A Joint Search for the EM Counterpart to the GW Binary Black Hole Merger Candidate S250328ae with DECam and PFS

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J-GEM, Subaru Telescope, and DESGW collaboration

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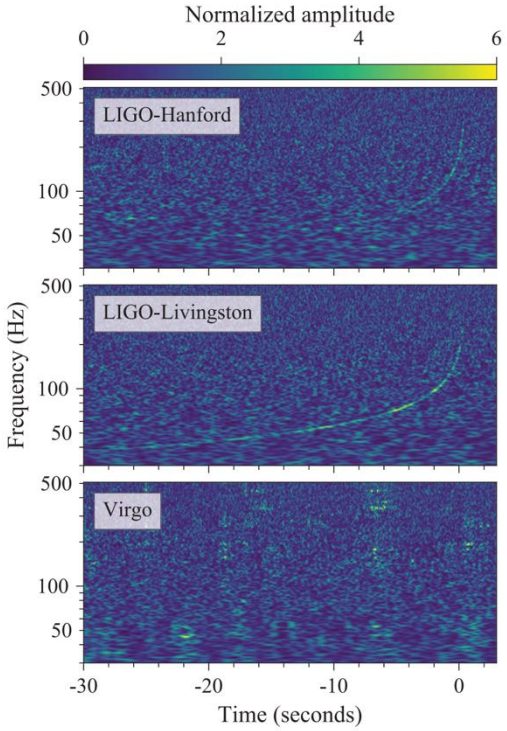
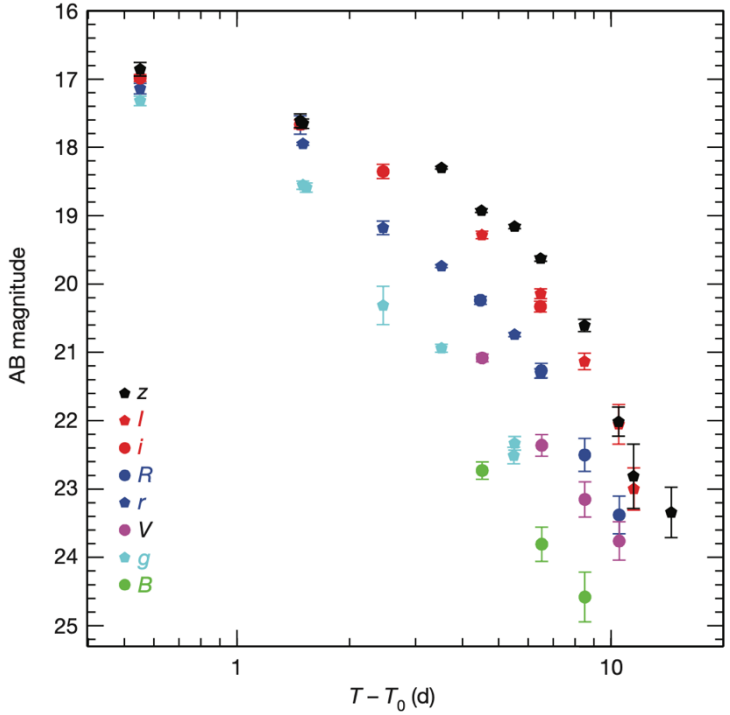
J-GEM: Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up
DESGW: Dark Energy Survey Gravitational Wave Collaboration

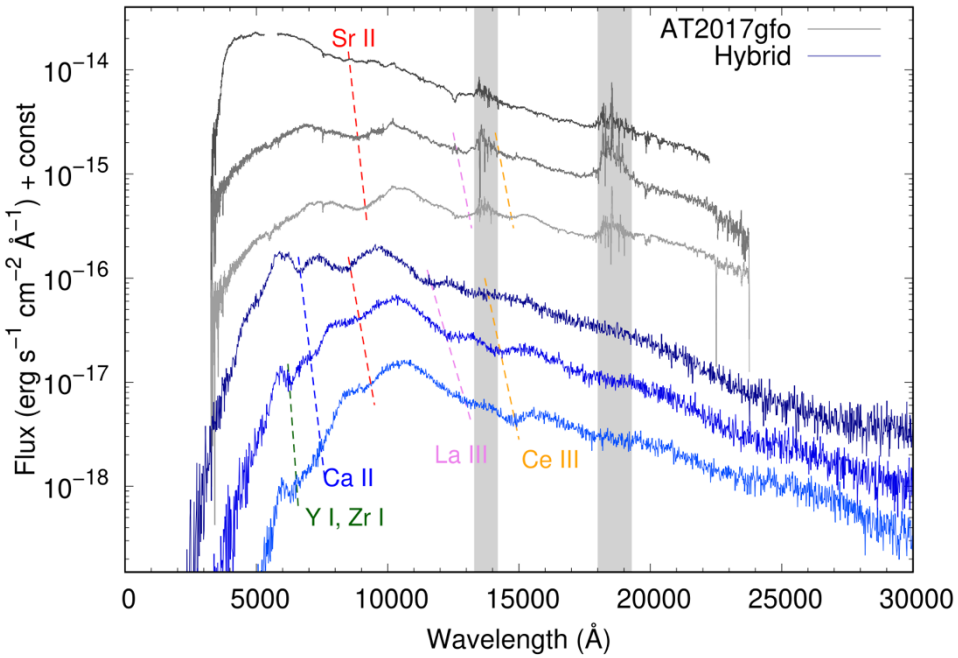
Electromagnetic counterparts to GW sources

- Ligo-Virgo-Kagra detect mergers including binary neutron star (BNS), binary black hole (BBH), and NSBH
- Successful example: GW170817 (BNS) with EM counterpart AT2017gfo (Kilonova)
- What we can learn: origin of heavy elements, cosmology (standard/dark siren), etc.



