Multi-messenger Astronomy

– Photon detection –

Part 1: optical counterparts

Ecole de Gif - 2024

A word of caution

- This course was insufficiently prepared!
  - My excuse: the commissioning of *SVOM*

- Consequences:
  - It stays at the general level
  - You’re encouraged to… Ask questions and correct me when needed

Today:
  - General comments on photonic signals for MM Astronomy
  - Optical observations

Tomorrow:
  - High-energy observations & GRBs: the *SVOM* case

Multi-messenger Astronomy

- The messengers of Astronomy (by decreasing speed)…
  - *Photons*, from radio to Very High-Energy gamma-rays ; v = c ; straight
  - *Gravitational Waves* ; v = c ; straight
  - *Neutrinos* ; v ≤ c ; straight
  - Particules (charged): Cosmic-Rays (1912) and solar particles ; v < c ; deflected
  - Matter: meteoroids, asteroids, interstellar bodies ; v << c
  - Other?

- Two obvious remarks:
  - The only messengers that can *really* impact our daily life are the asteroids and charged particles from the Sun (no astrology!)
  - *Multi-messenger* astronomy (MM) involves at least 2 messengers ☺, in contrast with *Multi-wavelength* astronomy (MWL), which involves only photons.
    - Here we'll consider messengers travelling in straight line at (≈) the speed of light: photons, GW and ν.
    - In the following: photons + another messenger

Scope of the course

1. Stress the importance of the photonic signal

2. Explain some difficulties associated with the detection of the counterparts of MM messengers

Two “flagship” examples

SN 1987A

- This *supernova* occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. It was first detected on Feb. 24th 1987, and it is the closest SN detected in the era of modern astronomy.
- Three collaborations working with neutrino detectors detected a short burst of MeV neutrinos (24 in few seconds) on Feb. 23rd, few hours before the emergence of the visible SN. Their origin was compatible with the LMC. These neutrinos marked the collapse of the stellar core.
- These joint observations led to significant progress in our understanding of SNe.

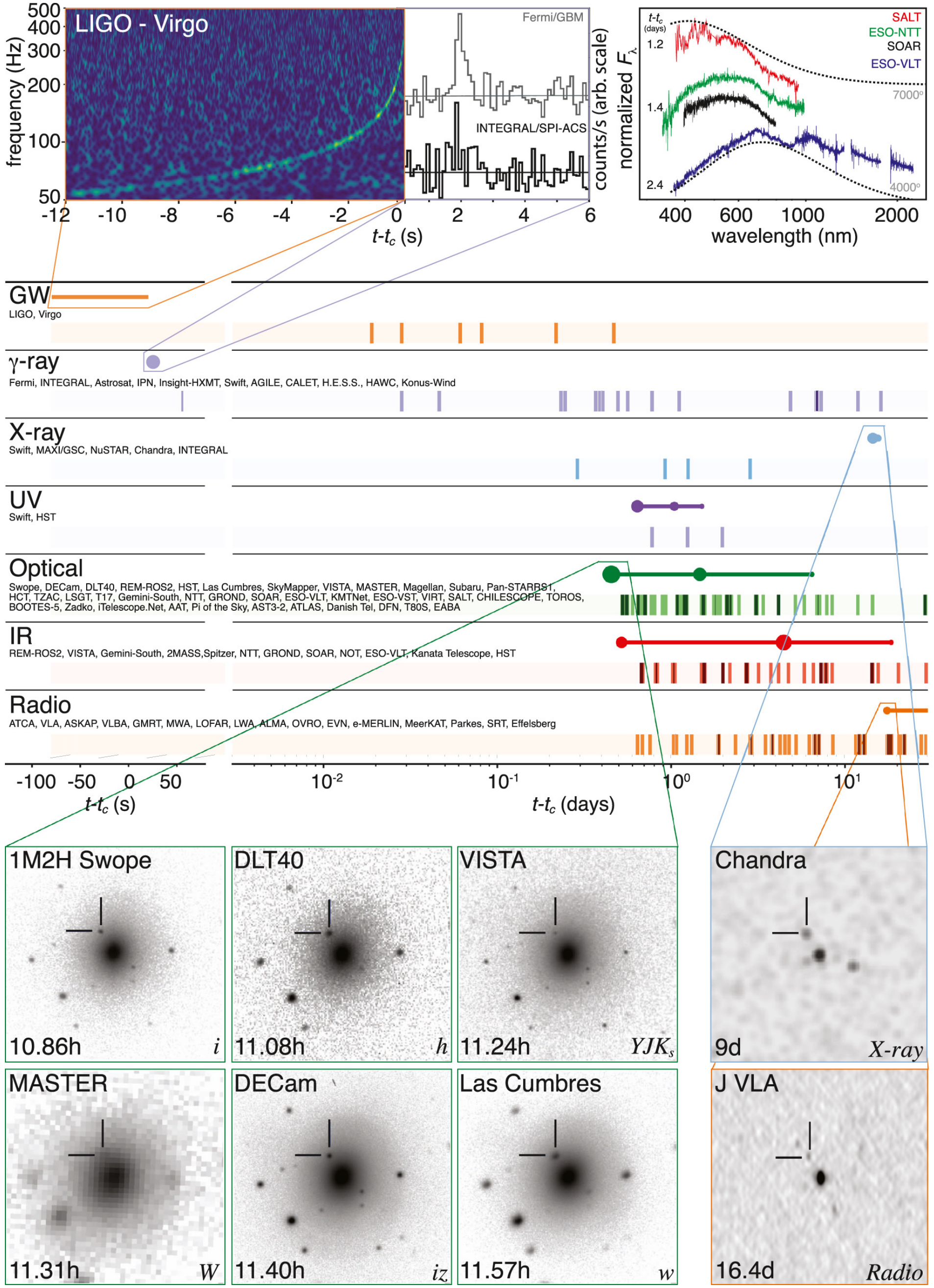
- No other case since then.

GW 170817

Abbott et al. 2017 (ApJ)

- On August 17th 2017, Fermi GBM detected and roughly localized GRB 170817A and issued a GCN.
- (Almost) simultaneously, the LVK collaboration detected GW170817, a transient signal of gravitational waves, originating from the same region of the sky.
- The characteristics of GW170817 pointed to a *binary neutron star (BNS) merger*.
- A huge effort was then undertaken to search the optical counterpart inside a ≈30 sq. deg. error box. The counterpart was eventually identified after ≈10 hours.
- Multi-wavelength observations of the counterpart showed the presence of a relativistic jet seen ≈20° off-axis and revealed a kilonova (KN) showing r-process elements in its spectrum.
- These observations provided unique information about BNS mergers.

- No other case since then.



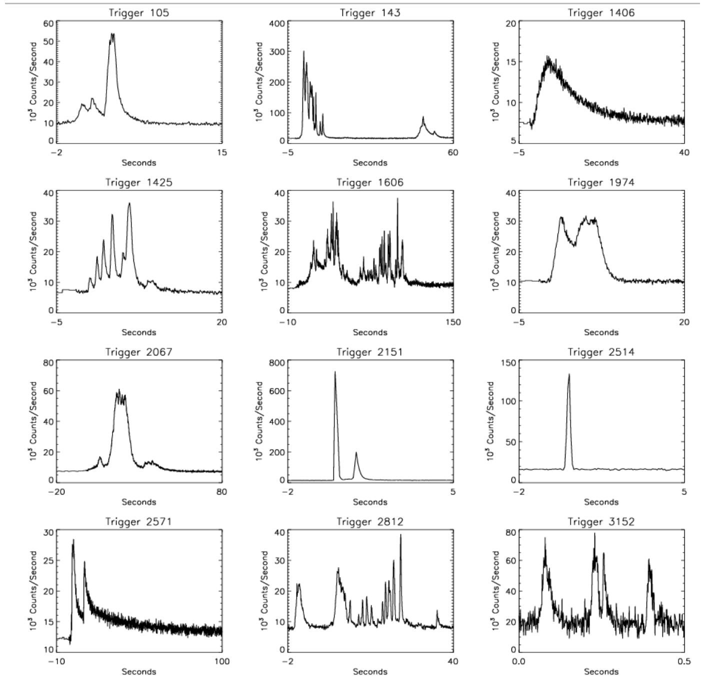
A summary

- Multi-messenger observations remain rare.
- In both cases, the photon signal was reported first – even if it was emitted after the non-photonic component.
- The association of GRB 170817A with GW170817 raised a huge interest, prompting extraordinary follow-up campaigns at all wavelengths, despite the size of the error box (≈30 sq.deg.).

