X-ray plateaus in gamma-ray burst light-curves from jets viewed slightly off axis

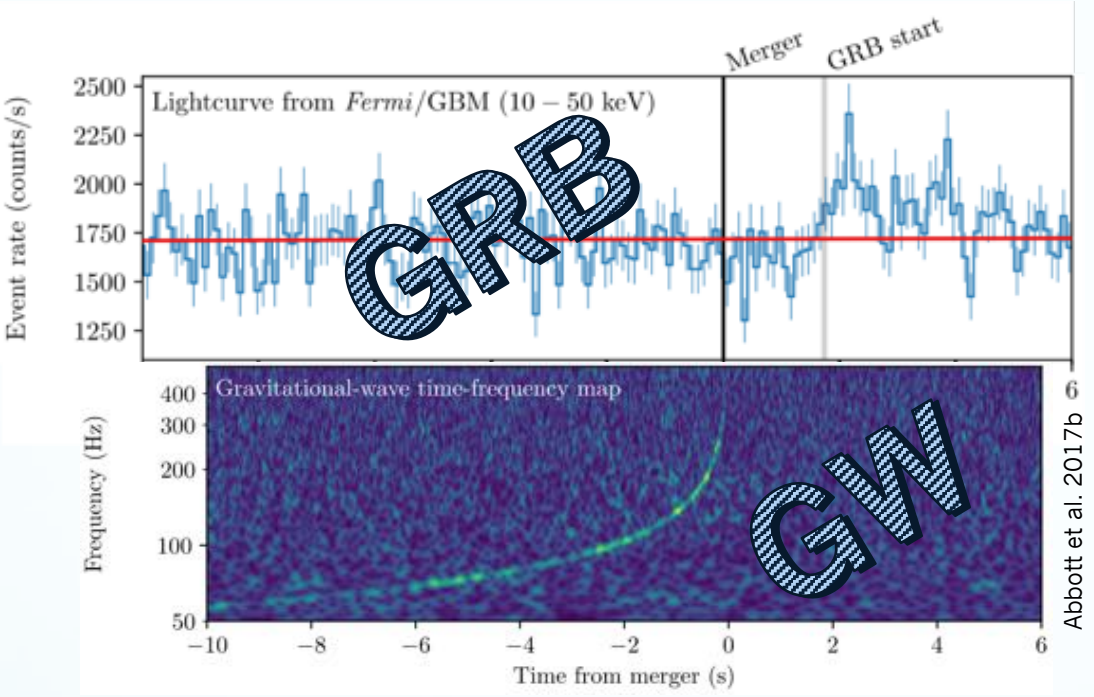
R. Duque, with F. Daigne, R. Mochkovitch & P. Beniamini

Elbereth Conference 2020 — Thursday February 27th

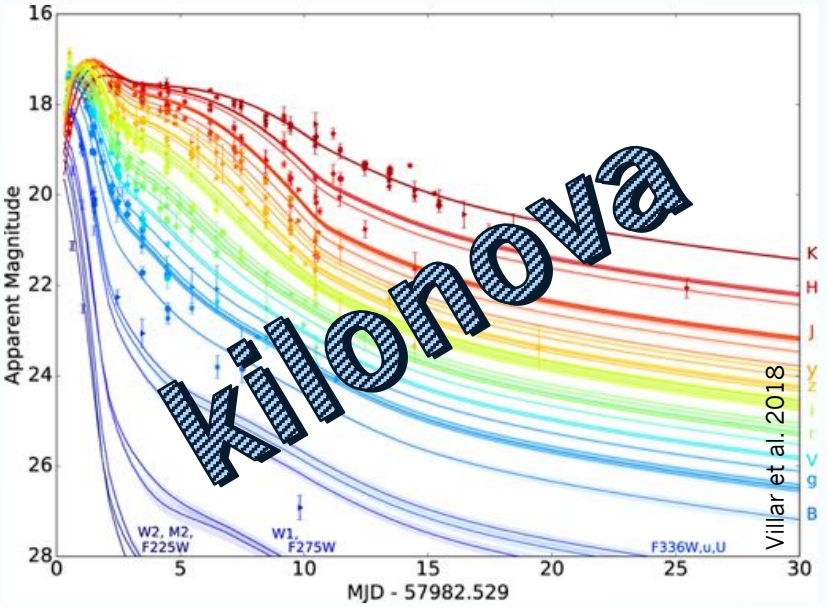
At Elbereth 2019:
talk on the GW170817 event!

Courtesy D. Hu

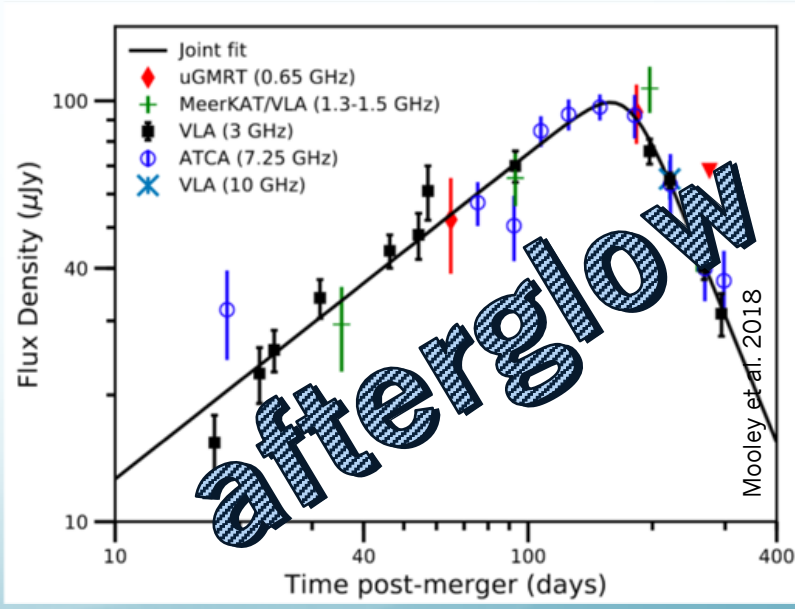
On August 17th 2017…



Abbott et al. 2017b

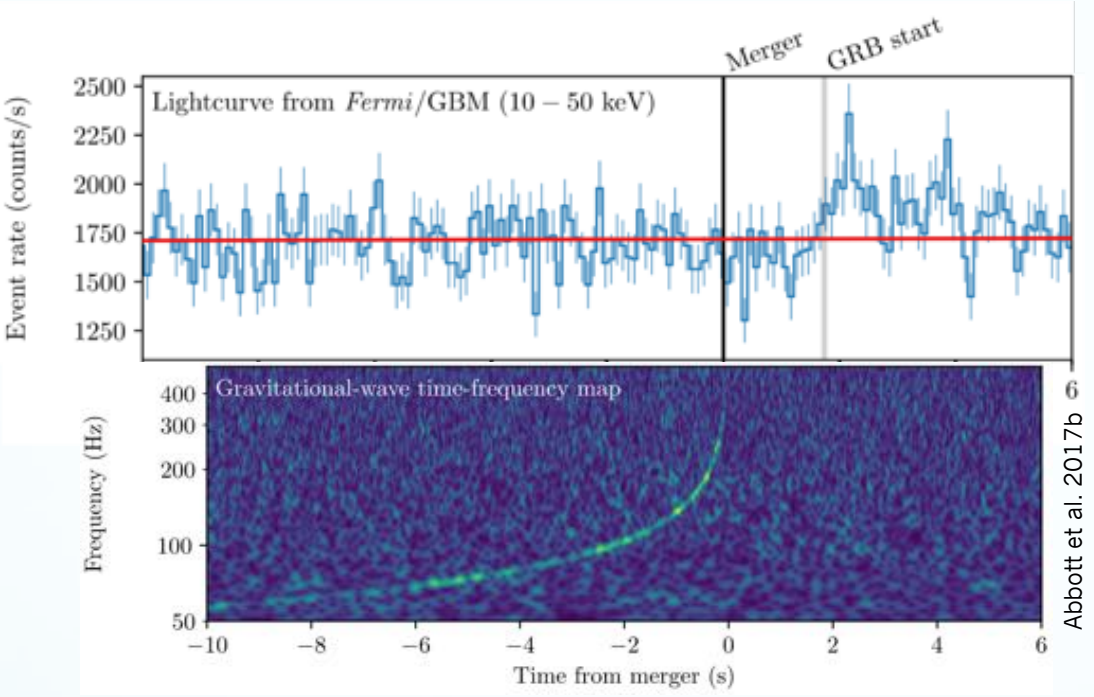


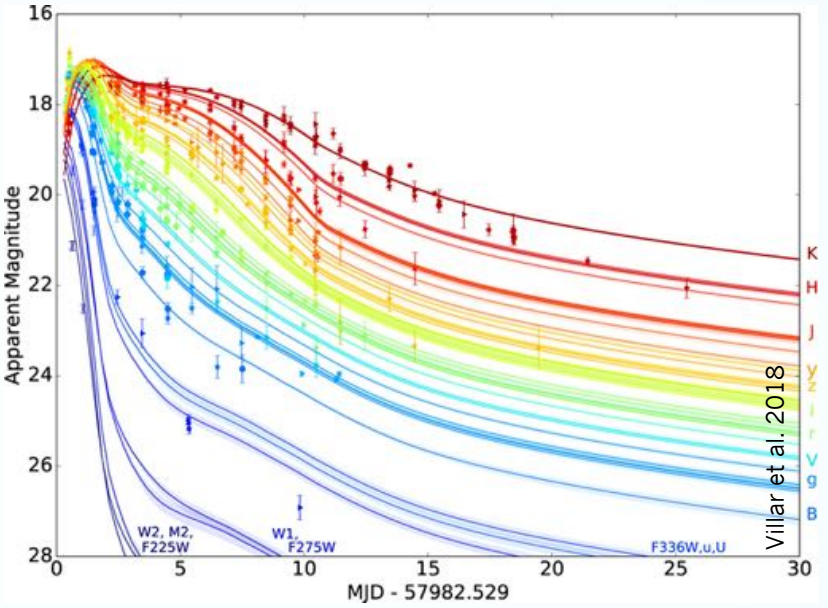
Villar et al. 2018

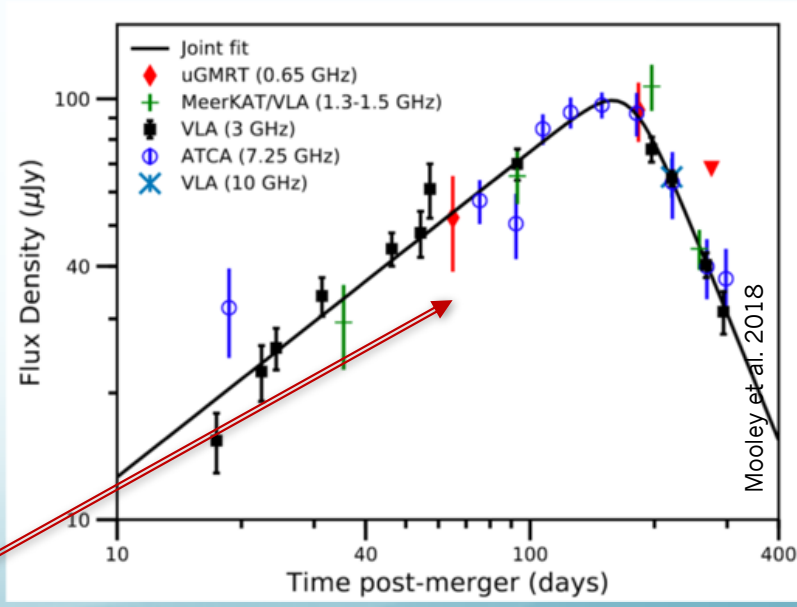


Mooley et al. 2018

On August 17th 2017…





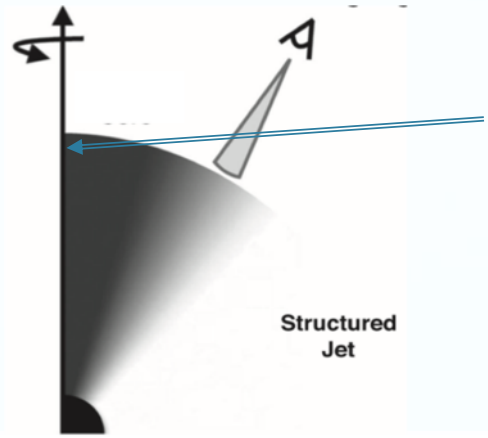


- Inauguration of the **era of multi-messenger astronomy with GW**
- **Largest multi-wavelength follow-up campaign** ever
- Confirmed **neutron star mergers as progenitors for short gamma-ray bursts**

