Vera Rubin Observatory and Einstein Telescope: kilonova studies to understand ET detector design

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GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
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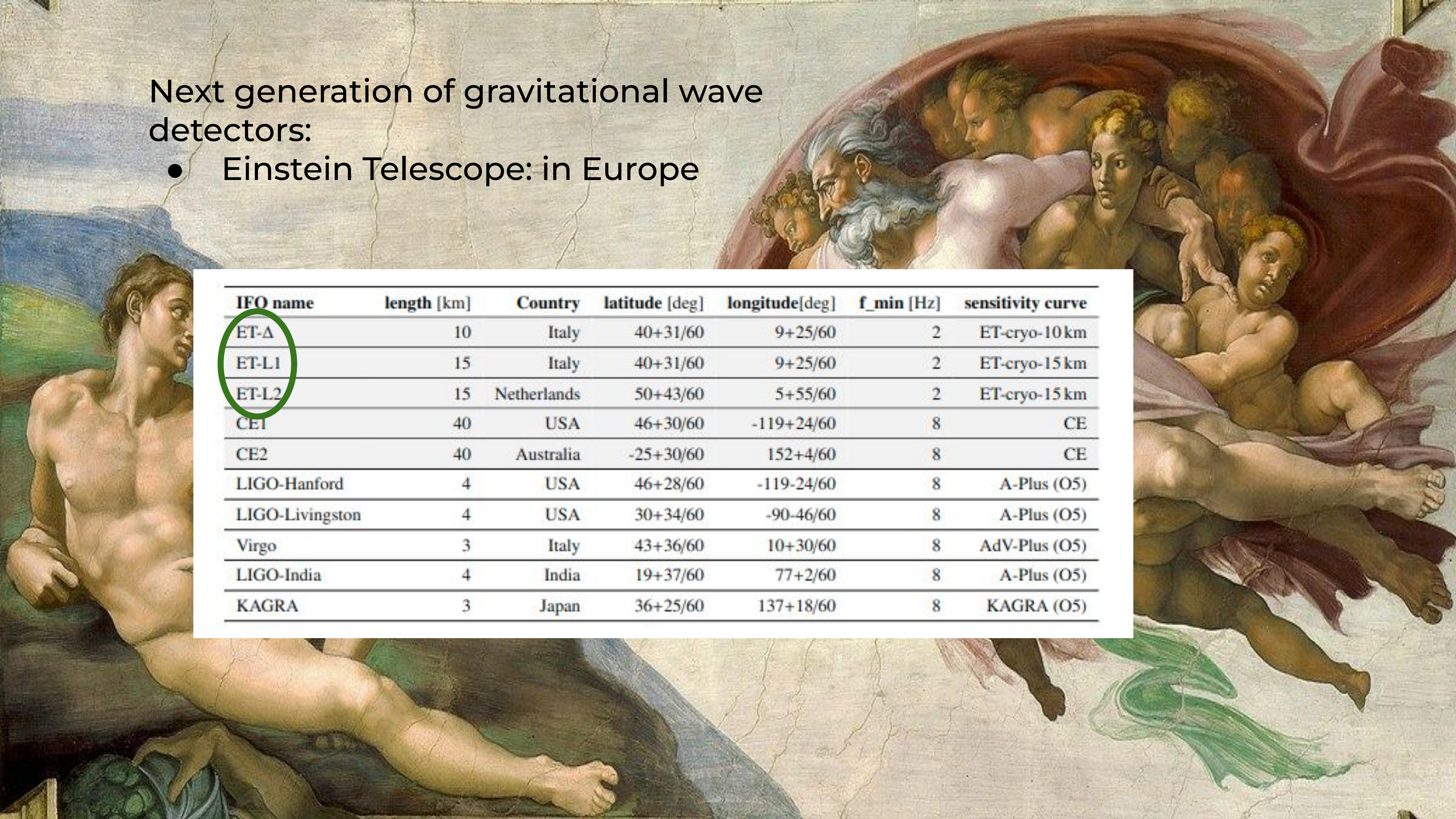
VERA C. RUBIN OBSERVATORY

EINSTEIN TELESCOPE

Next generation of gravitational wave detectors:

- Einstein Telescope: in Europe



IFO name	length [km]	Country	latitude [deg]	longitude[deg]	f_min [Hz]	sensitivity curve
ET-Δ	10	Italy	40+31/60	9+25/60	2	ET-cryo-10 km
ET-L1	15	Italy	40+31/60	9+25/60	2	ET-cryo-15 km
ET-L2	15	Netherlands	50+43/60	5+55/60	2	ET-cryo-15 km
CE1	40	USA	46+30/60	-119+24/60	8	CE
CE2	40	Australia	-25+30/60	152+4/60	8	CE
LIGO-Hanford	4	USA	46+28/60	-119-24/60	8	A-Plus (O5)
LIGO-Livingston	4	USA	30+34/60	-90-46/60	8	A-Plus (O5)
Virgo	3	Italy	43+36/60	10+30/60	8	AdV-Plus (O5)
LIGO-India	4	India	19+37/60	77+2/60	8	A-Plus (O5)
KAGRA	3	Japan	36+25/60	137+18/60	8	KAGRA (O5)

Synergies of GW+Optical observations:

- Better parameter estimation and characterization of progenitors of transients such as kilonovae
- Cosmology
- Nuclear physics

