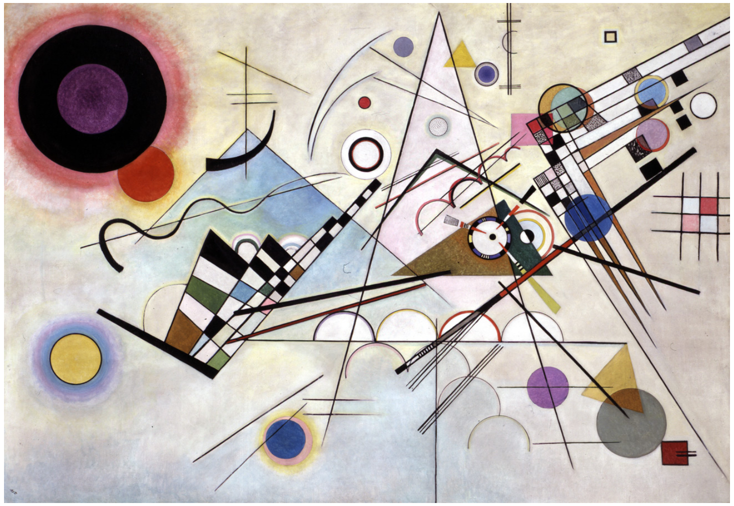
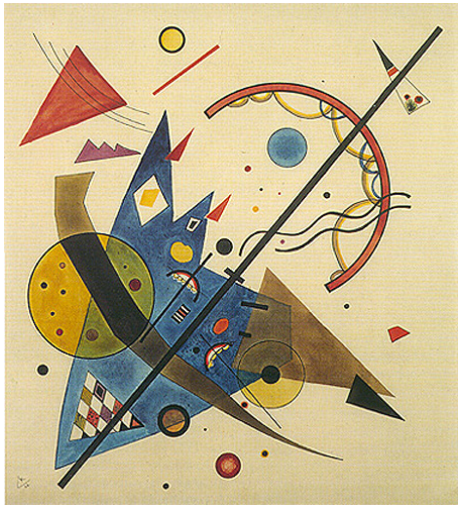
NS+NS/BH mergers: GW and em counterparts
Models and observations needed

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



Kandinksy – Ccomposition 8- 1923



Kandinksy – Curves and sharp angles - 1923

TS2020_II / Transient Sky 2020 National Workshop - 2nd Edition – 4-6 juin 2018 Montpellier

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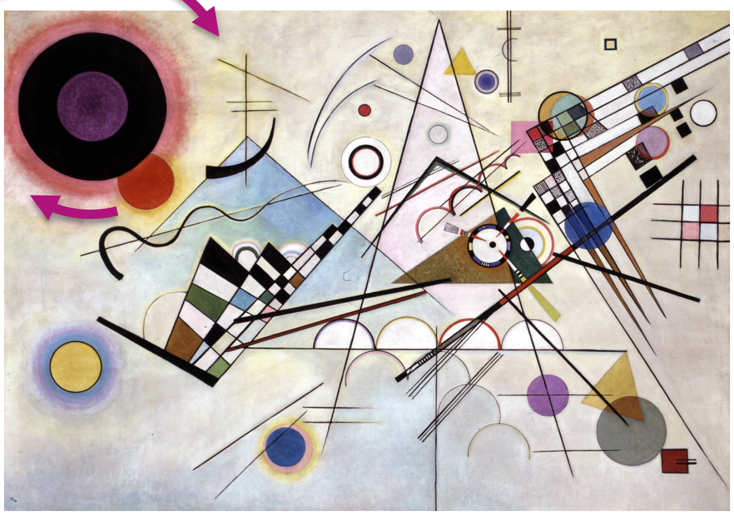
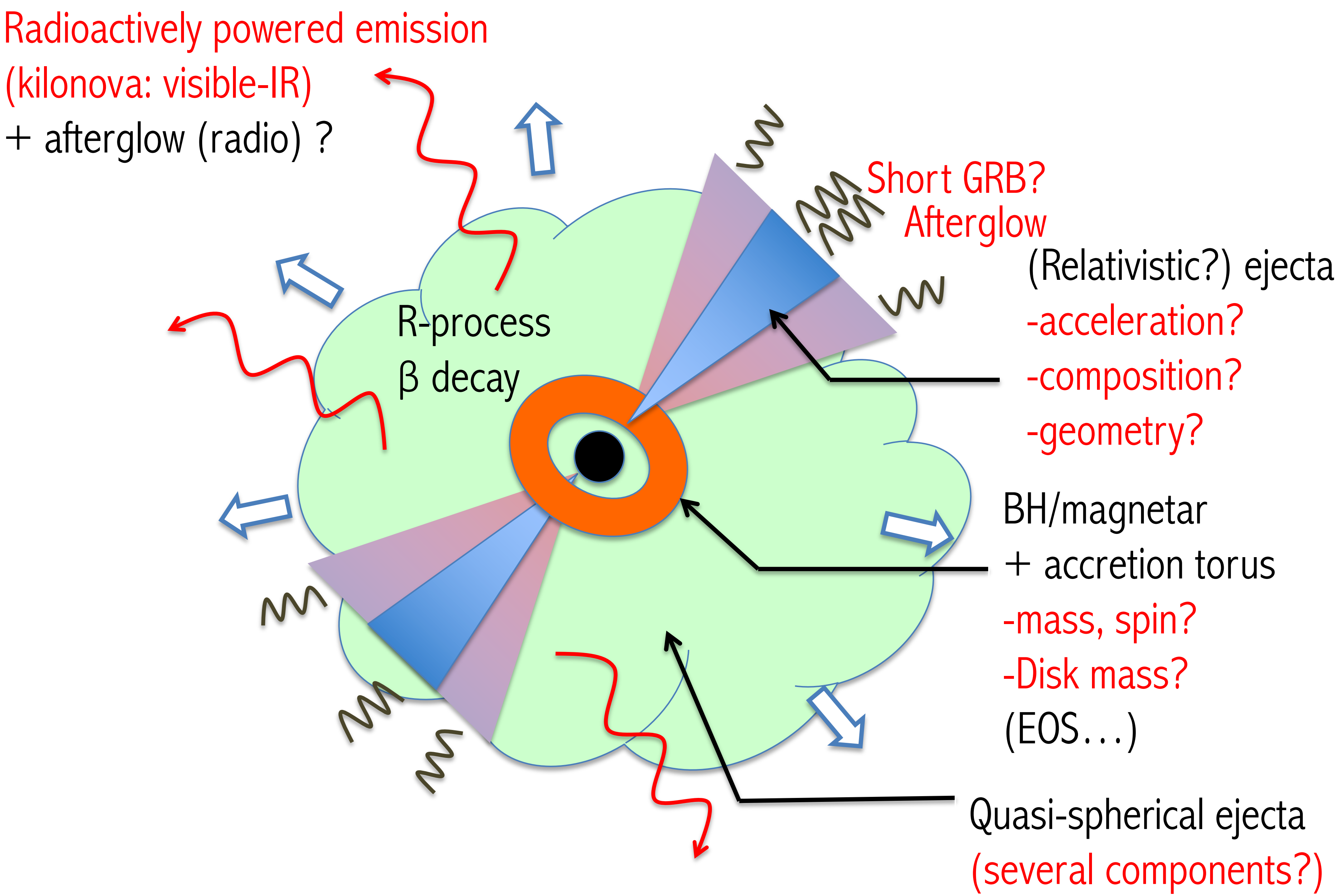


Kandinksy – Ccomposition 8- 1923

Kandinksy – Curves and sharp angles - 1923

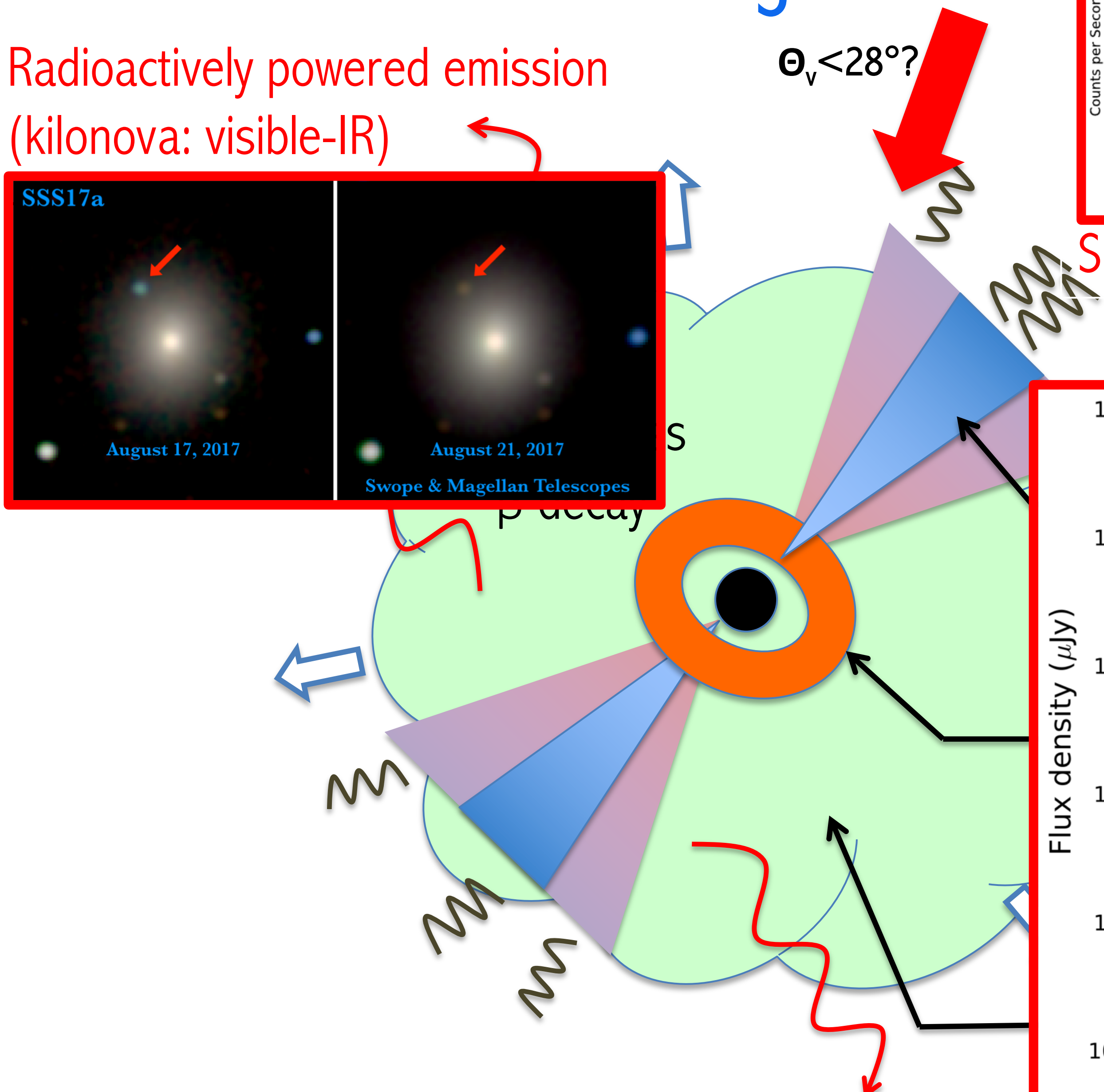
GW 170817 and counterparts

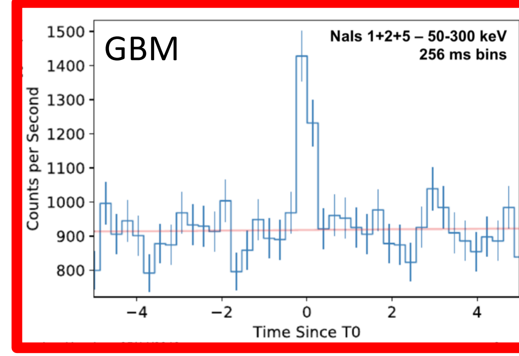
Remnant of a NS+NS merger



Remnant of a NS+NS merger

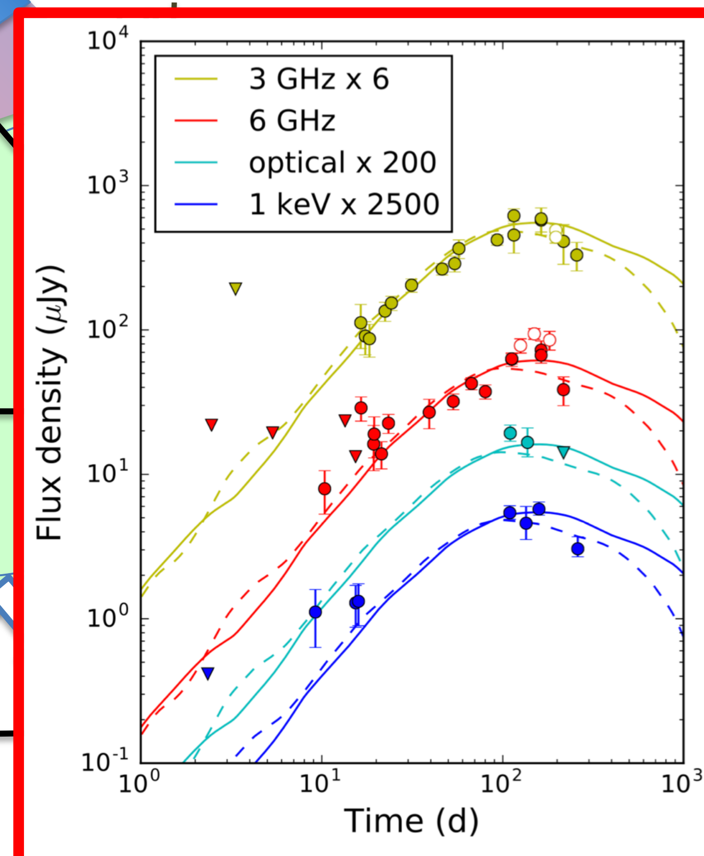
Radioactively powered emission
(kilonova: visible-IR)





?

Short GRB?



