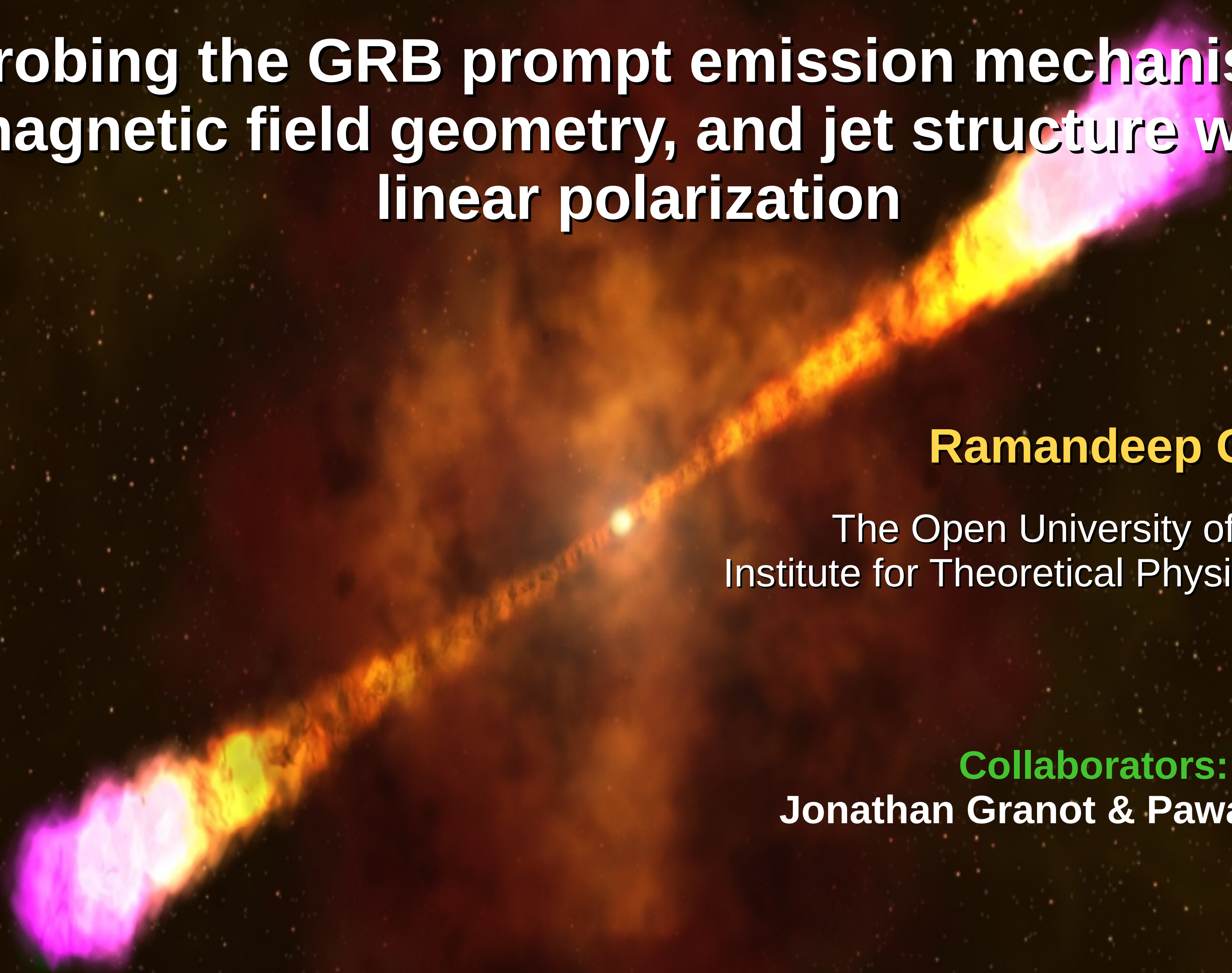
Probing the GRB prompt emission mechanism, magnetic field geometry, and jet structure with linear polarization



Ramandeep Gill

The Open University of Israel
Institute for Theoretical Physics, Frankfurt

Collaborators:
Jonathan Granot & Pawan Kumar

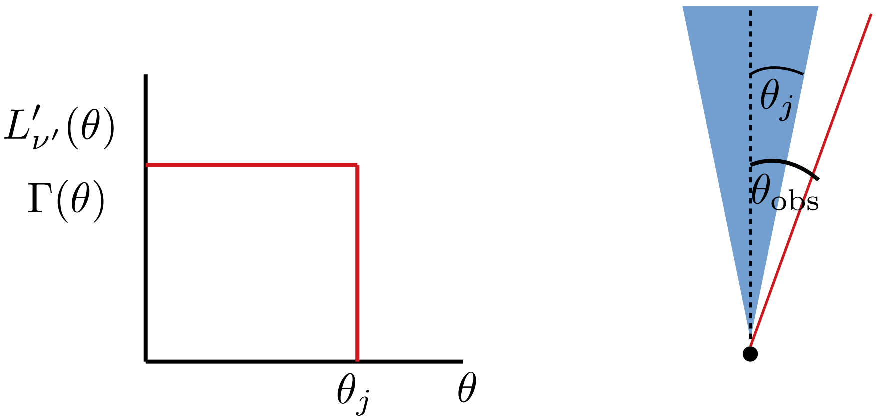
Outline of the talk

- **Structured jets**
  - Dependence of fluence on the viewing angle
  - Limitation to small viewing angles due to compactness
- **Polarization from different radiation processes: Top-hat jet Vs structured jet**
  - Synchrotron emission
    - Temporal evolution
    - Different B-field configurations
  - Non-dissipative photospheric emission
  - Compton drag
- **Change in net polararization when integrating over multiple pulses**
- **Monte-Carlo simulation of polarized emission from a large sample of GRBs**
  - What can we say about the B-field structure?
  - Can we infer anything about the jet structure?

Structured jets

Jet geometry

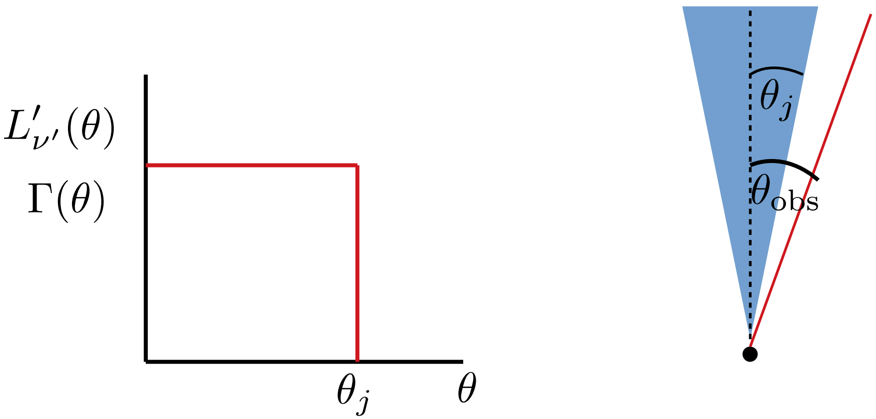
Top-hat jet



A uniform jet with a sharp edge

Jet geometry

Top-hat jet



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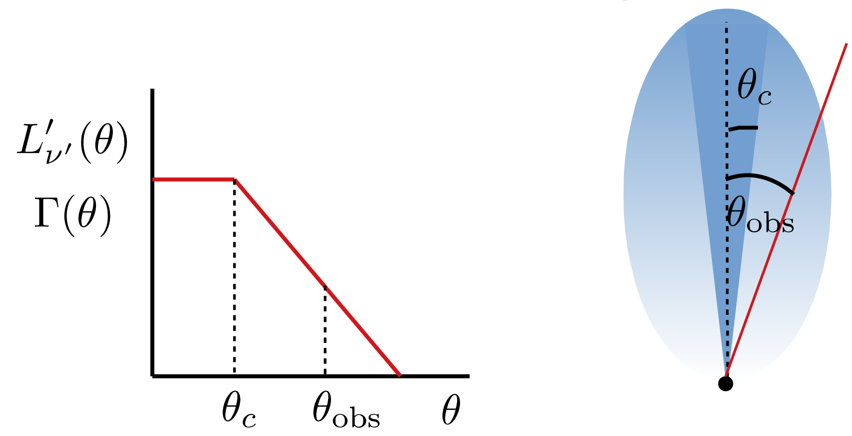
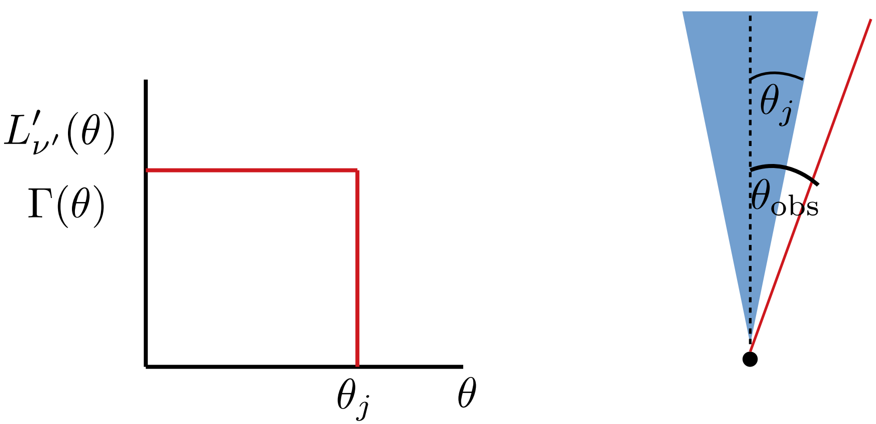


$L'_{\nu'} \propto \Theta^{-a}$ $\quad \Gamma(\theta) \propto \Theta^{-b}$ $\quad \Theta = \sqrt{1 + \left(\frac{\theta}{\theta_c}\right)^2}$

Jet geometry

Top-hat jet



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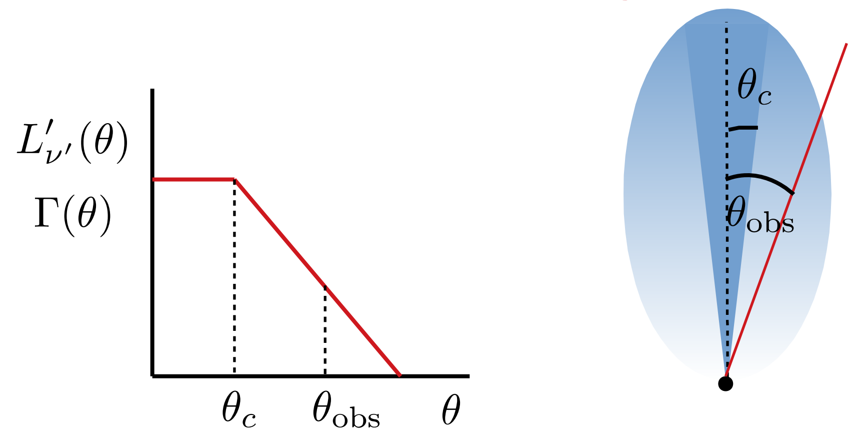
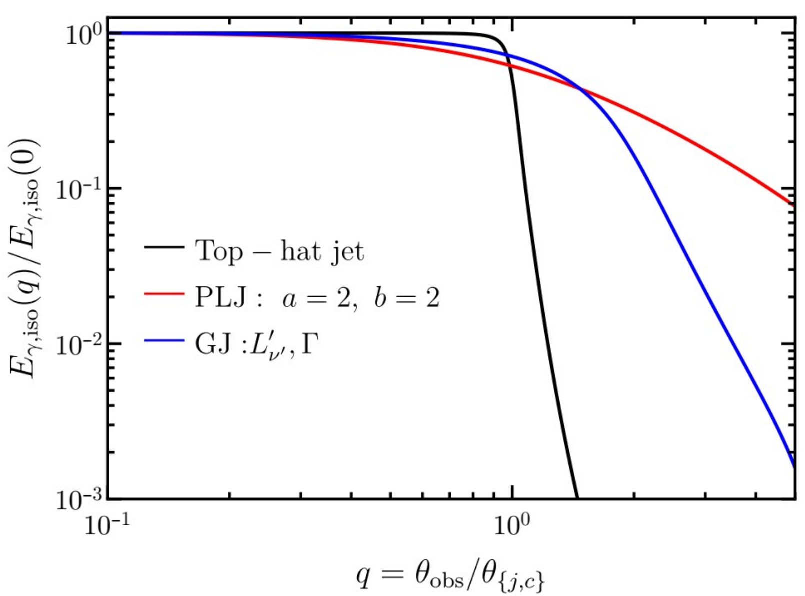


$$L'_{\nu'} \propto \Theta^{-a} \qquad \Gamma(\theta) \propto \Theta^{-b} \qquad \Theta = \sqrt{1 + \left(\frac{\theta}{\theta_c}\right)^2}$$

Off-axis to on-axis fluence ratio



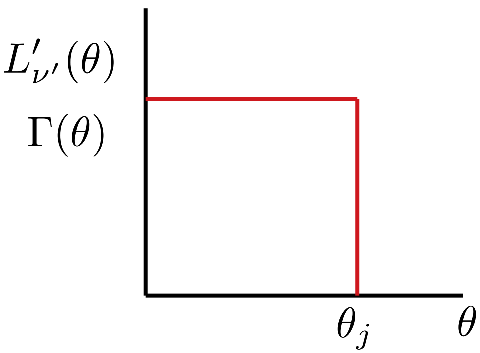
$$E_{\gamma,\rm iso} = \frac{4\pi d_L^2}{(1+z)} S_\gamma$$

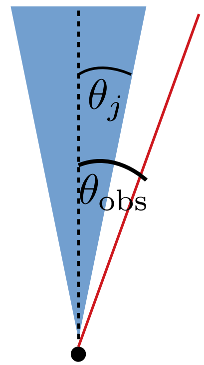
$$S_\gamma = \int dt_{\rm obs} \int_{\nu_1}^{\nu_2} d\nu F_\nu(t_{\rm obs})$$

- Fluence is suppressed for off-axis observers, which makes it hard to detect distant off-axis GRBs. (Granot+02; Yamazaki+03; Eichler & Levinson 04; Salafia+15)
- Structured jets are visible over much larger angular scales than top-hat jets.

