Perspectives for kilonovae multimessenger detection

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on behalf of
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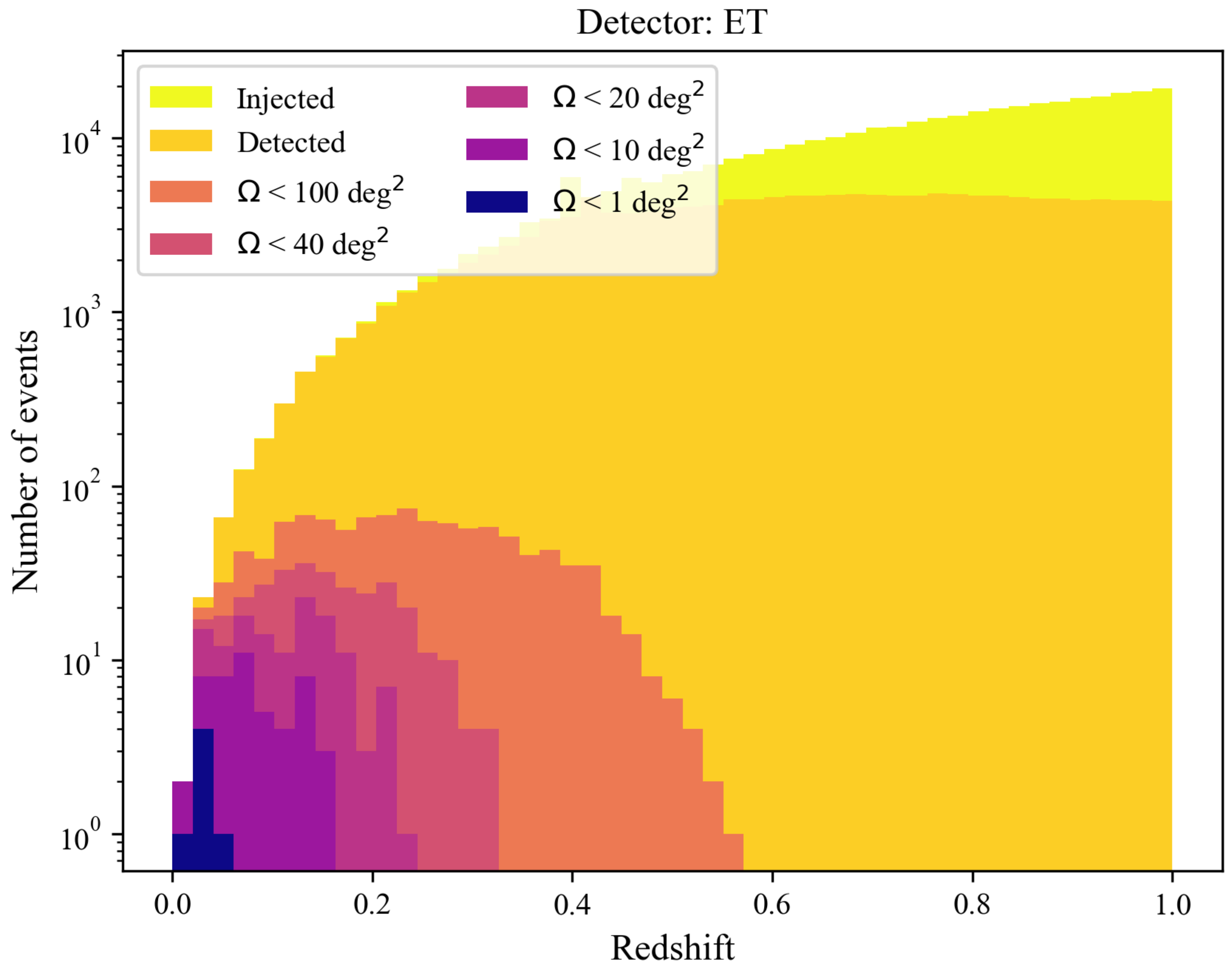
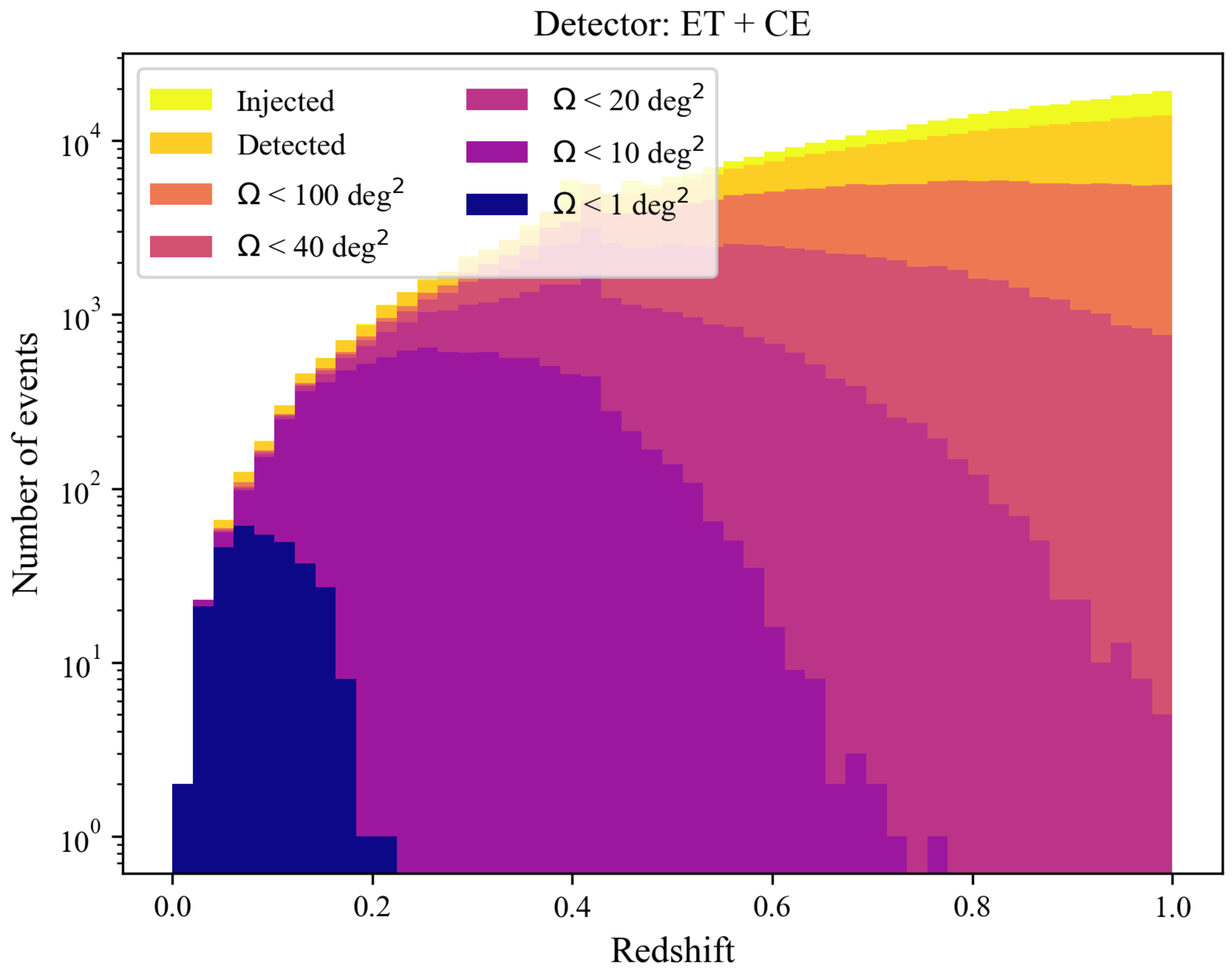
Prospects for kilonovae joint detection

- Kilonovae → UV/optical/IR signal, faint & rapidly evolving (one week)
- Sky-localisation from GW signals → key parameter for the follow-up with optical telescopes
- 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

