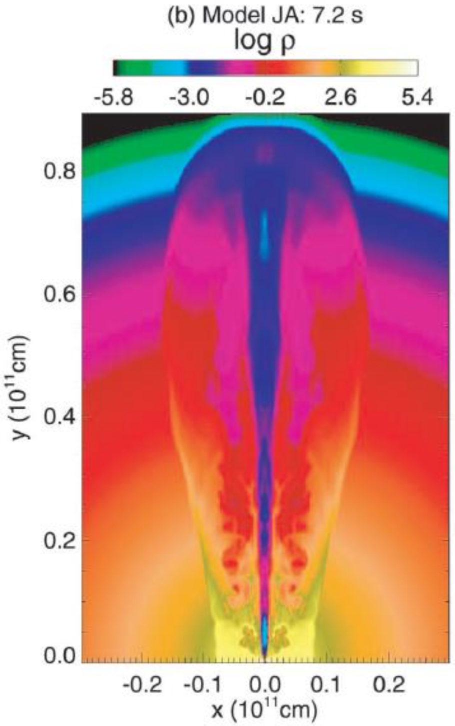
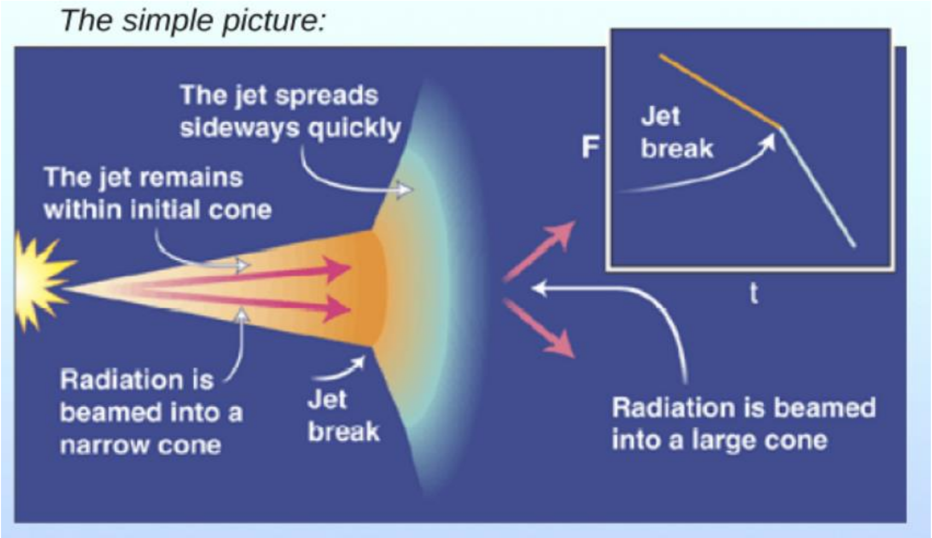
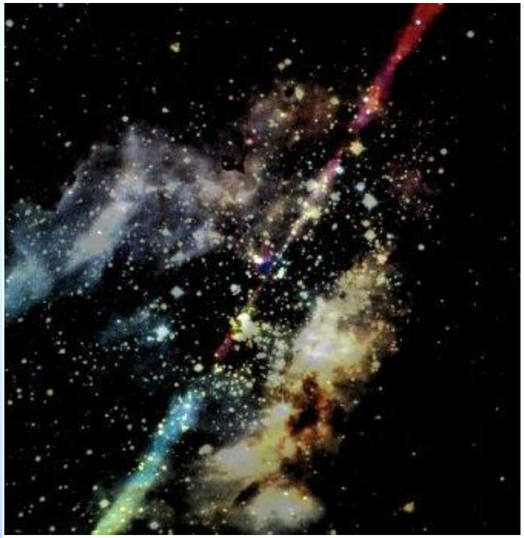
The Afterglow of Gamma-Ray Bursts







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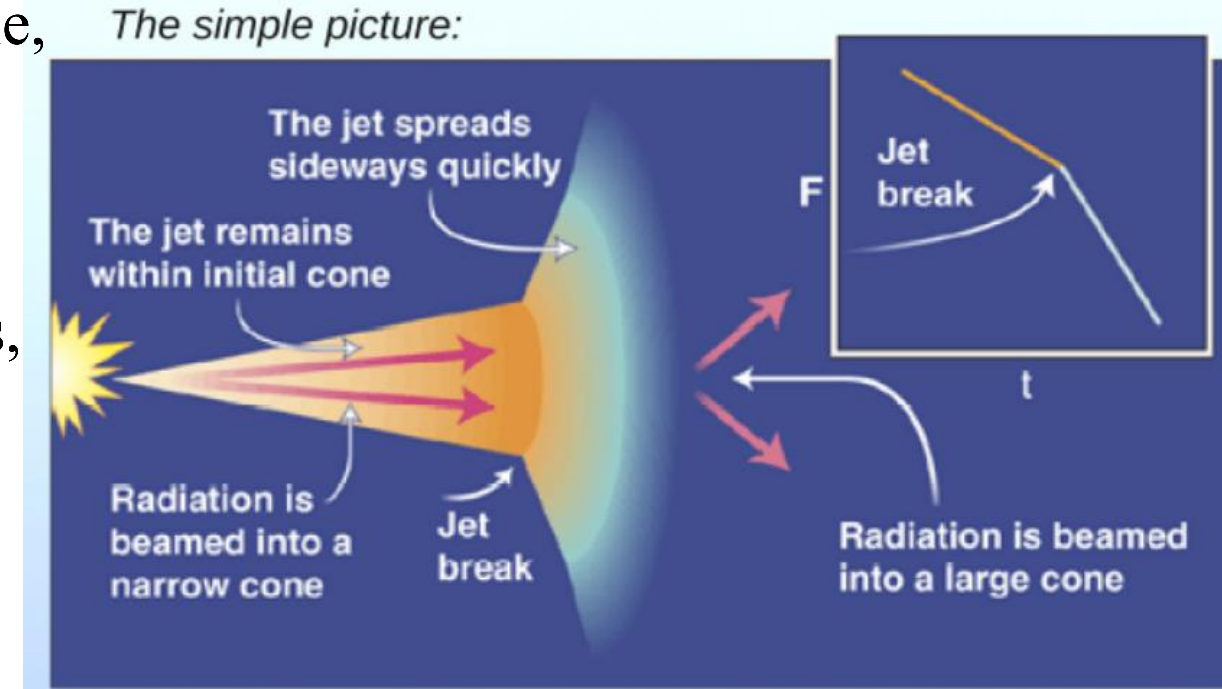
Garching, Germany

Afterglows used to be 'simple' van Eerten 2014

- A thin relativistic shell
- brief reverse shock (RS), too early to be seen
- emission from decelerating forward shock (FS) consisting of shocked external medium
- some medium structure, e.g. wind or ISM
- some turnover due to `jet break'
  - edges become visible, emission no longer beamed away from observer
  - jet spreads sideways, slows further



…this has changed, so I need to prioritize

Will not talk about

- GRB-SN
- Fermi GeV emission
- Using afterglows for host studies and/or cosmology

And will be short about

- Early (optical/NIR) afterglows
- Polarimetry

due to subsequent talks

Topical distribution of afterglow papers since 2012

ADS Search for "GRB" & "afterglow": 122 papers

- Plateau/rebrightening: 8
- GRB Surrounding: 7
- Polarisation: 5
- Short GRB AG: 4
- X-ray AG: flaring: 3
- Light curves – closure relations: 3
- Optical AG: 3
- Radio AG: 2
- Orphan AGs: 2
- Testing the shock scenario: 2
- GRB-SN: 2
- ……(individual objects: 49)

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- GRB-SN: 2
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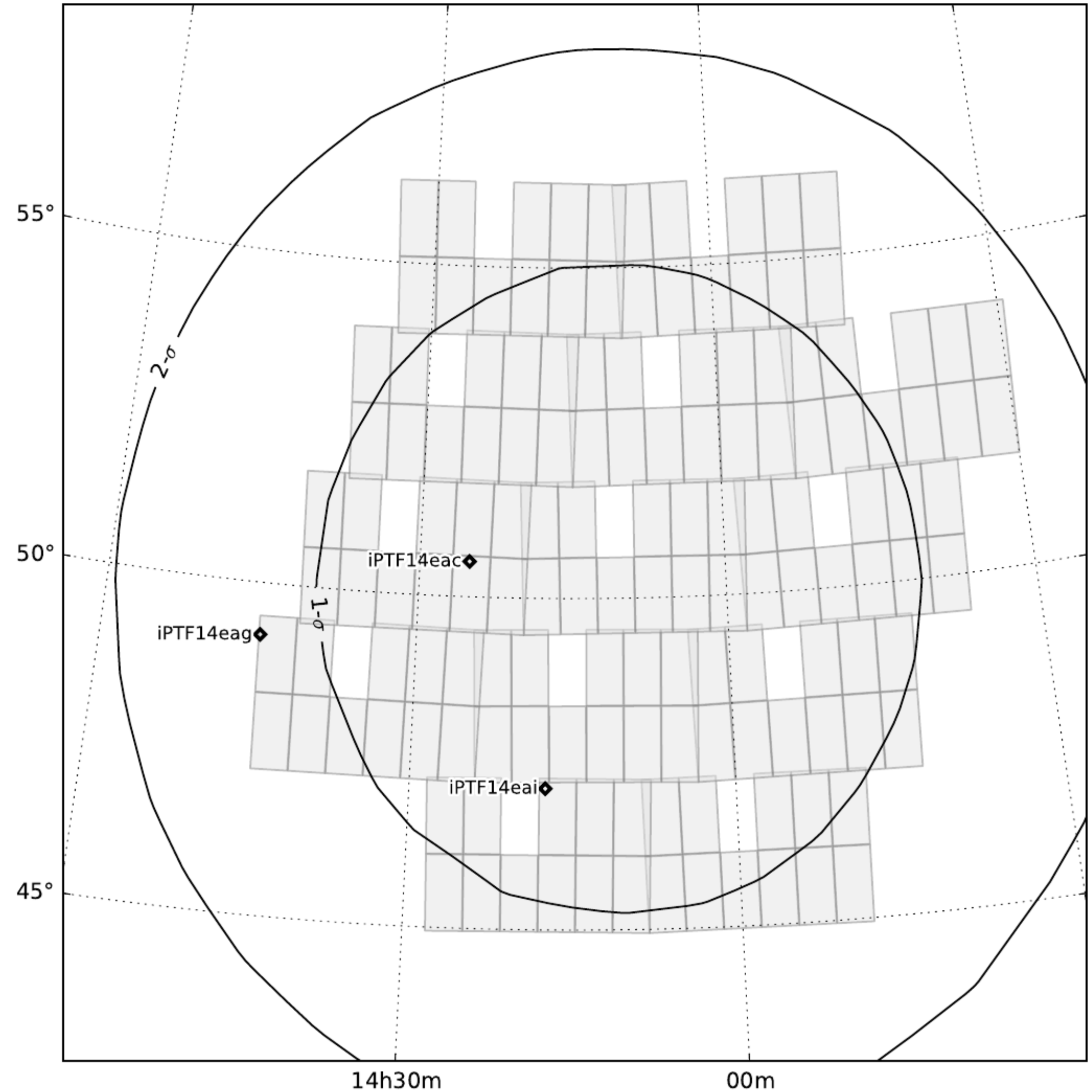
GBM+PTF = new cottage industry*

