Prospects for kilonovae detections with next-generation multimessenger observatories

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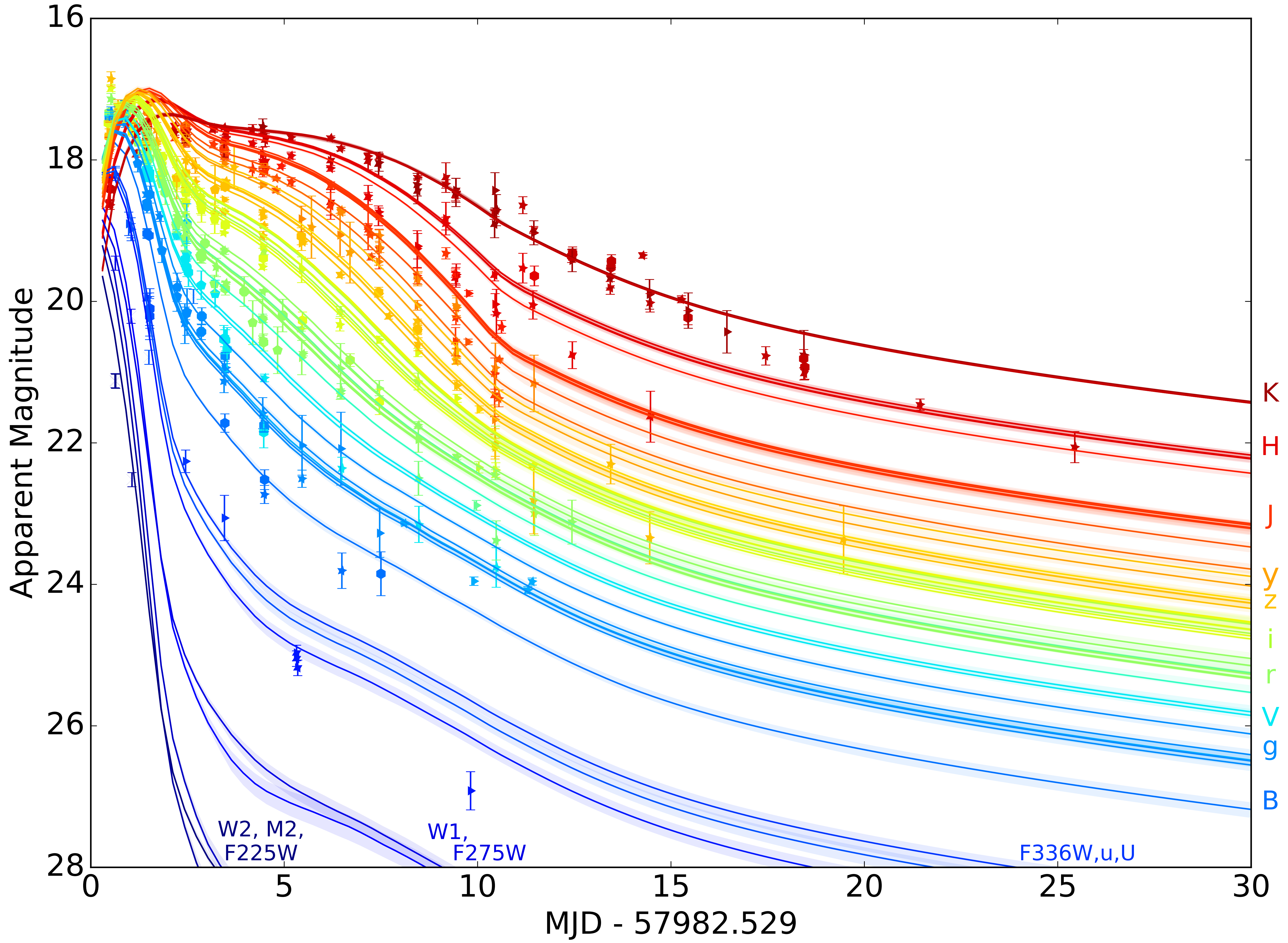
The detection of AT2017gfo

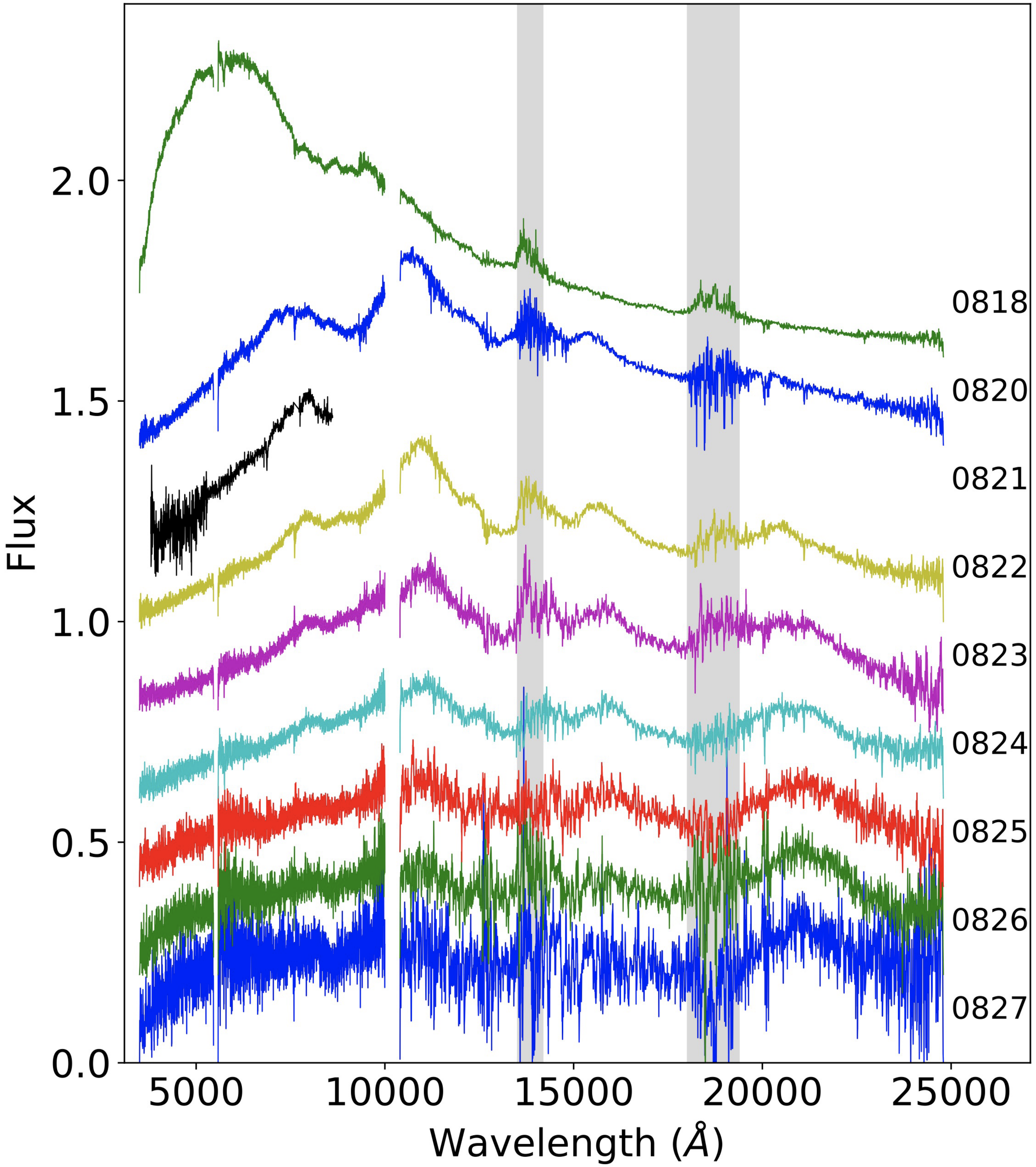
- AT2017gfo → kilonova (KN) associated with GW170817
- Quasi-thermal EM emission powered by nuclear decay of freshly synthesised heavy elements
- UV/optical/IR signal, faint and rapidly evolving (1 week), distinct colour evolution
- KN physics crucial to understand the origin of heavy elements in the Universe



