Afterglows from neutron star mergers and fast radio bursts

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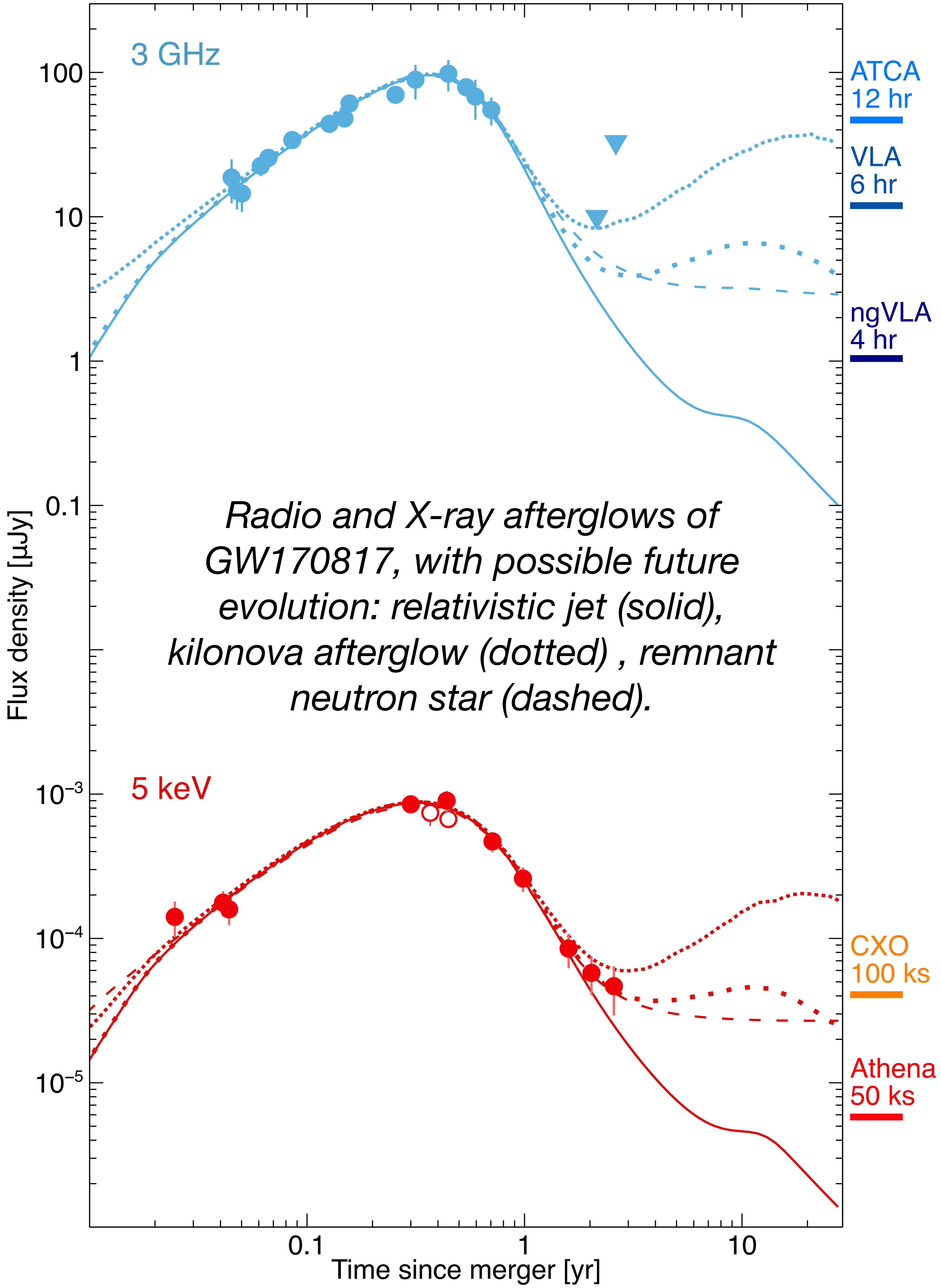
📷 D. Berry, SkyWorks Digital, Inc.

Outline

- Detectability of radio afterglows from neutron star mergers
- Implications for potential afterglows from fast radio bursts

Afterglows from neutron star mergers

- First joint GW-EM detection of a neutron star merger leads to the discovery of GW170817, GRB, kilonova and non-thermal afterglow.
- Afterglow:
  - Broadband long-lasting (observable ~a few years)
  - Well explained by synchrotron forward shock powered by a structured relativistic jet.
  - Late time re-rising is also expected: energy injection by a long-lived central engine / kilonova ejecta afterglow.
- It would be interesting to know what to expect regarding the afterglows of future mergers: e.g. the detection probability, joint GW-radio detection rate…



Radio and X-ray afterglows of GW170817, with possible future evolution: relativistic jet (solid), kilonova afterglow (dotted) , remnant neutron star (dashed).

