Ground-based complex for detailed investigation of atmospheric transient luminous events in the optical range

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or

What do astronomers
have in stock
to share
with
atmospheric scientists

Wide-field monitoring systems: plan of the talk

- **Why do astronomers need such systems?**
  - **Fast variability of the sky**
- **What have we done and reach so far**
  - **Our systems, our results and plans**
- **You, obviously, need it too**
  - **Sprites, elves, jets... you name it**
- **What do we have to offer you**
  - **High temporal resolution photometry, spectroscopy and polarimetry in a wide fields**

Fast variability of the sky:
the zoo of variable objects

← closer to Earth | more energetic →

Time scale	near-Earth	inside Galaxy	nearby galaxies	cosmological distances
< 0.1 s	meteors, satellites, debris	novae, flaring stars, stars occultations	nearby supernovae	GRBs
1 s	high-orbit satellites			
10 s				
100 s	asteroids		intra-day variable AGNs	
> 1000 s		variable stars, MACHOs		supernovae

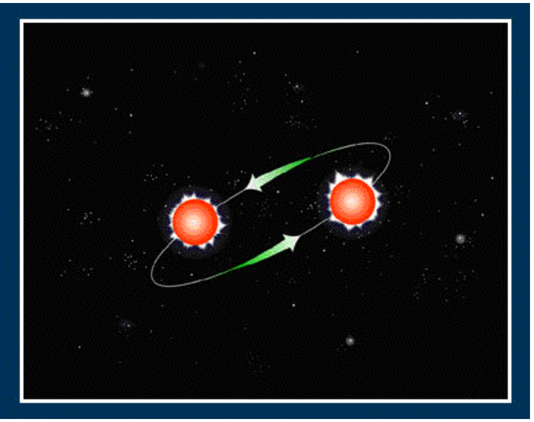
Gray background marks the classes of objects routinely targeted by existing wide-field surveys,like ASAS, LINEAR, MACHO etc

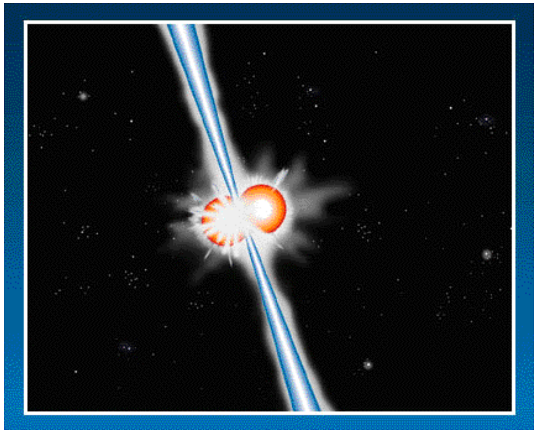
As a rule, fast optical transients have unpredictable localizations, both in time and on the sky

Fast transient phenomena on the sky: Gamma-ray bursts

Most energetic events in the Universe

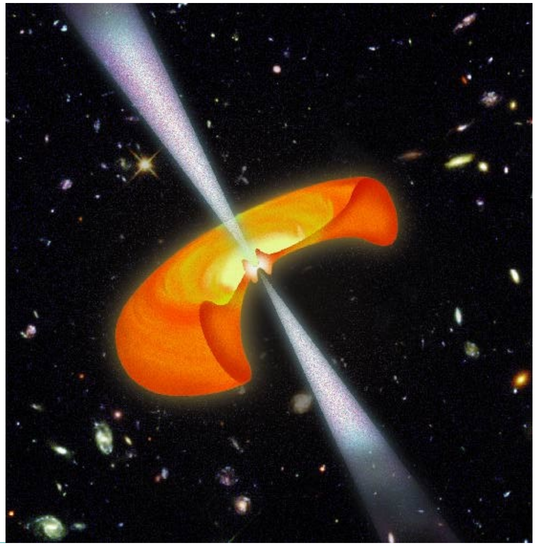
E~10^{51}-10^{54} Erg — rest-energy of the stars





Compact objects merging and formation of a black hole

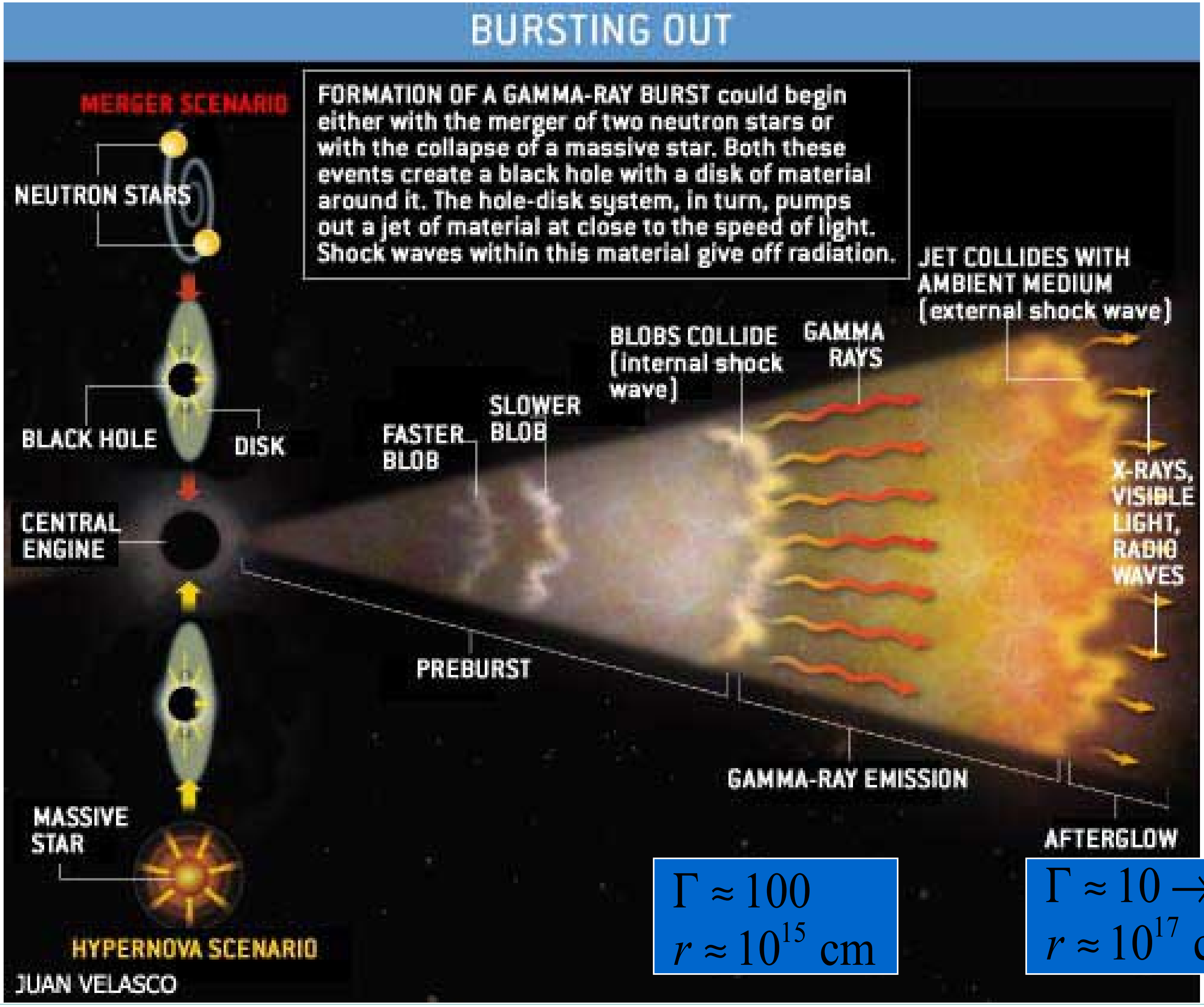
- NS+NS, NS+BH
- Orbital motion -> collimation
- Old objects in halos of old galaxies



Massive star collapse towards a black hole

- 100-150 Msun stars
- Rotation -> collimation of the ejecta
- Young objects in star formation regions
- Supernova imprints on late stages of the afterglow

Gamma-ray bursts: physical picture

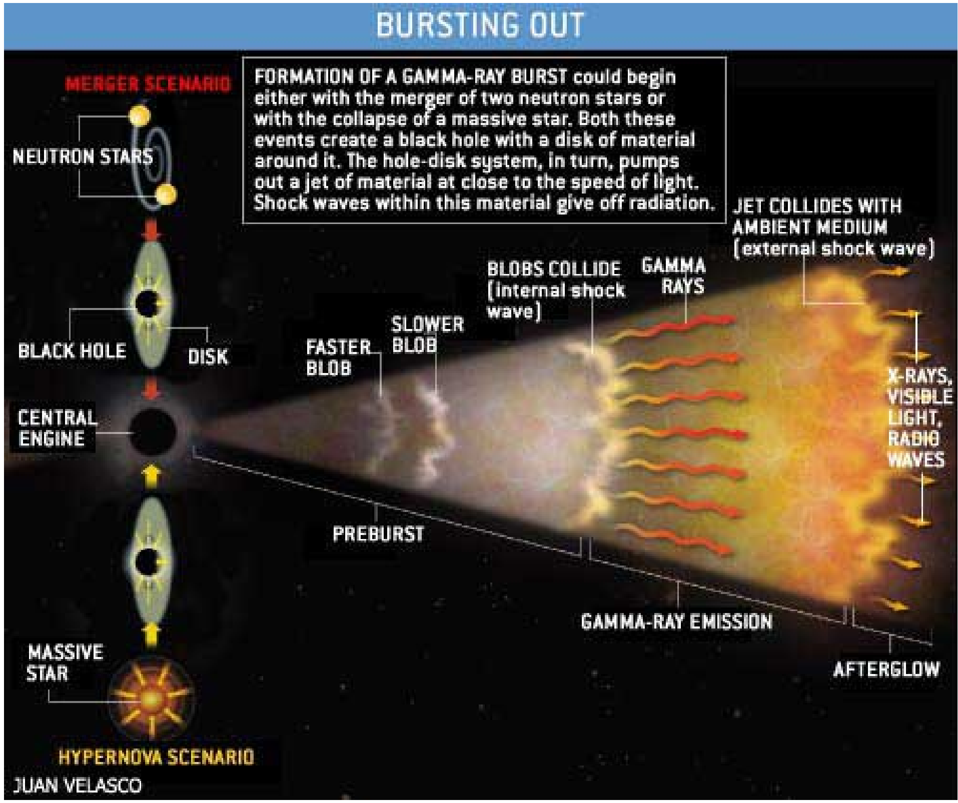


$$\Gamma \approx 100$$
$$r \approx 10^{15}\ \text{cm}$$

$$\Gamma \approx 10 \rightarrow 1$$
$$r \approx 10^{17}\ \text{cm}$$

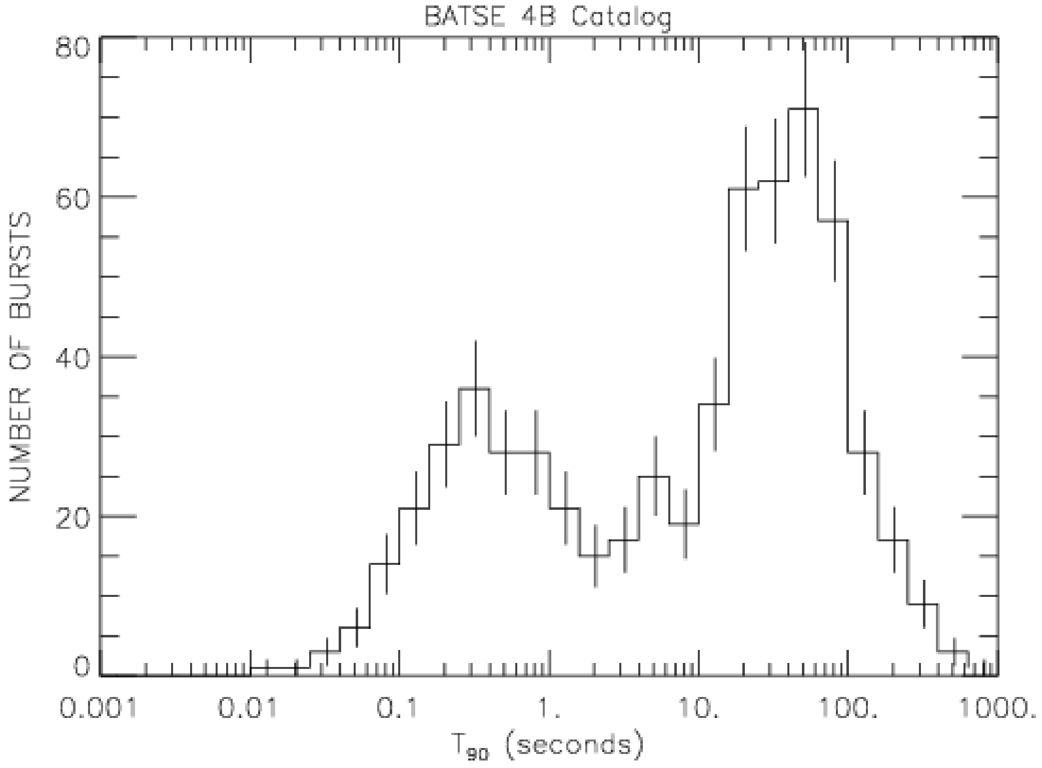
Gamma-ray bursts: what can variability tell?

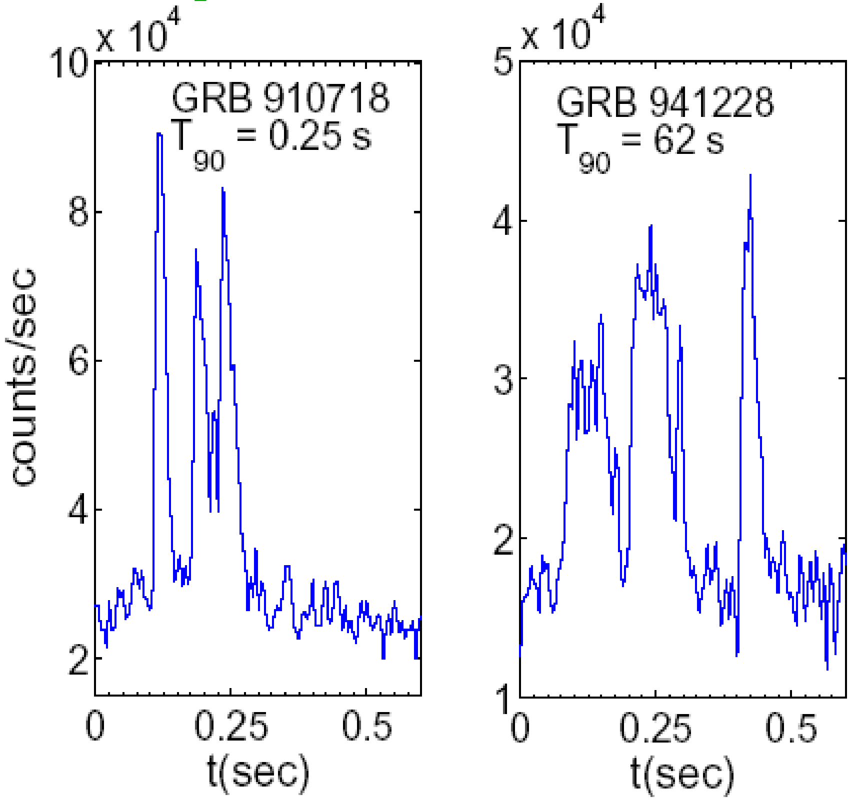
- Activity of central engine
  - Periodic behaviour?
  - Flares
- Dynamics of ejecta
  - Internal shocks
  - Instabilities
    - density fluctuations
    - magnetic reconnections
    - ...
  - Interaction with wind and interstellar medium



Gamma-ray bursts: high-energy emission

- Studied well by space-borne telescopes
  - BATSE, HETE-II, BeppoSAX, Swift, INTEGRAL
- Short durations and fine temporal structure

