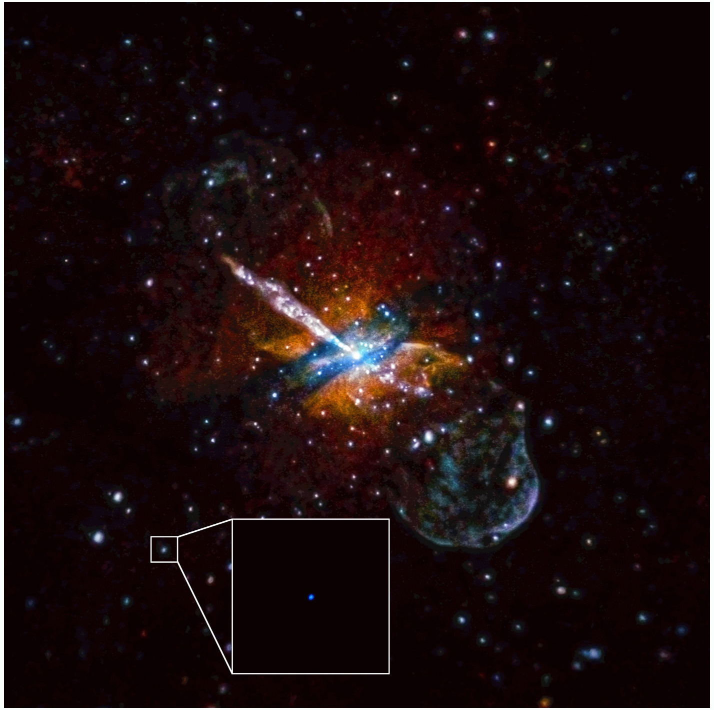
Gamma Ray Bursts:
A probe for Understanding Extra Galactic High Energy Physics

Mehul Goyal & Yashowardhan Rai
for Physics Journal Club

Time Domain Astronomy



Time Domain Astronomy

The GROWTH Collaboration

Astronomy is global and extremely collaborative.

If you'd like to be in zoom calls with people that have multiple different accents then astro is the place for you :)

Caltech | GROWTH

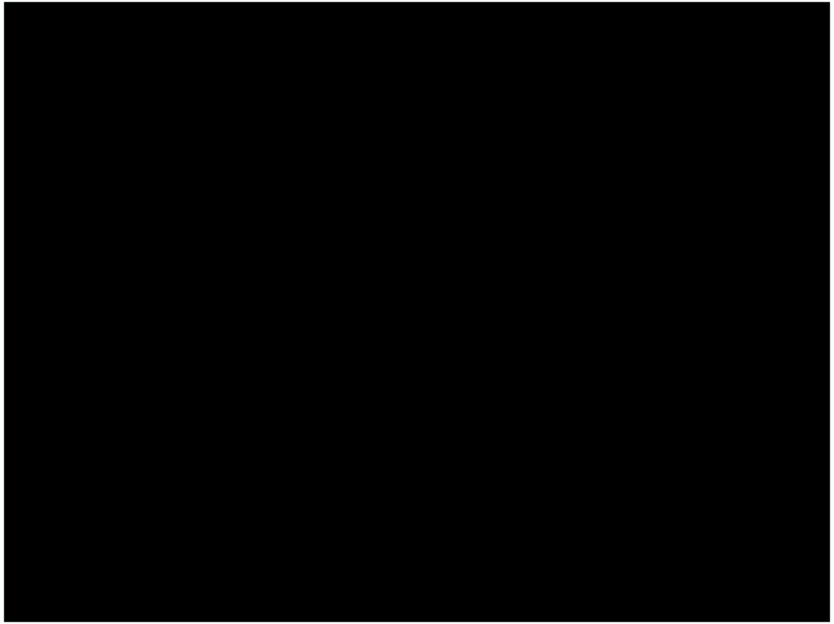
Global Relay of Observatories Watching Transients Happen

Contents

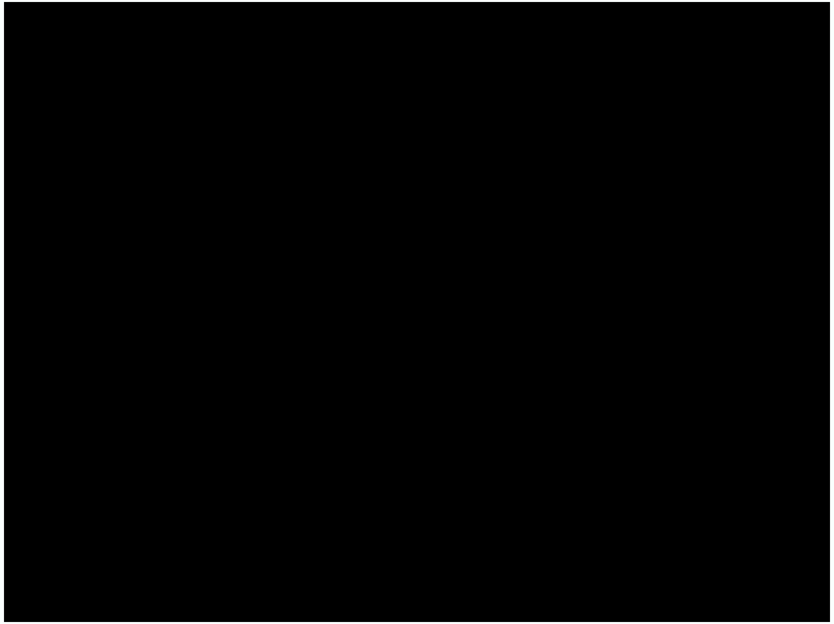
01

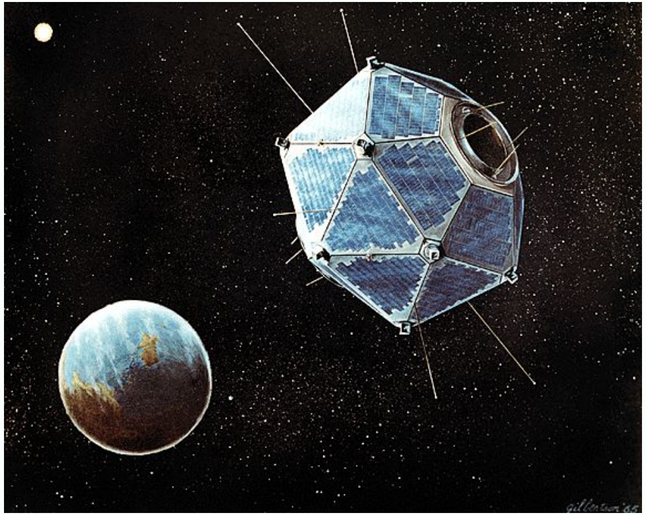
A short history lesson

Back to the 60s…

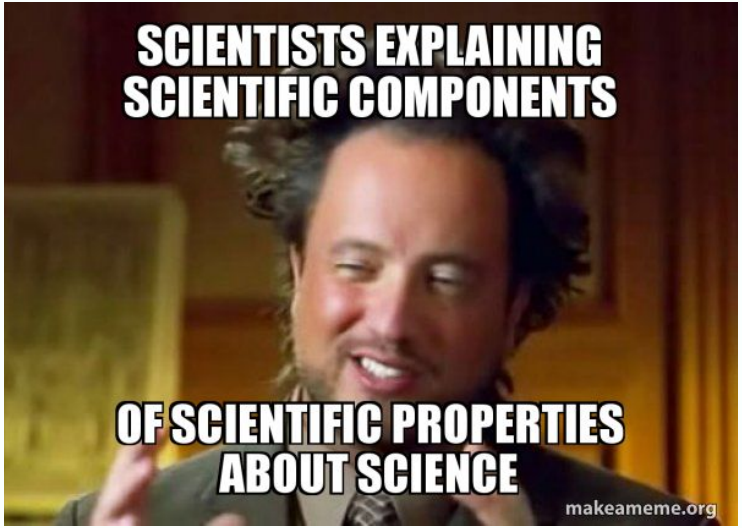


Back to the 60s...





VELA satellites by NASA

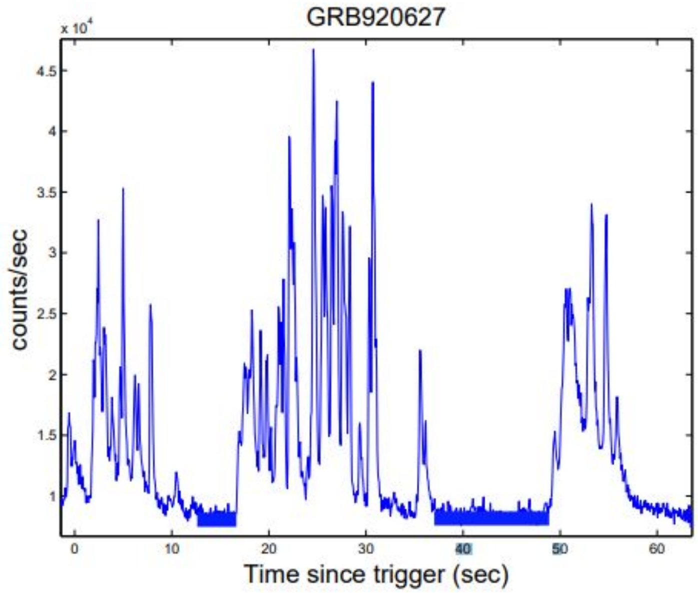


02

General Properties

A realisation of a GRB – A video

A typical Long GRB prompt lightcurve



The total duration of the burst is 52sec, while typical pulses are 0.8sec wide. Two quiescent periods lasting ~10 seconds are marked by horizontal solid bold lines

Credits : Tsvi Piran
Rev. Mod. Phys. 76, 1143

Significant properties of GRBs

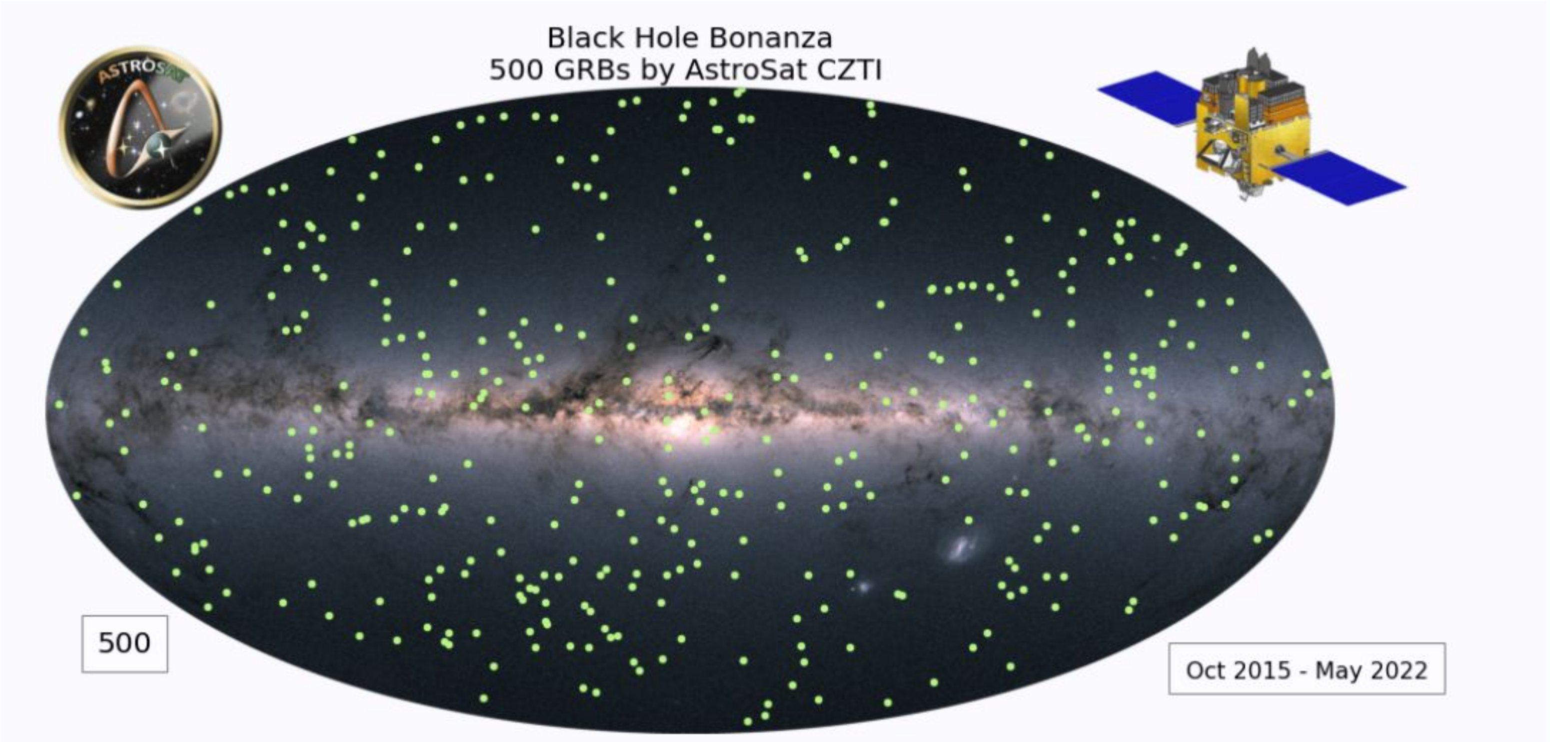
Extragalactic Origin
The distribution of Gamma Ray Bursts was found to be isotropic in the sky, hence the extragalactic origin.

Durations
Two distinct populations of gamma ray bursts have been observed. The bursts with durations greater than 2 sec are called long GRBs and ones with less than 2 sec are called short GRBs

Progenitors
Long GRBs are thought to originate due to collapse of supermassive stars in form of supernovae, while Short GRBs are thought to originate from kilonovae.
Certain exceptions have been found for LGRBs.

