

Follow-up observations of Gravitational Waves with the Subaru: What We Could and Could Not Achieve

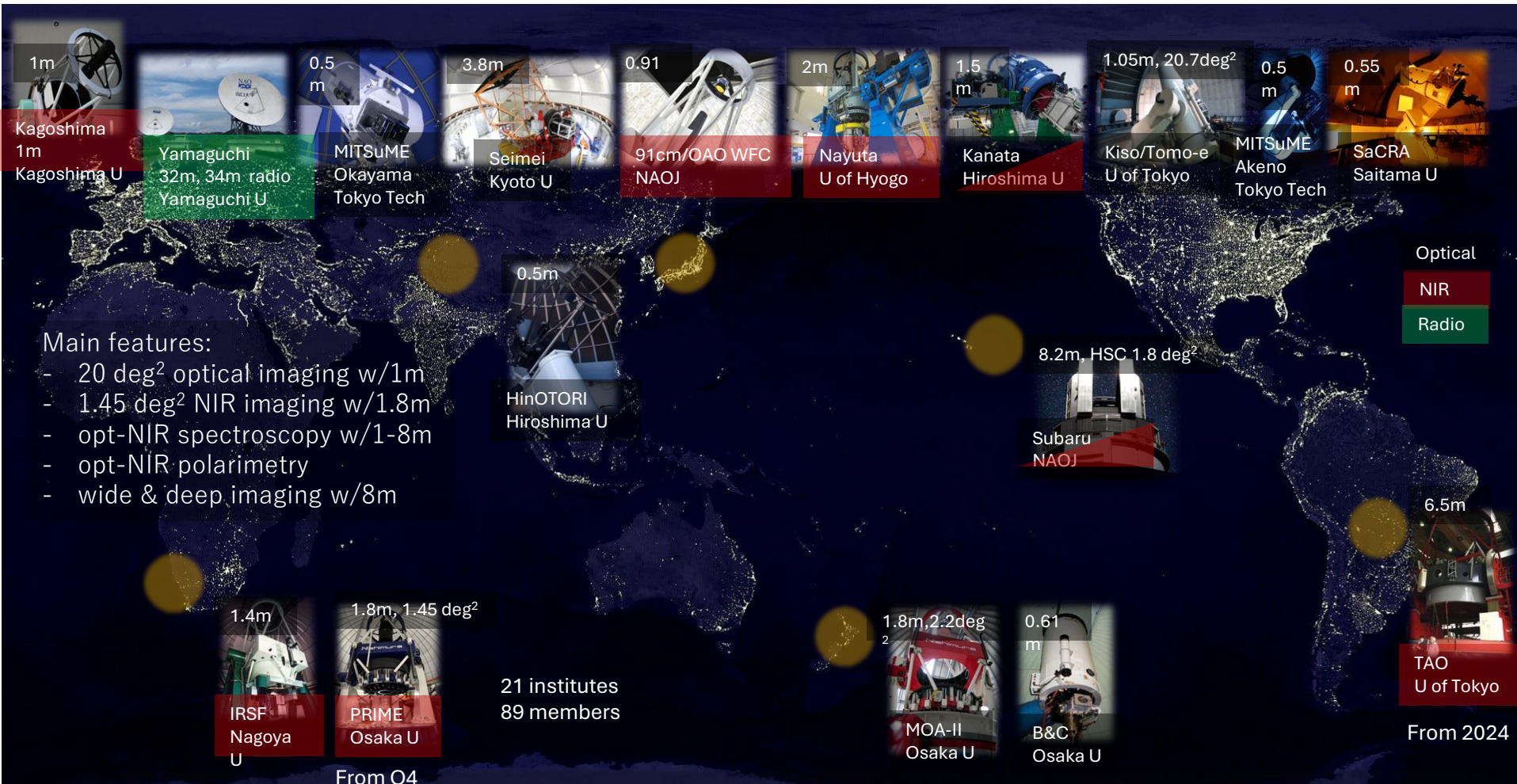
Nozomu Tominaga
(NAOJ/Konan)



30th Aug 2026
TeV Particle Astrophysics 2026

J-GEM

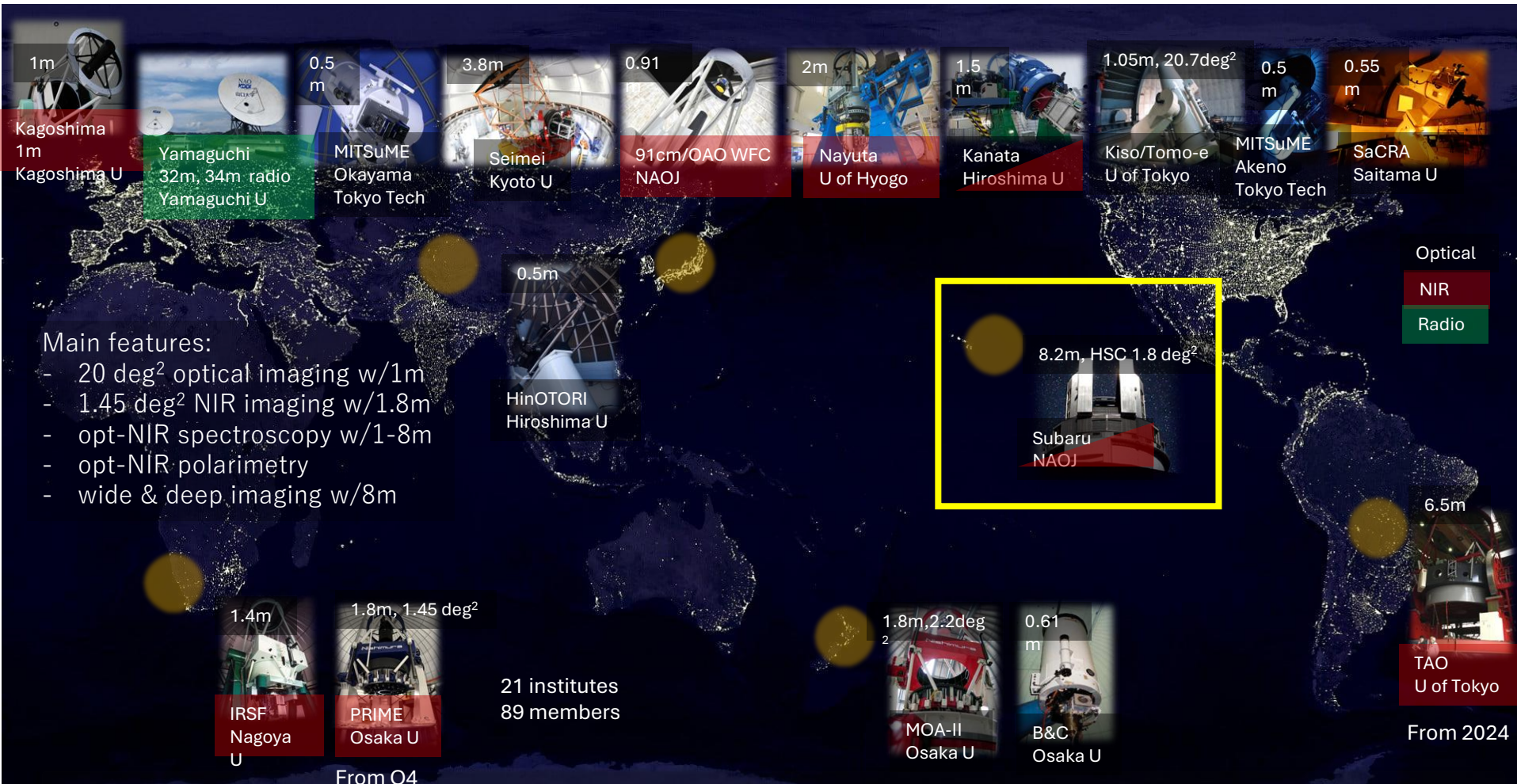
Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up



J-GEM Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

J-GEM

Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up



J-GEM Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

Subaru telescope



Wide-field capability

Imaging: Hyper Suprime-Cam

Spectroscopy: 'Ōnohi'ula Prime Focus Spectrograph

Deep observation with multi-instruments

Optical imaging/spectroscopy

NIR imaging/spectroscopy

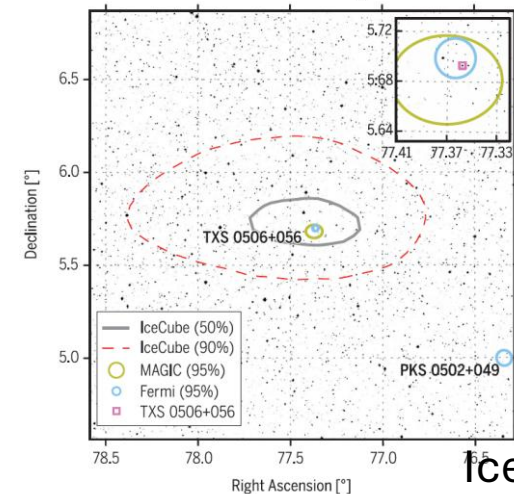
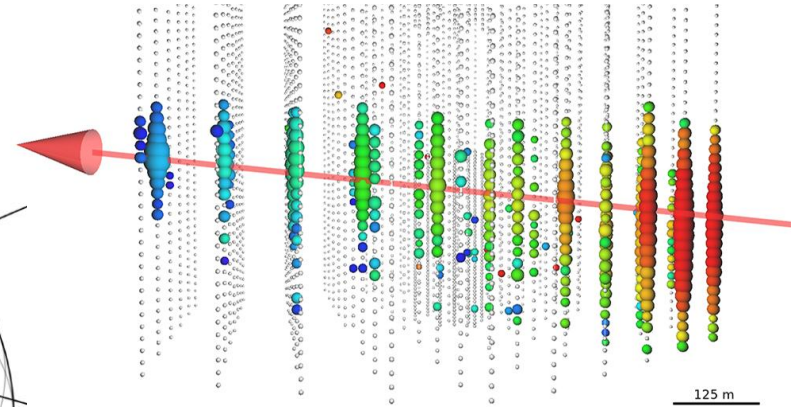
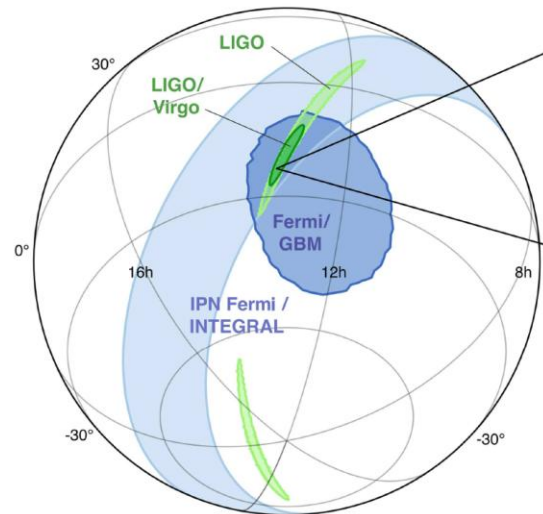
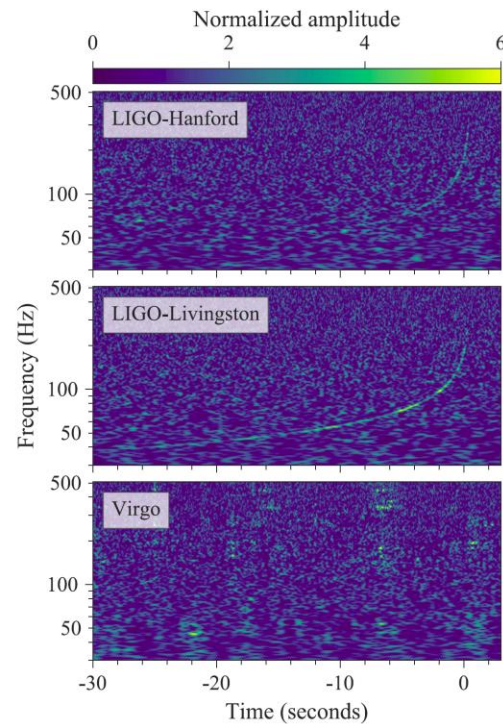


