4th Astro-COLIBRI Multi-Messenger Astrophysics Workshop

GRB 221009A and Ultra-Long GRBs

Amit Kumar Ror

MJP Rohilkhand University, Bareilly

Aryabhatta Research Institute of observational sciencES (ARIES)

In collaboration with:

Shashi B. Pandey (ARIES, INDIA), A. J. Castro-Tirado (IAA-CSIC, SPAIN)

Rahul Gupta (NASA, USA), S. R. Oates (Lancaster University, UK)

चरैवेति चरैवेति

महात्मा ज्योतिबा फुले
रुहेलखण्ड विश्वविद्यालय, बरेली

Gamma-Ray Bursts (GRBs)

Detection: Intense and short pulses

Distribution: Coming from all direction

Phases: Prompt and Afterglow

Distance: z range from 0.0085 - 9.4

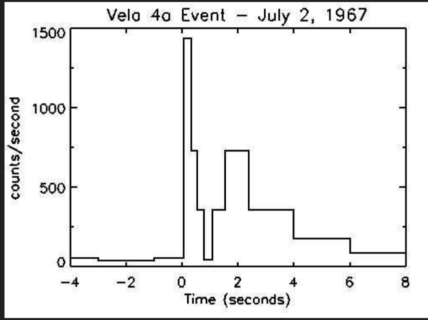
Energetics: 1e48 - 1e55 erg

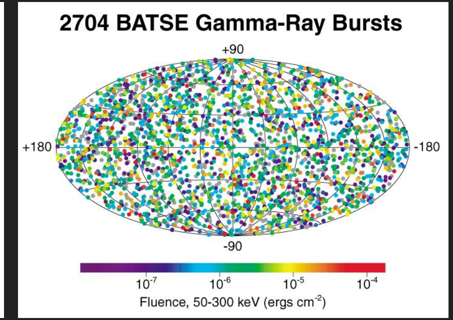
Bimodal: Short GRBs, Long GRBs

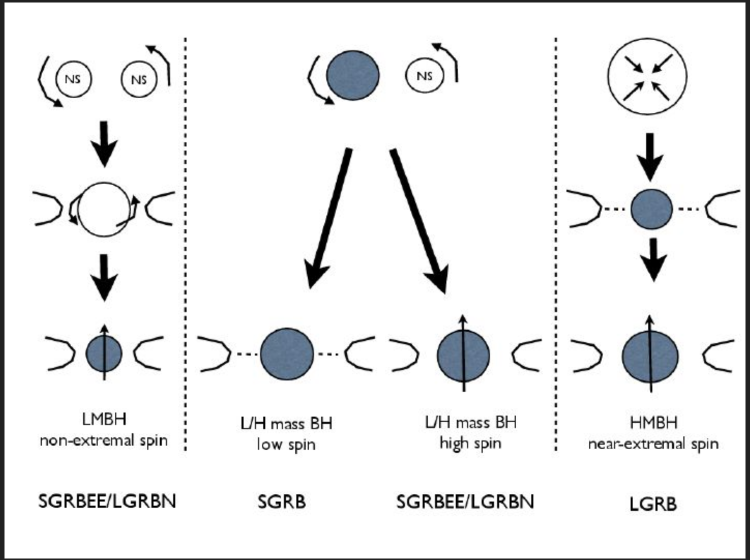
Origin: Merger or Collapsar

Ultralong GRBs (ULGRBs):

GRBs with prompt emission duration > 1000 s

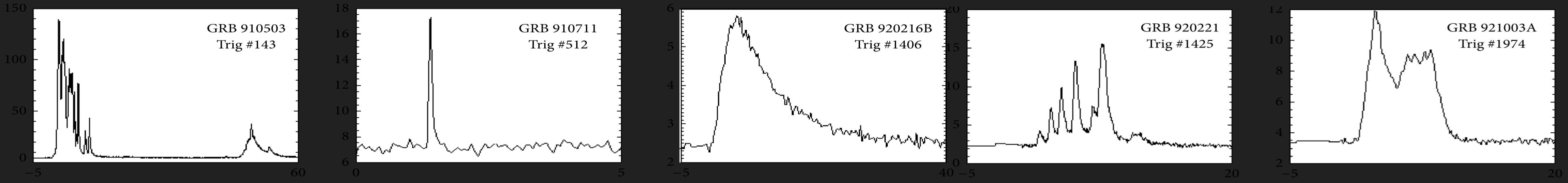


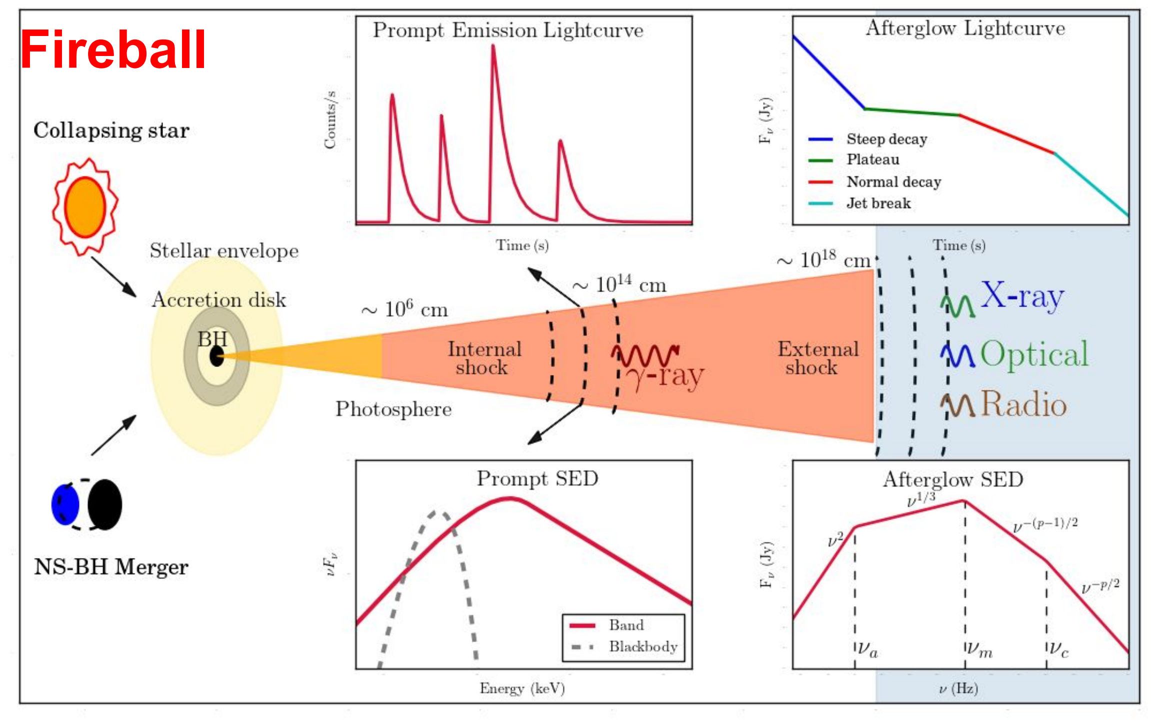




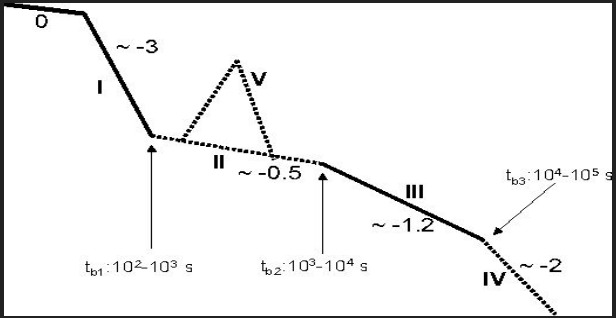
Credit: M. van Putten (2015)

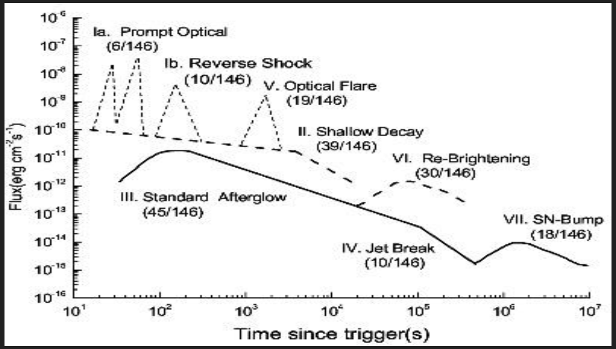
Origin of Prompt and afterglow emissions