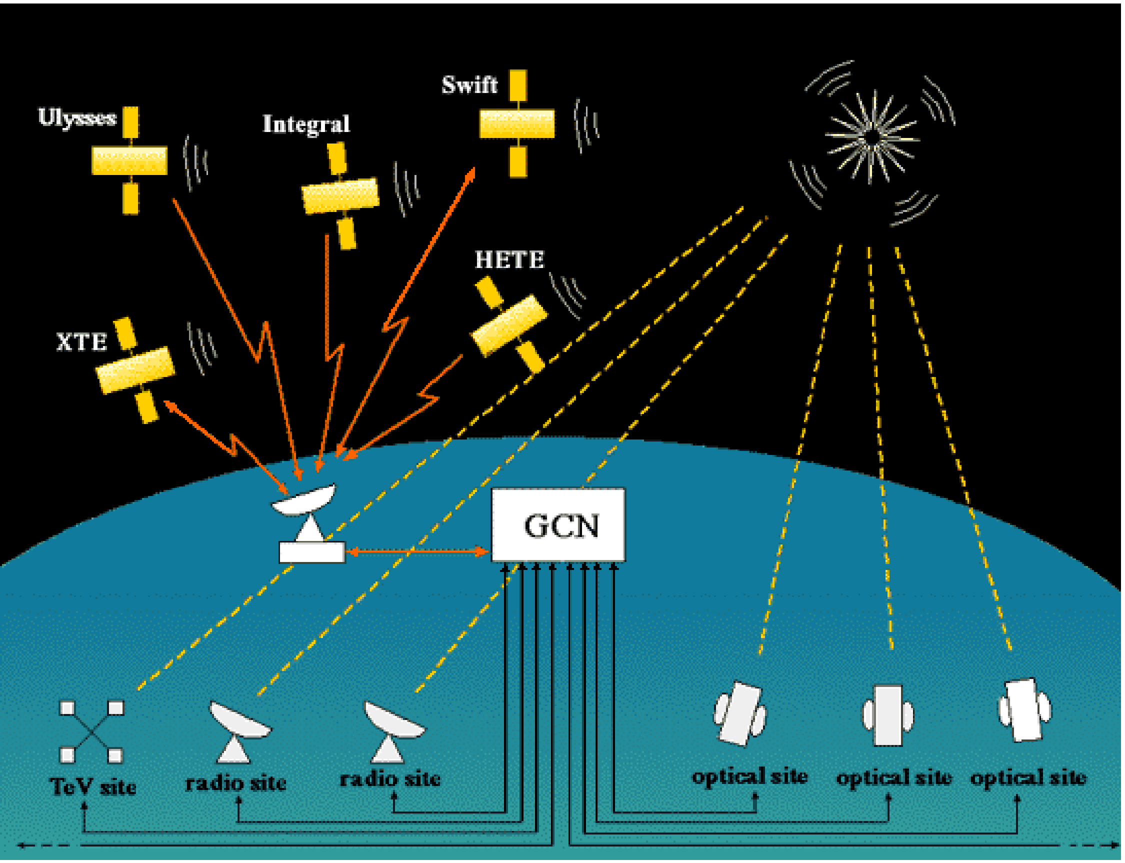




Gamma-ray bursts: optical emission

- Open questions
  - Prompt — afterglow transition
    - internal vs external shocks
  - Variability
    - modulation by central engine activity?
  - Relation to high-energy emission
    - multiwavelength spectrum and its variability
- To find answers, one have to look for very first moments of the burst in optics with high temporal resolution

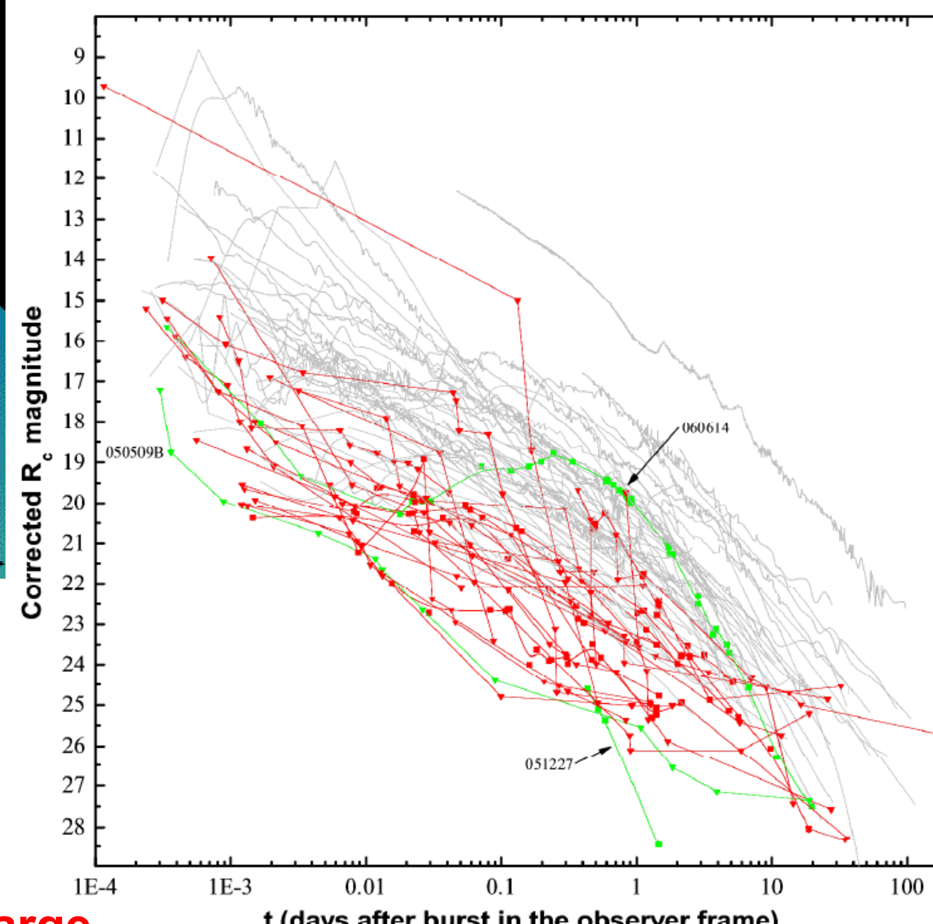
GRB optical emission: catching the tail of the burst



GRB Coordination Network

coordinates after ~10 seconds

For 50% of events optical prompt emission is lost!



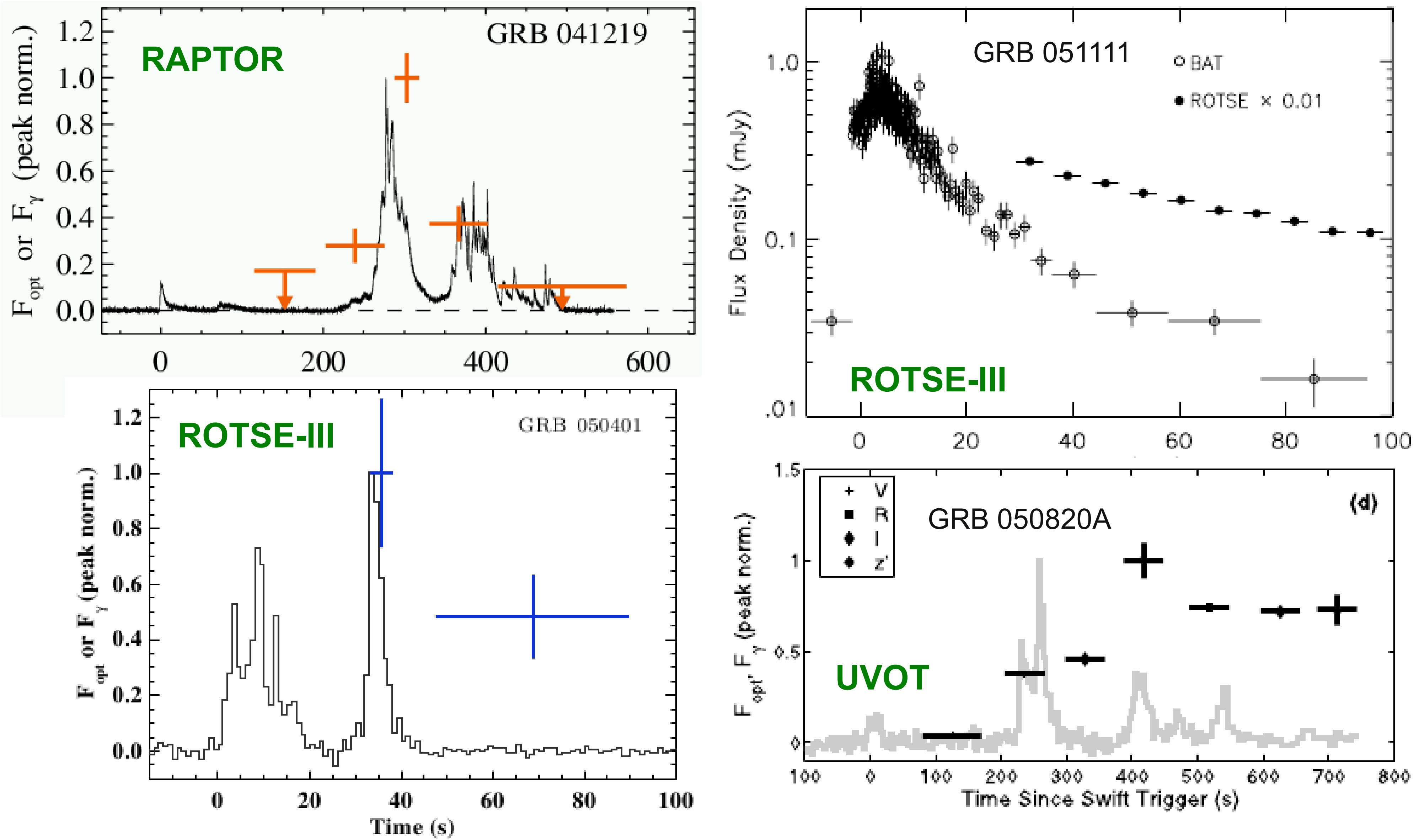
Up to now:

~ 350 afterglows

~ 20 prompts (~40 upper limits from 8 to 23 mag)

Response time of alert-based systems is too large

GRB optical emission: catching the tail of the burst



20 detections during gamma emission, 15 upper limits (14-22^m)

GRB optical emission: independent search for optical transients

- Need wide field of view
  - the shorter the focus — the better
- Need good detection limit
  - the larger the diameter — the better
- Need high temporal resolution
  - short exposures and fast read-out
  - low read-out noise

contradictory requirements

- Need real-time transient detection software

Independent search for optical transients: compromise solution

- Objective with large D/F (~1)
  - Large diameter
  - Relatively small focal length
- Fast CCD
  - Good frame rate (up to 10 fps)
  - Significant read-out noise
- Scaling image intensifier
  - Further reduces the focal length
  - Overcomes the read-out noise

Independent search for optical transients: FAVOR

FAVOR (FAst Variability Optical Registrator) camera — SAO RAS, since 2003

Built in collaboration with IPI and IKI (Moscow), supported by CRDF grant

Independent search for optical transients: TORTORA

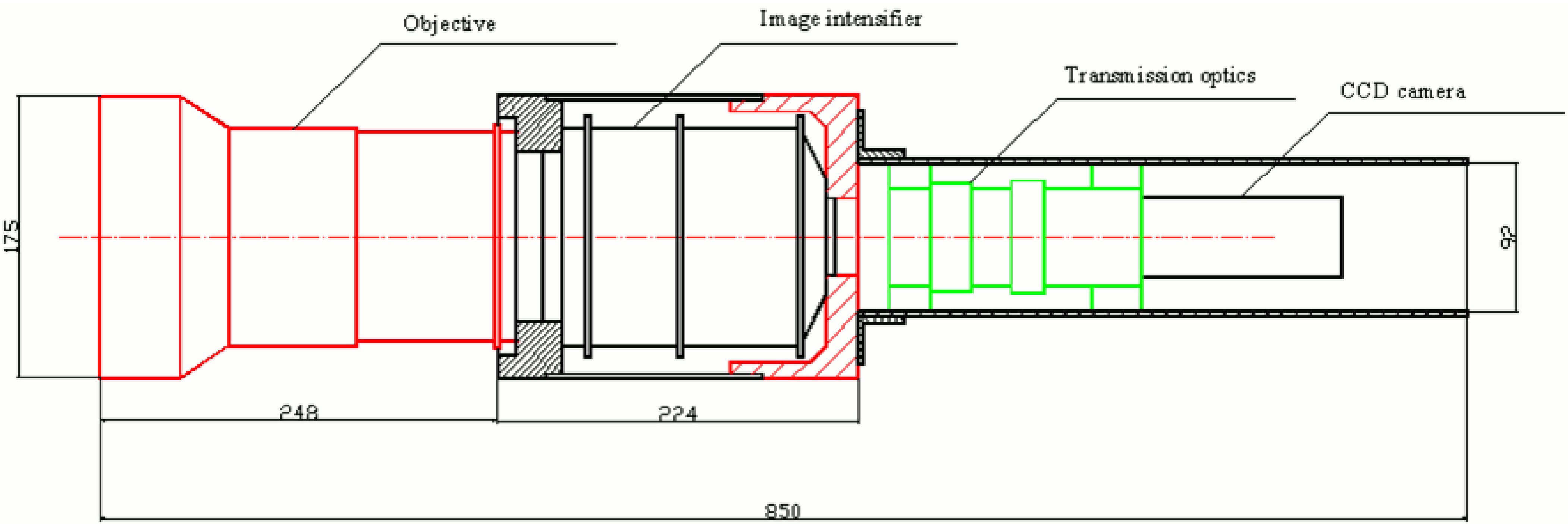
Telescopio Ottimizzato per la Ricerca Dei Transienti Ottici Rapidi

Two-telescope complex:
- independent detection
- automatic study

La-Silla, Chile
mounted on REM
since 2006

Team: SAO RAS, IPI (Russia), Bologna University, REM (Italy)

FAVOR & TORTORA systems: technical details



Objective

Diameter:	120 mm
Focal length:	150 mm
D/F:	1/1.2
Field of view:	32x24°

Image Intensifier

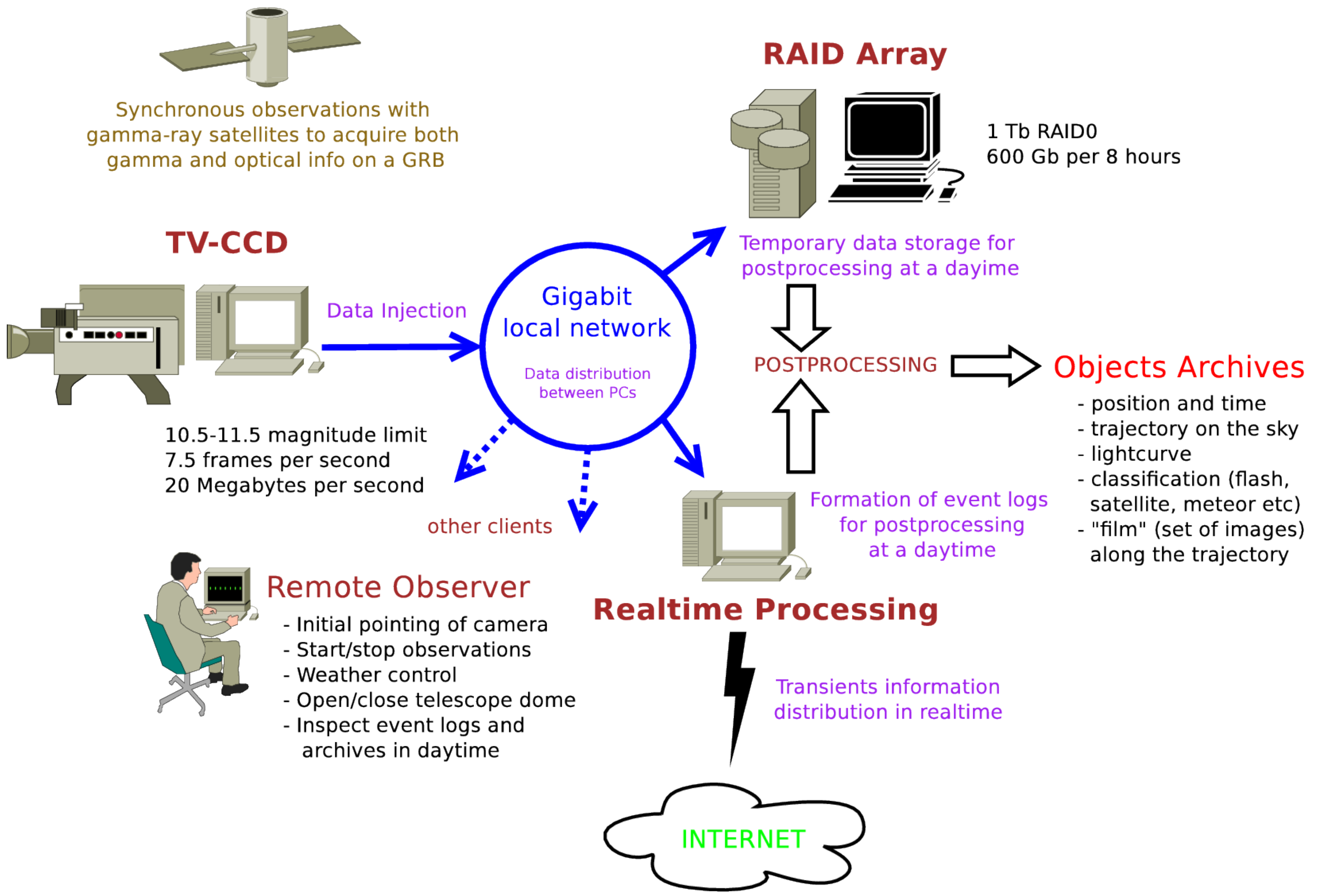
type:	S20
diameter:	90 mm
amplification:	120
downscale:	4.5/1
Q.E.:	10%