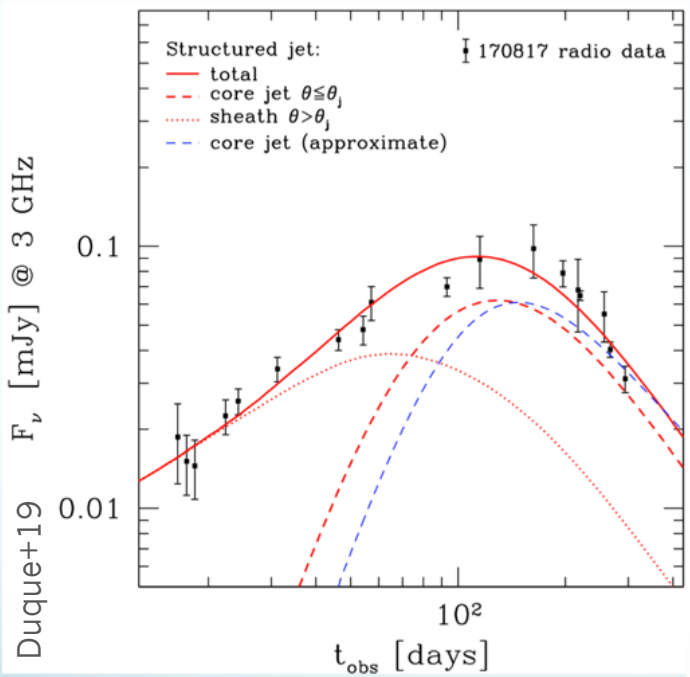
Particularly interesting: afterglow (radio ➔ X-rays, 10 ➔ 400 days)

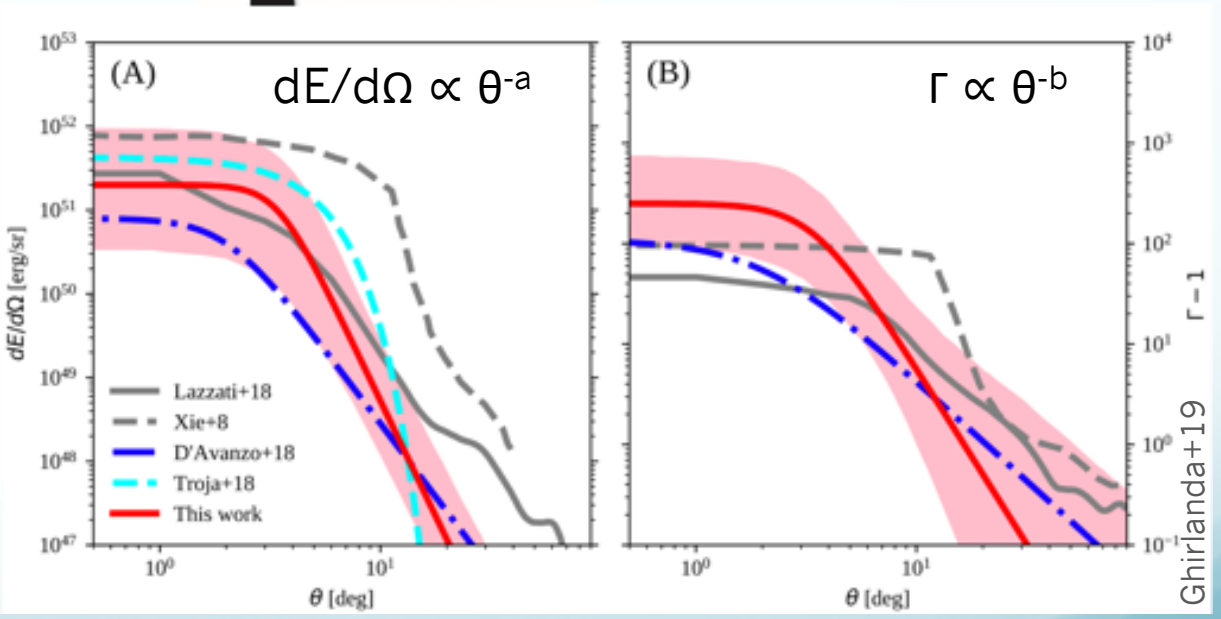
Structured jets in GRBs

GRB170817:
afterglow photometry
+ VLBI imagery
= Jet structure mapped!



Core initially beamed away from observer



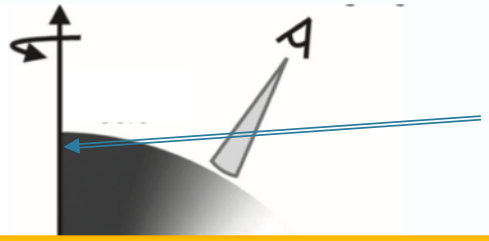


- Shallow jet structure
  a, b ≳ 2
- Jet opening angle ~ 5°
- Viewing angle ~ 25°

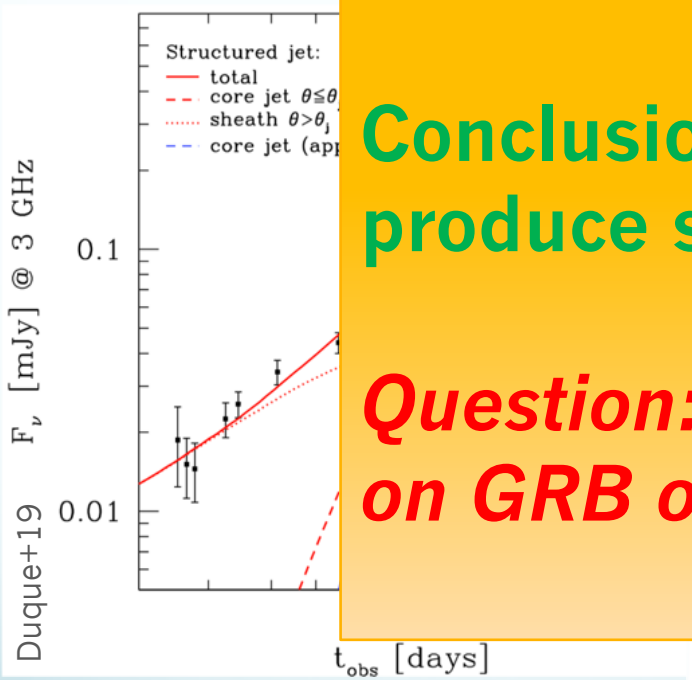
Most detailed GRB jet ever studied!

Structured jets in GRBs

GRB170817:
afterglow photometry
+ VLBI imagery:
= Jet structure mapped!

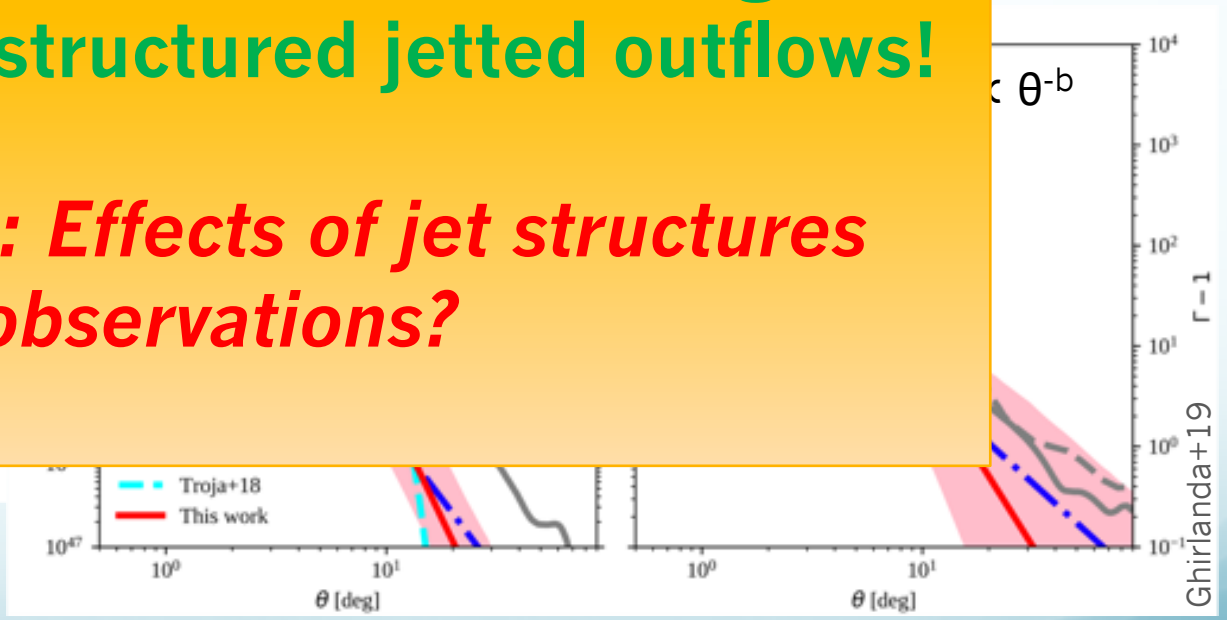


Core initially beamed away from observer



Conclusion: Neutron star mergers produce structured jetted outflows!