ET EINSTEIN TELESCOPE

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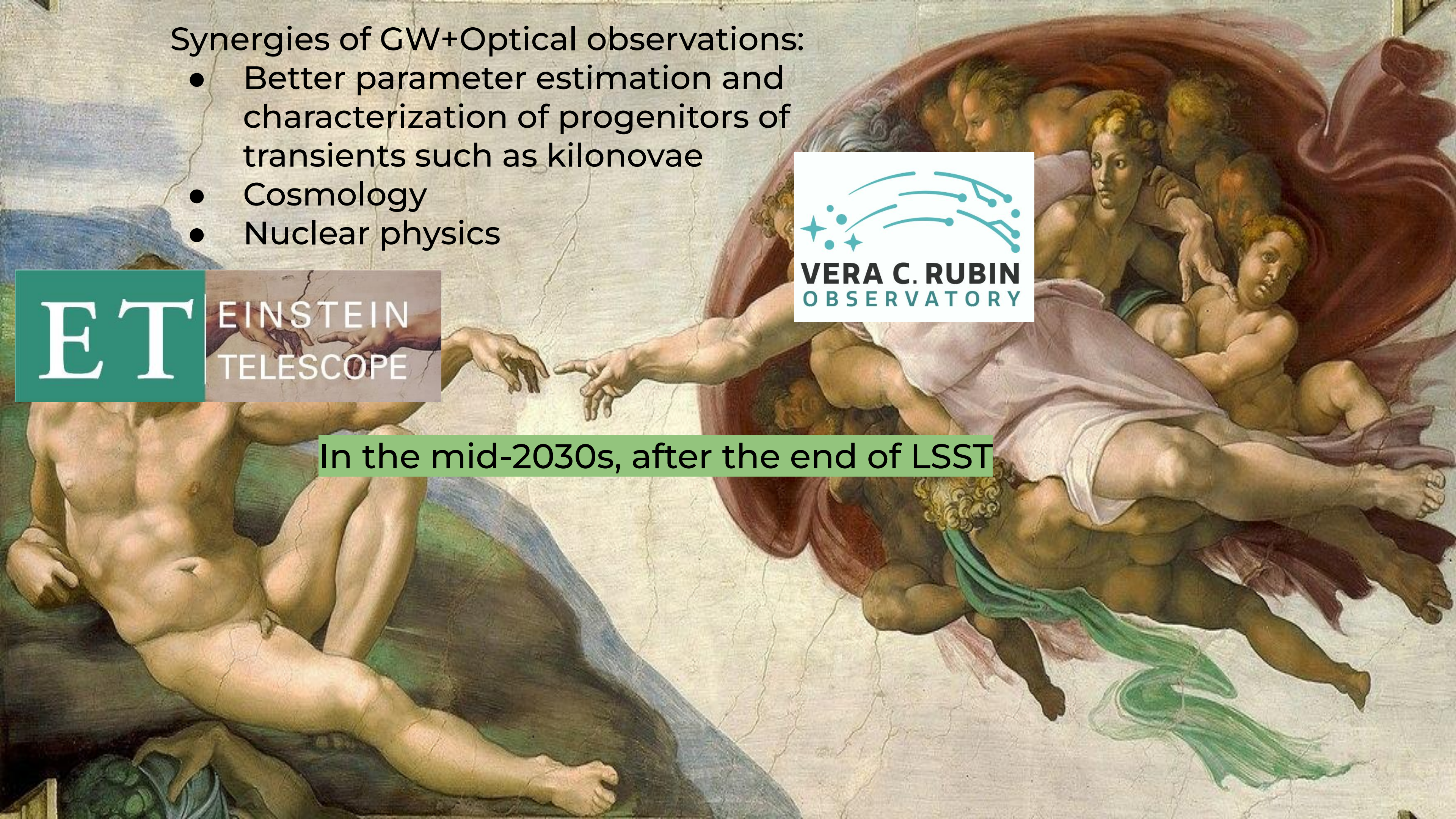
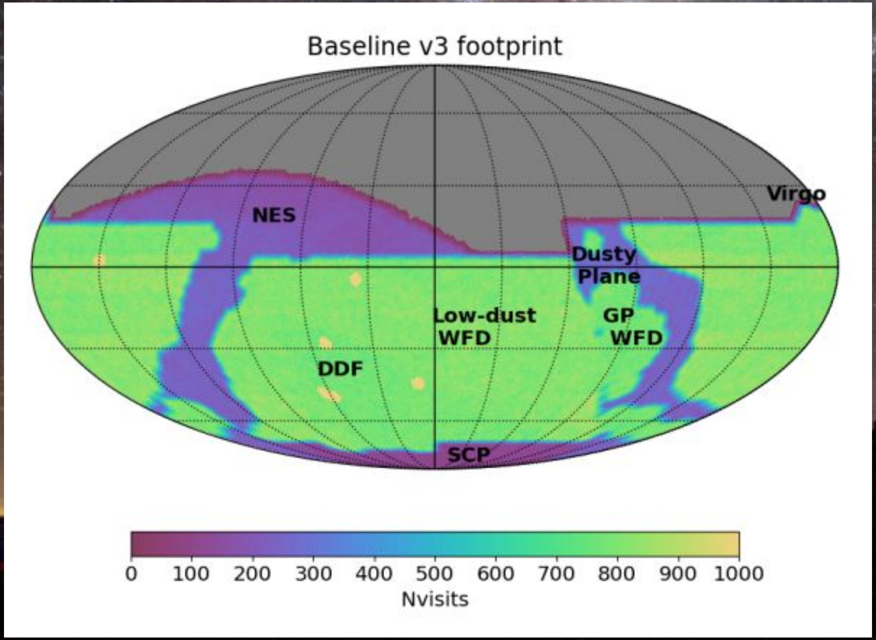
In the mid-2030s, after the end of LSST



The Vera Rubin Observatory

- Under construction in Cerro Pachón, Chile
- 8.4 m primary mirror
- 10-year survey of the Southern sky: **Legacy Survey of Space and Time (LSST)**
- Expected first light: 2024
- 3200 megapixel camera

The Vera Rubin Observatory



PSTN-055 (SCOC Phase 2 Recommendations)

- FOV: 9.6 deg^2
- ~18,000 deg^2
- *i*-band 5σ co-added depth at 10 years 26.3 mag
- Cadence: decided with input from the community *(Federica Bianco, chair of the SCOC)*

