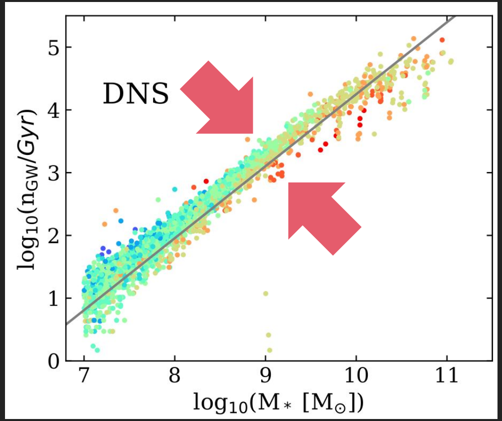
## 1. Position on the skymap




## 2. Distance



## 3. Host galaxy property



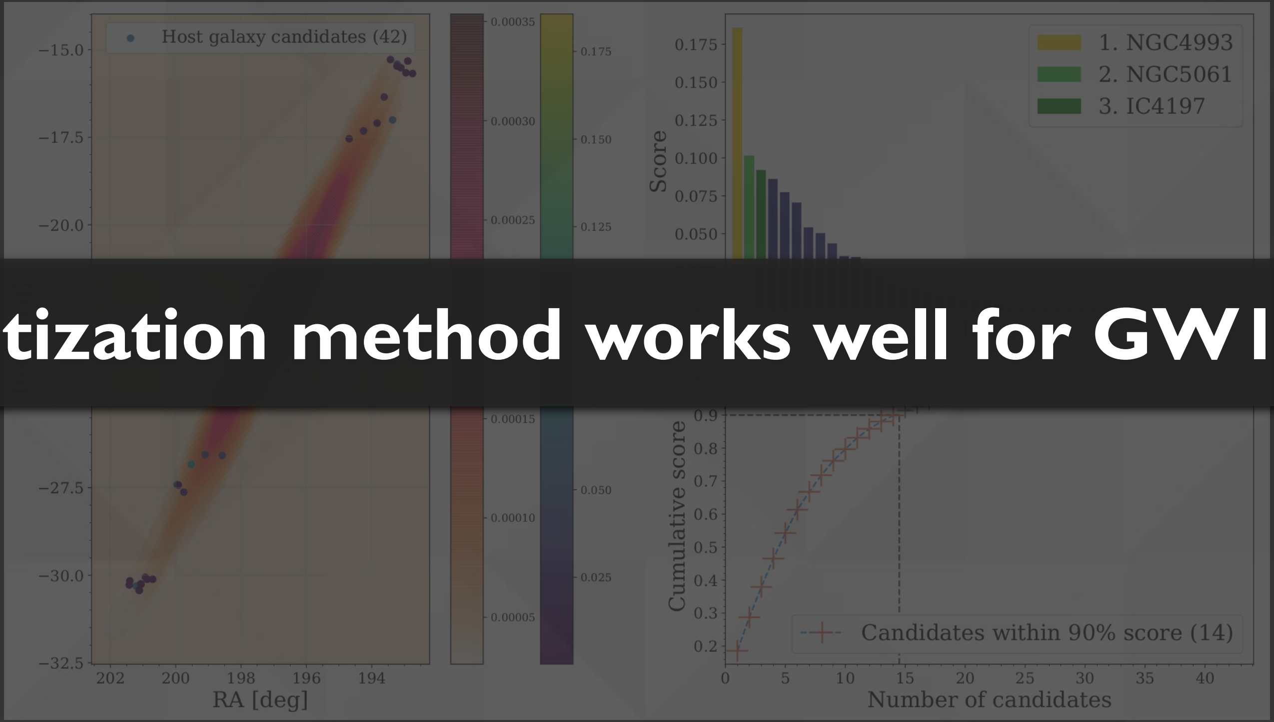

Artale+19

$$L_K \propto M_*$$

**More massive host galaxy**

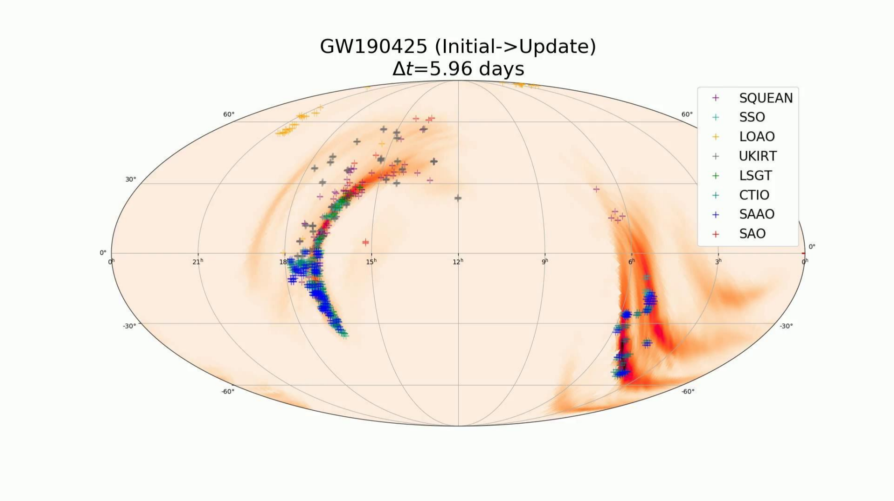
Higher BNS merger rate

# Application to GW170817




**Prioritization method works well for GW170817**

# Result of Follow-up Observation of GW 190425




EM counterpart for GW 190425 was **not found!**

| First Observation | Coverage [deg2] | # of covered galaxies | Covered score | Found transient | Median 5-σ Depth | GW EM Counterpart? |
|---|---|---|---|---|---|---|
| +90min | ~420(~4%) | 620(~10%) | ~27% | 10 | ~21.3 | No |

KMTNet has a dominant contribution on the coverage

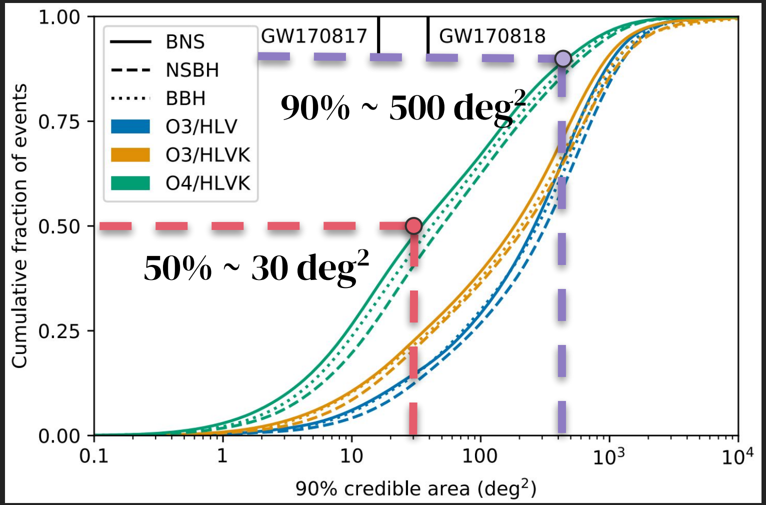
# Synergies of GECKO+Gemini

- **GECKO**
  - Real & bogus classification on the image
    - **AI tech.** with CNN+topology (S.H. Lee+22)
  - Transient type classification
    - **Color & brightness** criteria in broad (medium)-band
    - **Decay rate** filtering with time-series data

- **Multiple instruments of Gemini**
  - Deep imaging & spectroscopy from **optical to NIR**
  - Rapid follow-up : **Confirmation** and **characterization** of the GW EM counterparts
  - Long-term follow-up
    - **Characterization** of late-phase light curve
    - **Environment** of GW source

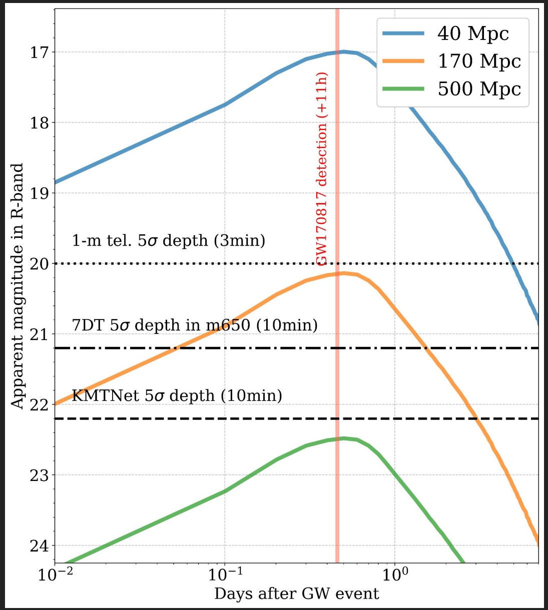
# Prospects on the LVK O4 run (23.03-)

