BNS mergers as multimessenger sources: population prospects and applications

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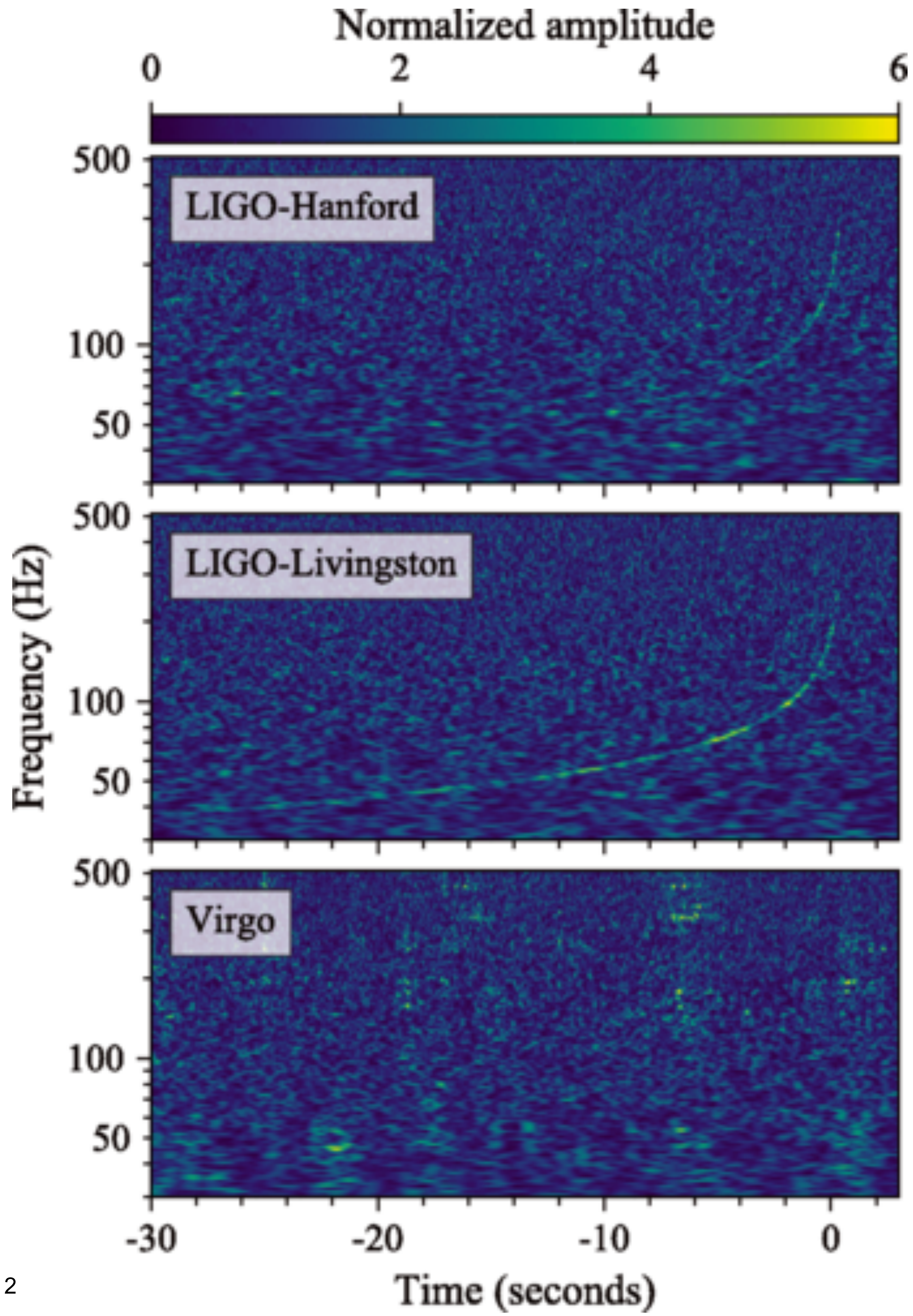
GdR ondes gravitationelles: joint meeting of March 10th, 2021

References:
1905.04495
2012.12836
2103.00943

GW170817…

…and counterparts: a rich multimessenger dataset

- GW170817: BNS inspiral signal
- GRB170817A: Short, hard, weak GRB
- AT2017gfo: Explosive nucleosynthesis-driven kilonova
- Relativistic deceleration shock afterglow: Photometry & Imagery
- (Slowly expanding ejecta afterglow: will data confirm?)



Abbott et al. 2017

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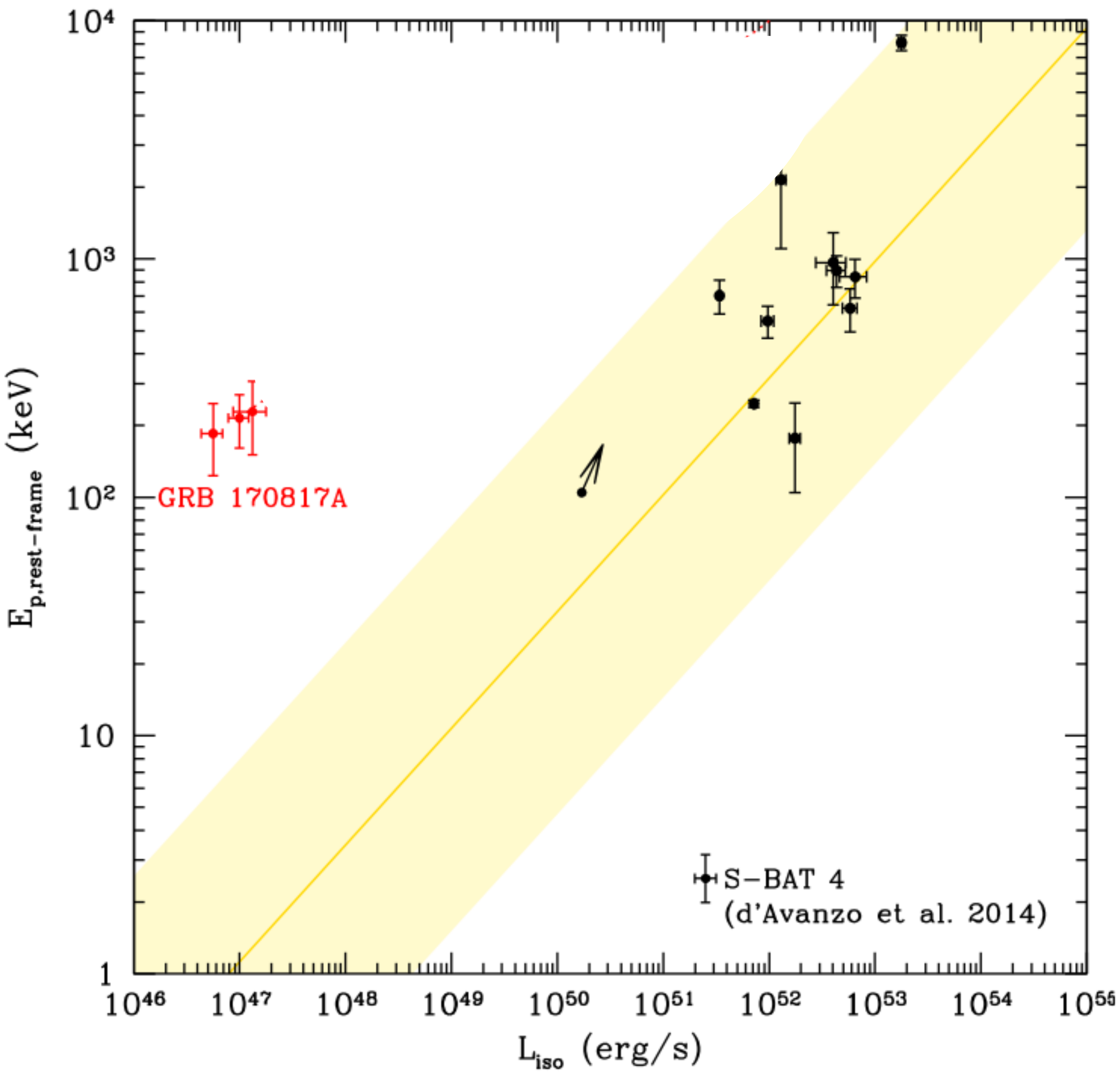