Afterglow Lightcurve





Short GRBs Long GRBs, and Ultra long GRBs

- Short GRB T90 < 2 s

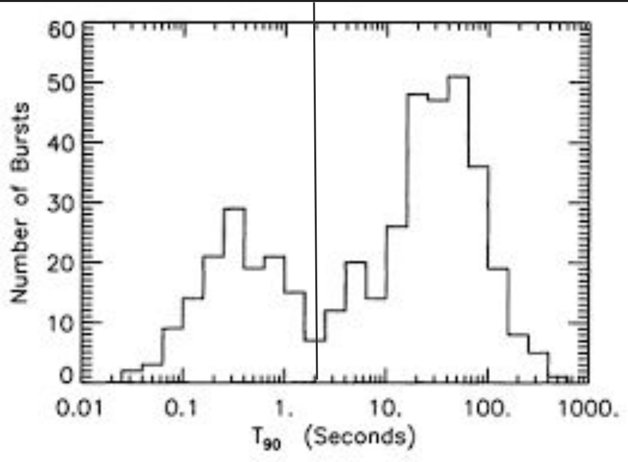
Neutron star-neutron star or neutron star-black hole mergers

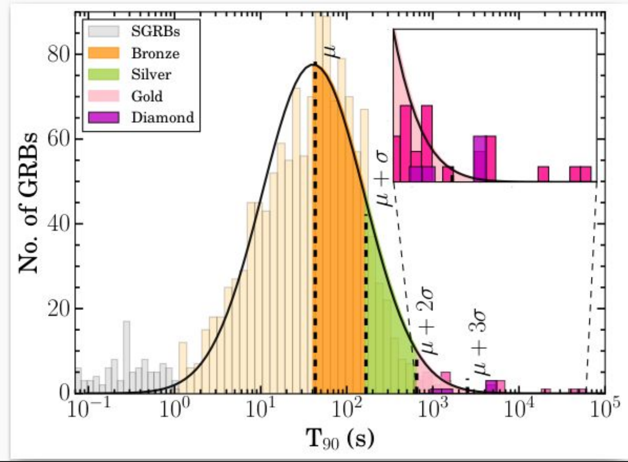
- Long GRBs T90 > 2 s

Often linked to the collapse of massive stars

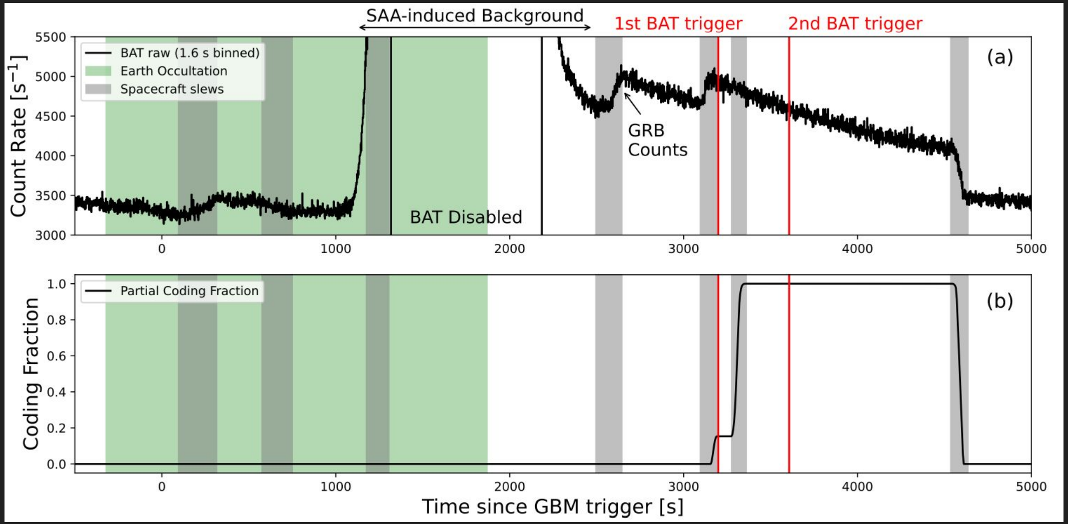
- Ultra Long GRBs > 1000 s

Potential origins including collapsars, tidal disruptions, or highly magnetized millisecond pulsars

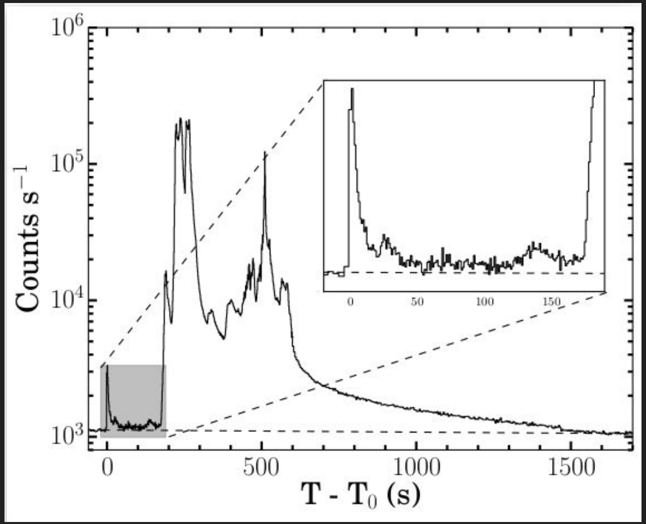




Importance of GRB 221009A in the context of ULGRBs



Williams et al. (2023)

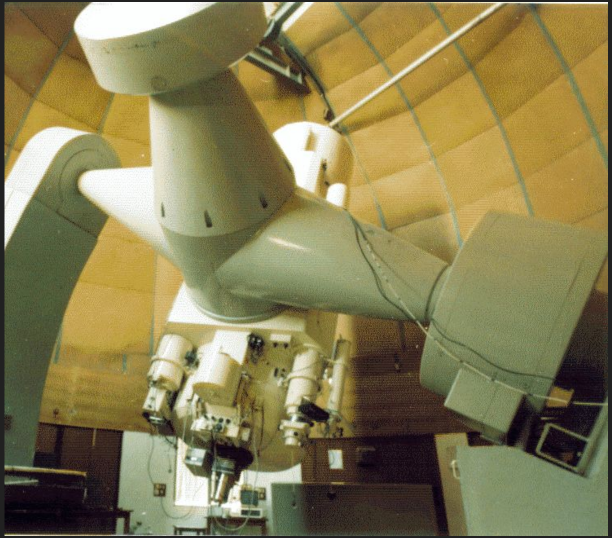


Ror et al. (2024)

- BAT from T0 -500s to T0 + 5000s
- Occulted by the Earth until T0 + 1870 s
- South Atlantic Anomaly, from T0+1317-2183s
- BAT triggered on T0 + 3200s
- Since 2004, first time BAT triggered on the afterglow phase

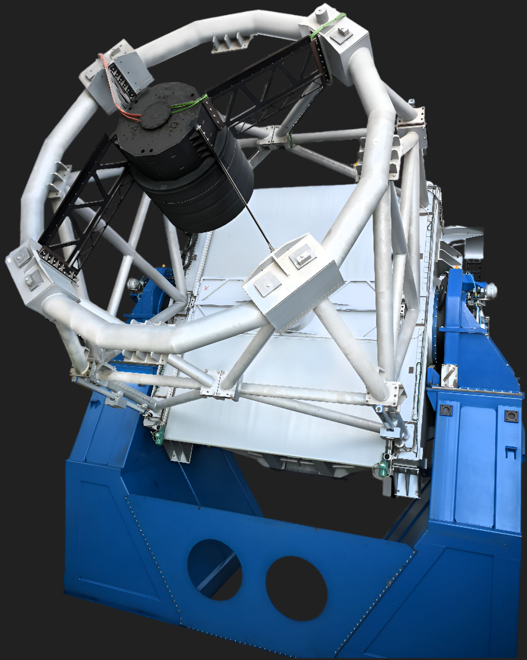
- Fermi GBM lightcurve of GRB 221009A
- Precursor at T0
- Quiescent phase
- Main emission episode (BOAT)
- Prompt emission remain above background for ~ 1500s (ULGRBs)

