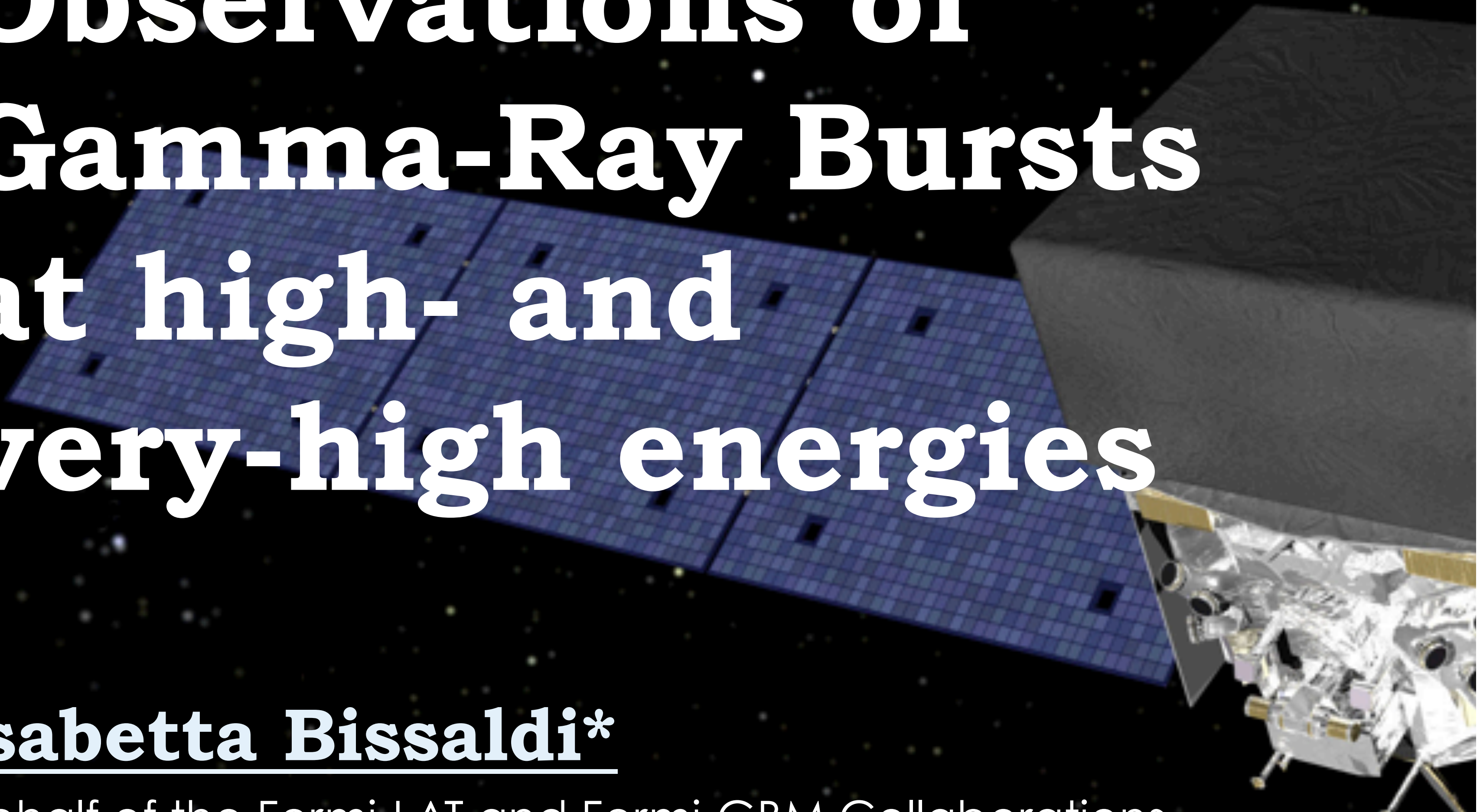
Observations of Gamma-Ray Bursts at high- and very-high energies



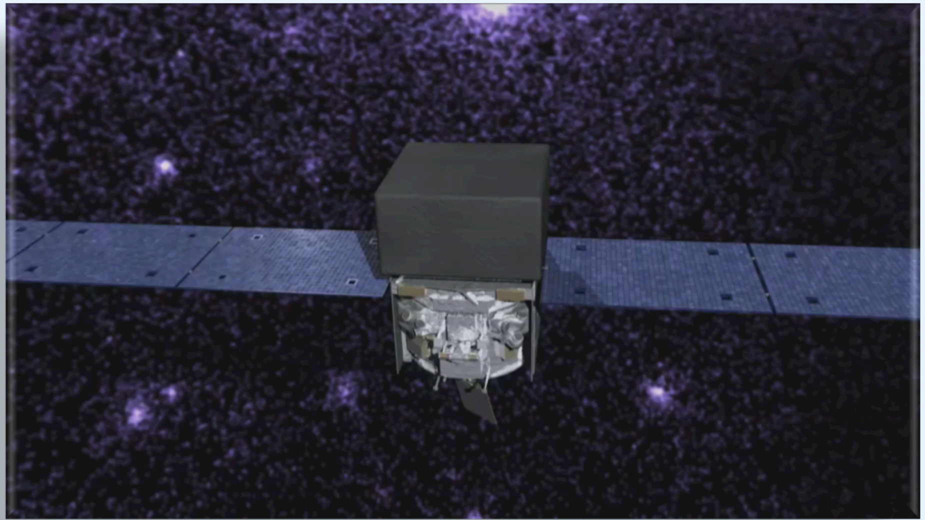
Elisabetta Bissaldi*

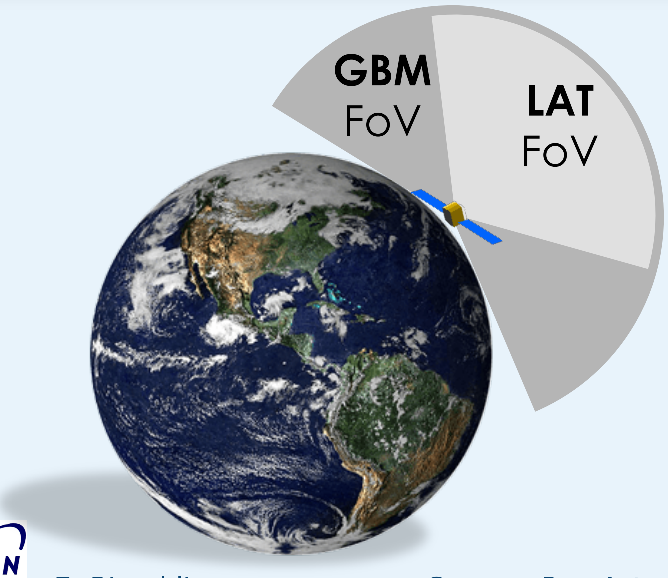
On behalf of the Fermi-LAT and Fermi-GBM Collaborations and for the CTA Consortium

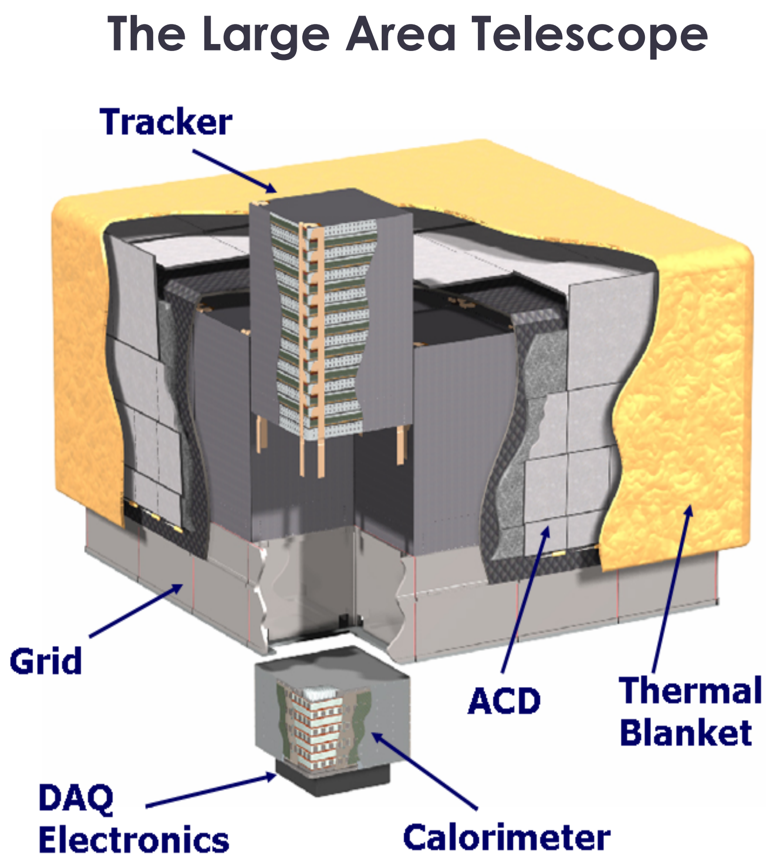
*Politecnico & INFN Bari – **elisabetta.bissaldi@ba.infn.it**

SEXTEN CENTER FOR ASTROPHYSICS

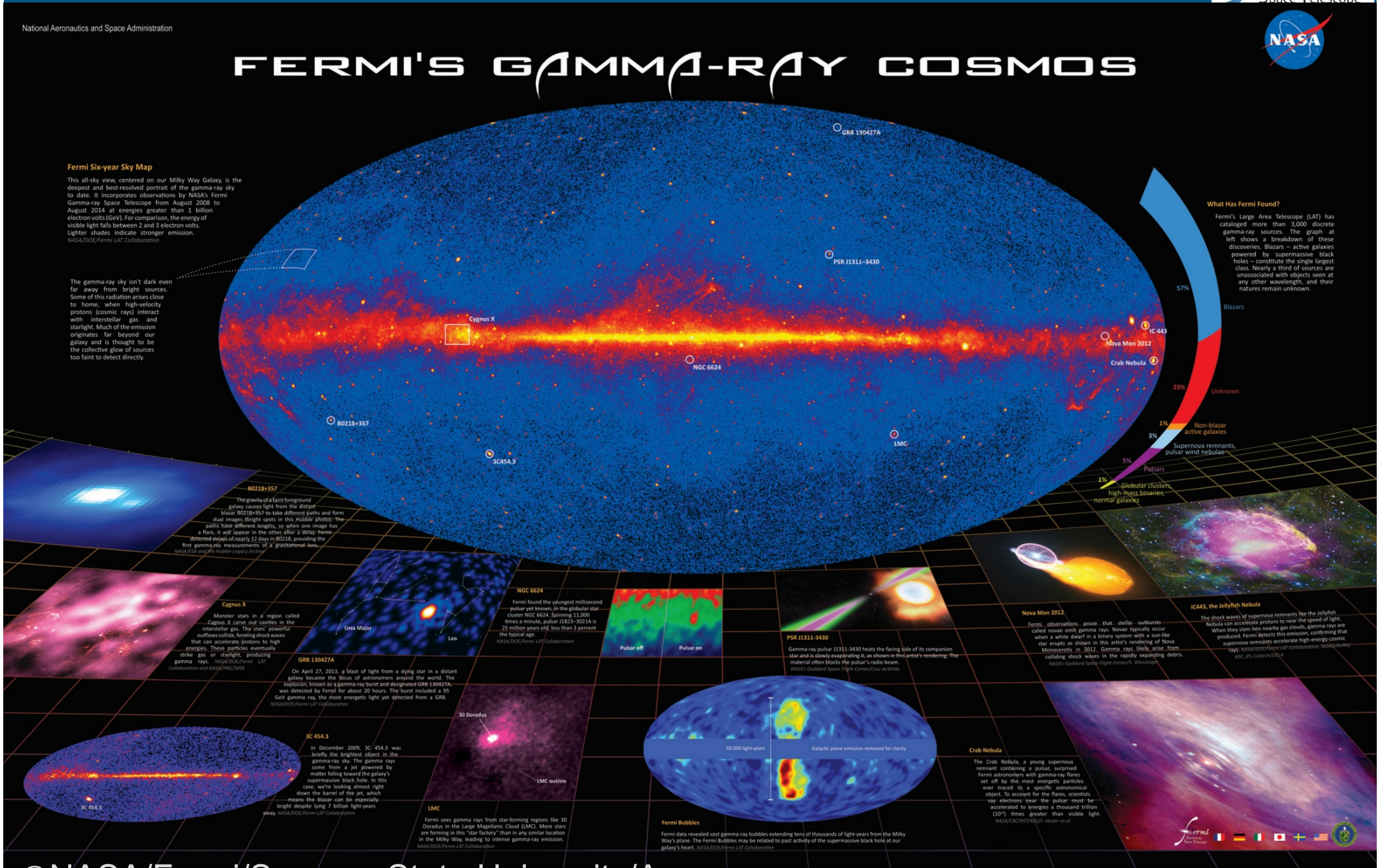
The Fermi Mission







What does LAT see?



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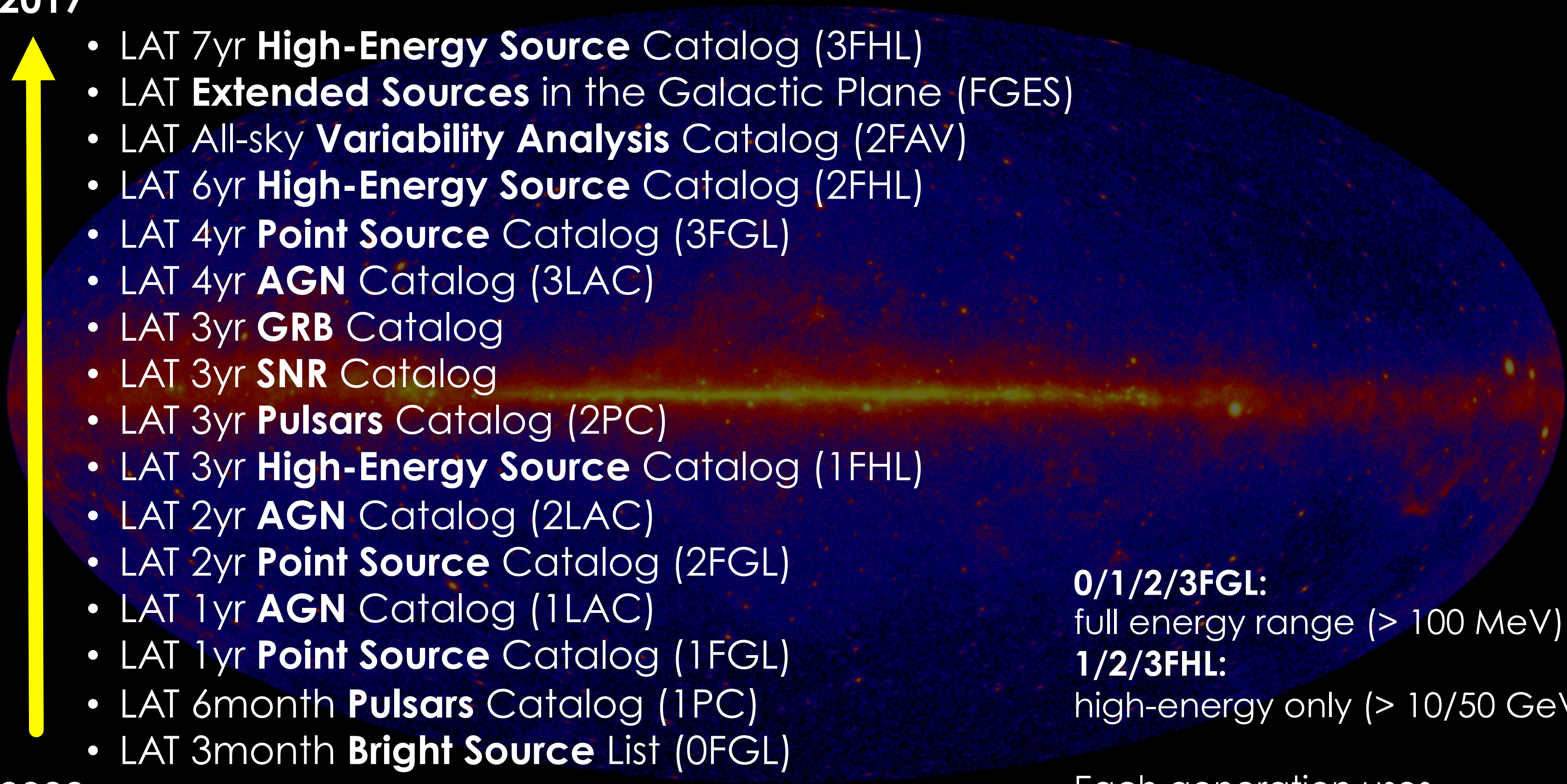
Fermi-LAT catalogs



2017

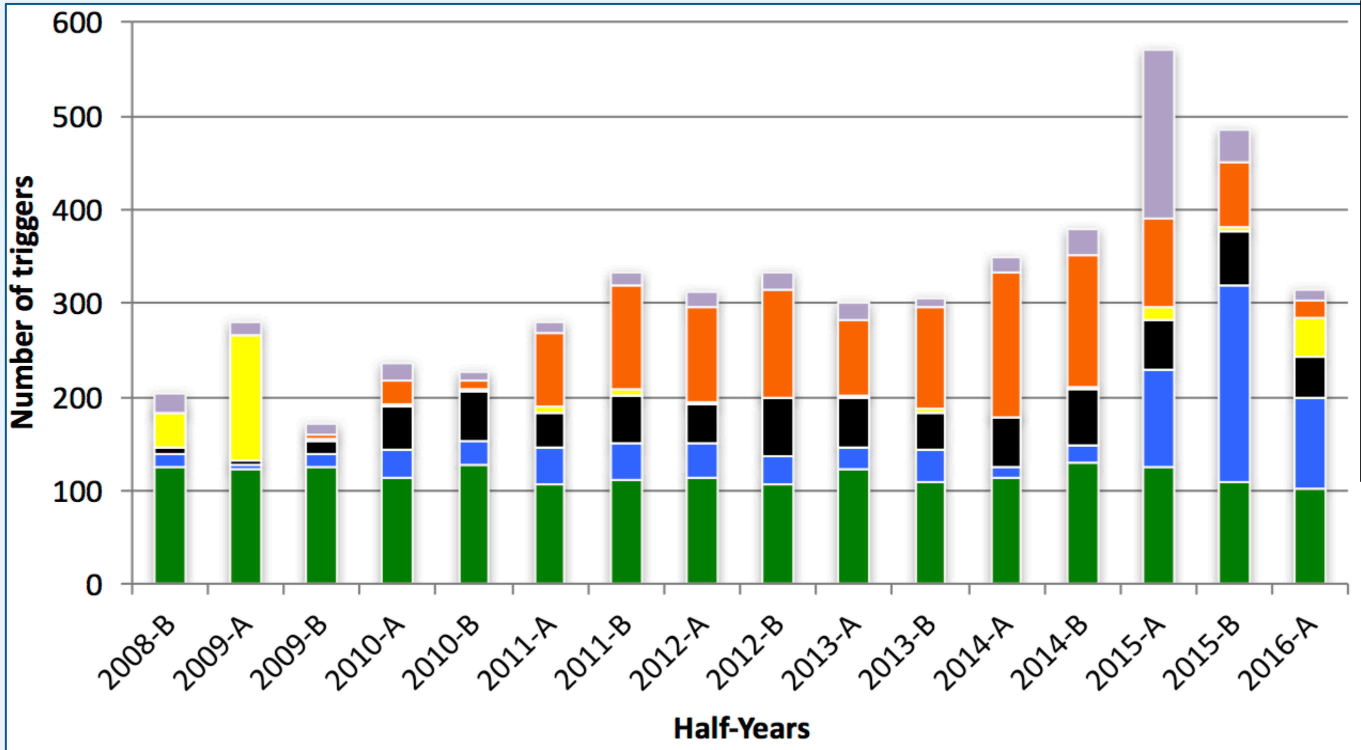
- LAT 7yr **High-Energy Source** Catalog (3FHL)
- LAT **Extended Sources** in the Galactic Plane (FGES)
- LAT All-sky **Variability Analysis** Catalog (2FAV)
- LAT 6yr **High-Energy Source** Catalog (2FHL)
- LAT 4yr **Point Source** Catalog (3FGL)
- LAT 4yr **AGN** Catalog (3LAC)
- LAT 3yr **GRB** Catalog
- LAT 3yr **SNR** Catalog
- LAT 3yr **Pulsars** Catalog (2PC)
- LAT 3yr **High-Energy Source** Catalog (1FHL)
- LAT 2yr **AGN** Catalog (2LAC)
- LAT 2yr **Point Source** Catalog (2FGL)
- LAT 1yr **AGN** Catalog (1LAC)
- LAT 1yr **Point Source** Catalog (1FGL)
- LAT 6month **Pulsars** Catalog (1PC)
- LAT 3month **Bright Source** List (0FGL)

2008

0/1/2/3FGL:
full energy range (> 100 MeV)
1/2/3FHL:
high-energy only (> 10/50 GeV)

Each generation uses
improved data/calibration:
P6 → P7 → P7Rep → P8

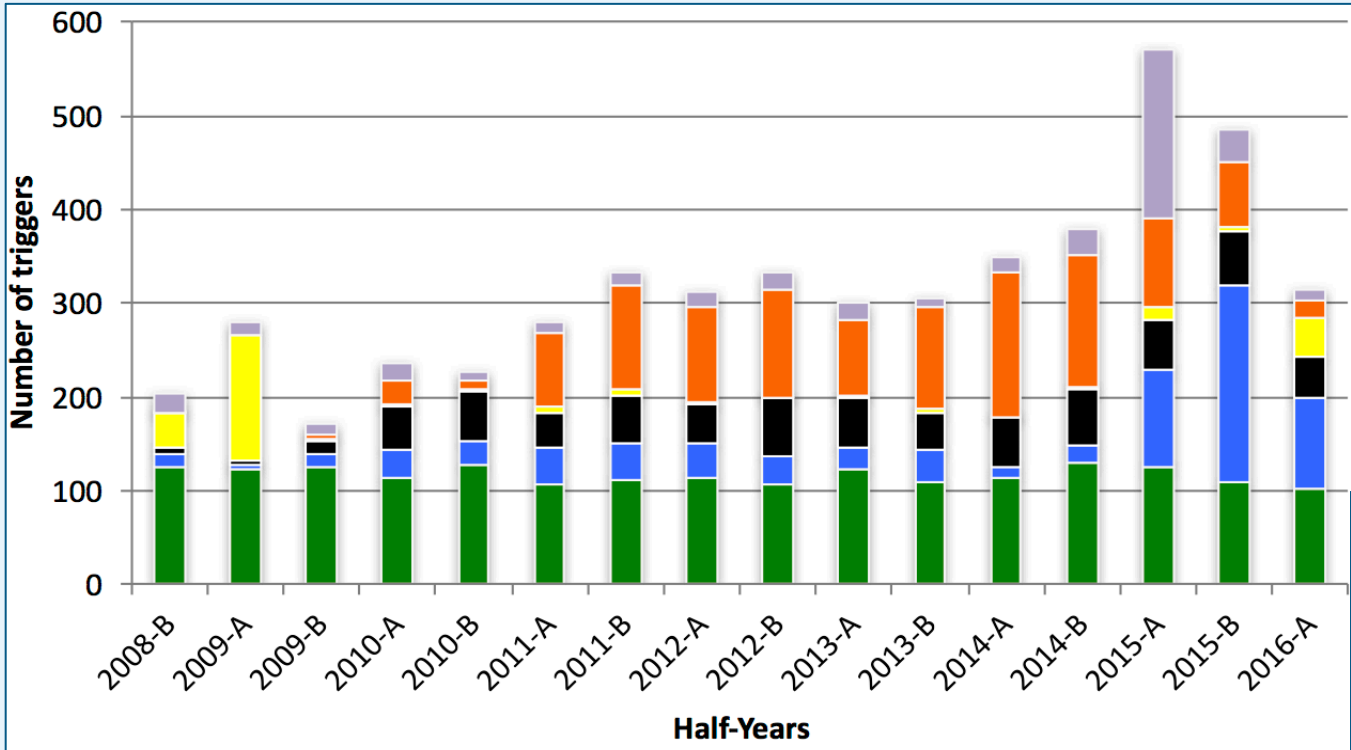
What does GBM see?



Fermi-GBM 8-year trigger statistics ©Paciesas/Fermi GBM Collaboration

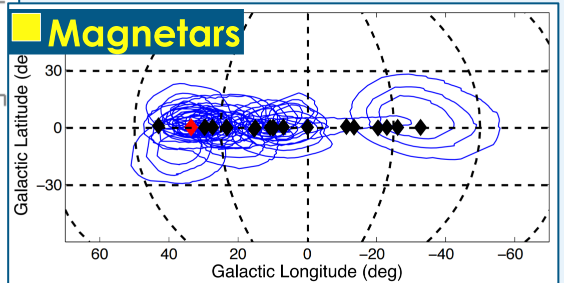
- GRBs: 1879
- Solar Flares: 1121
- TGFs: 690
- SGRs: 267 (from 8 sources)
- Particles: 746
- Others 435 (galactic XRBs, accidental, uncertain)

What does GBM see?

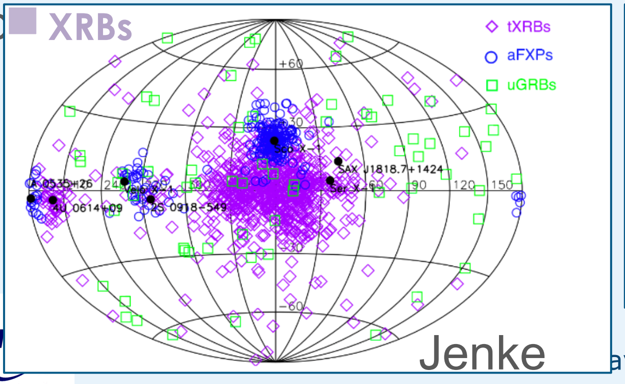


Fermi-GBM 8-year trigger statistics ©Paciesas/Fermi GBM Co

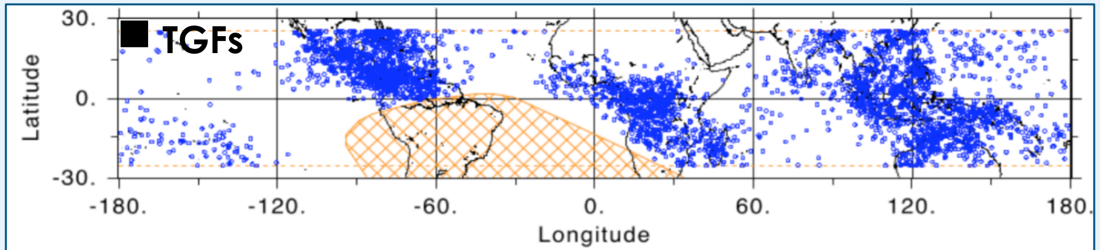
GRBs:	1879
Solar Flares:	1121
TGFs:	690
SGRs:	267
(from 8 sources)	
Particles:	746
Others	435
(galactic XRBs, accidental, uncertain)	



Collazzi

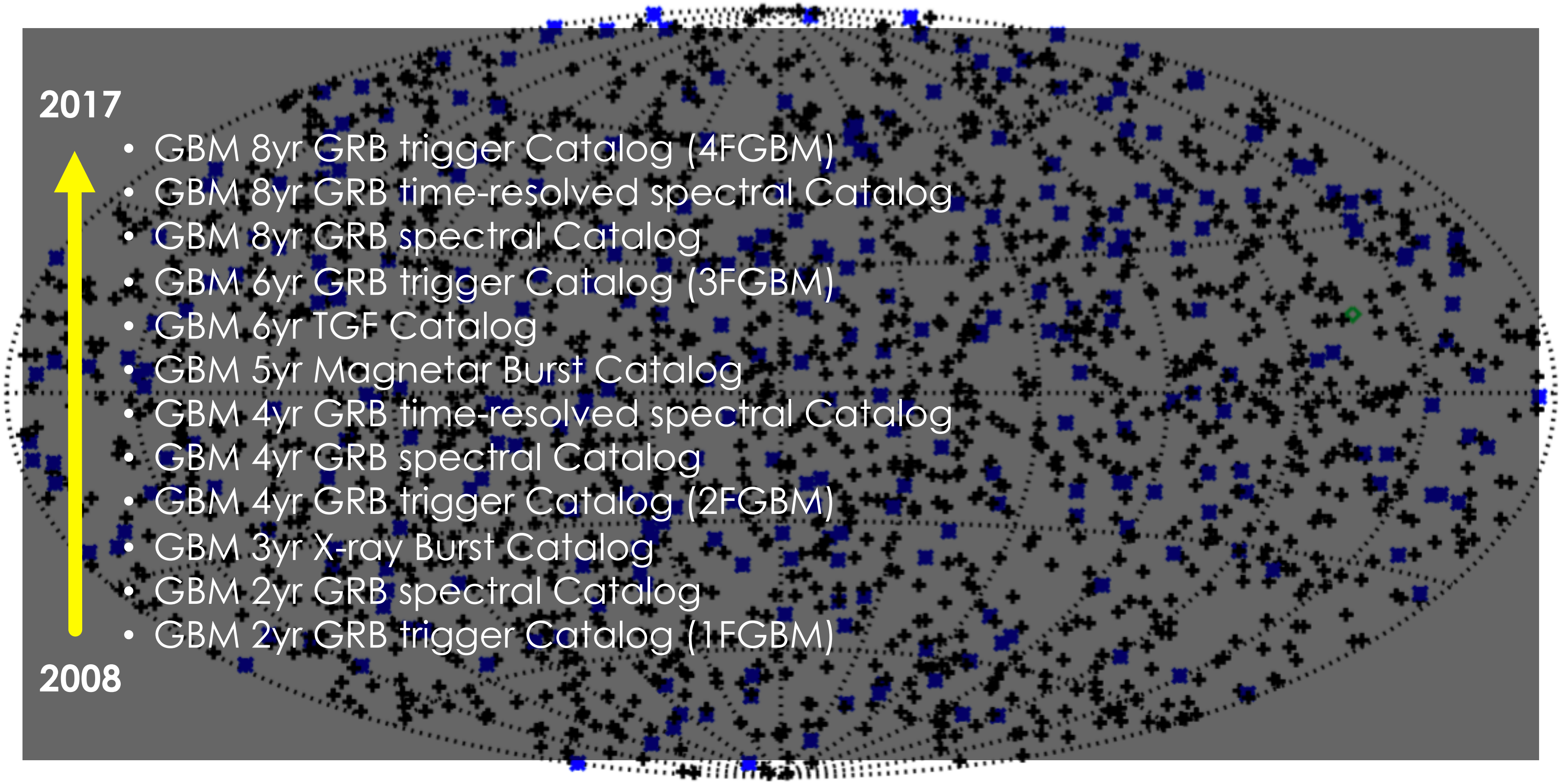


Jenke



Fermi-GBM 7-year TGF Map ©Fitzpatrick/Fermi GBM Collaboration

Fermi-GBM catalogs



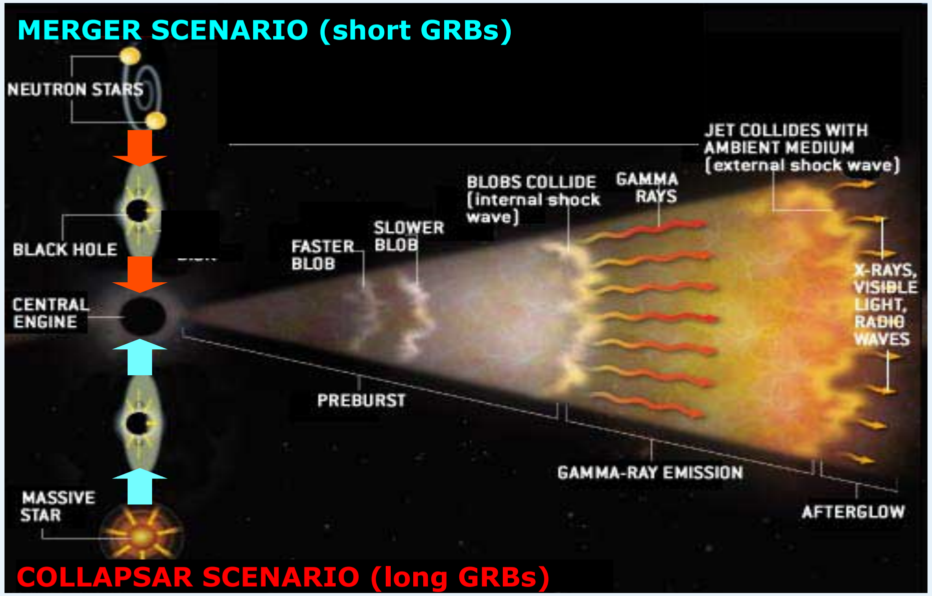
2017

- GBM 8yr GRB trigger Catalog (4FGBM)
- GBM 8yr GRB time-resolved spectral Catalog
- GBM 8yr GRB spectral Catalog
- GBM 6yr GRB trigger Catalog (3FGBM)
- GBM 6yr TGF Catalog
- GBM 5yr Magnetar Burst Catalog
- GBM 4yr GRB time-resolved spectral Catalog
- GBM 4yr GRB spectral Catalog
- GBM 4yr GRB trigger Catalog (2FGBM)
- GBM 3yr X-ray Burst Catalog
- GBM 2yr GRB spectral Catalog
- GBM 2yr GRB trigger Catalog (1FGBM)

