Title: Gamma-ray bursts and their afterglows as multi-messenger counterparts

Speakers: Hendrik van Eerten

Series: Strong Gravity

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Abstract: Merging neutron stars have long been speculated to produce Gamma-Ray Bursts (GRBs). While this has been the standard assumption for short GRBs for decades, this was only officially confirmed with the still relatively recent detection of gravitational wave counterpart GRB 170817A. In this presentation, I will discuss how we model short GRBs and their afterglows produced by the relativistic jets launched during the merger. A recent development of interest includes the apparent confirmation of some 'long' GRBs to also follow from mergers rather than collapsing massive stars, which has implication for the prospects of future multi-messenger detections. Joint modelling of GRB / afterglow data and GW signals makes it possible to further constrain the shared model parameters between the two, most notably the orientation of the system.

Zoom link: https://pitp.zoom.us/j/95551884959?pwd=bUVGVzhXK3pLb3MxMGV4ejZzUmRYdz09

Gamma-ray bursts and their afterglows as multi-messenger counterparts

Hendrik van Eerten

University of Bath, United Kingdom

Thursday, September 7, 2023

strong gravity group seminar

Perimeter Institute for theoretical physics

Waterloo, Canada

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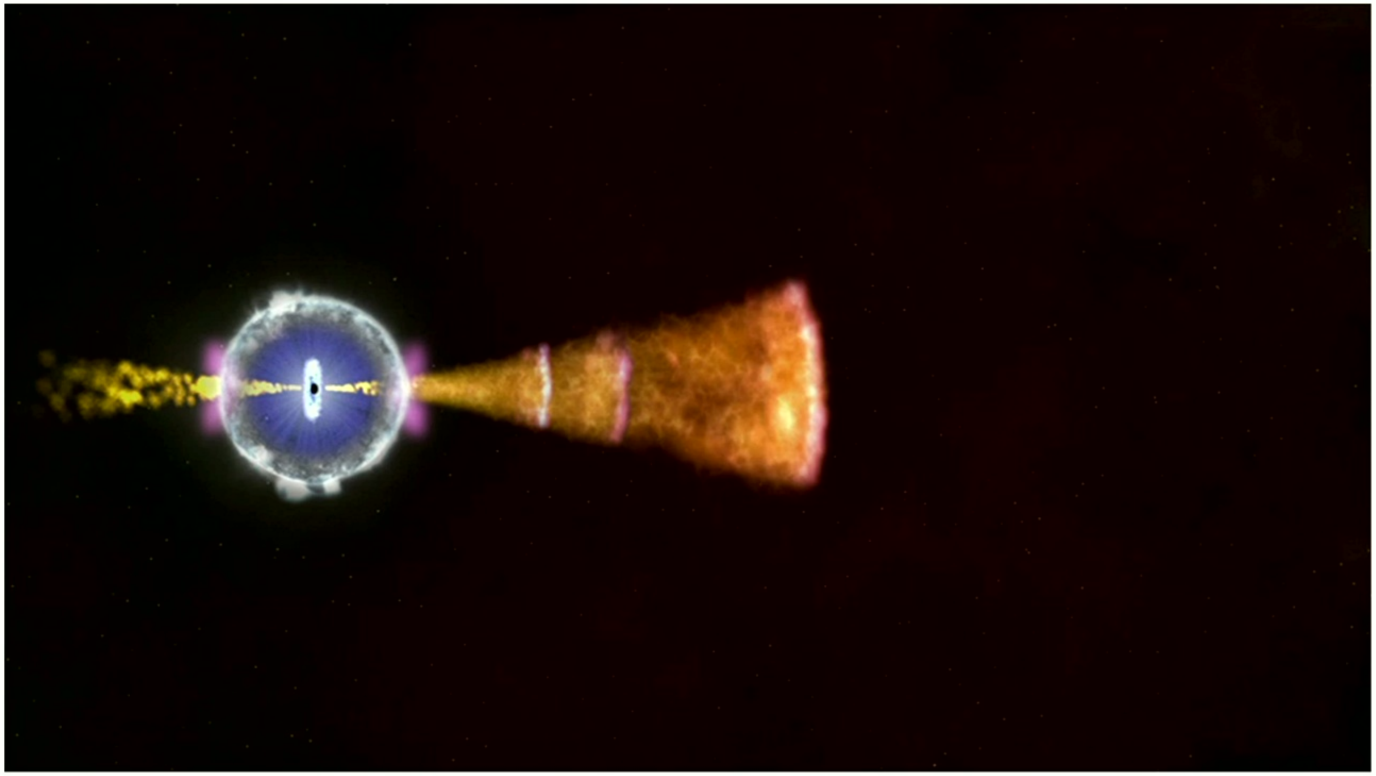
Gamma-ray bursts and their afterglows as multi-messenger counterparts

Hendrik van Eerten
University of Bath, United Kingdom

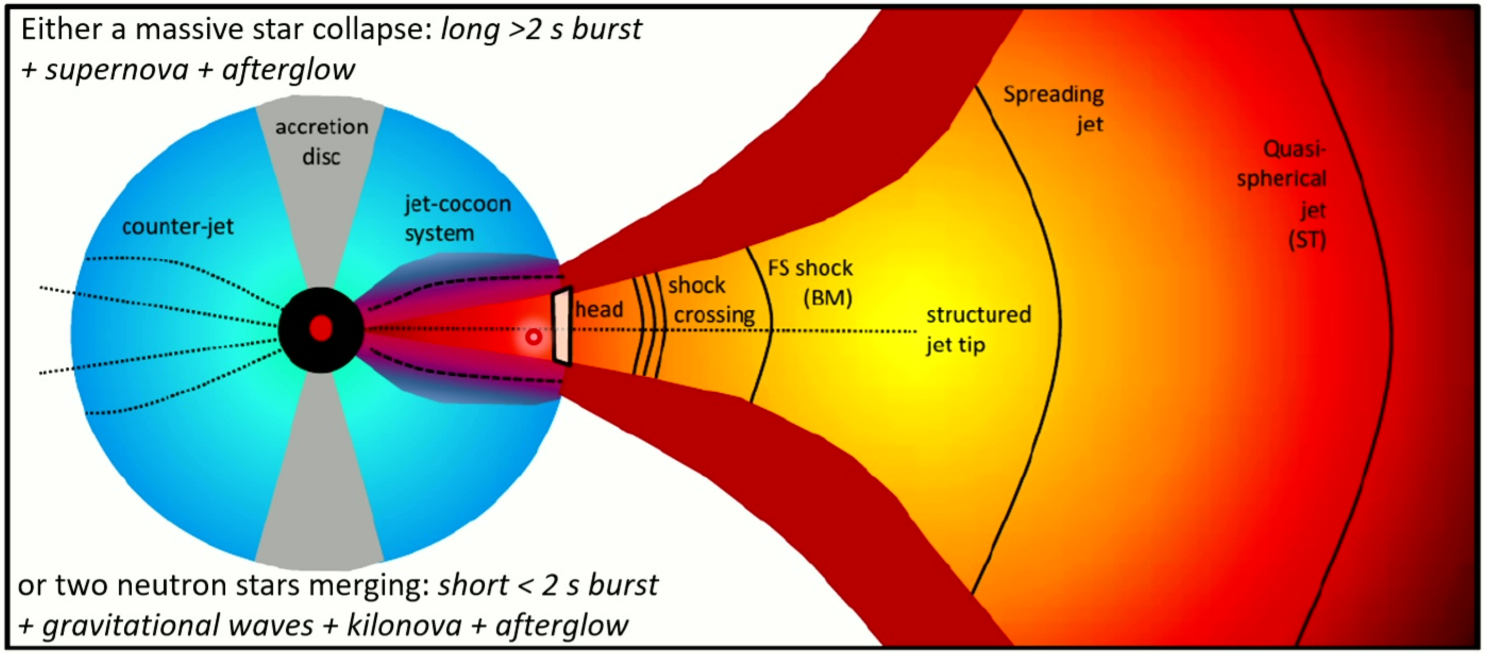
"Catherine was all eager delight; – her eyes were here, there, everywhere, as they approached its fine and striking environs" […] "Who can be tired of Bath?"
(Northanger Abbey, J. Austen)

Gamma-ray bursts from merging neutron stars ("short") and massive stellar collapse ("long")

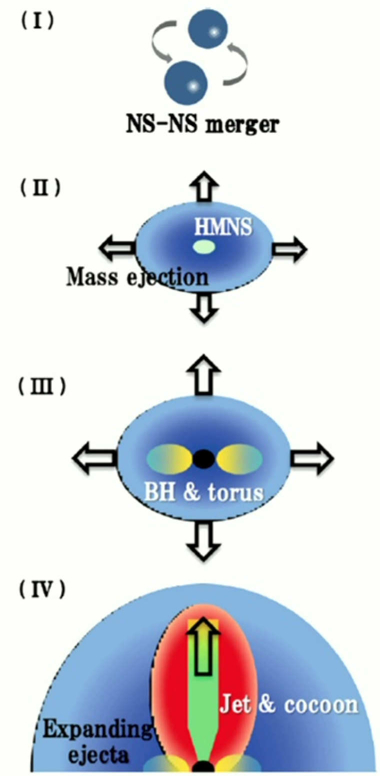


artist impression, apologies for any GRB(-adjacent) scientists in audience to whom video overfamiliar

Gamma-ray bursts and their afterglows (schematic)



IMG: Van Eerten



Nagakura+ 2014

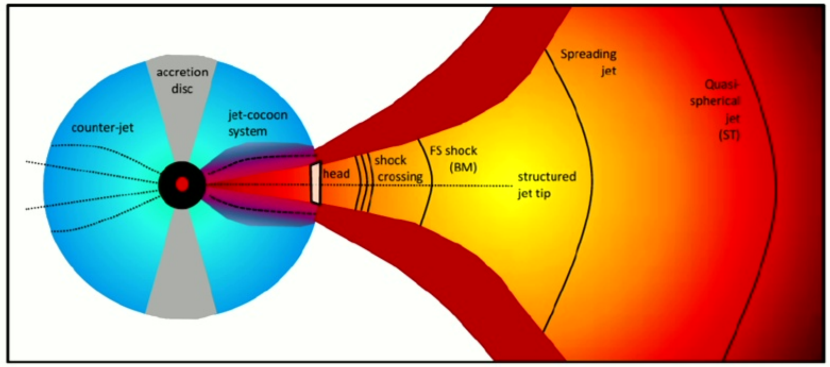
GRBs and gravity

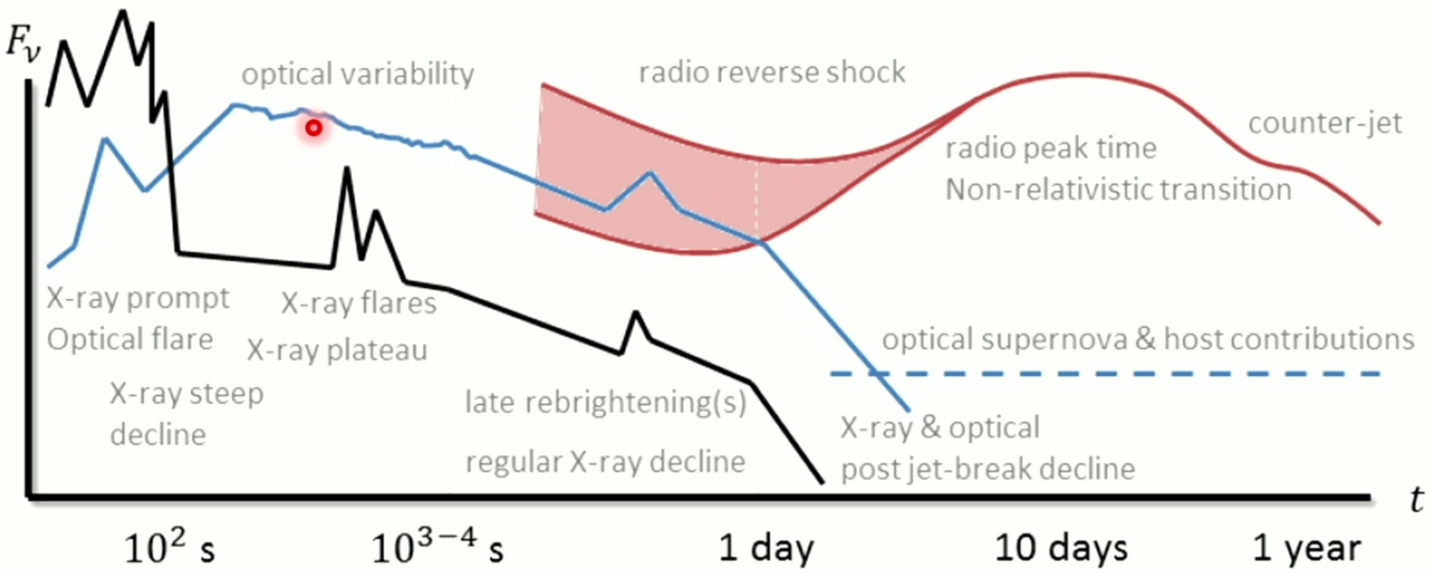
- launching GRB jets is a complicated problem involving general relativistic hydrodynamics, both for short & long GRBs
- afterglow-stage GRB jets don't need GR but still involve special relativity and outflows with $\Gamma \gg 1$.
- short GRBs are now confirmed as electro-magnetic counterparts to gravitational waves (GW) detected from neutron-star mergers

Some points of particular interest:

- GRB afterglow models share system orientation as a parameter with models for fitting GW signals from mergers
- both afterglow light curve and centroid motion on sky can constrain orientation
- community is recognizing how recent developments are challenging short / long GRB classification … neutron star mergers appear able to produce long GRBs

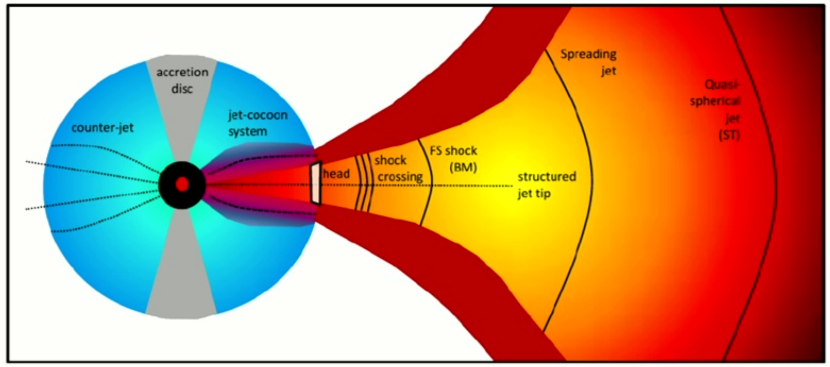
Gamma-ray bursts and their afterglows

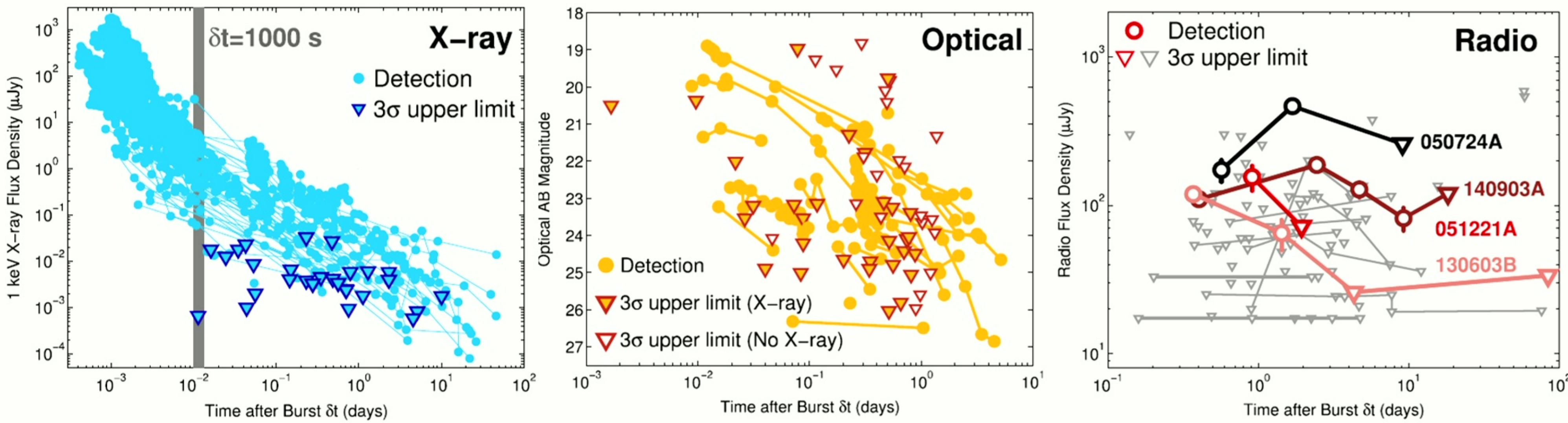




Schematic light curves for a long (massive star collapse) GRB, seen on-axis

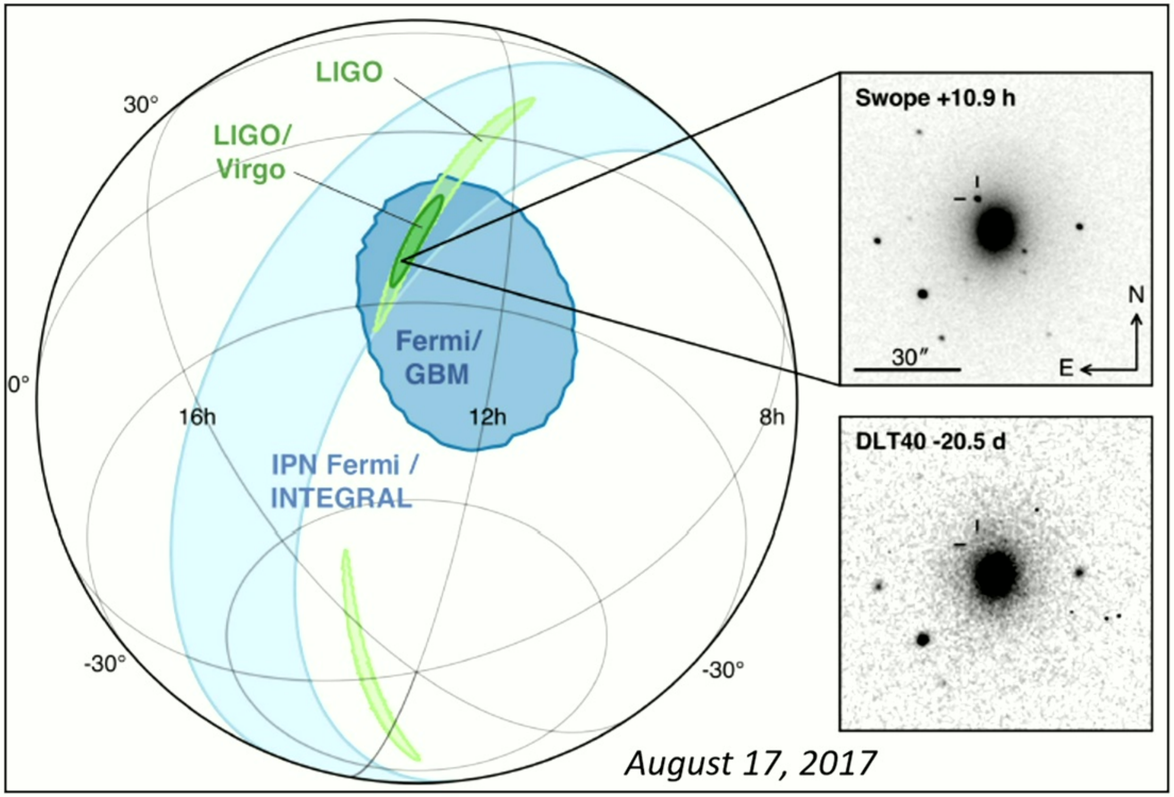
Gamma-ray bursts and their afterglows





Actual light curves for short (neutron star merger) GRBs seen on-axis. Images from Fong+ 2015, ApJ 815, 102