Multi-messenger signals

- requiring wide-field capability

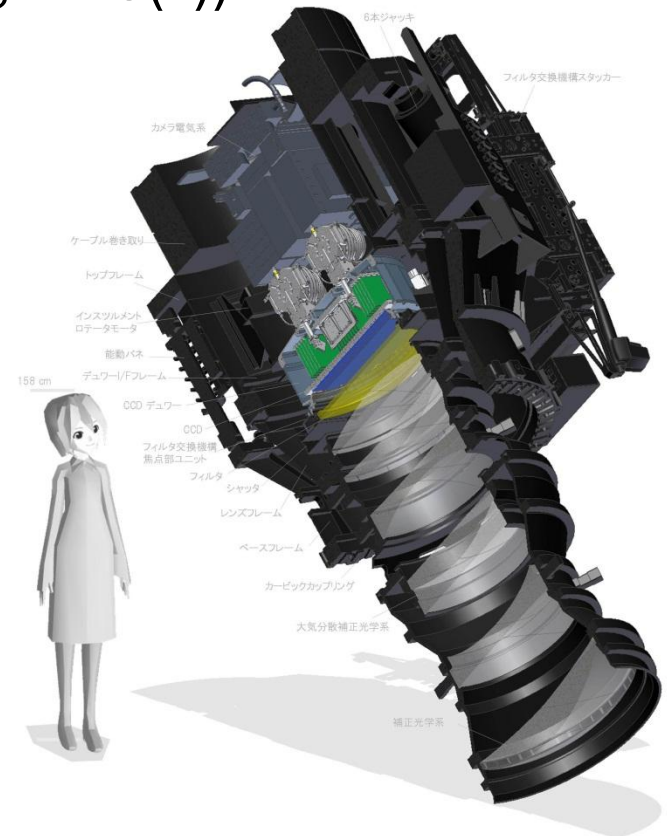
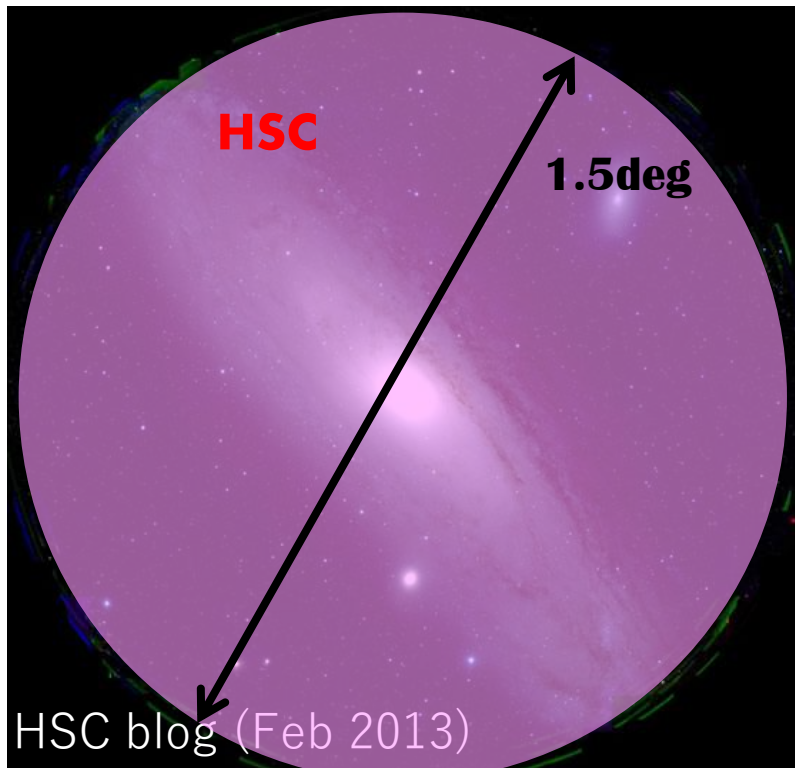
- Gravitational waves
~5-100deg²

- High-E neutrinos
~1deg²

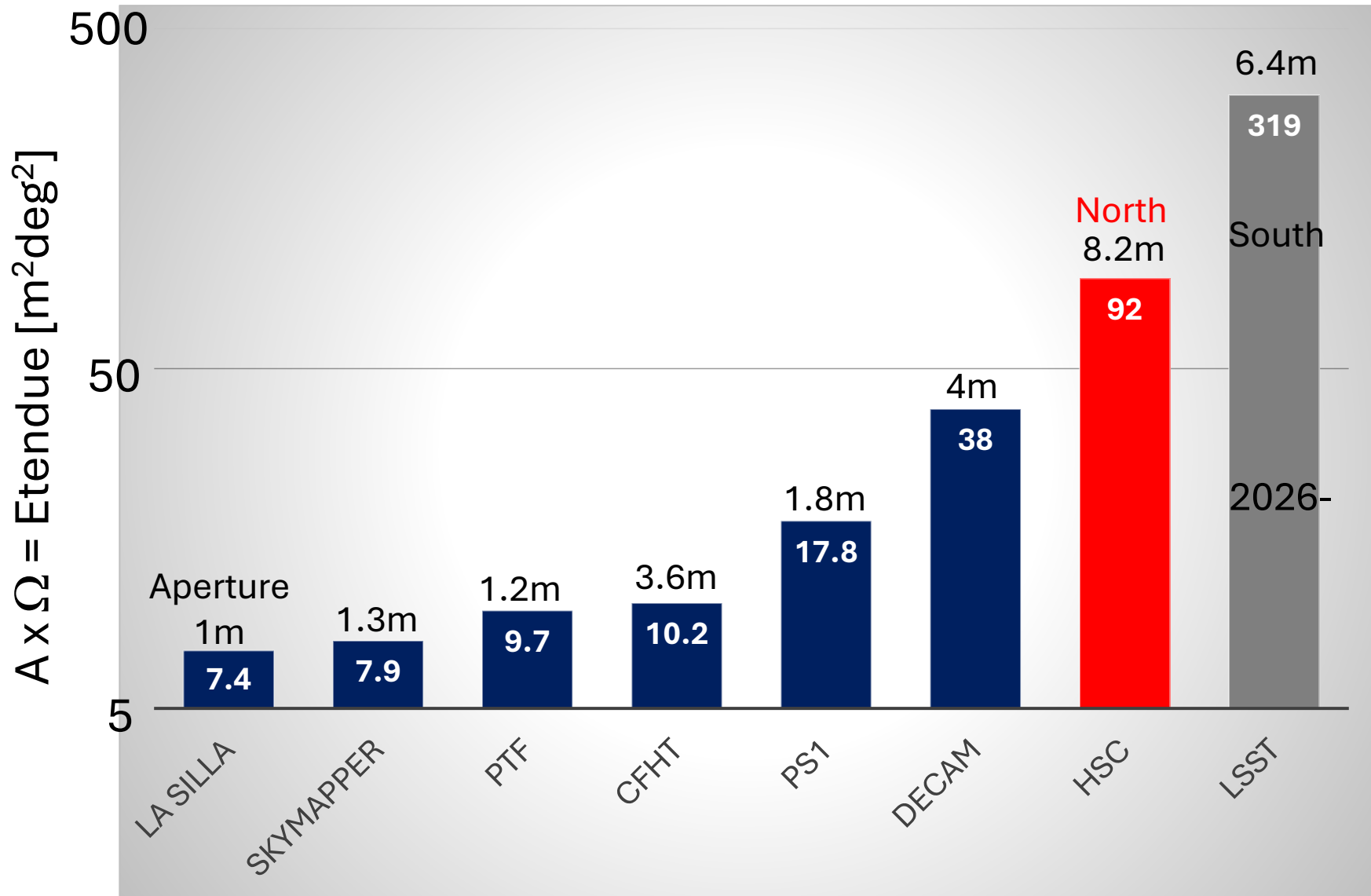


Subaru/Hyper Suprime-Cam

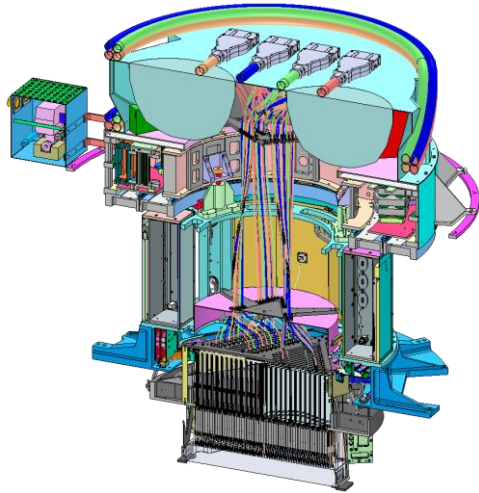
- Aperture: 8.2m, FoV: 1.77deg^2 , $\sim 900\text{M}$ pixels
- Lim. mag.(1min, 5σ): **24.5(i)**, **23.8(z)**
(DECam 1min: 23.3(i), 22.5(z))



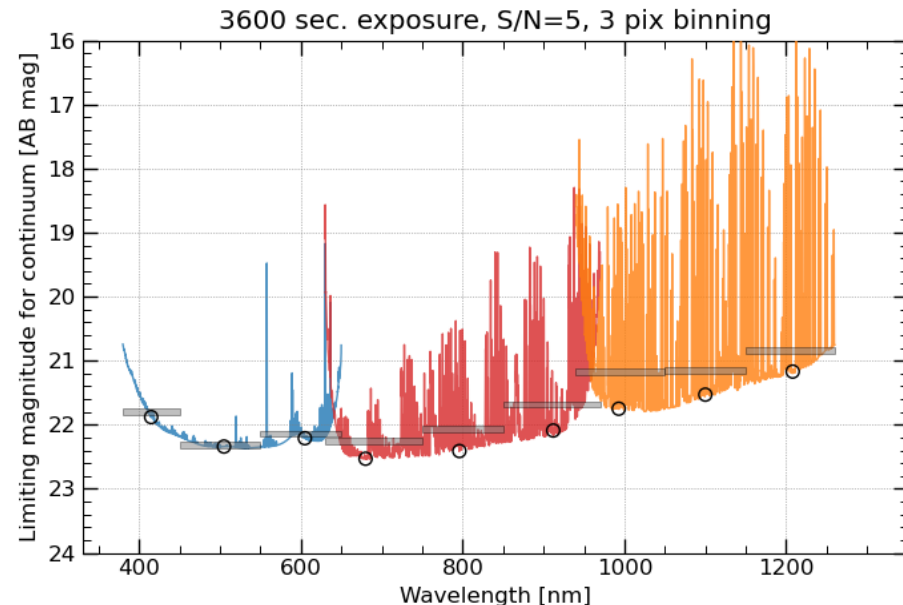
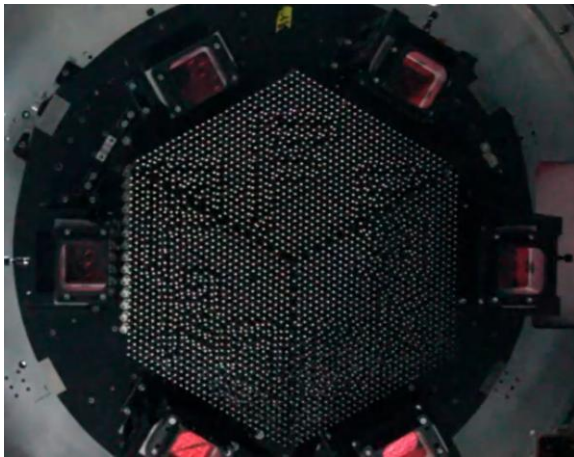
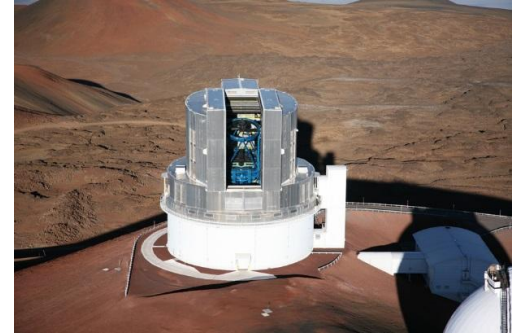
Survey power of optical telescopes



