Gamma-Ray Burst Polarization

Theoretical Overview & Current Status

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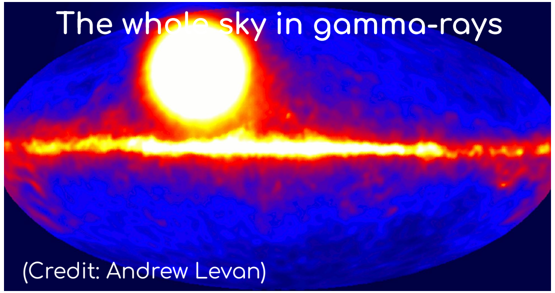
Theory Meeting Experiment: Particle Astrophysics & Cosmology **Quy Nhon** **Jan 07, 2023**

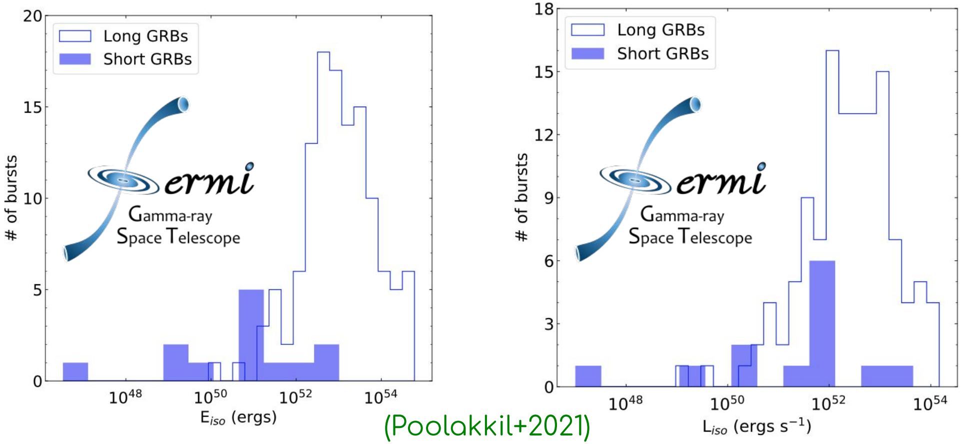
GRBs are bright cosmic beacons



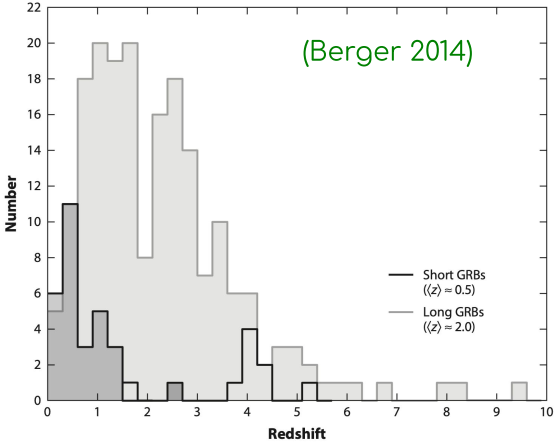
The initial bright ("**prompt**") phase is so intense it can outshine the entire sky in gamma-rays.

The cosmological distances of GRBs makes them excellent probes of **star-formation**, fundamental physics (LIV), **EBL**, etc.

Isotropic-equivalent gamma-ray energy and luminosity

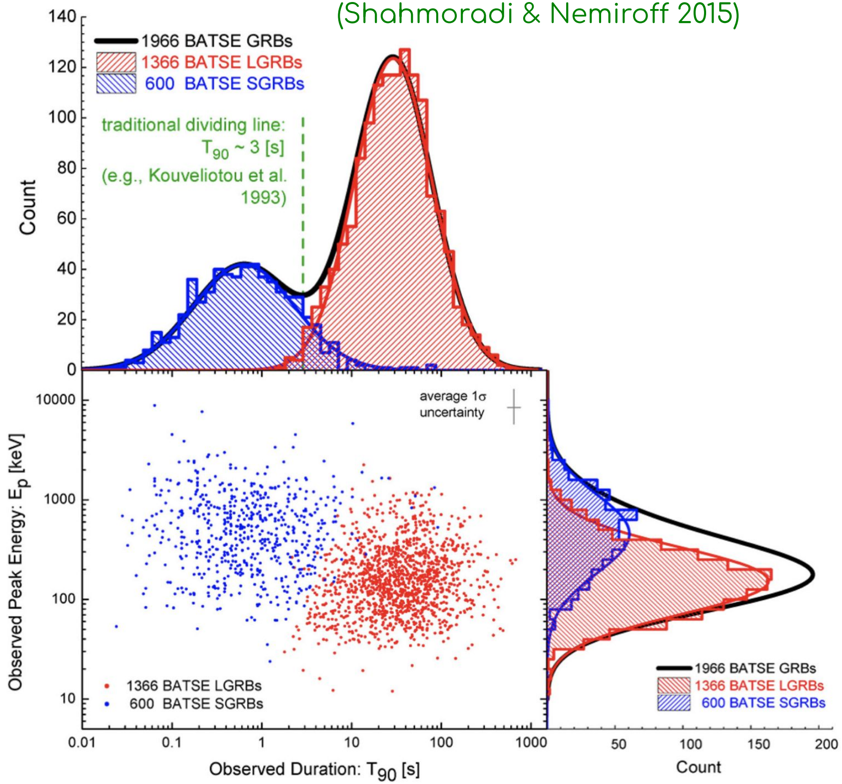


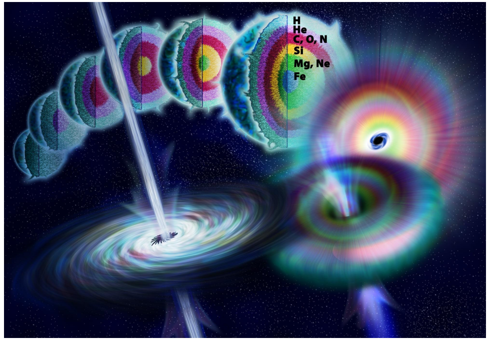
(Poolakkil+2021)



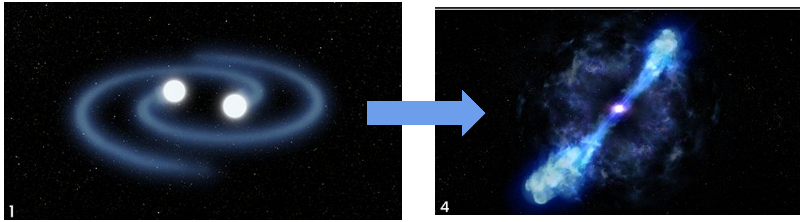
The long and the short

(Shahmoradi & Nemiroff 2015)



