국가과학난제도전융합연구개발사업
National Science Challenge Initiatives
중력파우주연구단

# Optical Follow-up Observations of GW Sources with GECKO and 7-Dimensional Telescope: Past, Present, and Future

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2026-10-26

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1. Seoul National University, 2. IfA/UH, 3. KHU, 4. DNSM, 5. IAP, 6. SPEX, 7. KASI, 8. EWU, 9. Postech

# 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)



GW Observatories
(LIGO, Virgo, KAGRA)

## EM OBSERVATIONS

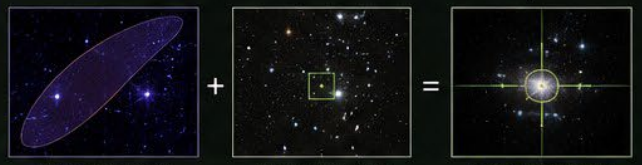
Wide-field telescopes scan rapidly across the sky



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

## 2. PRECISE LOCALIZATION

GW + EM localizations ⇒ < 1 arcsecond accuracy



GW Localization (~100–1000 deg²) + EM Localization (arcmin–arcsec) = Final Localization (< 1 arcsecond)

## 3. HOST GALAXY & ENVIRONMENT

Pinpointed location identifies the host galaxy and local environment

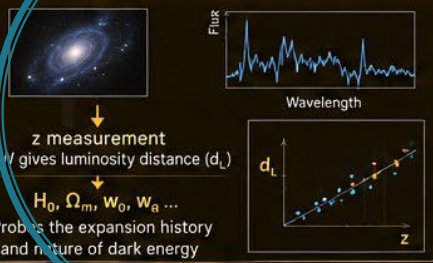


- Galaxy type & mass
- Metallicity
- Star formation rate
- Local density

Reveals where GW events occur in the universe

## 4A. REDSHIFT & COSMOGRAPHY

Host galaxy or kilonova gives redshift (z)




z measurement
GW gives luminosity distance ($d_L$)

$H_0$, $\Omega_m$, $w_0$, $w_a$ ...

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)

⇒ Heavy element production rate such as gold, platinum, uranium

## 4C. COSMIC CHEMICAL EVOLUTION

From KNe rate & yields ⇒ 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

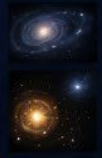
Tests models of short GRBs and relativistic jets



- 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 ~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

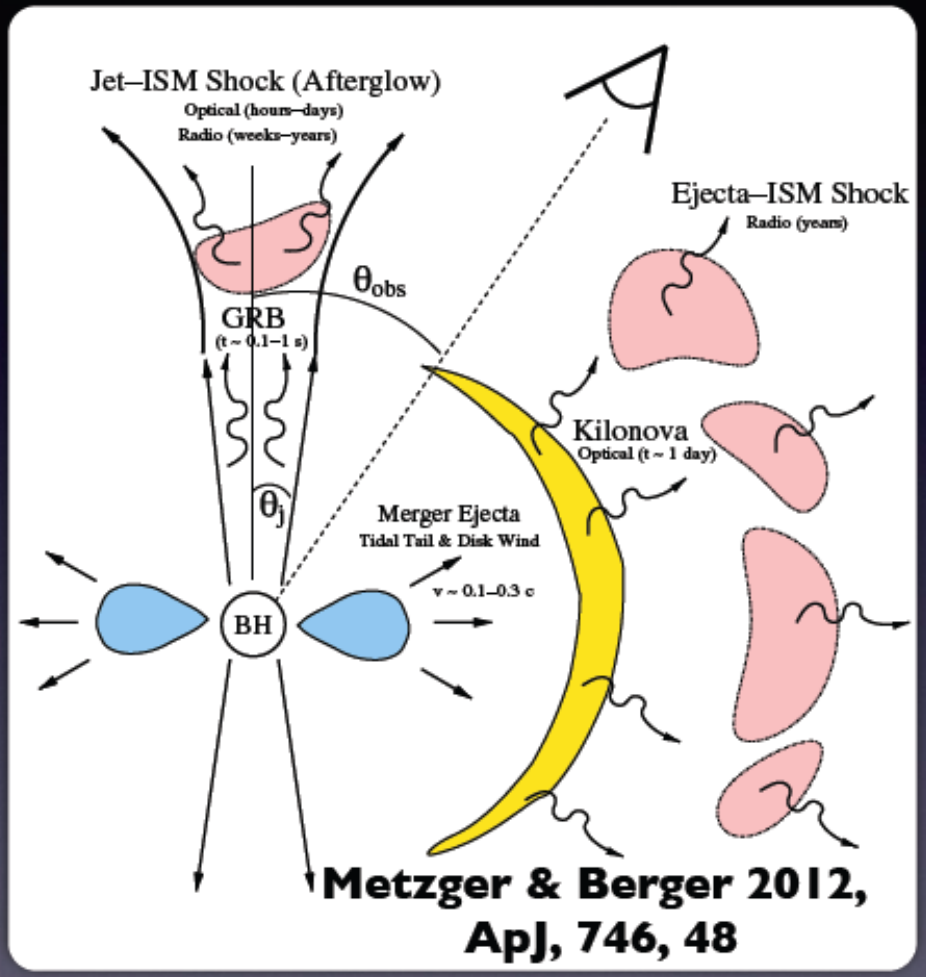
From neutron stars to nuclei, from galaxies to planets, from the Big Bang to life.

# EM signature from NS-NS merger

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

GRB 

Kilonova 




Taken from presentation by M. Tanaka

# GW EM Counterpart Korean Observatory (GECKO)



Korea: SNU 1.0m,
DOAO 1.0m, CBNUO 0.6m,
KHAO 0.8m, 0.4m, MAAO 0.7m,
BOAO 1.8m



Hawaii: Gemini-N

US: LOAO 1-m



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

Maidanak:
1.5m Telescope











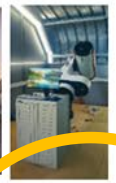

KMTNet 1.6m

South Africa: KMTNet



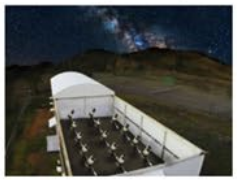
Australia: LSGT 0.43m (SSO), KMTNet





Chile: Gemini-S, KMTNet, KCT, KASA36 (0.4m), 7DT



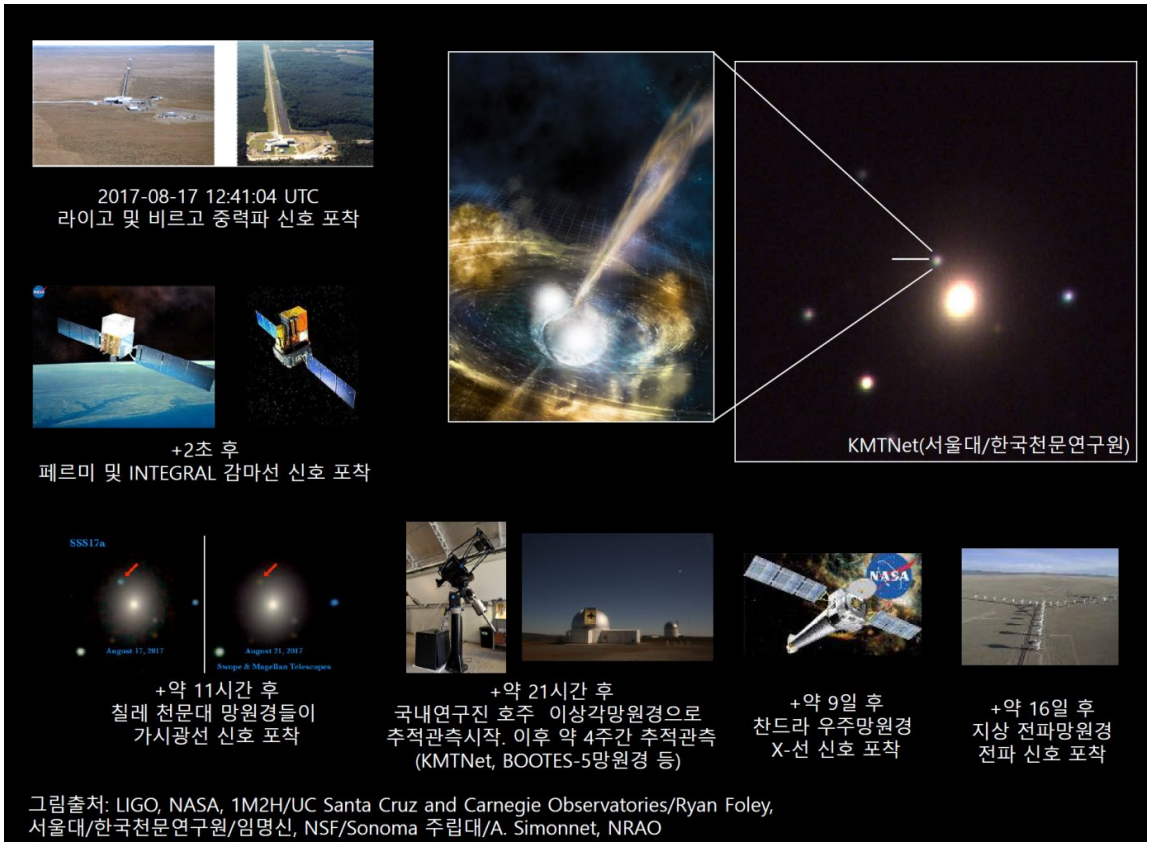


- Wide-field telescopes + narrow-field telescopes
- Imaging telescopes + spectrophotometry telescopes



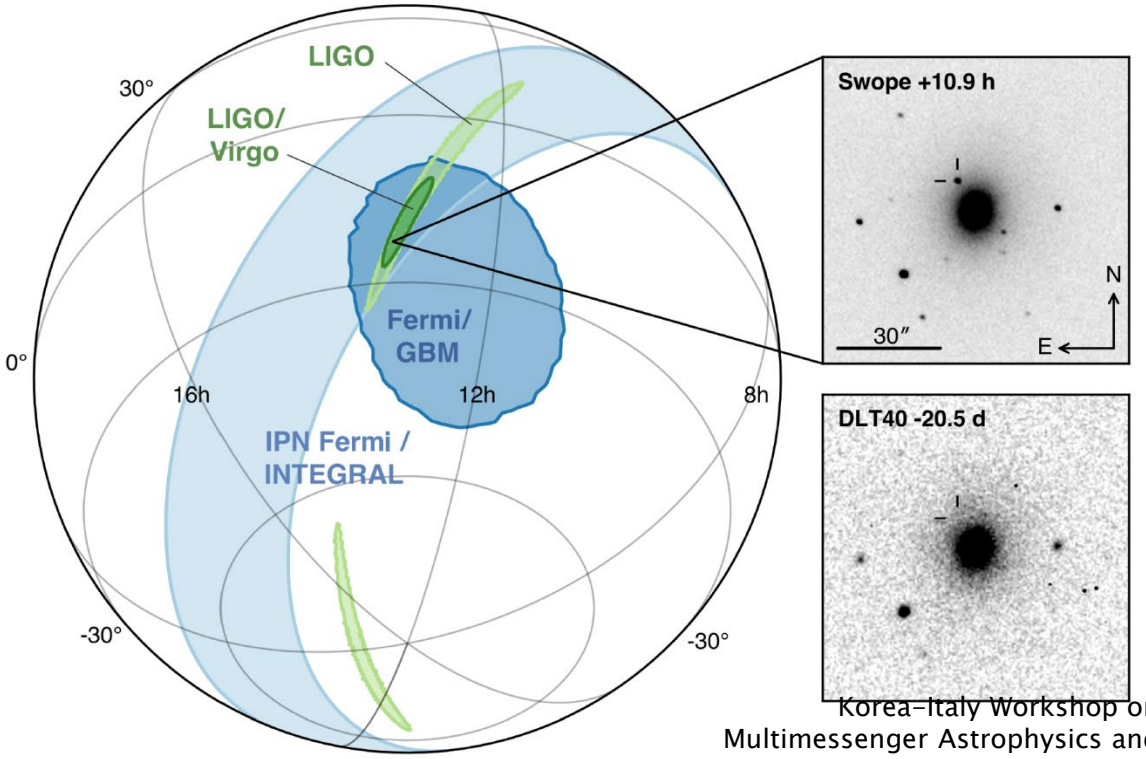
# GW170817: NS-NS merger Multi-Messenger Astronomy

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



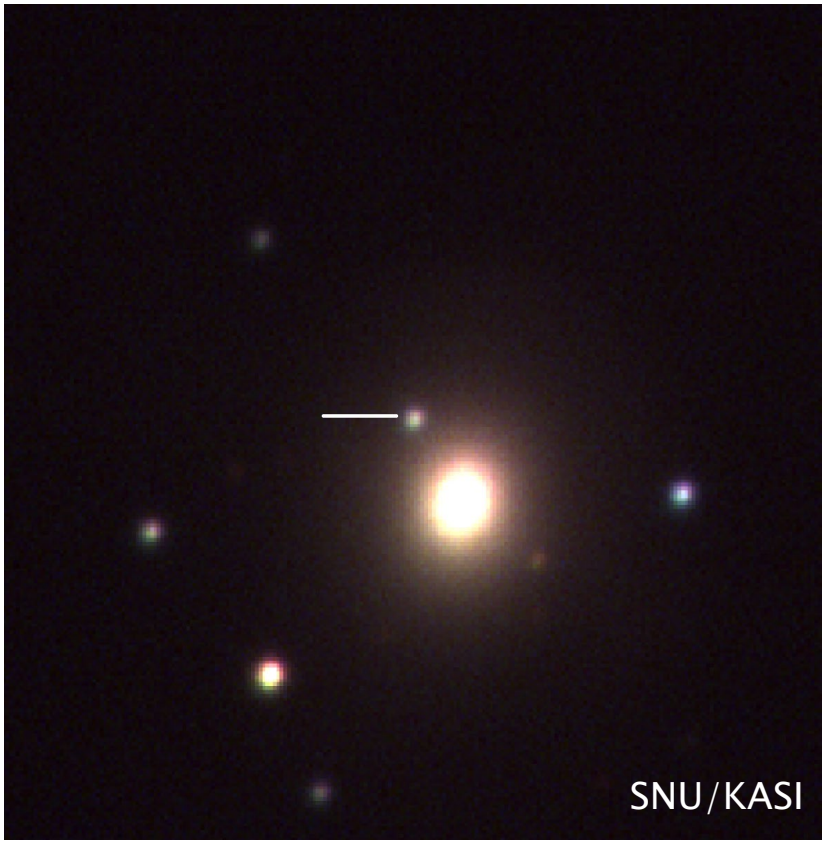
# GW170817: NS-NS merger Optical Counterpart Discovery

