Optical GRB follow-up observations with the TOMO-E GOZEN: the short GRBs associated with Kilonovae and the 2D and the 3D fundamental plane correlation

Dr. Maria Giovanna Dainotti

NAOJ, DIVISION OF SCIENCE, Tokyo
Sokendai University, Japan,
SPACE SCIENCE INSTITUTE (Colorado, USA)

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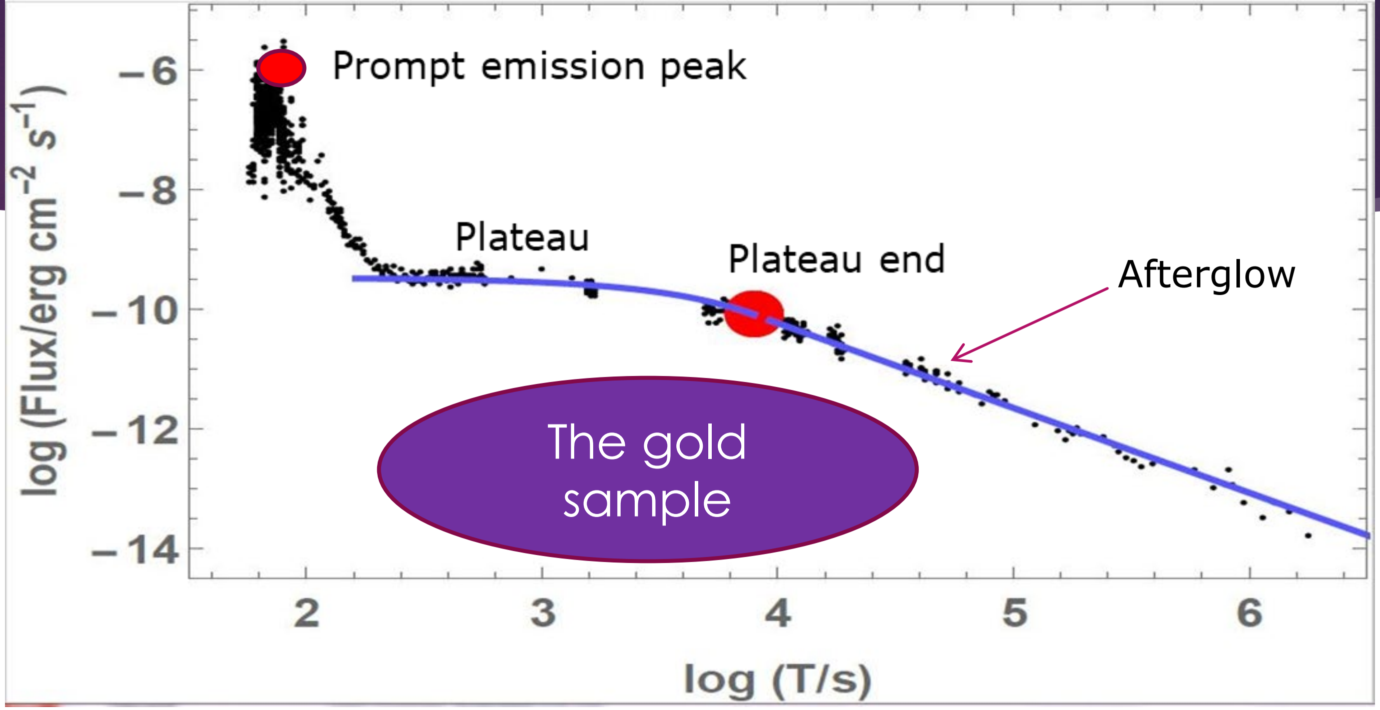
GRB phenomenology



Important features of a well-sampled GRB light curve observed by Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing). The blue line is the phenomenological Willingale model.

- **Flashes of high energy photons in the sky (typical duration is few seconds).**
- **Cosmological origin accepted (furthest GRBs observed z ~ 9.4 – 13.14 billions of light-years).**
- **Extremely energetic and short: the greatest amount of energy released in a short time (not considering the Big Bang).**
- **X-rays and optical and radio radiation observed after days/months (afterglows), distinct from the main γ-ray events (the prompt emission).**
- **Observed spectrum non thermal.**
- **GRBs are important for their energy emission mechanisms.**

Why are GRBs potential cosmological tools?

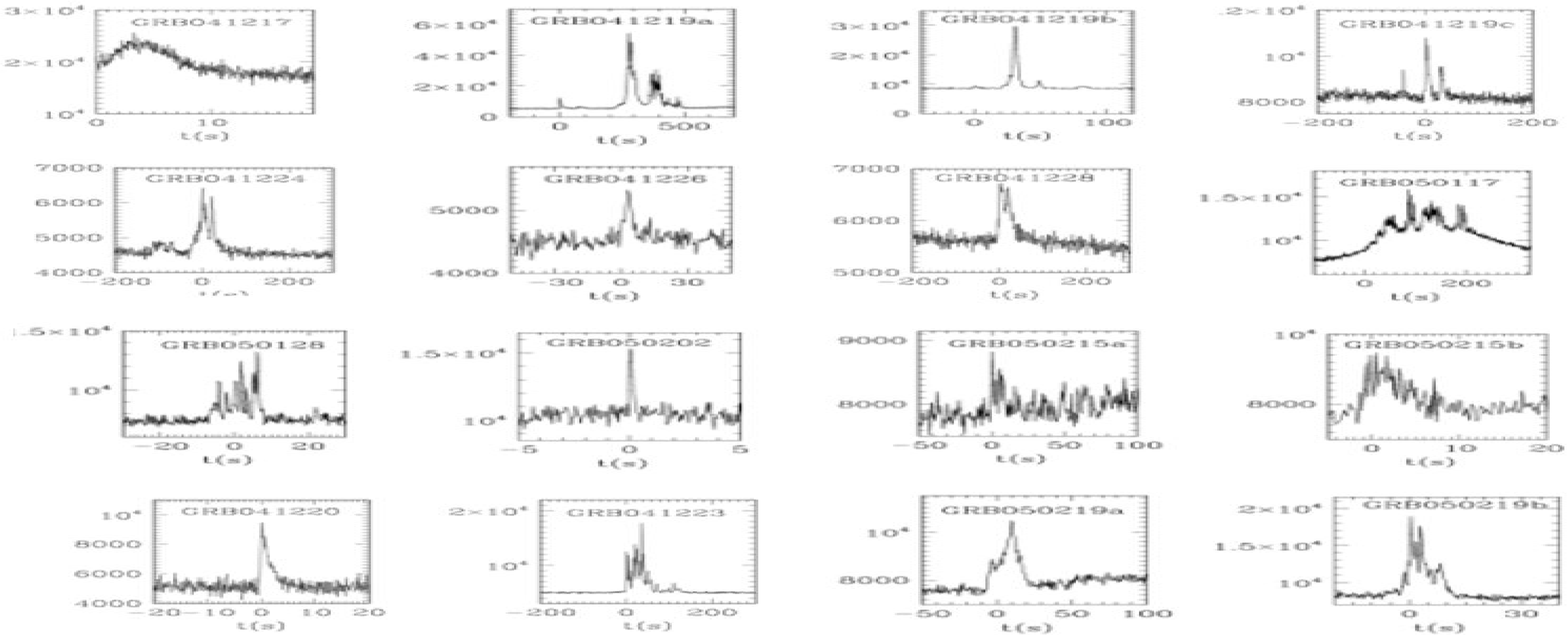
Because They…

- Can be probes of the early evolution of the Universe.
- Are observed beyond the epoch of reionization.
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than SN Ia (z=2.26) and quasars (z=7.54).

But They…

- Don't seem to be standard candles with their isotropic prompt luminosities spanning over 8 order of magnitudes.

For 20 years, we've been struggling: how to use GRBs as standard candles? Challenge: Light curves vary widely - "if you've seen one GRB, you've seen one GRB" -



Swift lightcurves taken from the Swift repository

Why the observations of sGRBs is appealing?

Why are BNS and NSBH mergers interesting?

- •Laboratories for physics at high densities (equation of state of NSs); at high energies (jet production and propagation)
•Possibly important sites of production of heavy elements.

•What are the compact products of a BNS mergers? Magnetar or BH?

•What are the properties of the kilonova as a population? Distributions of mass and velocities? Wind or dynamical component? Powered exclusively by radioactive decay or also by magnetars? The precise nature of the different ejection mechanisms and of the different ejecta components is still under debate (Tanaka et al. 2018)

•Do NSBH mergers produce EM counterparts?