GW170817 (Ligo and Virgo 2017)

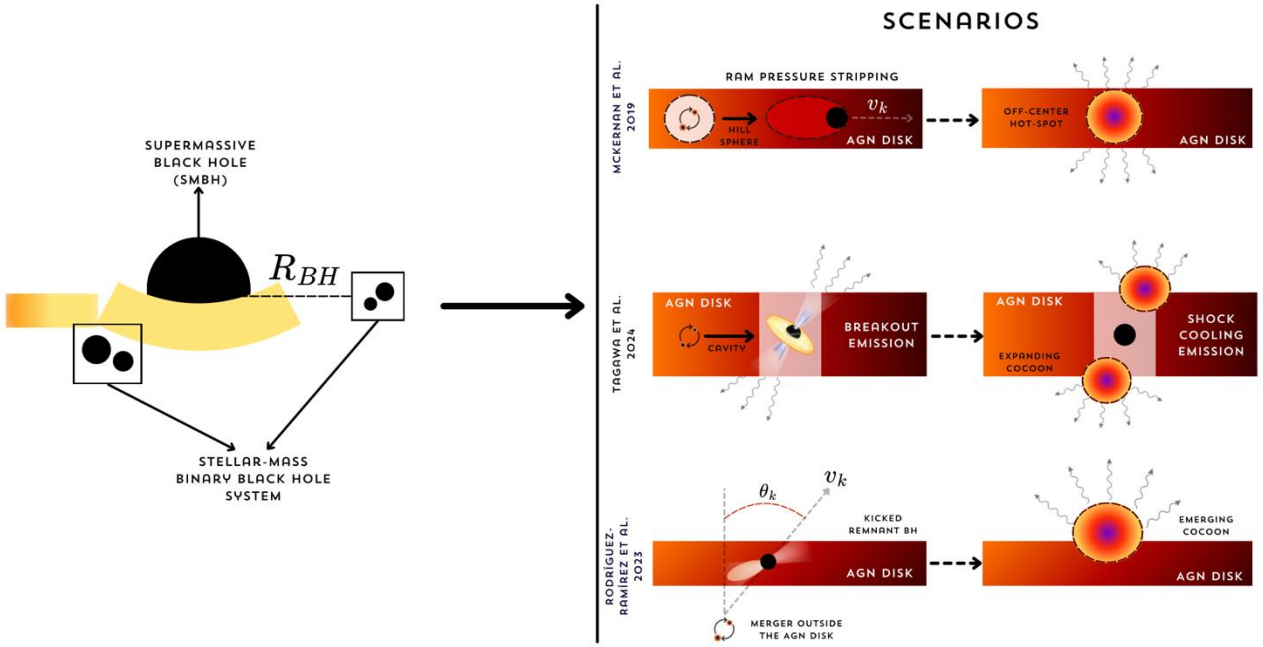




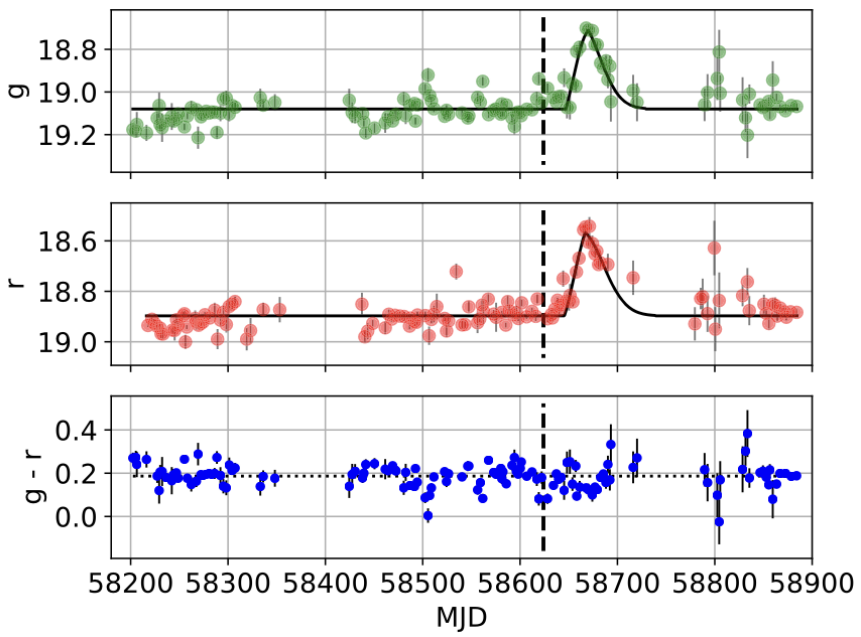
Kilonova AT 2017gfo (Pian et al. 2017; Domoto et al. 2022)

EM counterpart to BBH

- BNSs are rarely detected while BBHs are the major (≳90%) merger type detected by LVK
- But EM emission of BBHs is expected to be generally faint (under debate).
- Although predicted in some scenarios (e.g. mergers in AGN disks), there is no confirmed EM counterpart to BBH yet (a promising candidate of S190521g has been reported).