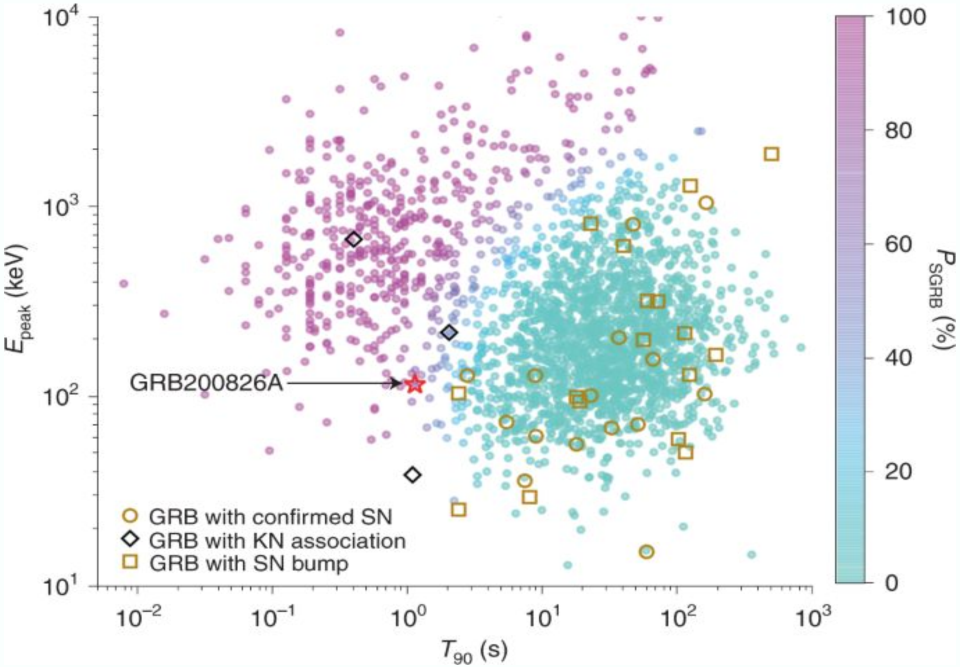
Energetics
GRBs have isotropic equivalent energy output of 10^{50}-10^{54} ergs. This is orders of magnitude higher than luminosity of Milky Way.

Map of Sky Positions



Credit: AstroSat CZTI team / Aswin Suresh, Gaurav Waratkar, Varun Bhalerao (IIT Bombay)

Duration & Hardness Distribution



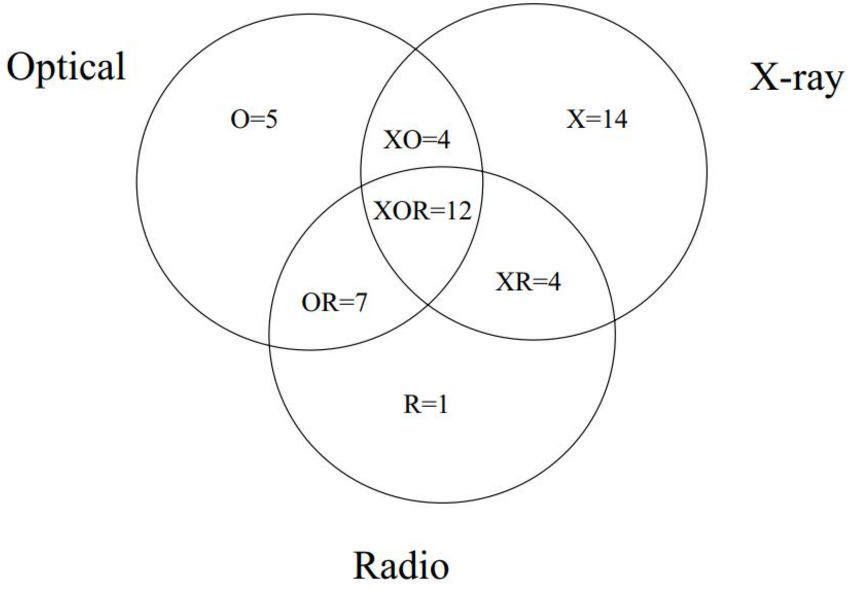
Credits : Ahumada, T., Singer, L.P., Anand, S. *et al. Nat Astron* 5, 917–927 (2021

Hardness ratio is the ratio of fluence of GRB in the high and low energy channels.
Short GRBs are observed to be harder than Long GRBs

Wavelength distribution of afterglows

What are Orphan GRBs?

GRBs in which only afterglow is observed without any prompt signal



What are Dark GRBs?

GRBs whose afterglow is not visible in optical wavelengths

Credits: talk given by D. Frail at the Sackler GRB workshop, Harvard, May 2001

Venn diagram of the distribution of 47 Afterglows observed in different wavelength

03

Open Questions

Progenitors

Under what conditions in the progenitors are GRBs produced?

Emission Mechanisms

What is the micro-scale description of the emission process?

Open Question (s)

Population Uniformity

Are all GRBs explainable using a single model or are there multiple subtypes, if so, how many?

Polarization

What is the micro-scale description of the emission process?

Active Research Areas

Afterglow Studies

Study of the Afterglow coming from the GRB
Information about structure of the jet comes from here

Spectro-polarimetry

What is the spectrum and polarisation levels of GRBs

Instrumentation, Detector Physics & Algorithms

Building detectors, satellites and software to process the event data

Multimessenger Astronomy

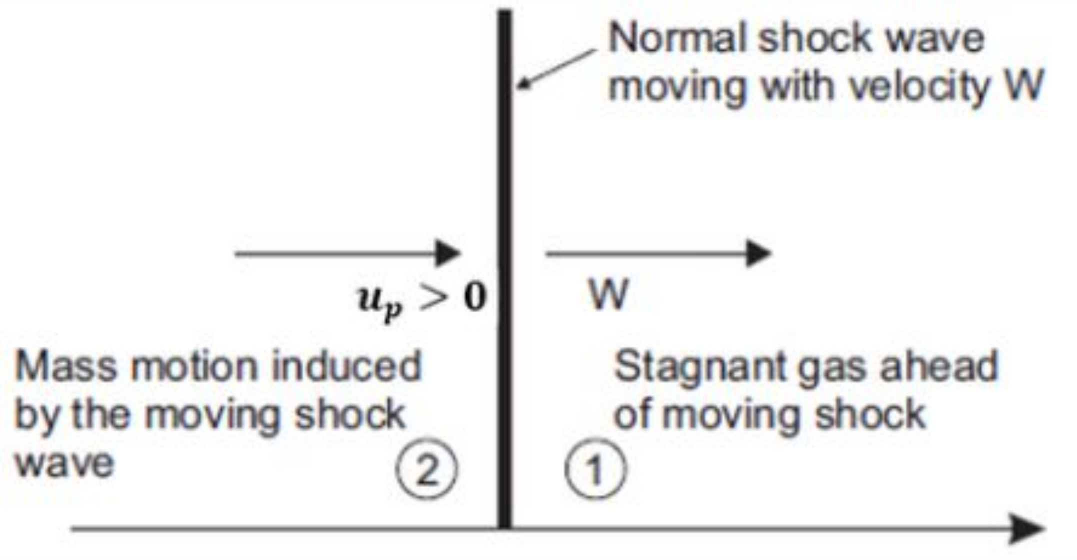
Relation of GRBs with other transients and finding electromagnetic counterparts to Gravitational Wave detections

Stop the clocks it's amazing ....

04

Afterglow

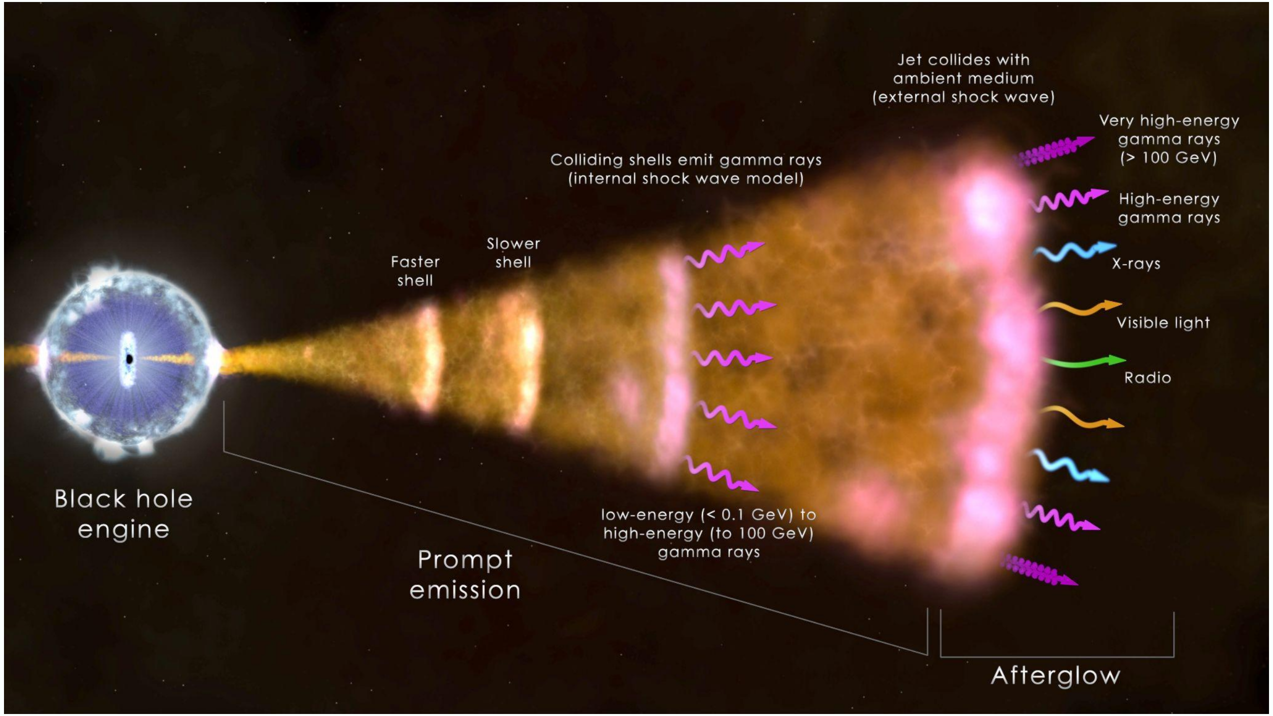
Shocks



Credits: Anderson, 1990

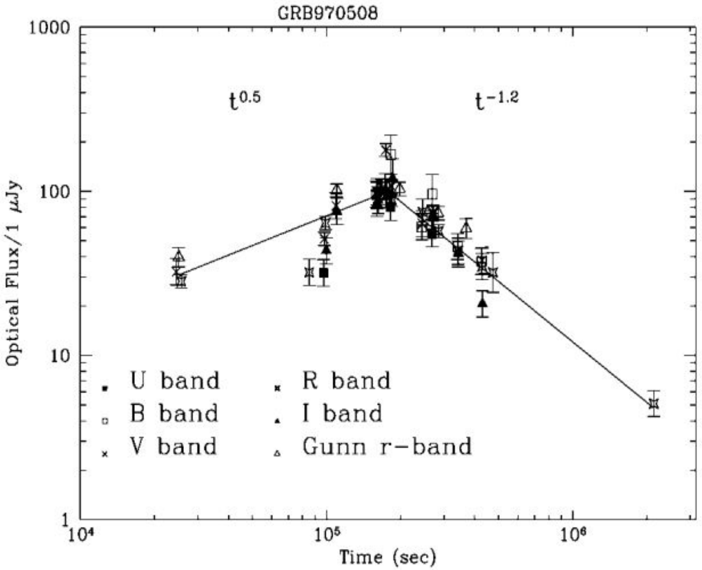
A shock is a sharp change in physical conditions—such as pressure, temperature, and density—that propagates through a medium faster than the speed of sound.

What is afterglow emission ?



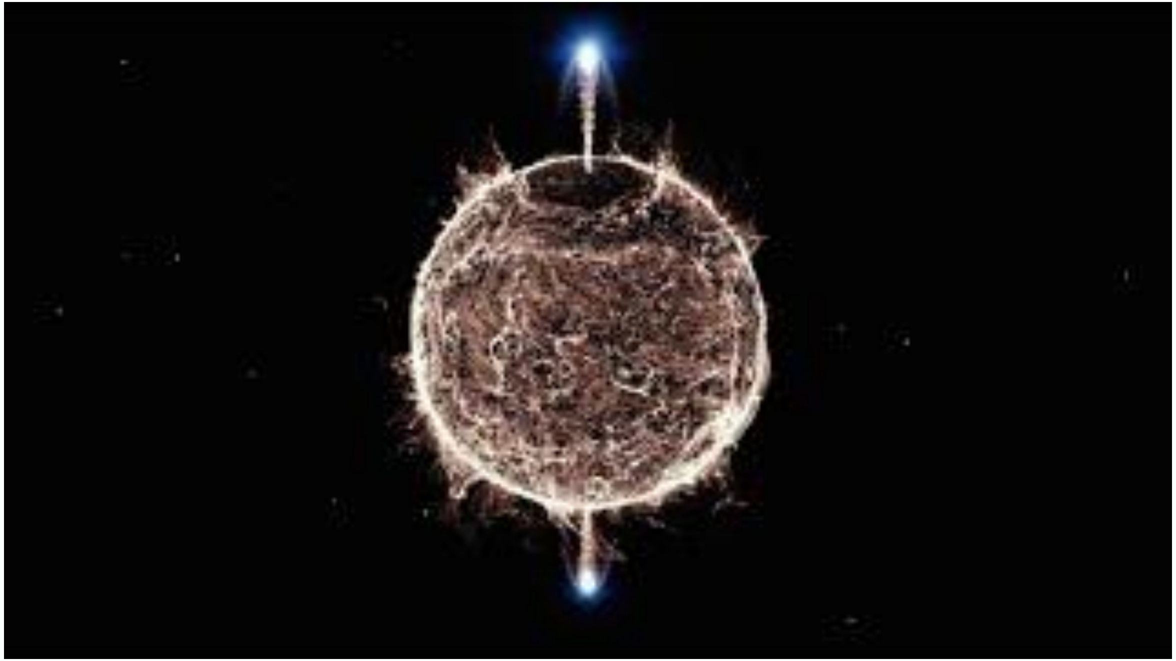
Discovery

- Existence was predicted by early models which explained prompt emission
- First ever afterglow detection by BeppoSax on Feb 28, 1977 of GRB 970228
- Advent of Swift Era and autonomous observations have increased discovery rate to one every few days
- Afterglow studies help pinpoint location, measure redshift, study energetics and help identify progenitors and host galaxies



