Perspectives for kilonovae multimessenger detection

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in collaboration with
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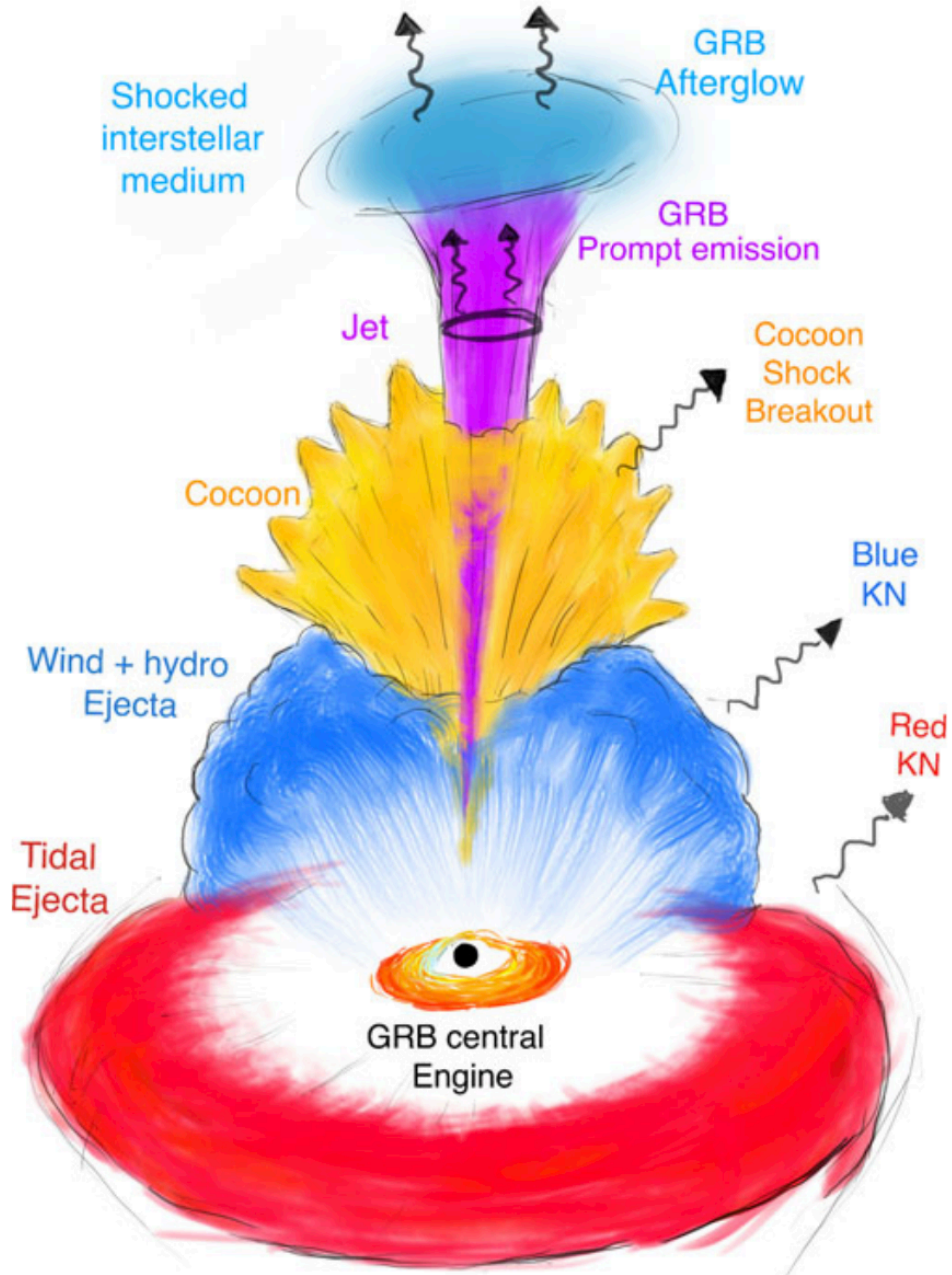
The Kilonova

- Ejection of neutron rich matter → heavy elements nucleosynthesis via neutron capture

- Thermal EM emission powered by nuclear decay of freshly synthesised heavy elements

- UV/optical/IR signal, faint & rapidly evolving (one week)

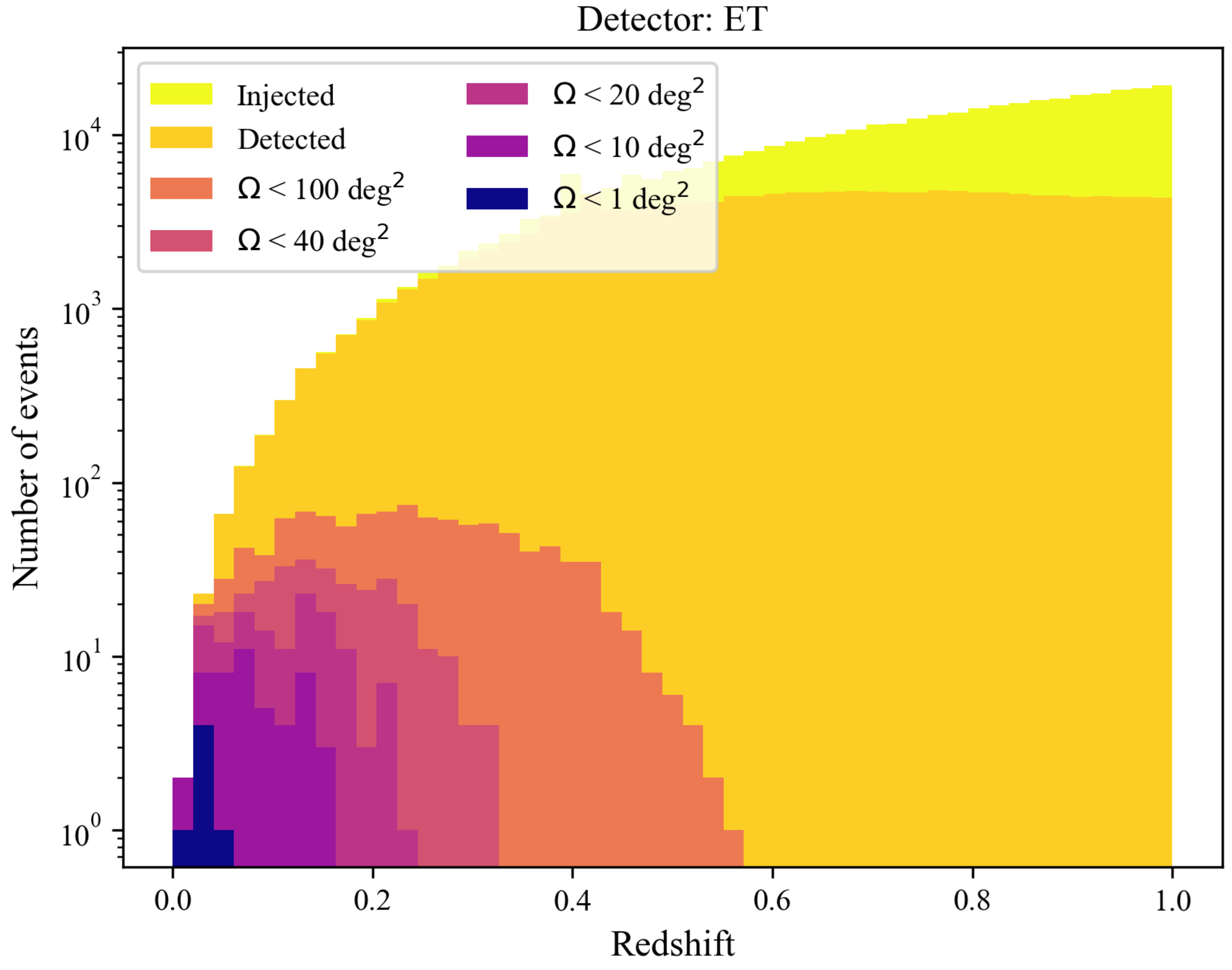
- Sky-localisation from GW signals → key parameter for the follow-up with optical telescopes

