Constraints on collimation of optical emission from Gamma-Ray Bursts

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Plan

- Introduction to Gamma Ray Bursts (GRB)
- “Pi of the Sky” experiment
- Data analysis in “Pi of the Sky” experiment
- Results and interpretation in terms of constraints on optical emission collimation
- Future of the experiment

Gamma Ray Bursts (GRB)

- short pulses (0.1 – 100 s) of gamma radiation coming from point sources on the sky, discovered in 1967 by VELA satellites

- gamma observation only from outside atmosphere – satellites, information is passed through GCN

- about 3 daily occur, over a dozen per month are detected by satellites
- extragalactic origin and huge energies : $E_{LONG} \sim 10^{51}$,$E_{SHORT} \sim 10^{49}$ ergs, Sun emits 10^{33} erg / s , it means ~ 30 billions years of Sun shine !

- Current models : long bursts due to death of massive star (collapsar or hypernova) short bursts collision of two neutron stars in a binary system (merger)

- they may be accompanied by optical flash (observed for ~ 50%)

- observation of optical emission in early time – even before gamma emission itself , cannot be realized by classical robotic telescopes
- Good understanding of GRB is needed to use them to probe universe

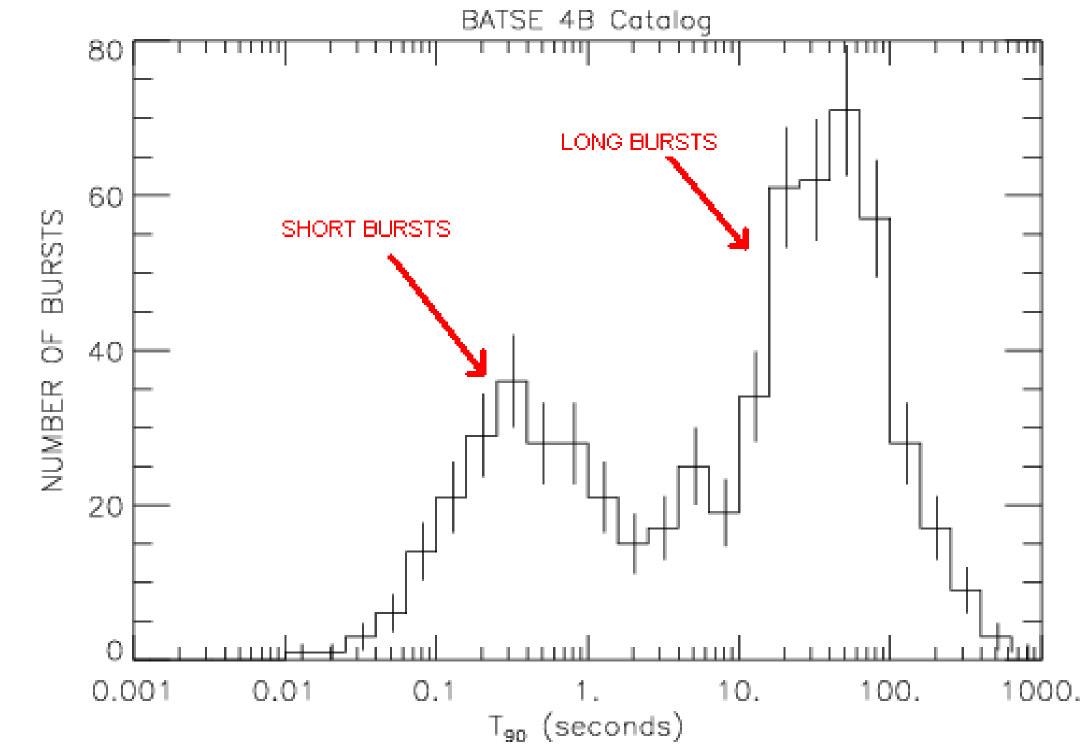
Gamma Ray Bursts (GRB)

- Observation of optical counterparts (Beppo-SAX in 1997) and redshift (z=3.14) measurements confirmed extragalactic origin of GRBs

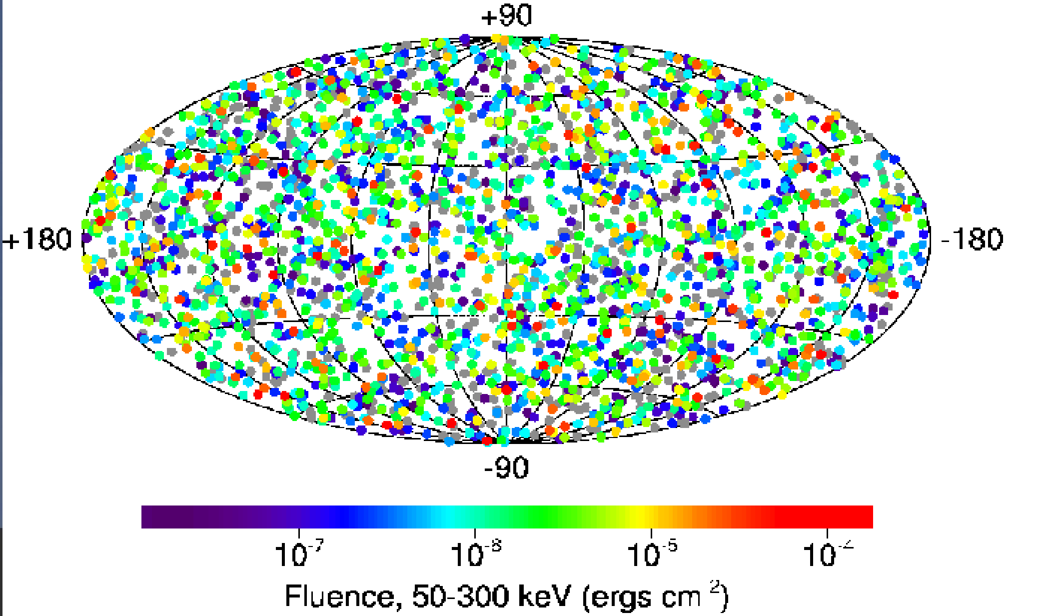
- Currently the most distant GRB050904 is z=6.29 (12.8 billions years)

- In most cases optical *afterglow* was observed hours after GRB (before the SWIFT)

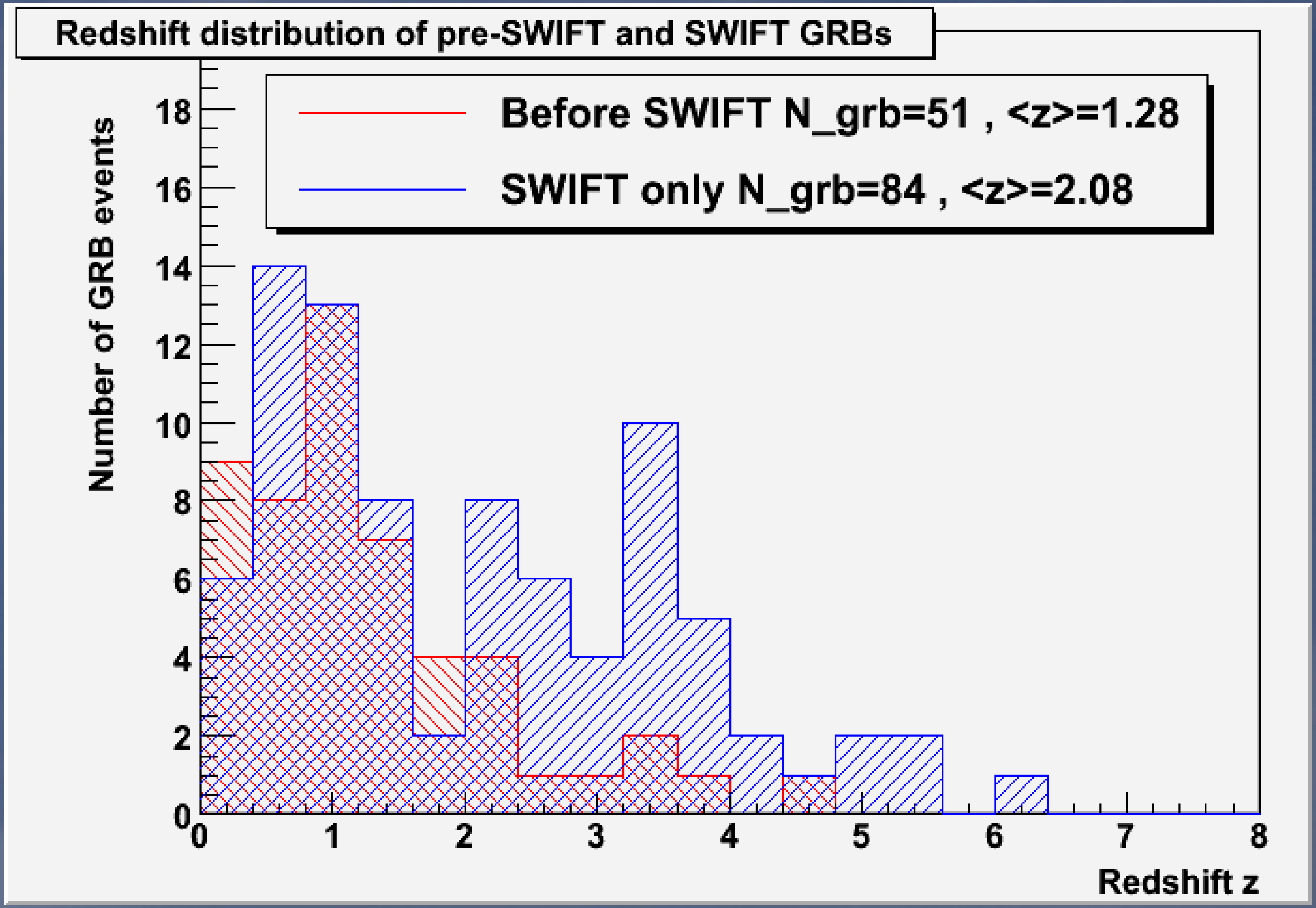
- Recently first optical counterparts of short bursts have been observed (typicaly z < 1)