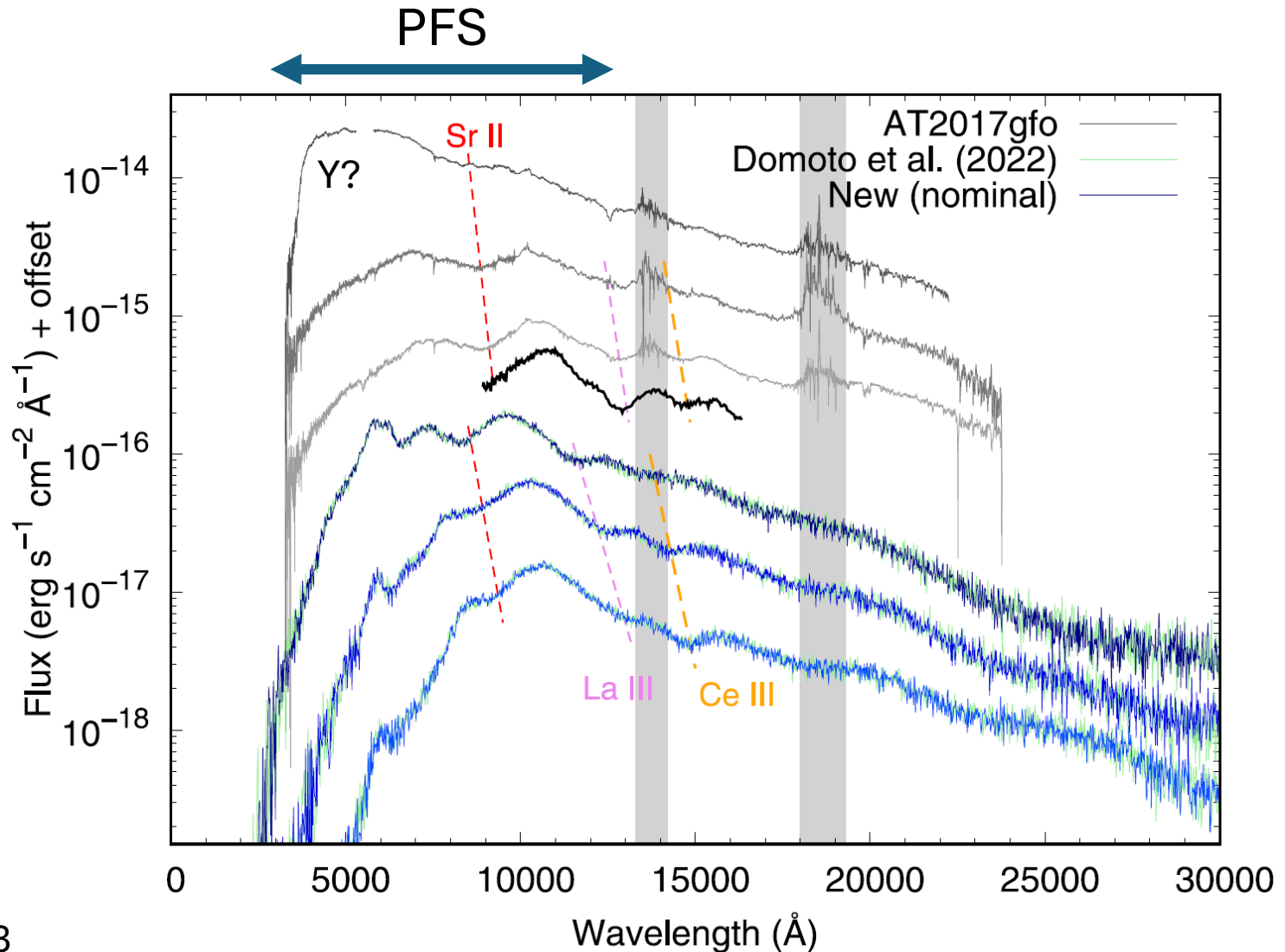
Subaru 'Ōnohi'ula Prime Focus Spectrograph



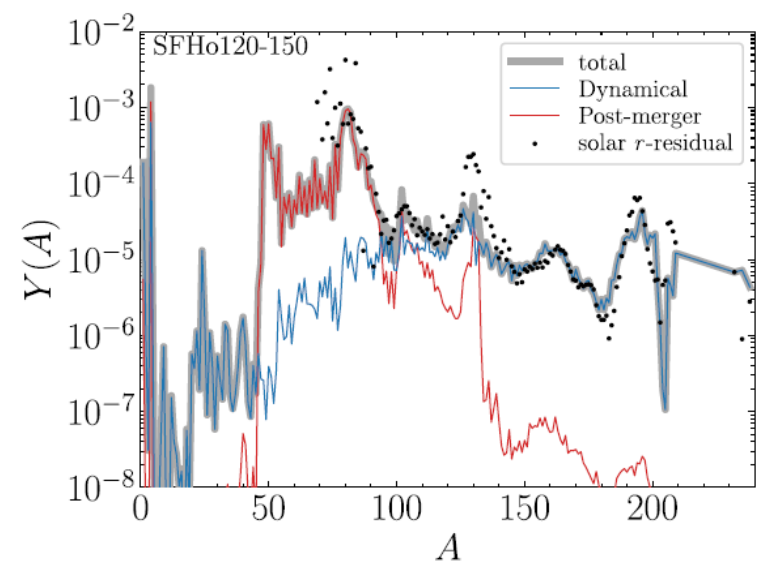
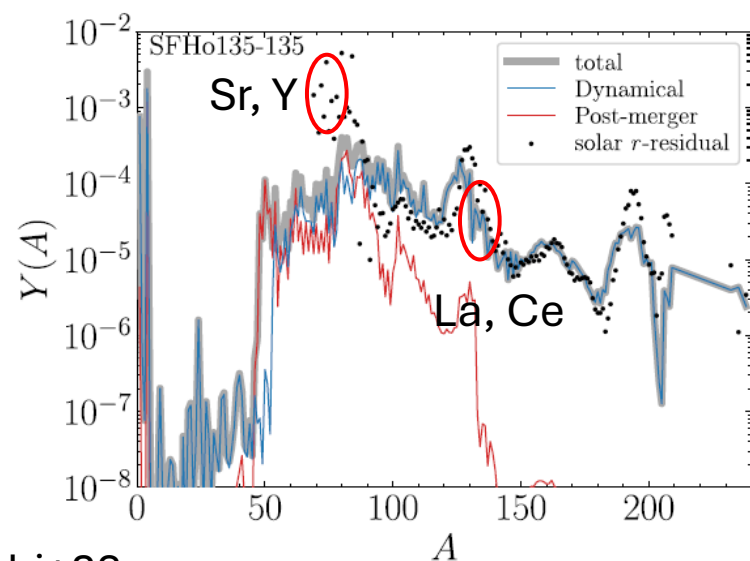
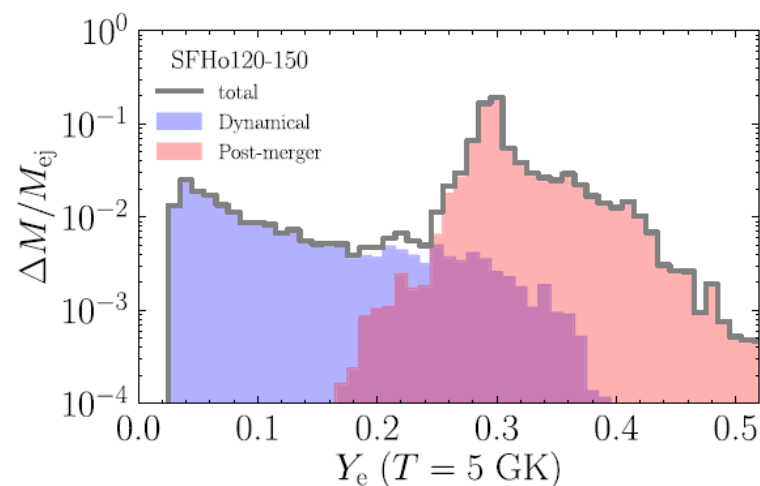
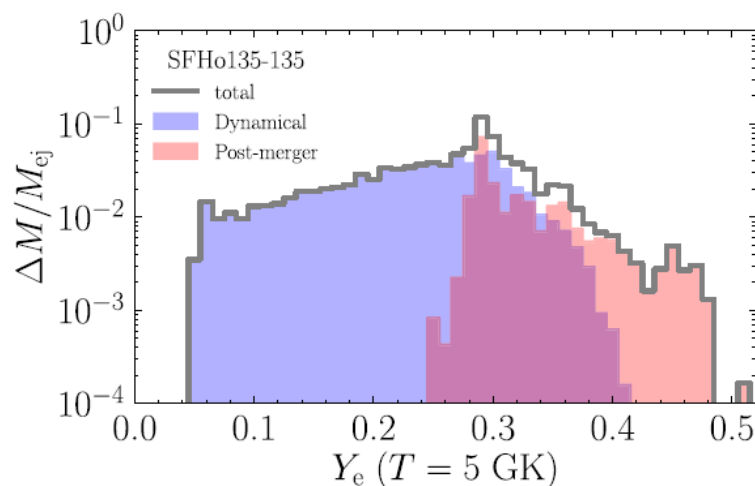
- 8m telescope
- FoV: 1.38deg²
- Fibers: ~2400
- Spectral coverage: 380-1260nm
- Lim.Mag.: 21.5mag (1hr)