Optical NIR Observations from ARIES (India)



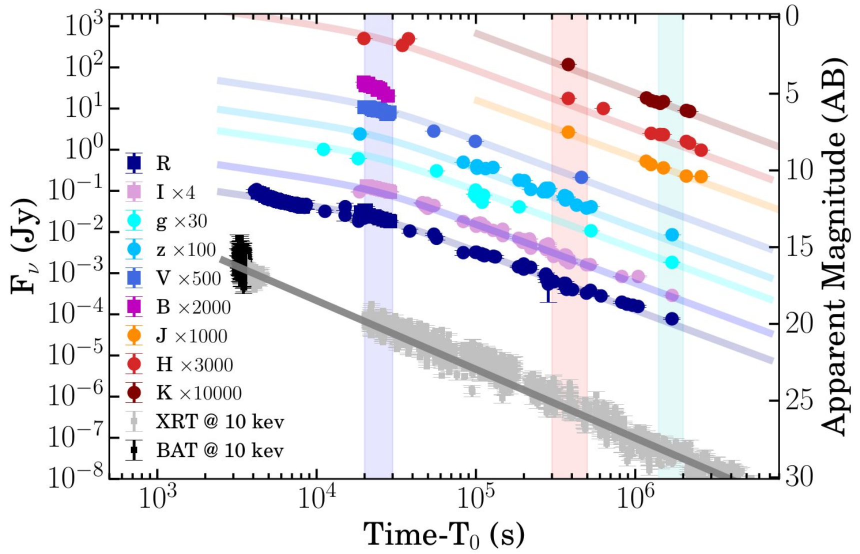
104 cm ST telescope

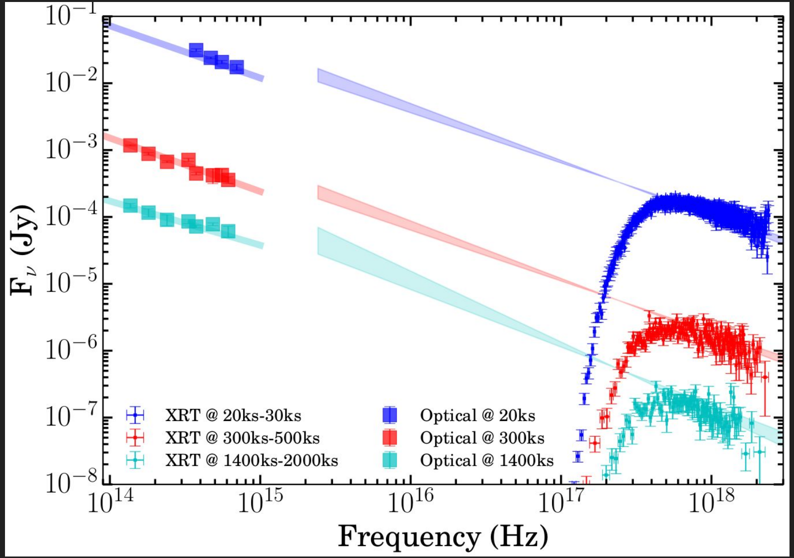
1.3 m DFOT



3.6 m DOT

Afterglow properties of GRB 221009A





Early photometric and spectroscopic observations of the extraordinarily bright INTEGRAL-detected GRB 221009A

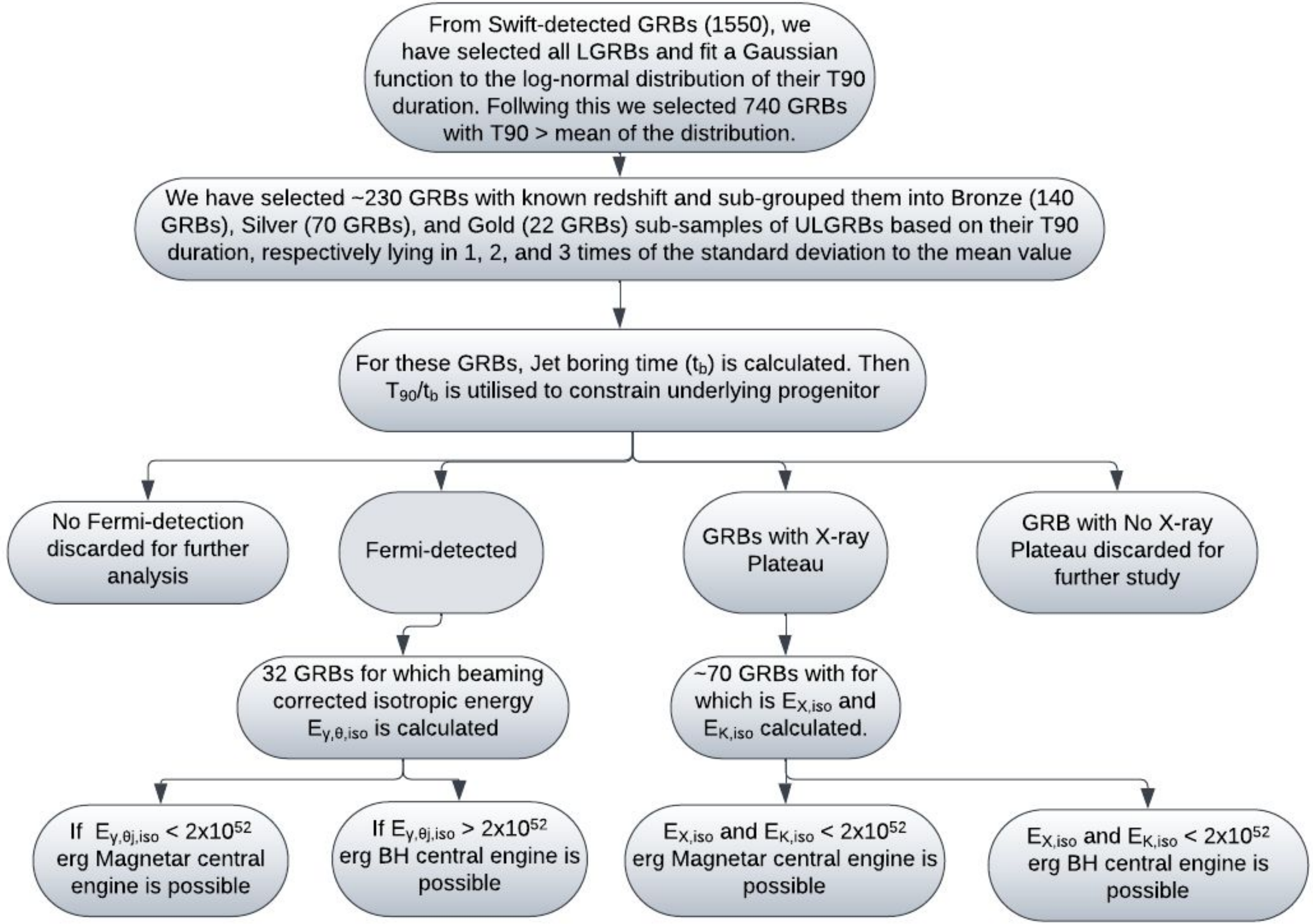
R. Sánchez-Ramírez[1,★], R. G. Lang[2], A. Pozanenko[3,4,5], H. Martínez-Huerta[6], Y.-D. Hu[1,35], S. B. Pandey[7], R. Gupta[7,8,9], A. K. Ror[7,32,★], B.-B. Zhang[10,11], M. D. Caballero-García[1], S. R. Oates[12], I. Pérez-García[1],

