CAMELOT:
Cubesats Applied for MEasuring and LOcalising Transients

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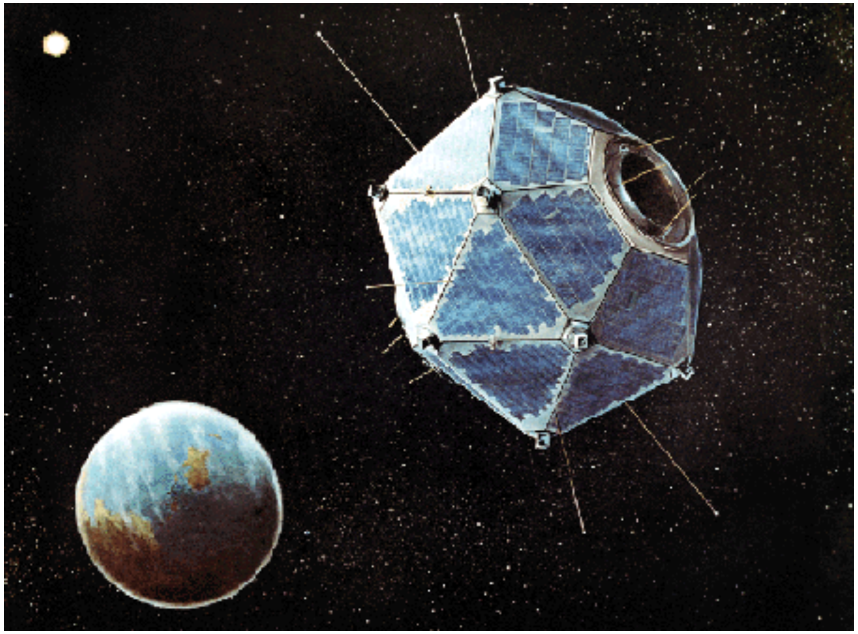
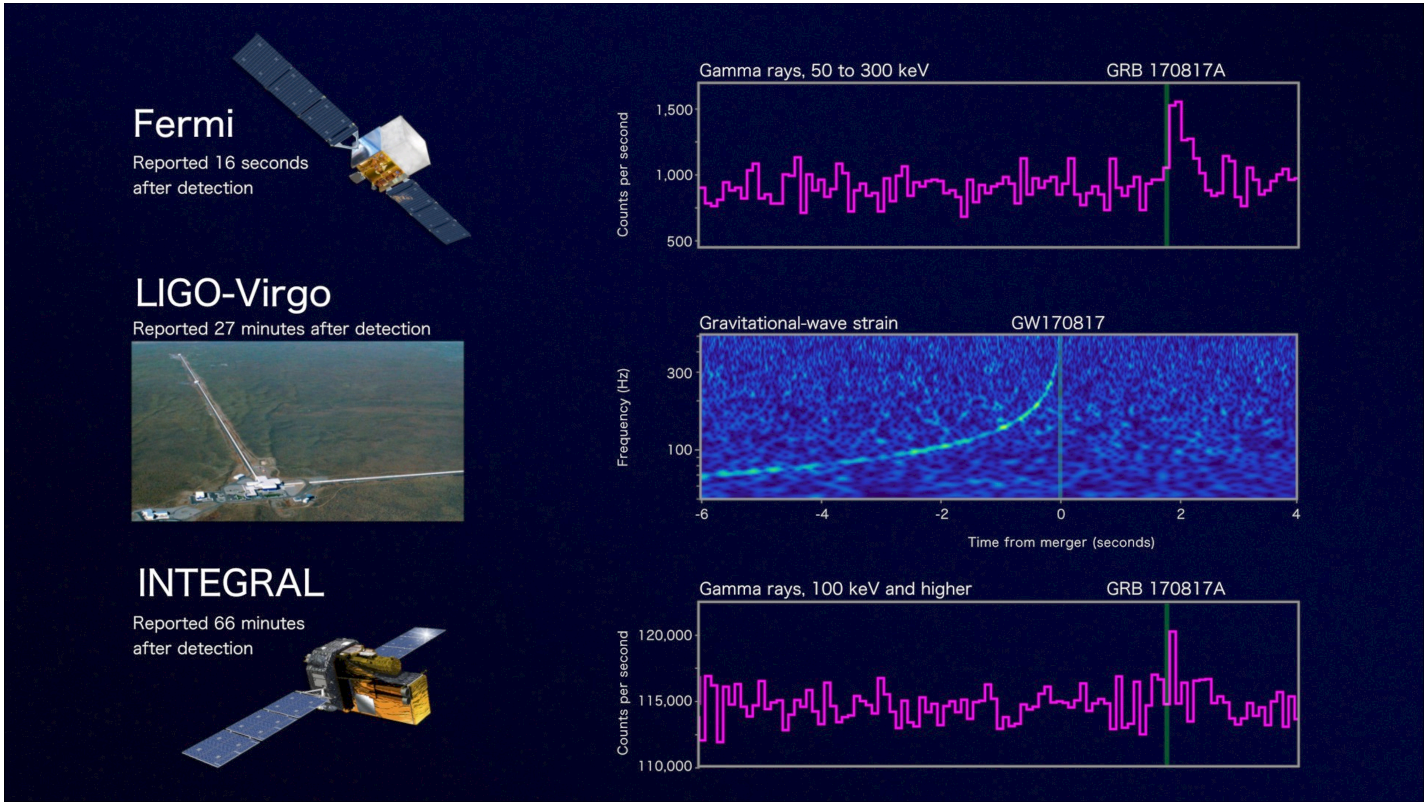
THE DISCOVERY OF GAMMA RAY BURSTS

- discovered in 1967 by the VELA satellites monitoring the nuclear test ban treaty
- nuclear explosion in space produces X-rays, gamma rays, and neutrons (no visible radiation or sound)
- orbits at altitude of 100,000 km (to be outside radiation belts and to detect detonations behind the Moon!)
- "*16 gamma-ray bursts of cosmic origin*" published in 1973 (Klebasadel et al. 1973, ApJ, 182, L85)



17. 08. 2017
THE BEGINNING OF MULTI-MESSENGER ASTROPHYSICS



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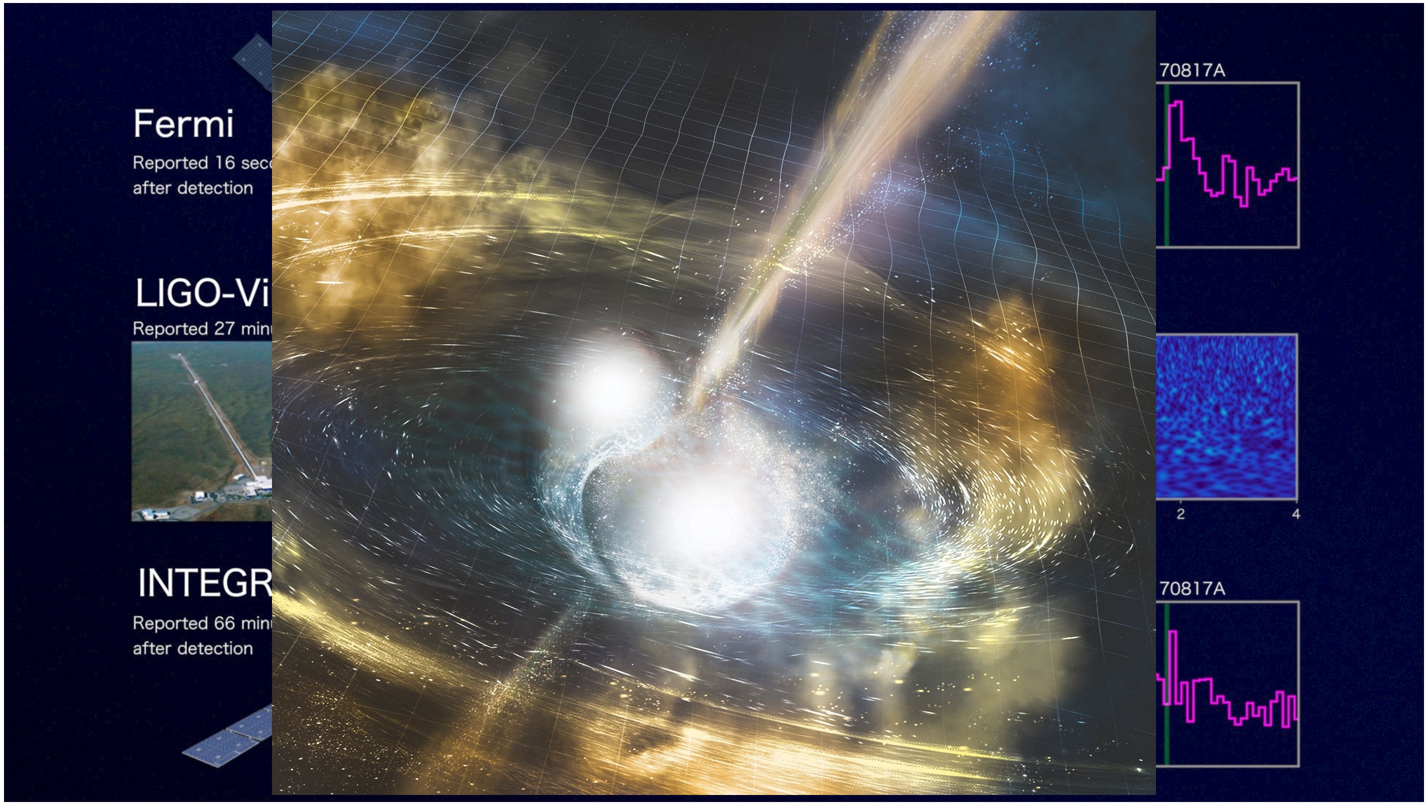

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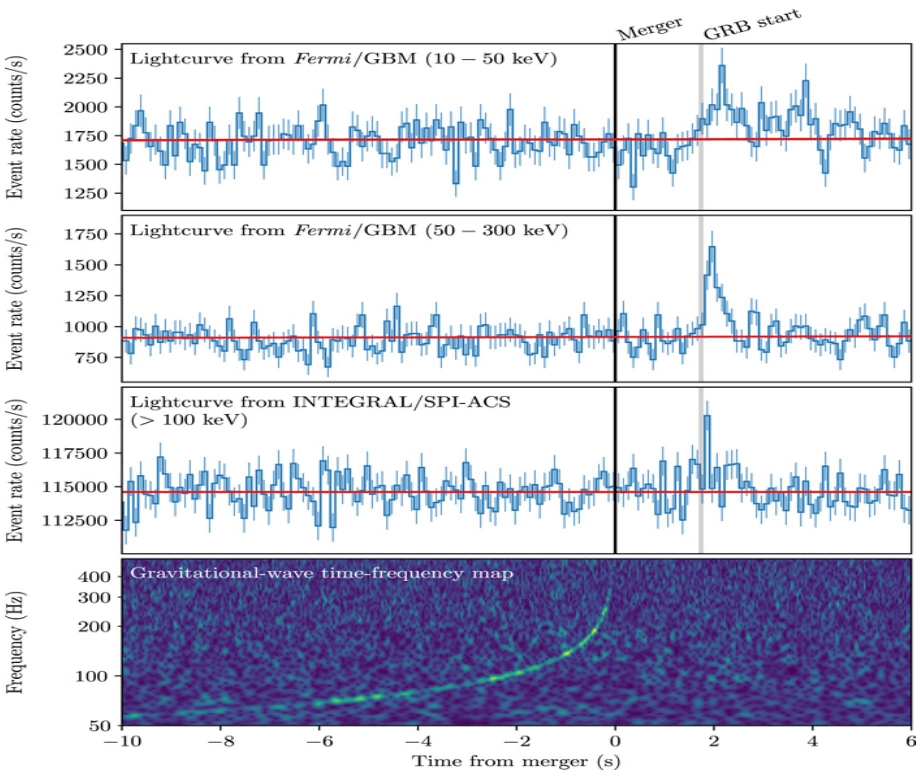
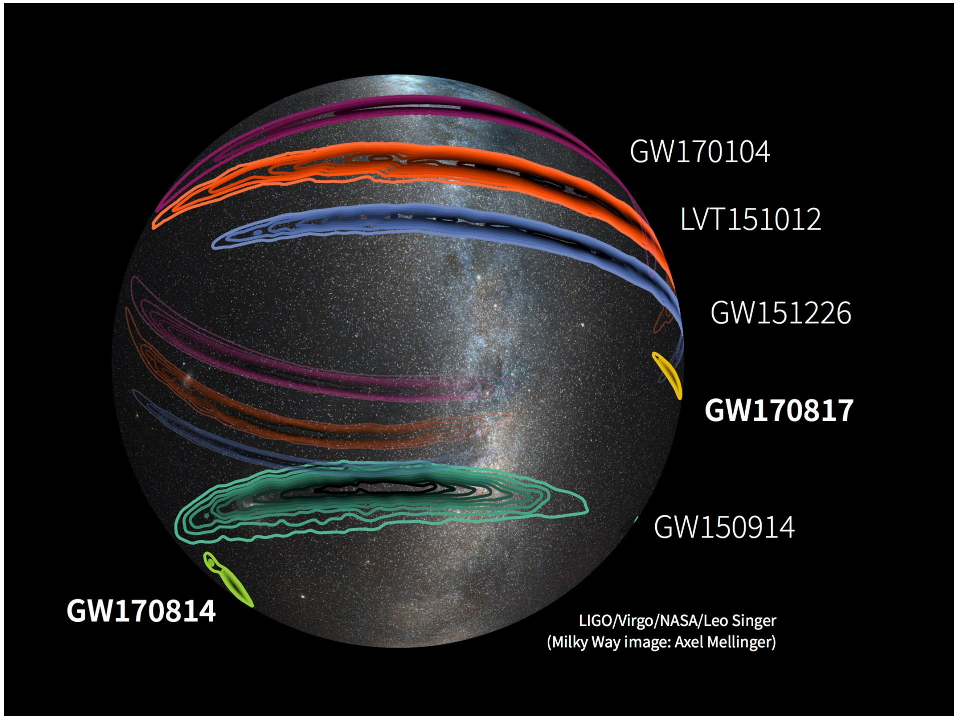
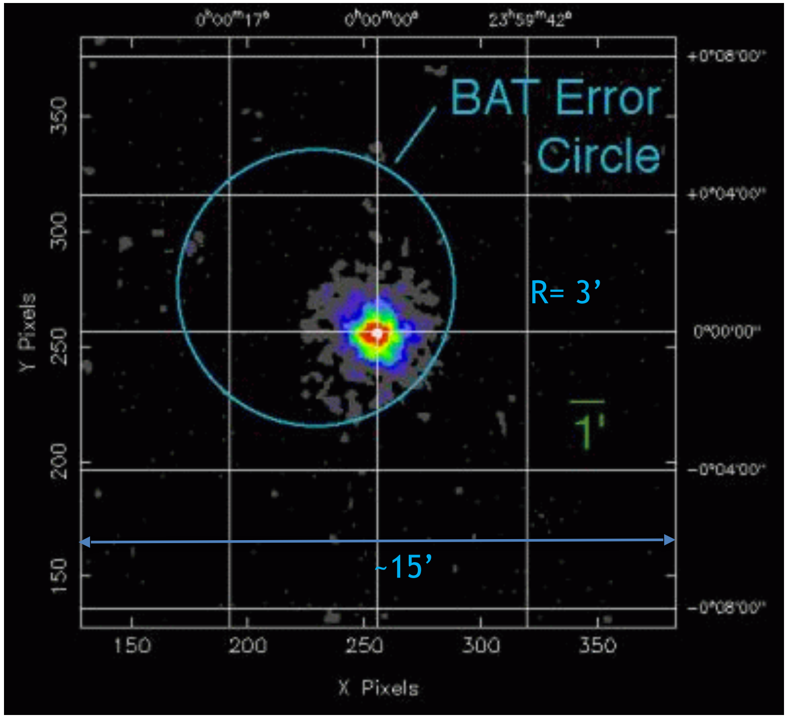