CCD

type:	SONY 2/3" IXL285
size:	1388x1036
exposures:	0.128 — 10 sec
scale:	80"/pixel
limit:	~10.5^m for 0.13c

Data flow rate — 20 Mb/s, per night— 600 Gb, ~200.000 frames

FAVOR & TORTORA systems: hardware & software



FAVOR & TORTORA systems: real-time data processing

- Fast differential imaging for detection of transients
- Simple classification of transients
  - Meteors — bright, fast and elongated
  - Satellites — slowly move across the field
  - Satellite flashes — do not move, but spatially coincident with satellite catalogue positions
  - Star flickering — positions near catalogue stars
  - Astrophysical flashes — everything else

3 consecutive frames (0.4s) is enough for classification

Independent search for optical transients: systems all around the world

Name	Field of View (degrees)	Exposure (seconds)	Limit
WIDGET	62x62	5	10
RAPTOR A/B	40x40	60	12
RAPTOR Q	180x180	10	10
BOOTES	16x11	30	12
Pi of the Sky	33x33	10	10.5
AROMA-W	25x35	5-100	10.5-13
MASTER-VWF	20x21	5	11.5
MASTER-Net	30x30	1	9
FAVOR	17x24	0.13	10-11.5
TORTORA	24x32	0.13	9-10.5

Only general-purpose systems are listed. There are also a lot of specialized (like meteor cameras) or narrow-field (like LINEAR) monitoring projects around the world.

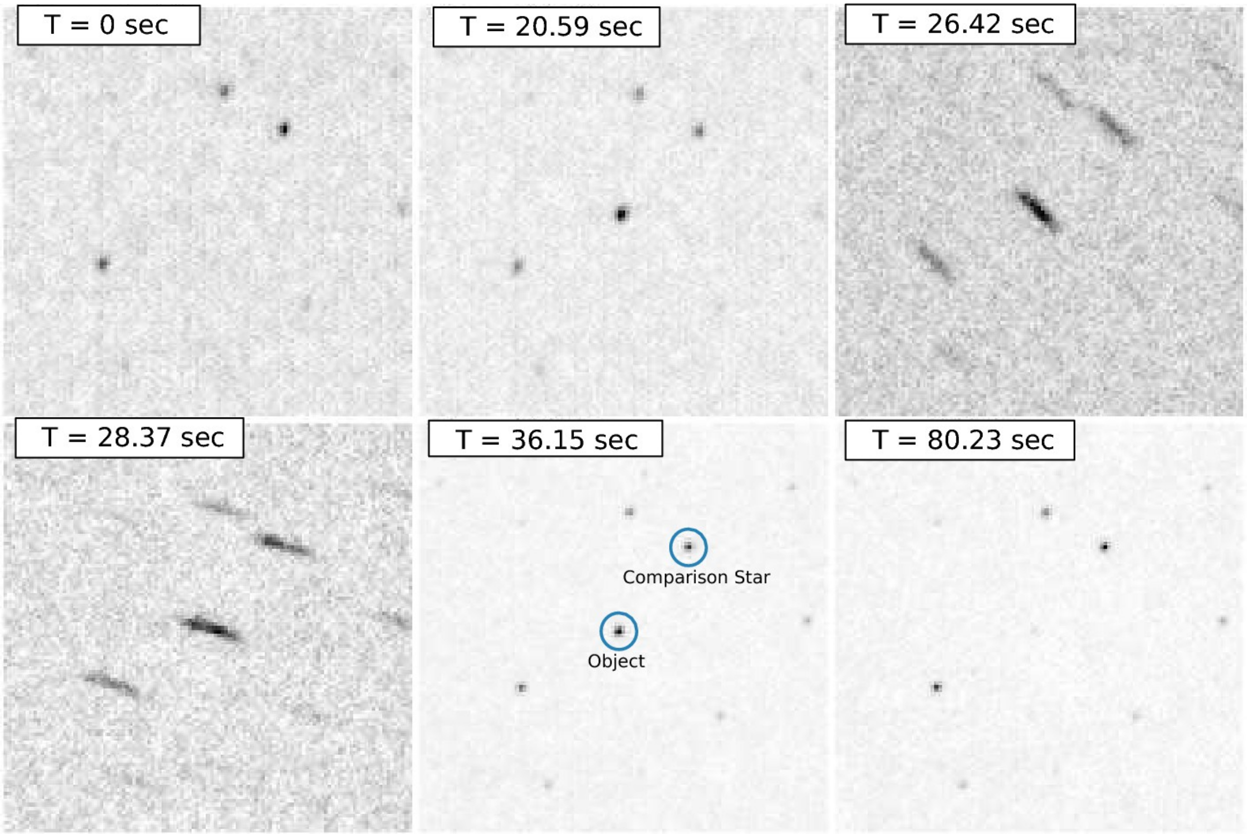
And we indeed had success with it

Independent search for optical transients: triumph of monitoring systems

- GRB 080319a: T_0 = 05:45:41 UT, T_{90}~40 s, R~21^m
- GRB 080319b: T_0 = 06:12:49 UT, T_{90}~60 s, V~5.5^m
- GRB 080319c: T_0 = 12:25:55 UT, T_{90}~20 s, R~17^m
- GRB 080319d: T_0 = 17:05:19 UT, T_{90}~24 s, V~19^m
- GRB 080320: T_0 = 04:37:38 UT, T_{90}~25 s, I' ~23^m

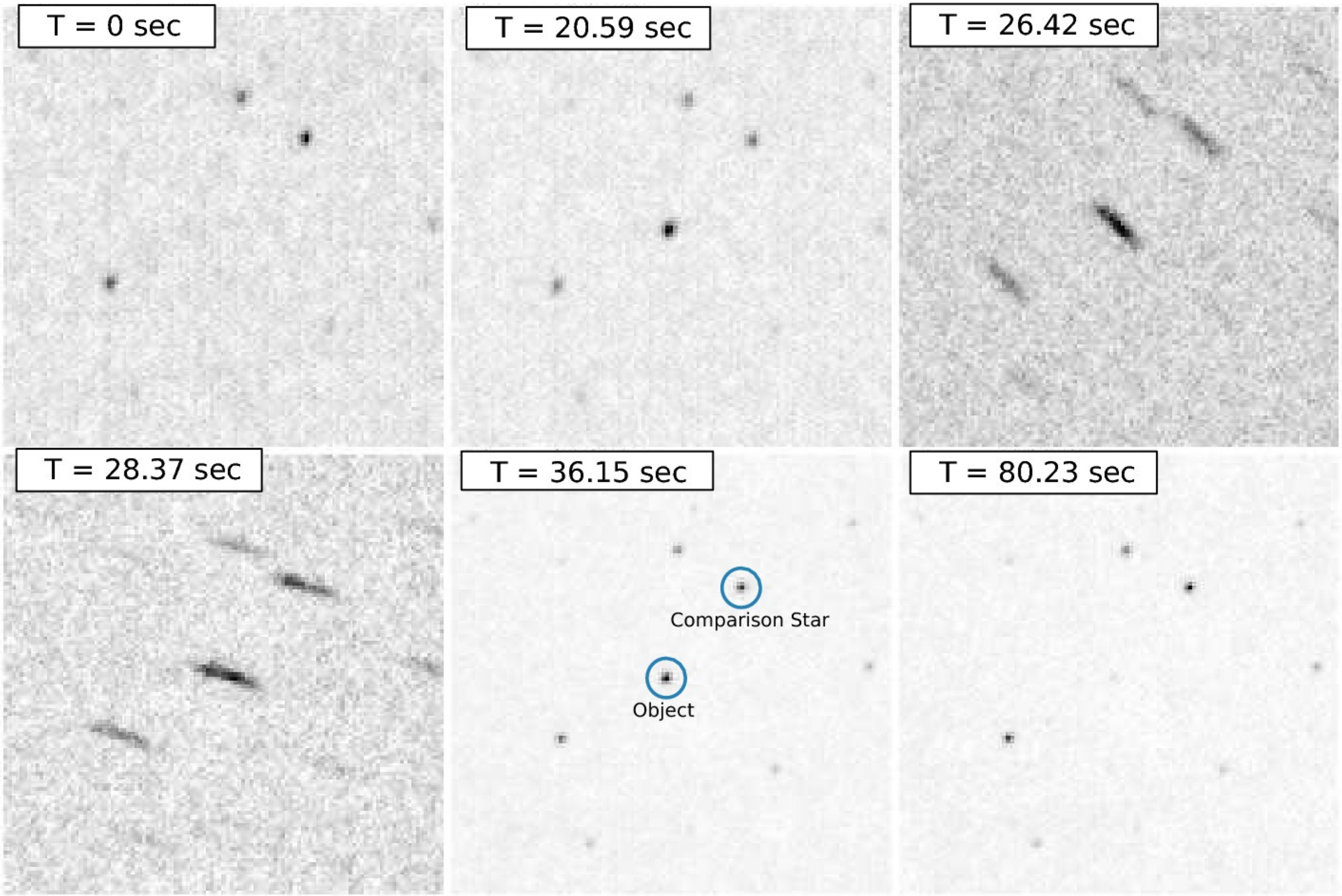
Naked-Eye Burst: optical emission in real-time

GRB 080319B — the brightest burst ever seen, and the only one detected independently by optical monitoring systems



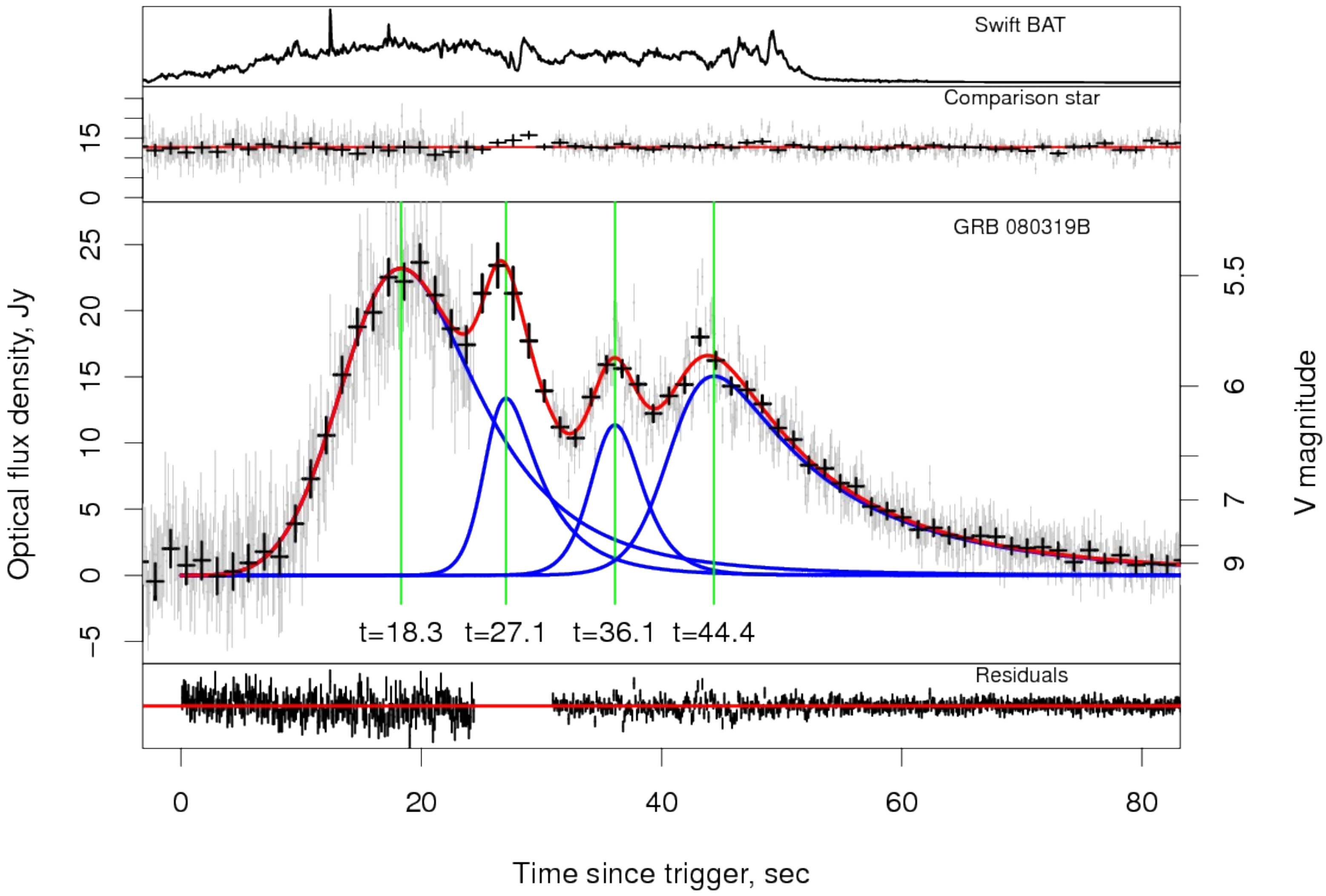
The only completely simultaneous high temporal resolution observations of GRB optical emission (TORTORA camera)

Naked-Eye Burst: optical emission in real-time



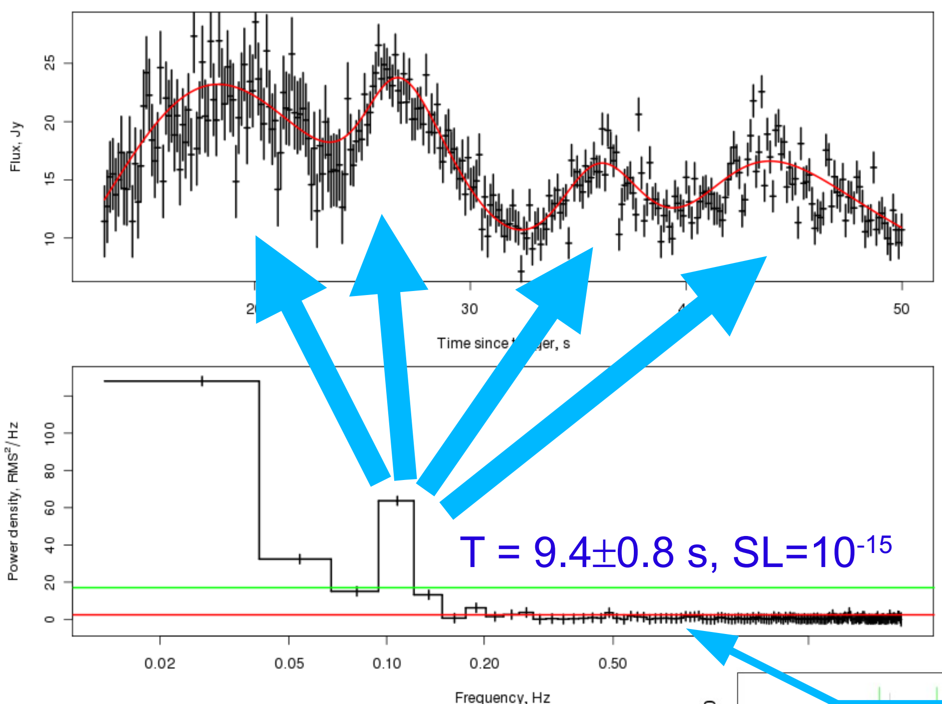
The first and the only completely simultaneous high temporal resolution observations of GRB optical emission