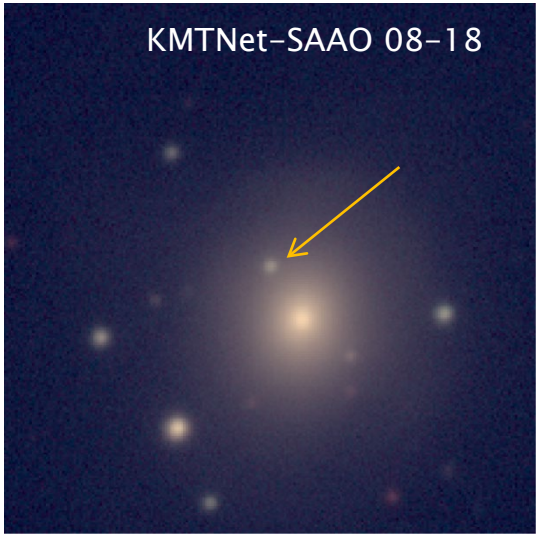
- 8 telescopes in Chile spotted GW counterpart at 11 hours after GW detection
- NGC 4993 at ~40 Mpc (RA:13h09m47s, Dec:-23d23m02s)

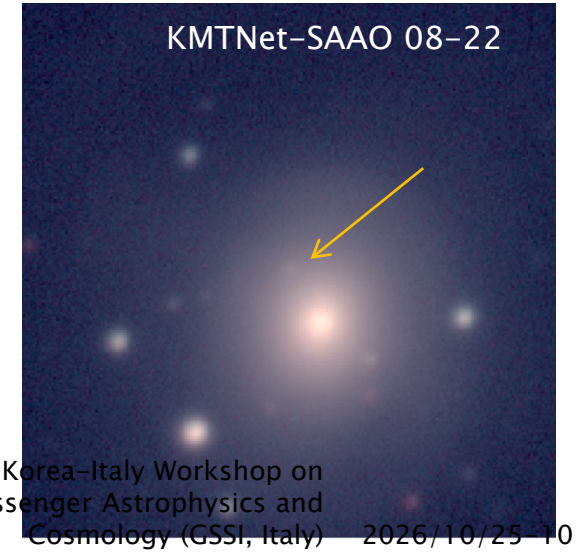



"MMA paper"
LIGO, Virgo,
Partner Astronomy Groups
2017, ApJL

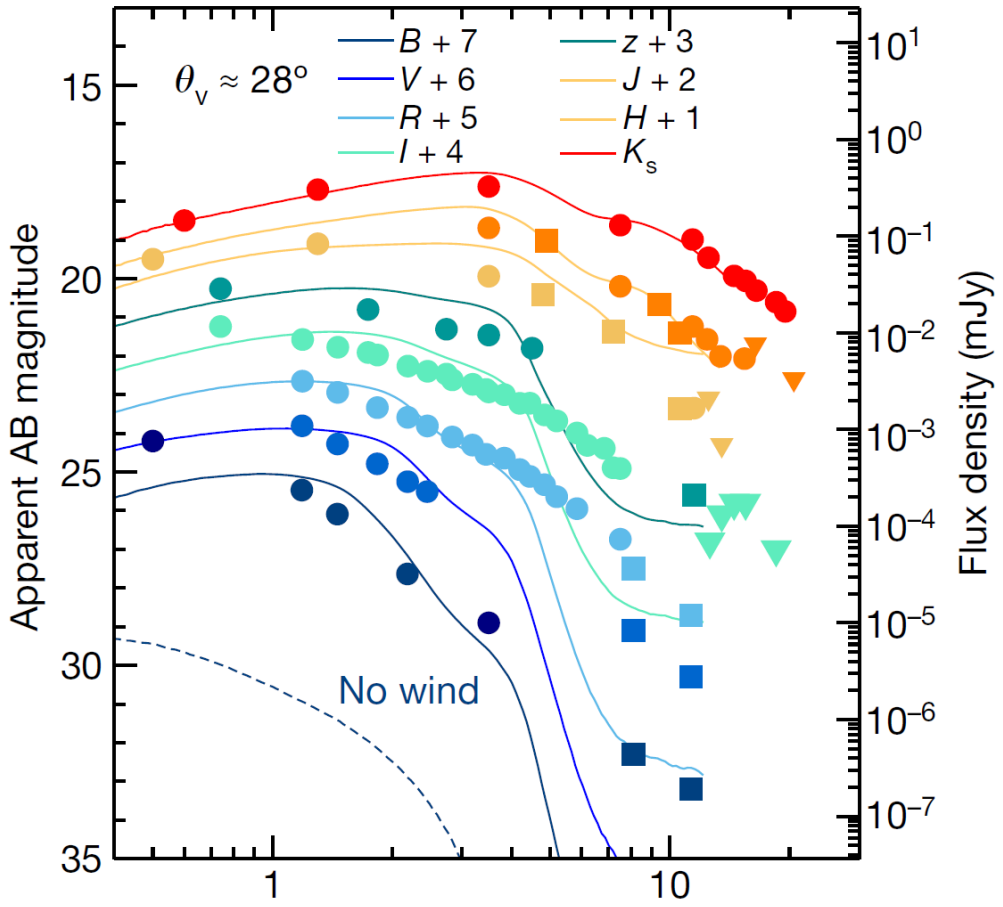
# KMTNet Image of GW170817



# Comparison with Kilonova Model




- Mej ~ 0.01 Msun
- Wind model

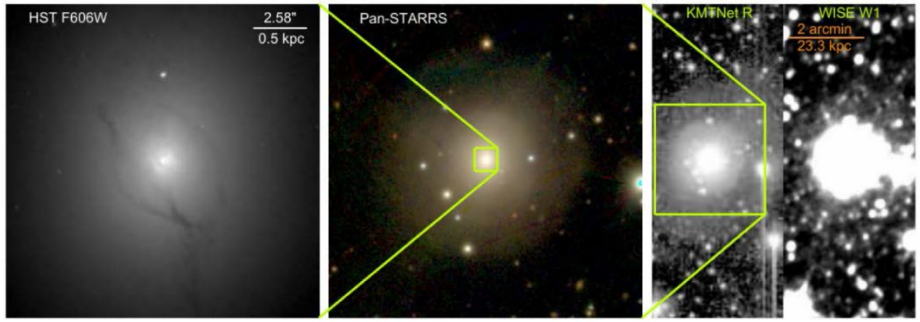
→ Kilonova!

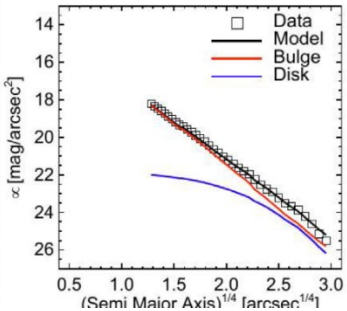
Troja+2017

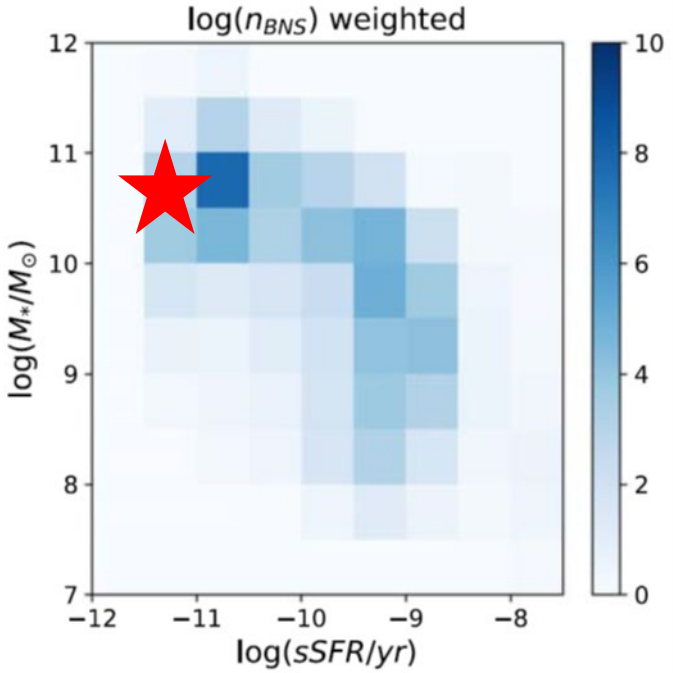
# GW170817 Host Galaxy

- KMTNet, LSGT, HST
- **Distance and properties** of NGC 4993 as host galaxy of a gravitational wave source, GW 170817", 2017, **ApJL**
- Early-type, M* = 0.3 – 1.2 x $10^{11}$ Msun, Age: > 2 Gyr, No SF, ~40 Mpc

Im et al. 2017 (Oct. 3, submitted, Oct. 13, accepted), 12 Korean co-authors



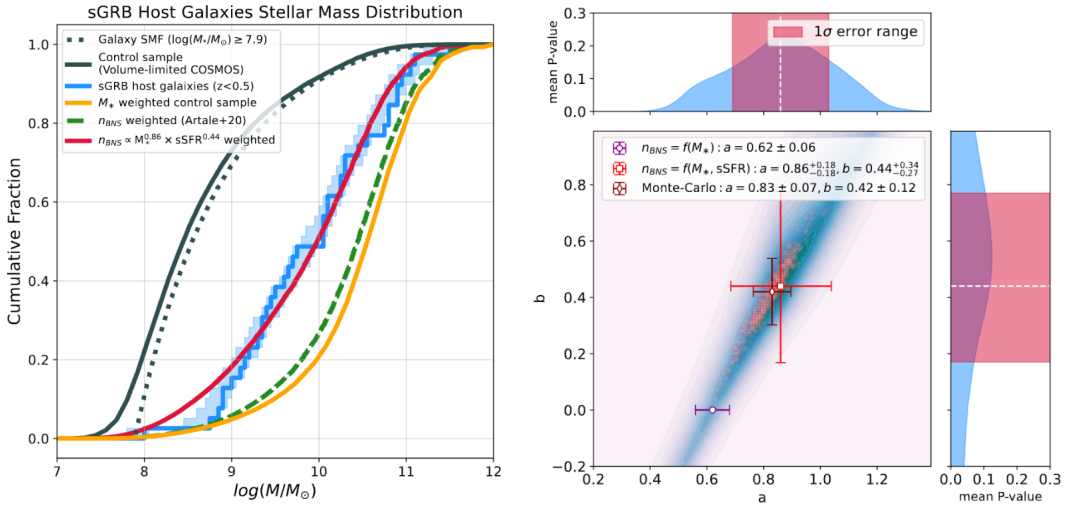



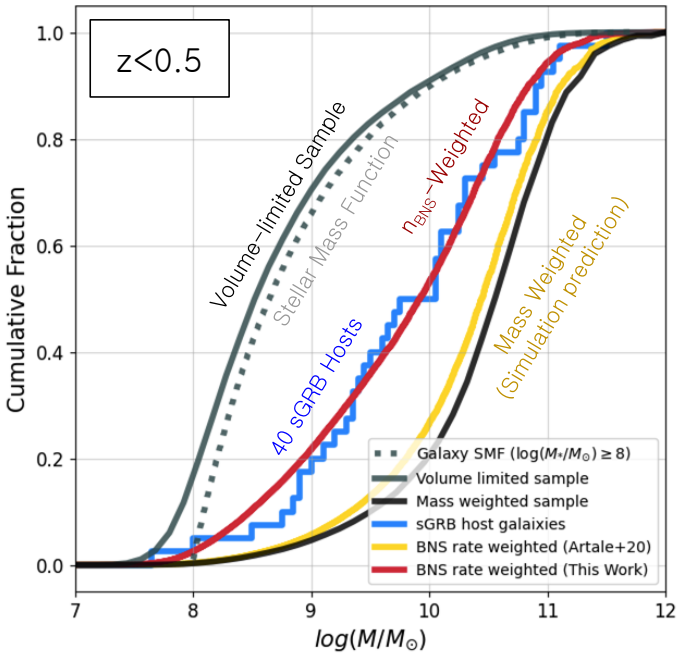
# Two Key Parameters for BNS merger rate: Stellar Mass (M)+ Star Formation Rate (SFR)

**Host Galaxy Properties of Gamma-ray Bursts Involving Neutron Star Binary Mergers and Its Impact on Kilonovae Rates**

MANKEUN JEONG[1] AND MYUNGSHIN IM[1]

[1]*SNU Astronomy Research Center, Astronomy Program, Department of Physics and Astronomy, Seoul National University, Gwanak-gu, Seoul 151-742, Korea*




- Stellar mass distribution of sGRB host galaxies
- Comparison w/ volume-limited control sample

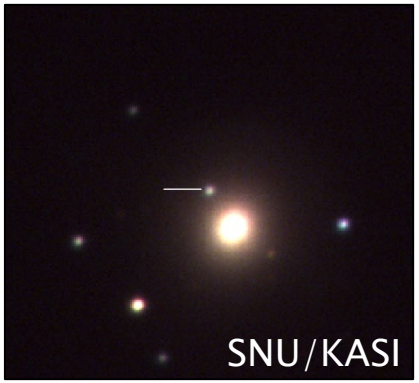
⇒ **$\log(n_{BNS}/\mathrm{Gyr}) = 0.86 \times \log(M/M_{sun}) + 0.44 \times (\mathrm{sSFR}/\mathrm{yr}) + 0.857$**

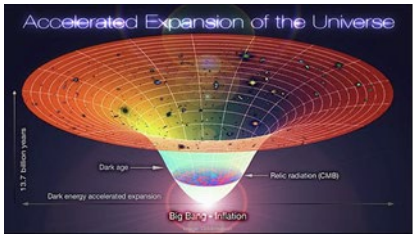
# GW170817 MMA Key Results

- Accurate localization
- Host galaxy & environment
- First MMA cosmography
- Cosmic heavy element production
- Kilonovae properties (blue to red)
- Proof for short GRB + BNS merger