What are our specific goals to observe with Kiso Schmidt Telescope ?

- Identify the KN or upper limits with a standalone campaign for all cases of sGRBs observable by KISO and DDOTI
- Increase the population of sGRBs for solving the issue if GRB rate follows the star formation rate at low z especially, see Dainotti et al. 2021, ApJL
- Understand how the sGRBs, the sGRBs with extended emission behave differently from the long GRBs in terms of GRB correlation studies
- Can we promote the short GRB fundamental plane as a standard candle with more cases?

Detections to date

- GW and EM:
  - 1 BNS merger: GW170817 GRB 170817A AT2017gfo
- GW only:
  - 1-3 BNS merger detected in O3: GW190425, S191213g, S200113t,
  - 2-4 NSBH merger in O3: GW190426 (marginal), GW190814 ($m_2 \approx 2.6$ $M_\odot$?), GW200105, GW200115
- EM only:
  - ≈ 500 Fermi SGRBs (growing at about 45 per year)
  - ≈ 150 Swift SGRBs (growing at about 10 per year)
  - Only 36 SGRBs with redshifts
  - Only 4 SGRBs with detection or constraints on kilonova. Other cases reconstructed as kilonovae, Rossi et al. 2020, A&A.

What are the steps?

- Detection (GW or EM)
- ⇩
- Localization to 1 arcsec (EM)
- ⇩
- Confirmation of optical brightness (EM)
- ⇩
- Detailed follow-up with large ground-based telescopes (EM)
- We can apply for time at Subaru and Gran Telescopio Canaria

Possible detections

1. LIGO/Virgo/KAGRA GW Events
2. Swift BAT SGRBs
3. Fermi GBM SGRBs

- GW detections have uncertainties of 100s to 1000s of deg^2
- Localizations using wide-field optical telescope and gamma-ray satellites.

On hold until O4 starting at the earliest in summer 2022

- Difficult. No EM detections of the 3-7 BNS or NSBH sources in O3.
- So far 1 EM counterpart from 8 possible events
- Combined GW-EM dataset is potentially very rich

1. Swift GRBs

- BAT detections - uncertainties of 3 arcmin radius
- The satellite slews autonomously to observe with XRT and UVOT
- Automatic localization with XRT and sometimes UVOT to 1-2 arcsec.
- Positions distributed rapidly and widely by GCN Notices.
- Confirmation of optical brightness with 0.5-2 meter telescopes
-

  This process is widely exploited by the community.
- Swift detects about 10 SGRBs per year.
- Not all are detected and followed-up optically.
- **ADVANTAGE OF FOLLOW-UP WITH TOMO-e GOZEN**

2. Fermi GRBs

- GBM detections - uncertainties of 100–1000 deg^2
- Need wide-field optical imager to localize candidate counterparts
- Similar to GW events

This process is not widely exploited by the community.

- Fermi detects about 45 SGRBs per year.
- **Potential to significantly increase our access to SGRBs**.

The importance of the KISO Schmidt Telescope for the current study

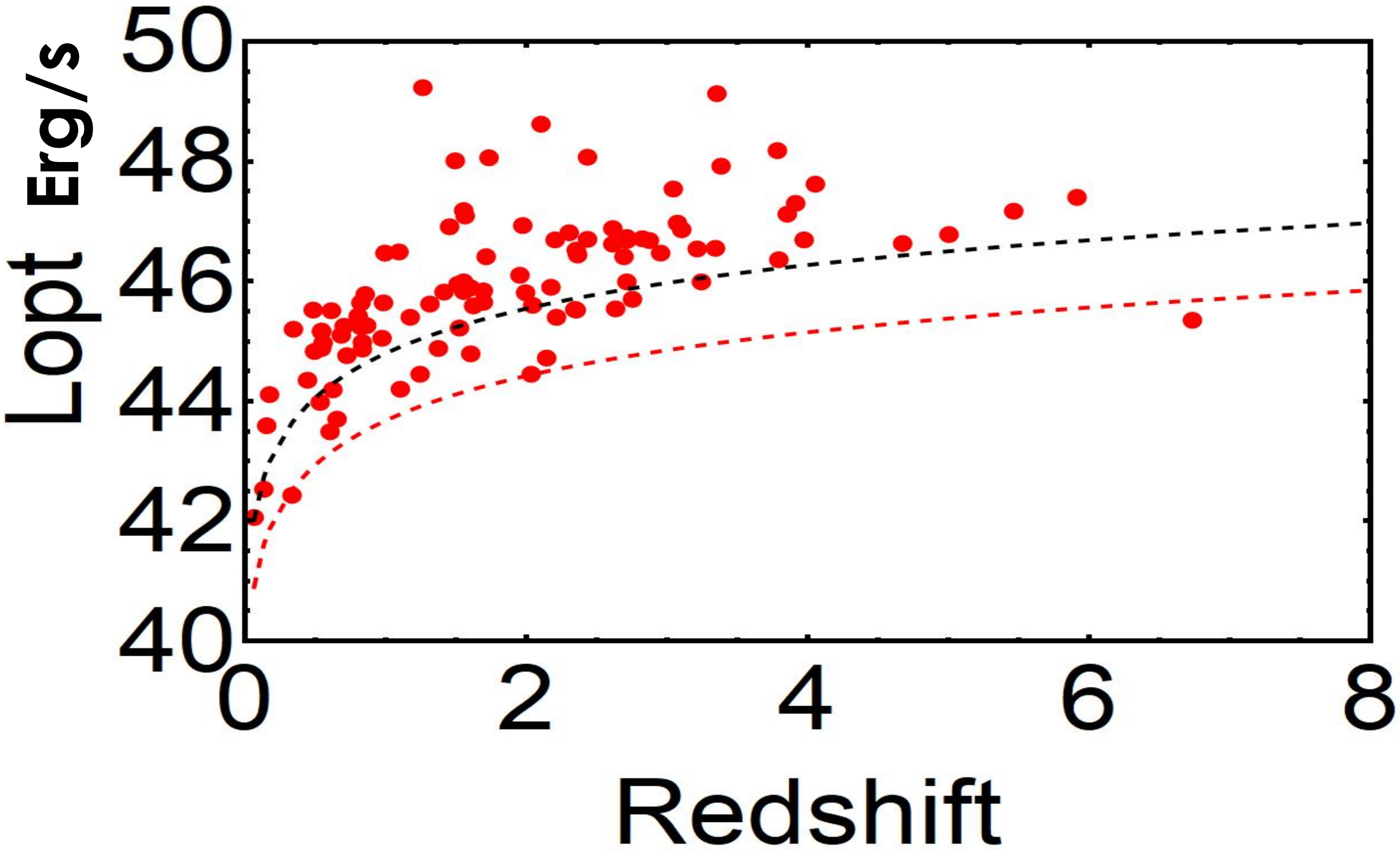
Due to the large field of view capability the KISO Telescope will help to:

- Able to follow up Fermi GRBs.
- Build self-consistent afterglow plateau with crafted pointing strategies.
- identify new plateaus.
- Reduce uncertainties in the error bars.

First feasibility study for the potential use of the KISO Telescope

- 27% of observations-100 nights observed by KISO
- 50% will be happening during the night.
- 70% will be visible, 30% will occur in the Southern Hemisphere.
- **Fraction of GRBs with optical plateaus and known redshift** 102/267=0.38%.
- Probability of observing all optical GRBs =0.5*0.7*0.27=0.094
- Probability of observing optical GRBs with plateaus=0.5*0.7*0.27*0.38= 0.036

Limiting luminosity of the KISO Telescope



102 optical GRBs with plateau

Flim=1.22 e^{-13}erg/(cm^2*s) for 20 mag in the g band for 100s, black line.

Flim=3.67 e^{-14} /(cm^2 *s) for 21.3 mag in the g band for 1000s, red line.

If we integrate over 1000 s, we will have a sufficient limiting magnitude to observe almost all of them.