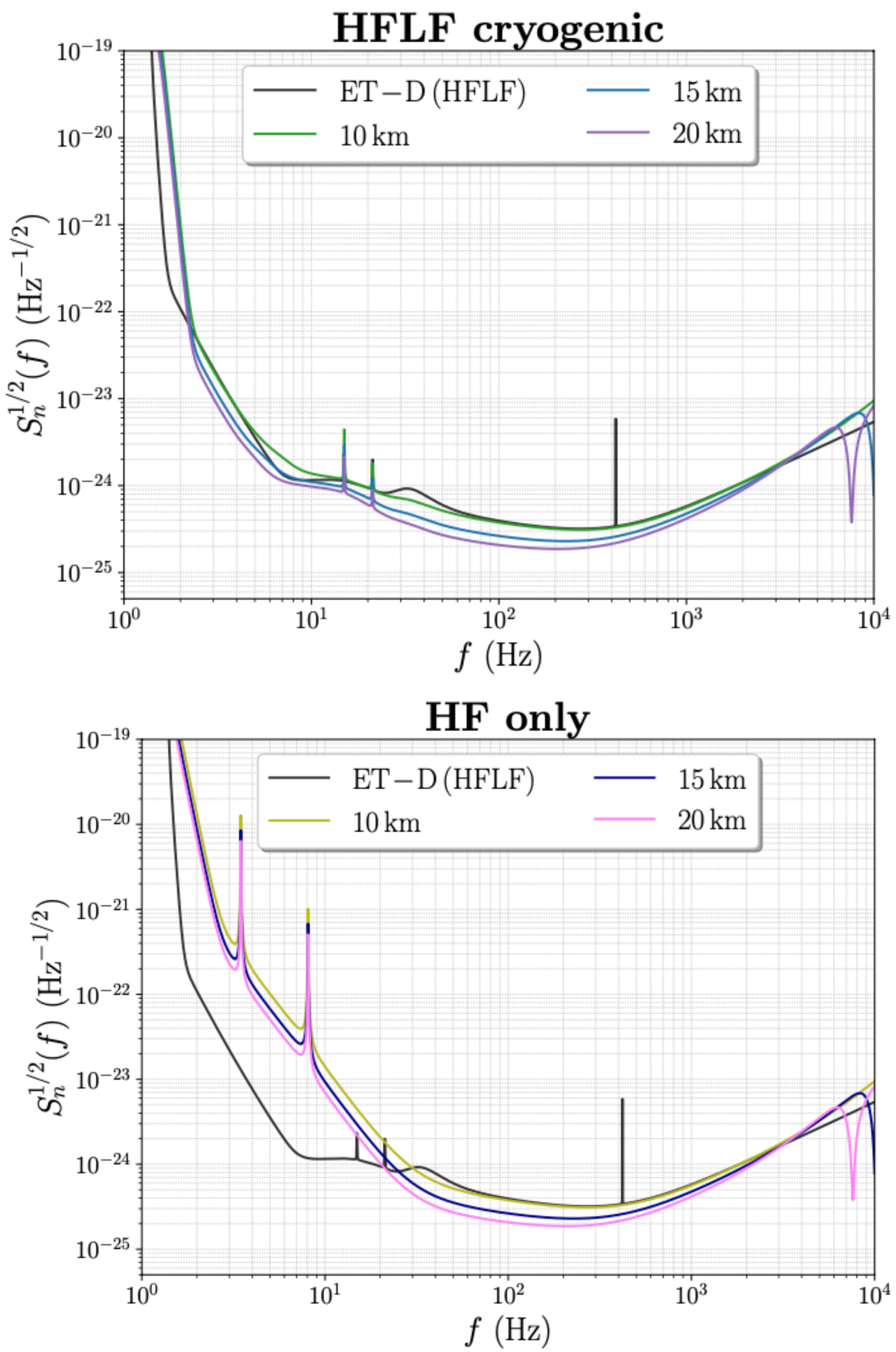




ET designs and configurations

- 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

Perspectives for kilonovae multimessenger detection

Our goals

Evaluating ET multi-messenger perspectives related to KN/GW detection by:

1. looking at different designs and configurations for ET
2. estimating joint detections for ET in synergy with Vera Rubin Observatory

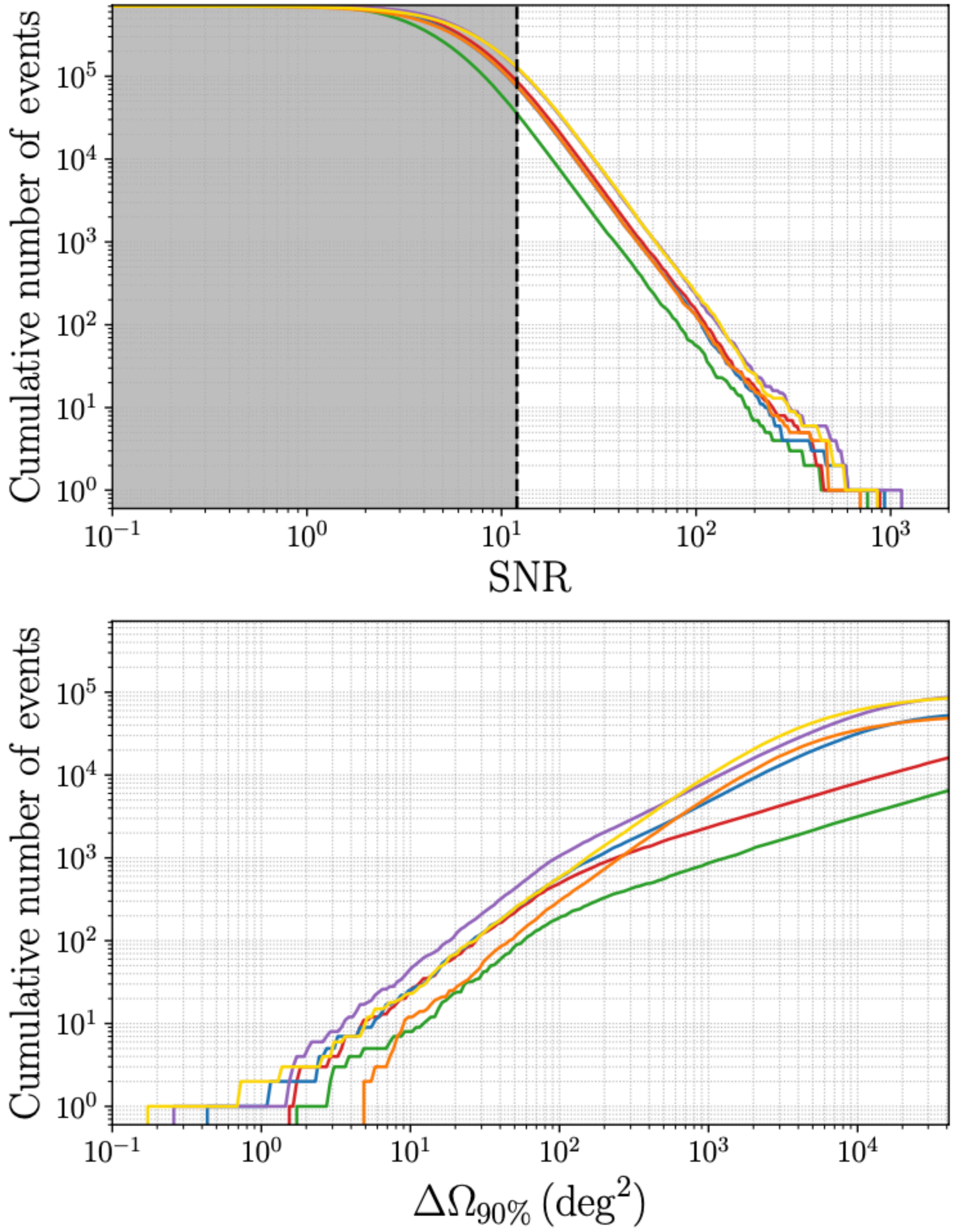
Assessing the impact of GWs and KNe joint detections:

1. on constraining the NS Equation of State
2. for cosmology studies.