Jet geometry

Top-hat jet





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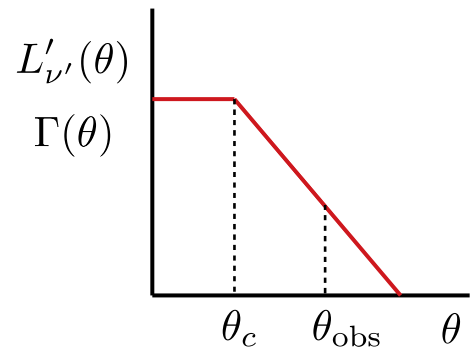
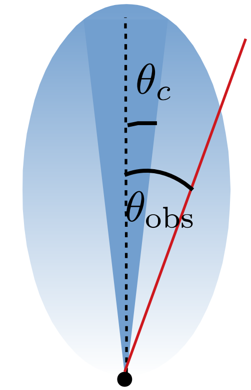




$$L'_{\nu'} \propto \Theta^{-a} \qquad \Gamma(\theta) \propto \Theta^{-b} \qquad \Theta = \sqrt{1 + \left(\frac{\theta}{\theta_c}\right)^2}$$

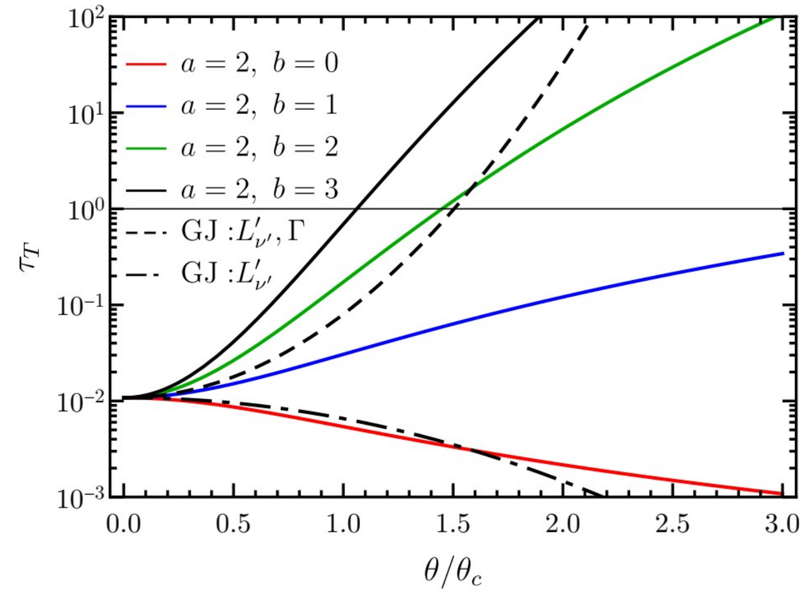
- Pair-production and its effect on the spectrum becomes important when the compactness of the flow is high.

$$\ell'_\gamma = \sigma_T \frac{U'_\gamma}{m_e c^2} \frac{R}{\Gamma} = f_{\gamma\gamma}^{-1} \tau_T$$

- High Thomson scattering optical depth due to pairs can suppress γ-ray emission

$$\tau_T \approx \epsilon_\gamma f_{\gamma\gamma} \frac{3\sigma_T}{8 m_e c^4} \frac{L_k(\theta)}{\Gamma^5 t_{v,z}}$$

Compactness constraints



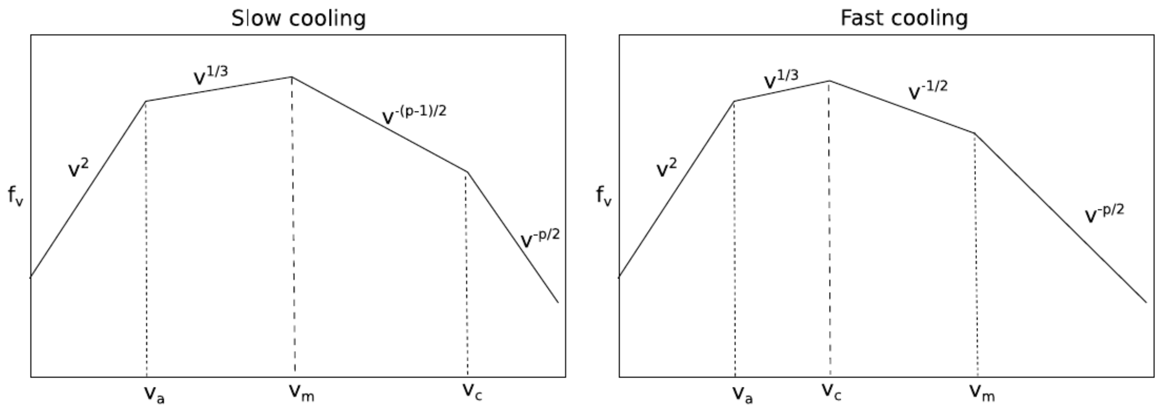
Polarization from different radiation processes

Synchrotron emission

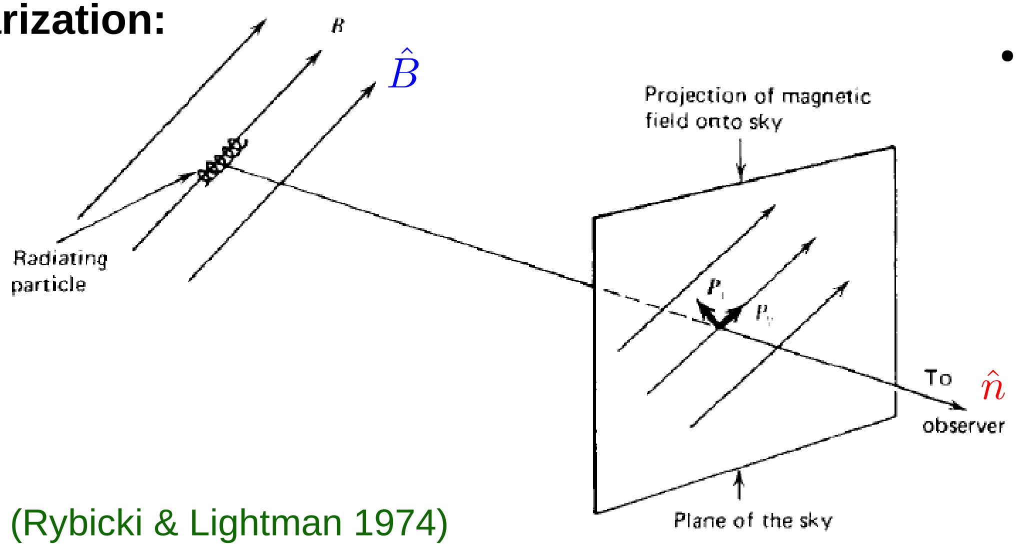
- Relativistic particles (e^- or $e^\pm$) gyrate around magnetic field lines and emit synchrotron photons.
- Energy distribution of particles follow a power law: $n_e(\gamma_e) \propto \gamma_e^{-p}$ $\quad \gamma_m < \gamma_e < \gamma_M$

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

(Sari+98; Granot & Sari 02)



Polarization:



(Rybicki & Lightman 1974)

- Synchrotron emission is generally partially **linearly polarized**

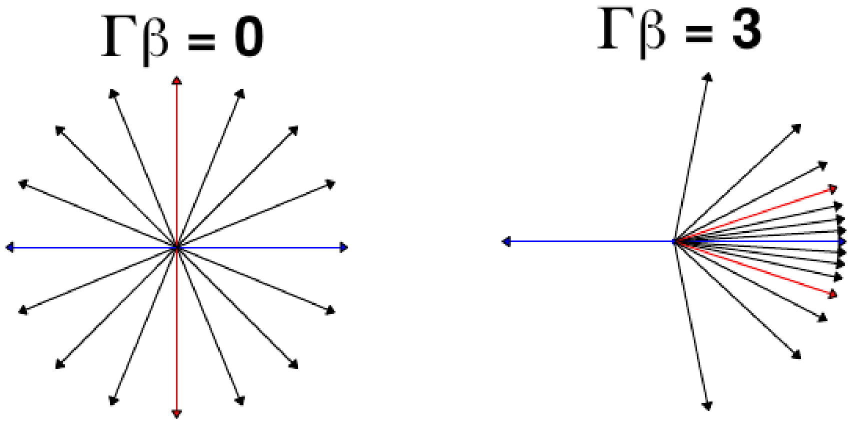
$$\hat{\Pi} = \hat{n} \times \hat{B}$$

$$\Pi_{\max} = \frac{\alpha + 1}{\alpha + 5/3} \xrightarrow[\text{cooling}]{\text{slow}} \frac{p+1}{p+7/3}$$

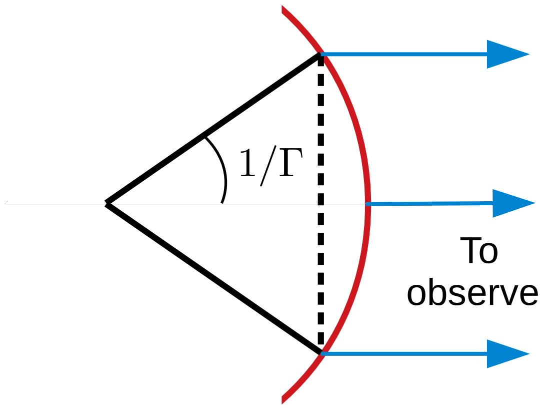
$$0.5 \leq \Pi_{\max} \leq 0.75$$

Synchrotron emission – random B-field

Abberration of light in a relativistic outflow



(Granot & Ramirez-Ruiz 2011)



$$\xi \equiv (\Gamma\theta)^2$$

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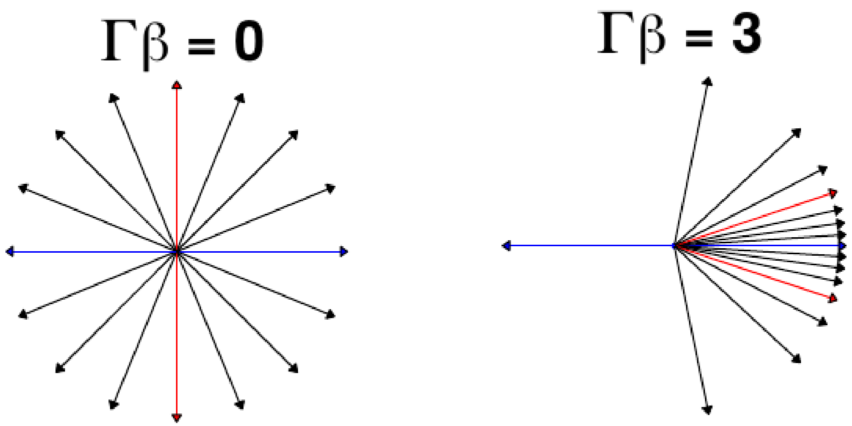