- 5 gravitational wave detections from BH-BH merger
- EM counterpart from NS-NS merger event GW170817/ GRB170817A
- Large campaign of follow-up observations identified a kilonova
- The gamma-ray counterpart is unusual
- **Regular detections/follow-up observations are needed to make progress**

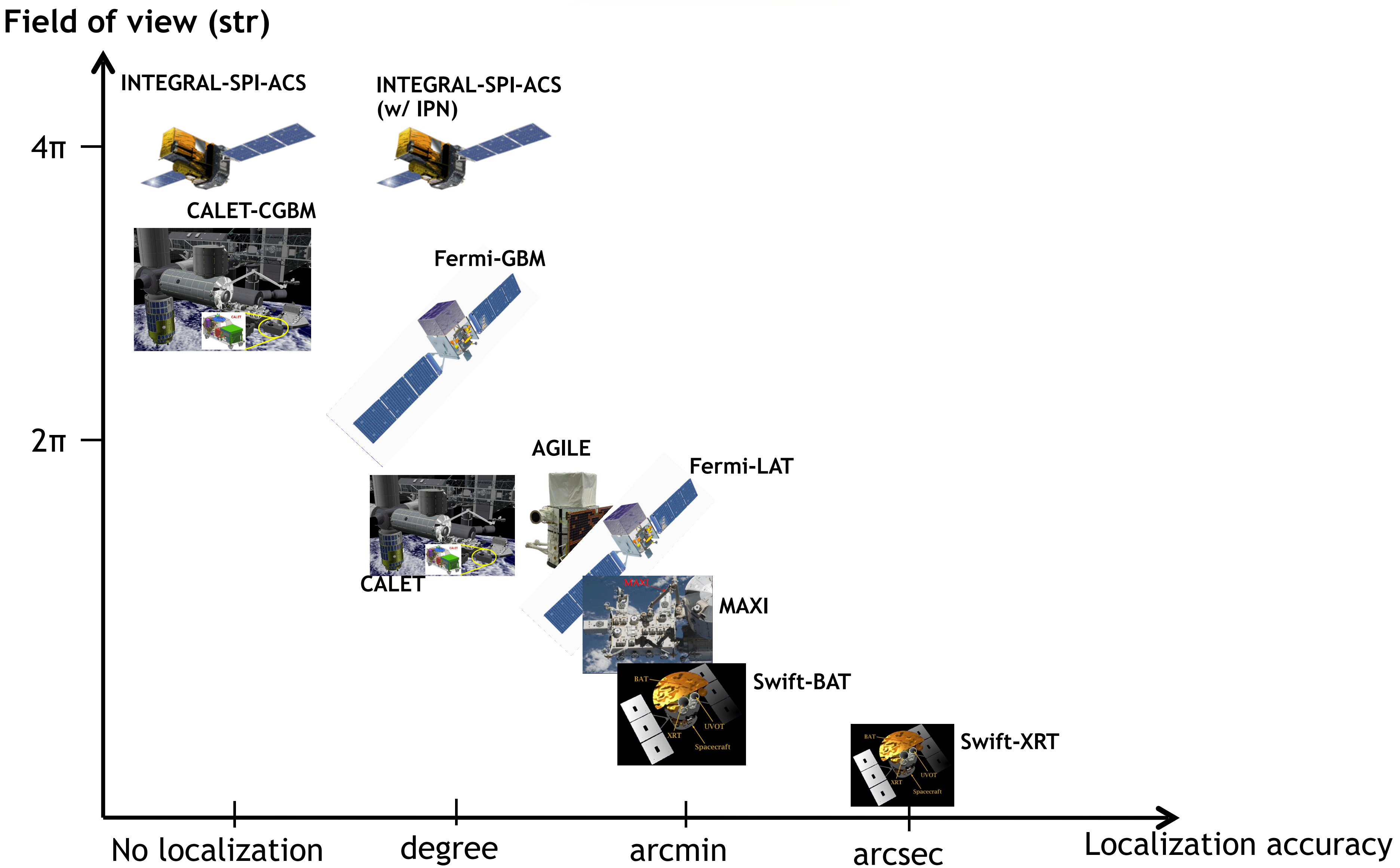
LOCALISATION CRITICAL FOR PROGRESS

- Localisation error of GW telescopes is several tens of degree^2
- FoV of optical telescope providing follow up observations is of the order of ~1 deg
- Quick localisation of prompt gamma ray emission with a precision of tens of arcmin critical to enable efficient follow up observations





AN EMPTY REGION IN PARAMETER SPACE



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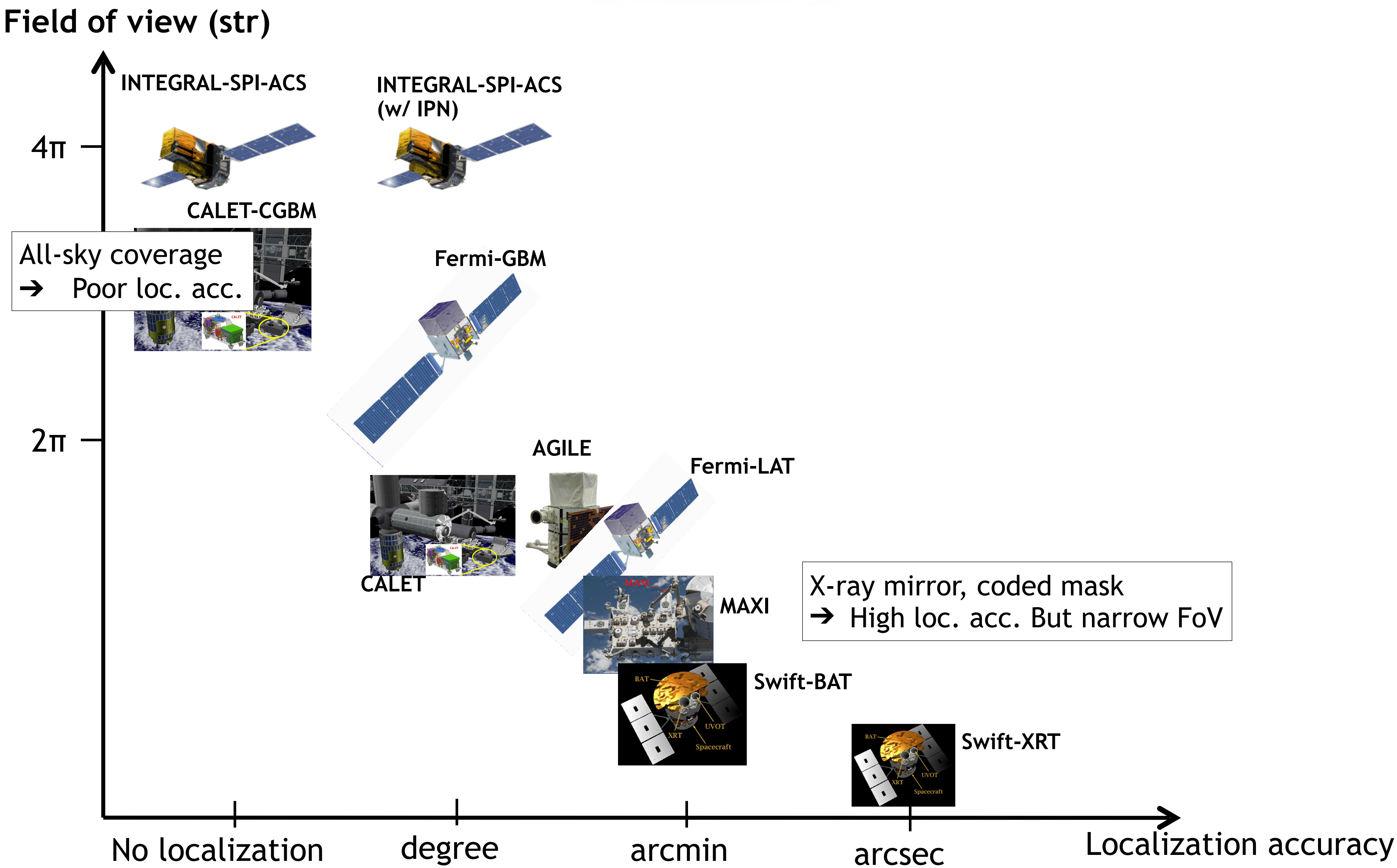

