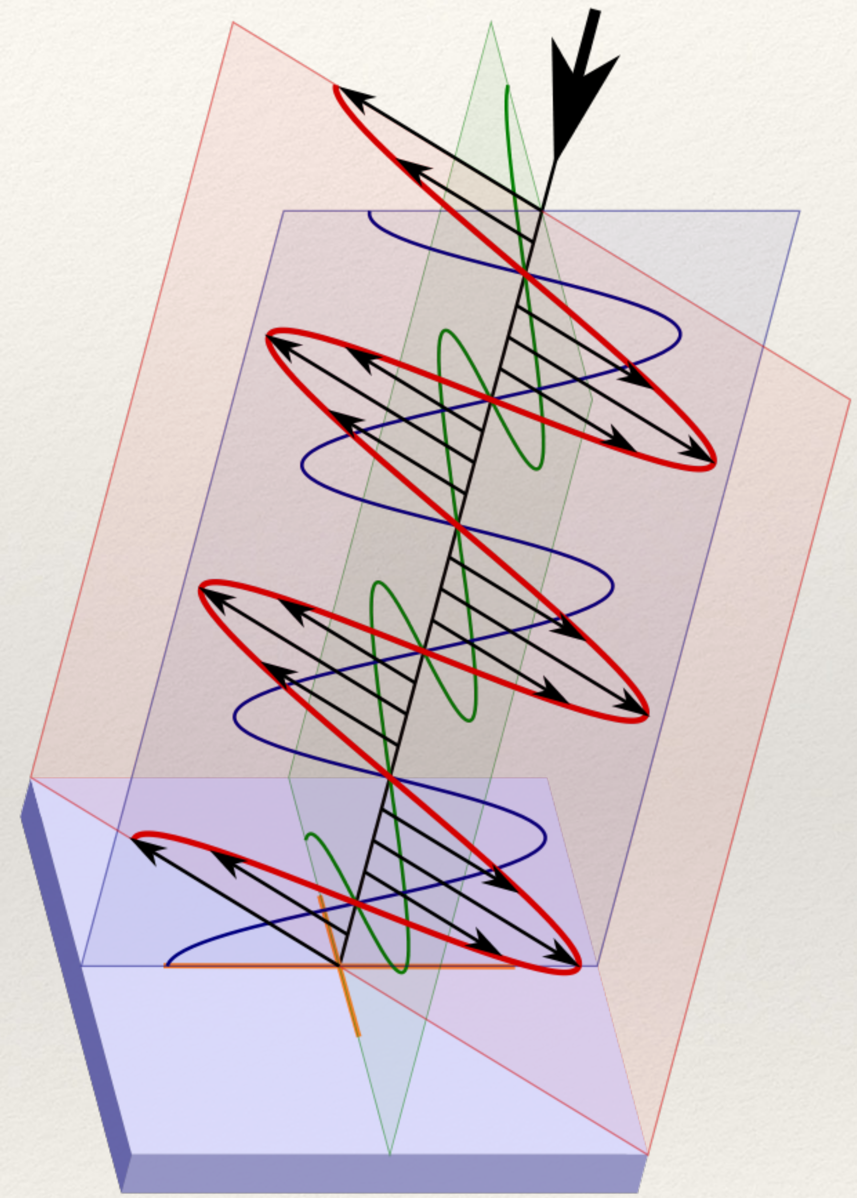
Klaas Wiersema *(kla:s wi:rsəma)*
University of Warwick

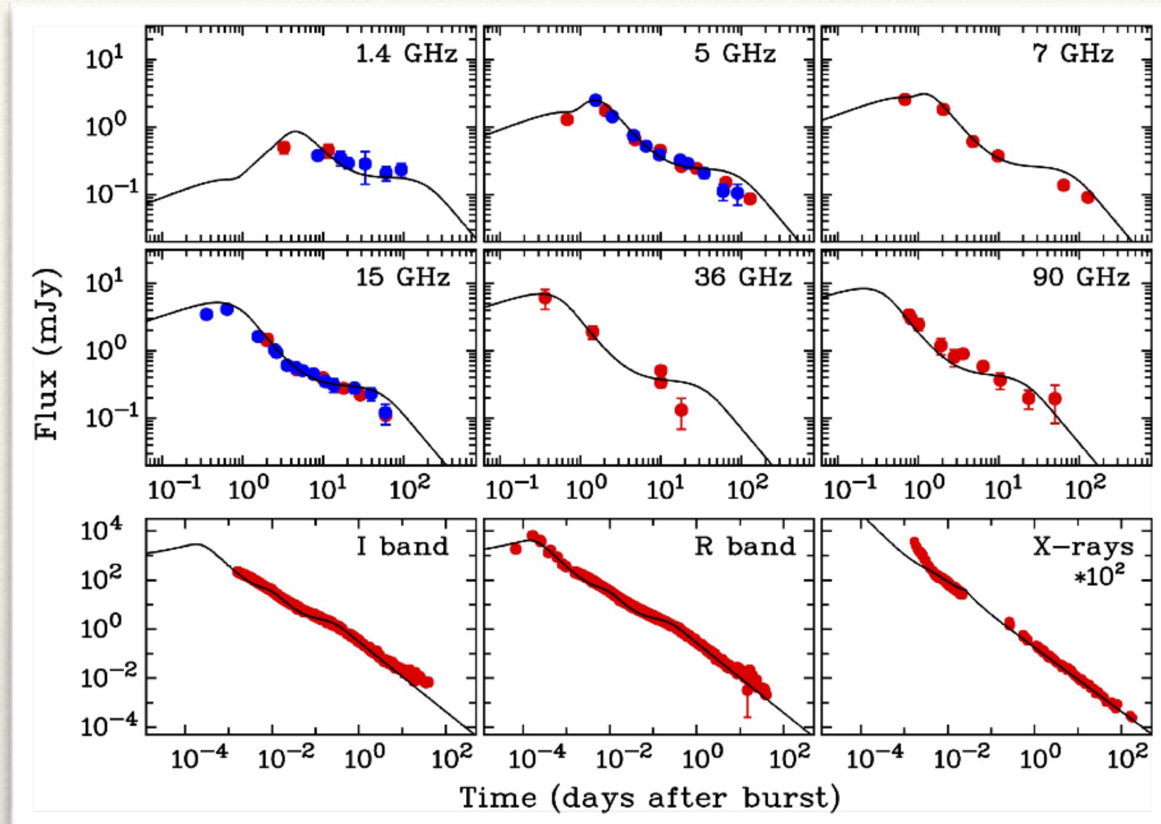
Polarimetry of GRB afterglows - and related transients

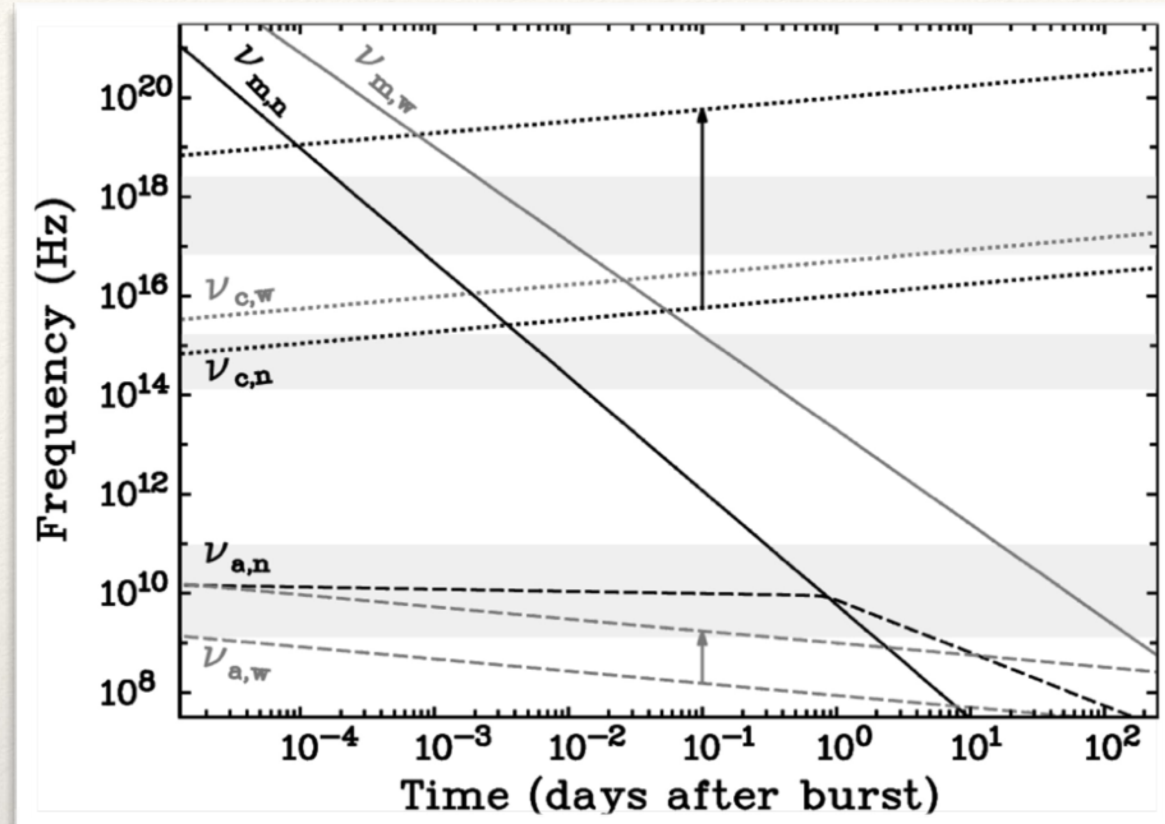
with (very) many collaborators, including:
S. Covino, A. Levan, N. Tanvir, J. Maund, R. Starling, A. Higgins, D. Steeghs, G. Leloudas, A. van der Horst, J. Gorosabel†, P. Curran†, N. Gehrels†, E. Rol, D. Russell, J. Fynbo, J. Greiner, M. Bulla, K. Toma, Y. Urata, N. Patat, D. Russell, S. Gonzalez-Gaitan, etc etc

STARGATE, ENGRAVE, SPLOT collaborations



Afterglows





van der Horst+ '14

Micro- and macrophysics of afterglows - fitting lightcurves and spectra.

Not as easy as it sounds:

- poor(ish) coverage at some wavelengths
- incomplete models (plateaus, flares, steep decays, etc)
- source selection biases
- break frequencies can spend long away from observable wavelengths
- degeneracy and confirmation bias

-> we need alternative information, e.g. *polarimetry*

Motivation to try polarimetry

Swift has produced a large number of high quality light curves (nearly 1400). Yet there are many questions that are not easily answered by simply increasing the sample size further. Independent information (e.g. polarimetry) can really help.

Open questions -

- Geometry (viewing angle, structure)
- energy injection(s)
- variation in circumburst properties
- nature of flares, plateaus, reverse shocks, etc

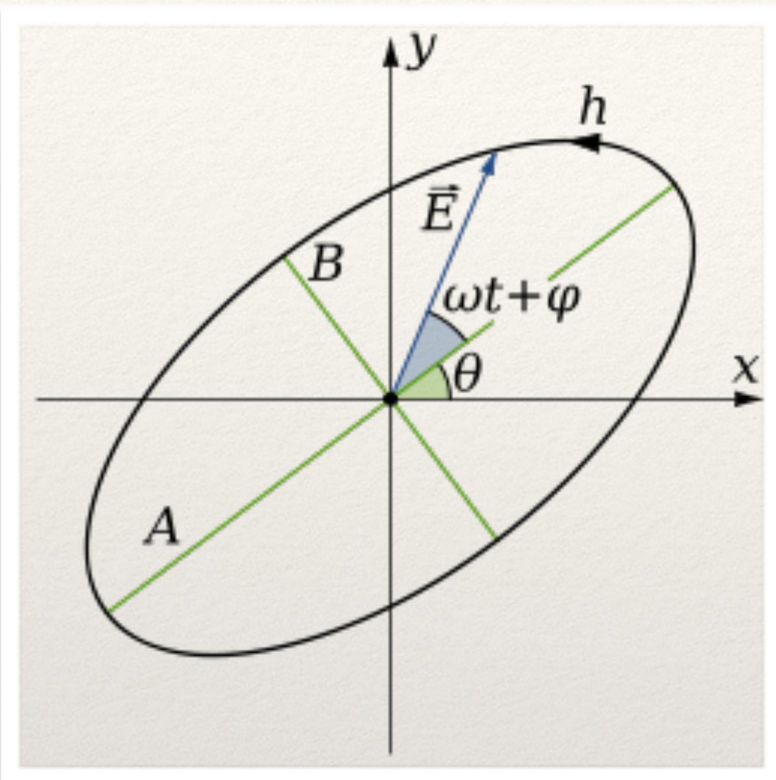
-> all hard to study within current observational datasets.