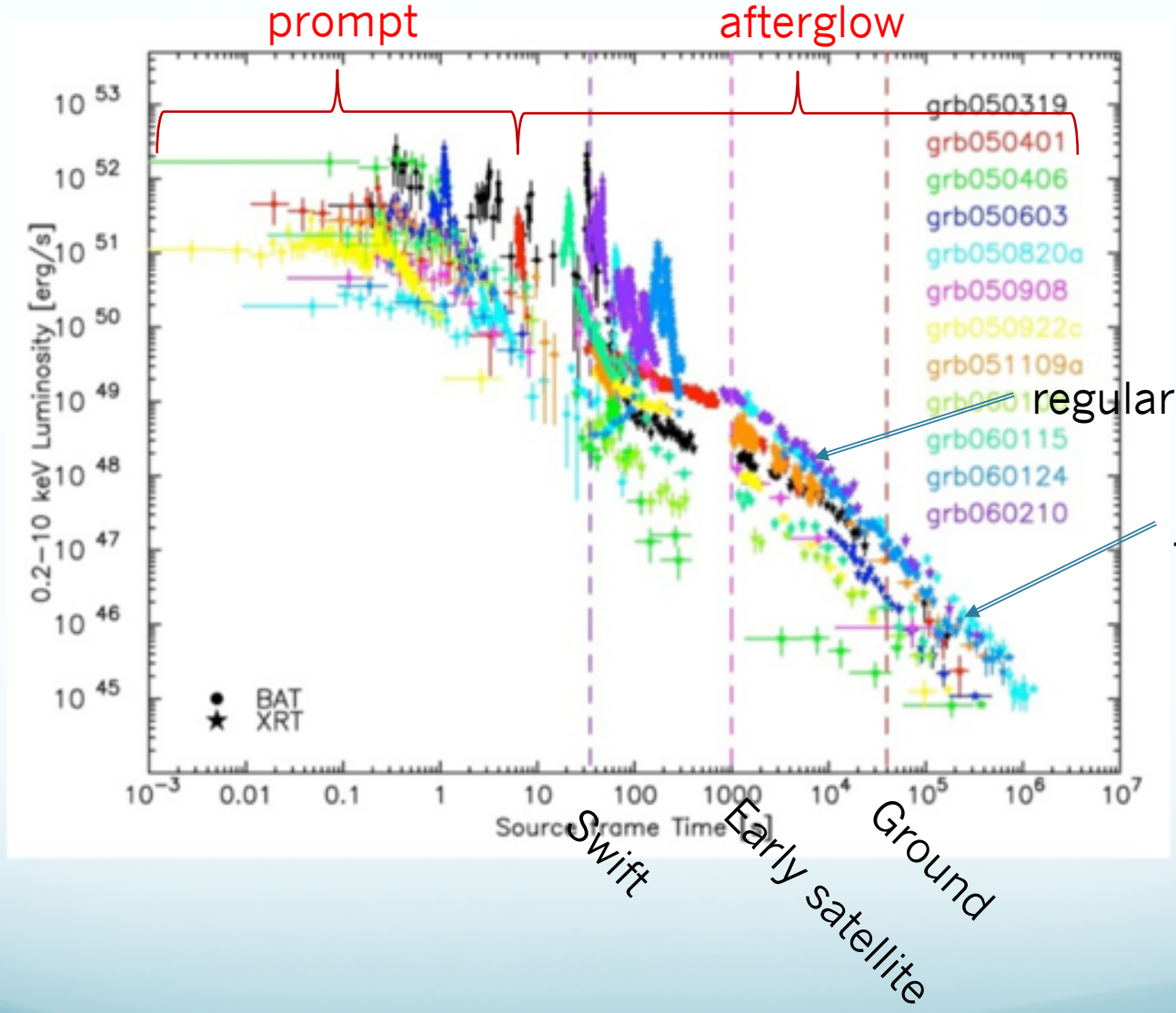
Question: Effects of jet structures on GRB observations?



- Shallow jet structure
  a, b ≳ 2
- Jet opening angle ~ 5°
- Viewing angle ~ 25°

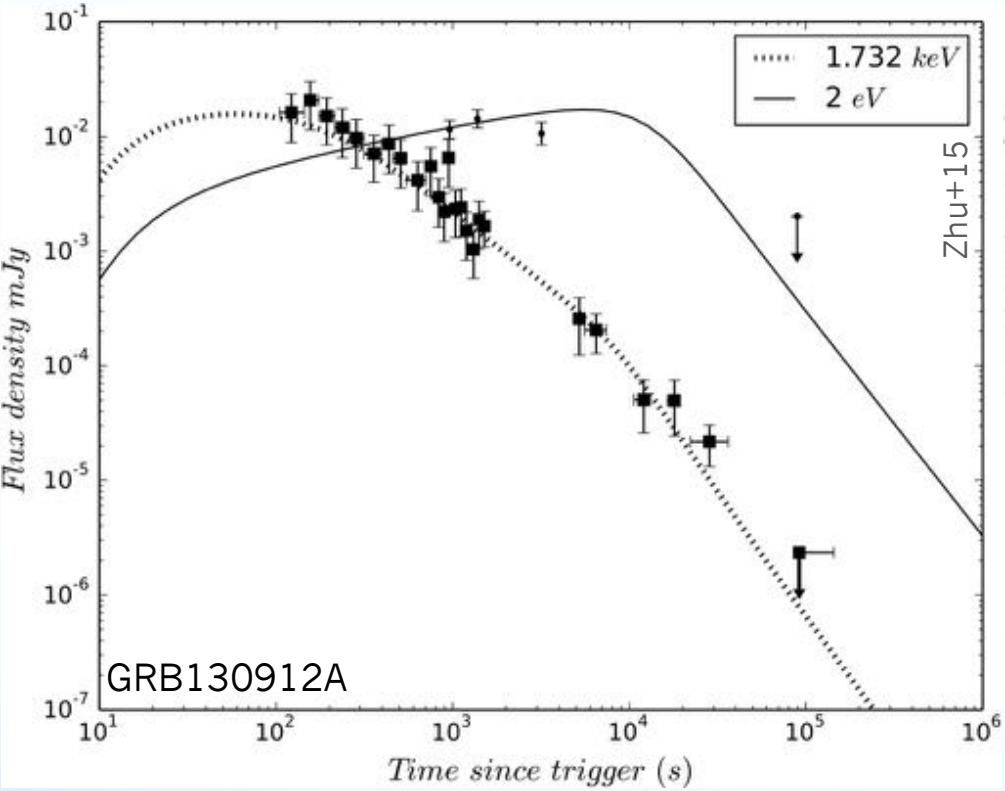
Most detailed GRB jet ever studied!