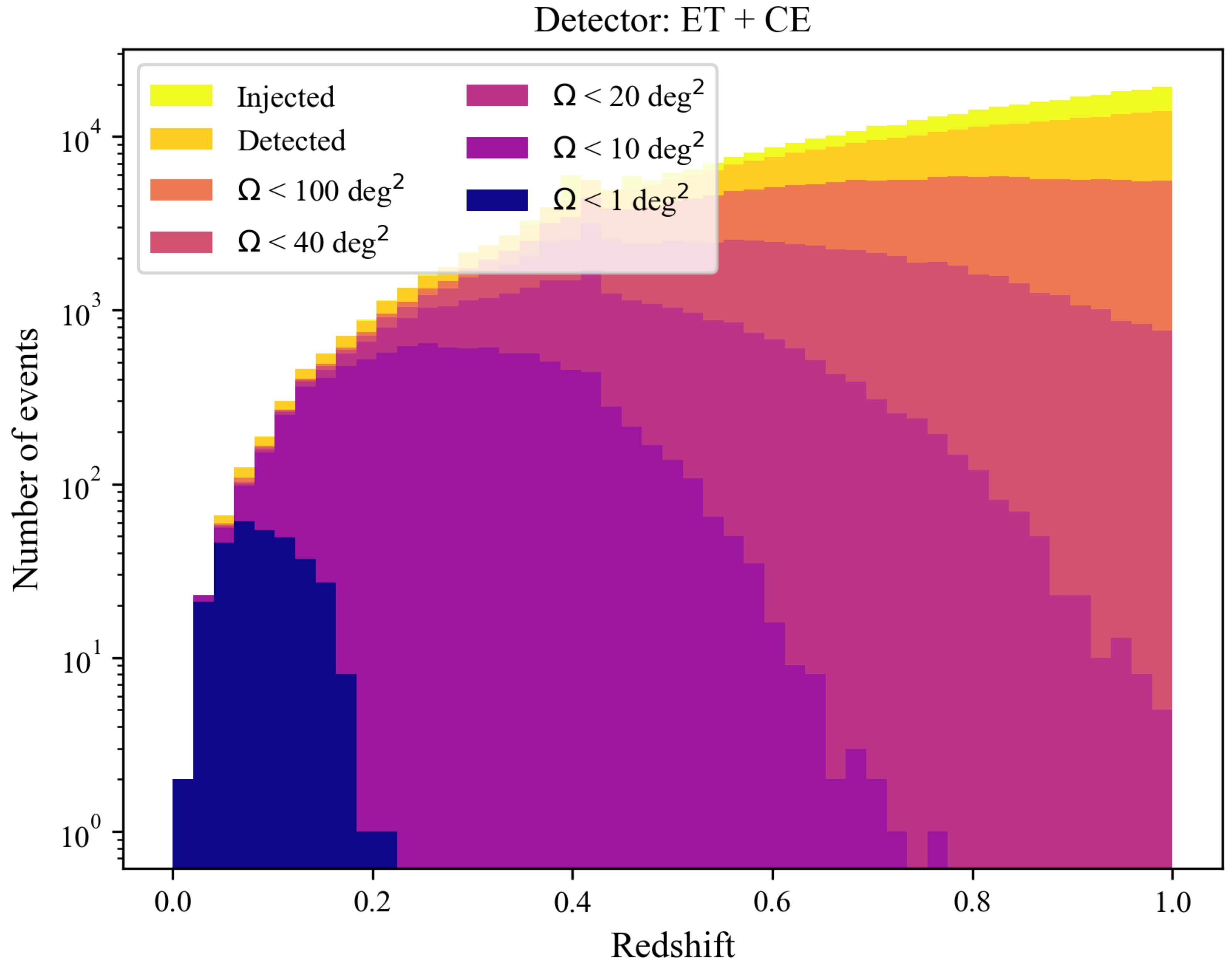


Credits: Ascenzi et al. 2021

Prospects for kilonovae joint detection

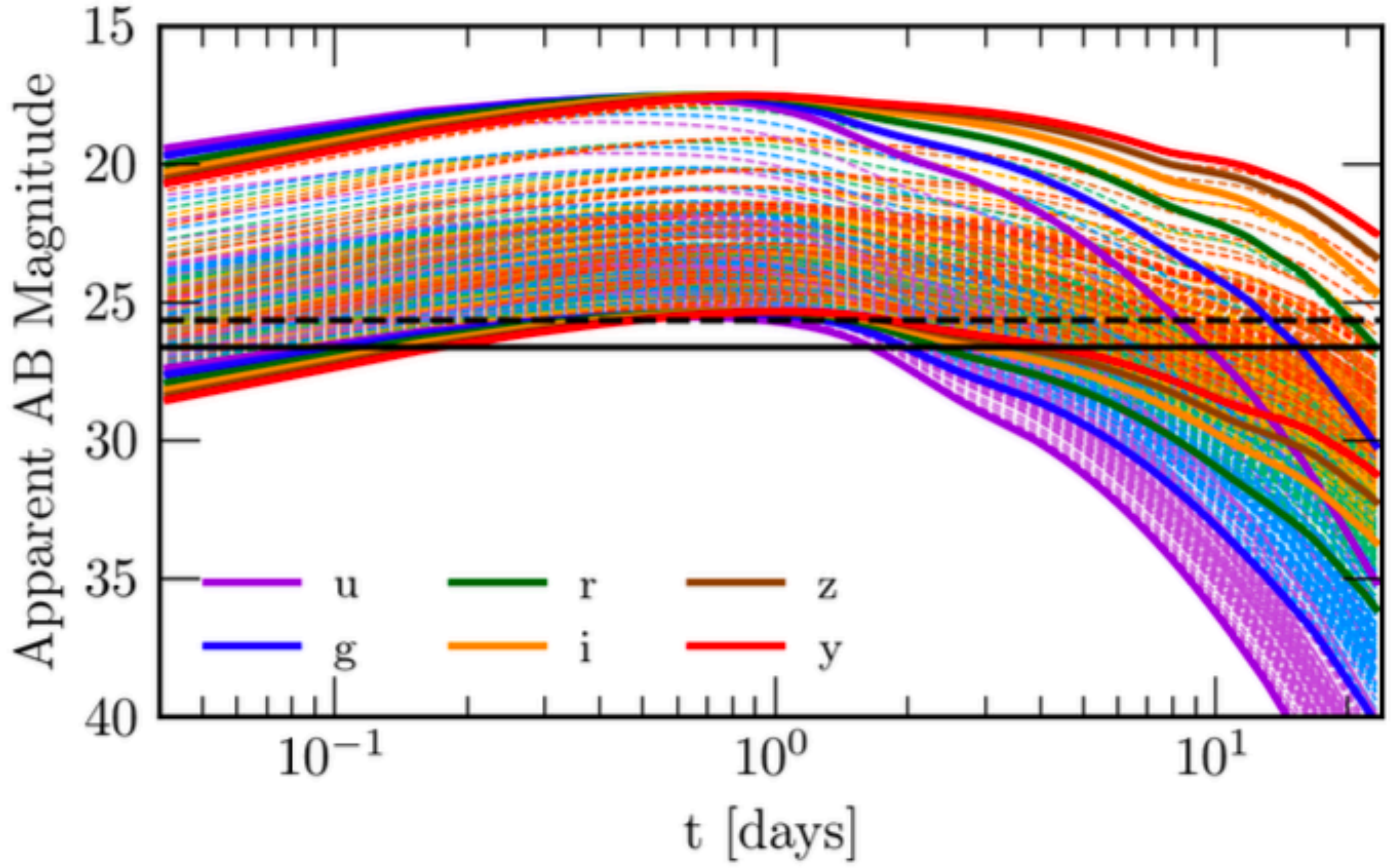
- LIGO, Virgo, KAGRA → expected to detect a few BNS mergers in O4 *(Abbott et al. 2020)*
- ET and CE will detect $\sim 10^5$ BNS mergers per year up to redshift $\sim 5 - 10$ *(Ronchini et al. 2022, Branchesi et al. 2023)*
- ET → hundreds BNS with sky-loc. < 100 deg^2
- ET + CE → thousands BNS with sky-loc. < 10 deg^2
- Evaluating optimal ET configurations for KN joint detection with Vera Rubin Obs.
- Assessing impact on constraining the NS Equation of State (EOS) and for cosmology

