Multi-Messenger Astronomy in the Near Future with Subaru/PFS

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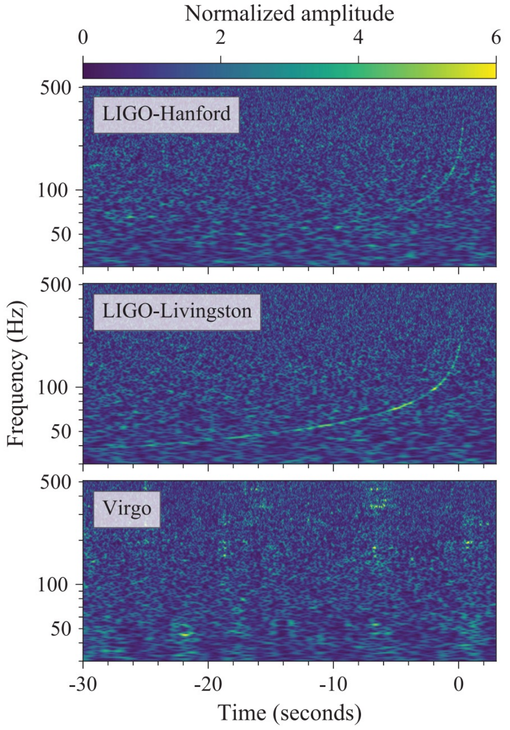
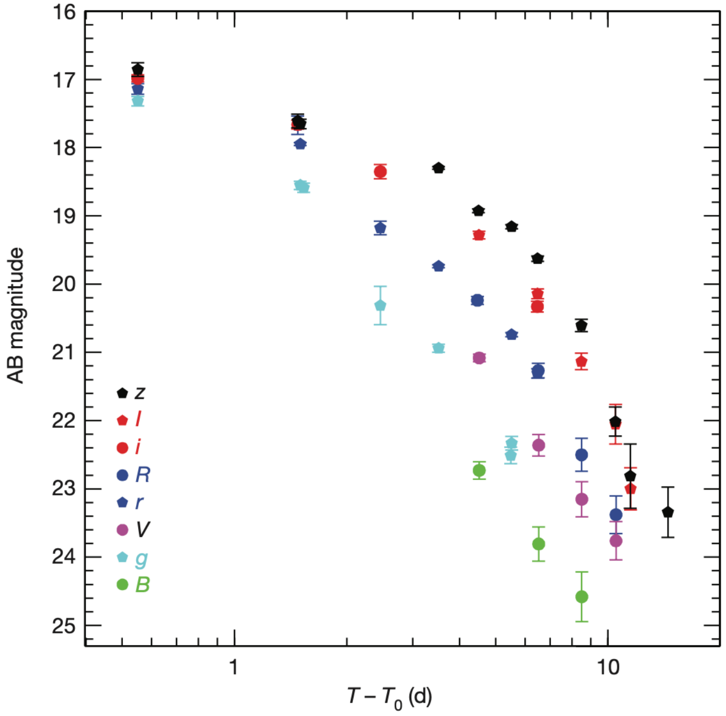
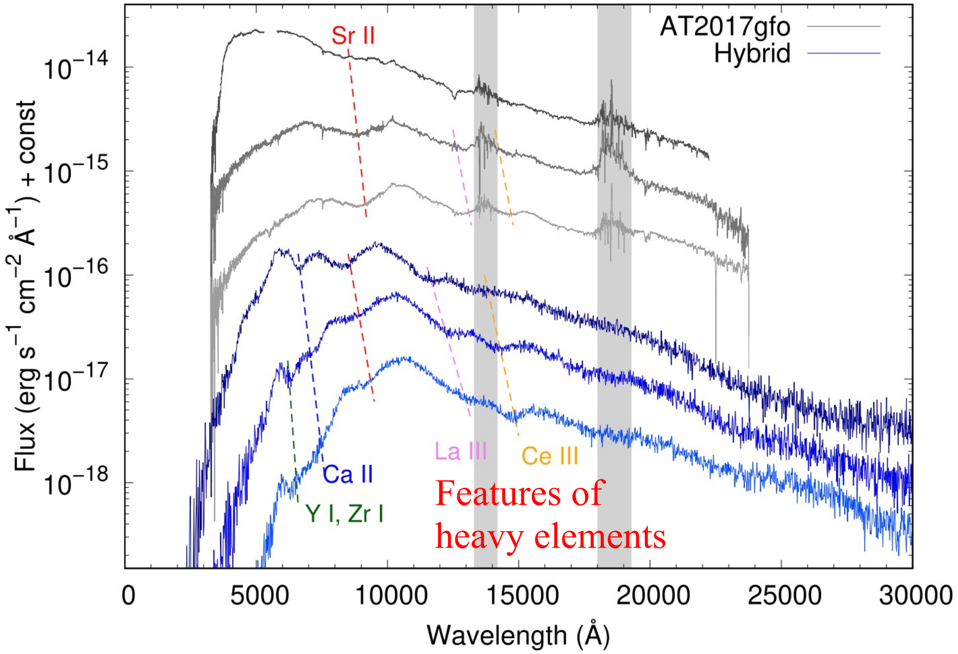
Multi-Messenger Astronomy

