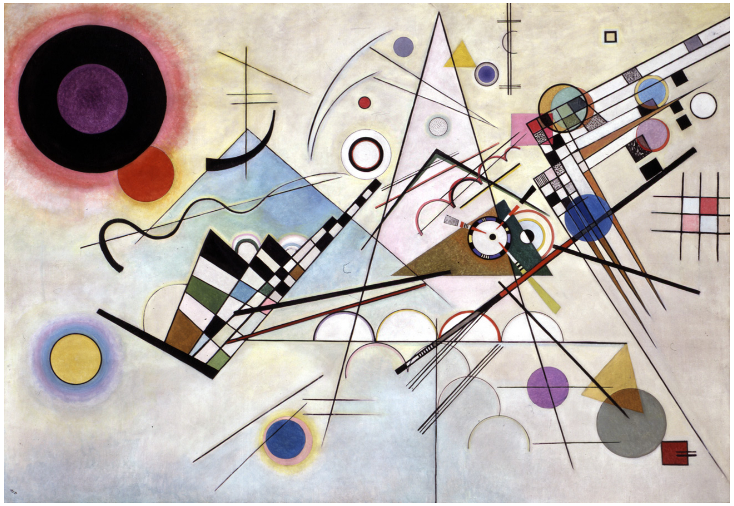
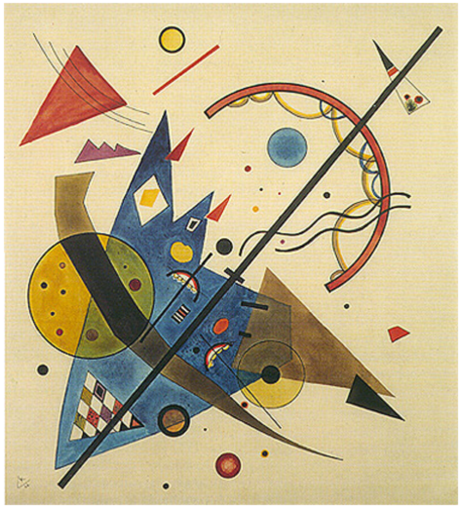
Electromagnetic counterparts to NS+NS mergers

Frédéric Daigne (Institut d'Astrophysique de Paris – Sorbonne Université)

with Robert Mochkovitch & Raphaël Duque



Kandinksy – Ccomposition 8 - 1923



Kandinksy – Curves and sharp angles - 1923

First workshop of the Mexican-French LIA ERIDANUS – 4 June 2019

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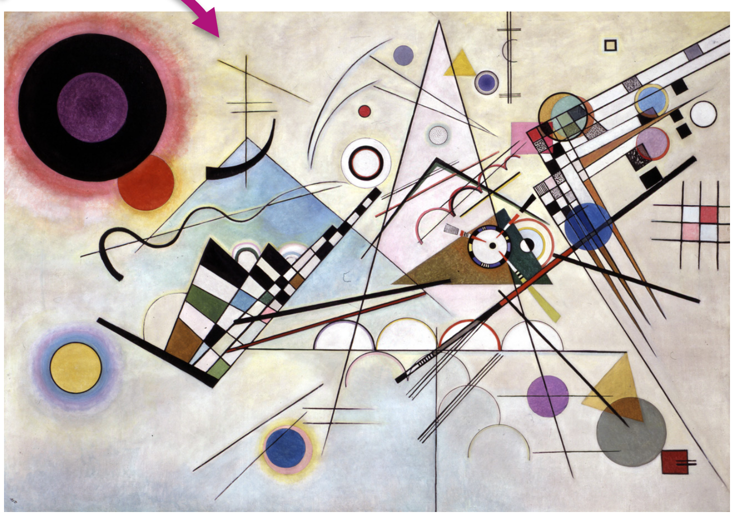


Kandinksy – Ccomposition 8 - 1923

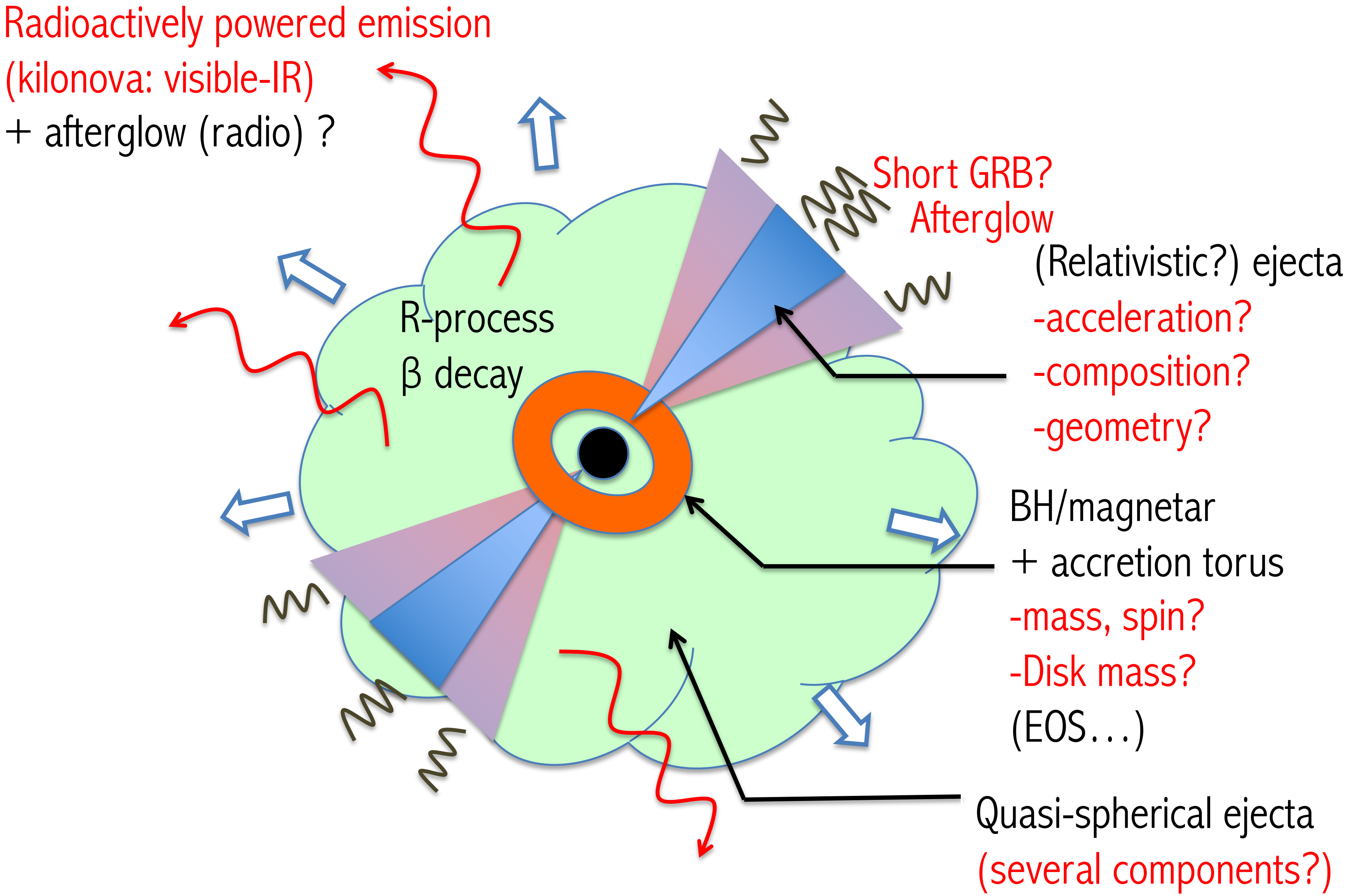
?

andinksy – Curves and sharp angles - 1923

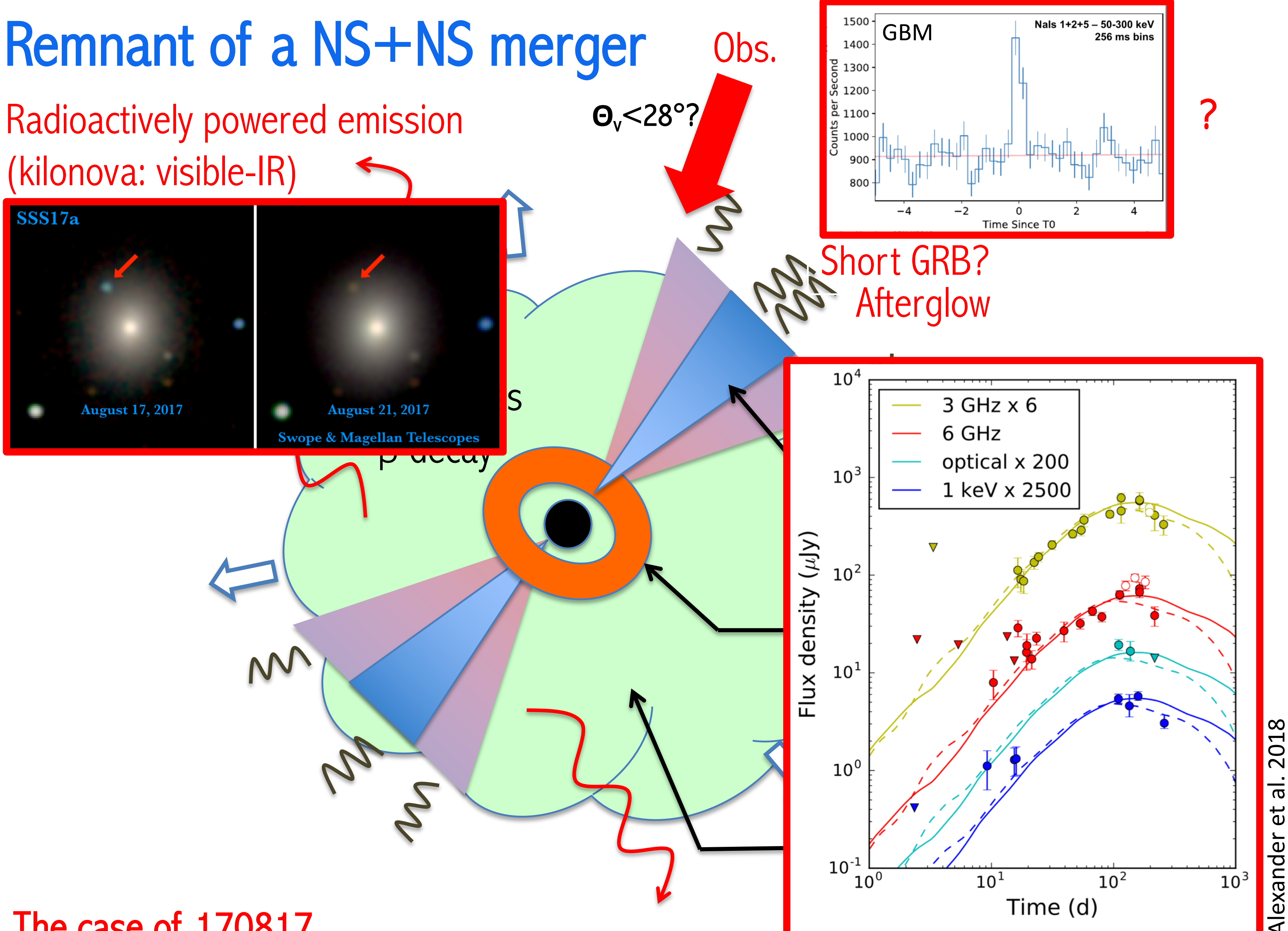
First workshop of the Mexican-French LIA ERIDANUS – 4 June 2019

