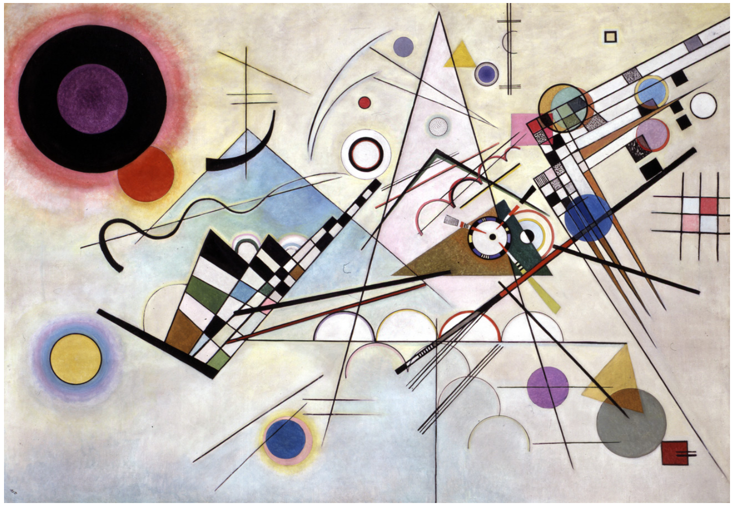
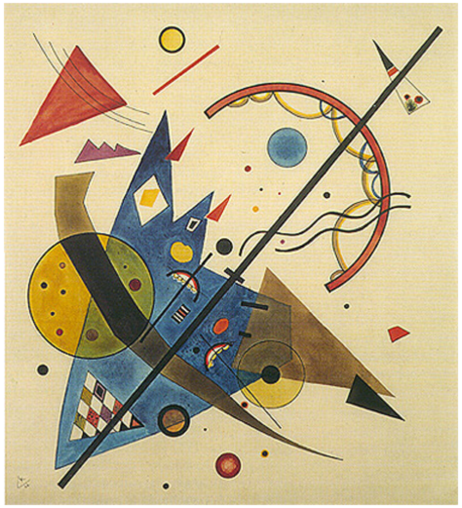
BNS Electromagnetic Counterparts: a population study

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

with Robert Mochkovitch & Raphaël Duque



Kandinksy – Ccomposition 8- 1923



Kandinksy – Curves and sharp angles - 1923

Assemblée générale du GDR Ondes Gravitationnelles – Jeudi 10 octobre 2019 – Lyon

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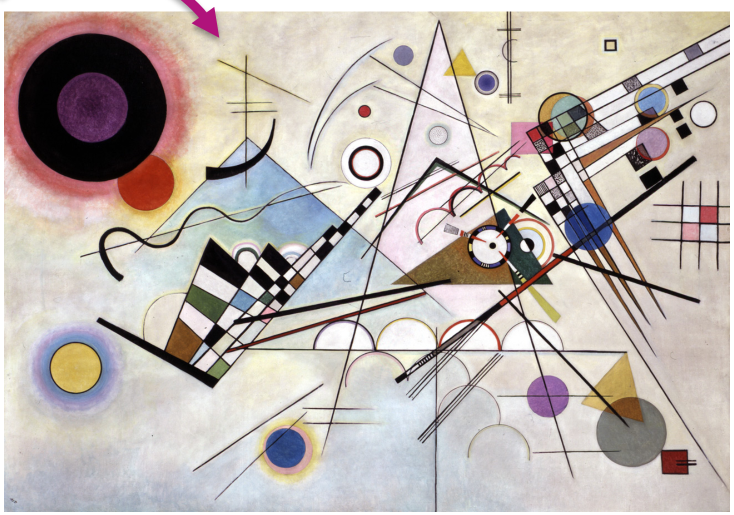

Kandinksy – Ccomposition 8 - 1923

?

andinksy – Curves and sharp angles - 1923

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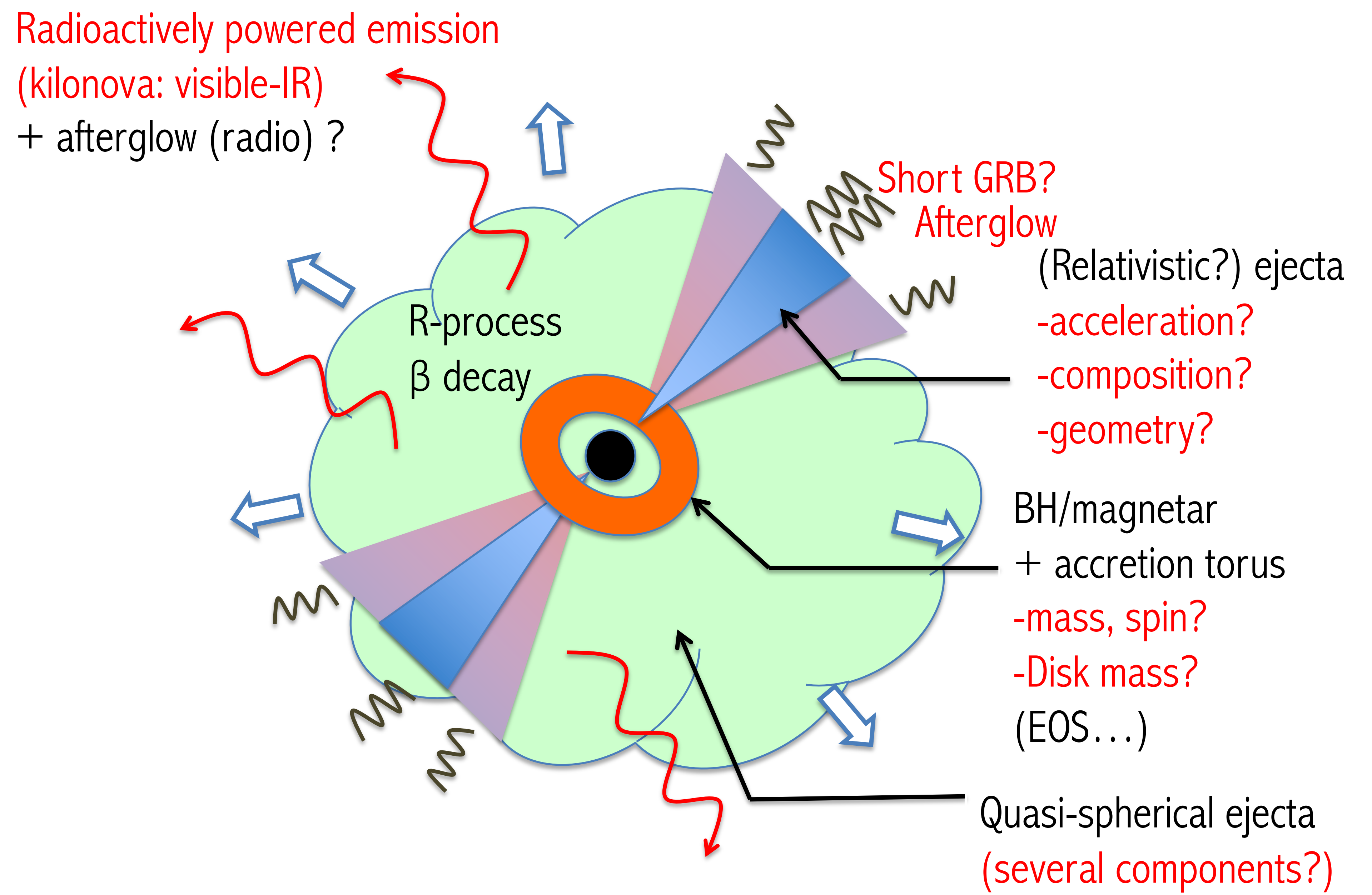
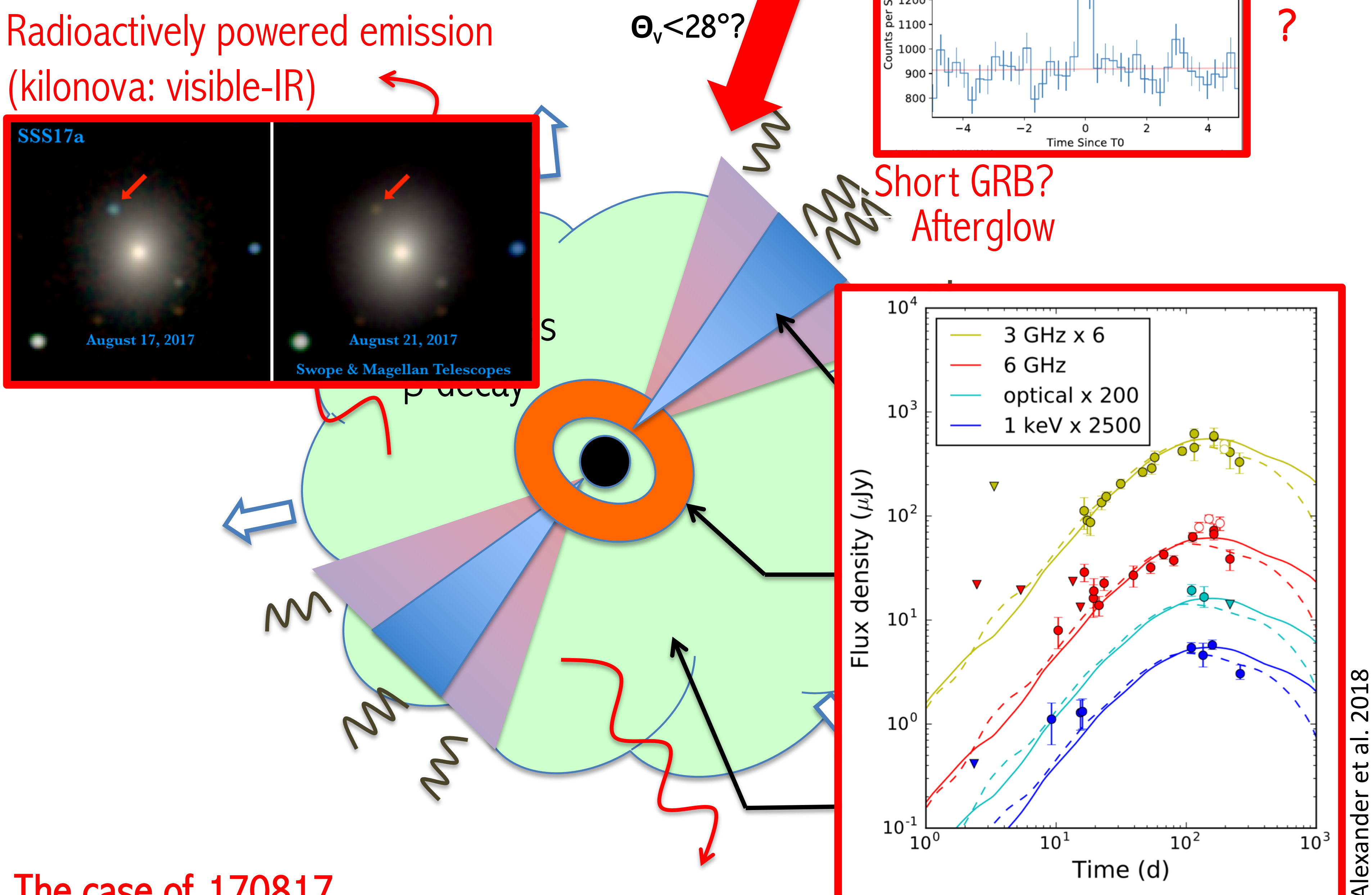
GW 170817 and counterparts

