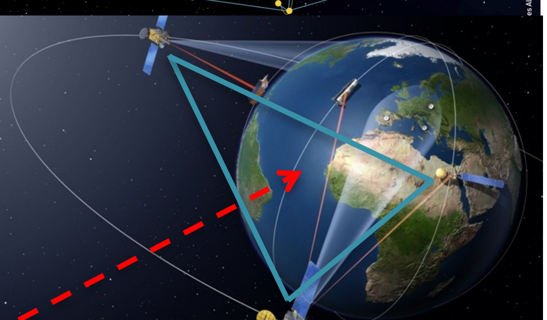


On the localisation capabilities of the HERMES + SpIRIT constellation

Andrea Sanna, University of Cagliari

On behalf of the HERMES collaboration

Please, visit our websites:
http://hermes-sp.eu

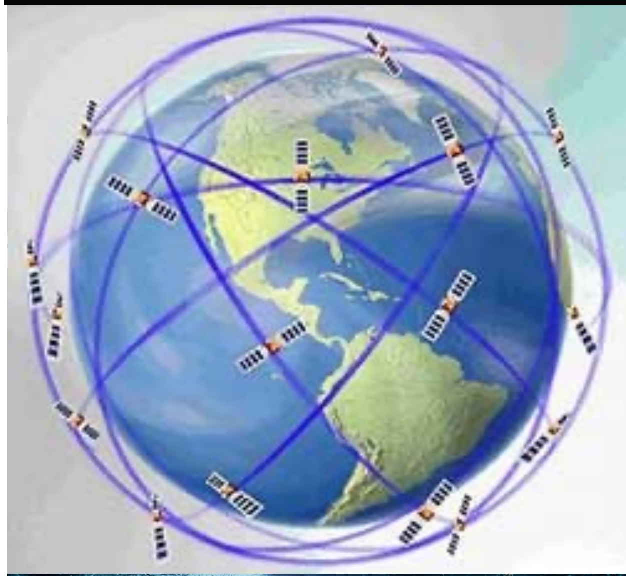
Congresso Nazionale GRB – 15/09/2022

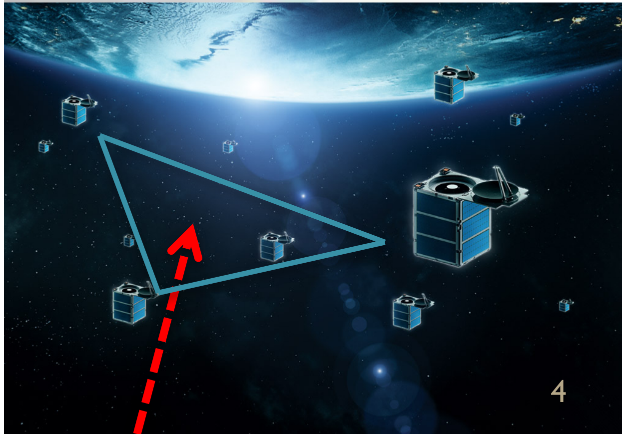
HERMES in a nutshell
High Energy Rapid Modular Ensemble of Satellites

Aims:
- **All-Sky Monitor** for fast and accurate detection of the position of bright, high-energy transients
- Study of the fine temporal structure of transients
- First dedicated experiment in Quantum Gravity

How:
temporal triangulation of signals detected by a **swarm of LEO nano/micro satellites** equipped with:
- keV-Mev scintillators,
- sub μs time resolution
- large FoV

Pros:
- modularity,
- limited cost,
- quick development



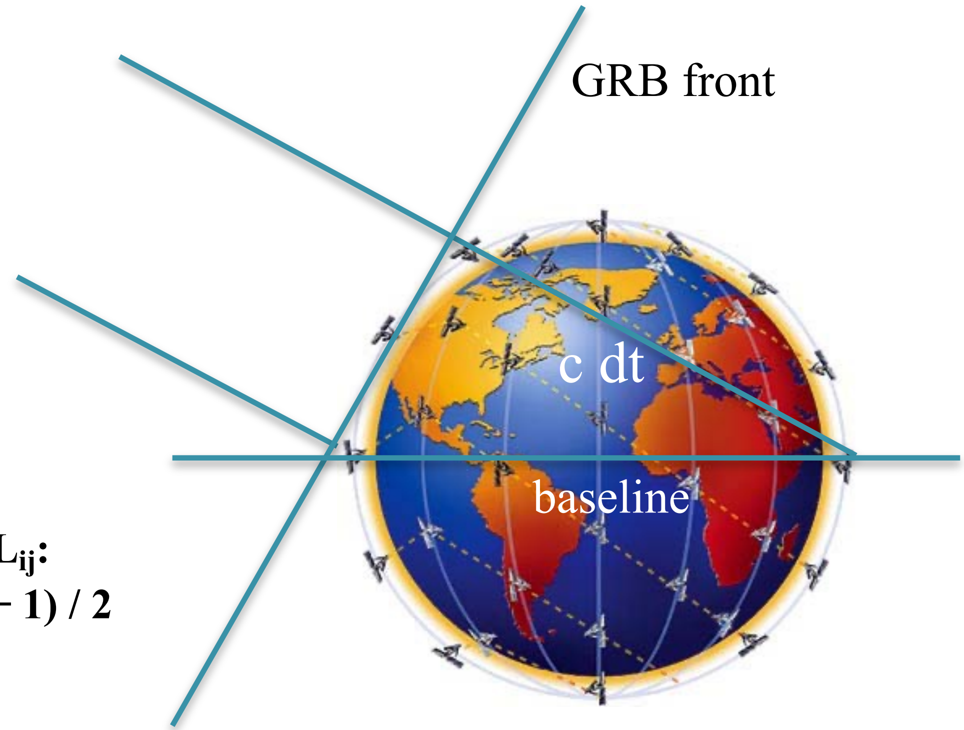


Principles of temporal triangulation

Determination of source position through delays in Time of Arrival (ToA) of an impulsive (variable) signal over 3 (or more) spatially separate detectors

position of the source in the sky:

α, δ (2 parameters, $N_{PAR} = 2$)



$i = 1, \ldots, N_{SATELLITES}$
$j = 1, \ldots, N_{SATELLITES}$

$DEL_{ij} = ToA(i) - ToA(j)$

$DEL_{ij} = -DEL_{ji}$; $DEL_{ii} = -DEL_{jj} = 0$

Number of (non trivial) different DEL_{ij}:

$N_{DELAYS} = N_{SATELLITES} \times (N_{SATELLITES} - 1) / 2$

Number of independent DEL_{ij}:

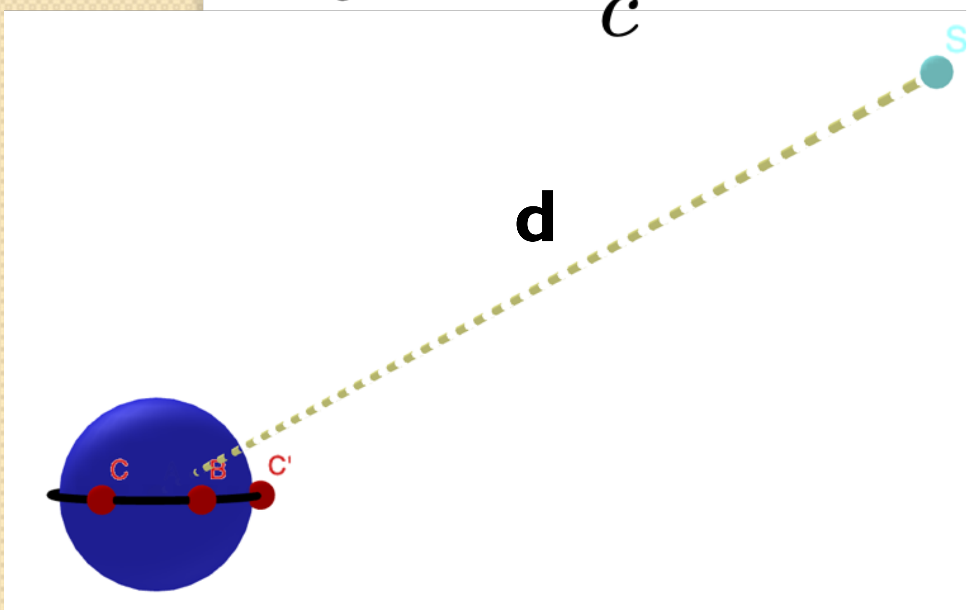
$N_{IND} = N_{SATELLITES} - 1$

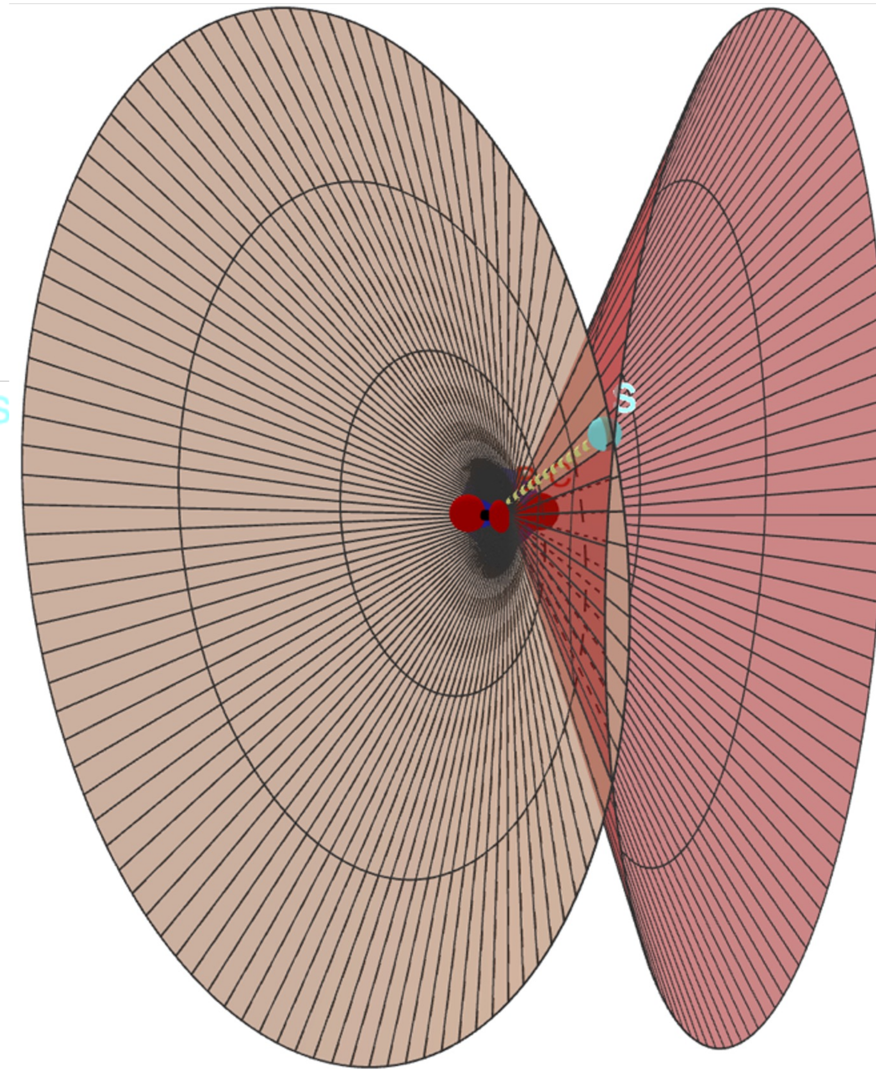
Accuracy in determining α and δ with $N_{SATELLITES}$:

$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA} / \langle baseline \rangle \times (N_{IND} - N_{PAR} - 1)^{-1/2}$

Temporal Triangulation

$$\Delta t_{ij} = \frac{\vec{\rho_{\mathbf{ij}}} \cdot \hat{\mathbf{d}}}{c}$$

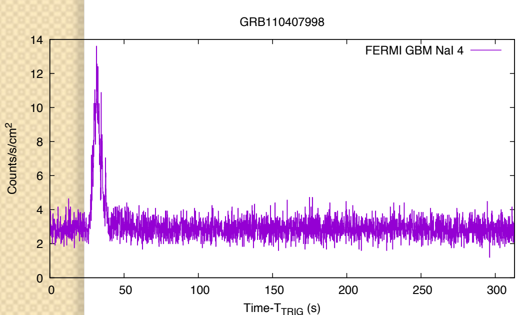




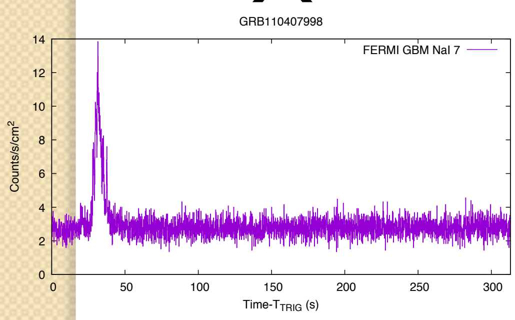
Cross-correlation techniques

Circular cross-correlation routines:

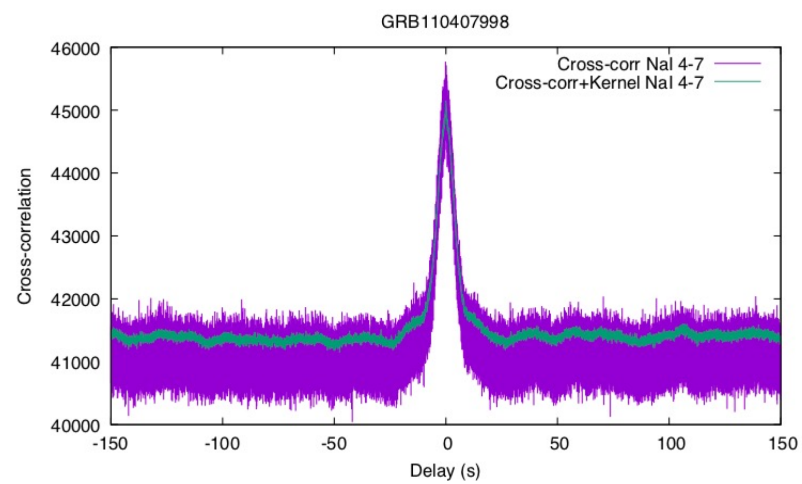
$$cc(\delta_i) = \sum_{i=0}^{n-1} lc_A(t_i) \times lc_B(t_i + \delta_i)$$