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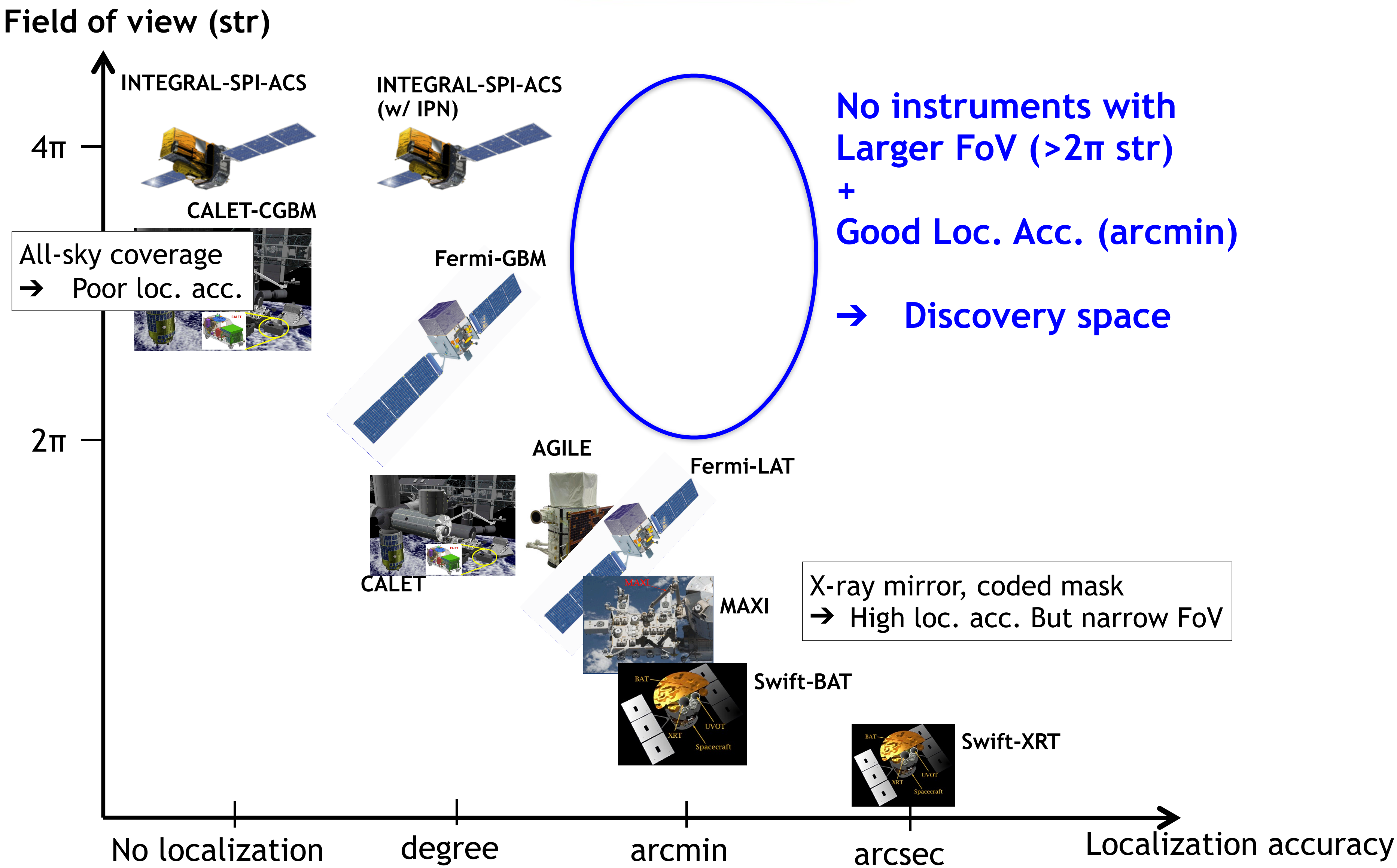
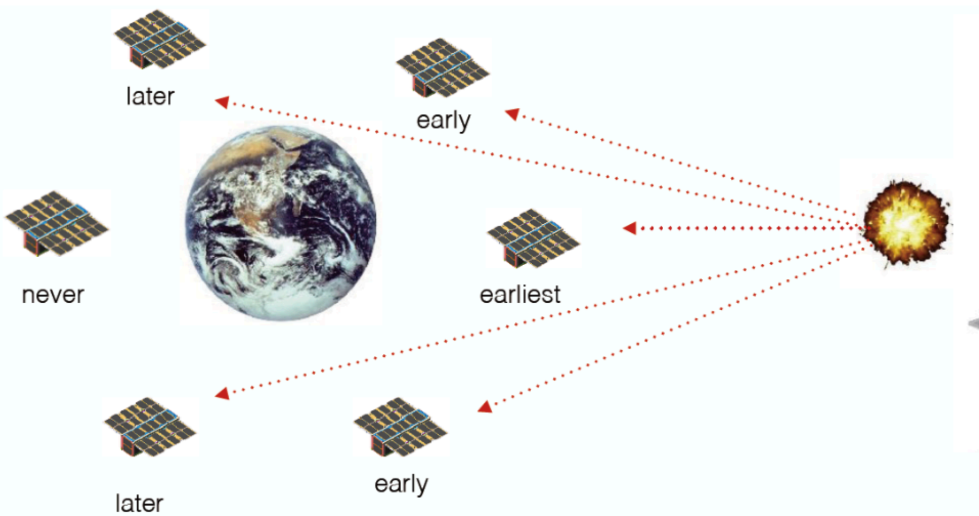
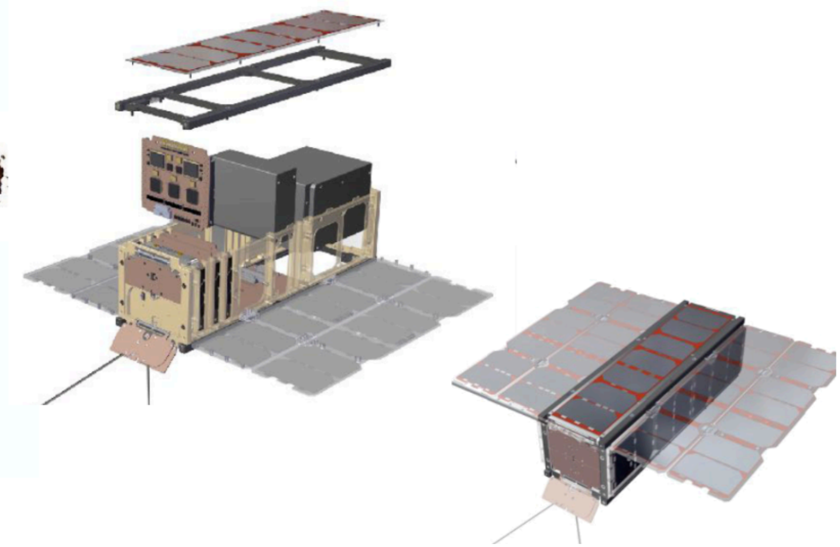


CAMELOT: CUBESAT ARRAY FOR MEASURING AND LOCALIZING TRANSIENTS



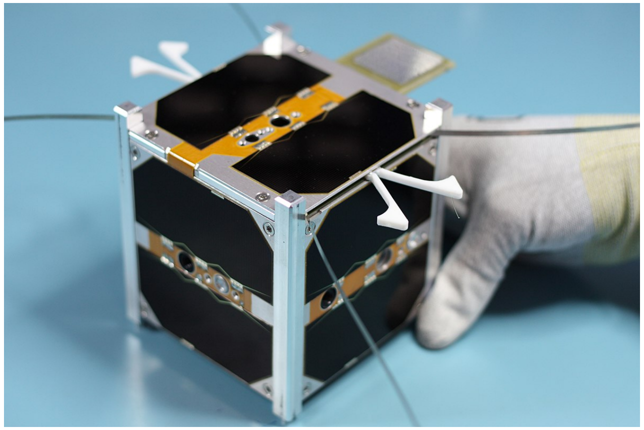


A constellation of at least 9 satellites can provide:

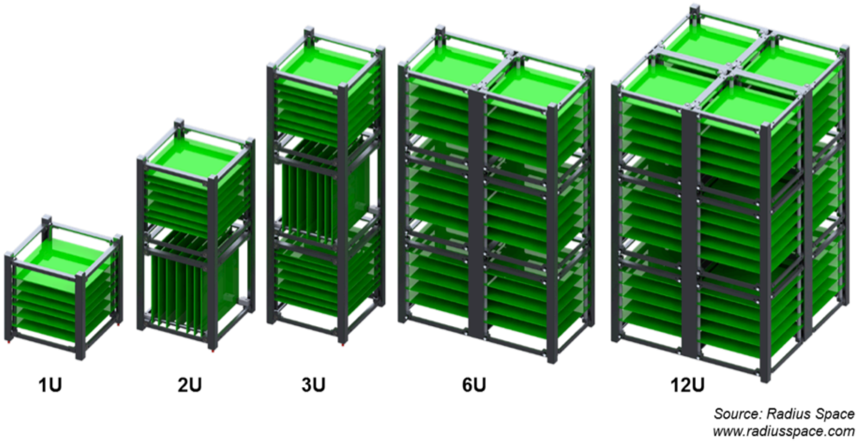
- all sky coverage with a large effective area
- Better than 0.1 millisecond timing accuracy
- ~10 arcmin localisation accuracy using triangulation

Each satellite will use a standard 3U cubesat platform developed by C3S LLC for the ESA sponsored RadCube mission. The cubsesats will be equipped with a *GPS receiver for precise time synchronisation* and *inter-satellite* (Iridium NEXT) *communication* equipment for *rapid data download*

THE NEW ERA OF NANOSATELLITES (CUBESATS)



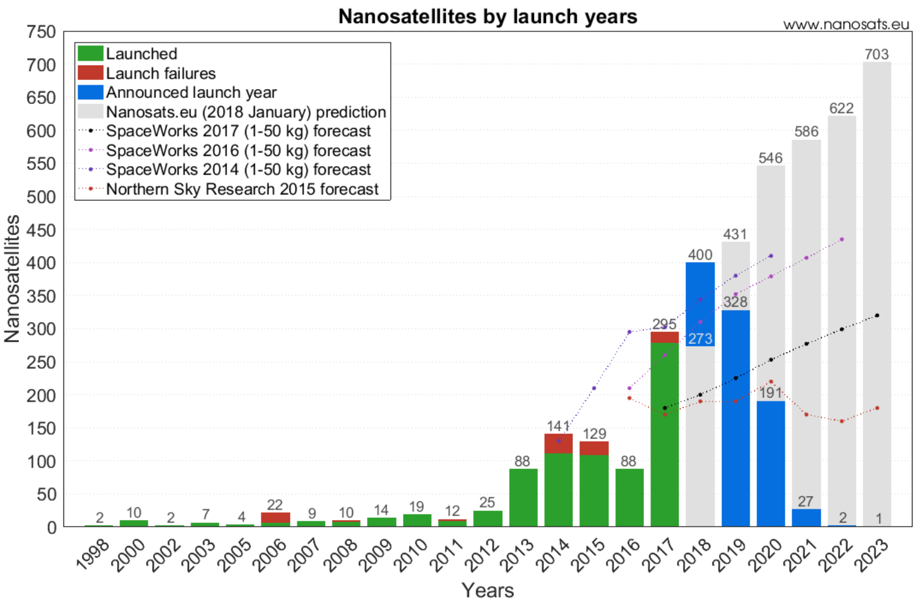
skCube

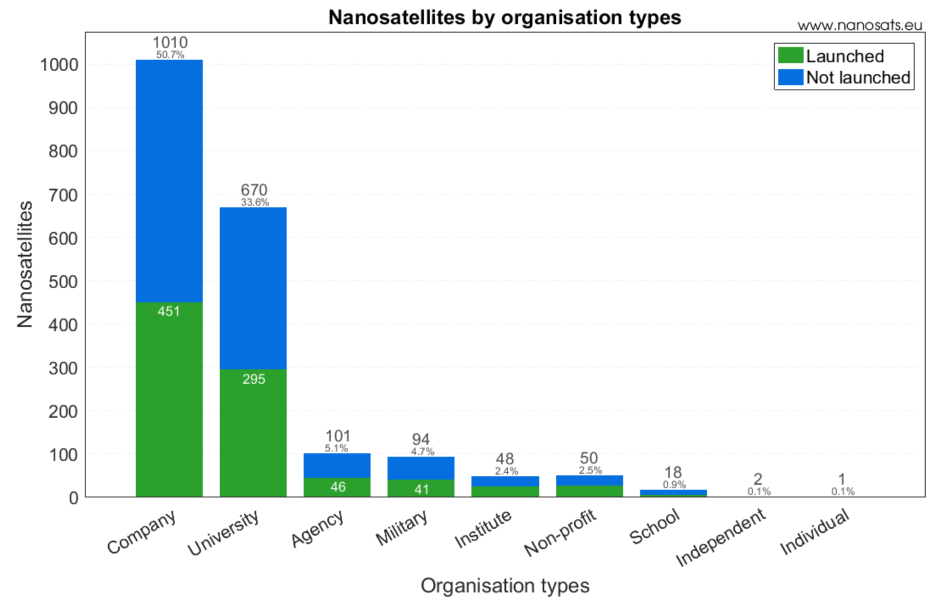


Standard cubesat sizes

Cubesats deployed from the Space Station

THE NEW ERA OF NANOSATELLITES (CUBESATS)



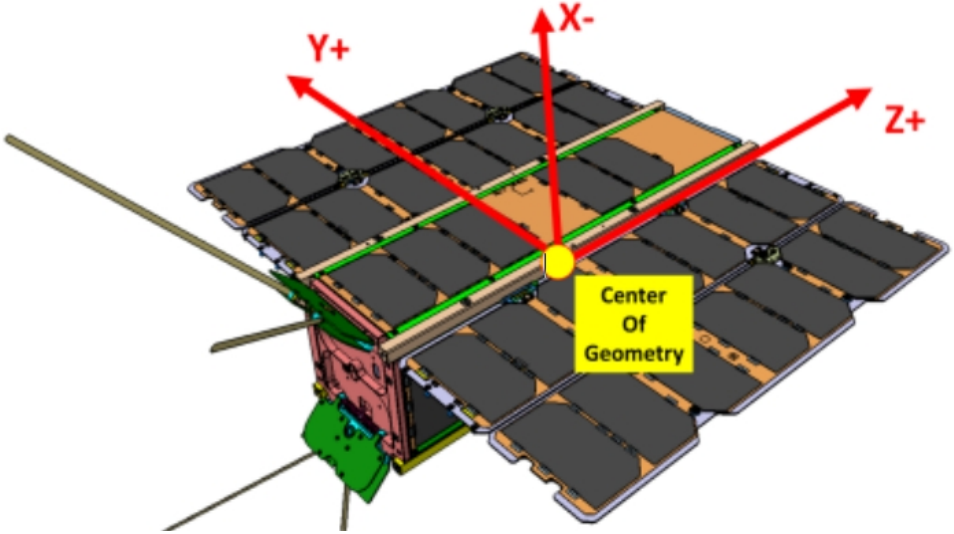


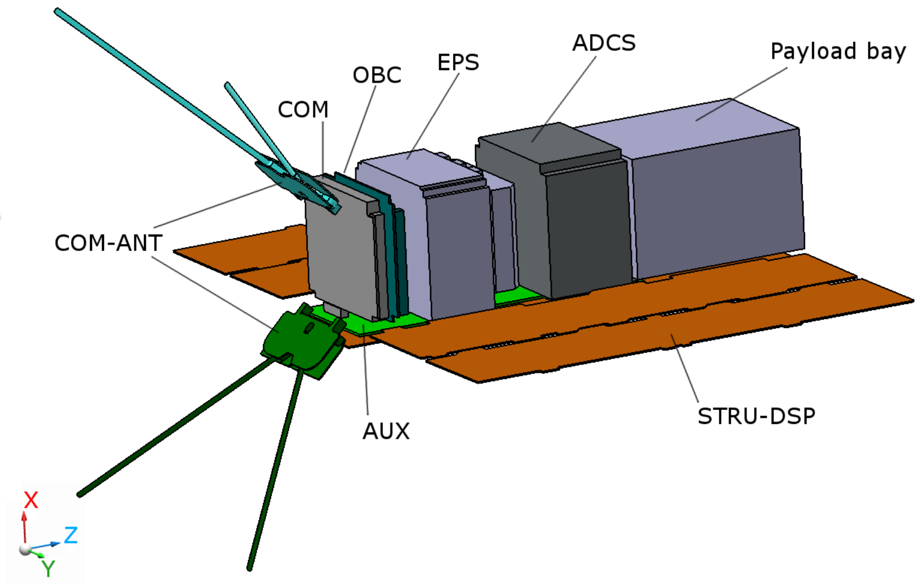
Three epochs of cubesat development:

1) **Small projects by students and enthusiasts**
2) **Demonstration of new technology for space applications**
3) **Breakthrough science and full scale commercial use**

Most cubesats built by private companies and universities, not space agencies

THE SATELLITE PLATFORM

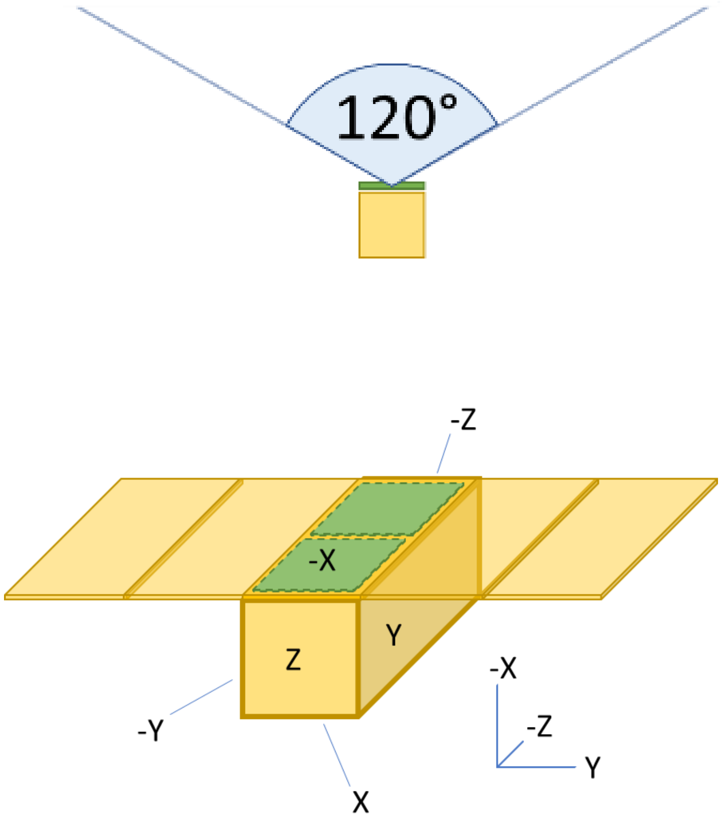


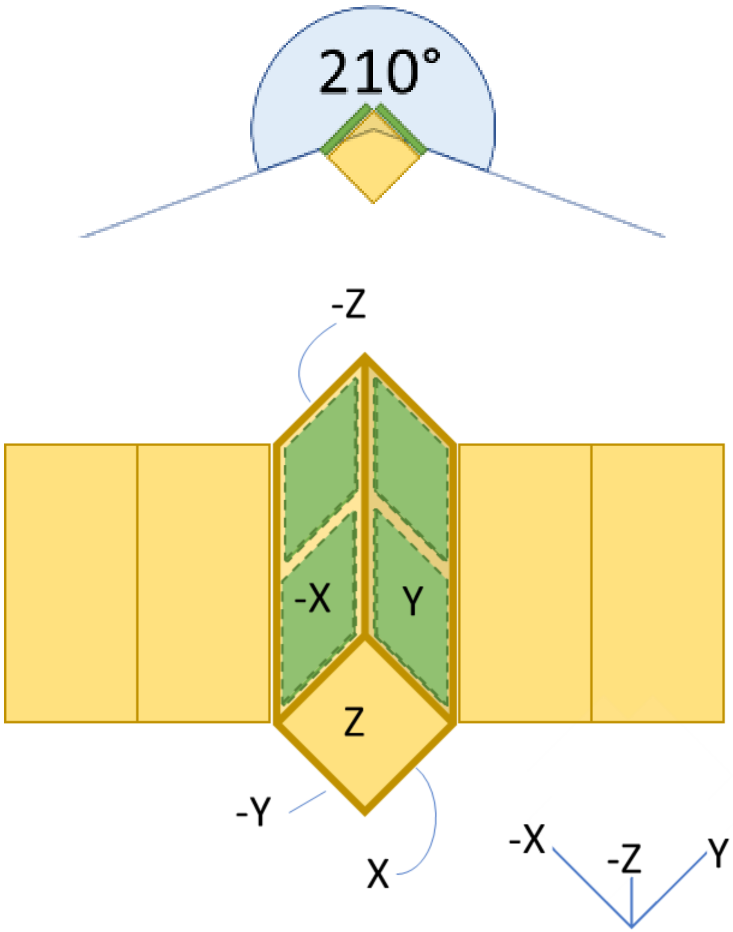


3U cubesat developed
by C3S LLC for the ESA sponsored
RadCube mission

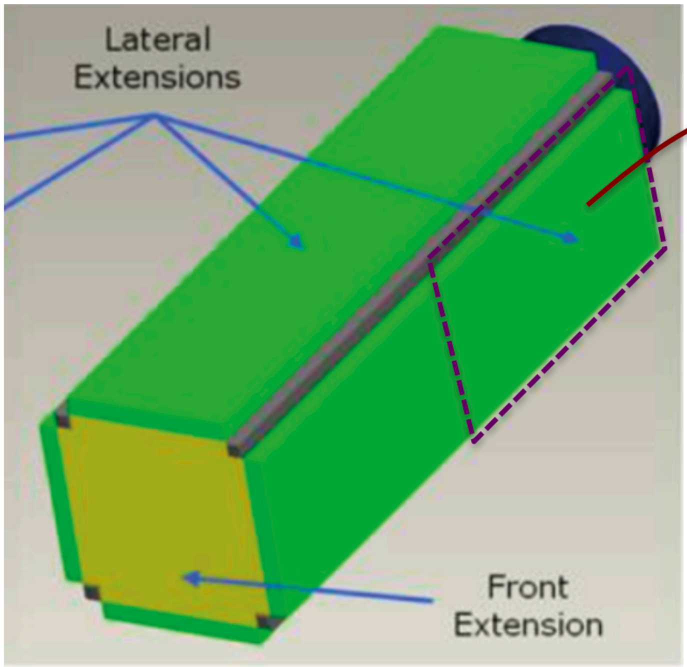
The platform can be reused with
small modifications for *CAMELOT*

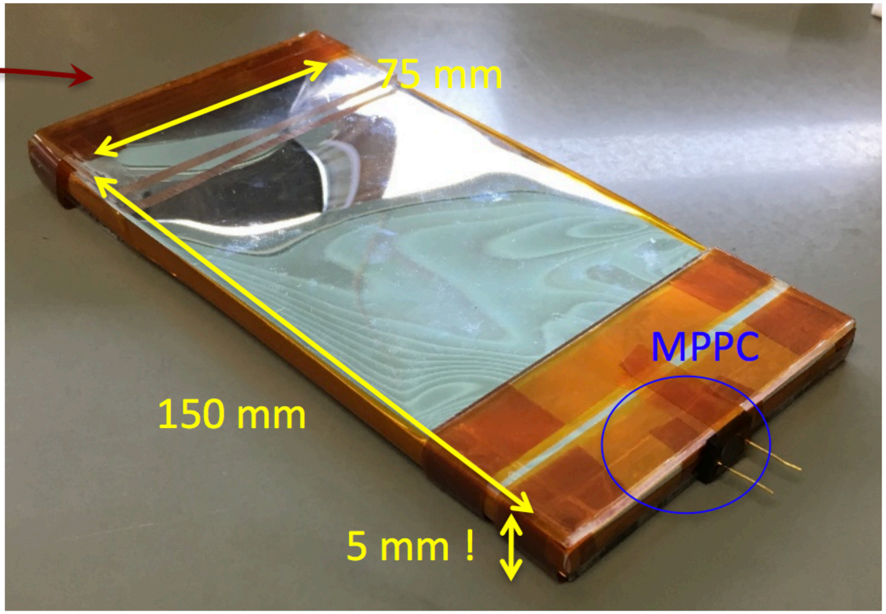
TWO POSSIBLE DETECTOR CONFIGURATIONS





THE DETECTOR DESIGN



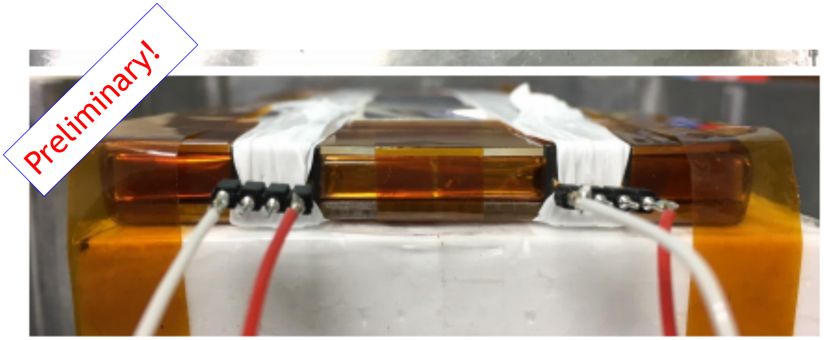


To maximise the effective area, the detectors based on CsI scintillators and Multi-Pixel Photon Counters (MPPC) will occupy two lateral extensions (8.3cm x 15 cm x 0.9cm x 4)

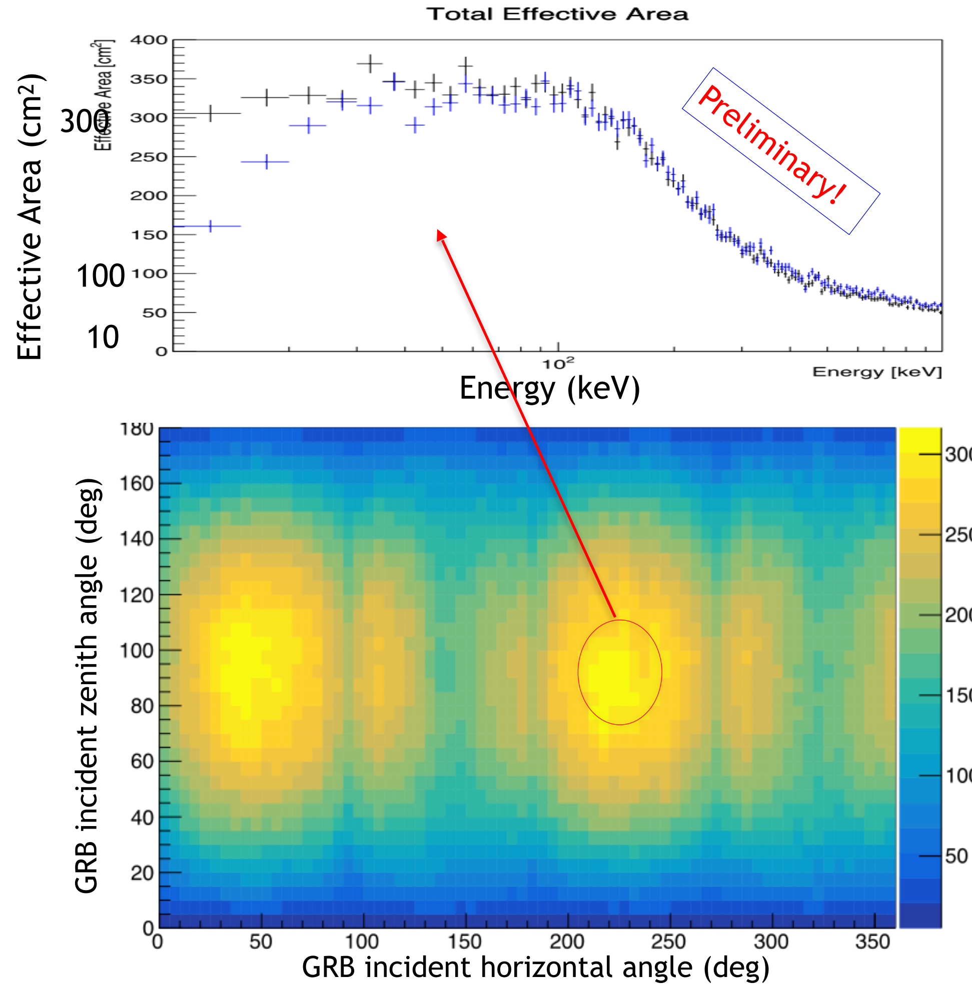
The large and thin detectors with small readout area are challenging

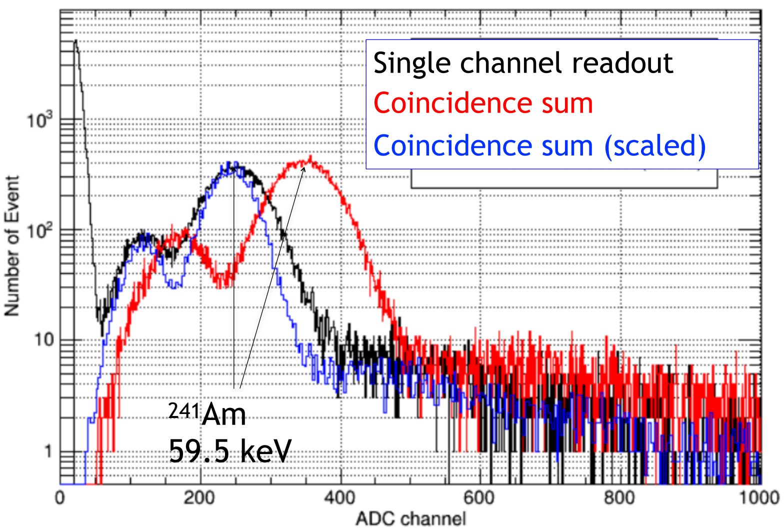
The read out of the CsI detectors with MPPC is currently being evaluated in the lab as part of our feasibility study. The system provides a large light yield, compact readout area and relatively low operational voltage.