Kilonovae: joint detection with ET and Vera Rubin

Method

- BNS mergers population from population synthesis code MOBSE, assuming Gaussian mass distribution and local merger rate 250 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ *(Mapelli et al. 17, Santoliquido et al. 21)*
- Consider ET in 2 possible shapes, different arm length, w/ or w/o cryogenic lasers
- Simulate mergers assuming waveform IMRPhenomD_NRTidalv2
- Number of detected mergers and estimate of source parameters performed with Fisher matrices using GWFish code *(Dupletsa et al. 23)*



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

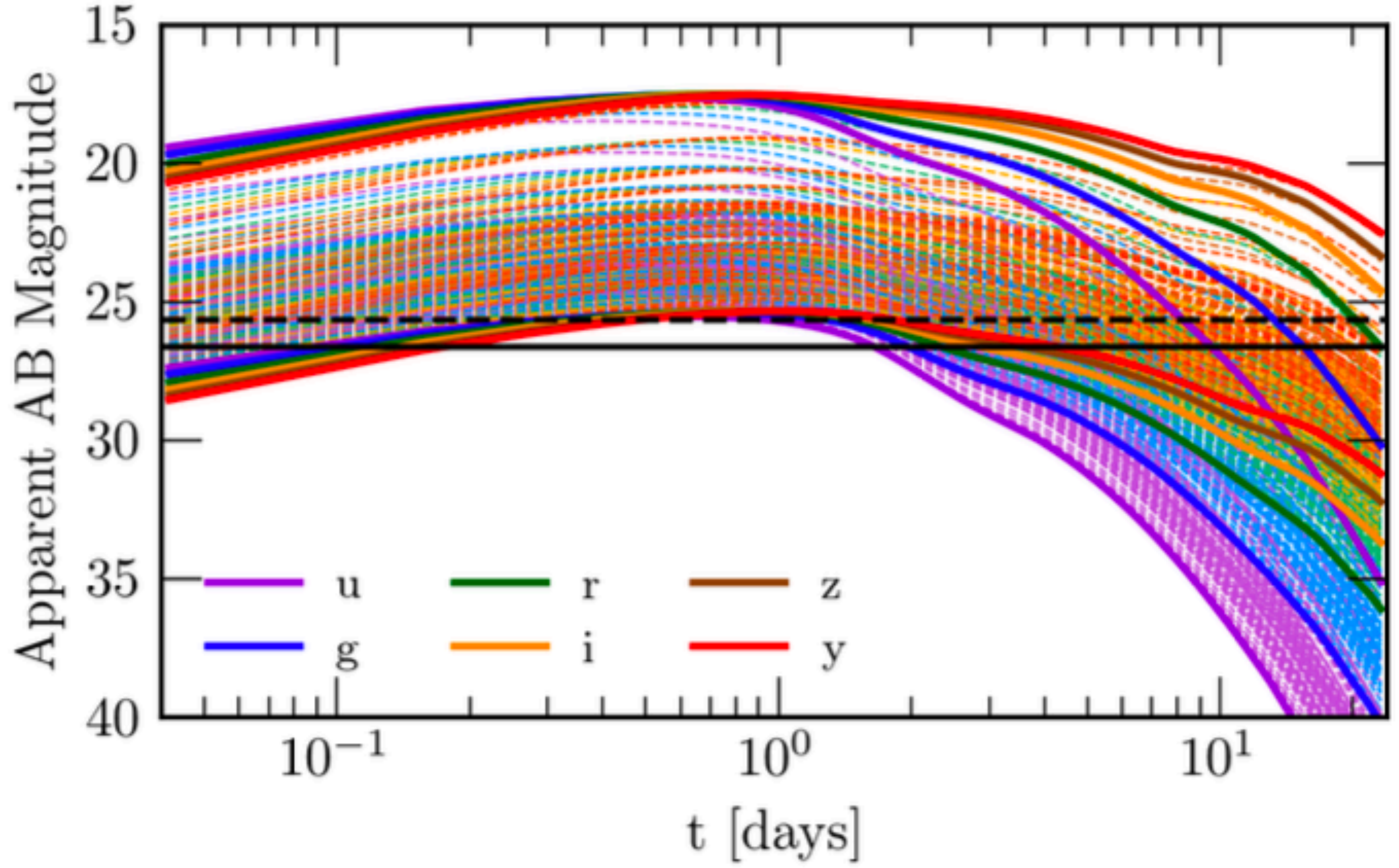
Kilonovae: joint detection with ET and Vera Rubin

Method

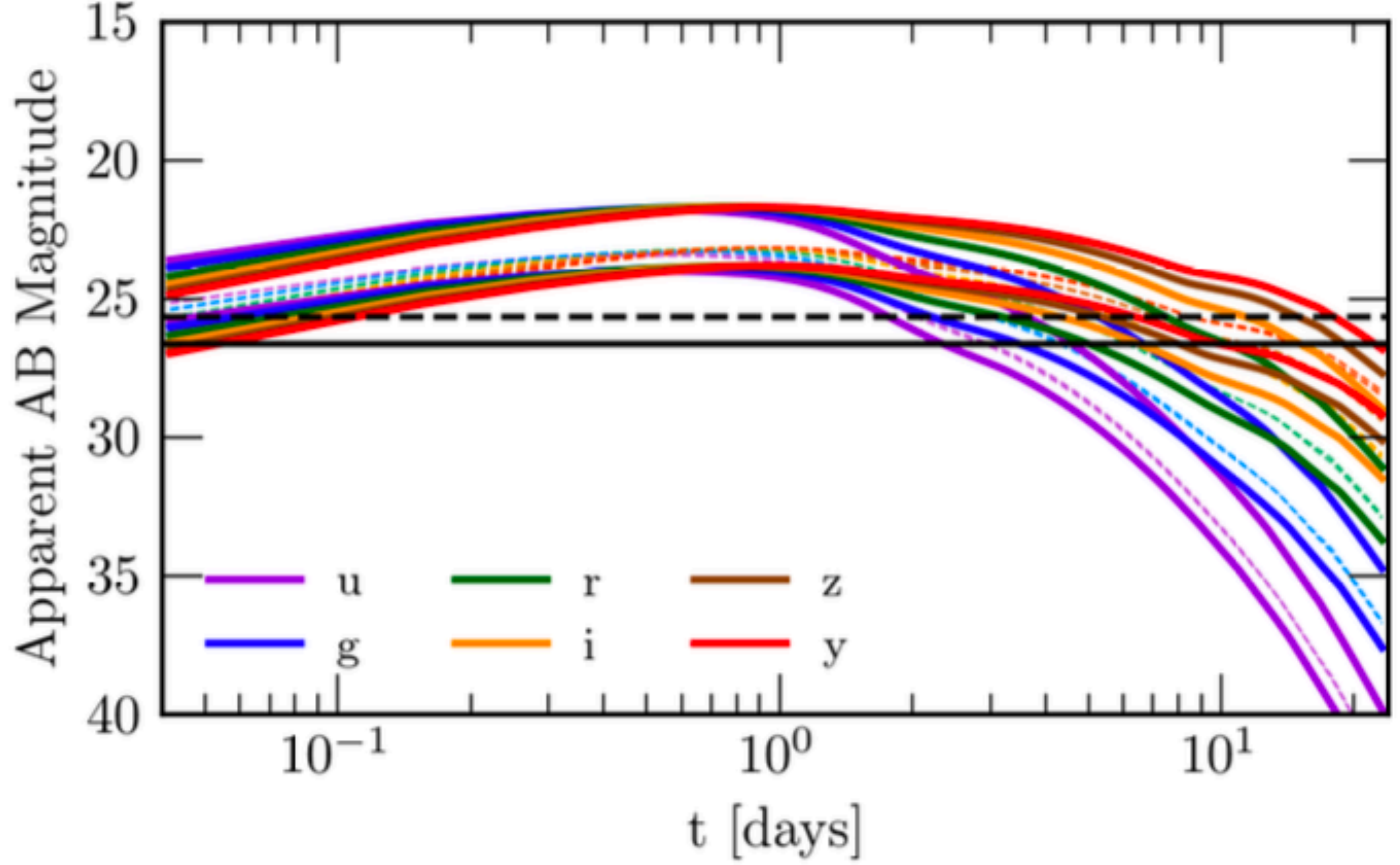
- KN lightcurves → AT2017gfo-like, semi-analitic model, anisotropic 3-component ejecta *(Perego et al. 17)*
- Consider viewing angle and cosmological K-correction
- Follow-up with Vera Rubin of events localised better than 20, 40 and 100 deg^2, filters g and i, pointing 600s or 1800s first and second night

