Parameter Estimation with Future Detectors

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Ground-based
- LIGO/Virgo
- ET
- CE
Space-borne
- LISA
- B-DECIGO
Detector design/
detector geometries/
orbits
- influence on PE
Influence of long
observation times
on parameter
estimation
Future Gravitational Wave
detectors
Multiband
parameter
estimation
Science Goals
- Astrophysics
- Fundamental
Physics
Sources
-stellar-mass BBH
-binary neutron stars
-intermediate-mass BBH
Detection&Parameter
Estimation capabilities


Detector physics
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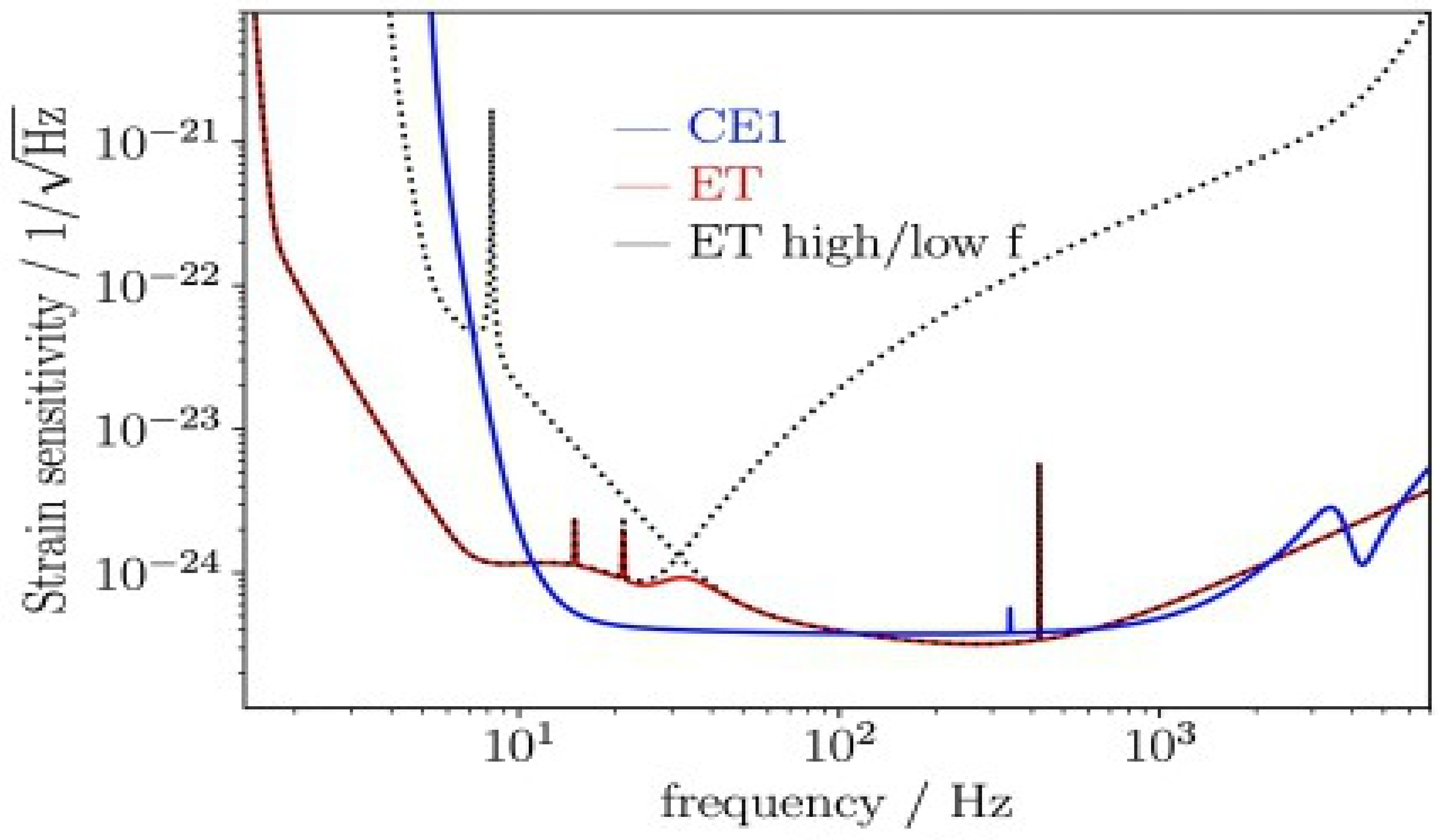
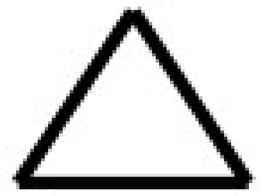
Estimation capabilities

