Gamma Ray Bursts in the *AstroSat*-CZTI era

THESIS DEFENCE

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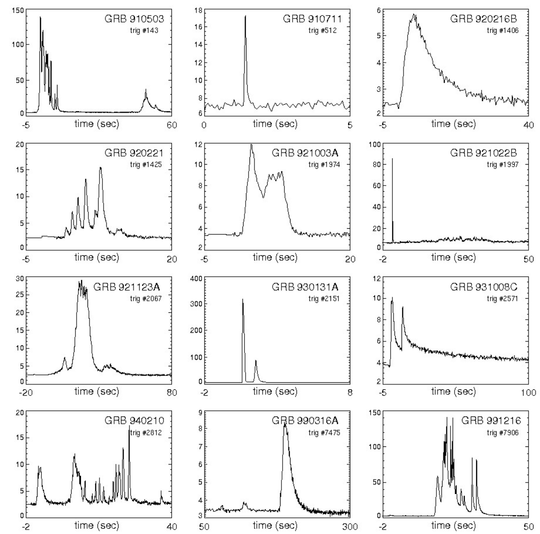
under the guidance of **Professor A R Rao**

Tata Institute of Fundamental Research, Mumbai, India

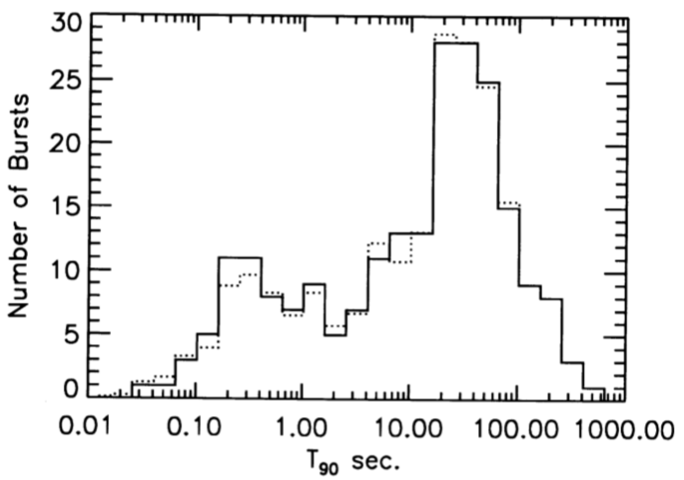
22nd October, 2019

Serendipitous discovery



NASA/Marshall Space Flight Center

Duration bi-modality

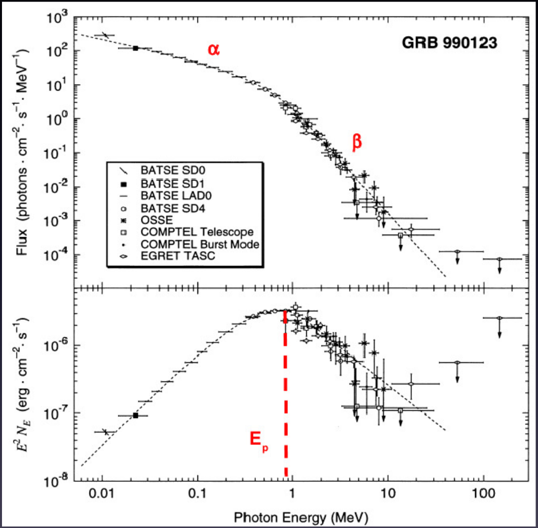


Kouveliotou+'93

What do we observe?

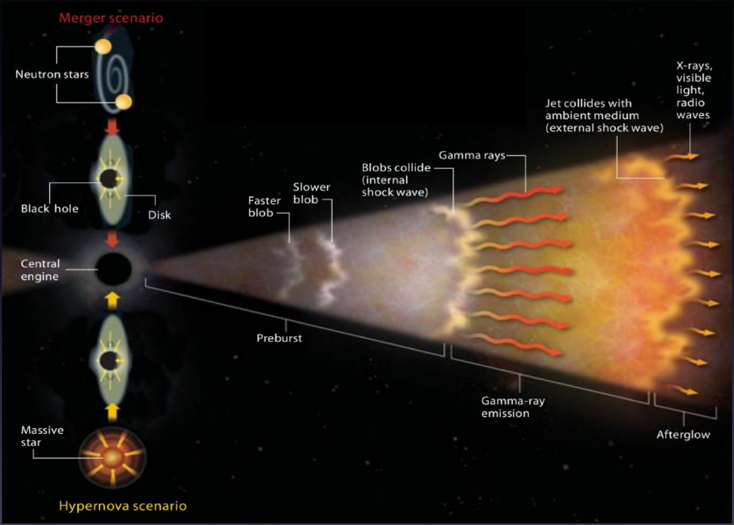
- Sudden flash of radiation in γ-rays to hard X-rays.
- Lasts for $\sim$ seconds to $\sim$ 100s of seconds.
- No repetitions ever $\implies$ cataclysmic events.
- Energy output several orders of magnitude higher.
- There are at least two kinds of bursts.

Spectra – “Band function”