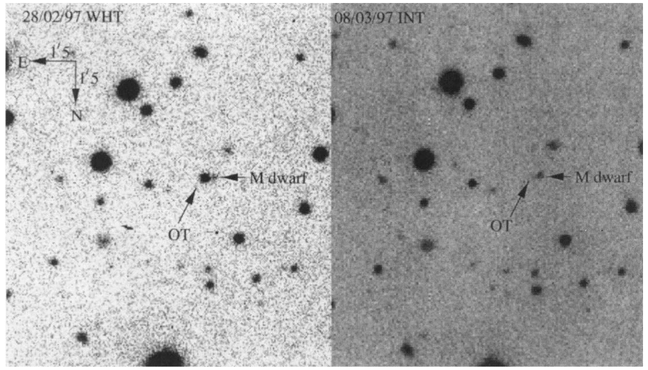
- In both cases, most of the energy was emitted in non-photonic components. However, the photonic signal was crucial to interpret the observations. Benefitting from centuries of astronomical observations ☺, photonic astronomy informs us about the distances, host galaxies and environment of (transient) MM sources.

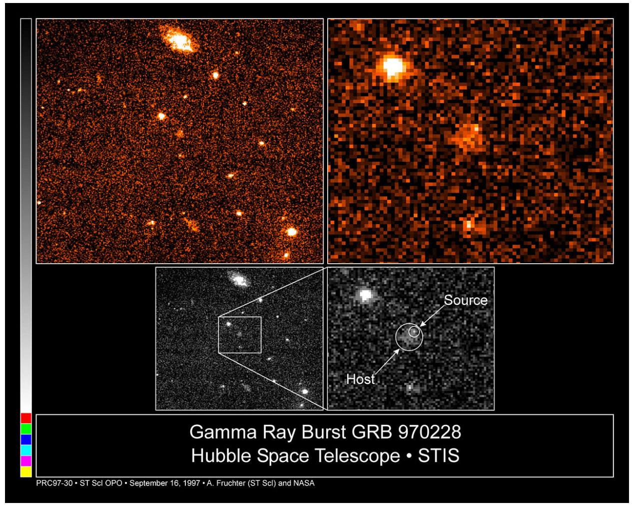
A comparison with GRBs (detour)

- During 30 yrs (1967 – 1997), we had only gamma-ray transients.
- The discovery of afterglows in 1997 allowed to use the means of classical astronomy to clarify the nature of GRBs:
  - Distance (z) and energetics -- host galaxies -- GRB formation history – etc.
- And to use GRBs as probes of the young and distant universe:
  - Metallicity – Star Formation Rate – re-ionisation – etc.



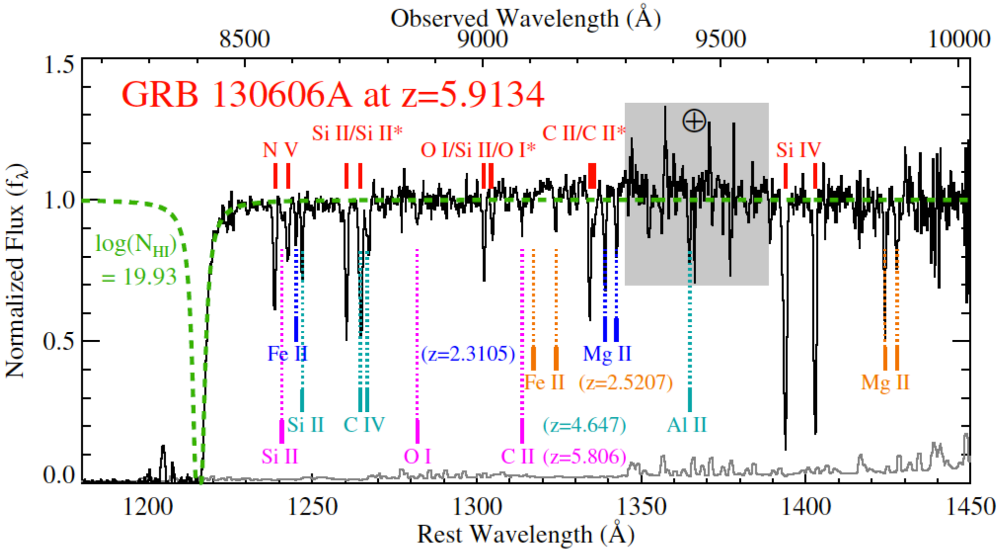
GRB 970228





Gamma Ray Burst GRB 970228
Hubble Space Telescope • STIS

PRC97-30 • ST ScI OPO • September 16, 1997 • A. Fruchter (ST ScI) and NASA



Photonic counterparts

- At this point you should be convinced of the importance of the photonic signal. Most often it permits better localizations and the measure of various characteristics of the source (distance, host galaxy, environment…). This last step, however, involves the optical spectroscopy of the transient or its host with large telescopes, which requires ≈1 arcsecond localizations.
- In the following, we will focus on the detection of the photonic counterparts of ***transient MM sources***** . These photonic counterparts may be detected…
  - Independently → Surveys (slides 12-20)
  - After a follow-up campaign → Follow-up (slides 21-22)

Photonic transients at large

- Transient signals are detected at all wavelengths, and so are the counterparts of MM transients.
  - *Radio* transients, including *Fast Radio Bursts* (FRB)

    → Outside my area of expertise. ☹
  - *Optical* transients: Stars (active, accreting, exploding), AGN, TDE, etc.

    → Not my area of expertise, but I'll try…
  - *X-ray* transients: Stars (active, accreting, exploding), AGN, TDE, GRBs
  - *Gamma-ray* transients: GRBs, SNe
  - *VHE gamma-ray* transients