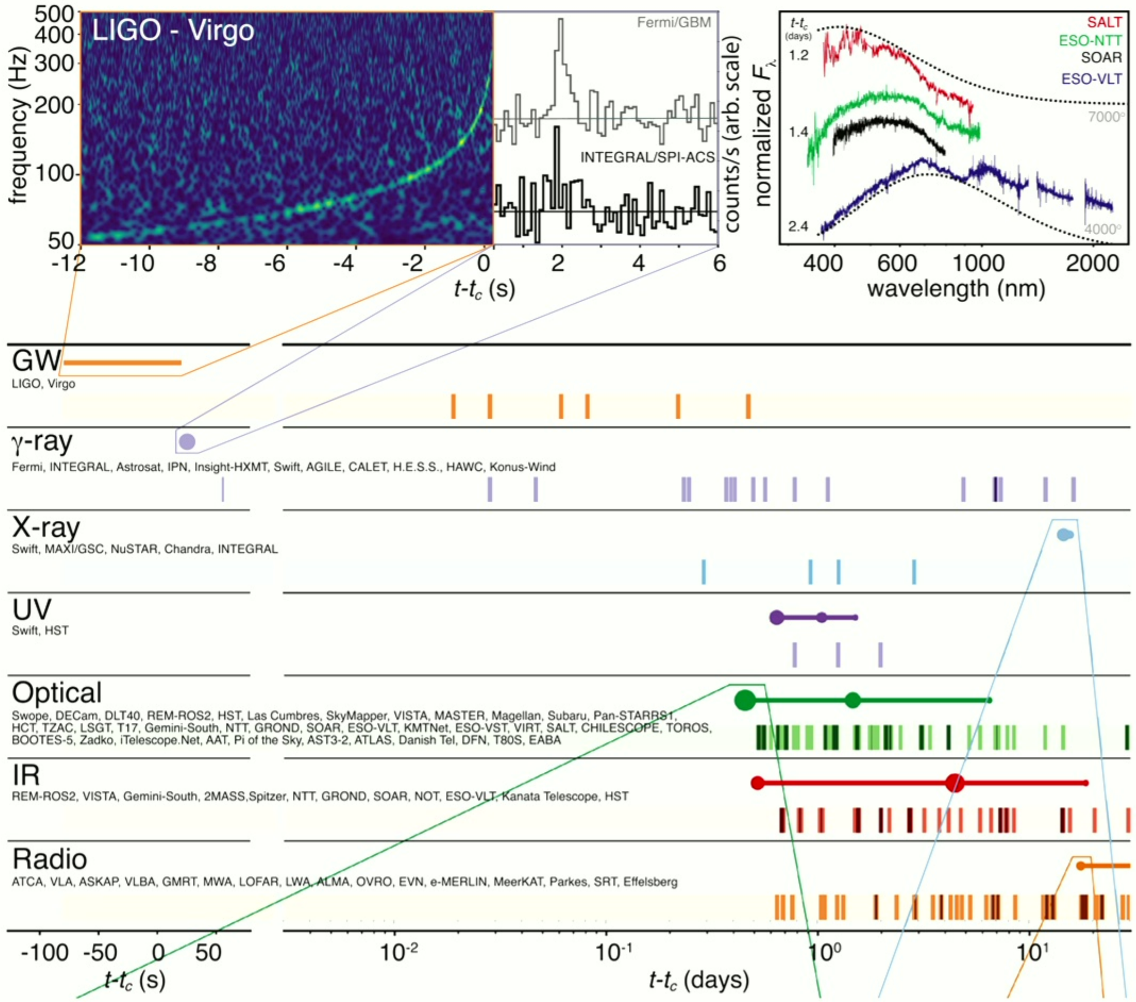
GW170817 / GRB 170817A



August 17, 2017

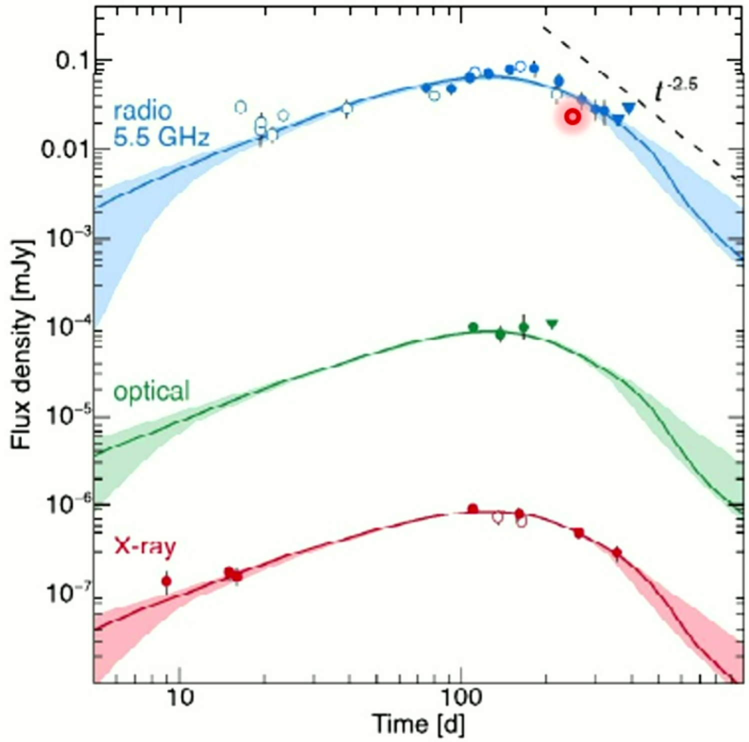
Abbott+ ApJL 848, L12 (2017)

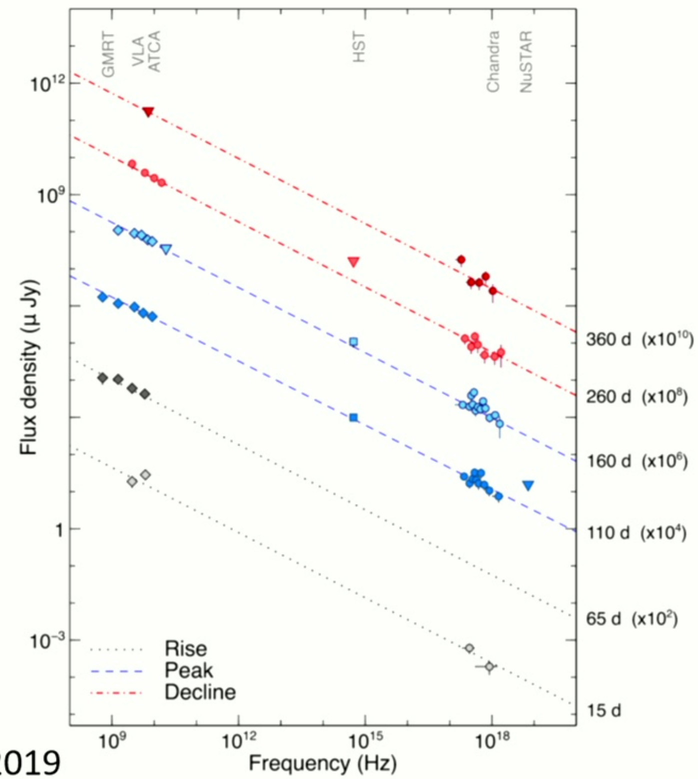
A massive broadband follow-up campaign to GW170817, first two weeks:



Abbott+ ApJL 848, L12 (2017)

Where we stand in long-term follow-up

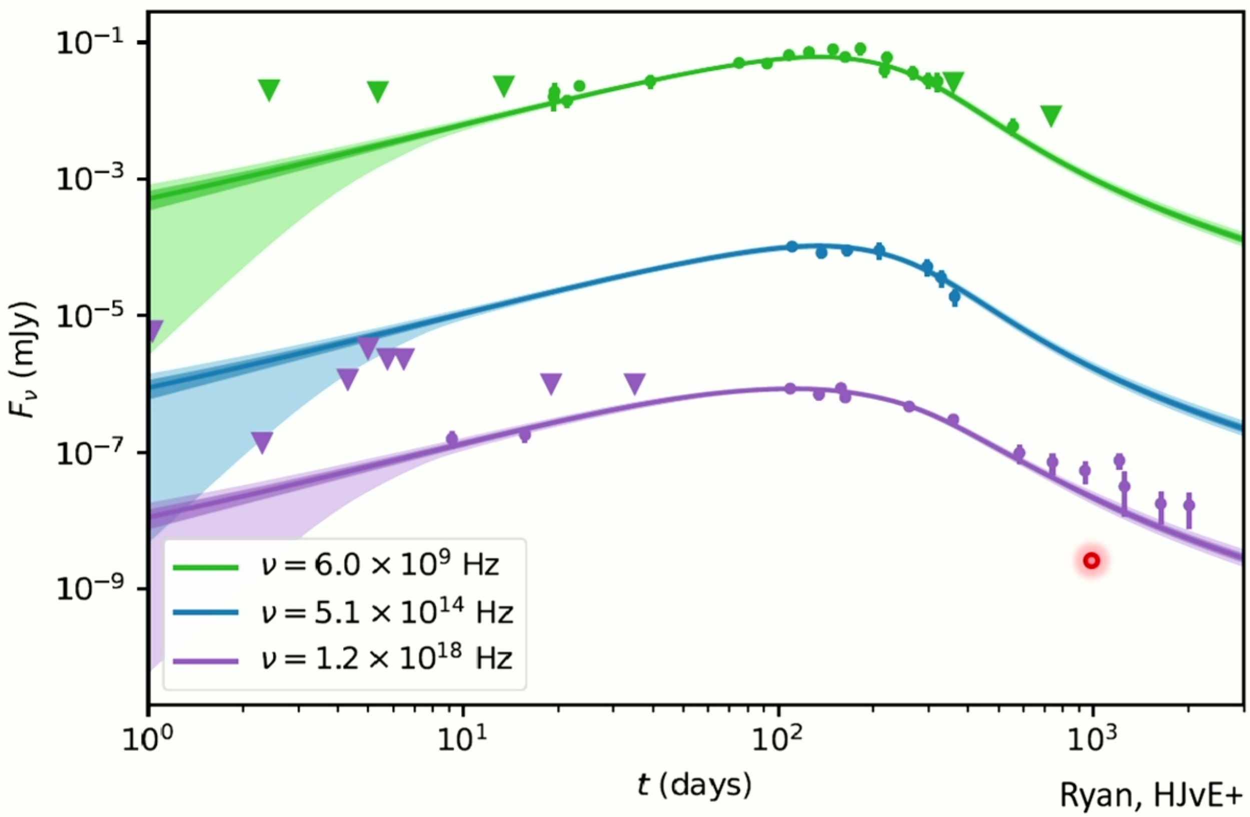




Troja, van Eerten+ 2019

see also Haggard+ 2017, Hallinan+2017, Kasliwal+ 2017, Mooley+2018, D'Avanzo+ 2018, Lyman+ 2018, Dobie+ 2018, Ruan+ 2018, Margutti+ 2018, Troja+ 2017, 2018, Lamb+ 2019, ...

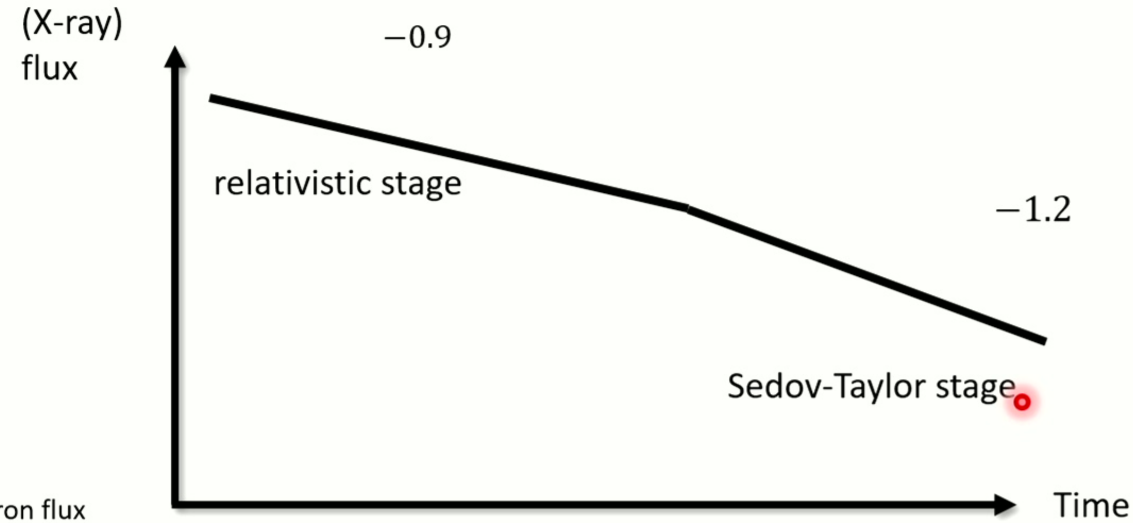
GRB 170817A Follow-up, latest

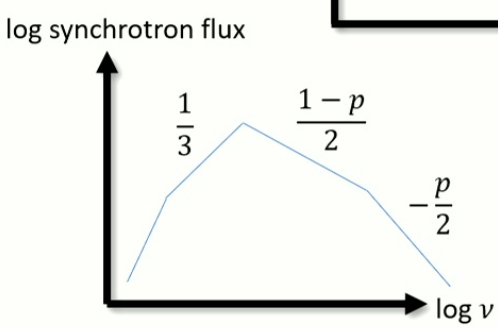


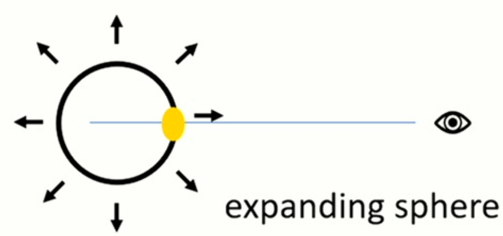
Ryan, HJvE+ in prep

see also Hajela+ 2021, Balasubramanian+ 2021, ...

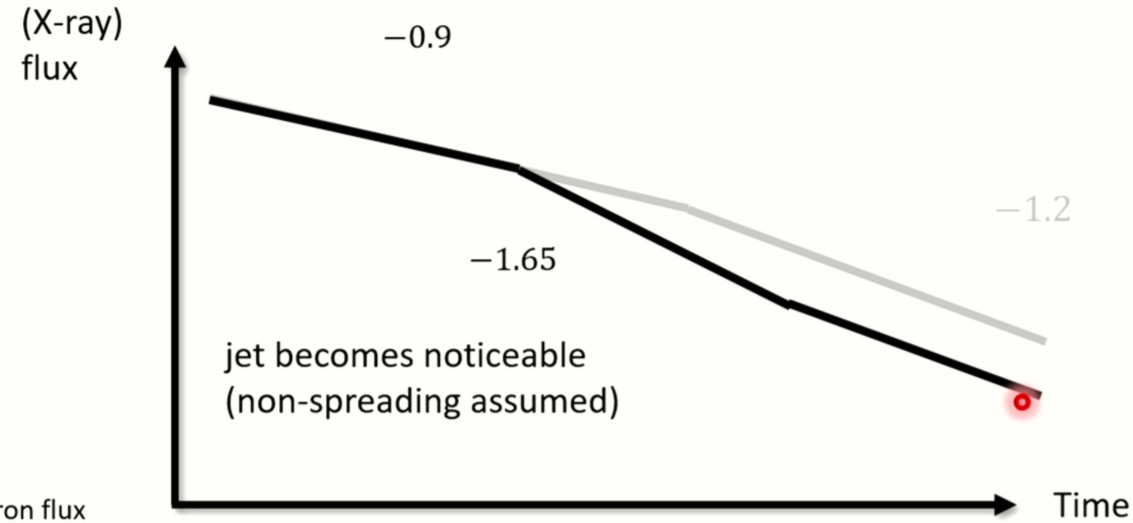
Observing & modeling gamma-ray burst afterglows

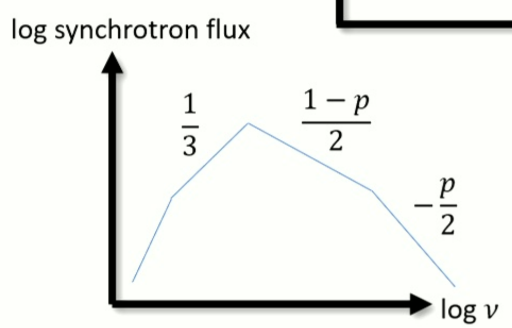


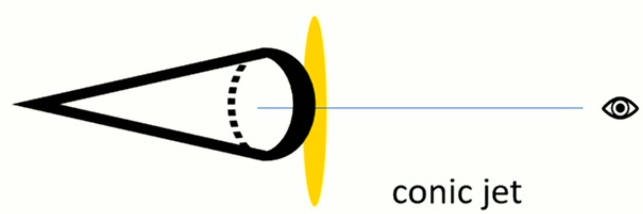




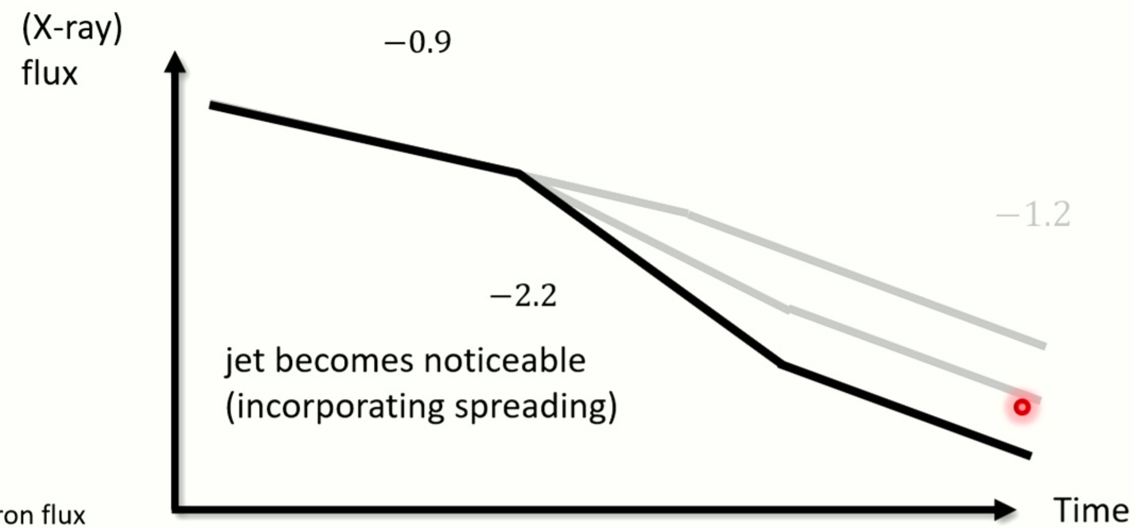
Observing & modeling gamma-ray burst afterglows