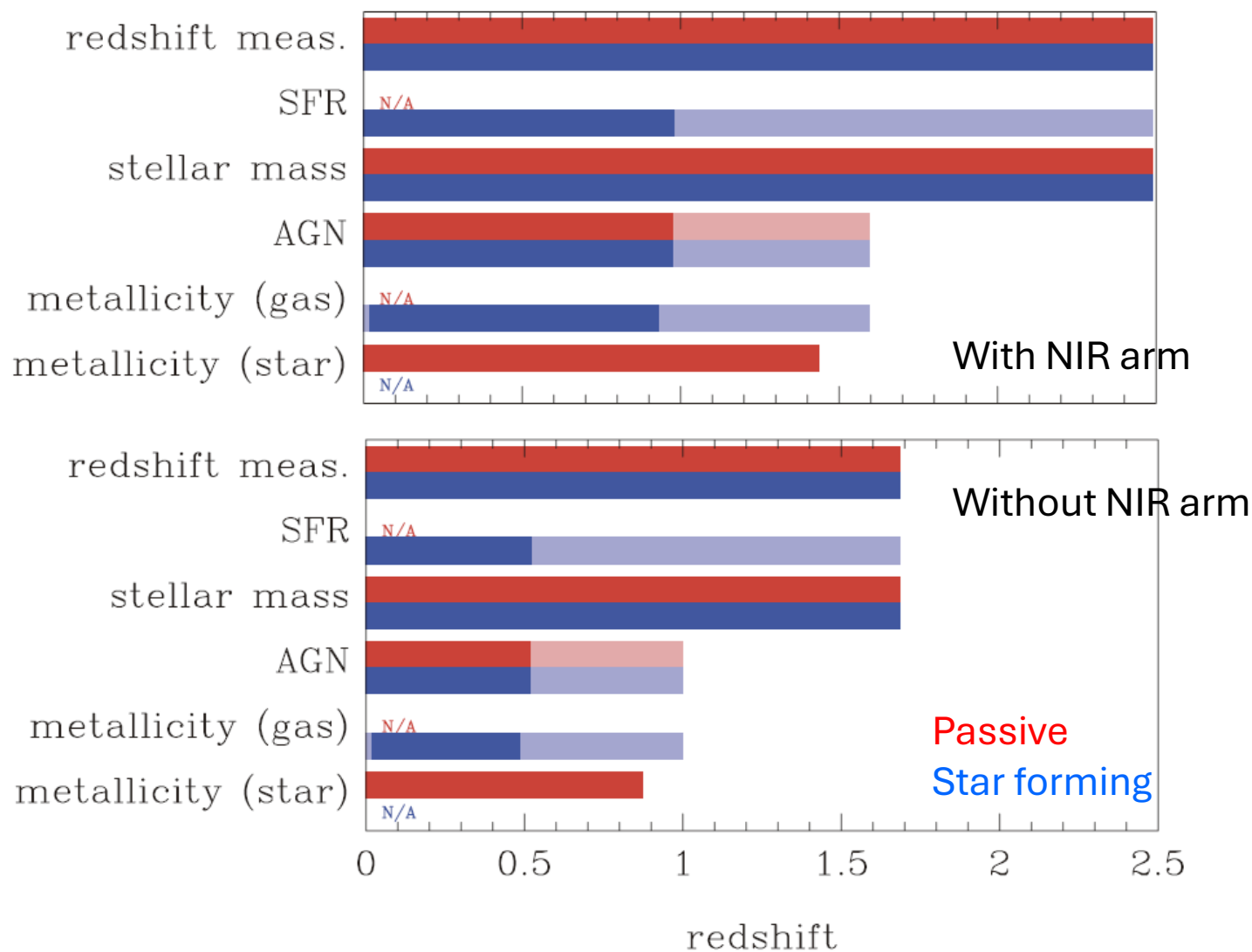
GW: Wide wavelength coverage



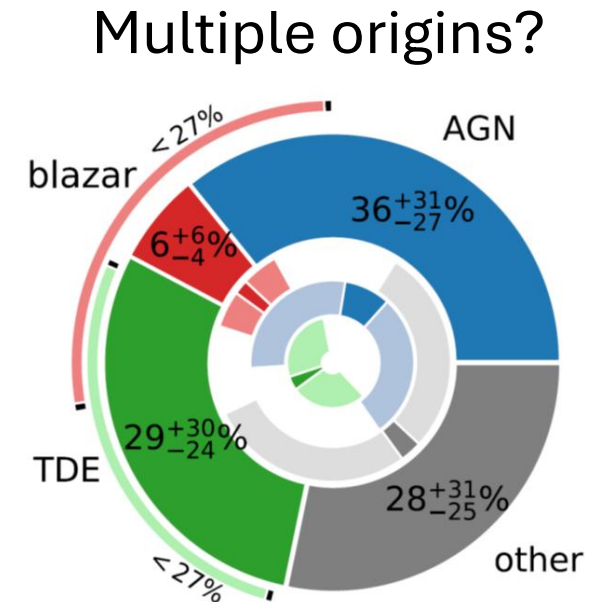
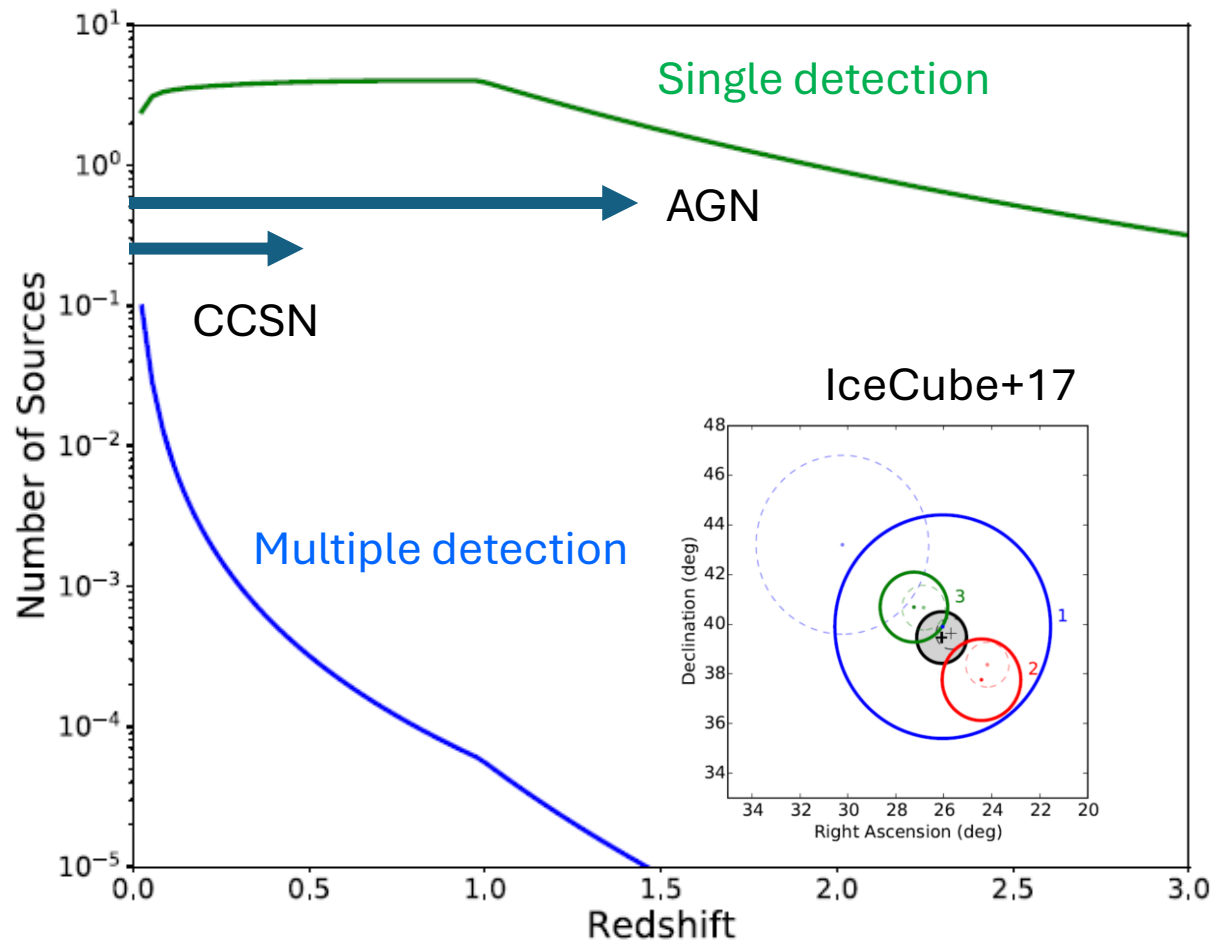
GW: Kilonova yields vs. r-process pattern



High-E ν : Redshift determination



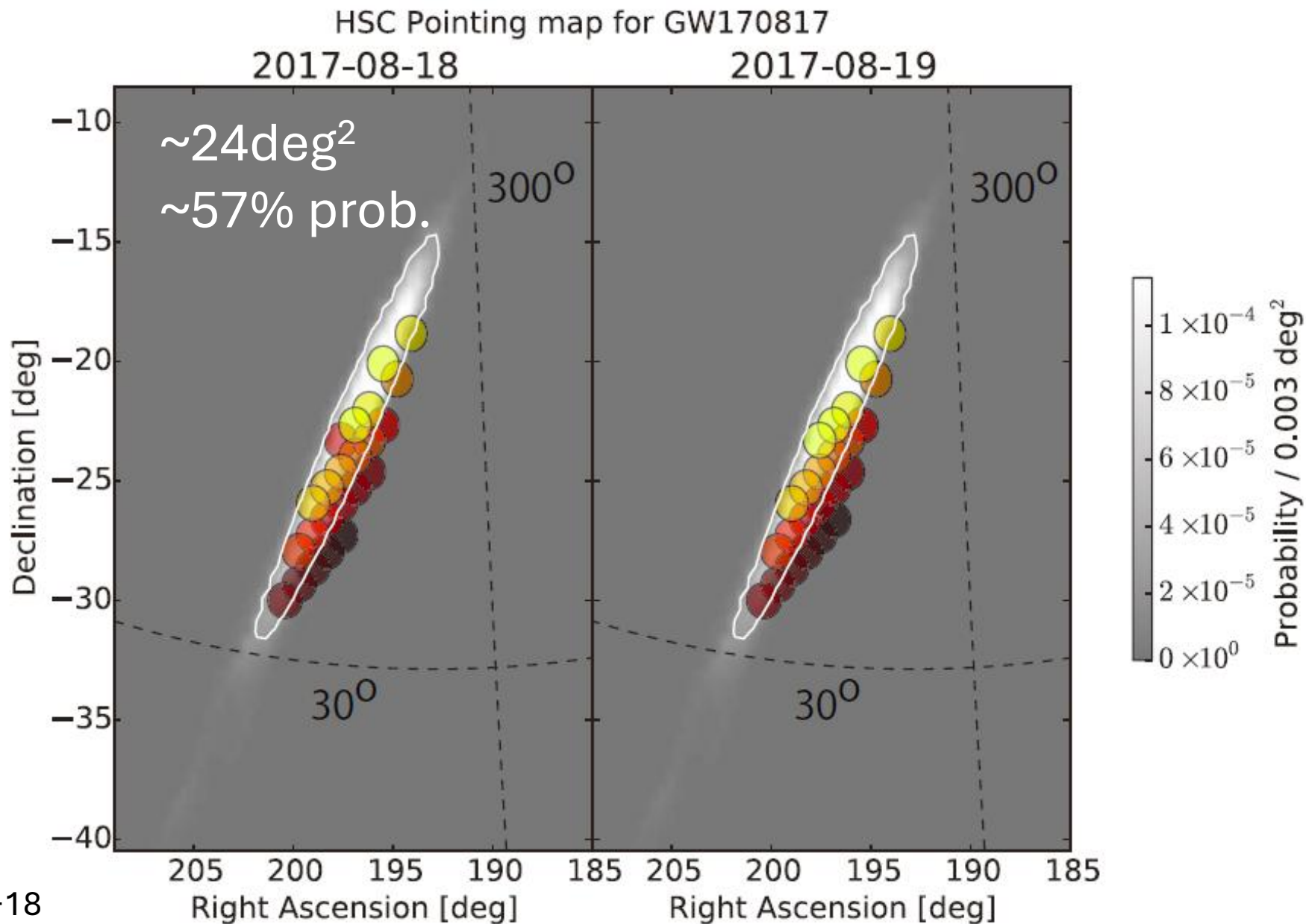
High-E ν : redshift distribution and classification of counterparts



GW170817 with HSC and MOIRCS

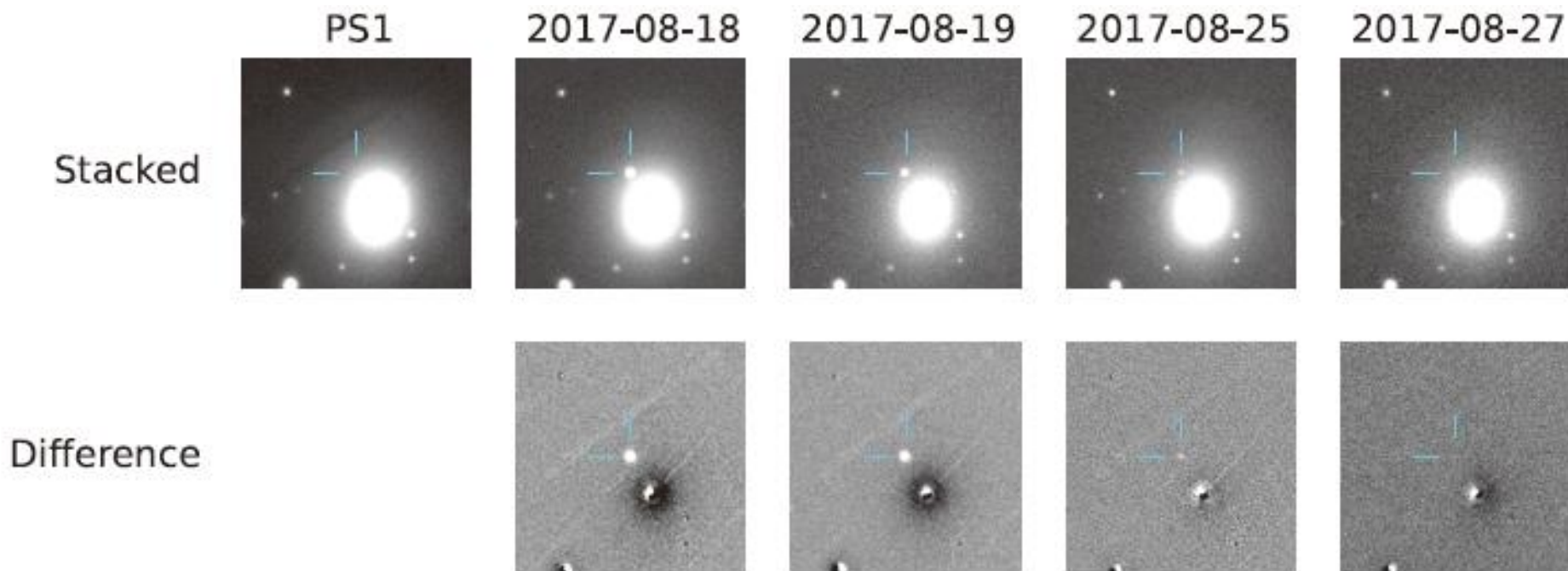
Utsumi, Tanaka, NT+ 2017, PASJ, 69, 101
NT+ 2018, PASJ, 70, 28