GW 170817 and counterparts

Remnant of a NS+NS merger



Remnant of a NS+NS merger

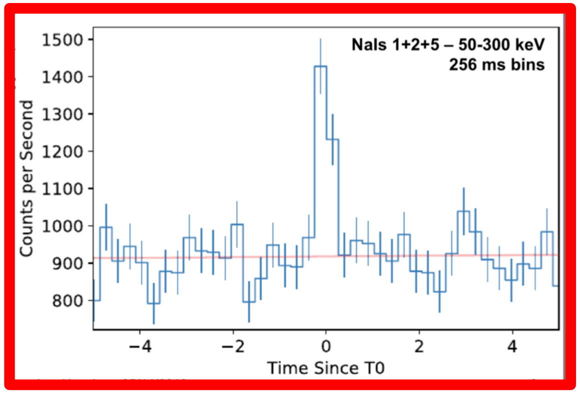


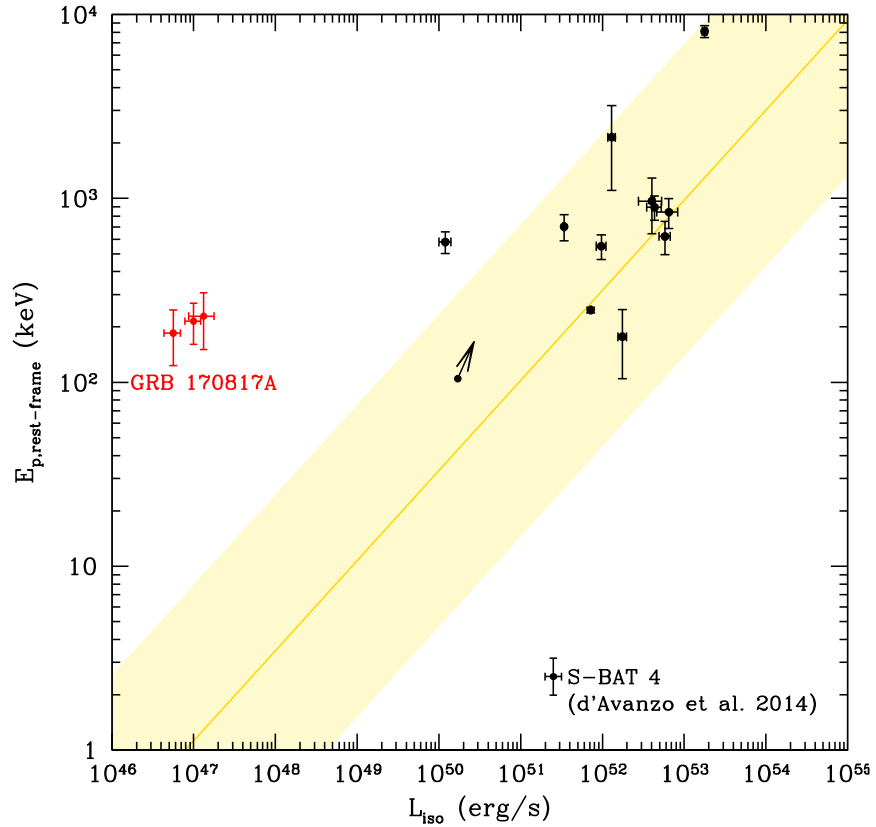
The case of 170817

Short GRB

Short GRB

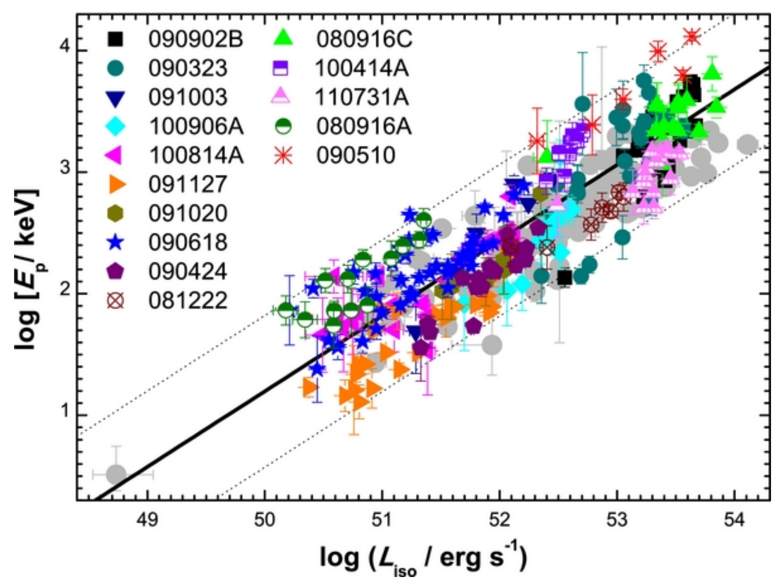
GRB170817A=puzzling
(not very hard, very under-luminous)





Delay 1.7s ; Duration 1.5 s

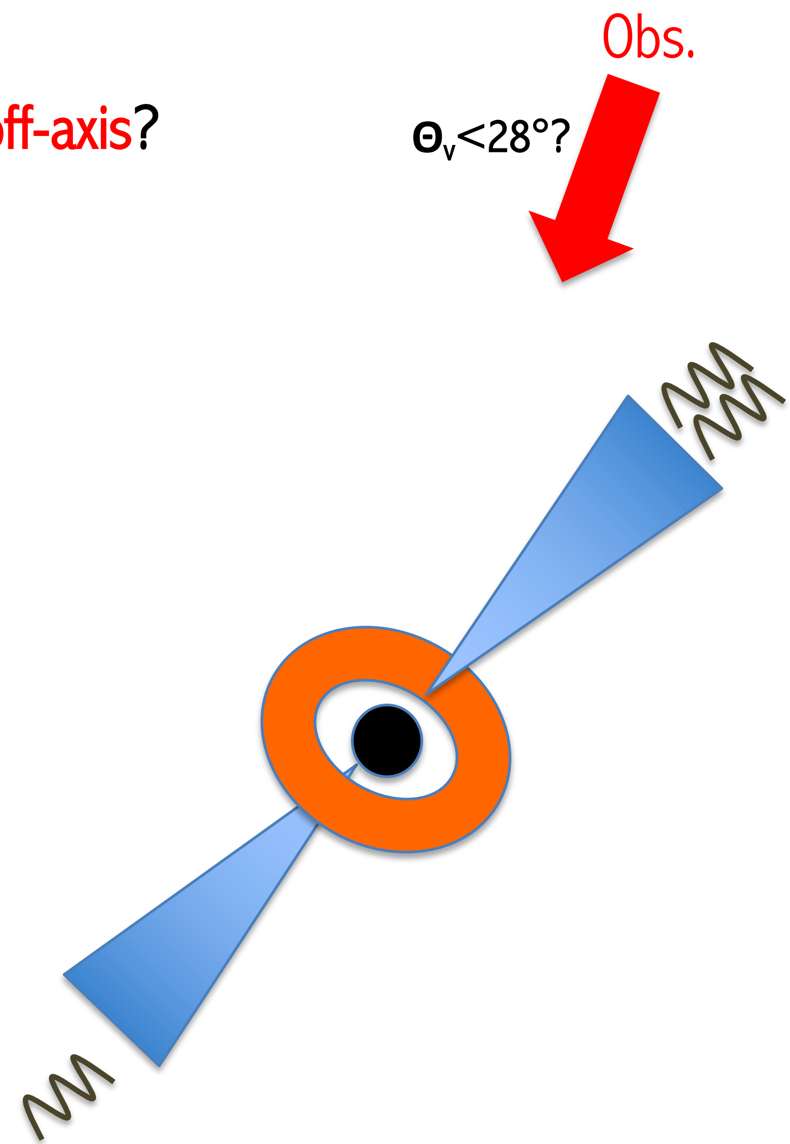
$L_p \sim 10^{47}$ erg/s ; $E_{\gamma,iso} \sim 4\times10^{46}$ erg



(Lu et al, 2012)

Short GRB:

relativistic jet, seen off-axis?



Short GRB

GRB170817A=puzzling
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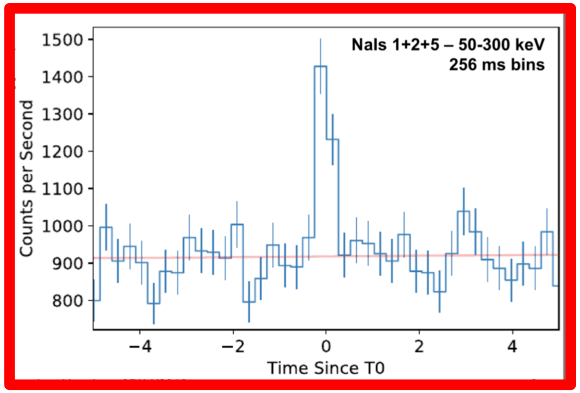
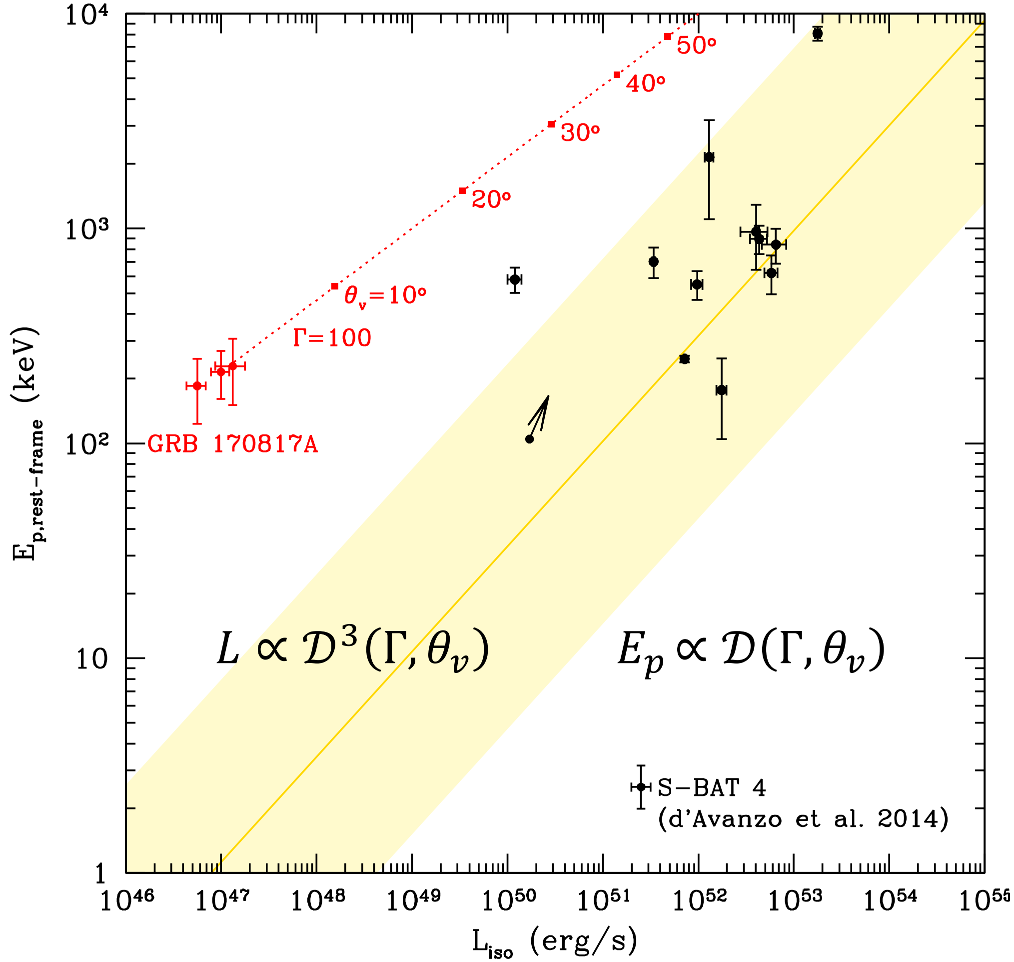


Delay 1.7s ; Duration 1.5 s

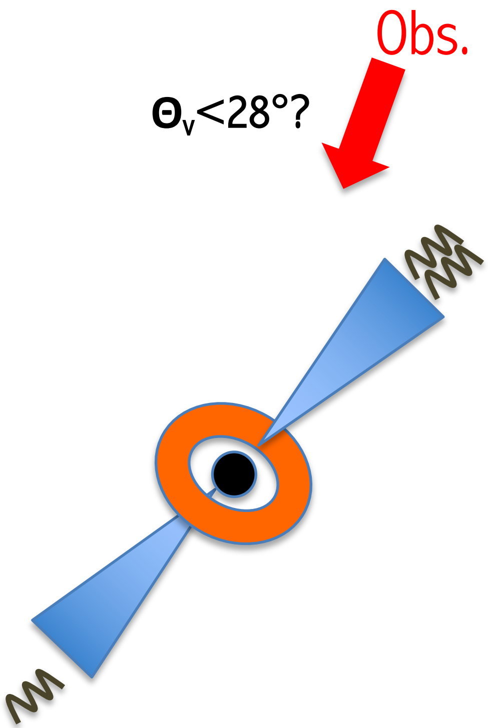
L_p ~ 10^{47} erg/s ; $E_{\gamma,iso}$ ~ 4×10^{46} erg