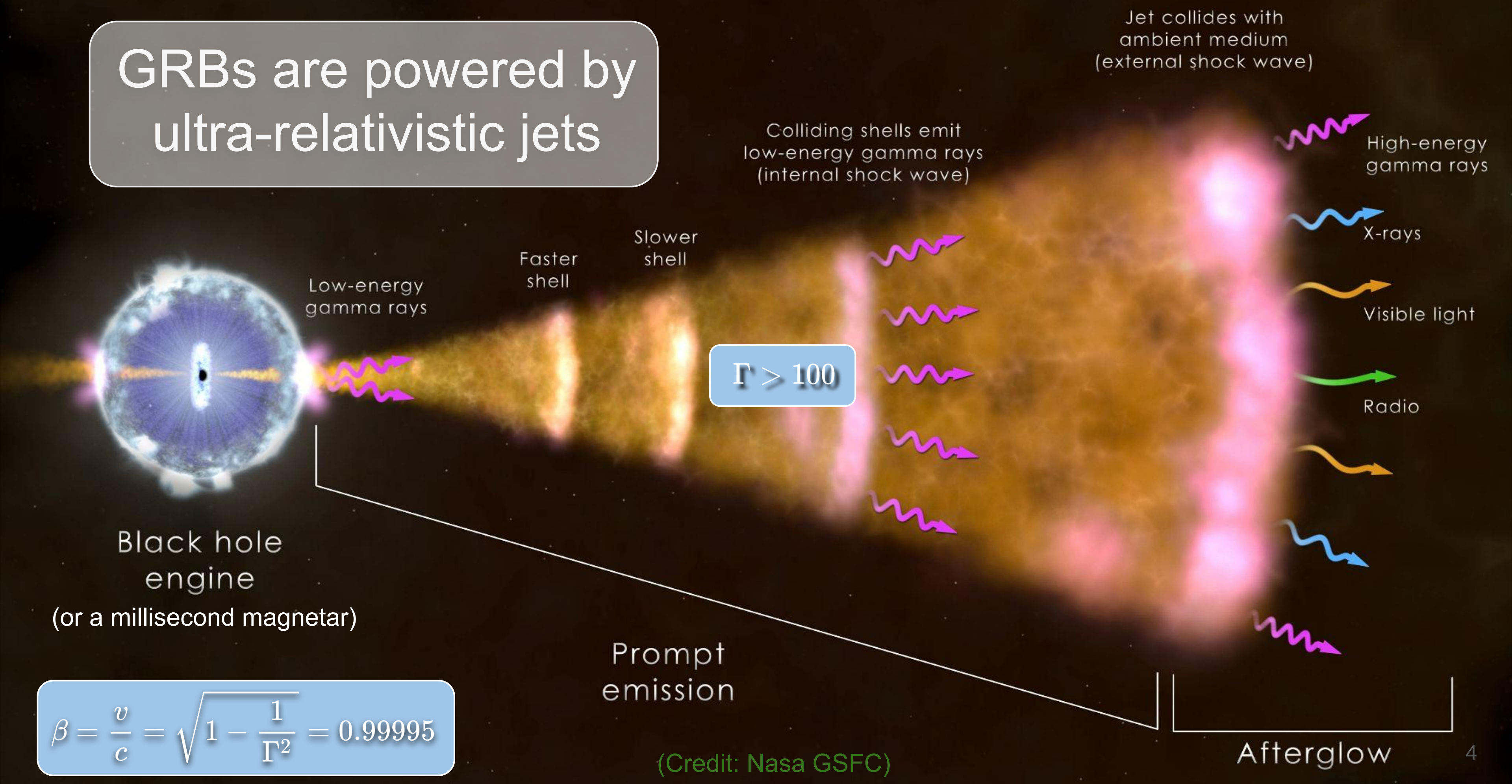


Progenitors of **long-GRBs** are massive Wolf-Rayet star that undergo core-collapse



At least some of the **short-GRBs** are produced by the mergers of two neutron stars **(e.g. GW170817)**

GRBs are powered by ultra-relativistic jets



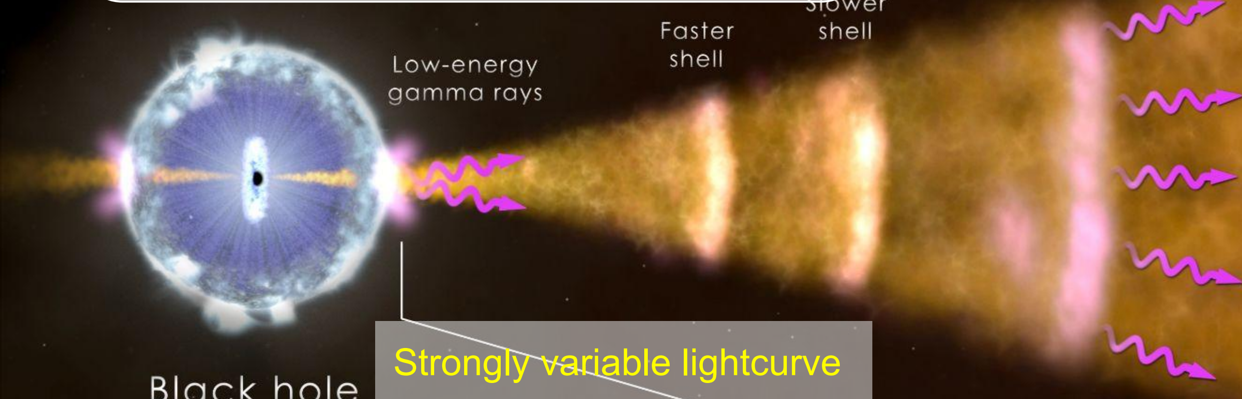
$\Gamma > 100$

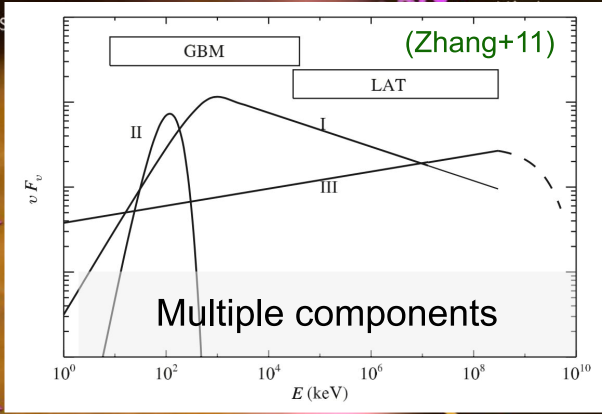
(or a millisecond magnetar)

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\Gamma^2}} = 0.99995$$

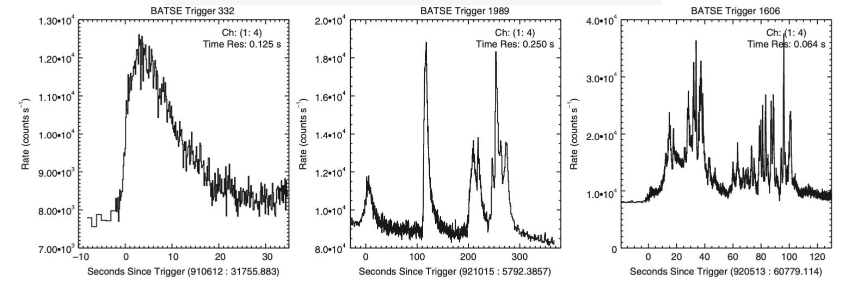
(Credit: Nasa GSFC)