GW170817: HSC z-band follow-up



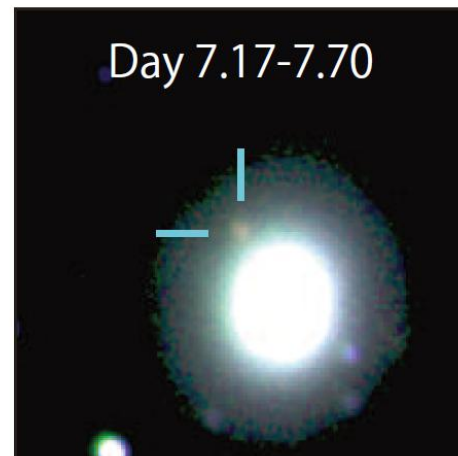
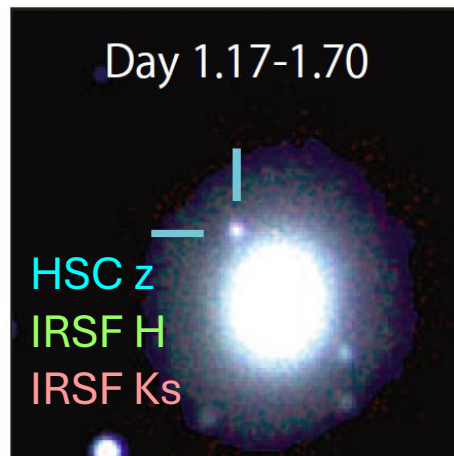
J-GEM17btc (SSS17a/DLT17ck/AT2017gfo)

The most likely and distinguished candidate in the prob. region.



Only HSC and DECam
(Soares-Santos+17) evidence
the uniqueness of the
counterpart.