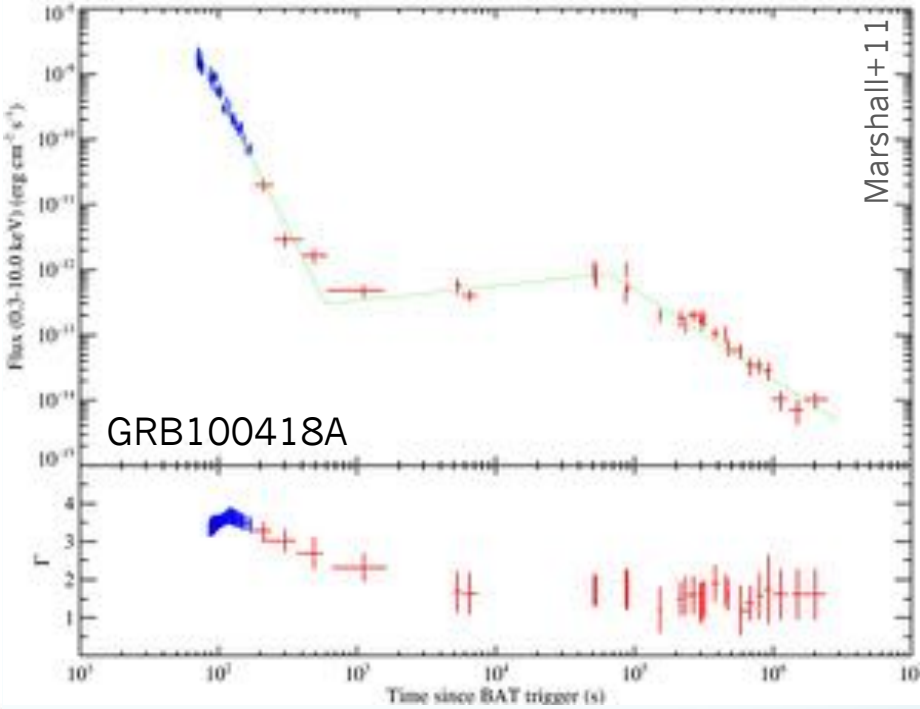
GRB afterglow plateaus: discovery



Afterglow diversity revealed by *Swift*: **plateaus**, **flares**

GRB afterglow plateaus: observations

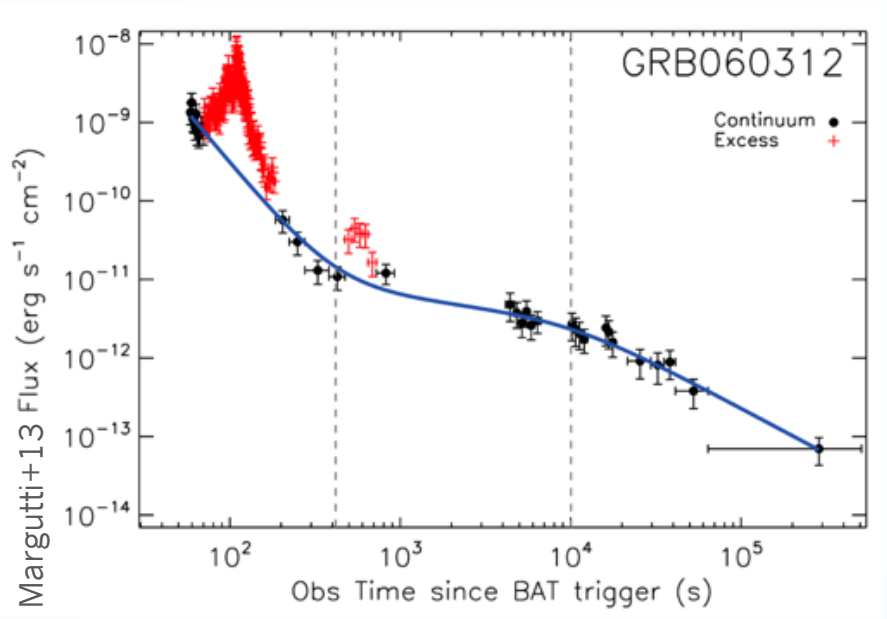


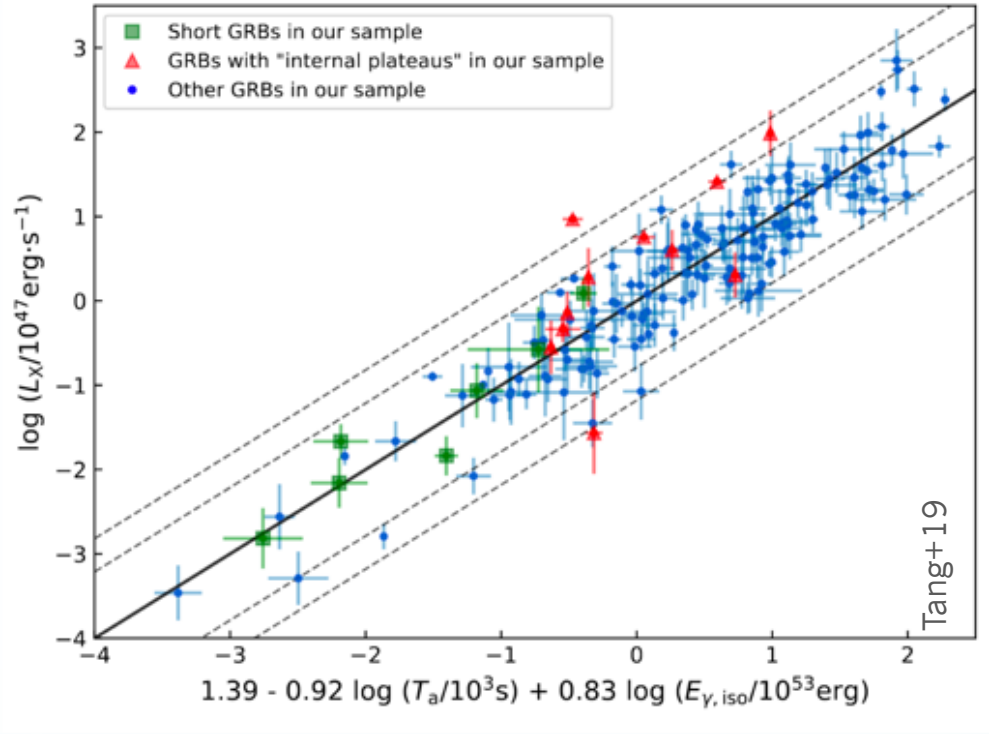


- ✓ **Shallow** increase/decrease
- ✓ **Chromatic** behavior

- ✓ **No evidence for spectral evolution** during plateau

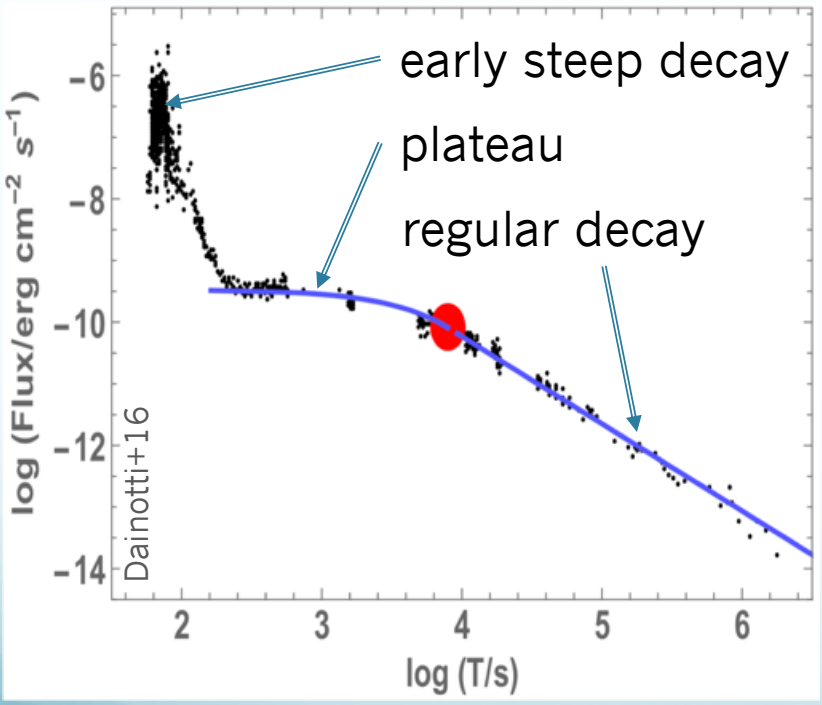
GRB afterglow plateaus: statistics





- ✓ Plateaus present in ~**50% of GRBs**
- ✓ **Correlations** of plateau properties
- ✓ **Plateau—prompt** correlations

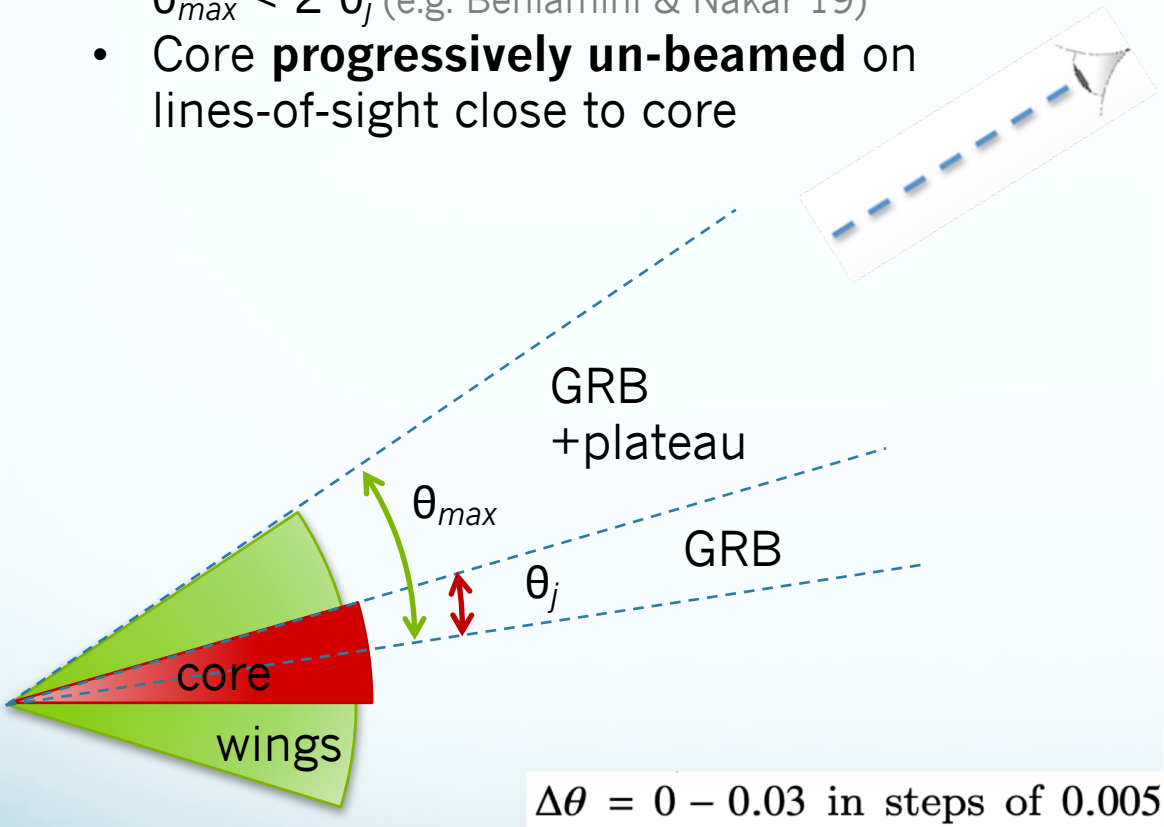
GRB afterglow plateaus: models

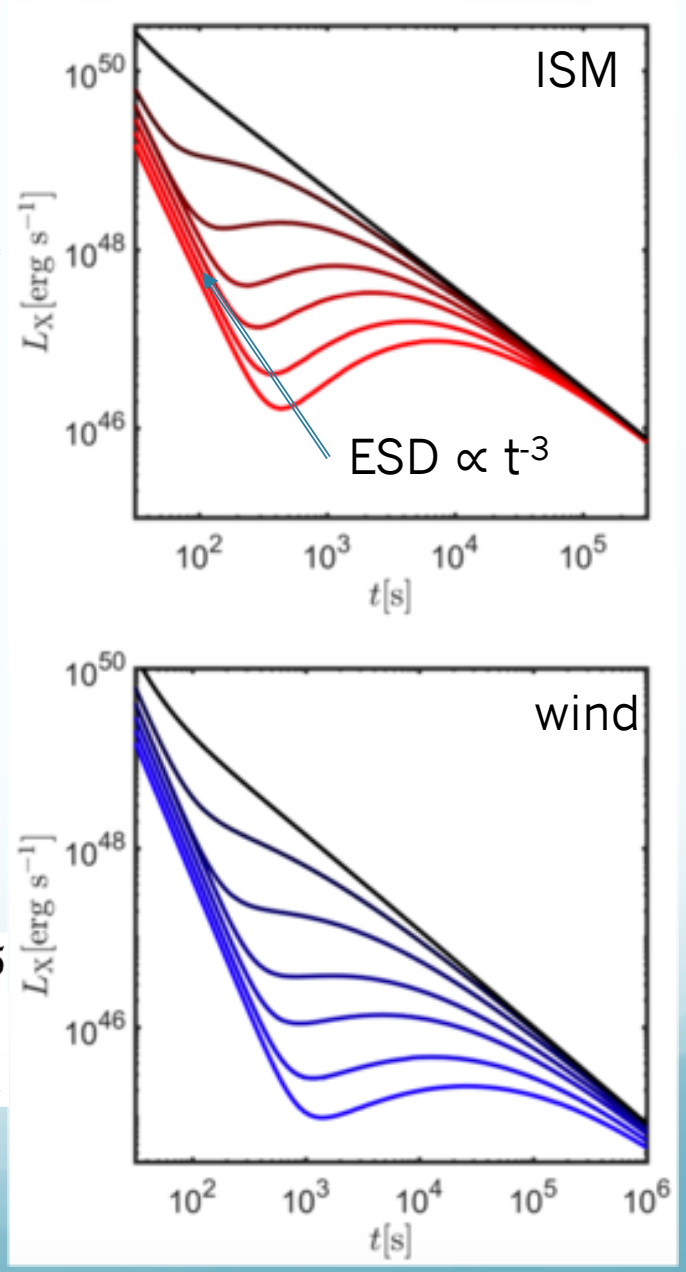


- **Late-time energy injection**
  Beniamini&Mochkovitch17
  Physical motivation? Prompt-plateau link?
- **Reverse shock emission** Hascoët+14
  Reverse shock in magnetized ejecta?
- **Delayed shock deceleration** Shen&Matzner+12
  Requires slow shock, compactness puzzle?
- **Prompt high-latitude emission tail**
  Oganesyan+19
  Does not explain absence of spectral evolution
- **Structured jets** Eichler&Granot06
- Inhomogeneous forward shock
- Time-dependent shock parameters
- Thick shell regime of external shock

Plateaus from structured jets

- GRB observed until **maximum angle** $\theta_{max} < 2\,\theta_j$ (e.g. Beniamini & Nakar 19)
- Core **progressively un-beamed** on lines-of-sight close to core



