Theory of off-axis GRBs and GW events

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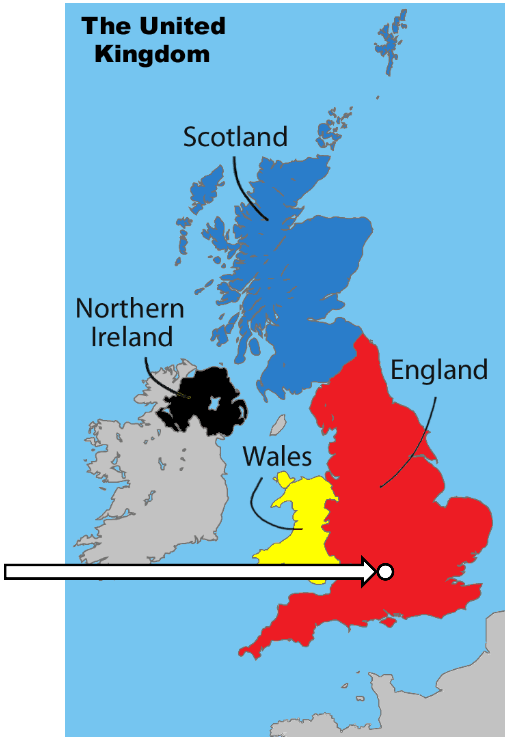
Vulcano, 21 May, 2018

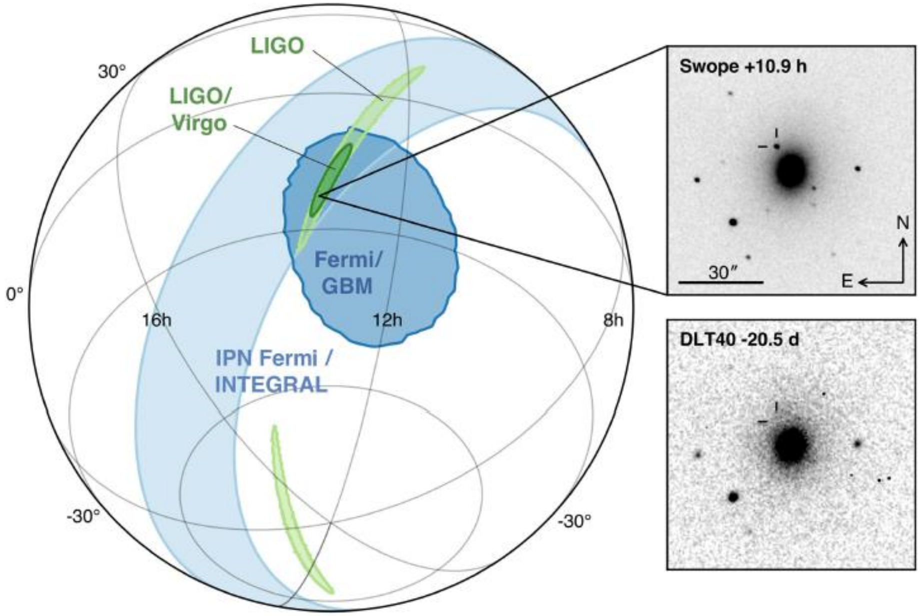


A range of electro-magnetic counterparts to GW170817

- Short gamma-ray burst ("GRB")
  unambiguous classification
  (but possibly atypical event?)

- Kilonova in optical and infra-red
  ridiculously rich data set and level of detail

- Afterglow in radio, optical and X-rays
  definitely atypical event: late rise (first detection ~9 days)



Note: to streamline the narrative, I will leave out discussion of many papers published during the timeline of this presentation that presented similar arguments for these models, e.g. Lamb & Kobayashi 2017, Margutti + 2018, Hallinan+ 2017, Kathirgamaraju+2018, Lyman+ 2018, Zhang+ 2018, Resmi+ 2018, Evans+ 2017, Mooley+ 2017, Lazzati+ 2017, Gottlieb+ 2017, etc...

Gamma-ray burst afterglows

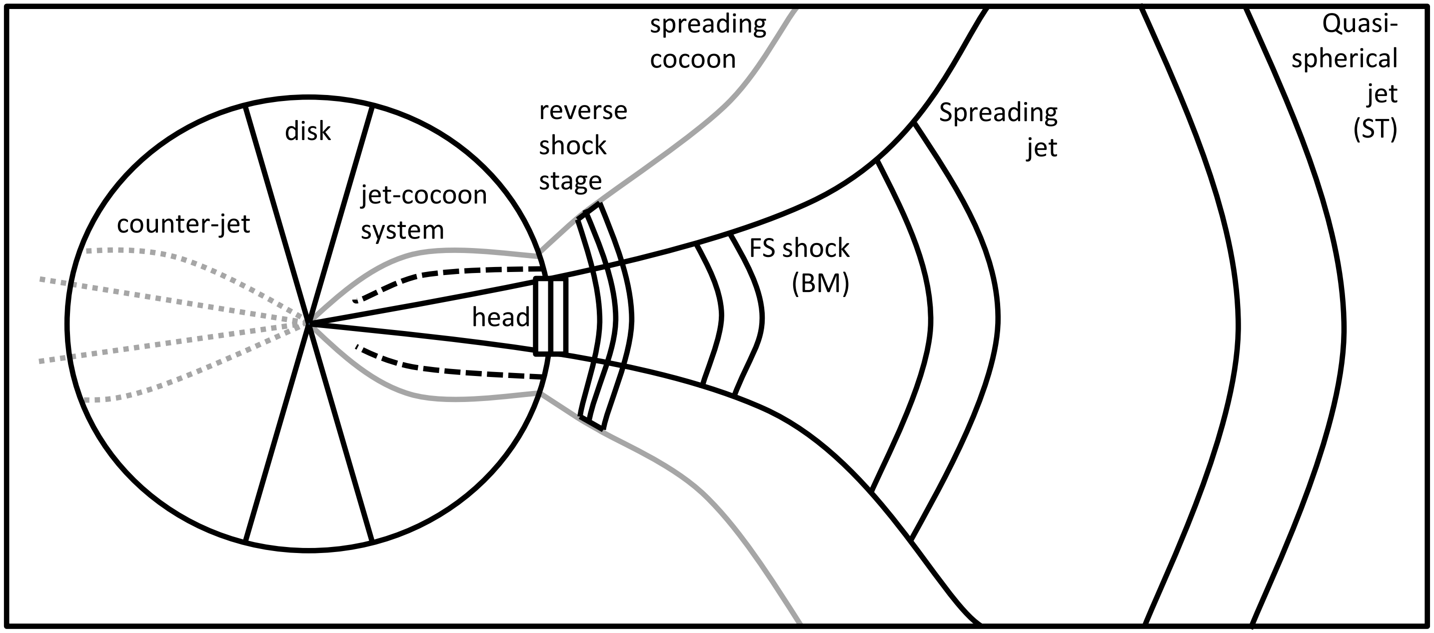


Fig from van Eerten, IJMPD (2018), ArXiv: 180101848

Gamma-ray burst afterglows

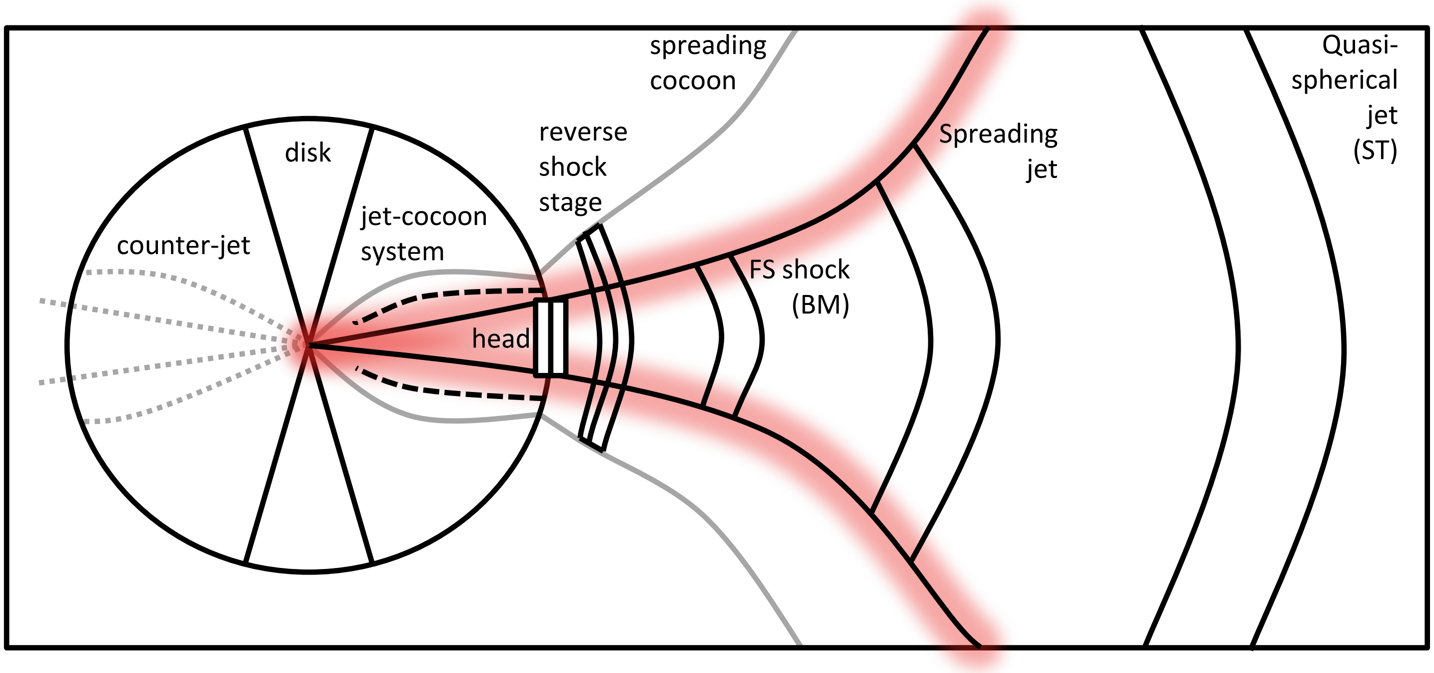


Fig from van Eerten, IJMPD (2018), ArXiv: 180101848

Hard edges not a given, likely some structure either imprinted by launching, clearing the envelope and/or cocoon interaction.

