Multi-channel Photometric Survey Telescope -- MEPHISTO

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Partners:

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Yunnan Observatories, Chinese Academy of Sciences
Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences

MEPHISTO in one sentence

- **MEPHISTO, a multi-channel survey telescope, first of its type in the world, will deliver real-time, high-quality colours of unprecedented accuracy for celestial objects, enable fast and robust classification of transients and variables, and deliver a panchromatic documentary of our evolving universe.**

Outline

- Motivations
- Telescope & cameras
- Surveys and data products
- Selected science topics
- Summary

Introduction

(Digital) Large-scale astronomical surveys with large format CCD mosaic play a key role in modern astrophysics, leading to new discoveries and revolutionizing our understanding of cosmic origin and evolution.

Name	Aperture (m)	FOV (sq deg)	Filter set	Limiting magnitude	Sky area	Hemi-sphere	First Light	Time domain
SDSS	2.5	1.5	*ugriz*	22 *(r)*	15000	N	Complete	NO
XSTPS-GAC	1.2	3.76	*gri*	19 *(r)*	7000	N	Complete	NO
PS1	1.8	7.0	$(grizY)_{P1}$	22.8 *(r)*	30000	N	Complete	YES
Gaia	1.0	0.45	*G*	20 *(G)*	41000	NS	2014	YES
Skymapper	1.35	5.2	*uvgriz*	22.6 *(r)*	20000	S	2014	YES
ZTF	1.2	47.0	*gr*	20.4 *(r)*	30000	N	2017	YES
LSST	8.4	9.6	*ugrizy*	27.7 *(r)*	20000	S	2021	YES
MEPHISTO	1.6	3.14	*uvgriz*	22.7/24.8 *(r)*	26000	N	2021	YES

SDSS
5 bands in sequence/once

LSST
6 bands in sequence/week

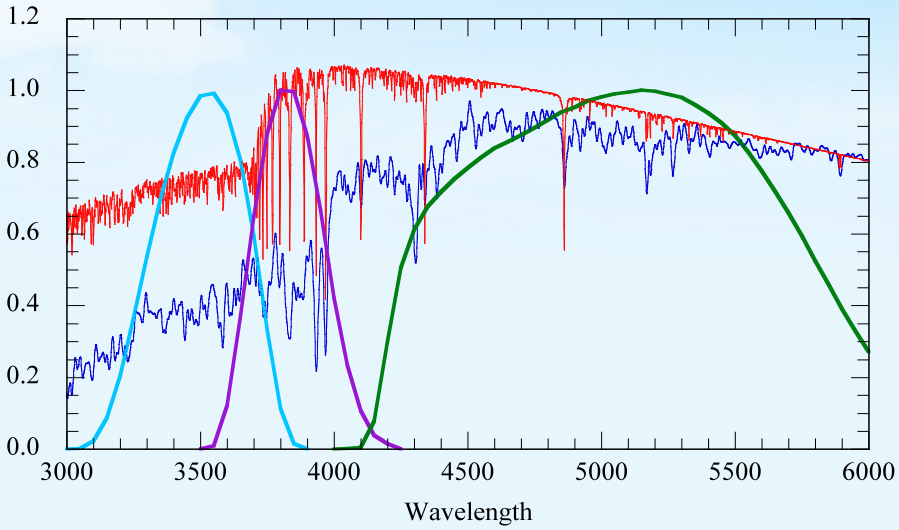
MEPHISTO
2×(3 bands simultaneously)/week

Snapshots → Monochromatic documentary → Coloured documentary

The power of colours

Colours:

- **Physical quantities ($T_{\rm eff}$, log g, [Fe/H] ……)**
- **Fast &robust identification & classification of transients**



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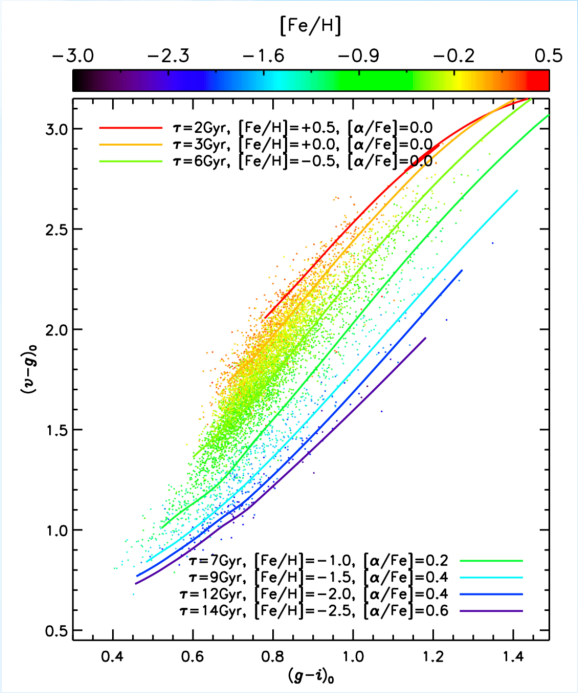
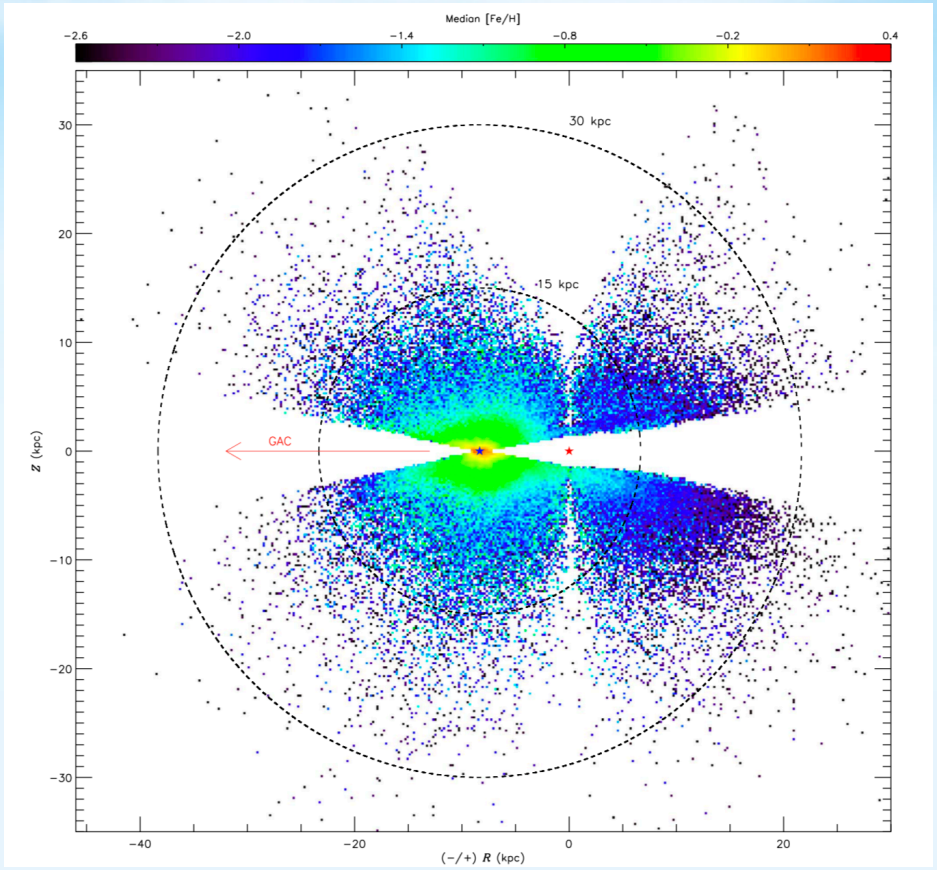


Huang et al. 2019



The power of colours

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- **Fast &robust identification & classification** of transients

Transient Alerts in LSST

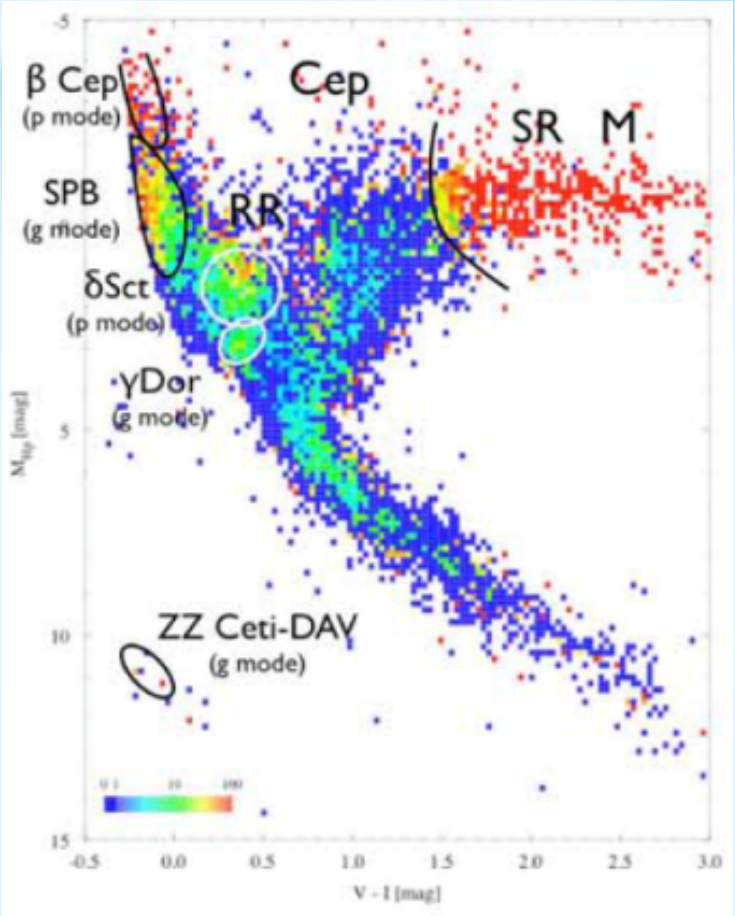
~10 M/night

Jeffrey Kantor
Large Synoptic Survey Telescope

1 Introduction

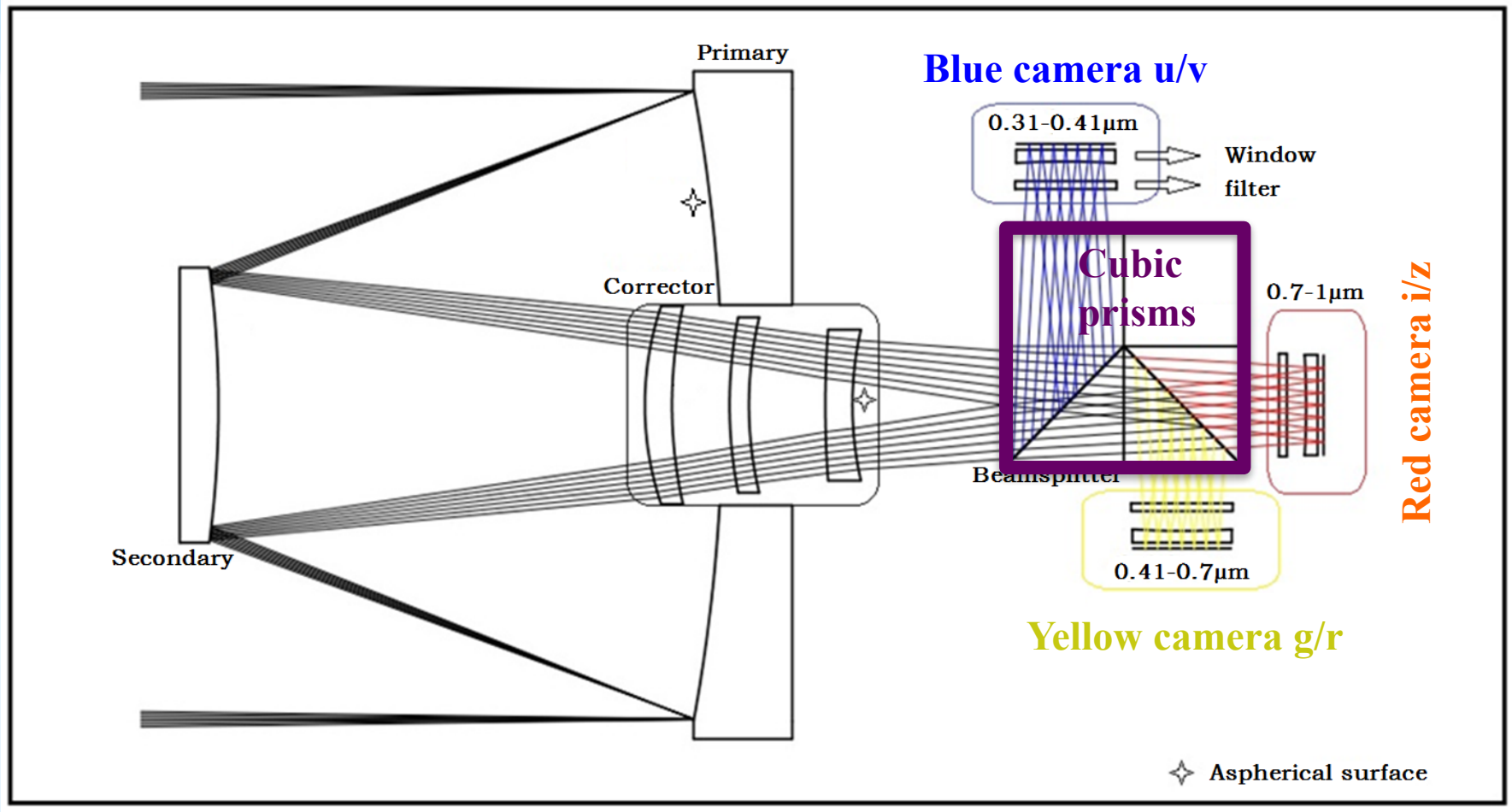
During LSST observing, transient events will be detected and alerts generated at the LSST Archive Center at NCSA in Champaign-Illinois. As a very high rate of alerts is expected, approaching 10 million per night, we plan for VOEvent-compliant Distributor/Brokers (http://voevent.org) to be the primary end-points of the full LSST

Variable objects (Flux changes)	Moving objects (Position changes)
Variable stars	Planets
Eclipsing binaries	Asteroids
Transits of extrasolar planets	Comets
Galaxies	Trans-Neptunian objects
AGN	
Burst (optical)	



MEPHISTO light path

- Ritchey-Chretien (RC) system with correctors: Large FOV
- Cubic prisms for beam-splitting: Multi-channel + High imaging quality



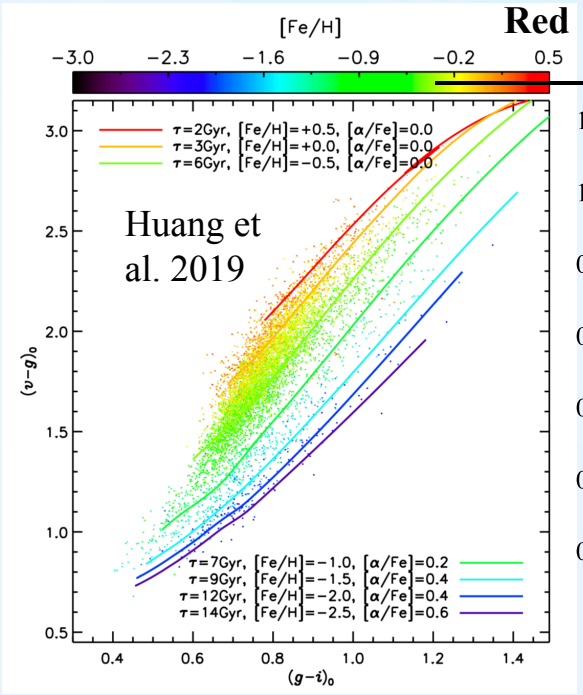
Main specifications

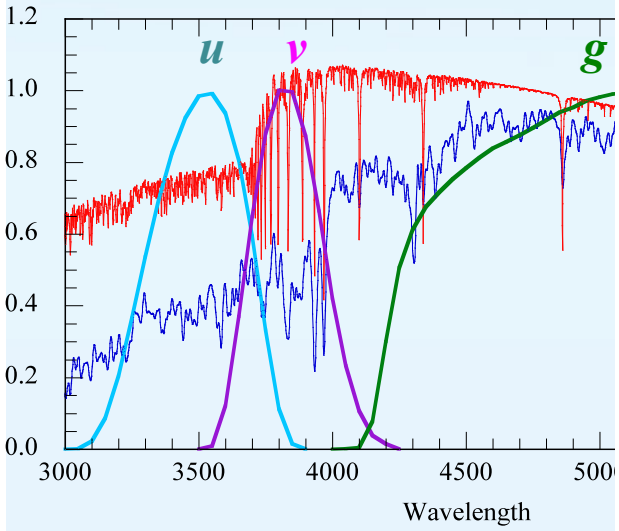
Quantity	Design
Aperture	1.6 m
Field of view	Ø252.5 mm/7200 mm [Ø 2 deg; 3.14 square deg]
Wavelength	[0.32~0.413], [0.413~0.700], [0.700~1.0] μm
f number	F#: 4.5
Primary Mirror	D1600 mm
Image quality	80% EE < 0.6"
Scale	10 um/pixel ~ 0.3"
Polar axis range	±175°
Declination axis range	−30° ~ 90°
Pointing accuracy	< 10" (RMS)
Tracking accuracy	< 0.3" (RMS)

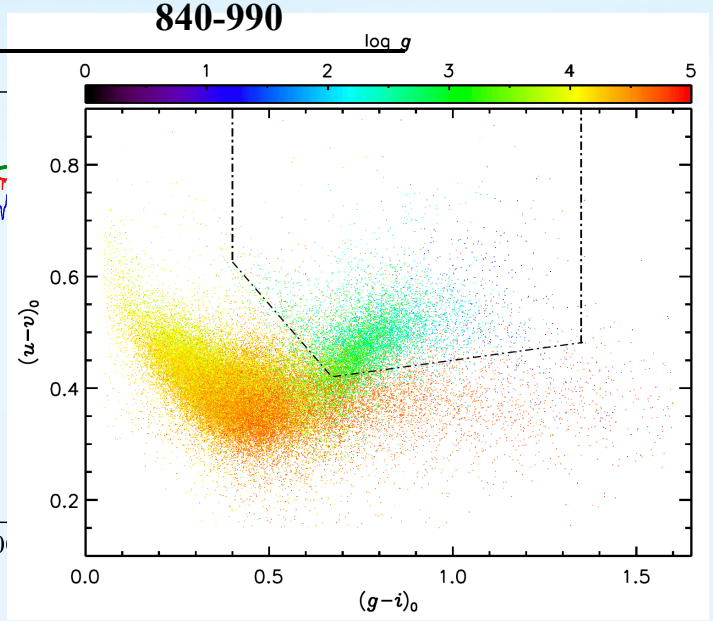
Band-passes

- **Filter set similar to Skymapper – *uvgriz***
- **Optimized for stellar/galactic astrophysics, allowing precise parameter determinations (T_{eff}, log *g*, [Fe/H]…) for stars and stellar populations**