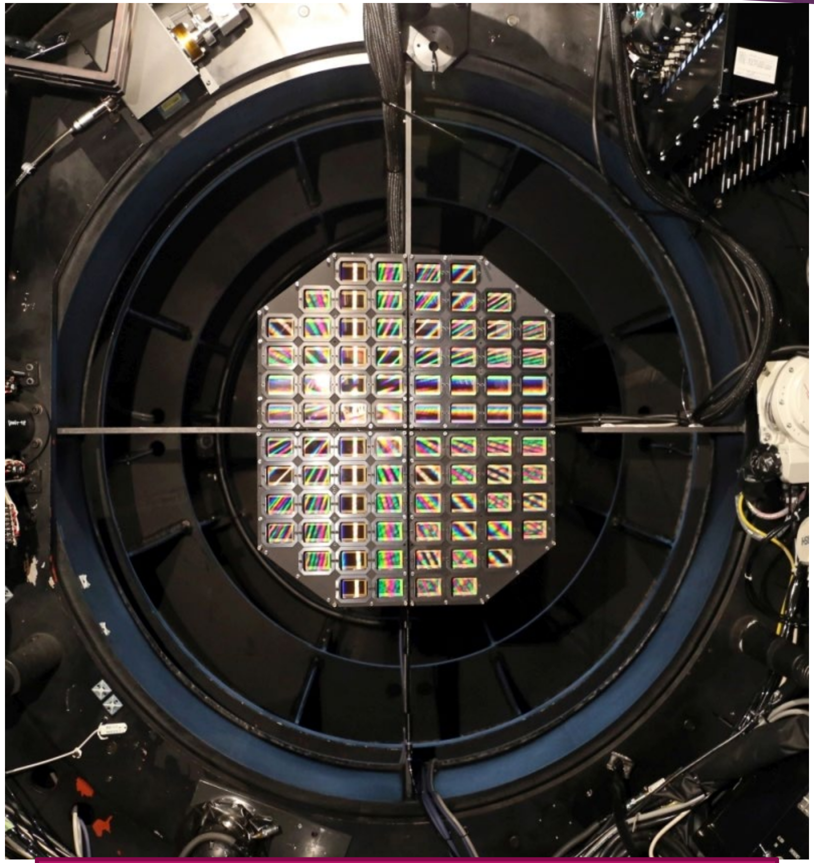
What could we observe with the KISO observatory?

- `From Swift, Fermi, and IPN 229 GRBs are observed each year.`
- `8 GRBs with plateaus, 22 GRBs per year`
- `Based on the probability 20 years of observations (1997-2016)`
- These below are events with plateaus

KN	XRR and XRFs	GRB-SNe	Long	Short	Ultra Long	Gold
0.2	13	5.6	7.5	2	0.88	1.5

Observing strategies:
for KN observations- 3 visits each hour for 100 s, follow-up with 8-10m Telescope
For population studies: 10 visits and the same the next night if needed until it fades

Parternship of Tomo-e Gozen with DDOTI Deca-Degree Optical Transients Imager



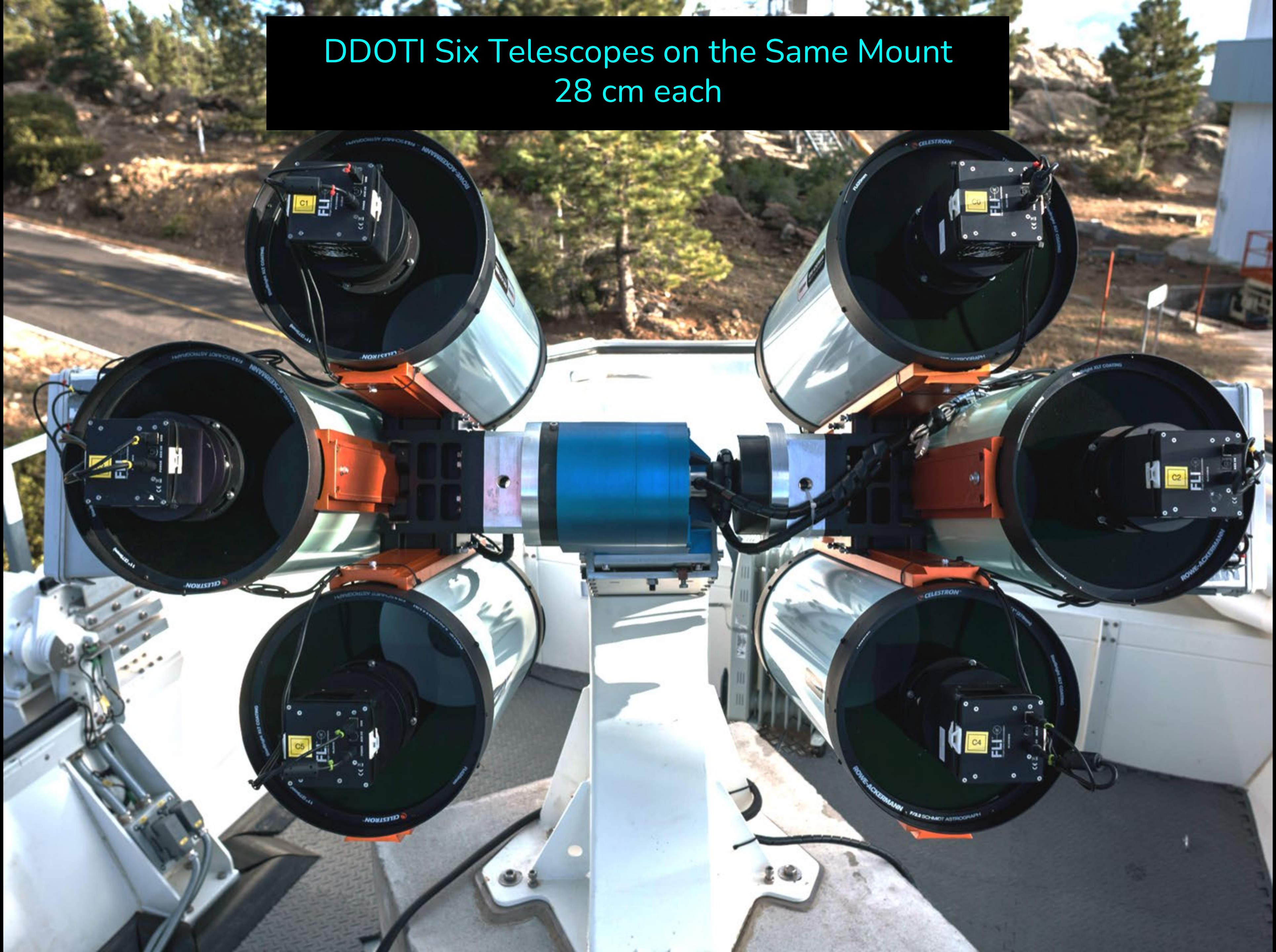
Tomo-e Gozen

DDOTI is separated by 108 degrees in longitude from KISO. The different location and the similar goals allow this alliance to be successful.

SGRBs with Tomo-e Gozen

- Discussion started in March 2021
- Combination is more sensitive than DDOTI
  - 36% of Fermi SGRBs can be observed within 3 hours
  - 100 nights of good weather condition
  - Can observe 10 Fermi SGRBs per year+6 from DDOTI=16 GRBs per year. **More than the rate of Swift alone!!!**
- Status:
  - We have developed an interface to the robotic scheduling system.
  - We are discussing rapid access to the SN transients pipeline.