Cocoon theoretically recent arrival on short GRB scene, requires dense environment

Basic ejecta modeling

Total energy is sum of cold ejecta kinetic energy and total hot swept-up gas energy

$$E = (\gamma - 1) M_{ej} c^2 + \frac{\beta^2}{3} (4\gamma^2 - 1) M_{sw} c^2$$

(employing shock-jump condition for a trans-relativistic equation-of-state)

The width of the blast wave is given by $\Delta R_{ej} = \Delta R_0$, and $\Delta R_{sw} = R/12\gamma^2$

If $M_{ej} \downarrow 0$, for the early, relativistic limit, we have

$$\gamma = 57 \left(\frac{E_{iso}}{10^{51} erg} \right)^{\frac{1}{8}} \left(\frac{\rho_{ext}}{10^{-2} m_p} \right)^{-\frac{1}{8}} \left(\frac{t_{obs}}{10^2 s} \right)^{-\frac{3}{8}}$$

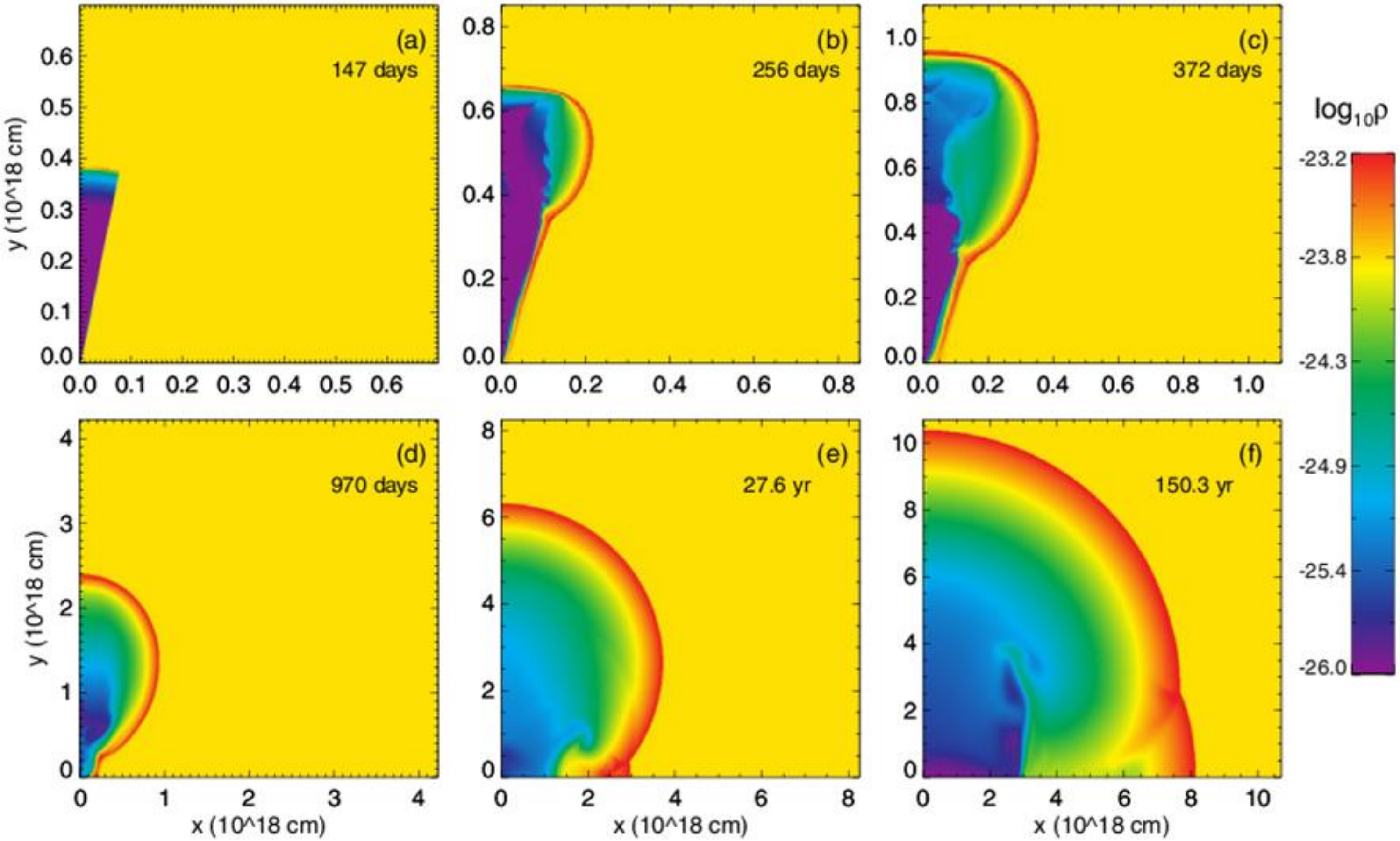
(accounting for arrival time compression $t_{obs} = t_{lab}/16\gamma^2$)

For the late, non-relativistic limit we have

$$R = 0.47 \left(\frac{E_j}{10^{49}} \right)^{\frac{1}{5}} \left(\frac{\rho_{ext}}{10^{-2} m_p} \right)^{-\frac{1}{5}} \left(\frac{t_{obs}}{10^8 s} \right)^{\frac{2}{5}}$$

- For jets with lateral structure (e.g. “Gaussian jets”), use $E \rightarrow E(\theta)$
- for jets with radial injection of energy (e.g. source activity, slower shells), use $E \rightarrow E(t)$
- for (late-time) sideways spreading, transition to larger rate $\dot{M}_{sw}$

blast wave simulations in 2D

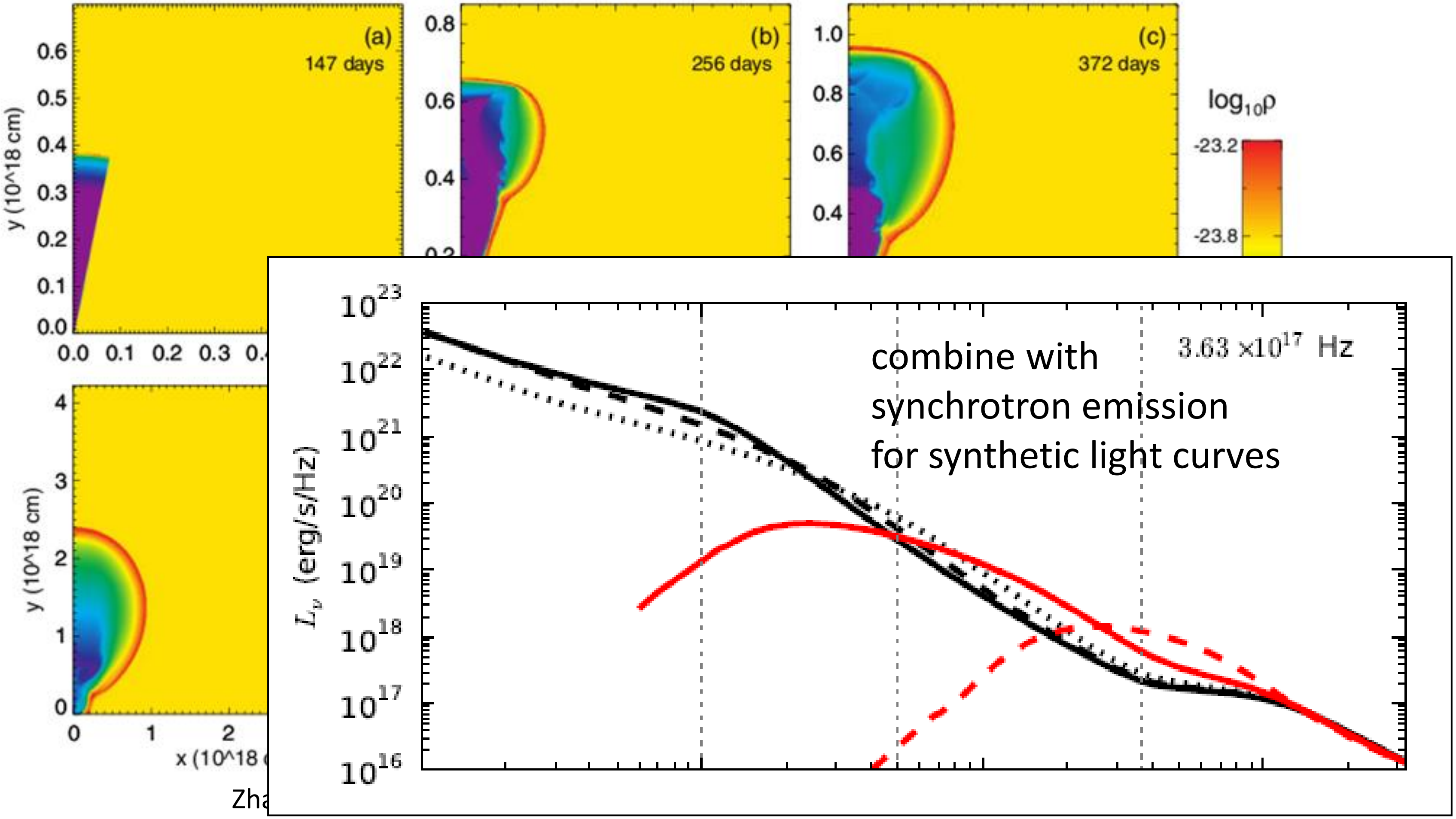


Zhang & MacFadyen (2009) ApJ 698, 1261; van Eerten, Zhang & MacFadyen (2010), ApJ 722, 235