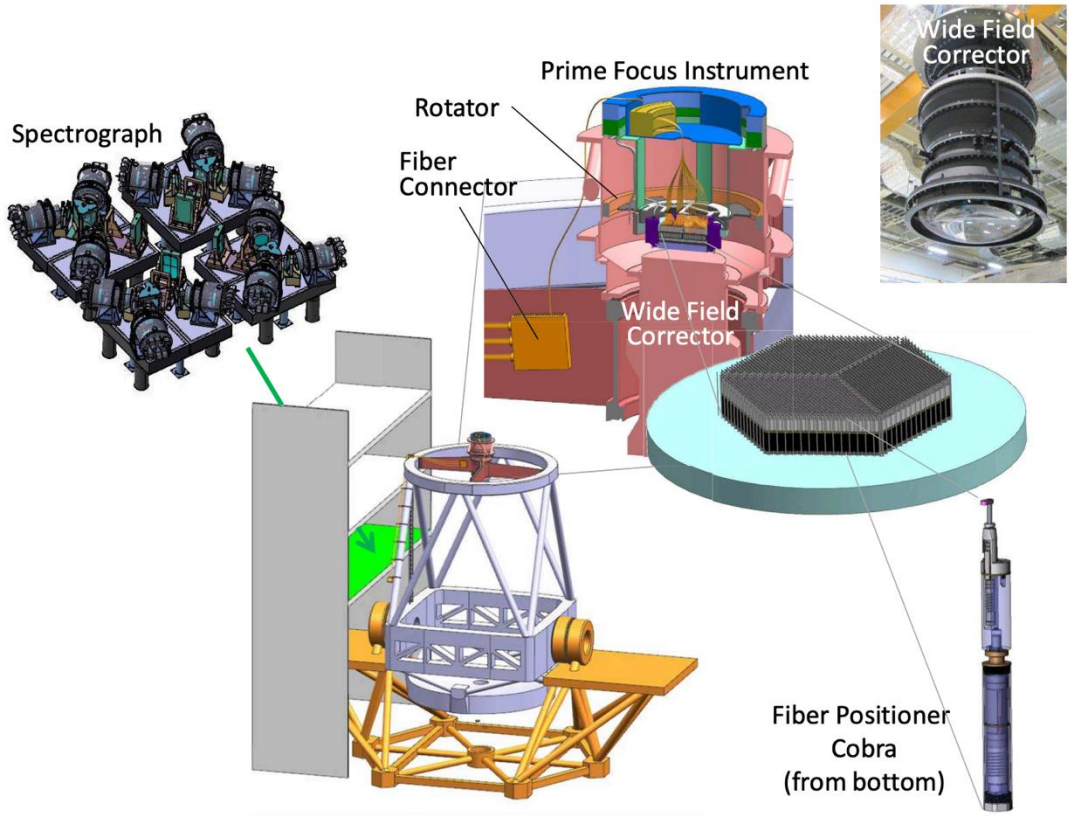
Mechanisms capable of producing EM counterparts to BBH mergers in AGN disks (Darc et al. 2025)



A promising counterpart candidate to GW S190521g (an AGN at z=0.438; Graham et al. 2020)

What is Subaru/PFS?

- Prime Focus Spectrograph



PFS design (Takada et al. 2014)

Prime Focus Instrument		
Field of view	~1.38 deg (hexagonal - diameter of circumscribed circle)	
Field of view area	~1.25 deg^2	
Input F number to fiber	2.8	
Fiber core diameter (1)	127 μm (1.12 arcsec at the FoV center, 1.02 arcsec at the edge)	
Positioner pitch	8 mm (90.4 arcsec at the FoV center, 82.4 arcsec at the edge)	
Positioner patrol field	9.5 mm diameter (107.4 arcsec at the FoV center, 97.9 arcsec at the edge)	
Fiber minimum separation (2)	~30 arcsec	
Fiber configuration time	~60-120 sec. [TBC]	
Number of fibers	Science fibers	Fixed fiducial fibers
	2394	96
Fiber density	~2000 deg^{-2} / ~0.6 $arcmin^{-2}$	
Number of A&G camera (3)	6	
Field of view of A&G camera	~5.1 $arcmin^2$ per one camera	
Sensitivity of A&G camera	r'~20.0 AB mag for S/N~30 (100) in 1 (10) sec. exposure	

Spectrograph				
Spectral arms	Blue	Red		NIR
		Low Res.	Mid. Res.	
Spectral coverage	380 - 650 nm	630 - 970 nm	710 - 885 nm	940 - 1260 nm
Dispersion	~0.7 Å/pix	~0.9 Å/pix	~0.4 Å/pix	~0.8 Å/pix
Spectral resolution	~2.1 Å	~2.7 Å	~1.6 Å	~2.4 Å
Resolving power	~2300	~3000	~5000	~4300
Spectrograph throughput (4)	~52% (@500nm)	~52% (@800nm)	~47% (@800nm)	~35% (@1100nm)

PFS parameters (https://pfs.ipmu.jp/)

Why using Subaru/PFS?