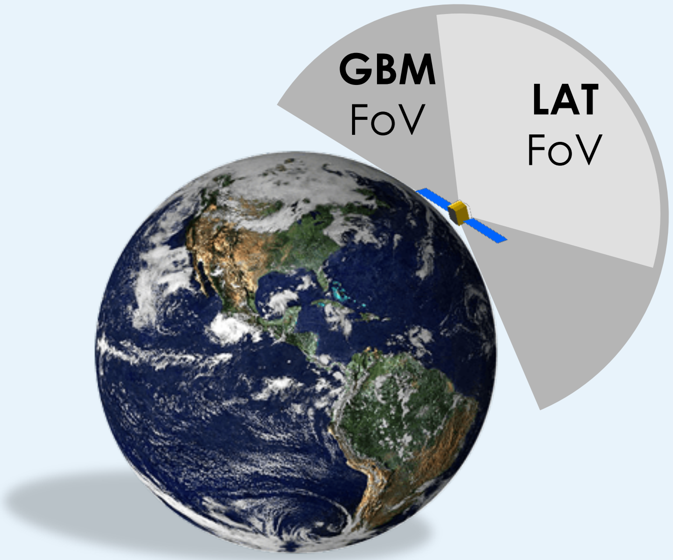
2008

Focusing on GRBs

- **What is the physics behind?**
  - **Prompt**: mechanism, jet properties, central engine (NS or BH?)
  - **Early afterglow**: mechanism (plateau phase), particle acceleration, B field generation
- **Tools to probe the Universe**
  - Cosmological relations
  - Extragalactic background light (deeper than AGN)
  - Intergalactic magnetic fields
- **Tests of UHECR origin, fundamental physics**
  - Search for signatures of:
    - Accelerated hadrons
    - Lorentz invariance violation



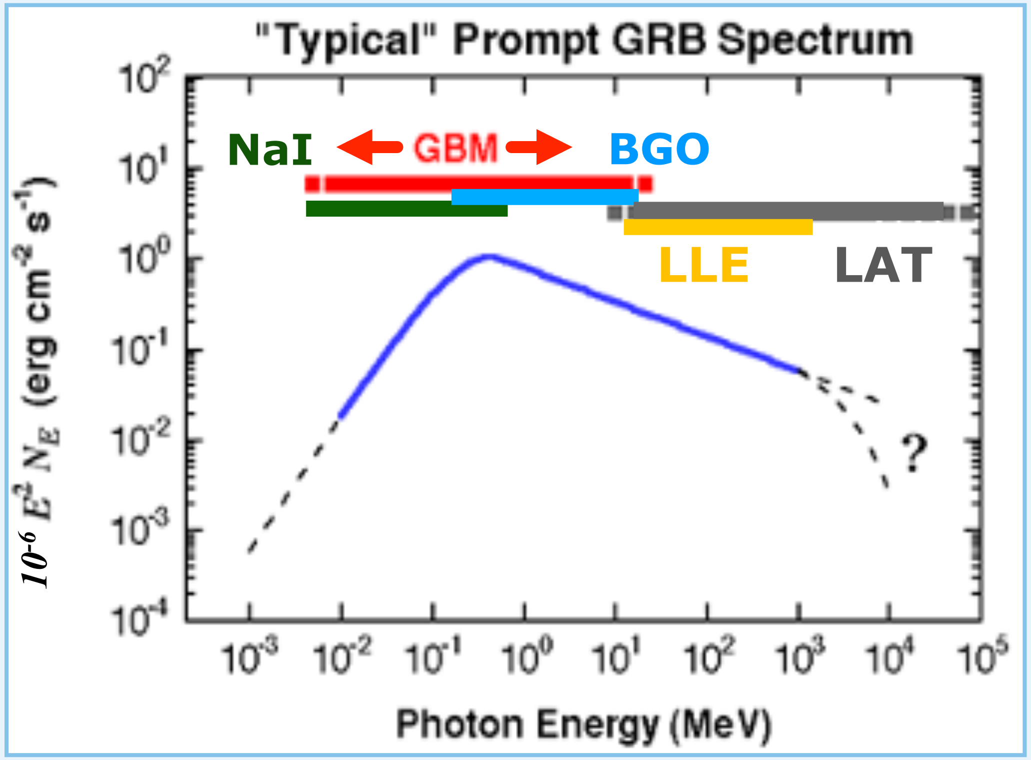
GRB observations in the Fermi Era



GBM energy coverage

NaI: 8 – 900 keV

BGO: 250 keV – 40 MeV



LAT energy coverage

LLE*: 10 MeV – 1 GeV

LAT: 100 MeV – 300 GeV

*LAT Low-energy Techinque:
forward-folding analysis of a background-subtracted binned event rate, using a Detector Response Matrix (DRM) for model-folding, and a looser event selection

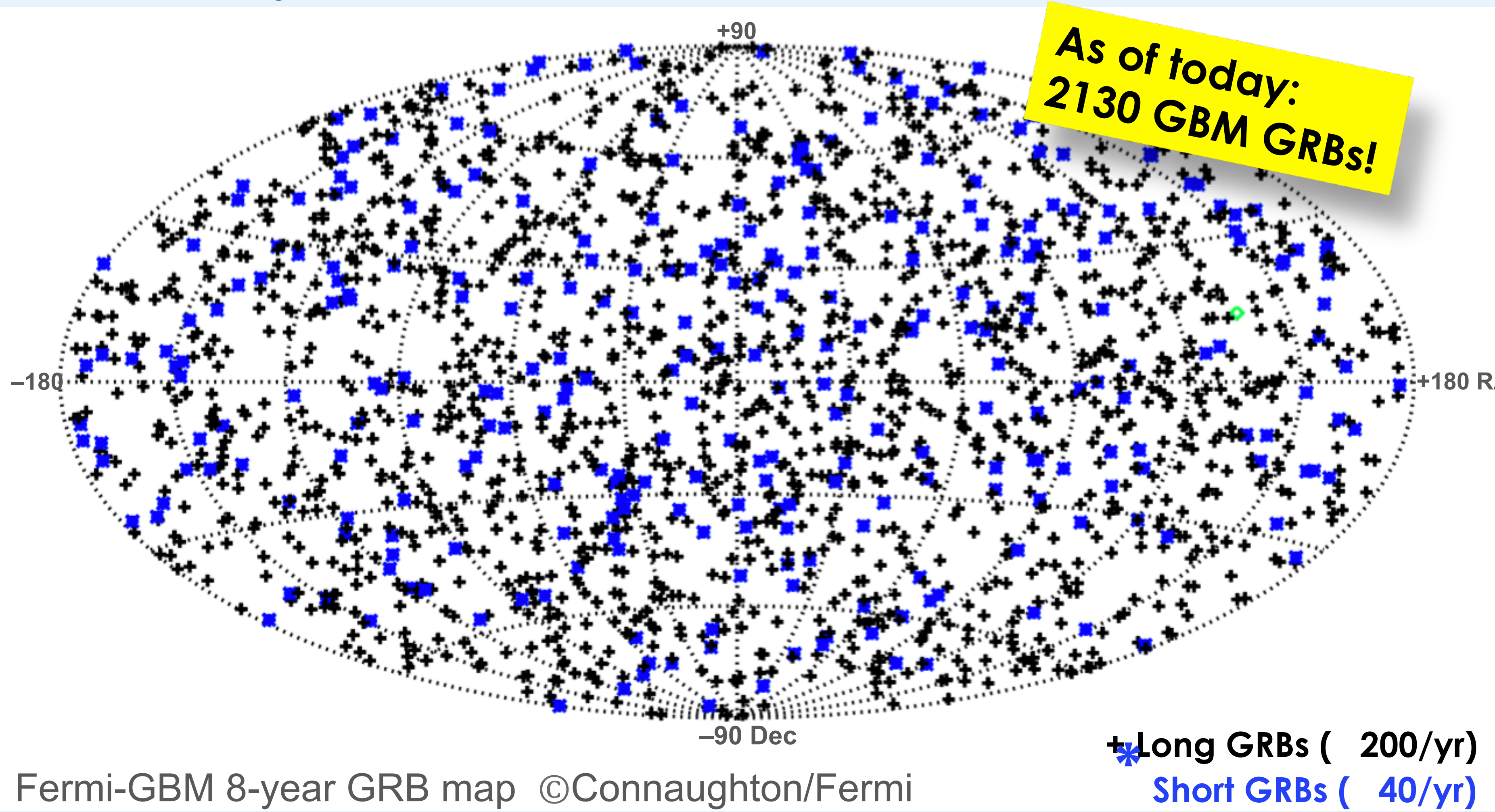
GRB observations in the Fermi Era

Fermi GRB publications

- **~30 GBM-led papers**
  - **6 catalogs**
  - Individual GRBs, Population studies, Correlations
- **~45 LAT-led papers**
  - >20 papers dedicated to individual GRBs
  - Prospects, UL, **1 catalog**, analysis techniques

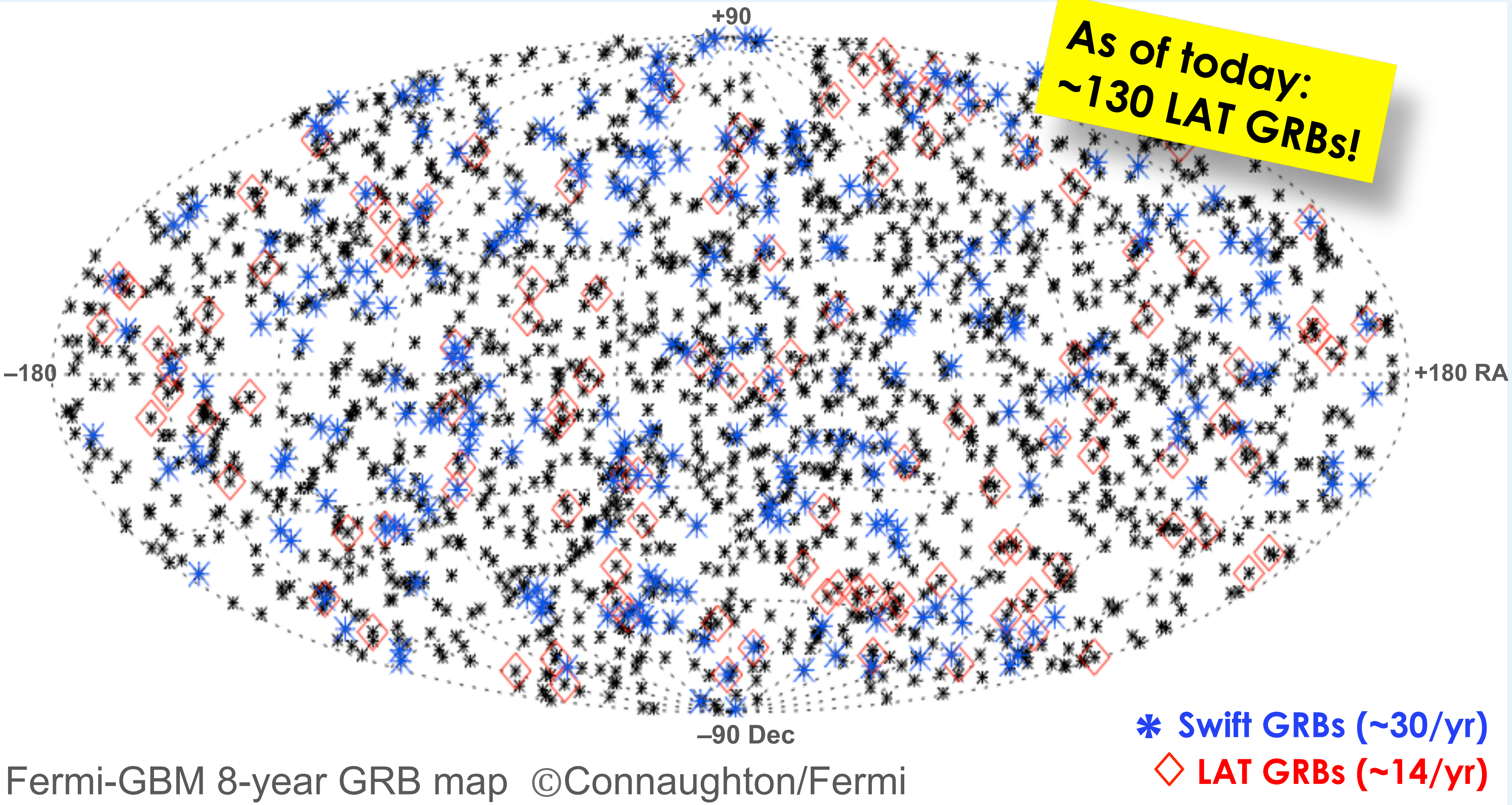
Online catalogs/tables
GBM http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
LAT http://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/table.php

Fermi GRB skymaps



Fermi-GBM 8-year GRB map ©Connaughton/Fermi GBM Collaboration

Fermi GRB skymaps



Fermi-GBM 8-year GRB map ©Connaughton/Fermi GBM Collaboration

Fermi GBM GRB highlights

3rd GBM GRB Catalog (6 years catalog)

The Astrophysical Journal Supplement Series, 223:28 (18pp), 2016 April
doi:10.3847/0067-0049/223/2/28
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THE THIRD *FERMI* GBM GAMMA-RAY BURST CATALOG: THE FIRST SIX YEARS

P. Narayana Bhat[1,2], Charles A. Meegan[1], Andreas von Kienlin[3], William S. Paciesas[4], Michael S. Briggs[1,2], J. Michael Burgess[5,6], Eric Burns[1], Vandiver Chaplin[1,7], William H. Cleveland[4], Andrew C. Collazzi[8], Valerie Connaughton[4,2], Anne M. Diekmann[9], Gerard Fitzpatrick[1,10], Melissa H. Gibby[9], Misty M. Giles[9], Adam M. Goldstein[11], Jochen Greiner[3,12], Peter A. Jenke[1,2], R. Marc Kippen[13], Chryssa Kouveliotou[14], Bagrat Mailyan[1], Sheila McBreen[10], Veronique Pelassa[1,15], Robert D. Preece[2], Oliver J. Roberts[10], Linda S. Sparke[16], Matthew Stanbro[1], Péter Veres[1], Colleen A. Wilson-Hodge[11], Shaolin Xiong[17], George Younes[14], Hoi-Fung Yu[3,12], and Binbin Zhang[1,18]

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[6] Department of Physics, KTH Royal Institute of Technology, AlbaNova University Center, SE-106 91 Stockholm, Sweden
[7] Vanderbilt University Institute of Imaging Science, 1161 21st Avenue South, Medical Center North, AA-1105, Nashville, TN 37232, USA
[8] SciTec Inc., 100 Wall Street, Princeton NJ, 08540, USA

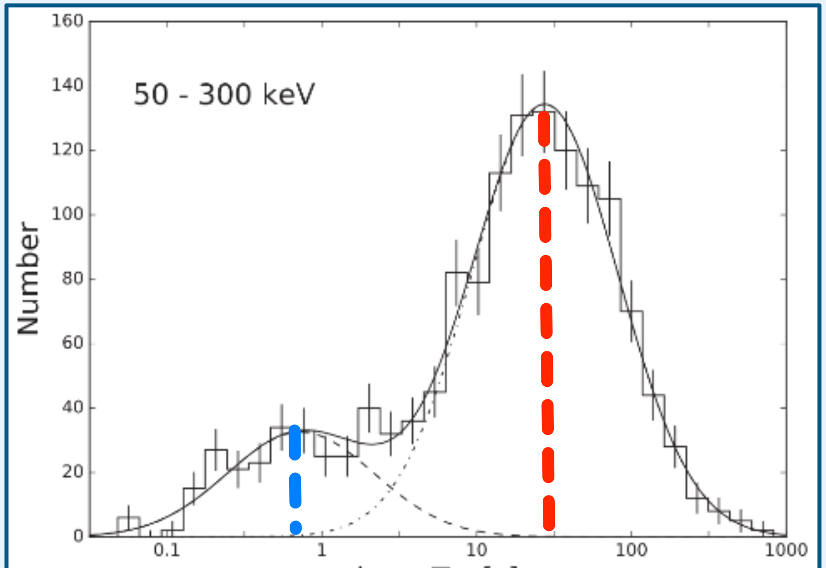
➔ For each GRB: **location, duration, peak flux & fluence**

Fermi GBM GRB highlights

3rd GBM GRB Catalog (6 years catalog)

Distribution of GRB durations

- "T_{90}" interval between the times where the burst has reached 5% and 95% of its maximum fluence
- Median T_{90} values:
  - **0.58 s (short)**, **26.62 s (long)**



Bhat+2016

➔ **GRB rate: 242 ± 6 / year**

- **Long GRB rate: ~200 /year**
- **Short GRB rate: ~40 /year**

GBM: ~ 40 sGRBs/year
Swift: ~ 9 sGRBs/year

Fermi GBM GRB highlights

3rd GBM GRB Catalog (6 years catalog)

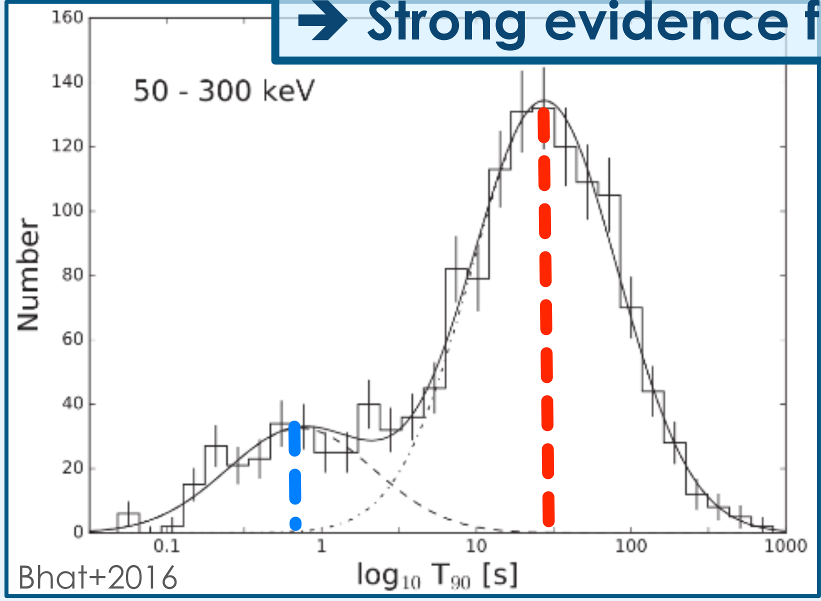
Distribution of GRB durations

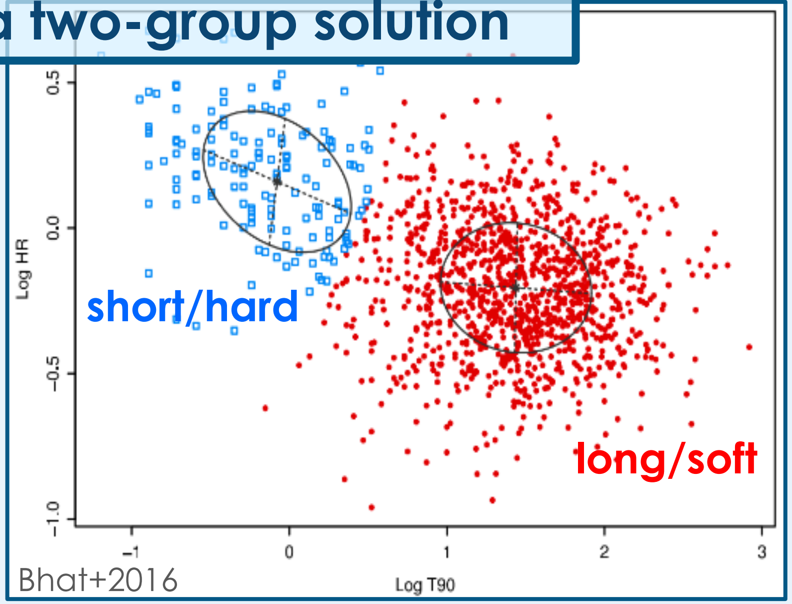
- "$\mathbf{T_{90}}$" interval between the times where the burst has reached 5% and 95% of its maximum fluence
- **Median $\mathbf{T_{90}}$ values:**
  - **0.58 s (short)**, **26.62 s (long)**

Hardness-duration diagram

- "**Hardness**": Ratio of burst fluence during the T_{90} intervals in the energy band **50–300 keV** to that in the **10–50 keV** band

➔ Strong evidence for a two-group solution





Ellipses show the best-fitting multivariate Gaussian models

Fermi GBM GRB highlights

2rd GBM GRB Spectral Catalog (4 years catalog)

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 211:12 (27pp), 2014 March doi:10.1088/0067-0049/211/1/12
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THE *FERMI* GBM GAMMA-RAY BURST SPECTRAL CATALOG: FOUR YEARS OF DATA

DAVID GRUBER[1,2], ADAM GOLDSTEIN[3], VICTORIA WELLER VON AHLEFELD[1,4], P. NARAYANA BHAT[3], ELISABETTA BISSALDI[5,6], MICHAEL S. BRIGGS[3], DAVE BYRNE[7], WILLIAM H. CLEVELAND[8], VALERIE CONNAUGHTON[3], ROLAND DIEHL[1], GERALD J. FISHMAN[9], GERARD FITZPATRICK[7], SUZANNE FOLEY[7], MELISSA GIBBY[10], MISTY M. GILES[10], JOCHEN GREINER[1], SYLVAIN GUIRIEC[11], ALEXANDER J. VAN DER HORST[12], ANDREAS VON KIENLIN[1], CHRYSSA KOUVELIOTOU[9], EMILY LAYDEN[3], LIN LIN[3,13], CHARLES A. MEEGAN[3], SINÉAD MCGLYNN[7], WILLIAM S. PACIESAS[3], VÈRONIQUE PELASSA[3], ROBERT D. PREECE[3], ARNE RAU[1], COLLEEN A. WILSON-HODGE[9], SHAOLIN XIONG[3], GEORGE YOUNES[8], AND HOI-FUNG YU[1]

[1] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
[2] Planetarium Südtirol, Gummer 5, I-39053 Karneid, Italy
[3] University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35805, USA
[4] School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Mayfield Road, EH9 3JZ Edinburgh, UK
[5] Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy
[6] Dipartimento di Fisica, Universita' di Trieste, I-34127 Trieste, Italy

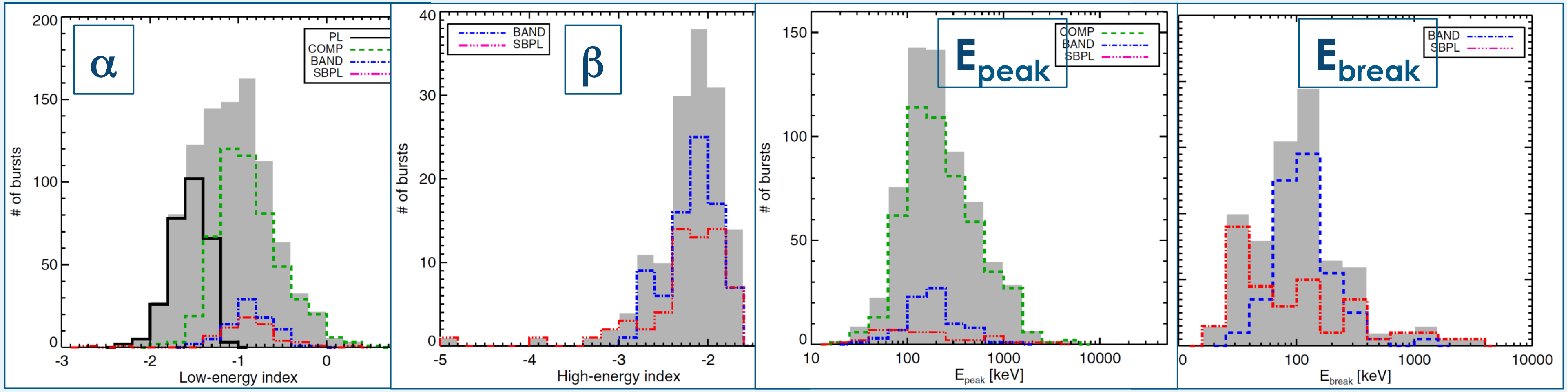
➔ Two types of spectra: **time-integrated spectral fits and spectral fits at the brightest time bin**

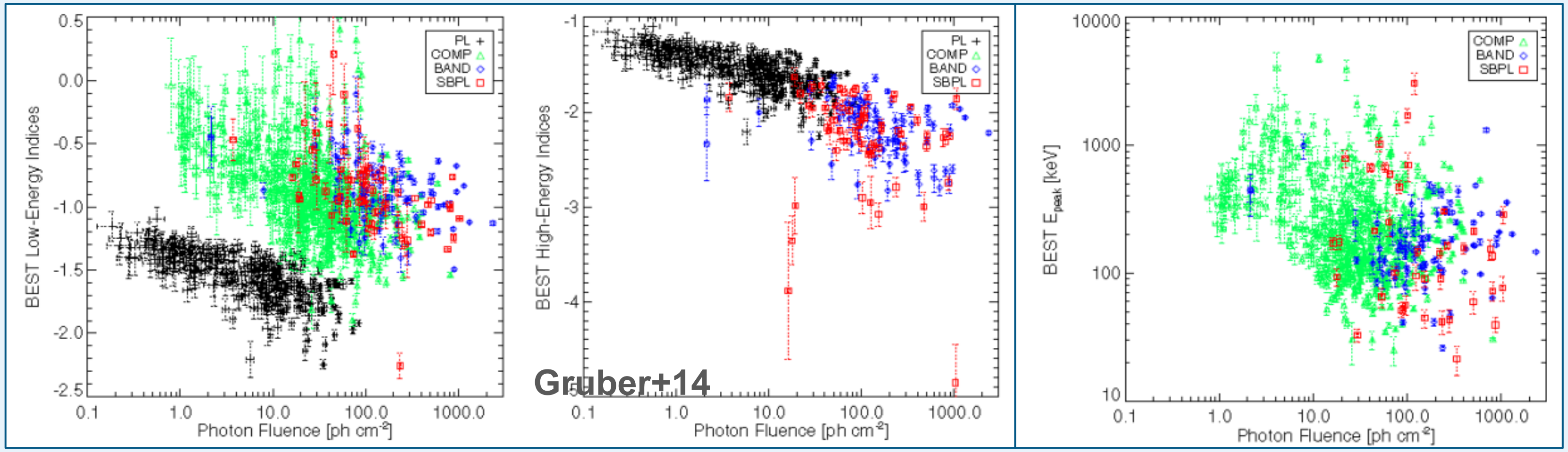
- **Four spectral models (PL, BAND, SBPL, COMP)**

Fermi GBM GRB highlights

Fermi Gamma-ray Space Telescope

2rd GBM GRB Spectral Catalog (4 years catalog)





➔ **Preferred model: "Comptonized"**

PL	SBPL	BAND	COMP
Fluence spectra			
282 (29.9%)	62 (6.6%)	81 (8.6%)	516 (54.7%)

Fermi GBM GRB highlights

Fermi Gamma-ray Space Telescope

1st Time-resolved spectral catalog (4 years catalog)

A&A 588, A135 (2016)
DOI: 10.1051/0004-6361/201527509
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Astronomy & Astrophysics

The *Fermi* GBM gamma-ray burst time-resolved spectral catalog: brightest bursts in the first four years★

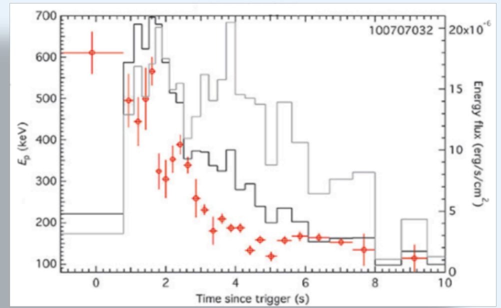
Hoi-Fung Yu[1,2], Robert D. Preece[3], Jochen Greiner[1,2], P. Narayana Bhat[4], Elisabetta Bissaldi[5], Michael S. Briggs[4,6], William H. Cleveland[7], Valerie Connaughton[4,6], Adam Goldstein[8], Andreas von Kienlin[1], Chryssa Kouveliotou[9], Bagrat Mailyan[4], Charles A. Meegan[7], William S. Paciesas[7], Arne Rau[1], Oliver J. Roberts[10], Péter Veres[4], Colleen Wilson-Hodge[8], Bin-Bin Zhang[4], and Hendrik J. van Eerten[1,★★]

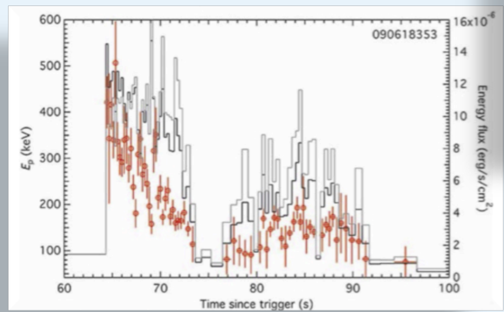
[1] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße 1, 85748 Garching, Germany
e-mail: sptfung@mpe.mpg.de
[2] Excellence Cluster Universe, Technische Universität München, Boltzmannstraße 2, 85748 Garching, Germany

➔ **Distributions** of parameters, **statistics** of the parameter populations, parameter **correlations**

Fermi GBM GRB highlights

1st Time-resolved spectral catalog (4 years catalog)





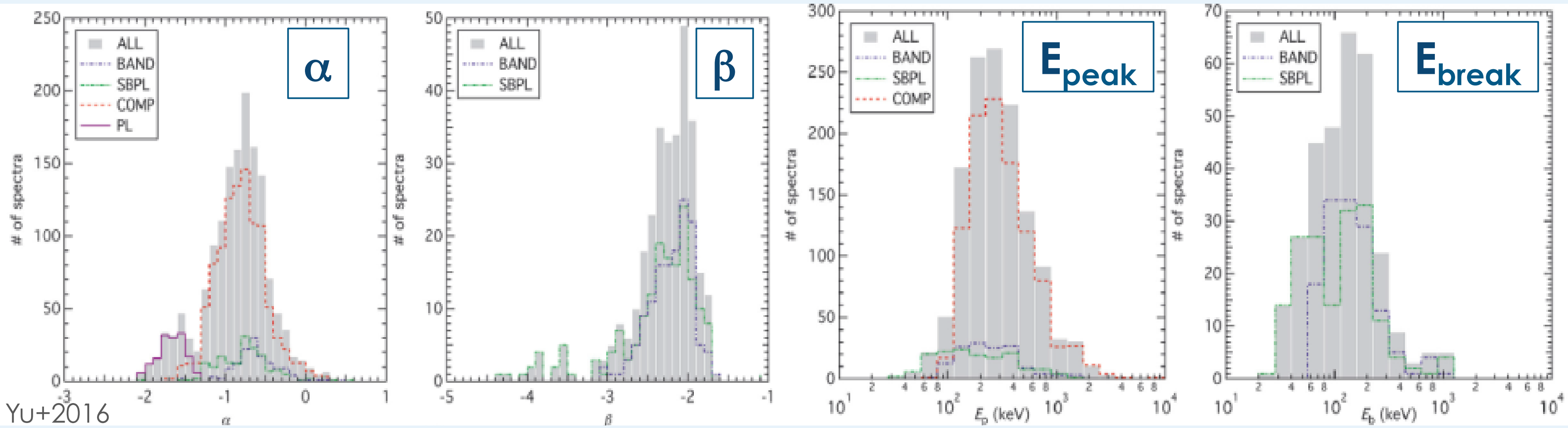
Bright GRB subsample

- **Selection criteria**
  - **fluence** ($f > 4 \times 10^{-5}$ erg cm^{-2})
  - **peak flux** ($F_p > 20$ ph s^{-1}cm^{-2})
  - **(S/N)**=30 in at least 5 time bins

➔ 81 GRBs for a total of **1802 spectra**

- **Four empirical models** fit to each spectrum: **PL, COMP, Band, SBPL**

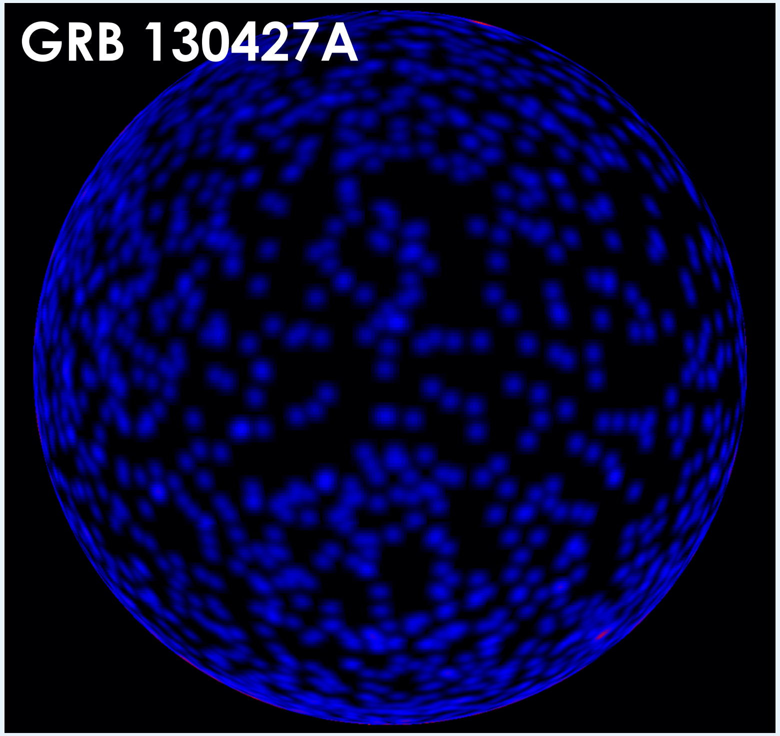
➔ **Preferred model (69%): "Comptonized"**

