High Energy Astrophysics and Cosmology in the era of all-sky surveys

Wide Field Survey Telescope (WFST)

Overview and Recent Progress

On behalf of the WFST team

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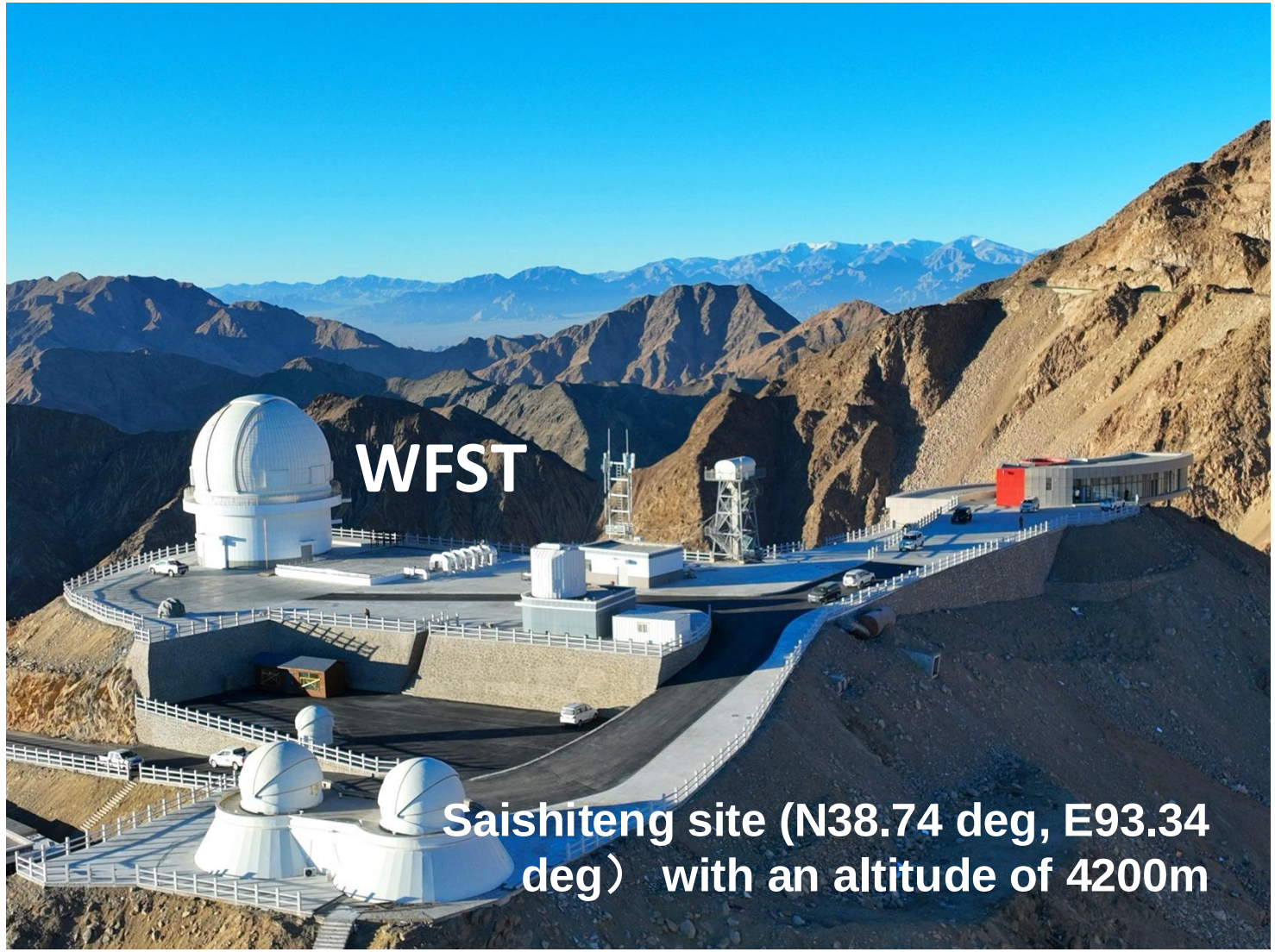
University of Science and Technology of China (USTC)

Outline

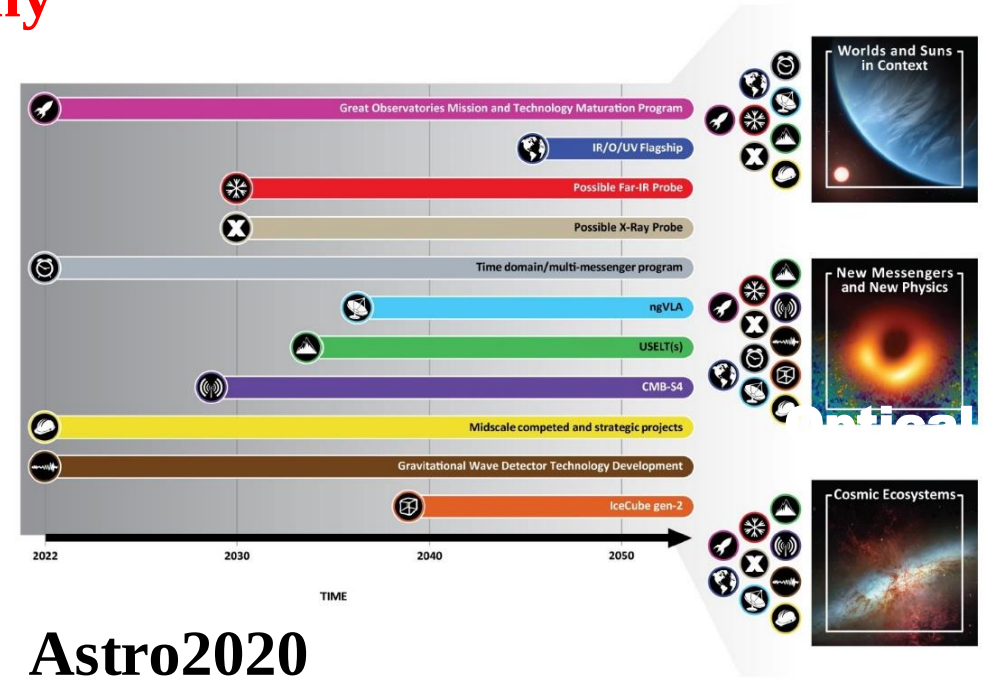
- Why WFST ?
- WFST Overview
- Key Science of WFST
- Progress: Pilot survey
- Summary



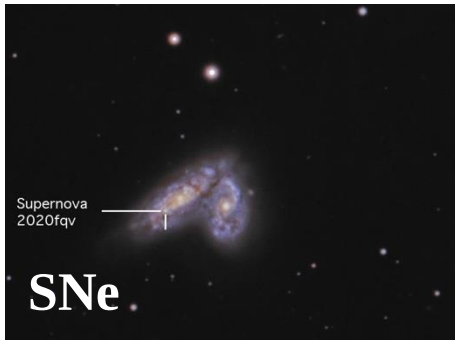
1. Why WFST ?

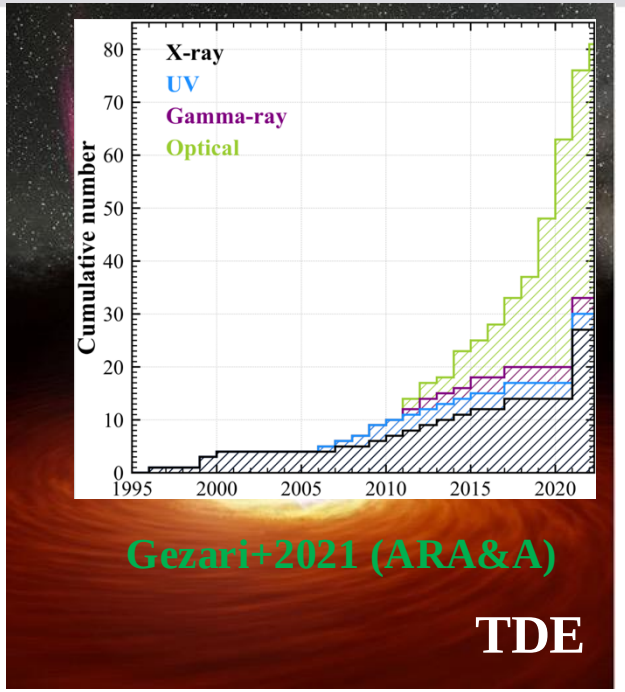
- Many astronomical objects show variabilities.
  - Transients; Moving objects; Variables
- Time variability encodes key information about the source physics -- Time Domain Astronomy