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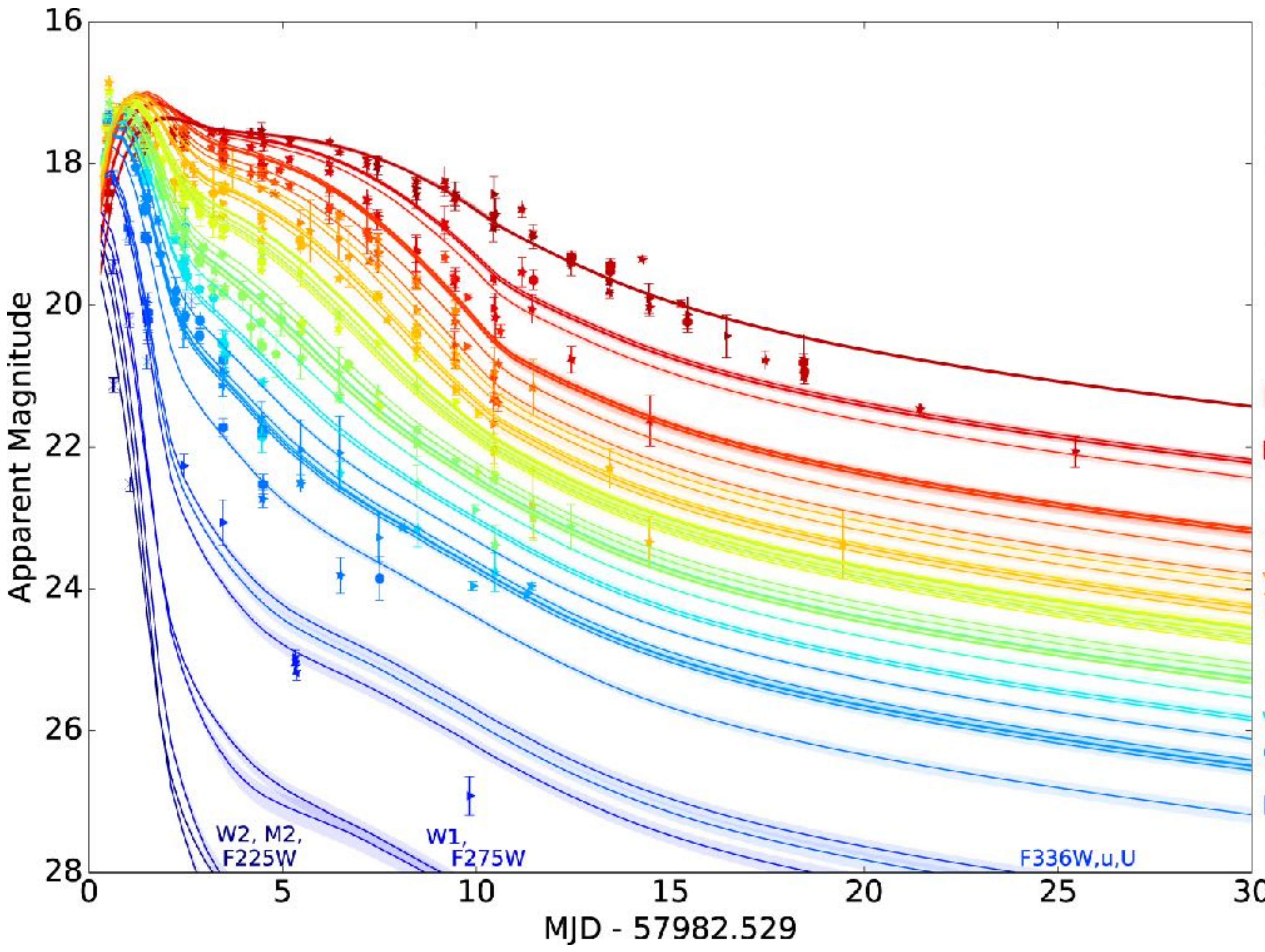

Villar et al. 2017

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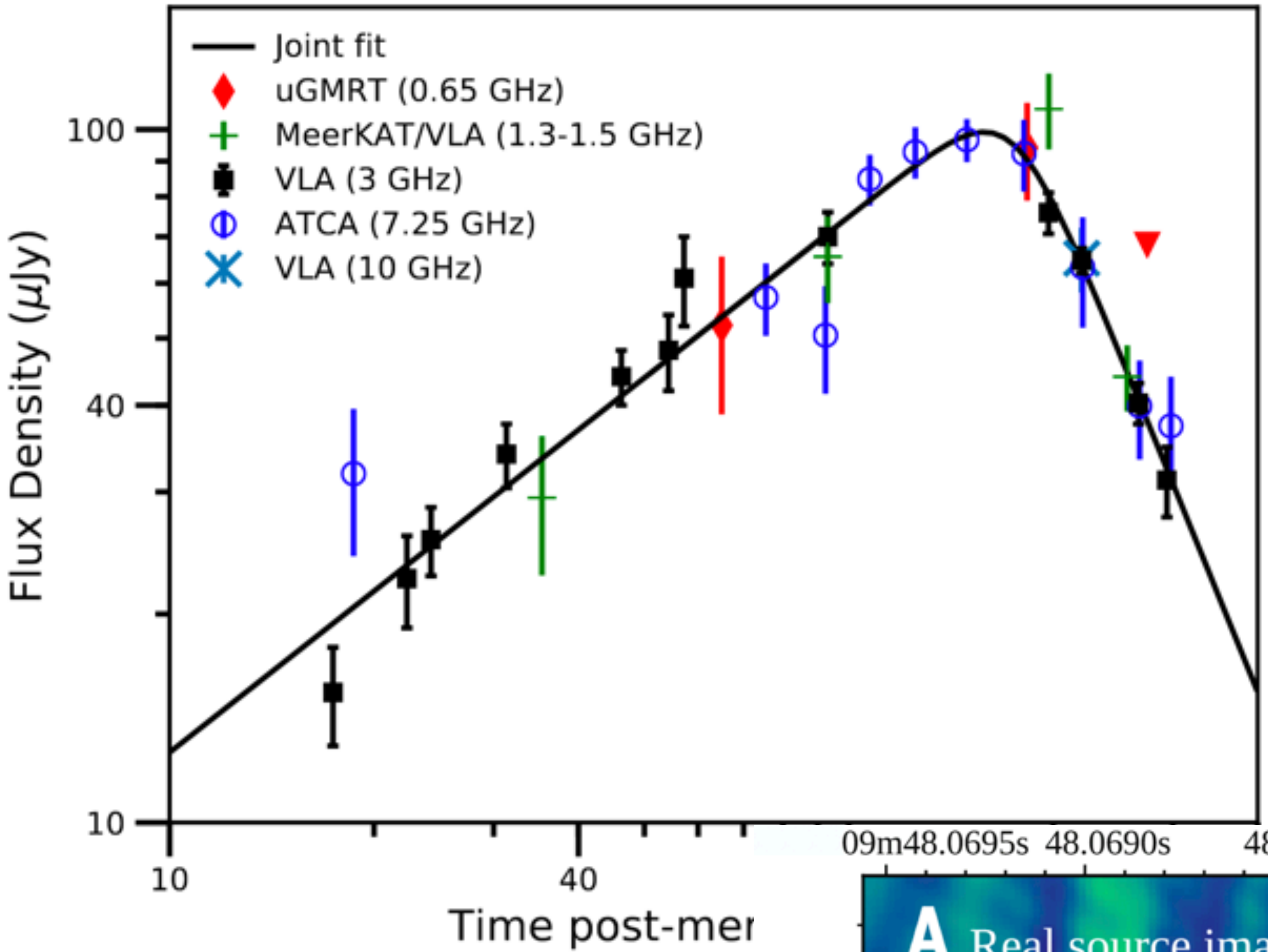
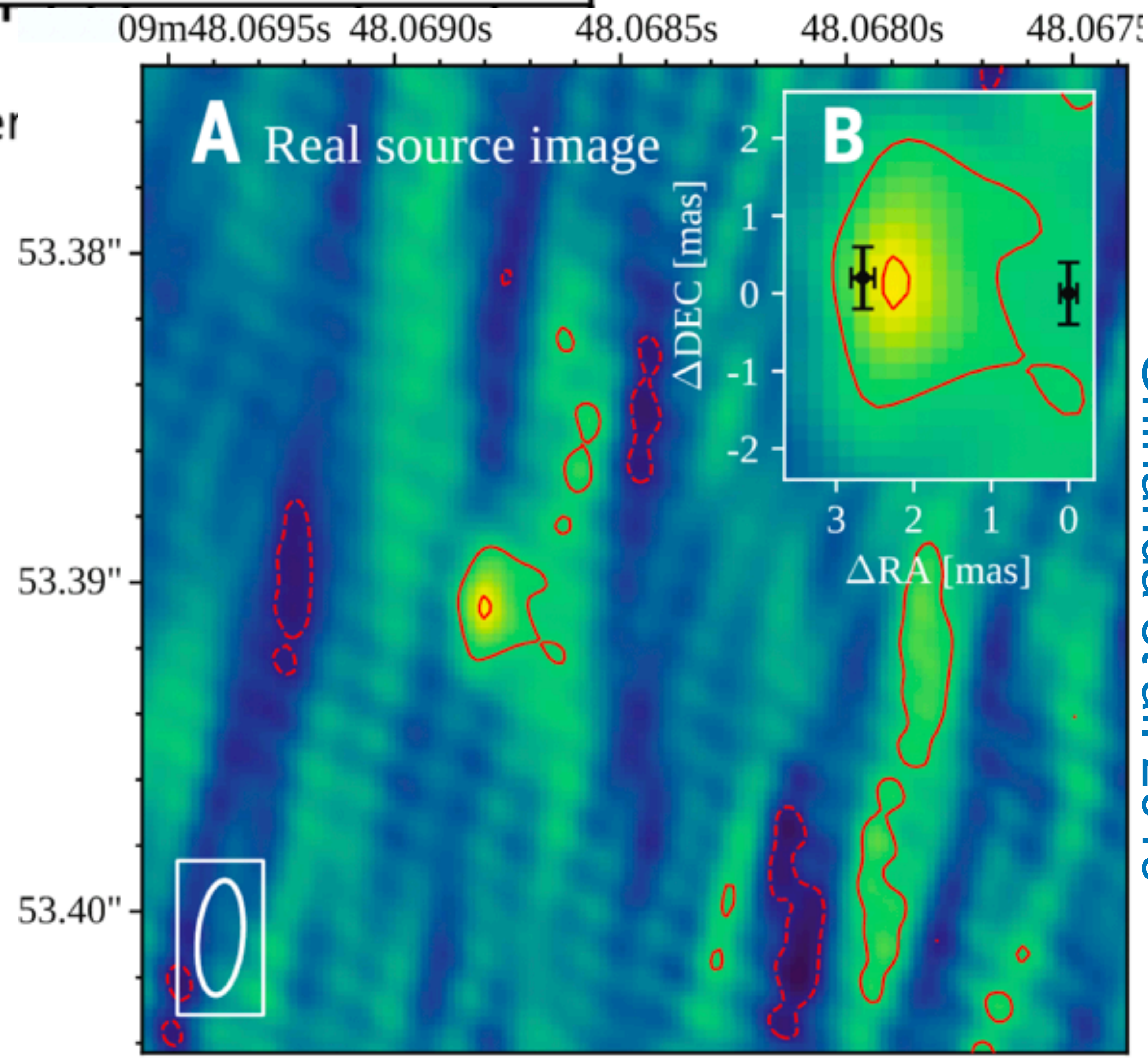