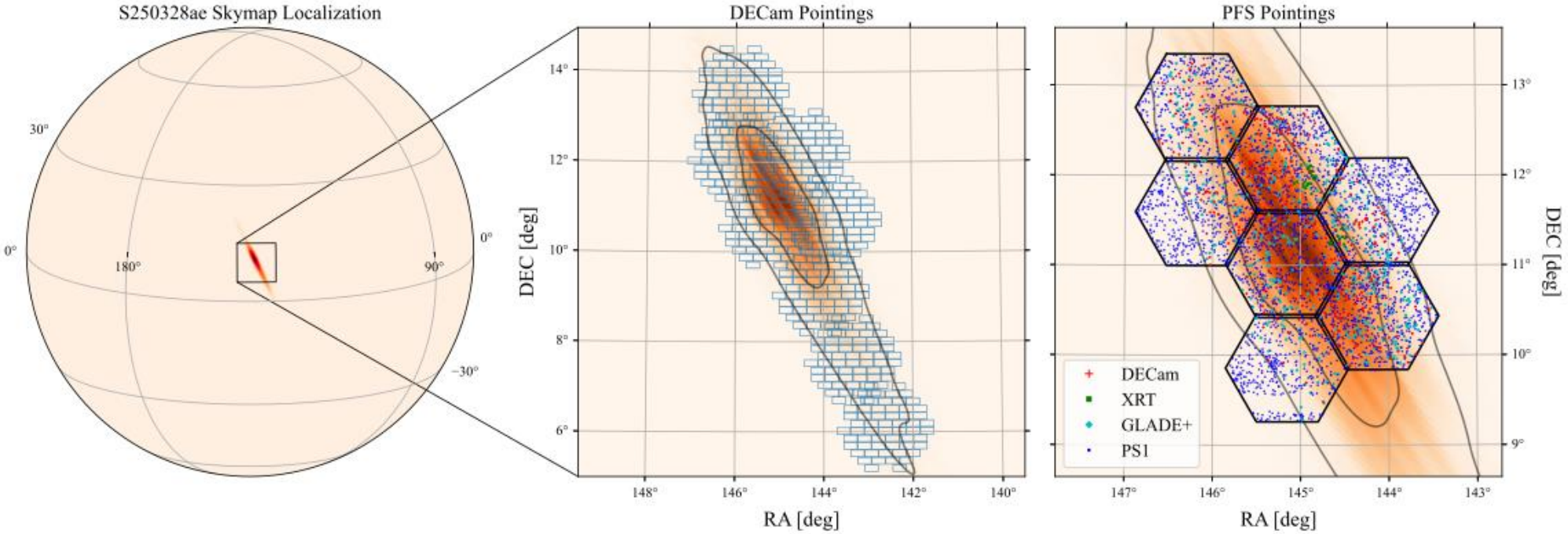
- Large field of view (1.25 deg^2)
- Wide wavelength coverage (380-1260 nm)
- >2000 objects can be observed simultaneously at one pointing.
- Precut slit masks are not needed (suitable for ToO observations)

Arm		Wavelength range [nm]	Throughput(1)	Resolving Power	Continuum sensitivity(2) [AB mag] mean(4)	Continuum sensitivity(2) [AB mag] representative(5)
Blue		380 - 450	10%	~2500	21.8	21.9 (@415nm)
		450 - 550	18%		22.3	22.3 (@505nm)
		550 - 650	21%		22.1	22.2 (@605nm)
Red	Low Res.	630 - 750	27%	~3000	22.3	22.5 (@680nm)
		750 - 850	26%		22.1	22.4 (@796nm)
		850 - 970	23%		21.7	22.1 (@912nm)
	Mid. Res.	710 - 775	25%	~5500	21.7	21.9 (@741nm)
		775 - 825	24%		21.6	21.9 (@796nm)
		825 - 885	22%		21.5	21.8 (@856nm)
NIR		940 - 1050	21%	~4500	21.2	21.8 (@993nm)
		1050 - 1150	19%		21.1	21.5 (@1100nm)
		1150 - 1260	14%		20.8	21.2 (@1208nm)

5σ, one hour exposure, 3 pixel binning
(https://pfs.ipmu.jp/)

Our target and observations

- Our target: GW BBH candidate S250328ae (at a luminosity distance of ~511±82 Mpc)
- Localization: 3 deg^2 at 50% confidence and 15 deg^2 at 90% confidence
- DECam covers >90% of the 90% confidence, while PFS covers ~50% of the 90% confidence
- PFS targets include DECam transients, X-ray candidates, and potential host galaxies.



Skymap for S250328a with DECam and PFS pointings (arXiv:2508.00291)

Timeline of our PFS observation

- 2025-03-28: LVK reported the GW event S250328ae.
- 2025-04-02: We made an observation plan, prepared the target list (including the DECam transient candidates observed on 3/29 and 3/30) and triggered the Target of Opportunity (ToO; P.I. Michitoshi Yoshida) observation.
- 2025-04-03: We confirmed the fiber design with the observatory members and carried out the observation for a half night.
- 2025-04-09: We received the quicklook (QL) reduced data.
- 2025-04-24: We completed spectral classification and visual inspection of 3897 targets, and reported possible EM counterpart candidates to S250328ae in GCN 40221.
- 2025-06-13: We received the fully reduced data.
- 2025-07-31: We reported our results in a paper submitted to ApJ (arXiv:2508.00291).

Observation depth and epoch

- DECam: 90 seconds per exposure; separated in 4 nights; carried out by the DESGW team)
- PFS: 1800 seconds per exposure in a half night (ToO observation; carried out by the J-GEM and Subaru team)
- Our observations reach $\gtrsim$21 mag (except for the PFS NIR arm)
- We expect to detect an EM counterpart if it is as bright as Graham+20.

Observation Night	Facility	Band: Limiting Magnitude m_{lim}
2025-03-29	DECam (Blanco)	$z : 21.4,\ \ i : 22.1,\ \ r : 22.7$
2025-03-30	DECam (Blanco)	$z : 21.9,\ \ i : 22.5,\ \ r : 22.8$
2025-04-03	PFS (Subaru)	$blue : 21.3,\ \ red : 21.3,\ \ NIR : 19.6$
2025-04-06	DECam (Blanco)	$z : 21.0,\ \ i : 21.2,\ \ r : 21.3$
2025-04-25	DECam (Blanco)	$z : 21.6,\ \ i : 22.1,\ \ r : 22.3$

Table 1. Observation dates and notes for DECam and PFS observations of S250328ae. DECam 10σ limiting magnitudes for the exposures are estimated using J. H. Neilsen et al. (2016). PFS limiting magnitudes are estimated for continuum using 5σ median noise of single pixels (pixel size $\sim$ 0.8 Å) in blue, red, and NIR spectral arms, respectively.