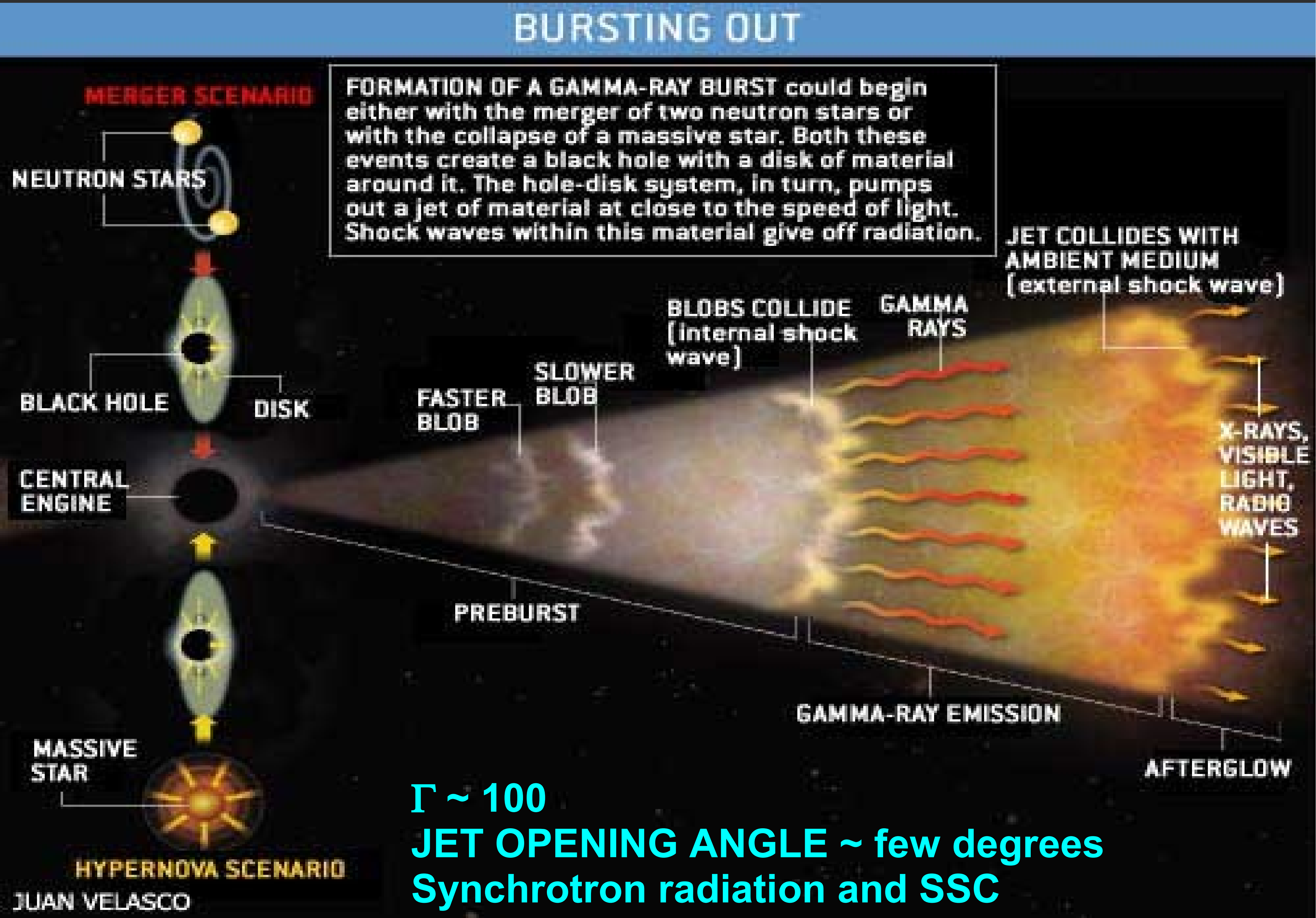
Isotropic distribution of GRBs



Optical observations in SWIFT era



Fireball model



$\Gamma \sim 100$

JET OPENING ANGLE ~ few degrees

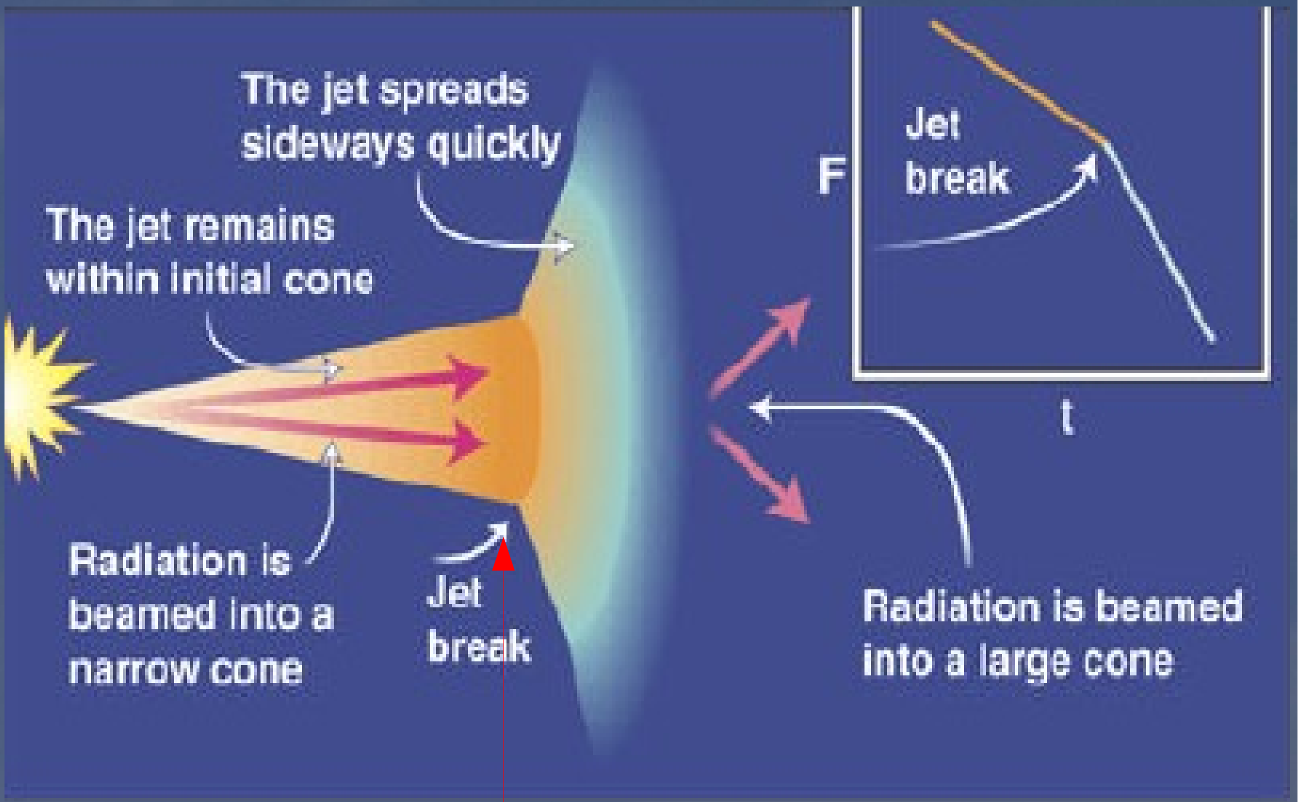
Synchrotron radiation and SSC

Optical emission

- "Classical afterglows" - hours/days after GRB due to collision with the Interstallar Medium
- Prompt optical signal – not well understood :
  - **Low energy tail of gamma emission (optical signal correlated with γ-ray signal)**
  - **Reverse shock between shells**
  - **Energetic structure of the jet , optical emission from lower energy material**
- In the latter two cases optical signal can be uncorrelated with gamma ray signal and also the collimation of optical emission can be different
- There may be "*failed GRB*" events, for which Γ factor is to low to produce γ-ray, but could be observed in optical band

Collimation of prompt optical signal

- **Collimation decreases as jet decelerates**
- **It is visible on the optical light curve as thejet break (days after the explosion)**
- **There might be mechanisms producing different collimation since the very begining**



$\Gamma \sim 1/\theta$ **(days after)**

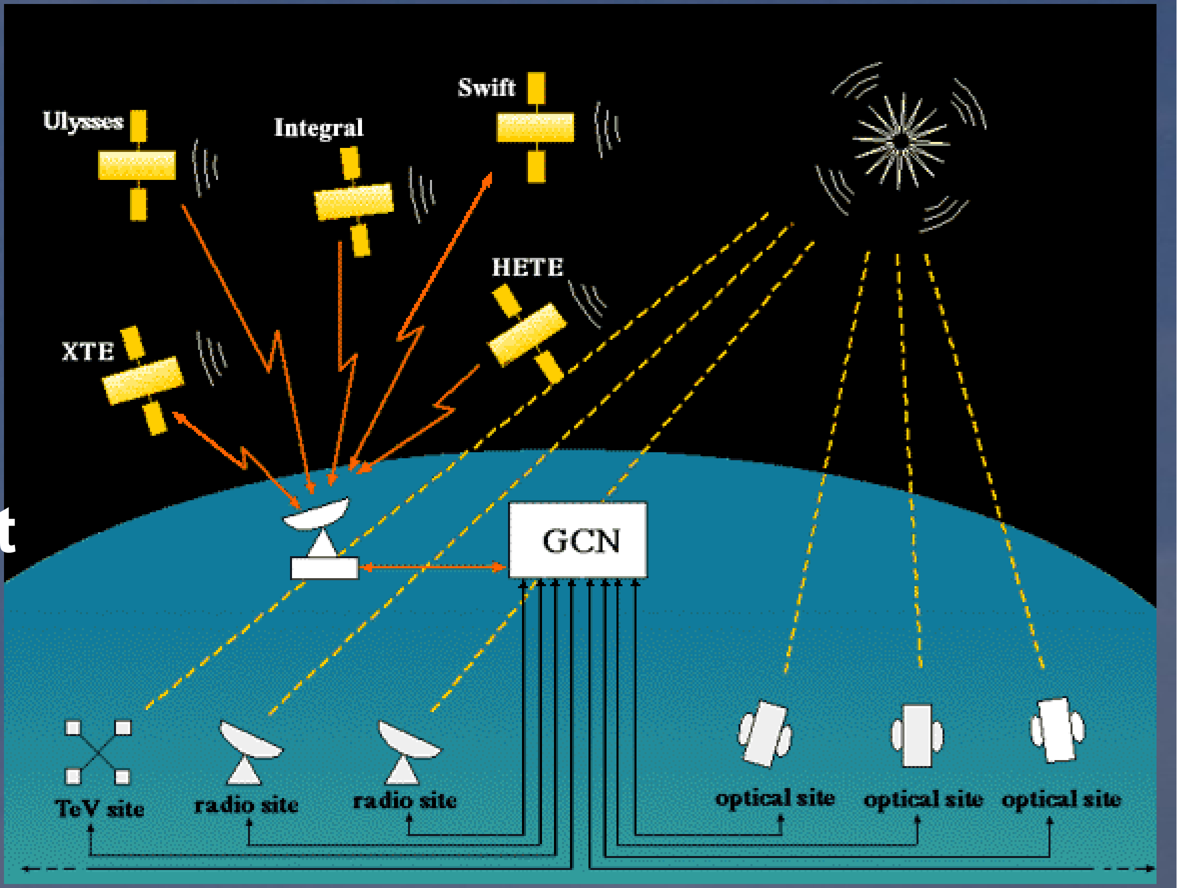
Optical observations of GRBs

- Information is passed from satellites to telescopes (reaction time seconds – minutes)
- Only in a few cases optical signal observed during gamma emission

To be improved :

- Reaction time (nobody knows where and when next GRB will occure)
- Time resolution
- Orphan optical flashes