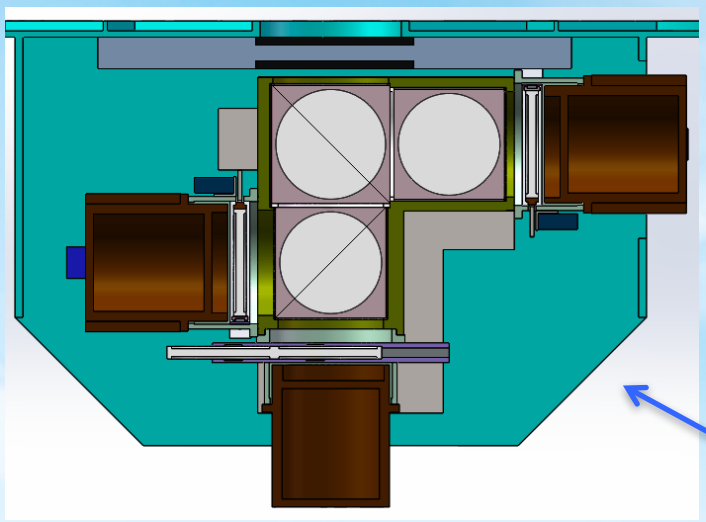
Channel	Filters	λ_c(nm)	λ-range (nm)
Blue	*u*	342	320-365
	v	385	365-405
Yellow	*g*	525	450-600
	r	625	550-700
Red	*i*	770	700-840
	z	915	840-990

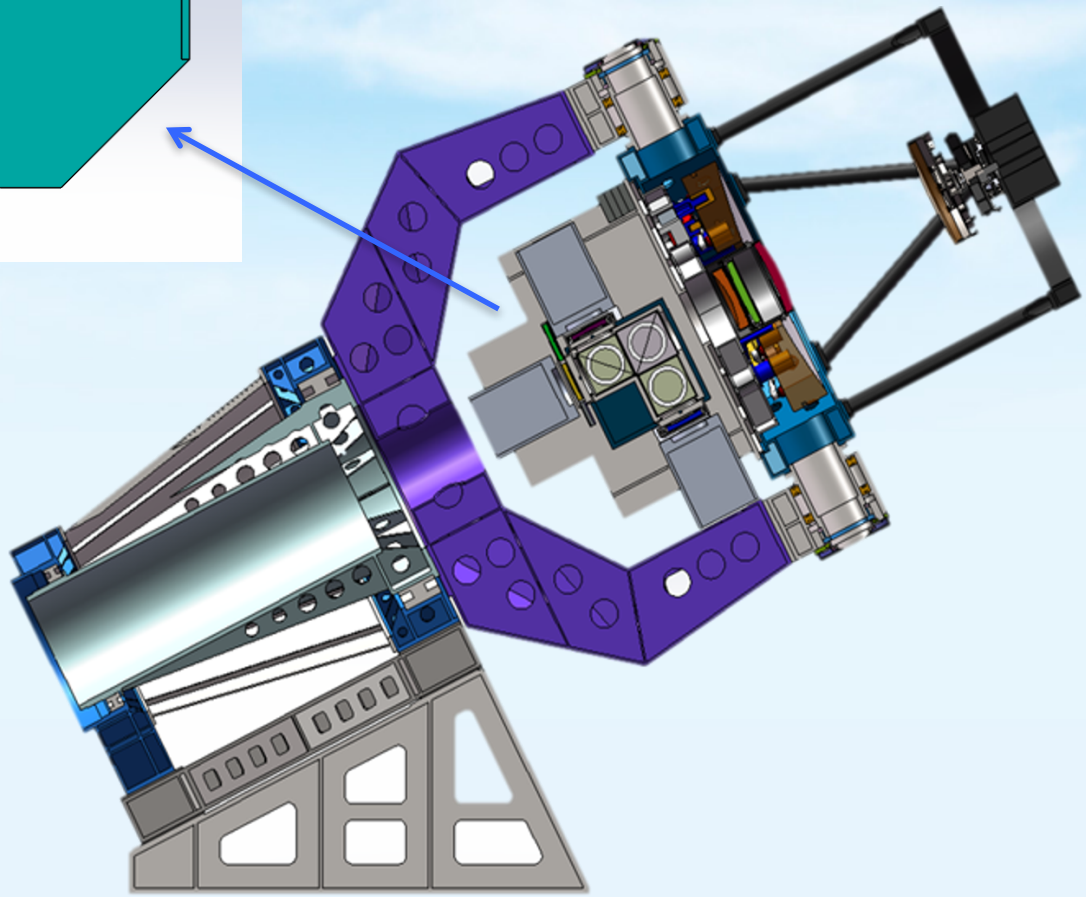




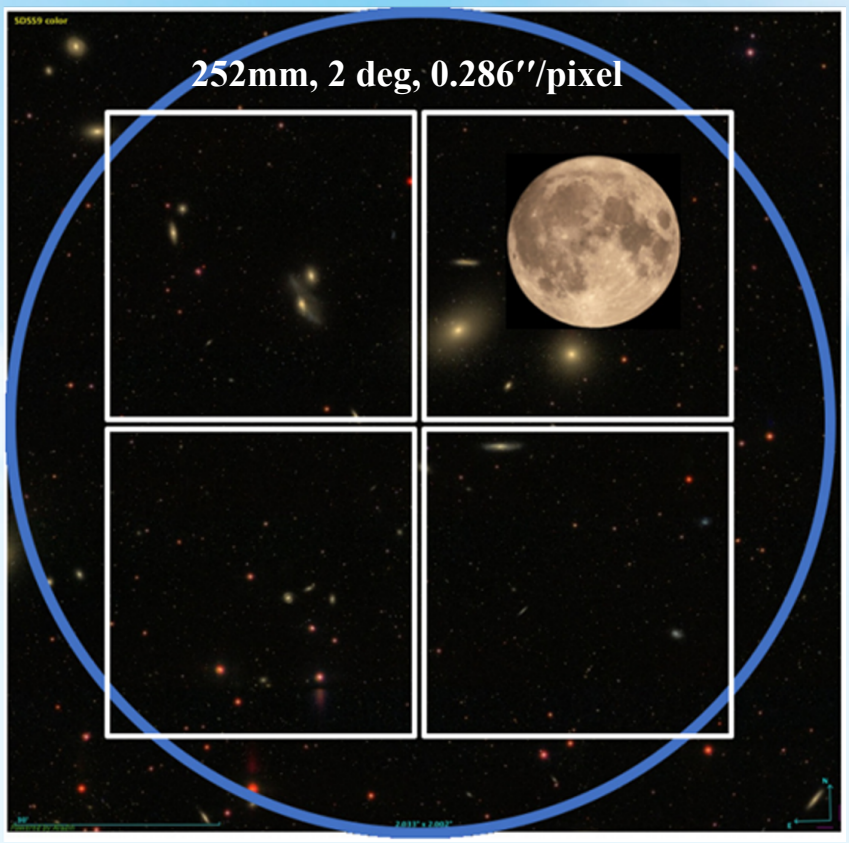


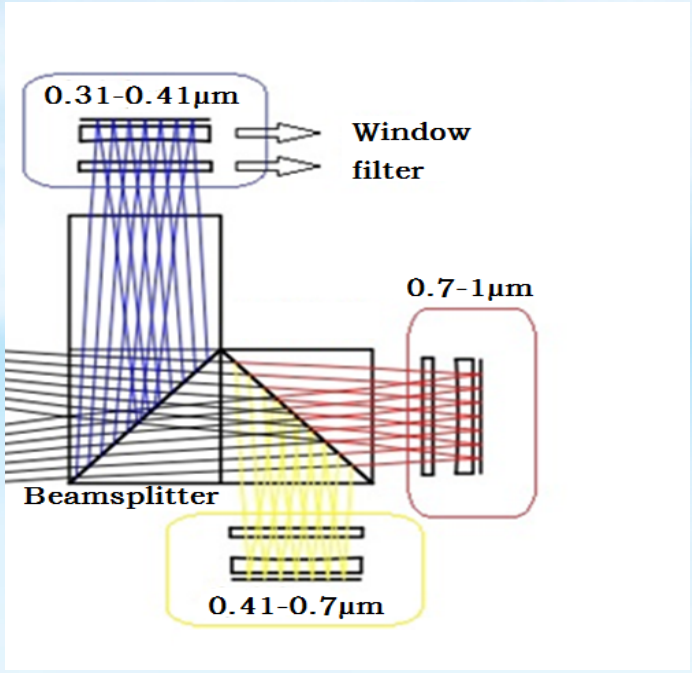
Focal plane assembly





The focal plane





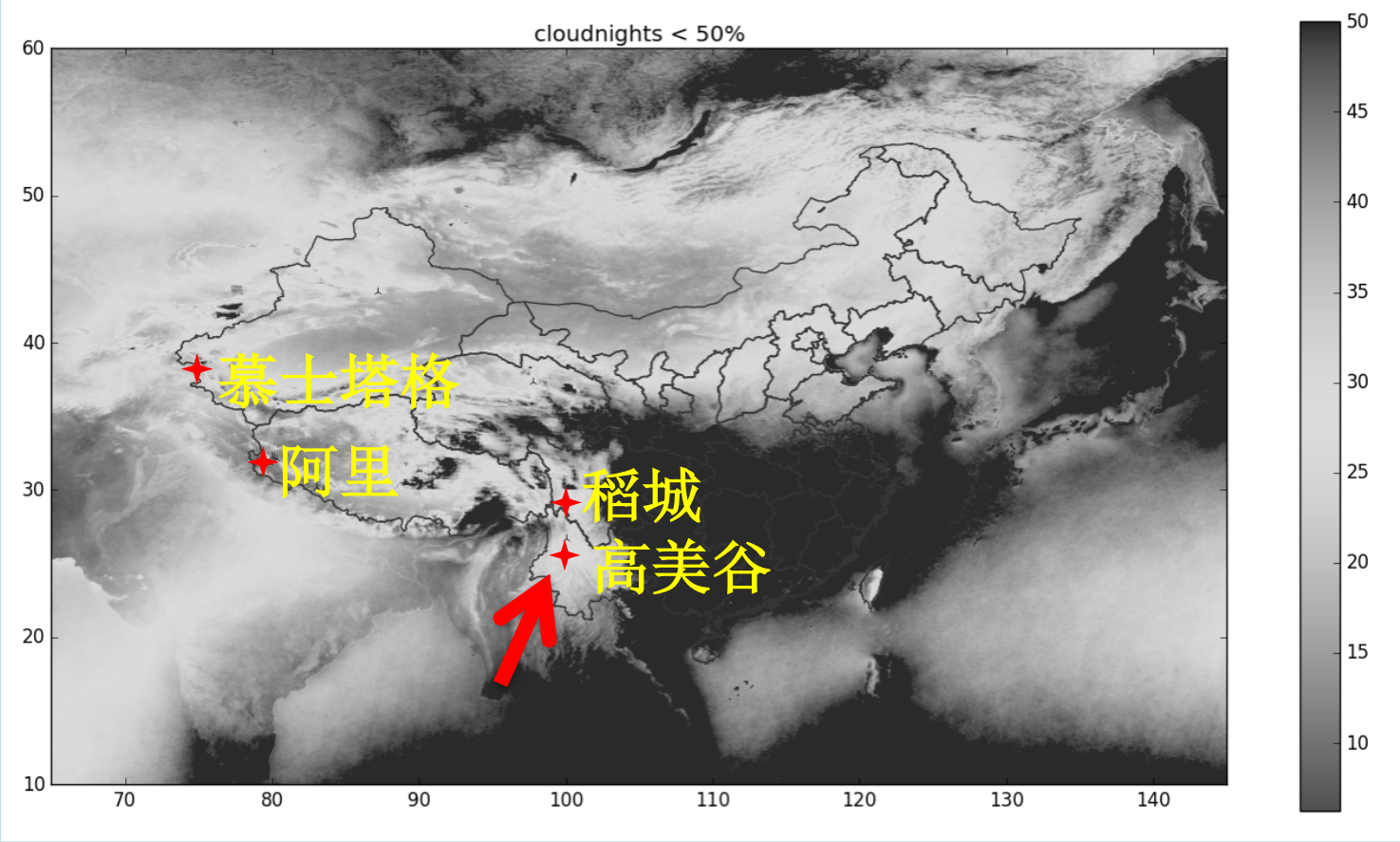
3 CCD mosaics for the blue-, yellow- and red-channels (2×2 e2v 290-99 sensors each)

Mephisto	LSST
1.0 Gigapix	3.2 Gigapix
3 × 3.14 deg^2	9.6 deg^2
0.286″/pixel	0.2″/pixel

Site

To be installed at Gaomeigu, Lijiang (100° 2′ E, 26° 42′ N, 3200m)

- **Median seeing: 1.2”**
- **Observable time: ~1866 hours/year (average between 2015-2018)**



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MEPHISTO features

- **Mephisto will be the first multi-channel photometric survey telescope that shall deliver:**
  - **Real-time colours (and variations), enabling fast and robust search and classification of different types of transient and variable for follow-up spectroscopic identification and observation;**
  - **Superb colour accuracies, 0.2-0.5%, better than LSST (0.7-1.4%), enabling accurate parameter determinations of stars and galaxies;**
  - **Fast survey speed: 1800 deg^2 in 3 bands per night, comparable to LSST;**

MEPHISTO milestones

2015.10 Concept of a multi-channel survey tel.

2017.01 Preliminary design by NIAOT

2017.09 SWIFAR established

2017.12 1st Mephisto science workshop

2018.01 Technical design peer review

2018.01 Project approved by the Univ. Board

2018.05 Primary blank arrived in NIAOT

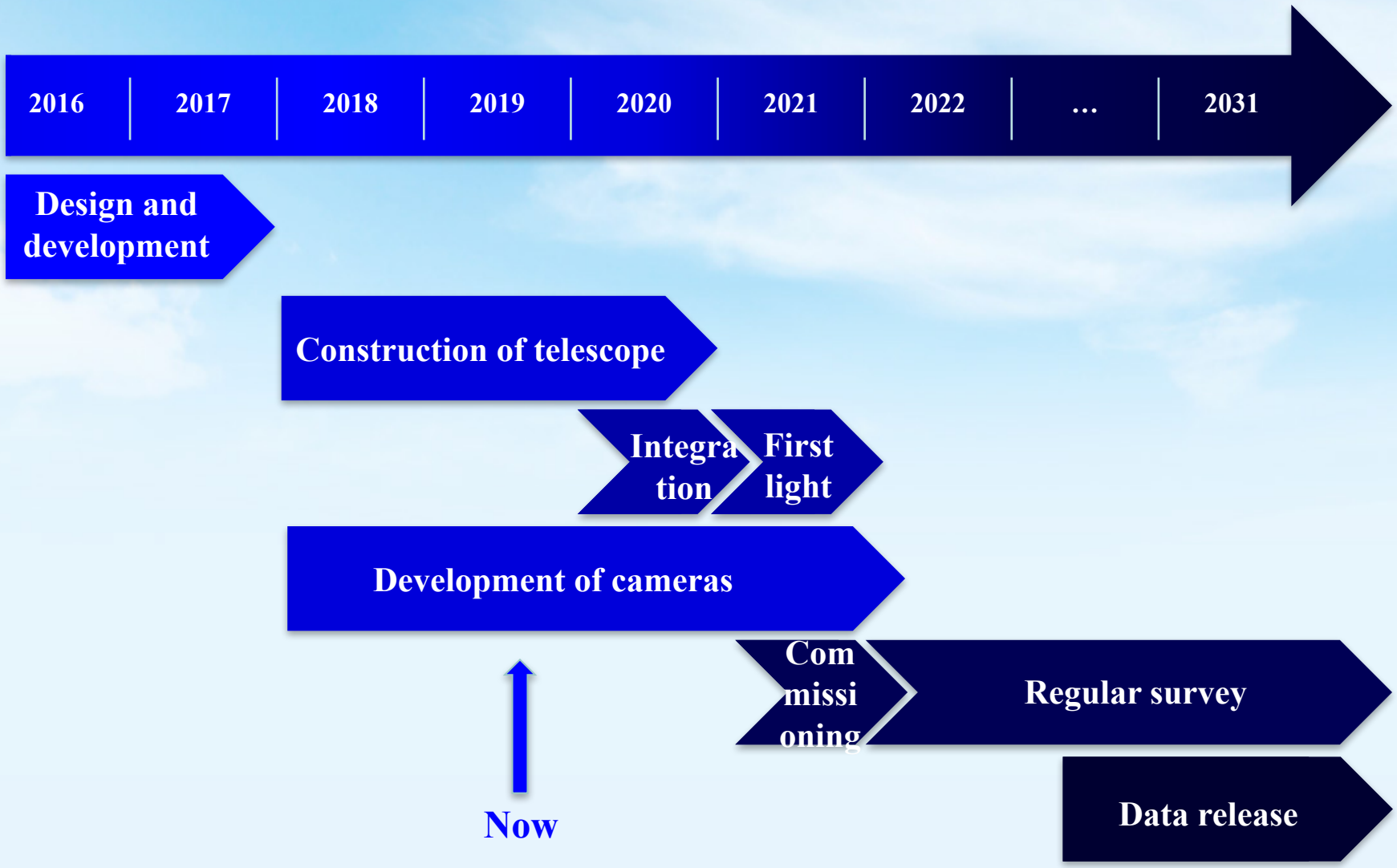
2018.05 Cameras & Detectors workshop

2018.10 Contract with NIAOT signed

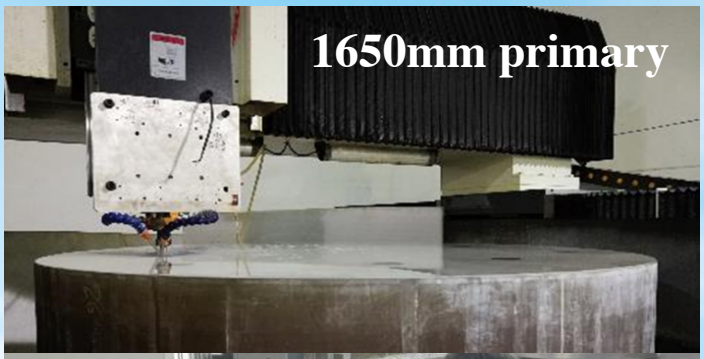
2018.12 Bidding process for MEPHISTO CCDs initiated