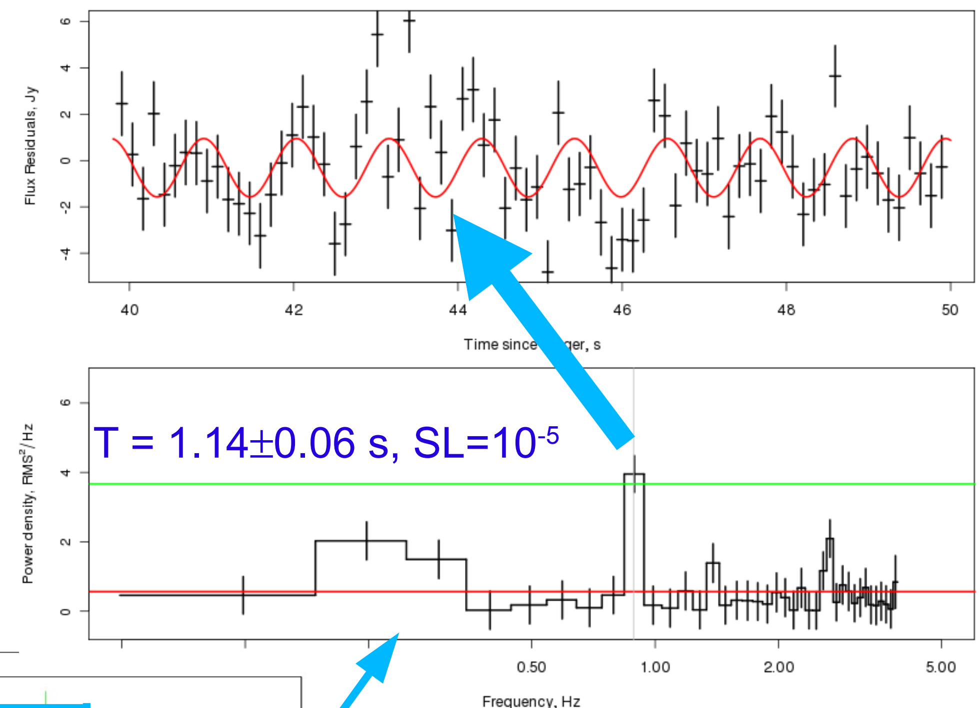
Naked-Eye Burst: optical emission in real-time



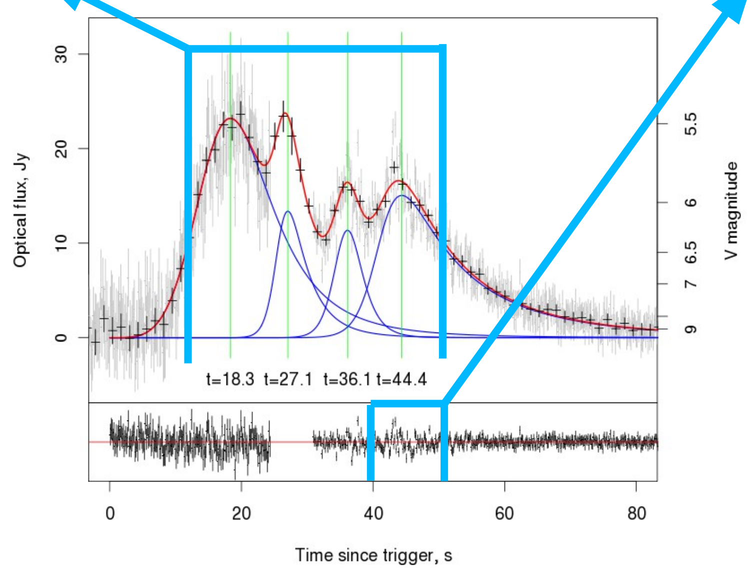
The first and the only completely simultaneous high temporal resolution observations of GRB optical emission

Naked-Eye Burst: periodicities in optical emission





4 equidistant peaks



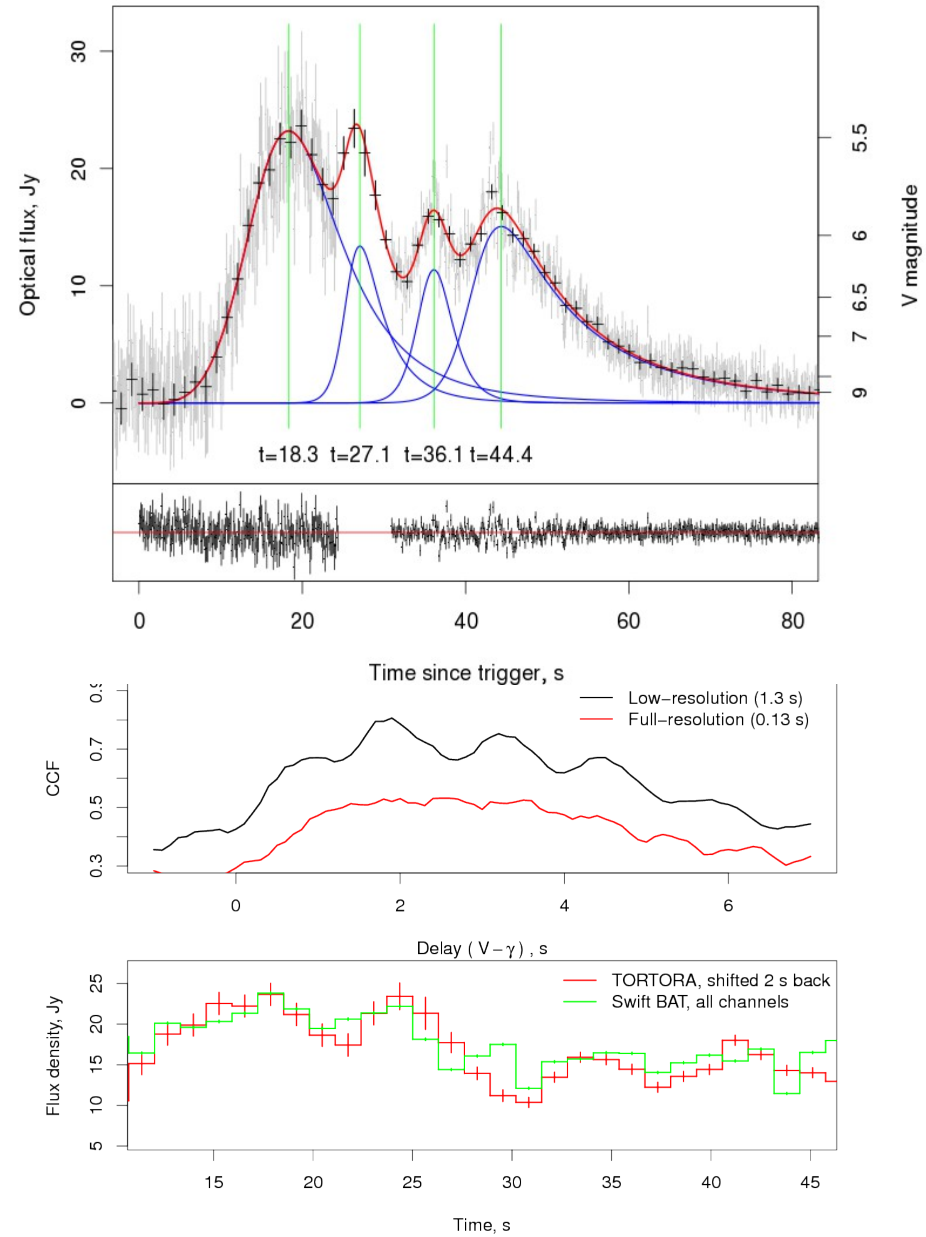
One-second periodicity during the last peak

Periodic activity of the central engine

Precession of the central engine

Gamma-ray bursts: lessons from the Naked-Eye Burst

- Peaked at V~5.3 m
- Fast optical variability
- ~9 seconds — four peaks
- ~1 second — around last peak
- Simultaneous start and end
- 0.82 correlation with 2 s optical delay
- Rules out large subset of theoretical models, like External Shock and Inverse Compton ones



Naked-Eye Burst demonstrated the importance of high temporal resolution in optical study of GRBs

Independent search for optical transients: moving on after the Naked-Eye Burst

- Increase field of view
- Improve the detection limit
- Keep (or improve) the temporal resolution
- Acquire (some) spectral information
  - multicolor imaging
  - low-resoluiton spectroscopy
- Measure the polarization

Independent search for optical transients: what are we building now

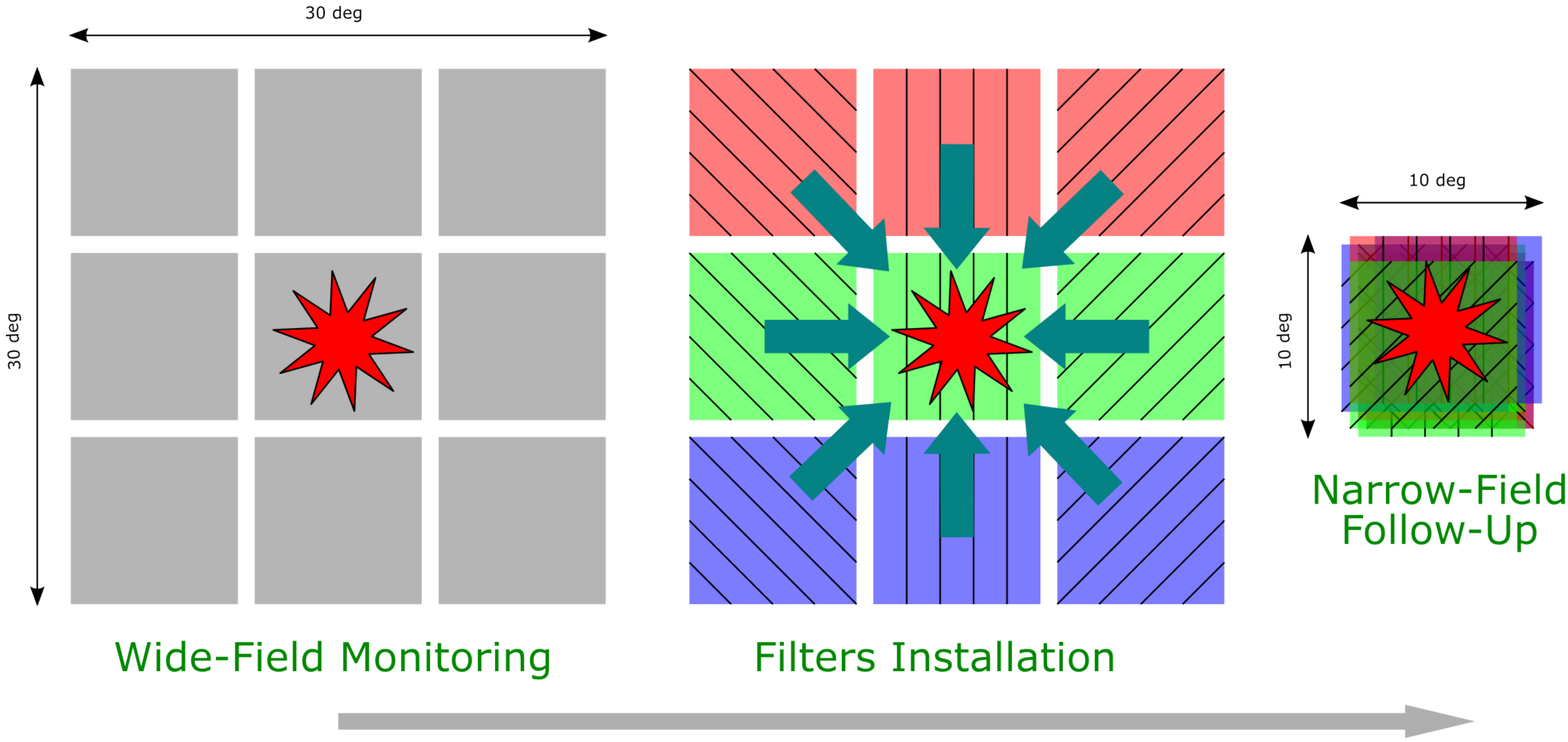
- **Multi-objective design**
- **Independent pointing of each channel**
- **Installable color/polarization filters**

As a result:

- **Wide field of view in monitoring mode**
- **Simultaneous multi-color and polarimetric measurements in follow-up mode**

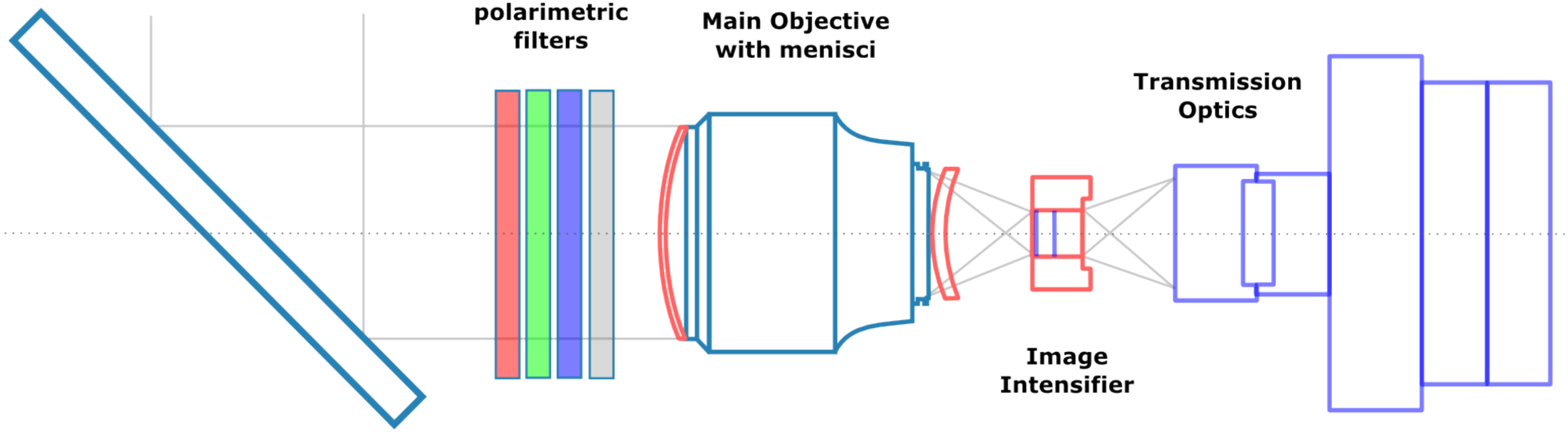
TORTORA x 9 = MiniMegaTORTORA

Independent search for optical transients: what are we building now



TORTORA x 9 = MiniMegaTORTORA

MiniMegaTORTORA: single channel



CANON EF85/1.2

Diameter:	71 mm
Focal Length:	85 mm
D/F:	1/1.2
Field of View:	10 deg

Image Intensifier

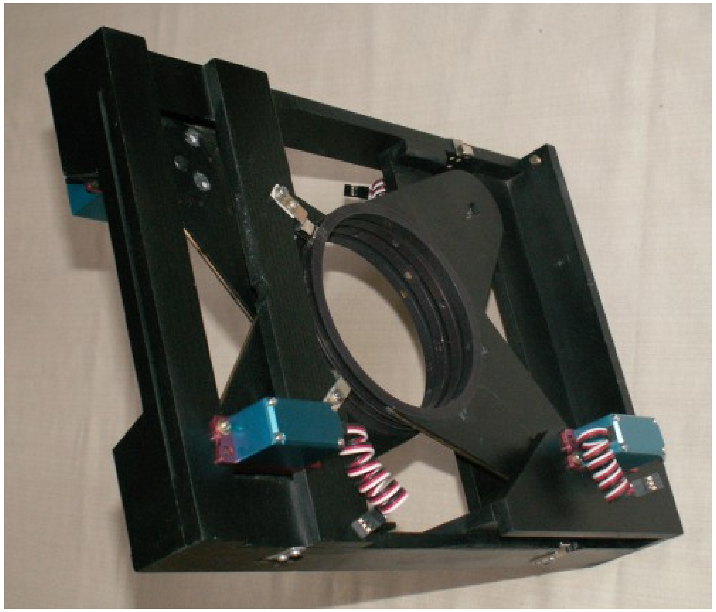
Photocathode:	GaAs
Diameter:	17.5 мм
Gain:	40000
Scaling:	1/1
QE:	30% at 4500AA

