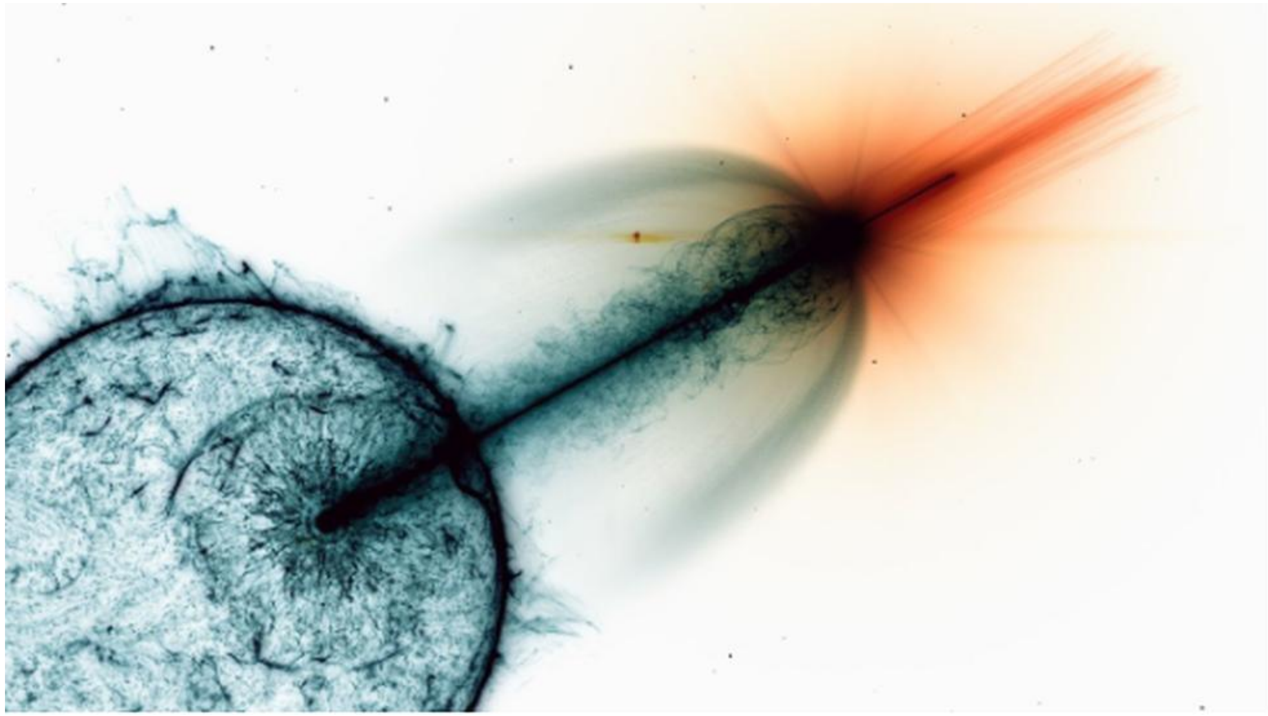
MODELS OF GAMMA RAY BURST EMISSION

- CURRENT STATUS AND CHALLENGES -



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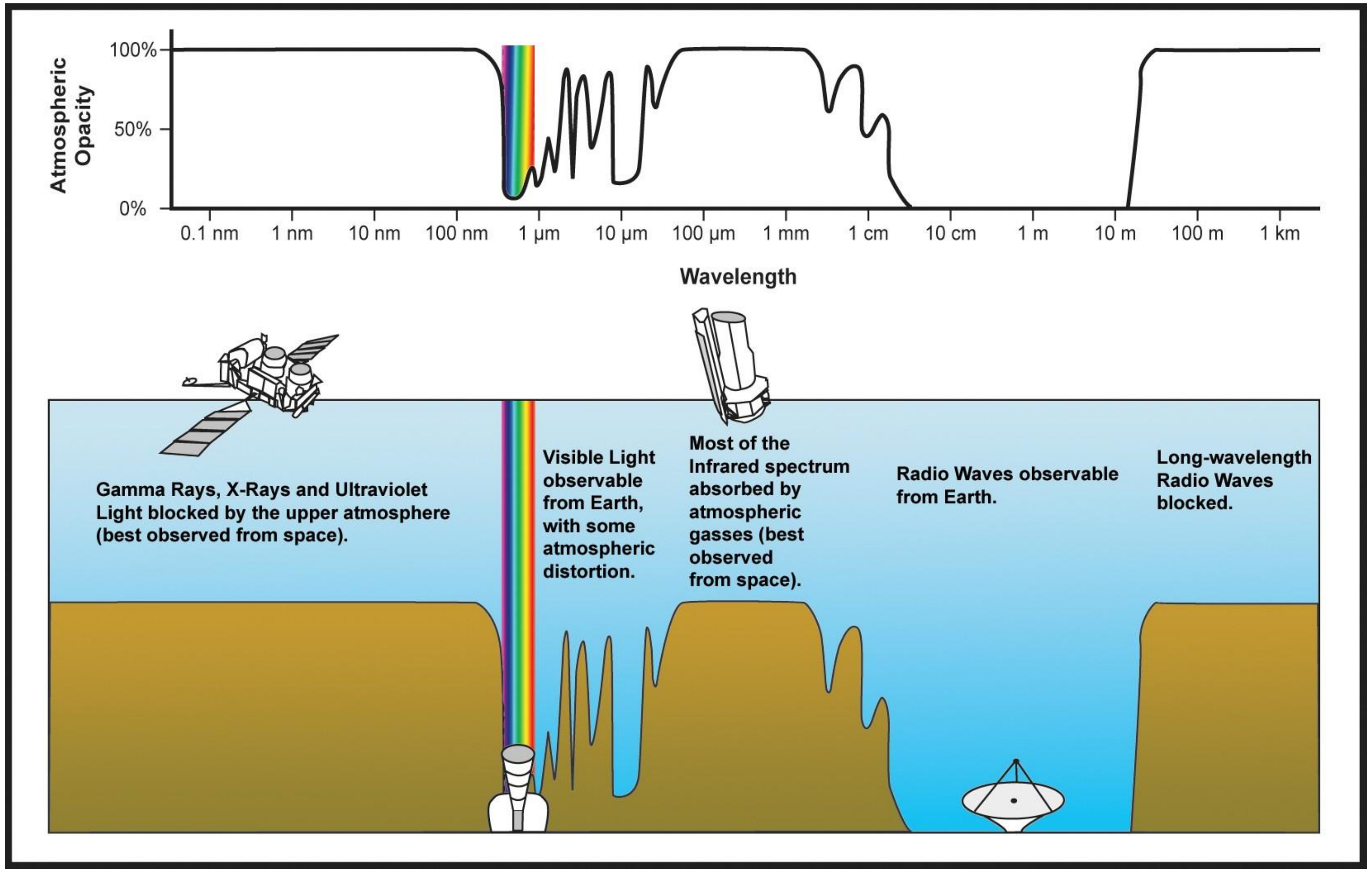
OVERVIEW

- Short historical overview
- GRB properties… long story short!
- GRB model supermarket
- GRB origin – collapsar vs. IGC
- GRB model checklist... Do they get it right?
- Art of approximation?
- Conclusions

SHORT HISTORICAL OVERVIEW

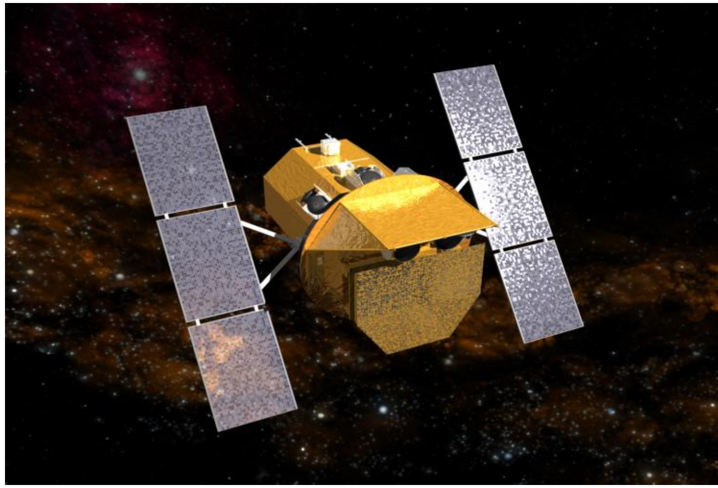


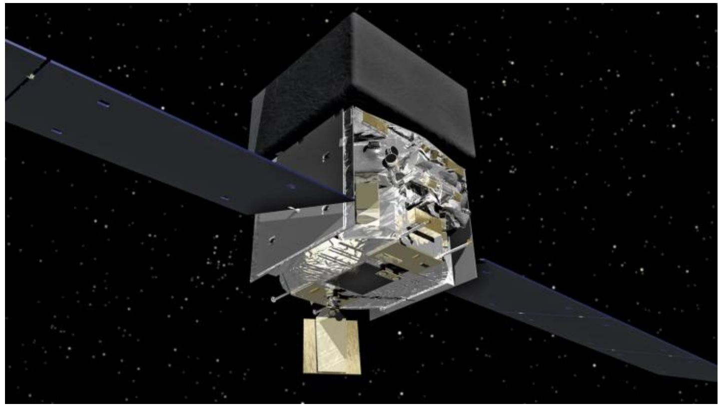
SHORT HISTORICAL OVERVIEW

- First GRB detection: July 2 1967, Vela satellite
- Official public announcement with additional 16 GRBs observed in 1973
  - Events outside our Solar system
- Early theoretical developments – proliferation of both galactic and extragalactic models
- Hartmann & Epstein, 1989 – isotropic distribution of events; indication of extragalactic origin
- BATSE onboard Compton Gammy Ray Observatory (CGRO), launch: April 5 1991
  - Confirmation of isotropic distribution of GRBs, around 3000 events
  - Identification of short ($T_{90} \leq 2s$), spectrally harder, and long, spectrally softer, ($T_{90} \geq 2s$) GRBs…
- BeppoSAX, launch: April 30 1996
  - GRB 970228 – first observation of the GRB afterglow and identification of a host galaxy at z = 0.695
  - GRB 980425 – first cross-identification of a GRB and Type Ic supernova SN 1998bw

SHORT HISTORICAL OVERVIEW

- The Neil Gehrels Swift Observatory, launch: November 20, 2004
  - BAT – fast detection and positioning, from 1 till 4 arcmin resolution, from 15keV to150keV
  - XRT – imaging and apectral analysis, 2 arcsec resolution, from 0.2keV till 10keV
  - UVOT – optical telescope with grism for wavelenghts from 170nm till 650nm
- Fermi Gamma-Ray Space Telescope, launch: June 11, 2008
  - LAT – pair conversion detector, from 20MeV till 30GeV
  - GBM – scintillation detector, from 8keV till 1MeV, and from 150keV till 30MeV