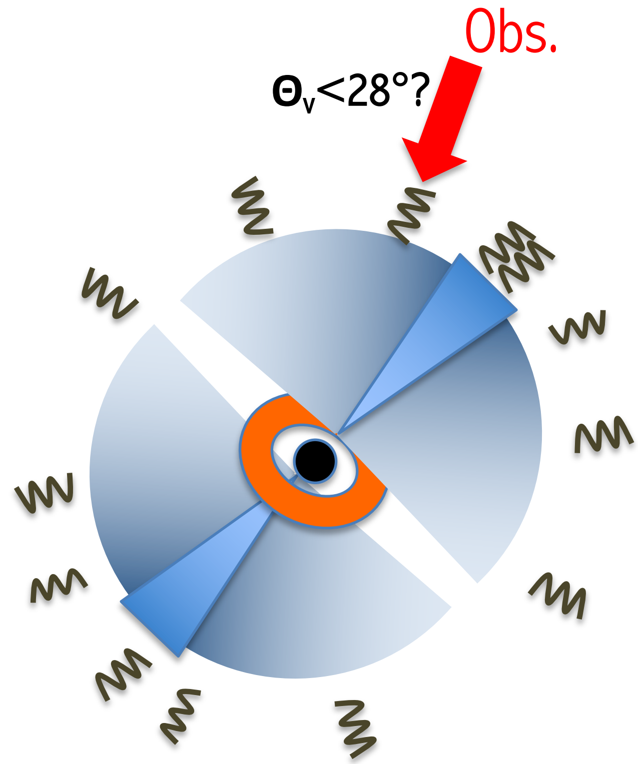


- Standard GRB seen off-axis: **unlikely**
  (Ep would be very high if seen on-axis)
- Gamma gamma opacity (Matsumoto+19)

Short GRB:

- Standard GRB physics under an unsual viewing angle (UR jet seen off-axis)
  or
- Mildly relativistic outflow pointing towards us? Emission mechanism?

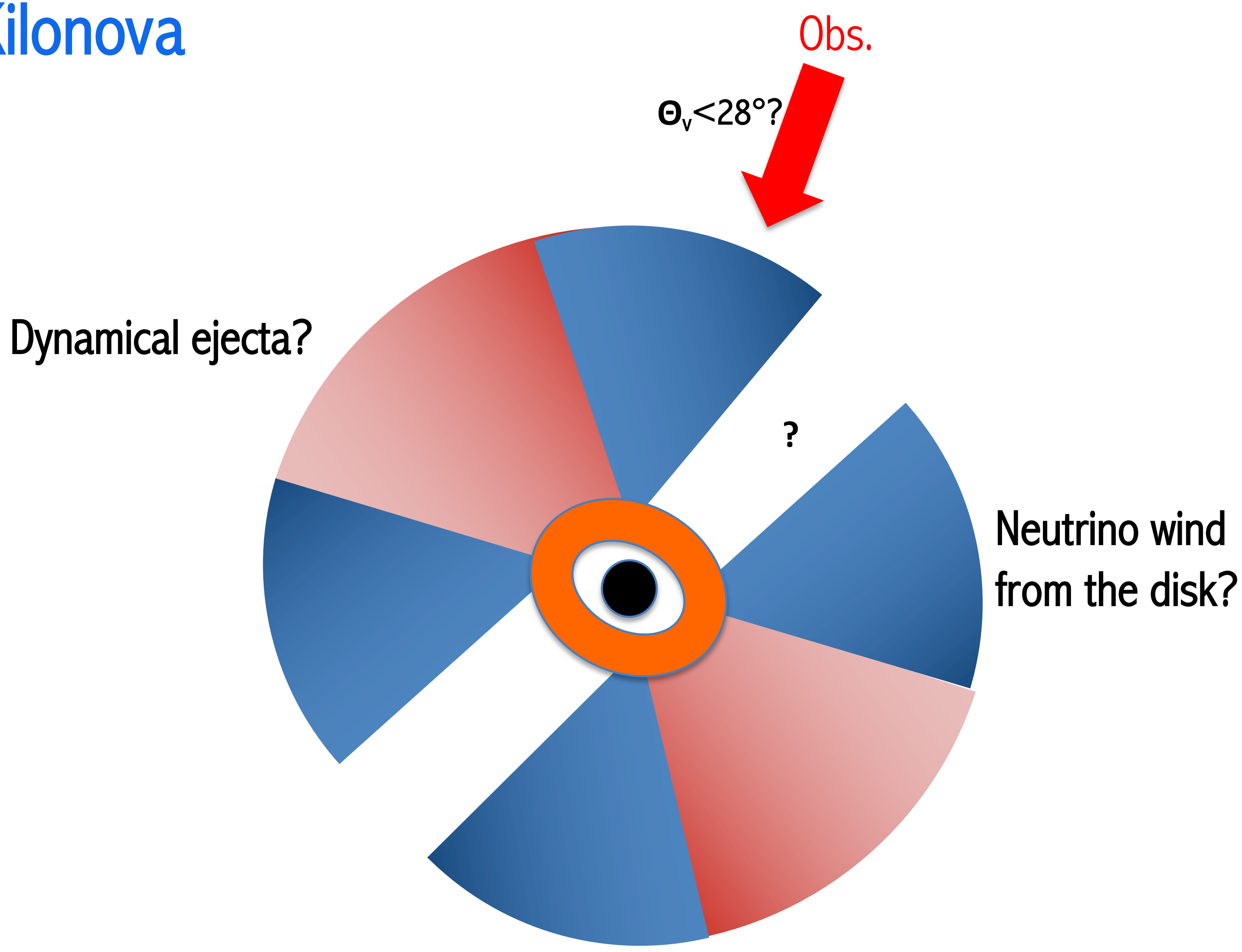




Kilonova

Robert Mochkovitch's talk this afternoon

Kilonova



Geometry of the ejection responsible for the kilonova?
Time sequence compared to other ejections?

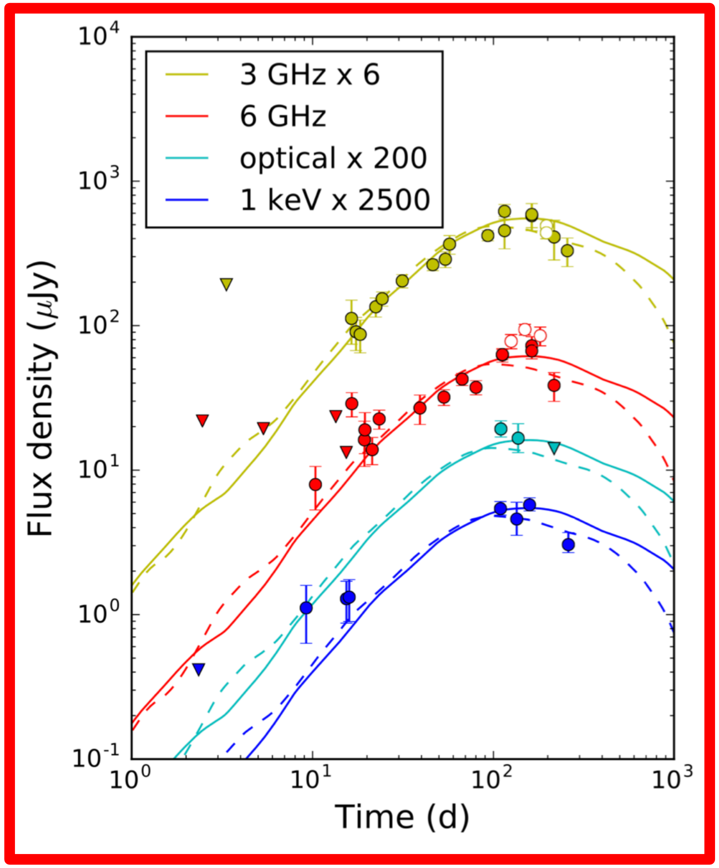
Afterglow

Afterglow

GW170817: X, V and radio = same spectral regime $\nu_m < \nu_{obs} < \nu_c$

Rise to maximum as $\sim t^{1.5}$

Peak at ~150 days



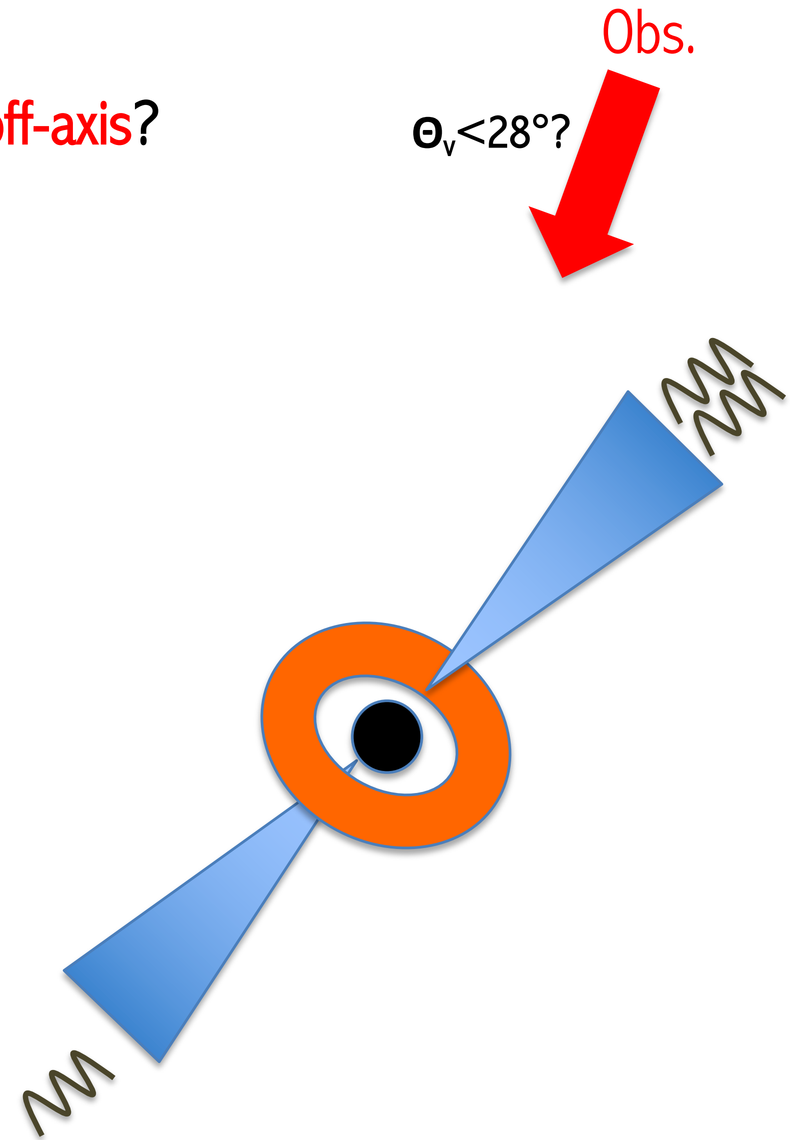
Alexander et al. 2018

Afterglow:

relativistic jet, seen off-axis?

Ruled out!