Credits : The Astrophysical Journal, Volume 488, Issue 2, pp. L105-L108

Emission Mechanisms



The dominant process that shapes the GRB afterglows is the synchrotron emissions at the shock front where ultrarelativistic outflow impacts the external medium

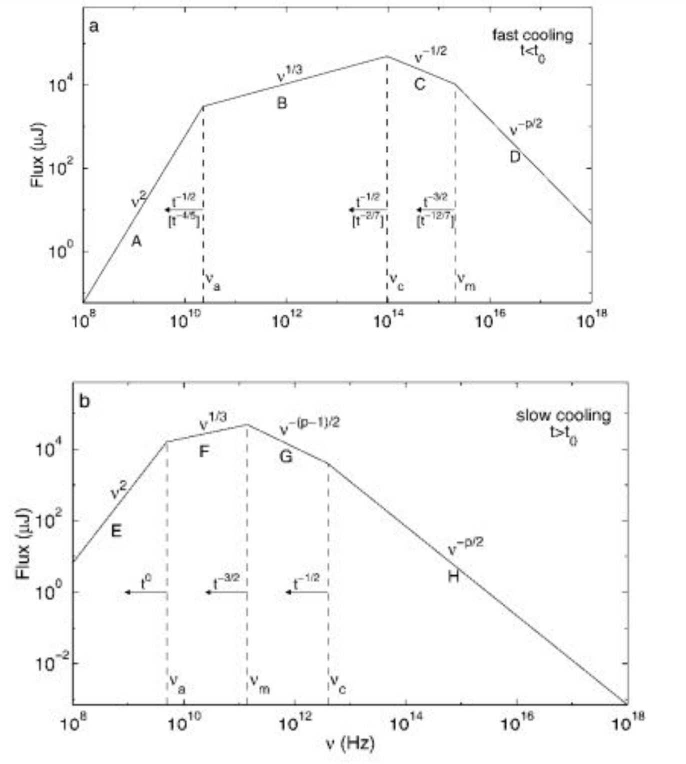
Credits : Deutsches Elektronen Synchrotron

Synchrotron emission

- Produced when relativistic electrons spiral around magnetic fields

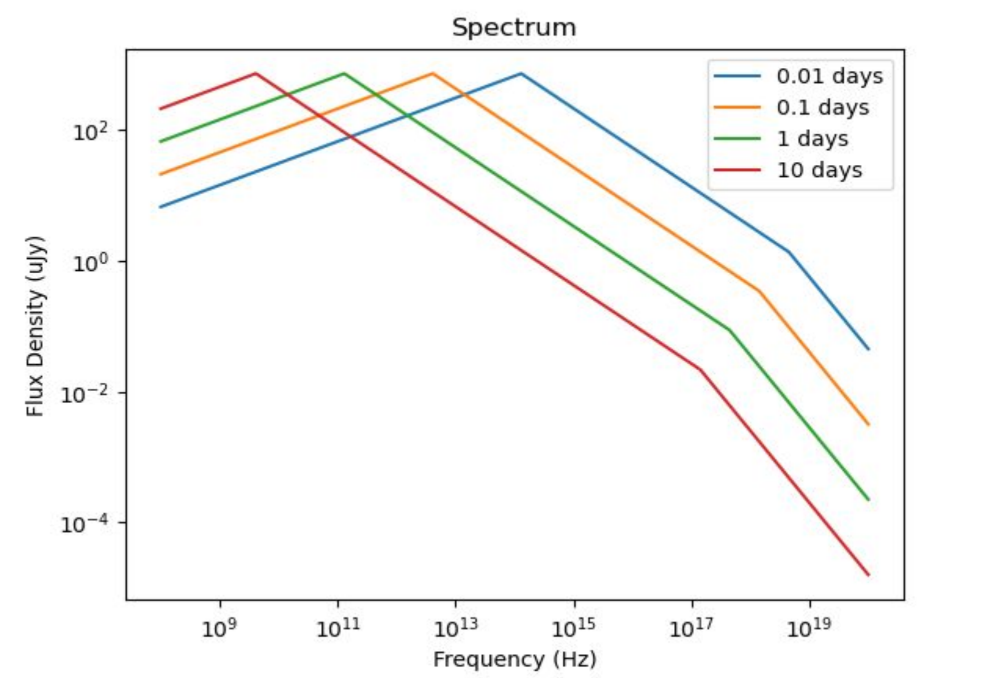
- The energy distribution of electrons follows a power law, $N(E) \propto E^{(-p)}$, where p is the electron index

- Key Frequencies
  - Self Absorption Frequency, below which the spectrum is dominated by black body
  - Maximum Frequency, at which electrons with typical bulk lorentz factor emit most of their energy
  - Cooling Frequency, beyond which the electrons lose energy by radiative loss, leading to a steep decline



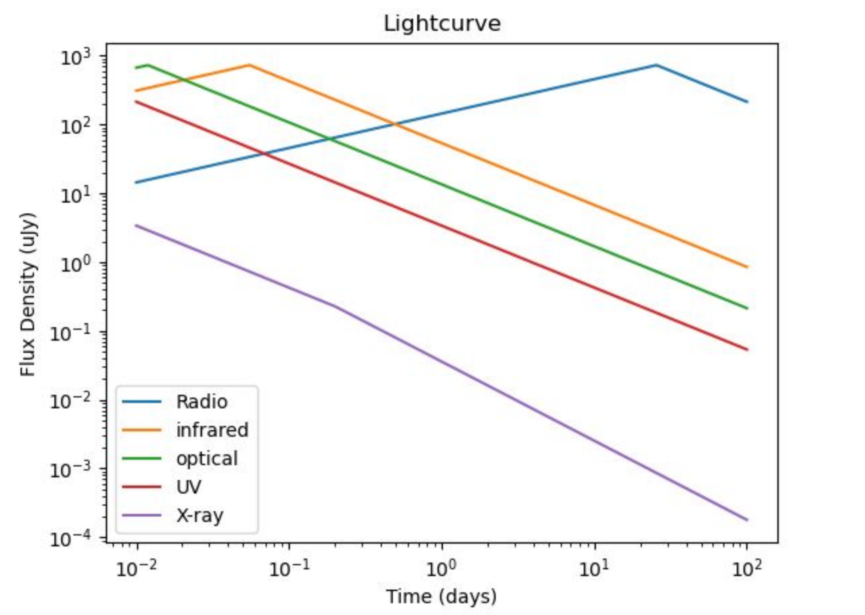
Credits: Sari et al 1998

Forward Shock Spectrum (ISM)

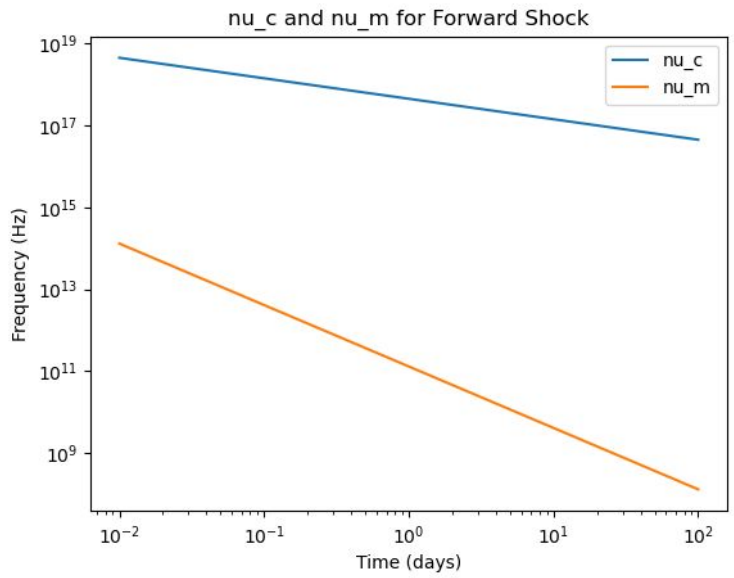


Forward Shock Spectrum at different time epochs. Flux increases at lower frequencies as maximum synchrotron frequency has not passed those frequencies yet

Forward Shock Lightcurve (ISM)

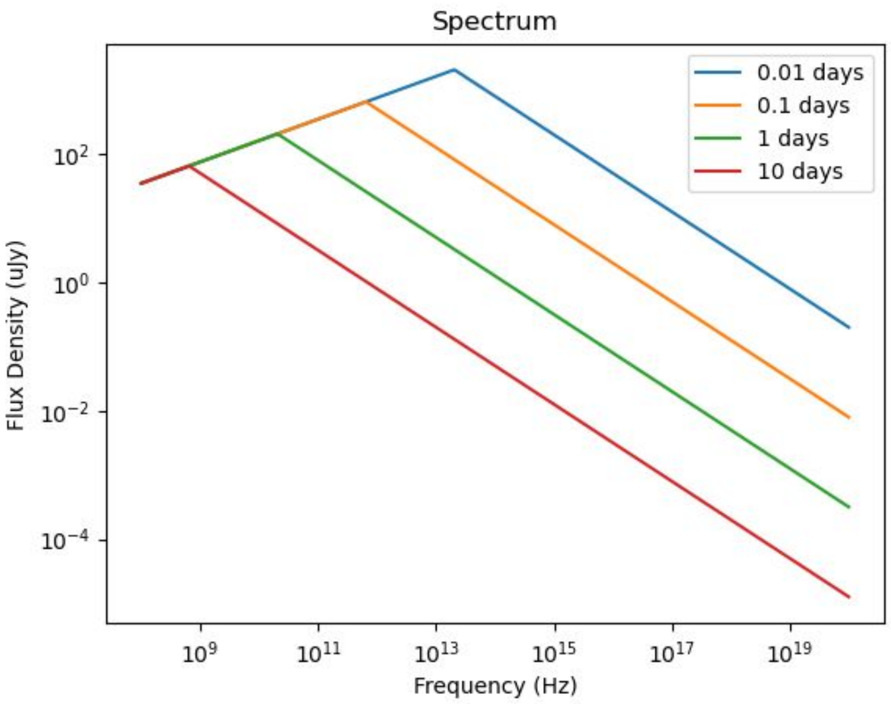


We can observe the cooling break in the X-Ray lightcurve and the maximum synchrotron frequency break can be observed in the radio lightcurve



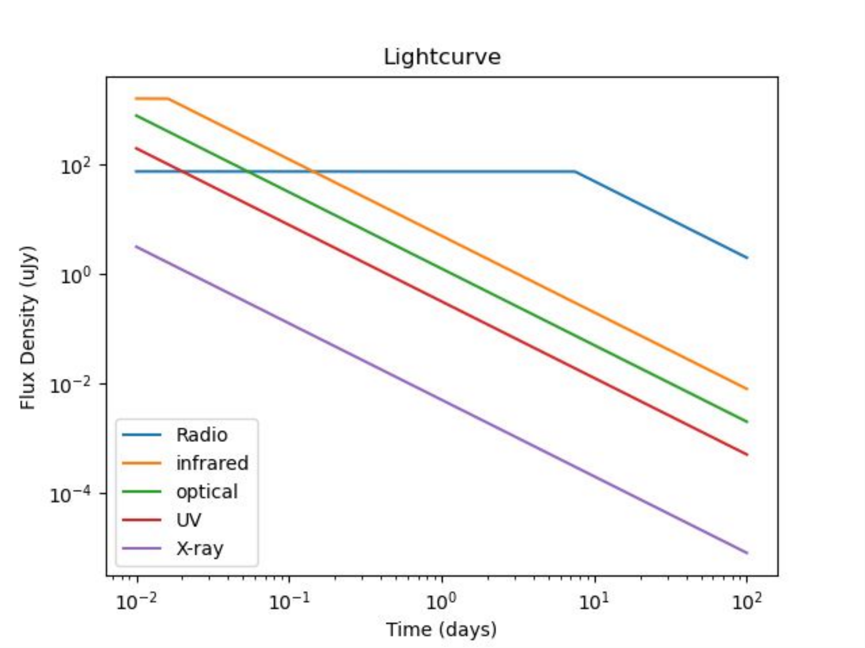
Evolution of cooling frequency and maximum synchrotron frequency

Forward Shock Spectrum (Wind)

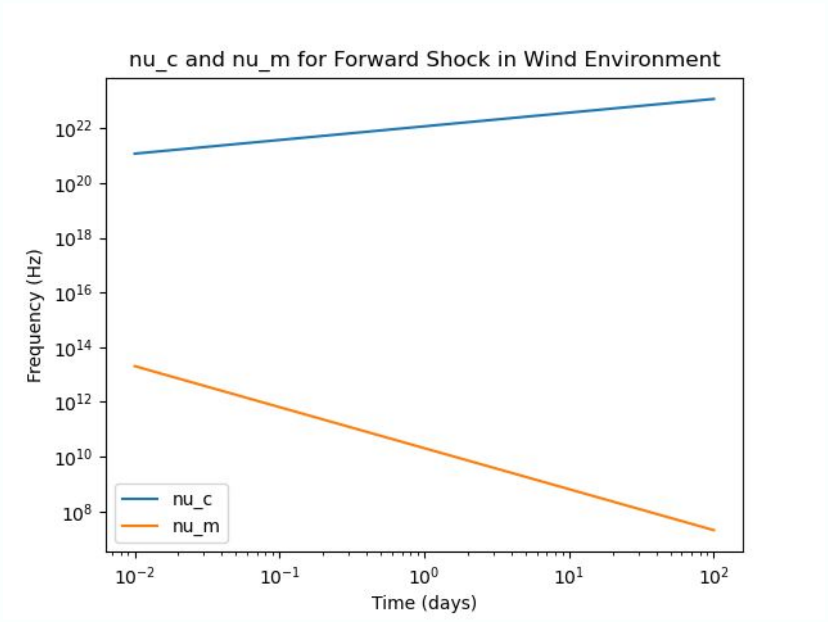


Forward Shock Spectrum at different time epochs in a wind environment. We observe constant flux in time before maximum synchrotron frequency break

