Population Prospects for Electromagnetic Counterparts to Neutron Star Mergers in the Gravitational Wave Era

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June 1st 2019

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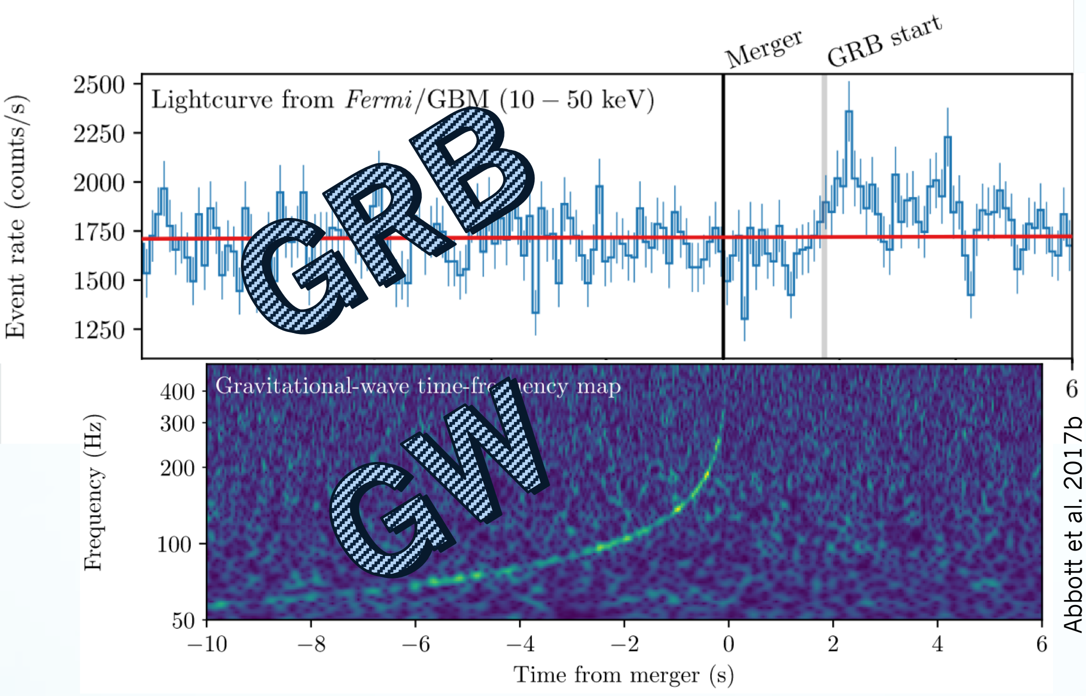
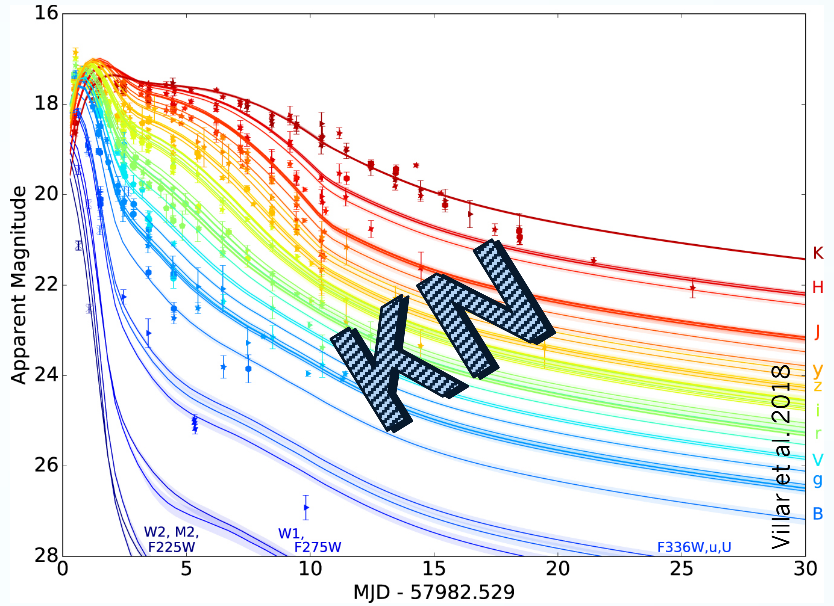
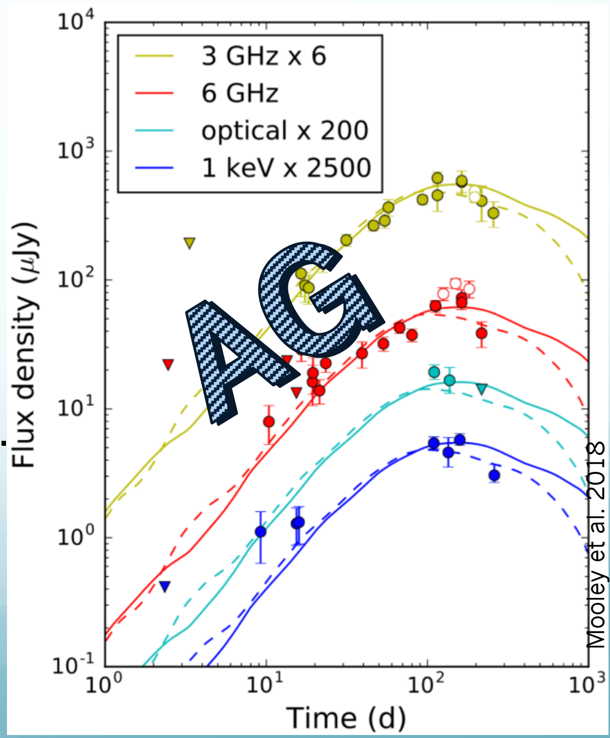
Cosmic Explosions 2019

On August 17th 2017...





- Confirmed NS-NS mergers as **progenitors for short GRBs**
- Inauguration of the **era of multi-messenger astronomy with GW**
- Other fundamental (astro-)physics: GR, NS EOS, Hubble constant measurement, r-process nucleosynthesis, etc.