Comparison of GRB 221009A with other TeV GRBs

TeV detected GRB	Light curve Morphology	z	E_p (keV)	$E_{\gamma,\text{iso}}$ (erg)	$L_{\gamma,\text{iso}}$ (erg/s)	Surrounding medium	X-ray flare	Supernova connection
160821B	Short and bright pulse	0.162	84±19	2.10×10^{50}	2.00×10^{50}	ISM	No	kilonova
180720B	Single broad multi-peak light curve	0.654	451±49	6.00×10^{53}	1.80×10^{53}	ISM	Yes	No
190114C	Bright multi-peak pulse followed by soft tail emission	0.424	926±17	2.50×10^{53}	1.67×10^{53}	wind/ISM	No	Yes
190829A	Two-episodes with 40 s quiescent gap	0.0785	11.5±0.4	3.00×10^{50}	3.00×10^{49}	ISM	Yes	Yes
201015A	Short overlapping pulses followed by soft and weak tail	0.426	41±14	3.86×10^{51}	3.86×10^{50}	ISM	No	Yes
201216C	Complex multi-pulsed structured light curve	1.1	352±12	6.32×10^{53}	8.78×10^{52}	wind	No	No
221009A	Two emission episodes followed by a long tail, extraordinarily brightness	0.15	1060 ± 30	$> 3\times10^{54}$	$> 1\times10^{52}$	wind	No	Yes

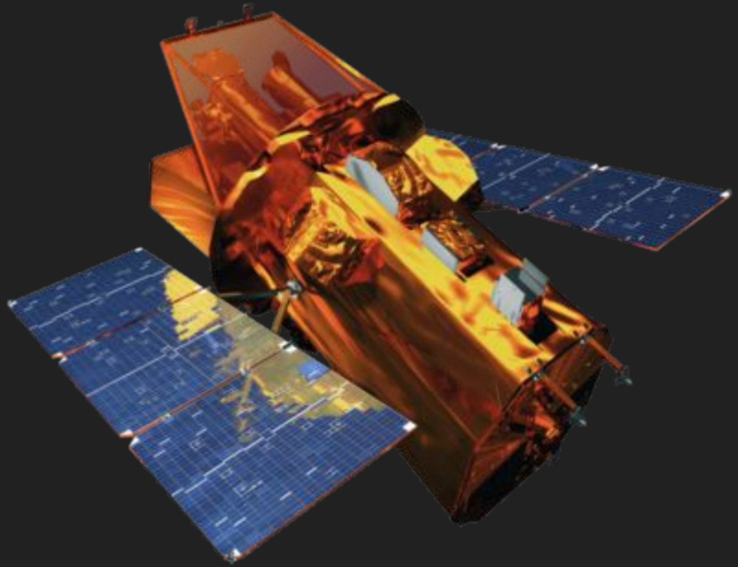
Prompt Emission and Early Optical Afterglow of Very-high-energy Detected GRB 201015A and GRB 201216C: Onset of the External Forward Shock

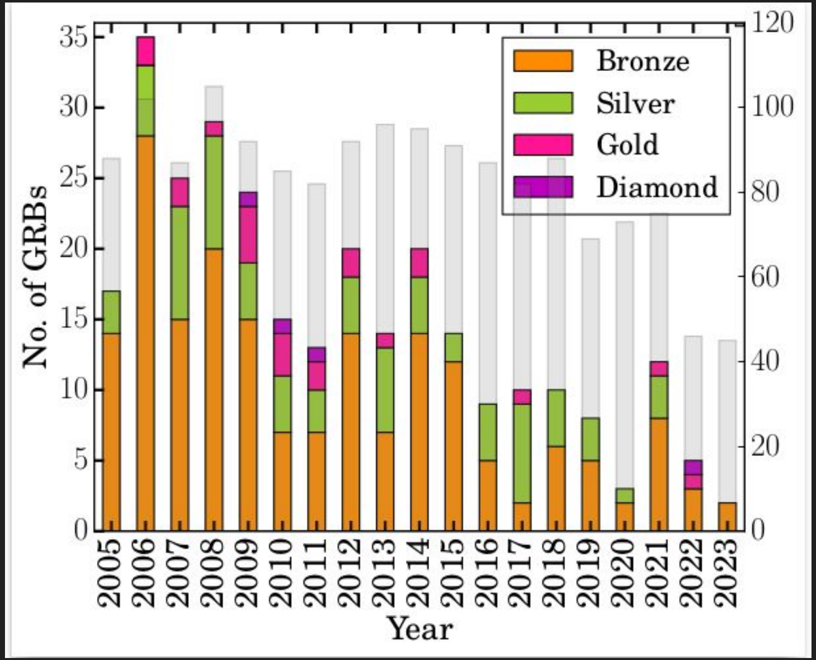
Amit Kumar Ror[1], Rahul Gupta[1,2], Martin Jelínek[3], Shashi Bhushan Pandey[1], A. J. Castro-Tirado[4,5], Y.-D. Hu[4], Alžběta Maleňáková[3], Jan Štrobl[3], Christina C. Thöne[3], René Hudec[3], Sergey Karpov[6], Amit Kumar[1,7], A. Aryan[1,2],


From Swift-detected GRBs (1550), we have selected all LGRBs and fit a Gaussian function to the log-normal distribution of their T90 duration. Follwing this we selected 740 GRBs with T90 > mean of the distribution.
We have selected ~230 GRBs with known redshift and sub-grouped them into Bronze (140 GRBs), Silver (70 GRBs), and Gold (22 GRBs) sub-samples of ULGRBs based on their T90 duration, respectively lying in 1, 2, and 3 times of the standard deviation to the mean value
For these GRBs, Jet boring time (t_b) is calculated. Then T_{90}/t_b is utilised to constrain underlying progenitor
No Fermi-detection discarded for further analysis
Fermi-detected
GRBs with X-ray Plateau
GRB with No X-ray Plateau discarded for further study
32 GRBs for which beaming corrected isotropic energy $E_{\gamma,\theta,iso}$ is calculated
~70 GRBs with for which is $E_{X,iso}$ and $E_{K,iso}$ calculated.
If $E_{\gamma,\theta j,iso} < 2x10^{52}$ erg Magnetar central engine is possible
If $E_{\gamma,\theta j,iso} > 2x10^{52}$ erg BH central engine is possible
$E_{X,iso}$ and $E_{K,iso} < 2x10^{52}$ erg Magnetar central engine is possible
$E_{X,iso}$ and $E_{K,iso} < 2x10^{52}$ erg BH central engine is possible

Swift Observatory

- Observed Fluence from ULGRBs is comparable to LGRBs. But, in case of ULGRBs, this Fluence stretched to longer duration makes ULGRBs Intrinsically faint
- Decreasing in number of ULGRBs per year
- Ageing of BAT instrument



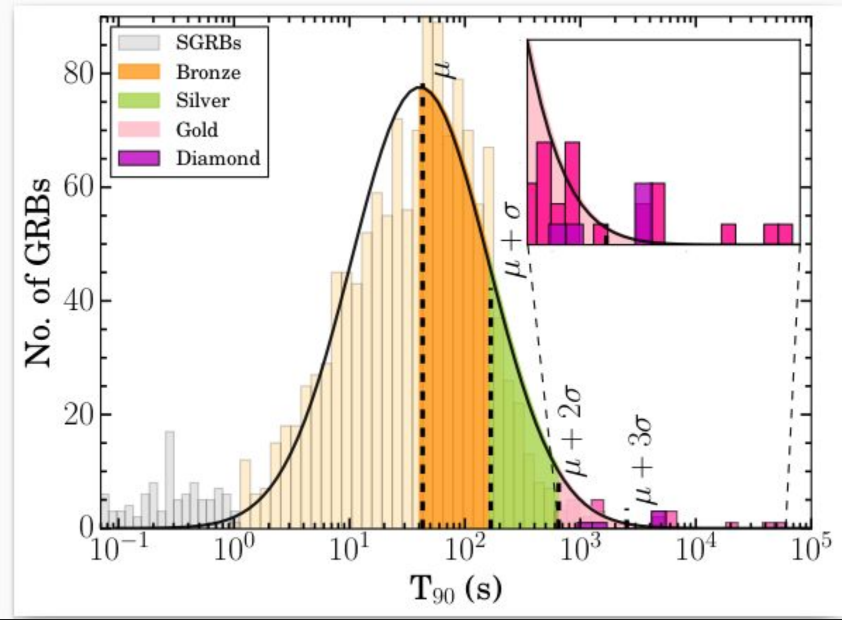


Following *Swift*, *SVOM* and *EP*, have already begun detecting ULGRBs

Bronze, Silver and Gold Sub-Sample of ULGRBs

- Gaussian function fit to the Swift detected LGRBs and GRB with T90 greater than the mean of the distributed are selected
- Selected GRBs further divided into Bronze Silver and gold subsample based on their T90 lie in 1, 2, 3 times of standard deviations.

