Wide-field INfrared Transient ExploreR

NIR searches for kilonovae with WINTER and Roman

Viraj Karambelkar, Caltech

Exploring the Transient Universe with the Roman Space Telescope Conference

Kilonovae are always bright in IR

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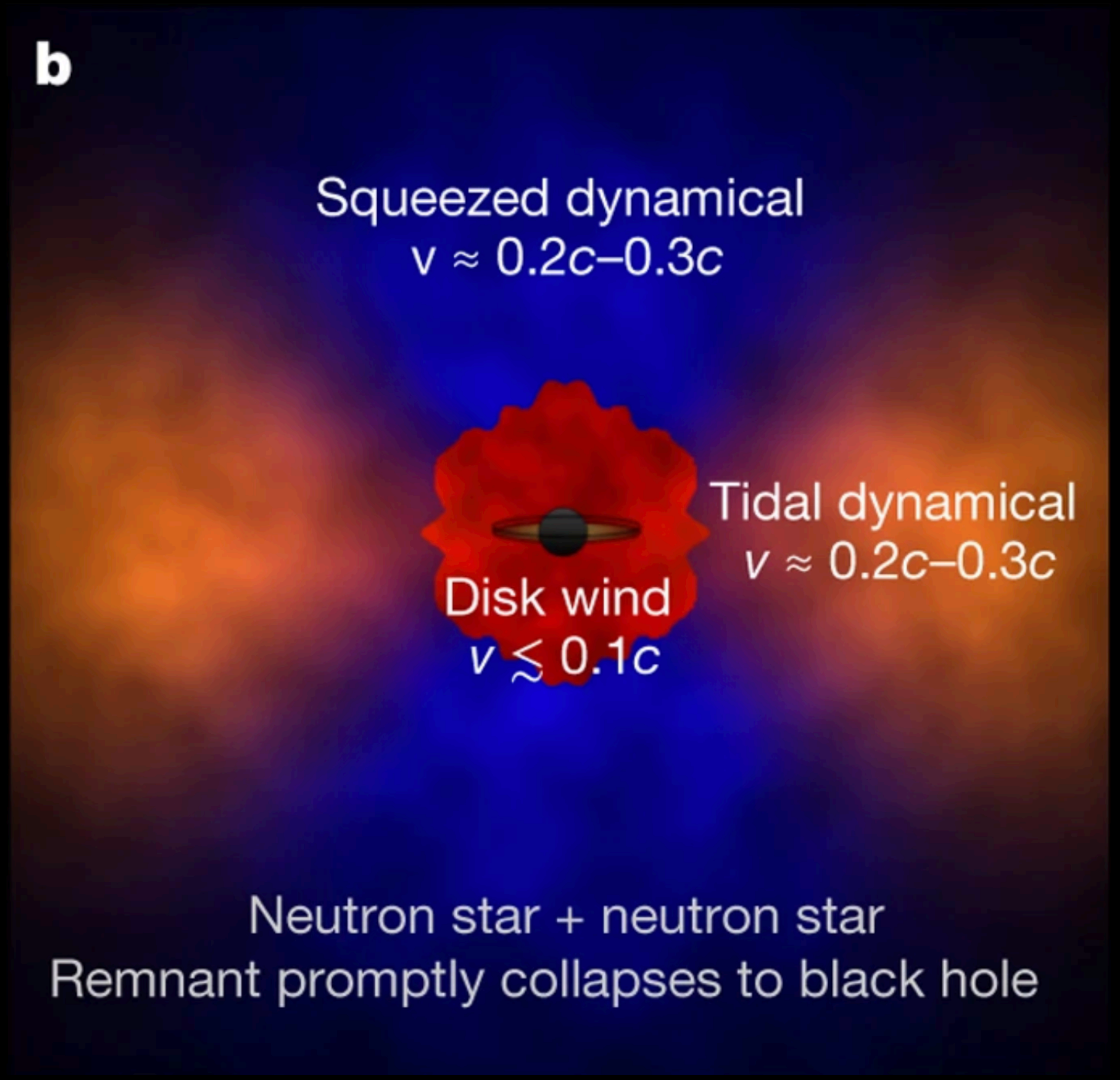
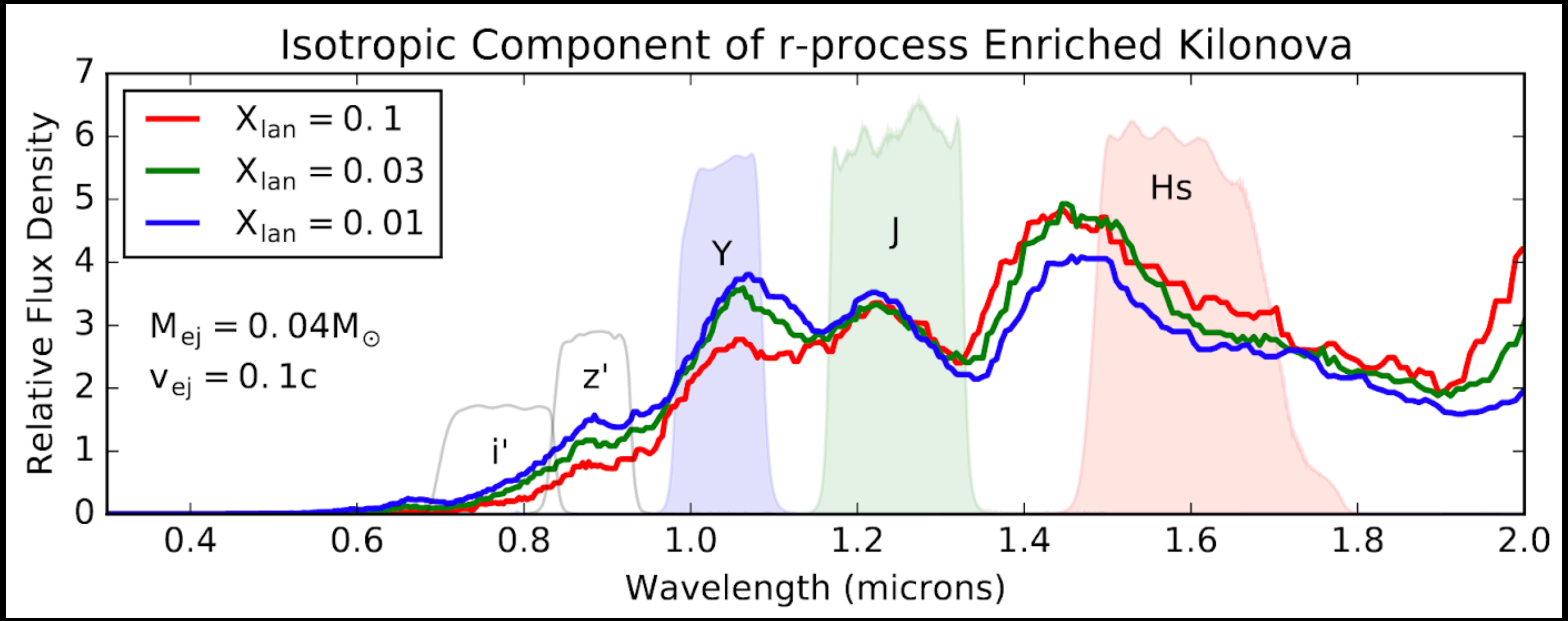
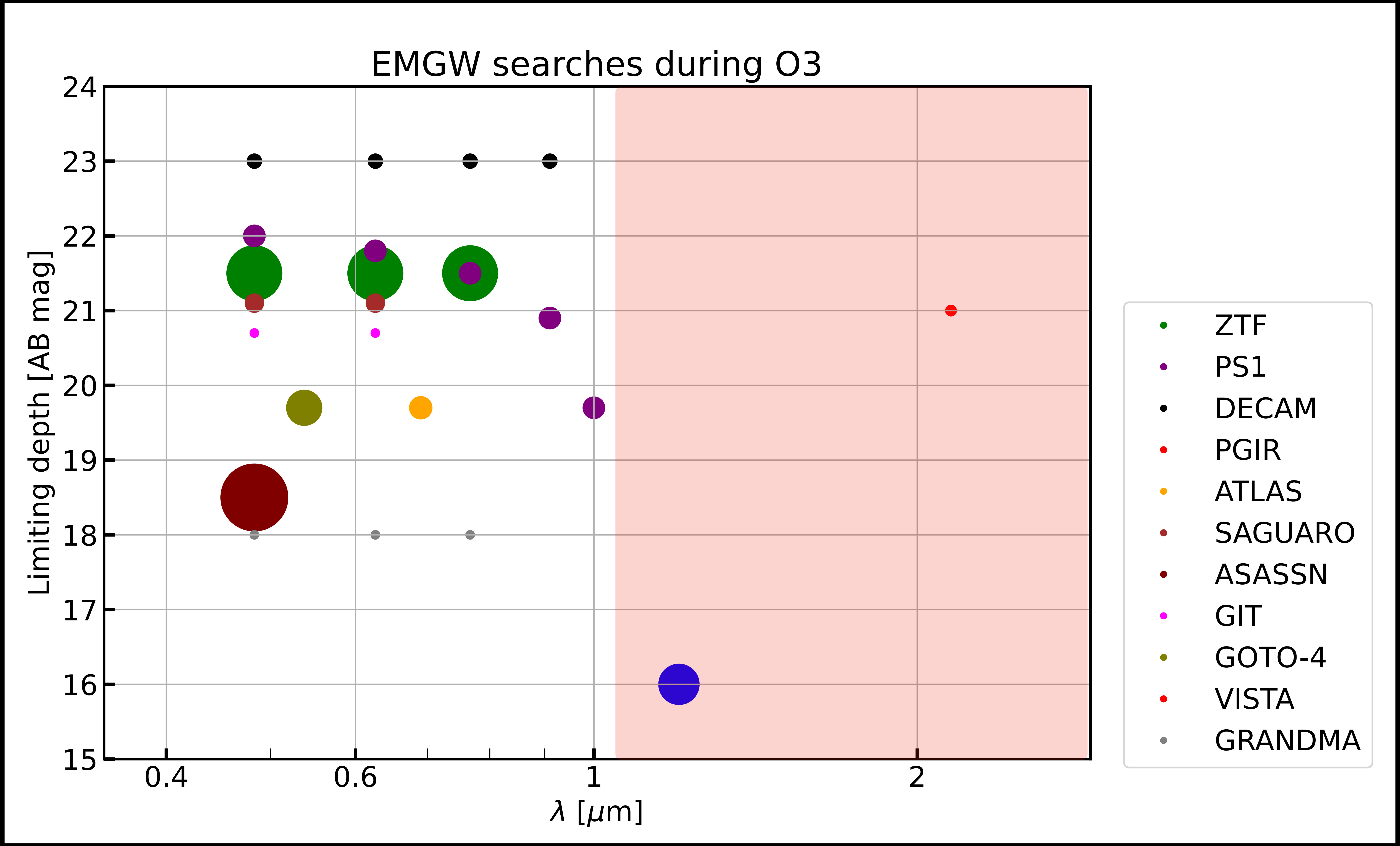




Simcoe et al. 2019, data from Kasen et al. 2017

Landscape of EMGW observations



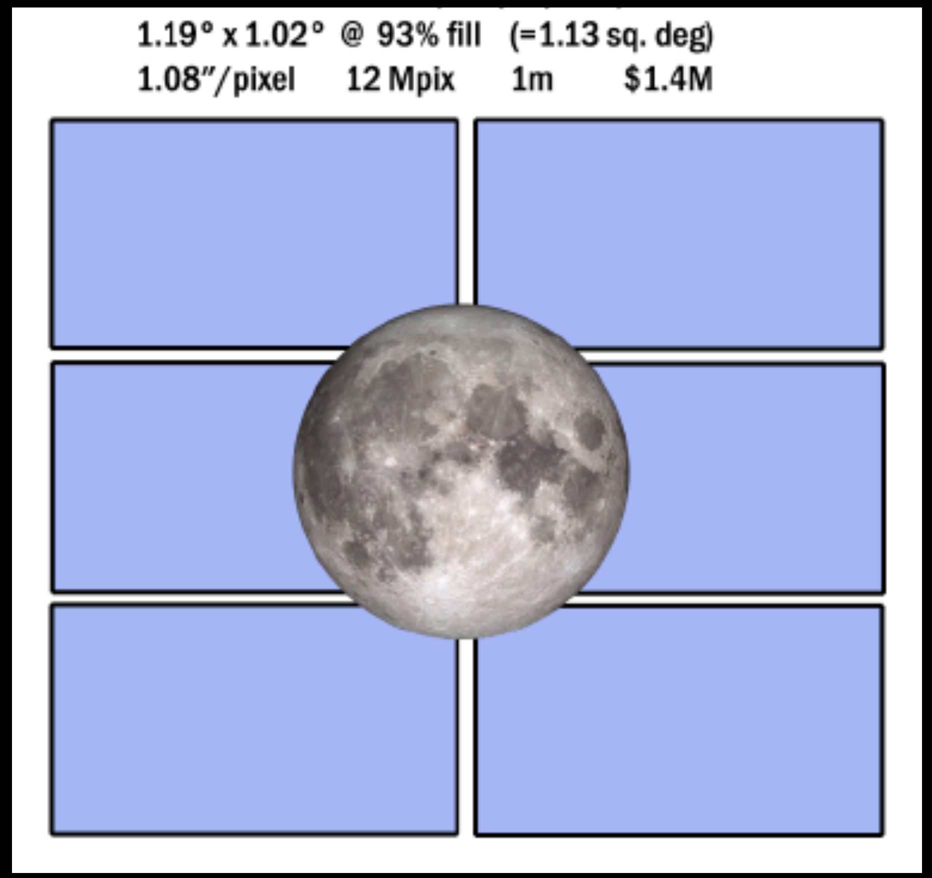
WINTER is coming!