See however Gill+19

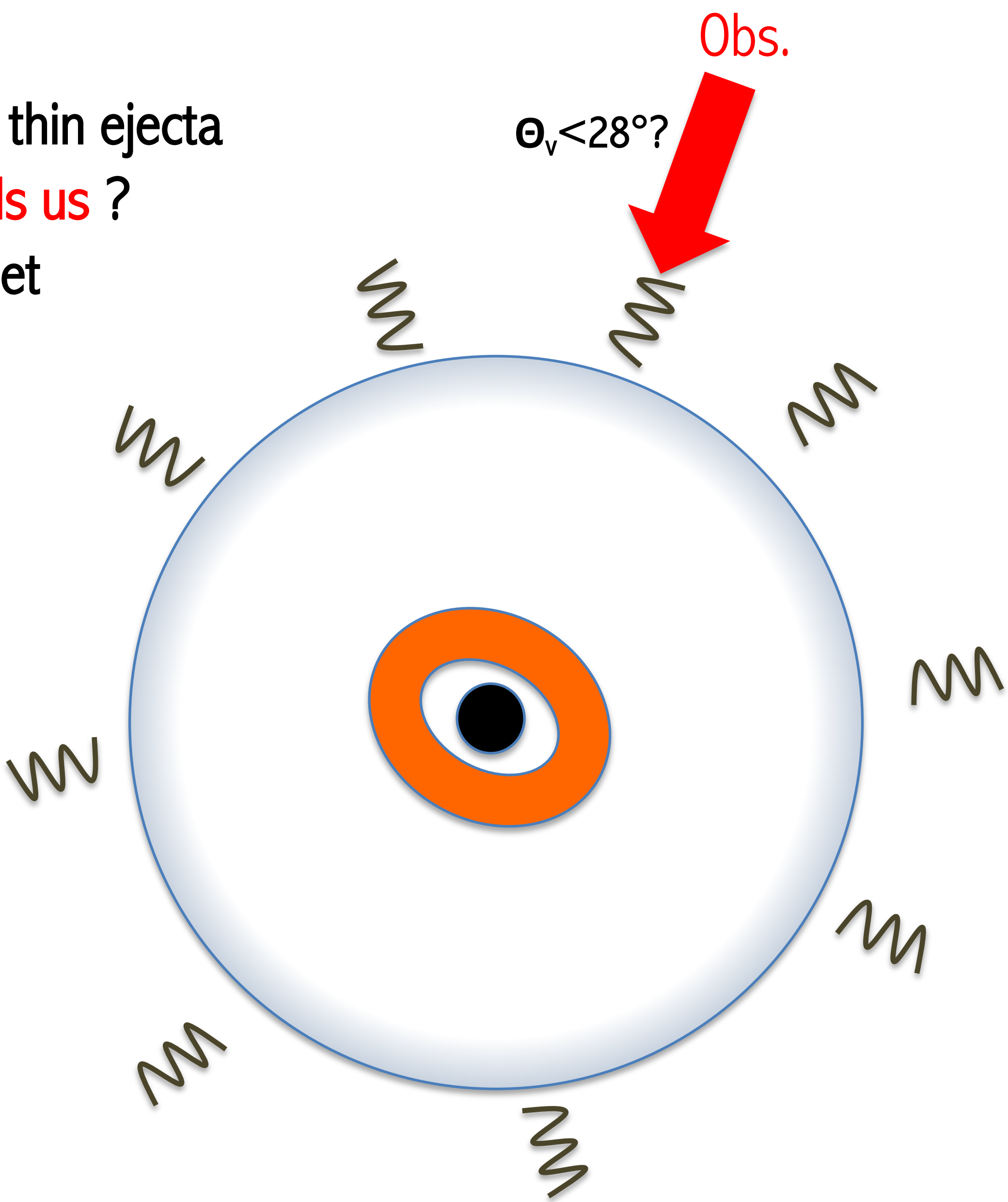


Kilonova ejectas not shown

Afterglow:

quasi-spherical thin ejecta
pointing towards us ?
without a core jet

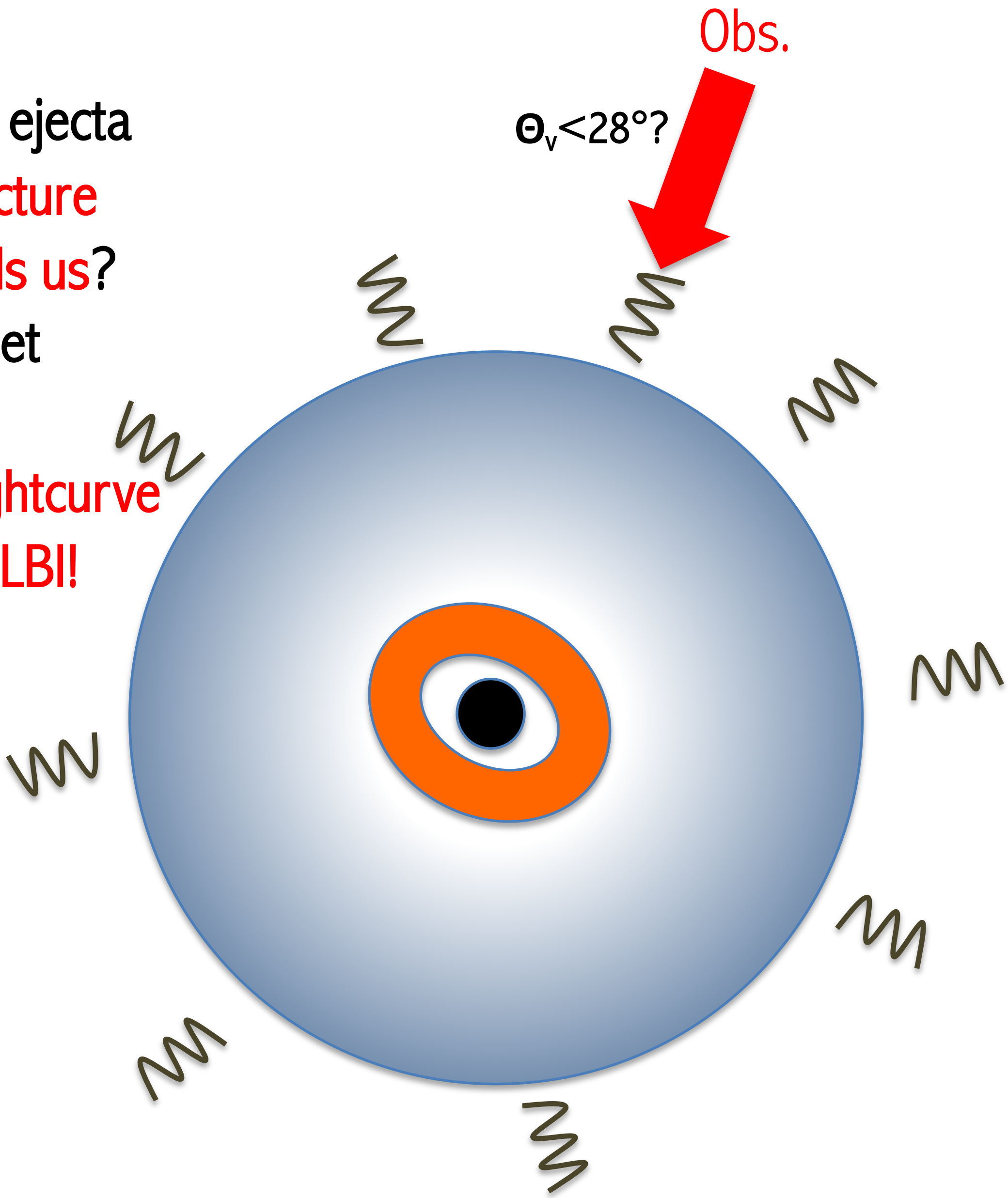
Ruled out!



Afterglow:

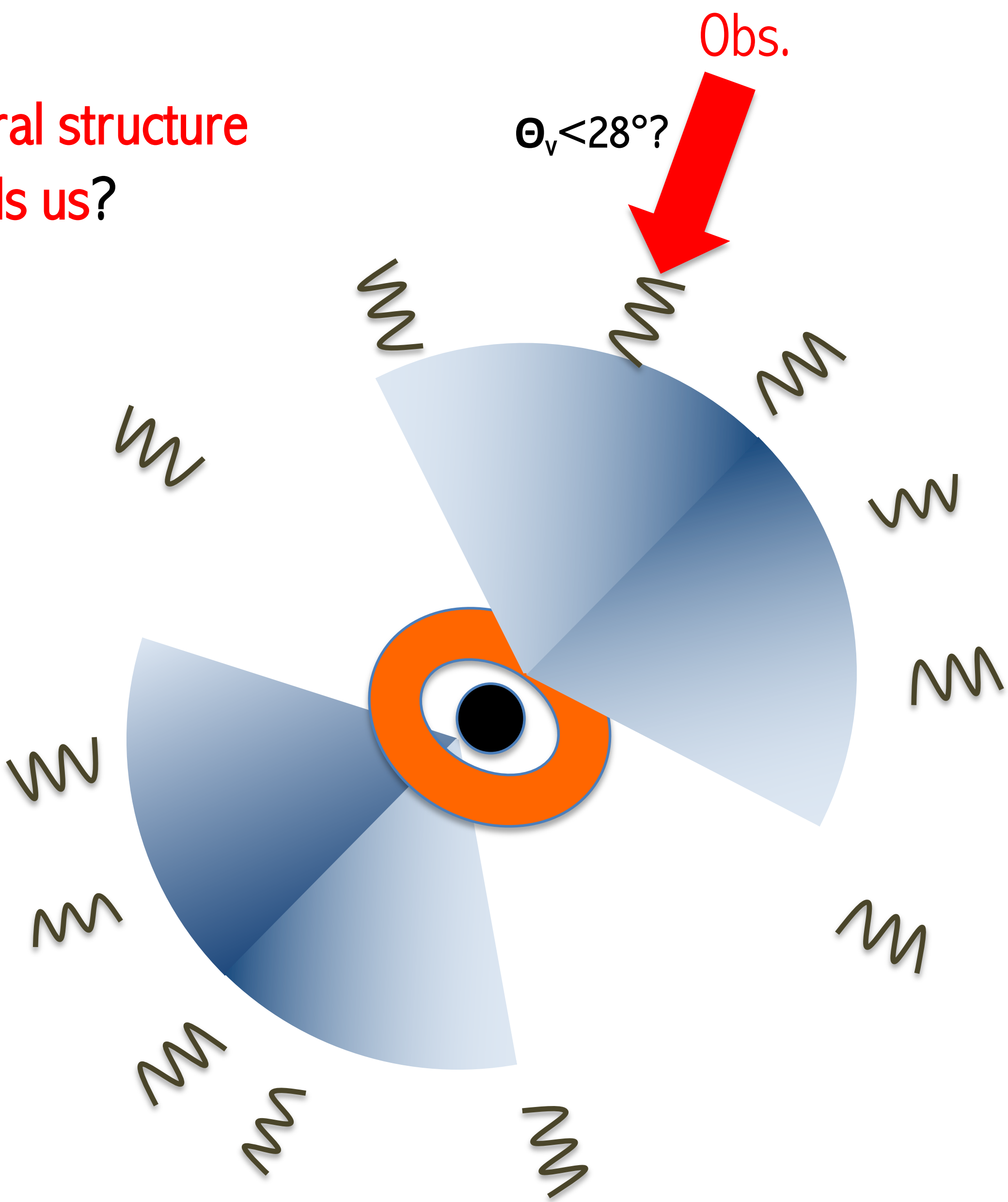
quasi-spherical ejecta
with radial structure
pointing towards us?
without a core jet

-Fits well the lightcurve
-Ruled out by VLBI!