Internal dissipation in the jet produces the short-lived prompt GRB

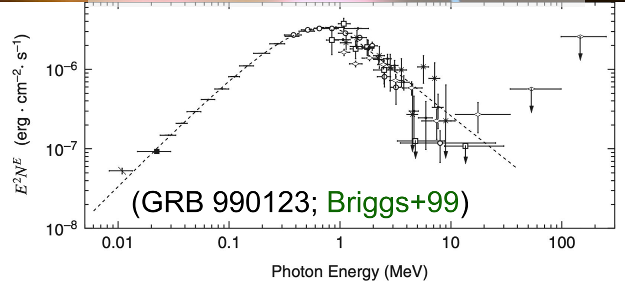




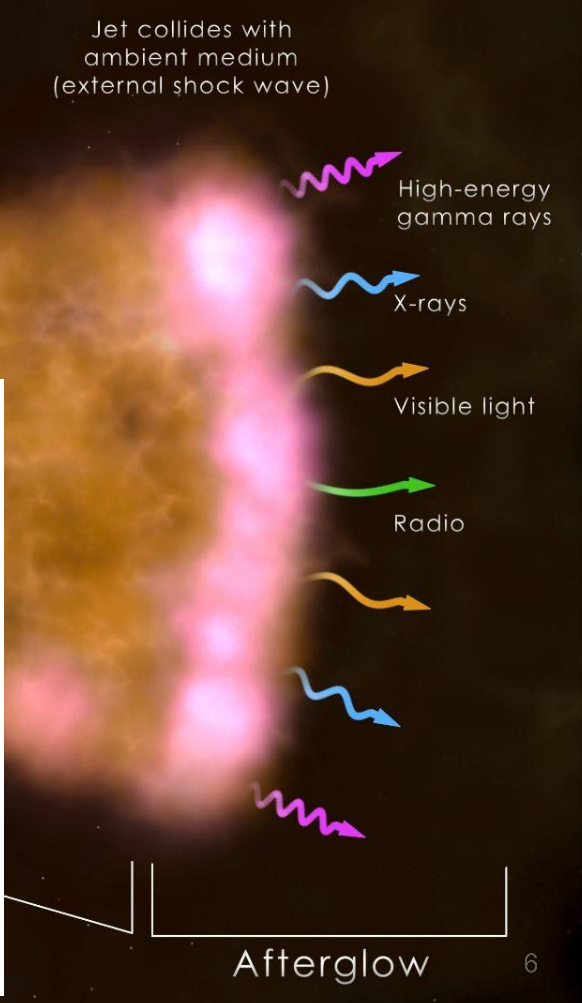
Strongly variable lightcurve

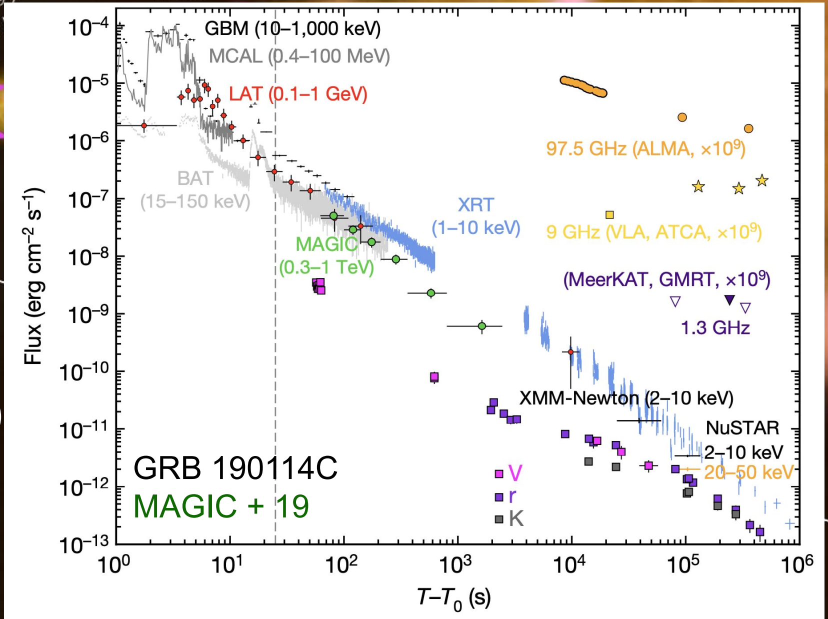


Non-thermal spectrum



Interaction of relativistic jet with surrounding medium produces the long-lived afterglow





What can we learn from prompt GRB polarization?

- Polarization is a very **useful probe of the radiation mechanism** of prompt GRB emission. Two of the main processes are:

  (a) Optically-thin synchrotron (b) Comptonization

- If the radiation mechanism is **synchrotron**, then polarization **can teach us about the configuration of the B-field**, e.g. its anisotropy and coherence length, in the emission region.

- This in turn will yield important clues for the composition of the flow:

  - **Kinetic-energy dominated**: B-field is generated in-situ as in internal shocks and has coherence length on the order of skin-depth scales

  - **Poynting-flux dominated**: B-field tends to be more ordered with large coherence length

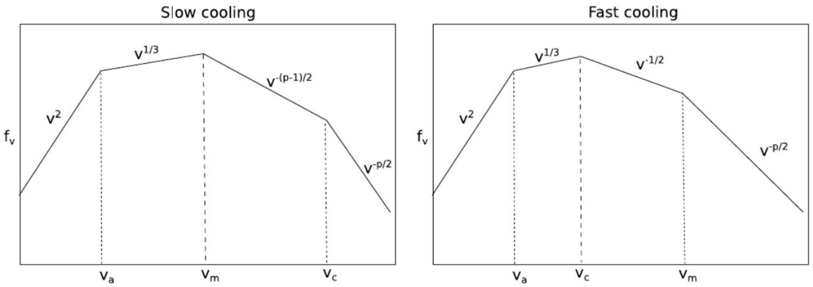
- Once the radiation mechanism is known, polarization **can help to constrain the outflow structure and viewing geometry**.

Synchrotron Emission

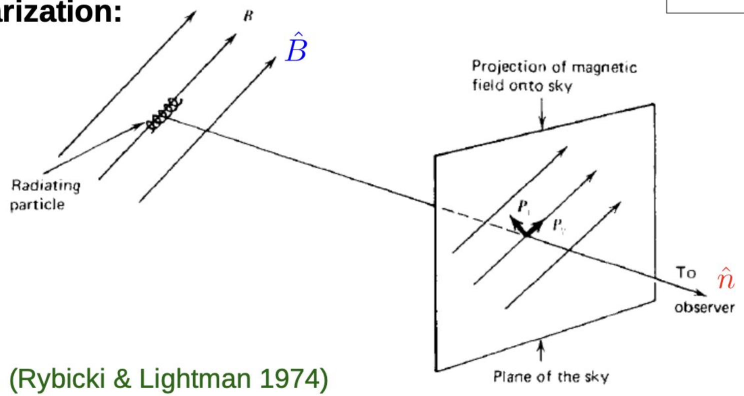
Relativistic charged particles gyrate around B-field lines and cool by emitting synchrotron photons

If the energy distribution follows are power law, $n_e(\gamma) \propto \gamma^{-p}$ $\gamma_m \leq \gamma \leq \gamma_M$,then the synchrotron spectrum is well known (Sari+98; Granot & Sari '02)

$$F_\nu \propto \nu^{-\alpha}$$



Polarization:



(Rybicki & Lightman 1974)

Synchrotron emission is generally partially linearly polarized:

$$\hat{\Pi} = \hat{n} \times \hat{B}$$

$$\Pi_{\max} = \frac{\alpha + 1}{\alpha + 5/3} \qquad 0.5 \leq \Pi_{\max} \leq 0.75$$