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

blast wave simulations in 2D

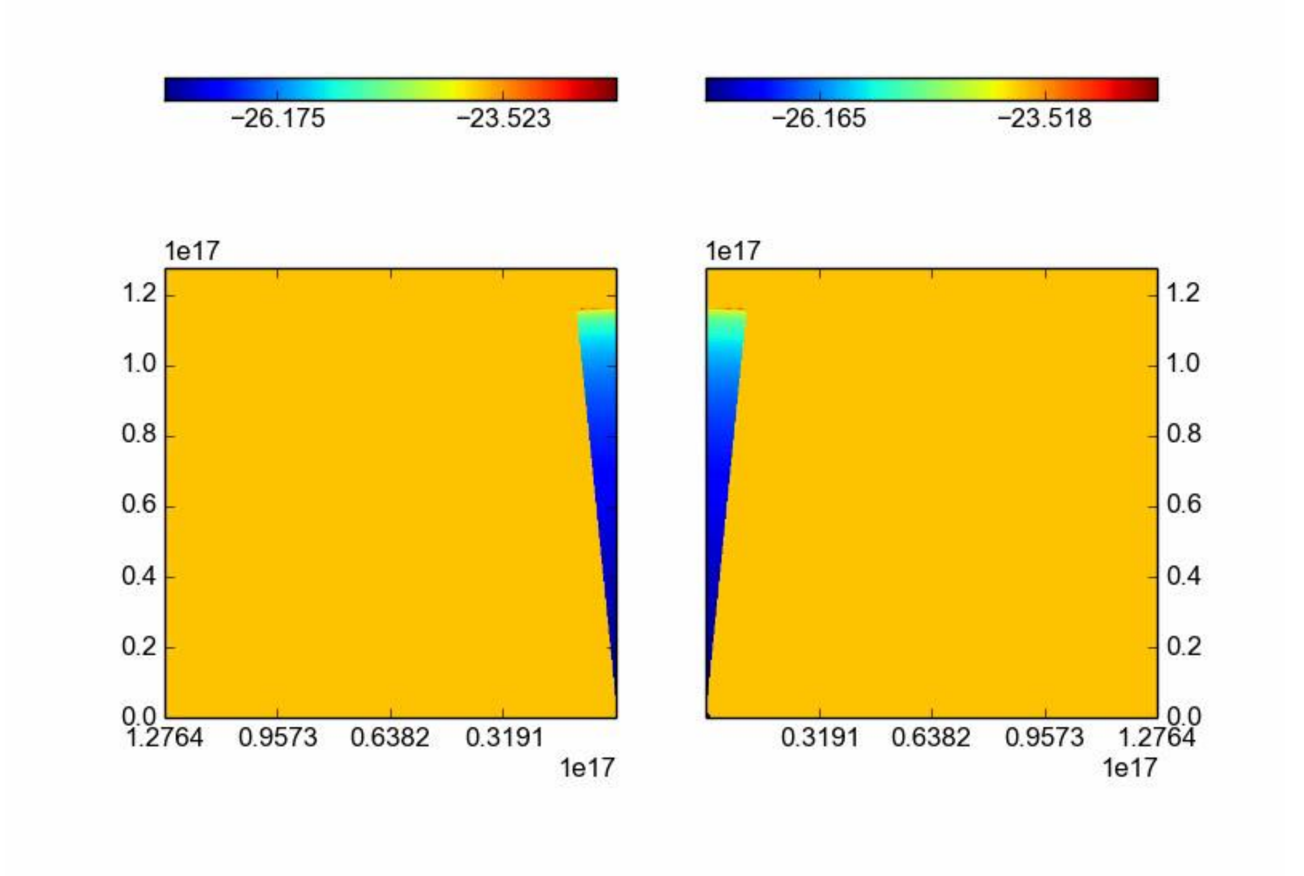


combine with
synchrotron emission
for synthetic light curves

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

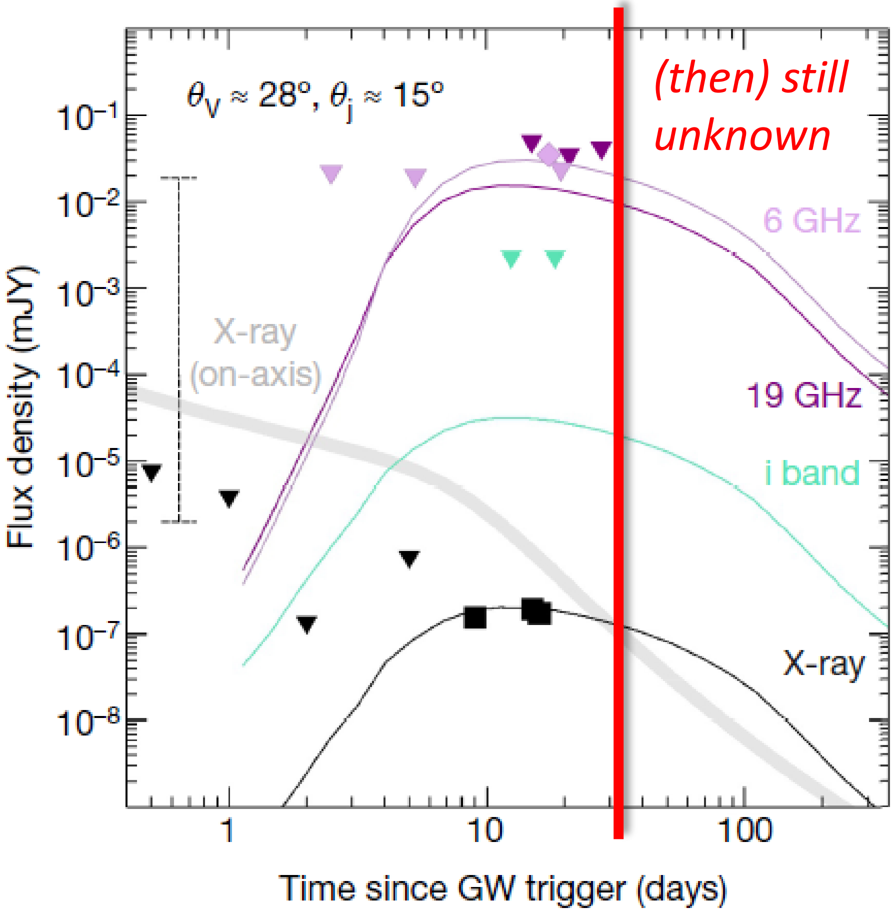
Making use of jet spreading simulations



Compress data and rescale -> loads of synchrotron spectral templates (BOXFIT, SCALEFIT)

van Eerten, van der Horst & MacFadyen 2012, ApJ 749, 44
van Eerten & MacFadyen 2012, ApJ 747, L30

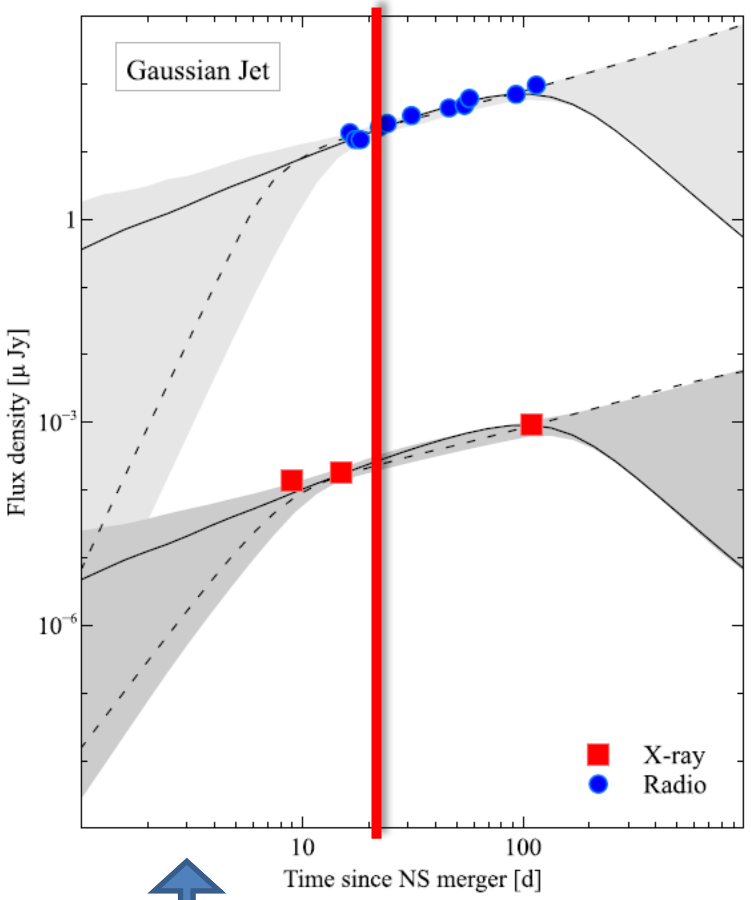
GRB170817, broadband light curves



(then) still unknown

Troja, Piro, van Eerten et al. 2017, Nature 551, 71

- *Assuming peaked emission (from radio "limit", flat X-rays)*
- *but: "At this stage we cannot rule out a broad flat X-ray/radio peak or additional brightening due to jet structure"*