Alexander et al. 2018

The case of 170817

GW

NS+NS/BH: GW observations needed

- **More events: merger rates**

- **NS+BH systems?**

- **More prompt small 3D error boxes:**
  - more em counterparts, <u>with different viewing angle</u>
  - face-on systems? (θ_v < a few degrees)

- **Post-merger GW emission:**
  nature/evolution of the central object after the merger (BH, NS, NS→BH, …)

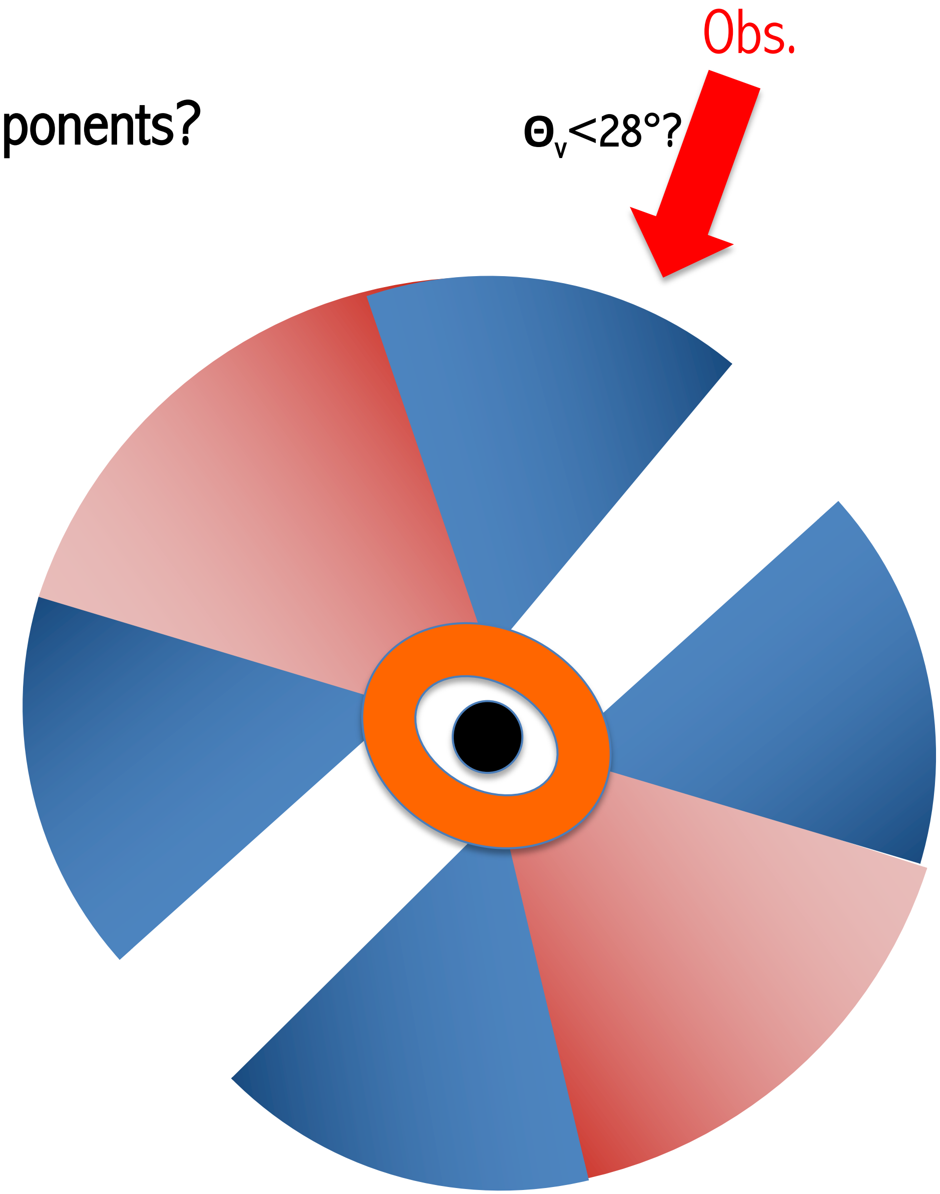
- Note for the search of em counterparts.
  After GW170817, we know that an afterglow can be found even without a GRB.
  KN detection
  → sub arcsecond localization → afterglow detection/severe upper limits

  Maximum distance for a KN detection?
  GW170817: $\mathcal{M}_{peak} \sim -15 \rightarrow m_{peak} \sim 20$ @ 100 Mpc

Kilonova

Kilonova:

at least two components?



Dynamical ejecta?

Neutrino wind from the disk?

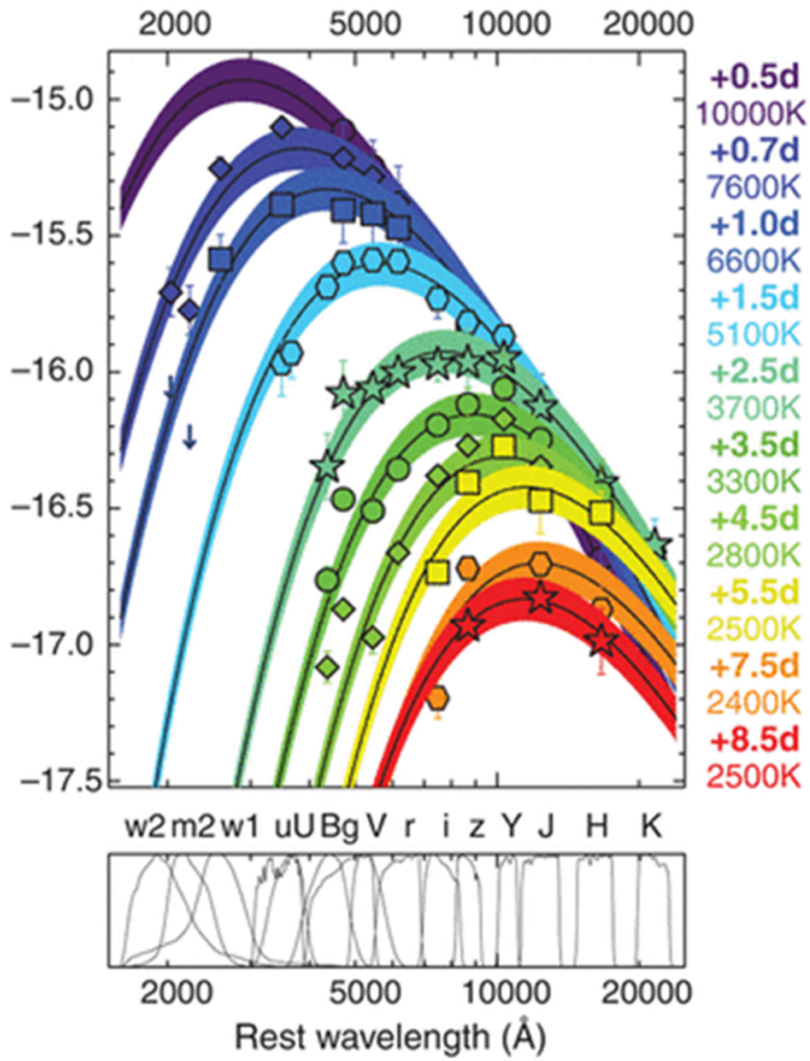
Kilonova: observations needed

- **Better estimates of the ejected mass/composition**
  Better understanding of the geometry of the kilonova ejectas
  (more events with spectro-photometric follow-up+better models)

- **Spectroscopic signature of heavy elements?**

- **KN associated to NS+BH?**

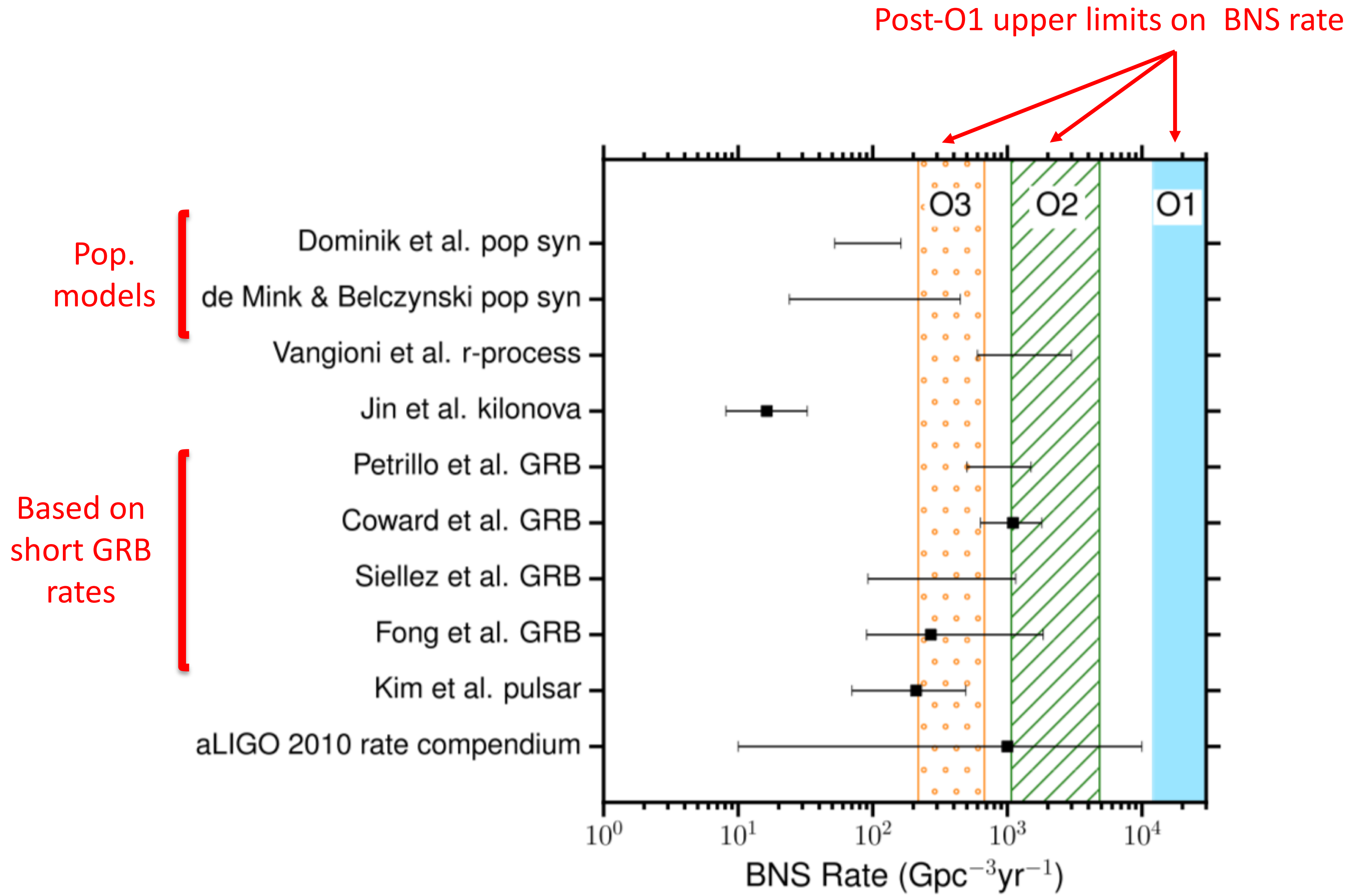
- **Notes: GW+KN**
  - **Better constraints on (D, θ_v)**
  - **H_0: many events needed**
  -
    indirect constraints on the nature of the post-merger central object, (if no post-merger GW signal) via the ejected mass



Drout et al., Science, 2017

Are NS+NS mergers the main astrophysical site for the production of r-process heavy elements?