Distribution



Total Swift GRB ~ 1550

740 GRB with T90 > 43

After Applying redshift cut we left with 232 GRBs

Out of these 32 has simultaneous fermi detection.

Bronze Sampe include = 140 GRBs

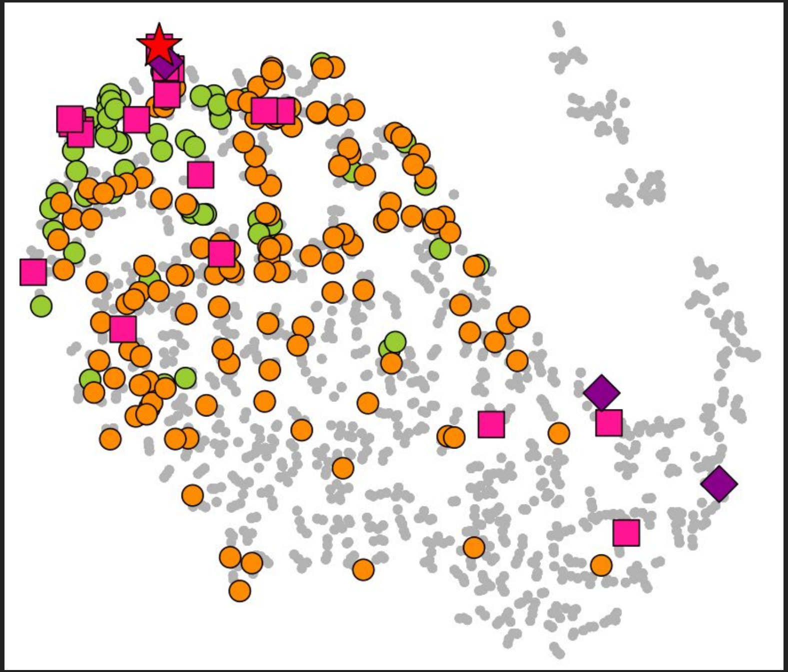
Silver Sampe include = 70 GRBs

Gold Sampe include = 22 GRBs

4 redshift unknown GRBs are such that they have not satisfy our selection criteria of Swift detection, but well know ULGRBS are included in diamond subsample

Machine learning mapping of prompt emission light curve

- The map represent the 2-D mapping of prompt emission Light Curves.
- Closed points are the Similar lightcurve
- X and Y axis do not have physical significance
- Bronz sample distributed among Long GRBs
- Silver sample show little clustering on left
- Gold sample mostly clustered on left
- 3 Gold + 2 Diamond GRBs on the right have reported less T90 but appear ULGRBs based on BAT survey data.

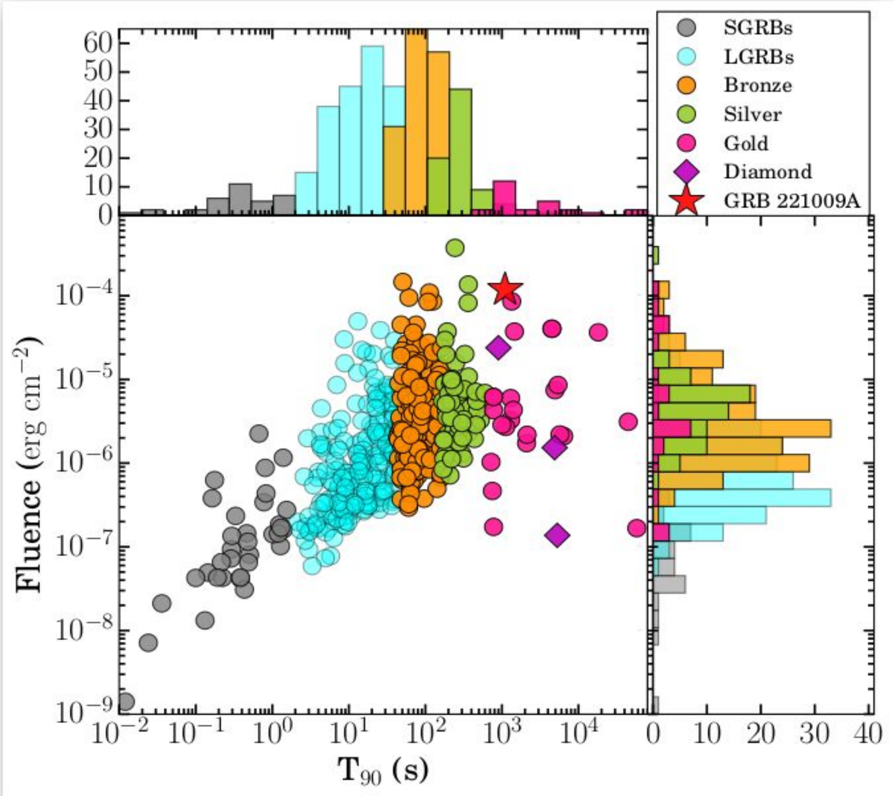


(t-SNE)
t-distributed Stochastic Neighbor Embedding

Therefore t-SNE map is highly dependent on observed duration of light curve and not a robust criteria to distinguish between long GRB and ULGRBs

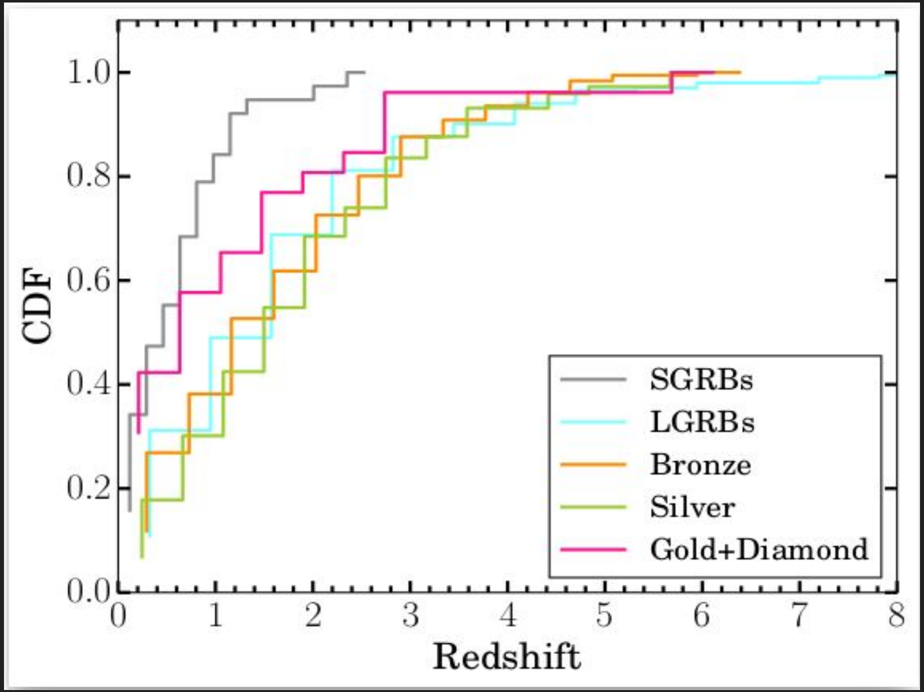
Fluence Distribution of Sub Samples

- The Observed fluence for GRBs vary linearly with their T90 duration
- GRBs included in the gold subsample deviate from the linear trend
- ULGRBs are relatively faint and more sensitivity instrument is required for their detection
- GRB 221009A exhibits exceptional fluence values, named as “BOAT”



Redshift Distribution of Sub Samples

- Since the fluence of ULGRBs is not very large compared to LGRBs
- This Fluence stretched over longer T90 make them intrinsically faint
- Many ULGRBs escape their detection at larger redshift
- SGRBs have lowest redshift suggesting of their distinct origin.
- Redshift distribution of Gold subsample at lower end (Pink Line) make them distinct event then LGRBs