Troja et al. 2020

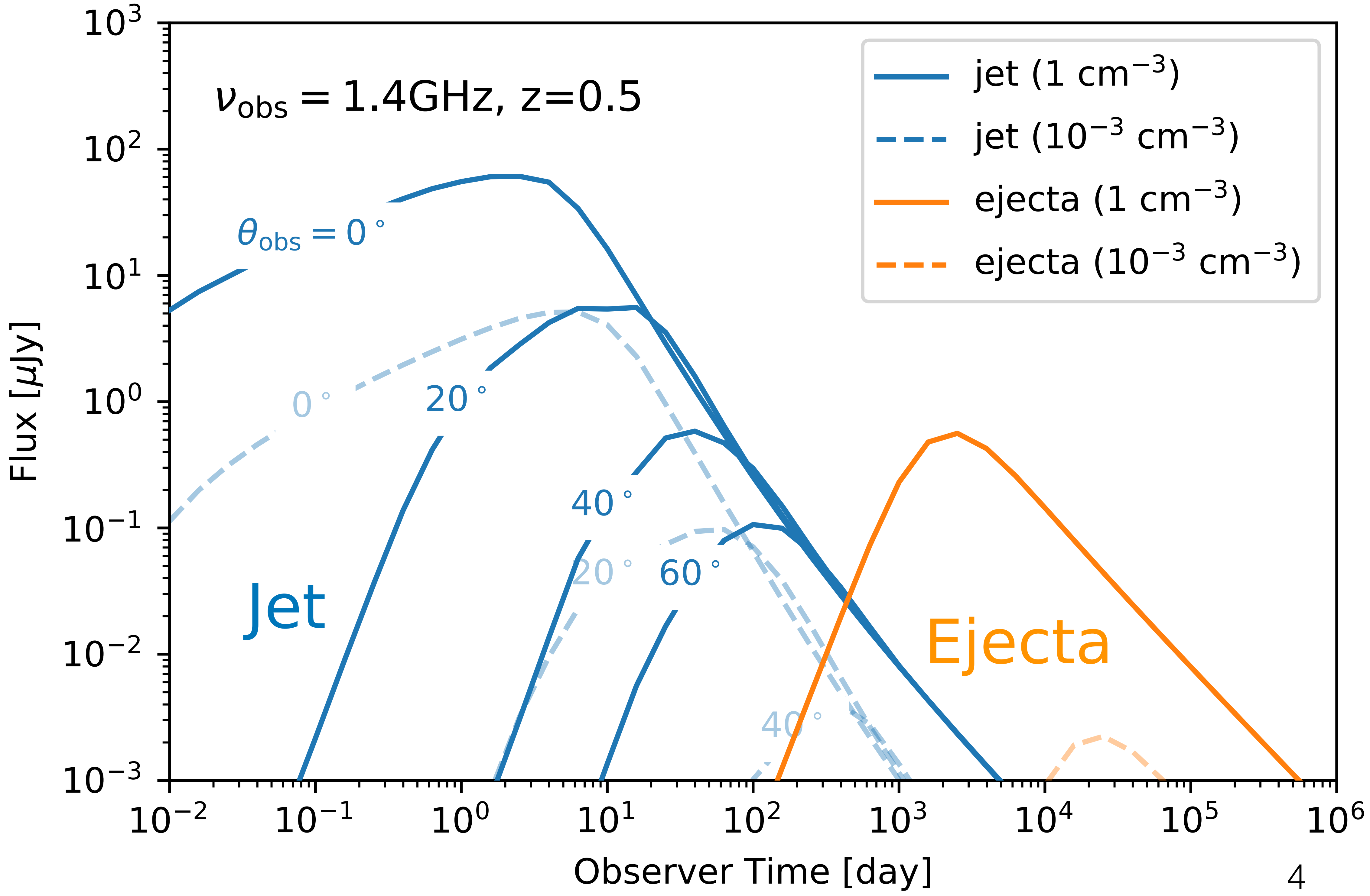
Detection probability of afterglow

We approach the question by quantifying the "detection probability" of afterglow in the following pattern:

1. Start from the prior knowledge from short GRB observations: distributions of isotropic energies, ambient densities, microphysical parameters, and jet half opening angle.
2. Calculate afterglows of relativistic jet and isotropic ejecta rising from the population of mergers, with intrinsic variability prescribed by these distributions.
3. Quantify the detection probability ($P_{\rm det}$) of radio afterglow as the observable fraction in the population, as a function of observed time T, source redshift z and detector sensitivity.

Parameters	Median	Standard Deviation
$\log(E_{\rm k,iso}\,[{\rm erg}])$	51.2	0.83
$\log(n\,[{\rm cm}^{-3}])$	-1.57	1.63
θ_j [deg]	5.8	1.2
p	2.39	0.23

Table 1. Median and 1σ scatter of Gaussian fit to the parameter cumulative distributions by short GRB afterglow observation (Fong et al. 2015).

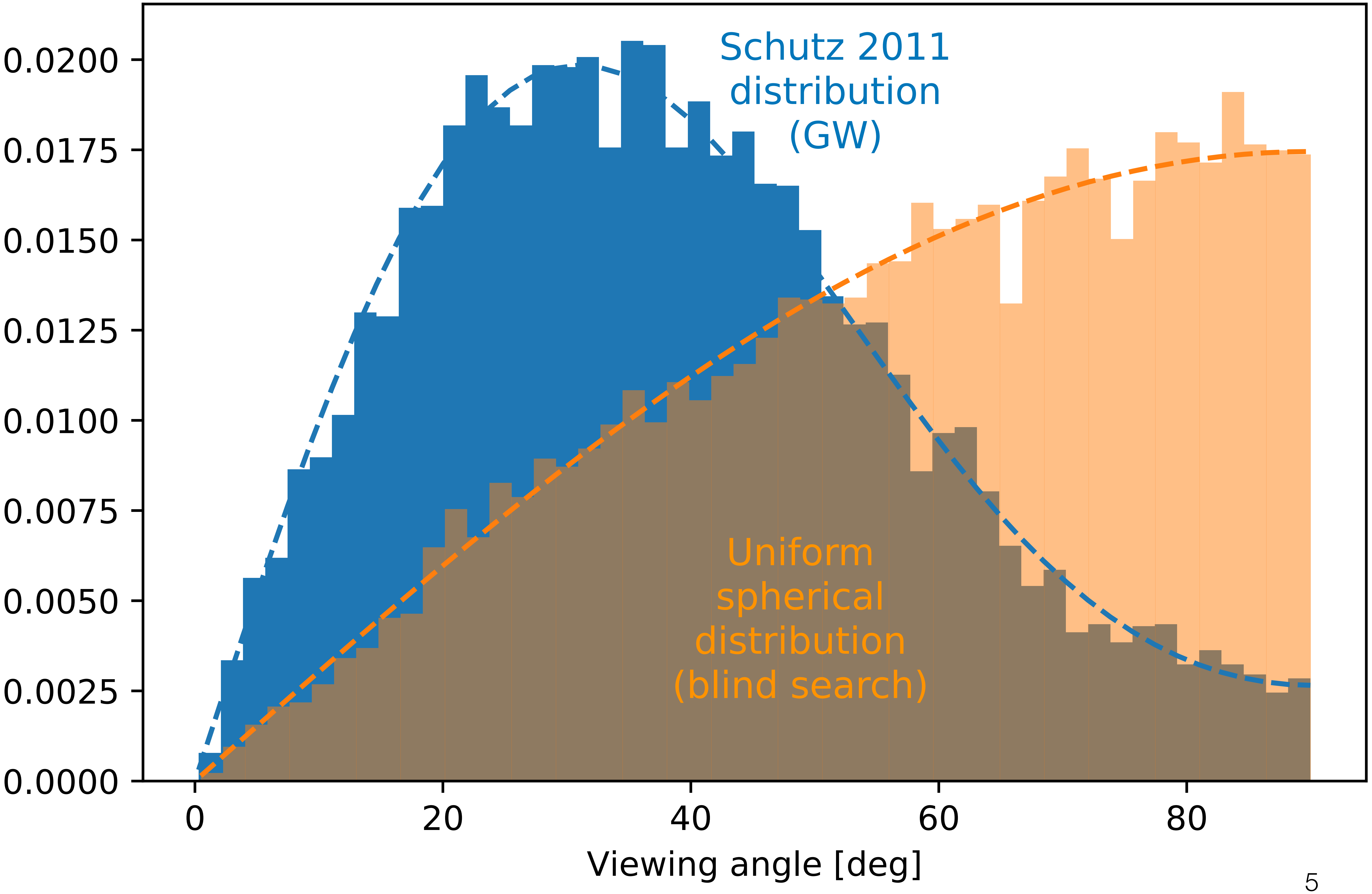


Distribution of viewing angle is essential in jet afterglow!

The jet afterglow flux level strongly depends on the viewing angle.

We consider 2 distributions of the viewing angle to reflect different search scenarios (untargeted search, GW follow-up).

- **Uniform PDF** <$\theta_{\rm obs}$>=60°, i.e. most jets are heavily off-axis, flux level comparable to ejecta afterglow.
- **GW PDF** <$\theta_{\rm obs}$>=38° (Schutz 2011). For those GW-detected mergers, the detected distribution is biased towards smaller viewing angles.