WINTER

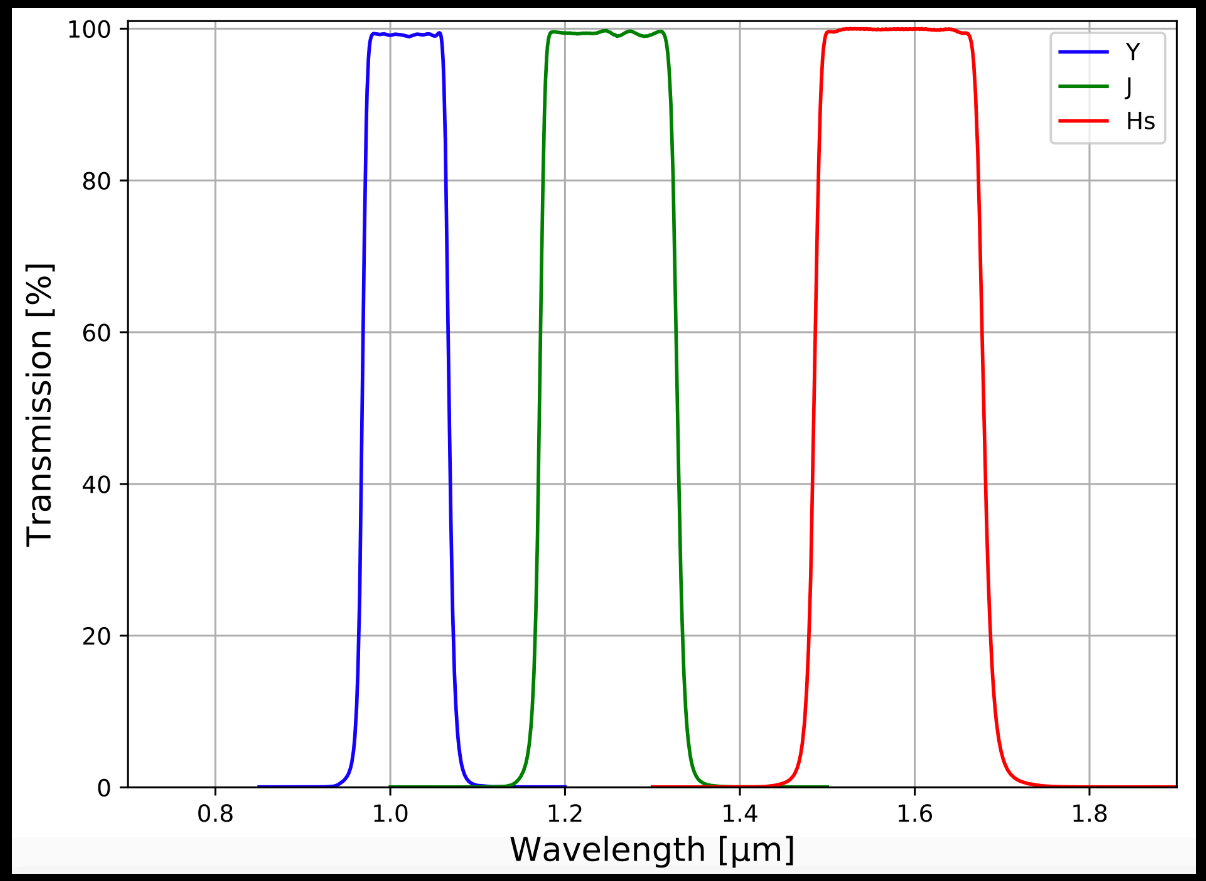
Poster by Danielle Frostig

Lourie et al. 2021

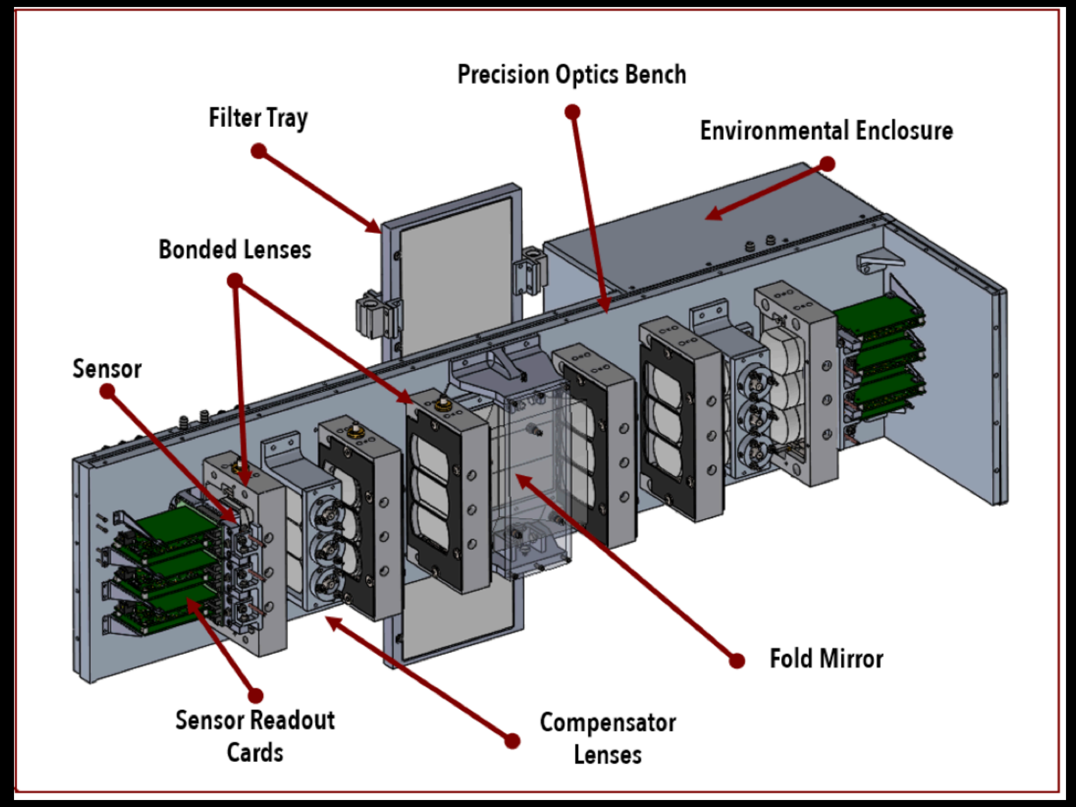
1-meter telescope



1.19 x 1.2 sq. deg FOV



Y, J, shortened H filters



Novel InGaAs sensors

On-sky Spring 2022, J-band all-sky survey to 21 mag

EMGW simulations with WINTER

arxiv : 2110.01622

with D. Frostig, S. Biscoveannu, G. Mo et al.