Fermi-429152043 = GRB 140808A

Singer+2014, GCN #16668

- P48 Observation started 3.25 hrs after GRB
- 13 fields, covering 95 □°
- Find 3 candidates
- iPTF14eag fades by 0.3 mag in 1.5 hrs
- GTC spectrum: z=3.29
- VLA/AMI radio detections



* Quote @ Kulkarni

Afterglow for GBM bursts

❖ Successful AG discoveries

GRB	discovery	redshift
130702A	iPTF	0.14
131011A	iPTF	1.87
140226A	iPTF	1.98
140508A	iPTF	1.03
140606B	iPTF	0.38
140620A	iPTF	2.04
140623A	iPTF	1.92
140801A	MASTER	1.32
140808A	iPTF	3.29

Singer+2013

❖ Impact:

6 AGs / 3 months (≡ 24/yr compared to ~90 Swift AGs/yr)
6 AGs with redshift (≡ 24/yr compared to ~30 Swift AGs/yr)

❖ New twist(s) due to being bright GRBs:

- looking for GRBs harder than seen by Swift,
- short GRBs,
- nearby GRBs

- Afterglow for GBM bursts
- First afterglow without γ-emission
- Rebrightening / Plateaus
- Polarisation
- Short GRBs

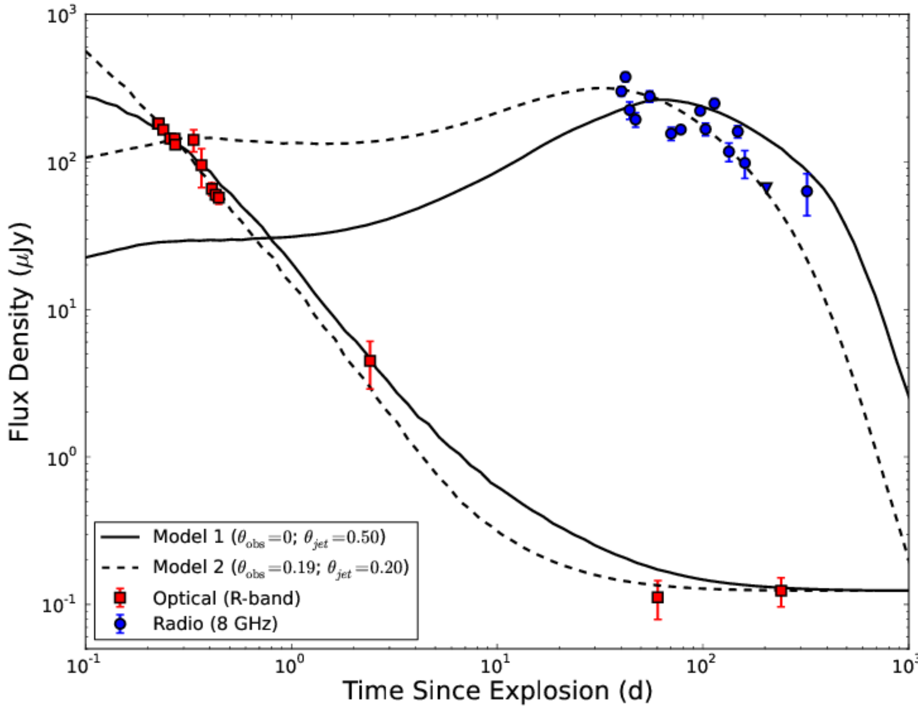
Orphan afterglows I

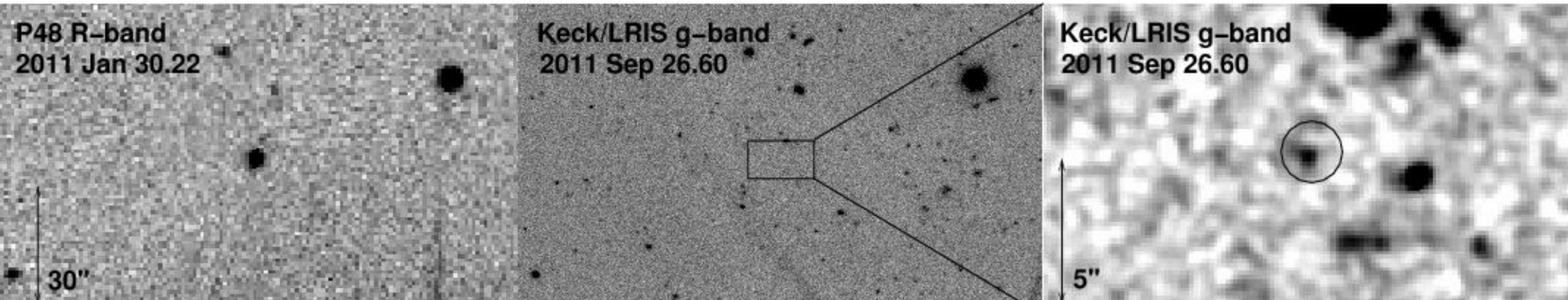
First GRB discovered without X/gamma-ray trigger

Cenko+2013

3 distinguishing features:

- detection at R=18.3 mag; rapid fading (ΔR=4 mag/2days)
- faint (R=26.2 mag) quiescent, blue counterpart
- year-long scintillating radio transient





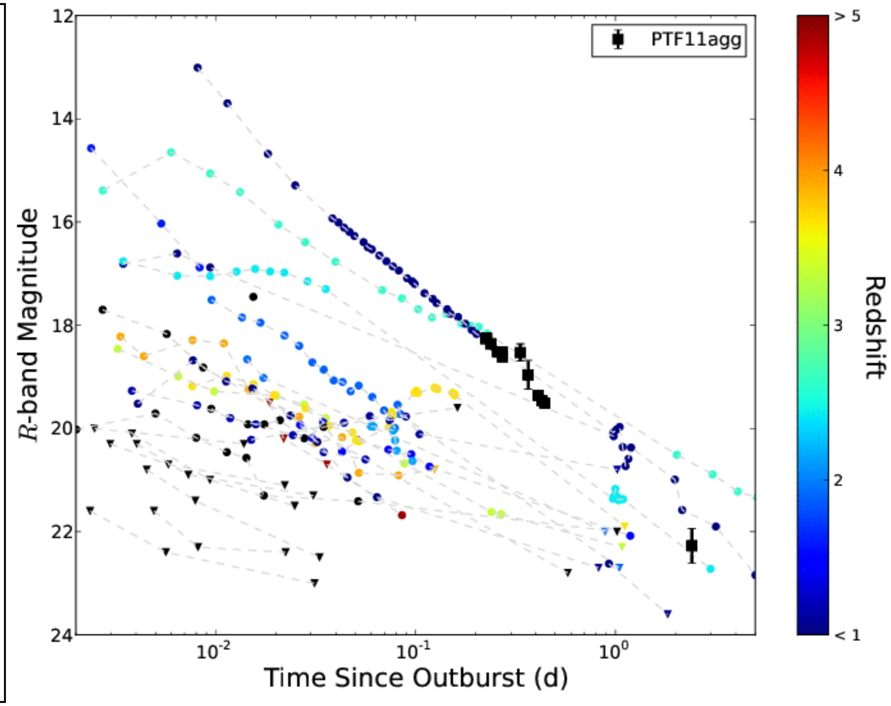
Orphan afterglows II

First GRB discovered without X/gamma-ray trigger

Cenko+2013

Unlikely/inconsistent with:

- ❖ known Galactic transients (Algol or RS CVn variable; late-type flare star; binaries with compact accretor; X-ray novae; AM CVn; dwarf novae)
- ❖ Blazar / relativistic TDF
- ❖ year-long scintillating radio transient



… but consistent with GRB optical AG whose γ-rays were undetected

❖Optical/radio lc ≡ afterglow; quiescent source ≡ host galaxy

❖On-axis GRB; $0.5<z<3$; $E_{KE} \sim 10^{53}$ erg

➔ But suggests rate ~ 4x normal GRB rate! TBC by CRTS/PTF/LSST

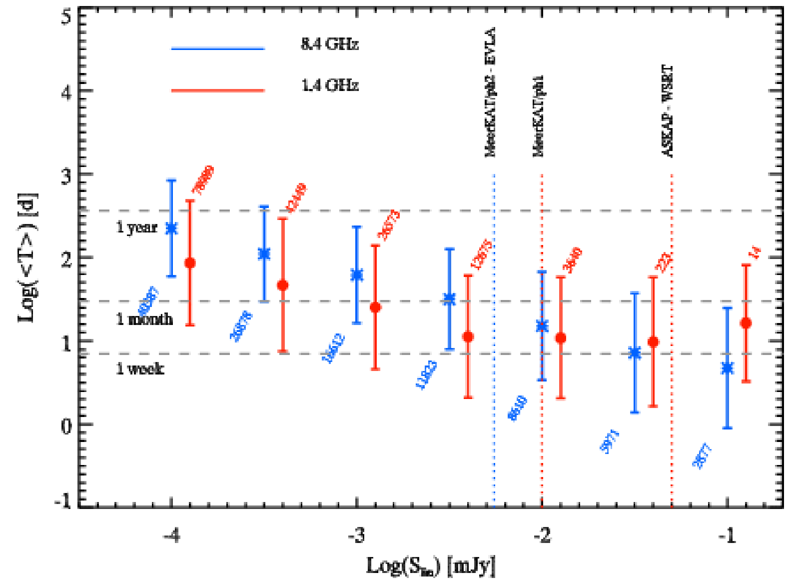
Orphan afterglows III

Predictions of radio orphan afterglows

Ghirlanda+2014

Easier search in the radio range:

- There should be 40x more off-axis GRBs than on-axis
  OA rate = 3.3×10^4 yr^{-1} sr^{-1}
  = 10 yr^{-1} deg^{-2}
- Radio afterglow peaks only after 1 yr, and remains bright for 1 yr: this allows for low cadence surveys
- Peak fluxes for OA are few μJy, so require future/upcoming surveys
- Predictions are made for various instrument/surveys → see table predictions consistent with previous upper limits, e.g. Gal-Yam+2006



Telescope name	ν [GHz]	$S_{\rm lim}$ [mJy]	Rate [deg^{-2} yr^{-1}]
ASKAP	1.4	0.05	3×10^{-3}
MeerKAT/Ph1	1.4	0.009	10^{-1}
MeerKAT/Ph2	8.4	0.006	3×10^{-1}
SKA/Ph1	1.4	0.001	6×10^{-1}
SKA/Ph2	1.4(8.4)	0.00015	$1.5(2\times10^{-1})$
WSRT/AperTIF	1.4	0.05	3×10^{-3}
EVLA	8.4	0.005	3×10^{-1}
LOFAR	0.2	1.3	...
MWA	0.2	1.1	...
GMRT	0.6	0.1	10^{-5}
GMRT	1.4	0.15	2×10^{-4}