Detection Probability

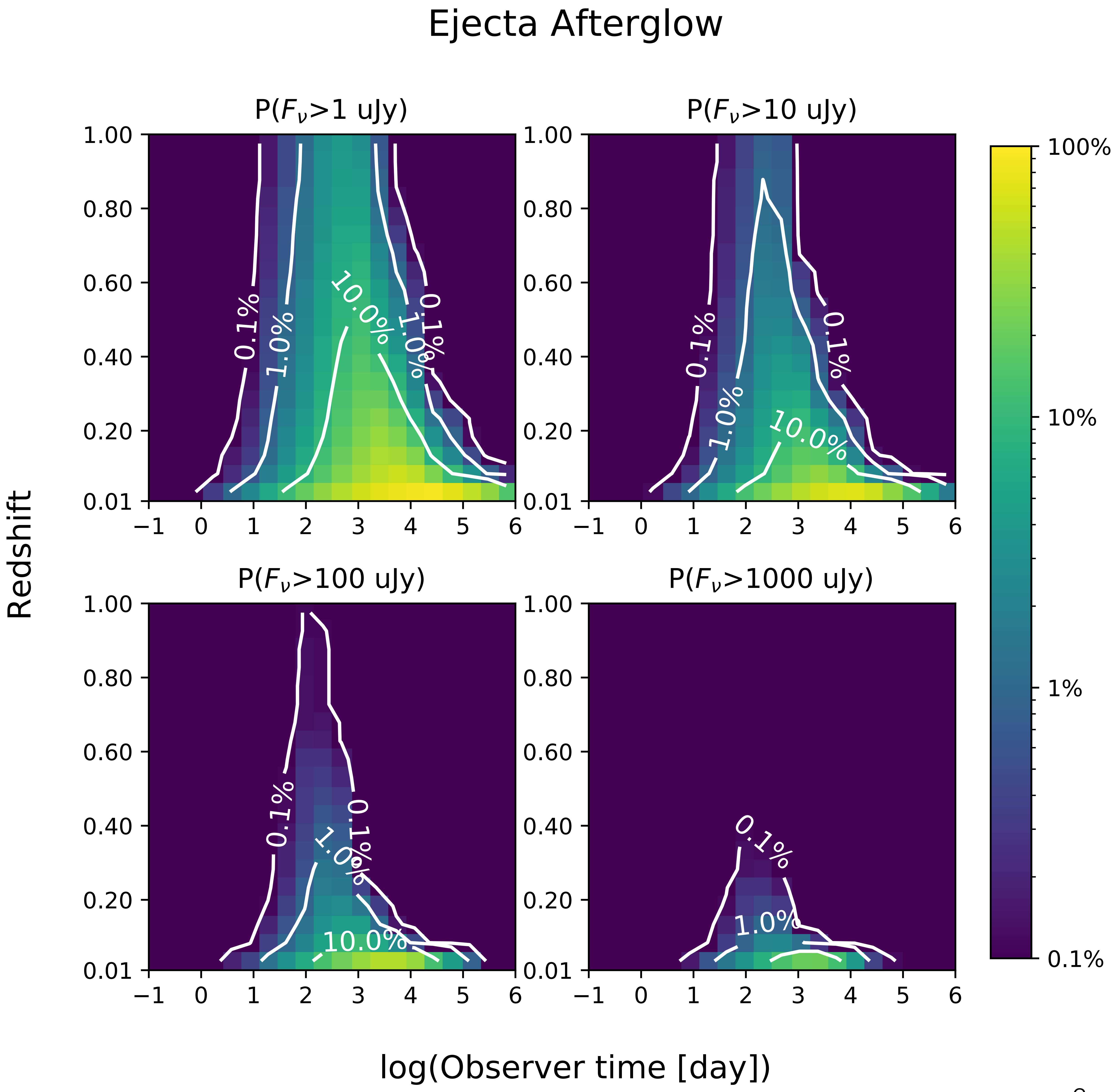
- Detection probability (P_{det}) is presented as a function of observed time, source redshift.
- 4 levels of sensitivities are shown, in which 10 μJy is comparable to e.g. VLA/ASKAP; 1 μJy is comparable to e.g. SKA and ngVLA.
- The observed frequency is fixed at 1.4 GHz.
- Synchrotron self-absorption is not significant, except for mergers in high density environment which occupies < 10% of the mock population.

Detection rate & detectable fraction of mergers

$$R_{\mathrm{det}} = \int dz \frac{dV}{dz} \frac{P_{\mathrm{det}}(z) R_{\mathrm{BNS}}(z)}{1+z}$$

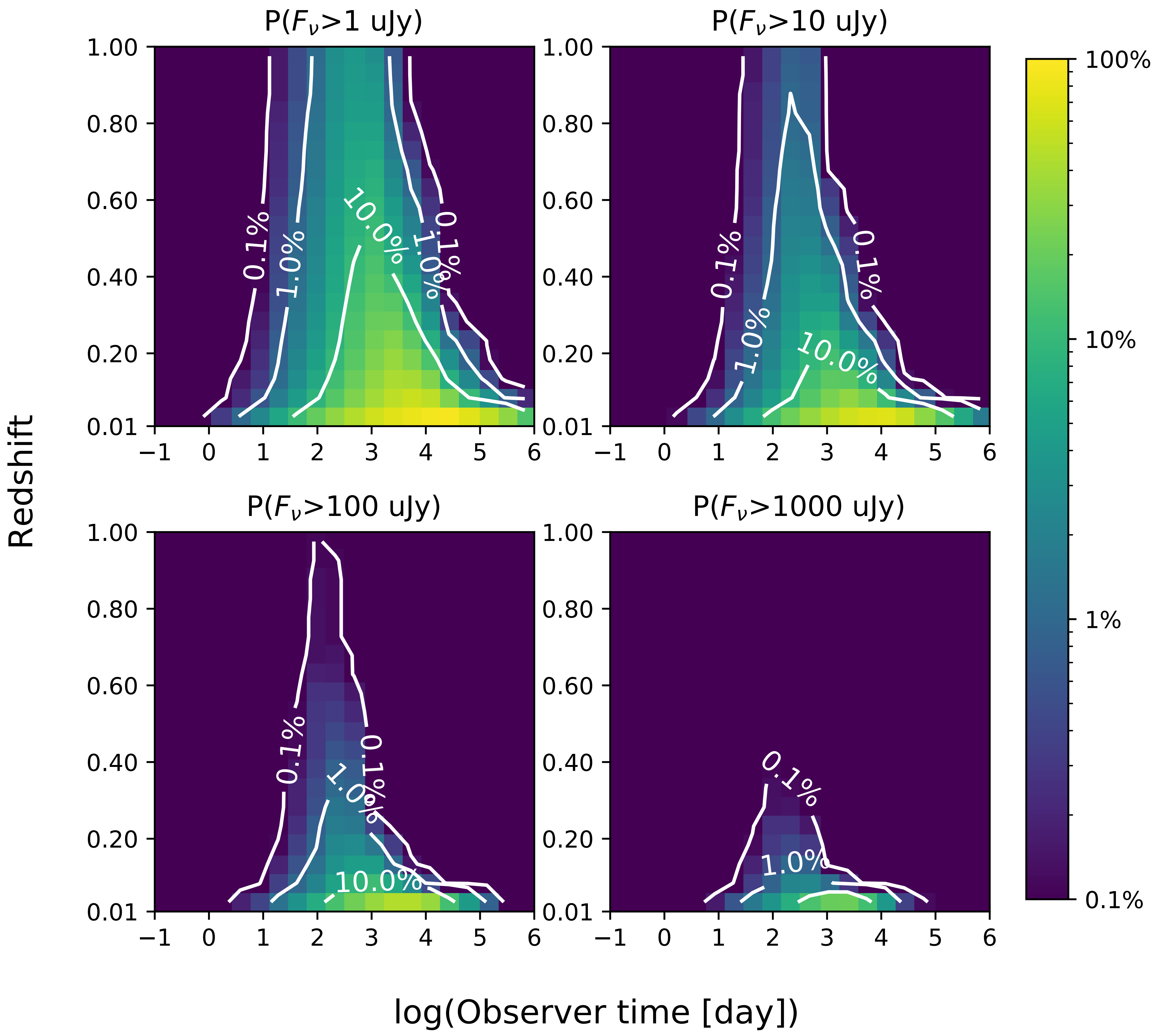
$$f_{\mathrm{det}} = \left[\int dz \frac{dV}{dz} \frac{P_{\mathrm{det}}(z) R_{\mathrm{BNS}}(z)}{1+z}\right] \Big/ \left[\int dz \frac{dV}{dz} \frac{R_{\mathrm{BNS}}(z)}{1+z}\right]$$