X



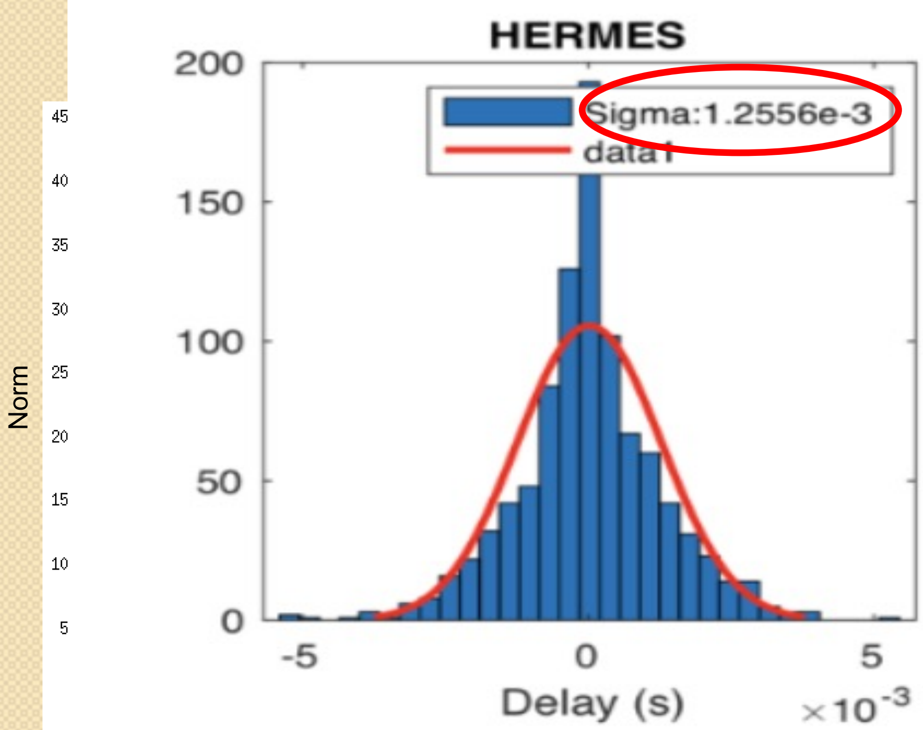
=

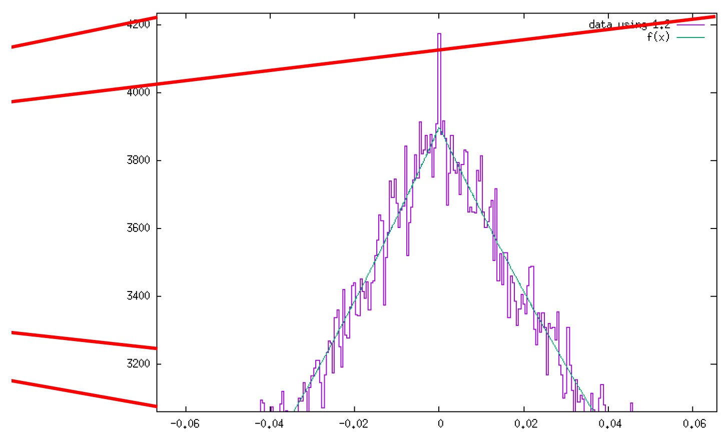


Cross-correlation: delay accuracy

Semi-automatic fitting algorithms and Monte Carlo simulations:

1000 Monte Carlo simulations



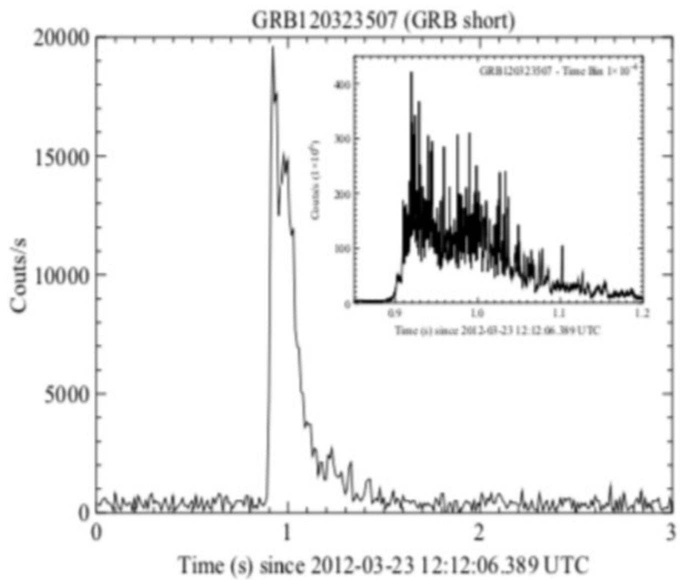


Cross-correlation accuracy from the best-fit of a single function (signal from 2 detectors)

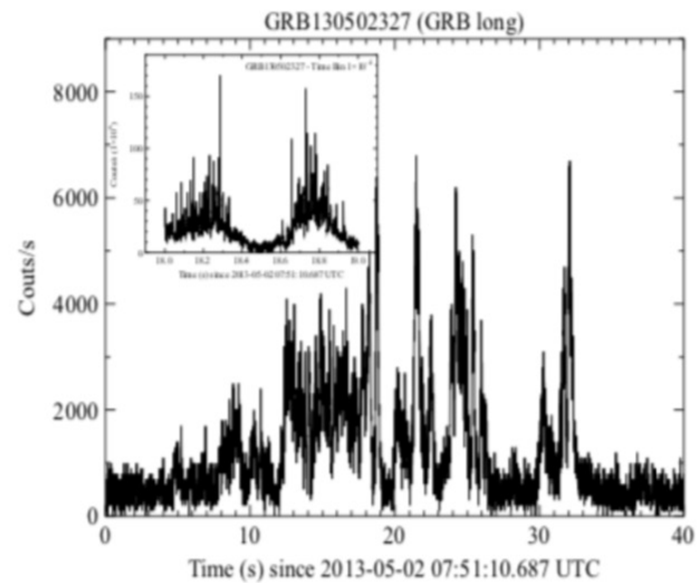
$\sigma_{cc} \backsim 4.7\times10^{-3}$ s

GRB simulations: templates

Template generation and GRB simulations:



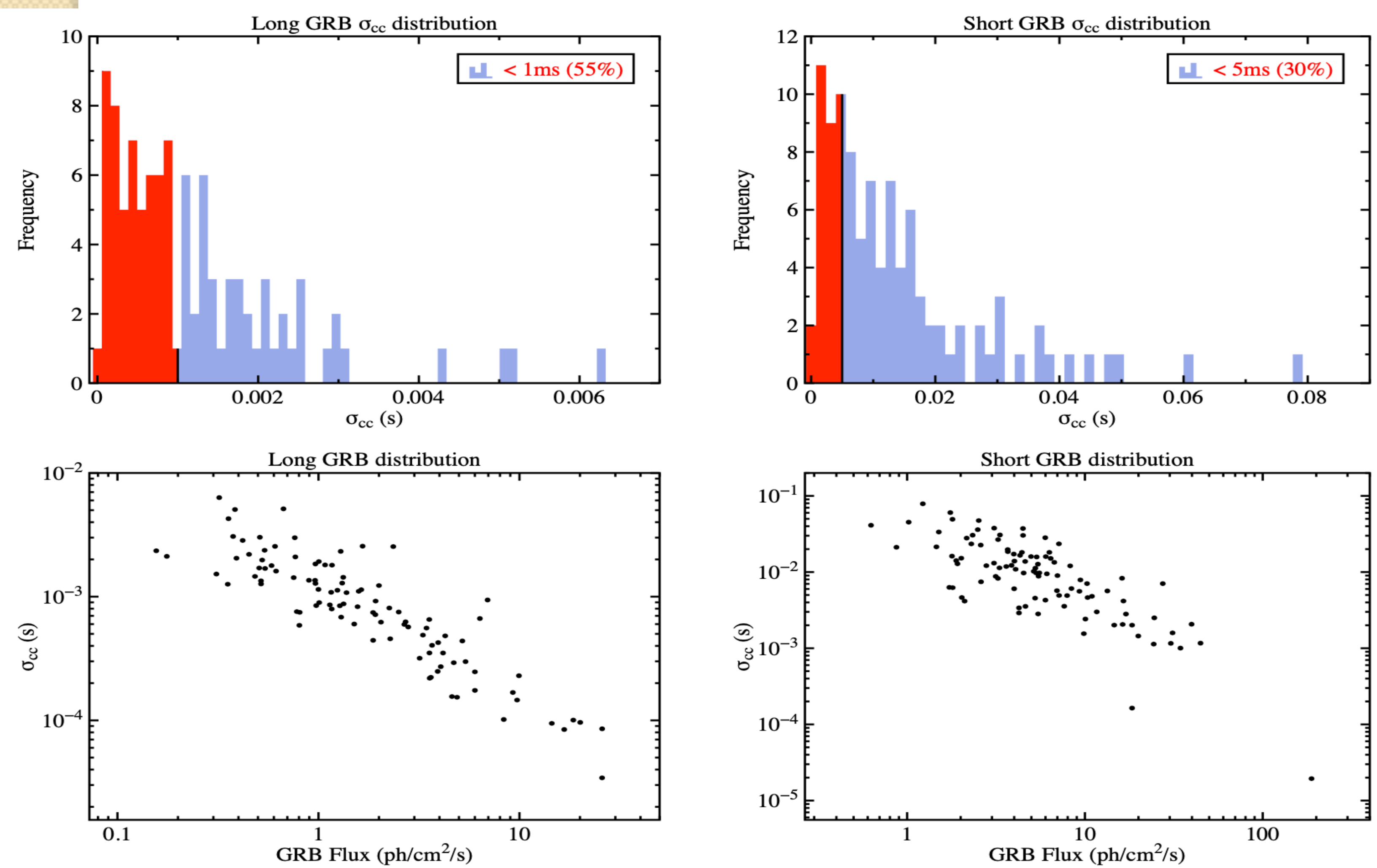
- 6 photons per bin
- 0.1 ms binsize



Starting from real GRB light curves, we generate templates adopting smoothing strategies to prevent artefacts due to Poissonian statistical fluctuations. An analytical light curve is then obtained as a linear piecewise interpolation of the smoothed light curve.

GRB simulations: sample studies

Simulations using a random sample of 100 short and long GRBs



GRB localisation

GRB localization and estimate of positional uncertainties:

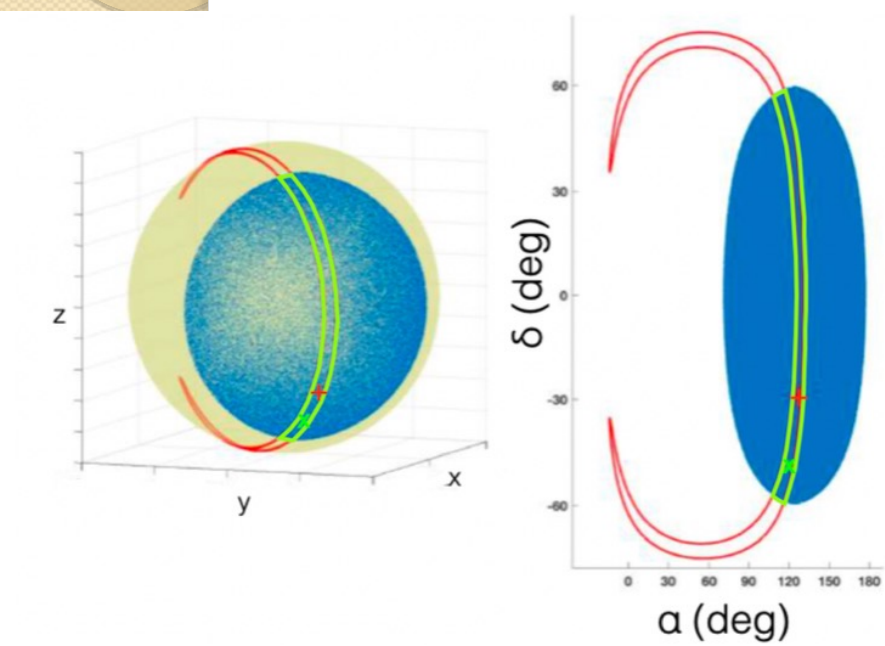
The direction of the GRB, expressed as a unitary vector **d**, is estimated comparing the measured ($\Delta\tau_{ij}$) and computed ($\Delta t_{ij}(\mathbf{d})$) delays between detectors using a non-linear least-squares minimization algorithm. The information about the location of each unit is stored in the input file. The χ^2 function, defined as the sum over each detector pair of the squares of the difference between the expected and observed time delay divided by its statistical error

$$\chi^2(\hat{d}) = \sum_{i=0}^{n-2} \sum_{j=i+1}^{n-1} \frac{(\Delta\tau_{ij} - \Delta t_{ij}(\hat{d}))^2}{\delta\Delta\tau_{ij}^2 + \delta\Delta t_{ij}^2},$$

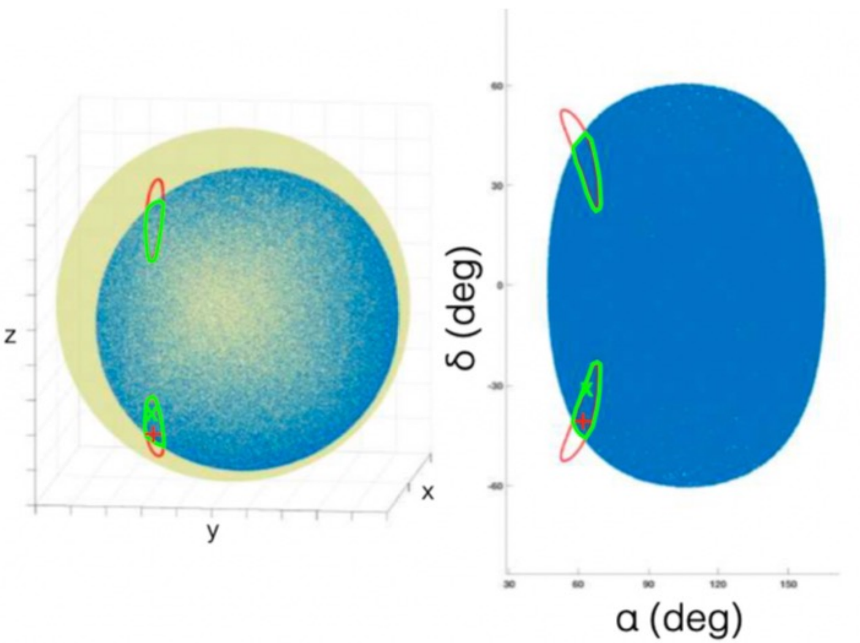
where $\delta\Delta t_{ij}$ is the uncertainty on the positional error of the nanosat expressed in light-seconds. Minimizing χ^2 with respect to **d** gives us the best estimate of the direction of the GRB. The tool calculates the confidence region for the GRB equatorial coordinates on the plane of the sky using a $\Delta\chi^2$ method as described in Anvi, Astrophysical Journal, 210, 612 (1976).

GRB localisation

<u>GRB localization and estimate of positional uncertainties:</u>



Positional confidence regions for a GRB (lat < 30 deg) observed simultaneously by 3 HERMES detectors located in equatorial orbit.