- Afterglow for GBM bursts
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- Polarisation
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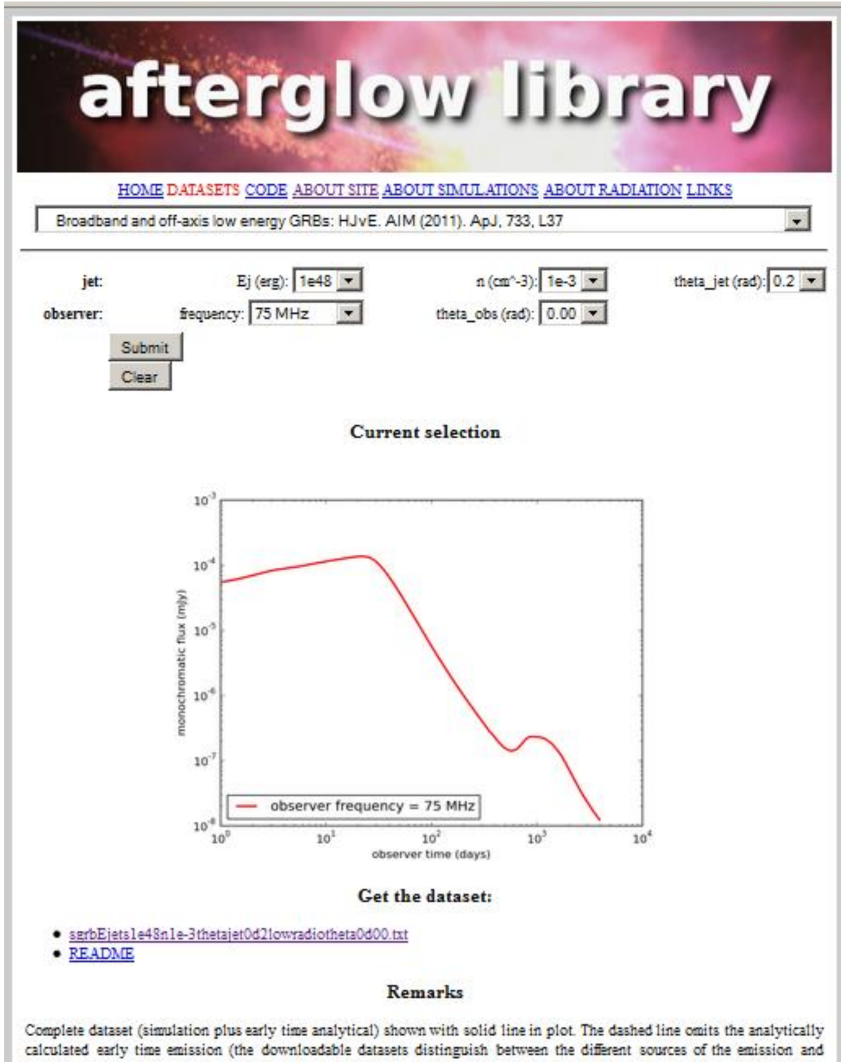
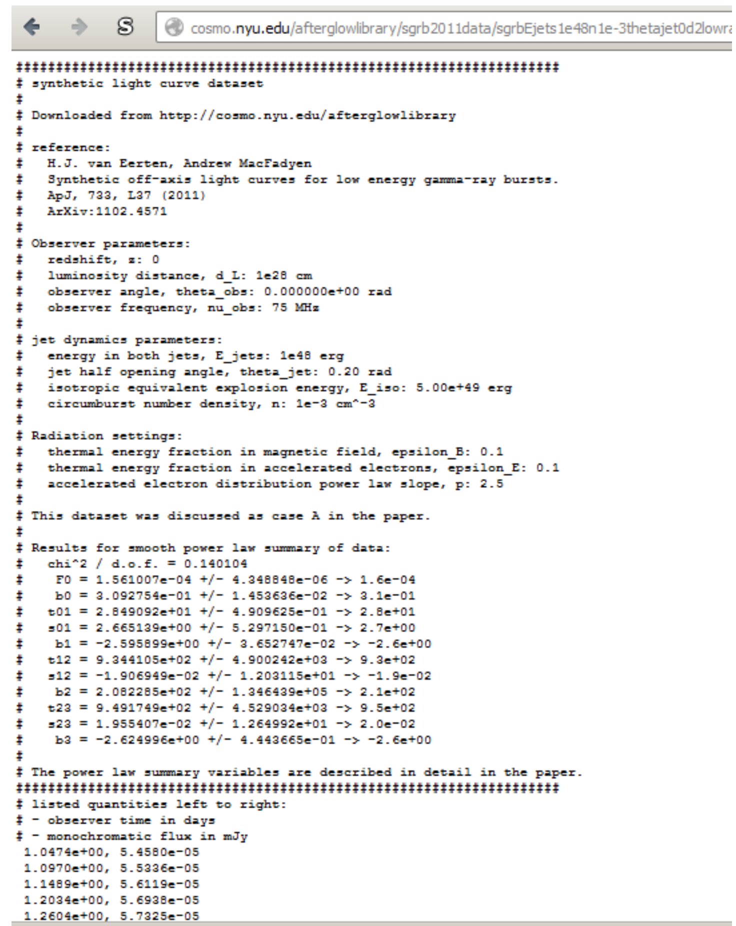
Publicly available afterglow fitting tool



van Eerten / McFadyen 2012/2014

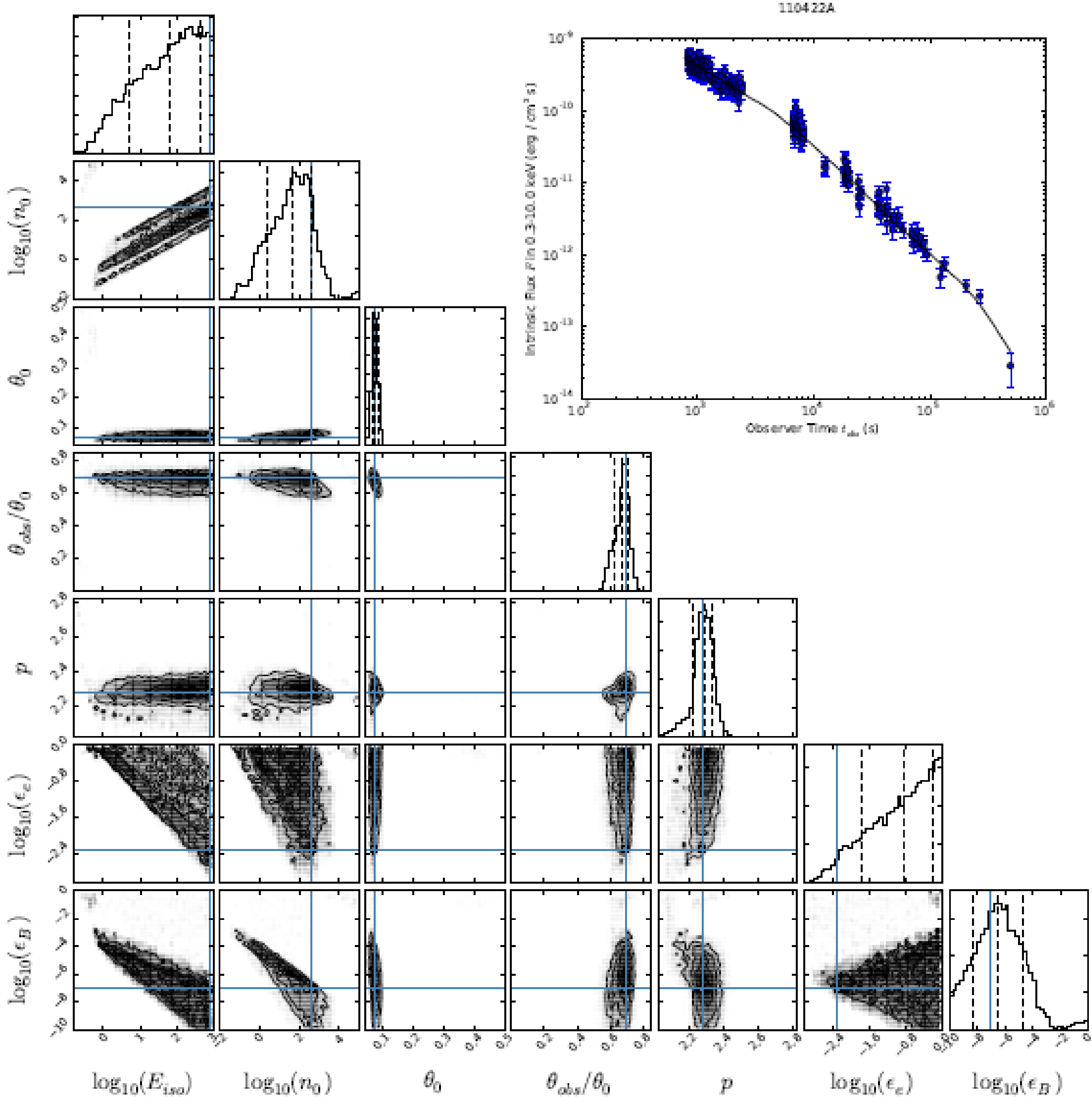



```
######################################################################
# synthetic light curve dataset
#
# Downloaded from http://cosmo.nyu.edu/afterglowlibrary
#
# reference:
#   H.J. van Eerten, Andrew MacFadyen
#   Synthetic off-axis light curves for low energy gamma-ray bursts.
#   ApJ, 733, L37 (2011)
#   ArXiv:1102.4571
#
# Observer parameters:
#   redshift, z: 0
#   luminosity distance, d_L: 1e28 cm
#   observer angle, theta_obs: 0.000000e+00 rad
#   observer frequency, nu_obs: 75 MHz
#
# jet dynamics parameters:
#   energy in both jets, E_jets: 1e48 erg
#   jet half opening angle, theta_jet: 0.20 rad
#   isotropic equivalent explosion energy, E_iso: 5.00e+49 erg
#   circumburst number density, n: 1e-3 cm^-3
#
# Radiation settings:
#   thermal energy fraction in magnetic field, epsilon_B: 0.1
#   thermal energy fraction in accelerated electrons, epsilon_E: 0.1
#   accelerated electron distribution power law slope, p: 2.5
#
# This dataset was discussed as case A in the paper.
#
# Results for smooth power law summary of data:
#   chi^2 / d.o.f. = 0.140104
#    F0 = 1.561007e-04 +/- 4.348848e-06 -> 1.6e-04
#    b0 = 3.092754e-01 +/- 1.453636e-02 -> 3.1e-01
#   t01 = 2.849092e+01 +/- 4.909625e-01 -> 2.8e+01
#   s01 = 2.665139e+00 +/- 5.297150e-01 -> 2.7e+00
#    b1 = -2.595899e+00 +/- 3.652747e-02 -> -2.6e+00
#   t12 = 9.344105e+02 +/- 4.900242e+03 -> 9.3e+02
#   s12 = -1.906949e-02 +/- 1.203115e+01 -> -1.9e-02
#    b2 = 2.082285e+02 +/- 1.346439e+05 -> 2.1e+02
#   t23 = 9.491749e+02 +/- 4.529034e+03 -> 9.5e+02
#   s23 = 1.955407e-02 +/- 1.264992e+01 -> 2.0e-02
#    b3 = -2.624996e+00 +/- 4.443665e-01 -> -2.6e+00
#
# The power law summary variables are described in detail in the paper.
######################################################################
# listed quantities left to right:
# - observer time in days
# - monochromatic flux in mJy
 1.0474e+00, 5.4580e-05
 1.0970e+00, 5.5336e-05
 1.1489e+00, 5.6119e-05
 1.2034e+00, 5.6938e-05
 1.2604e+00, 5.7325e-05
```