Mooley et al. 2018



Ghirlanda et al. 2019

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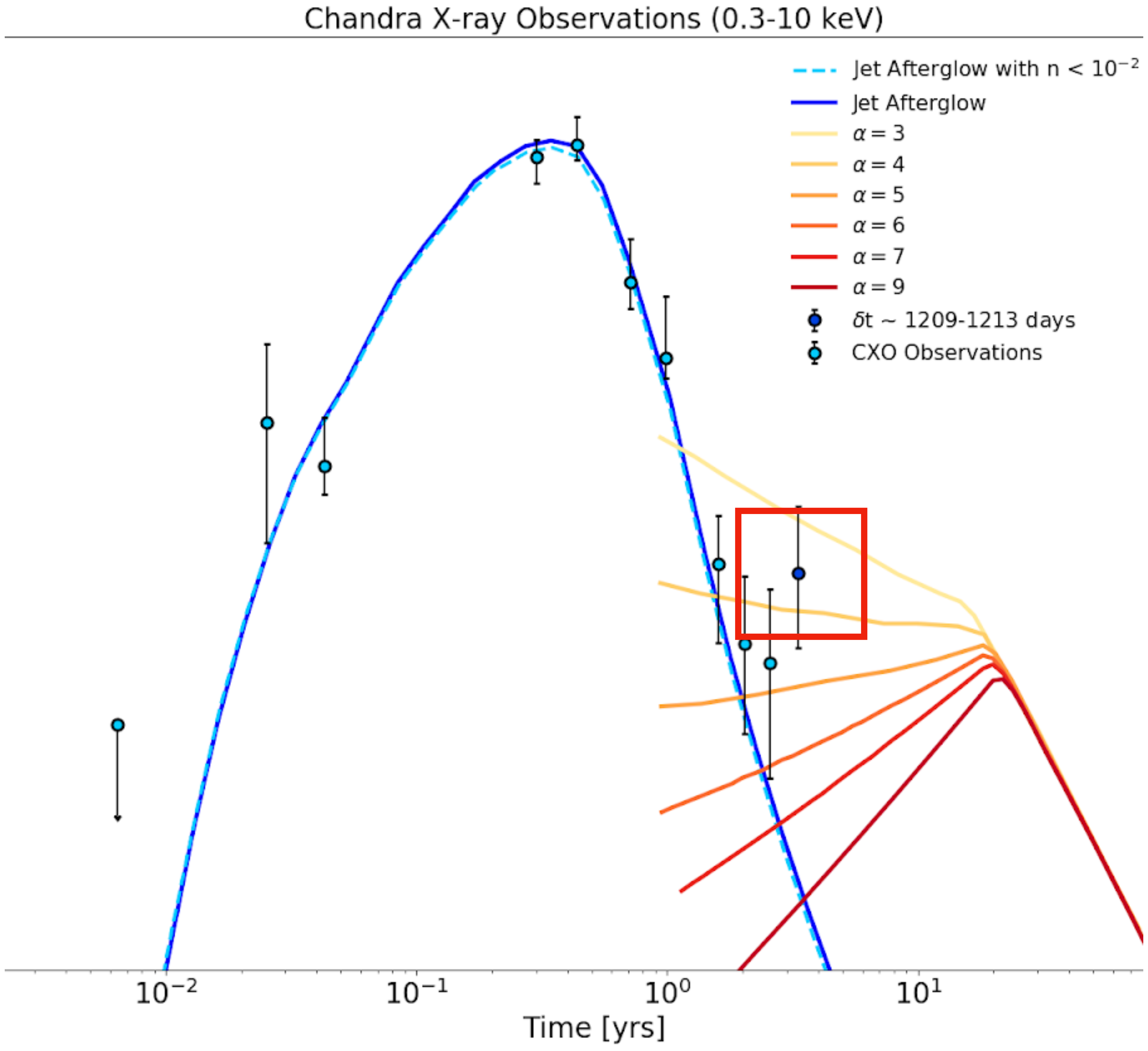

Hajela et al. 2020

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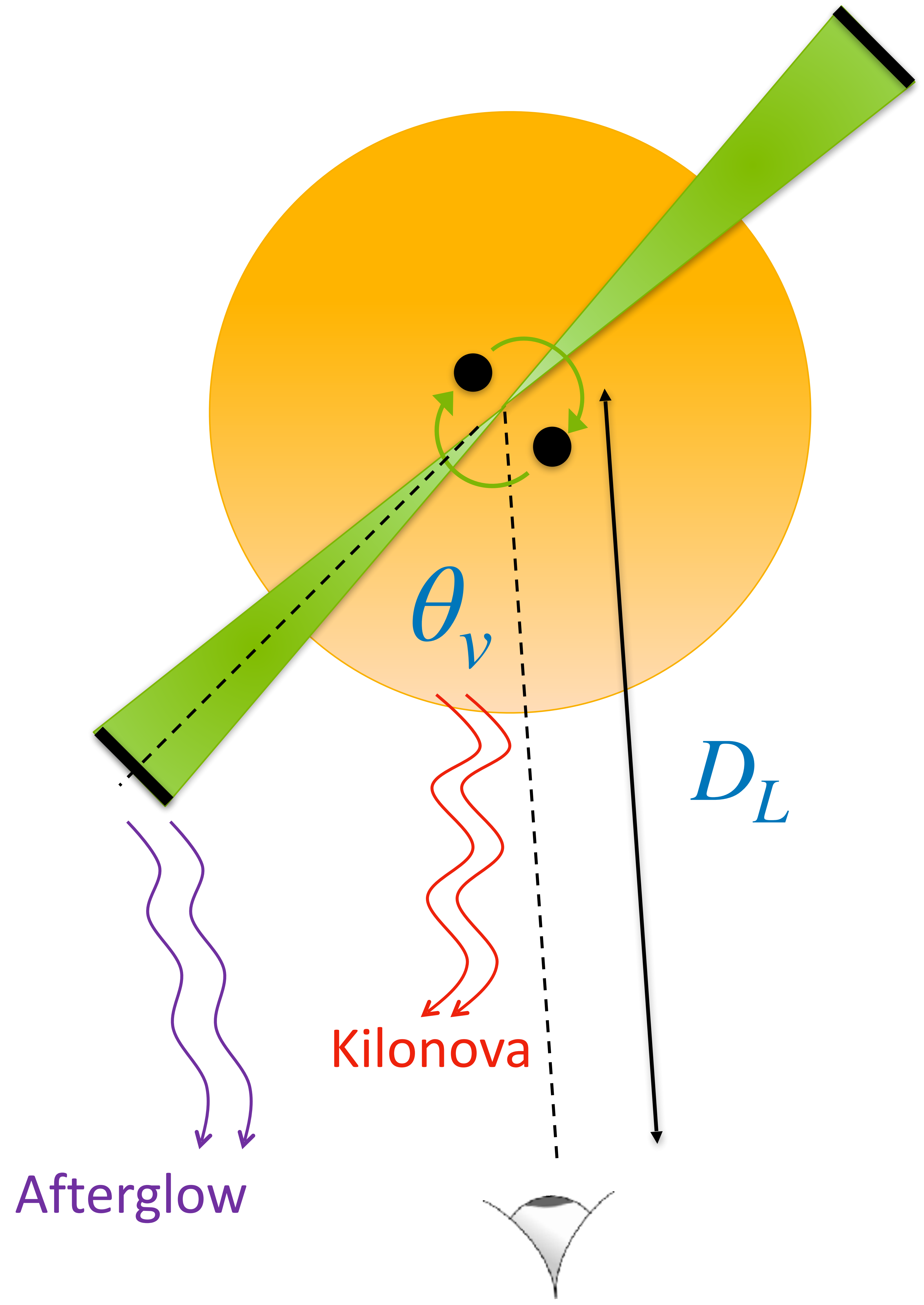


Why make multimessenger population prospects?

1. Replace GW170817 in its **population context**: *It was historic, but was it exceptional?*

2. Guide **designing of primary and follow-up instruments** by describing expected targets and their population features

3. Guide **multimessenger observation campaigns** by describing expected observables and correlations

4. Outline the sources and datasets which will be **available for future multimessenger studies**: merger physics or merger environment studies, multimessenger cosmology, etc.