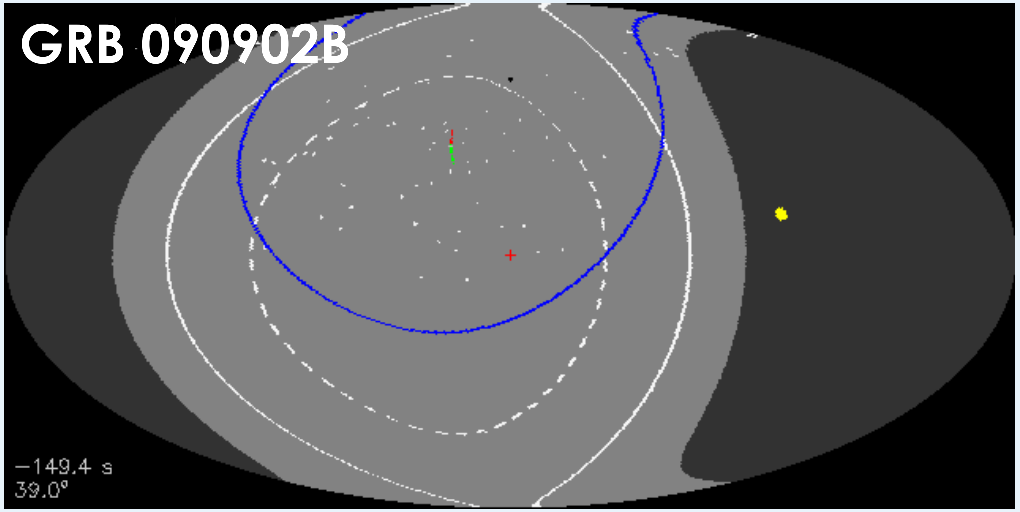


Yu+2016

Fermi LAT GRB highlights

- ~170 positive **Autonomous Repoint Recommendations (ARRs)** sent from GBM to LAT
- 6 onboard LAT triggers
- **Dedicated automated pipelines**
  - Search for **excess emission** in the LAT data
  - Triggers from **GBM, Swift, INTEGRAL, and MAXI**
  - Search at trigger time plus in **various intervals** in the hours afterward





Hammer-Aitoff representation of the whole sky in celestial coordinates

RED CROSS (center)	**GRB**
YELLOW DOT	**Sun**
GREEN/RED LINES	**Fermi solar panels**
BLUE CIRCLE	**LAT FoV**
DARK AREA	**Earth**
WHITE CIRCLE	**20° Earth avoidance**
DASHED WHITE CIRCLE	**50° Earth avoidance**

Fermi LAT highlights

1st LAT GRB catalog (3 years catalog)

The Astrophysical Journal Supplement Series, 209:11 (90pp), 2013 November 1 doi:10.1088/0067-0049/209/1/11

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THE FIRST *FERMI*-LAT GAMMA-RAY BURST CATALOG

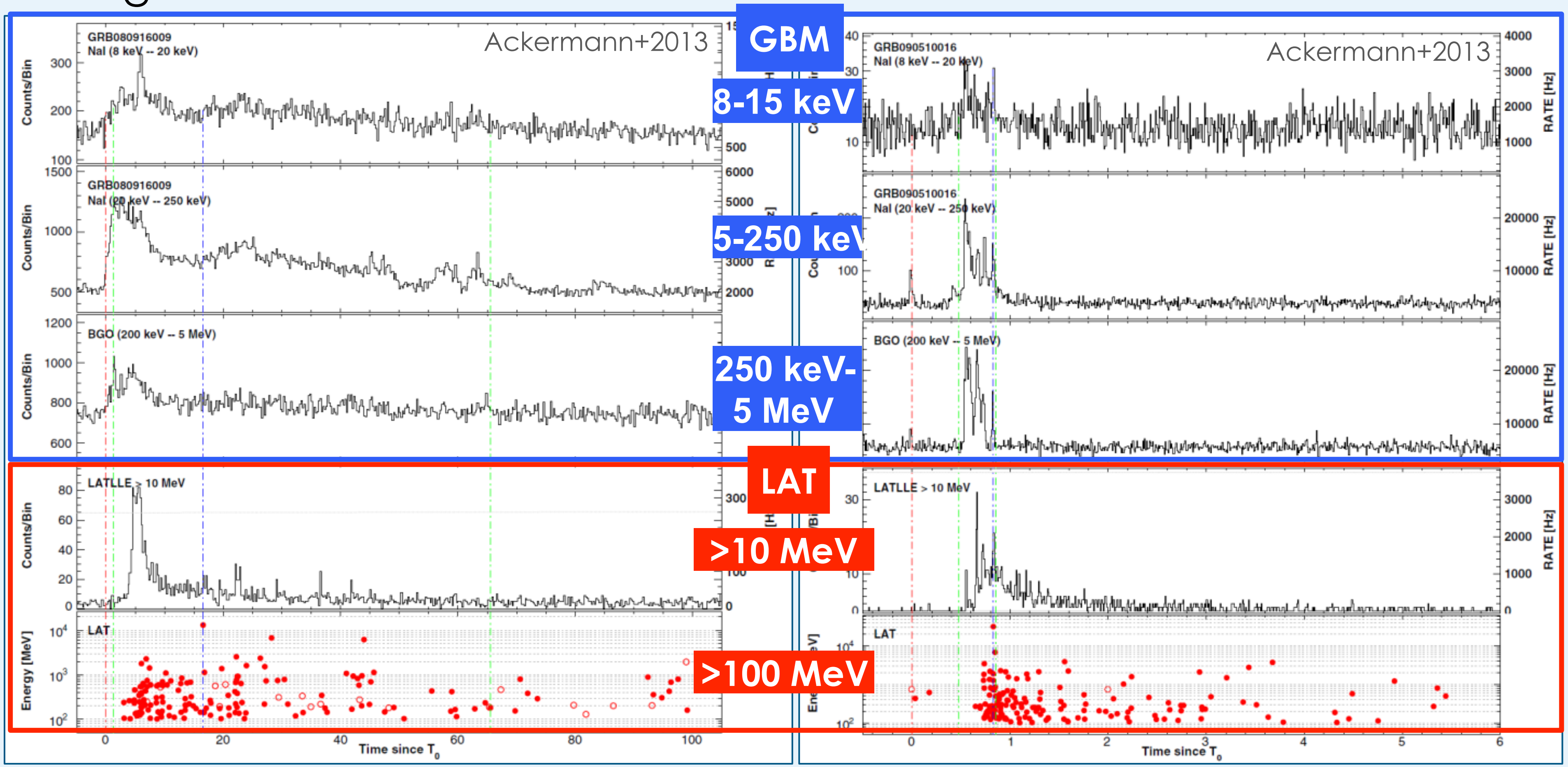
M. Ackermann[1], M. Ajello[2], K. Asano[3], M. Axelsson[4,5,6], L. Baldini[7], J. Ballet[8], G. Barbiellini[9,10], D. Bastieri[11,12], K. Bechtol[13], R. Bellazzini[14], P. N. Bhat[15], E. Bissaldi[16], E. D. Bloom[13], E. Bonamente[17,18], J. Bonnell[19,20], A. Bouvier[21], T. J. Brandt[19], J. Bregeon[14], M. Brigida[22,23], P. Bruel[24], R. Buehler[13], J. Michael Burgess[15], S. Buson[11,12], D. Byrne[25], G. A. Caliandro[26], R. A. Cameron[13], P. A. Caraveo[27], C. Cecchi[17,18], E. Charles[13], R. C. G. Chaves[8], A. Chekhtman[28,69], J. Chiang[13], G. Chiaro[12], S. Ciprini[29,30], R. Claus[13], J. Cohen-Tanugi[31], V. Connaughton[15], J. Conrad[5,32,33,70], S. Cutini[29,30], F. D'Ammando[34], A. de Angelis[35], F. de Palma[22,23], C. D. Dermer[36], R. Desiante[9], S. W. Digel[13], B. L. Dingus[37], L. Di Venere[13], P. S. Drell[13], A. Drlica-Wagner[13], R. Dubois[13], C. Favuzzi[22,23], E. C. Ferrara[19], G. Fitzpatrick[25], S. Foley[25,38], A. Franckowiak[13], Y. Fukazawa[39], P. Fusco[22,23], F. Gargano[23], D. Gasparrini[29,30], N. Gehrels[19], S. Germani[17,18], N. Giglietto[22,23], P. Giommi[29], F. Giordano[22,23], M. Giroletti[34],

- First **systematic study** of GRB **high-energy** emission
  - 28 GRBs detected >100 MeV, 7 GRBs >~10 MeV
  - Temporal and spectral properties

Fermi LAT highlights

1st LAT GRB Catalog (3 years)

Long **GRB 080916C** Short **GRB 090510**

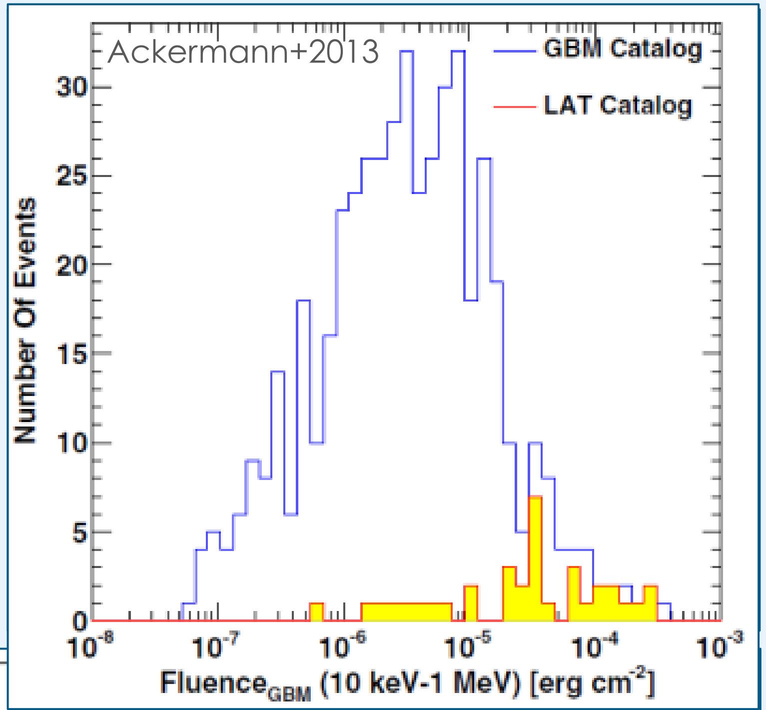


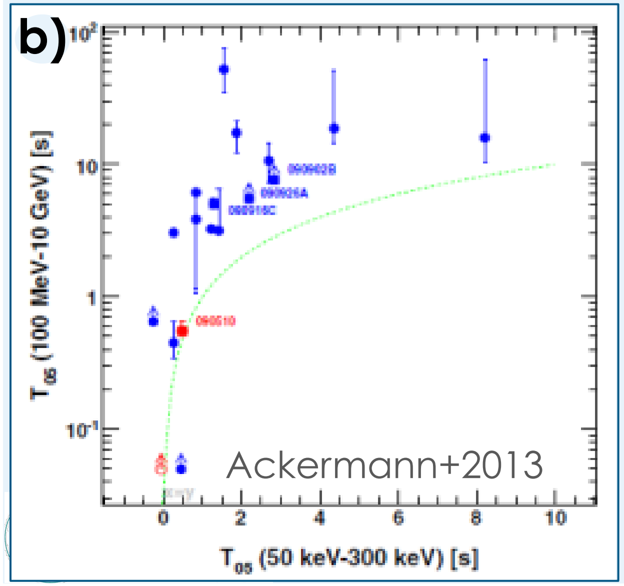
Fermi LAT highlights

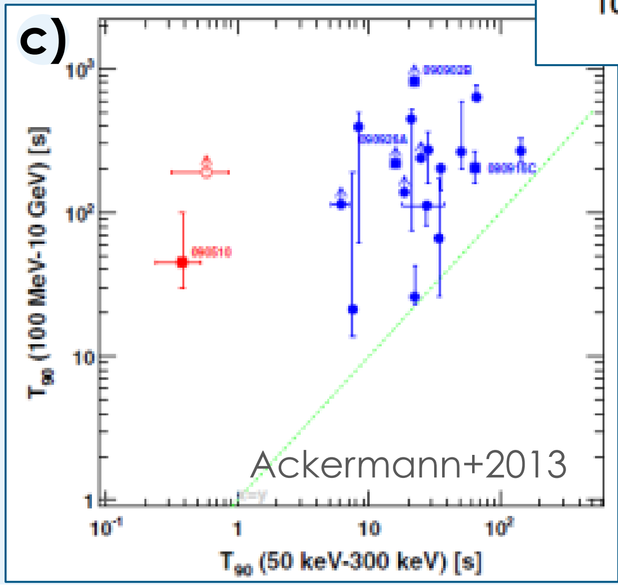
1st LAT GRB Catalog (3 years)

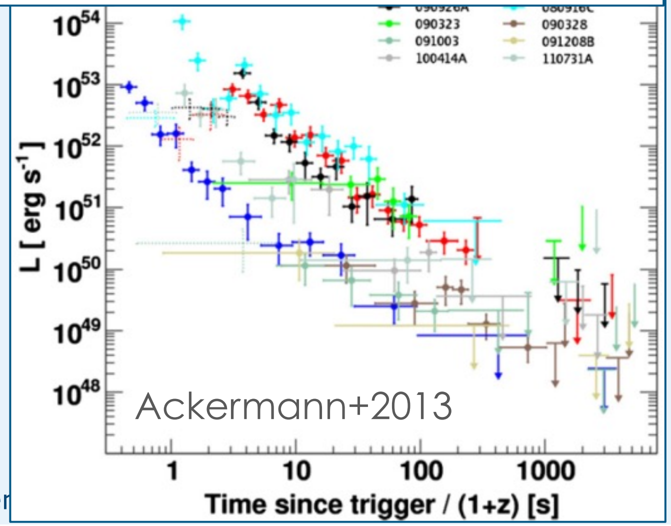
- High-energy features:
  a) Extra **PL component** required to fit spectra
  b) Emission >100 MeV systematically **delayed**
  c) Emission >100 MeV systematically **longer**
  d) Emission >100 MeV decays smoothly as a **PL (index -1)**

➔ **Not surprisingly, LAT GRBs are among the brightest GBM ones!**



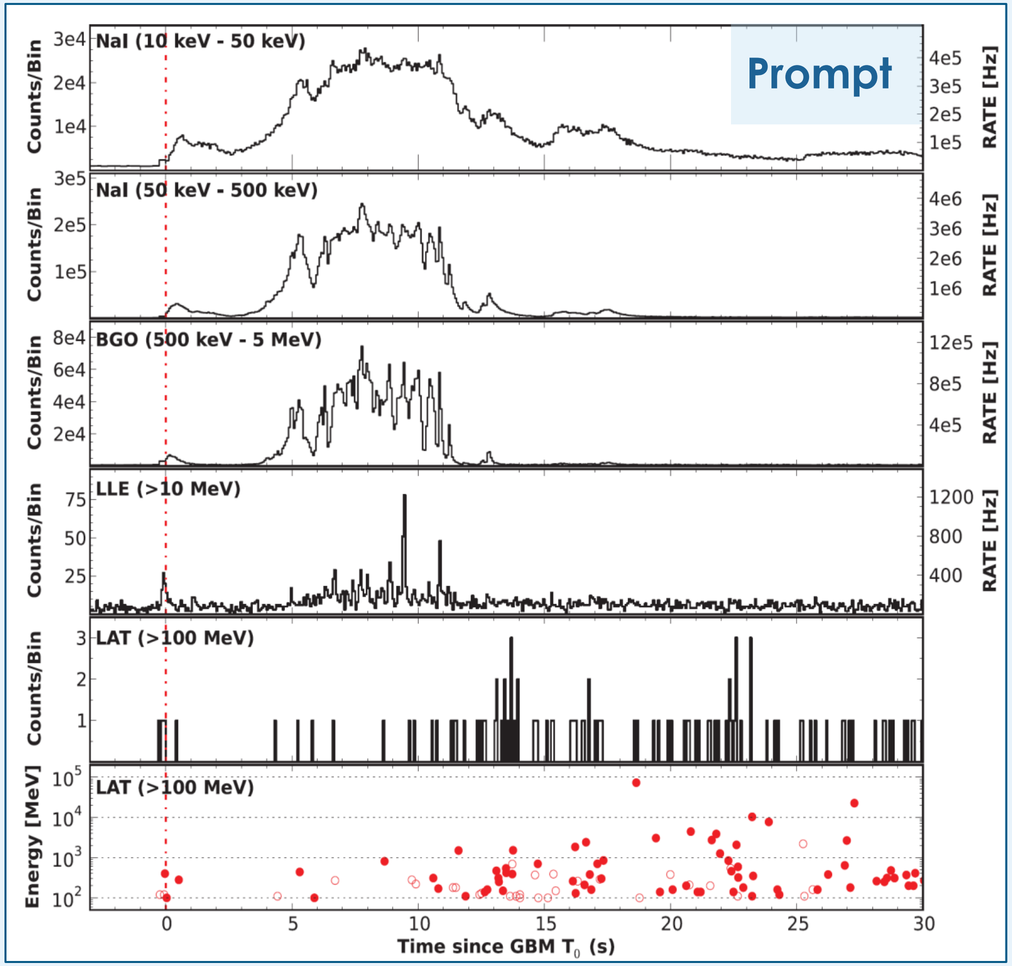


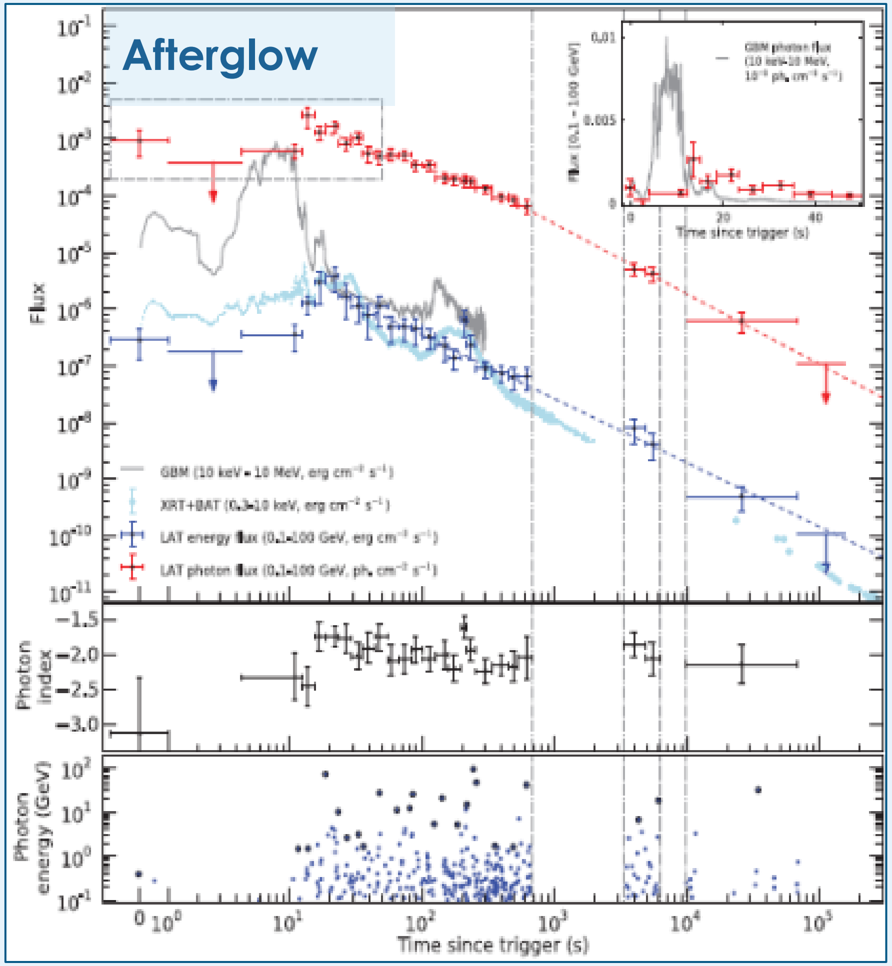




Fermi Gamma-ray Space Telescope

GRB 130427A – The "monster" burst

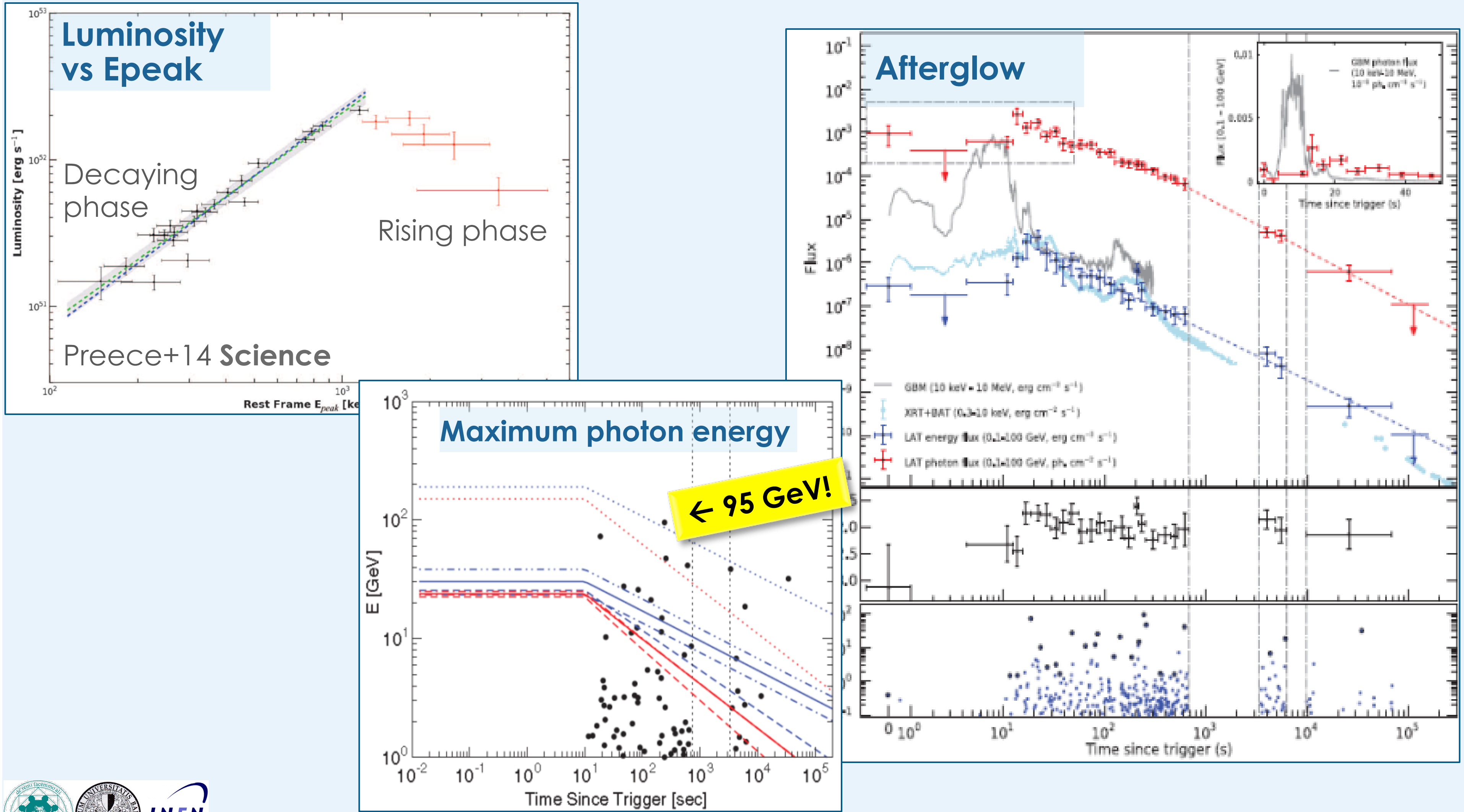




Ackermann+14 **Science**

Fermi LAT highlights

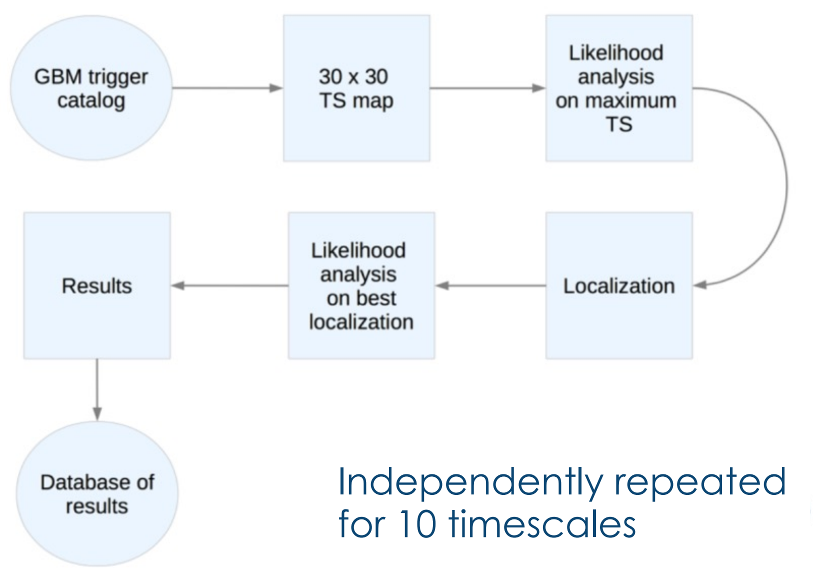
GRB 130427A – The "monster" burst

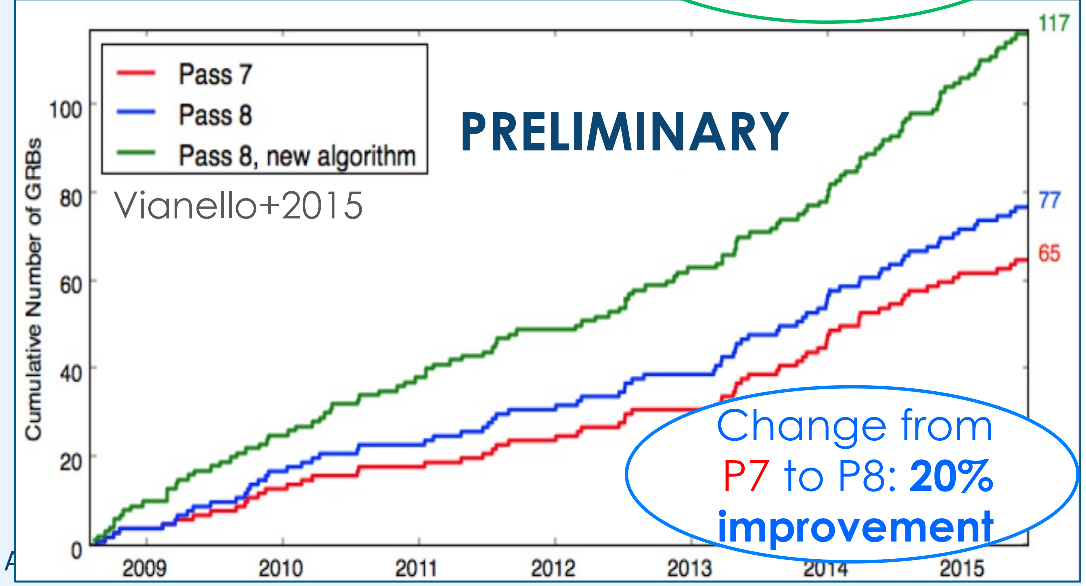


Fermi LAT highlights

- Towards the **2nd GBM catalog**
- New version of the LAT event reconstruction: "**Pass 8**"
  - Major improvements: larger effective area (especially at low energy) and smaller PSF;
- Development of a **new detection algorithm for GRBs**:
  - Overcoming large GBM systematic error on the localization
  - Search on different time scales
  - ➔ **Current LAT sample: 130 GRBs**
    - GRBs where only Pass 8 data are available + LLE-only

Change from old to new algorithm: **50% improvement**



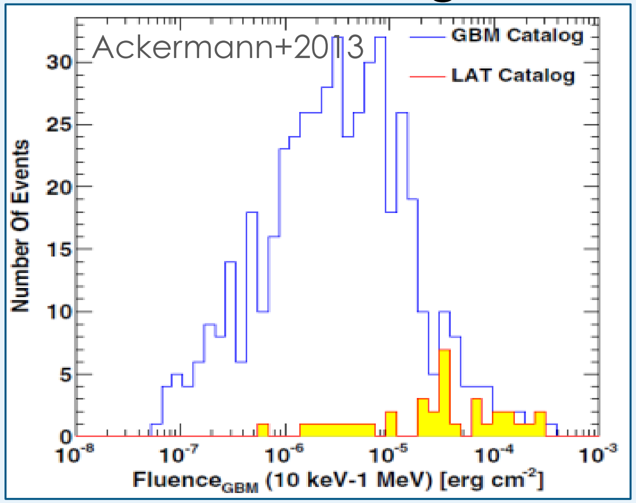


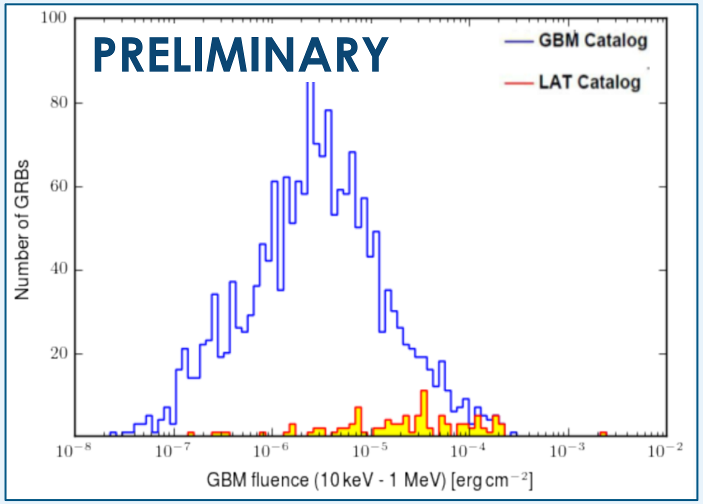
Change from P7 to P8: **20% improvement**

Fermi LAT highlights

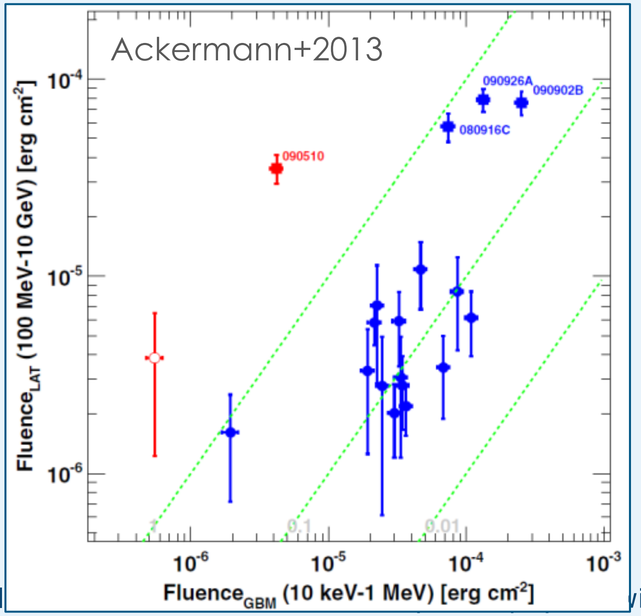
- Towards the **2nd GBM catalog**

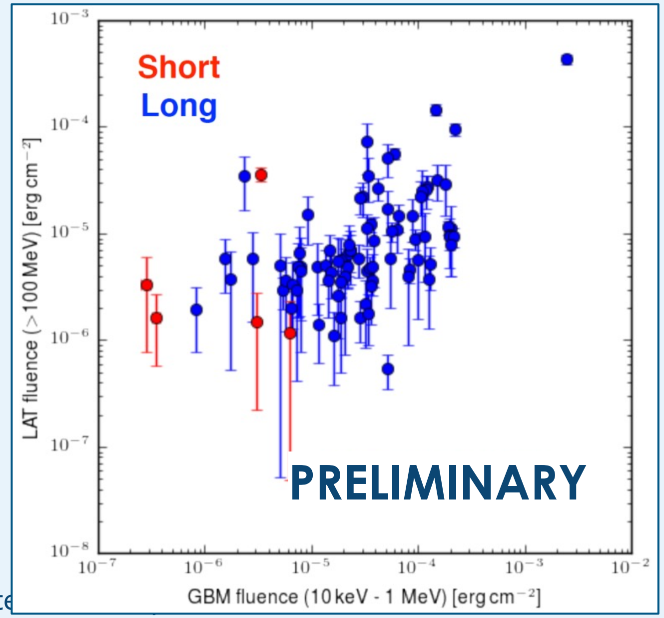
Similar fluence distribution (spanning a **broader fluence range**)





Filling the gap! **No separate class** of super-bright GRBs

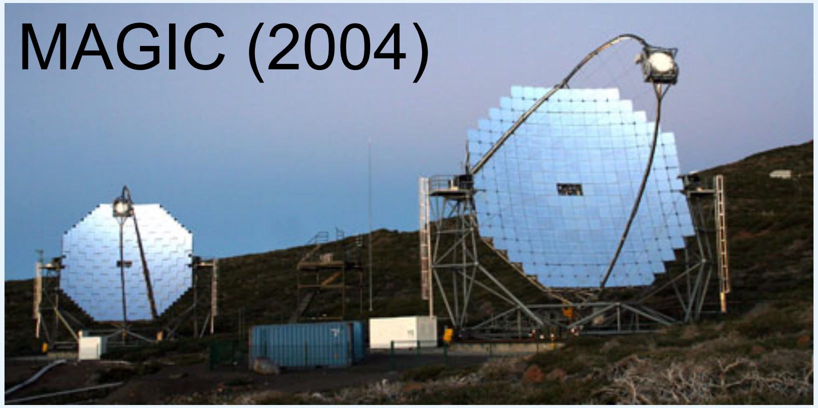




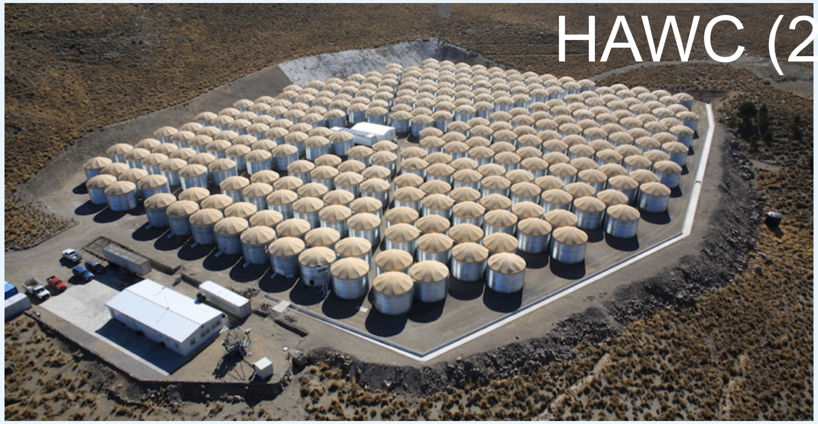
Moving towards higher energies!