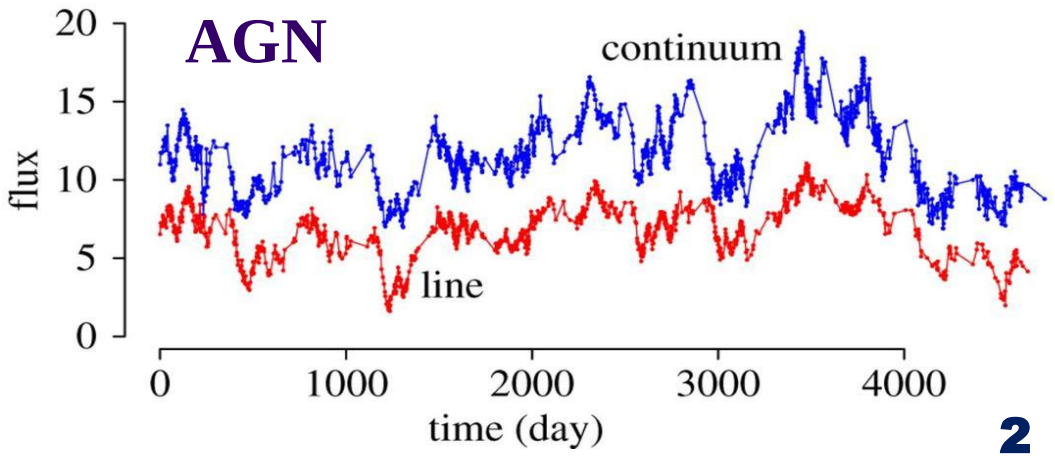
New Windows on the Dynamic Universe



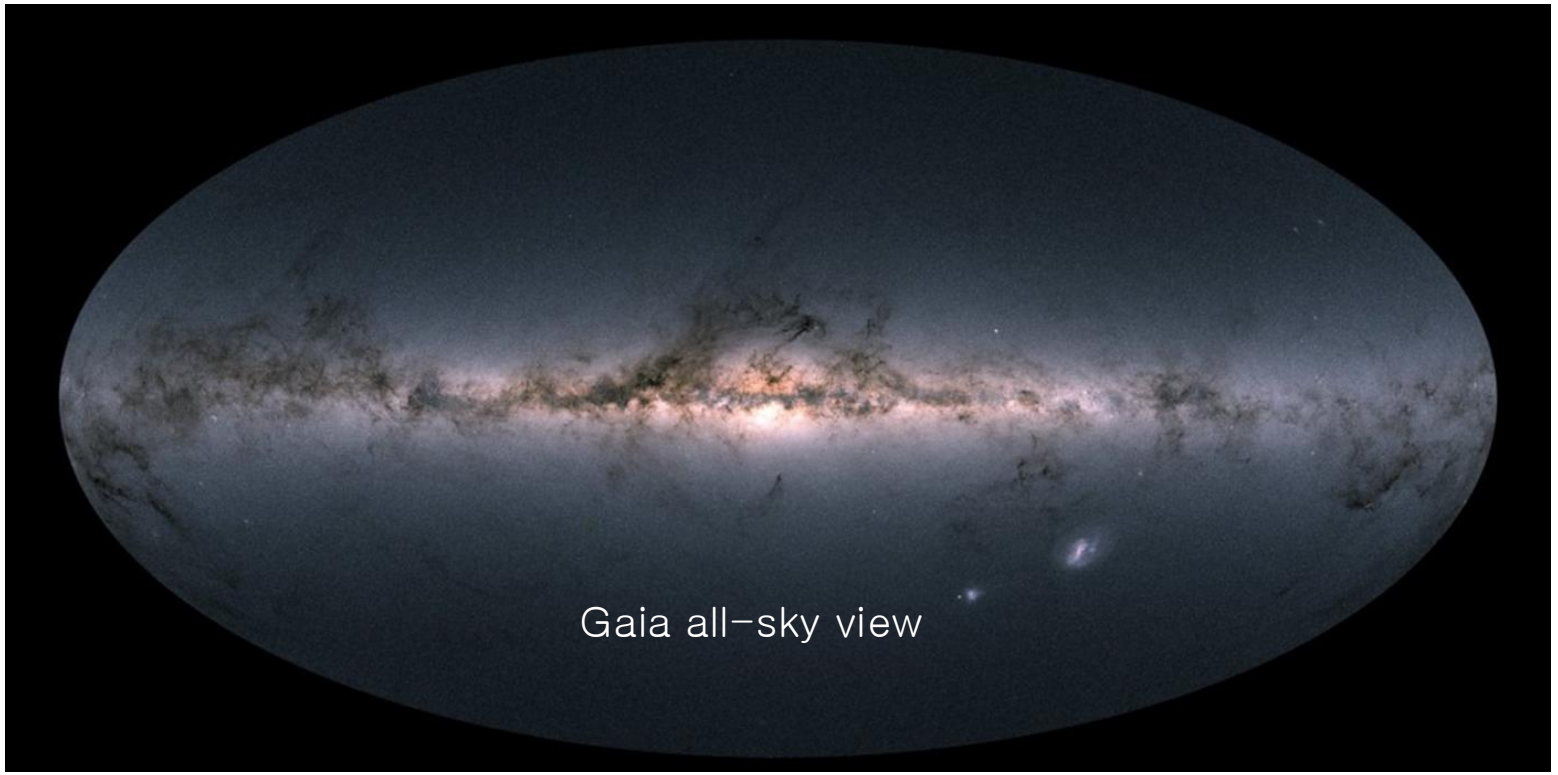
Astro2020



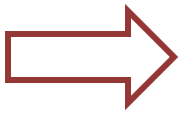




Telescopes for Time Domain Astronomy

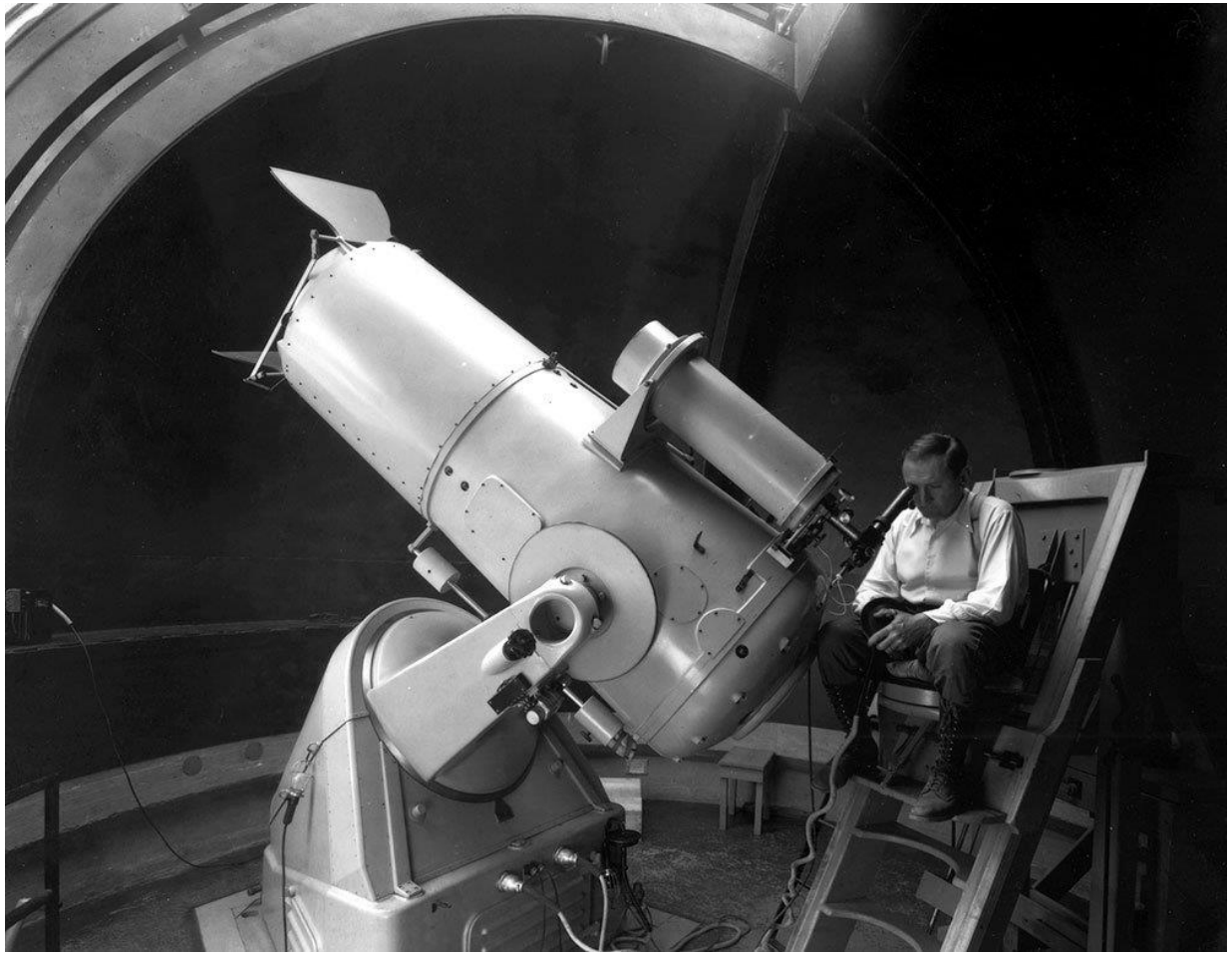


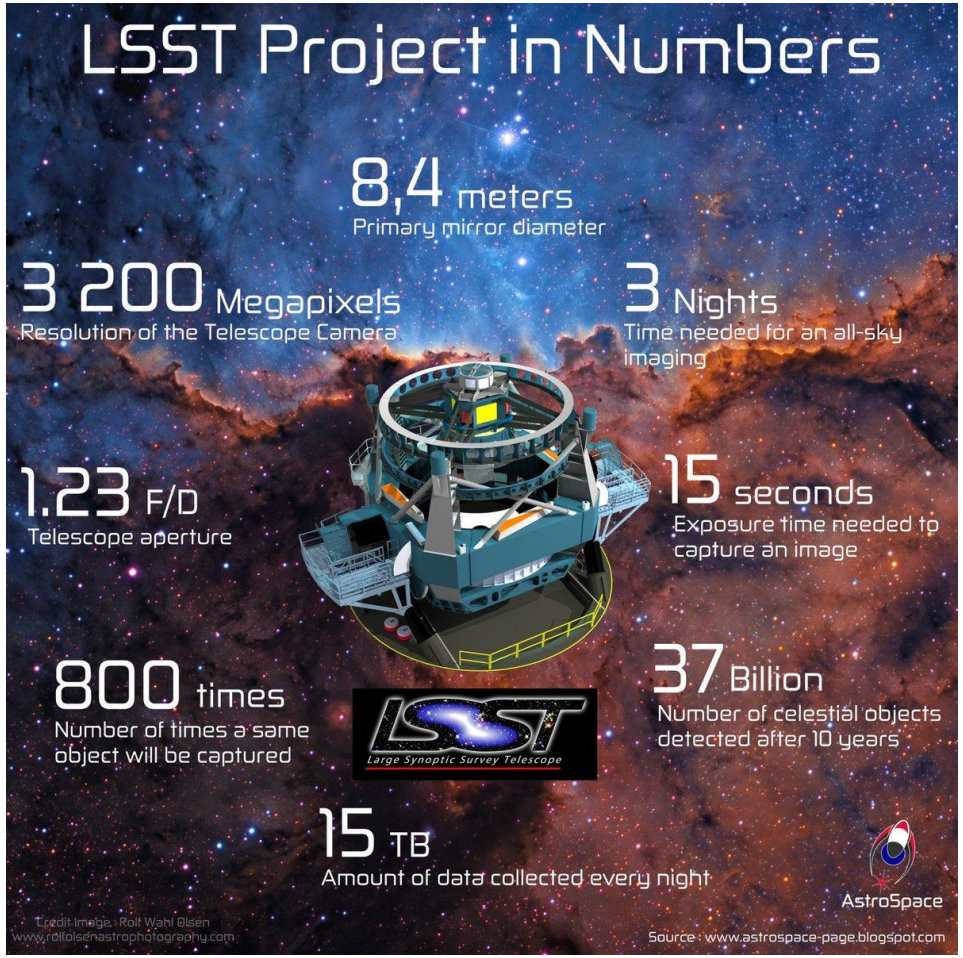
Need a **powerful** data acquisition facility in terms of both observation **depth** and sky **coverage**



Telescopes: with **large** field of view (FoV), **high** efficiency, and **high** image quality.

Zwicky Transient Facility (ZTF)





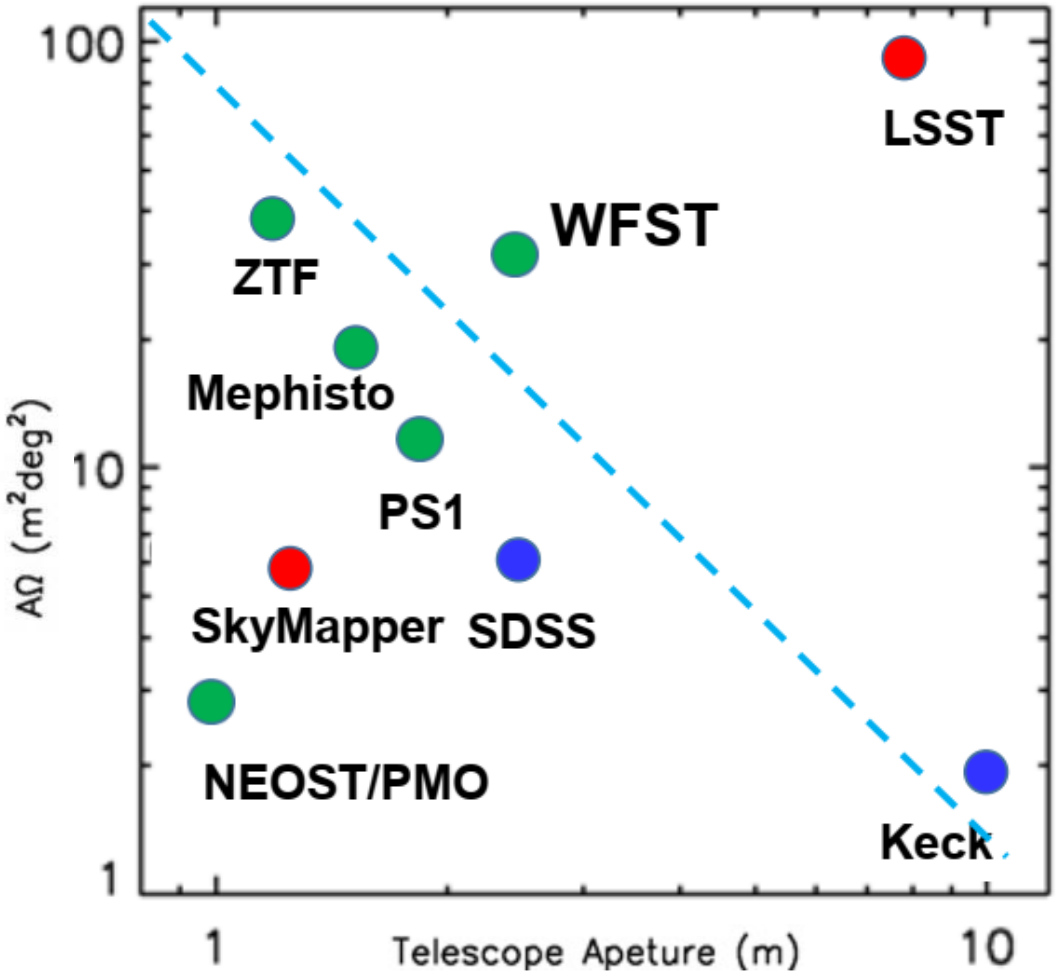
ZTF：48 inch, with a 47 sq. deg, CCD mosaic camera: FWHM ~ 2.0”; Limited mag: 20.4 mag; Filters: g、r

Rubin Observatory LSST in Chile

Beyond ZTF?

- In the Southern, LSST is the upcoming powerful time-domain facility
- In the Northern, however, ZTF is relatively small telescopes for TDA

Telescope	Location	A (M^2)	FOV Sq. deg	Filters	FWHM (arcsec)	Single Exp. depth
Panstarrs	19.824° N -155.473° E	2.00	7.0	grizy	1.19	22.0,21.8,21.5, 20.9,19.7
ZTF	33.357° N -116.865° E	0.78	47	gri	2.10	20.8,20.6,19.9 21.1,20.9,20.2
LSST	-30.245° N -70.749° E	32.4	9.6	ugrizy	0.76	23.9,25.0,24.7, 24.0,23.3,22.1
WFST	38.817° N 93.367° E	4.13	6.5	ugriz	1.00	22.4,23.4,23.0, 22.6,21.6

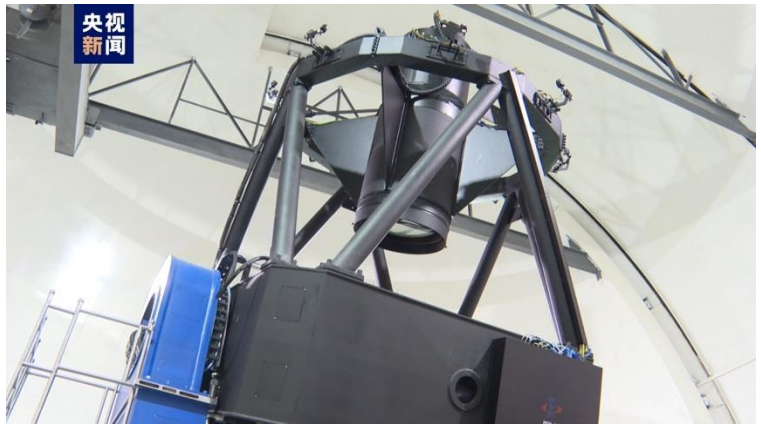


Develop a powerful optical survey telescope in terms of both observation depth and sky coverage on Northern sky → WFST

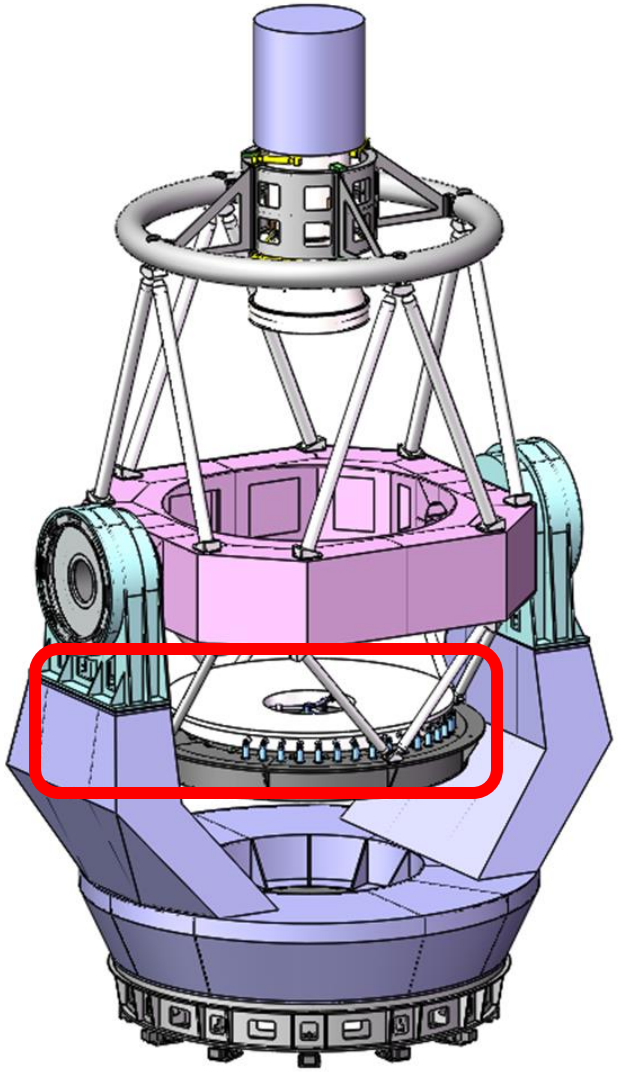
2. WFST Overview

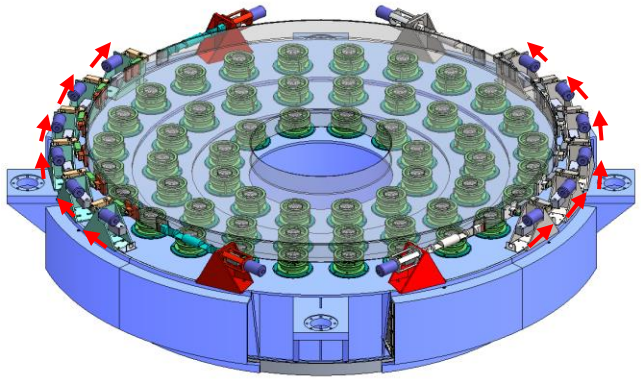
Wide Field Survey Telescope

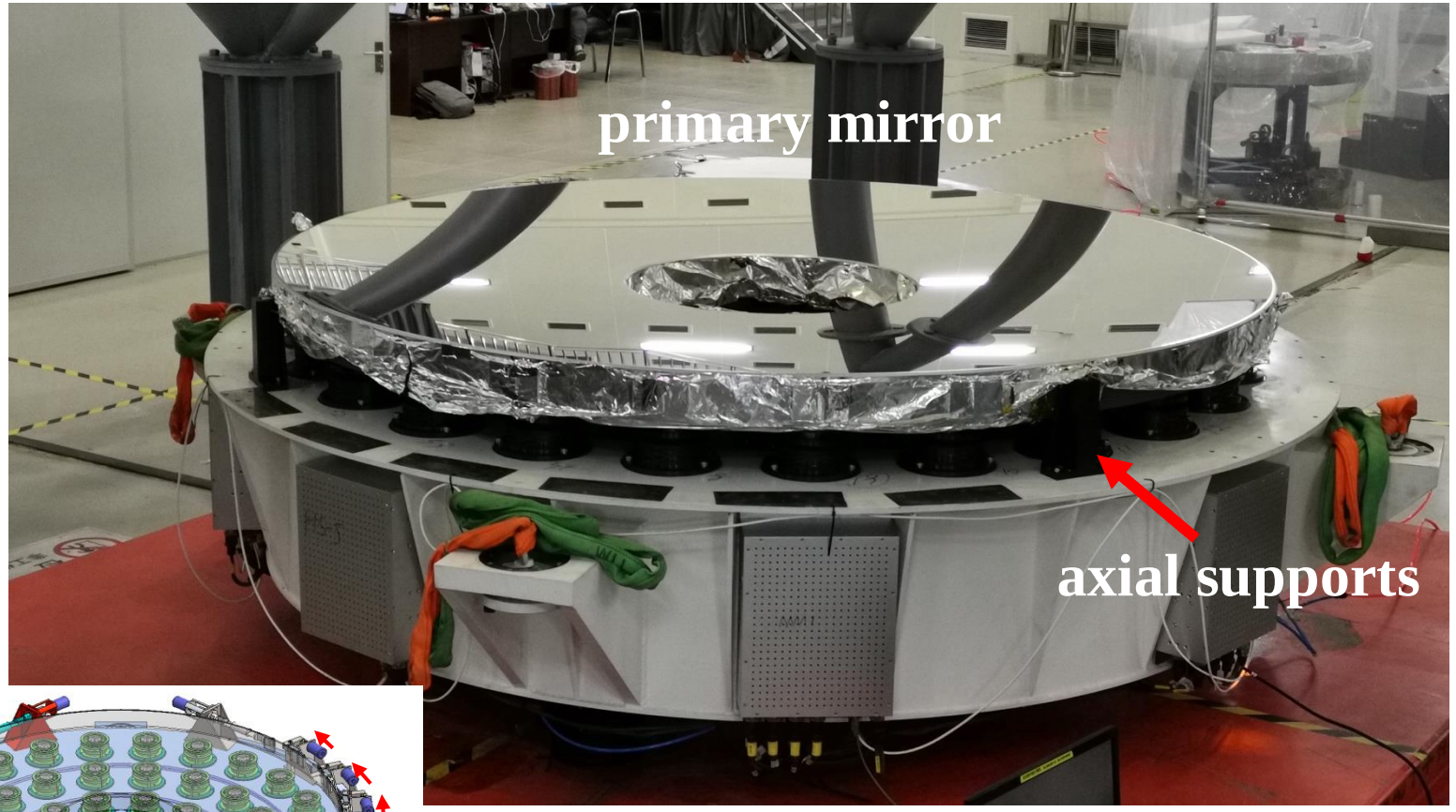
- 2.5-meter primary mirror
- A prime focus camera with a field of view of 6.55 square degrees; 0.765 gigapixels
- On high-quality astronomical site
- r ~ 23.0 mag in 30s, 6000 square deg/night



Telescope: Active optics system (AO)

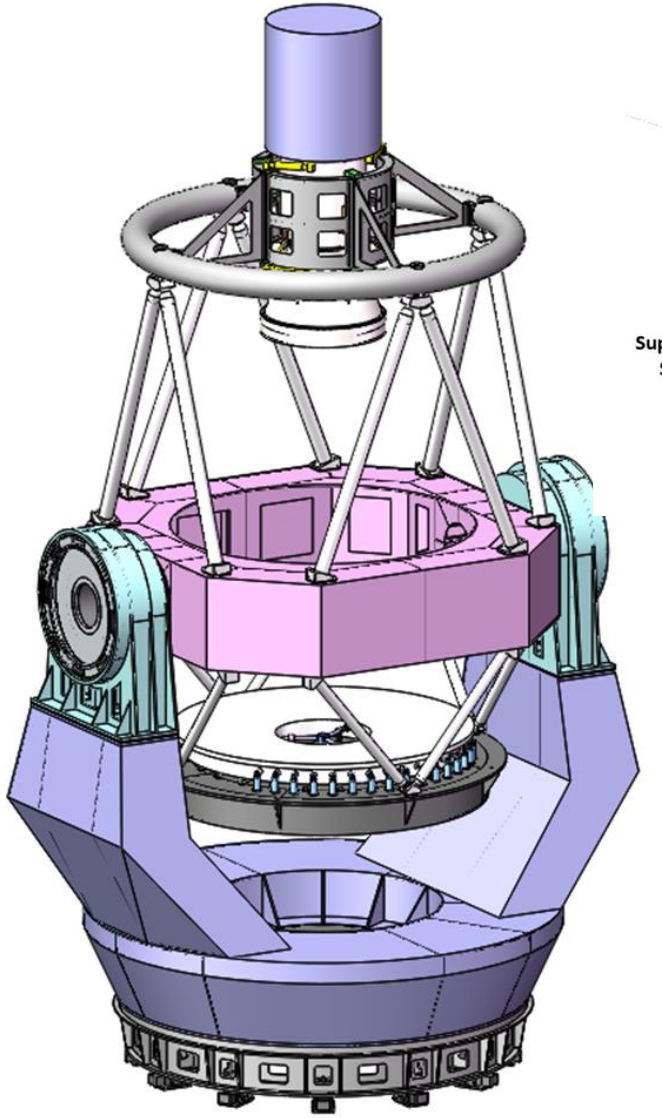


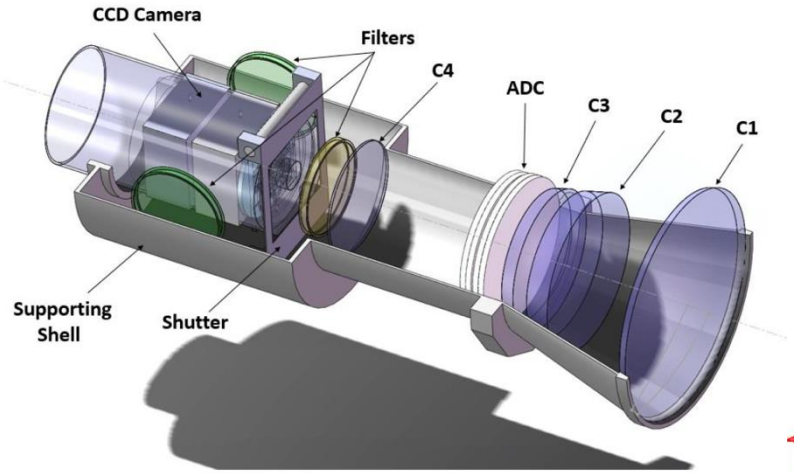




The 2.5m primary mirror is supported by 54 axial supports and 12 lateral supports.