DDOTI Six Telescopes on the Same Mount
28 cm each

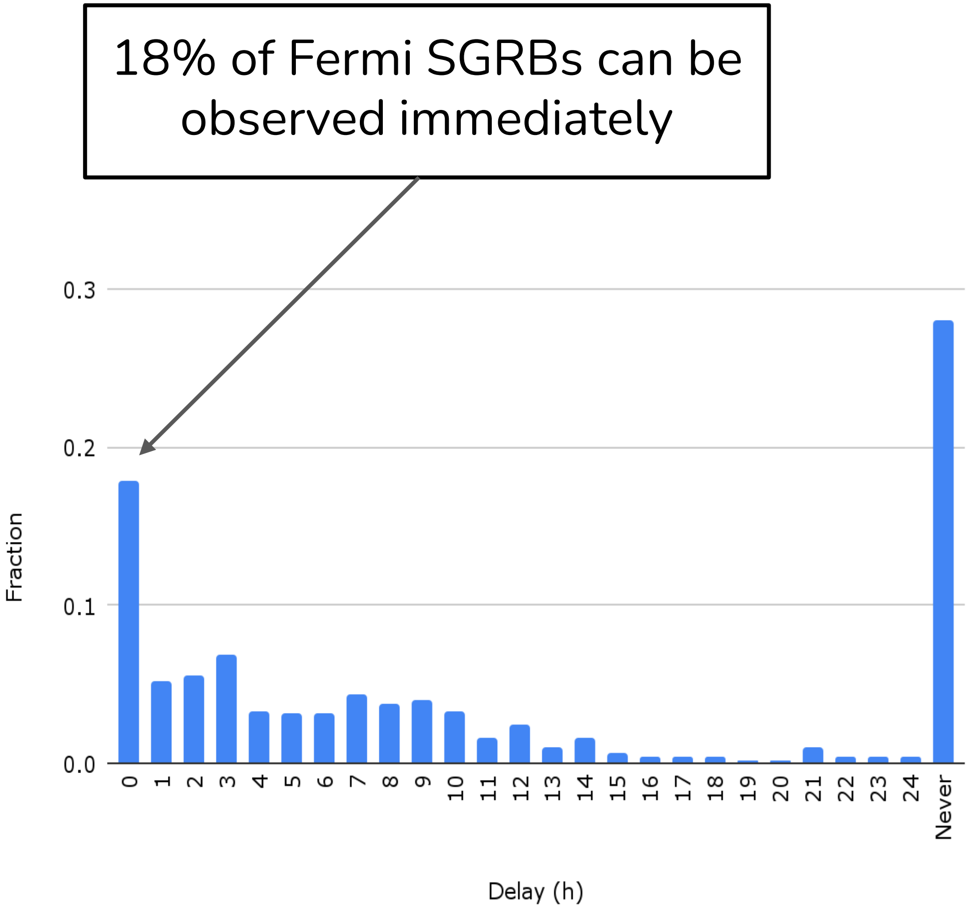


Expectations

- 45 Fermi SGRBs per year
- DDOTI needs to observe immediately
- 18% of historical Fermi SGRBs are observable immediately
    - SGRB: $z < 72$ deg $X < 3.2$
    - Sun: $z > 102$ deg
      astronomical twilight
- 80% good weather
- DDOTI can observe

45 x 0.18 x 0.80 ≈ 6 Fermi SGRBs per year

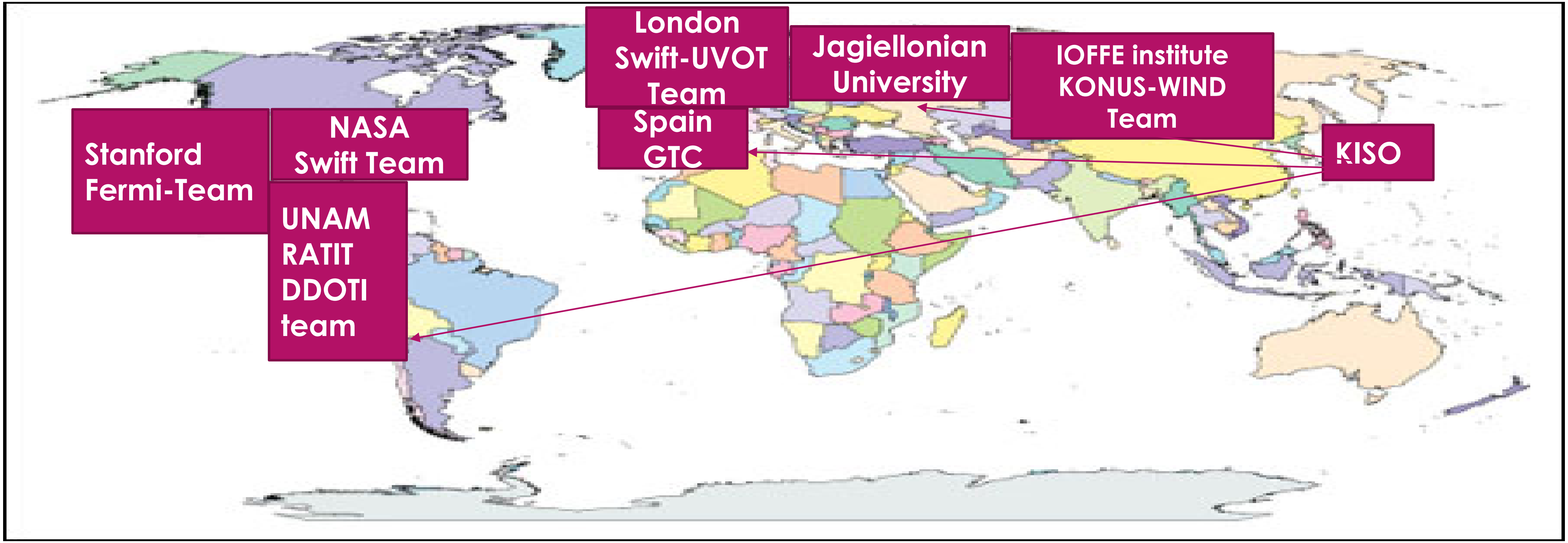
- Not all will be detected, but those that are are suitable for follow-up.
- DDOTI observes non-immediate GRBs too, but the chance of a detection is less.
- Confirm candidates with other robotic telescopes at the OAN (RATIR/COATLI/COLIBRÍ. Follow-up with Keck/Gemini/GTC
- Other sites could have similar rates.



18% of Fermi SGRBs can be observed immediately

The journey with the KISO Telescope has started. We will leverage this network. Collaboration with the co-PI of DDOTI The Deca-Degree Optical Transient Imager at UNAM has started.

Sharing and advancing our networks of scientists with common research interests



Software development, data analysis & Science Team collaboration

Science Team

Moriya Takashi (NAOJ)

Science Team and software Developers

Niino-san
University
of Tokyo

Tominaga-san
NAOJ

Alan Watson
co-PI of DDOTI at
UNAM, (Mexico)

Samantha Oates
(UCL, UK)

Aleksander Kann from IAA (Spain)