SHORT HISTORICAL OVERVIEW

- LIGO and Virgo, detection: August 17 2017
  - GW 170817 – binary NS merger identified in gamma rays as GRB 170817A by Fermi and INTEGRAL, further observations in optical, infrared and radio bands – kilonova AT 2017gfo in galaxy NGC 4993
- MAGIC, detection: January 14 2019
  - GRB 190114C – first GRB ever detected at TeV energies,

    z = 0.4245
- LHASSO, detection: October 9 2022
  - GRB 221009A – first GRB ever detected above 10 TeV,

    z = 0.151

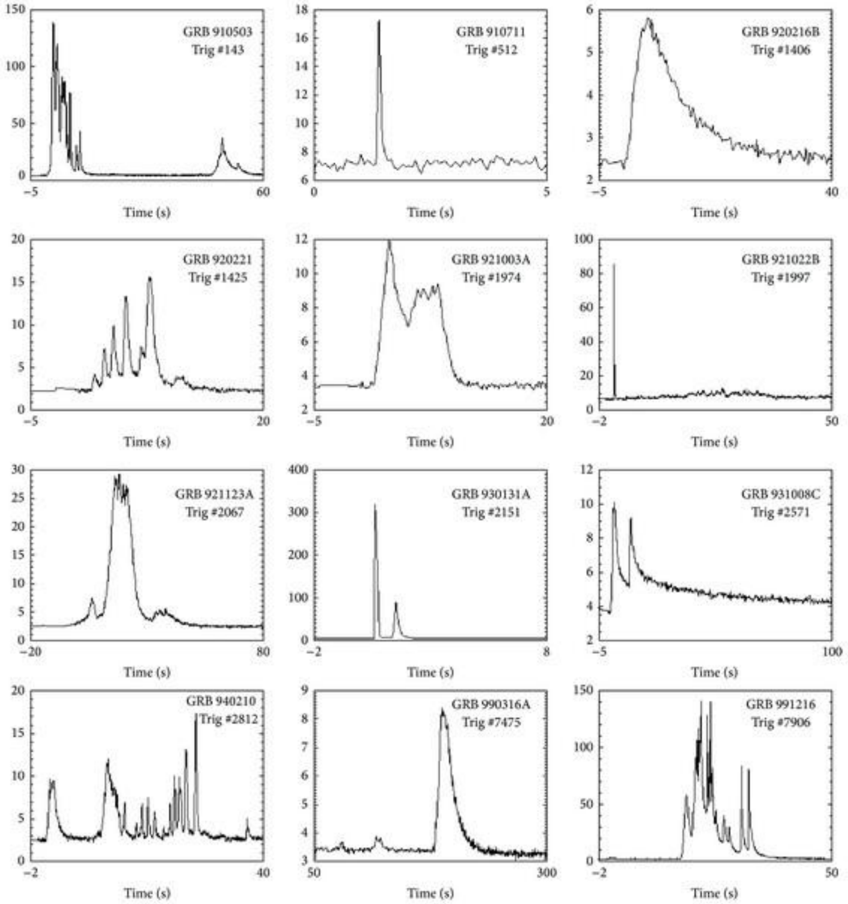
GRB PROPERTIES… LONG STORY SHORT!

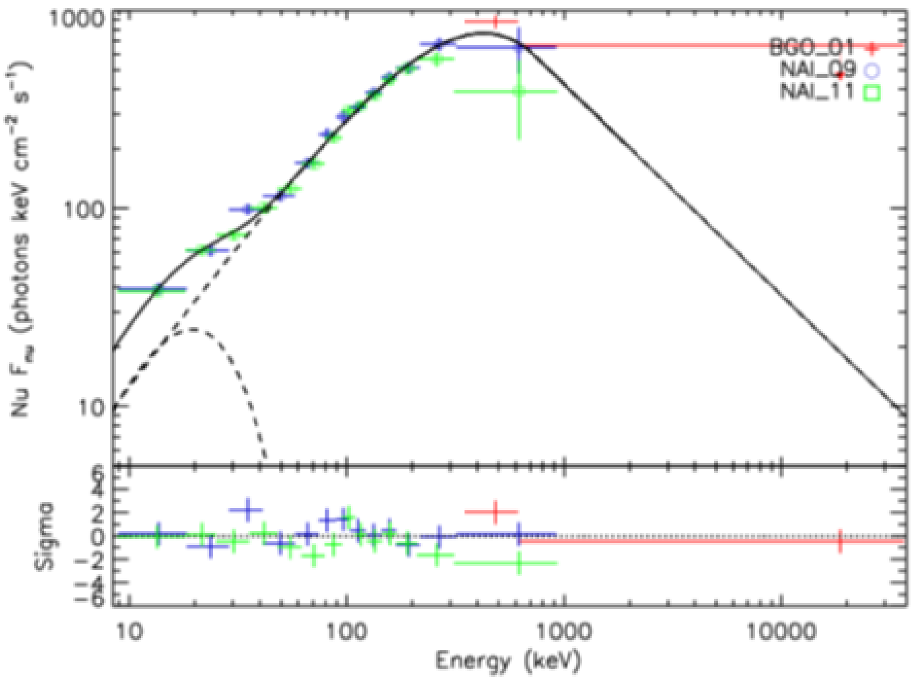
- Prompt emission
  - Principal part of GRB phenomena is the emission of gamma rays (above 10keV)
  - Isotropic luminosty, L_{iso} – between 10^{47}erg/s and 10^{54}erg/s
  - Isotropic energy, E_{iso} – between 10^{49}erg and 10^{55}erg
- Some groups propose the existence of ultra short (BH – NS merger) and ultra long GRBs (long activity of central engine – magnetar)
- Spectra generally described with the Band function:

$$N(E) = K_0 \times \begin{cases} \left[\frac{E}{100\ \mathrm{keV}}\right]^{\alpha} \exp\left[-\frac{(2+\alpha)E}{E_p}\right], & E \leq \frac{\alpha-\beta}{2+\alpha}E_p \\ \left[\frac{E}{100\ \mathrm{keV}}\right]^{\beta} \exp(\beta-\alpha)\left[\frac{(\alpha-\beta)E_p}{2+\alpha}\right]^{\alpha-\beta}, & E > \frac{\alpha-\beta}{2+\alpha}E_p \end{cases}$$

  - Some GRBs require addition of a thermal component into the spectra
  - Peak energy, E_p in range between few keV till couple MeV, spectral indices in ranges: $-1.5 \leq \alpha \leq 0.5$ and $-2.5 \leq \beta \leq -2$

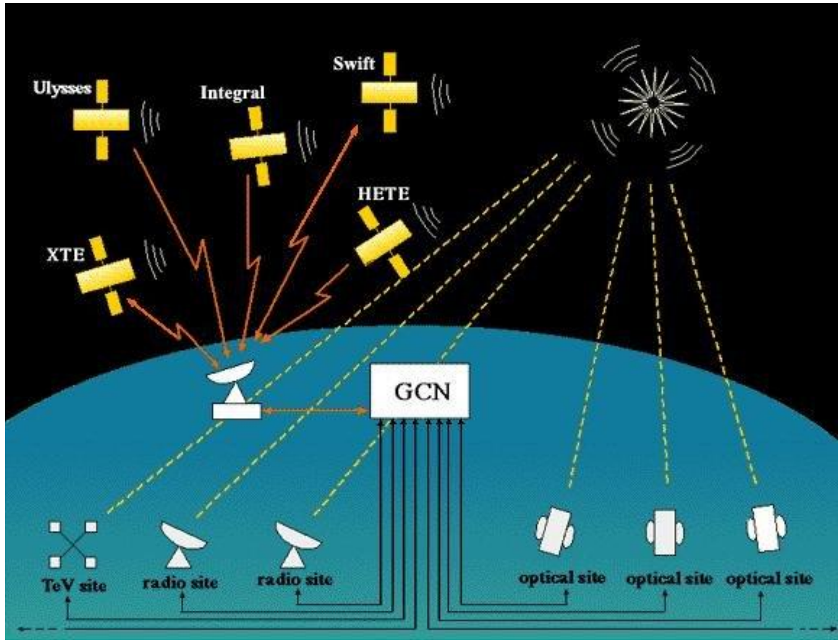
GRB PROPERTIES… LONG STORY SHORT!





GRB PROPERTIES… LONG STORY SHORT!

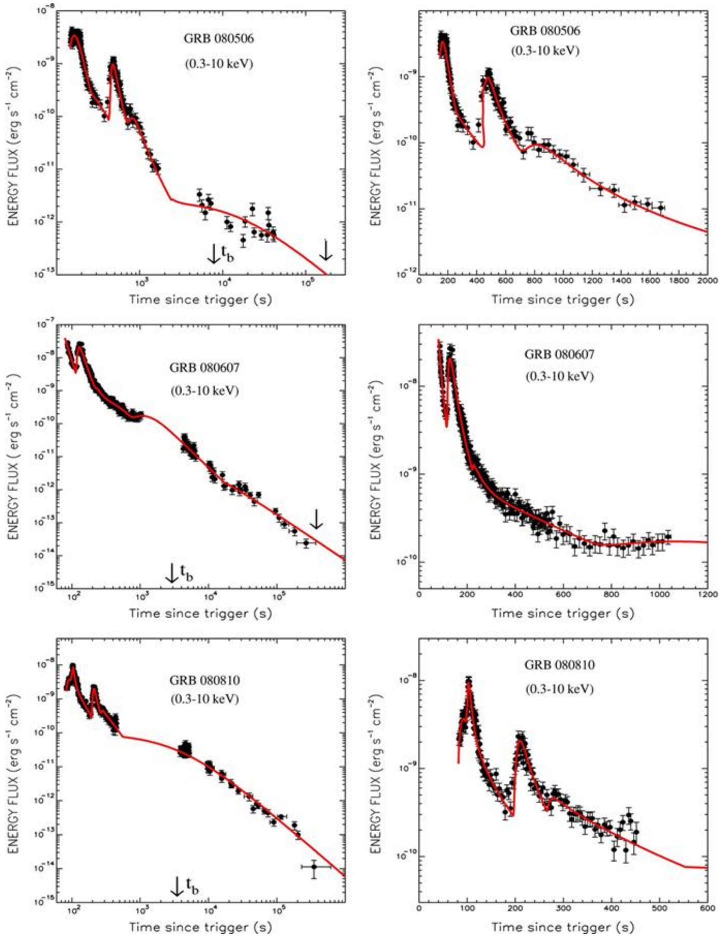
- Parameters of Band function
  - No physical meaning, though they relate to physical processes
  - Spectral softening within temporal evolution of the GRB pulse
- GRBs are mostly gamma ray energy band related phenomena
  - Observations in other energy bands are important, but technically constricted
  - Extension into the optical band gives out characteristic brightness around 18 mag – for comparison magnitude limit of ROTSE III is around 17 mag
  - Prospective use of future all sky surveys like e.g. LSST
  - Some extreme cases: GRB990123 (9 mag), GRB080319 (5.3 mag, known as "naked eye GRB")

