Lessons from the Swift XRT GRB sample:

from scale-invariance to light curve flux spread
&
from plateau correlations to reverse shock properties

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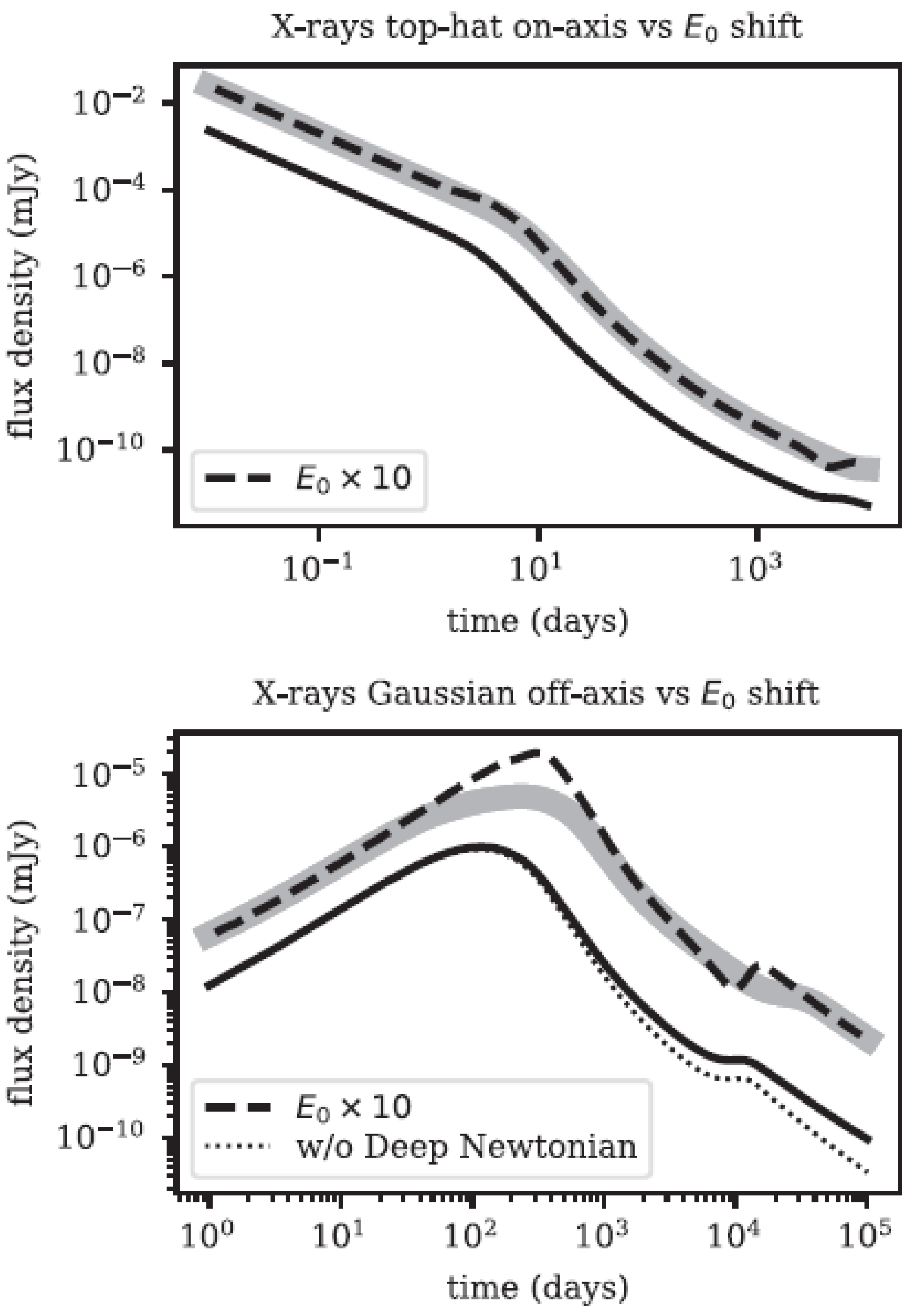
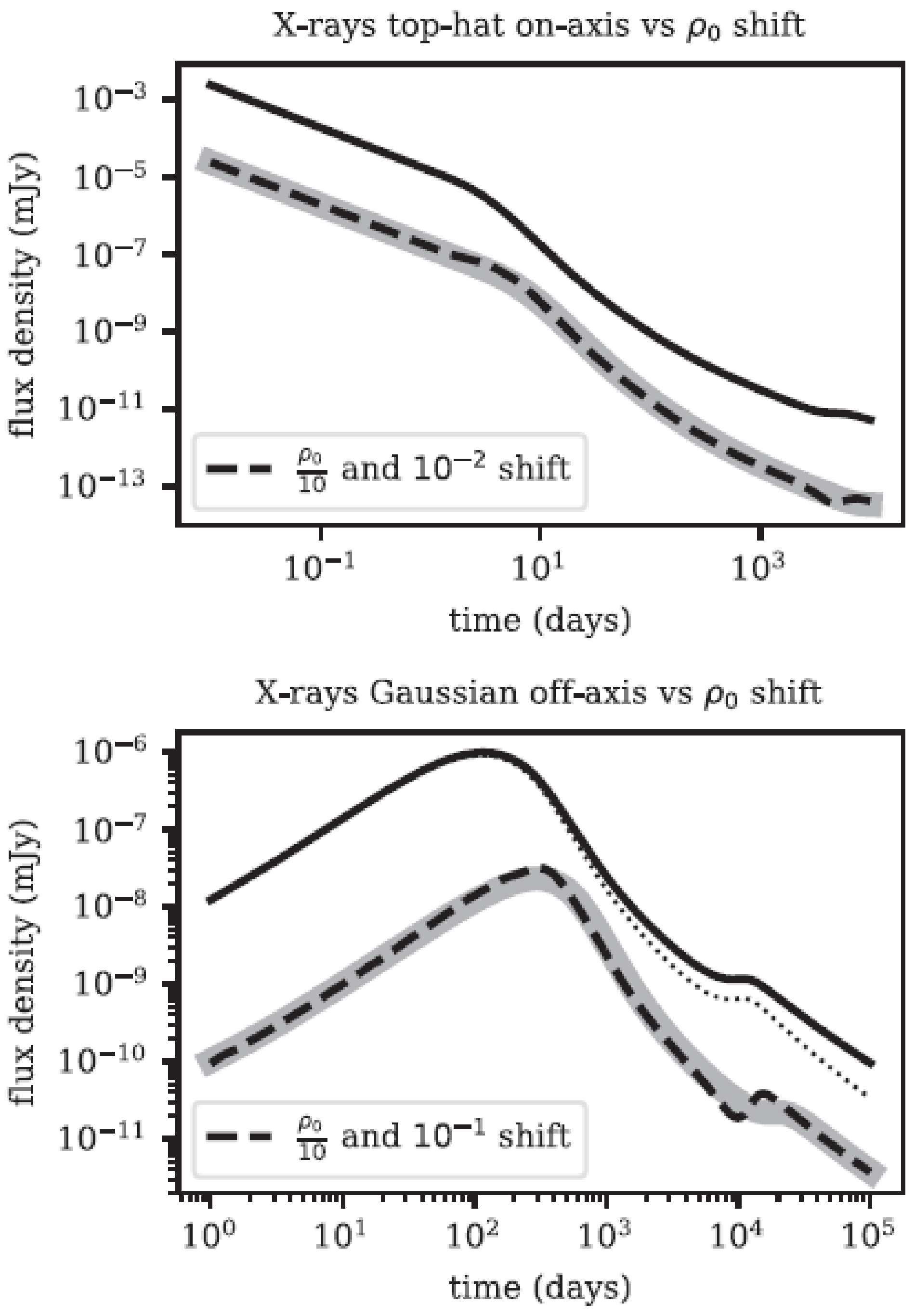
Scale invariance in gamma-ray burst afterglow light curves