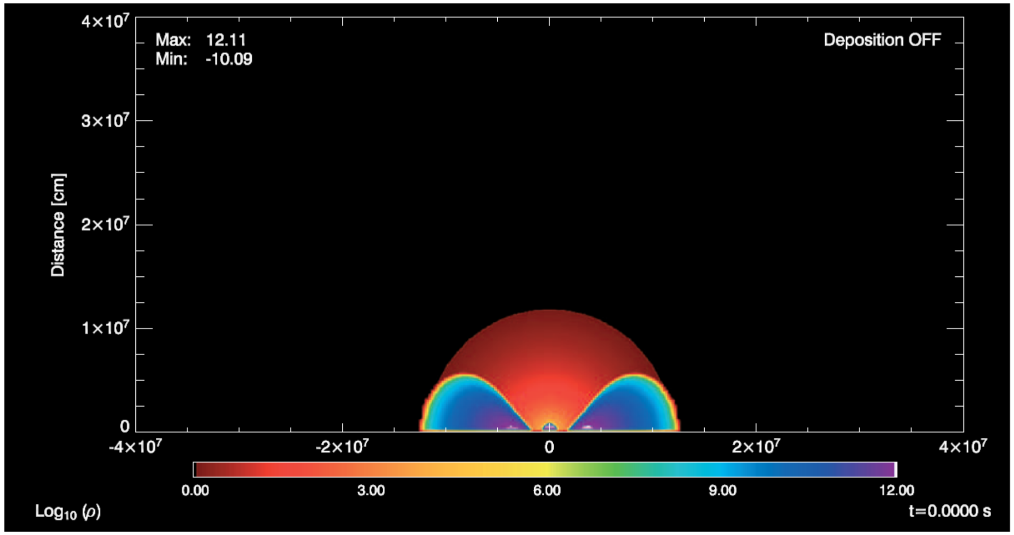


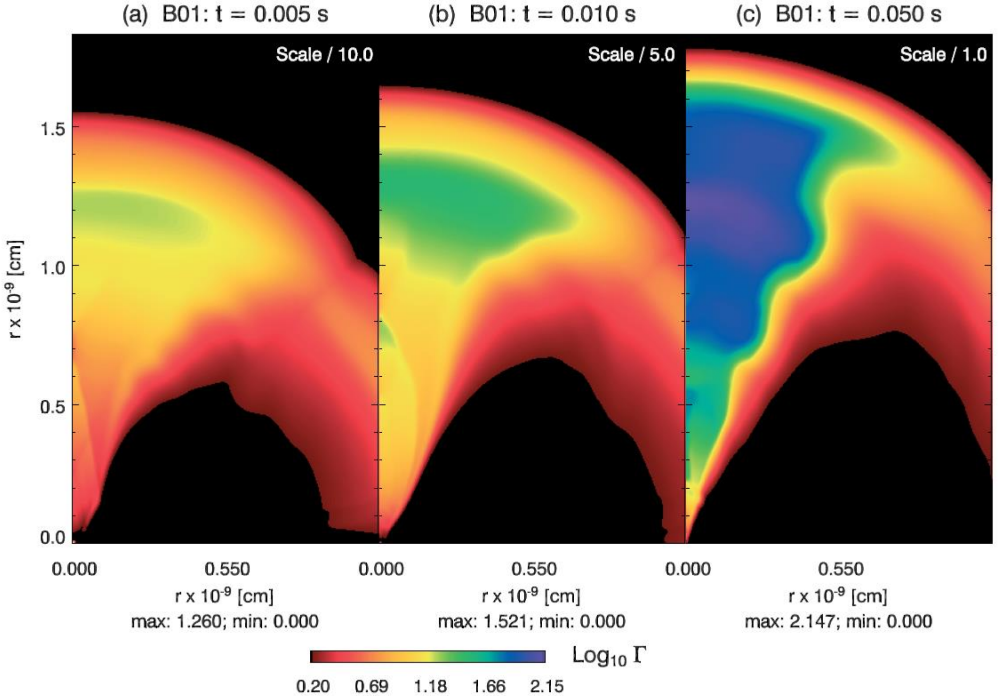
Troja, Piro, Ryan, van Eerten et al. (2018), MNRAS

(whew!)

...so much for the template database built from simulations starting from non-structured jets ☹

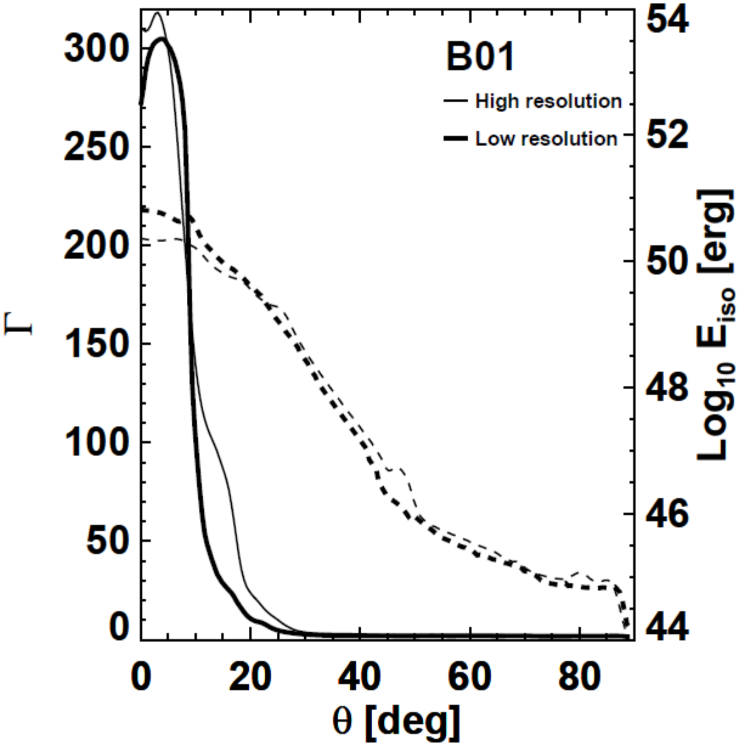
Structured jet as a natural configuration



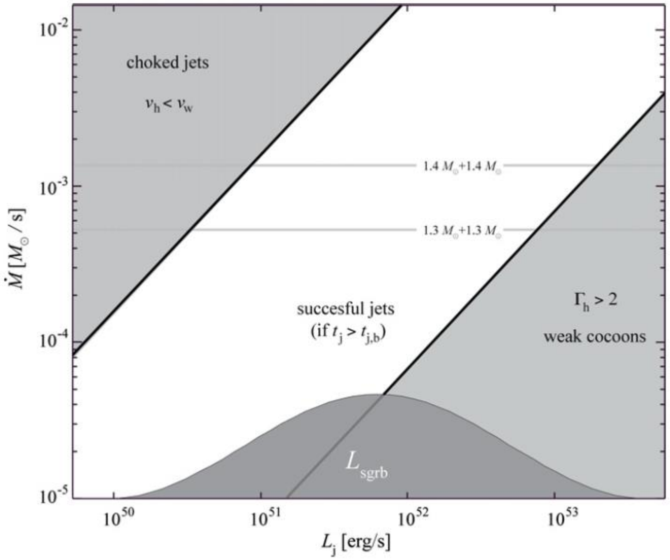


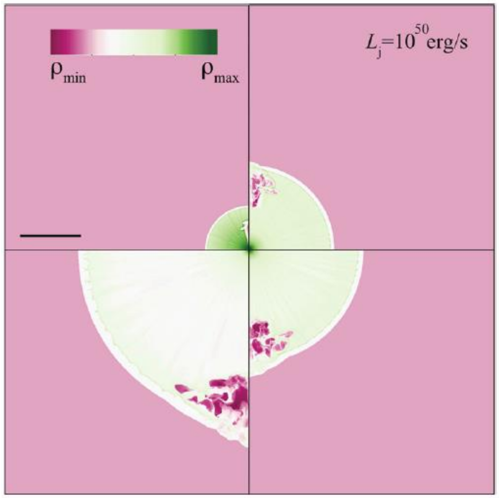
Structured jets are a natural
outcome of simulations
of short GRB jets

e.g. through jet-torus interaction during launching, see e.g.
Aloy, Janka, Mueller 2005
(torus mass $M \sim 0.1 - 0.2 M_{sun}$)