Gamma-Ray bursts Coordinates Network

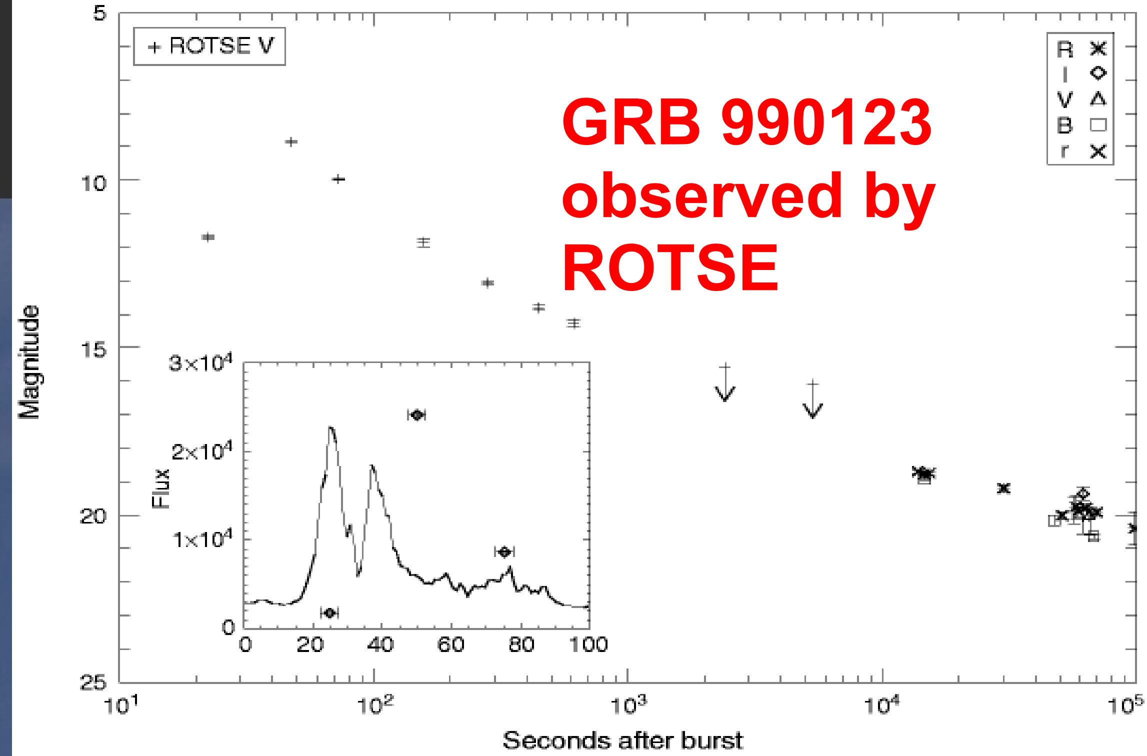


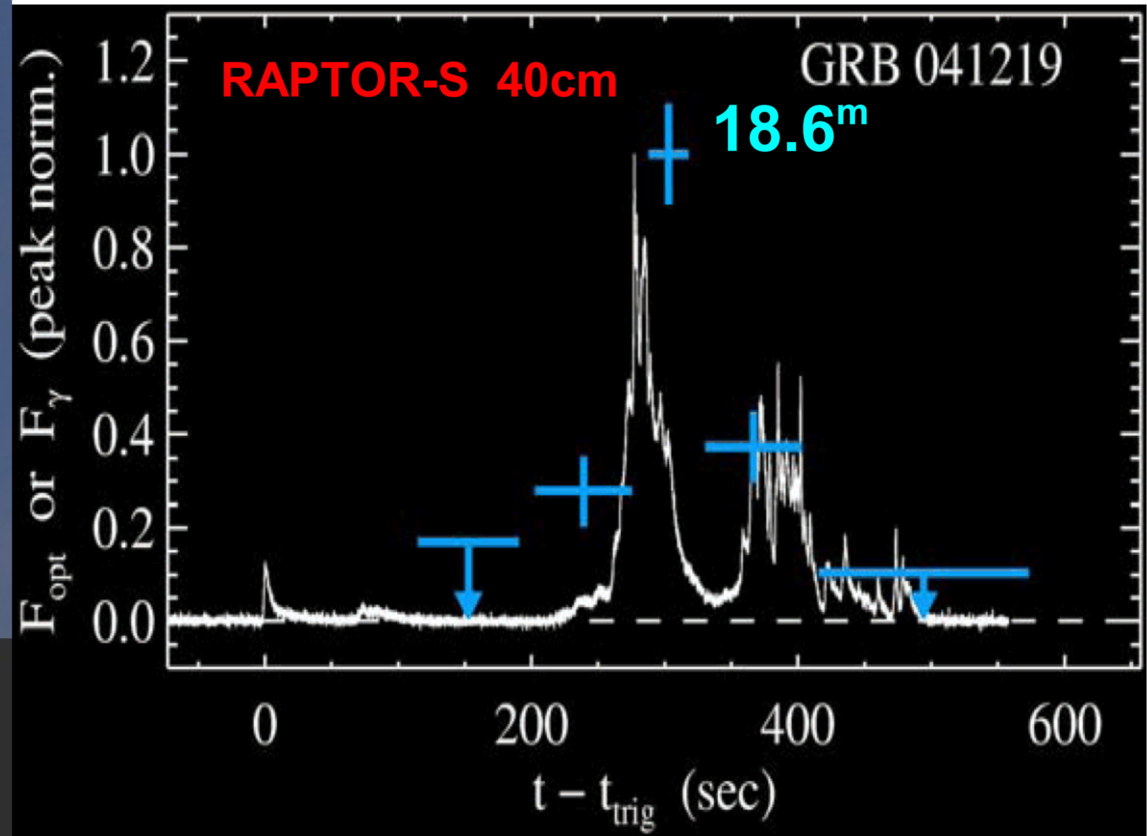
The earliest optical observations

- Only a few events were observed by optical telescopes during the γ-ray emission

- Mechanisms of optical emission remain unclear and seems to differ between bursts

- New approach is needed to obtain more data

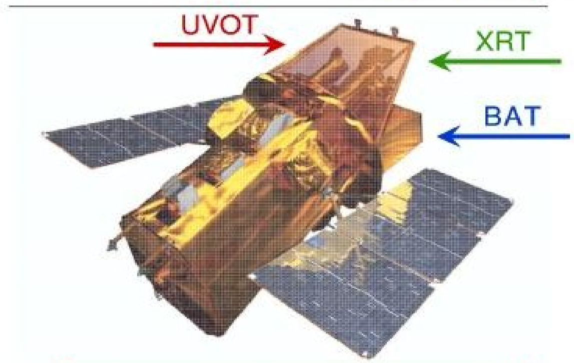




Optical observations in SWIFT era

- Almost immediate optical observations by UVOT telescope on board the SWIFT satellite
- However, still reaction time is limited at ~60 seconds (time needed to slew the spacecraft)
- In order to observe GRB in optical band during the γ-ray emission continuous sky monitoring is required

The *Swift* satellite



BURST ALERT TELESCOPE

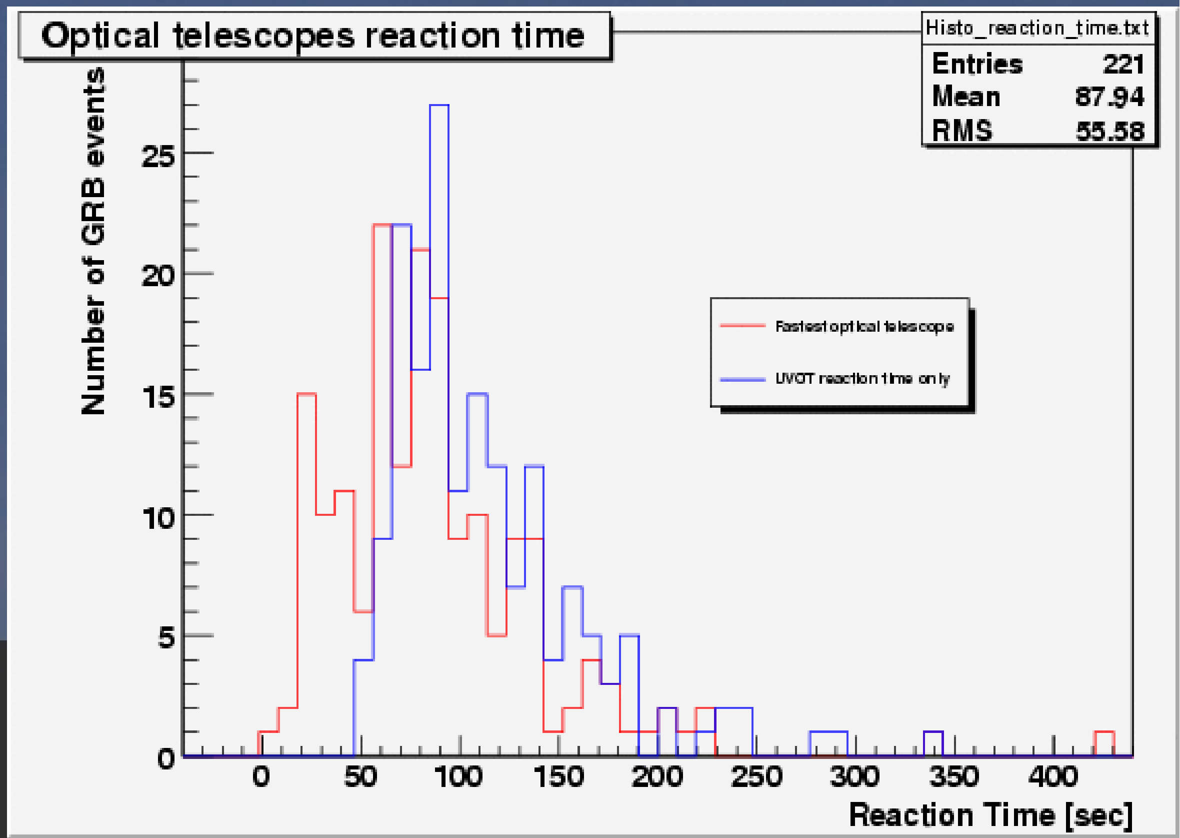
* Imaging: 15-150 keV
* Precision: 2-3 arcmin
* Field of view: 1/6 of sky

UV/OPTICAL TELESCOPE

* Imaging: 1700 – 6500 Å
* Precision: 0.5 arcsec
* Sensitivity: $V = 20$

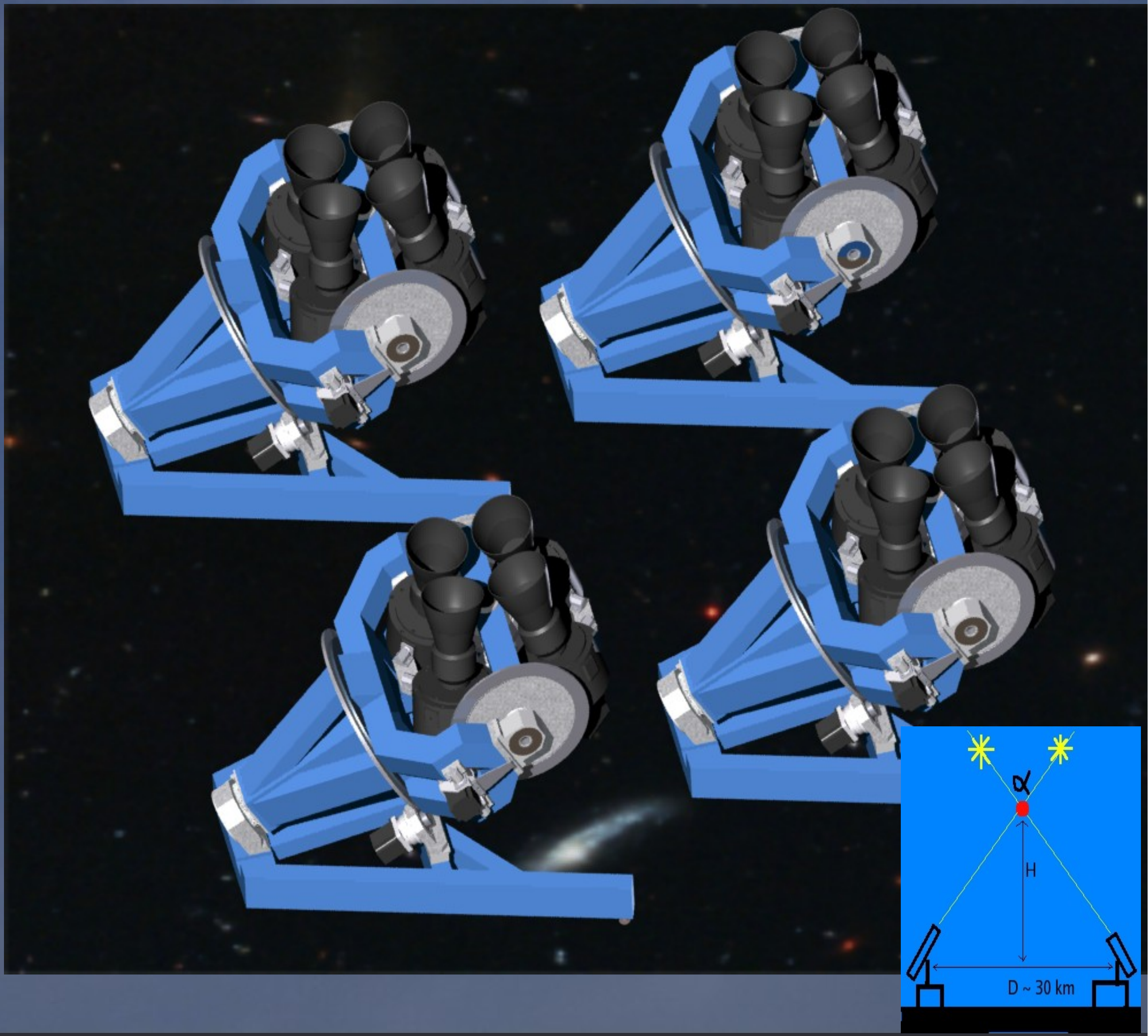
X-RAY TELESCOPE

* Imaging in 0.2–10 keV
* Precision: 3 arcsec
* Sensitivity: 2×10^{-14} cgs



New approach - “Pi of the Sky” system

- **Continuous monitoring of large part of the sky. Corresponding to FOV of the SWIFT and GLAST satellites**
- **Every detected GRB by these satellites will by in our FOV (reaction time < 0 !)**
- **Own real-time trigger for optical flashes**



Prototype system in LCO

- Custom designed 2 cameras on paralactic mount working in coincidence
- Field of View ~ 20° x 20°
- Limiting magnitude ~11m on 10s exposure, up to ~13m on 20 averaged images
- On-line flash recognition algorithm
- Cataloging of measurements to the database
- Off-line algorithms for identification of brightness increases and new objects in the sky
- System is autonomous and sends e-mails and SMS in case of troubles

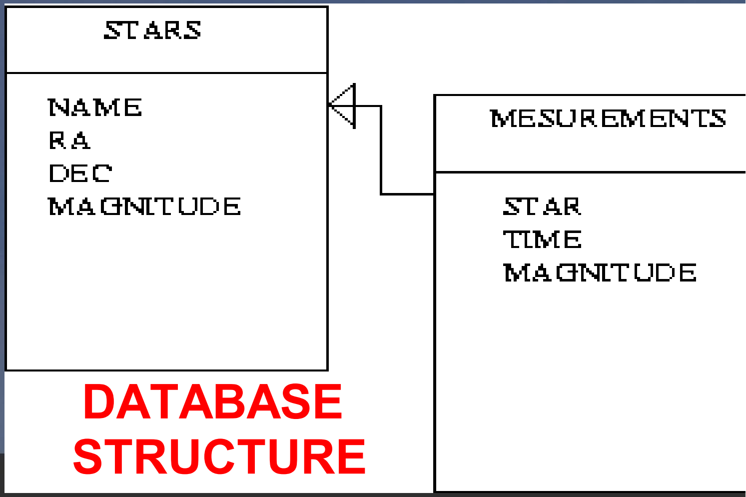
Prototype system in Las Campanas Observatory (LCO) in Chile Working since June 2004

Data analysis

- On-line algorithm based on simple pixel based comparison of images it acts in 10s timescale (single images + coincidence) or in 22s timesceale (confirmation on next images)