http://cosmo.nyu.edu/afterglowlibrary/

Scalefit

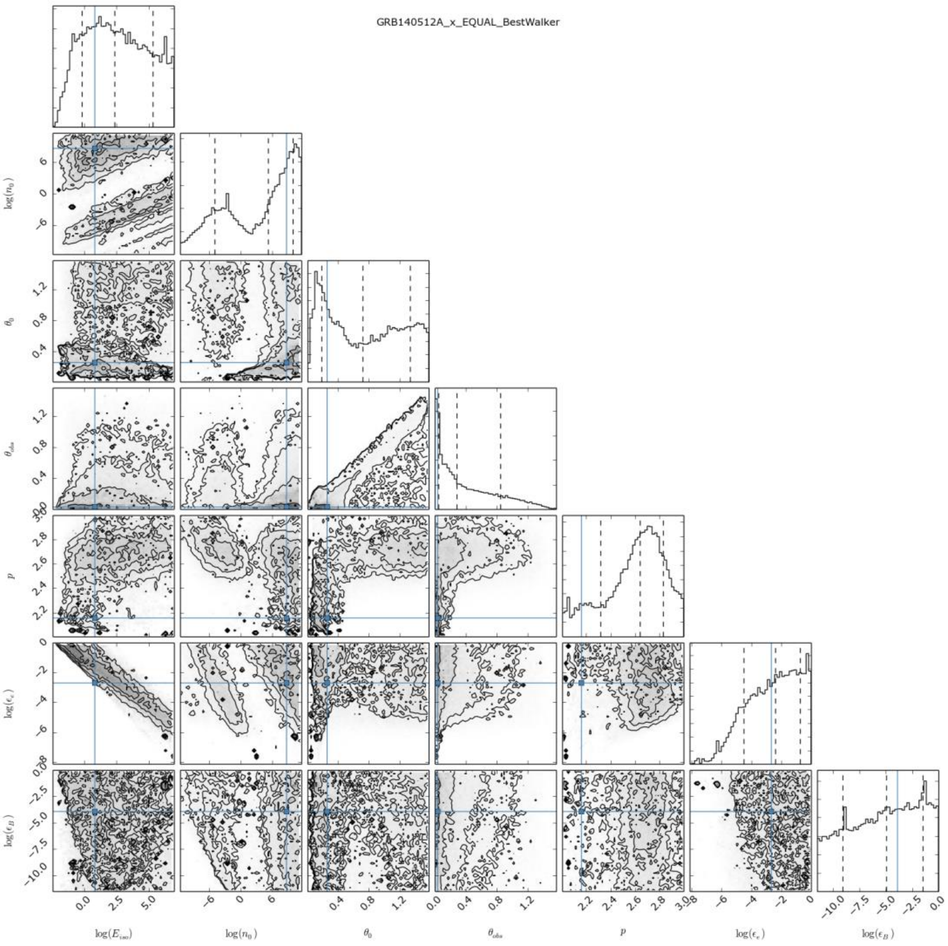
- Analysis of Swift/XRT data
- Monte-Carlo to decide location of ν_m and ν_c
- Directly fitting physical parameters, rather than powl
- Result: GRBs are viewed offaxis

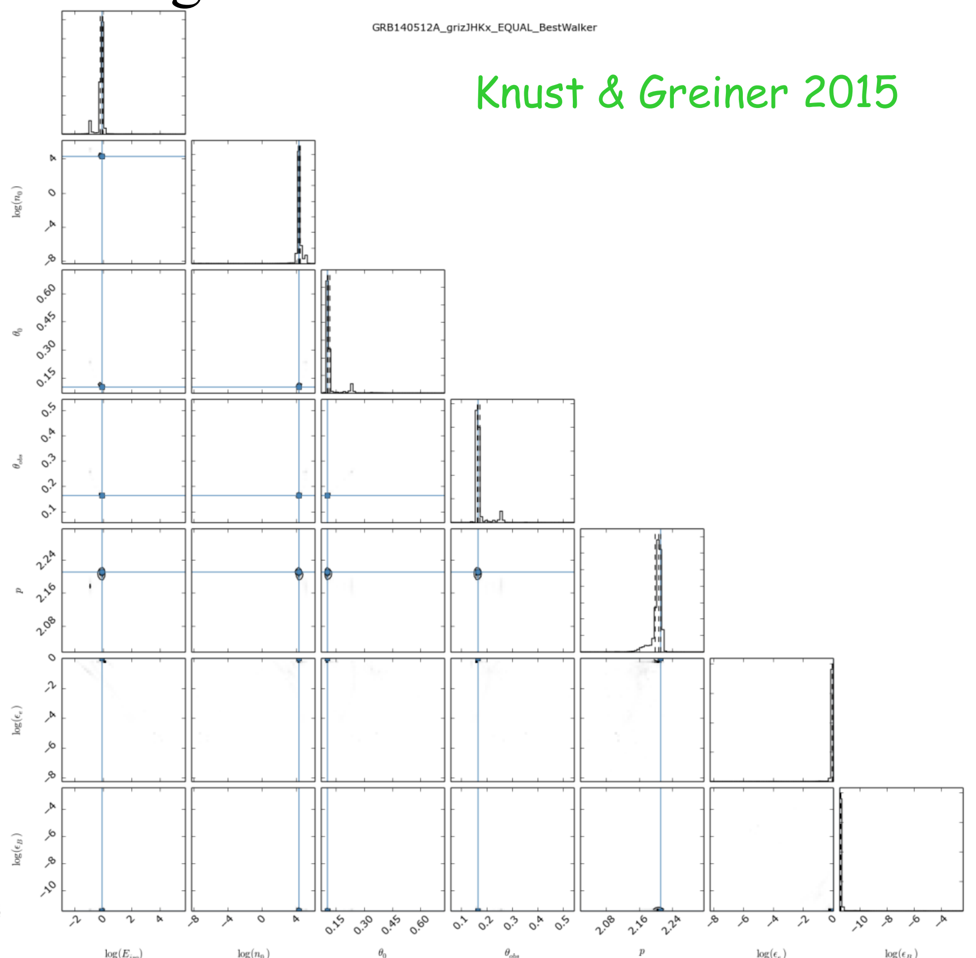


Ryan et al. 2014

Scalefit of X-ray & Optical data

- Fit Swift/XRT and 7-channel GROND data together
- Location of one spectral break fixed through data
- Much less ambiguity in parameter ranges



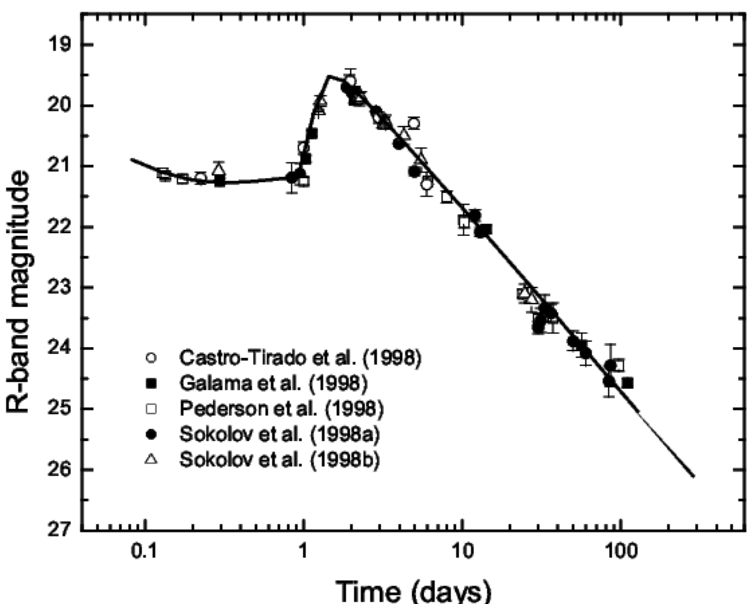


Knust & Greiner 2015

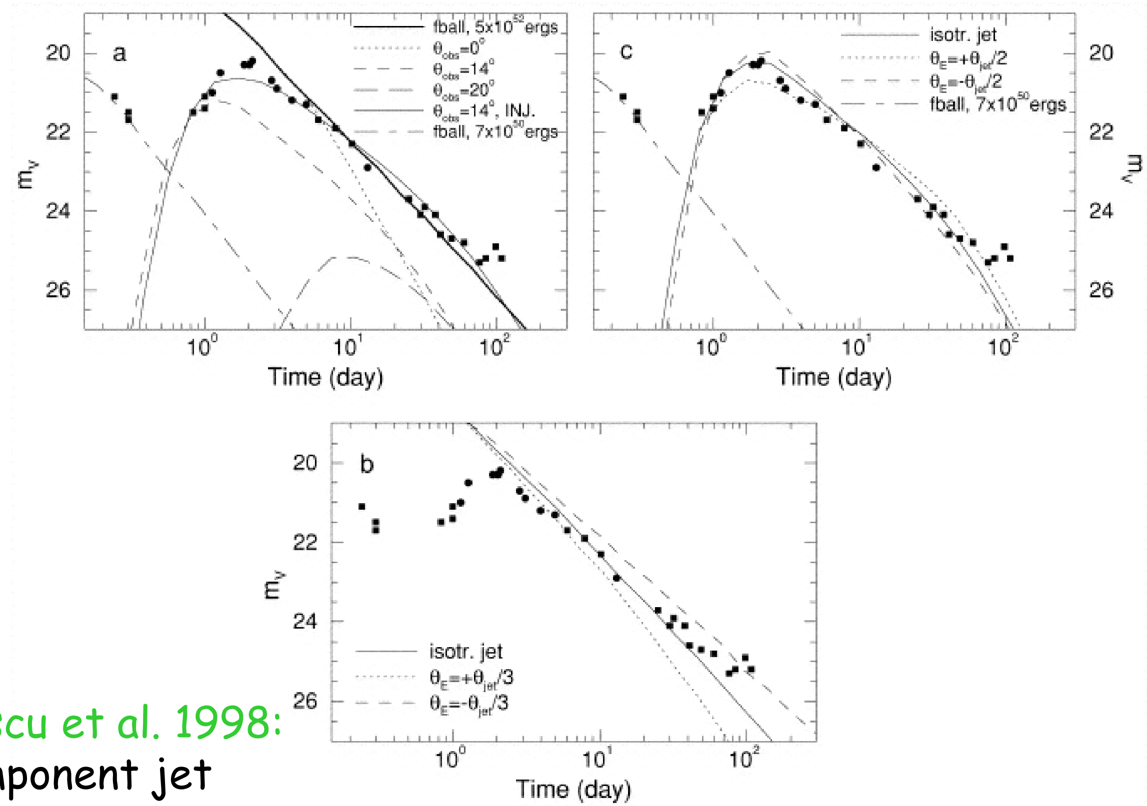
Late-time re-brightenings

- Re-brightening known since 2nd GRB afterglow
- Lacking understanding, no clear systematics developed, but mixed with flares, plateaus, or supernova bumps
- proposed explanations: (i) density jump, (ii) two-component jets, (iii) residual shell collisions, (iv) delayed energy injection