Data reduction and visual inspection

- The DECam transient candidates are selected by DESGW team.
- In total, 3897 targets (including transients and host galaxies) are observed by PFS.
- The PFS data are reduced by the Subaru data reduction team.
- We adapt Redrock (DESI spectral fitter) and obtain the initial spectral type and spec-z.
- Visual inspection is then carried out individually by two people (Mitsuru Kokubo and Haibin Zhang), with a modified spectrum viewer based on the DESI viewer (prospect).
- We only use confident candidates (VI scores of A and B) in the following analysis.

Epoch	Initial Candidates	`autoscan` > 0.7	Multiple Detections	Within 90% Region	Visual Inspection
1	4103	816	816	598	20
2	15858	1738	443	281	25
3	20474	2477	129	80	26
4	38448	3955	459	289	3

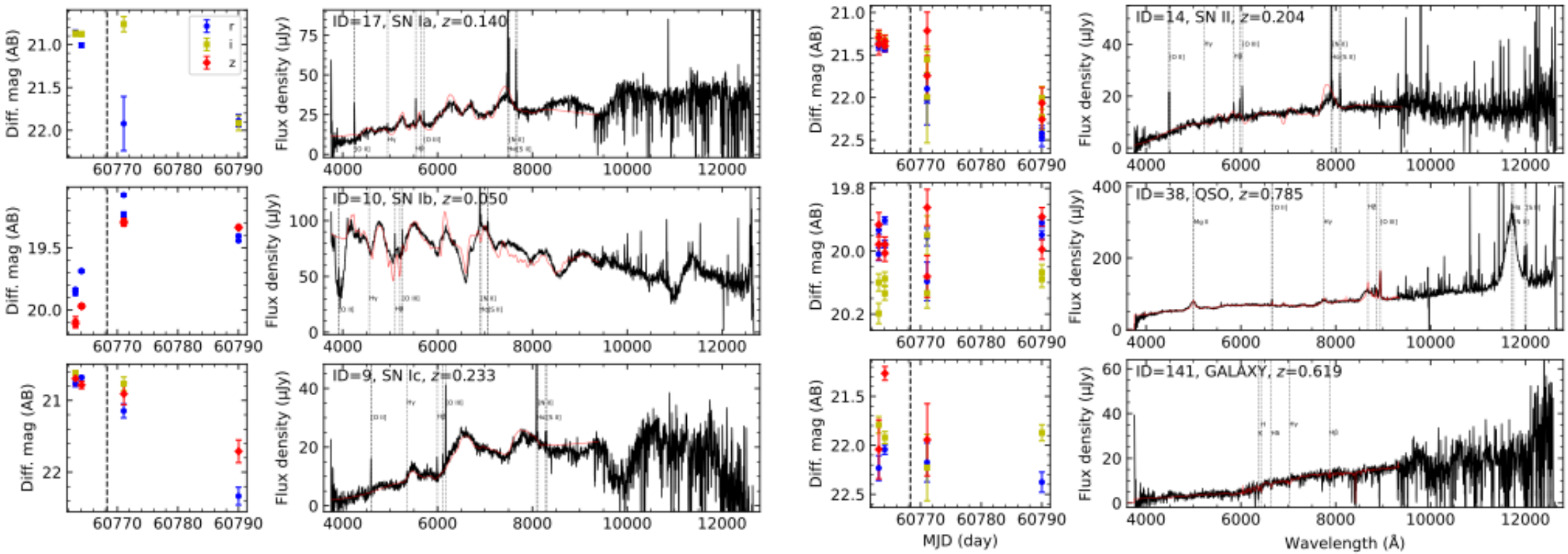
DECam transient candidates

Score	Criteria	Number of Targets
A	At least two secure spectral features	3093
B	At least one secure spectral feature with multiple weak features	147
C	One strong spectral feature but without other features to confirm what it is	37
D	Clear signal but without identified features or contaminated by nearby bright stars	167
E	No signal	453

PFS visual inspection criteria

Example PFS spectra

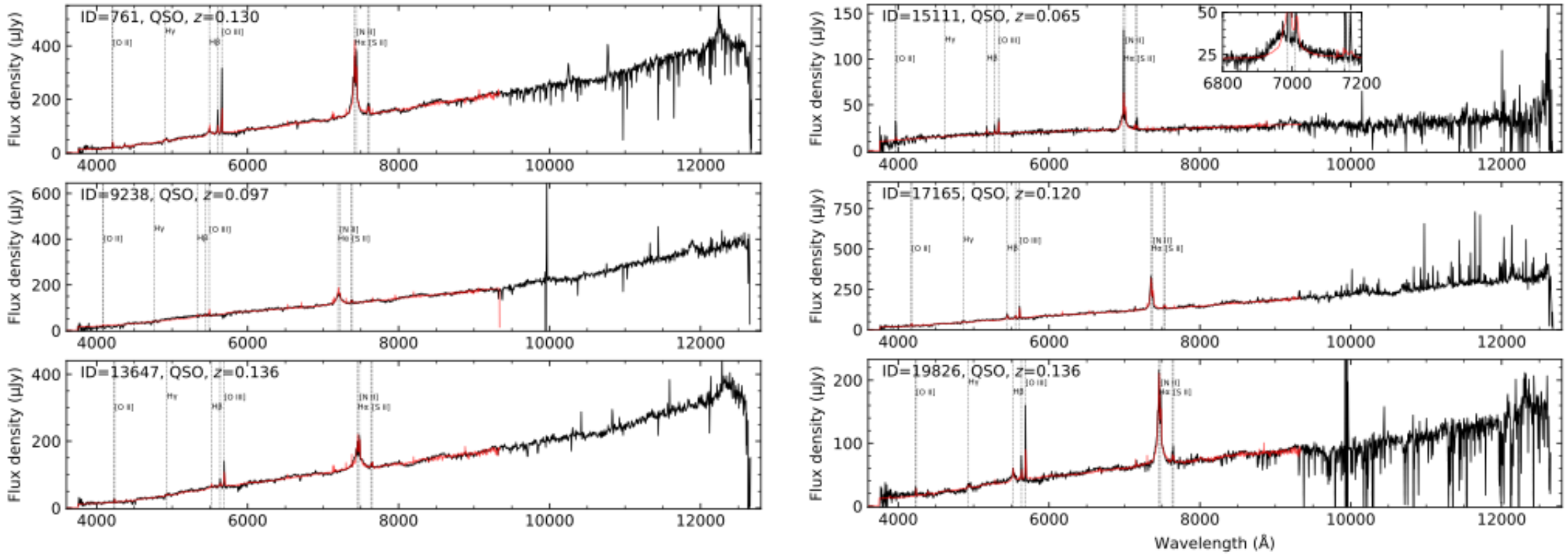
- In total, 12 SNe, 159 QSOs, 2975 galaxies, and 131 stars.