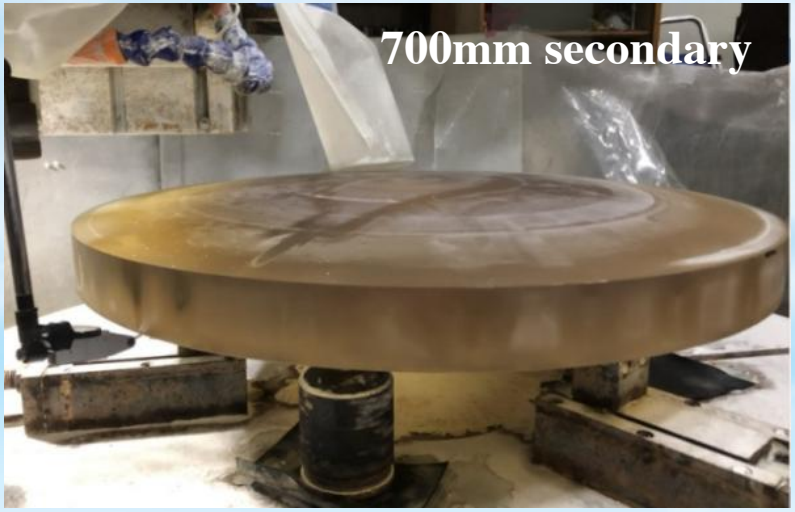
2019.02 Site construction initiated

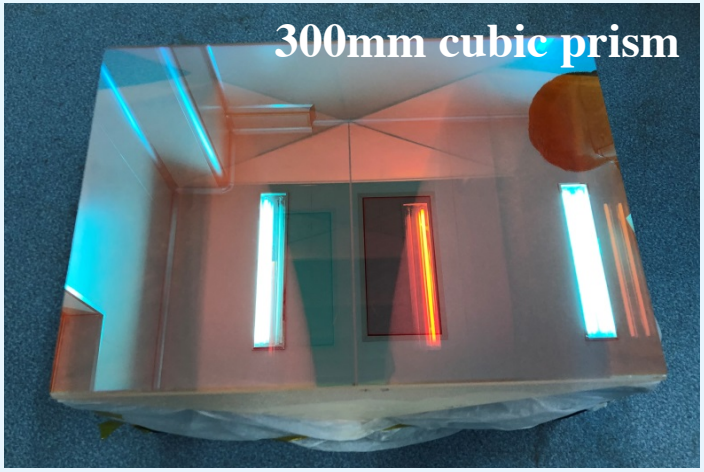
MEPHISTO timeline

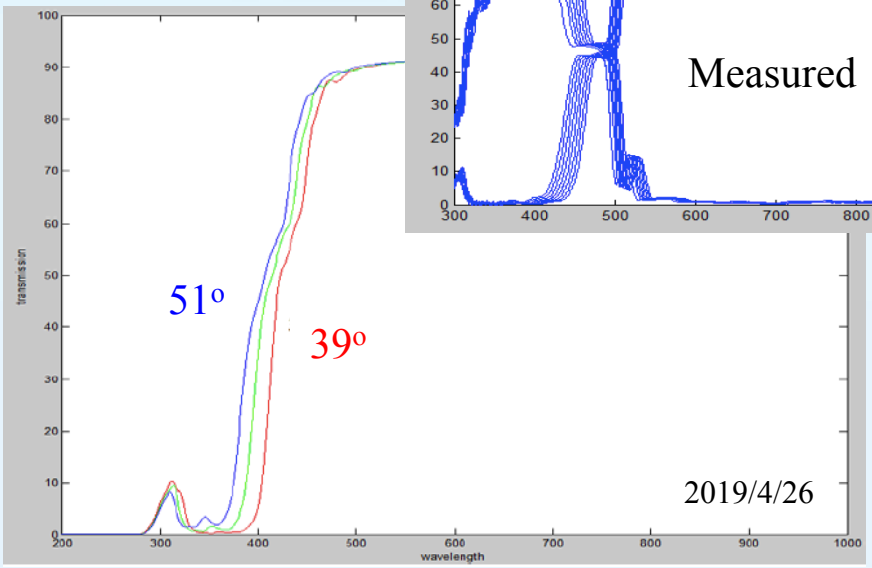


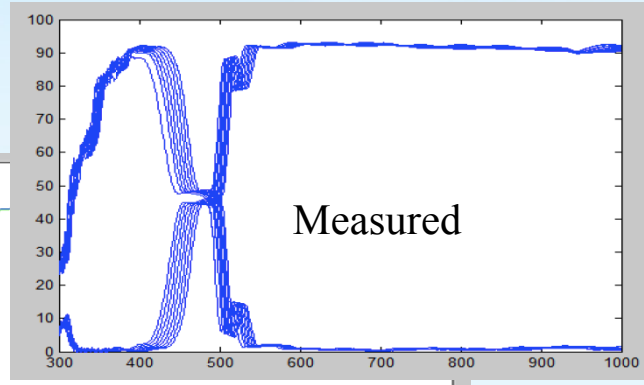
Progress


1650mm primary


700mm secondary

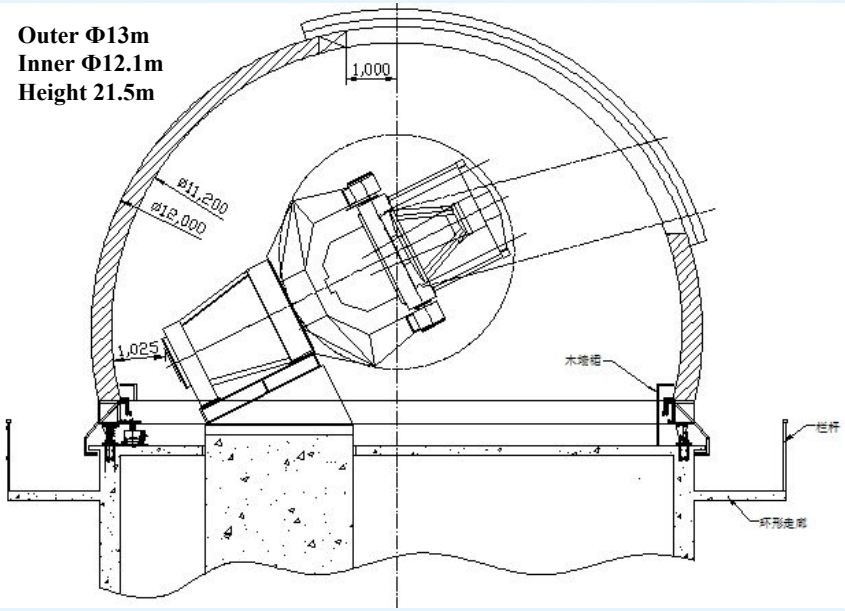

300mm cubic prism

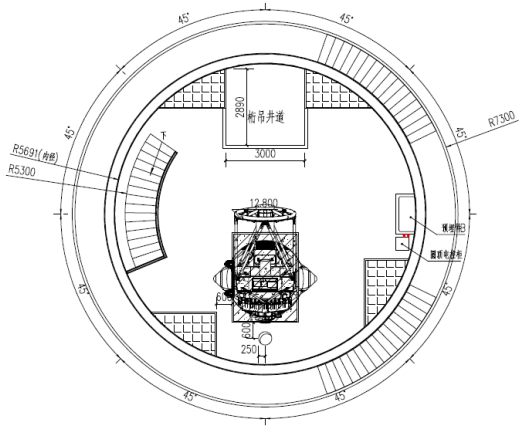

Transmission
51°
39°
2019/4/26
wavelength
transmission


Measured

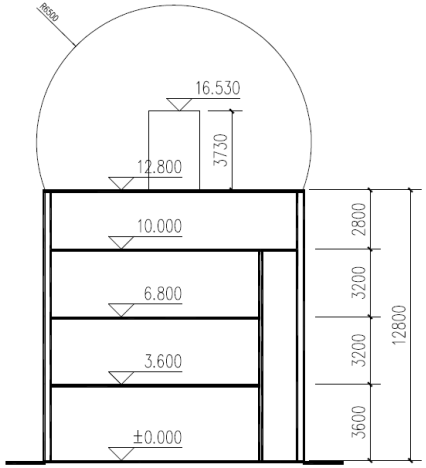
Dome, data storage & processing centre

Outer Φ13m
Inner Φ12.1m
Height 21.5m





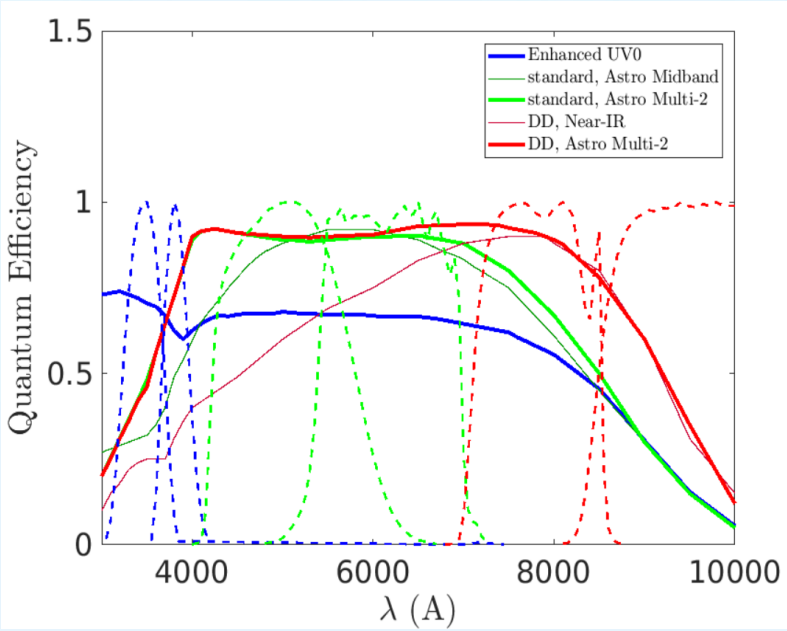
五层平面图 1:100
本层建筑面积：116.55㎡

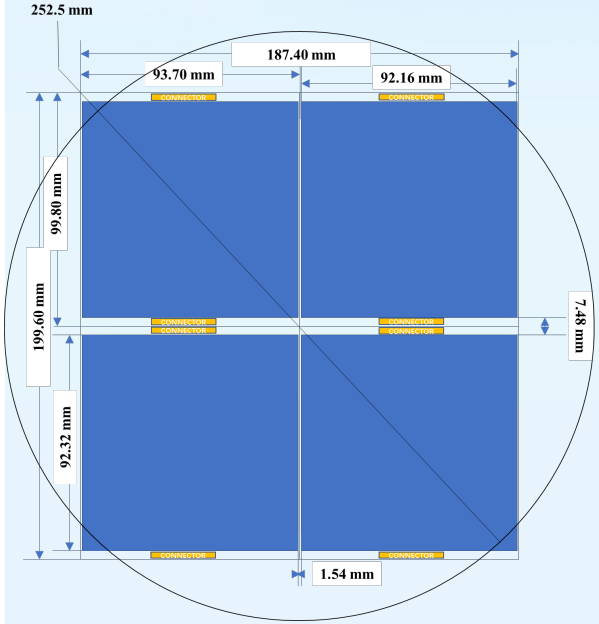


层高示意图

Current status

- Telescope under construction by NIAOT, completion expected 2020/12
- Site and dome (NAIRC, Nanjing) construction by YNAO starting from 2019/11
- CCD mosaic cameras
  - 15 e2v CCD 290-99 9216×9232 10μm back-illuminated sensors
    - 5 standard silicon enhanced UV0
    - 5 standard silicon multi-2
    - 5 deep-depletion multi-2
  - Single chip and 2×2 mosaic CCD cameras building from 2020/1 by NAOC






e2v CCD 290-99

KMTNet

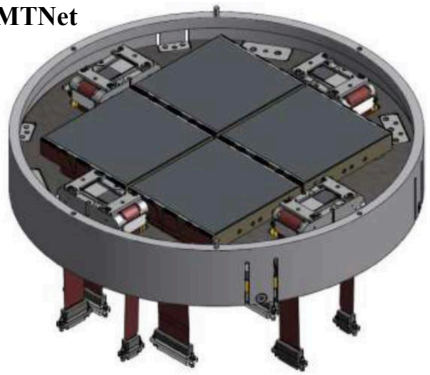
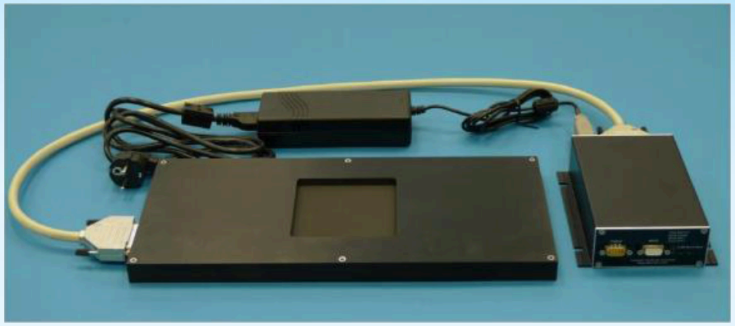


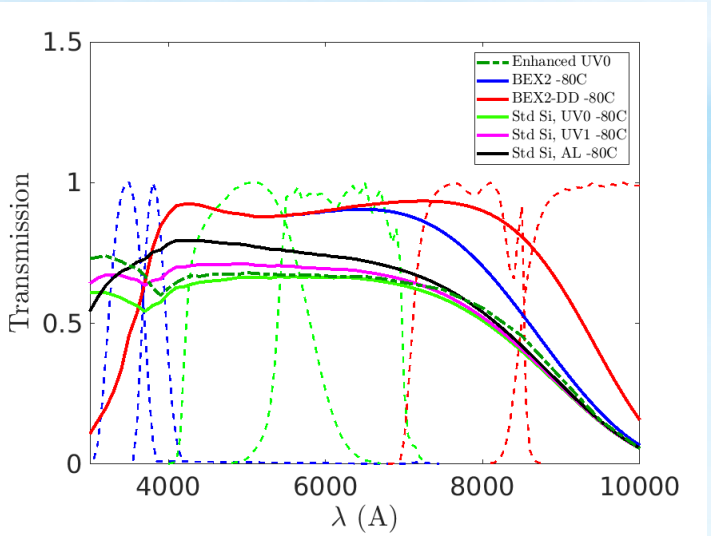
Figure 3: The KMTNet Focal Plane Array with four CCD290-99 and four CCD47-20.

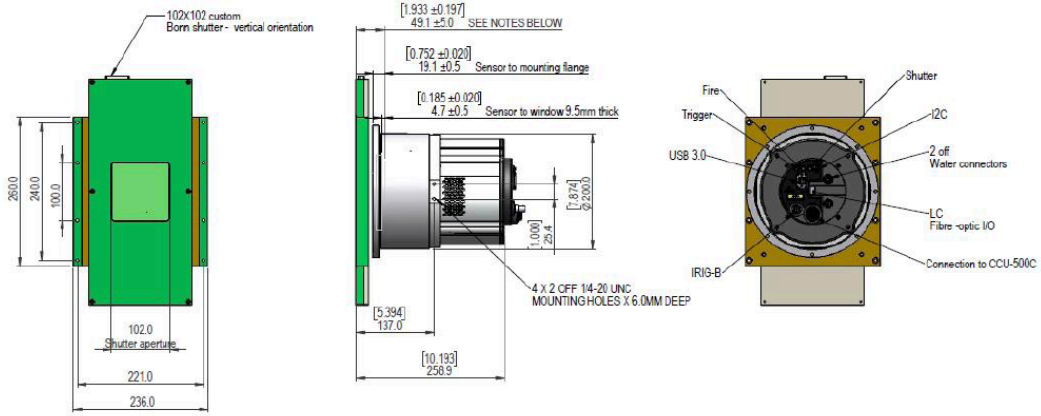
Pilot cameras

- **Oxford Instruments/Andor Technology iKon-XXL CCD cameras**
  - **e2v CCD 231-C6 6144×6160 15μm back-illuminated sensors**
    - **Standard silicon AL UV**
    - **Standard silicon BEX2**
    - **Deep-depletion BEX2**

Bonn Shutter
102mm×102mm







Working groups & project meetings

- 5 working groups set up
- Project meetings held every 2 weeks to discuss progress and problems

Science drivers

Survey strategy and scheduler

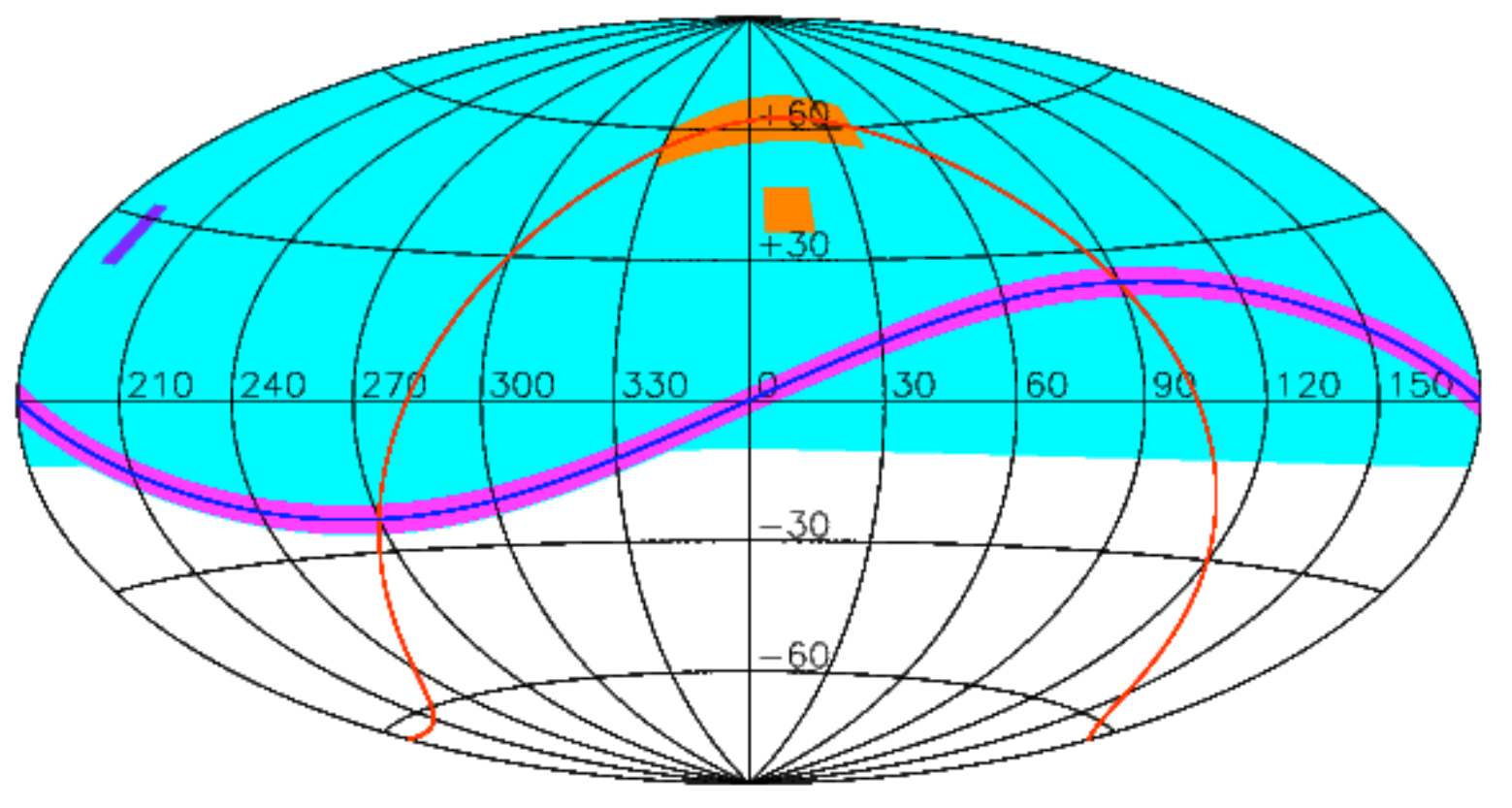
Image processing pipeline: Astrometric & photometric calibration