Ground-based detectors today...

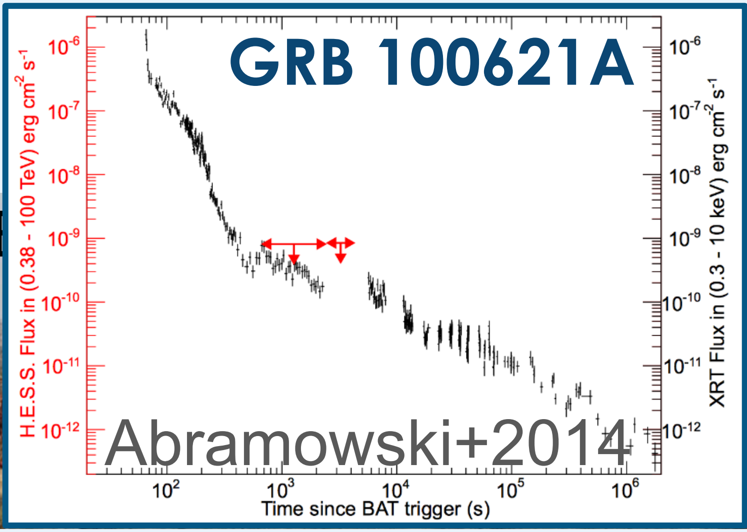

H.E.S.S. (2002)

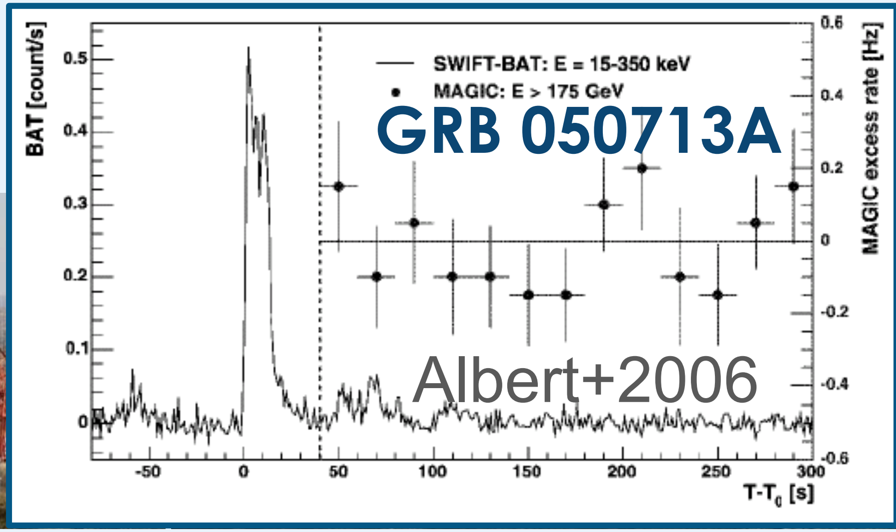

MAGIC (2004)

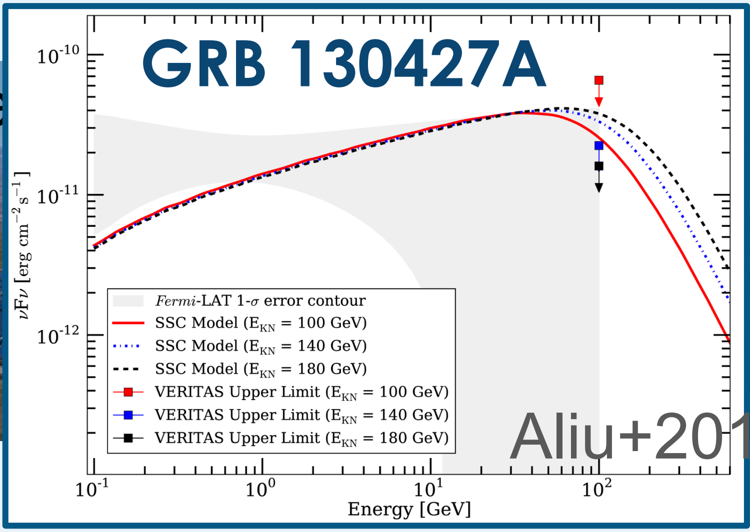

Veritas (2007)

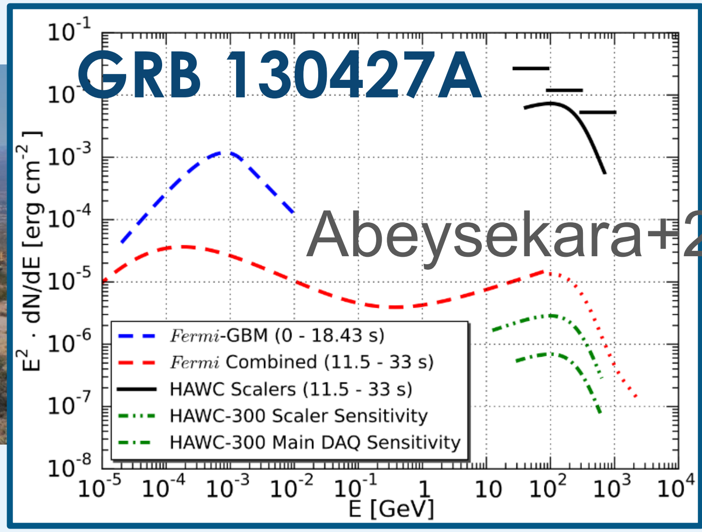

HAWC (2

VHE GRB observations

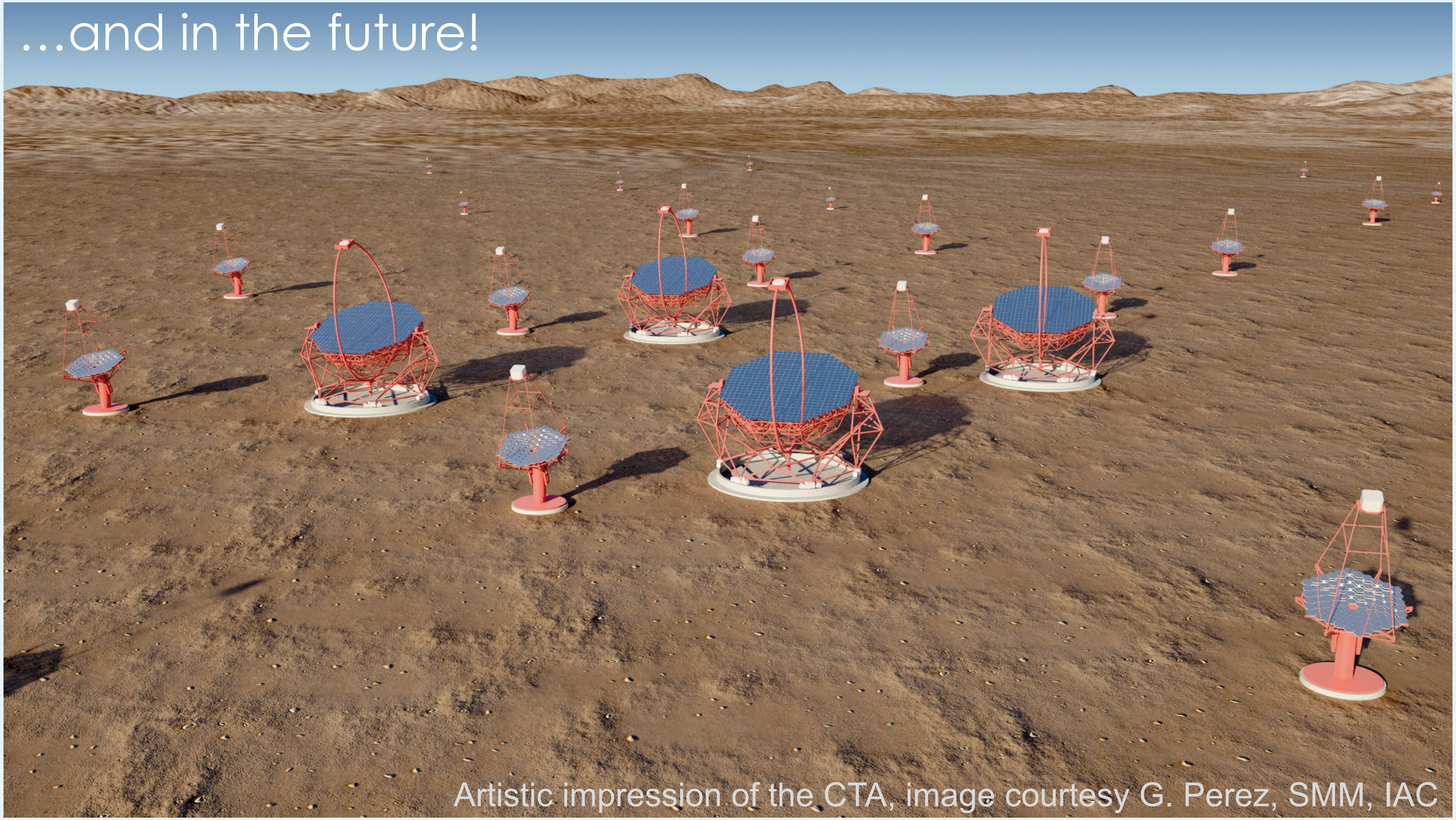






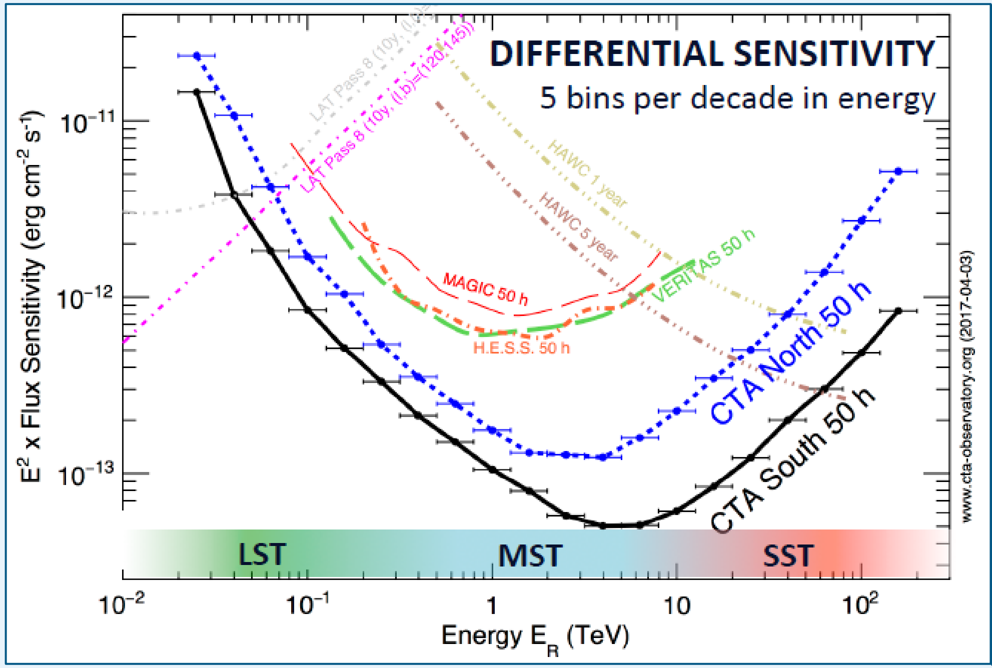


The Cherenkov Telescope Array (CTA)

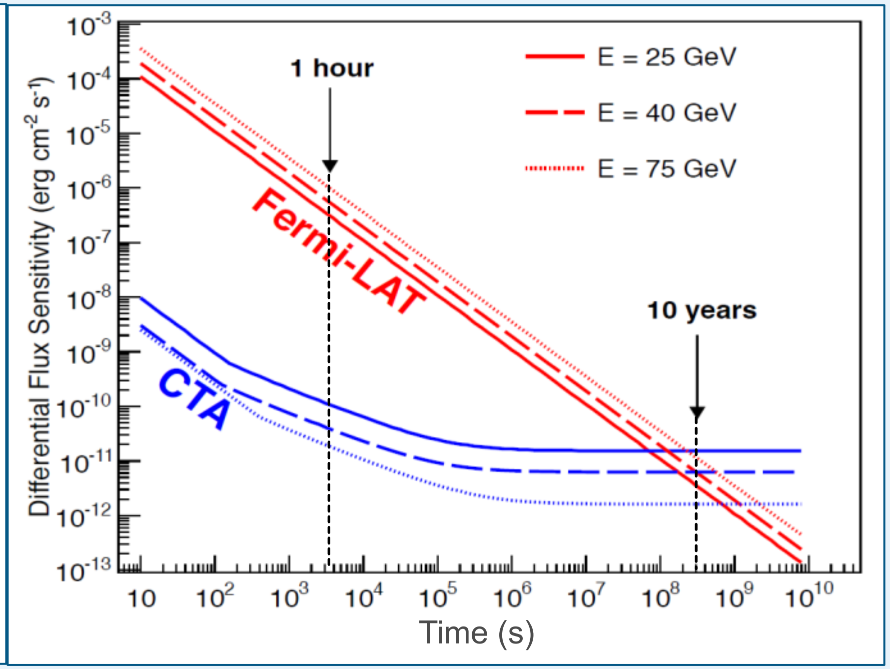


CTA sensitivity

Differential energy flux sensitivity for a point–like γ–ray source



Sensitivity per energy bin as a function of observation time

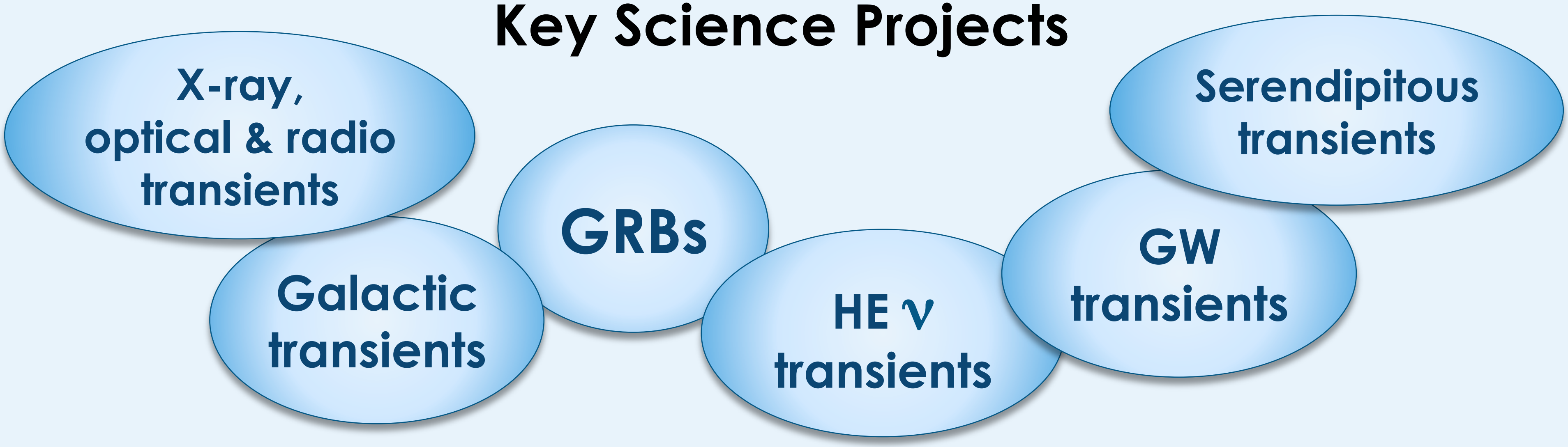


Pros: – Big advantage for **transients observation**
– CTA Effective area ~$\mathbf{10^4}$ x LAT @30GeV

Cons: Limited FoV, limited duty cycle

CTA KSP: Transients

Key Science Projects



- **VHE transient survey:** To be performed via *divergent pointing* and concurrently with parts of the extragalactic survey
  - Comprehensive Monte Carlo predictions for the expected performance are needed!

CTA observations of GRBs

- **Science goals**

Determine:

- velocity of the **jet**
- location of the **emission site**
- mechanisms of **particle acceleration** and radiation for
  1) **prompt** emission
  2) **early afterglow** emission

Test:

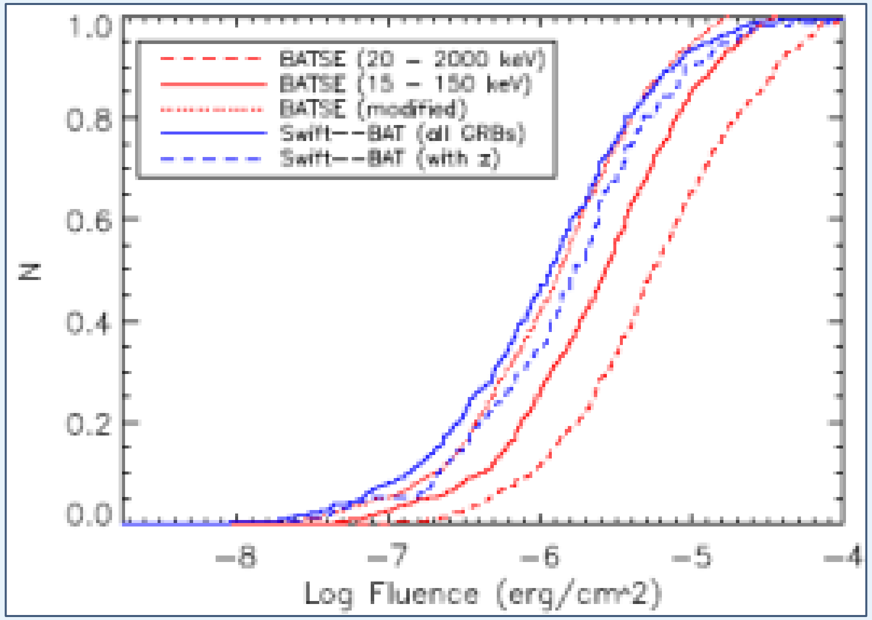
- GRB origin of **UHECRs**
- Lorentz invariance violation (**LIV**)

Clarify:

- **global evolution** of stars and super-massive black holes (SMBHs) in the universe over a large range of **redshifts**

Prospects for GRB detection by CTA

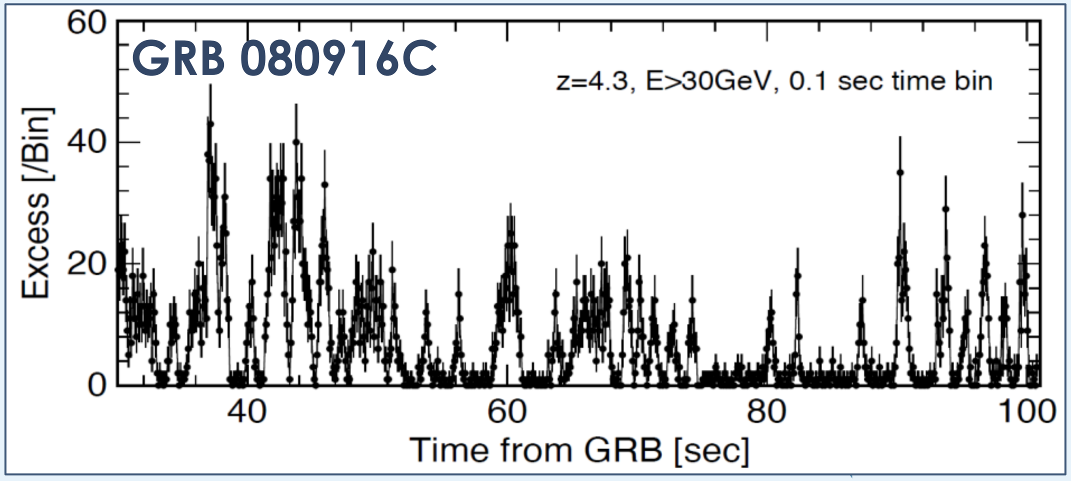
- Studies done in the past relied on extrapolations taken from:
  - Spectral parameters from the **BATSE and Swift** catalogs



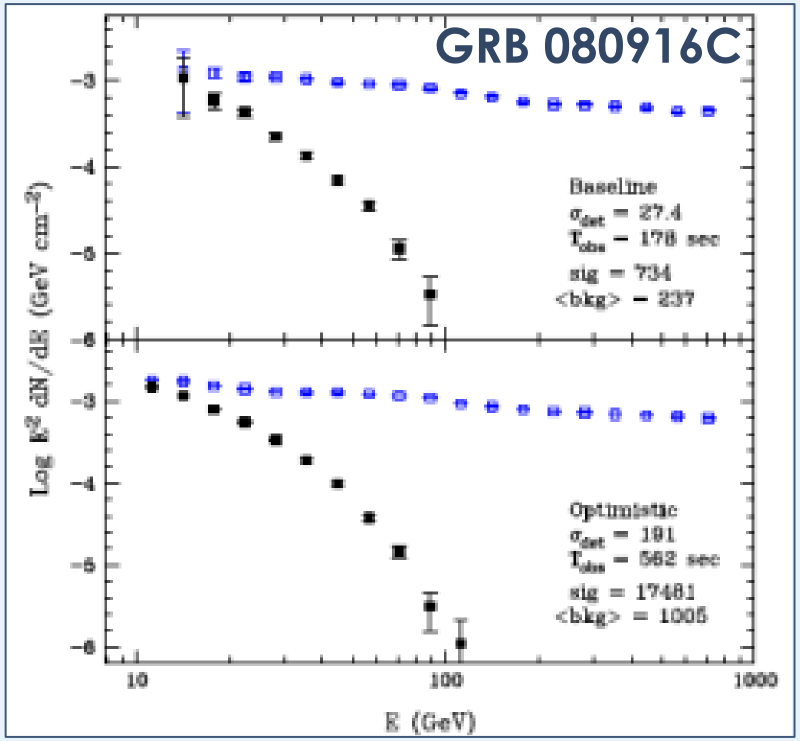
Gilmore+(2013) ExpAstr 35, 413

Prospects for GRB detection by CTA

- Studies done in the past relied on extrapolations taken from:
  - Spectral parameters from the **BATSE and Swift** catalogs
  - A couple of **very energetic GRBs** detected by Fermi before 2012



Inoue+(2013) AstroPh 43, 252



Gilmore+(2013) ExpAstr 35, 413

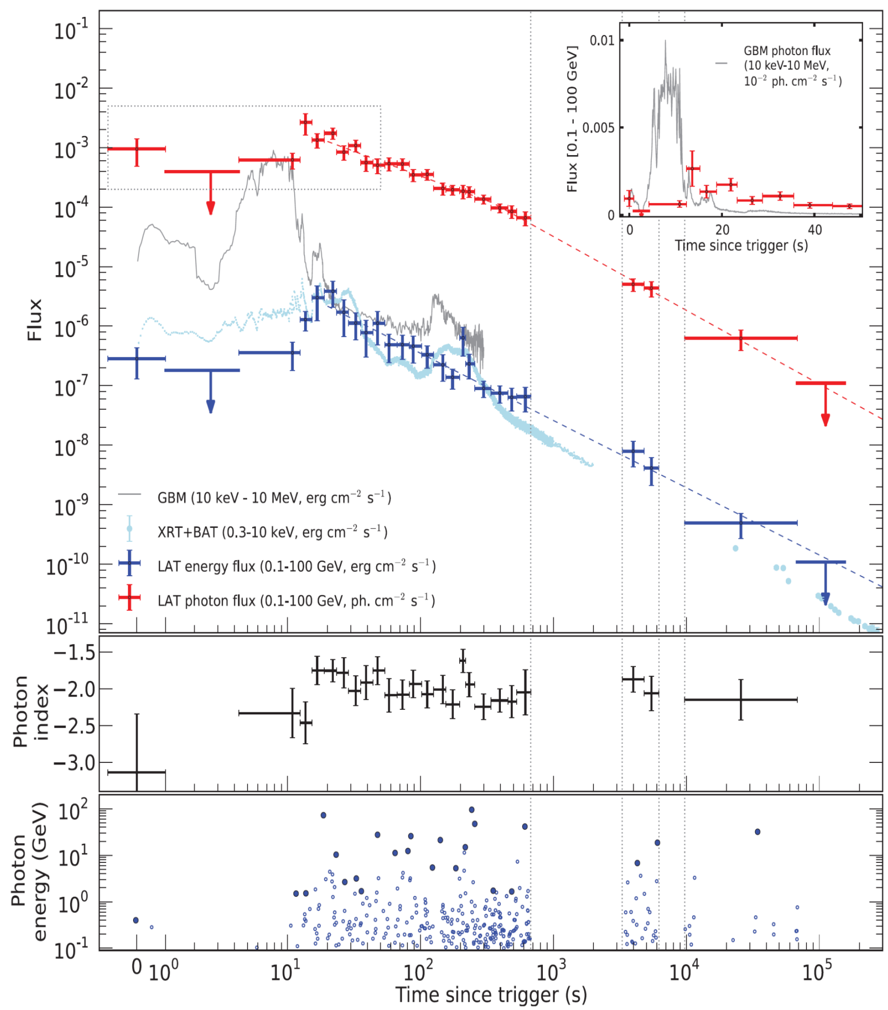
New CTA-GRB group project

- This work focuses on **Fermi-like GRBs** with measured redshift
- Main goal:
  - Setting up a **library of GRBs** observed at **different epochs** after the trigger
- **Procedure**:
  - Extrapolation of the LAT flux to CTA energies
  - Flux estimation at different post triggers epochs, taking into account the flux temporal evolution
  - Simulation of a fixed time-window observation
- Preliminary results
  - Proceedings of RICAP16 & Scineghe16 conferences (Bissaldi +16, Bissaldi+17)

GRB Test cases

1. **GRB 130427A**
   - **Long** GRB
   - Max photon energy: **95 GeV** (current record!)
   - Redshift **z = 0.34**
   - Spectral index γ = **−2.2** (almost constant from 400 s up to 70 ks after the trigger)
   - Temporal index τ = **−1.35** (valid for t > 380 s)

➔ VERITAS UL at 10ks: 3.3×10^{-12} erg/s/cm^2

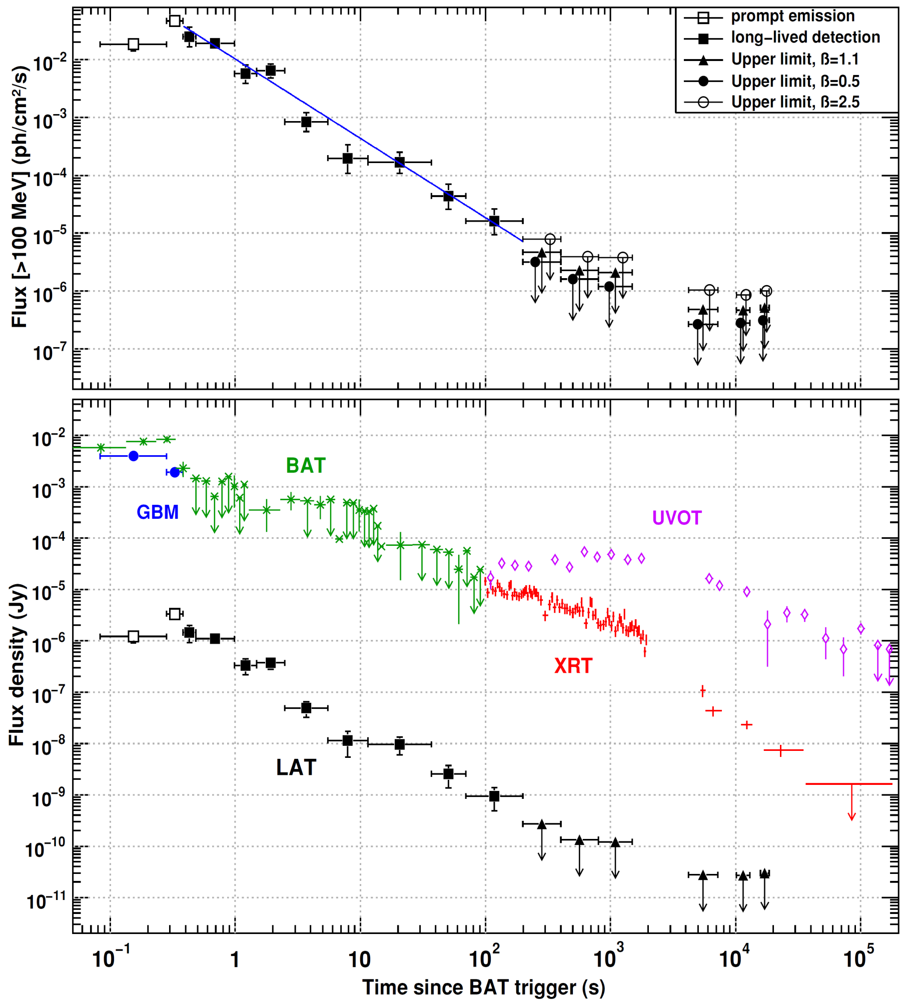


Ackermann+(2014) Science 343, 42

GRB Test cases

2. GRB 090510

- **Short** GRB
- Max photon energy: **31 GeV**
- Redshift **z = 0.9**
- Spectral index
  γ_1 **= −1.6** (for t<200 s)
  γ_2 **= −2.5** (for t>200 s)
- Temporal index
  τ = −1.35



De Pasquale+(2010) ApJL 709, 146

GRB simulations with `ctools`

- **Software package** specifically developed for the scientific analysis of CTA data, including:
  - **ftools-like binary executables** with a command-line interface allowing for interactive step-wise data analysis
  - Python module allowing to control all executables, Python scripts complementing the binary executables

➔ http://cta.irap.omp.eu/ctools/about.html

ctools
cherenkov telescope array

CTA
Cherenkov Telescope Array Science Analysis Software

About | Download | For Users | For Developers | Help

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About

ctools is a software package developed for the scientific analysis of Cherenkov Telescope Array (CTA) data. Analysis of data from existing Imaging Air Cherenkov Telescopes (such as H.E.S.S., MAGIC or VERITAS) is also supported, provided that the data and response functions are available in the format defined for CTA.