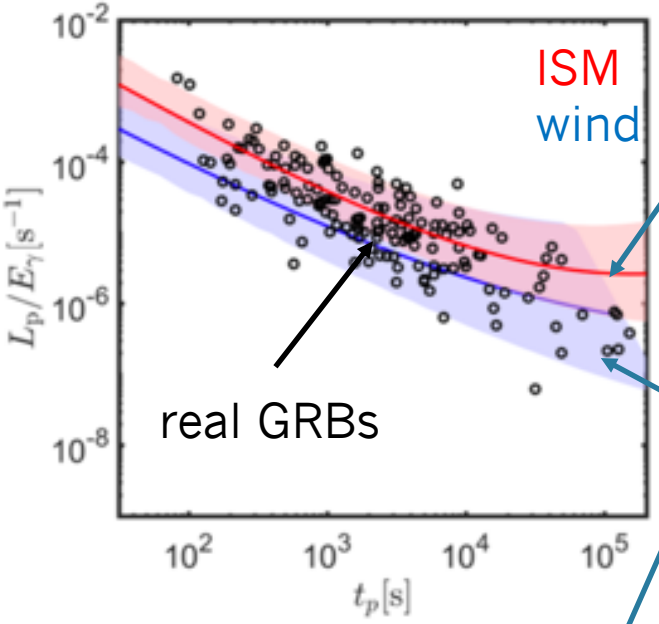


$\Delta\theta = 0 - 0.03$ in steps of 0.005

$E_{\rm kin,iso} = 10^{54}\,{\rm erg},\ \theta_j = 0.1,\ \Gamma_j = 400,\ \eta_\gamma = 0.1,$
$\epsilon_e = 0.1,\ \epsilon_B = 0.01,\ p = 2.2\ \alpha = 8,\ \beta \gg 1$

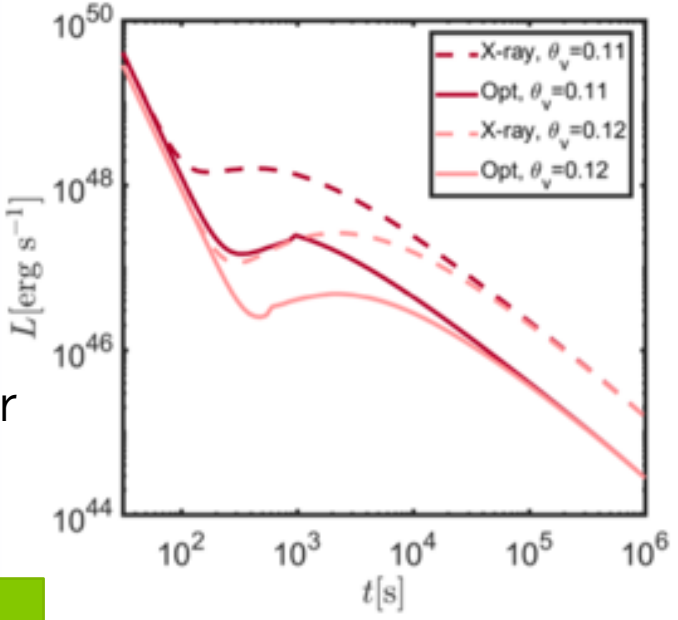
Plateaus from purely geometric effect!

Model features



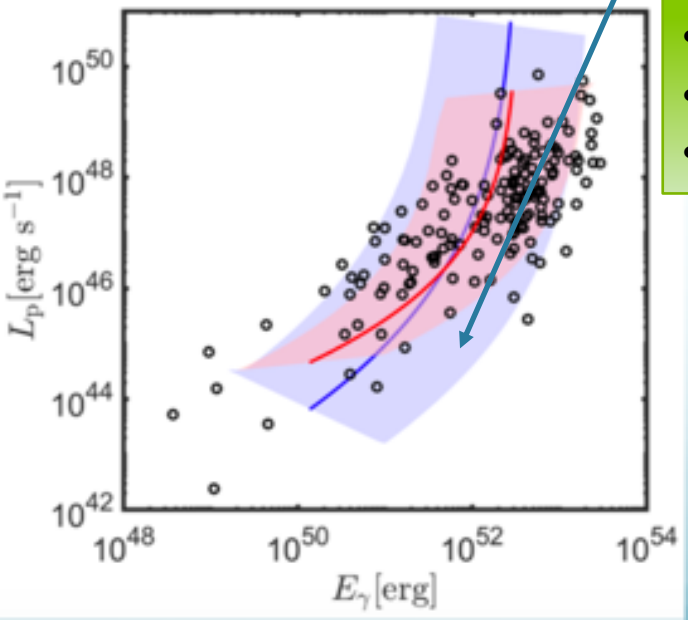
median line parametrized by viewing angle

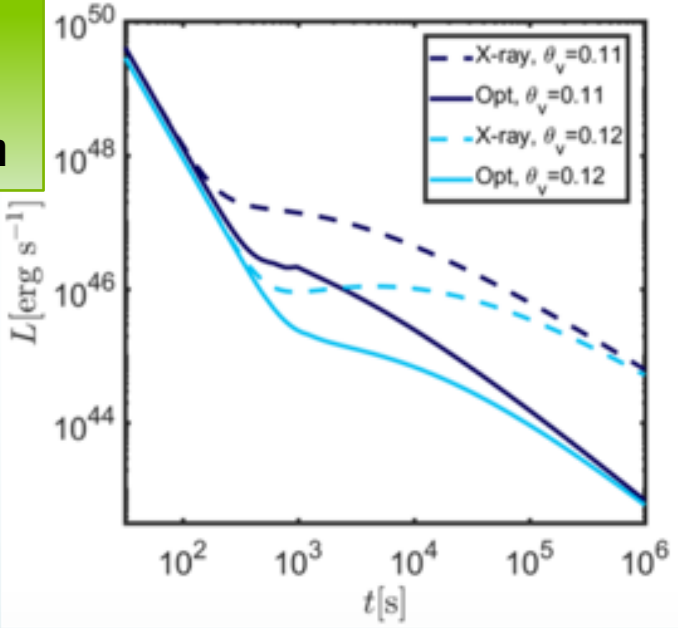
regions spanned by GRB/shock parameter ranges



Natural features:

- **Correlations**
- **Chromaticity**
- **No spectral evolution**





Caveats and puzzles

- Doesn't the **core spread?**

  ➔ Core spreading controlled (analytically)

- Doesn't a steep structure **turn off** the line-of-sight material?

  ➔ LOS material still ultra-relativistic and contributes

- Yes but **170817's structure was shallow**

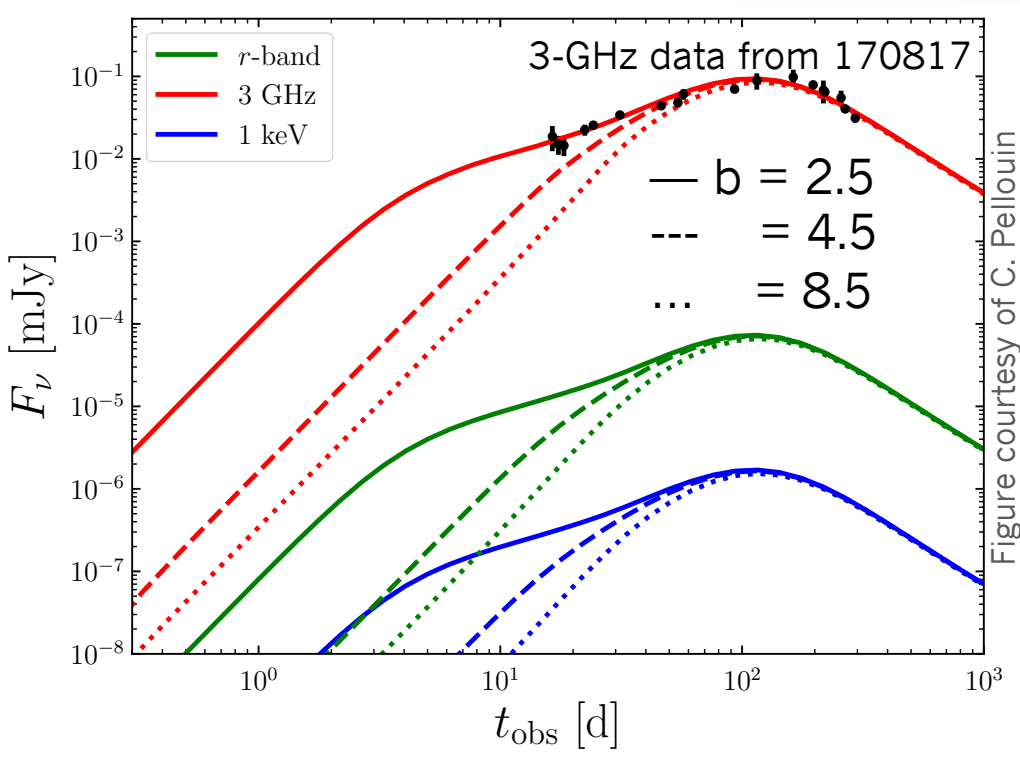
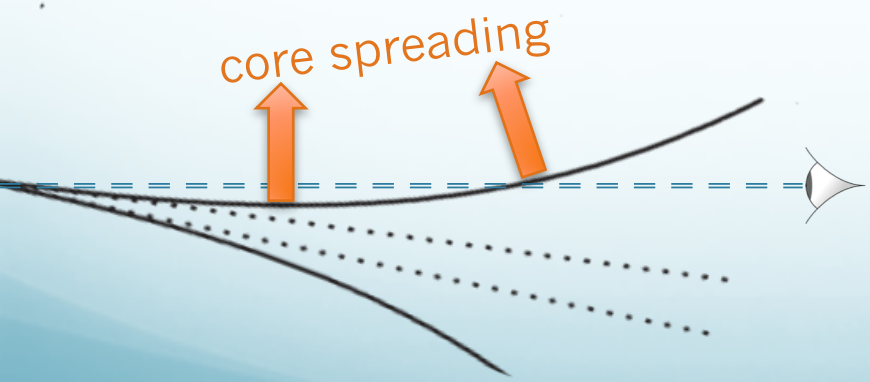
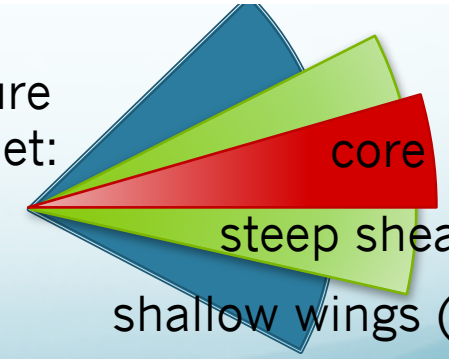


Figure courtesy of C. Pellouin



Consistent picture of 170817-like jet:

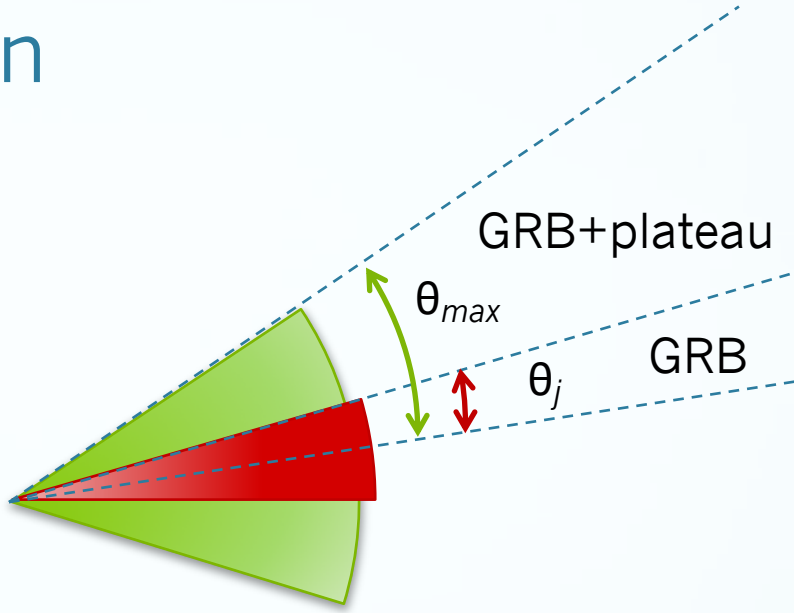


Discussion

- Plateau statistics:
  ➔ Insight on **core/wings and GRB dissipation**?
  ➔ **Short vs. long** GRB jet structures?