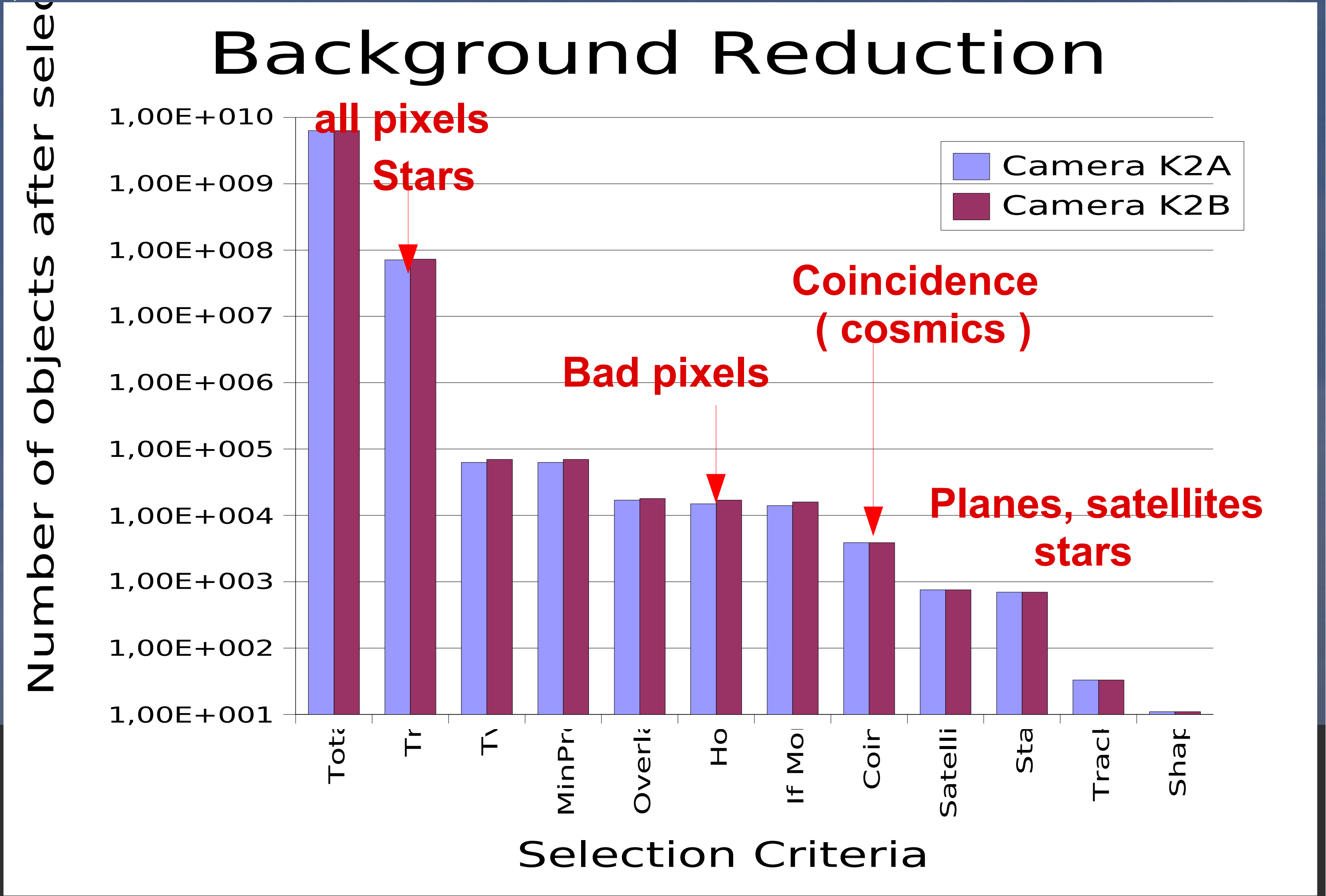
- Data is reduced :
  - **PHOTOMETRY - identifies stars and calculates chip (X , Y) coordinates**
  - **ASTROMETRY – finds transformation from (X , Y) -> (RA , DEC)**
  - **CATALOGING – saves reduced data to database (PostgreSQL)**

- Off-line algorithms analyse lightcurves in database to find increase of brightness or find objects newly added to catalog



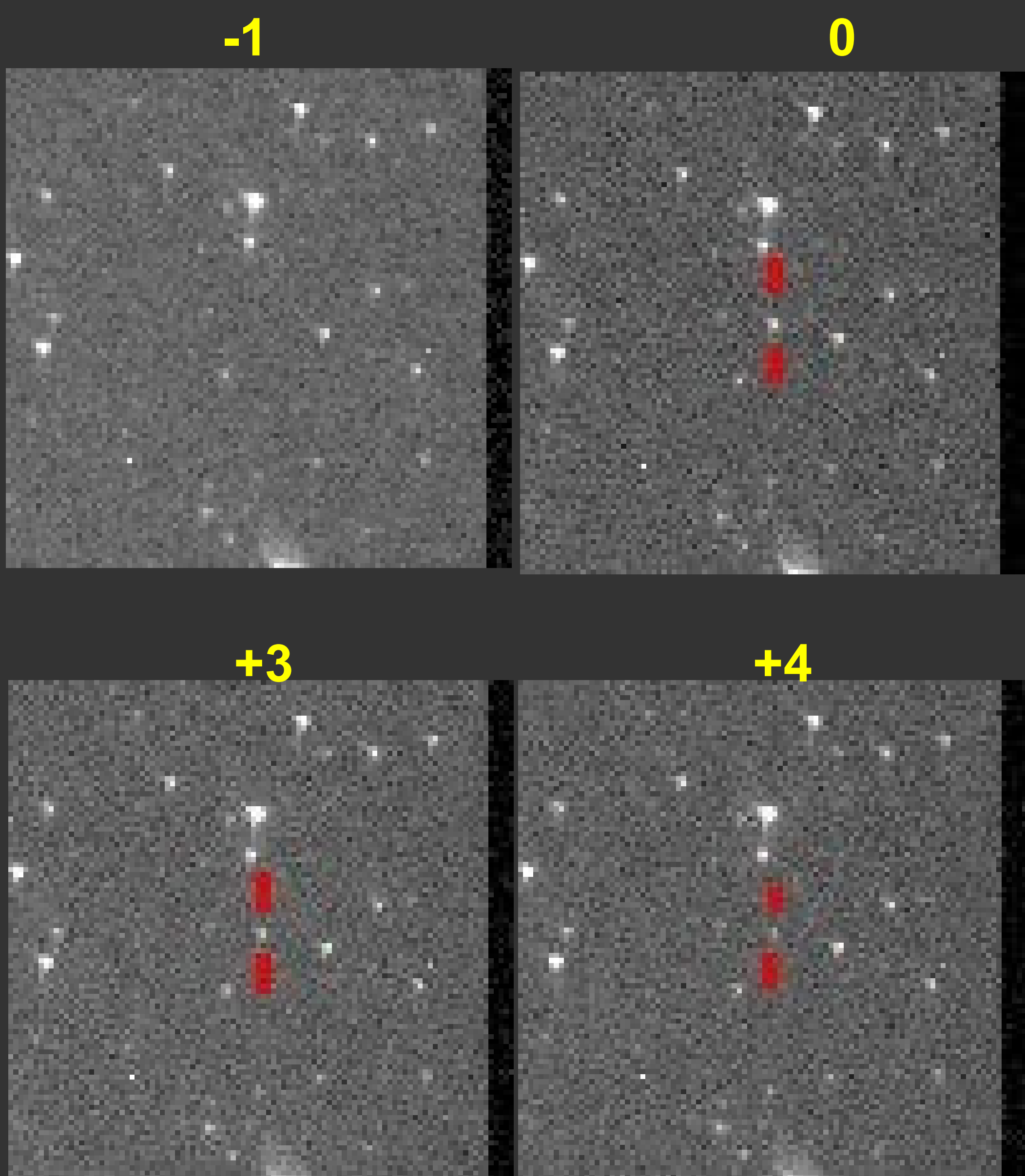
On-line Data Analysis

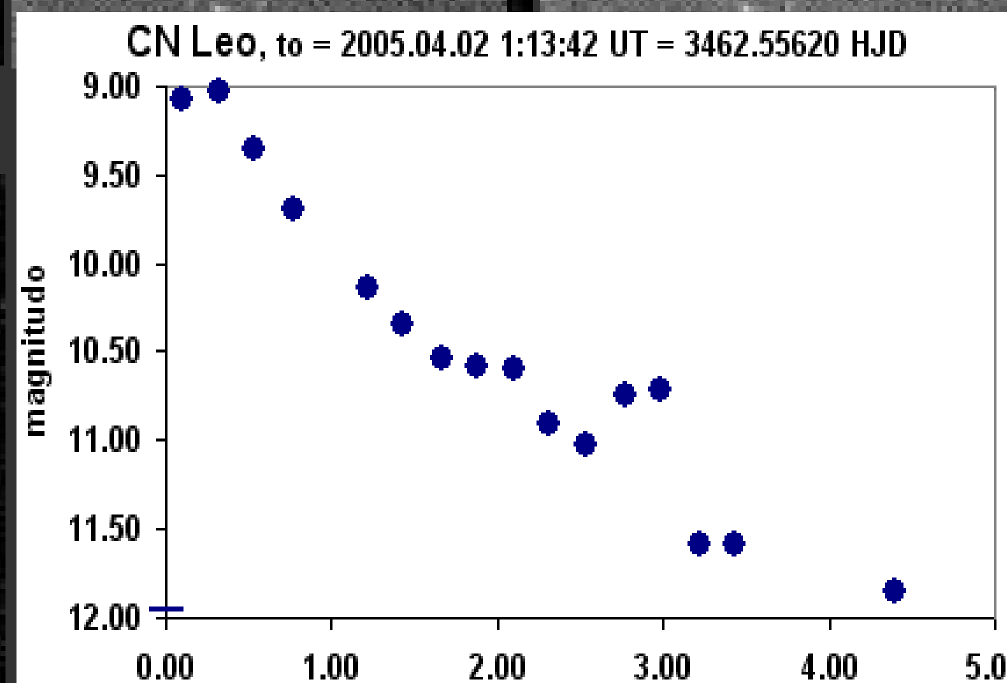
- Flash recognition algorithm, compares new image with series of previous images. Finds new objects not present on previous images (every image ~2×10^4 stars)
- Rejection of background from cosmic rays, flashes from artificial satellites, constant stars, meteors, clouds, UFOs etc ...
- Flash recognition in real time multilevel trigger concept – ideas from particle physics



On-line Data Analysis Results

- 1 sure astrophysical event – outburst of flare star CN Leo
- 8 flashes visible on 2 consecutive images, but single camera
- 150 flashes visible on both cameras, but single 10s exposure





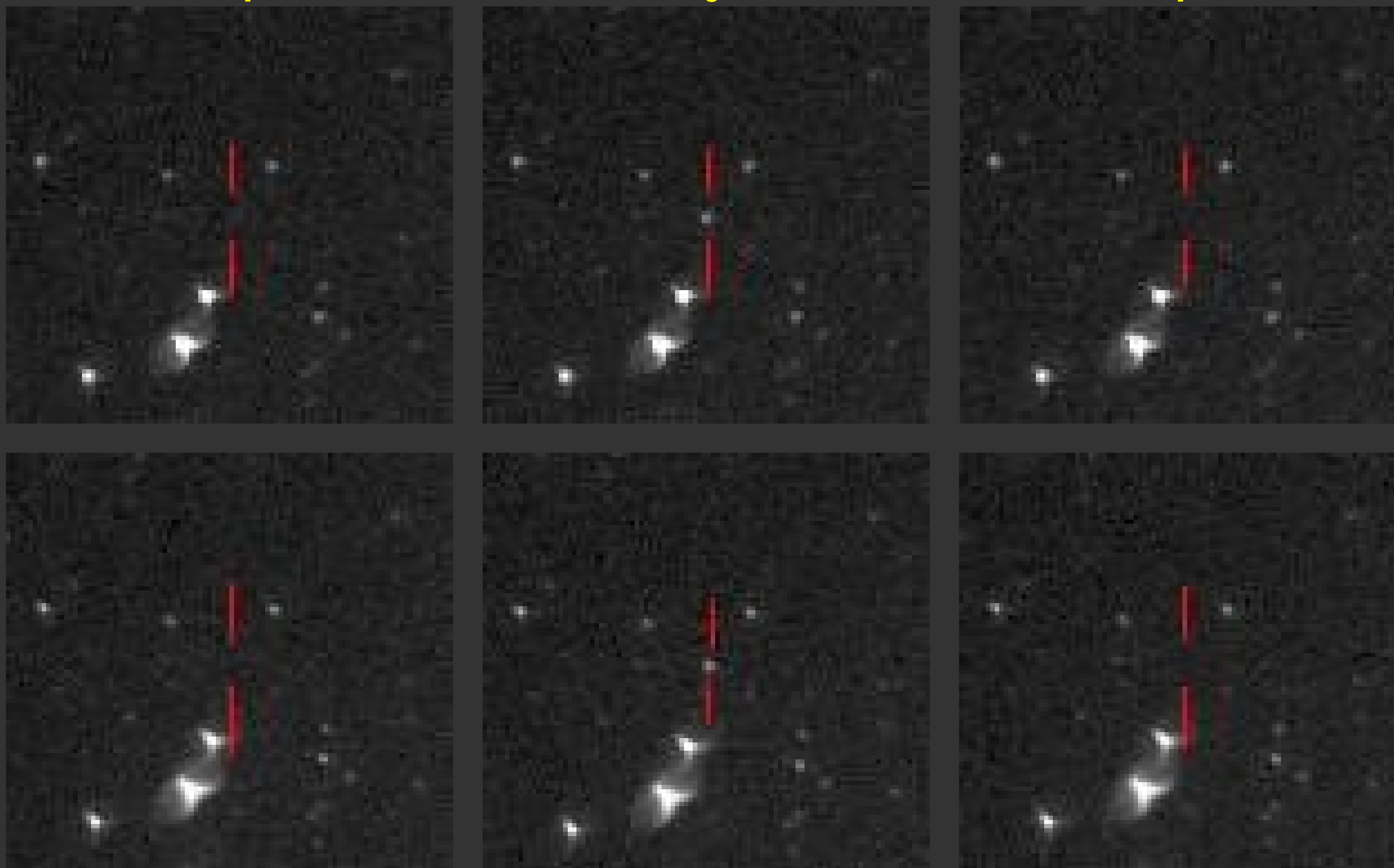
Example of single image flash visible on both cameras