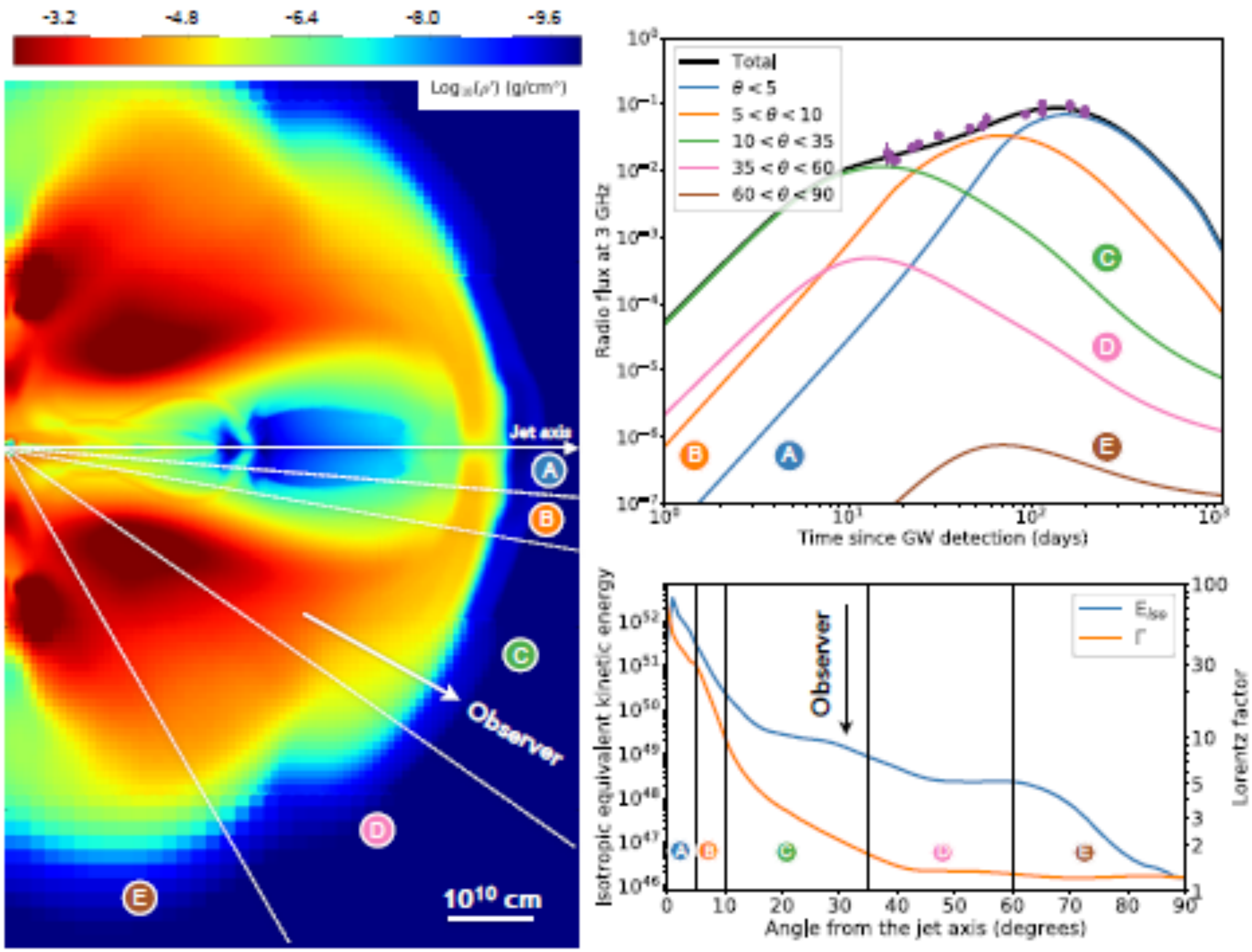


Afterglow:

ejecta with lateral structure pointing towards us?



Afterglow



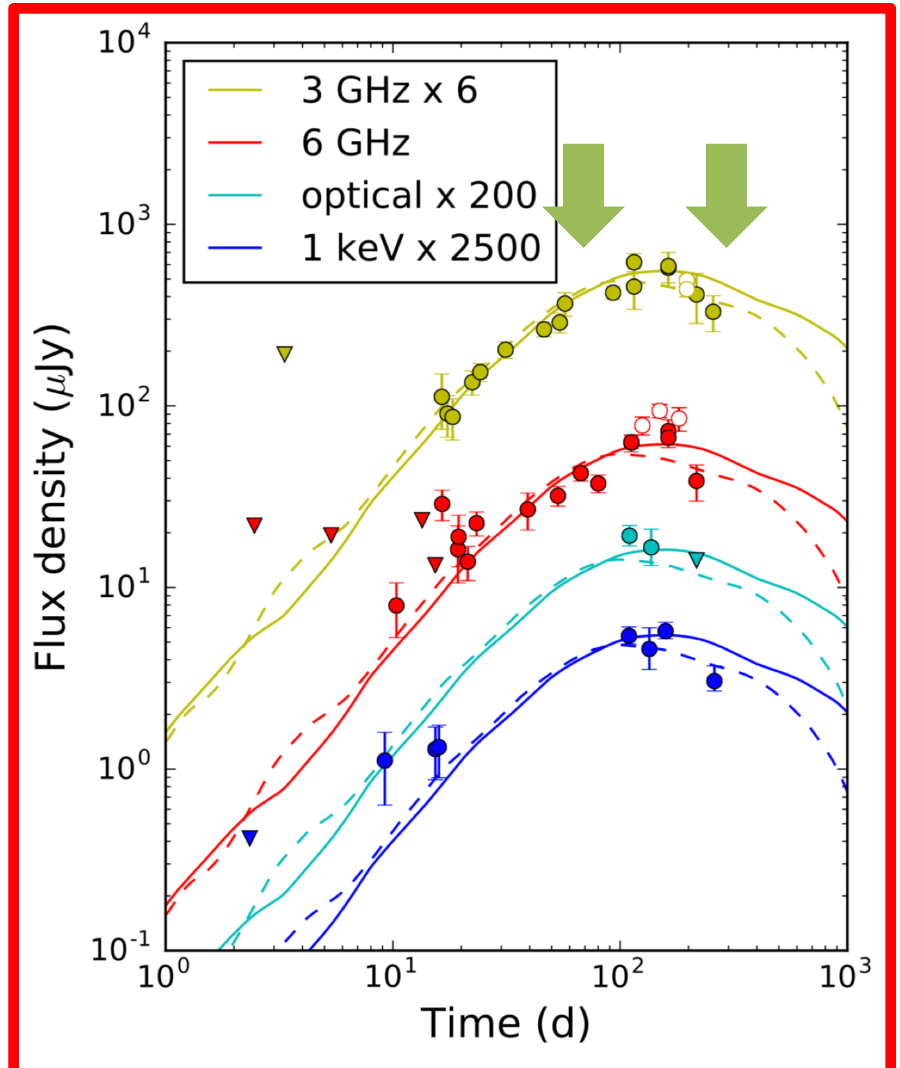
Lazzati et al. 2018

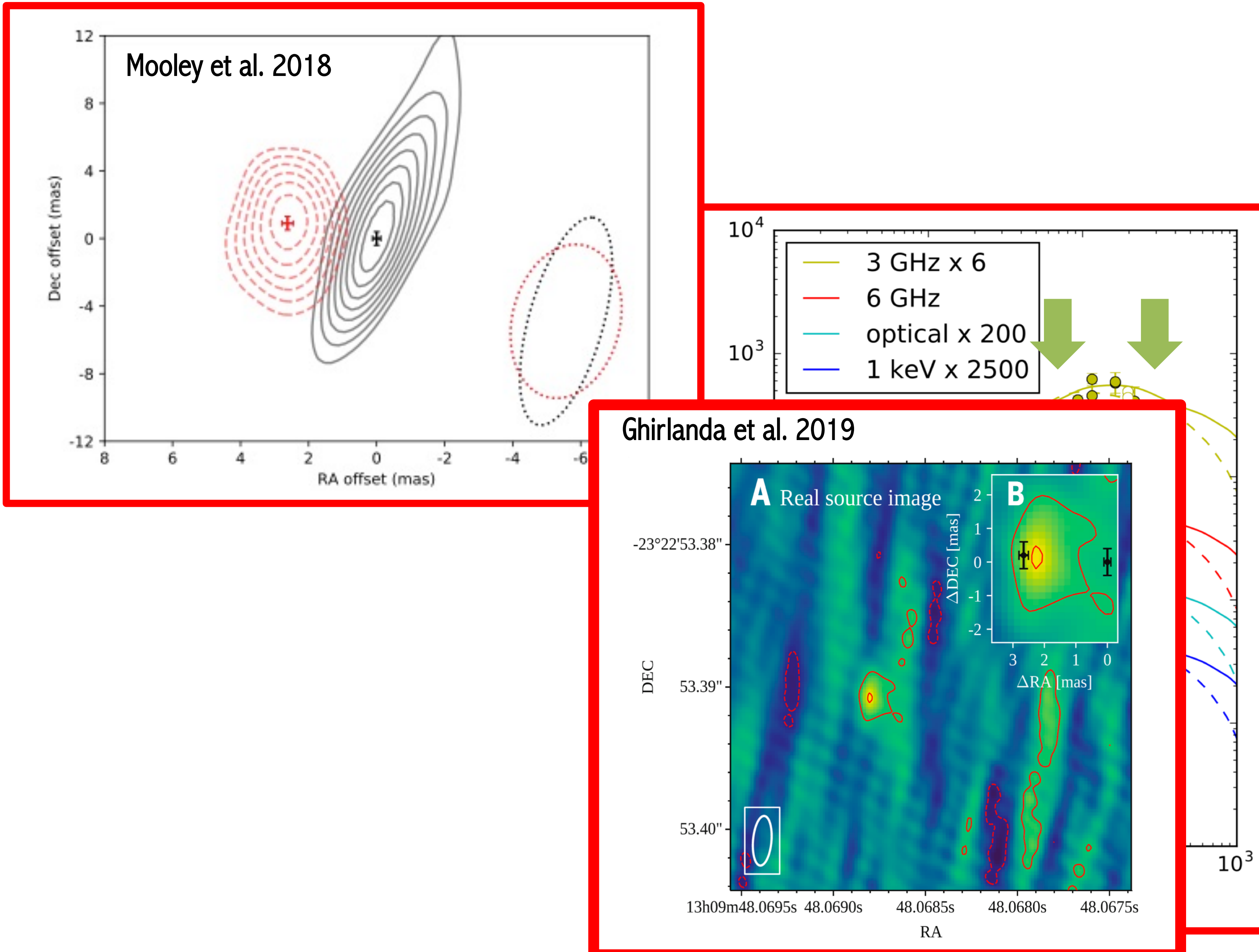
Here: the central jet ($E_{iso,on}$~10^{52} erg) contributes at 100 days

Radio afterglow: latest observations

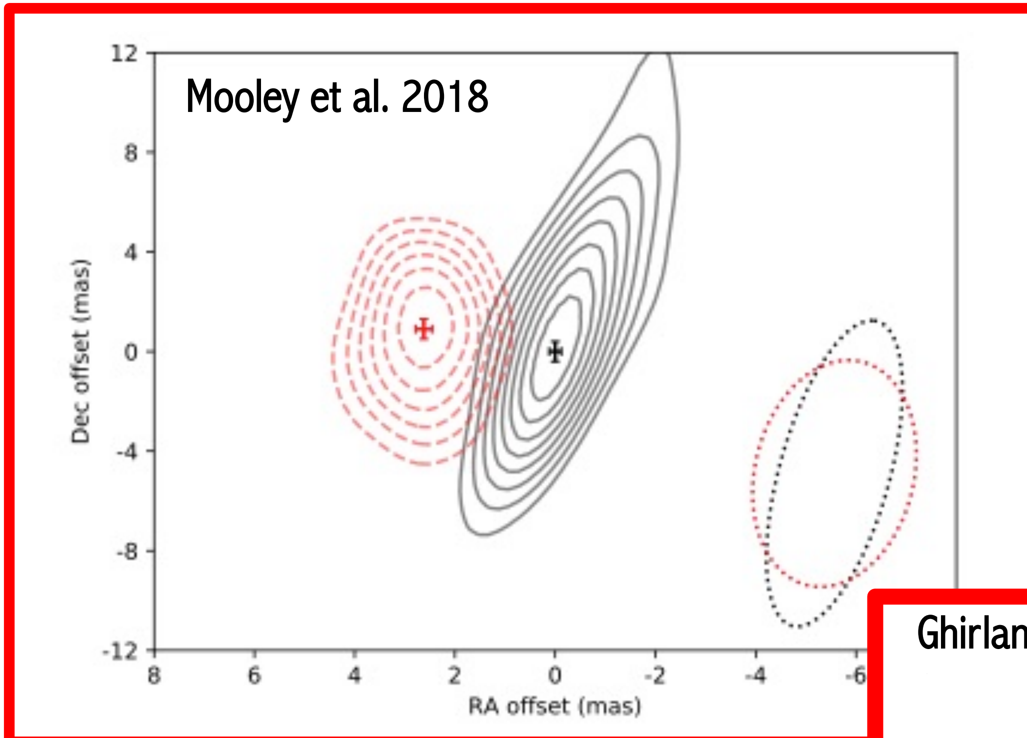
- VLBI: motion of the centroid (Mooley et al. 2018) between 75 and 230 days