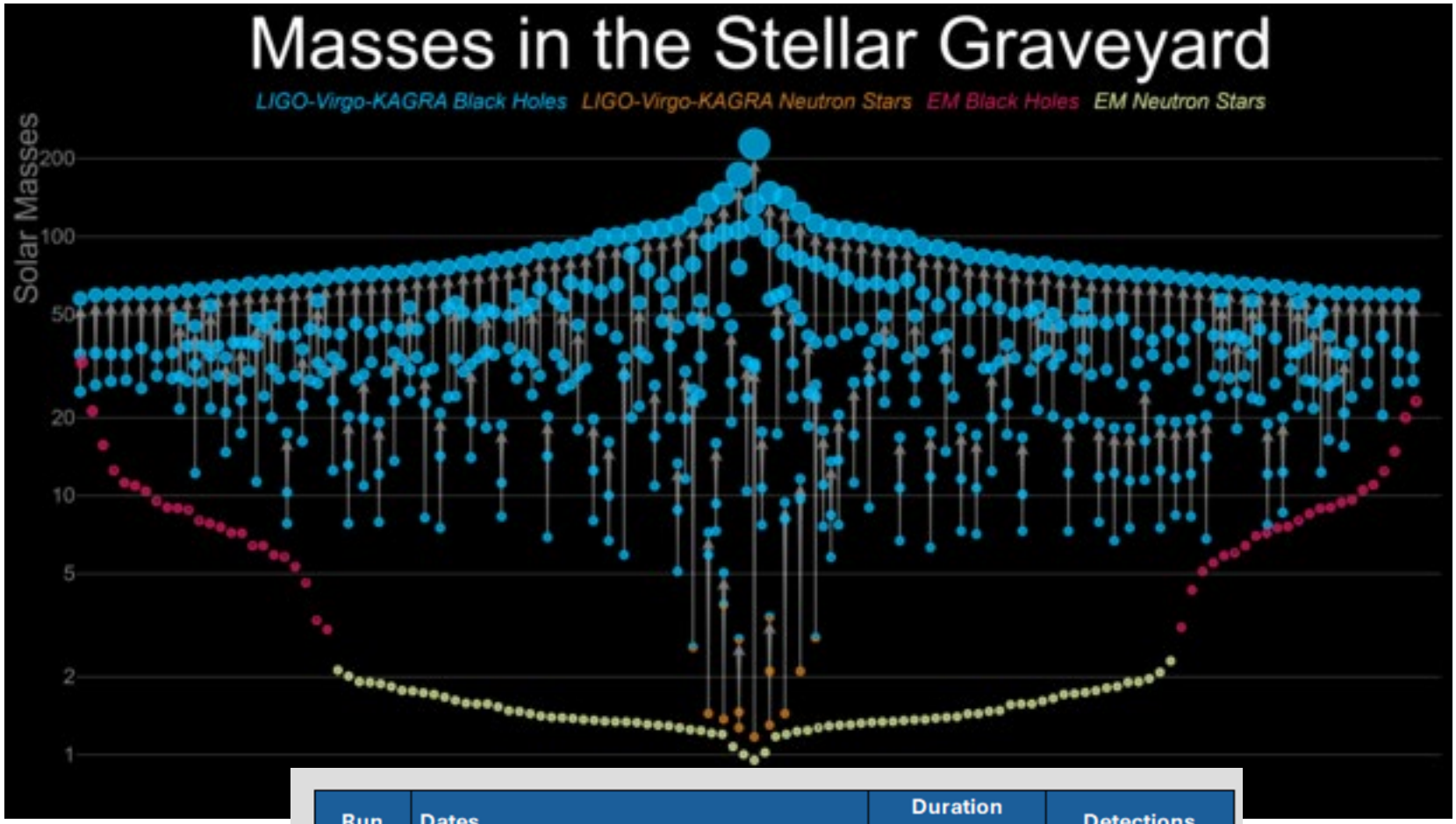


Gold!
(200 $M_E$)



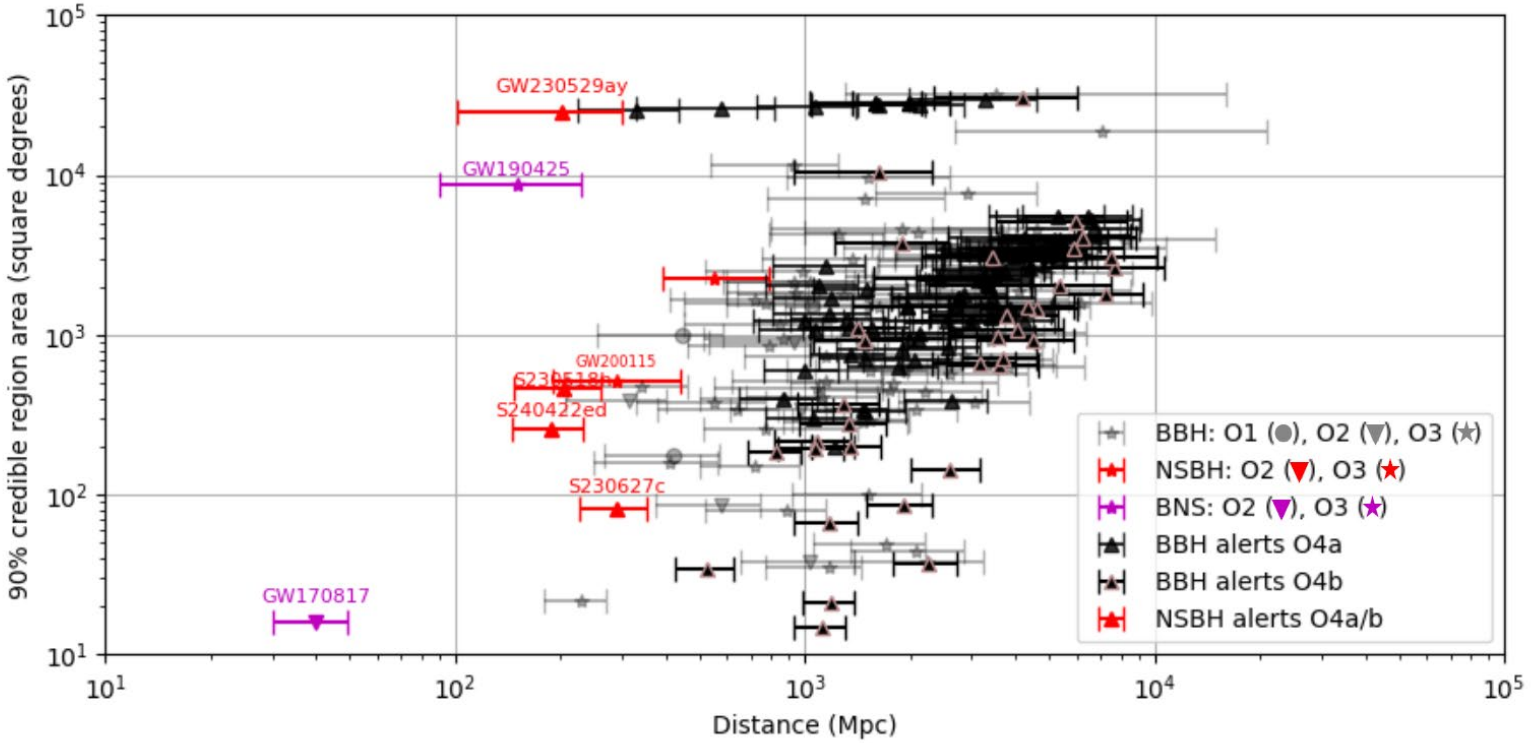

$H_0$ from GW
(but need more)




| 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 |

# O3 (’19 – ’20) + O4(’23 – ’25)

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




Pillas+25

# GW170817: NS-NS merger Multi-Messenger Astronomy

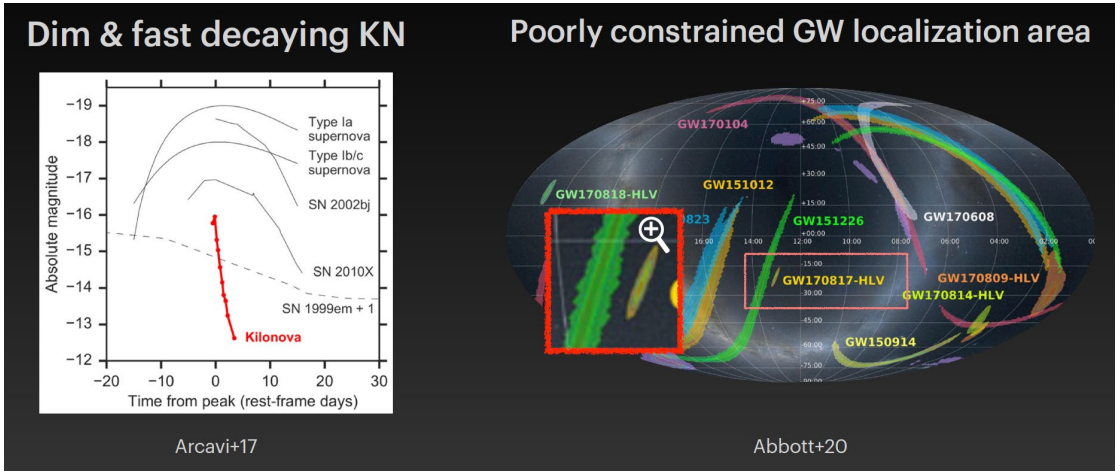
- **2017-08-17 GW event marked the start of MMA using GW and EM signals**
- Many promises of MMA: kilonova, cosmology, heavy element production, compact merger environment, etc




**The only GW event with EM counterpart ID so far**

# Challenges to overcome for MMA

- Search aera is too wide (~100 deg$^2$ or more)
- Kilonovae (KNe): Faint, fast-decaying transient (> 20 mag)
  : A KN needs to be found fast (first 1-2 days)
- Too many other tranients (10-100/deg$^2$)



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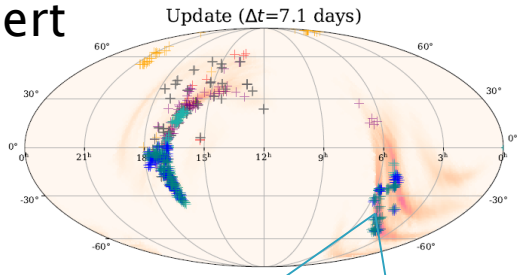
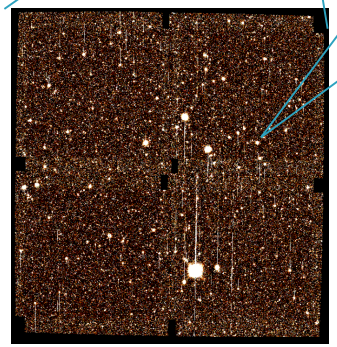
**Rapid, wide-field spectral mapping is desired**

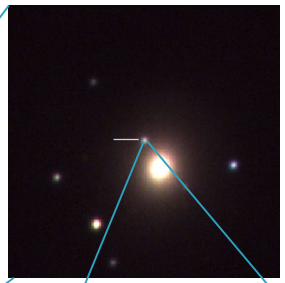
# Search for KN

GW Alert

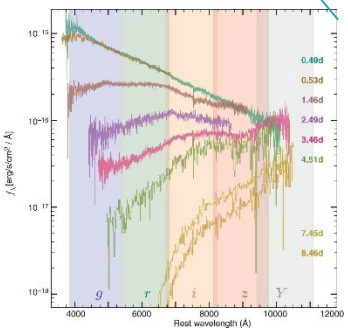


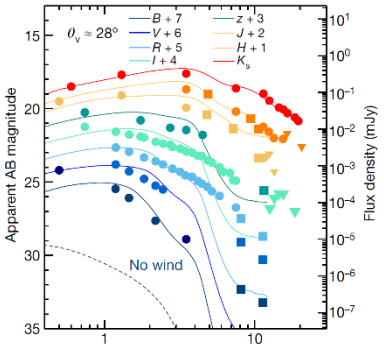
Imaging Observations
(~a few 100,000 sources per field)



Transient search



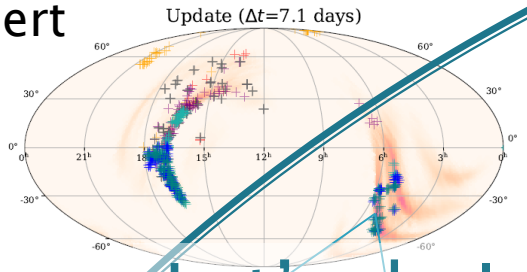

Spectroscopy and
KN identification

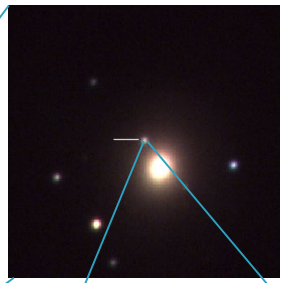



Time series
follow-up

# Search for KN

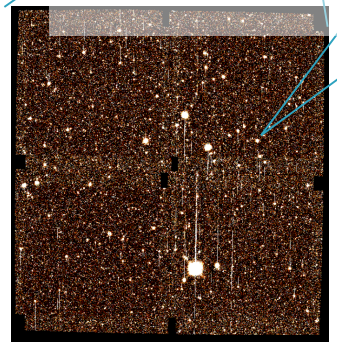
GW Alert



Transient search

Let's do Imaging + Spectroscopy Simultaneously!