These can still be flashes from non cataloged artificial satellites reflecting sunlight only parallax in the full system will give a chance to reject them (if d < 70000 km)

-1 0 +1

k2a

k2b

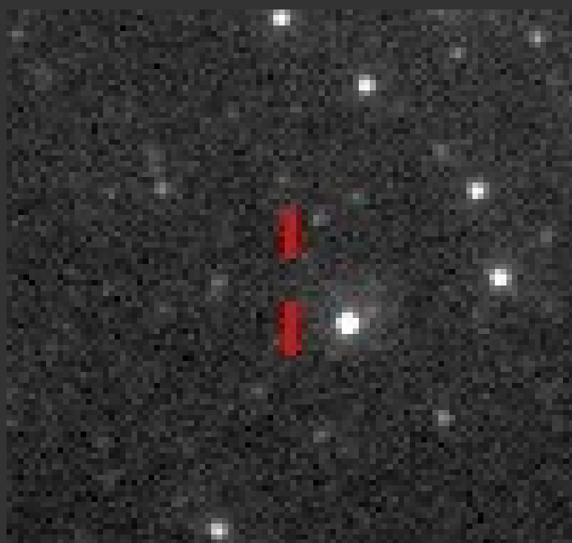


Short timescale (22s) optical flashes

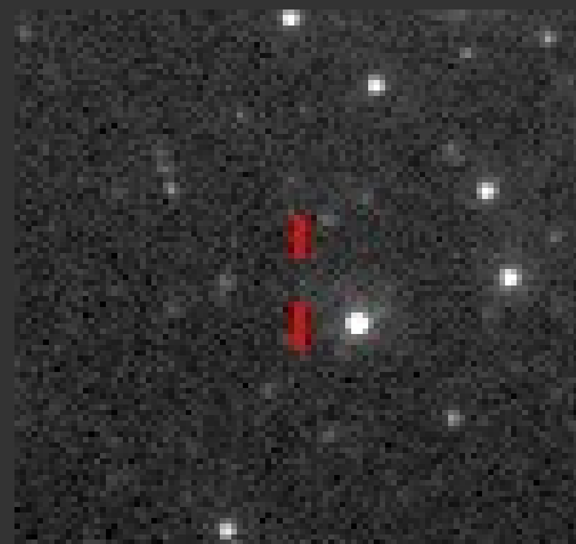
Event visible on 2-3 consecutive images, observed on 2006.10.10 02:44:43 UT and not assigned to any known source. Only single camera was working at that moment