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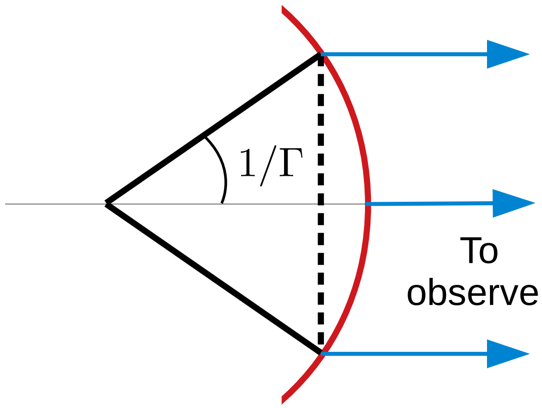
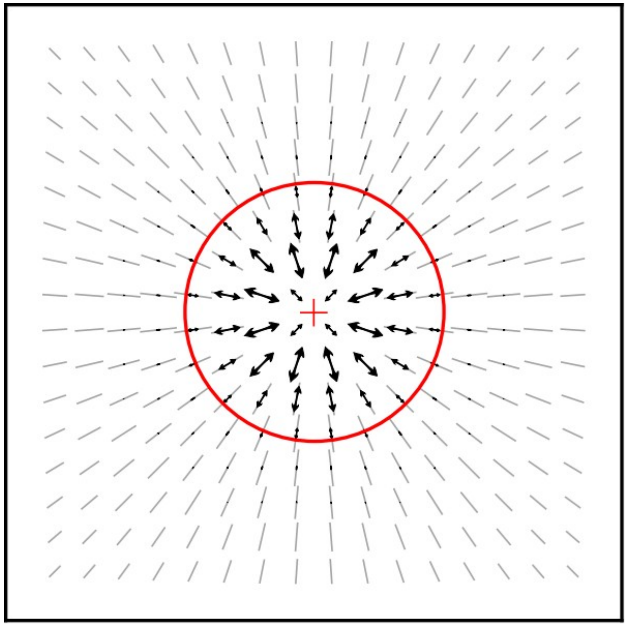


$\xi \equiv (\Gamma\theta)^2$

- Greater degree of symmetry in the polarization vectors, when observed over the entire GRB image, leads to smaller degree of **net** polarization



Random B-field $(B_\perp)$

Synchrotron emission – random B-field

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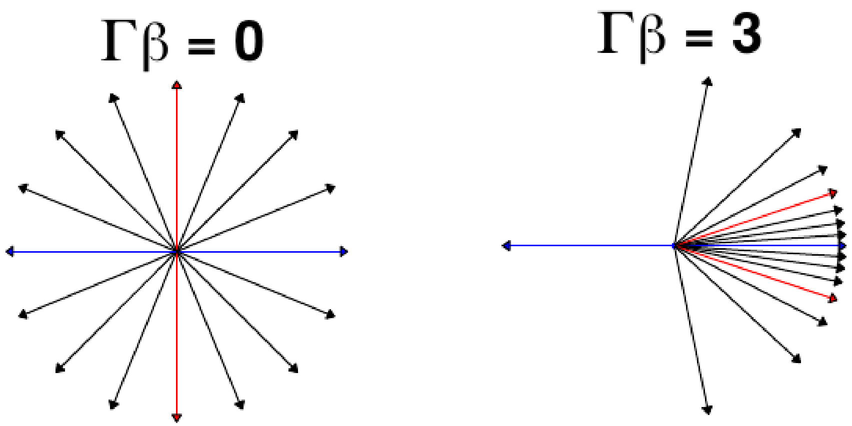

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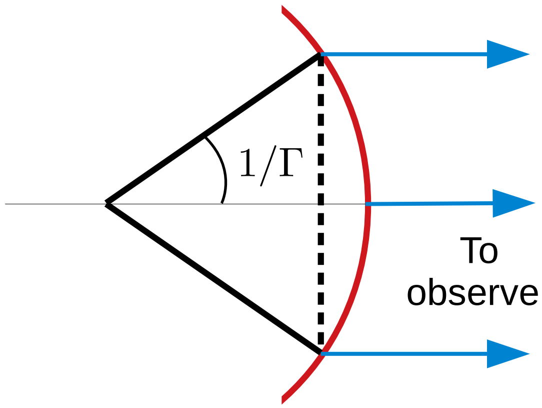
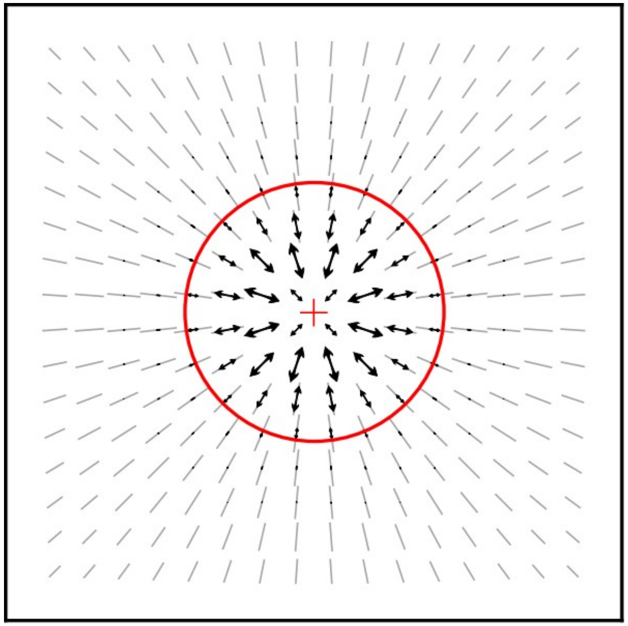


$$\xi \equiv (\Gamma\theta)^2$$

- Greater degree of symmetry in the polarization vectors, when observed over the entire GRB image, leads to smaller degree of **net** polarization

- One way to **break the symmetry** is by having the line-of-sight close to the jet edge (in a top-hat jet), which will not cancel all the polarization. (**Waxman 03**)

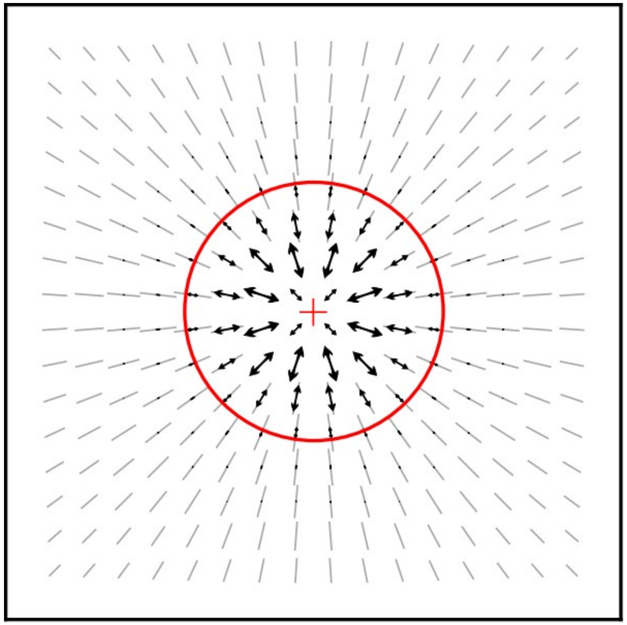


Random B-field $(B_\perp)$

Synchrotron emission – B-field structure

- Large scale B-field breaks the symmetry and yields higher levels of polarization.

(Granot & Ramirez-Ruiz 11; Gill+18, in prep.)



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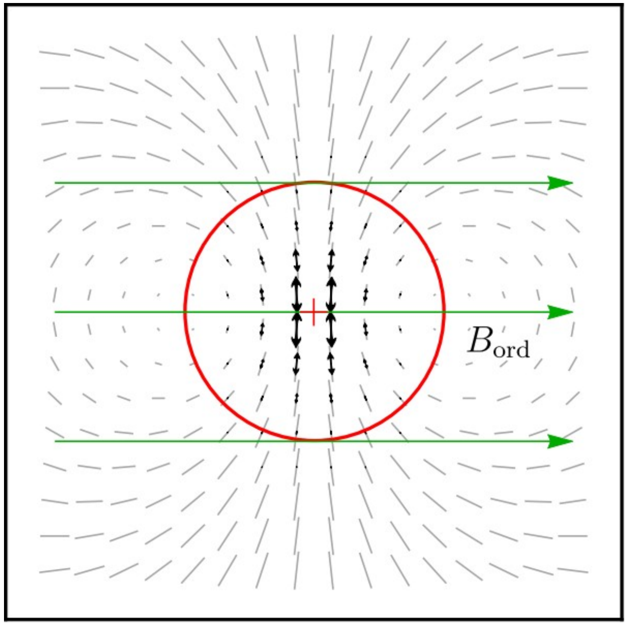
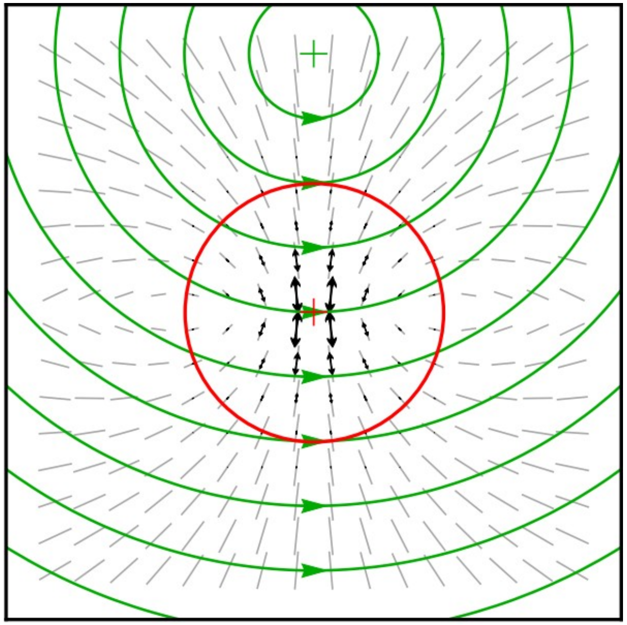


Ordered B-field

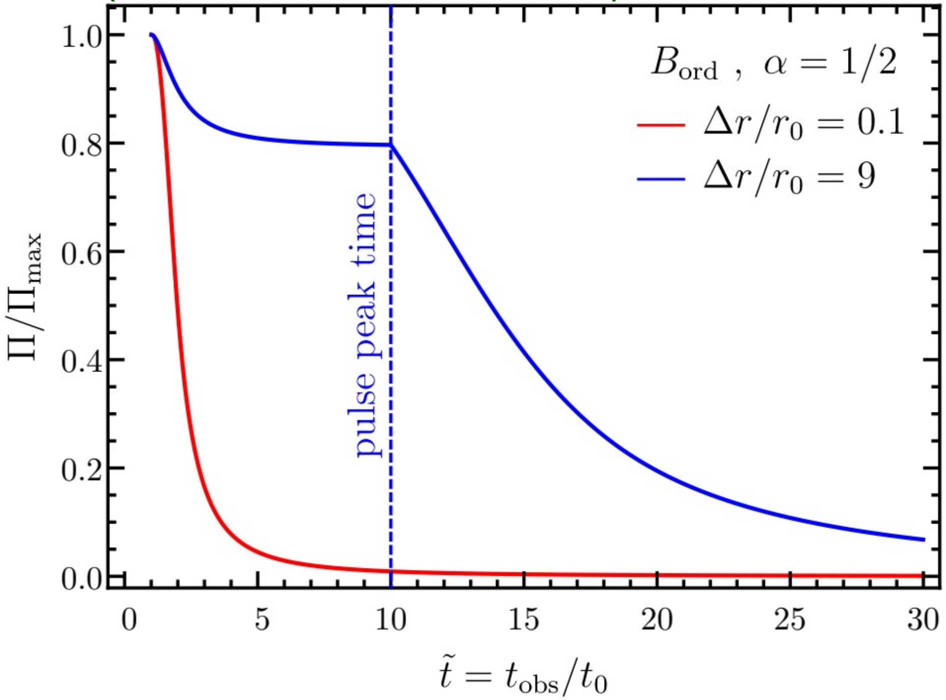


Toroidal B-field $(B_{\rm tor})$

- Random B-field in the plane transverse to the radial vector
- We also consider B-field parallel to radial vector $B_{||}$

Temporal evolution of polarization over a single pulse

(see Nakar, Piran, Waxman 03)



- Consider an **ordered B-field** in the entire observed region and a **relativistic spherical shell** emitting between radii

  $r = r_0$ and $r = r_0 + \Delta r$

- Emission arrives over two timescales:

  Radial time: $$\frac{t_{\rm obs,r}}{(1+z)} = \frac{\Delta r}{2\Gamma^2 c}$$

  Angular time: $$\frac{t_{\rm obs,\theta}}{(1+z)} = \frac{r_0}{2\Gamma^2 c}$$

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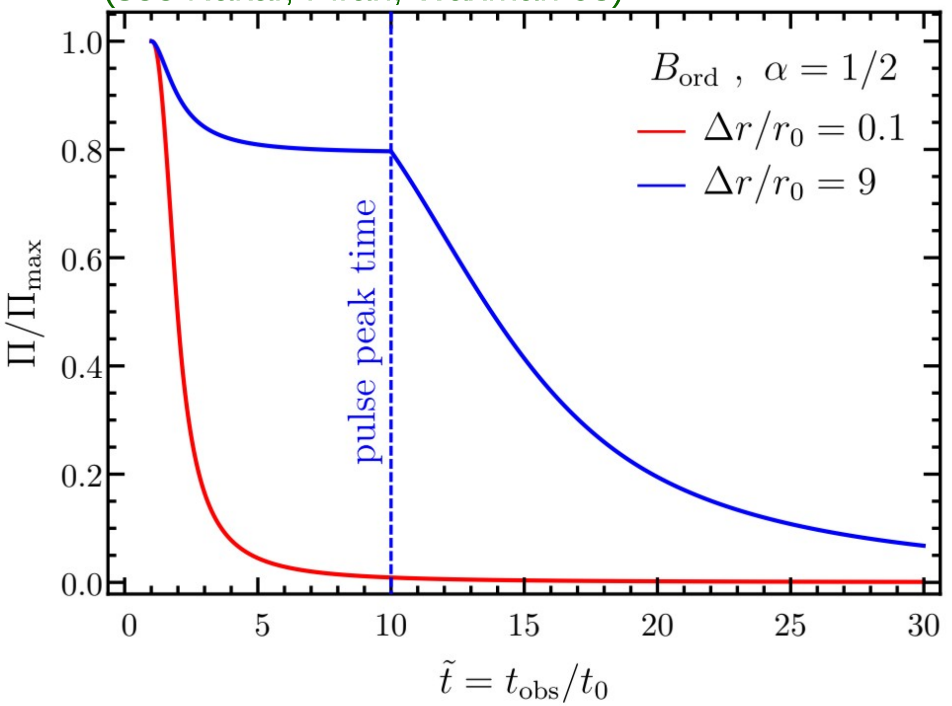

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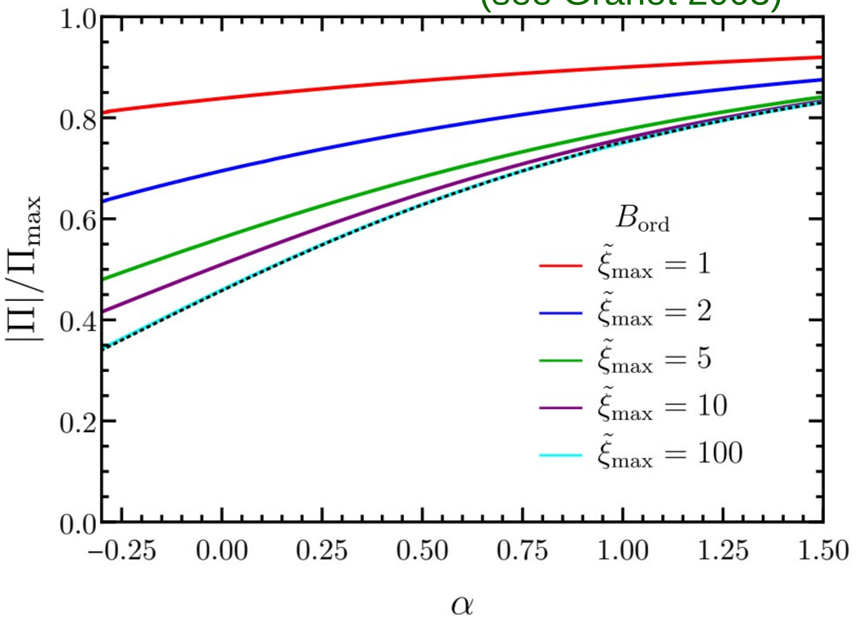
Integration over the entire pulse

- **Simplifying assumption**: Synchrotron emissivity and properties of the emission region do not vary with radius

- This is equivalent to delta-function emission in radius, and the total polarization is obtained by integrating over large angular scales around the LOS:

$$\tilde{\xi}_{\rm max} = (\Gamma\tilde{\theta}_{\rm max})^2 > 1$$

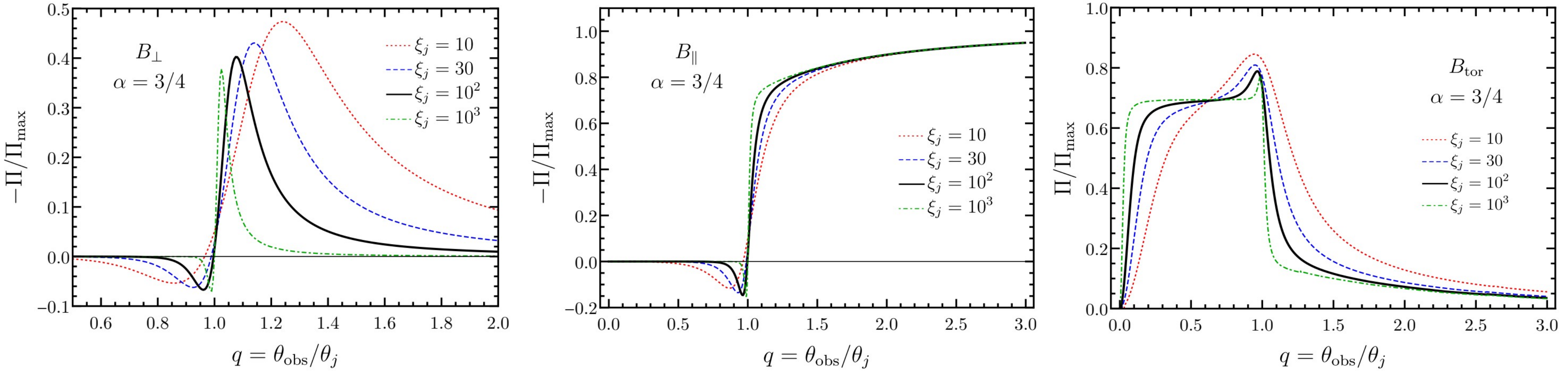
(see Granot 2003)



Synchrotron emission – Polarization

Top-hat jet

(**Granot 03; Granot & Taylor 05;** Gill+18, in prep.)



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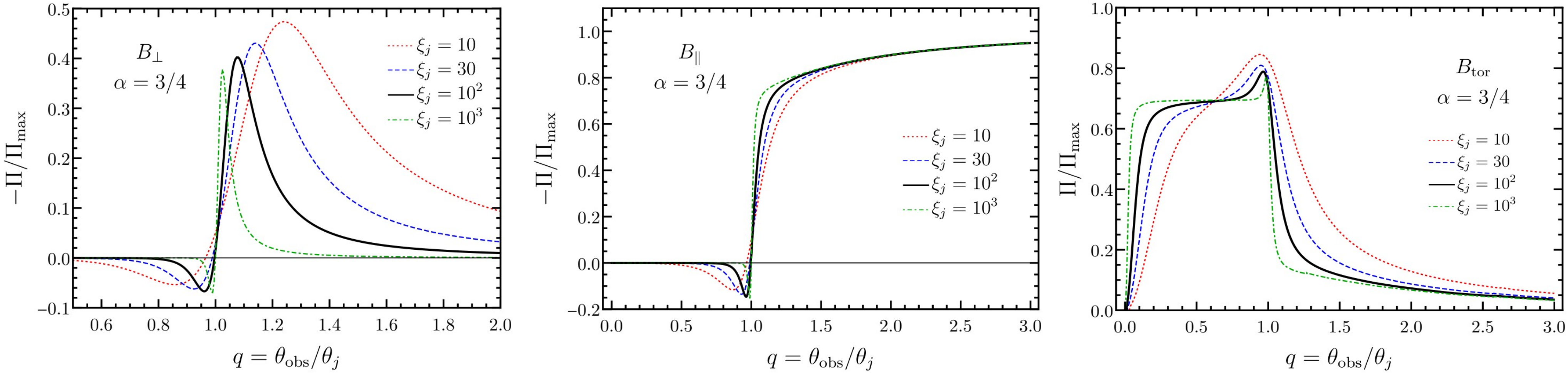
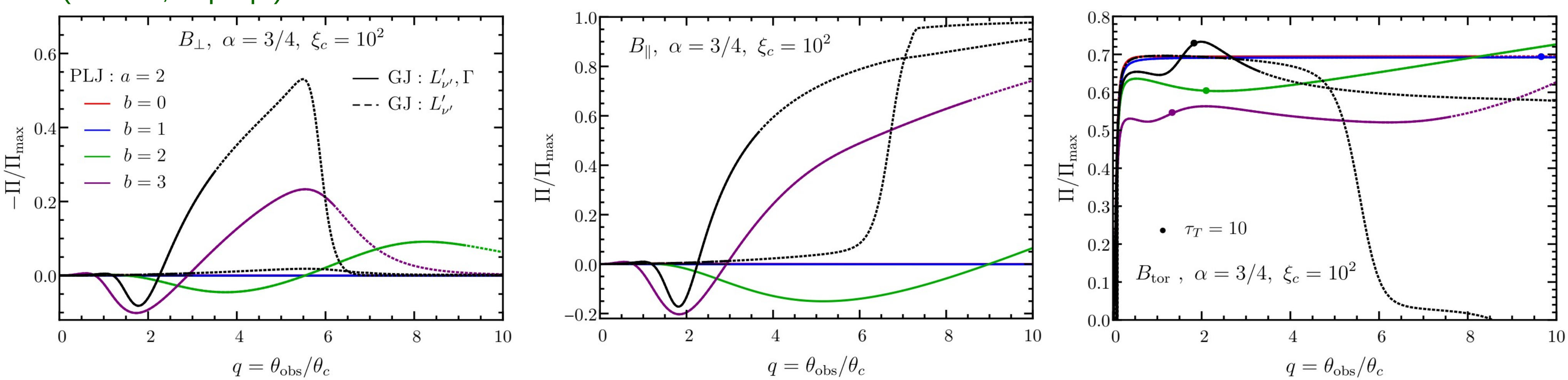


Structured jet

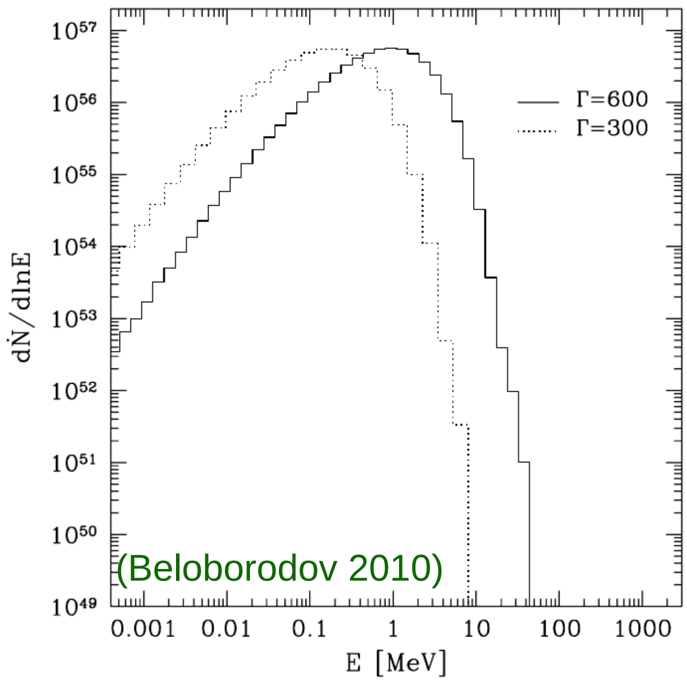
(Gill+18, in prep.)



Photospheric emission

- Close to the central engine, the flow is launched highly optically thick to pair-production where it is thermalized via Comptonization.
- Adiabatically cooled thermal radiation is released at the photosphere. (**Goodman 86, Paczynski 86**)
- Dissipation below and above the photosphere produces the non-thermal GRB spectrum.
(Thompson 94; Eichler & Levinson 00; Meszaros & Rees 05; Lazzati+09; Peer & Ryde 11; Begue+13; Thompson & Gill 14; Gill & Thompson 14; Vurm & Beloborodov 16)

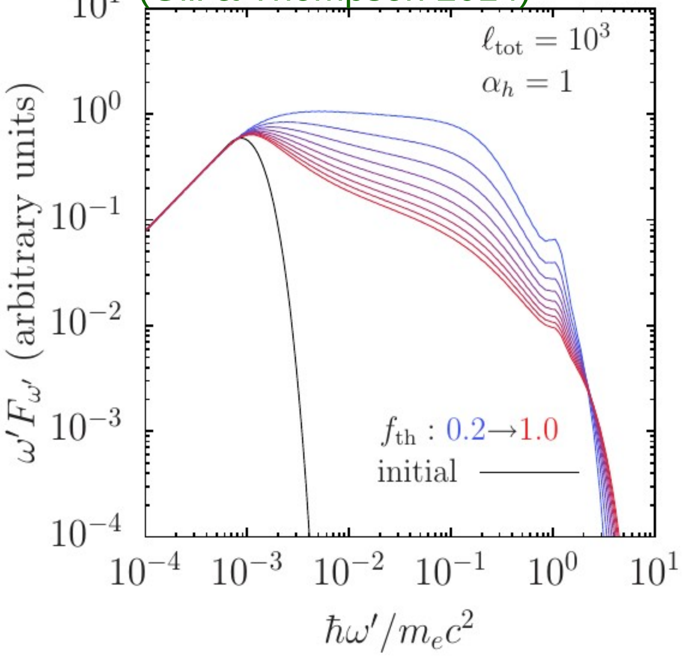
Non-dissipative outflow



(Beloborodov 2010)

Heated outflow

(Gill & Thompson 2014)



- Spectrum shown in the comoving frame, with different levels of heating.