    → Outside my area of expertise. ☹

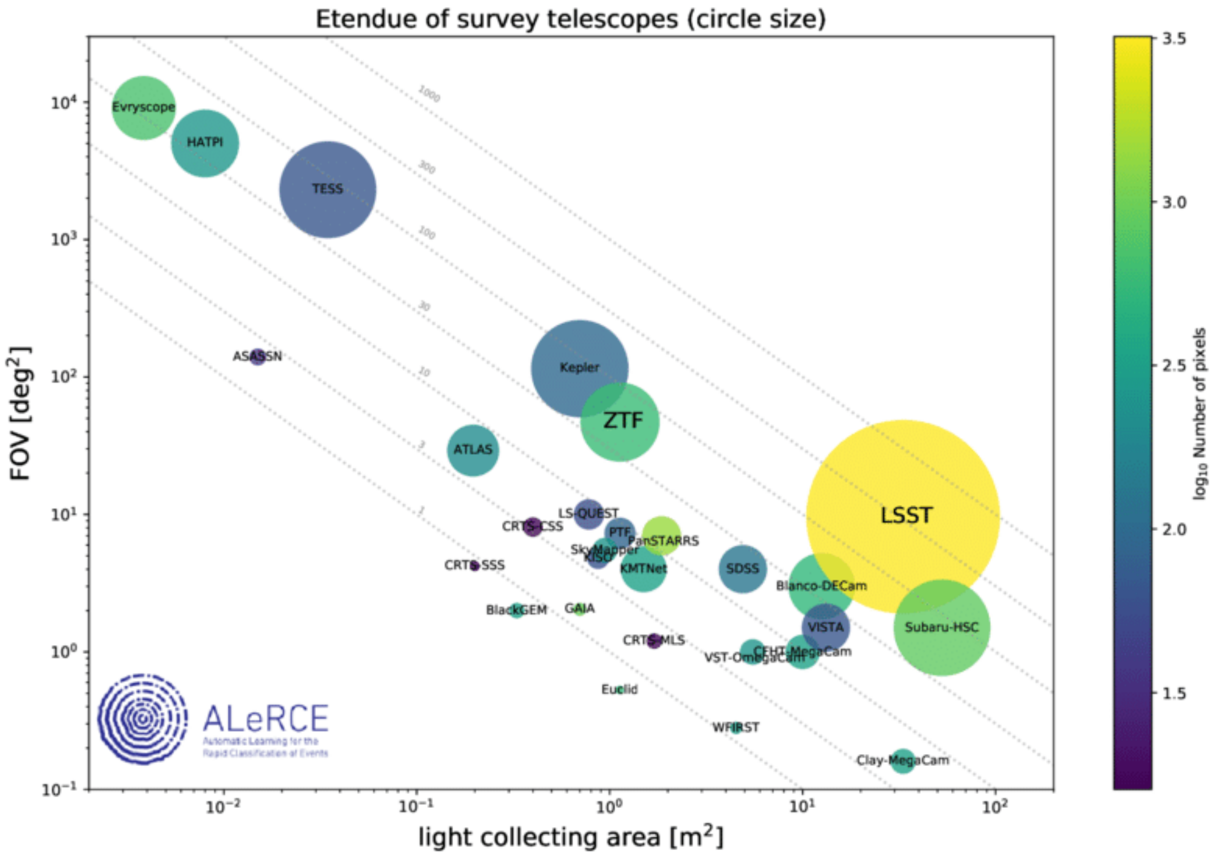
Optical surveys

- Let's focus now on *optical transients*. We'll not discuss the detectors themselves but rather the systems needed to identify the counterparts of MM signals, and some difficulties connected with the search for MM counterparts.
- MM detectors observe the full sky (or half) searching for rare and unpredictable transients. The independent detection of their optical counterparts requires a wide field of view, a high duty cycle and a sufficient sensitivity.
- What are we looking for?
  - For VHE ν transients: AGN activity? A GRB?
  - For BNS mergers: the optical afterglow of a short GRB and/or a kilonova, depending on the orientation of the source (the afterglow is beamed while the kilonova is ≈ isotropic).
  - For BHNS merger: similar to BNS counterparts?

Optical surveys: etendue

- Etendue is more or less proportional to the product Ω A (it is the integral of dΩ dS cos(θ))
- The larger the etendue, the greater the number of sources detected.

- Optical surveys are unique tools in many areas of astronomy.
- In the coming years, the study of the transient sky is expected to become an important field of astronomy, thanks to the advent of new telescopes / detectors / computing facilities.



Optical surveys:

- Instrument requirements:
  - Sky coverage / Effective area / Filters / Number of pixels

  - *Sky coverage*: the sky is large: ≈ 41253 sq. deg.
    - 1 sq. deg. is already a large field of view for an astronomical telescope (Moon is 30' in diameter).
    - Nights are short: 10 hrs = 600 minutes: in 1 night a telescope with 1 sq. deg. FoV doing ≈1 minute exposures will cover only 1-2% of the sky.
  - *Effective area* can range from few 100 cm^2 to several m^2.
  - *Filters* are essential for the classification of events (and for astronomy in general). It is necessary to observe the sky with many filters in parallel (or in sequence).
  - *Pixels*: With a typical sky resolution of e.g. 0.3", about 10^8 pixels are needed to cover a field of 1 sq. deg. The number of pixels can reach or exceed 10^9 ($3.2\ 10^9$ for the camera of the VRO – $0.64\ 10^9$ for *SVOM*/GWAC)

- Duty cycle: it must be as high as possible, avoiding to loose time for changing filters, reading the detectors, pointing the telescope, etc.

Optical surveys: observing strategy

- The observing strategy must consider the typical timescale and brightness of the sources under study
- Many instrumental parameters need to be considered
  - Pointing strategy
  - Duration of exposures
  - Sequence of filters
  - Quality of the sky
  - Presence of the moon
  - Strategy of revisit
  - Background rejection: artificial satellites, cosmic rays, instrumental effects…
- As an example, the survey strategy of the VRO-LSST has been studied and optimized by a dedicated science group. It consists of 2 visits of the same field with 2 different filters, separated by 33 minutes, which are followed by another visit 2-4 days later (this is the simple version). Takes into account the time to switch filter, to slew to the new pointing, to read the detectors, etc…
- For less expensive projects, it is recommended to adapt the parameters of the survey to the type of object studied, building dedicated surveys.
- There are many projects surveying the sky now, in the context of MM astrophysics.

Optical surveys: source identification

- Numerous transient sources
    - Typically few 10^5 /night for ZTF and few 10^6 /night for VRO-LSST
- Use *catalogs* to find new sources (if you are not the most sensitive ☺)
- Eventually, build your own catalog.
- Check variability, photometric evolution, colors
- Big data helps!

- Follow-up spectroscopic observations of interesting sources with larger telescopes. One advantage of optical surveys is that the candidates are usually localized with arcsecond precision, sufficiently well to engage big telescopes. This is not the case for candidates detected at higher energy.
- Big telescopes have a high pressure, so you must be highly confident about the quality of your candidate when you request an observation.

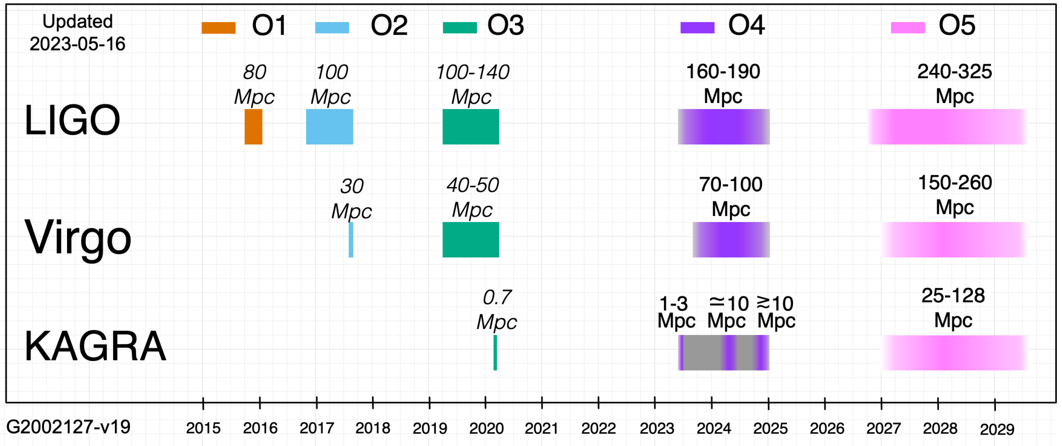
ZTF, an example

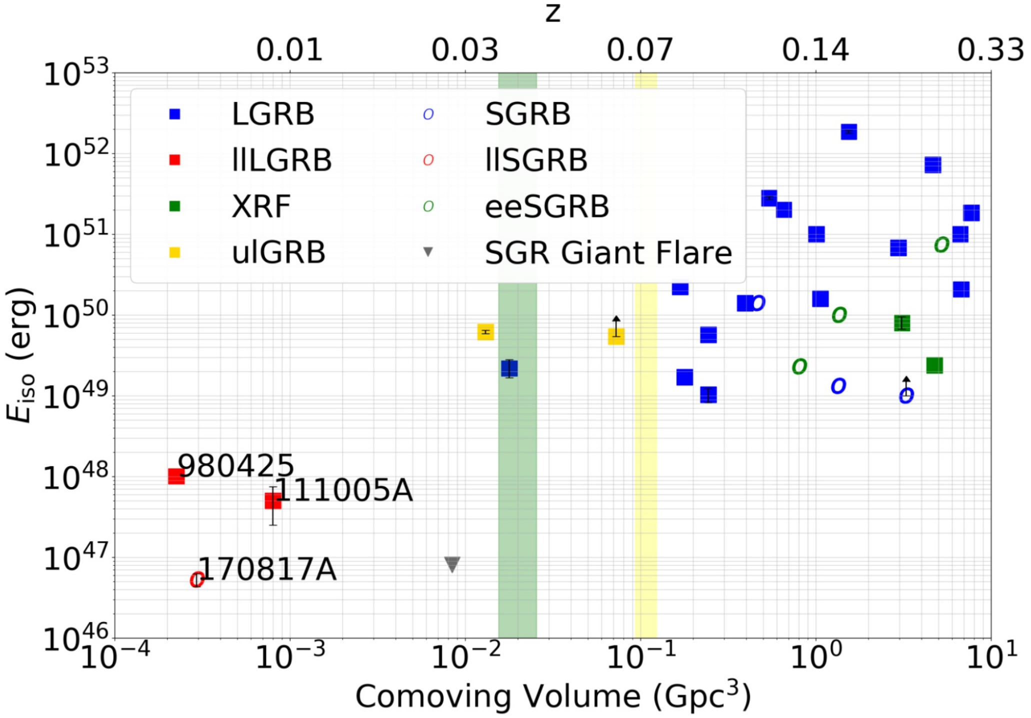
Optical surveys: the clients

- Detection of many transients types, of interest for various communities. MM community usually not the main “client”.
  - Variable stars
  - Exoplanet transits
  - Explosive events: novae, kilonovae (MM), supernovae (MM)
  - Solar system objects: Asteroids, KBOs
  - Microlensing events
  - Background events: artificial satellites, cosmic-rays, instrumental features (ghosts, persistence…)
  - Etc.
- Brokers (seven of them for VRO) permit a first classification of transients, and the distribution of selected types to selected clients, among them MM.