Ingredients current models

- Particle acceleration, photon emission/transport (*emission process*)
- Ultra-relativistic motion (*aberration*)
- Physical beaming/collimation (*jets, symmetry*)

Give predictions for, or constrains on, lightcurves, spectra and *polarisation degree and angle*

Brief intro - polarisation

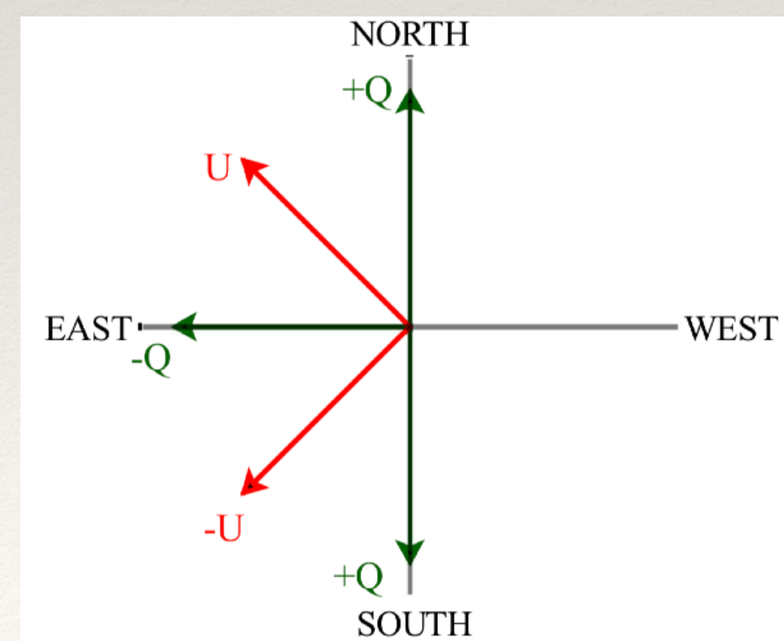


$$\vec{S} = \begin{pmatrix} Q \\ U \\ V \\ I \end{pmatrix}$$

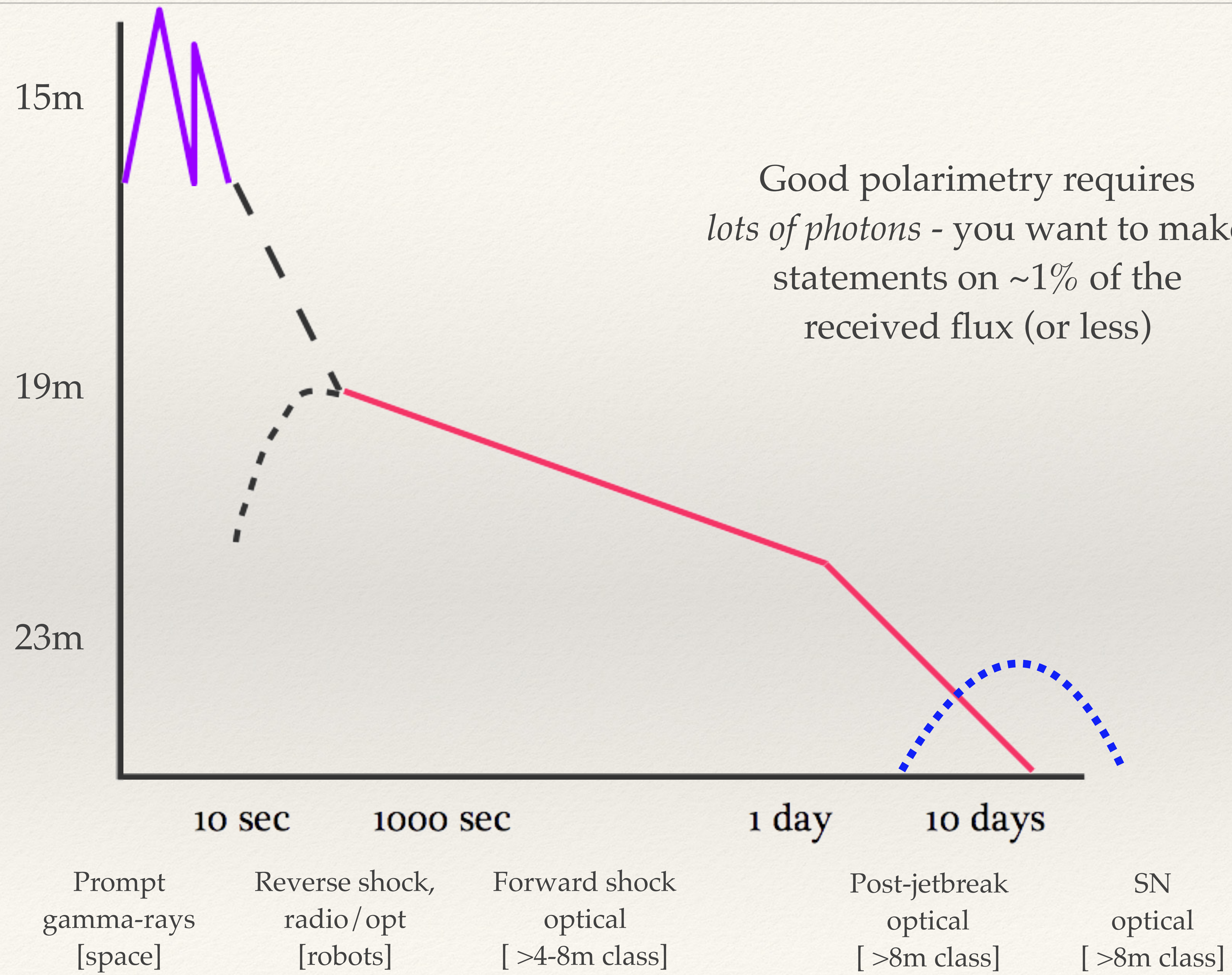
$$\begin{aligned}
I_p &= A^2 - B^2 \\
Q &= \left(A^2 - B^2\right)\cos(2\theta) \\
U &= \left(A^2 - B^2\right)\sin(2\theta) \\
V &= 2ABh \\
P_{\mathrm{lin}} &= \sqrt{Q^2 + U^2} \\
\theta &= \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right) + \mathrm{const.} \\
I_p &= \sqrt{Q^2 + U^2 + V^2}
\end{aligned}$$

Very convenient - you can express optics, radiative transport, coordinate transformations etc as matrix operations on the Stokes vector.

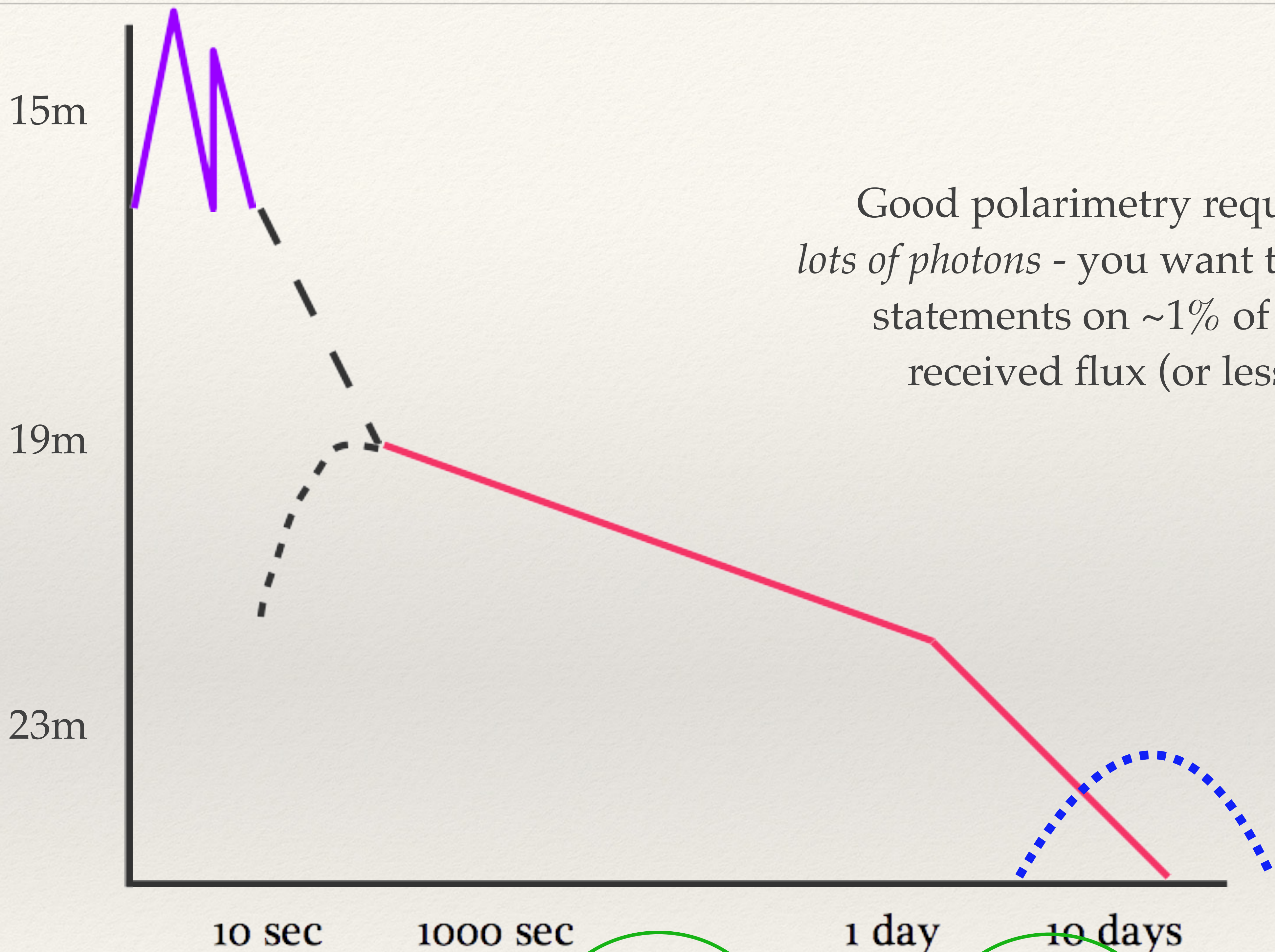
Exploit the 180° symmetry of the polarisation ellipse.
In the following I will often use $q,u,v = Q/I, U/I, V/I$



Linear polarimetry of GRB forward shocks



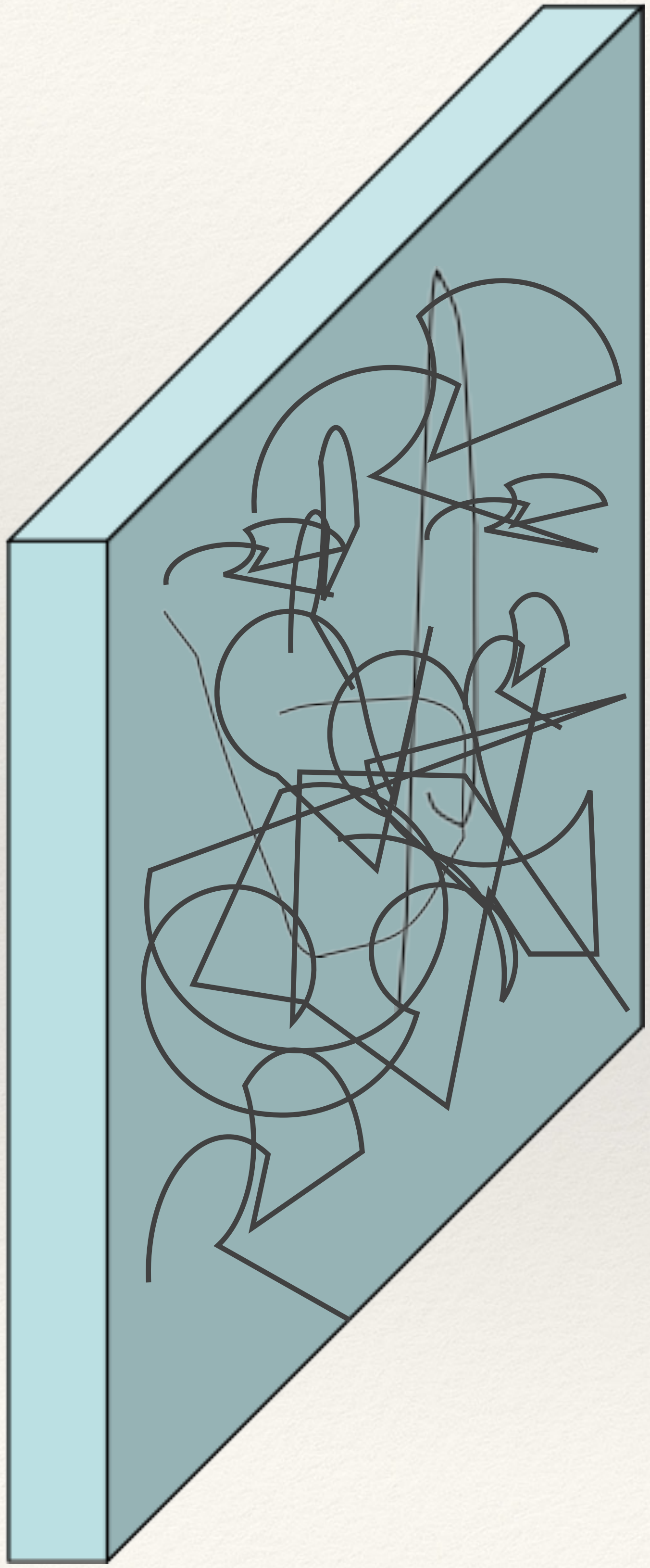
Linear polarimetry of GRB forward shocks



Good polarimetry requires *lots of photons* - you want to make statements on ~1% of the received flux (or less)

Prompt gamma-rays [space]	Reverse shock, radio/opt [robots]	Forward shock optical [>4-8m class]	Post-jetbreak optical [>8m class]	SN optical [>8m class]

Linear polarimetry of GRB forward shocks



Large polarisation?

- Synchrotron + strong coherent field
- (compton) scattering
- Synchrotron + small-scale random field at particular viewing angle

Small patches of strong coherent fields?
Observe summed signal over the observed part of the jet, erratic variations of polarisation angle

Jet break? When you experience the edge of the jet, polarisation appears

The B fields parallel and perpendicular to the shock normal could have significantly different averaged strengths (Medvedev & Loeb '99)
Some degree of alignment if observed edge-on.

Linear polarimetry of GRB forward shocks

Large polarisation?