NO COINCIDENCE WITH GRB OR OTHER ASTROPHYSICAL EVENT WAS FOUND

-2

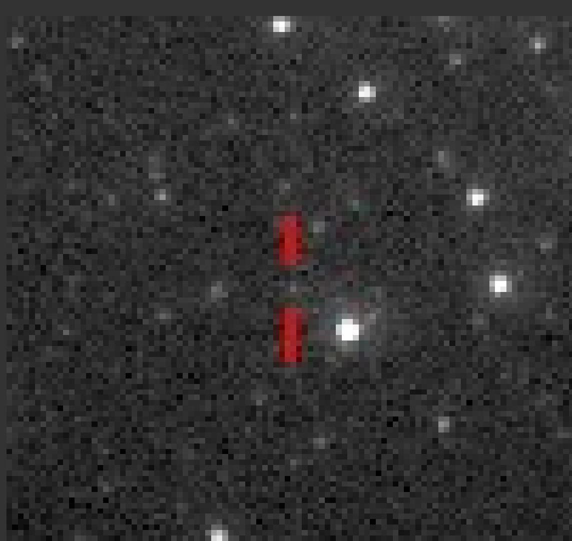


-1

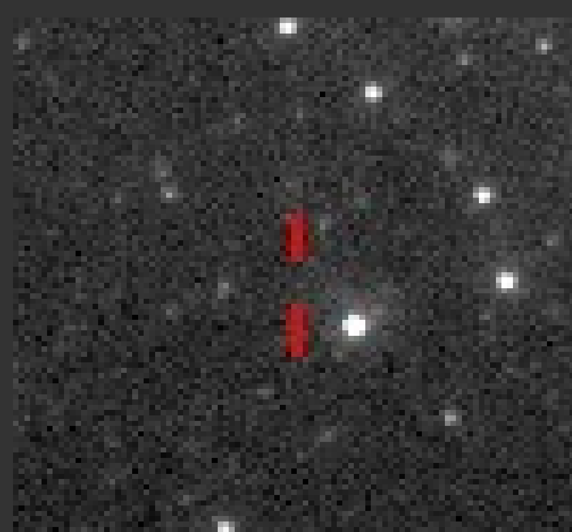


0

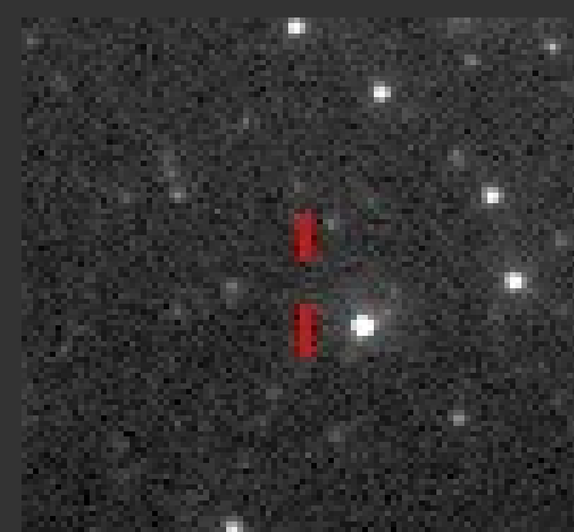
+1



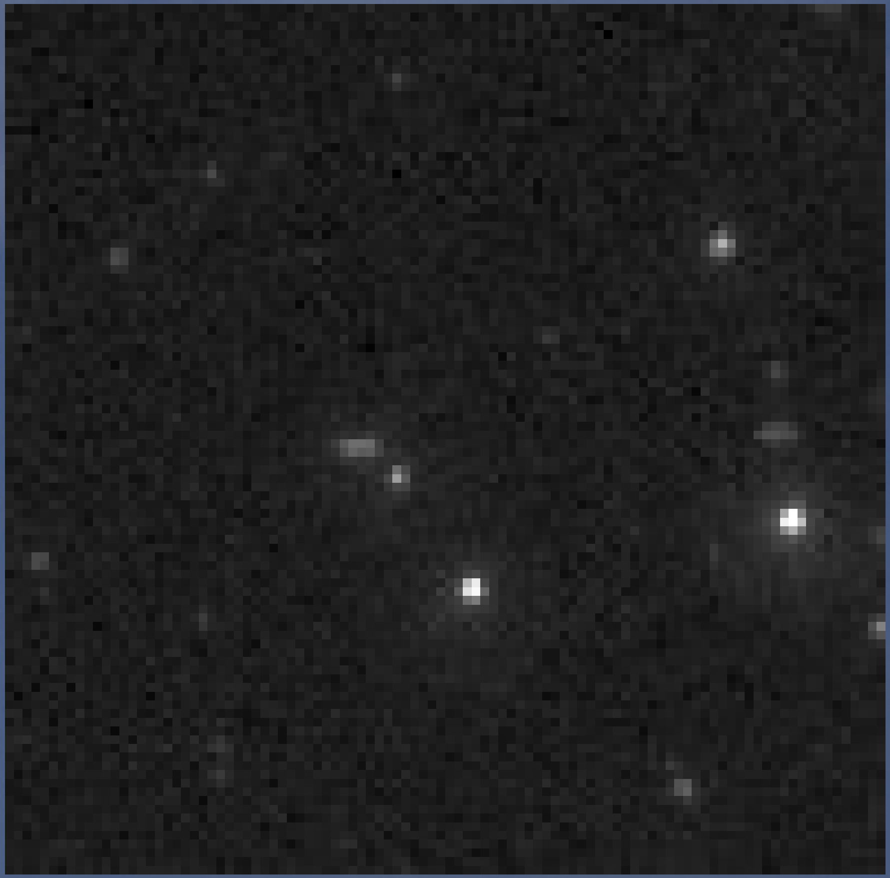
+2



+3



Example background examples



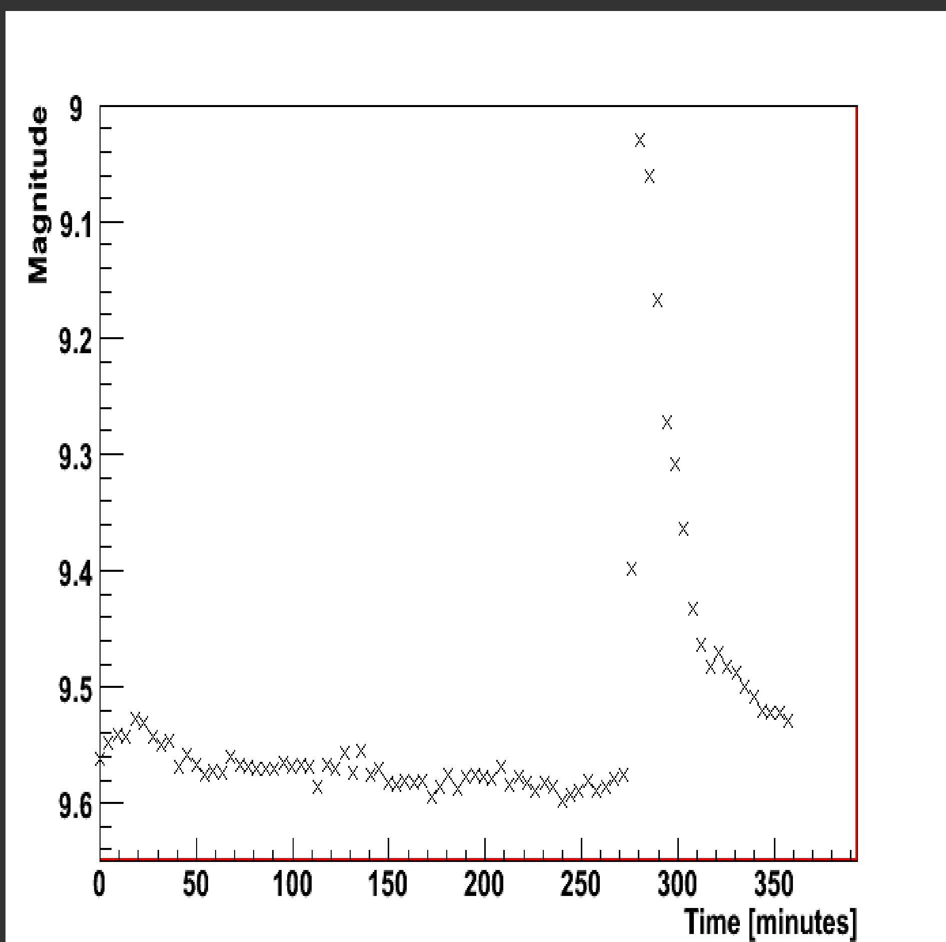
"Star Wars" like background

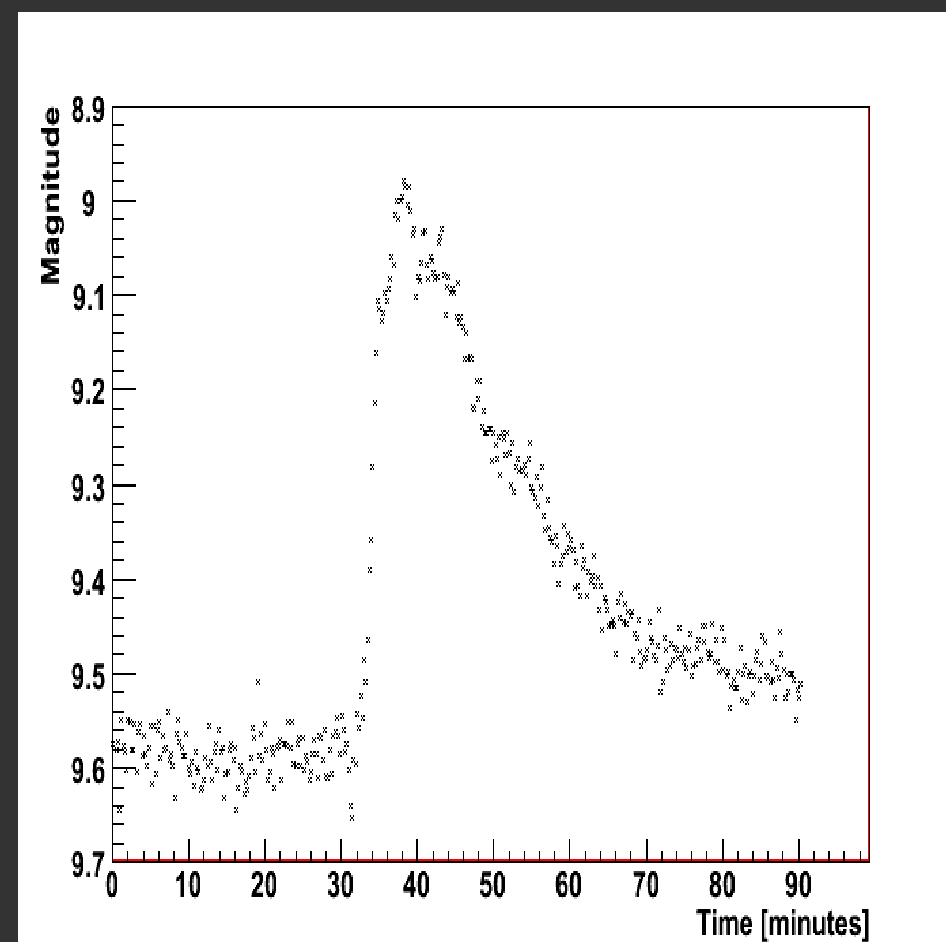
Meteors

Off-line Data Analysis - Algorithms

- Identification of new objects in star catalog (nova-like events)
- Identification of brightness increase of existing objects

Automatic detection of outburst of flare star GJ 3331A / GJ 3332

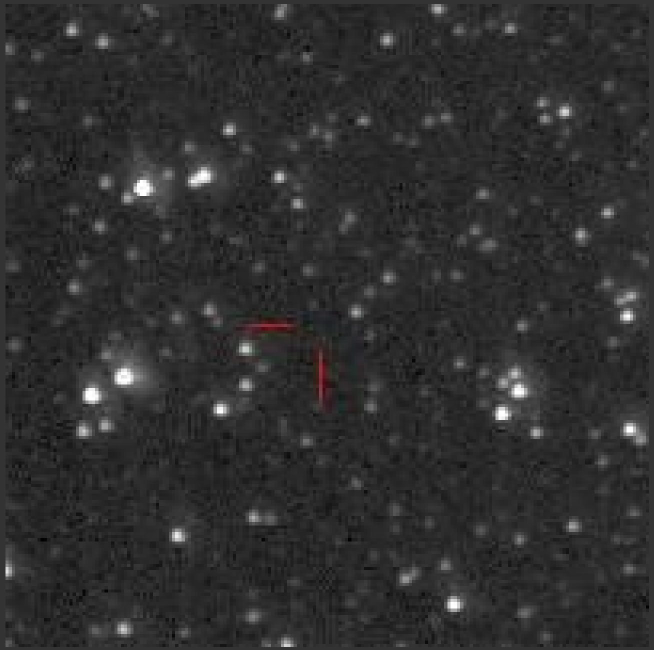




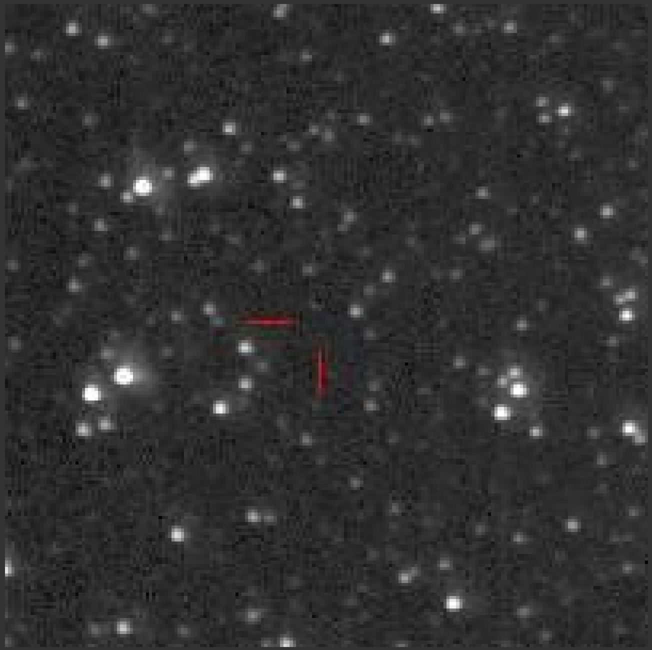
Nova-like identification algorithm

Algorithm checks all objects newly added to the star catalog and rejects background from star fluctuations, hot pixels etc

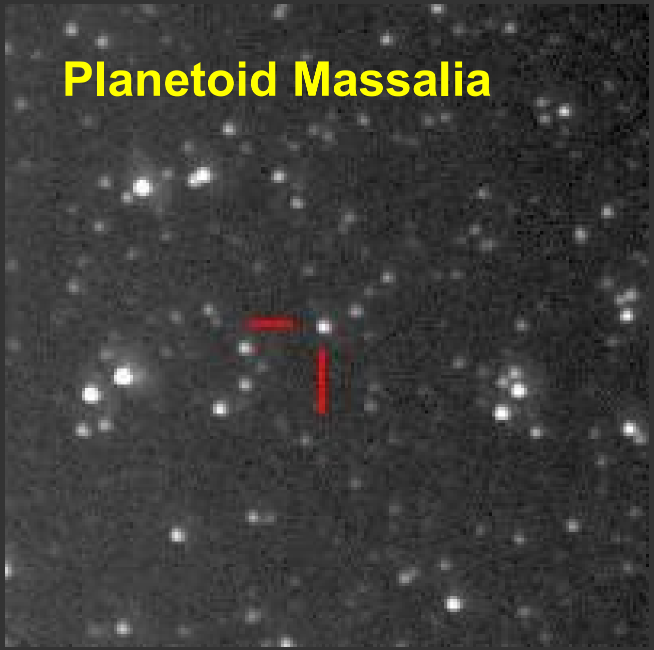
2006-12-28



2006-12-29



2007-01-09 (11 images)



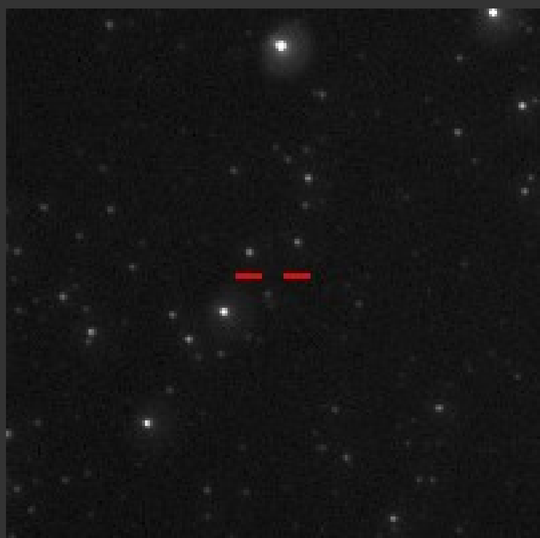
Currently only background events from planetoids are found, but they are good tool for testing.

OUTBURST OF NOVA 1RXS J023238.8-371812

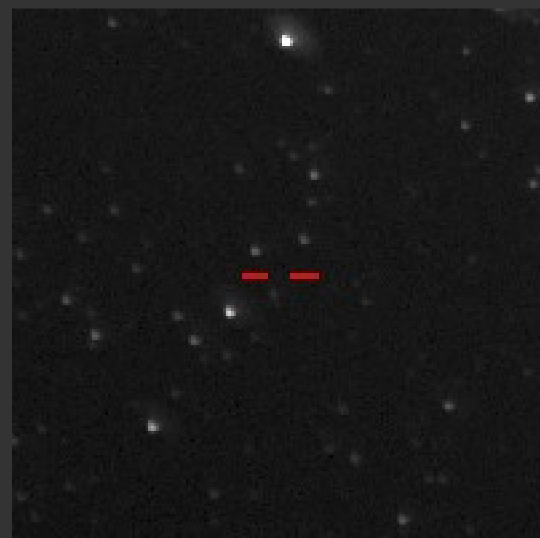
Outburst of nova star at RA = 02 32 38, DEC = -37 17 43 between 2007-09-15 and 2007-09-16. Indetified by algorithm identifying new objects on data collected by all sky scan (performed twice a night).