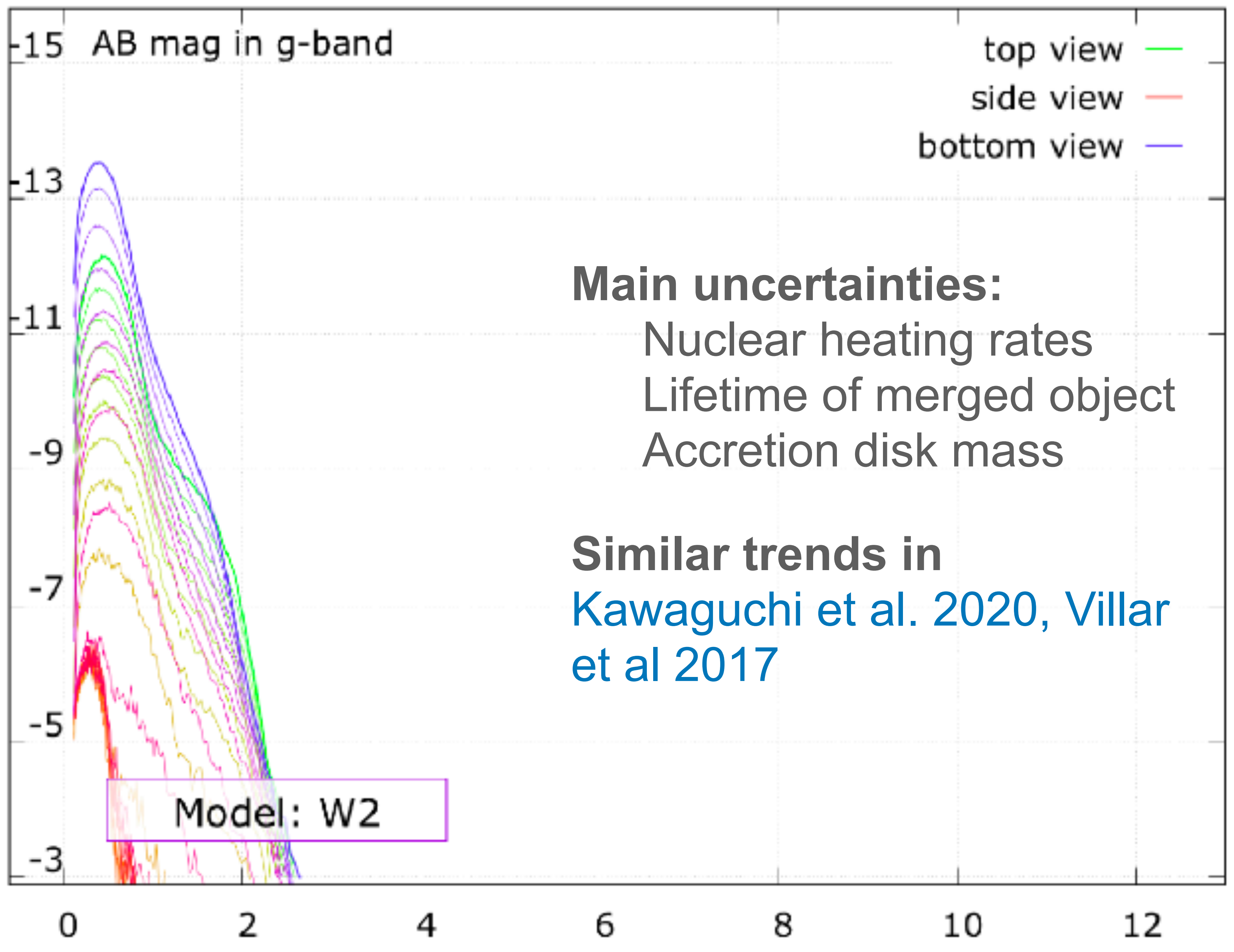
Emission models

Kilonova angle-dependence

- Based on state-of-the-art kilonova modelling with: numerical hydro, nuclear networks, realistic thermalization, radiation transfer, heavy element opacities, etc.

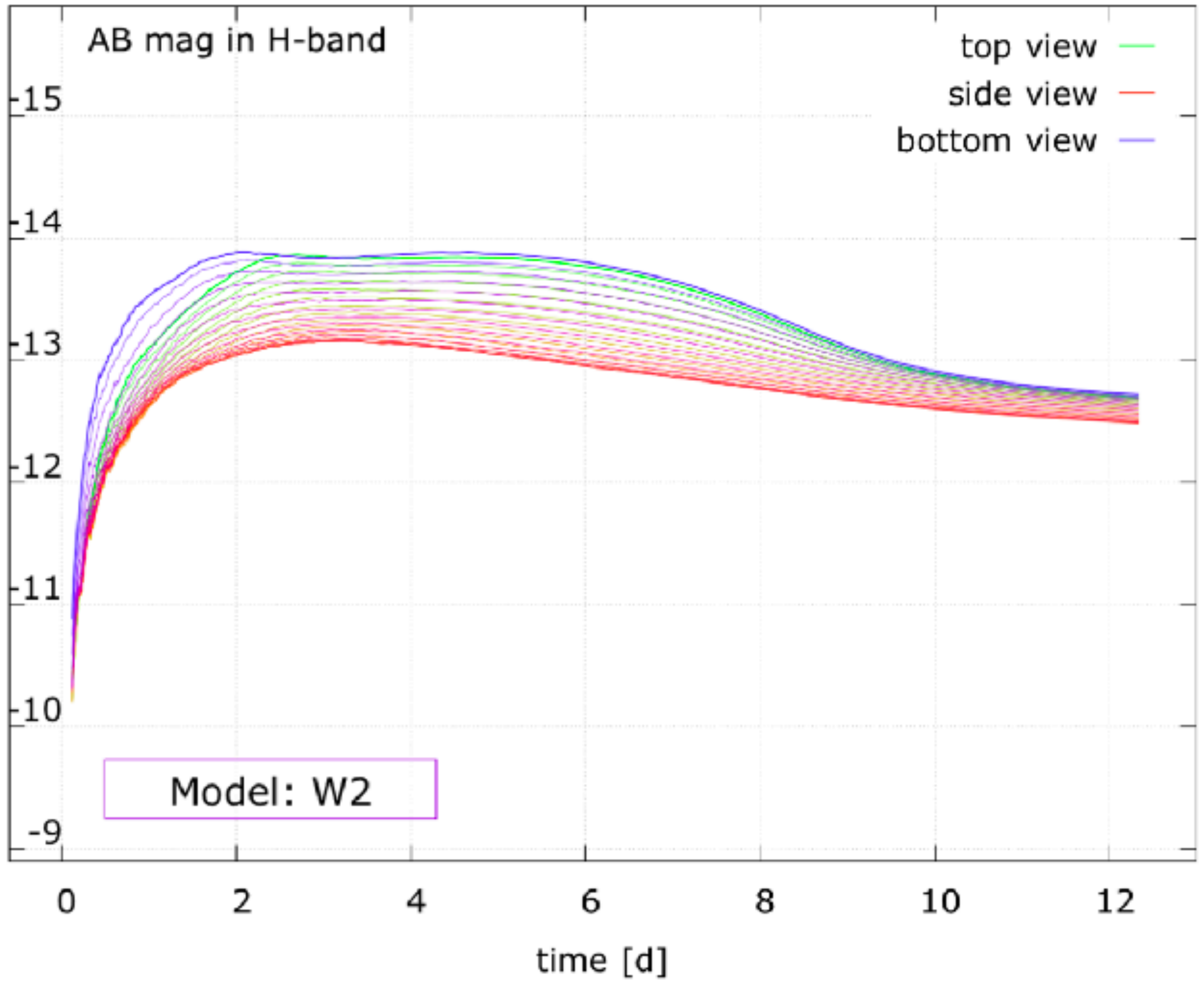
- **Empirical fit** of polar-to-side contrast (valid for $\theta_v < 60$ deg): $M_\lambda(\theta_v) - M_{\lambda,\mathrm{polar}} \propto 1 - \cos\theta_v$

- **Calibration** of polar peak magnitude on **AT2017gfo** using best estimate for 170817's viewing angle ($\theta_v^{170817} = 15^{+2.5}_{-1.7}$ deg, Ghirlanda et al. 2019)



Main uncertainties:
Nuclear heating rates
Lifetime of merged object
Accretion disk mass