Detector design



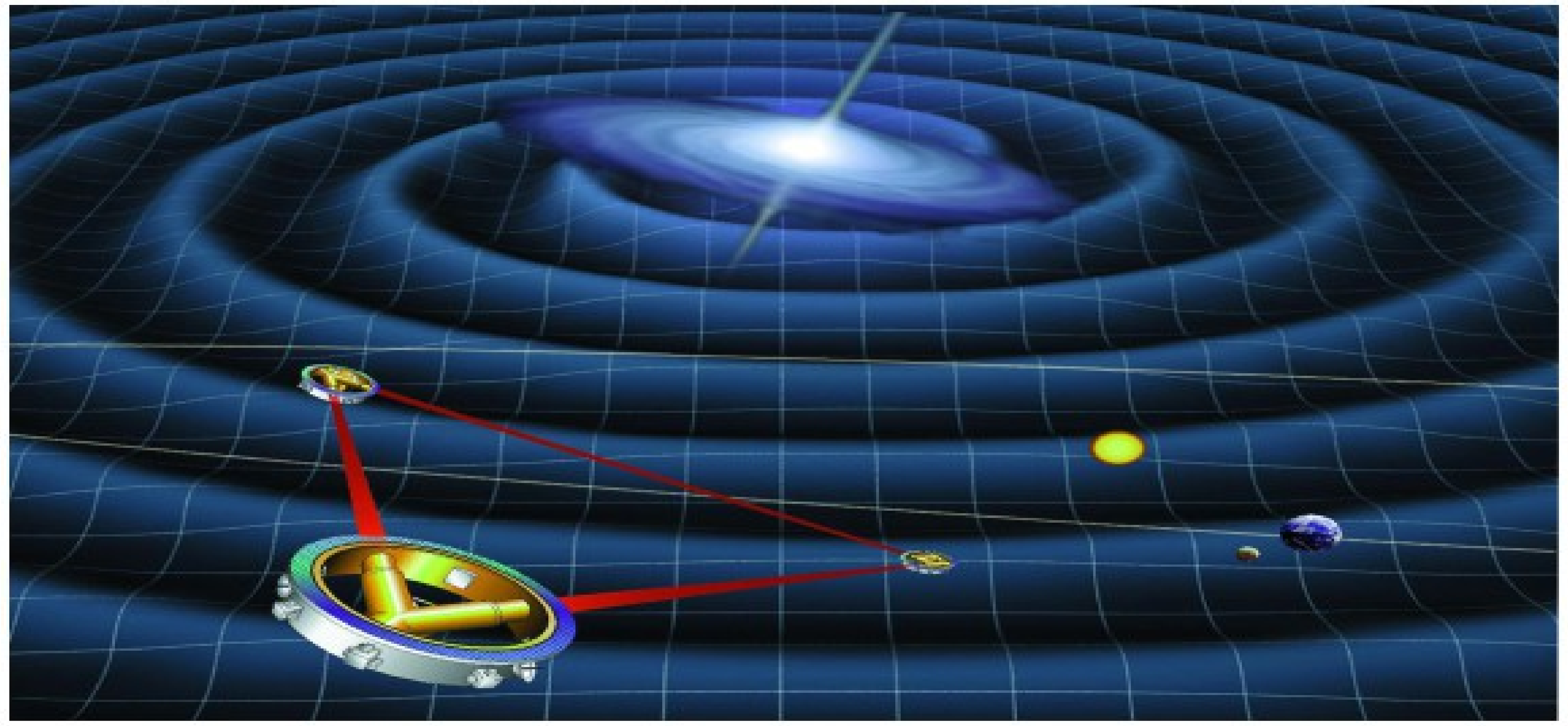
sensitivities

L-shape



triangular shape

geometries

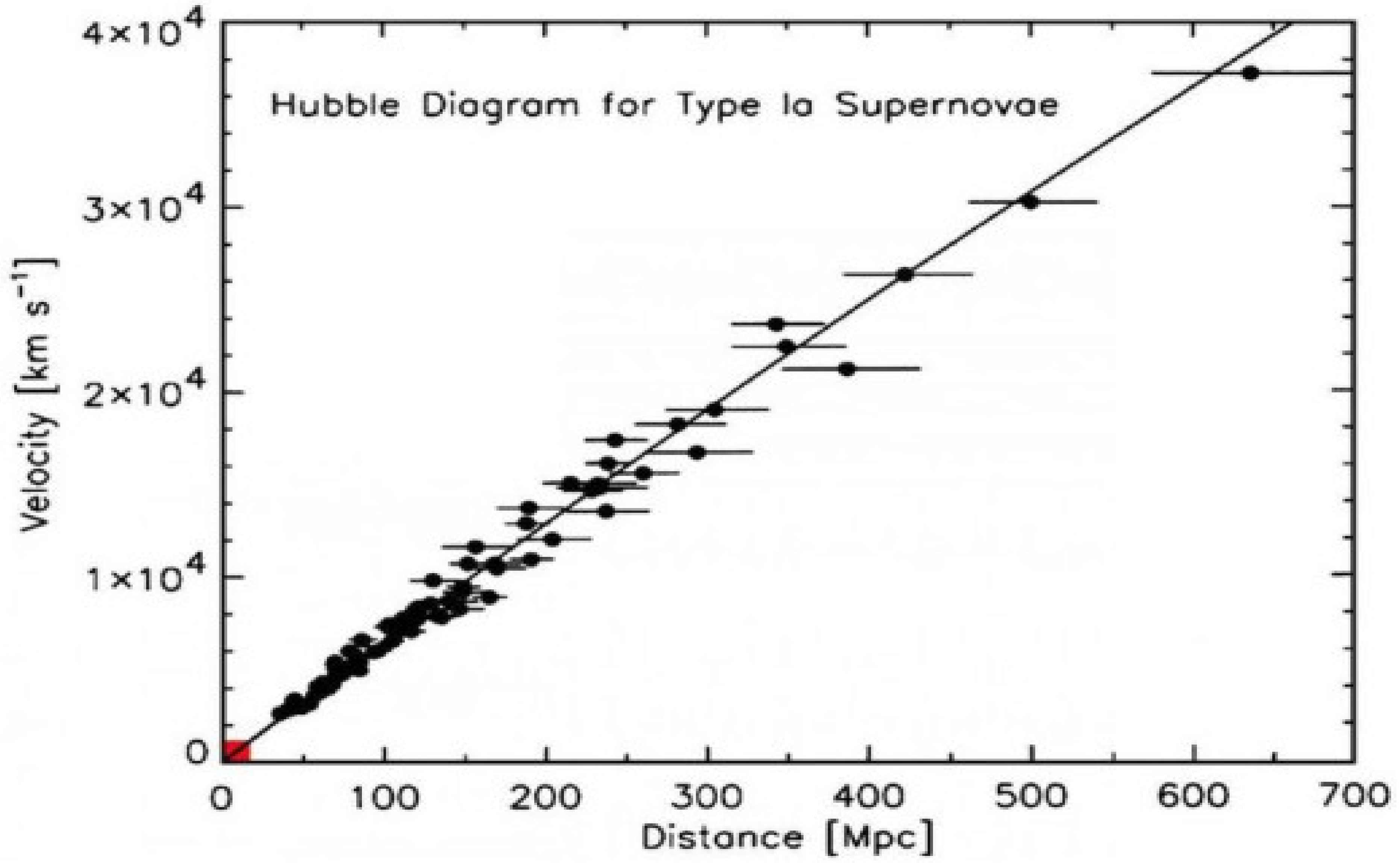


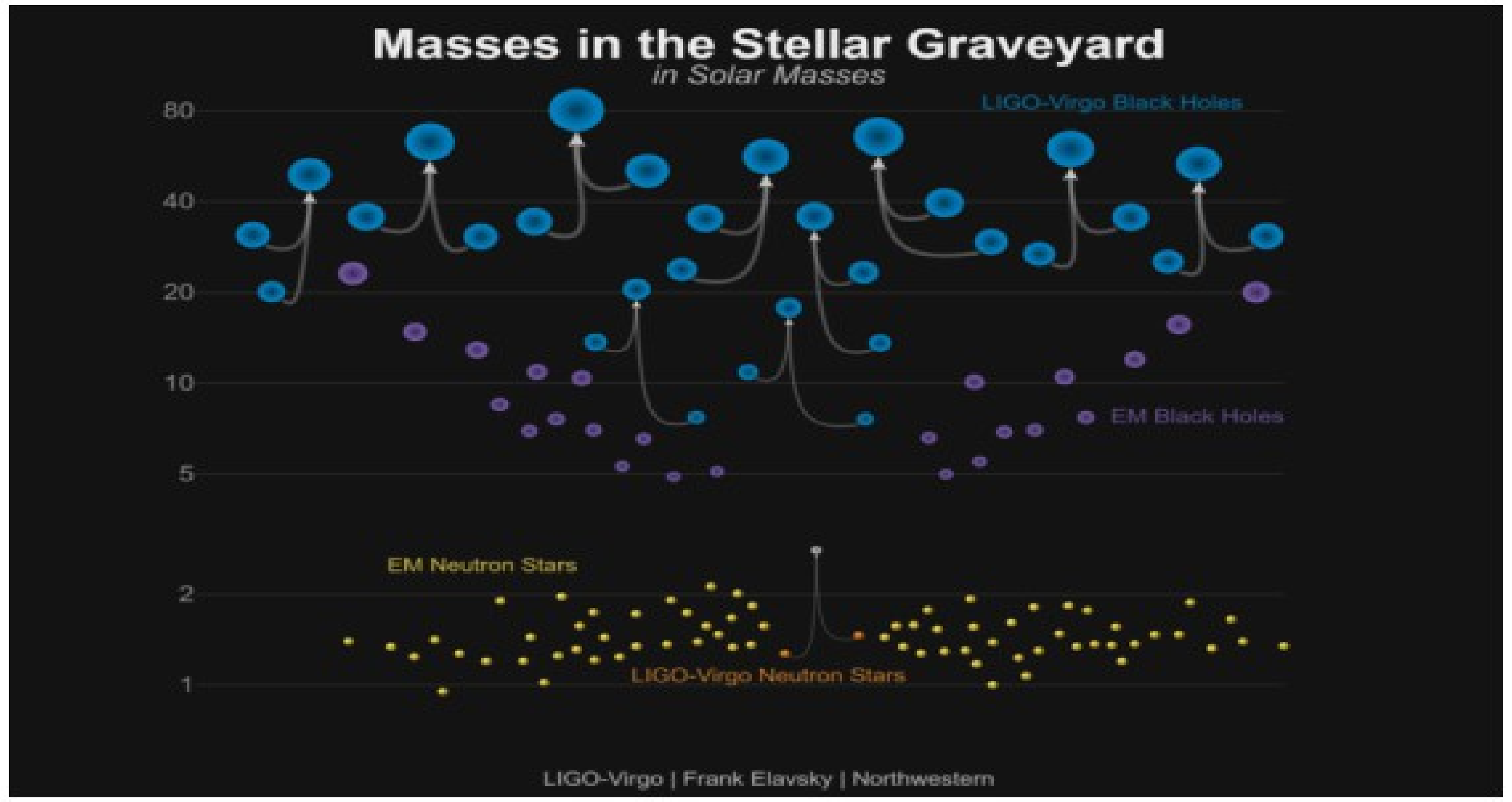
orbits

influence

inform

Science Goals





Scientific Questions

- How many sources can future detectors detect?
- How well can the individual detectors reconstruct source parameters?
- How does parameter estimation benefit from combining information from different detectors (multiband approach)?
- How does the detector geometry influence parameter estimation?
- What are the prospects for multimessenger observations with ET?

Introduction/Motivation

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Analysis framework

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Detector performances
Multiband parameter estimation

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3G detector geometries
Multimessenger prospects

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Summary and Outlook

Introduction/Motivation

- Gravitational Waves
- Future Detectors
- Multiband PE
- Multimessenger observations
- Science goals