Some problems…

- Many MM sources are not expected to emit visible radiation:
  - Binary Black Hole (BBH) mergers
  - choked GRBs?
- For the others, the phenomenology of the expected visible emission may be poorly known (exception: SNe).
- Pre-defined survey strategy may lead to miss the counterpart.
- The emission pattern of GWs and their optical counterparts may be very different (e.g. the afterglow) or the optical counterpart may be faint (kilonova).
- If we except GRB 170817A, the horizon of GW detectors is smaller than the distance of the closest short GRB detected to date (fig.). However, this may change in few years with the improved sensitivity of GW detectors.





Arcier et al. 2020

Short conclusion

- Optical surveys are essential to search for the optical counterparts of MM phenomena.
- This is however a very difficult task, made even more complex by the number of transient optical sources in the sky, the rarity of MM transients, the poorly known phenomenology of the optical counterparts, and the size of the error boxes of MM transient events.
- But…
  - New facilities (instruments, computing) are coming every day and the field is progressing extremely rapidly.
  - Broad and deep optical surveys are useful tools in many areas of astronomy, not only MM.
- A lot of progress is to be expected from these facilities in the coming years.
- Spectroscopy of the candidate sources is the ultimate goal. This is the best way to secure the nature of the candidates, their distance, etc.

- Another, less costly, approach involves the fast follow-up of MM detections. This approach presents different challenges that we discuss now.

Optical follow-up

- Optical follow-up uses the information from a MM instrument to look for the counterpart. This information may come from a neutrino detector or a detector of GWs, with very different constraints.
  - VHE neutrino detectors (IceCube, KM3NeT) provide few sq. deg. localizations, but no distance indication. Until now, counterparts have been active sources (blazars, AGNs), not transient sources.
  - GW detectors usually provide poor localizations 10’s to 1000’s of sq. deg., an estimate of the nature of the source (BBH, BNS, NSBH) and its distance.
  - Both types of instruments provide low latency alerts (few to several seconds)

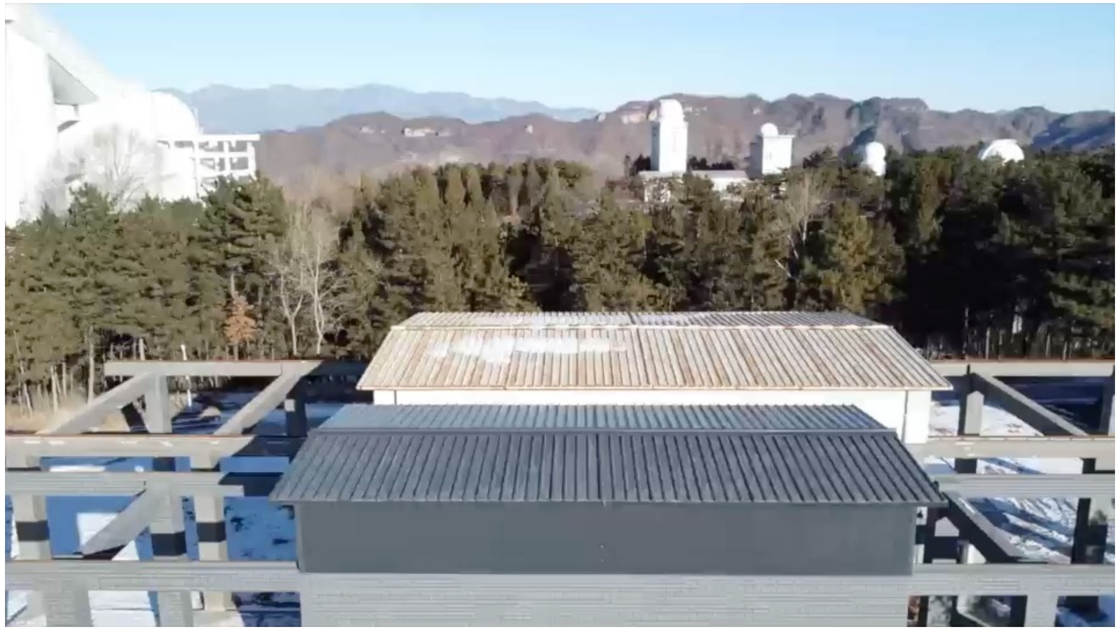
- Optical follow-up can be performed by dedicated instruments but also by survey instruments interrumpting their survey, this is especially relevant for large GW error boxes.

Optical follow-up vs survey

- Pros:
  - Reduces the region to be surveyed.
  - Ensures observations within a short delay after the MM transient.
  - In general we know what we are looking for, for instance a kilonova in case of a BNS merger. This allows to adjust the observing strategy: exposure time, filters, etc…
  - Can spend much more time monitoring a single source → better sensitivity and temporal evolution.
  - May be designed (optimized) for specific sources: GRBs, GWs, etc.
- Cons:
  - Observations not always performed in the best conditions: far from zenith, close to dusk or dawn, bad or moderate seeing, etc.
  - May react to many false alarms.
- Let's discuss two examples, from the SVOM mission:
  - *SVOM*/GWAC (courtesy of NAOC GWAC team) as a survey and follow-up instrument
  - The Colibrí telescope designed for the follow-up of GRBs detected by *SVOM*/ECLAIRs.

GWAC

- Installed at Xinglong Obs. China
  - ✓ Two domes
  - ✓ 10 mounts
  - ✓ 40 cameras + sCMOS 4040
  - ✓ V ~ 16 mag @ 10 exposure
  - ✓ ~ 3600 degrees
- Dedicated follow-up telescopes
  - 2*60cm + 50cm + 30cm, optical.



GWAC

More 14 WACs join GWAC network in China

Located at Jilin

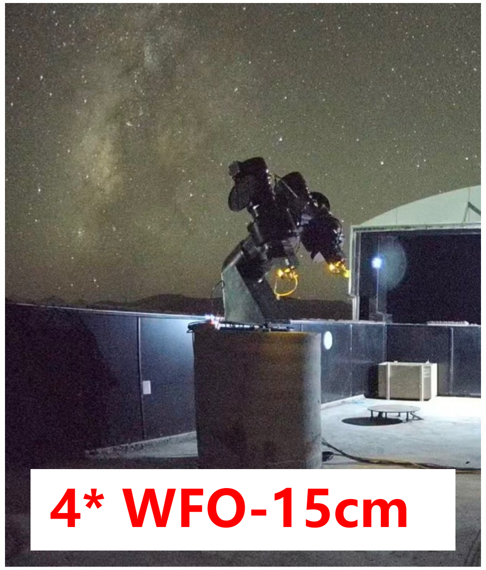
D： 150mm; f： 160mm
No. ： 4
Cameras： CMOS 4040
4K*4K, 9μm *9μm
V： ~14.5 mag @10 sec
FoV： 696 Sq.deg
Pixel scale： 11.6 arc sec.


4* WAC-15cm

D： 280 mm; f： 324mm
No： 6
Cameras： CMOS 4040
4K*4K, 9μm *9μm
V： ~17.0 mag @10 sec
FoV： 253 Sq.deg
Pixel scale： 5.7 arc sec


6* WAC-28cm

Located at Xingjiang


4* WFO-15cm

D： 150mm; f： 3200mm
No. ： 4
Cameras： CMOS 4040
4K*4K, 9μm *9μm
V： ~14.5 mag @10 sec
FoV： 380 Sq.deg
Pixel scale： 8.61 arc sec.