Transients and variables: Identification and classification

Observatory control system
Data storage & processing centre

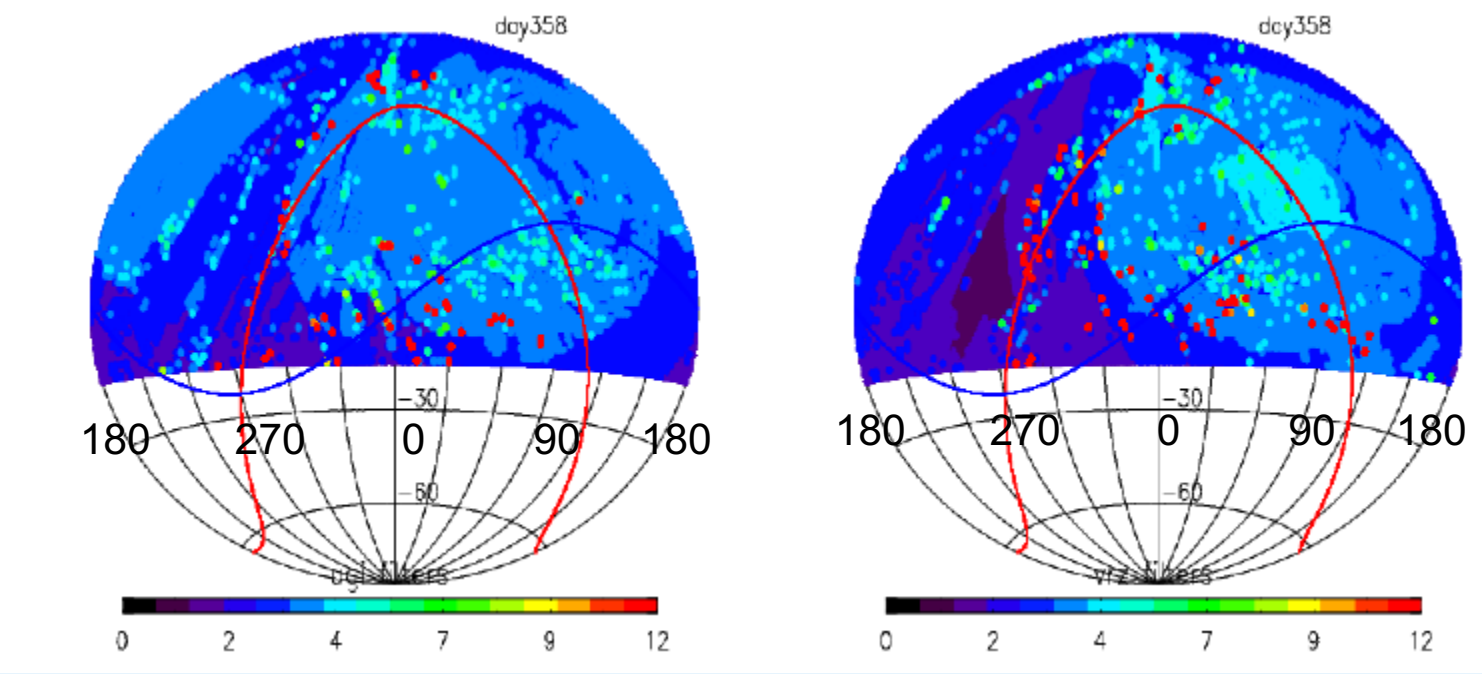
MEPHISTO surveys

- **MEPHISTO surveys will last for 10 years:**
  - **Wide multi-channel survey of over 26,000 deg^2 northern hemisphere (Mephisto-W)**
  - **Multi-channel surveys of variables and transients of cadences of days, hours and minutes (Mephisto-D, Mephisto-H and Mephisto-M).**



MEPHISTO-W

- All the time of 2022 and 30% time of 2023-2031
- 2 × 20s exposures, typical 5σ depth r ~ 22.7 mag
- Two visits of a given field per night, with a 15 – 60m time interval between
- 2022: 6 visits of all fields in both the *ugi* & *vrz* filter combinations
- 10 years operation: 24 visits of all fields for both *ugi* & *vrz* filter combinations



ugi filters

vrz filters

MEPHISTO-W

- 2023, Release of the first true-colour sky atlas, plus one-year-long 6-point multi-band light and real-time colour curves for all detected sources
  - Co-added 5σ depth (*u, v, g, r, i, z*) = (22.7, 22.8, 24.1, 23.9, 23.3, 22.3)
  - Astrometry better than 0.02", photometry better than 1%
  - Precision of colour calibration 0.3% (0.5% for *u* and *v*)

- Final data release: Deep true-colour sky atlas and 10-year-long 24-point multi-band light & real-time colour curves for all detected objects
  - Co-added 5σ depth (*u, v, g, r, i, z*) = (23.8, 23.8, 24.9, 24.7, 24.1, 23.2)
  - Astrometry better than 0.01", photometry better than 1%
  - Precision of colour calibration 0.2% (0.5% for *u* and *v*)
  - Parallaxes for (r < 16, 17, 18, 19, 20) = (0.12, 0.18, 0.32, 0.6, 1.0) mas
  - Proper motions for (r < 16, 17, 18, 19, 20) = (0.07, 0.10, 0.18, 0.34, 0.6) mas/yr

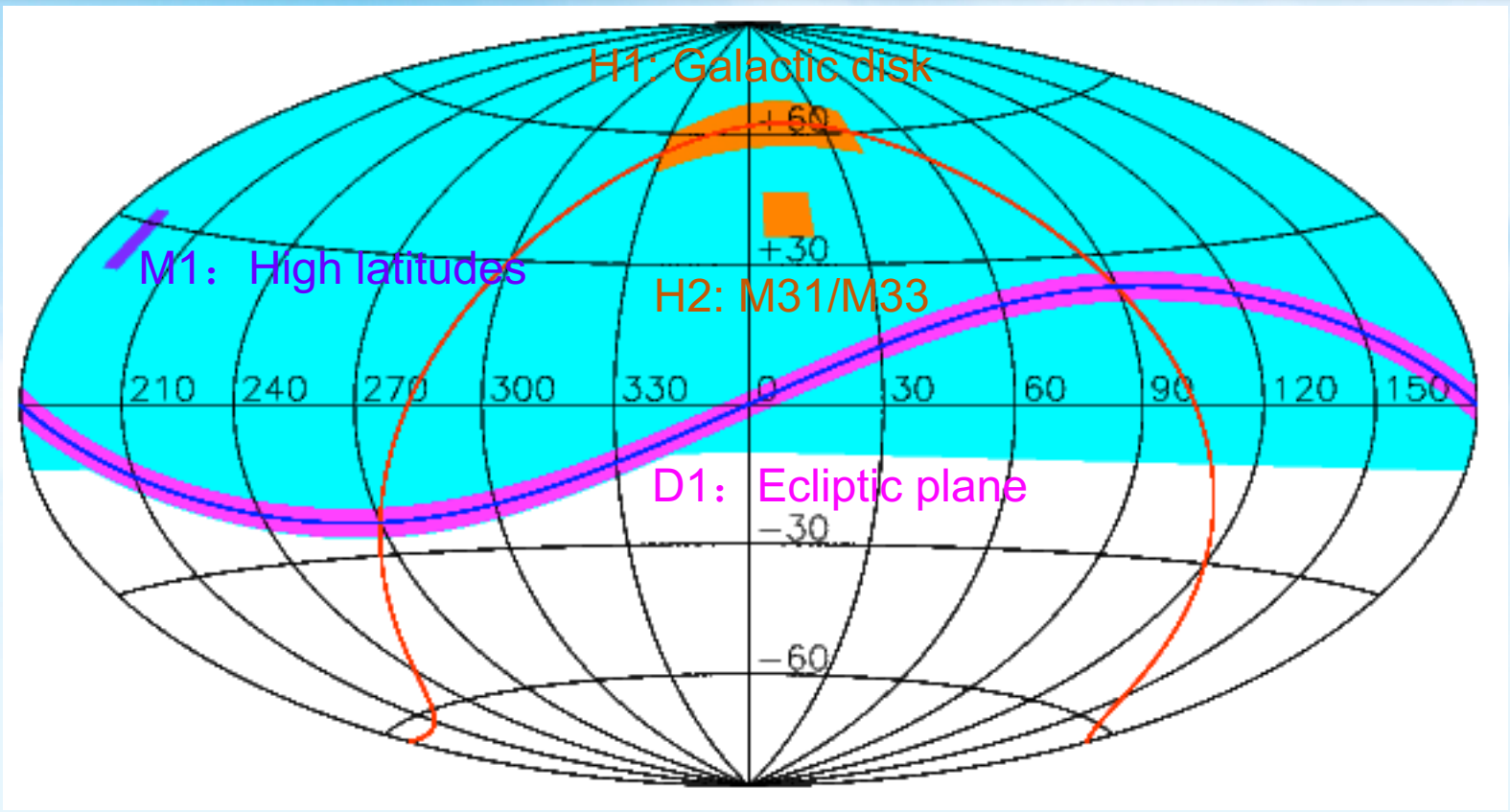
MEPHISTO-D, H & M

- For 2023 – 2031, 70% observing time will be allocated to Mephisto-D, -H and -M surveys.

Survey	Area	Cadence
Mephisto-D	N*1800 deg^2	> Day
Mephisto-H	N*180 deg^2	> Hour
Mephisto-M	N*18 deg^2	> Minute

- Comparing to the Mephisto-W survey, Mephisto-D, -H and -M surveys have better temporal sampling, more total integration time and deeper limiting magnitudes, and provide high-quality data for time-domain sciences.
- Real-time colours & variations: Fast & robust transient classifications

Example D, H & M footprints

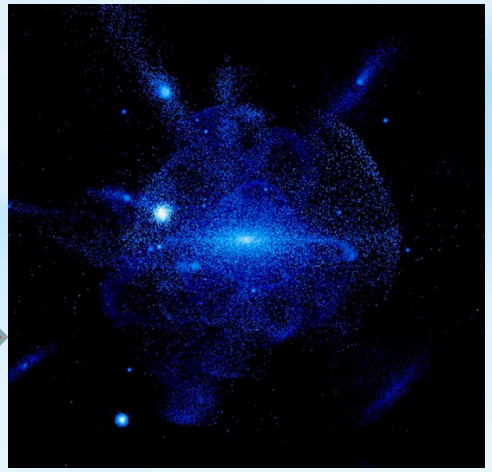


- **Ecliptic plane**: Small bodies in the Solar System, near-Earth objects;
- **Galactic disk**: Rotation of young stars, disk structure, chemistry and kinematics, variable stars, binaries, exoplanets;
- **M31/M33**: (Variable) stars; globular clusters and satellite galaxies; time-domain sciences; structure, chemistry and kinematics of M31, proper motion of M31
- **High Galactic latitudes**: Cosmic transients, galaxies and quasars, Galactic halo

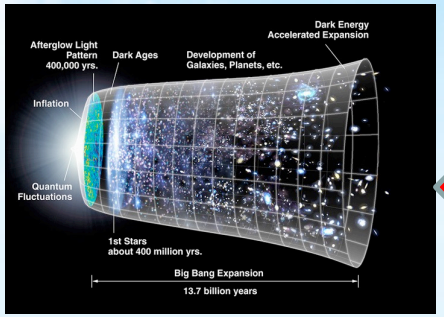
MEPHISTO science themes

Probing the transients

Galactic archeology



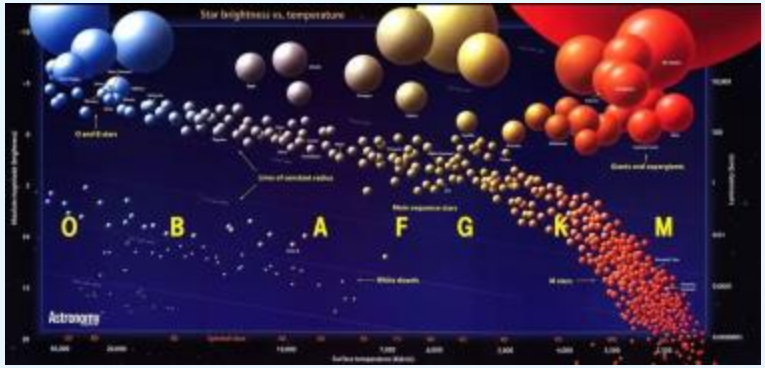
Galaxies and cosmology



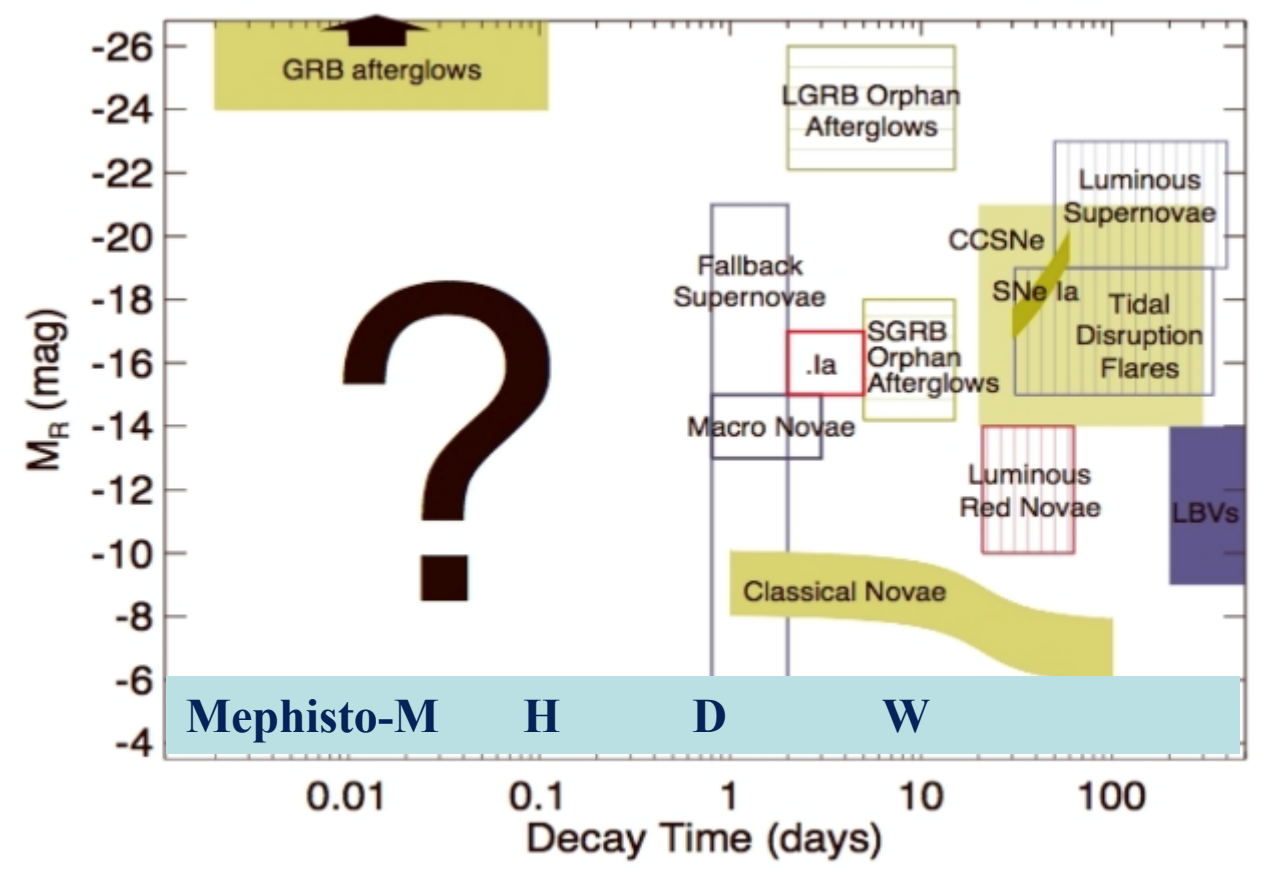
MEPHISTO
Real-T, high-Q colours
Large FOV
High survey efficiency

The Solar system objects

Stellar and stellar population astrophysics



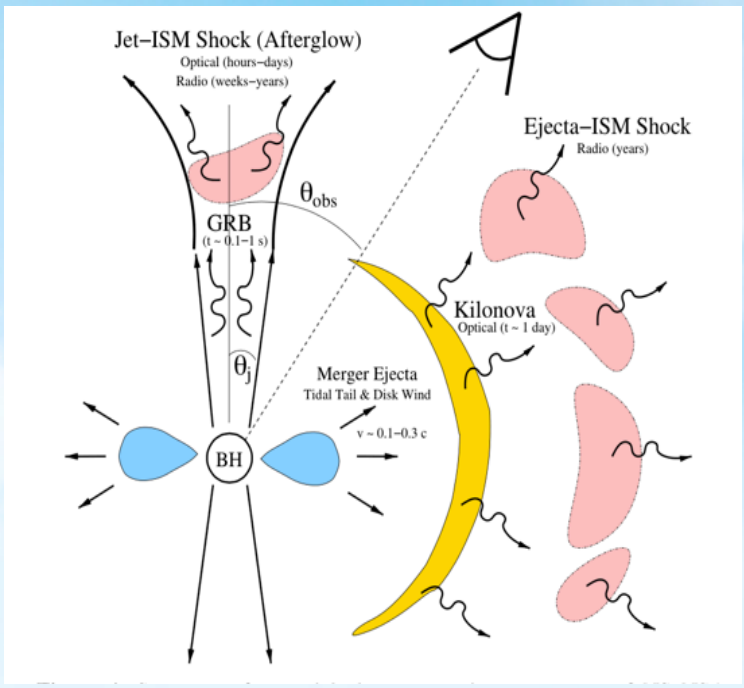
Example science: Cosmic transients

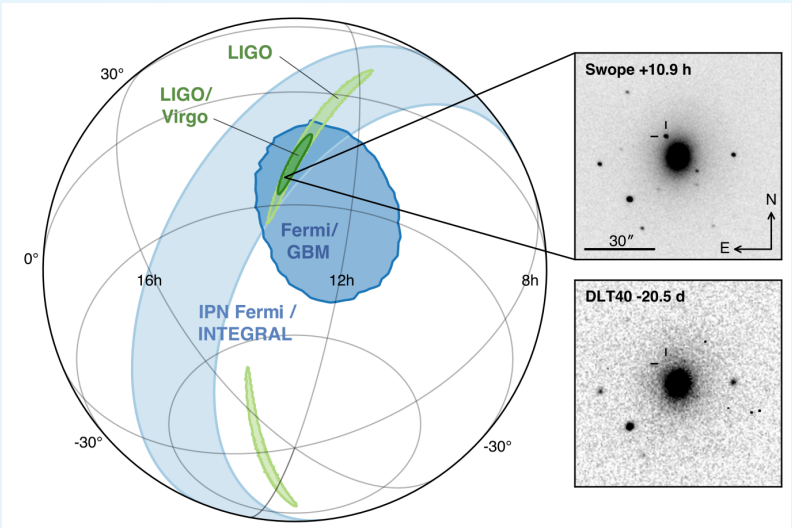


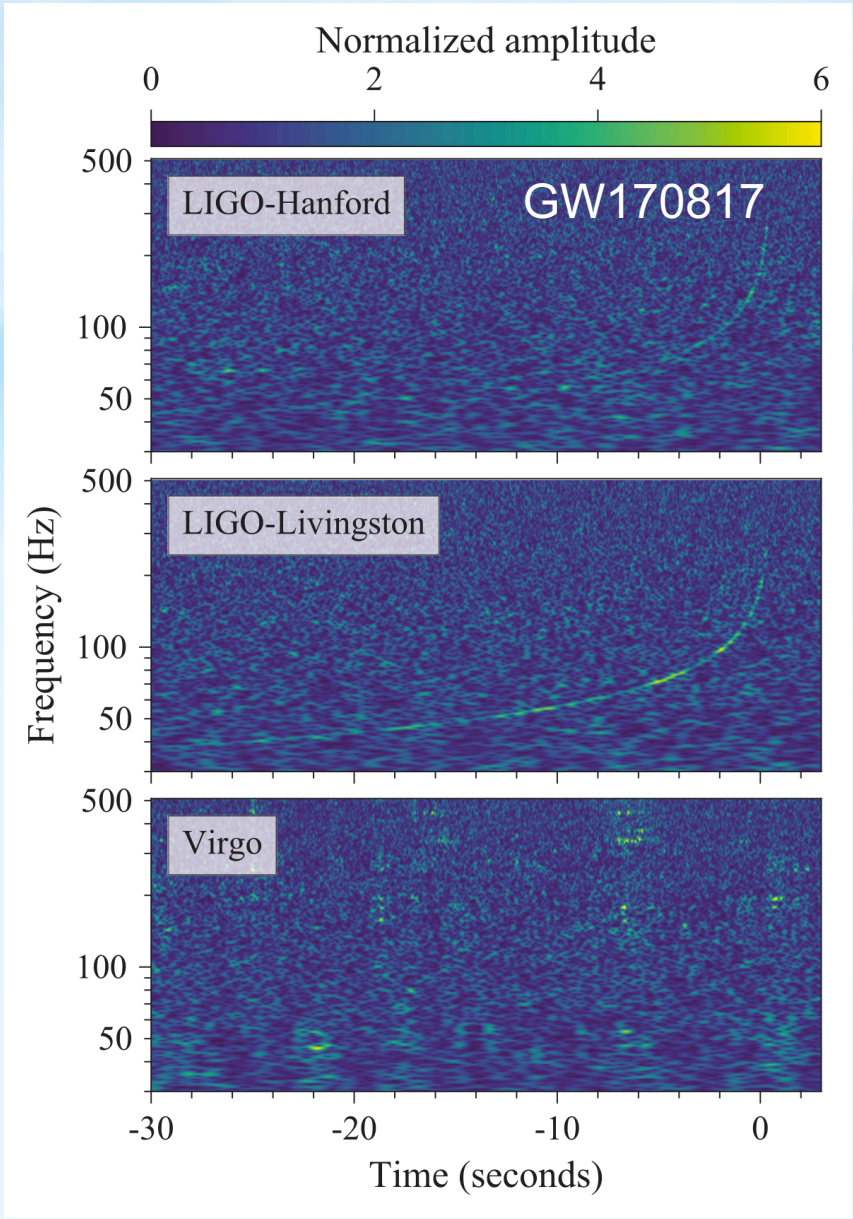
Ivezic et al. (2008)