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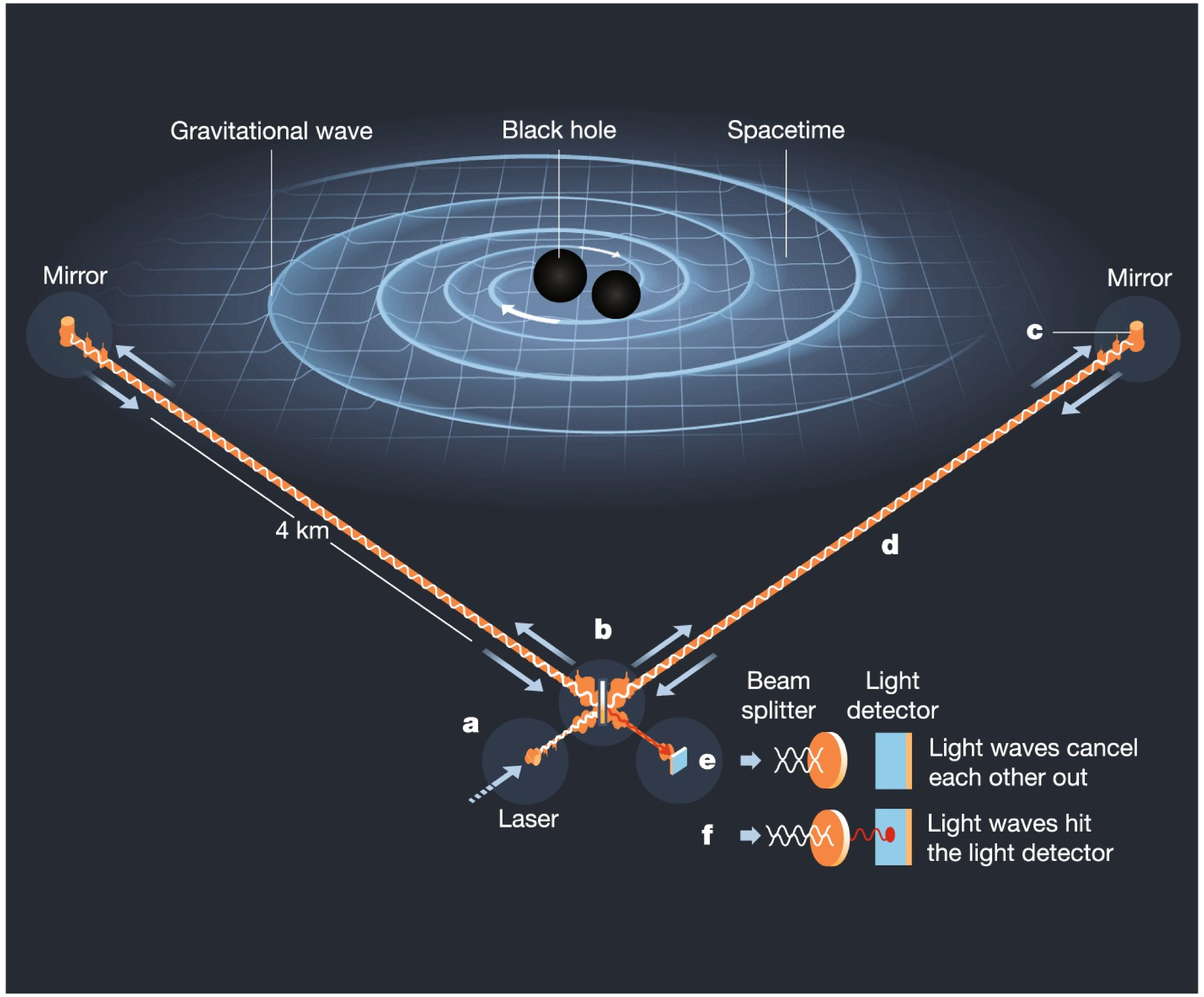
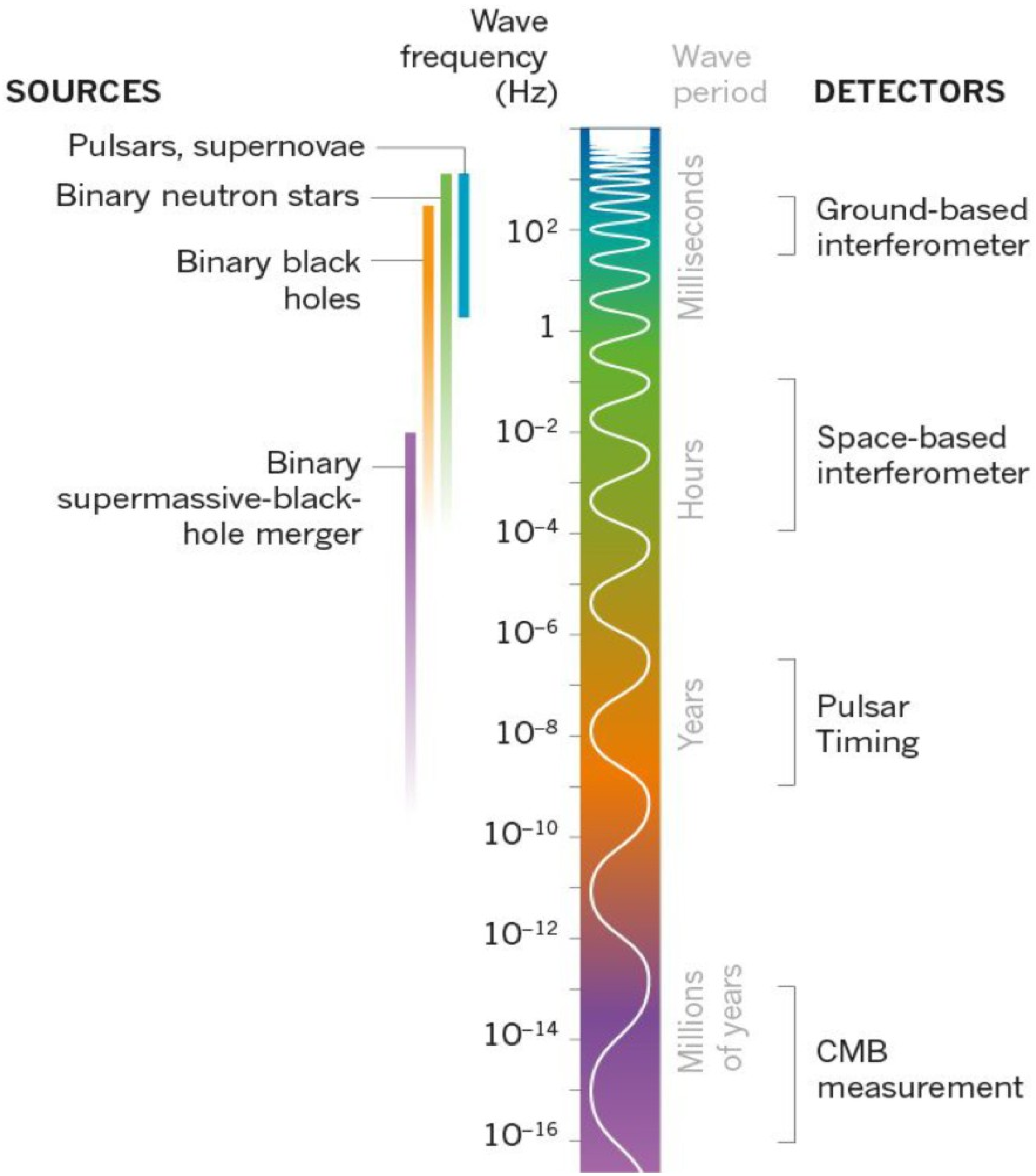
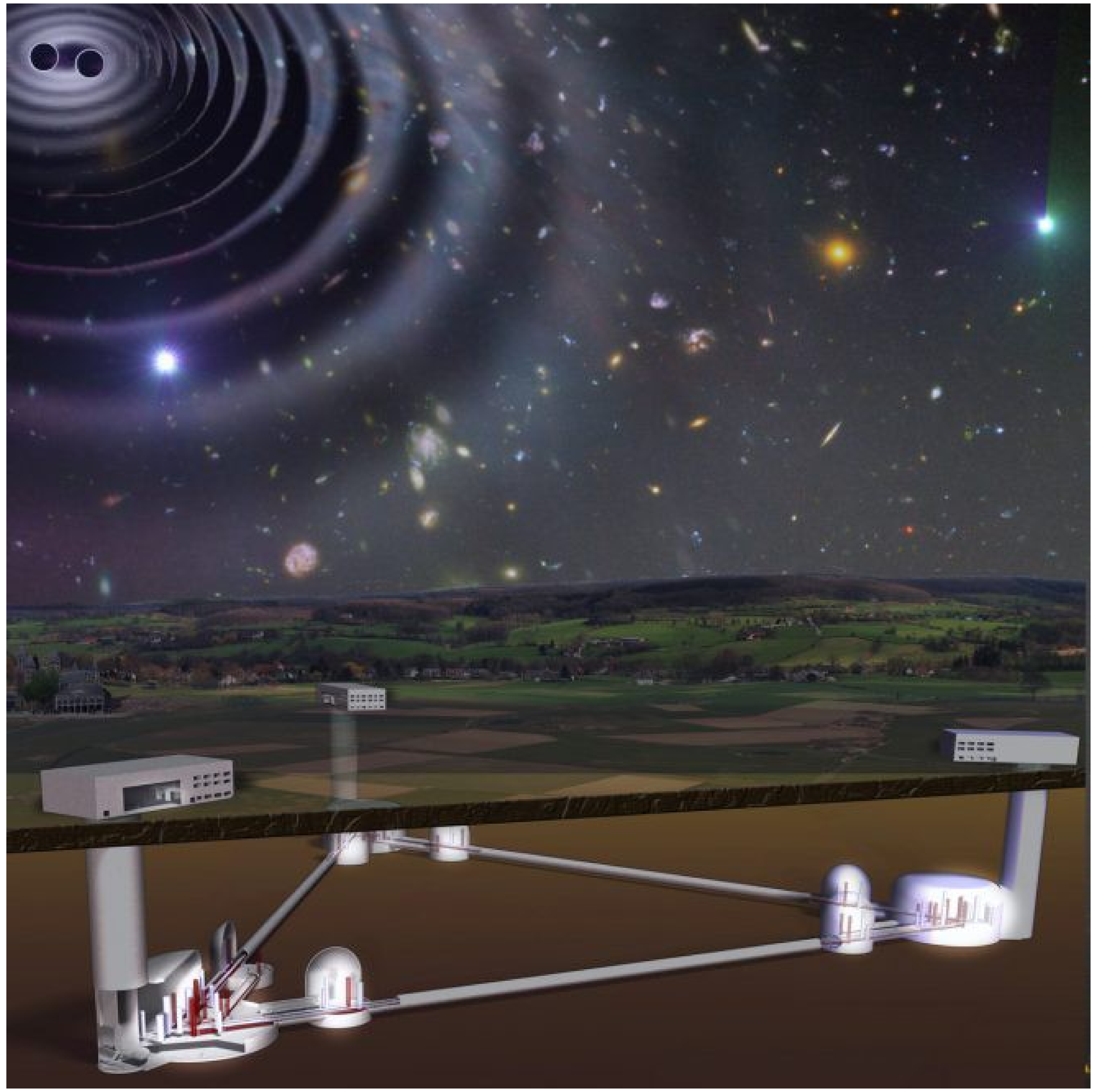
Summary and Outlook