Magnetic field structure

4 types of physically motivated B-field configurations

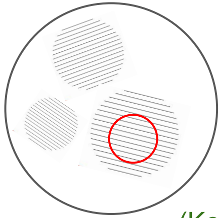
$B_{\rm ord}$: ordered field within a radiating patch with coherence length larger than the beaming cone: $1/\Gamma \leq \theta_B \ll \theta_j$ (Granot '03)

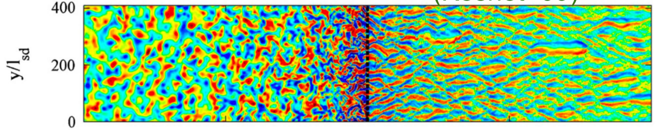
$B_{\perp}$: small-scale ($\Gamma\theta_B \ll 1$) field generated by streaming instabilities. It is confined completely in the plane transverse to the shock normal (radial with no lateral expansion). (Medvedev & Loeb '99; Gruzinov '99; Sari '99; Granot & Konigle '03)

$B_{\parallel}$: ordered field aligned along the local velocity vector of the outflow (Gruzinov '99; Sari '99; Granot & Konigle '03)

$B_{\rm tor}$: globally ordered toroidal field symmetric around the jet axis (naturally arises in a high-magnetization outflow) (Lyutikov+03; Granot & Taylor '05)

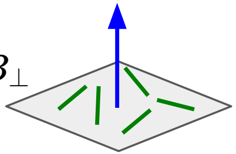
$B_{\rm ord}$



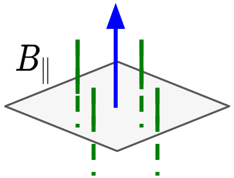


(Keshet+09)

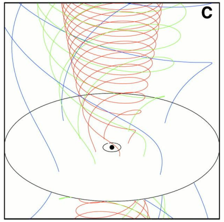
$B_{\perp}$



$B_{\parallel}$



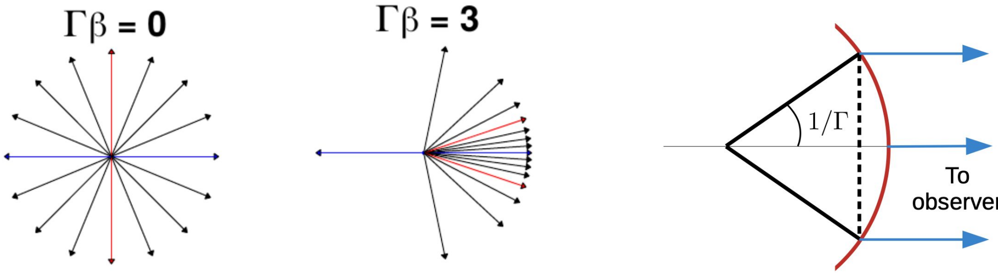
$B_{\rm tor}$



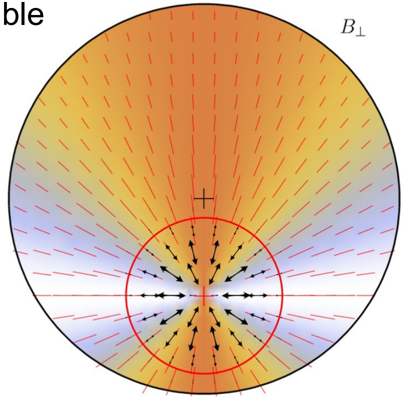
(Meier+01)

Polarization from B$_\perp$ in a uniform (top-hat) jet

In a relativistic flow, aberration of light causes only a small region of angular size $1/\Gamma$ to be visible



(Granot & Ramirez-Ruiz '11)



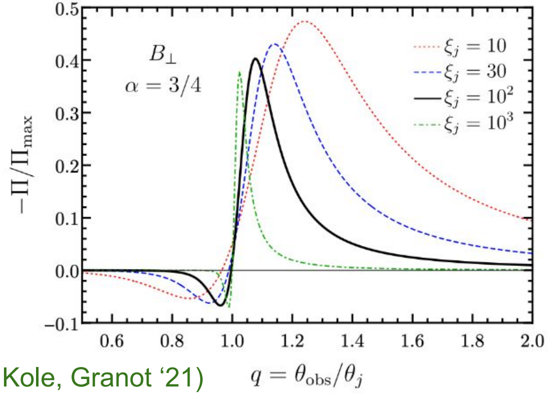
At viewing angles away from the **top-hat jet** edge

$$\theta_{\rm obs} < \theta_j - \Gamma^{-1}$$

the polarization vanishes due to complete symmetry of the polarization vectors around the LOS.

This symmetry is broken when the beaming cone starts to move outside the edge of the jet, causing the polarization angle to swing by

$$\Delta\theta_p = 90^\circ$$

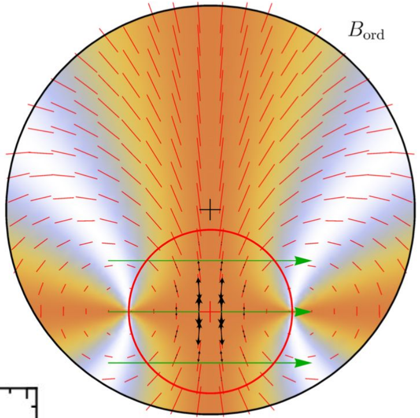


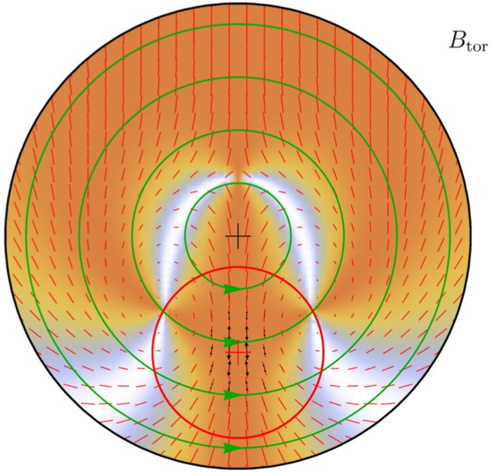
(Gill, Kole, Granot '21)

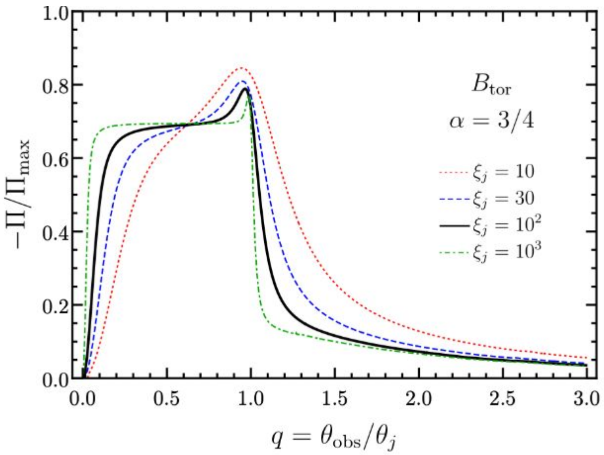
Π from ordered field - Breaking the symmetry

A large scale ordered B-field breaks the symmetry and produces higher levels of polarization.

A similar effect is obtained when the field is globally ordered, e.g. in a toroidal field.