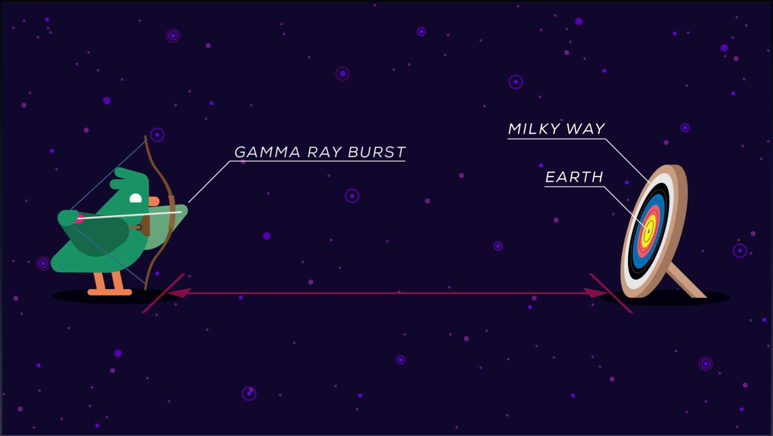
Briggs+’99

Current understanding



http://personal.psu.edu/wnb3/astro130/images/

Beaming

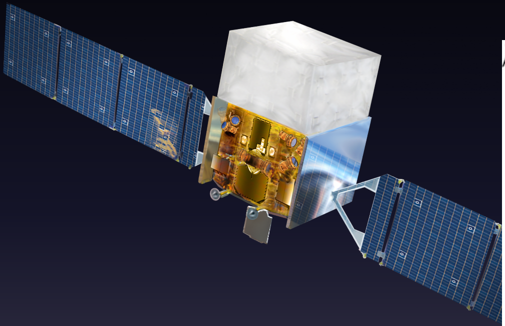


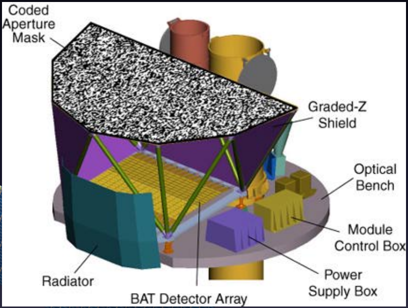
https://gigazine.net/gsc_news/en/20160802-gamma-ray-bursts

GRBs are studied via

- Observations:
  - detecting individual GRBs;
  - following up individual GRBs for detailed studies;
  - empirical modelling of the population.
- Theoretical modelling;
- Simulations.

The state of the art



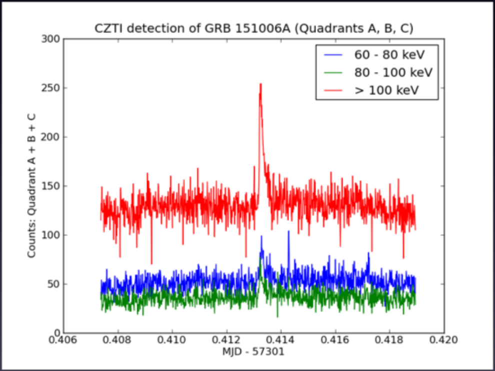


Swift
https://swift.gsfc.nasa.gov/about_swift/bat_desc.html

Fermi
https://science.nasa.gov/toolkits/spacecraft-icons

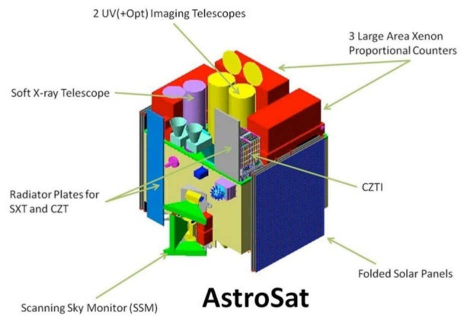
Advancing the state of the art

- *AstroSat* launched on 28th September, 2015.
- CZT Imager headed by Professor Rao detected a GRB the first day.

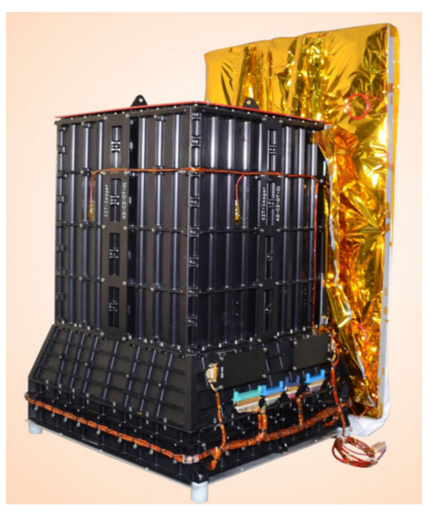


CZTI team

AstroSat

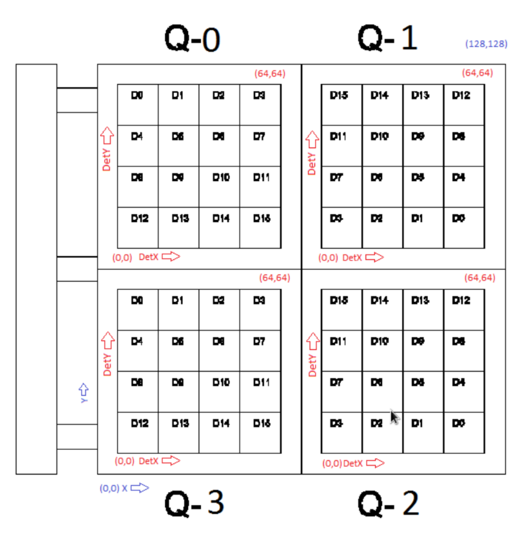


AstroSat team



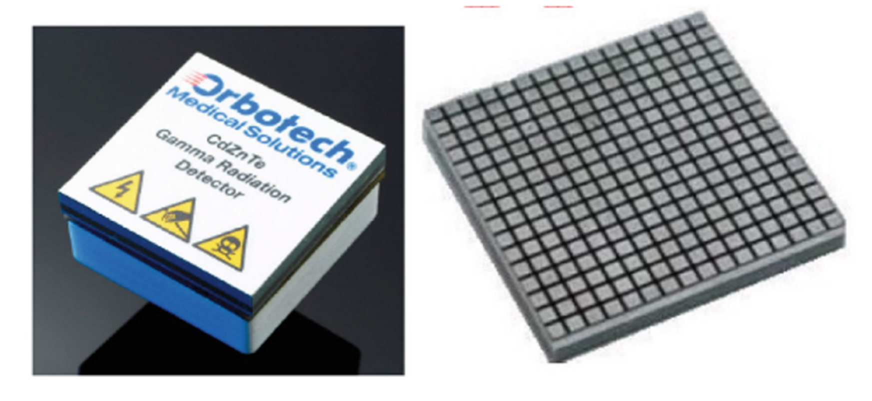
Bhalerao+'17

CZT Imager (CZTI)



CZTI team

The pixelated detectors



Chattopadhyay+'14

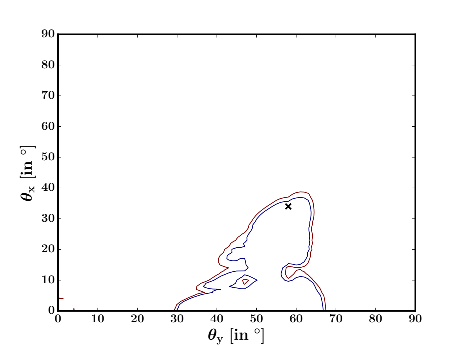
CZTI as a GRB detector

- Timing; Spectroscopy.
- Complements the capabilities of *Swift* and *Fermi*.
- What about localisation?