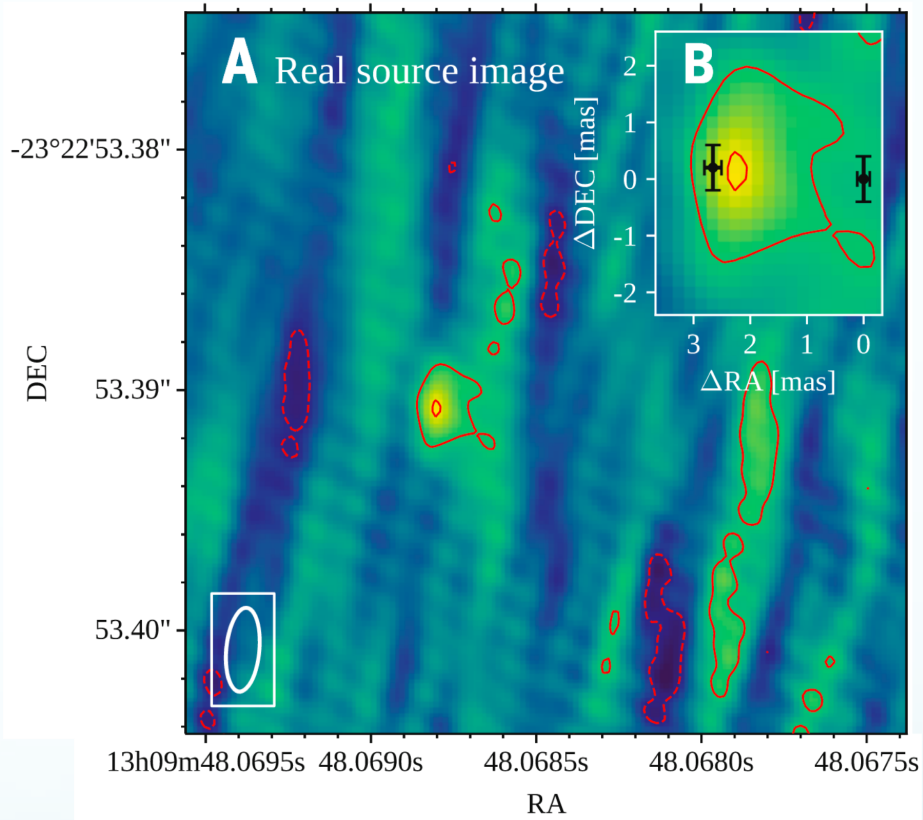


Afterglows and kilonovae: What should we expect for O3?

From GRB170817A to O3...

Afterglow, kilonova
= great wealth of information!

- ✓ Localization
- ✓ External medium density
- ✓ Jet kinetic energy
- ✓ Jet geometry
- ✓ Viewing angle
- ✓ Magnetic field
- ✓ And more!



Ghirlanda et al. 2018

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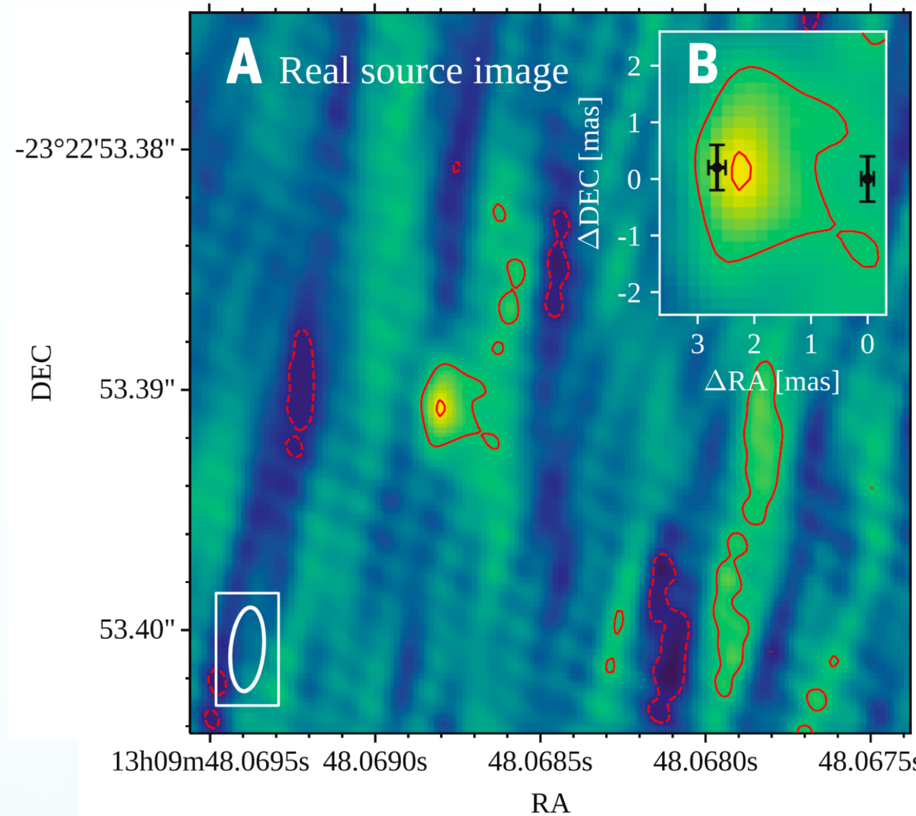


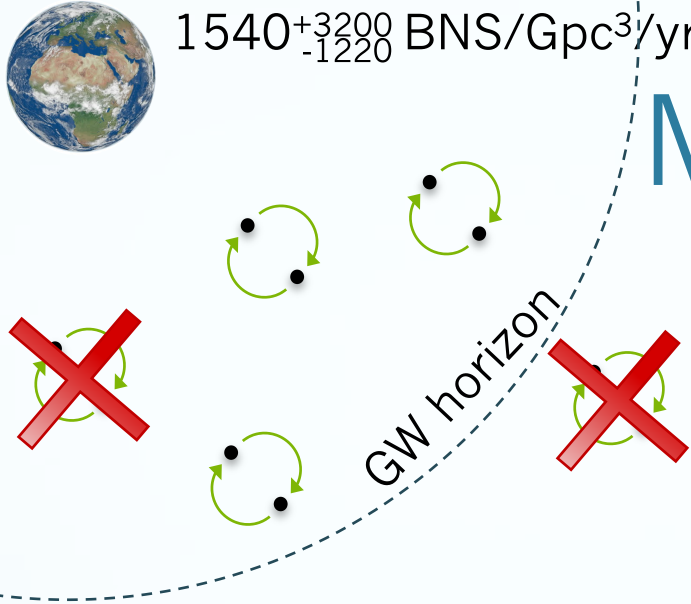
Ghirlanda et al. 2018

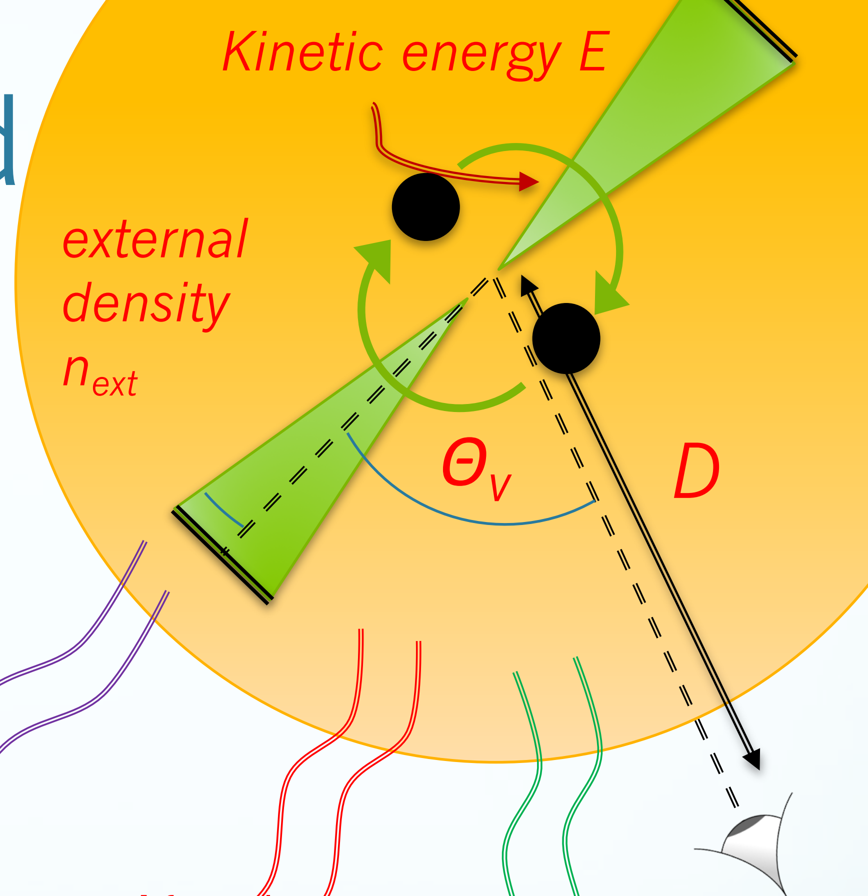
O3 is here
→ More GW with afterglow and kilonova!