## GW Localization




Abbott+20

## GW Distance




2023A : 23.02.01-07.31
5 month overlapped

BNS merger rate
$10^{+52}_{-10}$/year

$\Rightarrow 4^{+22}_{-4}$/5 month

50% events could be covered early by GECKO+Gemini facilities

More than 2 early KNe

# Take Home Messages 🏠

- ❑ More GW EM counterparts are important to understand the nature of GW sources & resolve Hubble tension

- ❑ GECKO is GW EM counterpart follow-up campaign in Korea

- ❑ GECKO+Gemini will identify early EM counterparts in O4 run

*Fin.*

# Supplementary

# GW EM Counterpart Korean Observatories

# To the Fast Identification of GW EM counterpart

**GW Alert & Fast Optical follow-up**

↓

**Filter Transient Candidates**

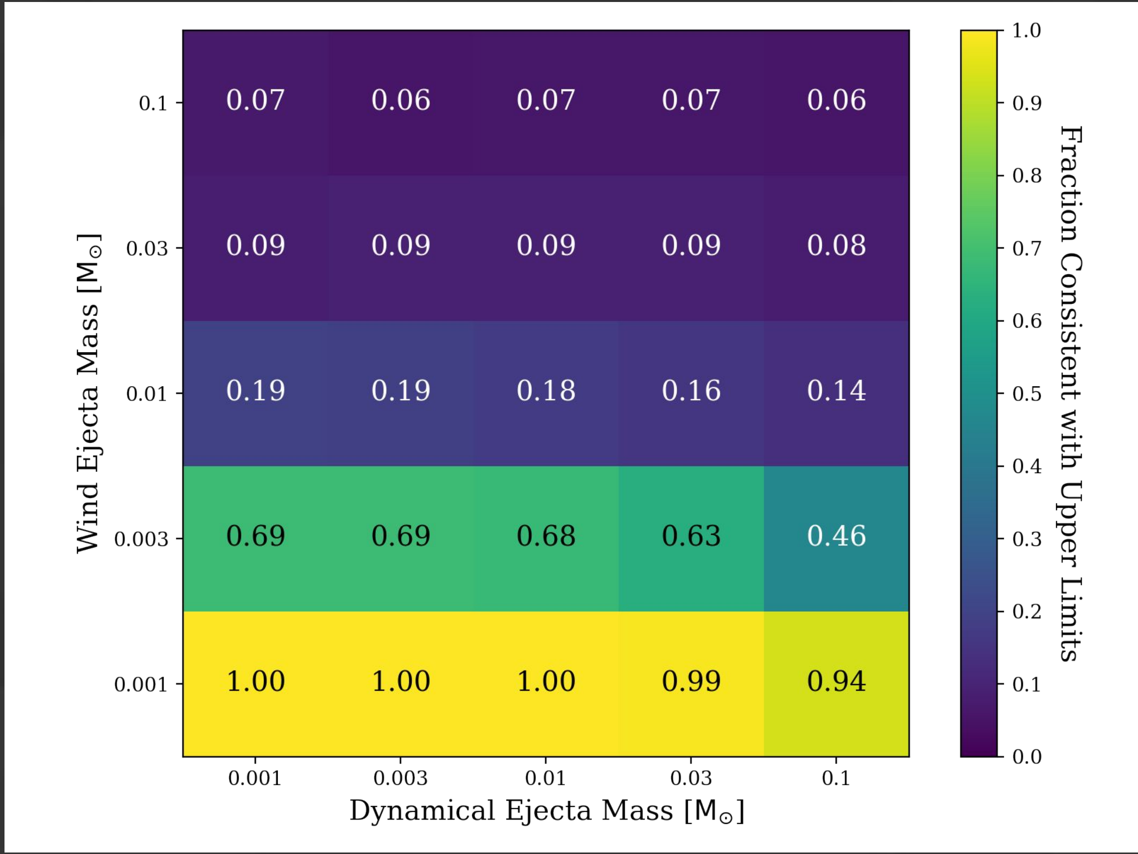
↓

**Classification (KNe or not?)**

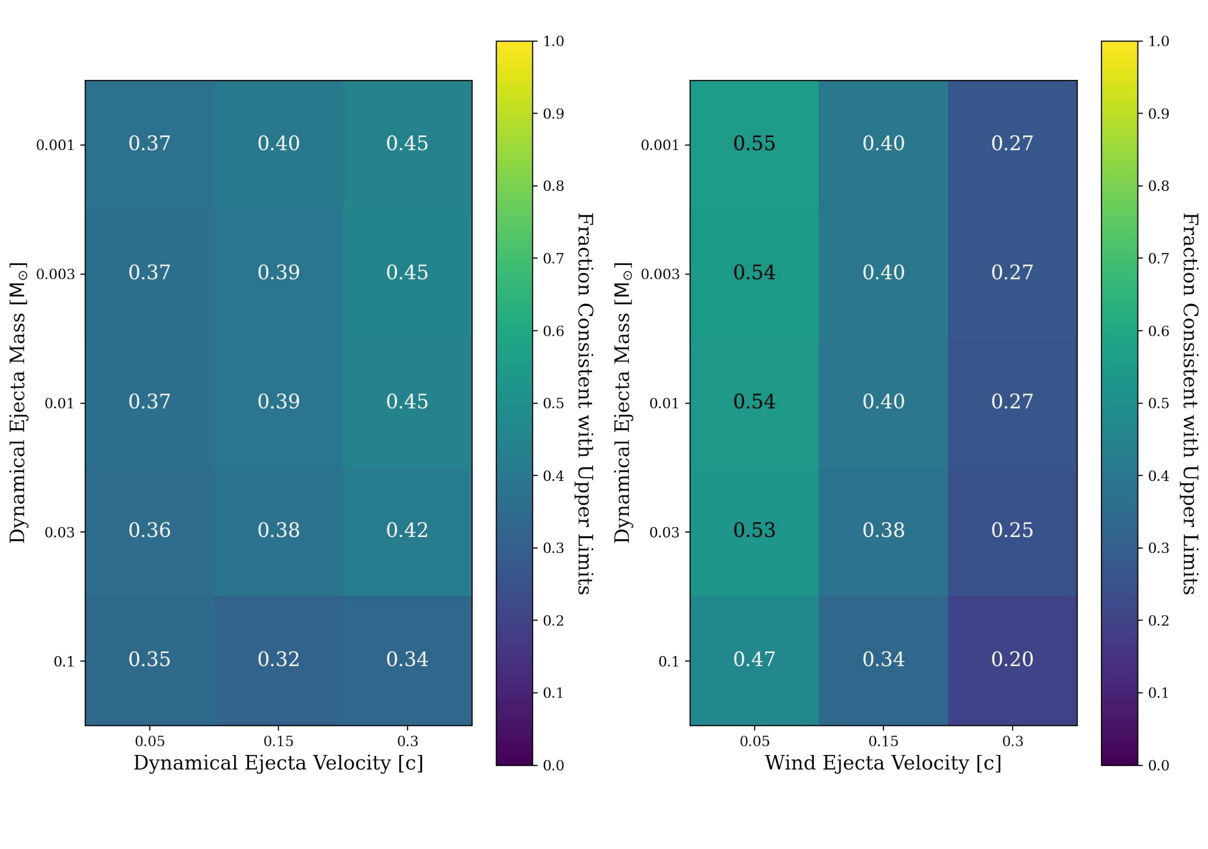
↓

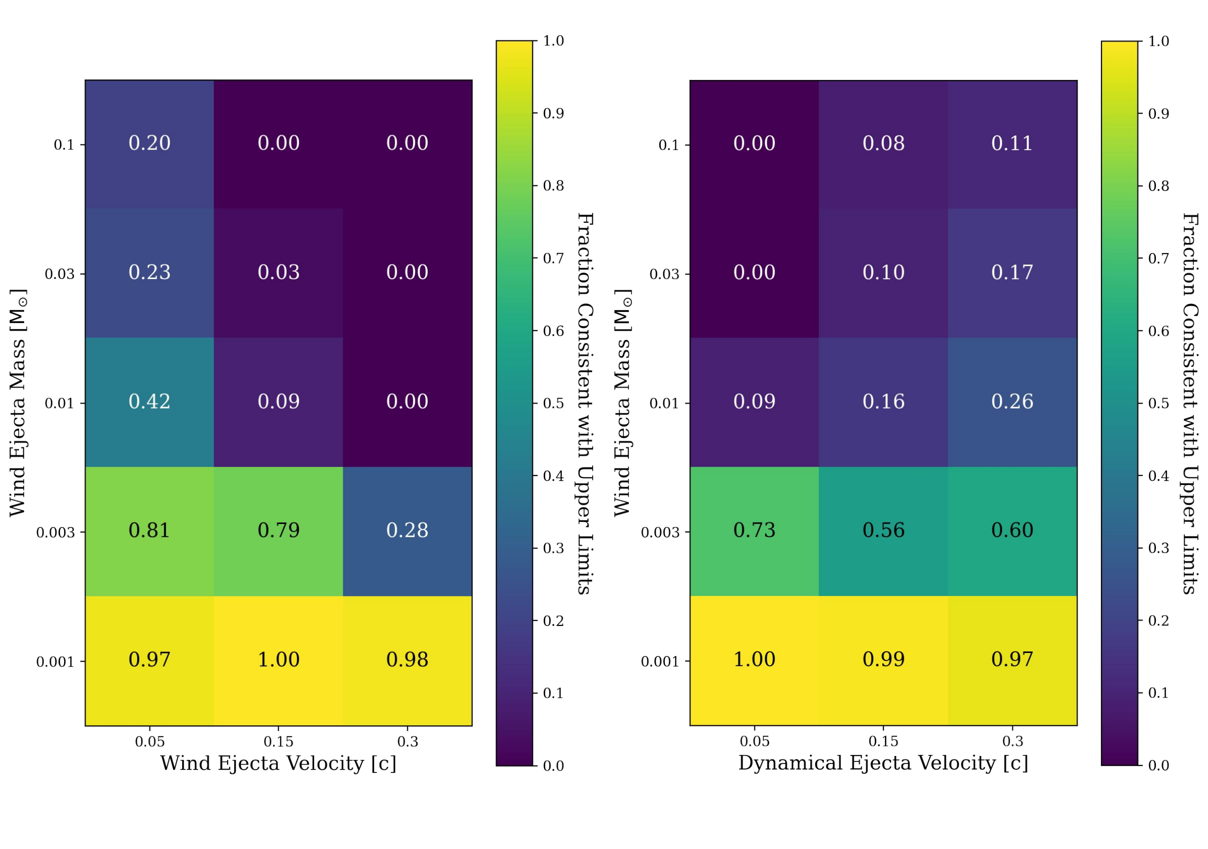
**Follow-up with Gemini**

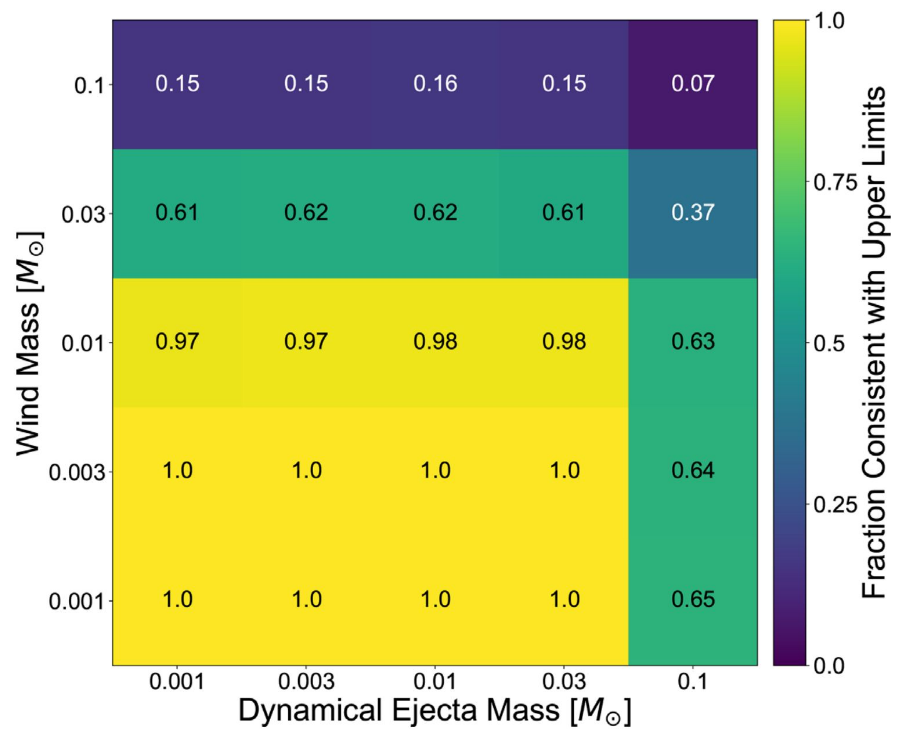
- ➢ **Rapid follow-up**
  - Confirmation and characterization of the GW EM counterparts