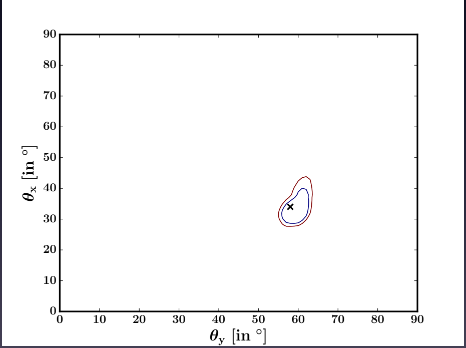
GRB151006A

Rao+'16; Collaborators:

- Professor A R Rao; NPS Mithun (PRL, Ahmedabad)
- Professor Dipankar Bhattacharya (IUCAA, Pune)

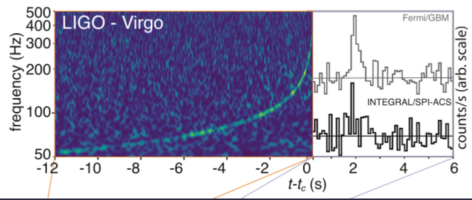


Data

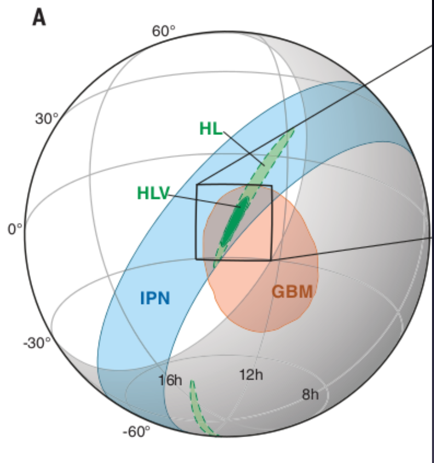


Simulations

How many GRBs can it detect?



Abbott+'17e



Kasliwal+'17

The Luminosity Function (LF), $\Phi(L)$

$$\mathrm{d}N \equiv T\,\Delta\Omega \times \dot{R}(z)\mathrm{d}V \times \Phi(L)\mathrm{d}L,$$

with

$$\dot{R}(z) = f_{\mathrm{B}} C\,\Psi(z),$$

$$\Psi(z) = \int\limits_{z_{\min}(z)}^{\infty} \dot{\rho}_\star(z')\,P\left(\tau[z,z']\right)\frac{\mathrm{d}\tau}{\mathrm{d}z'}\mathrm{d}z'.$$

Aim: To model $\Phi(L)$.

Motivations:

- To measure the true source rate.
- To predict the number distribution for newer instruments.

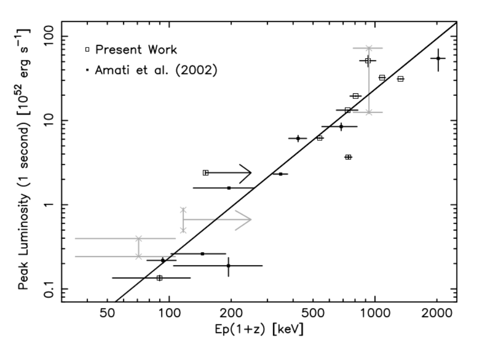
Review: Proposed methods

- Measured redshift (z) distribution:
  Statistical limitation + selection bias.
- Measured flux (P) distribution:
  Intrinsic parameters (z, L) $\rightarrow$ Measured parameter (P)?
  - Limit to “flux-complete” sample: Statistical limitation.
- Different instruments give different results.

Yonetoku correlation

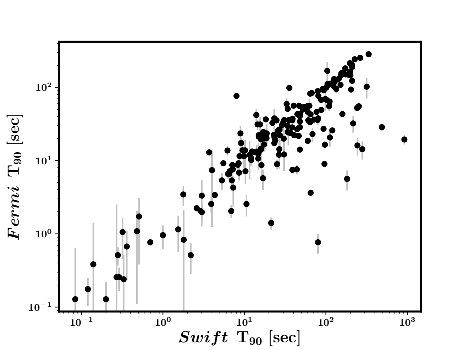
$$L = P\,4\pi d_L(z)^2 \times k(z;\,\mathrm{spectrum})$$

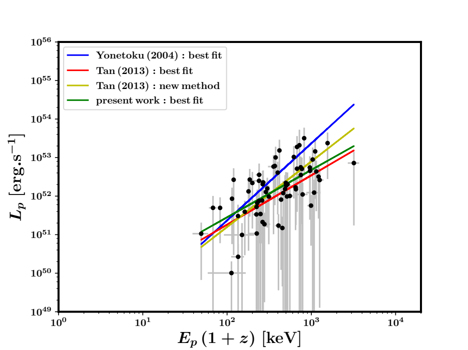
z is measured only for a small fraction of GRBs.