Remnant of a NS+NS merger



Remnant of a NS+NS merger



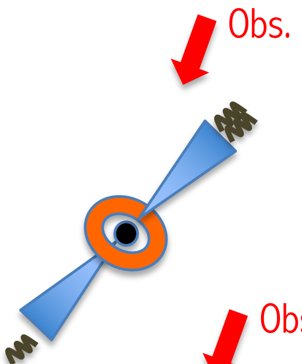
The case of 170817

Afterglow

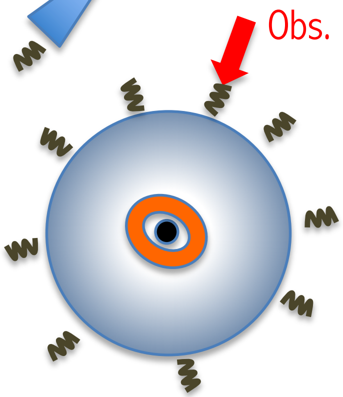
Afterglow

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

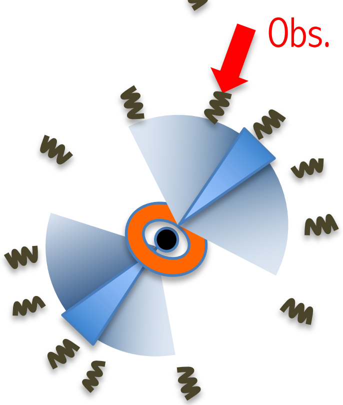
Rise to maximum as $\sim t^{1.5}$ Peak at ~150 days



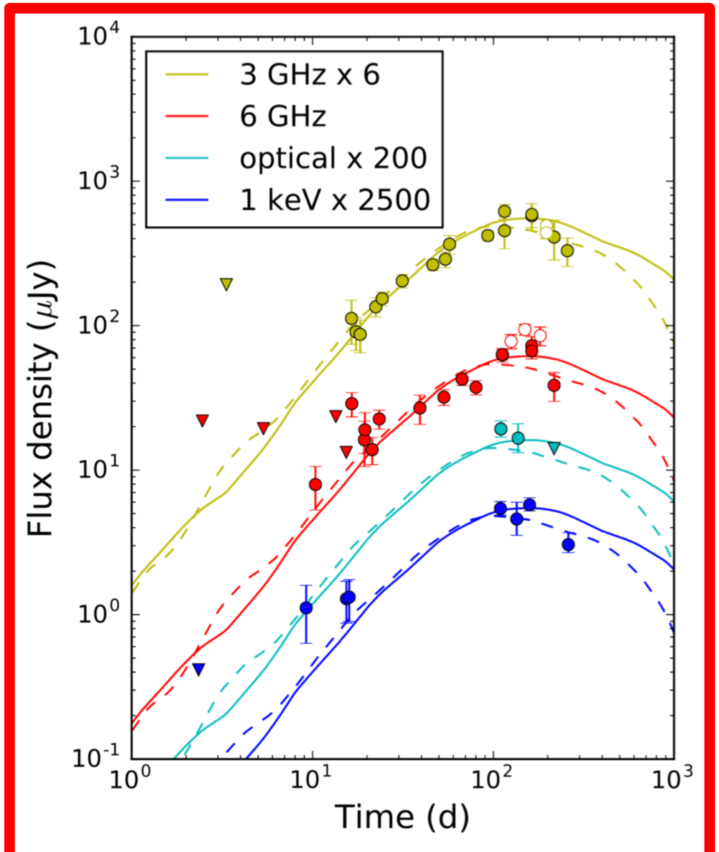
A relativistic jet see off-axis? ruled out (slow rise)



Quasi-spherical outflow with a radial structure? Ruled out (lightcurve OK ; VLBI)