DECam light curves and PFS spectra (black: observed; red: best-fit template)

Possible EM counterpart to GW S250328ae

- No confident candidates. We do not find clear variability in these candidates, but cannot rule out the association as the variability of BBH EM counterparts could be faint.



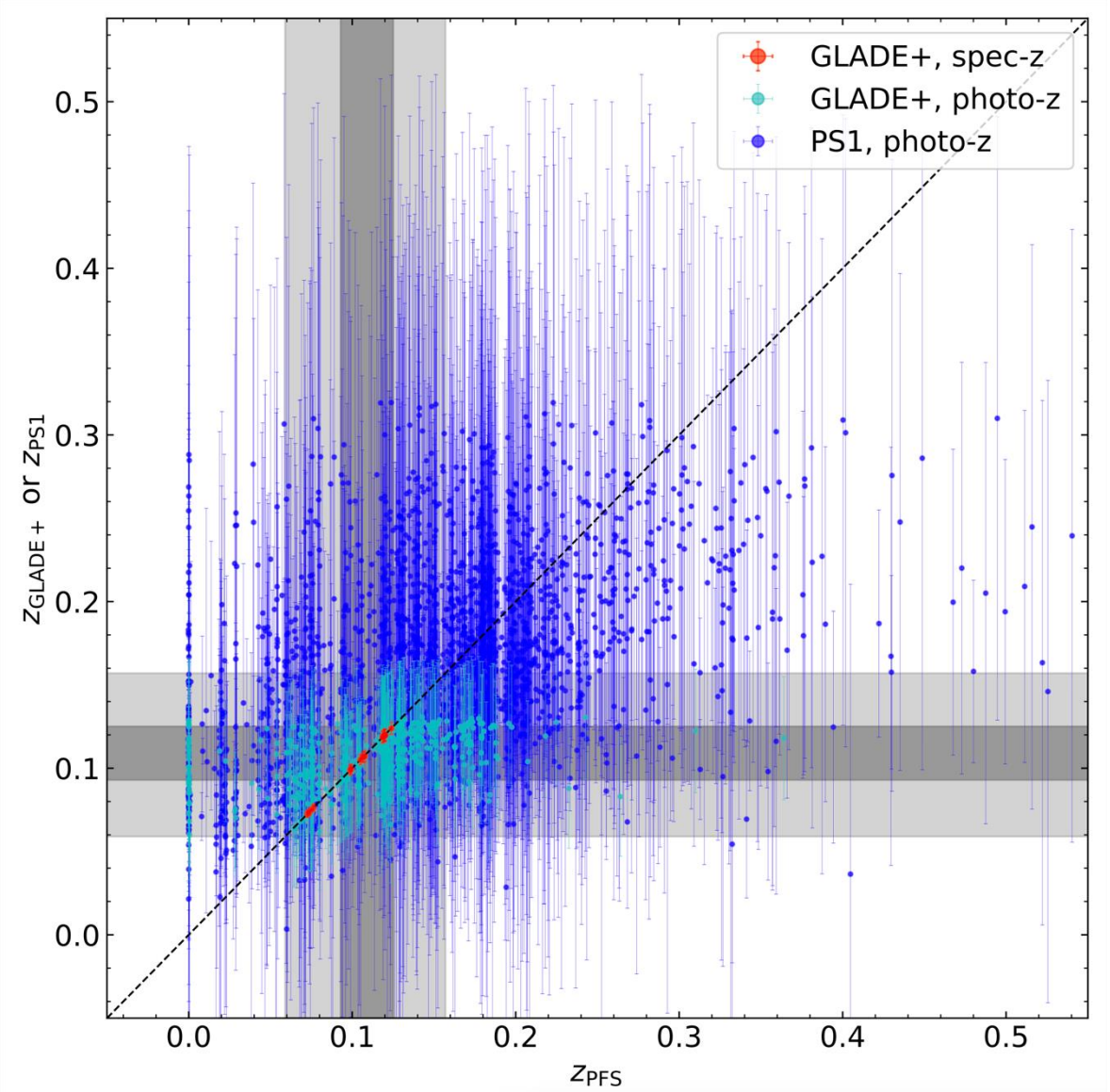
PFS spectra of possible candidate to S250328ae (black: observed; red: best-fit template)

Comparison with archival redshifts

- The numbers of targets with GLADE+ spec-z, GLADE+ photo-z, and PS1-STRM photo-z are 14, 464 and 2572, respectively.