Yonetoku+'04

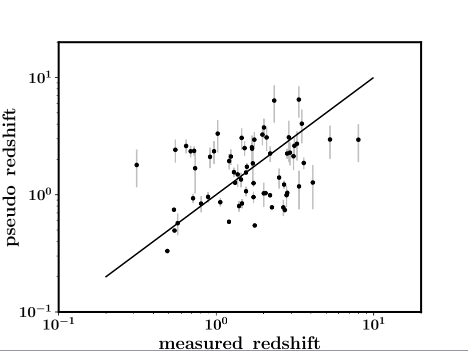
Yonetoku correlation – re-tested

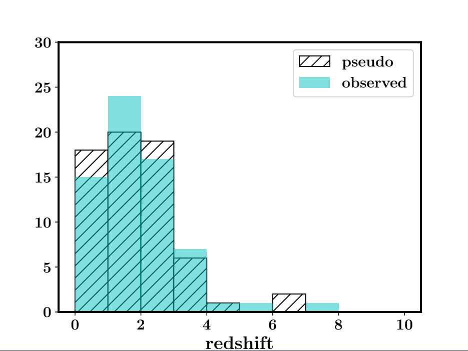




Discussion credits: Eric Burns (Burns+'16)

‘Pseudo’ redshifts





- Long GRBs cannot be used as standard candles. But...
- ... the statistical use of pseudo redshifts is reasonable.

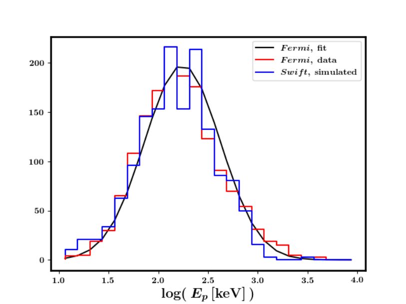
GRBs used for modelling

- First use of *Fermi* GRBs.
- Largest sample of GRBs **ever** used.

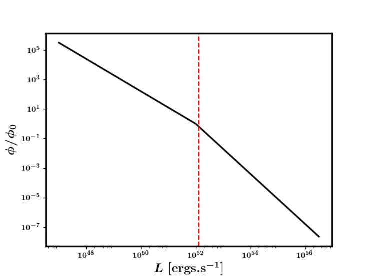
Only the Band function is adhered to for generalisation.

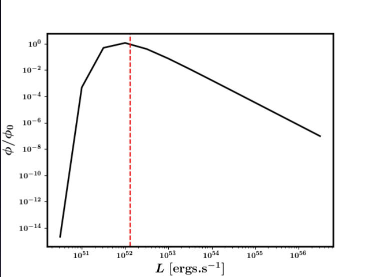
Table 1. The type of *Fermi* and *Swift* long GRBs used for modelling, and how they are referred. The total number is 2067.

Type	Redshift measured	Number	Modelled as
Both *Fermi* and *Swift*	Yes	66	*Fermi*
Only *Fermi*, or both	No	1278	
Only *Swift*	No	499	*Swift*
Only *Swift*	Yes	224	



Models tested against data





Broken **P**ower**L**aw (BPL):

$$\Phi(L) = \Phi_0 \begin{cases} \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu_1}, & L \leq L_\mathrm{b} \\ \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu_2}, & L > L_\mathrm{b}. \end{cases}$$

Exponential-**C**utoff **P**ower**L**aw (ECPL):

$$\Phi_z(L) = \Phi_0 \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu} \exp\left[-\left(\frac{L}{L_\mathrm{b}}\right)\right]$$

Long GRB formation rate

Known, that for *Fermi*, $T \sim 8.5$ yr, for *Swift*, $T \sim 12$ yr.
Assuming $\frac{\Delta\Omega}{4\pi} \sim \frac{1}{3}$ for *Fermi*, and $\frac{1}{10}$ for *Swift* :

$$f_B C(0) = \begin{cases} 0.981 \times 10^{-8}\,\mathrm{M}_\odot^{-1}, & \textit{Fermi}, \\ 1.022 \times 10^{-8}\,\mathrm{M}_\odot^{-1}, & \textit{Swift}. \end{cases} \tag{1}$$

for ECPL, &

$$f_B C(0) = \begin{cases} 0.597 \times 10^{-8}\,\mathrm{M}_\odot^{-1}, & \textit{Fermi}, \\ 0.653 \times 10^{-8}\,\mathrm{M}_\odot^{-1}, & \textit{Swift}. \end{cases} \tag{2}$$

for BPL.

Reference	$\dot{R}(0)$ $\mathrm{yr^{-1}Gpc^{-3}}$
Amaral-Rogers+'17	0.04-0.24
Paul'18a	0.12-0.20

Predictions for *AstroSat*-CZTI

The models are used to predict 140-150 GRB detections per year for CZTI.

In the first year, $\sim$ 100 have been found (subjective).

$\therefore$ 40-50 are missing in triggered searches!

Good news + testing ground for automated search algorithms being developed...

Publicly available tool for any new instrument.

...and others

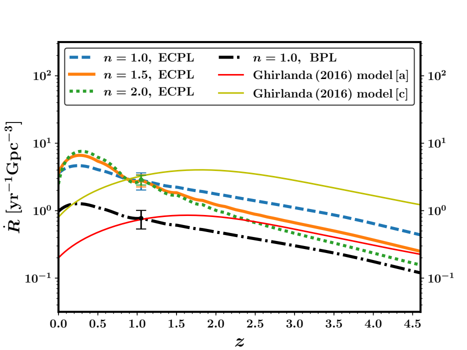
Instrument	Predicted numbers $[\mathrm{yr}^{-1}]$
XMM-Newton /EPIC-pn	11-13
Chandra /HRC-I	10-14
Athena /WFI	16-20

Daksha (proposal accepted by ISRO)

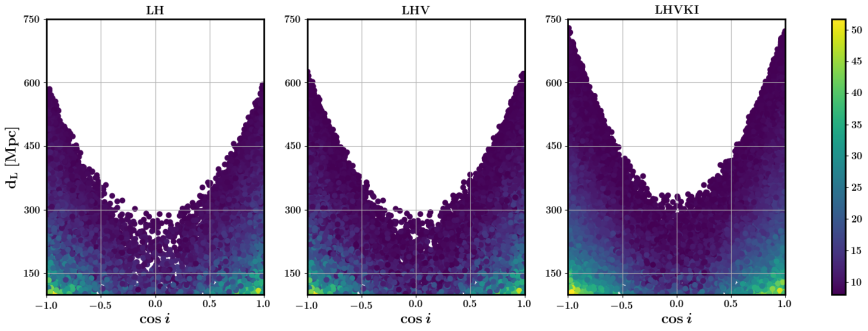
Wavelength range [keV]	Sensitivity $[\mathrm{erg\,cm^{-2}\,s^{-1}}]$	Predicted numbers $[\mathrm{yr}^{-1}]$
1-10	0.3×10^{-8}	210-246
20-200	1.7×10^{-8}	229-274