End-to-end simulation study

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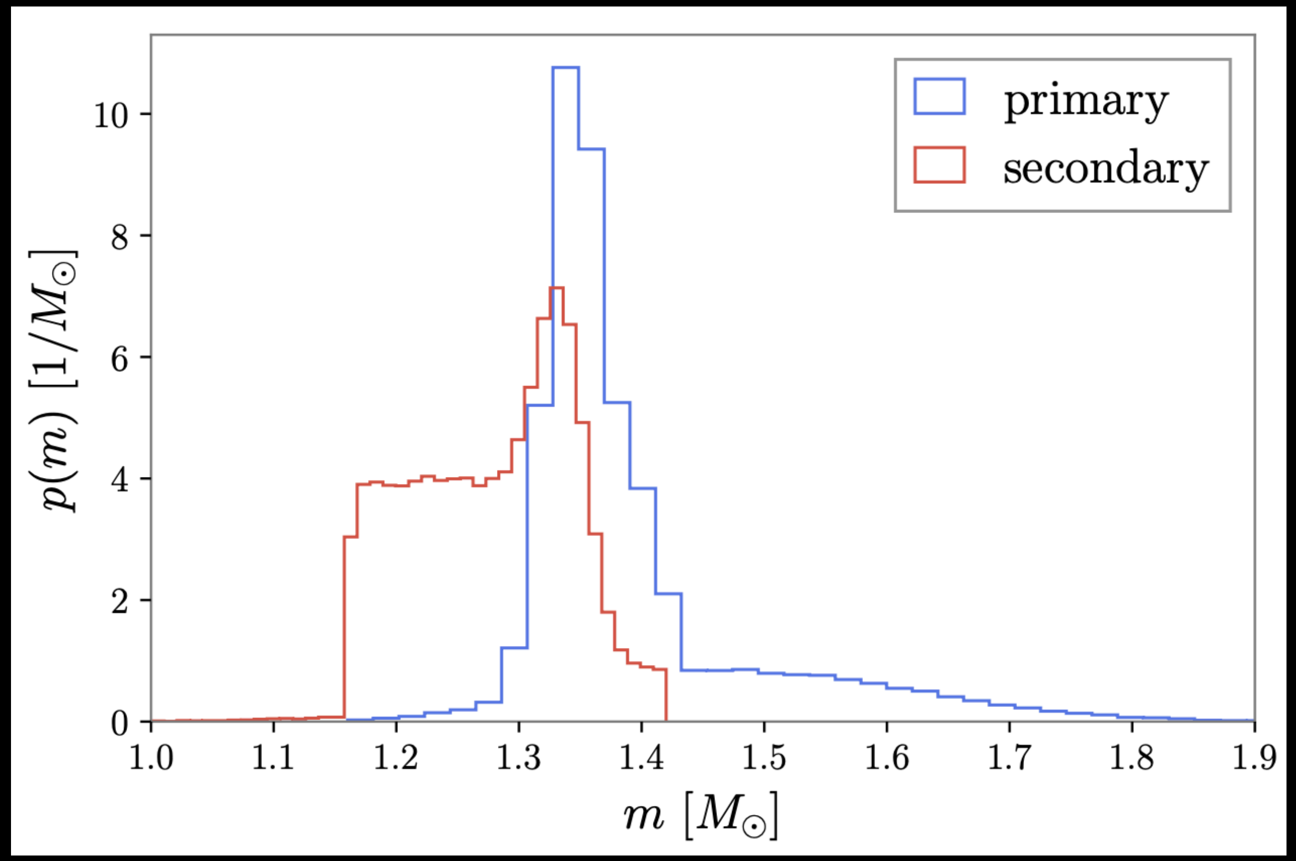
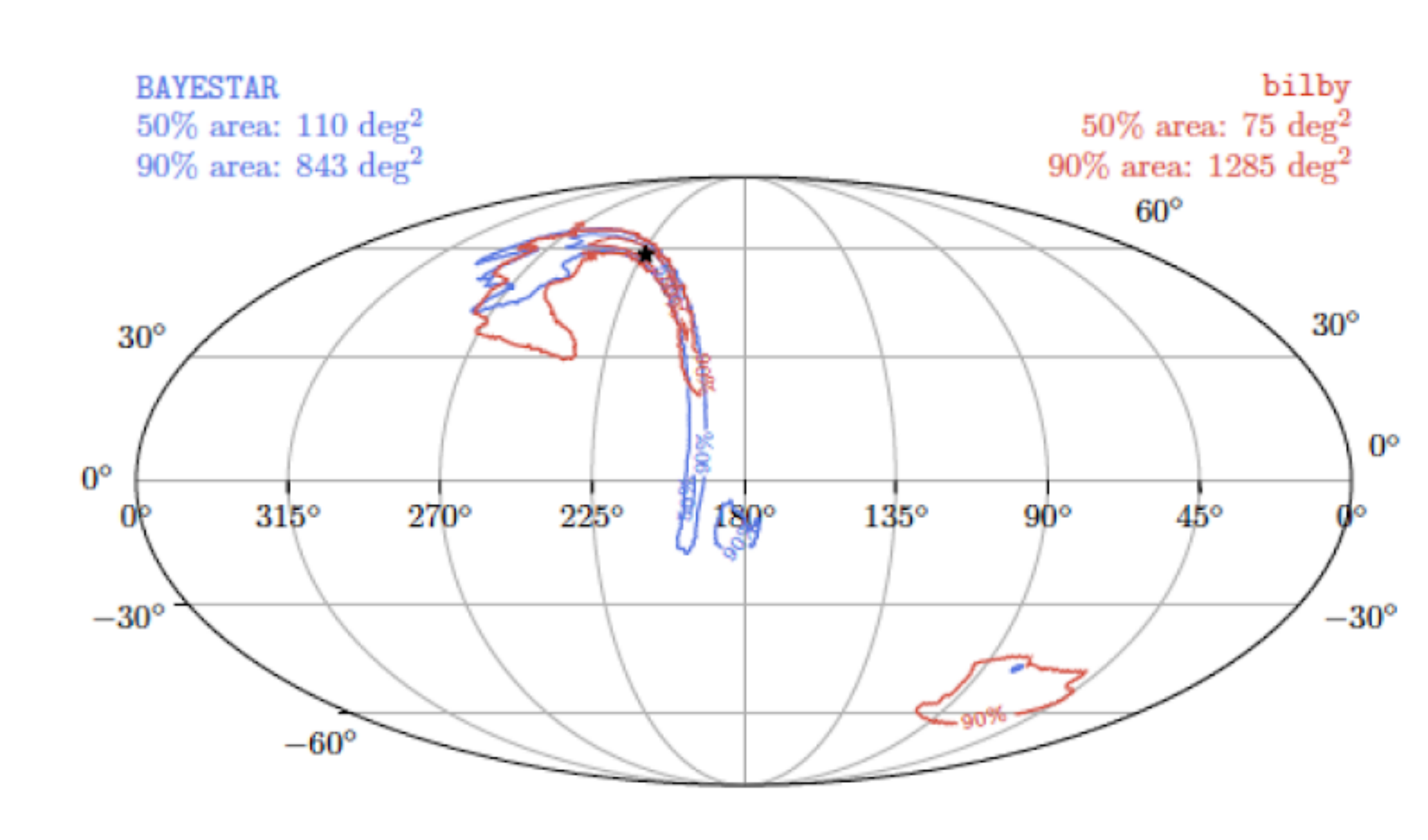
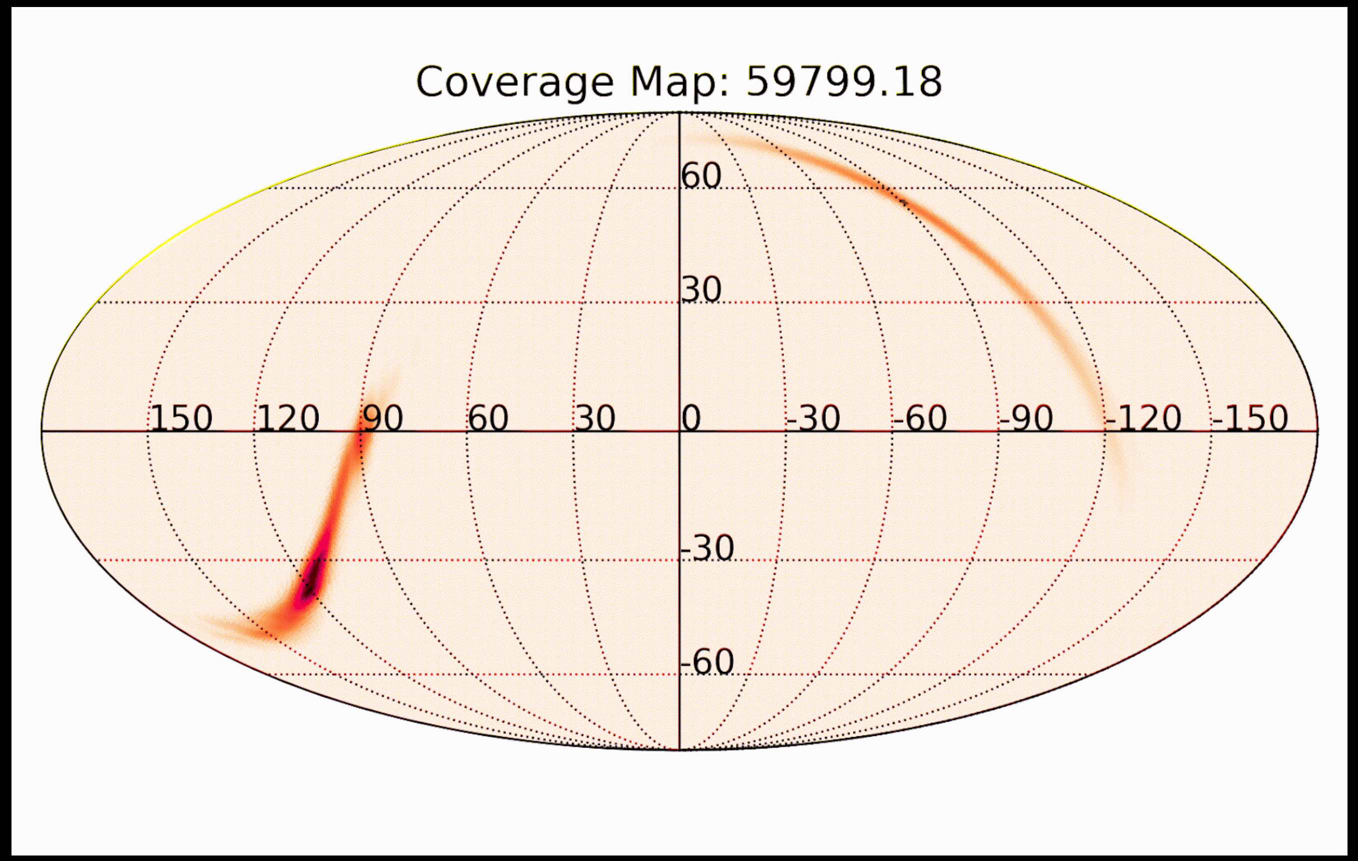