- Combining observations of EM radiation (e.g. UV to Radio), gravitational waves, neutrinos, and cosmic rays.
- Potential targets: kilonova, supernova, AGN, tidal disruption events, etc.
- **Kilonova**: binary neutron-star merger, an origin of heavy elements



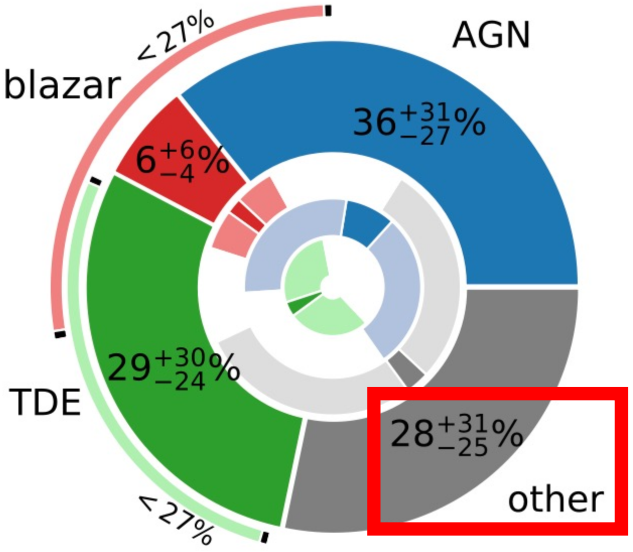
GW170817 (Ligo and Virgo 2017)