Credits: Villar et al., APJL, 2017

The detection of AT2017gfo

- Precise sky-localisation ≃ 28 deg^2 → effective and prompt follow-up with optical/NIR telescopes
- Small lum. distance ≃ 40 Mpc → galaxy targeting strategy and candidate identification
- Deep multi-wavelength photometry and spectroscopy →characterisation of KN candidate
- Theoretical predictions on colour evolution, timescale, luminosity → crucial to recognise KN signature
  [Li & Paczyński 1998; Kulkarni 2005; Metzger + 2010; Kasen + 2013; Barnes & Kasen 2013; Grossman + 2014]



Credits: Pian et al., Nature, 2017

Prospects for GW/KN joint detections

- Current and next runs of LVKI → expected detection of a few up to several tens of BNS mergers
  [Abbott + 2020, 2023; Colombo + 2022]

- Einstein Telescope (ET) and Cosmic Explorer (CE) → 10^5 BNS mergers per year up to $z \simeq 5 - 10$, large number of events with much better parameter estimation
  [Maggiore + 2020; Evans + 2021; Branchesi + 2023]

- Next-generation optical and NIR telescopes as Vera Rubin → enhance chances of KN detection and characterisation

1 - ET optimal configurations for GW/KN detections?

2 - Prospects for GW/KN detections considering present uncertainties in BNS merger rate, NS mass distribution and EOS?