- Fraction of solid angles:

$$\frac{\theta_{\rm max}^2 - \theta_j^2}{\theta_{\rm max}^2} \approx 0.5,$$



- From **plateau correlations to jet structures**:
  Should we expect more events with detailed jet studies?
  ➔ **Population study!**

N/ N_{GW} (%)

Pop. model	G16	WP15
GW+KN	100	100
GW+KN+JAG(p)	38	11
GW+KN+JAG(e)	15	2.6
GW+KN+JAG(e)+KNAG	3.0	1.5
GW+KN+JAG(e)+VLBI	14	1.9
GW+KN+JAG(e)+KNAG+VLBI	2.9	1.3
GW+GRB	1.7	1.7

afterglow photometry + VLBI

Duque+19

Detailed jet study rare…

Conclusion

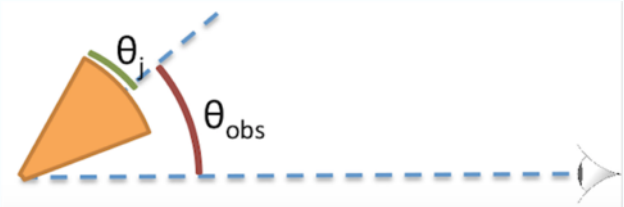
- **Purely geometric interpretation** of plateaus in GRB X-ray afterglows
- Able to reproduce **light-curves and observed correlations** with reasonable parameters
- Gives insight on **GRB statistics and GRB jets**

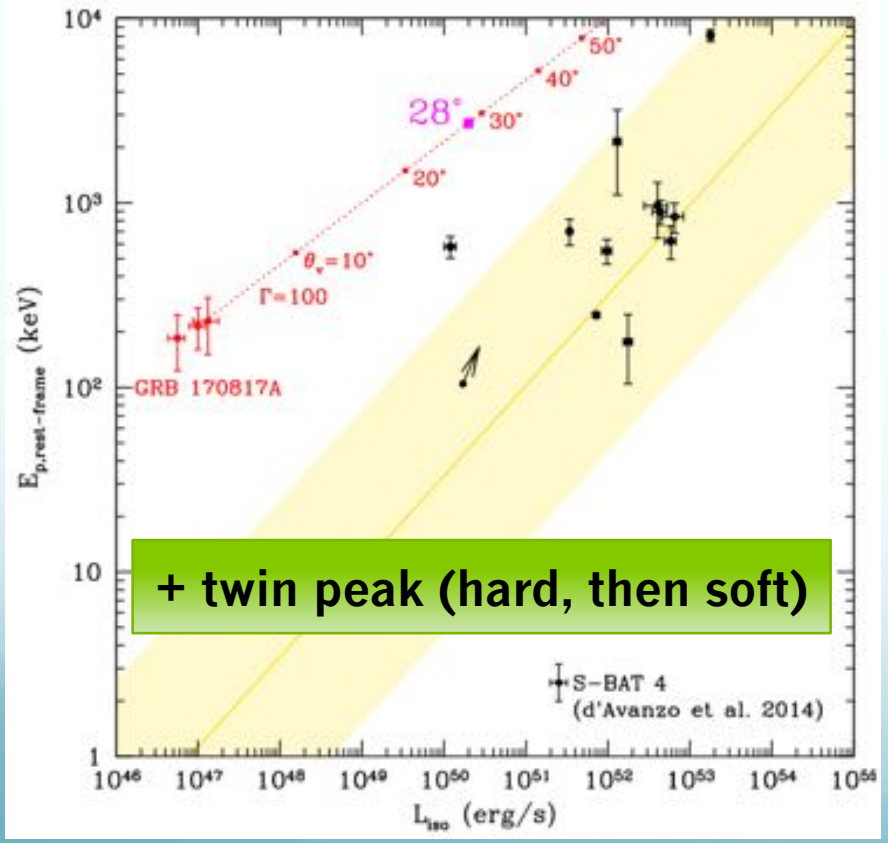
Future

- Fitting of **individual plateaus**
- Relationship of **plateau correlations to jet structure** (universal jet?)
  ➔ Quantitative comparison of **short-long GRB jets structures**?
- Exciting prospects of **GW counterparts**
  ➔ Jet studies with afterglows without prompt?

GRB170817A

Not a regular short GRB!





Alternative model:
Shock break-out (Nakar 2012)

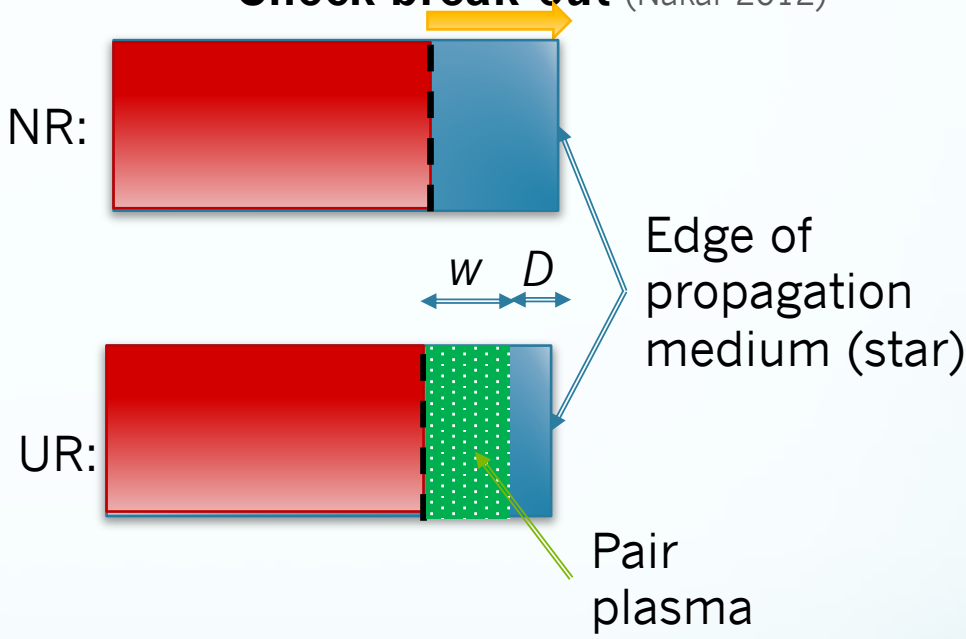


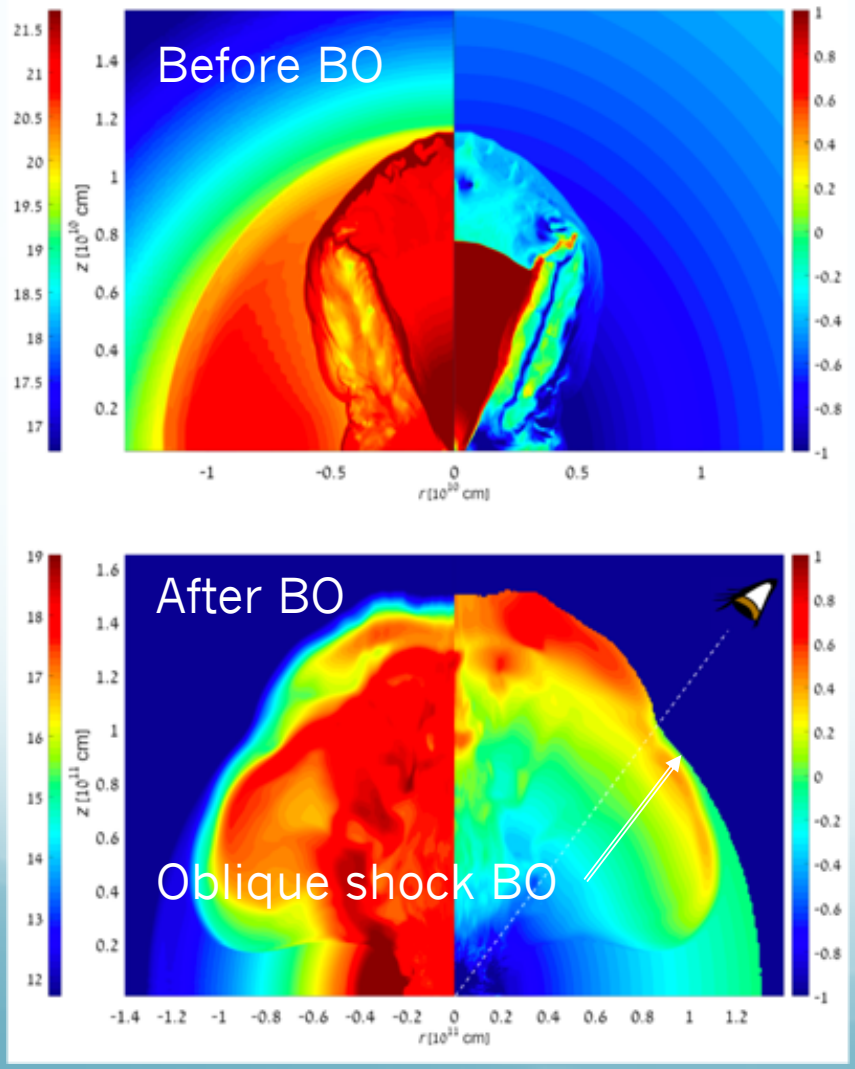
Figure courtesy F. Daigne

Photon leak: $\tau = 1/\beta_{sh}$
UR shock: pairs increase τ
➔ $w \sim D$ at breakout
➔ Hard → Soft spectral evolution

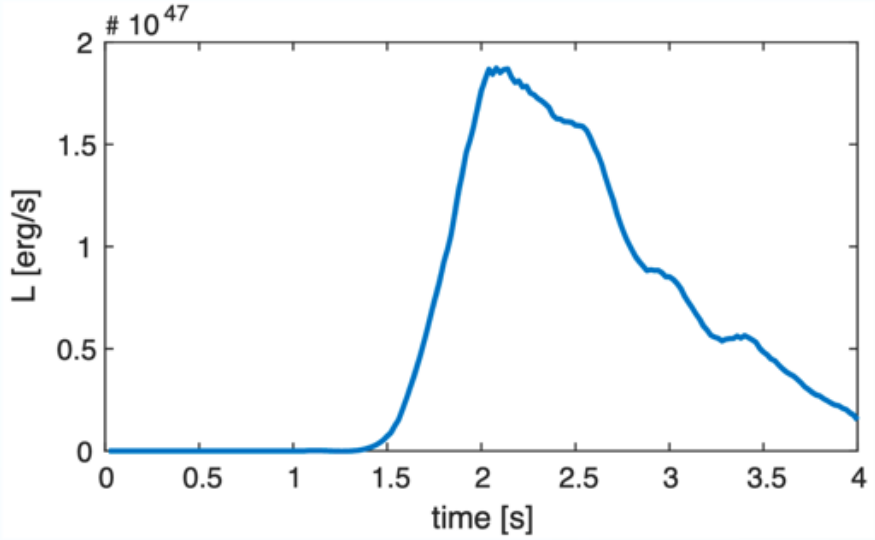
also works in SN, planet formation, etc.