Short GRB formation rate

Reference	$\dot{R}(0)$ $[\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}]$
Ghirlanda et al. (2016), model [a]	0.13-0.24
Guetta & Piran (2005)	0.1-0.8
Yonetoku et al. (2014)	0.24-0.94
Ghirlanda et al. (2016), model [c]	0.65-1.10
present work	0.61-3.89
Coward et al. (2012)	5-13
Guetta & Piran (2006)	8-30

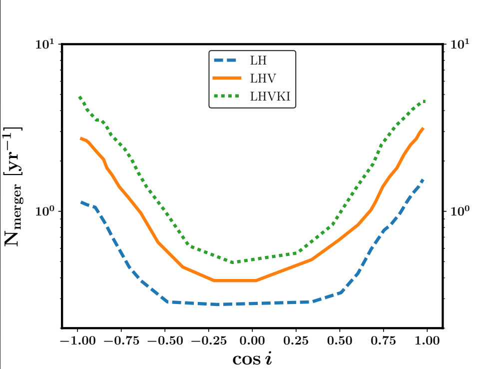


Binary neutron star merger (BNSM) rate – aLIGO/VIRGO



Saleem+'18

Binary neutron star merger (BNSM) rate – aLIGO/VIRGO



- **lower limits** [yr^{-1}]: LH: 0.95; LHV: 1.87; LHVKI: 3.11.
- Inferred rate from GW/EM170817: $1\,\mathrm{yr}^{-1} \implies \gtrsim 2\,\mathrm{yr}^{-1}$ from the next observing runs.

True sGRB and BNSM rates

- $f_{\mathrm{B}} = 1 - \cos\theta_j$, where θ_j is the jet opening angle.
- $\theta_j = 3\text{-}26^\circ$ (Margutti+'12; Fong+ '12, '15).
- sGRB formation rate, $R_0 = \frac{\dot{R}(0)}{f_{\mathrm{B}}} = 6\text{-}2838\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$.
- Abbott+'17e: BNSMr $= 320\text{-}4740\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$.
- Each BNSM creates a sGRB : allowed.

Constraints are weak.

AstroSat-CZTI

Prediction: 14-42 yr^{-1}.

Observed: $\sim$ 36* in 2 yr.

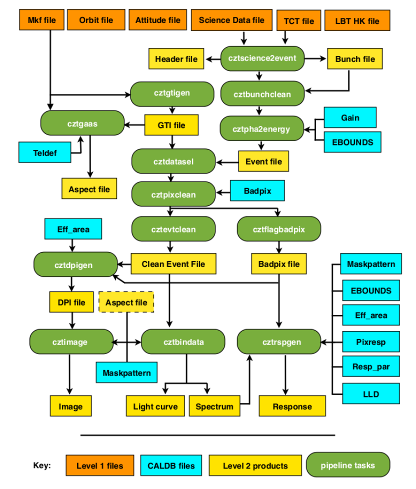
* Subjective:
initial triggered searches by Vidushi Sharma $+$
latter systematic searches by Ajay Ratheesh
[Feb'16 – Oct'17].

Still a good number missing.

Daksha:

- Soft [1-10 keV]: 11-12 yr^{-1}.
- Hard [20-200 keV]: 34-35 yr^{-1}.

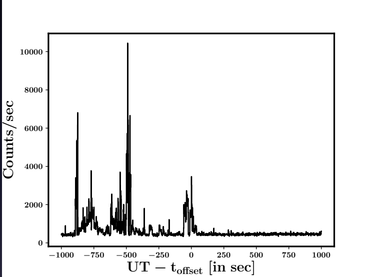
CZT Imager (CZTI) – pipeline



CZTI handbook (CZTI team)

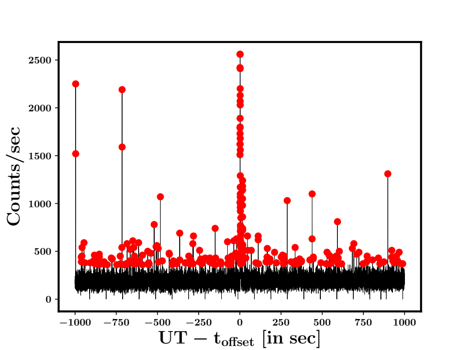
Definitions

- What is 'data'? $\{t, \mathrm{det_x}, \mathrm{det_y}, E\}$.

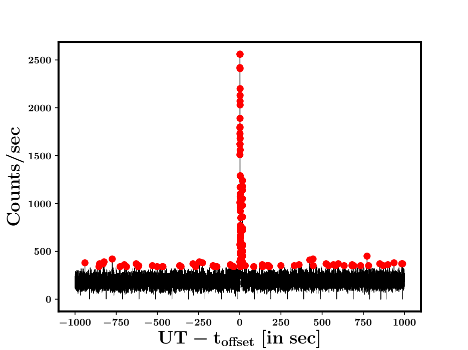


- What is 'background'? A continuous stream of data.
- What is 'noise'? That is what the project is about.

Magic!