Table Of Contents

- ctools are based on **GammaLib**
  - multi-instrument capabilities, supporting the joint analysis of CTA (or any IACT providing data in the CTA format), Fermi/LAT and COMPTEL data
- Developed by **J. Knoedlseder**+(2016) arXiv:1606.00393

GRB simulations with `ctools`

- Input parameters:

Case 1
- Observation: on Axis
- Zenith Angle 20°
- 50 GeV – 1 TeV
- EBL absorption by Franceschini+2008

Case 2
- Observation: on Axis
- Zenith Angle 20°
- 50 GeV – 100 GeV
- No EBL included

- We simulate two possible observations:

Case 1

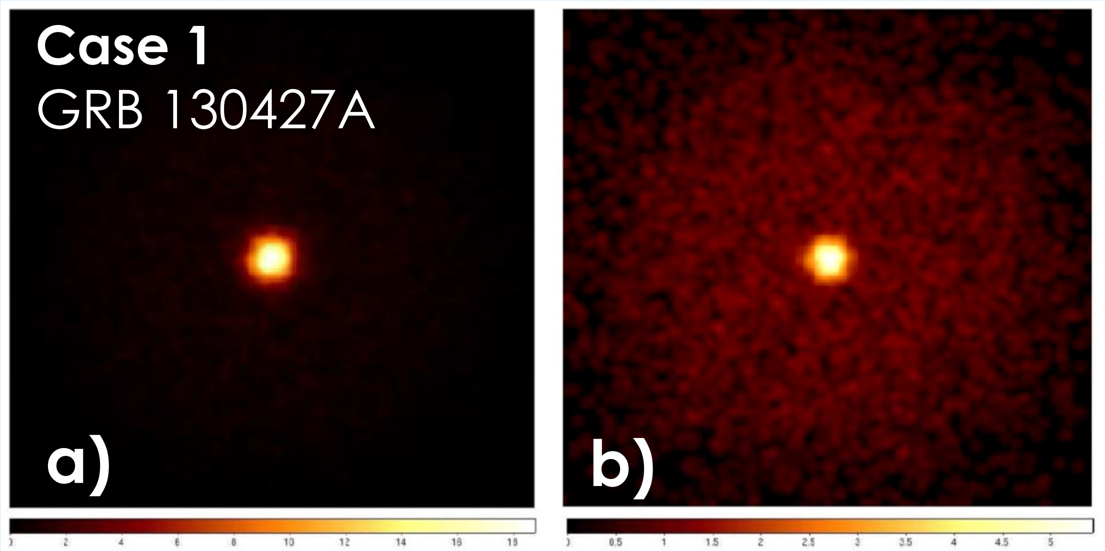
a) $T_{start} = T_0 + 1$ ks, $\Delta t = 10$ min
b) $T_{start} = T_0 + 10$ ks, $\Delta t = 1$ hour

Case 2

a) $T_{start} = T_0 + 100$ s, $\Delta t = 100$ s
b) $T_{start} = T_0 + 1$ ks, $\Delta t = 500$ s

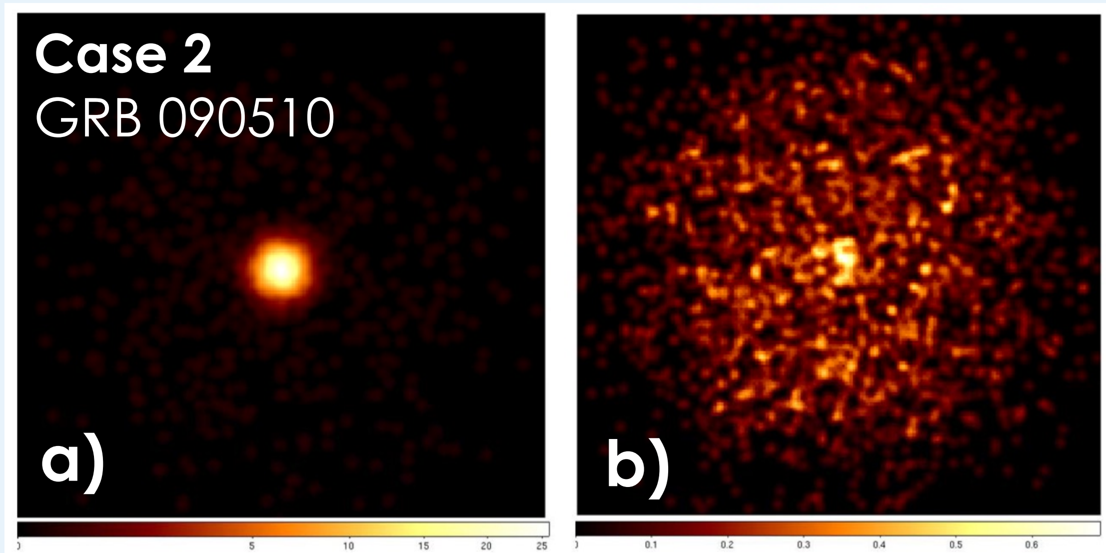
- Instrument Response Functions (IRFs):
  - a) North_0.5h , b) North_5h

First GRB simulation results



- Camera images are divided into **200×200 bins of 0.02°**

Bissaldi+16



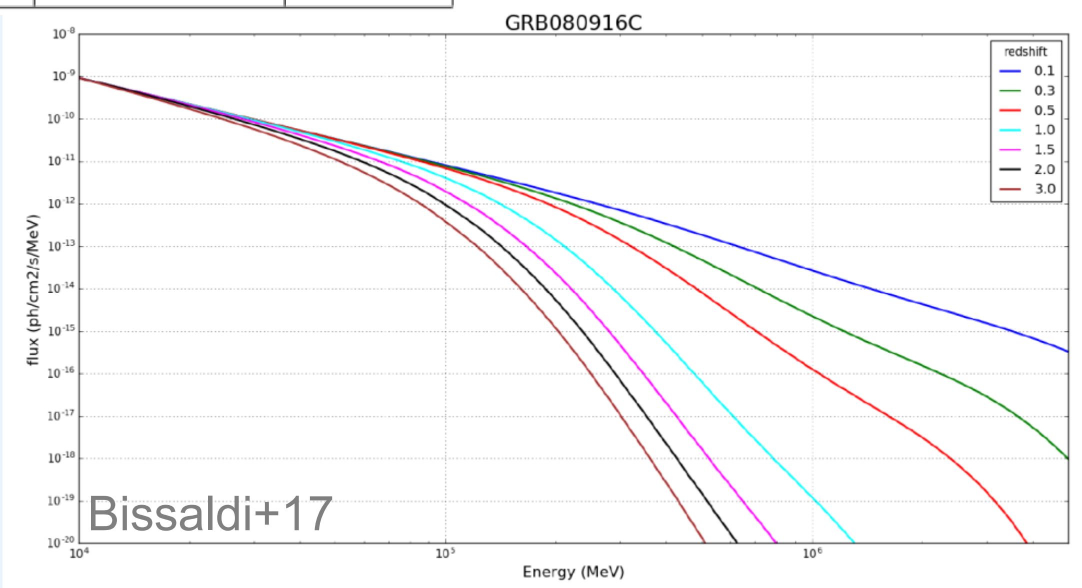
- Colour scale gives the **counts/bin** after Gaussian smoothing

Expanding the GRB sample

Name	F_p (ph/cm^2/s $\times 10^{-5}$)	En.index [β]	Time index [α]	$t_p(s)$
GRB080916C	500±100	2.05±0.07	1,37 ± 0.07	6,6 ± 0,9
GRB090323	6±3	2.3±0.2	1,0 ± 0.3	40 ± 30
GRB090328	9±4	2.0±0.2	1,0 ± 0.3	40 ± 30
GRB090510	3900±600	2,05±0.07	1,8 ± 0.2	0,9 ± 0,1
GRB090902B	600±100	1,95±0.05	1,56 ± 0.06	9 ± 1
GRB090926A	700±100	2,12±0.07	1,9 ± 0.2	11 ± 2
GRB091003	8±3	2,1±0.2	1,0 ± 0.2	22 ± 9
GRB100414	70±30	2.0±0.2	1,7 ± 0.3	20 ± 10
GRB110731A	220±60	2,4±0.2	1,8 ± 0.2	4,8 ± 0,7
GRB130427A	150±30	2.2±0.2	1.35 ± 0.08	20 ± 5

T. Gasparetto (master thesis – University of Trieste)

➔ Example study of **EBL absorption** for GRB 080916C placed at 7 different redshifts (z = 0.1 – 3)



“Time-window optimization” GRB analysis

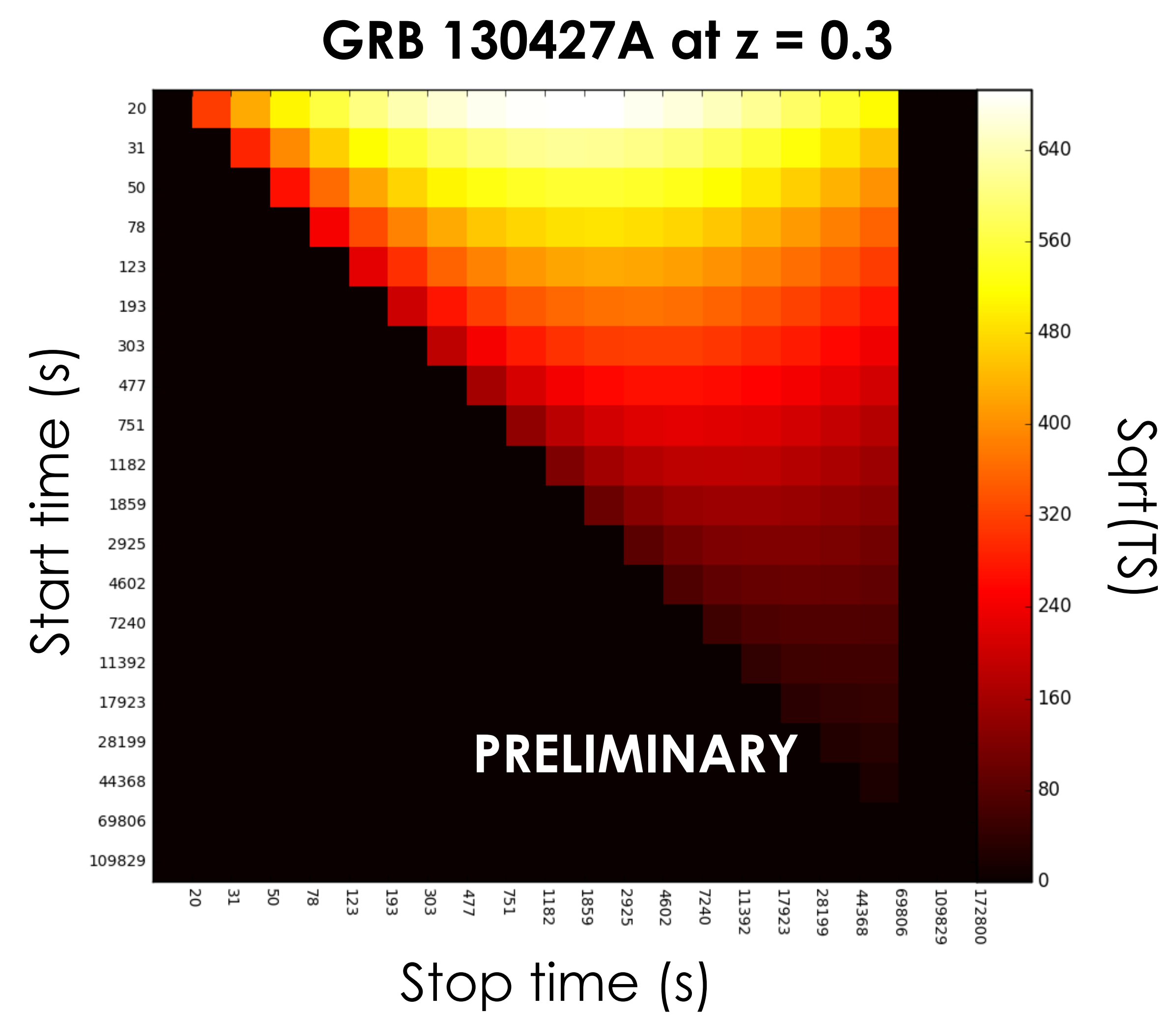
- Refined simulation of the flux extrapolated at late times by considering **smaller time bins**
  - Extrapolations from LAT measured HE spectral index and time decay power-law index (“afterglow” phase)
  - Considering **larger energy range** (from **20** GeV to **5** TeV)

➔ Calculation of the **GRB detection TS** and of the GRB flux estimation as function of the **observation time** (T_{start} and T_{stop})

- Placing the GRBs at **different redshifts** (z = 0.1 – 3)
  - Simulation of the effect of EBL absorption

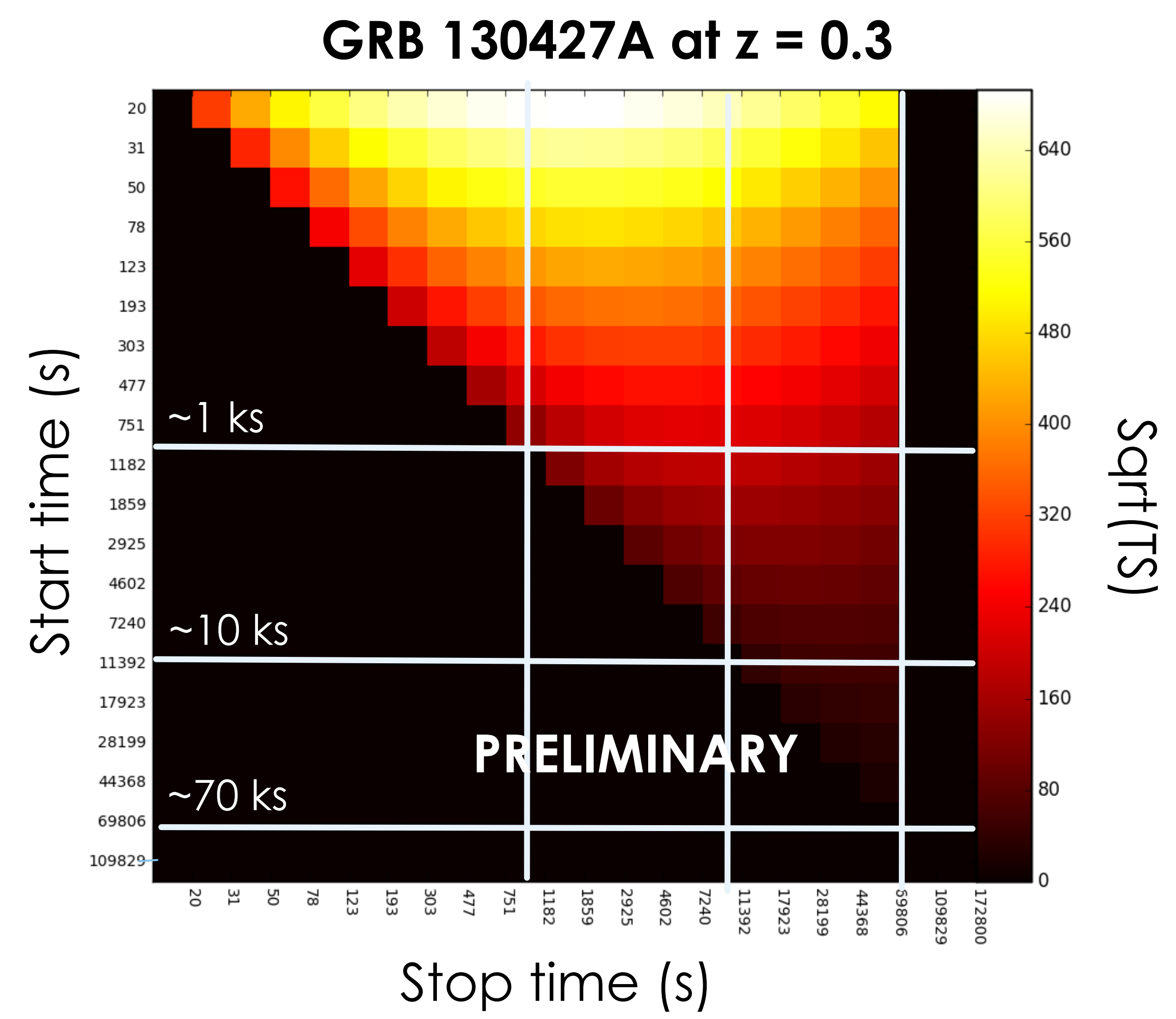
"Time-window optimization" GRB analysis

Calculation of the GRB detection TS (√TS) as function of the observation start and end time



"Time-window optimization" GRB analysis

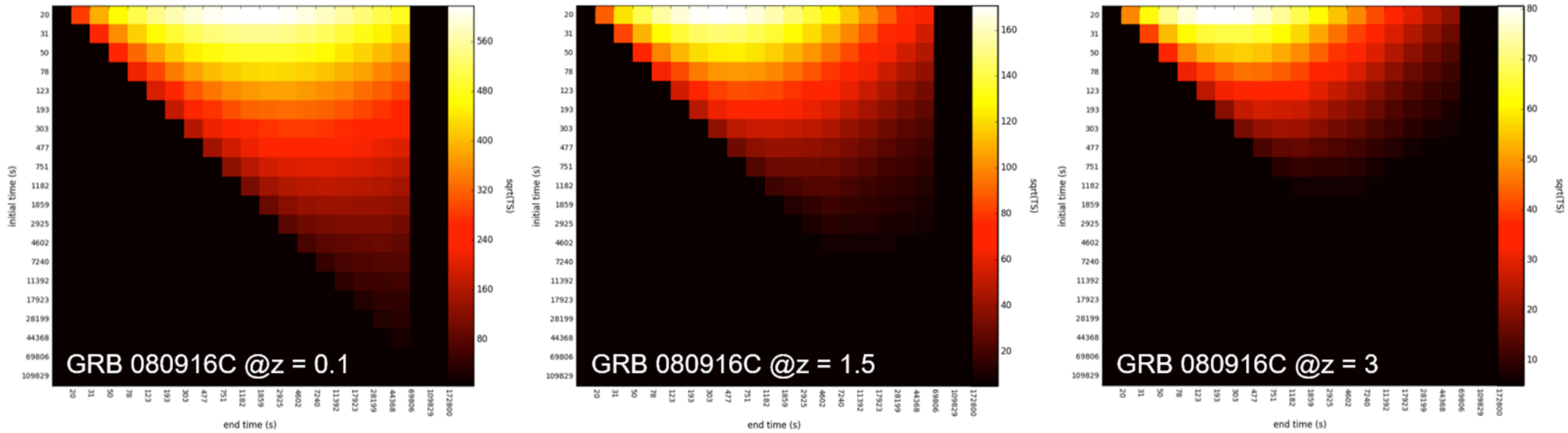
Calculation of the GRB detection TS (√TS) as function of the observation start and end time



"Time-window optimization" GRB analysis

- GRB 080916C

z = 0.1 **z = 1.5** **z = 3**



Bissaldi+

Summary – Fermi

- **Fermi GRB catalogs** provide a wealth of data on individual burst characteristics and for larger population studies
  - More GBM catalogs and the 2nd LAT catalog are coming soon!

    ➔Come to the 7th Fermi Symposium in Garmisch in October!

- **BTW…GBM and LAT** are ideal partner instruments in the **search for EM signals** in coincidence with GW detections
  - Both Teams have set up a series of **tools to monitor** and follow-up GW events
  - Looking forward to weaker GW signals from **NS-NS merger events**!

    ➔ Barbara's talk next!

Summary – CTA

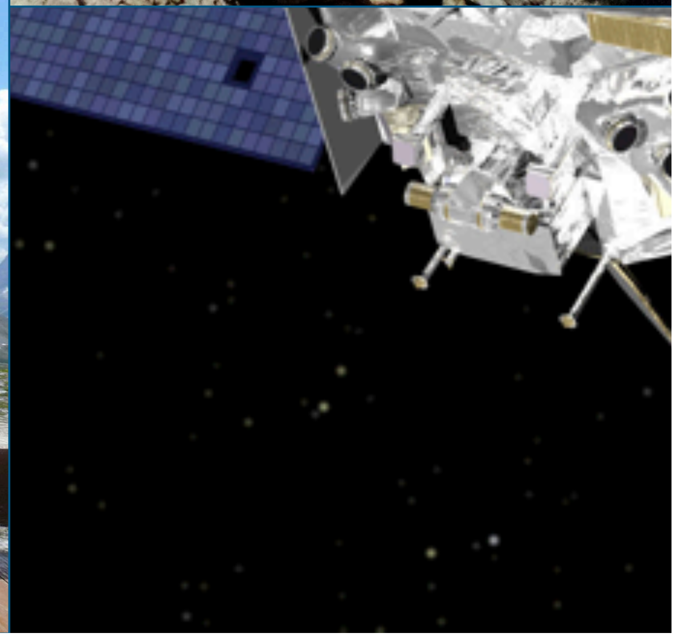
Ongoing work in the **CTA-GRB group**!

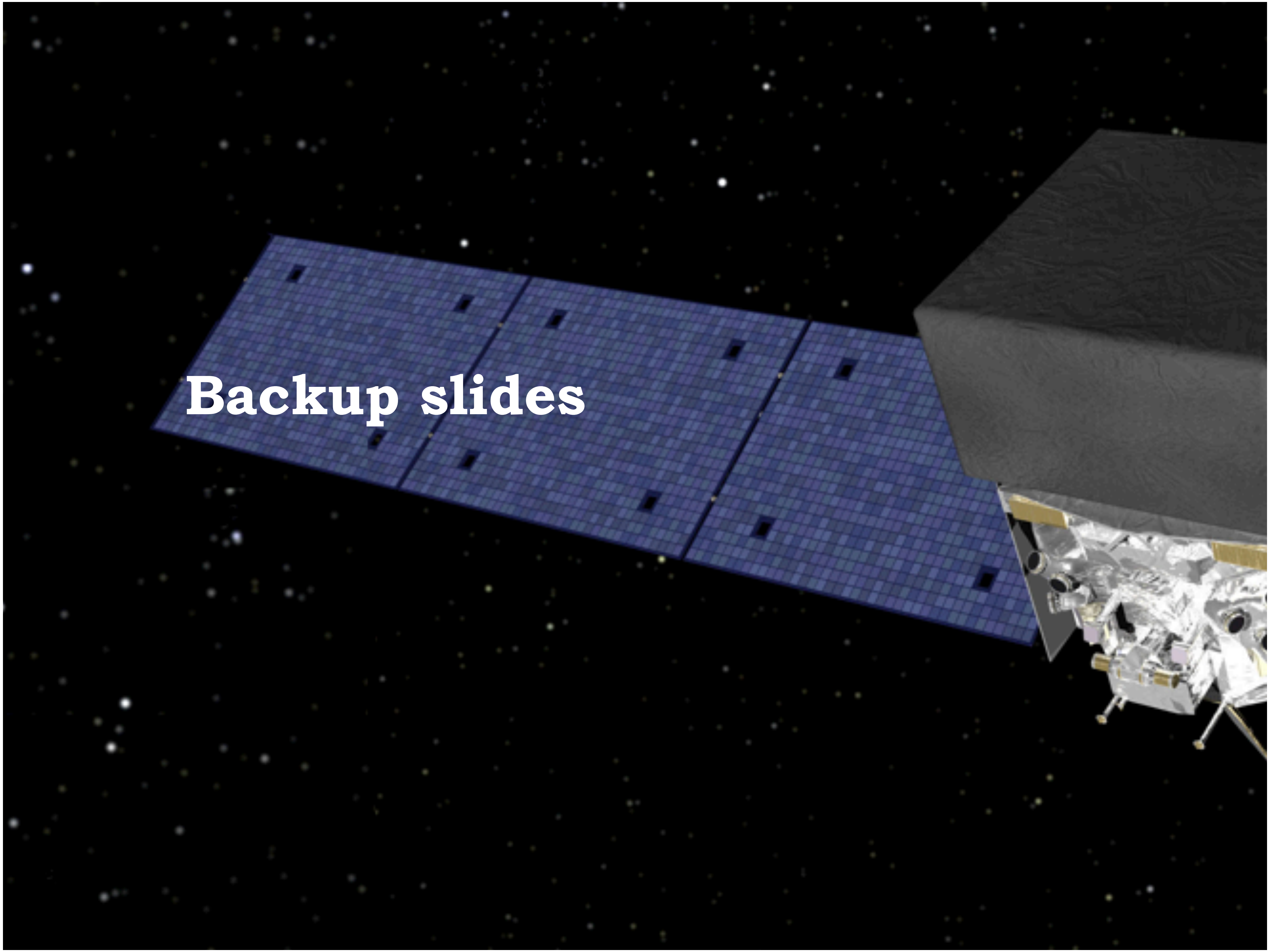
- Improving the **simulation tools**
  - Use of new IRFs and of South+North IRFs
- Extending the GRB sample from the upcoming LAT 2nd GRB Catalog
  - Working towards prompt phase studies!
- Setting up of an **Italian GRB network** with the CTA Transient WG
  - Population studies (G. Ghirlanda, S. Vergani et al.)
  - Theoretical approach to GRB emission in the prompt and afterglow phases (Z. Bosnijak et al., L. Nava et al., A. Carosi et al.)

Thank you!

Dolomites 1990

Dolomites 2013



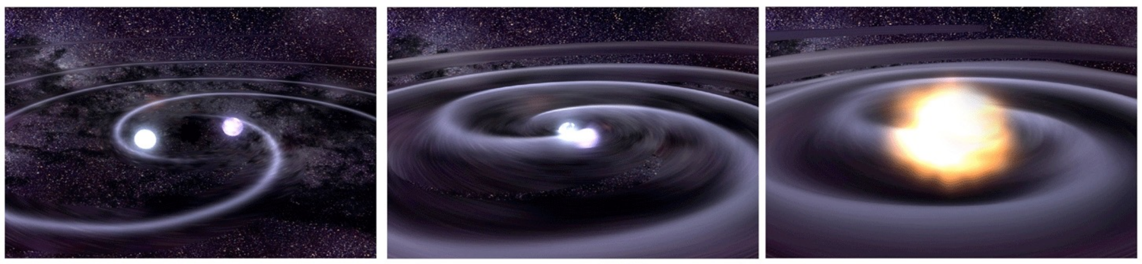

Backup slides

Untargeted GBM offline searches

- **Dedicated search algorithms** for untriggered transient sources
  - Magnetar bursts (~200)
  - TGFs (> 1000)
  - Other Galactic sources
  - Short GRBs (sGRBs)
    - Initially developed for TGF search
    - Analysis using 10 timescales, 5 energy ranges and 2 detectors with favorable geometry
    - Soft and long duration candidates are removed

→ **Additional ~ 35 per year**, most of them undetected by other instruments (verification in progress)

Short GRBs → NS-NS, NS-BH



Untriggered GBM sGRB candidates

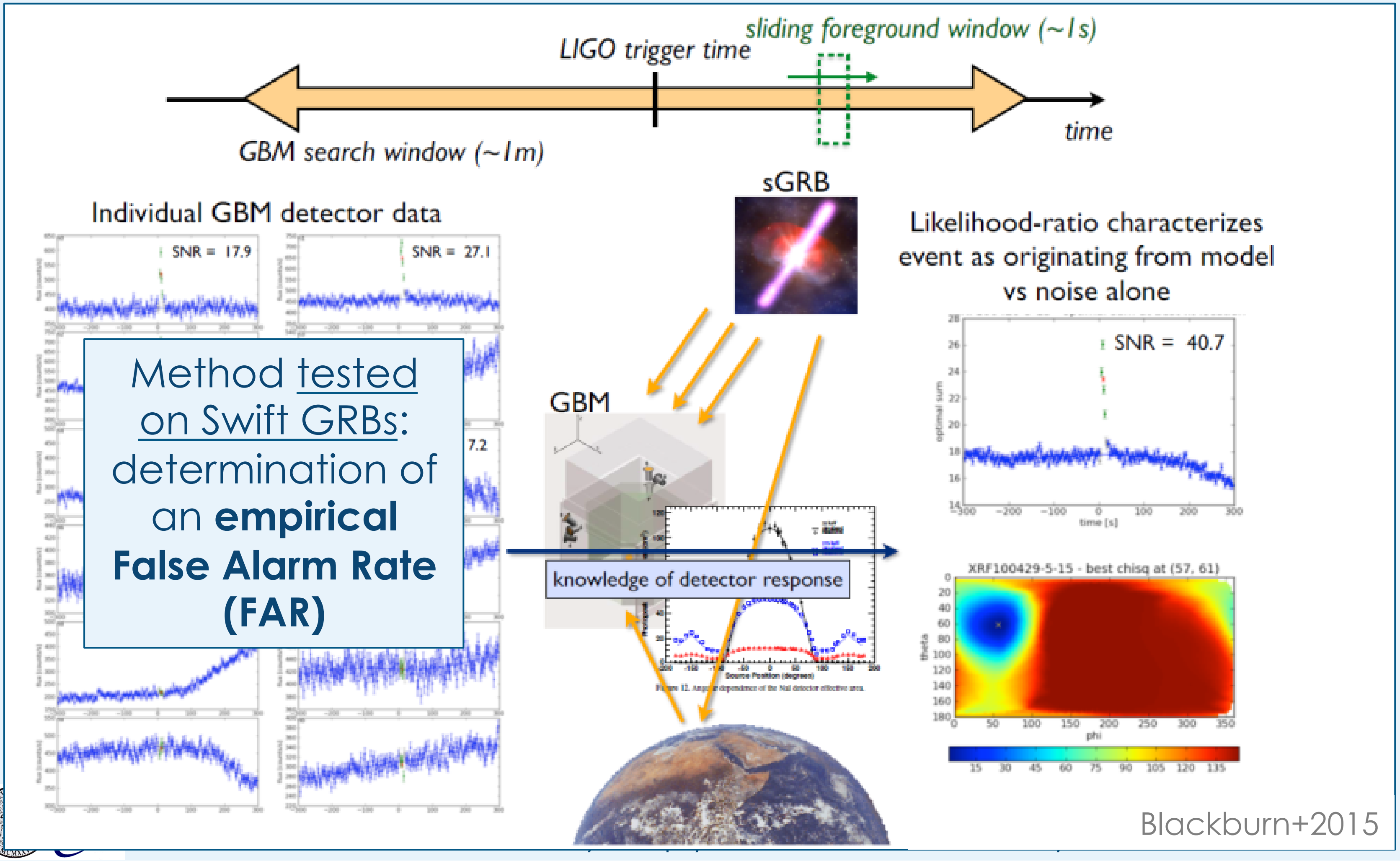
Short GRB Candidates

MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)	COMMENT
392494389.500	3.17E-0007	2013-06-09	18:13:6.500	323.24	+21.54	13.83	
392551943.650	2.55E-0007	2013-06-10	10:12:20.650	73.68	-19.40	11.76	
• • •							
423745096.625	1.91E-0016	2014-06-06	10:58:13.625	232.07	+37.47	18.86	Swift GRB, also ACS
424708158.025	2.36E-0007	2014-06-17	14:29:15.025	359.06	-32.47	5.59	
424757010.500	1.92E-0016	2014-06-18	04:03:27.500	278.84	+64.38	4.67	ACS confirmation
424968038.500	2.80E-0007	2014-06-20	14:40:35.500	319.45	-17.40	17.05	
426588599.600	7.75E-0014	2014-07-09	08:49:56.600	12.77	-49.36	6.53	ACS confirmation

- A **list of untriggered sGRB** candidates (June 2014 to present) are listed at http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html
- Working towards creating **automated GCNs**, will be distinct from triggered events type

Targeted GBM Searches to GW events

- During **LIGO S6 observing run**, GBM developed a **coherent search over all detectors**, seeded with LIGO time and (optionally) position



The transient “GW150914-GBM”

- **Targeted search around GW150914:**
  - Initial 60s (± 30s) search window (selected a priori)
  - **2 candidates**
    - Soft transient: T_{GW} +11 s, 2s long: Gal.Cent. Regio
    - Hard transient: T_{GW} +0.4 s, 1s long: **GW150914-GBM**
      - **0.2% probability of occurring by chance (2.9σ)**

FAR = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

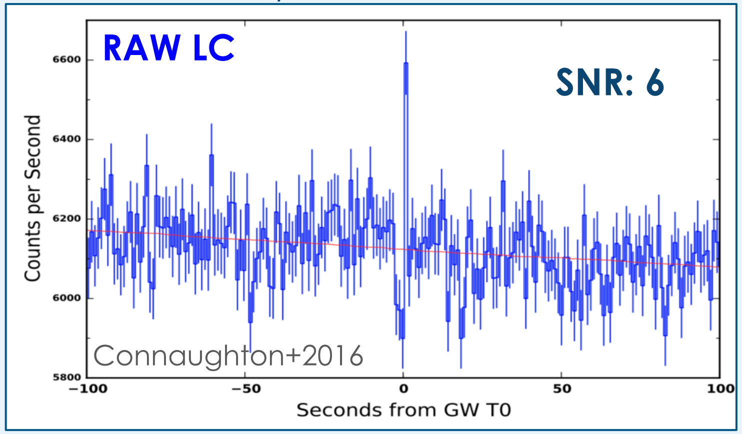
P = 2 x (4.79 × 10–4 Hz) × 0.4 s × (1 + ln(30 s / 0.256 s)) = 0.0022

Factor of 2 to account for offset in time in either direction

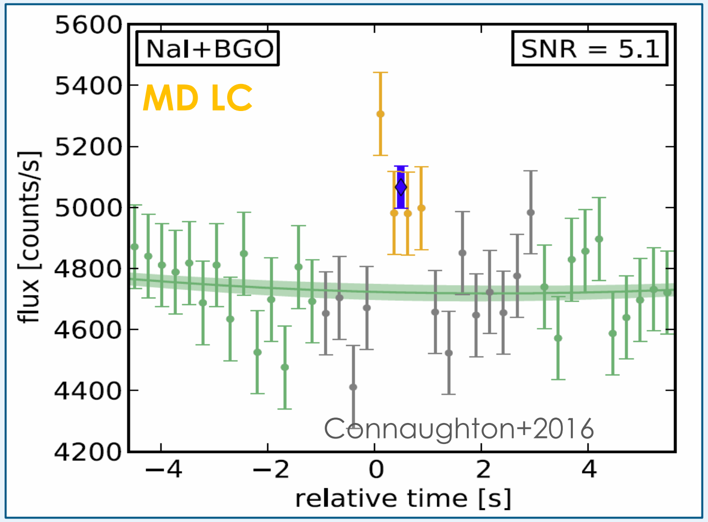
Offset between GW T0 and GBM event start

Effective trials factor for non-independent, variable time bins (30s is maximum offset set by the search window, 0.256 is the minimum set by native CTIME data)

Raw count rates:
Sum of all GBM detectors: 12 x NaI + 2 x BGO
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV

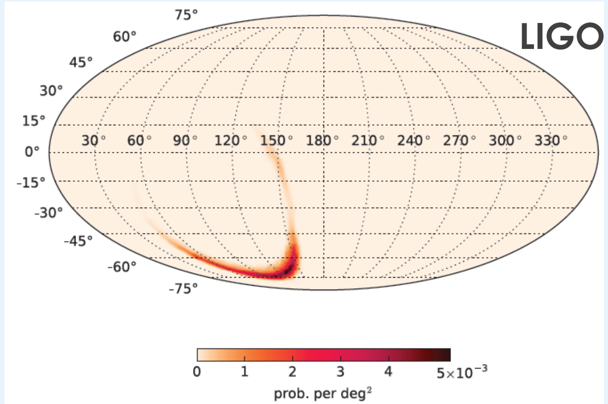


Model-dependent count rates:
Raw count rates weighted & summed to max signal-to-noise for a modeled source



The transient "GW150914-GBM"

- Unusual detector pattern:
  nearly equal count rates in all NaI detectors
  - Localization: source direction **underneath** the spacecraft, **163° to the spacecraft pointing** direction (similar to Swift-GRB130306A)



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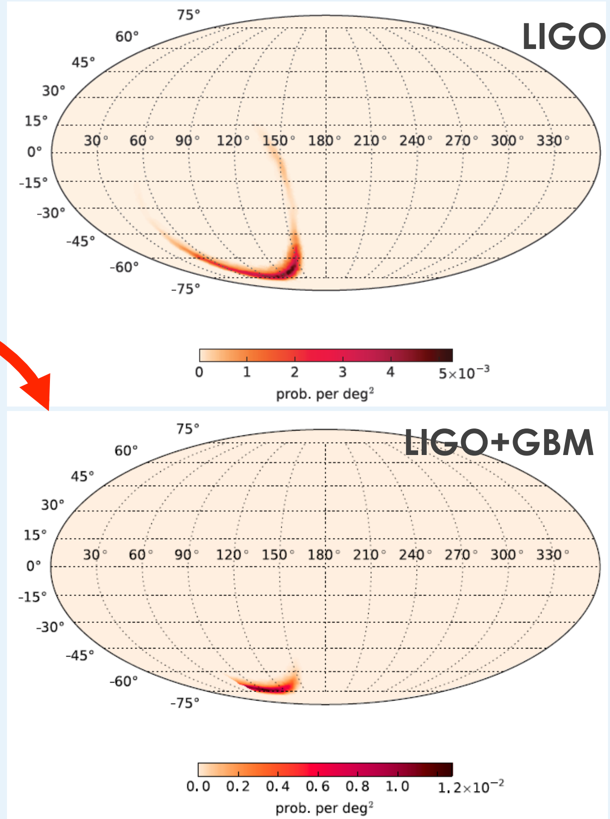
  - If association with GW150914 was true: **shrink LIGO localization by 2/3**



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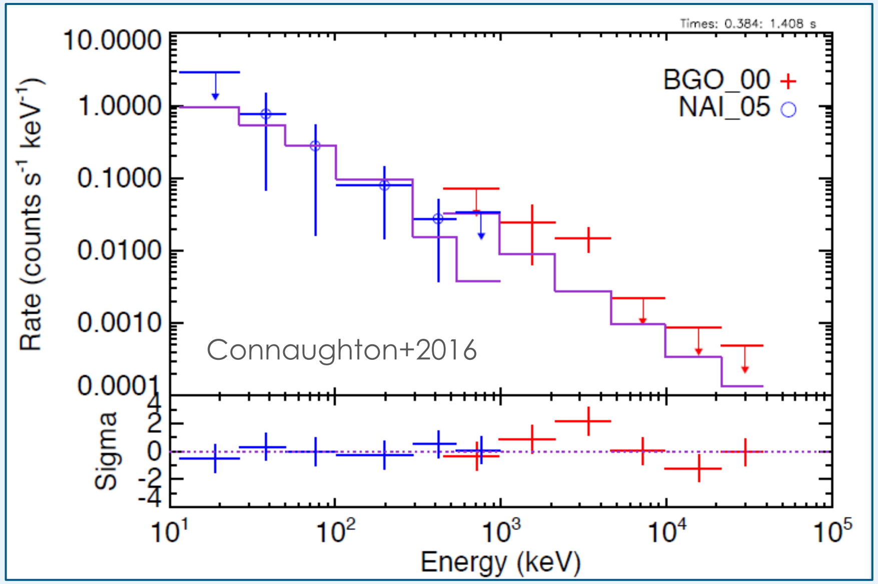
  - If association with GW150914 was true: **shrink LIGO localization by 2/3**

- **Energy spectrum**:
  - Peaking in BGO energy range. Best fit **simple PL** with index **–1.4** (average for sGRBs), Fluence **2.4 x 10^{-7} erg cm^{-2}** (weaker than average for sGRBs)



Association with GW150914?