Imaging Observations
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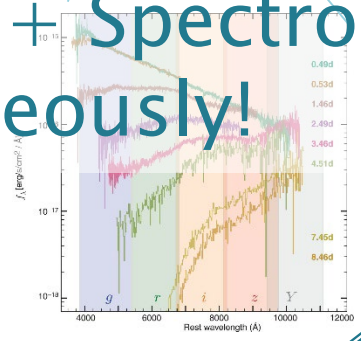
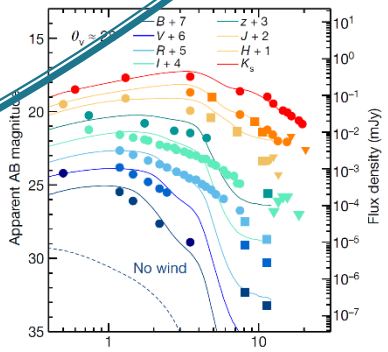


Spectroscopy and KN identification




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)
- Currently, 16 telescopes with simultaneous 32 wavelenegth coverage
- Pixel scale 0.5”, 1.25 – 25 $deg^2$ Field of view
- 7D = x,y,z (3) + time (1) + flux (1) + wavelength (1) + radial velocity (1)

http://7ds.snu.ac.kr

# 7DT Telescope

- 20, 0.5-m wide-field telescopes (Planewave Instruments, 3 deg field size)
- High precision telescope mount



Planewave DR500 telescope for 7DT

# 20 x 60M pixel cameras

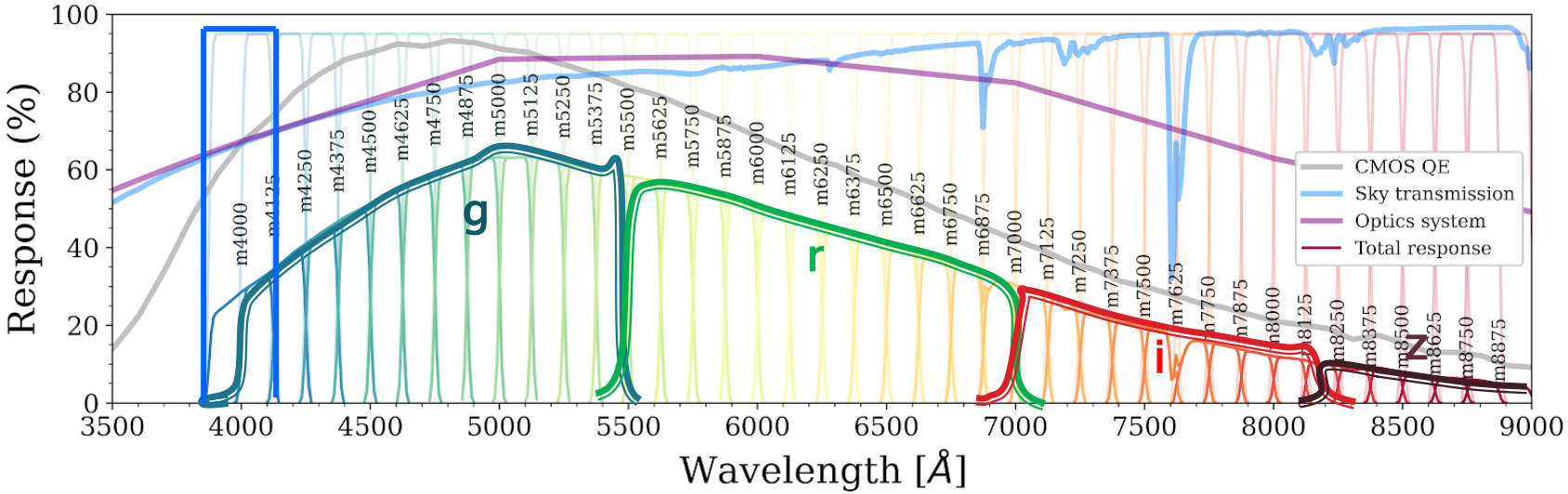
- Moravian C3-61000 PRO cameras with back-illuminated CMOS chips (9576 x 6388)
- Pixel size: 3.76 micron (or about 0.5") ➔ 1.35 x 0.9 $deg^2$
- **1.2 Gpixels (1/3 of the Rubin Observatory)**



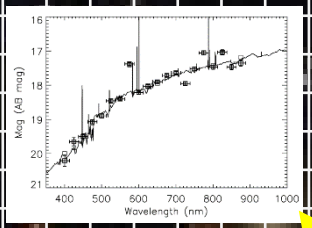
# 40 Medium-band Filters

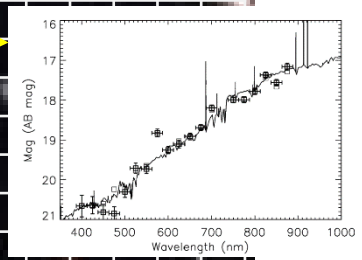
- Width: 25nm (vs broad-band 150nm) at 400 – 900 nm
- Interval: 12.5nm
- R ~ 40 low resolution spectra ➔ Good S/N with small telescopes
- Spectra for every pixel in the field of view (1.3 deg$^2$)

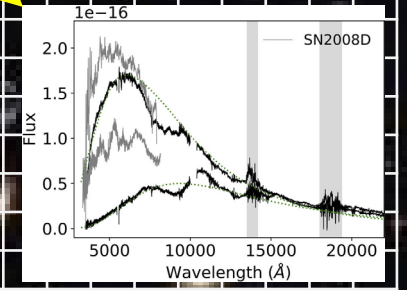
Medium-band vs Broad-band filters

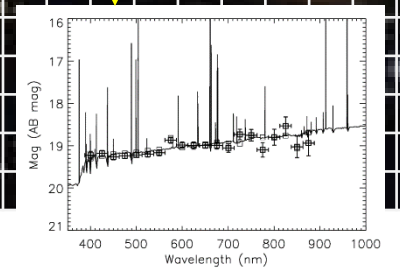


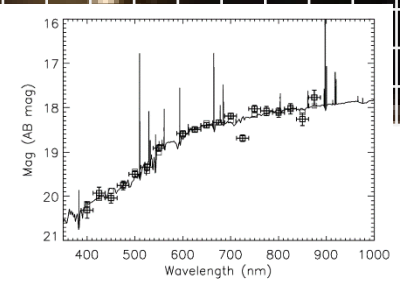
# Wide-field spectral mapping can identify KN fast