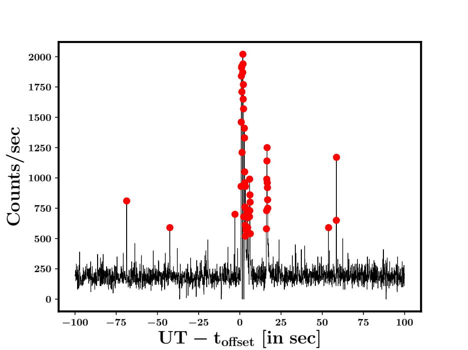


Counts/sec
2500
2000
1500
1000
500
0
−1000
−750
−500
−250
0
250
500
750
1000
UT − t_{offset} [in sec]



Counts/sec
2500
2000
1500
1000
500
0
−1000
−750
−500
−250
0
250
500
750
1000
UT − t_{offset} [in sec]

Magic!



Counts/sec
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1750
1500
1250
1000
750
500
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0
−100
−75
−50
−25
0
25
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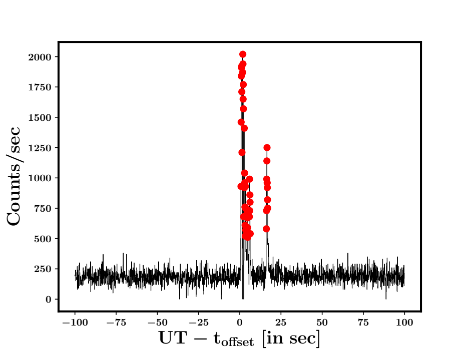

Counts/sec
2000
1750
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1250
1000
750
500
250
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−100
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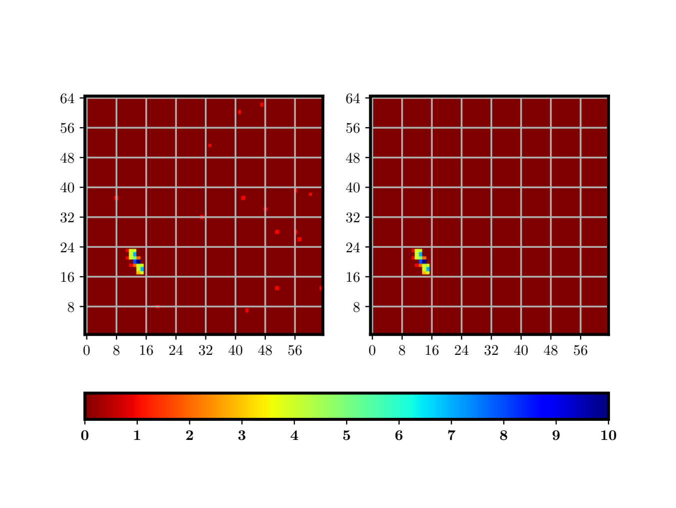
−50
−25
0
25
50
75
100
$\mathrm{UT} - \mathrm{t_{offset}}$ [in sec]

Culprits



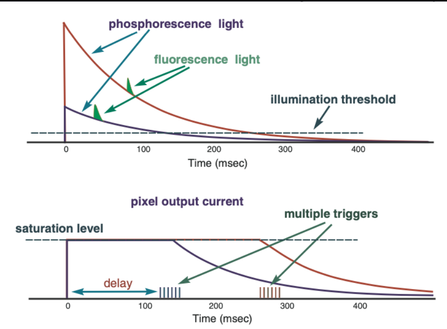
My contribution

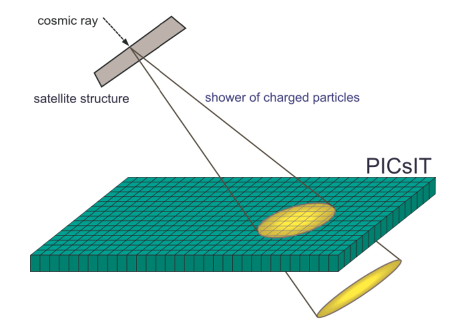
- A thoroughly tested algorithm has been implemented to catch the culprits.
- This is my main contribution to this work.

	Q0	Q1	Q2	Q3
Before	4.968	6.909	11.333	10.293
After	8.482	10.163	19.753	17.496

Table: GRB160802A Signal to Noise ratio improvement.