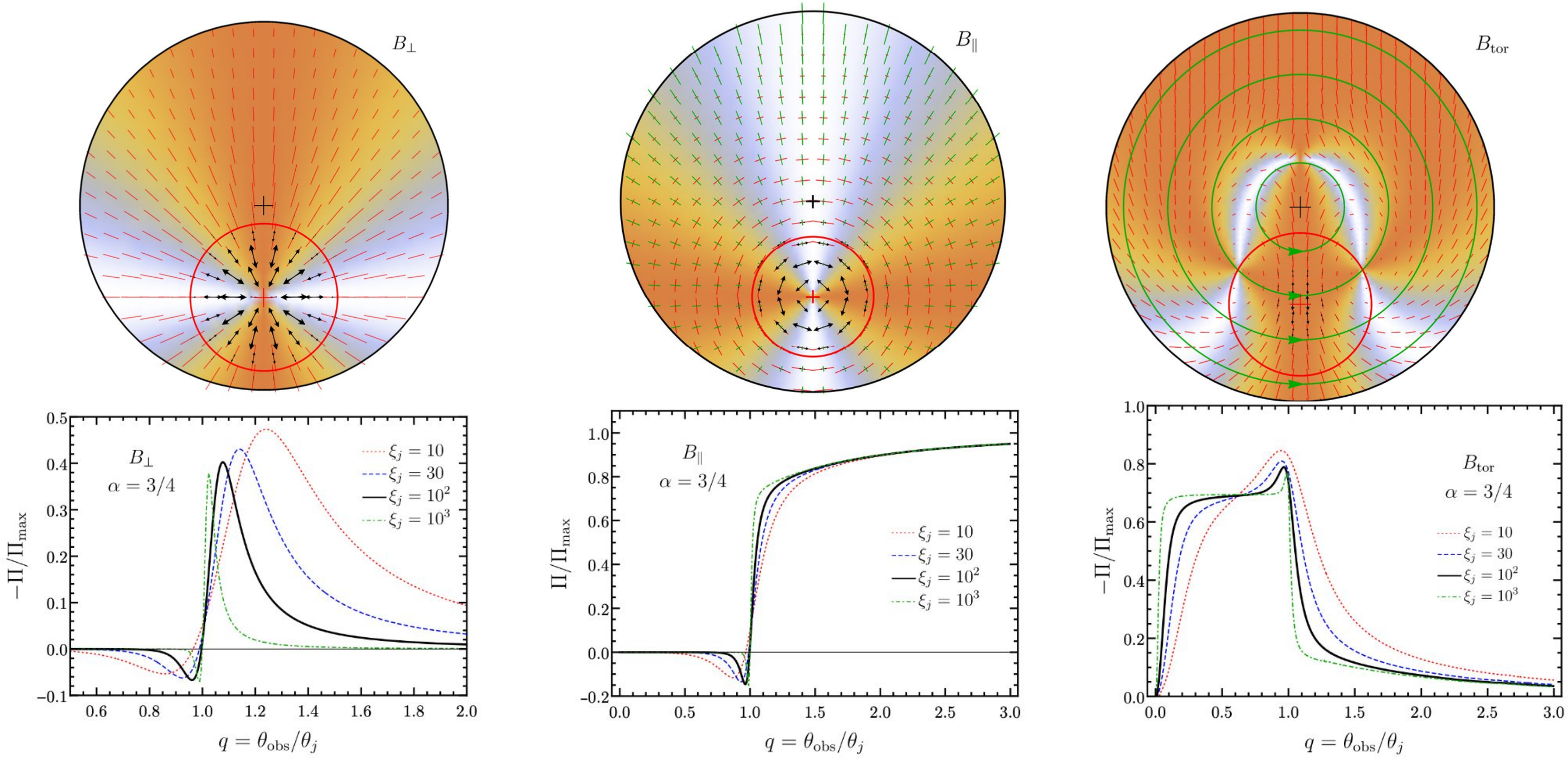






(Gill, Kole, Granot '21)

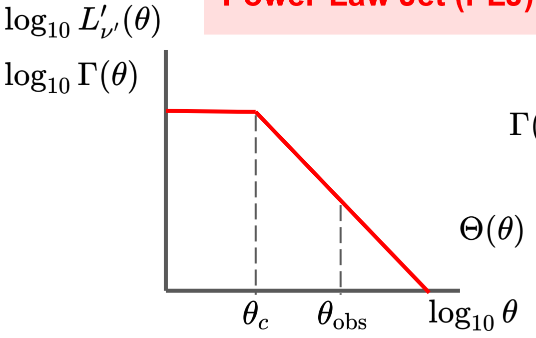
Time-integrated synchrotron polarization



(Granot ‘03; Granot & Taylor ‘05; Gill, Granot, Kumar ‘20)

Angular structure - another way to break symmetry!

Power-Law Jet (PLJ)



$$L'_{\nu'}(\theta) \propto \Theta^{-a}$$

$$\Gamma(\theta) - 1 \propto \Theta^{-b}$$

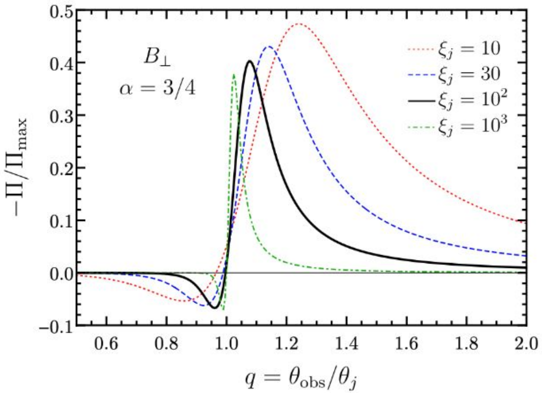
$$\Theta(\theta) = \sqrt{1 + \left(\frac{\theta}{\theta_c}\right)^2}$$

The symmetry is broken by different weight given to emission arising from different regions due to the jet angular structure.

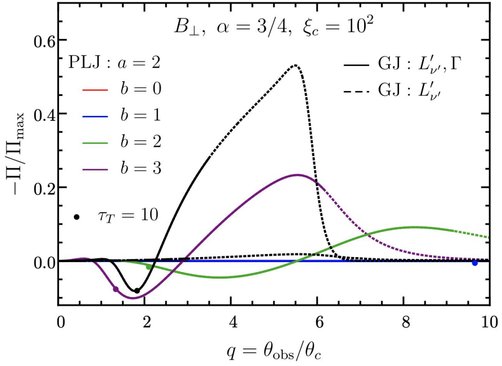
Gaussian Jet (GJ)

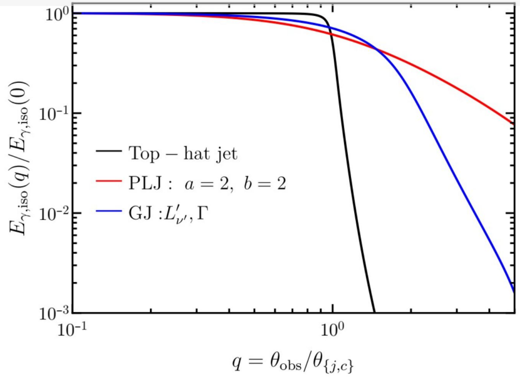
$$L'_{\nu'}(\theta) \propto \Gamma(\theta) - 1 \propto \exp\left(-\frac{\theta^2}{2\theta_c^2}\right)$$

Less fluence suppression in structured jets at large angles



(Gill, Granot, Kumar '20)