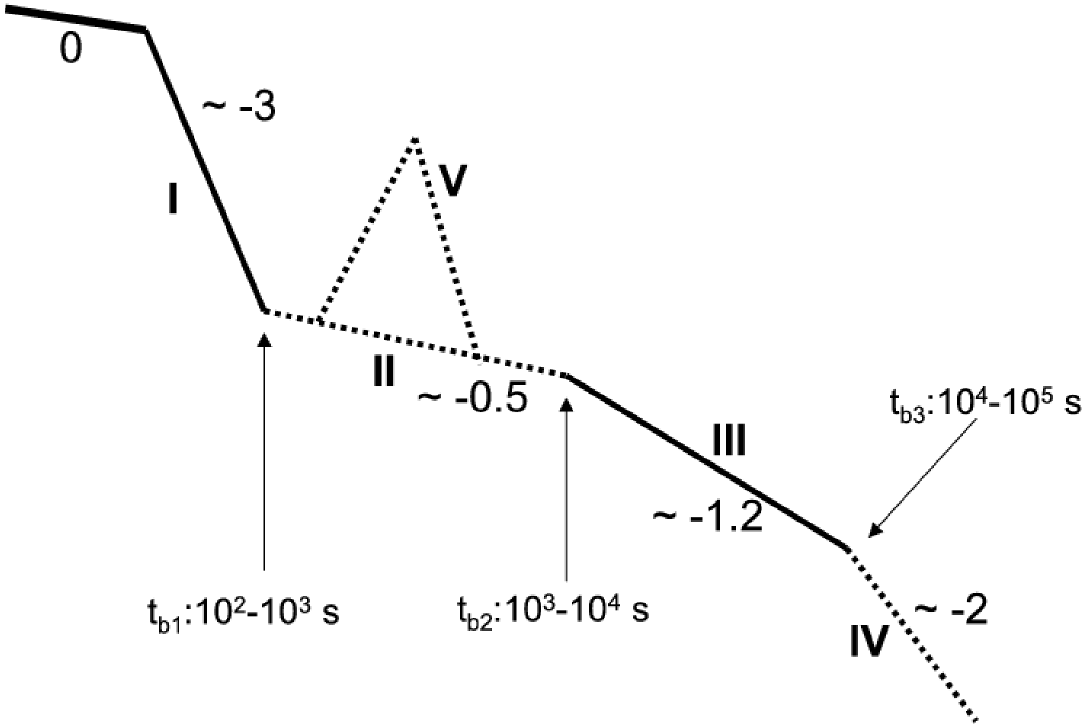


GRB PROPERTIES… LONG STORY SHORT!

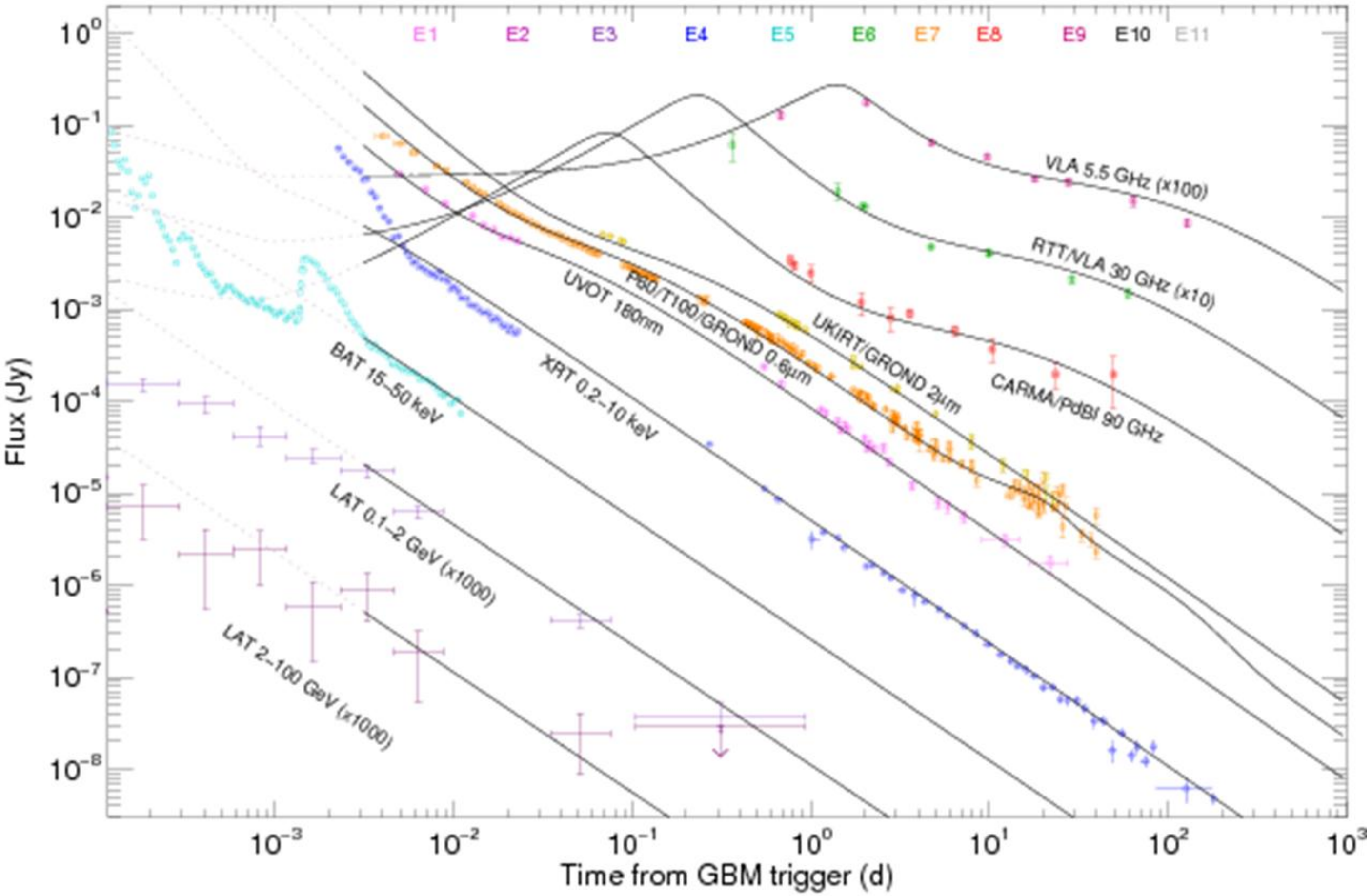
- GRB afterglow – late phase emission generally observed in X-rays
  - Reasons why we don't always observe GRB afterglows in optical and radio bands still not clarified – intrinsic processes vs. intergalactic (or interstellar) extinction
- Afterglow fluxes are generally described with $F_\nu \propto \nu^{-\alpha} t^{-\kappa}$, though both α and κ are functions of both energy and time
- Afterglow activity faster at higher energies
  - Optical band – rise in few days, coalescence with background in few months, signatures of polarization and dust interaction
  - Radio waves – rise in few weeks and months, coalescence with background within a year
- Some GRB afterglows exhibit achromatic breaks which were treated as geometric signature of a relativistic jet
  - In Swift era there were no observations of achromatic breaks in X-rays

GRB PROPERTIES… LONG STORY SHORT!



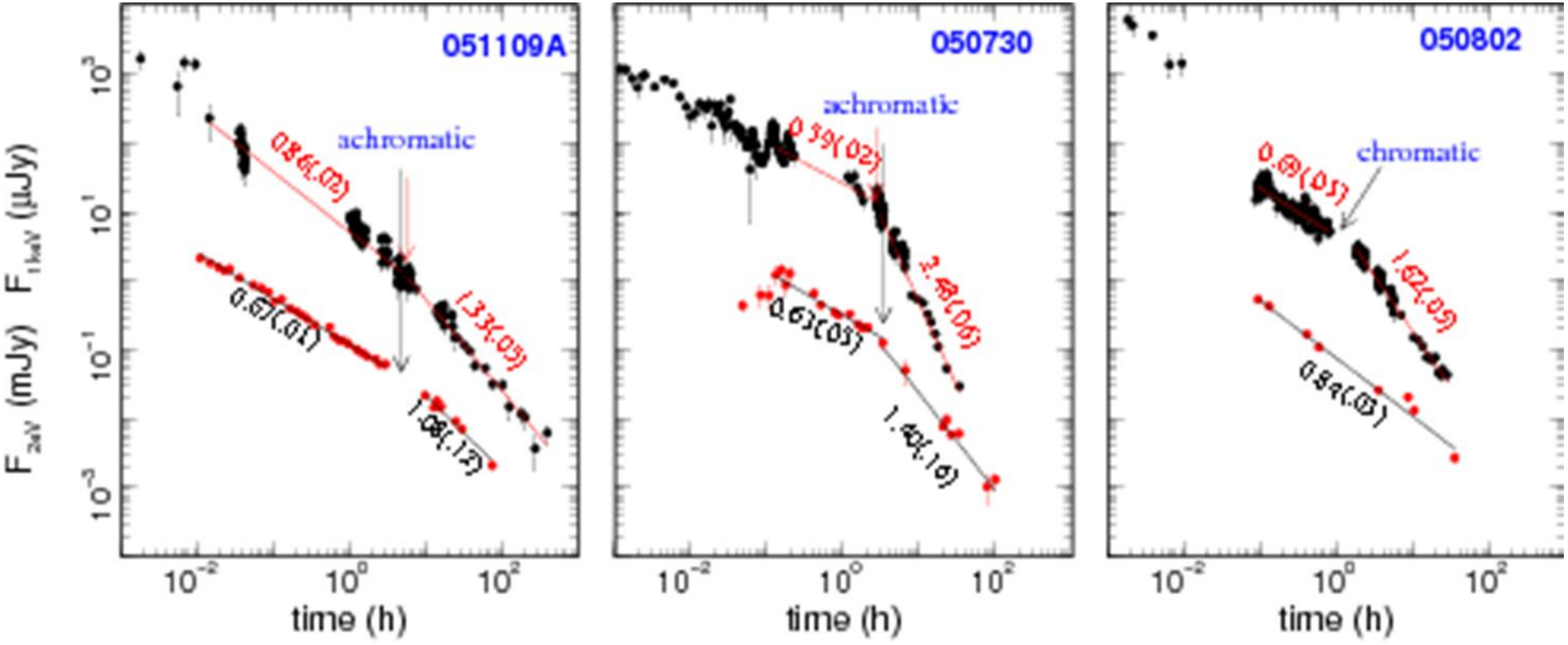


GRB PROPERTIES… LONG STORY SHORT!