Models for GRB afterglow dynamics and synchrotron spectra are known to exhibit various scale invariances, owing to the scale-free nature of fluid dynamics and the power-law shape of synchrotron spectra. Since GRB 170817A, off-axis jet models including a lateral energy structure in the initial outflow geometry have gained in prominence. While scale-invariance means that also high-resolution structured jet simulations can be *completely* rescaled across parameter space, it also implies that the scale-invariance for arbitrary jet structure and dynamical stage can be expressed locally as a function of jet temporal light-curve slope. As shown in the figures, this approach is effective wherever the light curves are approximately power laws, which means that this *local approximate* rescaling can even be useful in the absence of an underlying generating model (simulation, analytics), and can be applied to observational data directly (see Van Eerten+ 2024, including analytical scaling expressions).



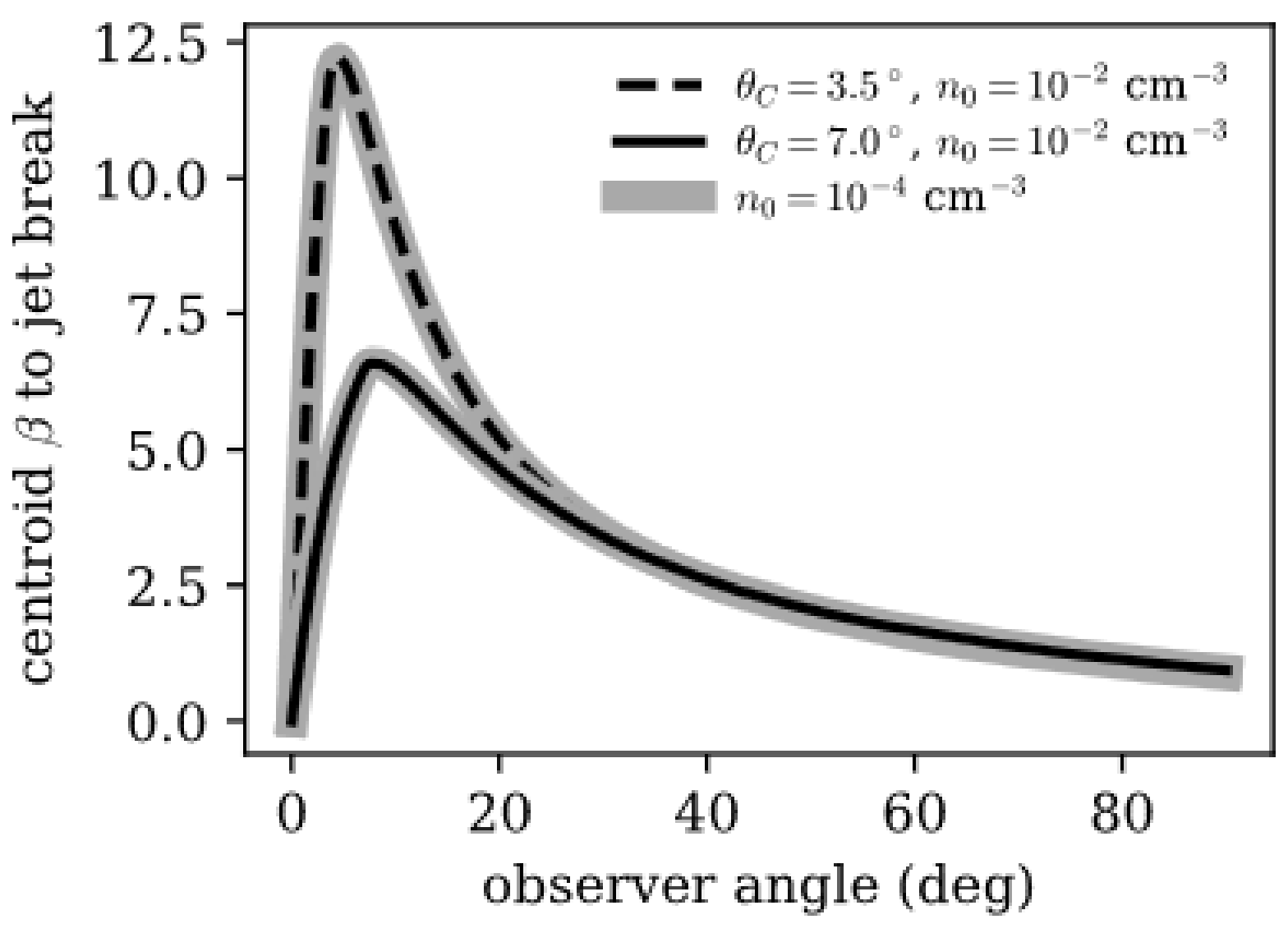
The figures here demonstrate how light curves can be rescaled across explosion energies and circumburst density. Not shown are the possible rescaling across and standard synchrotron parameters for electron population and magnetic field