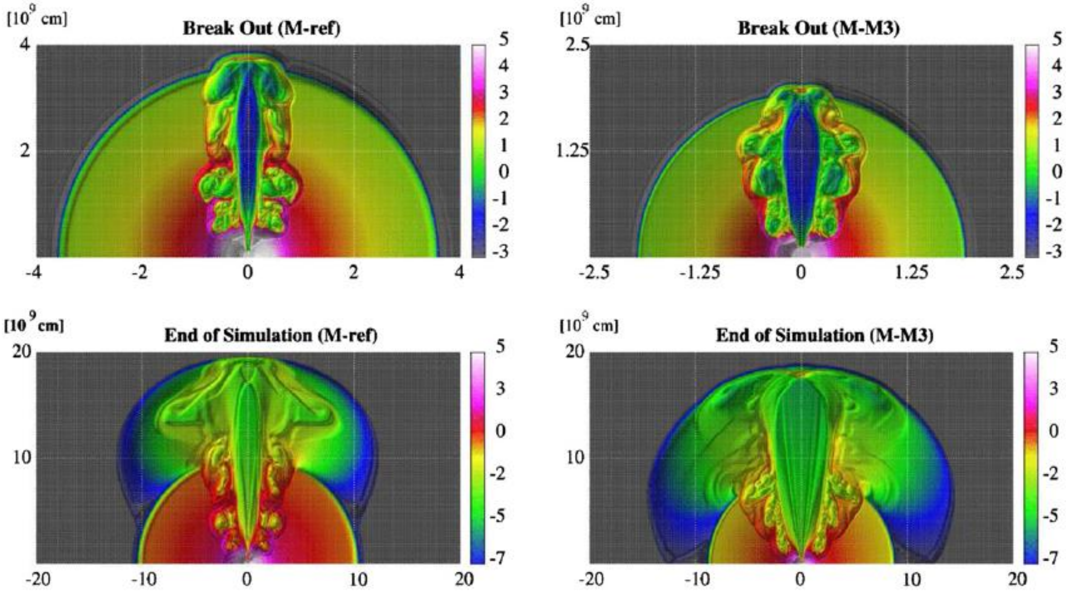


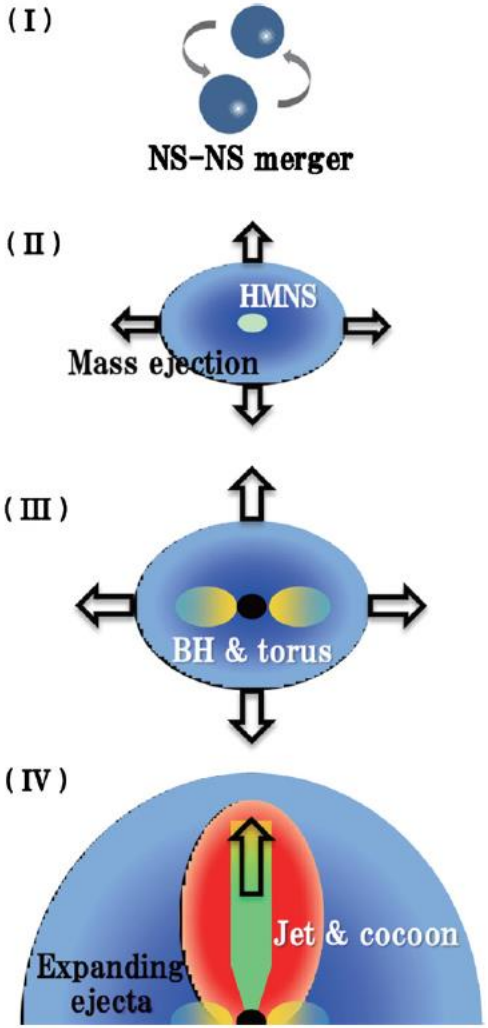
since 2014, cocoon models



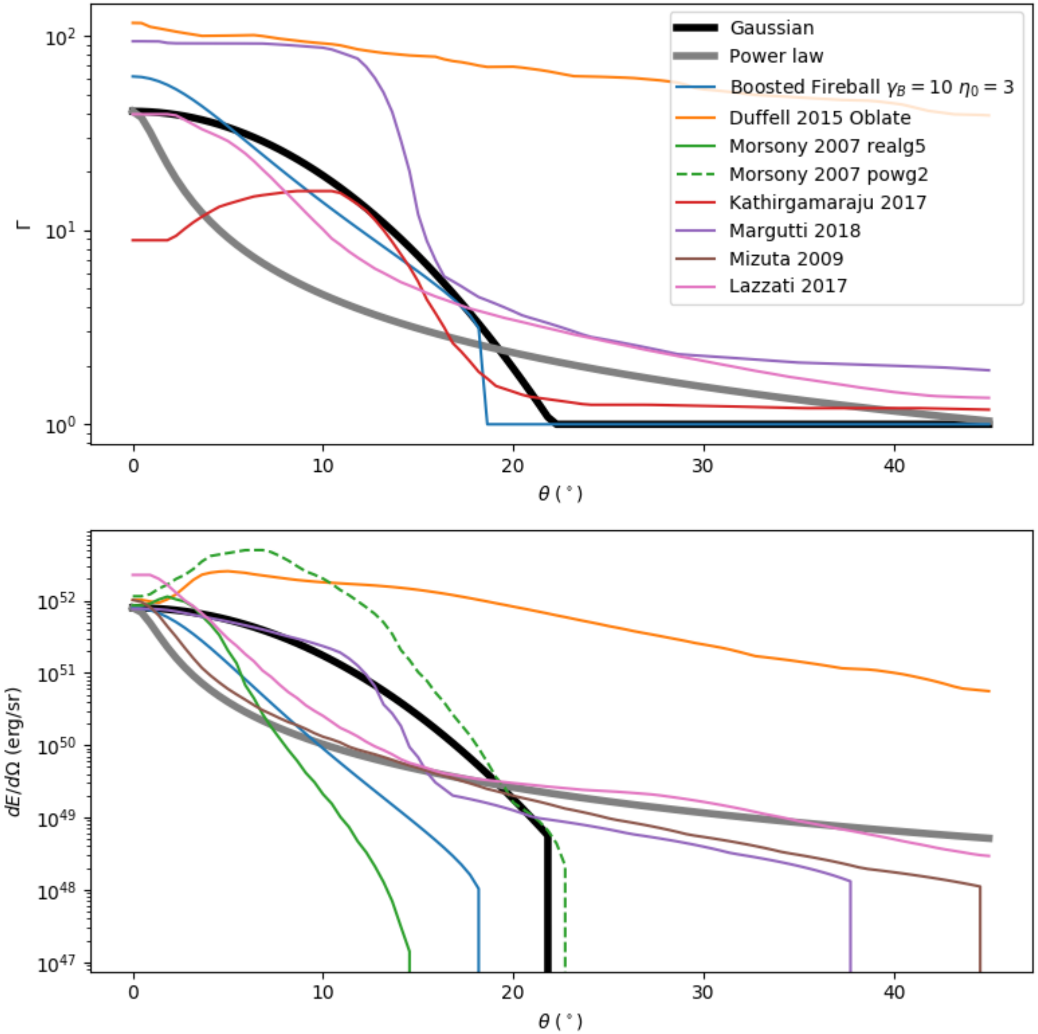


above: dense neutrino-driven wind, e.g. $\dot{M} = 10^{-3} M_{sun} s^{-1}$ (Murgua-Berthier+ 2014)
below and right: NS merger ejecta, $M \sim 10^{-2} M_{sun}$ (Nagakura+ 2014)





Structured jet as a natural configuration

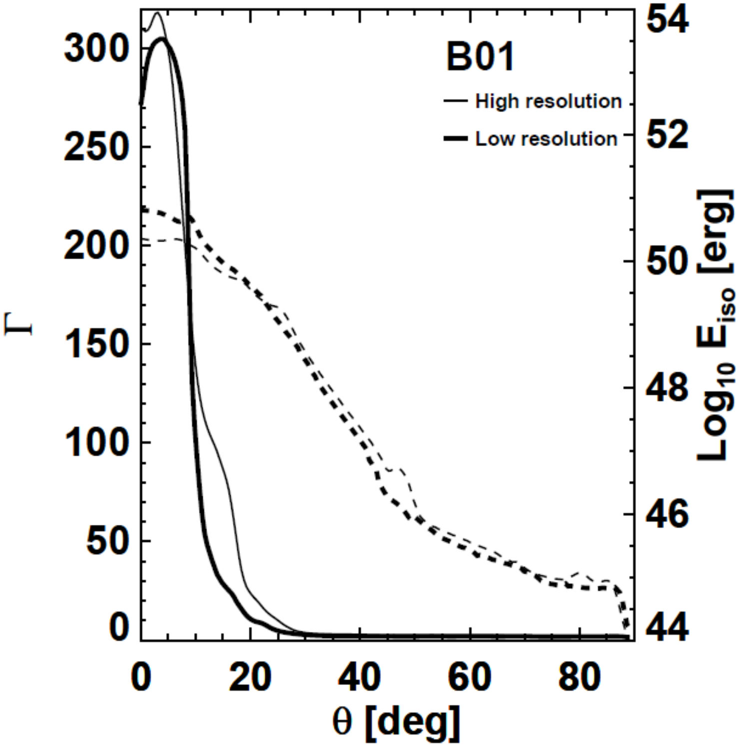


Gaussian jet structure: $E = \exp(-{}^{\theta^2}/_{2\theta_c^2})$

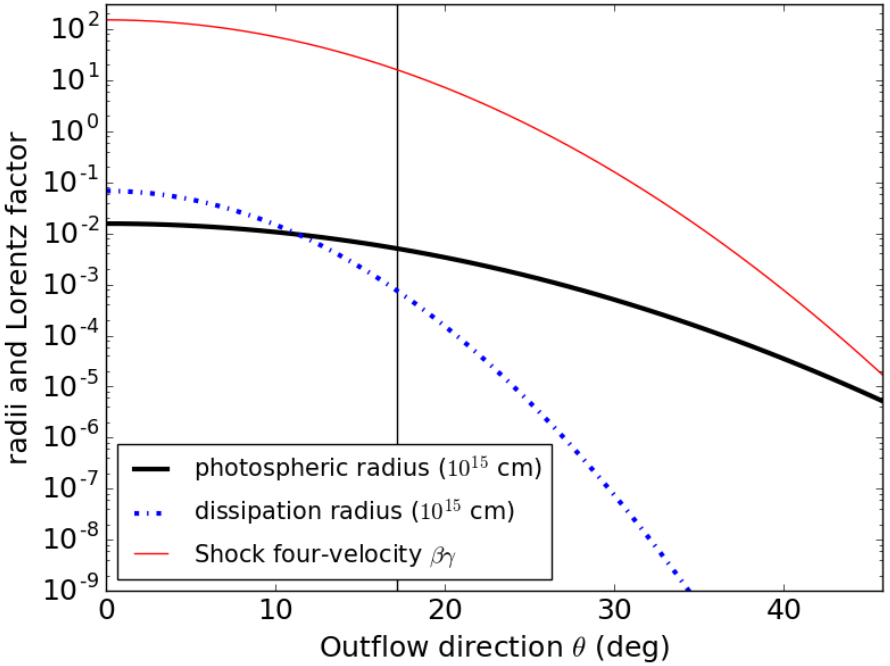
post-deceleration stage, Γ similar, via $E = \Gamma^2 M c^2$

Structured jets are a natural outcome of simulations accounting for breakout

or jet-torus interaction during launching, see e.g.
Aloy, Janka, Mueller 2005, image below