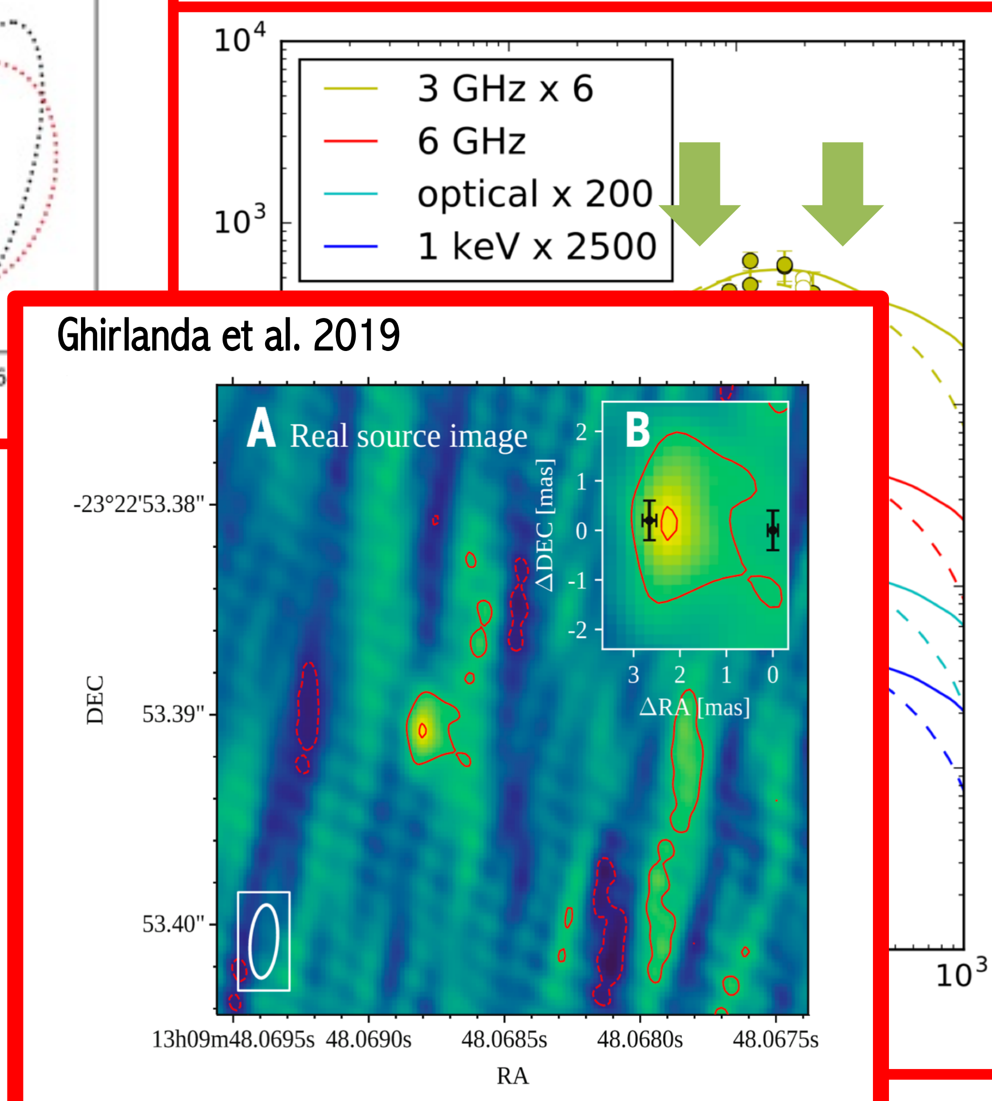
  + high resolution images: source still very compact (Ghirlanda et al. 2019)





Mooley et al. 2018
Dec offset (mas)
RA offset (mas)
3 GHz x 6
6 GHz
optical x 200
1 keV x 2500
Ghirlanda et al. 2019
A Real source image
B
ΔDEC [mas]
ΔRA [mas]
DEC
RA
-23°22'53.38"
53.39"
53.40"
13h09m48.0695s
48.0690s
48.0685s
48.0680s
48.0675s





- Supeluminic apparent motion
- Still compact size at late times

- Favors a emerging jet at ~20° !

Radio afterglow: latest observations

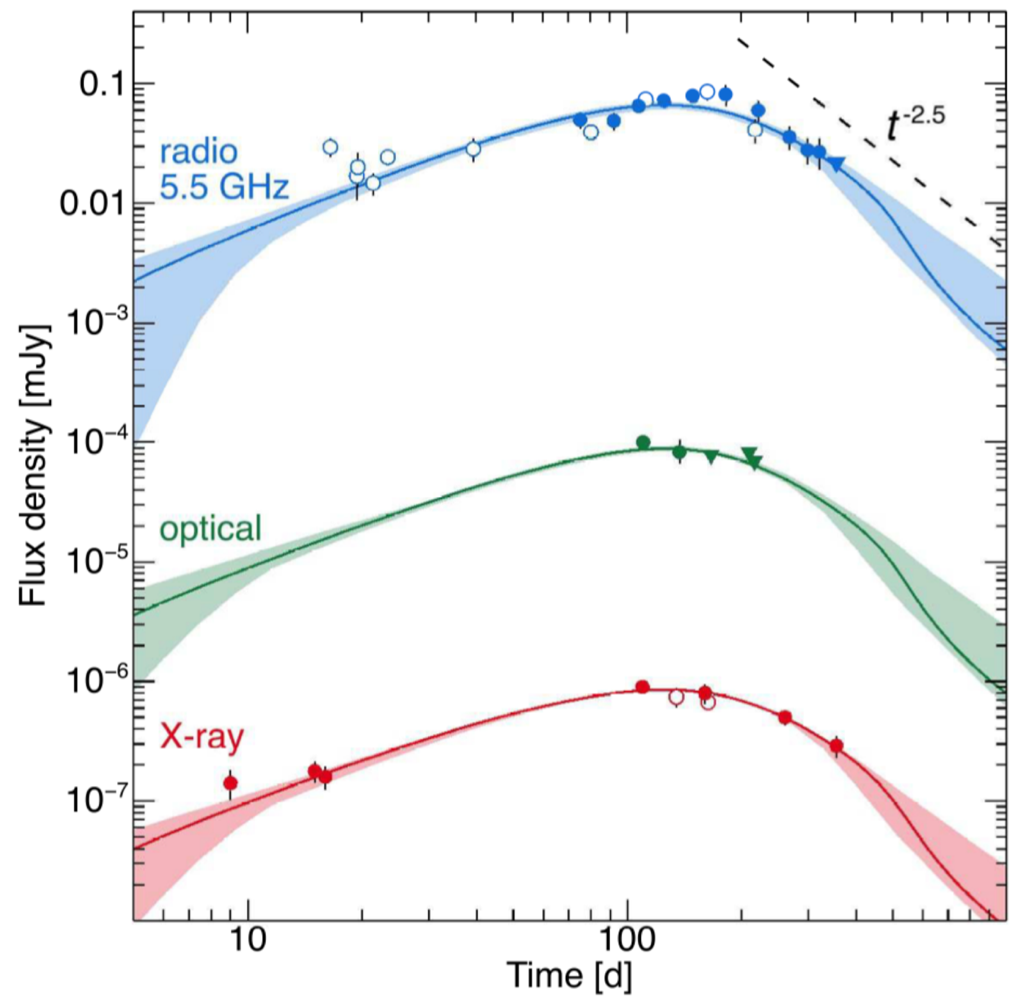
- Best model:
  -lateral structure
  -core jet emerges at the maximum of the lightcurve

  -off-axis observer at ~20°

  -external density ~ 0.003 cm^{-3}

  -central jet:
  E_{iso}~2 10^{52} erg
  opening angle ~4°

(Mooley et al., 2018, Ghirlanda et al. 2019, Troja et al. 2018, Granot et al. 2018, ...)



Best fit by a structured jet (Troja et al. 2018)

Afterglow

- Origin of the lateral structure? Which post-merger behavior?

  1. relativistic ejection is delayed, jet has to go through the blue kilonova ejecta
     → formation of a coocon (afterglow) ; jet breakout (GRB?)
     → jet emerges or not – successful in the case of GW170817

  2. the whole ejection is produced at the same time after the merger, with structure
     → in the core: ultra-relativistic jet (bright GRB if on-axis)
     → intermediate latitude: mildly rel. ejecta (afterglow) with radial/lateral structure
     → larger latitudes: blue kilonova ejecta

Short GRB:

- Origin of the observed short GRB?

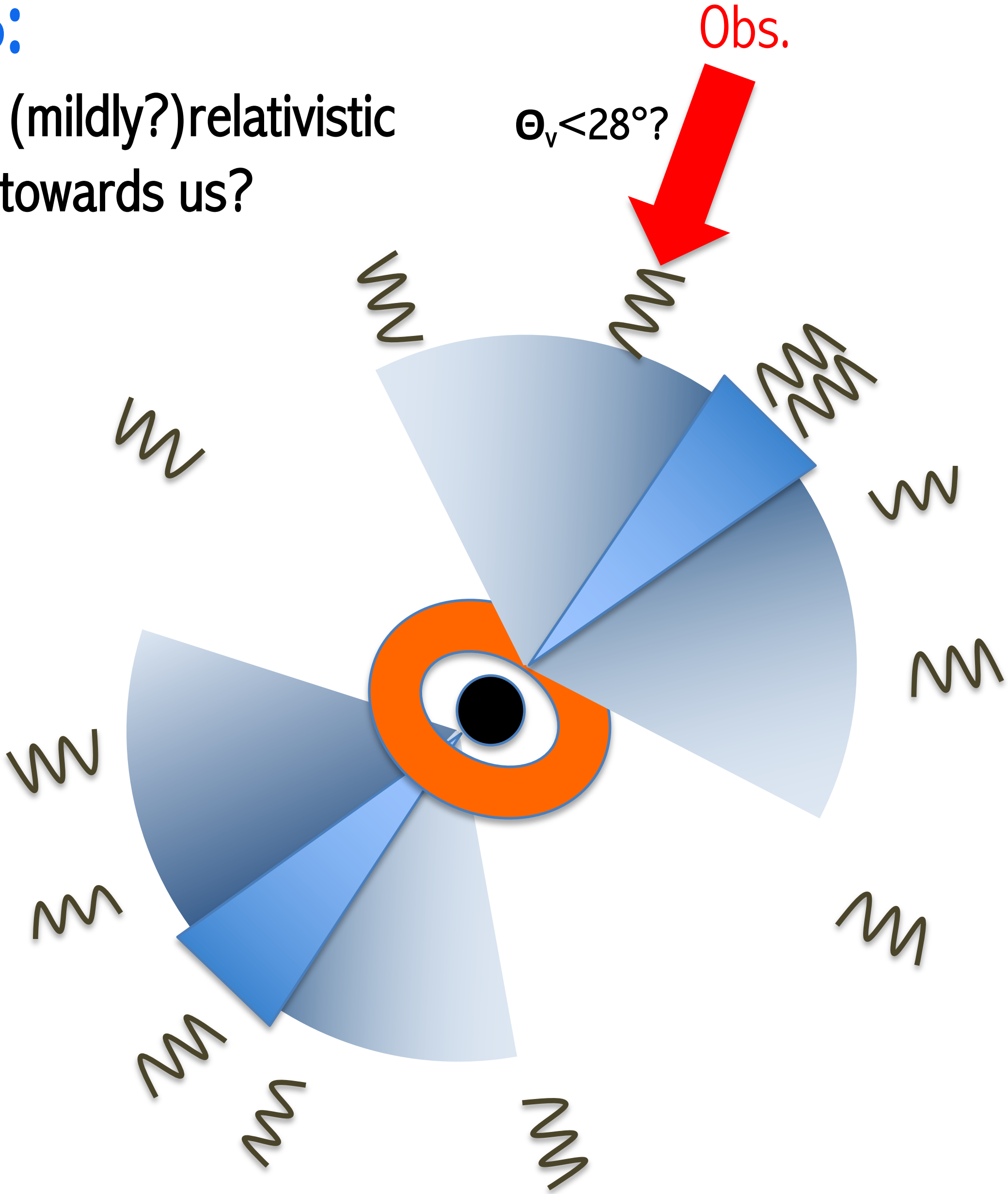
  In the emerging picture from the late radio afterglow:
  - there is a core jet
  - there is lateral structure around it

  Two possibilities remain:
  - GRB 170817A = off-axis observation of a GRB produced by the core jet with standard mechanism? Very unlikely

  - GRB 170817A = emission from the material surrounding the core jet? (region pointing towards us)
    standard emission mechanism
    OR new mechanism (e.g. shock breakout)

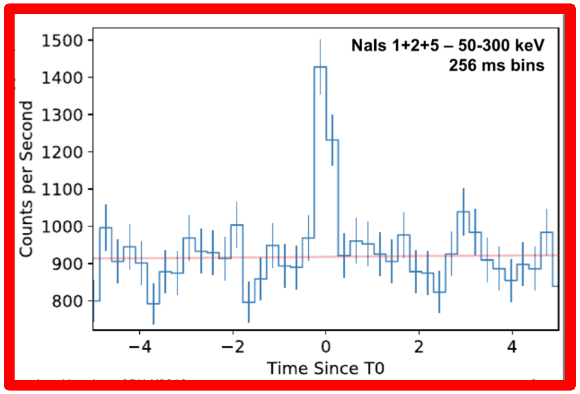
Short GRB:

dissipation in a (mildly?)relativistic ejecta pointing towards us?