TYPE OF NOVA STILL NOT ESTABLISHED , OBJECT IS OBSERVED BY COMMUNIT

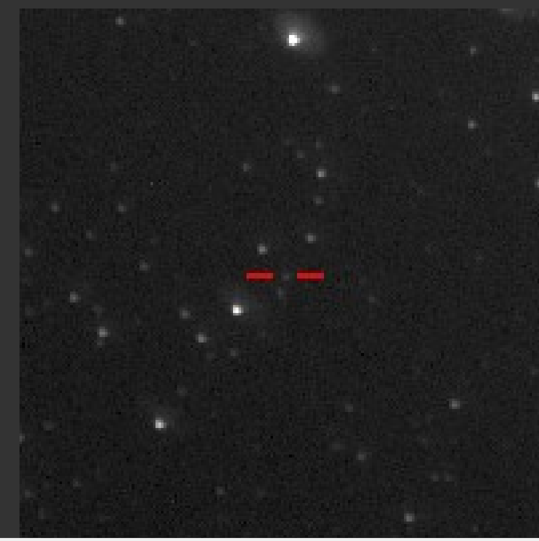
2007-09-13 03:00:27 UT



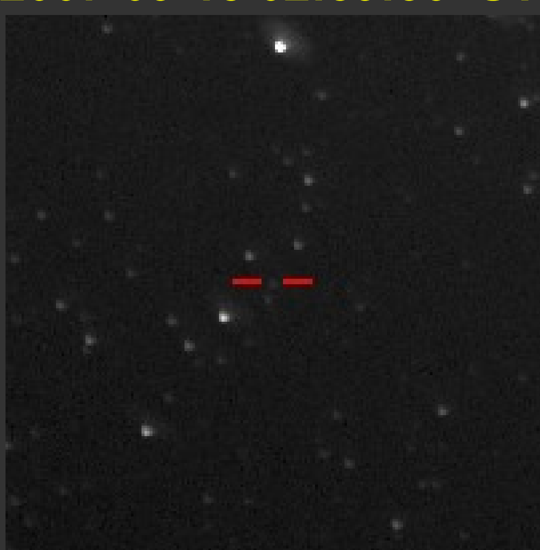
2007-09-14 03:00:46 UT



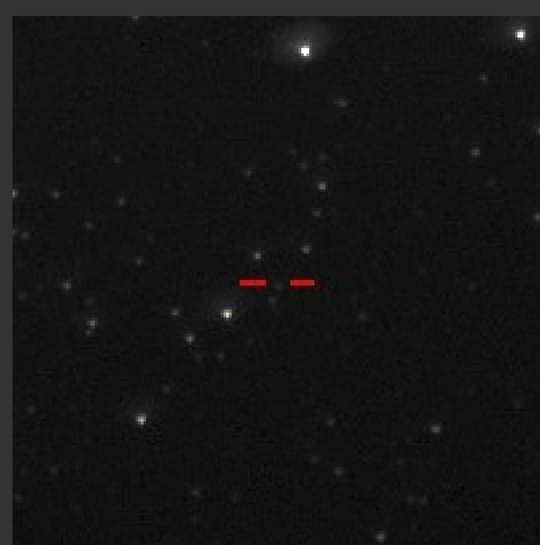
2007-09-16 08:53:44 UT

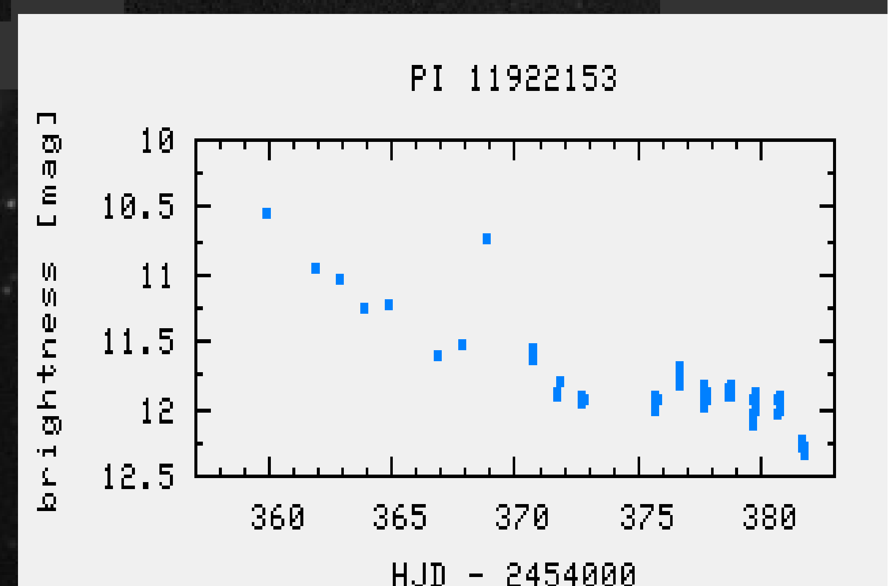


2007-09-18 02:59:56 UT



2007-09-18 08:59:51 UT

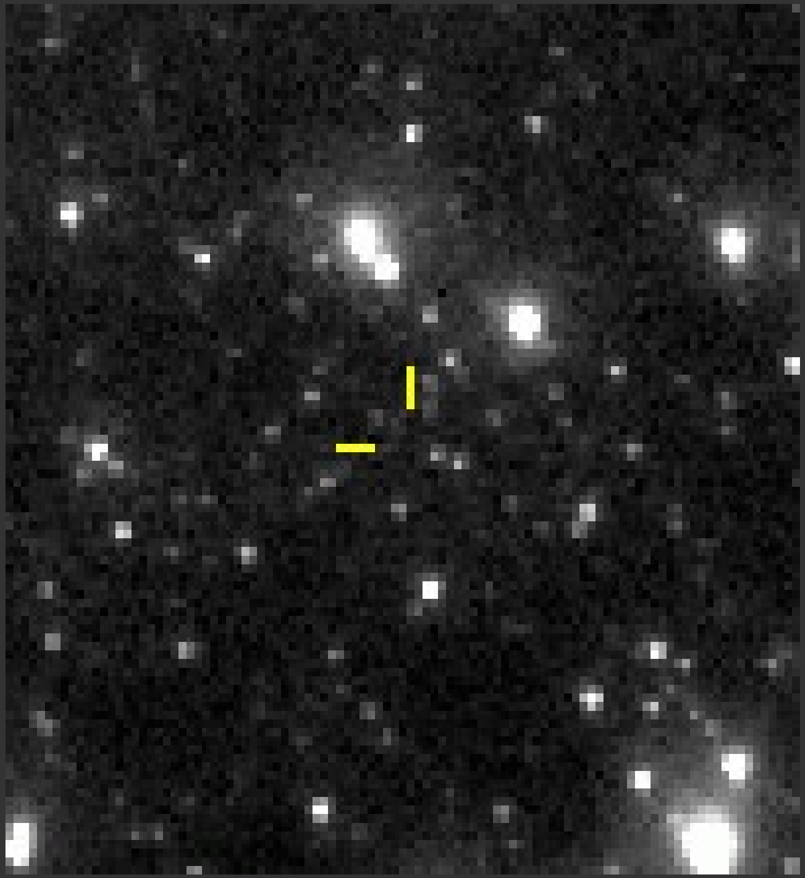




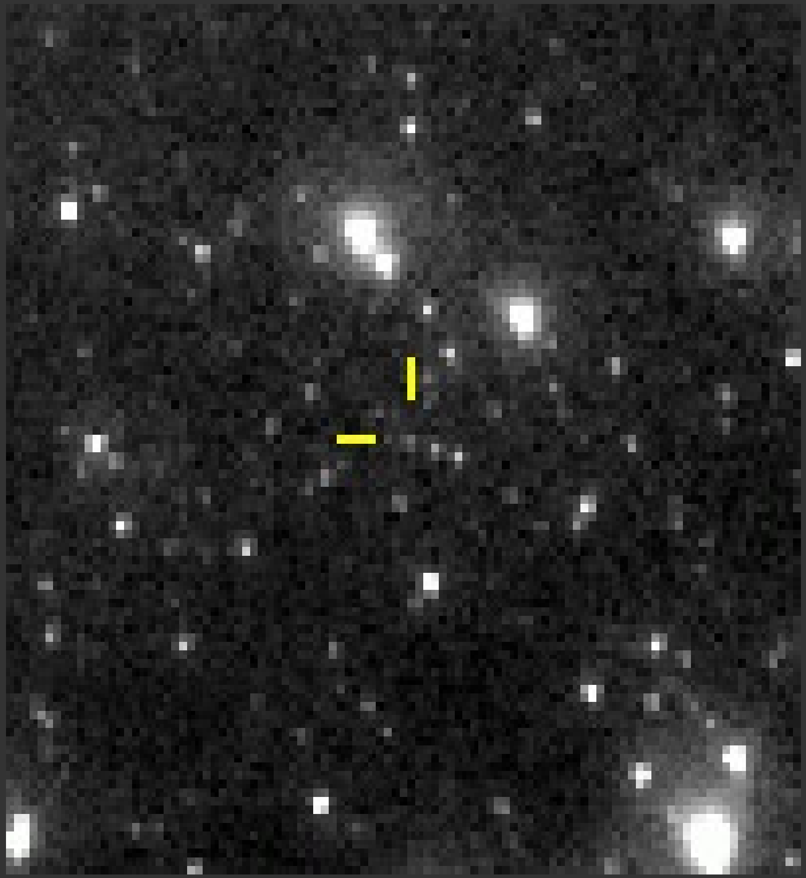
OUTBURST OF NOVA VSX J111217.4-353828

Outburst of nova star at $11^h12^m17.4^s$, Dec = $-35^o38^m29^s$ which corresponds to 20.88^m star GSC2.3 S55U020591.
The brightness at maximum was 11.5^m

2007-12-17/18

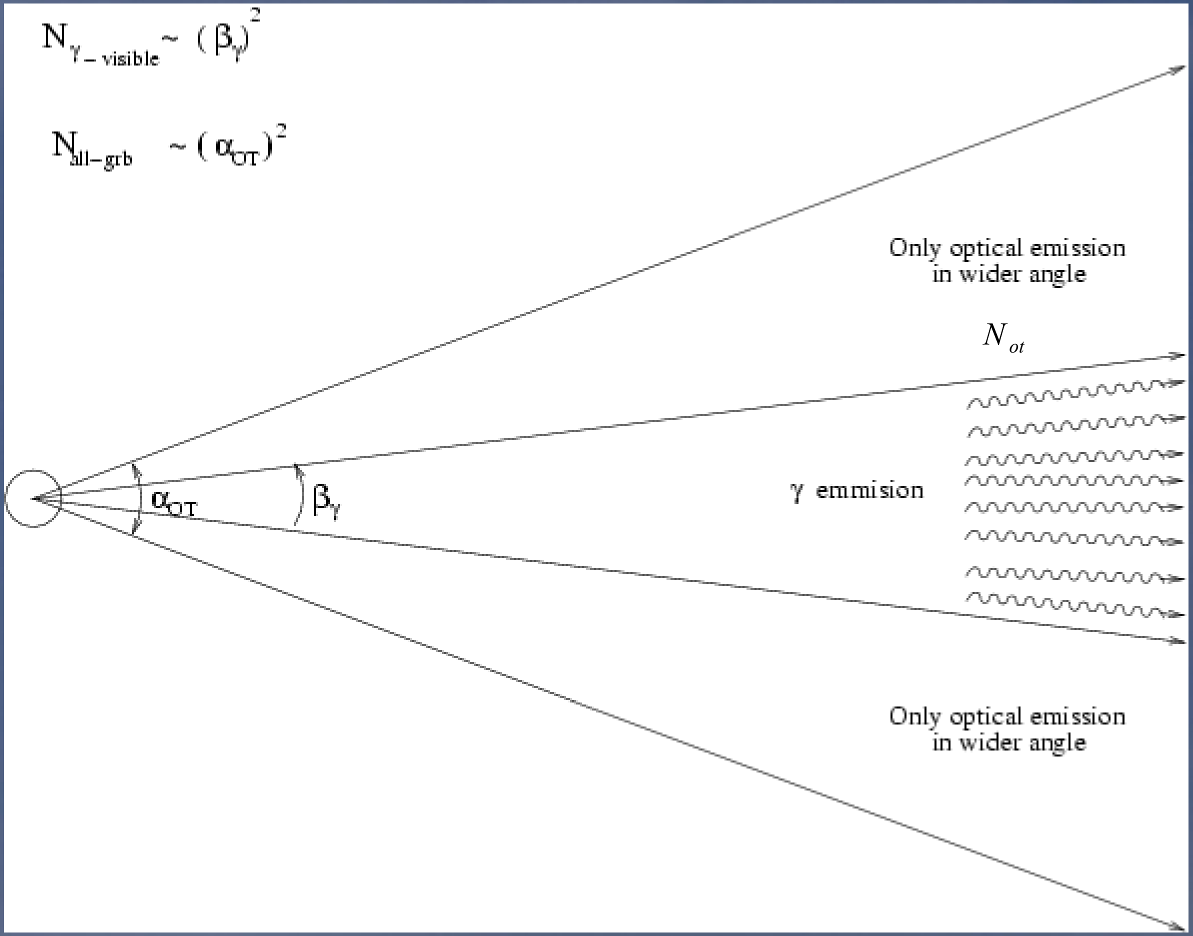


2007-12-19/20



Constraints on collimation of prompt optical signal

If collimation of γ-ray and optical emission are different, then the number of events observed from the Earth will differ in gamma and optical band



$$(\alpha / \beta)^2 \sim f_c = N_{OT} / N_{GRB}$$

$$N_{GRB} \approx 2.5$$

In order to obtain ratio of collimation angle number N_{OT} of optical flashes related to GRB events without γ-ray signal is needed

Determination of N_{OT}

If we assume that optical short timescale (< 60 sec) flashes observed by the "Pi of the Sky" system are such "orphan afterglows" - GRB events without γ-ray signal visible from the Earth Then we can obtain N_{OT} . In the prototype there is no way to reject all flashes from artificial satellites , thus :

- Short timescale (10 – 22 sec) events detected by on-line algorithms
- Only events visible on at least 2 consecutive images collected in time period since July 2006
- This gives only one event (shown ealier)
- Observation time normalized to 4π is $T_{obs} \approx 0.78$ days

  which gives $N_{\pi\text{-}OT} = 1.28$ / day / 4π

Acceptance correction

- The range of the "Pi of the Sky" telescope is limited at $\sim 12\text{-}13^m$ and only $f_{bright} \sim 8\%$ of total number of GRBs have optical counterpart brighter then 12^m.

- The average efficiency of identification of optical flashes brighter then 12^m is $\varepsilon_\pi \sim 35\%$.

- N_{OT} can be obtained from number of observed optical flashes $N_{\pi\text{-}OT}$ after correction for our acceptance :

$$N_{OT} = N_{\pi\text{-}OT} / (f_{bright} * \varepsilon_\pi) \sim 45.8 / day / 4\pi$$

Upper limit on ratio of collimation angles

- Finally we obtain :

$$f_c = (\alpha / \beta)^2 \sim N_{OT} / N_{GRB} \leq 48.3 / 2.5 \approx 19.3$$

- Which gives :

$$\alpha \leq 4.4\, \beta$$

- γ-ray collimation is measured at the level of $\beta \approx 5\text{-}20^{\circ}$

- The obtained limit is not very strong, but it is probably the first limit on the ratios of prompt emission collimations

- Full system of 16 cameras can improve this limit by factor of 16 (by increasing the total time of observations)

Other collimation measurements

Performed for classical afterglows – long time scale optical flashes. Experiments were looking for new objects on the sky in time scale of days.