Part 1

GWAC network at three sites in China

(~4930 Sq.deg)

Xinjiang

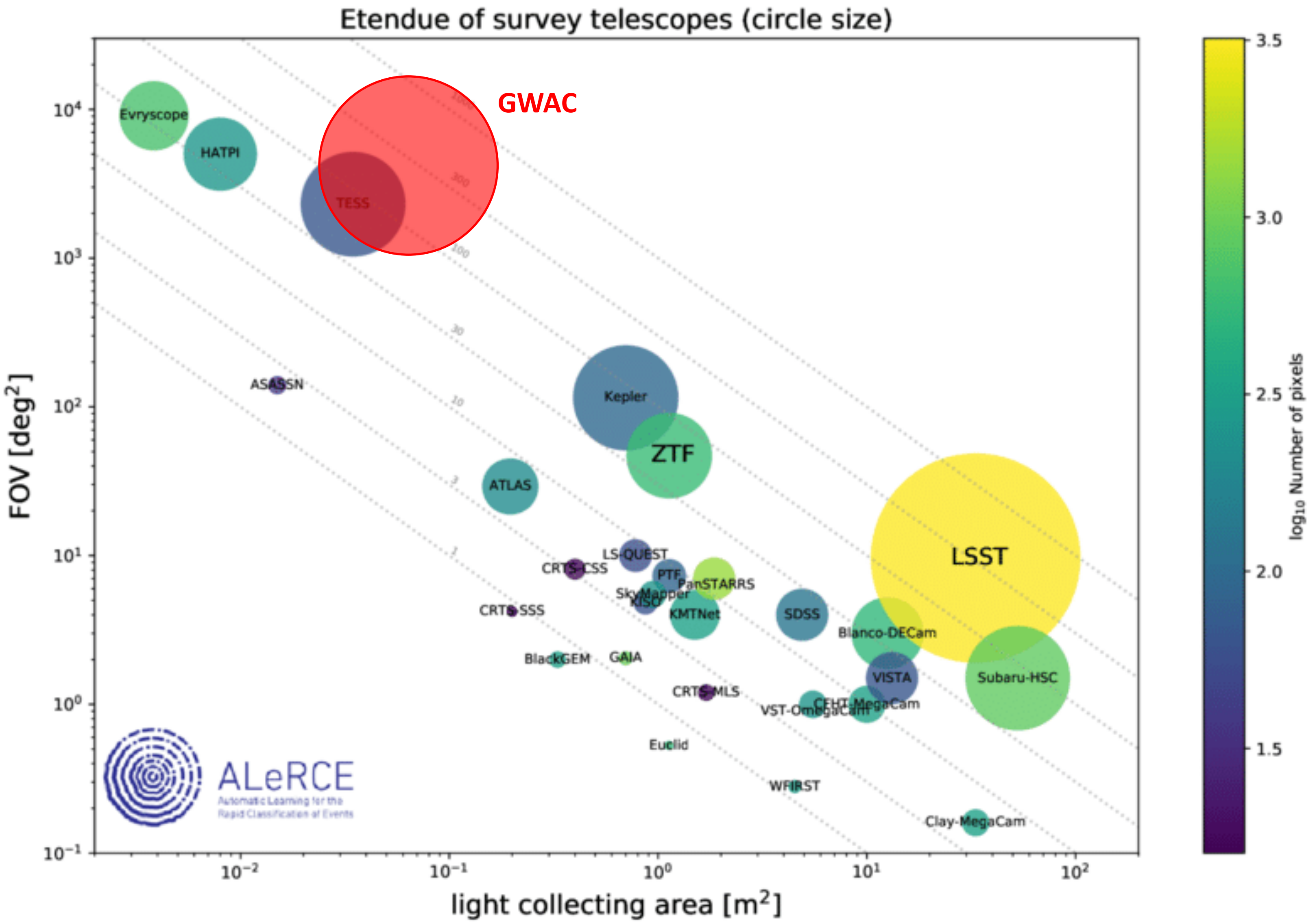
380 Sq.deg

Xinglong

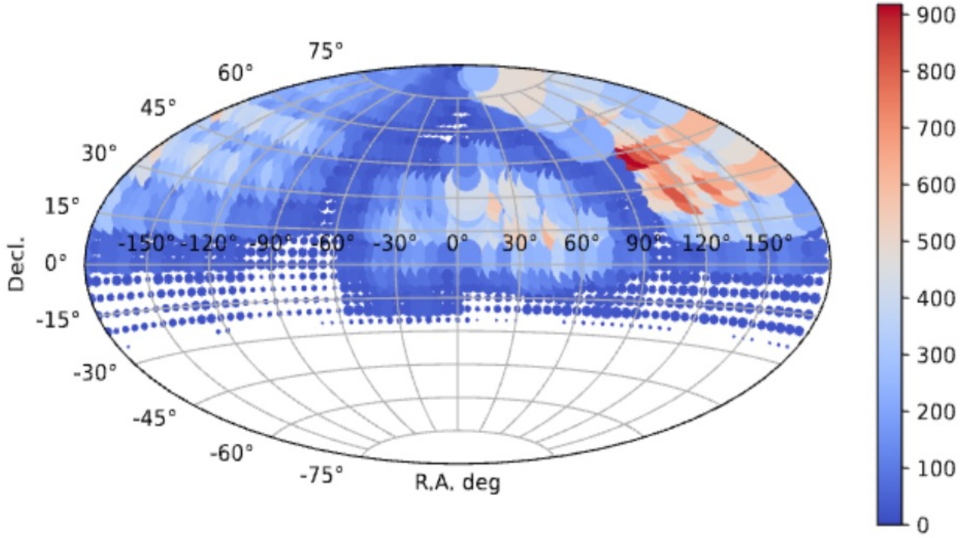
3600 Sq.deg

Jilin

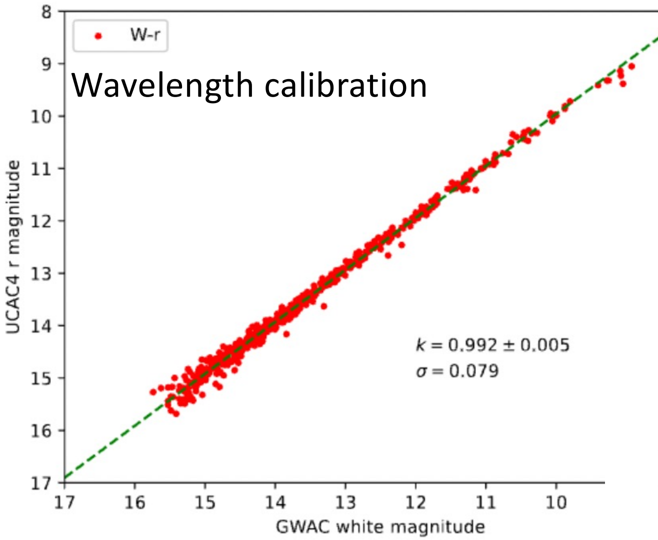
950 Sq.deg


Etendue of survey telescopes (circle size)
GWAC
Evryscope
HATPI
TESS
ASASSN
Kepler
ZTF
ATLAS
LS-QUEST
CRTS-CSS
PTF
PanSTARRS
SkyMapper
KISO
KMTNet
CRTS-SSS
SDSS
Blanco-DECam
LSST
BlackGEM
GAIA
VISTA
Subaru-HSC
CRTS-MLS
VST-OmegaCam
CFHT-MegaCam
Euclid
WFIRST
Clay-MegaCam
ALeRCE
Automatic Learning for the Rapid Classification of Events
300
100
30
10
3
1
10^4
10^3
10^2
10^1
10^0
10^{-1}
FOV [deg^2]
10^{-2}
10^{-1}
10^0
10^1
10^2
light collecting area [m^2]
3.5
3.0
2.5
2.0
1.5
$\log_{10}$ Number of pixels