VERA C. RUBIN
OBSERVATORY

Importance of ToO studies for kilonovae

- Serendipitous discovery rate of kilonovae from LSST Wide Fast Deep(WFD) will be low: 32-334(23-238) with baseline(rolling) cadence, only 3-29(3-32) characterizable (Andreoni et al. 2022)
- 30 s of exposure in survey: 24.9 mag in *g*, 24 in *i*
- We will only detect the closest, brightest events
- GW170817: was a bright “unicorn” event, the only binary neutron star merger we observed with an electromagnetic counterpart

Image credit: S. Ronchini

Studying ToO strategies to compare ET detector designs:

- GW170817-like kilonovae
- Using a Fischer matrix method for parameter estimation of GW signals from binary neutron star mergers

Science with the Einstein Telescope: a comparison of different designs

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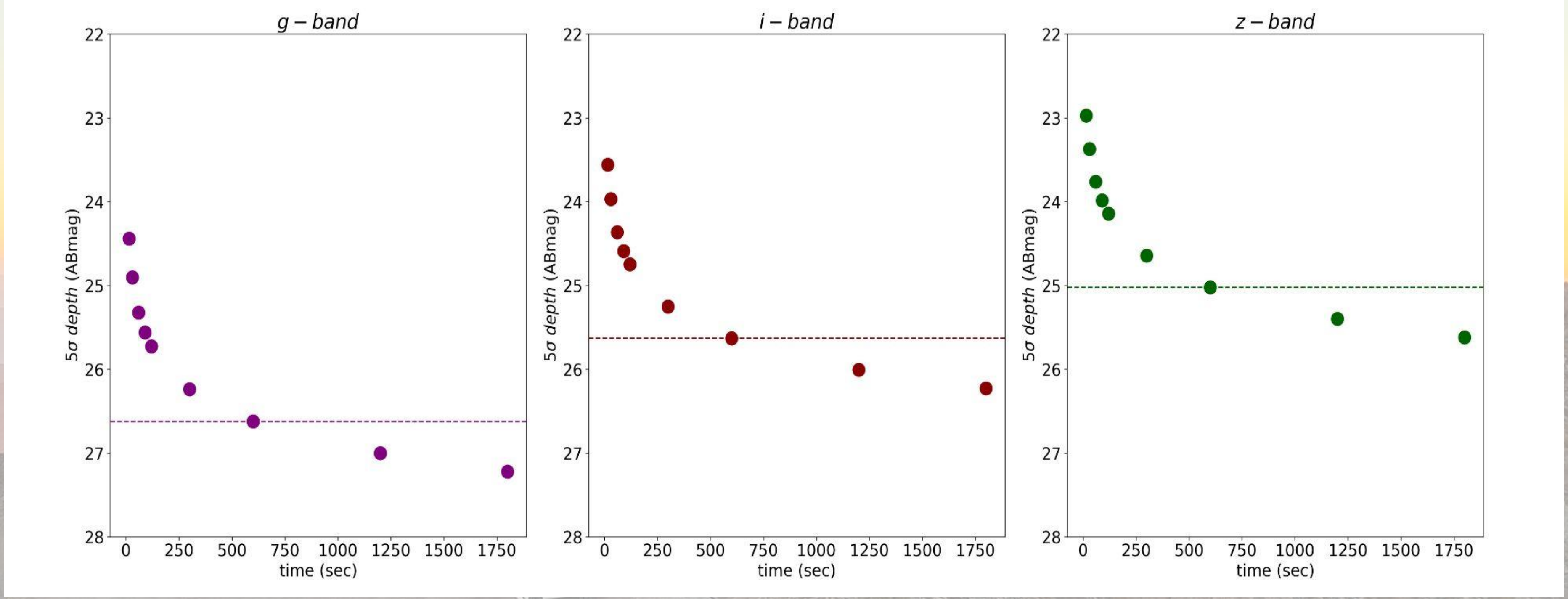
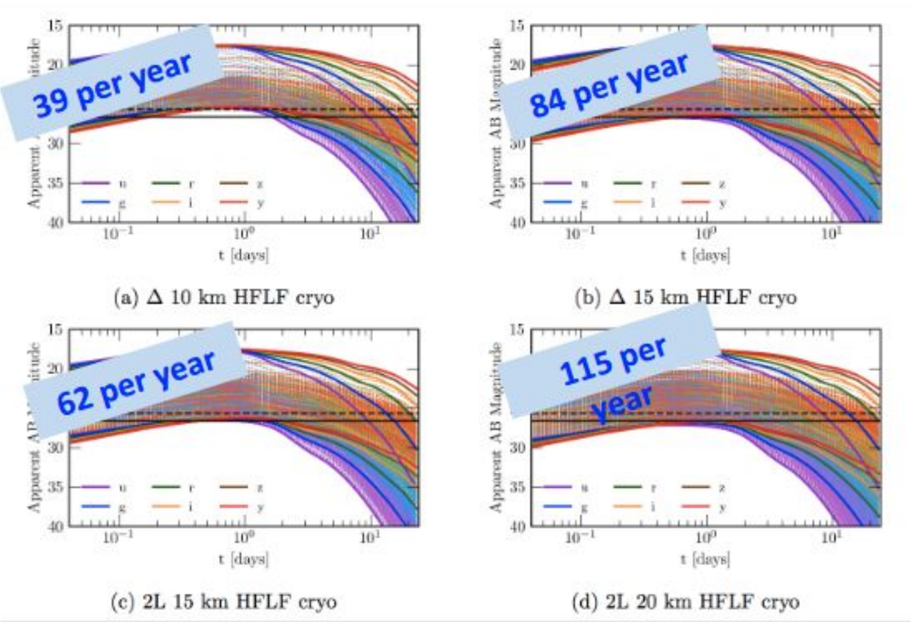
Studying ToO strategies for Rubin