Recent measurements :

- $f_c < 11$ obtained by F.Malacrino et al (astro-ph/0701722)
- $f_c < 12500$ obtained by A. Rau et al (astro-ph/0603284)
  (not sufficient amount of data)

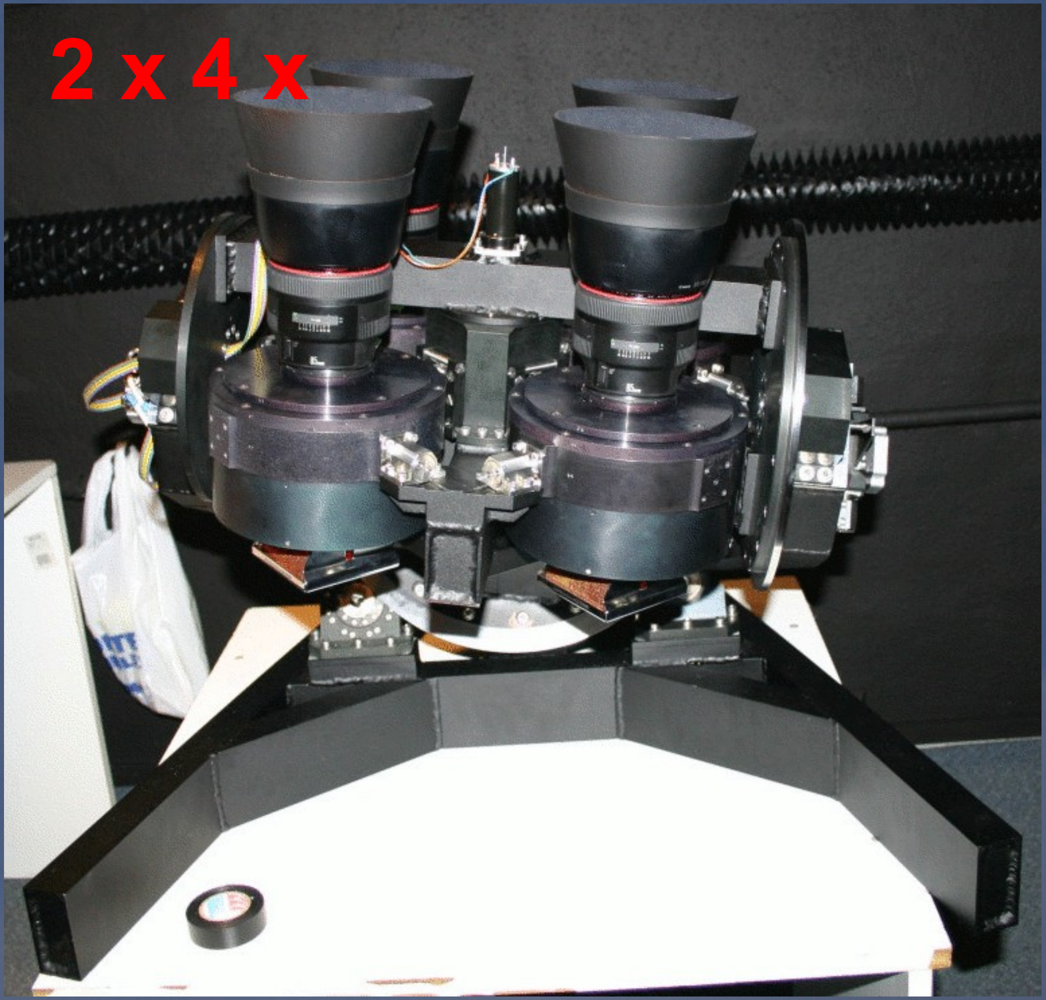
Theoretical predictions :

- 75 by Guetta et al (2005)
- 500 by Frail et al. (2001)

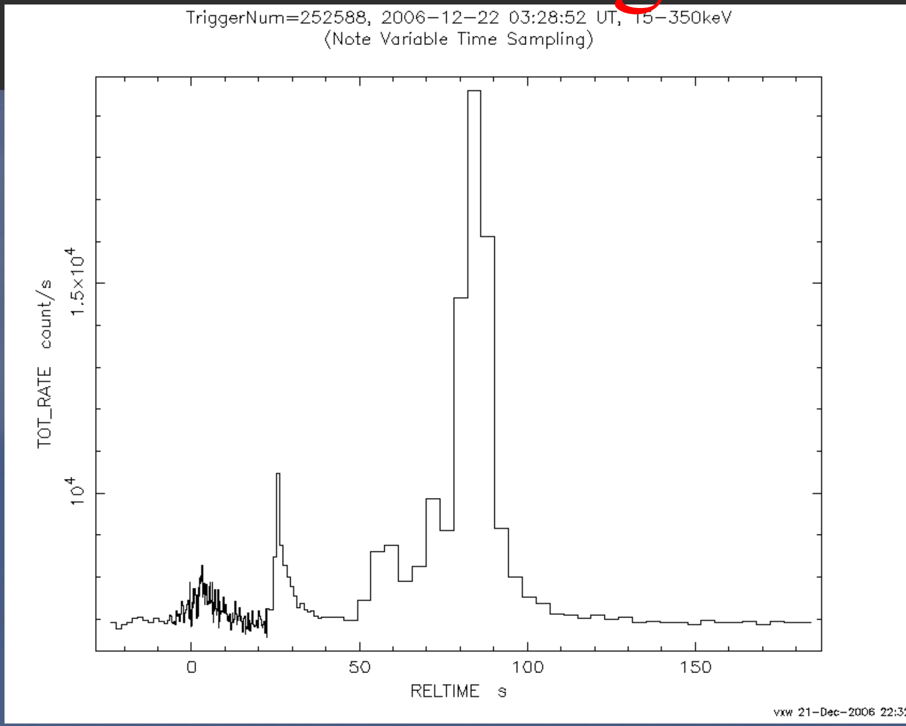
All above are related to "classical" , long time scale afterglows and I didn't find yet any results concerning the prompt emission during the γ-ray emission

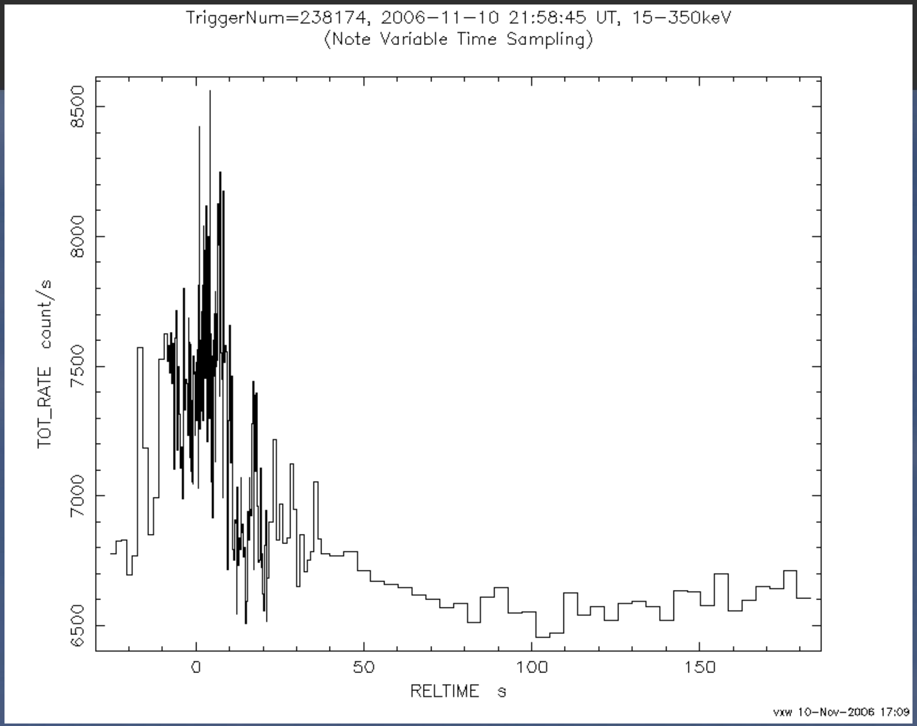
The future

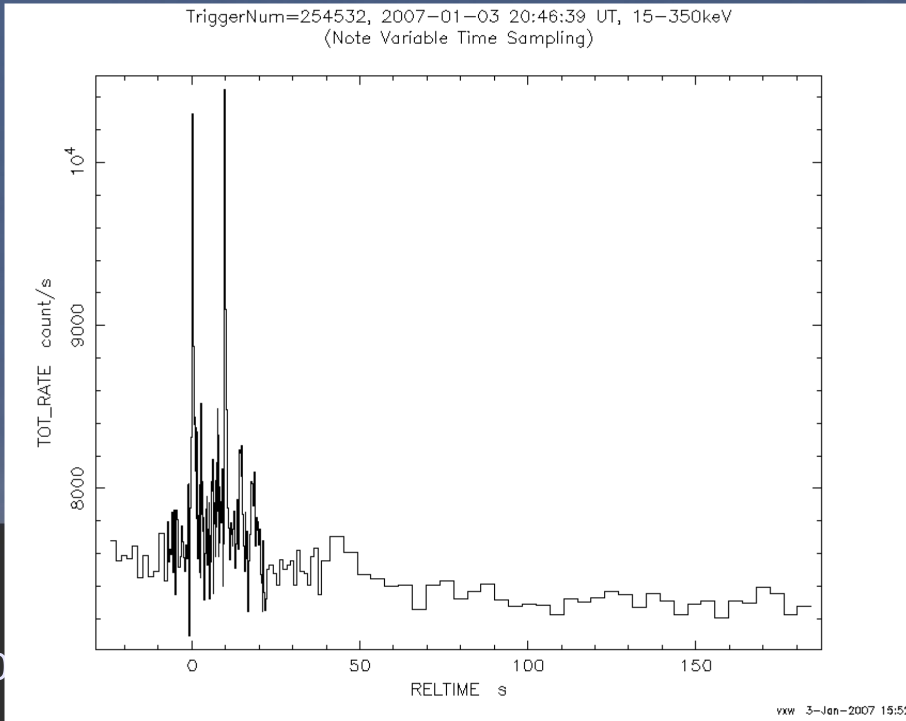
- From the studies of already observed optical counterparts GRBs , about 50% have optical counterparts and ≈2.5 / year should be observed by the full system
- Limit on collimation will be improved by factor of 16
- More nova events will be hopefully discovered

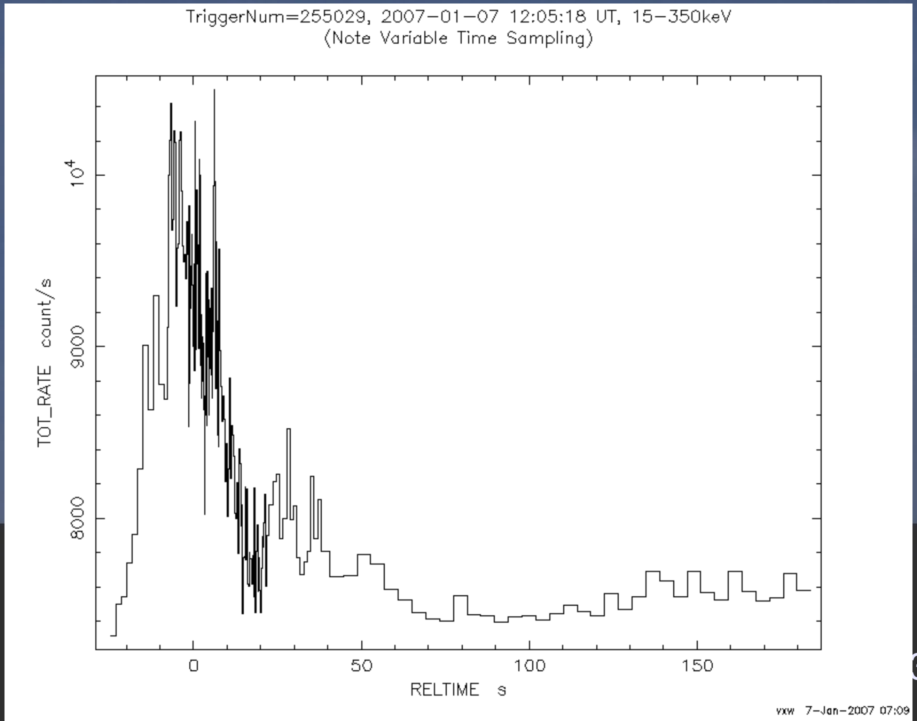


Long GRBs from SWIFT









Short burst from SWIFT