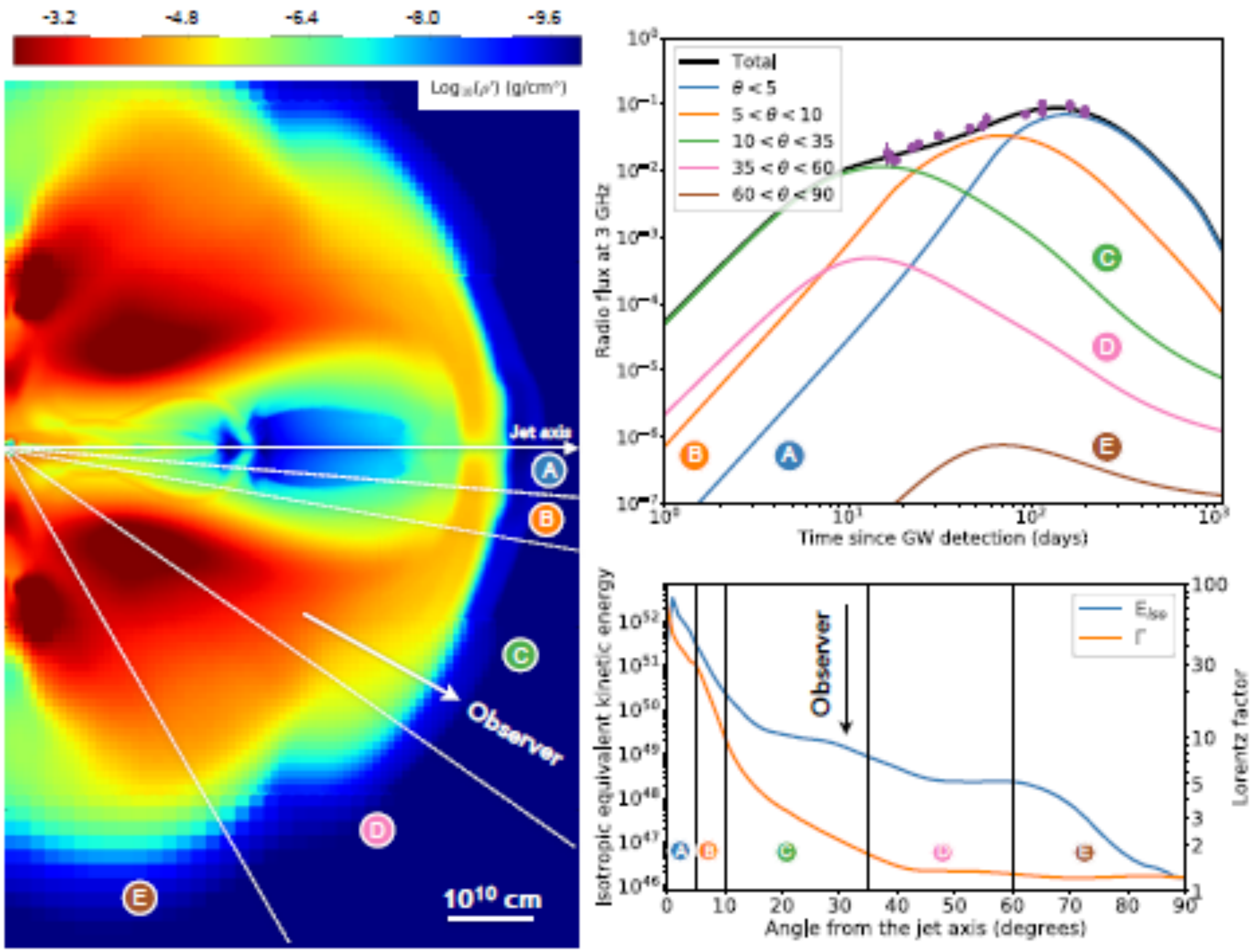


Core jet + lateral structure seen off-axis?
OK: lightcurve & VLBI



Alexander et al. 2018

Afterglow



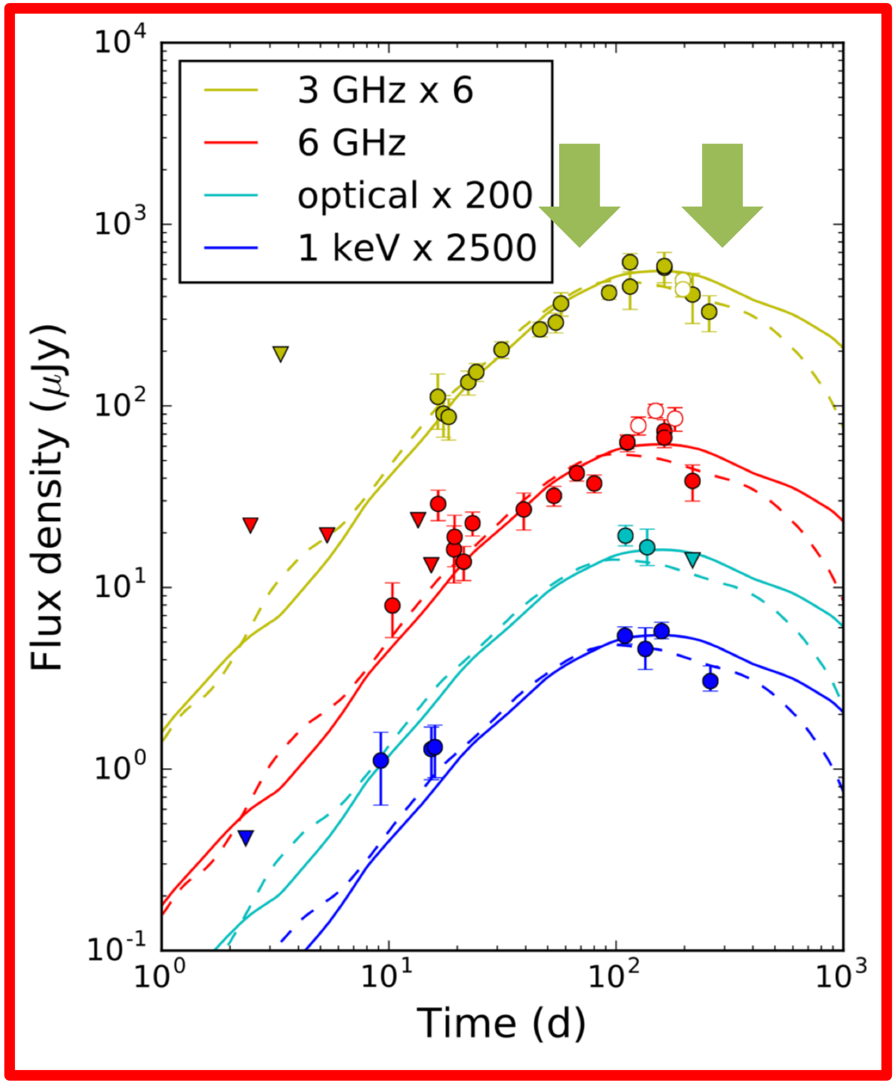
Lazzati et al. 2018

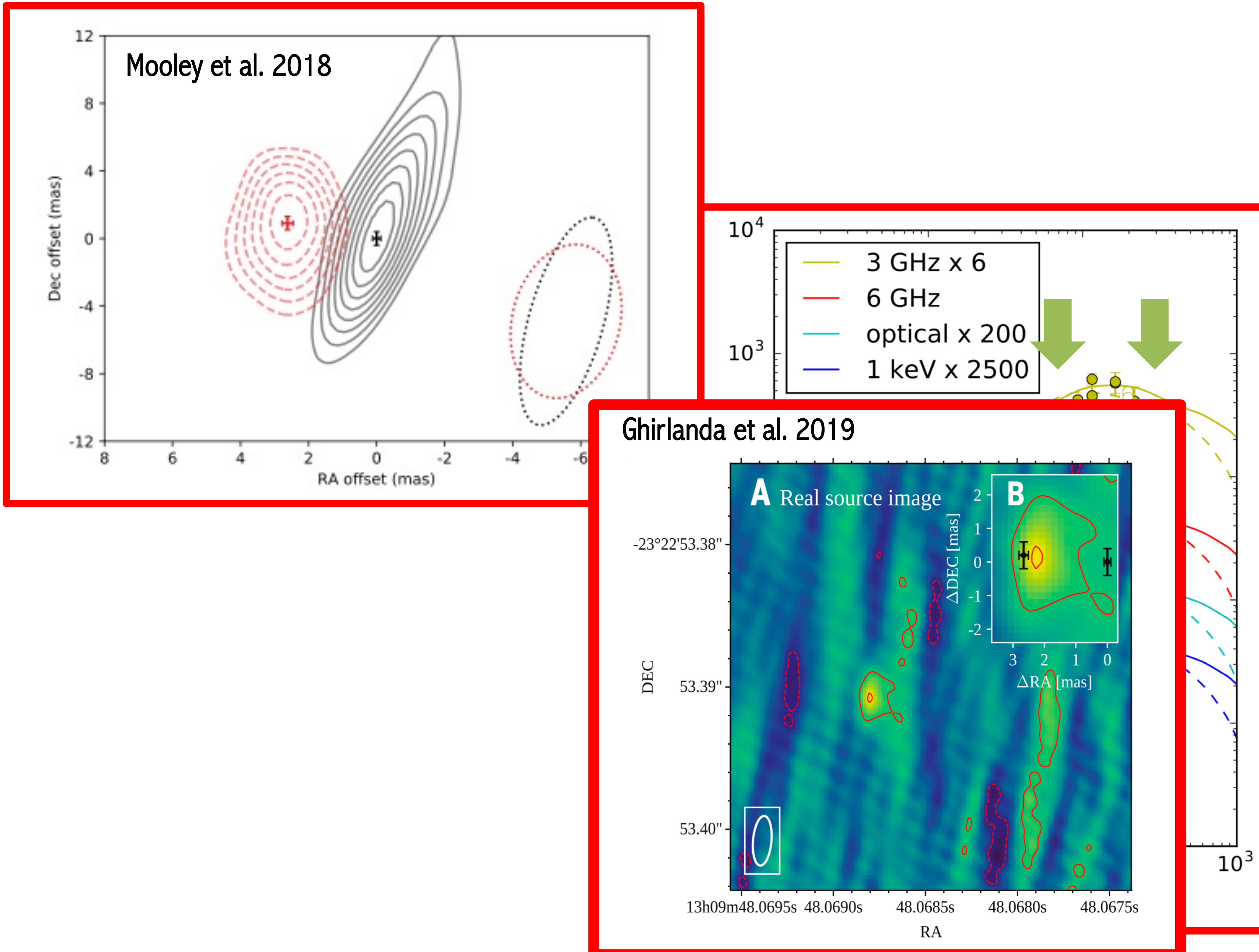
Here: the central jet ($E_{iso,on}$~10^{52} erg) contributes at 100 days

Radio afterglow: latest observations

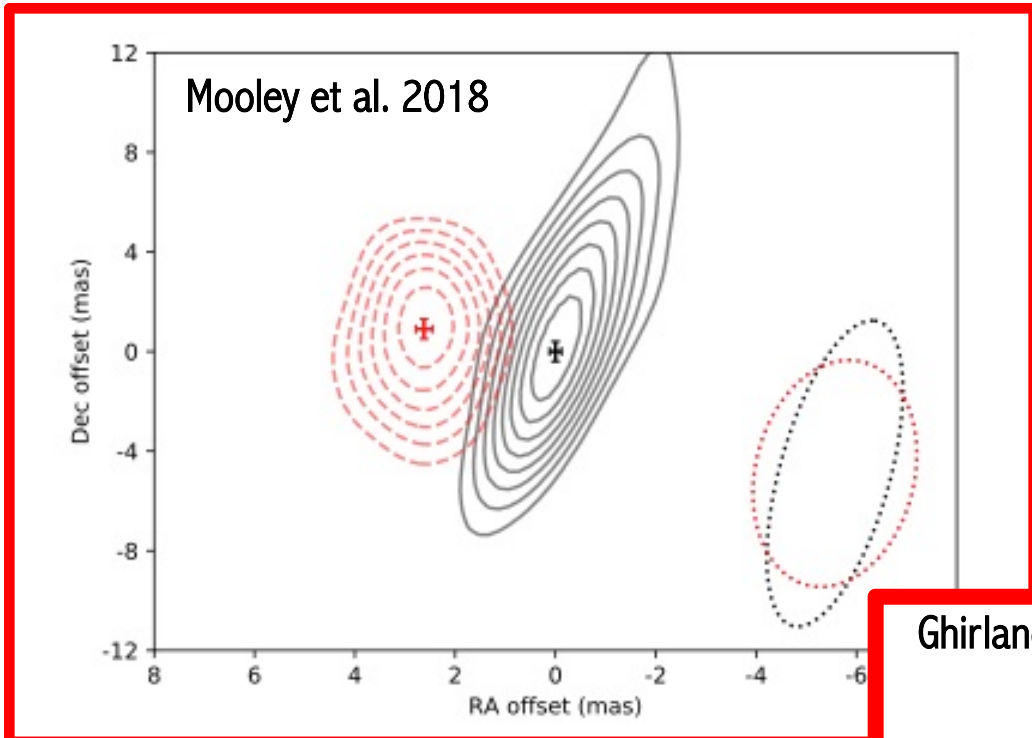
- VLBI: motion of the centroid (Mooley et al. 2018) between 75 and 230 days

