Gamma-ray burst afterglow jet analysis in the multi-messenger era

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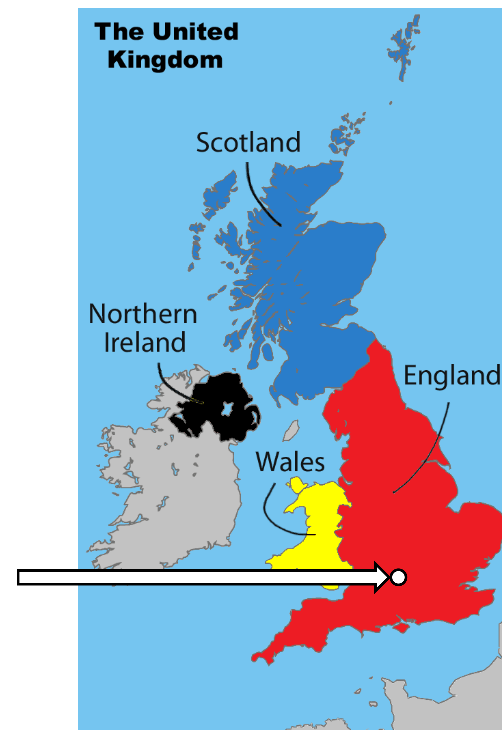
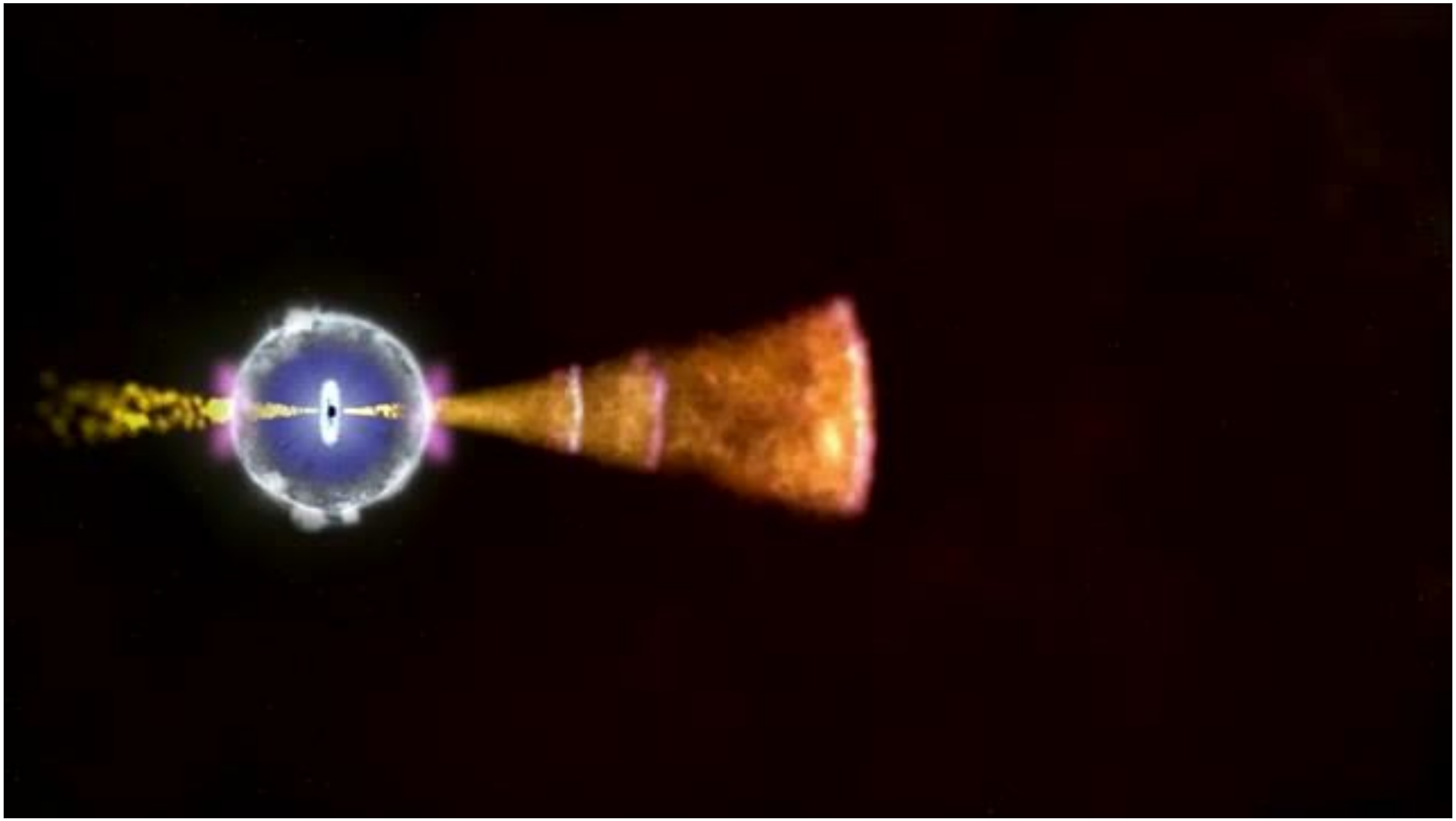
October 21 2019



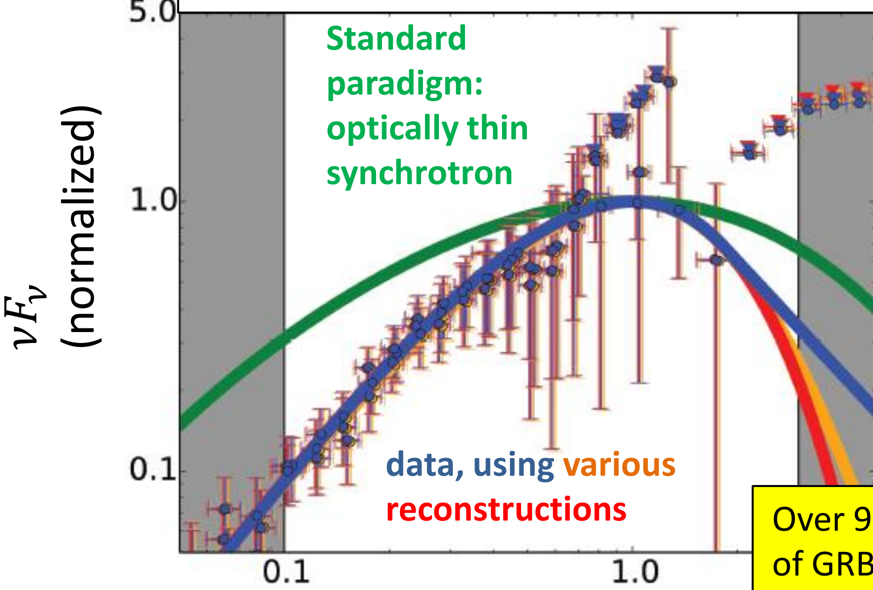
Gamma-ray bursts, the global picture



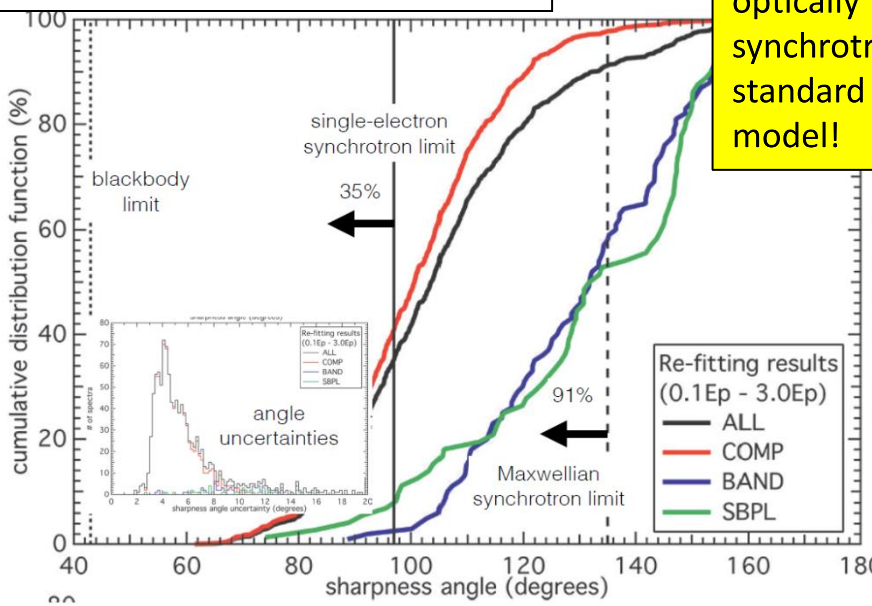
Assuming...
- ...the engine to be a black hole and not a magnetar
- ...the prompt emission to be colliding shells and not e.g. photospheric or reconnection
- ...the jet makes it out, and does not have a radically different profile from shown above

general GRB progress: GRB prompt emission

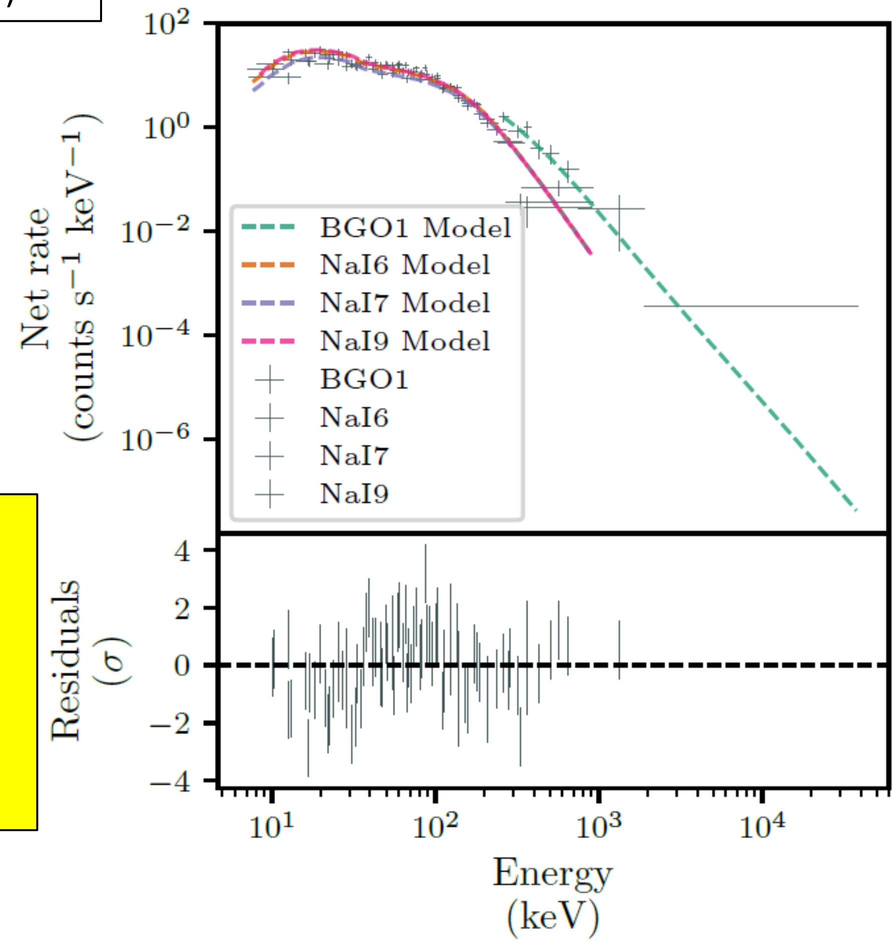
GRB prompt peak energy (normalized from 561 keV)



Yu, van Eerten+ 2015, A&A 583, A129



Over 90 % of GRBs are too sharp for optically thin synchrotron standard model!

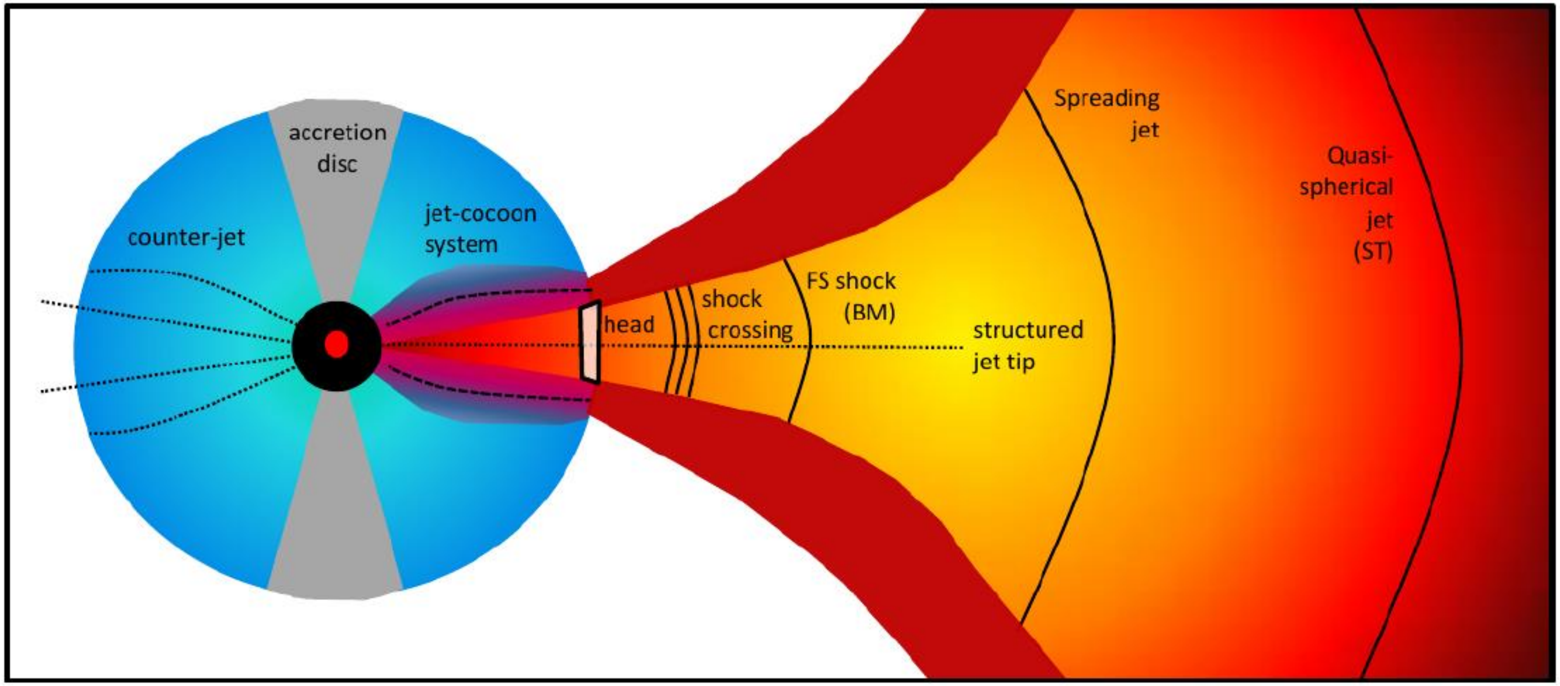


On the other hand... synchrotron is not *that bad a fit even for sharp spectra*

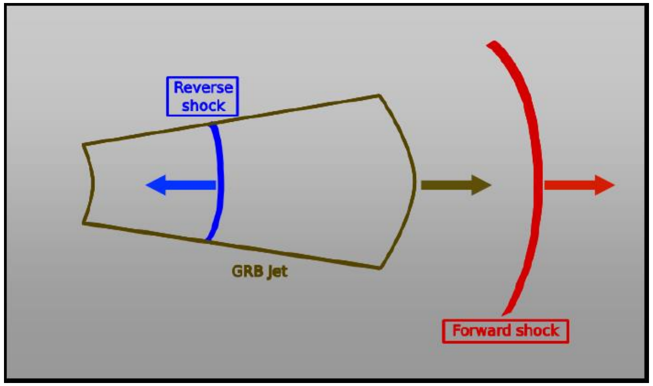
Burgess 2019 A&A 629, A69

(but extremely steep electron power laws *p >> 2)*

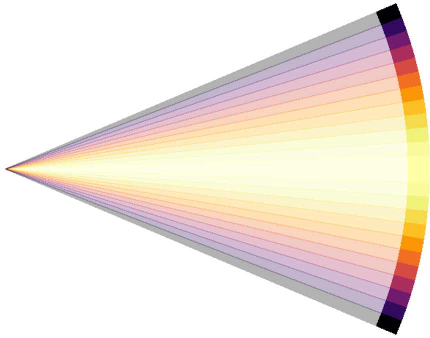
Gamma-ray burst afterglow jets



van der Horst, van Eerten & Fong, ‘observations & theory of gamma-ray burst jets’, New Astronomy Reviews, in prep