GW Detection

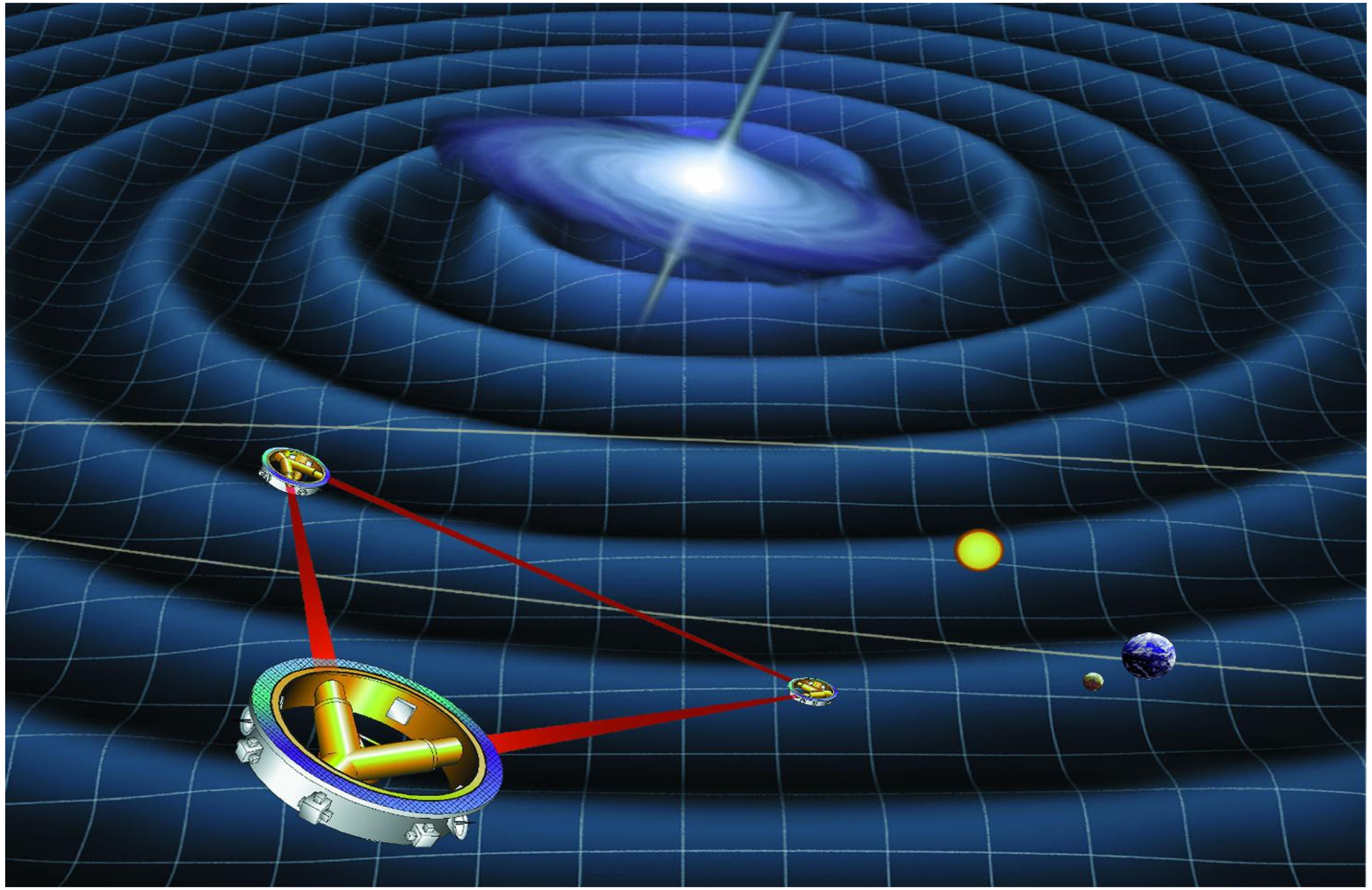




Future Detectors



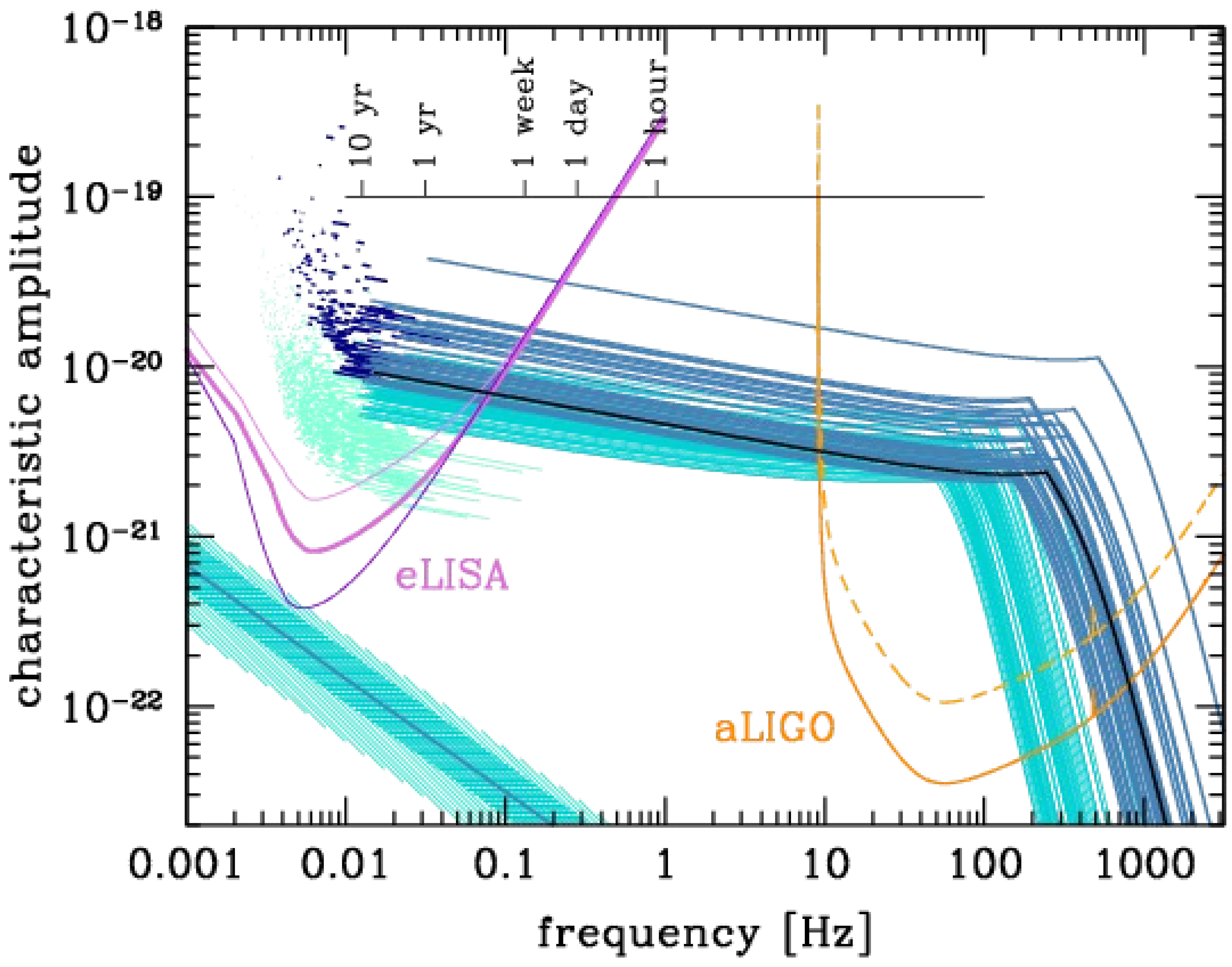
Einstein Telescope (ET)



Laser Interferometer Space Antenna (LISA)