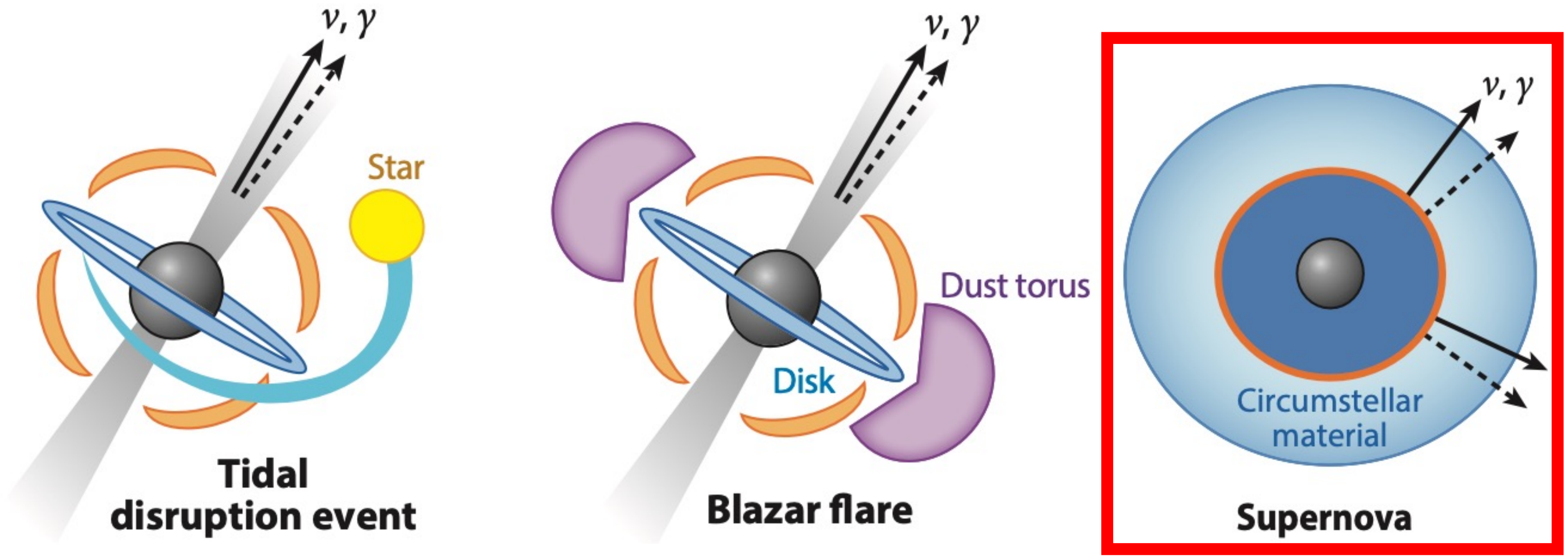


Light curves and spectra of Kilonova AT 2017gfo (Pian et al. 2017; Domoto et al. 2022)

- Another question: missing sources of >TeV neutrino flux detected by IceCube
- Contribution from supernovae (especially Type IIn due to expected dense CSM; e.g. Zirakashvili et al. 2016)?



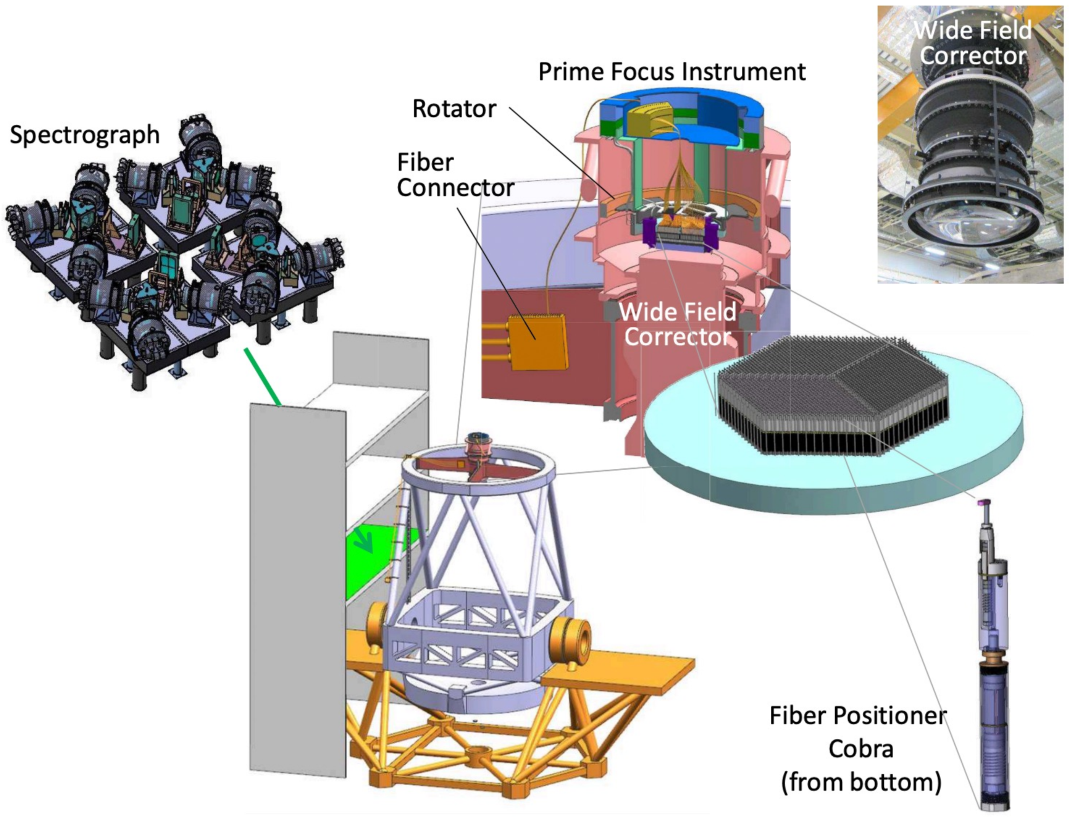
IceCube pie chart (Bartos et al. 2021)



Schematic picture of various transients (Murase et al. 2019)

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?