Non-dissipative photospheric emission - Polarization

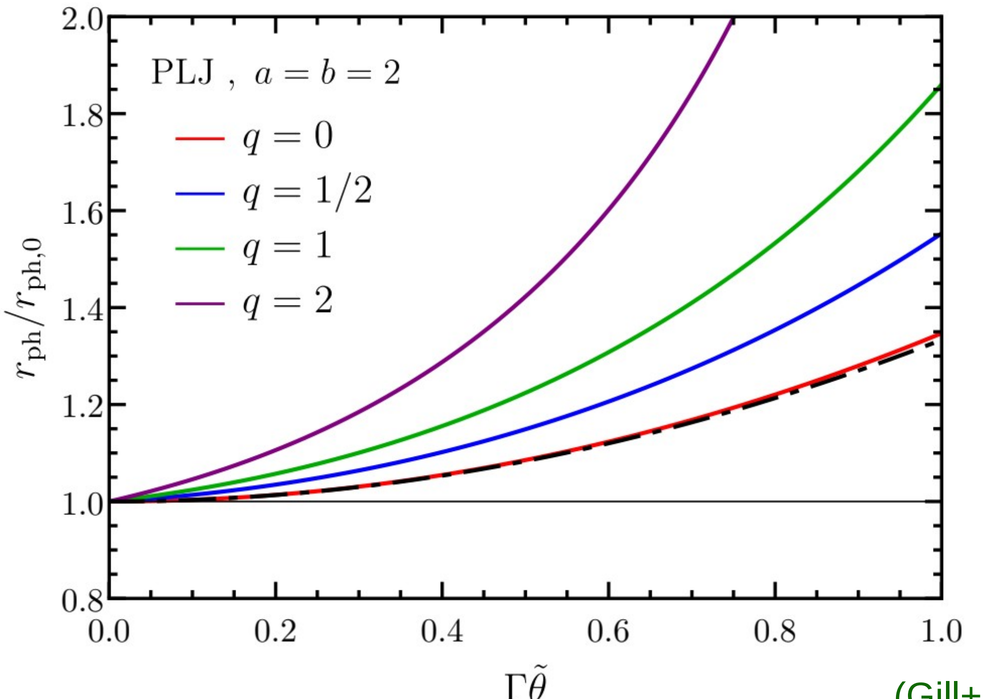
- We solve the equations of radiative transfer for an **ultra-relativistic spherical flow** and calculate the Stoke parameters in the comoving frame (see next talk by A. Beloborodov):

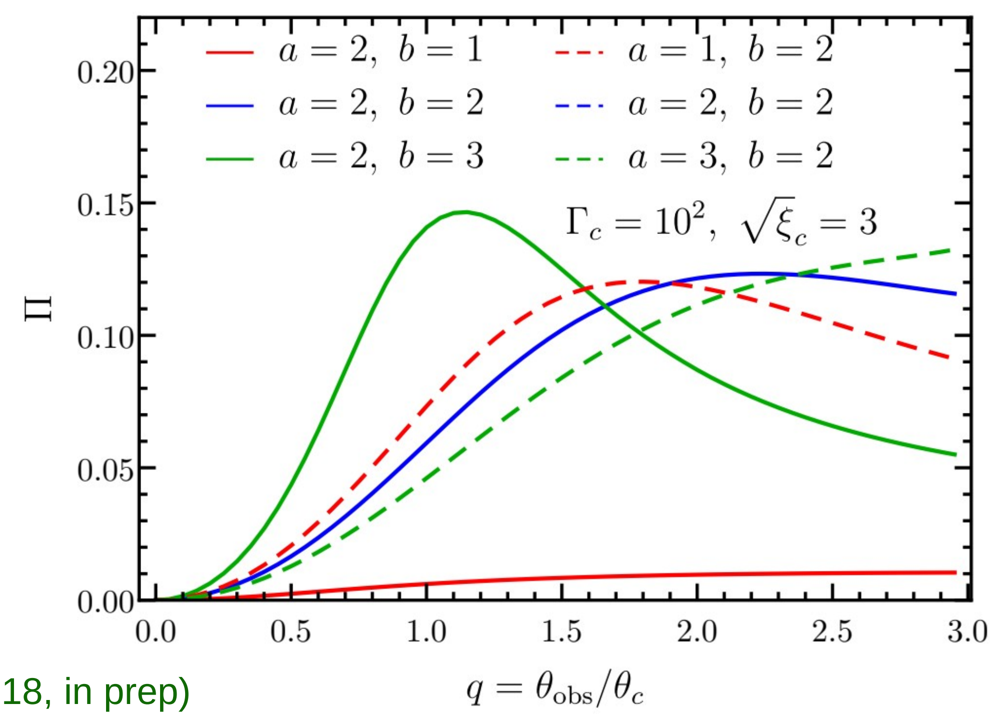
$I'(r_{\rm ph},\mu)$ and $Q'(r_{\rm rph},\mu)$ $$1=\tau_T(r_{\rm ph})=\int_{r_{\rm ph}}^{\infty}n'_e(r)\sigma_T\Gamma(1-\beta)dr$$

- From the comoving quantities, we calculate the total and polarized flux:

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

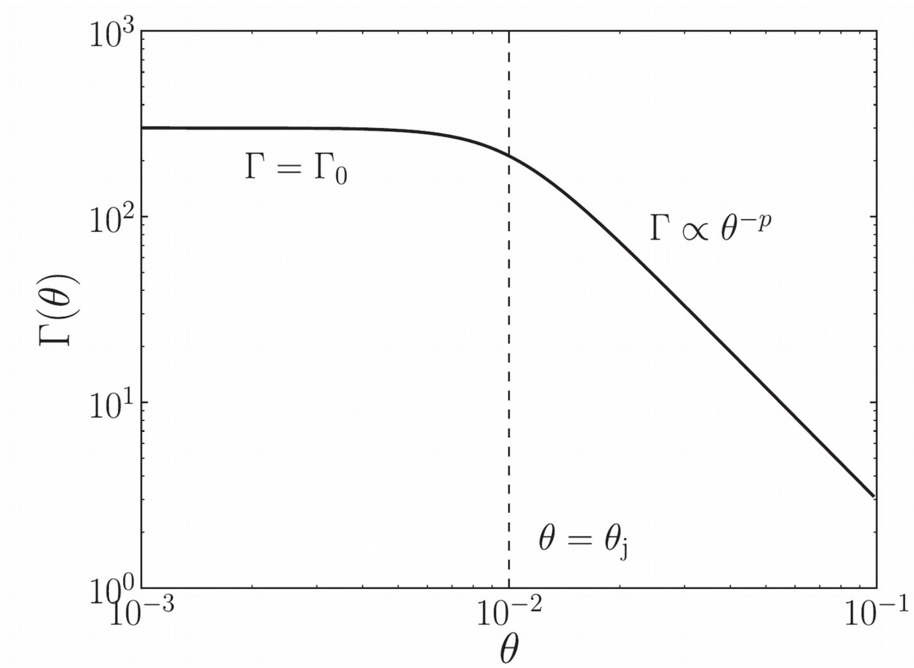
$dS_\perp$ = differential area on the plane of the sky

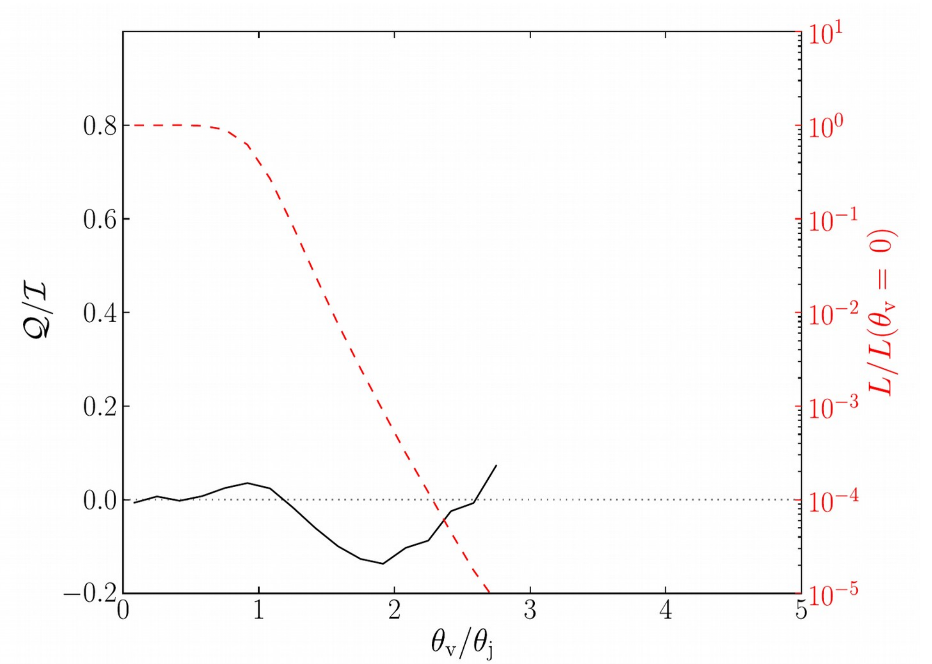




(Gill+18, in prep)

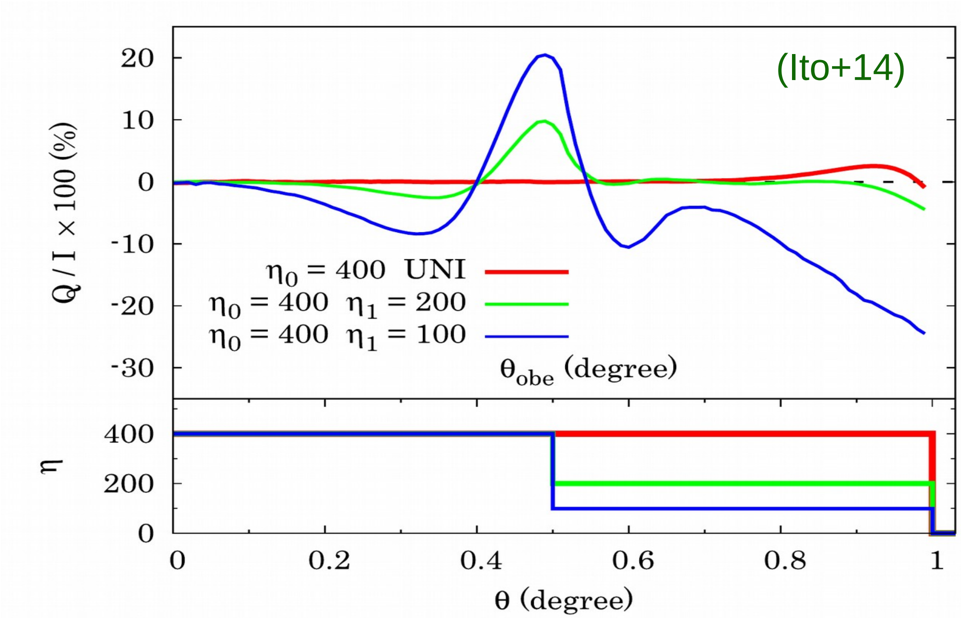
Comparison with MC simulation results





(Lundman, Peer, Ryde 14)

- Both works find Π ~ 10% - 20%
- Also find a 90 deg change in PA



Compton drag - Polarization

- Cold electrons in the comoving frame moving at relativistic speeds with the bulk flow in the lab frame upscatter ambient soft seed photons. (**Begelman & Sikora 87**; Zdziarski+91; Shemi 94; Lazzati+00; Ghisellini+00)

$$E_{\rm scatt} \sim \Gamma^2 E_{\rm seed}$$

- Source of soft seed photons can be the radiation field from the exploding star in a long GRB or radiation from the walls of the funnel in which the relativistic jet propagates.