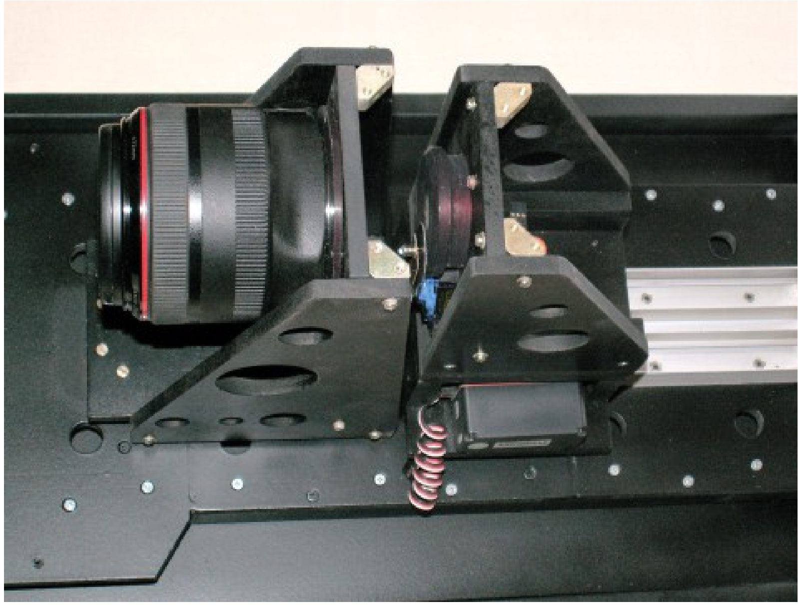
TV-CCD CSDU285

Chip:	SONY 2/3" IXL285 interline
Size:	1388x1036 pixels
Pixel:	6.45x6.45um
Exposure:	0.128 — 10 s
Angular resolution:	30-40"/pix

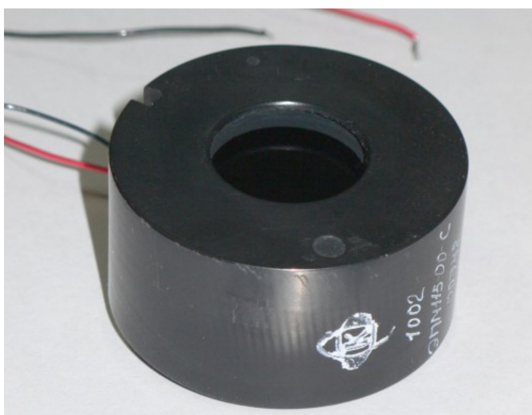
MiniMegaTORTORA: single channel

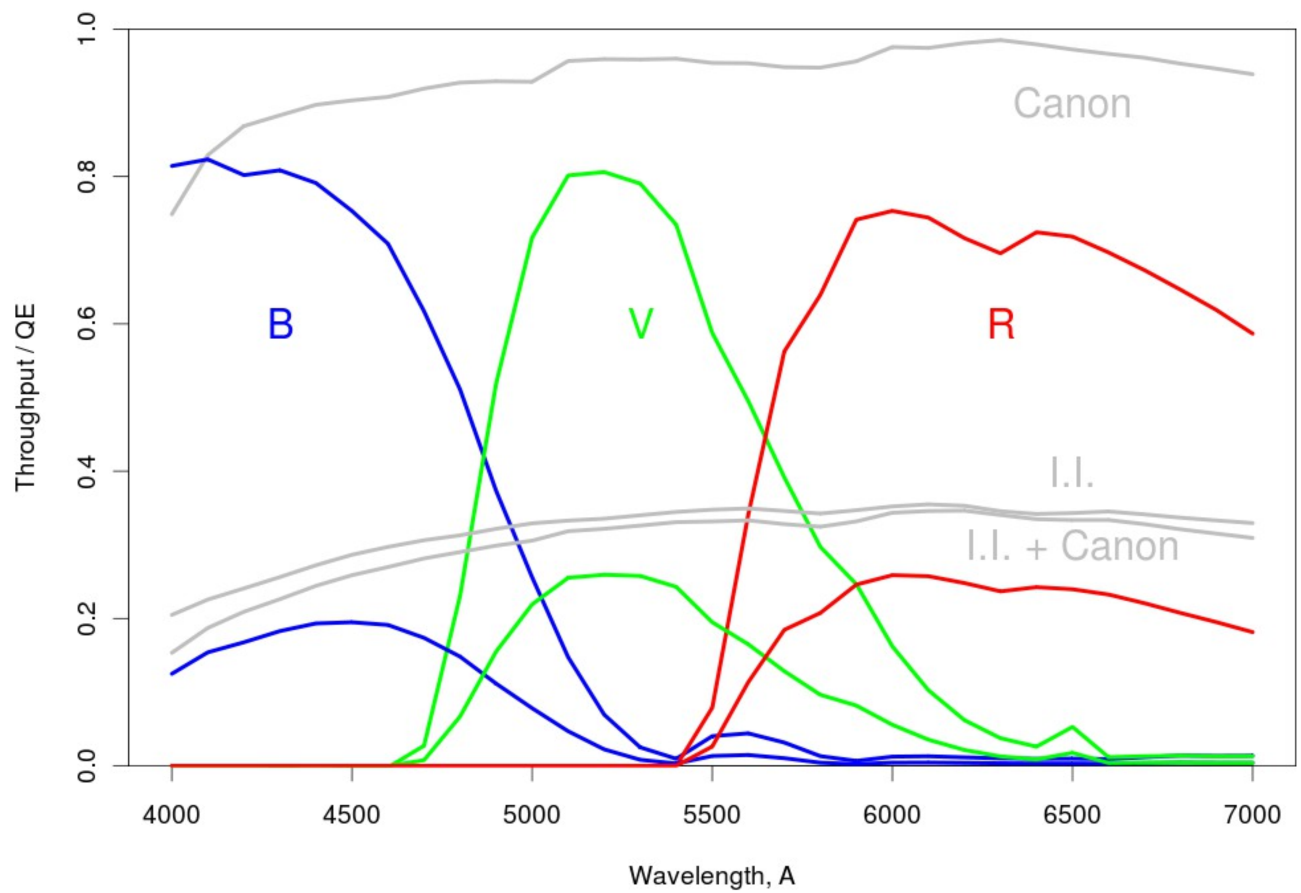
- Celostate for fast repointing, +/- 20 degrees
- Installable BVR and polarimetric filters
- Image intensifier and fast CCD





MiniMegaTORTORA: single channel





Johnson-Morgan photometric system

B = 4400 +/- 490 A

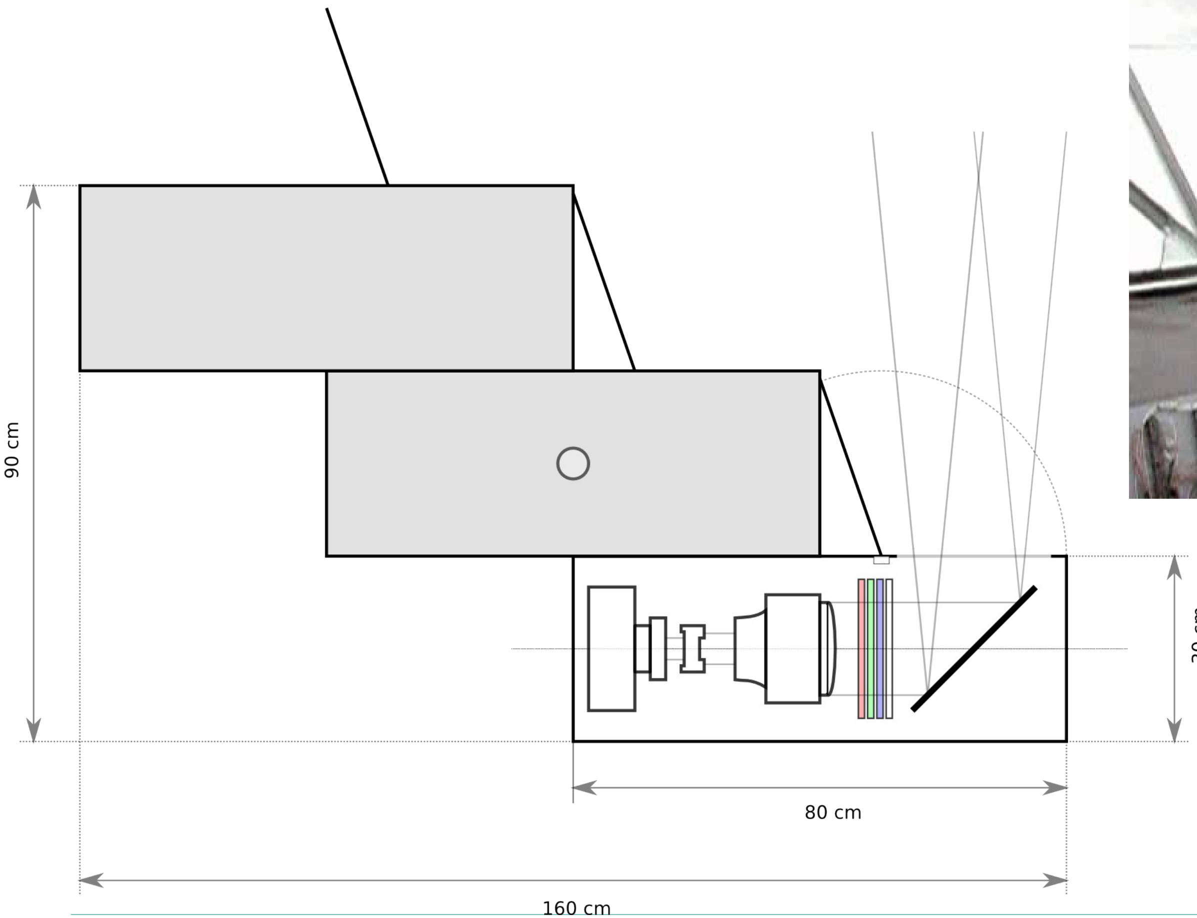
V = 5500 +/- 445 A

R = 7000 +/- 1100 A

MiniMegaTORTORA: single channel

MiniMegaTORTORA: nine channels

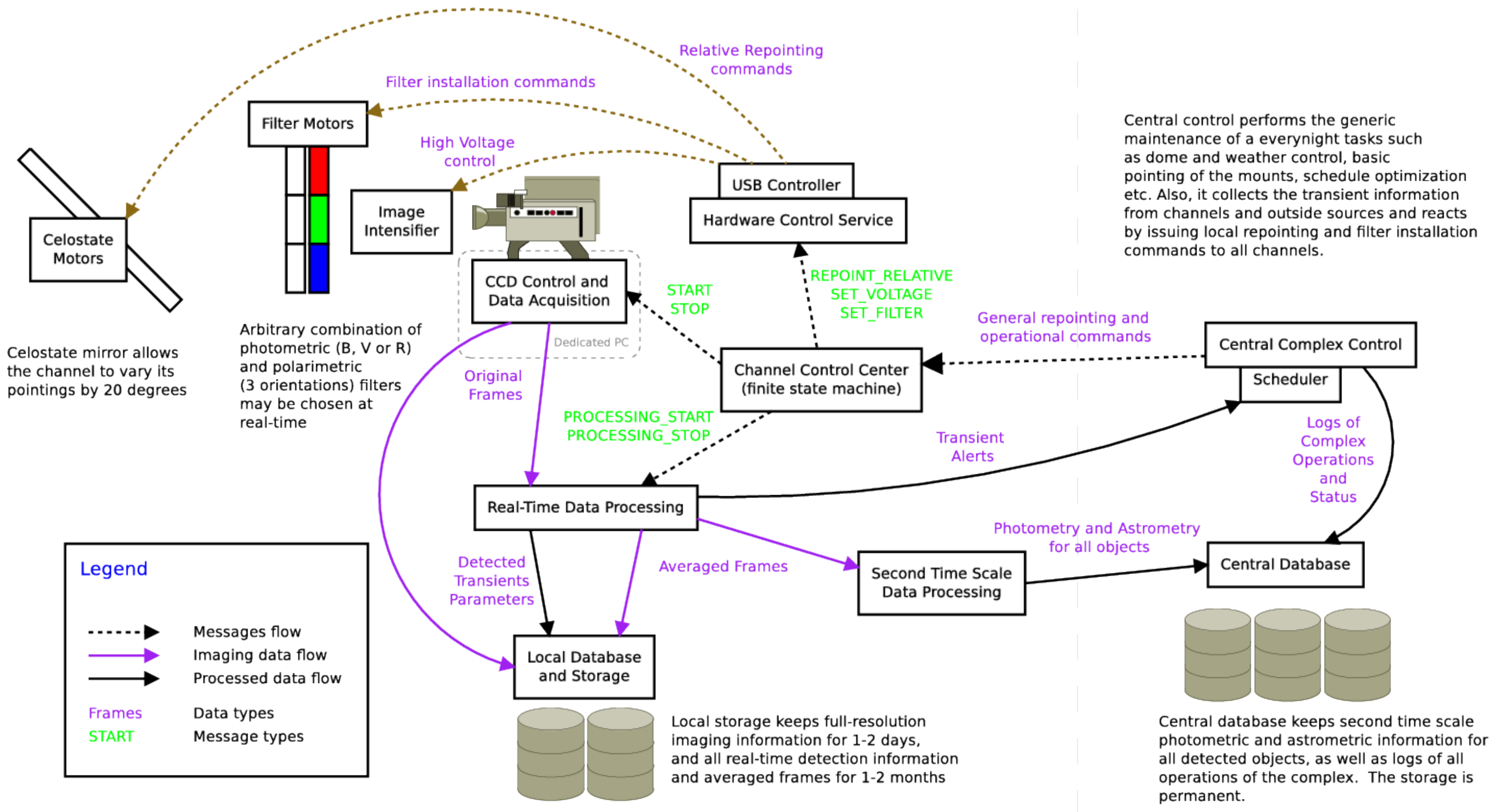
9 channels on a dedicated equatorial mount, ~100 kg