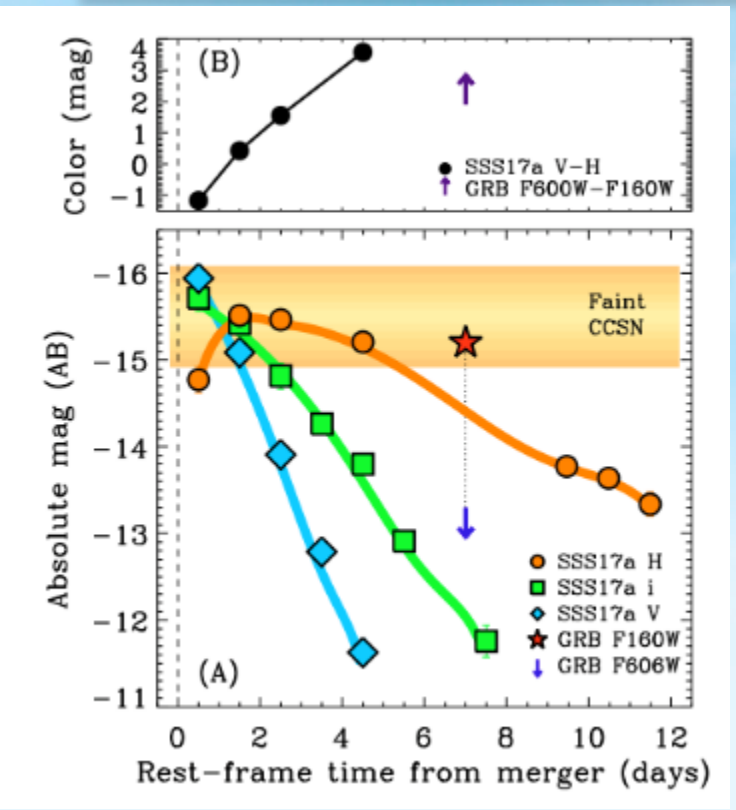
- **Mephisto-W, -D, -H, -M surveys probe transients and variables of time-scales from minutes to years**
- **Accurate real-time colour and multi-band light curves: Fast and robust classifications of transients and variables**

EM counterparts of GW events



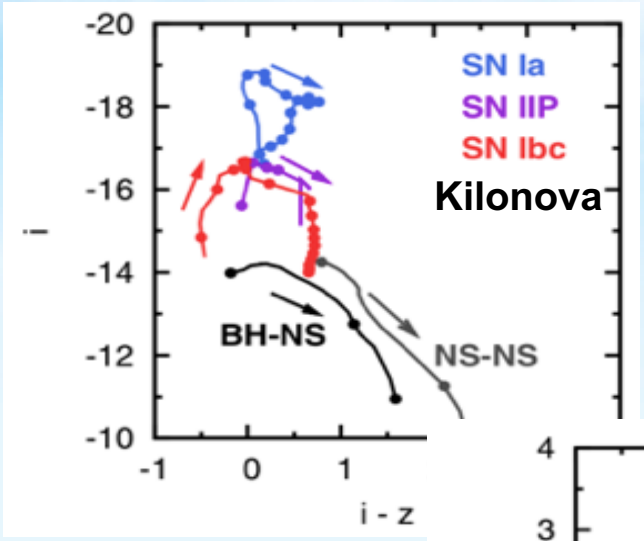


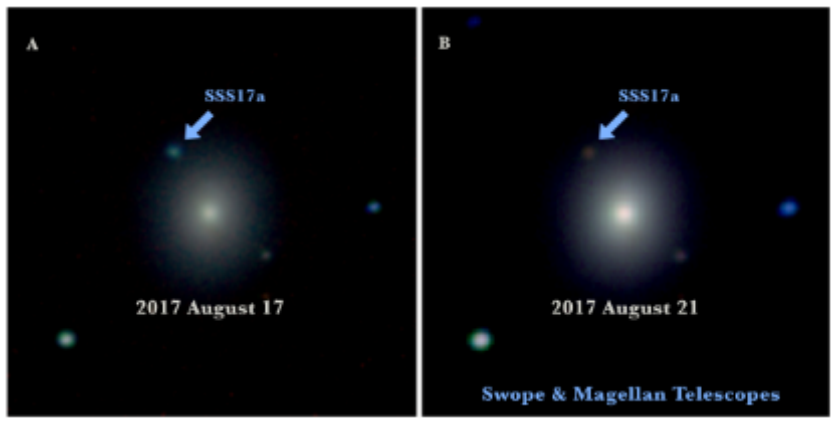


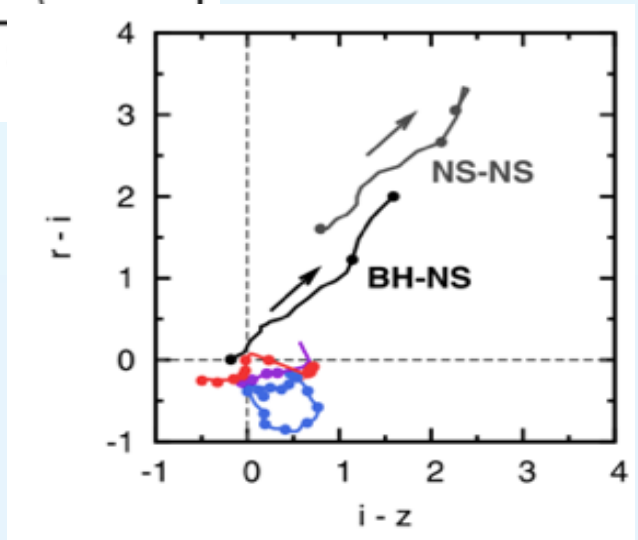


MEPHISTO high-quality real-time colours allow

- Rapidly classification of Kilonovae
- Differentiate between NS-NS and NS-BH mergers
- Help identify weak GW events





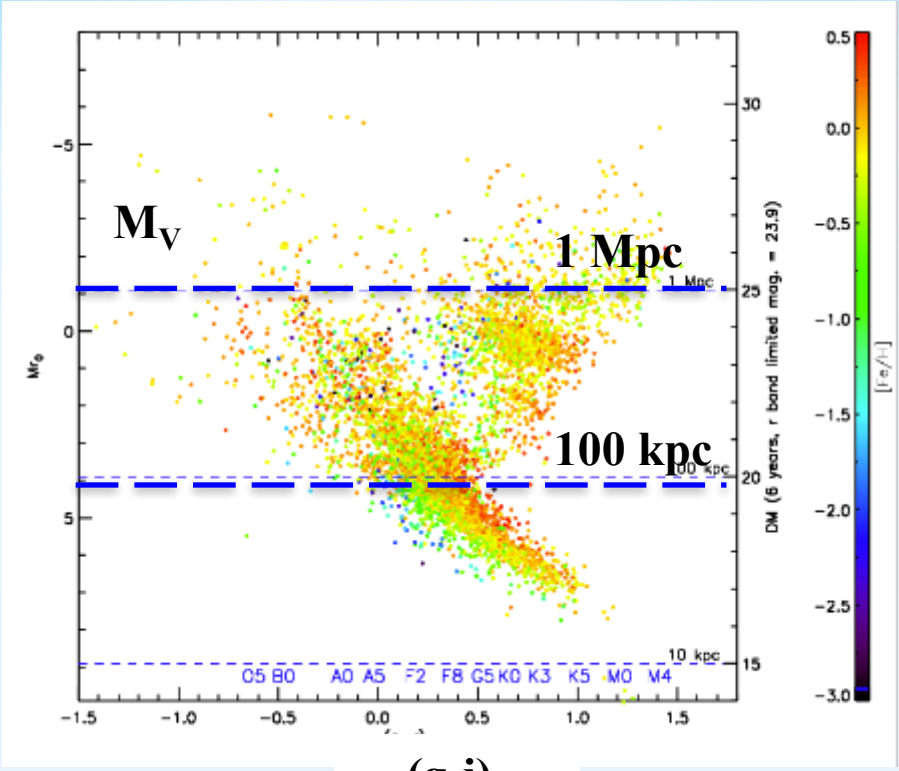


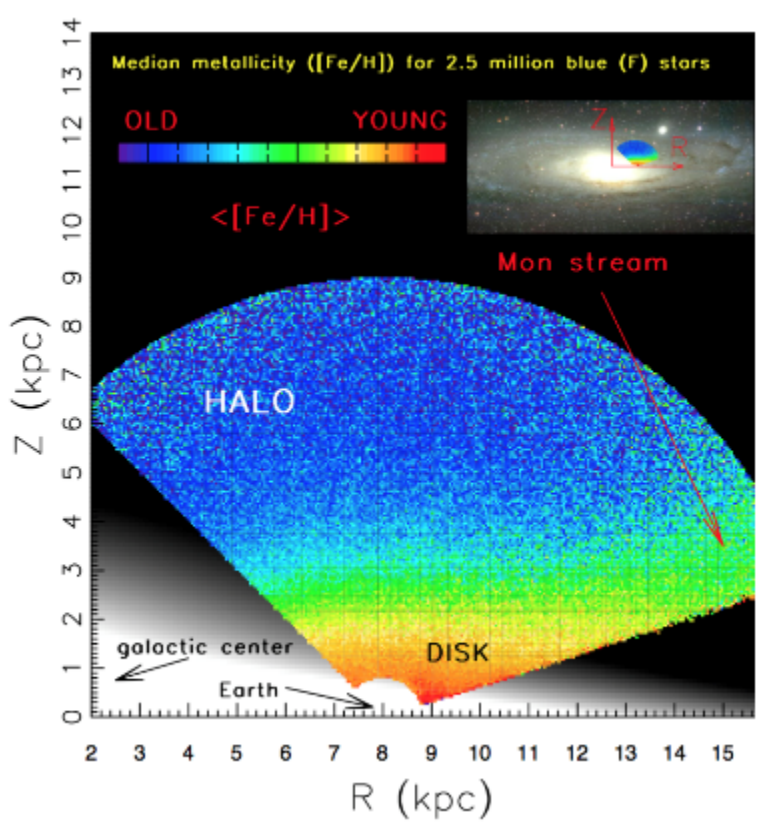
Mapping the Milky Way

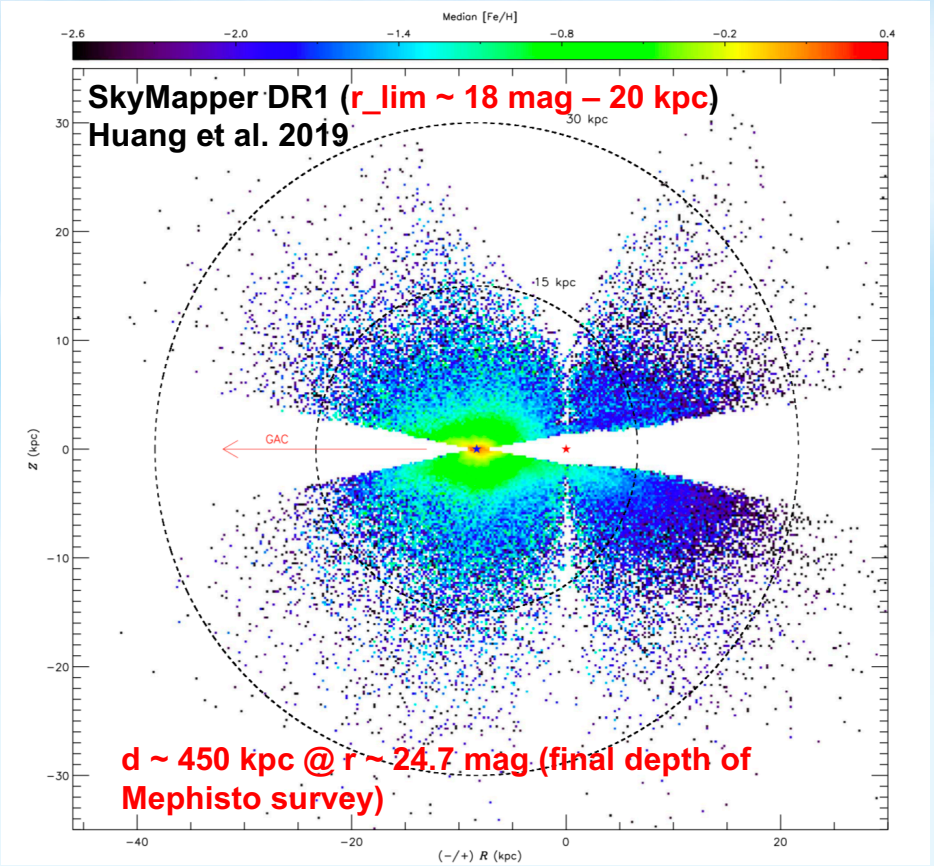
MEPHISTO-W will detect > 1% Galactic stars. The high quality colour and astrometric data, in particular those of the *u* and *v* bands will yield:

Type	Distance
M0 dwarf	10 kpc
MS turn-off	100 kpc
Red giant	500 kpc

- **2B MS stars and 50M giants with accurate distance and extinction estimates**
- **Metallicities for MS stars of accuracy 0.1-0.15 dex, for giants of accuracy 0.15-0.2 dex**
- **Effective temperatures for MS and giant stars of uncertainties 50-100 K**
- **Tangential speeds accurate to 10-20 km/s for stars out to 10 kpc**







Mapping the Milky Way with MEPHISTO:

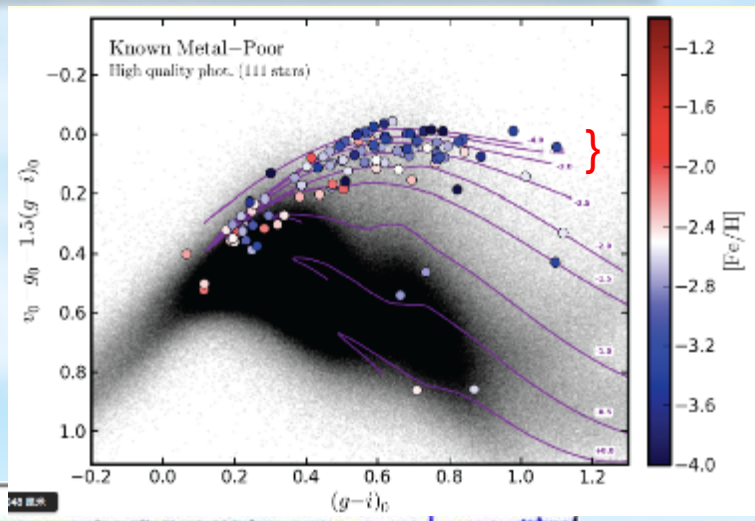
- The interstellar medium
- Galactic structure/substructure, chemistry and kinematics
- Satellite galaxies

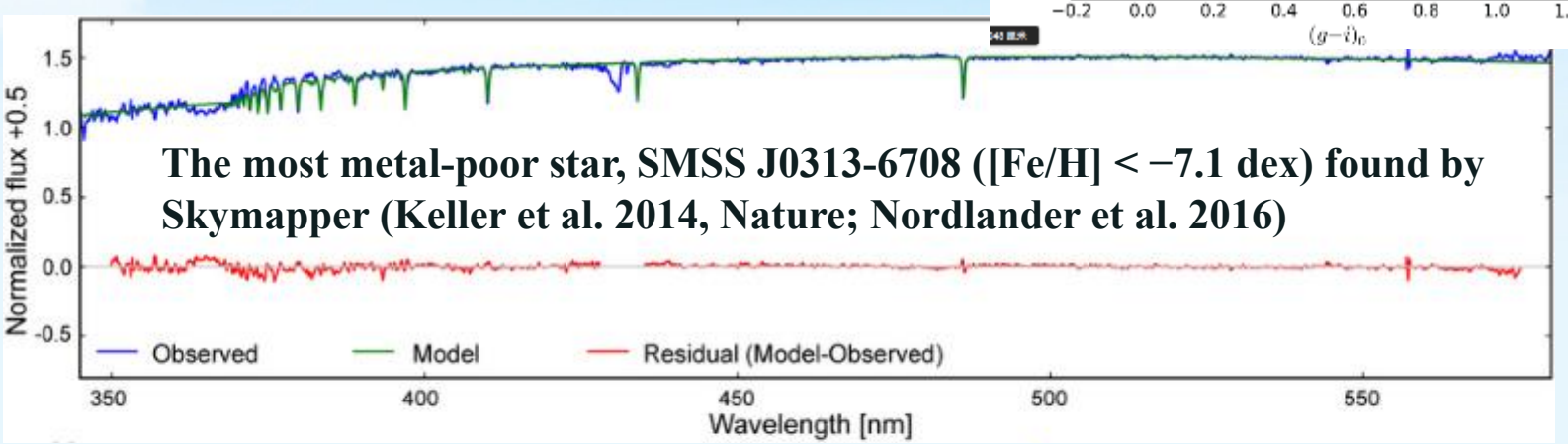
EMP stars

Extremely metal-poor stars are fundamental probers of the nature of the first generation stars and the formation of the Milky Way.

High precision colours are key to select candidates of [Fe/H] < −3.0 dex.