GRB PROPERTIES… LONG STORY SHORT!

- Chromatic breaks can't be explained as a canonical jet transitions

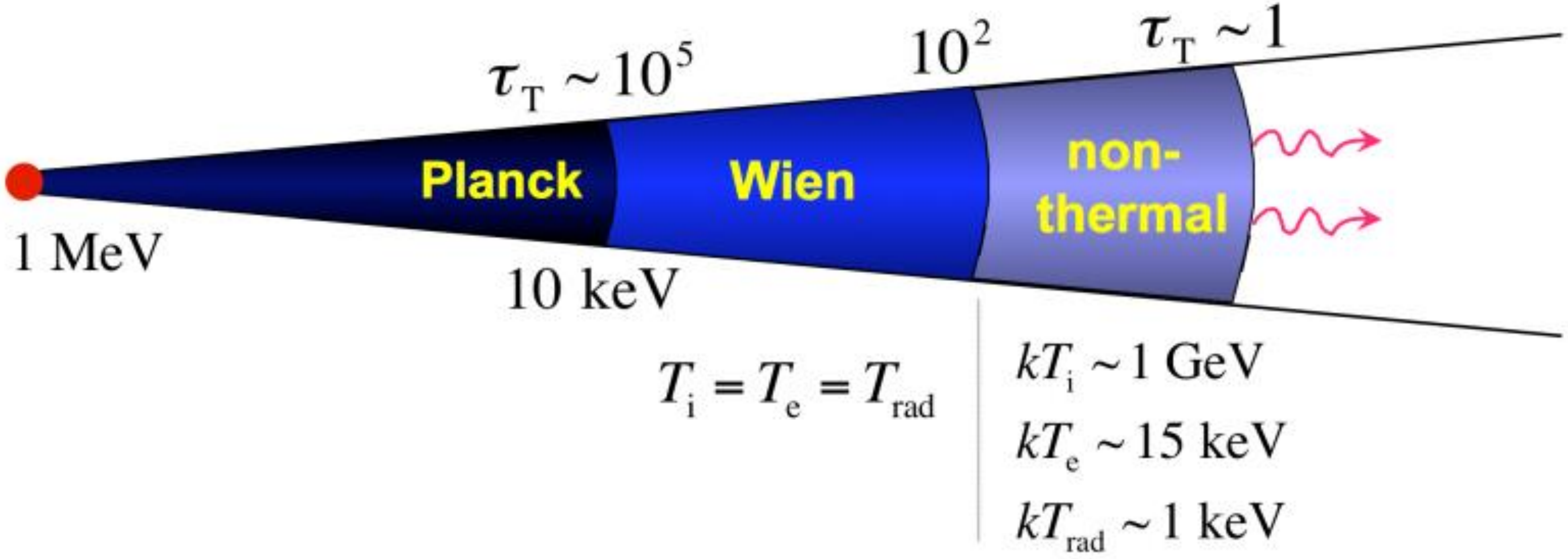


GRB PROPERTIES... LONG STORY SHORT!

- GRB model requirements
  - Cosmological distances – measured via optical band observations, they require very energetic models
  - Relativistic expansion – very energetic models if not extended in volume pose compactness issue e.g. optical depth for $\gamma\gamma \rightarrow e^+e^-$ process
  - To resolve that relativistic expansion with Lorenz factor $\Gamma > 100$ is invoked
- Particle acceleration – active and open topic in GRB modelling
  - Fermi processes of first and second order, magnetic reconnection, monopolar inductor, betatron acceleration etc… (maybe a sperate talk later)
- Thermal and non thermal radiation processes
  - Blackbody, Comptonised black body, Synchrotron, Inverse Compton…

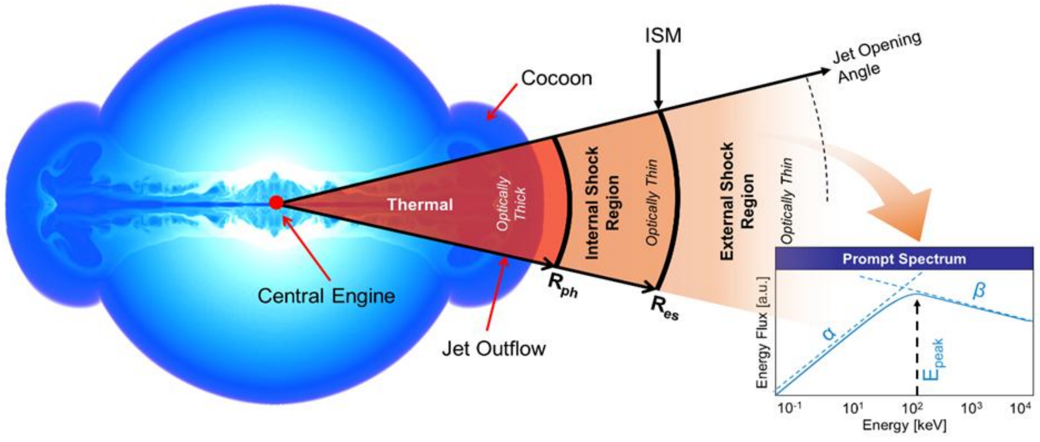
GRB MODEL SUPERMARKET

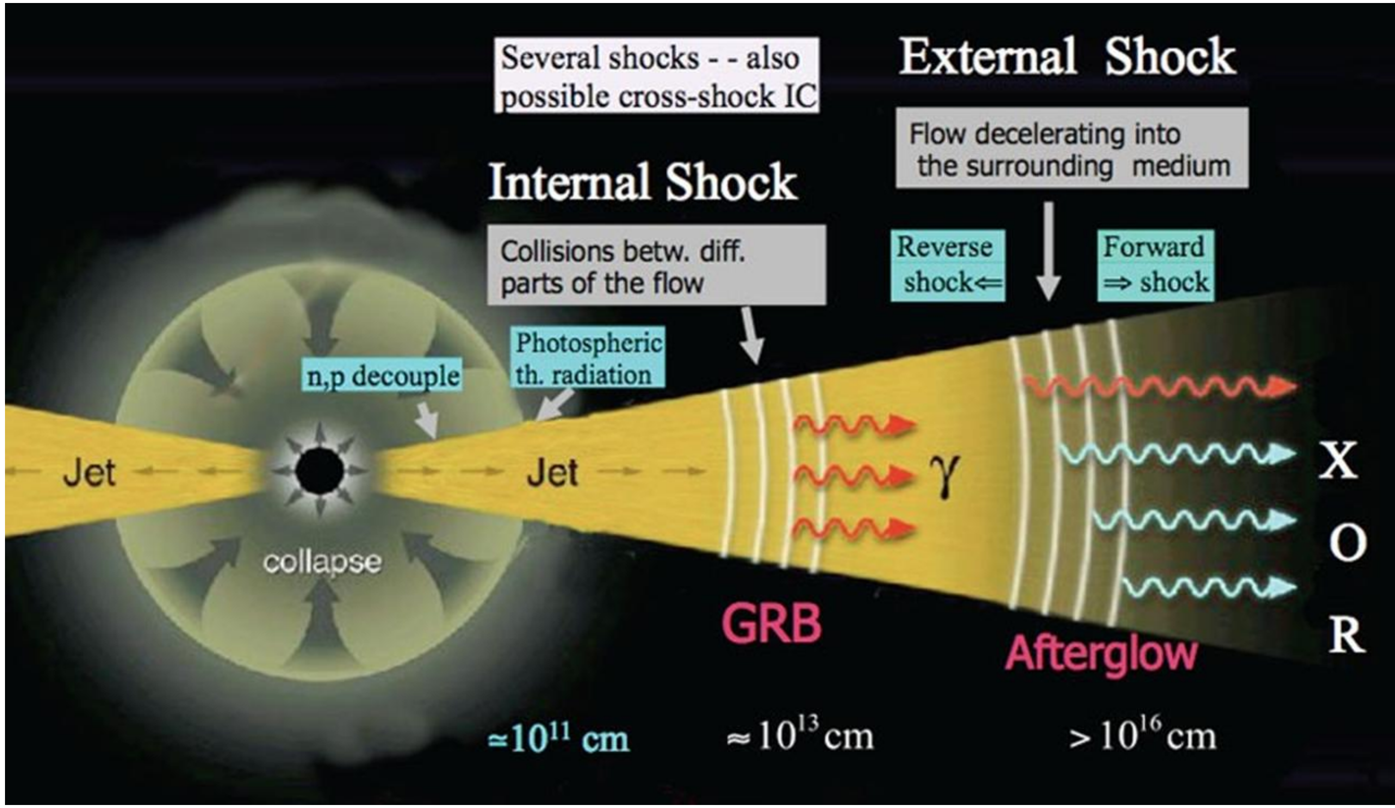
- Photospheric model



GRB MODEL SUPERMARKET

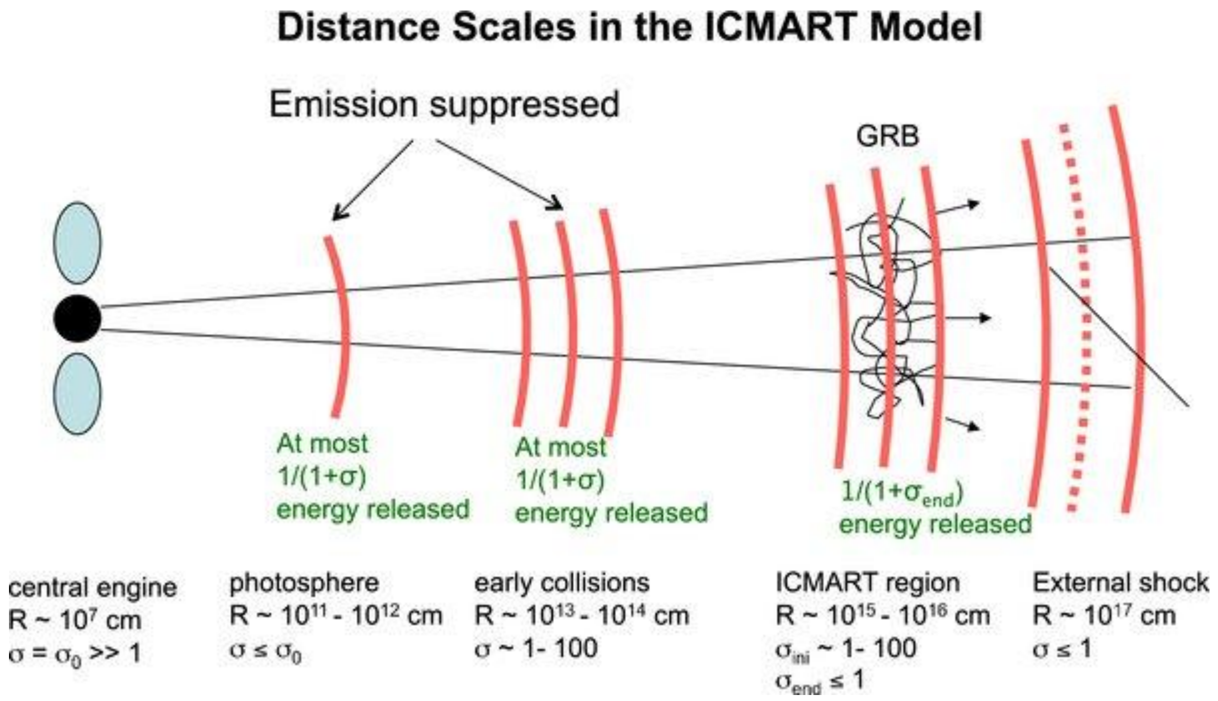
- Fireball model – most popular item in the market