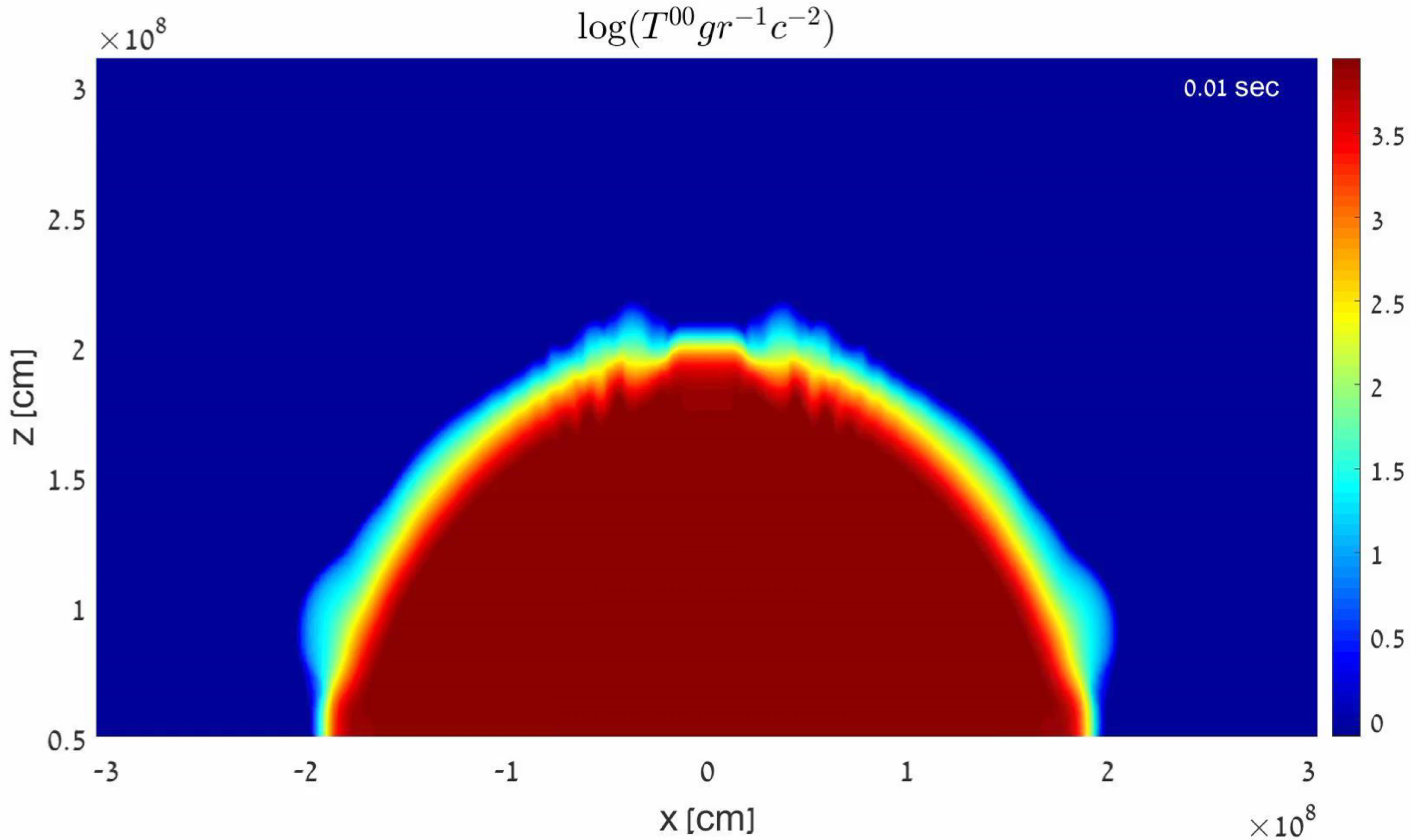
Short GRB: emission mechanism?

GRB170817A=puzzling (not very hard, very under-luminous)



- Dissipation in a mildly relativistic outflow pointing towards us?
  (jet with lateral structure, cocoon, . . .)

Cocoon+shock breakout

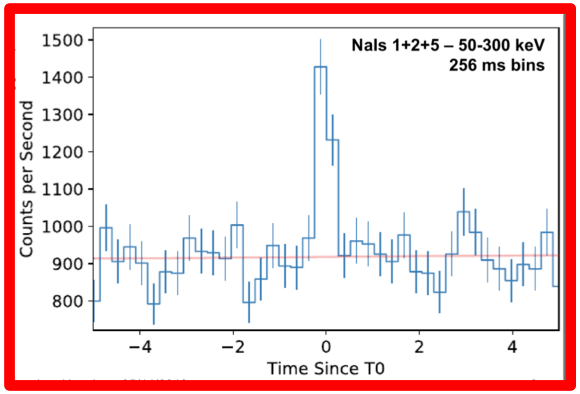


(Gottlieb et al, 2018)

- The central engine (newly formed BH, magnetar) launches a jet, which interacts with the KN ejecta: cocoon.
- This jet can be successful (i.e. continuing to propagate after breaking-out) or not

Internal shocks?

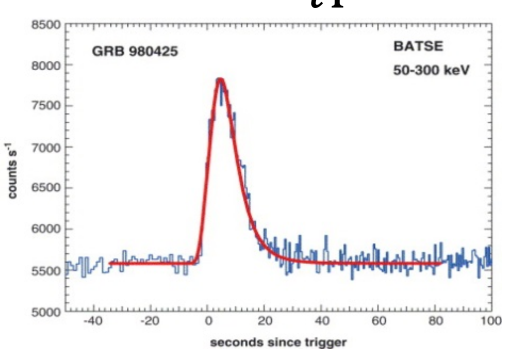
GRB170817A=puzzling (not very hard, very under-luminous)



- Standard dissipation process?
  Example: internal shocks can explain GRB170817A for a low Lorentz factor/moderate kinetic energy flux

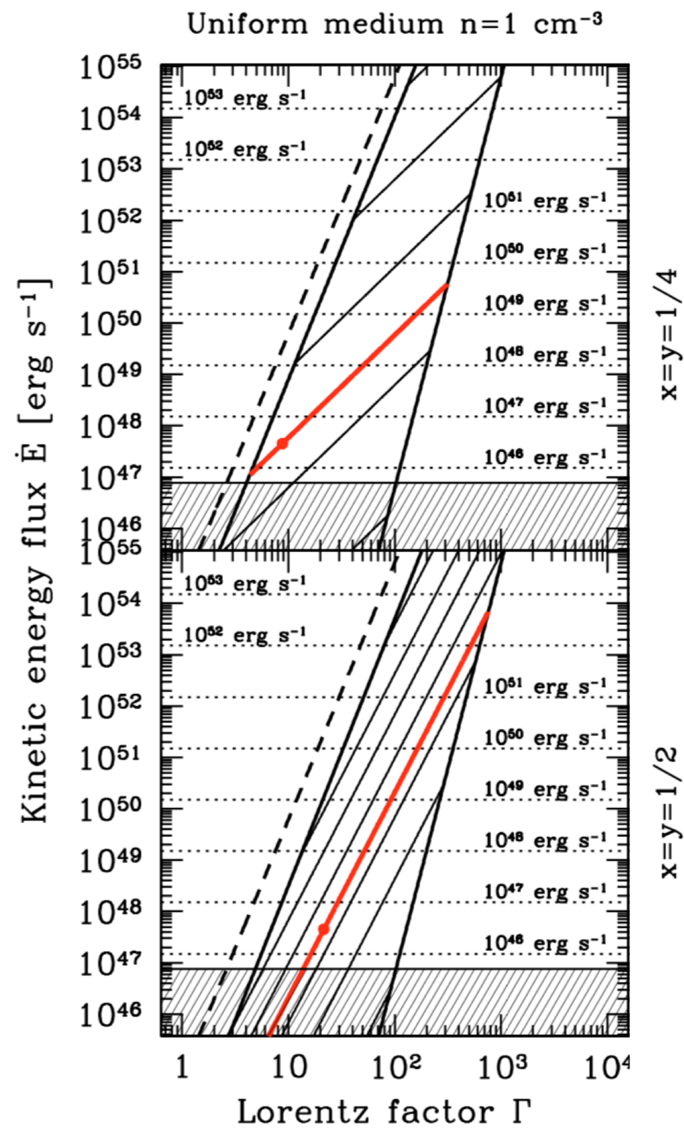
$$E_p \propto \frac{\dot{E}^{1/2}\,\varphi(\kappa)}{\tau\Gamma^2}$$

$\dot{E}$: kinetic power
τ: variability timescale
Γ: Mean Lorentz factor
κ: « constrast » of the Lorentz factor



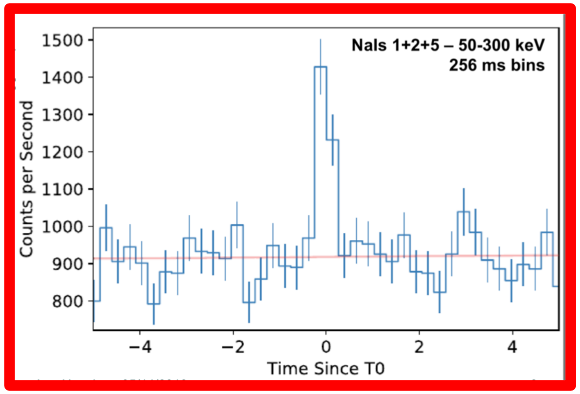
D=34 Mpc
$L_g = 10^{48}$ erg.s^{-1} ; Ep ~ 100 keV

GRB980425 at 34 Mpc
(Daigne & Mochkovitch 2007)



Short GRB: emission mechanism?

GRB170817A=puzzling (not very hard, very under-luminous)



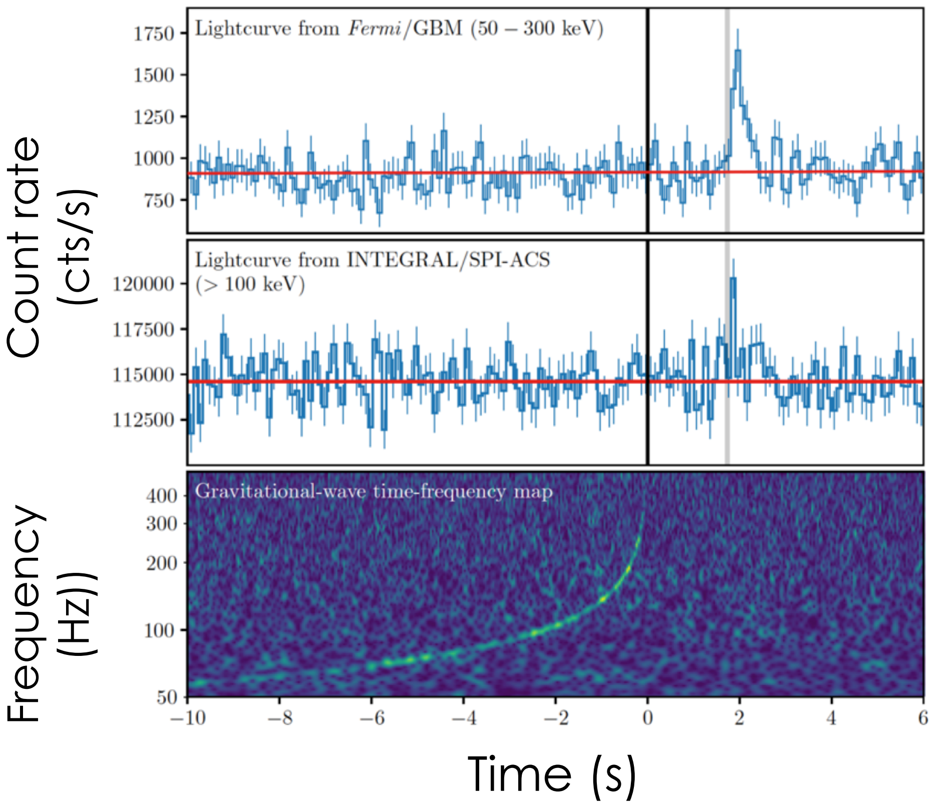
- Dissipation in a mildly relativistic outflow pointing towards us?
- Cocoon + shock breakout : OK (fine tuning for the delay?)
- Standard dissipation mechanisms (internal shocks/reconnection) in a mildly relativistic outflow pointing towards us can probably explain GRB 170817A (work in progress)

Short GRB: GW-GRB delay?