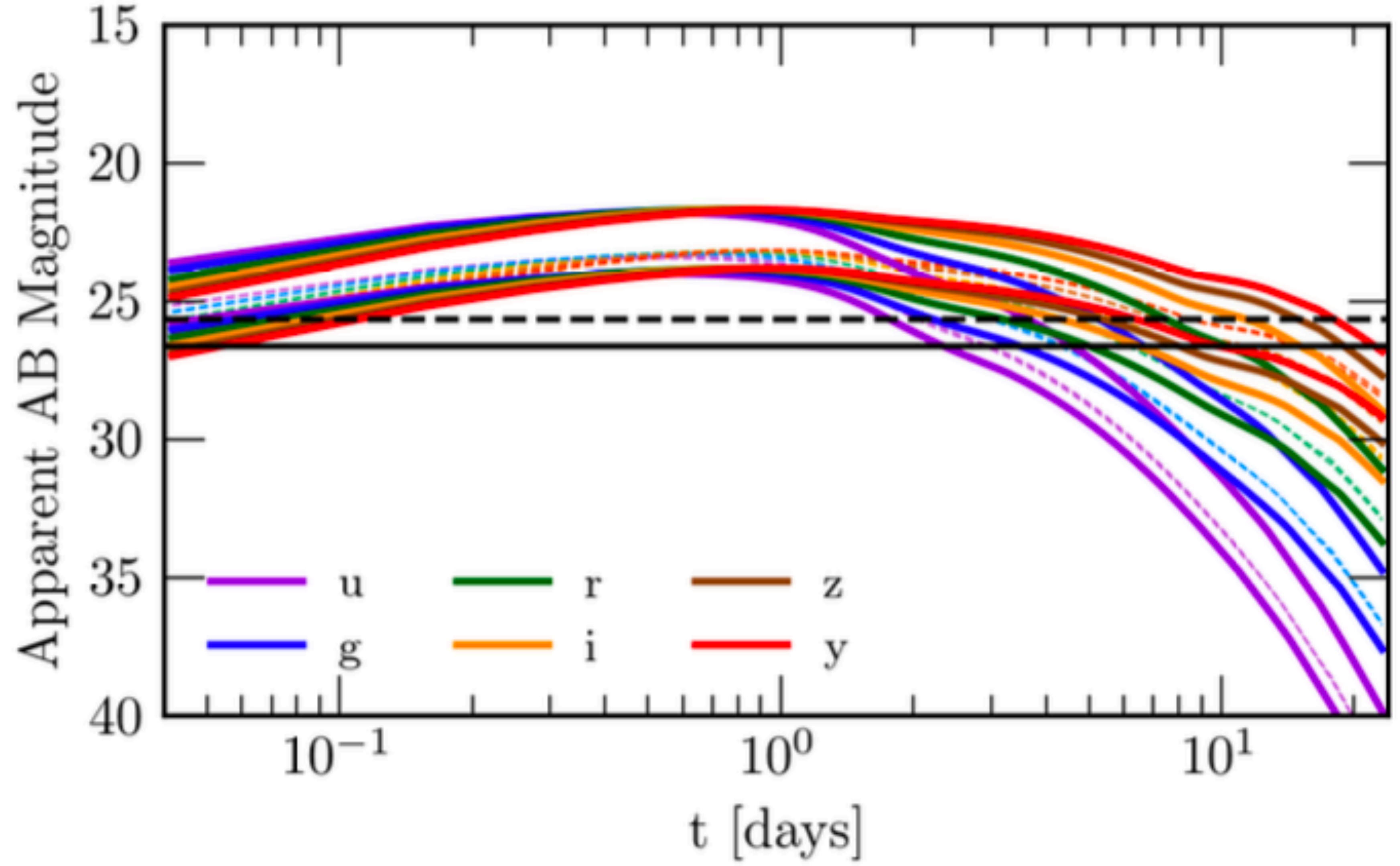




Joint detection with ET and Vera Rubin → method

- BNS mergers population from population synthesis code MOBSE, Gaussian mass distribution and local merger rate 250 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ *(Mapelli et al. 17, Santoliquido et al. 21)*
- ET (Δ or 2L), different arm length, w/ or w/o cryogeny → **Iacovelli's talk**
- Number of detected mergers and estimate of source parameters with Fisher matrices using GWFish code *(Dupletsa et al. 23)*
- KN lightcurves → AT2017gfo-like, semi-analitic model, anisotropic 3-component ejecta *(Perego et al. 17)*
- Follow-up with Vera Rubin T.O. → **Hazra's talk**





Reference: Science with the Einstein Telescope: a comparison of different designs, *Branchesi, Maggiore,…, EL, …, 2023*

Some results: optimal ET configuration for KNe detection

- ET 2L 20km w/ cryogenic laser and misaligned arms → best performing, joint detection of several tens/few hundred KN per year
- ET 15km triangle slightly better than ET 2L 15km (30% more detections)
- Low frequencies pivotal for ET to operate as single observatory

Full (HFLF cryo) sensitivity detectors

Configuration	$N_{GW,VRO}$ $\Omega < 20\,\mathrm{deg}^2$	VRO time	$N_{GW,VRO}$ $\Omega < 40\,\mathrm{deg}^2$	VRO time	$N_{GW,VRO}$ $\Omega < 100\,\mathrm{deg}^2$	VRO time
Δ10	14 (14)	1.1% (3.3%)	36 (39)	5.1% (15%)	96	40%
Δ15	38 (42)	3.3% (9.8%)	84 (101)	14.2% (42%)	163	> 100%
2L 15	28 (28)	2.2% (6.5%)	62 (77)	10.6% (31%)	189	93%
2L 20	55 (64)	5% (14.9%)	115 (152)	23.1% (68%)	324	> 100%

Reference: Science with the Einstein Telescope: a comparison of different designs, *Branchesi, Maggiore, ..., EL, ..., 2023*

Step forward: bracketing uncertainties on KNe population

- Uncertanties on BNS merger rate (**Sgalletta's talk**) → 2 populations from population synthesis code SEVN with local merger rate $\mathscr{R}_{\rm BNS} = [23,\ 107]\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ *(Iorio et al. 23)*