- Which **kilonovae and afterglows** to expect and **what will they look like**?
- How will they help to study **the evolution of NS binaries**?
- What insight will they bring on the **GRB jet structure**?

Method

1540^{+3200}_{-1220} BNS/Gpc^3/yr (Abbott+2018)





Population model with ingredients: D, Θ_v, E, n_{ext}, ...
+ **Detection criterion**
→ Deduce **GW+AG observed** population of mergers

Detection depends on D, Θ_v
... *and* ***GW horizon***

O3: 250 Mpc
Design: 450 Mpc

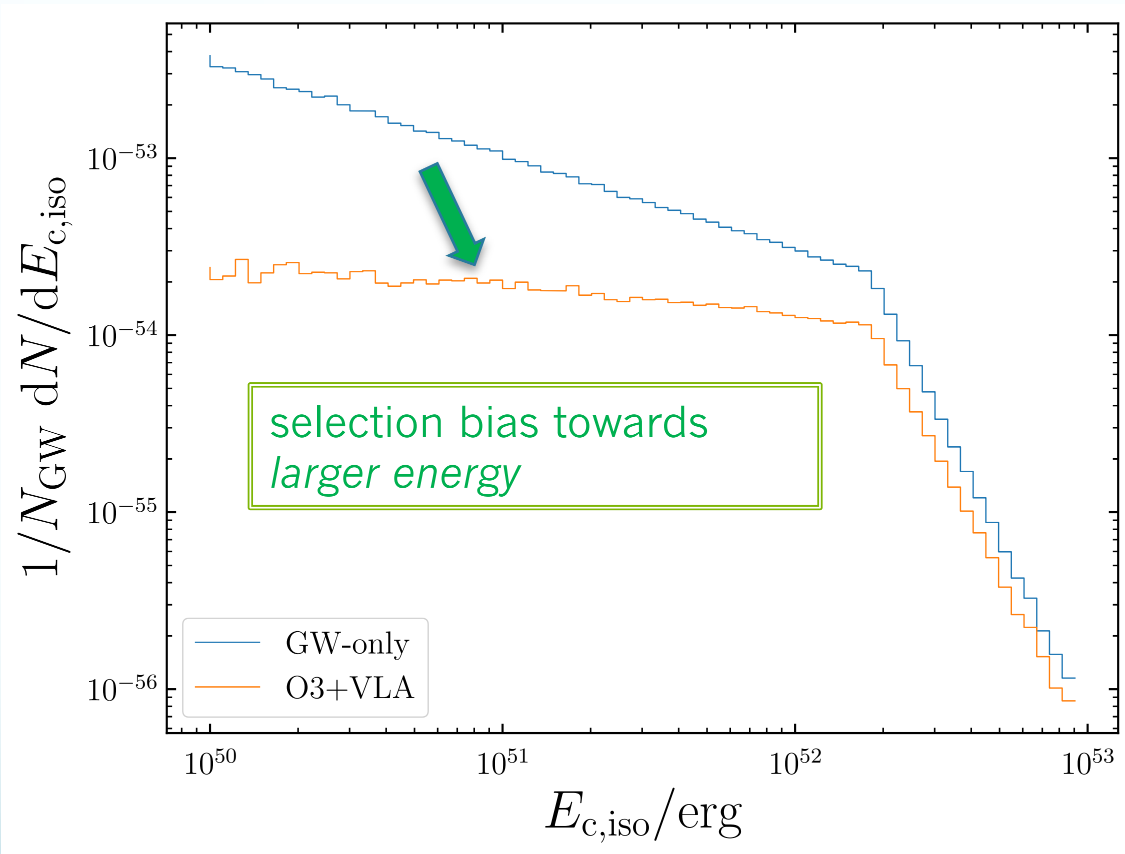
Detection depends on D, Θ_v, E, n_{ext},
... *and* ***radio sensitivity***

VLA: 10 μJy @ 3GHz
SKA1-Mid: 1 μJy

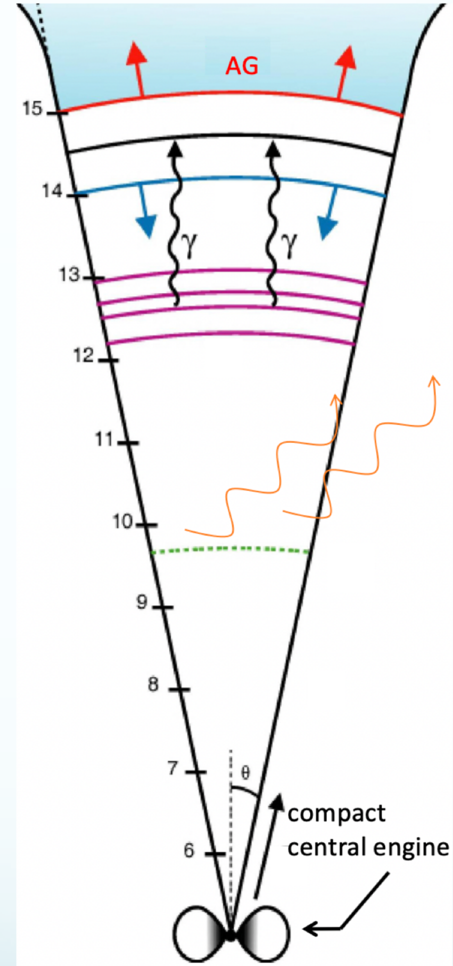
Detection depends on D, Θ_v
... *and* ***Vis.-IR follow-up depth***

Population model distributions:

Energy



RD, Daigne, Mochkovitch (1905.04495)



Reference model:

- *Energy*: BPL, break energy 2.10^{52} erg, slopes +0.5 and -2 (Ghirlanda et al. 2016)