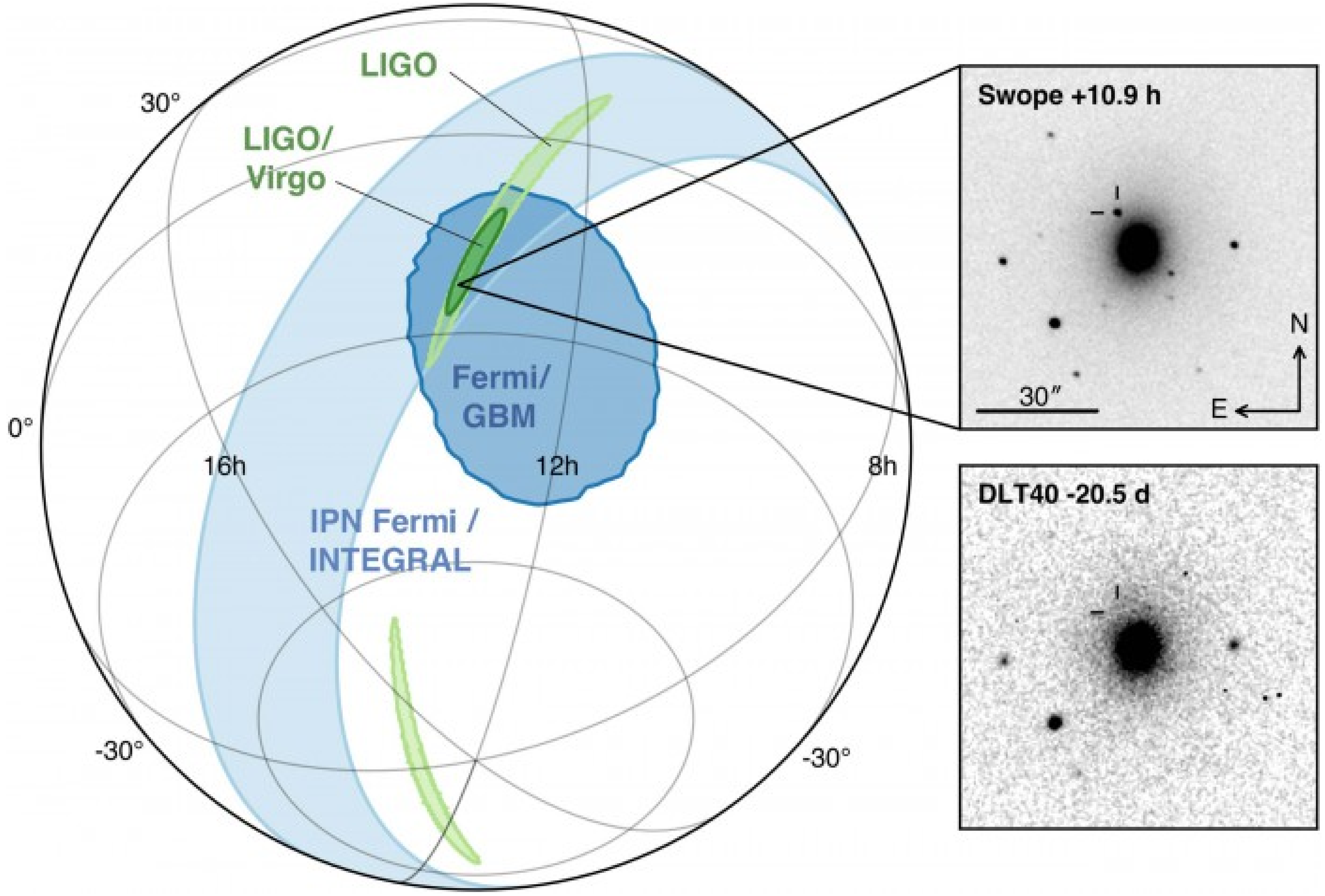
Multiband approach

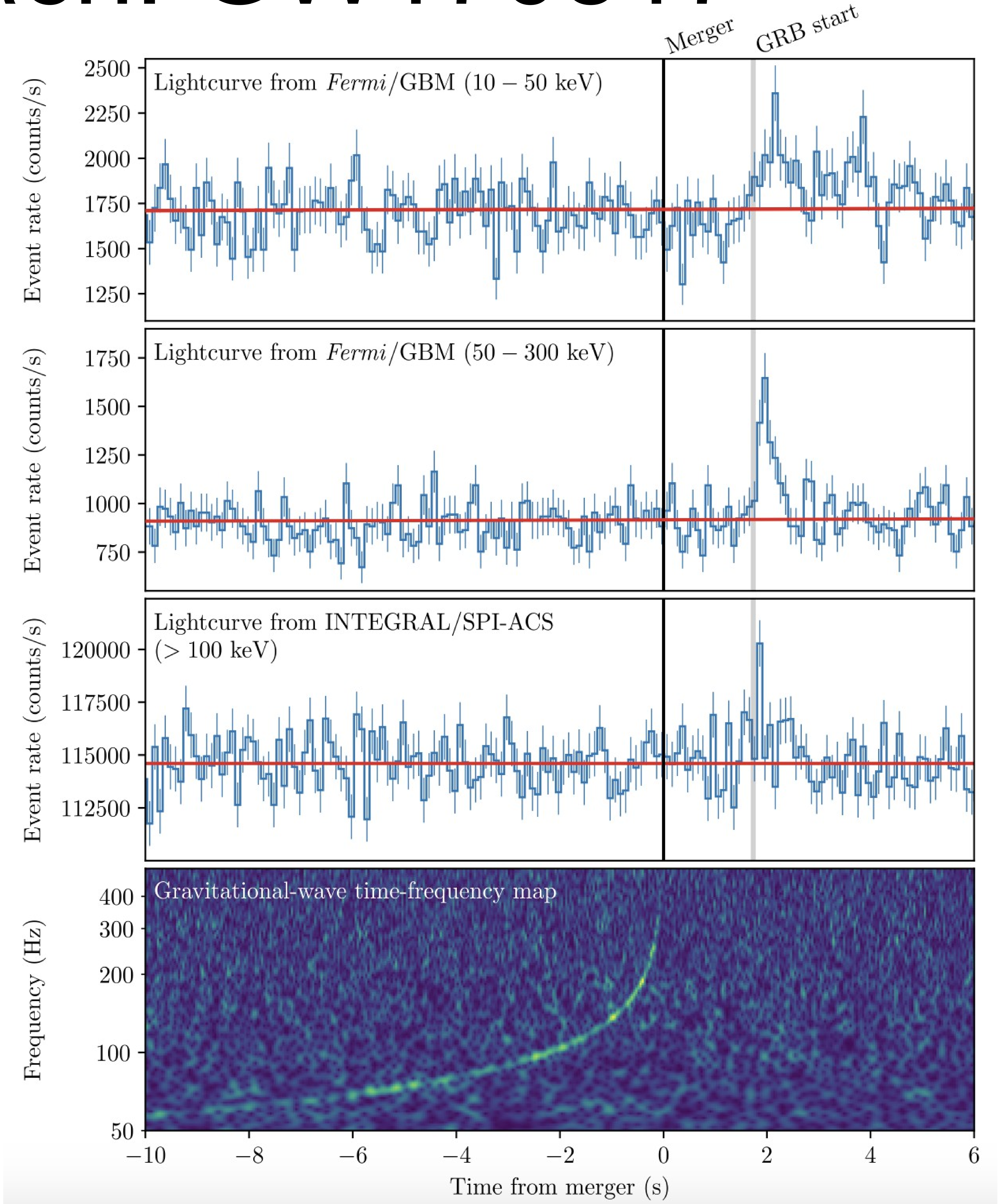
Observe the same source first at low frequencies in space-borne detectors, then in ground-based detectors