Explanation for PICsIT

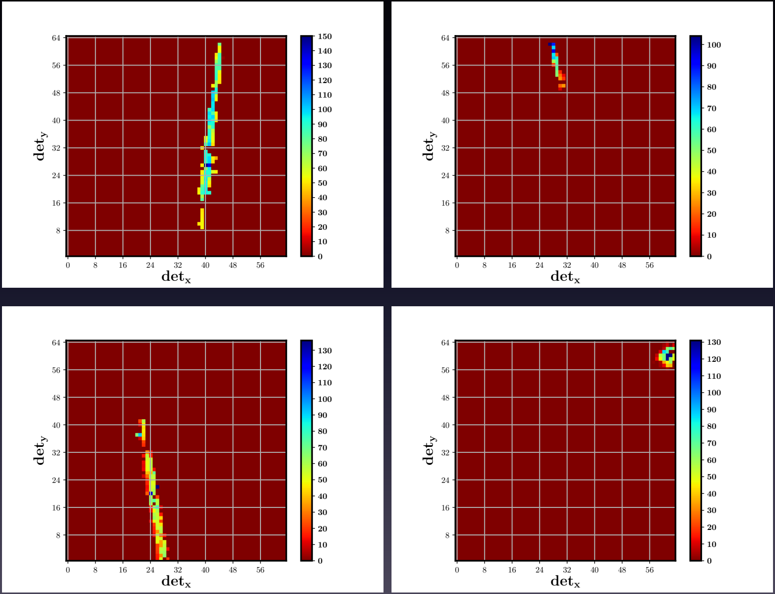




$$\delta = \tau \log\left(\frac{N_0}{N_{\rm sat}}\right)$$

Segreto+'03

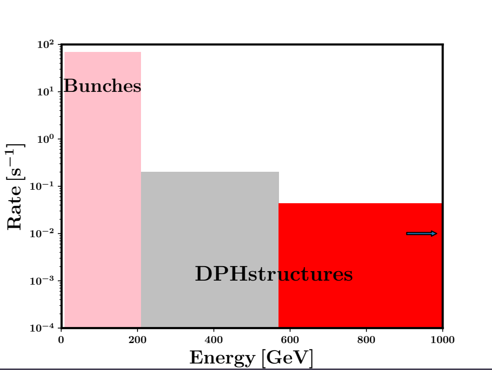
Detector Delay Histograms



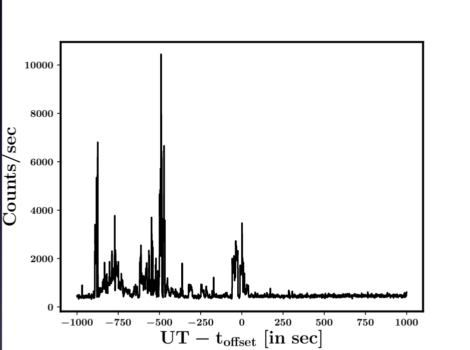
Energy limits

$$\frac{dN}{dE} = 1.8\,\frac{\mathrm{nucleons}}{\mathrm{s\,m^2\,sr\,GeV}}\left(\frac{E}{1\,\mathrm{GeV}}\right)^{-2.7}$$

Bunches: $70\,\mathrm{s}^{-1}$; DPHstructures: $0.2\,\mathrm{s}^{-1}$, $0.044\,\mathrm{s}^{-1}$.



Summary



Counts/sec
10000
8000
6000
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−1000
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−250
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250
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750
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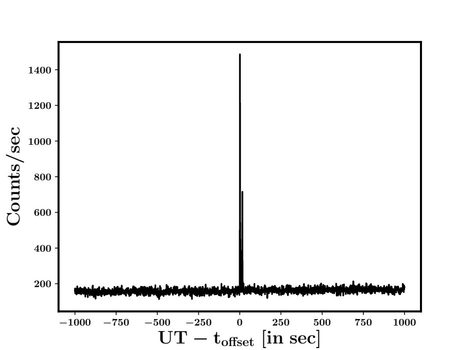
UT − t$_{\text{offset}}$ [in sec]



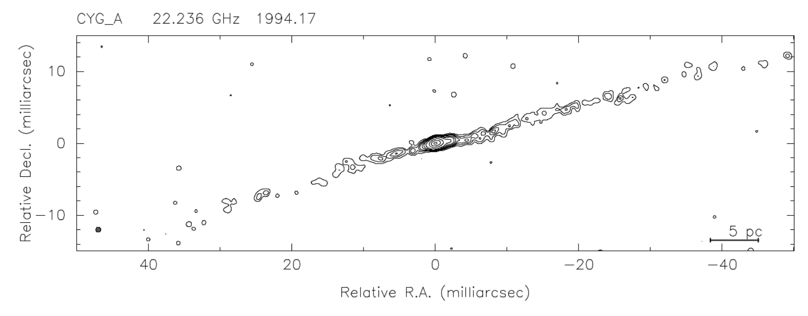
Counts/sec
1400
1200
1000
800
600
400
200
−1000
−750
−500
−250
0
250
500
750
1000
UT − t$_{\text{offset}}$ [in sec]

Theoretical modelling

... of partially self-absorbed quasi-static synchrotron emission.

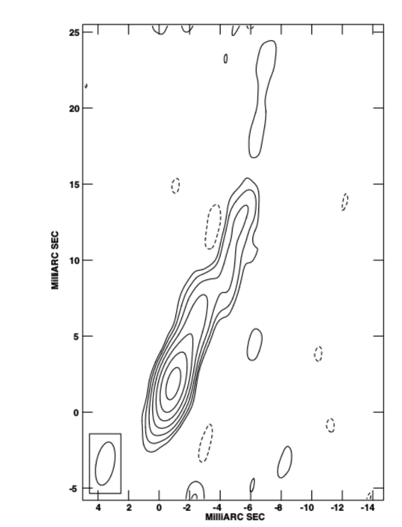
Why?

Bipolar emission in radio



Cygnus A: Krichbaum et al. (1997)

Cygnus X-1: steady jet



Stirling et al. (2001)

Motivation

- Early theoretical studies to explain observed properties of relativistic jets (Blandford & Rees, 1974; Blandford & McKee, 1976; 1977; Blandford & Konigl, 1979 [BK'79]; Lind & Blandford, 1985) identified the observed radiation with non-thermal emission from relativistic particles.
- Specifically, synchrotron radiation in the presence of magnetic fields.
- Unlike GRS 1915+105 or Cygnus X-3, Cygnus X-1 radio emission is steady over $\sim$ days (Stirling et al., 2001; Russell and Shahbaz, 2014).
- In the BK'79 model, a steady jet fed by a central engine powers the radio emission.

Motivation

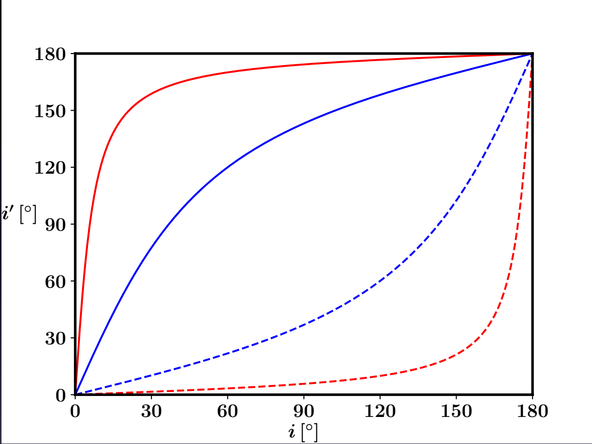
BK'79:

- $\alpha = 0$ if the jet is partially self-absorbed, i.e. τ varies.
- However, do not consider the dependence of F on δ_j & i.

Zdziarski, **Paul**, Osborne, Rao (2016):

- set out to correct that;
- re-derive constraints on Γ_j.