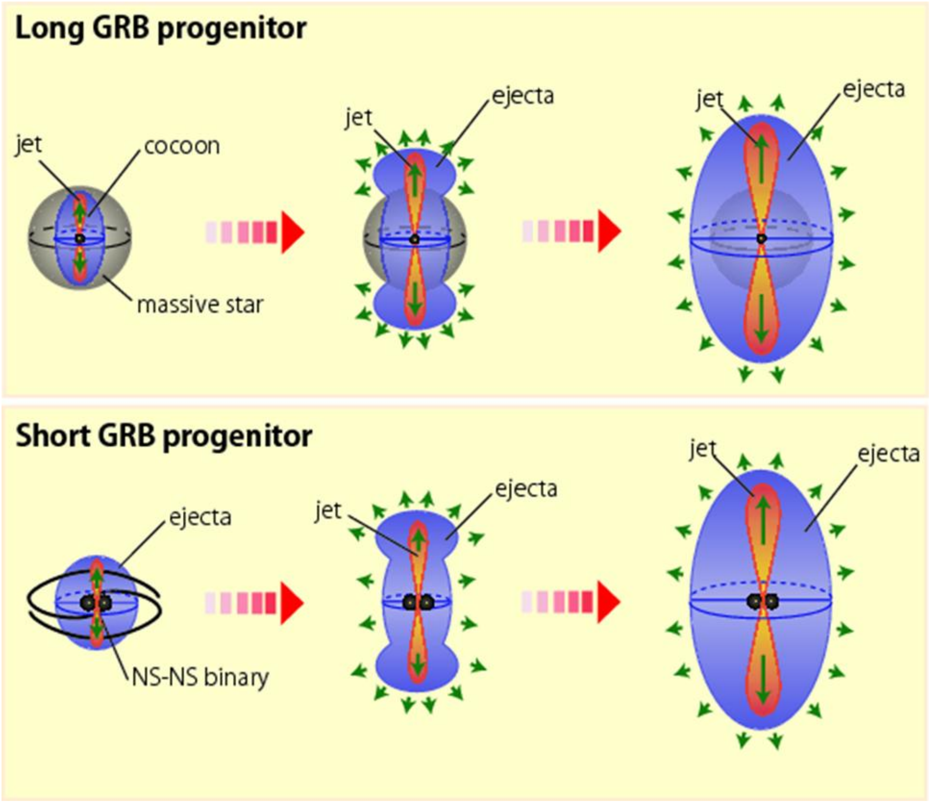


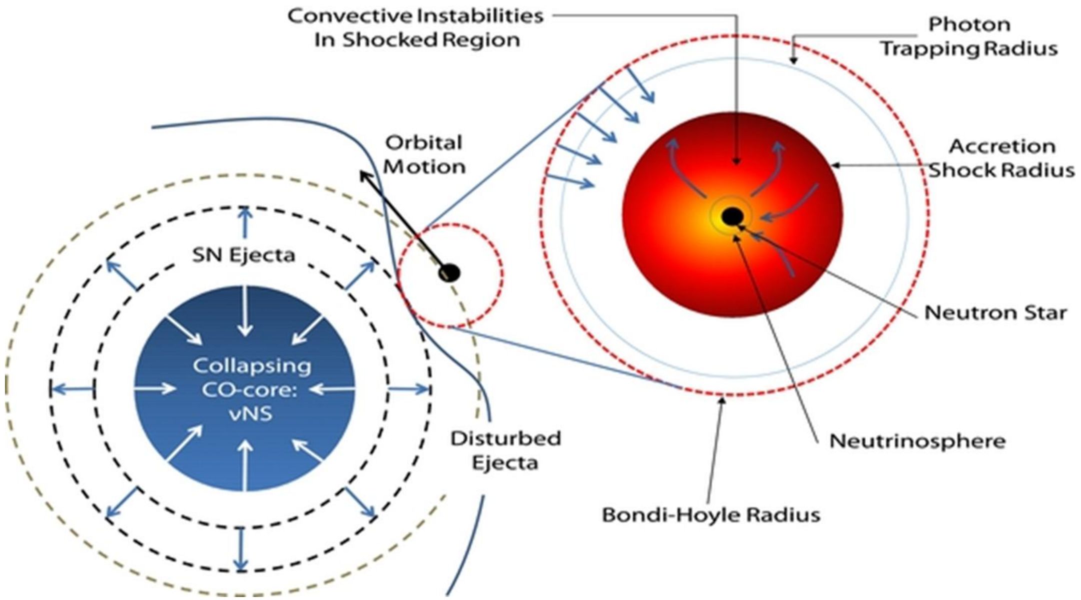
GRB MODEL SUPERMARKET

- ICMART magnetic model



GRB ORIGINS – COLLAPSAR VS. IGC



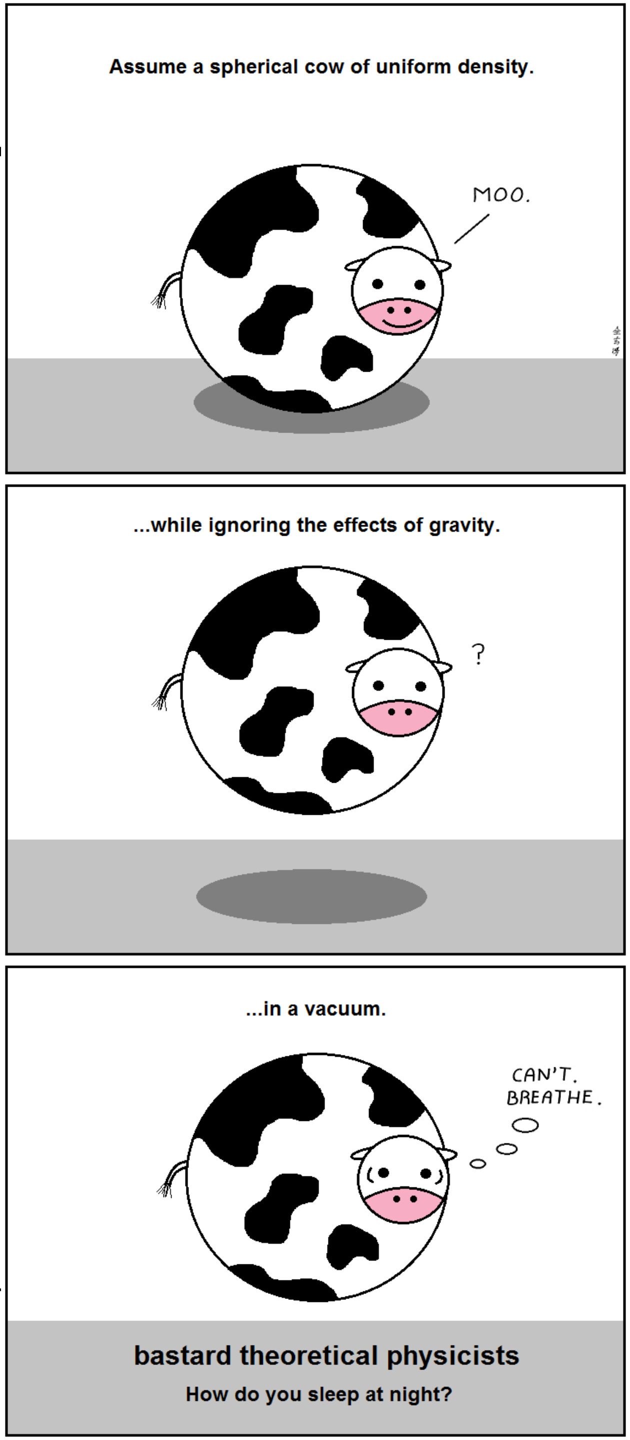


Criterion	Photosphere	Internal shock	ICMART
Lightcurve:			
Slow variability	Yes	Yes	Yes
Fast variability	Yes	Yes	Yes
Superposition	Yes	Yes	Yes
E_p evolution: hard-to-soft	No	Yes(?)	Yes
E_p evolution: tracking	Yes	Yes(?)	Yes(?)
Spectral lags	No	No(?)	Yes
Power density spectrum	Yes	Yes	Yes
Spectra:			
Origin of E_p	Yes	Yes	Yes
$\alpha \sim -1$	Yes(?)	Yes(?)	Yes(?)
$\alpha > -2/3$	Yes	No(?)	No(?)
β	Yes	Yes	Yes

Criterion	Photosphere	Internal shock	ICMART
Spectra:			
Narrowness	Yes	Yes(?)	Yes(?)
E_p distribution	Yes(?)	Yes(?)	Yes(?)
Thermal component	Yes	No	No
High-energy component	No(?)	Yes(?)	Yes(?)
Other:			
γ-ray radiative efficiency	Yes	Yes(?)	Yes
γ-ray polarization	Yes(?)	Yes(?)	Yes
Optical polarization	No(?)	No(?)	Yes
Neutrino upper limit	No(?)	No(?)	Yes
Three-parameter correlations	No(?)	No(?)	Yes(?)
Narrowness	Yes	Yes(?)	Yes(?)
E_p distribution	Yes(?)	Yes(?)	Yes(?)