A. Sesana, PRL 116, 231102 (2016)

Multimessenger Approach: GW170817





Science Goals

Astrophysics

- Star formation in the universe
- Binary evolution
- Intermediate-mass BBHs
- Astrophysics of Neutron Stars
- Kilonovae
- Supernovae

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Fundamental Physics

- Tests of GR
- Propagation speed of GW
- Exotic compact objects
- Expansion of the Universe

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Introduction/Motivation

Analysis framework

Simulated detectors
Fisher Matrix approach
Waveform&Projection
Segmented Fourier transformation

Detector performances
Multiband parameter estimation

3G detector geometries
Multimessenger prospects

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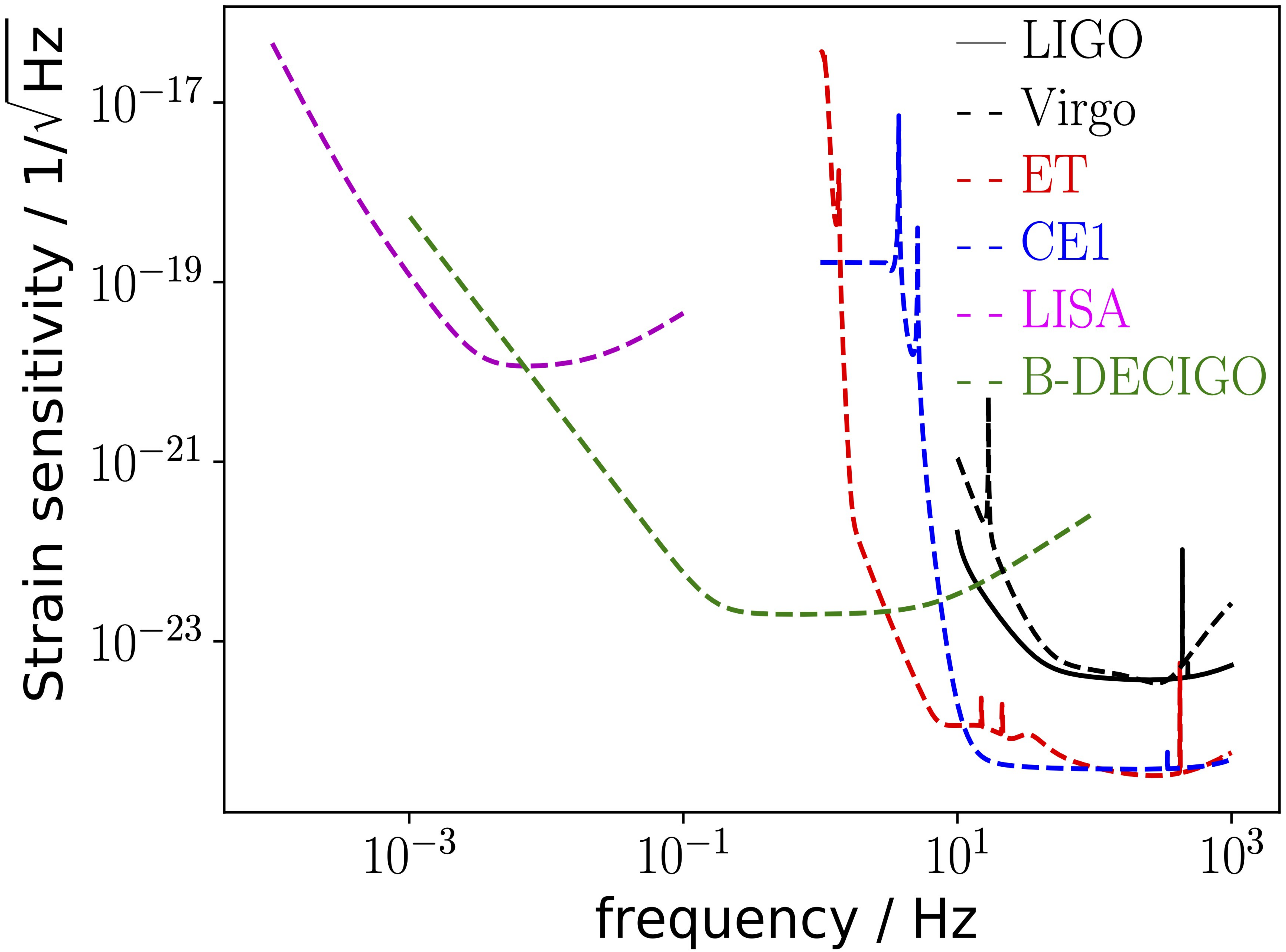
Summary and Outlook

Detectors

- 2G detectors: LIGO/Virgo, LIGO India, KAGRA
- Einstein Telescope (ET)
- Cosmic Explorer (CE)
- LISA
- B-DECIGO
  - geostationary orbit
- B-DECIGO
  - LISA-like orbit



Fisher-matrix formalism

- Signal in detector $s=h(\theta)+n$

- Noise-weighted inner product $(a,b)=4\Re\int_0^\infty \frac{a(f)b^*(f)}{S_n(f)}df$

- Likelihood $P(s,\theta)\propto\exp(-(s-h(\theta),s-h(\theta))/2)$
- Expand around true source parameters
- Fisher-matrix $F_{kj}=(\partial_k h(\theta=\theta_0),\partial_j h(\theta=\theta_0))$
- Standard deviation $\Delta\theta_i=\sqrt{(F^{-1})_{ii}}$
- SNR $\mathrm{SNR}=\sqrt{(h,h)}$

Analysis framework

- Metric perturbation
$$\begin{pmatrix} H_{+} & H_{x} & 0 \\ H_{x} & -H_{+} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$H_{+}=\frac{c}{2r}\left(5\frac{M_c^5}{t_c-t}\right)^{1/4}\left(1+\cos^2(\alpha)\right)\cos\left(\phi(t)+\phi_c\right)$$

$$H_{x}=\frac{c}{2r}\left(5\frac{M_c^5}{t_c-t}\right)^{1/4}2\cos^2(\alpha)\sin\left(\phi(t)+\phi_c\right)$$

- Rotate into detector frame
$$H_{\mathrm{det}}=R\,H\,R^T$$

- Project onto detector arm vectors
$$h(t)=\frac{1}{2}\left(e_1^T H_{\mathrm{det}}\,e_1-e_2^T H_{\mathrm{det}}\,e_2\right)$$