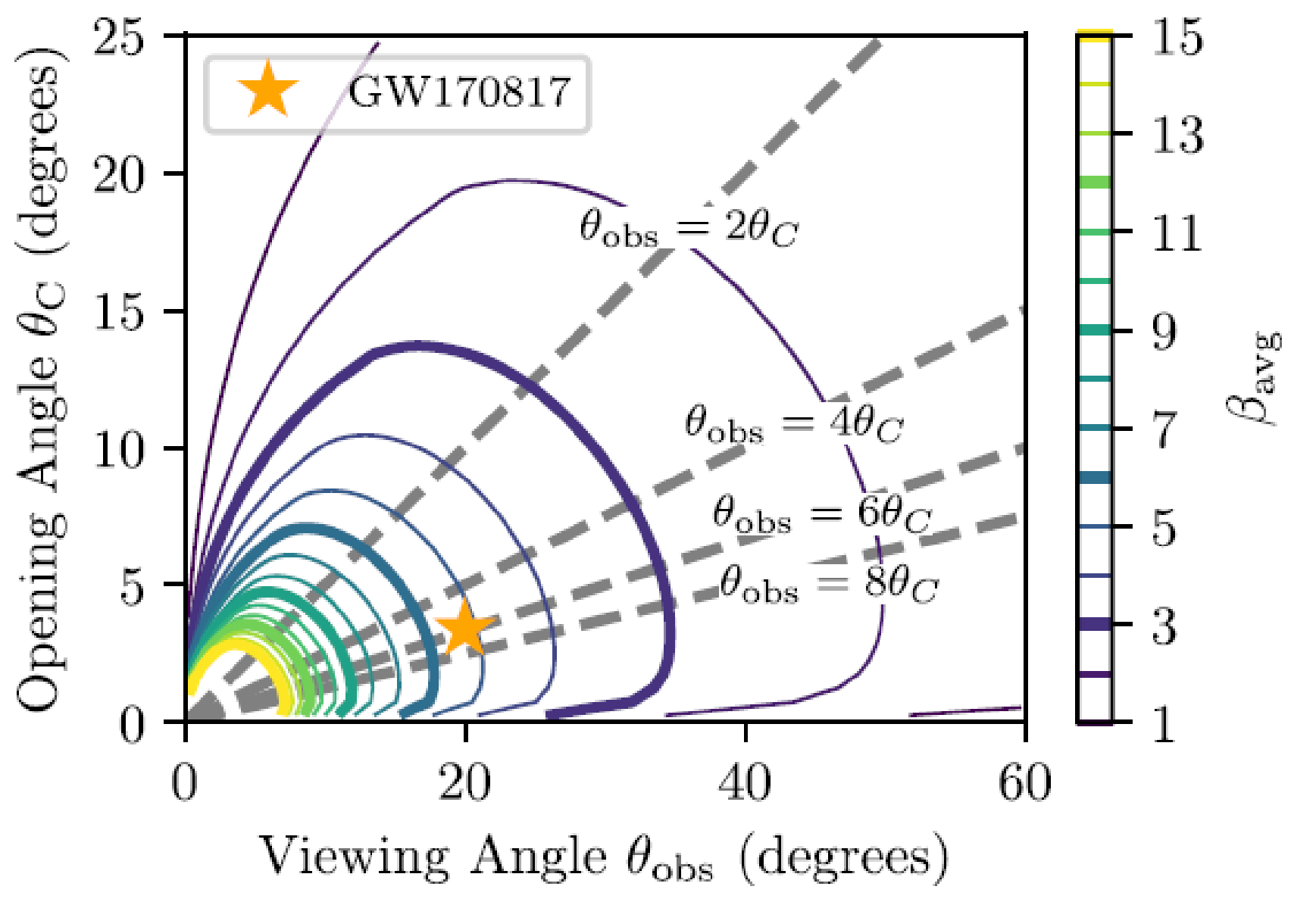
Solid black: original afterglow-generated; black dashed: local approximate rescaling; thick grey: complete rescaling dotted: afterglowpy w. Deep Newtonian

Quick interpretation of observations using invariance

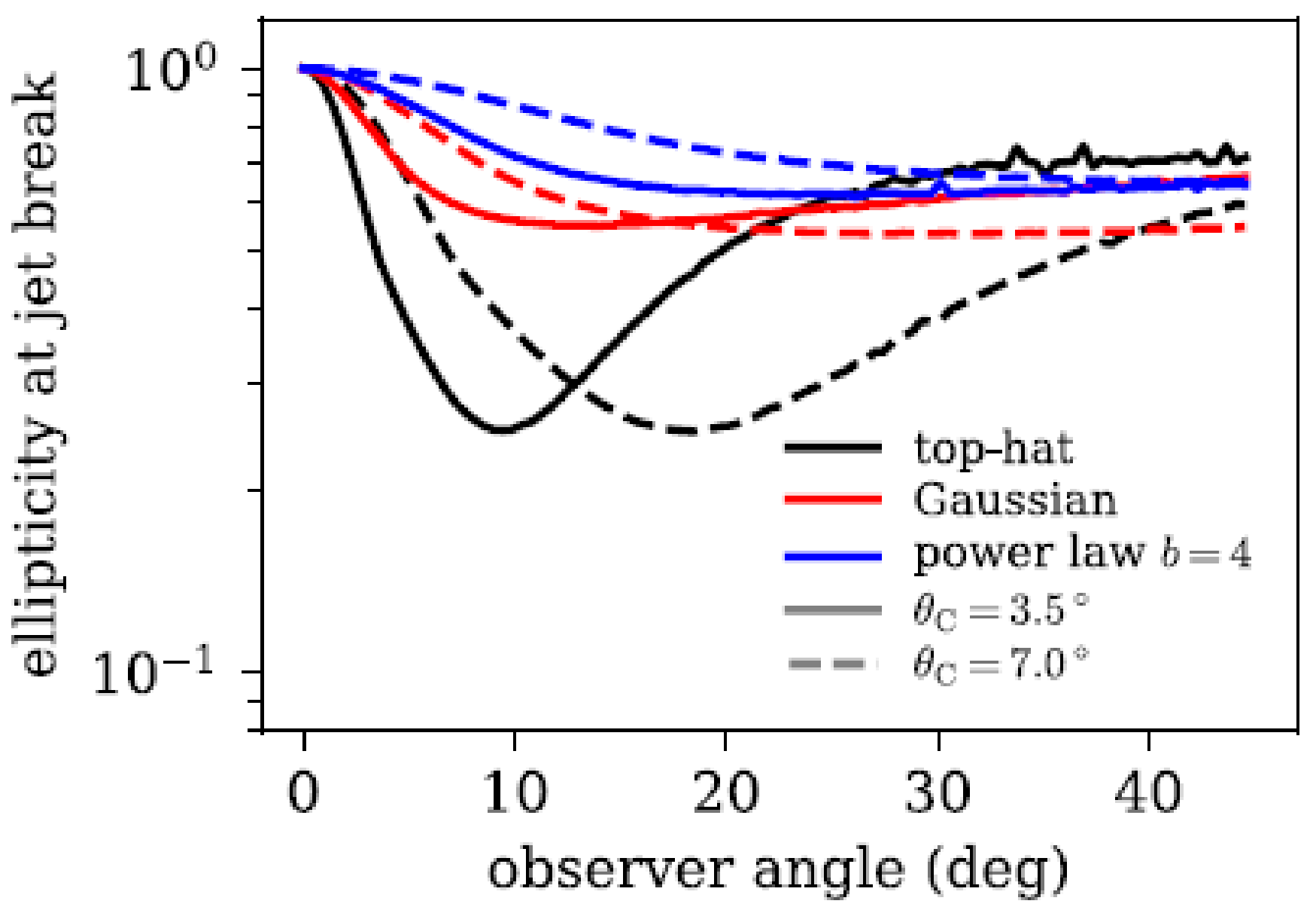
the scale-invariance of light curves can be leveraged to obtain strong constraints on the physics from only a small number of observations. Shown here are examples involving models of VLBI observations of GRB afterglows. These involve observations taken at the peak time of the (off-axis) light curve.