Forward Shock Lightcurve (Wind)

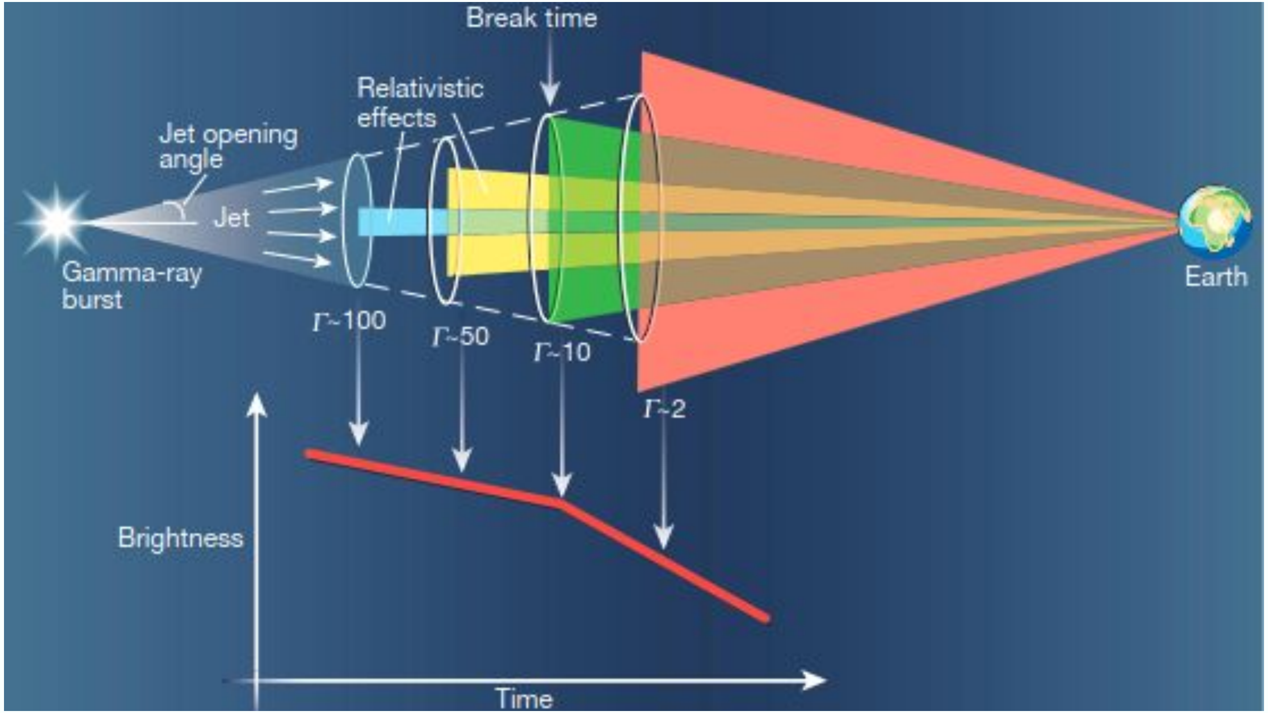


The temporal evolution of lightcurve is constant before the maximum synchrotron frequency break



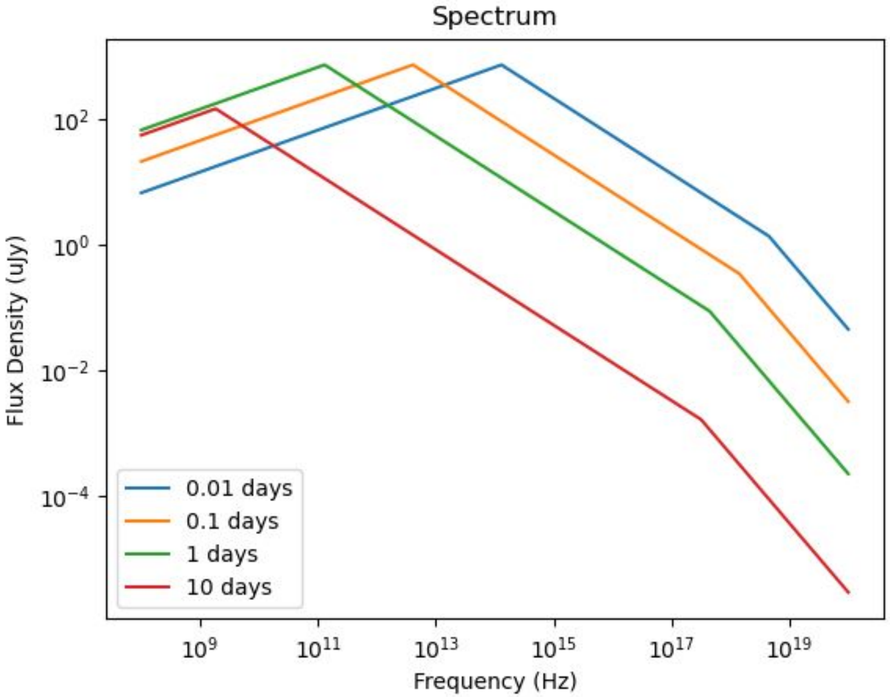
Evolution of cooling frequency and maximum synchrotron frequency

Jet Break – Edge Effect & Sideways Expansion



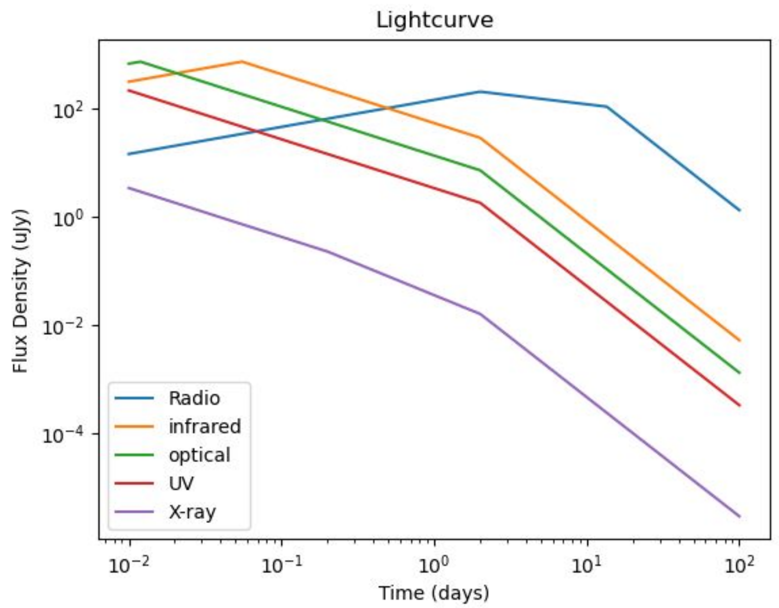
Credits : Woosley, S. Blinded by the light. *Nature* **414**, 853–854 (2001).

Forward Shock Spectrum (Jet Break)

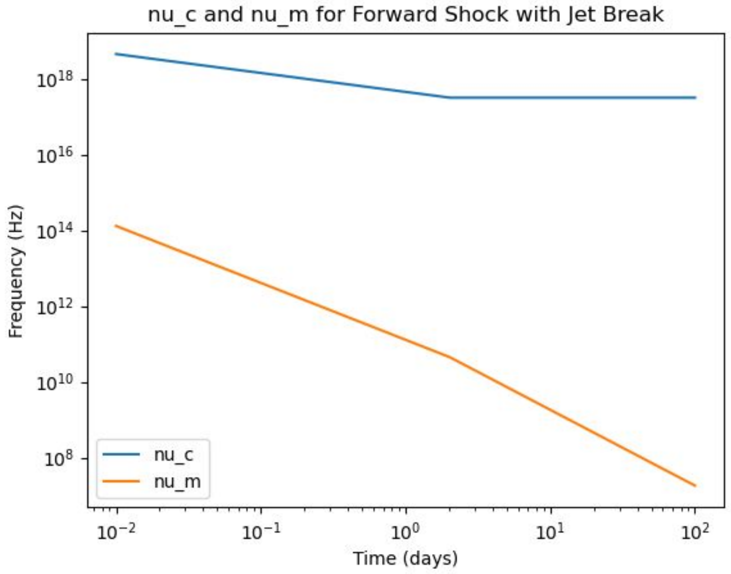


Forward Shock Spectrum at different time epochs with a jet break at 2 days. We can observe a steep decrease in flux across all frequencies

Forward Shock Lightcurve (Jet Break)

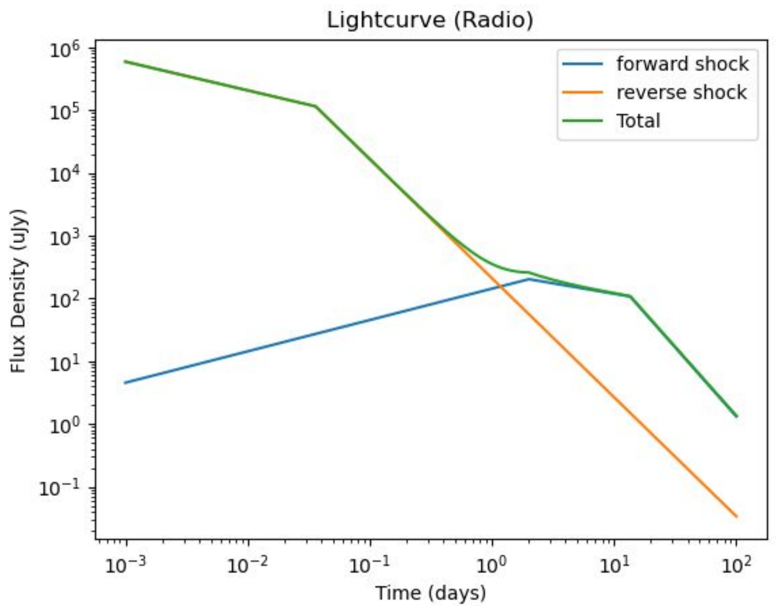


The temporal evolution of lightcurve with a jet break at 2 days. Different slope for radio band is due to its different spectral regime

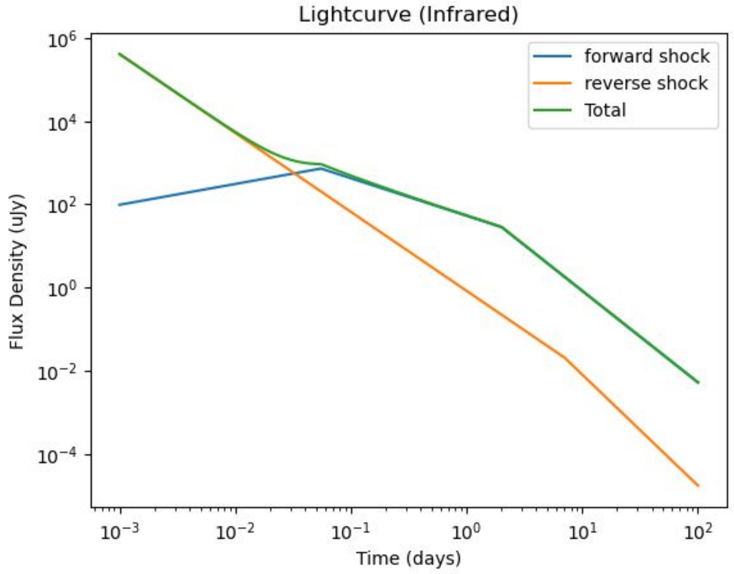


Evolution of cooling frequency and maximum synchrotron frequency. Cooling frequency becomes constant post break

Reverse + Forward Shock Lightcurves

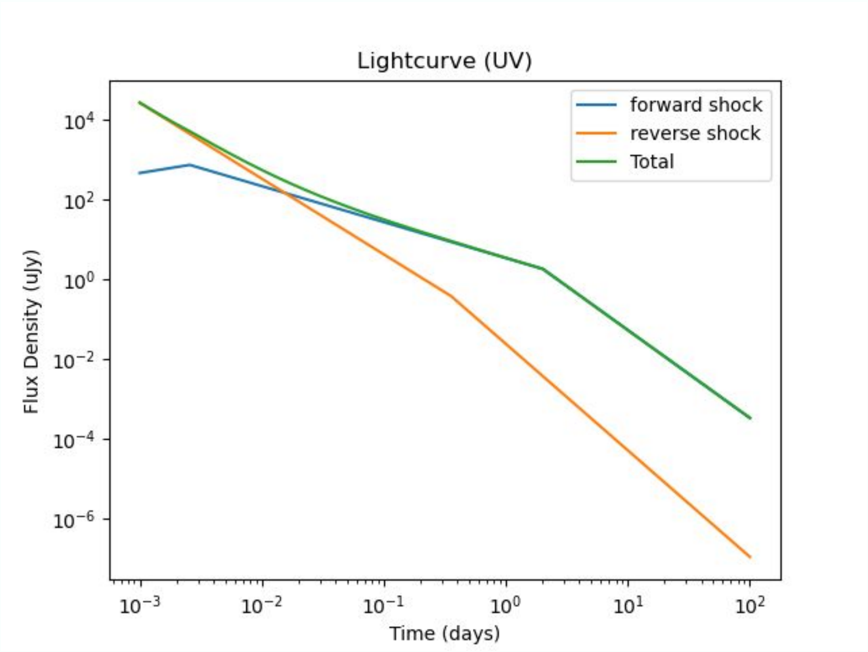


Reverse Shock dominates the early radio afterglow. We ignored self absorption frequency, therefore the early time features may not be observed. Shown here for theoretical completion