G. Da Costa





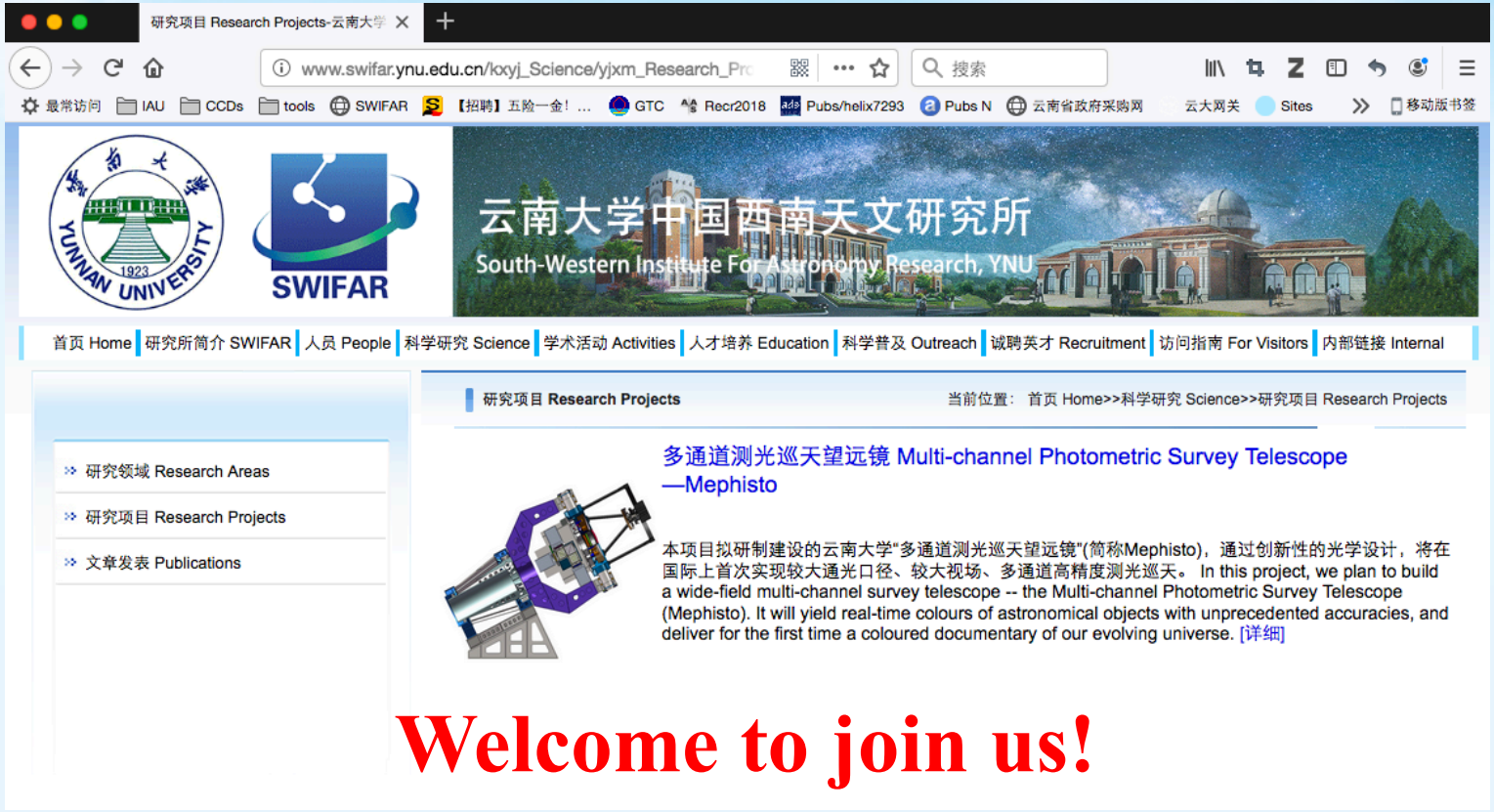
The most metal-poor star, SMSS J0313-6708 ([Fe/H] < −7.1 dex) found by Skymapper (Keller et al. 2014, Nature; Nordlander et al. 2016)

	Colour Accuracy	10-σ depth	Sky area	Time
MEPHISTO	0.2 - 0.5%	r = 24.3	North 26000 deg^2	2022−2031
Skymapper	1 - 5%	r = 22	South 20000 deg^2	2015−2020

MEPHISTO-W will detect ~ 20,000 EMP stars

MEPHISTO in one sentence

- **MEPHISTO, a multi-channel survey telescope, first of its type in the world, will deliver real-time, high-quality colours of unprecedented accuracy for celestial objects, enable fast and robust classification of transients and variables, and deliver a panchromatic documentary of our evolving universe.**



Welcome to join us!

Thank you!

Introduction

(Digital) Large-scale astronomical surveys with large format CCD mosaic play a key role in modern astrophysics, leading to new discoveries and revolutionizing our understanding of cosmic origin and evolution.

Name	Aperture (m)	FOV (sq deg)	Filter set	Limiting magnitude	Sky area	Hemi-sphere	First Light	Time domain
SDSS	2.5	1.5	*ugriz*	22 *(r)*	15000	N	Complete	NO
XSTPS-GAC	1.2	3.76	*gri*	19 *(r)*	7000	N	Complete	NO
PS1	1.8	7.0	$(grizY)_{P1}$	22.8 *(r)*	30000	N	Complete	YES
Gaia	1.0	0.45	*G*	20 *(G)*	41000	NS	2014	YES
Skymapper	1.35	5.2	*uvgriz*	22.6 *(r)*	20000	S	2014	YES
ZTF	1.2	47.0	*gr*	20.4 *(r)*	30000	N	2017	YES
LSST	8.4	9.6	*ugrizy*	27.7 *(r)*	20000	S	2021	YES
MEPHISTO	1.6	3.14	*uvgriz*	22.7/24.8 *(r)*	26000	N	2021	YES

SDSS LSST MEPHISTO

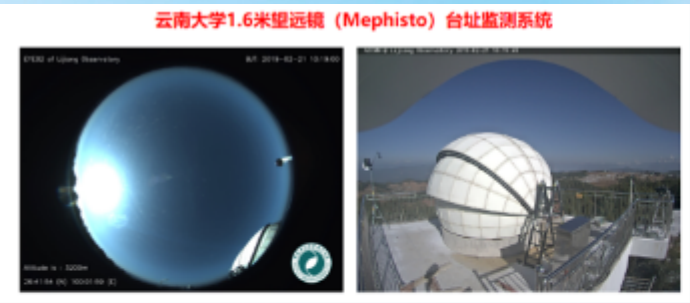
Snapshots → Monochromatic documentary → Coloured documentary

MEPHISTO: First true-colour survey telescope

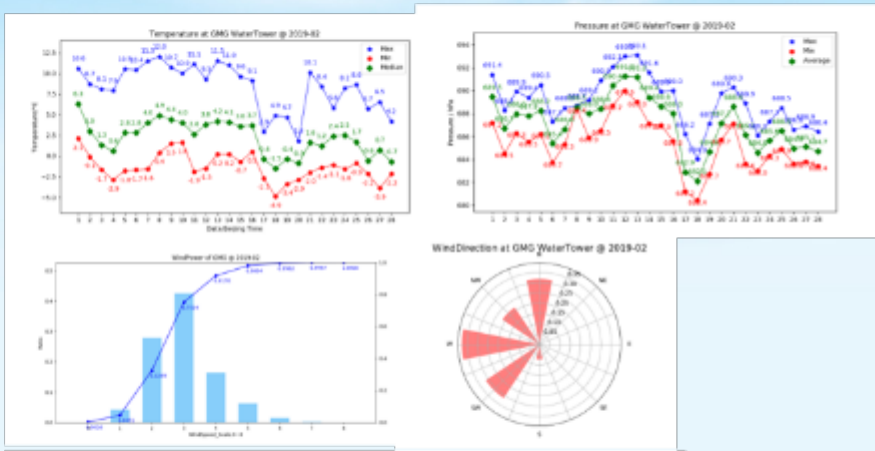
Étendue = 3 × 4.8 m^2deg^2 (LSST: 319 m^2deg^2)

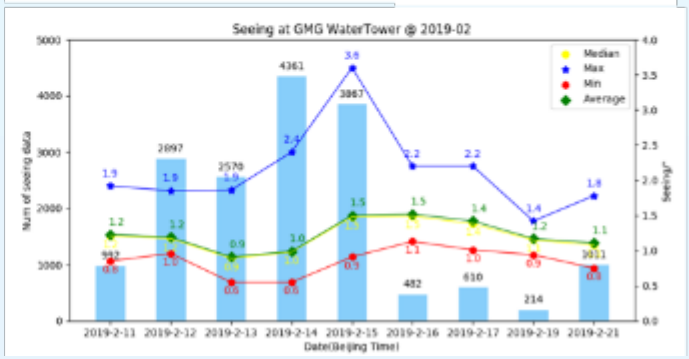
Site monitoring system for Mephisto

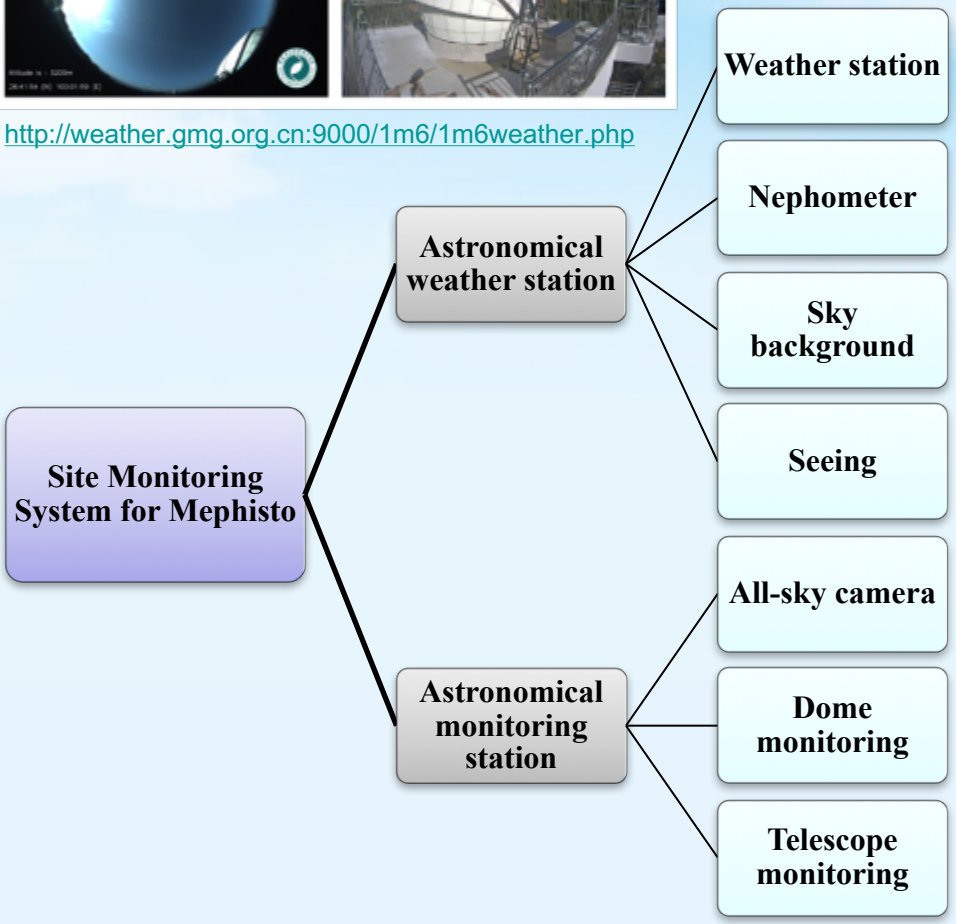
- A site monitoring system for Mephisto has been operating since 2019/03



http://weather.gmg.org.cn:9000/1m6/1m6weather.php







Progress

Inspection Data

OHARA®

Year Month Day
2018/05/29

TO E0510A OHARA GmbH

Part No E/CCZHS350CFBE Lot No W03J1850009

Ohara Inc.

Glass Type CCZ

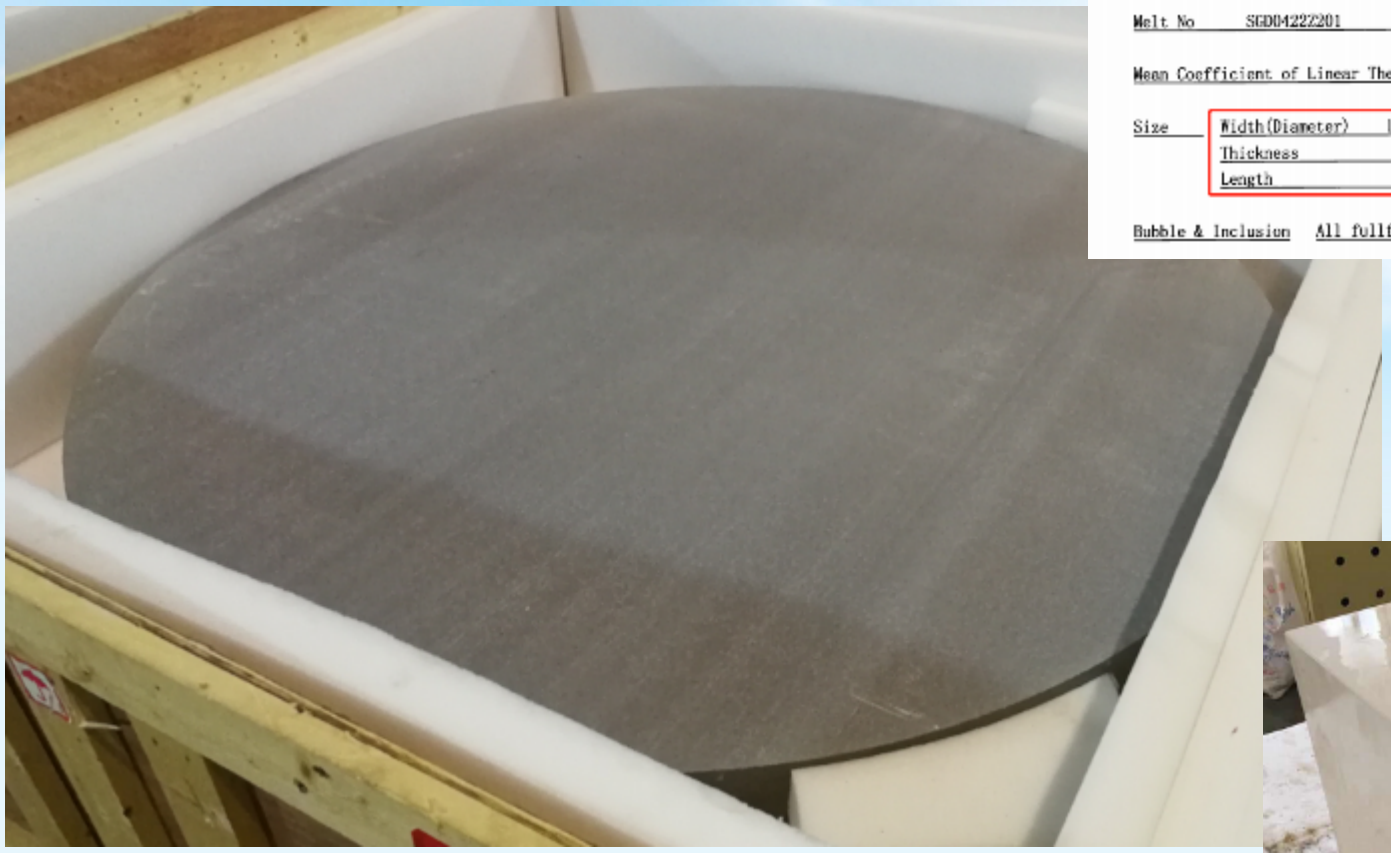
In Langgewann 4, 65719 Hofheim, Germany

Melt No SGDM222201 Geram No Q001 GLASS HS

Mean Coefficient of Linear Thermal Expansion -0.1×10^{-7} /K (0℃ to +50℃)

Size			
	Width(Diameter)	1,650.00	10.00 / -10.00
	Thickness	350.00	10.00 / -10.00
	Length	0.00	0.00 / 0.00

Bubble & Inclusion All fullfil



1650mm primary arrived at NIAOT in 2018/08

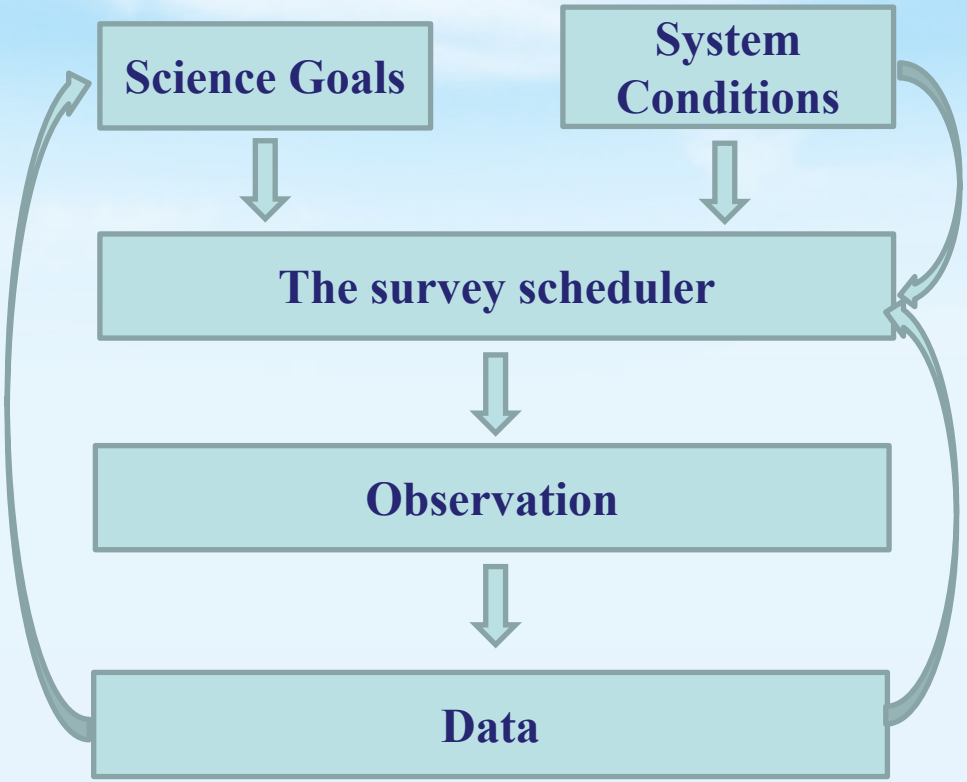
300mm uncoated cubic prism arrived at NIAOT in 2018/10

Mephisto survey scheduler (MSS)

- **Survey strategy, simulations**
- **Schedule observations depending on telescope, weather and seeing conditions, as well as survey progress**