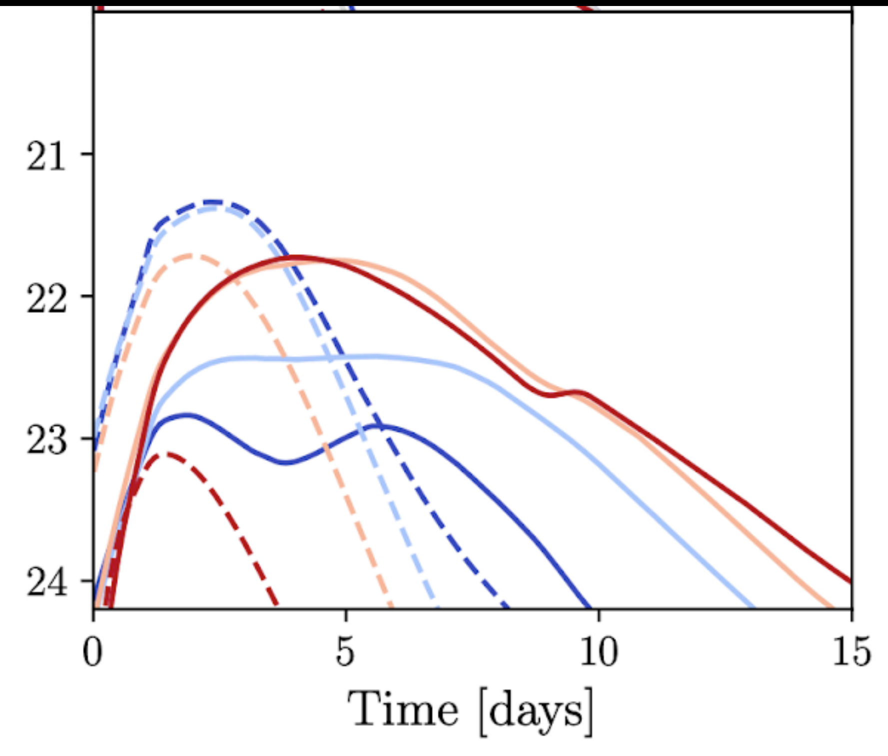




Simulate BNS mergers in the universe

Generate LVK skymaps

Optimal tiling with WINTER



Simulate expected electromagnetic emission

1 year of simulated BNS trigger followup during O4

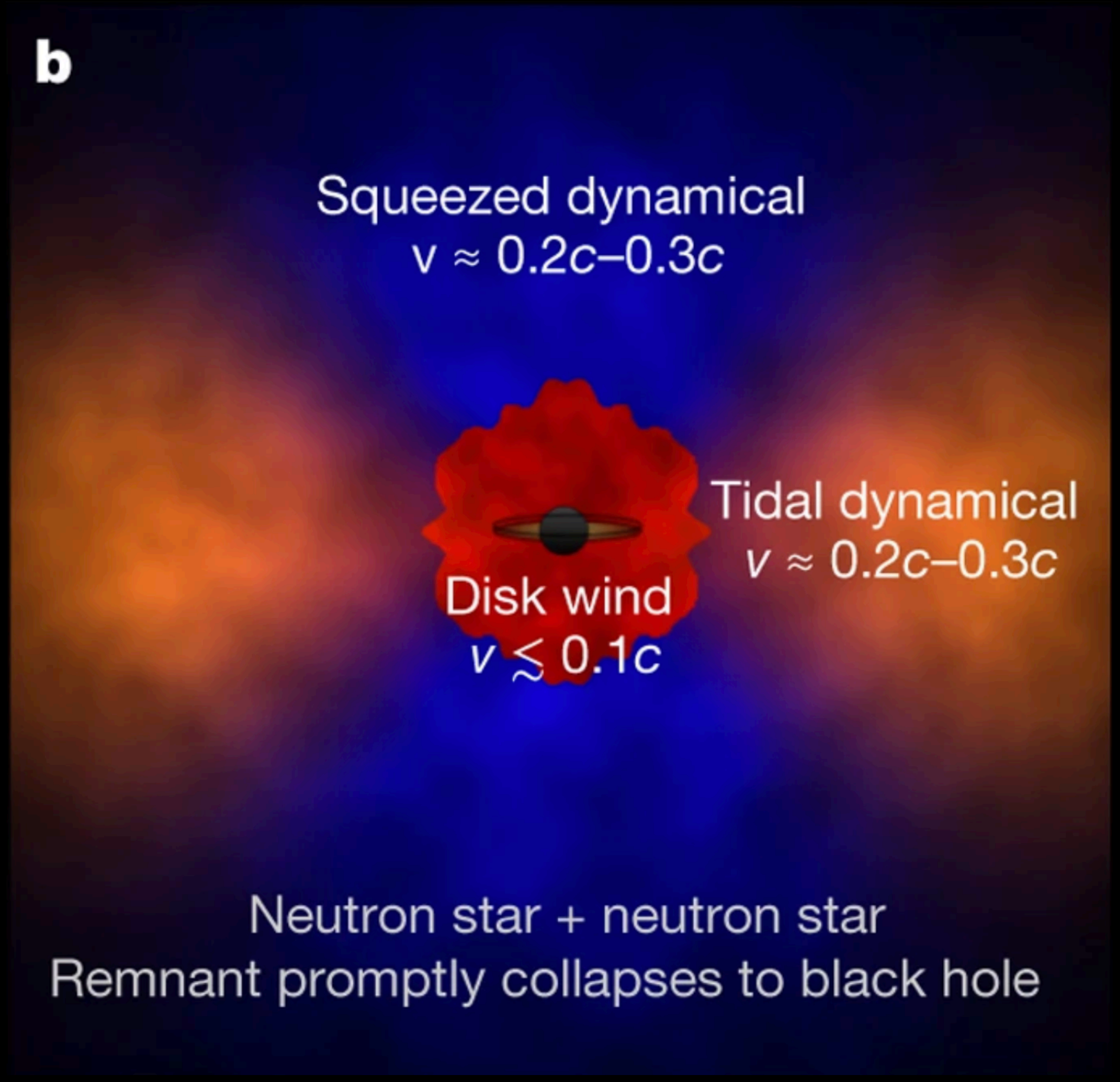
Simulation results

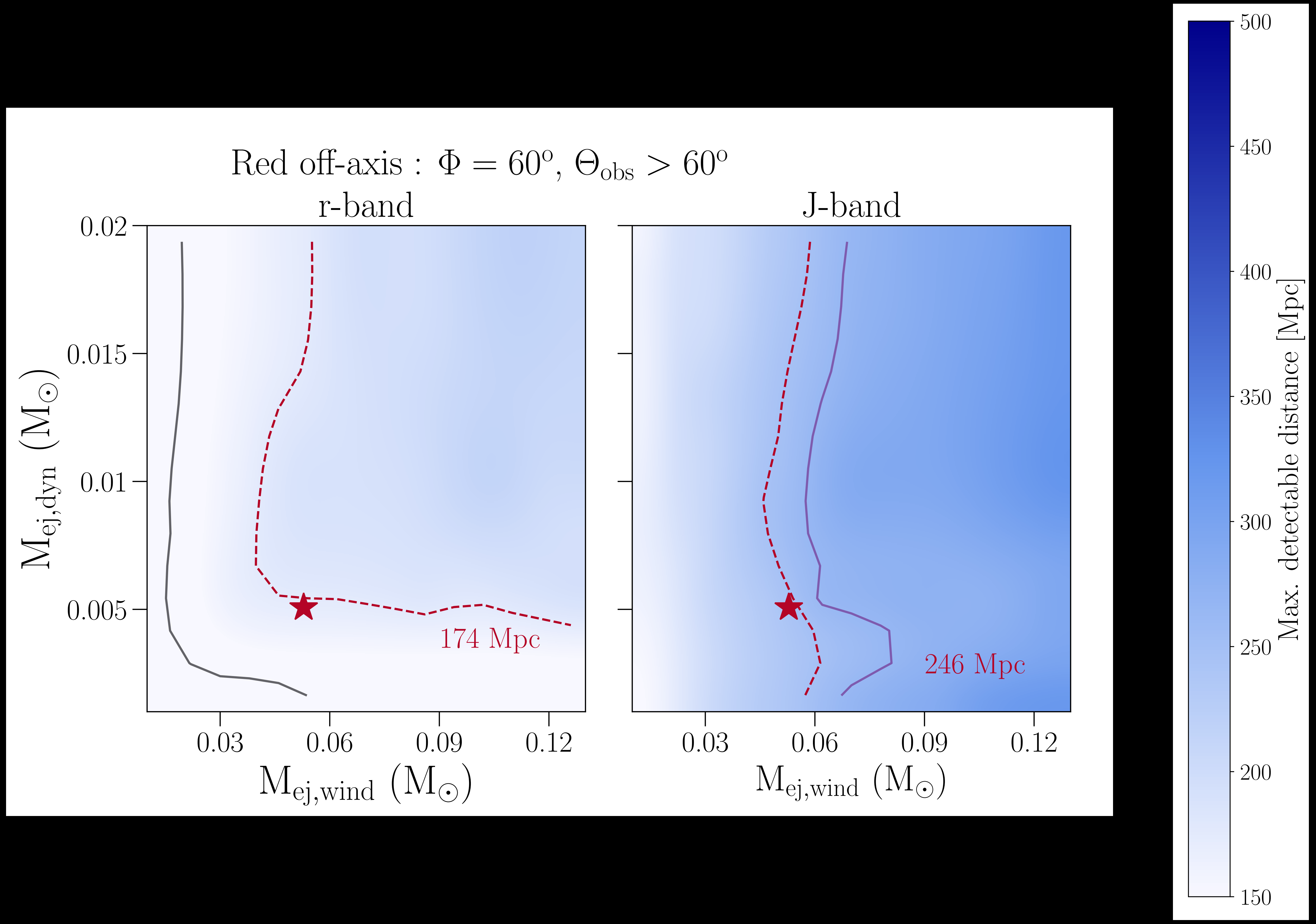
Rate	GW triggers	EM Accessible	Localized	Discovered			
				Bulla		Kasen	
	Events	Events	Events	Φ [°]	Events	$X_{\rm lan}$	Events
Realistic	16^{+6}_{-5}	11^{+5}_{-5}	5^{+3}_{-3}	30	1^{+2}_{-1}	10^{-2}	2^{+3}_{-2}
				45	1^{+2}_{-1}	10^{-3}	3^{+2}_{-2}
				60	1^{+2}_{-1}	10^{-4}	1^{+2}_{-1}
						10^{-5}	0^{+1}_{-0}

Even with a 1 sq. deg FOV, WINTER can efficiently tile localization areas and discover kilonovae!

Advantages of NIR

Off-axis, red BNS mergers are detectable to much larger distances

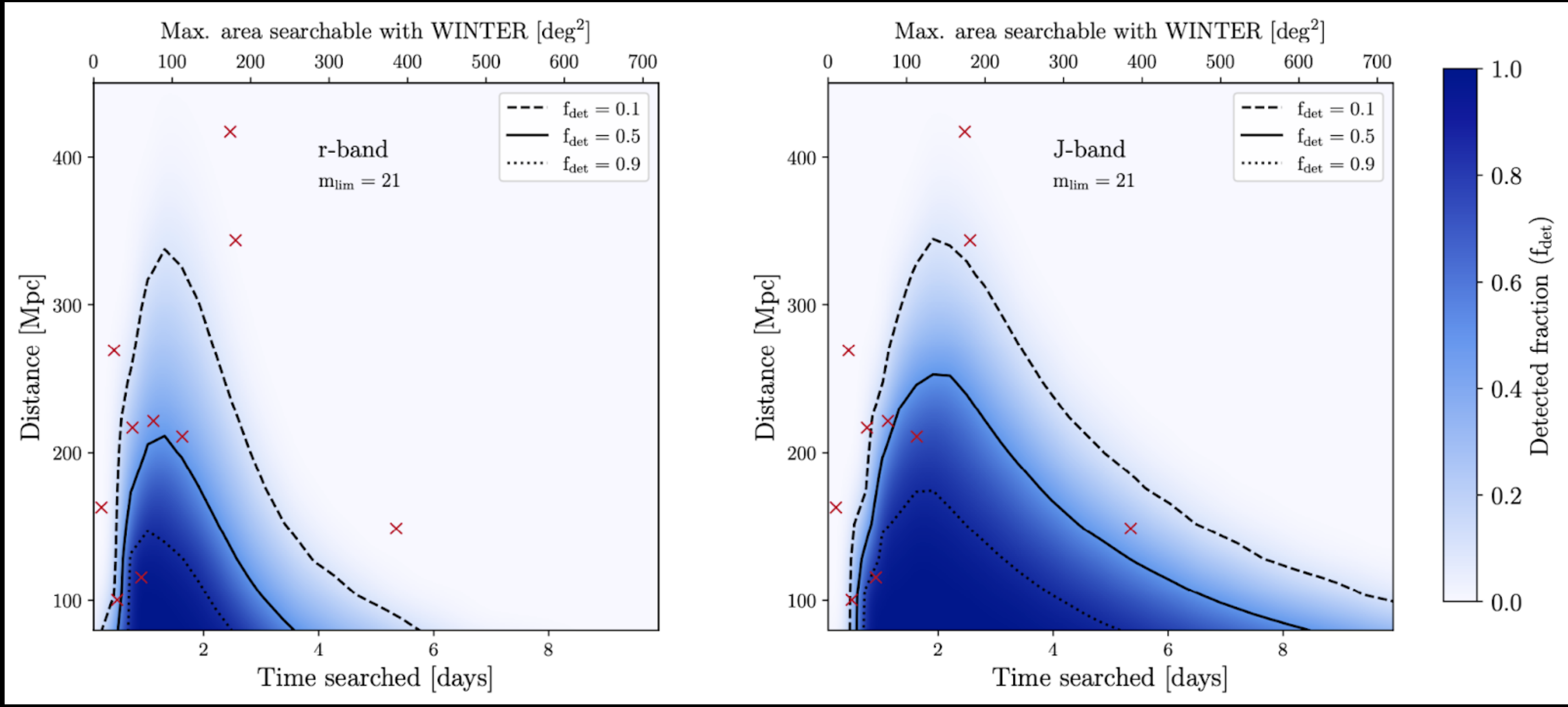




~ 25% of LIGO detected BNS mergers are "off-axis"

Advantages of NIR

BNS mergers are 2x longer lived in the NIR



NSBH mergers are even redder!

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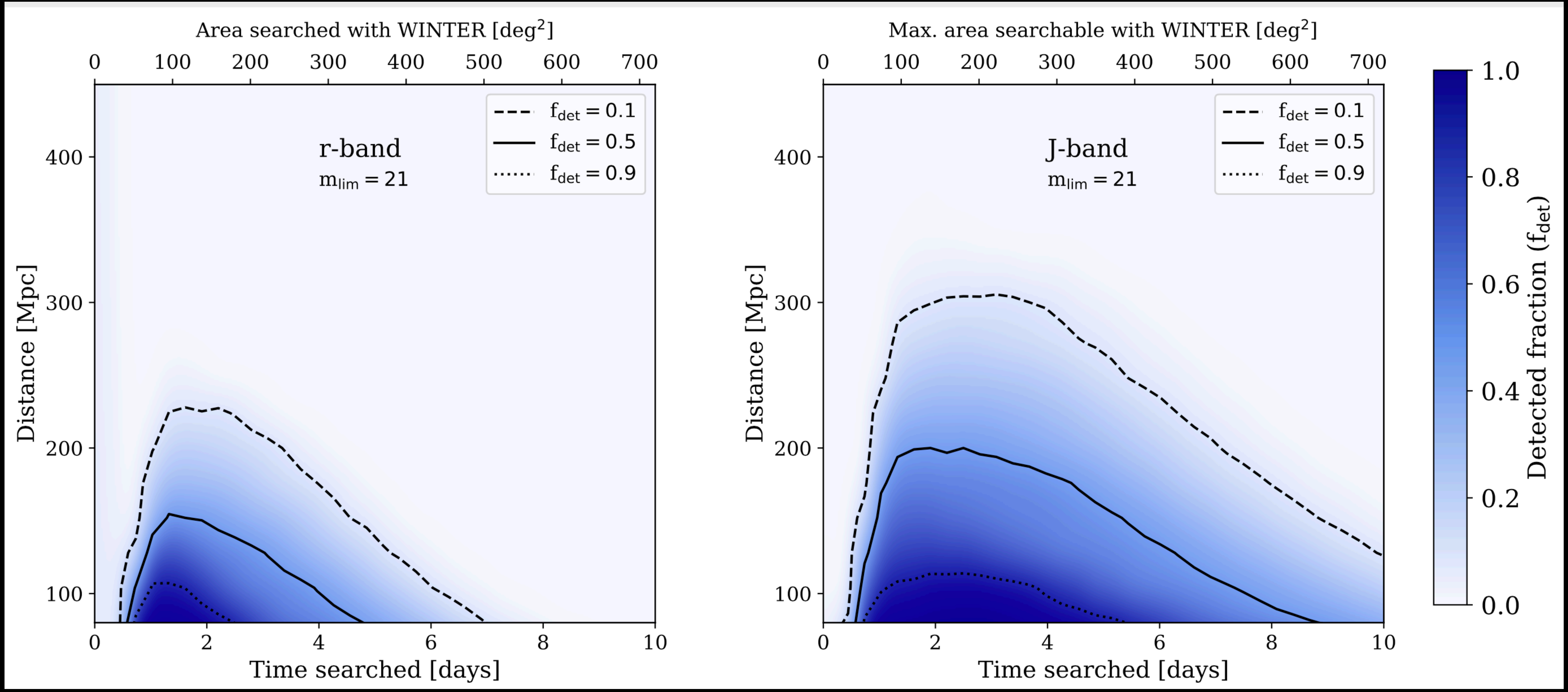