- Synchrotron + strong coherent field
- Synchrotron + small-scale random field at particular viewing angle
- (compton) scattering

Small patches of strong coherent fields?
Observe summed signal over the observed part of the jet, erratic variations of polarisation angle; ~70% / sqrt(N)

Jet break? When you experience the edge of the jet, polarisation appears

The B fields parallel and perpendicular to the shock normal could have significantly different averaged strengths (Medvedev & Loeb '99)
Some degree of alignment if observed edge-on.

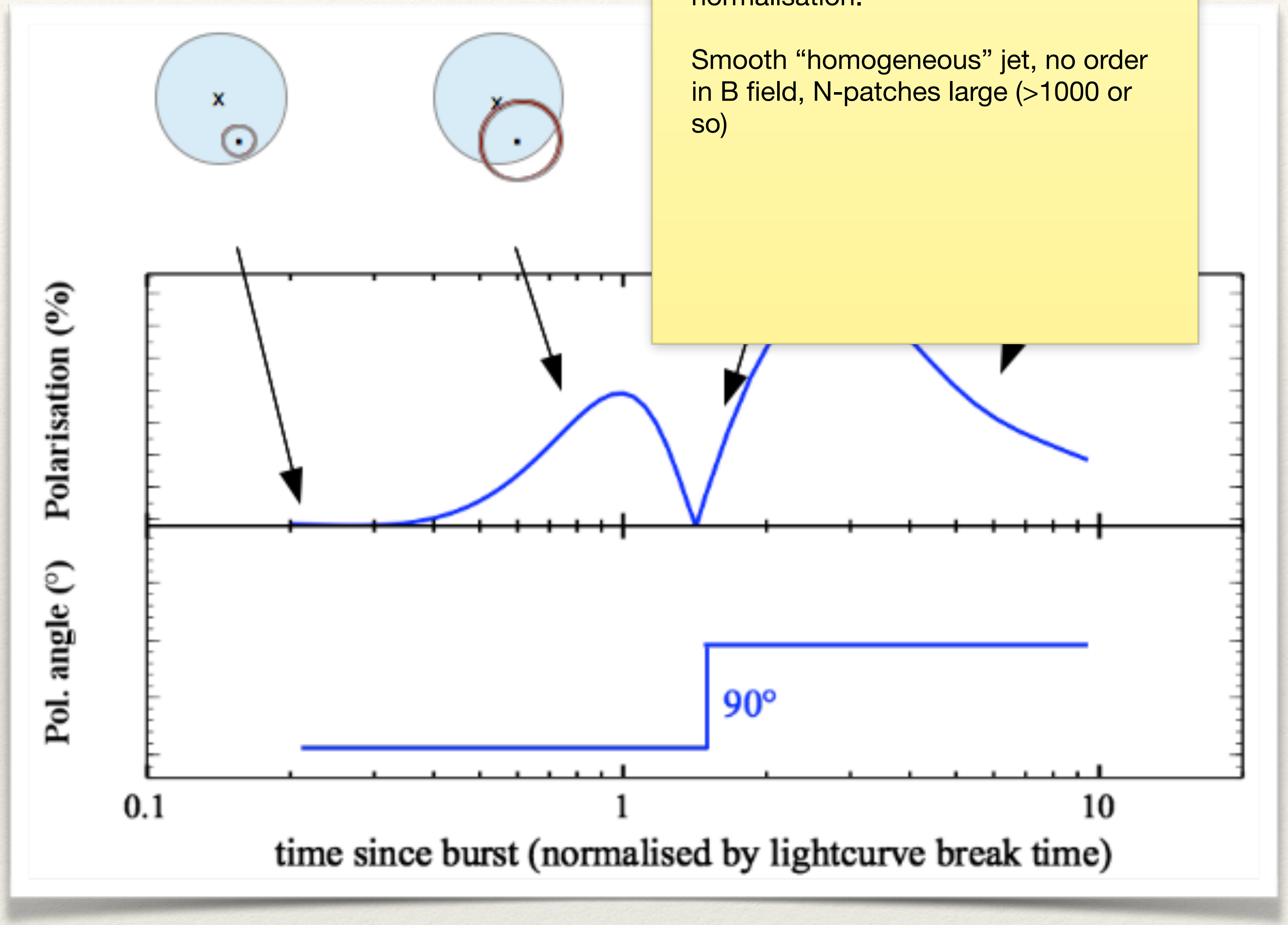
A different perspective: linear polarimetry

If the shock generated B field in the jet is incoherent (but in the shock), and the jet is smooth, P averages out over the ring: radiation of ring is polarised in local radial direction, and we see summed emission over ring. But at late times, the ring "sees" the jet edge: netto polarisation emerges as radial components don't add up to zero anymore. [Lazzatti '06]

- *Polarisation probes jet opening angle and viewing angle*

Two linear polarisation bumps, with 90° angle shift around time when half the ring falls off the jet.

- *Shape of the polarisation curve depends on jet structure and B-field geometry and viewing angle*

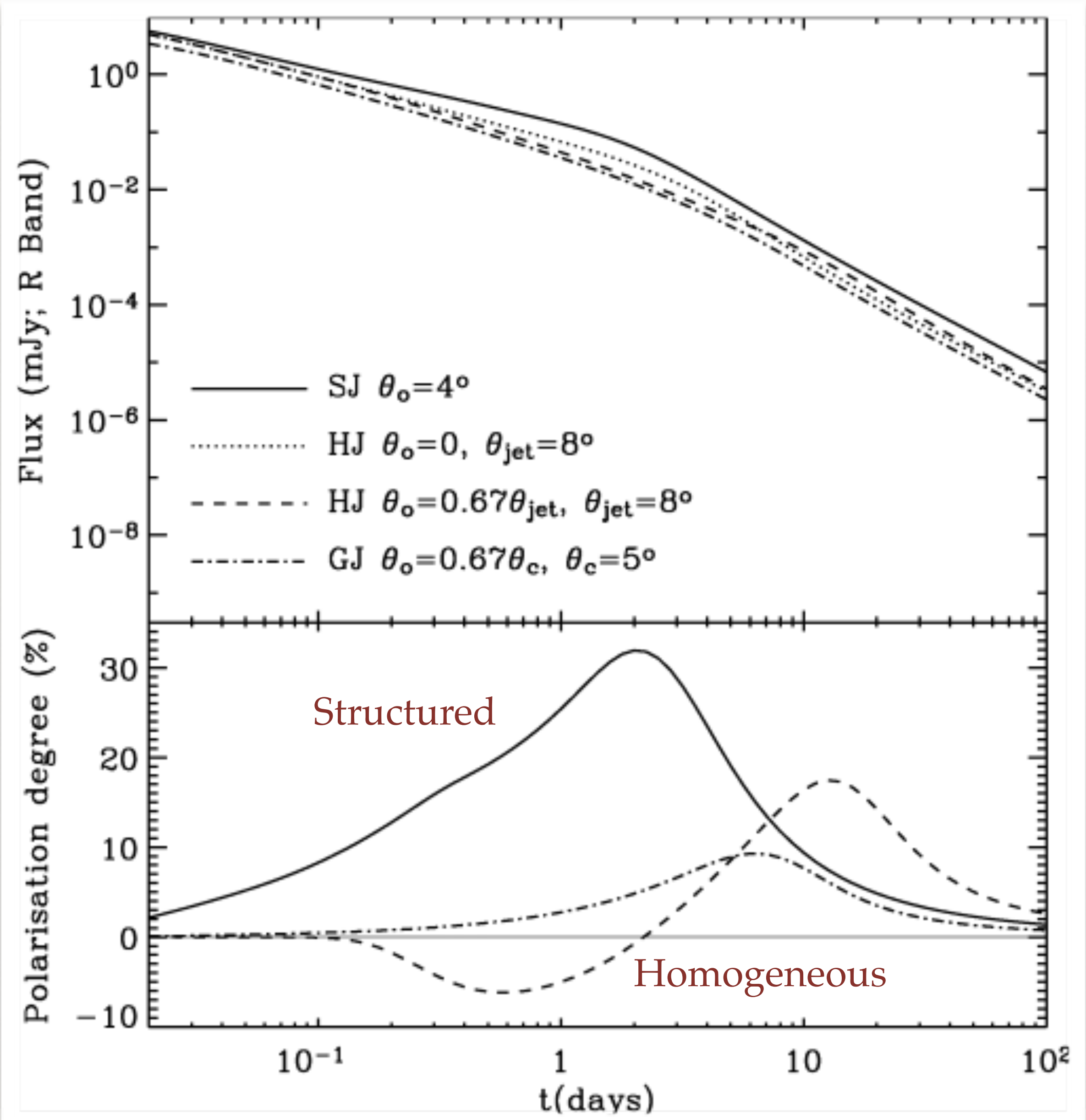


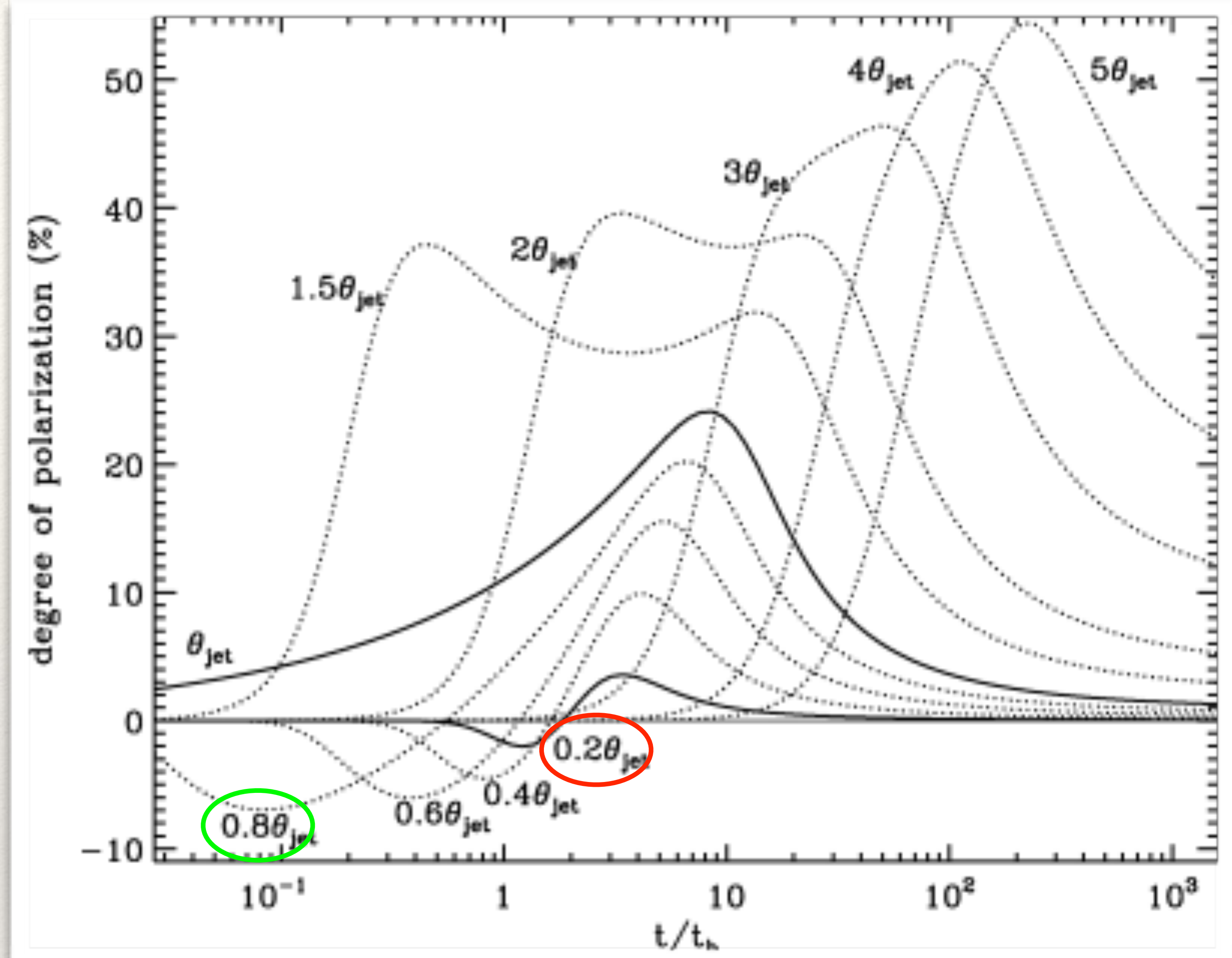
Because of relativistic effects (rel. beaming of electrons, bulk rel motion (light travel time effects)), the visible part is a ring-like shape, which expands.

Seeing edge: break in light curve, aka "jet break": this is used as normalisation.