- ➢ **Long-term follow-up**
  - KN/short GRB afterglow
    - model comparison
      - constraint on the viewing angle
  - Environment of GW source
    - Properties of host galaxy
      - **Redshift**, SFR, ⋯
  - ⇒ GW Hubble constant

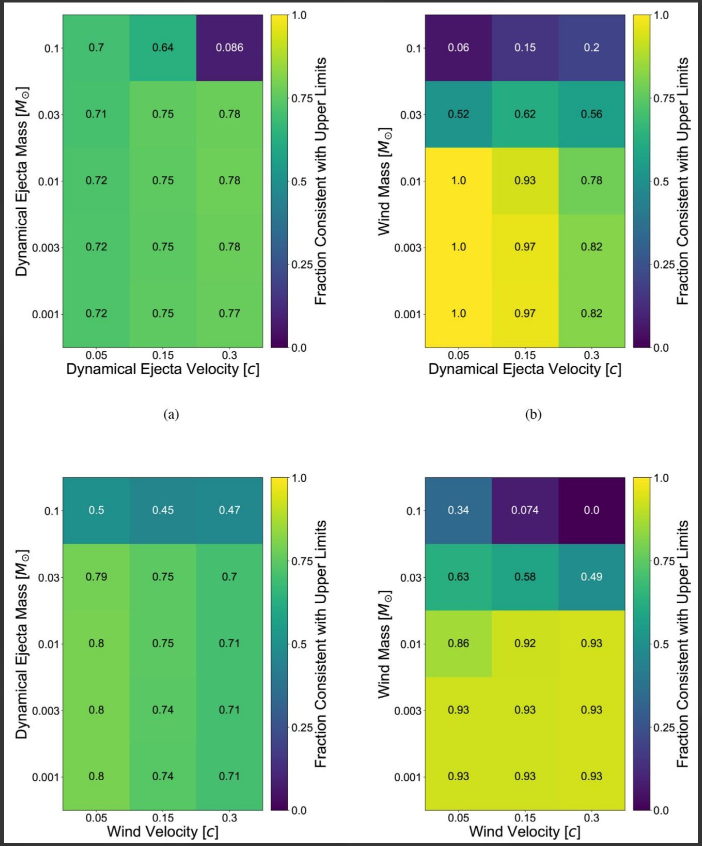


0.07 0.06 0.07 0.07 0.06
0.09 0.09 0.09 0.09 0.08
0.19 0.19 0.18 0.16 0.14
0.69 0.69 0.68 0.63 0.46
1.00 1.00 1.00 0.99 0.94
Wind Ejecta Mass [M⊙]
0.1
0.03
0.01
0.003
0.001
0.001
0.003
0.01
0.03
0.1
Dynamical Ejecta Mass [M⊙]
Fraction Consistent with Upper Limits
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


0.001
0.003
0.01
0.03
0.1
Dynamical Ejecta Mass [M⊙]
0.37 0.40 0.45
0.37 0.39 0.45
0.37 0.39 0.45
0.36 0.38 0.42
0.35 0.32 0.34
0.05
0.15
0.3
Dynamical Ejecta Velocity [c]
Fraction Consistent with Upper Limits
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0.55 0.40 0.27
0.54 0.40 0.27
0.54 0.40 0.27
0.53 0.38 0.25
0.47 0.34 0.20
Wind Ejecta Velocity [c]