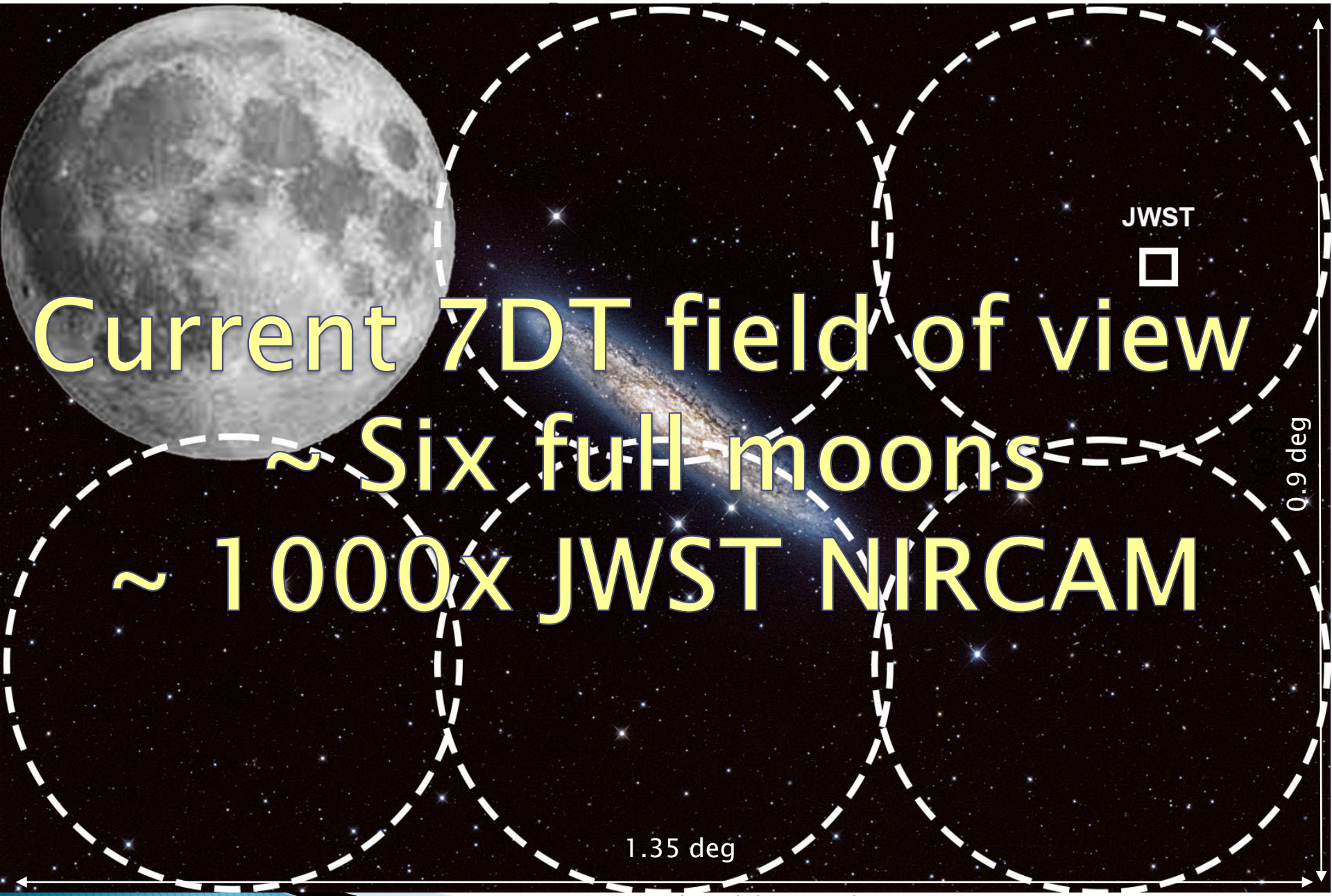


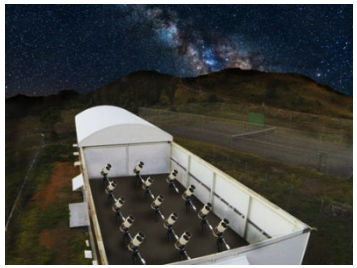






# Current 7DT field of view
## ~ Six full moons
## ~ 1000x JWST NIRCAM

# 7DT, Three Observing Modes

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

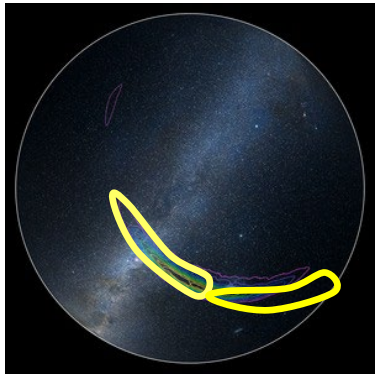


=



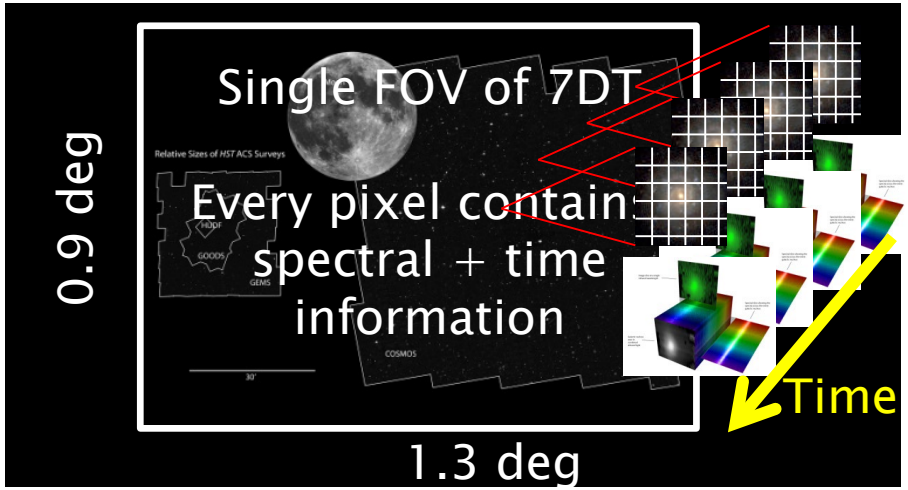
7DT SDSS

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

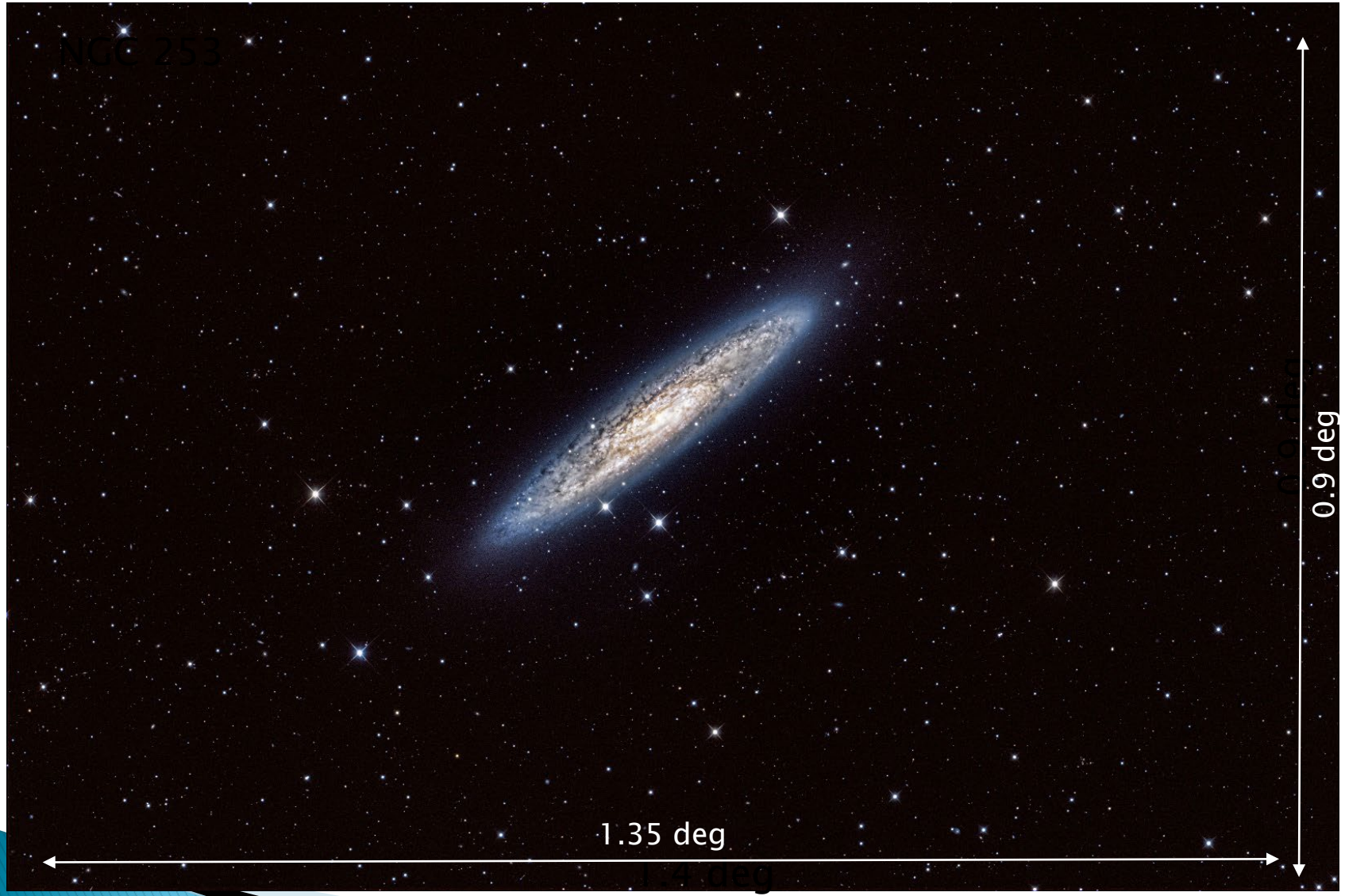


# 2026: Current Status

## 16 + 1 telescopes are in place
## 7-Dimensional Sky Survey ongoing



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




https://sites.google.com/view/7dtfirstimages

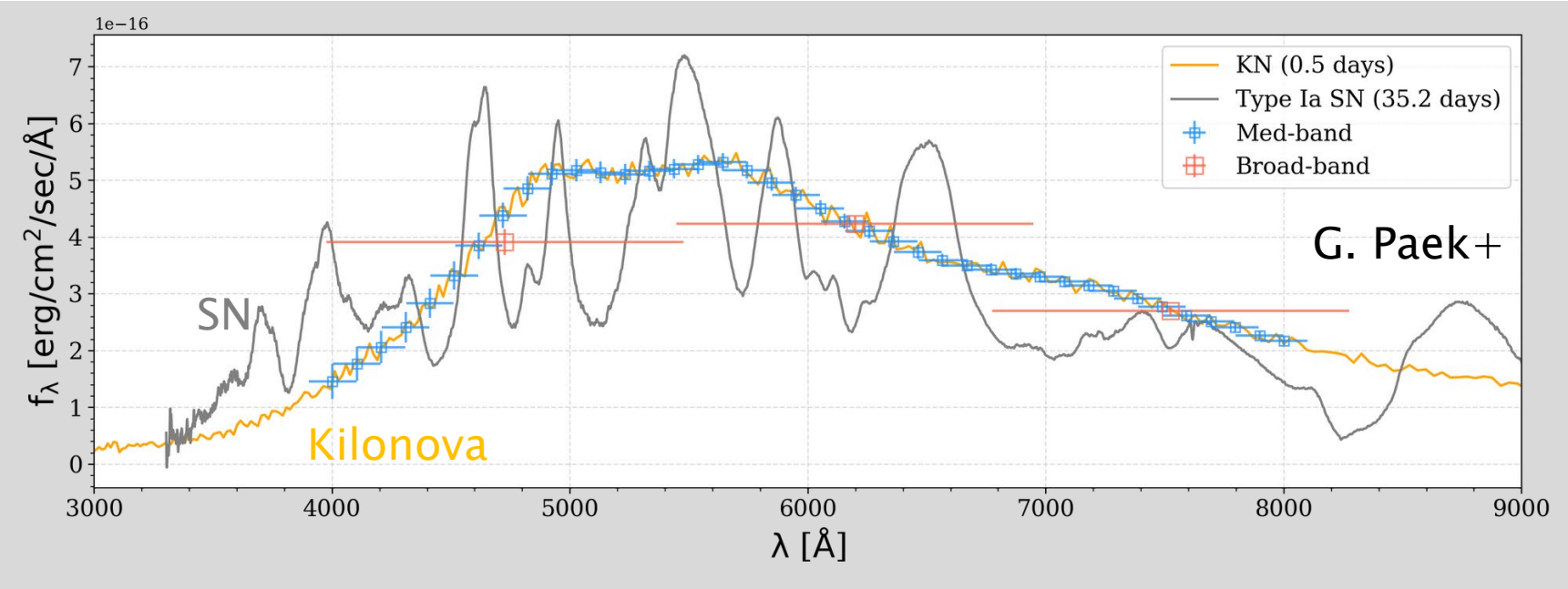
# 7DT image of Trifid Nebula (NGC 6514)



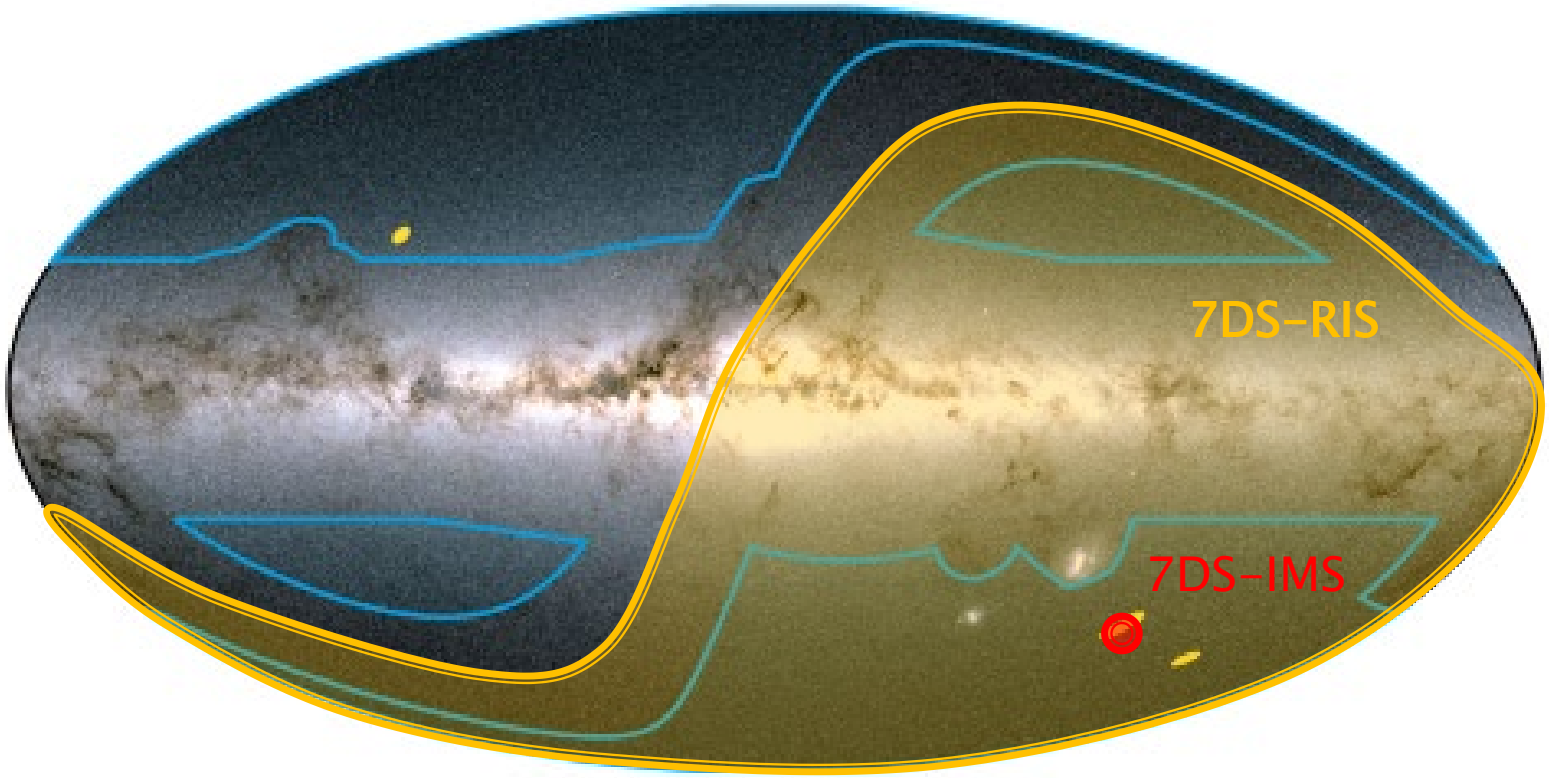
https://sites.google.com/view/7dtfirstimages

# Multi-messenger Astronomy with 7DT

- R ~ 40 spectroscopy for the entire field of view
- Best suited for sampling broad continuum features and broad emission lines continuum ➔ good for KN spectral id in one shot



# 7-Dimensional Sky Survey (7DS)

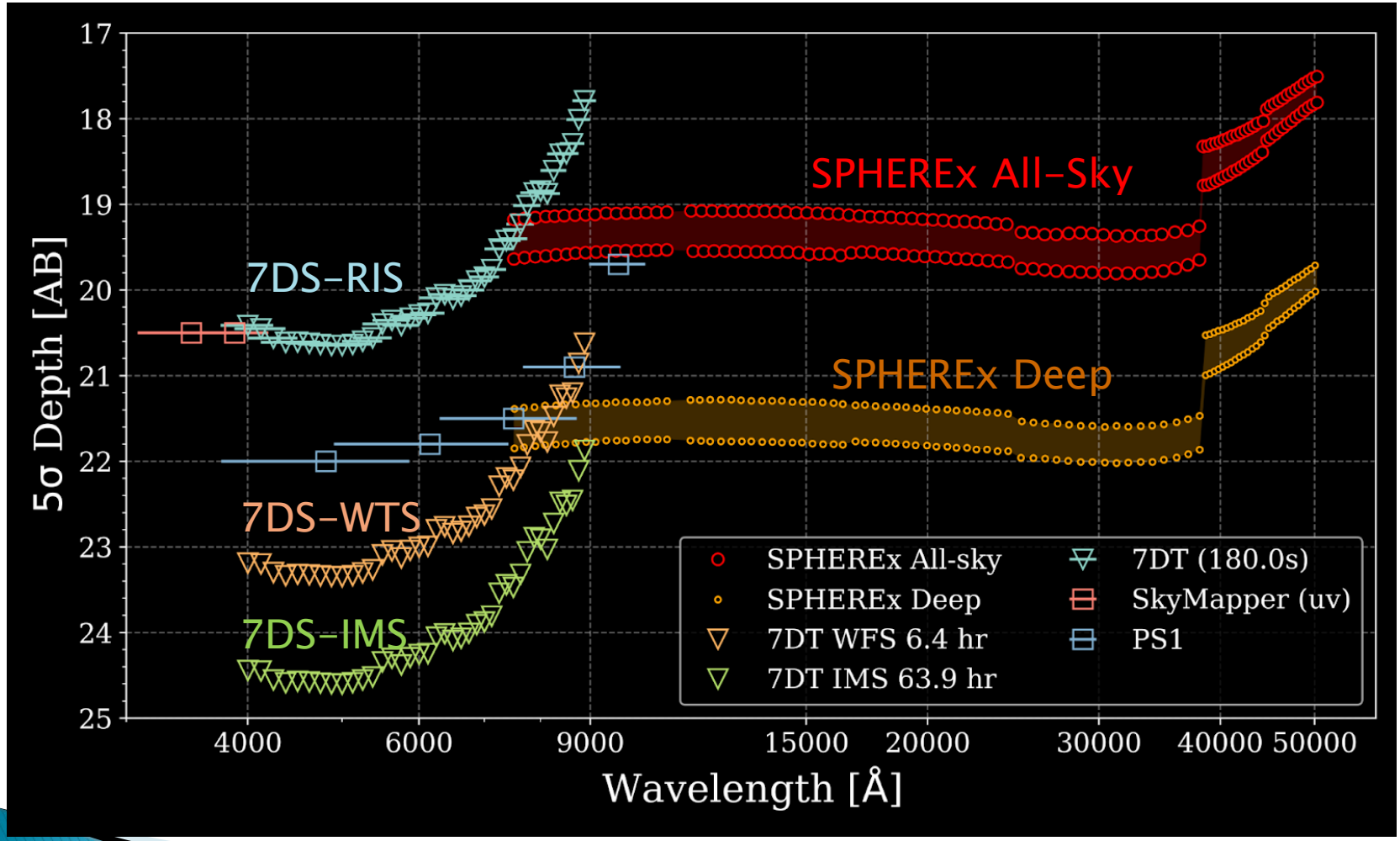



**7DS-RIS: Reference Image for Entire Southern Hemisphere ~60% complete so far**

7DS-WTS: TBD (some in the equatorial field, some near SCP)

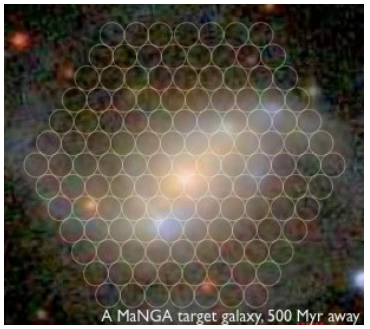
7DS-IMS: Overlap with Euclid-deep, SPHEREx deep fields