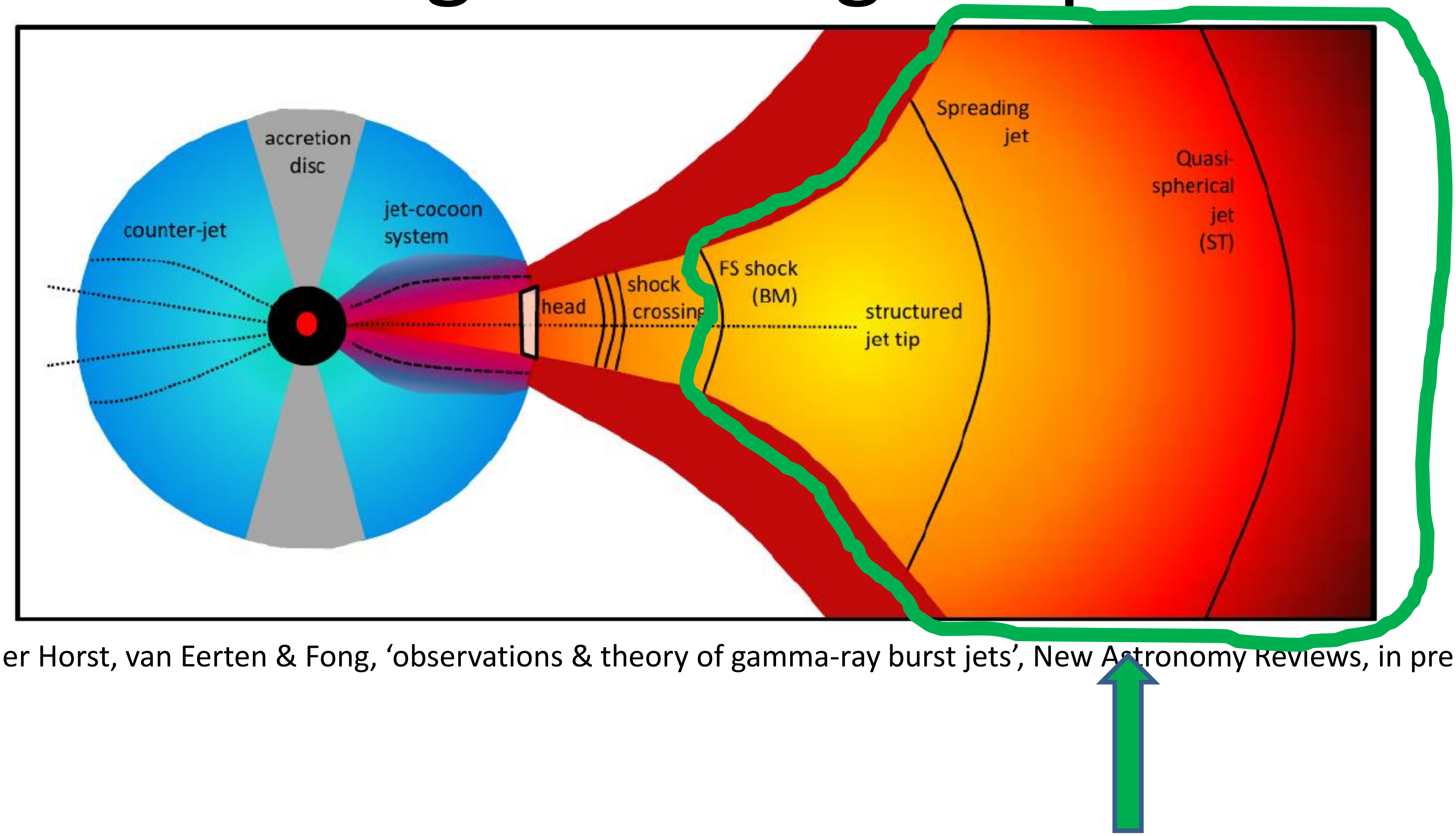


The “reverse shock” (RS)



Lateral structure imposed during launching

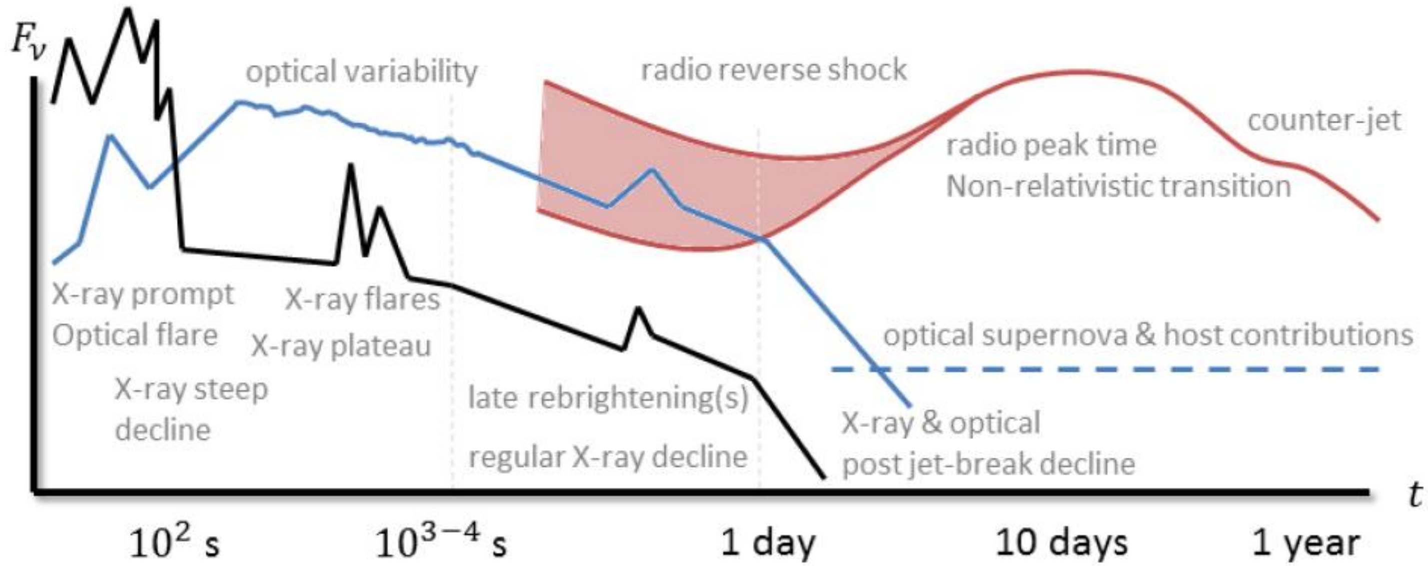
The emergent afterglow picture

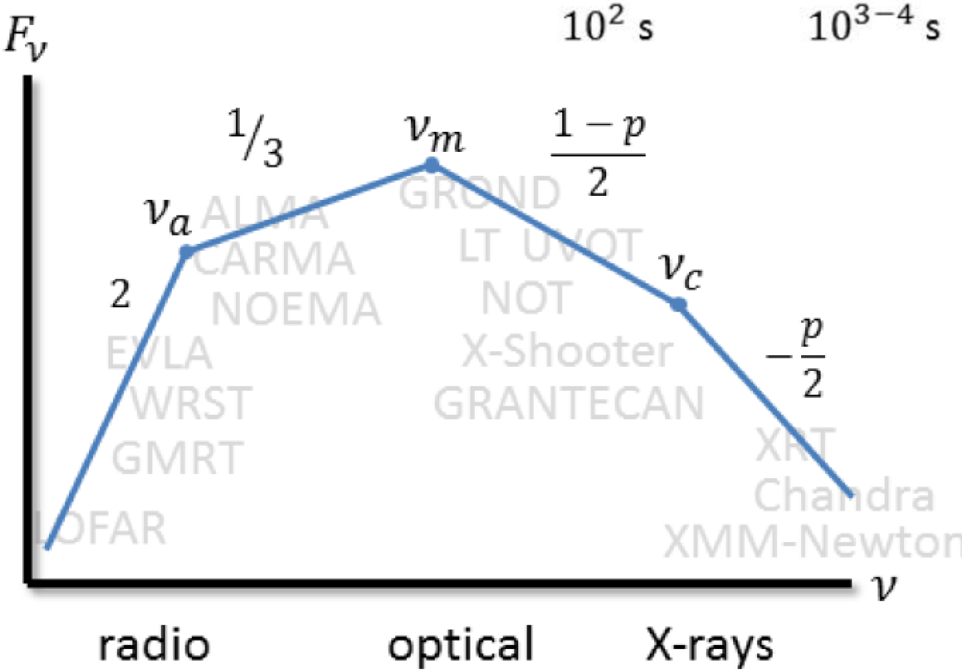


van der Horst, van Eerten & Fong, 'observations & theory of gamma-ray burst jets', New Astronomy Reviews, in prep

What was usually considered for afterglow modeling and long-term afterglow simulations

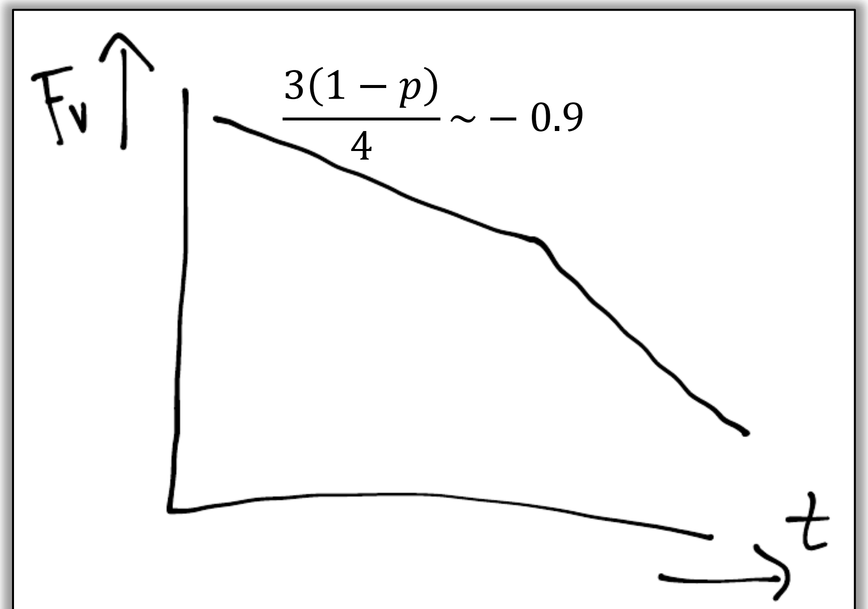
We rely on *afterglow* for information

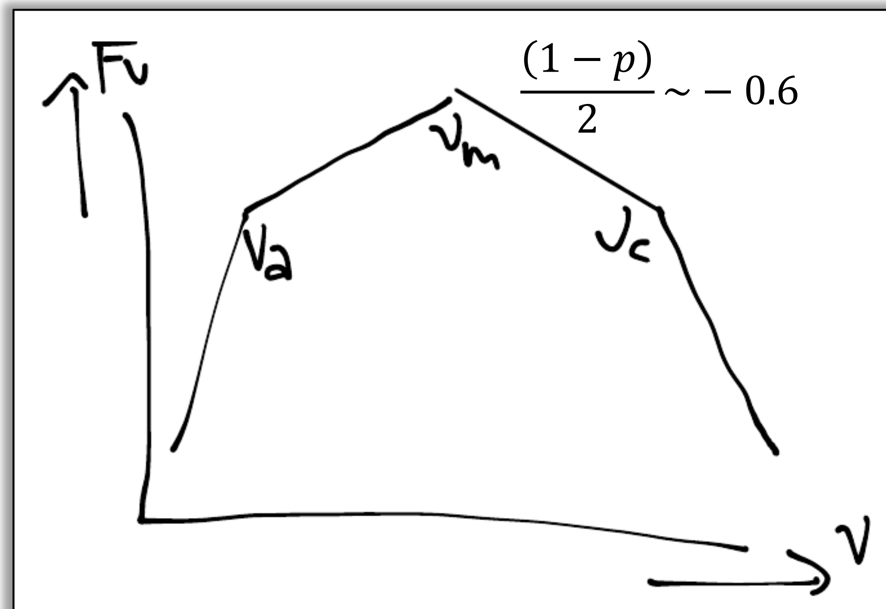




images from:
van der Horst, van Eerten & Fong
'observations & theory of gamma-ray burst jets'
New Astronomy Reviews, in prep

GRB afterglow models & closure relations



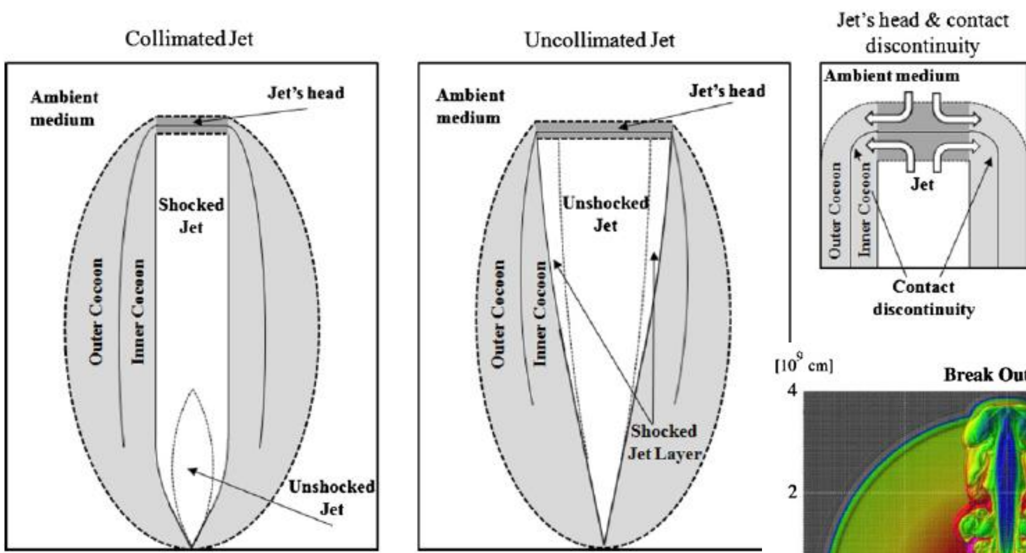


Theoretical models predict temporal decay slope and spectral shape. Example:

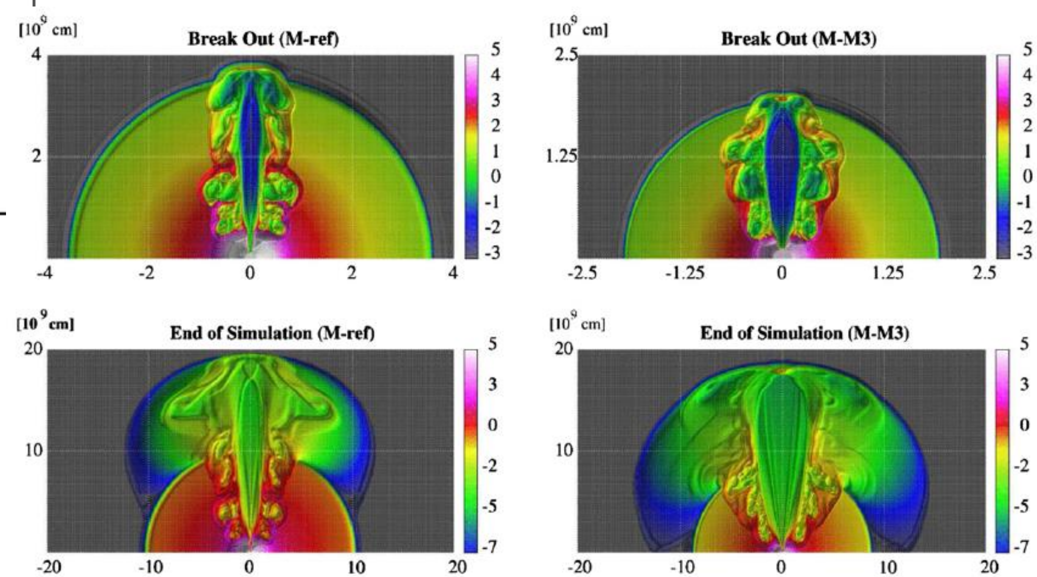
- time: forward shock in homogeneous interstellar medium, no jet structure, relativistic limit
- frequency: slow-cooling synchrotron spectrum above particle injection break
- $p \sim 2.2$ is the power-law slope of the non-thermal electron population $n_e \propto \gamma_e^{-p}$ in energy

Example closure relation: $F_\nu \propto t^{-\alpha}\nu^{-\beta} \longrightarrow 3\beta/2$