Telescope: Prime Focus System

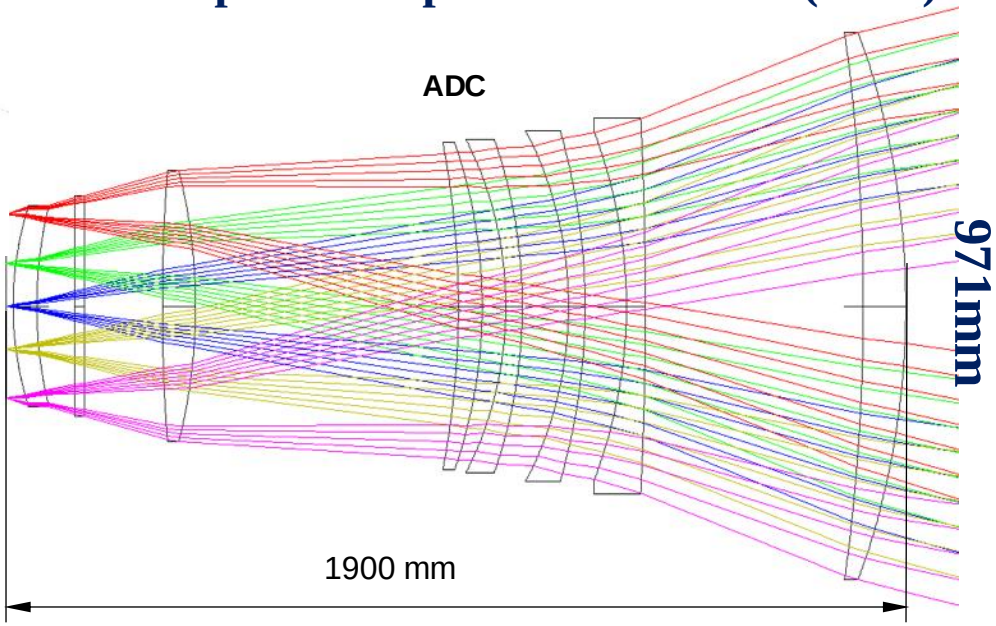




Institute of Optics and Electronics (IOE), Chinese Academy of Sciences

Wide FOV (d = 3 deg), high efficiency, wide band coverage (ugrizw) and high image quality.

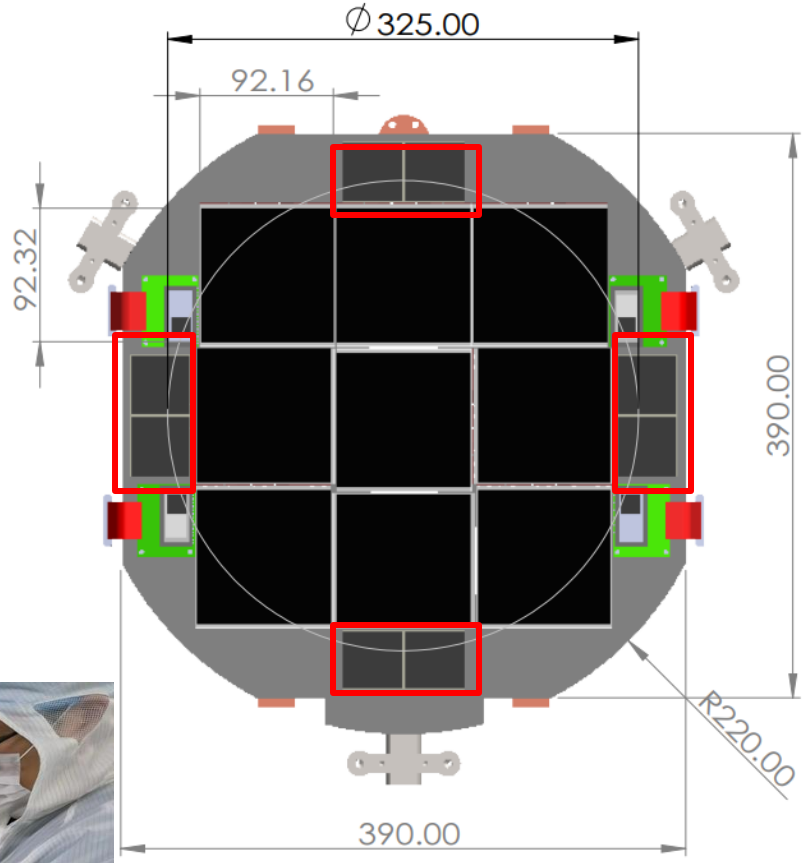
Atmospheric Dispersion Corrector (ADC)



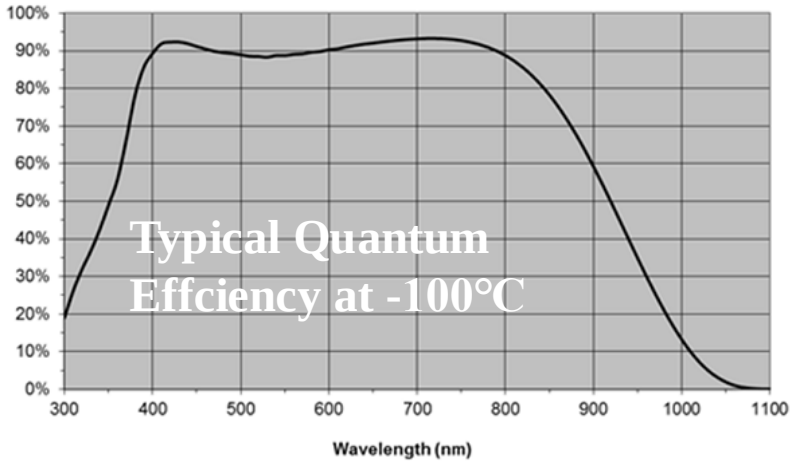
80% of the spot energy is encircled within a diameter of 0.4″ across the full 6.55 sq. deg.

Camera

- **Focal plane: Φ 325 mm**
  - **Scientific imaging array: 9 pieces of 9K×9K CCD chips (E2V CCD290-99) with 10 μm × 10 μm pixels, with flatness less than 20 μm.**
  - **Wavefront sensors (for AO): 8 pieces of 4K×4K CCD chips (CCD 250)**
  - **Guiding sensors: 4 additional chips**

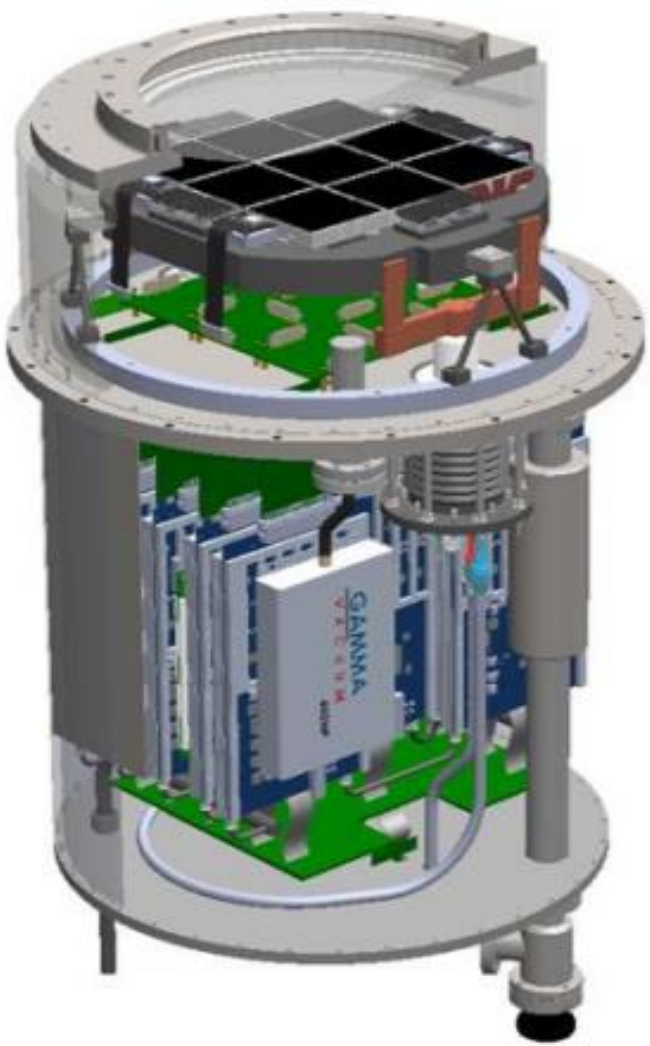


CCD290-99

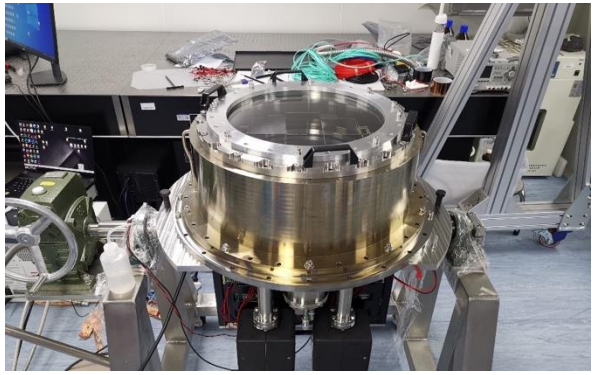


Camera of WFST, at the international advanced level.