0.20
0.00
0.00
0.23
0.03
0.00
0.42
0.09
0.00
0.81
0.79
0.28
0.97
1.00
0.98
Wind Ejecta Mass [M⊙]
0.1
0.03
0.01
0.003
0.001
0.05
0.15
0.3
Wind Ejecta Velocity [c]
Fraction Consistent with Upper Limits
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.08
0.11
0.00
0.10
0.17
0.09
0.16
0.26
0.73
0.56
0.60
1.00
0.99
0.97
Wind Ejecta Mass [M⊙]
Dynamical Ejecta Velocity [c]
Fraction Consistent with Upper Limits

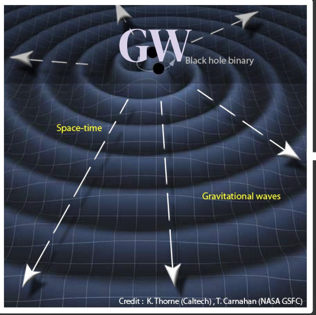

0.15 0.15 0.16 0.15 0.07
0.61 0.62 0.62 0.61 0.37
0.97 0.97 0.98 0.98 0.63
1.0 1.0 1.0 1.0 0.64
1.0 1.0 1.0 1.0 0.65
0.1
0.03
0.01
0.003
0.001
Wind Mass [$M_\odot$]
0.001 0.003 0.01 0.03 0.1
Dynamical Ejecta Mass [$M_\odot$]
1.0
0.75
0.5
0.25
0.0
Fraction Consistent with Upper Limits


0.7 0.64 0.086
0.71 0.75 0.78
0.72 0.75 0.78
0.72 0.75 0.78
0.72 0.75 0.77
Dynamical Ejecta Mass [$M_\odot$]
Dynamical Ejecta Velocity [$c$]
0.05 0.15 0.3
Fraction Consistent with Upper Limits
0.06 0.15 0.2
0.52 0.62 0.56
1.0 0.93 0.78
1.0 0.97 0.82
1.0 0.97 0.82
Wind Mass [$M_\odot$]
Dynamical Ejecta Velocity [$c$]
0.5 0.45 0.47
0.79 0.75 0.7
0.8 0.75 0.71
0.8 0.74 0.71
0.8 0.74 0.71
Dynamical Ejecta Mass [$M_\odot$]
Wind Velocity [$c$]
0.34 0.074 0.0
0.63 0.58 0.49
0.86 0.92 0.93
0.93 0.93 0.93
0.93 0.93 0.93
Wind Mass [$M_\odot$]
Wind Velocity [$c$]

(a)

(b)

# GW Standard Siren




GW luminosity
**Distance**

Hubble Constant ($H_0$)


Dark Siren (w/o EM)

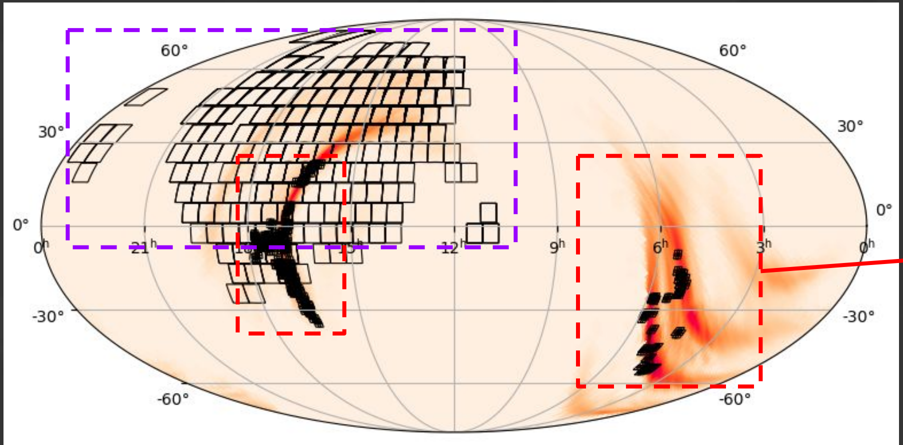
Bright Siren (w/ EM)

**Redshift**

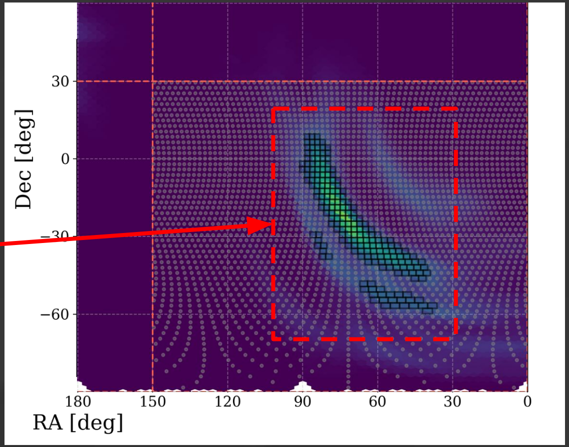

Practicality to resolve the **Hubble Tension**

# $GECKO_{KMTNet} + GROWTH_{ZTF}$

**Purple : ZTF / Red : KMTNet**



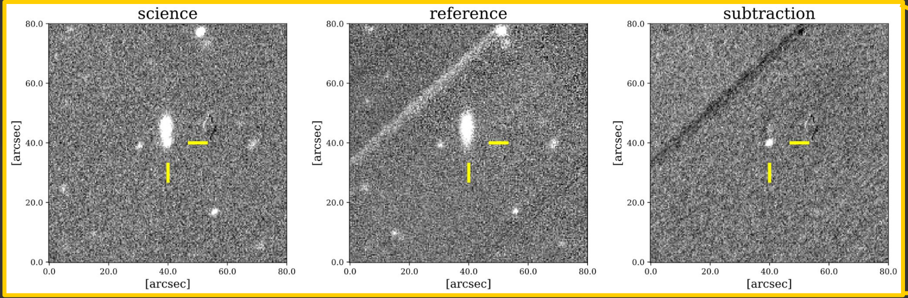

**(What if…) Tiling Observation**

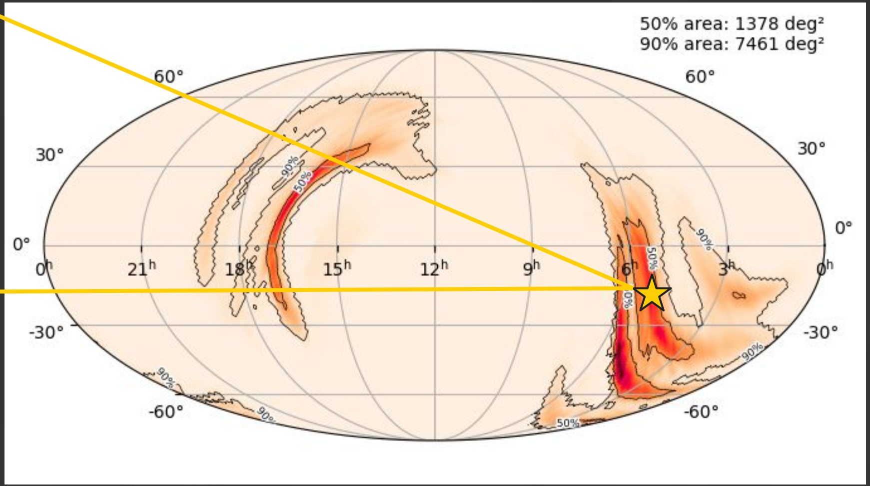



| Obs. | Coverage [deg$^2$] | 5σ Depth [AB] |
|---|---|---|
| ZTF<br>Coughlin+19 | 3000 | r~21 |
| KMTNet | 400 | R~21.5 |

- 400 deg$^2$ → 600 deg$^2$ (150% improvement)
- Tiling observation is more efficient for KMTNet