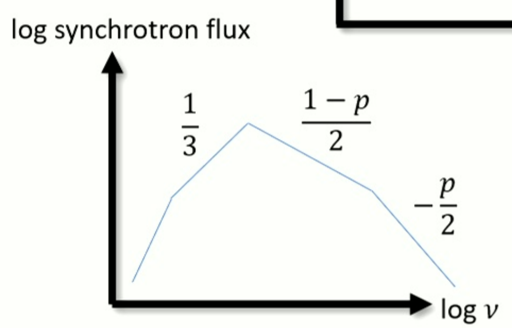


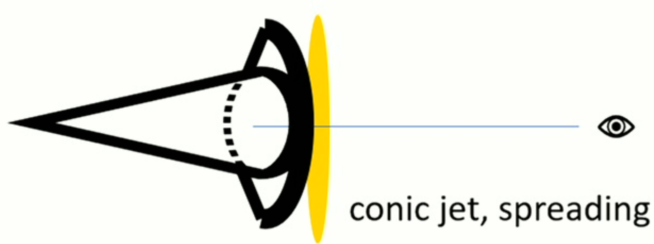




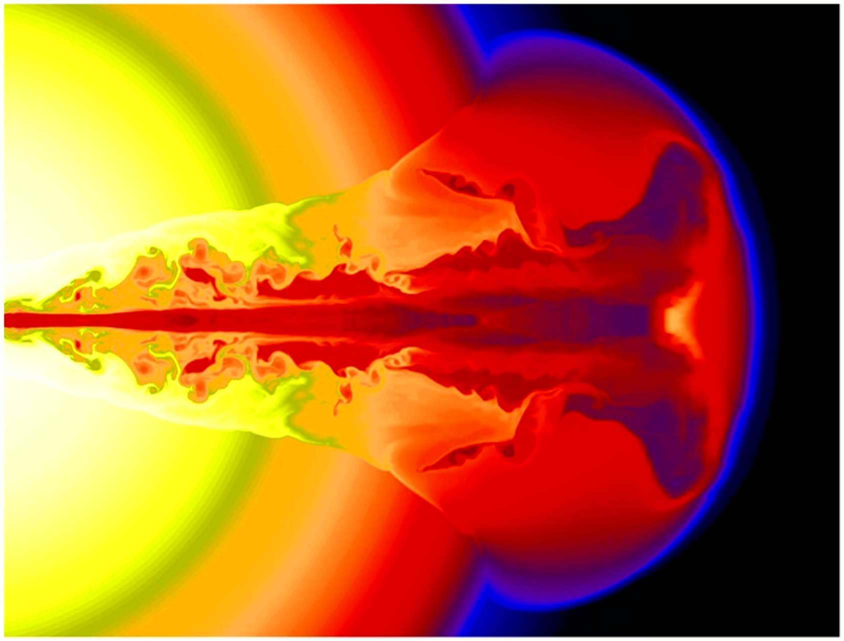
Observing & modeling gamma-ray burst afterglows



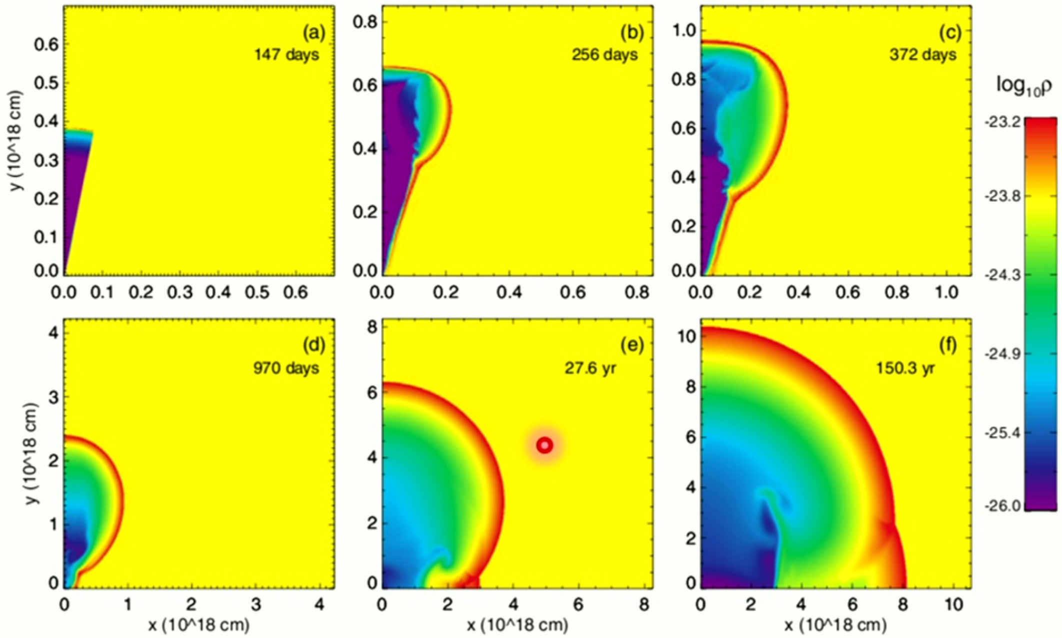




Gamma-ray bursts according to simulations



Zhang & MacFadyen 2006



Zhang & MacFadyen 2009
van Eerten, Zhang & MacFadyen (2010)

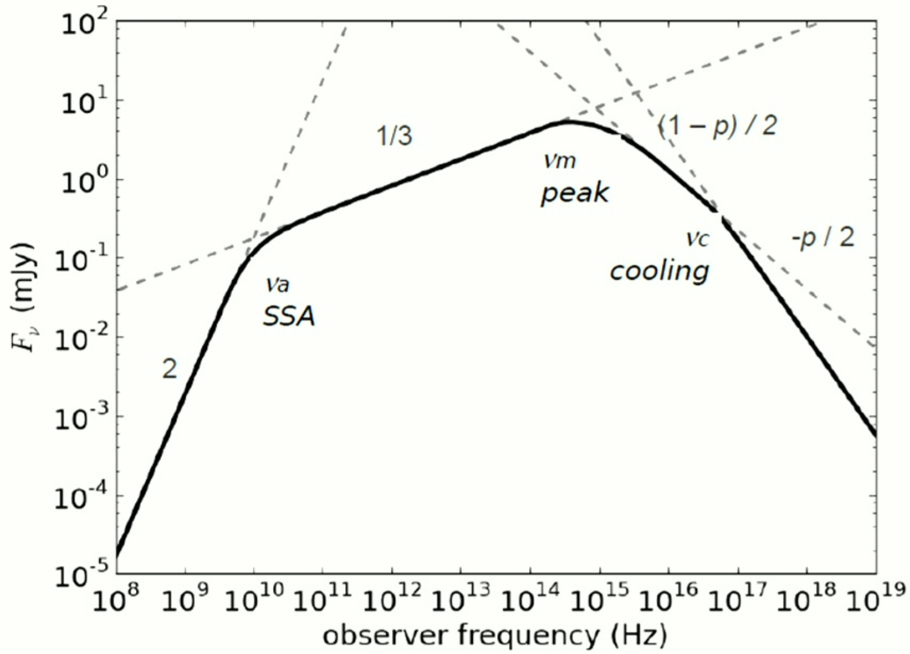
At first: A jet pushing through with $T_{engine} \gtrsim T_{breakout}$
long: $T_{breakout} \sim 15$ s (e.g. Bromberg+ 2011)
short: $T_{breakout} \sim 0.2$ s (e.g. Hamidani & Ioka 2021)

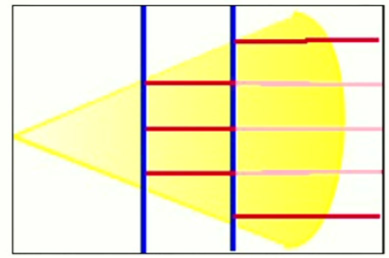
afterwards: A shell and then blast wave where
$\triangle R_{shock} \ll R$

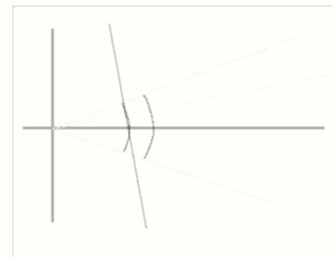
Synchrotron spectrum & radiative transfer

A power law distribution of non-thermal particles, slope -*p*

parametrization: $\epsilon_e, \quad \epsilon_B, \quad \xi_N, \quad p$



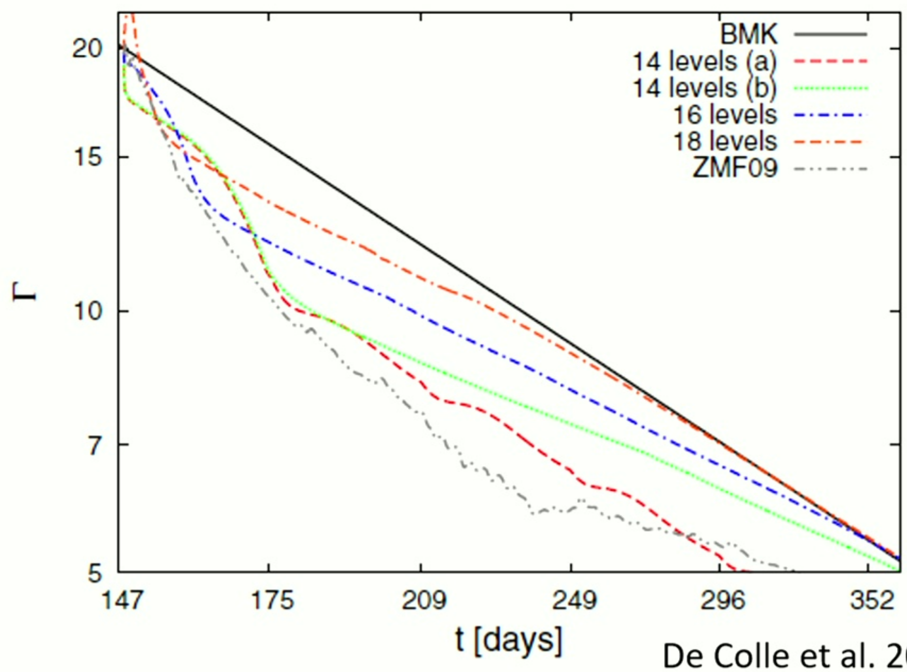




$$\frac{dI_\nu}{dz} = j_\nu - \alpha_\nu I_\nu$$

$$F_{peak} \propto \frac{\sigma_T m_e c^2}{q_e} \gamma^2 \xi_N n B$$

A technical point: Initial shell extremely thin

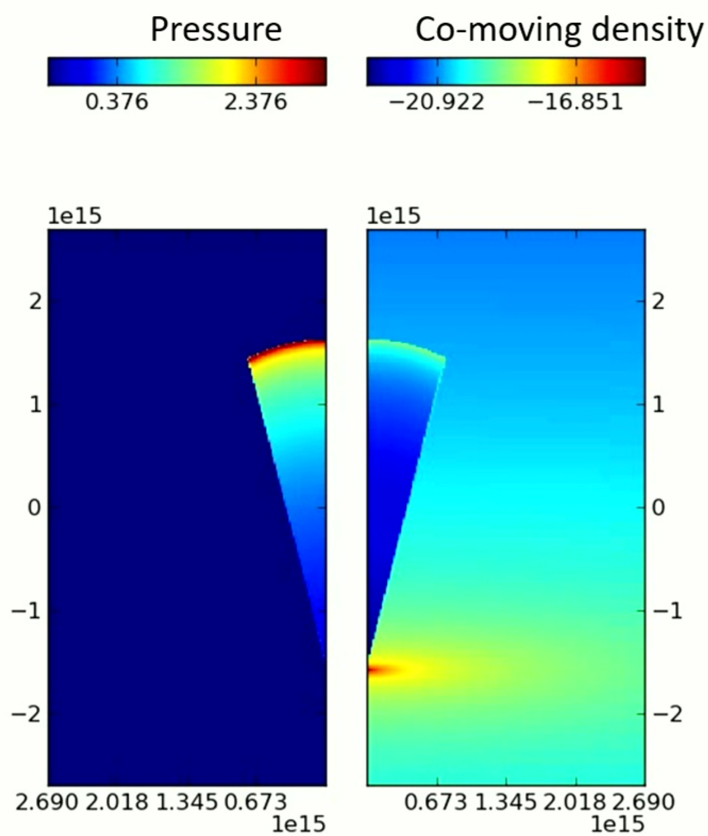


De Colle et al. 2012

$$\Delta R \sim \frac{R}{12\Gamma^2}$$

numerically tricky… since we want a resolved $\Gamma \gg {}^{1}/_{\theta_0}$
to ensure simulation resolved prior to causal contact across jet

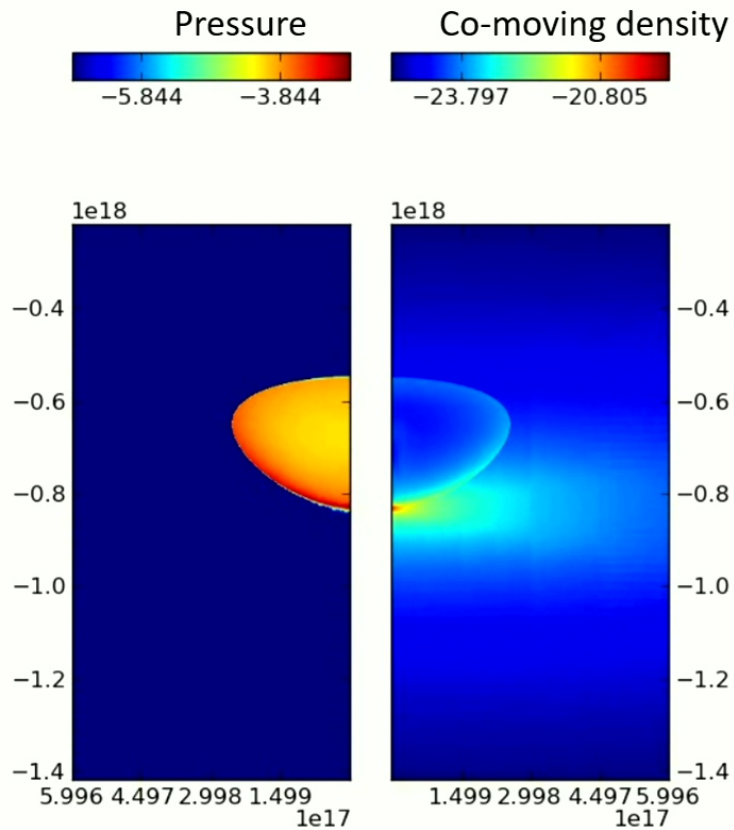
boosted frames, stellar winds



van Eerten & MacFadyen 2013, ApJ 767, 141

LOW RESOLUTION EXAMPLE: Stellar wind environment, boost $\Gamma = 5$

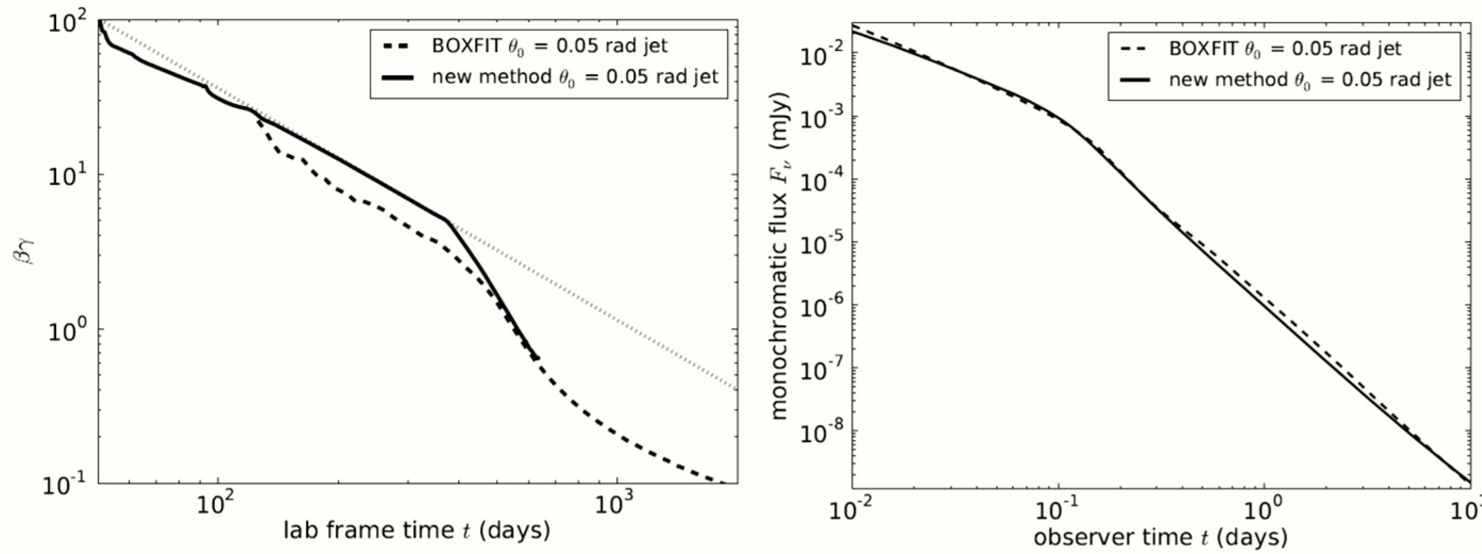
boosted frames, stellar winds



van Eerten & MacFadyen 2013, ApJ 767, 141

LOW RESOLUTION EXAMPLE: Stellar wind environment, boost $\Gamma = 5$

The benefit of boosted frames



van Eerten & MacFadyen 2013, ApJ 767, 141

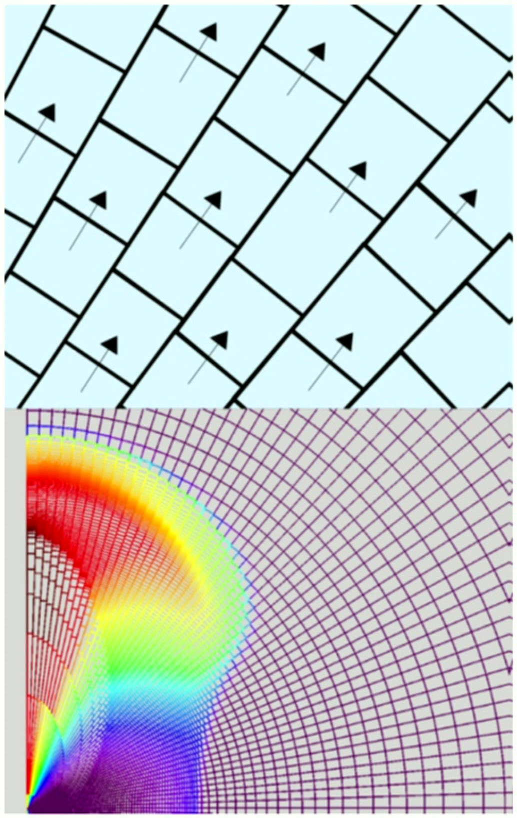
Using lab frame simulations:

- *Original range of angles BOXFIT sample OK*
- *But careful with synchrotron self-absorption*