NT+18; Utsumi, Tanaka, NT+17



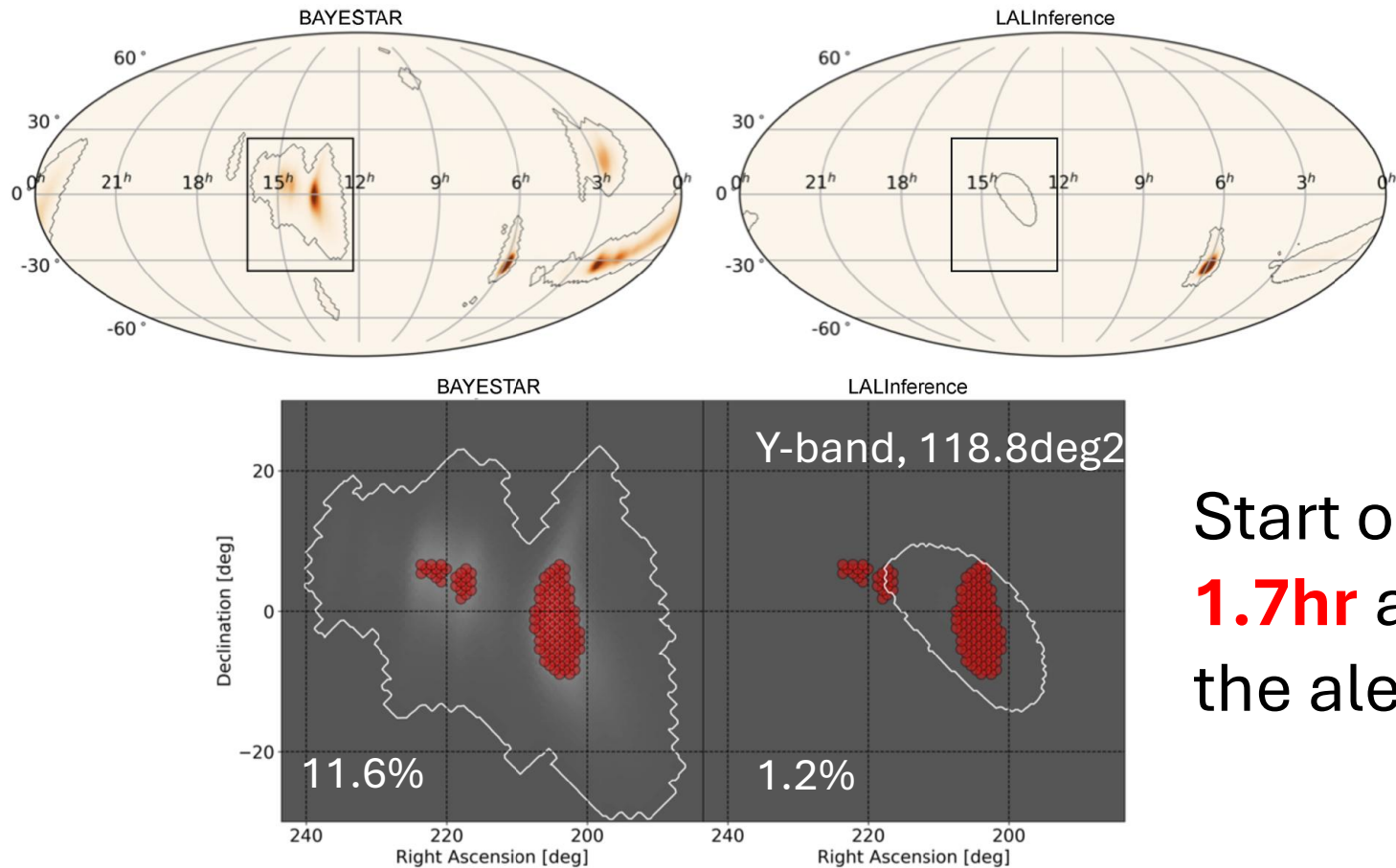
LIGO-Virgo O3 run

Ohgami, NT+ 2021, PASJ, 73, 350

Ohgami, NT+ 2023, ApJ, 947, 9

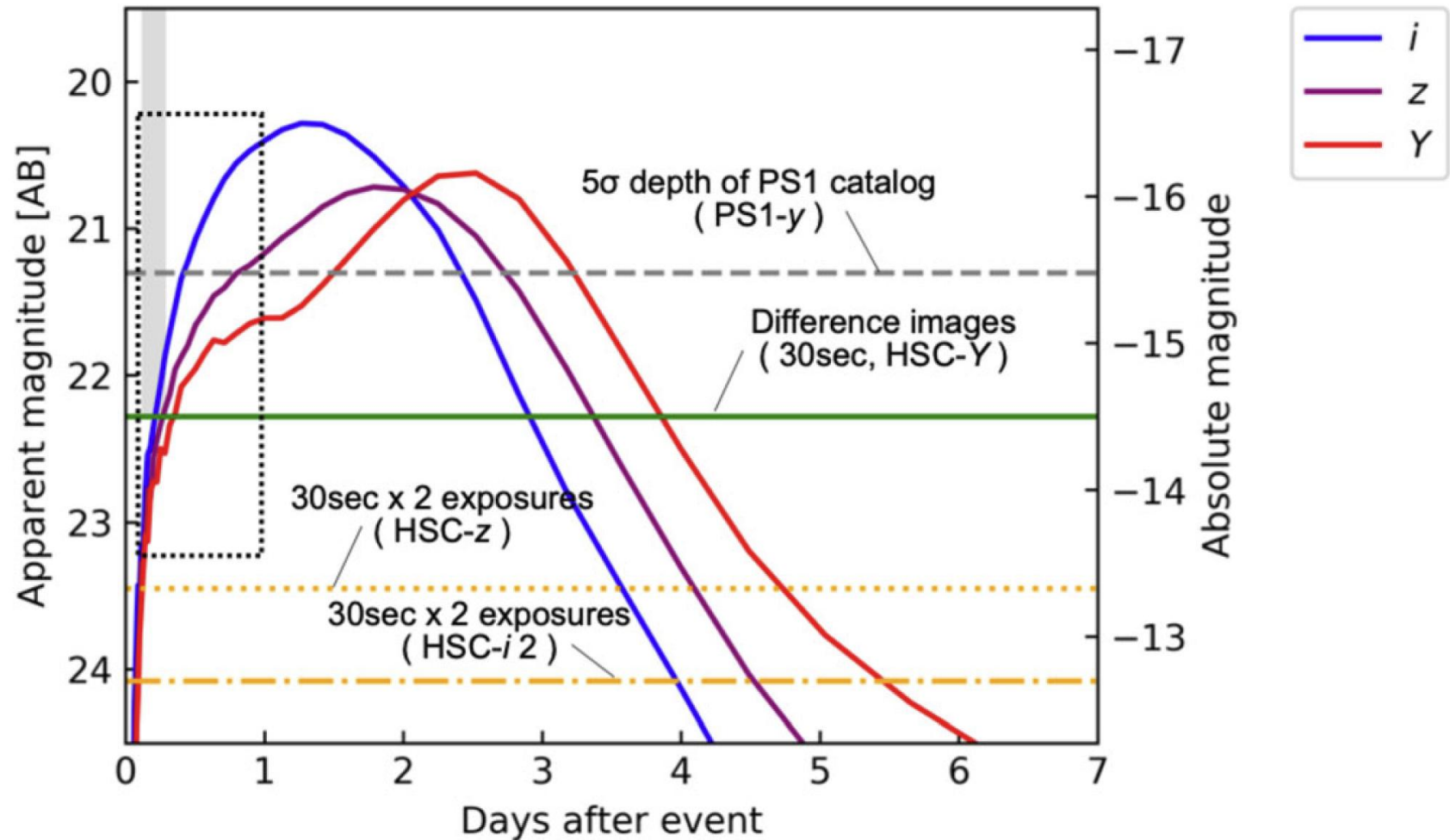
S190510g

- BNS → Terrestrial



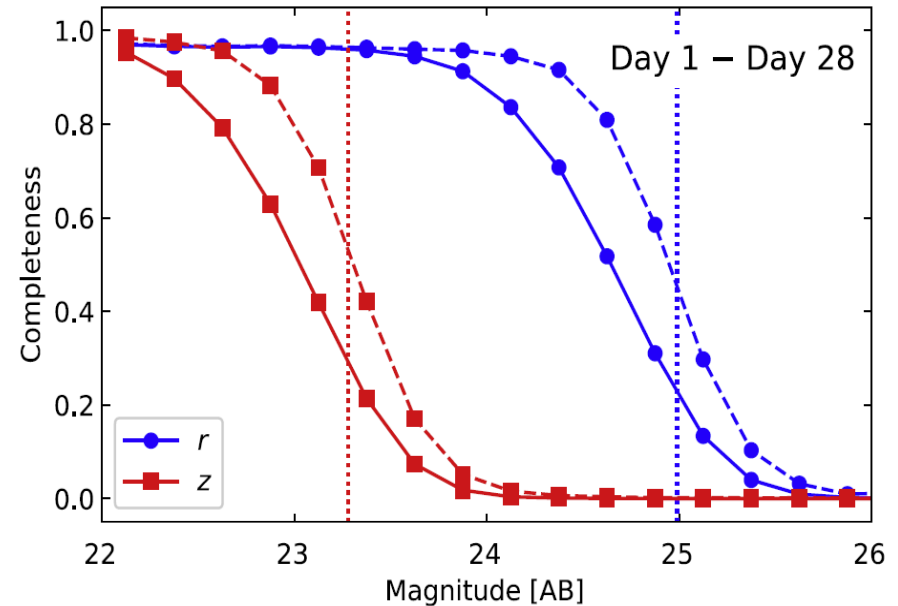
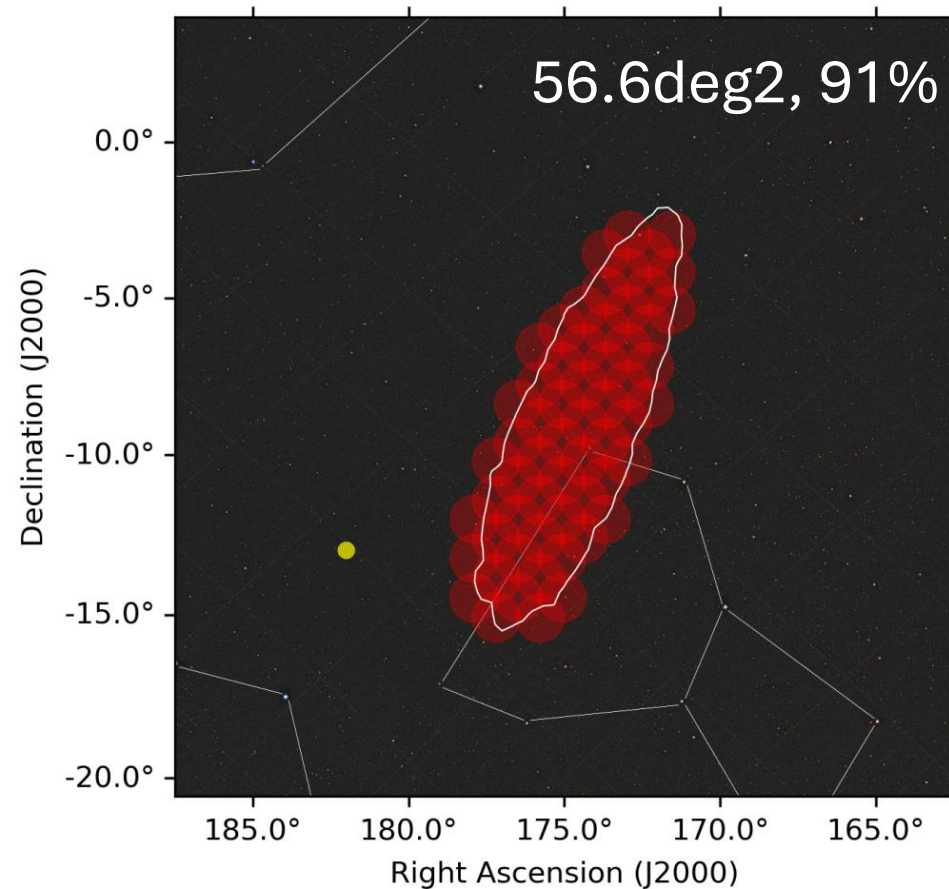
Start obs.
1.7hr after
the alert

In O3: fast and deep follow-up was realized



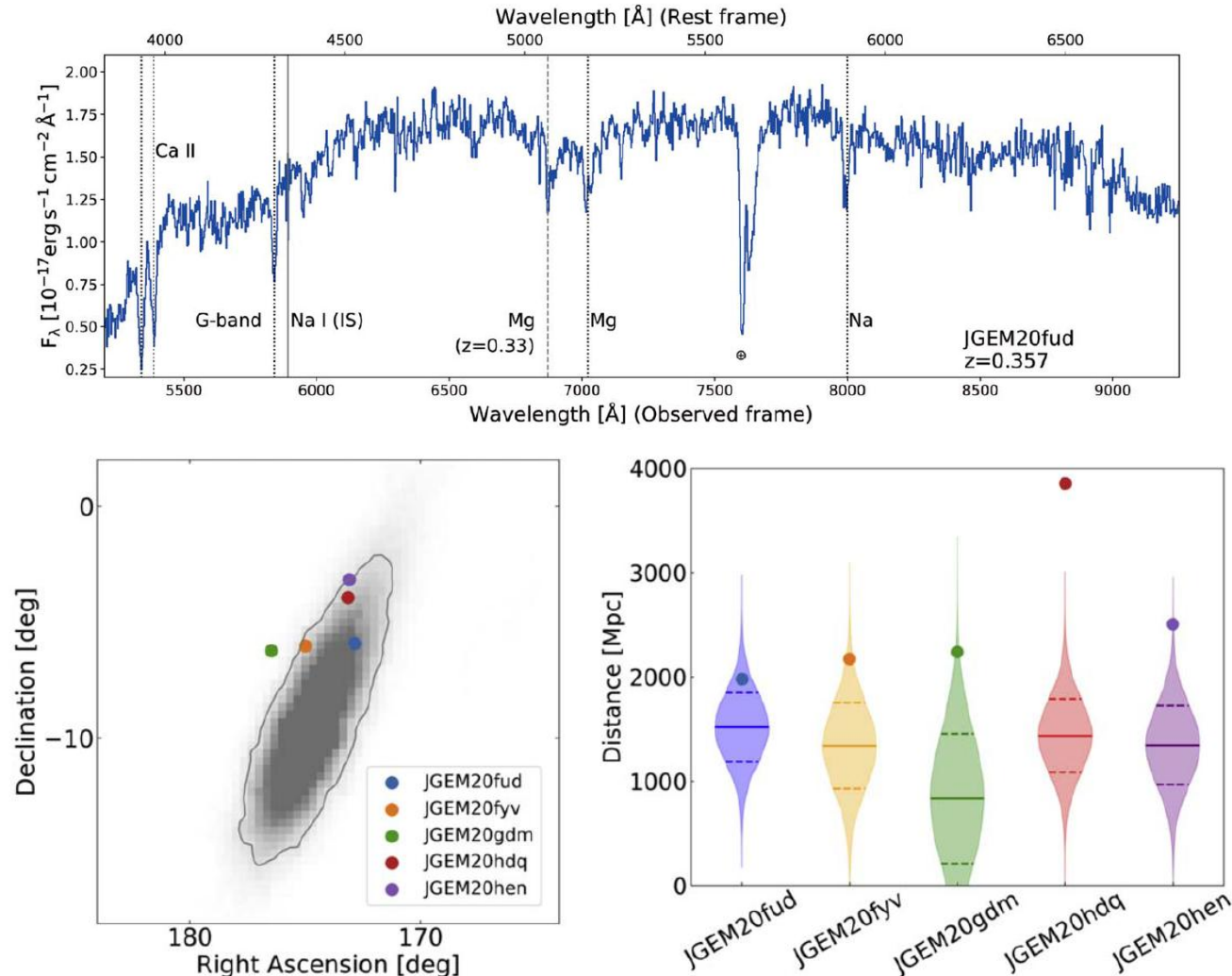
GW200224_222234

BBH



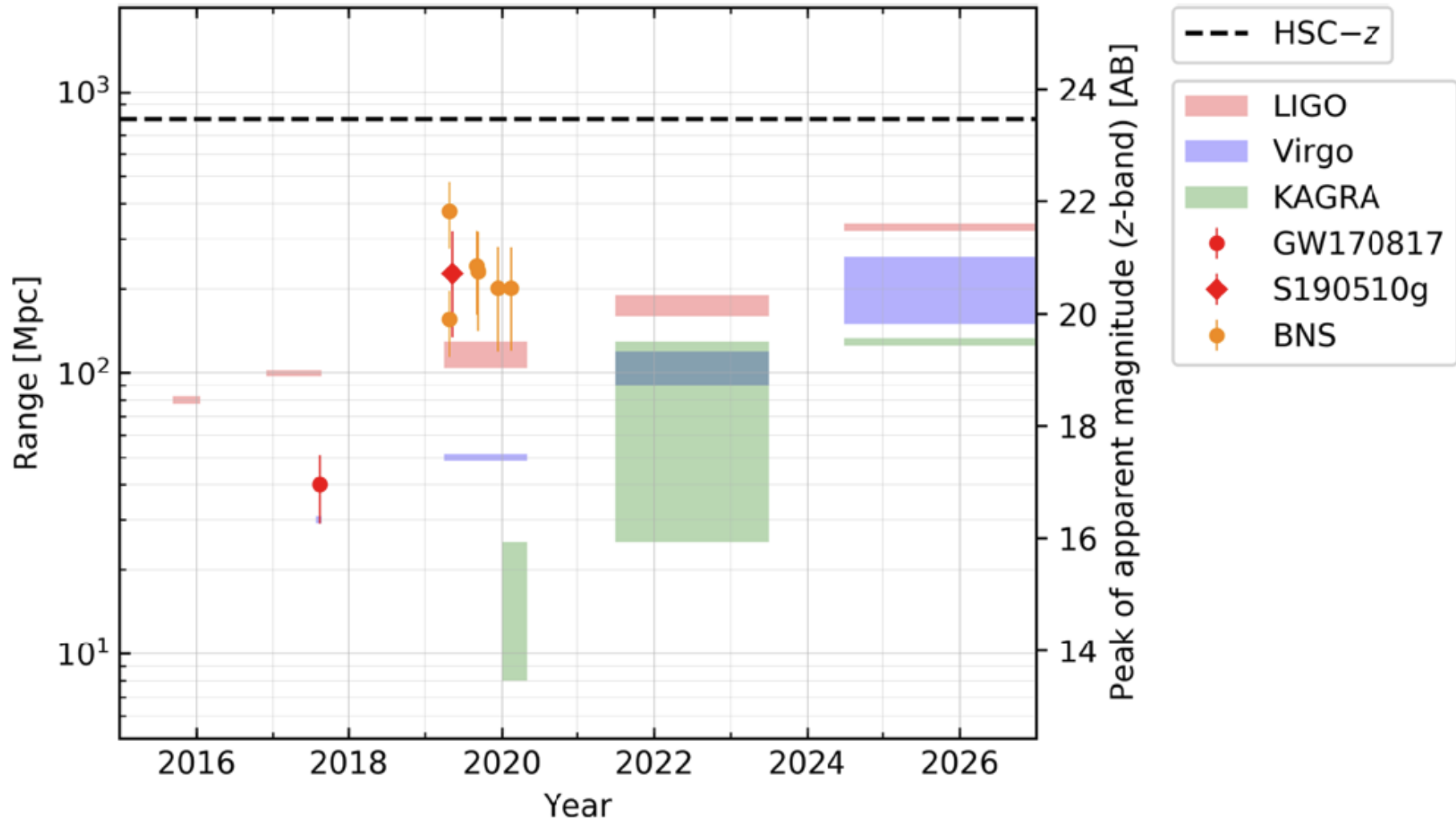
- Deep and (almost) complete follow-up was realized.

Spectroscopy of host galaxies of 5 candidates with GTC/OSIRIS



No firm counterpart was found.