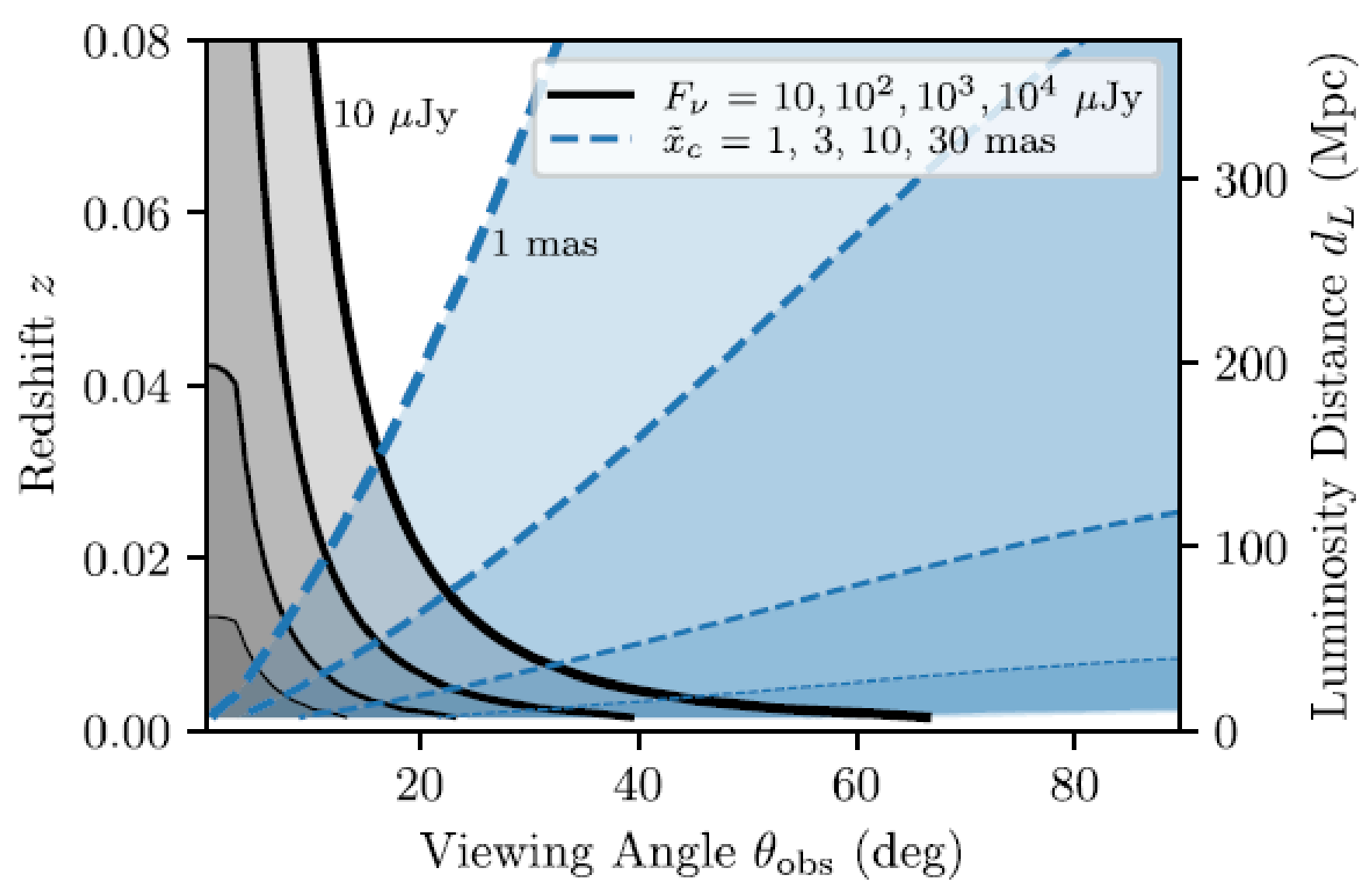
example: the average centroid velocity shows a universal behaviour