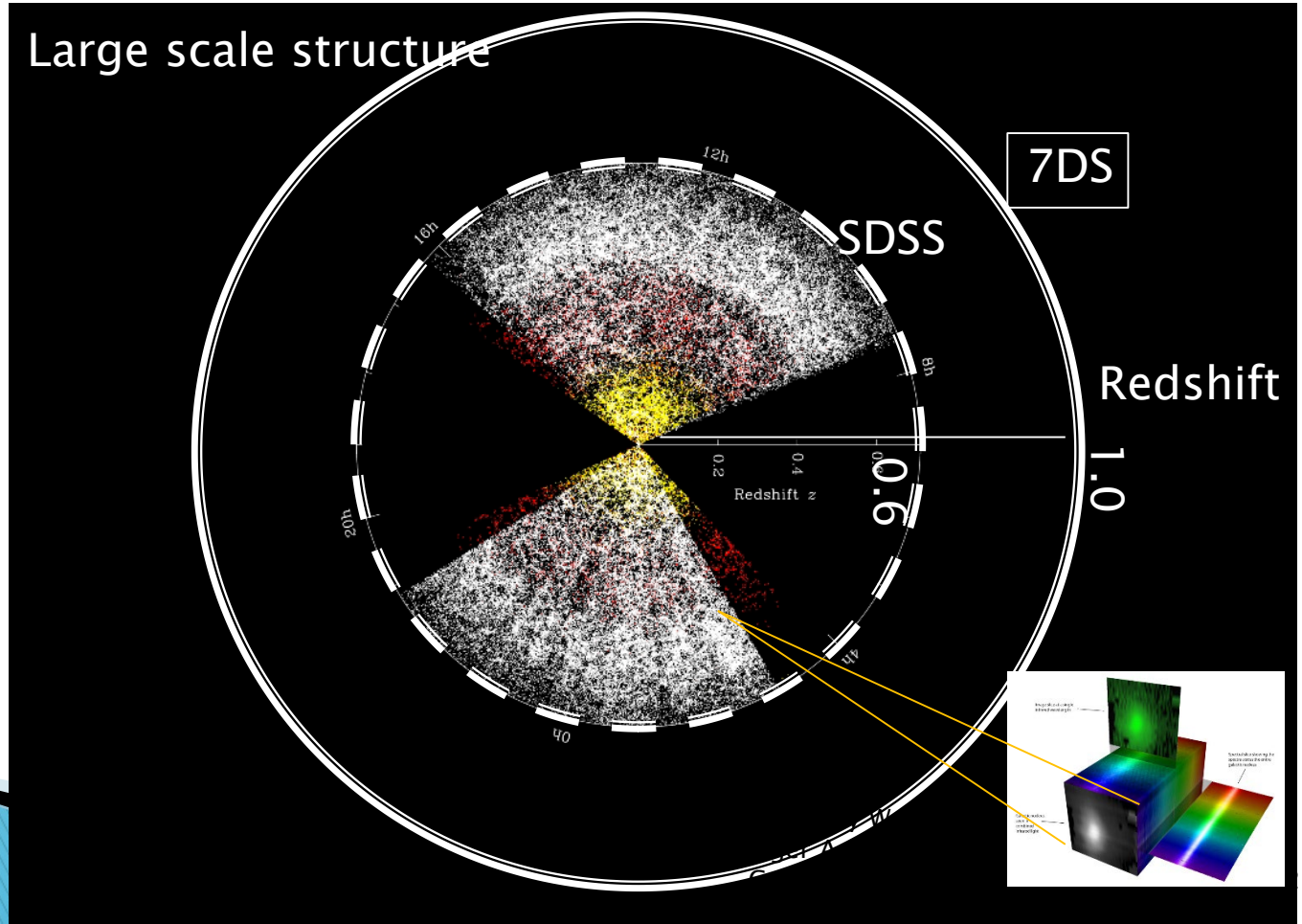
# 7DS detection limits



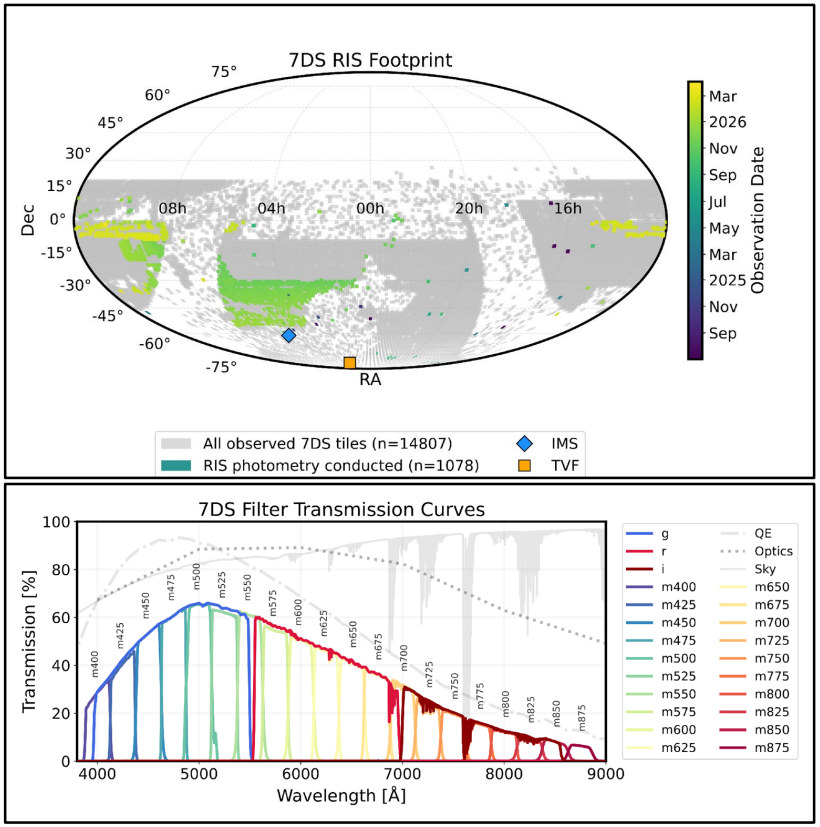
# 7DS Galaxy Map

- Galaxy redshifts at 0.2–1% accuracy (Ko+25, Bae+26)
  ➔ Galaxy/QSO catalog for dark siren study
- Spatially resolved stellar population for 10M galaxies ➔ local environment of GW events can be studied



# 7DS Reference Imaging Survey (RIS)




- **Coverage**

  Dec < 20° southern all-sky (currently ~15,000 deg$^2$ visited)

- **Filters**

  gri + 20 medium bands (m400–m875, $\Delta\lambda$ = 25 nm, $R \approx 20$)

  + 15 additional medium band filters (2026.07-)

- **Depth**

  300 sec per band, 5σ limiting mag $m_{625} \approx 20$ AB

- **Key strength**

  Resolves spectral features (4000 Å break) more directly

  → more precise photo-z than broad-band catalogs

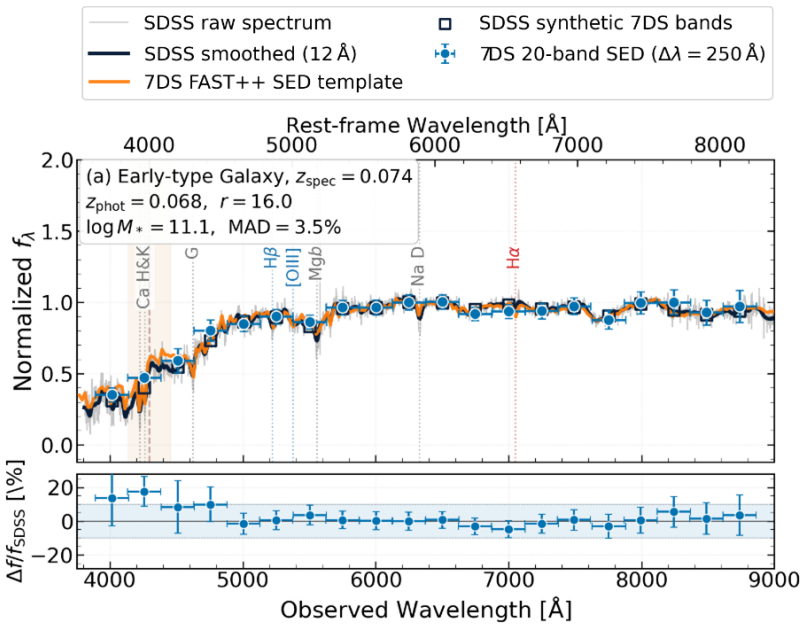
  (c.f. GLADE+ (Dálya+21), REGALADE (Tranin+26))

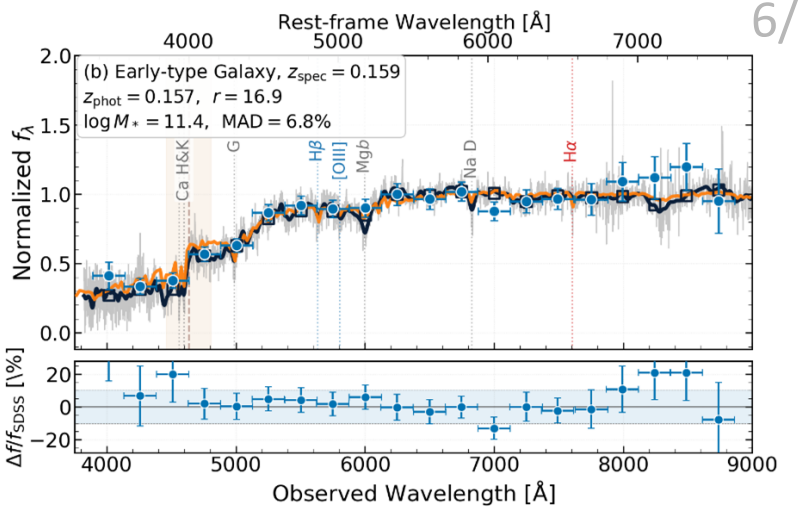
- **Products**

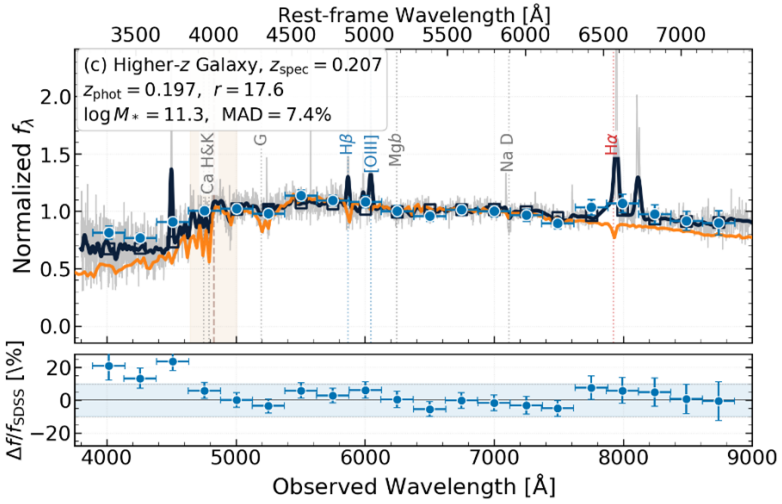
  Homogeneous reference images

  legacy SED/photo-z catalog for time-domain & follow-up

**7DS SED (Phot7DS) vs. SDSS Spectrum**

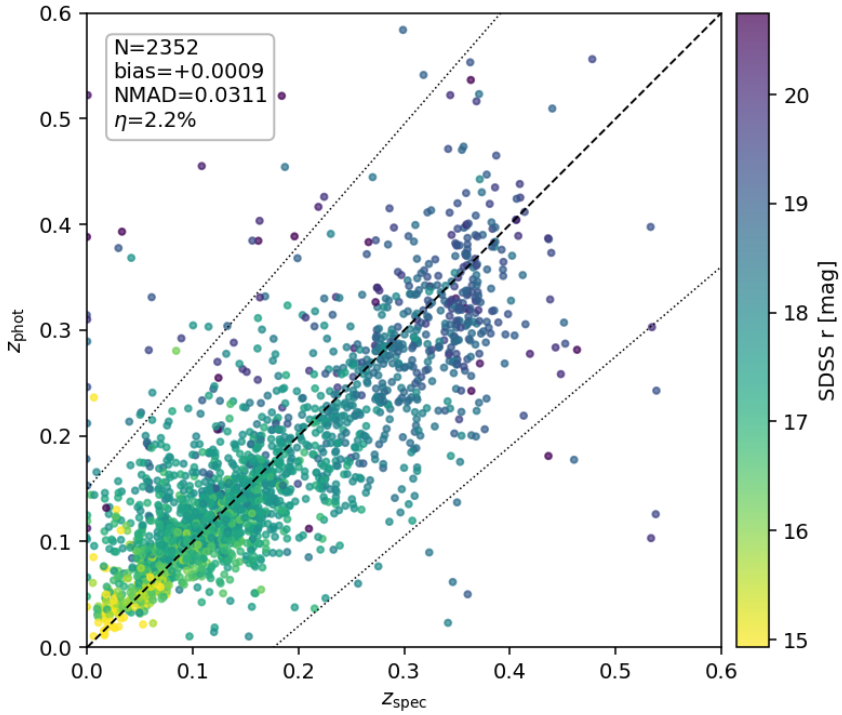



| r-mag | 14-16 | 16-17 | 17-18 | 18-19 | 19-21 |
|---|---|---|---|---|---|
| $N_{galaxy}$ | 134 | 434 | 1062 | 411 | 208 |
| MAD (5000 -8500Å) | 8.1% | 10.1% | 14.1% | 20.7% | 32.1% |

# Medium-band photo-z at single-visit depth



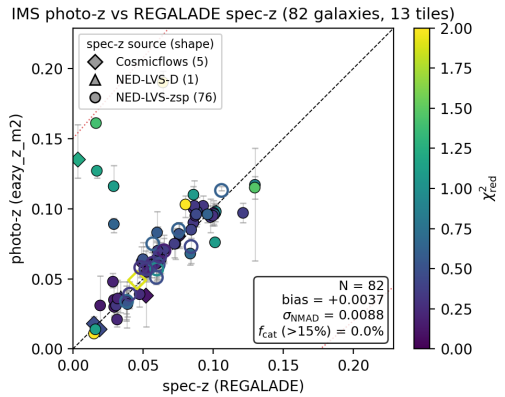

RIS vs. SDSS DR16 spec-z (19 tiles, z_spec < 0.6, N = 2,352)

**0.031**
σ_NMAD

**2.2 %**
outliers η

**+0.0009**
median bias

$$\sigma_{\mathrm{NMAD}} = 1.48 \times \mathrm{median}\left(\frac{|\Delta z - \mathrm{median}(\Delta z)|}{1 + z_{\mathrm{spec}}}\right)$$




**0.0088**

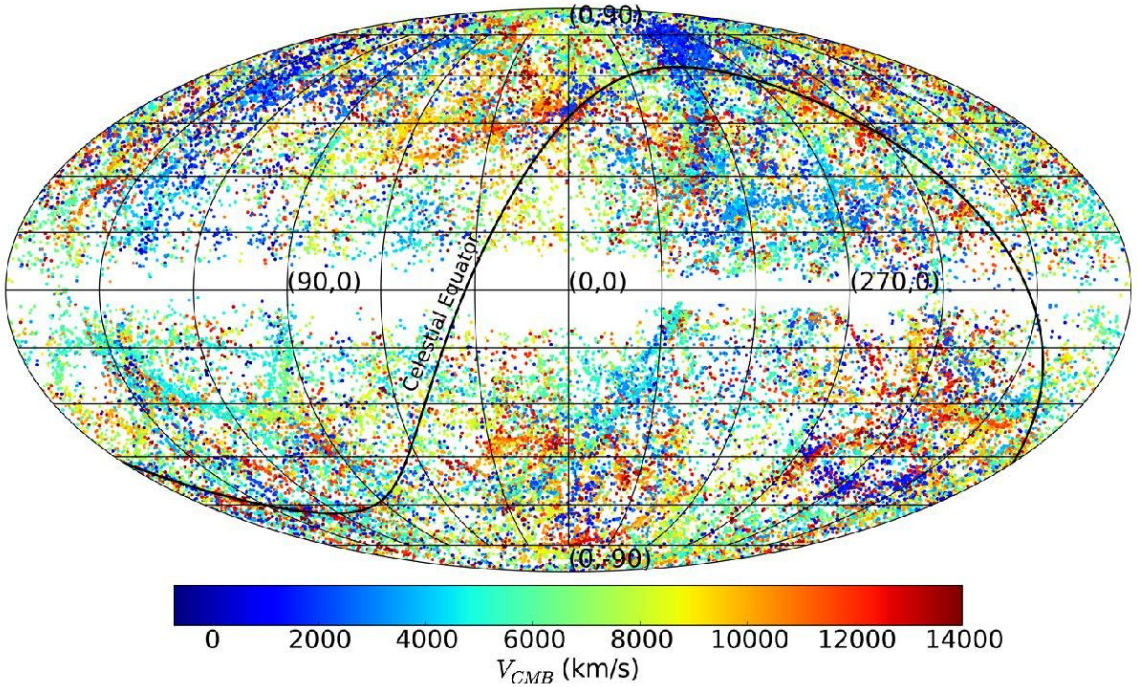
σ_NMAD, deep (N = 82)

m625 prior calibrated on SDSS + DESI spectra

Deep IMS coadds (m625 ≈ 22) vs. spec-z

# Galaxies + Quasars near Galactic Plane

- Galaxy and quasar catalog is highly incomplete near Galactic plane

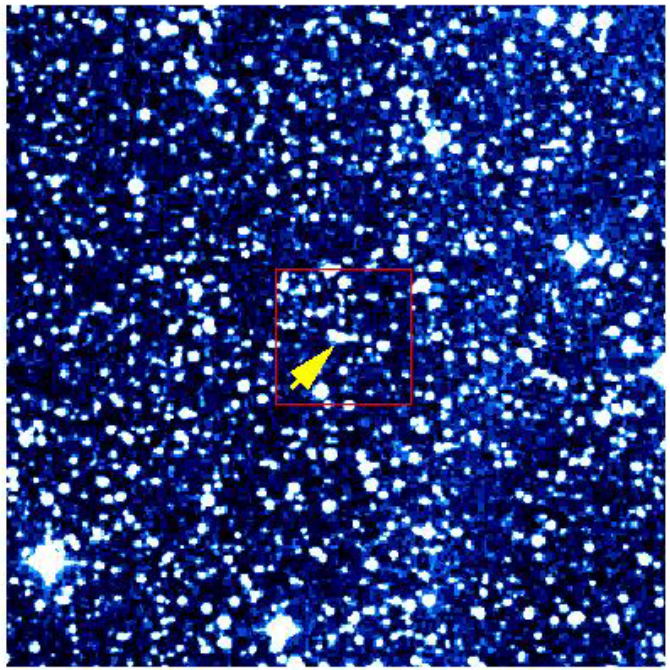


# 7DS will find ~5,000,000 galaxies and 20,000 Quasars in the zone of avoidance

**Quasar in High Galactic Latitude vs Quasar in the Zone of Avoidance**



3C273 (High Galactic Latitude Quasar)