$R_{\mathrm{BNS}}(z)$ Cosmic volumetric merger rate



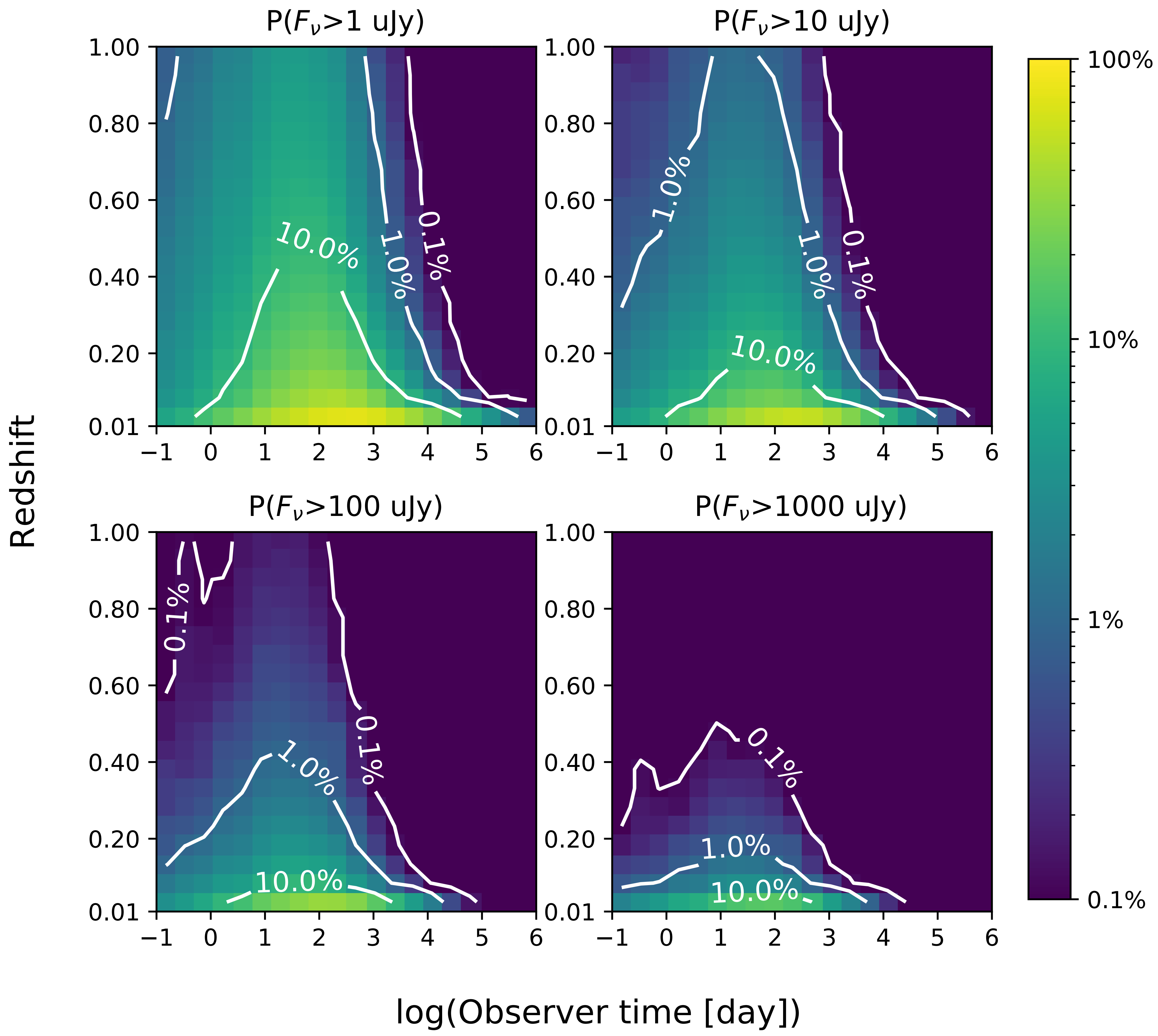
Detection Probability (untargeted search)