# Interesting KN Candidate



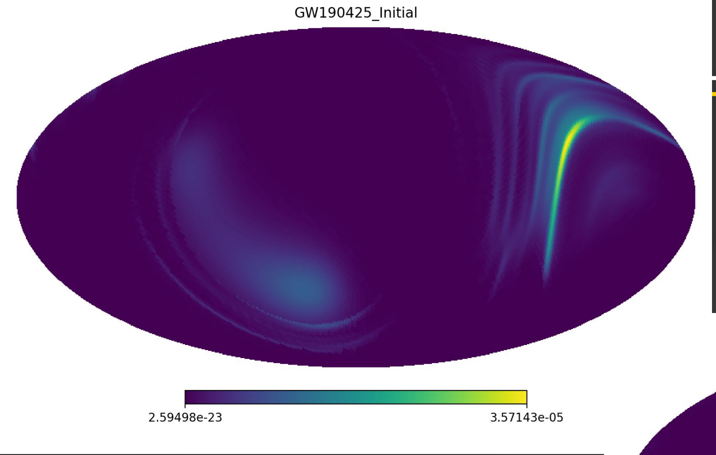



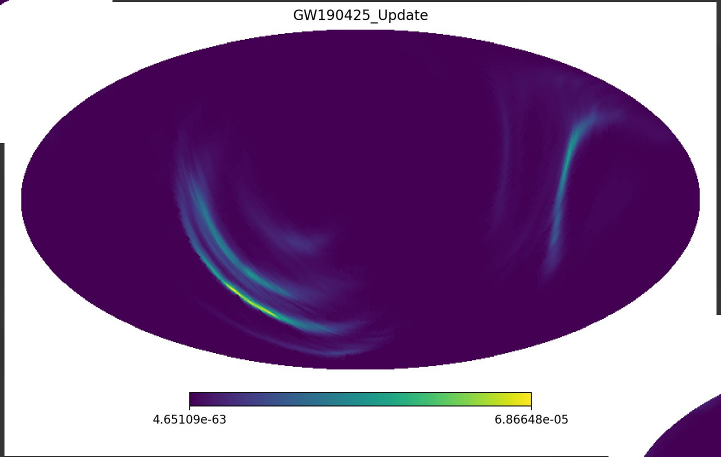

| Name | GECKO 190427a |
|---|---|
| DATE-OBS | 2019-04-**27**T17:12:57 |
| FILTER | R-band |
| OBS | KMTNet |
| App. Mag [AB mag] | 20.30 ± 0.05 |

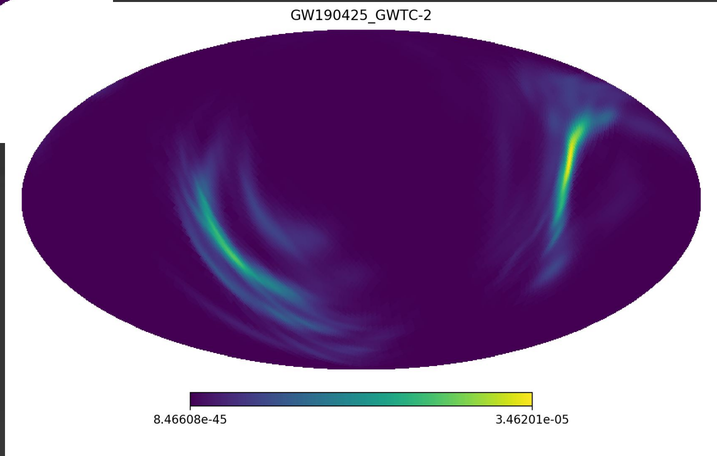
No report from archive

Phot-z from Host galaxy → 700 Mpc

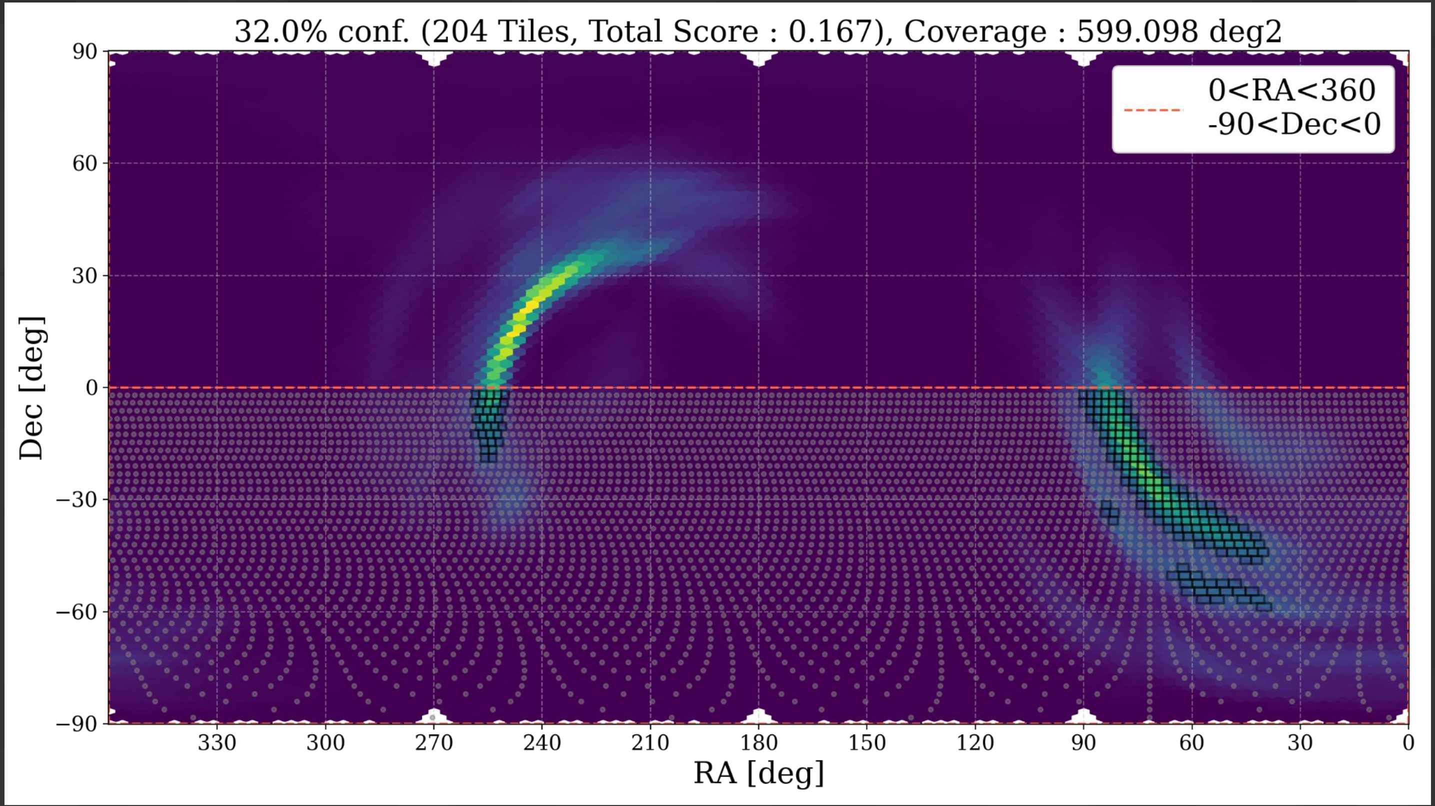
(GW 190425; 156 Mpc)