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

ET Δ 10 km HFLF



ET Δ 10 km HF



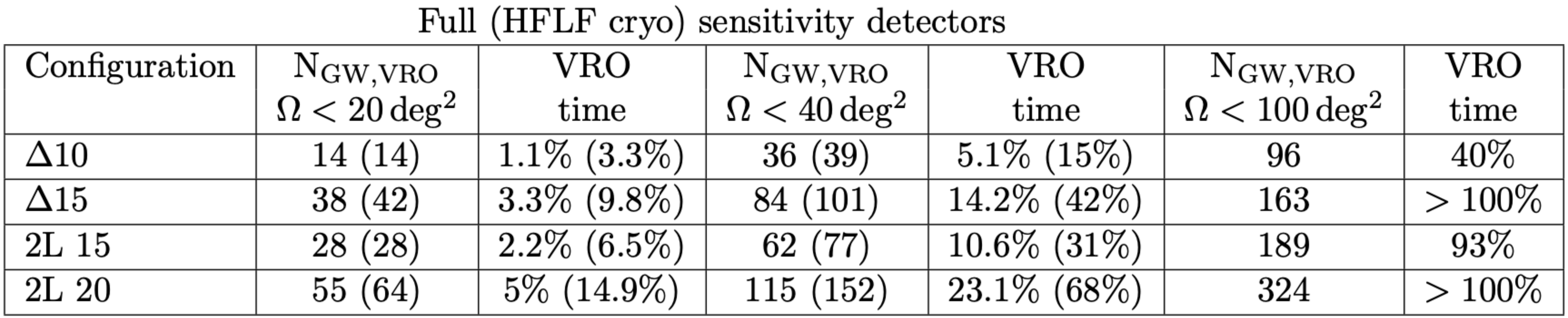
Optimal ET configuration for KNe joint detection

Results

- 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

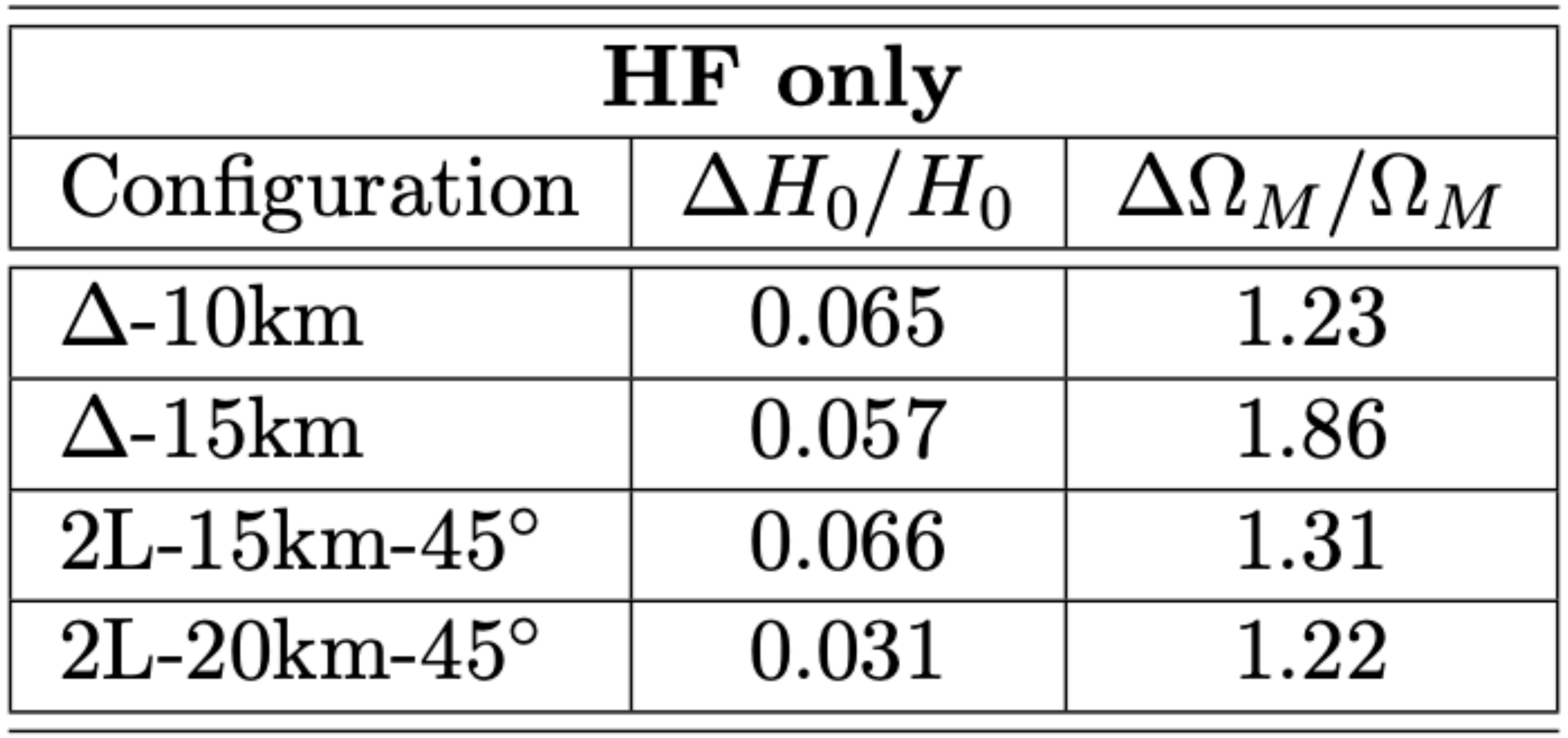
Configuration	$N_{\mathrm{GW,VRO}}$ $\Omega < 20\,\mathrm{deg}^2$	VRO time	$N_{\mathrm{GW,VRO}}$ $\Omega < 40\,\mathrm{deg}^2$	VRO time	$N_{\mathrm{GW,VRO}}$ $\Omega < 100\,\mathrm{deg}^2$	VRO time
Δ10	14 (14)	1.1% (3.3%)	36 (39)	5.1% (15%)	96	40%
Δ15	38 (42)	3.3% (9.8%)	84 (101)	14.2% (42%)	163	> 100%
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 et al., 2023*