example: average centroid velocity and light curve rising slope for an off-axis jet combine to fix orientation and opening angle



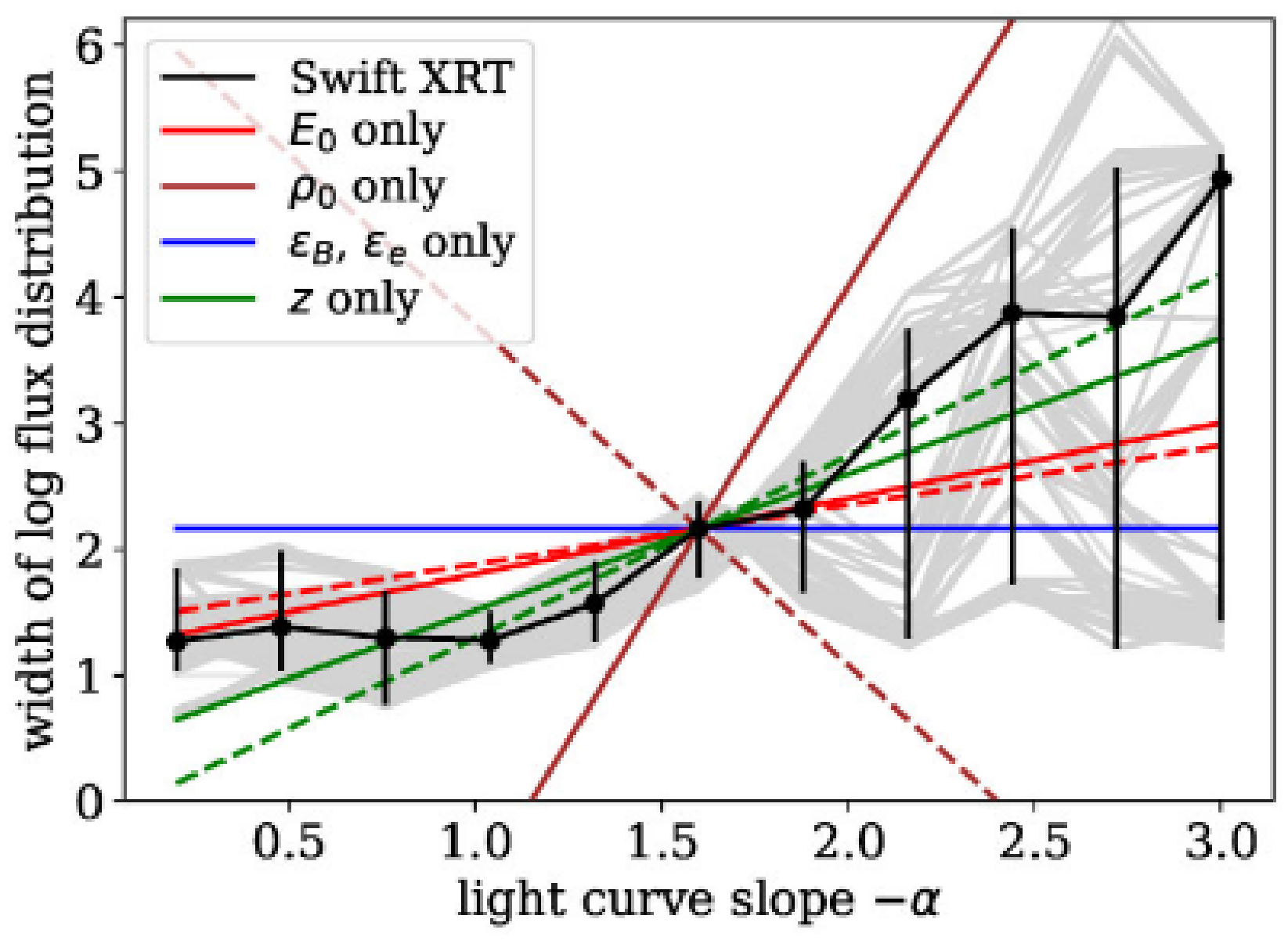
example: The ellipticity is similarly universal



example: the best case for a GRB 170817-like burst VLBI observation finds the middle ground between brightness and orientation