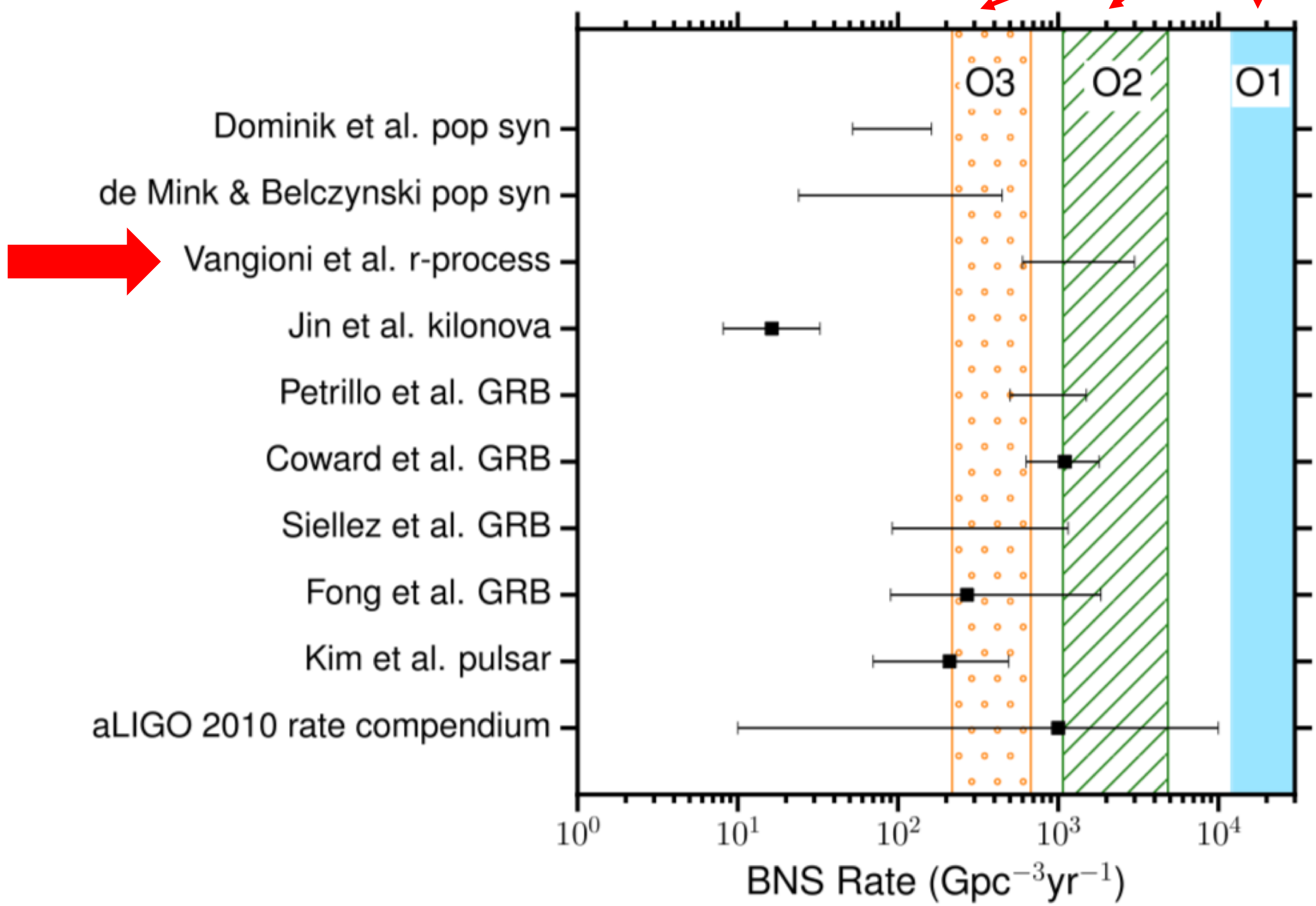
Merger rate: BNS



Abbott et al. 2016, post-O1

Merger rate: BNS

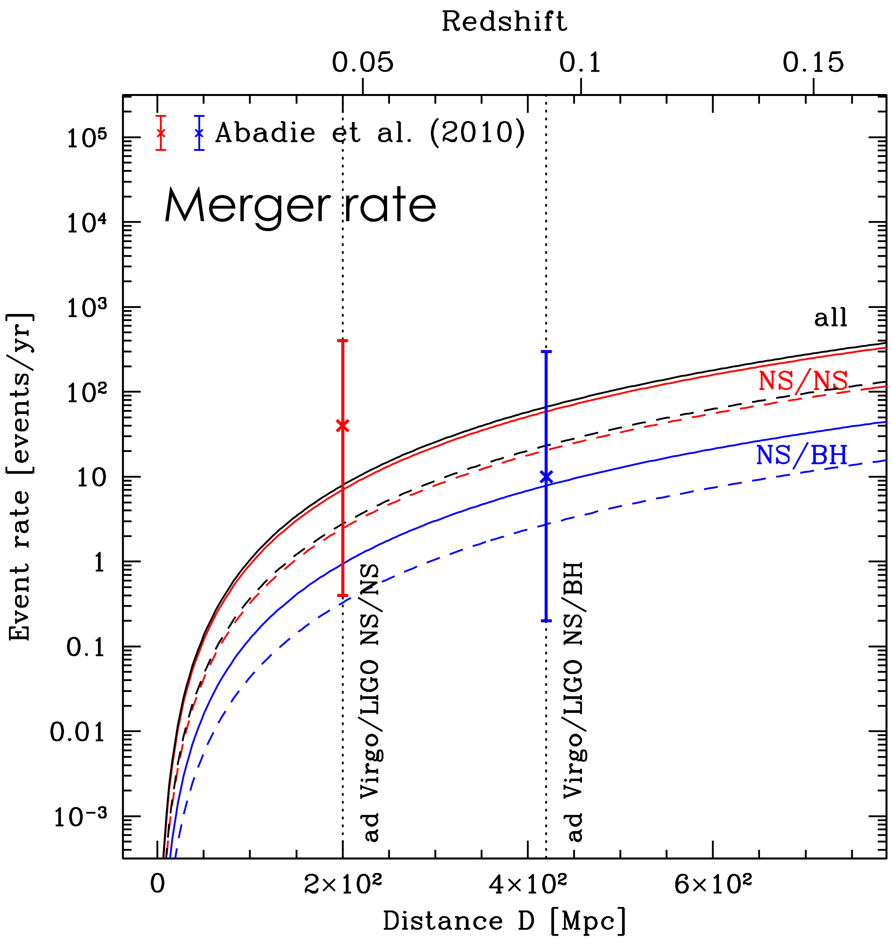
Post-O1 upper limits on BNS rate

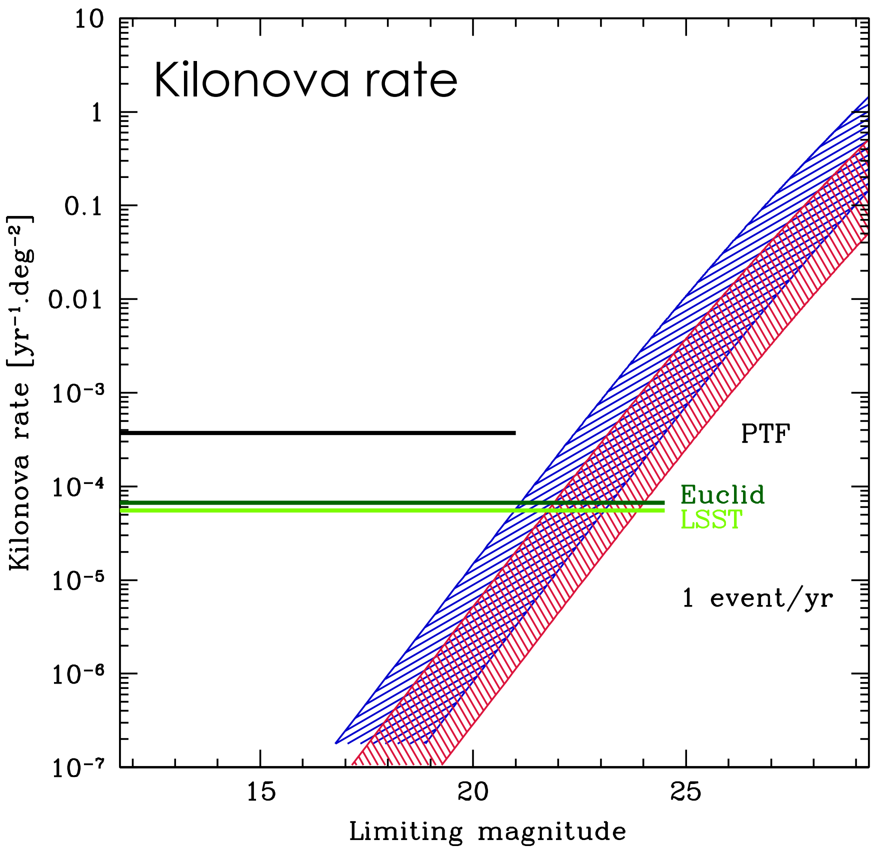


Abbott et al. 2016, post-O1

Merger rate: BNS

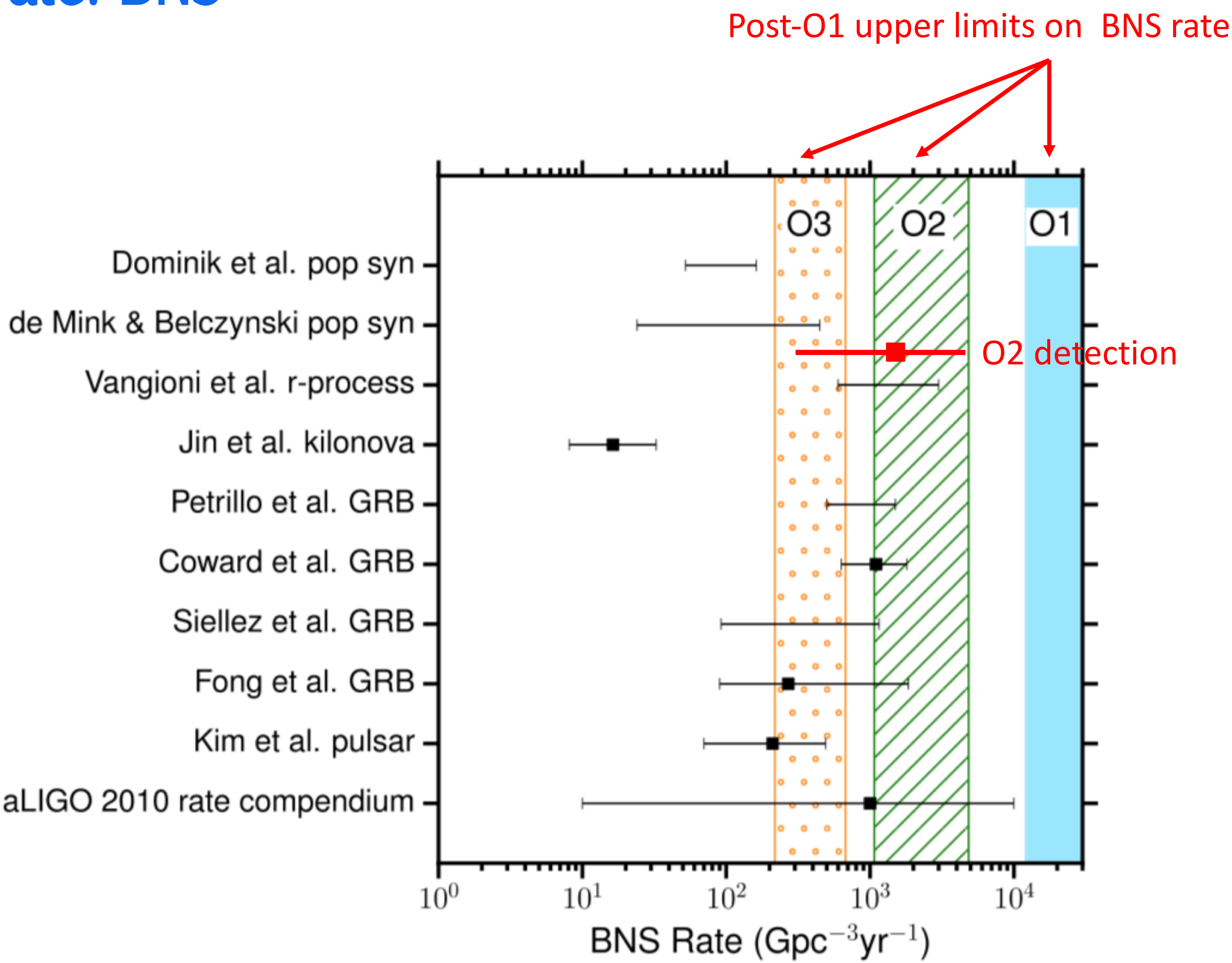
- **Model:** estimate the BNS rate assuming that most of the r-process elements are produced by NS+NS mergers
- **Observations:** Eu measured in metal-poor halo stars in the Milky Way = tracer of the time evolution of the r-process





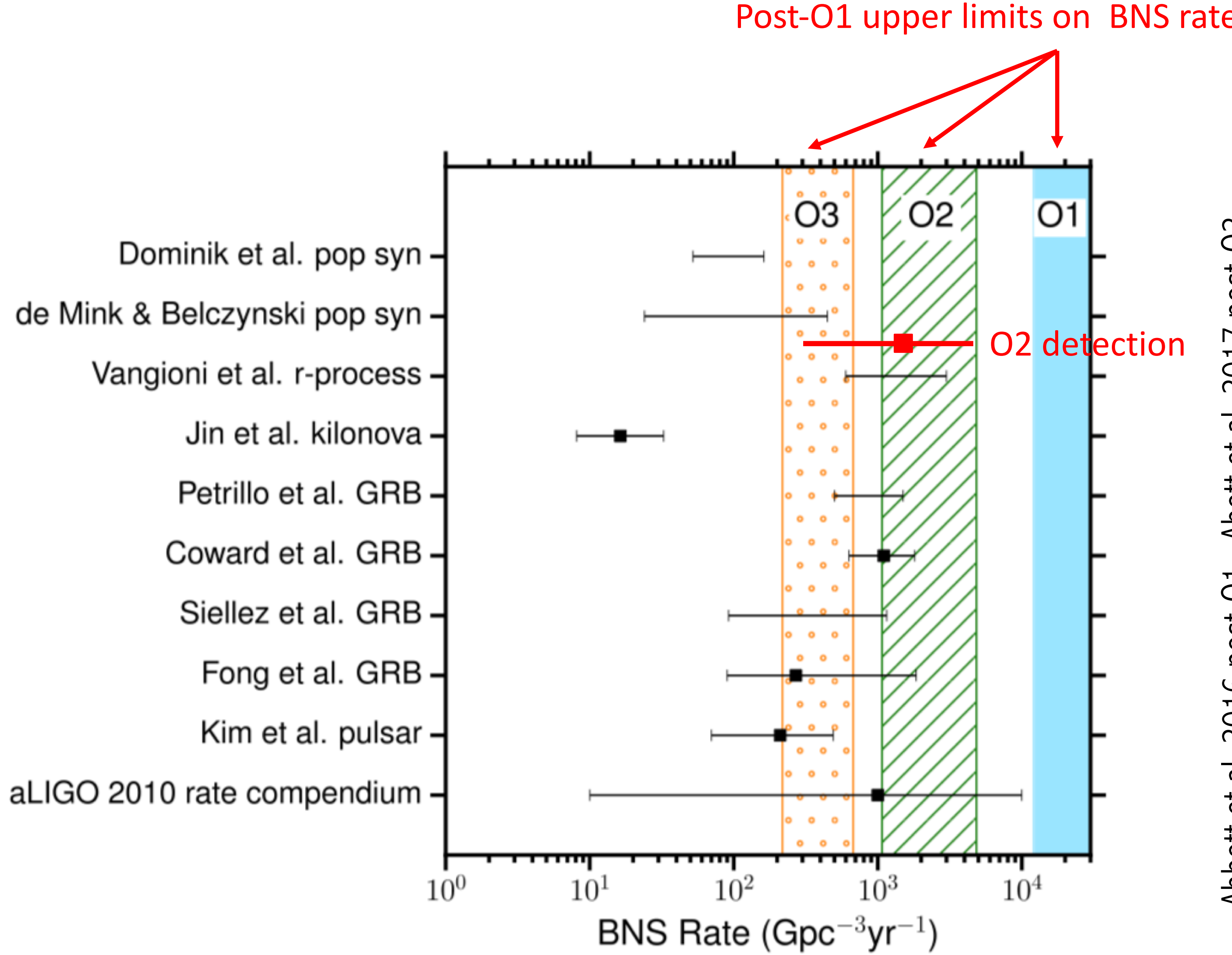
Vangioni, Goriely, Daigne, François & Belczynski (2016)

Merger rate: BNS



Abbott et al. 2016, post-O1

Merger rate: BNS



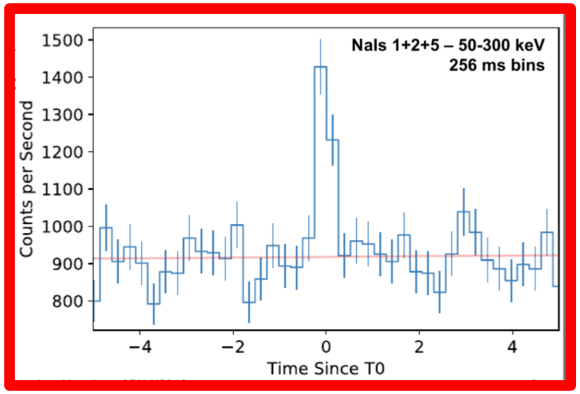
Abbott et al. 2016 post-O1, Abott et al. 2017 post-O2

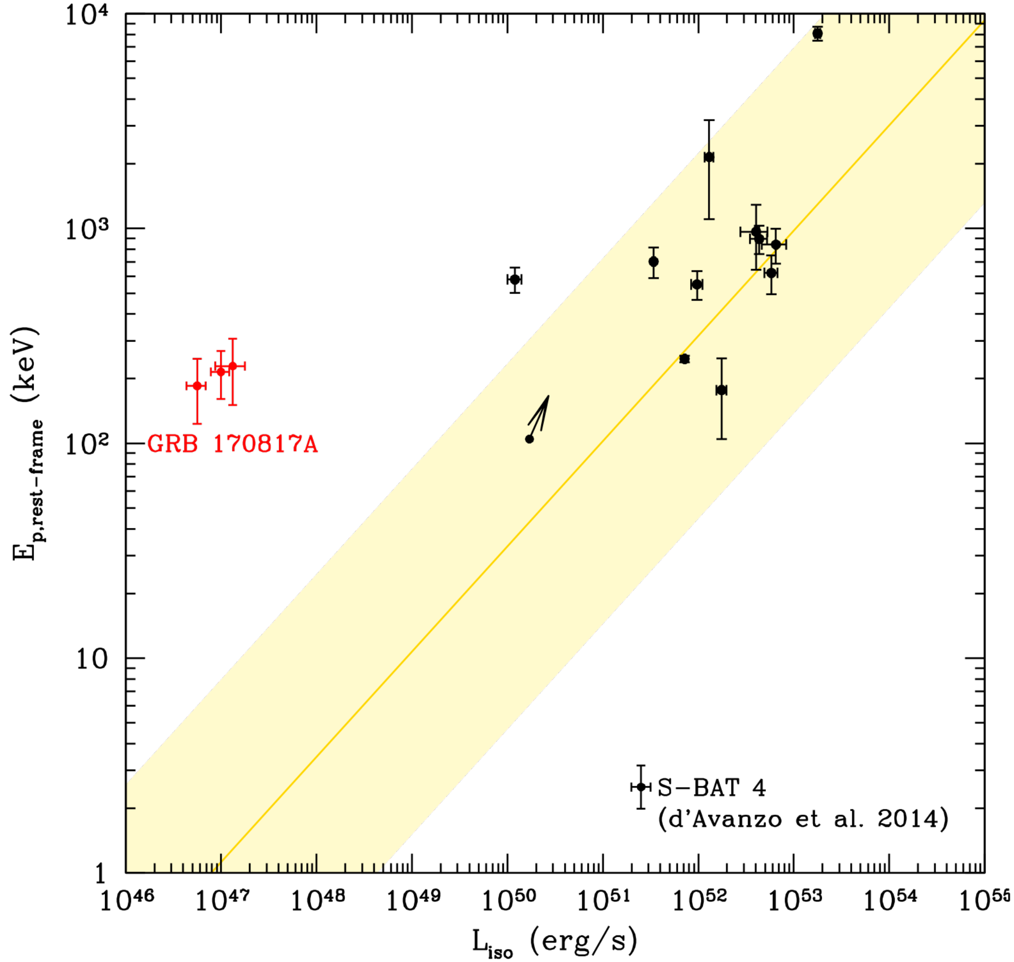
To confirme that mergers are the main contributers of r-process elements: more evidence for heavy elements formation, estimate of the ejected mass, …