GW190425_Initial
2.59498e-23
3.57143e-05


GW190425_Update
4.65109e-63
6.86648e-05


GW190425_GWTC-2
8.46608e-45
3.46201e-05

# Tiling with KMTNet



# Modified GLADE catalog

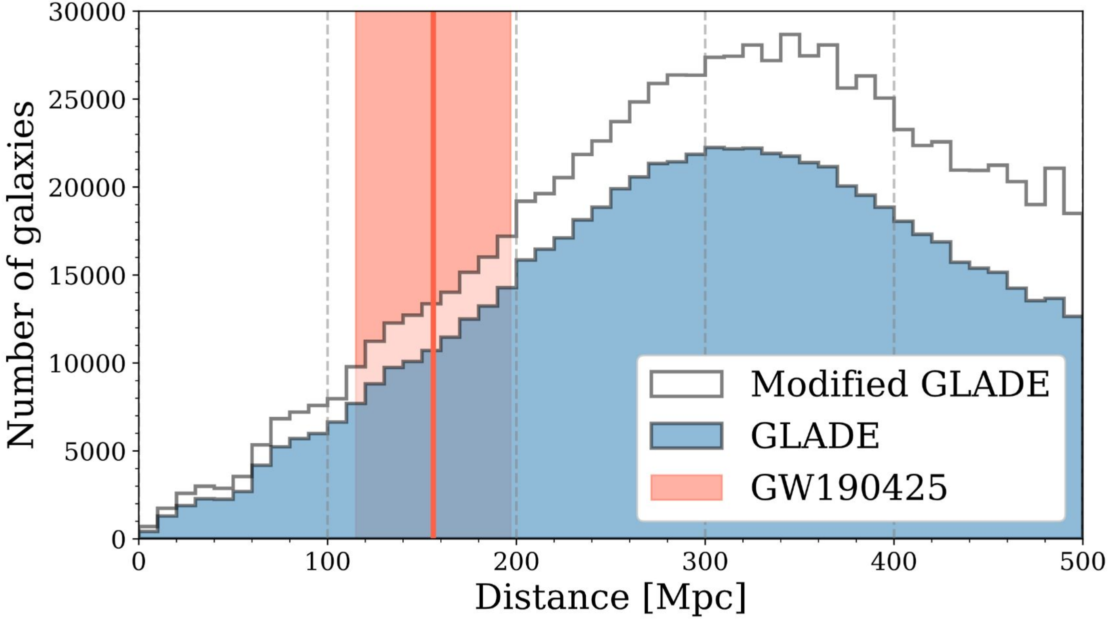
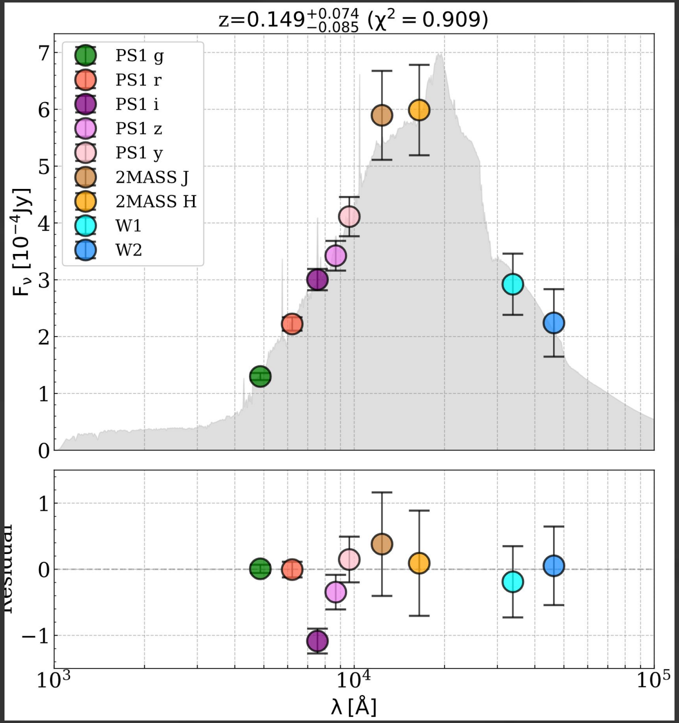



**Figure 2.** Histogram for including K-band and distance information of galaxy in catalog. Blue shaded region shows GLADE catalog and hollow region shows modified GLADE catalog added K-band information from 2MASS PSC detailed in Section . Red line and red shaded region represent mean distance and distance range of GW190425, $156 \pm 41$Mpc.

# Found Transients

| Object | Observatory | Filter | Date-obs UTC | Median Δt days | R.A. | Dec. | Mag. ABmag | Mag. error ABmag |
|---|---|---|---|---|---|---|---|---|
| AT2019dws | KMTNet-SSO | R | 2019-04-25 13:12:38 | 0.204 | 16:48:11.15 | +01:04:00.6 | 19.06 | 0.06 |
| AT2019hae | KMTNet-SAAO | R | 2019-04-25 21:16:51 | 0.541 | 16:55:14.93 | -17:52:54.2 | 18.06 | 0.03 |
| AT2019dnv | KMTNet-SAAO | R | 2019-04-25 21:38:33 | 0.556 | 16:56:08.22 | -08:11:54.6 | 19.32 | 0.05 |
| SN2019dzw | KMTNet-SAAO | R | 2019-04-25 22:10:28 | 0.578 | 17:31:09.96 | -08:27:02.8 | 19.94 | 0.05 |
| AT2019dta | KMTNet-CTIO | R | 2019-04-26 03:11:02 | 0.787 | 16:42:54.80 | -19:41:22.3 | 19.73 | 0.06 |
| AT2019hae | KMTNet-CTIO | R | 2019-04-26 03:16:57 | 0.791 | 16:55:14.94 | -17:52:54.2 | 18.09 | 0.03 |
| AT2019ocg | KMTNet-CTIO | R | 2019-04-26 03:16:57 | 0.791 | 16:52:45.01 | -19:05:38.8 | 20.11 | 0.05 |
| AT2019dnv | KMTNet-CTIO | R | 2019-04-26 03:31:59 | 0.801 | 16:56:08.23 | -08:11:54.7 | 19.18 | 0.04 |
| SN2019dzw | SQUEAN | i | 2019-04-26 08:38:24 | 1.014 | 17:31:09.60 | -08:27:54.0 | 19.57 | 0.04 |
| SN2019dzk | SQUEAN | i | 2019-04-26 08:47:02 | 1.02 | 17:13:29.76 | -09:56:31.2 | 18.45 | 0.05 |
| GECKO190427a | KMTNet-SAAO | R | 2019-04-27 17:12:57 | 2.371 | 05:03:39.04 | -23:47:38.8 | 20.29 | 0.05 |
| AT2020czk | KMTNet-SAAO | R | 2019-04-27 17:26:17 | 2.38 | 05:48:03.51 | -25:08:49.1 | 19.9 | 0.03 |
| AT2019flz | KMTNet-SAAO | R | 2019-04-27 17:26:17 | 2.38 | 05:45:20.45 | -26:50:51.0 | 18.53 | 0.02 |

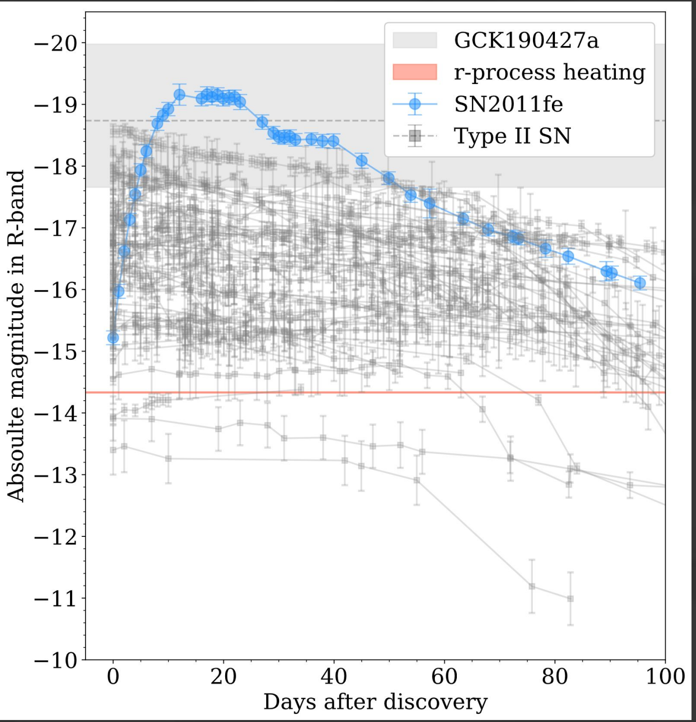
# 반박 증거 (1) : Host galaxy




- $z_{phot}$ from SED fitting
  - optical+NIR+IR
- Distance difference
  - $D_{GW}$~156 ± 41 Mpc
  - $D_{Host}$~710 Mpc (h=0.7)