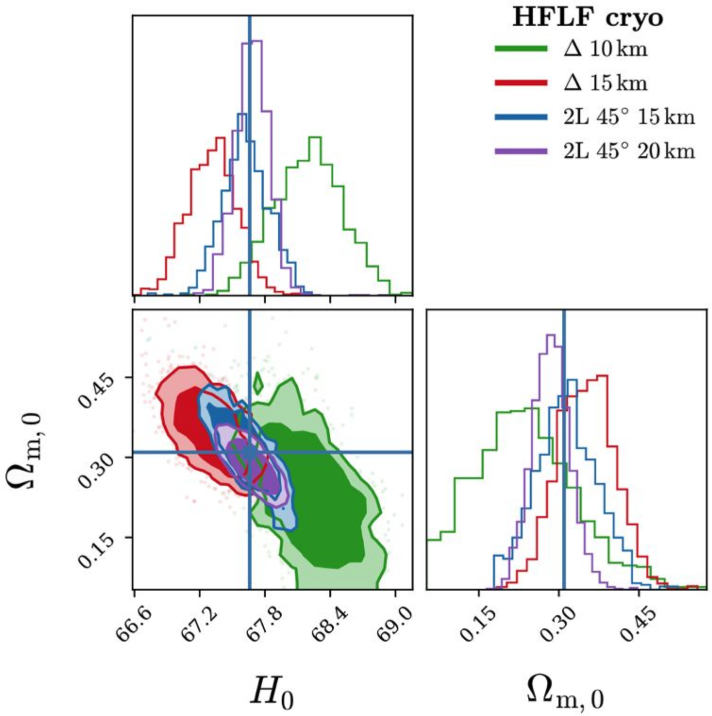
- Optical follow-up strategy with Rubin: 0.5 duty cycle, randomly selected
- In 2 nights: 5 hours and 24 hours after merger
- Exposures of 600s, 1800s as test cases
- Using *g* and *i*: study color evolution, without compromising depth



Studying ToO strategies to compare ET detector designs:

BNSs detected with a sky-localization < 40 deg^2





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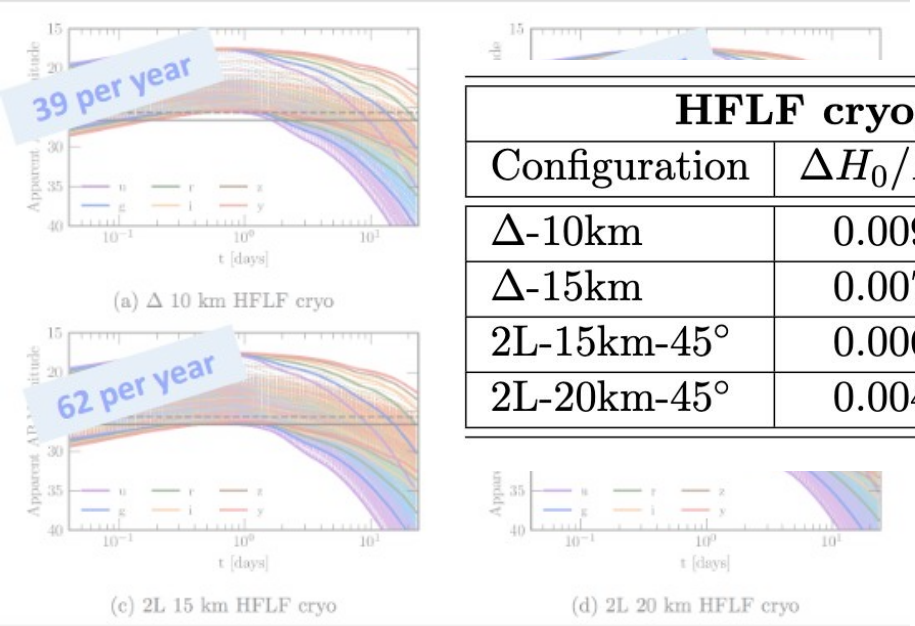
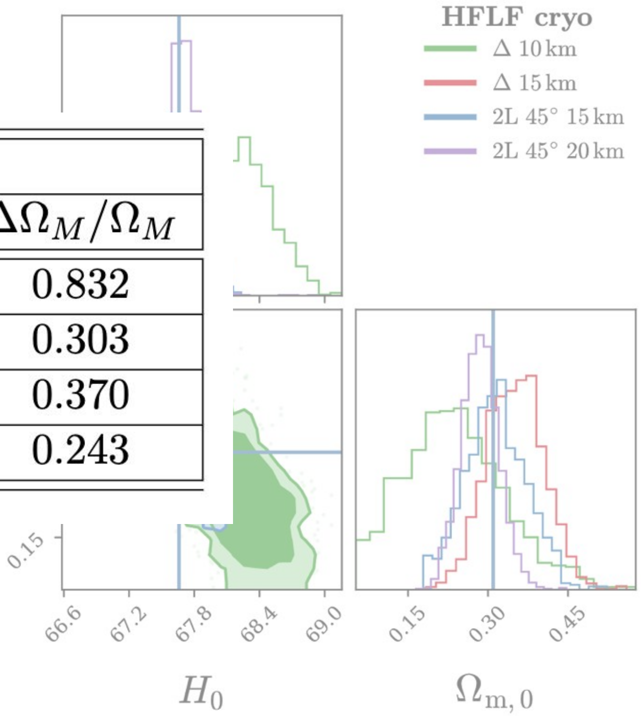