Short GRB

Short GRB

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

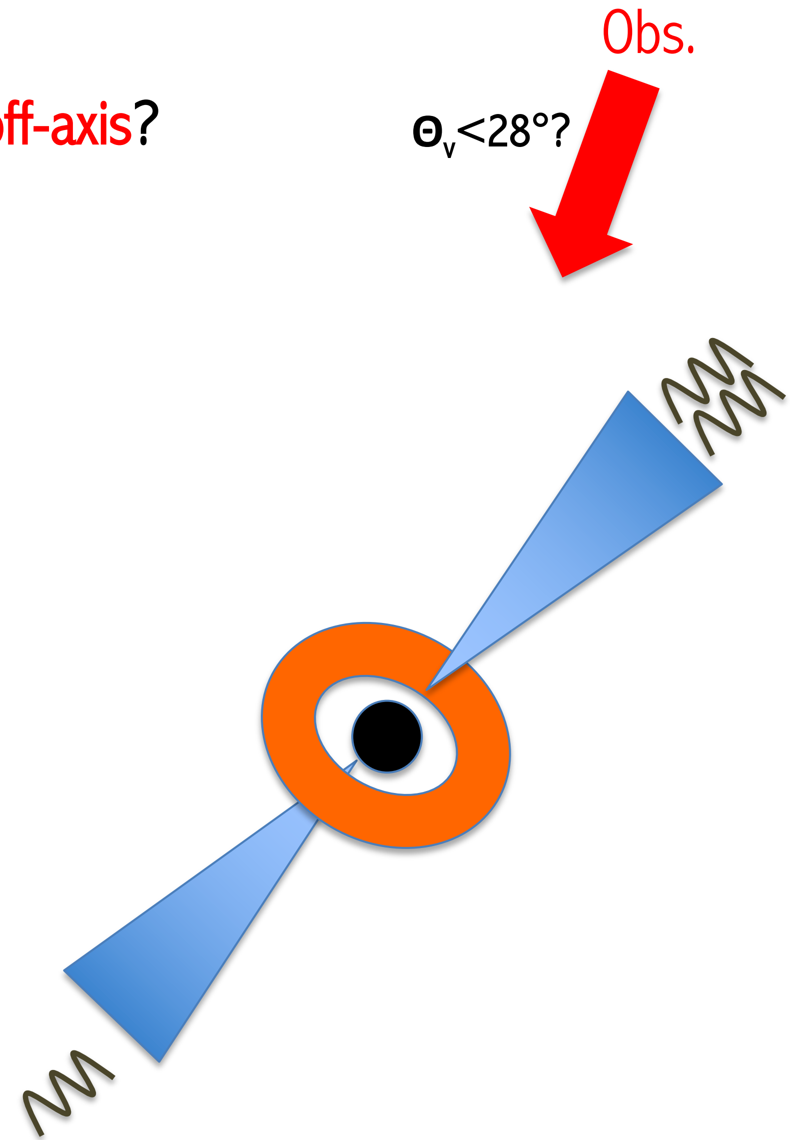




- Standard GRB seen off-axis unlikely
  (Ep would be very high if seen on-axis)

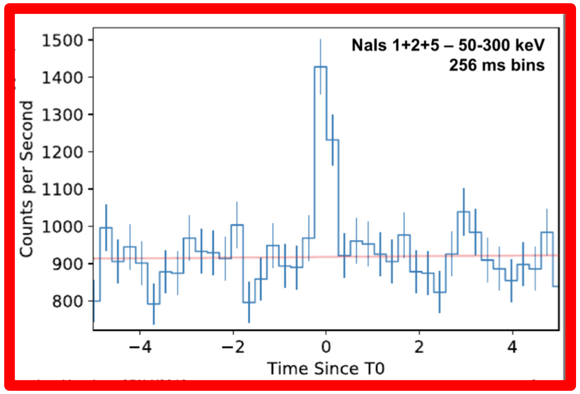
Short GRB:

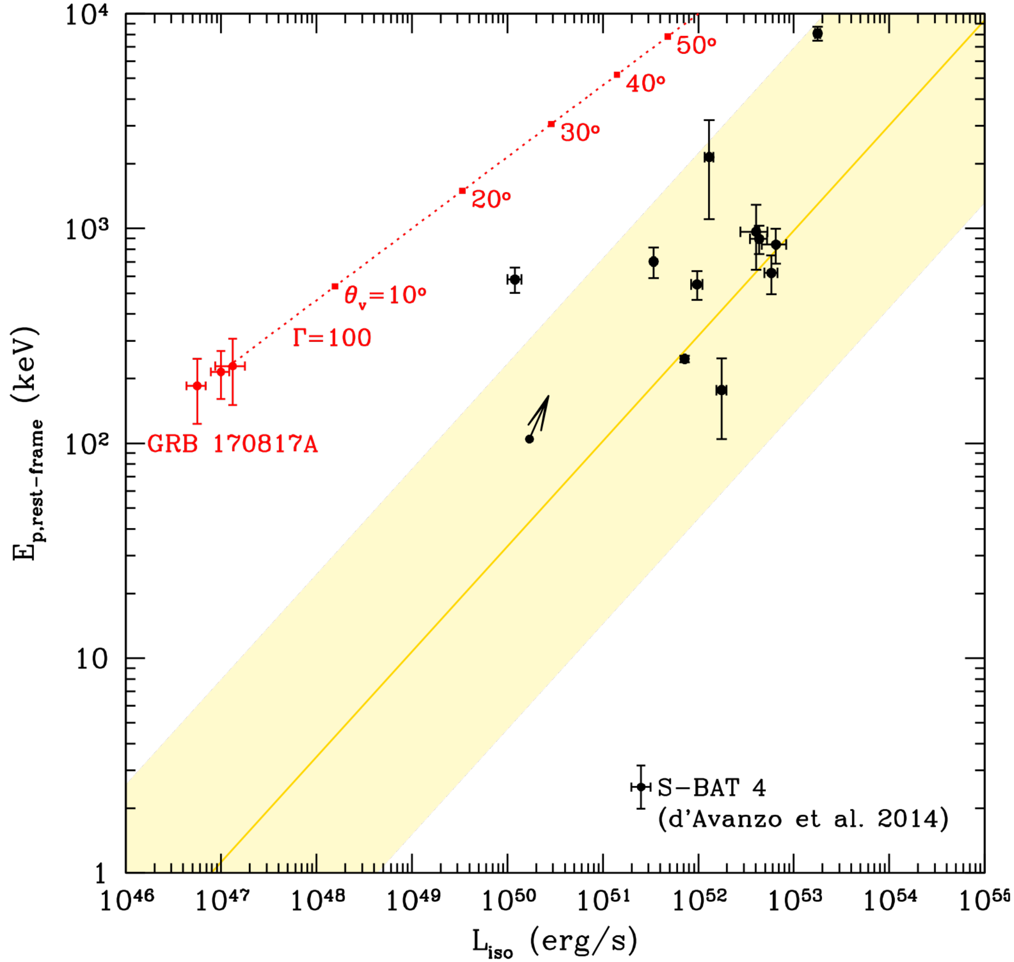
relativistic jet, seen off-axis?



Short GRB

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

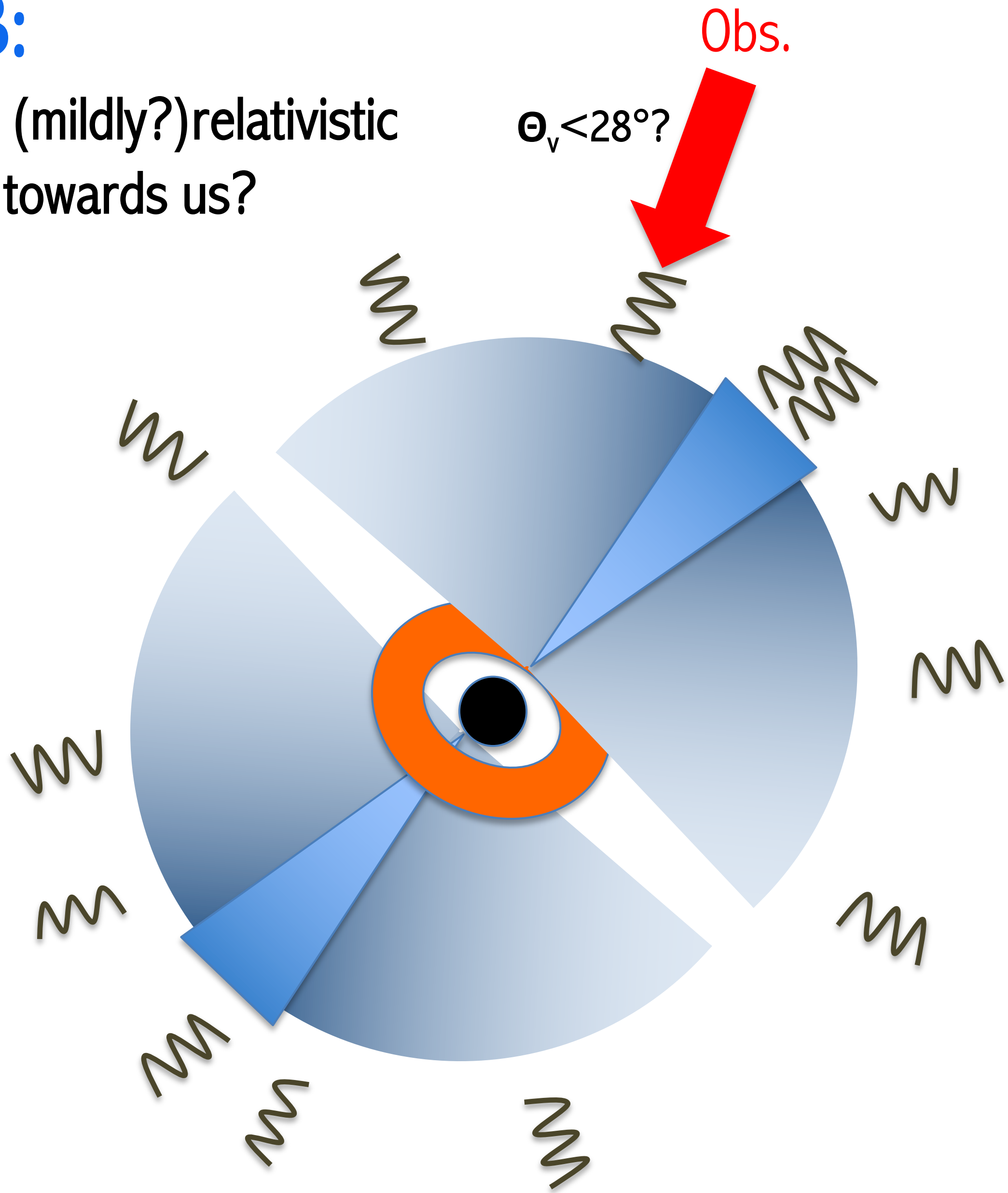




- Standard GRB seen off-axis: very unlikely
  (Ep would be very high if seen on-axis)

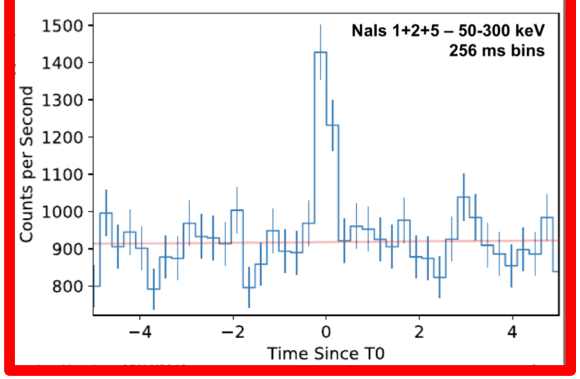
Short GRB:

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



Short GRB: emission mechanism? Observations needed

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

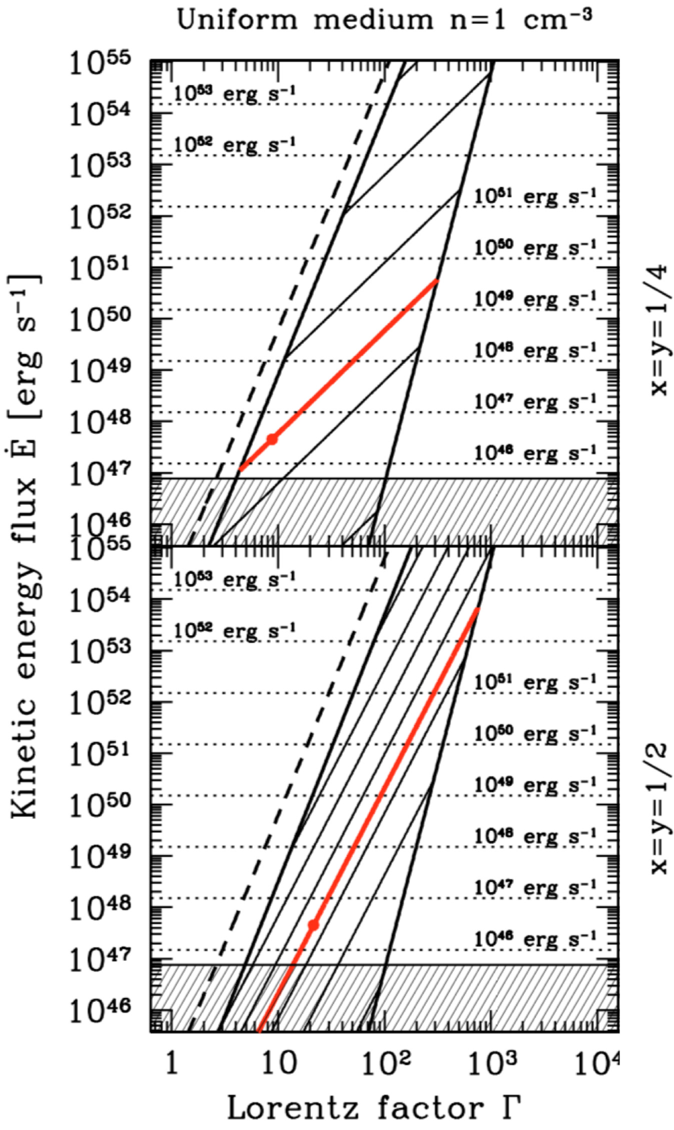


- **Dissipation in a mildly relativistic outflow pointing towards us?**
  (jet with lateral structure, cocoon, …)

- Example: internal shocks can explain
  the peculiar properties of GRB170817A
  for a low Lorentz factor/moderate kinetic energy flux

- **Needs more detections: intensity = f(θ_v) ?**

GRB980425 at 40 Mpc
(Daigne & Mochkovitch 2007)



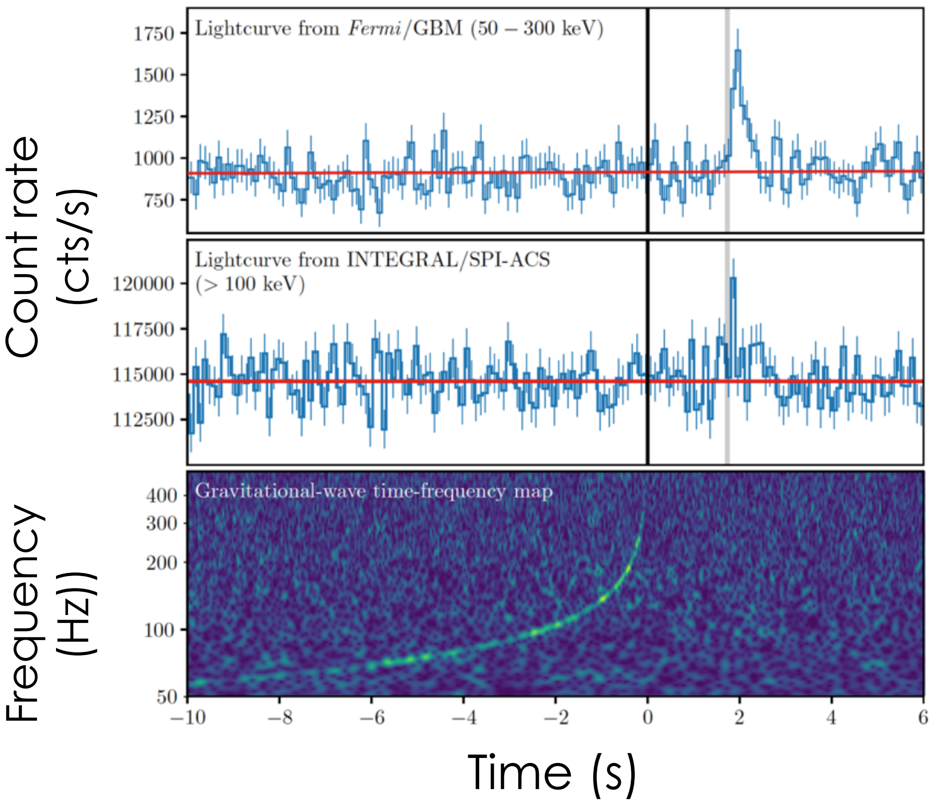
Short GRB: GW-GRB delay? Observations needed

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

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

- is natural
  1) if the relativistic ejection occurs rapidly after the merger (i.e. << s)
  2) if the emission occurs above the photosphere (shocks, recon.)