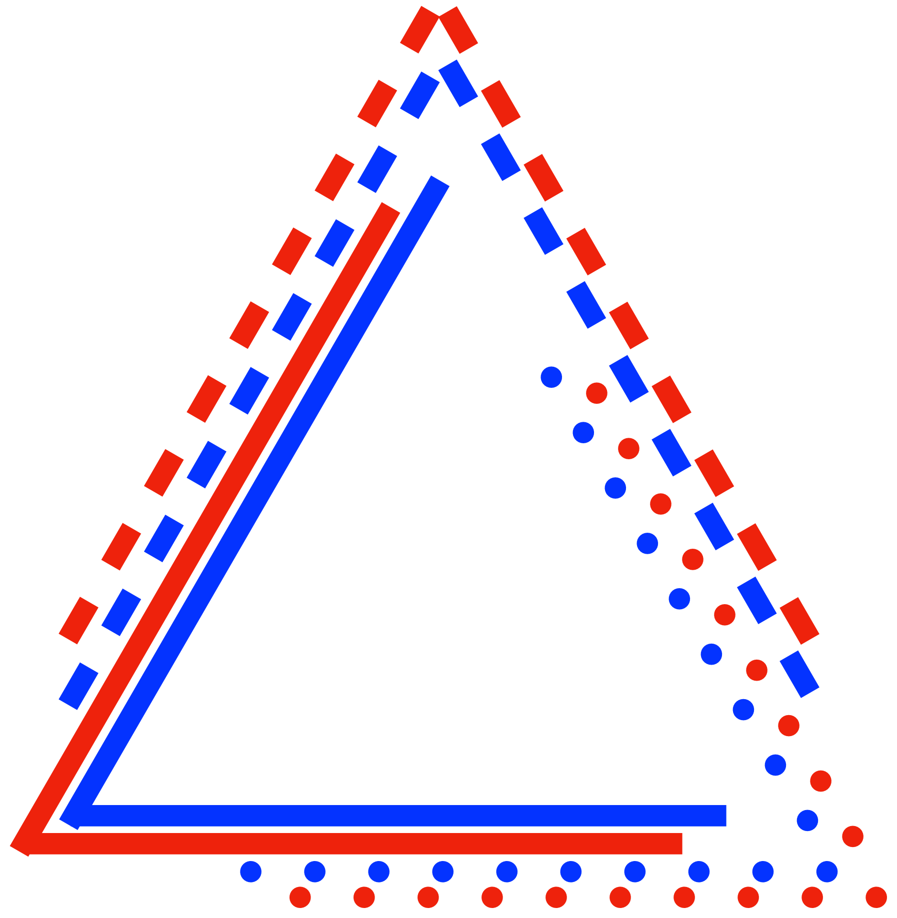
The Vera Rubin Observatory

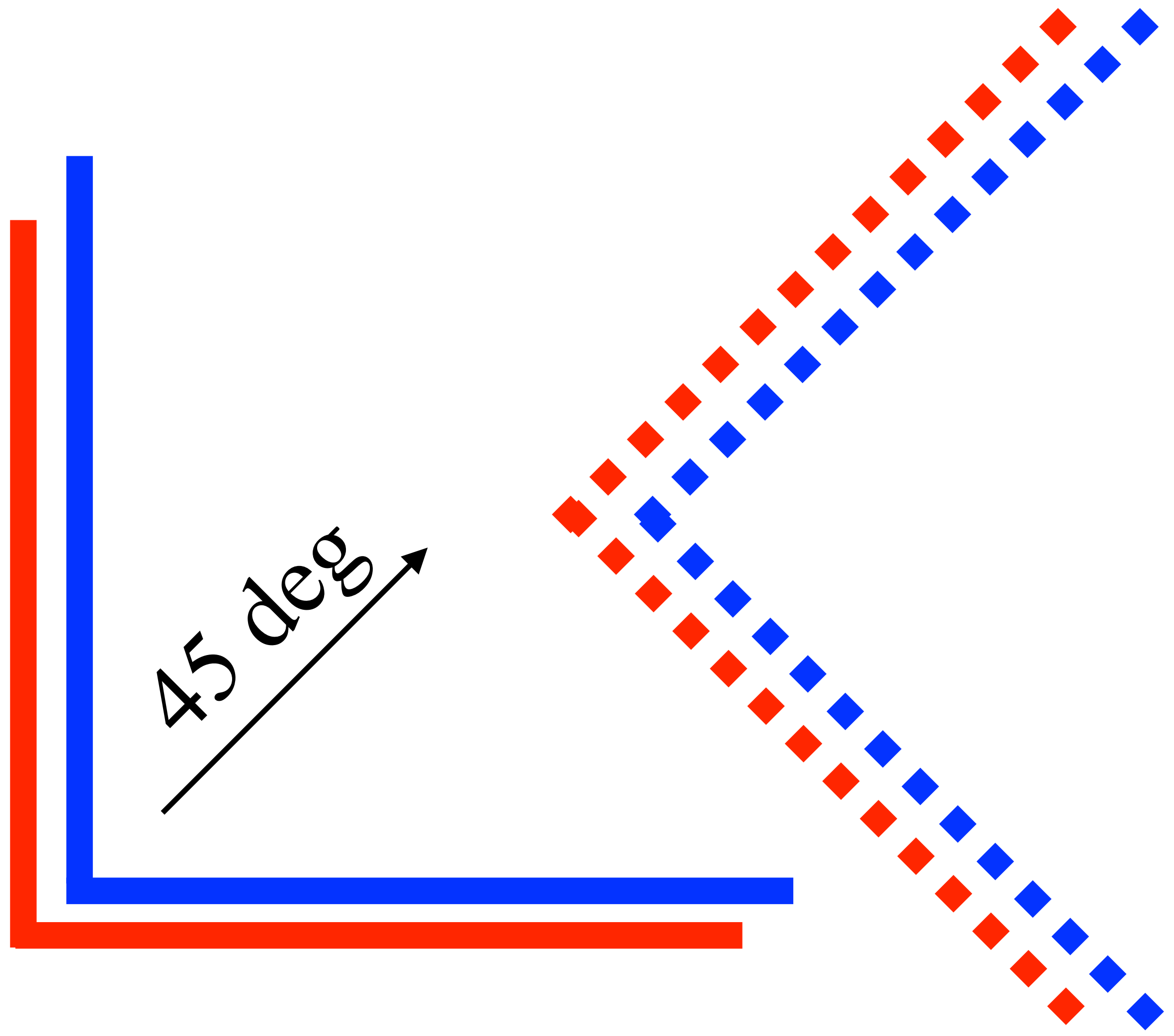
- Next-generation ground-based telescope under construction in Chile (Cerro Pachón)
  [Ivezić + 2019]
- Optimised for UV/optical/NIR frequencies
- Wide field of view of 9.6 sq. degrees (40 times the Moon’s area)
- Extremely fast slewing time

The Einstein Telescope

- Next-generation GW detector, triangular-shaped, underground
- Reference design → triangular-shaped, 10 km arms, xylophone configuration with high-frequency and low-frequency lasers (HFLF)
- 2L vs Δ and HFLF vs HF (high-frequency) only
- Recent broad study (180 pages) to evaluate the science case under variations of the reference design

  [Branchesi et al. JCAP 2023]





The entire methodology

STEP 1

Population of isolated BNS mergers

COSMORATE

MOBSE

↓

Properties of each BNS (masses, redshift, sky-position, inclination, …)

STEP 2

Assign waveform approximant to each merger & perform parameter estimation for each GW detector

GWFISH

↓

Number of detected mergers, source parameters, and errors (e.g. sky-loc.)

STEP 3

Modelling of KN emission: AT2017gfo-like events

↓

KN light curve for each detected merger

STEP 4

Follow-up strategy with Rubin of events within a certain sky-localisation

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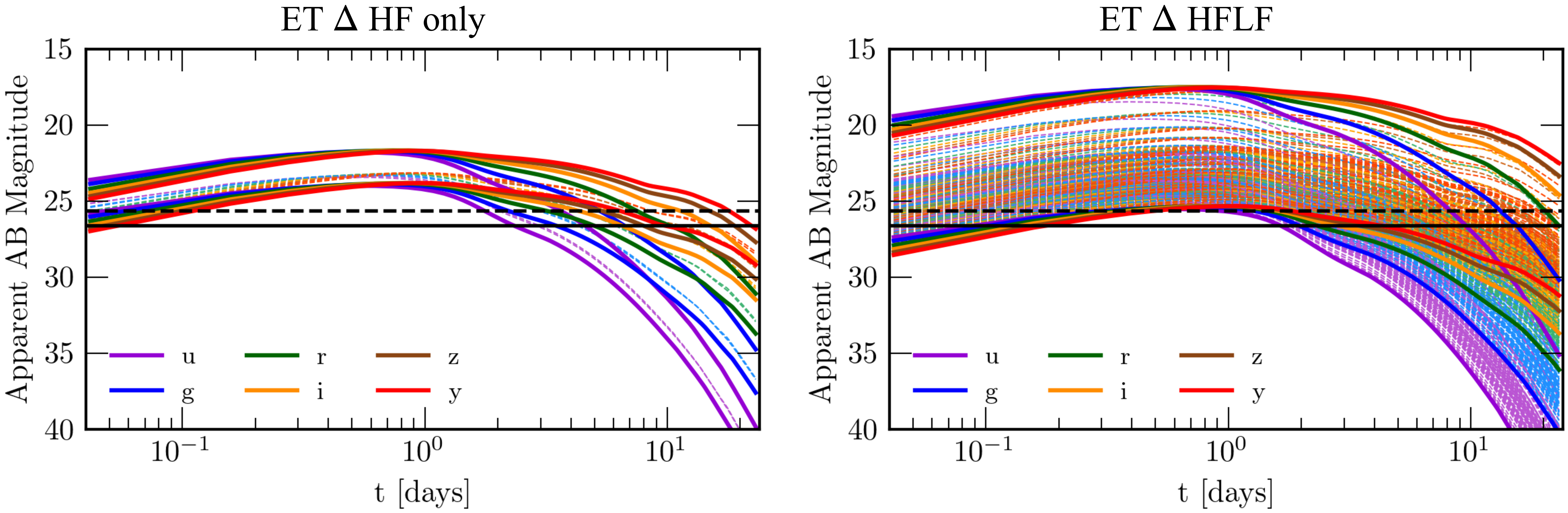
Number of KNe detected over 2 nights