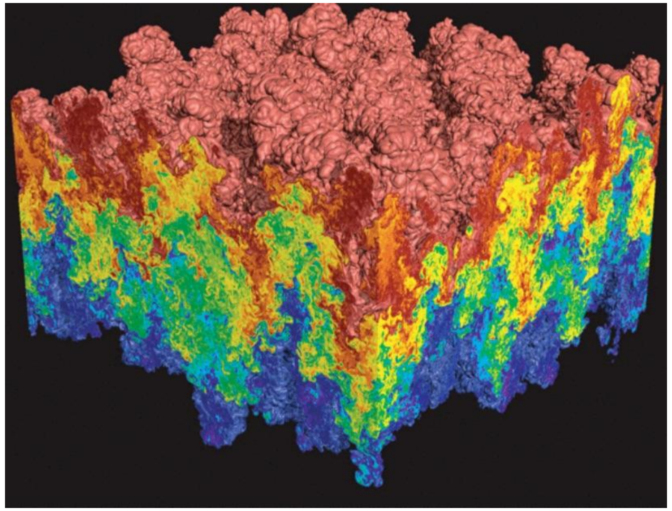
ART OF APPROXIMATIONS?

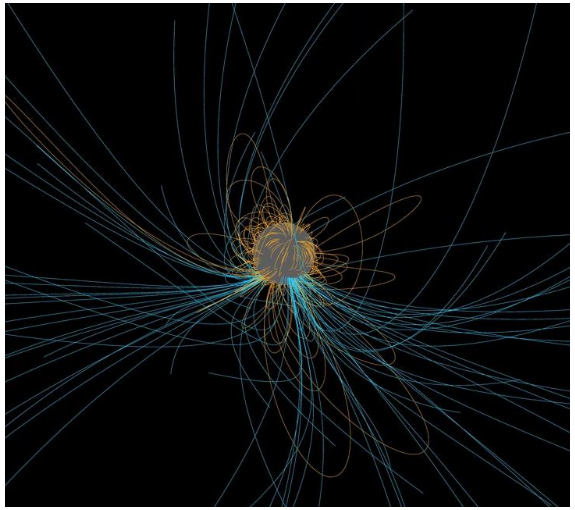
- Each model to accommodate observations adds additional levels of complexity, whether it is acceleration mechanisms invoked, structure of the relativistic outflow, details of magnetic field evolution etc.
- To the knowledge of the author none of the models addresses the issue of the nonhomogeneous nature of magnetic fields and its signature on the non thermal synchrotron emission.
- NAR (Nonhomogeneous Astrophysical Radiators) Model
- PRELIMINARY RESULTS – WORK IN PROGRESS



ART OF APPROXIMATIONS?

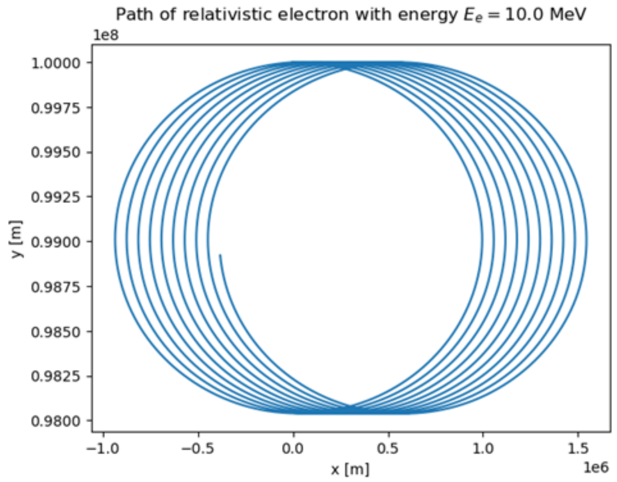
- Common assumptions when modelling GRB emission spectra
  - Emitter and accelerator are separate, and emitter is way greater than the accelerator
  - Magnetic field of the emitter (whether it is homogeneous or chaotic) is of singular value
- Both observational and theoretical experience points toward nonhomogeneous magnetic fields

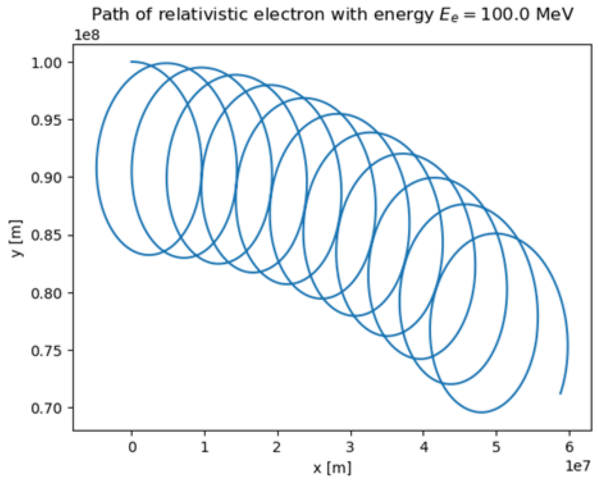


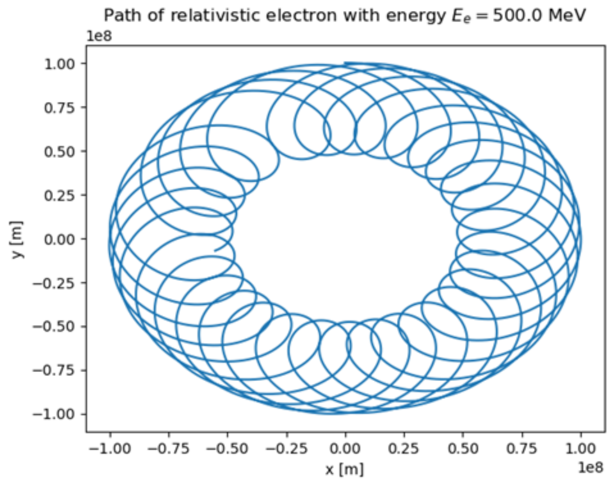


ART OF APPROXIMATIONS?

- Are assumptions for the standard derivation of synchrotron radiation universally valid?
- Scaling factor $\delta = \lambda_B \gamma / r_L$ – synchrotron ($\delta \gg 1$) vs. "jitter" ($\delta \ll 1$) radiation
- Assumptions used in standard derivation of synchrotron emissivity are still valid at low energies of relativistic charged particles. For that it seems synchrotron radiation in radio and optical band can be promising to scan the structure of emitter's magnetic field.







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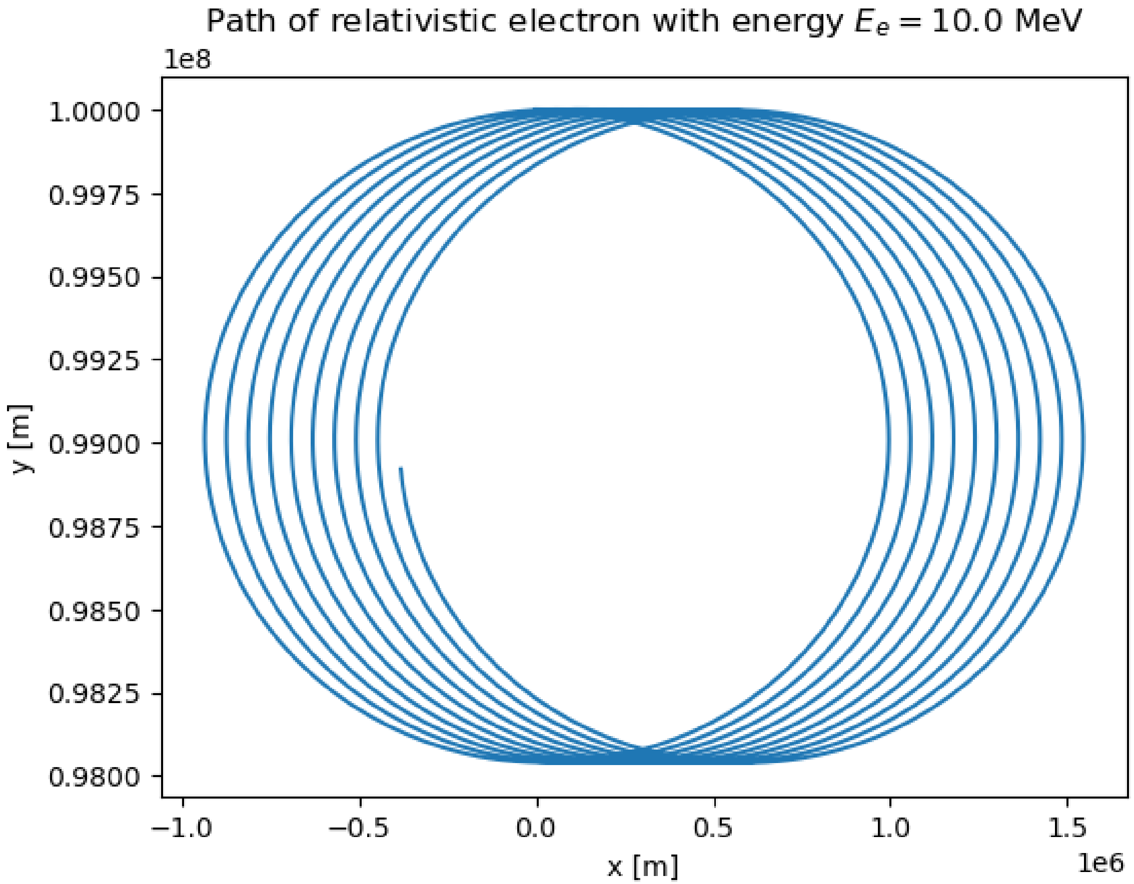