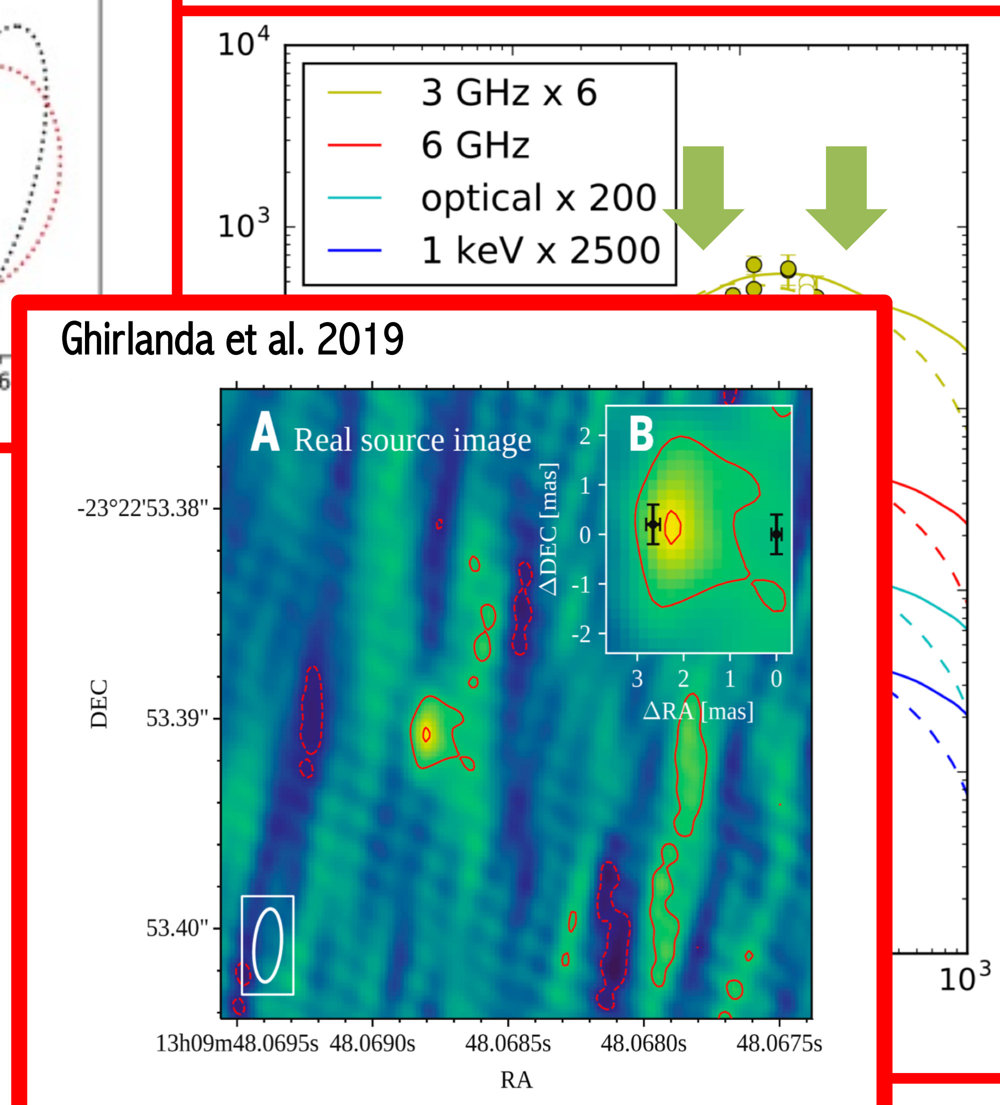
  + high resolution images: source still very compact (Ghirlanda et al. 2019)





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]
-23°22'53.38"
53.39"
53.40"
DEC
13h09m48.0695s
48.0690s
48.0685s
48.0680s
48.0675s
RA





- Supeluminic apparent motion
- Still compact size at late times

- Favors a emerging jet at ~20° !