Similar trends in
Kawaguchi et al. 2020, Villar et al 2017



Wollaeger et al. 2018

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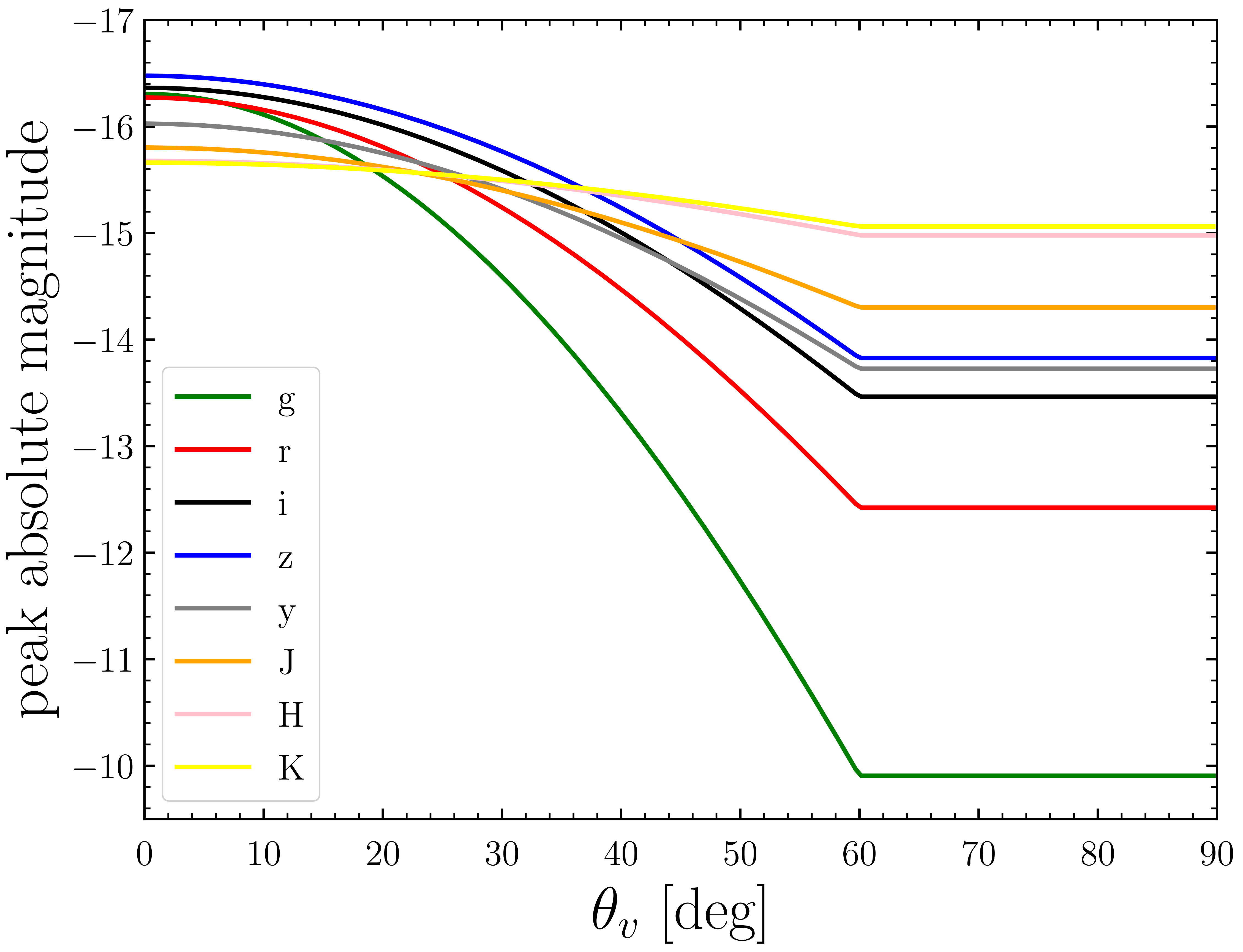
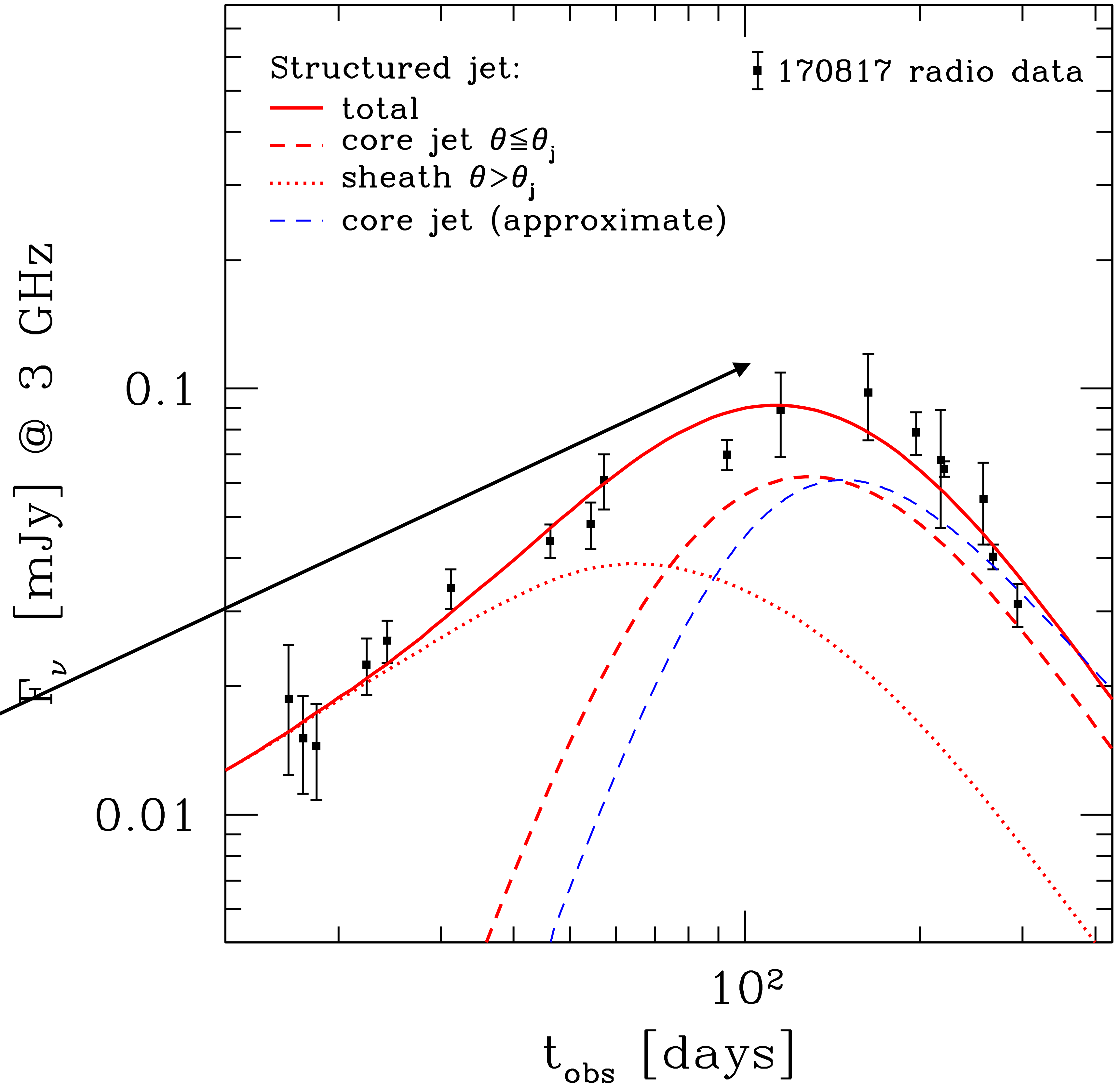
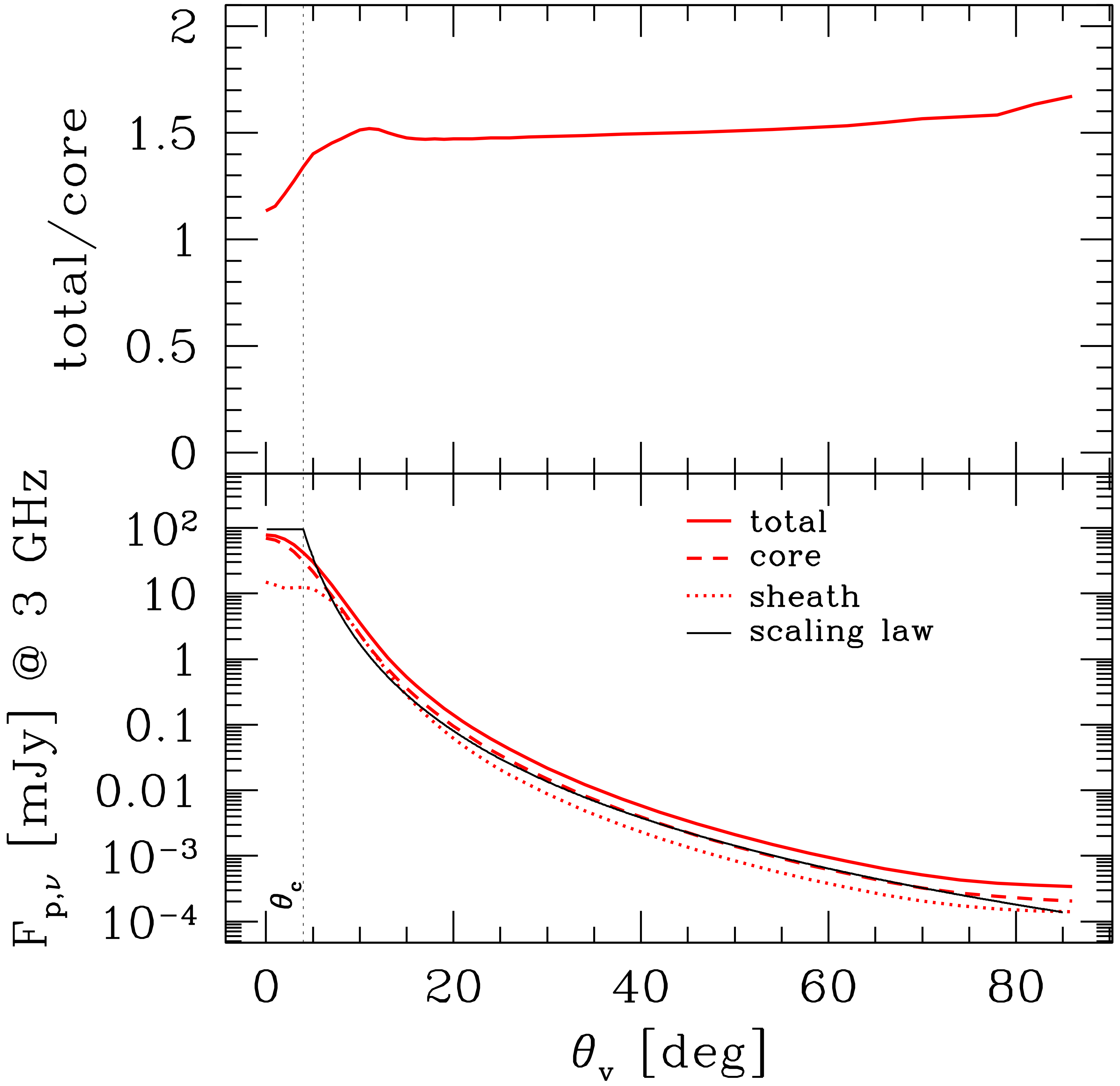


Emission models

Relativistic afterglow photometry



Peak flux depends on E, n etc.