Me

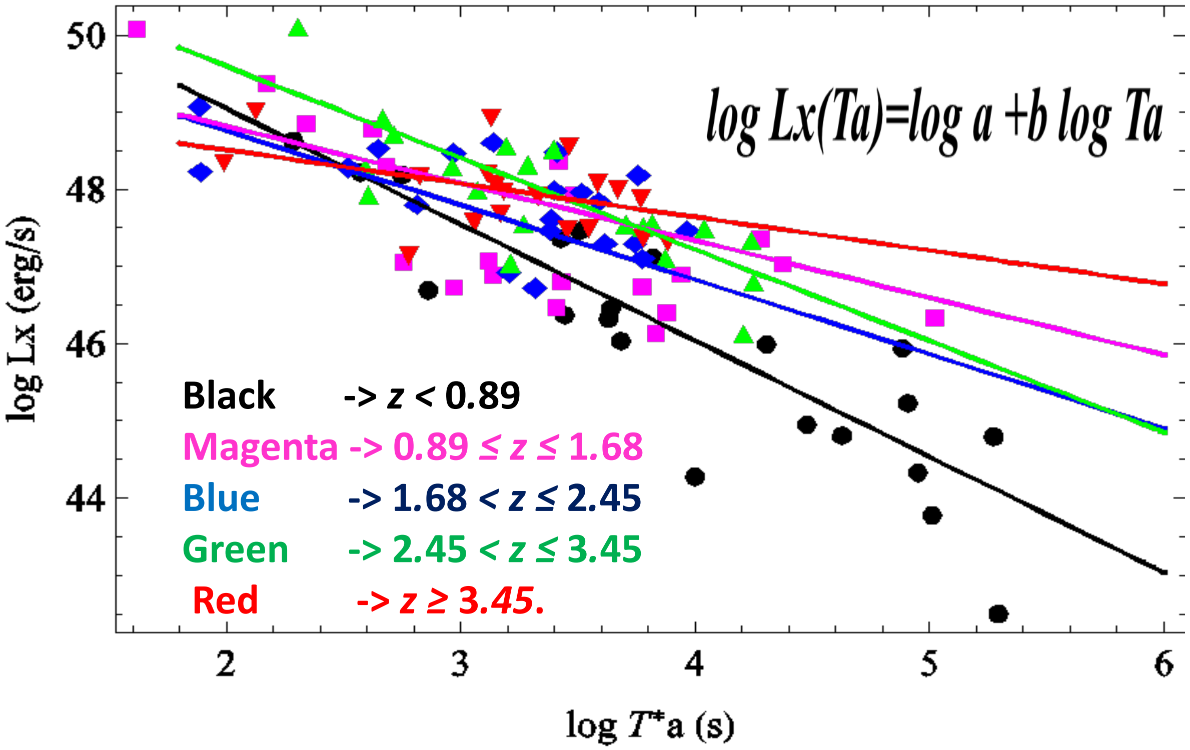
software developers

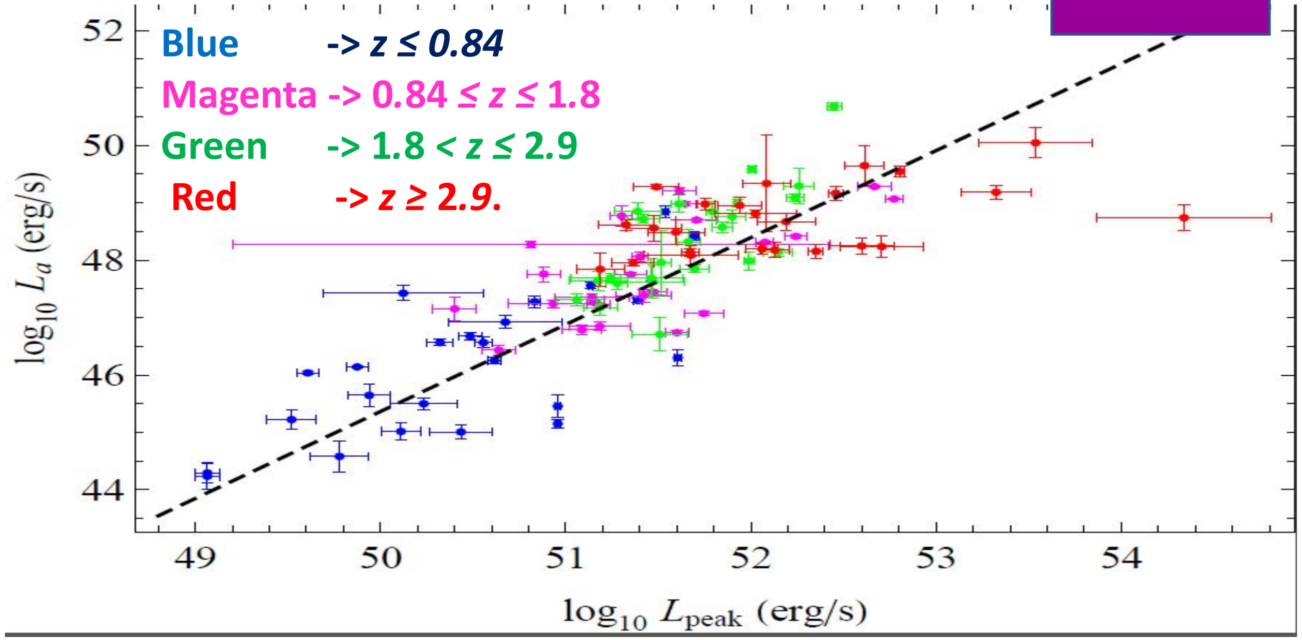
Alexandra Rabeda   Kamil Kalinowski

Students Jagiellonian University, Poland

How will this help in highlighting GRB correlations?

Possible reliable candidates are the $L_X - T^*_a$ and Lpeak-La correlations





Log Lx(Ta)= log A +B log Lpeak

b=-1.0 -> Energy reservoir of the plateau is constant

La-Ta correlation first discovered by **Dainotti, et al. (2008), MNRAS, 391, L 79D**, later updated by **Dainotti et al. (2010), ApJL, 722, L 215; Dainotti et al. (2011a), ApJ, 730, 135; Dainotti et al. (2015a), ApJ, 800, 1, 31. The La-Lpeak first discovered by Dainotti et al., MNRAS, 2011b, 418, 2202.**

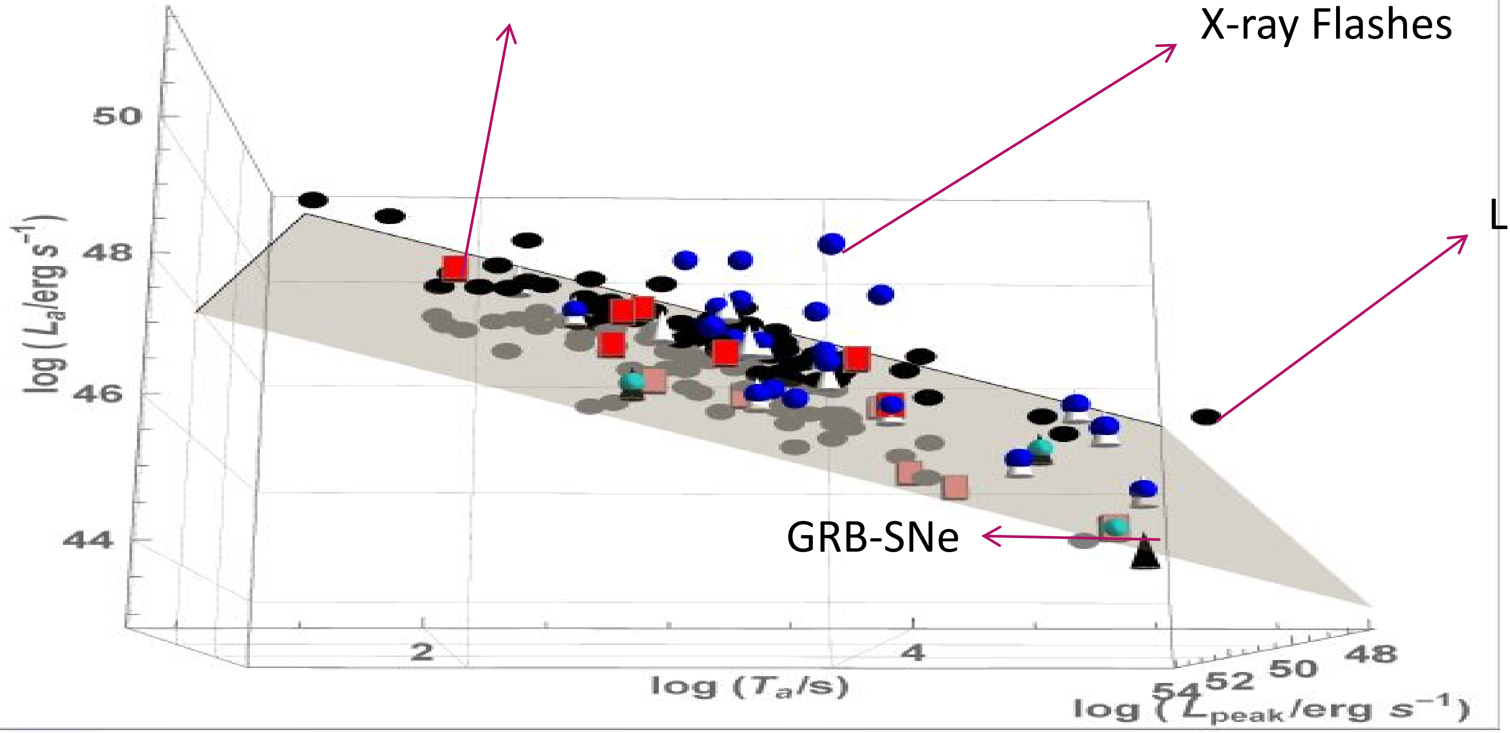
To account for selection biases **Dainotti et al. 2013, ApJ, 774, 157 and Dainotti et al. 2015b, MNRAS, 451, 4** showed that both **these correlations are intrinsic to GRB physics and not to selection biases.**

AN EXTENSION OF THE LX-TA AND LX-LPEAK CORRELATIONS GIVEN THEIR INTRINSIC NATURE

Press release by NASA:
https://swift.gsfc.nasa.gov/news/2016/grbs_std_candles.html
Mention in Scientific American, Stanford highlight of 2016, INAF Blogs, UNAM gaceta, and many online newspapers took the news.

Dainotti, Postnikov, Hernandez, Ostrowski 2016, ApJL, 825L, 20

- the 3D Lpeak-Lx-Ta correlation **is intrinsic** and it has a reduced scatter, σ_{int} of 24 %.