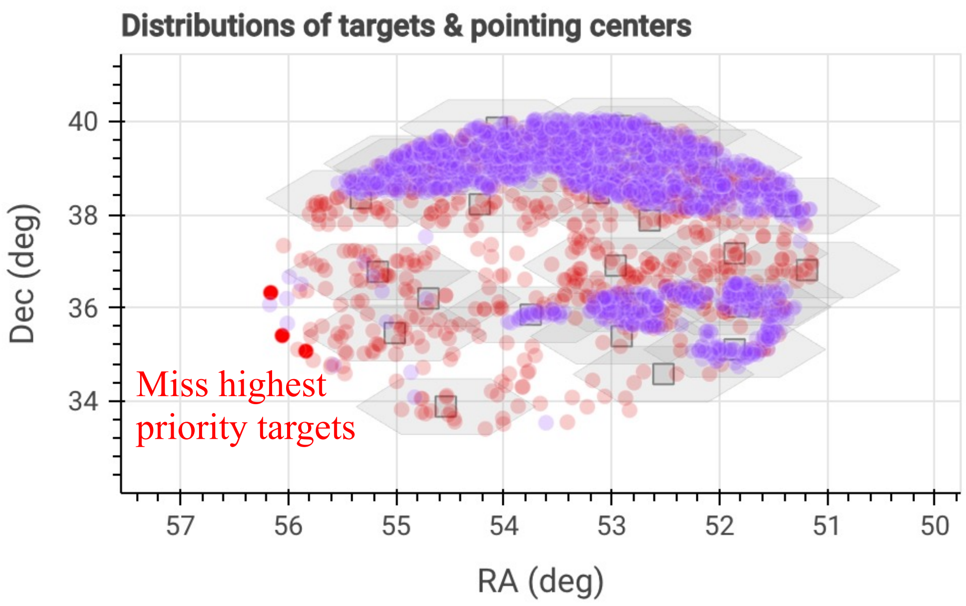
- Large field of view (1.25 deg^2)
- Wide wavelength coverage (380-1260 nm)
- >2000 objects can be observed simultaneously at one pointing.
- Precut slit masks are not needed (suited for ToO observations)

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

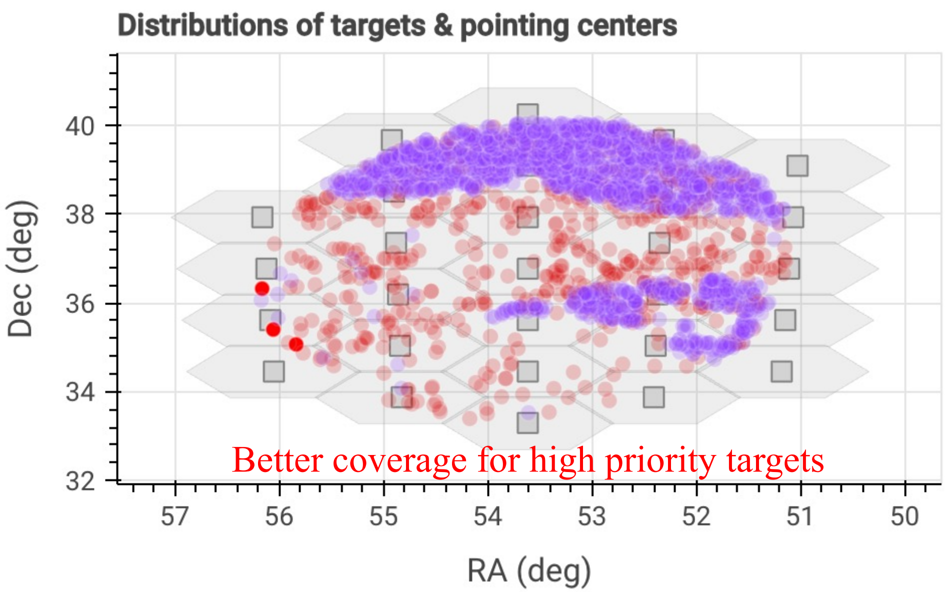
Target Preparation

- Host galaxies: spec-z and photo-z catalogs (e.g. GLADE+ and PS1-STRM)
- Transients: identified by other imaging instruments.
- PFS Target Uploader: use hexagonal pointing instead of default pointing
- Half-night observation: cover ~20 deg^2 with >18 mag (5σ per pixel)