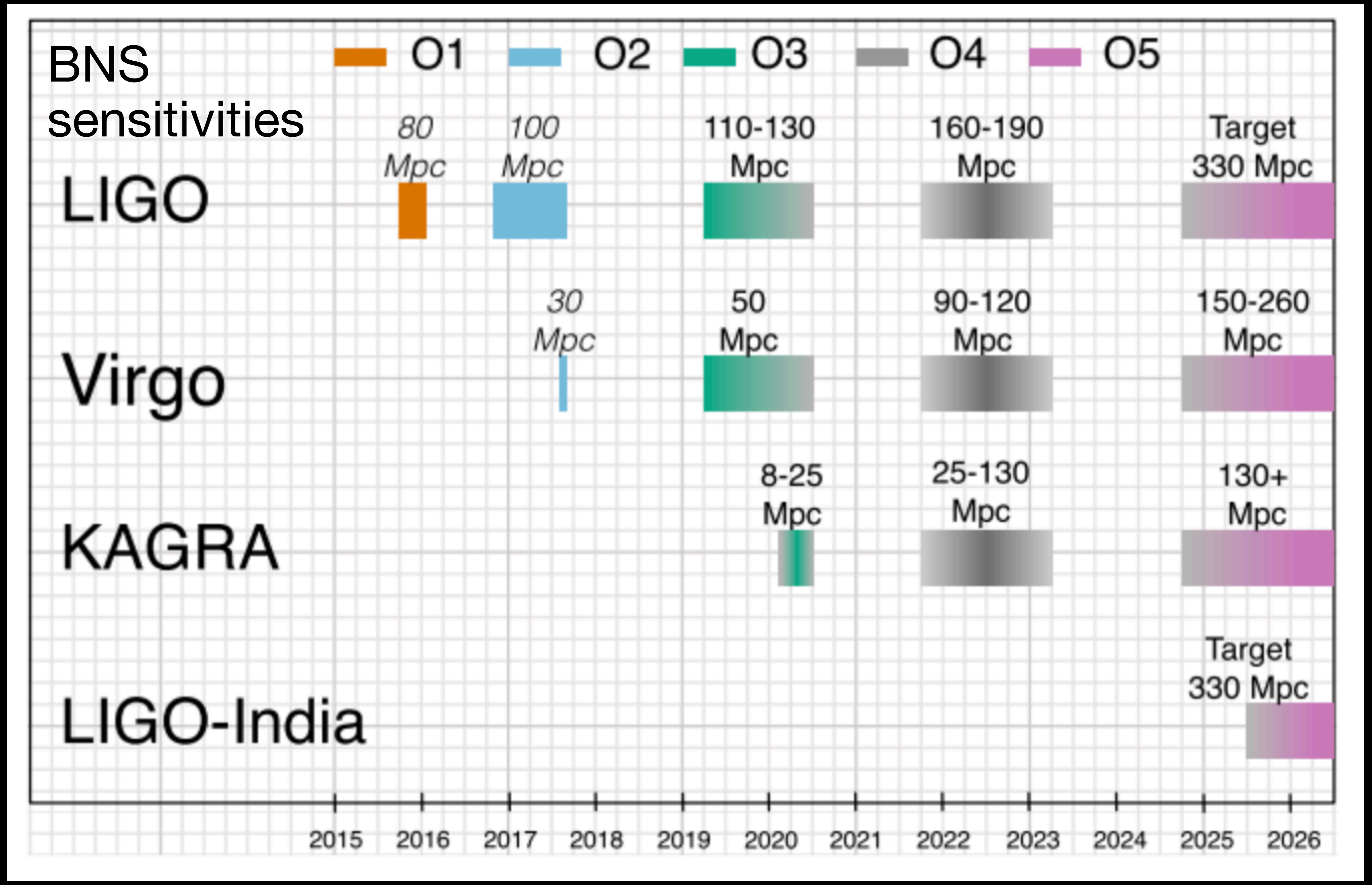
Takeaways from WINTER simulation

- 1 sq. deg NIR telescope can tile O4 localizations and discover kilonovae
- NIR searches have ~2x longer to search for kilonovae than optical searches
- NIR searches are especially crucial to search for red, off-axis BNS mergers (1/4 of all BNS mergers) and all NSBH mergers.

Looking forward

Wide-field INfrared Transient ExploreR

- Improved GW detectors!



LIGO LRR

NSBH target sensitivities ~600 Mpc

- New wide-field NIR telescopes!

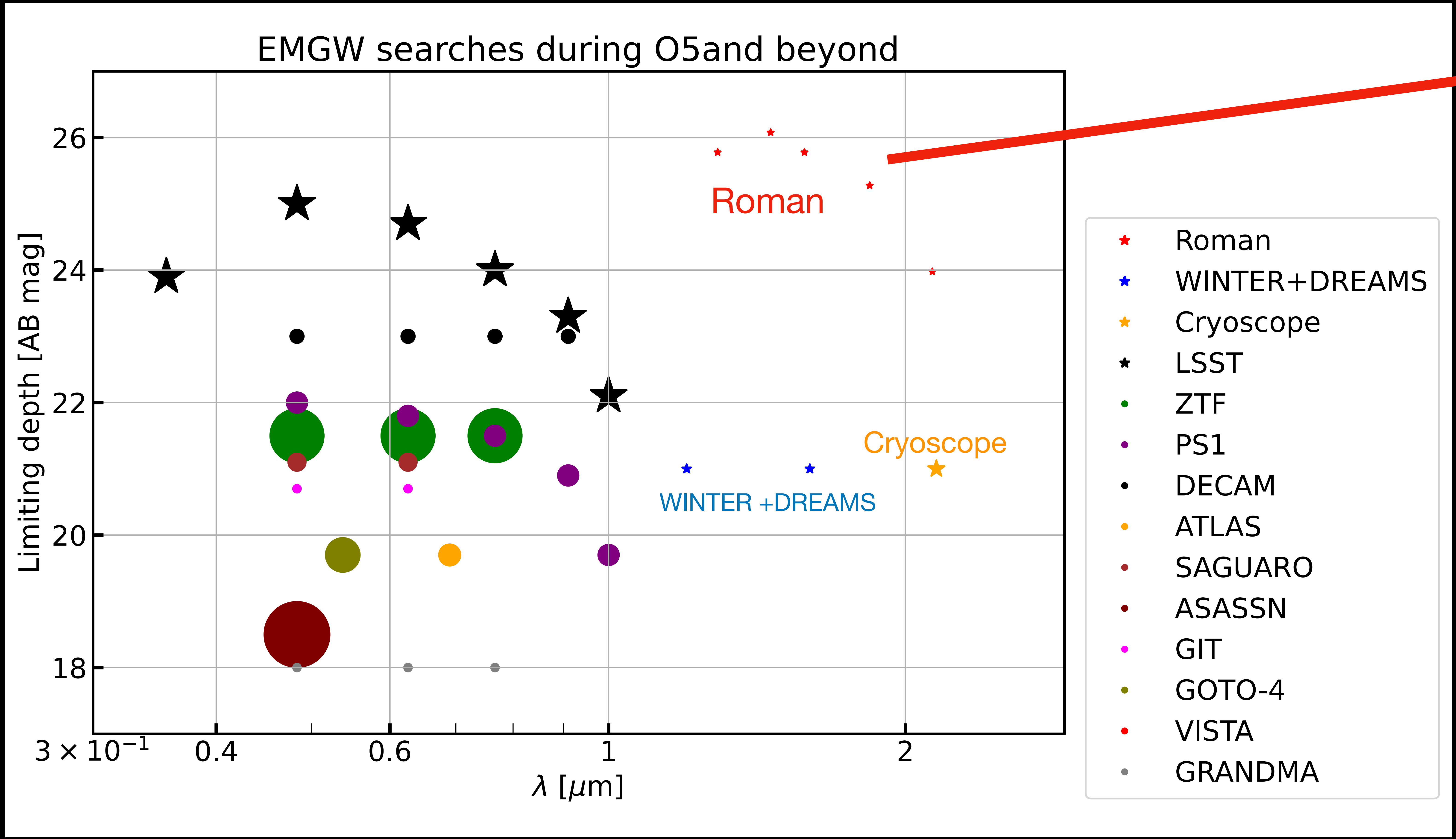
DREAMS at Siding Springs

Cryoscope at Palomar

Roman!

Image credit : NASA

Roman era



Roman era will have 4 active GW detectors.

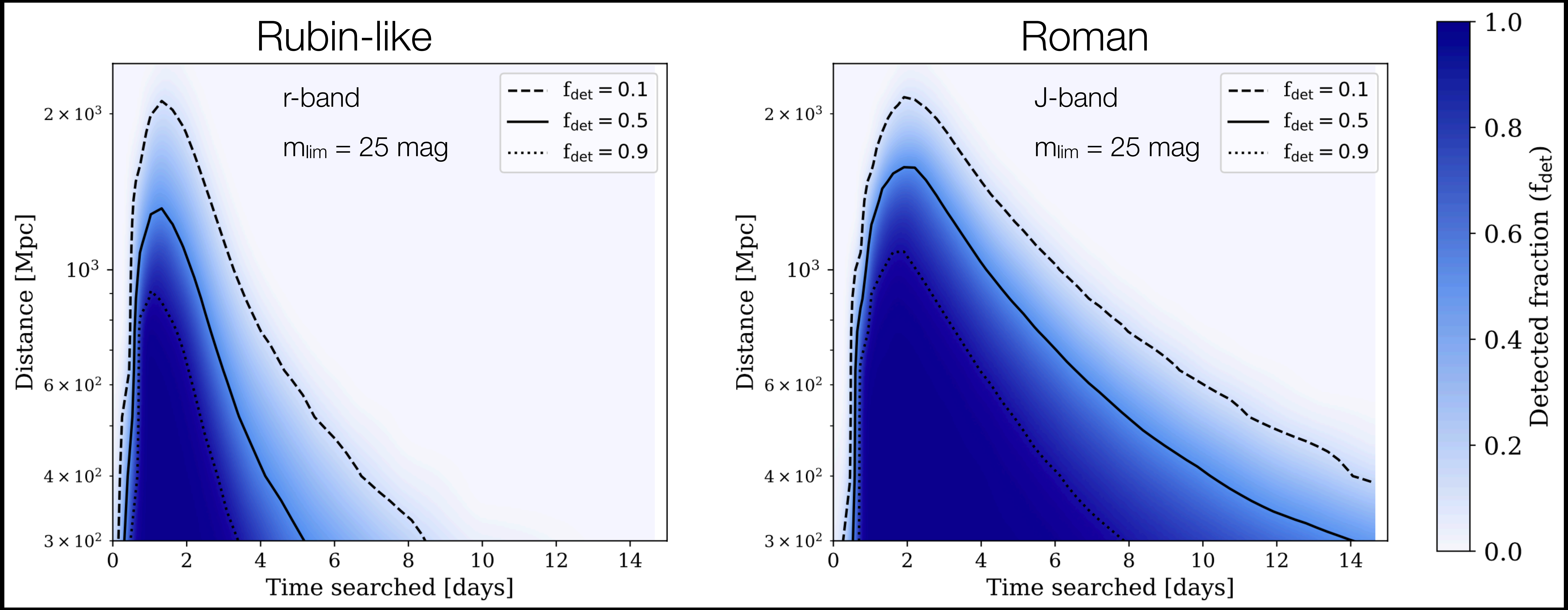
We expect several (tens) events localized to areas better than 10 sq. deg

Abbott et al. 2020b, Petrov et al. 2021

Advantages of Roman

Wide-field INfrared Transient ExploreR

BNS mergers



Summary

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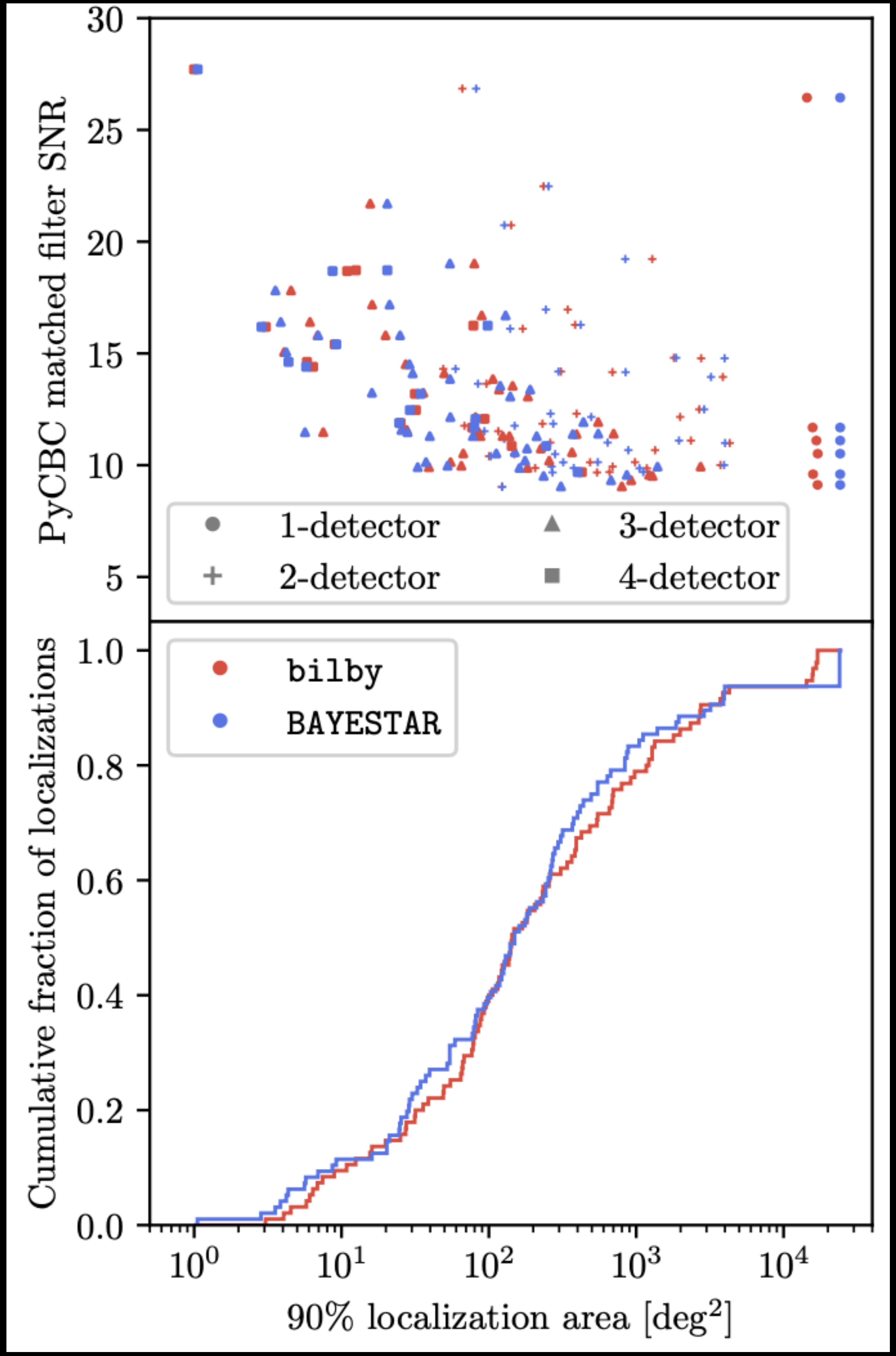
- WINTER simulation shows it is possible to discover kilonovae with ~1 sq. deg. NIR telescopes during LIGO O4.
- In LIGO O5+, NIR observations will be especially crucial to map out the phase space of distant BNS and NSBH mergers.
- In the Roman era, the GW localizations are predicted to be small enough that they can be tiled with a few Roman-pointings.
- Roman promises to be a pioneering telescope to increase our understanding of the fireworks accompanying gravitational waves !