GRB 970508

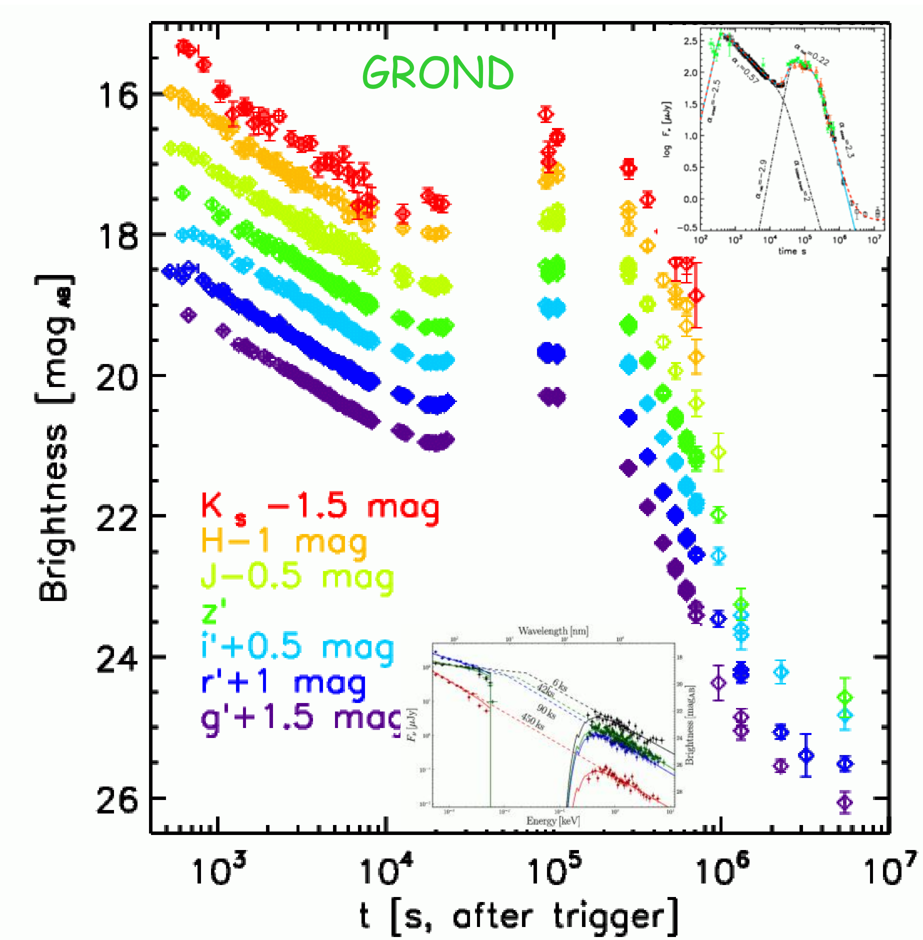


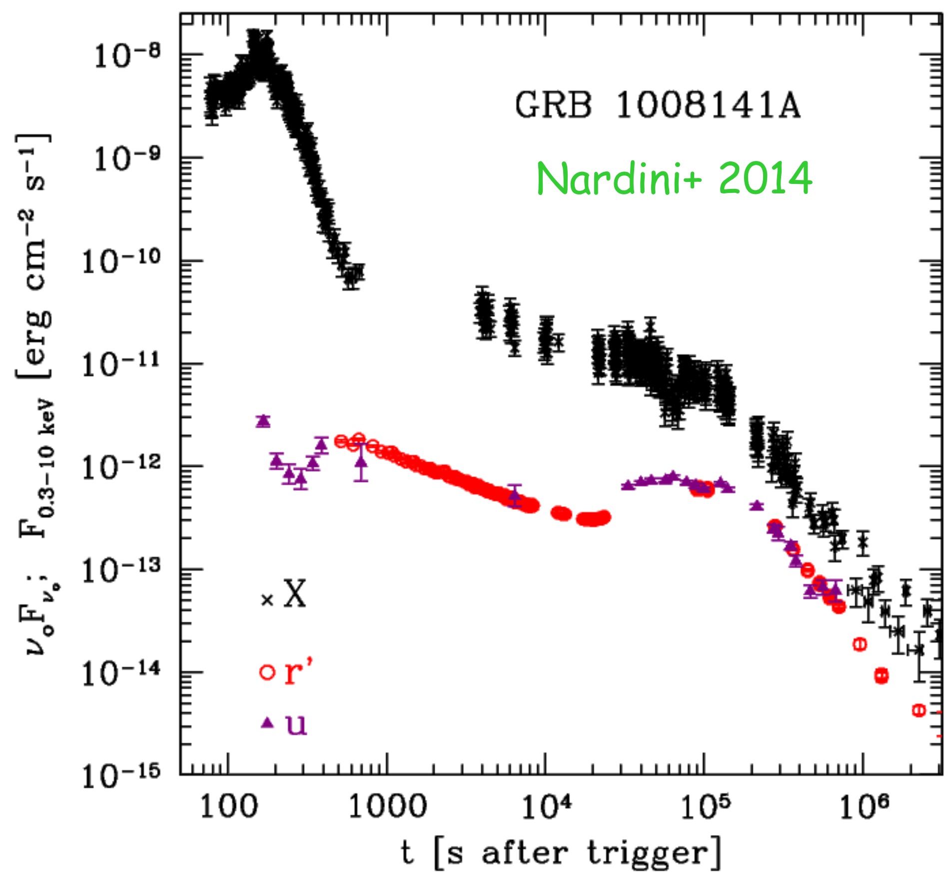
Tam et al. 2005:
density jump



Panaitescu et al. 1998:
two-component jet

Late-time re-brightenings



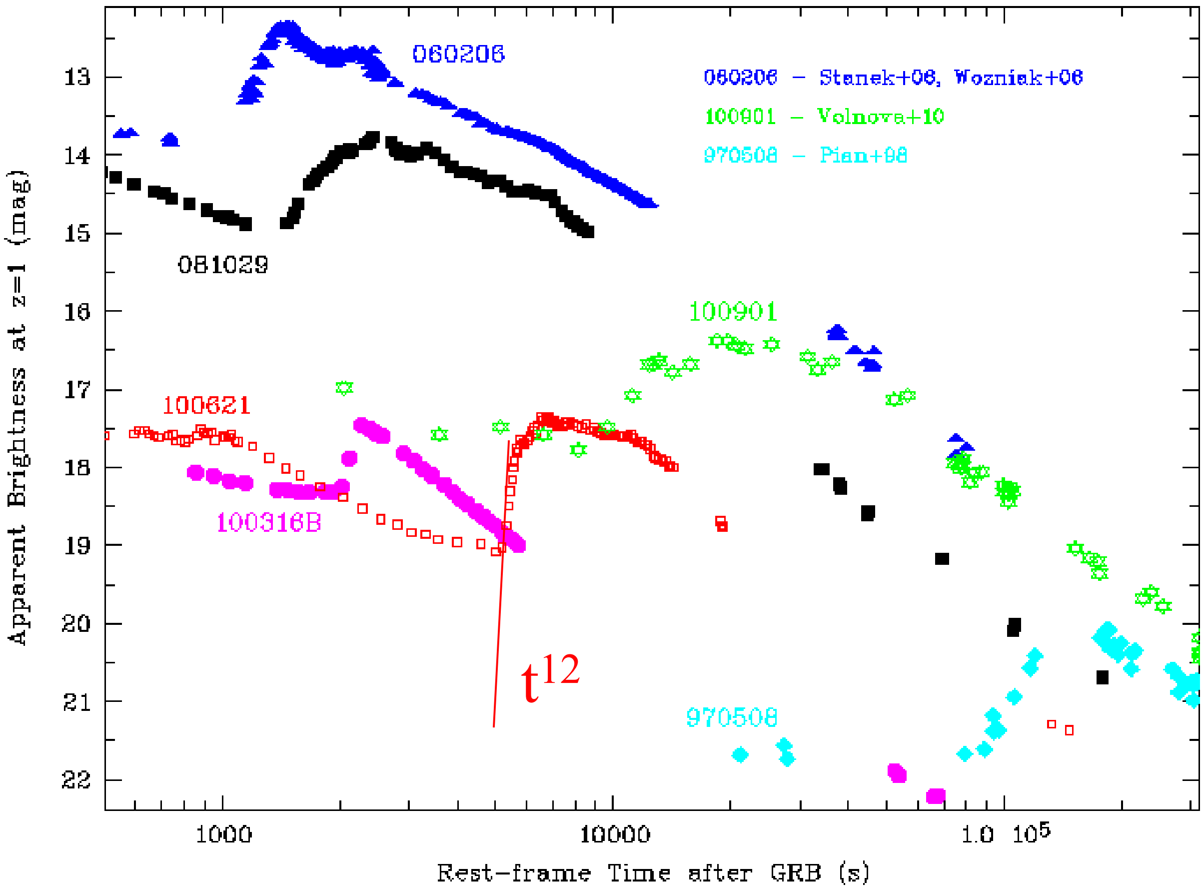


- But now we're getting much better data, both in X-rays and optical/NIR -- allowing to also check closure relations

The collection: optical/NIR properties

At least 6 well-sampled light curves

- 1 BeppoSAX GRB
- 5 Swift GRBs (3 with GROND coverage)



Jumps occur at all times

Steepness of rise varies

Steepness does not correlate with flux or time of occurrence

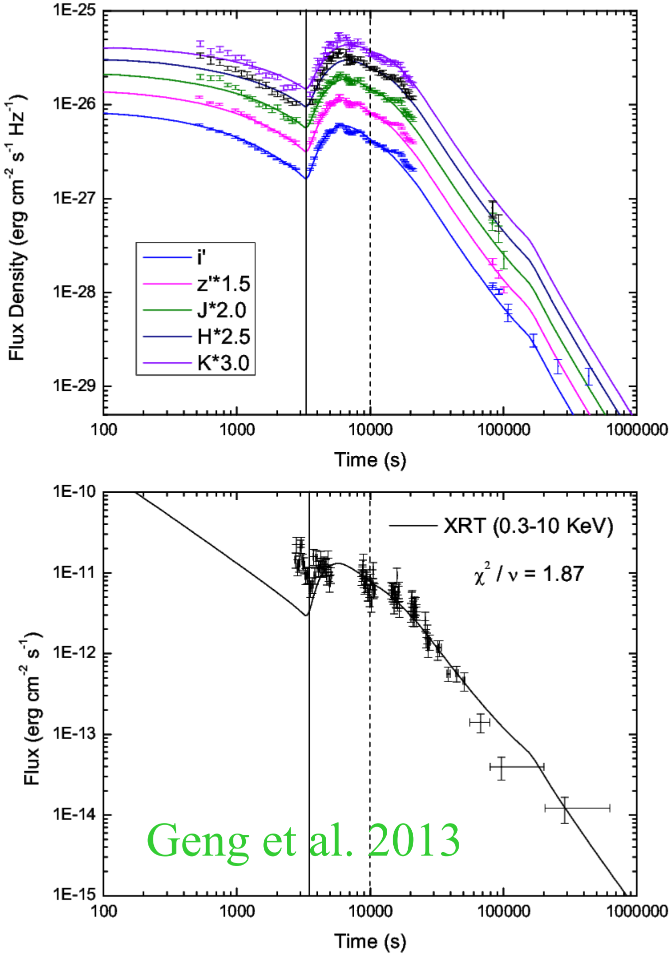
Peak brightness does not correlate with peak time