(Detectable) Event rates for NS-NS

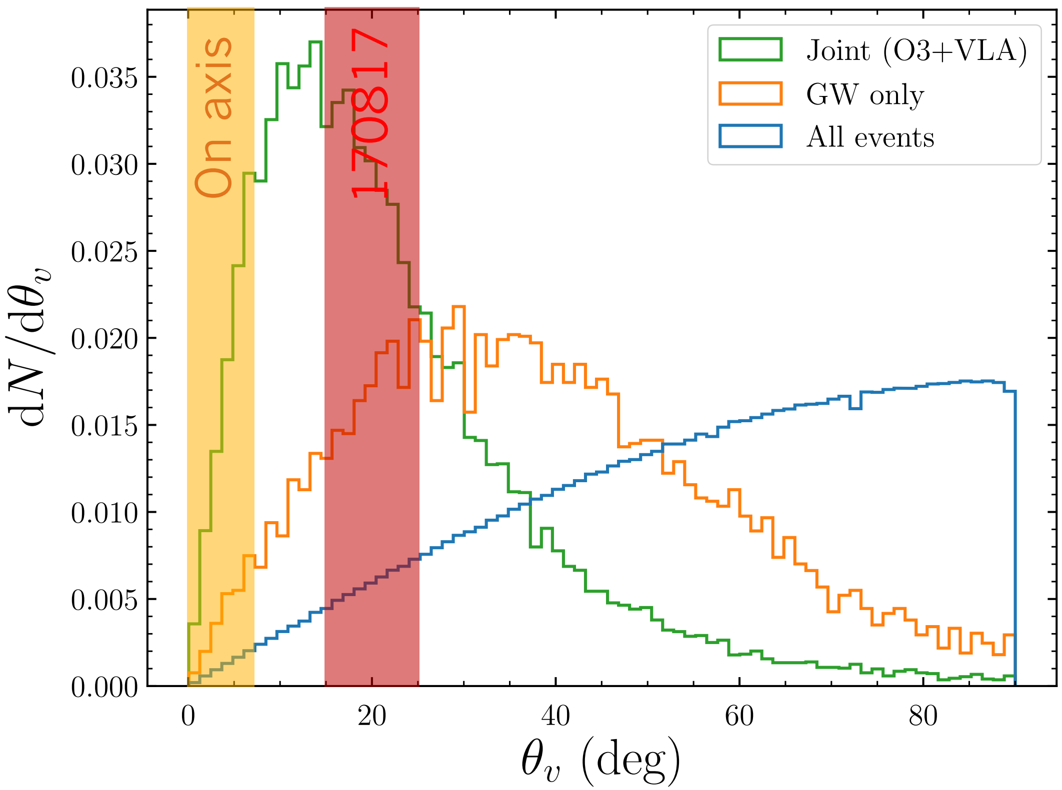
Detector conf.	#GW	#(GW+AG)	#(GW+KN)
O3 + VLA	9	3	
Design + VLA	21	5	**100%**
Design + SKA	21	10	

Can we **detect** all **detectable** events?

Uncertainties: $^{+200\%}_{-73\%}$ (intrinsic rate from LIGO-Virgo O2/O3)
+ uncertainty on population model

- In general: **10-30% events have detectable AG** (depending on energy distribution)
- Large deviation from this **= constraints on population!**

Properties of joint events: viewing angle



RD, Daigne, Mochkovitch (1905.04495)

- Most events seen off axis!
- Mean angle ~20-30°
- New insight on GRB physics

→ ***Jet geometry? Origin of lateral structure?***

→ **GRB dissipation mechanisms** (thermal tail?)

→ $\lesssim$10% **on axis (GRB!)**

+ Other distributions:
distance, peak flux, proper motion, …

GW+GRB ~ 1-10% (O3)
(Beniamini et al. 2018)

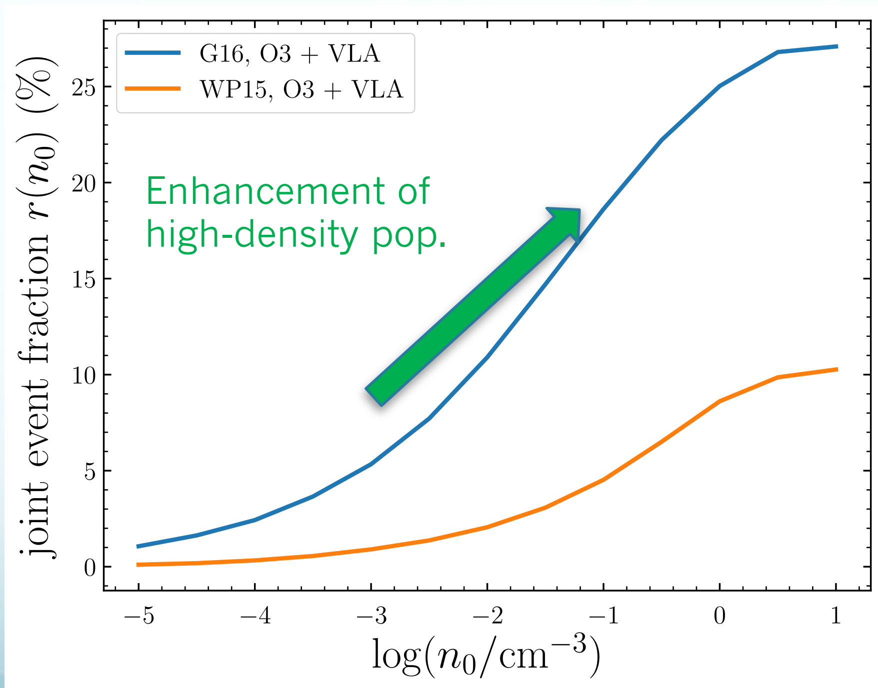
Binaries in high density media

Formation medium density (high)

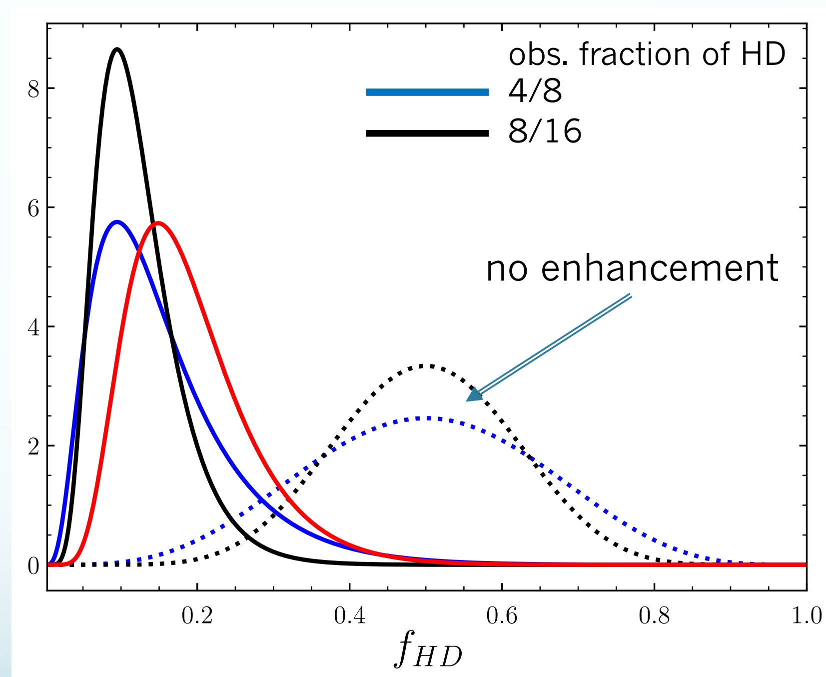
?