Duque et al. 2019

- Standard **synchrotron process** from front shock-accelerated electrons, most often in the slow cooling regime
- In principle, light curve depends on **jet angular structure**… Numerical computation shows that for a **peak-flux-related criterion**, it is enough to consider the core only.

Emission models

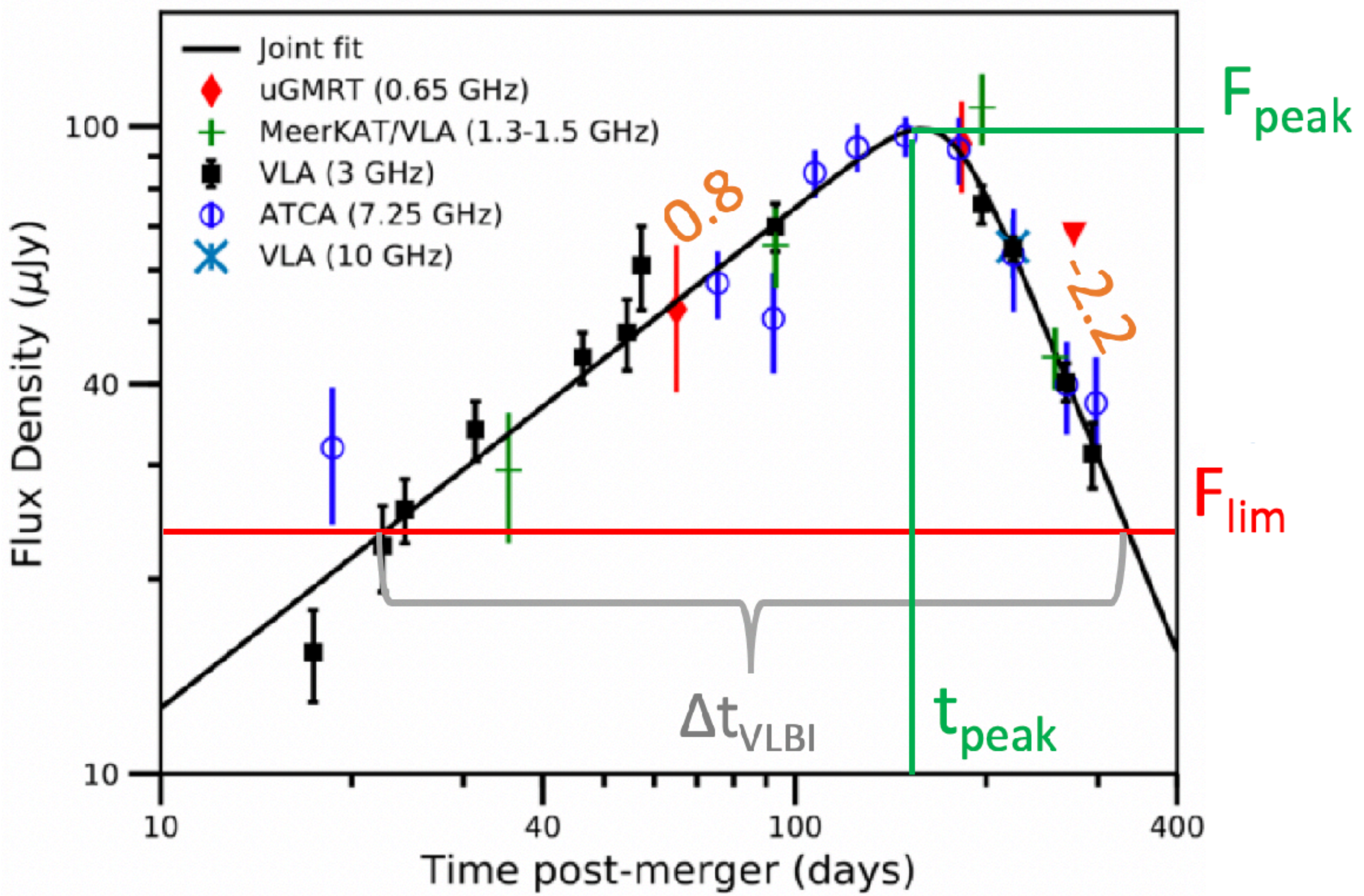
Relativistic afterglow imagery

- Total displacement:

$$\Delta\theta = \Delta t_{\mathrm{VLBI}} \times \frac{\mathrm{d}\theta}{\mathrm{d}t}\Big|_{\mathrm{peak}}$$

- Determine Δt_{VLBI} from the **afterglow slopes, which are independent of θ_v** (Beniamini et al. 2020)

- Determine $\frac{\mathrm{d}\theta}{\mathrm{d}t}\Big|_{\mathrm{peak}}$ from $\Gamma \times \theta_v = 1$, valid at the peak.

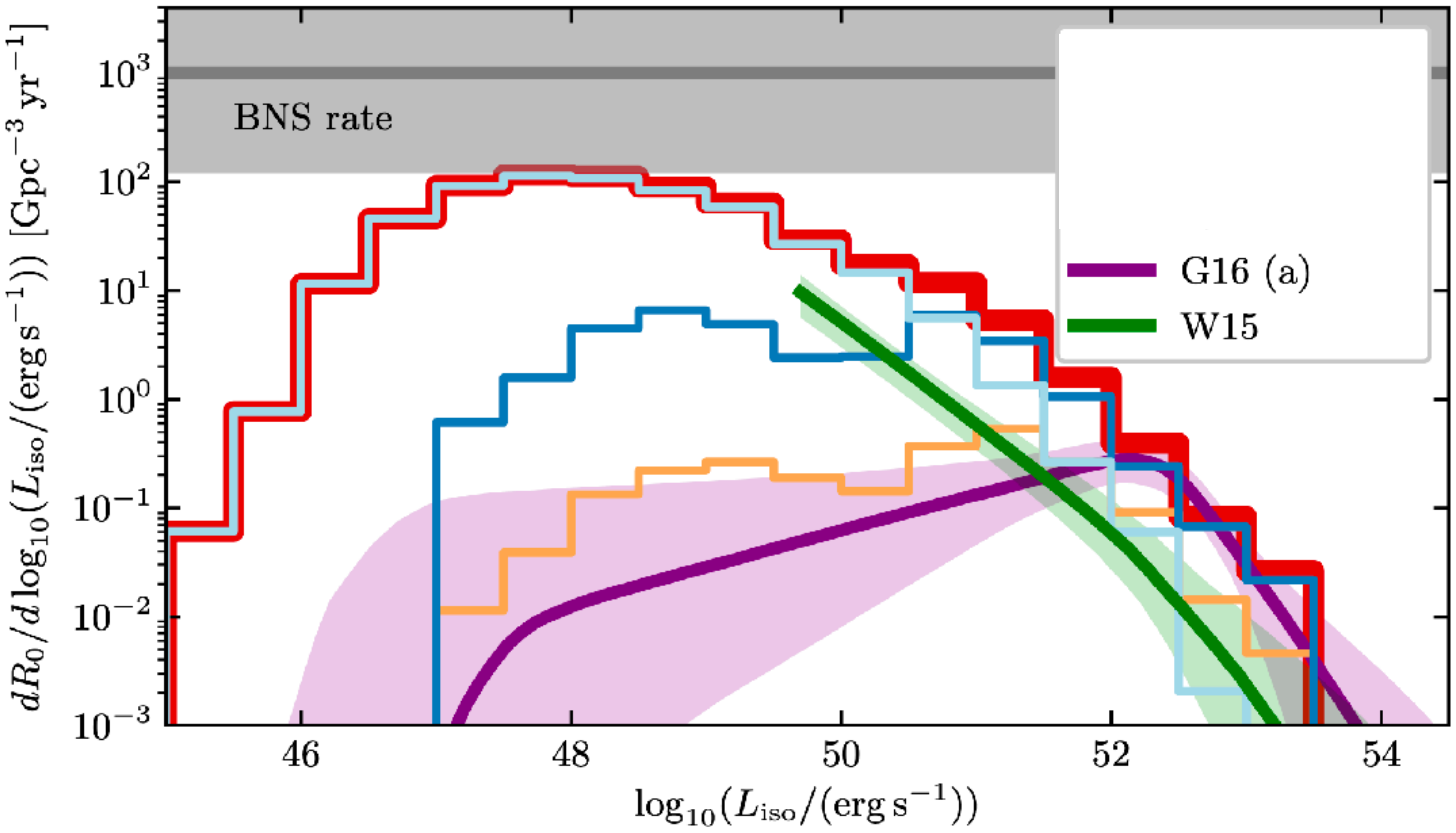


Population model

Which distribution for the jet energy?