Results - The importance of low-frequencies

- Events localised better than 40 deg^2

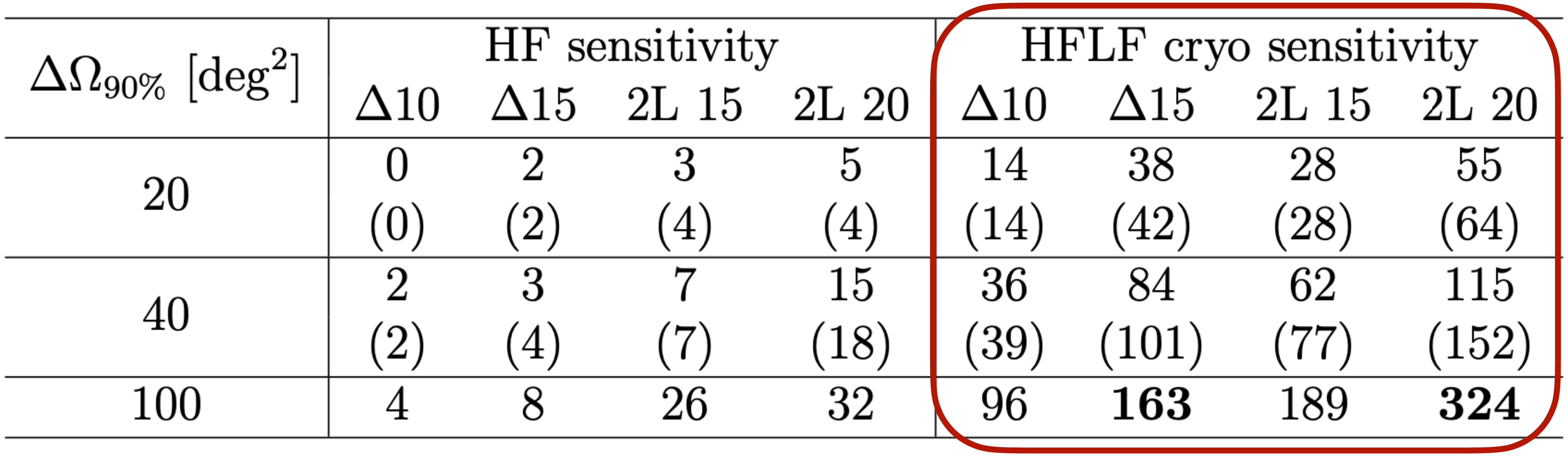


- KN detections in one year: 2 vs 36
- Low frequencies pivotal for ET to operate as a single observatory

Credits: Branchesi et al. JCAP 2023

Results - Comparing ET configurations

- ET 2L 15 km ouperforms (factor 2) ET Δ 10km
- ET 2L 20km with low frequency lasers → best performing, joint detection of several tens/few hundred KN per year
- ET 15km triangle slightly better than ET 2L 15km (30% more detections)



$\Delta\Omega_{90\%}$ [deg^2]	HF sensitivity				HFLF cryo sensitivity			
	Δ10	Δ15	2L 15	2L 20	Δ10	Δ15	2L 15	2L 20
20	0 (0)	2 (2)	3 (4)	5 (4)	14 (14)	38 (42)	28 (28)	55 (64)
40	2 (2)	3 (4)	7 (7)	15 (18)	36 (39)	84 (101)	62 (77)	115 (152)
100	4	8	26	32	96	**163**	189	**324**