Progenitor of GRBs in our Subsample

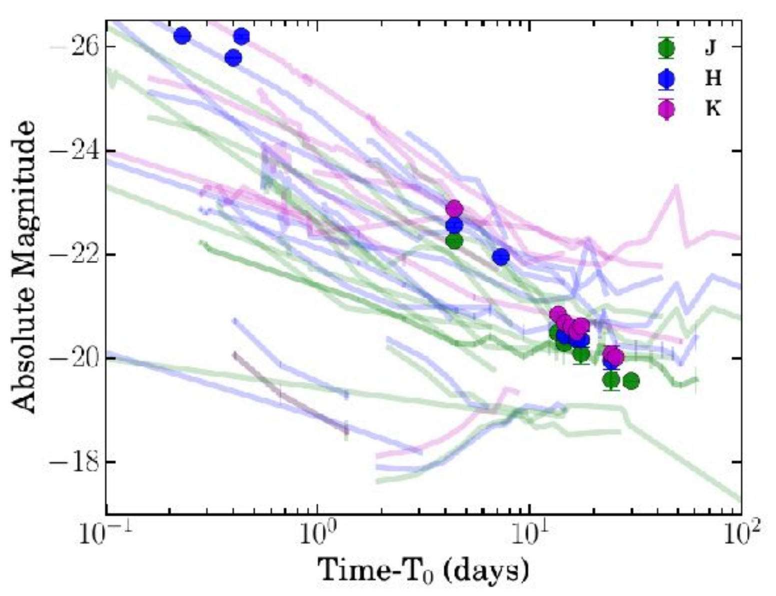
The are two method to constrain GRB progenitors:

First method or Direct method:

Late time afterglow observation from GRBs display a red bump due to emergence of underlying Supernova

Such Superona bump found associated with GRB 060218A, GRB 100316D and GRB 111209A.

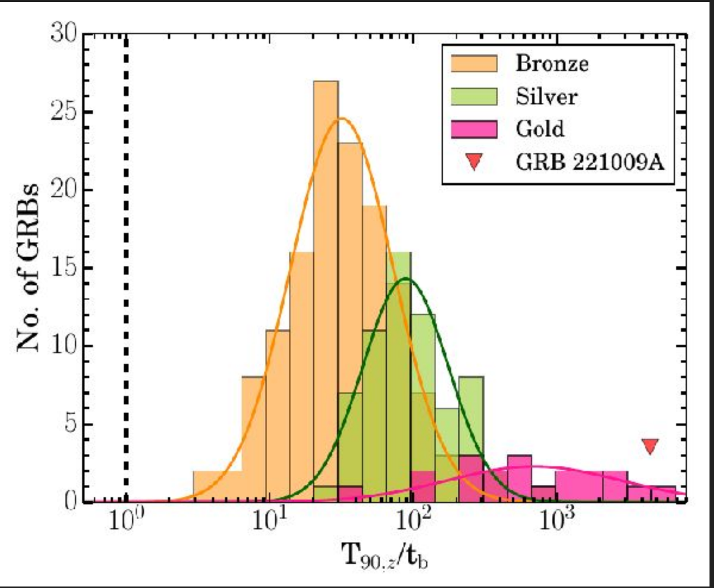
For GRB 221009A we conducted the NIR observation from 3.6m DOT. Our observations shows negative results from any bright supernovae



Second Method or Indirect method:

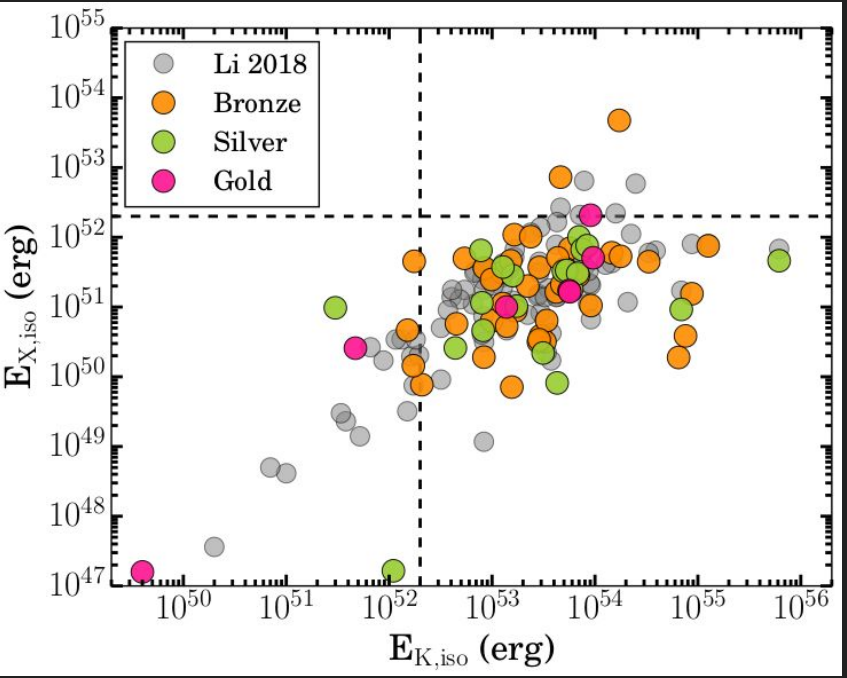
$$t_b(s) \sim 15\epsilon_\gamma^{1/3} L_{\gamma,iso,50}^{-1/3} \theta_{j,10^\circ}^{2/3} R_{11}^{2/3} M_{15\odot}^{1/3}$$

- First, we calculated the jet bore time (tb)
- This require Calculation of Jet opening angle
- For GRB with clear Jet break X-ray, we calculated jet opening angle for that
- For other GRBs Jet break calculated from last data points
- Finally tb is calculated using given equation
- If tb > T90 origin is colapsar
- If tb < T90 origin is different from collapsar



Constraining central engine from Fireball Kinetic Energy

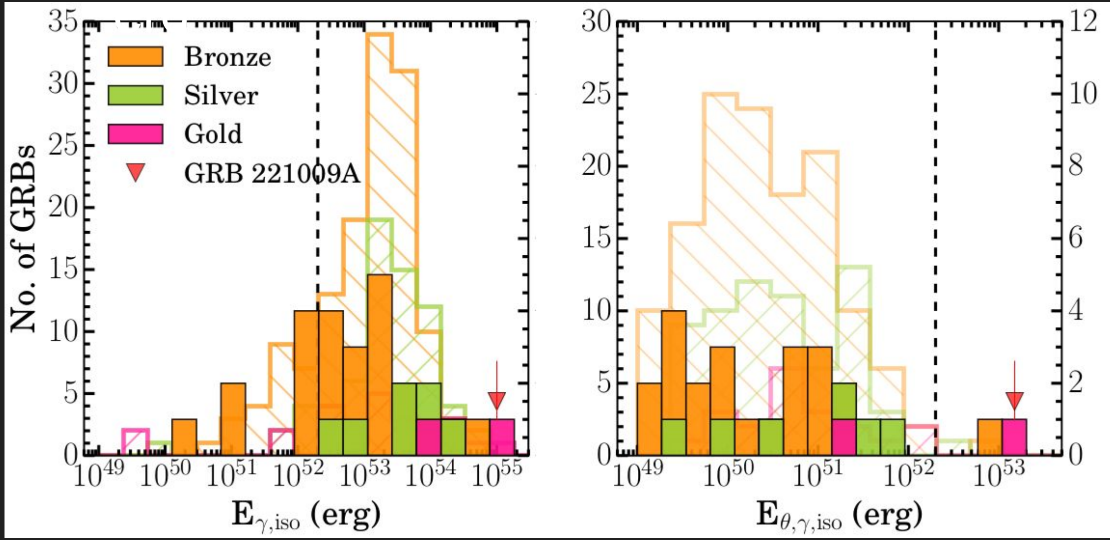
- This is another method to constrain GRB central engine
- For GRBs with X-ray Lightcurve has a plateau we calculated the X-ray energy release ($E_{X,iso}$) during the plateau
- We also calculated the Kinetic energy ($E_{K,iso}$) of the Fireball
- If Both $E_{K,iso}$ and $E_{X,iso}$ are greater than 1e52 a Black hole central engine is required.
- Otherwise a Magnetar central engine is favoured
- This method is only useful of GRBs with plateau in X-ray Light curve