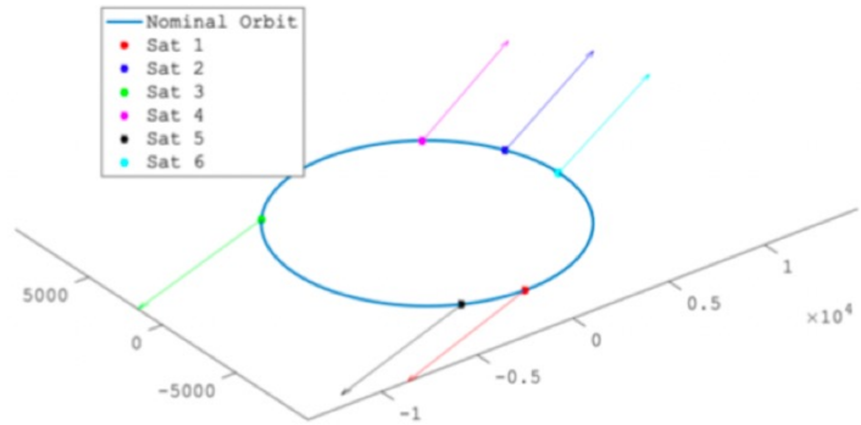


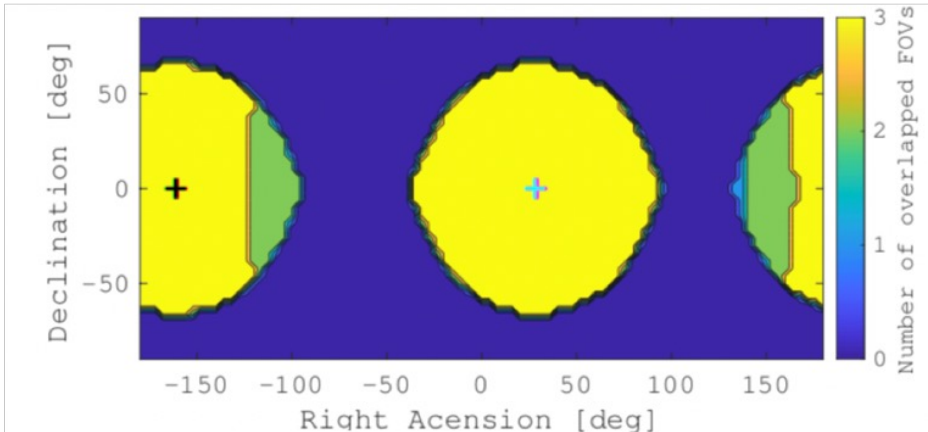
Positional confidence regions for a GRB (lat > 70 deg) observed simultaneously by 3 HERMES detectors located in equatorial orbit.

GRB localisation: simulations

- Low Earth Equatorial Orbits:
  a) h=500 km ; h=550 km
  b) circular orbits (e=0)
  c) equatorial orbits (i=0)

- 6 satellites in two triplets with initial true anomaly separation of 220 deg
- n ≥ 3 payload l.o.s. directions on a LVLH-selected direction (i.e. line-of-sights aligned on the zenith direction of a specific satellite in the fleet)
- 2 years mission (1 min segments)



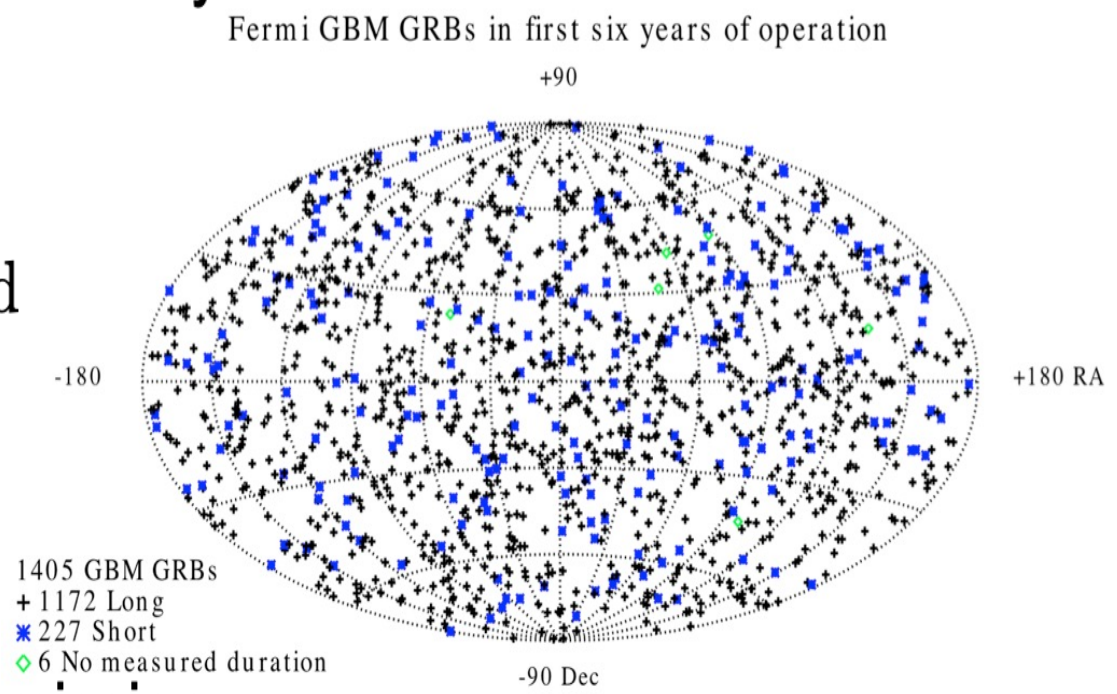


GRB localisation: simulations

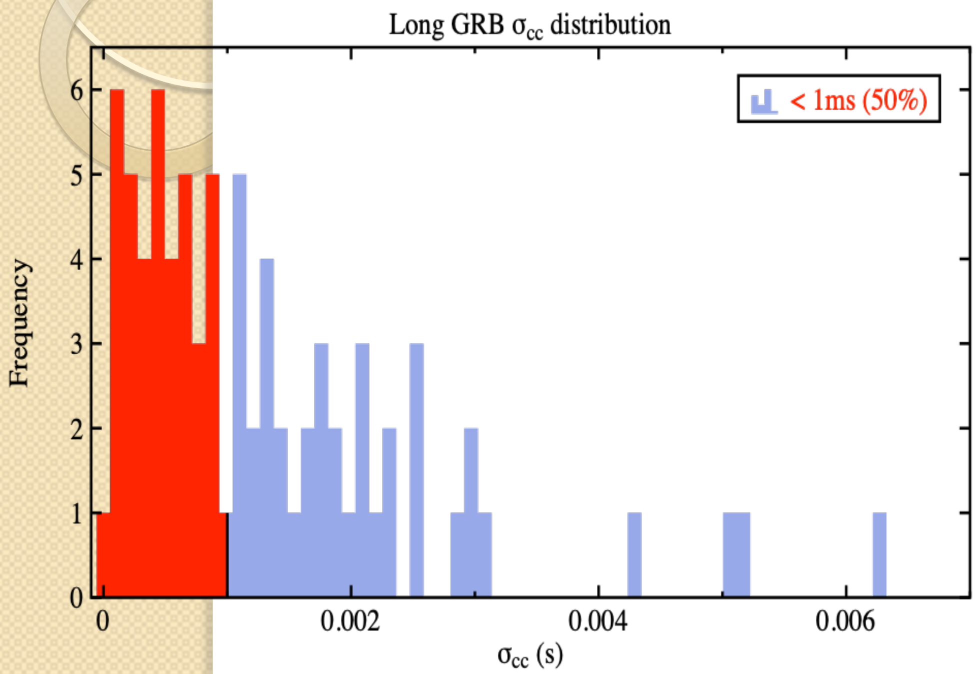
- GRB uniformly distributed in the sky
- Fermi/GBM detection rate

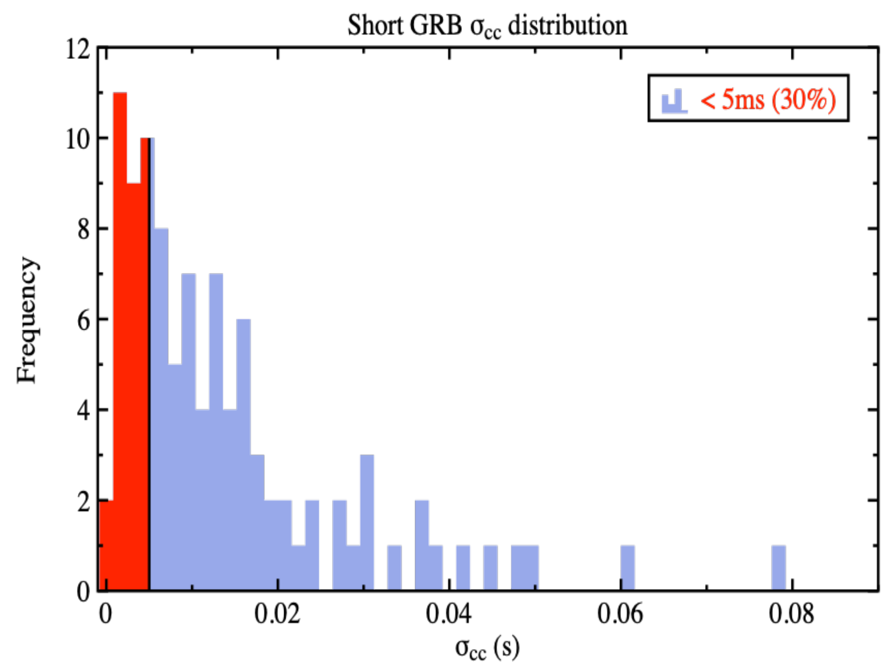
$$\alpha_{GBM} = 0.083\,\mathrm{GRB/sr/d}$$

~ 760 GRBs for 2 years of mission
- ~ 631 Long GRBs
- ~ 129 Short GRBs



GRB localisation: simulations



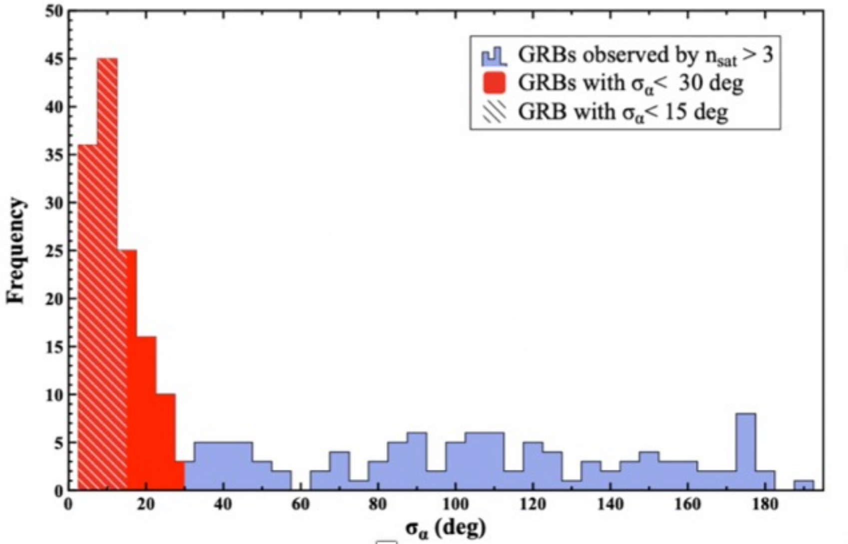


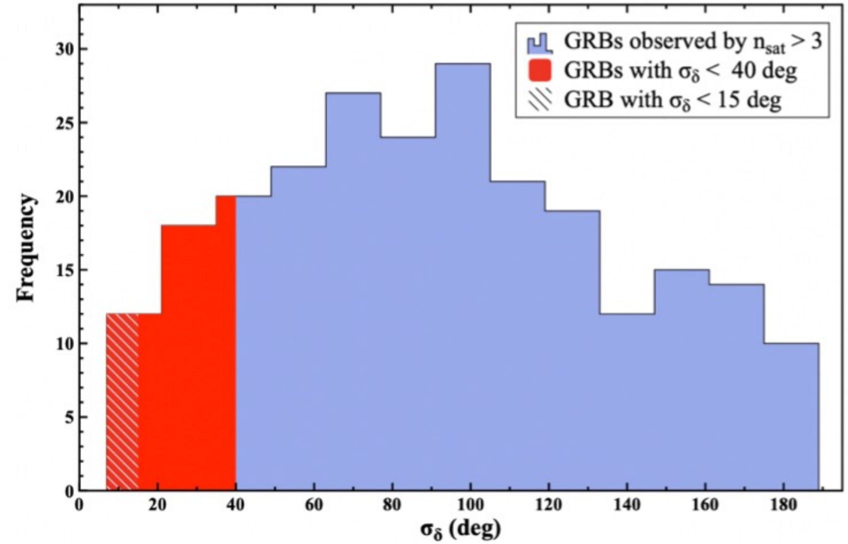
631 Long GRBs

129 Short GRBs

760 GRBs for 2 years of mission

GRB localisation: results long GRBs





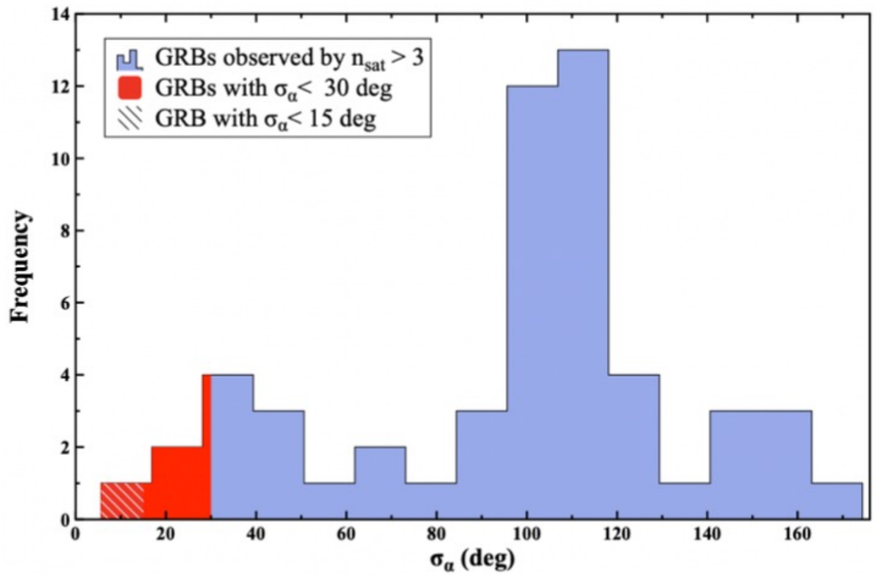
1000 Monte-Carlo simulation:

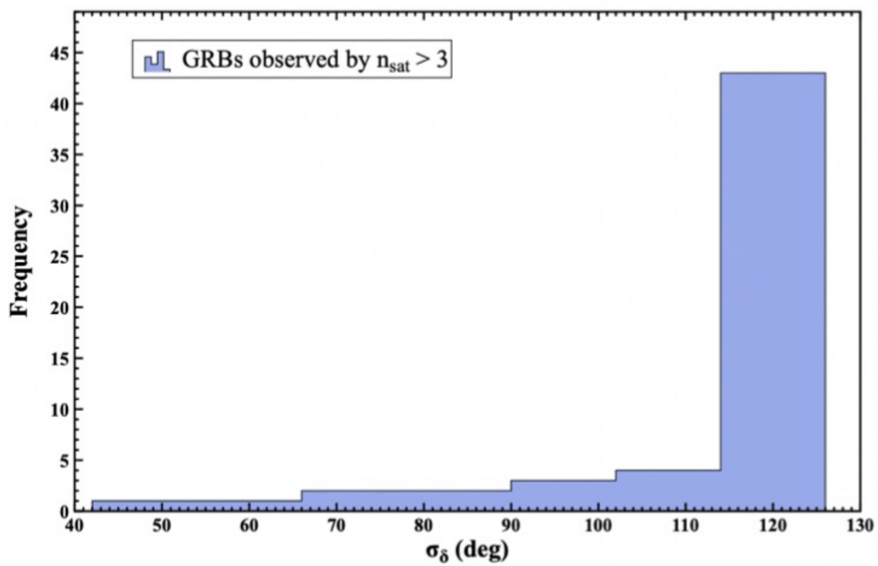
630 long GRBs for each simulation, 240±11 detected by N≥ 3 satellites simultaneously.