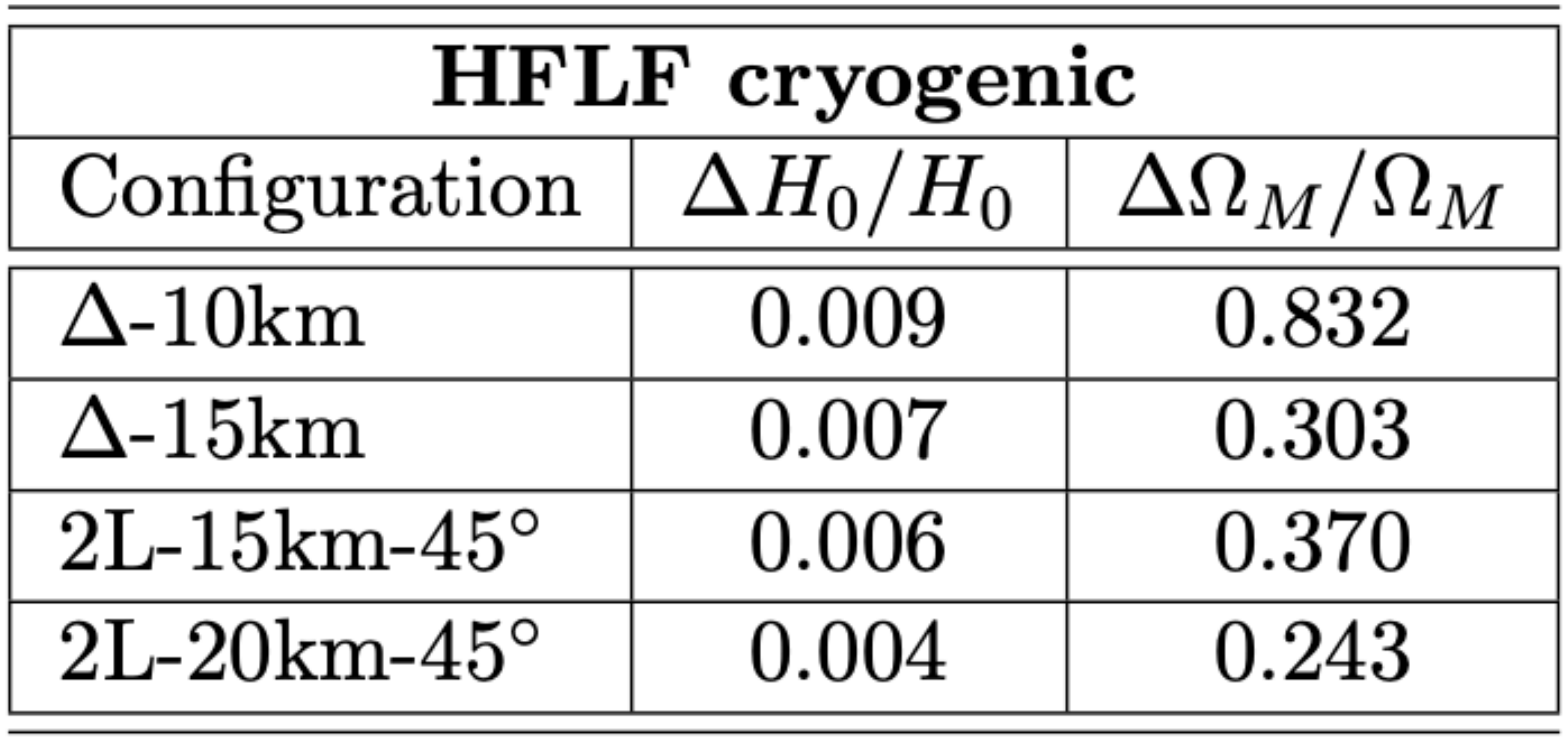
Estimate of H_0 with ET and Vera Rubin

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



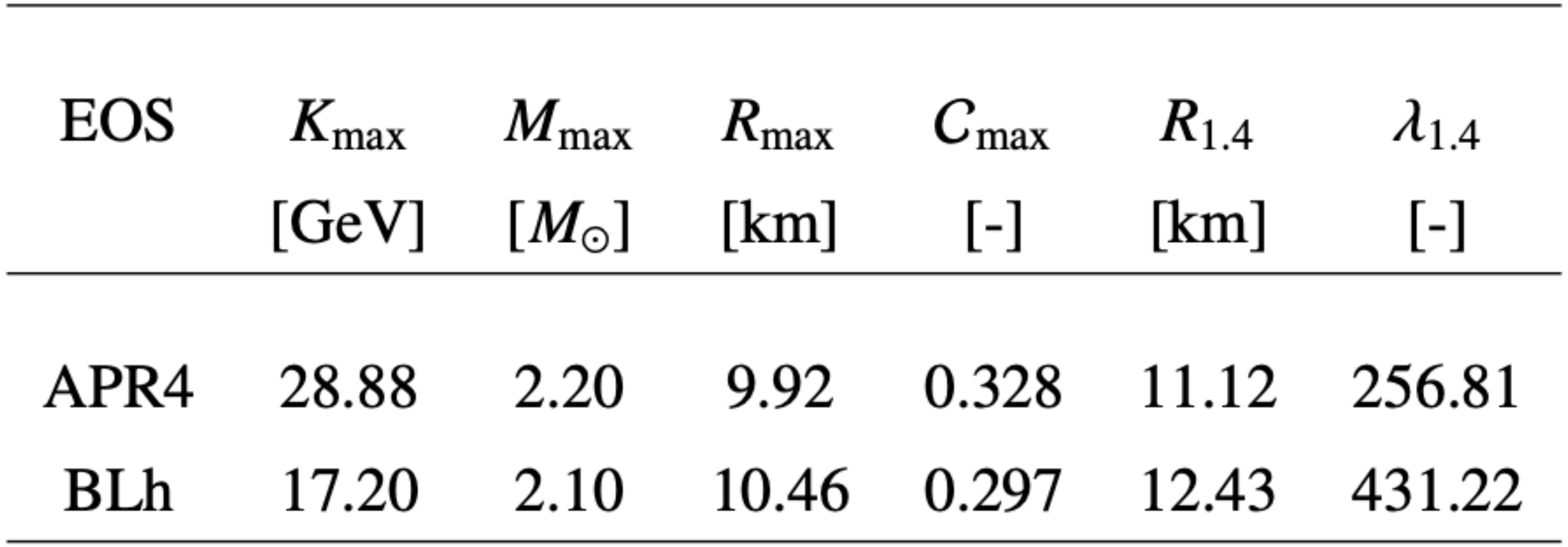
HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

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

KNe joint detection: a step forward

BNS population

- BNS merger rate? 2 populations with local merger rate $\mathscr{R}_{\mathrm{BNS}} = [23,\ 107]\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ *(Iorio et al. 23)*
- NS mass distribution? Extreme cases: Gaussian and Uniform
- NS Equation of State? Explore 2 cases: APR4 and BLh



EOS	K_{max} [GeV]	M_{max} [$M_{\odot}$]	R_{max} [km]	C_{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

Loffredo et al., paper in prep.

KNe joint detection: a step forward

KN ejecta modelling

- Given masses and EOS of each BNS → mass and velocity of dynamical ejecta and disc mass from 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)*

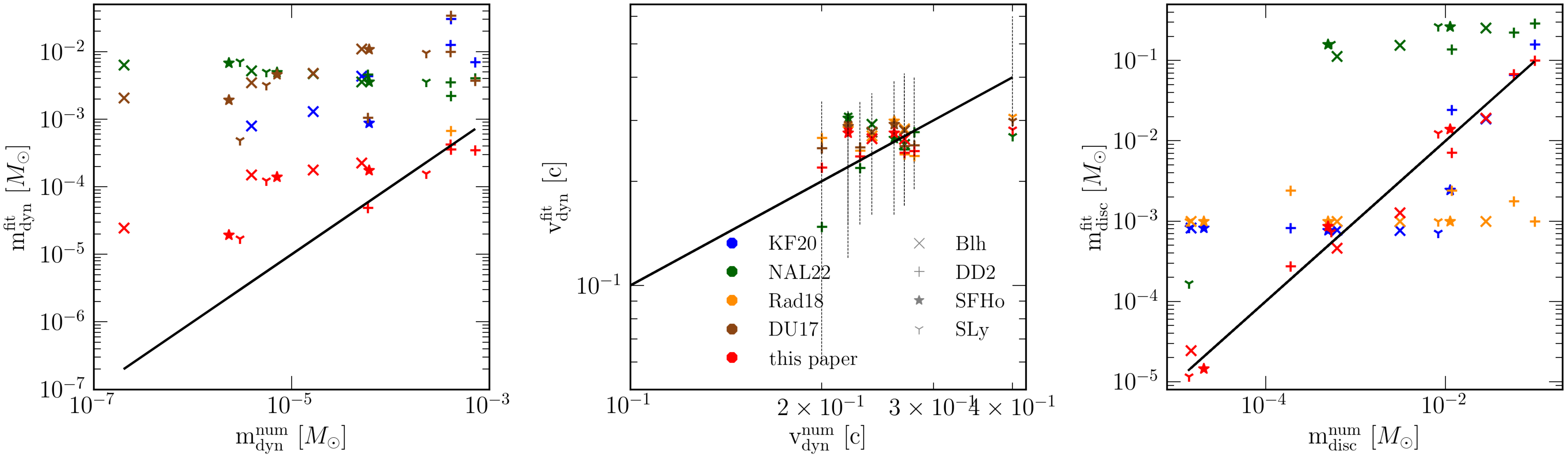
$$m_{\mathrm{dyn},190425} = a\tilde{\Lambda}(q^{-1} - b)e^{c/q}$$

$$v_{\mathrm{dyn},190425} = \left[a\frac{M_1}{M_2}(1 + c\,\mathscr{C}_1)\right] + (1 \leftrightarrow 2) + b$$

$$\log_{10}\left(m_{\mathrm{disc},190425}\right) = \min\left(-1,\ a + bq + c\tilde{\Lambda}q^2\right)$$

KNe joint detection: a step forward

KN ejecta modelling



Loffredo et al., paper in prep.