(a) Δ 10 km HFLF cryo

(c) 2L 15 km HFLF cryo

(d) 2L 20 km HFLF cryo

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



ToO time burden on Rubin

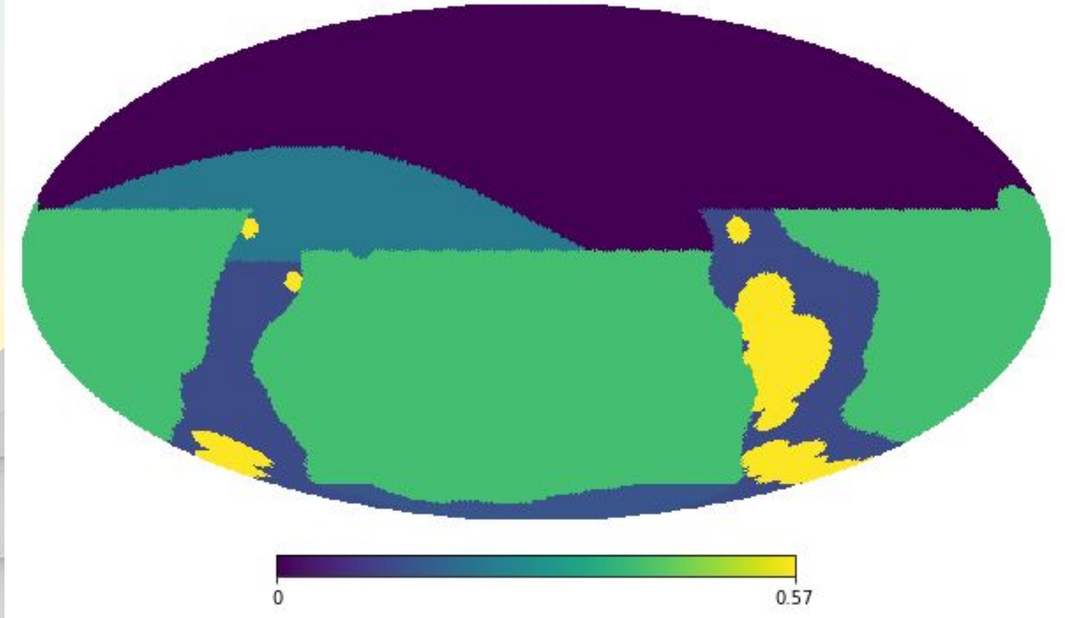
Full (HFLF cryo) sensitivity detectors

Configuration	$N_{GW,VRO}$ $\Omega < 20\,\deg^2$	VRO time	$N_{GW,VRO}$ $\Omega < 40\,\deg^2$	VRO time	$N_{GW,VRO}$ $\Omega < 100\,\deg^2$	VRO time
$\Delta 10$	14 (14)	1.1% (3.3%)	36 (39)	5.1% (15%)	96	40%
$\Delta 15$	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%

- Even with a low % of Rubin's total annual observing time, we detected a significant number of KNe with 600s exposures
- 1800s exposures were not a viable strategy for a population of BNS mergers

Strategy refinements: 10 year populations

2 EOSs x 2 mass distributions x 8 detector networks x 2 merger efficiencies



- Change in the observing strategy: using the EuclidOverlapFootprint of LSST, considering two-filter (*g* and *i*) multi-epoch follow-up
- Factoring sunrise and sunset times, observations starting 1.5 hours after merger
- Locating the event within a mosaic defined by the GW sky localization

Optical afterglow: gamma-ray bursts (GRBs)

(Eleonora's talk)

- We add the optical on-axis and off–axis afterglow to a fraction of our KNe population
- Compare the rates of observed KNe with/without the afterglow

Loffredo, NH et al. (in prep)

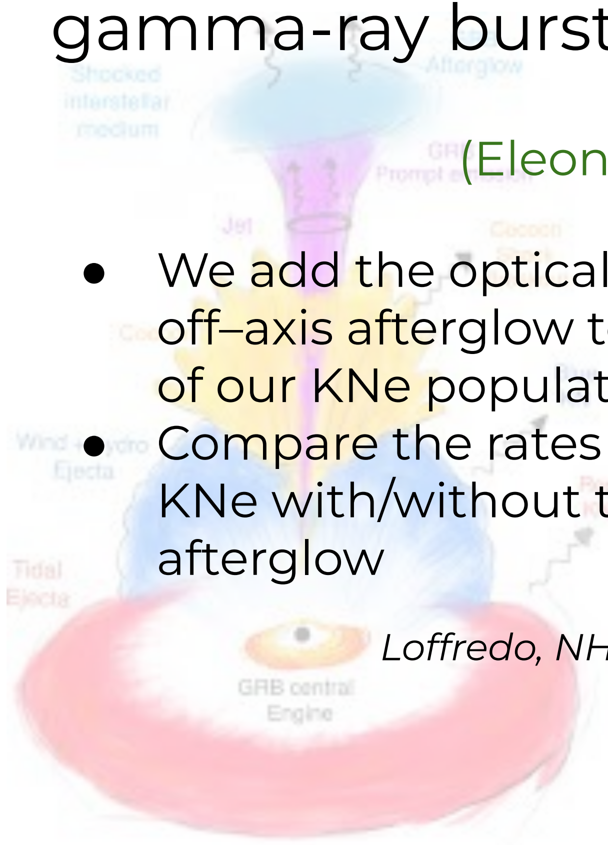
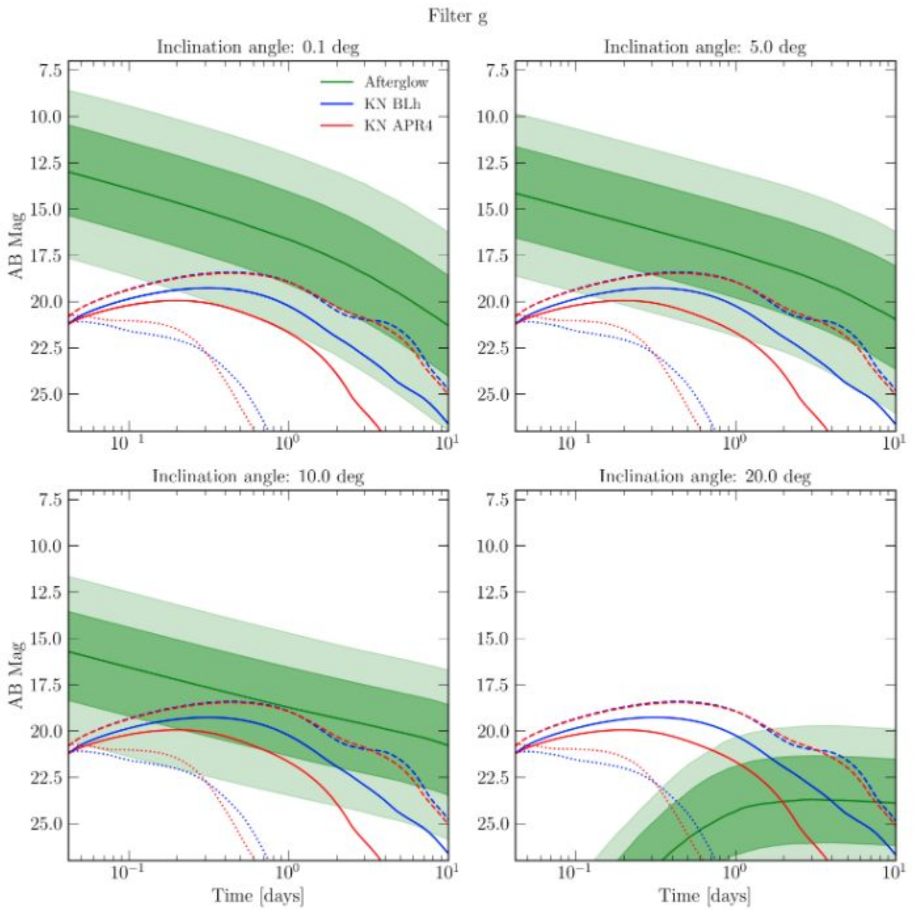