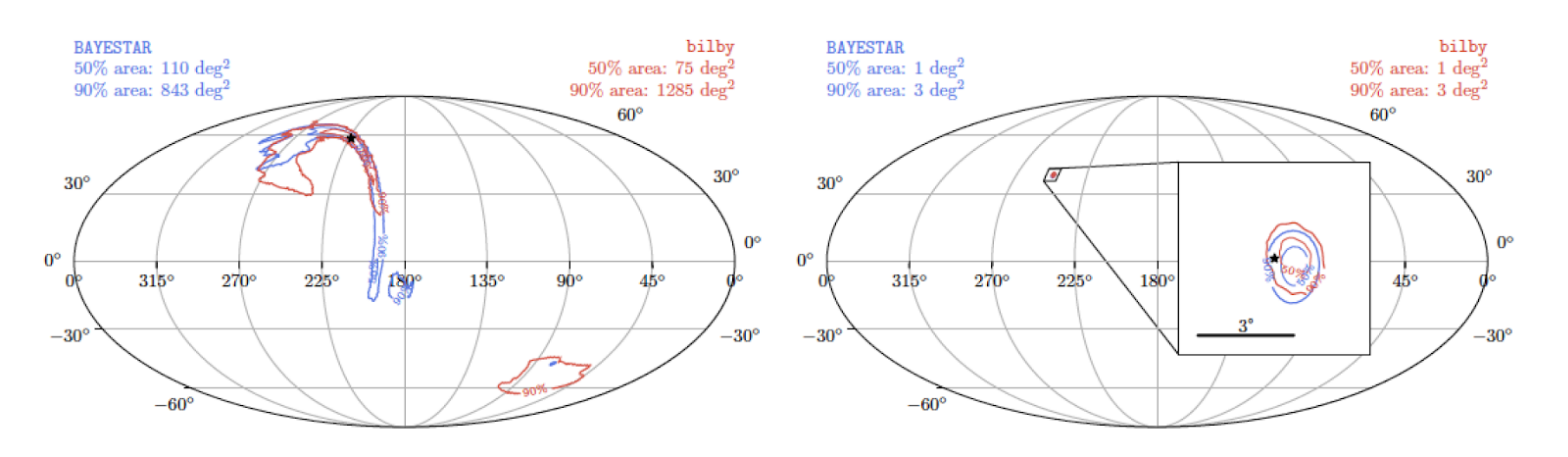
Backup

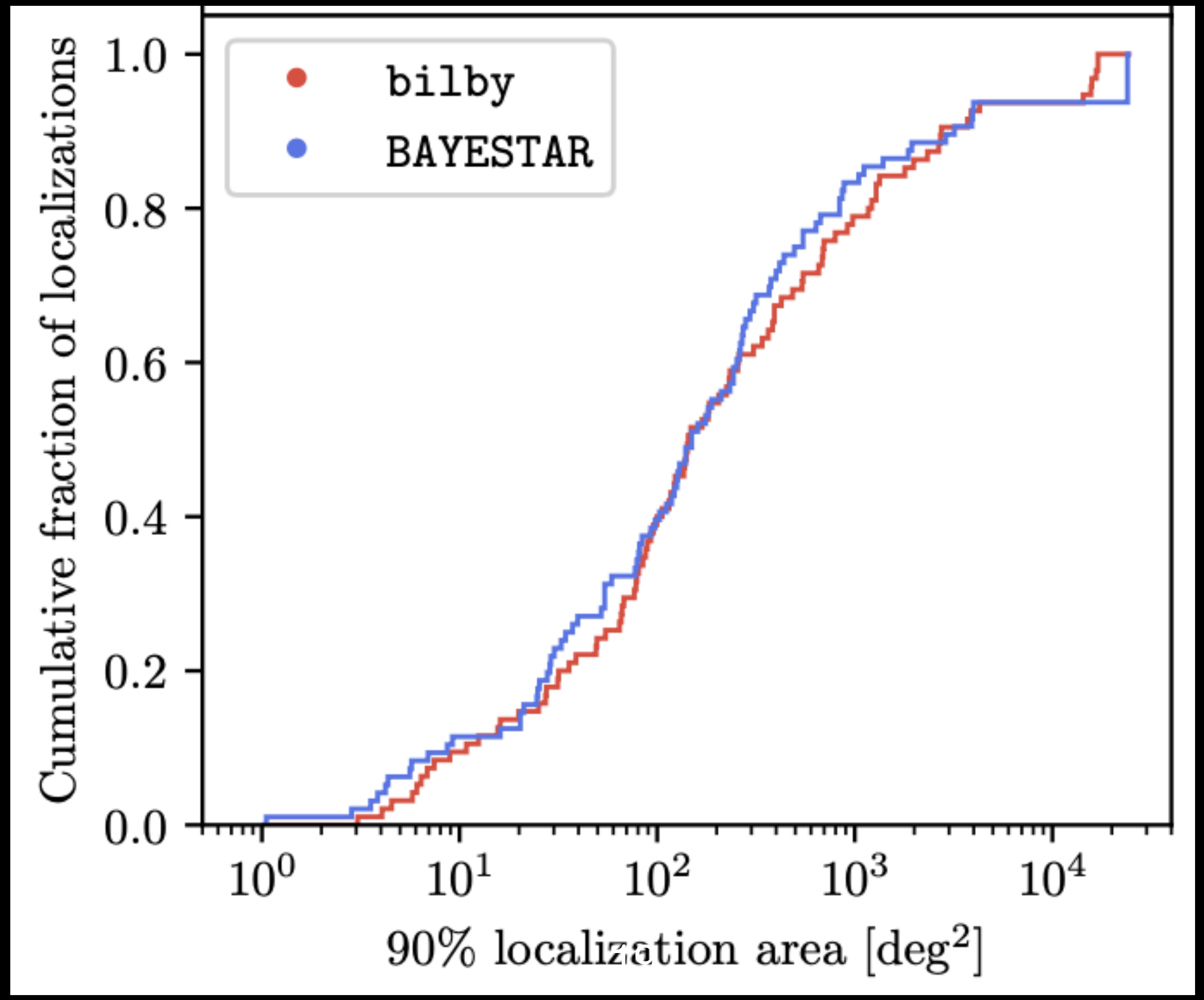
Backup



PyCBC matched filter SNR
30
25
20
15
10
5
1-detector
2-detector
3-detector
4-detector
bilby
BAYESTAR
Cumulative fraction of localizations
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1
10^2
10^3
10^4
90% localization area [deg^2]

Skymap comparisons





WINTER team

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  - Nate Lourie (Project Scientist)
  - Erik Hinrichsen (Mechanical Engineer)
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  - Kishalay De (Postdoc)
  - Kevin Burdge (Postdoc)
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  - Hsin-Yu Chen (Postdoc)
  - **Sylvia Biscoveanu (PhD Student)**
  - **Geoffrey Mo (PhD Student)**

Wide-field INfrared Transient ExploreR

2. LVK search + skymaps

- Events searched with PyCBC-Live
  - Four detectors with noise and sensitivities from latest observing scenarios paper
  - TaylorF2 model template bank
- SNR > 9 : criterion for detection
- Low latency skymaps with Bayestar ~ O(10 seconds)
- Medium latency skymaps with bilby ~ O (few hours)

4. Lightcurves

- Many kilonova models exist in literature
- Need to know how much mass is ejected during the merger

Graphic credit : NASA

m_1, m_2

Fitting formulae to NR simulations

$$\log_{10} M_{\rm ej}^{\rm dyn} = \left[a \frac{(1-2C_1)\, m_1}{C_1} + b\, m_2 \left(\frac{m_1}{m_2} \right)^n + \frac{d}{2} \right] + [1 \leftrightarrow 2] \quad (4$$

$$v_{\rm ej} = \left[a'' \frac{m_1}{m_2} (1 + c''\, C_1) + \frac{b''}{2} \right] + [1 \leftrightarrow 2],$$

Graphic credit : GRANDMA collaboration

M_{ej}^{dyn}, M_{ej}^{wind}, v_{ej}

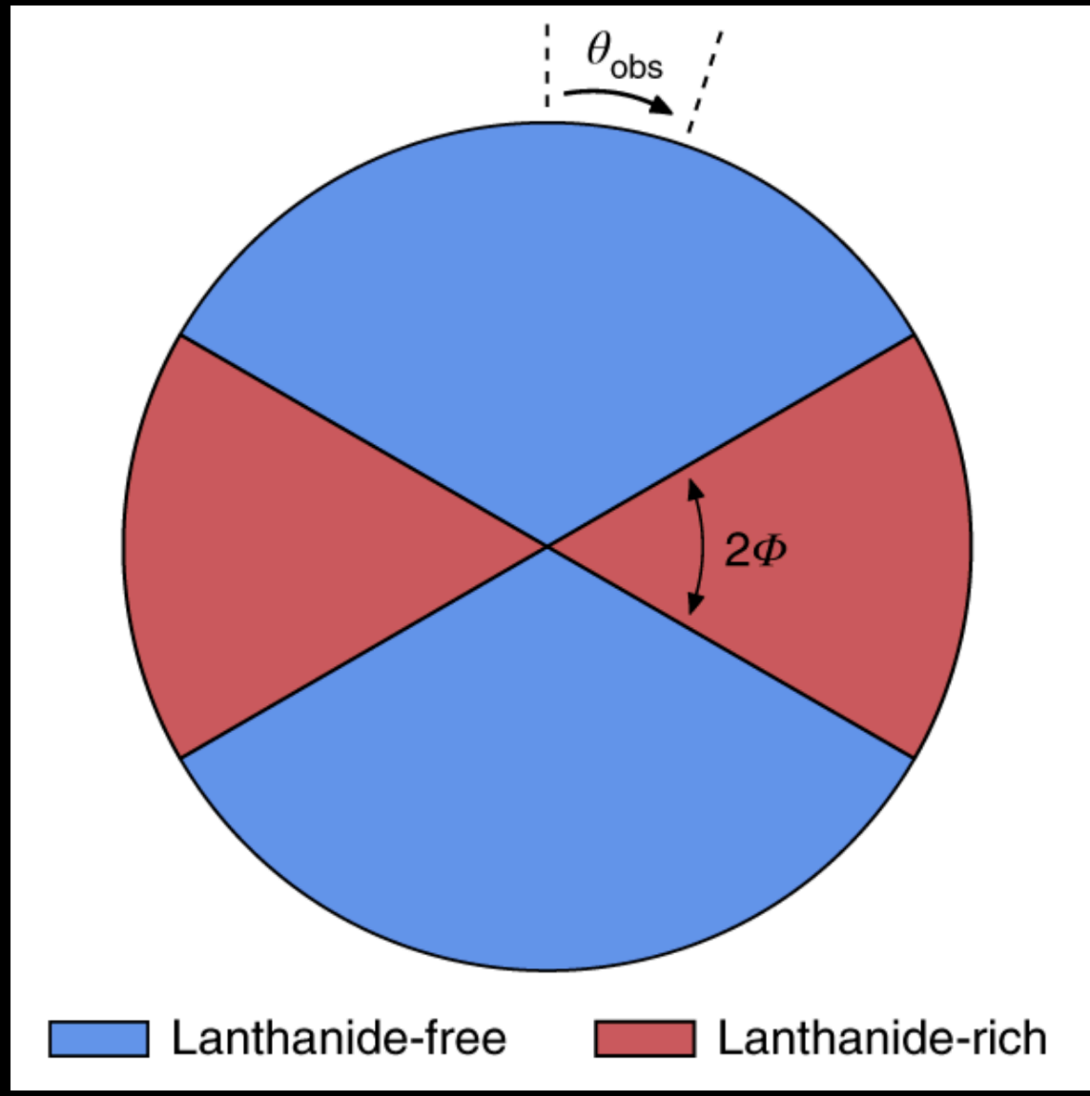
Anand et al. 2020, Coughlin et al. 2019, Dietrich et al. 2020