Structure and photospheric radius



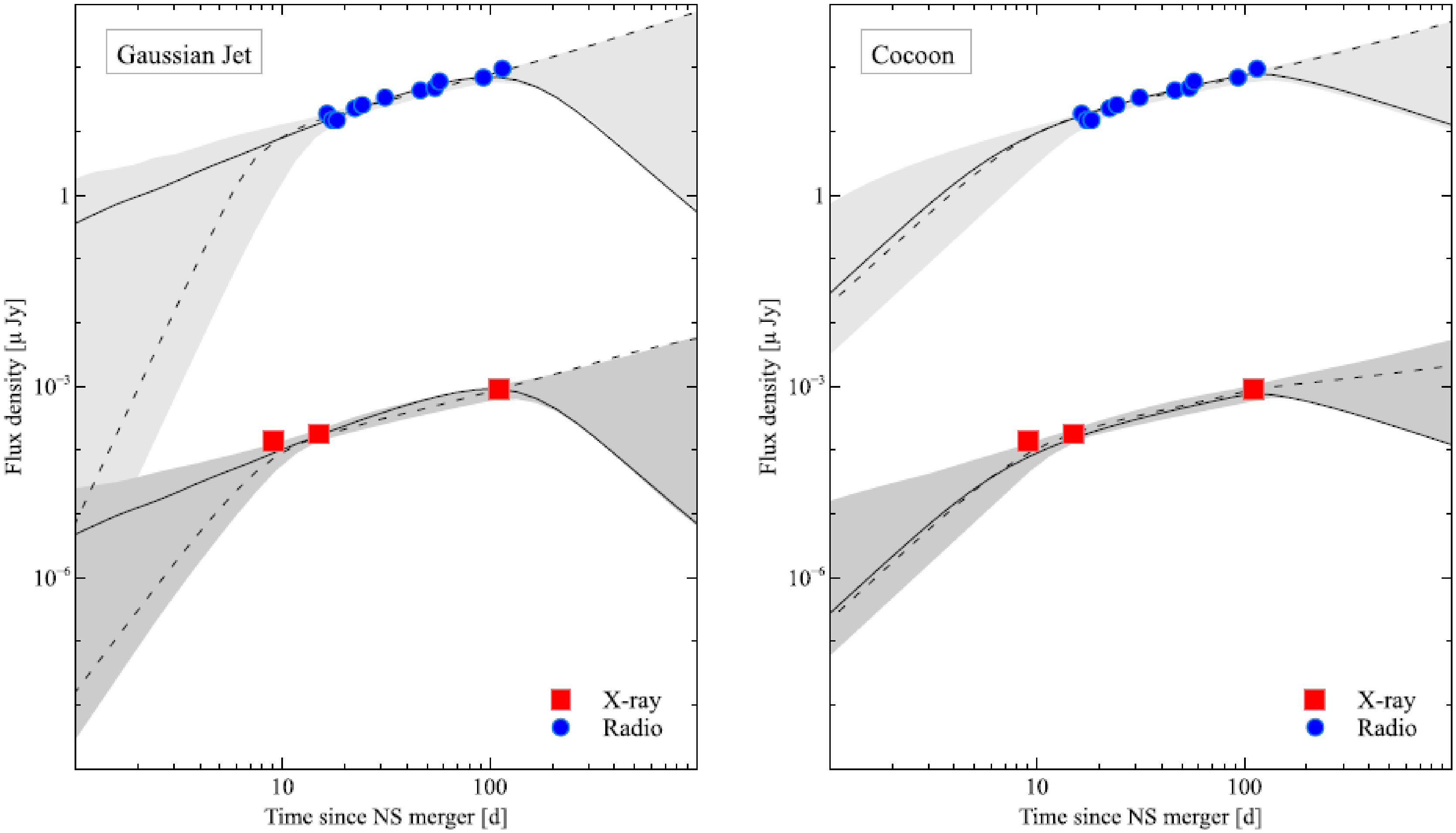
A fireball containing
Baryons would also have electrons providing opacity that tends to imply optically thin prompt emission only natural near the jet tip:

GRB 170817 would have been typical if seen on-axis, but was maybe genuinely 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

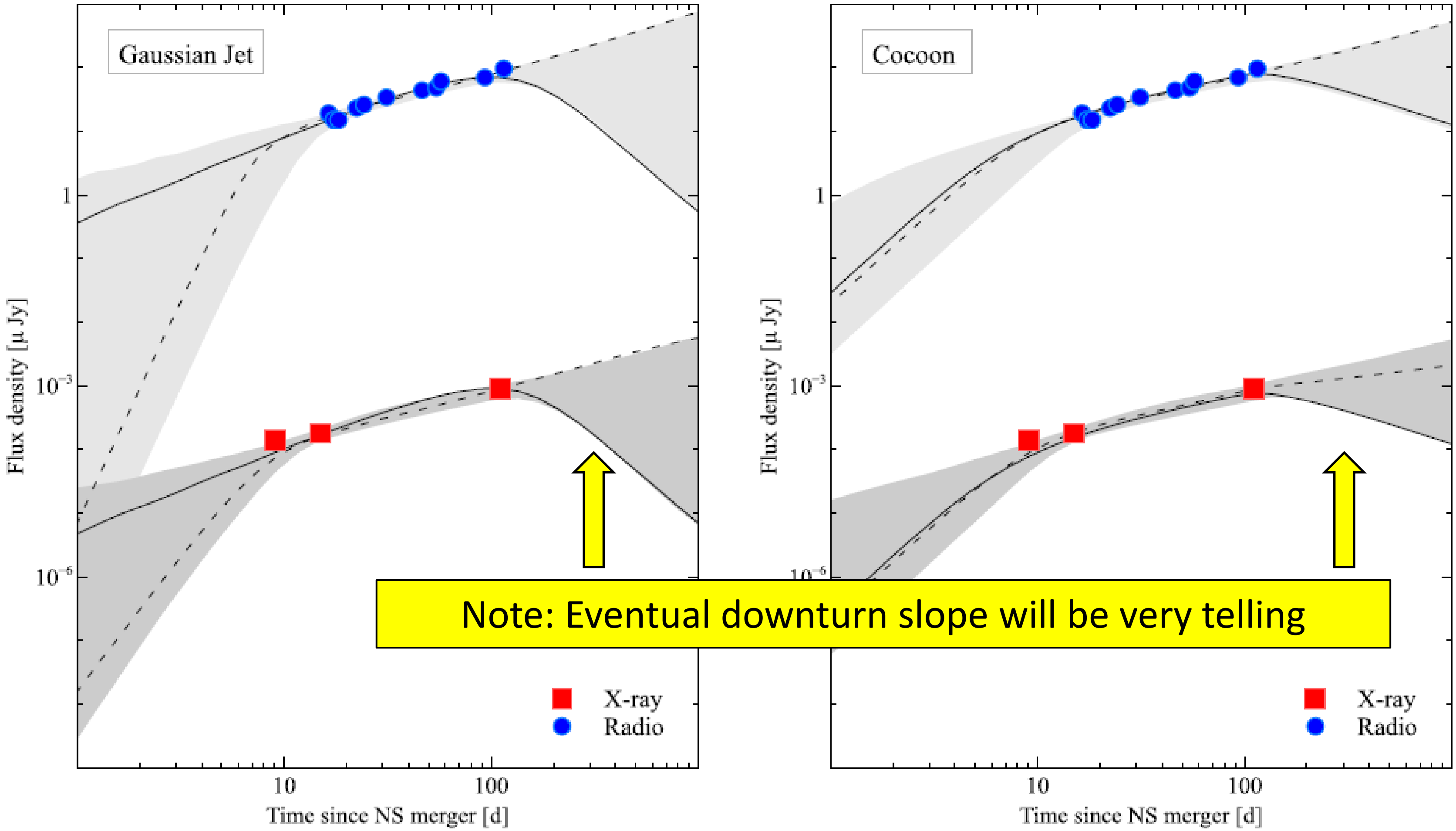
$R_\gamma \sim \sigma_\tau E_{iso}/4\pi R^2 m_p c^2 \Gamma$, from $\tau = \sigma_T n R \equiv 1$ and $\Gamma = {}^{E_{iso}}/_{Mc^2} = {}^{E_{iso}}/_{n m_p V}$
for the photospheric radius

Structured jets and cocoons



Troja, Piro, Ryan, van Eerten et al., 2018, MNRAS accepted, ArXiV 1801.06516

Structured jets and cocoons



Note: Eventual downturn slope will be very telling

Troja, Piro, Ryan, van Eerten et al., 2018, MNRAS accepted, ArXiV 1801.06516

(more recent broadband data –not included in Figure- indeed suggests turnover)

Summarizing models

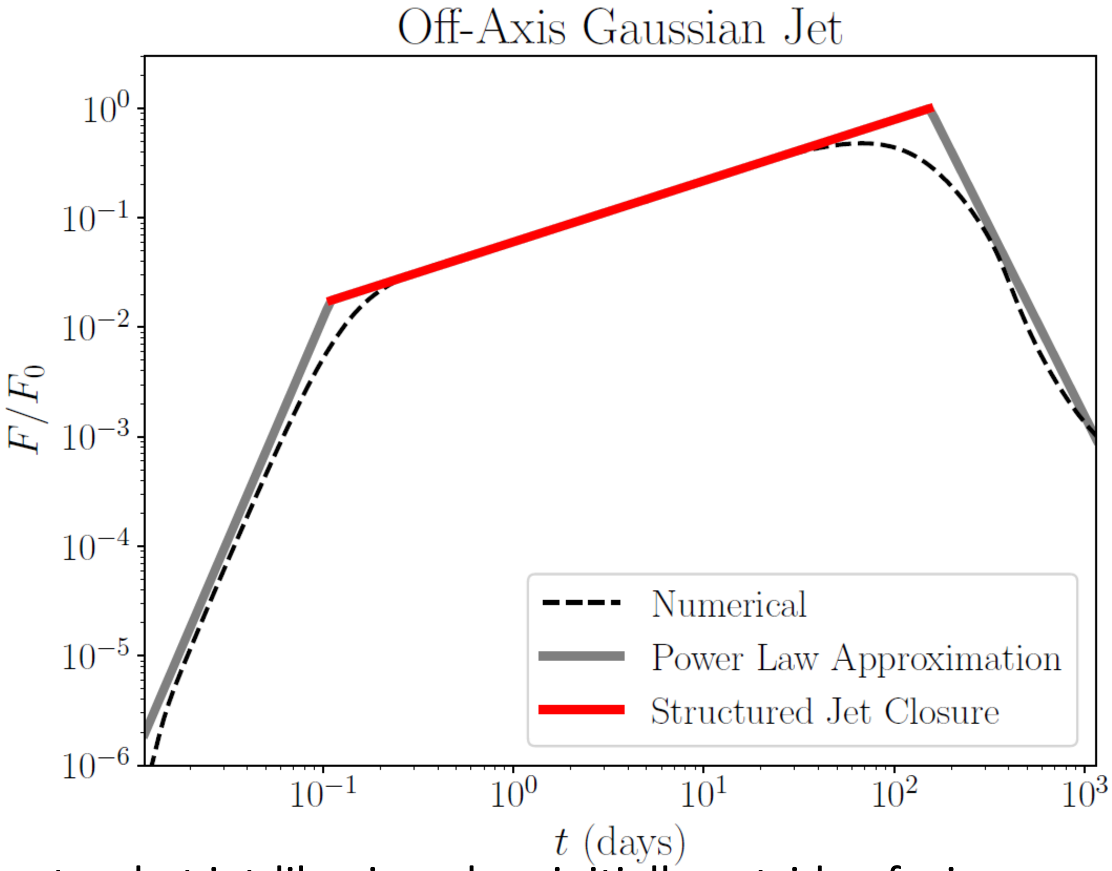
Model	Features	Verdict
Top hat jet, either semi-analytic or simulated	- Sharp rise, brief peak - prompt emission seen off-axis	**afterglow fine**, **prompt not ideal**
Universal structured jet	power-law drop in energy with angle	**too bright early on**
Gaussian jet	Exponential drop in energy with angle	**afterglow fine** **thermalized or scattered prompt?**
Basic cocoon model	Single isotropic shell, mildly relativistic	**wrong peak time**, **new type of prompt?**
Velocity stratification cocoon model	Late low velocity shells catching up, containing bulk of energy.	**afterglow fine** **new type of prompt?**