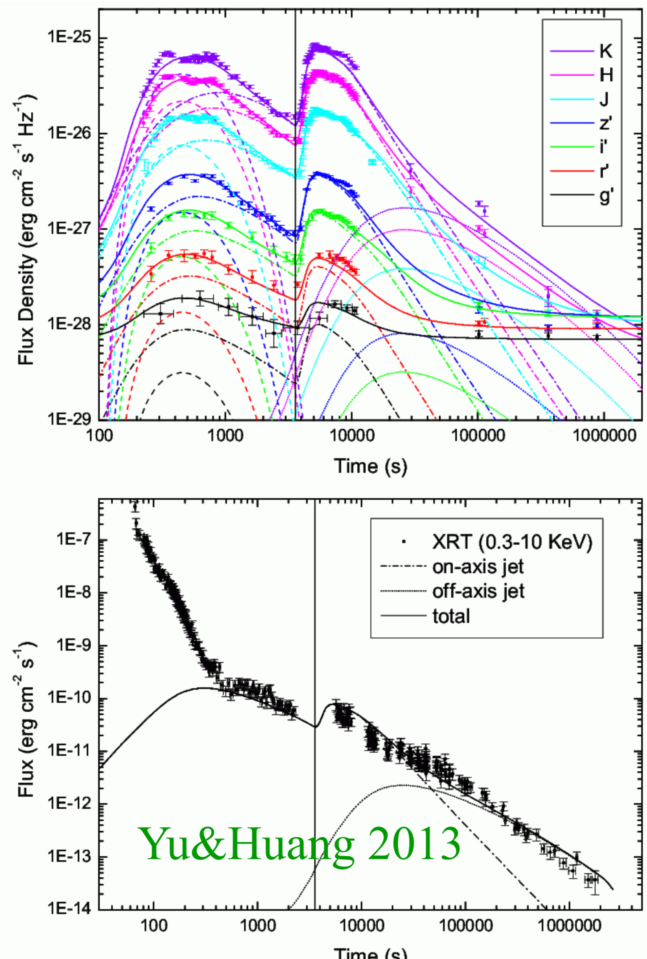
Shape of post-jump is diverse: 1, 2 or many FREDs

No consistent explanation yet

Heuristic modelling

- One possibility: Modelled as 2-step energy injection
- In the framework of BH accretion system, the energy flow from the fall-back accretion will be delayed by the fall-back time





- Delayed energy causes a notable rise of Γ of the internal shock, creating a bump in the light curve
- Requires a fall-back mass of 3.5 (1.0) M_{Sun} $(M_{BH}/3M_{Sun})^{-2/3}$ for GRBs 081029 (100621A)

Plateaus

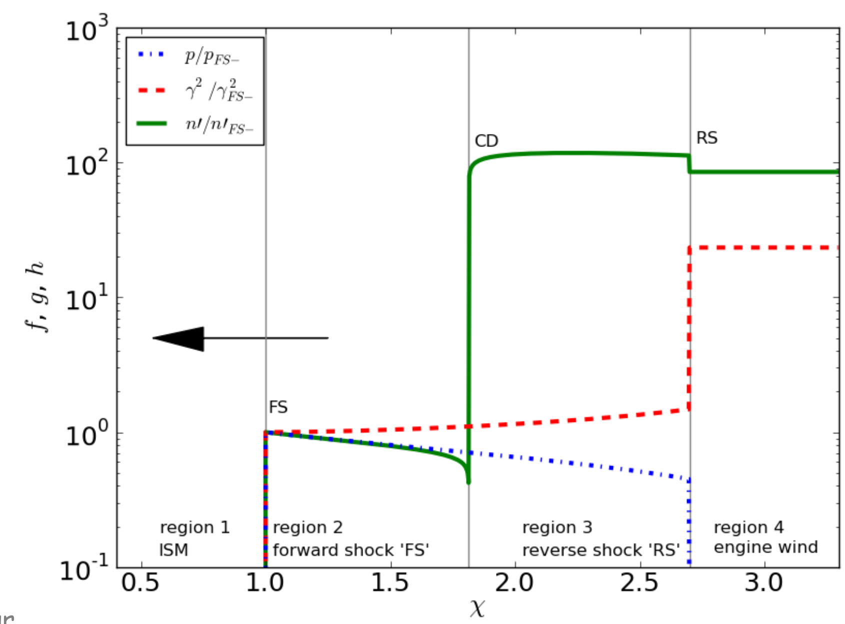
- …are different, but likely also due to energy injection
- Plus: there are correlations between plateau end time and end time L

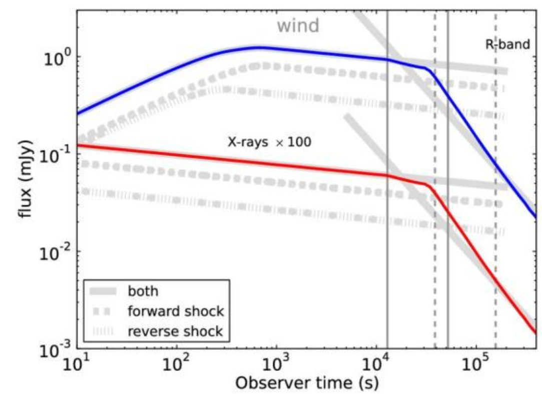
$$L_X(T) \propto T^{-(1.07^{+0.20}_{-0.09})} \qquad L_O(T) \propto T^{-0.78\pm0.08}$$

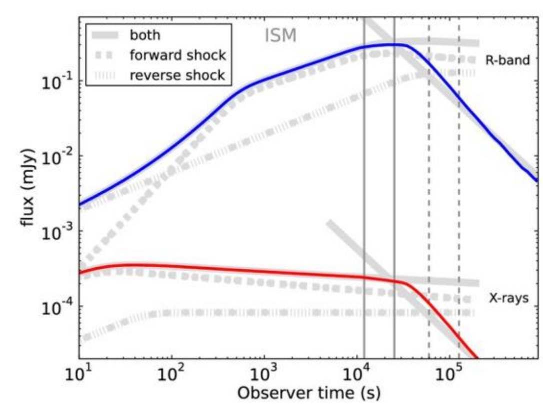
(Dainotti+ 2008, 2010, 2012; Margutti+ 2013 | Li+ 2012; Panaitescu & Vestrand 2011)

- Modelled as combination of RS & FS

(van Eerten 2014a,b)



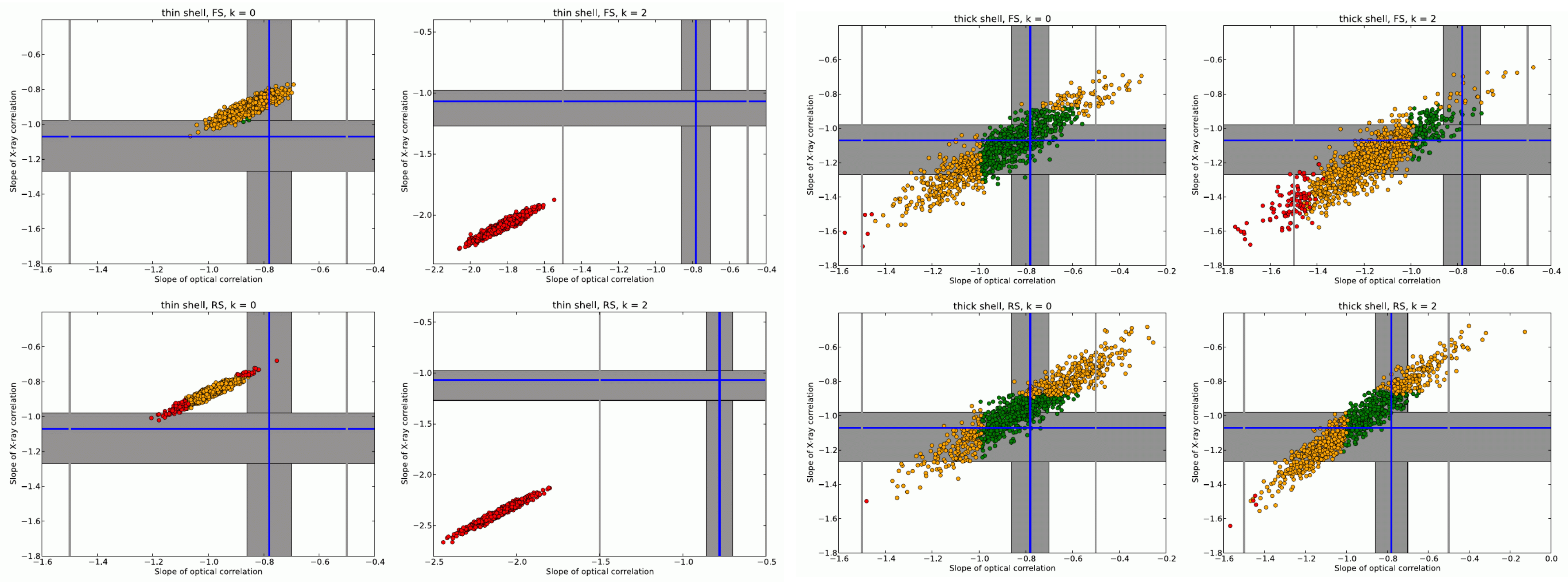




Thin vs. thick shells

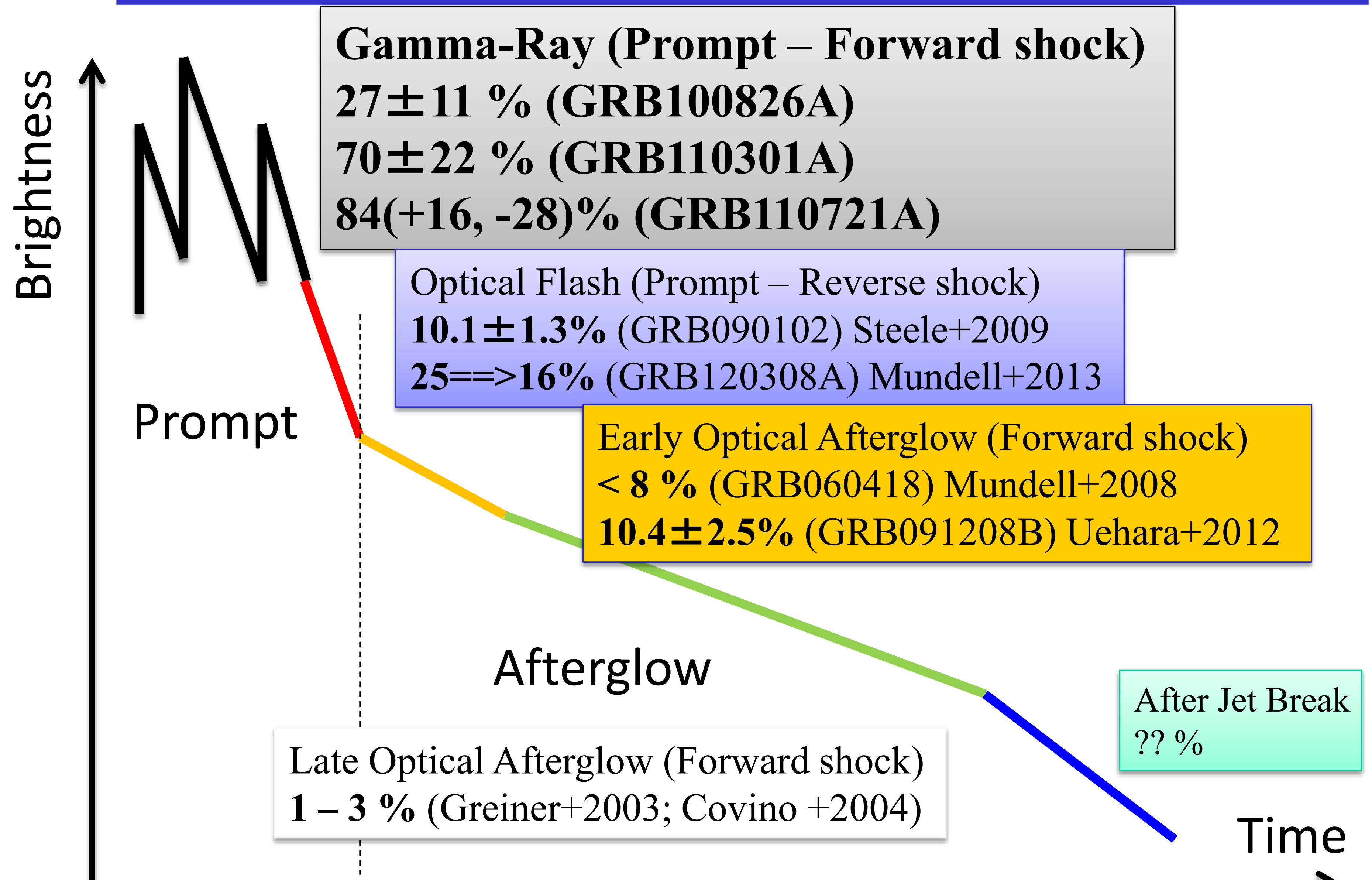
- Thin shell model fails to reproduce correlations for all 4 combinations of RS/FS and wind/ISM
- Thick shell model can reproduce correlations
- Reverse shock contribution often important, if not dominant