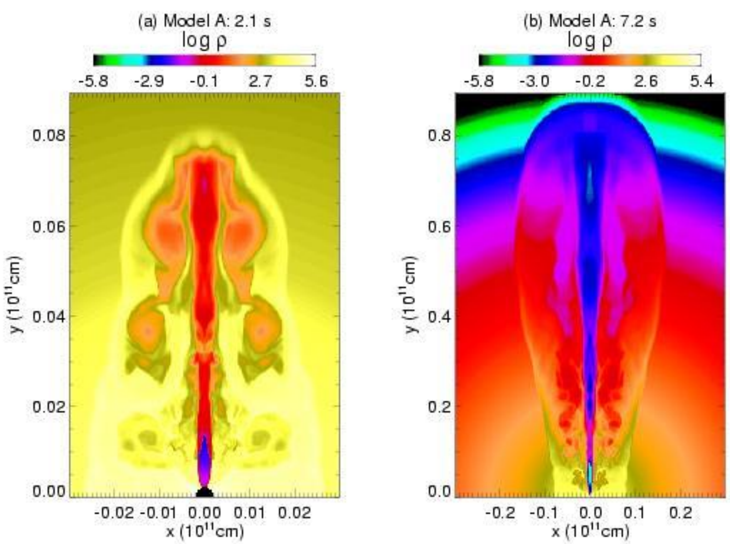
general GRB progress: Early jet stages, including breakout also applied to NS mergers



Bromberg+ 2011
Mizuta & Aloy 2009



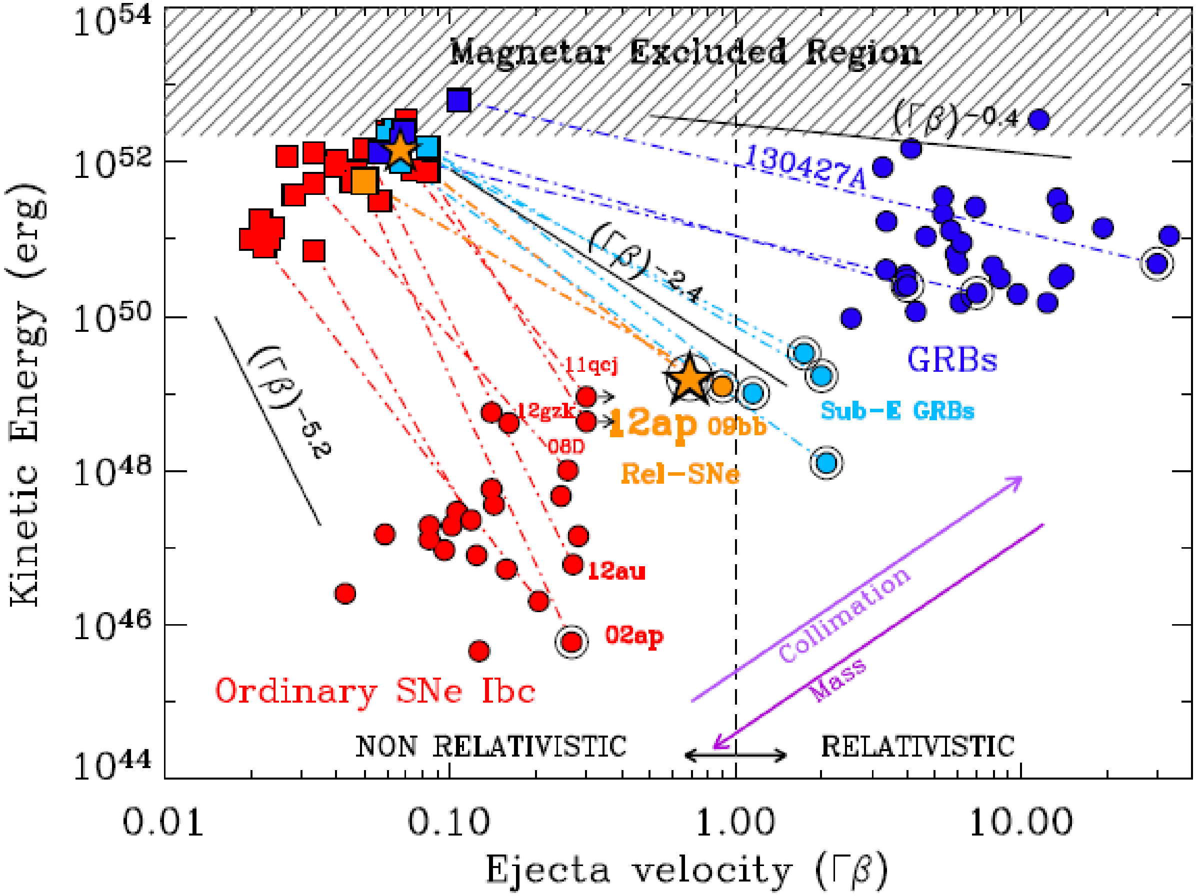
Nagakura+2014



Zhang & MacFadyen 2006

general GRB progress: An emergent continuum of ejecta velocities

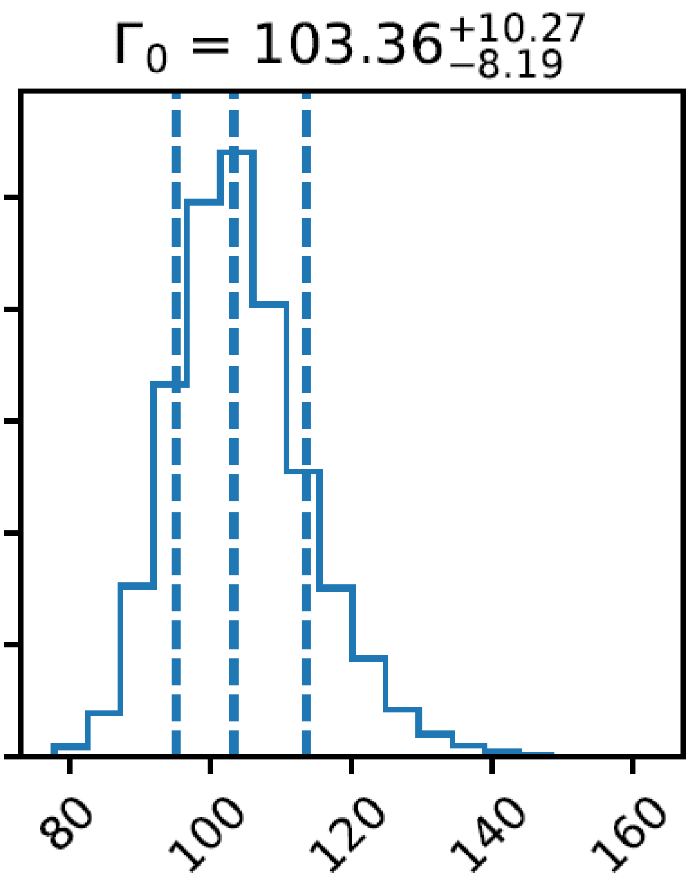
which makes them akin to phenomena like supernovae and tidal disruption events



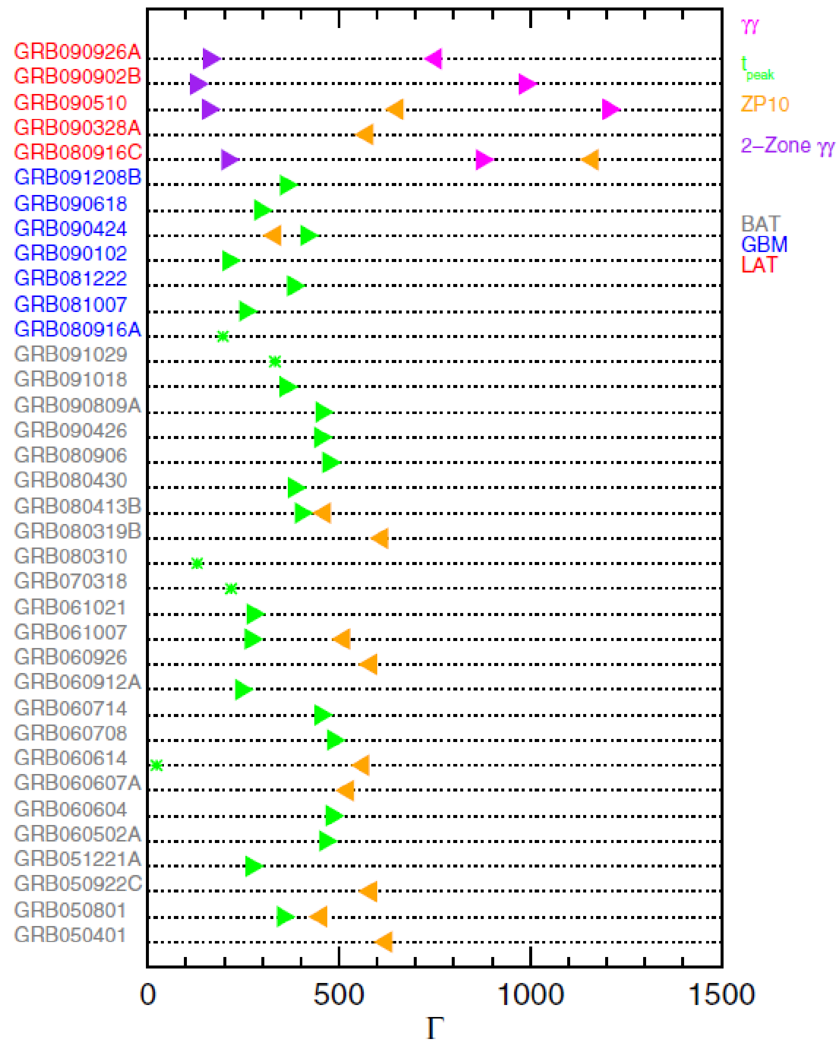
sample study showing a continuum of supernova and GRB ejecta energies and velocities (circles) (Margutti+ 2014)

Artist impression of tidal disruption event J1644

general GRB progress: accruing measurements of extremely fast Lorentz factors



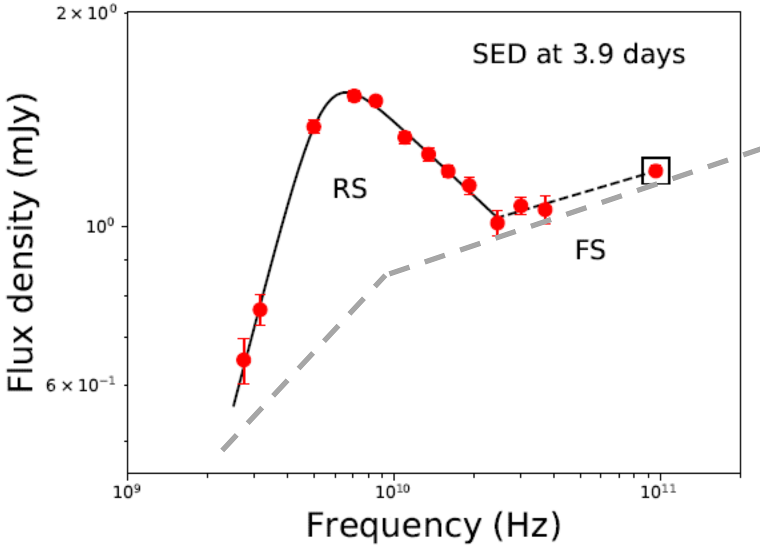
Initial ejecta Lorentz factor obtained from reverse shock analysis (Laskar, van Eerten+, 2019 ApJ 884, 121)

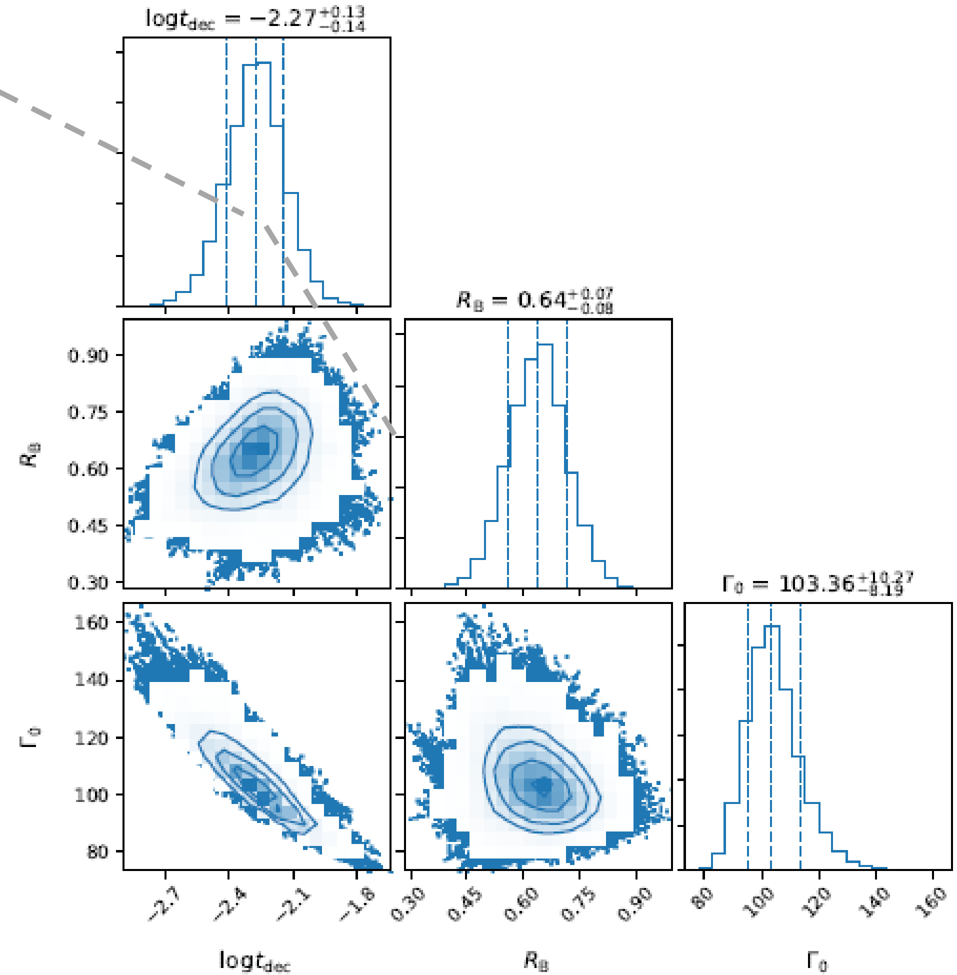


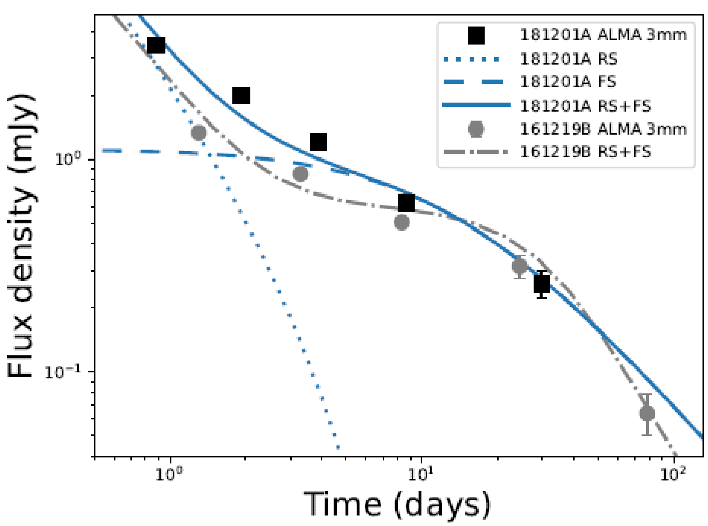
A sample of initial Lorentz factors, obtained by various means (Racusin+ 2011)