Why we care: *cocoon / failed GRB would be a new phenomenon;*
structured jet definitive proof GRB NS-merger connection AND
allows for true multi-messenger analysis through jet orientation

Current best fit cocoon models: range of velocities up to Lorentz factor 10, surrounding density 10^{-5} cm^{-3},
total energy 10^{51-54} erg

Current best fit structured jet models: jet core about 7 deg, orientation 12-24 deg, wings 35 deg
total energy around 10^{50} erg, density around 10^{-3} cm^{-3}

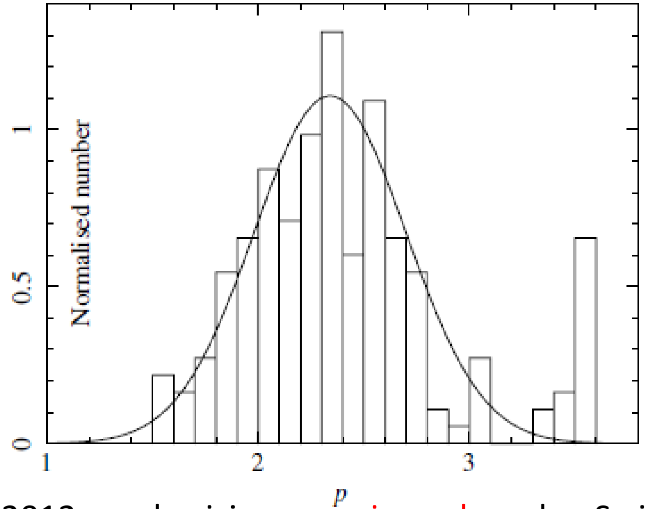
The light curve of a $E \propto \exp[-\theta^2/2\theta_c^2]$ "Gaussian" jet



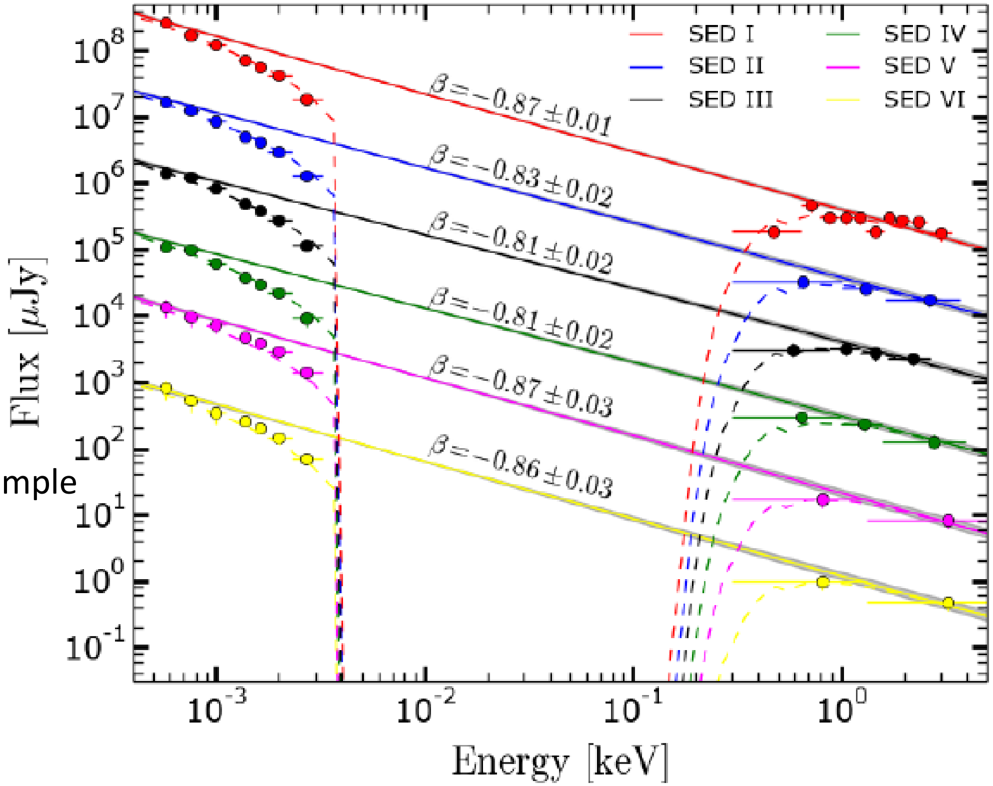
Ryan et al. (in prep)

- A sharp top-hat jet-like rise when initially outside of wings
- a shallow rise
  containing information about jet structure (!), depends on rate at which annuli with different Lorentz factors come into view
- a post "jet-break" decay, segueing into trans-relativistic dynamics

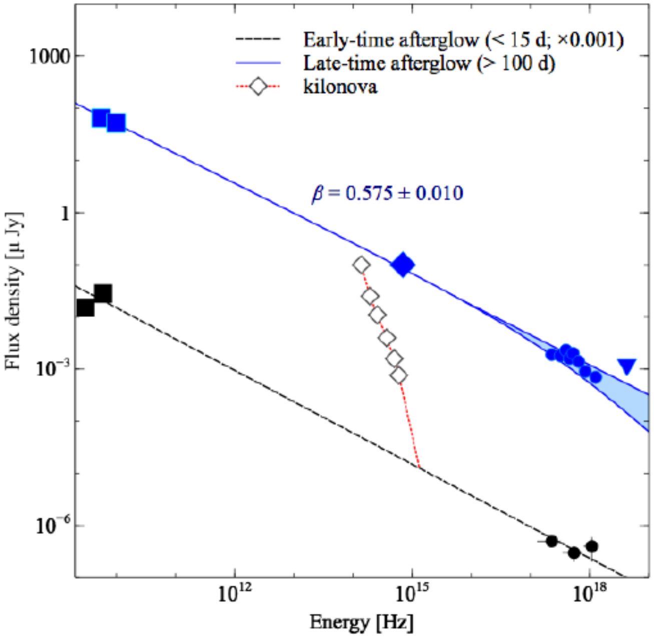
particle acceleration at the shock front



Curran 2012 emphasizing no universal *p* value Swift sample



Varela et al. 2016, demonstrating $p = 1.73 \pm 0.03$ throughout long-term (up to 107 ks) evolution of (long) GRB 120424A

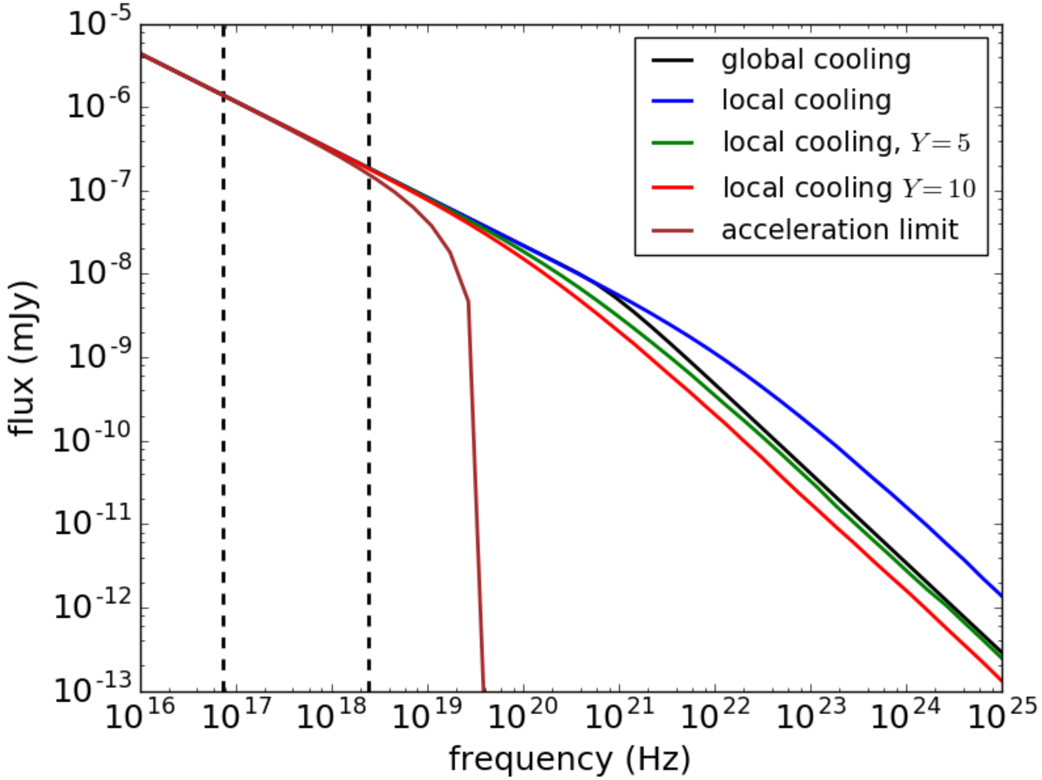


p = 2.17 demonstrated for GRB170717A
Troja et al. 2018

Margutti et al. 2018: *"We find p = 2.17 ± 0.01, which indicates that radiation from ejecta with Γ ~ 3–10 dominates the observed emission."*

now that last bit is a VERY strong claim...