- Uncertainties on NS mass distribution → 2 extreme cases: Gaussian and Uniform

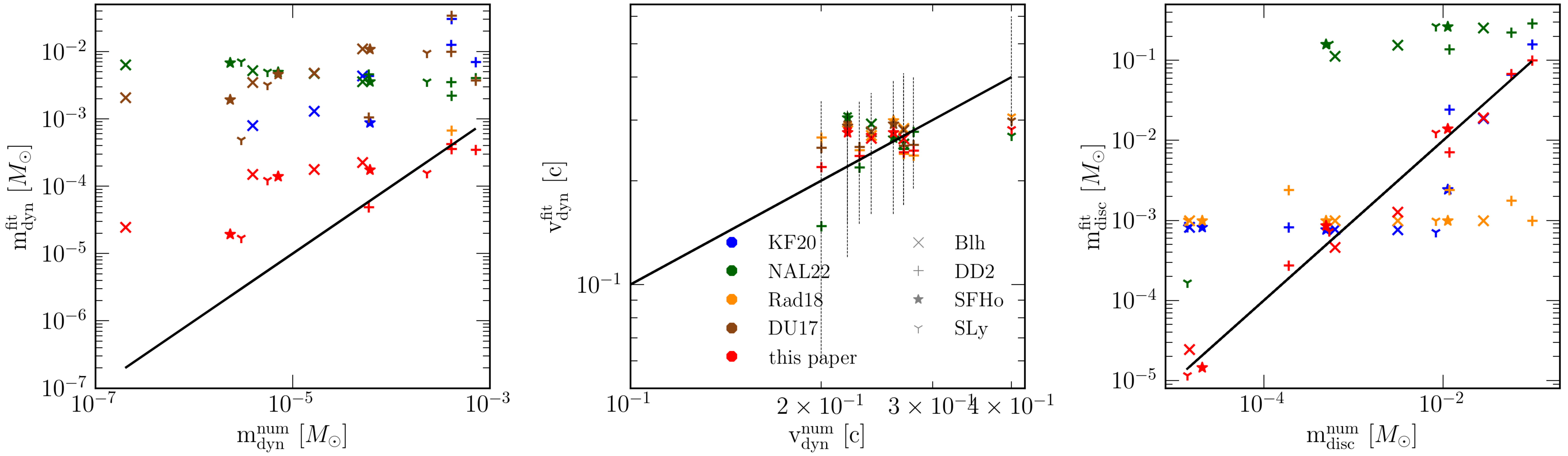
- Uncertainties on NS Equation of State → 2 cases: APR4 and BLh

EOS	$K_{\rm max}$ [GeV]	$M_{\rm max}$ [$M_\odot$]	$R_{\rm max}$ [km]	$C_{\rm max}$ [-]	$R_{1.4}$ [km]	$\lambda_{1.4}$ [-]
APR4	28.88	2.20	9.92	0.328	11.12	256.81
BLh	17.20	2.10	10.46	0.297	12.43	431.22

EL, N. Hazra et al., paper in prep.

Step forward: improving KN ejecta modelling

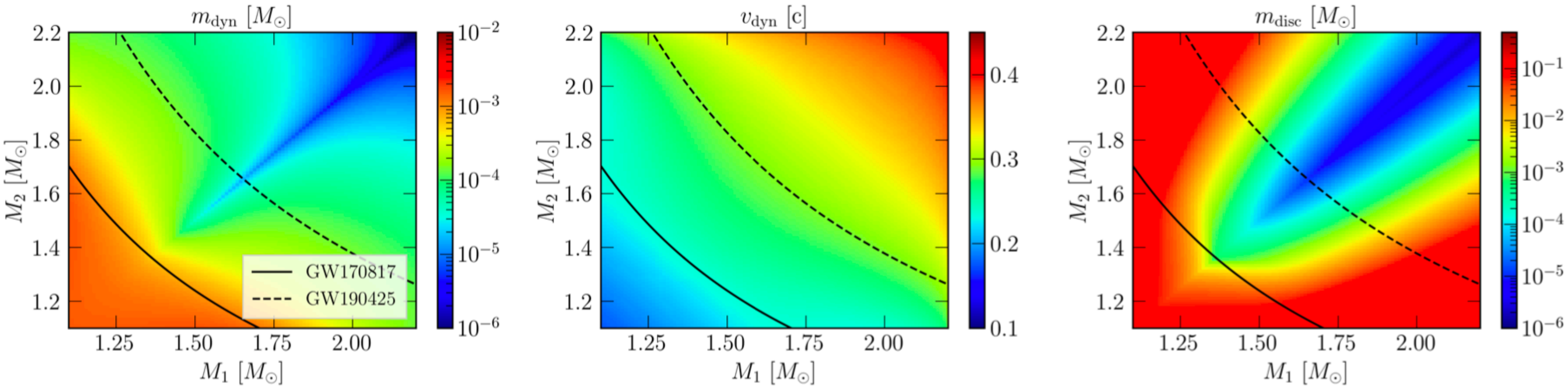
- From masses and EOS of BNS → KN ejecta properties via numerical-relativity (NR) informed fitting formulae
- State-of-the-art fitting formulae disagree outside of calibration region, limited to GW170817 *(e.g. Henkel et al. 23)*
- We develop new fits calibrated on GW190425-targeted NR simulations *(Camilletti et al. 22)*



EL, N. Hazra et al., paper in prep.

Step forward: improving KN ejecta modelling

- Take into account prompt collapse → mass threshold from NR informed fits, dependence on mass ratio and nuclear incompressibility at max NS density *(Perego et al. 22, Kashyap et al. 22)*
- Below PC → use state-of-the-art fitting formulae calibrated on GW170817-targeted simulations *(Radice et al. 18, Krüger & Foucart 20)*
- Above PC → our new fitting formulae calibrated on GW190425



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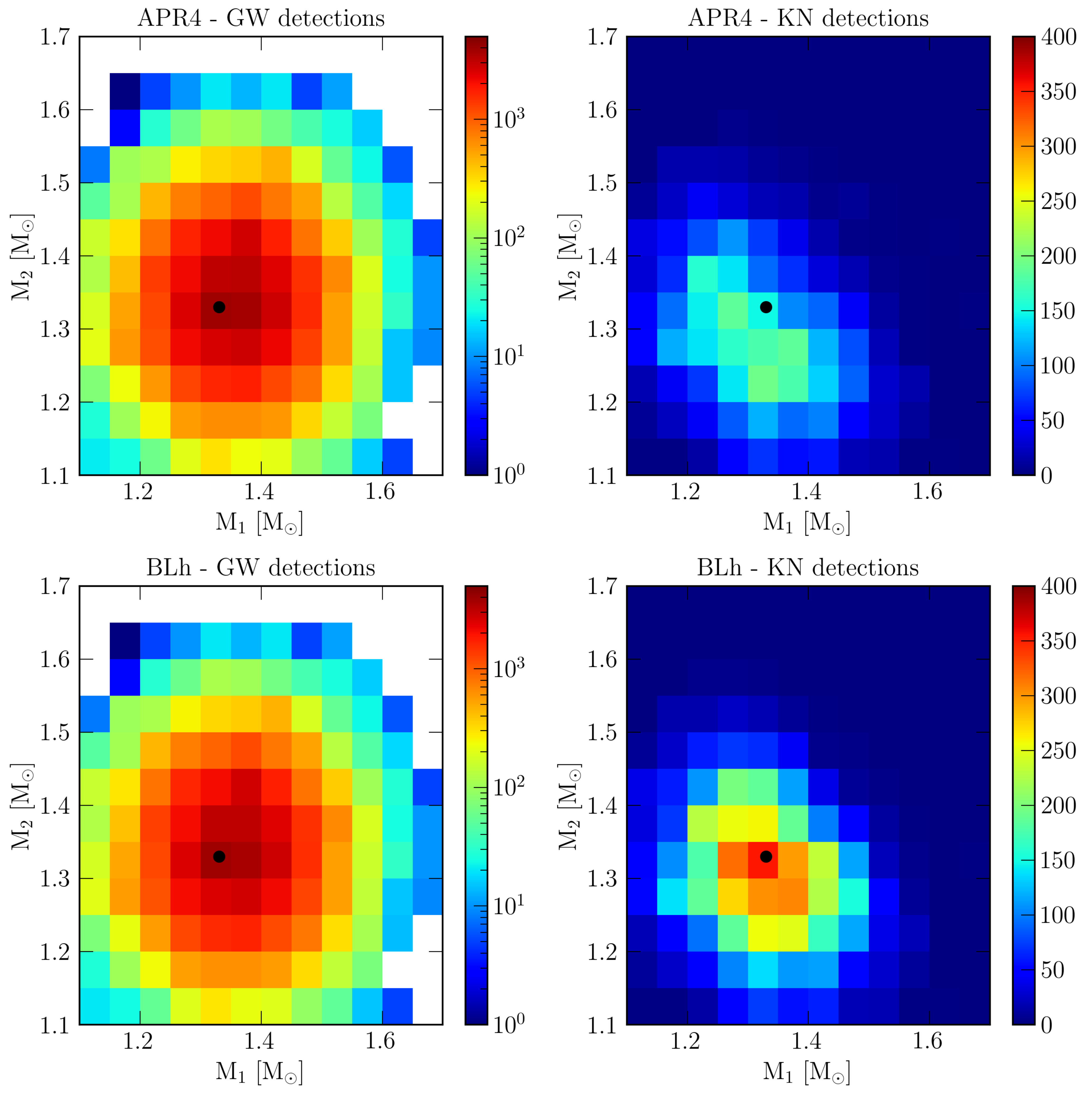
Simulating the amount of joint detections: method