Smooth "homogeneous" jet, no order in B field, N-patches large (>1000 or so)

Linear polarimetry of GRB forward shocks



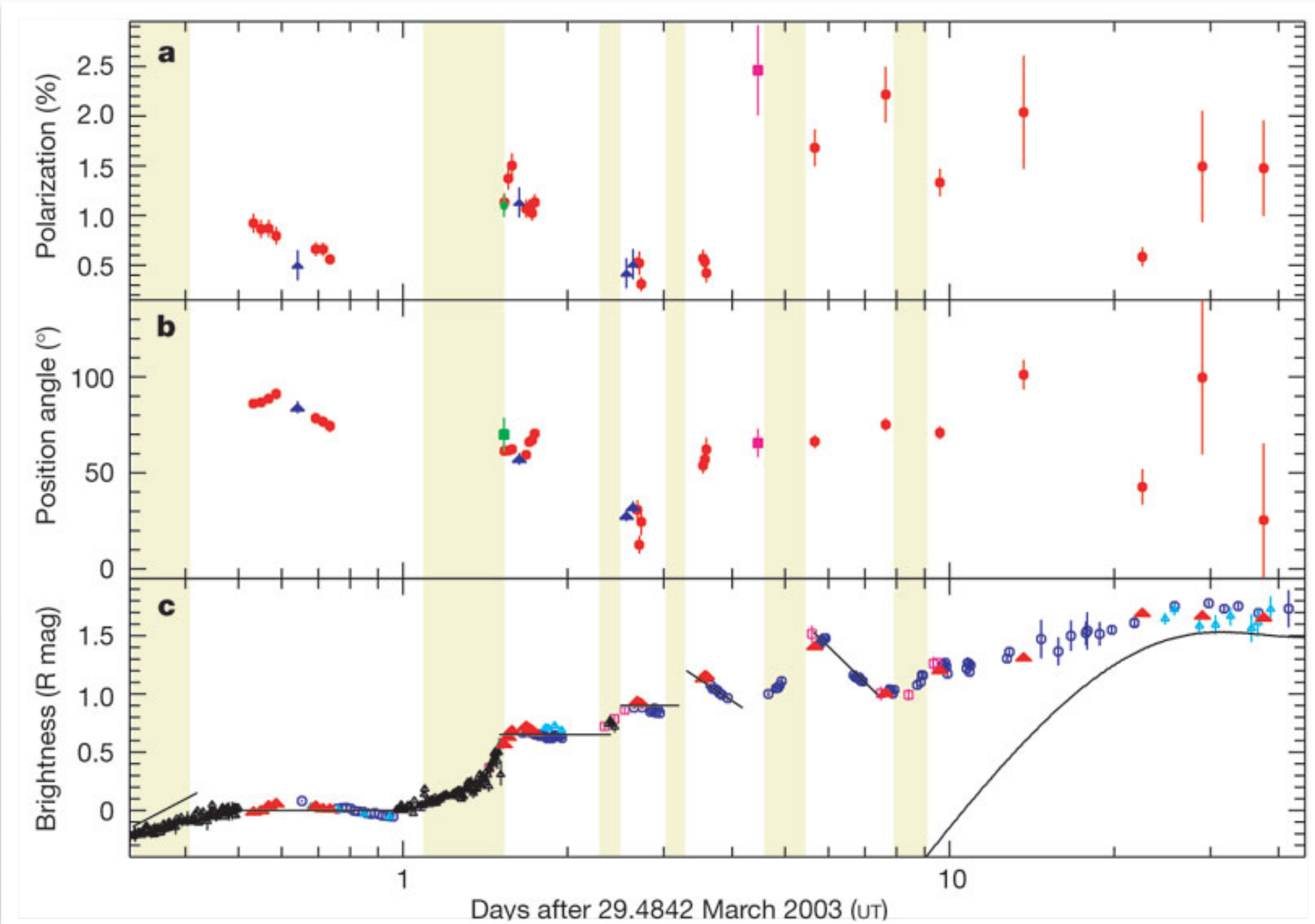


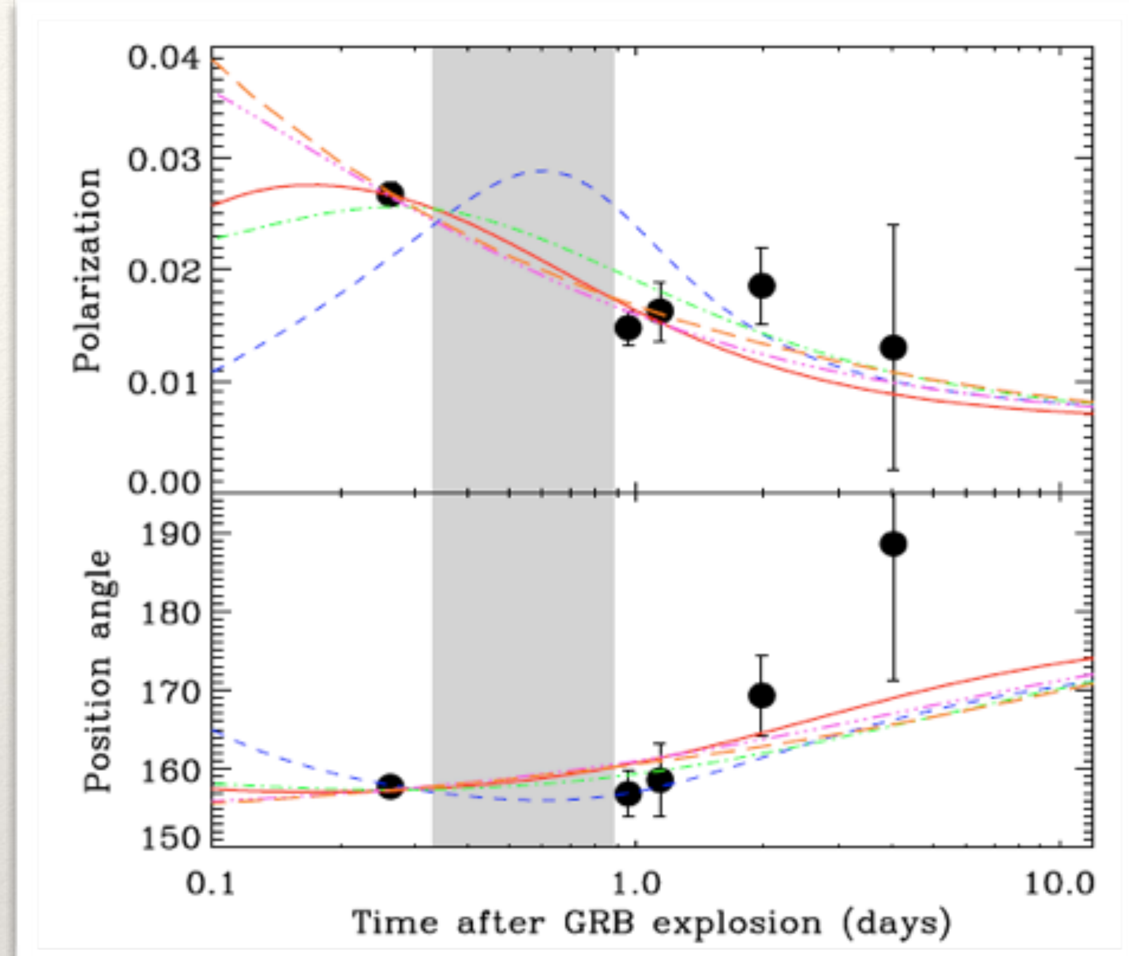
Rossi+ '04

- Jet emission structure
- B-field structure
- viewing angles

Give very different polarisation curves, while light curves are hardly affected.

pre-Swift



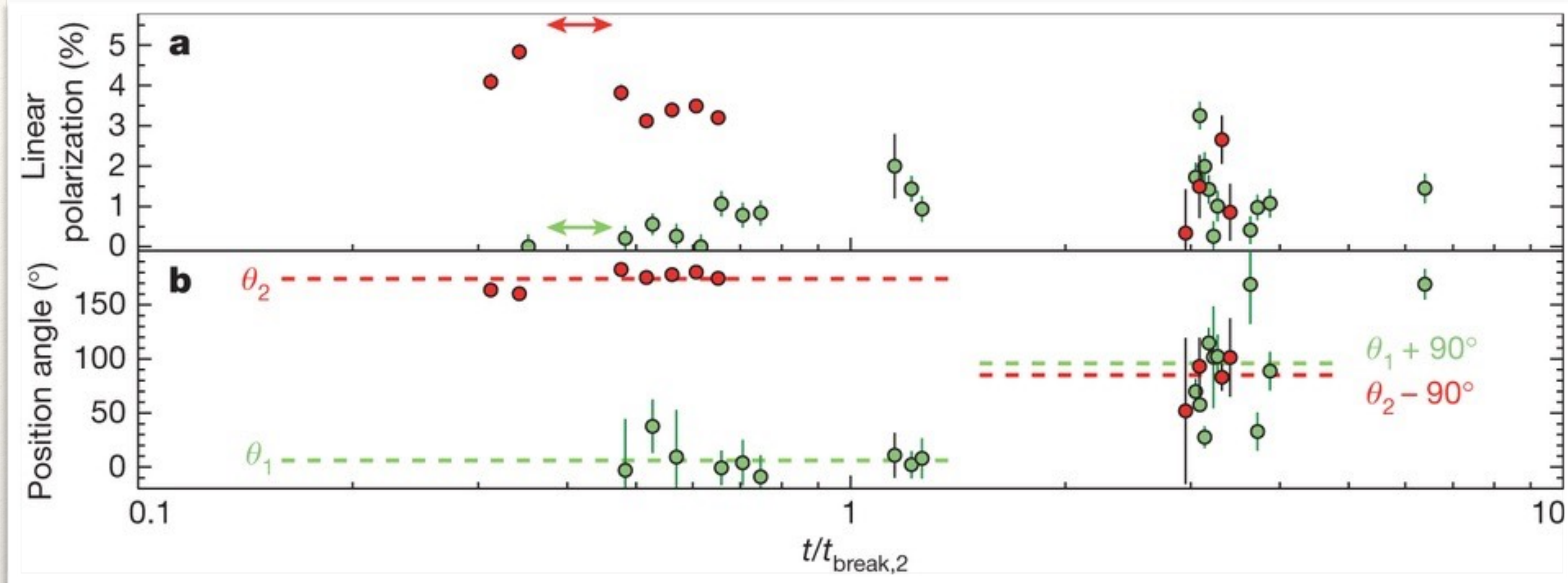


Greiner+ 03

Lazzati+ 04

The bumpy and the smooth: 030329 and 020813
No PA swing - perhaps *P* dominated by large scale ordered field, while emissivity dominated by random tangled field made by post-shock turbulence. P varies as result of changes in the ratio of the ordered-to-random mean-squared field amplitudes? (Granot+)
Predicts small P around t_{jet}, little PA change, bumps in light curve produce P changes.

Linear polarimetry of GRB forward shocks

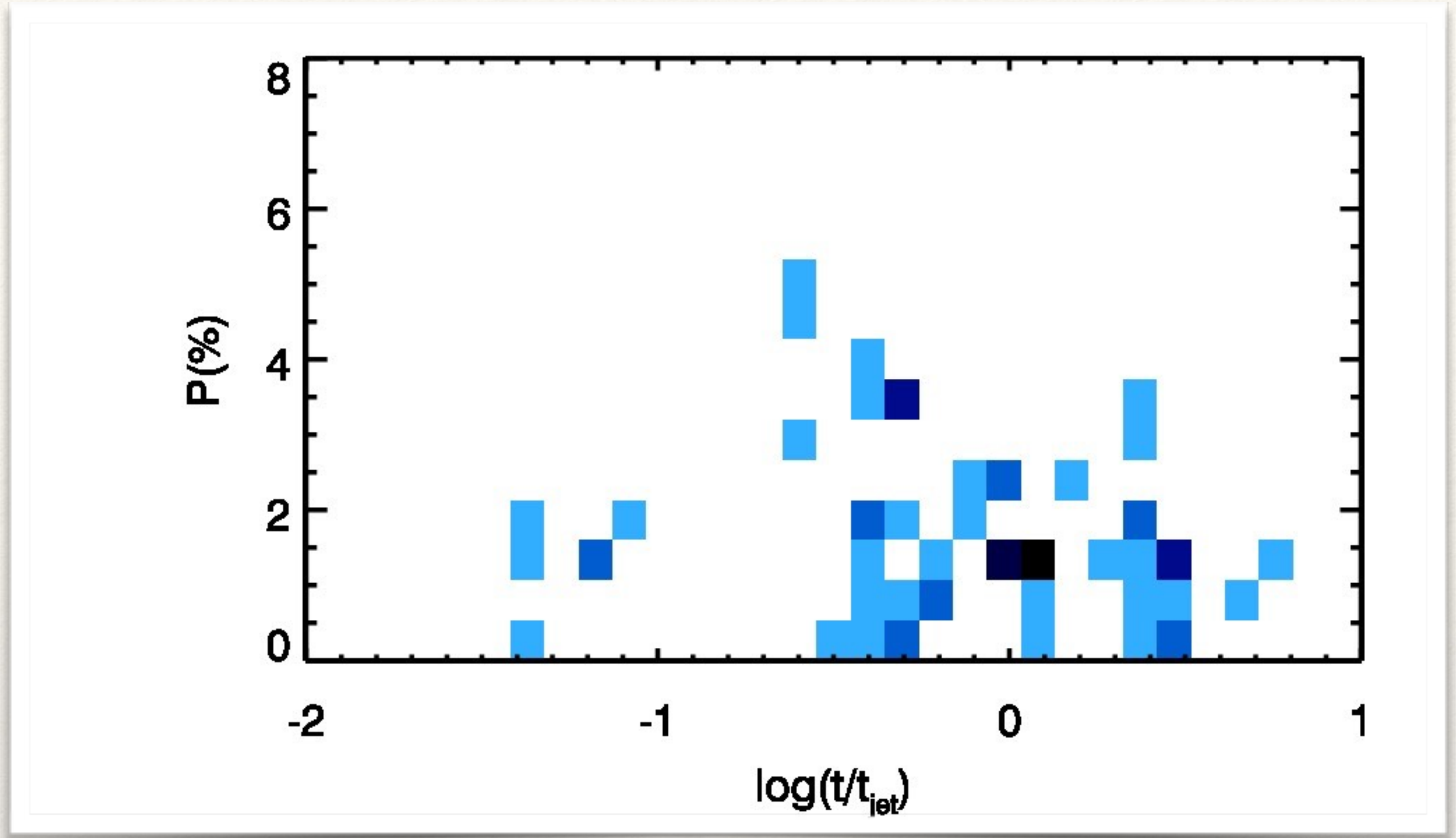


VLT FORS2
GRB091018, 121024
KW+ '12,
KW+ '14 Nature 509, 201

A first hint at a 90 degree flip. These datasets are *very* difficult to get.

We can use a snapshot survey approach to boost our understanding now.