Merger medium density (low)

- **Evidence found** for **fast-merging** binary population (*r*-process element abundance, sGRB rate vs. cosmic SFR, Galactic binary population)
- May be due to high **eccentricity,** efficient **common envelope** phase or **Kozai-Lidov** type mechanisms (Beniamini+2016)
- These merge in **high density** media producing **brighter AG** and are **more likely detected** ($F \sim n^{4/5}$)



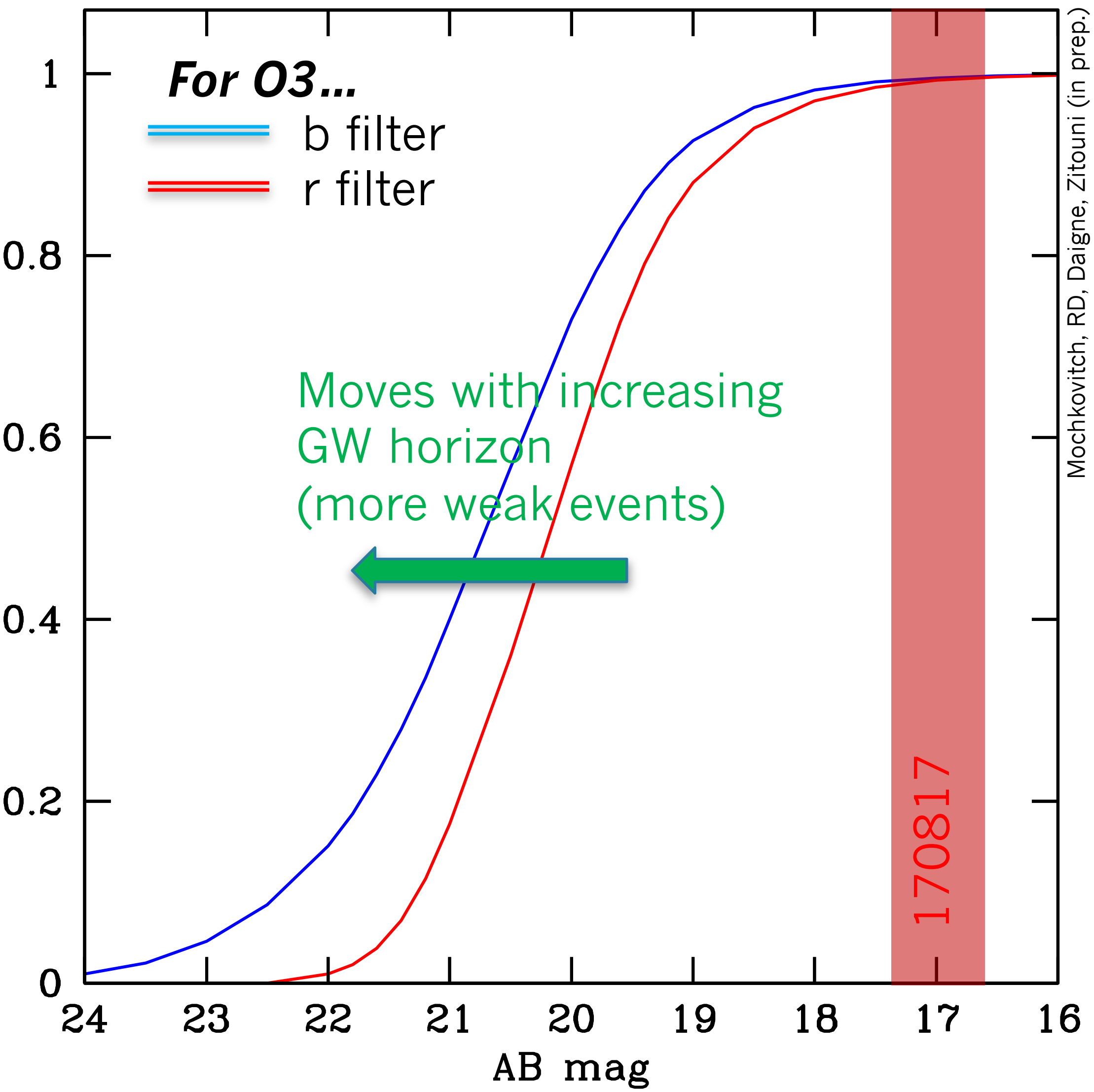
Beniamini, RD, Mochkovitch, Daigne (in prep.)

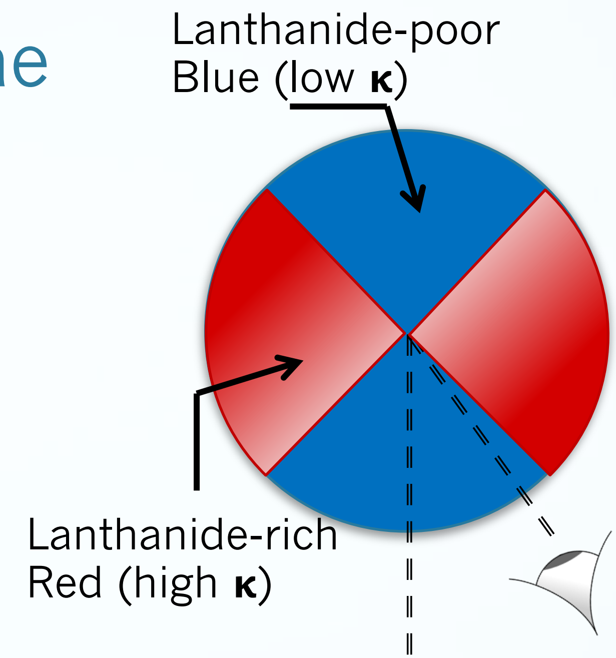


Beniamini, RD, Mochkovitch, Daigne (in prep.)

→ **Tight constraints** on fast merging binaries **from only a few events**

Expectations for kilonovae





- Vis.-IR signal depends on **viewing angle** because of ejecta contrasts in physical conditions

For O3:

✓ **Magnitude OK** *a priori*

✗ Volume to explore potentially **100x larger** than for 170817

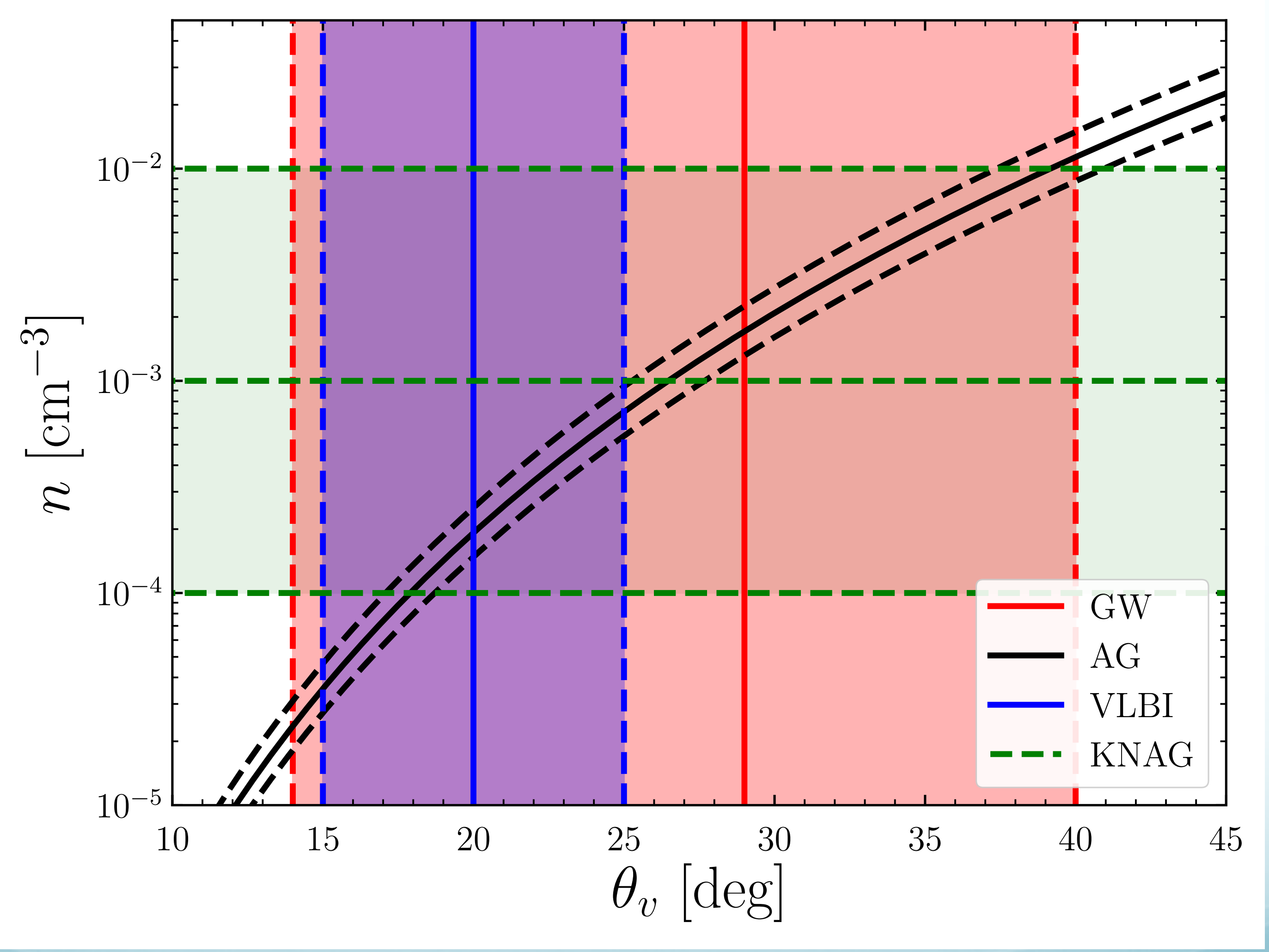
✗ Contrast with host galaxy

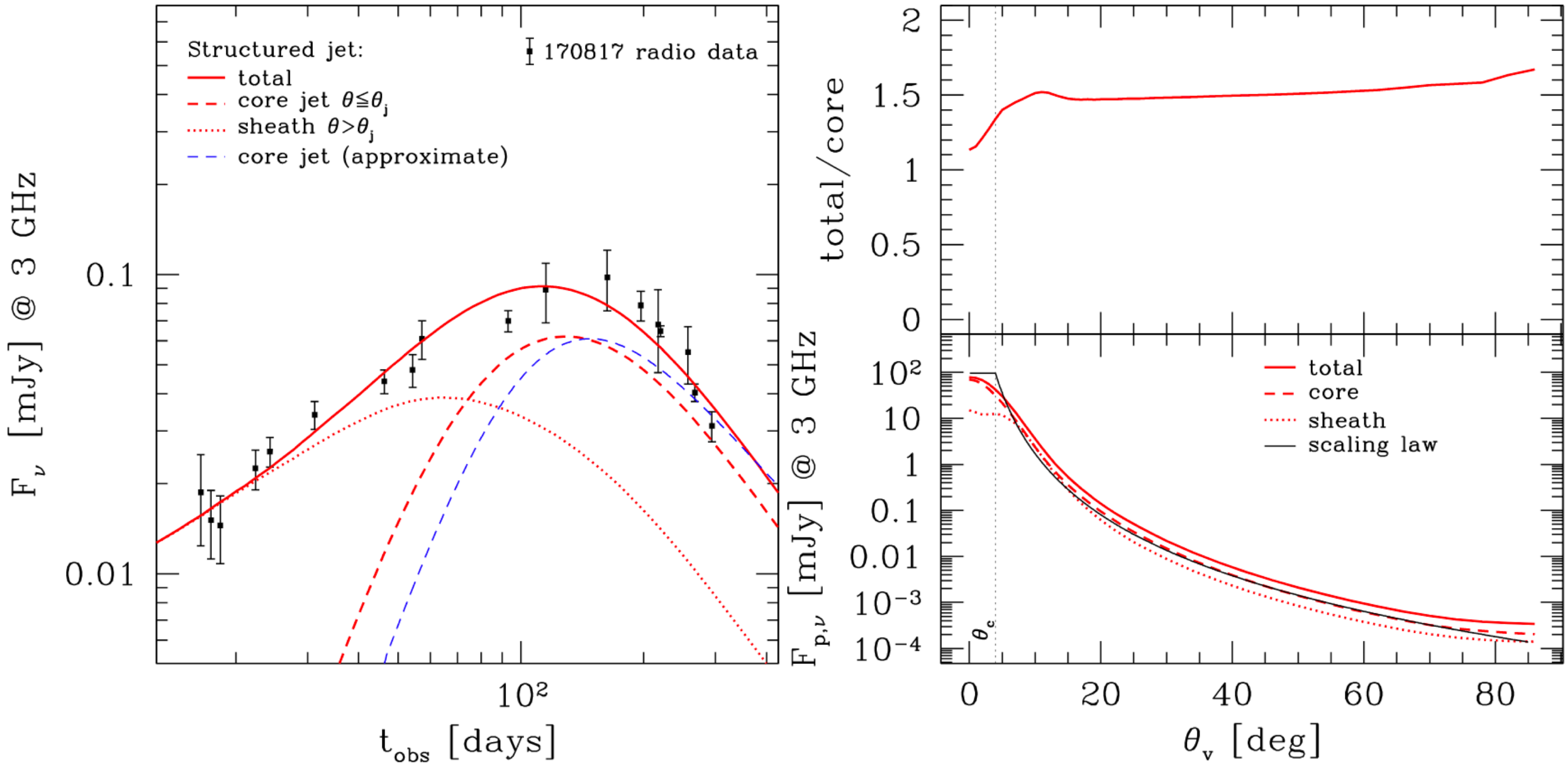
→ **Finding the OT challenging!**

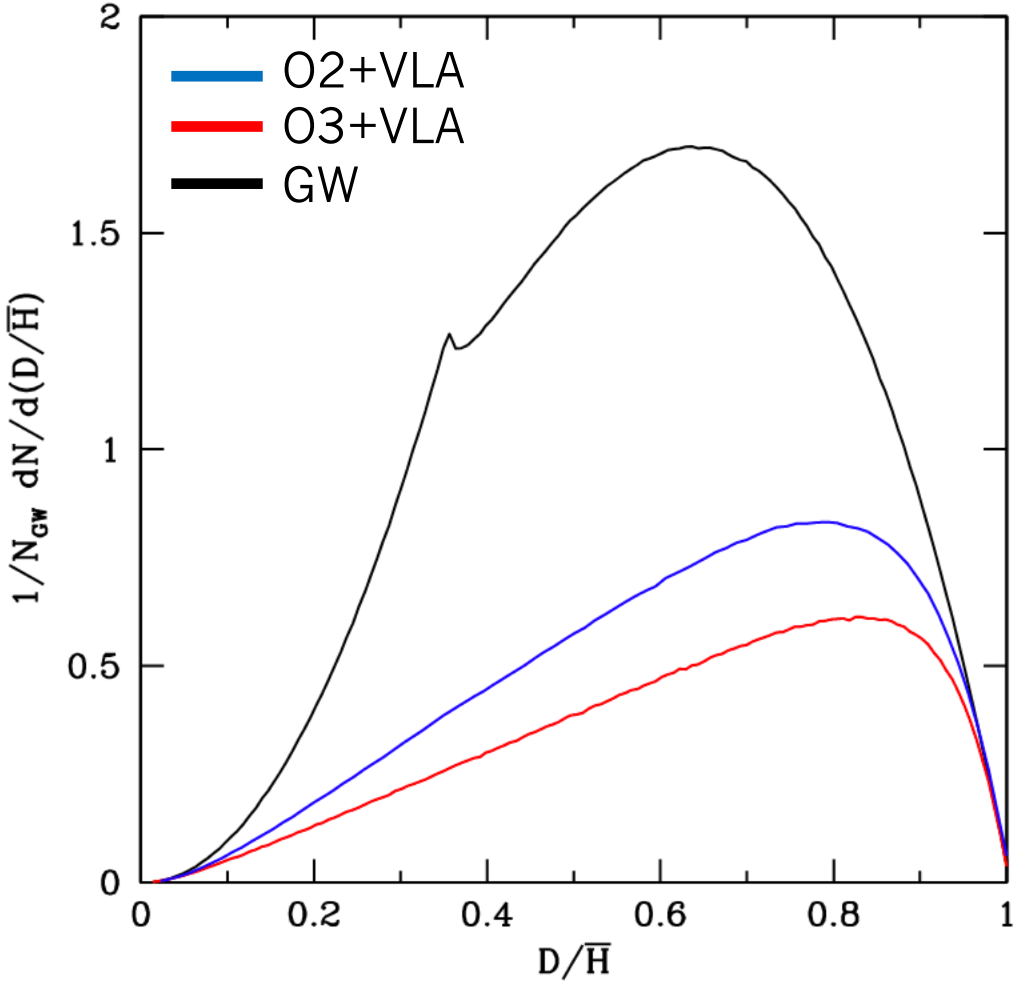
Conclusion

- 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 (flux and apparent motion) with distance
- Most events are seen **off-axis,** allowing to **probe the jet geometry** and **emission therein**
- Only a **few events** are necessary **to constrain the** population of **fast-merging** binaries.
- **Now**: wait for events, and GRB prompt!

Determining viewing angle and density from multi-messenger observations