4. Lightcurves

Models

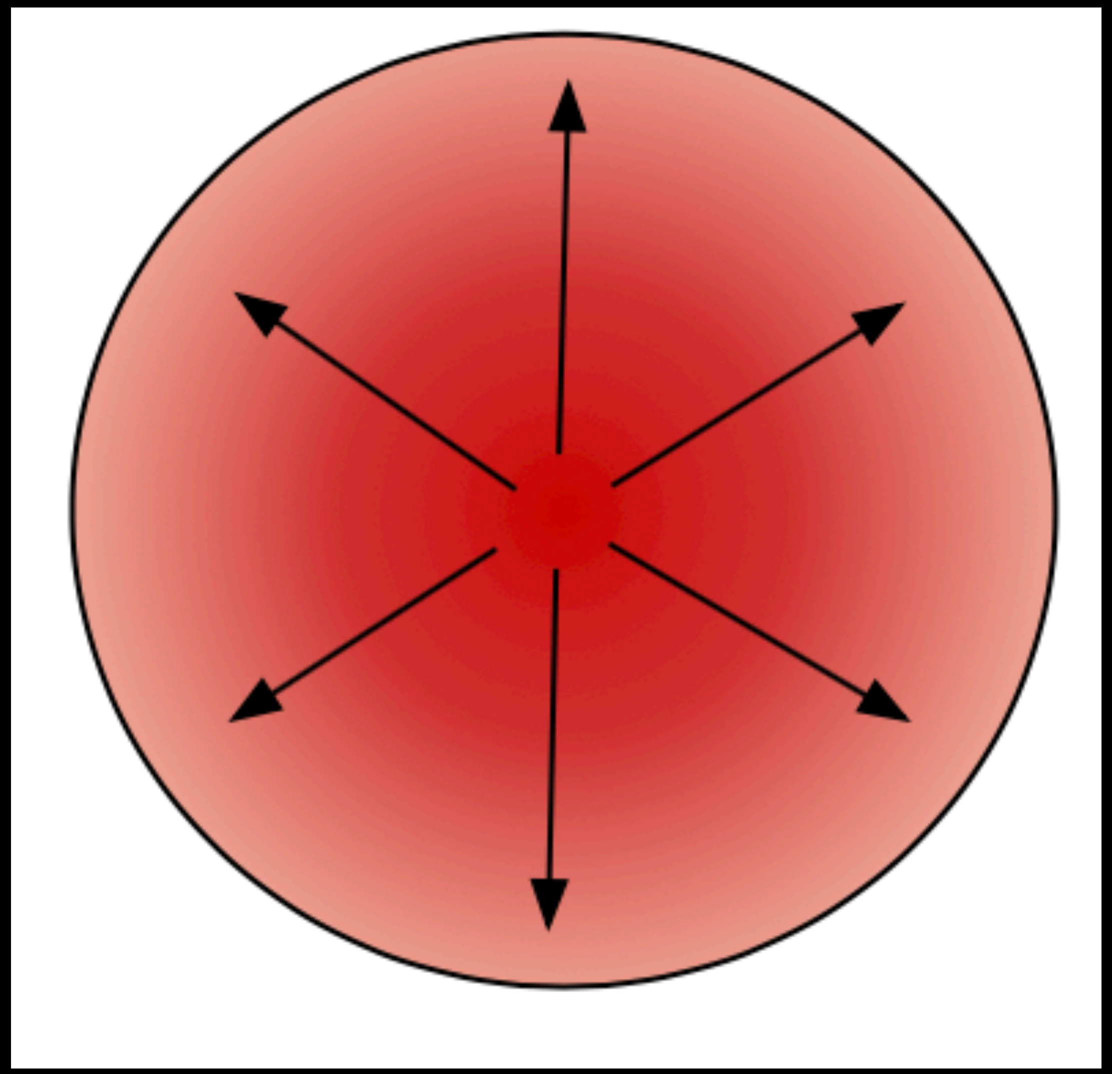
Bulla et al. 2019

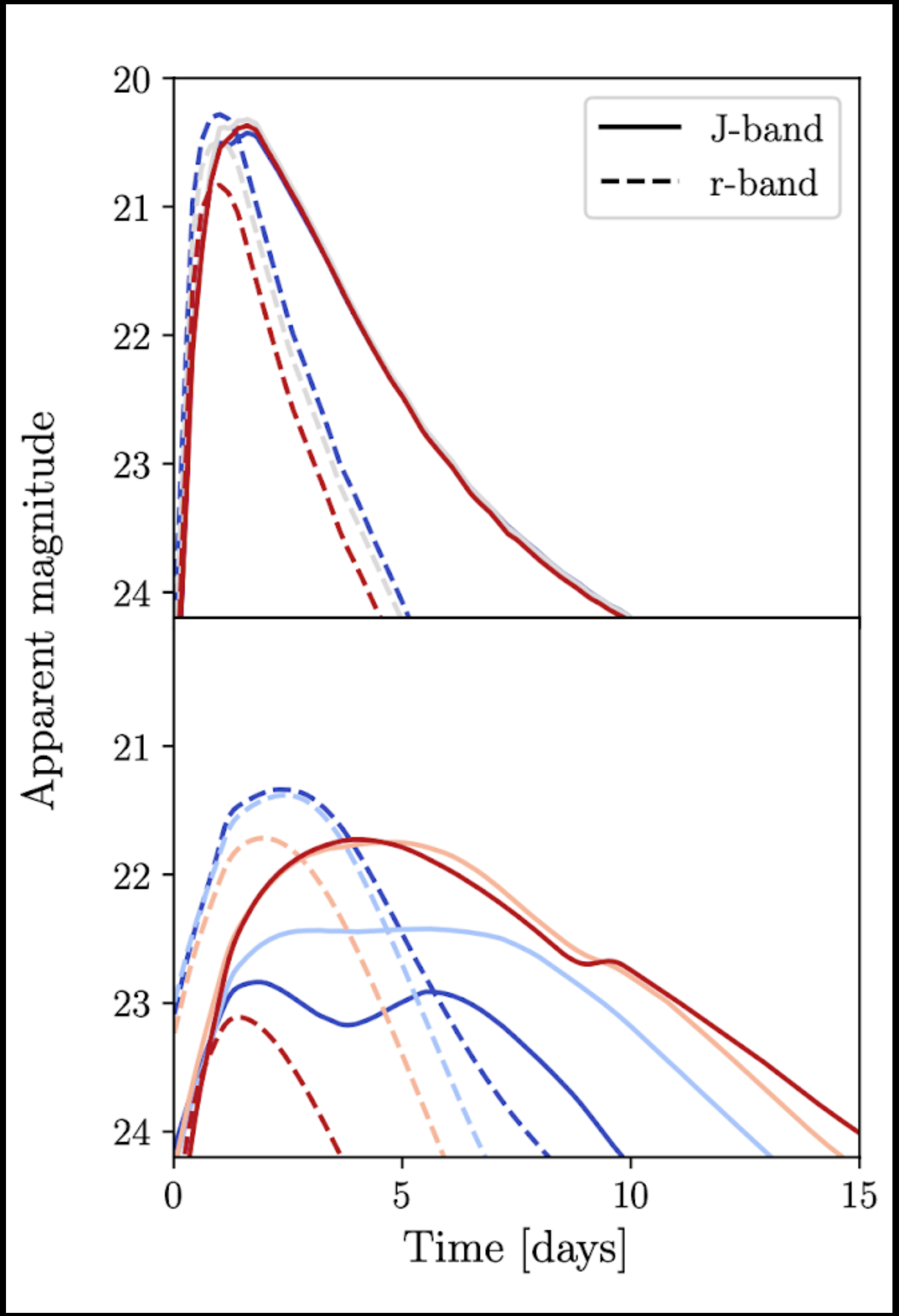
- Realistic geometry
- No control on composition



Kasen et al. 2017

- Spherically symmetric
- Detailed microphysics





Graphic credit : D. Frostig

Observing strategies

What exposure times to use?

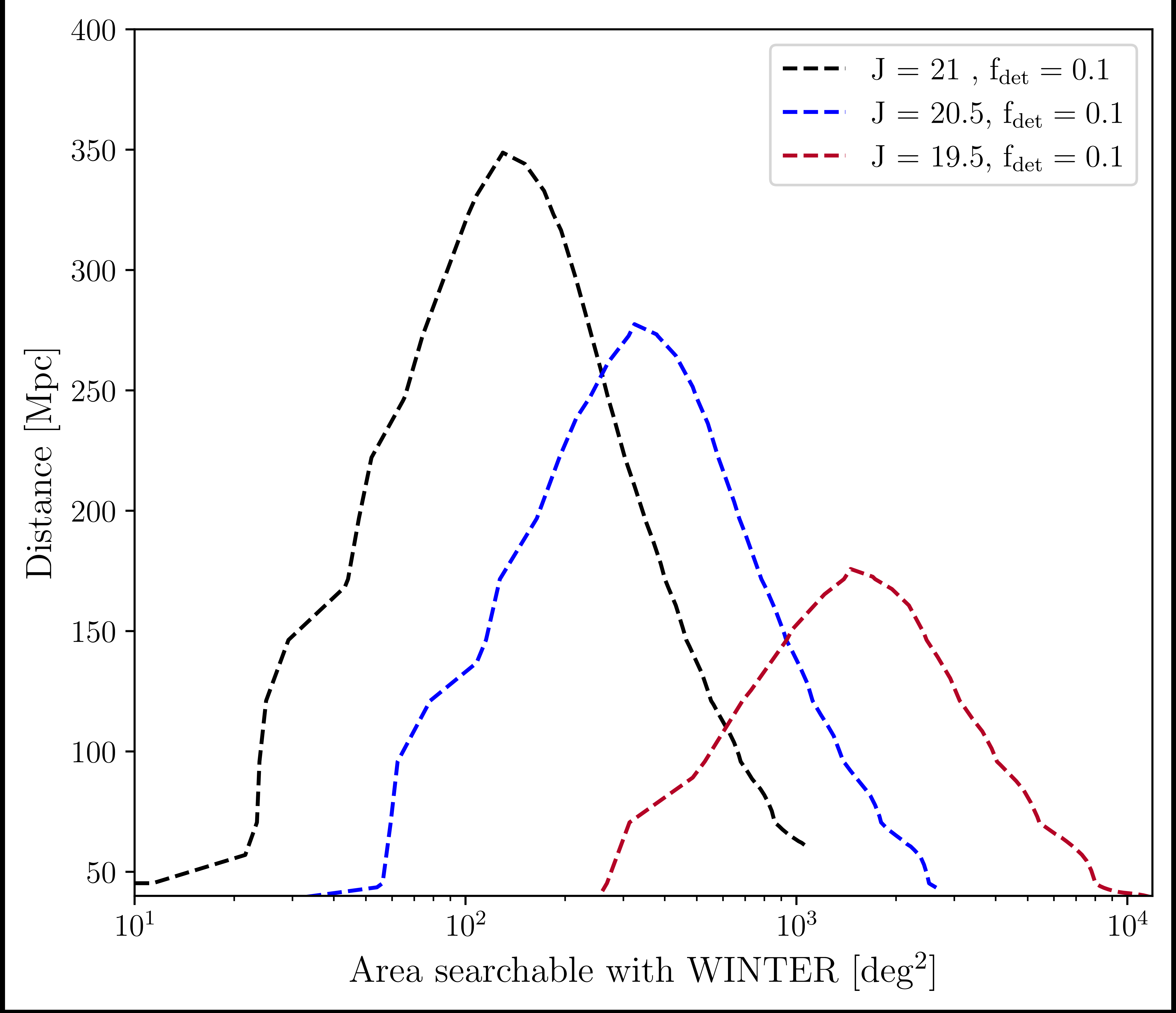
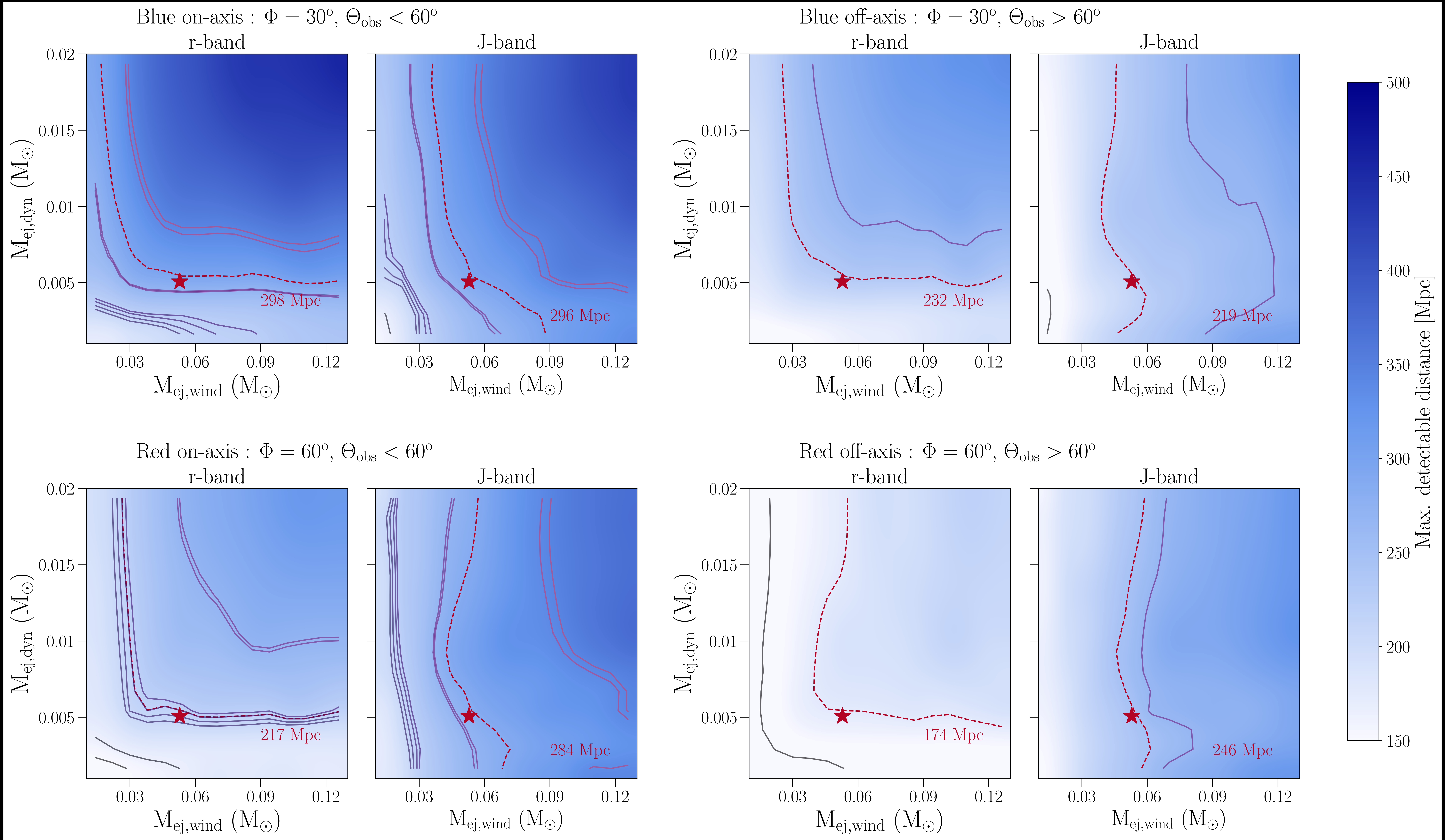