**Too far from GW Dist.**

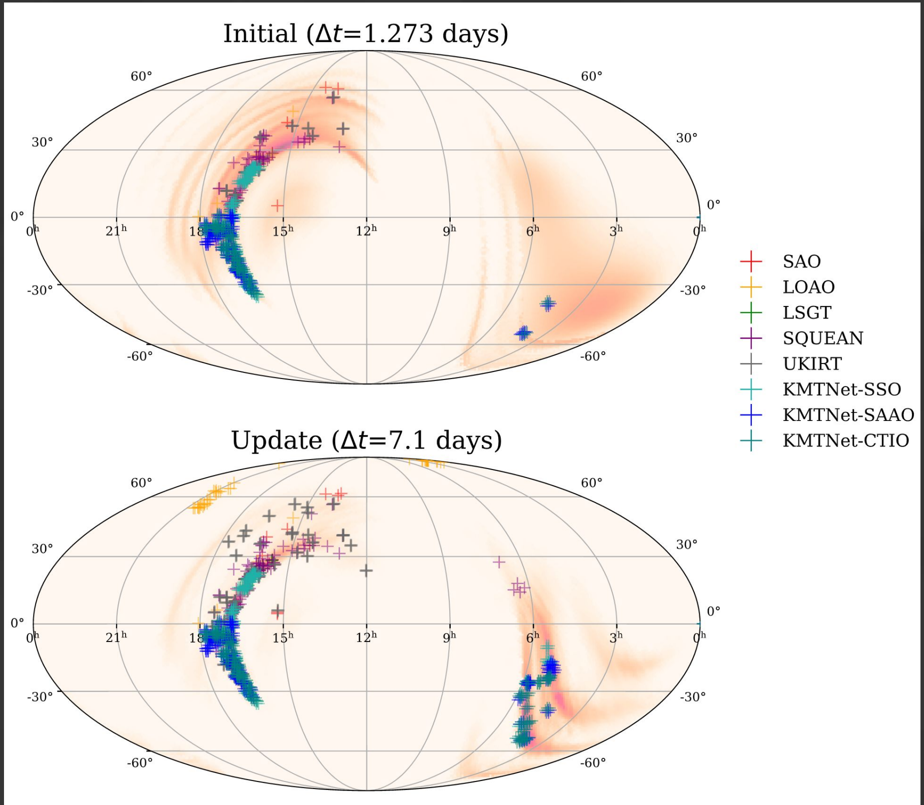
# Brightness



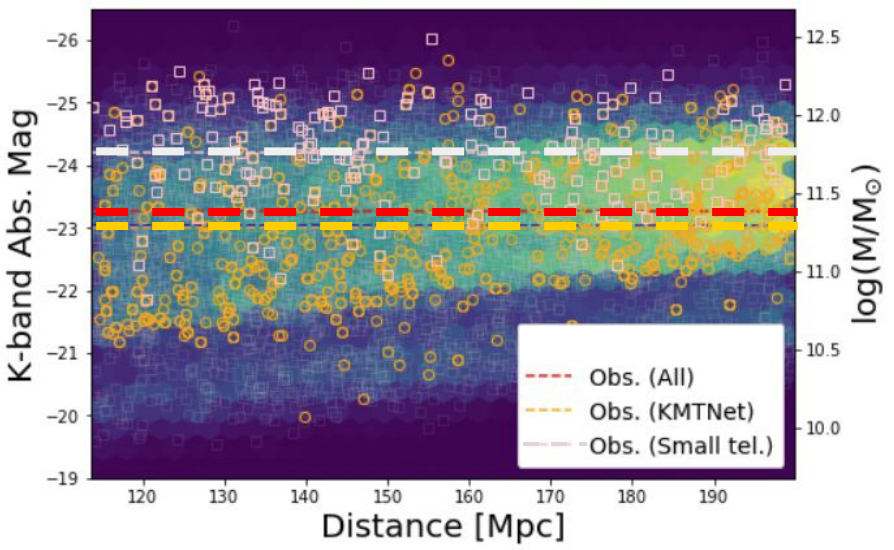

- **100 times brighter** than expected luminosity of GW170817-like KN
- Candidates
  - Bright Type II SNe
  - Type Ia SN at peak phase
  - Faint KN

**Too bright to be KN**

# Follow-up Observation



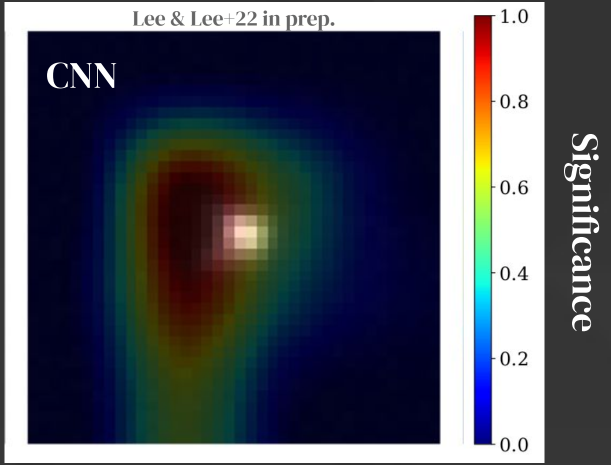
# Assessment of follow-up observation




- Narrow FoV telescopes covered massive galaxies
  - $\log(M/M_{\odot}) \sim 11.8$
- KMTNet (wide FoV) observed massive galaxies, but contained other galaxies.
  - $\log(M/M\odot) \sim 11.3$

# CNN+TDA Net

| Paper | Training set | Performance |
|---|---|---|
| Duev+19 | ZTF | FPR & FNR < 1-3% |
| Killestein+21 | GOTO | FPR & FNR < 1% |
| Makhlouf+21 | GRANADA | Acc. 93%-98% |



# Automated alert system

GW alert

Candidate Prioritization

Target list generator

Send mail to staff

< 10 min

Summary

Target list

Skymap

Artwork by Sandbox Studio, Chicago with Corinne Mucha

# Follow-up observation

**Observation**

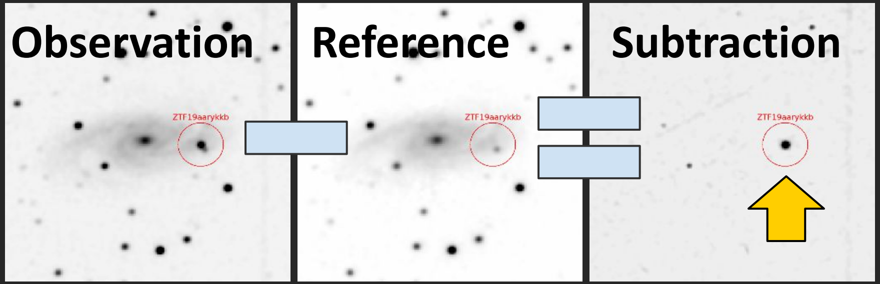
Data acquisition

Pre-processing

Subtraction

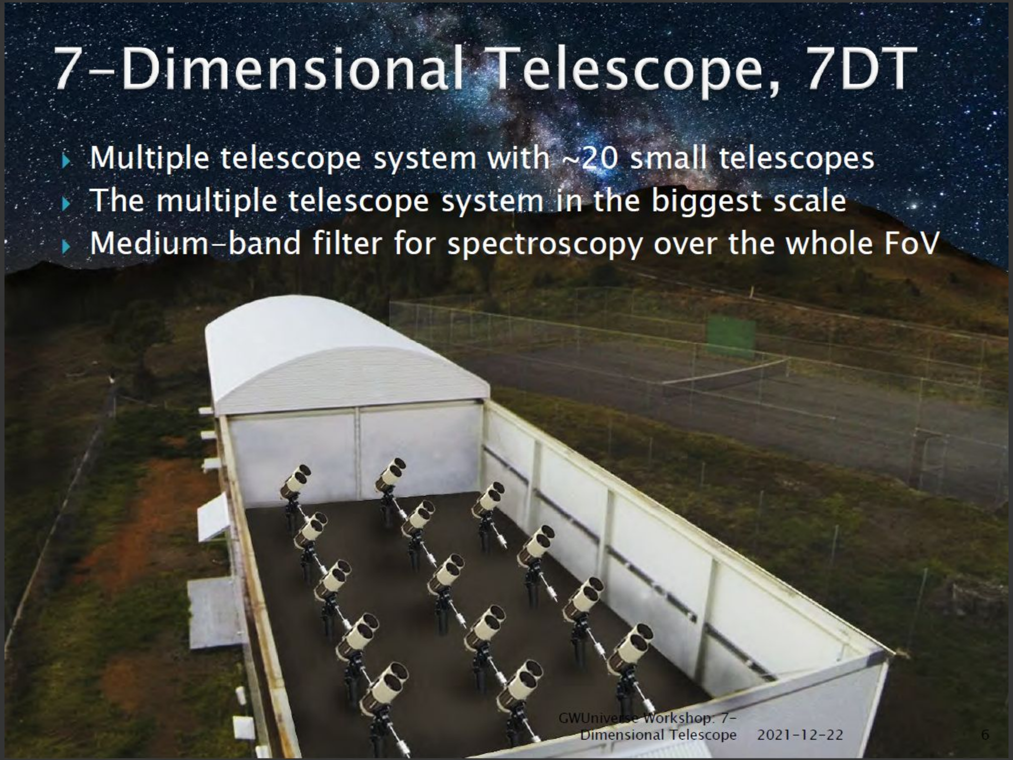
Transient search &
Photometry

Subtraction example




1. Photometry
2. Matching with transient archive (e.g. Transient Name Server)
3. Spectroscopy to confirm the type (e.g. Gemini)