Progress of the Camera development



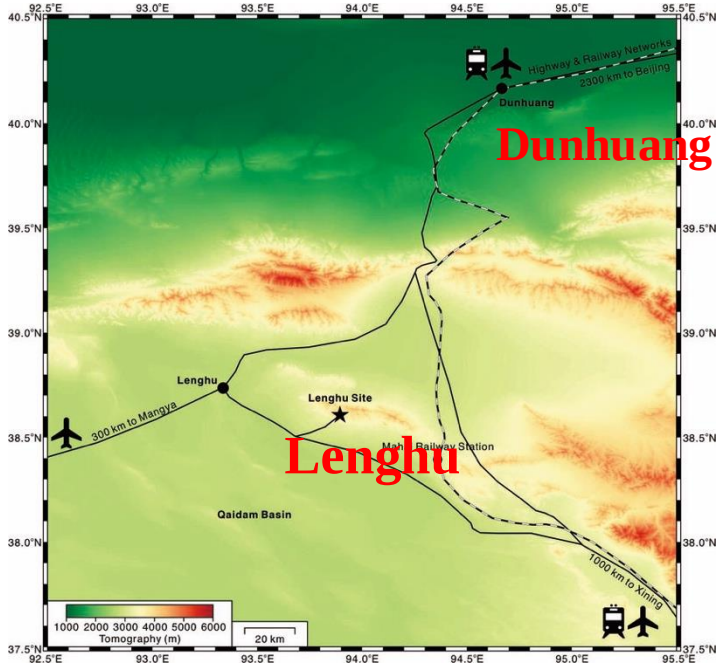
Design

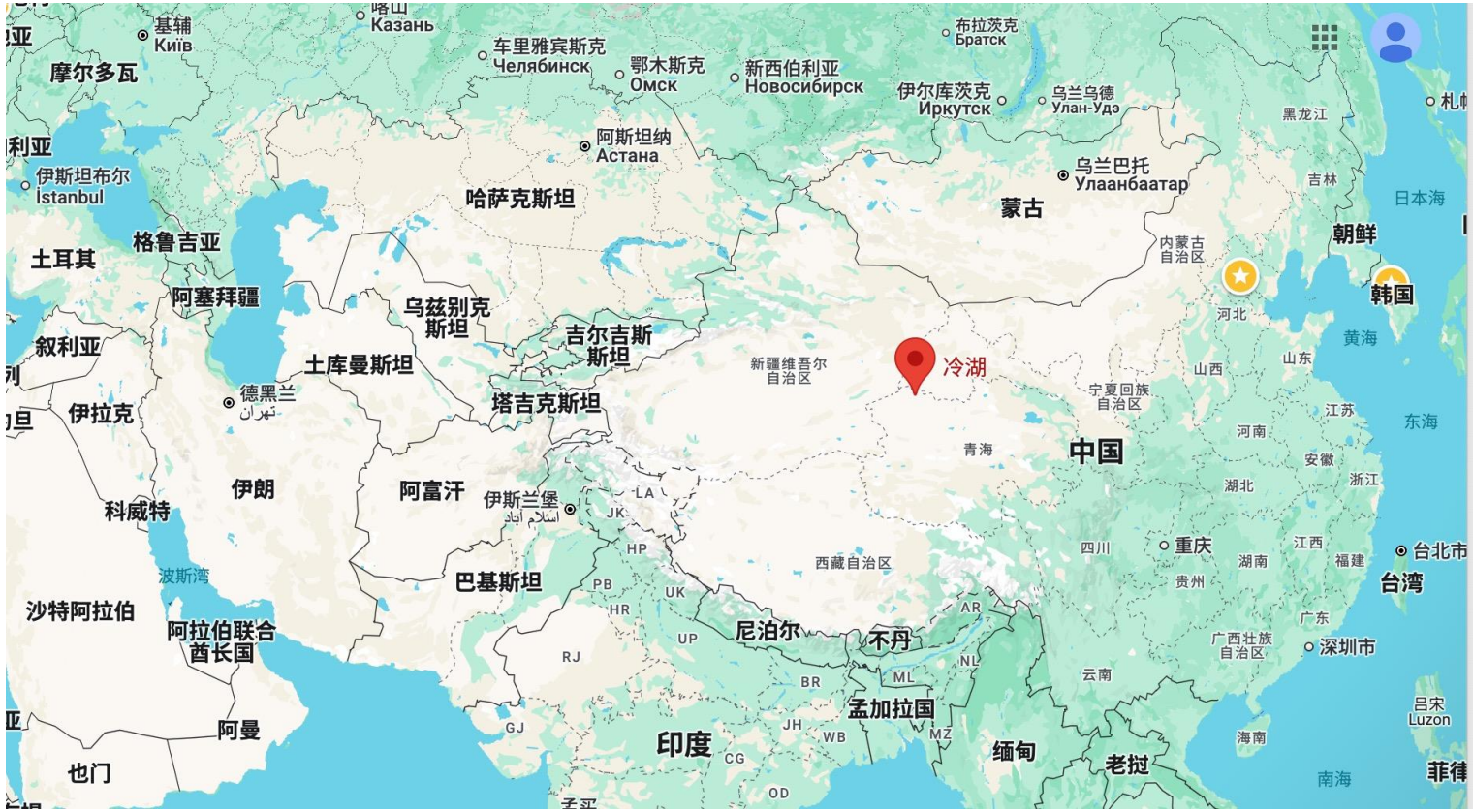


Development

Developed

Site of WFST

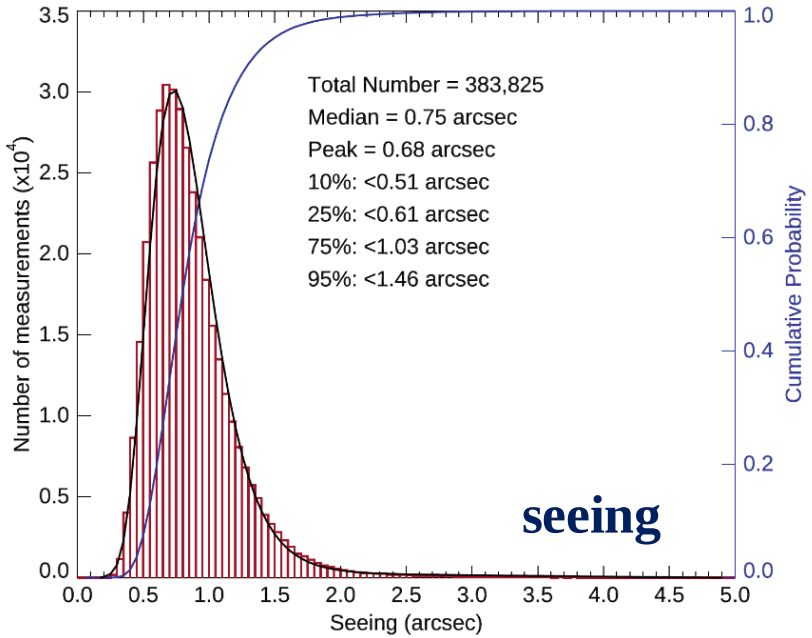


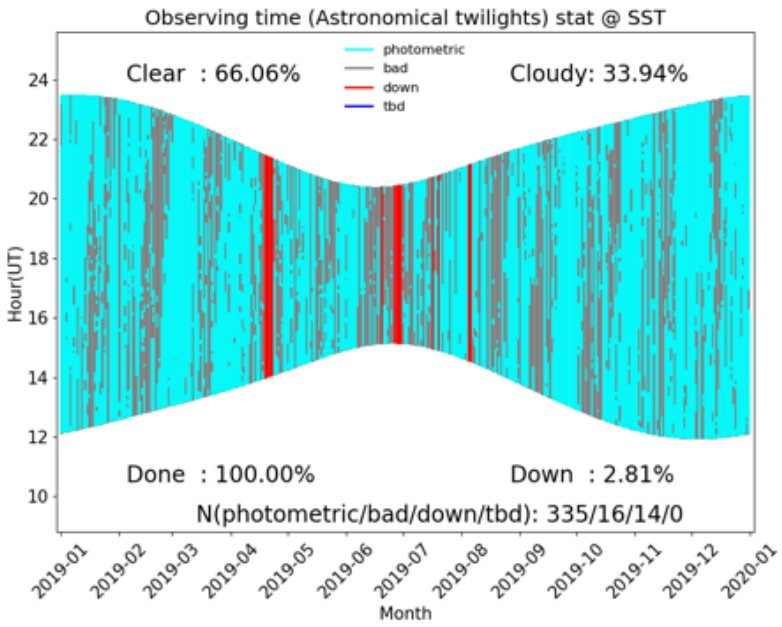


On the top of Saishiteng mountain near the town of Lenghu, Qinghai province. The site is located at N38.74 deg and E93.34 deg with an altitude of 4200m.

The nearest international airport in Dunhuang, is 260 km away from Lenghu Town.

Site of WFST



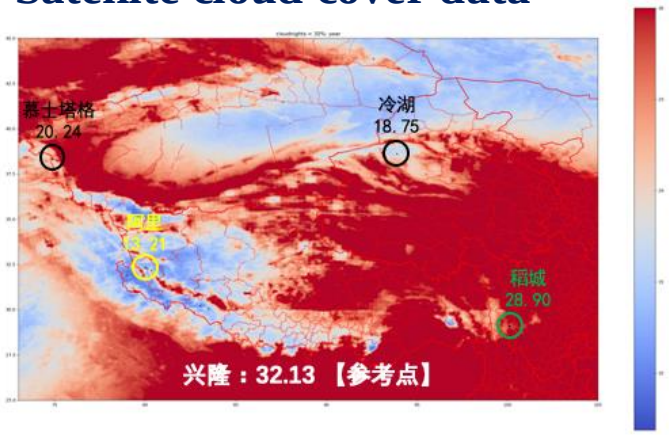


Data Since 2018:

- The median seeing is 0.76″
- The observable nights are 75% (clear 66%)
- The median night sky background is 22.3 magV

Deng et al. (2021, Nature)

Satellite cloud cover data



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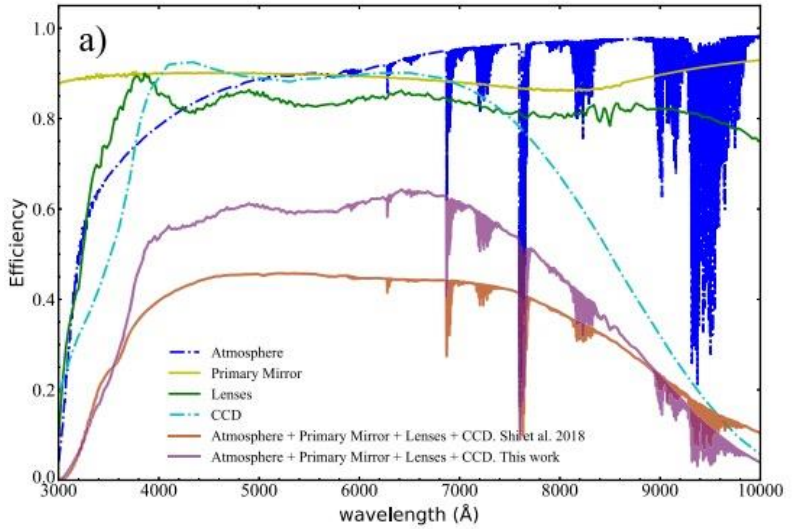
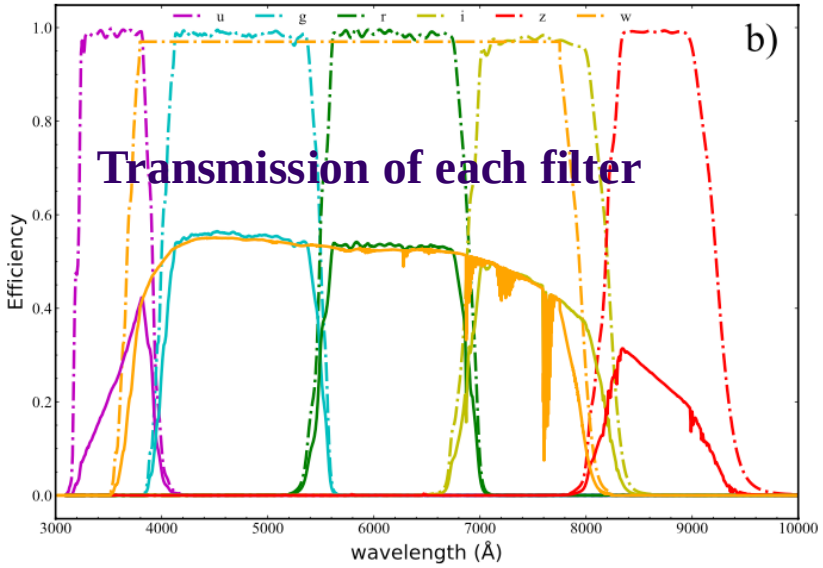
Now

Overall Performance





5σ Limiting Magnitudes of WFST When Airmass = 1.2, Seeing = 0.75 Arcsec, Precipitable Water Vapour (PWV) = 2.5 mm and Moon-object Separation is 45°

Exposure time	Moon Phase	*V* band sky	*u*	*g*	*r*	*i*	*z*	*w*
30 s	0°	22.30	22.31	23.42	22.95	22.43	21.50	23.61
30 s	45°	22.10	22.27	23.30	22.89	22.40	21.49	23.54
30 s	90°	21.29	22.04	22.86	22.62	22.26	21.43	23.23
30 s	135°	20.28	21.64	22.34	22.21	21.99	21.31	22.79
30 s	180°	18.90	20.97	21.62	21.58	21.49	21.00	22.13
100 × 30 s	0°	22.30	24.86	25.95	25.48	24.96	24.03	26.13
100 × 30 s	45°	22.10	24.82	25.84	25.42	24.93	24.02	26.06
30 × 100 s	90°	21.29	24.58	25.38	25.14	24.78	23.96	25.74
100 × 30 s	135°	20.28	24.17	24.85	24.72	24.51	23.83	25.30
100 × 30 s	180°	18.90	23.48	24.12	24.09	24.01	23.51	24.64
30 s	0°	22.00	22.26	23.32	22.83	22.30	21.37	23.47
30 s	45°	21.80	22.21	23.19	22.77	22.28	21.37	23.40
30 s	90°	20.99	21.95	22.74	22.48	22.12	21.29	23.09
30 s	135°	19.98	21.52	22.19	22.07	21.85	21.18	22.64
30 s	180°	18.60	20.83	21.47	21.44	21.35	20.86	21.99
100 × 30 s	0°	22.00	24.81	25.85	25.36	24.83	23.90	25.99
100 × 30 s	45°	21.80	24.76	25.72	25.30	24.80	23.89	25.92
100 × 30 s	90°	20.99	24.48	25.25	25.01	24.65	23.83	25.60
100 × 30 s	135°	19.98	24.05	24.71	24.58	24.37	23.70	25.15
100 × 30 s	180°	18.60	23.34	23.98	23.95	23.86	23.38	24.49

ugrizw = [22.31, 23.42, 22.95, 22.43, 21.50, 23.61] (30s exp.)

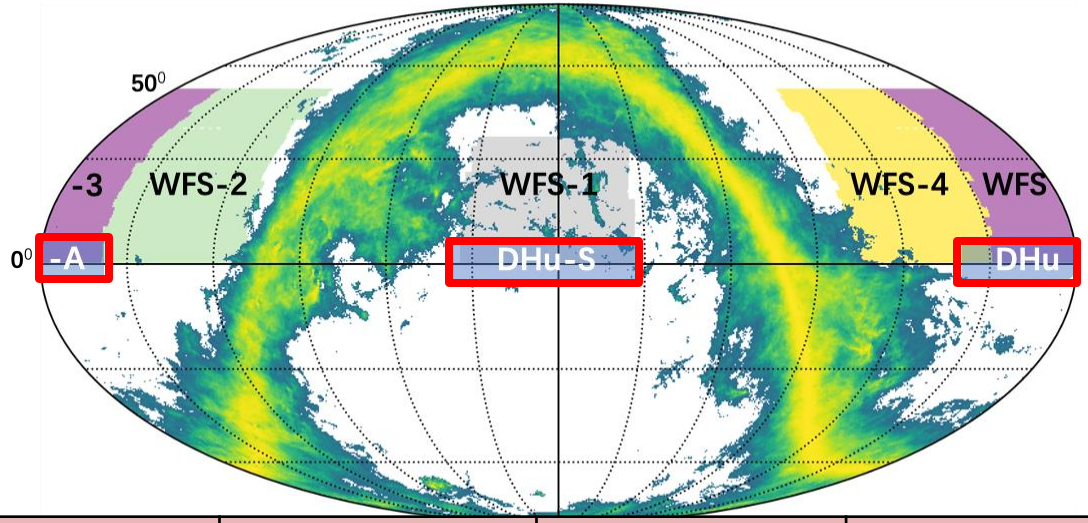
= [24.86, 25.95, 25.48, 24.96, 24.03, 26.13] (50m exp.)

Lei, Zhu, KX et al. (2022)

Strategy of the WFST 6-year Survey

- **Stage-1** (first two years): Wide Field Survey (**WFS**) ~ 45%; Deep High cadence u-band Survey (**DHu**) ~ 45%; **ToO** ~10% (GW/GRB/FRB/ Neutrinos/SN/ TDE et al., co-observation with **EP,SVOM** and…)

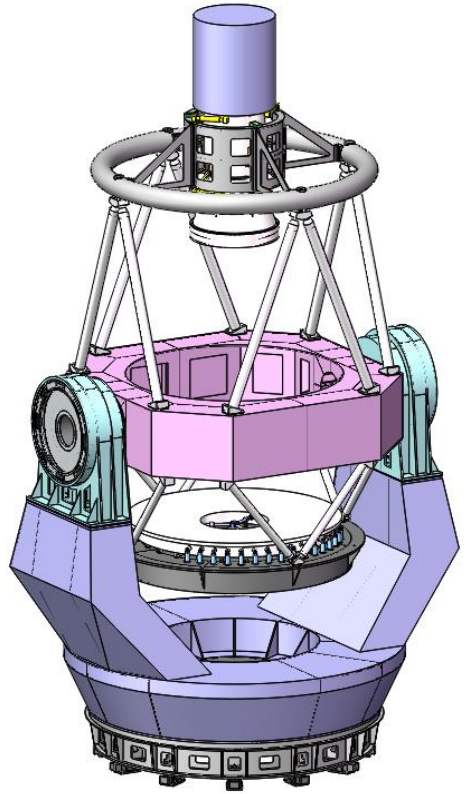
- **From the 3rd year**, time for **WFS will be increased** (45% → 49% → 55%); DHu will be decreased



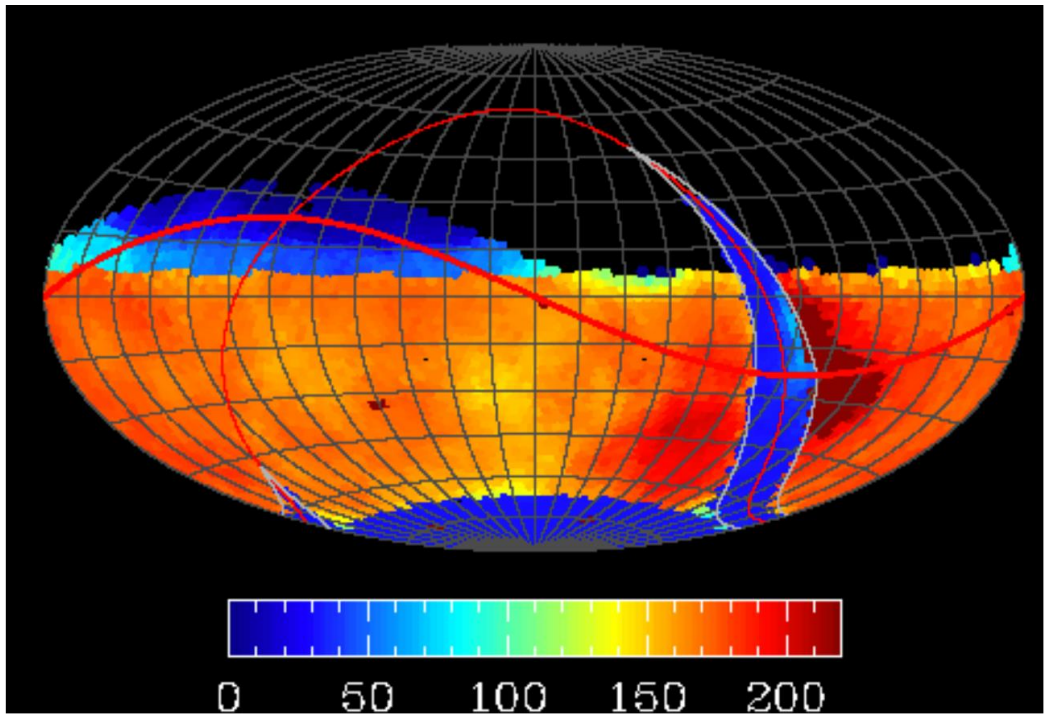
Parameters Surveys	Time Ratio	Observing Schedule	Exp. Time	Total Survey Area (1 yr)	Cadences in one month	Integration Time (1 yr)	Filters
Wide-field Survey	45%	Every observable night (900 sq. deg/night)	30s	8,000 sq. deg (4000*2 semesters)	6.8 times/lunar month in u, g/r	20.25 min in u/gr	2 bands/night
Deep High-cadence u-band Survey	45%	± 9d from the new moon (320 sq. deg/night)	90s (g & r) 90/150s (u)	640 sq. deg (320*2 semesters)	Daily	4.8 hrs in u; 4.0 hrs in g; 2.8 hrs in r; 2.3 hrs in i;	2–3 times in total 2 or 3 bands/night
Small Surveys* (specific targets or regions...)	10%	± 4d from the full moon; twilight; dark/grey nights in Oct–Mar, etc.	-	-	-	-	-

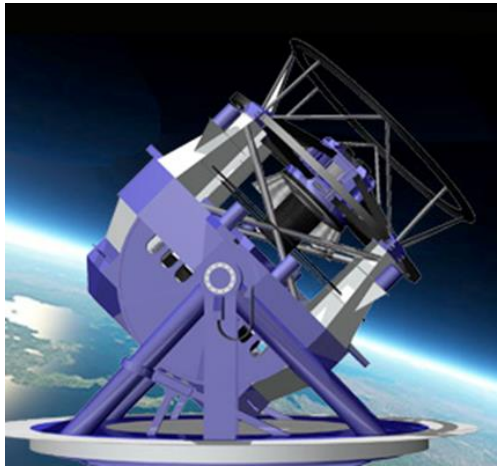
Top-level specifications for WFST

Item	Specifications
Optical Configuration	Prime-focus with corrector lenses
Aperture	2.5 m diameter
Focal Length	6.2 m
Focal Ratio	F/2.48
Field of View	3 deg diameter, 6.55 sq. deg
Etendu	29.3 m^2 deg^2
Wavelength	320 ~ 960 nm (ugriz,w)
Image Quality	Diameter ≤ 0.4 arcsec (80% ee)
Plate Scale	33 arcsec/mm
Pixel size	10μm ×10 μm
# of Pixels	0.765 Giga (0.73G in FoV)
Survey Depth	r ~ 23 @ 30s exposure



Time Domain Optical Imaging Survey in the Northern

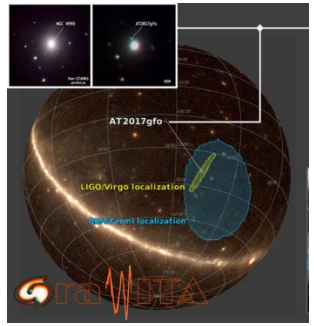




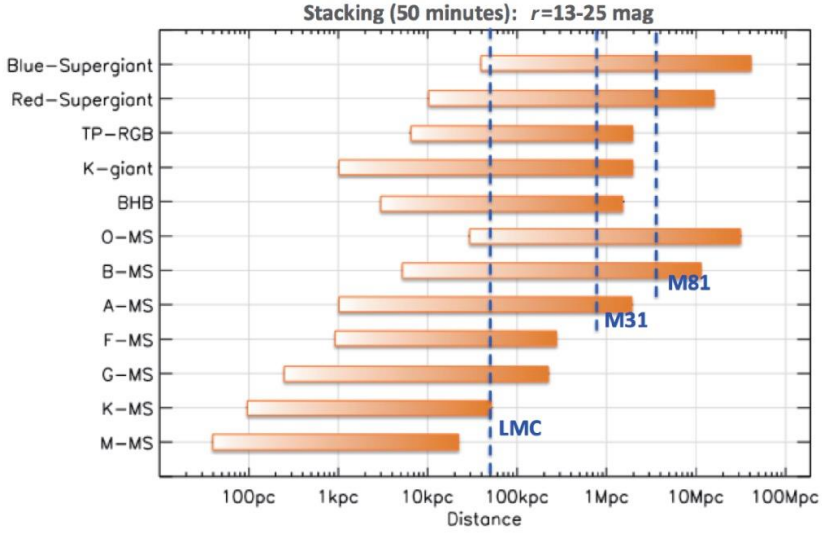
Complementary to LSST latitude and longitude;
Complementary to ZTF longitude.