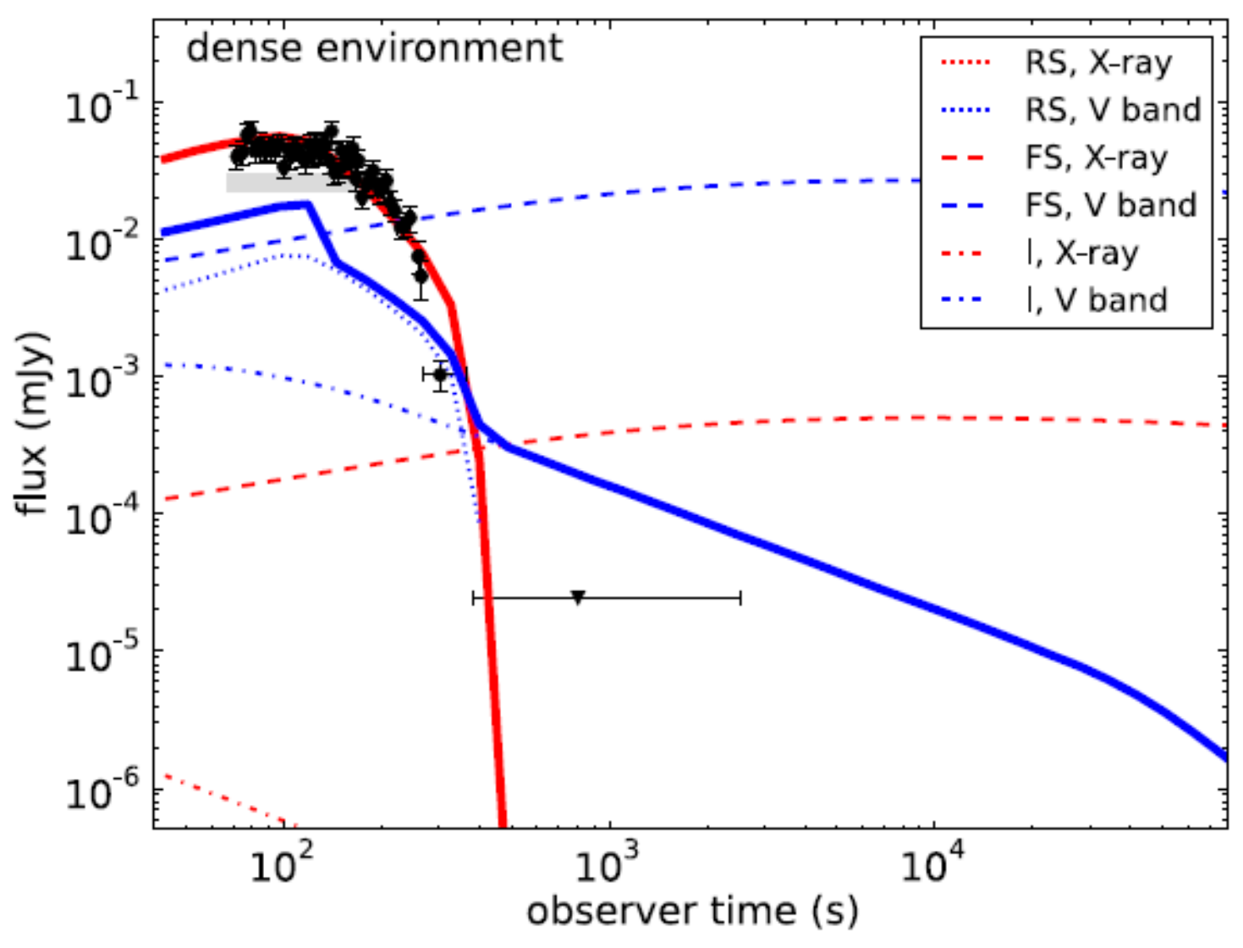
Scale-invariance and the Swift XRT sample

Swift XRT afterglow light curves show a wide variety in temporal slopes between bursts and within single bursts. If the fluxes of the sample are binned by their slope, it is therefore possible to check for trends in the *ranges* of flux levels as a function of this slope. Scale-invariance, as discussed above, predicts that the sensitivity of the light curve to physics parameters such as explosion energy is higher for some slope values than for others. The figure here shows in black the spread in slopes for the sample, with error bars from repeating a Monte Carlo set of draws. The coloured lines show what this spread would have been had a single physics parameter been dominating this spread by being intrinsically a wide distribution in nature.