- Use distribution derived from **short GRB luminosity function**
- Supposes that short GRB ≡ BNS merger ≡ relativistic jet
- Use two **extreme** luminosity functions from literature: Wanderman, Piran 2015 (WP15) and Ghirlanda 2016 (G16)

⟹ **important source of pop. model uncertainty**



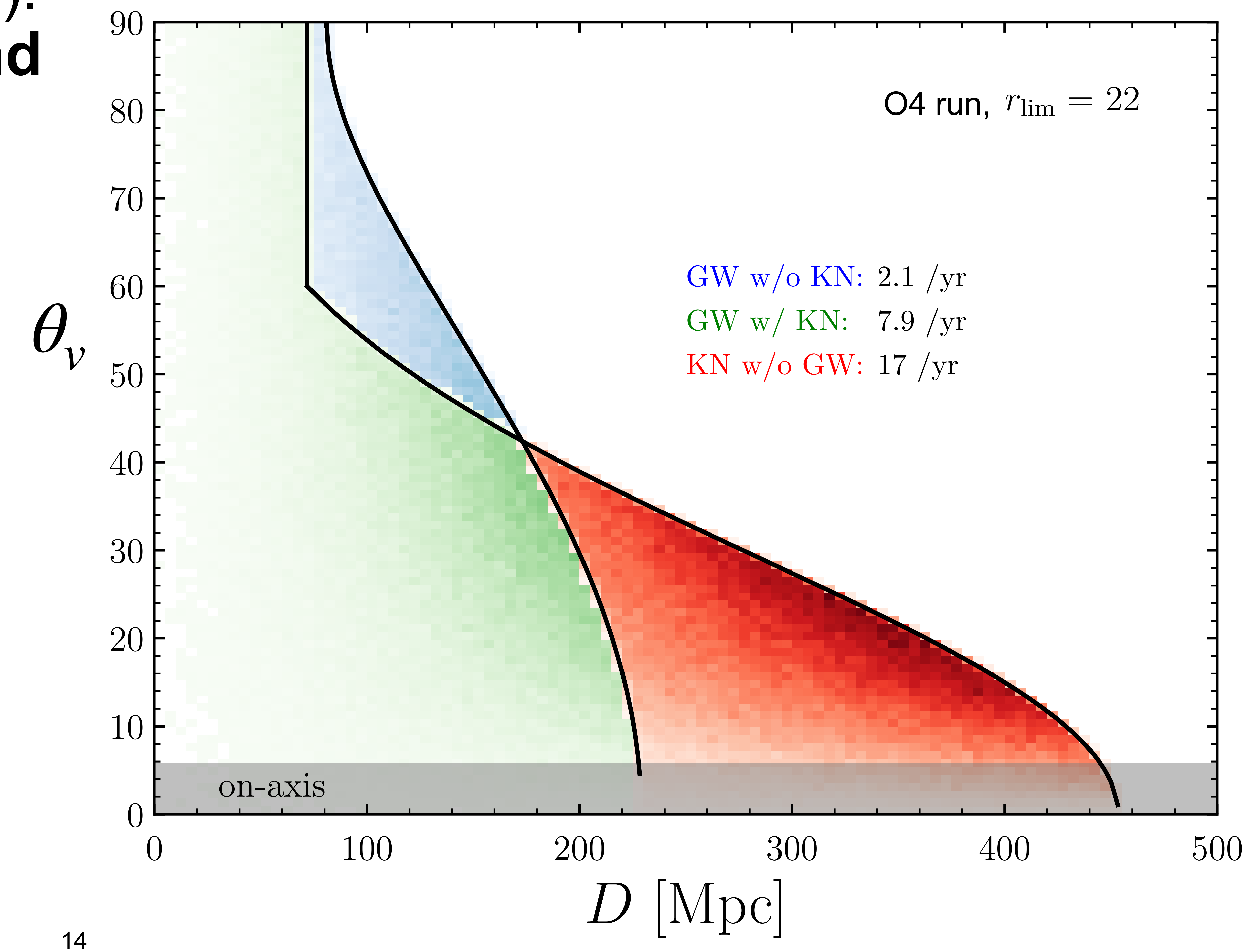
Salafia et al. 2020

Mastrogiovanni et al. subm.

Results

- As of O3: **EM sector becomes limiting** for multimessenger campaigns, with **large fraction of undetectable KN** ($\mathrm{mag}_{\mathrm{lim}} = 21$). Still **tens KN /year for deep searches and design IFOs**.
- Among the KN events, 10-20% have a detectable radio afterglow. Detectable **source displacement is extremely rare**.
- Deep surveys can probe "orphan kilonovae", with **likely short GRB associations** (~2 /year for $r_{\mathrm{lim}} > 21$)
- Especially for ToO endeavors: **detectable is not detected!**

GW Run	Electromagnetic information level				
	KN	… + AG light curve		… + source PM	
		WP15	G16	WP15	G16
O2-like	52%	4%	12%	0.67%	7%
O3-like	45%	1.56%	6.13%	0.18%	1.70%
O4-like	26%	0.37%	3.50%	0.01%	0.25%

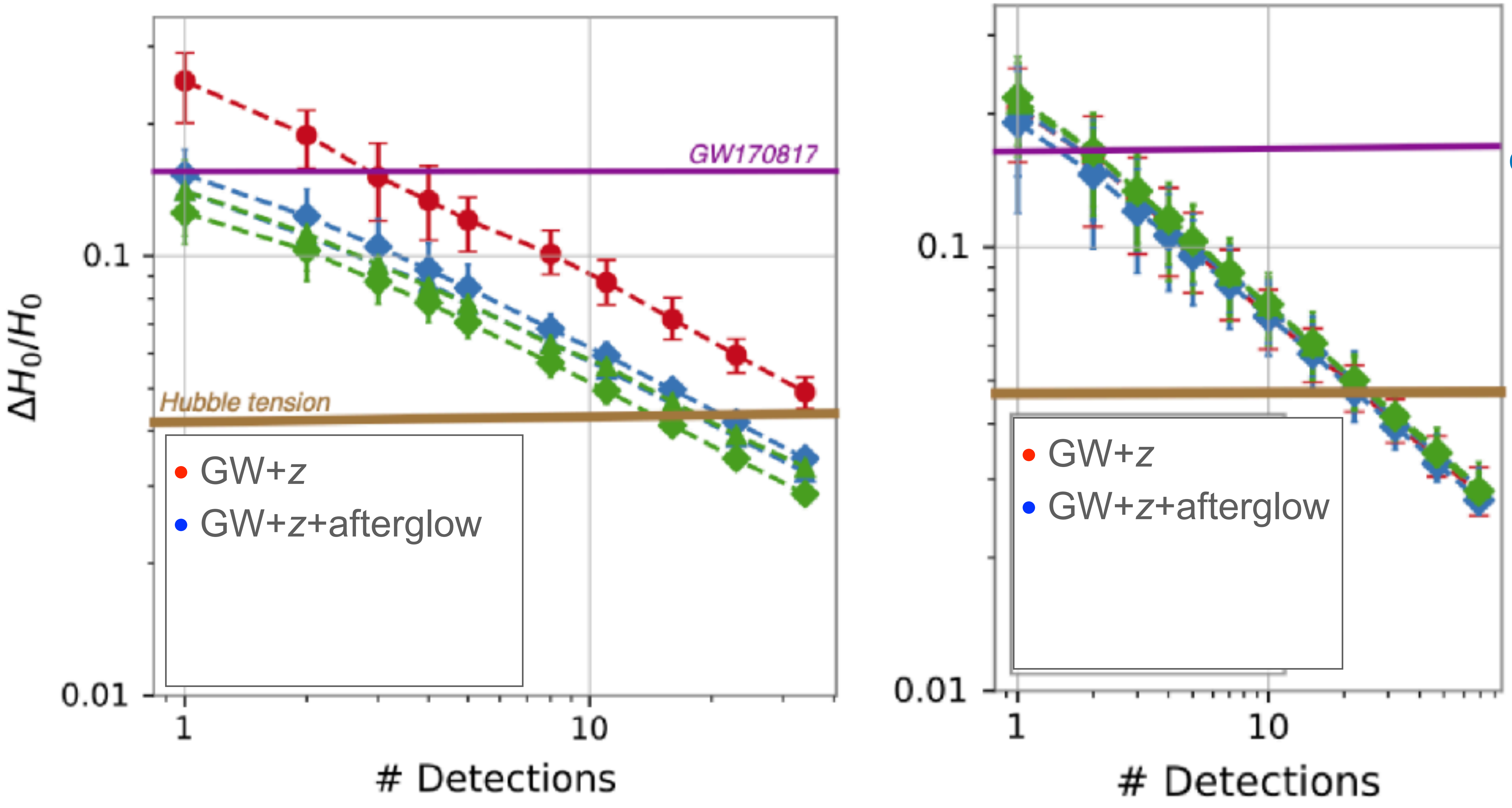


Mochkovitch et al. subm.