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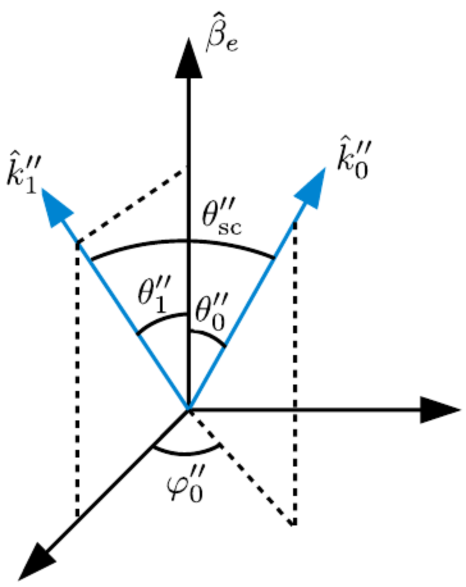
Polarized emission from inverse Compton scattering by cold relativistic electrons



- The degree of polarization of the scattered photon is:

$$\Pi_{\rm max} = \frac{1-\cos^2\theta_{\rm sc}''}{1+\cos^2\theta_{\rm sc}''}$$

- In comparison to synchrotron emission, $0 \le \Pi_{\rm max} \le 1$

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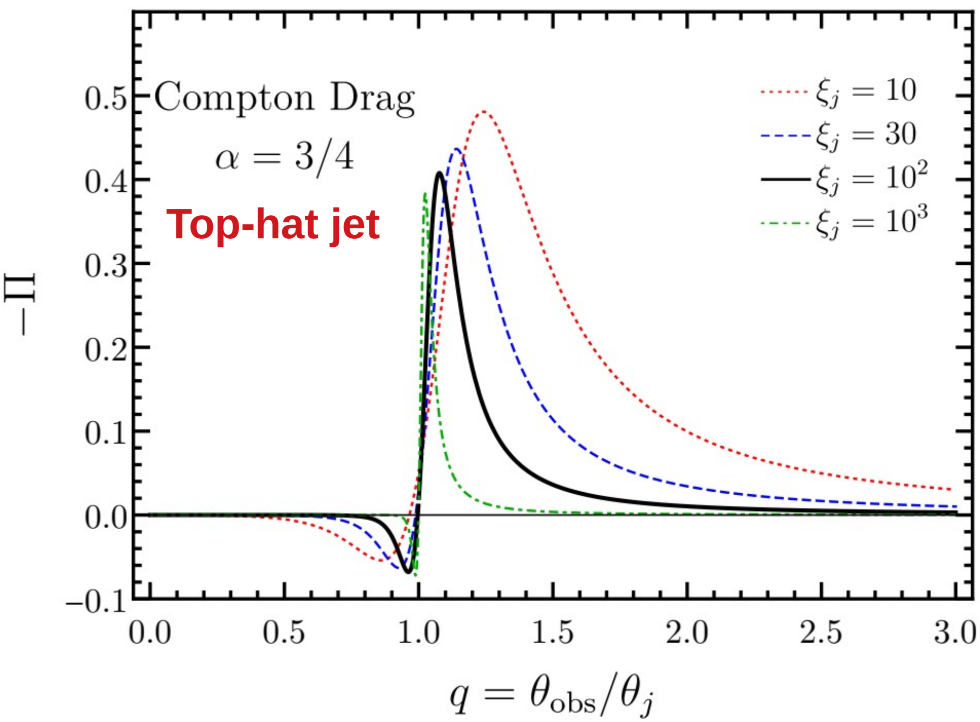
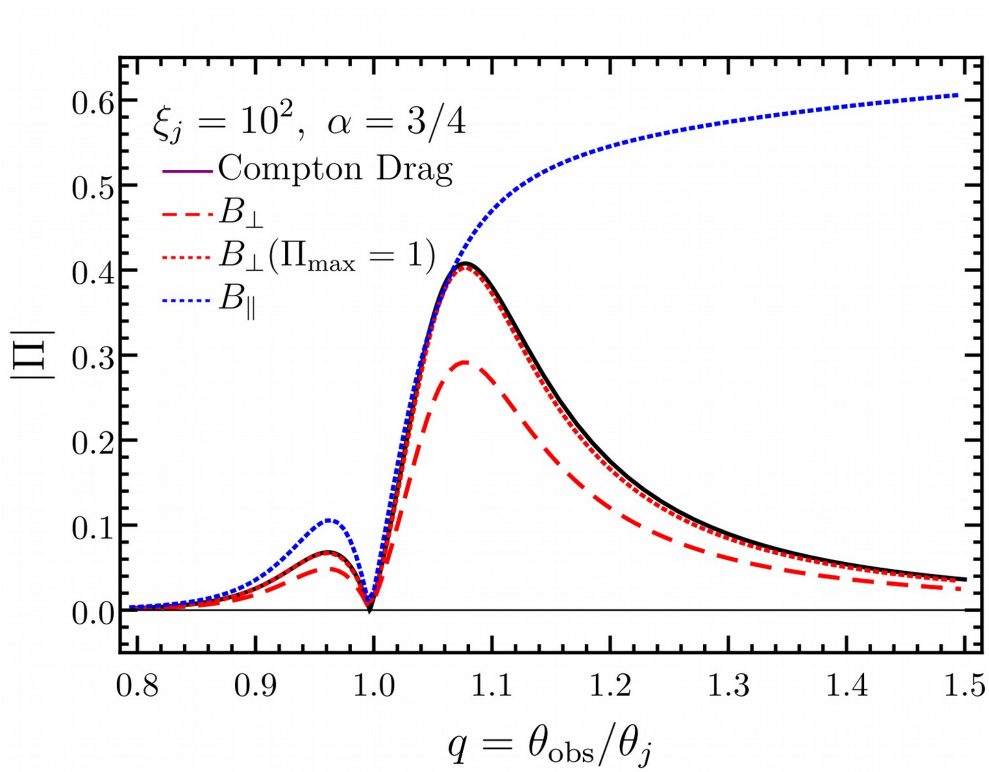
(Lazzati+04, Toma+09, Gill+18 in prep.)





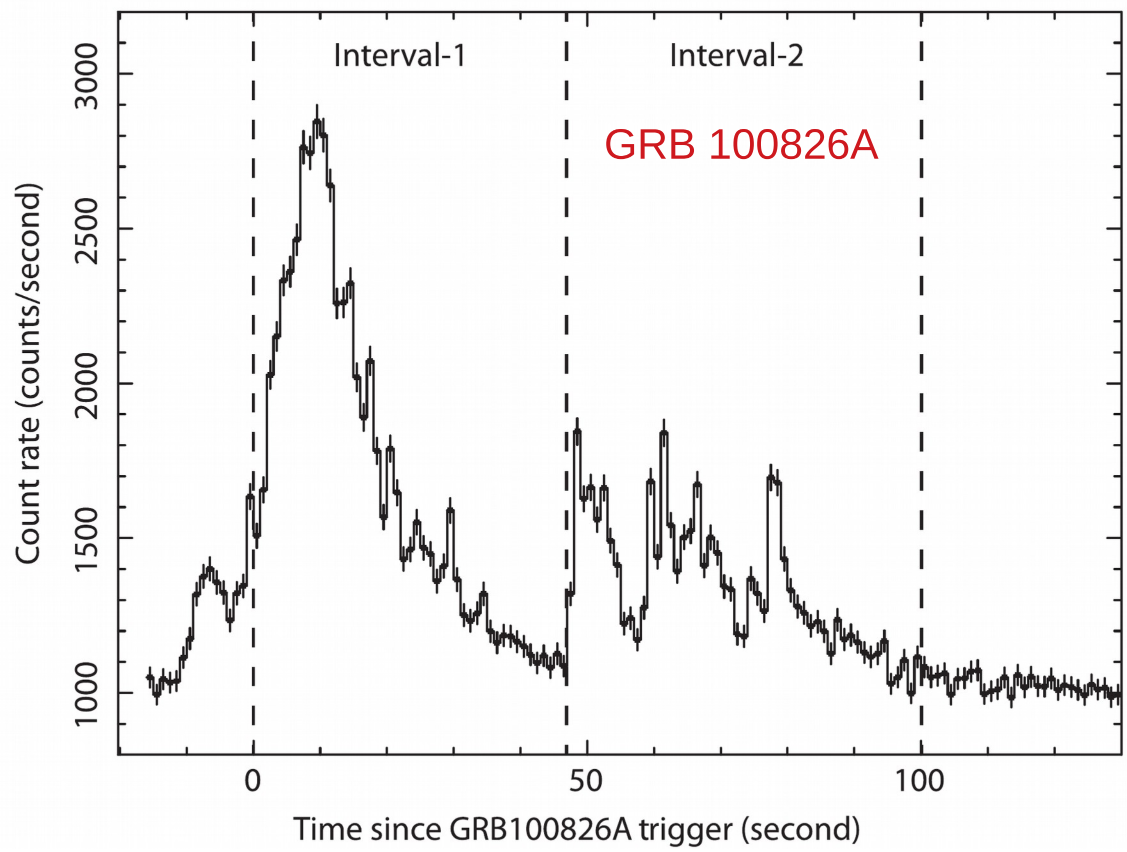
Integration over multiple pulses

Contribution of multiple pulses to an emission episode

- GRB emission is highly variable and multiple pulses contribute to each emission episode.
- The degree of polarization can vary from pulse to pulse, where the net polarization is obtained from the following for N_p number of pulses

$$\Pi = \frac{\sum_{i=1}^{N_p} Q_i}{\sum_{i=1}^{N_p} I_i}$$

(Yonetoku+11)



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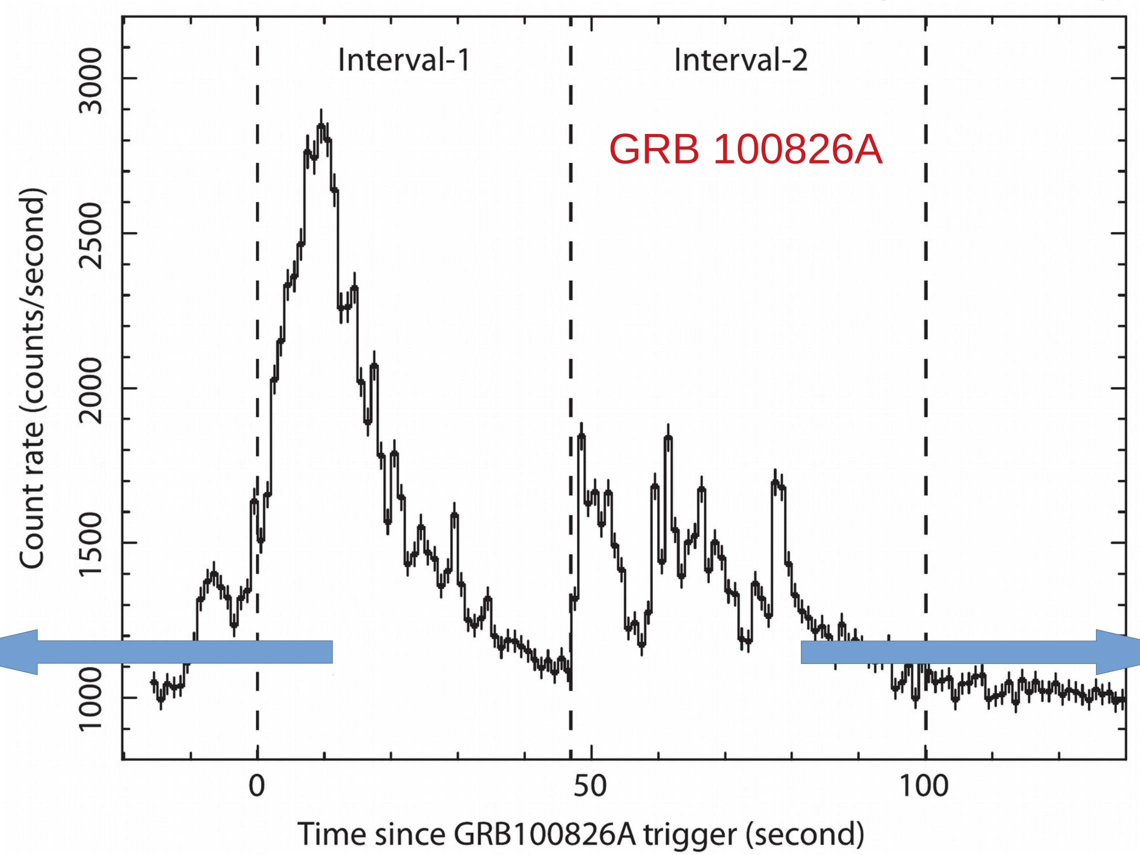
(Yonetoku+11)

$\Pi = 0.25 \pm 0.15$

$\theta_p = 159^\circ \pm 18^\circ$



$\Pi = 0.31 \pm 0.21$

$\theta_p = 75^\circ \pm 20^\circ$

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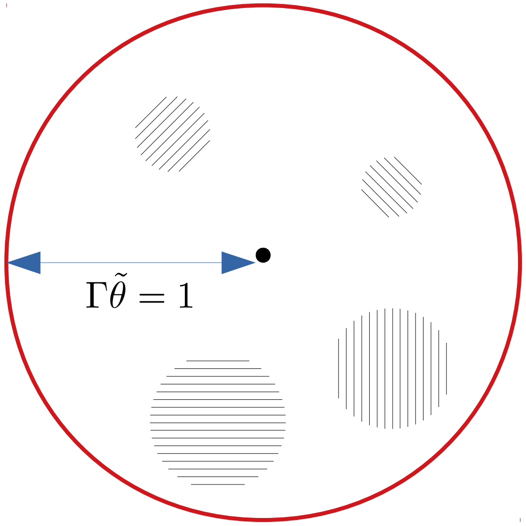
Synchrotron emission from multiple incoherent patches