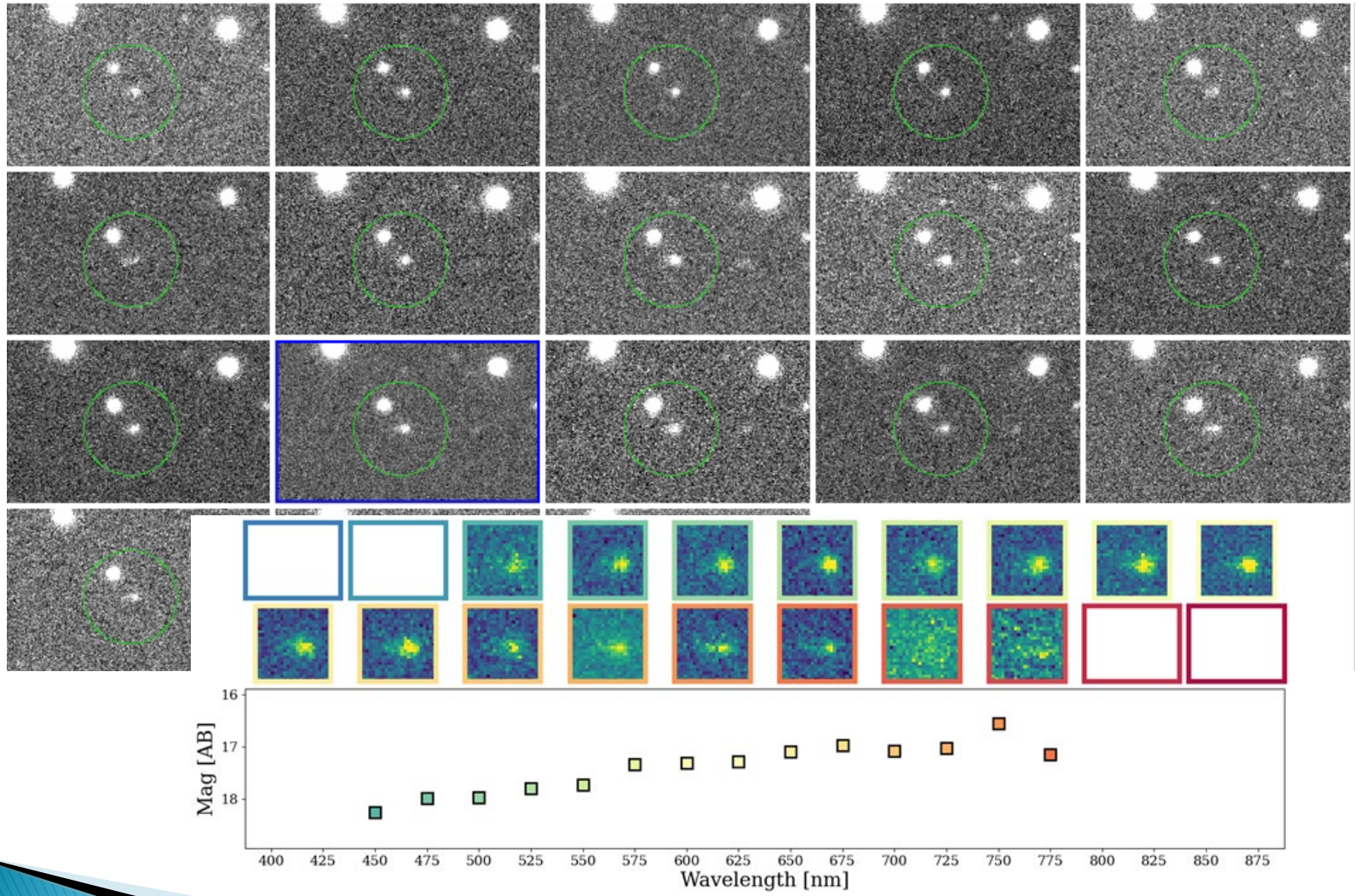
SNUQSO J2109+3532
(Quasar in the Zone of Avoidance)

Im+07

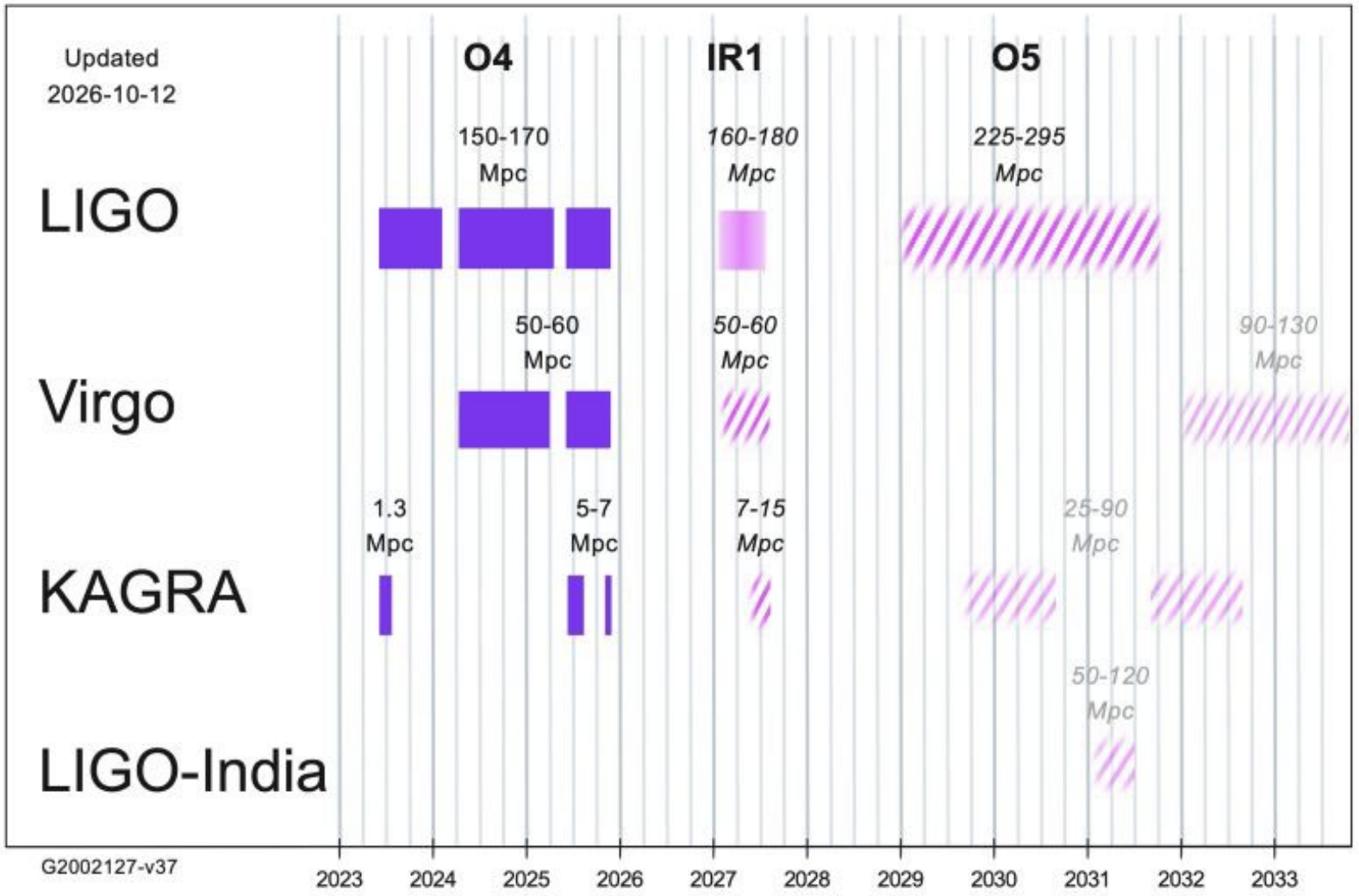
# GW Events Observed by 7DT

| Name | Class | FAR [1/yr] | CR90 [deg$^2$] | Dist(err) [Mpc] | Notes |
|---|---|---|---|---|---|
| S240422ed | Terr 93%, BNS 5% | 1/35 days | 259 | 188(43) | NSBH 99%, early |
| S240910ci | BBH | 1/100 | 394 | 662(166) | NSBH 31%, early |
| **S240915b** | **BBH** | **1/100** | **18** | **872(149)** | **NSBH 14%** |
| S240925n | BBH | 1/7.9e+11 | 14 | 331 (70) | NSBH 26%, early |
| S241125n | BBH | 1/33 | 76 | 4174 (1591) | |
| S250206dm | NSBH 55%, BNS 37% | 1/25 | 547 | 373 (104) | HasRemnant 30% |
| S250328ae | BBH | 1/100 | 14 | 511 (82) | Massgap 7% |

# 7DT data of GECKO24l in S240915b (BBH event at 870 Mpc, with CR90 = 18 deg²)



# Near Future Prospects

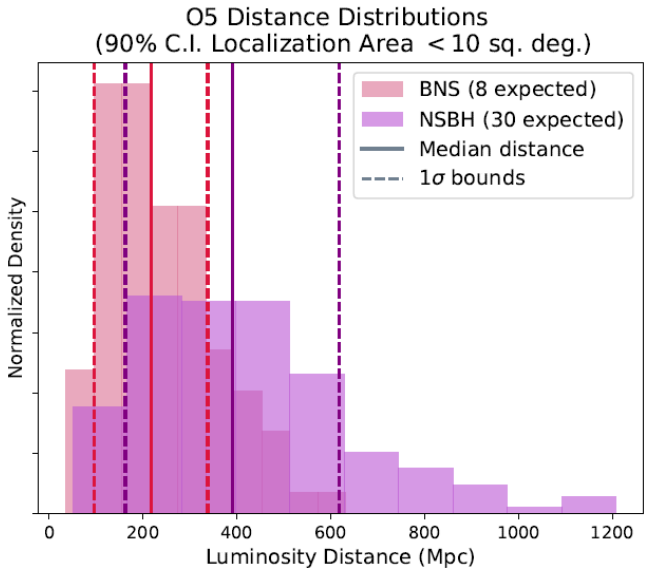


# Forecast for O5

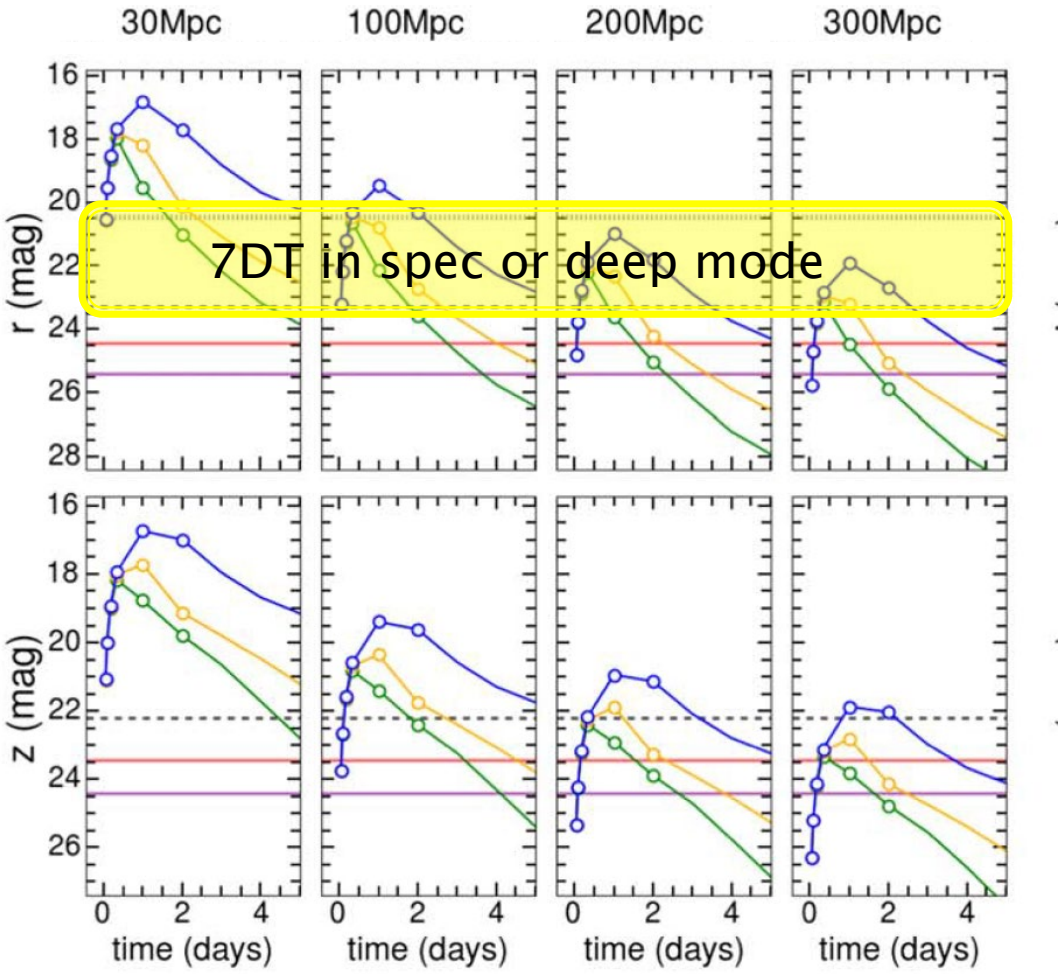
Andreoni+22, 24

| | O5 | | |
|---|---|---|---|
| | Total | $20 < \Omega_{90\%} \leqslant 100$ | $\Omega_{90\%} \leqslant 20$ |
| 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 | $480^{+280}_{-180}$ | $104^{+61}_{-39}$ | $70^{+41}_{-26}$ |