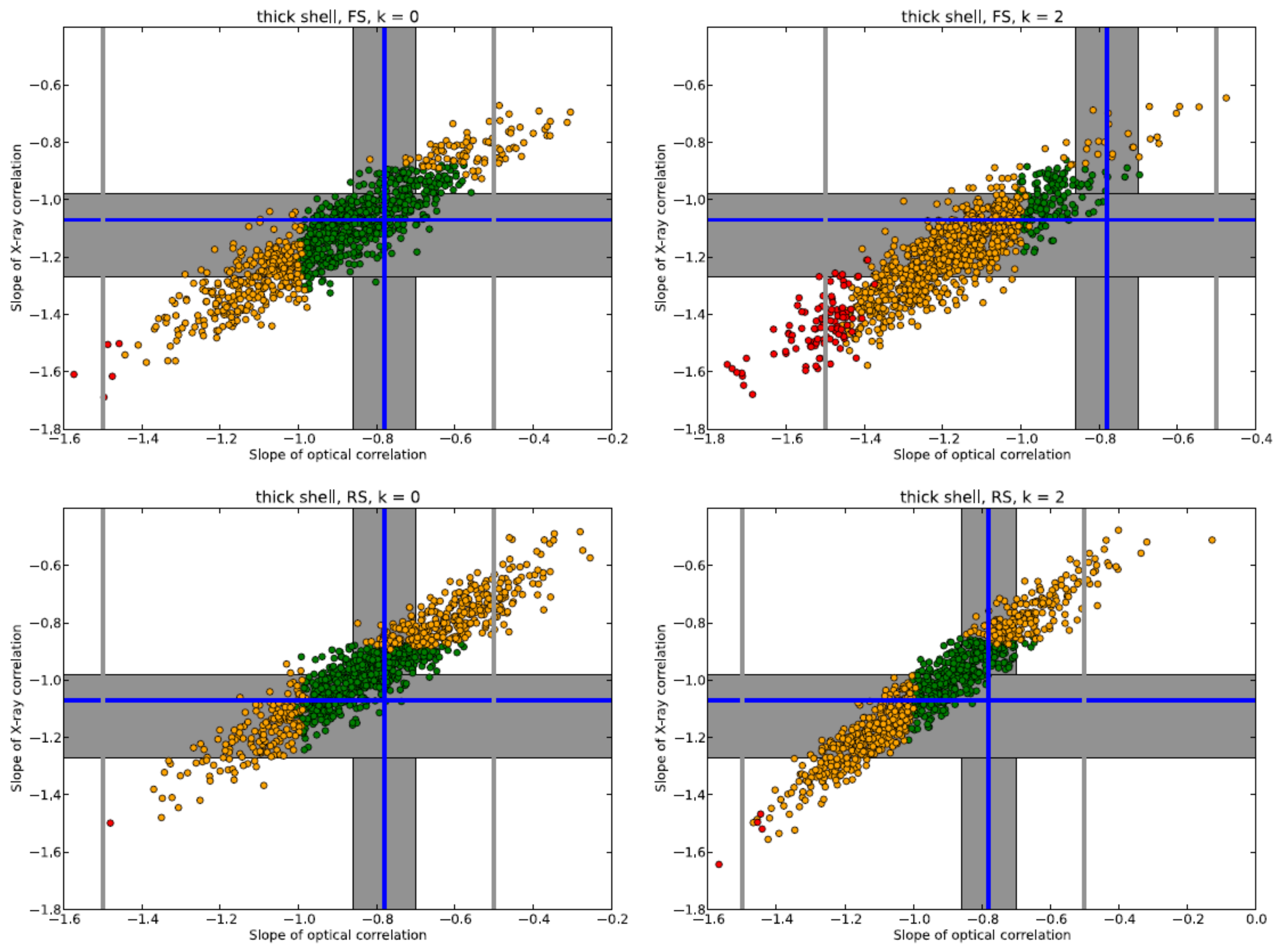


A Swift XRT study from the past: X-ray plateaus make a case for *strong* reverse shock and *thick shell* models over *thin shell* models

it can be shown (Van Eerten 2014) that Swift XRT plateaus are consistent with thick shell models, where the reverse shock achieves relativistic velocity in the frame of the inflowing plasma. This is a constraint resulting from X-ray (and optical) plateau end times correlating with end time flux level (e.g. Dainotti et al. 2013, ApJ 774, 147; Li et al. 2012, ApJ 758, 27).



This can be confirmed with a population study, succeeding to reproduce the correlations in a thick shell model (shown), but failing for thin shells. Thick shell models can also be used to explain sharp drops following the plateau stage (top right figure, GRB 09515).



Publications covered by this poster:

- Van Eerten 2014, MNRAS 442, 3495, *Self-similar blast waves with energy injection*
- Van Eerten 2014, MNRAS 445, 2414, *Gamma-ray burst afterglow plateau break time–luminosity correlations favour thick shell models over thin shell models*
- Ryan, Van Eerten et al. 2024, ApJ 975, 131, *Modeling of Long-term Afterglow Counterparts to Gravitational Wave Events: The Full View of GRB170817A*
- Van Eerten et al. 2024, MNRAS 530, 4094, *Scaling relations for gamma-ray burst afterglow light curves and centroid motion independent of jet structure and dynamics*