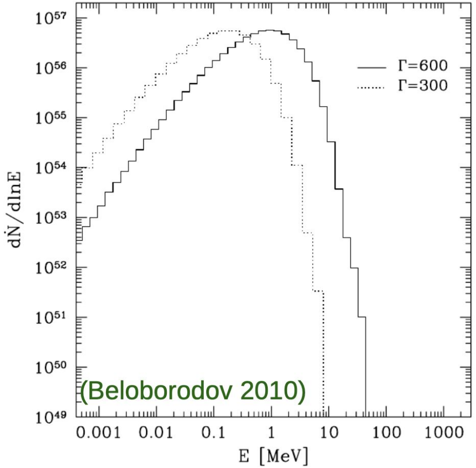
Photospheric emission

Adiabatically cooled thermal radiation is released at the photosphere (Goodman 86; Paczynski 86)

Dissipation above and below the photosphere produces the observed non-thermal prompt GRB spectrum (Thompson 94; Eichler & Levinson 00; Meszaros & Rees 05; Lazzati+09; Peer & Ryde 11; Thompson & Gill 14; Gill & Thompson 14; Vurm & Beloborodov 16; Gill+20; …)

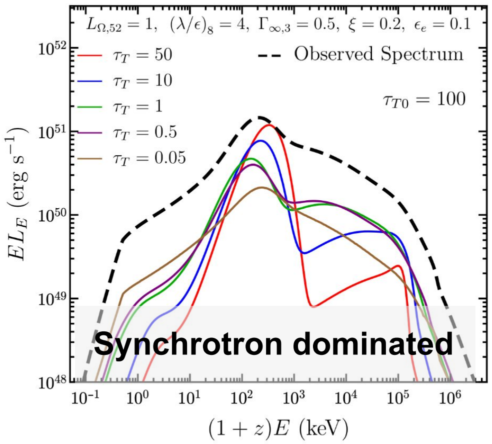
A heated flow with synchrotron dominated spectrum will show energy dependent polarization in a uniform jet.

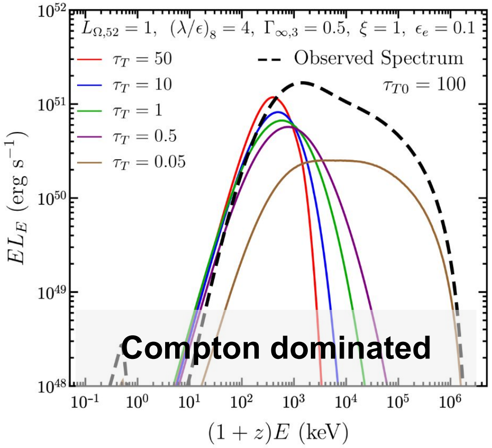
Non-dissipative outflow



Heated outflow

Gill, Granot, Beniamini '20



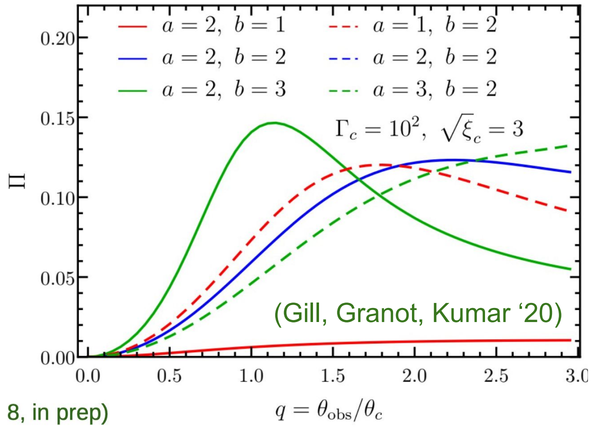


Π for non-dissipative photospheric emission

Polarization can be calculated from the equations of radiative transfer of the Stokes parameters in the comoving frame (Beloborodov '10)

Integration over the observed surface then gives the net polarization:

$$\Pi = \frac{Q}{I} = \frac{\int \delta_D^4 Q'(r_{\rm ph}, \mu) dS_\perp}{\int \delta_D^4 I'(r_{\rm ph}, \mu) dS_\perp}$$



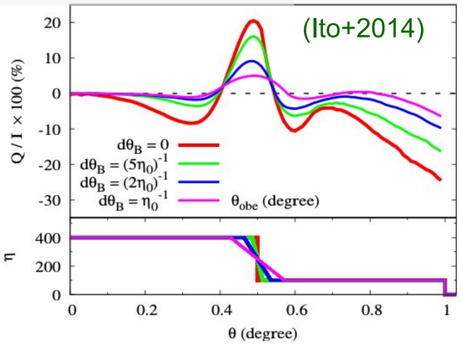
8, in prep)

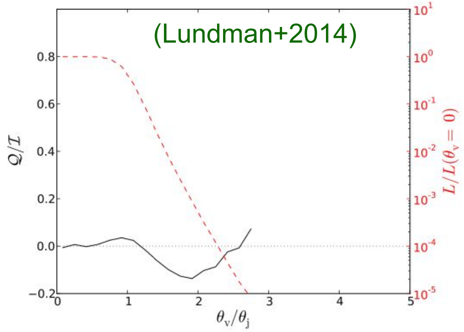
Polarization up to ~15% can be obtained only in jets with steep angular structures.

Uniform jets will give zero net polarization.

Monte Carlo simulations of photospheric emission with steep angular jet structure find similar results (also see Parsotan+20).

They also find 90-deg change in PA





Theory Vs Observations

Polarization measurements of gamma-ray photons is still very challenging!

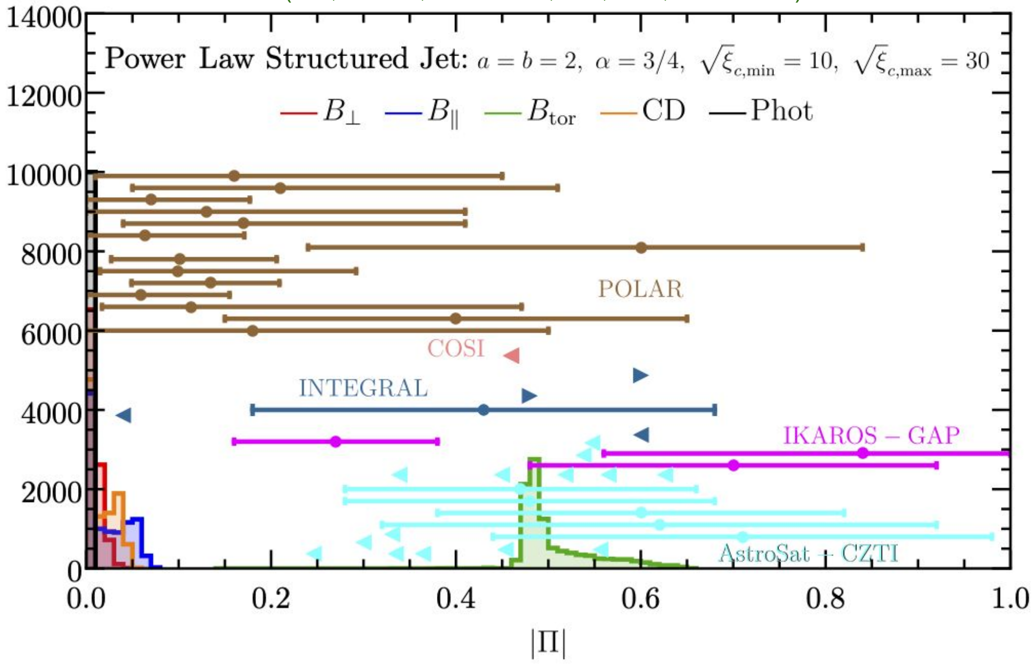
POLAR measurements favor low GRB polarization

Monte Carlo simulations of polarization from different mechanisms and B-field structures, includes:

- Integration over multiple pulses
- Different bulk-Gamma between pulses
- Different viewing angles & fluence suppression

Most mechanisms yield polarization below 10%, except a jet with large scale ordered B-field.