Default pointing

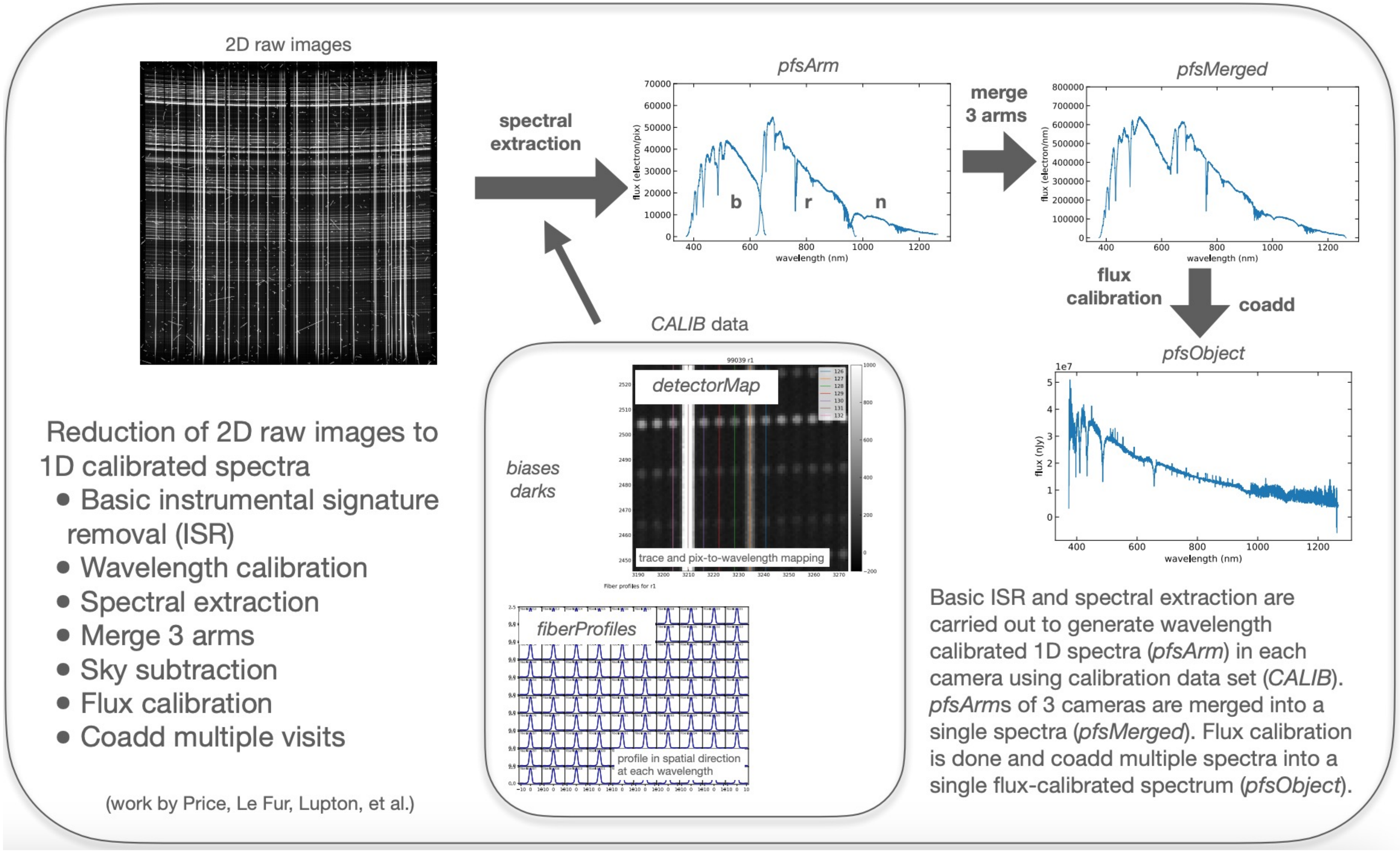
vs.