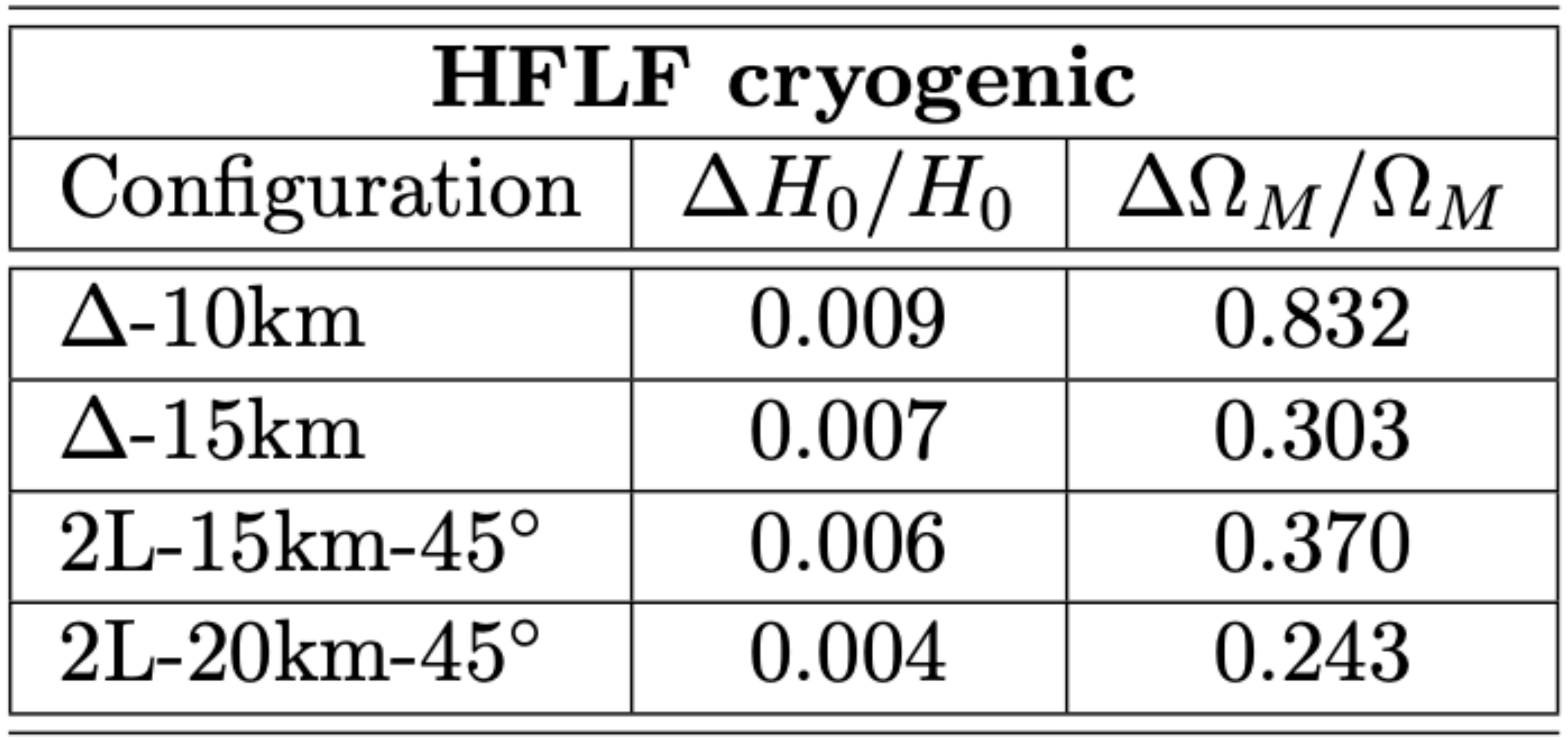
← 600 s

← 1800 s

Credits: Branchesi et al. JCAP 2023

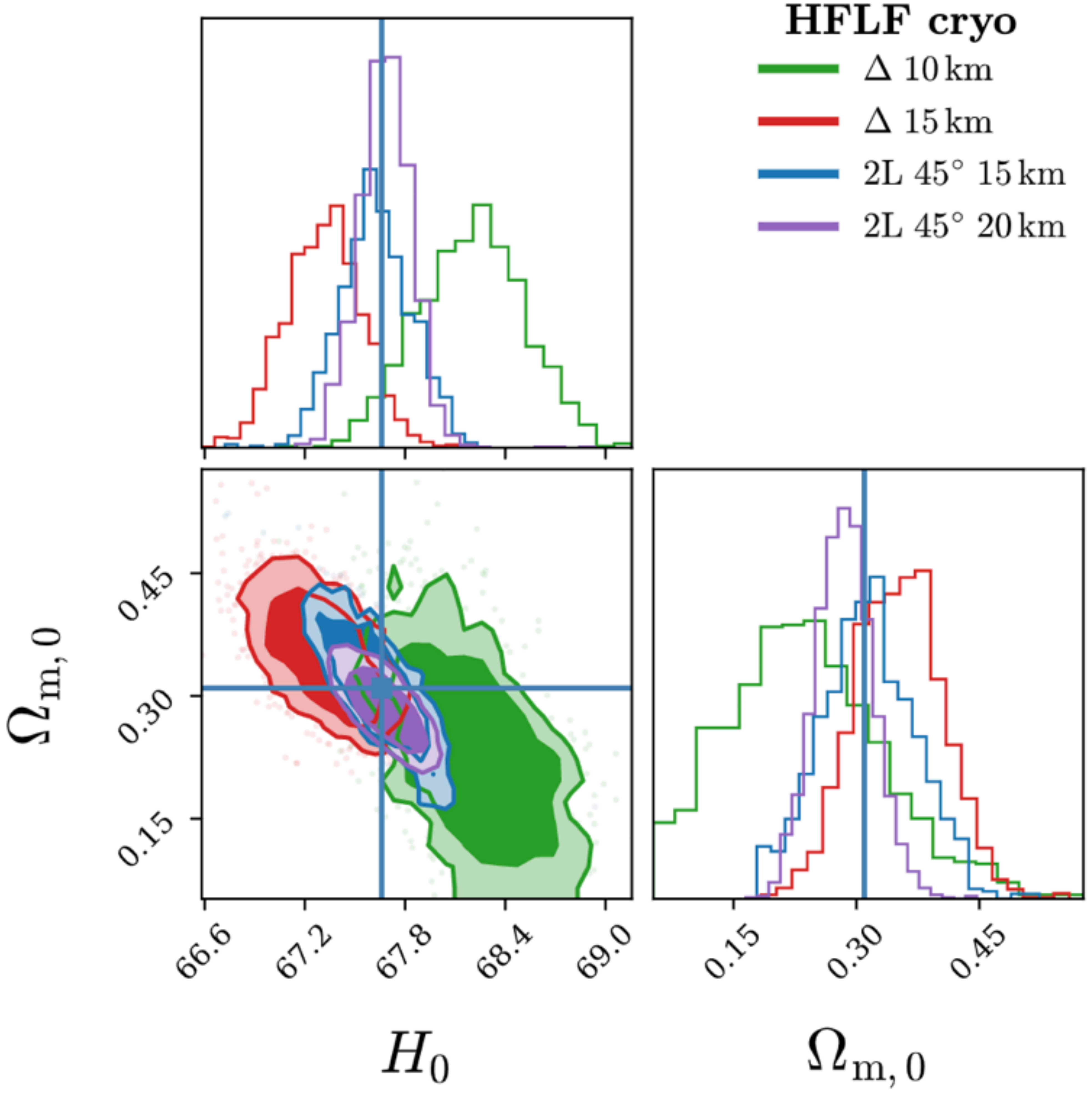
Results - Estimate of H_0

- Joint GW/KN detections used to evaluate ET science case for cosmology
- ET accessing also low-frequencies (HFLF) allows constraining H_0 with percent precision, a factor 7 better than ET with HF only



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



Credits: Branchesi et al. JCAP 2023

New goals

Evaluating prospects for GW/KN detections considering networks of current and next-generation GW detectors and present uncertainties in

- BNS merger rate
- Neutron Star mass distribution
- Equation of State (EOS) of Neutron Stars

Soon on ArXiv:

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↓

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GWFISH

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Number of detected mergers, source parameters, and errors (e.g. sky-loc.)

STEP 3

Modelling of KN emission

↓

KN light curve for each detected merger

STEP 4

Follow up strategy (mosaic ToO) with Rubin of events within a certain sky-loc.

↓

Number of KNe detected in *g* and *i* over 2 nights

New goals: improved methodology

- Enhanced statistics (10 years of observations)
- ET alone or in a network of current and next-gen. detectors
- Explore physical parameters of BNS merger population (NS mass distribution, NS EOS)
- 64 simulations for several GW network scenarios
- Improved KN modelling
- Refined follow-up strategy with Rubin

STEP 1

STEP 2

STEP 3

STEP 4

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within a
ky-loc.