Applications

Multimessenger cosmology

- GW170817: afterglow data provides **independent information** on $\iota\ (=\theta_v)$, which is **degenerate with** D_L in GW data $\Longrightarrow$ improved standard-siren H_0 measurement 3-fold
- Question: *What role will afterglow counterparts play in multimesseger cosmology?*
- Answer: They will be **too rare** to contribute to H_0 measurement…
- Discussion: But KN could help (if models improve and allow to measure θ_v). However: beware of **EM systematics** on H_0 and **selection effects**.



Afterglow rate = GW rate **Realistic afterglow rate**

Mastrogiovanni et al. subm.

Applications

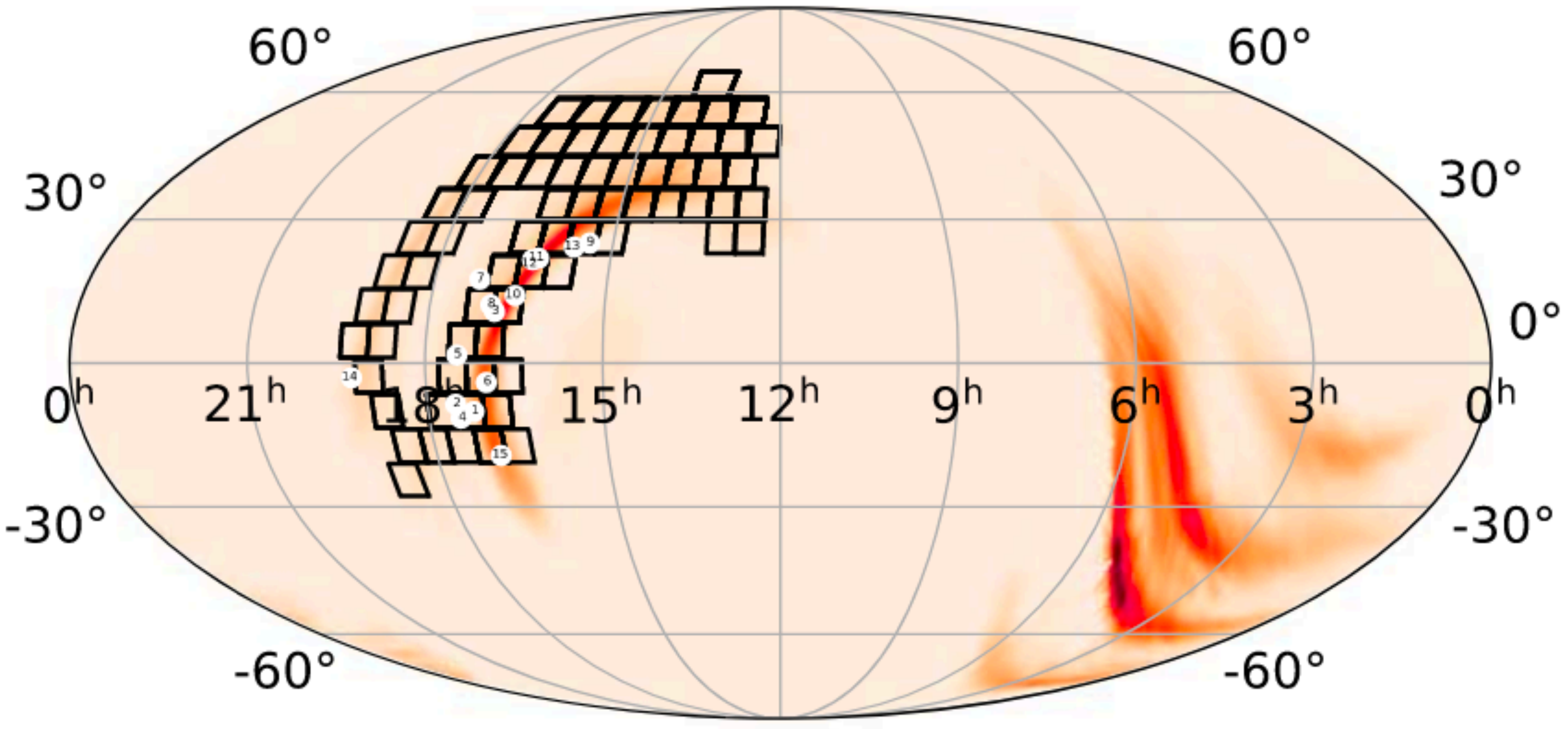
Constraints on GW190425

- Only likely BNS merger since GW170817, very poorly localized event. Followed-up extensively in optical and NIR: **no kilonova detection.**

- The system was either

1. not located in the searched areas, or

2. too faint



Coverage of GW190425 by ZTF

Coughlin et al. 2019

- Proof of concept of **viewing angle constraint from KN non-detection**. Method will be effective with genuine non-detections in **smaller GW skymaps**, and with **better KN models**.

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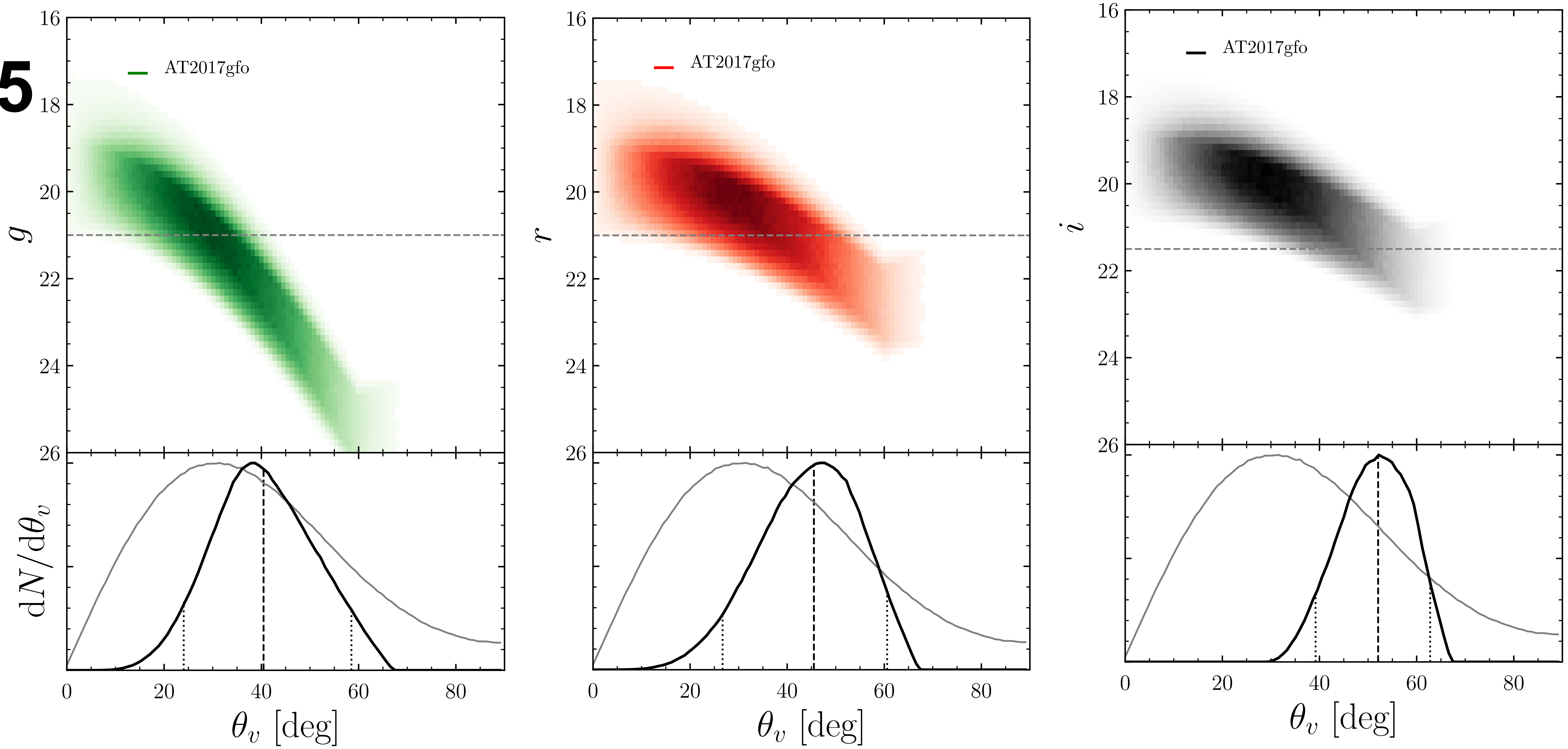

Mochkovitch et al. subm.

$$\theta_v^{190425} = 53 \pm 10\,\mathrm{deg}$$

- Proof of concept of **viewing angle constraint from KN non-detection**. Method will be effective with genuine non-detections in **smaller GW skymaps**, and with **better KN models**.

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Conclusions

- Population model for kilonova and afterglow counterparts to BNS inspiral GW signals
- As GW sensitivity improves: smaller and smaller detection fraction for kilonovae, still tens/year during design-level GW observing runs. Expect only **a few with radio afterglow lightcurve sampling**, and almost none with source proper motion resolution.
- Applications: we showed that **afterglow counterparts should not accelerate resolution of the Hubble tension**, and that kilonovae non-detections can inform us on the viewing angle of upcoming BNS events.

References:
1905.04495
2012.12836
2103.00943