Ejecta Afterglow



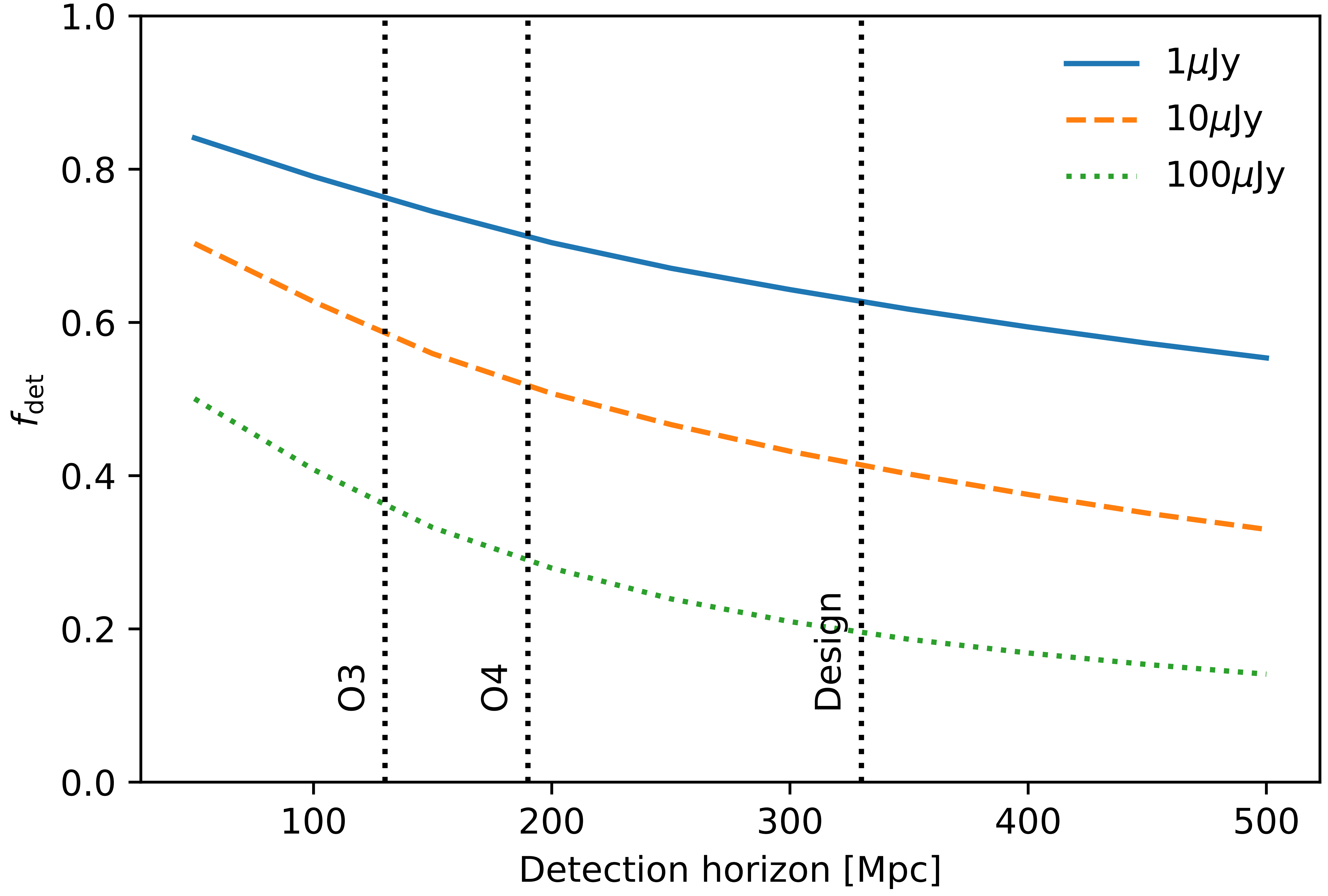
$$f_{\rm det} = 2\,\%\,(10\mu{\rm Jy}), 8\,\%\,(1\mu{\rm Jy})$$

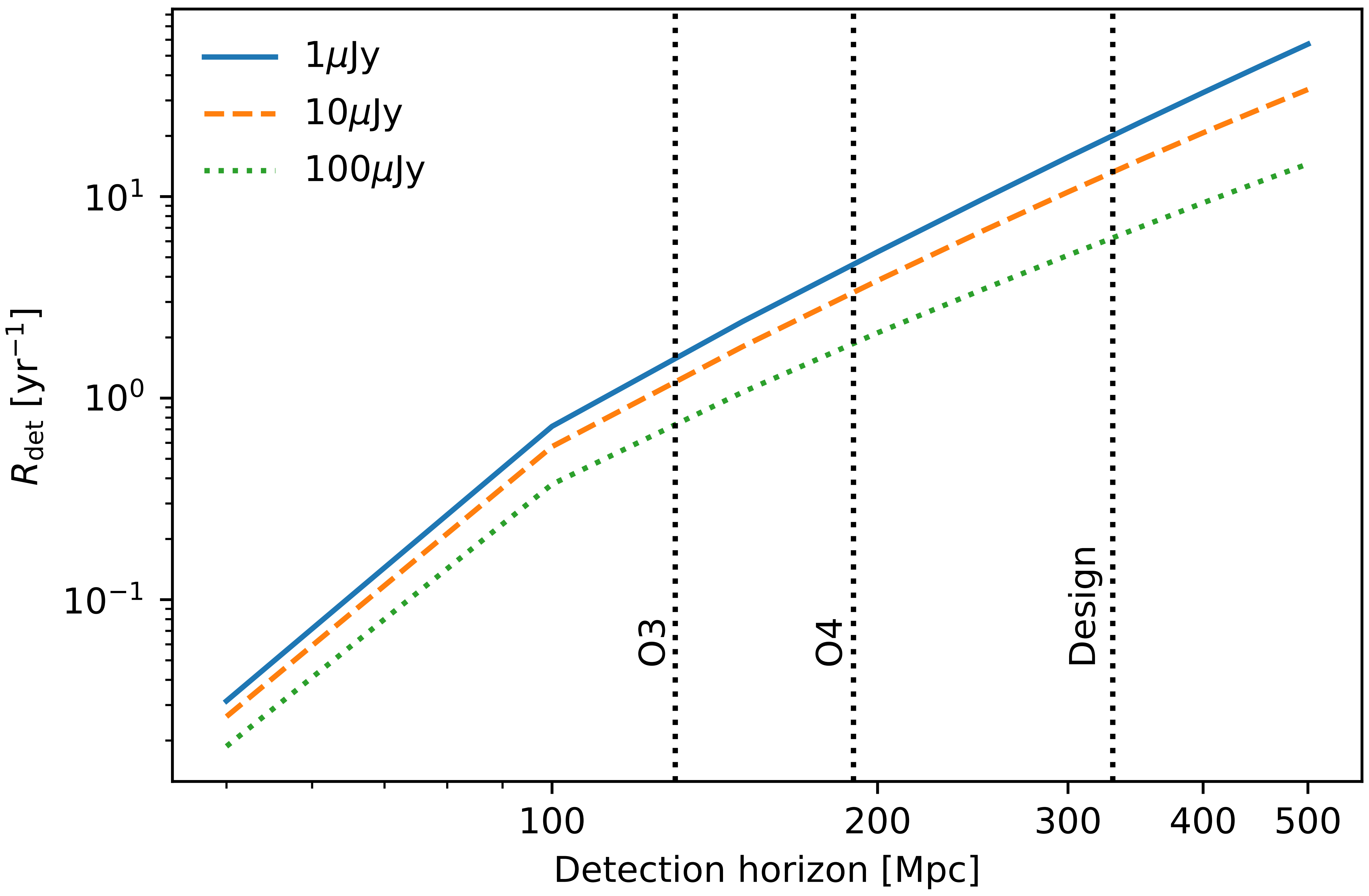
Jet Afterglow (uniform PDF)



$$f_{\rm det} = 2\,\%\,(10\mu{\rm Jy}), 7\,\%\,(1\mu{\rm Jy})$$

Detection Probability (GW follow up; within detection horizon)