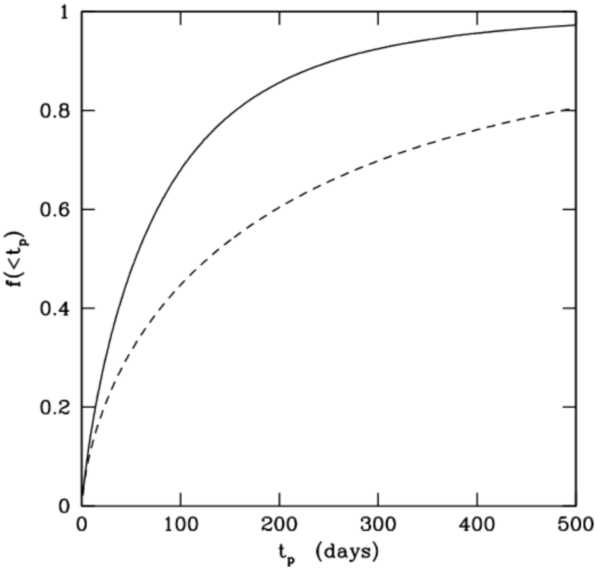

Structured jet:
total
core jet θ≦θj
sheath θ>θj
core jet (approximate)
170817 radio data
0.1
0.01
10²
t_obs [days]
F_ν [mJy] @ 3 GHz
total/core
2
1.5
1
0.5
0
10²
10
1
0.1
0.01
10⁻³
10⁻⁴
F_p,ν [mJy] @ 3 GHz
total
core
sheath
scaling law
θc
0
20
40
60
80
θv [deg]



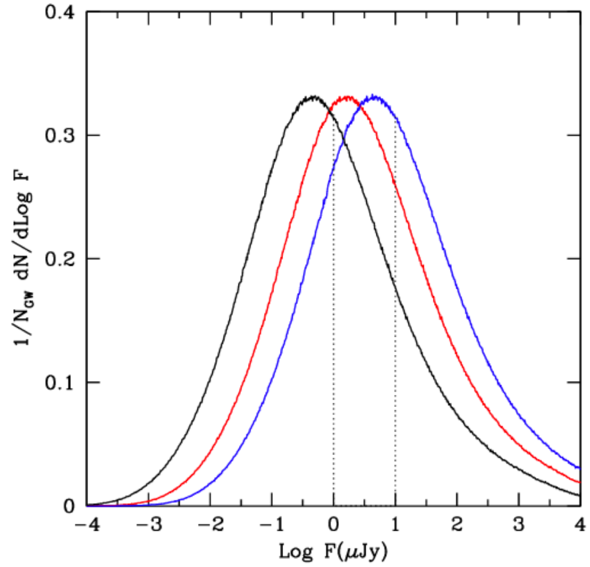
Distance

GW Criterion:

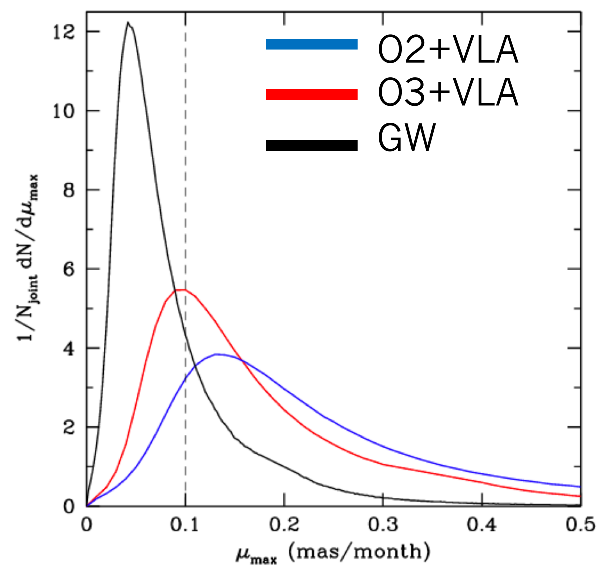
$$\sqrt{\frac{1+6\cos^2\theta_v+\cos^4\theta_v}{8}} > \frac{D}{\bar{H}}$$



AG Peak time



AG Peak flux



Remnant proper motion

Long run

Link pop. coalescence — pop. sGRB

Interpretation tools for observations of GRBs in the multi-messenger context:

① Modeling of EM counterparts of CO fusions: sGRBs and afterglows

➡ Context: observations by LIGO–Virgo (~2019)

② Modeling of the general population of GRBs and afterglows

➡ Context: present and future observations: Swift, Fermi, INTEGRAL, **SVOM**

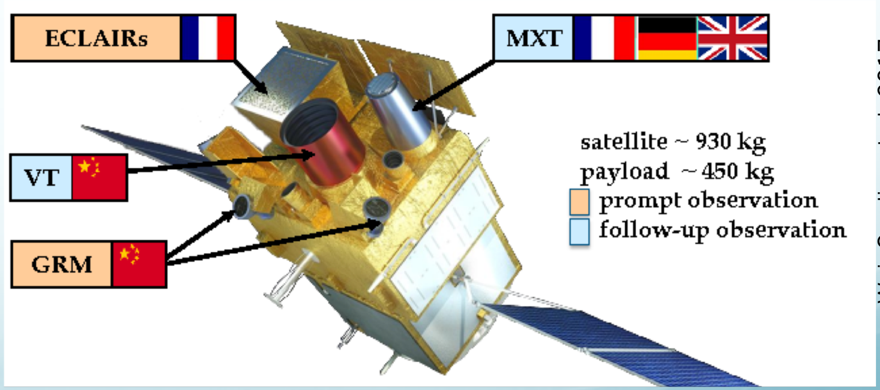
1: GRBs & CO fusions

- Distinguish NS-NS and BH-NS?
- Nature of final object? Link with ring-down signal?
- **Systematic fusion/GW/sGRB/kilonova/afterglow association?**
- **GW/GRB delay?**

2: General population of GRBs

Rates: (Wei, Cordier et al. 2017a):
- SVOM: 60-70 yr^{-1}
- Swift, Fermi, INTEGRAL: ~100 yr^{-1}

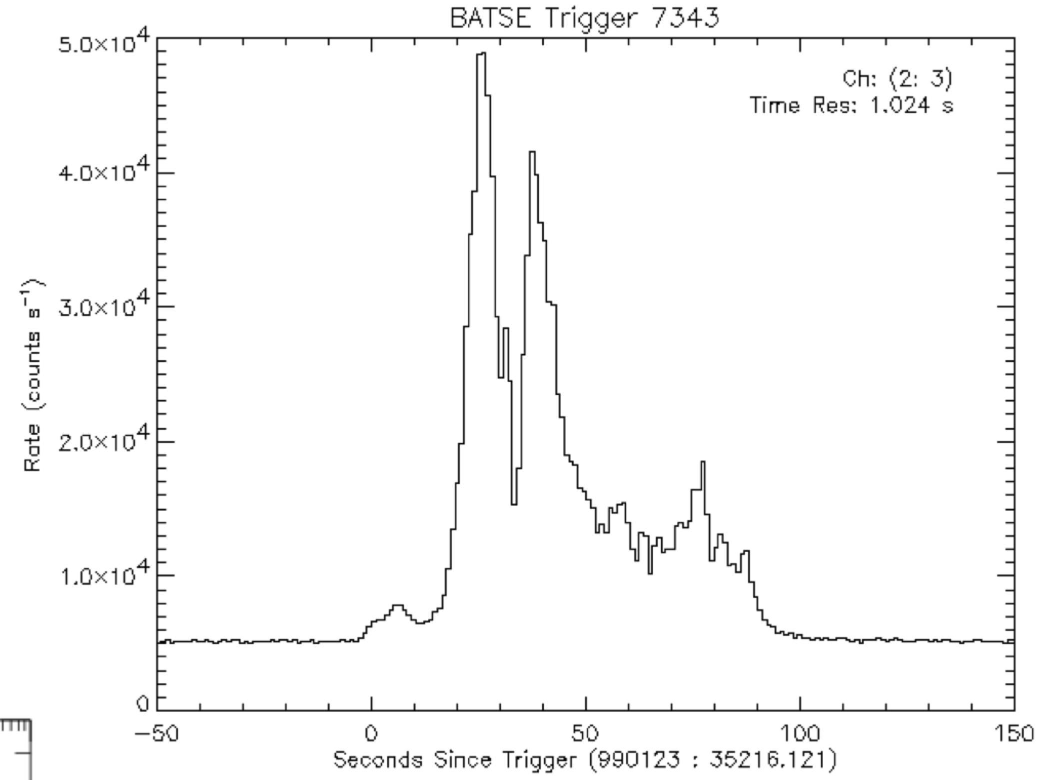
- **Radiative processes in GRB (shocks/magnetic reconnection)?**
- Ejecta magnetization?
- **Other afterglow observables (polarization, imaging)?**



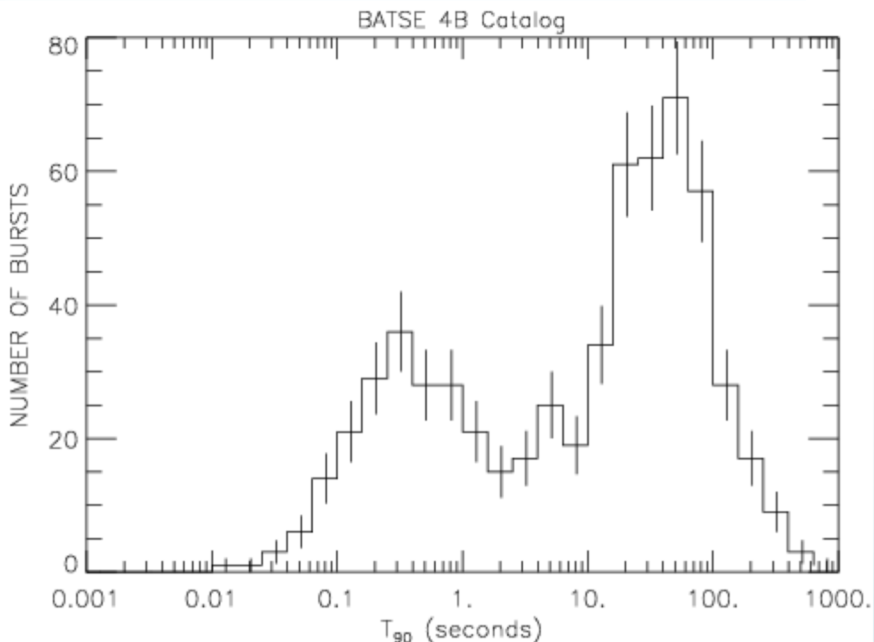
Wei, Cordier et al. 2017a

Gamma-ray bursts

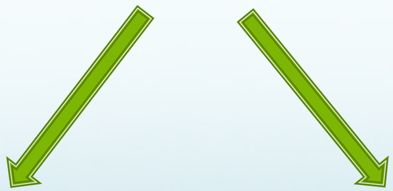
Light curves:
- Strong variability
- Shape diversity
- Variation time-scale diversity



Paciesas et al. 1996



Duration



Paciesas et al. 1996

Longs (ccSNe):
- > 2s
- Soft
- High SFR galaxies

Short (compact object mergers):
- < 2s
- Hard
- Early-type galaxies

Gamma-ray bursts