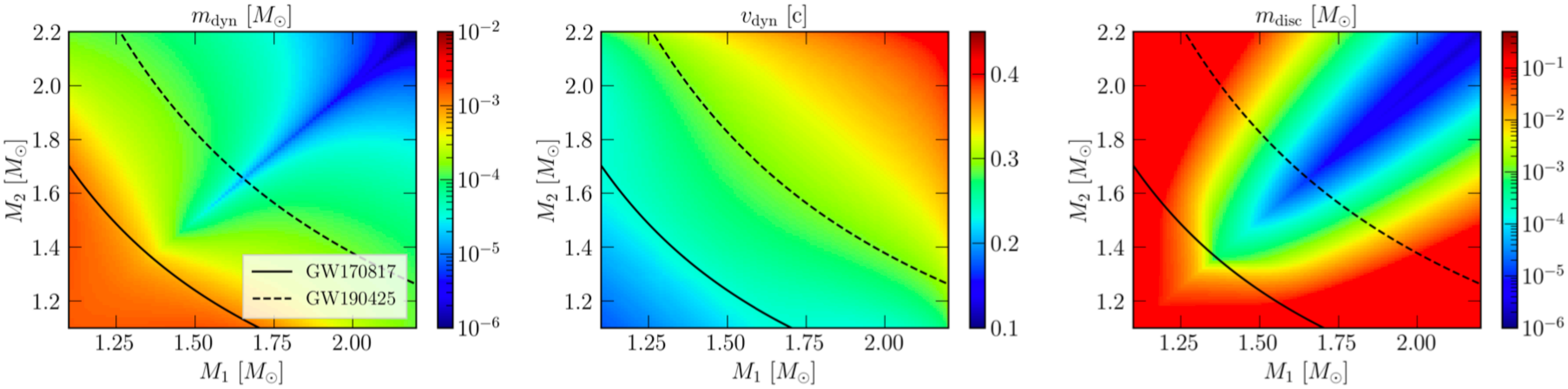
KNe joint detection: a step forward

KN ejecta modelling

- Take into account prompt collapse → mass threshold from NR informed fits, it depends 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



Loffredo et al., paper in prep.