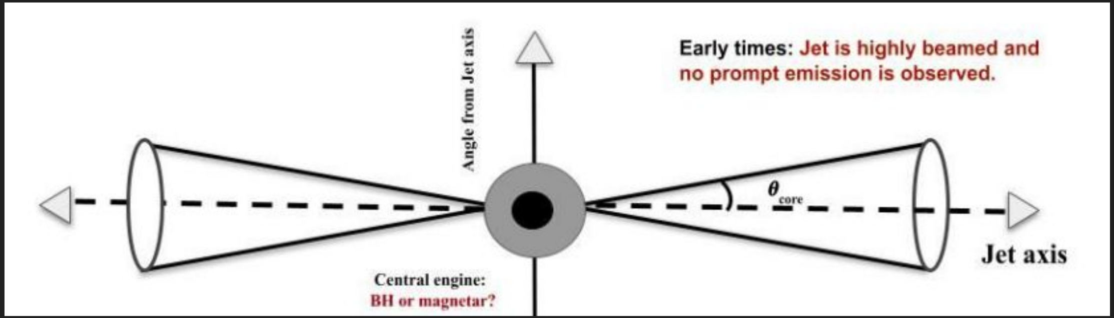


Central Engine From Beaming Corrected energy

- GRBs with beaming corrected energy > 2e52, could not be power by a magnetar and a Black Hole central engine is required
- GRB 060218A and GRB 100316D favour magnetar engine
- GRB 221009A is consistent with Black hole engine
- For all other GRBs in gold subsample Black hole central engine is required

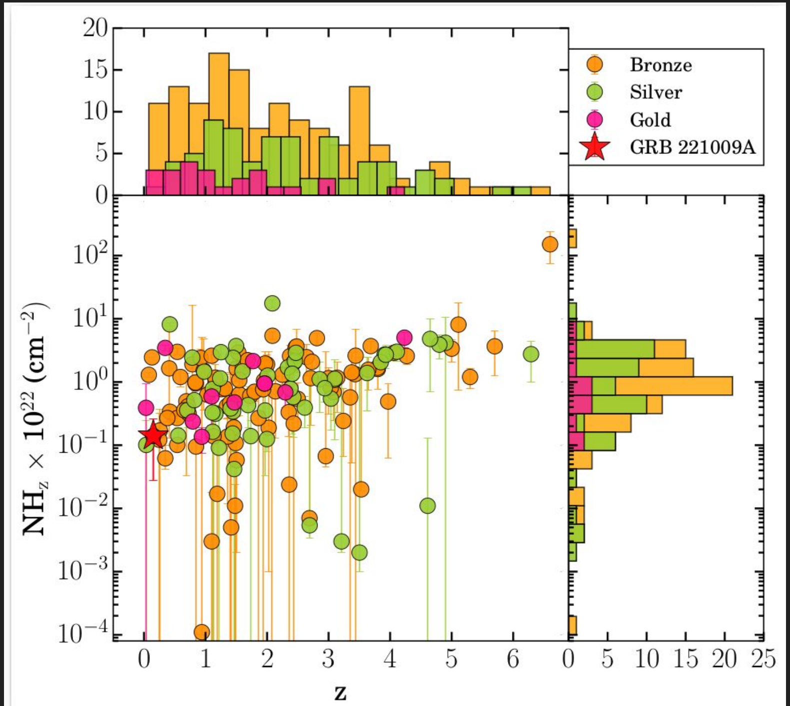
Magnetar total energy budget is 210^{52}

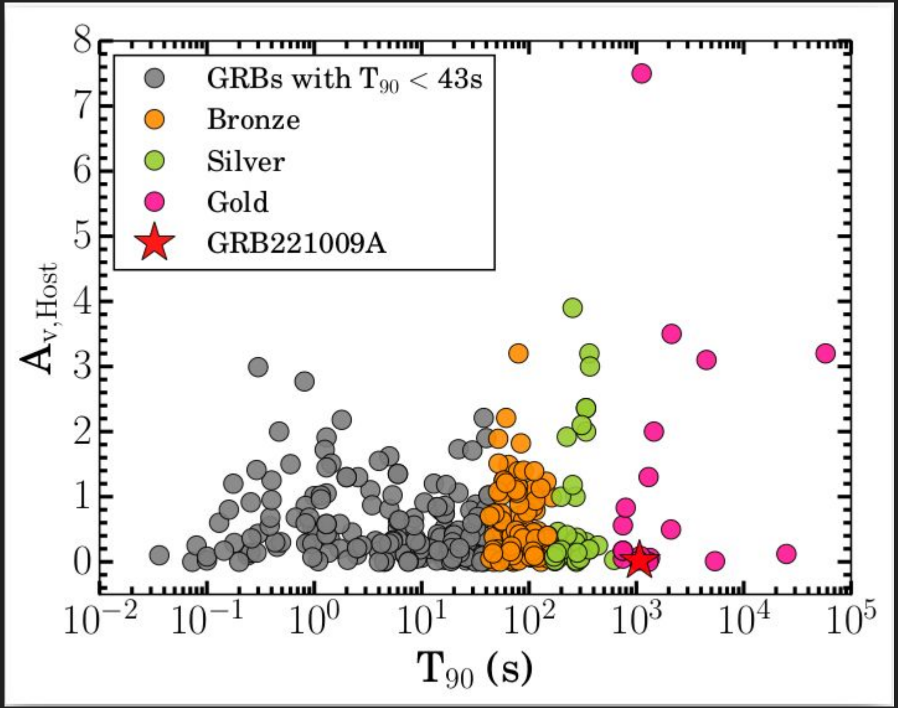




Environment of ULGRBs

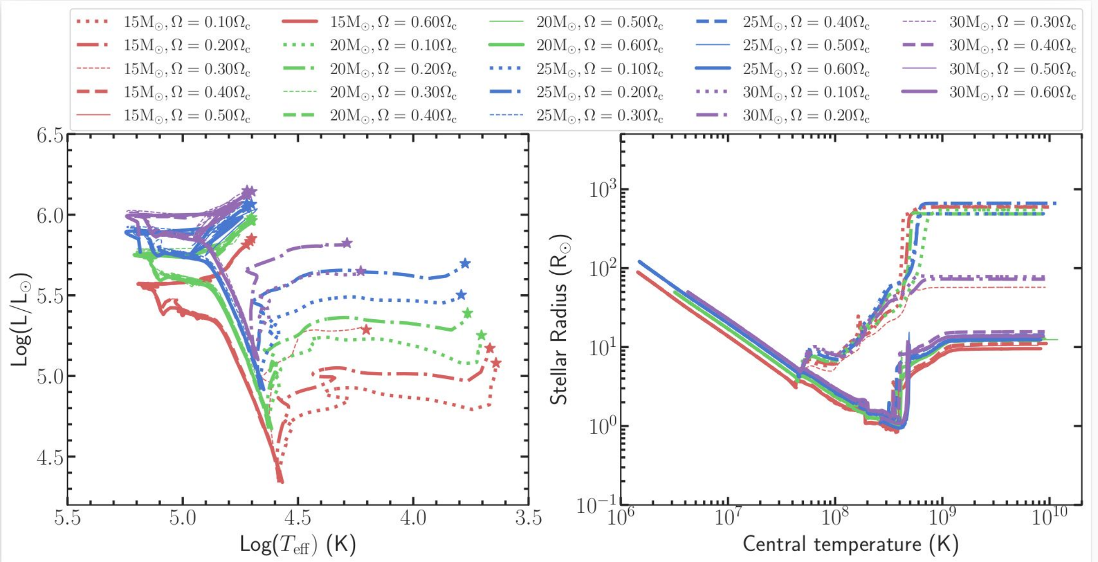
Evan et al. (2014) suggest the ULGRBs might be different from LGRBs due to their low density environment. To study the density surrounding the burst, we utilised the parameters NHz and Av.