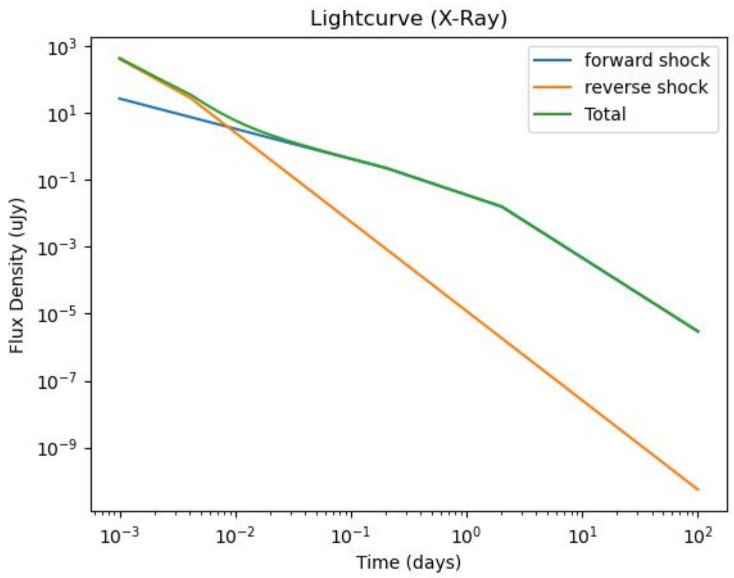


We observe re-brightening of lightcurve due to the rising phase of forward shock in infrared

Reverse + Forward Shock Lightcurves

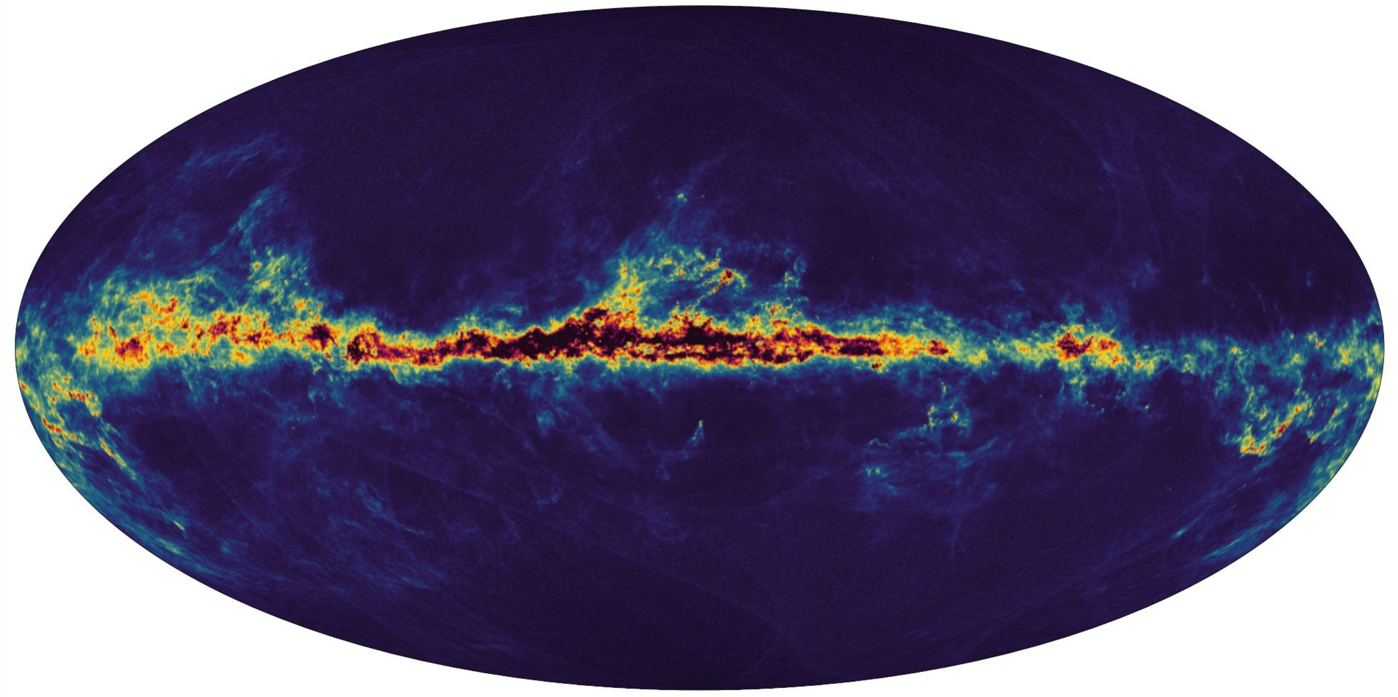


No re-brightening is observed in UV. The break in reverse shock due to passing of cut-off frequency remains hidden

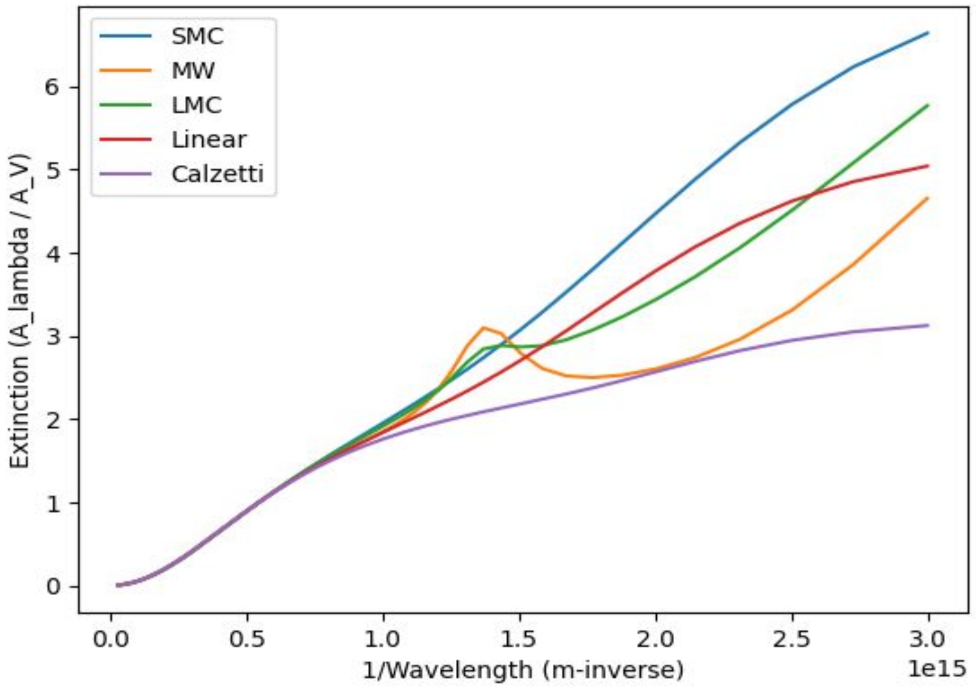


The break in reverse shock due to passing of cut-off frequency is visible

Guess What? – Its dust



Extinction Models



Life threatening fun fact :-

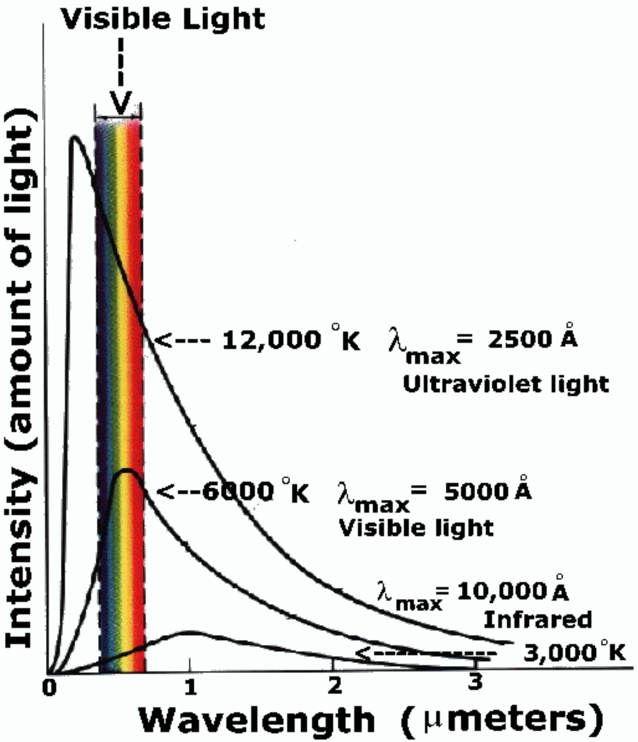
Gamma ray bursts (GRBs) could have caused the Ordovician-Silurian extinction event on Earth, about 440 million years ago

05

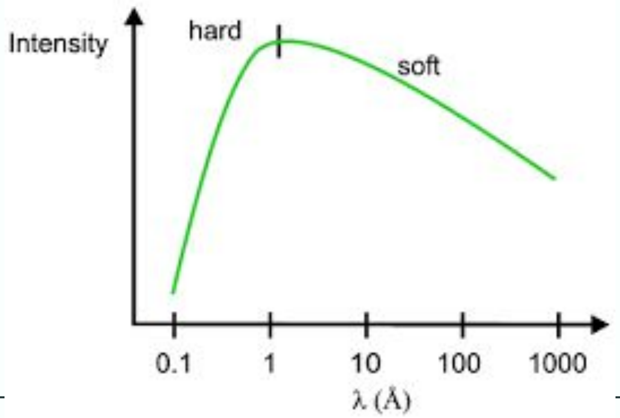
Prompt Emission

Phenomenology : The Band Function

Frequency Spectra : ad hoc models and assumptions

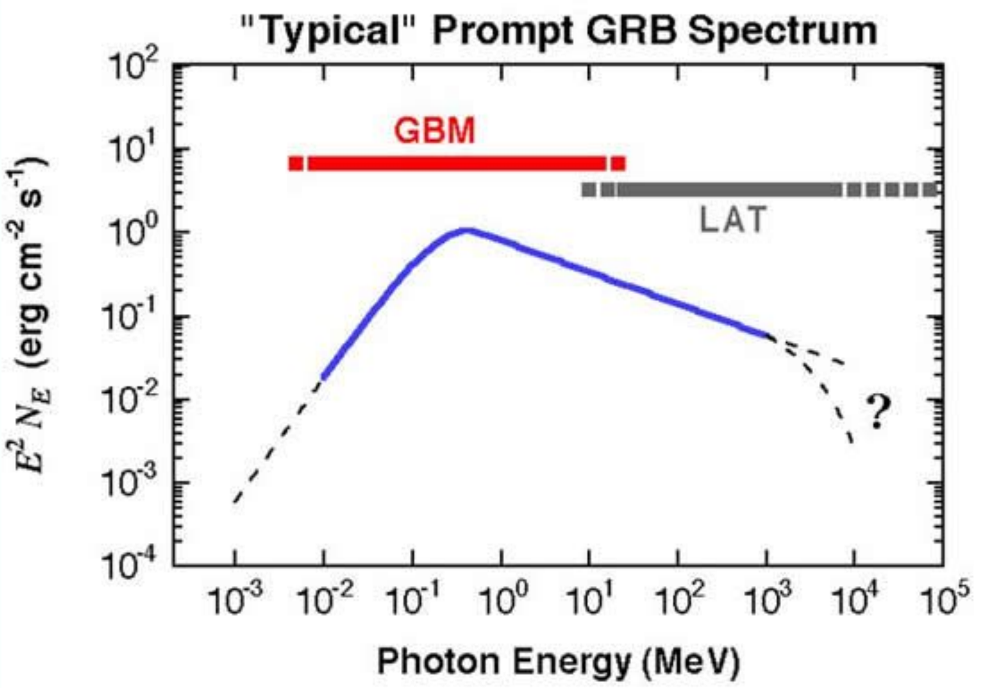


All stars emit according to the blacbody spectra,
Whatever nuclearfusion goes on at the core is
re-emitted at the surface after a process of
“thermalisation”
at some level, any blackbody is equivalent to photons in
a 3D dimensional Box
However there are distinctly “non thermal” emission
mechanisms like synchrotron emission



Phenomenology : The Band Function

What exactly is the GRB's spectra?