GRB170817A=puzzling (not very hard, very under-luminous

- **GW-GRB delay: ~burst duration**

$$\Delta t_{\rm GW-GRB} = \Delta t_{\rm ejection} + \frac{1-\beta}{\beta} \frac{R_{\rm emission}}{c}$$



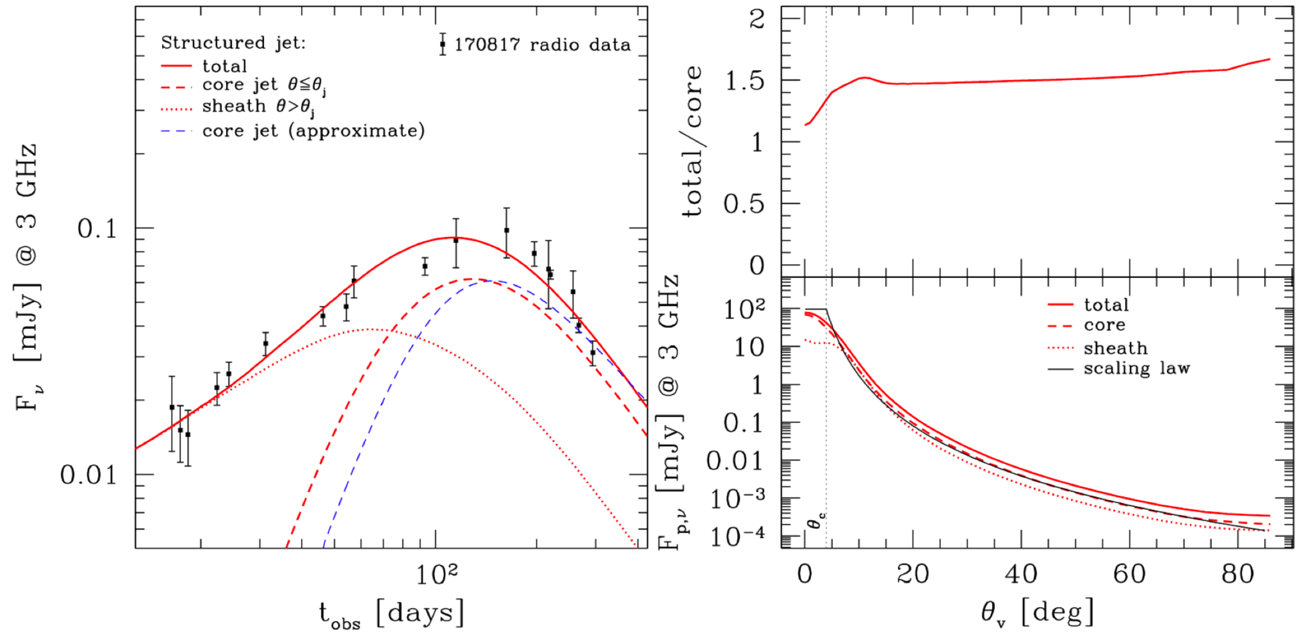
- is natural
  1) if the relativistic ejection occurs rapidly after the merger (i.e. << s)
  2) if the emission occurs above the photosphere
  (shocks, reconnection: $R_{\rm emission} \simeq 2\Gamma^2 c \Delta t_{\rm var}$)

- is less natural if the GRB is due to a shock breakout

Short/mid-term prospects

Population model: BNS+afterglow

- Core jet: 0.1 rad dominates at the peak



- Kinetic energy: deduced from SGRB luminosity function
- External density: log-normal (mean 10^{-3} per cm^3)
- Microphysics: ε_e=0.1 ; p=2.2 ; ε_B=log-normal (mean 10^{-3})
- Distance: homogeneous population (local Universe)
- Viewing angle: isotropic
- Detection: GW Horizon: O3=250 Mpc ; design = 450 Mpc
  Radio VLA=10 μJy ; SKA1-Mid = 1 μJy

Population model: results

- 10-30% of events have detectable afterglows

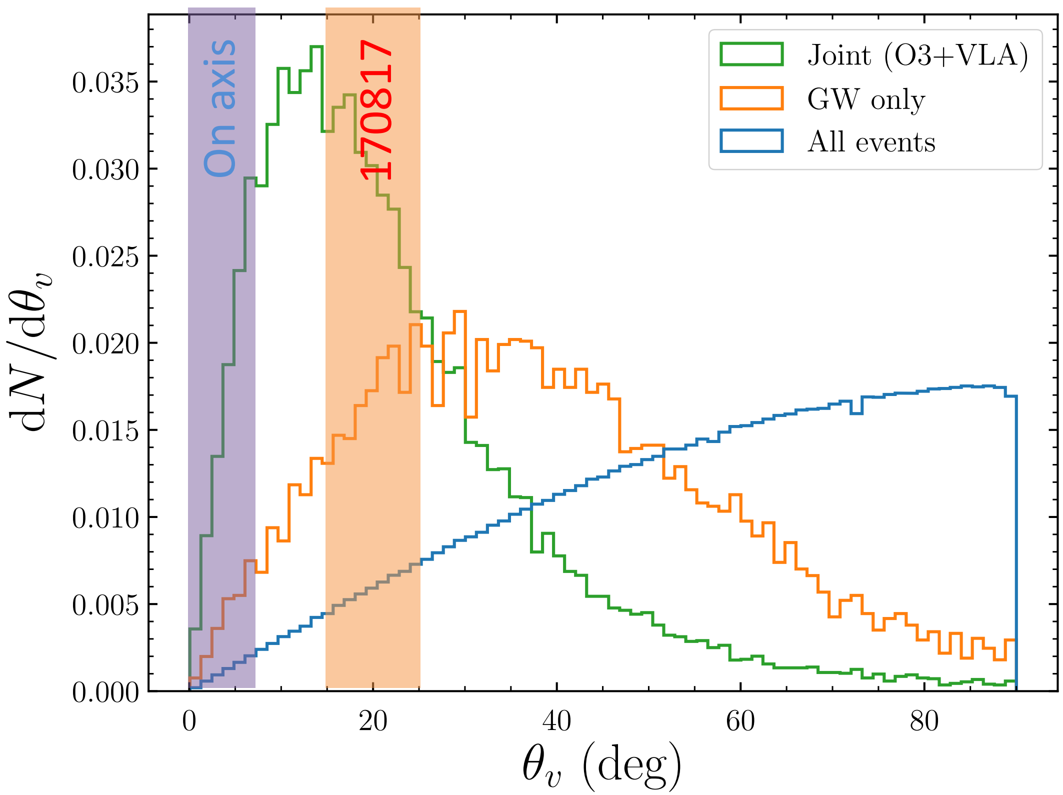
Detector conf.	#GW	#(GW+AG)
O3 + VLA	9	3
Design + VLA	21	5
Design + SKA	21	10

- Uncertainties: $^{+200\%}_{-73\%}$ (intrinsic rate from LIGO-Virgo O2/O3) + uncertainty on population model
- Large deviations from these estimates? Constraints on the intrinsic population.

- How to detect « detectable » events?

Population model: results

- Viewing angle:



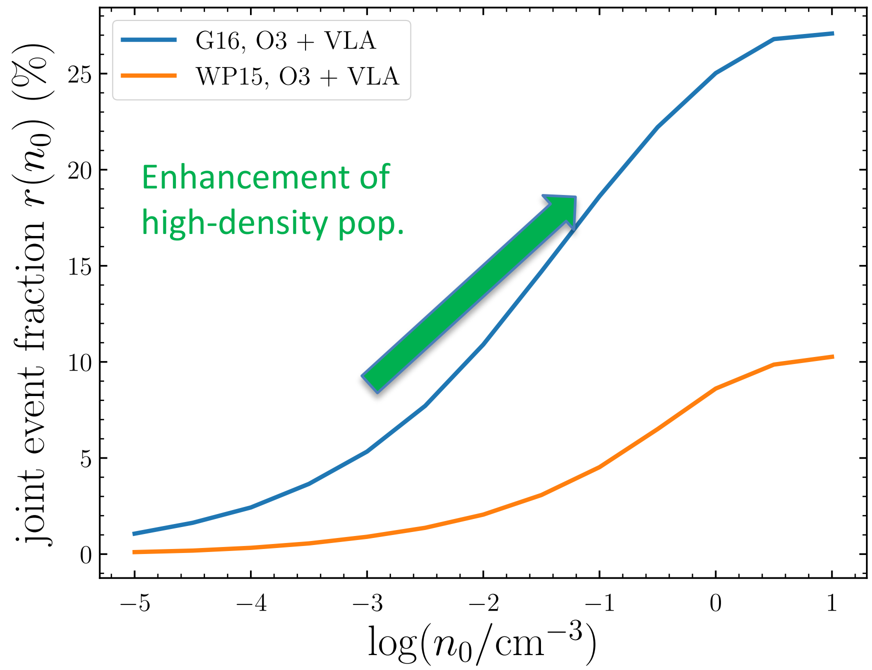
- Most events seen off axis!
- Mean angle ~20-30°
- ≲10% on axis (classical SGRB?)

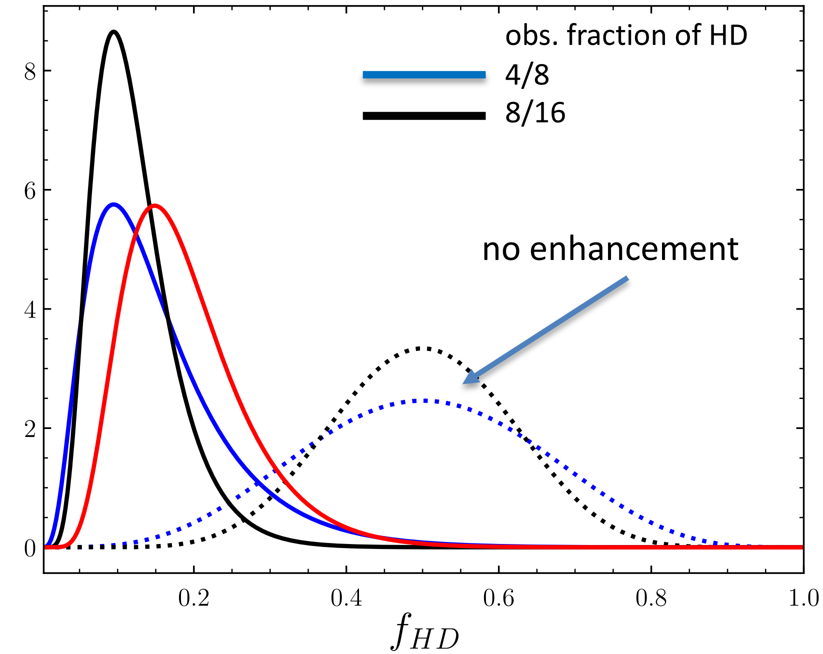
Beniamini+18: 1-10% (O3)

Duque, Daigne, Mochkovitch (1905.04495)

Population model: BNS in high-density media?

- Evidence for fast-merging binaries
  (r-process element abundance, sGRB rate vs. cosmic SFR, Galactic binary population)
- High density medium: brighter AG, more likely detected ($F \sim n^{4/5}$)
- Tight constraints on this population, even with a few events





Beniamini, Duque, Mochkovitch, Daigne (in prep.)

Summary

Summary

- The 170817 event favors the short GRB-merger connection
  - detection of GRB170817A
  - evidence of a core jet from the late radio afterglow

  BUT - the origin of the observed short GRB is uncertain

- More observations to come (O3, …): more diversity?

  Prospects:
  - kilonova detection: most probable (R. Mochkovitch's talk)
  - afterglow: more difficult
  - short GRB: very difficult

- O3 is here: several BNS events are expected, a few with detectable afterglow, all with detectable KN
- Detectable is not detected!
  1. Difficulty to find KN during O3…
  2. Increasing difficulty of VLBI imagery with dist.

- Most events off-axis: probe jet geometry and emission therein
- New constraints on the population of fast-merging binaries.