Sample, biases

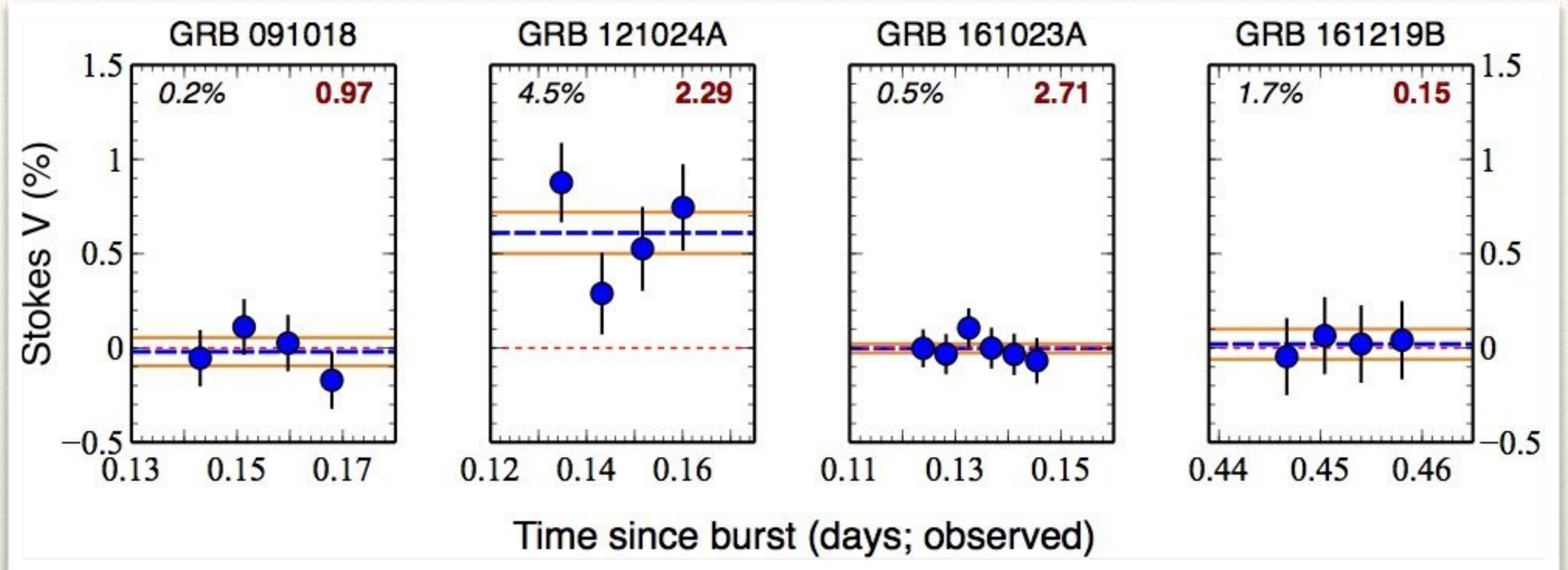


KW 13

Sample of afterglows with polarimetry is ~35 sources, majority has 1 or 2 datapoints few hours after burst. Biggest provider is VLT. Very few with good polarimetry considerably after t_{jet}. Very early data limited to robots, brightest sources (VLT RRM low success rate). P is generally low around jet break time (not like expectation from structured jets toy model).

Some classes poorly studied: no polarimetry of short GRB afterglows. only 1 ultralong (121027A, which has P~5%, Starling+ in prep), no high-z or very dusty bursts

Optical circular polarisation P_{cir}

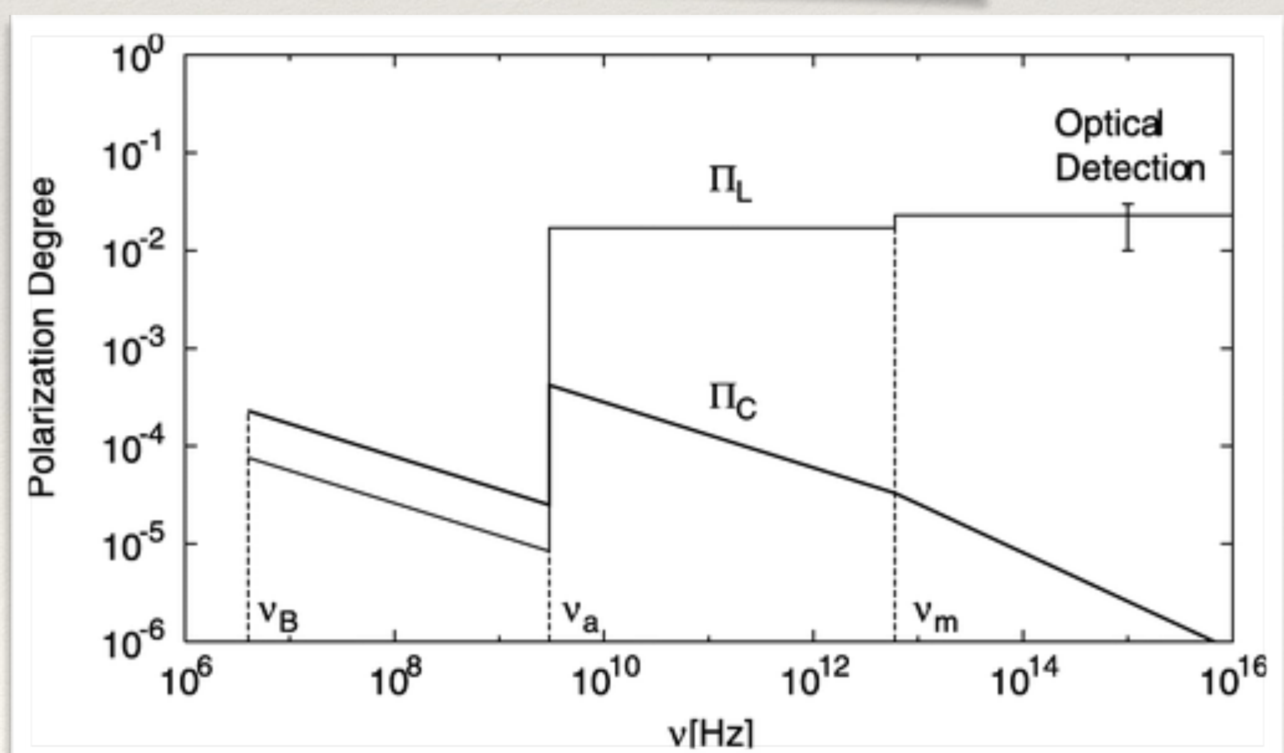


KW+ '14, KW+ in prep

In 121024A we saw non-zero P_{cir}. Restframe UV (z=2.3) P_{cir} / P_{lin} ~0.1, high! Some intrinsic explanations proposed and some refuted (KW+ '14; Nava+ 16'; Mao+ '17; Batebi+ '16; Lin+ '17)

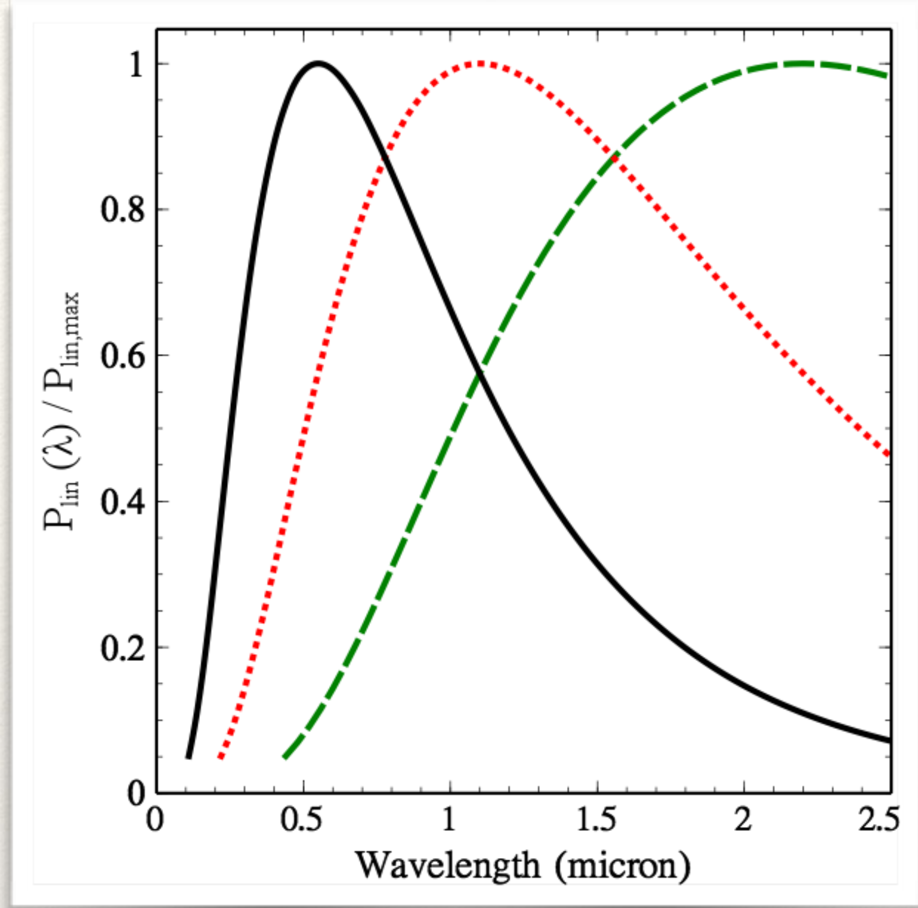
Since then, a further 2 sources showed no P_{cir} detection, but these also have much lower P_{lin}.

Radio: some good limits (e.g. van der Horst+ '14)



Toma+ '08

Dusty lines of sight: polarisation



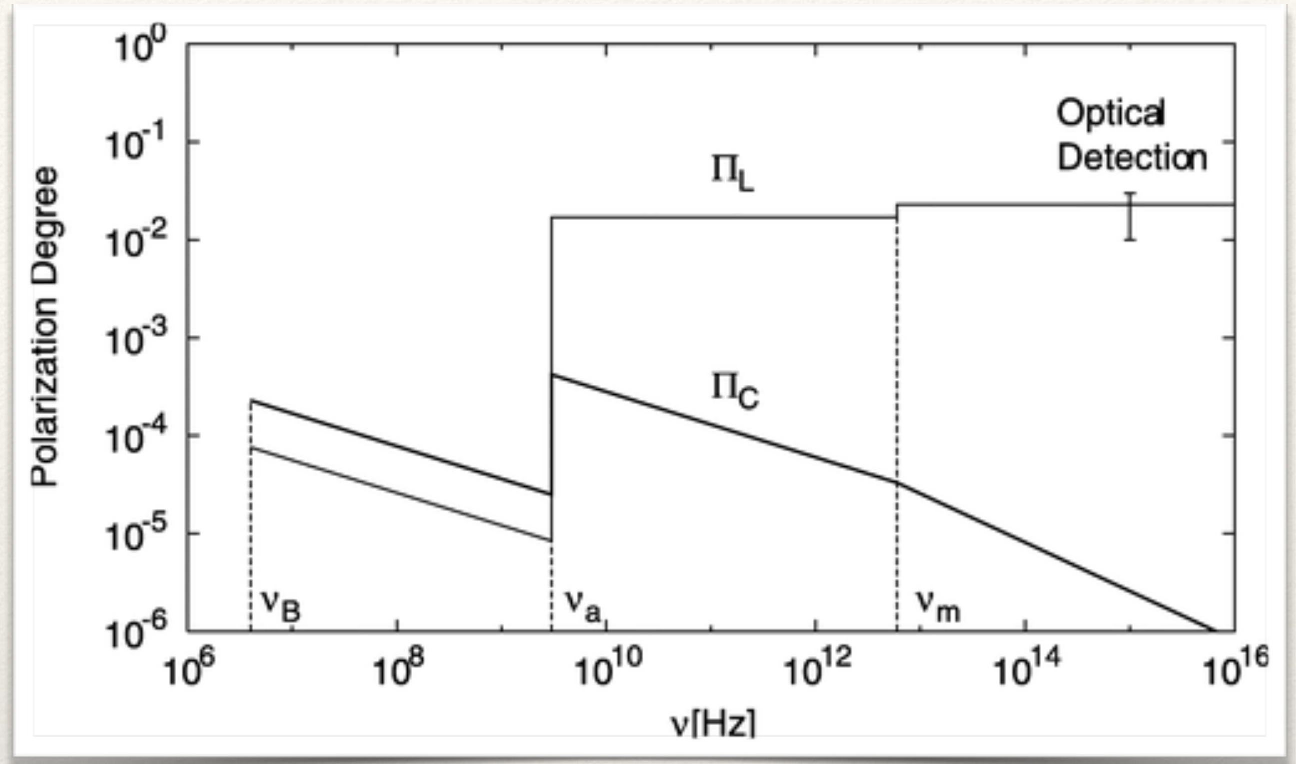
Dust scattering to increase P_{cir}:

- Multiple scattering in optically thick medium of dust grains
- Dichroic scattering by non spherical, partly aligned grains
- Dichroic extinction of linearly polarised radiation by partly aligned grains

Level of P_{lin} and P_{cir} depends on degree of alignment, source inclination and dust column

Likely these effects don't play a role for the GRBs with circular polarimetry, but interesting to study for a bright dusty GRB sightline.