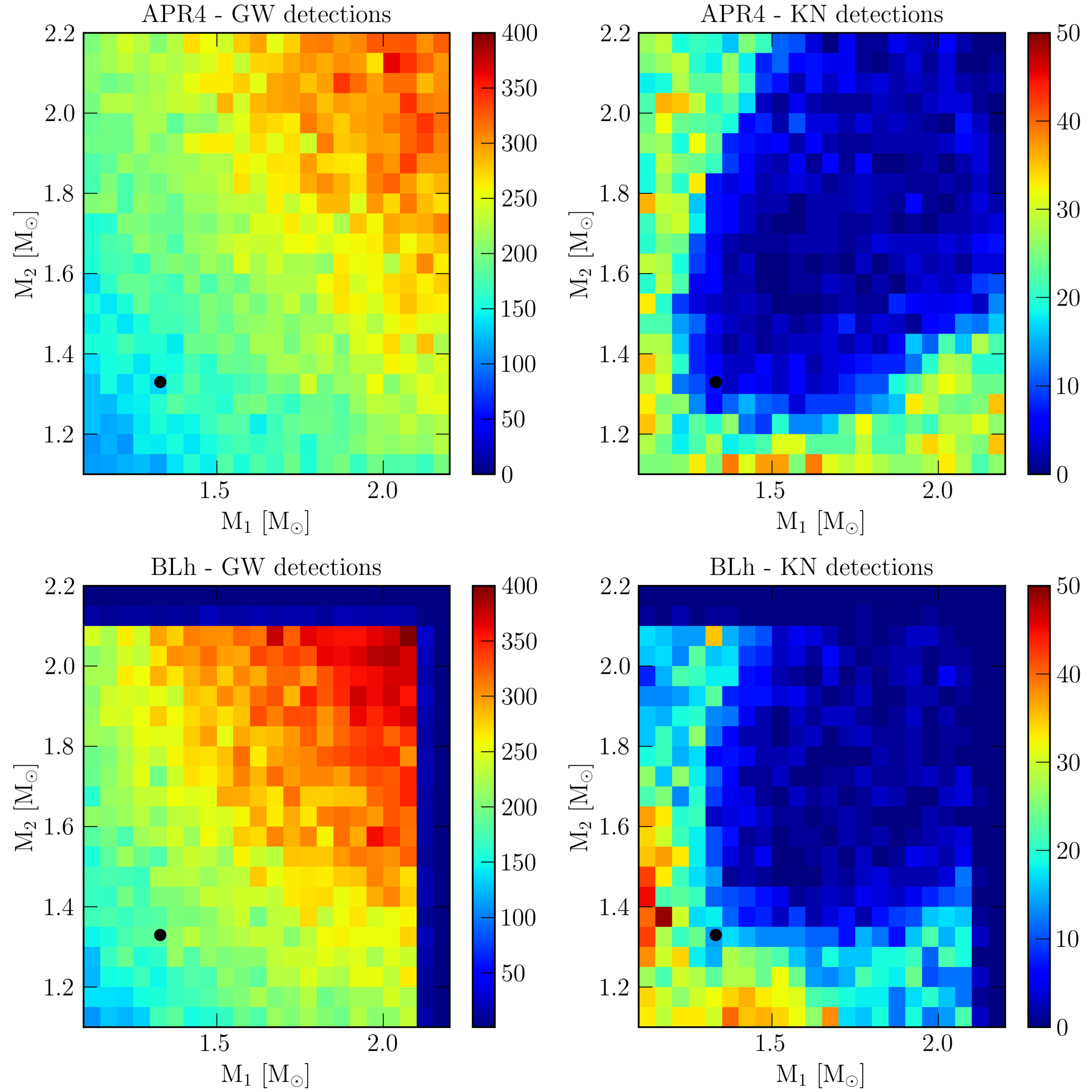
- Ejecta properties + luminosity distance, redshift and inclination angle of each BNS → population of KN lightcurves
- Include optical afterglow from the jet *(Ronchini et al. 22)*
- 2 ET geometries (delta and 2L) in 4 different GW networks (ET alone, ET+LVKI, ET+1CE, ET+2CE)
- Number of detected mergers and estimate of source parameters with Fisher matrices using GWFish code *(Dupletsa et al. 23)*
- Follow-up with Vera Rubin Observatory → **Hazra's talk**
- 64 simulations for 10 years of BNS merger

KNe joint detection: some results

Gaussian NS mass distr.



Uniform NS mass distr.



EL, N. Hazra et al., paper in prep.

KNe joint detection: some results

- Number of KNe detections strongly influenced by NS mass distribution and EOS

- Fix mass distribution:

If gaussian mass distr. → 20% - 40% more detections for BLh compared to APR.

If uniform mass distr. → 3% - 23% more detections for APR4 compared to BLh.

- Fix the EOS:

If APR4 → 10% more detections for uniform than gaussian mass distribution

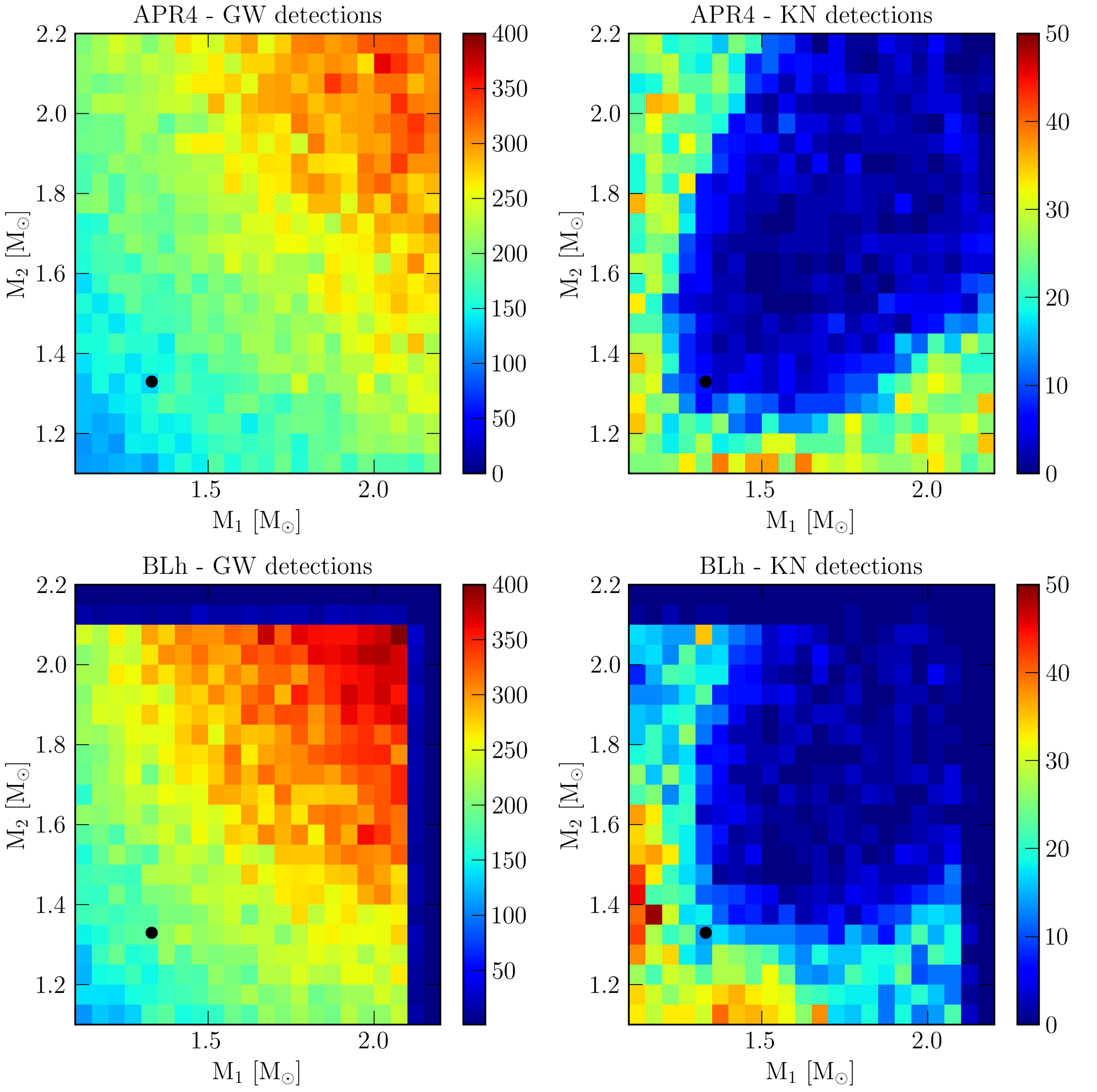
If BLh → 50% - 80% more detections for gaussian than uniform mass distribution