Hexagonal pointing

(S240919bn; 90% area = 21 deg^2; 28 PFS pointings)

PFS Pipeline



2D pipeline (Kiyoto Yabe PFS DRP development team)

- PFS products we will use:

  2D pipeline: psfSingle (flux-calibrated spectra of each single exposure)

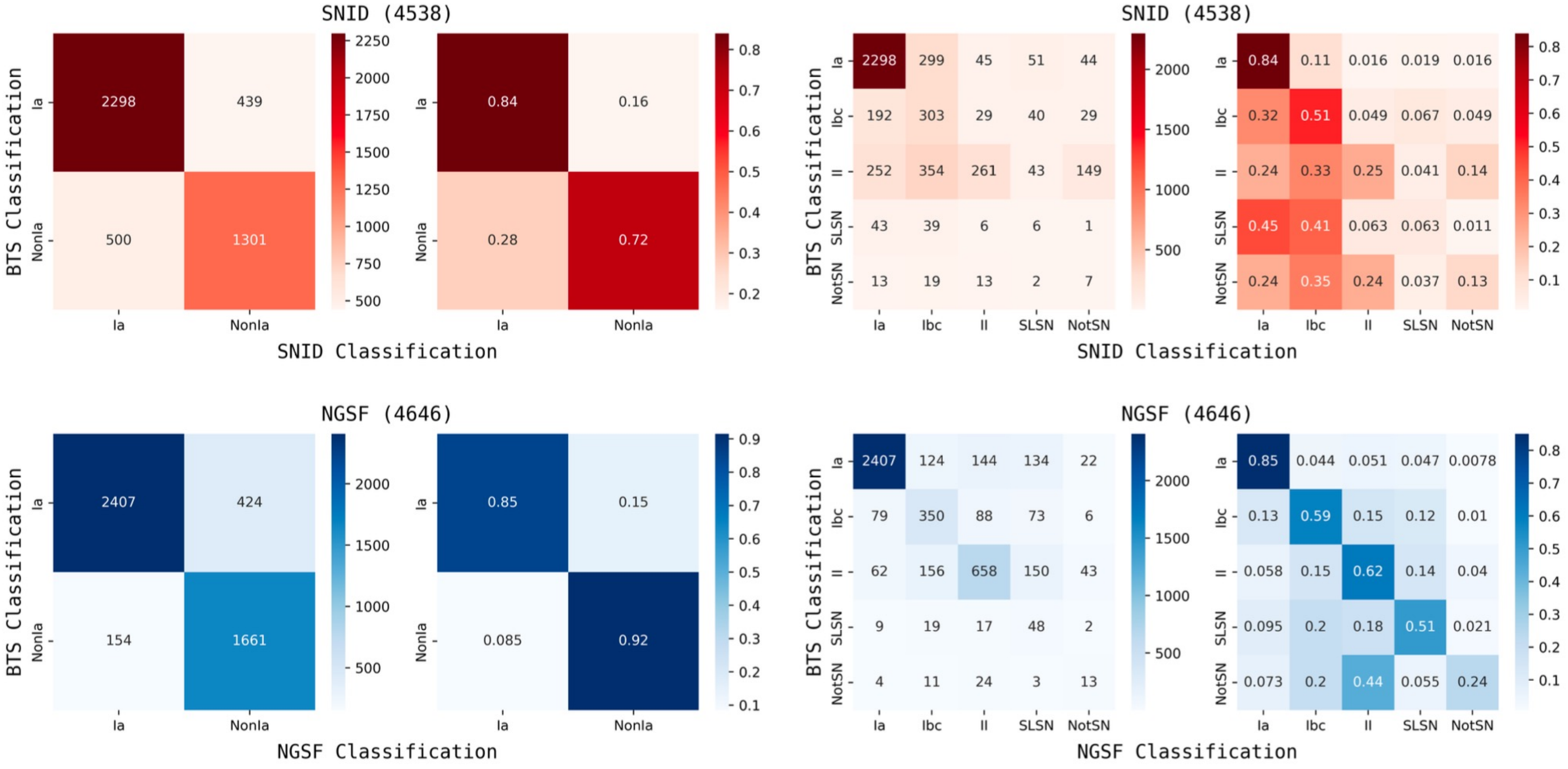
  1D pipeline: spec-z catalog of host galaxies

- We have successfully installed and tested the 2D pipeline with mock data.

- The 1D pipeline is being improved by the pipeline team.