Multi-wavelength polarimetry



Toma+ '08

Nowadays, multi-wavelength polarimetry is possible. Some recent examples

- 130427A: WSRT + WHT polarimetry
  (van der Horst+ '14; KW+ in prep)

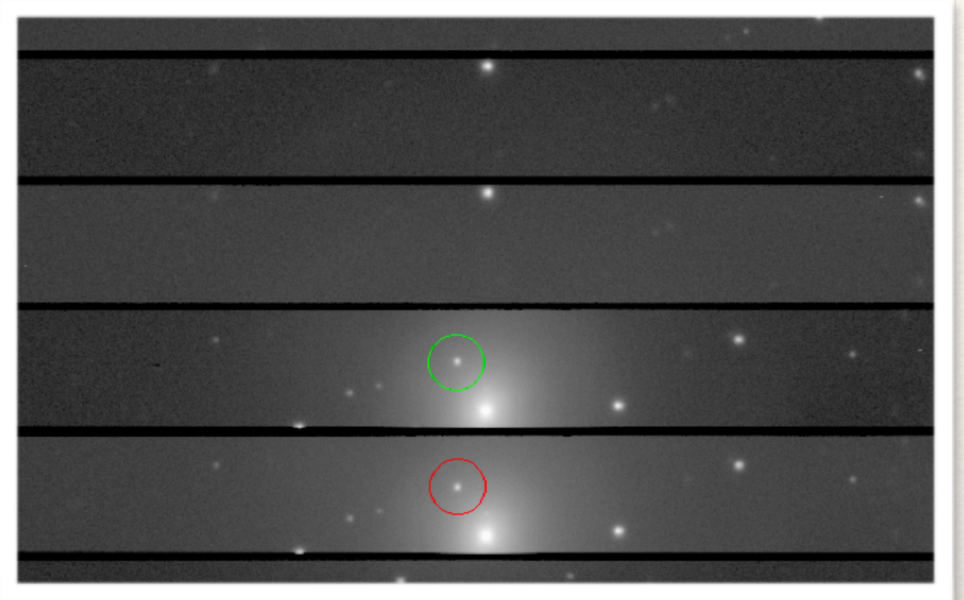
- *190114C*: ALMA + VLT polarimetry (lin + circ)
- *190829A:* ALMA + VLT polarimetry (lin)

These last two are MAGIC/HESS sources.

In future we may even see X-ray polarimetry of afterglows (e.g. eXTP), crucial for understanding plateaus and flares (e.g. Geng+ '18)

170817 again

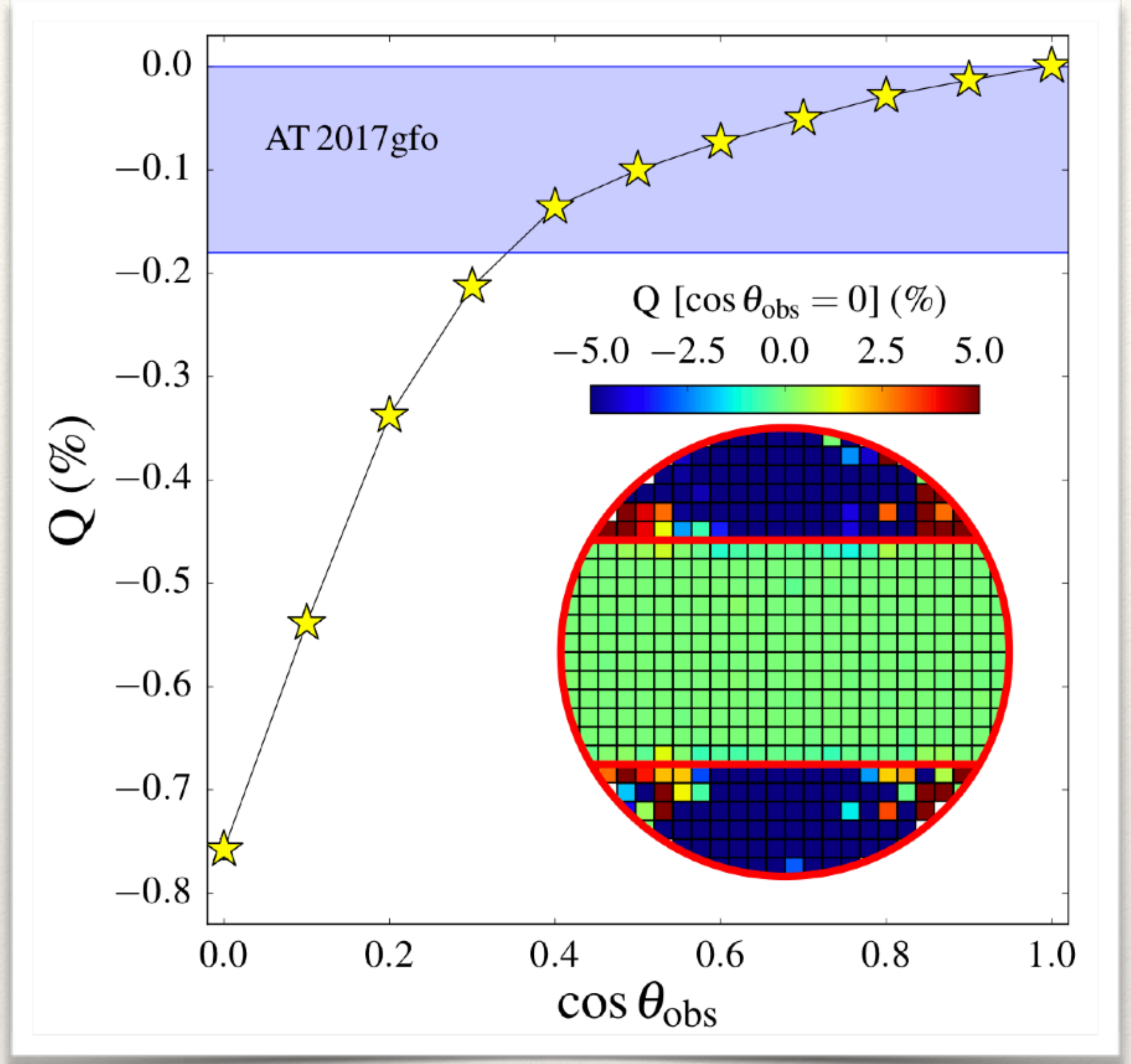
T-T$_{GW}$ (days)	Q/I	U/I	Polarization (%)	Position Angle (deg)	Magnitude (AB)
1.46	-0.0021 ± 0.0008	$+0.0046 \pm 0.0007$	0.50 ± 0.07	57 ± 4	17.69 ± 0.02
2.45	-0.0025 ± 0.0016	$+0.0044 \pm 0.0032$	< 0.58	-	18.77 ± 0.04
3.47	-0.0009 ± 0.0015	$+0.0034 \pm 0.0024$	< 0.46	-	19.27 ± 0.01
5.46	-0.0029 ± 0.0033	$+0.0026 \pm 0.0050$	< 0.84	-	20.39 ± 0.03
9.48	$+0.0412 \pm 0.0216$	-0.0095 ± 0.0126	< 4.2	-	20.69 ± 0.11

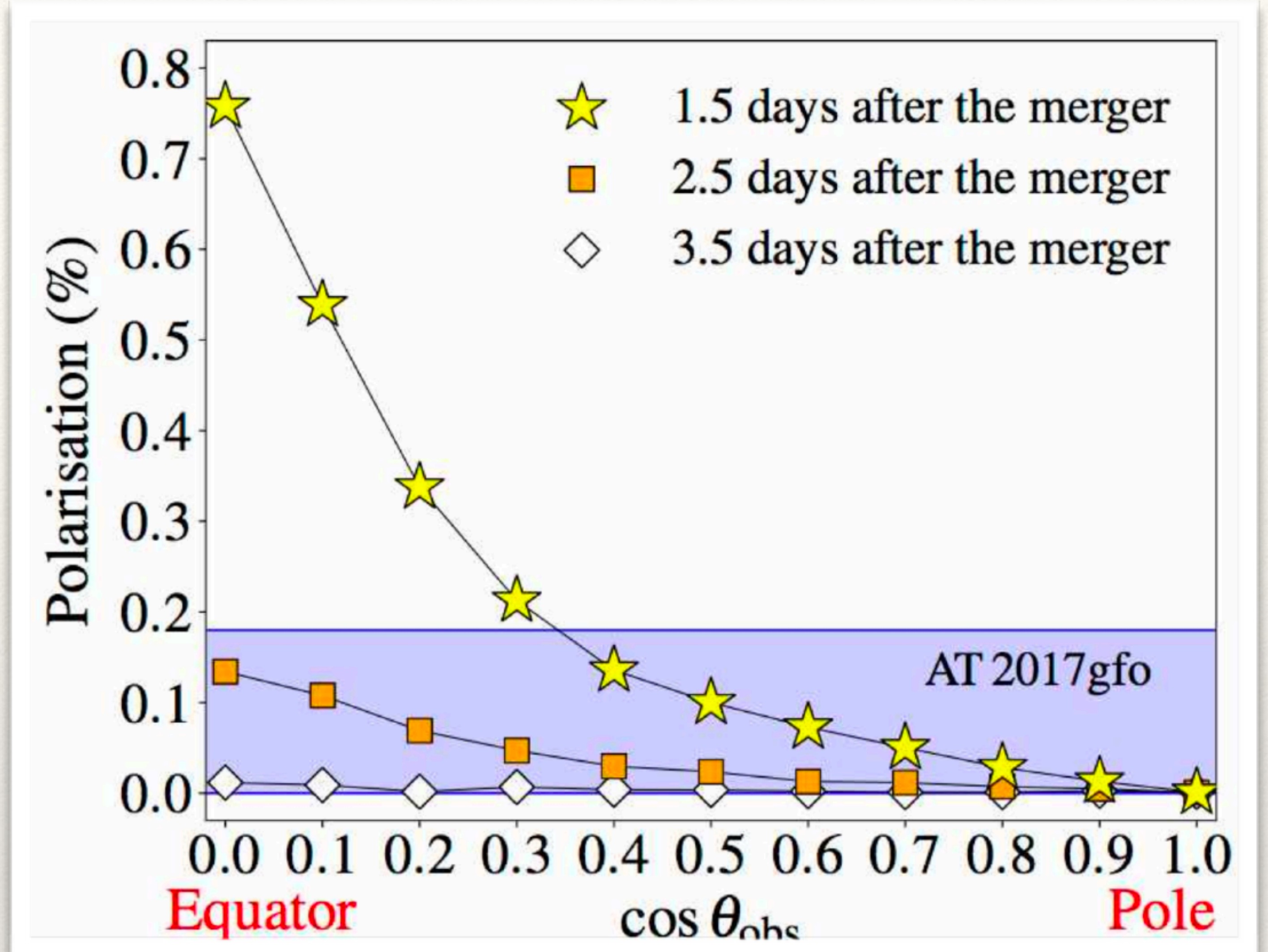


KW+ ’17
Covino, KW+ ’17

I will leave out GRB-SN polarimetry, but will discuss…..: GW170817. Intensive FORS2/VLT polarimetry campaign. Challenging: bright host and twilight! The only polarimetric dataset of a KN to date.
=> Low polarisation KN

170817 again





Bulla+ '18; Bulla+ in prep

Red KN: depolarised by line interaction, blue KN polarised by electron scattering. Radiaton propagation sims for prediction. Polarisation gone after ~2-3 days. Low polarisation KN: constraint on viewing angle (within ~60° of pole).

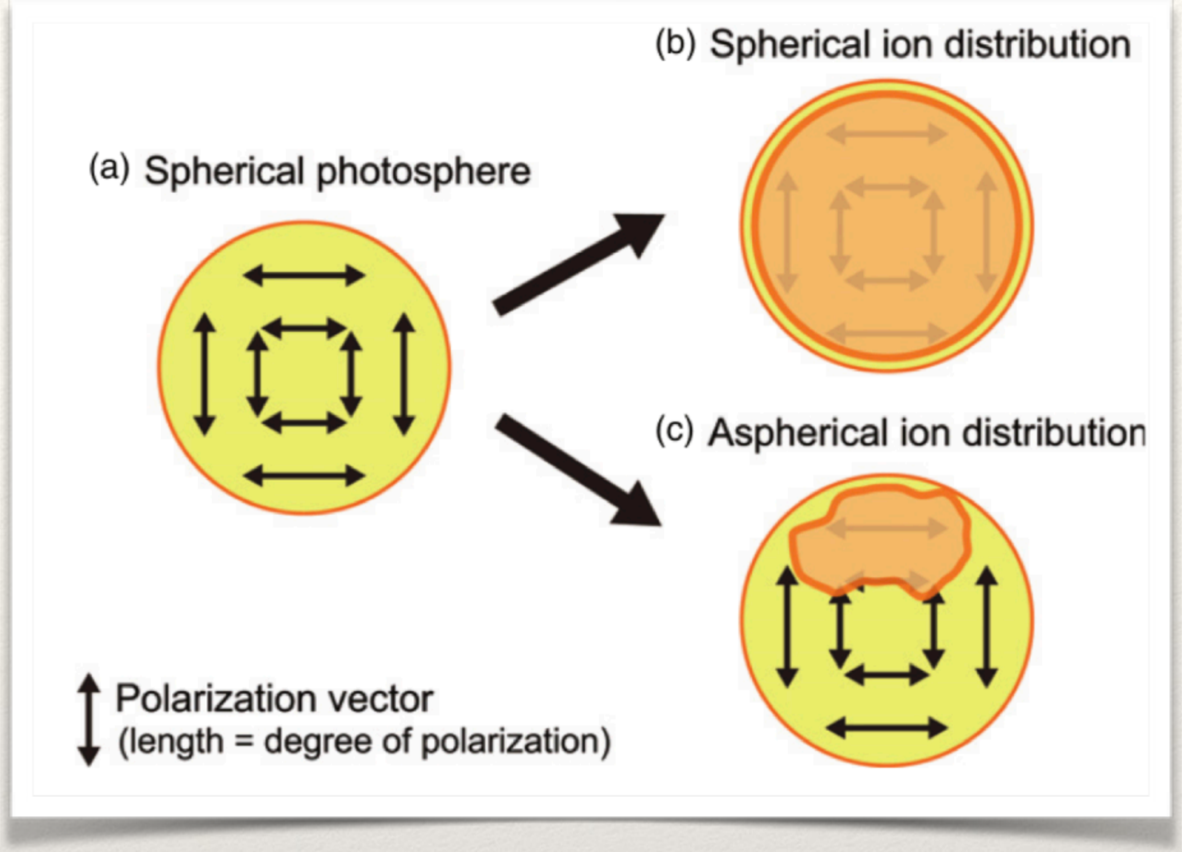
Off-axis, likely structured jet - but why no radio polarisation (Corsi+ '18)? B field component normal to shock? (Gill & Granot '19)

GRB-SN polarimetry

At (very) late times we can see the SN.