- Among these targets, 14, 442, and 2255 (100%, 95%, and 88%) targets have redshift differences of < 0.1(1 + z), respectively.

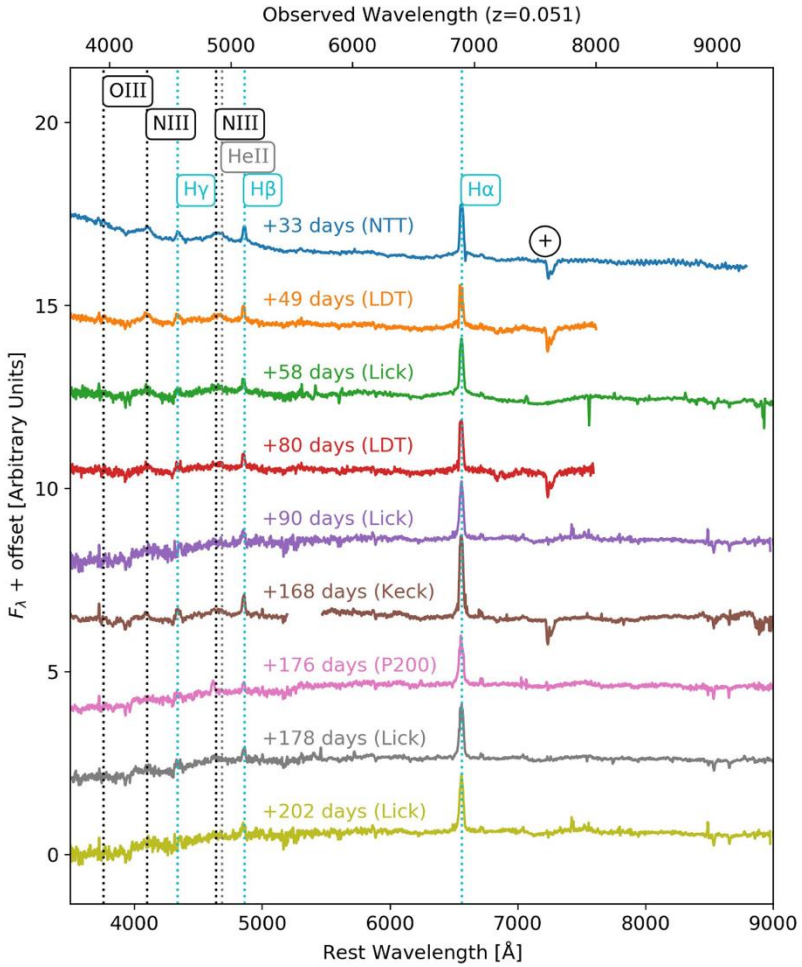
- Among 547 cross-matched targets with DESI DR2, 540 (~99%) targets have consistent spec-z and type.



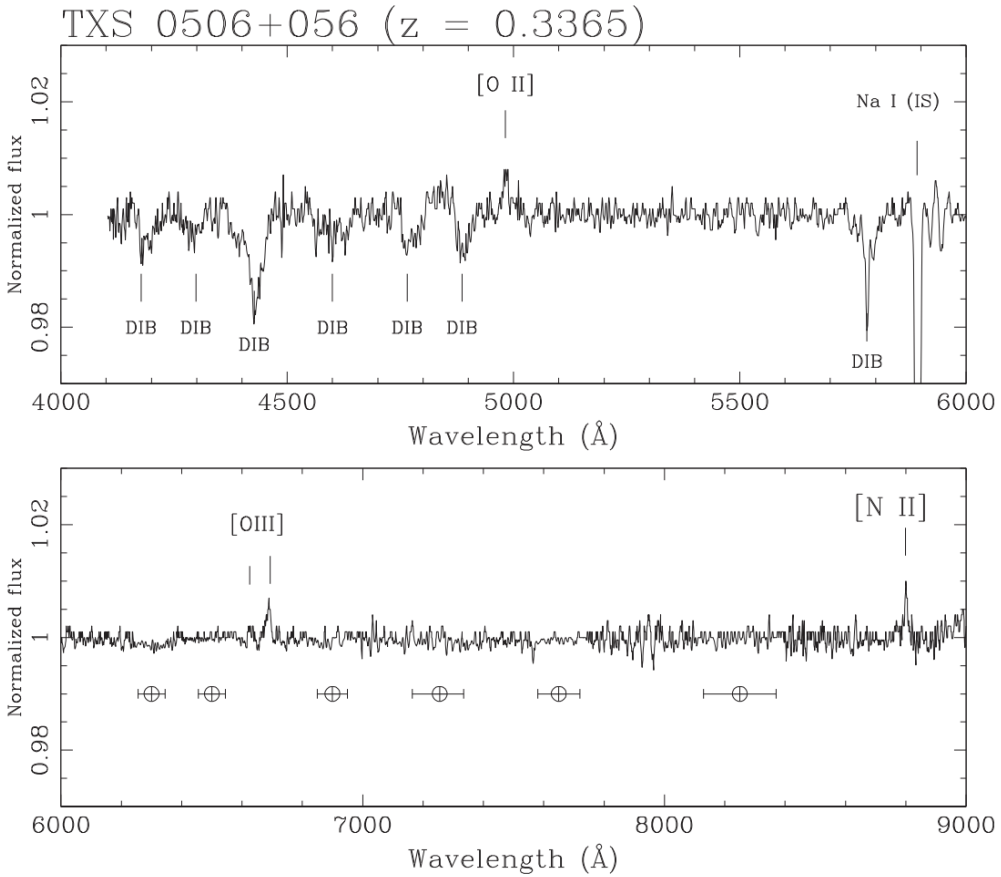
Future perspective

- We will carry out cosmology (dark siren) study using the spec-z we obtained. We also plan to observe more GW BBH mergers to improve the accuracy of the cosmological parameters.
- PFS is a powerful instrument and very efficient for wide field surveys (e.g. transient search).
- Future joint PFS observations of transients with DECam, LSST, etc. are promising.
- Similarly, our observing strategy can be also applied to other multi-messenger studies (e.g. the optical counterpart search of cosmic neutrinos).