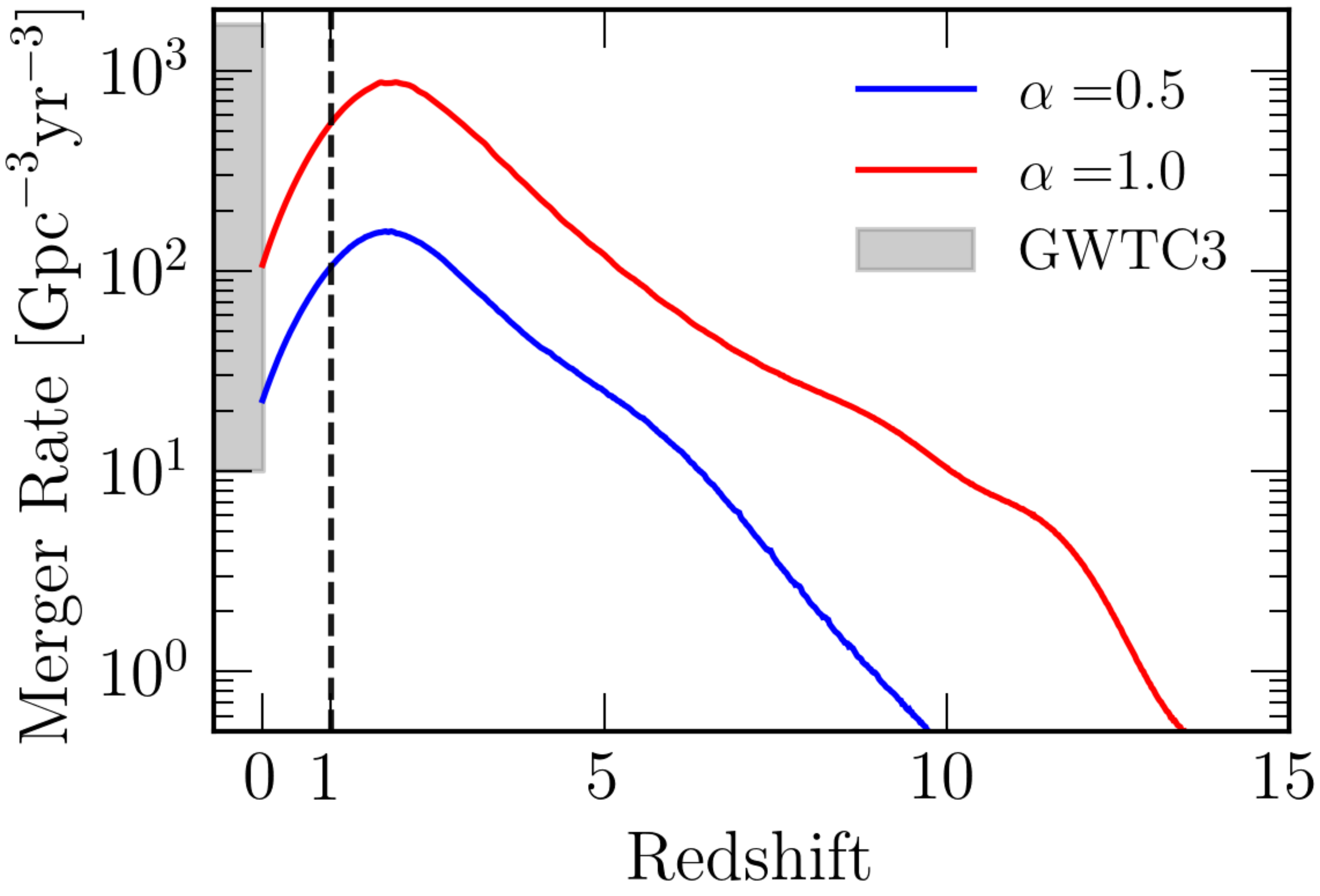
Proper
BNS
redshift,
inclination, …)

(e.g. sky-loc.)

of KNe
n g and i

Method - BNS merger populations

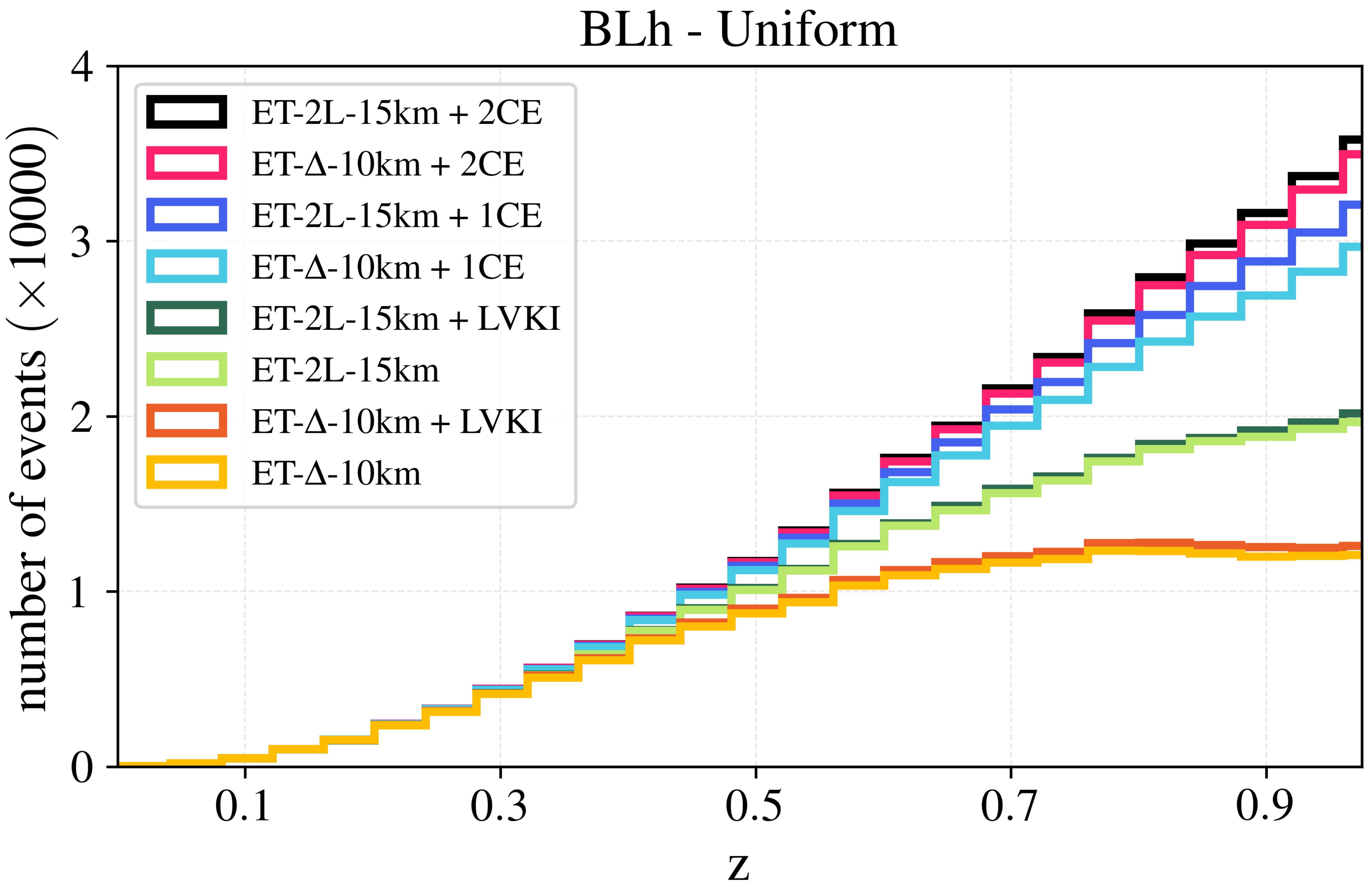
- Two populations from population synthesis code SEVN [Iorio + 2023]
- NS mass distribution? Gaussian and uniform
- NS EOS? APR4 (more compact NSs) and BLh (less compact NSs)



Credits: Loffredo E., Hazra N., Dupletsa U., et al, in prep.