(Gill,Granot,Kumar ‘20; Gill,Kole,Granot ‘21)



A single **secure** measurement of Π ~ 50% **or** Π > 20% in a large sample would favor large scale B-fields

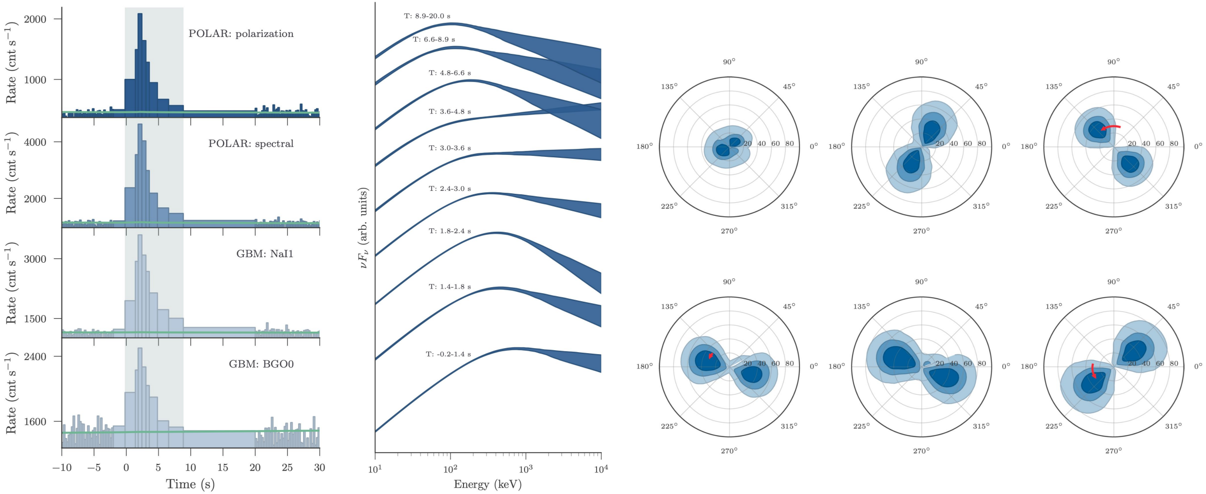
Time-resolved spectro-polarimetric measurements

Time-resolved polarization measurements show gradual changes in both the polarization and polarization angle

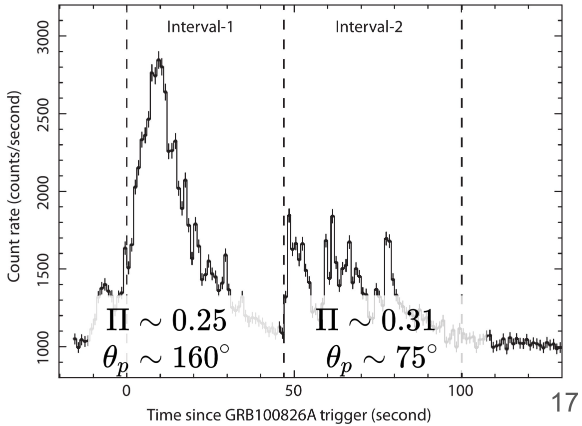
This requires time-dependent theoretical models that address:

- (1) pulse profiles (2) spectral evolution (3) polarization change (4) polarization angle change

(GRB 170114A; Burgess+2019)

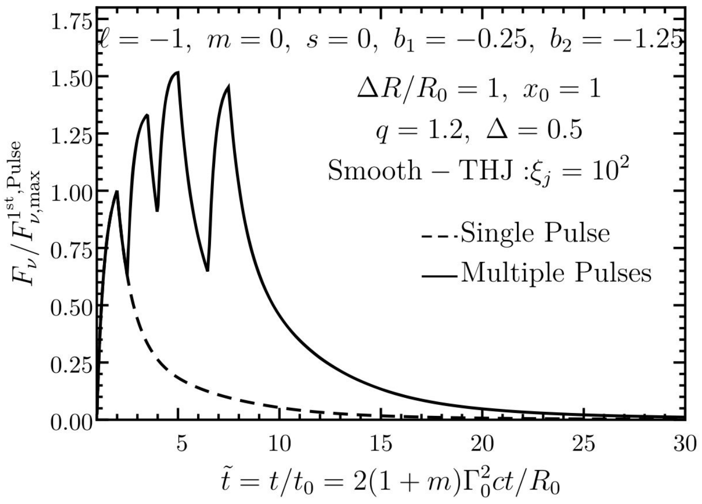


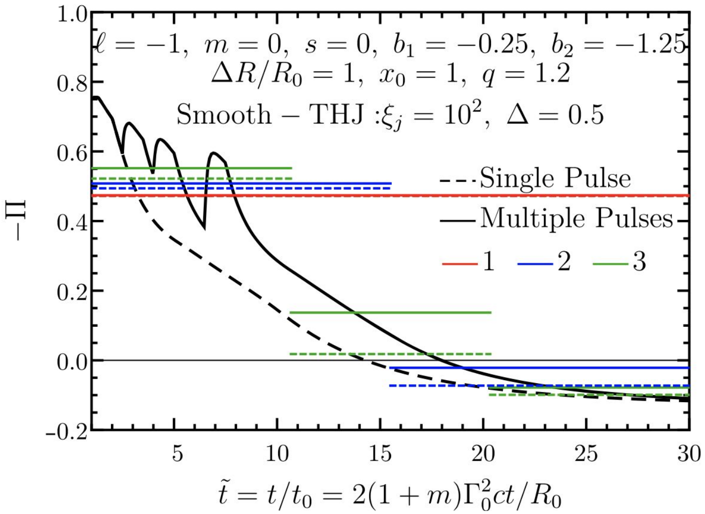
(GRB 100826A; Yonetoku+11)



Polarization evolution over single/multiple pulses: B_{tor}

(Gill & Granot '21)





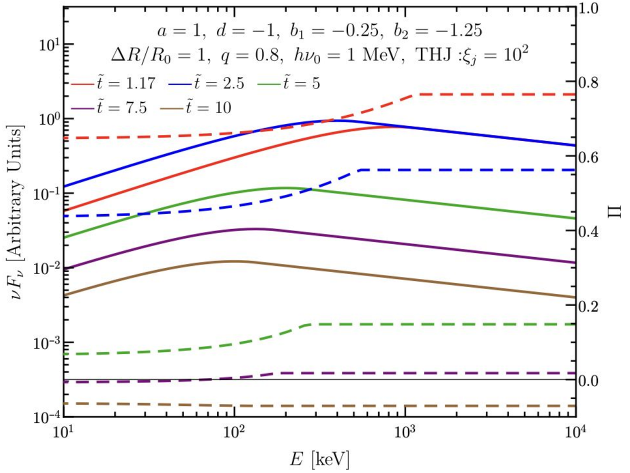
Multiple temporal segments can yield different levels of polarization.