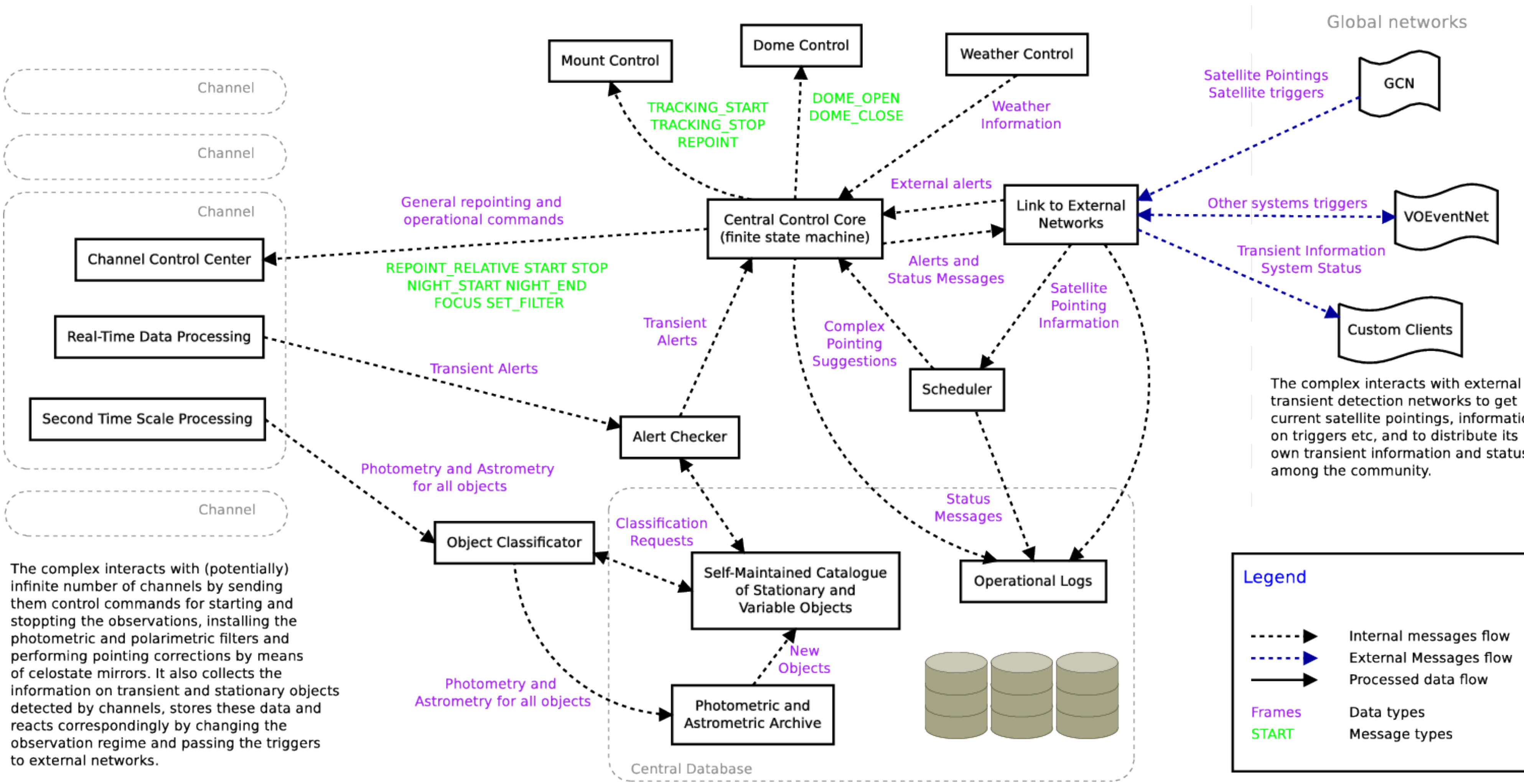
MiniMegaTORTORA: software

- Real-time data processing
  - Transient detection and classification in 0.4 s
- Complex as a whole
  - Follow-up of detected transients
  - Regular all-sky survey on different time scales
- Data products
  - Transient alerts for global networks
  - High-resolution data on detected transients
  - All-sky photometric variability catalogue

MiniMegaTORTORA: single channel software



MiniMegaTORTORA: central server software



The complex interacts with external transient detection networks to get current satellite pointings, information on triggers etc, and to distribute its own transient information and status among the community.

The complex interacts with (potentially) infinite number of channels by sending them control commands for starting and stoppting the observations, installing the photometric and polarimetric filters and performing pointing corrections by means of celostate mirrors. It also collects the information on transient and stationary objects detected by channels, stores these data and reacts correspondingly by changing the observation regime and passing the triggers to external networks.

MiniMegaTORTORA: performance

Wide-field monitoring

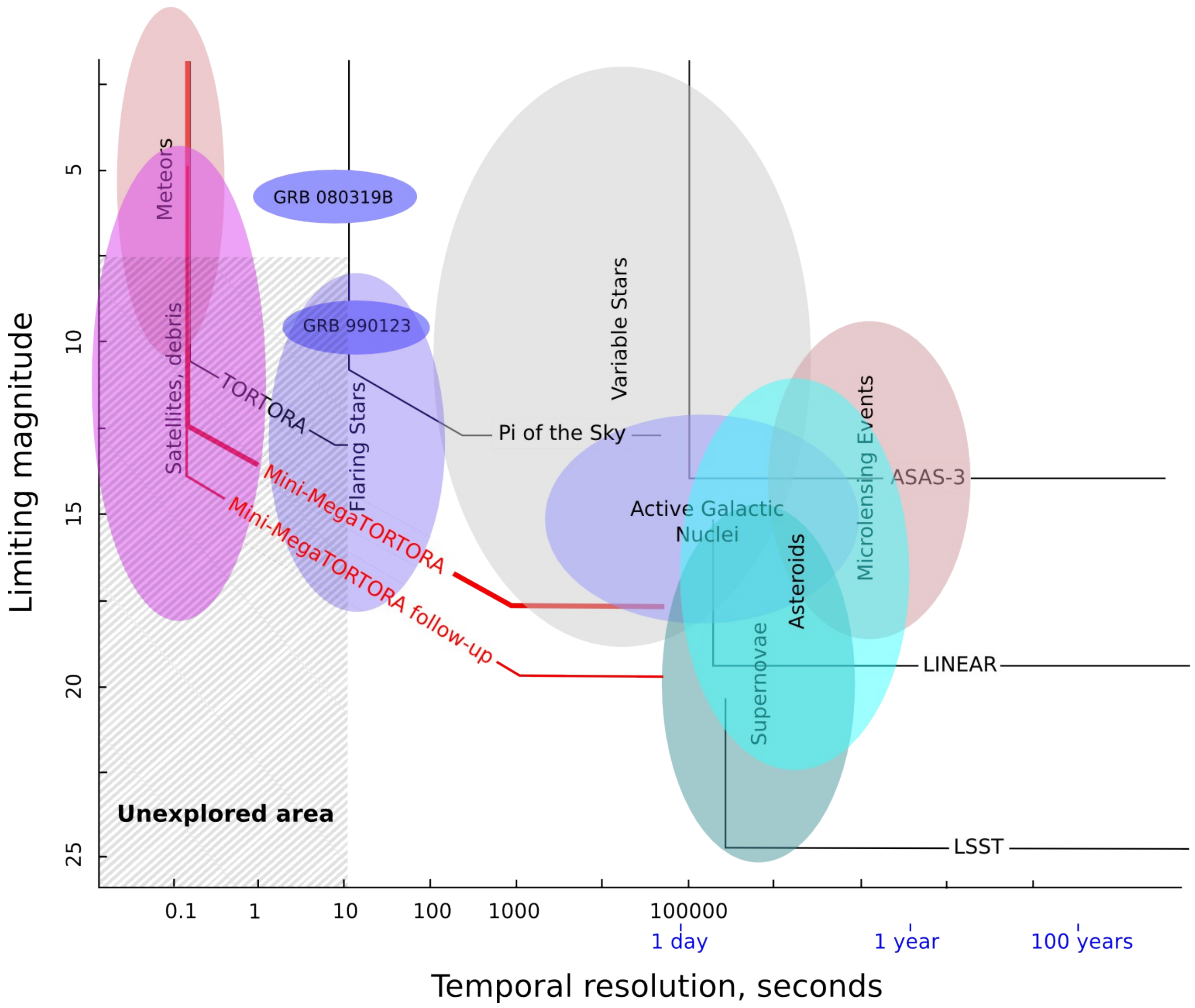
- ~900 square degrees field of view
- ~12.5^m limit in B filter for 0.13s
- ~14^m for 13s, ~17.5^m for 1300 s

Narrow-field follow-up

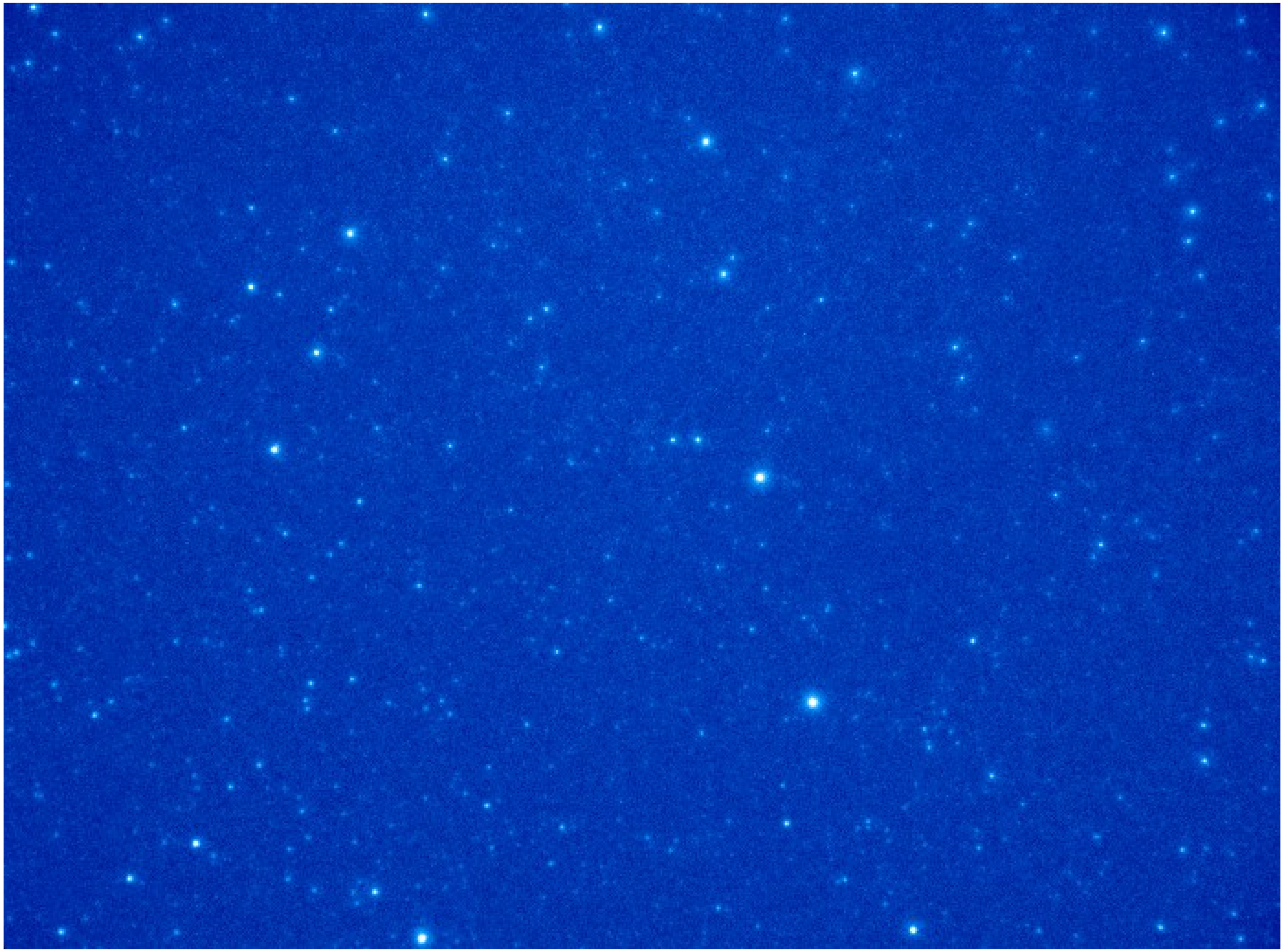
- ~100 square degrees field of view

Timescale	B filter	B + 3 polarizations	BVR	BVR + 3 polarizations
0.13	13.7	11.0	13.0	10.5
13	16.2	13.2	15.5	13.0
1300	18.7	15.9	18.0	15.5

MiniMegaTORTORA: performance

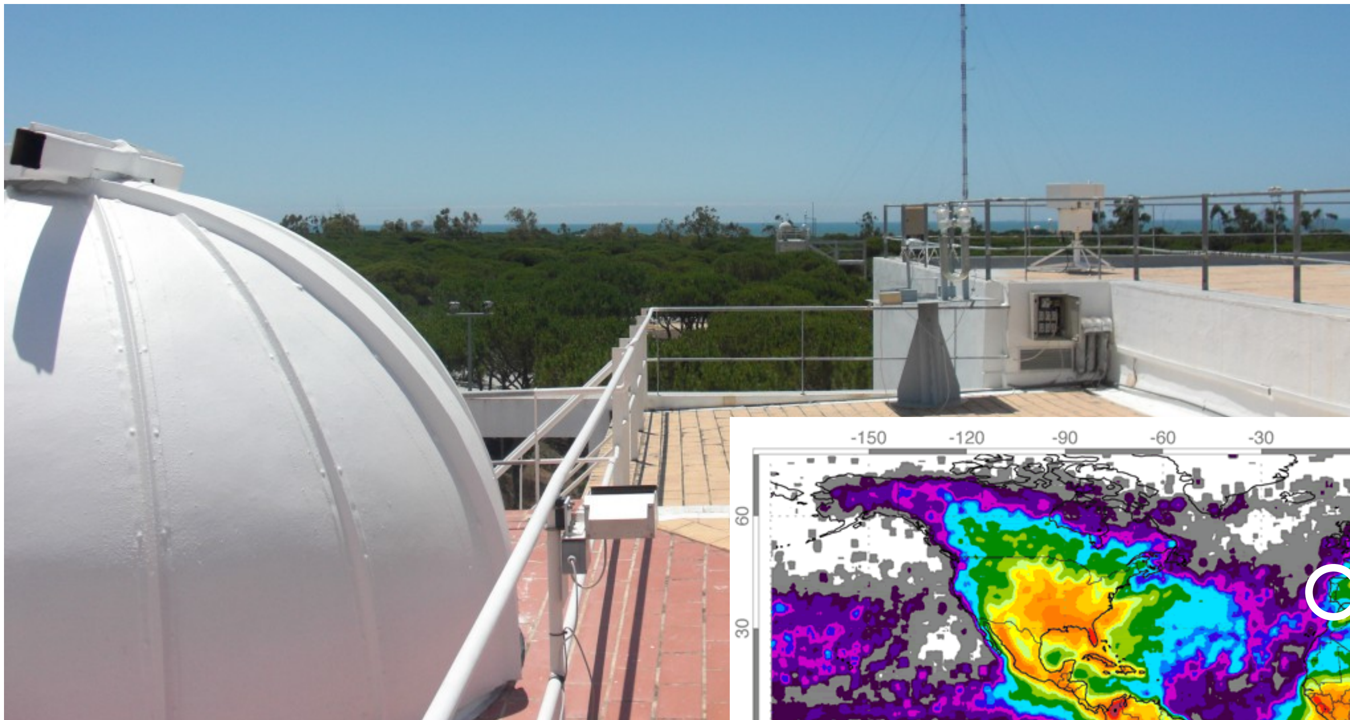


MiniMegaTORTORA: first light / Jun 2010



FOV 10 x 8 degrees, limit down to B~12.0 in 0.13 s

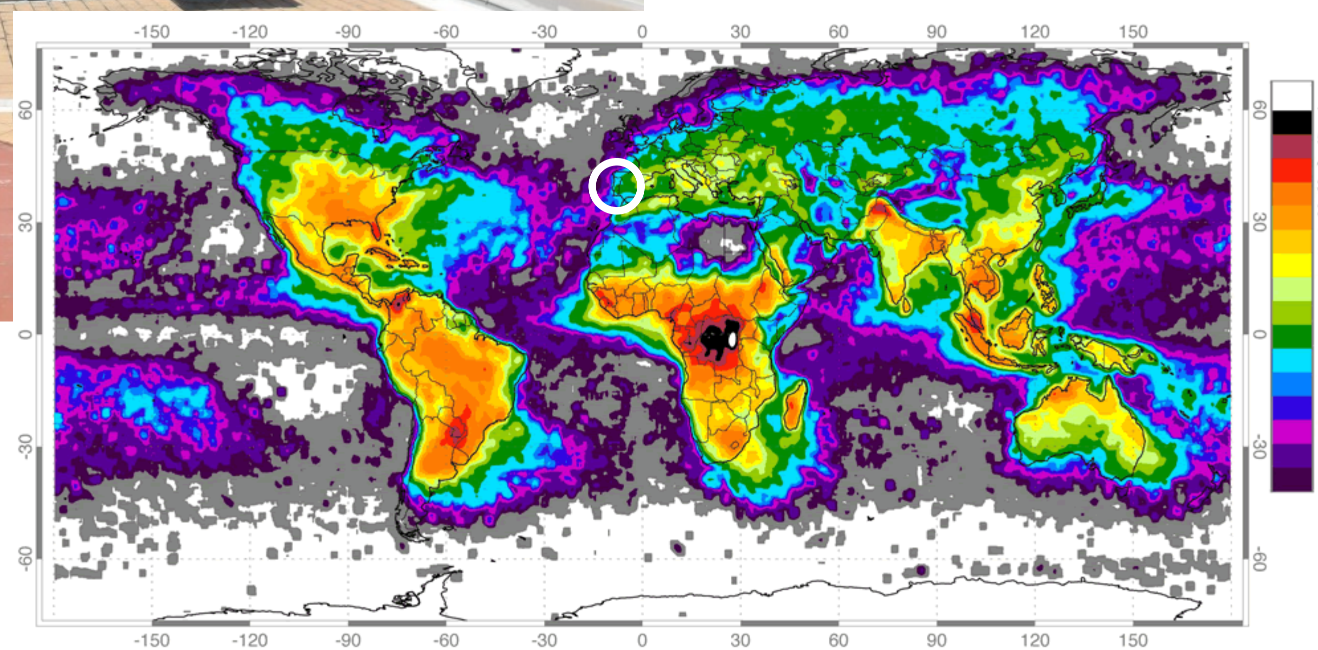
MiniMegaTORTORA: where to settle it down



El Arenosillo Atmospheric Station Huelva, Spain

http://iono.inta.es/

The station will host ***MiniMegaTORTORA*** *complex since 2011 under Russian-Italian-Spanish agreement*



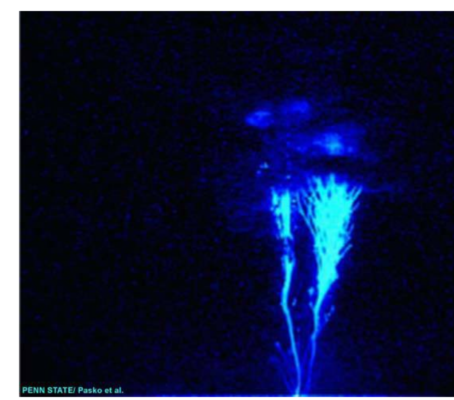
Low Resolution Full Climatology Annual Flash Rate

Global distribution of lightning April 1995-February 2003 from the combined observations of the NASA OTD (4/95-3/00) and LIS (1/98-2/03) instruments.