More details:

- 66 ± 5 events with $\sigma_\alpha < 30°$;
- 20 ± 3 events with $\sigma_\alpha < 30°$ and $\sigma_\delta < 40°$;
- 57 ± 4 events with $\sigma_\alpha < 15°$;
- 16 ± 2 events with $\sigma_\alpha < 15°$ and $\sigma_\delta < 40°$;
- 7 ± 2 events with $\sigma_\alpha < 5°$;
- 4 ± 1 events with $\sigma_\alpha < 5°$ and $\sigma_\delta < 40°$;
- 1 ± 0.6 events with $\sigma_\alpha < 5°$ and $\sigma_\delta < 10°$;

GRB localisation: results short GRBs



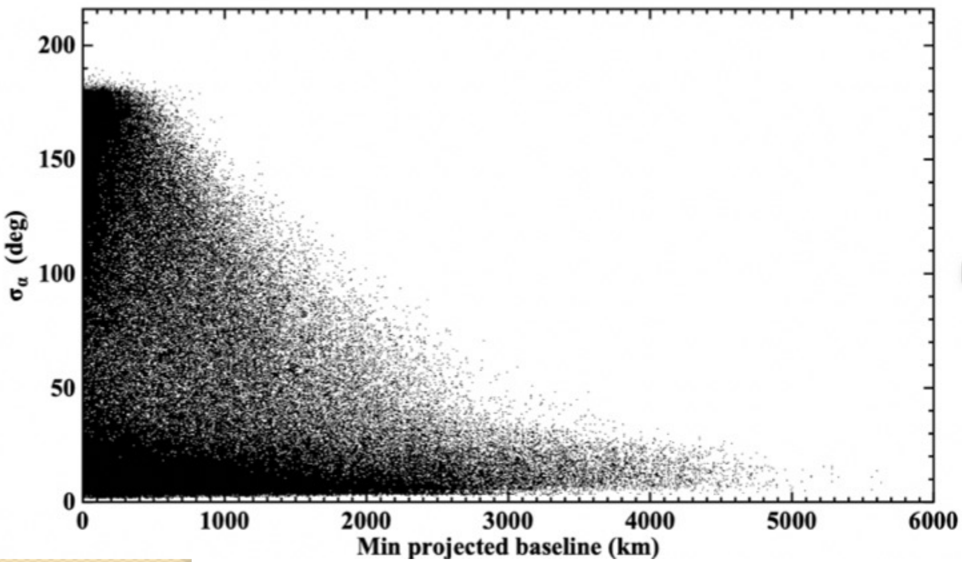


1000 Monte-Carlo simulation:
130 short GRBs for each simulation, 48±5 detected by N≥ 3 satellites simultaneously.

More details:

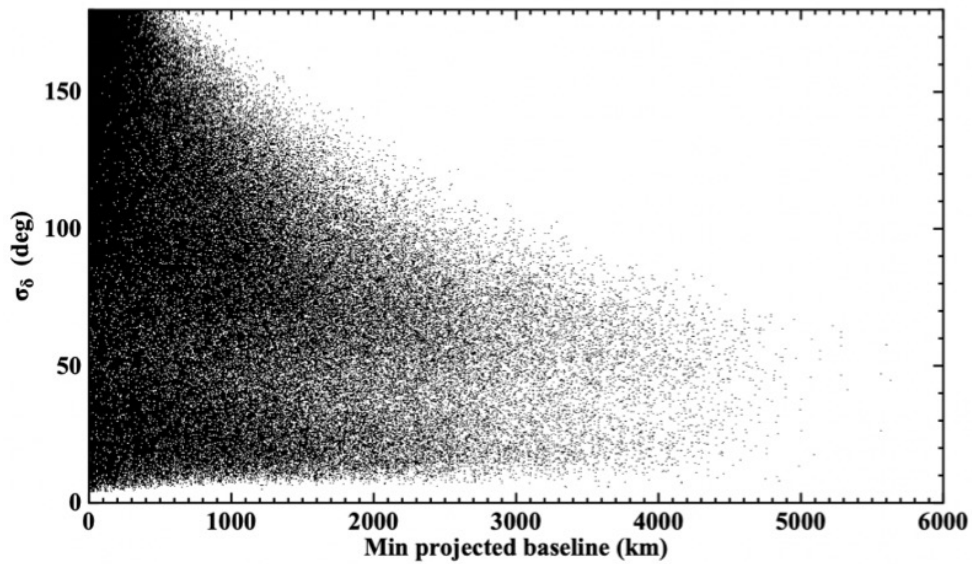
- 2±1 events with $\sigma_\alpha < 30°$

GRB localisation: further analysis

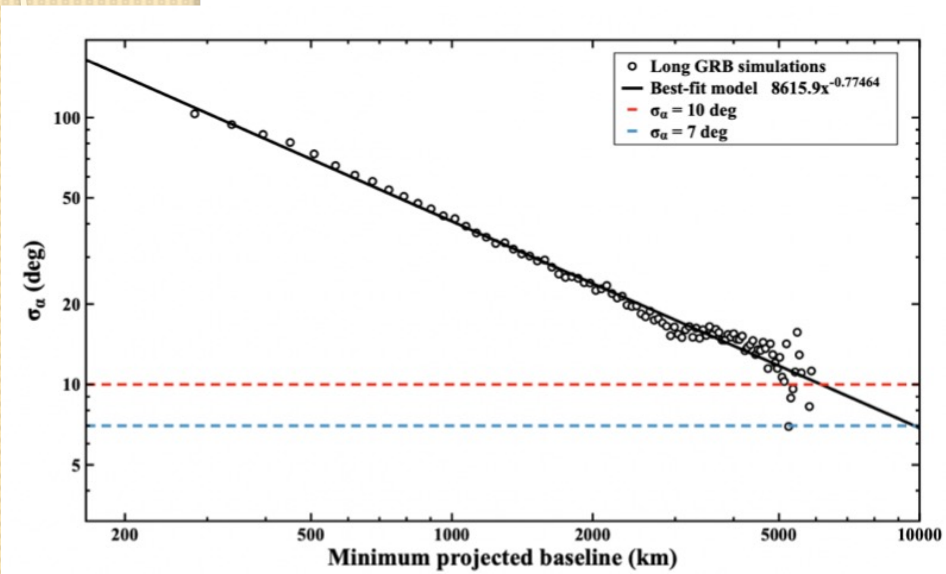


~ 240000 long GRBs

~ 50000 short GRBs



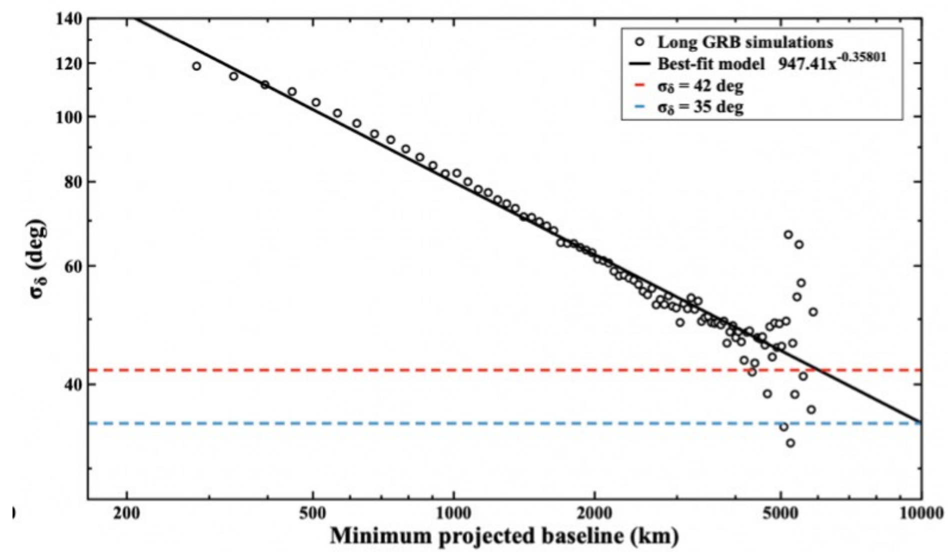
GRB localisation: results short GRBs



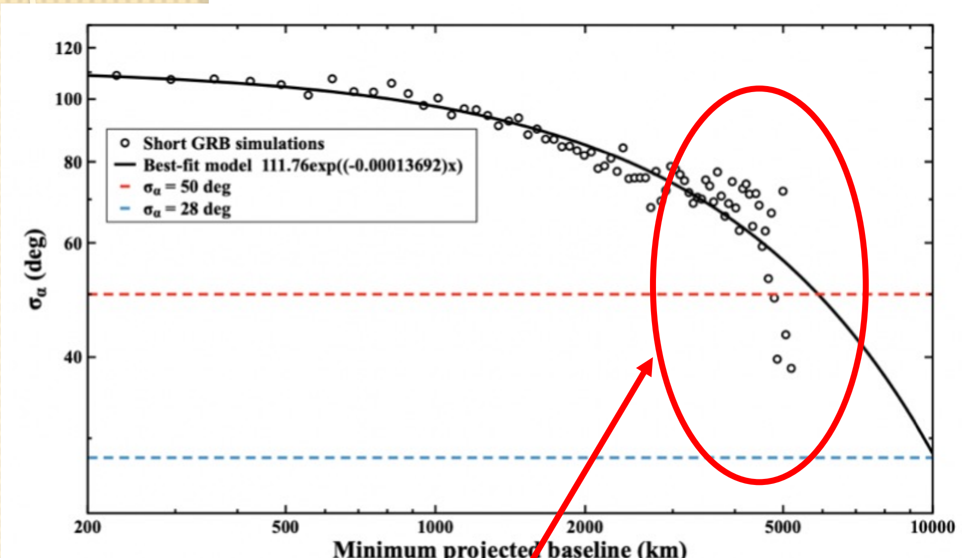
Localisation

Vs

Satellite baseline

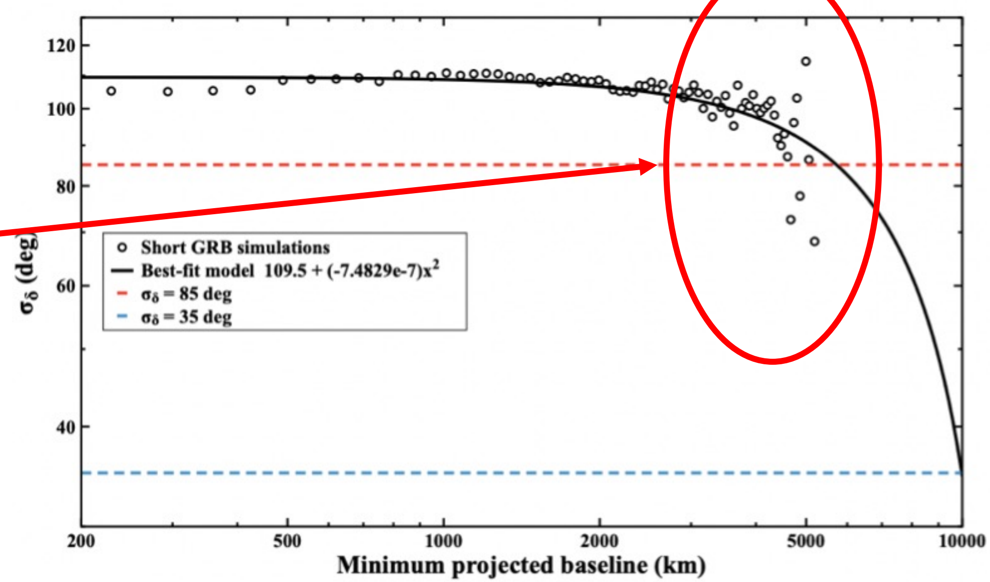


GRB localisation: results short GRBs

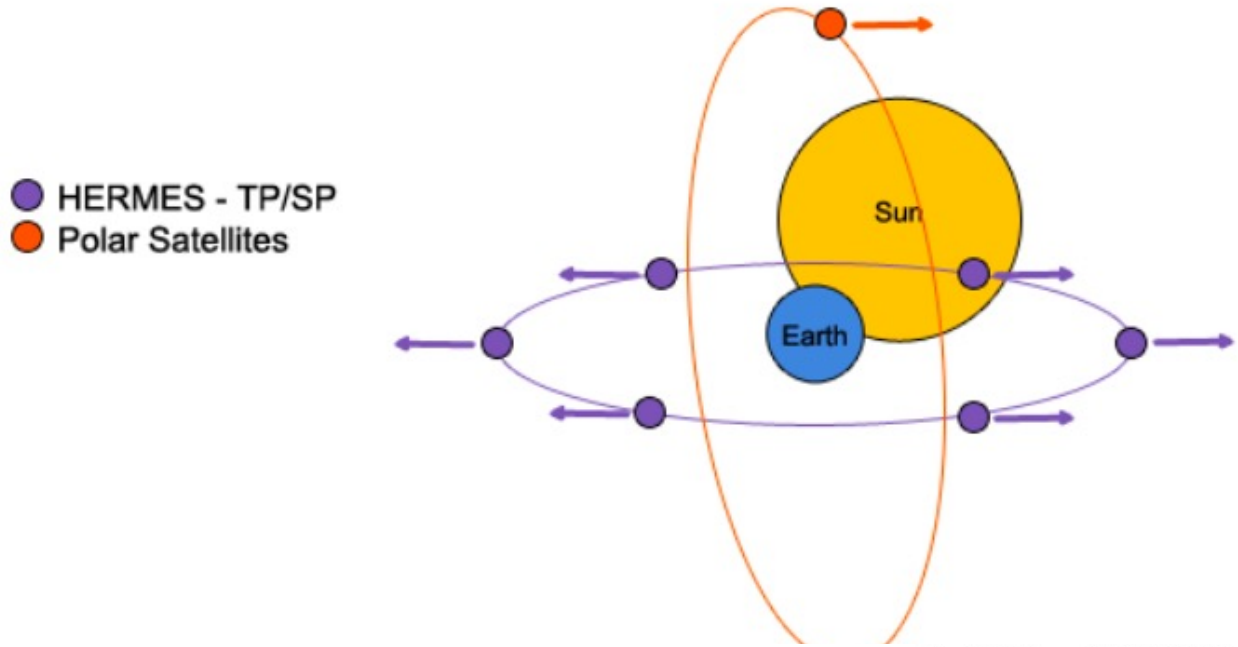


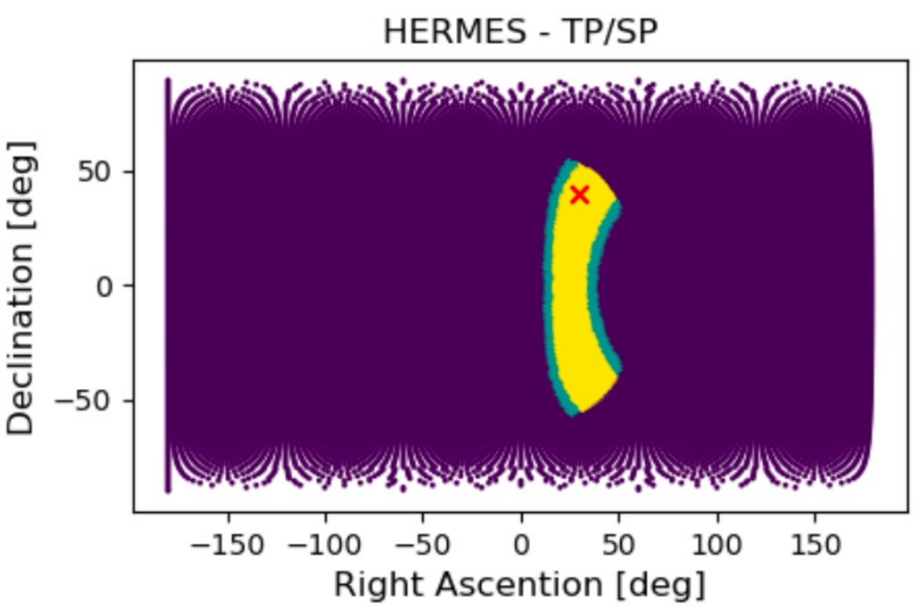
Localisation
Vs
Satellite baseline

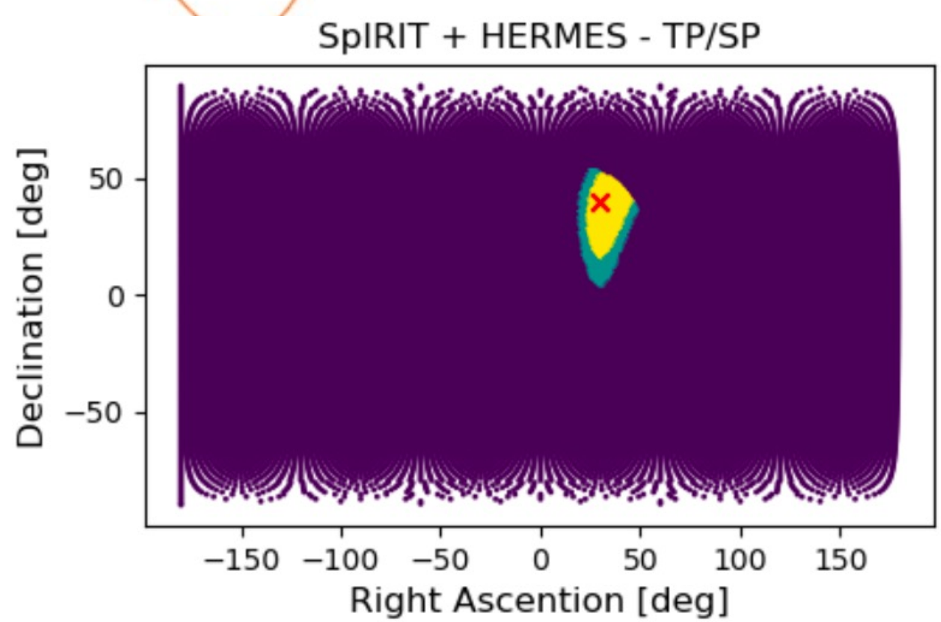
Poor
Statistics?