Reverse shock Lorentz factor estimate

Thanks to early ALMA observations

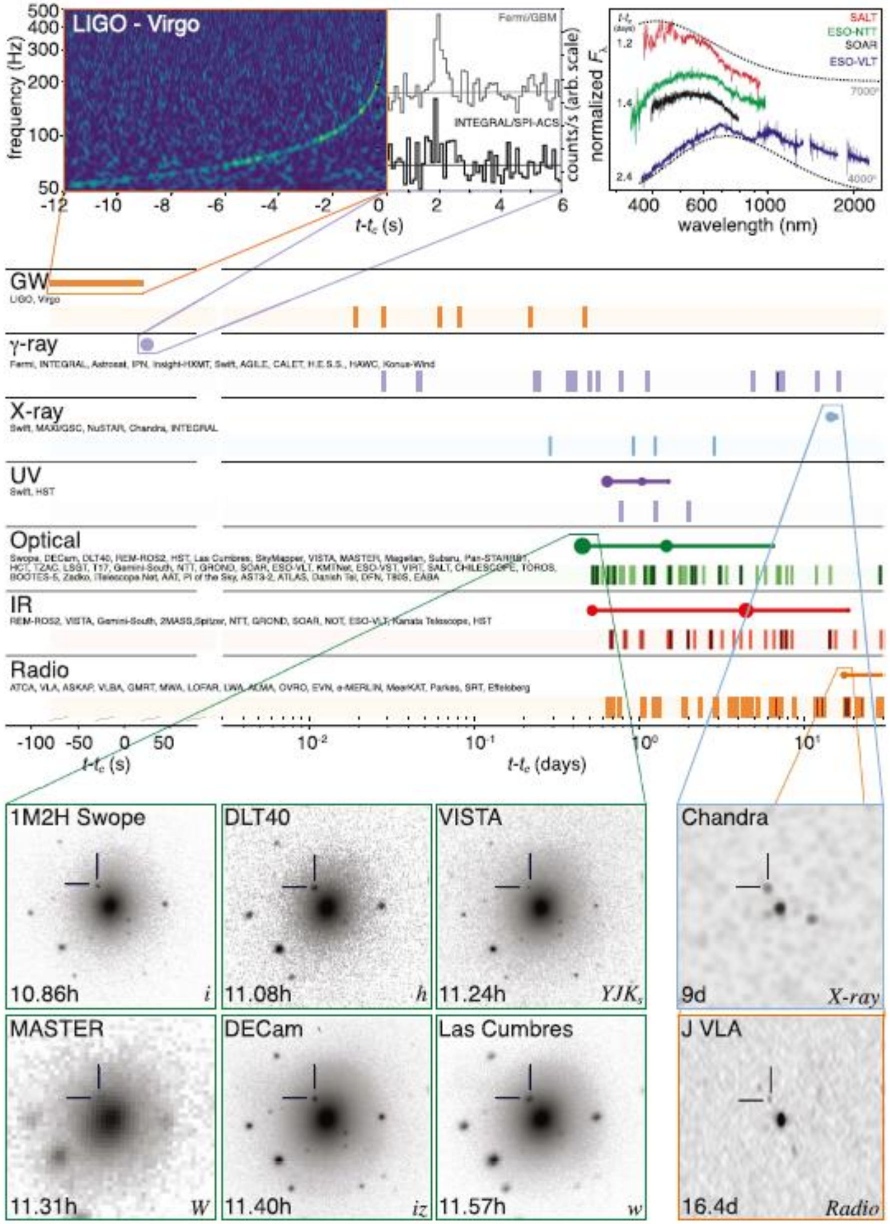


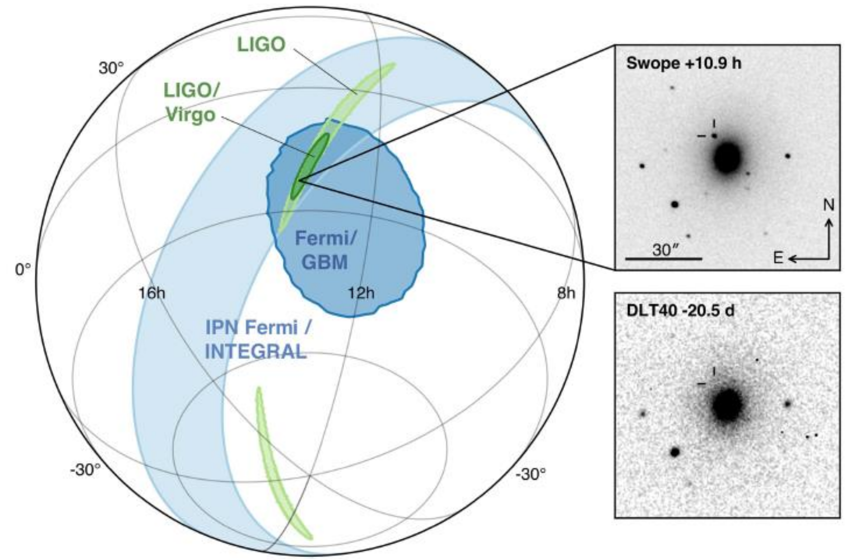




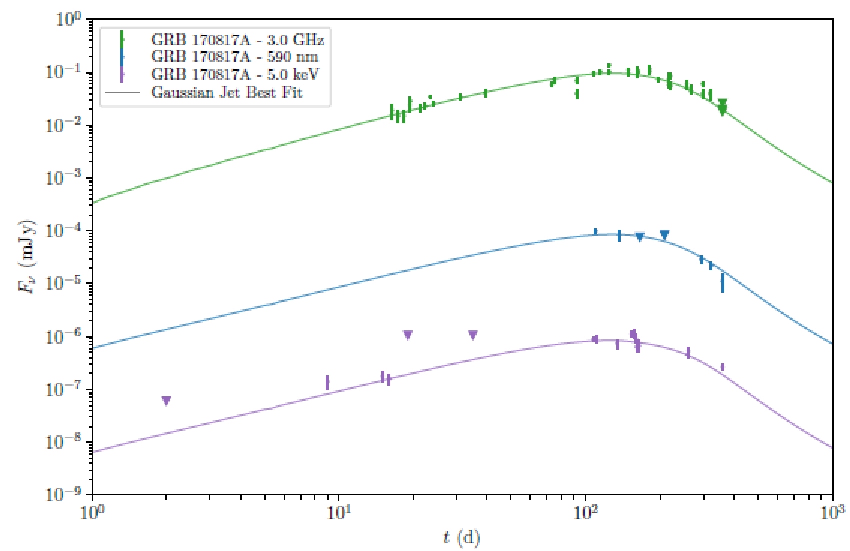
Laskar, van Eerten+, 2019 ApJ 884, 121

170817: Start of multi-messenger era for GRBs



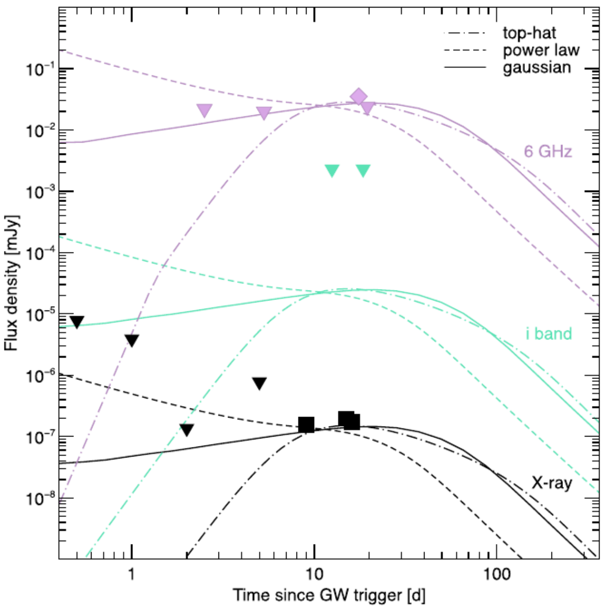


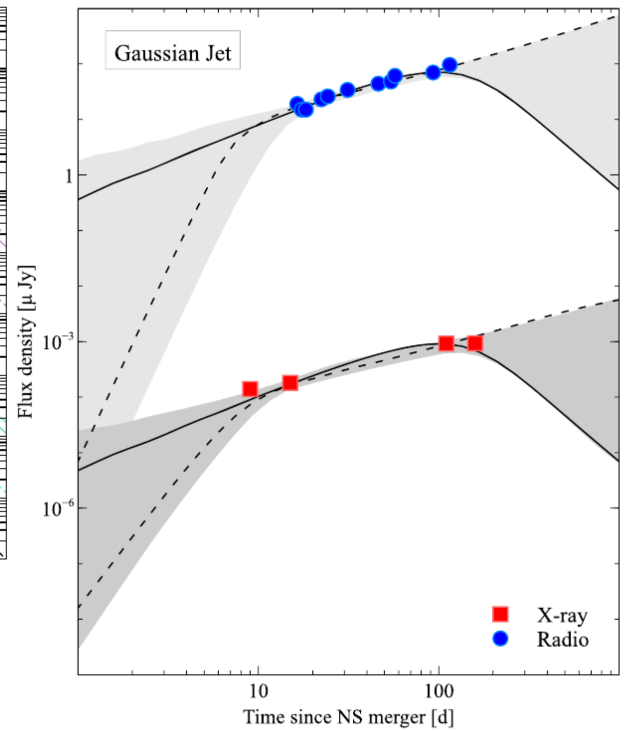
Abbott+ 2017, ApJL 848, L12

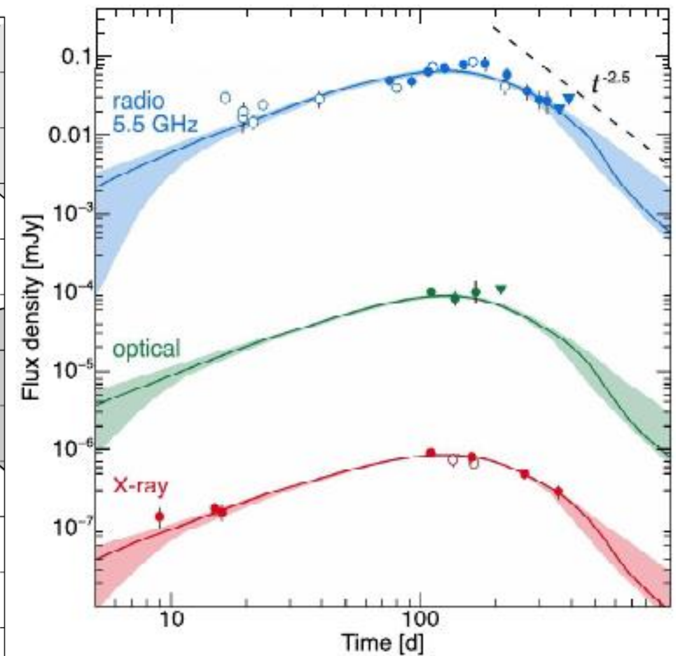


Ryan, van Eerten, Piro & Troja 2019, ArXiv 1909:11691

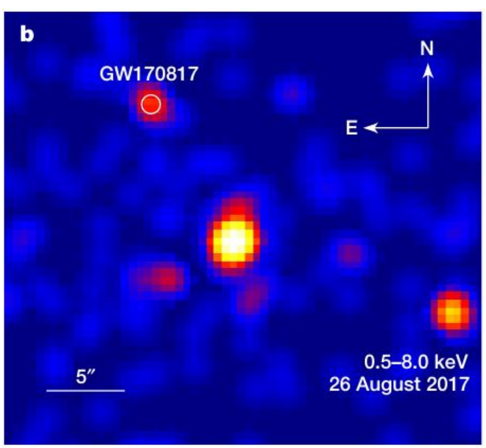
personal 170817 Afterglow timeline





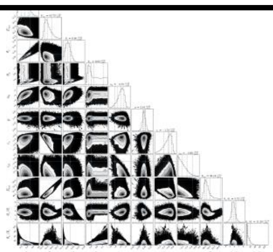


Troja, Piro, van Eerten+ 2017,
X-ray discovery Nature paper
also proposing a structured jet

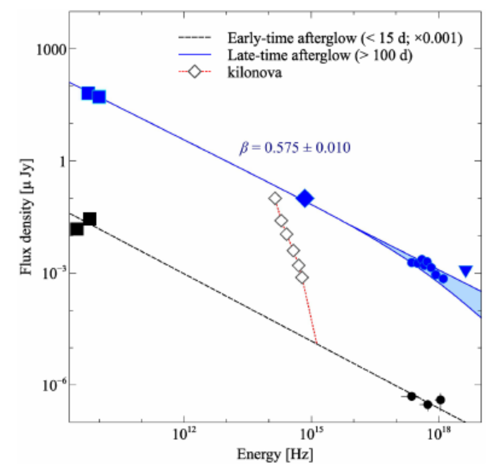


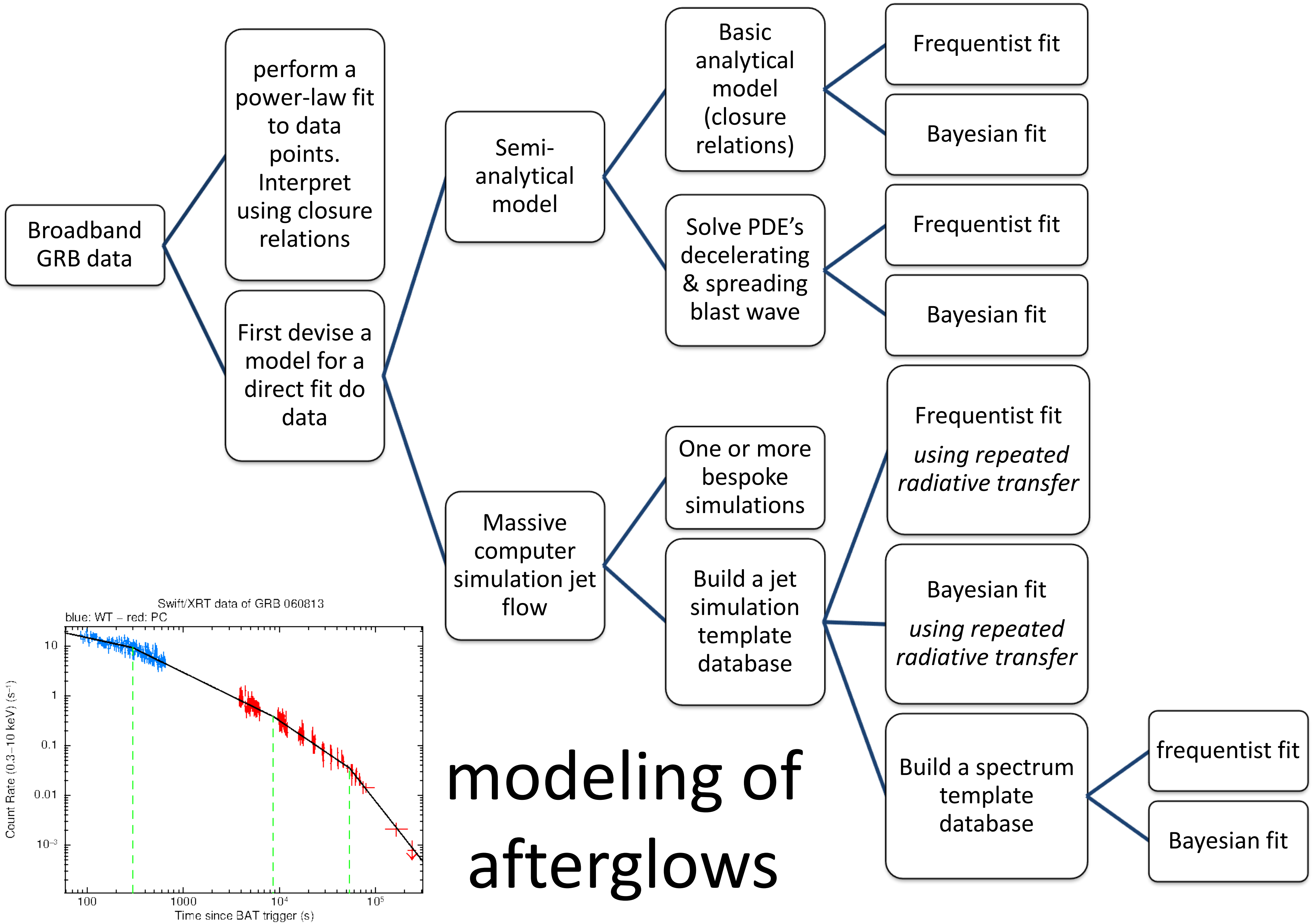
Troja, Piro, Ryan, van Eerten+ 2018

- *Bayesian comparison spherical cocoon / successful jet models*
- ***prediction** steep decay for successful jet model*
- *analysis **including** prior directly from GW data*