3. Key Science

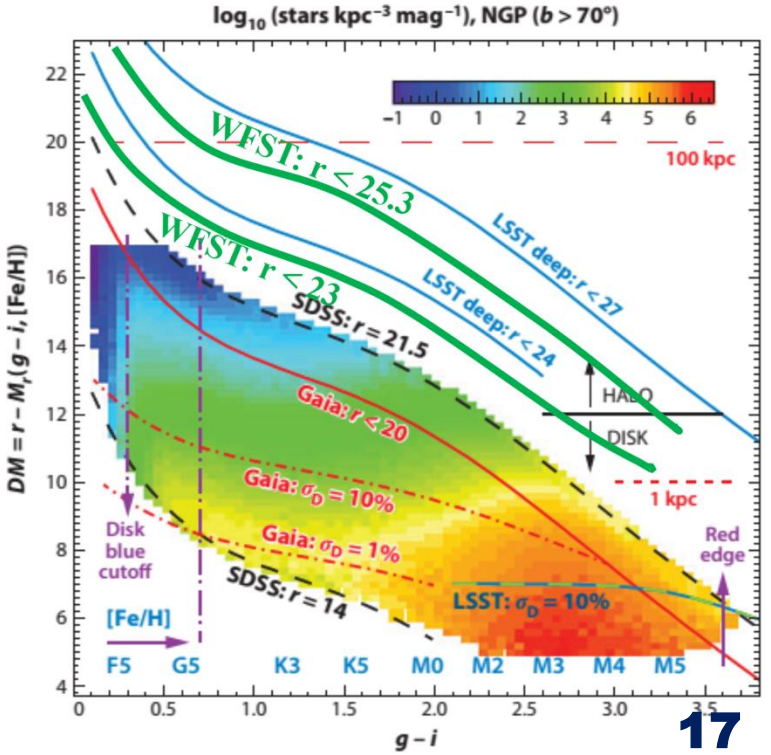
- **New Frontier: Time-domain Astronomy**



- **Taking an inventory of the solar system (NEOs)**
  - **Panoramic view: asteroids, comets, Trojans (Planet X), …**
  - **Search and monitor Near-Earth Objects**
- **Mapping the Milky Way & Local Group (stacking)**
  - **Structure; Formation History; Archaeology in LG**



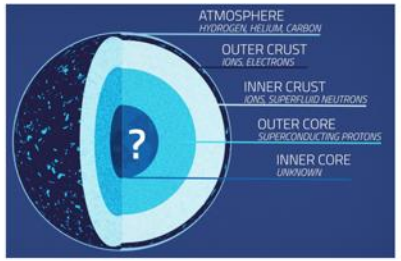
High-precision astrometric and photometric catalogs of objects down to r < 25 mag (image stacking) → disk, halo, clusters, tidal streams, stellar populations, formation and accretion history



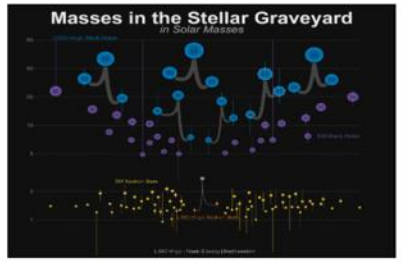
New Frontier： Time-Domain Astronomy

- EMC of Gravitational Events
- Tidal Disruption Events
- Supernova
- Gama-ray Bursts
- Binary of Compact objects
- AGNs
- **Unknown Events**

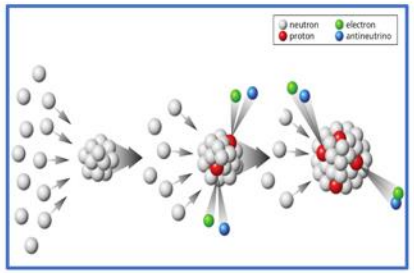
What happens?



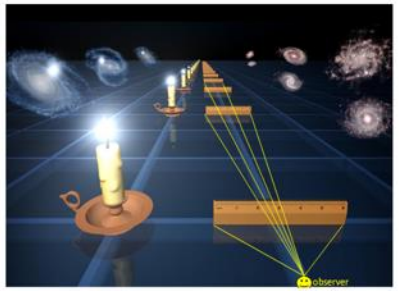
Optical counterparts of GW events

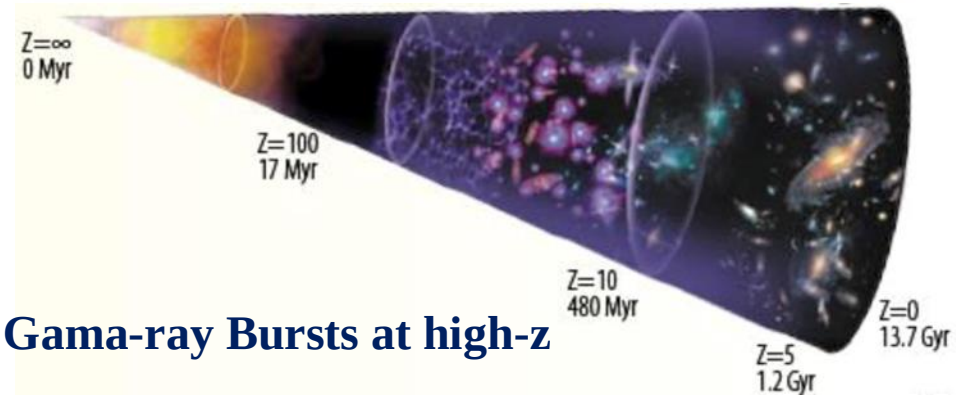


The origin of heavy elements

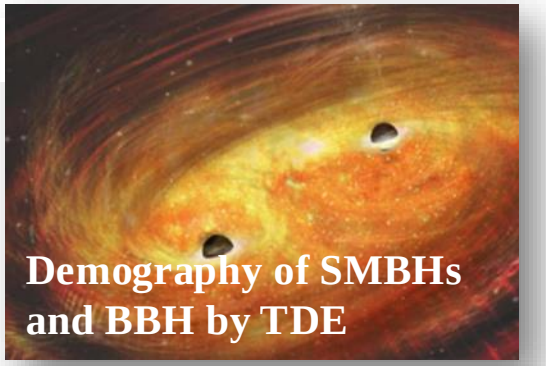


Hubble constant tension





Gama-ray Bursts at high-z

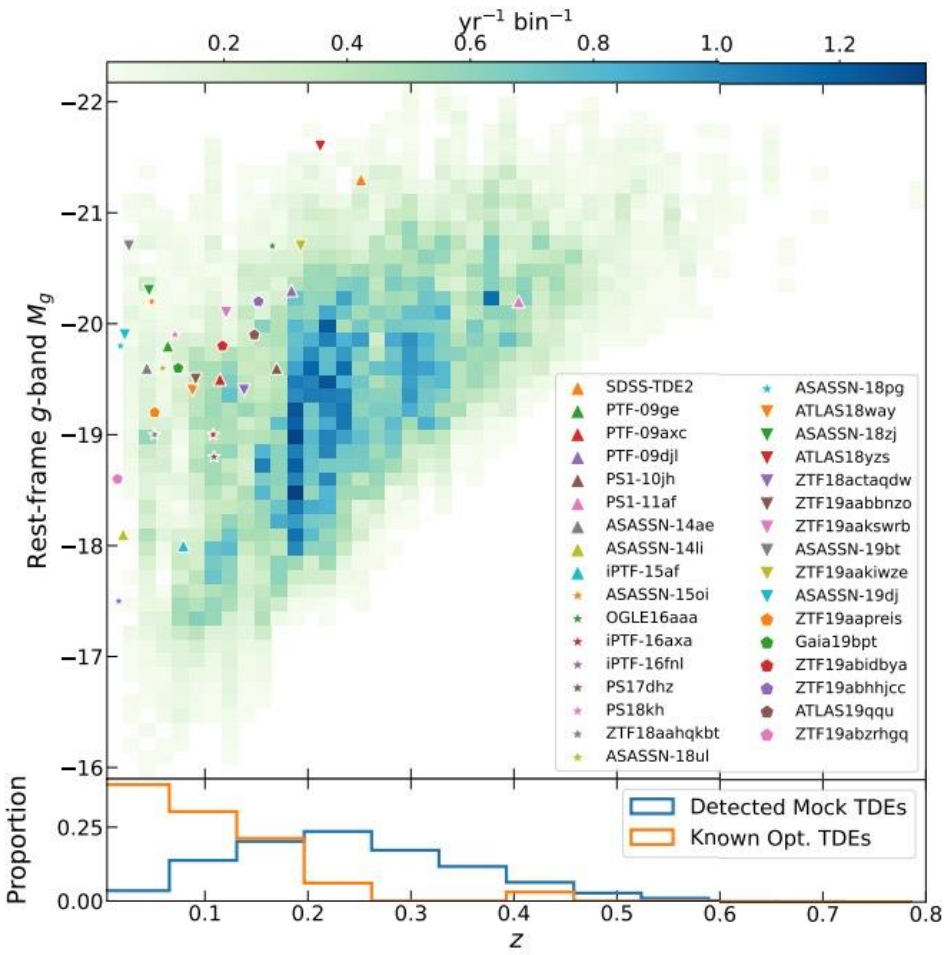


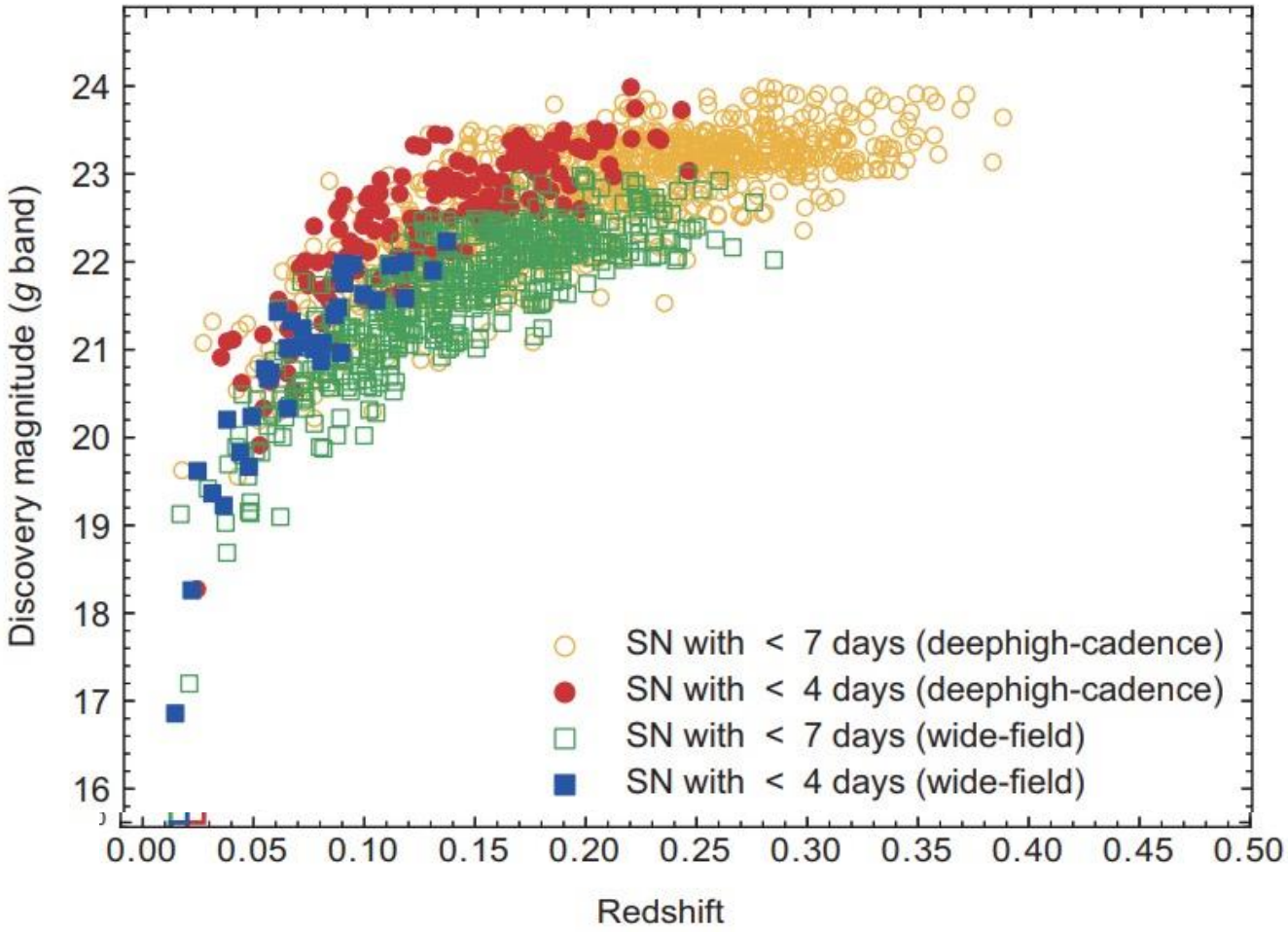
Demography of SMBHs and BBH by TDE

Hunting for IMBHs by TDEs

Shock breakout

TDE & SN search with WFST： Simulation



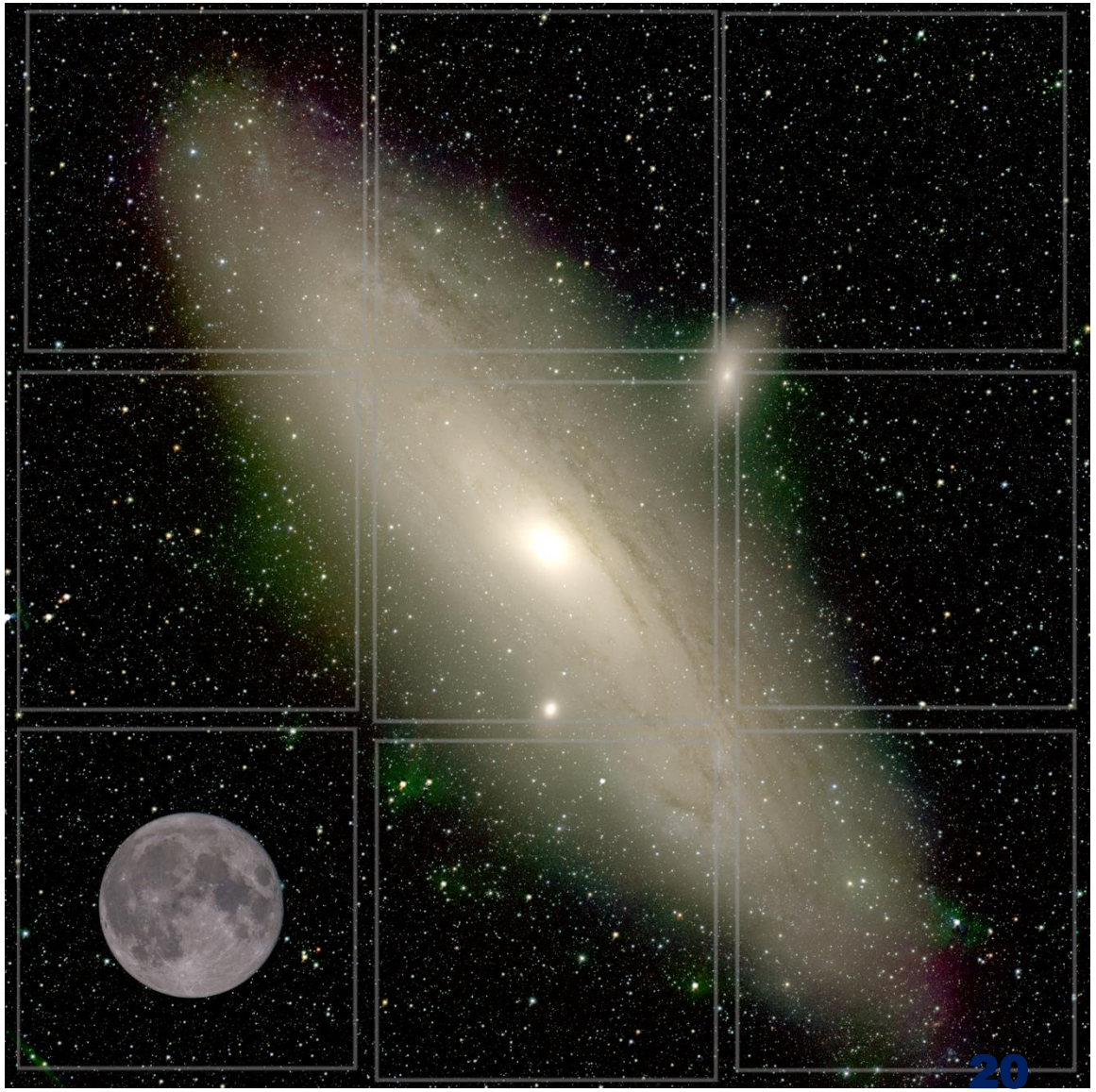


Lin, Jiang, KX (2022, MNRAS): Hundreds of TDEs per year in WFS/DHu

Hu + (2023,Universe): expect to discover more than 1000 SNe Ia per year.