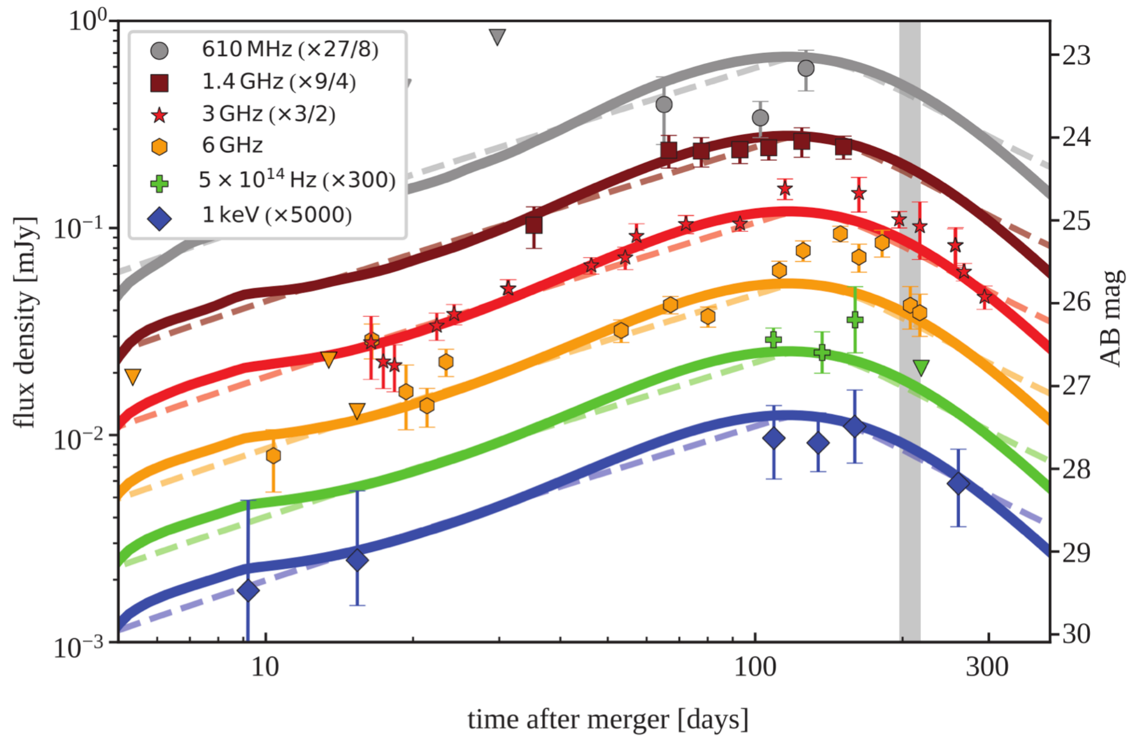
Radio afterglow: latest observations

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

  -off-axis observer at ~15-20°

  -external density ~ 0.001 cm^{-3}

  -central jet:
  E_{iso}~2-3 10^{52} erg
  opening angle ~3-4°

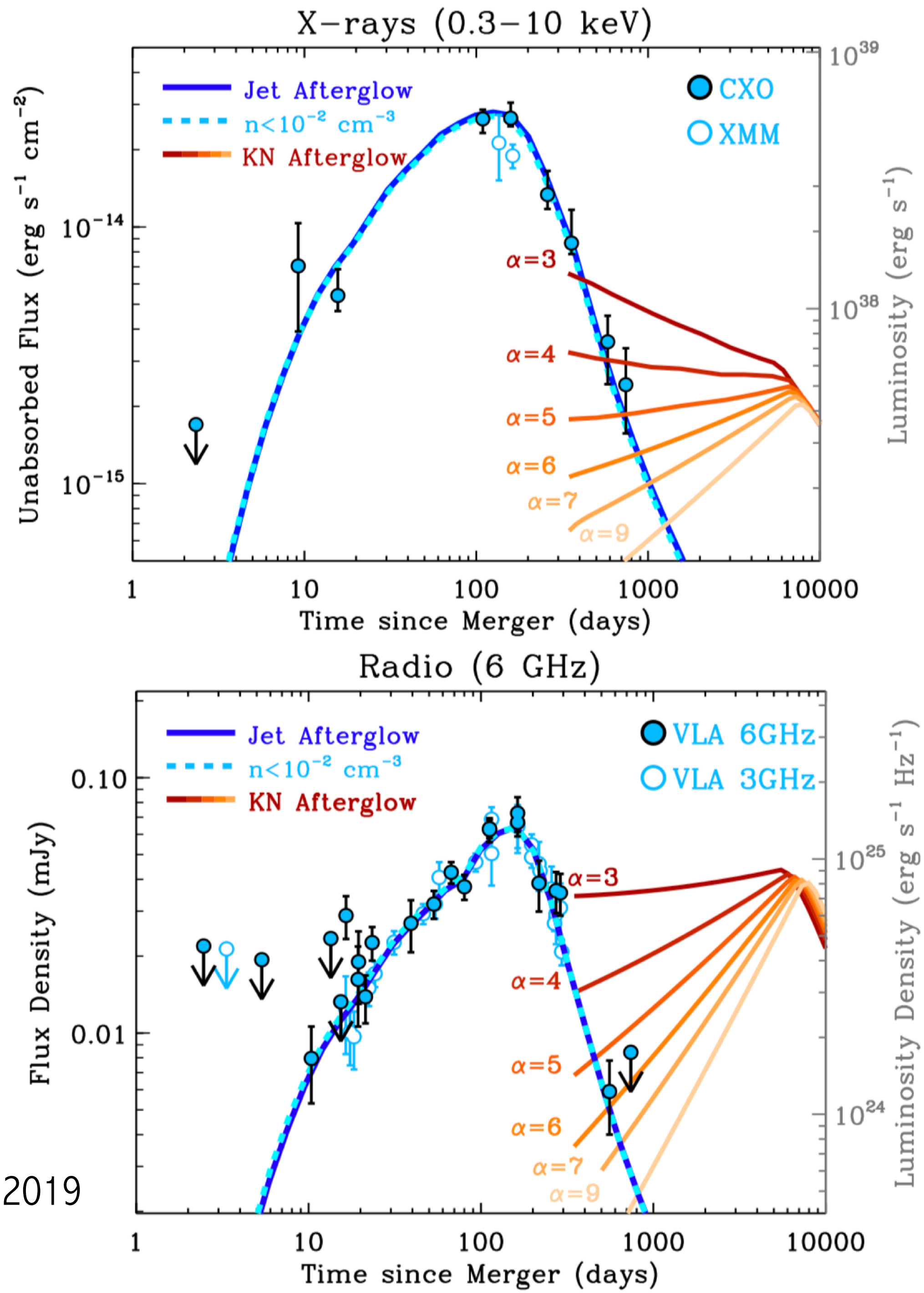


Ghirlanda et al. 2019

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

Very late observations

- Radio (VLA):
  detected at 588 days after merger
- X-rays (Chandra):
  detected at 743 days after merger



Hajela et al. 2019

Afterglow / Short GRB

- New questions:
  - Origin of the lateral structure? Which post-merger behavior?
    (propagation through the KN ejecta?)
  - Origin of the prompt GRB emission?
    (core jet seen off-axis or materical pointing towards the observer?
    Standard GRB mechanism or new mechanism ?)

- Consequences of the emerging geometry for GRB physics:
  cosmic population is seen on-axis/slightly off-axis, effect of the lateral structure?
  e.g. plateaus, Beniamini, Duque, Daigne & Mochkovitch 2019 (arXiv:1907.05899)

Short/mid-term prospects: a population model

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=226 Mpc ; design = 429 Mpc
  Radio VLA=15 μJy ; SKA1-Mid = 3 μJy ; SK2/ngVLA = 0.3 μJy

Population model: results

- 20-30% of events have detectable afterglows

LVC Run	Radio Configuration Instrument	s (μJy)	GW Events N_{GW}	Joint Events N_{joint}	Fraction of detectable events (assuming fiducial model)
O3	VLA	15	9^{+19}_{-7}	3^{+6}_{-2}	31.4%
Design	VLA	15	21^{+44}_{-16}	4^{+10}_{-4}	19.8%
Design	SKA1	3	21^{+44}_{-16}	7^{+18}_{-7}	34.7%
Design	SKA2/ngVLA	0.3	21^{+44}_{-16}	13^{+33}_{-13}	62.5%

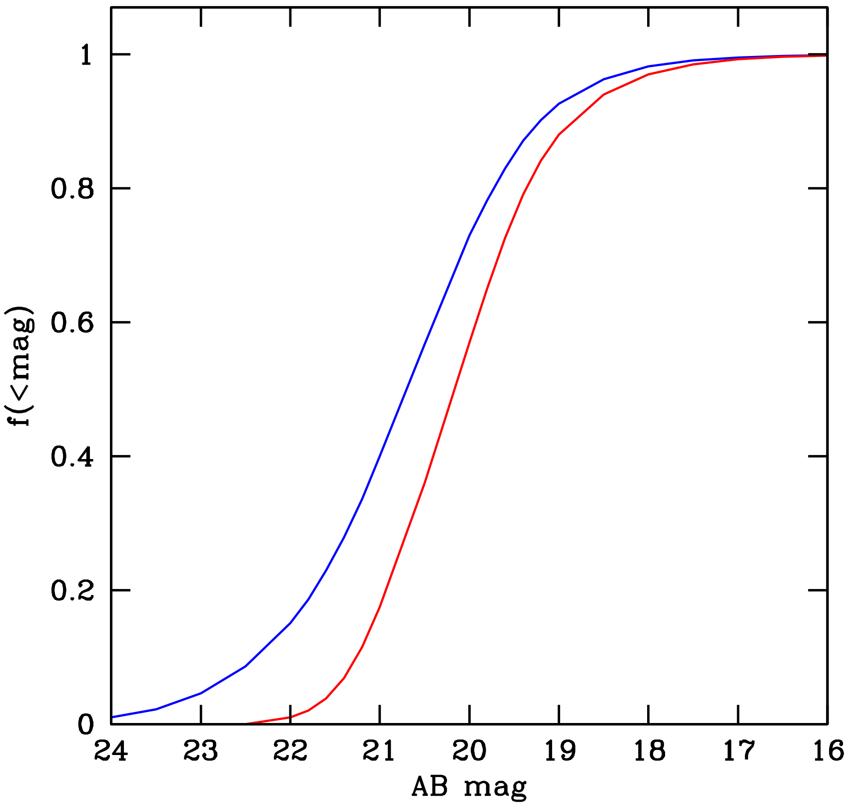
- Uncertainties: $^{+200\%}_{-73\%}$ (intrinsic rate from LIGO-Virgo O2/O3)
  + uncertainty on population model
- Large deviations from these estimates? Constraints on the intrinsic population.

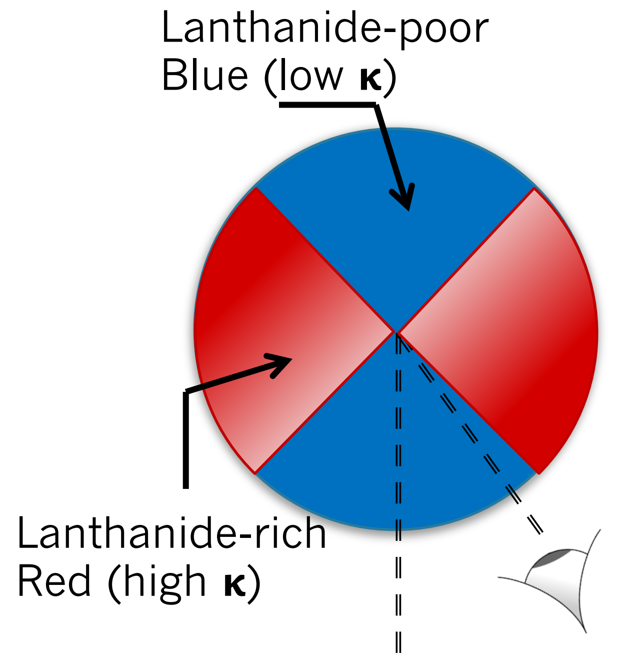
- How to detect « detectable » events?

Duque, Daigne, Mochkovitch 2019 (1905.04495)