- **Evidence for:**
  - 3 sigma False Alarm Probability
  - GBM signal localized to a region consistent with the LIGO sky map
  - Cannot be attributed to other known astrophysical, solar, terrestrial or magnetospehric activity

- **Evidence against:**
  - Low significance
  - Lack of corroboration by other experiments
  - Nature of the LIGO event is a BH-BH merger

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Magneto spheric	No	?	?	No	No	No
Solar Activity	?	No	No	No	N/A	No
Something New	?	?	?	?	?	Maybe? Unlikely
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

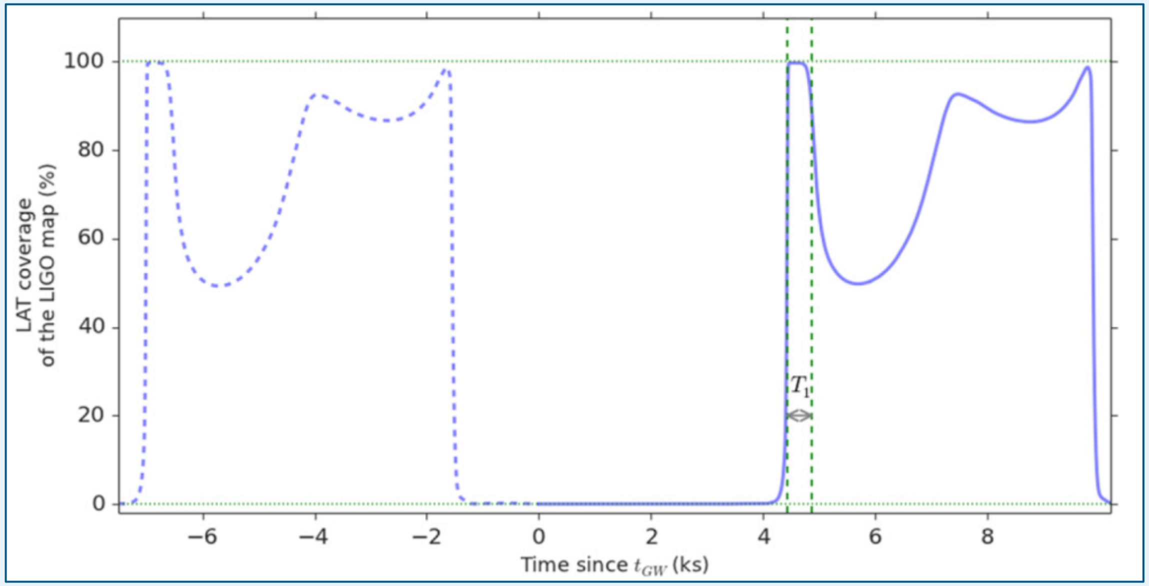
MOST LIKELY

Fermi-LAT follow-up of GW 150914

- Development of a **novel technique** to search for EM counterpart in LAT data starting from LIGO probability maps (Vianello+17)
  - Release of probability maps (in HELPix) by the LIGO/Virgo Collaboration
  - **Downscaling the maps** to match the Fermi LAT PSF (~4 degrees at 100 MeV)
  - Centering of the ROI in each pixel + **standard likelihood analysis (Unbinned)**
  - Adopting **several timescales** to be sensitive to transients of different duration

Fermi-LAT coverage

Green dashed vertical lines: boundary of the interval T1 used in the analysis, at 4ks post trigger



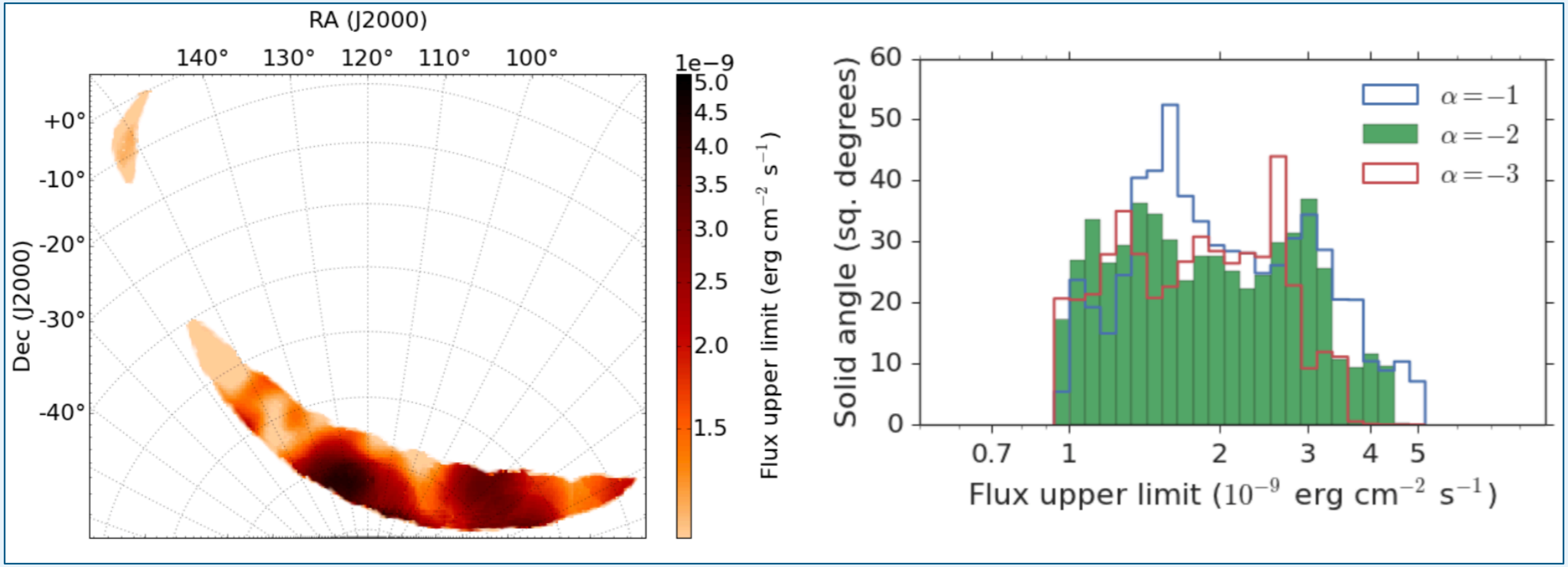
Fermi-LAT follow-up of GW 150914

- **GW150914:**
  - Search in the time interval having more than 90% coverage (from T0+4400, T0+4500)
  - Fixed window of 10ks
  - "Adaptive" time window (entry-exit for each pixel in the sky), over an interval of 10 days (before and after the trigger).
- For comparison: **LVT151012 & GW151226**
  - Fixed (short) time windows of T0-10s, T0+10s
  - Fixed (long) time windows
    (8ks for GW151012 and 1.2 ks and 10ks for GW151226)
  - "Adaptive" time windows, as defined above
- Long baseline search
  - ASP: integration time of 6 hours, 1 day
  - FAVA: integration time of 1 week

No significant excess was detected
Upper Limits calculations

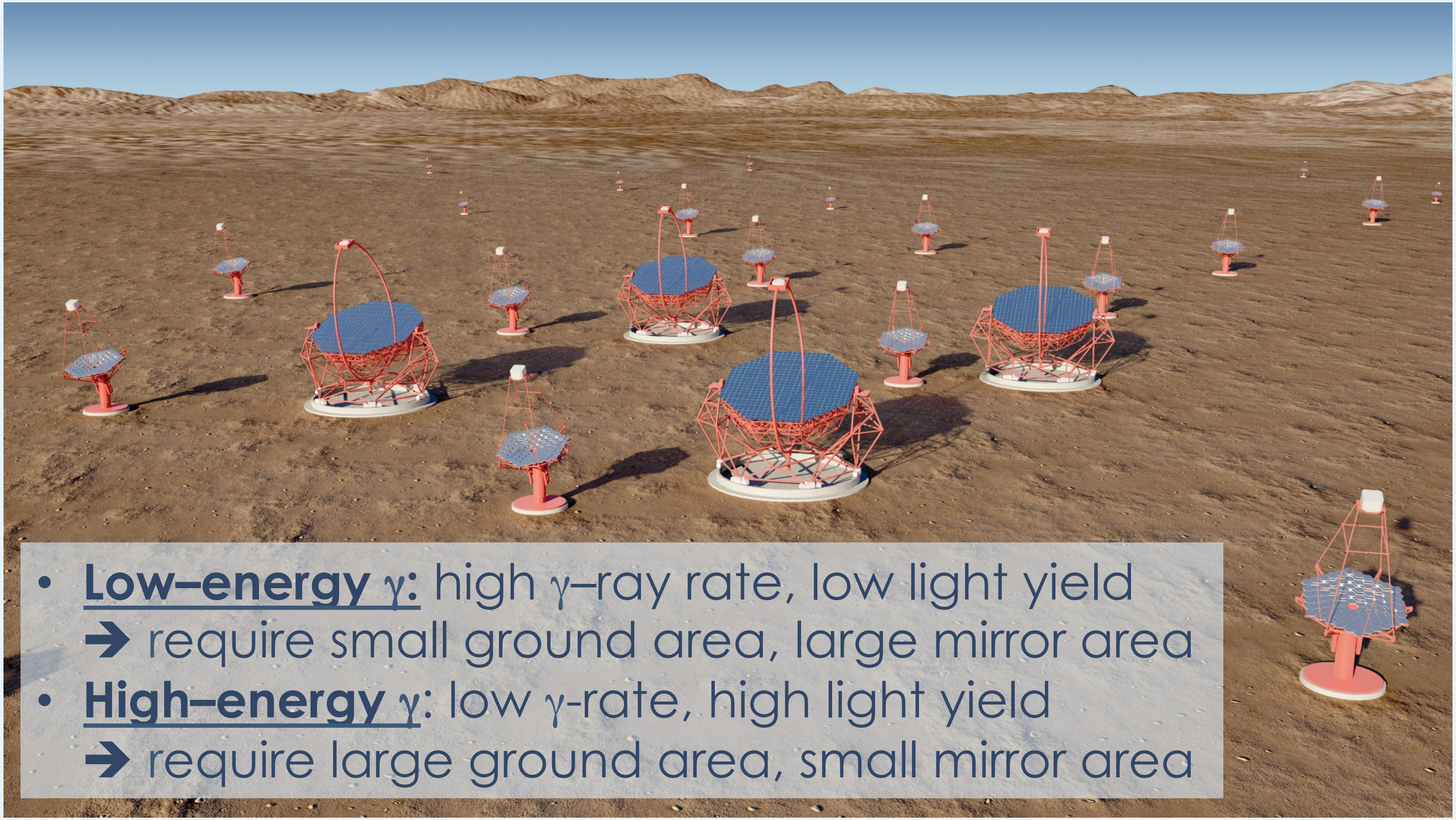
Fermi-LAT follow-up of GW 150914

- **Upper limit map** for the fixed time window search (from T0+4400, T0+4500)
  - Assuming a **power-law spectrum** for the source, with a photon index **α** of −2 (typical of afterglows of GRBs) → **green histogram**



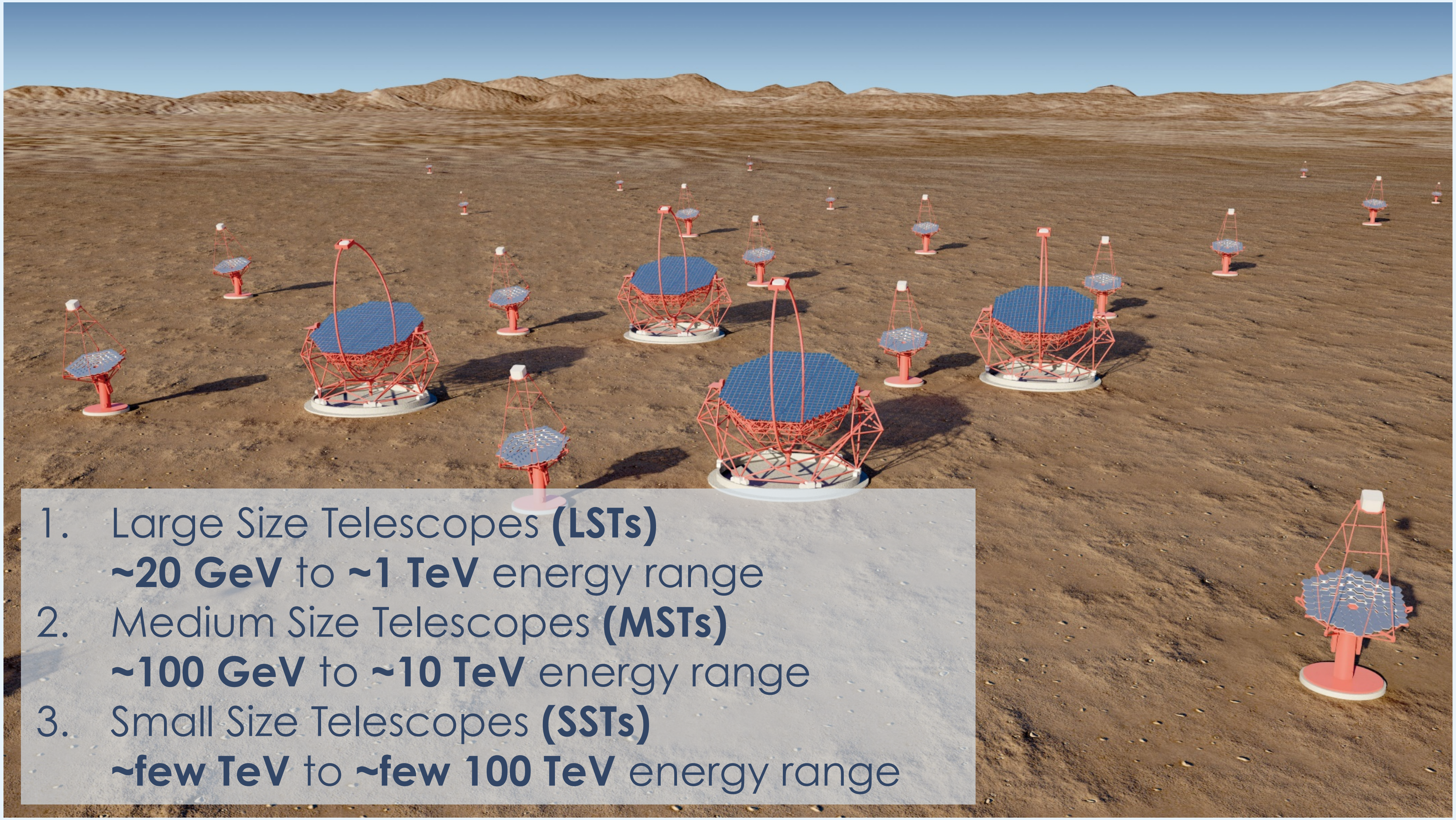
Upper limits largely independent of the photon index assumed!

CTA requirements and drivers



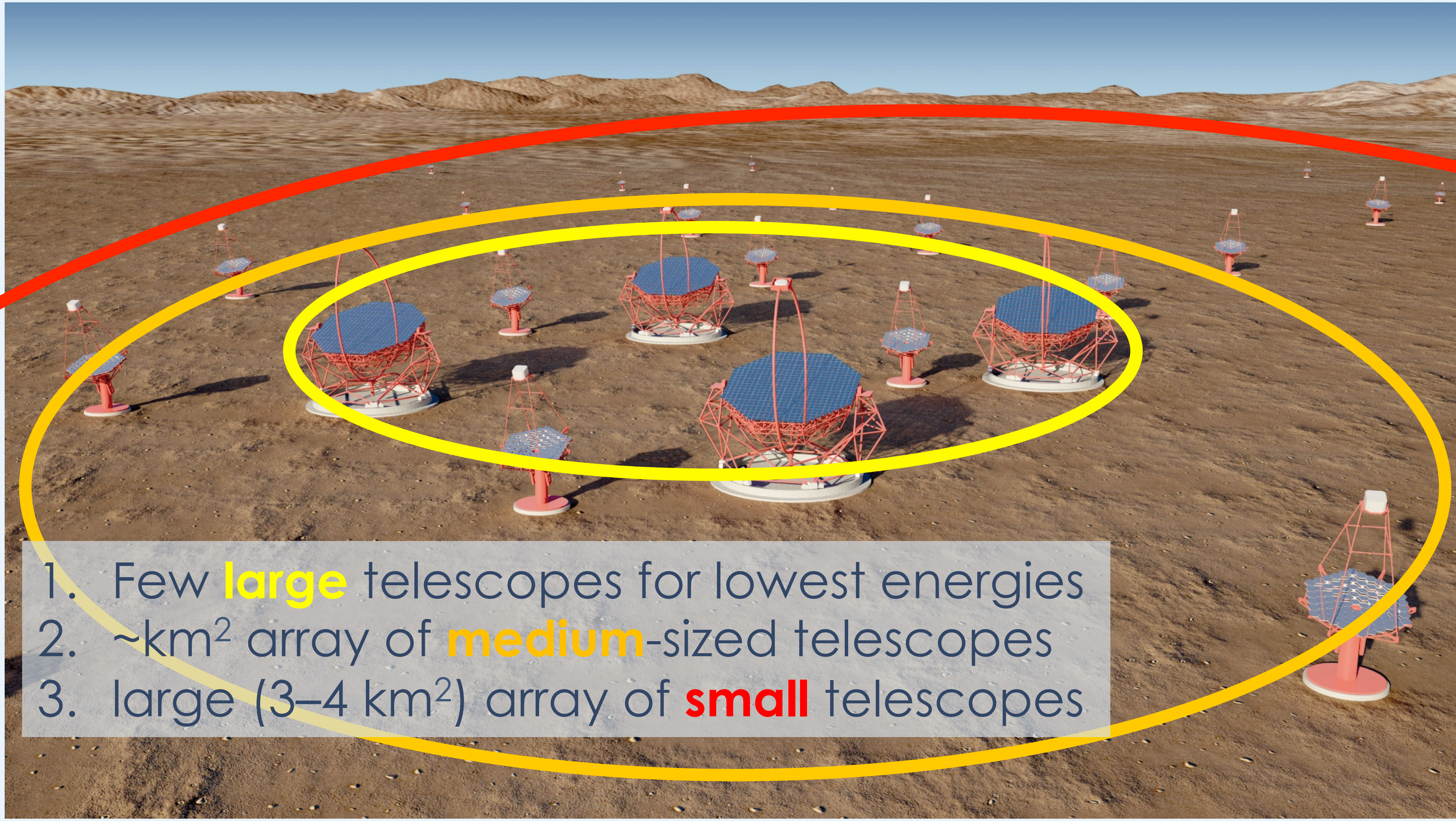
- **Low–energy γ:** high γ–ray rate, low light yield
  ➔ require small ground area, large mirror area
- **High–energy γ:** low γ-rate, high light yield
  ➔ require large ground area, small mirror area

CTA requirements and drivers



1. Large Size Telescopes **(LSTs)**
   ~20 GeV to **~1 TeV** energy range
2. Medium Size Telescopes **(MSTs)**
   ~100 GeV to **~10 TeV** energy range
3. Small Size Telescopes **(SSTs)**
   ~few TeV to **~few 100 TeV** energy range

CTA requirements and drivers



1. Few **large** telescopes for lowest energies
2. ~km^2 array of **medium**-sized telescopes
3. large (3–4 km^2) array of **small** telescopes

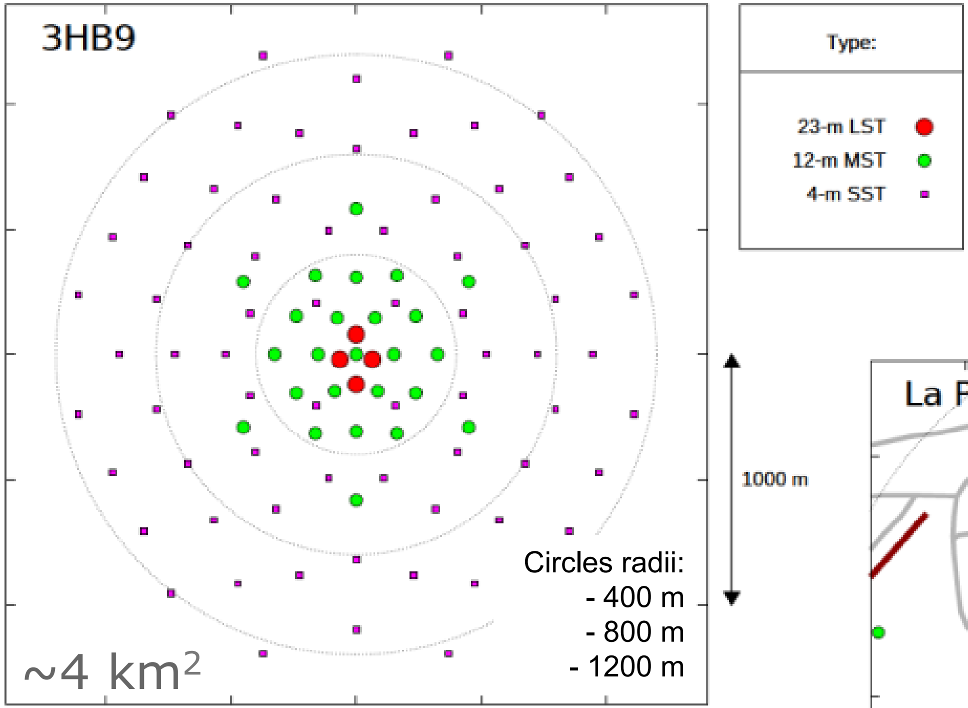
The CTA array sites

The CTA Consortium
32 countries
88 parties
202 institutes
1308 members (438 FTE)

North Site: La Palma (IAC)

South Site: Chile (negotiations progressing with ESO)

CTA baseline array layouts

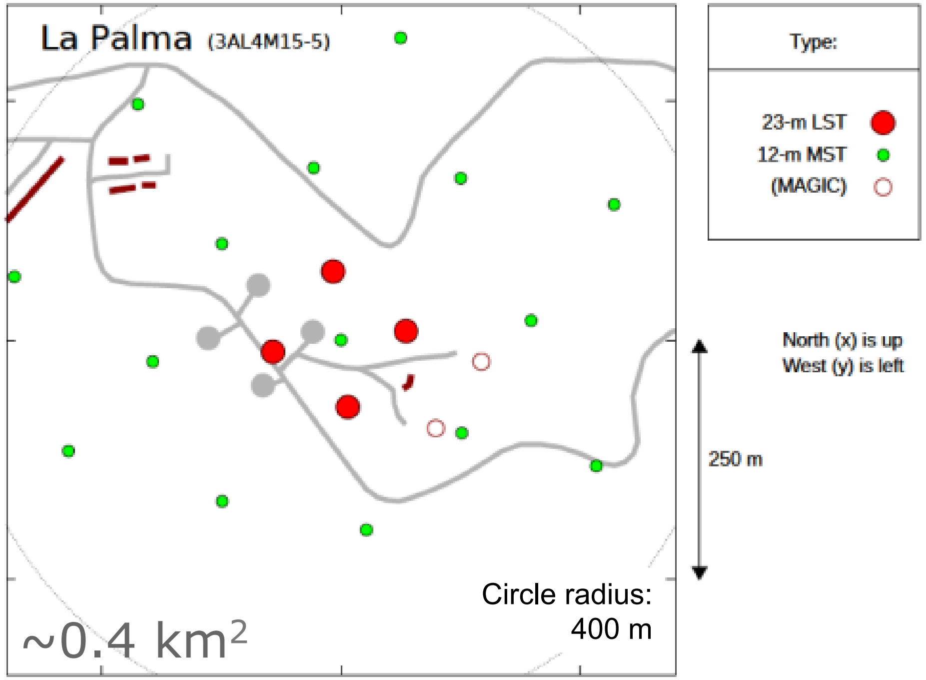


South Site:

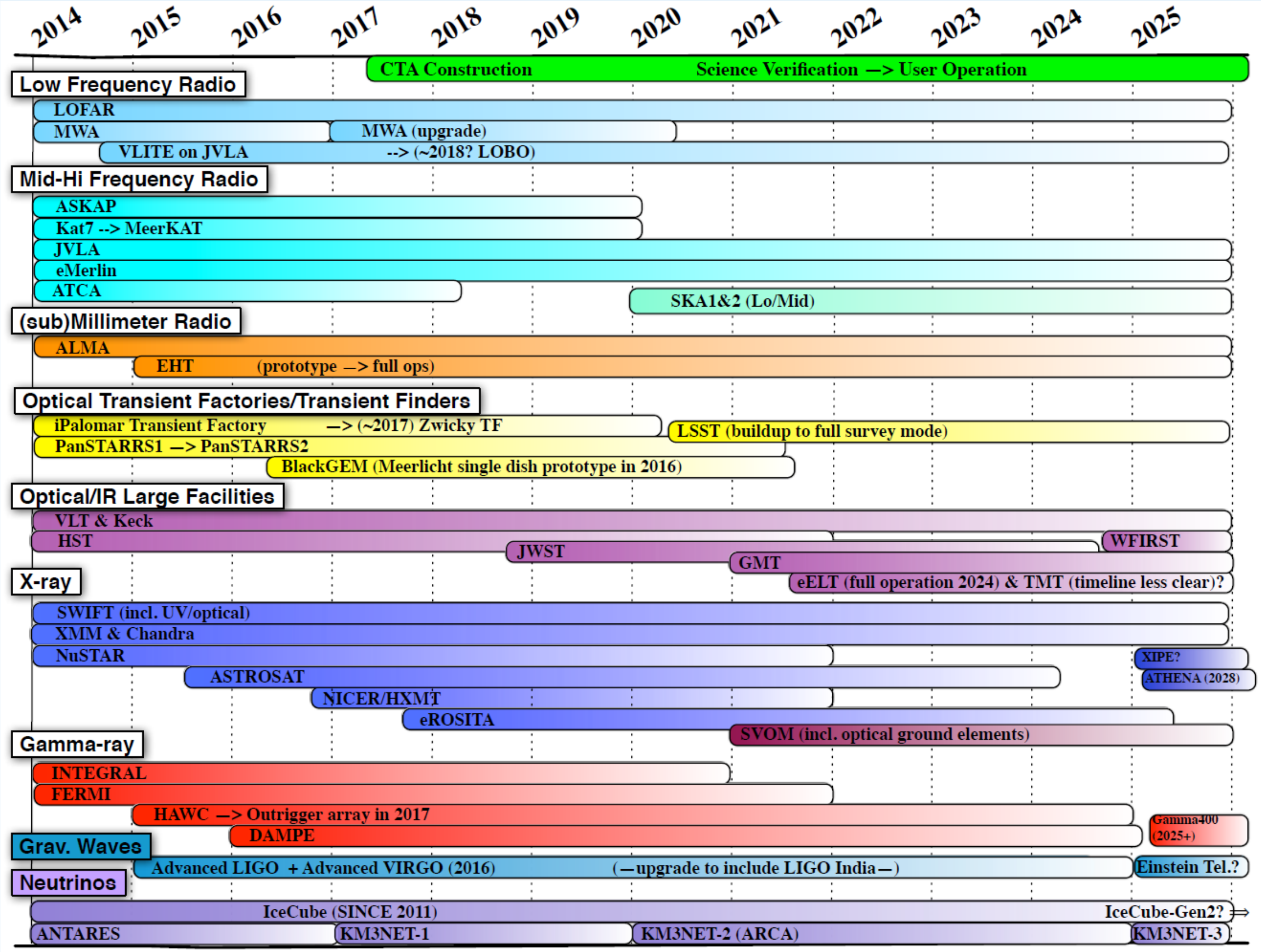
4 LST
25 MST
70 SST

North Site:

4 LST
15 MST



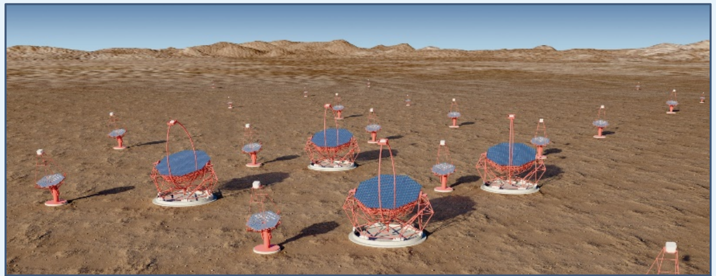
CTA multi-wavelength/messenger synergy

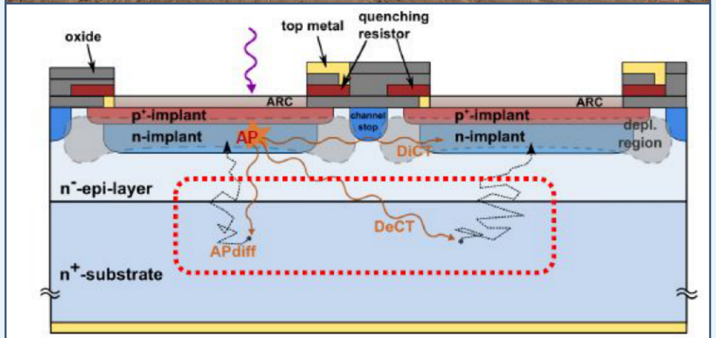


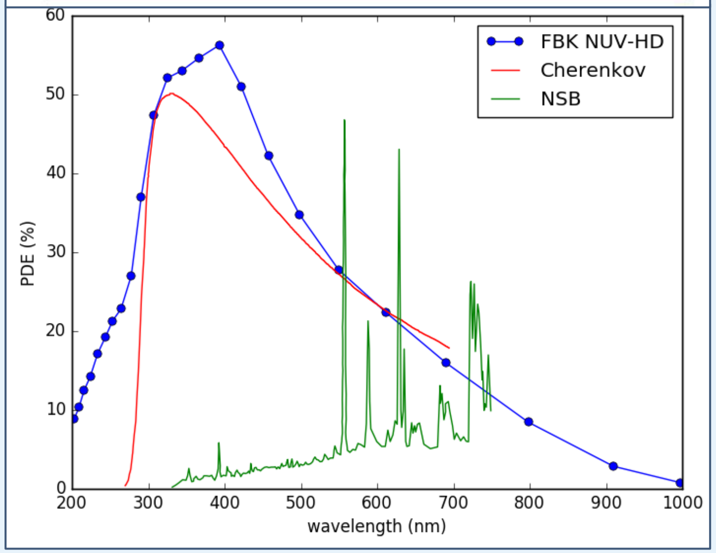
CTA and Silicon Photomulitpliers

- SiPMs as **camera photosensors**
  - **Smaller** areas (<1cm$_2$), hence **higher pixel angular resolution**
  - Higher **photo-detection efficiency** at UV wavelengths (c.a. 50%)
  - **Fast** response O(1-10) ns
  - Not damaged by moonlight, can be operated during bright Moon nights **enhancing the DAQ duty cicles**
  - Can be operated with **low bias voltages** <100V
  - **Low power consumption** (μW)
  - **Light weigth**

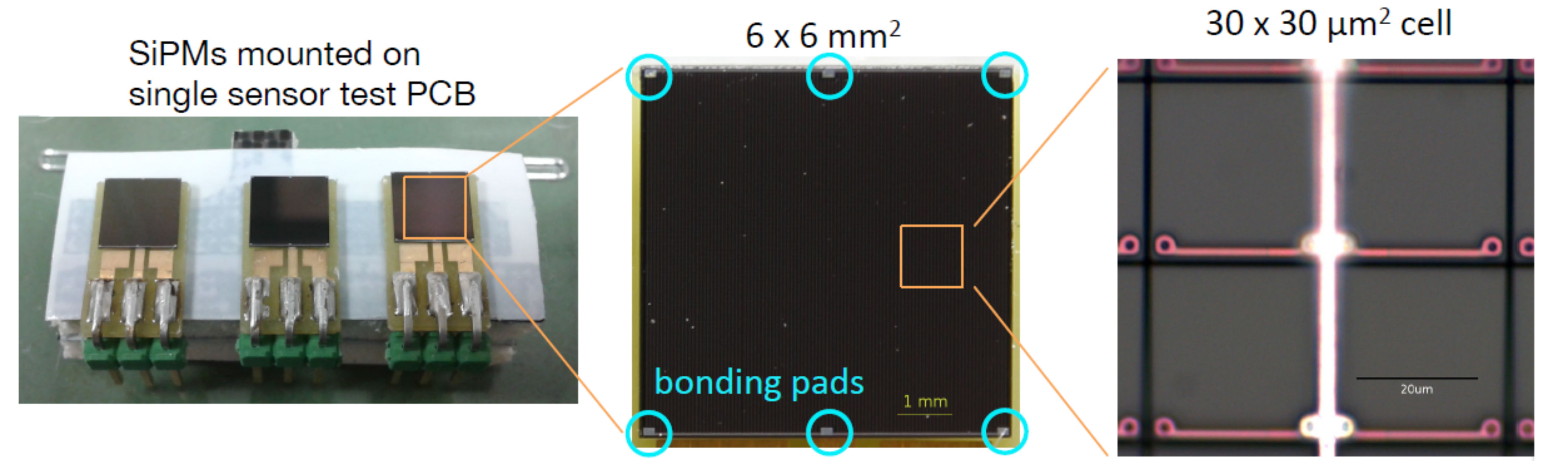
- Readout electronics:
  - wide dynamic range
  - high-level trigger logic to discriminate Cherenkov photons from night sky bg
  - deep sampling buffer to sample and store whole waveforms.