KNe joint detection: a step forward

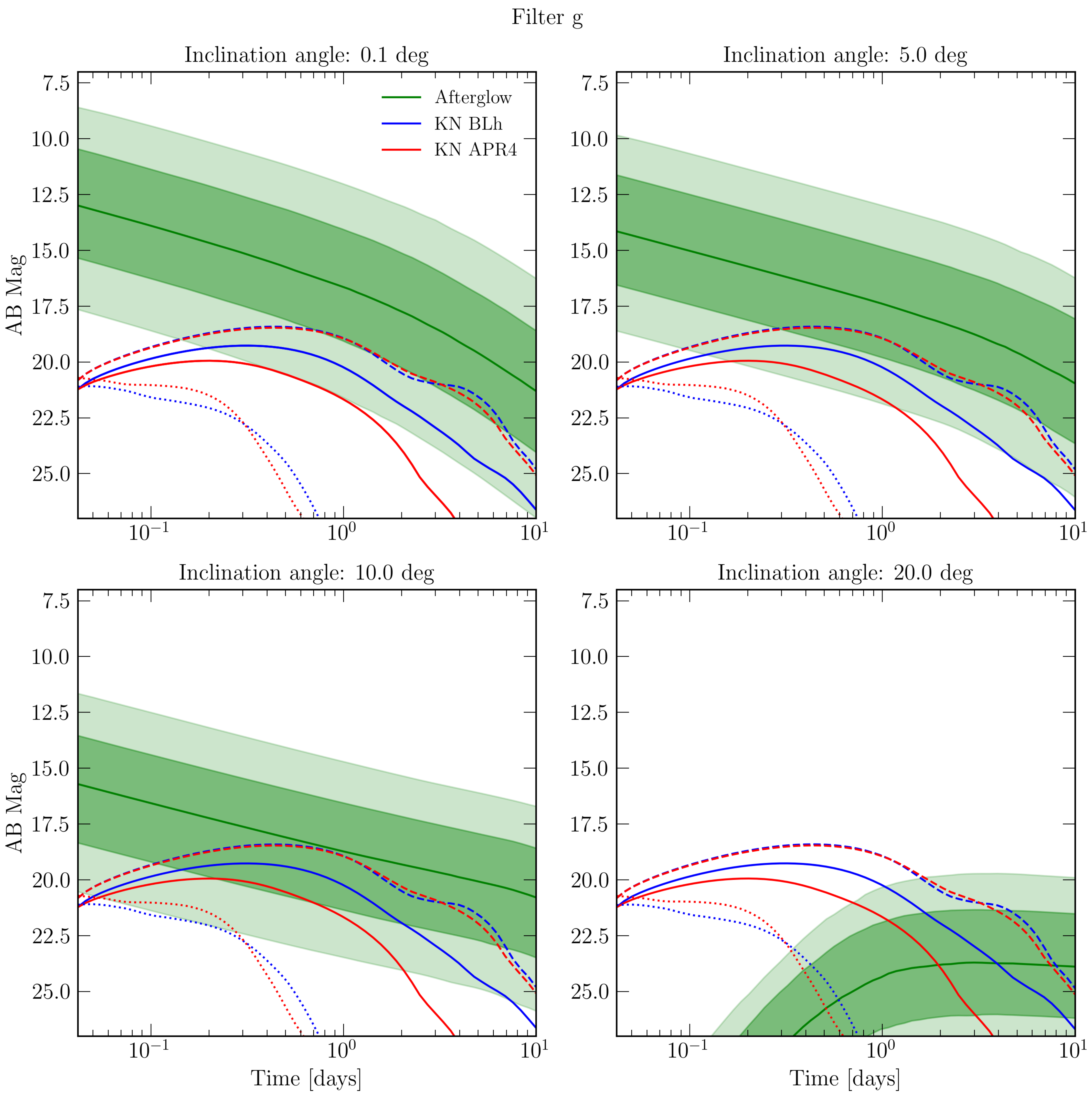
KN lightcurves

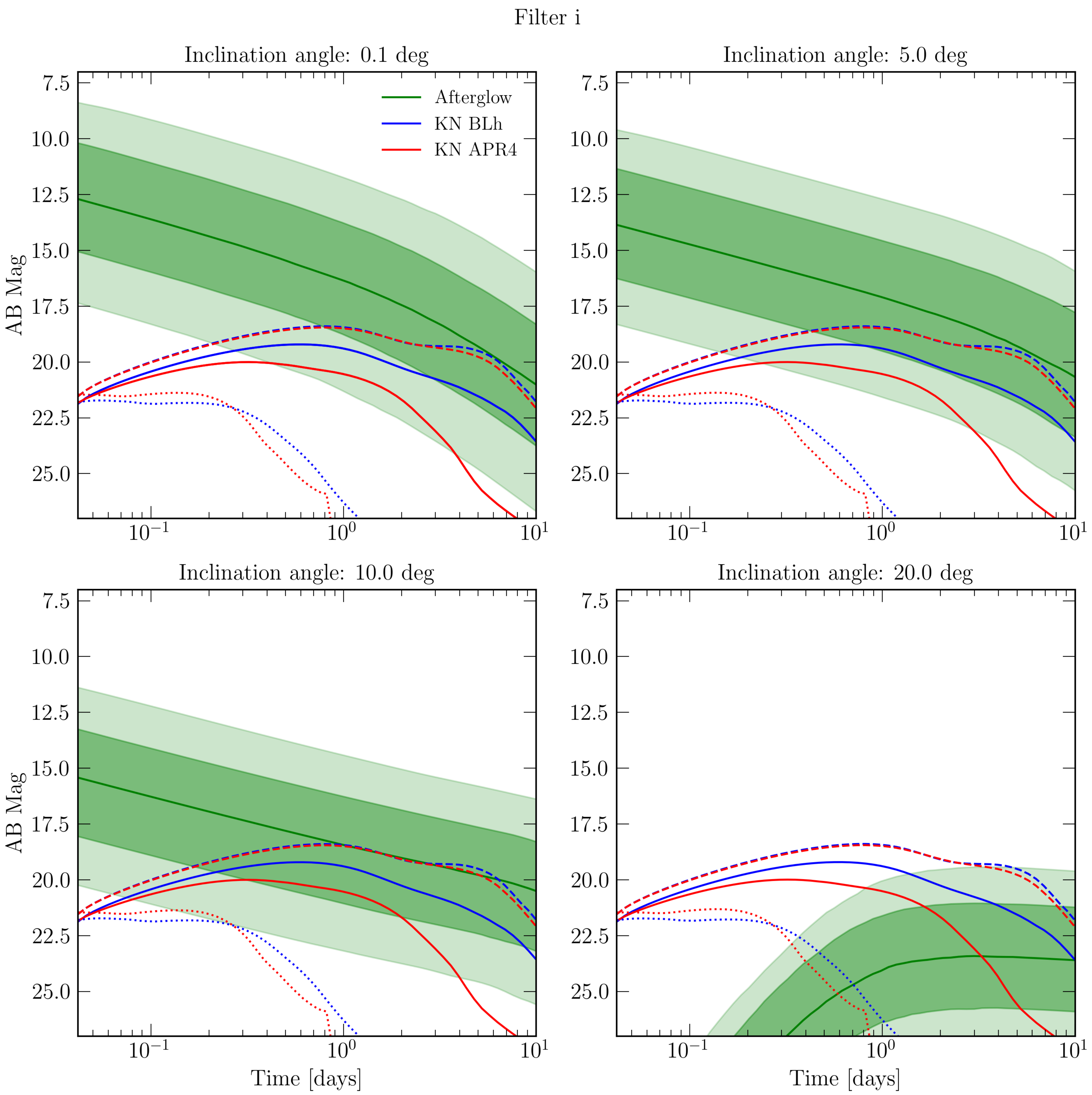
- Ejecta + luminosity distance, redshift and inclination angle of each BNS → KN lightcurves
- Modelling of KN lightcurves with xkn framework (derived from radiative transfer equation, with optically thin correction included) *(Ricigliano et al. 23, Wollaeger et al. 18)*
- Consider optical afterglow from 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) operating with Vera Rubin Observatory
- 64 simulations for 10 years of BNS merger

KNe joint detection: a step forward

KNe and GRB afterglow

Loffredo et al., paper in prep.





KNe joint detection: a step forward

Results and Outlook

- GW detection enhanced for uniform mass distribution (larger chirp mass) and APR4 EOS (smaller tidal deformability → longer inspiral)
- However, GW+EM detection enhanced for BLh EOS (more massive ejecta and larger prompt-collapse mass threshold → brighter KNe)
- Which is the optimal strategy for Vera Rubin TO? Up to which redshift can we detect KNe?
- Can we constrain NS EOS with KNe joint detections?
- Implications for cosmology?

KNe joint detection: a step forward

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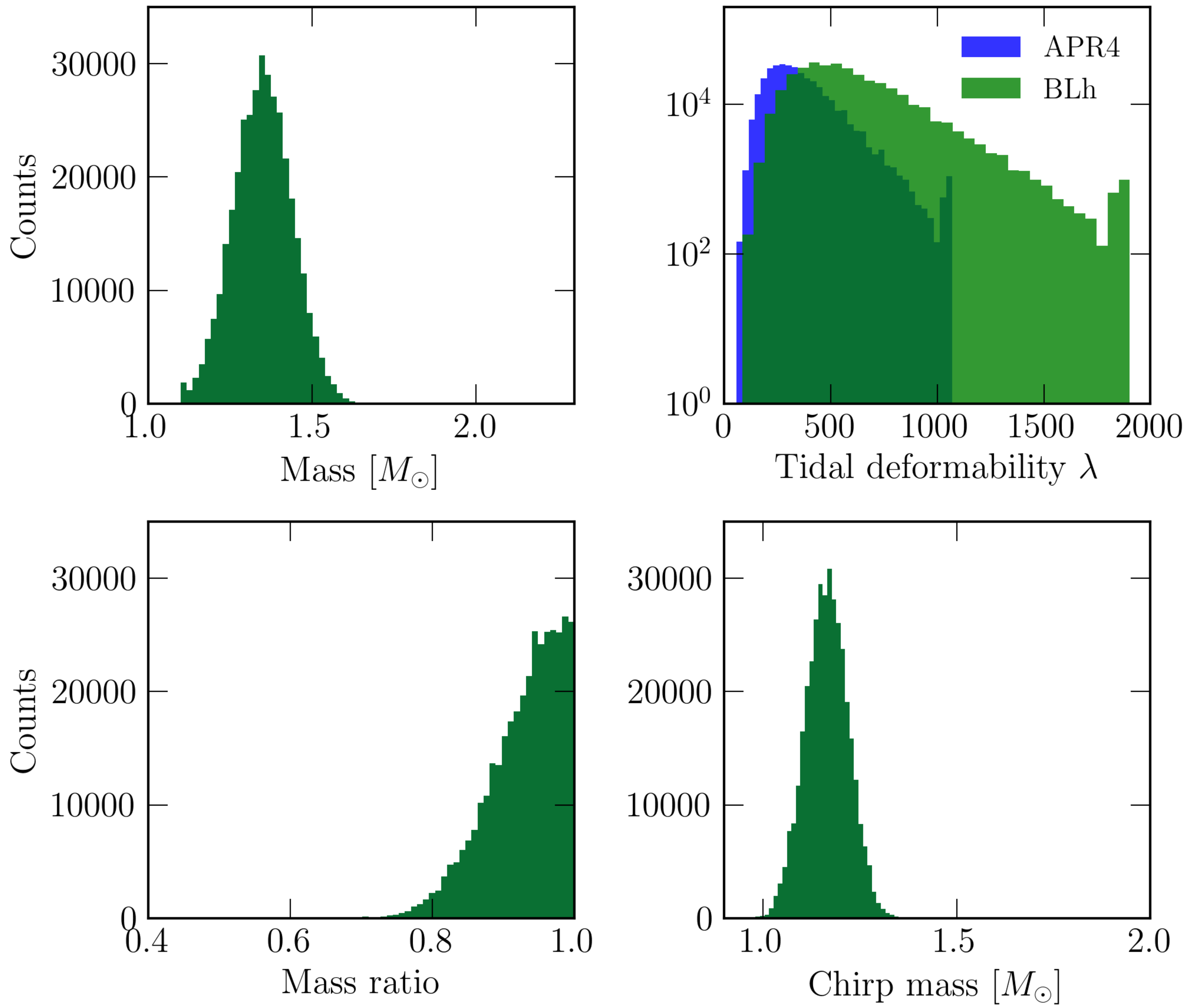
Thank you for you kind attention!