Shock breakout from jet in merger ejecta

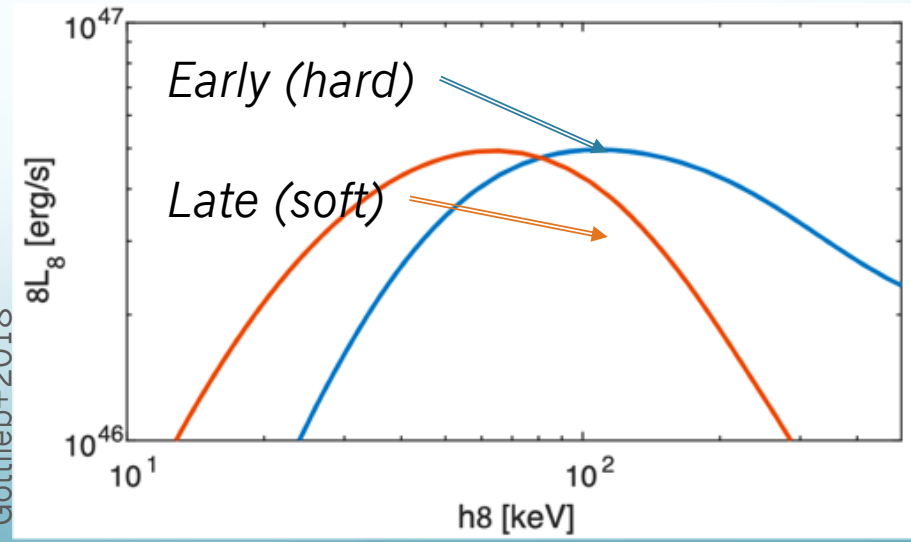
Initial jet **propagates within merger ejecta**, and **breaks out**



Light-curve:



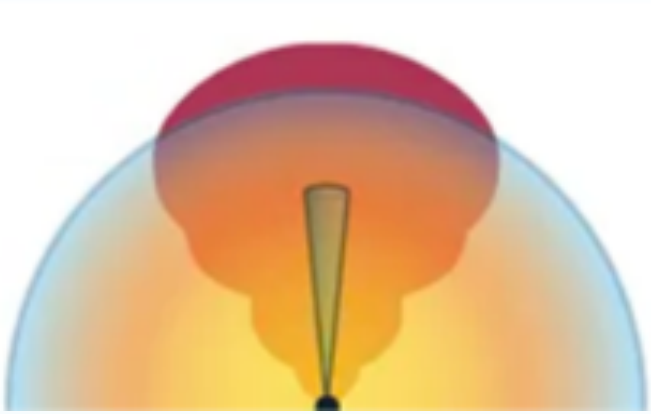
Spectrum:



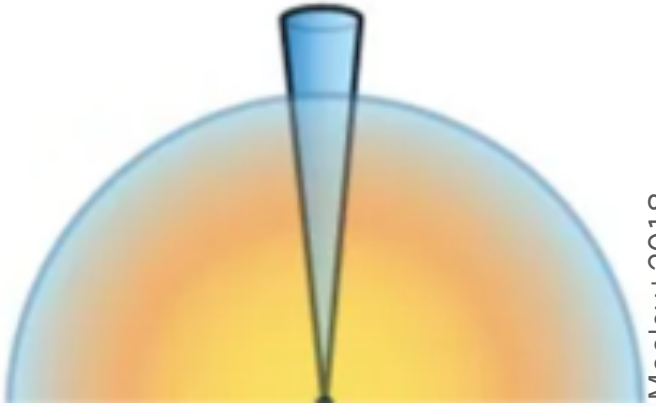
Gottlieb+2018

Emergence of jet structure post-breakout

Jet/ejecta interaction **may or may not give rise to collimated jet**!
➔ Depends on jet energy, opening angle, ejecta velocity profile



vs.



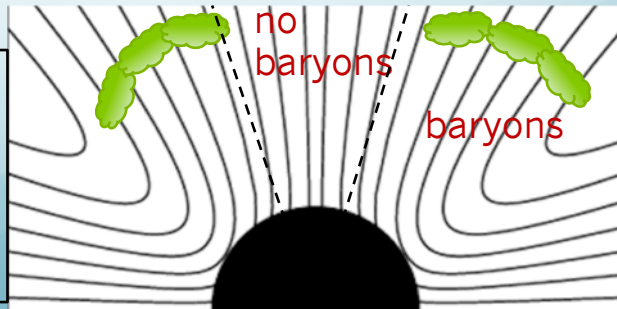
Mooley+2018

- Chocked jet
- Cocoon
- **Shallow structured outflow**

➔ Structured jet!

- Successful jet
- Structured jet
- Core+wings/sheath
- Mildly-relativistic outflow
- **Steep structured outflow**

Levinson & Eichler, 1993: Structured outflow as solution to **baryon loading puzzle**

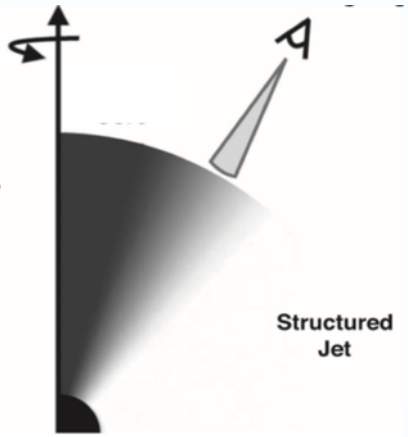


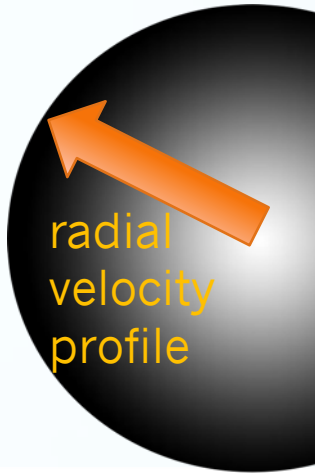
Was there a jet in GRB170817A?

Early expectations:

- ✓ Jet hydro and analytic estimates (Duffel+18)
  - ➔ Yes, most jets are successful!
  - + if jet can break-out, then jet successful
  - + negligible thermal energy deposited by jet ir ejecta
- ✓ short GRB statistics (Beniamini+18)
  - ➔ Yes, most mergers result in collimated jets

angular *vs.* radial



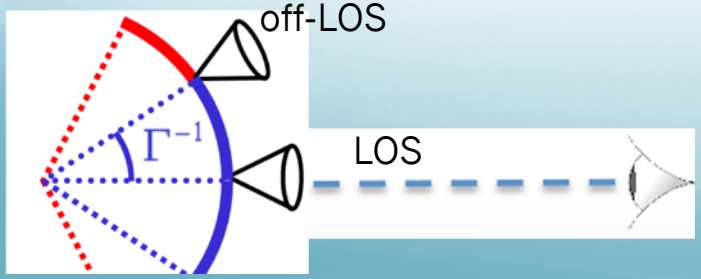


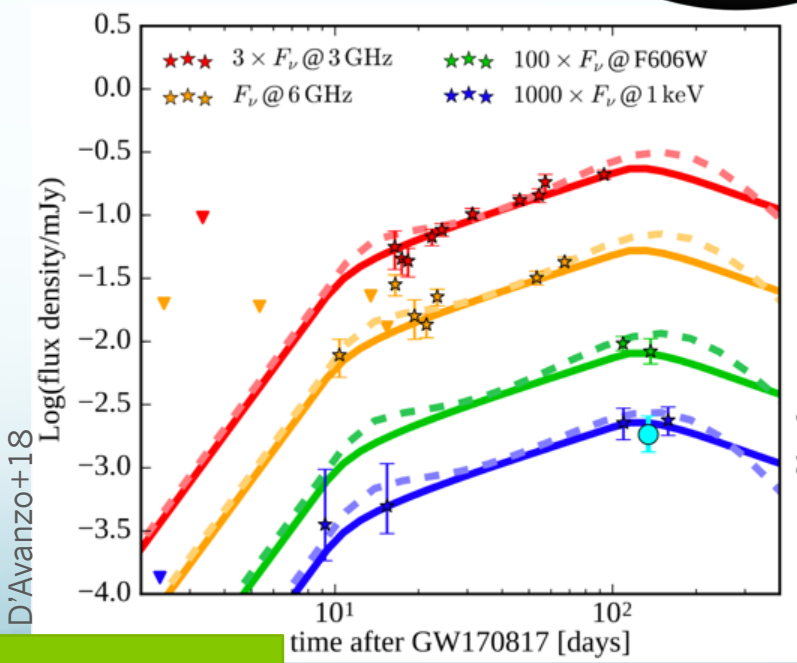
- **Information from afterglow**:

Either 1) Dominated by **LOS material** and there is **energy injection** (*radial structure*)

or

2) Off-LOS energetic material **progressively seen** (*angular structure*)



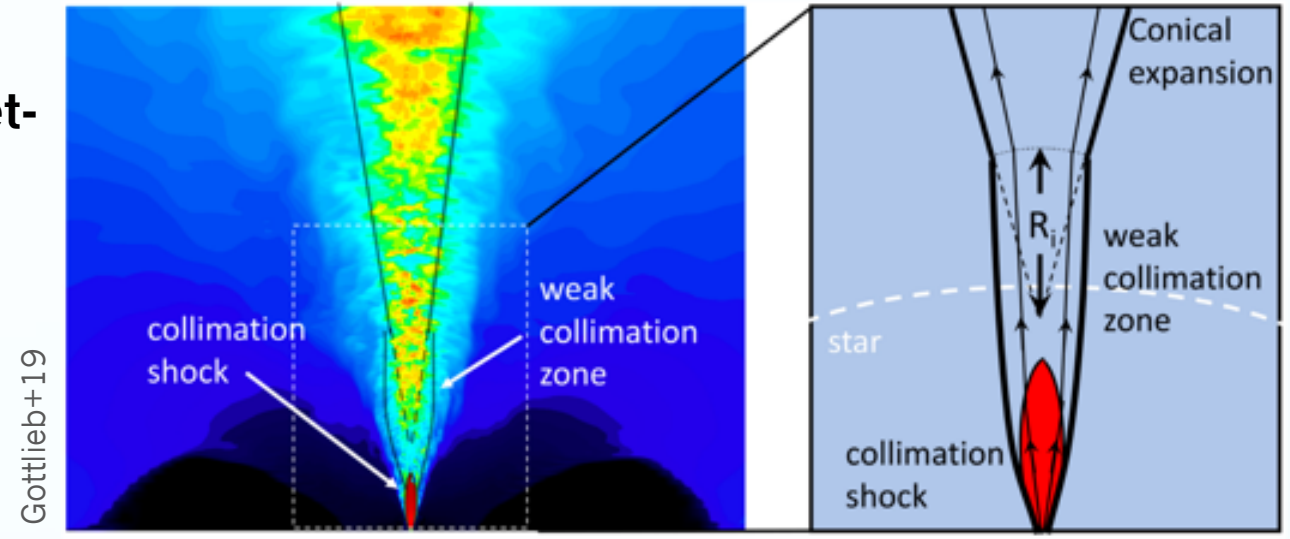


Both work well!

see also Lazzati+17, Margutti+18, Lamb+17,...