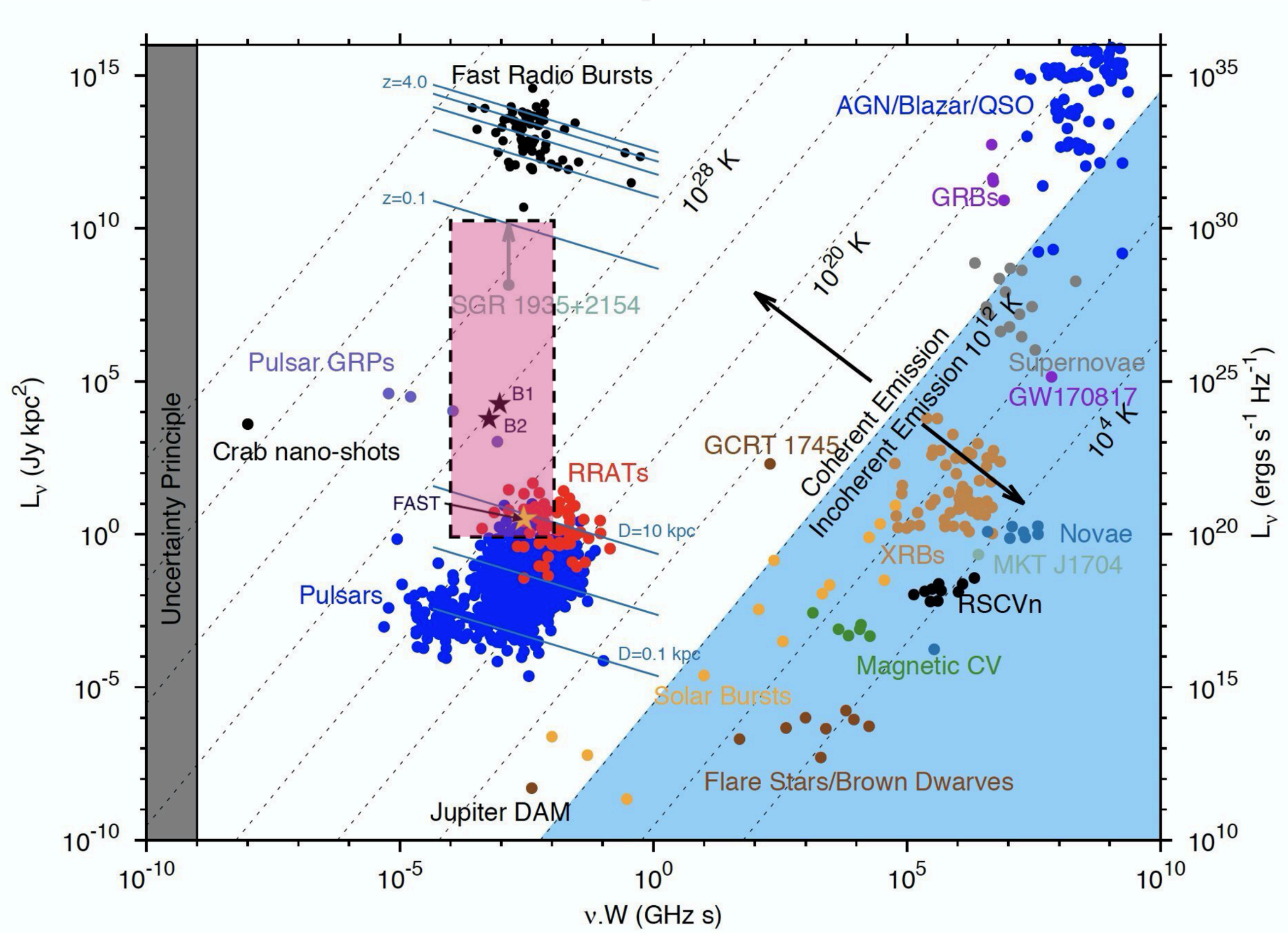


$\gtrsim$ half of the GW-detected mergers have observable radio afterglows!

Joint GW-radio detection rate ~ 1-10 per year (depends on the neutron star merger rate)

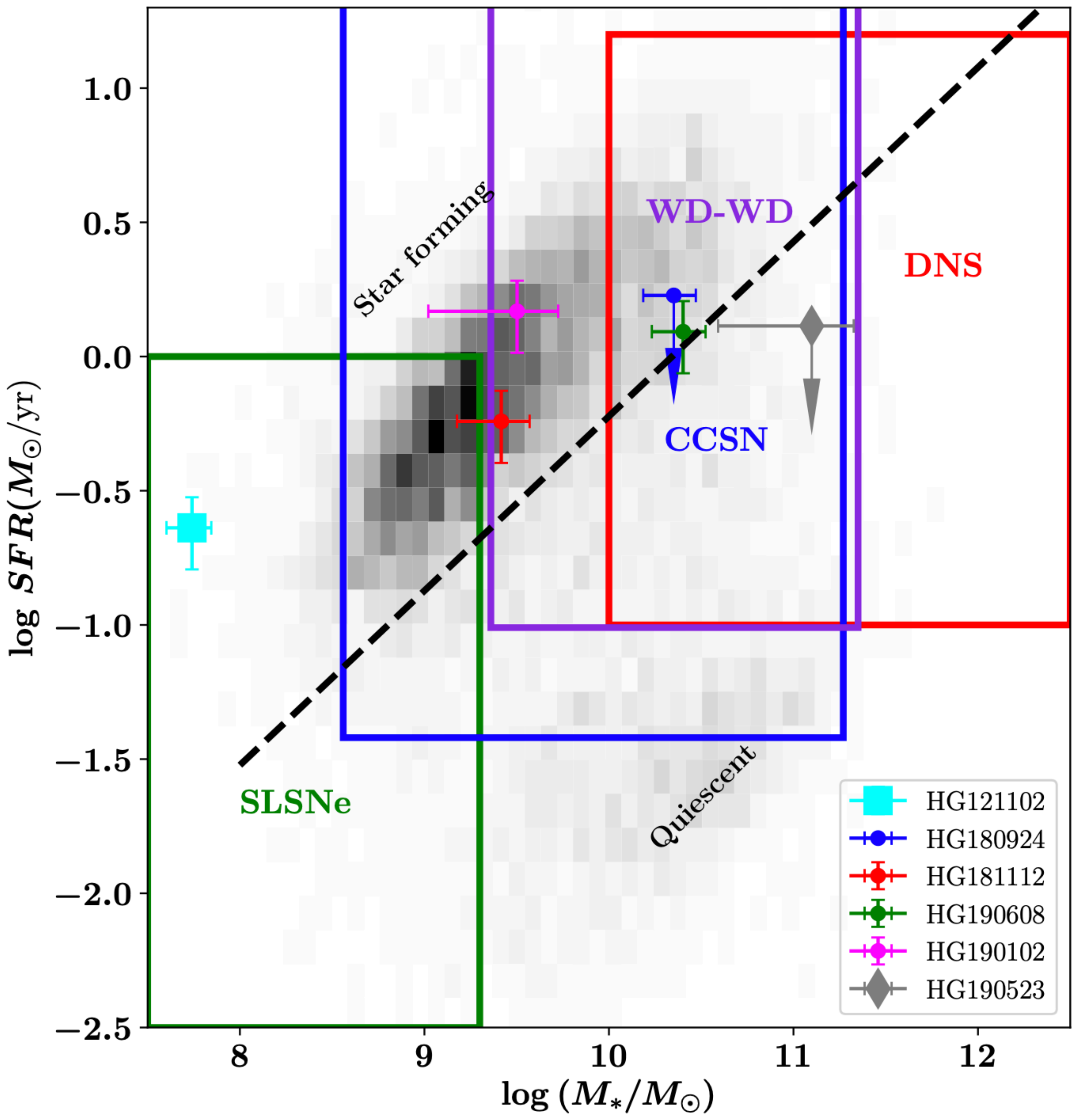
Fast Radio Bursts (FRBs)