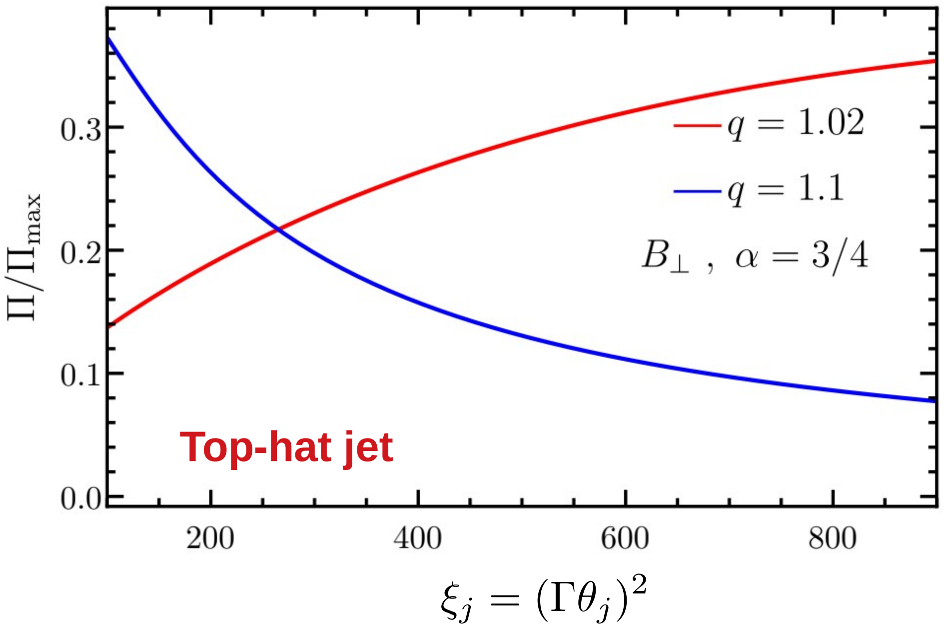
- Consider emission from multiple patches with magnetic field coherence length as large as the size of the patch
- The net polarization will be reduced to (Gruzinov & Waxman 03 – showed for afterglow polarization)

$$\Pi \sim \frac{\Pi_{\max}}{\sqrt{N_p}}$$

- Also, the PA will fluctuate from pulse to pulse

Variation of Γ and/or θ_j over multiple pulses

- It is possible that Γ and/or θ_j fluctuates between multiple pulses.
- This would effectively change ξ_j, which can reduce the net polarization upon integration over multiple pulses due to cancellation.
- This, however, requires a special LOS for a top-hat jet geometry.



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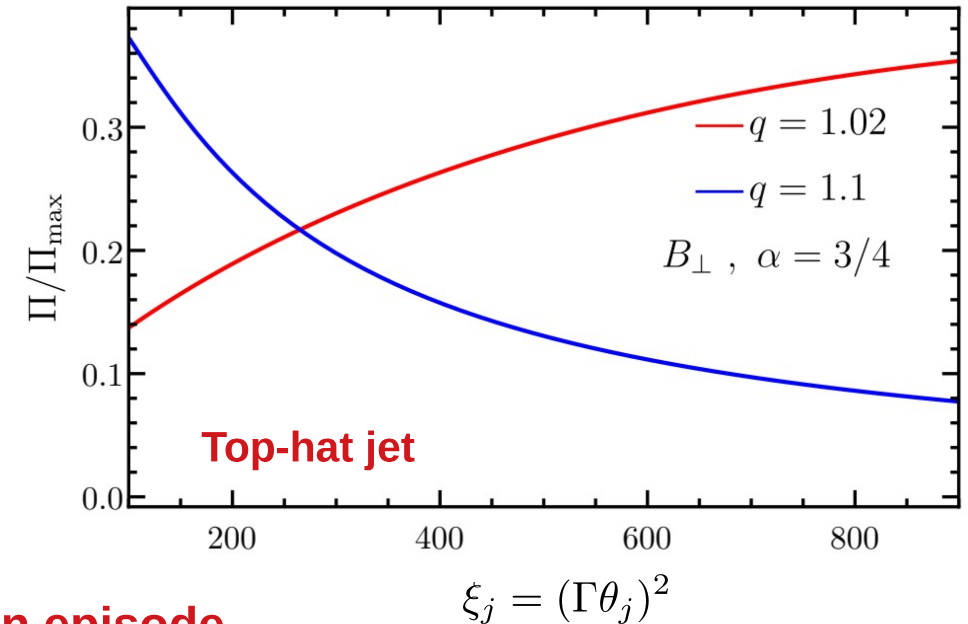
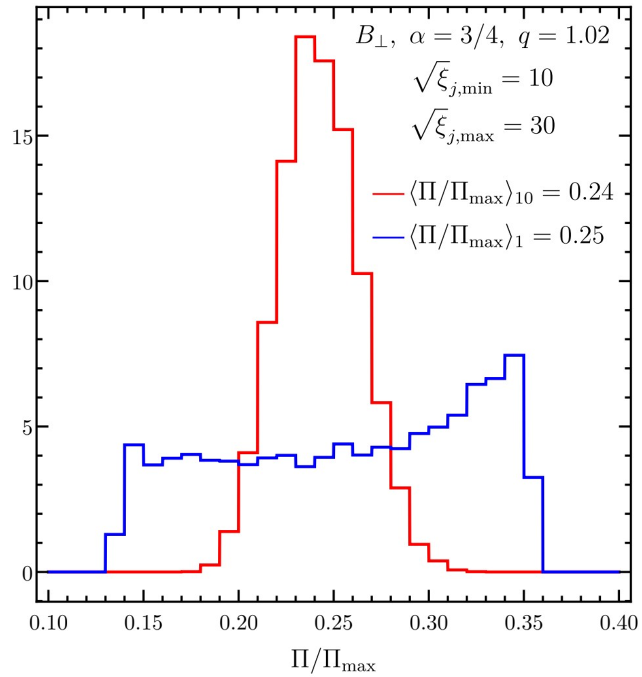
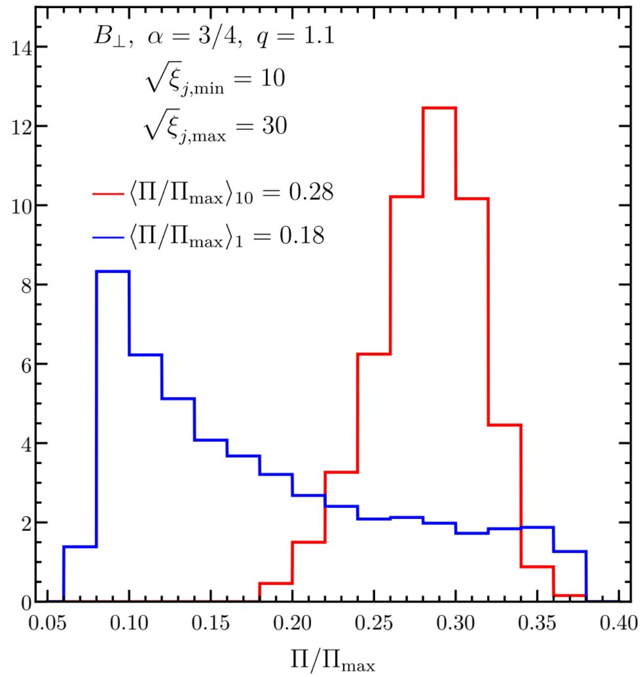
- This would effectively change ξ_j, which can reduce the net polarization upon integration over multiple pulses due to cancellation.
- This, however, requires a special LOS for a top-hat jet geometry.



MC simulations of a single emission episode





(Gill+18, in prep.)

Monte Carlo simulations of a large sample of GRBs

Monte Carlo simulations of a large sample of GRBs

- To determine the most likely level of linear polarization from different radiation processes.

- Take into account different jet structures and fluence suppression for off-axis observers.

- Integrate over multiple pulses in an emission episode with different pulses having different ξ_j

Distribution of ξ_j and q

Three basic quantities can affect Π

1) For a fixed $\theta_{\{j,c\}}$, variations in Γ can change

$$\sqrt{\xi}_{\{j,c\}} = \Gamma\theta_{\{j,c\}}$$

- We consider three distributions:

$$P(\sqrt{\xi}_j) = (\sqrt{\xi}_{j,\max} - \sqrt{\xi}_{j,\min})^{-1}$$

  - Also uniform in $\ln\sqrt{\xi}_j$ and a log-normal distribution.

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$$\Rightarrow P(q) = \theta_j P(\theta_{\rm obs}) \propto q$$

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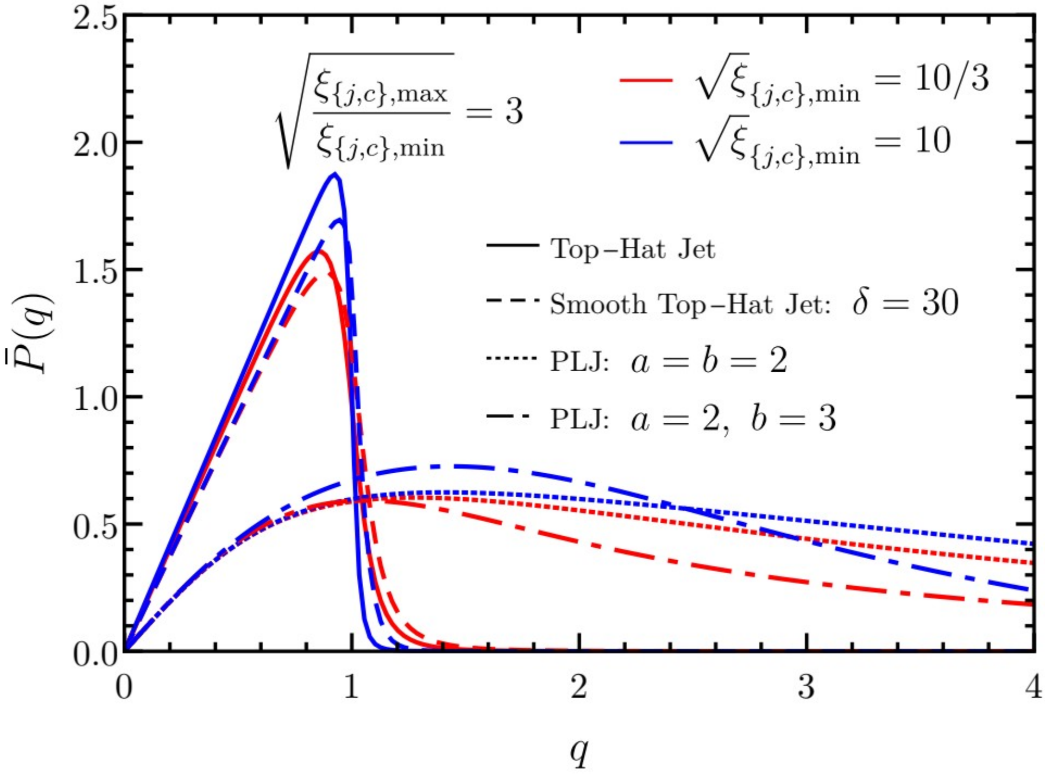
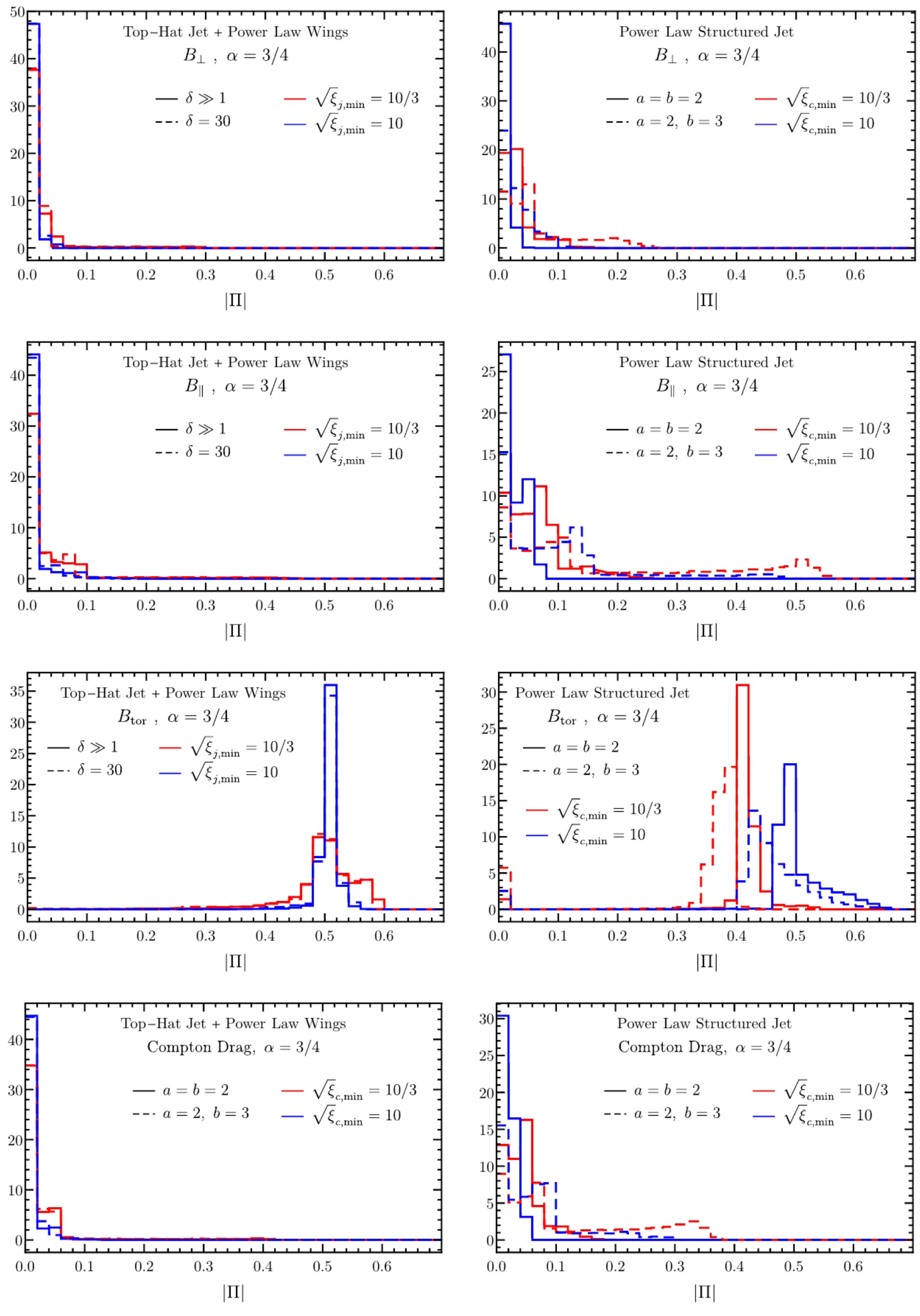