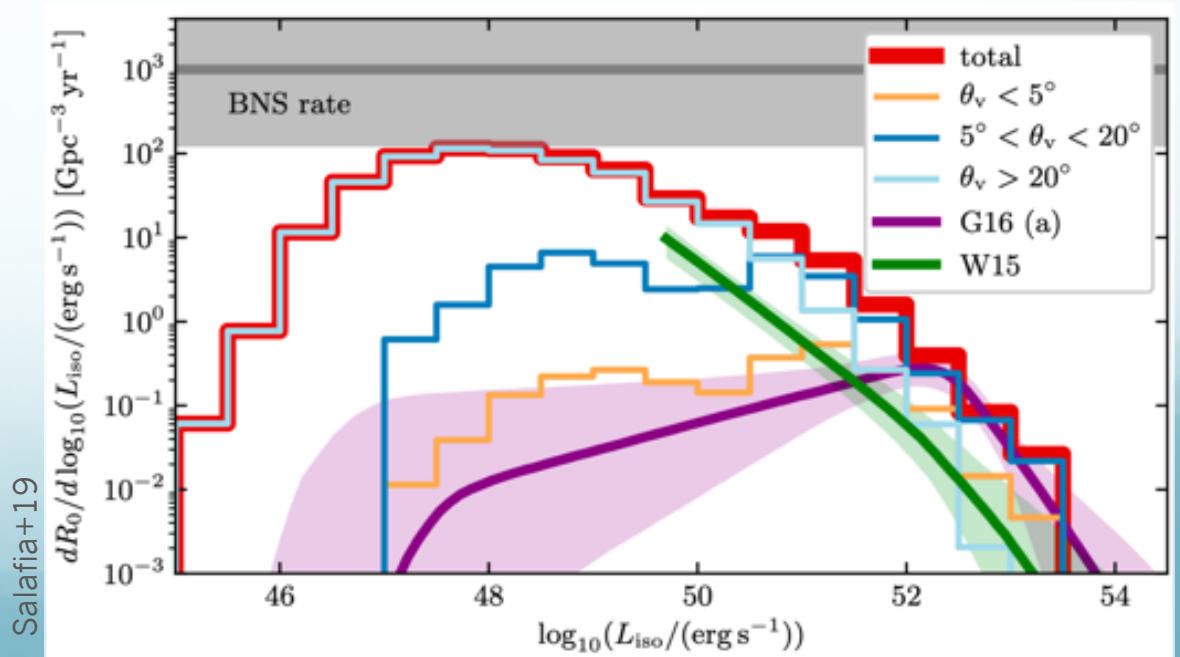
Jet formation & in-jet physics

Gottlieb+2018: Link of **jet-cocoon interaction with photospheric emission**



Gottlieb+19

Salafia+2019: Link of **universal jet structure with short GRB luminosity function**



Salafia+19

see also Kathirgamaraju+19, Gill+19

What now?

Should we expect more events with detailed jet studies?
➔ **Population study!**

N/N_{GW} (%)

Duque+19

Pop. model	G16	WP15
GW+KN	100	100
GW+KN+JAG(p)	38	11
GW+KN+JAG(e)	15	2.6
GW+KN+JAG(e)+KNAG	3.0	1.5
GW+KN+JAG(e)+VLBI	14	1.9
GW+KN+JAG(e)+KNAG+VLBI	2.9	1.3
GW+GRB	1.7	1.7

afterglow photometry + VLBI

1540^{+3200}_{-1220} BNS/Gpc^3/yr (Abbott+2018)

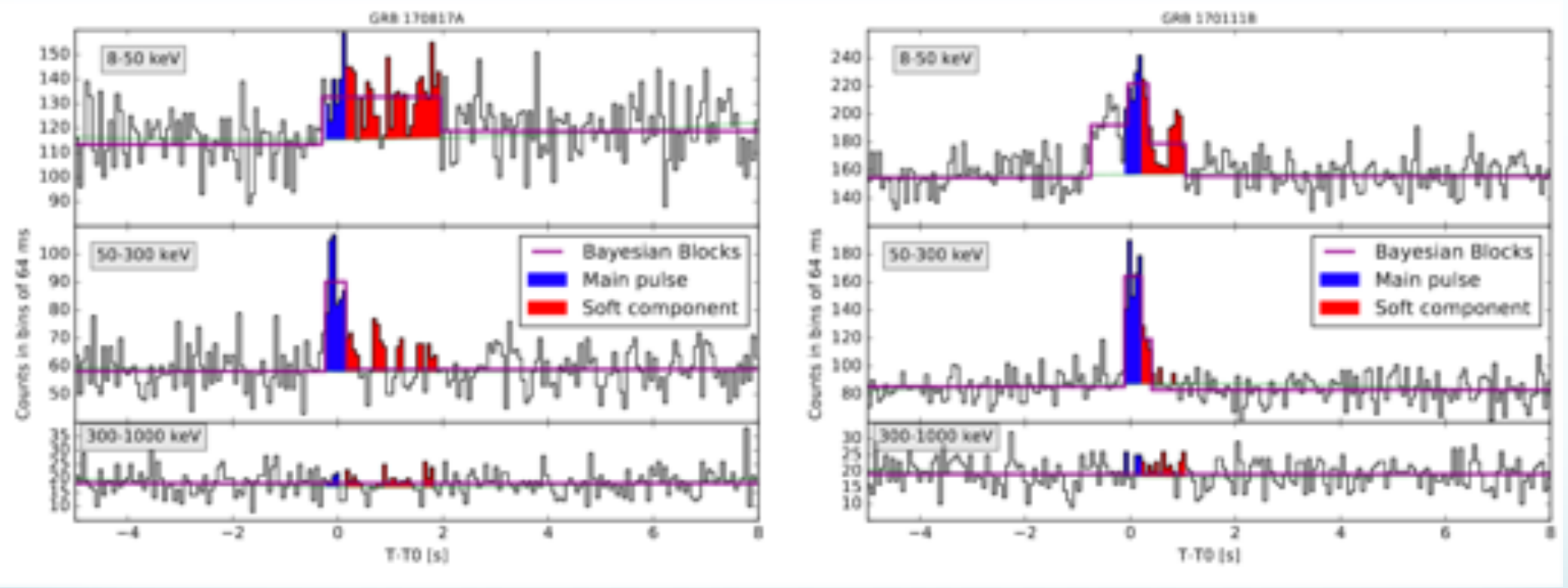
see also Gottlieb+19, Salem+18

Afterglow: OK
VLBI: rare…

Depends on jet energy function

One spectacular event and then nothing?
No… now we have new IDEAS!

Von Kienlin GRBs

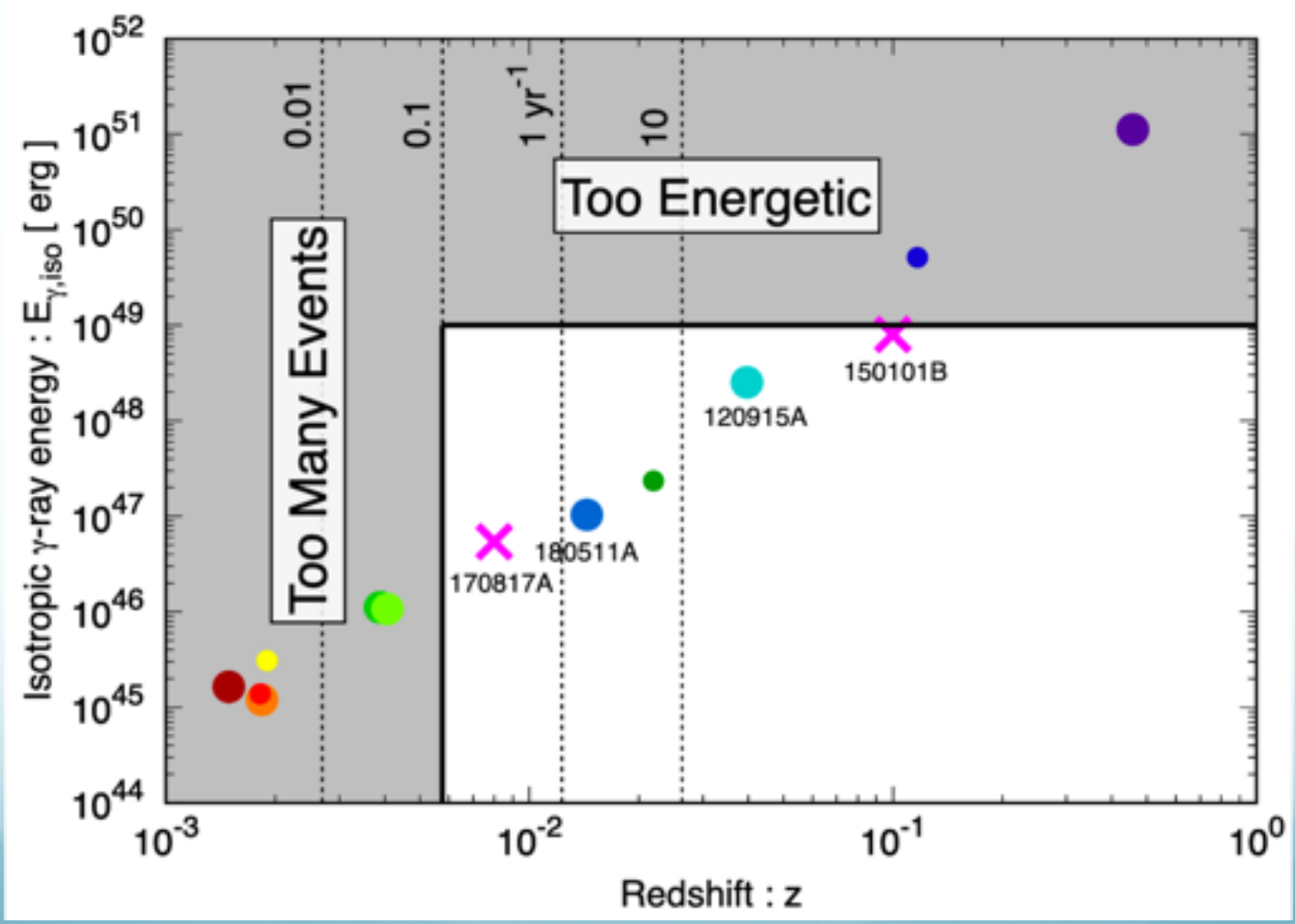


Von Kienlin+2019

Cosmological GRBs

von Kinelin+2019: Fermi GBM short GRBs similar to GRB170817A (double peak: hard then soft)

➔ Consistent with shock break-out radiation?



Matsumoto+19