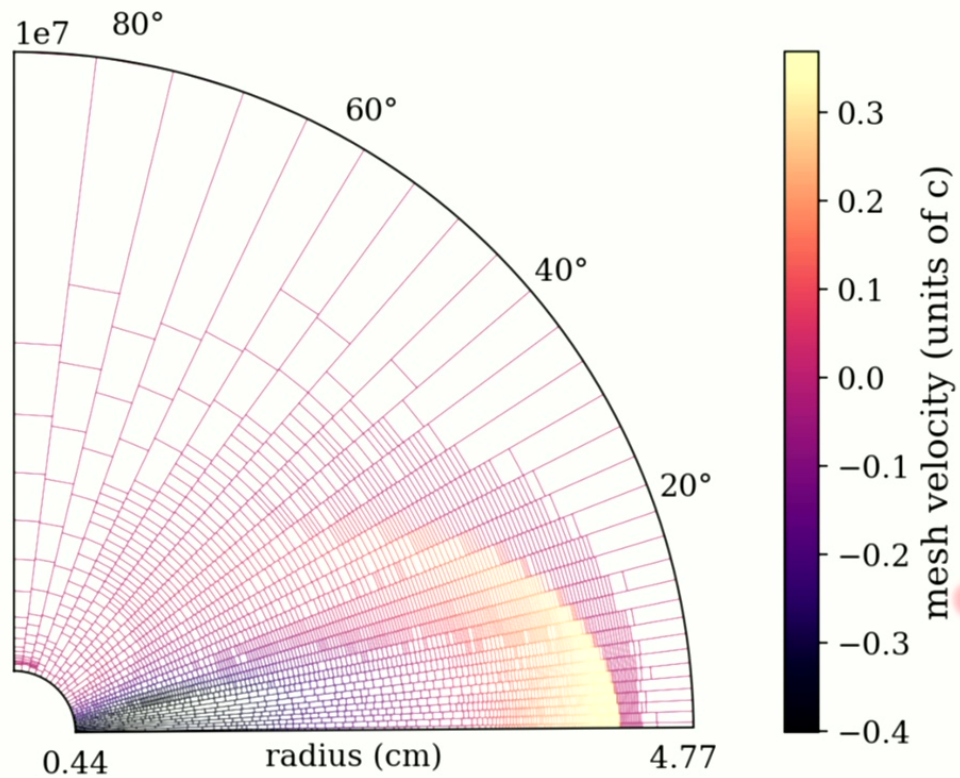
Boosted frame simulations:

- *Stellar winds*
- *very narrow jets*
- *carefree self-absorption*

alternative to boosted reference frame, we just move the mesh along

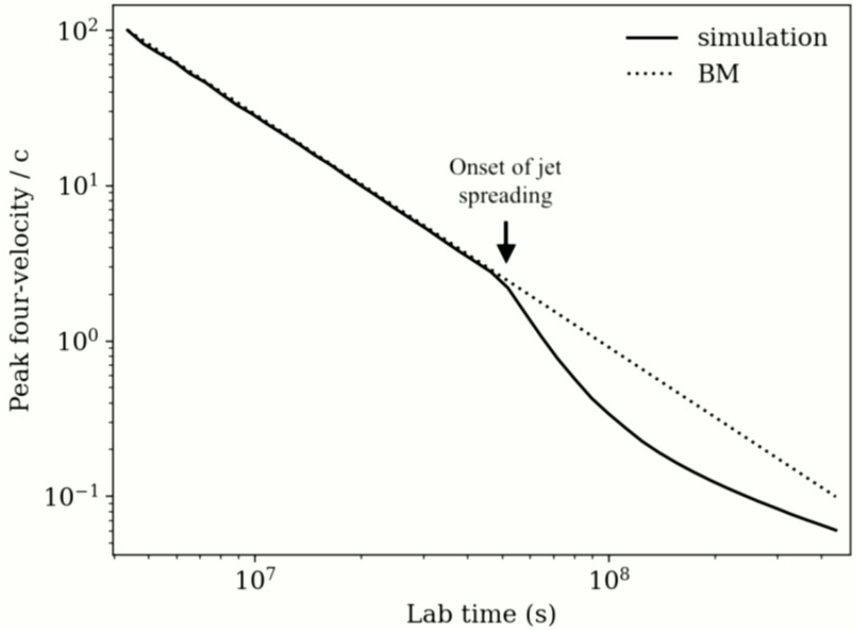


'JET', Duffell & MacFadyen 2013
(see also 'JETFIT' based papers)



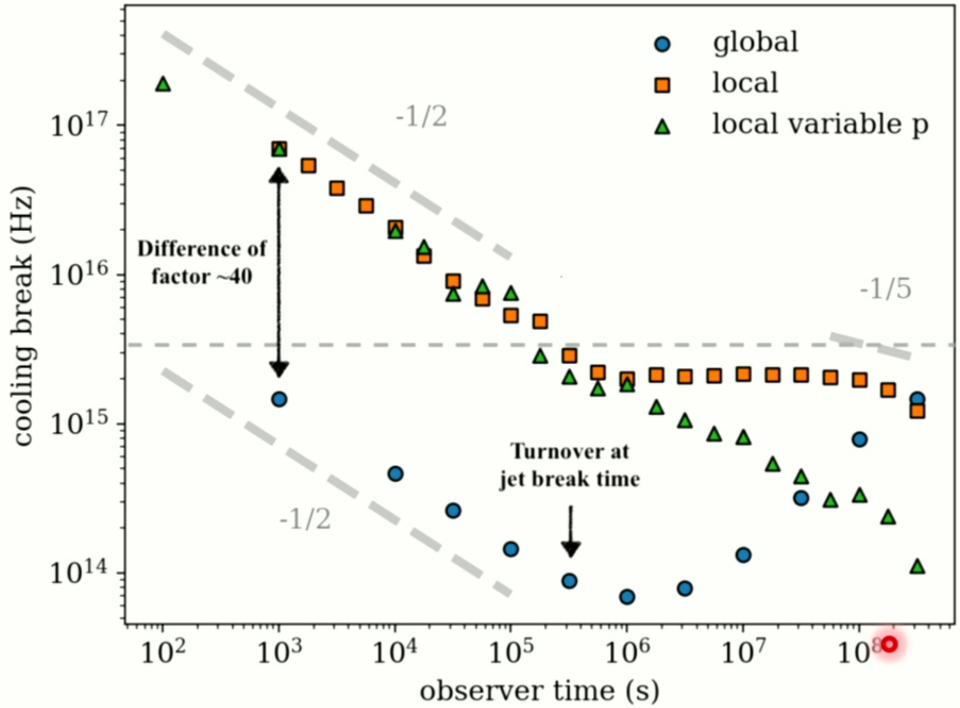
'GAMMA', Ayache, Van Eerten & Eardsley 2021

Moving meshes make massive difference for simulation reliability and inferred physics

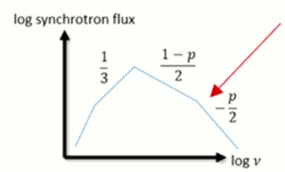


Ayache, Van Eerten & Eardsley 2021

Can actually resolve the jet dynamics at high Lorentz factor

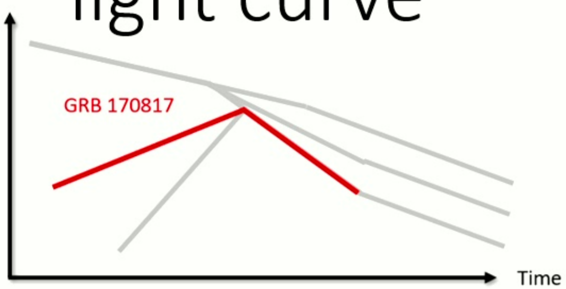


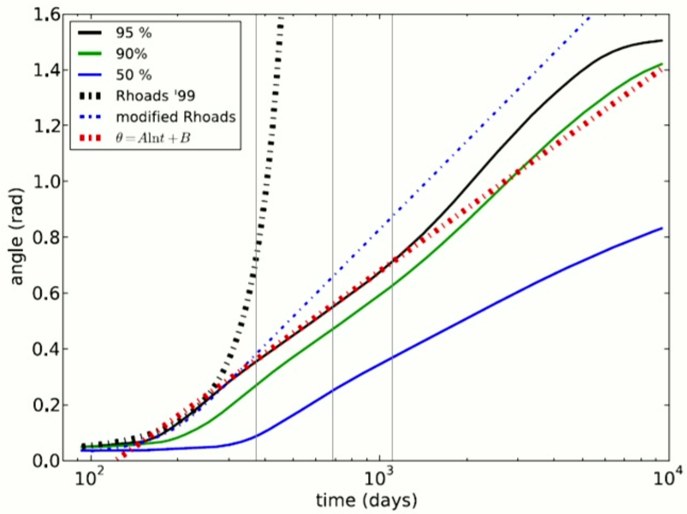
Ayache, Van Eerten & Eardsley 2021



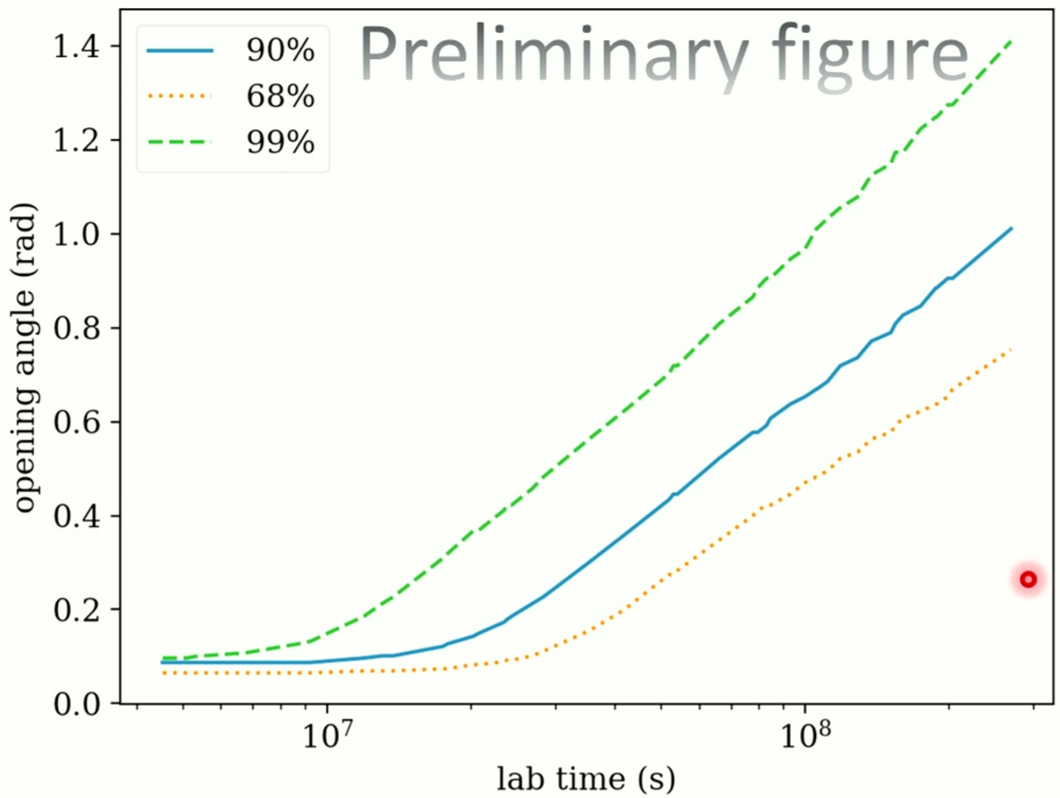
A qualitative difference in behaviour of the synchrotron spectrum (shown cooling break)

Next step, fully resolve the long-term evolution of structured jets and implication for late-time slope light curve



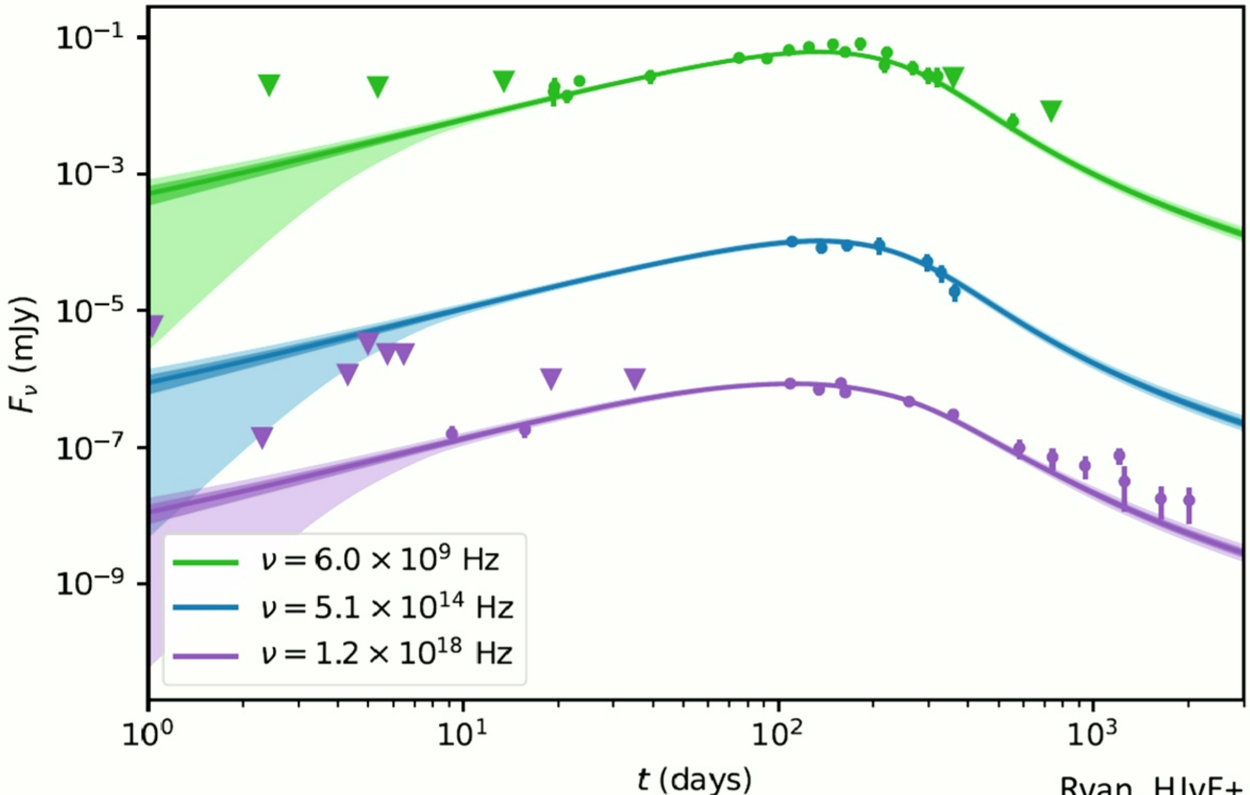


Van Eerten & MacFadyen 2013
standard 'top-hat' jet 0.5 rad



Ayache & Van Eerten, in prep.

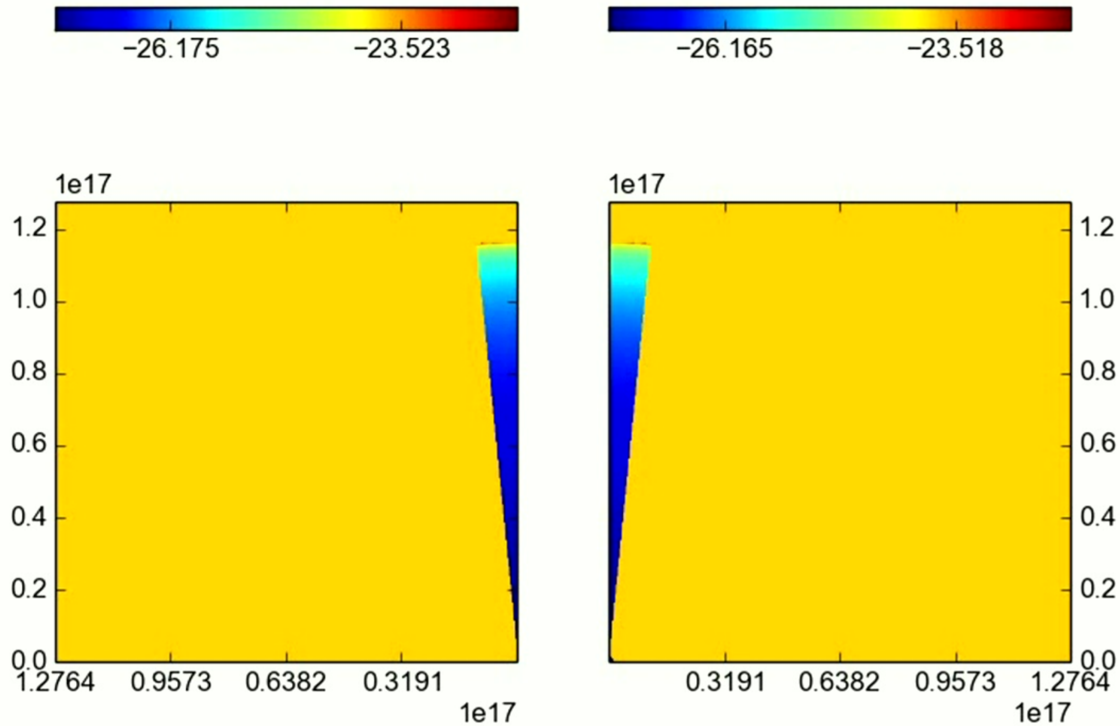
GRB 170817A Follow-up, latest



Ryan, HJvE+ in prep

see also Hajela+ 2021, Balasubramanian+ 2021, ...