The emission angle transformation

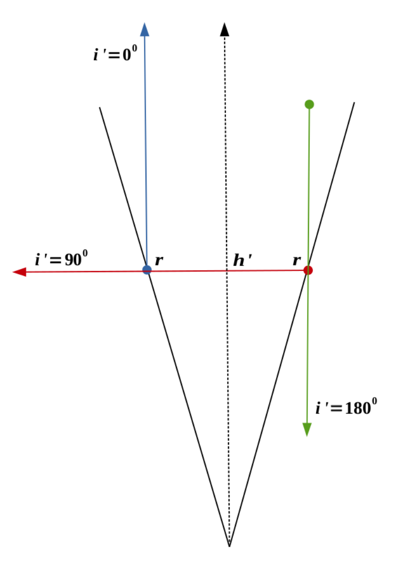


$$\sin i' = \delta_j \sin i$$

$i' > 90^\circ$ for most viewing angles in the observer's frame.

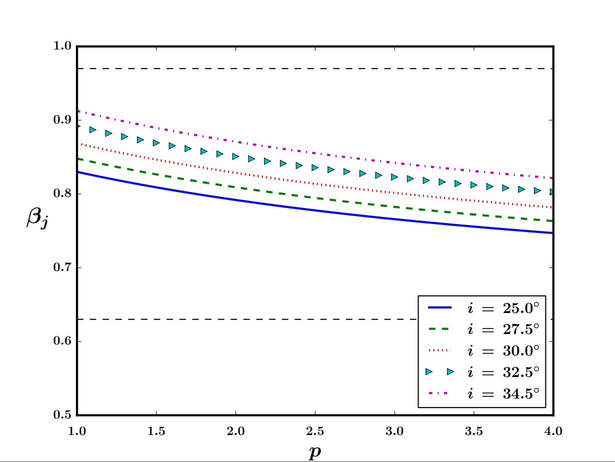
Unparalleled in classical mechanics.

The three regimes



Observational predictions

$$R = \left(\frac{\delta_j}{\delta_{cj}}\right)^{\frac{3p+7}{p+4}} \implies \beta_j = \frac{1}{\cos i}\,\frac{R^{\frac{p+4}{3p+7}} - 1}{R^{\frac{p+4}{3p+7}} + 1}$$



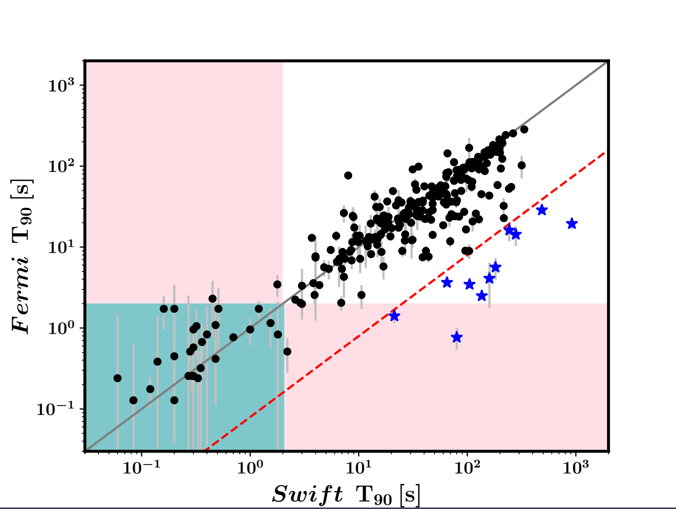
Extension to GRBs...

... is not simple.

- Synchrotron cooling;
- probably synchrotron self-Comptonisation.
- The time-dependence of the whole set-up.

Complicated, but nevertheless important.

T_{90} comparison

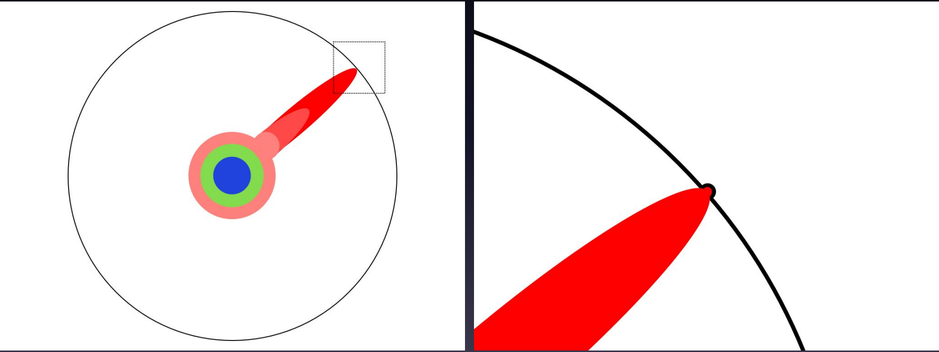


Take away

- Luminosity Function models for long and short GRBs pinned down.
- Rigorous noise analysis done for *AstroSat*-CZTI data.
- Anisotropy pattern of partially self-absorbed synchrotron relativistic jets analytically calculated.

Bigger picture

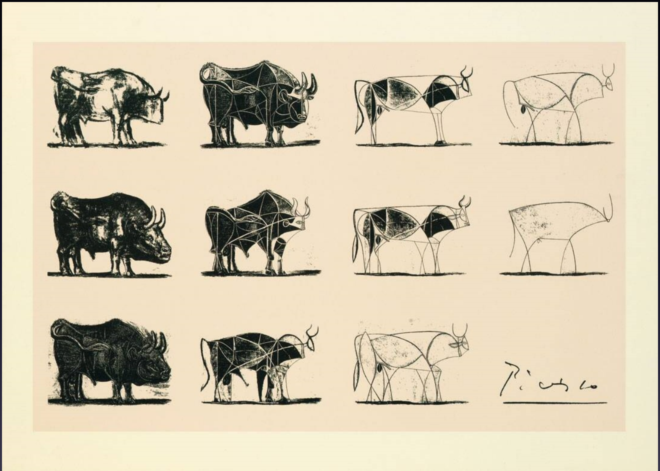
The study of GRBs is observational, empirical, and theoretical.



http://matt.might.net/articles/phd-school-in-pictures/

I think I have pushed the boundaries a tiny bit.

Thank you!



"**All models are false, some are useful.**"
– George E. P. Box, British statistician (1919-2013)