Method - Simulating GW detections

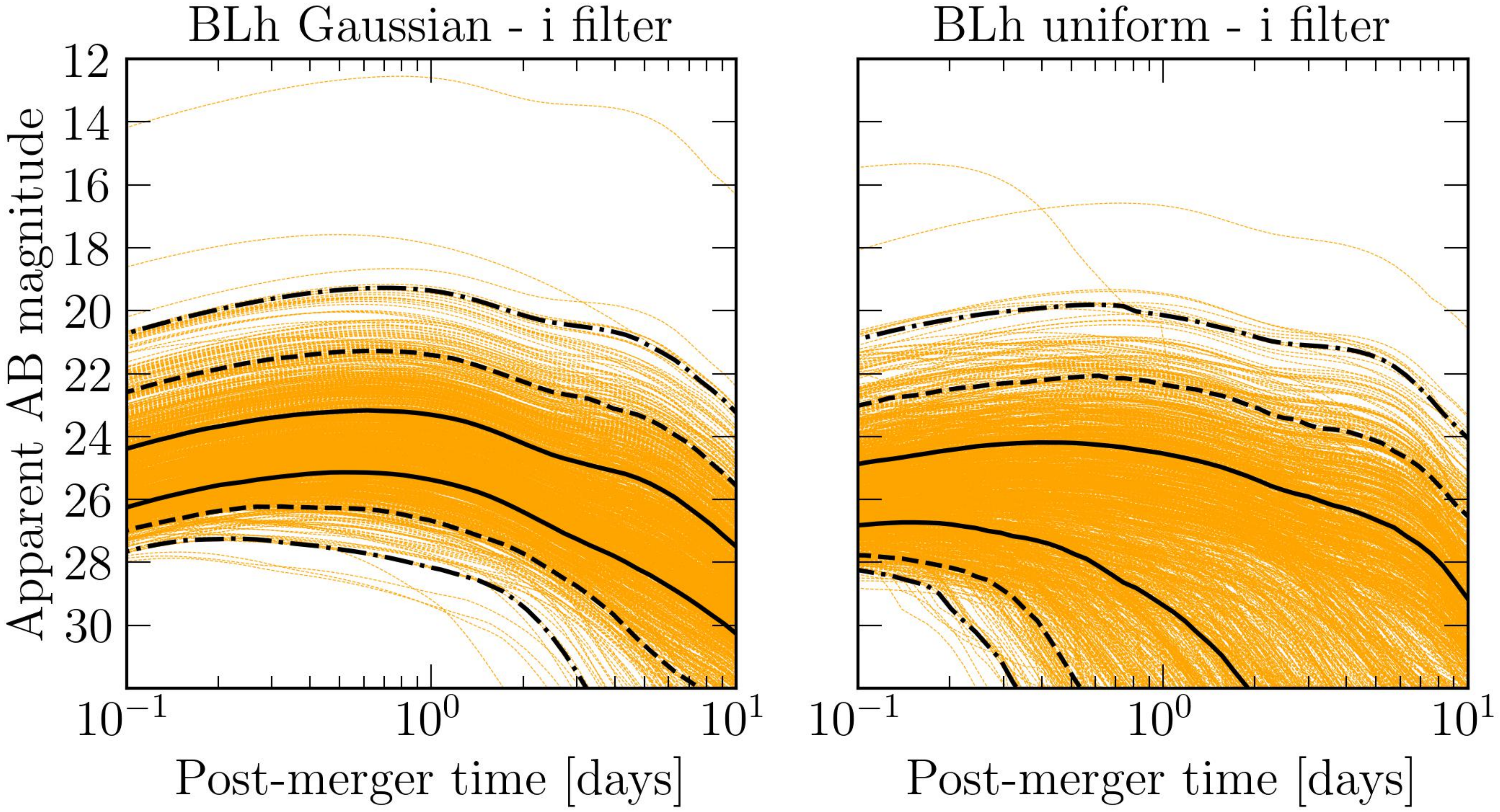
- Two ET configurations: **2L** and **Δ**
- GW networks → ET, ET + LVKI, ET + 1CE (40 km), ET + 2CE (USA, Australia)
- 64 simulations for 10 years of mergers randomly distributed in the sky up to redshift $z = 1$



Credits: Loffredo E., Hazra N., Dupletsa U., et al, in prep.