- Increase in number of detections up to 40% if we include jet afterglow (percentage strongly dependent on GW network)

EL, N. Hazra et al., paper in prep.

KNe joint detection: outlook

- Which is the optimal strategy for Vera Rubin TO? Up to which redshift can we detect KNe? → **Hazra's talk**
- Can we constrain NS EOS with KNe joint detections?
- Implications for spectroscopy? → **Bisero's talk**
- Implications for cosmology?



EL, N. Hazra et al., paper in prep.

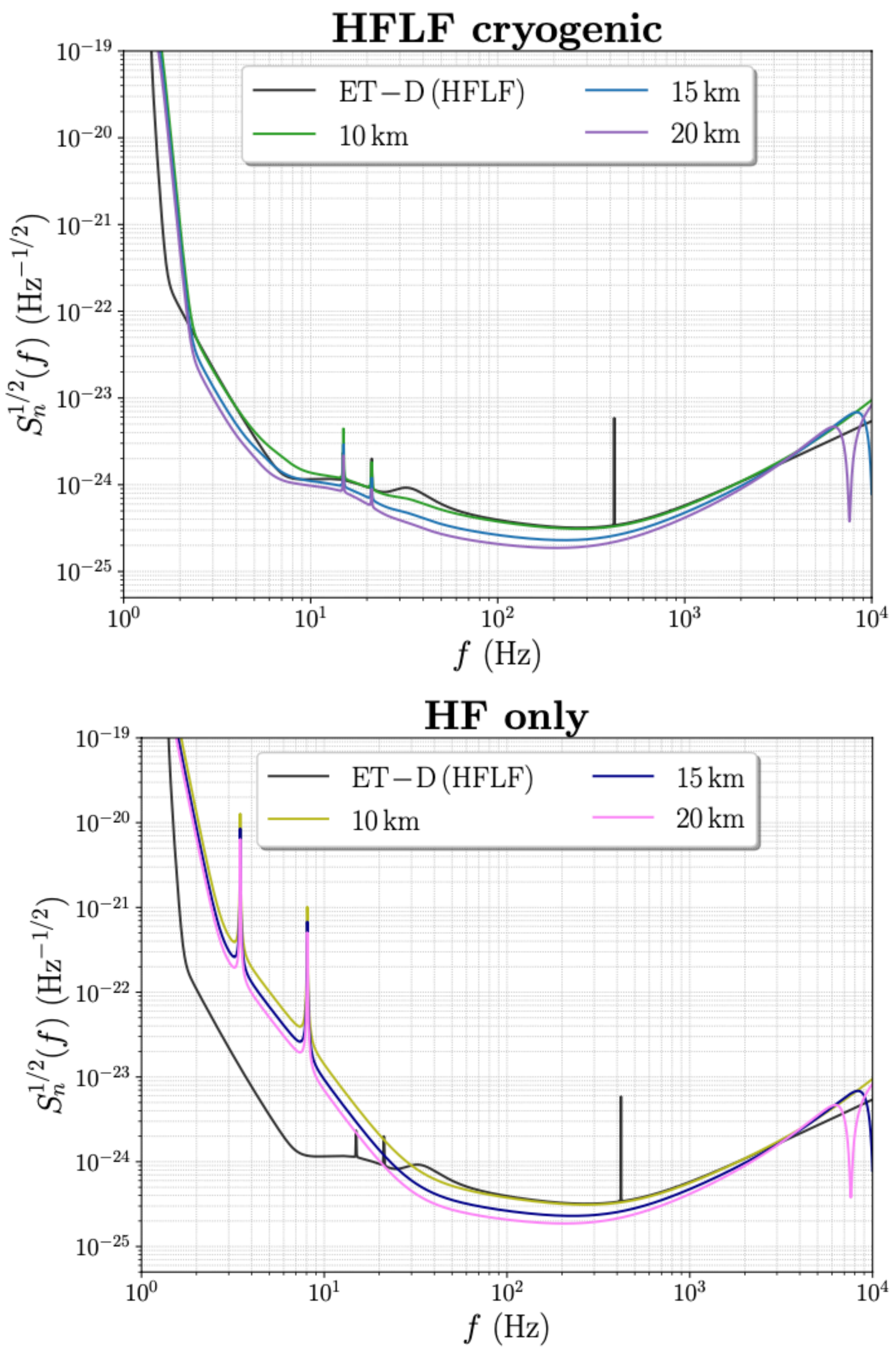
Thank you for you kind attention!

Appendix

ET designs and configurations

- Reference configuration: triangular shape, each arm 10 km, high-frequency and low-frequency lasers (HFLF)
- Different geometries: 2L vs Triangle
- Different arm lengths: 10 km vs 15 km
- Lasers: HFLF vs HF (high-frequency) only

Credits: Dupletsa Ulyana



Credits: Branchesi, Maggiore et al. 2023

Estimate of H_0 with ET and Vera Rubin

Results

- Detection efficiency of KNe larger than 99% up to redshift z = 0.3
- ET accessing also low-frequencies (HFLF) allows constraining H_0 with percent precision, a factor 7 better than ET w/ high-frequency only