Summarizing long-term jet 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

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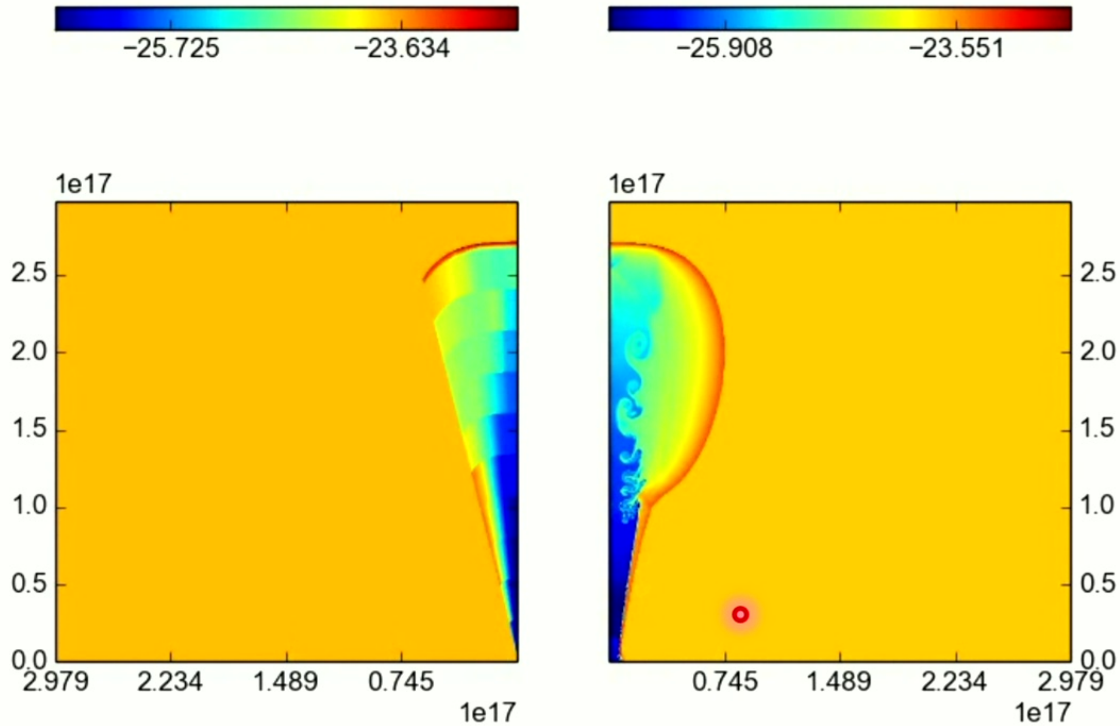

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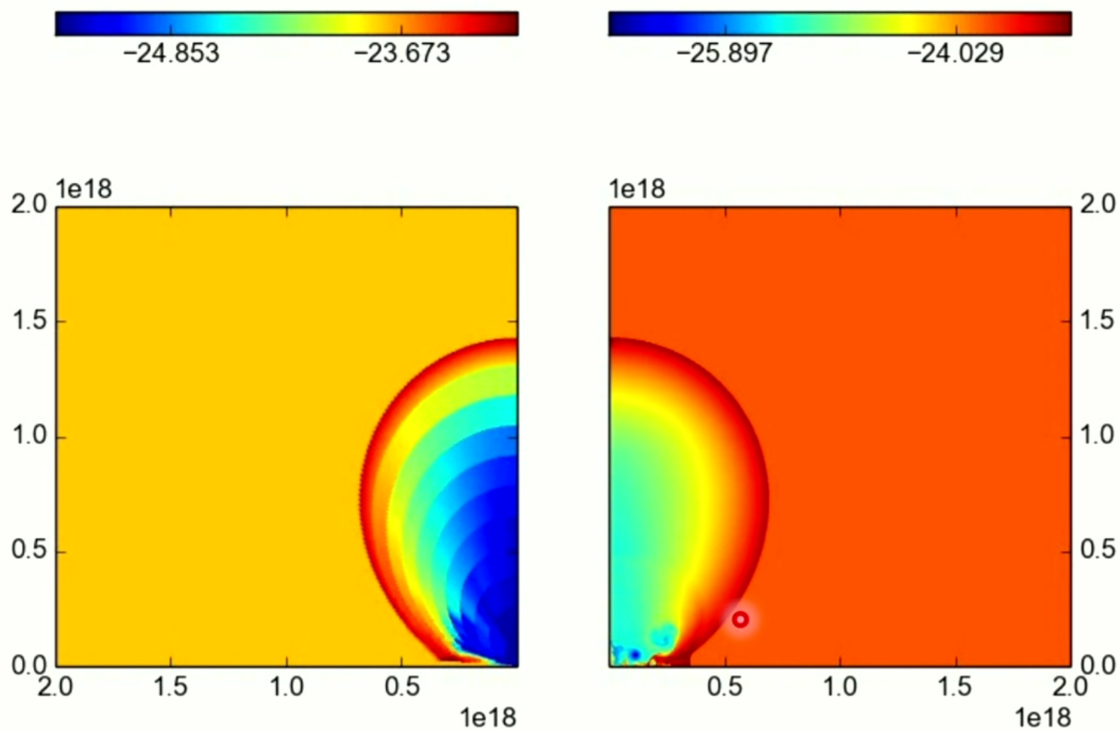

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Scale invariance explained

Blandford & McKee (*relativistic)*

$$E_{iso},\ \rho_0,\ c;\ \ r,t \rightarrow\ \ A \equiv \frac{r}{ct} \sim 1,\ \ B \equiv \frac{E_{iso} t^2}{\rho_0 r^5} \rightarrow$$ *self-similarity*

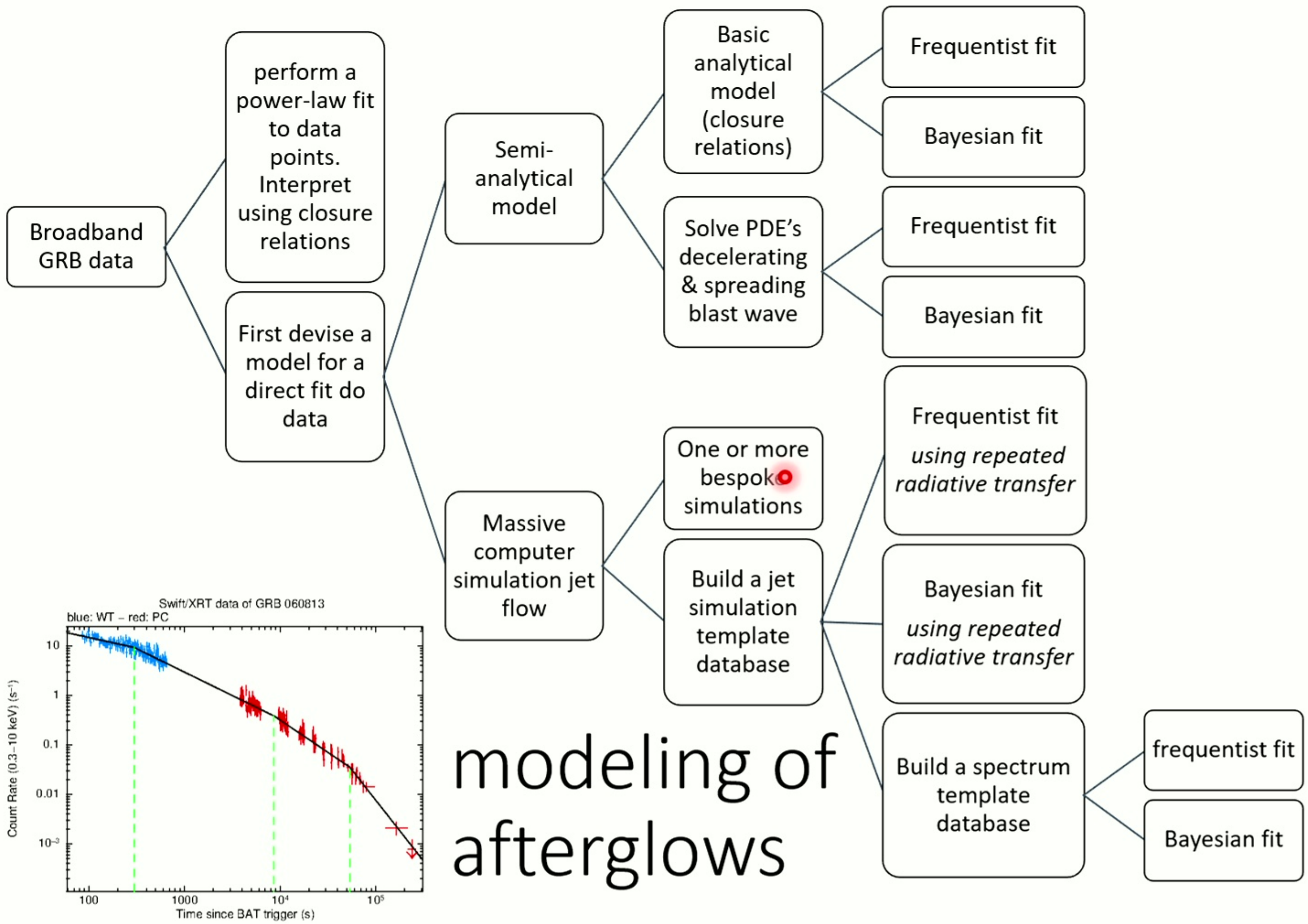
Sedov – Taylor – von Neumann (*Newtonian)*

$$E_{iso},\ \rho_0,\ c;\ \ r,t \rightarrow\ \ A \equiv \frac{r}{ct} \sim 0,\ \ B \equiv \frac{E_{iso} t^2}{\rho_0 r^5} \rightarrow$$ *self-similarity*

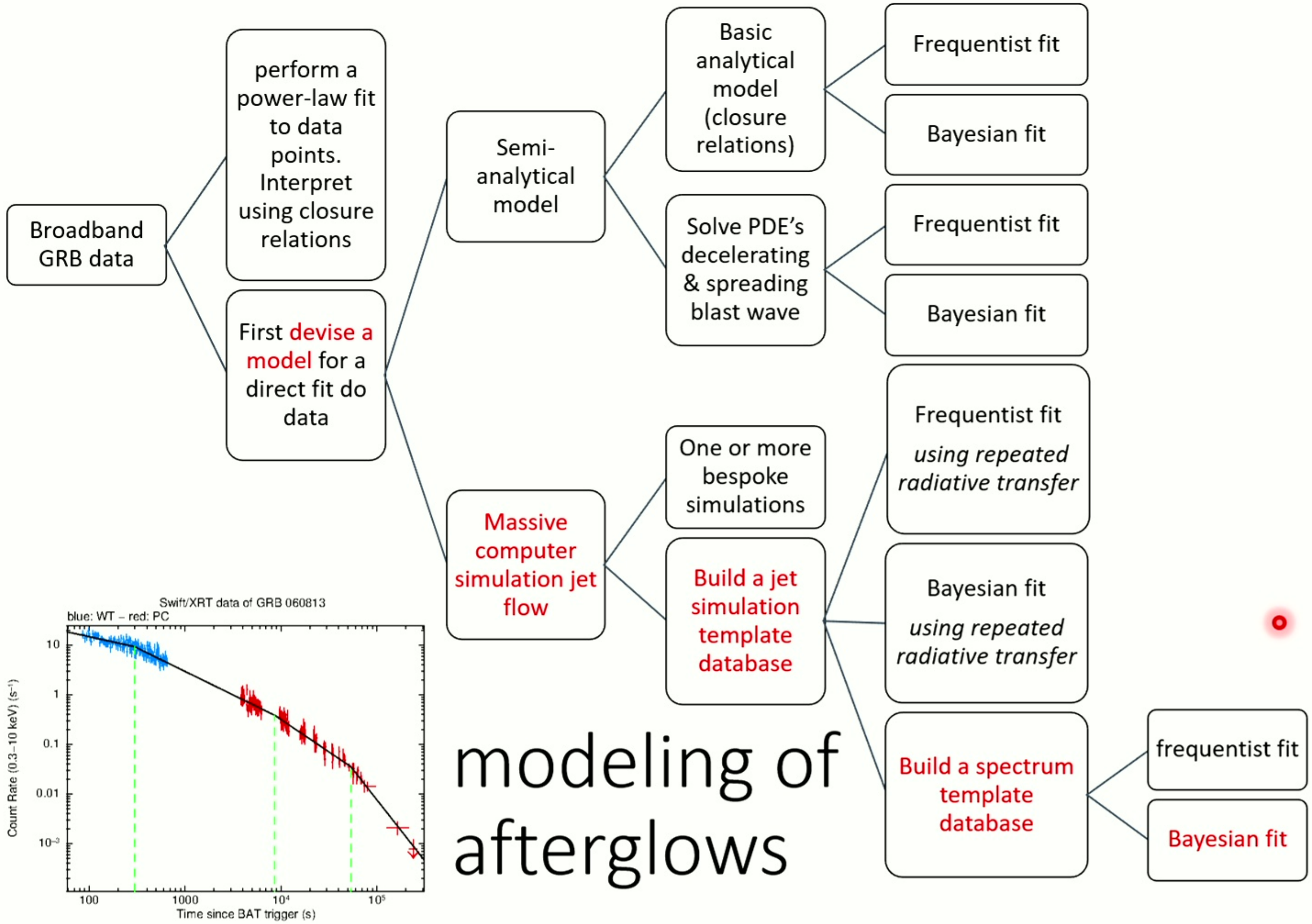
Scale-invariance (*throughout)*

$$\begin{aligned} E'_{iso} &= \kappa\, E_{iso} \\ r' &= \kappa^{1/3}\, r \\ t' &= \kappa^{1/3}\ t \\ \theta' &= \theta \end{aligned} \quad \rightarrow \quad \begin{aligned} A' &\equiv A \\ B' &\equiv B \end{aligned}$$

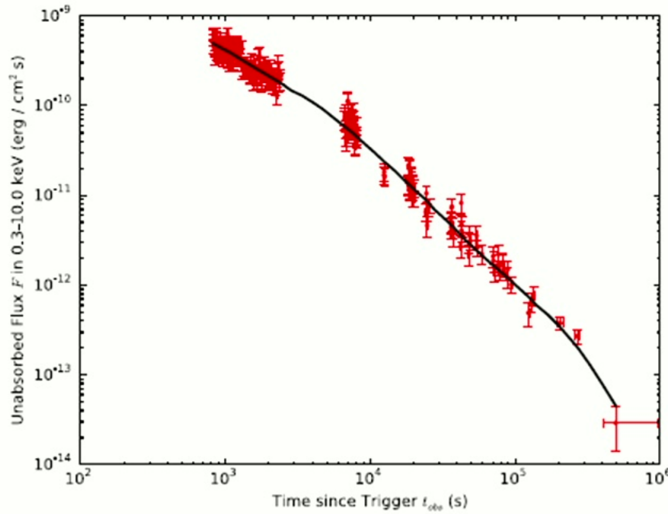
$$t'_{obs} = \kappa^{1/3}\, t_{obs} \qquad \rightarrow \qquad F'_{peak} = \kappa^{\cdots} F_{peak},\ \nu'_m = \kappa^{\cdots} \nu_m,$$ etc.

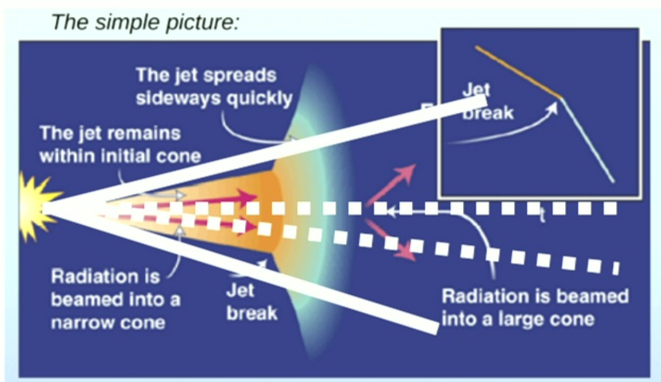

Broadband GRB data
perform a power-law fit to data points. Interpret using closure relations
First devise a model for a direct fit do data
Semi-analytical model
Basic analytical model (closure relations)
Frequentist fit
Bayesian fit
Solve PDE's decelerating & spreading blast wave
Frequentist fit
Bayesian 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
Swift/XRT data of GRB 060813
blue: WT – red: PC
Count Rate (0.3–10 keV) (s^{-1})
Time since BAT trigger (s)
10
1
0.1
0.01
10^{-3}
100
1000
10^4
10^5

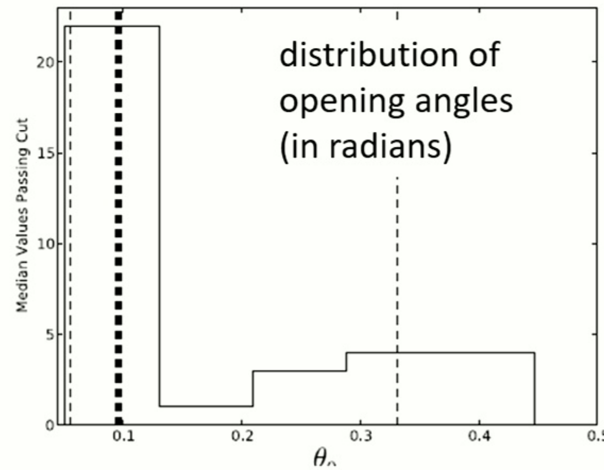
The *Scalefit* approach (Van Eerten & MacFadyen 2012; Ryan, Van Eerten+ 2015; Ryan & van Eerten, in prep)

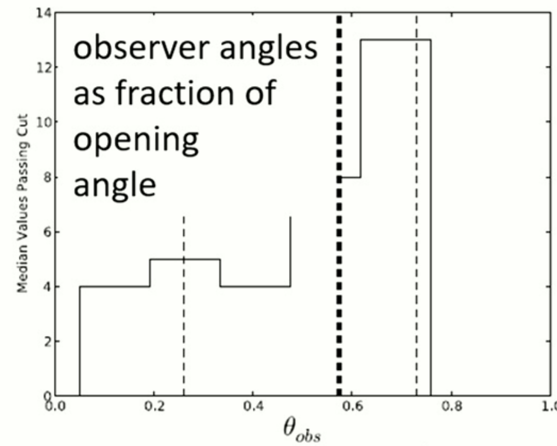


Example: scalefit application to Swift XRT sample



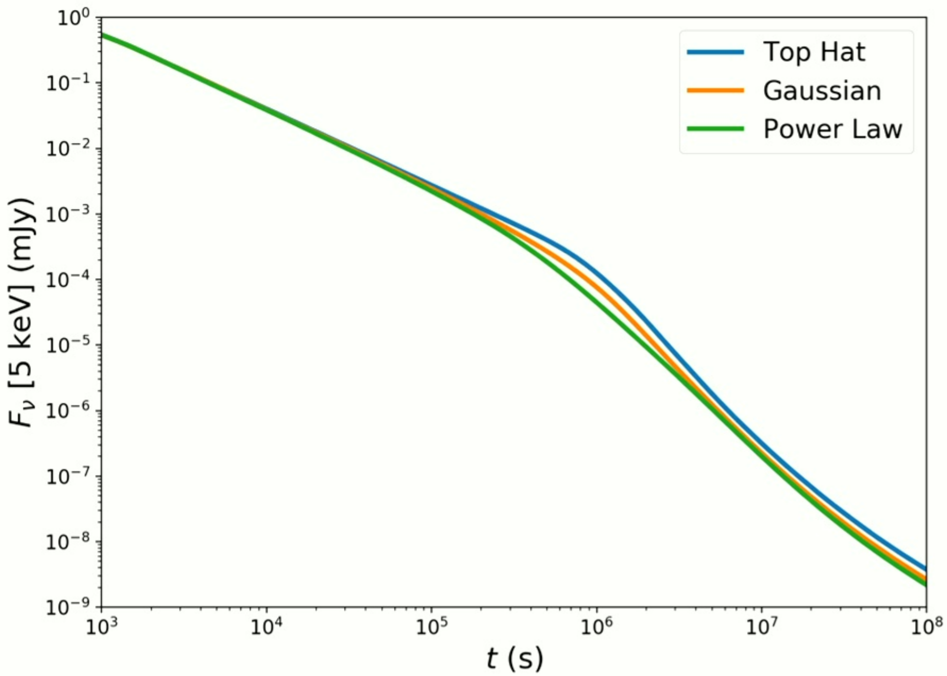


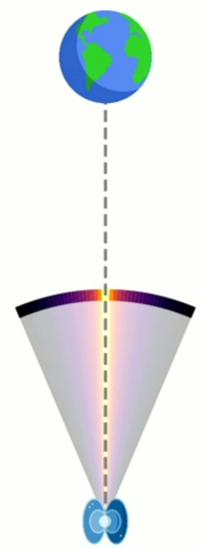




Ryan, van Eerten et al. 2015, ApJ 799, 3

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





Ryan, van Eerten+ 2020, ApJ 896, 166

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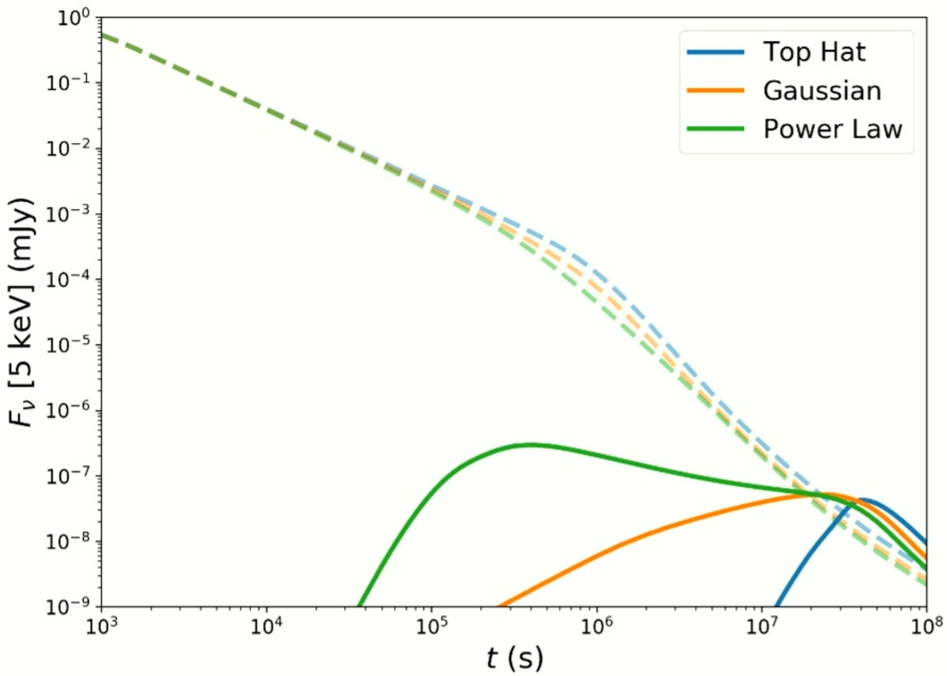
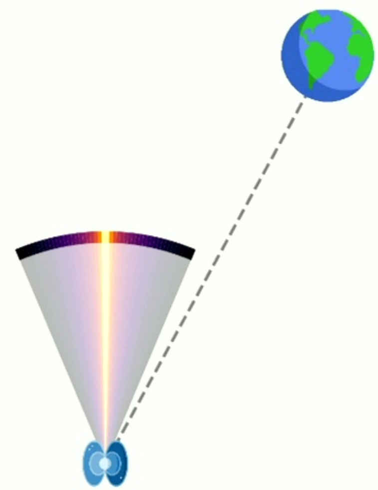