Subaru/HSC is deep enough in O5



LIGO-Virgo-KAGRA O4 run

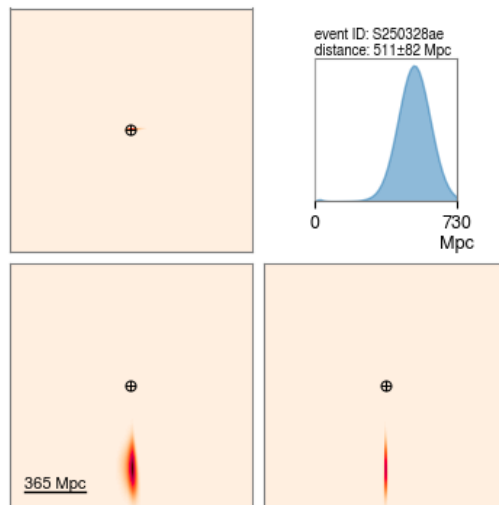
Zhang, Kokubo, MacBride, McMahon, Utsumi, NT et al. submitted
arXiv:2508.00291



Haibin Zhang

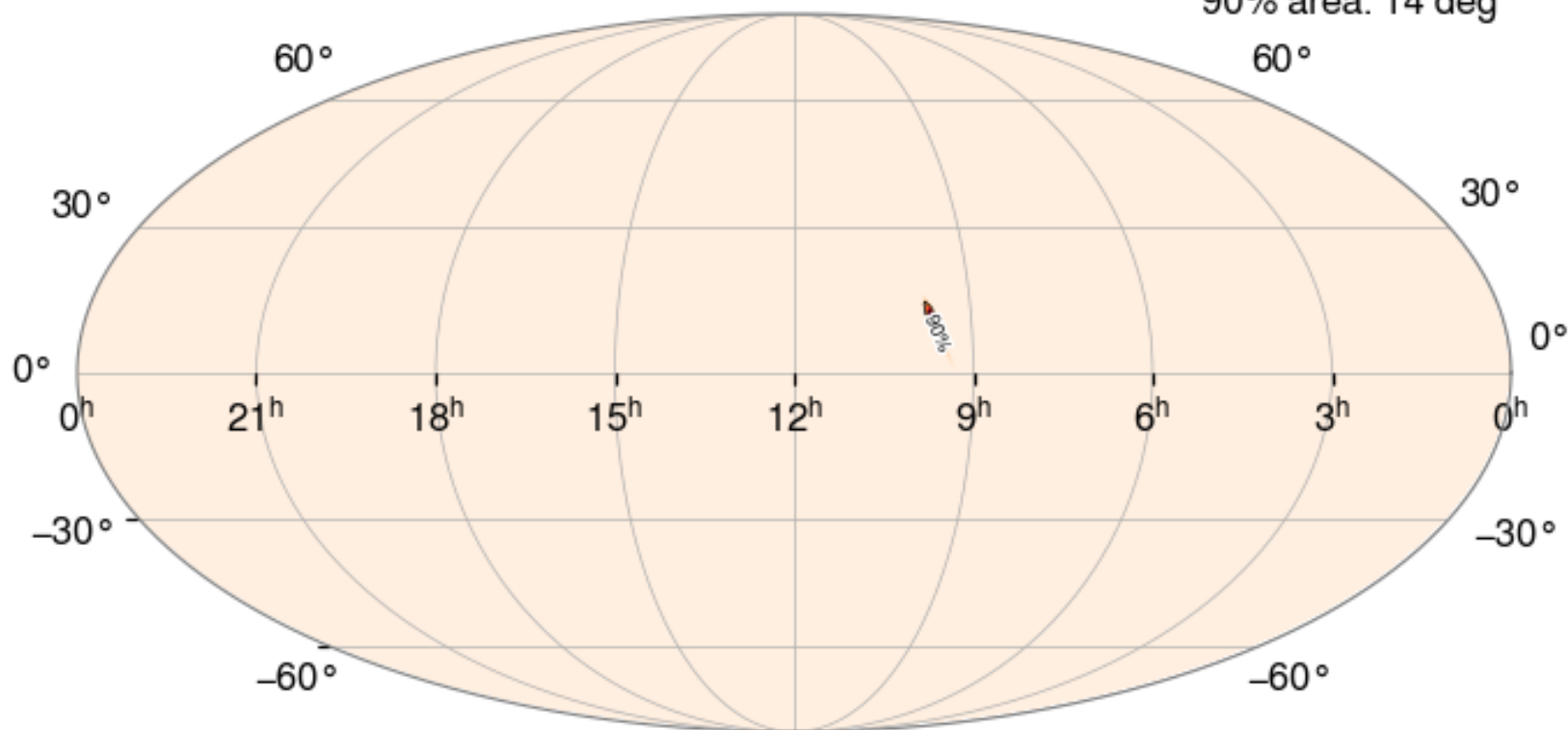
S250328ae

BBH



BBH	>99%
Terrestrial	<1%
NSBH	<1%
BNS	0%

event ID: S250328ae
50% area: 3 deg²
90% area: 14 deg²



Subaru schedule

Current latency
is ~1.5 days.

Schedule for March 2025

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						Mar 01
						S25A-TE193-K Weisz HSC
Mar 02	Mar 03	Mar 04	Mar 05	Mar 06 ☉	Mar 07	Mar 08
S25A-UH027-A(0.6) de Boer HSC	Queue HSC				S25A-026 (Cancelled) [Telescope] Hashimoto CRS+SCEXAO+NIRWFS+NGS	S25A-026 (Cancelled) [Telescope] Hashimoto CRS+SCEXAO+NIRWFS+NGS
Queue(0.4) HSC					Eng (Cancelled) [Telescope]	S25A-134(0.1) (Cancelled) [Telescope] Kuzuhara --- SSP(0.4) (Cancelled) [Telescope] IRD+NGS-AO
Mar 09	Mar 10	Mar 11	Mar 12	Mar 13 ☾	Mar 14	Mar 15
S25A-026 (Cancelled) [Telescope] Hashimoto CRS+SCEXAO+NIRWFS+NGS	S25A-026 Hashimoto CRS+SCEXAO+NIRWFS+NGS	S25A-TE009-G Jiang VAM+SCEXAO+NIRWFS+NGS	S24A-023I Currie CRS+SCEXAO+NIRWFS+NGS		Eng AO188+LLT	S25A-040 Ichikawa MOIRCS
Eng (Cancelled) [Telescope] SCEXAO	SSP IRD	Eng SCEXAO			S24A-023I Currie CRS+SCEXAO+NIRWFS+NGS	S24A-023I Currie CRS+SCEXAO+NIRWFS+NGS
Mar 16	Mar 17	Mar 18	Mar 19	Mar 20	Mar 21 ☉	Mar 22
S25A-025 Takeda MOIRCS	S24A-113 Matsumoto MOIRCS	S25A-026 [compensation] Hashimoto CRS+SCEXAO+NIRWFS+NGS	Eng (Cancelled) [Telescope] PFS	Eng PFS		S25A-UH006-B(0.75) Sanders PFS
	Obs MOIRCS	S25A-134(0.1) Kuzuhara --- SSP(0.4) IRD+NGS-AO				Queue(0.25) PFS
Mar 23	Mar 24	Mar 25	Mar 26	Mar 27	Mar 28 ●	Mar 29
S25A-UH006-B(0.75) Sanders PFS	S25A-039 Lee PFS	Queue PFS		Queue PFS	Queue PFS	Queue PFS
Queue(0.25) PFS				SSP PFS	SSP PFS	SSP PFS
Mar 30	Mar 31					
Queue PFS	Queue PFS					
SSP PFS	SSP PFS					

First PFS science run

Schedule for April 2025

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		Apr 01	Apr 02	Apr 03	Apr 04 ☉	Apr 05
		Queue PFS	S25A-070 (ToO) Yoshida PFS	Queue PFS	S25A-092 Zhang HDS	Obs HDS
		SSP PFS	SSP PFS			S25A-085 Okada HDS
Apr 06	Apr 07	Apr 08	Apr 09	Apr 10	Apr 11	Apr 12 ☾
S25A-091 Li HDS	Obs FOCAS	S25A-093 Maeda FOCAS	S25A-091 Maeda FOCAS	S25A-013 Aoki HDS	S25A-UH017-B Huber HDS	
S25A-132 Taniguchi HDS	S25A-093 Maeda FOCAS	S25A-UH010-B Li HDS	S25A-091 Li HDS	S25A-091 Li HDS		
Apr 13	Apr 14	Apr 15	Apr 16	Apr 17	Apr 18	Apr 19 ☉
Eng SUKA (Telescope)	Obs HDS	S25A-046 Misawa FOCAS	S25A-016 Ichikawa FOCAS		S25A-124 Kikuta FOCAS	S25A-024 (ToO) Maeda FOCAS
S25A-UH010-B Li HDS	S25A-UH010-B Li HDS	S25A-UH010-B Li HDS			S25A-093 Maeda FOCAS	S25A-093 Maeda FOCAS
Apr 20	Apr 21	Apr 22	Apr 23	Apr 24	Apr 25	Apr 26 ●
S25A-106 Suzuki FOCAS	Queue HSC		S25A-TE028-G Hudson HSC	S25A-UH014-B Tholen HSC	Queue(0.85) HSC	Queue(0.85) HSC
			Queue HSC	Queue HSC	S25A-UH031-A(0.15) Kleyna HSC	S25A-UH031-A(0.15) Kleyna HSC
Apr 27	Apr 28	Apr 29	Apr 30			
Queue(0.85) HSC	S25A-131 Yoshida HSC		S25A-UH014-B Tholen HSC			
S25A-UH031-A(0.15) Kleyna HSC			Queue(0.35) --- S25A-UH031-A(0.15) Kleyna --- HSC			

GCN circulars – follow-up

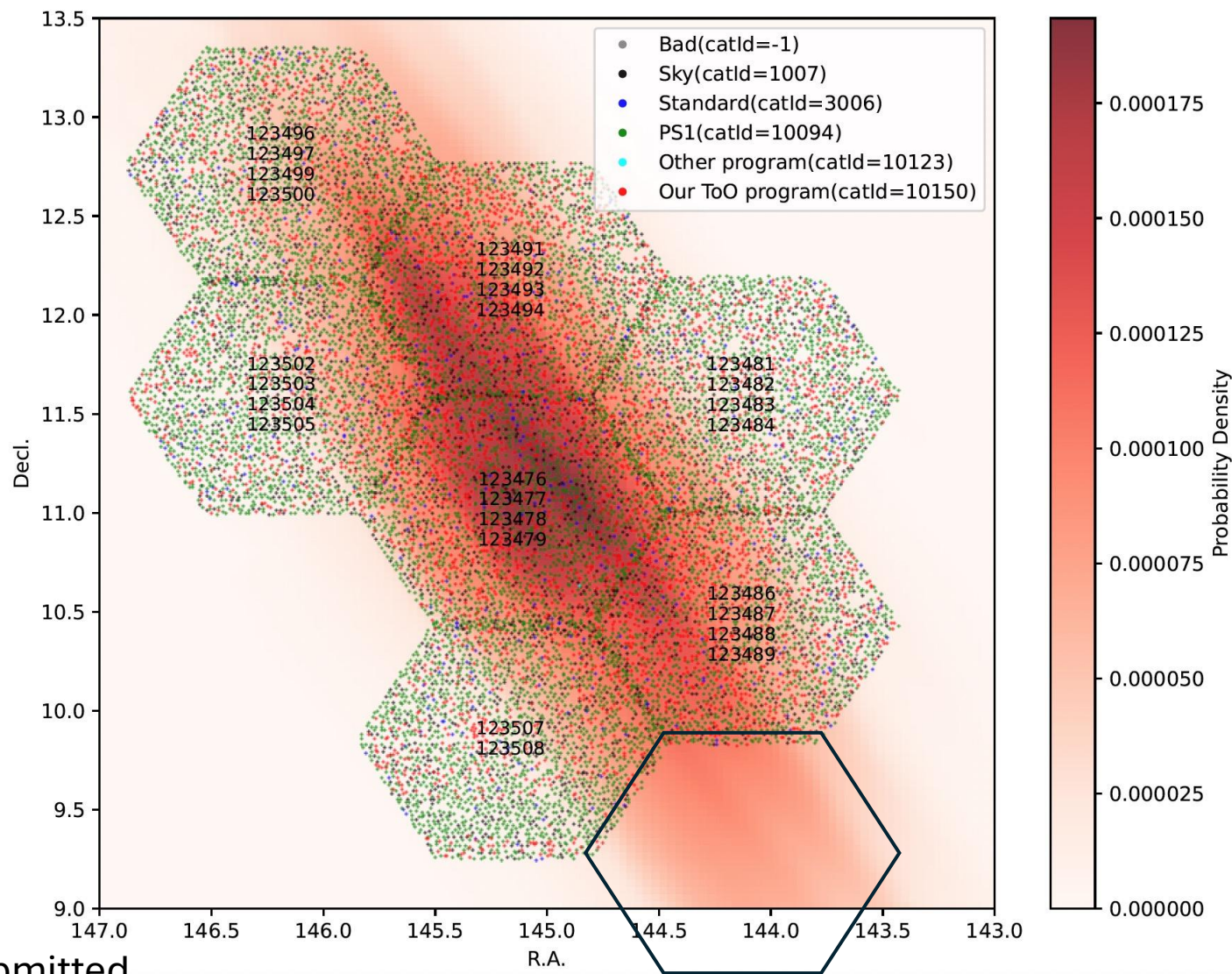
- 39934: DECam DESGW Candidates (Epoch 1)
 - 90% prob., 20 candidates (8 AGN?, 8 SN, 3 unknown, 1 AGN)
- 39972: Swift XRT observations, 34 possible X-ray sources
 - 68% prob.,
- 39992: DECam DESGW Candidates (Epoch 2)
 - 90% prob., 25 candidates (15 AGN, 10 SN), No X-ray sources
- **40221: Subaru/PFS Spectroscopic Follow up and Candidates**
- 40455: DECam DESGW Candidates (Final Epochs)

Our priorities

- Priority 0: transients in the two vetted GCN lists (39934 and 39992);
- Priority 1: transients detected on both days;
- Priority 2: transients detected on only one day (March 29 or 30);
- Priority 3: Swift X-ray sources (GCN 39972)
- Priority 4: galaxies from GLADE+;
- Priority 5: galaxies from PS1-STRM with photo-z errors <0.05 ;
- Priority 6: galaxies from PS1-STRM with photo-z errors of 0.05-0.1;
- Priority 7: galaxies from PS1-STRM with photo-z errors of 0.1-0.2.