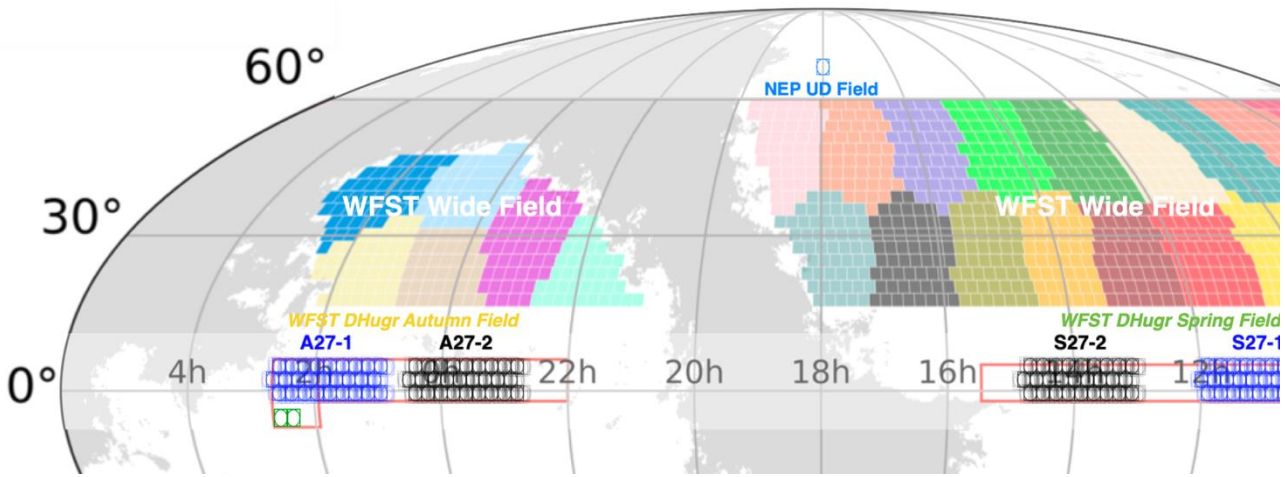
4. Progress of WFST

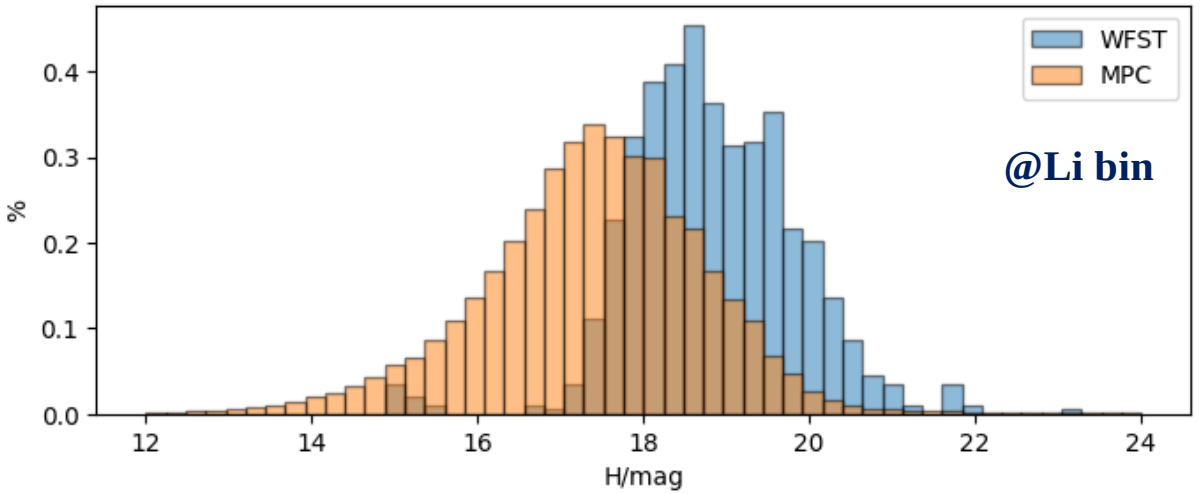
- ¥ 200 million, an joint project by USTC (University of Science and Technology of China) and PMO (Purple Mountain Observatory)
- Schedule: Development, Integration and Commissioning form March 1, 2018 to August 30, 2023
- First light: Sept. 17, 2023, releases the first-light image, high resolution image of M31 (g/r/i-band)
- Pilot survey: March 06–July 10, 2024, for about four months



WFST Pilot Survey: Overview

Projects	DH*ugr*	UD	MP	GW	GRB	IceCube	Globular Cluster	MW Satelite	Variable	Others
Period	Intranight/ Daily	Daily	Daily	ToO	ToO	ToO	Days	Days	Days	Filler/Internal request
Typical Exp time	90s	180s	60s	180s	60/90s	180s	60/90s	30-180s	30s	30-180s





WFTS can detect fainter asteroids.

multi-wavelength images about 300 TB; > 900 supernova candidates, ~ 20 TDE candidates, > 1000 new asteroids have been discovered, including 15 newly discovered near-Earth asteroids.

WFST-PS: Supernova Discoveries

AstroNote 2024-230

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2024-08-28 14:12:42 Type: Announcement-Campaign/Survey Bibcode: 2024TNSAN.230....1J

545 supernova candidates from the WFST pilot survey

Authors: Ji-an Jiang (USTC), Zelin Xu (USTC), Weiyu Wu (USTC), Dezheng Meng (USTC), Zhengyan Liu (USTC), Junhan Zhao (USTC), Ziqing Jia (USTC), Xinzhi Li (USTC), Handan Li (USTC) on behalf of the WFST collaboration

Source Group: WFST

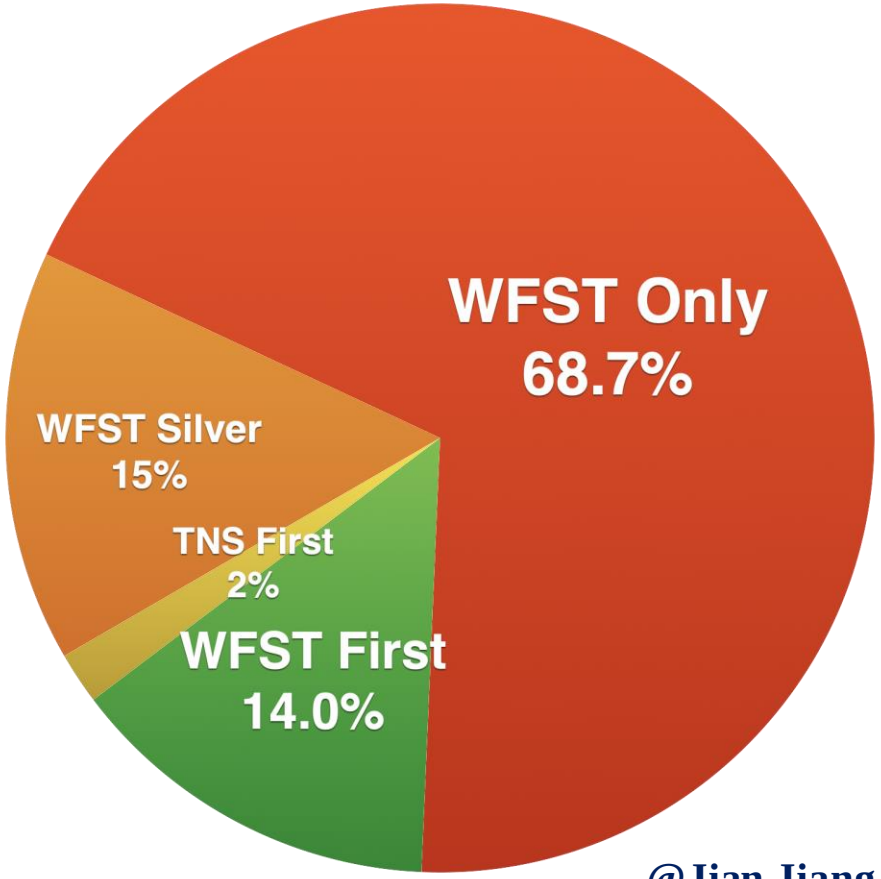
Keywords: Time-domain, Surveys, Transient, Supernova, Photometry, Optical

Abstract: We report 545 supernova candidates discovered by the 2.5-m Wide Field Survey Telescope during a pilot survey from March 6th to July 10th, 2024.

The Wide Field Survey Telescope (WFST), jointly built by the University of Science and Technology of China (USTC) and the Purple Mountain Observatory (PMO), is the largest time-domain survey facility in the northern hemisphere. WFST is characterized by a 2.5-meter primary mirror and a prime-focus camera with a field of view 6.5 square degrees filled with 9 × 9K × 9K mosaic CCD detectors (Wang, T., et al., 2023, SCPMA, 6609512). Data processing is carried out at USTC that combines automatic data reduction with the WFST pipeline, coordinate cross-matching with astronomical catalogs, machine learning image recognition, visual check for promising transient candidates (WFST collaboration, in prep). More information can be found on the WFST homepage.

Here we report 545 reliable supernova candidates (including 13 spectroscopically identified supernovae on TNS) discovered by the pilot survey of the 2.5-m Wide Field Survey Telescope (WFST-PS) from March 6th to July 10th, 2024 (Jiang, J.-a., et al. in prep). After crosschecking with the existing TNS reports, 408 supernova candidates are newly reported* and 120 previously reported SNe/candidates were firstly discovered by WFST. A list of all WFST-PS supernova candidates can be found here.

WFST transient alerts are expected to be issued in real time during the six-year WFST Time-Domain Survey Project from October 2024 (Wang, T., et al., 2023, SCPMA, 6609512). Spectroscopic classifications and follow-up observations of future WFST transients are encouraged.

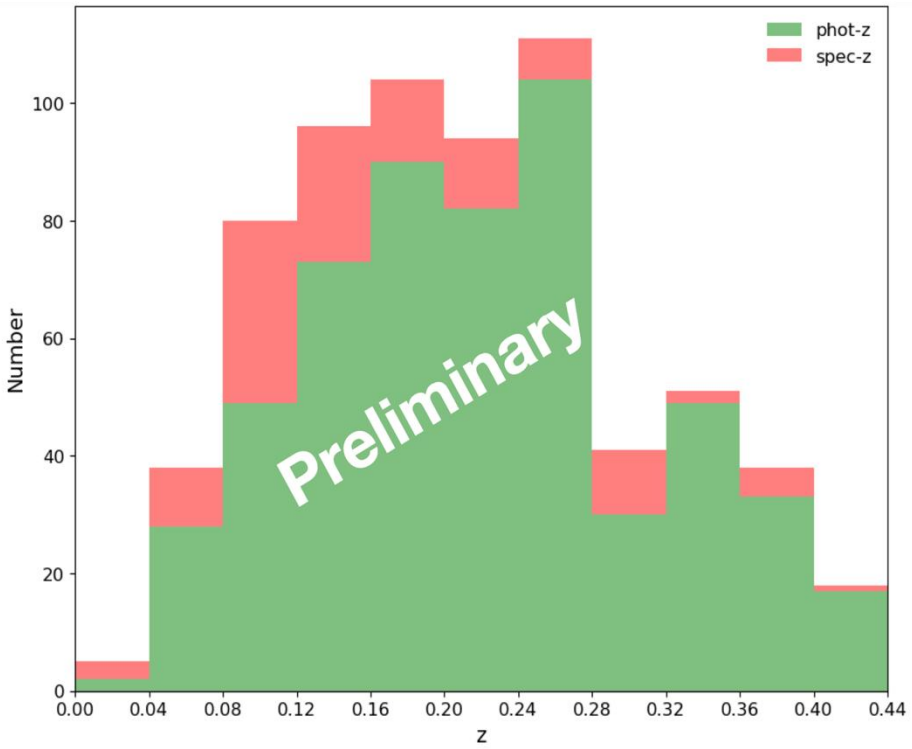


https://www.wis-tns.org/astronotes/astronote/2024-230

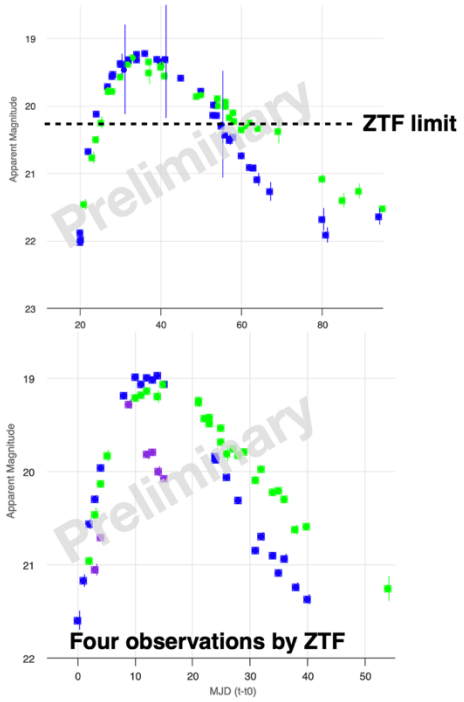
@Jian Jiang

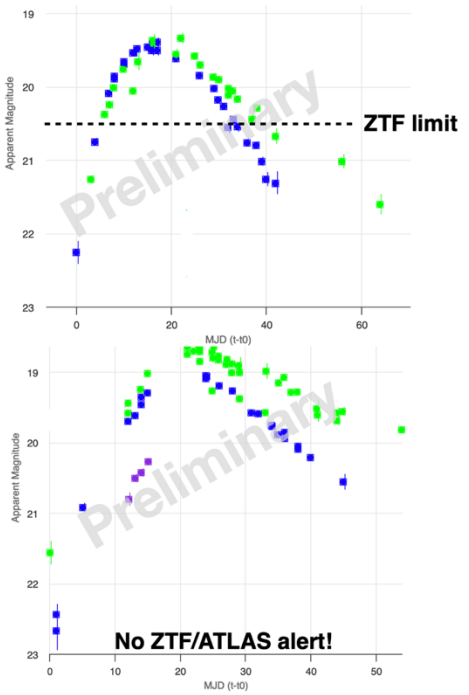
900+ SN candidates have been discovered during WFST-PS!

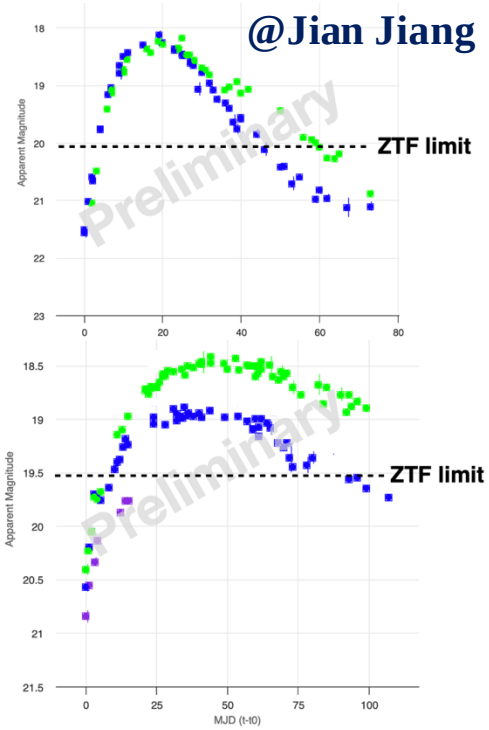
WFST-PS: Supernova Discoveries



Redshift Distribution of WFST-SN







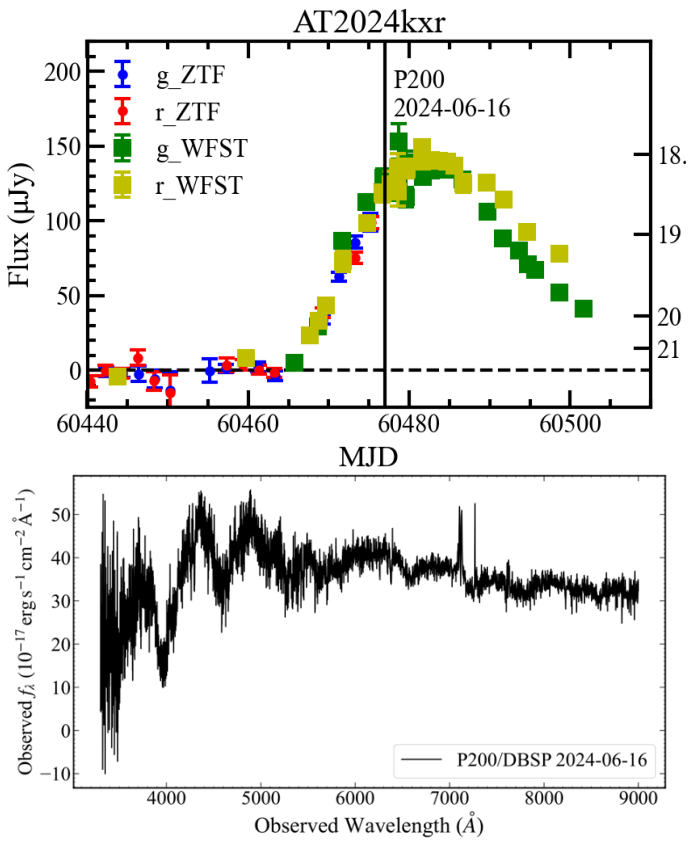
Early-phase Supernovae

Nearly 40 SNe have been discovered within ~ 3 days of the explosion; 10+ superluminous supernova candidates (high-z?) have been discovered.