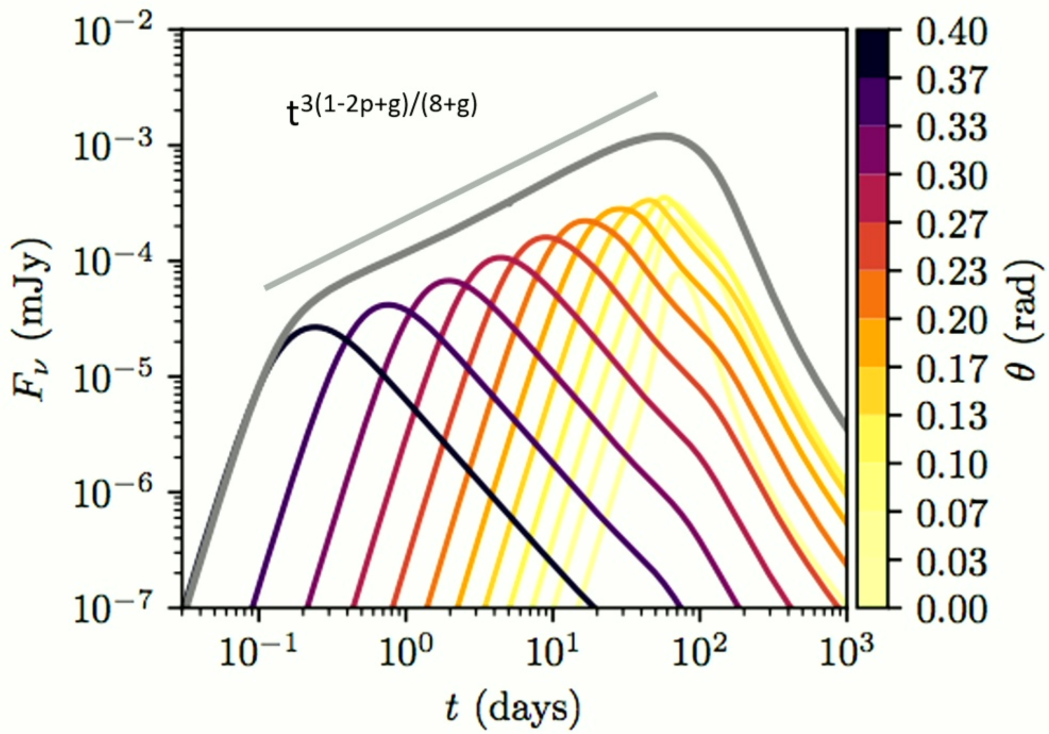
Ryan, van Eerten+ 2020, ApJ 896, 166

Structured jet behaviour and analytics

As first shown by Ryan, Van Eerten+ 2019, the resulting slope of a structured jet can be captured using a variable

$$g = (\theta_{\rm obs} - \theta)\frac{d\log E}{d\theta} \approx \frac{\theta_{\rm obs}^2}{4\theta_c^2}$$

(last step specific to a Gaussian; other structures similar)



implications for GW 170817A:

rising slope α = 0.90±0.06

⟹ g=8.2

⟹ $\theta_{\rm obs} = 5.7\ \theta_{\rm core}$

Note: Orientation is important to interpret gravitational wave emission, constraining distance and therefore for cosmology

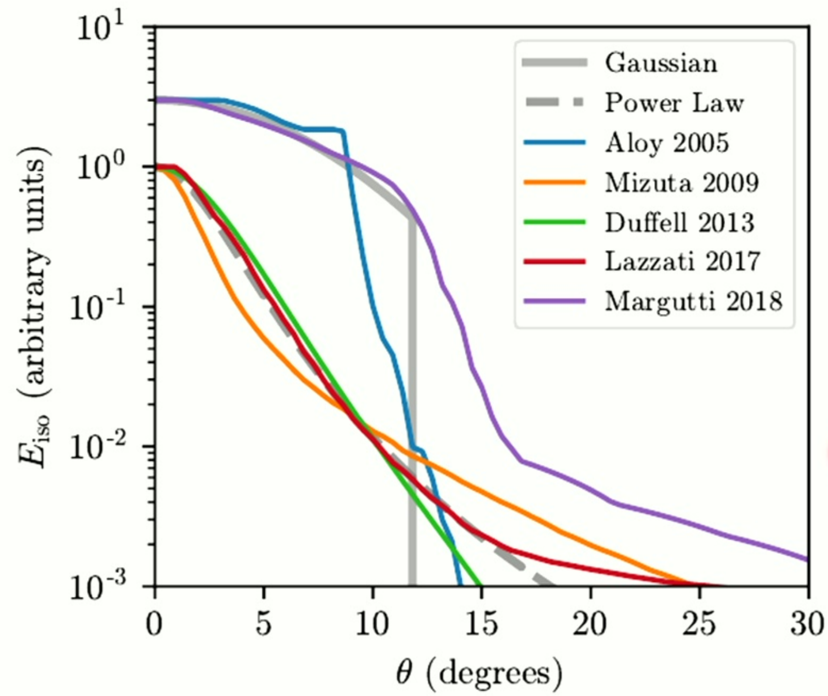
Ryan, van Eerten+ 2019

Structured jets can be modeled in various ways

- Shell models, initialized with a functional form for the jet lateral structure (eg Lamb+ 2019, Troja, ..HJvE+ 2018, 2019, 2020, Ryan, HJvE+ 2020, Beniamini+ 2020...)
  in python: "pip install afterglowpy"

- Long-term simulations, mapped onto the data set (eg Lazzati+ 2017, Fong+ 2019, Margutti+, Xie+ 2018, Wu & MacFadyen 2018...)

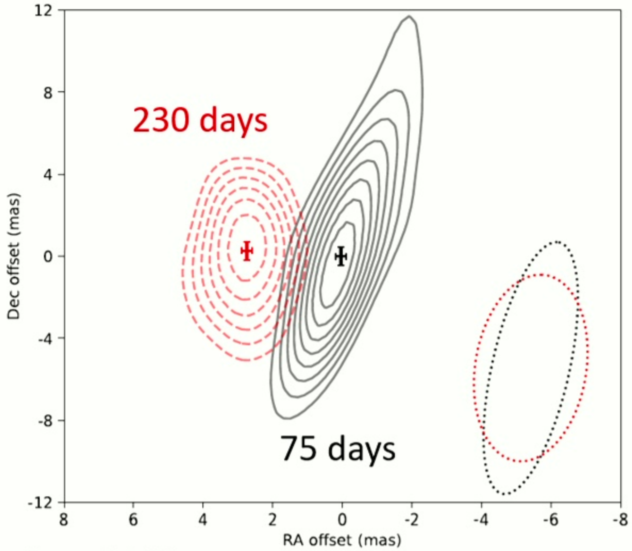
- early-stage simulations, and then mapping structure onto shell model (e.g. Nativi+ 2022, Nathanail 2021)



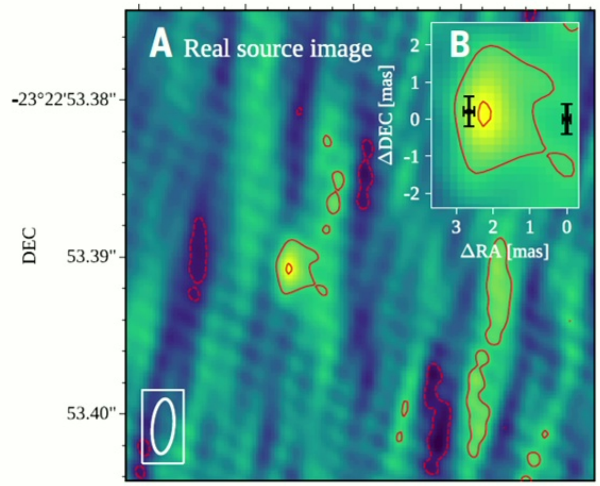
Ryan, HJvE+2020

Various actors responsible for shaping jet structure: (MHD) launching process, jet-torus interaction, neutrino wind from accretion disc, propagation through NS merger debris... (eg Kathirgamaraju+ 2018, Lazzati+ 2017, Nathanail+2020, Nativi+ 2021, ...)

NS-merger jets and multi-messenger analysis
jet constraints from the various channels, like VLBI



Mooley+ 2018
Centroid positions at 75 and 230 days

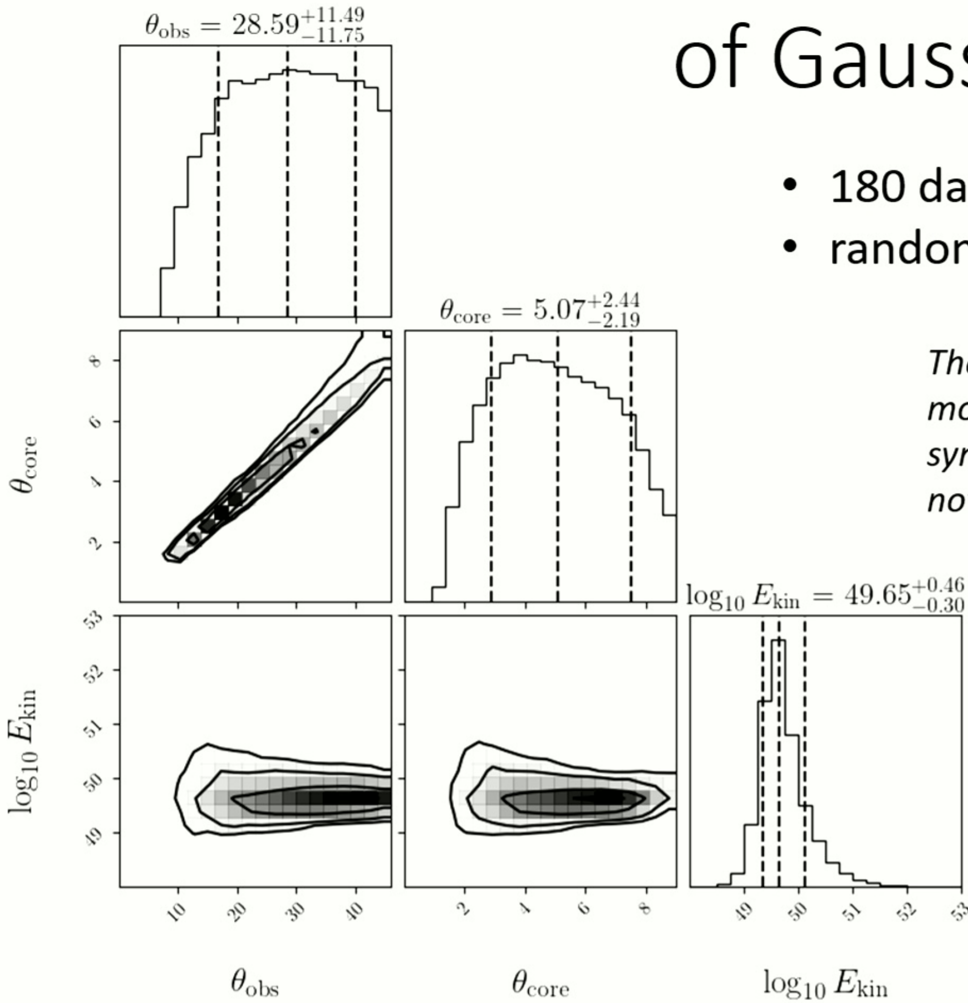


Ghirlanda+ 2018
Centroid at 207.4 days

Centroid can be used to confirm successful jet launch (with some caveats, Zrake+ 2018 got a choked jet to match too)

(alternatively, use light curve downwards slope, see Troja, Piro, Ryan, HJvE+ 2018 decay slope $\gtrsim 2$ **prediction** followed by Troja, … HJvE+ 2019 confirmation)

Evolution of the posterior of Gaussian jet model

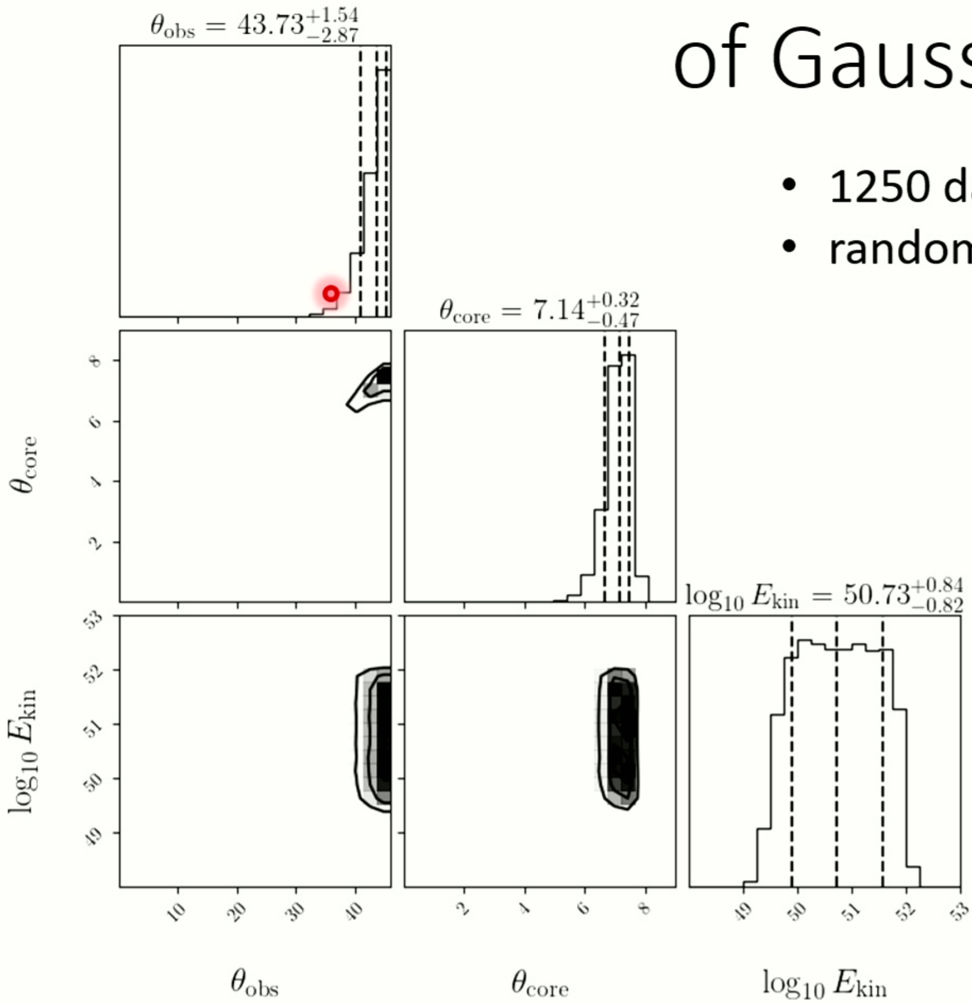


- 180 days
- random sky orientation prior

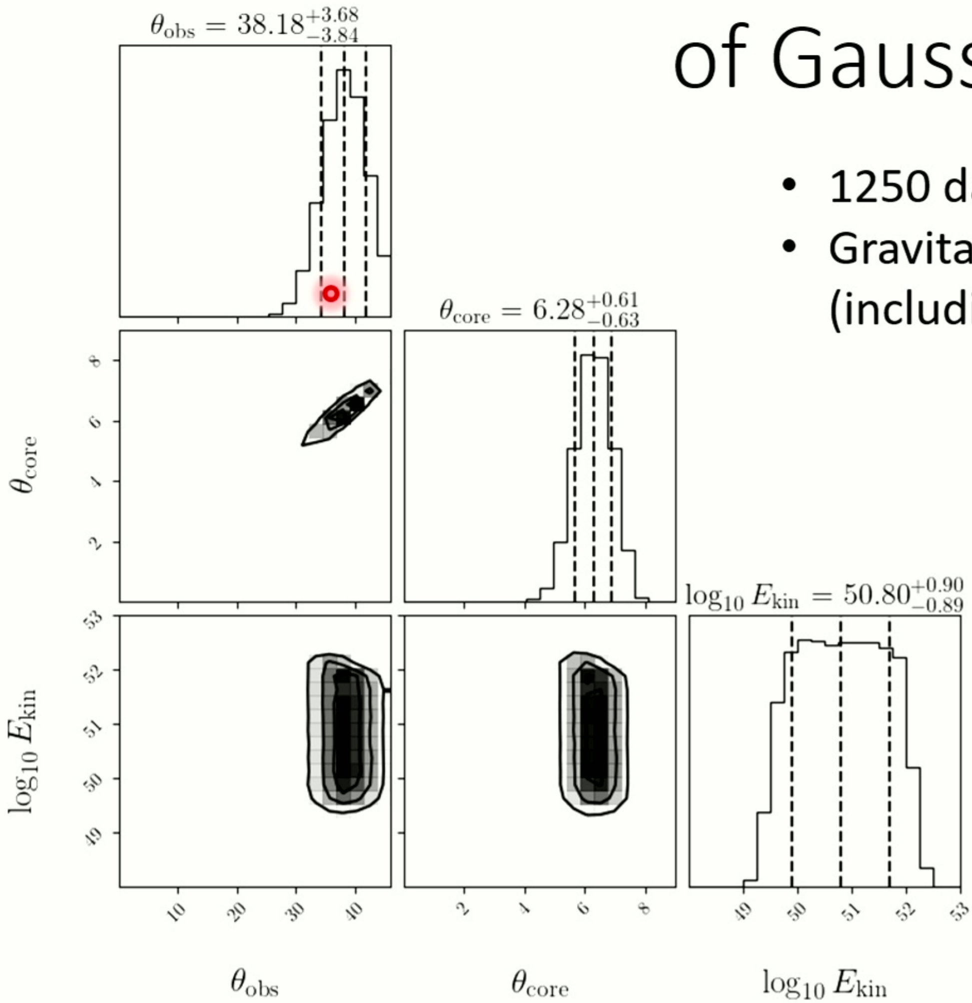
The actual fit included more model parameters (environment, synchrotron model, etc). These are not shown here to avoid clutter