- Visually Similar to a synchrotron emission spectrum
- An analytical form was proposed by Band et al
-

Phenomenology : The Band Function

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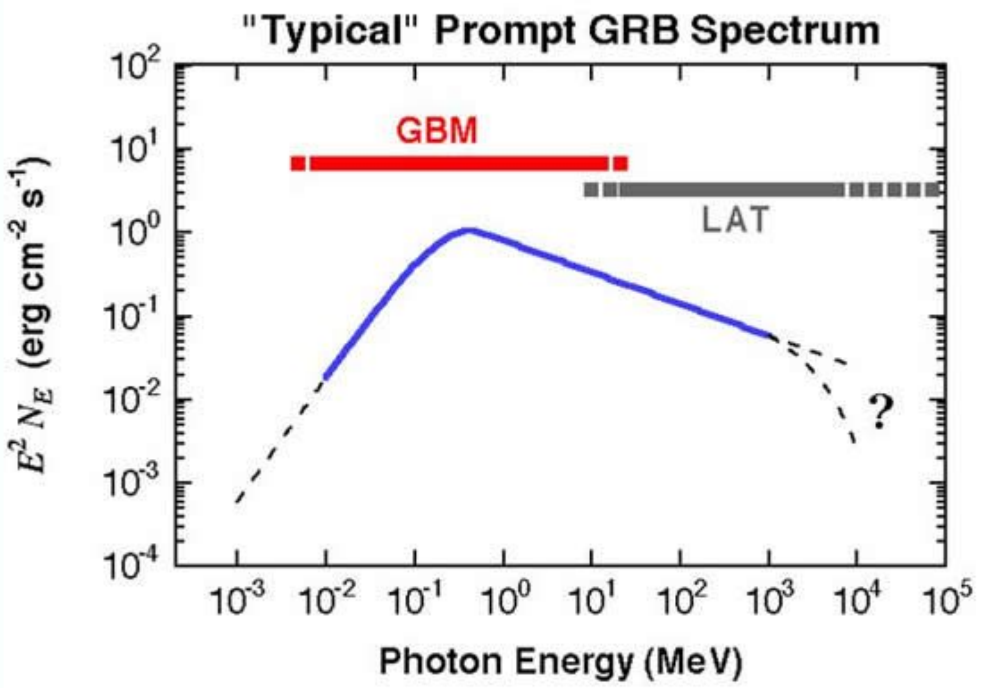


- Very Similar to a synchrotron emission spectrum
- An analytical form was proposed by Band et al
-

$$f(E) = \begin{cases} A(E/100)^{\alpha} e^{-E(2+\alpha)/E_{\mathrm{peak}}} \\ \quad \text{if } E < \dfrac{(\alpha-\beta)E_{\mathrm{peak}}}{(2+\alpha)} \equiv E_{\mathrm{break}} \,, \\ A\left[\dfrac{(\alpha-\beta)E_{\mathrm{peak}}}{100(2+\alpha)}\right]^{(\alpha-\beta)} \exp(\beta-\alpha)(E/100)^{\beta} \\ \quad \text{if } E \geq \dfrac{(\alpha-\beta)E_{\mathrm{peak}}}{(2+\alpha)} \,. \end{cases} \qquad (1)$$

YIKES!
Sadly, we don't know what microscopic process can produce this
(Like we know photons in a 3D box produces blackbody spectrum)

Phenomenology : The Band Function

Theoretical Models constrain what's allowed :

Theory Behind Synchroton Emission tells us about a synchrotron 'line of death'

Essentially the low energy spectral index ALPHA has to be between -⅔ and -3/2

Other explanations put other constraints on the observed spectra .

$$
f(E) = \begin{cases} A(E/100)^{\alpha} e^{-E(2+\alpha)/E_{\text{peak}}} \\ \quad \text{if } E < \dfrac{(\alpha-\beta)E_{\text{peak}}}{(2+\alpha)} \equiv E_{\text{break}} \,, \\ A\left[\dfrac{(\alpha-\beta)E_{\text{peak}}}{100(2+\alpha)}\right]^{(\alpha-\beta)} \exp(\beta-\alpha)(E/100)^{\beta} \\ \quad \text{if } E \geq \dfrac{(\alpha-\beta)E_{\text{peak}}}{(2+\alpha)} \,. \end{cases} \tag{1}
$$

……yet most GRBs remain unexplained

-Several GRBs have shown violation of the synchrotron line of death

-GRBs with multiple pulses may show temporal evolution of these parameters

-Different pulses can be consistent with different models

-Other models include Compton Drag, Photospheric emission

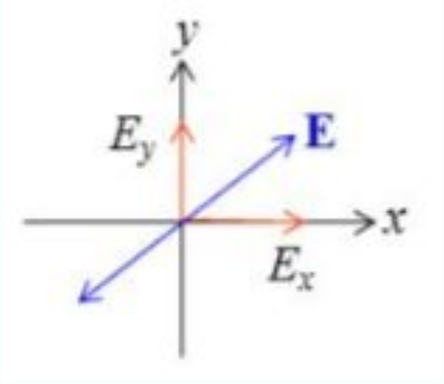
-Thus spectroscopy itself is proving to be insufficient for characterisation of GRBS

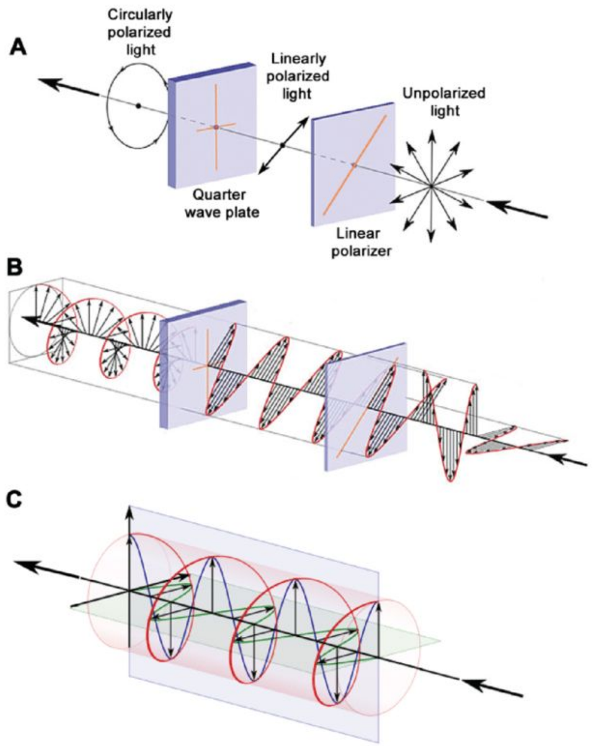
A Promising Approach : Polarimetry!

Refresher on polarisation -

Example equations for linear polarisation
E_x ——--> E_x * Cos(wt)

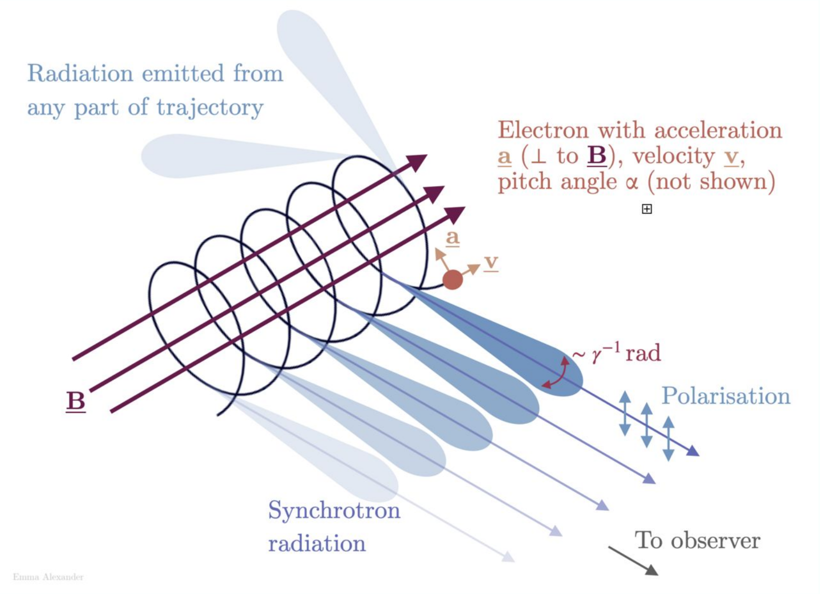
E_y ——--> E_y * Cos(wt + theta)





A Promising Approach : Polarimetry!

Are GRBs polarised? Yes and it matters.



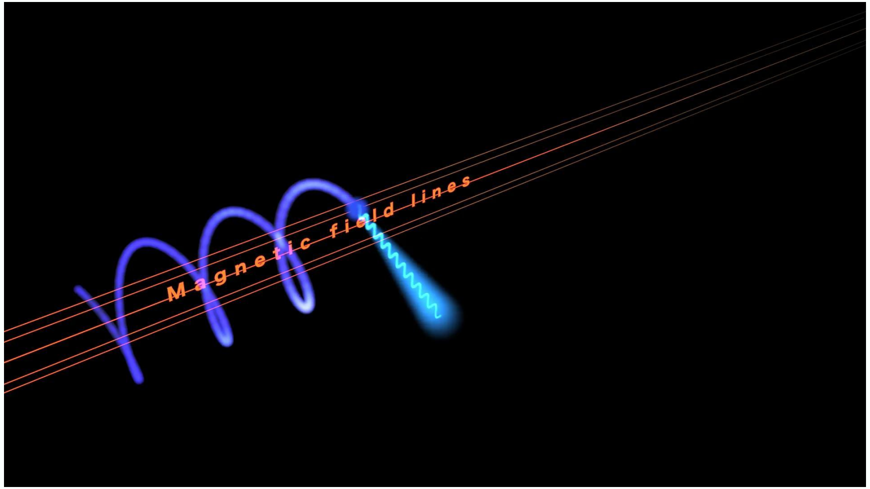
The Burst is produced from Hot (High KE), magnetised matter.

Magnetisation causes charged nano-scale particles to emit radiation
(Synchrotron emission for instance)

The radiation picks up a preferential polarisation depending on the direction of the magnetic field at the source.

A Promising Approach : Polarimetry!

Are GRBs polarised? it matters.



However,

polarisation at micro-scale
!=
macro-scale observable polarisation

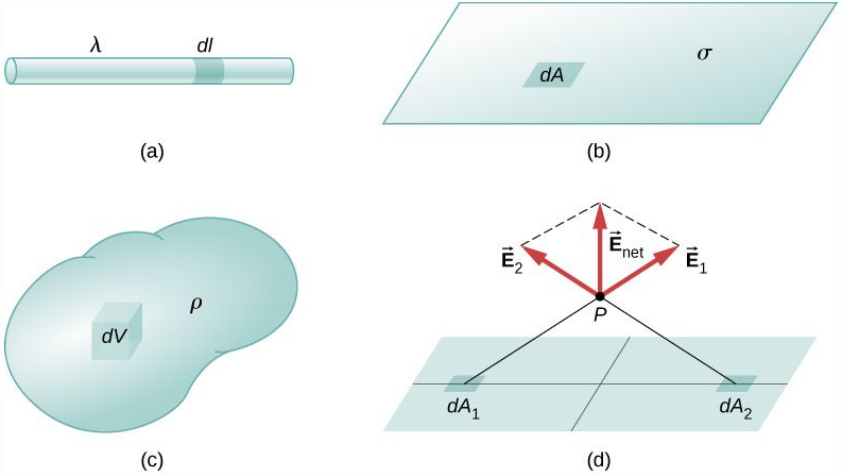
The net effect of the polarisations summed could still be 0.

For example the magnetic field could be completely random, giving no preferred direction.

However certain macro-scale geometries could give rise to overall net polarisation if special features are involved!

The central problem of jet physics
An analogy from electrostatics:

If I gave you a charge distribution could you tell me the electric potential?



Yes ! absolutely, we have been calculating electric fields and potentials for a long time now, since we were in school

The central problem of jet physics
An analogy from electrostatics:

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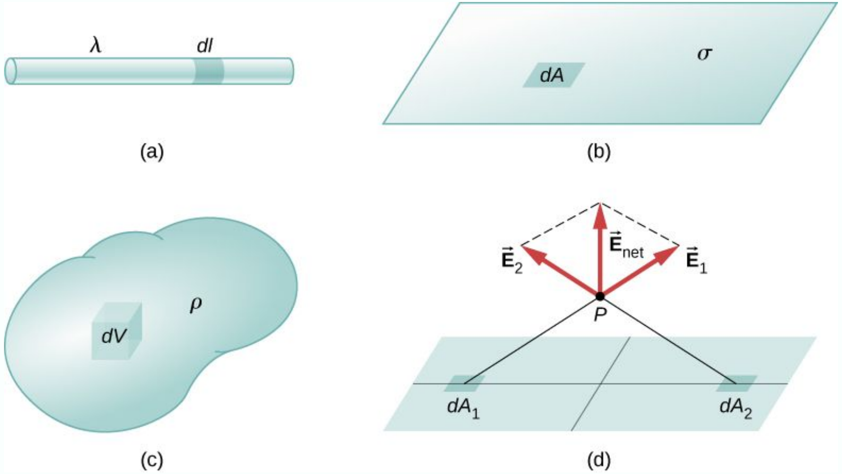


But what about the reverse? what if you had to find the charge distribution instead from a potential?

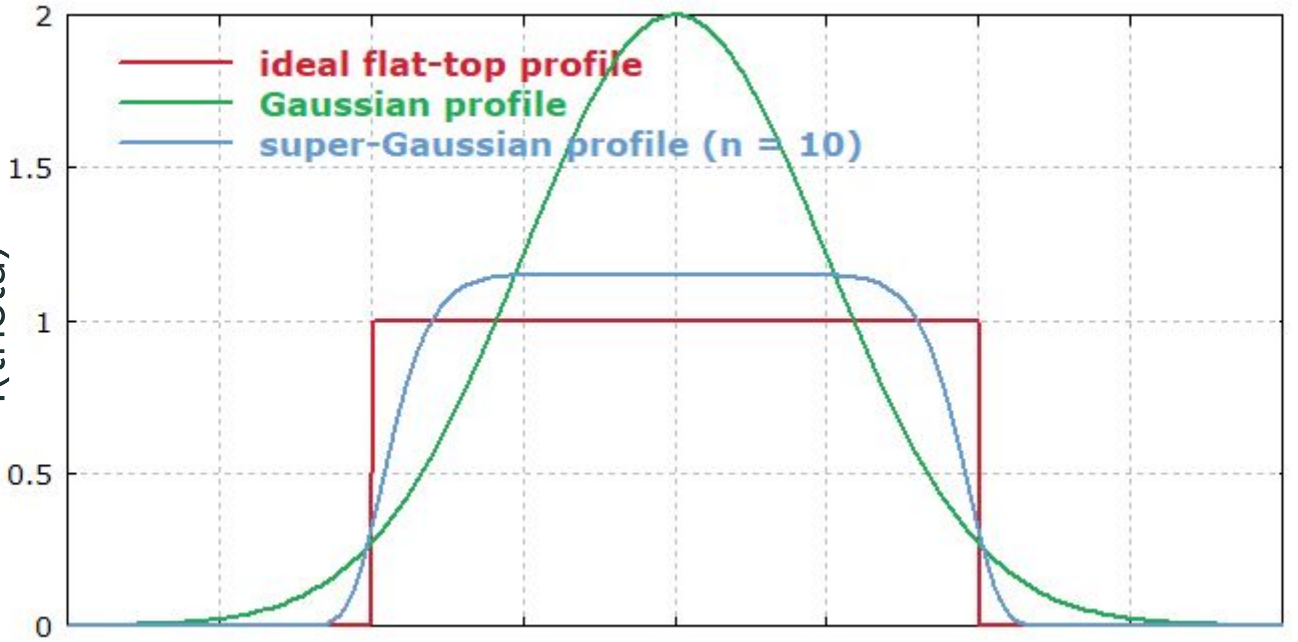
$$\nabla^2 V = -\frac{\rho_v}{\epsilon_0}$$

Yes ! absolutely, we have been calculating electric fields and potentials for a long time since school.