Spectro-polarimetry of GRB-SNe has given small but nice sample (4 GRB-SNe if I counted right). Electron scattering at photosphere, spherical SNe are unpolarised. Asymmetry, or asymmetric distribution of an ion, can give net polarisation (line (de)polarisation can be detected).

Circular polarimetry can also be used to search for magnetar energy injection in regular stripped-envelope SNe (Cikota+)



Cano+ '16

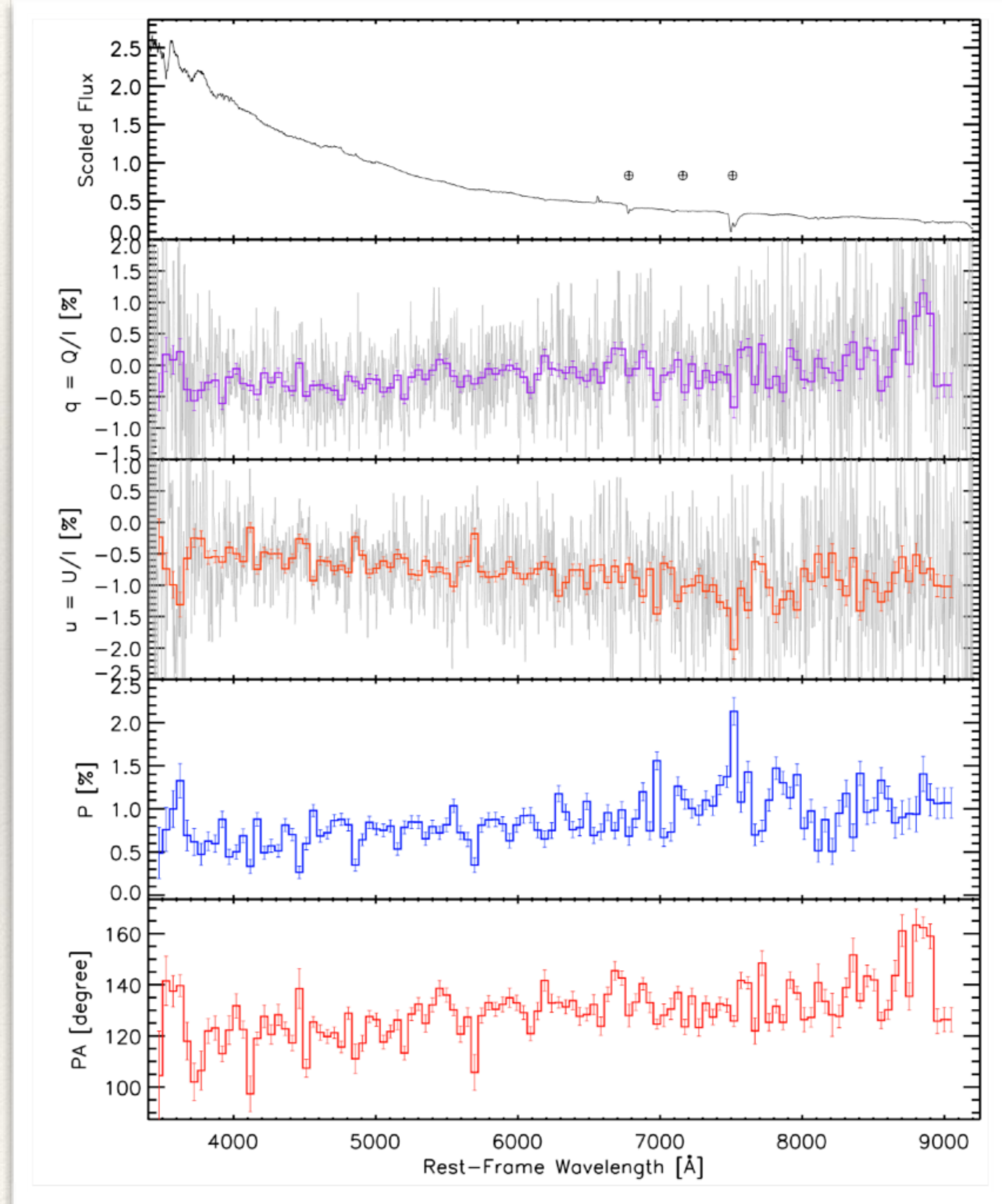
AT2018cow

Weird source (Prentice+ 2018; Rivera-Sandoval+ 2018; Ho+ 2018; Perley+ 2018; Kuin+ 2018; Huang+ 2019; Margutti+ 2019). SN? TDE? Bright radio+mm source (synchrotron from sub-rel shock in dense medium), X-ray emission at late times (engine?), fast rise+hot temperature and weak features at optical. Unlike previous transients.

Asymmetry/engine/non-thermal: motivation for polarimetry.

- 2 epochs ALMA: P<0.10% at 97.5 GHz and <0.15% at 233 GHz (Huang+ 2019), spectral break
- Opt. spectropolarimetry: Bok and VLT (Melandri+ in prep)
- Opt+ IR imaging polarimetry: WHT and TNG (Melandri+ in prep)

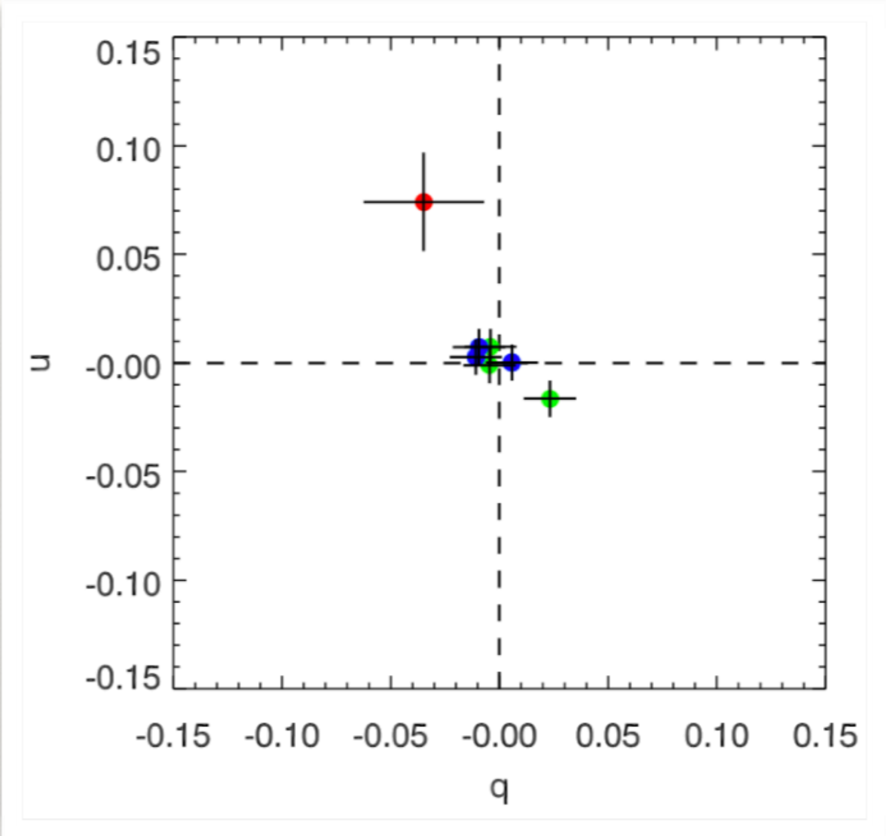
Continuum polarisation rises from ~0.7 % at $t-t_0$~5 d to >2% at 20 d, angle stays constant.



Yang+; Melandri+ in prep

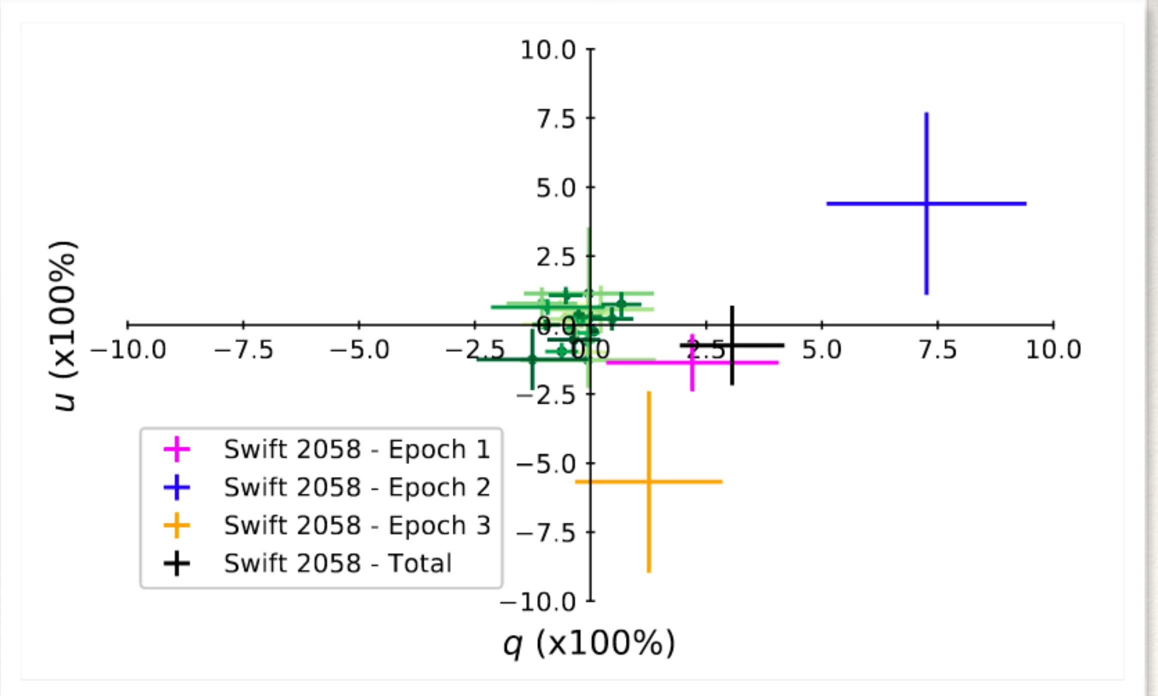
Relativistic TDEs

Small sample of TDE candidates with a bright X-ray and radio counterpart. Radio evolves as expected from a relativistic outflow. Complex SEDs.
In XRBs we often see polarisation in optical/IR from the jet, even if emission dominated by disks.



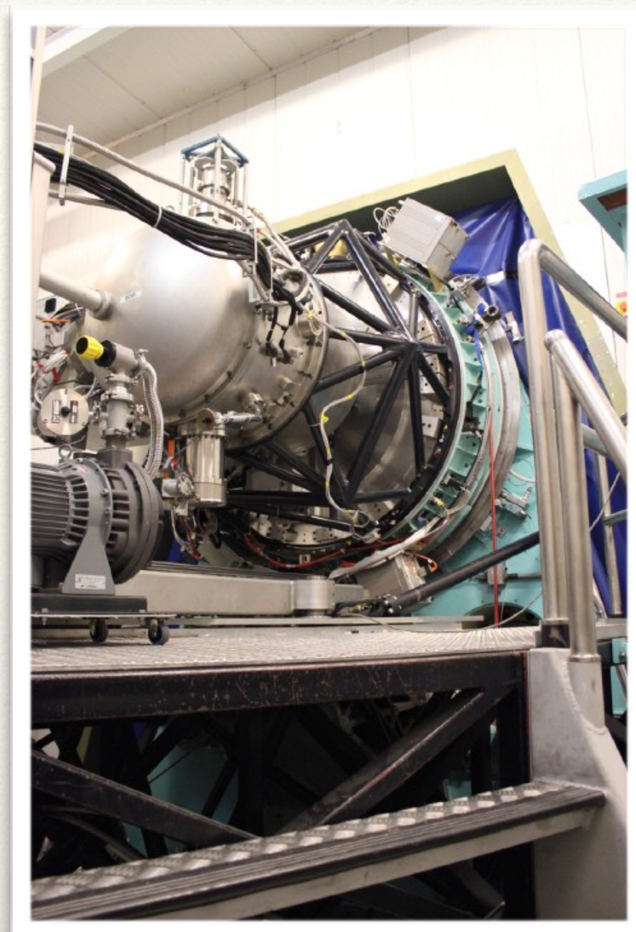
Both Swift J1644 and J2058 show non-zero IR/optical linear polarisation

- Swift J1644 (KW+ '12), K band: P~7.5%
- Swift J2058 (KW+ '19), V band: P~8%



(Better) polarimetry should help diagnose emission geometry and mechanisms!
Rate will likely go up with ZTF, eROSITA, etc