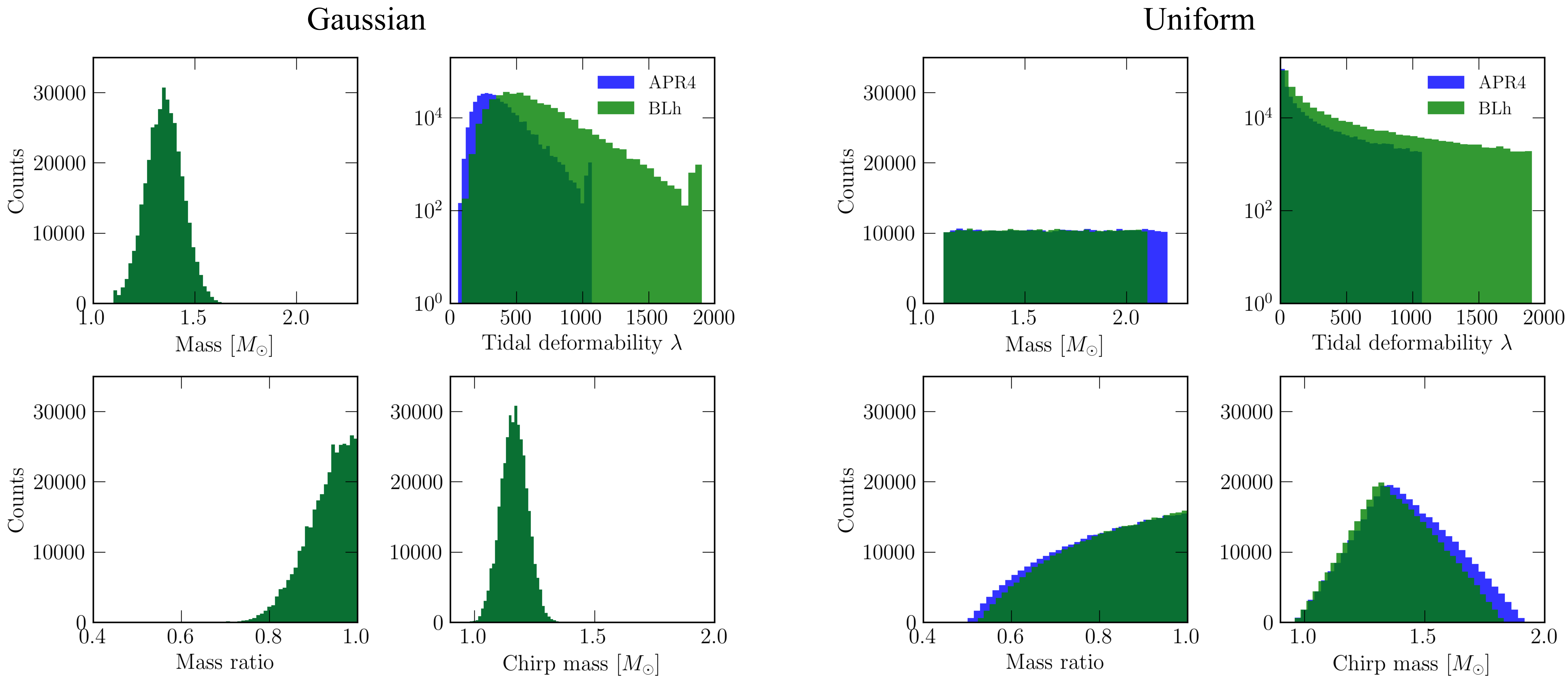
HF only		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.065	1.23
Δ-15km	0.057	1.86
2L-15km-45°	0.066	1.31
2L-20km-45°	0.031	1.22

HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

Reference: Science with the Einstein Telescope: a comparison of different designs, *Branchesi, Maggiore et al., 2023*