- Short-duration (~10μs–10ms), bright (~0.1–100 Js ms) radio transients.
- 2 populations: some bursts seen to repeat (repeater), some appear as single (one-off).
- Repeaters and one-offs seem to have distinct distributions of observed **pulse width** and **bandwidth**: unclear if intrinsic or due to propagation (CHIME/FRB Coll.).
- Multiple FRB-like bursts were detected from SGR 1935+2154 -> some FRBs from magnetars?
  - Their intrinsic energies have large span (~10^{19-26} erg/Hz) and are much lower than typical FRBs (> 10^{29} erg/Hz).



Hessel's talk from FRB 2020 Thailand meeting
http://frb2020.phys.wvu.edu

Neutron star mergers as FRB progenitors?



Localized ASKAP FRBs in Bhandari+20

- FRBs are naturally related to compact objects (e.g. frbtheorycat.org), as required by the extreme energy released in a short duration.
- Neutron star merger is one promising origin of both one-off/repeater FRBs (e.g. Totani 13; Zhang 14; Wang 16; Yamasaki+18; Margalit+19).
  - **Event Rate?** Consistent with ~ O(10^3) / sky / day assuming z_max=1 (e.g. Petroff+19 and references therein), though higher FRB rate (~10^4) is reported in some studies (e.g. Ravi+19, Luo+20). Still both estimates are highly uncertain at the moment.
  - **Host Galaxy?** SFR and stellar mass are roughly consistent compared with those of ASKAP FRBs (Figure on the left).
  - **Counterparts?** From GW/GRB/optical targeted searches (e.g. Niino+14, 18; Abbott+16; Madison+19; Marnoch+20; Andreoni+20), no strong constraint was derived.
  - **Radio Counterpart?** Persistent radio limits typically of 15-20 μJy have been obtained by ASKAP -> ***constraints on the merger model***?

FRB radio constraints v.s. radio afterglow

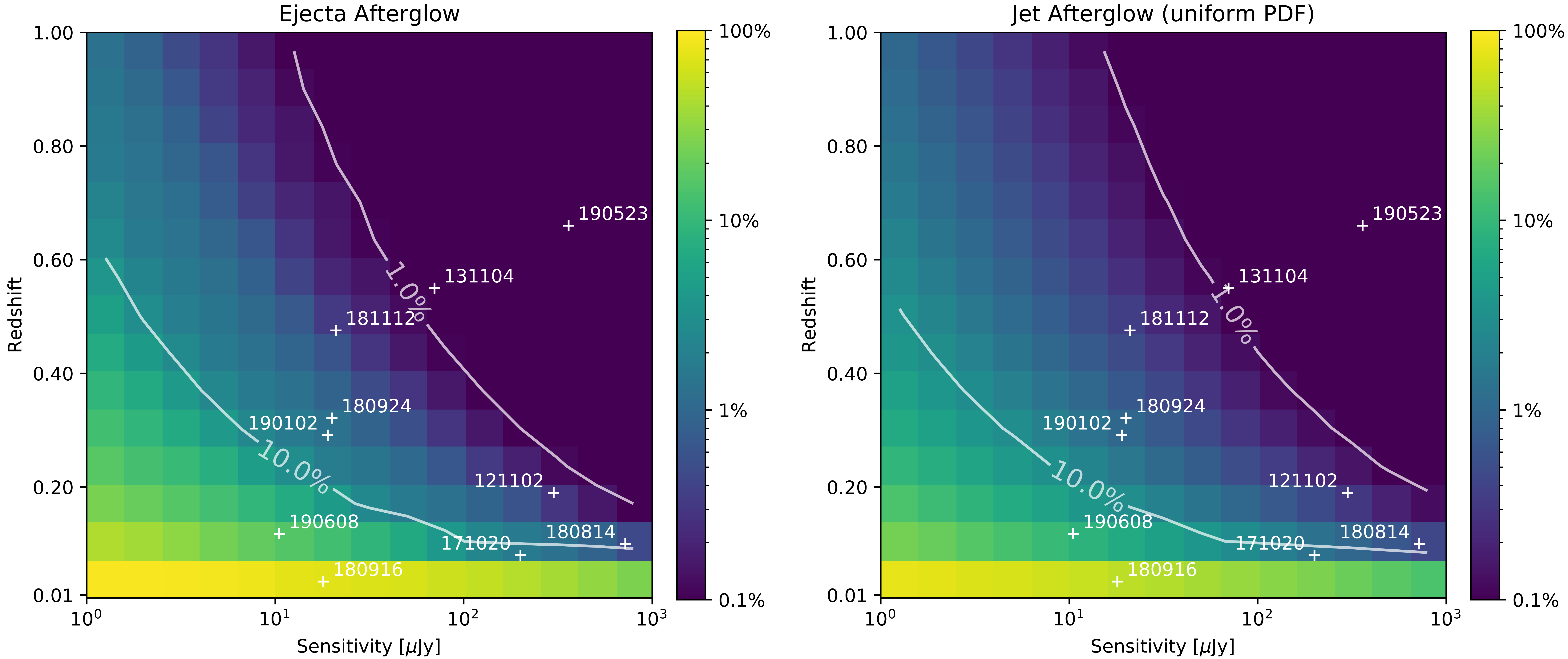
Current persistent radio limits on FRBs: **15-20 μJy**

- Relativistic jet: ~**100 μJy** in GW170817; ~**O(10) μJy** for on-axis short GRB afterglow (Berger 13)
- Kilonova ejecta: not yet detected in any observation, predicted to be ~ **10-100 μJy** for GW170817.
- Radio limits on FRBs ≈ flux levels of radio afterglow -> interesting to make comparison!

Before comparison, what should we assume about the distribution of viewing angle?

- If most FRBs are produced by neutron star mergers, then simply from the comparison of their event rates, FRB cannot be strongly beamed.
- Large beaming fraction is not unreasonable, as the beaming fractions of pulsar emission are typically 50 to 100% (Lorimer 08).
- -> the distribution of viewing angle should be **uniform PDF**.

Detection probability vs FRB radio limits



- Most FRBs have only 1—10% detectable afterglows at their follow-up sensitivities.
- Considering the sample # < 10, we conclude no strong constraint on merger model.