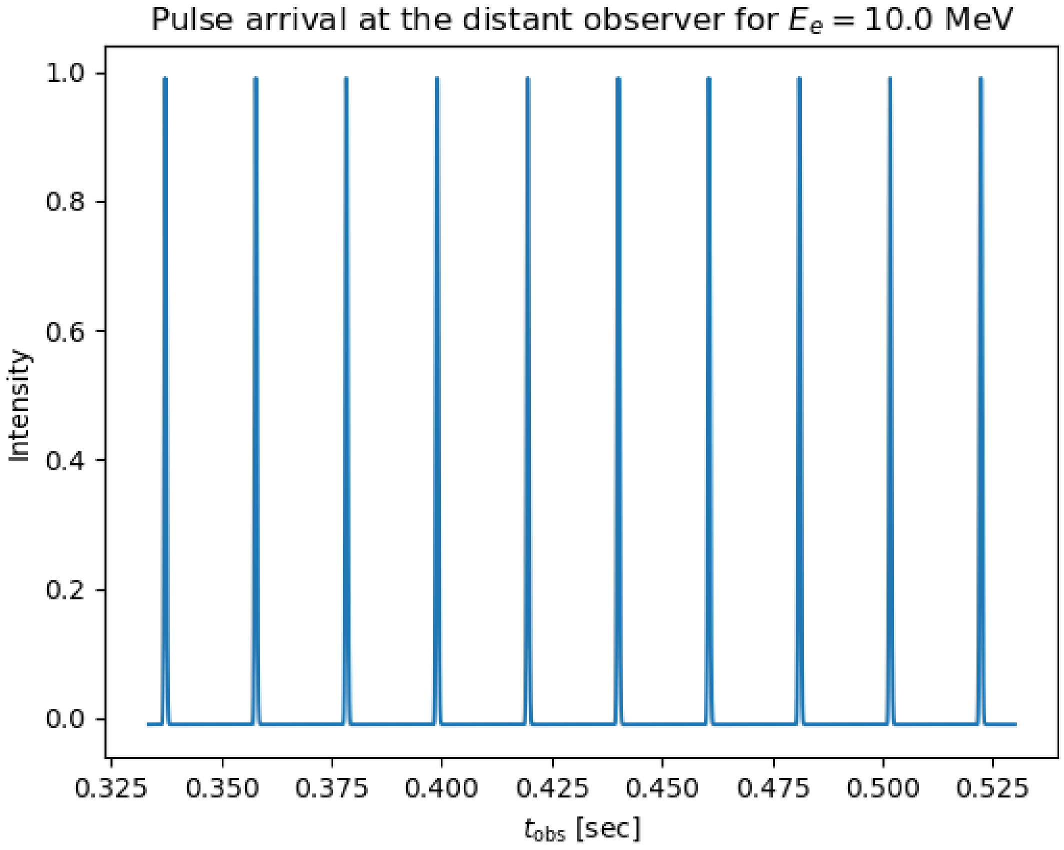

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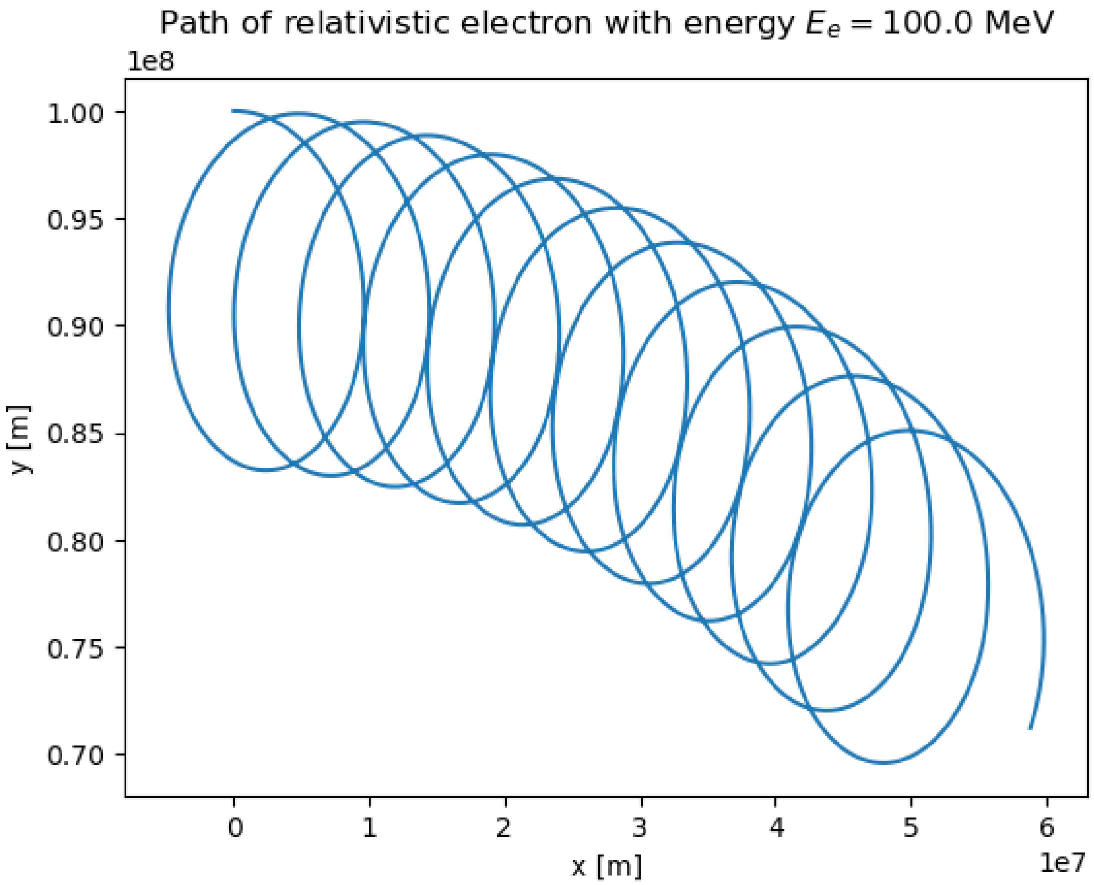