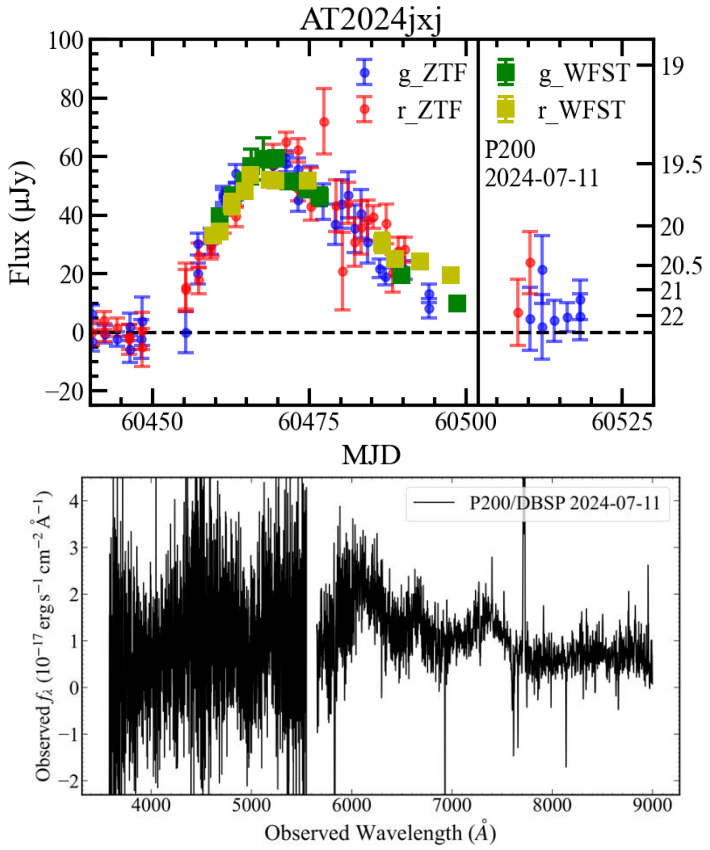
WFST-PS: TDE Search

@Ning Jiang

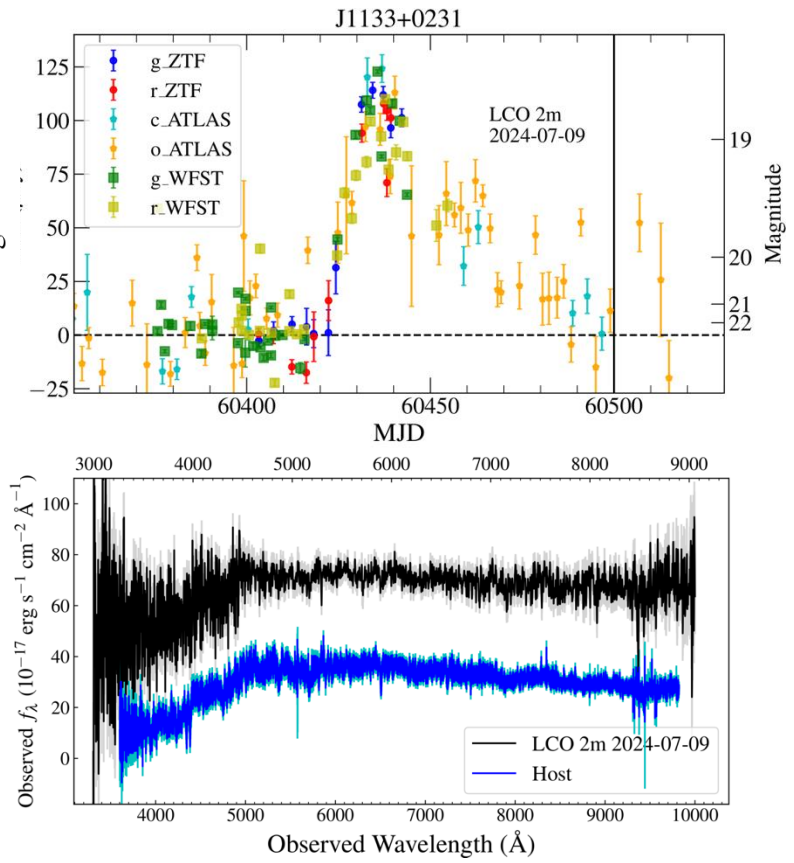
- **TDE Selection**: blue nuclear flares (not AGNs). Need spectra to exclude supernova contamination
- **~20 TDE candidates**: most **without timely spectroscopic** observations due to limited resources !!!



TAP/P200: a SN at z=0.08

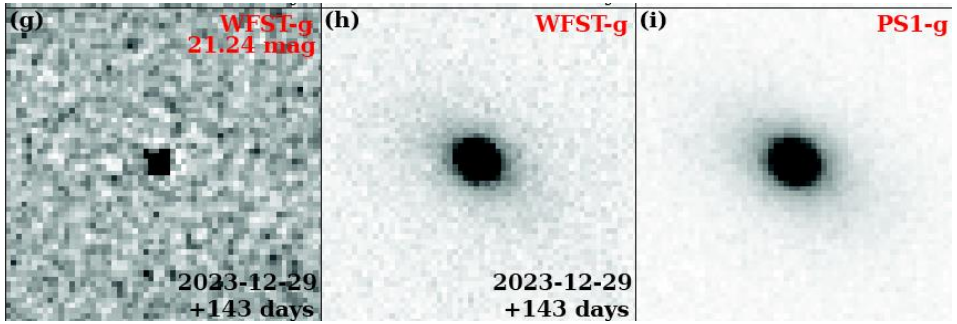


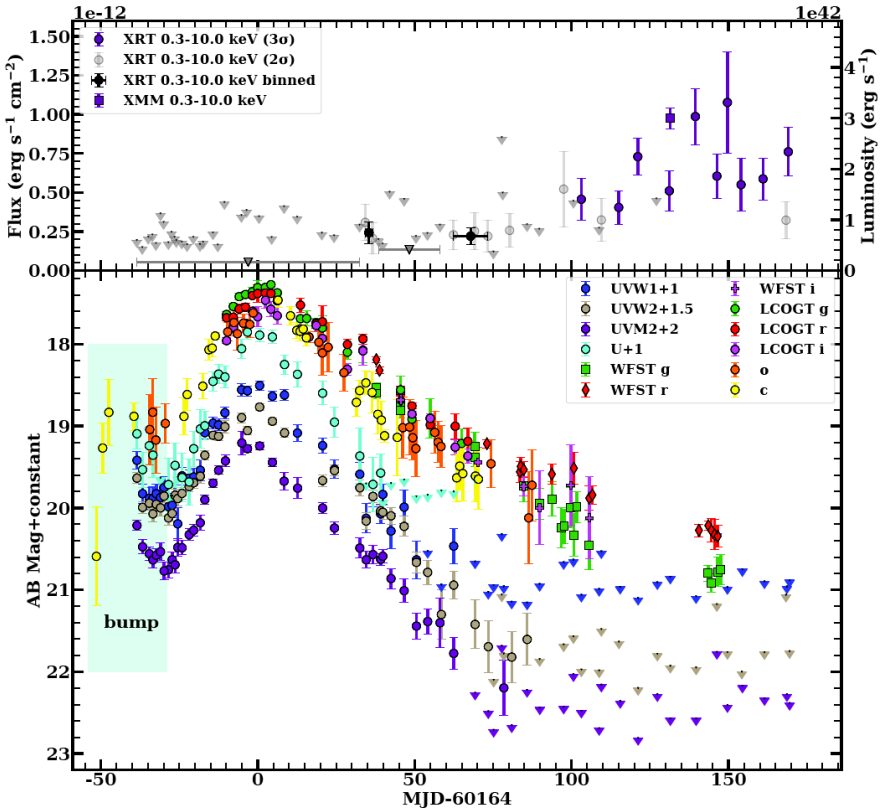
ZTF/P200: a SLSN at z=0.33?



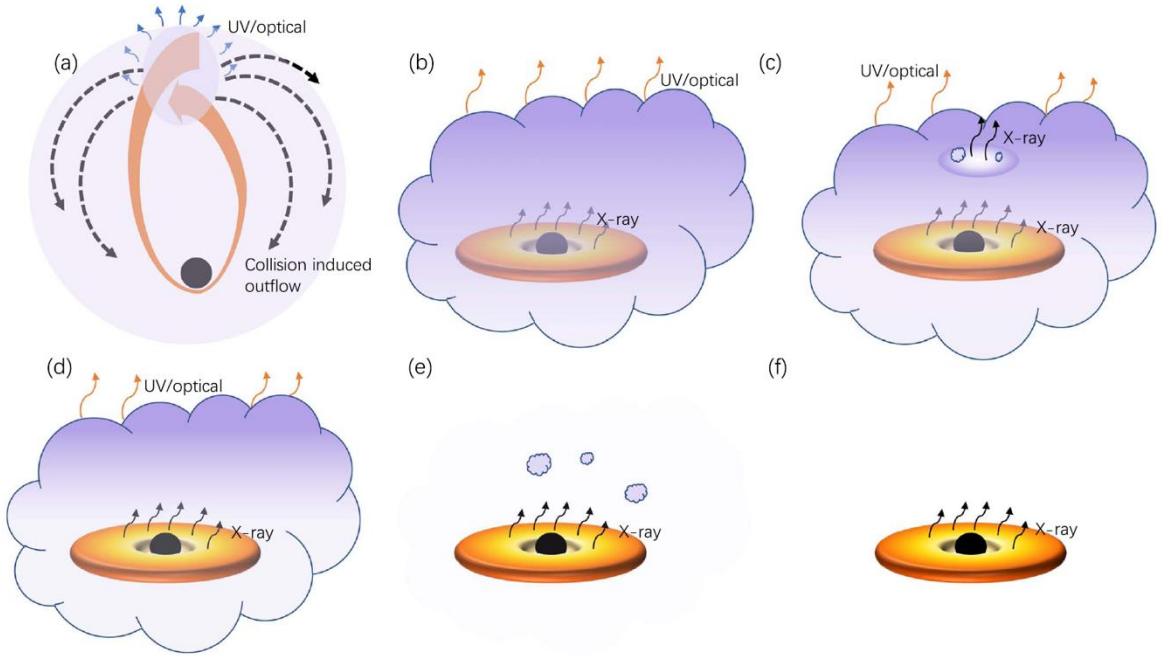
LCO 2m, too low S/N

WFST-PS: TDE AT2023lli





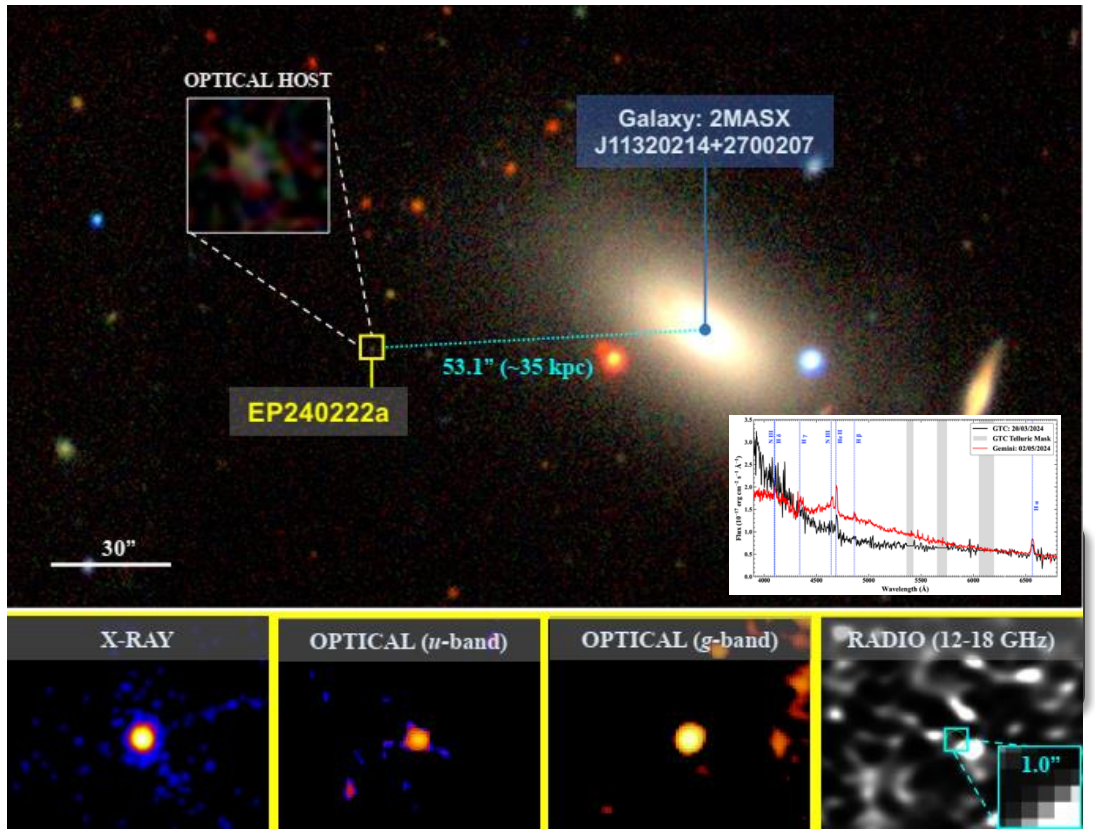
- **New phenomenon**: the most notable **early bump** before optical peak and episodic X-ray emission post peak, giving strong evidence for the two-phase model
- **WFST**: providing the key **late** photometry and revealing the steepest decline rate with aid of its high sensitivity.



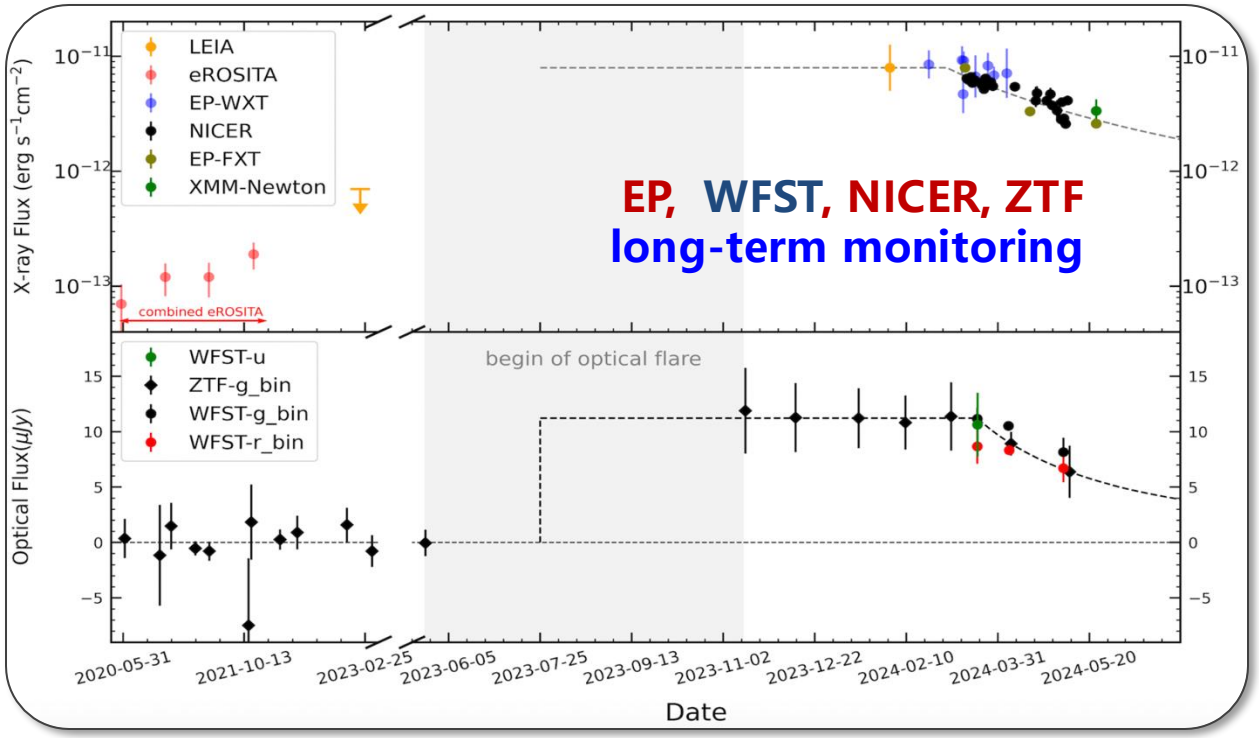
Huang,Jiang+2024,ApJL,964,L22

WFST-PS: Follow-up of IMBH-TDE EP240222a

- Discovered by **EP/WXT** on 2024 March 11: The first **off-center IMBH-TDE** promptly captured.
- **WFST** identifies the **optical counterpart**: coordinate and magnitude (g, Mar.14), color (ugr, Mar. 20), triggering spectroscopic follow-up and successful confirmation (GTC, GEMINI)