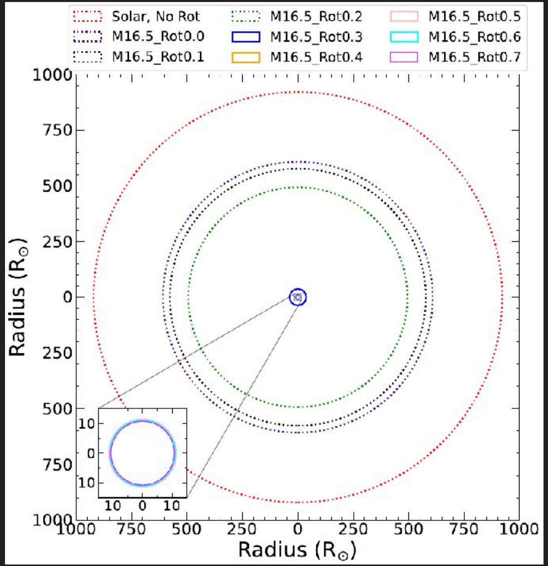




Evolution of massive star with MESA

Star Type	Radius ($R_\odot$)	T_{ff} (s)	Reference
Wolf-Rayet (WR)	~ 1	100	Crowther (2007)
Blue Supergiant (BSG)	10 – 50+	3,000 – 10,000	Meynet & Maeder (2000)
Red Supergiant (RSG)	>100	1,000,000	Levesque et al. (2005)





Evolution of massive star with MESA

M_{ZAMS} ($M_\odot$)	Ω/Ω_c	M_{final} ($M_\odot$)	R_{final} ($R_\odot$)	$M_{Fe-core}$ ($M_\odot$)	$\log(T_{eff})$ (K)	Log (L) ($L_\odot$)	t_{ff} (s)	t_b (s)
15	0.1	14.96	603.23	1.55	3.64	5.08	1438579.51	140.7
15	0.2	14.96	593.52	1.65	3.67	5.17	1403955.16	138.4
15	0.3	14.95	57.19	1.91	4.20	5.29	42011.37	13.3
15	0.4	13.62	11.11	2.05	4.70	5.85	3768.59	2.6
15	0.5	13.42	10.51	1.90	4.71	5.83	3494.82	2.4
15	0.6	13.26	9.55	1.93	4.72	5.81	3043.96	2.2

Ror et al (2024)

Ω/Ω_c	M_{final} ($M_\odot$)	R_{final} ($R_\odot$)	$M_{Fe-core}$ ($M_\odot$)	$\log(T_{eff})$ (K)	Log (L) ($L_\odot$)	t_{ff} (s)	t_b (s)
0.0	16.474	607.8	1.539	3.644	5.097	1385926.3	141.8
0.1	16.475	577.0	1.490	3.659	5.115	1281711.9	134.6
0.2	16.452	493.6	1.733	3.721	5.226	1014838.8	115.1
0.3	15.928	37.6	1.501	4.414	5.759	21663.6	8.8
0.4	14.878	11.2	1.937	4.708	5.885	3636.7	2.6
0.5	14.674	11.4	1.923	4.705	5.890	3773.7	2.7
0.6	14.528	11.0	1.840	4.709	5.875	3600.7	2.6
0.7	14.418	10.7	1.899	4.712	5.865	3477.0	2.5

Aryan and Ror et al (2024)

Calculation of free fall time

Using the final stage mass and radius obtained

from mesa simulation of massive star we constrain the

Density (ρ), Then following the given equation,

we have calculate the free fall time of envelope

$$t_{\rm ff} = \frac{1}{\sqrt{24\pi G\bar{\rho}}}$$

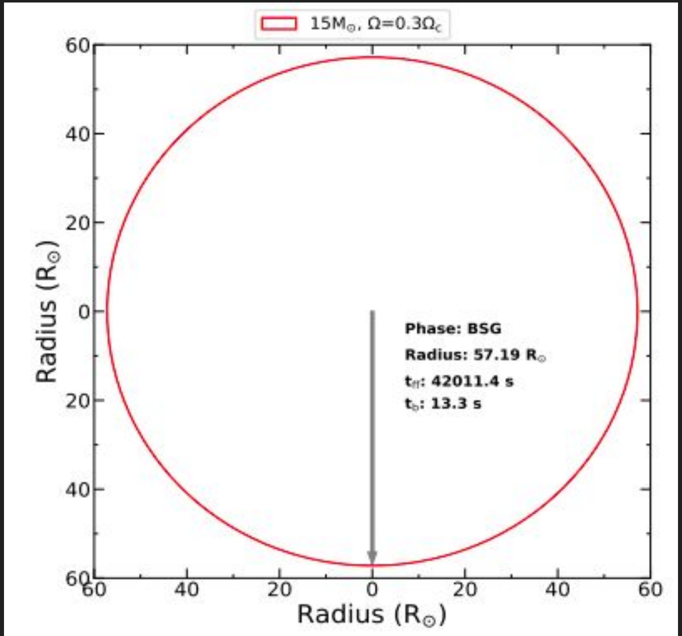
Perna et al. (2018)

- Observed free fall time of Red Supergiant stars with (R > 500) are too large to form GRBs
- Free fall time from Blue Supergiant star (R ~ 50) is comparable to the observed T90 of ULGRBs
- Free fall time from WR (R < 10) is comparable to the observed T90 of long GRBs

Jet bore calculation and Confirmation

Using the final radius from MESA we have calculated the Jet Bore time using the relation:

$$t_b = \frac{R_{\text{final}}}{(u\Gamma)}$$



Γ is the lorentz factor and u is speed

Our final value of tb are comparable to the relation

given by Bromberg et al. (2011)

$$t_b(s) \sim 15\epsilon_\gamma^{1/3} L_{\gamma,iso,50}^{-1/3} \theta_{j,10^\circ}^{2/3} R_{11}^{2/3} M_{15\odot}^{1/3}$$

Summary

- GRB 221009A is the BOAT, display ULGRBs characteristic.
- Three subsample Bronze, Silver and Gold, where gold subsample have relatively soft spectral characteristic.
- Our Gold subsample emerge as a new class of ULGRBs
- All GRBs in Subsample have Collapsar origin
- No bright Supernova found for GRB 221009A
- Mixed type of deriving engine (Magnetar or Black hole) found for these bursts, A Black hole central engine is also required for GRB 221009A
- Environment properties of ULGRBs consistent with typical GRBs
- Evolution of massive star with MESA, suggest that BSG stars could be the progenitor of ULGRBs

Exploring the Origin of Ultralong Gamma-Ray Bursts: Lessons from GRB 221009A

Amit Kumar Ror[1,2], Rahul Gupta[1,3,8], Amar Aryan[1,4], Shashi Bhushan Pandey[1], S. R. Oates[5], A. J. Castro-Tirado[6,7], and Sudhir Kumar[2]

The brightest gamma-ray burst (GRB) ever, GRB 221009A, displays ultralong GRB (ULGRB) characteristics, with a prompt emission duration exceeding 1000 s. To constrain the origin and central engine of this unique burst, we analyze its prompt and afterglow characteristics and compare them to the established set of similar GRBs. To achieve this, we statistically examine a nearly complete sample of Swift-detected GRBs with measured redshifts. We categorize the sample to bronze, silver, and gold by fitting a Gaussian function to the log-normal of T_{90} duration distribution and considering three subsamples respectively to 1, 2, and 3 times of the standard deviation to the mean value. GRB 221009A falls into the gold subsample. Our analysis of prompt emission and afterglow characteristics aims to identify trends between the three burst groups. Notably, the gold subsample (a higher likelihood of being ULGRB candidates) suggests a collapsar scenario with a hyperaccreting black hole as a potential central engine, while a few GRBs (GRB 060218, GRB 091024A, and GRB 100316D) in our gold subsample favor a magnetar. Late-time near-IR observations from 3.6 m Devasthal Optical Telescope rule out the presence of any bright supernova associated with GRB 221009A in the gold subsample. To further constrain the physical properties of ULGRB progenitors, we employ the tool MESA to simulate the evolution of low-metallicity massive stars with different initial rotations. The outcomes suggest that rotating ($\Omega \geqslant 0.2\,\Omega_c$) massive stars could potentially be the progenitors of ULGRBs within the considered parameters and initial inputs to MESA.

Thank You

mitturor77894@gmail.com

Recent discoveries or Future

GRB 250702B, C, D, E