Spectral feasibility



Torigoe+ 2018



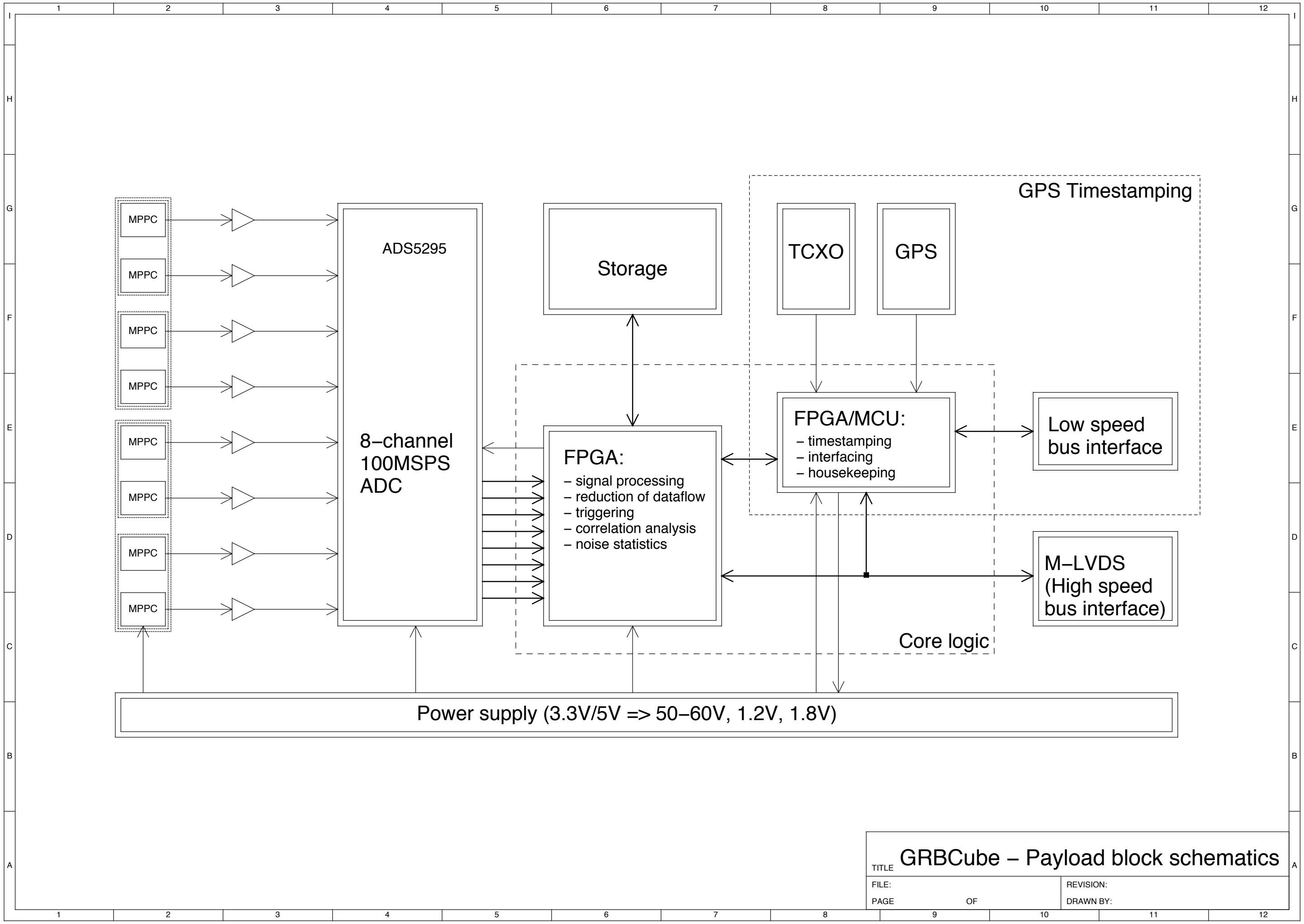


Energy threshold of ~10 keV is achieved for both single/multi channel readout
Energy range: 10-1000 keV (TBD)

Effective area for any incident angle is estimated by the Monte-Carlo simulation, 200~300 cm² (@100 keV)

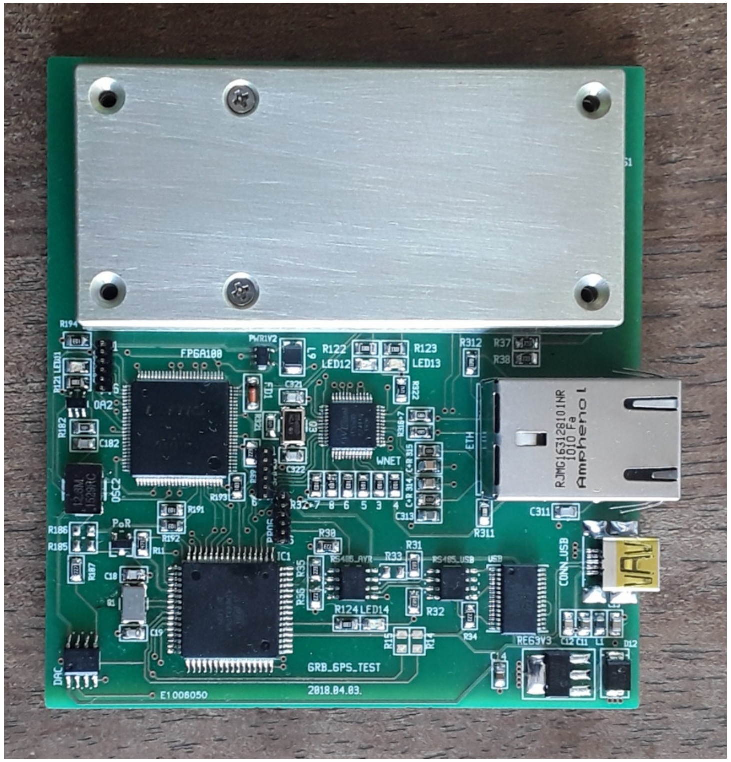
Sensitivity of one satellite is comparable to Fermi-GBM