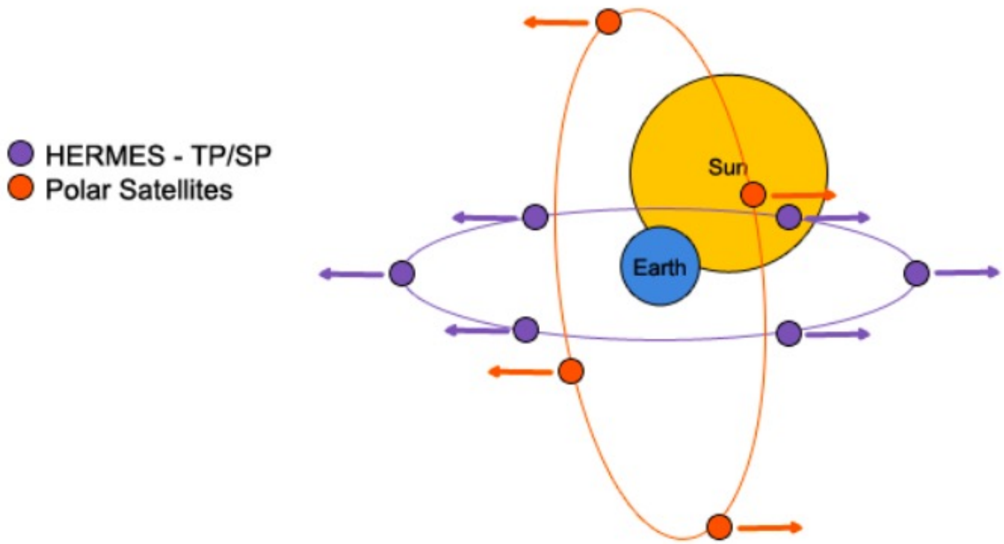
GRB localisation: HERMES + SpIRIT

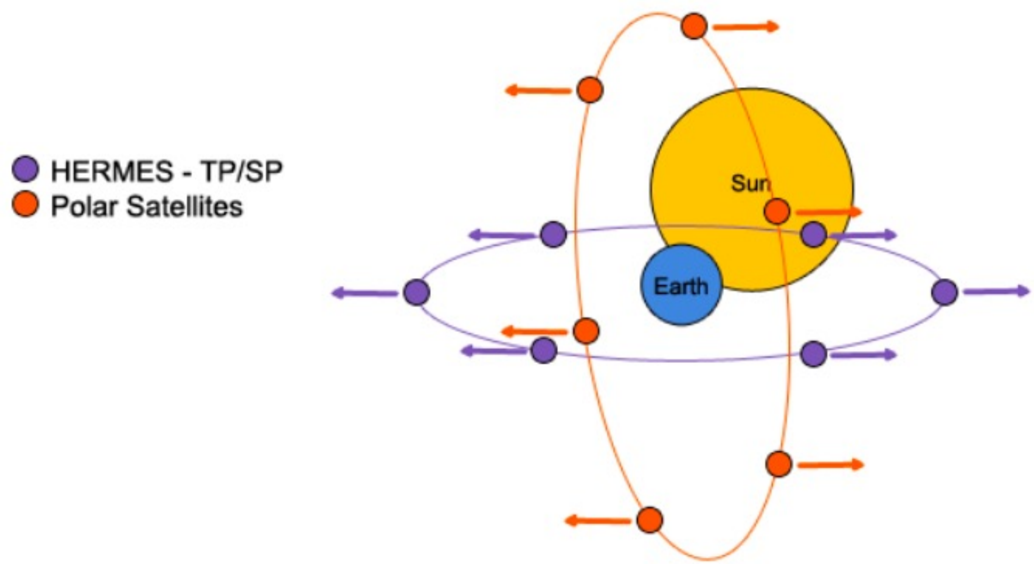




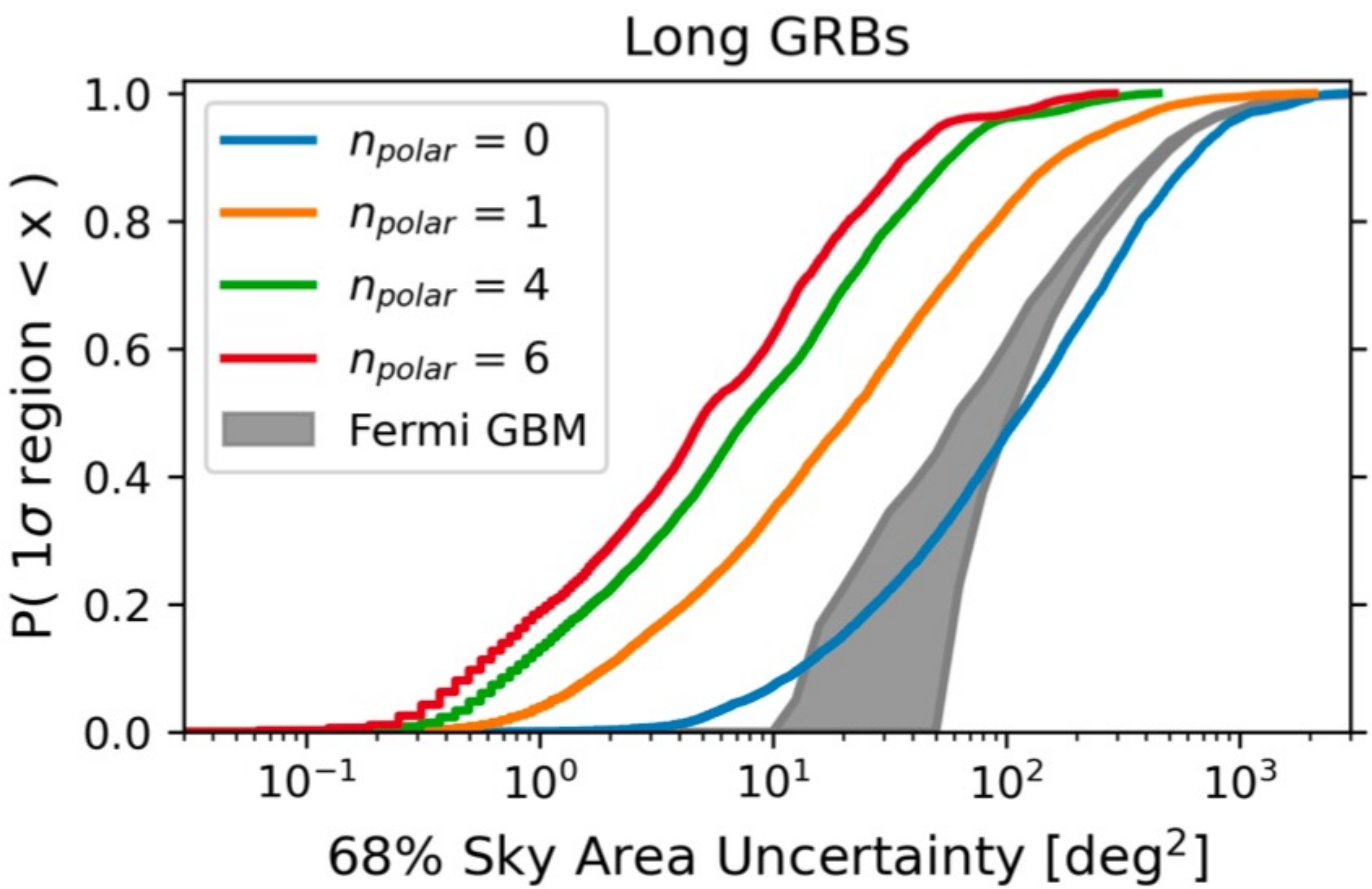


GRB localisation: HERMES + SpIRIT

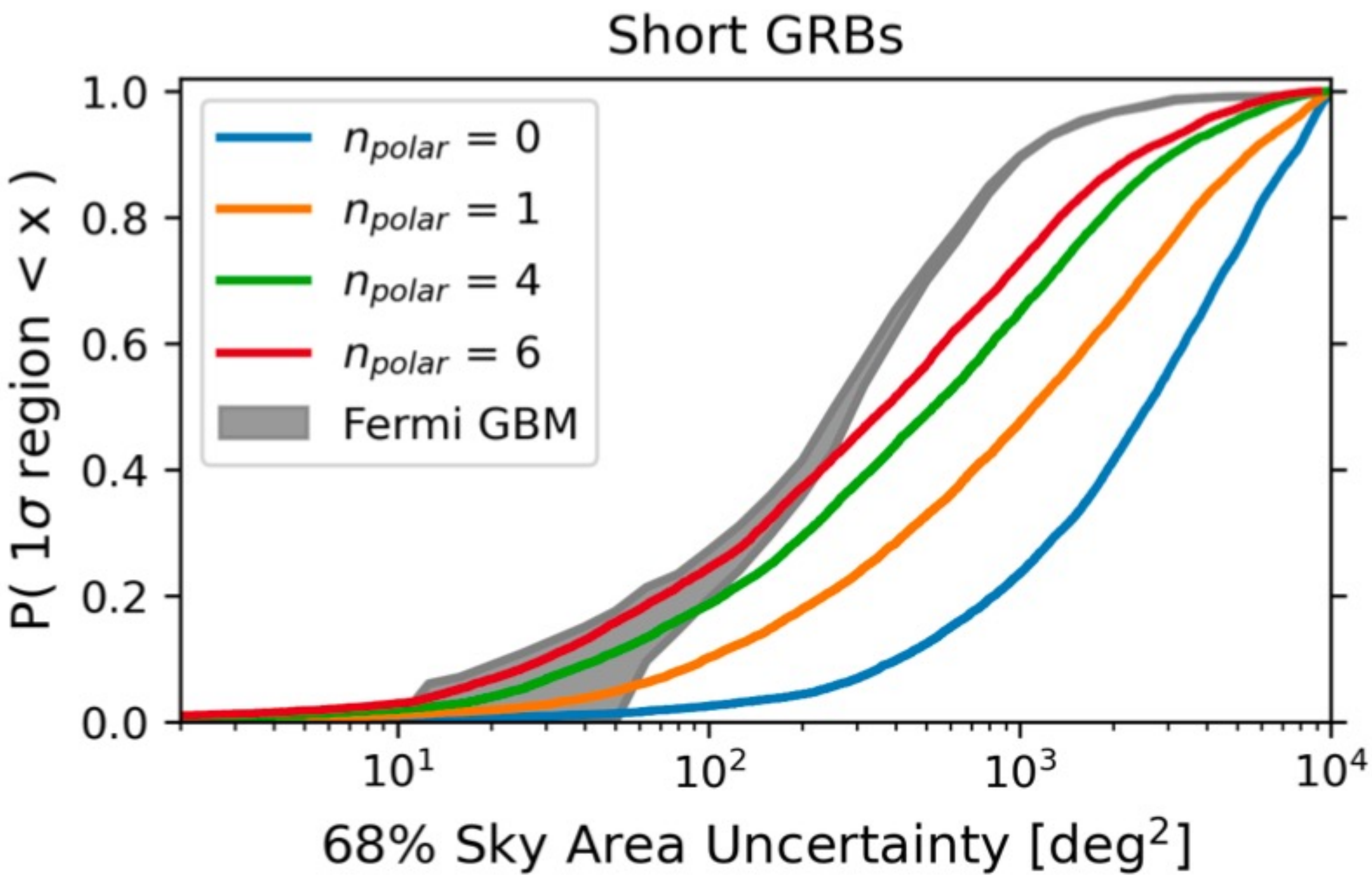




GRB localisation: HERMES + SpIRIT



GRB localisation: HERMES + SpIRIT

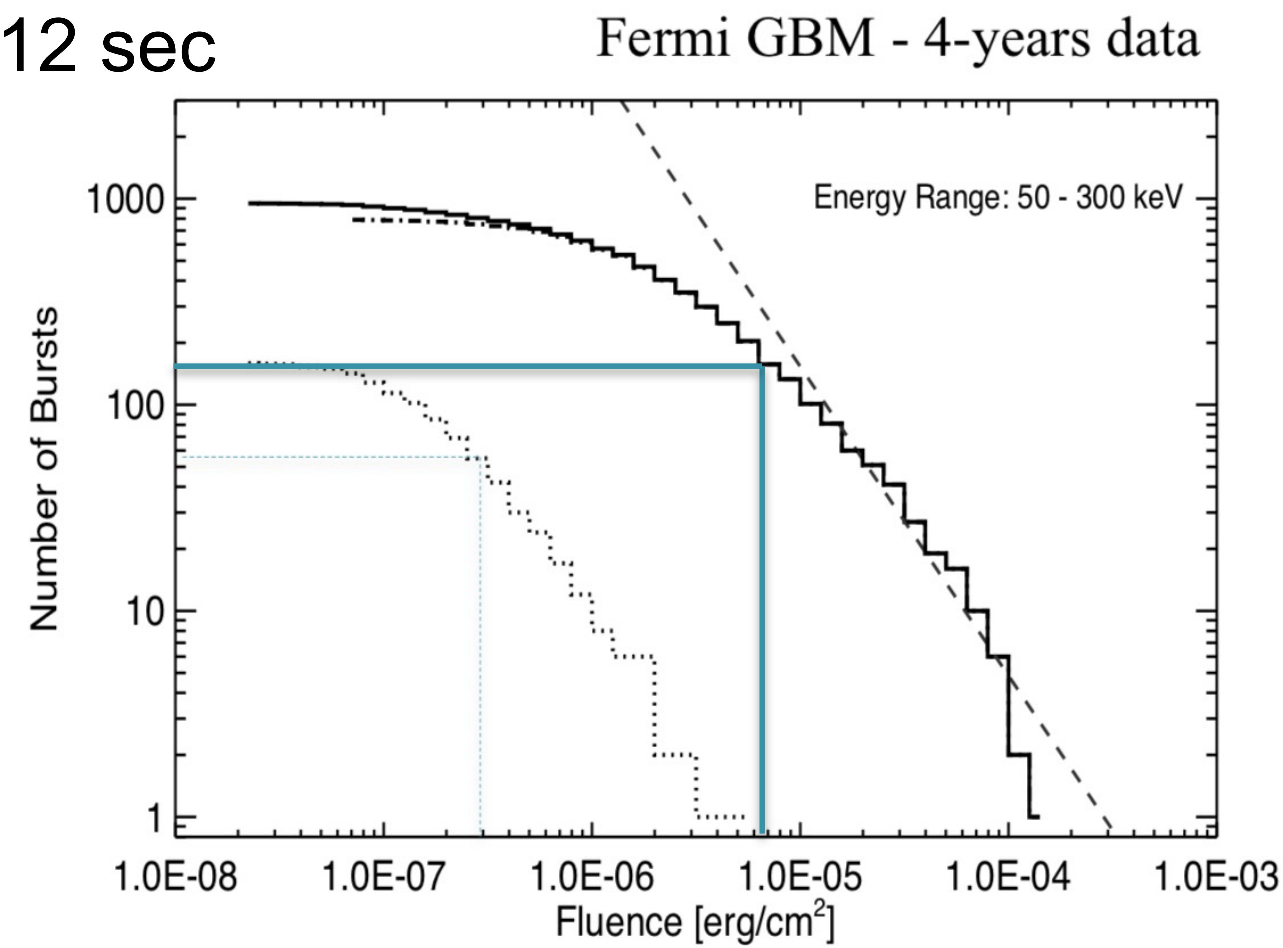


GRB localisation: more realistic

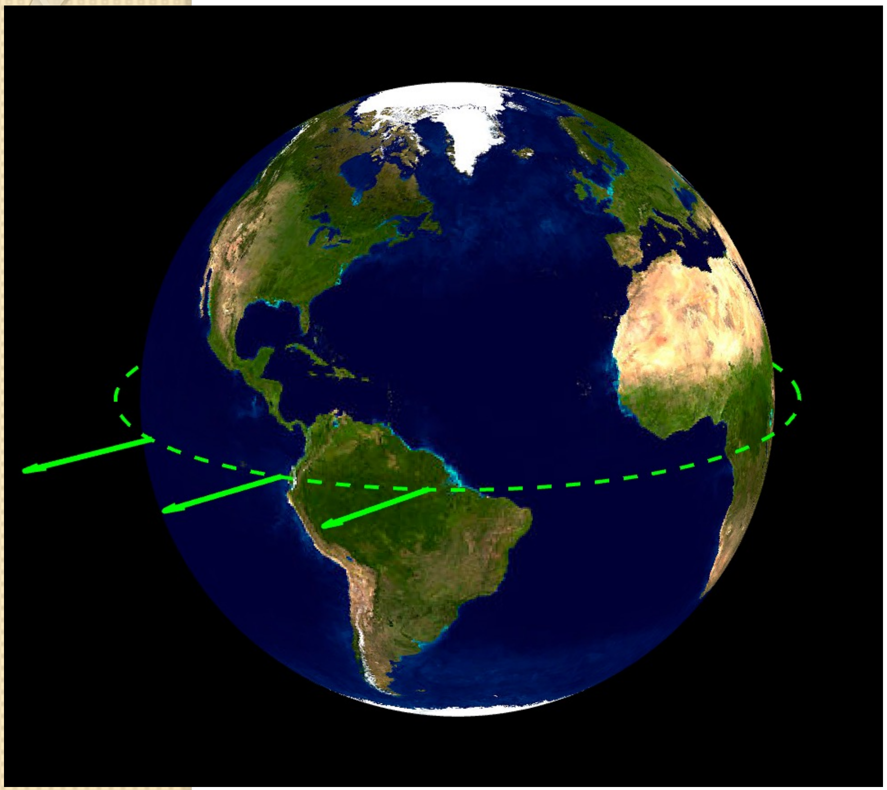
<u>*GRB localisation – investigating mission scenarios:*</u>