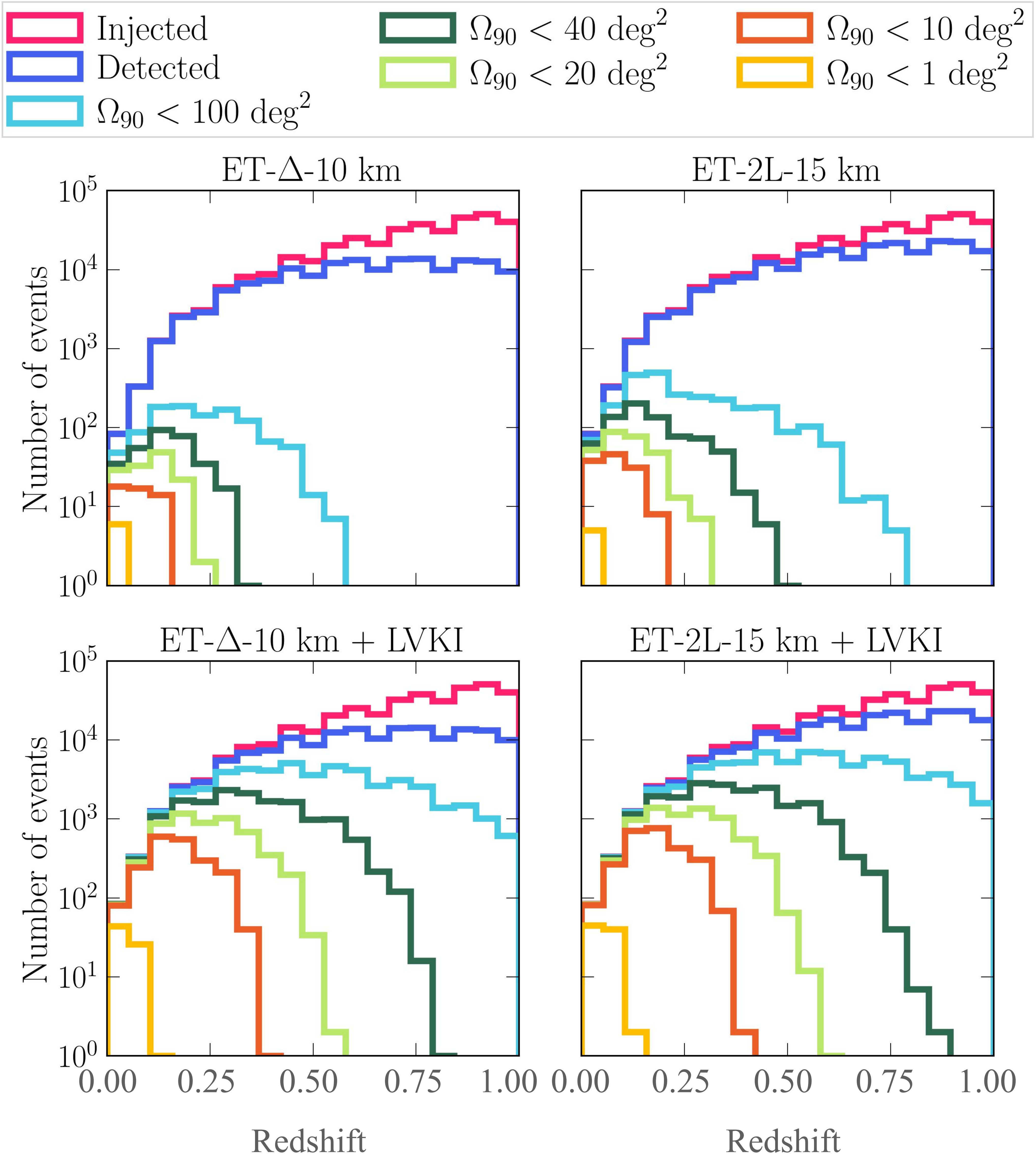
Method - Population of kilonovae

- BNS masses and EOS → KN ejecta properties via numerical relativity (NR) informed fits
  [e.g. Radice + 2018, Krüger & Foucart 2020]
- New fits considering NR simulations targeted to GW170817 and GW190425
- Include effect induced by prompt collapse to black hole
  [Perego + 2022; Kashyap + 2022]



Credits: Loffredo E., Hazra N., Dupletsa U., et al, in prep.

Results - GW detections

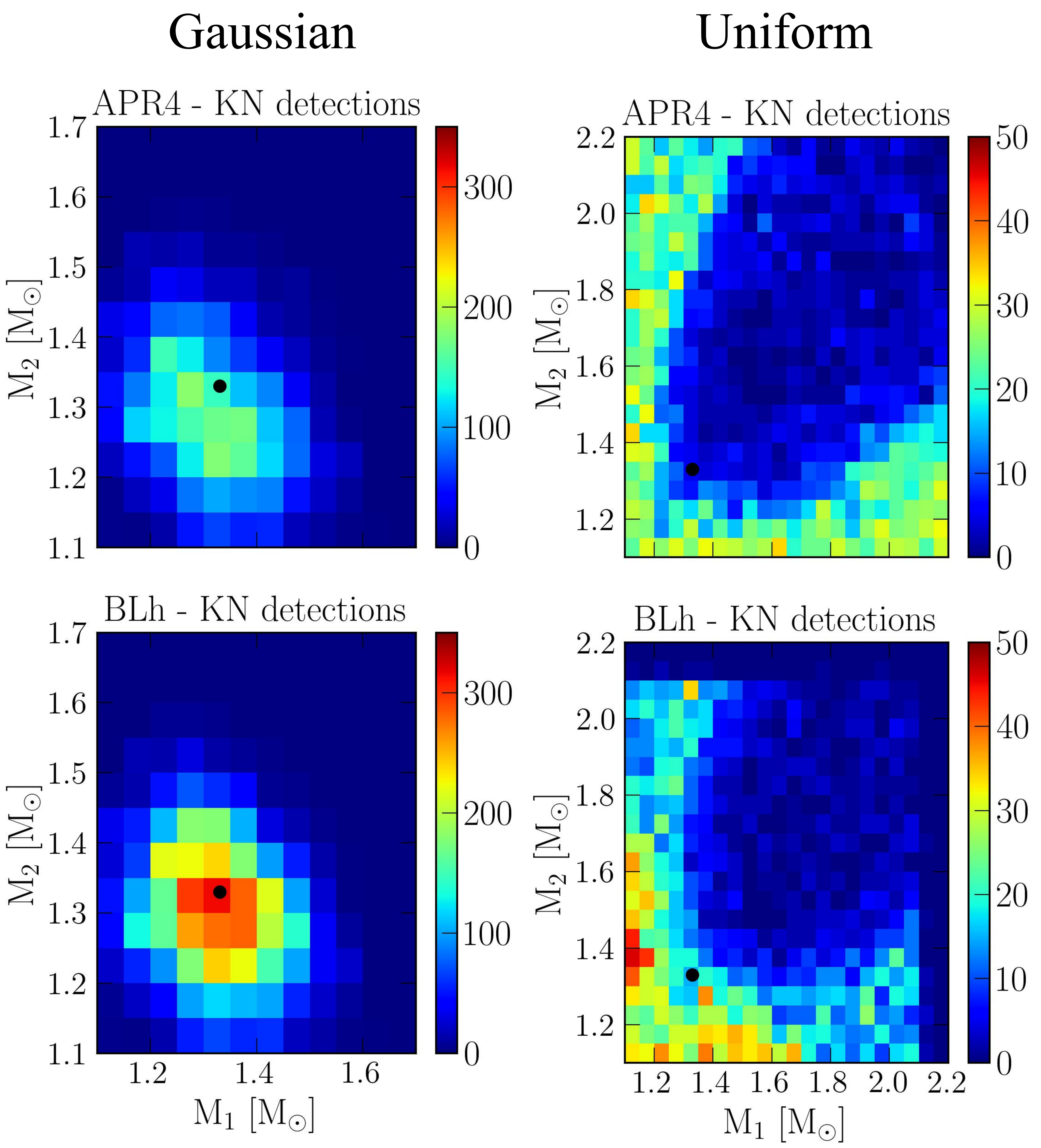


- ET alone → up to 25k events per year ($z < 1$). Increase by 70-90% for ET + 1-2 CEs
- ET + LVKI extremely good sky-loc. → up to 10k events per year with $\Delta\Omega_{90} < 100$ deg^2
- ET 2L better sky-loc than ET Δ → 2.4 more events localised within $\Delta\Omega_{90} < 100$ deg^2
- **Uncertainties: population (factor 5), NS mass distribution (20-25%), NS EOS (5%)**

Credits: Loffredo E., Hazra N., Dupletsa U., et al, in prep.

Results - GW/KN joint detections

- ET alone → 10 - 100 KNe detections per year
- ET 2L outperforms ET Δ when operating as a single observatory or with LVKI. Not significant difference when operating with CE
- ET + LVKI→ up to several hundreds joint detections per year
- **Uncertainty dominated mainly by merger rate (factor 5), second order by ET configuration, then NS mass distribution & EOS**



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Conclusions

1. For KN science, low frequencies crucial for ET operating as a single observatory

2. ET as single observatory allows the joint detection of 10-100 KNe per year

3. For KN science, ET 2L outperforms ET Δ if operating as a single observatory or with LVKI

4. Uncertainties on the number of detections dominated by merger rate, followed by NS mass distribution, EOS, KN modelling

5. Current and future detectors expected to improve constraints on merger rate and NS mass distr., making more effective the EOS impact

Thank you!