Evolution of the posterior of Gaussian jet model

- 1250 days
- random sky orientation prior



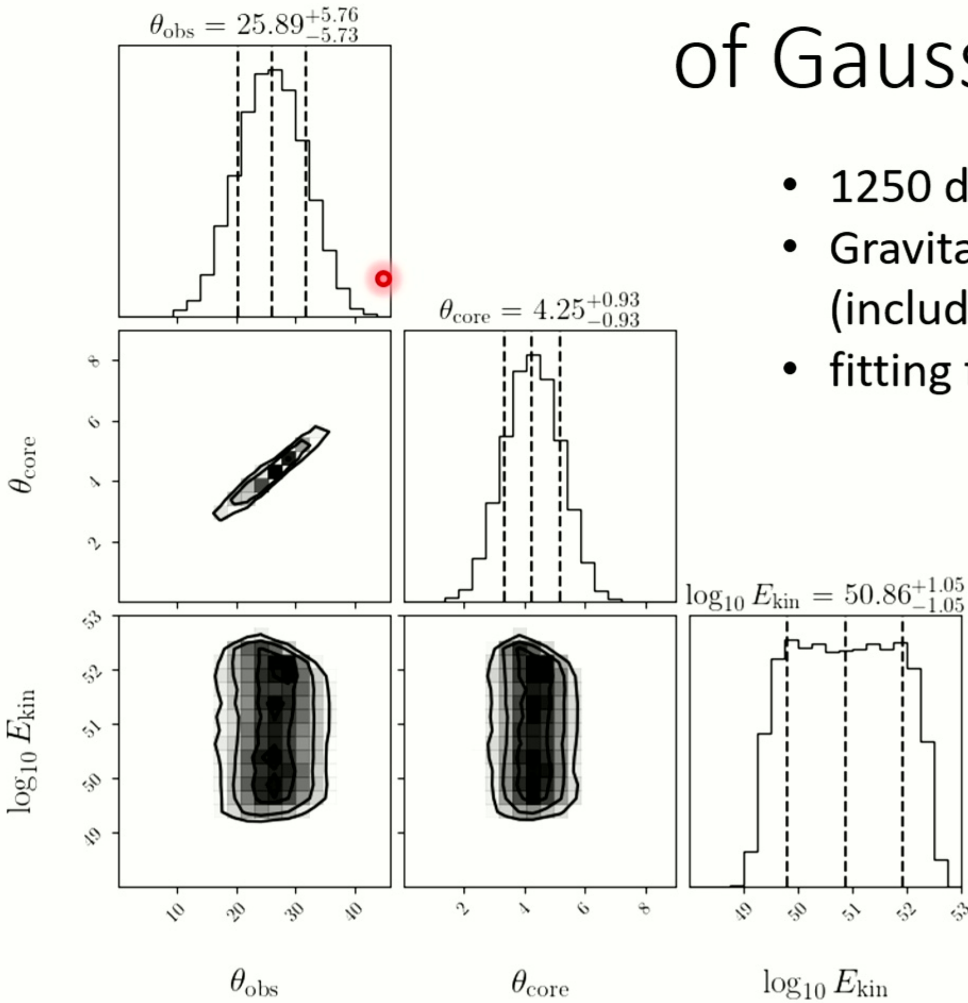
Evolution of the posterior of Gaussian jet model



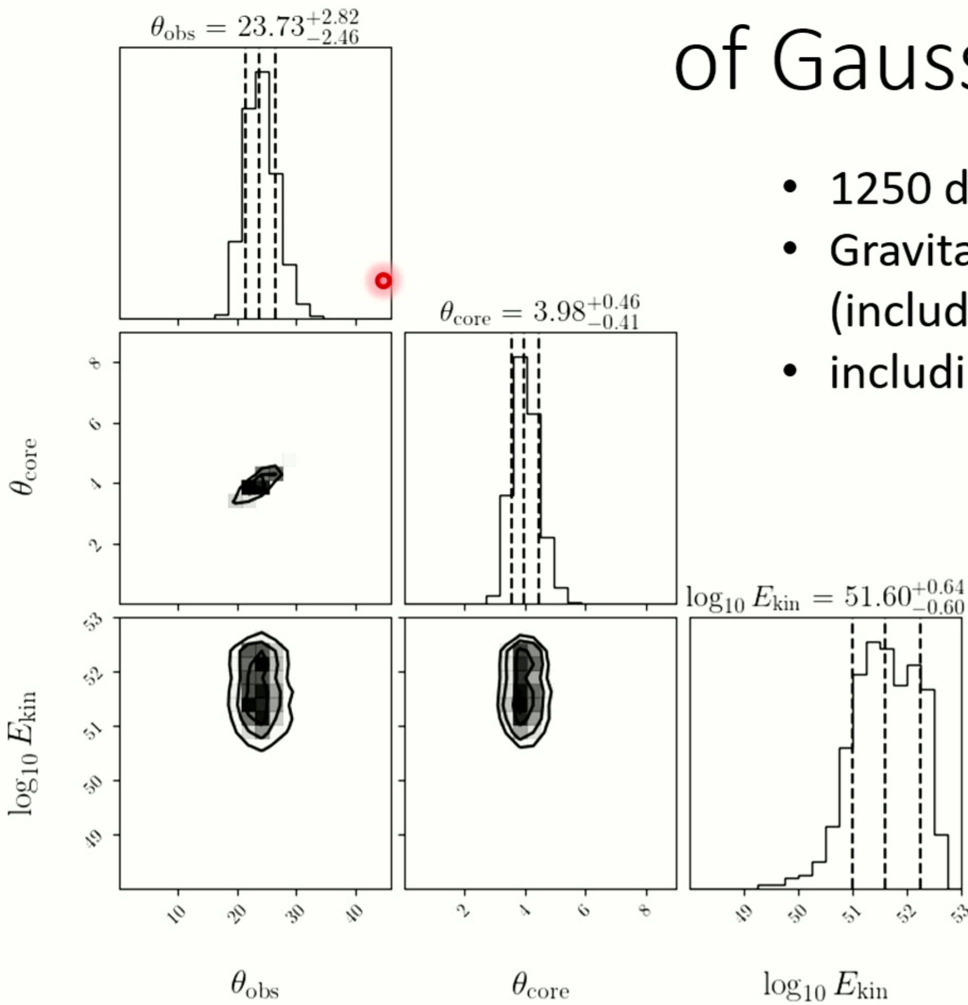
- 1250 days
- Gravitational wave prior (including H_0 assumption)

Evolution of the posterior of Gaussian jet model

- 1250 days
- Gravitational wave prior (including H_0 assumption)
- fitting for extra luminosity too

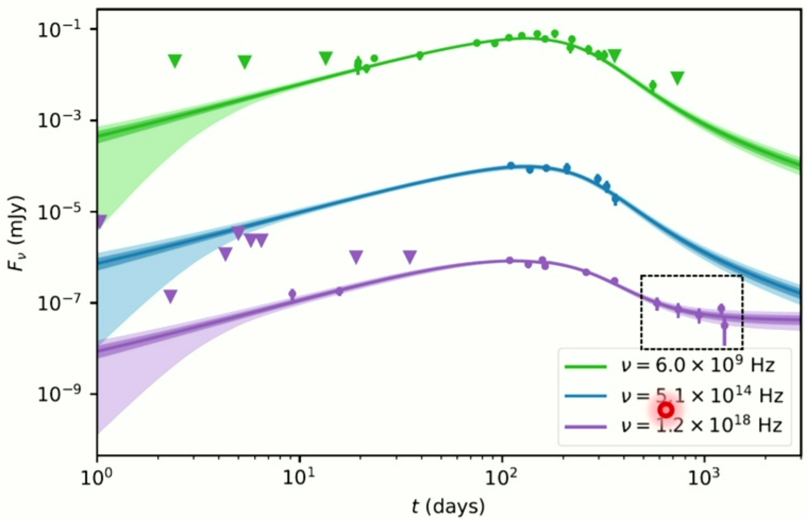


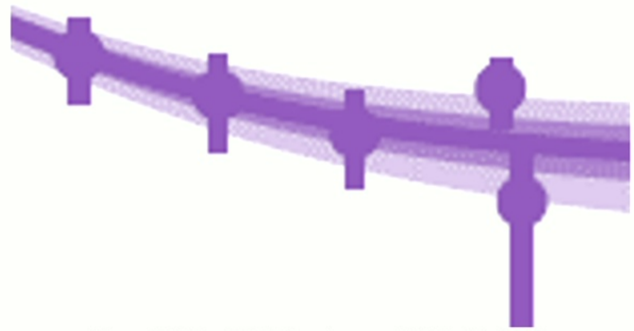
Evolution of the posterior of Gaussian jet model

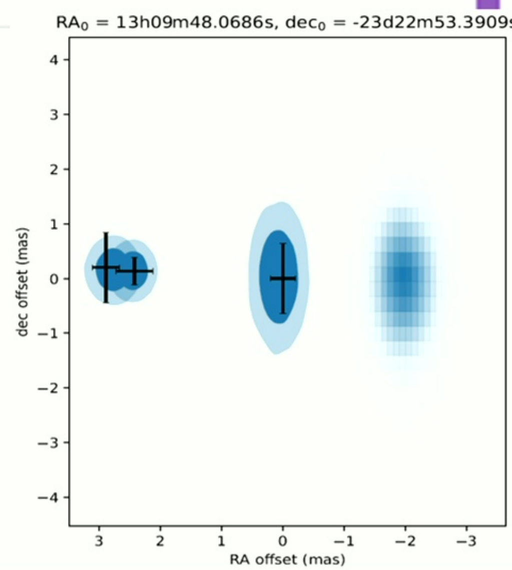


- 1250 days
- Gravitational wave prior (including H_0 assumption)
- including centroid motion in fit

Light curve result, extra luminosity L_X







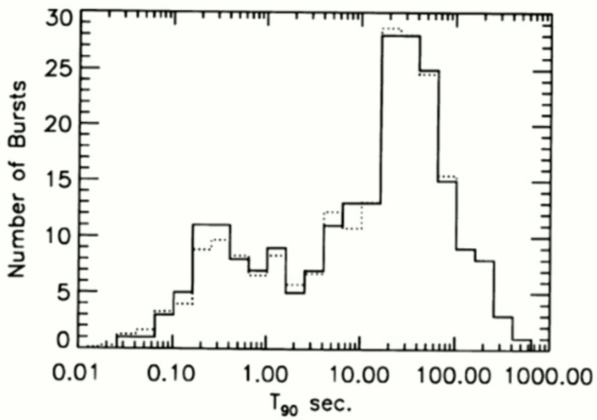
- Fits use Gaussian structured jet (PL fits show similar results)
- Direct co-fit for VLBI observations
- gravitational wave-based prior for orientation
- includes Deep-Newtonian synchrotron regime (mimics PL in momentum space, avoids lower cut-off electron population gamma < 1)
- Luminosity modeled as a constant term (agnostic about its origin)

Ryan, Van Eerten+, in prep

Properties of the two classes of gamma-ray bursts

- Long gamma-ray bursts (massive stellar collapse)
  prompt emission > 2 seconds
  larger redshifts peaking around peak of star formation ($z \sim 2$)
  come with a supernova (broad-lined Ic)

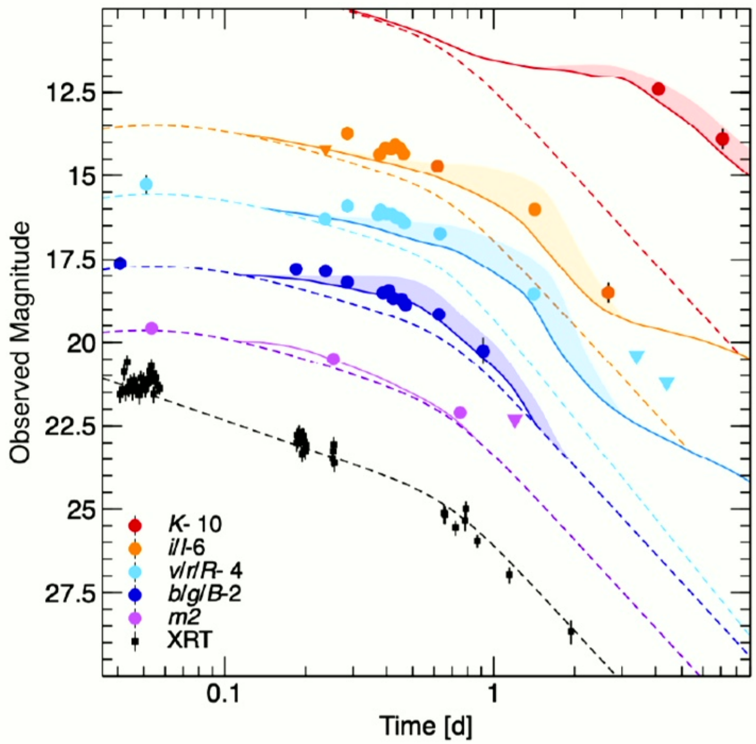
- **short gamma-ray bursts (merging neutron stars)**
  prompt emission < 2 seconds
  offset from host galaxy
  come with a kilonova (very rarely detected)
  gravitational waves (one multi-messenger detection so far)

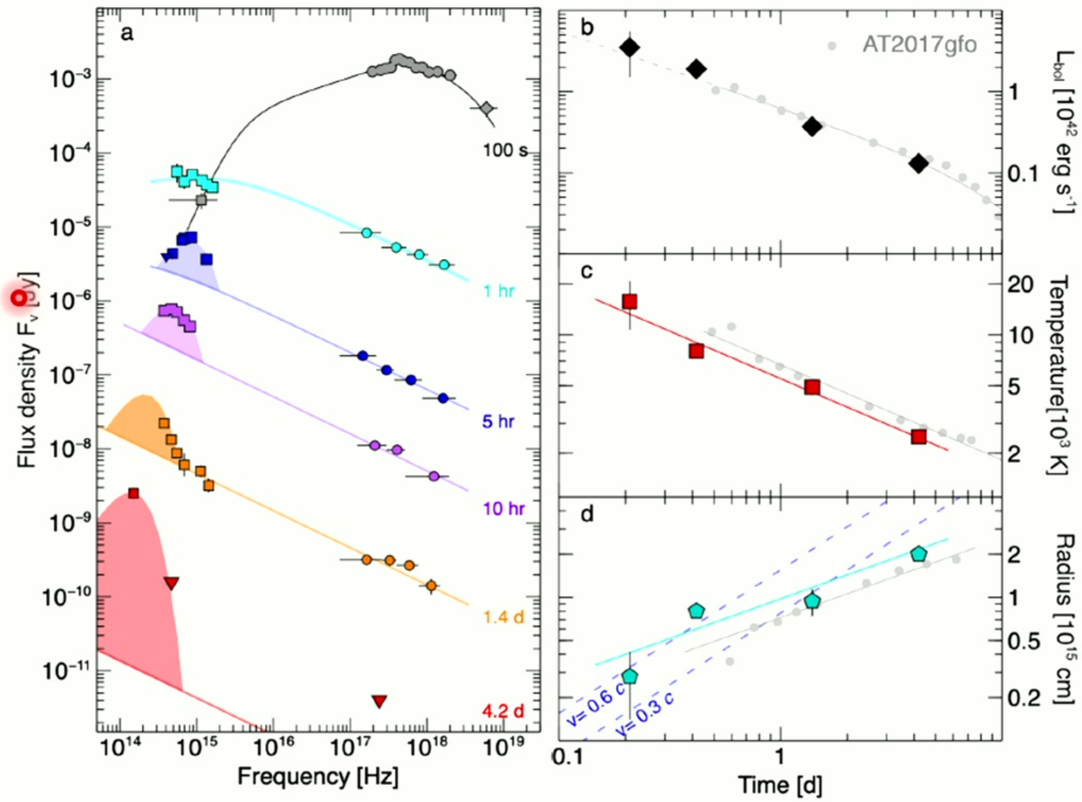


Kouvoliotou+ 1993

Short/long divide not always unambiguous…

GRB 211211A, extremely bright duration 10 seconds, plus another 60 seconds or so
but **also** a signature of a NS-merger produced kilonova at 345 Mpc

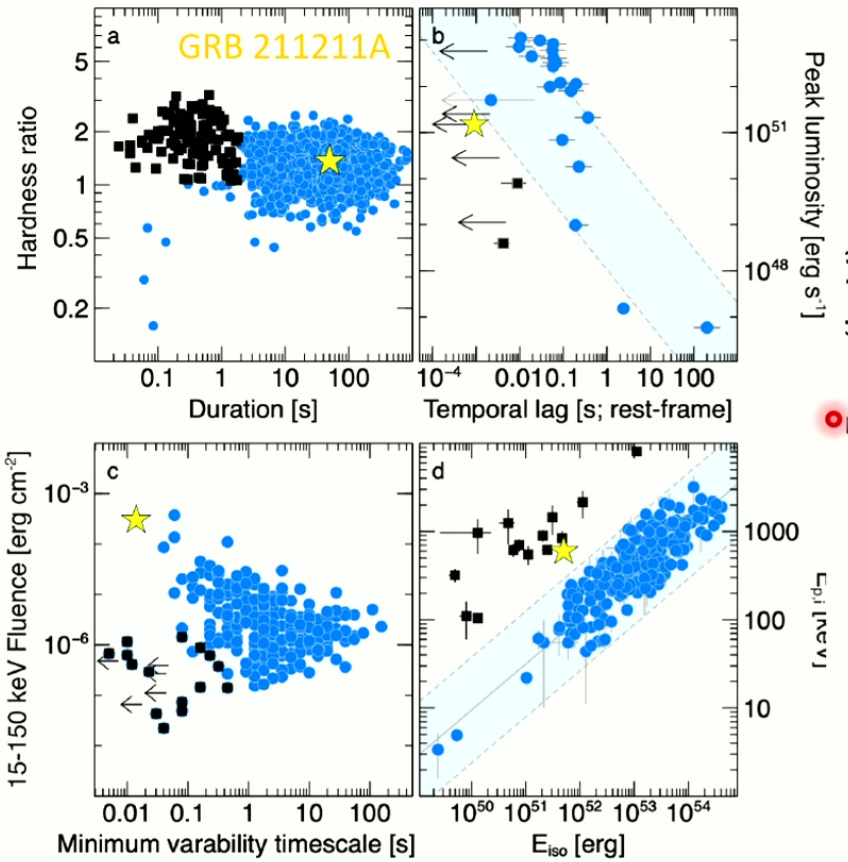




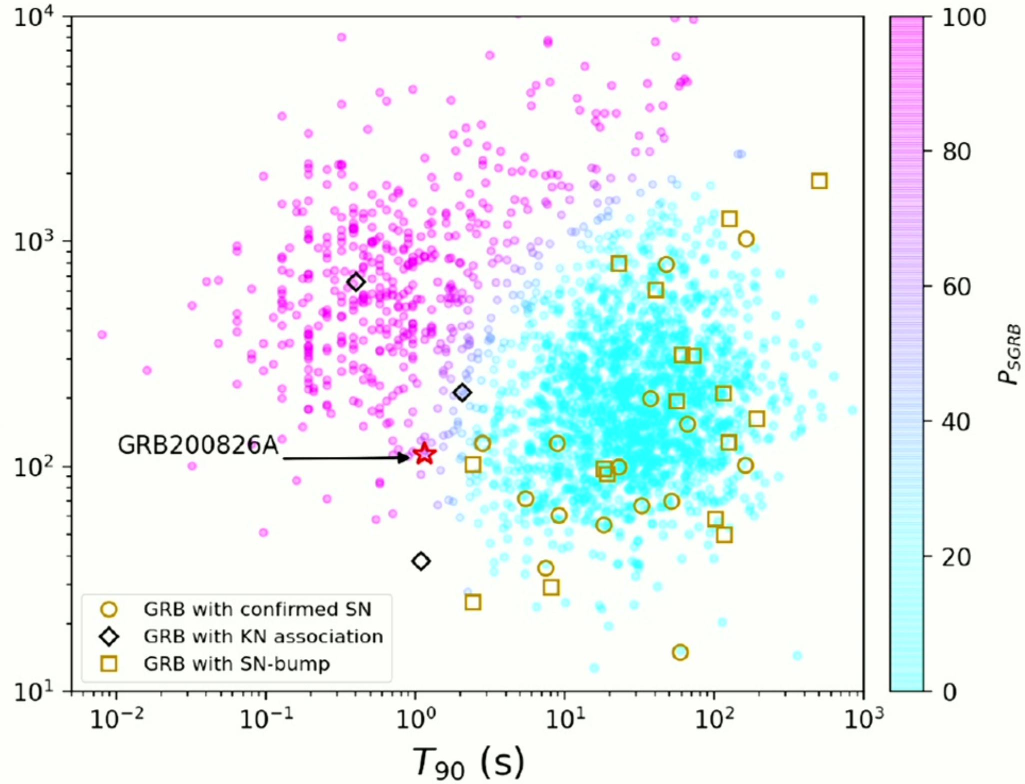
(there exist more examples of ambiguous cases)