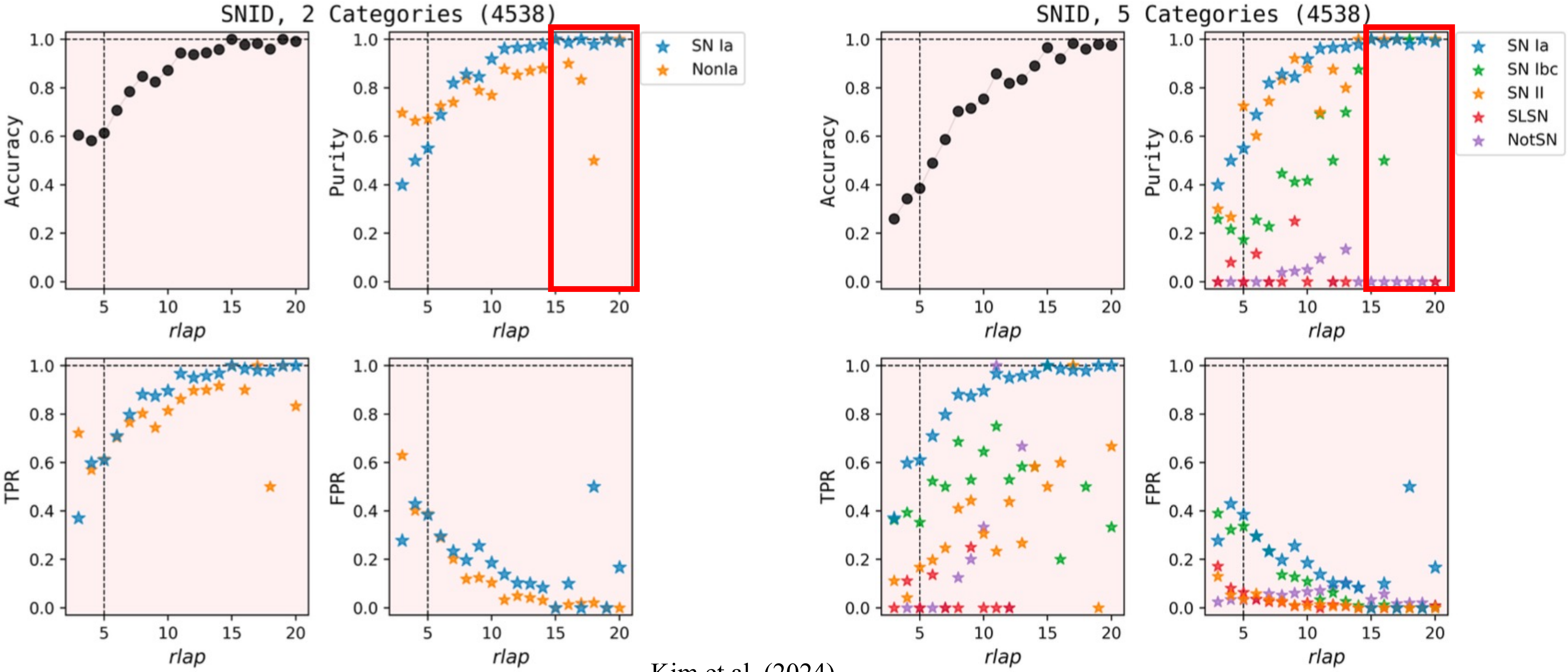
Supernova Identification Tools

- Current tools are only accurate for SN Ia. Visual inspection is required.



Kim et al. (2024), consistent with our tests

- But can be used to remove SN Ia with high purity (~ 99%).
- For example, either of
  1. SNID rlap > 15 (rlap = goodness of fit; Kim et al. 2024)
  2. SNID rlap > 5, known spec-z, and Mag < −17.5 (our tests)