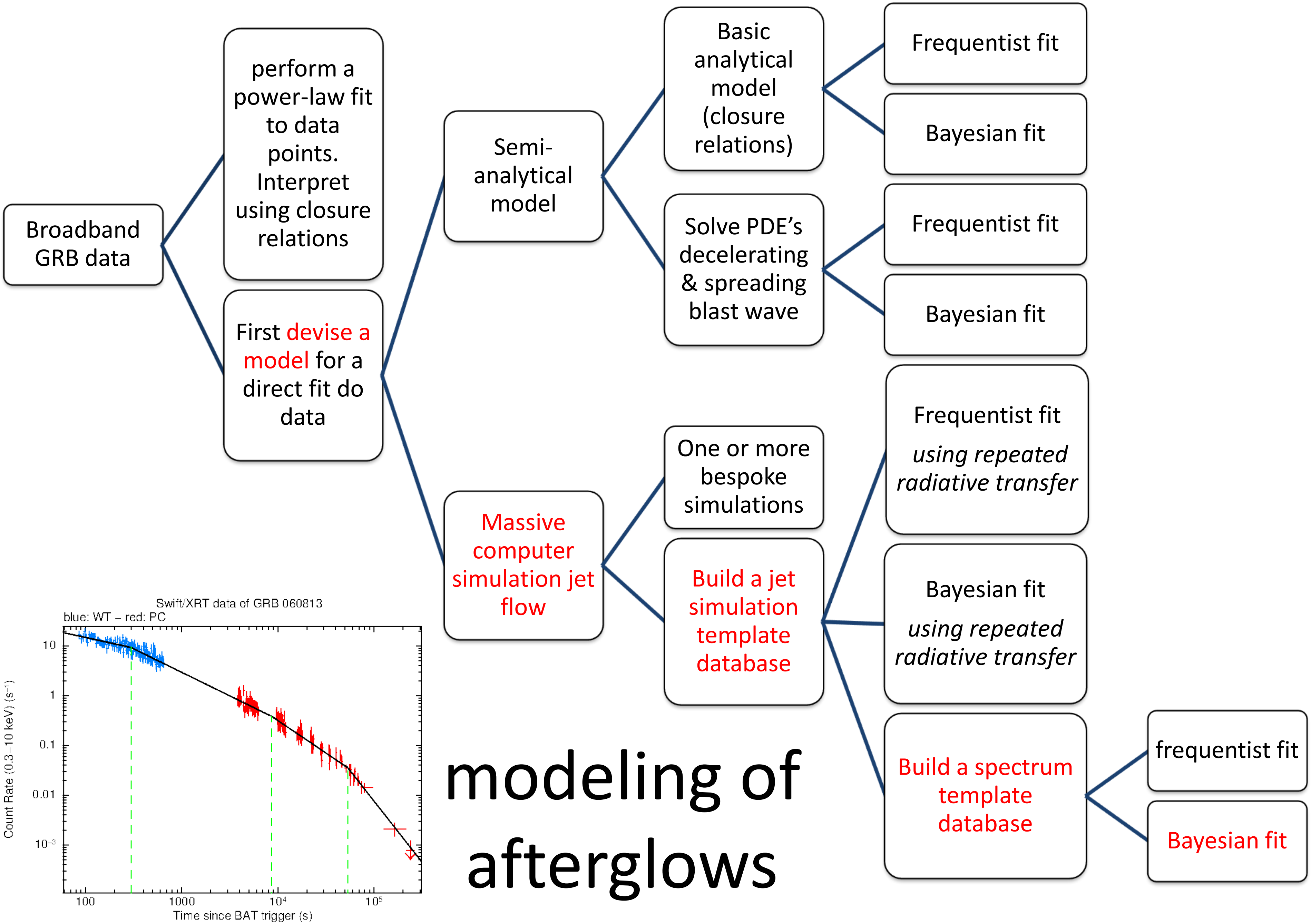
Troja, van Eerten+ 2018
steep decay falsifies choked jet





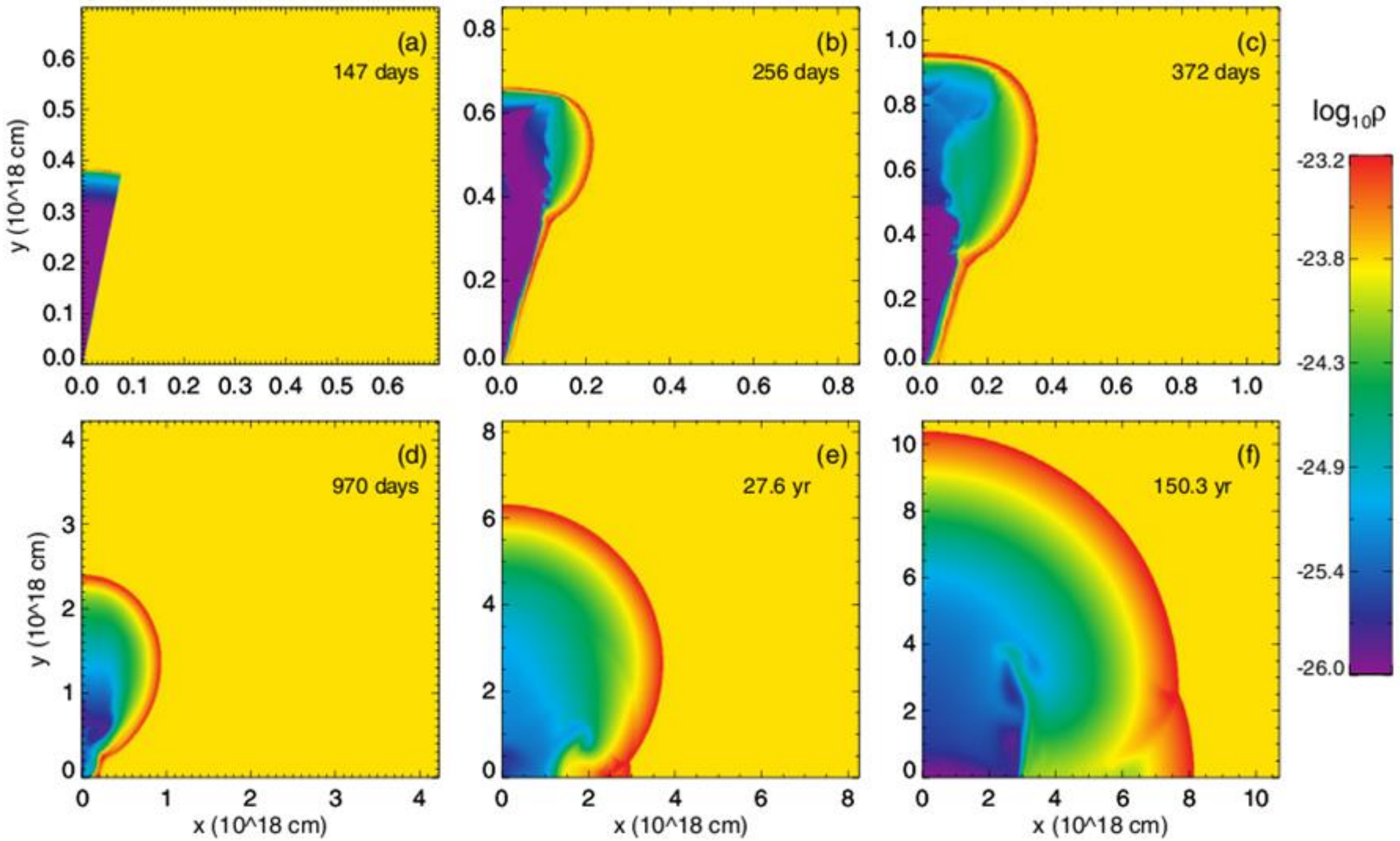
Broadband GRB data
perform a power-law fit to data points. Interpret using closure relations
First devise a model for a direct fit do data
Semi-analytical model
Massive computer simulation jet flow
Basic analytical model (closure relations)
Solve PDE's decelerating & spreading blast wave
One or more bespoke simulations
Build a jet simulation template database
Frequentist fit
Bayesian fit
Frequentist fit
Bayesian fit
Frequentist fit *using repeated radiative transfer*
Bayesian fit *using repeated radiative transfer*
Build a spectrum template database
frequentist fit
Bayesian fit
Swift/XRT data of GRB 060813
blue: WT – red: PC
Count Rate (0.3–10 keV) (s⁻¹)
10
1
0.1
0.01
10⁻³
100
1000
10⁴
10⁵
Time since BAT trigger (s)
modeling of afterglows

The *Scalefit* approach (van Eerten & MacFadyen 2012; Ryan, van Eerten+ 2015)



modeling of afterglows

Long-term jet simulations

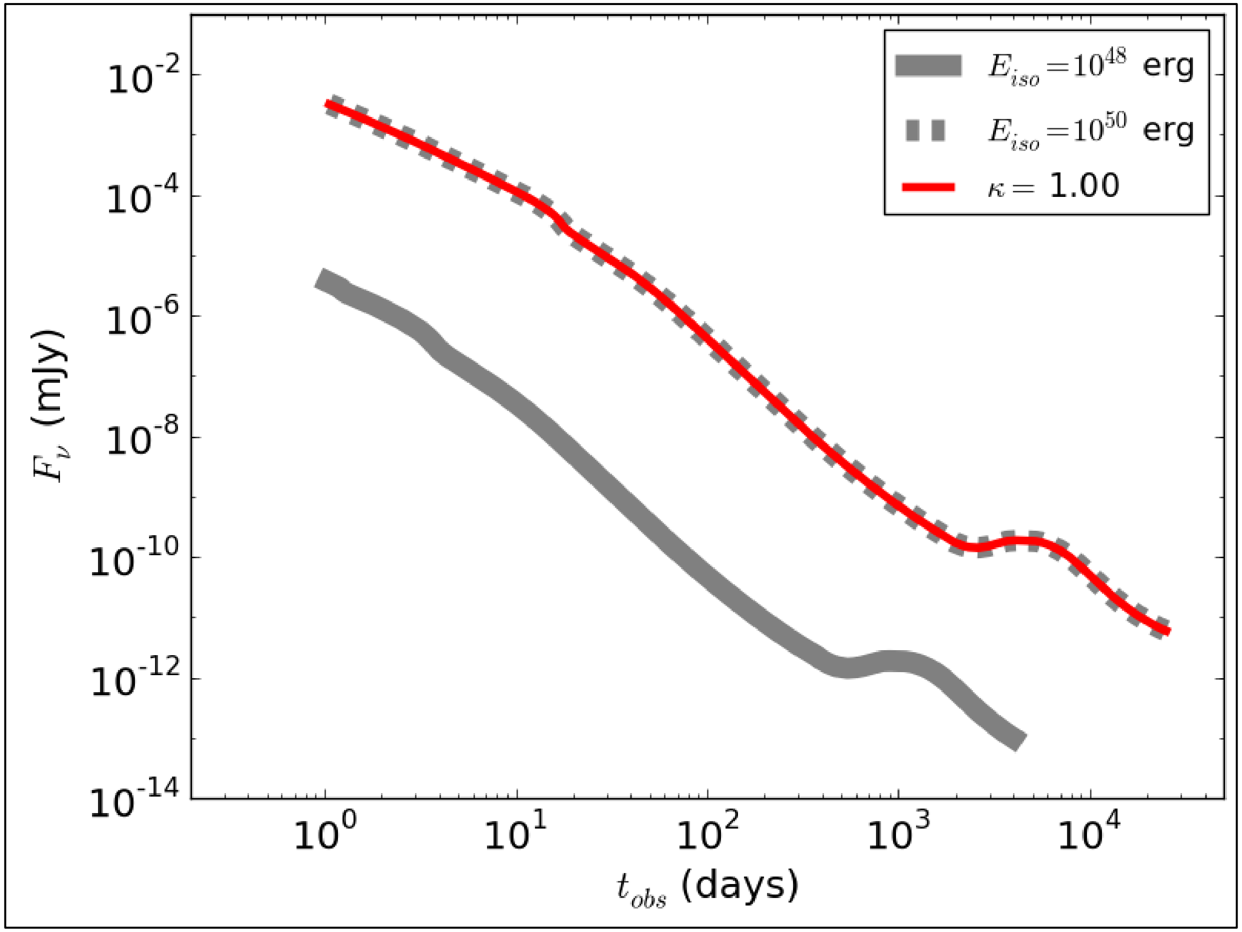


Zhang & MacFadyen (2009) ApJ 698, 1261; van Eerten, Zhang & MacFadyen (2010), ApJ 722, 235

5th order WENO, adaptive-mesh refinement, parallel RHD simulation -> ~500 GB data
17 levels of refinement, effective resolution of 10^7 cells

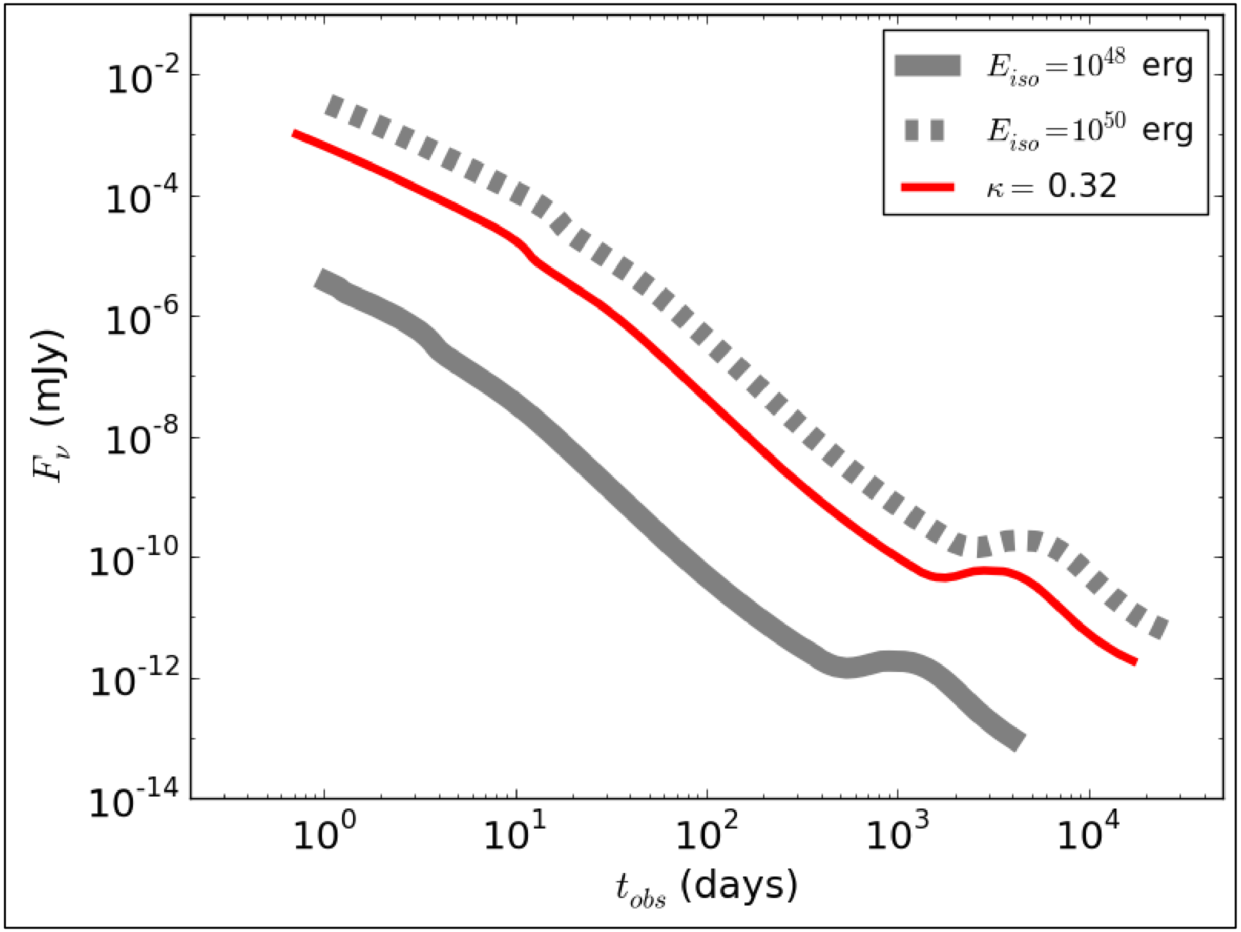
SPREADING IS ACTUALLY VERY SLOW

light curve scale invariance



- compute synchrotron spectrum templates for different jet opening angles and orientations
- Rescale between explosion energies, surrounding densities and synchrotron microphysics model parameters, using dimensional analysis