Therefore, can't simply assume the time-integrated polarization when making comparison of observations with theoretical estimates.

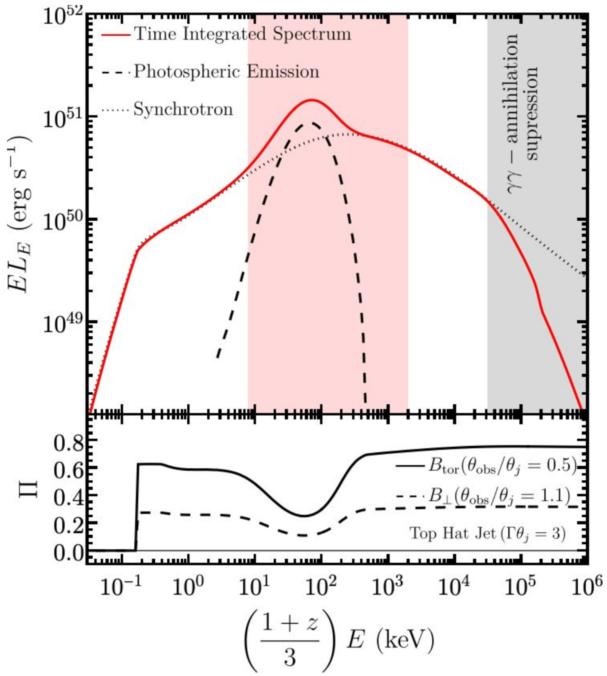
Energy dependence of prompt GRB polarization

Energy dependence of optically thin synchrotron polarization can be easily calculated (e.g. Gill & Granot ‘21).

Photospheric emission models require detailed radiation transfer of Stokes parameters to yield more accurate results (Lundman+14, Parsotan+22).



(Gill, Kole, Granot ‘21)



Flux weighted polarization evolution with energy is one way to achieve that (e.g. Lundman+18).

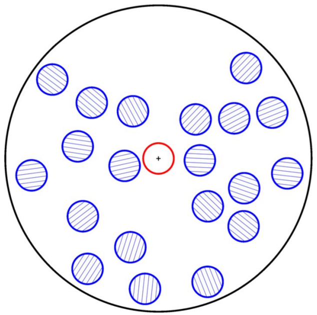
Gradual change in the PA: non-axisymmetric jets

To obtain a gradually changing polarization angle (PA), **the flow / B-field structure must be non-axisymmetric or highly time-variable:**

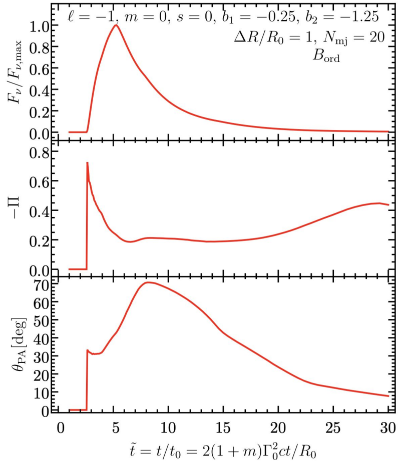
Synchrotron model: by having mini-jets or jets within a jet with randomly oriented ordered field lines.

Photospheric model: MC radiation transfer finds that off-axis jets show temporally evolving polarization angle

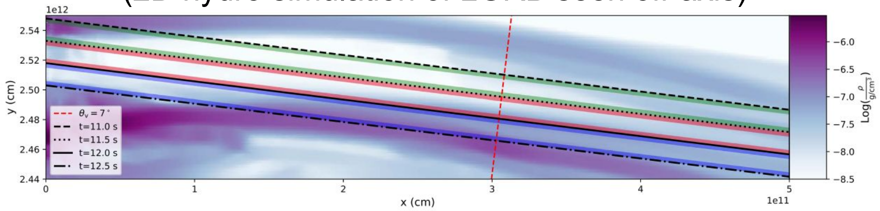
(Gill & Granot, in prep.)

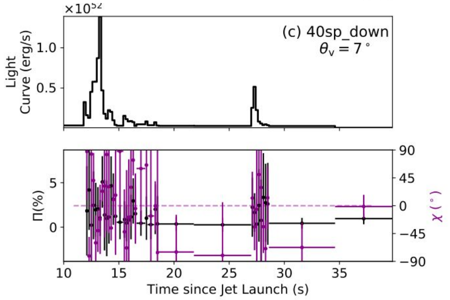


Mini-jets with randomly oriented ordered field lines



(2D hydro simulation of LGRB seen off-axis)

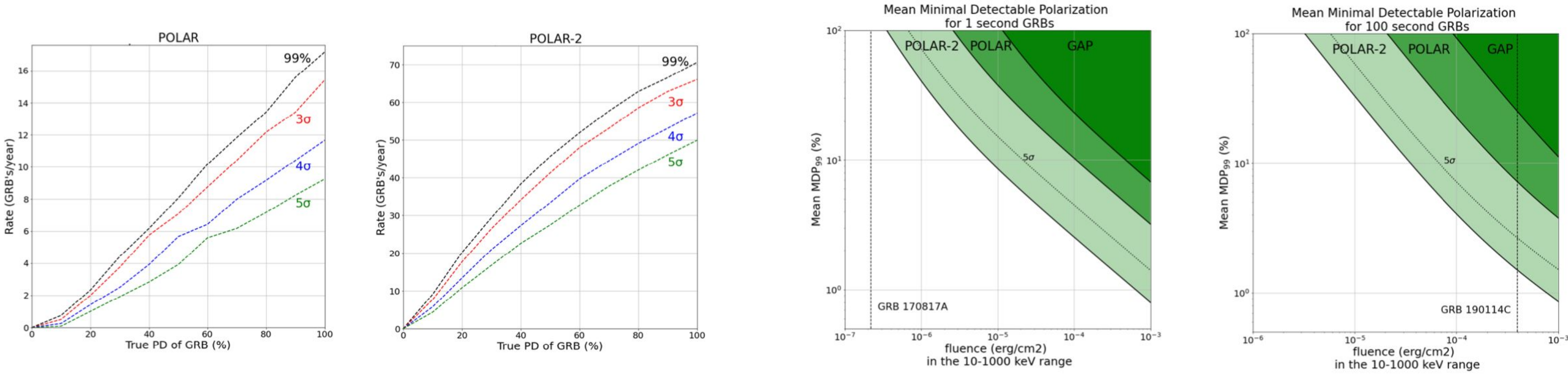




(Parsotan+22)

Prospects for future observations & modeling

New gamma-ray polarimetry missions (e.g. **POLAR-2, LEAP, SPHiNX, Daksha** in the ~10 keV - 1 MeV energy; **AMEGO** in the MeV energy) range are slated for development / launch in this decade.



(Gill, Kole, Granot '21, Kole+22)

No energy resolved GRB polarization measurements yet – crucial for distinguishing between different spectral components in the prompt spectrum. New missions will address this!

More realistic (simulation based) time and energy dependent spectro-polarimetric models of prompt GRB emission will be needed (soon!) for accurate model comparisons.

Thanks!