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



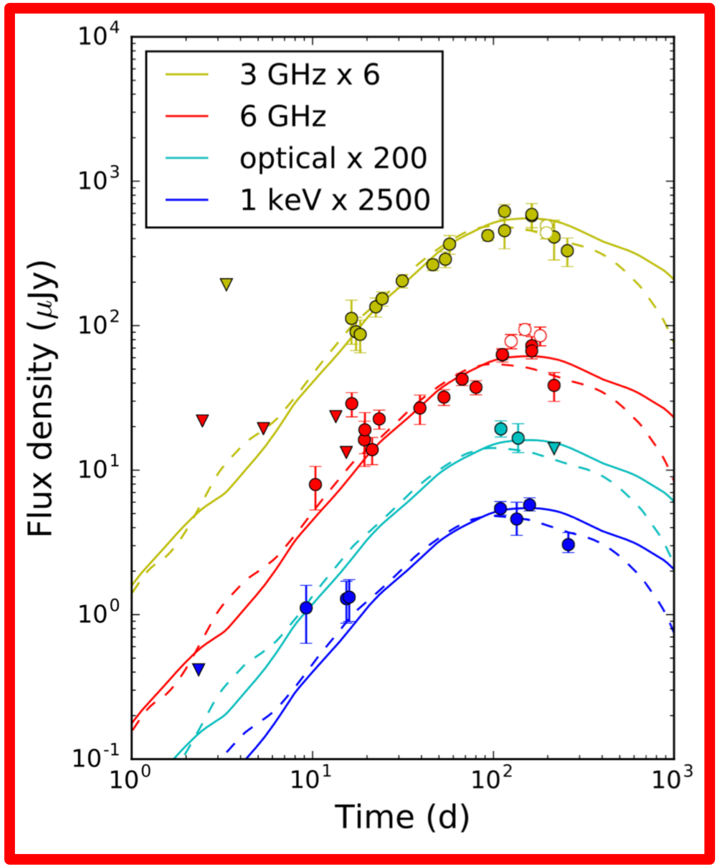
- **Needs more detections, with some statistics on the measured delay**

Afterglow

Afterglow

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

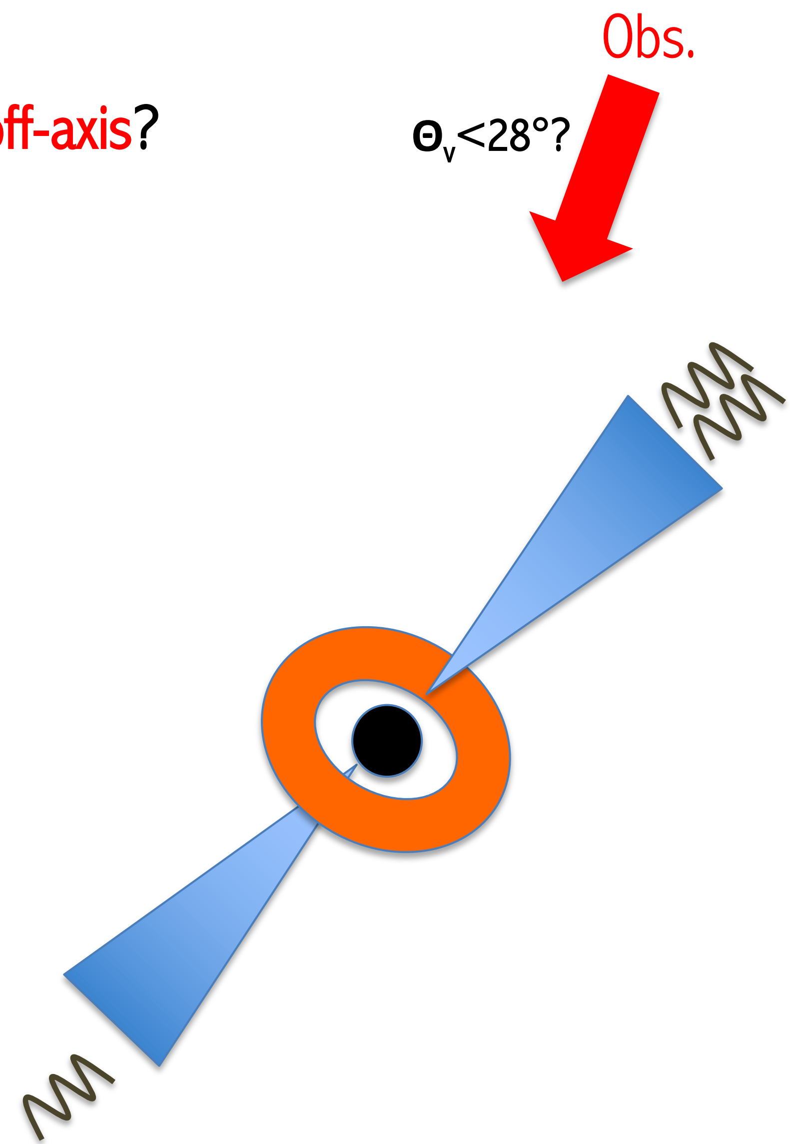
Rise to maximum as $\sim t^{1.5}$ / decline confirmed at 250 days



Alexander et al. 2018

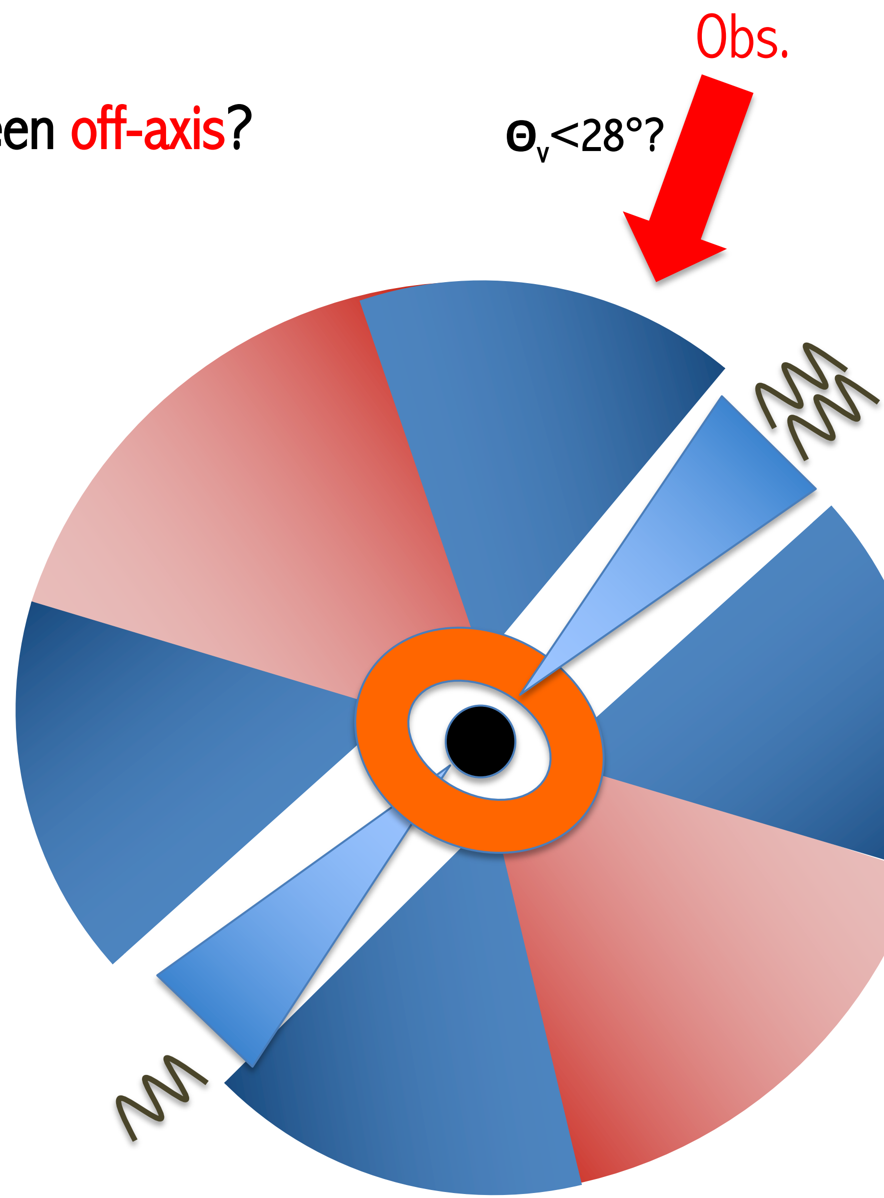
Afterglow:

relativistic jet, seen off-axis?



Afterglow:

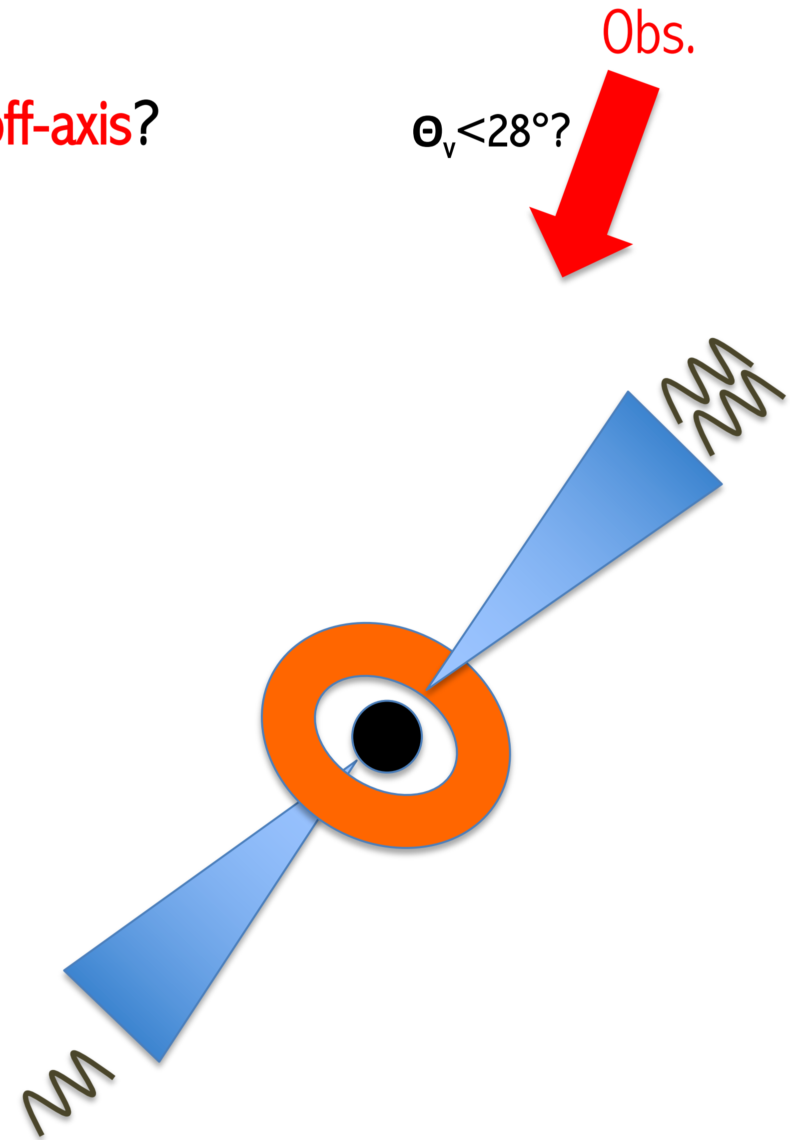
relativistic jet, seen off-axis?



Kilonova ejectas not shown

Afterglow:

relativistic jet, seen off-axis?

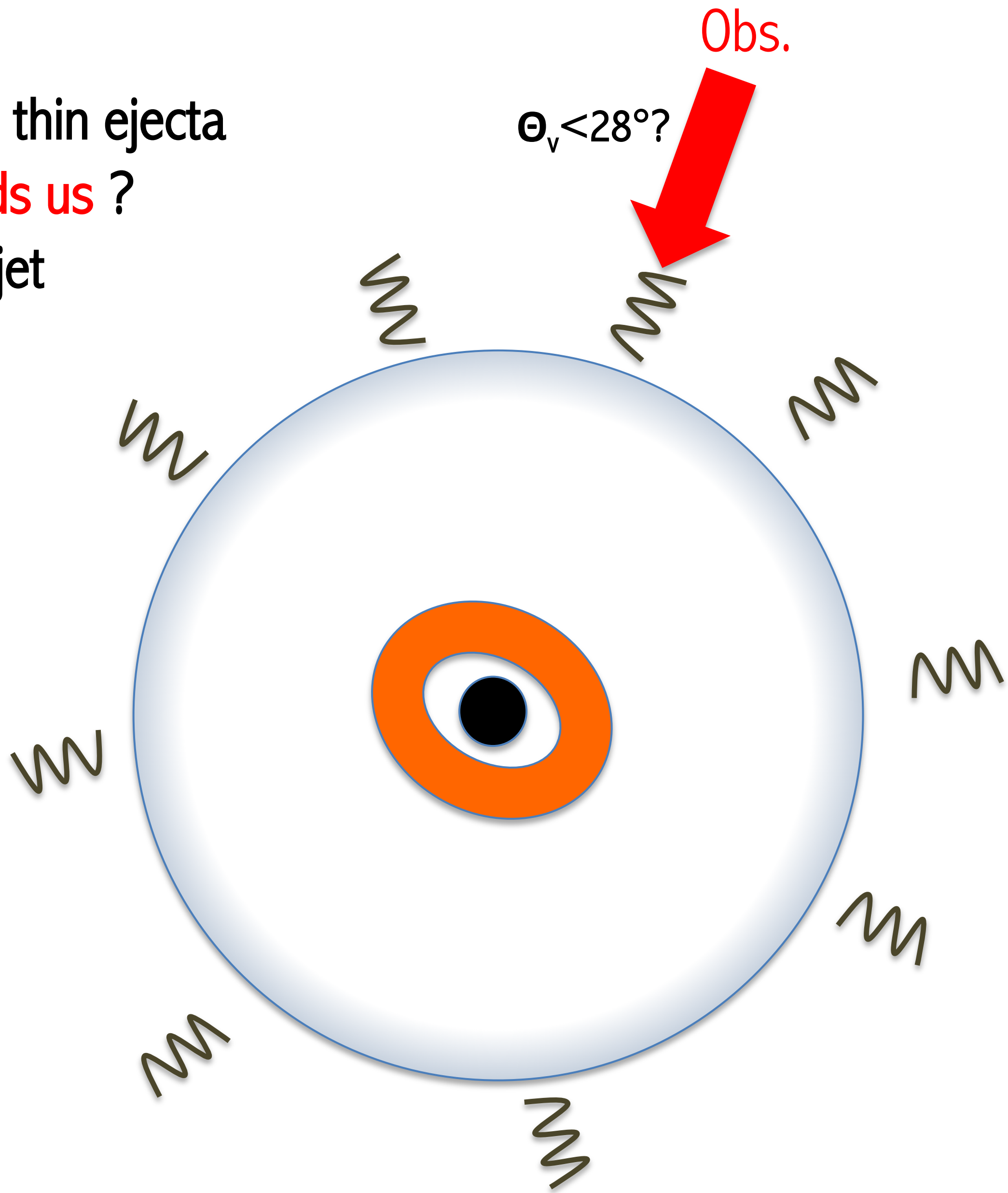


Afterglow

- Afterglow of a jet seen off-axis? No acceptable fit

Afterglow:

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

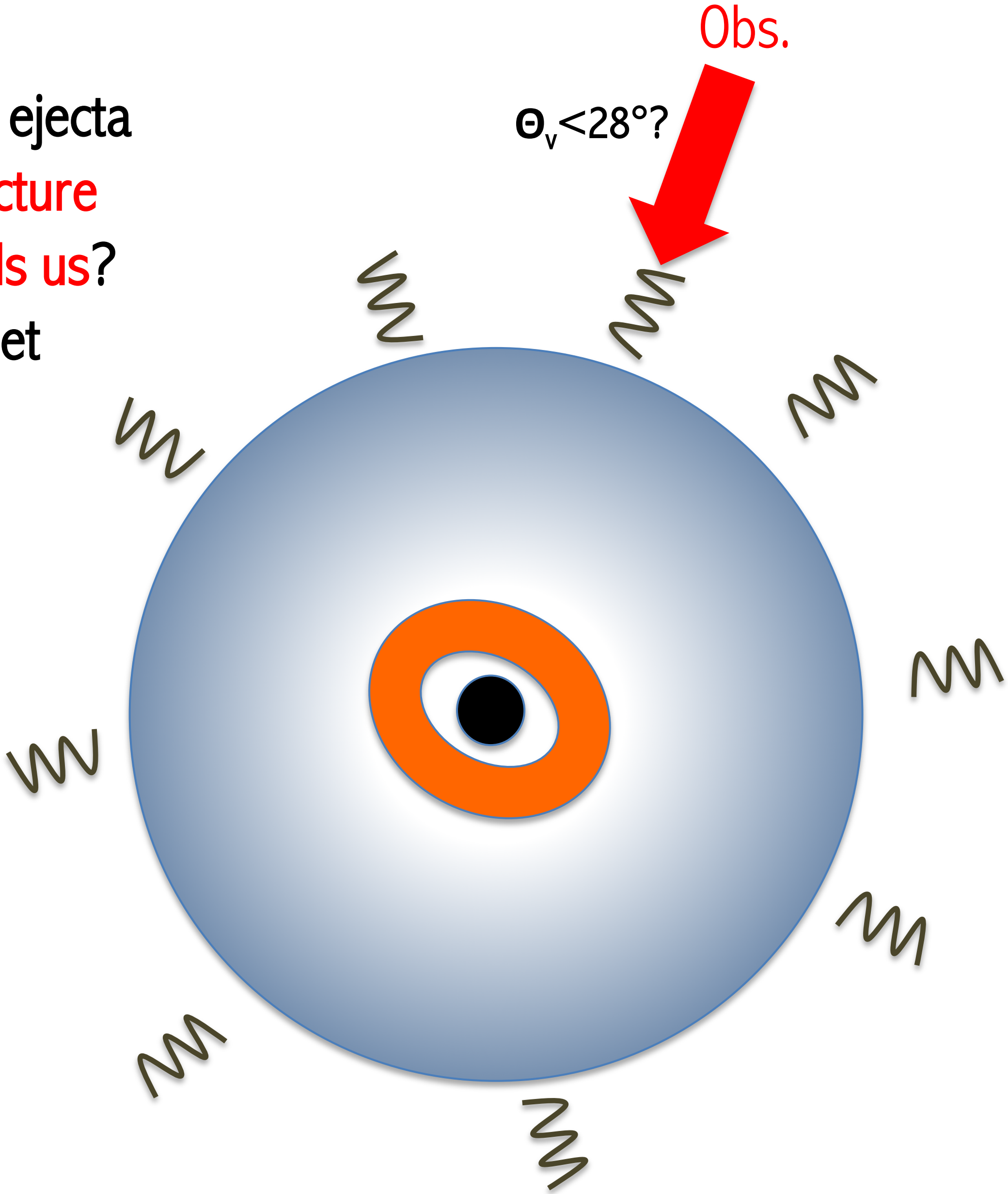


Afterglow

- Afterglow of a jet seen off-axis? No acceptable fit
- Expanding thin quasi-spherical ejecta seen on-axis? No acceptable fit

Afterglow:

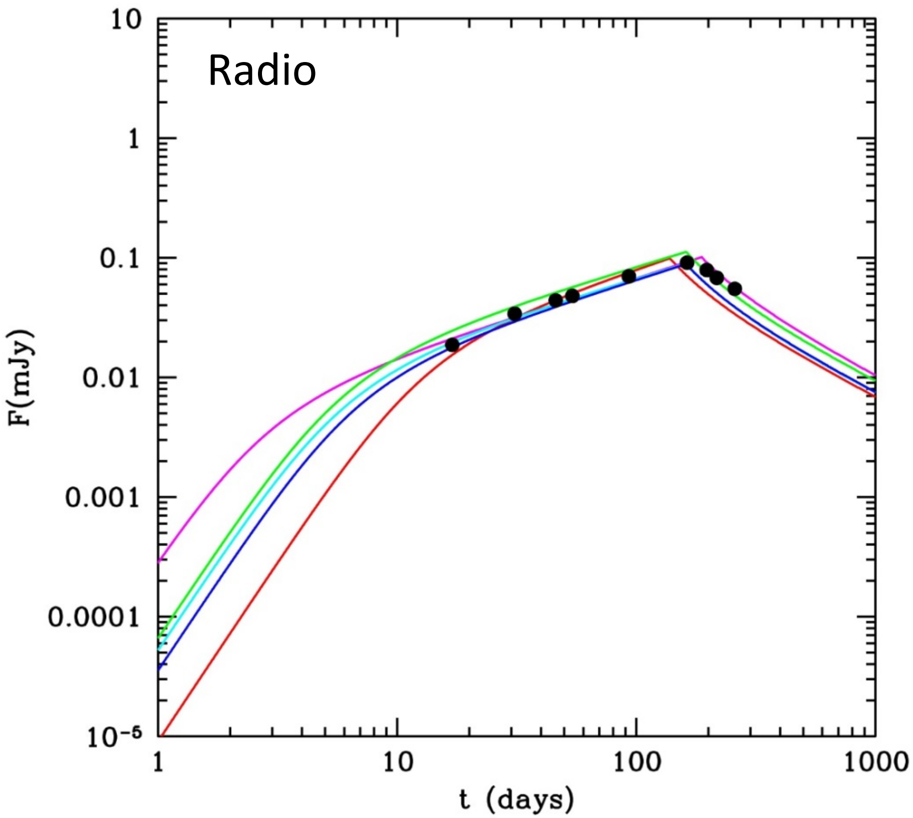
quasi-spherical ejecta
with radial structure
pointing towards us?
without a core jet



Afterglow

- Afterglow of a jet seen off-axis? No acceptable fit
- Expanding thin quasi-spherical ejecta seen on-axis? No acceptable fit

- Expanding quasi-spherical ejecta with radial structure: OK, large degeneracy in model parameters



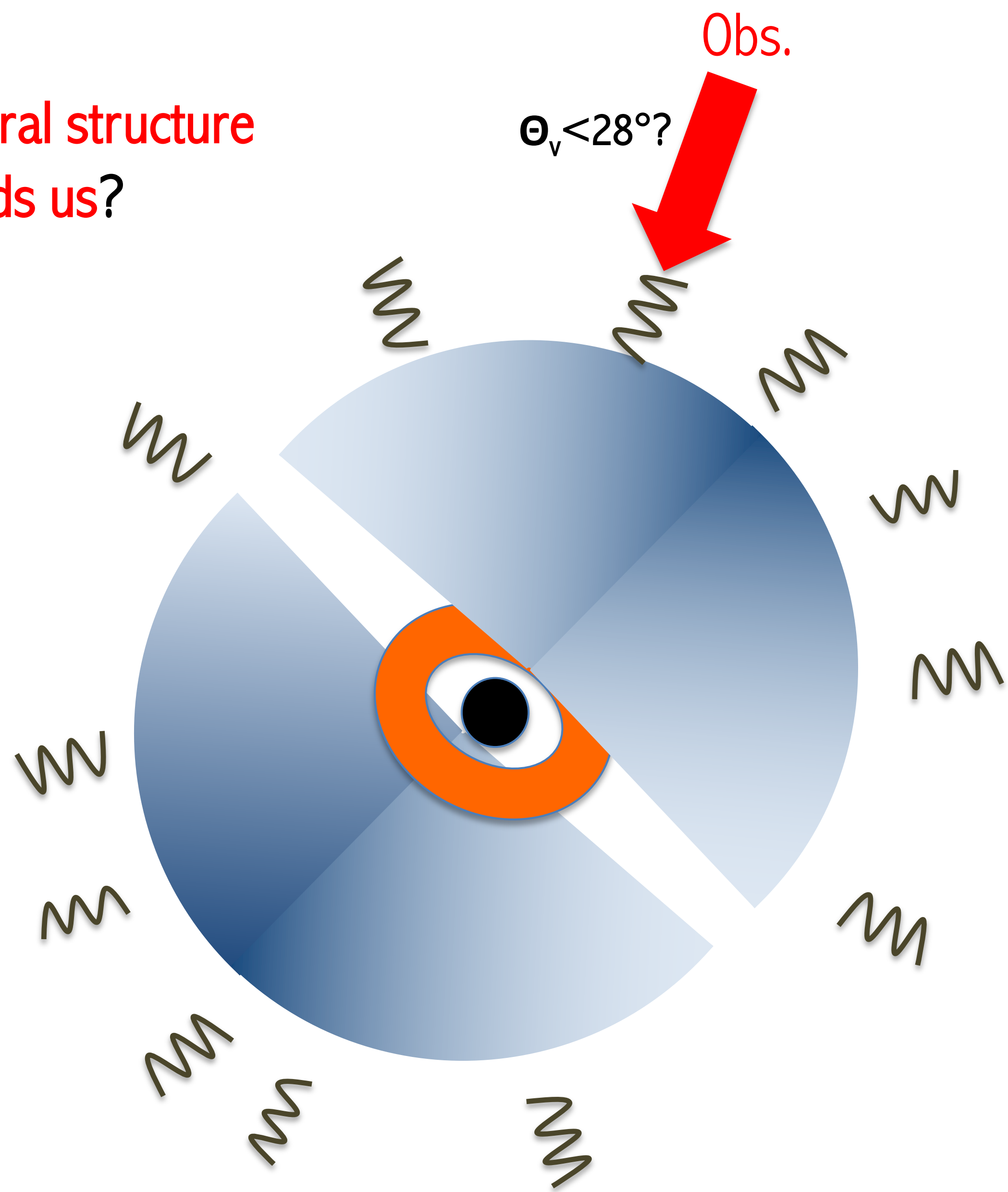
(Duque, Mochkovitch & Daigne)

- Note : multi-lambda does not help (except for p)

E_{50}	$(\beta\Gamma)_m$	$(\beta\Gamma)_M$	n	ε_B	
0.56	1.0	2.0	$3\ 10^{-3}$	10^{-2}	red
1.0	0.79	2.5	10^{-2}	$3\ 10^{-3}$	magenta
1.78	1.26	3.2	10^{-3}	$3\ 10^{-3}$	cyan
3.16	1.0	2.5	10^{-2}	$3\ 10^{-4}$	blue
5.62	1.26	3.2	$3\ 10^{-3}$	$3\ 10^{-4}$	green

Afterglow:

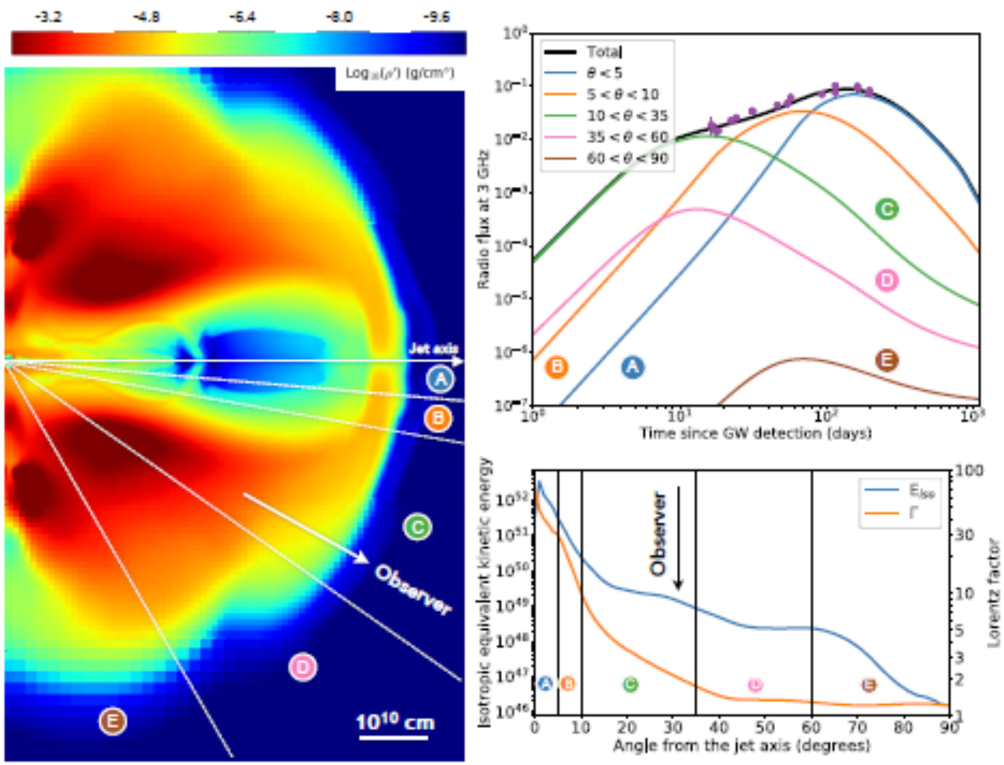
ejecta with lateral structure pointing towards us?