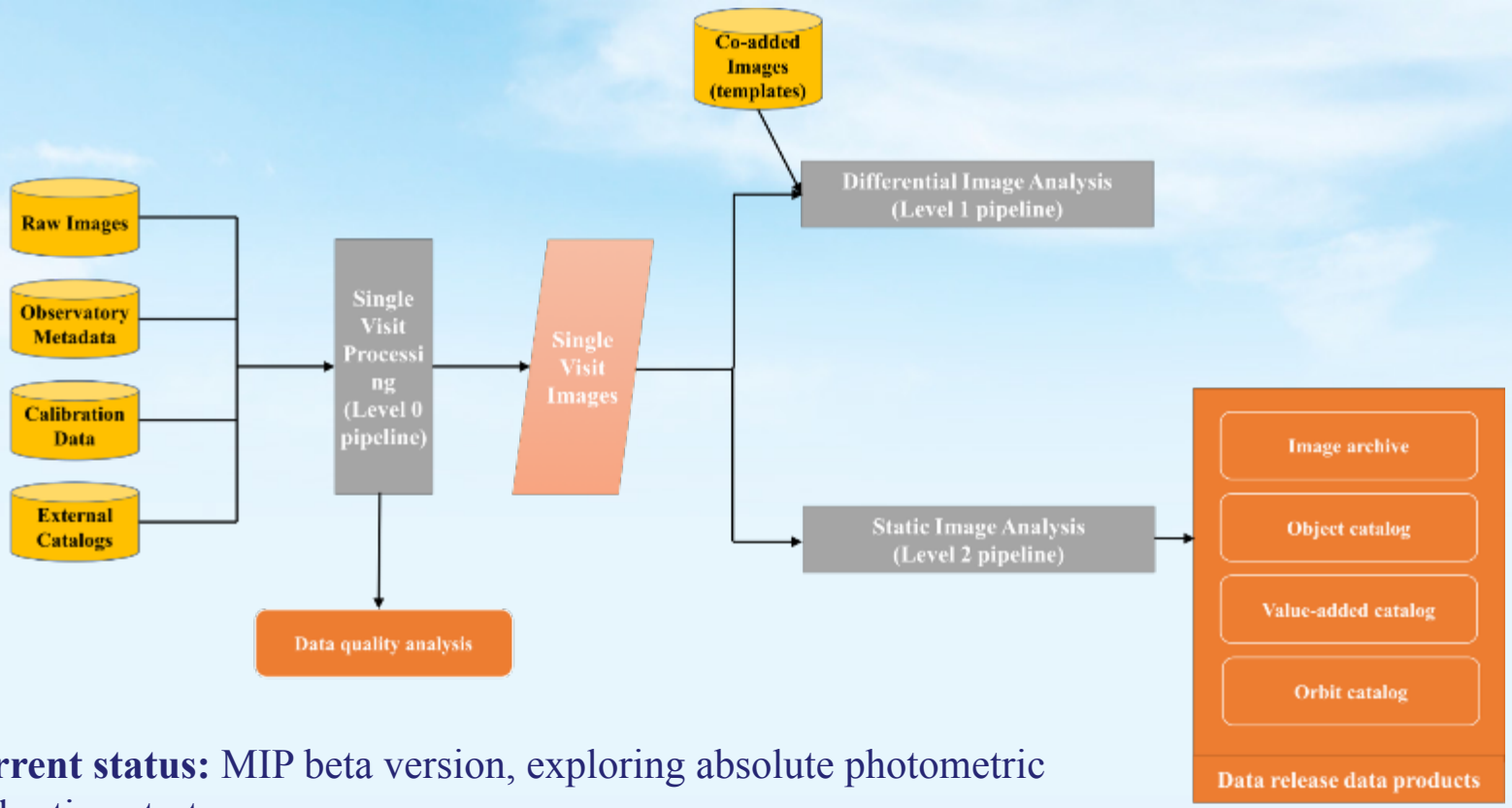
Current status:
Mephisto-W survey simulation

2019.01-2019.07:
Develop Mephisto survey scheduler
2019.08-2019.12:
10-years survey simulation



Mephisto image processing pipeline (MIP)

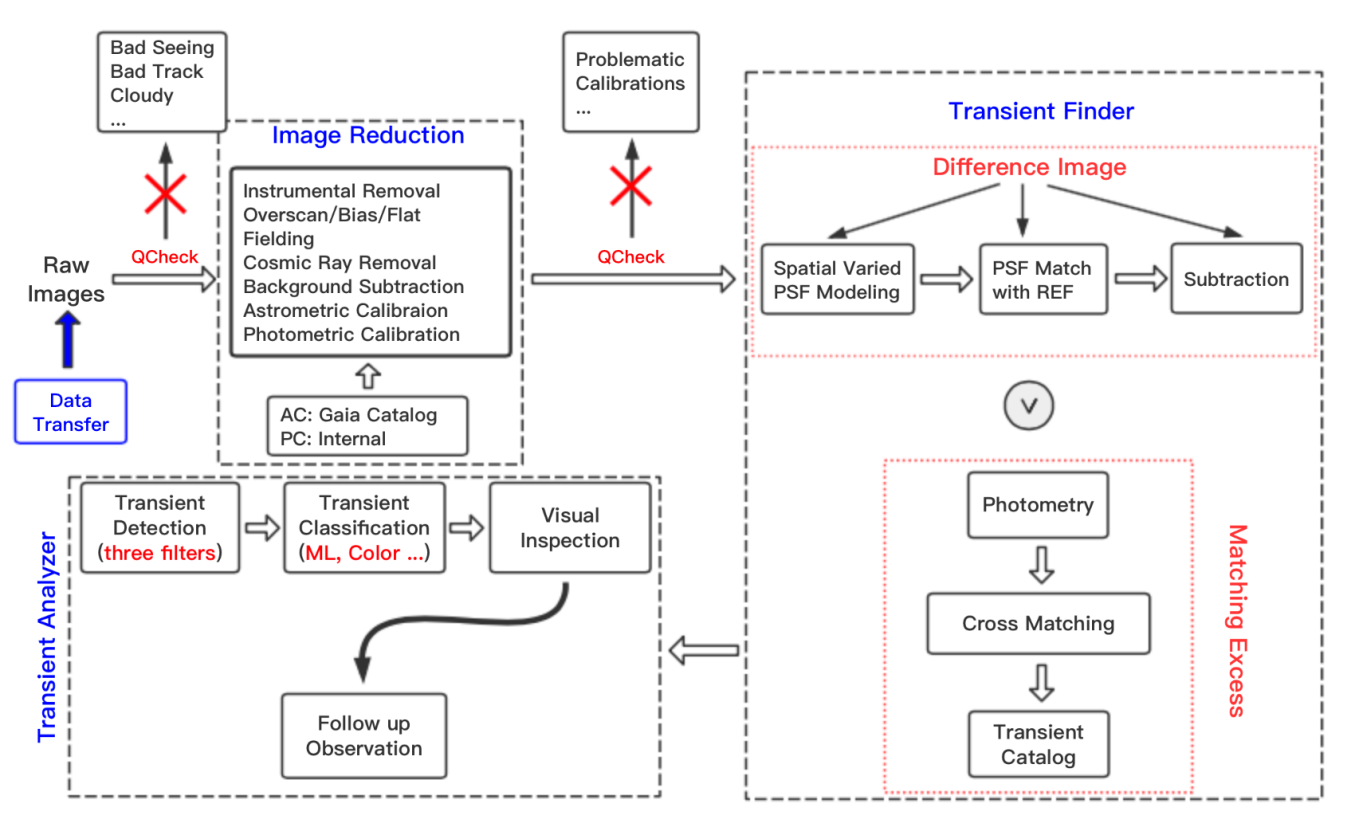
- **Imaging data processing, astrometric and photometric calibration, quality control, data products and release.**



Current status: MIP beta version, exploring absolute photometric calibration strategy

Transients and variables

- **Identifying and classifying transients and variables; fast and robust**
- **Transient Alert Pipeline: `TransFinder`**



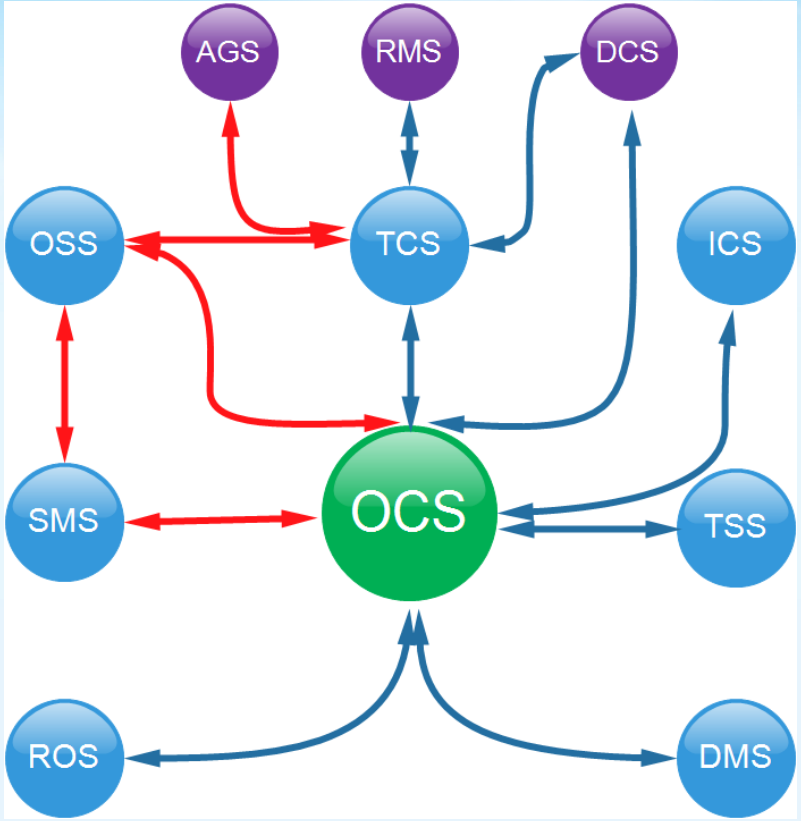
Current status: Develop image differencing module
2019.09-2020.06: Develop transient alert module
2020.07-2020.12: Integrating all the modules and validating the performance

Observatory control system (OCS)

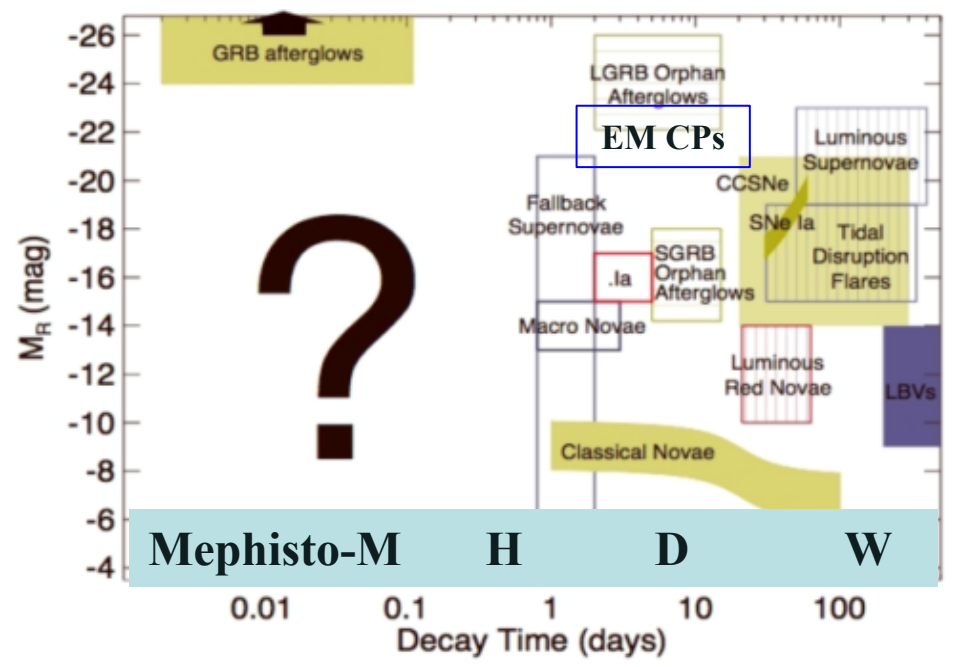
- **OCS: Master control system that commands, coordinates, and monitors the observatory. The OCS is responsible for the high level operations including user interfacing, observation sequencing, resource allocation and system monitoring and maintenance.**

An unmanned fully robotic observatory

Current status:
Discuss and refine the optimal architecture and interface

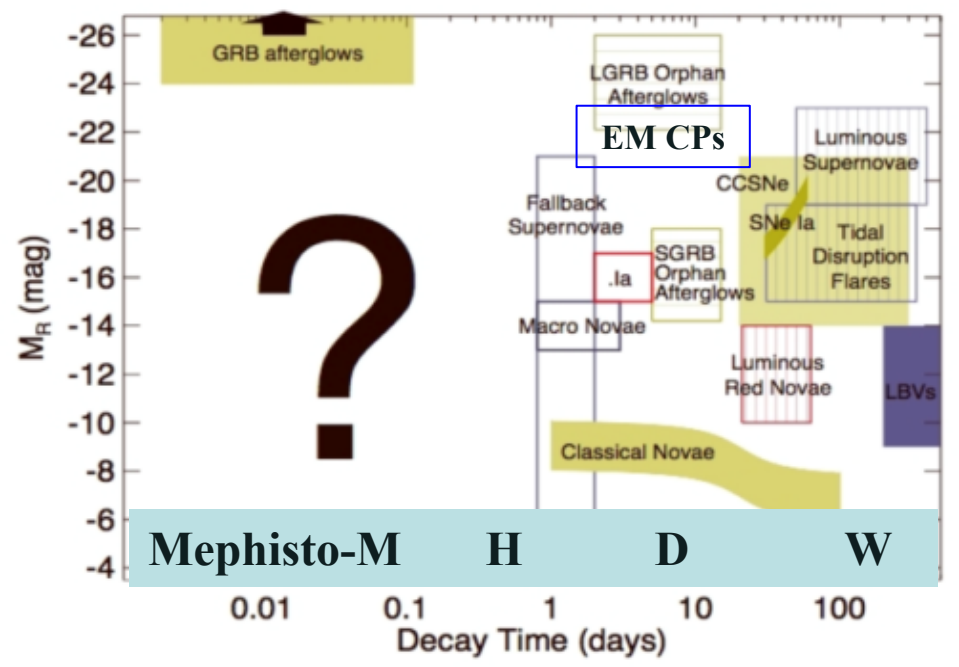


MEPHISTO key sciences

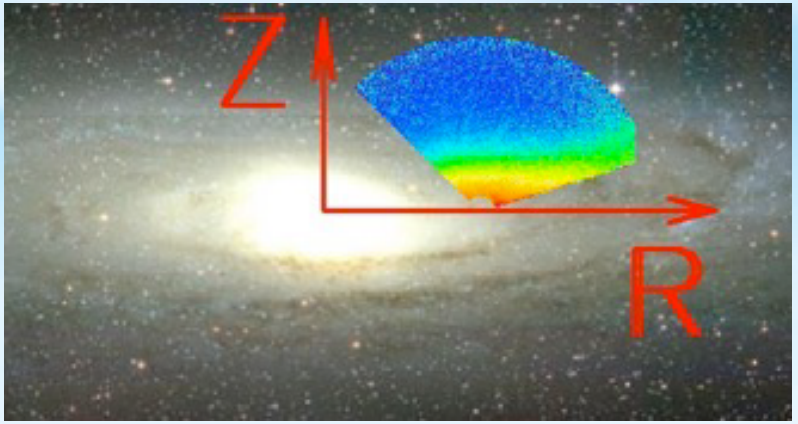


Cosmic transients and physics in extremely conditions

MEPHISTO key sciences

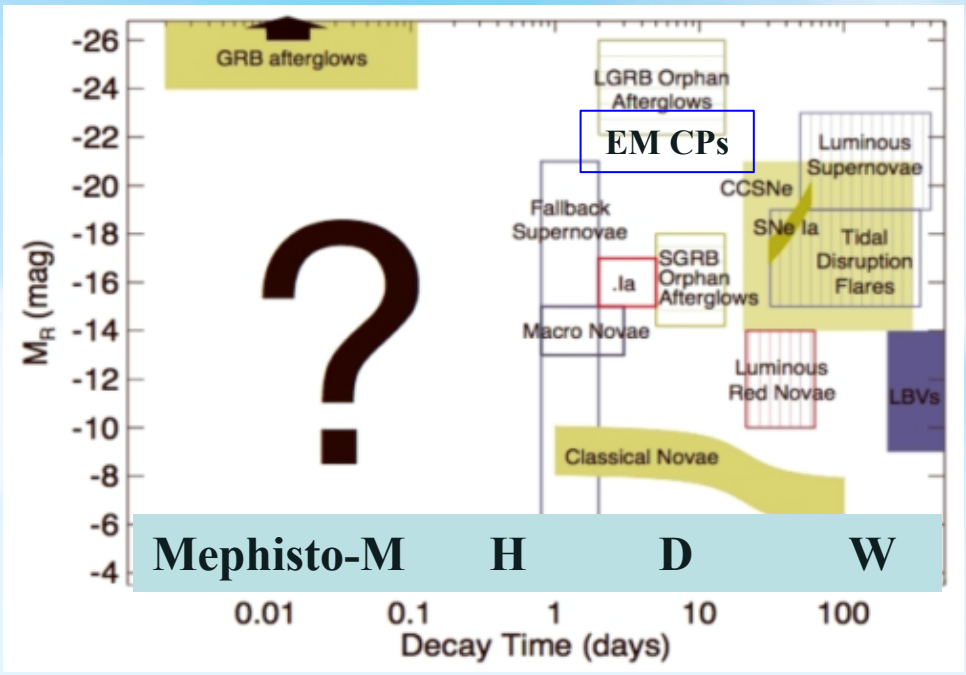


Reveal the true multi-dimensional structure and evolution history of the Milky Way

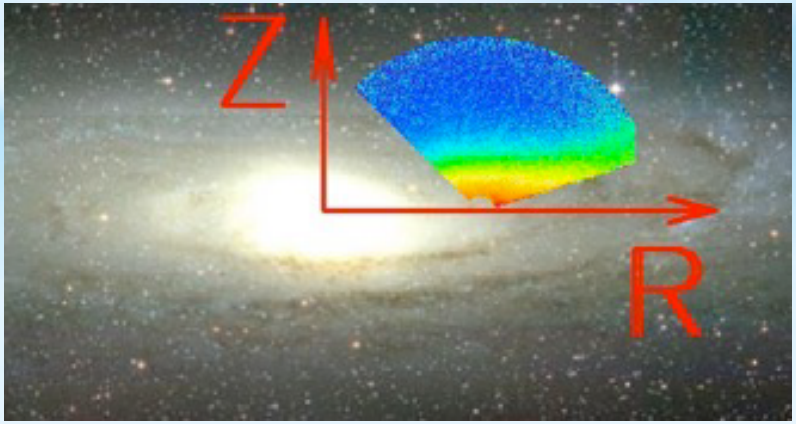


Cosmic transients and physics in extremely conditions

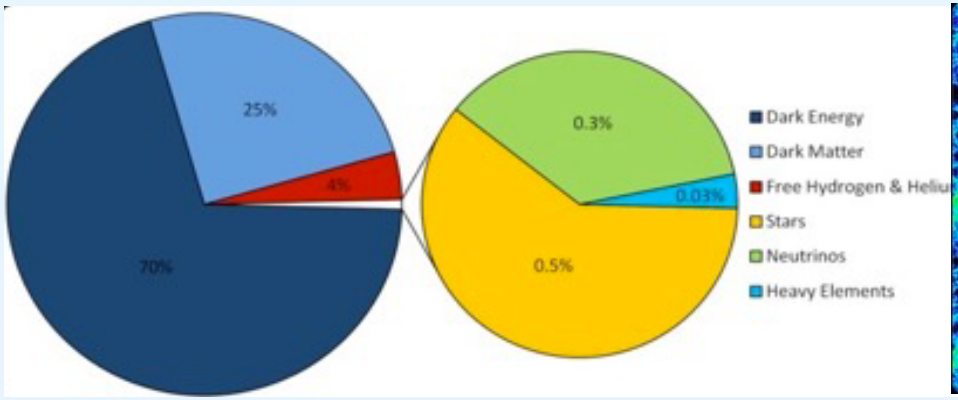
MEPHISTO key sciences

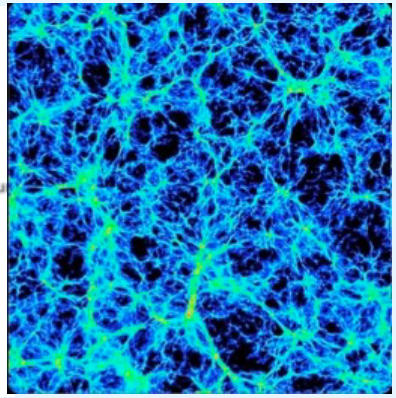


Reveal the true multi-dimensional structure and evolution history of the Milky Way