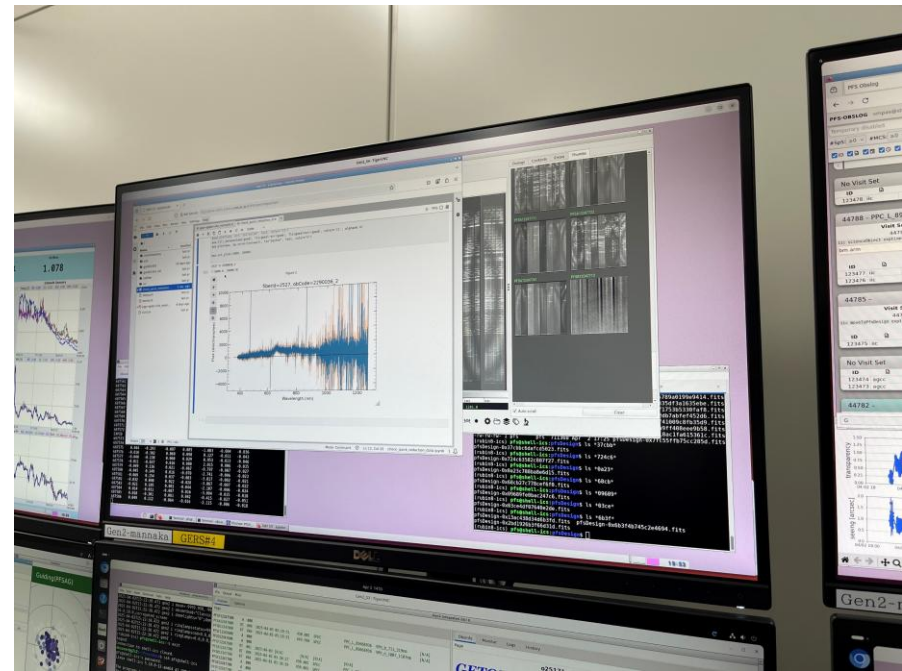
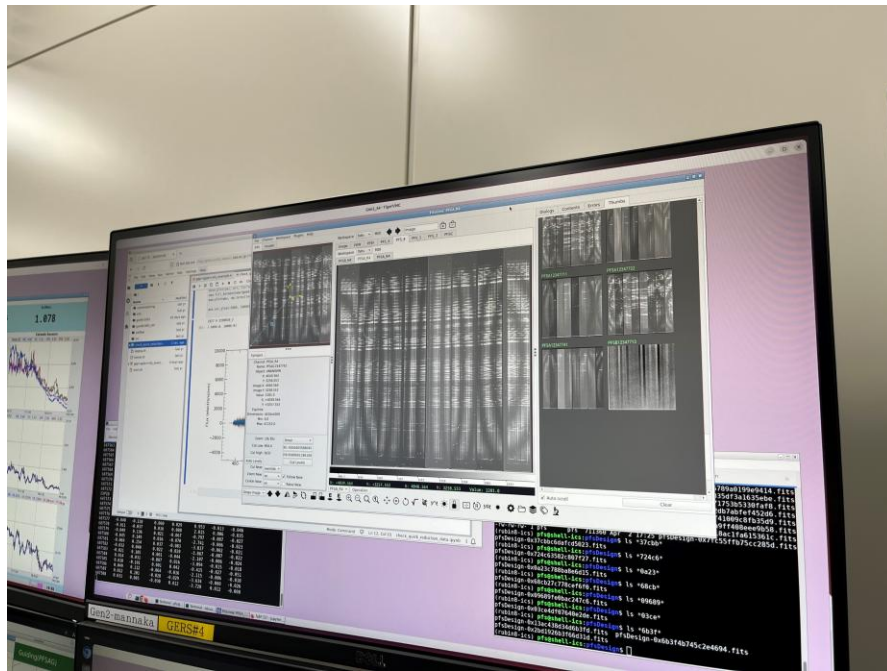
Survey fields

>50% probability region
~4000 targets are observed.

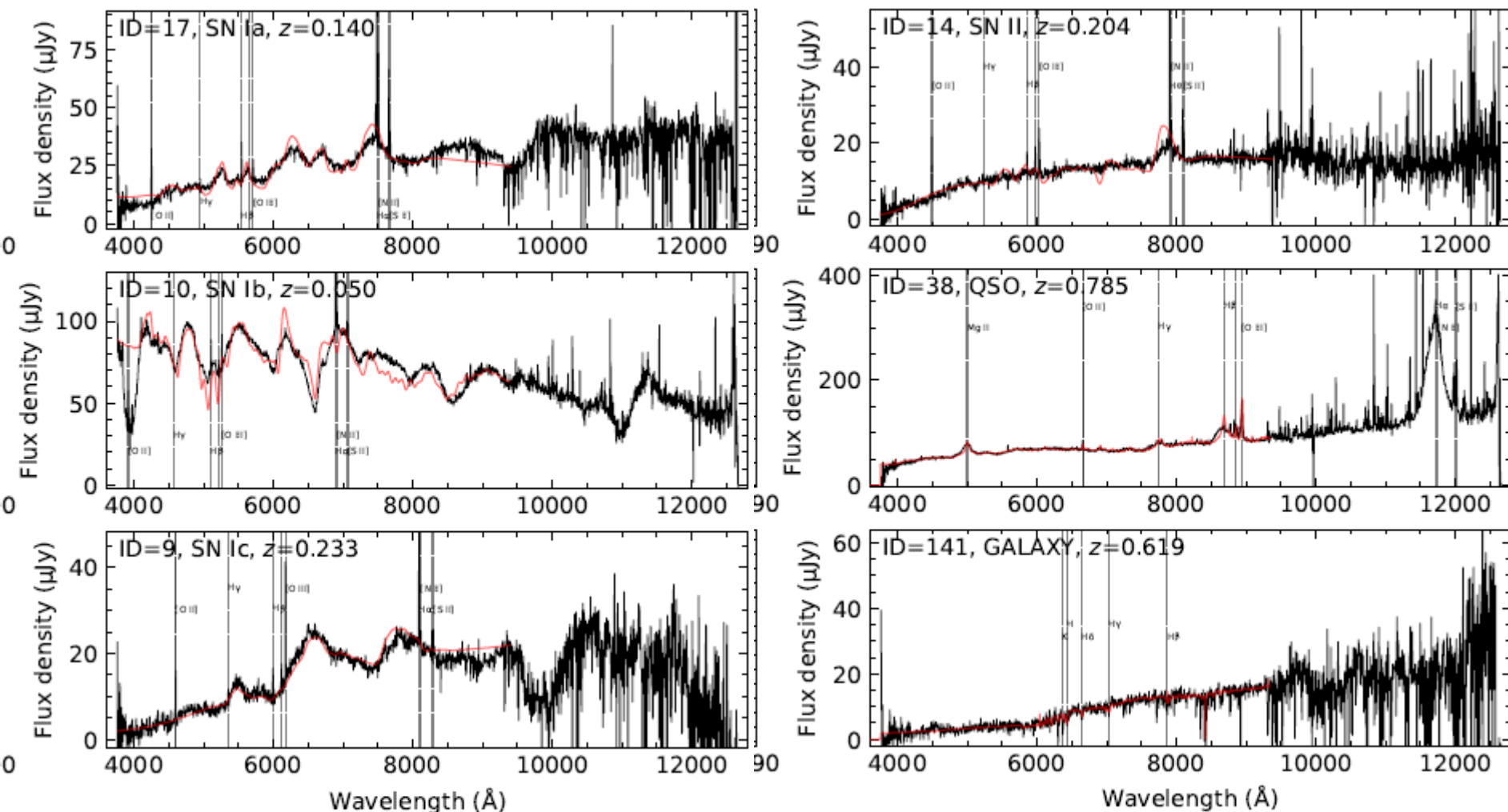


Data analysis

- Quick look data is available just after the exposure. → GCN circular
- Science ready data will be available in several months.



Example of spectra



Classification

ID_DESGW	ATNAME	RA [deg]	Dec [deg]	Type_DESGW	Type_PFS	Redshift
2290036	AT2025gek	145.199481	10.828527	SN_LIKE	SN Ic	0.233
2290467	AT2020woa	144.388798	10.255536	SN_LIKE	SN Ib	0.050
2292782	AT2025geo	144.928578	10.349243	SN_LIKE	SN Ia	0.182
2290334	AT2025geq	145.235616	12.469694	SN_LIKE	SN Ia	0.186
2290623	AT2025gen	144.112464	11.641817	AGN_LIKE	SN II	0.204
2291223	N/A	146.389563	13.131801	AGN_LIKE	QSO	0.540
2293190	AT2025cvb	144.191297	10.828462	SN_LIKE	SN Ia	0.140
2290143	AT2025ggv	146.033906	11.088812	SN_LIKE	QSO	1.437
2292040	AT2025ges	144.438216	9.885617	AGN_LIKE	SN Ia	0.434
2290059	N/A	144.679961	10.018211	AGN_LIKE	QSO	0.209
2292786	N/A	144.037664	10.810454	AGN_LIKE	SN Ia	0.254
2293517	AT2025geu	145.956024	12.381673	AGN_LIKE	QSO	0.507
2295862	N/A	145.361115	12.521385	AGN_LIKE	QSO	0.969
2290563	N/A	145.149074	11.756403	AGN_LIKE	QSO	0.255
2289995	AT2025ggx	144.57373	10.274445	SN_LIKE	SN II	0.358

Zhang+25
(GCN 40221)

Improvements of Subaru operation

-Available from S27A (Feb 2027)

- Rare ToO (≤ 5 nights, ≤ 3 years)
 - For targets below a certain event-rate threshold
 - Current threshold of occurrence rate is $< 10/\text{sky}/\text{yr}$, corresponding to 0.5 trigger/semester.
 - Accept proposals above a TAC-defined threshold for each semester.
 - Indicative cap on total rare ToO nights (~ 100 nights)
- Intensive ToO (5-40 nights, ≤ 3 years)
 - Typically 0-2 accepted proposals in each semester

Summary

- Subaru is the most suitable telescope for follow-ups of multi-messenger sources.
 - Wide-field imager: Hyper Suprime-Cam (HSC)
 - Wide-field multi-fiber spectrograph: 'Ōnohi'ula Prime Focus Spectrograph (PFS)
 - Optical/infrared imaging/spectroscopy
- Hyper Suprime-Cam
 - GW170817: Uniqueness of AT2017gfo
 - S190510g: Low latency, started at ~ 1.7 hr after the alert
 - GW20024_222234: 91% of probability area is covered with the depth of $r < 25$
- 'Ōnohi'ula Prime Focus Spectrograph
 - BBH S250328ae: Spectra of ~ 4000 objects are taken in 0.5 night.
 - Latency: ~ 1.5 days after trigger (to be improved)
- New ToO schemes (Rare ToO, intensive ToO) are now available.