How to detect “detectable” events: kilonovae

- Simulate KN including the expected dependance on the viewing angle





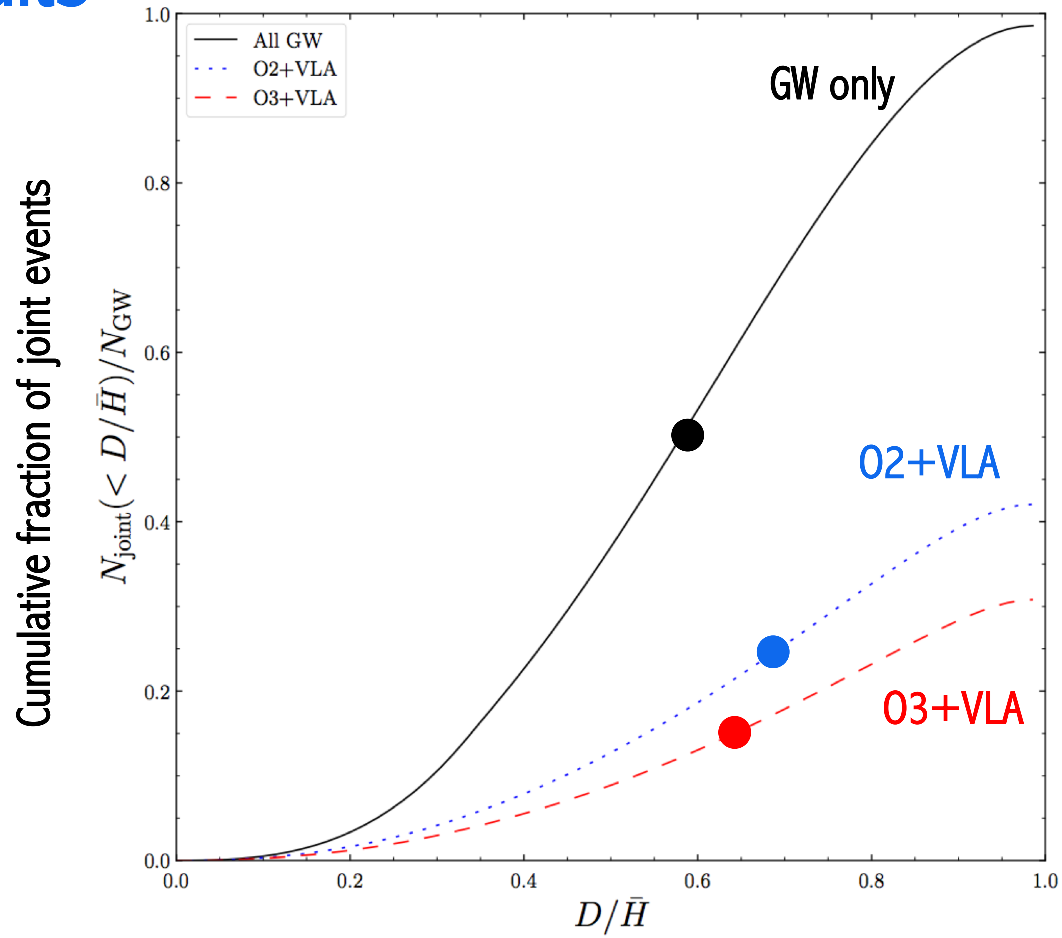
(prescription from Wollaeger+ 18)

- O3: most kilonovae are detectable for $m_{lim} = 21$
- Problems:
  - GW error box (typical volume to explore = 100 x 170817)
  - Contrast KN/host galaxy
  - Etc.
- Need for efficient wide-angle follow-up/surveys (LSST, etc.)

Mochkovitch, Duque, Daigne & Zitouni in preparation

Population model: results

- Distance:

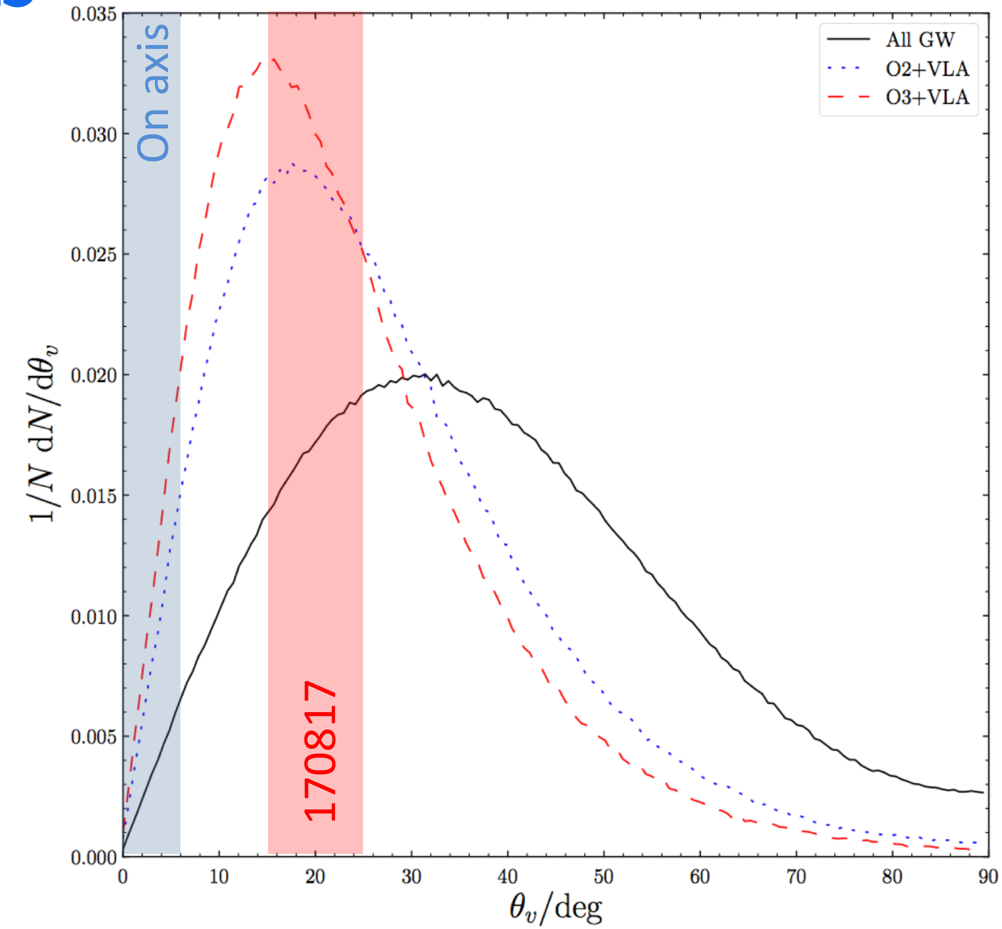


Distance / sky-position averaged GW horizon
O2 : 86 Mpc ; O3 : 143 Mpc ; Design : 272 Mpc

Duque, Daigne, Mochkovitch 2019 (1905.04495)

Population model: results

- Viewing angle:



- Most events seen off axis!
- Mean angle ~24° (O3+VLA)

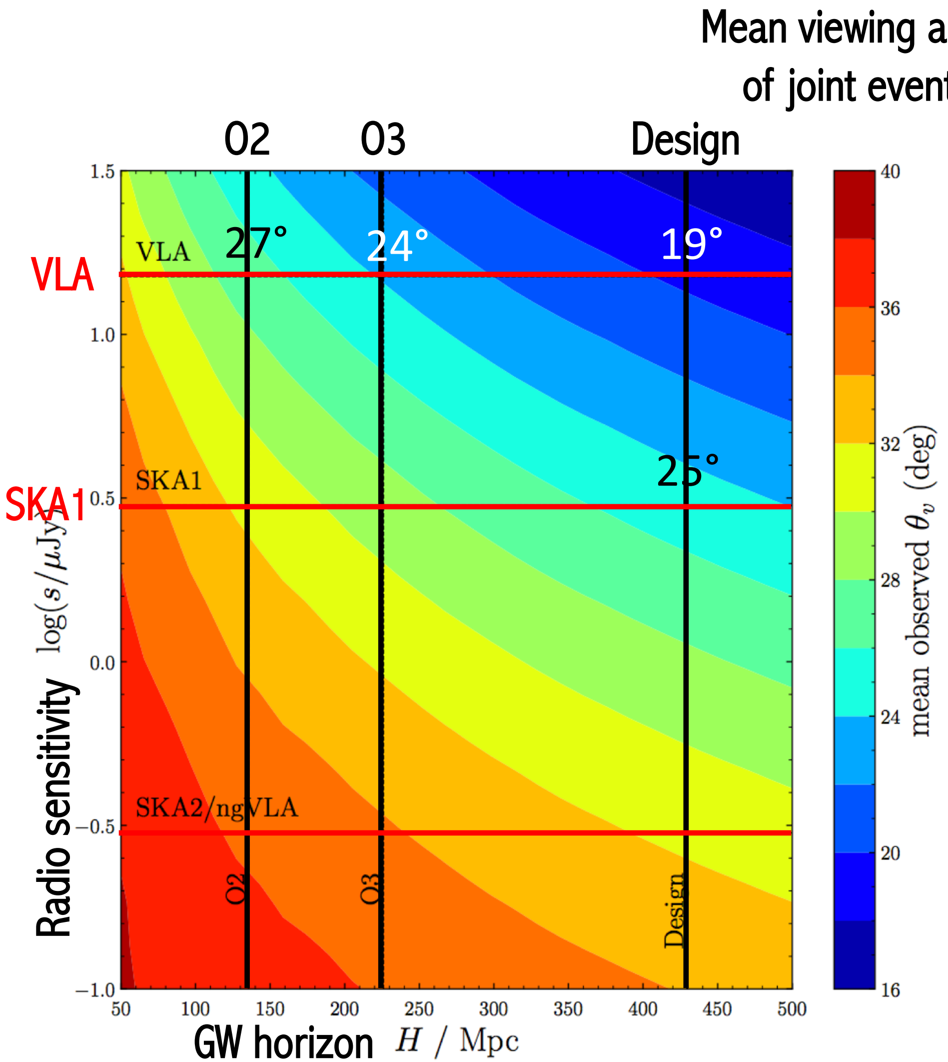
- ≲10% on axis (classical SGRB?)