Short

X-ray Flashes

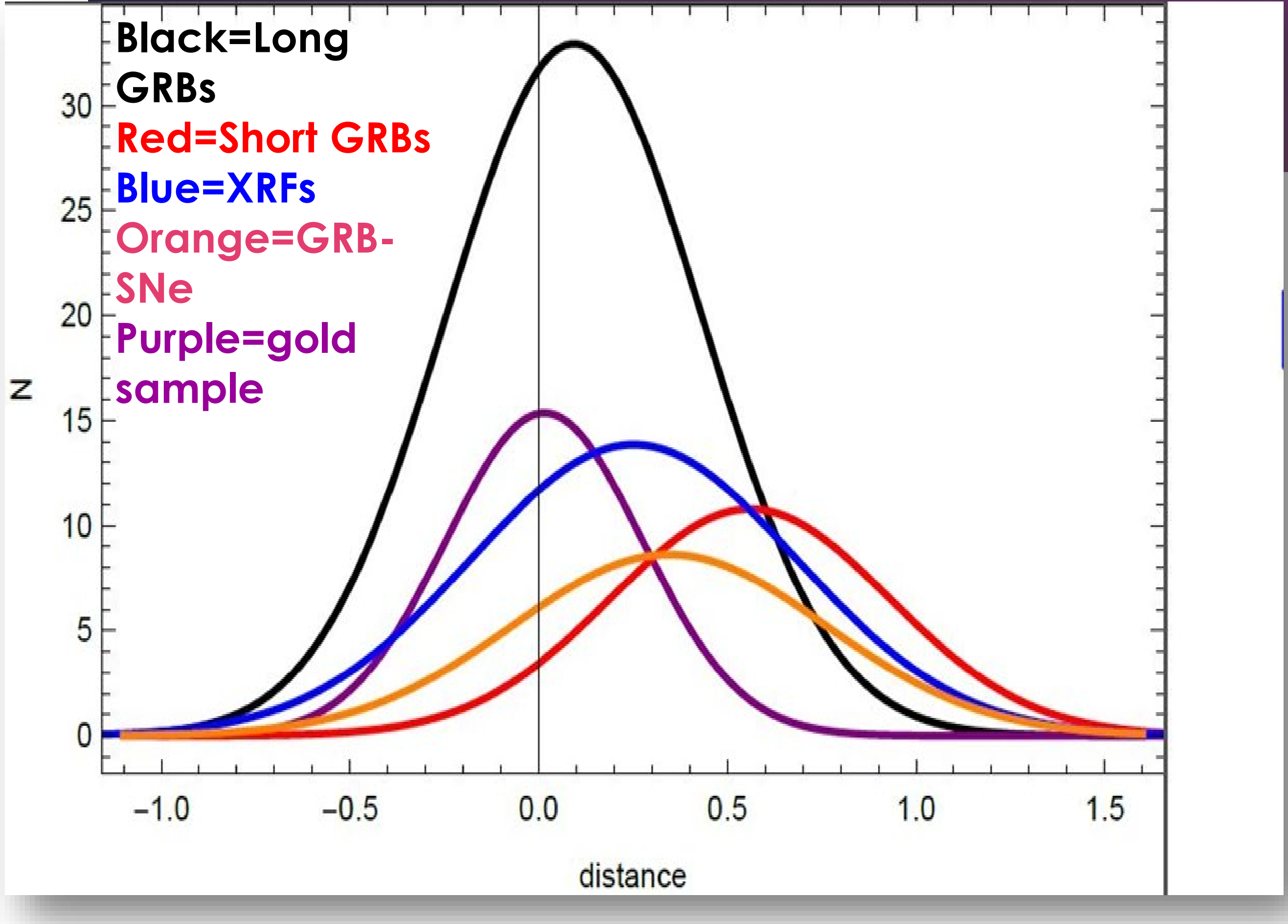
Long

GRB-SNe

Distance from the planes

Total sample of 184 GRBs

Dainotti, Hernandez, Postnikov, Nagataki, Obrien, Willingale, Striegel, 2017, ApJ, 848, 88



the gold sample fundamental plane is a reference (placed in 0). The gold sample has the smallest scatter.

Press releases by INAF, Nature-Index, a research highlight at Stanford, and Le Scienze (Scientific American in Italian): tinyurl.com/22fjy2ak, tinyurl.com/3dy26pkv

Marie Curie Fellow of the week
5-12 May 2018

Facebook Marie Curie: tinyurl.com/ehvyjaj3

Interviewed by the Italian National daily news on Women day

The fundamental plane relation for new classes: Ambushing the standard candle in its own nest

Dainotti, Lenart, Sarracino, Nagataki, Capozziello & Fraija 2020, ApJ, 904, issue 2, 97, 13

- **The platinum sample:** a subset of the gold sample obtained after removing gold GRBs with at least one of the following features:
  - Tx is inside a large gap of the data, and thus has a large uncertainty.
  - A small plateau duration <500 s with gaps after it. This could mean that the plateau phase is longer than the one observed.
  - Flares and bumps at the start and during the plateau phase.
  - It reduces the scatter of 31%, σint=0.22.

Press release distributed by the AAS, issued by Jagiellonian, Space Science Institute, and by INAF (Italian National Astrophysics Institute) and interview by INAF.

The fundamental plane relation for new classes (Ambushing the standard candle in its own nest)

Dainotti et al. 2020, ApJ, 904, issue 2, 97, 13

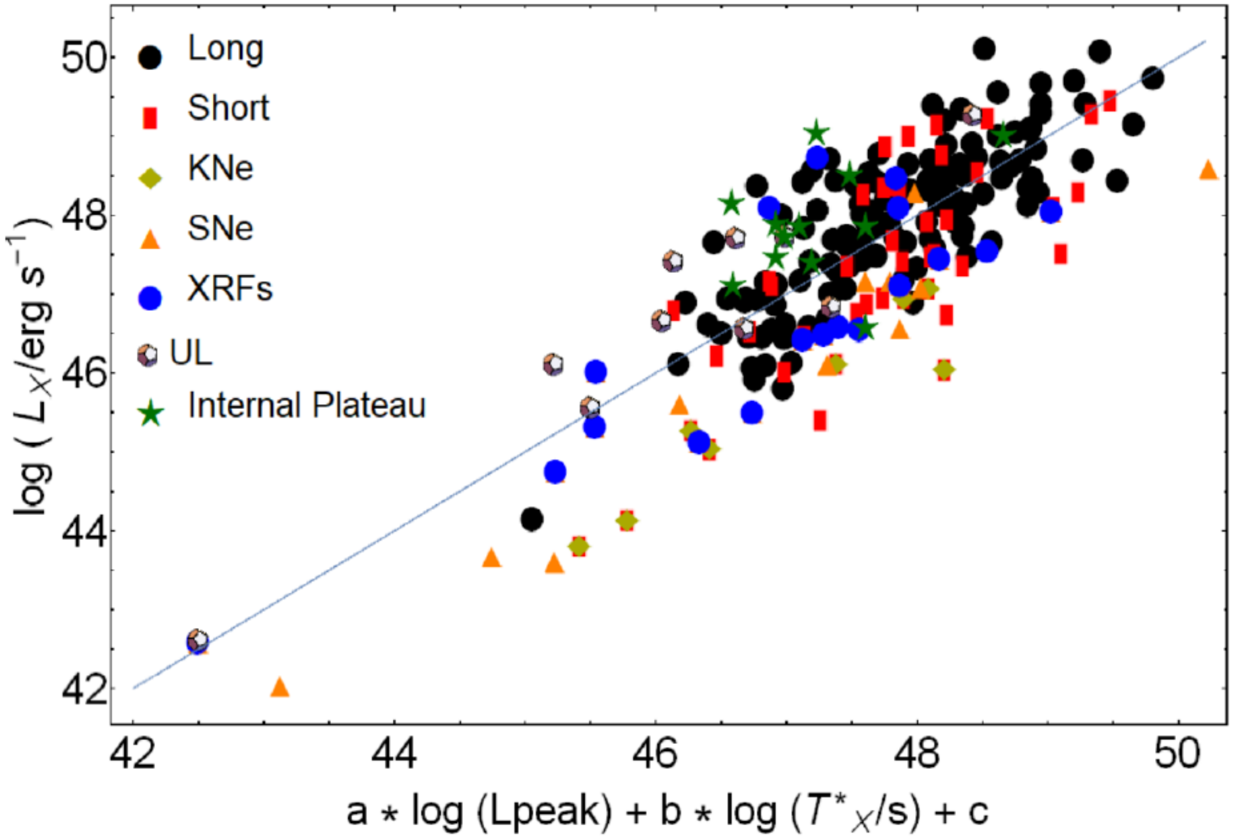
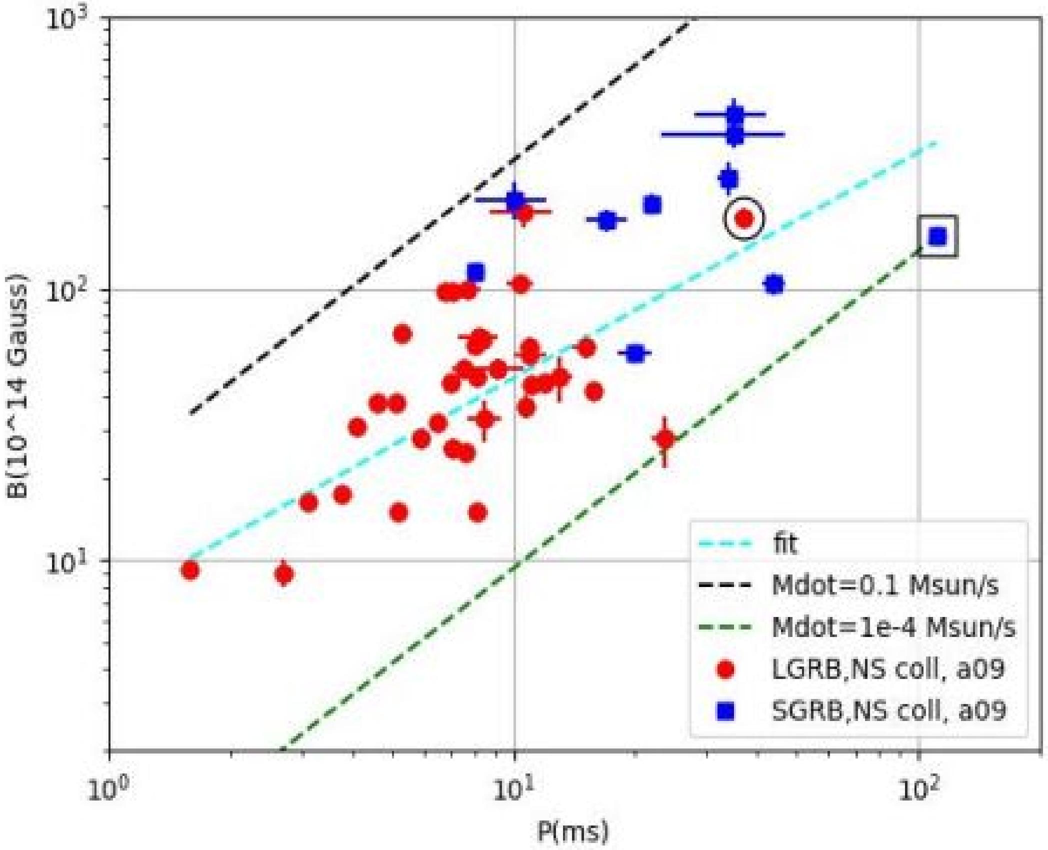