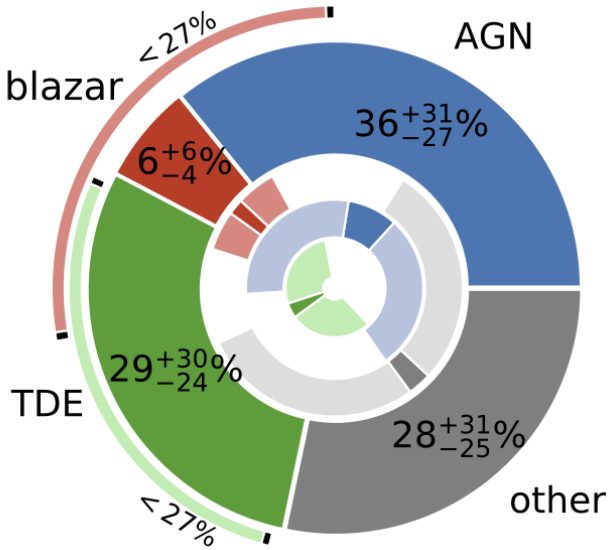
- Another question: missing sources of IceCube neutrino flux
- Contribution from supernovae (e.g. SN IIn; Zirakashvili et al. 2016; Garrappa et al.2025)?



TDE AT2019dsg (Stein et al. 2021)



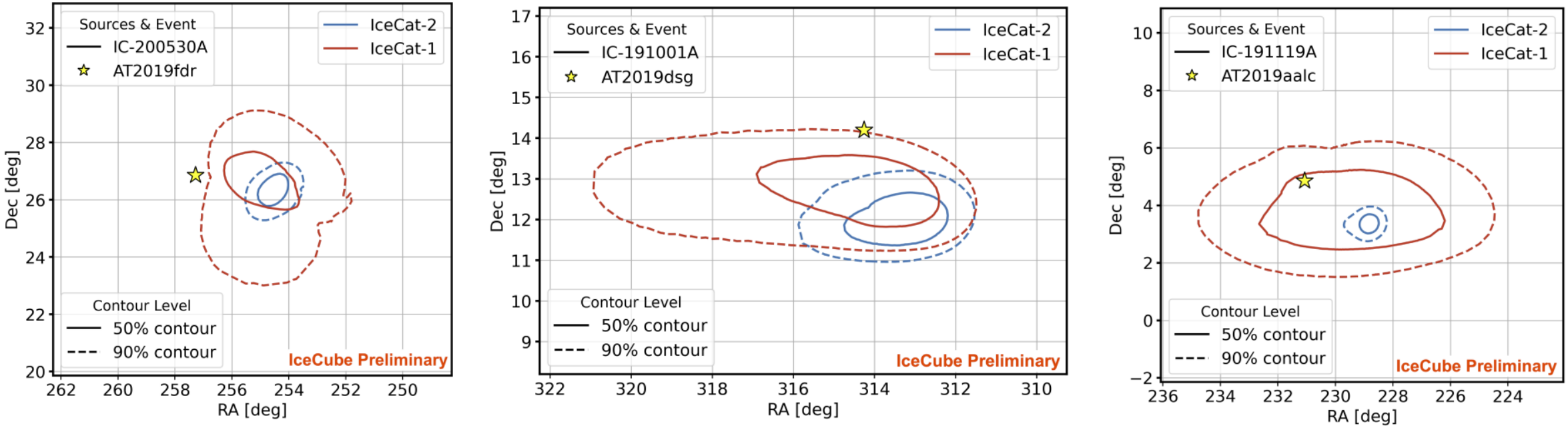
Blazar TXS 0506+056 (Paiano et al. 2018)



IceCube pie chart (Bartos et al. 2021)

- Recently, the updated IceCube sky map (IceCat-2) rules out previous TDE candidates (Zegarelli et al. 2025).

- Our ongoing project: 3 ToO nights of Subaru/PFS (Search for Optical Counterparts of Cosmic High-Energy Neutrinos; PI: Haibin Zhang; S26A semester), spectroscopic follow-up of Rubin/LSST transient candidates of IceCube Gold events. No trigger so far.



(a) AT2019fdr **(b)** AT2019dsg **(c)** AT2019aalc

Sky maps showing spatial coincidences between IceCat track alerts and several TDEs (Zegarelli et al. 2025)

Summary

- We carried out a joint search for the EM counterpart to the GW BBH merger candidate S250328ae with DECam and PFS.
- Confident spectral classification and spec-z of >3000 targets were obtained after template fitting and visual inspection.
- We do not find any confident EM counterpart candidates to S250328ae, although the association with 6 QSOs (and 3 transients not observed by PFS) cannot be ruled out.
- We greatly appreciate the rapid PFS ToO observations and would like to continue joint PFS observations of transients with DECam, LSST, etc. in the future.
- Similarly, our observing strategy can be also applied to other multi-messenger studies (e.g. the optical counterpart search of cosmic neutrinos).