Essentially that is the aim of spectro-polarimetry but even more powerful.
Finding out the angular structure of the jet and spectrum of emission, in one go!

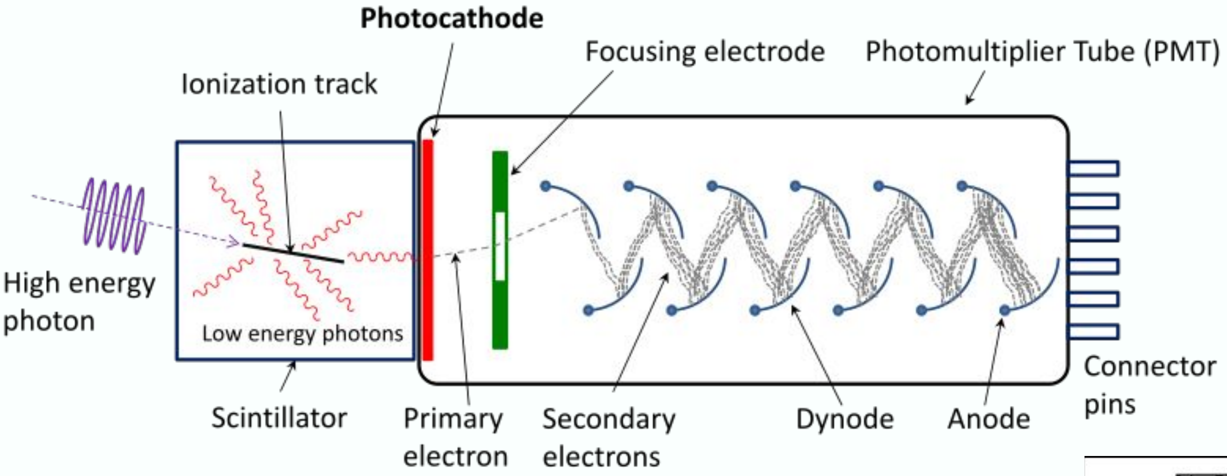
Examples of jet geometries:

Intensity of the jet I(theta)



Angular distance from the Centre

Observing Polarisation : Electronics!



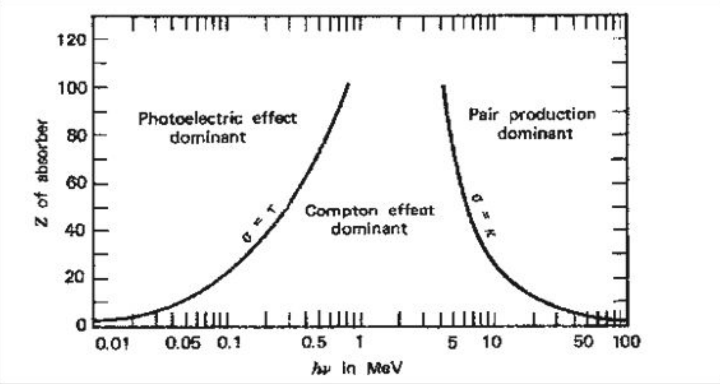
Most preferred device configuration for detections in this energy range (> 10 keV)

Three types of interactions dominate this energy range.

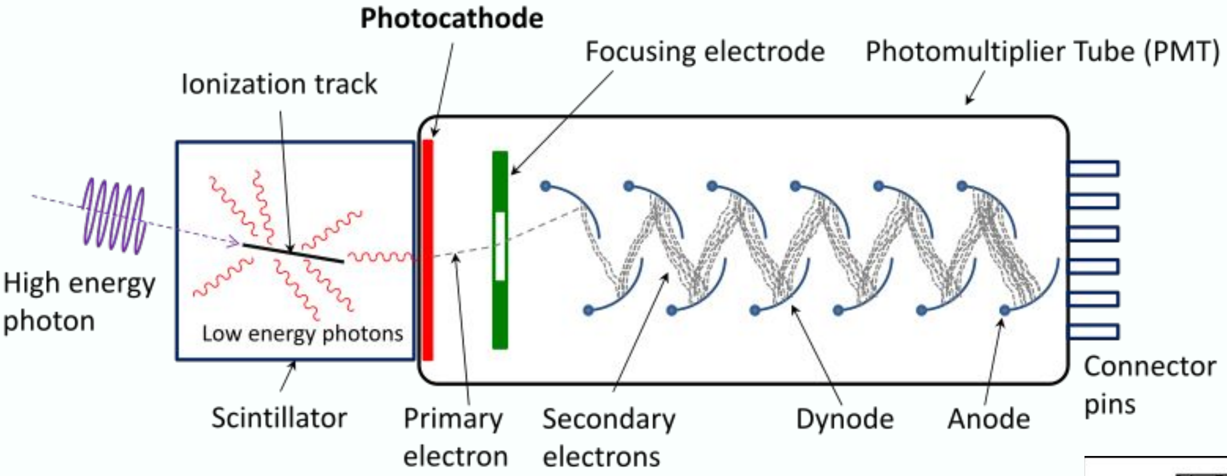
Photo electric effect : photon interacts with atom to release electron

Compton Scattering : High energy photon interacts with atom/electron to give scattered lower energy photon

Pair Production : Gamma rays above 2*rest mass energy of an electron spontaneously produce electron and positron (anti annihilation)



Observing Polarization : Electronics!



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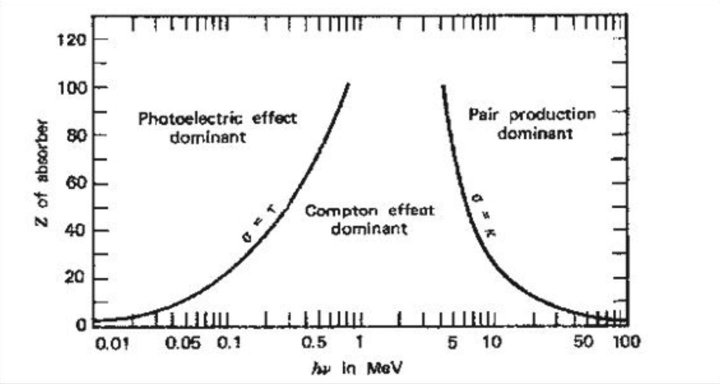
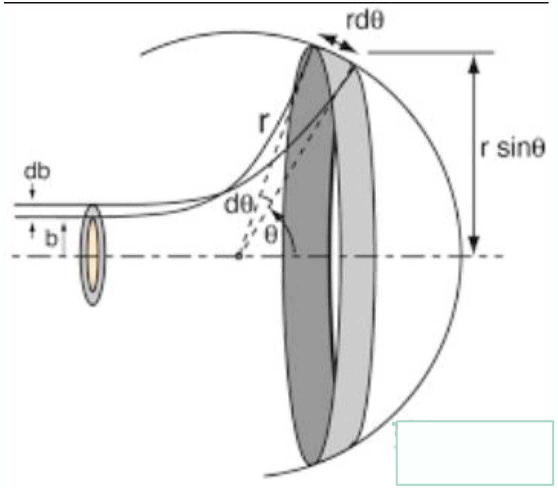
All of these have polarization dependence!



A Promising Approach : Polarimetry!

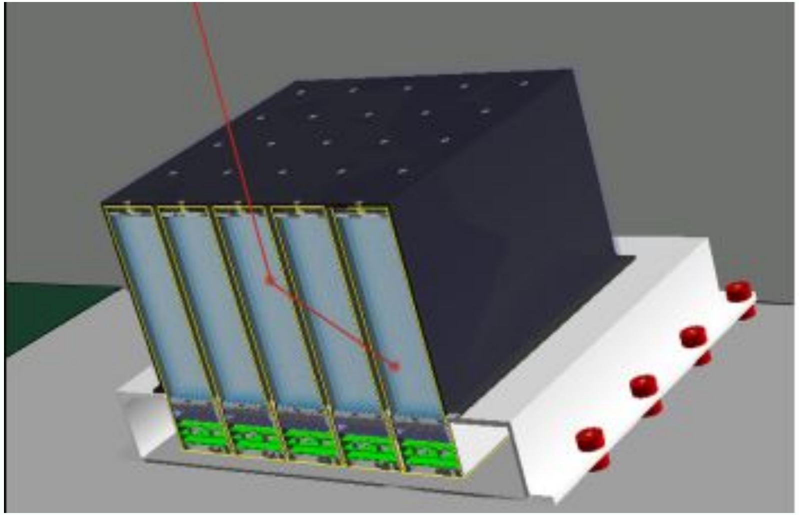
The Compton scattering's klein nishina cross section

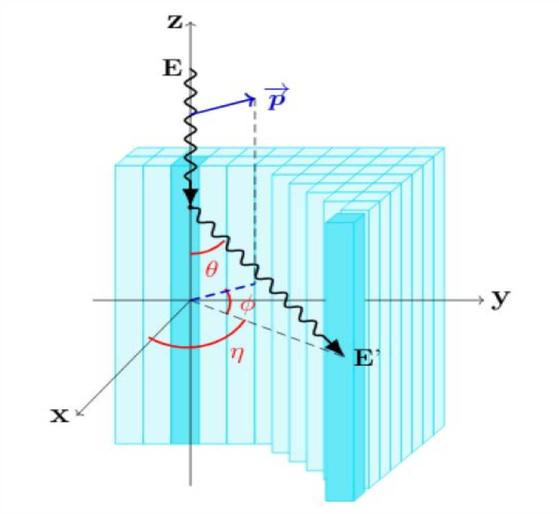


$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right).$$

A Promising Approach : Polarimetry!

Compton Double Counts





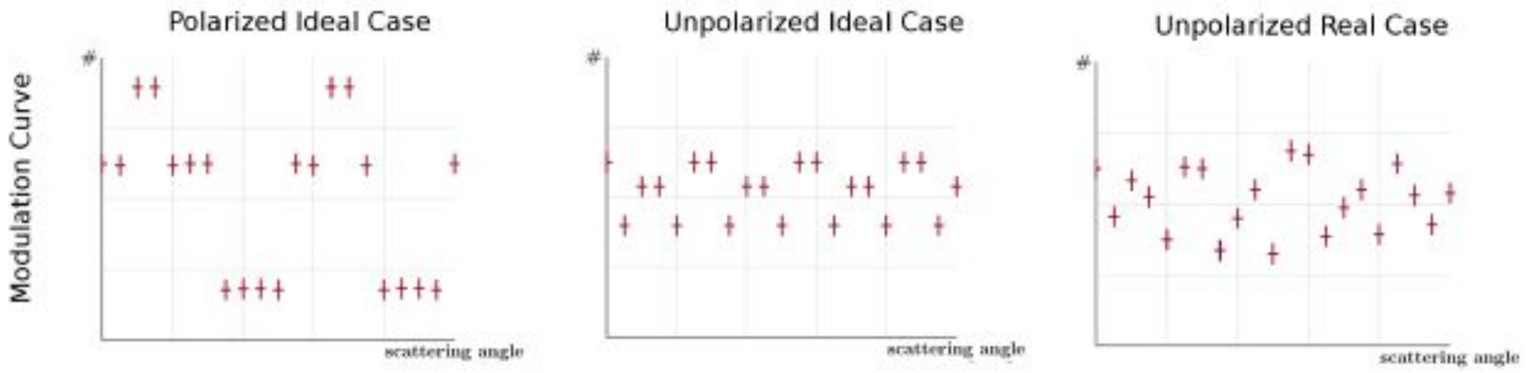
$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right).$$

max at ?

min at ?

picture credits : Merlin Kole and Jinchao Sun, “Gamma-ray Polarimetry of Transient Sources with POLAR”

The Modulation Curve



FIND A GRB (GOOD LUCK FUNDING A SATELLITE)

BUILD A MODULATION CURVE (GOOD LUCK FINDING COMPTON DOUBLE COUNTS)

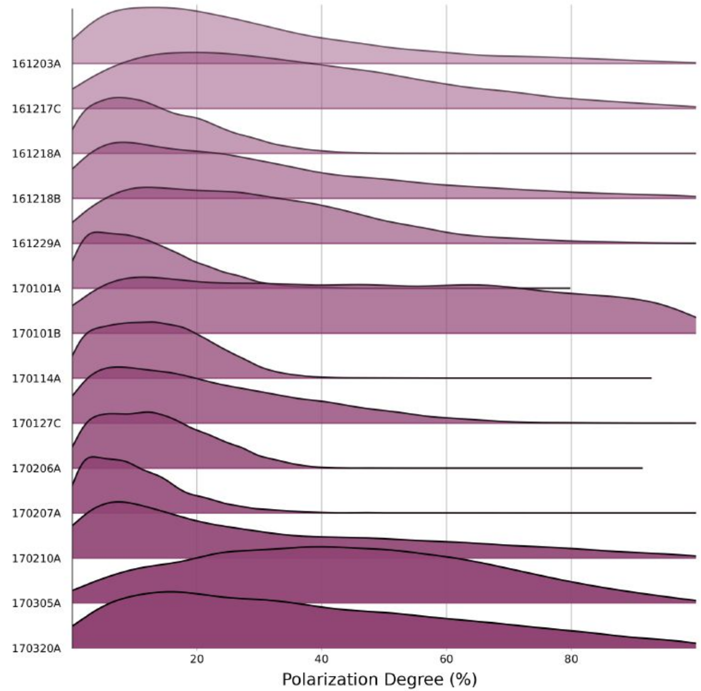
ADD IT TO THE CATALOGUE (PRAY DIFFERENT SATELLITES AGREE)

Where is the research at right now?