Appendix

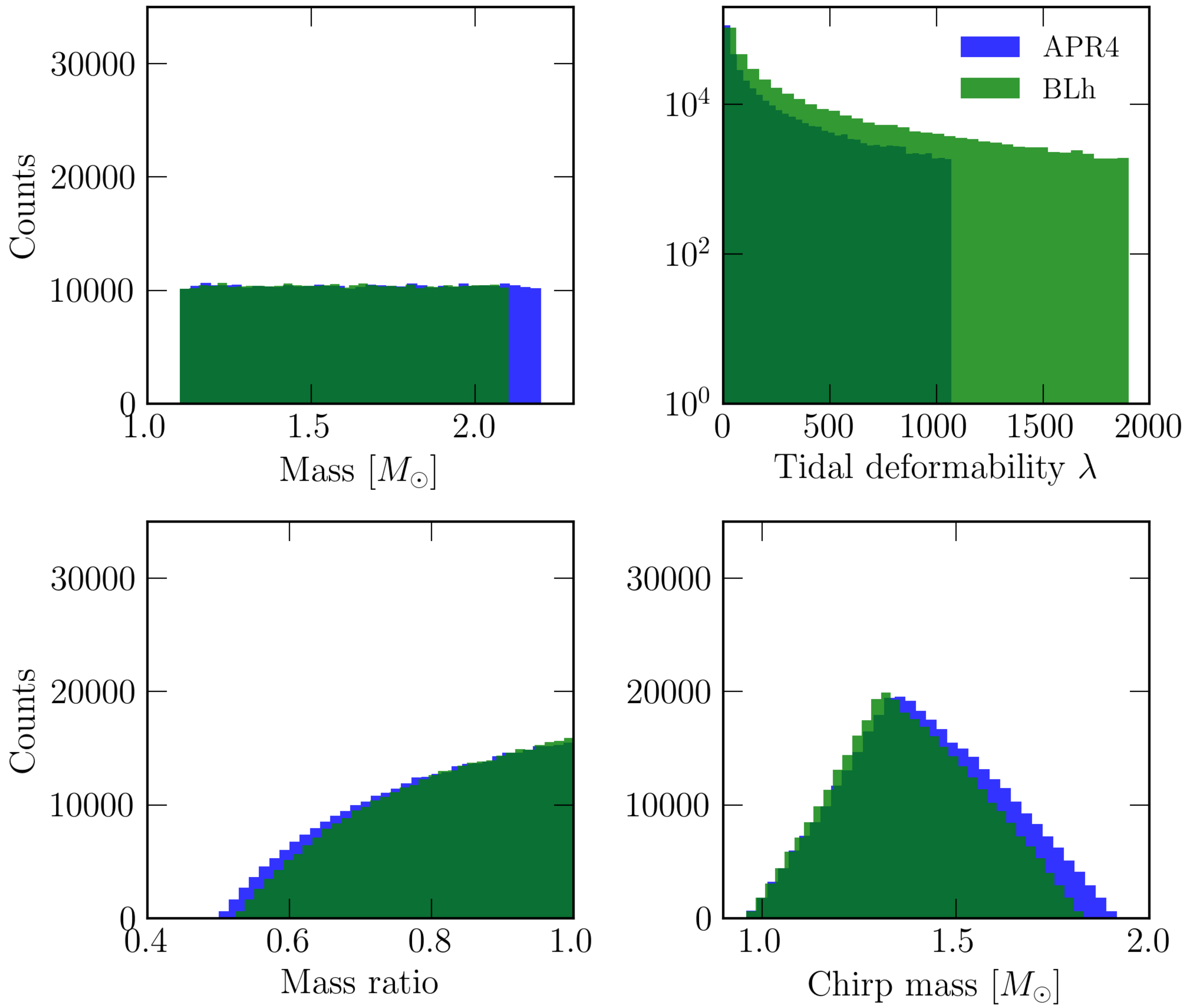
KNe joint detection: a step forward

BNS population

Gaussian



Uniform



Loffredo et al., paper in prep.

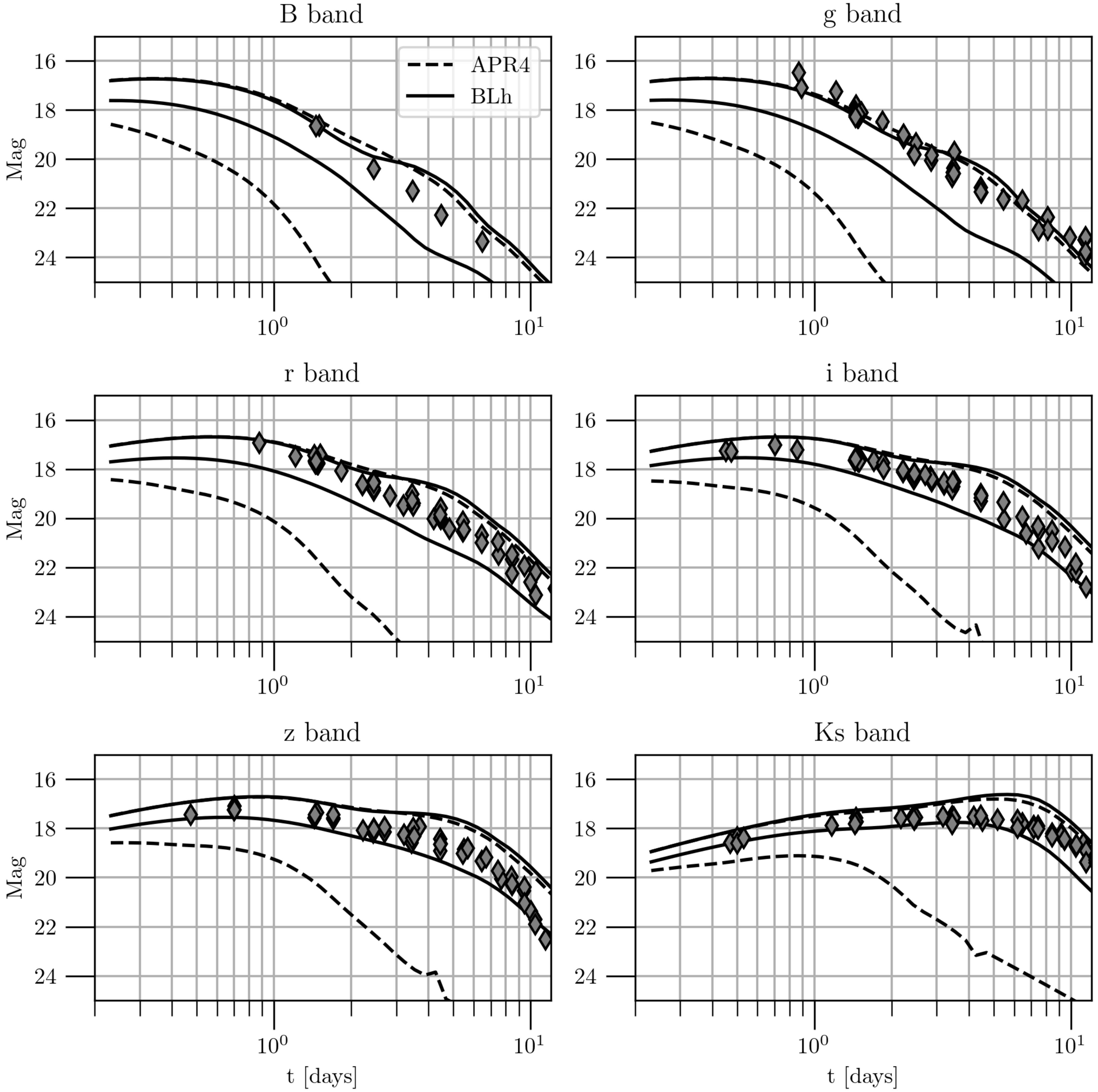
KNe joint detection: a step forward

Testing KN lightcurves

Test of modelling procedure on AT2017gfo data:

- Consider BNS population with Gaussian mass distr. and $\mathscr{R}_{\text{BNS}} = 107\ \text{Gpc}^{-3}\ \text{yr}^{-1}$
- 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

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