Independent search for optical transients: and what about TLEs?

Phenomenology

- **Upper-atmospheric events above thunder fronts — elves, sprites, jets**
  - **Timescales down to nanoseconds**
    - **but only 10^{-4} s does really matter**
  - **Spatial scales down to tens of meters**
  - **Accelerated electrons, nonthermal emission?..**
    - **Variable spectrum**
    - **Polarization???**



Transient Luminous Events: how do you observe it?

- Satellites — nadir mode (ISS, Tatiana, ...)
  - Loses vertical structure
- Satellites — tangential mode (ISUAL, ...)
  - Low spatial resolution due to large distance
- Ground-based — PM arrays (PIPER, ...)
  - Low spatial resolution
- Ground-based — video cameras (ILAN, ...)
  - Low temporal resolution
- Ground-based — fast imagers (Fairbanks, ..)

Transient Luminous Events: is MiniMegaTORTORA of any help here?

- Moderately large field of view
- Good spatial resolution
- Independent, autonomous operation
- Simultaneous color and polarimetric information
- Temporal resolution?
  - Use faster detectors with lower readout noise
    - EM-CCD
    - Intensified CMOS

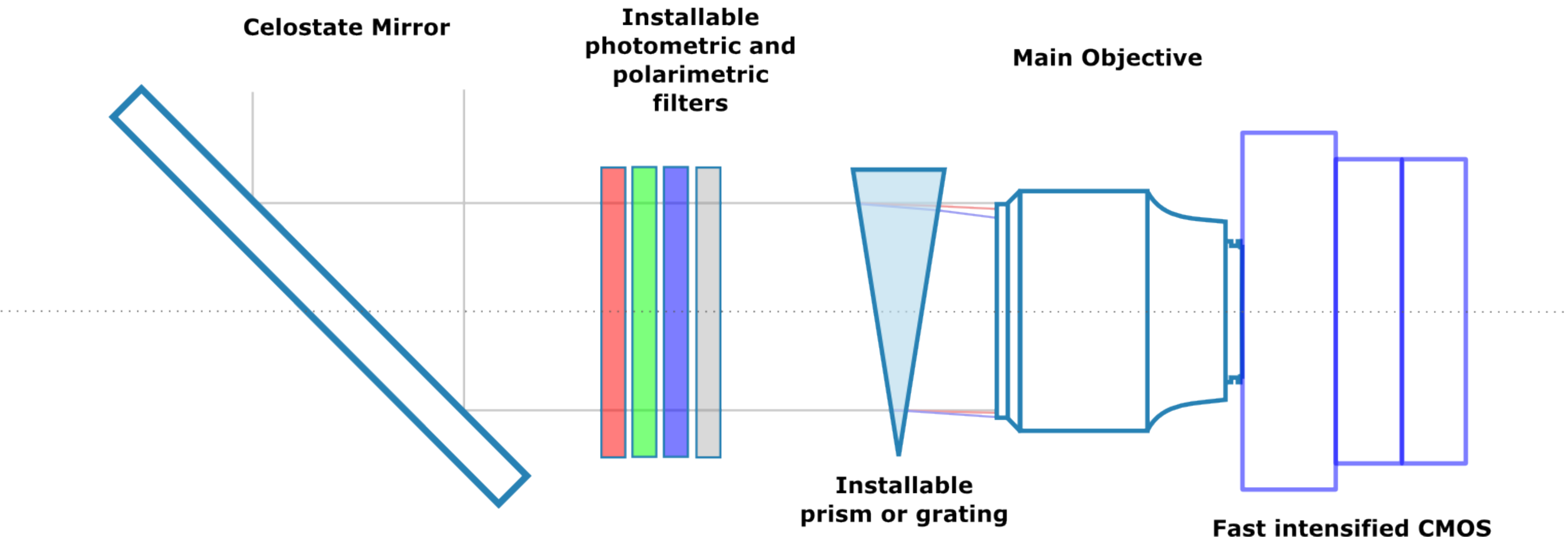
MiniMegaTORTORA: detectors for better temporal resolution

- Electron-Multiplying CCDs
  - up to 1024x1024, 13um pixel
  - read-out noise reduction due to charge multiplication
  - frame rates from 10 (full) till 1k (64x64)
- CMOS sensors
  - up to 4096x4096
  - fps from 2k (full) till 100k (64x64)
  - large read-out noise
    - may be reduced by image intensifier

Andor iXon+888

Photron FASTCAM APX-i2

MiniMegaTORTORA: modification for TLE observations



CANON EF85/1.2

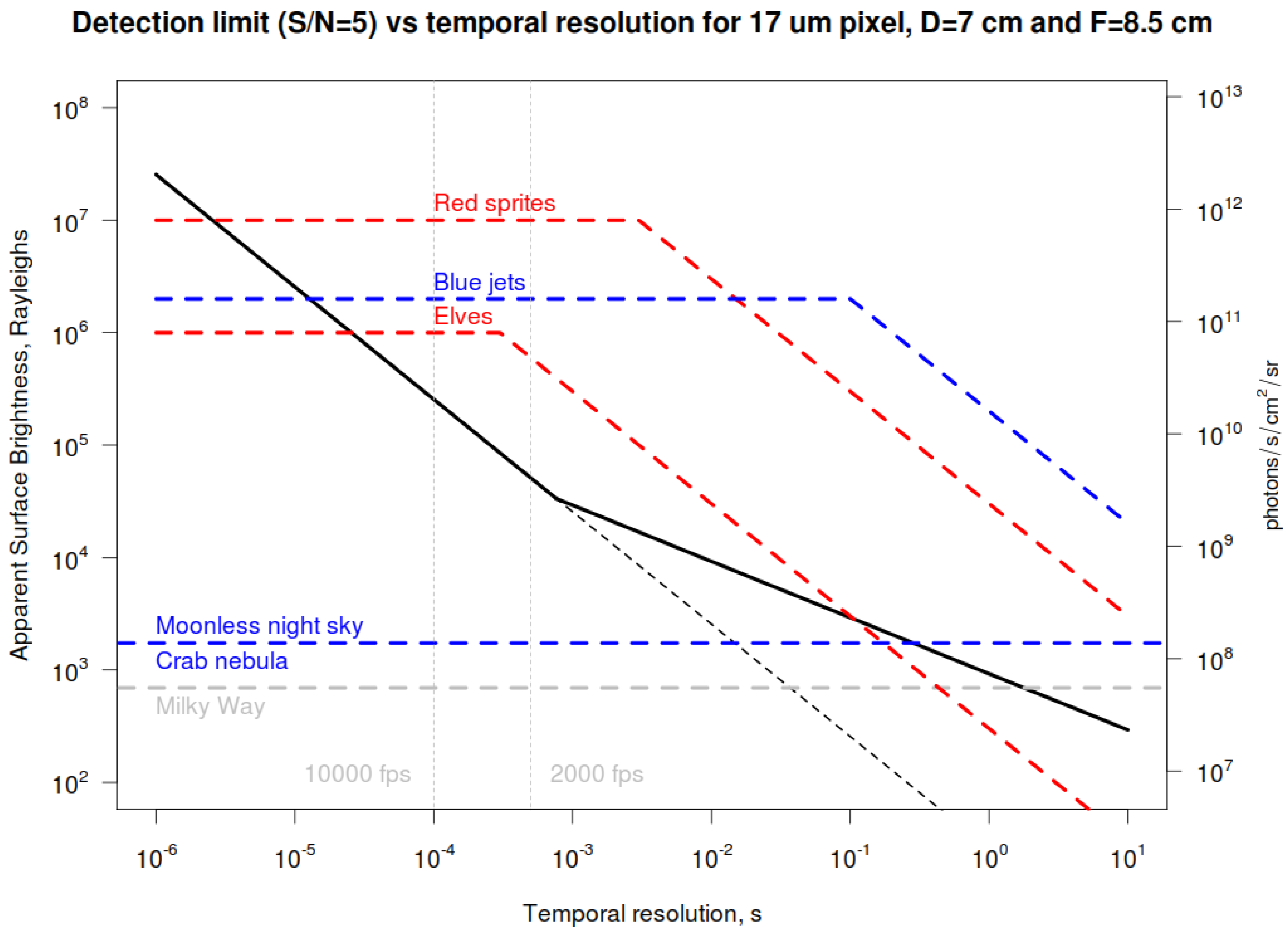
Diameter: 71 mm
Focal Length: 85 mm
D/F: 1/1.2
Field of View: 10 deg
Resolution: 41"/pixel

Intensified CMOS

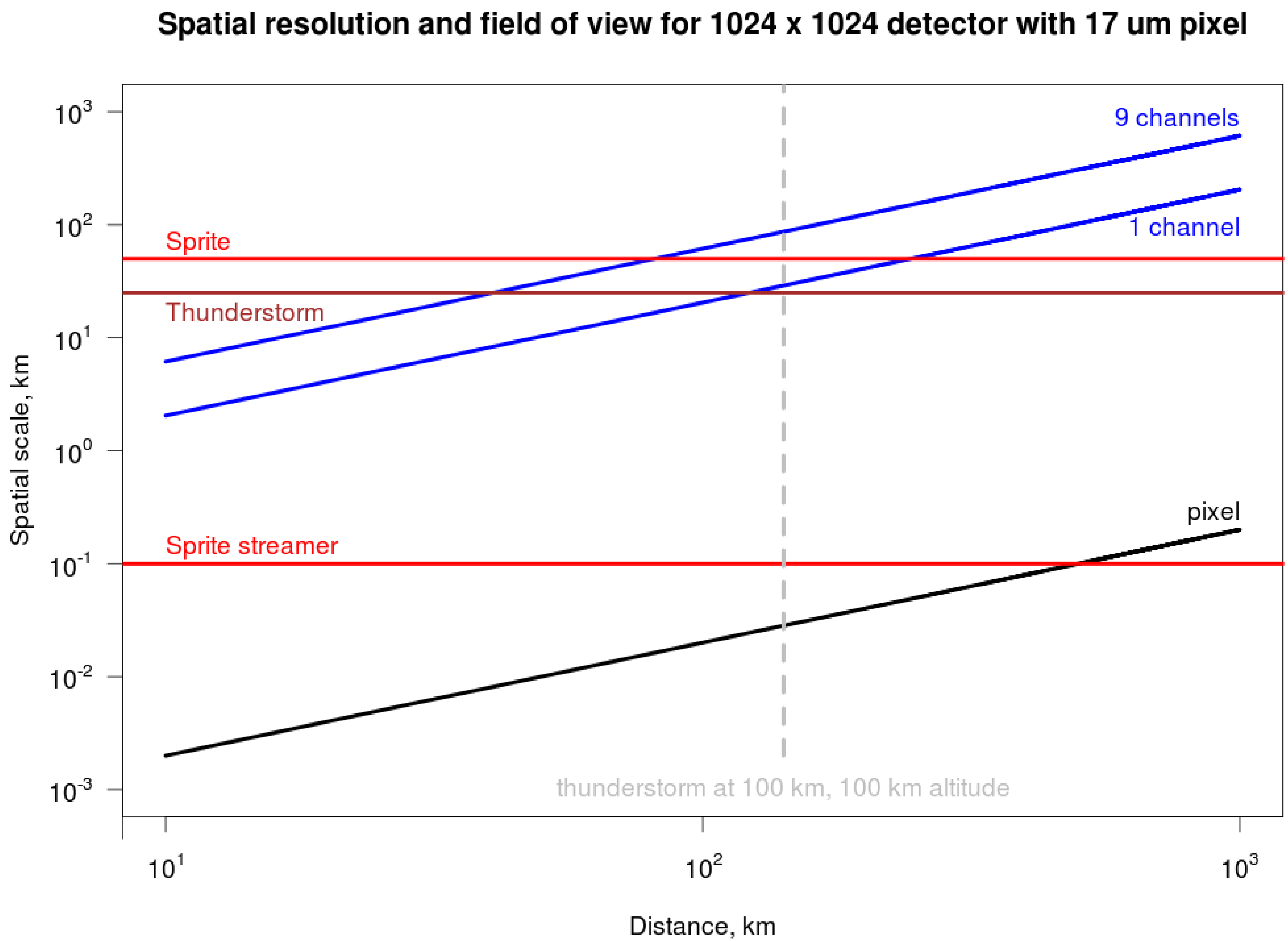
Chip: Photron FASTCAM ultima APX-i2
Size: 1024x1024 pixels
Pixel: 17x17um
Frame rate: 2000 (full) – 100000 (128x32)
QE: up to 50%, 4000-7000A

8 Gb internal buffer, ~3 s (6000 frames) coverage. External trigger to download to PC.

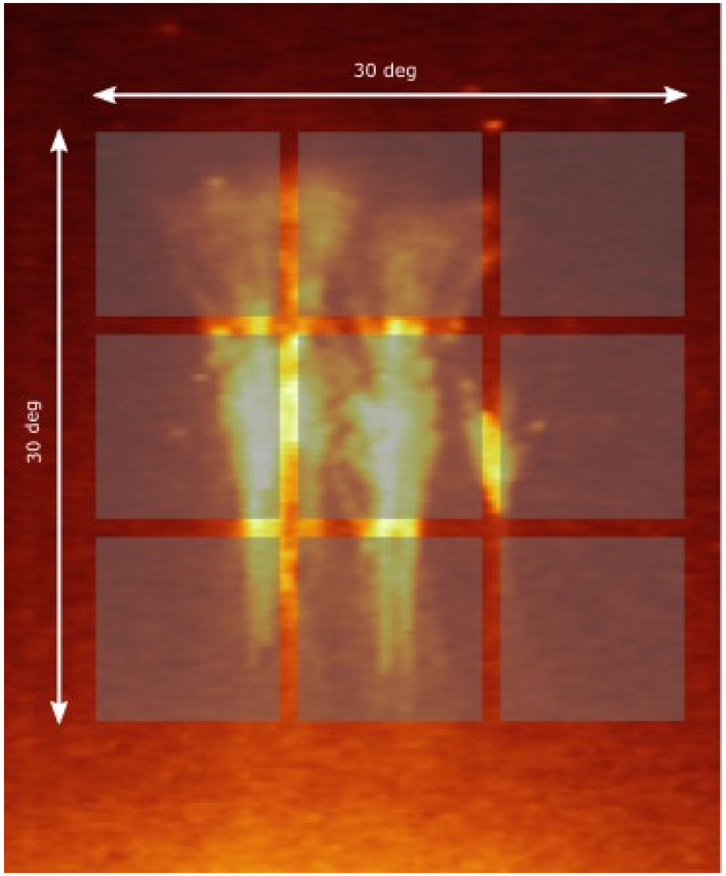
Transient Luminous Events: how bright are they?