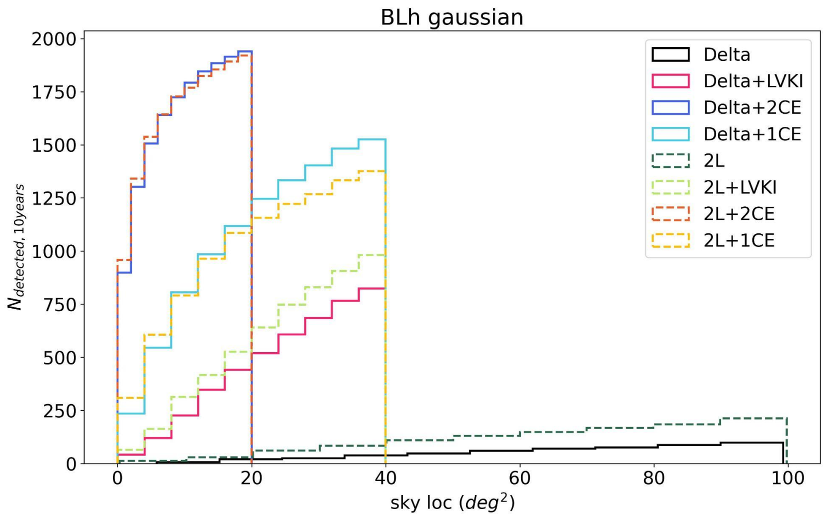
Image credit: S. Ascenzi



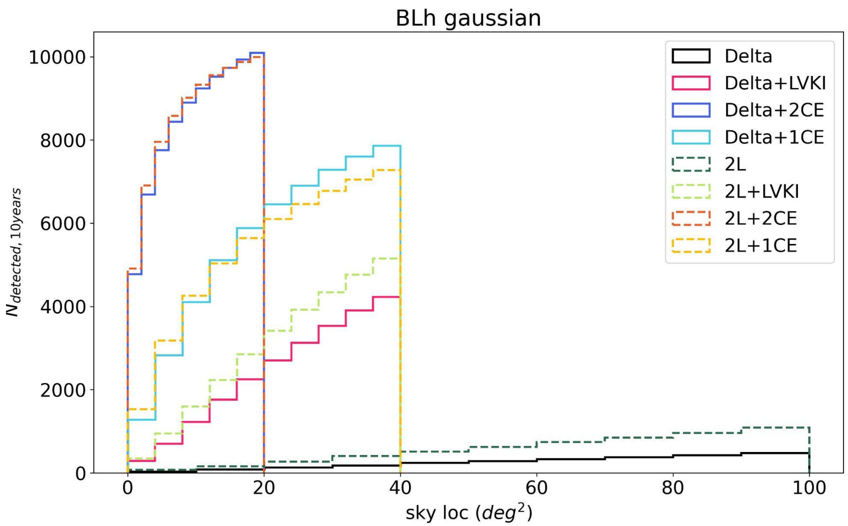
64 simulations: 10 years

More statistics, covers larger part of the parameter space

Only KNe: 10 year detection rate already higher than a serendipitous search



alpha=0.5 (pessimistic)