Figure 1. The 2D projection of the $L_X - T^*_X - L_{peak}$ relation for the 222 GRBs of our sample, with a plane fitted including LGRBs (black circles), SGRBs (red rectangles), KN-SGRBs (dark yellow rhombuses), SN-LGRBs (orange triangles), XRFs (blue circles), ULGRBs (dodecahedrons), and GRBs with internal plateaus (green stars).

* KNe are transient objects which are derived by the mergers of two neutron stars.
* Several KN have been associated with short GRBs.
Here we consider all cases presented in Rossi et al. 2020

* The temporal power-law (PL) decay index of the plateau, α_i: a very steep decay, $\alpha_i \geq 3$ for Li et al. (2018) and $\alpha_i \geq 4$ for Lyons et al. (2010), indicates the possible internal origin of the plateau (Willingale et al. 2007) related to the magnetar.

Two different classes within the magnetar scenario

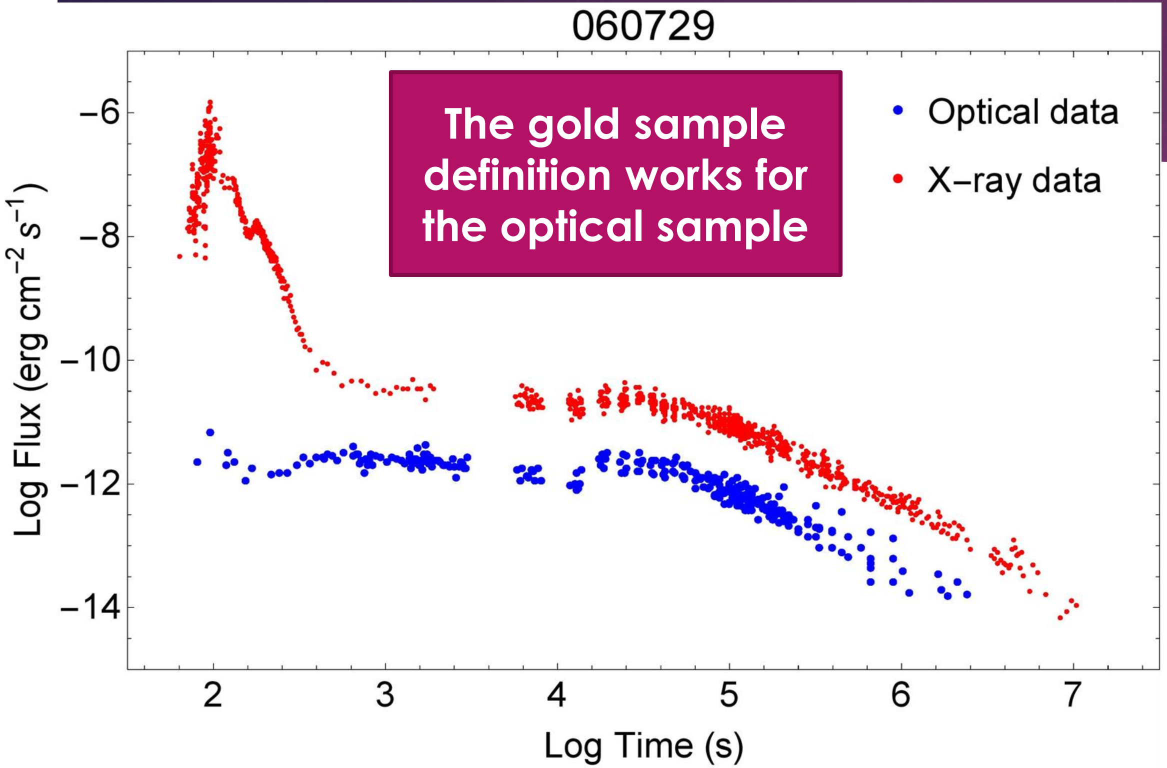


Stratta, Dainotti, Dall'Osso, Hernandez, de Cesare 2018, ApJ, 869, 155

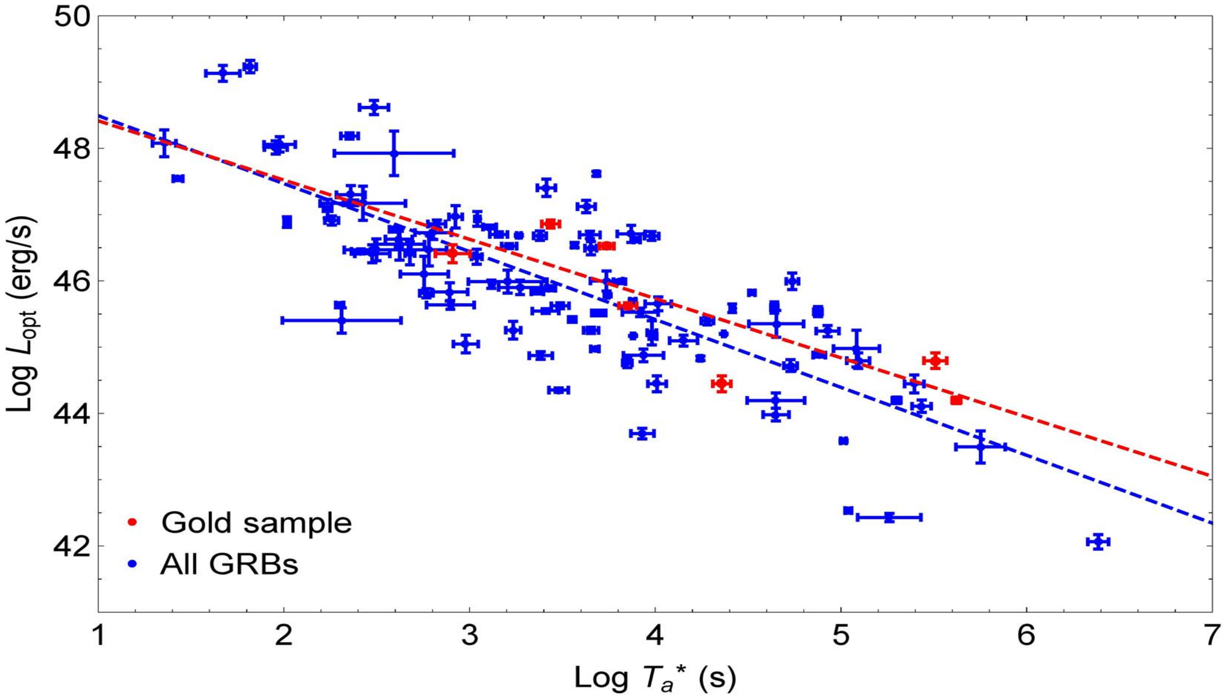
- The spin-down luminosity of the magnetar is entirely beamed within ѳjet.
- The long GRB 070208 (circle) and the peculiar GRB 060614A (square).
- Previous literature: Dall'Osso et al. 2011, Bernardini et al. 2012, 2013, 2015, **Rowlinson et al. 2014 including Dainotti, Rea et al. 2015 (ncluding Dainotti)**, Beniamini et al. 2017, Beniamini & Mochkovitch 2017. See Liang et al. 2018 for comparison with isotropic emission.
- Within the external shock model (Srinivasagaravan, **Dainotti et al. 2020**, Warren et al. 2017).