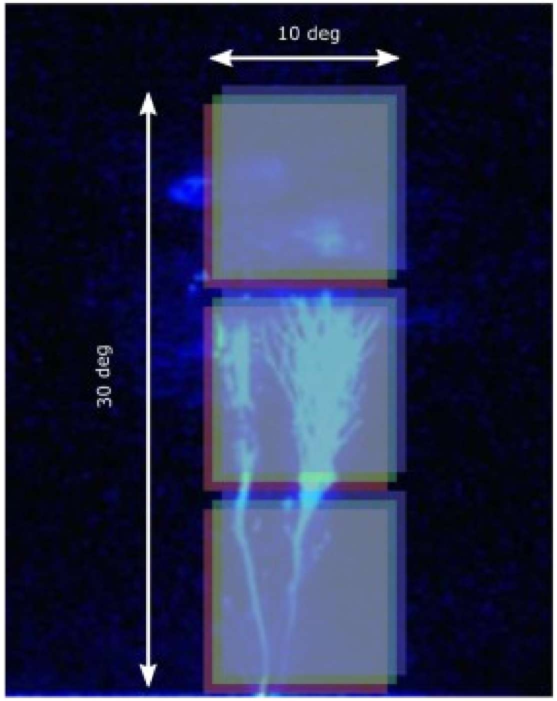


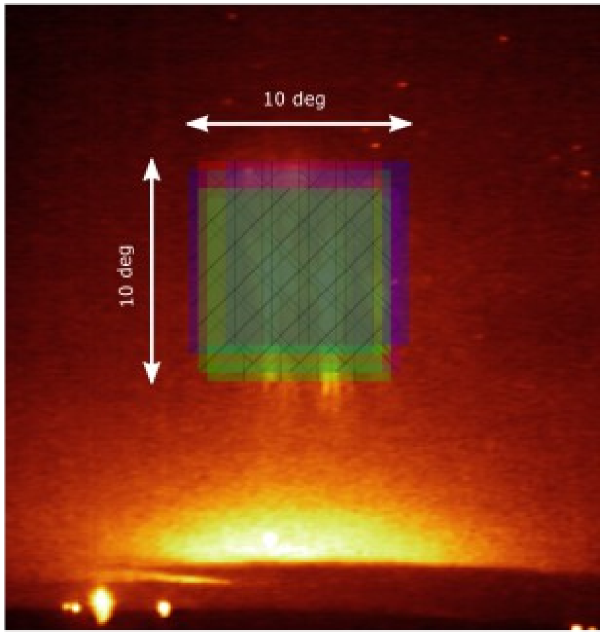
Transient Luminous Events: spatial scales



Transient Luminous Events: observing with MiniMegaTORTORA







Wide field, single color

No filters or one filter

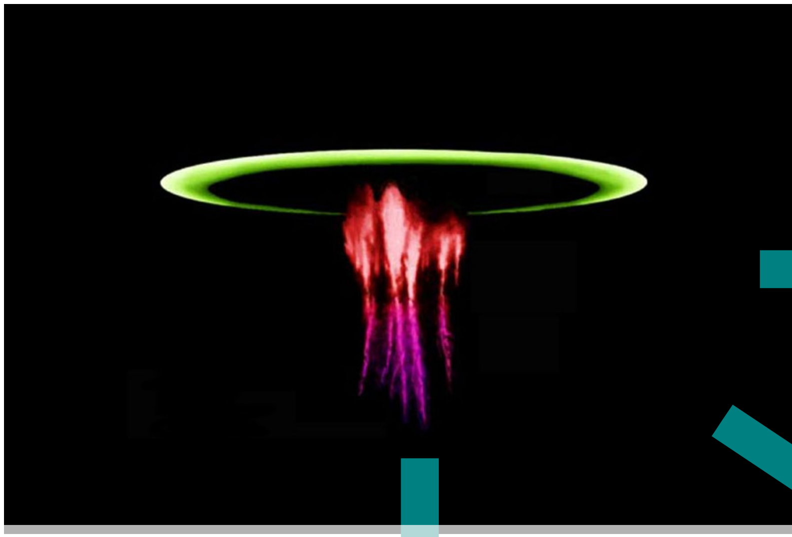
Medium field, three colors

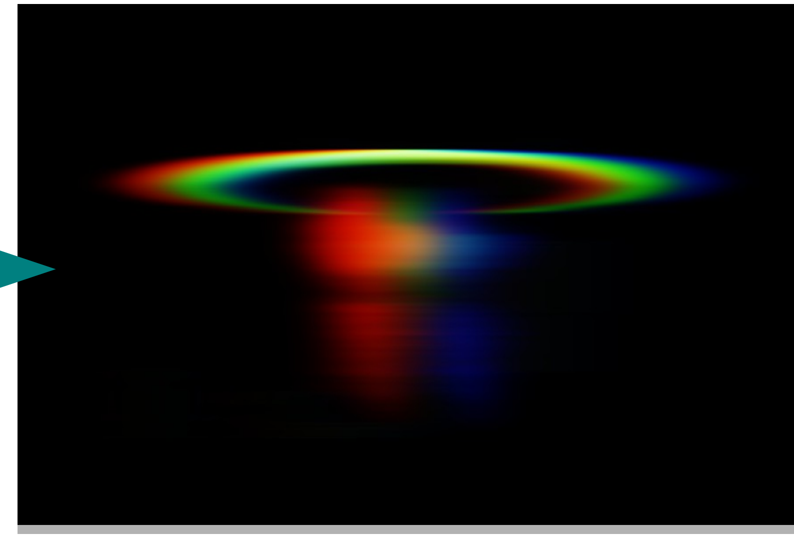
Color filters

Narrow field, three colors, three polarizations

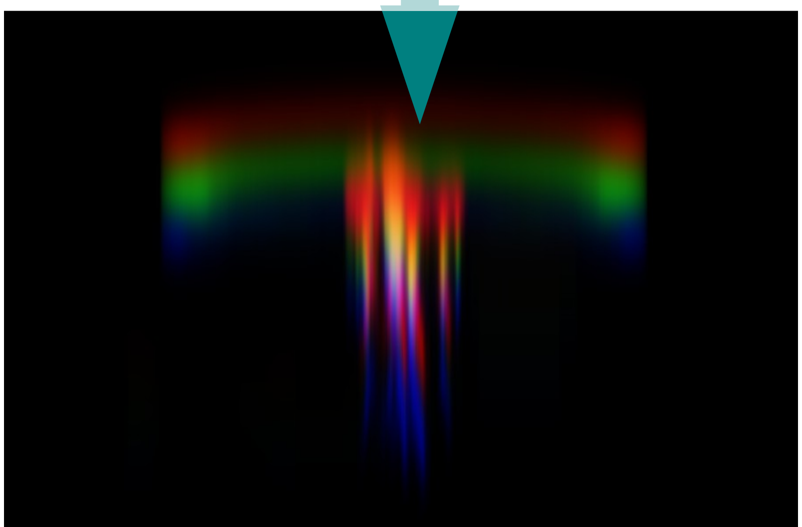
Color + pol. filters

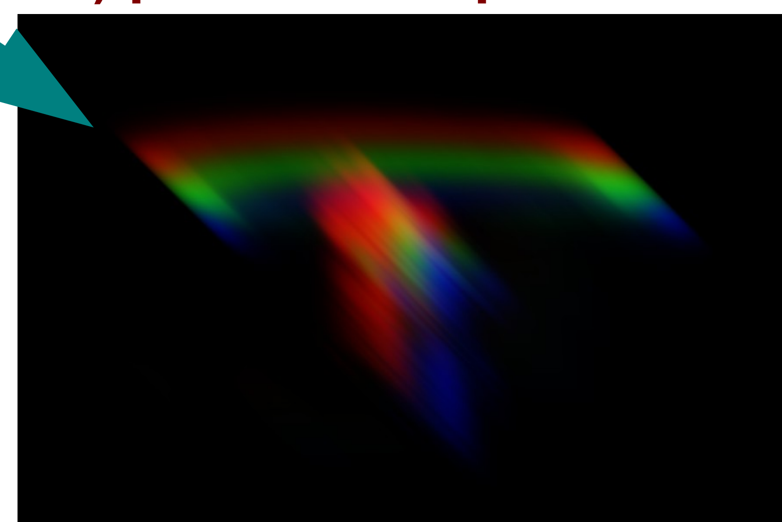
Transient Luminous Events: observing with MiniMegaTORTORA





Narrow field, low-resolution (r~20-100) panoramic spectra





Several images with different orientation of objective prisms

MiniMegaTORTORA for TLE observations: summary

- Provides good spatial resolution and coverage
- Allows to observe TLEs in different modes
  - Wide-field, single color for near-by thunders
  - Narrow-field, three colors and polarizations for distant events
- May be easily adapted to provide good temporal resolution
  - FPS up to 2k-10k with full resolution and FOV
  - FPS up to 100k with limited spatial resolution

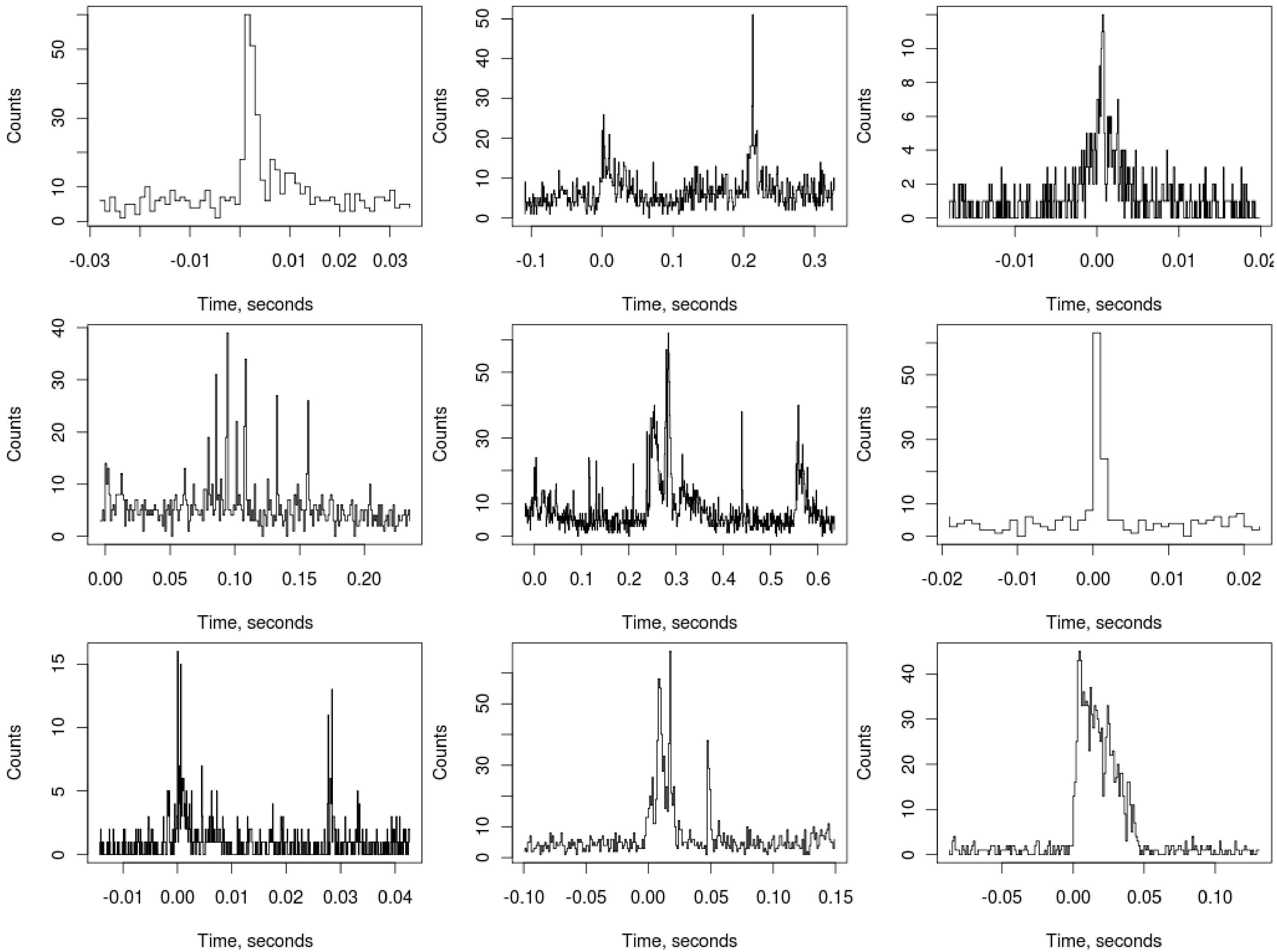
MiniMegaTORTORA for TLE observations: summary

- Able to acquire panoramic spectra with objective prisms
  - Different orientations — reconstruction of field
  - Simultaneous polarimetry?..
- Able to detect and measure transients autonomously
  - We have software for astronomical / near-earth transient detection and classification. It works.
  - Adaptation for atmospheric ones is straightforward

MiniMegaTORTORA for TLE observations: summary

That's all about our wide-field efforts

Transient Luminous Events:
as seen by 6-m telescope



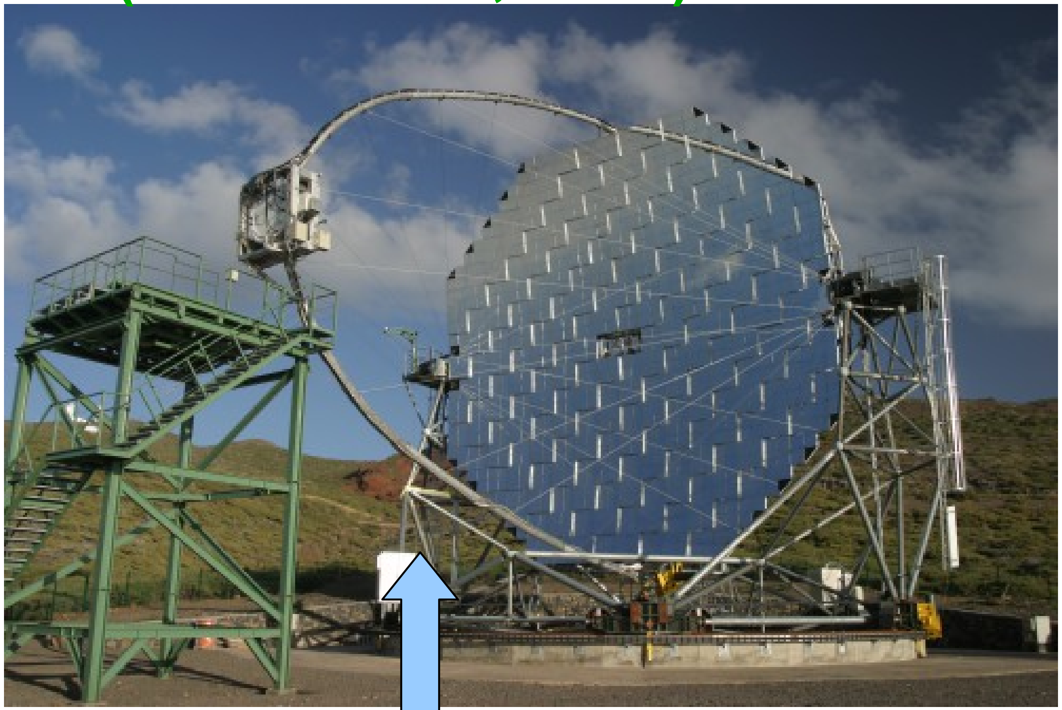
SAO RAS, Russian 6-m telescope, position sensitive photon-counter, 15'' field

Thank you

Independent search for optical transients: re-using existing hardware?..

Large telescopes with «bad» mirrors (Beskin et al, 1999)

- Size: 10-30 m
- Detectors: 10-1000 PMT (< 1us)
- FOV: 10-20 square degrees
- Angular resolution: 5-30 arcmin
- Limit: up to 18^m for 1ms



Cerenkov telescopes

(MAGIC, H.E.S.S., VERITAS...)

Solar concentrators

(PETAL, ...)