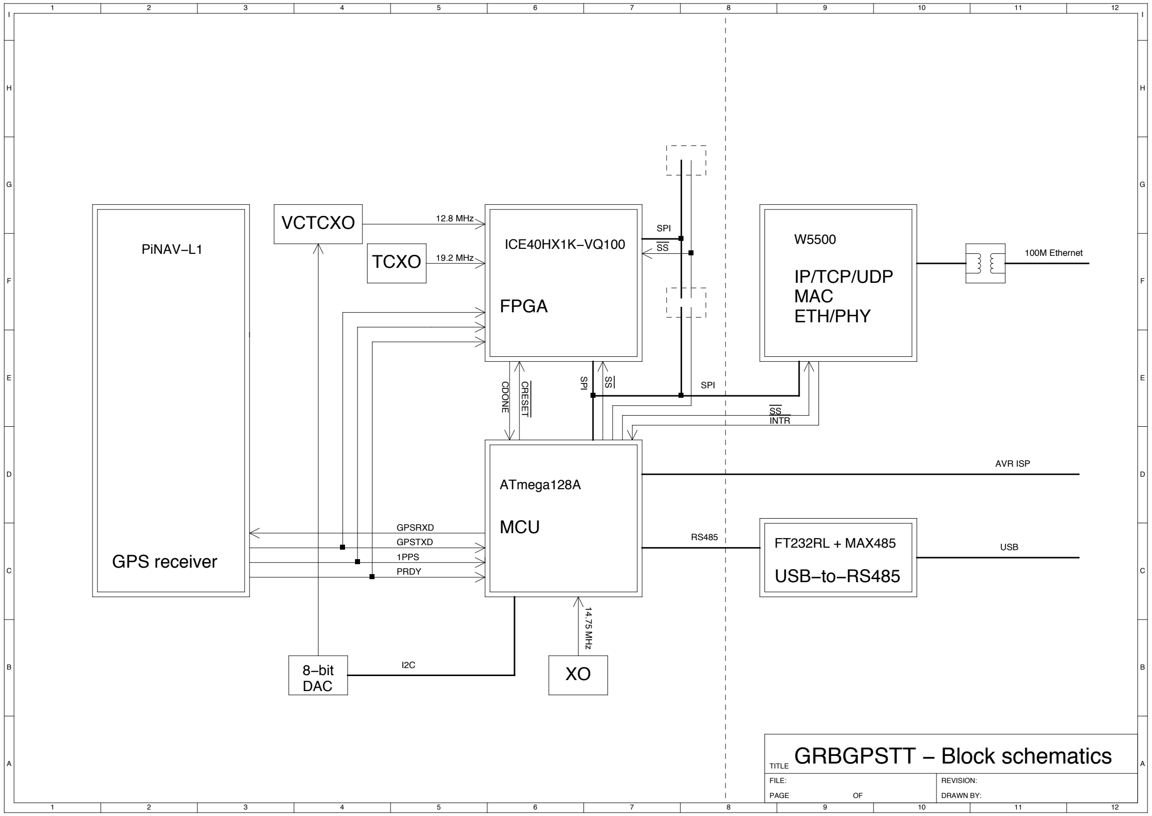
BLOCK DIAGRAM OF THE CAMELOT PAYLOAD



Pál et al. 2018

CAMELOT GPS TIME-STAMPING TEST BOARD





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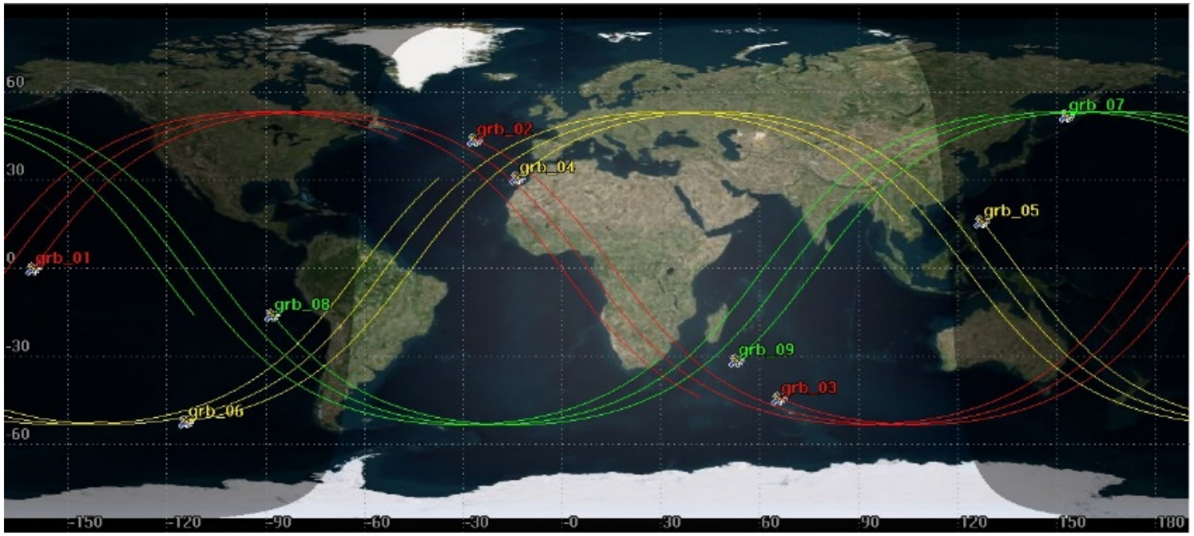
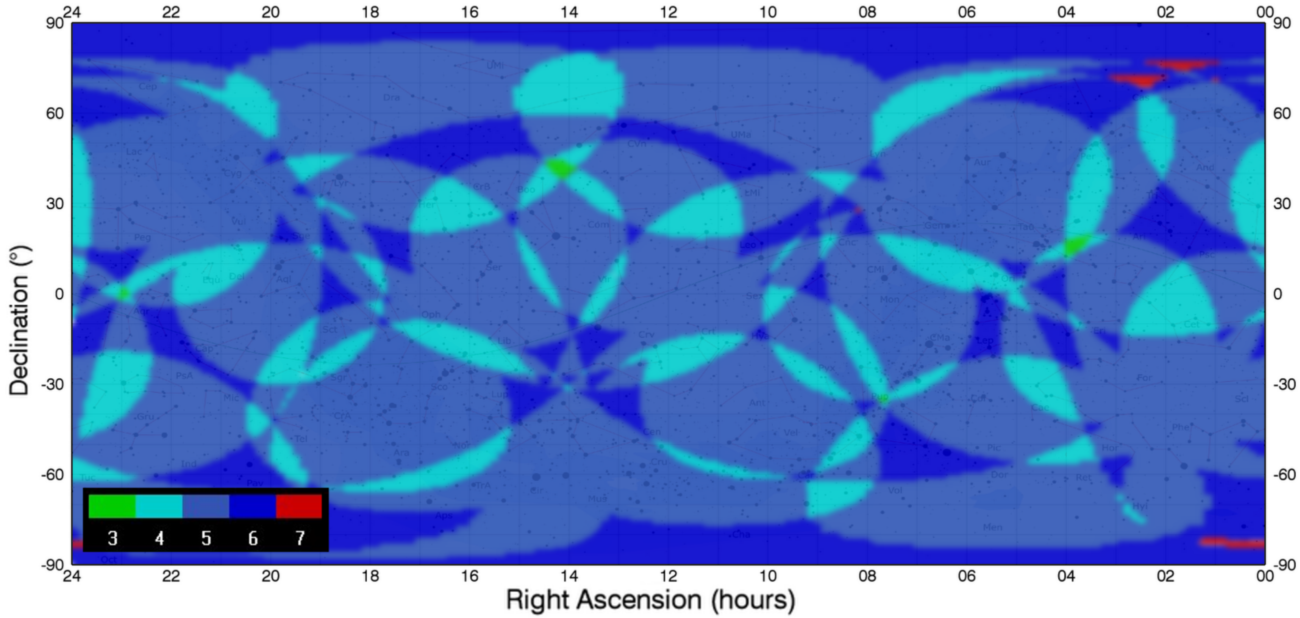
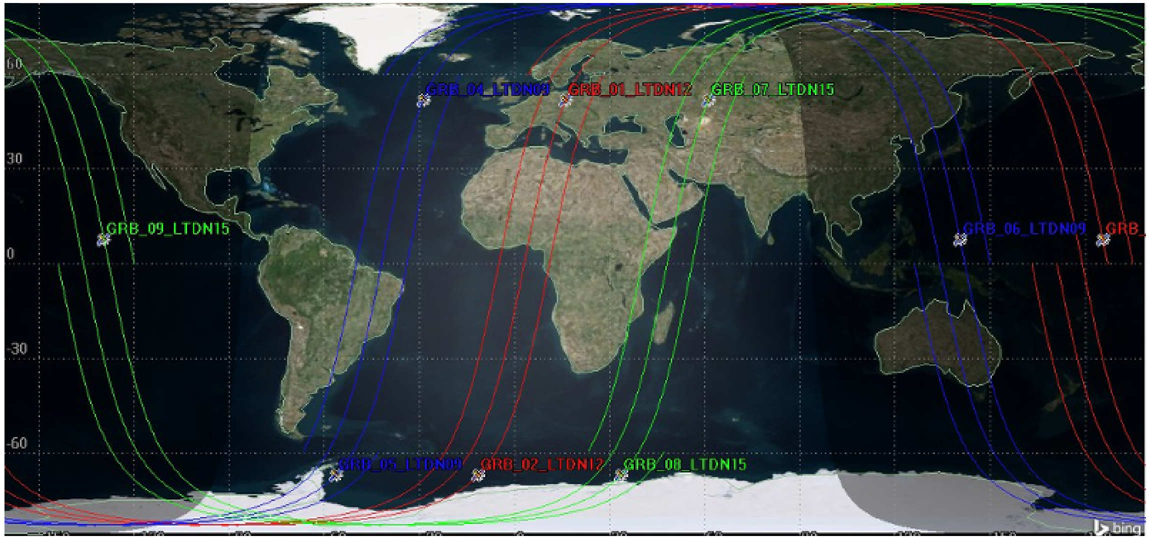
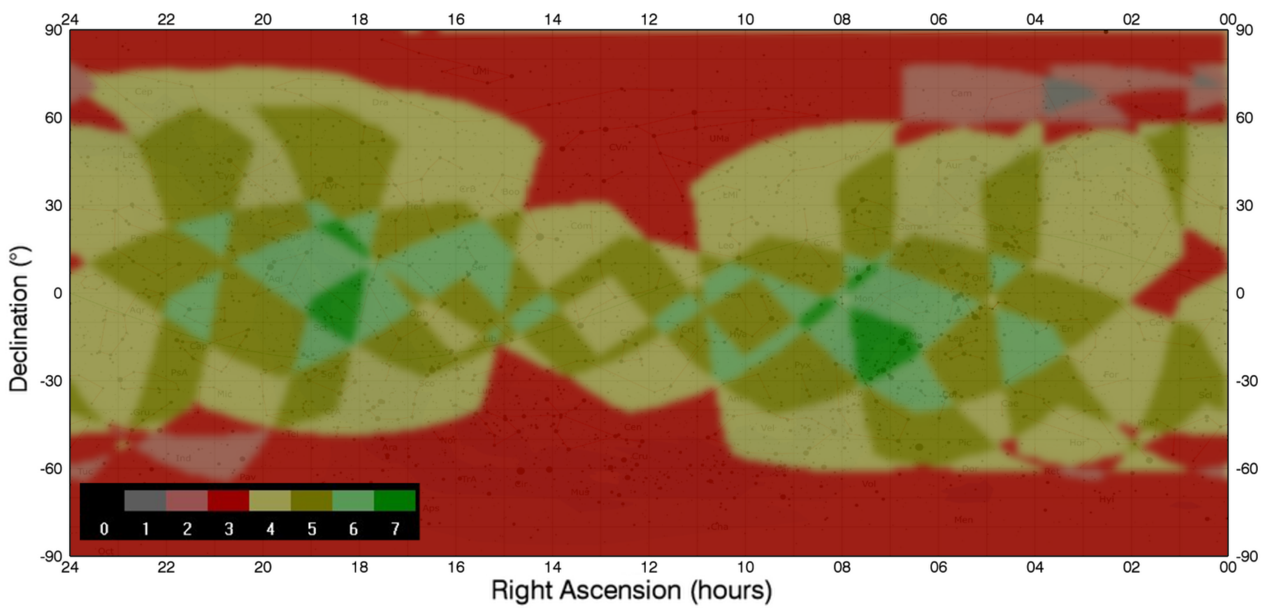
SKY VISIBILITY ON 53 DEG WALKER ORBITS



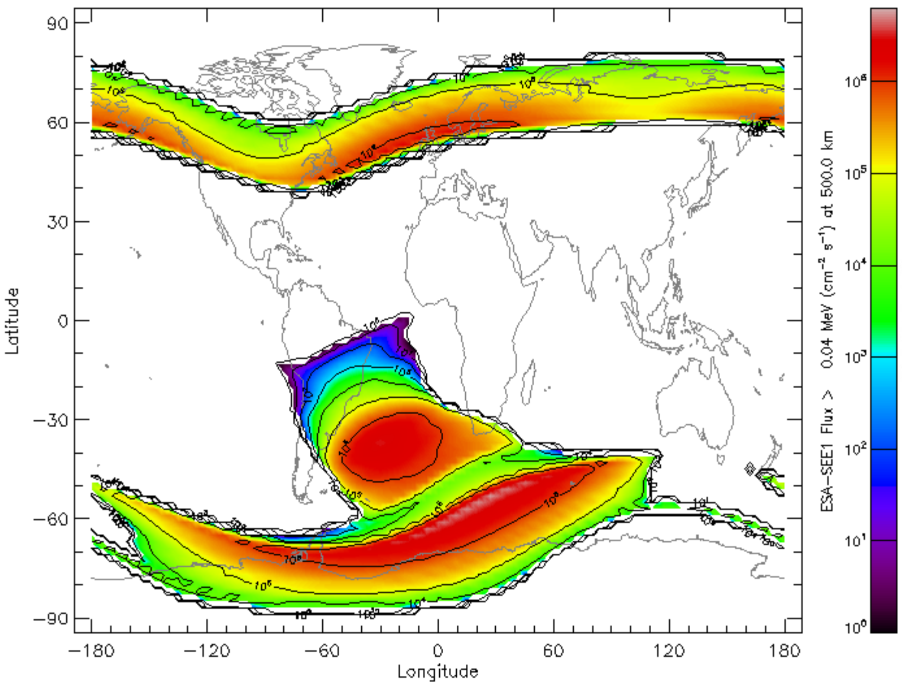


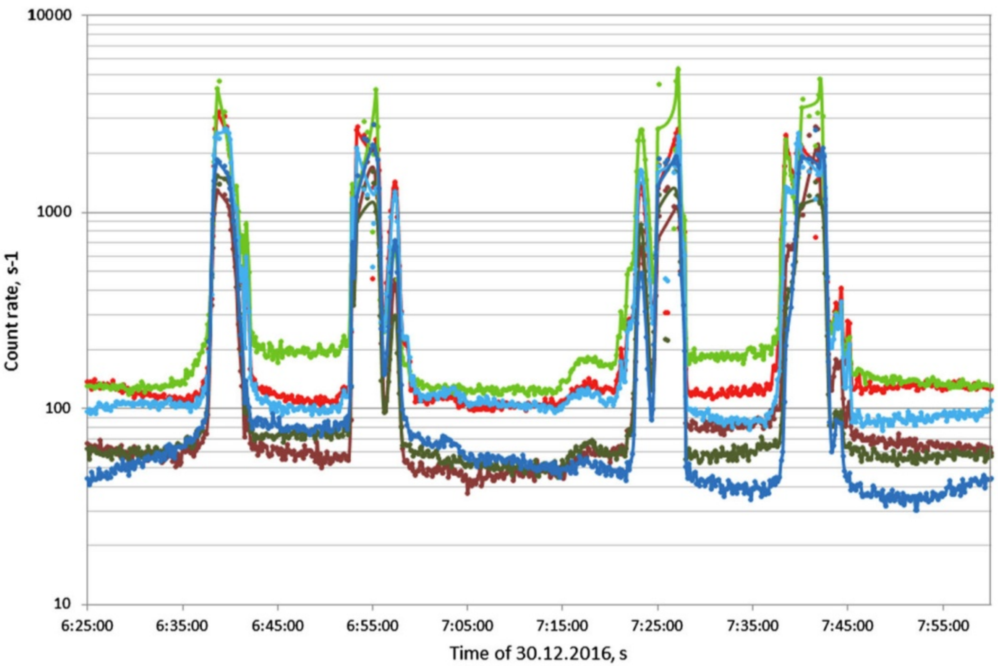
SKY VISIBILITY ON SUN-SYNCHRONOUS POLAR ORBITS