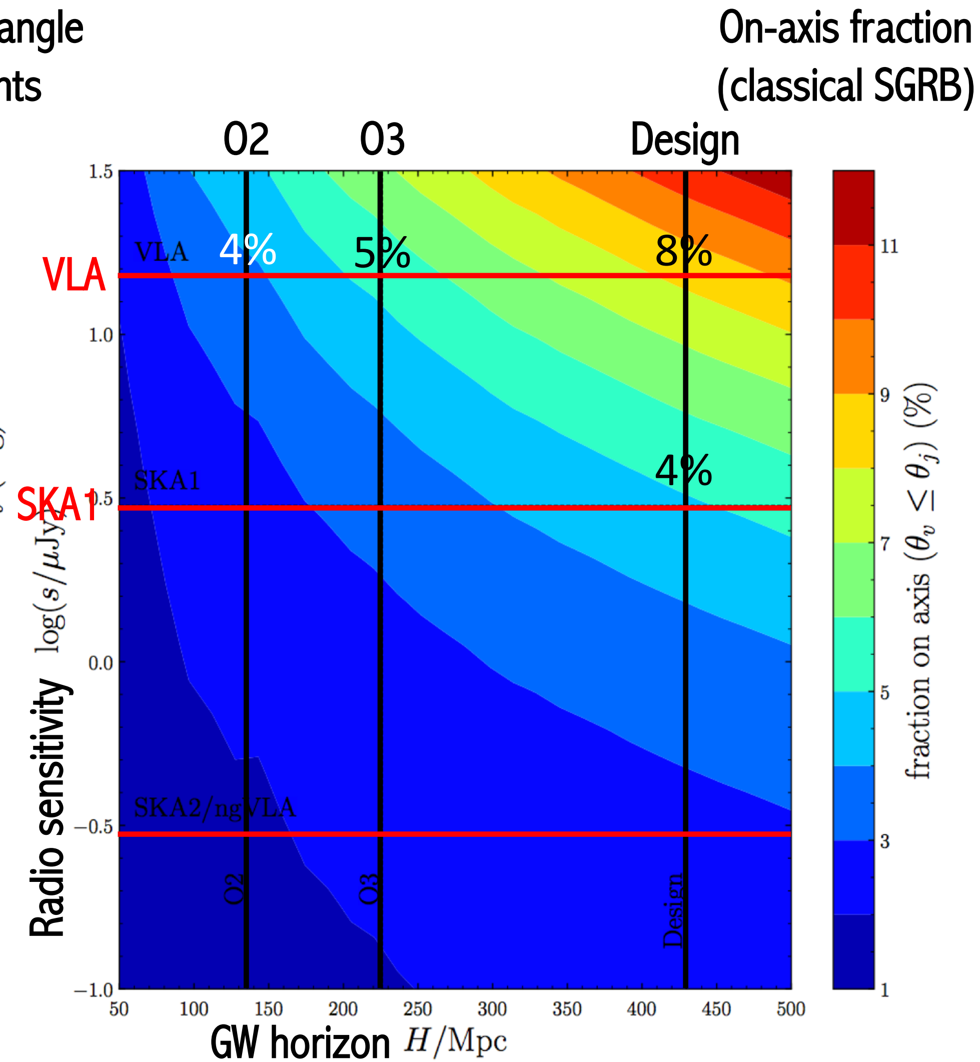
Beniamini+18: 1-10% (O3)

Duque, Daigne, Mochkovitch 2019 (1905.04495)

Population model: results

- Even at constant radio sensitivity, the off-axis fraction remain high at design configuration for LIGO/Virgo



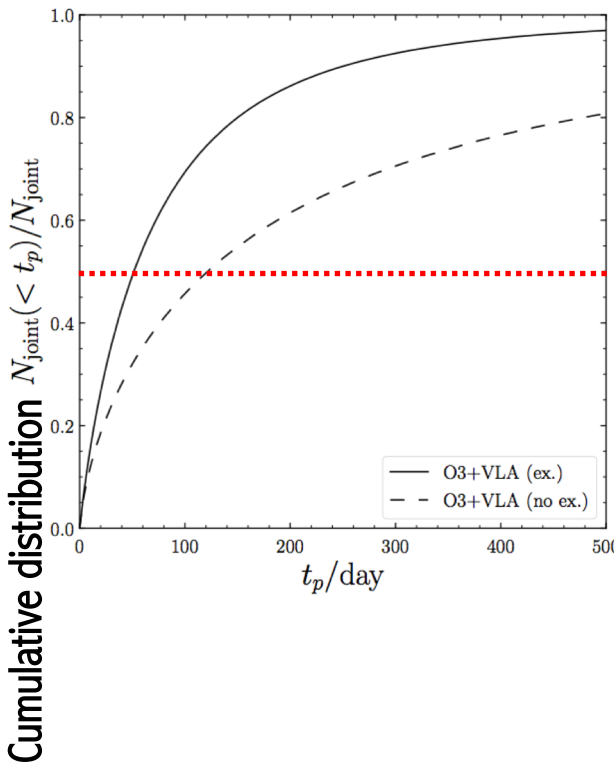


Duque, Daigne, Mochkovitch 2019 (1905.04495)

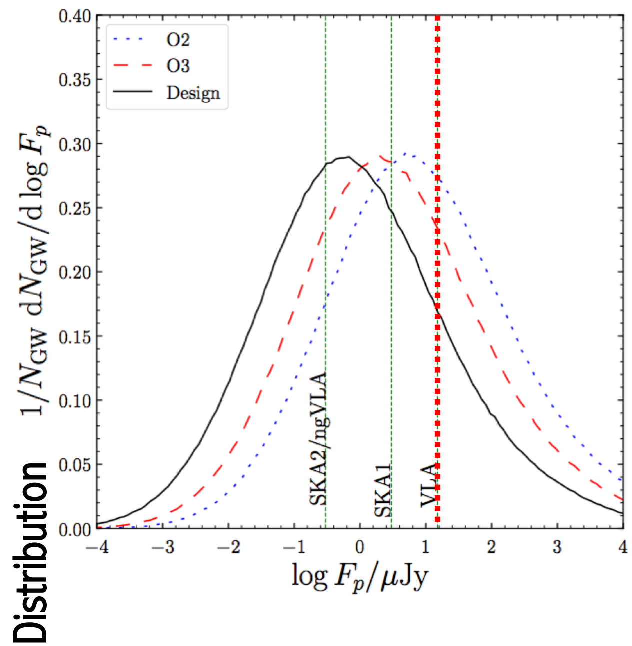
Population model: results

- Radio afterglow peaks before 150 days in 55-81% of cases (O3+VLA)
  Uncertainty: lateral expansion of the jet?
- VLA sensitivity is above the mean peak flux in O2-O3-design configuration
- Fraction of joint-events with a detectable proper motion decreases when GW sensitivity increases

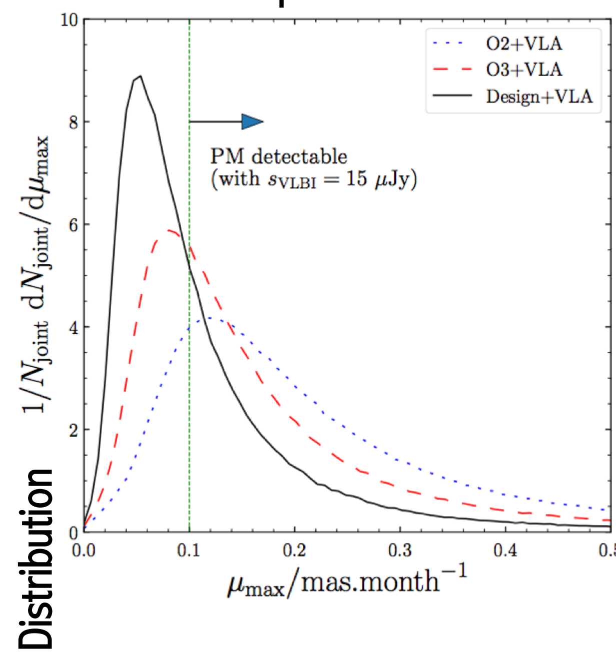
Peak time



Peak flux



Proper motion



Duque, Daigne, Mochkovitch 2019 (1905.04495)

Population model: results

- Orphan radio afterglows:
  add ~25% of events compared to GW+radio joint detections
  (O3+VLA, fiducial model)

Configuration	N(radio)/N(radio + GW)
O3-VLA	1.26
Design-VLA	1.15
Design-SKA1	1.30
Design-SKA2	1.72