KNe joint detection: a step forward

BNS population

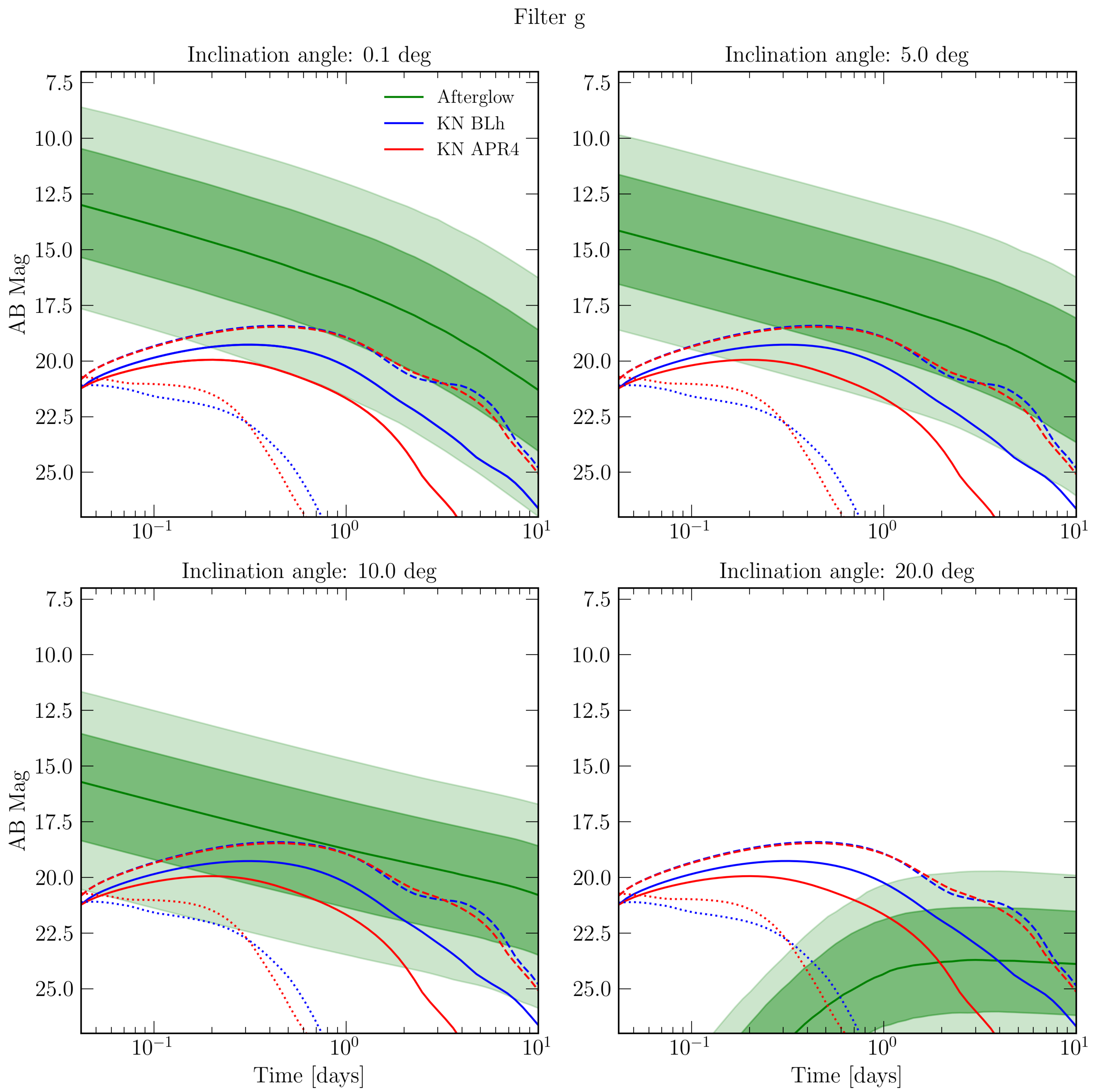


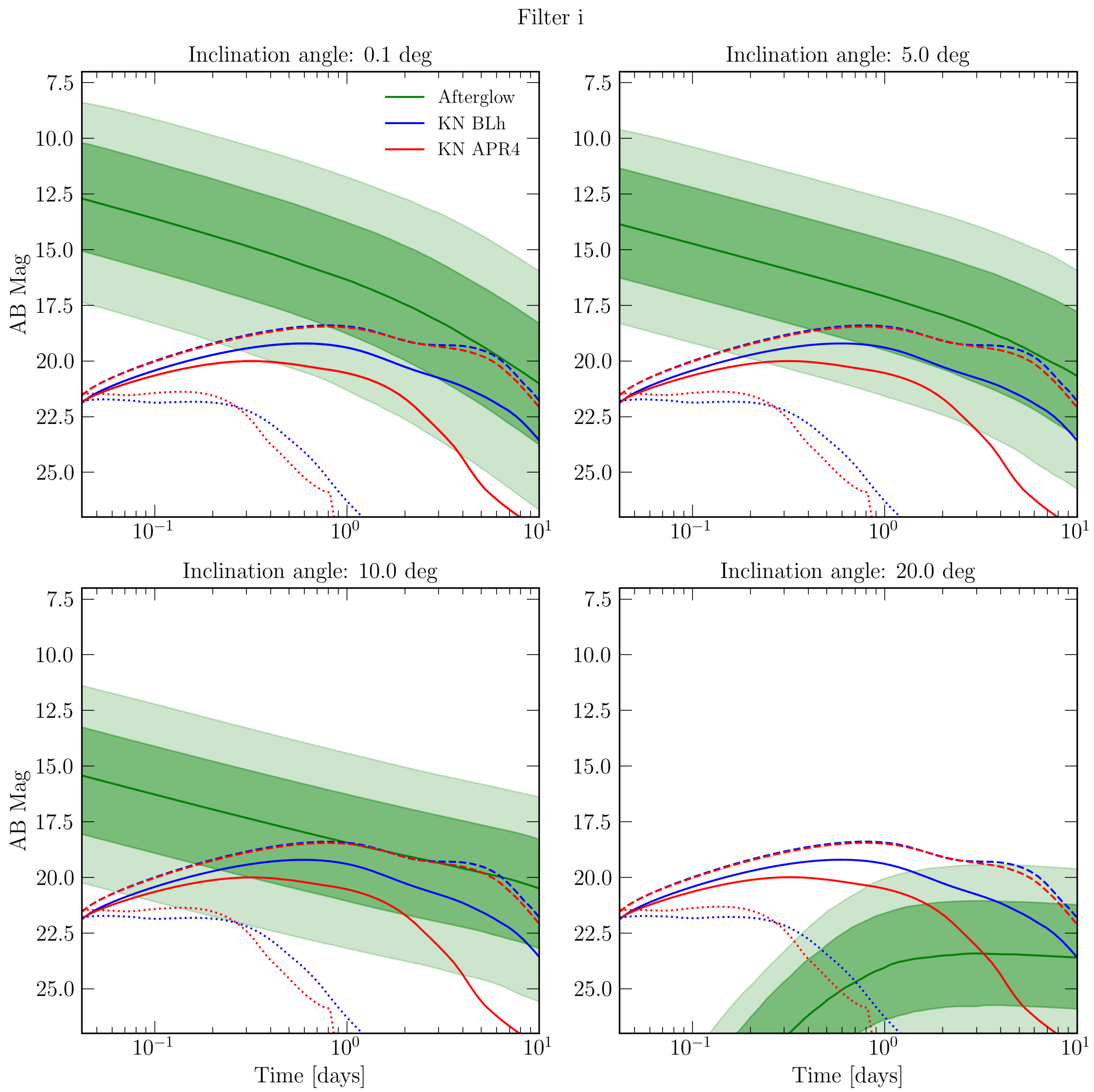
Loffredo et al., paper in prep.

KNe joint detection: a step forward

KNe and GRB afterglow

Loffredo et al., paper in prep.



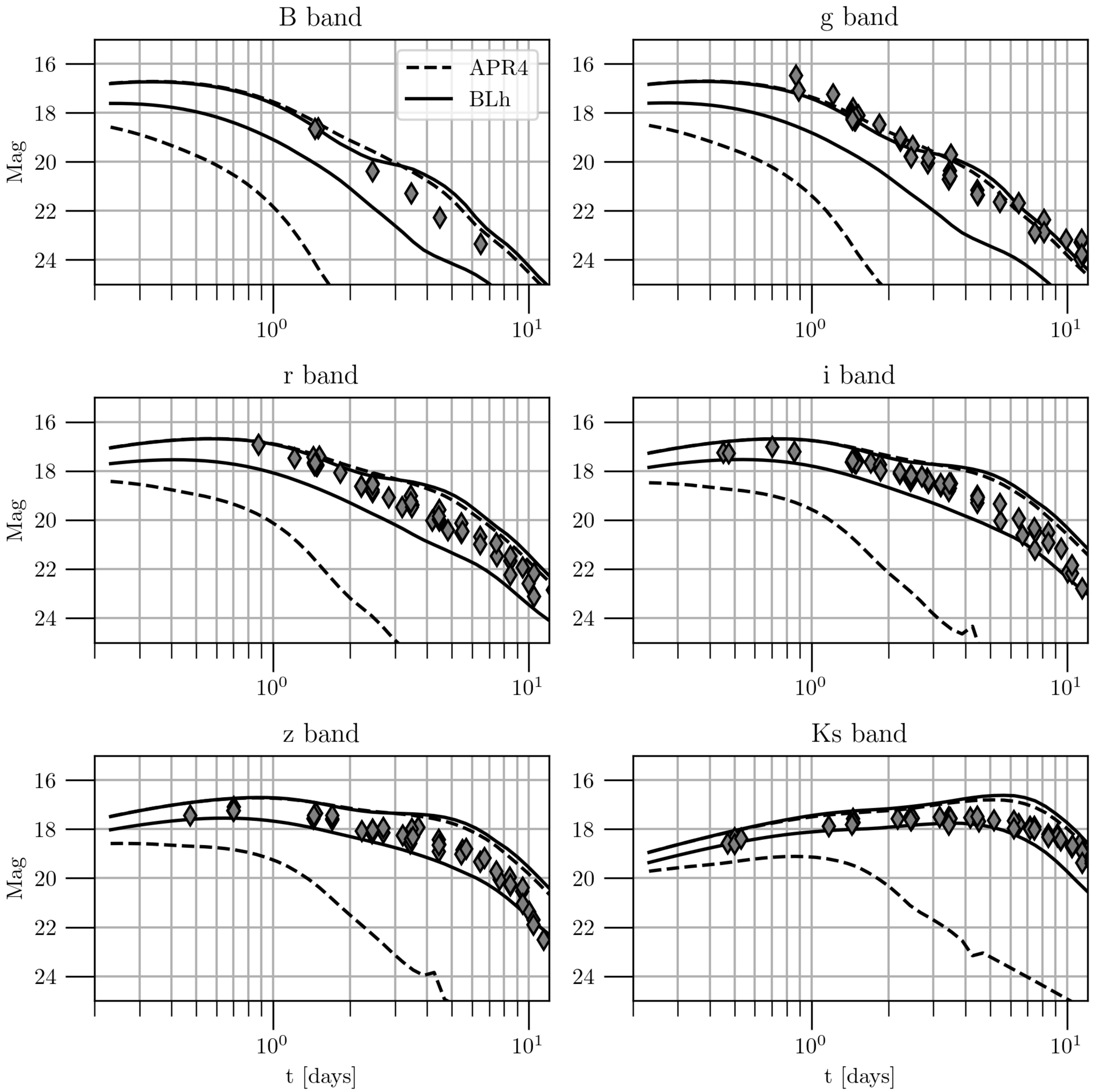


KNe joint detection: a step forward

Testing KN lightcurves

Test of modelling procedure on AT2017gfo data:

- Consider BNS population with Gaussian mass distr. and $\mathscr{R}_{\rm BNS} = 107\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Select binaries with $\mathscr{M}_c = 1.186 \pm 0.005$ and $q > 0.725$
- Compute KNe ligthcurves for APR4 and BLh and select brightest and faintest



Loffredo et al., paper in prep.

KNe joint detection: a step forward

Prompt collapse modelling

- Numerical relativity informed fit of prompt collapse mass threshold
- Reference papers: Perego et al. 22, Kashyap et al. 22
- Mass threshold depending on $K_{\max}$ and mass ratio
- Asymmetric binaries have smaller mass threshold

$$f(q) = \alpha(q)q + \beta(q) = \begin{cases} \alpha_l q + \beta_l & \text{if } q < \tilde{q}\,, \\ \alpha_h q + \beta_h & \text{if } q \geq \tilde{q}\,. \end{cases}$$