HIGH BACKGROUND ON POLAR ORBITS

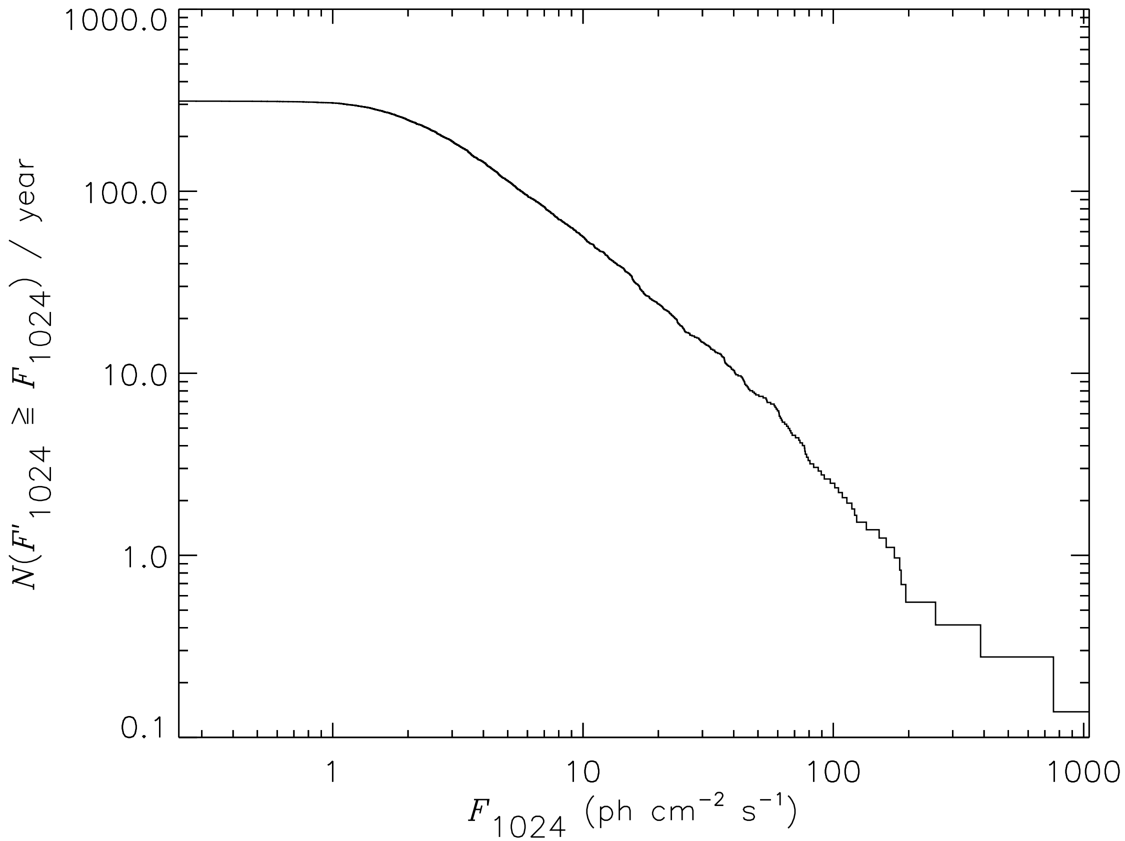




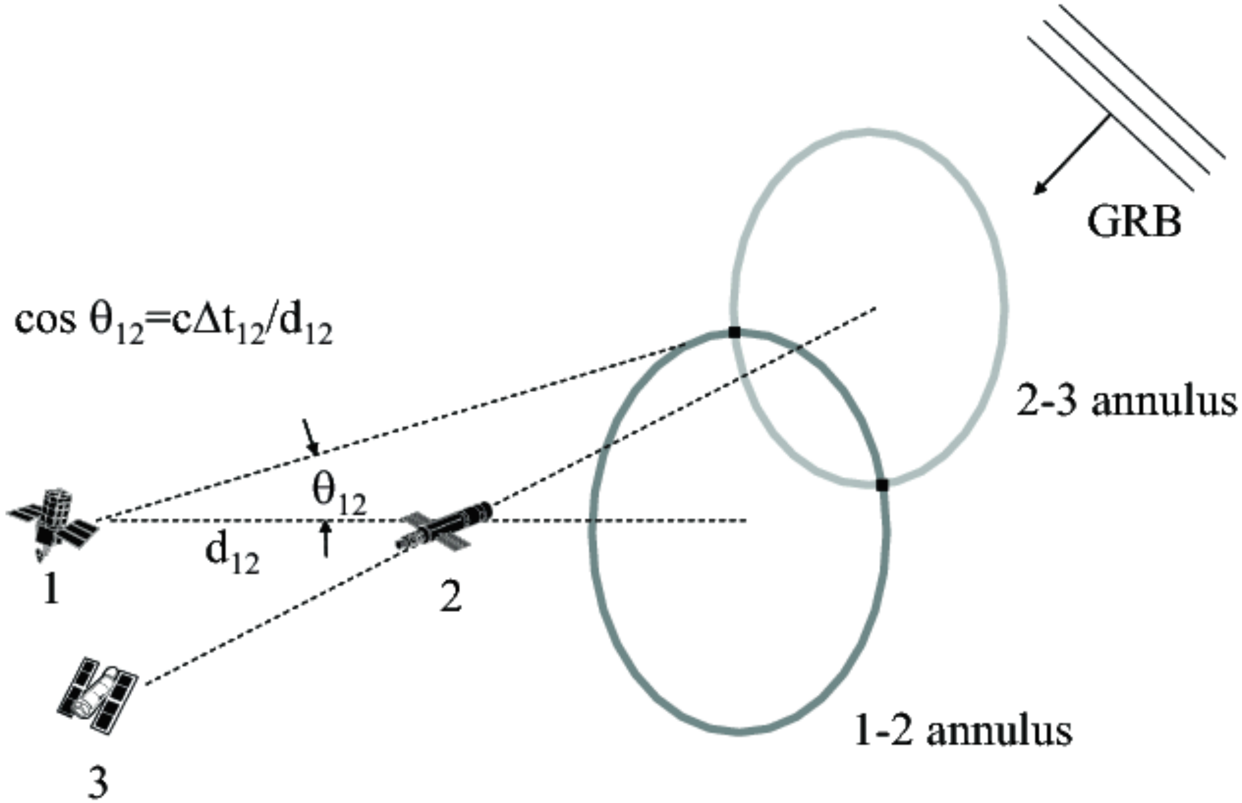
On polar orbit, each satellite will loose 30-40% of observing time

WHAT DO WE EXPECT TO SEE?

- Over **300 GRBs** detected per **year**
- Many **terrestrial gamma ray flashes**, solar flares, soft gamma ray repeaters, binaries, etc.



TIMING BASED LOCALIZATION



- <u>localization by photon arrival time</u>

High timing synchronization by GPS ➔ 10μ-sec timing accuracy results several arcmin localization accuracy ?

Hurley+13

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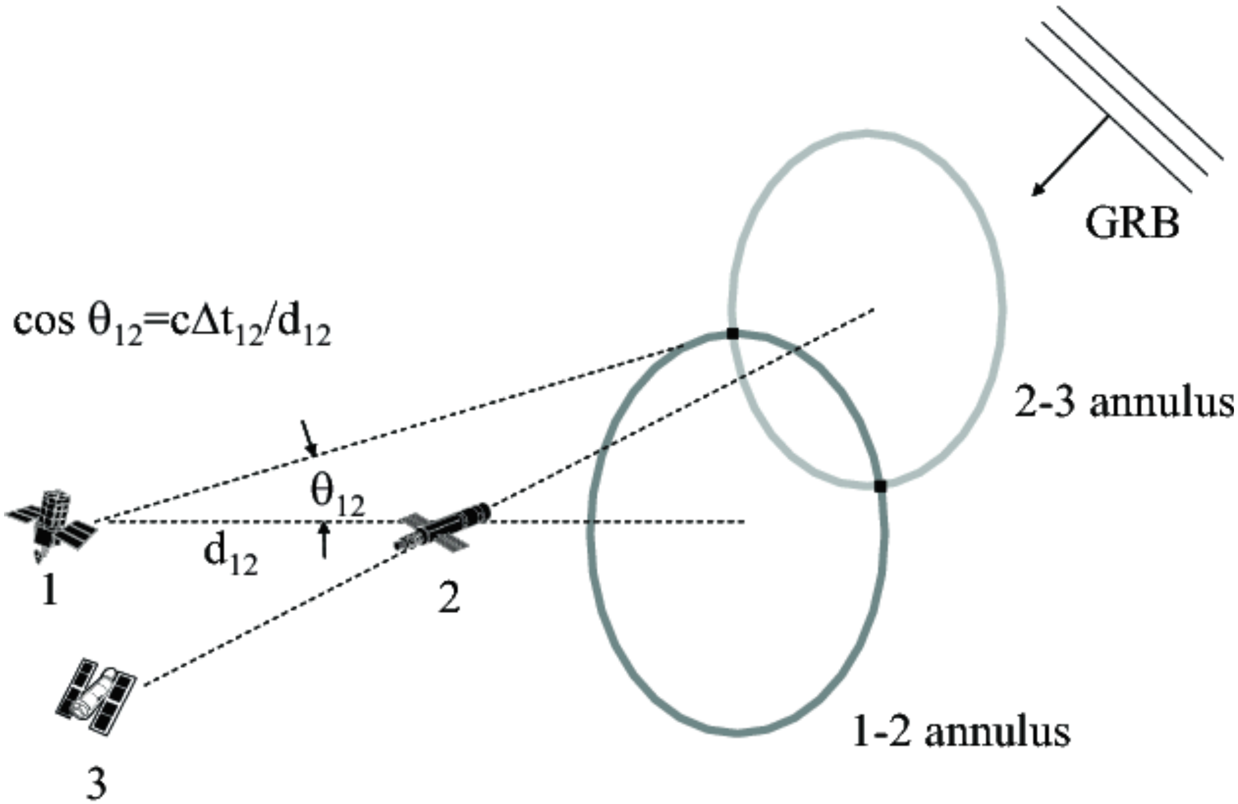

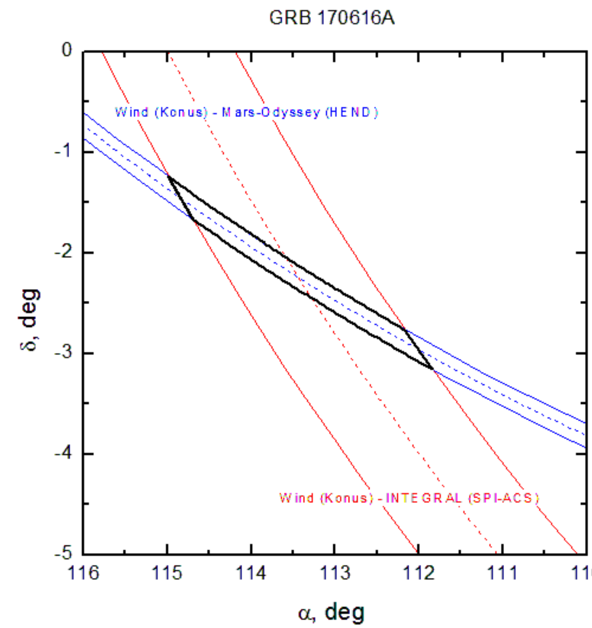

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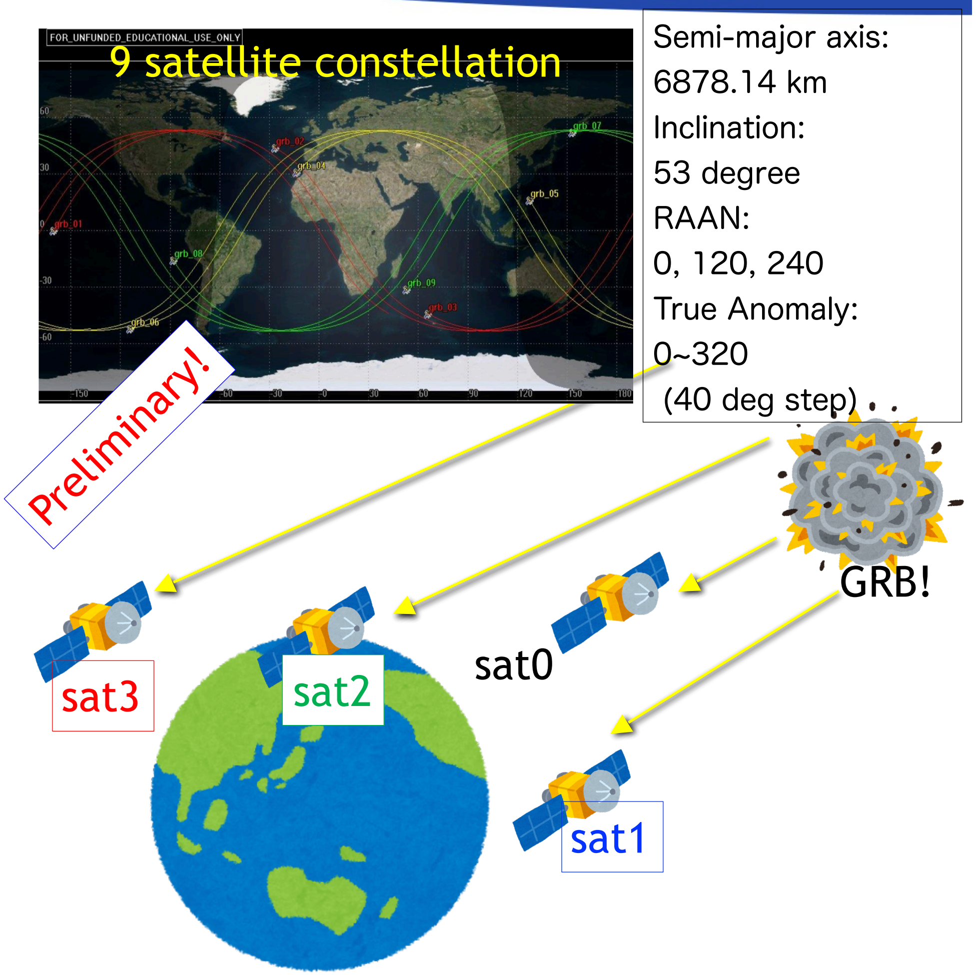
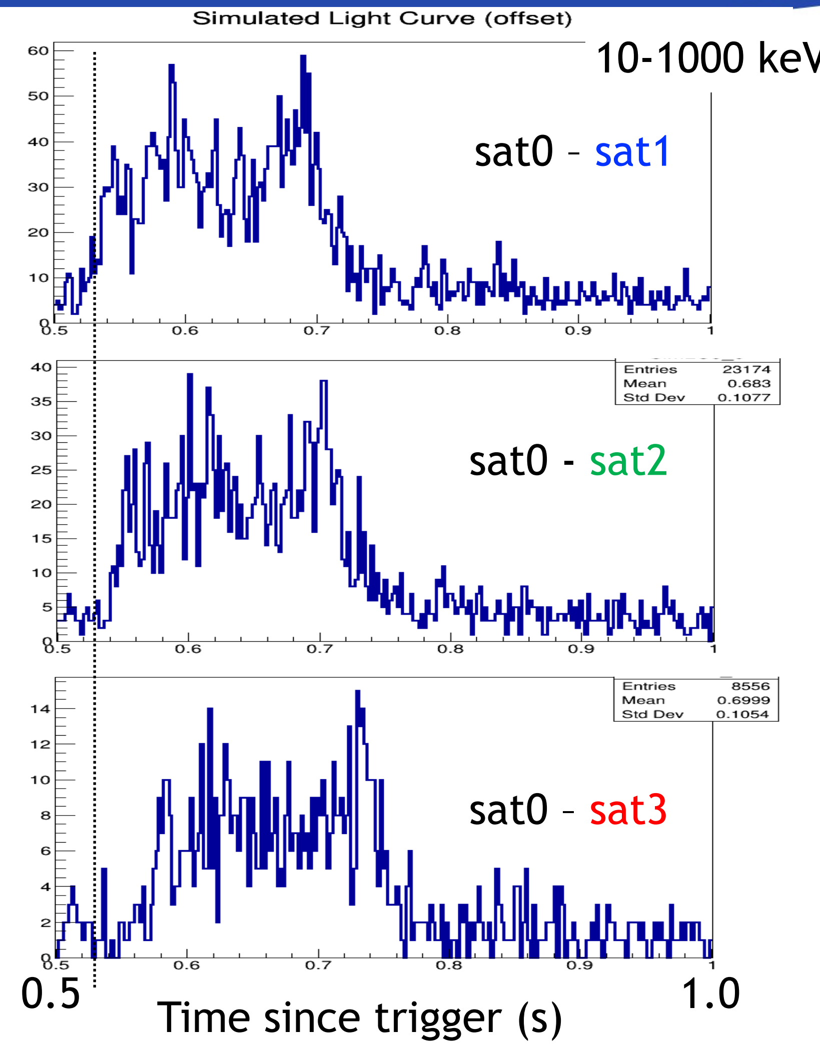
Hurley+13