Troja, …, HJvE 2022, Nature

Differentiating between long and short bursts

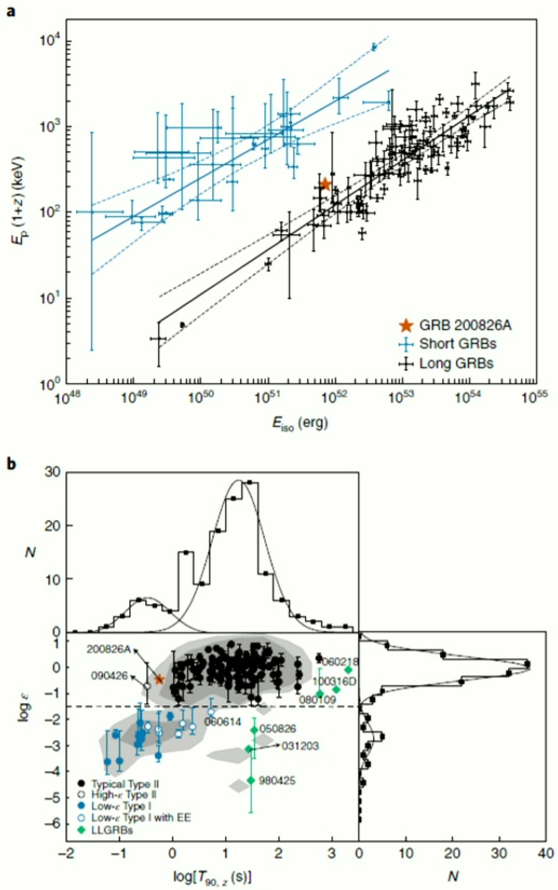


Troja, ..., HJvE 2022, Nature in press
"A long gamma-ray burst from a merger of compact objects"

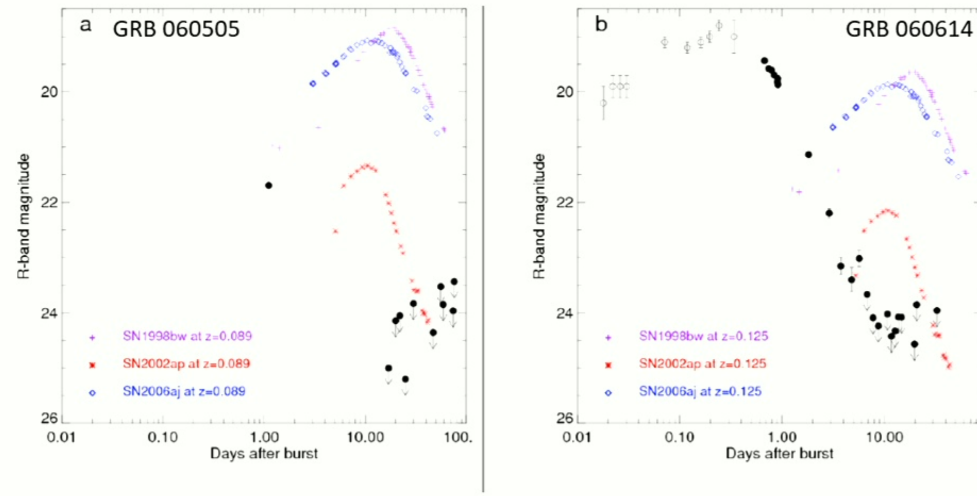


Ahumada+ 2021, Nature Astronomy, 5, 917
"Discovery and confirmation of the shortest gamma-ray burst from a collapsar"

Differentiating between long and short bursts

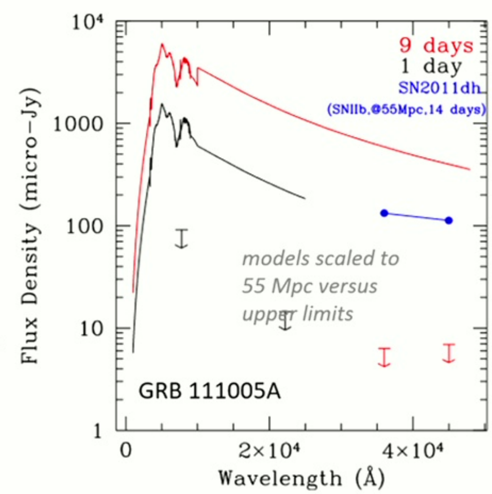


Zhang, BB+ 2021, Nature Astronomy Letters 5, 911
"A peculiarly short-duration gamma-ray burst from massive star core collapse"

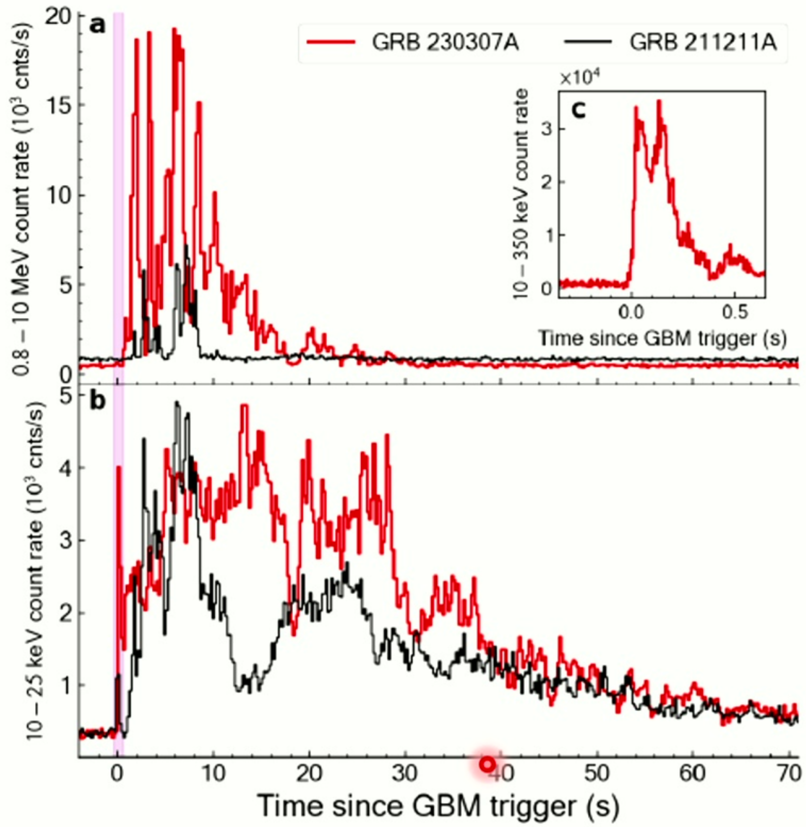


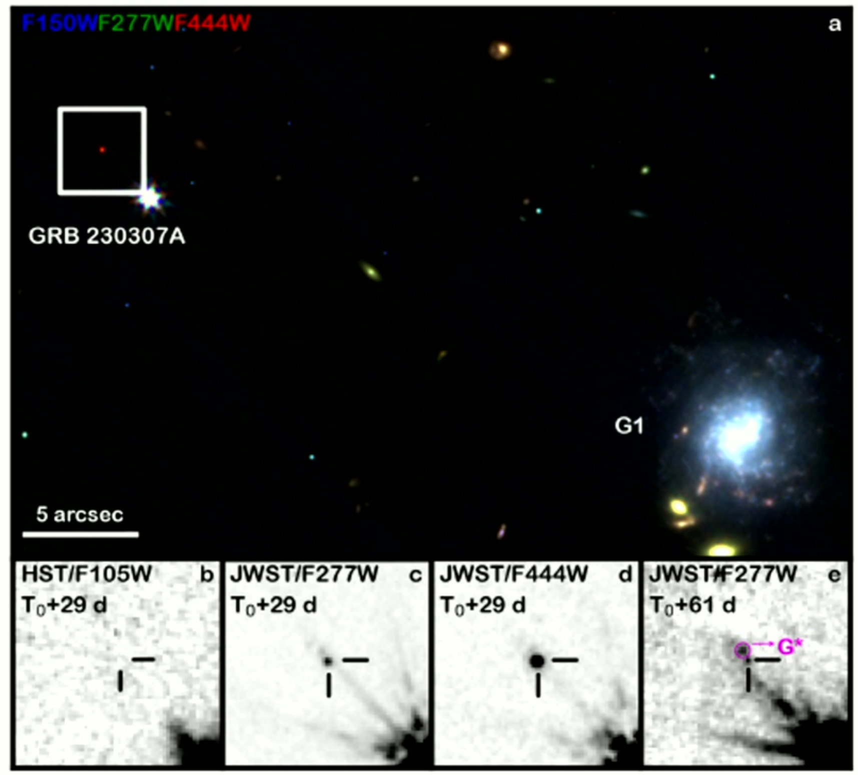
Fynbo+ 2006, Nature 444, 1047
"No supernovae associated with two long-duration γ-ray bursts"

Michalowski+ 2018, A&A 616, A169
"The second-closest gamma-ray burst: sub-luminous GRB 111005A with no supernova in a super-solar metallicity environment"



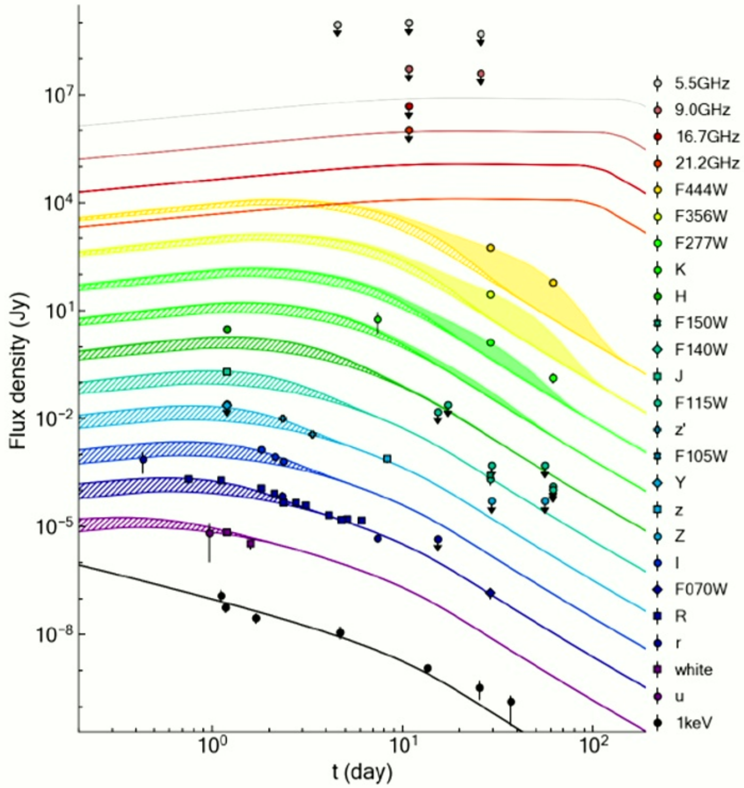
latest long GRB / kilonova combi: GRB 230307A



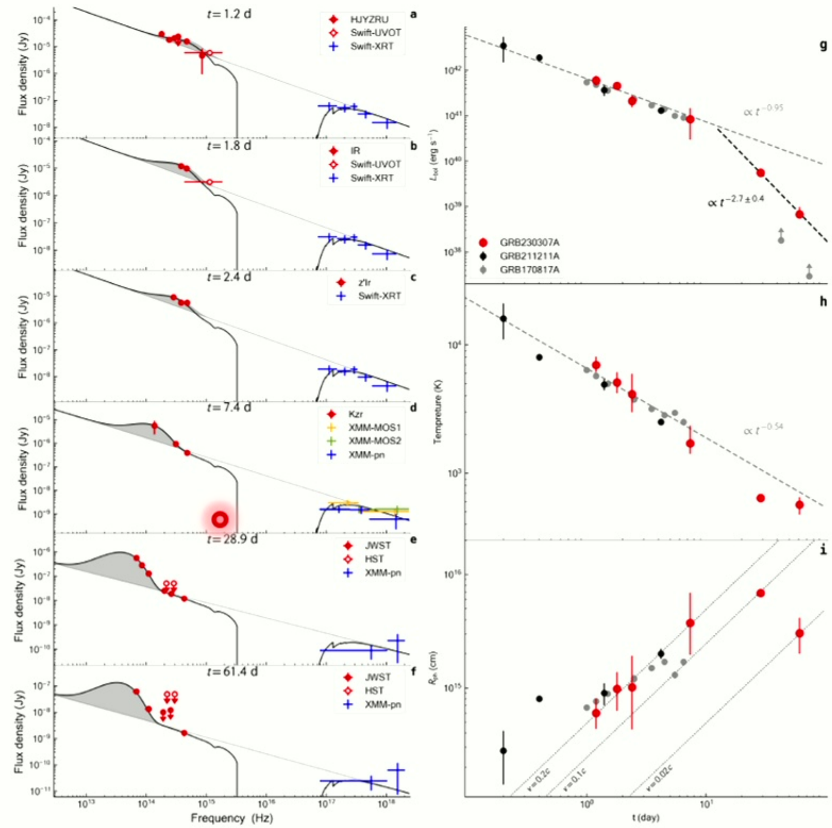


Yang, ... , Ryan, HJvE+, submitted

latest long GRB / kilonova combi: GRB 230307A



(most light curves shifted up for clarity of presentation)

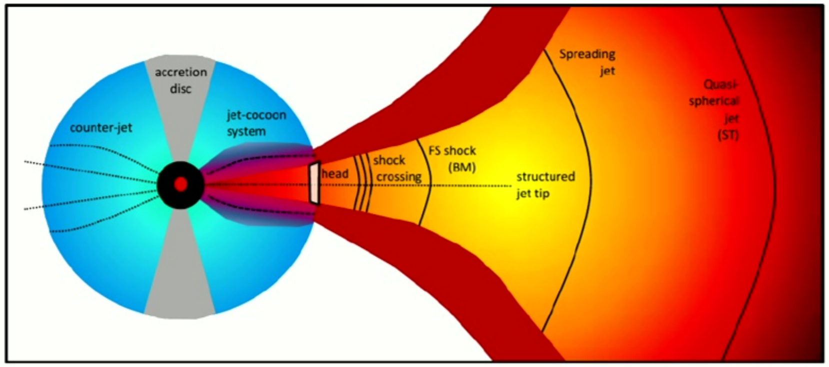


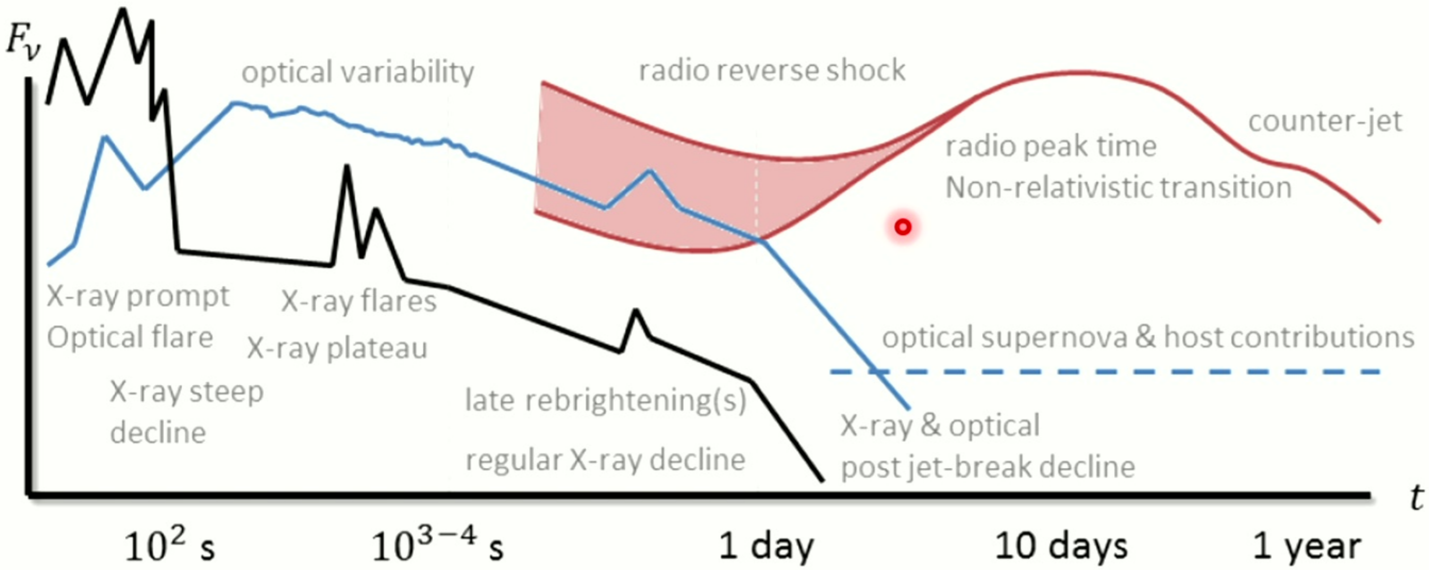
Yang, … , Ryan, HJvE+, submitted

summary

- short GRBs confirmed as EM counterparts to GW emission. Potentially a subclass of long GRBs will be too, at some point?
- modelling GRB jets when seen off-axis requires accounting for structure
- numerical challenges of GRB afterglow jet modelling: range of scales, thin shock fronts
- simulations & resulting spectra can be rescaled and packaged into templates for fast model-fitting to data
- co-fitting afterglow, centroid & GW offers tight constraints on jet orientation from NS mergers, in turn constraining distance better than GW alone. Can be matched to independent redshift measurements for calibrating cosmological parameters

Gamma-ray bursts and their afterglows





Schematic light curves for a long (massive star collapse) GRB, seen on-axis