van Eerten 2014



- **Afterglow for GBM bursts**
- **First afterglow without γ-emission**
- **Rebrightening / Plateaus**
- **Polarisation**
- **Short GRBs**

Evolution(?) of polarization

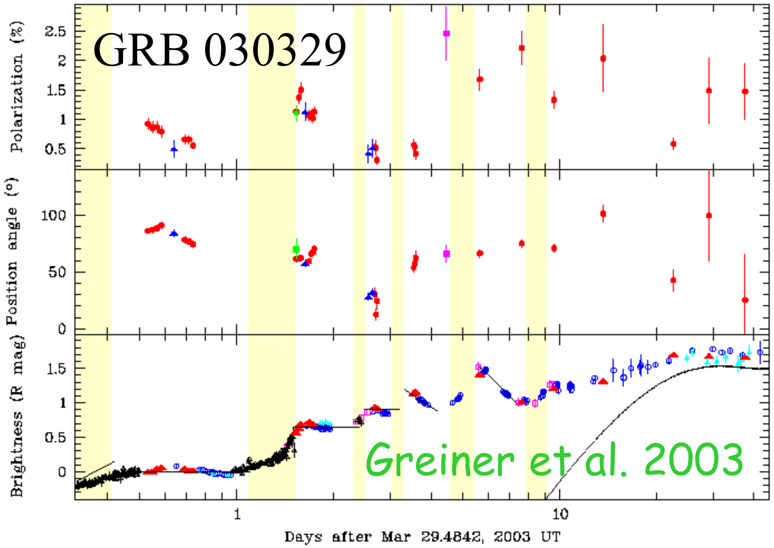


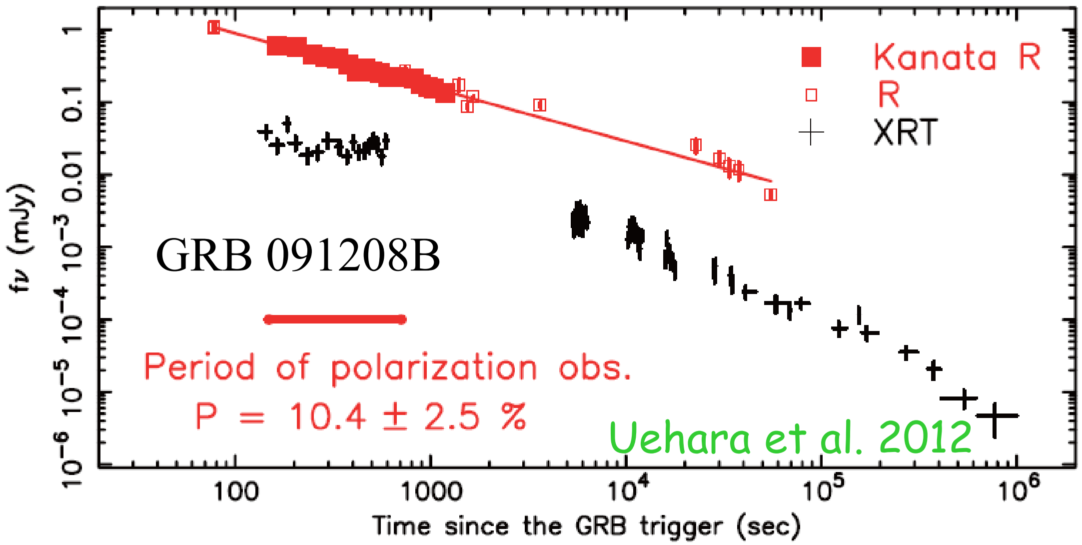
Early optical polarisation

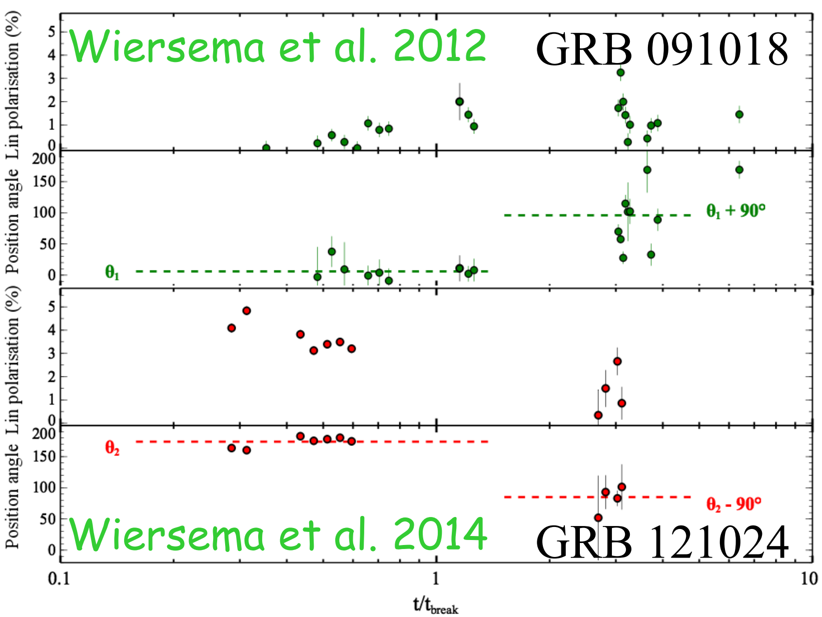
Adapted from King+ 2014

GRB	t_{start}(s)	t_{exp}(s)	Polarization	Interpretation
120308A (Mundell+ 2013)	90	135	28-15%	RS
090102 (Steele+ 2009)	63	24	(10±1)%	RS
110205A (Cucchiara+ 2011)	76	?	<16%	RS
060418 (Mundell+ 2007)	82	12	<8%	Both
100906A (Gorbovskoy+ 2012)	48	3600	<2%	FS
091208B (Uehara+ 2012)	72	551	(10.4±2.5)%	FS
131030A (King+ 2014)	285	2894	<2%	FS

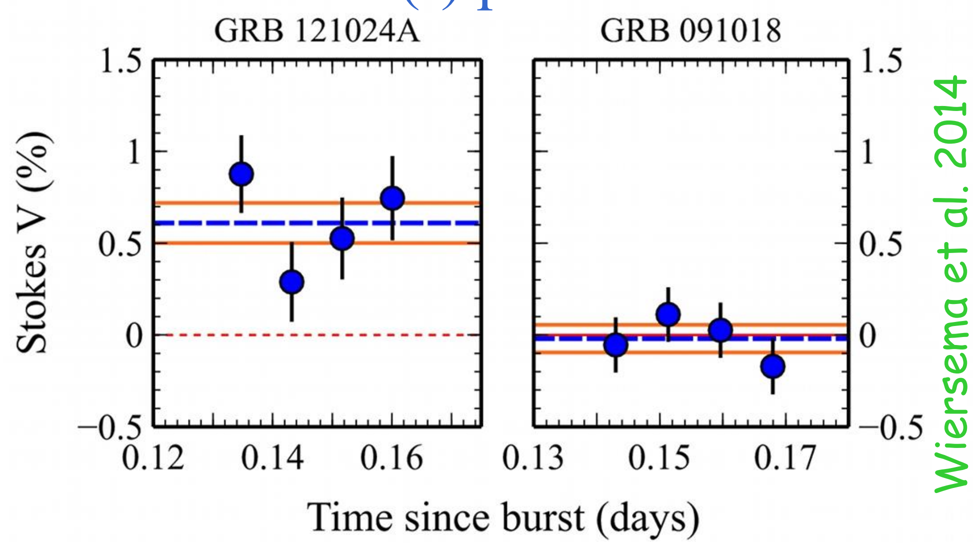
Examples of optical polarisation measurements







Circular(!) polarisation



- Afterglow for GBM bursts
- First afterglow without γ-emission
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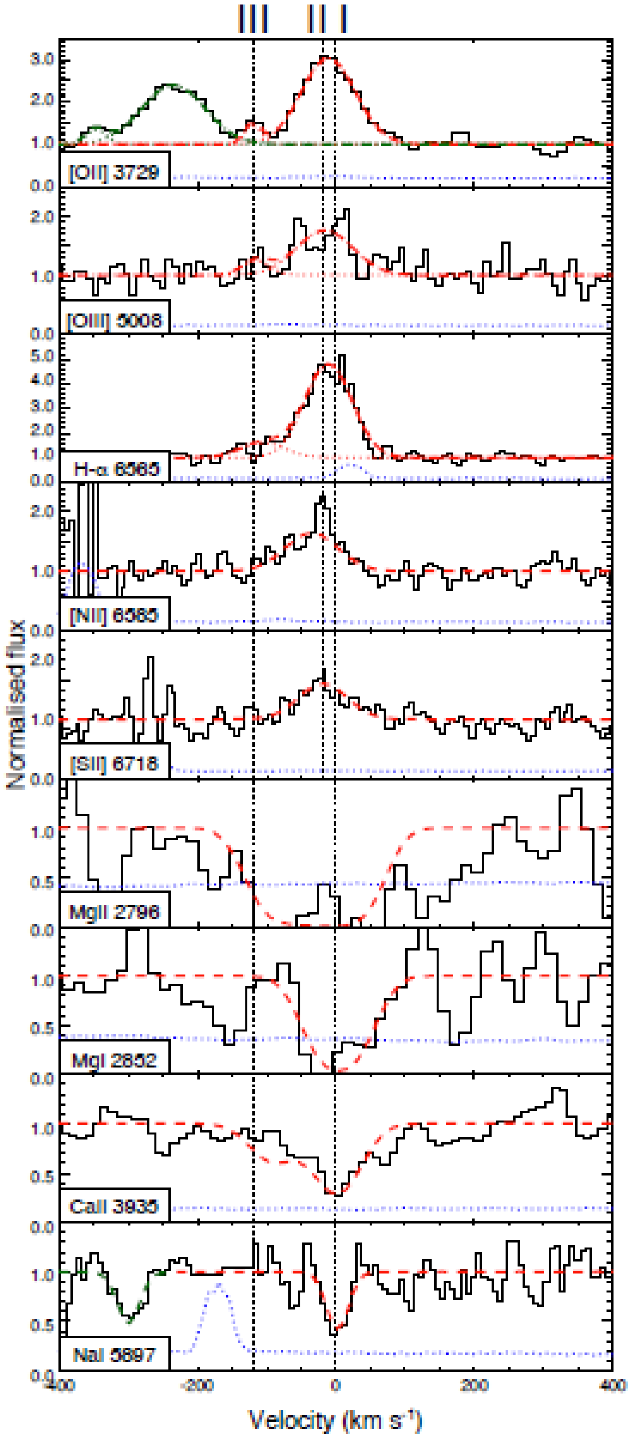
- Short GRBs