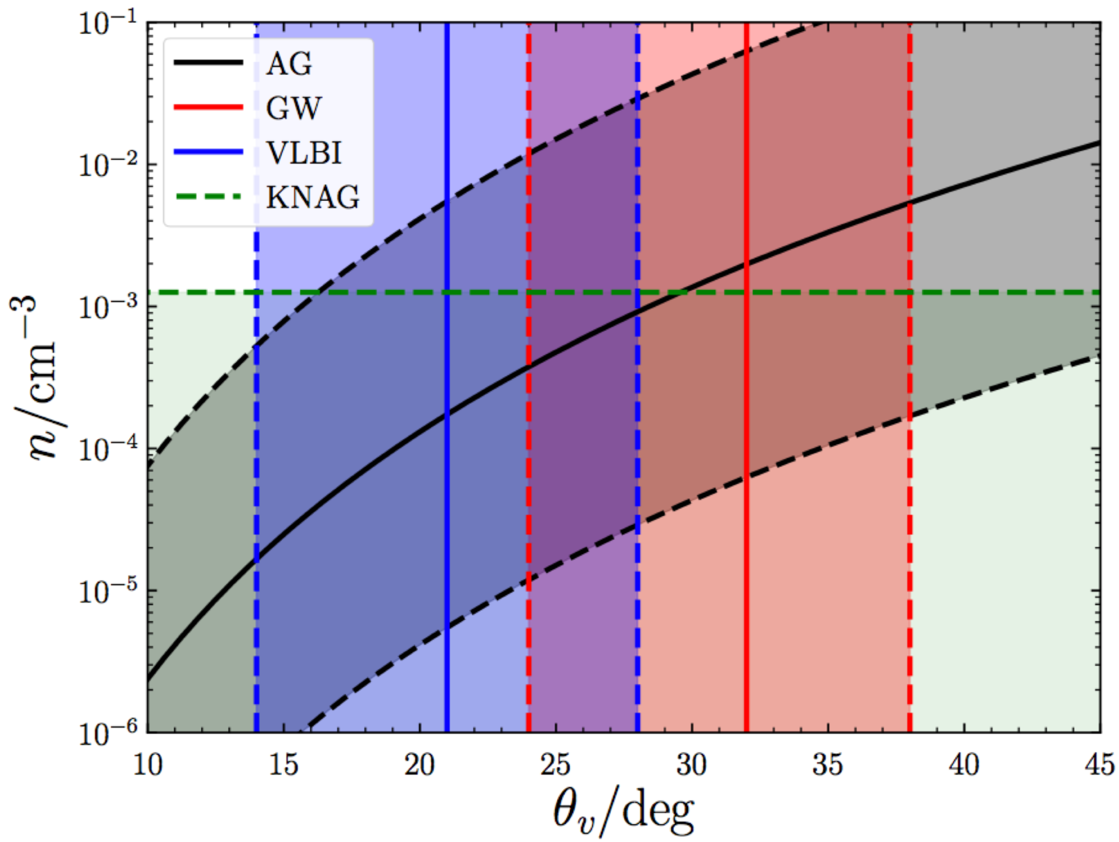
- Result depends on the mean external density.
  E.g. for a mean density of 1 cm^{-3} in O3+VLA: N(radio)/N(radio+GW) = 3.0

Duque, Daigne, Mochkovitch 2019 (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 ($F \sim n^{4/5}$)

- Good constraints on external density: the case of 170817

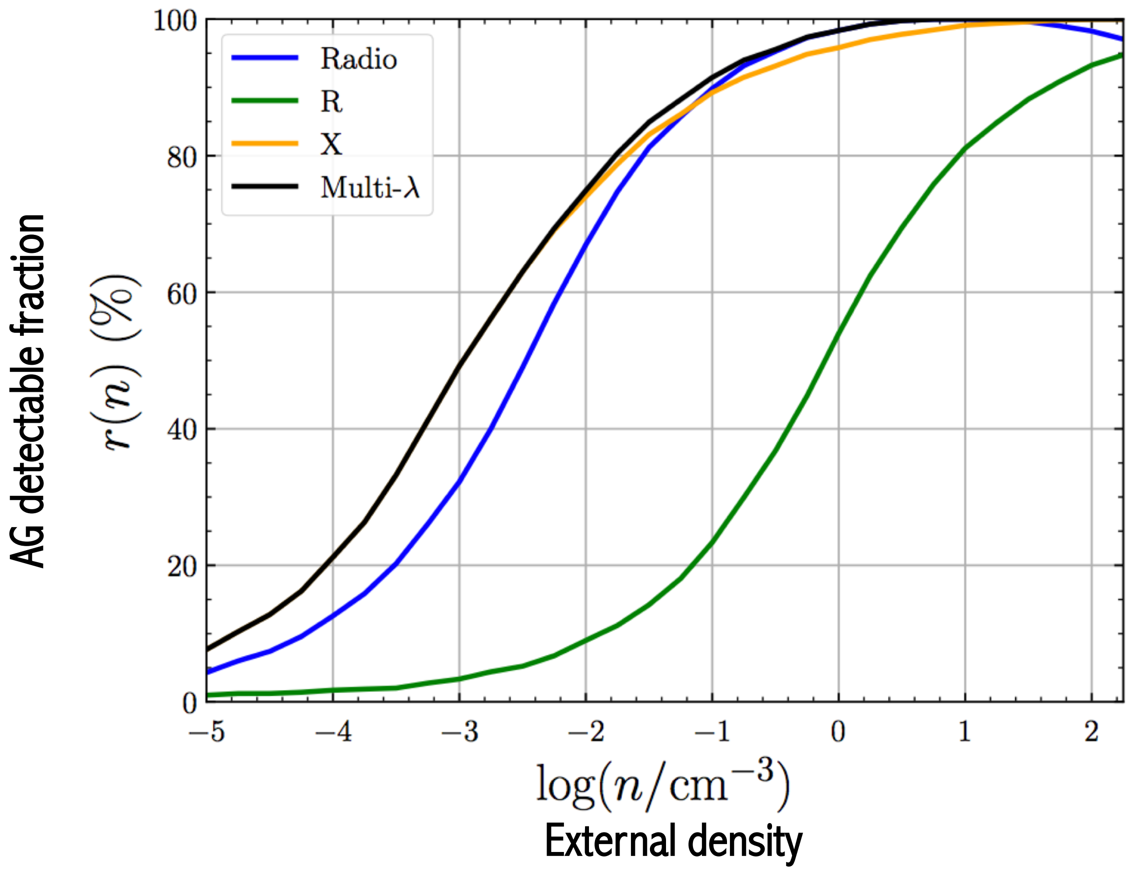


Duque, Beniamini, Daigne, Mochkovitch, (in prep.)

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 ($F \sim n^{4/5}$)

- High-density events (if they exist) have an enhanced apparent fraction

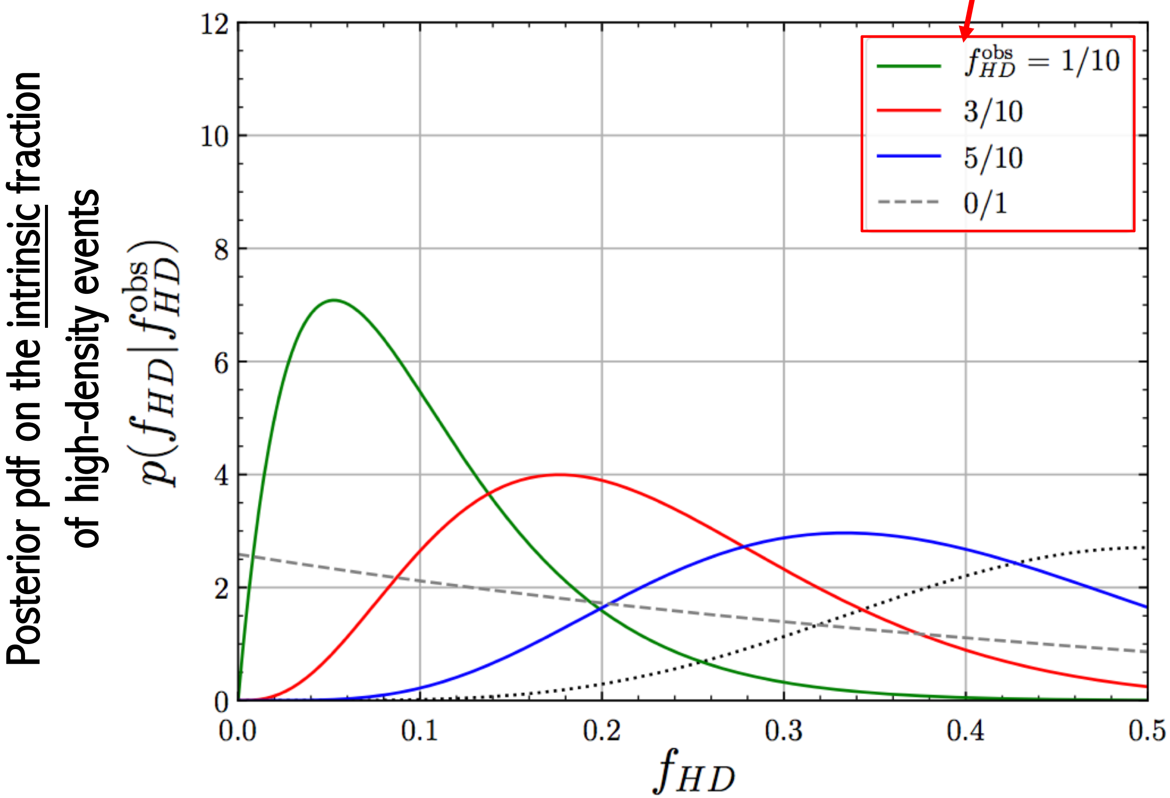


Duque, Beniamini, Daigne, Mochkovitch, (in prep.)

Population model: BNS in high-density media?

- Fraction of high-density events in the population of radio+GW joint detections car strongly constrain the fraction of BNS occuring in high density media (i.e. short merger times)

Observed fraction of high-density events



Intrinsic fraction of high-density events

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

Summary

Summary

- Afterglow observations play a major role for the interpretation of 170817
- Many constraints: external medium, ejecta/jet structure/geometry, …
- VLBI: additional constraint on geometry, viewing angle, Lorentz factor

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

- O3 is here: several BNS events are expected
  a few with detectable afterglow, all with detectable KN

- BUT detectable is not detected! 1. Difficulty to find KN during O3…
  2. Increasing difficulty of VLBI imagery with dist.

(Candidates after the first six months of O3: BNS~4-6 and NSBH~4)

- Most events off-axis: probe jet geometry and emission therein
- Orphan kilonovae/afterglows?
- New constraints on the population of fast-merging binaries.
- Extension to larger distances, rate(z), …