CZTI Polarization results (INDIA)

GRB Name	N_{compt}	Bayes Factor	PF (%)[a]	CZTI PA (°)[b]	sky PA (°)
GRB 160325A	764	1.72	< 45.02	–	–
GRB 160623A	1714	1.02	< 56.51	–	–
GRB 160703A	433	0.76	< 62.64	–	–
GRB 160802A	1511	0.69	< 51.89	–	–
GRB 160821A	2851	0.87	< 33.87	–	–
GRB 170527A	1638	0.79	< 36.46	–	–
GRB 171010A	3797	0.98	< 30.02	–	–
GRB 171227A	1249	0.84	< 55.62	–	–
GRB 180103A	4164	8.52	71.43 ± 26.84	34.67 ± 7.00	122.13
GRB 180120A	705	3.95	62.37 ± 29.79	−3.65 ± 26.00	61.21
GRB 180427A	986	9.25	60.01 ± 22.32	16.91 ± 23.00	47.22
GRB 180806A	555	0.86	< 95.80	–	–
GRB 180809B	3294	0.98	< 24.63	–	–
GRB 180914A	2276	1.2	< 33.55	–	–
GRB 180914B	7765	3.52	48.48 ± 19.69	26.99 ± 19.00	68.41
GRB 190530A	1859	3.08	46.85 ± 18.53	43.58 ± 5.00	154.05
GRB 190928A	4492	1.77	< 33.10	–	–
GRB 200311A	1082	0.86	< 45.41	–	–
GRB 200412A	911	0.89	< 53.84	–	–
GRB 200806A	534	0.71	< 54.73	–	–

POLAR Polarization results (Swiss)



How will polarisation be used to resolve confusions regarding spectral models?

Using assumptions about the shape of the jet, the underlying emission mechanisms, structure of the magnetic field we perform

MAGNETO-HYDRODYNAMIC

and

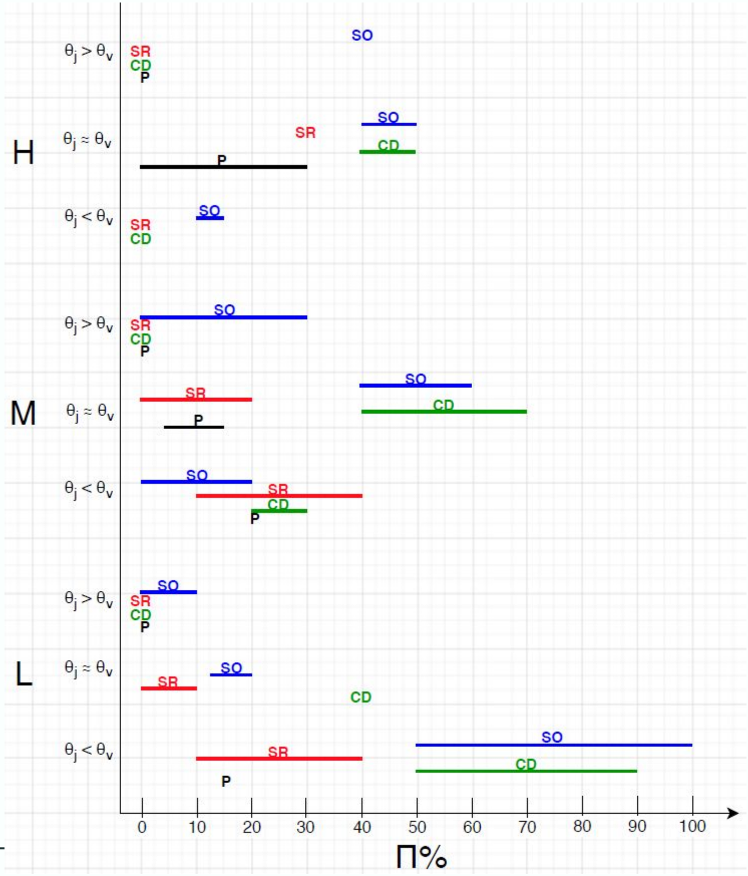
RELATIVISTIC FLUID DYNAMICS

simulations.

We also simulate the entire spacecraft the detector is on (a whole field of study unto itself)

THE RESULTS?

Predictions for the observed polarisation percentage from various models.



Where is the research at right now?

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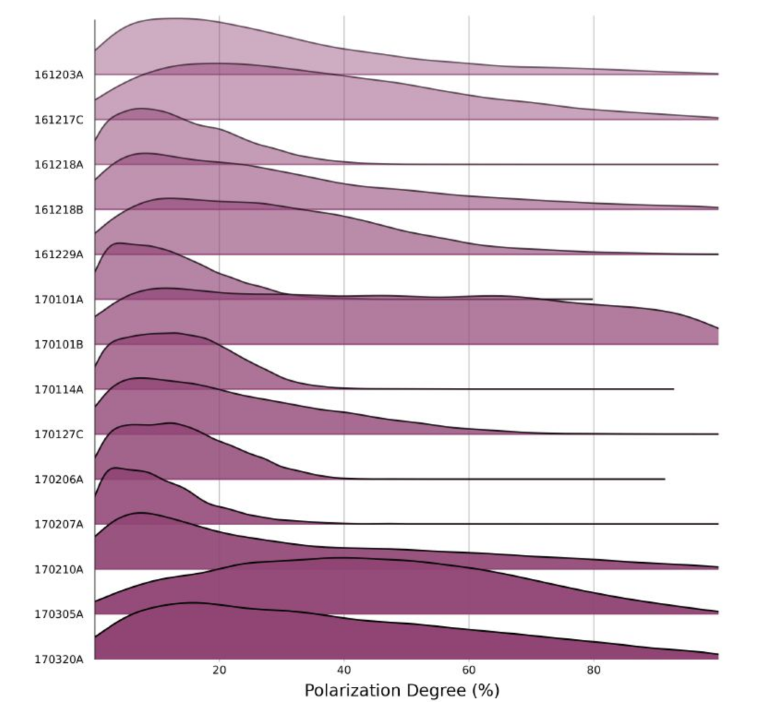
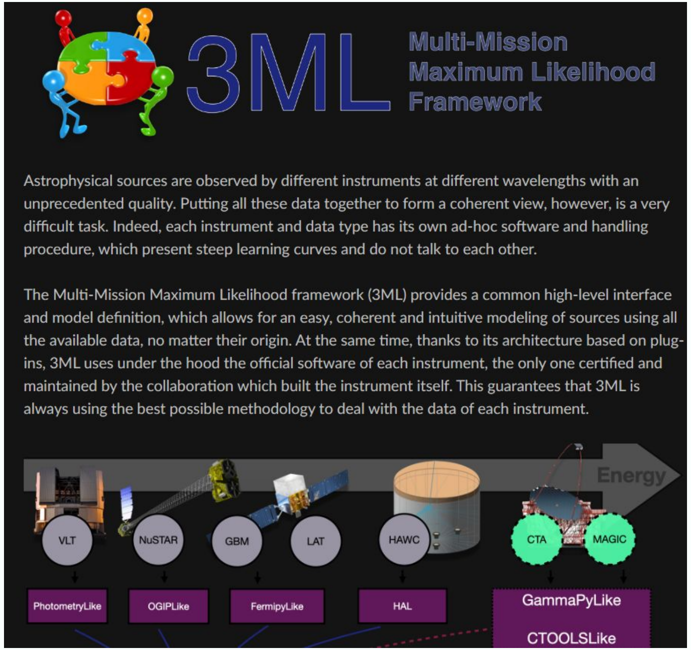
100-300 keV

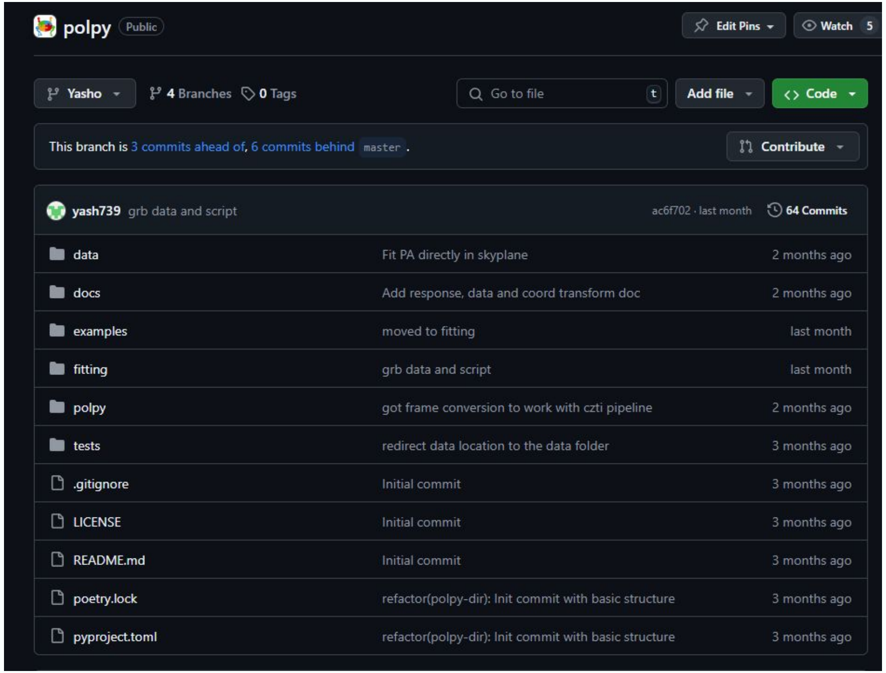
POLAR Polarization results (Swiss)



50-500 keV

Solution : Write software that can analyse both Data Sets





06

How you can get involved

By now you should realise, astronomy involves :

Physics

Pure Astronomy
Electromagnetism
Nuclear Physics
Detector Physics
Quantum Mechanics
Special Relativity
RELATIVISTIC FLUID DYNAMICS
MAGNETOHYDRODYNAMICS

Engineering

Instrumentation
Calibration
Spectral Analysis
Physics Modelling
Monte Carlo simulations
Statistical Inference
Manufacturing

Software/Coding

Building the pipelines
Merging Pipelines
Writing Firmware
Hardware interfacing
Machine Learning
Scheduling Observations

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Engineering

Instrumentation
Calibration
Spectral Analysis
Physics Modelling
Monte Carlo simulations
Statistical Inference
Manufacturing
Actually building and launching an effin' satellite

Software/Coding

Building the pipelines
Merging Pipelines
Writing Firmware
Hardware interfacing
Machine Learning
Scheduling Observations

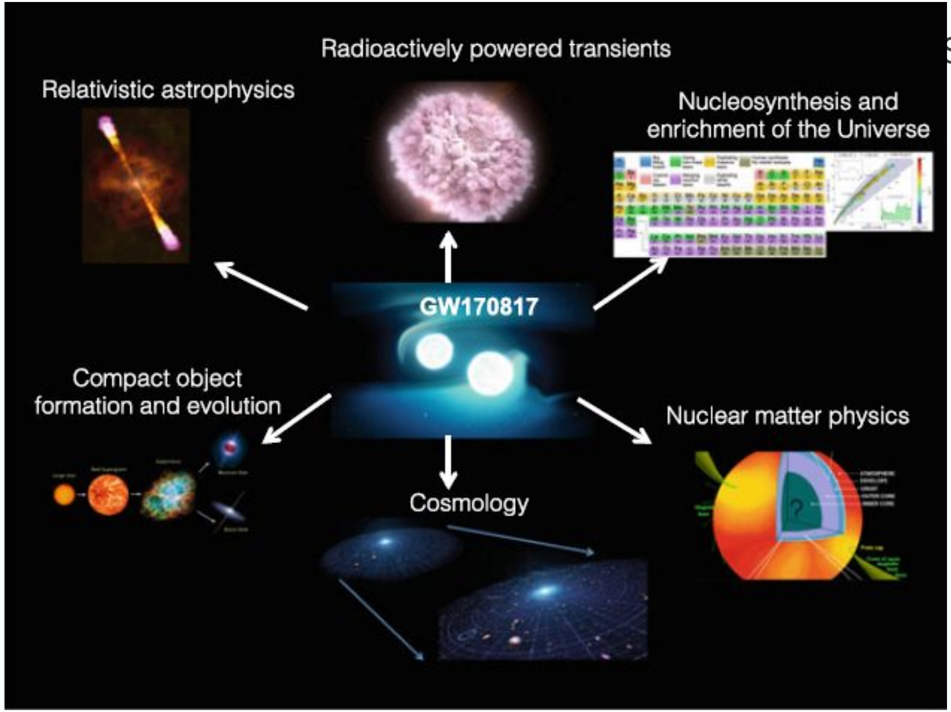
Writing Software to jointly analyse datasets… should be applicable across types of signals!

Enter the era of Multi-Messenger Astronomy.

Event type	Electromagnetic	Cosmic rays	Gravitational waves	Neutrinos	Example
Solar flare	yes	yes	-	-	SOL1942-02-28[5][failed verification]
Supernova	yes	-	predicted[6]	yes	SN 1987A
Neutron star merger	yes	-	yes	predicted[7]	GW170817
Blazar	yes	possible	-	yes	TXS 0506+056 (IceCube)
Active galactic nucleus	yes	possible		yes	Messier 77[8][9] (IceCube)
Tidal disruption event	yes	possible	possible	yes	AT2019dsg[10] (IceCube) AT2019fdr[11] (IceCube)

If the universe's most powerful explosions are not your thing, dont worry!
There is probably a group of physics students analysing all the other stuff coming from the sky

THE GOAT OF TIME DOMAIN



Simultaneous GW, GRB, X-ray, Optical signals were observed by over 70 observatories of various kinds around the world.

The detection of GW170817 serves as a model for the power of MMA and the need for even more satellites and detectors.

Yes. It is going to be expensive.
But hey, unlike Particle Physicists,

We know what we want to detect
and
We know it exists ;)

THANK YOU