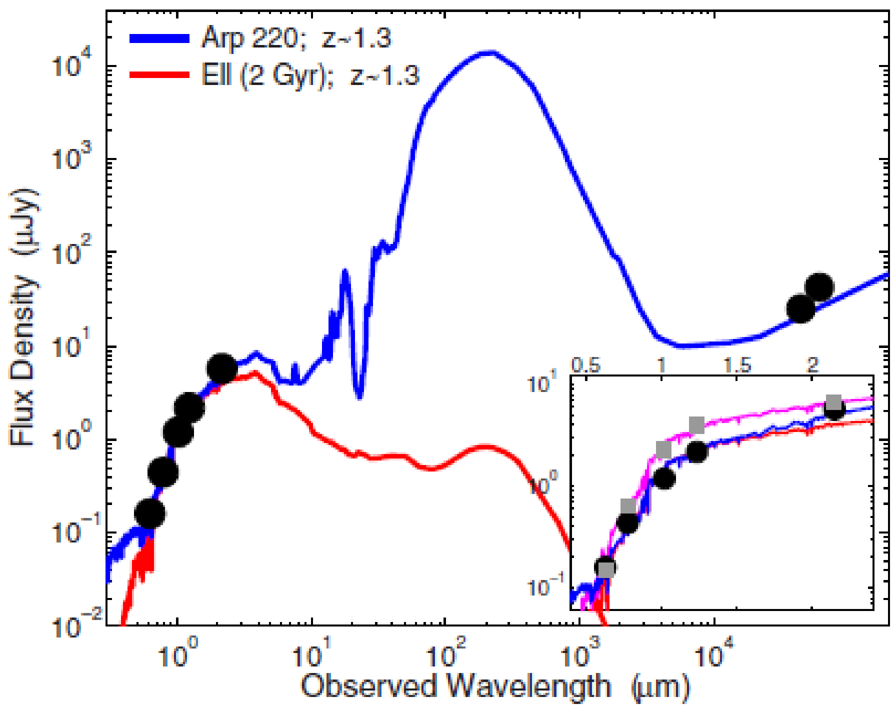
Afterglows of short GRBs

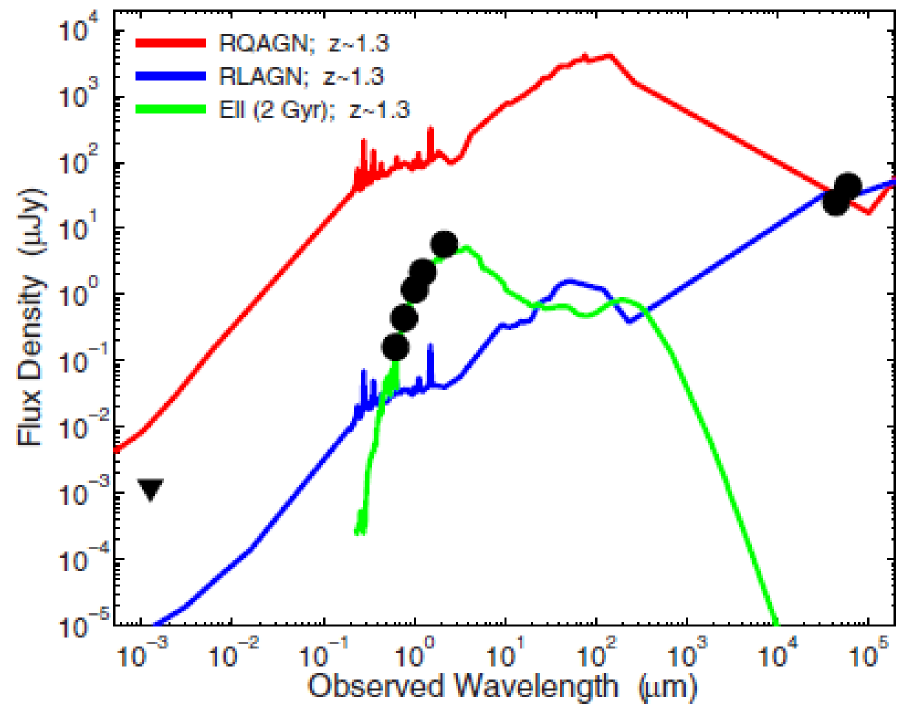
- **Difficult to measure due to faintness (low fluence, low n)**
- **Only 1 afterglow spectrum so far:**
  ➔ GRB 130603B (z=0.36)
  shows rich absorption line dynamics
  (3 velocity systems),
  A_V = 0.86 ± 0.15 mag,
  suggesting origin in dense region
  (Cucchiara+2013, de Ugarte Postigo+ 2014)
- **~14 sGRBs with redshift (13 from host association and emission lines)**



Hosts seem to form mixed bag

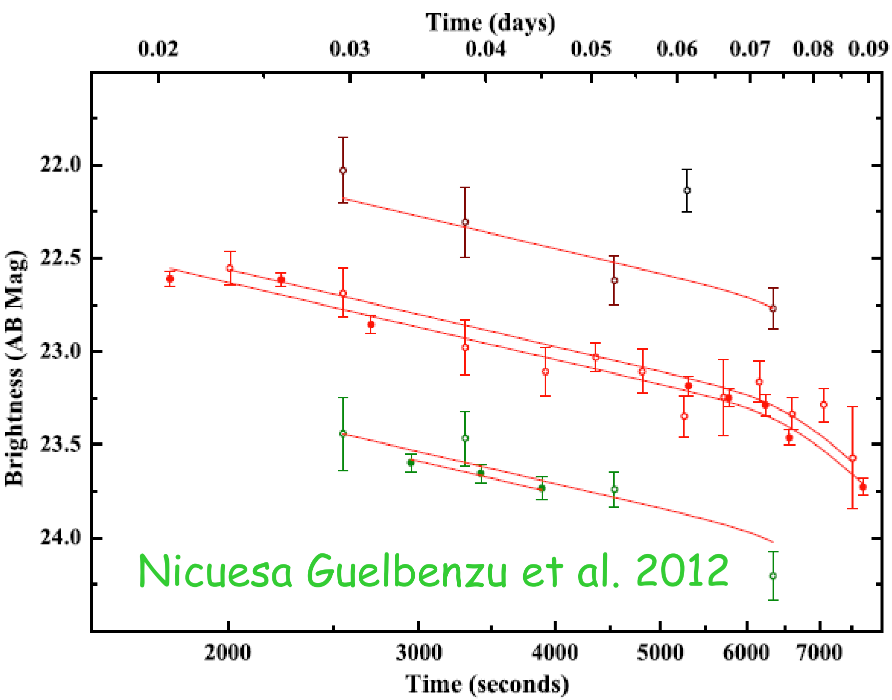
- **Likely first short 'dark' GRB 120804A** (Berger+ 2013)
- **L.o.s. $A_V \sim 2.5$ mag, z=1.3**
- **AG SED suggests $n \sim 10^{-3}$ cm^{-3}**
- **Host SED fits scaled Arp 220 SED, with SF = 330 M_{sun}/yr**

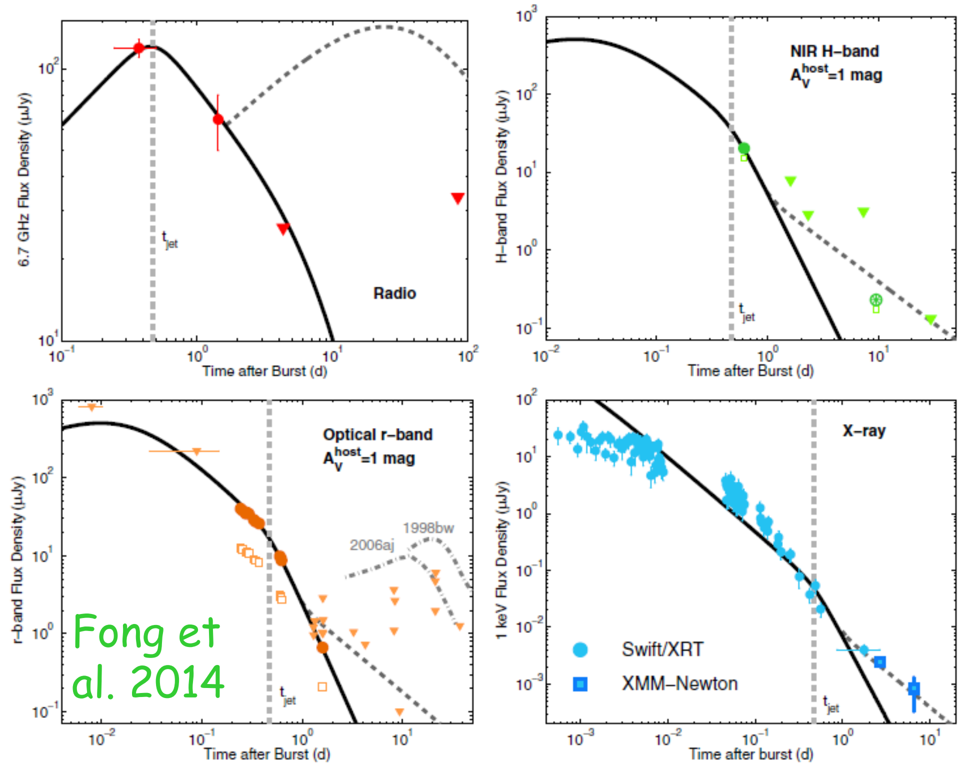




Jet breaks in short GRBs?

- ❖ Breaks in light curves found – but interpretation as jet breaks is uncertain
- ❖ Limits on jet breaks suggest opening angles >10°





Summary & Future

- Short GRBs are still elusive and puzzling
- Similarly, growing polarisation measurements do not yet provide consistent picture
- Modelling of multi-λ data gets to the point where predictions can be verified/falsified
- New GBM localization data products, combined with wide-field imaging and powerful transient detection routines find optical afterglows in 100's □^{2}
- New observatories coming online at high & low energies, and multi-messenger
  - HAWC (wide-field TeV observatory), CTA, SKA
  - Synoptic surveys in optical and radio
  - Unique opportunities for joint gravitational wave/photon detections of GRBs (binary mergers) with ALIGO/Fermi