Cosmic transients and physics in extremely conditions

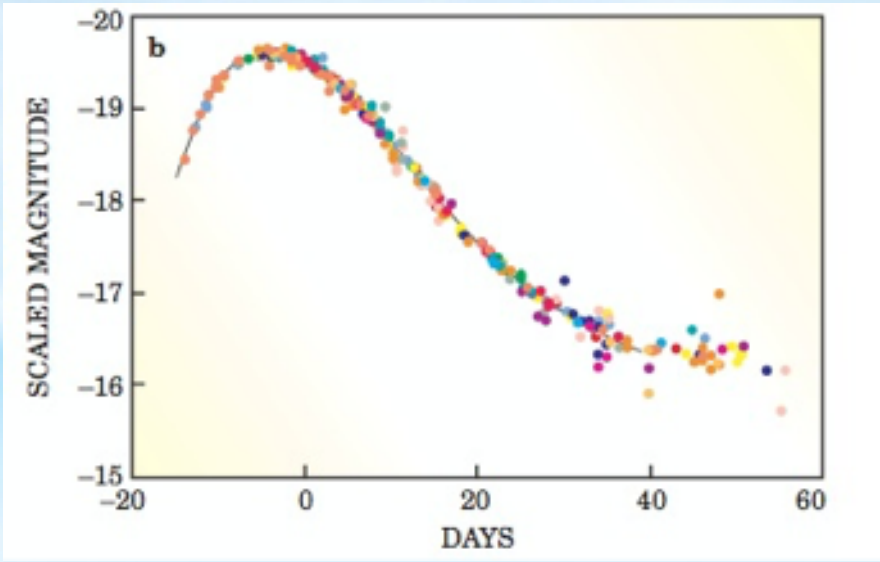


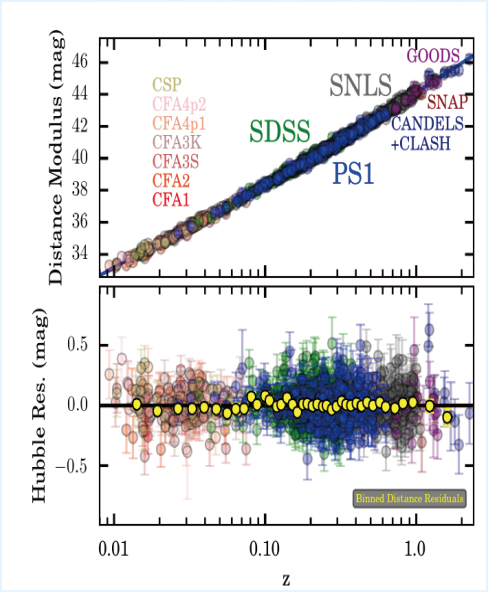


- **The large scale structure of the universe;**
- **Galaxy formation and evolution;**
- **The nature of dark matter and dark energy**

SNe Ia

- **SN Ia: The most useful, precise and mature tools for cosmic distance determinations;**
- **Observations of SN Ia have revealed the presence of dark energy and are being used to measure its properties;**
- **The nature of Type Ia explosions, the progenitors involved remain elusive.**





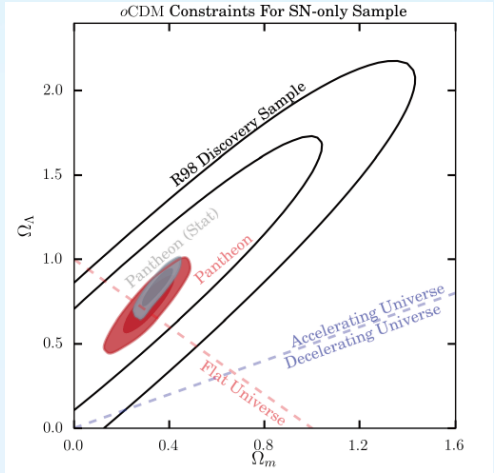


Figure 18. Evidence for dark energy from SN-only constraints. Here we show confidence contours at 68% and 95% for the Ω_m and Ω_Λ cosmological parameters for the oCDM model for both the Riess et al. (1998) discovery sample and the Pantheon sample. The Pantheon constrains with systematic uncertainties are shown in red and with only statistical uncertainties are shown in gray (line).

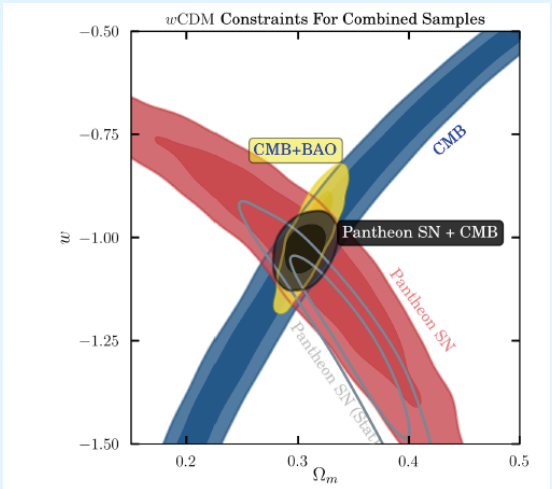
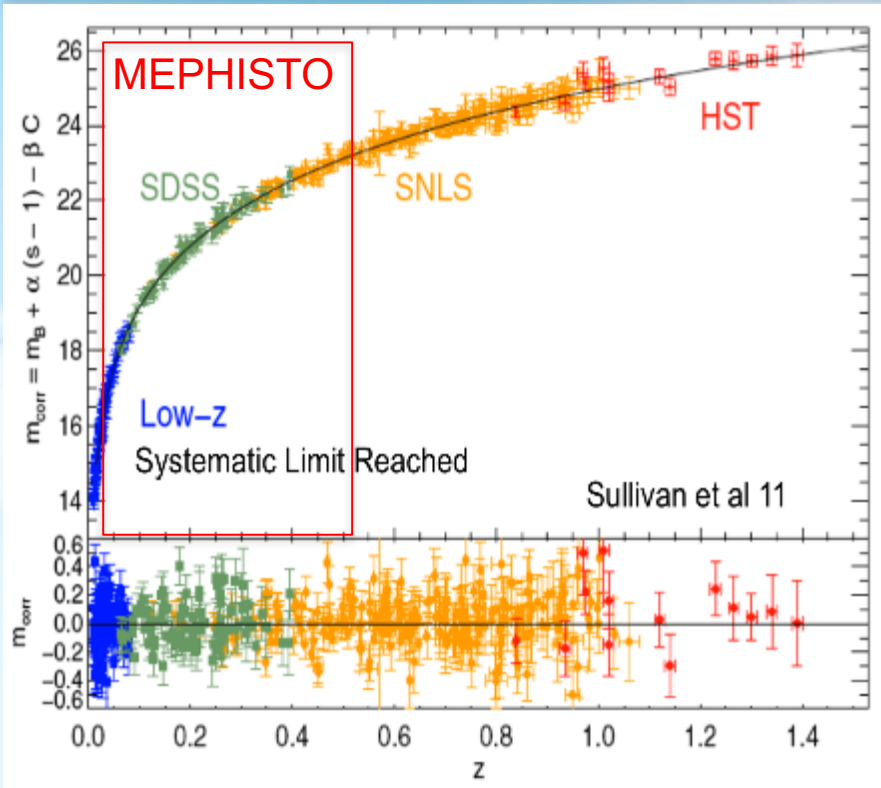
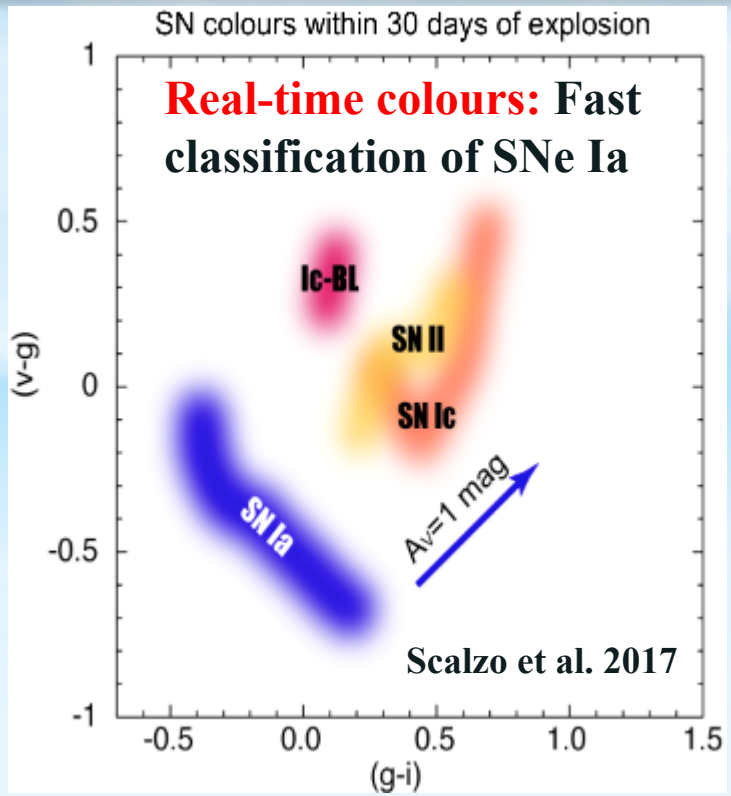


Figure 20. Confidence contours at 68% and 95% for the Ω_m and w cosmological parameters for the wCDM model. Constraints from CMB (blue), SN - with systematic uncertainties (red), SN - with only statistical uncertainties (gray-line), and SN+CMB (purple) are shown.

SNe Ia





Currently samples totaling ~10^3 SNe Ia are available for constraining cosmology. Yet,

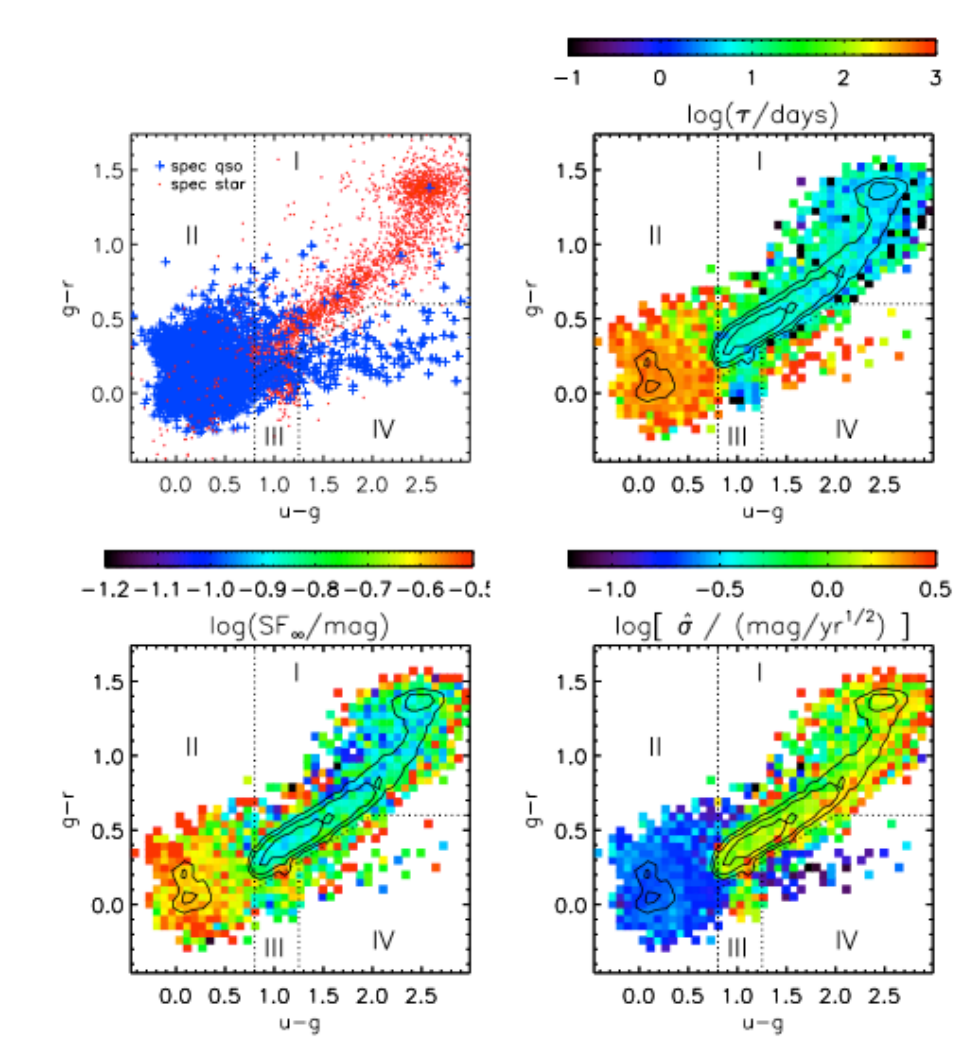
- **Observed by a variety of telescopes**
- **Sensitive to subtle, systematic effects; Uncertainties in the intrinsic colour variations**
- **Effects of the dust extinction**

MEPHISTO-D survey will obtain high quality, real-time colour and multi-band light curves for 30,000 SNe Ia; MEPHISTO-W will discover 500,000 candidates. These will allow us to explore the physics of supernovae themselves, to constrain the cosmic models, and to probe the nature of dark energy.

AGNs/QSOs

- Photometric (colours & variations) and astrometry (no proper motions) data from MEPHISTO-W will allow the construction of clean and complete samples of over 10 million AGNs and QSOs in the northern hemisphere.

- The samples will complement those of LSST, and help improve our understanding of the AGN and Quasar phenomena.



Subsecond universe revealed by star trails

- **CCDs: Readout time limits time resolution to a few seconds**
- **Star trail technique enables wide-field photometry to a few milliseconds:** Howell, S. B., & Jacoby, G. H. 1986, 98, 802; Thomas, D., & Kahn, S. 2018, The Astrophysical Journal, 868

- **Subsecond photometry: Compact objects, occultations, eclipses and transients**
  - **KBOs, Oort objects (numbers, sizes;** Kenyon, S. J., & Bromley, B. C. 2004, AJ, 128, 1916)
    - **Stellar occultations by km-size trans-Neptune objects (≈ 10^{-3} per star per yr of duration ≈ 200ms; Zhang, et al. 2013, AJ, 146, 14)**
  - **Stellar flares (**Schmidt et al, 1809.04510; Yang et al., 2017, AJ, 868)
    - **A few to tens of minutes; reconnection of magnetic field lines in the stellar outer atmospheres**
  - **X-ray binaries, polars, symbiotic stars, CVs**
    - **Rotation, pulsation, accretion (seconds to milliseconds**
  - **Blazars (**Raiteri et al., 1812.0315)
    - **Flares by a factor of 100; shortest timescale (emitting region size, jet properties)?**
  - **Gamma-ray bursts**
  - **Fast radio bursts (**Keane, E. F. 2018, Nature Astronomy, 2, 865; Macquart, J.-P. 2018, Nature Astronomy, 2, 836; Raiteri et al., 1812.0315)
    - **Thousands a day of duration milliseconds to tens of milliseconds**

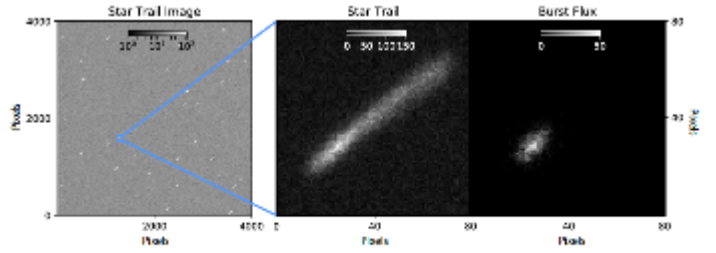


Figure 1: A star trail image corresponding to a 1 second exposure on a single LSST CCD in the r filter. The two zoom-ins on the right show a star trail exhibiting variability.

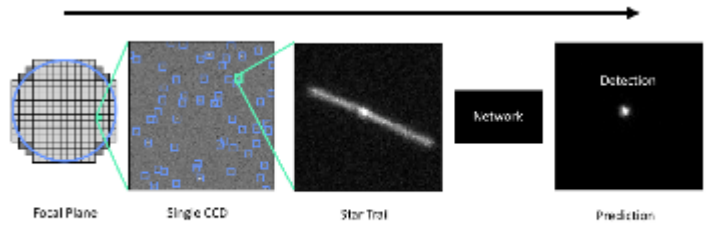


Figure 2: The image processing pipeline. We extract the individual star trails from the image and classify them with a neural network.

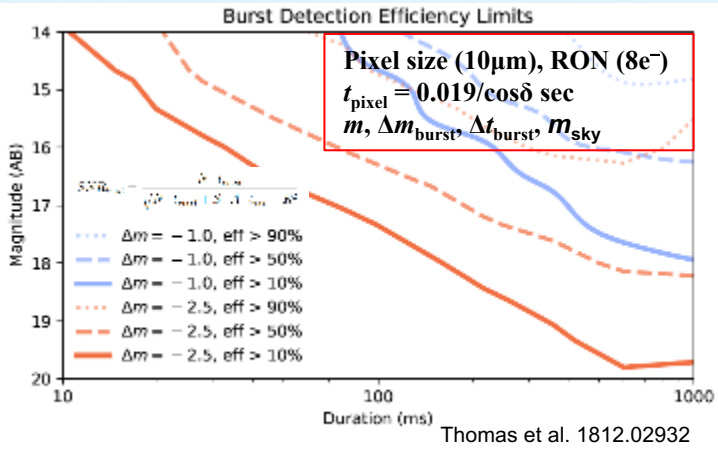


Figure 3: Detection accuracy and performance limits for 15 second star trails.

Optimal t_{pixel} can be control to vary from shorter than 0.019/cosδ sec to a few seconds.

MEPHISTO
0.286 arcsec per 10um pixel
52.448cosδ pixel per second

The Solar System

- **MEPHISTO-D will include the Ecliptic plane and take an inventory of the Solar System, and characterize the objects with high precision colours and variations:**
  - **5M Main belt asteroids (MBA)**
  - **40,000 Trans-Neptunian objects (TNO)**
  - **50,000 Trojans/Greeks/Hildas**
  - **Unknown objects such as Planet X**

- **Help understand the formation and evolution of the Solar system**

Courtesy: R. Hurt