light curve scale invariance



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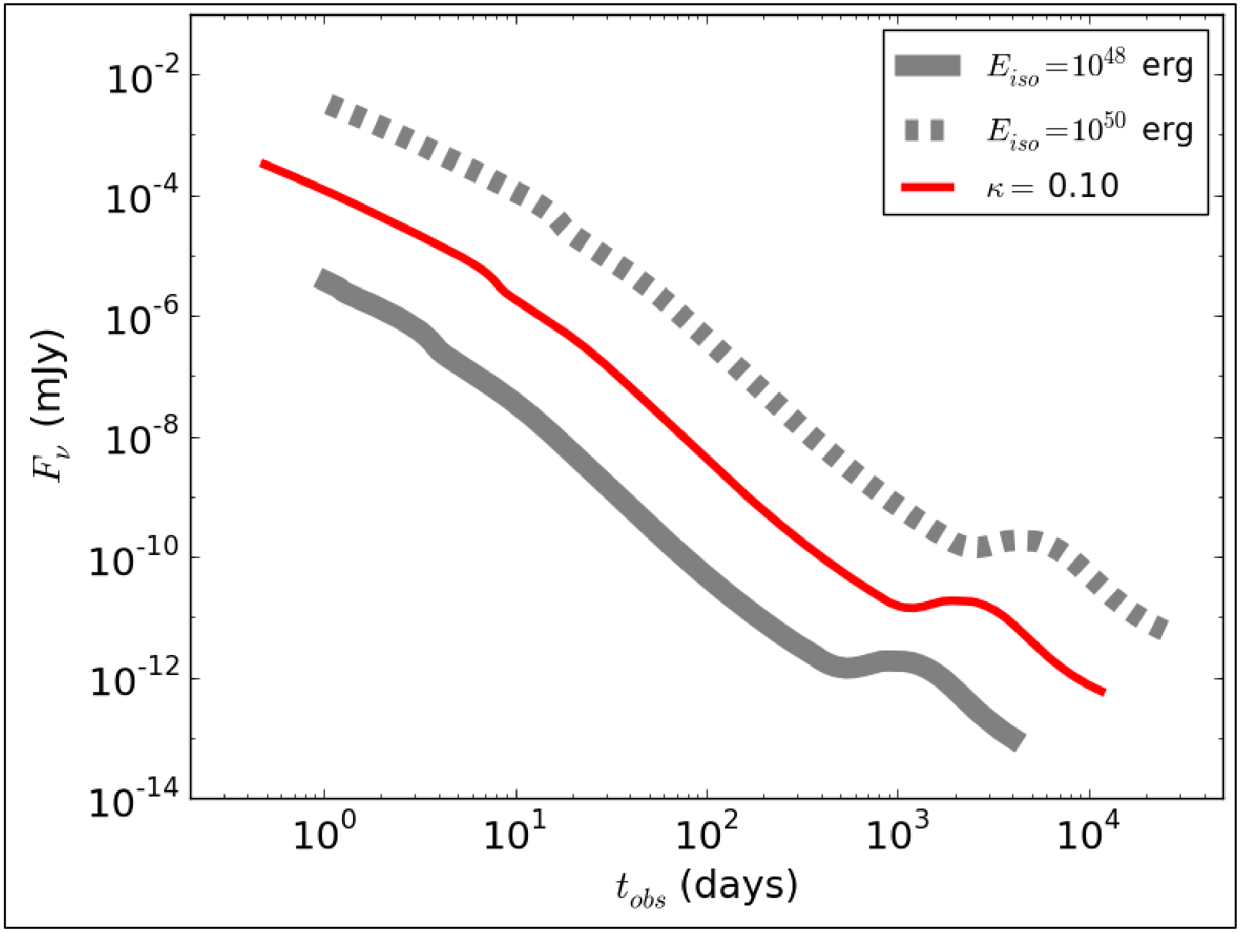
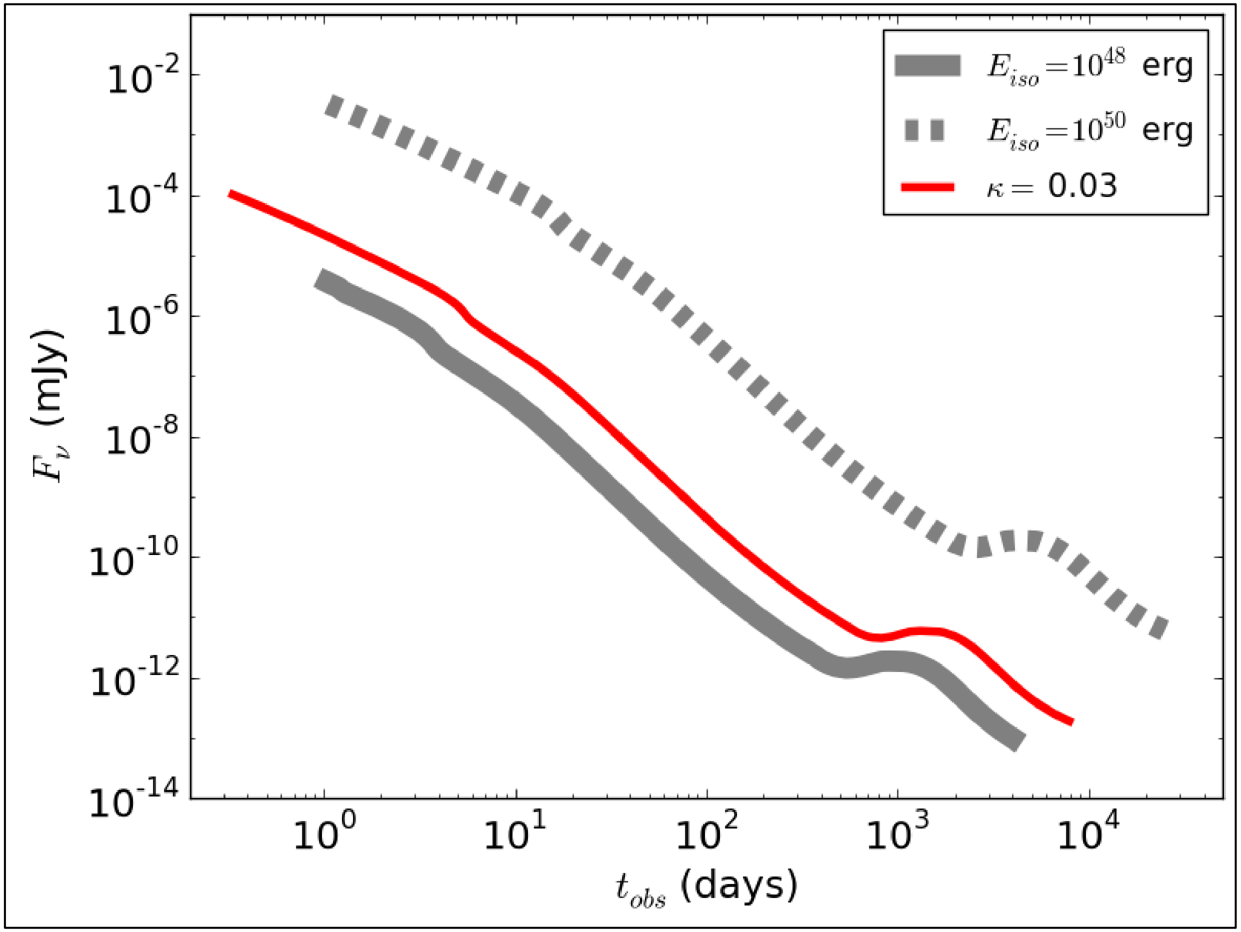
light curve scale invariance



- compute synchrotron spectrum templates for different jet opening angles and orientations
- Rescale between explosion energies, surrounding densities and synchrotron microphysics model parameters, using dimensional analysis

light curve scale invariance



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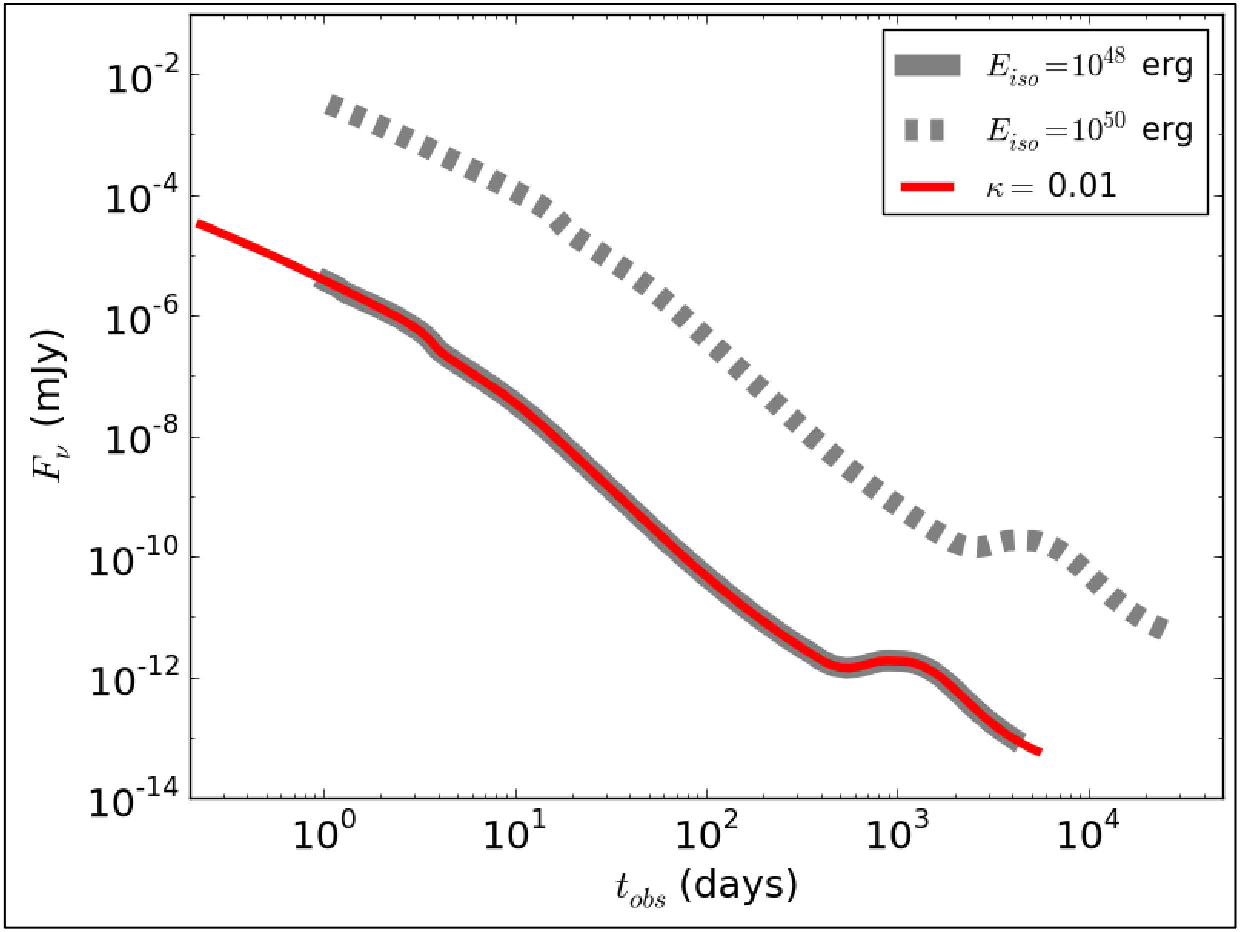
light curve scale invariance



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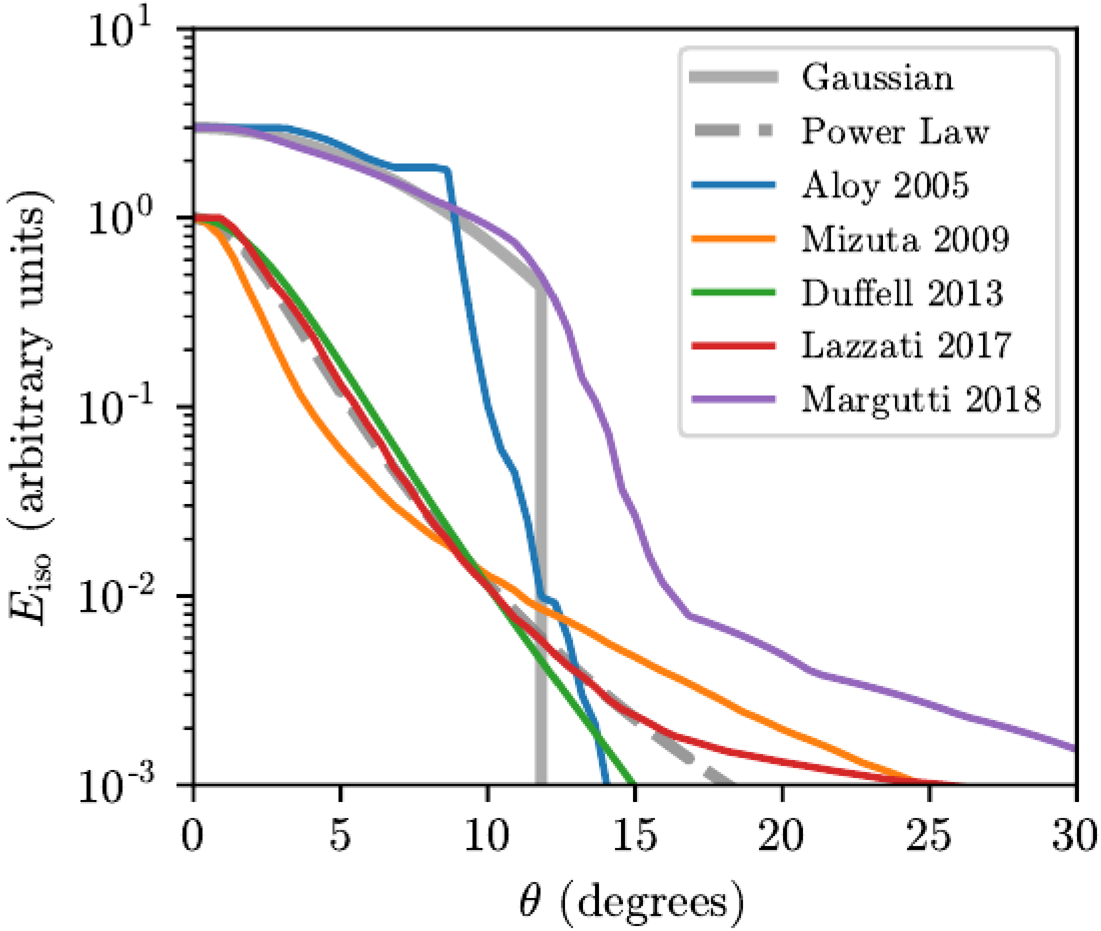
post 170817 modeling: structured jets

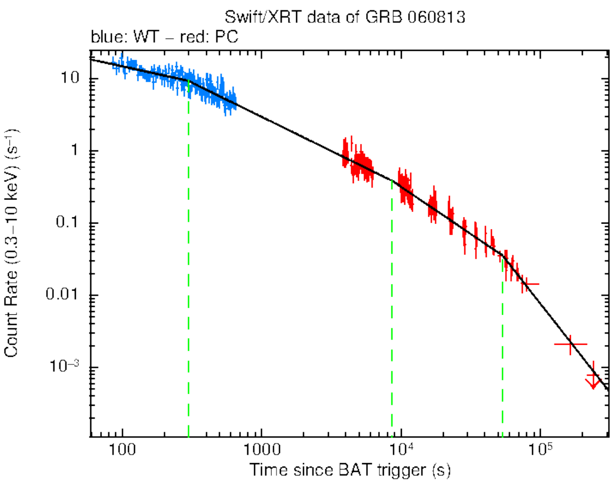


Ryan, van Eerten+ 2019 (ArXiv 1909.11691)

- All jet numerical simulations show jets get launched with structure.
- Long GRBs form additional 'cocoon' structure due to interaction with stellar envelope
- short GRBs potentially form additional 'cocoon' structure if sufficient neutron star debris in the launch path (Nagakura 2014, Murguia-Berthier+ 2014)

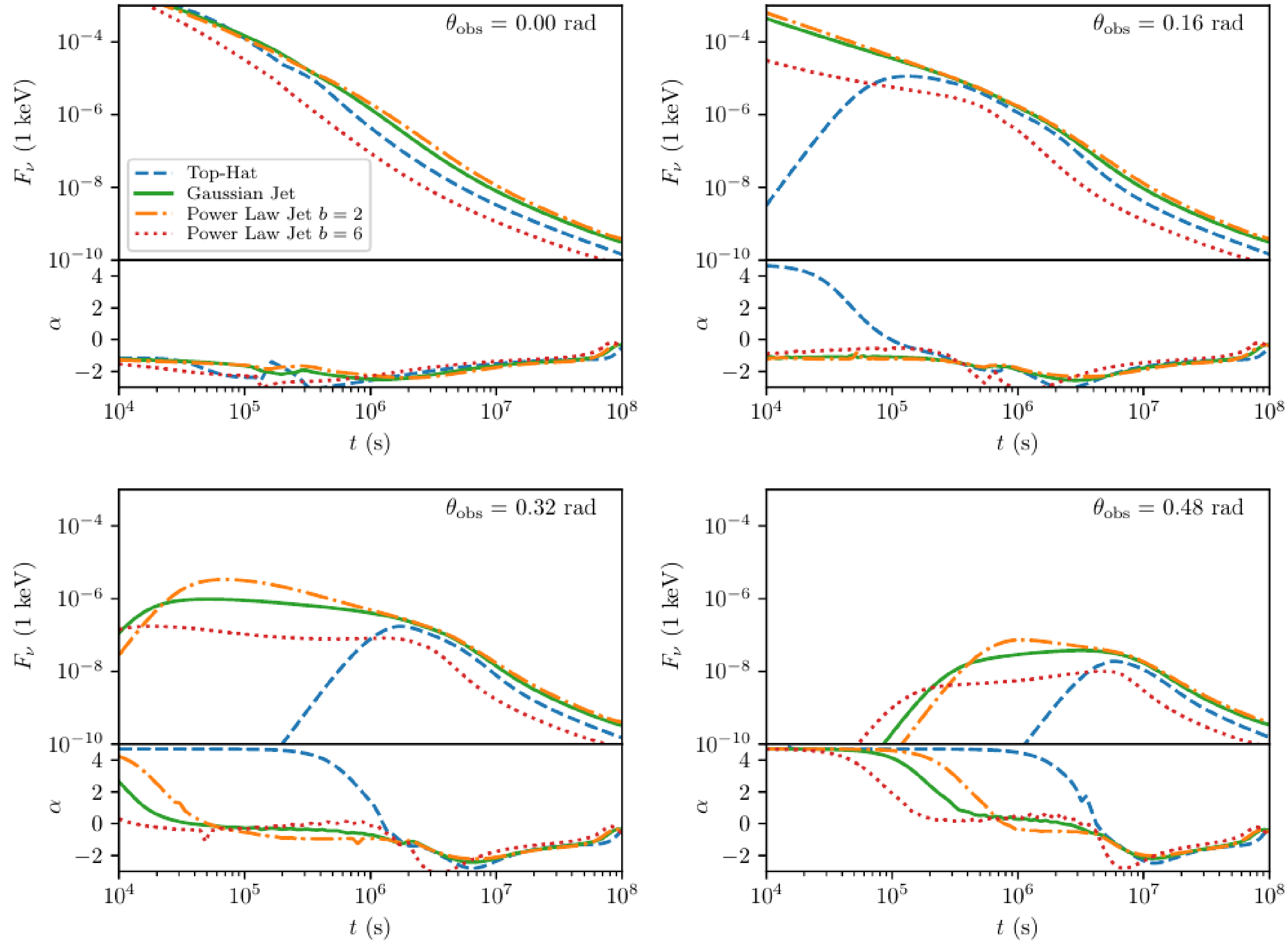
Our Post-170817 GRB modeling toolkit (Ryan, van Eerten+, ArXiv 1909.11691)