LOCALISATION FEASIBILITY





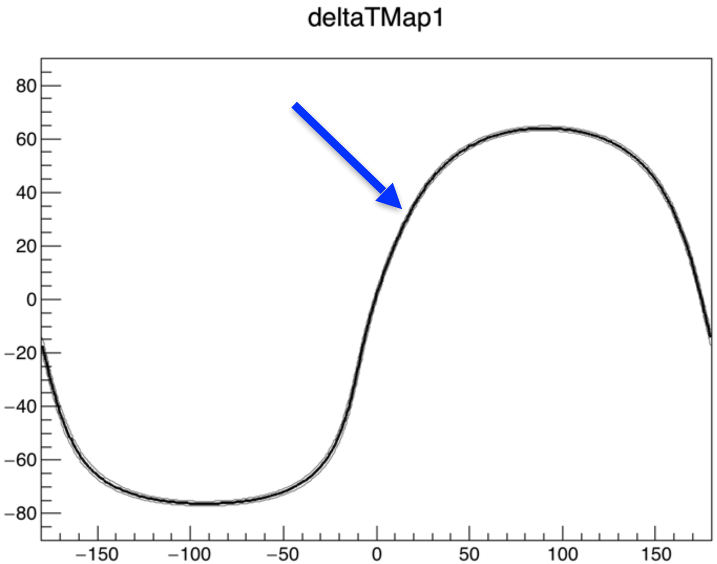
Satellite attitude, GRB position, predicted photon count/arrival time estimated using orbit and detector simulations.

Simulated photon arrival time is estimated by the cross correlation analysis ➔ triangulation annulus

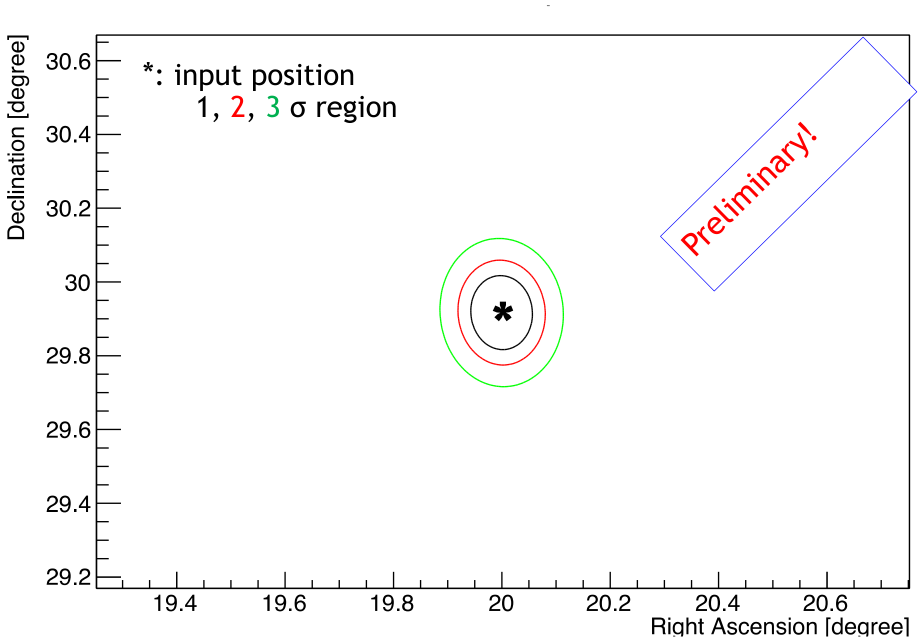
Ohno et al. 2018

LOCALISATION ALGORITHM

Intersection of annuli
➔ GRB position!



How can we estimate the most probable position and error ?



$$\chi^2 \equiv \sum_{i=0}^{N} \frac{\left\{\delta t_{\mathrm{sim,i}} - \mathrm{Norm} \times \cos\theta_{\mathrm{model,i}}(\mathrm{R.A.}, \mathrm{Dec.}) \times \mathrm{D/c}\right\}^2}{\sigma^2_{\mathrm{sim,i}}},$$

GRB position and error is estimated by simple x^2 minimization (Tanaka+ 17)
~0.1 $\mathrm{deg}_{1\sigma}$ (~6 arcmin) accuracy is achievable for bright/high-visibility case

Best fit position
R.A. = 20.0 (+/- 0.06) deg
Dec. = 29.9 (+/-0.10) deg

Ohno et al. 2018

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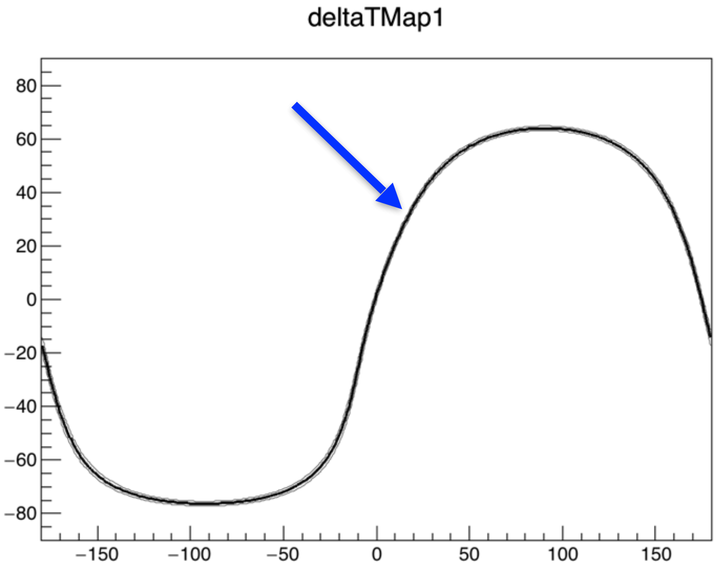

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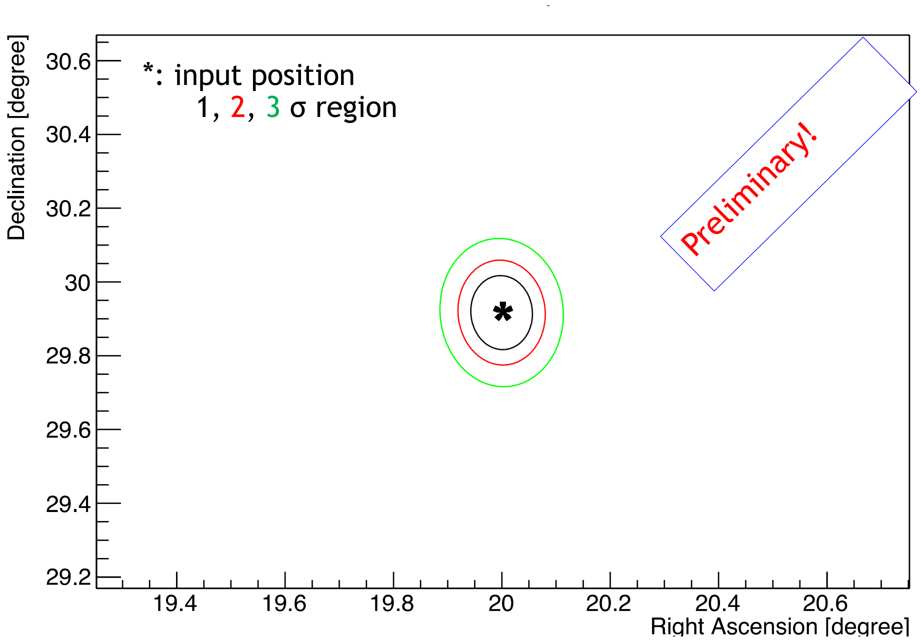

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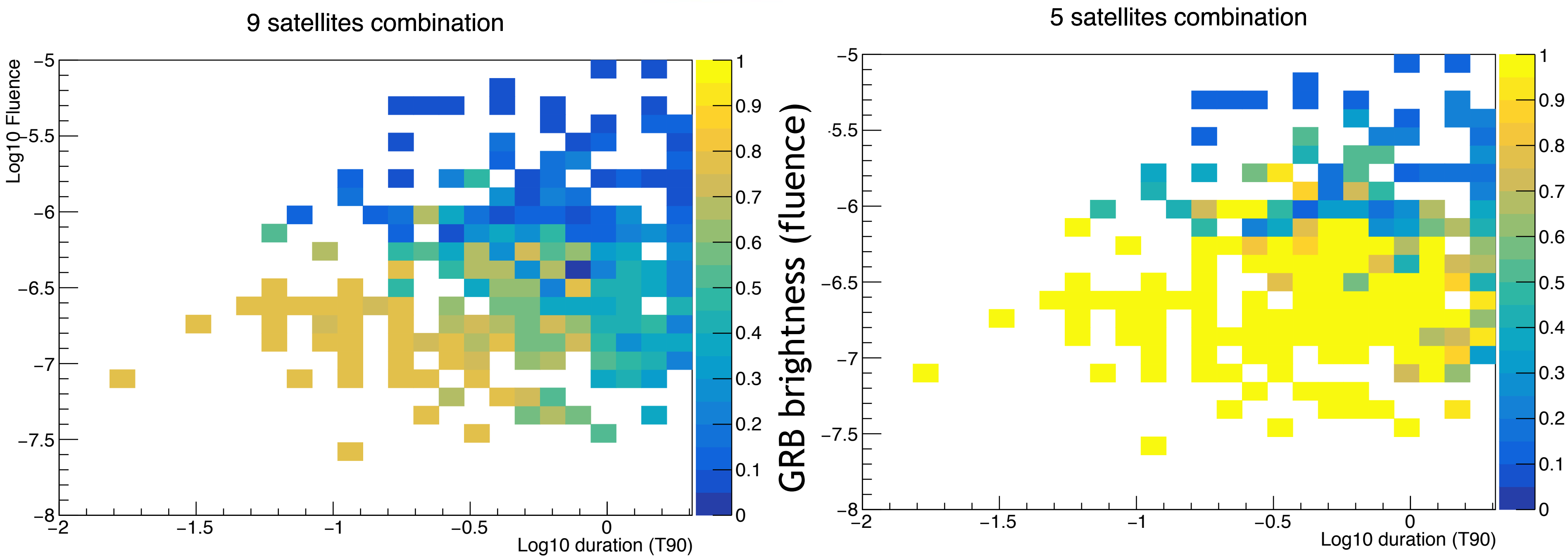
LOCALISATION ACCURACY



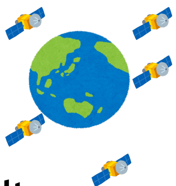
Localization accuracy of our concept is examined for all short GRBs listed in Fermi 3rd GRB Catalog (Bhar+16 T_{90}<2s: 326 samples)

- **High localization accuracy for good photon statistics (brighter/longer)**
- **5-10 arcmin accuracy in the best case**
- **Ten short GRBs per year localised to within 20 arcmin**

Ohno et al. 2018

SUMMARY

- We are proposing the ***CAMELOT* mission,** a constellation of nine 3U cubesats in three orbital planes on low Earth orbit, to provide an **all-sky coverage** and **~10 arcmin localisation accuracy**
- Each nanosatellite shall equipped with **four thin**, 9 mm, and relatively **large, 8.3 × 15 cm, CsI(Tl) based detectors** as lateral extensions on its surface read out by MPPCs. The large thin detectors provide **high sensitivity** (comparable with *Fermi* GBM), while leaving enough room for electronics.
- Timing based localisation demands precise **time synchronization** between the satellites and **accurate time stamping** of detected photons. This will be **achieved by using GPS receivers.**



Rapid localisation by gamma-ray observations is critical for the study of GW sources

- Rapid follow up observations at other wavelengths require the **capability for fast simultaneous downlink of data** for the triggered events from all satellites in the fleet. This can be achieved using **satellite-to-satellite communication networks** such as *Iridium NEXT.*
- *CAMELOT* will also provide **important secondary science**, such as monitoring of outbursts of soft gamma-ray repeaters, gamma-ray flares on the Sun, **terrestrial gamma-ray flashes** (produced in thunderstorms), and space weather phenomena.
- CAMELOT provides ample **potential for international cooperation**. Because the proposed **fleet is scalable** and extendable, we envision collaboration with future partners using different satellite designs, **extending the capabilities of the constellation**.

Werner et al. arXiv: 180603681
Ohno et al. arXiv: 180603686
Pal et al. arXiv: 180603685

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