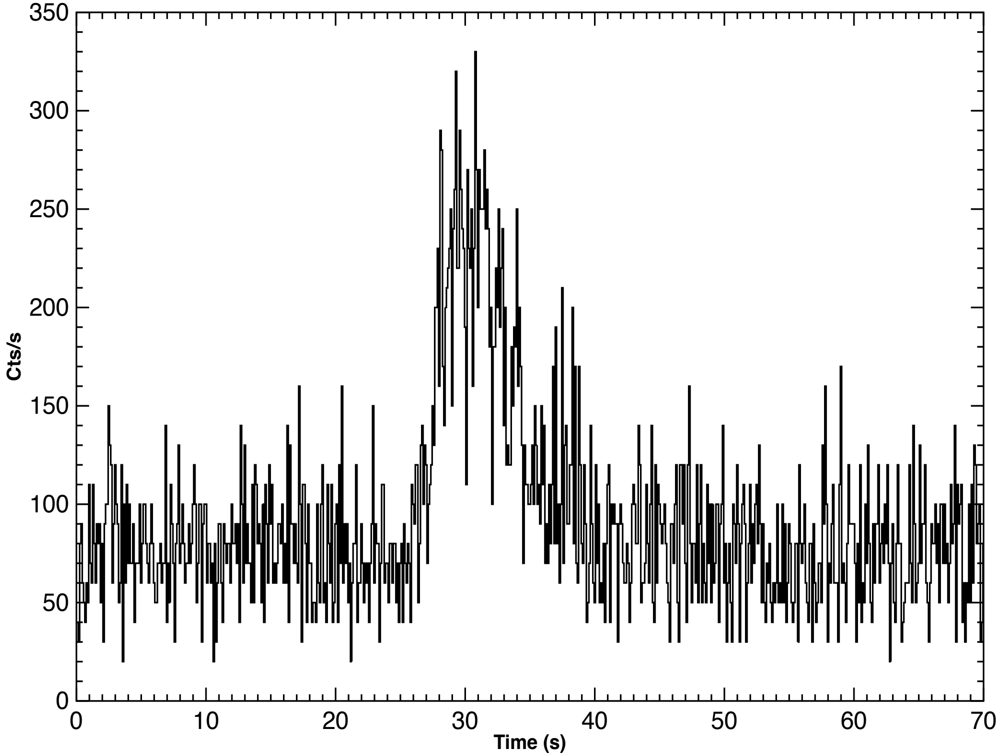
LONG GRB: GRB090820027

T90 ~ 12 sec

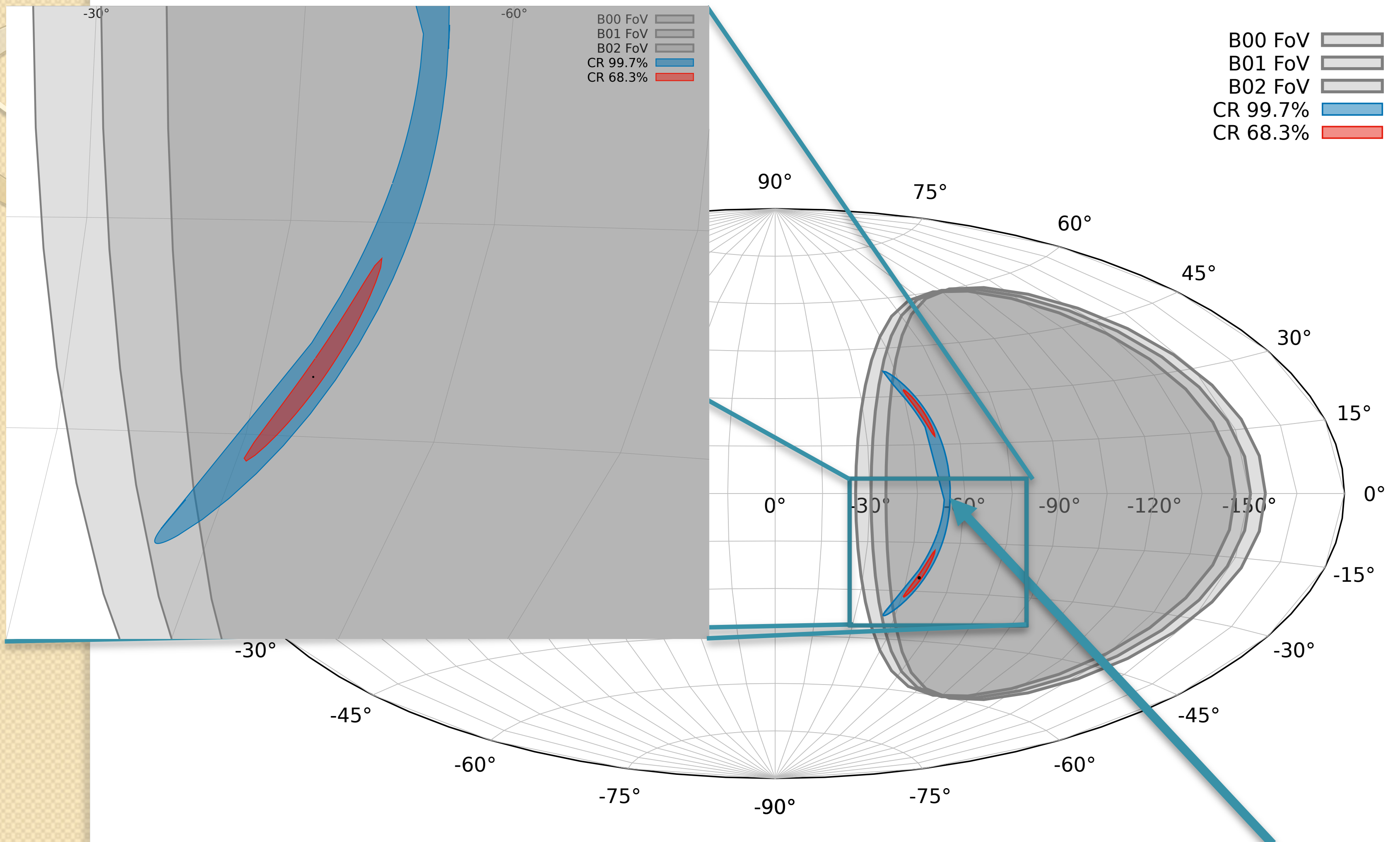


GRB localisation: more realistic



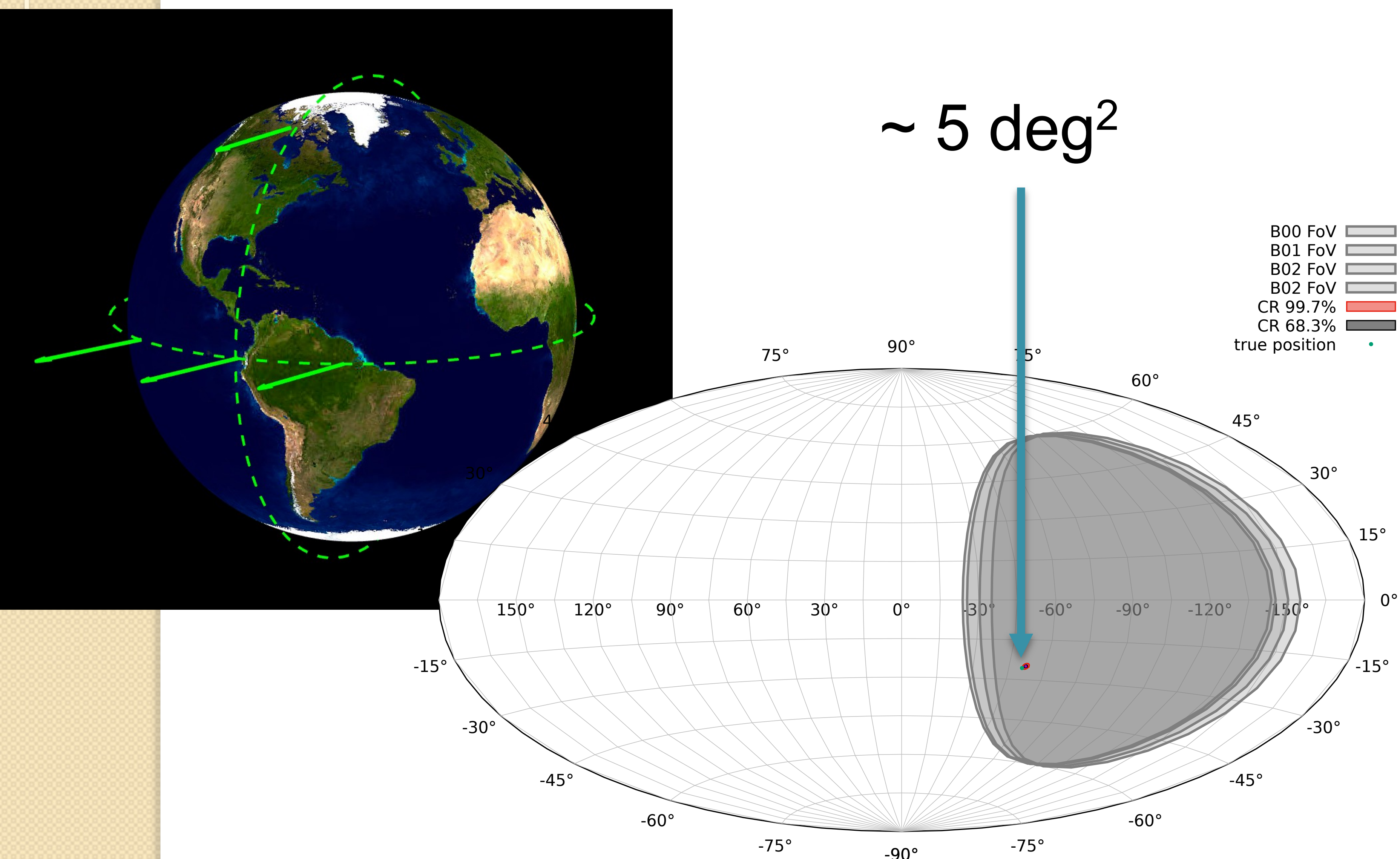


GRB localisation: more realistic



~ 275 deg^2

GRB localisation: more realistic

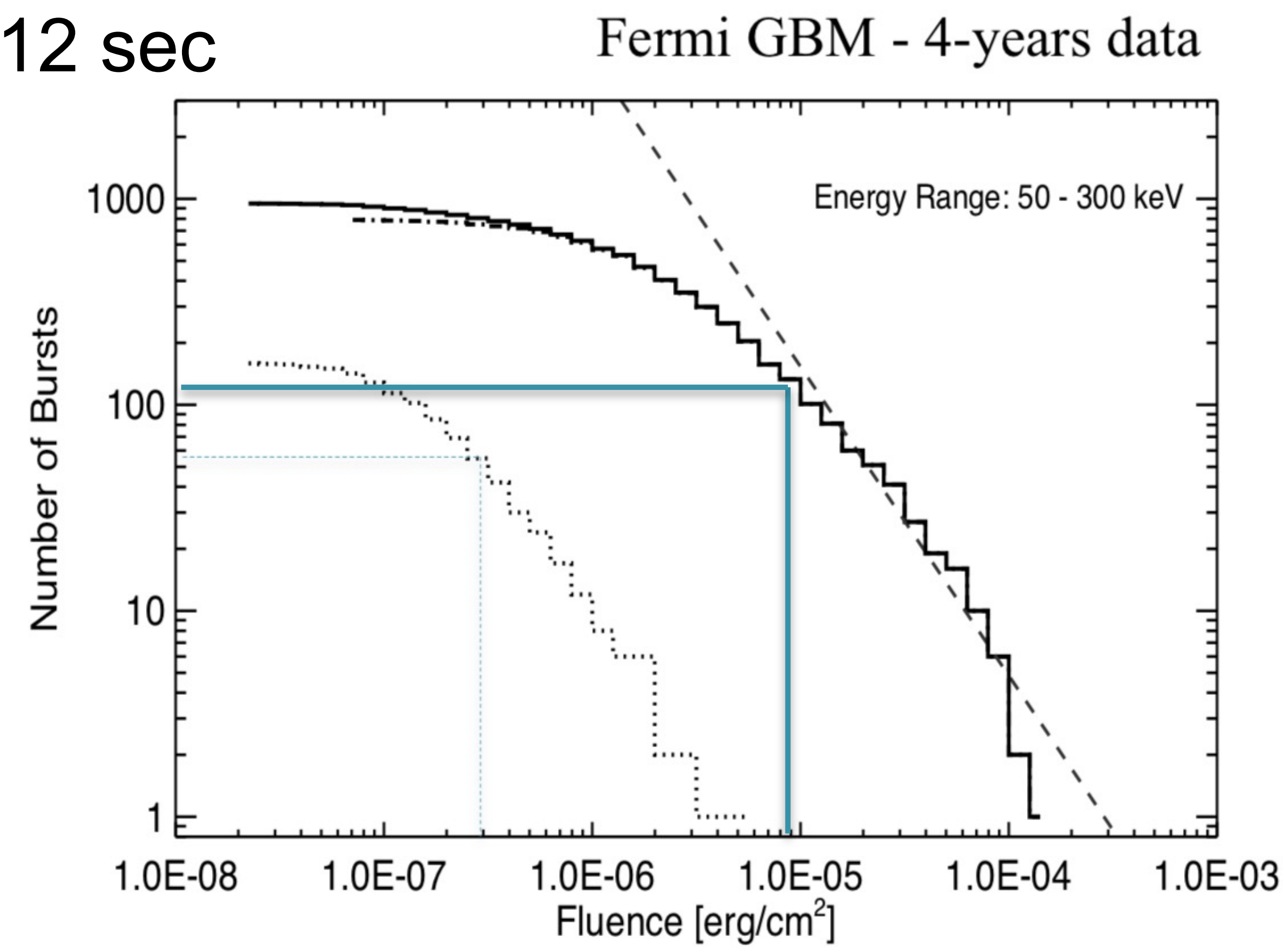


GRB localisation: more realistic

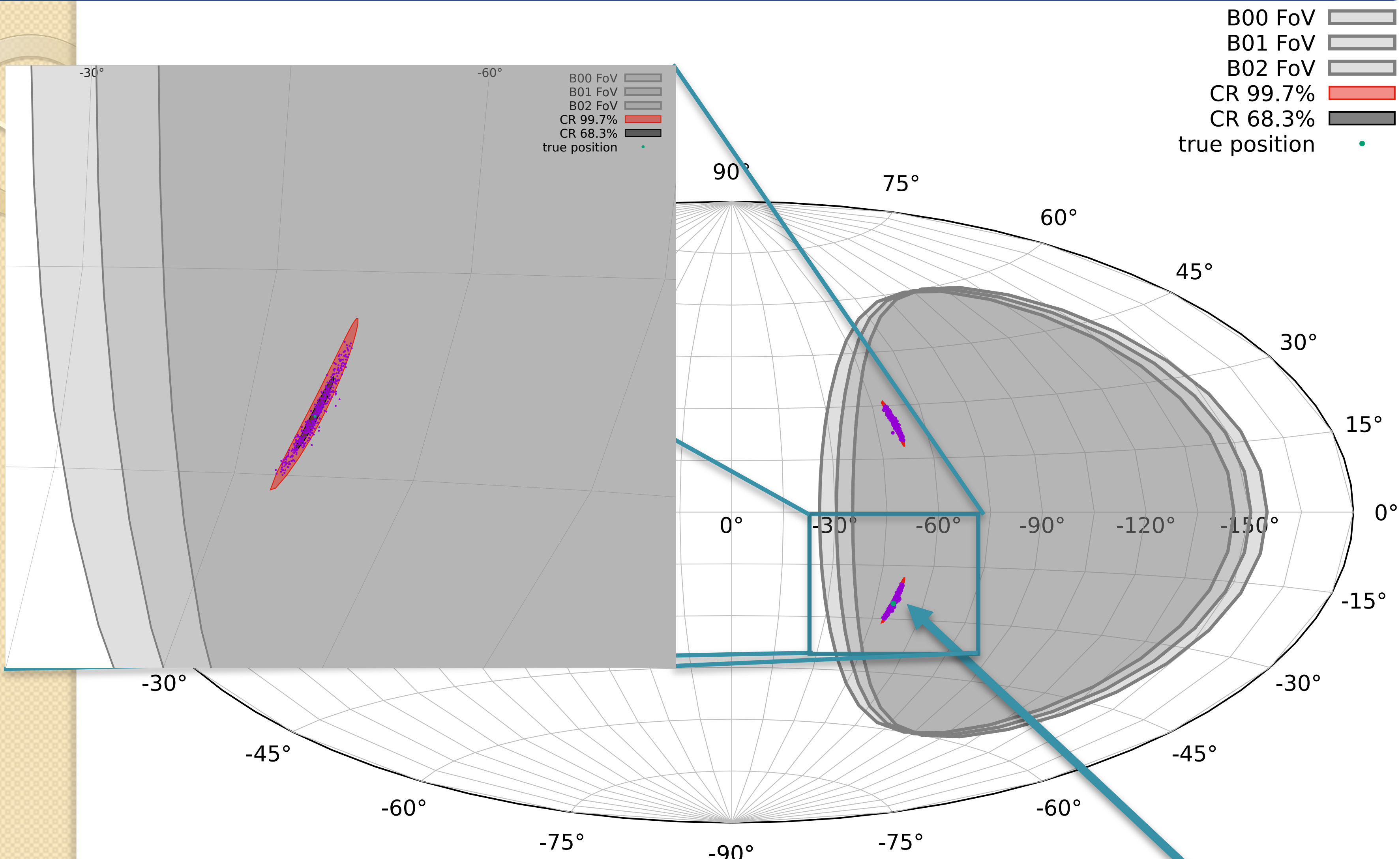
<u>*GRB localisation – investigating mission scenarios:*</u>

LONG GRB: GRB090820027

T90 ~ 12 sec

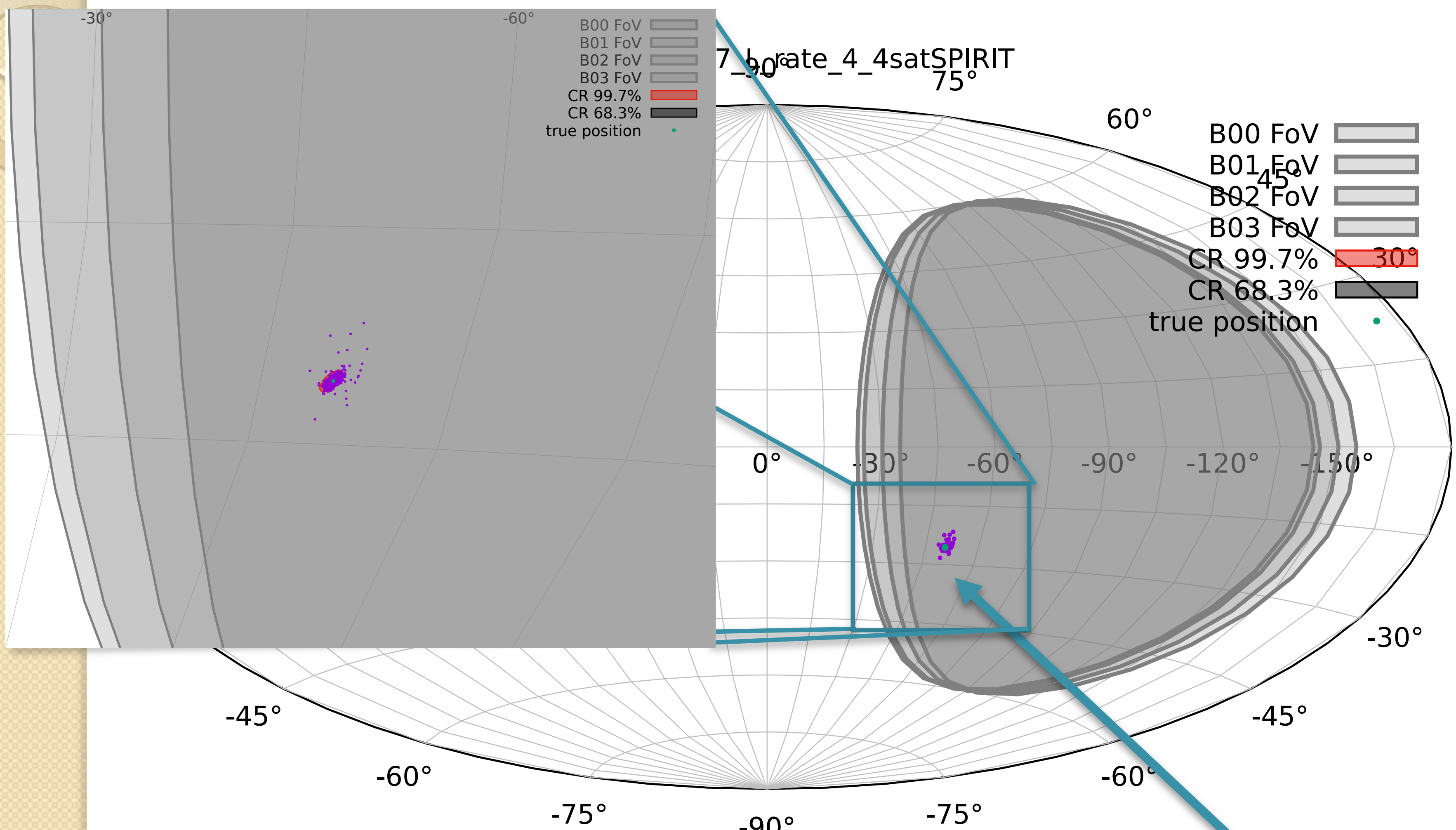


GRB localisation: more realistic



~ 24 deg^2

GRB localisation: more realistic



~ 1.4 deg^2

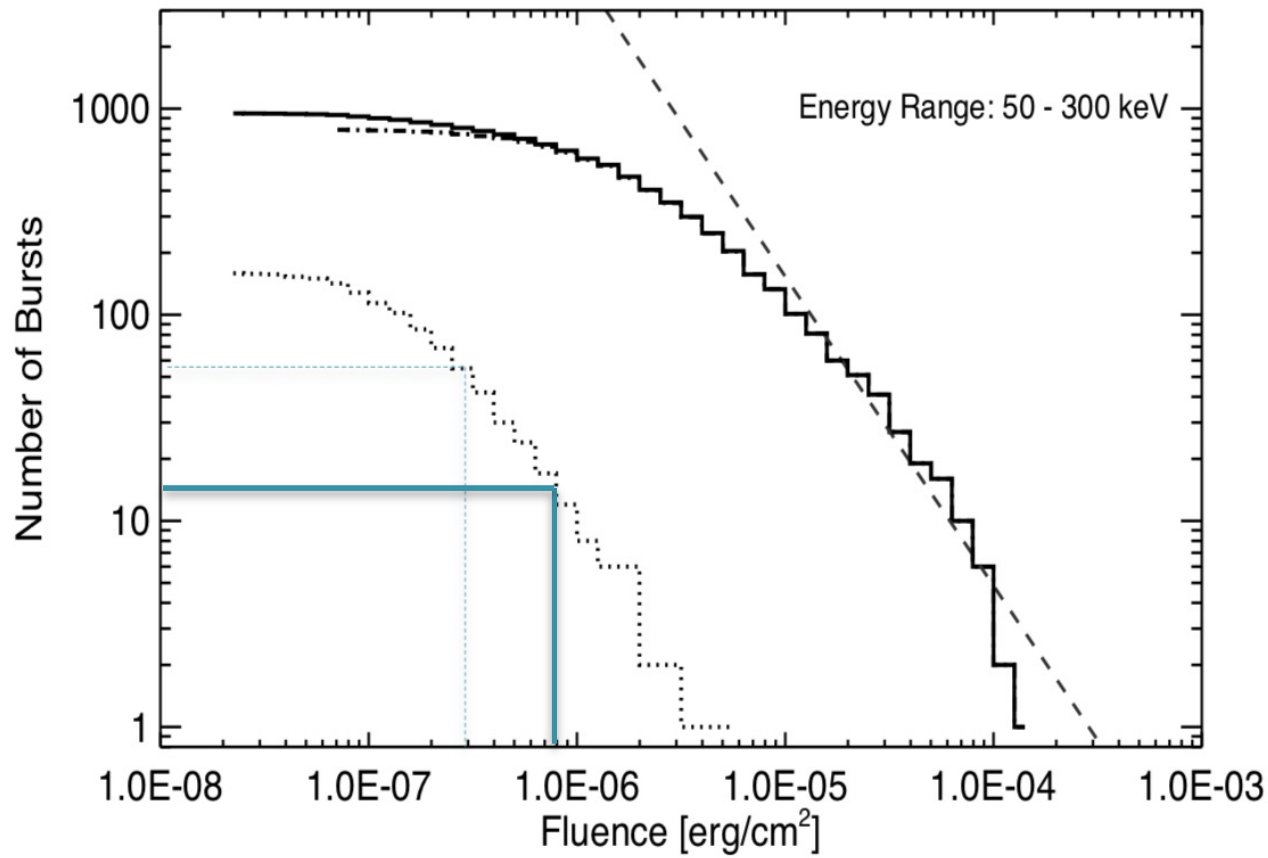
GRB localisation: more realistic

GRB localisation – investigating mission scenarios:

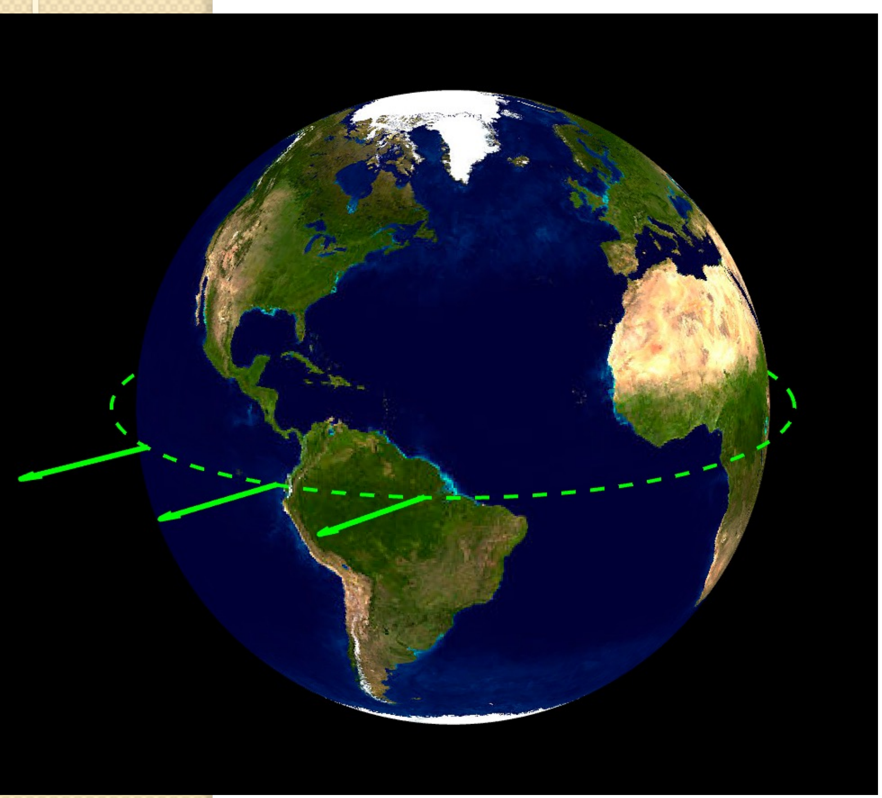
SHORT GRB: GRB090820027

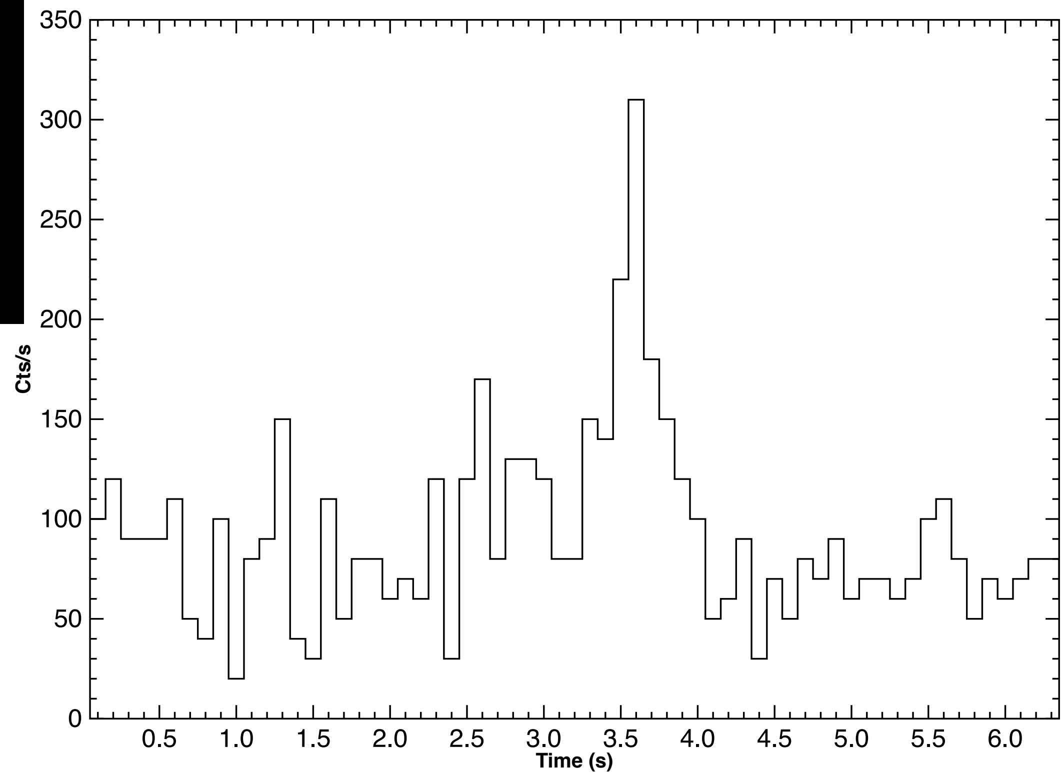
T90 ~ 0.5 sec

Fermi GBM - 4-years data

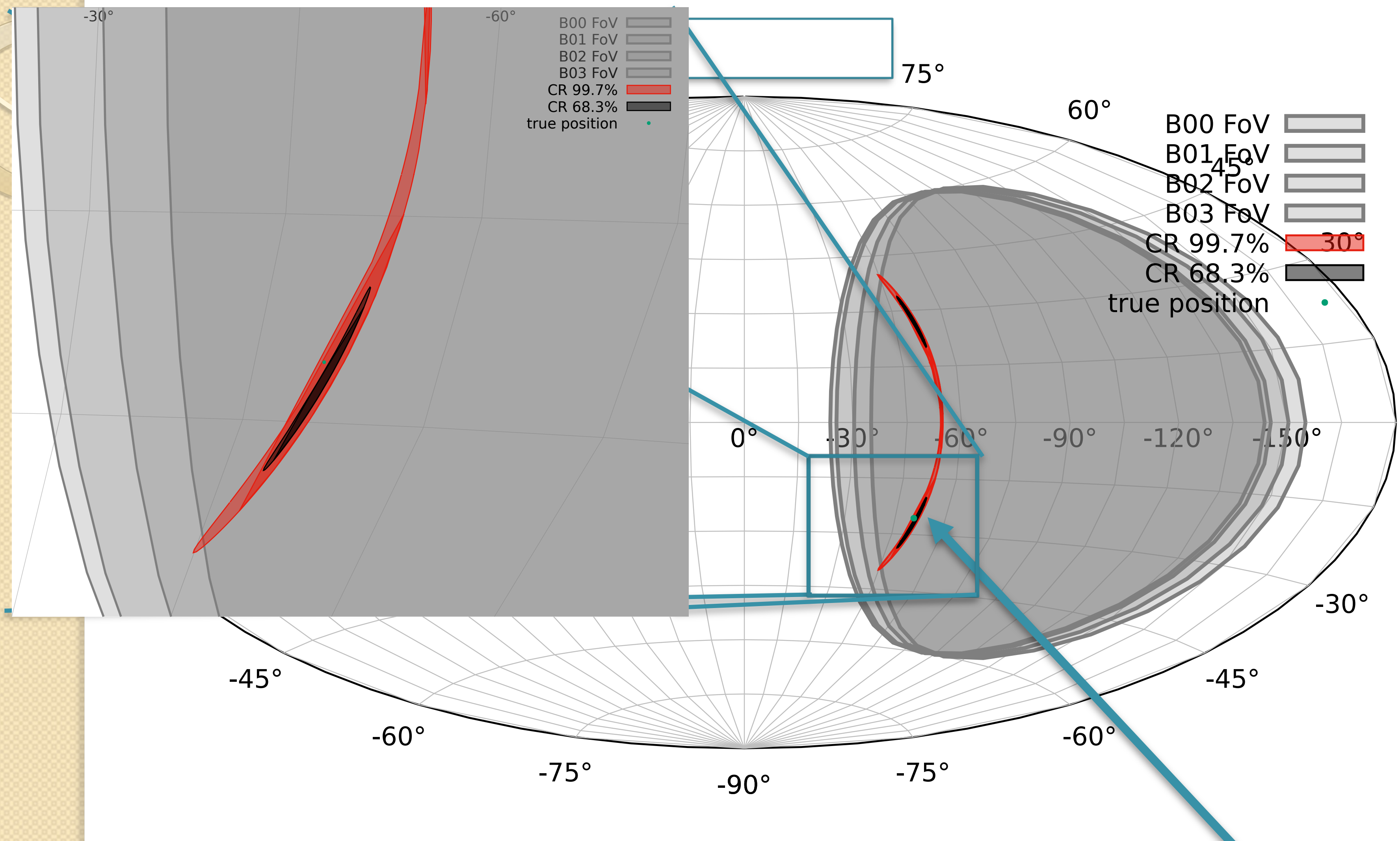


GRB localisation: more realistic



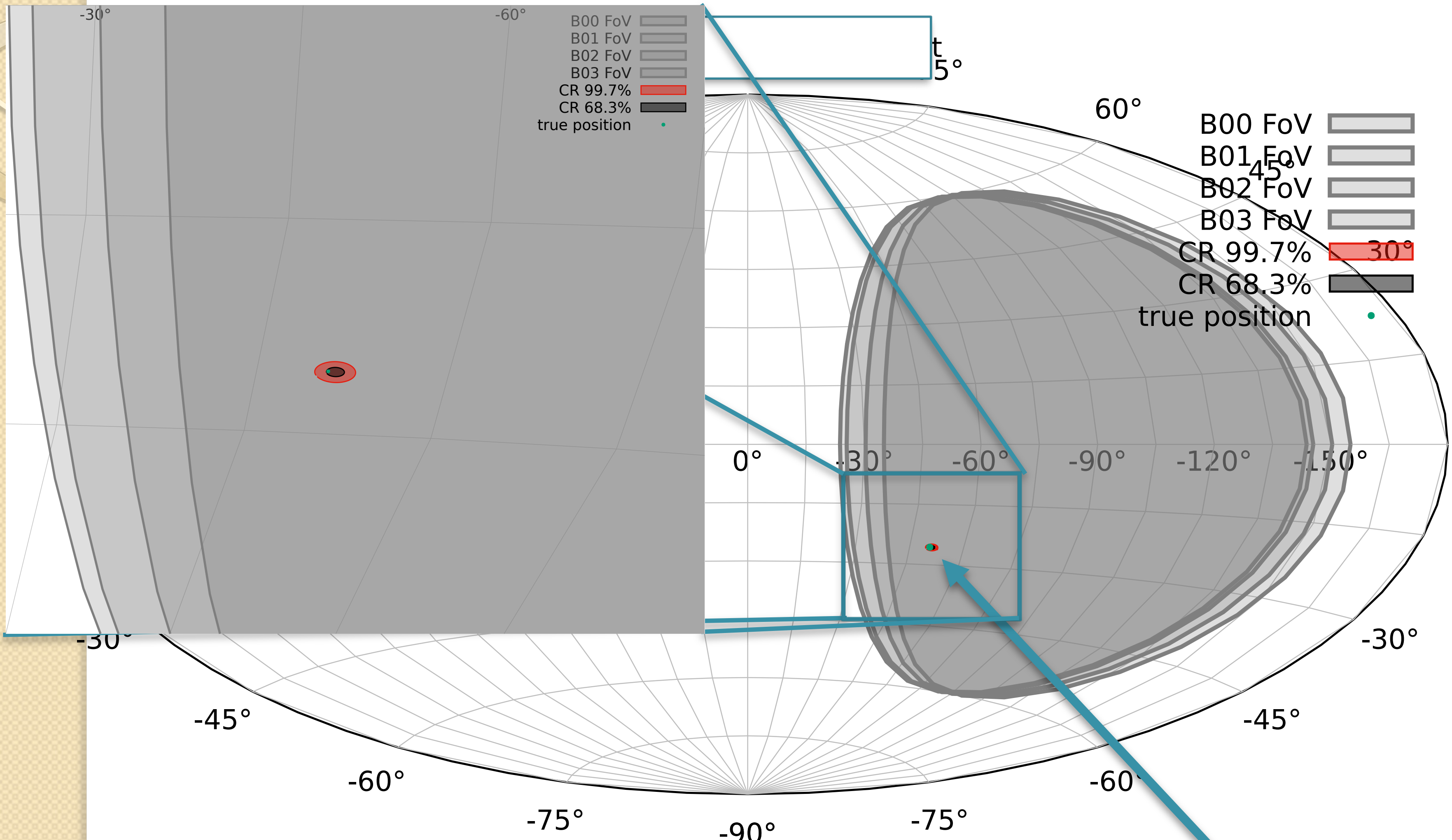


GRB localisation: more realistic

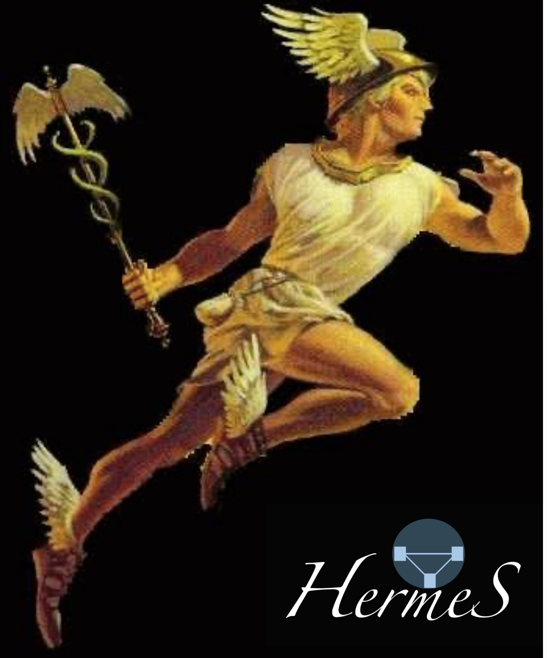


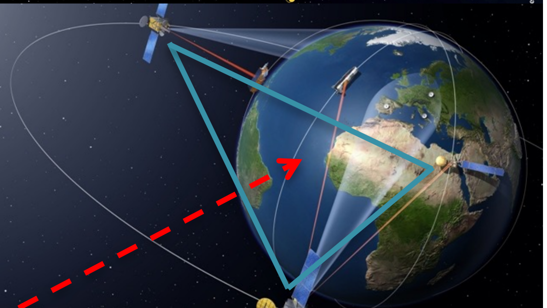
~ 140 deg^2

GRB localisation: more realistic



~ 3.2 deg^2





The HERMES project: the movie

Visit here to join to HERMES Science Team:
https://www.hermes-sp.eu/?page_id=3643#ScienceTeam

Thanks
for your
attention!