Afterglow

- Afterglow of a jet seen off-axis? No acceptable fit
- Expanding thin quasi-spherical ejecta seen on-axis? No acceptable fit

- Expanding quasi-spherical ejecta with radial structure: OK
- Lateral structure instead of radial structure: equally good fits



Lazzati et al. 2018

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

Afterglow

- Afterglow of a jet seen off-axis? No acceptable fit
- Expanding thin quasi-spherical ejecta seen on-axis? No acceptable fit

- Expanding quasi-spherical ejecta with radial structure: OK
- Lateral structure instead of radial structure: equally good fits

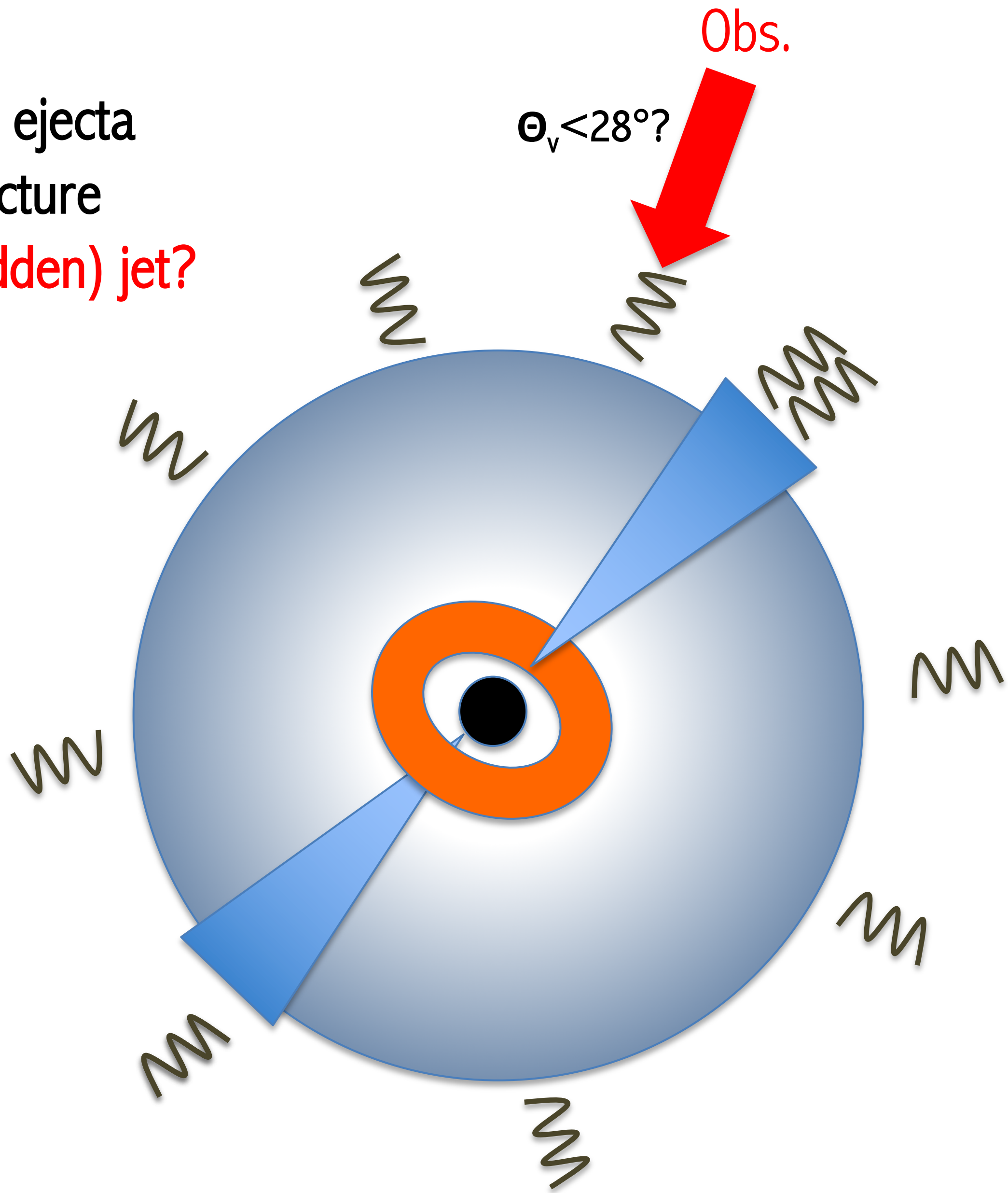
- These two classes of models can apply to two different post-merger behaviors:

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

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), or not
   →intermediate latitude: mildly rel. ejecta (afterglow) with radial/lateral structure
   →larger latitudes: blue kilonova ejecta

Afterglow:

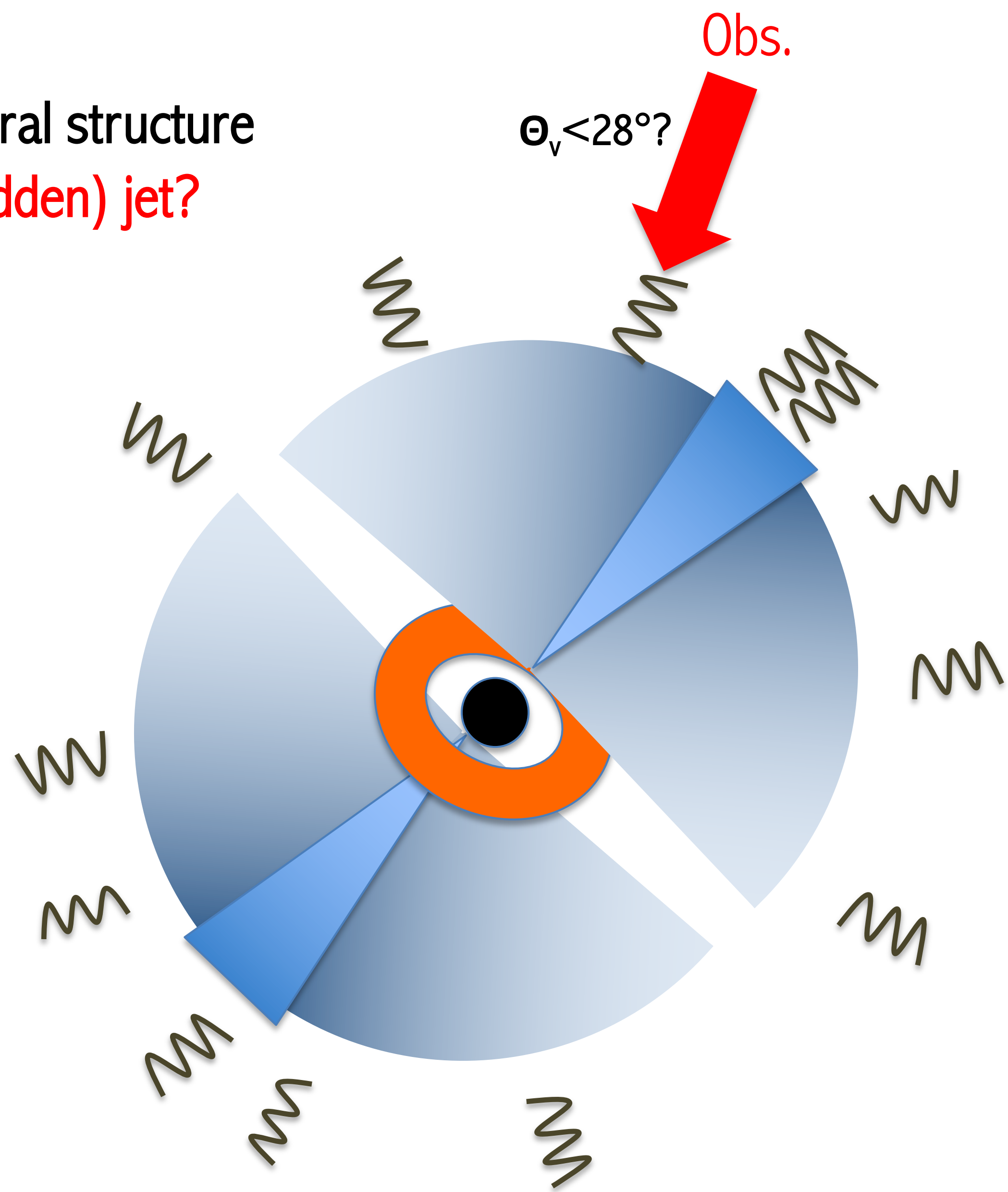
quasi-spherical ejecta
with radial structure
with a core (hidden) jet?



Afterglow:

ejecta with lateral structure

with a core (hidden) jet?

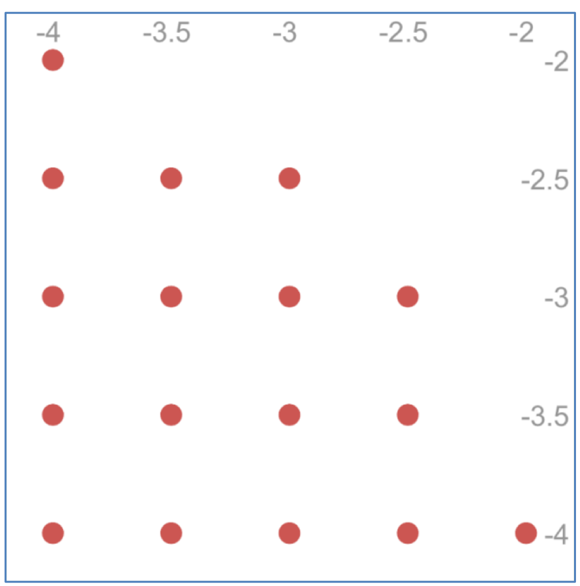


Afterglow

- Expanding quasi-spherical ejecta with radial structure: OK
- Lateral structure instead of radial structure: equally good fits

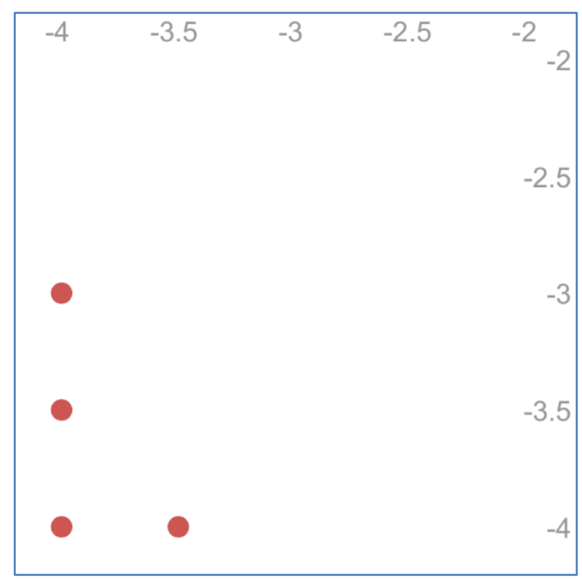
- Hidden central ultra-relativistic jet? Example for θ_j=5°, θ_v=25°, ε_e=0.1
  (note: if θ_v decreases, it is more difficult to hide the jet)

Log n



Log ε_B

$E_j=10^{51}$ erg



Log ε_B

$E_j=10^{52}$ erg

(Duque, Mochkovitch & Daigne)

Afterglow

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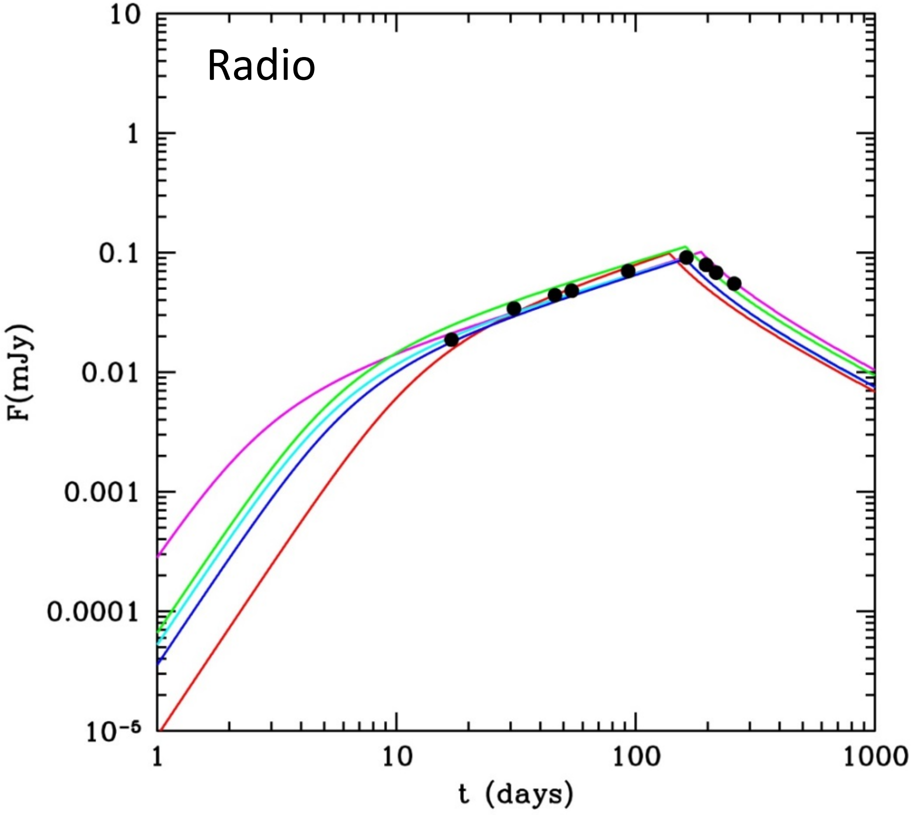
- Hidden central ultra-relativistic jet?

Example for θ_j=5°, θ_v=25°, ε_e=0.1



(Duque, Mochkovitch & Daigne)

Afterglow

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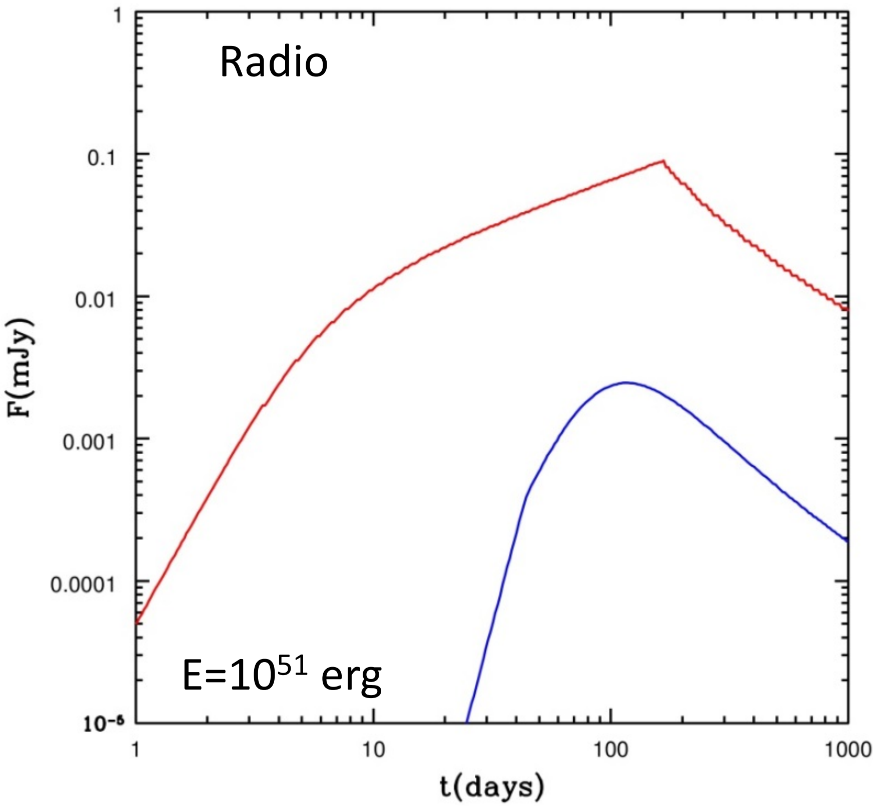
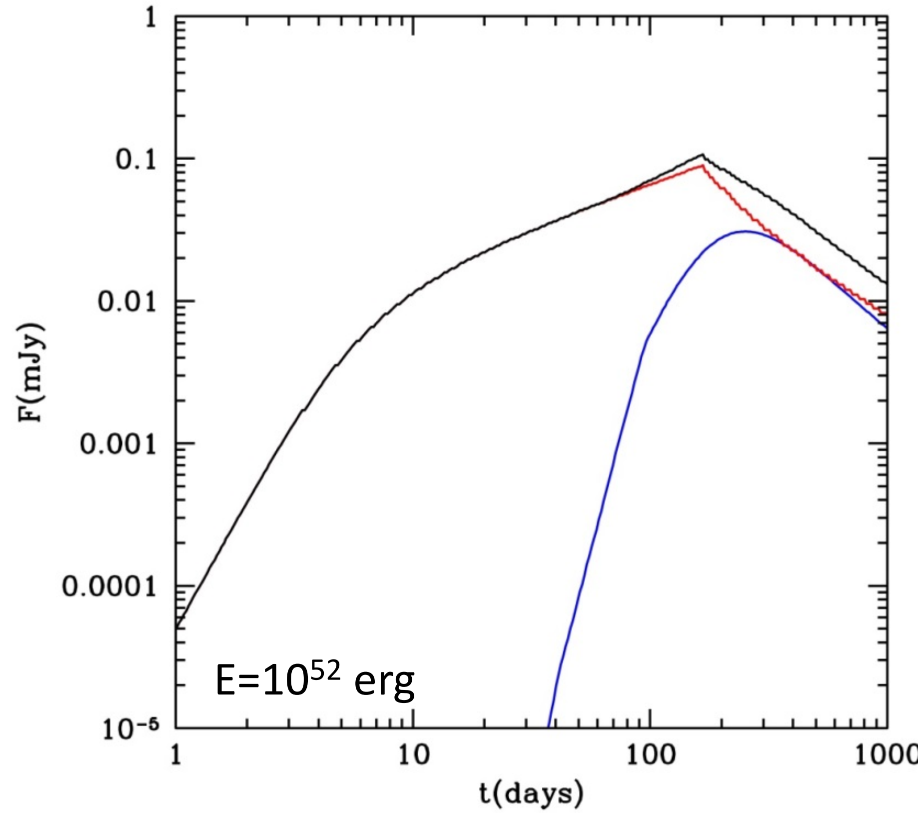
Example for θ_j=5°, θ_v=25°, ε_e=0.1