GWAC performance and tests

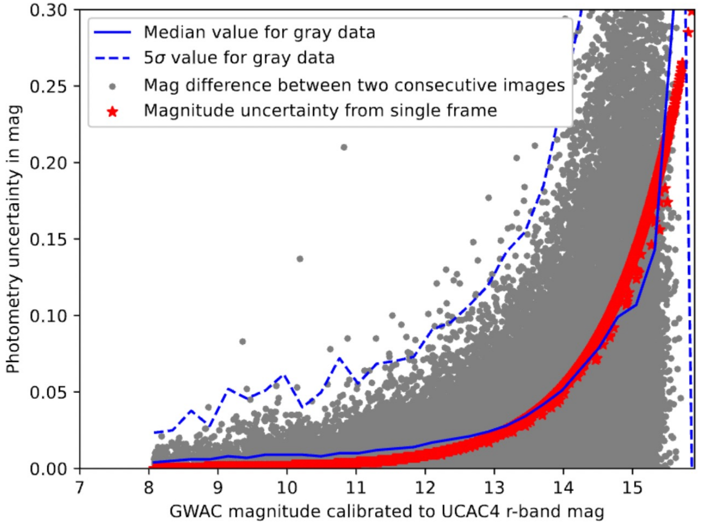


GWAC system test in hours
(Jan. 2017~May 2023)



r limit~15.5mag OR
V limit~16.1 mag

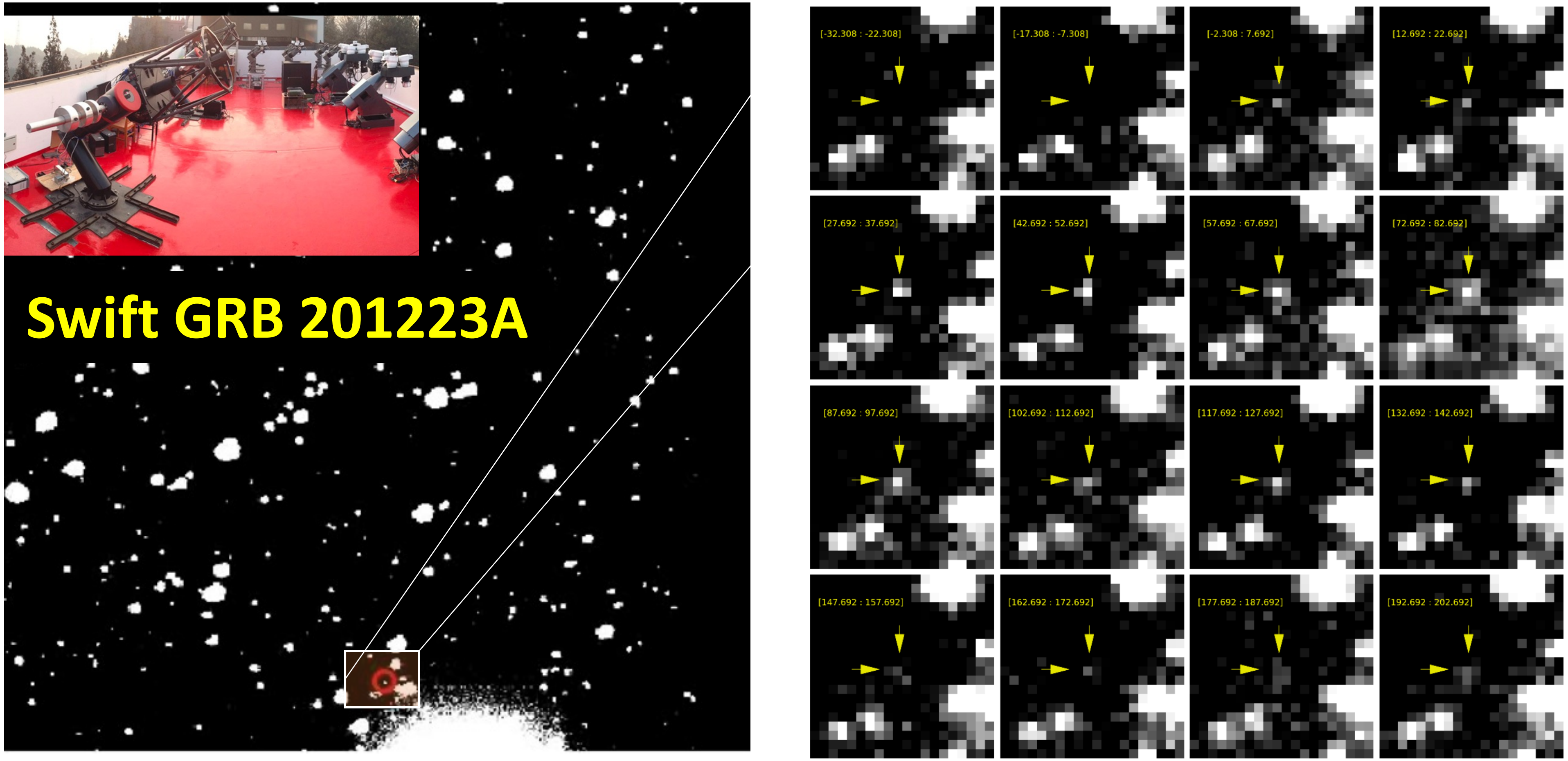
@10sec exposure



Xin et al., in prep

Early science with GWAC on gamma-ray burst

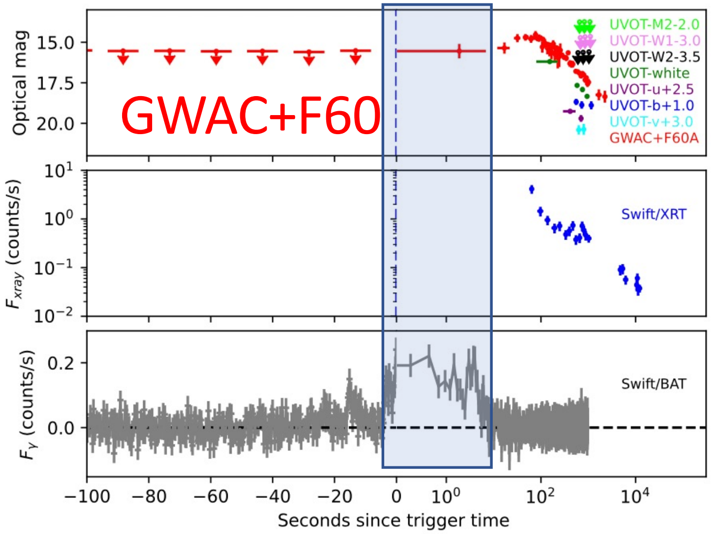
GWAC records the total event before, during and after the trigger time