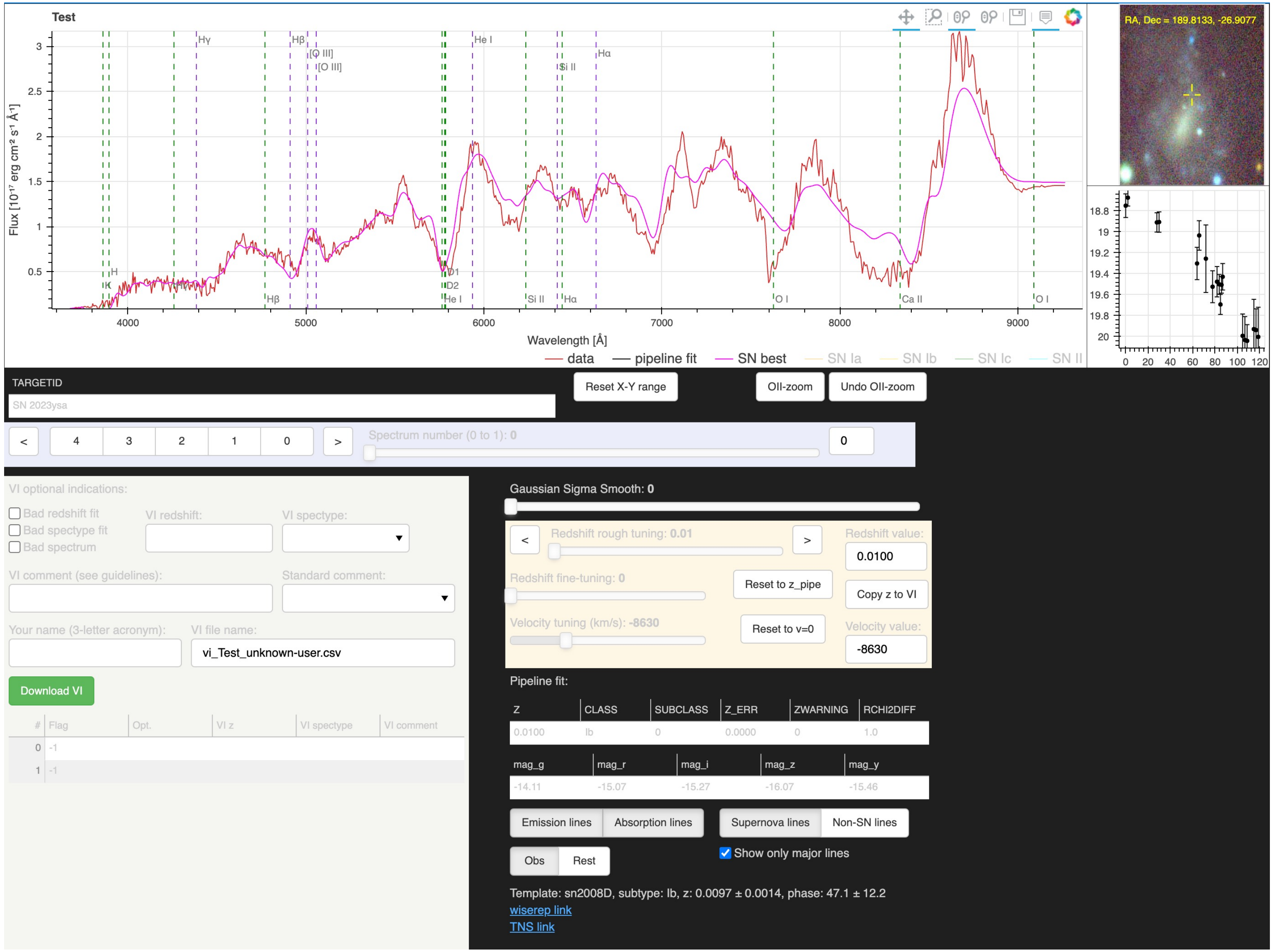
Kim et al. (2024)

Visual Inspection Tool

Have been tested with PFS EDR data and SN spectra in the literature.

Current functions:

- Show observed/model spectra
- Adjust redshift and velocity
- SNID fitting results
- Images and light curves
- Show/hide emission/absorption lines
- Show/hide SN/galaxy lines
- Other information (e.g. photometry)
- Save VI results



Discovery Report and Data Sharing

- We will share the reduced PFS data and information (SN type, spec-z, etc.) among the J-GEM collaboration as soon as possible (maybe using the Image Server).

- We will submit a discovery report to the Astronomer's Telegram and General Coordinates Network (GCN) if there is an important discovery (e.g. kilonova).

- We will complete and submit a paper ASAP (hopefully within two weeks) after an important discovery.

Summary

- We will carry out Subaru/PFS observations for multi-messenger astronomy in the near future.
- Our targets will be transients (Kilonova, SN, etc.) and their host-galaxies.
- We have prepared tools for target selection, data reduction, and visual inspection.
- **We are ready** for the PFS science operation scheduled from 2025.