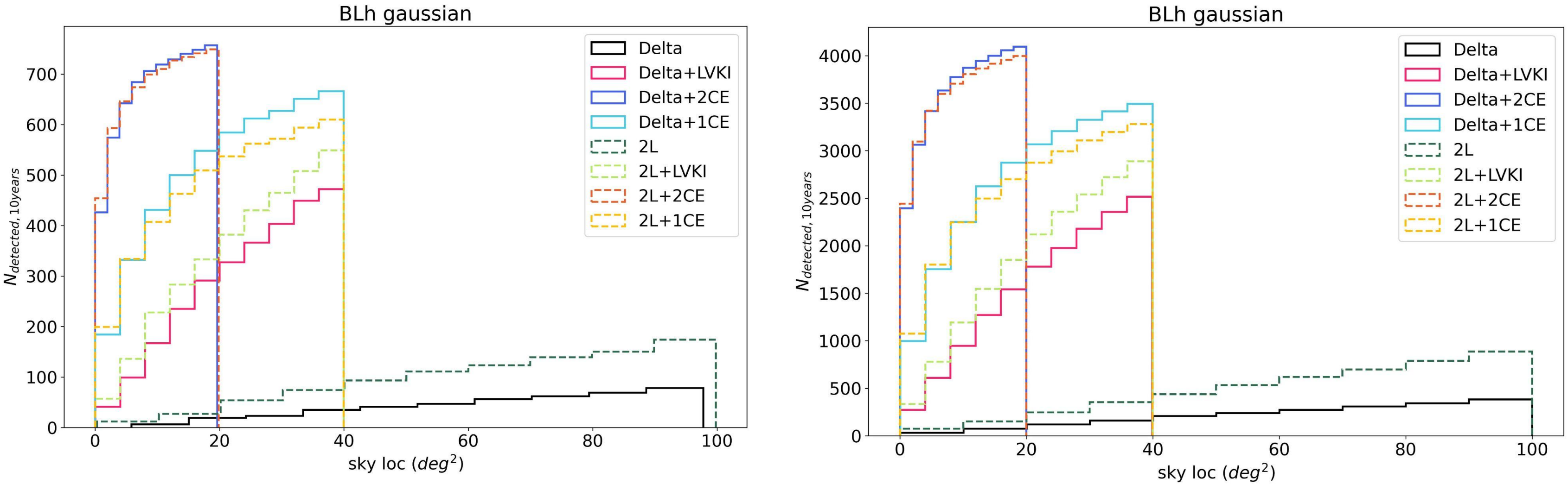


alpha=1.0 (optimistic)

Loffredo, NH et al. (in prep)

But how many characterizable?

Detected in 2 epochs, with g-i color information

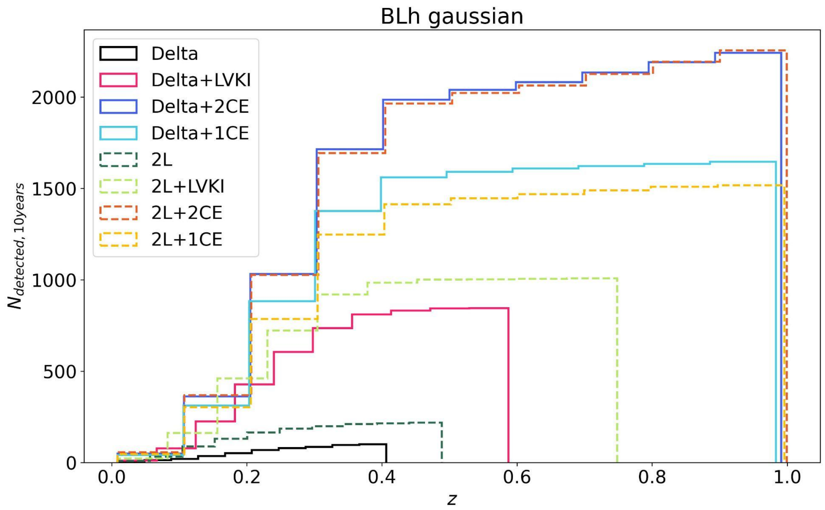


alpha=0.5 (pessimistic)

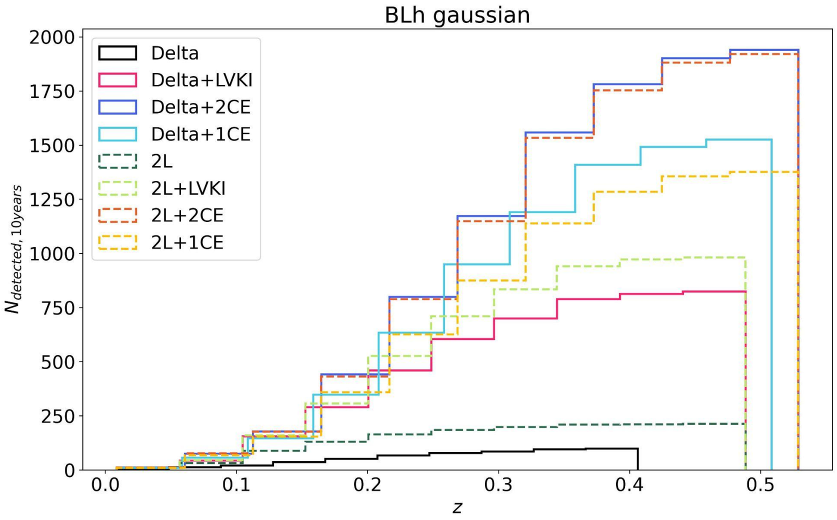
alpha=1.0 (optimistic)

Loffredo, NH et al. (in prep)

Redshift horizon?