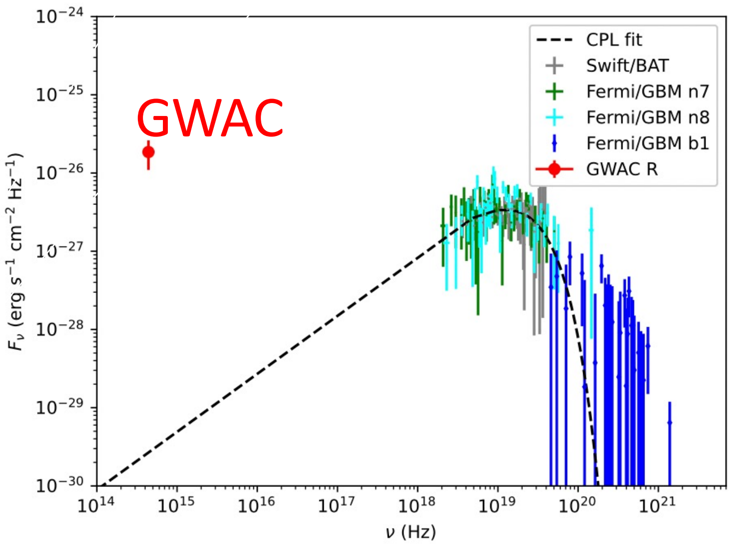


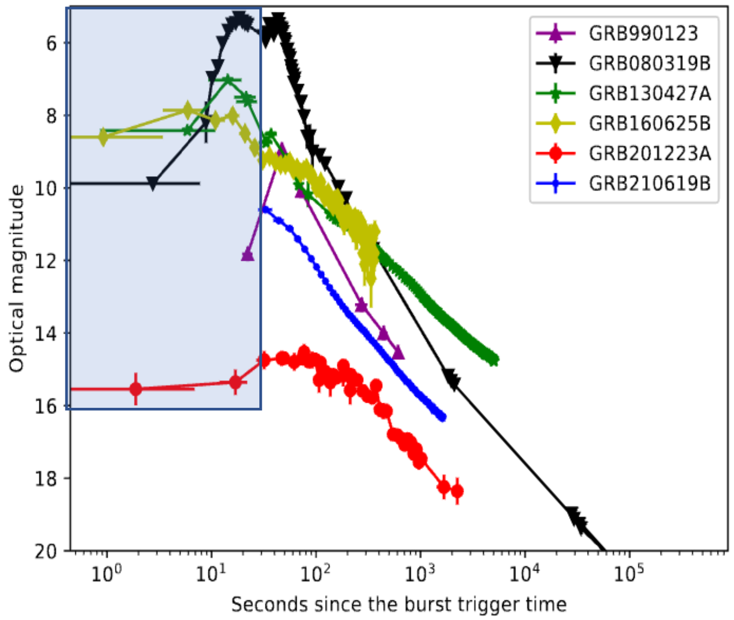
Xin et al., 2023, Nature Astronomy

Early science with GWAC on gamma-ray burst

Swift GRB 201223A， T_{90}~29s

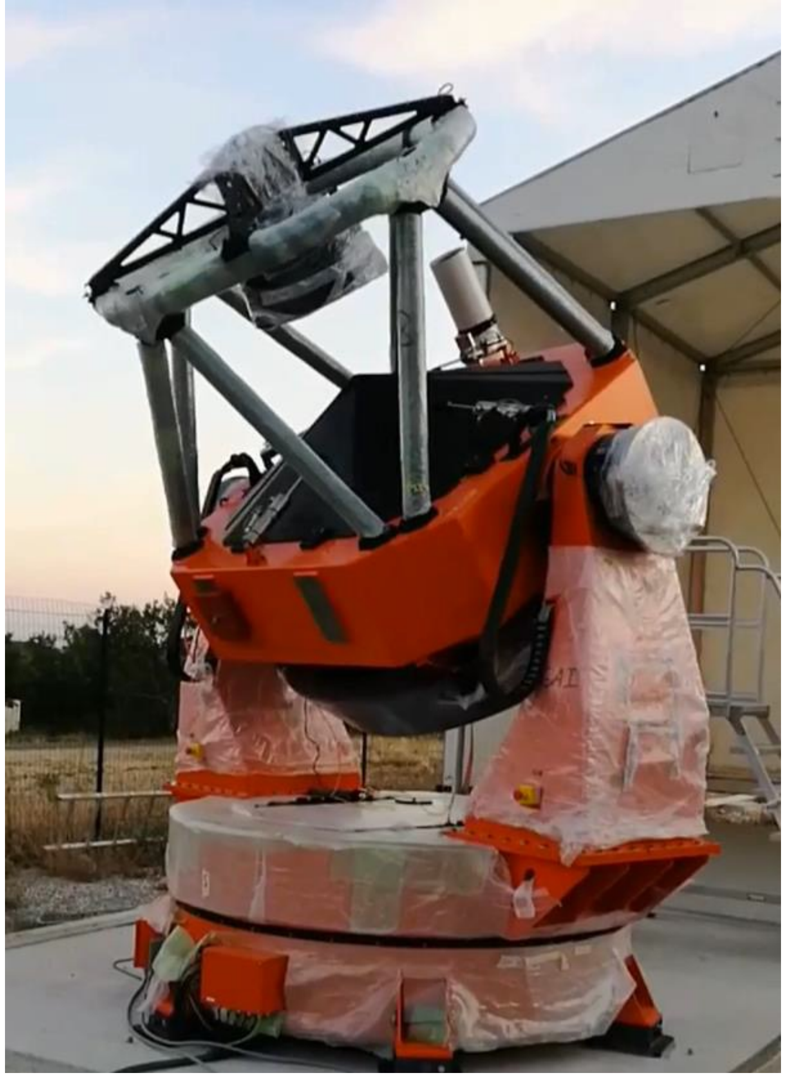






Xin et al., 2023, Nature Astronomy

The Ground Follow-up telescopes – GFTs



Colibri being tested at Haute-Provence Observatory
←

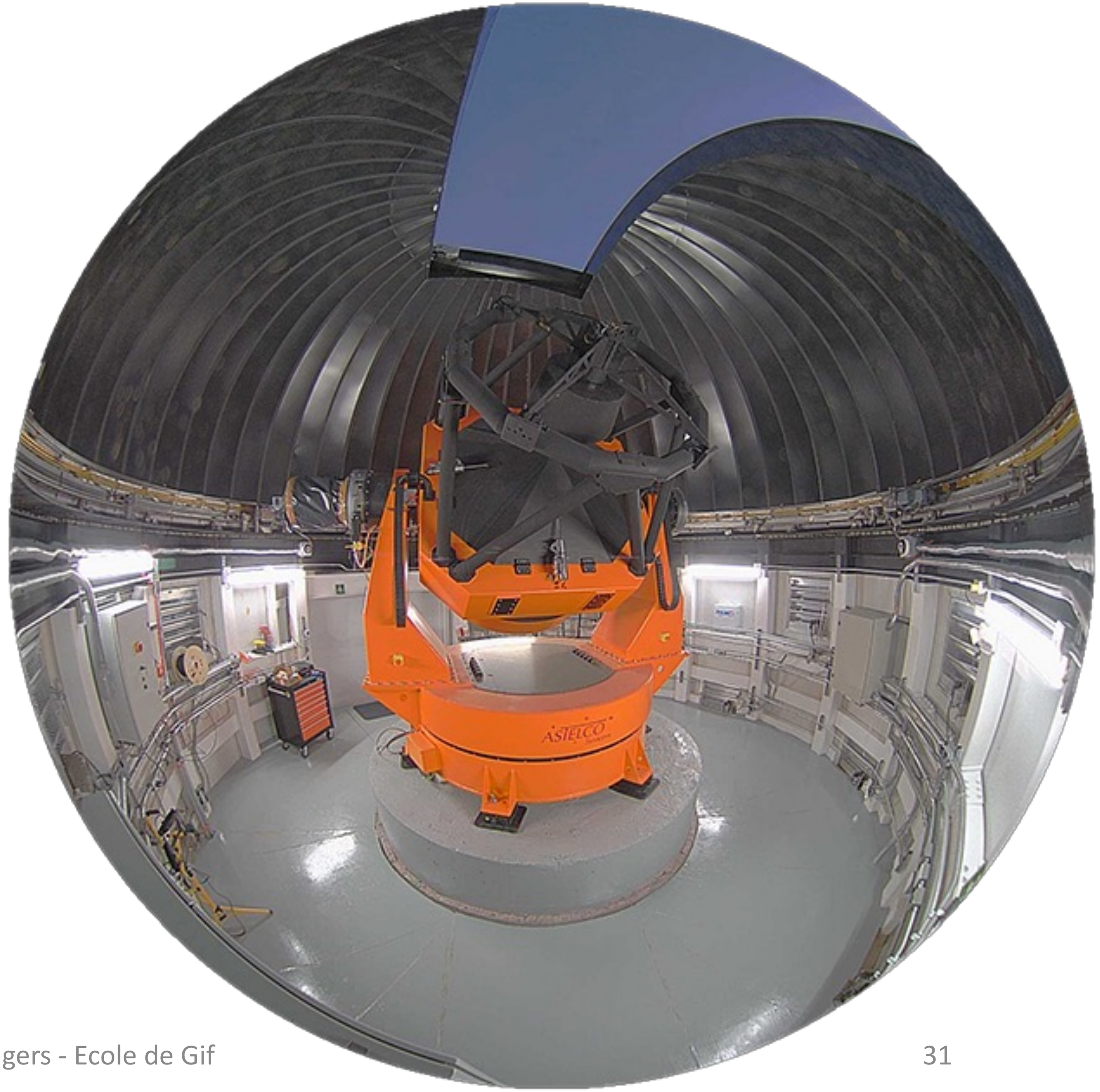
Diameter : 130 cm
FOV: 26 x 26 arcmin
400 – 1700 nm

The Chinese GFT at Jilin Observatory →

Diameter : 120 cm
FOV: 90 x 90 arcmin
400 – 900nm

Colibrí

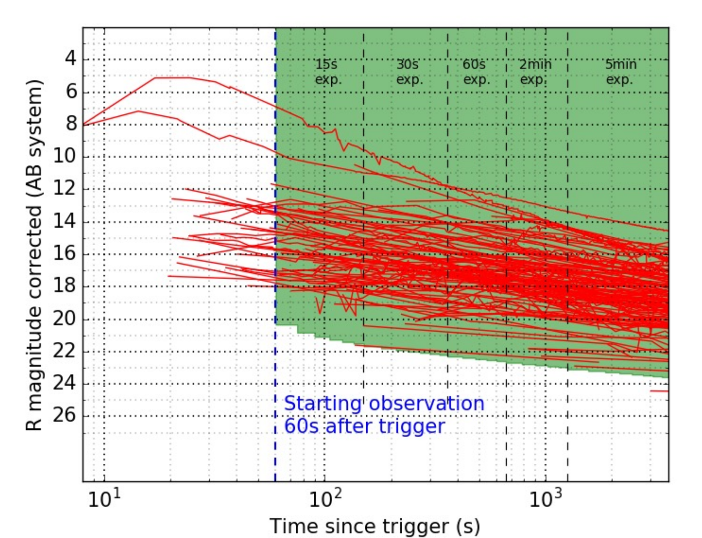
- Goal: fast follow-up of GRBs and other HE transients localized by *SVOM*/ECLAIRs.
- Some consequences:
  - Rapidly rotating alt-az telescope: on the source in ≤ 20 second.
  - Rapidly rotating dome.
  - FoV adapted to ECLAIRs error boxes: 26' in visible and 21.7' in NIR.
  - 1.3 meter primary mirror (the best you can afford with the available budget and our constraints: speed, FoV)
  - Three imaging instruments at the Nasmyth focus: blue camera, red camera, NIR camera (equivalent to 3 telescopes).