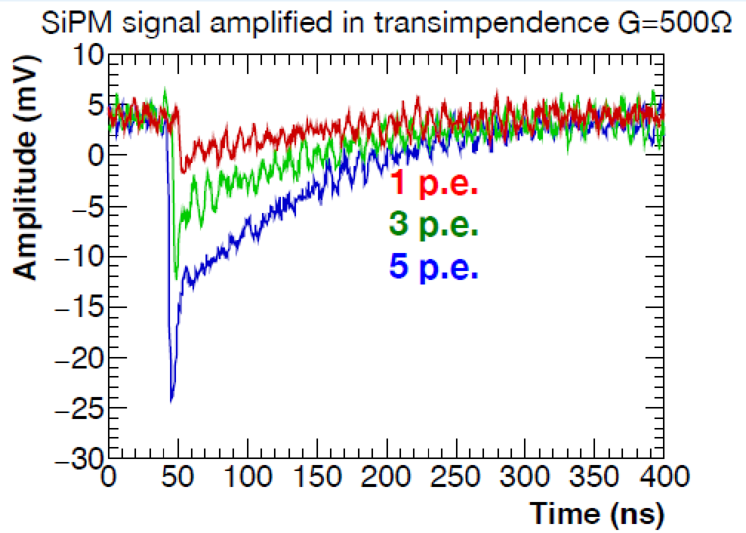


FBK NUV high-density (HD) SiPM sensors



- Produced at Fondazione Bruno Kessler (FBK, Trento)
  - p-n SiPM
  - Active area: 6.03 x 6.06 mm^2
  - Microcell size: 30 x 30 µm^2
  - Fill Factor: 76 %
  - High PDE (50 %) for UV photons

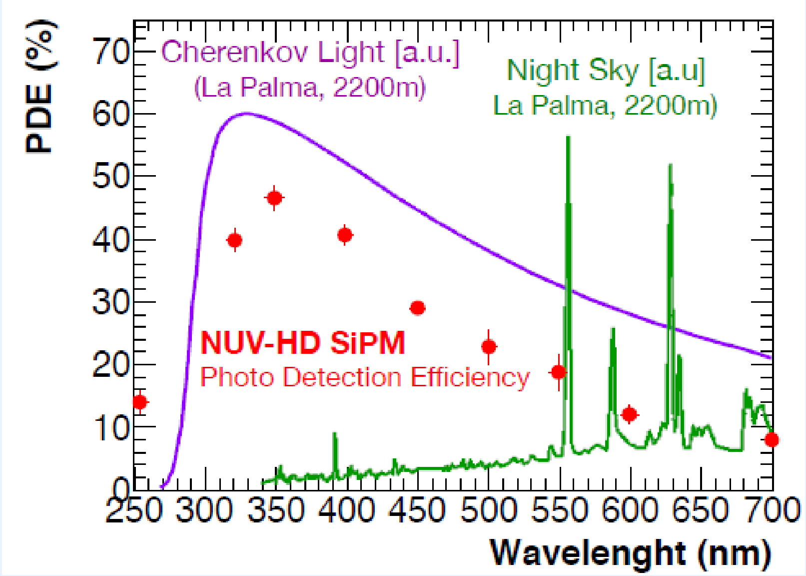
➔ NUV-HD technology successful, development of further improvements are ongoing

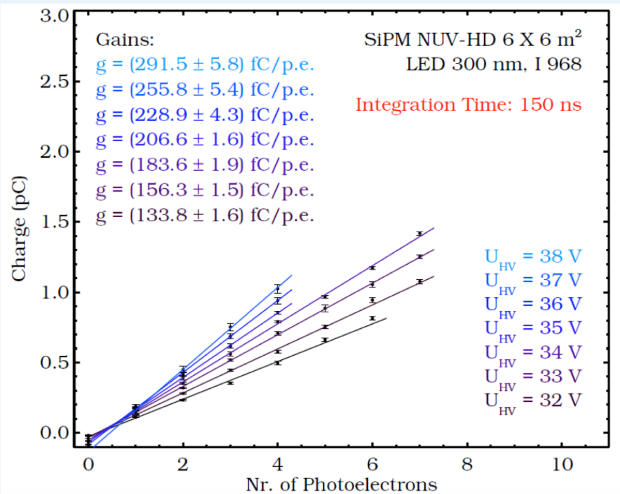


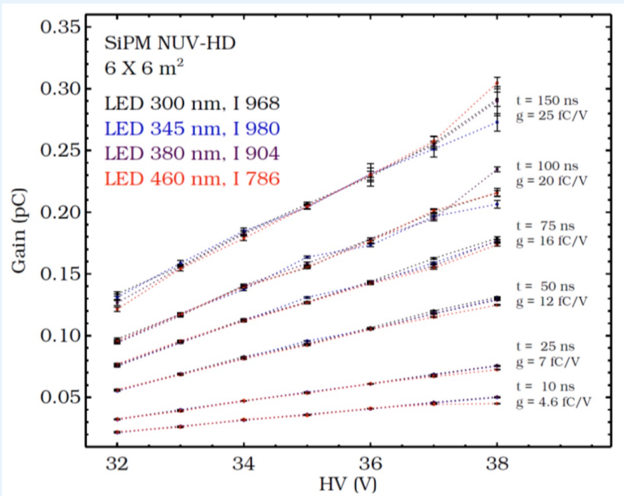
FBK NUV-HD SiPM sensors

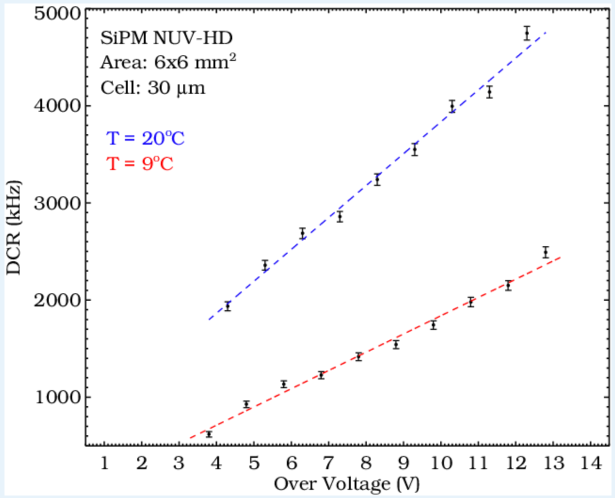
- NUV-HD SiPM sensitivity peaks towards the NUV (Cherenkov signals) with maximum at 50%
- Wide dynamic range and high gains, discrete DCR

➔ Test campaigns ongoing in Bari since 2013 on various generations of FBK SiPMs



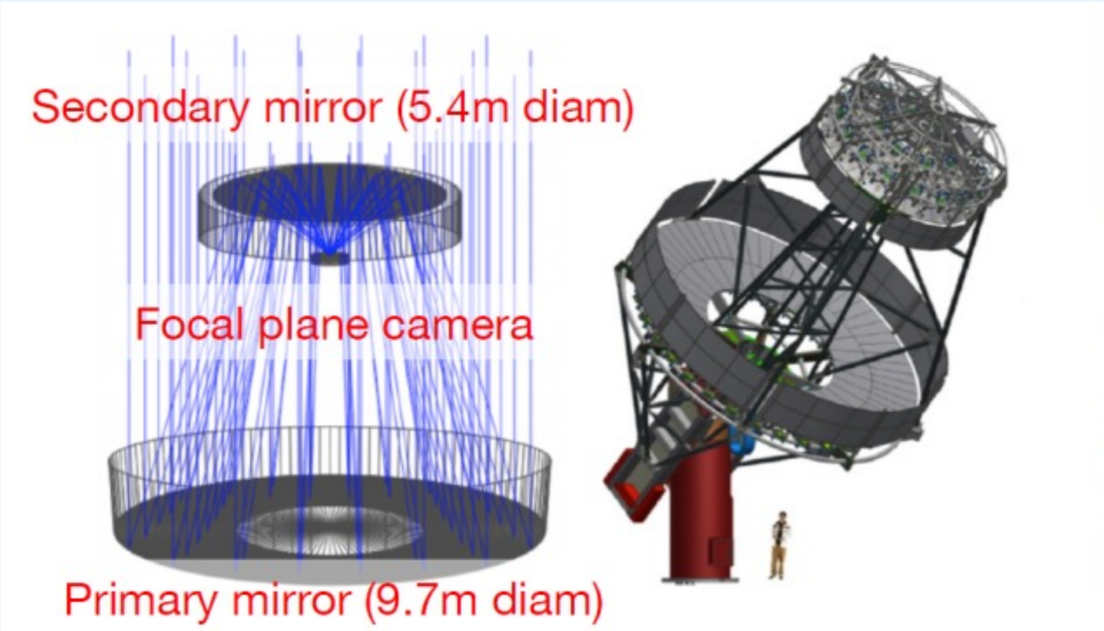






CTA SCT telescopes

Schwarzschild-Couder Medium Size Telescope

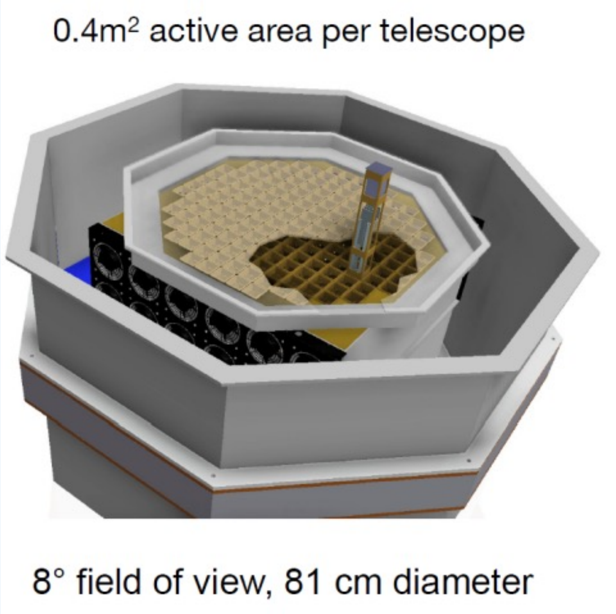


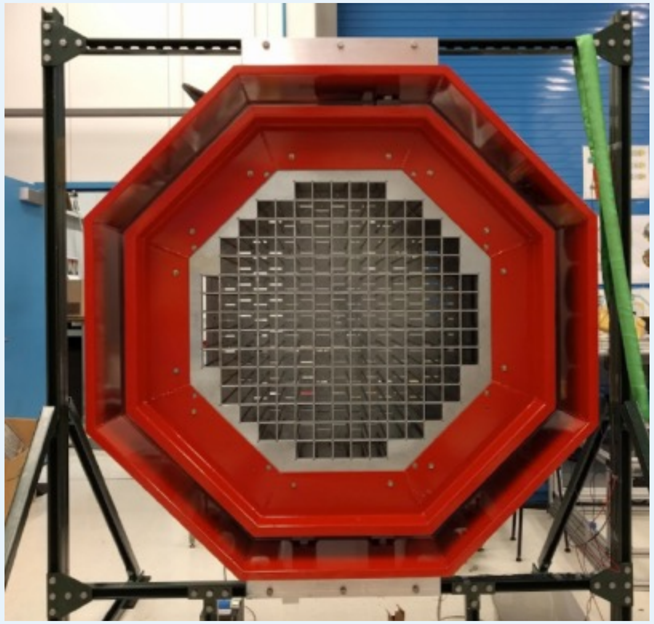
- **Dual mirror optics**
  - Designed to cancel aberration and de-magnify images
  - compatible with compact high-resolution SiPM camera
  - Smaller PSF and improved angular resolution than single-mirror telescopes

➔ **Mechanical stability** and **mirror alignment** are the main challenges

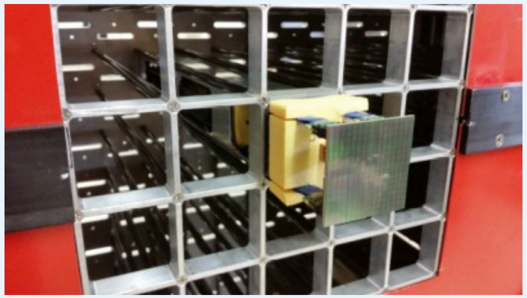
pSCT telescope

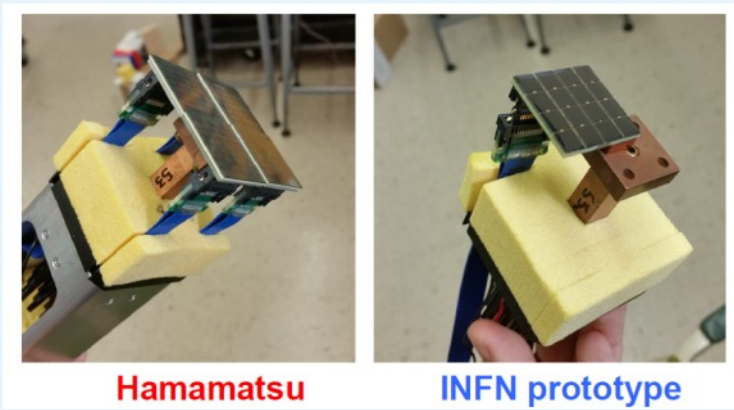
- Prototype demonstrator for the Medium Size SCT





pSCT camera mechanics at the University of Wisconsin, Madison





FBK 6x6mm^2 SiPM will replace some of the original Hamamatsu SiPMs and equip a part of the pSCT camera

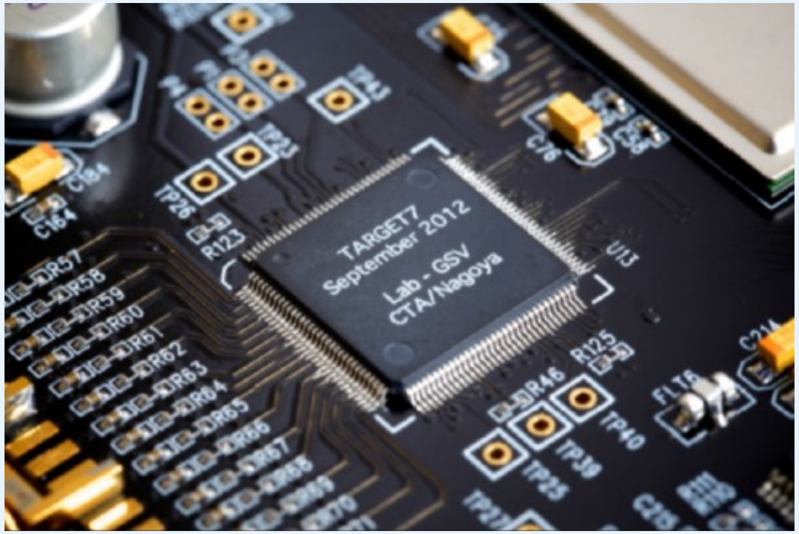
pSCT focal plane modules

PCB modules are **assembled** with **SIPM sensors** in the laboratories of **INFN**.

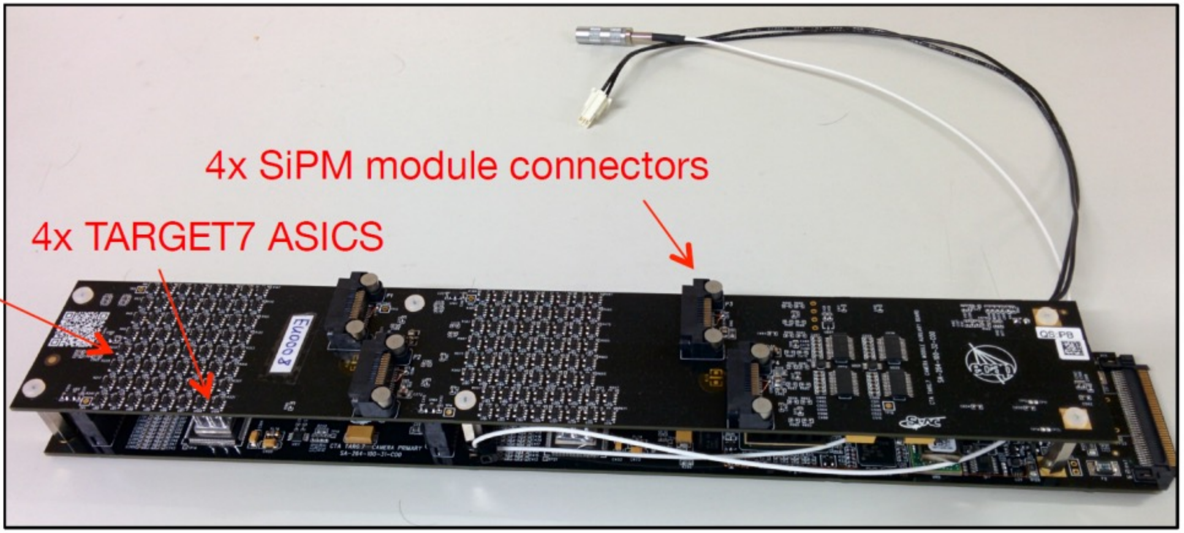
SiPMs are positioned on the PCBs using a die-bonder machine

SiPM module readout

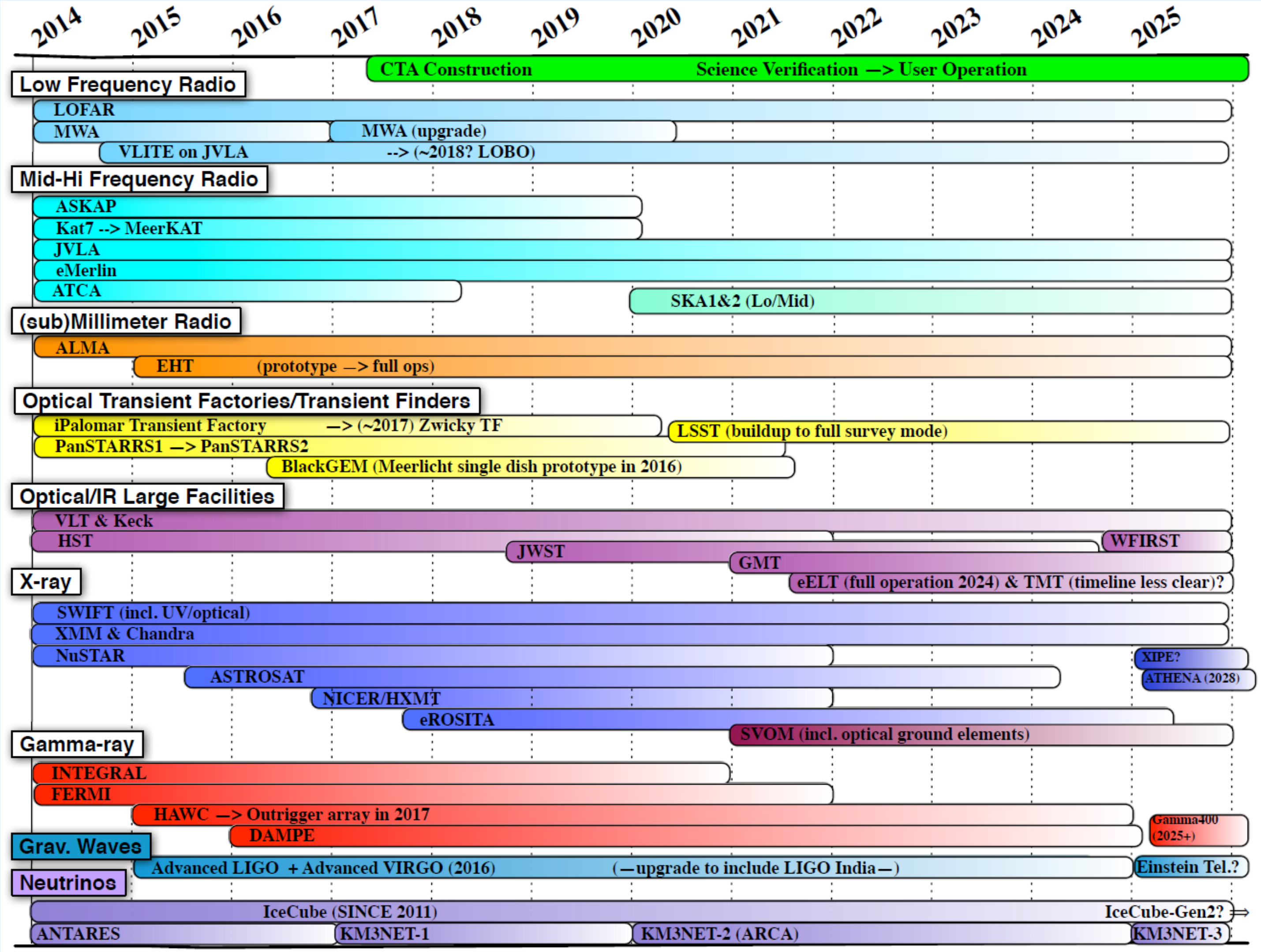
- Module signal readout using "TeV Array Readout with GS/s sampling and Event Trigger" (**TARGET7**) board
  - 16 input channels
  - Analogue ring buffer of 16384 capacitors
  - Switched Capacitors Array
  - Storage of **analogue** waveforms in a limited period of time
  - Compact chip for high density channel camera



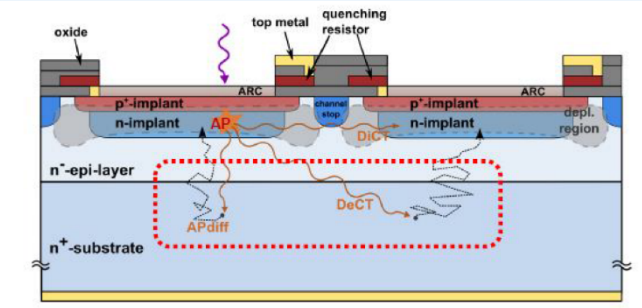
Pre-amplifier stage
pulse shaping
pole zero cancellation network
two-stage AD8014

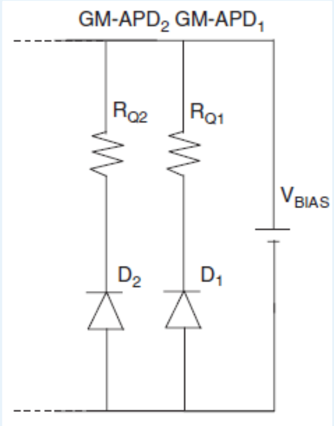


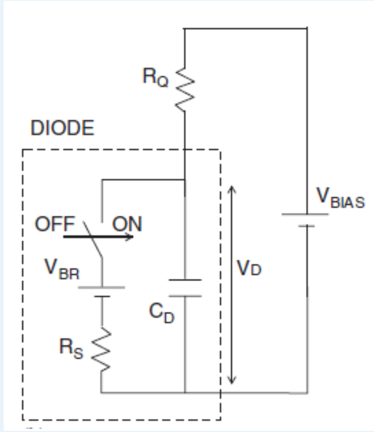
CTA multi-wavelength/messenger synergy

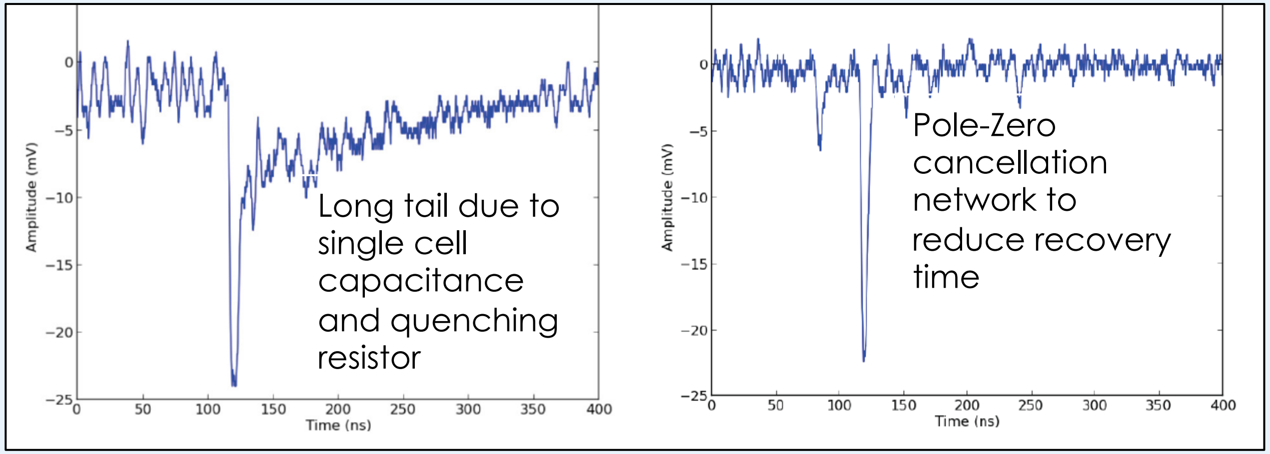


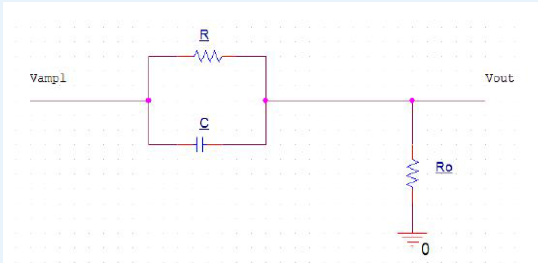
Silicon Photomultilpiers

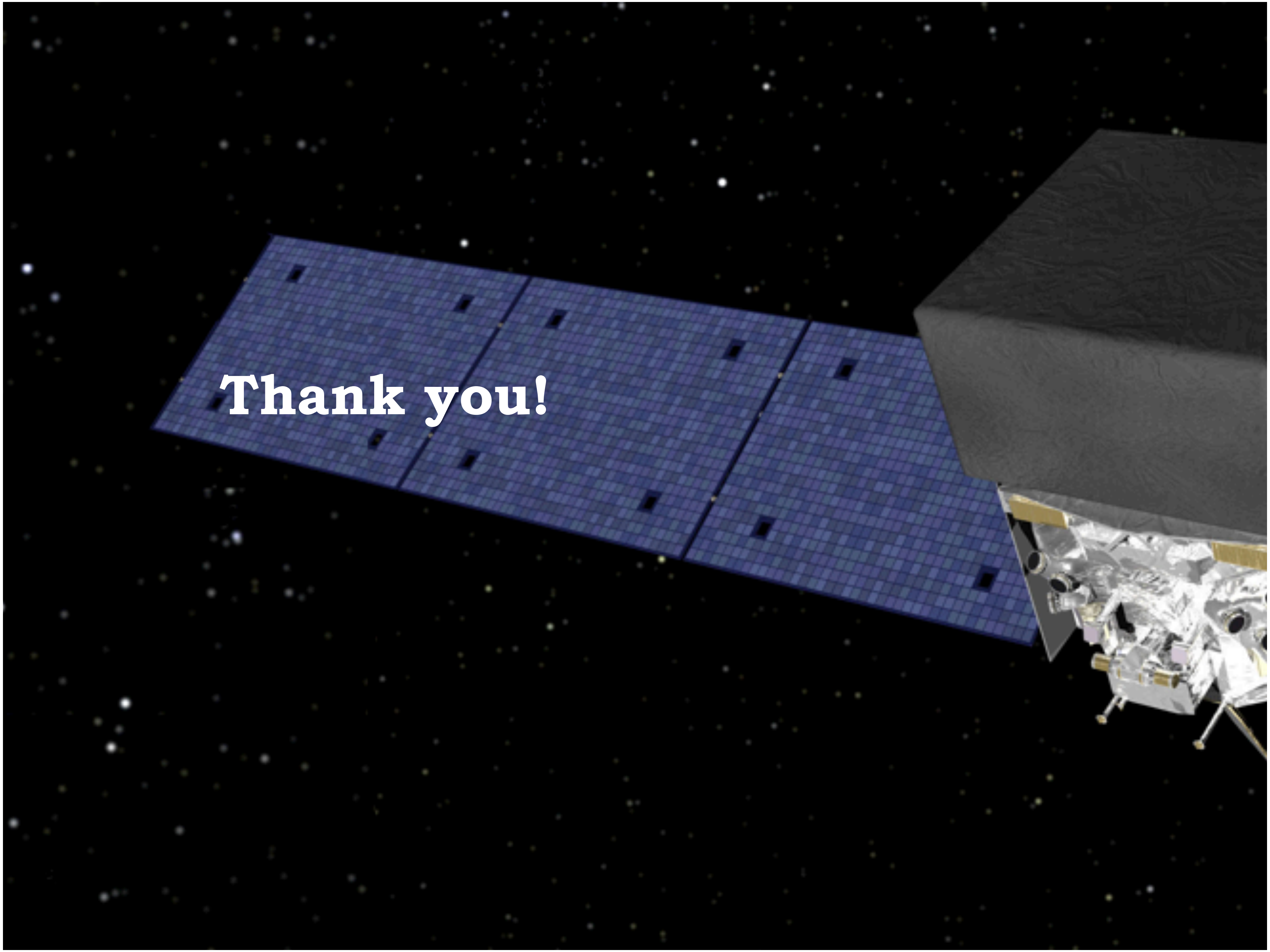


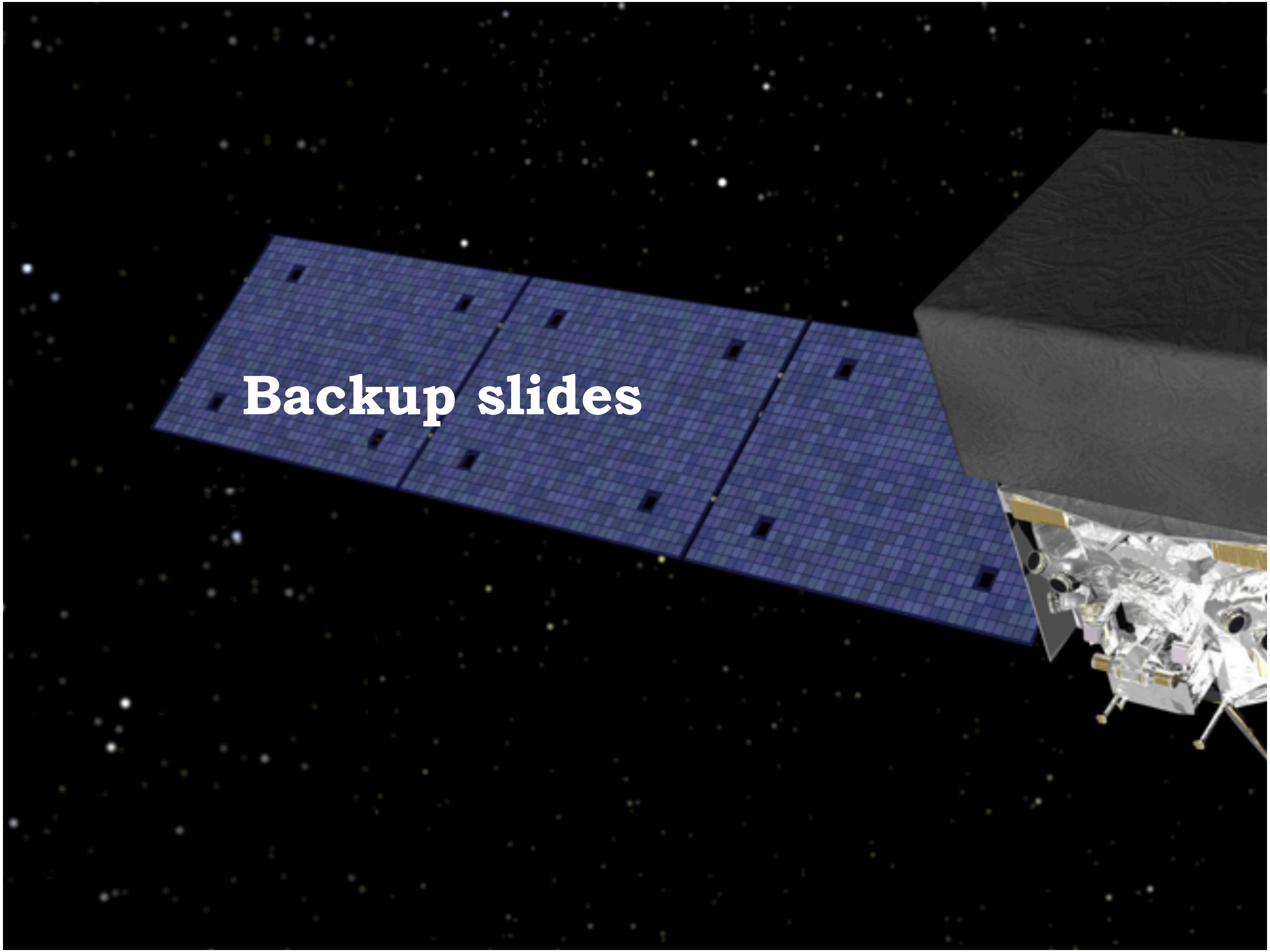









Thank you!