KNe+GRB afterglow: redshift distribution

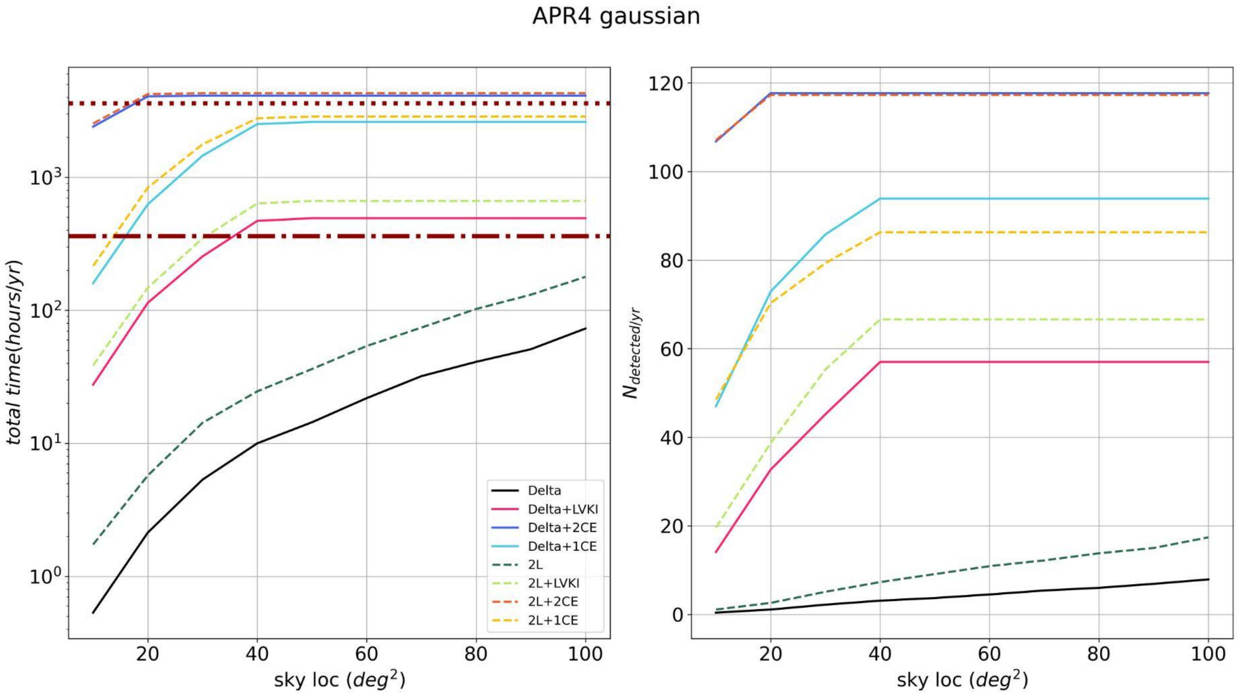


Only KNe: redshift distribution

Loffredo, NH et al. (in prep)

Interpretations: Work in Progress

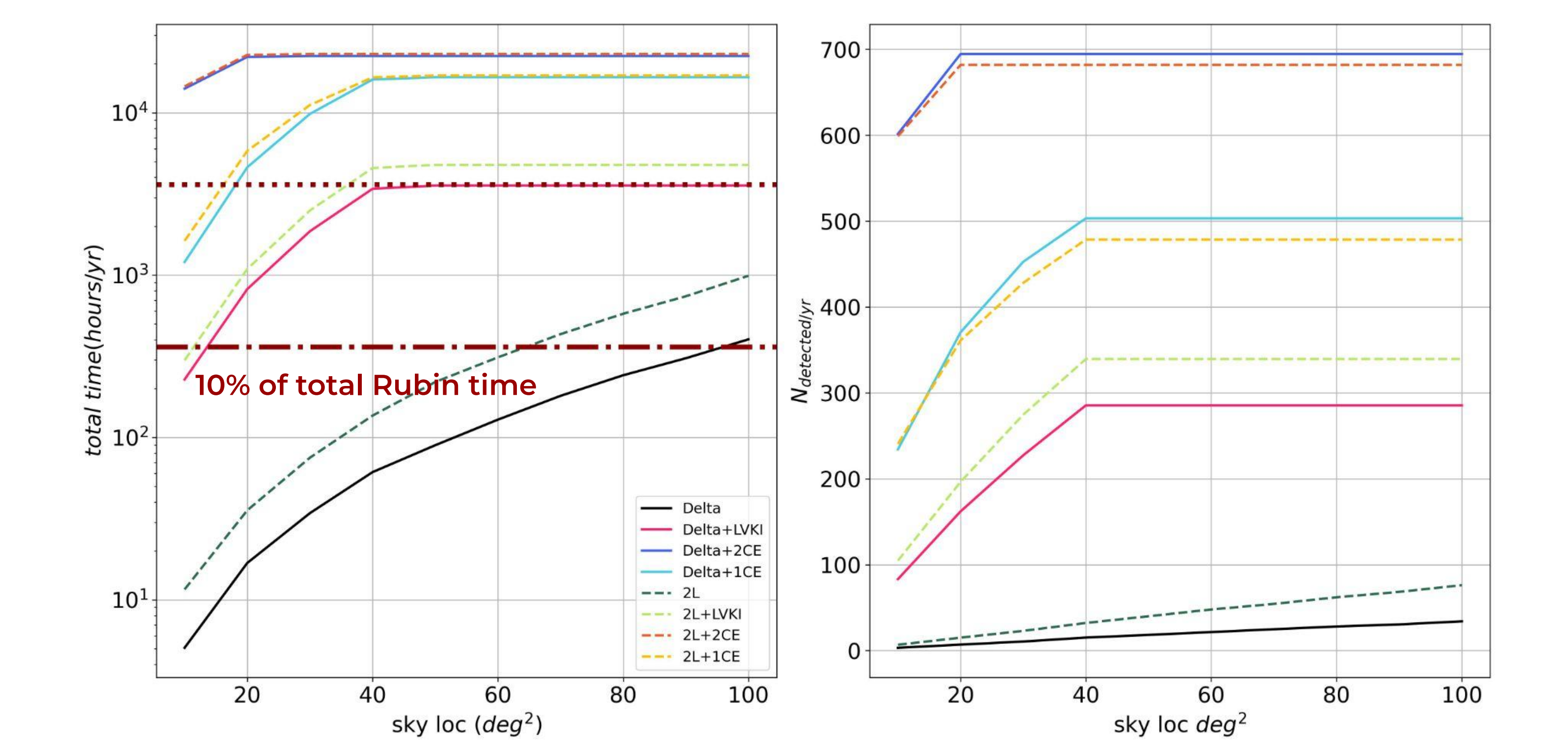
Interesting trends in rates of detection, implications for cosmology, nuclear physics of NS as well as for ET detector performance in networks for different configurations



Solid: ET triangle
Dashed: ET 2L

Loffredo, NH et al. (in prep)

Stay Tuned!



E. Loffredo, N. Hazra, U. Dupletsa, M. Branchesi et al. (in prep)

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