Published FRBs with radio limits v.s. detection probability

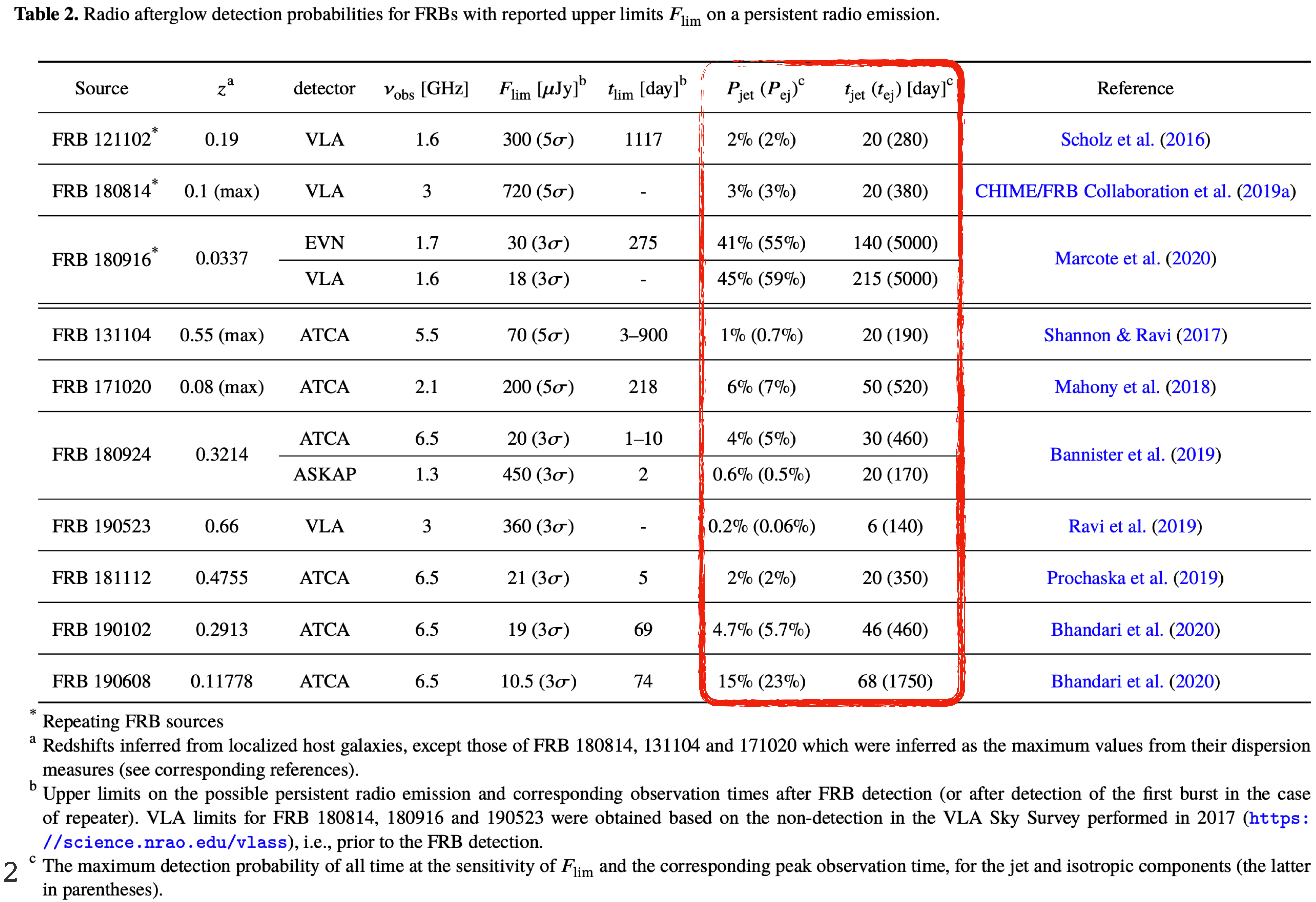


Table 2. Radio afterglow detection probabilities for FRBs with reported upper limits $F_{\rm lim}$ on a persistent radio emission.

Source	z[a]	detector	$\nu_{\rm obs}$ [GHz]	$F_{\rm lim}$ [μJy][b]	$t_{\rm lim}$ [day][b]	$P_{\rm jet}$ ($P_{\rm ej}$)[c]	$t_{\rm jet}$ ($t_{\rm ej}$) [day][c]	Reference
FRB 121102[*]	0.19	VLA	1.6	300 (5σ)	1117	2% (2%)	20 (280)	Scholz et al. (2016)
FRB 180814[*]	0.1 (max)	VLA	3	720 (5σ)	-	3% (3%)	20 (380)	CHIME/FRB Collaboration et al. (2019a)
FRB 180916[*]	0.0337	EVN	1.7	30 (3σ)	275	41% (55%)	140 (5000)	Marcote et al. (2020)
		VLA	1.6	18 (3σ)	-	45% (59%)	215 (5000)	
FRB 131104	0.55 (max)	ATCA	5.5	70 (5σ)	3–900	1% (0.7%)	20 (190)	Shannon & Ravi (2017)
FRB 171020	0.08 (max)	ATCA	2.1	200 (5σ)	218	6% (7%)	50 (520)	Mahony et al. (2018)
FRB 180924	0.3214	ATCA	6.5	20 (3σ)	1–10	4% (5%)	30 (460)	Bannister et al. (2019)
		ASKAP	1.3	450 (3σ)	2	0.6% (0.5%)	20 (170)	
FRB 190523	0.66	VLA	3	360 (3σ)	-	0.2% (0.06%)	6 (140)	Ravi et al. (2019)
FRB 181112	0.4755	ATCA	6.5	21 (3σ)	5	2% (2%)	20 (350)	Prochaska et al. (2019)
FRB 190102	0.2913	ATCA	6.5	19 (3σ)	69	4.7% (5.7%)	46 (460)	Bhandari et al. (2020)
FRB 190608	0.11778	ATCA	6.5	10.5 (3σ)	74	15% (23%)	68 (1750)	Bhandari et al. (2020)

[*] Repeating FRB sources

[a] Redshifts inferred from localized host galaxies, except those of FRB 180814, 131104 and 171020 which were inferred as the maximum values from their dispersion measures (see corresponding references).

[b] Upper limits on the possible persistent radio emission and corresponding observation times after FRB detection (or after detection of the first burst in the case of repeater). VLA limits for FRB 180814, 180916 and 190523 were obtained based on the non-detection in the VLA Sky Survey performed in 2017 (`https://science.nrao.edu/vlass`), i.e., prior to the FRB detection.

[c] The maximum detection probability of all time at the sensitivity of $F_{\rm lim}$ and the corresponding peak observation time, for the jet and isotropic components (the latter in parentheses).

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Summary

- We calculate detection probability of radio afterglow of jet/ejecta components from neutron star mergers, in different searching scenarios (blind search, GW follow-up).
  - For blind search of jet/ejecta afterglow, the detectable fraction is only a few %.
  - For GW-detected mergers, $\gtrsim$half have detectable radio afterglows.
- Compared with reported radio limits on FRBs, we conclude that at the moment no strong constraint can be drawn on neutron star merger origin, considering the number of current FRB sample with radio limits is small.
- A larger FRB sample ~ O(100) with stringent radio limits would start to give a meaningful constraint, or lead to a detection of a radio afterglow.