**few mins / set of images**



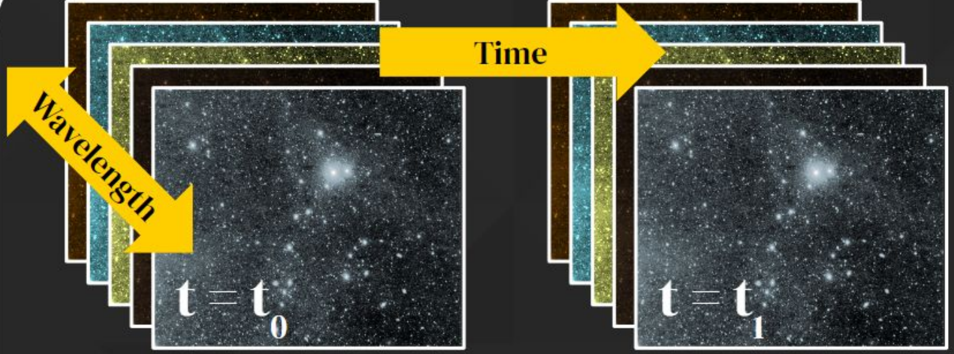

PI : Myungshin Im

# Why '7'DT?

(x, y, z) + (Time) + (Flux) + (Wavelength) + (Radial velocity) ⇒ **7 Dimensions**

- ❑ **Wide-field**
- ❑ **Time-domain**
- ❑ **Low-resolution *IFU**

*Integral Field Unit



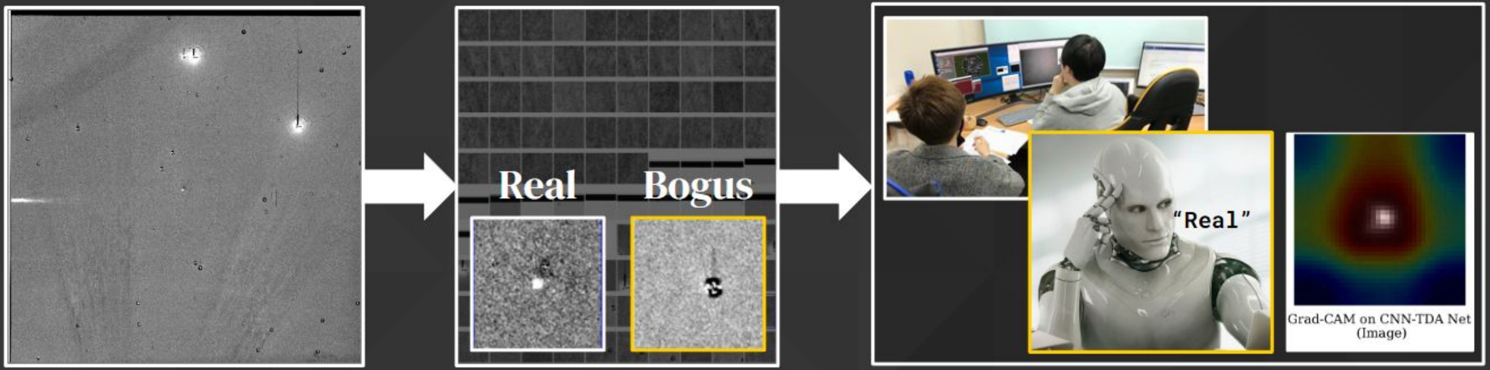

**60M spectral movie of the Universe**

# Real/Bogus Classification with AI

Subt. image

Postage Stamp (~1K)

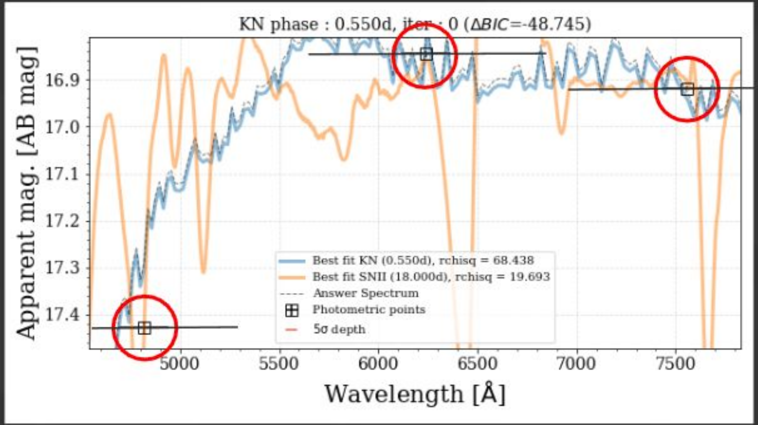
Vetting




CNN + TDA Net, Lee & Lee et al. 2022 (POSTECH)

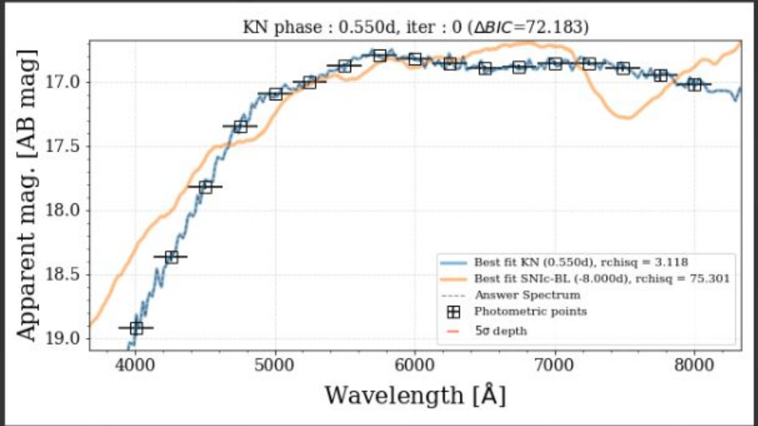
**AI vetting is faster & more stable than Human vetting**

## Broad-band




**Hard to distinguish the KN SED from other transients**

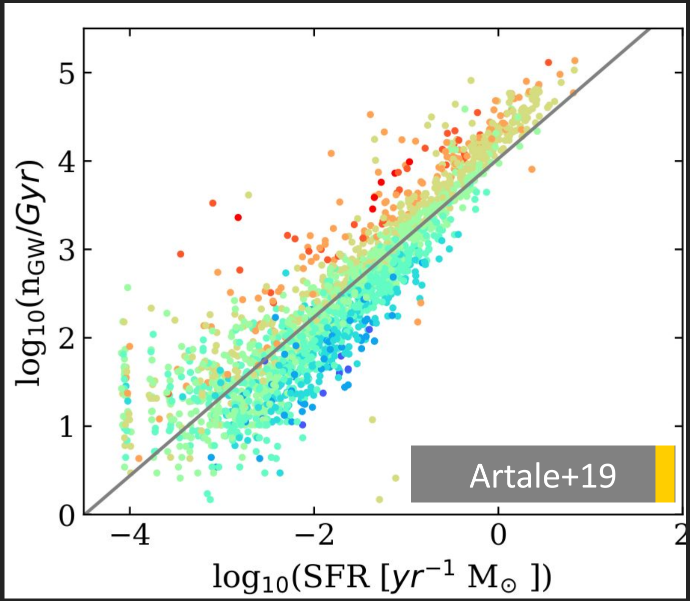
## ✨Medium-band




**Med-band makes well-defined SED ⇒ Easier to classify KN!**

# Simulation result

BNS merger rate & Host galaxy properties




*Previous Studies*

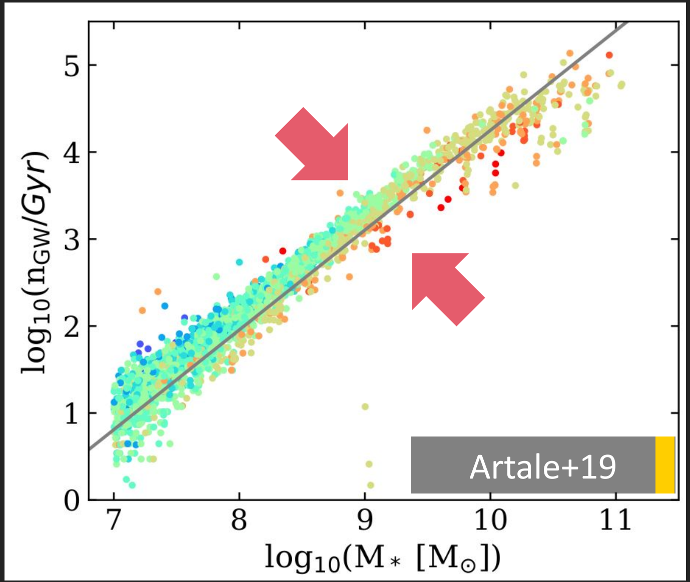
Gehrels+16
Drout+17
Yang+19
...

Star Formation Rate
(B-band Luminosity)

Larger
BNS merger rate

# Simulation result

BNS merger rate & Host galaxy properties




*This Study*

More massive host galaxy

$L_K \propto M_*$

Larger BNS merger rate