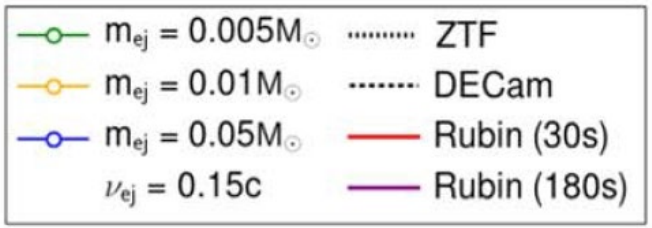
- 10 – 100 NS-involved events in O5
- Many at < ~300 Mpc



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



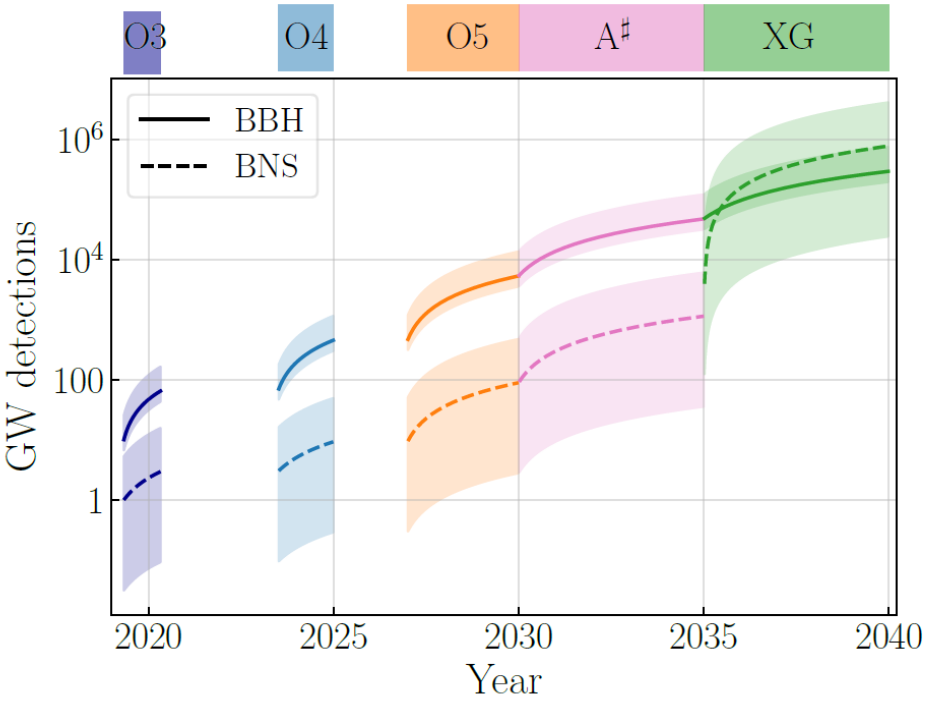

- 7DT can catch close KNe in spec-mode, distant ones in deep mode
- Large facilities (DECam, Rubin) will play important roles

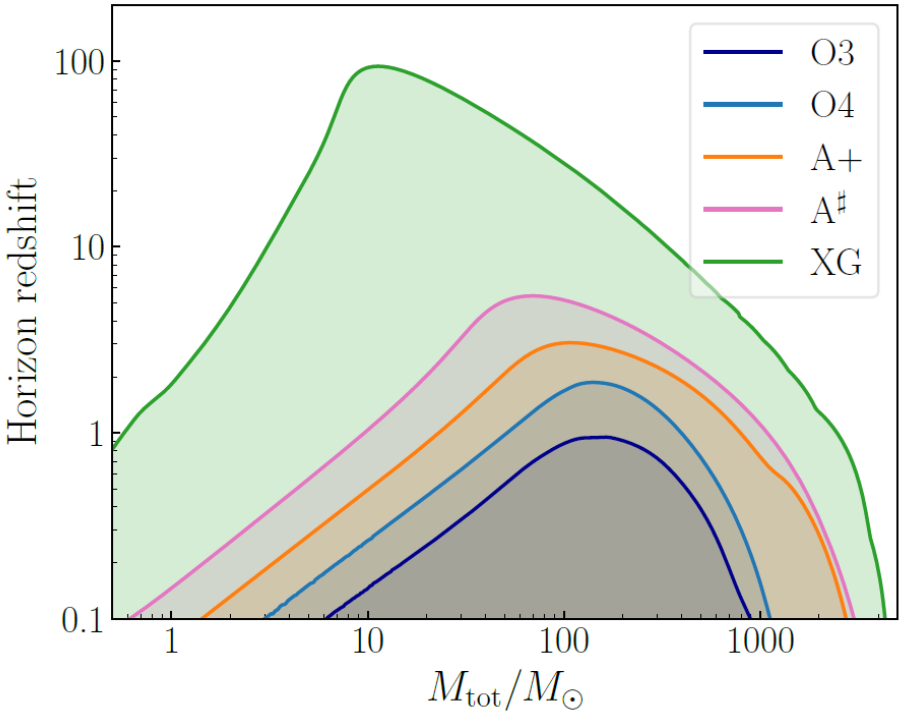



Andreoni+22

# Distant Future Prediction

Chen+24

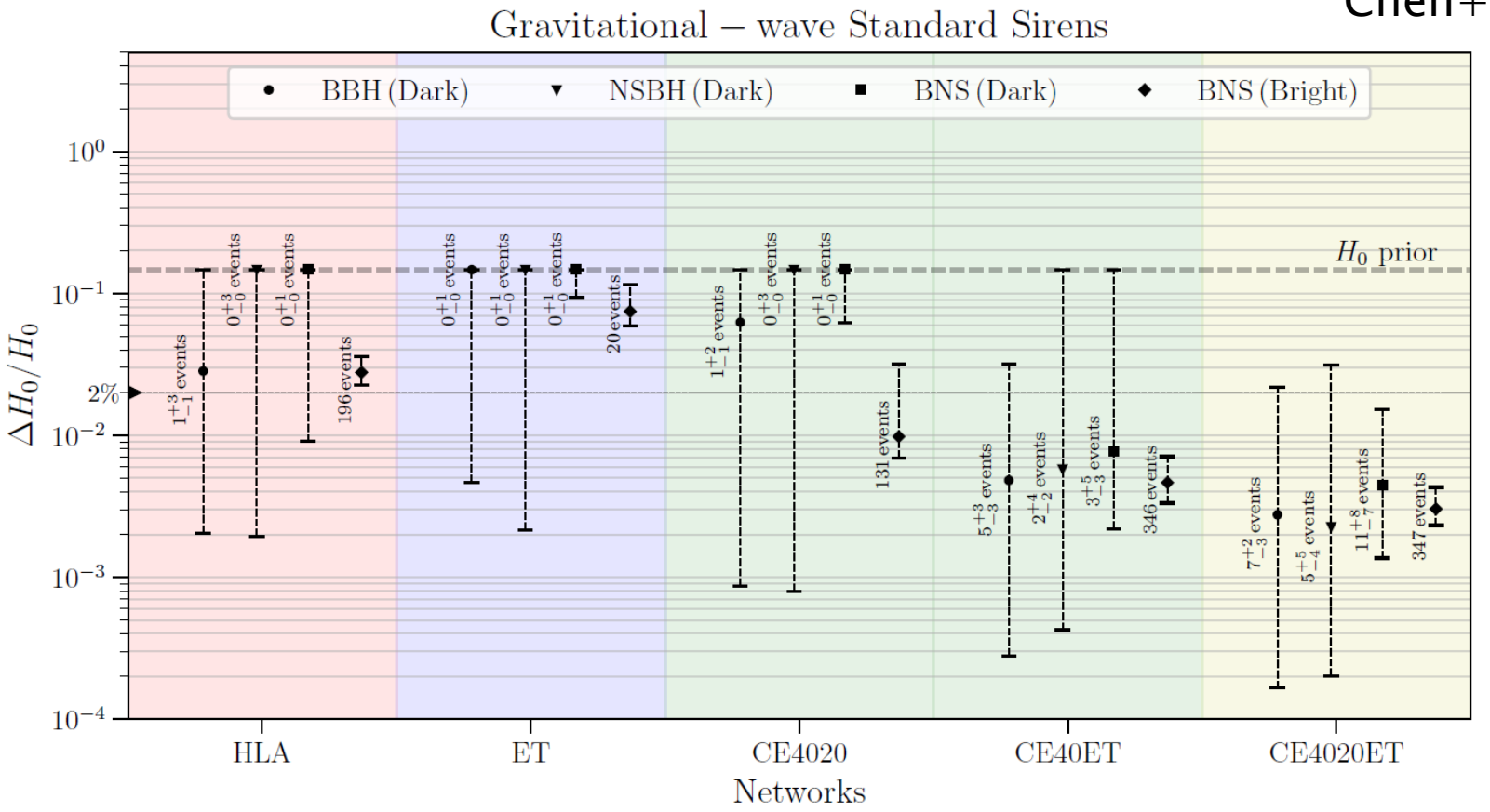



- Currently, BNS merger rate of 1/yr at D < 200 Mpc
- In future, $10^4$ to $10^6$ such events out to 10,000 Mpc

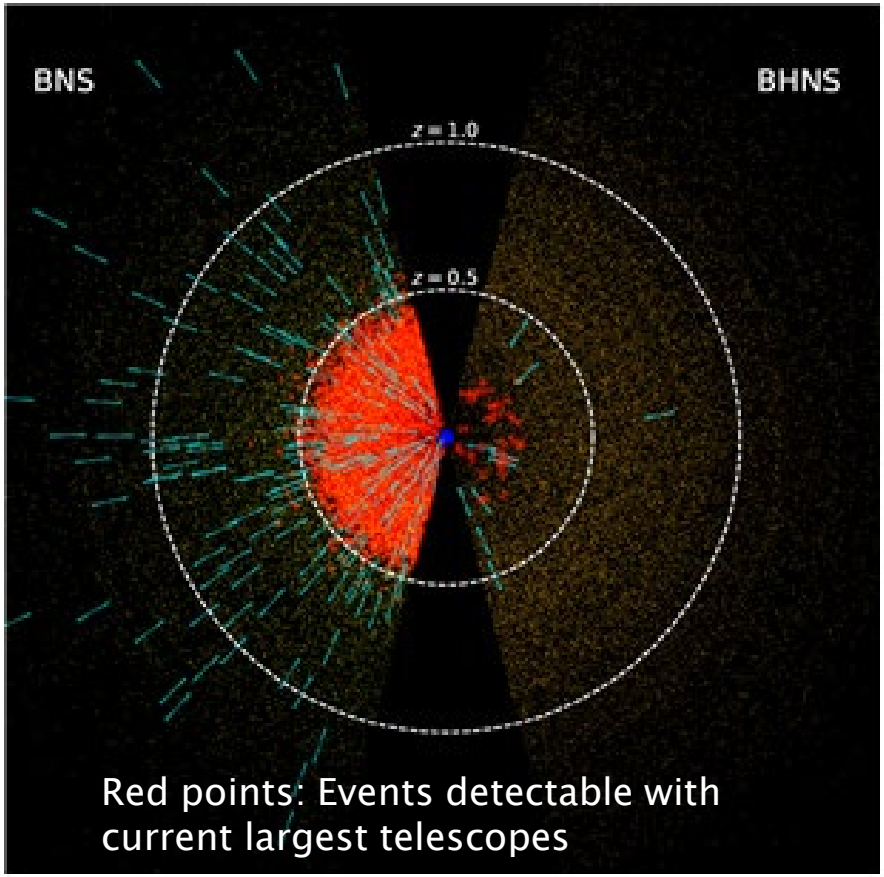
# Future Prediction for H0

Chen+24




- < 1% accuracy for H0

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

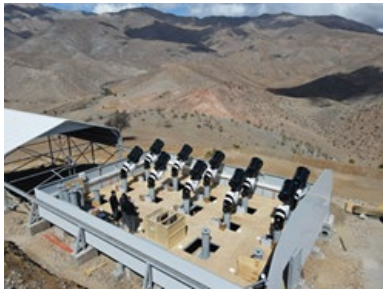



ET Blue Book

- Discovery: Wide-field, grounad-based large telescopes
- Characterization: Space telescopes
- Too many events for existing optical facilities (>1000s per year)
- Distance limit of $z < 0.5$ hampers cosmological investigation
- Need more like Rubin, Roman, or something more powerful

# What optical telescopes will be available in future?

Discovery



7DT, ZTF, ….



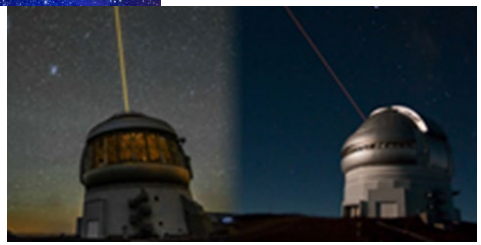
Rubin, DECam, VST, …

Characterization



JWST, Roman, CSST…

Gemini, Subaru, VLT, …



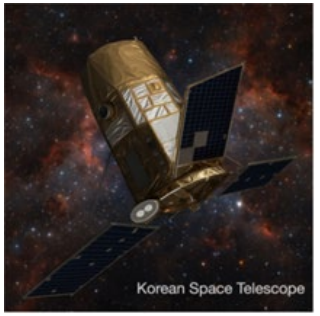


GMT, TMT, ELT

Future facilities?



ng7DT (planning)




Korean Space Telescope (1.4m, planning)

# Next Generation 7-Dimensional Telescope (ng7DT)

- World's most powerful wide-field spectral imaging facility with 50 x wide-field 1-2m telescopes ($D_{eff}$ ~ 14 m, FoV = 3 – 7 $deg^2$)

- Scientific Goals

* Multimessenger Astronomy

- Super-Rubin-type wide-field survey &
- super 7DT-type spectral mapping survey of the Universe

- Currnet list of PI/CoI: M. Im, HM Lee, C. Kim, GW Gang, HW Lee, J Kim, YM Kim, JH Kim, SW Chang, DG Tak, A. Shafieloo, + more
- Proposing as a large facility R&D project through Korean Physical Society & Korean Astronomical Sociey:
  - Total budget ~ 150M USD (10 year, including operation)

# Summary

- Past MMA efforts with GW170817 ➔ MMA study of cosmology, heavy element production, and more
- GECKO with 7DT will be powerful facilities for MMA
- Future prospect is too good for MMA ➔ But, $z < 0.5$ limit from optical facilities ➔ We need more powerful facilities