The L-T correlation in optical for more than 100 GRBs

(Dainotti, al. 2020, ApJL, Vol. 905, Issue 2, id.L26, 8)



The gold sample definition works for the optical sample



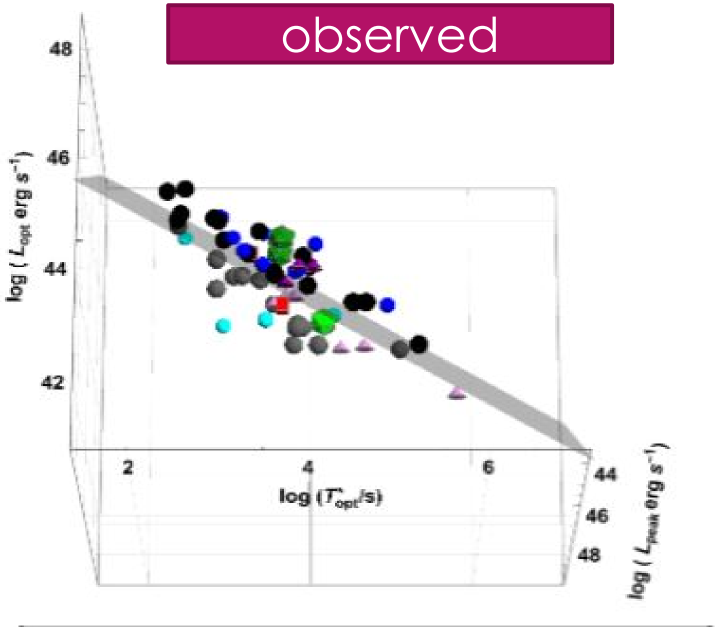
The gold sample reduces σ by 52.4% compared to the total sample. For all GRBs **bopt**=-1.02 ± 0.16, σ^2=0.65. For the gold sample **bopt**=-0.89 ± 0.64, σ^2 =0.30. X-ray and optical slopes are within 1 σ. See **Dainotti et al. 2008, 2010, 2011a, 2013a, 2015a, 2017a.**

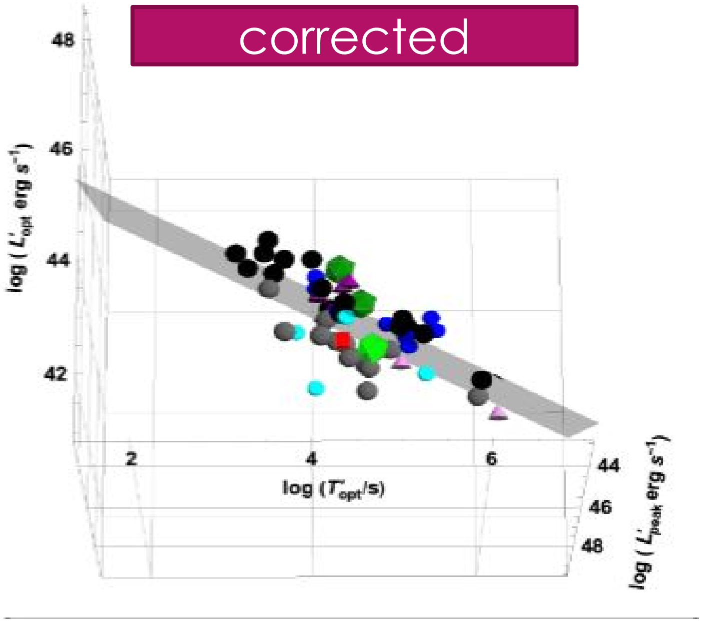
The gold sample : Flat plateau (< 41°)

Minimum 5 points at the beginning of the plateau

Stanford blog, press release issued by Jagiellonian University.

The 3D optical correlation exists for 59 GRBs ApJ submitted


observed


corrected

For comparisons see **Dainotti et al. 2016, 2017b, 2020a**

- **Black circle→ 31 Long**
- **Blue sphere→ 4 XRF, 19 XRR**
- **Red cuboids→ 2 Short**
- **Purple cones→ 9 GRB-SNe Ib/c**
- **Green icosahedron->3 Ultra-long**

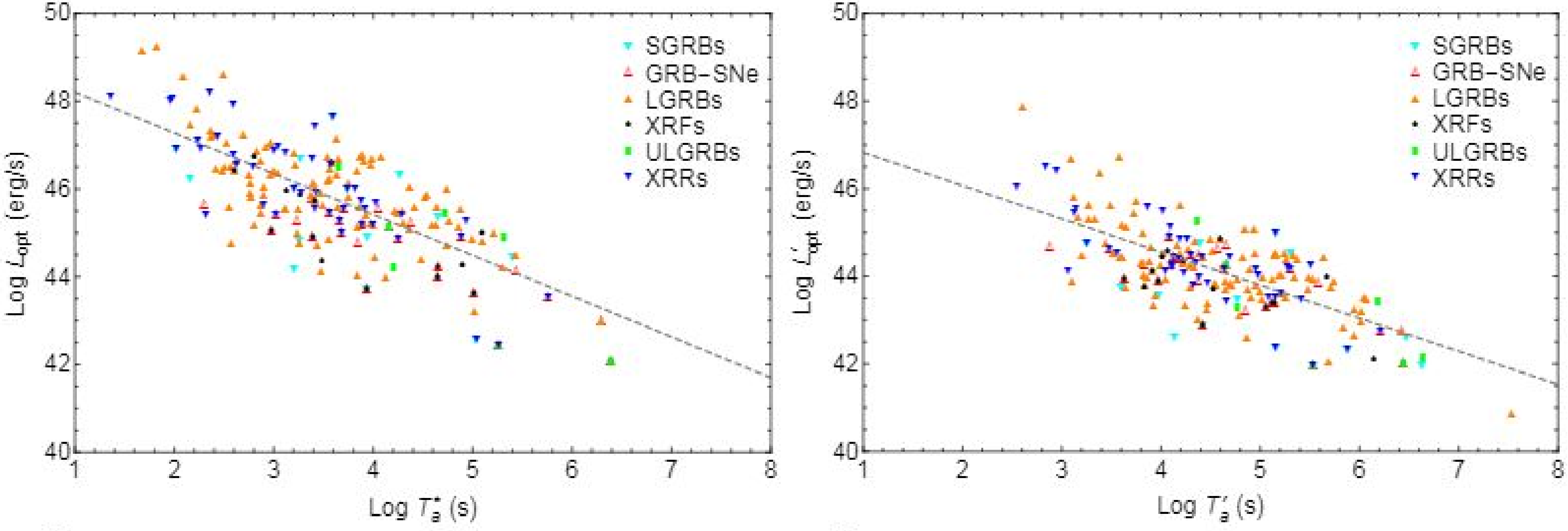
students from the Scientific Caribbean Foundation from Puerto Rico

Student from University of Pennsylvania

Where the sGRBs observed by KISO will be placed for the 2D and 3D?

- Shall be different from the rest of the population?
- Shall be interpreted within magnetar?

OPTICAL LUMINOSITY-TIME CORRELATION



THANK YOU VERY MUCH FOR YOUR ATTENTION AND YOU ARE INVITED TO JOIN US !!!

Contact me

Email:maria.dainotti@nao.ac.jp

DOMO ARIGATO