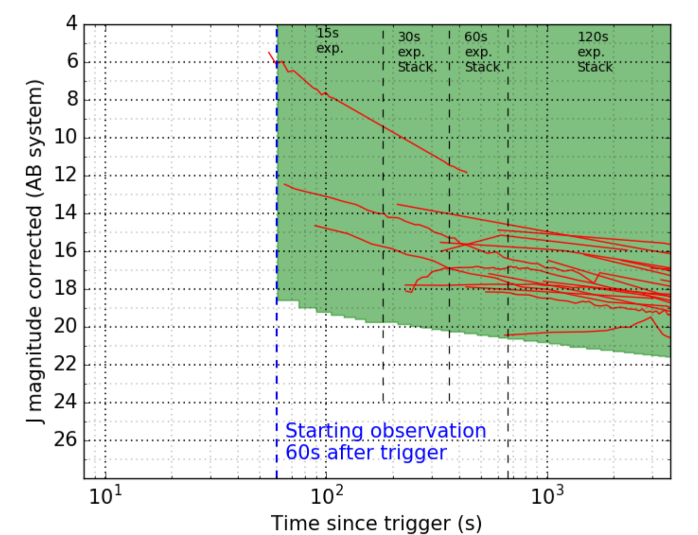


Colibrí (continued)

- Fully robotic observatory:
  - Dome opening & telescope and instrument preparation at dusk
  - Alert reception
  - Follow-up (or not) decision
  - Data acquisition
  - Pre-processing
  - Data analysis
  - Transient search
  - Alert distribution
  - …
  - Dome closing & telescope and instrument at dawn

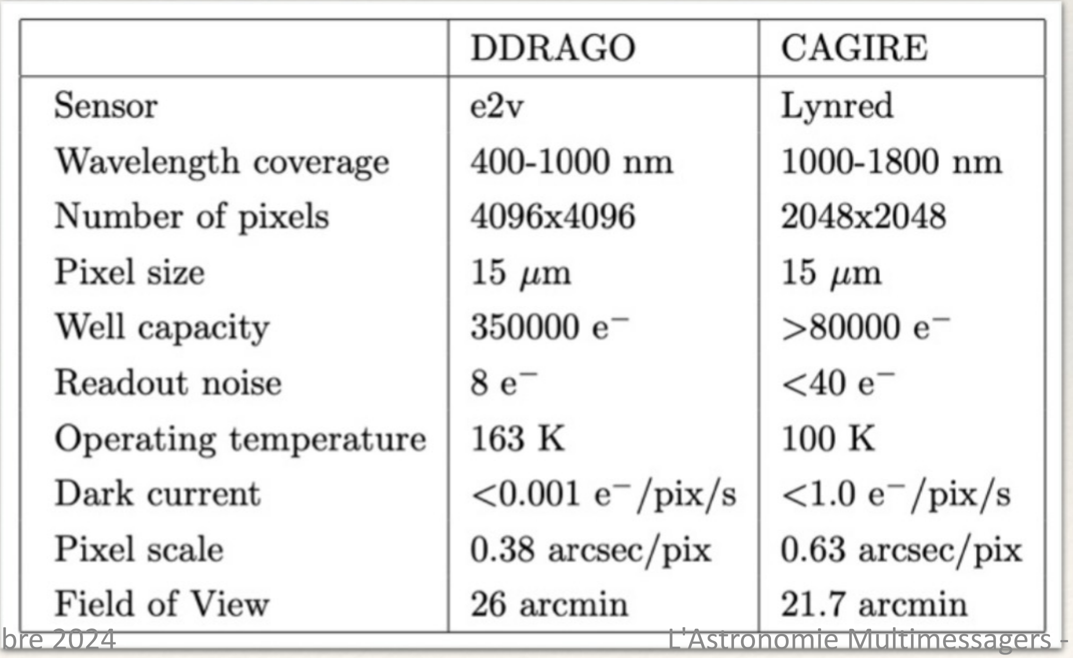
- Colibrí must be able to identify GRB visible/NIR counterparts in less than 5 minutes.



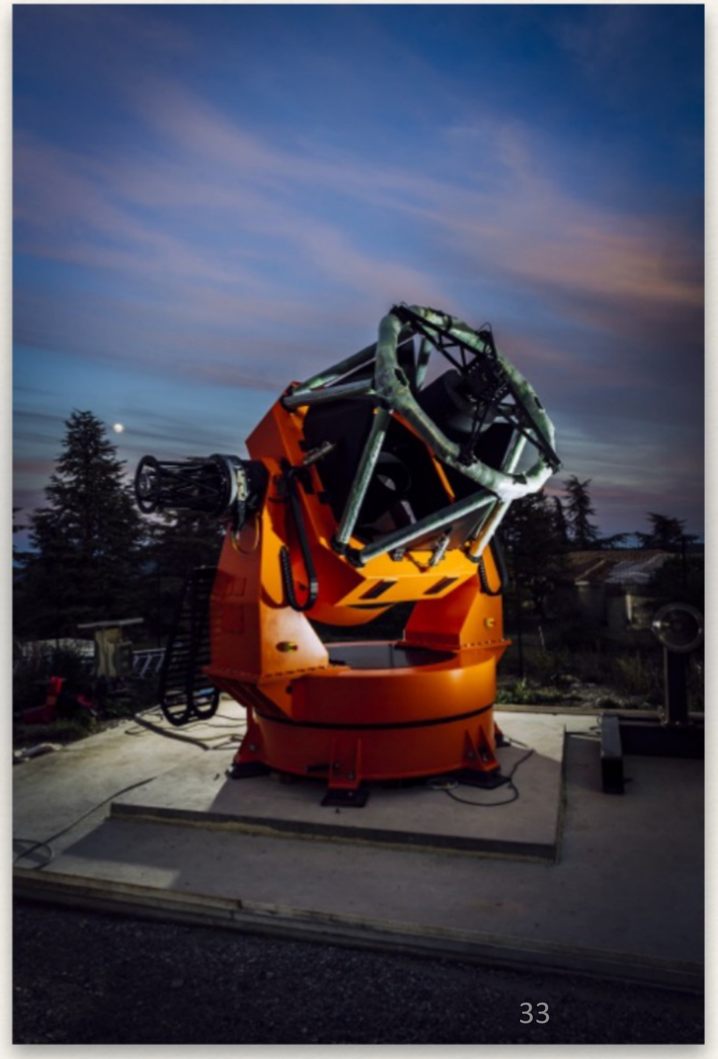


COLIBRI, the French follow-up telescope

❖ Three simultaneous arms:
- Wide field of view: 26 arcmin.
- Visible domain: B to SDSS z bands.
- Infrared domain: up-to H band.



	DDRAGO	CAGIRE
Sensor	e2v	Lynred
Wavelength coverage	400-1000 nm	1000-1800 nm
Number of pixels	4096x4096	2048x2048
Pixel size	15 μm	15 μm
Well capacity	350000 e^-	>80000 e^-
Readout noise	8 e^-	<40 e^-
Operating temperature	163 K	100 K
Dark current	<0.001 e^-/pix/s	<1.0 e^-/pix/s
Pixel scale	0.38 arcsec/pix	0.63 arcsec/pix
Field of View	26 arcmin	21.7 arcmin



Colibrí

- Colibrí has been designed to follow-up GRBs detected by ECLAIRs, but it will also follow alerts from neutrino or GW detectors.

- Colibrí is just one of the numerous tools dedicated to the study of the transient sky and multi-messenger astronomy. Its combination of speed, sensitivity and wavelength coverage is unique in the world.

Colibrí was inaugured on September 7th 2024

Conlusion

A huge effort has been engaged by the astronomical community to accompany the development of non-photonic astronomical observatories.

Questions ?

Comments ?