Backup slides

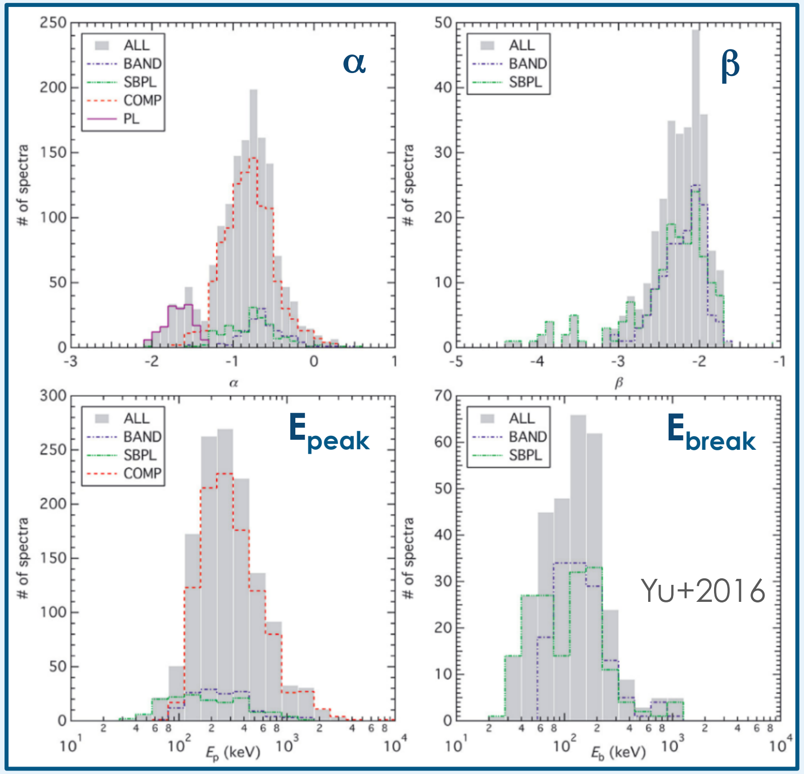
GBM GRB catalogs

- **1st Time-resolved spectral catalog**
  - Data from 4 year burst catalog (954 GRBs)

Bright subsample

- ❑ energy fluence and/or peak photon flux
- ❑ 81 GRBs / 1802 time resolved spectra

Distributions of the BEST sample spectral par.

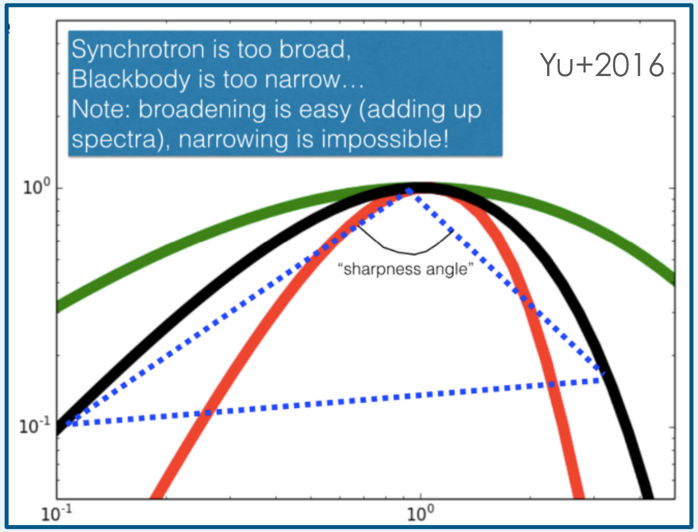


Data analysis:

- ❑ Band-, Compt-, SBPL-, PL- fit models
- ❑ 1491 "BEST" model fits
- ❑ Preferred model: COMP (69%)

Sharpness of prompt GRB spectra

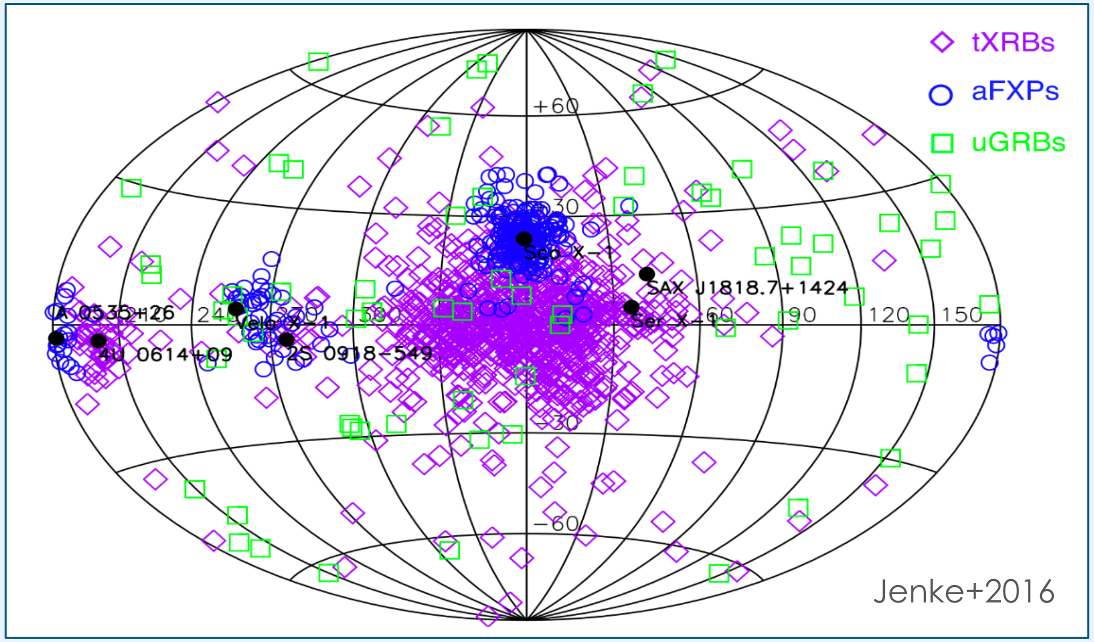
- ❑ H. Yu et al., A&A, 588, A135 (2016)
- ❑ 91% of the spectra in the sample are inconsistent with any kind of standard synchrotron radiation function



Other GBM catalogs

- **The Fermi-GBM Three-year X-ray Burst Catalog**
  - Systematic search for transients in the 12–25 keV E-channel, with a time resolution of 8.2 s
  - 1084 events, classified using spectral analysis, location, and spatial distributions

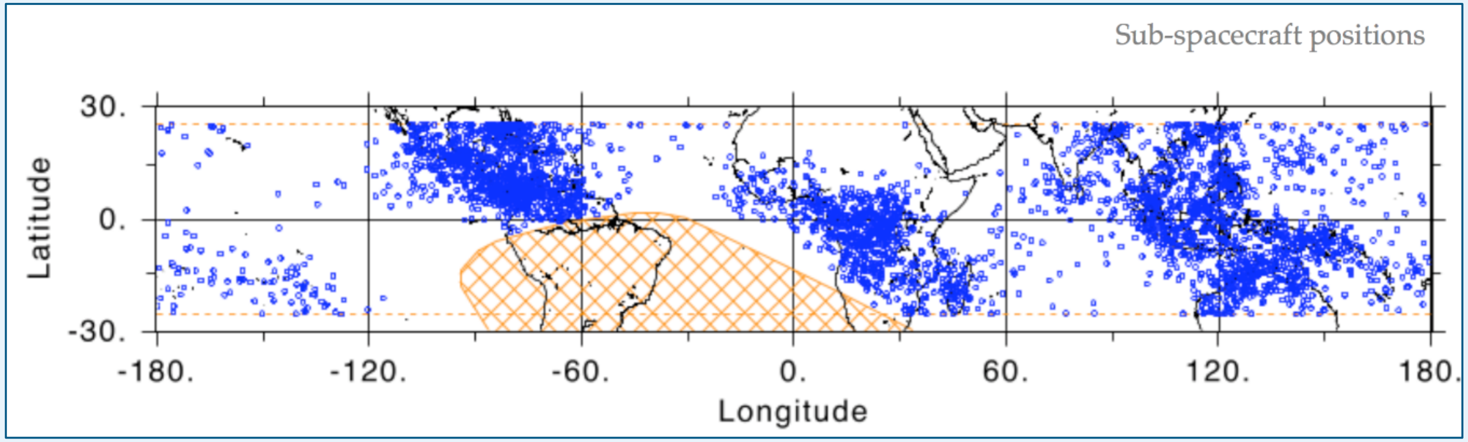
752 thermonuclear X-ray bursts
267 accretion flare events
+ X-ray pulses
65 untriggered GRBs



  - Thermonuclear bursts have peak blackbody temperatures broadly consistent with photospheric radius expansion (PRE) bursts

Other GBM catalogs

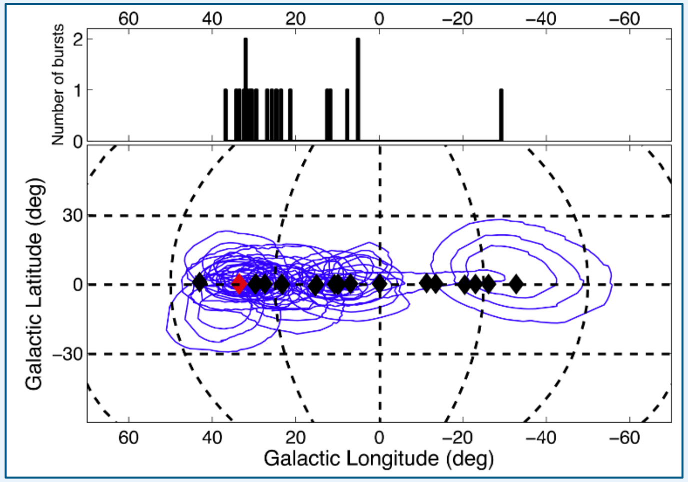
- **2nd GBM TGF catalog**
  - Now **online** including VLF locations
    - http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/
  - 3356 TGFs from 2008 Jul 11 – 2015 June 23



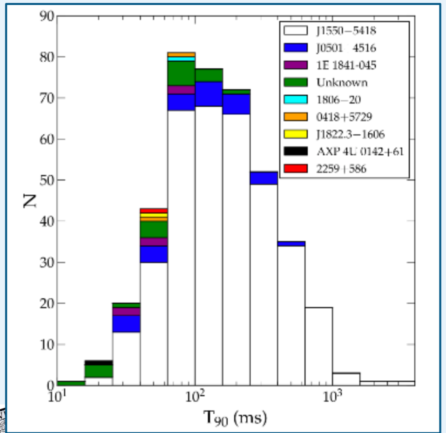
-
  -
    - **Triggered TGFs**: 579 TGF (8 TGFs are not on the Offline Search Table)
    - **Offline search Table**: 3348 TGFs (2777 untriggered, i.e. >80%)
      - Terrestrial Electron Beams (TEBs): 16 reliable, 8 possible
  - Over 1000 GBM TGFs have **VLF geo-locations** good to ~10km

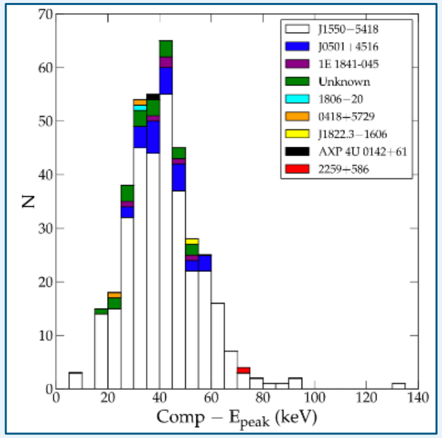
Catalogs from GBM

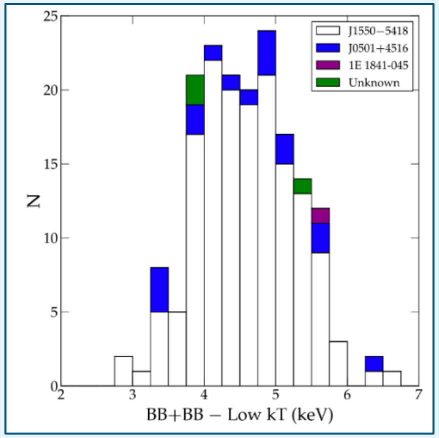
- **5 Year Magnetar Burst Catalog**
  - Sample from July 2008 to June 2013
  - Temporal & spectral analysis of **446 magnetar bursts**
  - Small sample of magnetar-like bursts of **unknown origin**
  - Combined durations and spectral parameters:
    - T90 ~100ms,
    - COMP E_{peak} ~40 keV
    - Temperatures of BB+BB center around **~4.5 and ~15 keV**

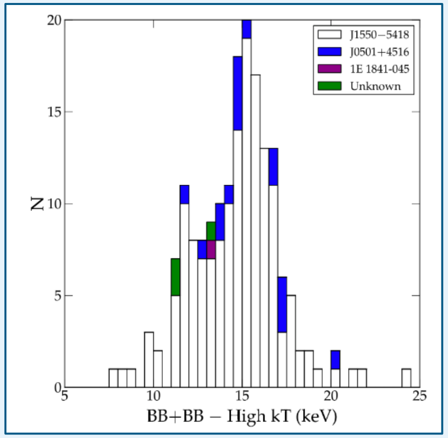


Collazzi+2015



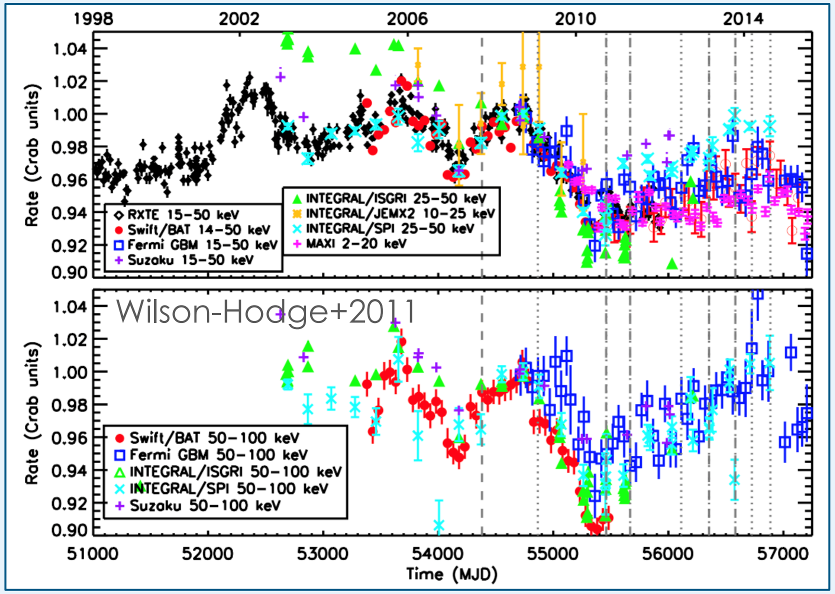






GBM earth occultation observations

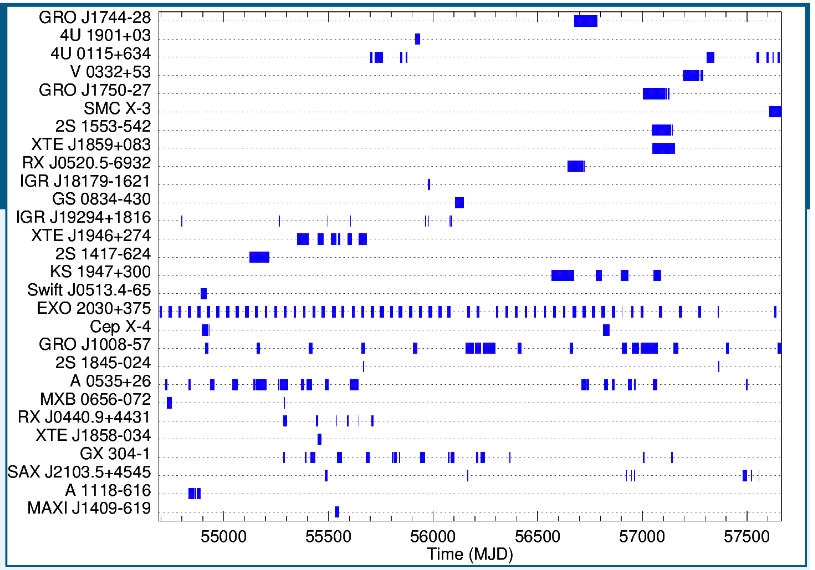
- **GBM Earth Occultation Project**
  - PI Colleen Wilson-Hodge
  - Crab Nebula Hard X-ray Variations
  - > 200 sources are monitored
    - http://heastro.phys.lsu.edu/gbm/



GBM Earth Occultation Monitored Sources

#	SOURCE NAME	RA (DEG)	DEC (DEG)	*L* (DEG)	*B* (DEG)	OBJECT TYPE	MISSION AVG FLUX (MCRAB)	5 DAY AVG FLUX (MCRAB)	2 DAY FLUX (MCRAB)
1	SUN	NA	NA	96.337	-60.189	Star	36.31 ± 0.83	29.59 ± 14.76	ND
2	IGR_J00234+6141	5.740	61.685	119.561	-1.000	CV	3.64 ± 0.91	193.15 ± 27.07	261.40 ± 36.16
3	V709_CAS	7.204	59.289	120.042	-3.456	CV/DQHer	5.98 ± 0.91	88.59 ± 24.16	86.87 ± 28.65
4	BD+6270	9.300	61.380	121.227	-1.445	Star	8.01 ± 0.90	ND	ND
5	FERMIJ0109+6134	17.445	61.558	125.115	-1.236	AGN	4.28 ± 0.80	ND	ND

GBM pulsar monitoring

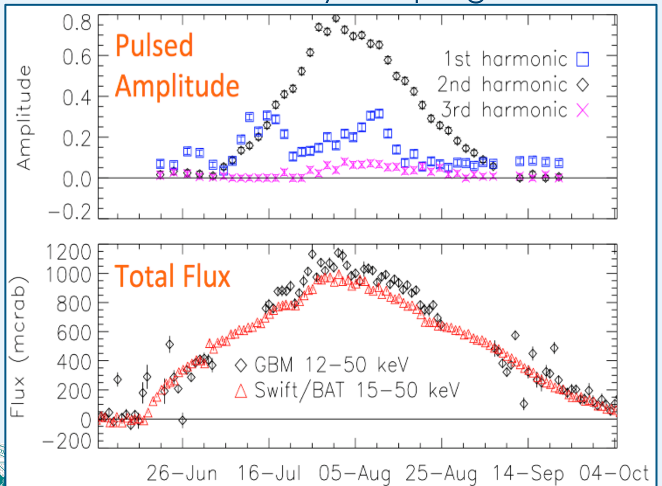


Times of Transient Outburst Detections

- **Monitoring Program**
  - 37 sources monitored, 34 detected
  - 8 Persistent, 26 transients
  - PI Colleen Wilson-Hodge
    - http://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

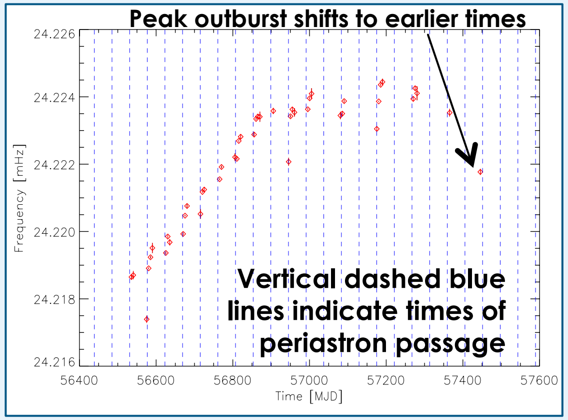
V0332+53

- 4.3 s X-ray pulsar orbiting an O8-9Ve star
- Major outbursts in 1983, 1989, 2004, **2015**
- 2015 outburst shows considerable pulse profile evolution
- New orbital analysis in progress



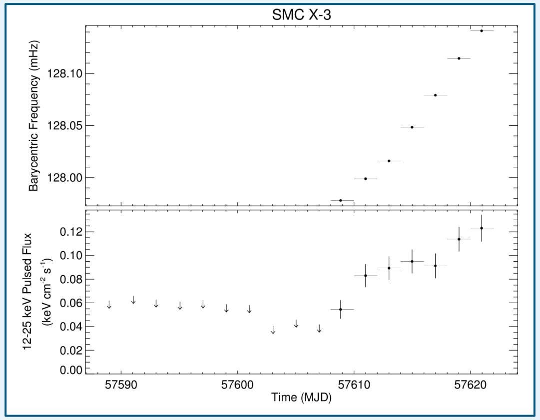
EXO 2030+375

- GBM discovers latest rare torque reversal in the Be X-ray binary
- Last seen in 1994 / Possible shift in orbital phase of the peak of the outburst



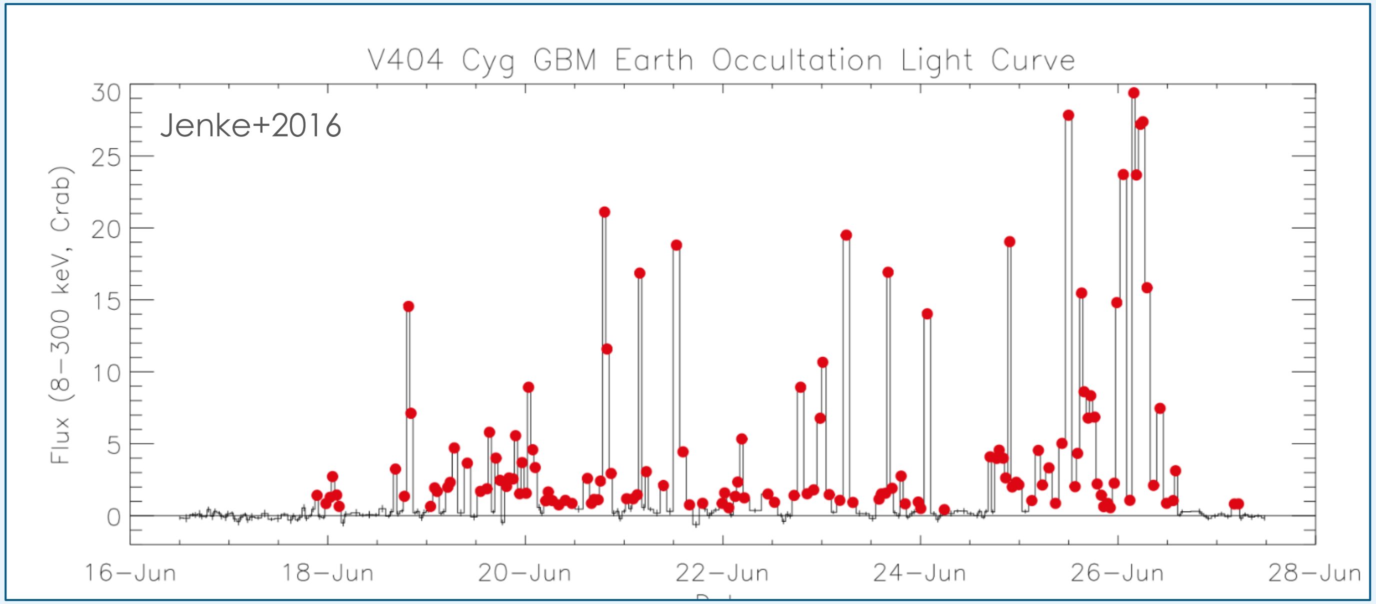
SMC X-3

- GBM monitors rare X-ray outburst of the Be binary last seen in 2003



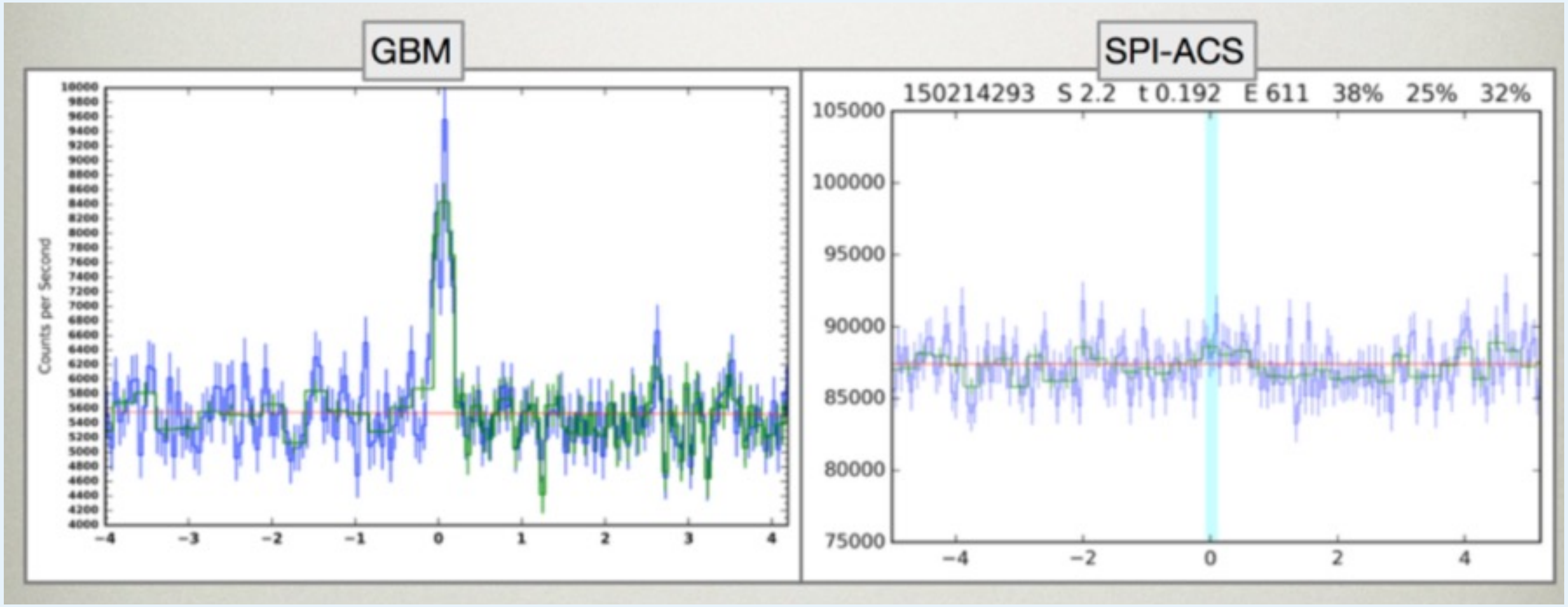
GBM Observations of V404 Cygni

- 10 $M_\odot$ Black hole only 2.4 kpc away
- Discovered by the Ginga X-ray satellite during its only previously observed X-ray outburst in 1989. Two other confirmed outbursts were seen in the optical band in 1938 and 1956.
- 169 GBM Triggers over 13 days starting June 15, 2015
- 73 Distinct flaring episodes
- Reached a brightness of 30 Crab with emission to 300 keV



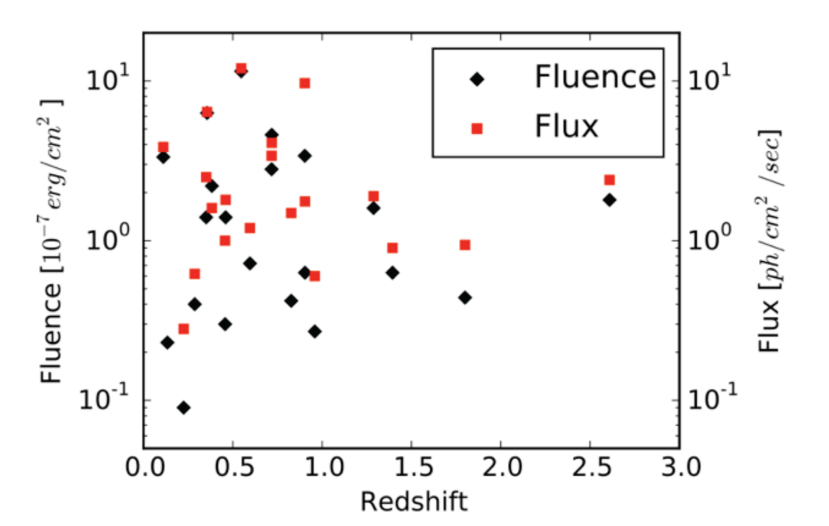
GRB 150214293

- Hard spectrum, bright enough to trigger GBM
- Comparable in fluence and PL spectrum to GW150914-GBM



GBM and weak sGRBs

- Weak short GRBs are not necessarily more distant than bright short GRBs and may lie within the detection horizon of LIGO/Virgo: GBM team developed search for short GRBs too weak to trigger on-board Fermi
  - Extrapolating from sGRBs with known redshift gives <0.5 - 5 per year sGRB for GBM within LIGO/Virgo horizon (nearby z uncertain)
  - This number is doubled with unseeded search for GRBs that do not trigger on-board



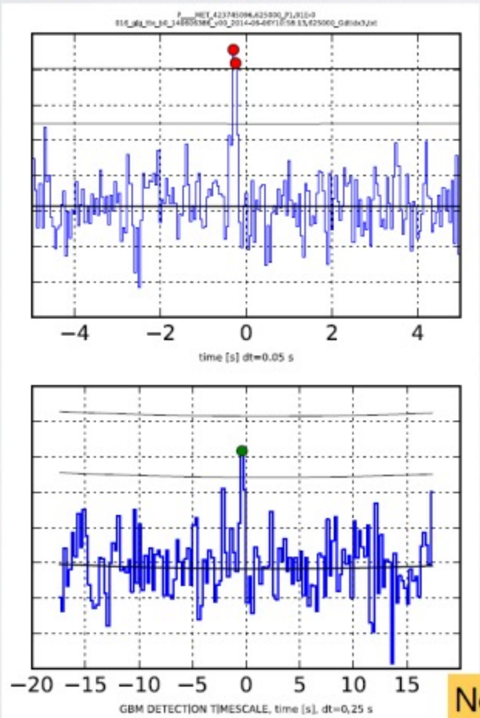
GBM candidate event

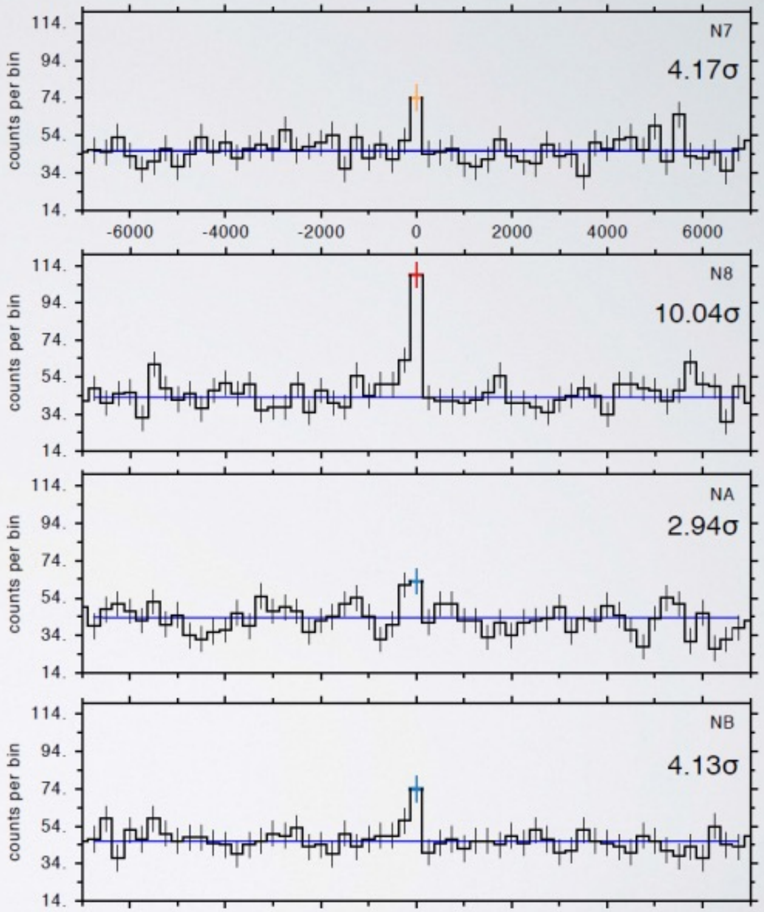
- 2014-06-06 10:58:13.625
- **Swift GRB 140606A**
- Found in 0.25s time binning
- 93 - 494 keV energy range
- P=1.91e-16

INTEGRAL ACS lightcurve

ACS native time bin

GBM timescale





Not all GBM triggered short GRB are detected by ACS.

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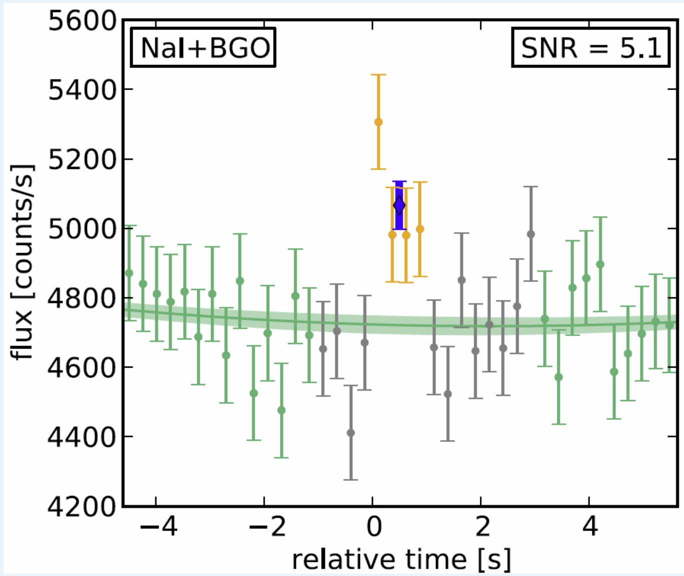
GW150914-GBM

- Association of a likelihood value with a false alarm rate (FAR) based on 2 months of GBM data from 2009 to 2010
  - FAR = 1.6 x 10^{-4} Hz (close to reporting threshold)



- Significance of event
  - Two-paramter ranking method
  - Post-trial false alarm probability FAP = 0.0022 (2.9σ)

Detection rate of GBM triggered short GRBs in the Integral SPI-ACS

The SPI-ACS data was tested for excesses >= 4.5 sigma in intervals of the duration of each GBM SGRB. The plot shows the dependence of detection rate on fluence.

The shaded region indicates the GBM fluence (+/- 1 sigma) for GW-150914-GBM