- Broadband GRB data
  - perform a power-law fit to data points. Interpret using closure relations
  - First devise a model for a direct fit do data
    - Semi-analytical model
      - *including long-term effect of initial additional lateral / radial structure*
      - Basic analytical model (closure relations)
        - Frequentist fit
        - Bayesian fit
      - Solve PDE's decelerating & spreading blast wave
        - Frequentist fit
        - Bayesian fit
    - Massive computer simulation jet flow
      - One or more bespoke simulations
      - Build a jet simulation template database
        - Frequentist fit *using repeated radiative transfer*
        - Bayesian fit *using repeated radiative transfer*
        - Build a spectrum template database
          - frequentist fit
          - Bayesian fit



modeling of afterglows

initial structure was always there, but only key feature for off-axis observers



Ryan, van Eerten+ 2019, ArXiv:1909.11691

(this is not news: Rossi+ 2002, Dalal 2002, Granot & Kumar 2003, etc...)

Numerical model – afterglowpy
Ryan, van Eerten+ 2019 (ArXiv 1909.11691)

- Python interface to a fast C integrator, can drive MCMC.
- Evolves jets semi-numerically from ultra-relativistic to Newtonian phases
- Includes jet spreading, refreshed shock material, energy injection
- Publicly available software tools!

afterglowpy (install with pip)
https://github/com/geoffryan/afterglowpy

some details of the semi-analytical model

$$\dot{R} = \frac{4u\gamma}{4u^2+3}c$$

shock radius using jump conditions

$$E = (\gamma - 1)M_{\rm ej}c^2 + \frac{4\pi}{9}\rho_0 c^2 R^3 (4u^2+3)\beta^2 f_\Omega$$

$$f_\Omega = 2\sin^2(\theta_j/2) \ .$$

Energy conservation

$$\beta_\perp = \sqrt{\frac{2u^2+3}{4u^2+3}}\frac{\dot{R}}{2\gamma c}$$

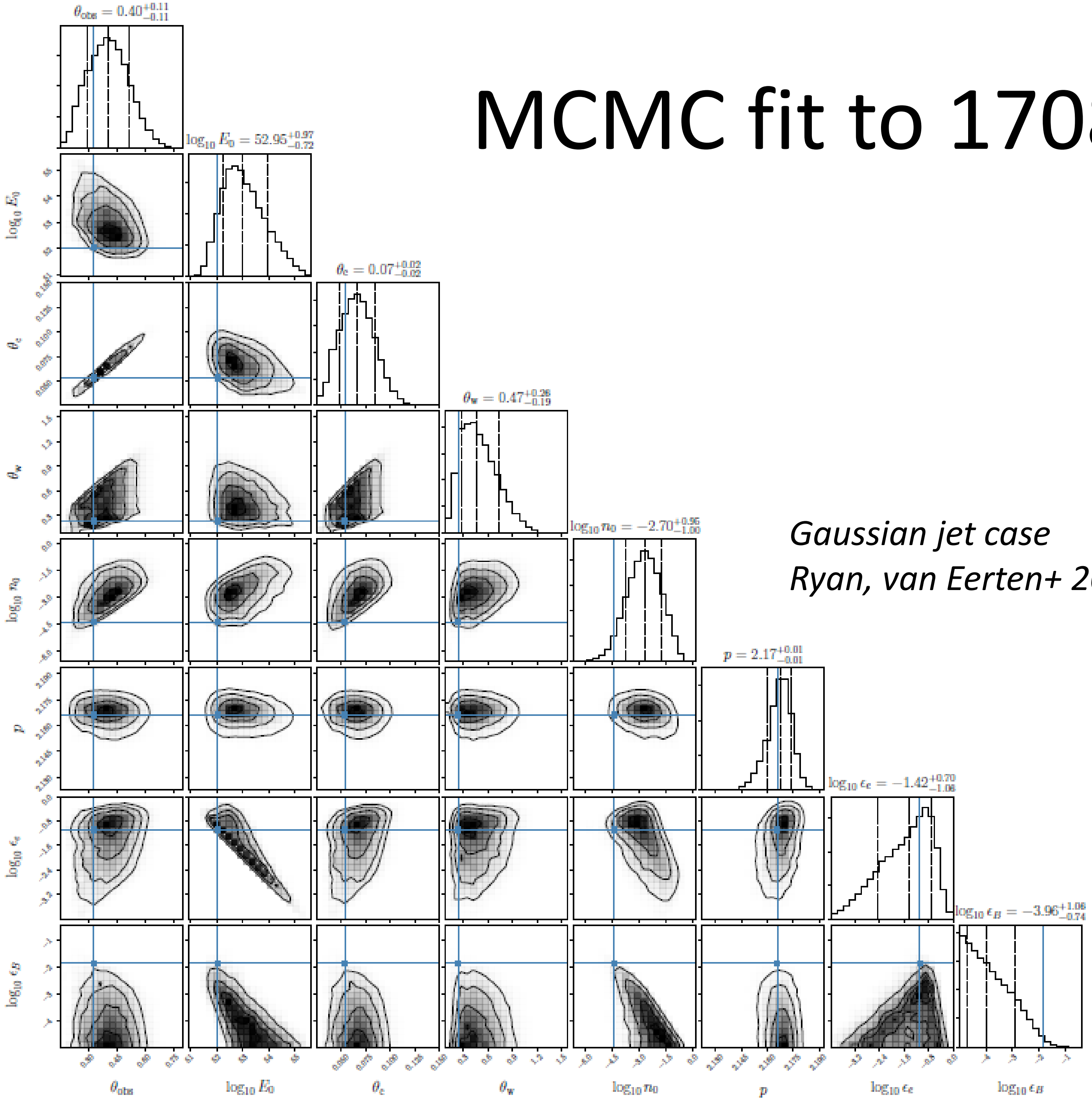
a lateral spreading sound wave
(truth lies in between sound wave and light speed)

$$\dot{\theta}_j = \begin{cases} 0 & \text{if } u > 1/(3\sqrt{2}\theta_c) \\ \beta_\perp c/R & \text{otherwise} \end{cases}$$

novel features: fully **structured** jet evolving from extremely relativistic to non-relativistic using a trans-relativistic equation of state and spreading approximation tuned to simulations

General approach is certainly not a new thing, e.g. Katz & Piran 1997, Chiang & Dermer 1999, Piran 1999, Huang+ 1999, Johannesson+ 2006, van Eerten 2013, Nava+ 2013....

MCMC fit to 170817



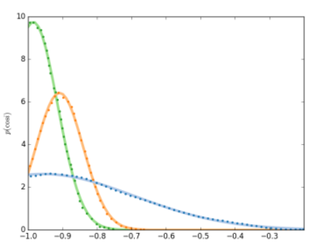
Gaussian jet case

Ryan, van Eerten+ 2019 ArXiv 1909.11691

Parameter inferences

Table 3. Parameter estimation priors and marginalized posteriors for the GW170817A afterglow using the `afterglowpy` Gaussian and power law jet models, including viewing angle constraints from LIGO assuming the *Planck* value of H_0. Given posterior values for each model are the median, 16%, and 84% quantiles. Parameters in the lower section are derived from the posterior distributions of the fit parameters in the upper sections.

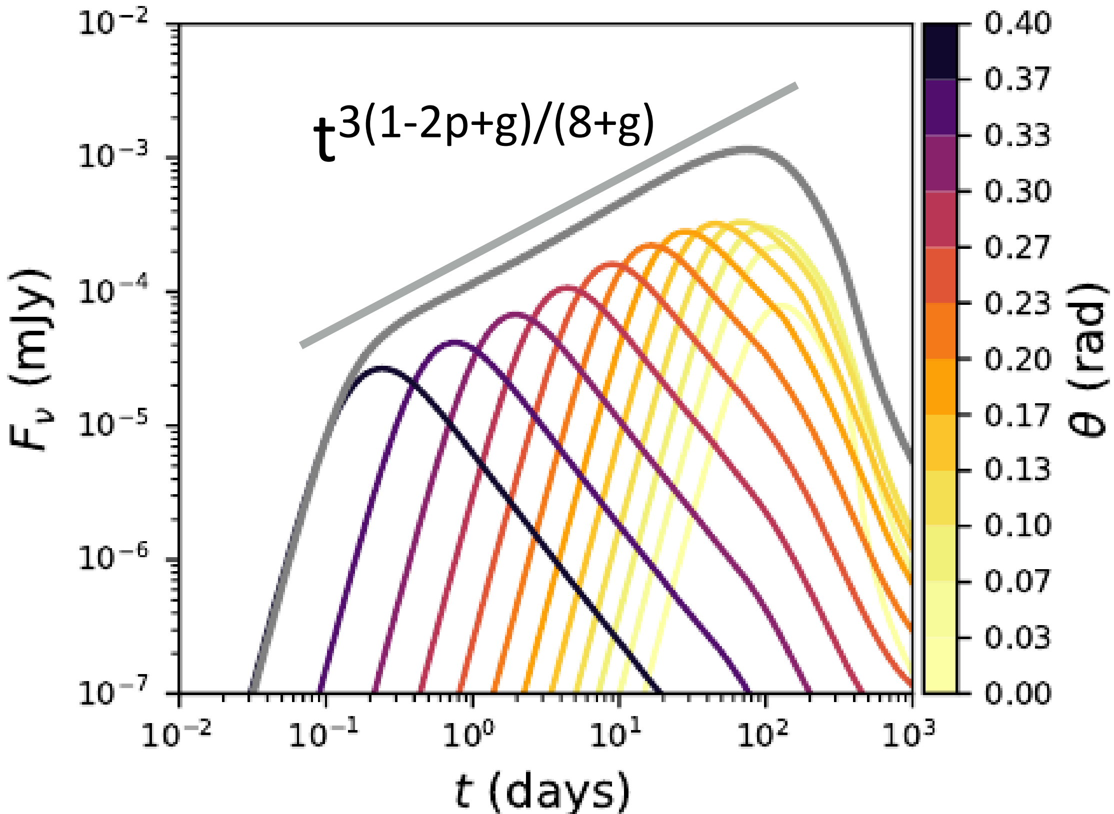
Parameter	Unit	Prior Form	Bounds	Gaussian Jet Posterior	Power Law Jet Posterior
$\theta_{\rm obs}$	rad	$\sin\theta_{\rm obs} \times p_{\rm LIGO}(\cos\theta_{\rm obs})$	$[0, 0.8]$	$0.40^{+0.11}_{-0.11}$	$0.44^{+0.12}_{-0.12}$
$\log_{10} E_0$	erg	uniform	$[45, 57]$	$52.96^{+0.97}_{-0.72}$	$52.93^{+1.1}_{-0.75}$
$\theta_{\rm c}$	rad	uniform	$[0.01, \pi/2]$	$0.066^{+0.018}_{-0.018}$	$0.046^{+0.013}_{-0.013}$
$\theta_{\rm w}$	rad	uniform	$[0.01, 12\theta_{\rm c}]$	$0.47^{+0.26}_{-0.19}$	$0.238^{+0.071}_{-0.69}$
b	–	uniform	$[0, 10]$	–	$9.03^{+0.70}_{-1.1}$
$\log_{10} n_0$	$\rm cm^{-3}$	uniform	$[-10, 10]$	$-2.70^{+0.95}_{-1.0}$	$-2.6^{+1.1}_{-1.1}$
p	–	uniform	$[2, 5]$	$2.168^{+0.063}_{-0.0075}$	$2.1653^{+0.0085}_{-0.010}$
$\log_{10} \varepsilon_{\rm e}$	–	uniform	$[-5, 0]$	$-1.42^{+0.70}_{-1.1}$	$-1.24^{+0.73}_{-1.2}$
$\log_{10} \varepsilon_{\rm B}$	–	uniform	$[-5, 0]$	$-3.96^{+1.1}_{-0.74}$	$-3.76^{+1.1}_{-0.87}$
$\log_{10} E_{\rm tot}$	erg	–	–	$50.57^{+0.92}_{-0.66}$	$50.46^{+1.1}_{-0.73}$
$\theta_{\rm obs}/\theta_{\rm c}$	–	–	–	$6.12^{+0.18}_{-0.18}$	$9.38^{+0.73}_{-0.56}$
$\log_{10} E_0/n_0$	$\rm erg\ cm^3$	–	–	$55.69^{+1.1}_{-0.85}$	$55.62^{+1.2}_{-0.83}$



Ryan, van Eerten+ *2019 (ArXiv* 1909.11691)

Thinking through the model features: Shaping a light curve through jet structure

NEW closure relations: $$g = (\theta_V - \theta)\frac{d\log E}{d\theta} \approx \frac{1}{4}\frac{\theta_V^2}{\theta_C^2}$$ (Gaussian Jet)



GW170817A

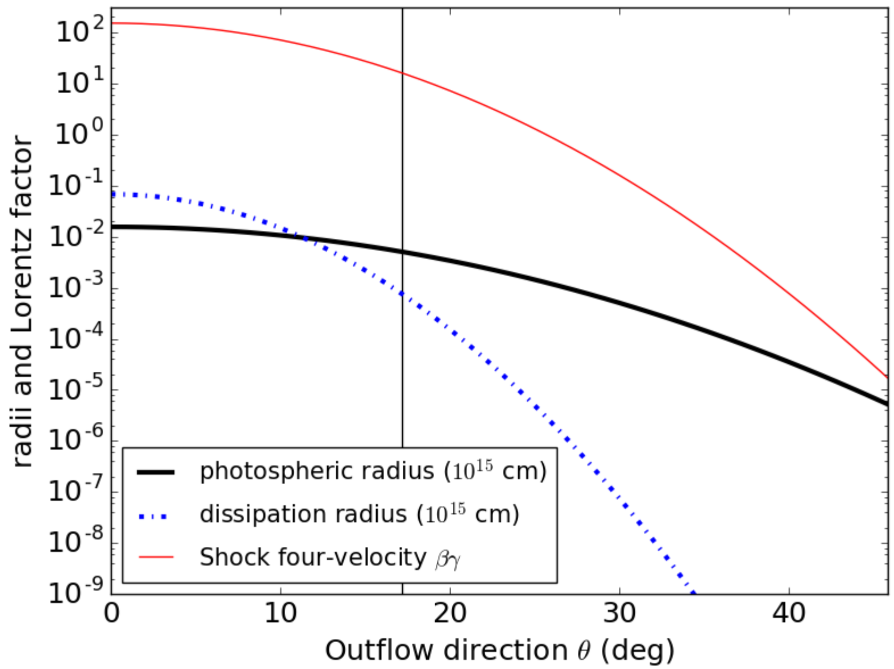
$\alpha = 0.9$

$\Longrightarrow$ g=8.2

$\Longrightarrow$ $\theta_v \approx 6\theta_c$

Ryan, van Eerten+ 2019 (*ArXiv* 1909.11691)

New open questions: prompt GRB, structure & photospheric radius



A fireball containing Baryons would also have electrons providing opacity that tends to imply optically thin prompt emission only natural near the jet tip:

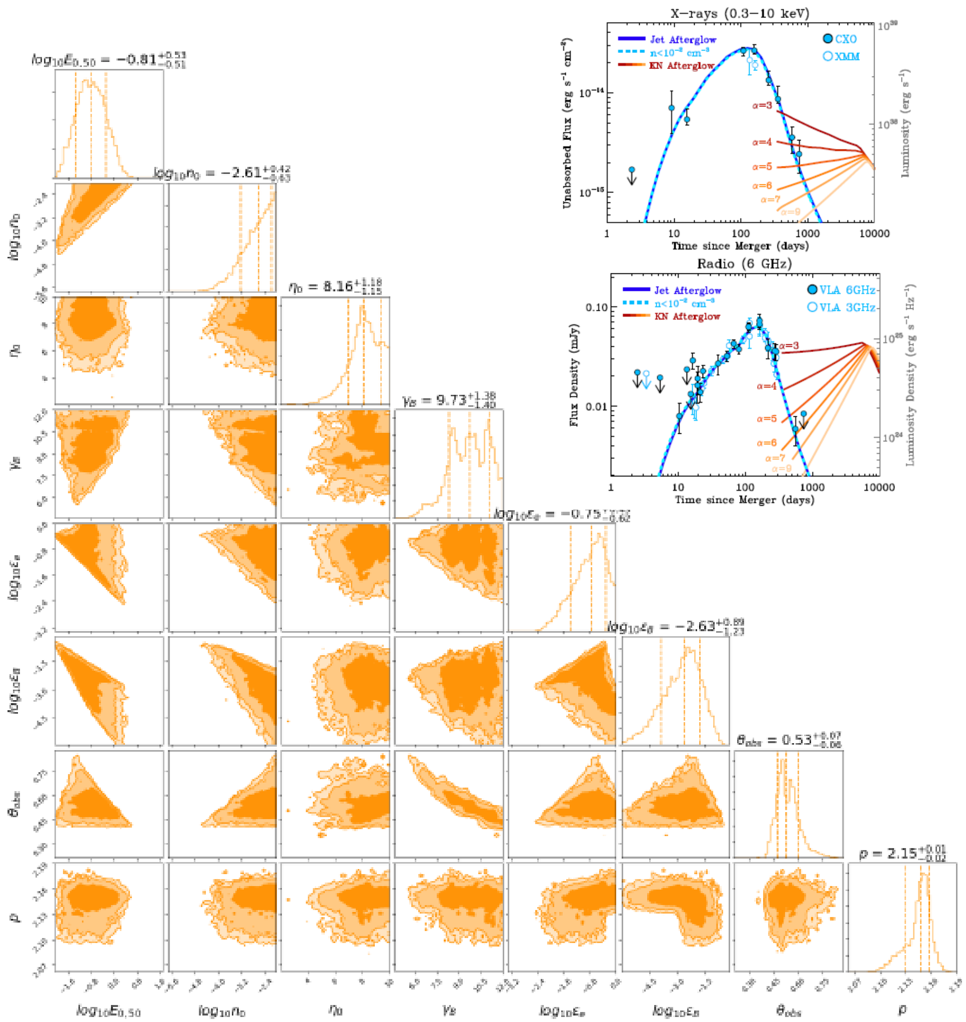
GRB 170817 would have been typical if seen on-axis, but was atypical off-axis?

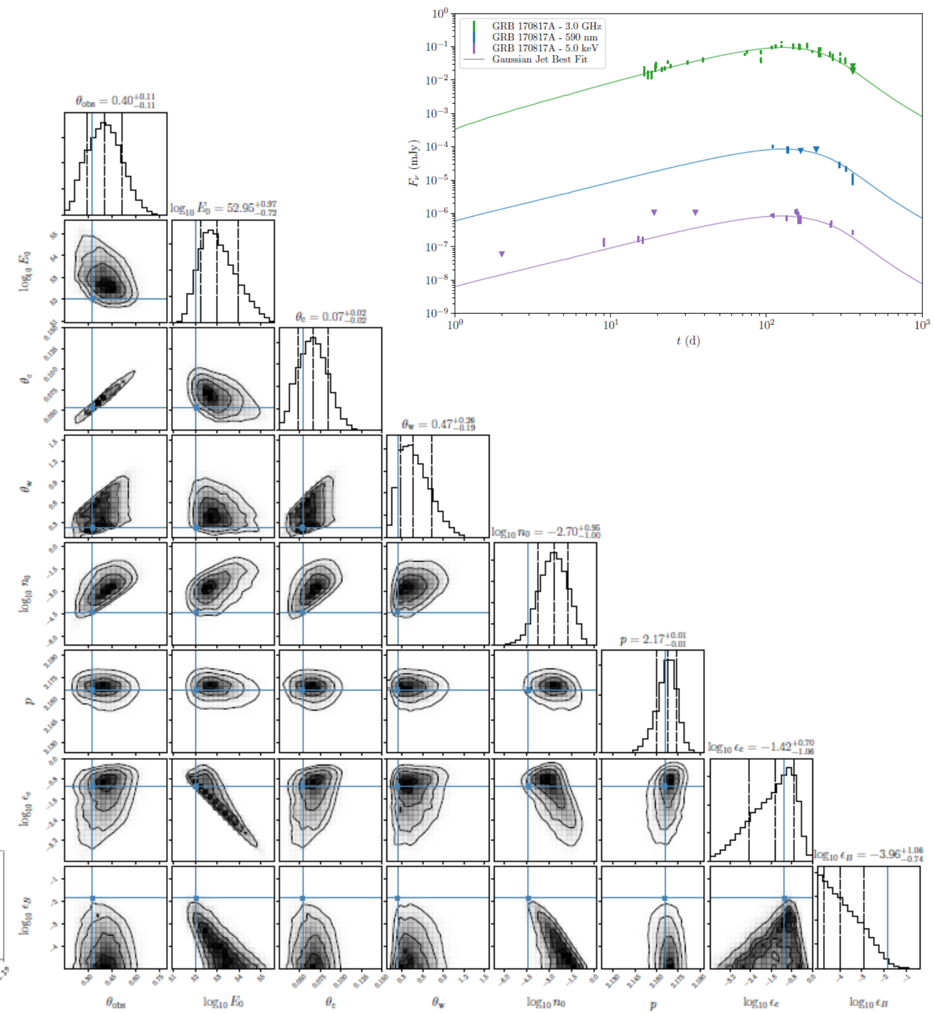
$R_d \sim \Gamma^2 c\delta t \sim 3 \cdot 10^{13} \delta t_{-1} \Gamma_2^2$ cm for the dissipation radius

$R_\gamma \sim \sigma_\tau E_{iso}/4\pi R^2 m_p c^2 \Gamma$, from $\tau = \sigma_T n R \equiv 1$ and $\Gamma = {}^{E_{iso}}/_{Mc^2} = {}^{E_{iso}}/_{n m_p V}$ for the photospheric radius

Where did the gamma rays for GRB 170817A really come from?
Line of sight? Reprocessed emission originating from closer to the jet axis?
see also discussions in Matsumoto, Nakar & Piran 2019, Shoemaker & Murase 2018 etc.

New open questions: different paths to structured jets

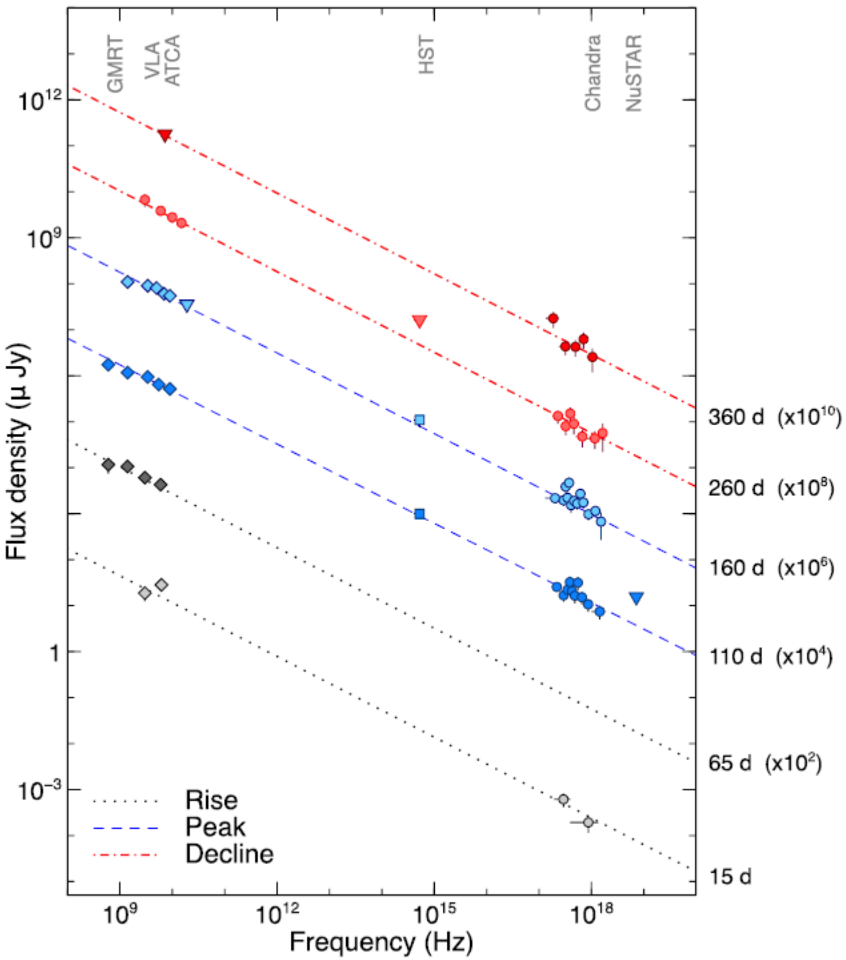




Hajela+ 2019, ArXiv 1909.06393
A *boosted* fireball, not a cocoon / jet emergence model

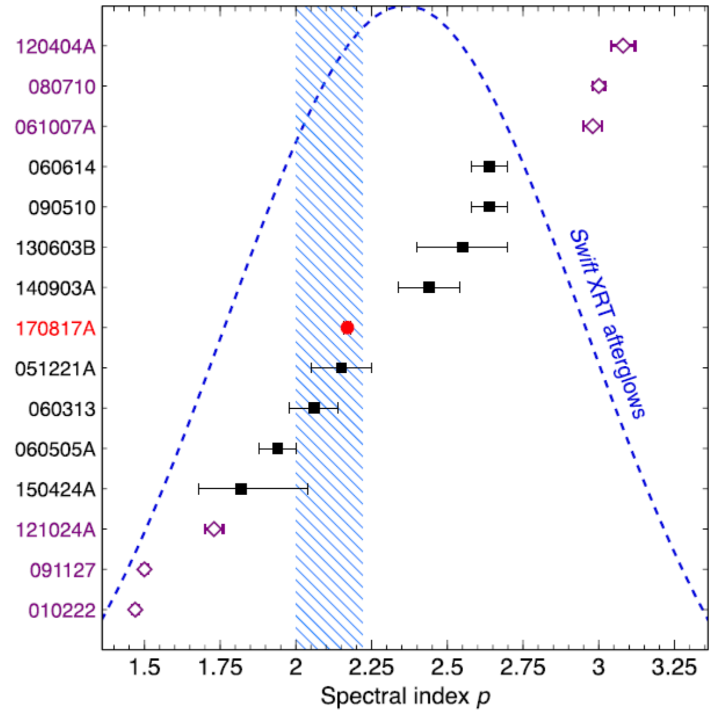
Ryan+ 2019, ArXiv 1909.11691
General Gaussian structured jet

New open questions: so what about *p*?



Troja+ 2017, Margutti+ 2018, Troja, van Eerten+ 2019

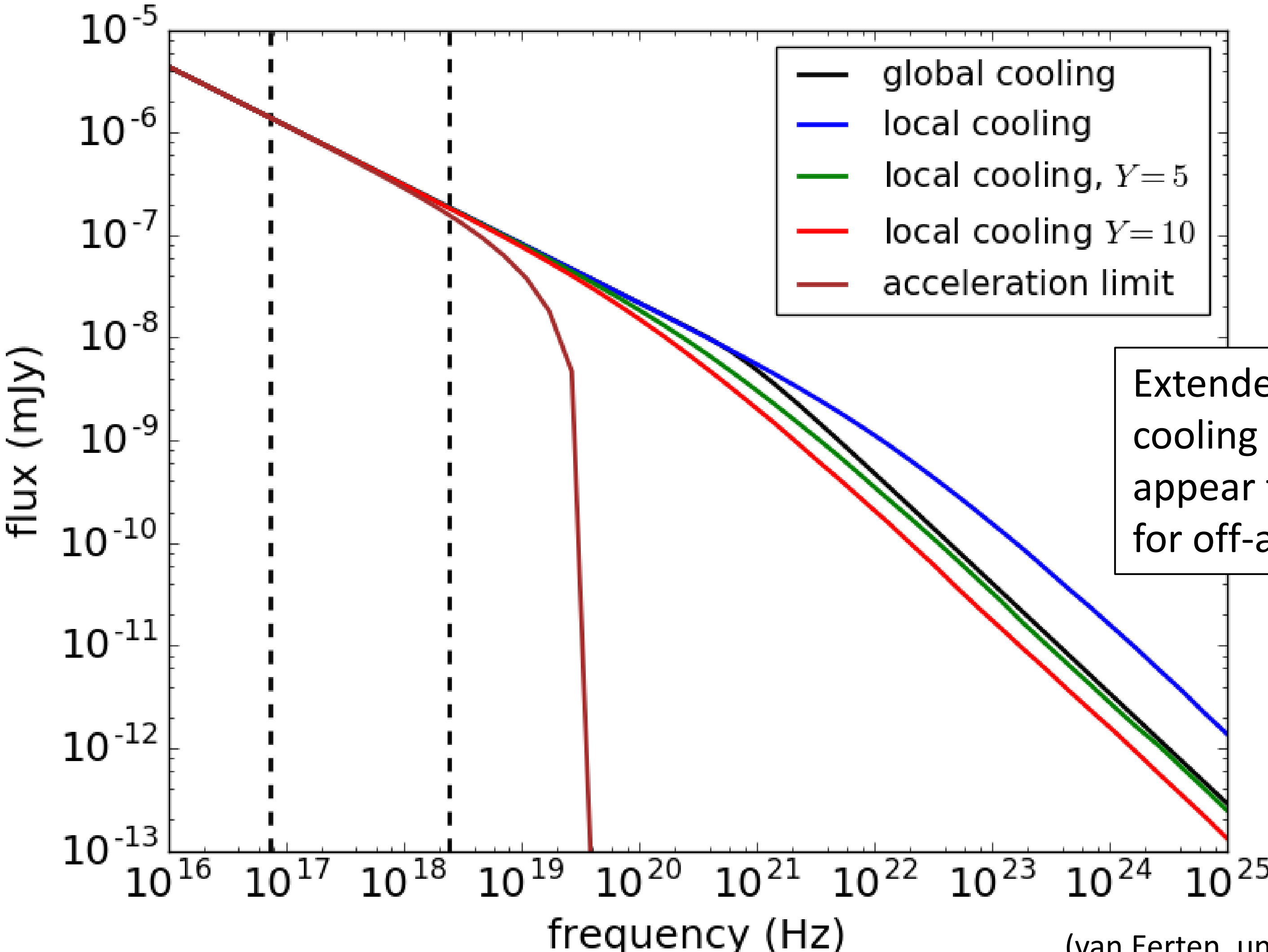
GRB 170817A : p = 2.17 *tight* constraint



Troja, van Eerten+ 2019

- Not reasonable to interpret measurement as some mid-point between relativistic and non-relativistic given larger *p* sample.
- But BIG question remains: why DOESN'T *p* evolve for 170817A? How can *different* GRBs pick a different p value and *stick* with it even when evolving over all these scales?

Electron cooling, Inverse Compton cooling, etc.



Extended absence of cooling break does not appear to be big issue for off-axis view case

(van Eerten, unpublished)

spectra around 150 days, `typical' GRB parameters, `typical' off-axis view

Summary

GRB field has been progressing steadily separate of 170817...

- random example: prompt emission data analysis under ongoing refinement
  (are spectra too sharp?)
- random example: better understanding break-out & cocoons phases
- random example: better and more constraints on (large) initial Lorentz factors
- random example: an emerging continuum of ejecta kinetic energies GRB<->SN
- (simulation-based) template fitting is maturing (using mapping of synchrotron templates)

GRB 170817A was nevertheless a game-changer that cannot be ignored

- First multi-messenger joint Bayesian data analysis (focus on jet orientation to observer)
- A forced recalibration of jet models: lateral jet structure inescapable
- Simulation-based fitting has responded: structured jets, boosted fireballs...
- semi-analytical models structured jets now available, including updated ‘closure-relations’
- 170817 prompt gamma-rays remain puzzling: from cocoon breakout? reprocessed jet emission?
- An extremely clear but puzzling view of electron shock-acceleration (ie p is and stayed 2.17)

By now numerous papers have been published on 170817A, and this presentation only carved a narrow and biased path through this vast and growing landscape....