Table 1. Number of BNS mergers occurring and detected in gravitational-waves for each rate considered in this manuscript during one calendar year of O4. The first column indicates the total number of mergers, while the second column gives the median and 90% symmetric credible interval on the number of systems detected in gravitational waves obtained by averaging over the 101 different realizations of BNS merger combinations. Also included are the number of unique pairs of events that are found in gravitational waves within one day and one week of each other.

Rate	Mergers	Found	1 day	1 week
Pessimistic	21	3^{+3}_{-2}	0^{+0}_{-0}	0^{+1}_{-0}
Realistic	105	16^{+6}_{-5}	1^{+1}_{-1}	6^{+7}_{-5}
Optimistic	210	33^{+7}_{-7}	4^{+4}_{-3}	26^{+19}_{-11}



Blue on-axis : Φ = 30°, Θobs < 60°
Blue off-axis : Φ = 30°, Θobs > 60°
Red on-axis : Φ = 60°, Θobs < 60°
Red off-axis : Φ = 60°, Θobs > 60°
r-band
J-band
Mej,dyn (M☉)
Mej,wind (M☉)
0.005
0.01
0.015
0.02
0.03
0.06
0.09
0.12
298 Mpc
296 Mpc
232 Mpc
219 Mpc
217 Mpc
284 Mpc
174 Mpc
246 Mpc
Max. detectable distance [Mpc]
150
200
250
300
350
400
450
500

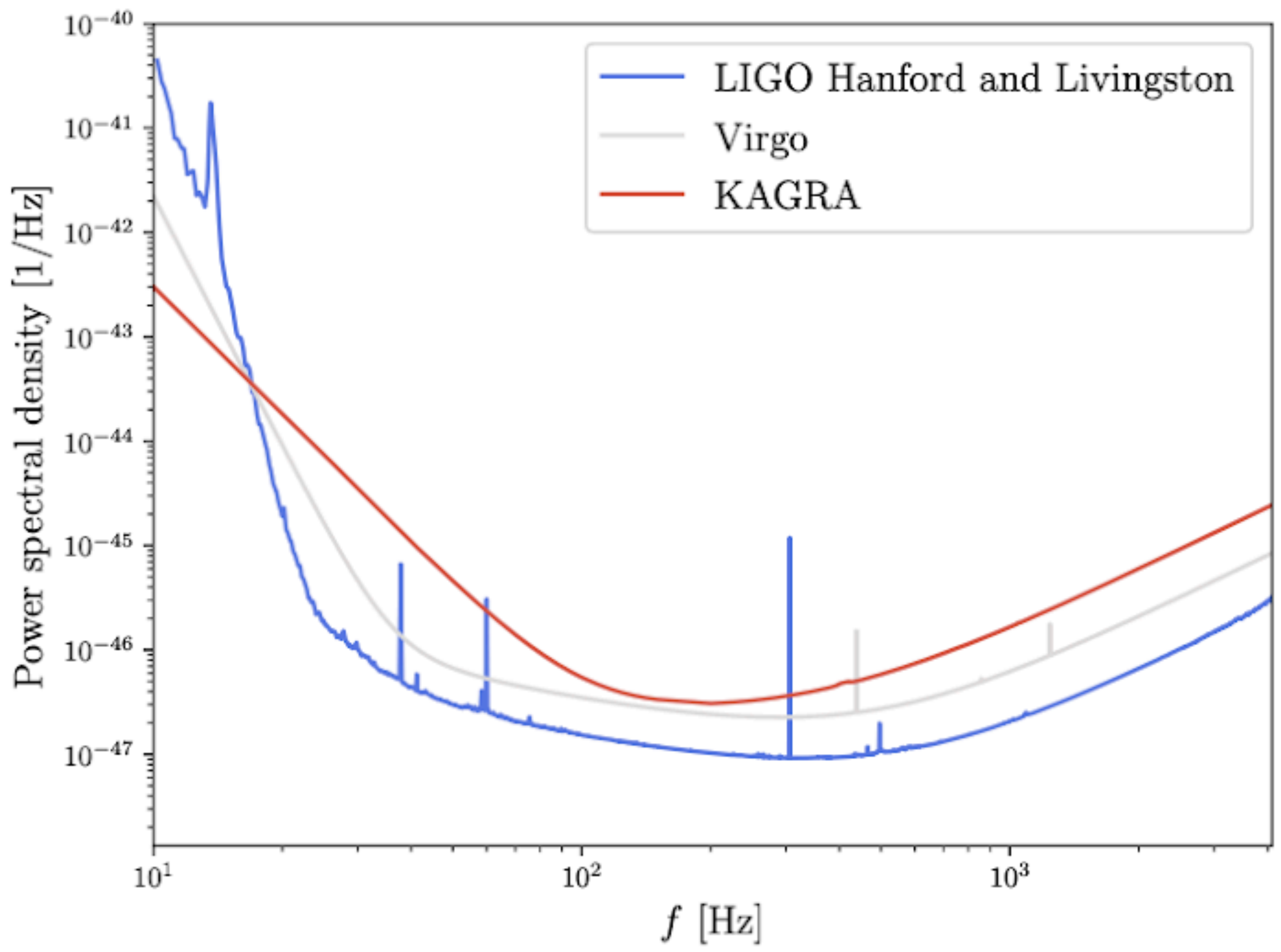


Figure 2. Predicted power spectral densities during O4 of the four interferometers included in this study. These curves correspond to BNS ranges of 160-190 Mpc for the LIGO detectors, 90-120 Mpc for Virgo, and 80 Mpc for KAGRA (Abbott et al. 2020a).

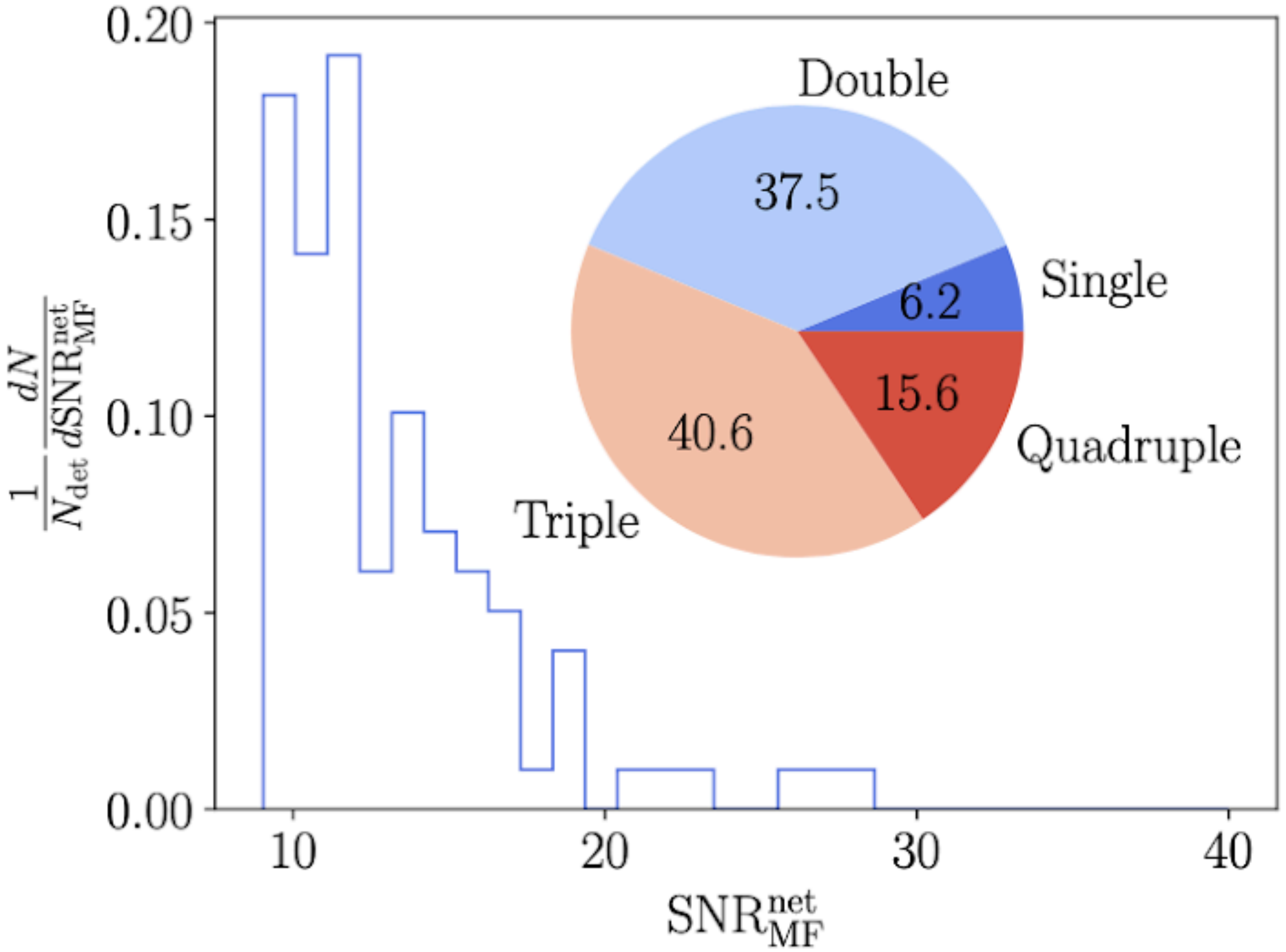


Figure 3. Distribution of the network matched filter $\mathrm{SNR}_{\mathrm{GW}}$ recovered by `PyCBC Live` for the 96 total found events. The inset shows the fraction of the total number of found events detected with each number of interferometers.