SPLOT: Snapshot-survey for polarised light in optical transients



SPLOT 2016/17/18
EFOSC2+SofI@NTT
UL50

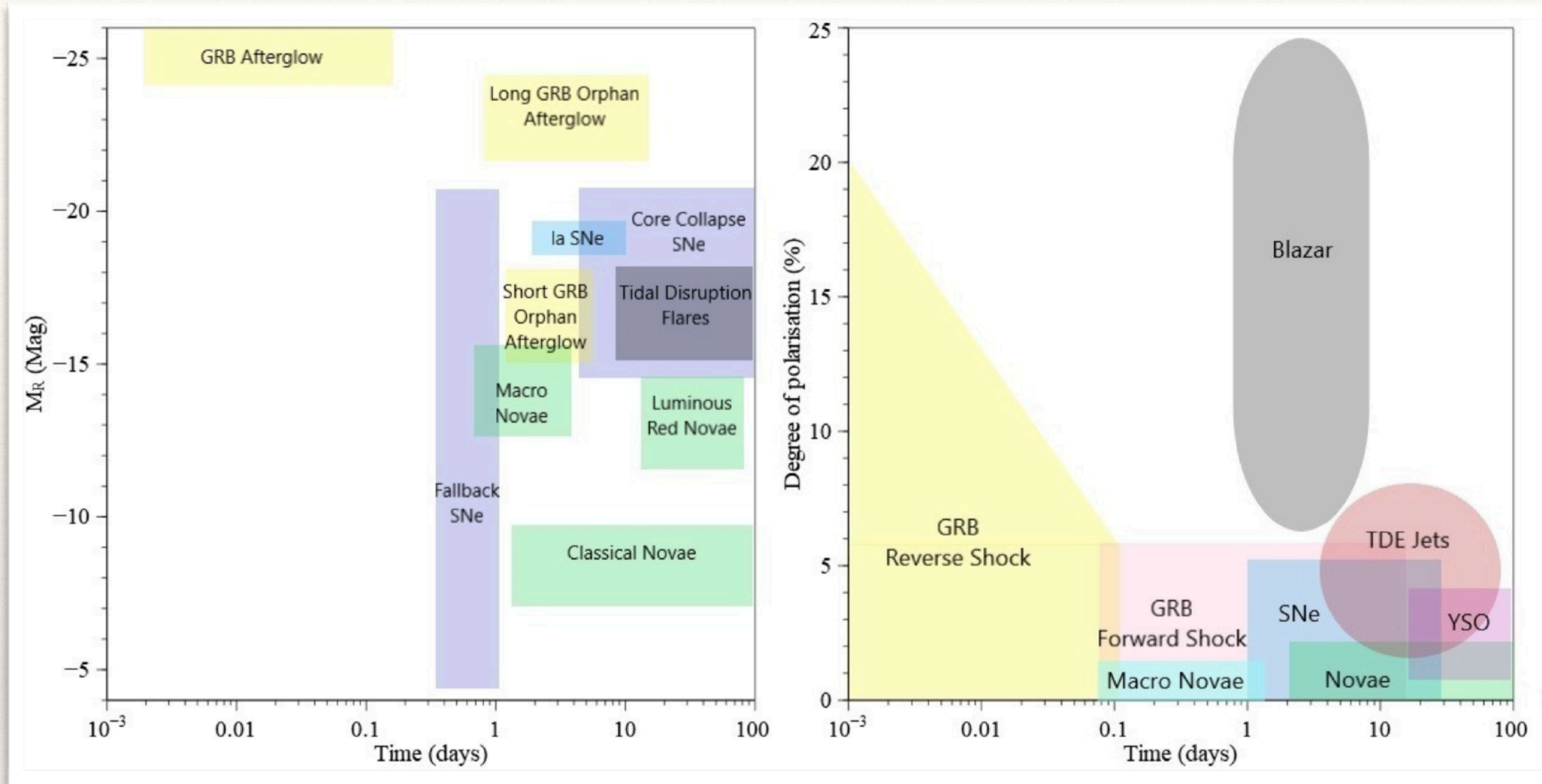
KW, Higgins+ '18;
Higgins, KW+ '19;
KW+ in prep

New surveys will produce vast numbers of transients (e.g. LSST, eRosita, ZTF, Gaia, etc). Robust candidate detection, verification, and classification is a formidable challenge. Lightcurves, radio/X-ray/optical flux ratios, position, galaxy correlation, morphology, spectroscopy - will all be used.

How will we select *interesting* targets for follow-up from a huge transient stream?

Perhaps polarimetry can provide an additional axis to the multi-dimensional parameter space of interest. to select sources of astrophysical interest.

SPLOT: Snapshot-survey for polarised light in optical transients



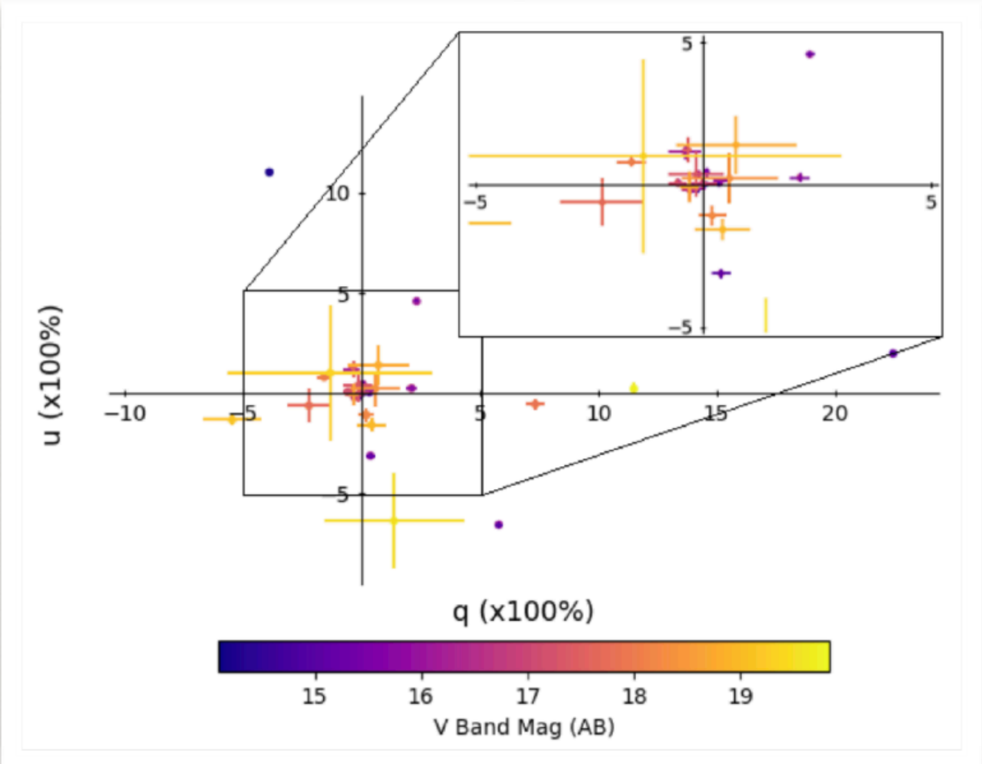
SPLOT 2016/17/18
EFOSC2+SofI@NTT
UL50

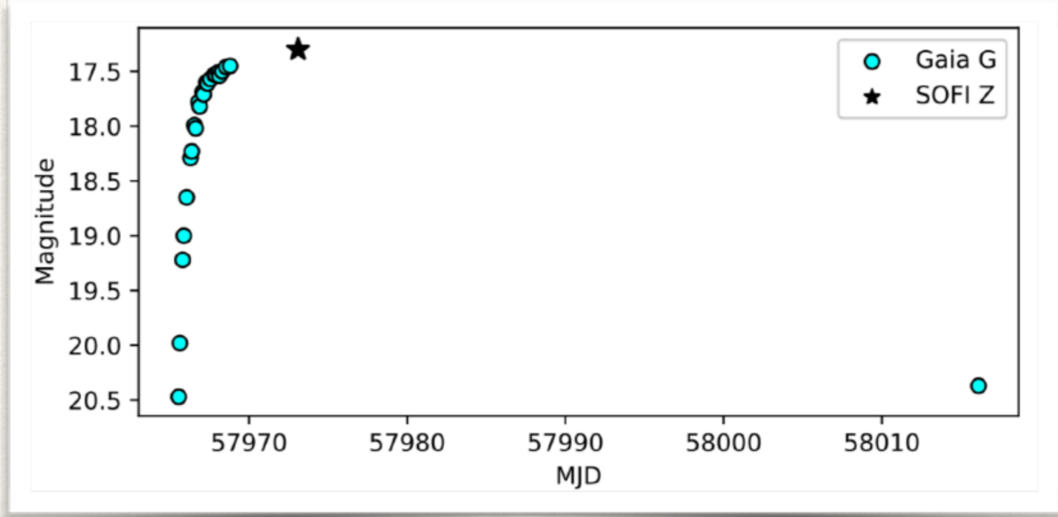
KW, Higgins+ '18;
Higgins, KW+ '19;
KW+ in prep

Perhaps polarimetry can provide an additional axis to the multi-dimensional parameter space of interest - ran a 10 night test survey on NTT, for 75 (more or less) randomly selected transients.

Challenges: calibration (KW+ '18), availability polarimeters, cost, operation modes, etc

SPLOT: Snapshot-survey for polarised light in optical transients



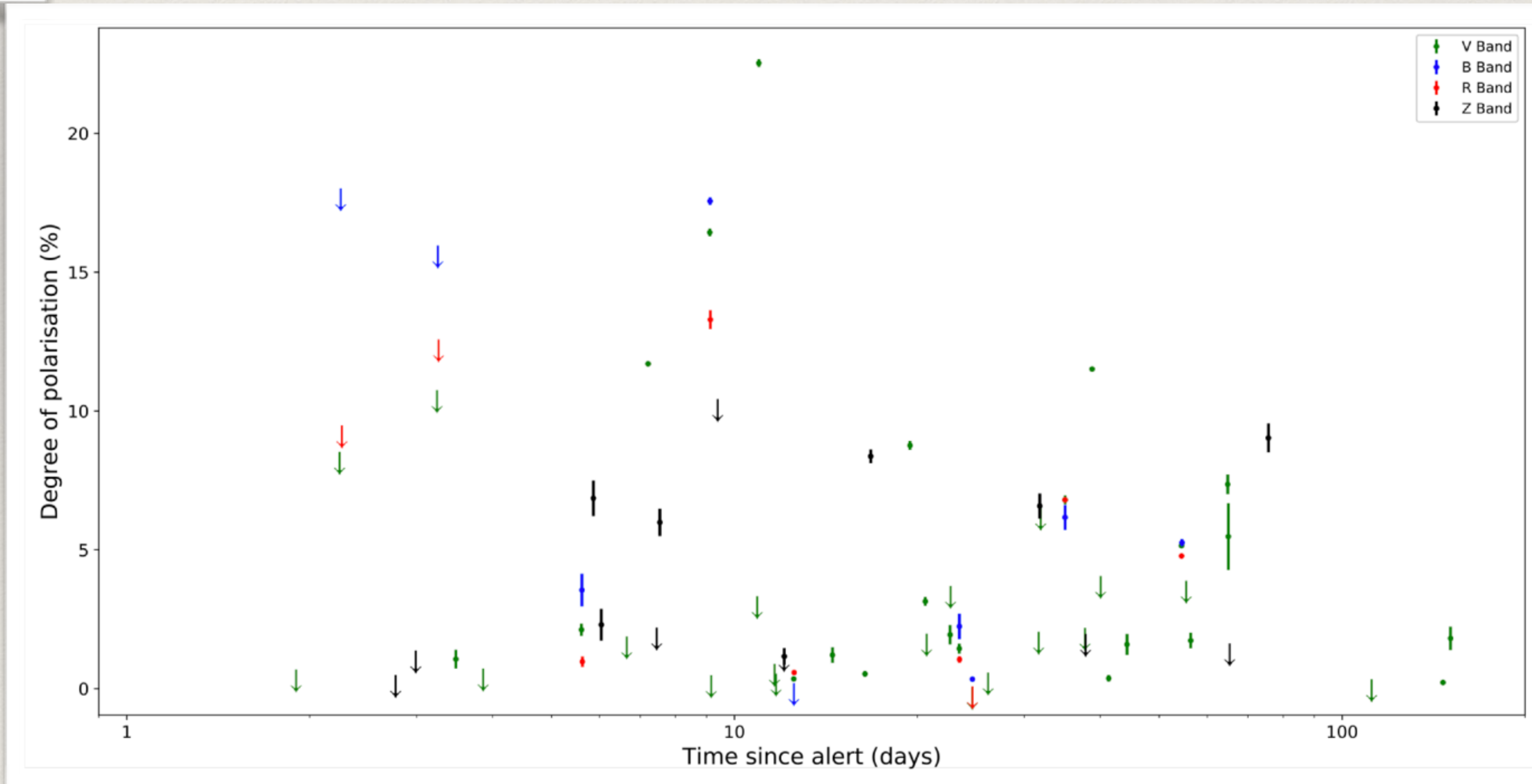


SPLOT 2016/17/18
EFOSC2+SofI@NTT
UL50

KW, Higgins+ '18;
Higgins, KW+ '19;
KW+ in prep

- (Nearly) random target selection
- Calibration, calibration, calibration
- V<20.5mag (<1hr per source)
- Snapshots
- ~75 sources
- Rapid pipelines, VOEvents
- Some infrastructure not yet present

It works - some unusual sources found. (Snapshot) polarimetry can form meaningful added value stream.



Conclusions

- Polarimetry provides interesting information on relativistic jet sources, modelling constraints independent on lightcurves/spectra
- Many GRB classes/types poorly studied in polarisation space: single datapoints matter
- Polarimetry is great for GRB-SNe and KNe
- Multiwavelength polarimetry is coming up - requires some coordination
- Polarimetric surveys enrich transient streams for all transient types, but there's some infrastructure that needs to develop to exploit it fully.

Quick announcement!

Keep the date:

Astrophysical Polarimetry in the Time-Domain Era
Lecco (lake Como), Italy, September 1-4 2020

Polarimetry of transients and extreme variables