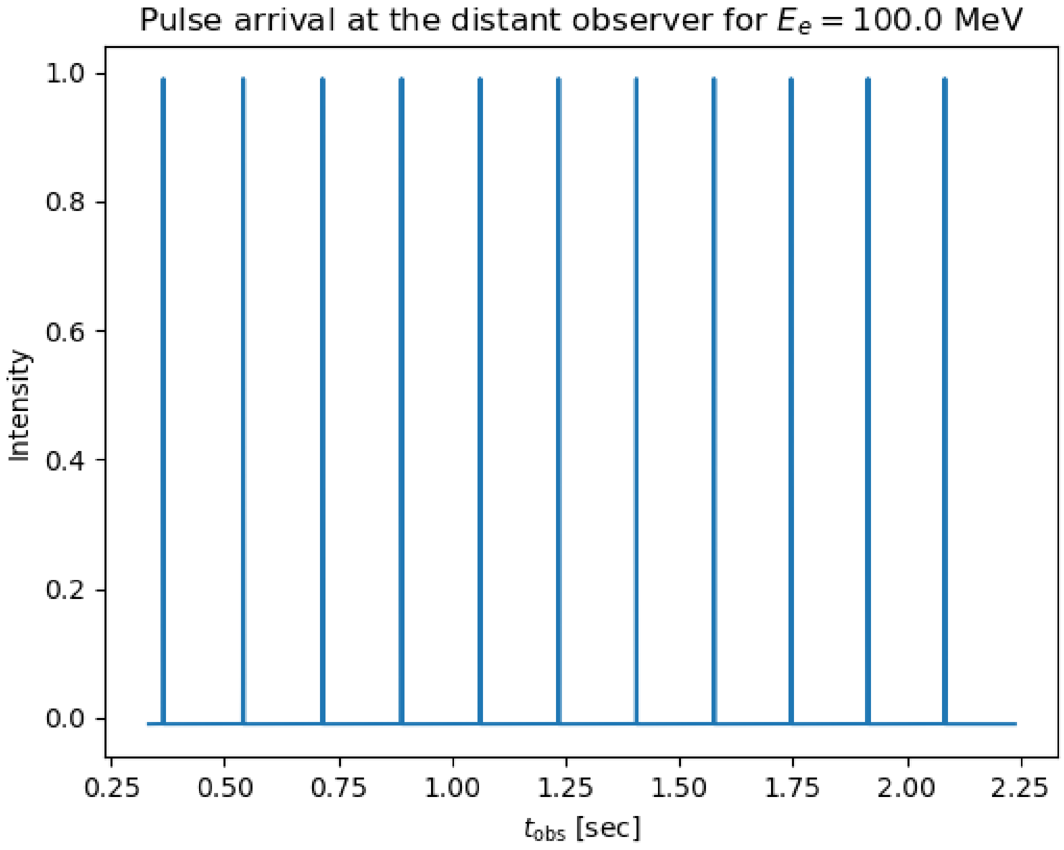

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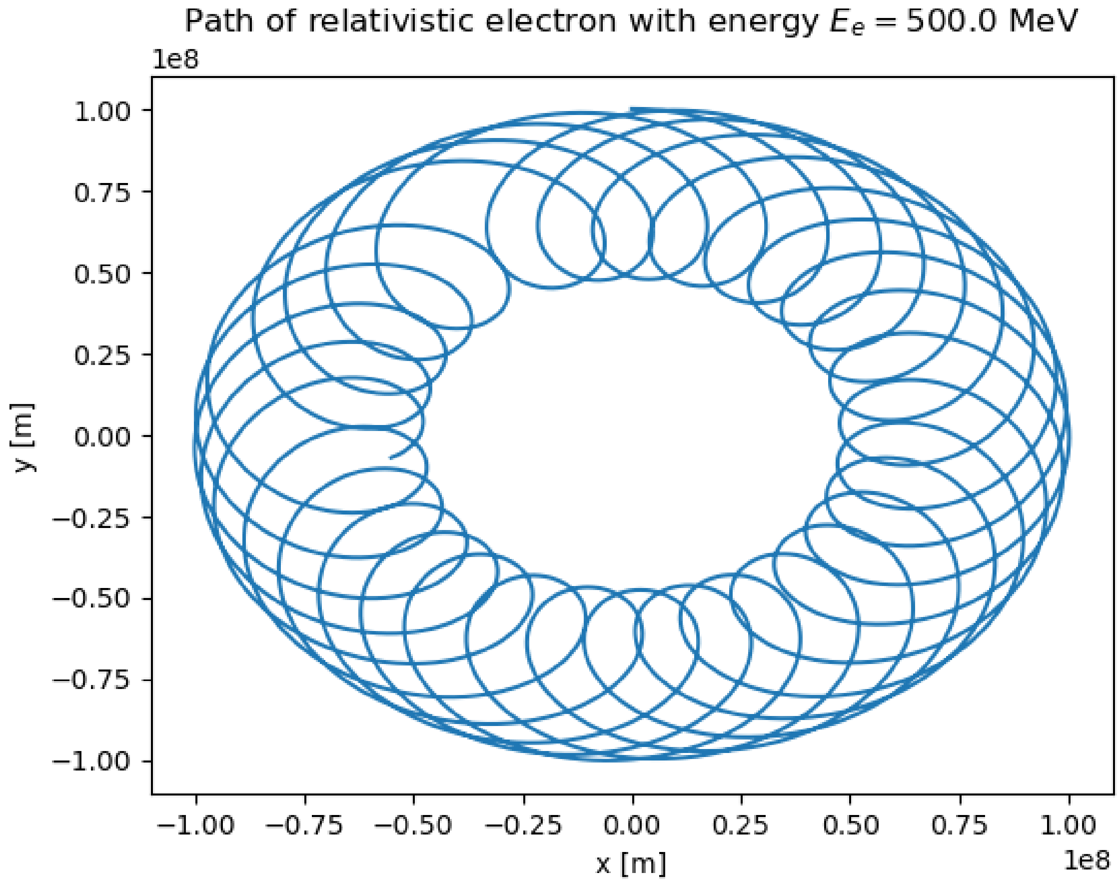
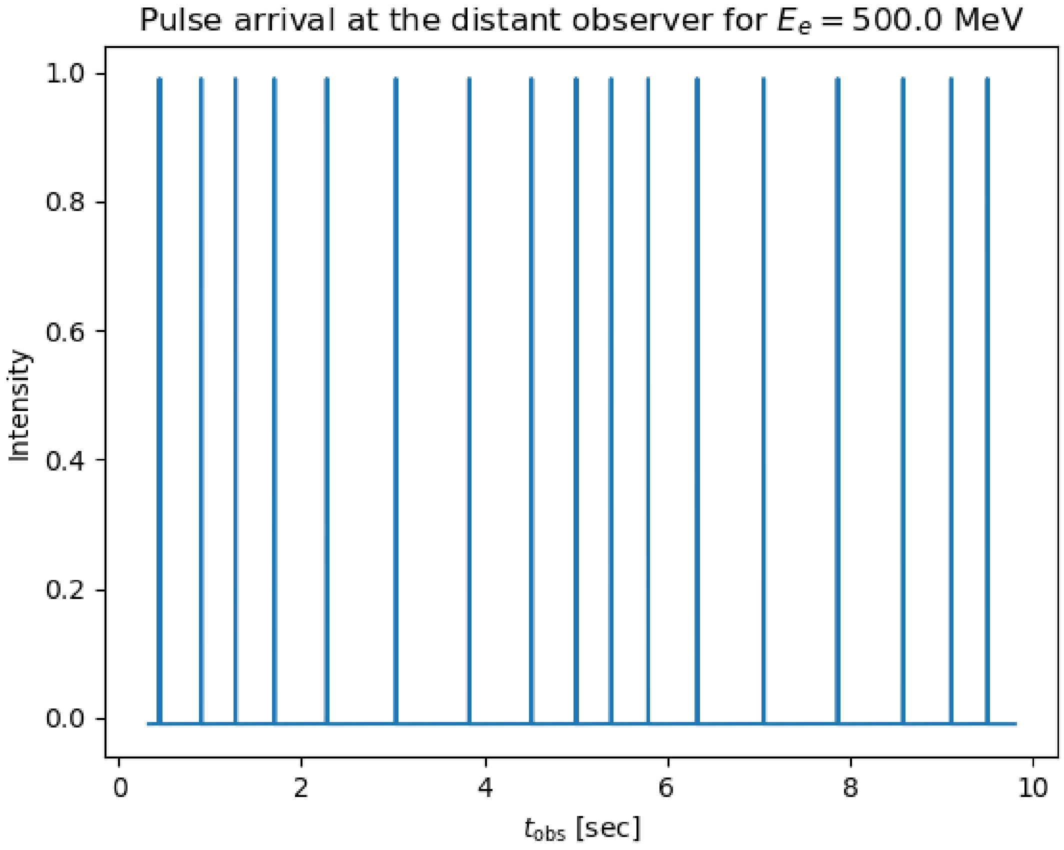




ART OF APPROXIMATIONS?

- For simplicity let us for now hold onto standard synchrotron derivation as presented in standard literature. This is valid for low energy charged particles emitting from non-homogeneous magnetic field.

$$F_\nu = \int_V \int_{E_{\min}}^{E_{\max}} P(\nu, E, B(\vec{r}))\, n(E, \vec{r})\, dB\, d^3r$$

- For start we will address the regular non-homogeneous magnetic fields (since chaotic magnetic fields have additional level of complexity) in which particle energy distribution can be presented zonally as a function of magnetic field's strength.

$$F_\nu = \int_{B_{\min}}^{B_{\max}} \int_{E_{\min}}^{E_{\max}} P(\nu, E, B)\, \mathcal{P}(B)\, n(E, B)\, dE\, dB$$

ART OF APPROXIMATIONS?

- Proper calculation of synchrotron flux, even with this crude approximations, would require the solution of diffusion-loss equation – additional crude approximation in which our emitter is non-homogeneous, regular and small. In this case it is safe to assume uniform energy distribution of relativistic charged particles within a non-homogeneous magnetic field.

$$F_\nu \approx \int_{B_{\mathrm{min}}}^{B_{\mathrm{max}}} \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} P(\nu, E, B)\, \mathcal{P}(B)\, n(E)\, dE\, dB$$

- Take note, even this approach is very simplified!!!

- For our emitter we take an n-sphere of dimensionality n ≤ 3 with volume:

$$V_n = \frac{\pi^{n/2}}{\Gamma(n/2+1)}\, r^n$$

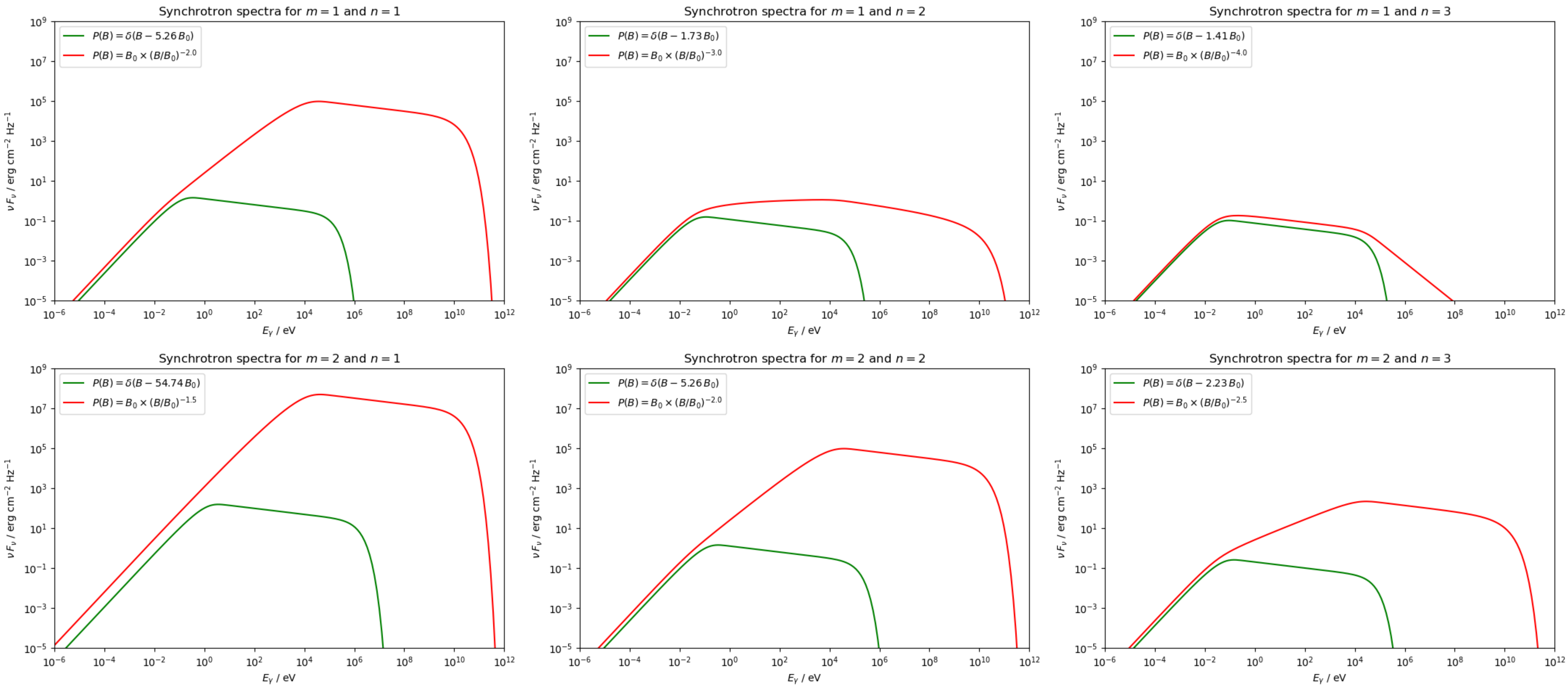
- For our magnetic field structure, we take centrally symmetric regular structure given by:

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^{-m}$$

- From this assumption our magnetic field distribution function is given by:

$$\mathcal{P}(B) = -\frac{dV}{dB} = \frac{\pi^{n/2} r_0^n}{m\,\Gamma(n/2+1)} \left(\frac{B}{B_0}\right)^{-(m+n)/m}$$

- In our preliminary analysis, using this crude approximation, we used electron energy distribution given by $n(E) = K_0\, E^{-3.3}$



Synchrotron spectra for $m = 1$ and $n = 1$
$P(B) = \delta(B - 5.26\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-2.0}$
Synchrotron spectra for $m = 1$ and $n = 2$
$P(B) = \delta(B - 1.73\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-3.0}$
Synchrotron spectra for $m = 1$ and $n = 3$
$P(B) = \delta(B - 1.41\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-4.0}$
Synchrotron spectra for $m = 2$ and $n = 1$
$P(B) = \delta(B - 54.74\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-1.5}$
Synchrotron spectra for $m = 2$ and $n = 2$
$P(B) = \delta(B - 5.26\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-2.0}$
Synchrotron spectra for $m = 2$ and $n = 3$
$P(B) = \delta(B - 2.23\,B_0)$
$P(B) = B_0 \times (B/B_0)^{-2.5}$
νF_ν / erg cm^{-2} Hz^{-1}
E_γ / eV

CONCLUSIONS

- Modelling GRB emission, especially of prompt emission is still very open question for discussion.
- For proper modelling we need to know whether our ingredients are applicable to the framework
- Standard synchrotron approach – developed in the frame of Earth laboratories, has been a useful tool in modelling the emission of astrophysical objects. Nevertheless, an update, especially in the case of extended high energy sources is necessary.
- Low energy relativistic charged particles are still well described by standard synchrotron theory and can be used to investigate the structure of astrophysical magnetic fields. Higher energy relativistic charged particles have complex trajectories which require additional theoretical investigation.
- We need to be careful when assigning charged particle injection spectra to the astrophysical source before understanding the magnetic field structure of the source. This is important for understanding of particle acceleration processes which take place and their overall efficiency.

“A METHOD IS MORE IMPORTANT THAN A DISCOVERY, SINCE THE RIGHT METHOD WILL LEAD TO NEW AND EVEN MORE IMPORTANT DISCOVERIES.”

“MOST IMPORTANT PART OF DOING PHYSICS IS THE KNOWLEDGE OF APPROXIMATION.”

- LEV DAVIDOVICH LANDAU (1908 – 1968)