Results from Monte Carlo modeling

(Gill+18, in prep.)

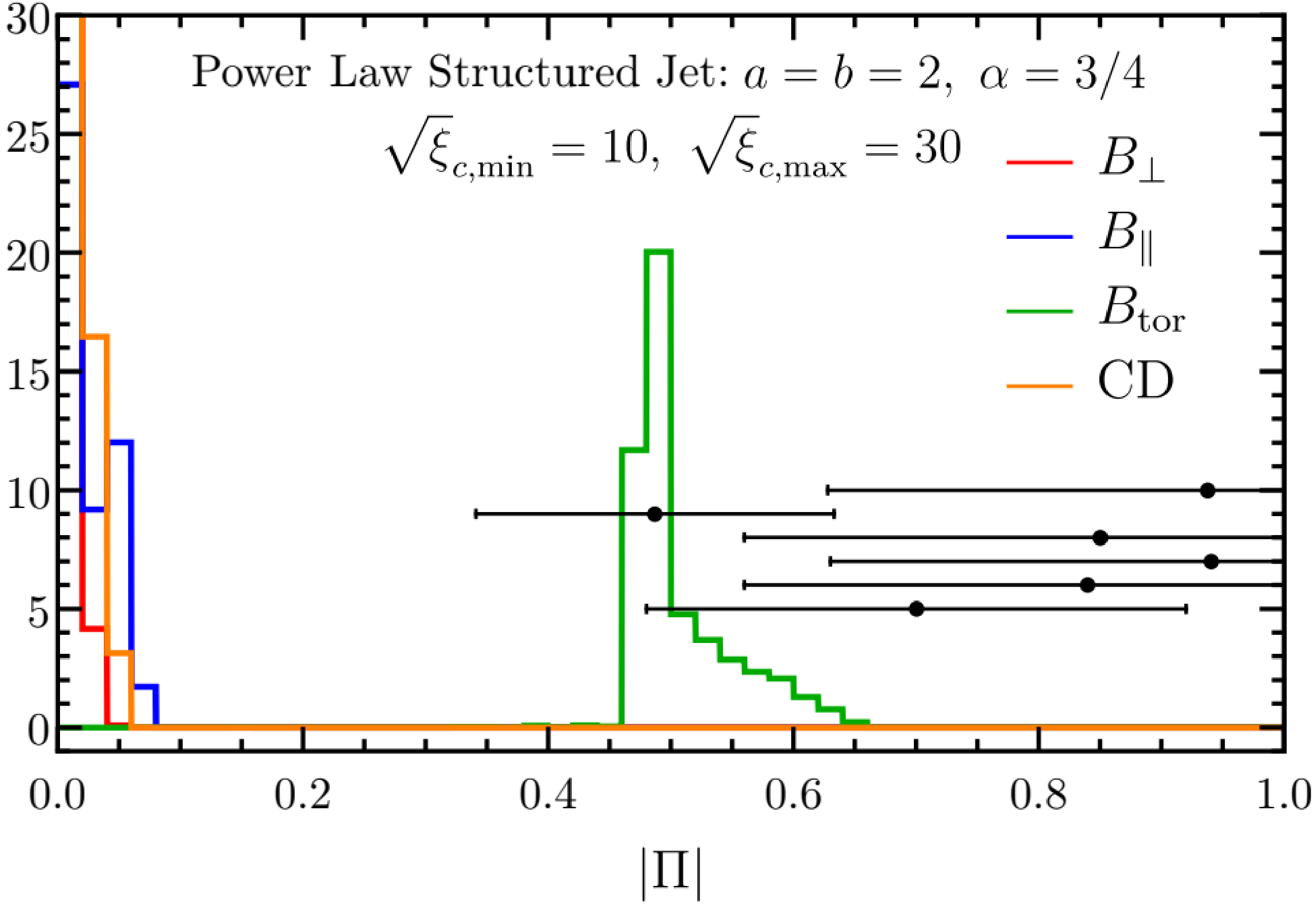


Observations of polarized prompt emission

GRB	Π (%)	PA (°)	$\sigma_{\rm det}$ (Π > 0%)	Instrument	Ref.
021206	80 ± 20	-	> 5.7	*RHESSI*[d]	Coburn & Boggs (2003)
	0		-		Rutledge & Fox (2004)
	41^{+57}_{-44}		-		Wigger et al. (2004)
041219A	98 ± 33		~ 2.3	*INTEGRAL*-SPI[e]	Kalemci et al. (2007)
	63^{+31}_{-30}[a]	70^{+14}_{-11}	~ 2		McGlynn et al. (2007)
	43 ± 25[b]	38 ± 16	< 2	*INTEGRAL*-IBIS	Götz et al. (2009)
100826A	27 ± 11[c]	159 ± 18 , 75 ± 20	2.9	*IKAROS*-GAP	Yonetoku et al. (2011b)
110301A	70 ± 22	73 ± 11	3.7	*IKAROS*-GAP	Yonetoku et al. (2012)
110721A	84^{+16}_{-28}	160 ± 11	3.3	*IKAROS*-GAP	Yonetoku et al. (2012)
160106A	68.5 ± 24	−22.5 ± 12	< 2	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160131A	94 ± 31	41.2 ± 5.0	⩾ 3	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160325A	58.75 ± 23.5	10.9 ± 17	< 2	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160509A	96 ± 40	−28.6 ± 11.0	~ 2.5	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160802A	85 ± 29	−36.1 ± 4.6	⩾ 3	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160821A	48.7 ± 14.6	−34.0 ± 5.0	⩾ 3	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160910A	93.7 ± 30.92	43.5 ± 4.0	⩾ 3	*AstroSat*-CZTI	Chattopadhyay et al. (2017)
160802A	85 ± 29	~ −32	~ 3(?)	*AstroSat*-CZTI	Chand et al. (2018a)
171010A	~ 40	variable (?)	(?)	*AstroSat*-CZTI	Chand et al. (2018b)

Comparison with current measurements

(Gill+18, in prep.)



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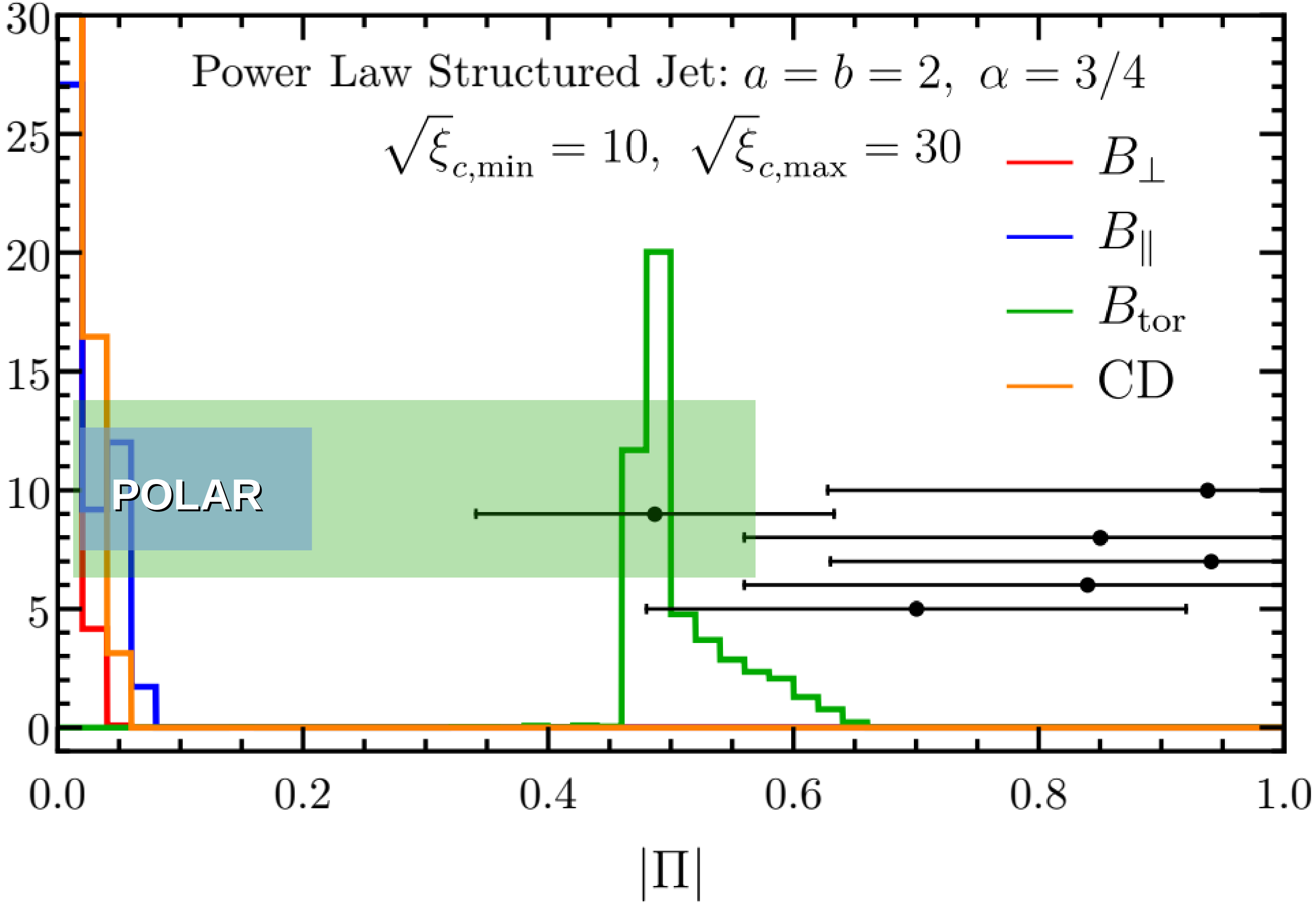

Conclusions

- Synchrotron emission from $B_\perp$ and $B_{||}$, and from Compton drag, can yield high polarization but require a special viewing angle in the case of a top-hat jet.
  - For the case of $B_\perp$: $25\% \lesssim \Pi \lesssim 45\%$
- Non-dissipative photospheric emission requires large gradients in $\Gamma(\theta)$ to produce detectable polarization.
  - We find that $\Pi \lesssim 15\%$
- Only synchrotron emission from a large scale ordered field (like a toroidal field) can yield high levels of polarization.
  - Can get polarization as high as $50\% \lesssim \Pi \lesssim 65\%$
  - This model will also be favoured if most GRBs have $\Pi \gtrsim 20\%$
- If only ~10% of GRBs have $\Pi \gtrsim 20\%$ and the rest are weakly polarized then:
  - Large scale ordered fields (e.g. toroidal field) will be disfavored
  - It would mean that the structure of the jet is very close to that of a top-hat jet.

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Thanks!