n=10^{-3} cm^{-3}, ε_B=10^{-3}

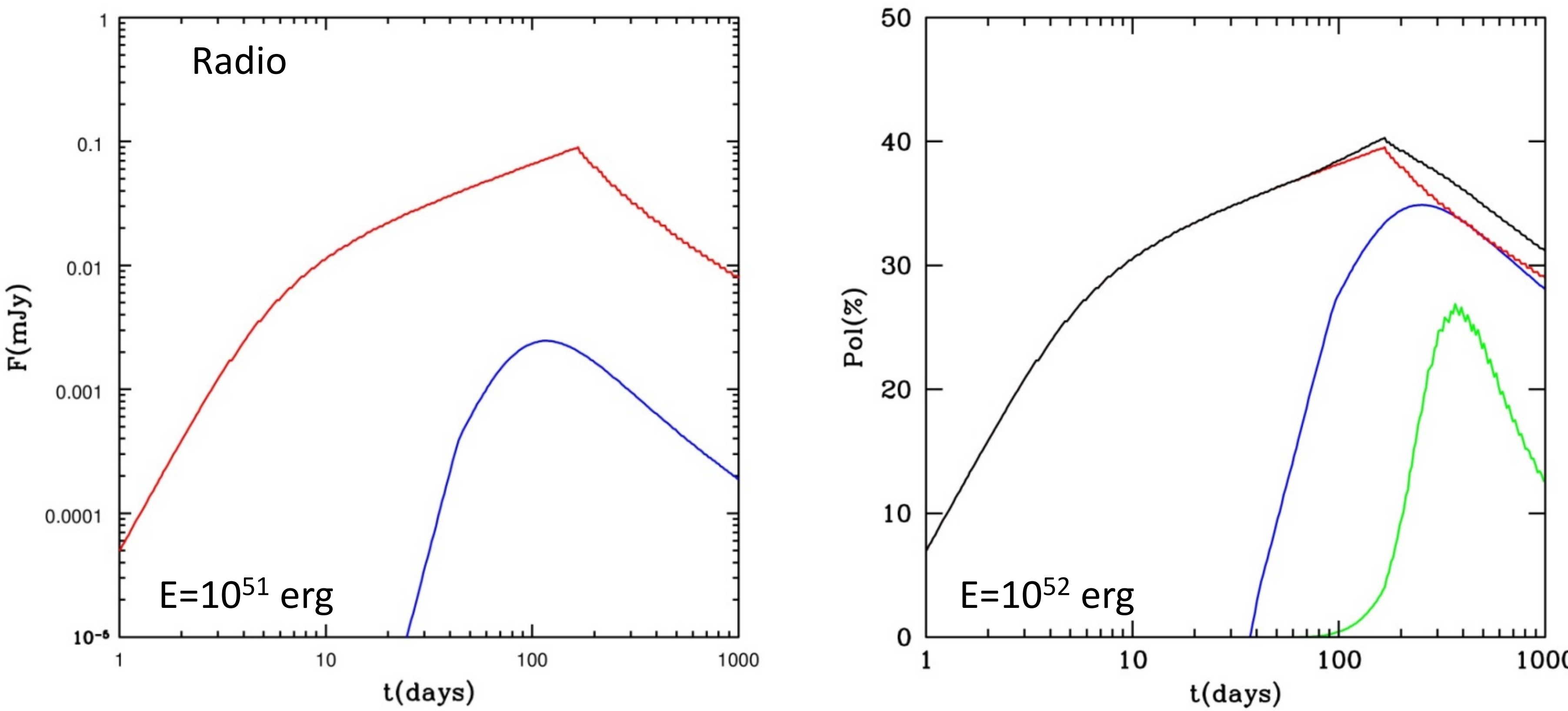
(Duque, Mochkovitch & Daigne)

Afterglow

- Expanding quasi-spherical ejecta with radial structure: OK
- Lateral structure instead of radial structure: equally good fits

- Hidden central ultra-relativistic jet?

Example for θ_j=5°, θ_v=25°, ε_e=0.1



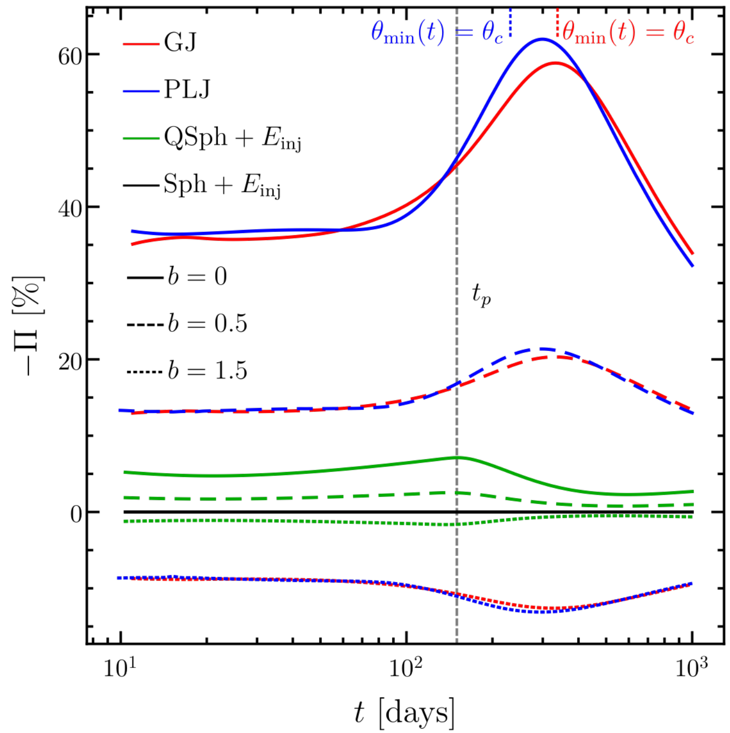
(Duque, Mochkovitch & Daigne)

- Possible diagnostic: polarization (maximum polarization: ~28% at ~ one year)

Afterglow: observations needed

- More detection, at different viewing angles!
- Additional diagnostics to break the radial/lateral structure degeneracy:

Polarization @ 3 GHz:



Gill & Granot 2018

GJ: Gaussian jet
PLJ: Power-law jet

Lateral structure

vs

radial structure

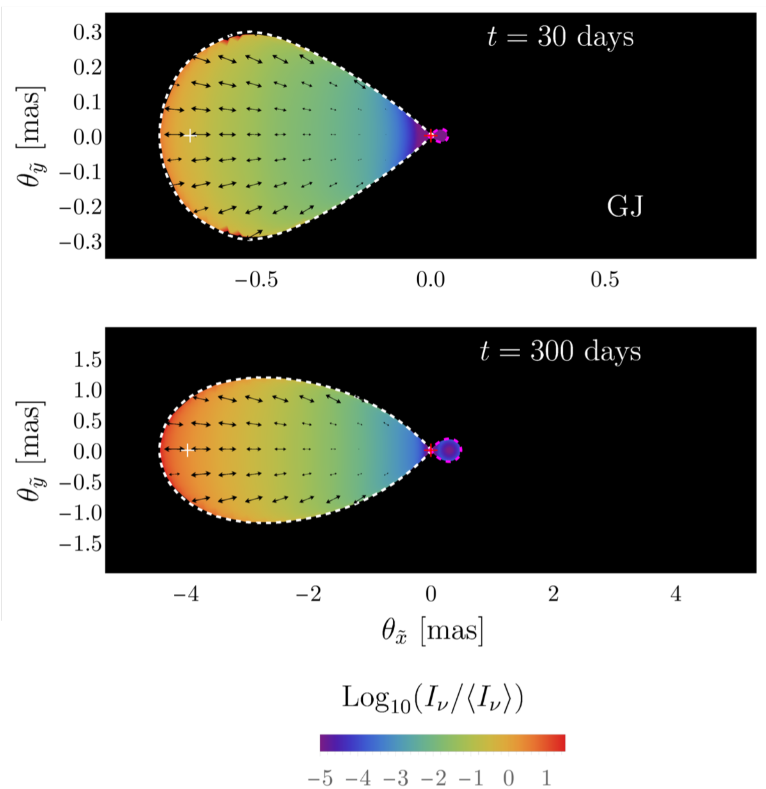
QSph+E_{inj}: quasi-spherical
Sph+E_{inj}: spherical

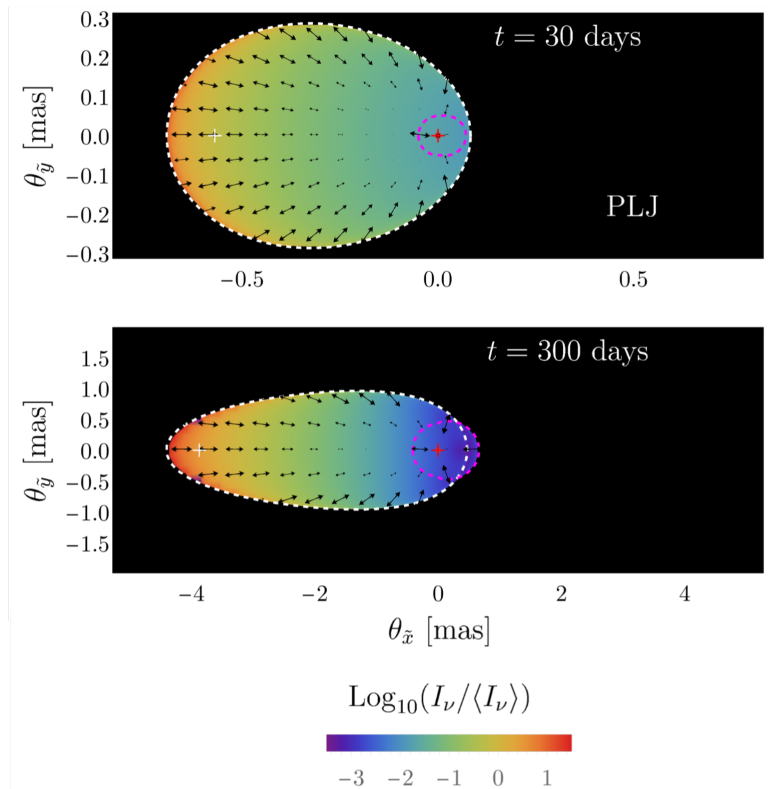
Afterglow: observations needed

- More detection, at different viewing angles!
- Additional diagnostics to break the radial/lateral structure degeneracy:

GJ: Gaussian jet
PLJ: Power-law jet
Lateral structure

Radio afterglow imaging (VLBI)





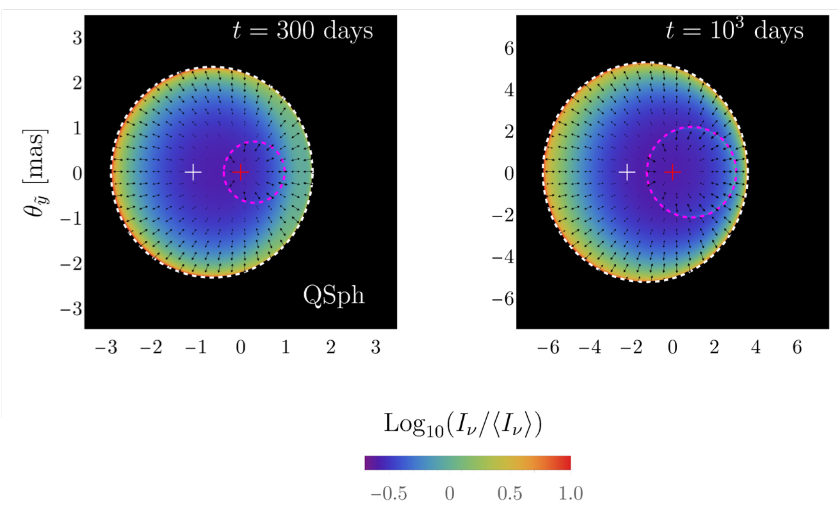
Gill & Granot 2018

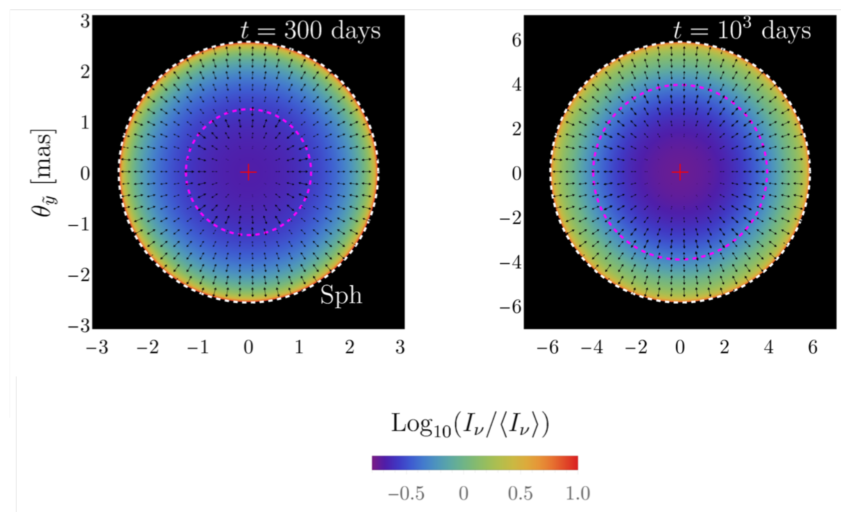
Afterglow: observations needed

- More detection, at different viewing angles!
- Additional diagnostics to break the radial/lateral structure degeneracy:

Radio afterglow imaging (VLBI)

QSph+E_{inj}: quasi-spherical
Sph+E_{inj}: spherical
Radial structure





Gill & Granot 2018

Conclusion

Conclusions: observations needed

- More GW events, with different viewing angles
- NS+BH?
- Post merger GW signal
- Rates

- More KN events, with different viewing angles (change in color? Intensity?)
- Universal? NS+BH?
- Statistics: ejected mass?
- Composition? Spectroscopic signature of r-process elements?

- More GRBs, with different viewing angles (change in intensity? Hardness? No GRB?)
- Better description of lightcurve+spectrum
- Statistics: GW-GRB delay

- More afterglows, with different view angles (different components?)
- Polarization? Imaging (radio afterglow: VLBI?)

Conclusions: not discussed here

- Variability in the afterglow (flares?)
- Indirect constraints on the nature of the post-merger central object
- Information brought from the study of the host galaxy/source environment
- Cosmology/Fundamental physics
- …

- Modelling tools at IAP:
  - Short GRB: detailed internal shock model
  - Afterglow: detailed model
    - fitting procedure
    - radial/lateral structure
    - polarization
    - soon: imaging
    - soon: reverse shock emission
  - Kilonova: very naive model