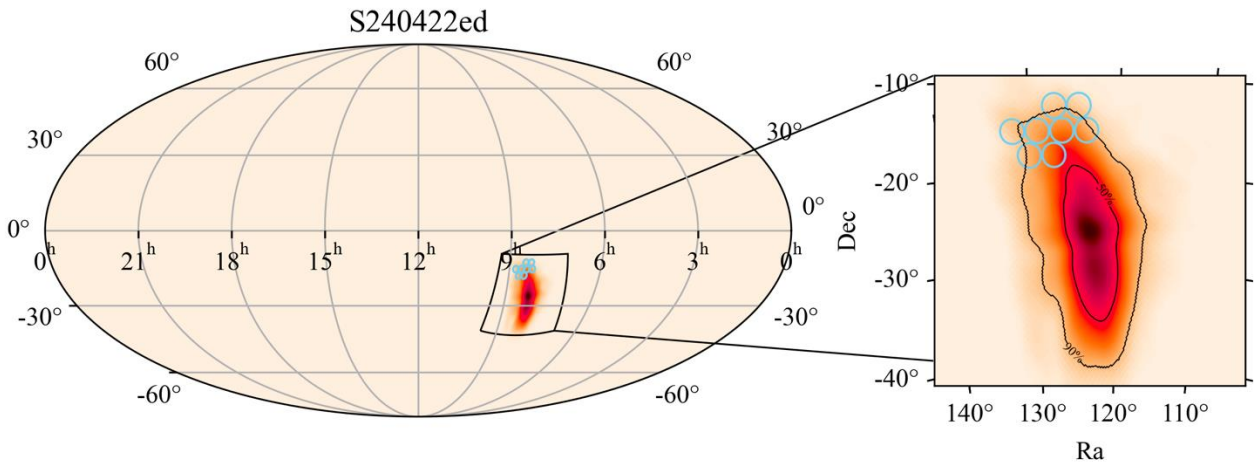
Chandra WFST WFST VLA



Jin et al., 2024, in prep.

WFST-PS: EMC of Gravitational Events

@Wen Zhao

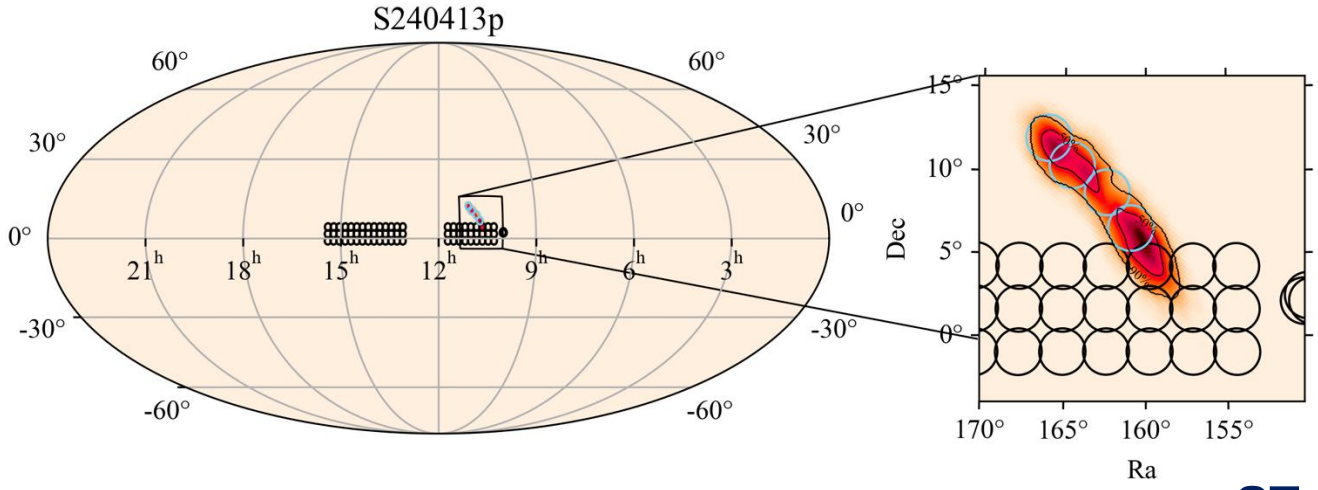


S240422ed (NSBH candidate):

- Observed 8 pointings in the 90% localization region, from Apr. 23-29
- obtained 7 candidates: 4 moving objects; 1 related to stars; 2 residuals of galaxies with z ~0.2
- 0 kilonovae!

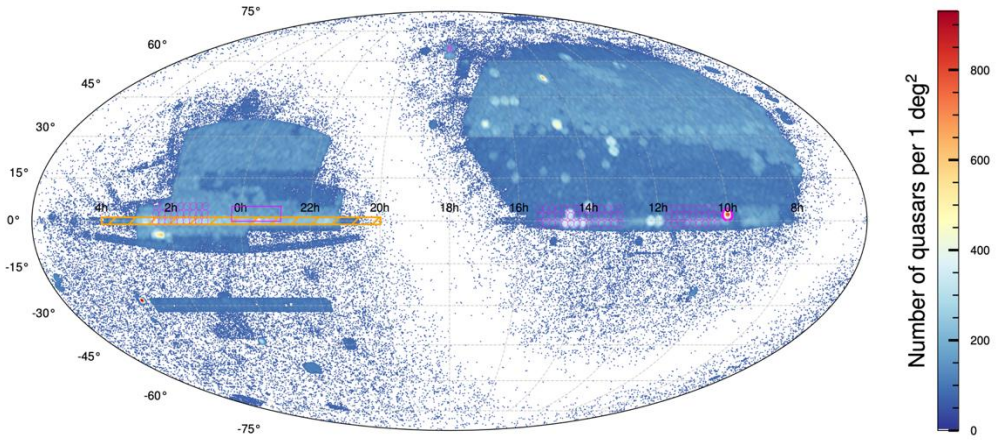
S240413p (BBH candidate):

- Survey the region for 3 months [11 deg^2 (50%) 34 deg^2 (90%)].
- Selection and Filtering： 5049 AGNs in surveying area.
- No EM counterparts!

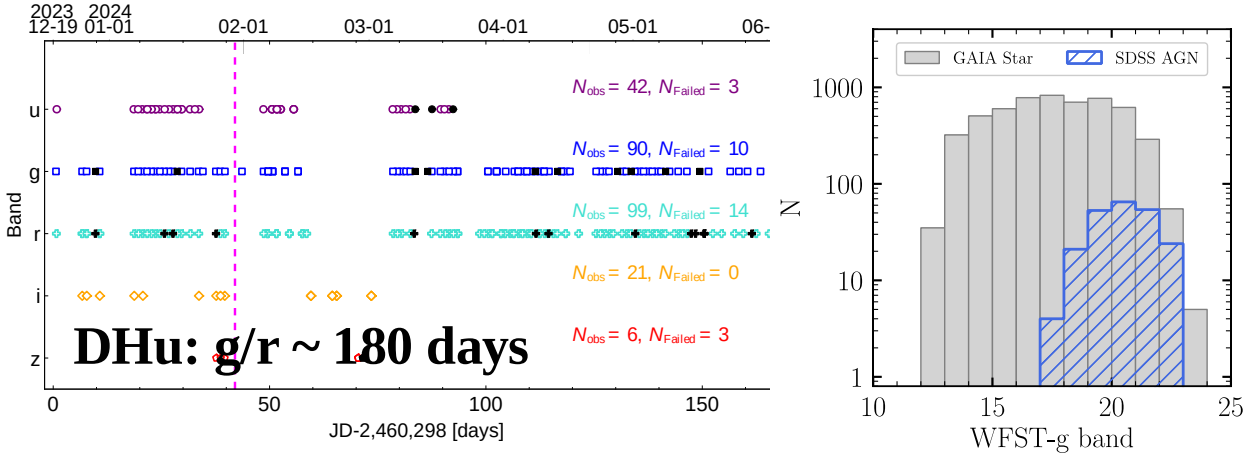


WFST-PS: AGNs (DHu + NEP + COSMOS…)

@Zhengyi Cai



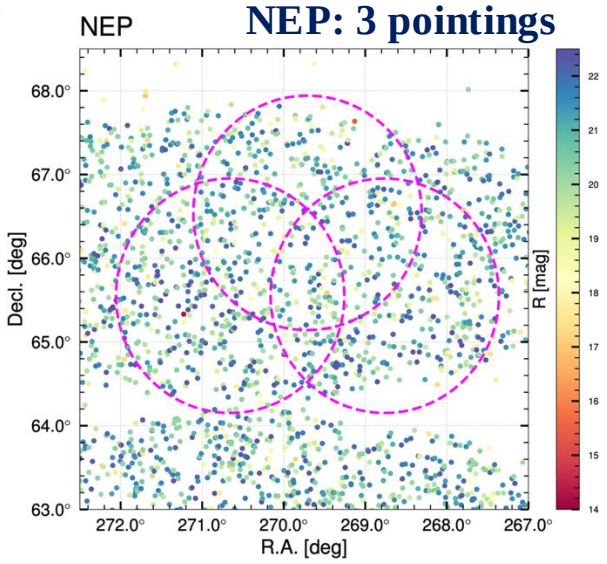
Distribution of million quasars



1 pointing: "Invariable" STAR: 5589; Variable AGN: 221

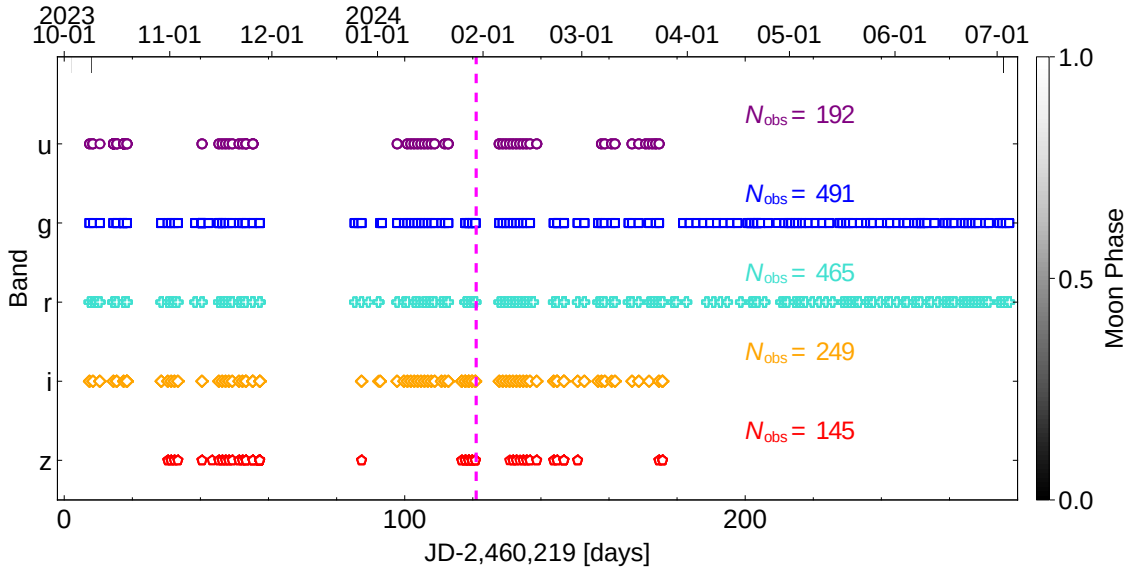
WFST PS	$m_r < 22.5$ AGN	t_{exp} (s)	Band	Cadence	Baseline (m/yr)	Archive Data	AGN scientific goals
~640 deg² DHu	~21,000	90	(u)gr(i)	~ d	~ 6	SDSS, PS, ZTF, ...	① Relations between variation and physical properties
~10 deg² NEP	~1000	180	(u)gri	~ hr - d	~ 9	——	② Multi-band variation coordination
~10 deg² COSMOS	~1200	180	(u)gri	~ hr - d	~ 6	multi-band	

WFST-PS: Multi-band variation coordination of AGNs

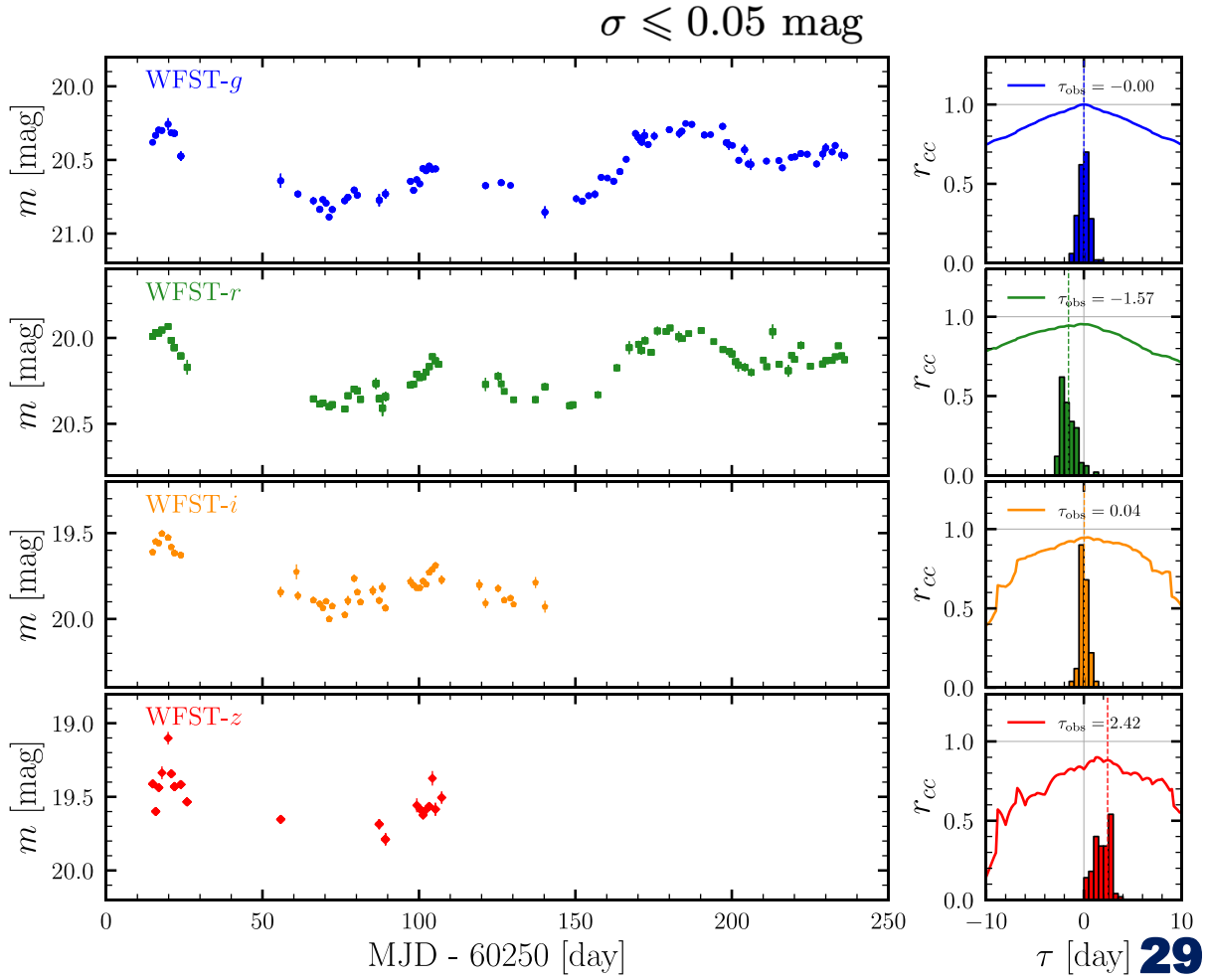


Obs. Times per night	$m_r < 22.5$ AGN No.
1	~ 1000
2	~ 300
3	~ 70

g/r ~ 270 days



WFST will provide daily cadence and precise photometry for a large AGN sample



Summary

WFST is a Powerful Survey Machine in the Northern Hemisphere.

- **High sensitivity**
  - Large collection area (D = 2.5m, no secondary mirror)
  - Less scattering background light
  - High u-band throughput + high-altitude site: @ 4200m
- **High quality imaging** (seeing-limited)
  - With atmospheric dispersion corrector (ADC)
  - With distortion corrector (distortion < 0.1% at edges)
  - Homogeneity of image quality (80% < 0.4")
- **High Survey Power**
  - AΩ = 29.3 (Pan-STARRS1: 13.5, SDSS: 5.9/25.3, LSST: 308)
  - Survey speed 6000□°/night @ 30s exposure.

Looking for International collaboration, especially follow-up spectral observation cooperation

Thank you for your attention!

Science with the 2.5-meter Wide Field Survey Telescope (WFST): https://arxiv.org/pdf/2306.07590