Electron cooling, Inverse Compton cooling, etc.



global cooling: assume steady state solution particle injection and cooling losses,
equate cooling time to time since launch explosion (single plasma)

local cooling: each fluid parcel gets populated with shock-accelerated electrons
upon crossing the shock front. Cooling time is time since crossing

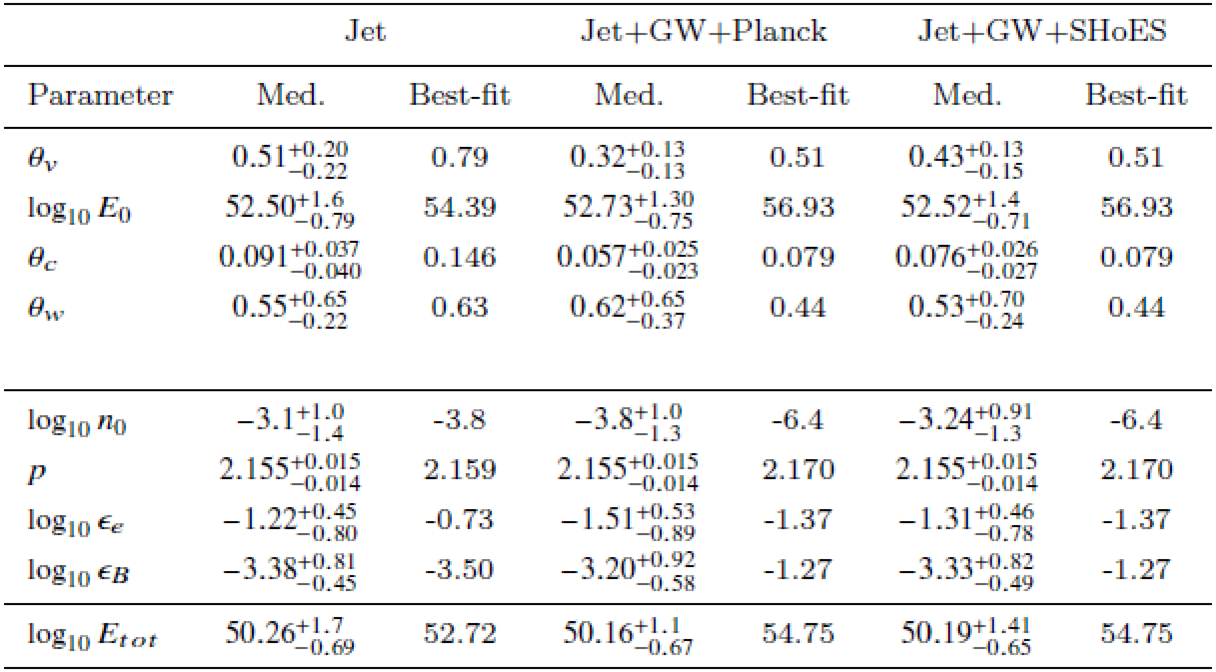
as usual, both lead to same power law time evolution emission, but different normalizations

Summary

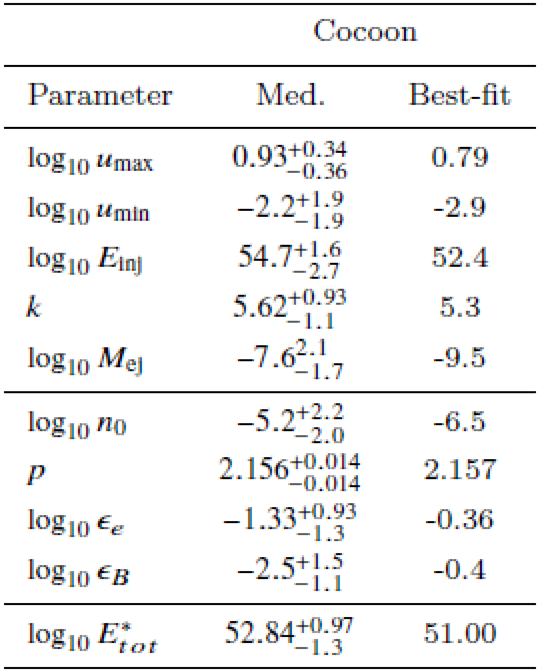
- long-lasting afterglow emission from off-axis event GW170817 / GRB170817A
- basic cocoon models would peak too soon, basic jet models would have had shorter peak duration
- if directed jet, then plausibly cementing short GRB – neutron star merger connection
- if ‘failed’ GRB, or pure cocoon, then new phenomenon
- afterglow best modeled using structure in flow (lateral or radial)
- either type of structure is reasonably expected.
- an ultimately steeply decaying afterglow signal, would be tell-tale signature of directed flow (when fast moving tip comes into view, and a lack beyond that point becomes apparent; contrast gradual decline spherical signal once energy injection into sphere ceases)
- model either using multi-dimensional simulations, or shell models based on energy conservation in the shell
- clear non-thermal synchrotron-like afterglow spectrum, $p = 2.17$
- a wide range of accelerated electron power-law slopes has been seen in GRBs

END

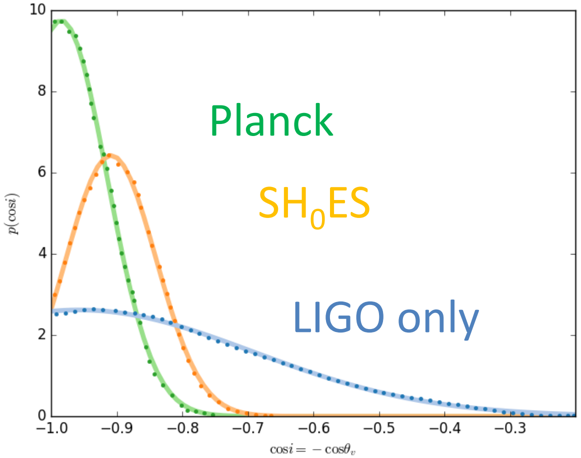
The era of multi-messenger astronomy!



	Jet		Jet+GW+Planck		Jet+GW+SHoES	
Parameter	Med.	Best-fit	Med.	Best-fit	Med.	Best-fit
θ_v	$0.51^{+0.20}_{-0.22}$	0.79	$0.32^{+0.13}_{-0.13}$	0.51	$0.43^{+0.13}_{-0.15}$	0.51
$\log_{10} E_0$	$52.50^{+1.6}_{-0.79}$	54.39	$52.73^{+1.30}_{-0.75}$	56.93	$52.52^{+1.4}_{-0.71}$	56.93
θ_c	$0.091^{+0.037}_{-0.040}$	0.146	$0.057^{+0.025}_{-0.023}$	0.079	$0.076^{+0.026}_{-0.027}$	0.079
θ_w	$0.55^{+0.65}_{-0.22}$	0.63	$0.62^{+0.65}_{-0.37}$	0.44	$0.53^{+0.70}_{-0.24}$	0.44
$\log_{10} n_0$	$-3.1^{+1.0}_{-1.4}$	-3.8	$-3.8^{+1.0}_{-1.3}$	-6.4	$-3.24^{+0.91}_{-1.3}$	-6.4
p	$2.155^{+0.015}_{-0.014}$	2.159	$2.155^{+0.015}_{-0.014}$	2.170	$2.155^{+0.015}_{-0.014}$	2.170
$\log_{10} \epsilon_e$	$-1.22^{+0.45}_{-0.80}$	-0.73	$-1.51^{+0.53}_{-0.89}$	-1.37	$-1.31^{+0.46}_{-0.78}$	-1.37
$\log_{10} \epsilon_B$	$-3.38^{+0.81}_{-0.45}$	-3.50	$-3.20^{+0.92}_{-0.58}$	-1.27	$-3.33^{+0.82}_{-0.49}$	-1.27
$\log_{10} E_{tot}$	$50.26^{+1.7}_{-0.69}$	52.72	$50.16^{+1.1}_{-0.67}$	54.75	$50.19^{+1.41}_{-0.65}$	54.75



	Cocoon	
Parameter	Med.	Best-fit
$\log_{10} u_{\rm max}$	$0.93^{+0.34}_{-0.36}$	0.79
$\log_{10} u_{\rm min}$	$-2.2^{+1.9}_{-1.9}$	-2.9
$\log_{10} E_{\rm inj}$	$54.7^{+1.6}_{-2.7}$	52.4
k	$5.62^{+0.93}_{-1.1}$	5.3
$\log_{10} M_{\rm ej}$	$-7.6^{2.1}_{-1.7}$	-9.5
$\log_{10} n_0$	$-5.2^{+2.2}_{-2.0}$	-6.5
p	$2.156^{+0.014}_{-0.014}$	2.157
$\log_{10} \epsilon_e$	$-1.33^{+0.93}_{-1.3}$	-0.36
$\log_{10} \epsilon_B$	$-2.5^{+1.5}_{-1.1}$	-0.4
$\log_{10} E^*_{tot}$	$52.84^{+0.97}_{-1.3}$	51.00



Troja, Piro, Ryan, van Eerten et al., 2018, MNRAS subm., ArXiV 1801.06516

- *Different assumptions about cosmology give different likelihoods for orientation of system based on GW data*
- *Orientation for GW data informs afterglow prior!*