Analysis framework

- Perform Fourier Transform

$$\partial_i h(t) \rightarrow \partial_i h(f)$$

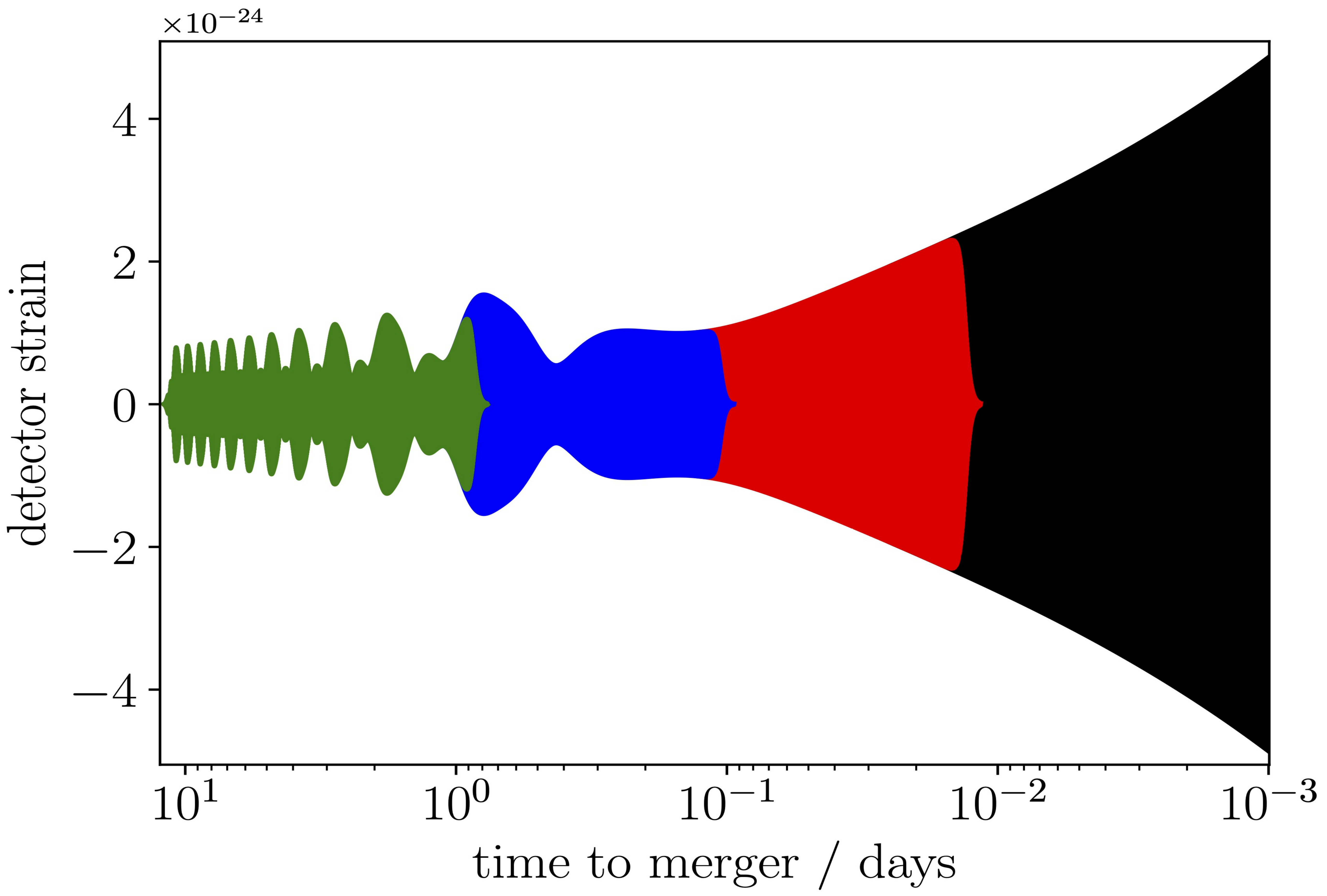
- Compute Fisher matrix

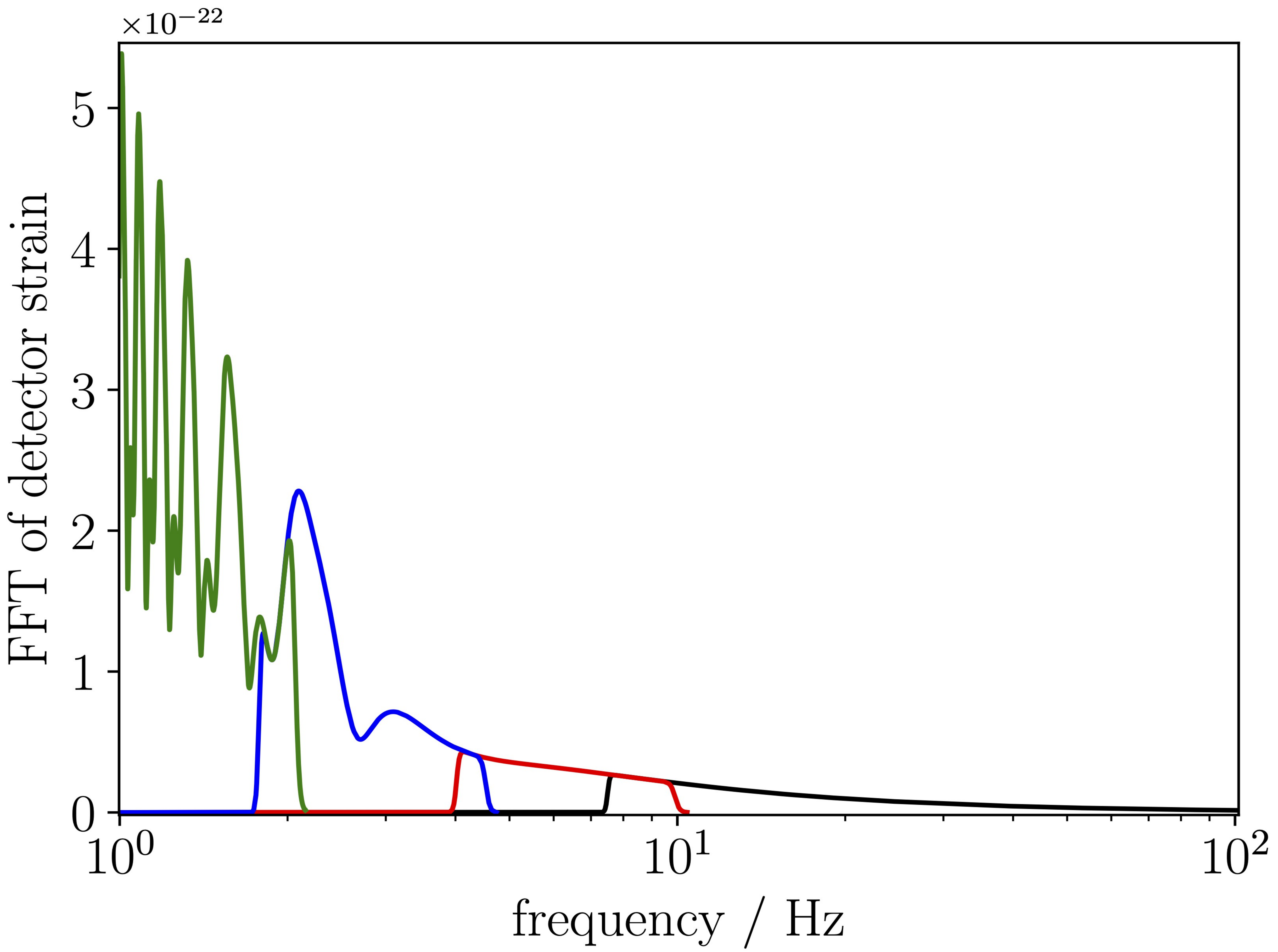
$$F_{kj} = \left(\partial_k h, \partial_j h\right)$$

- Invert Fisher matrix

$$\Delta\theta_i = \sqrt{\left(F^{-1}\right)_{ii}}$$

Segmented Fourier Transform





Choose in each segment the time resolution corresponding to the highest frequency in the segment!

Introduction/Motivation

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Analysis framework

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Detector performances
Multiband parameter estimation

→ Number of detections
→ Parameter estimates
→ Multiband parameter estimates

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3G detector geometries
Multimessenger prospects

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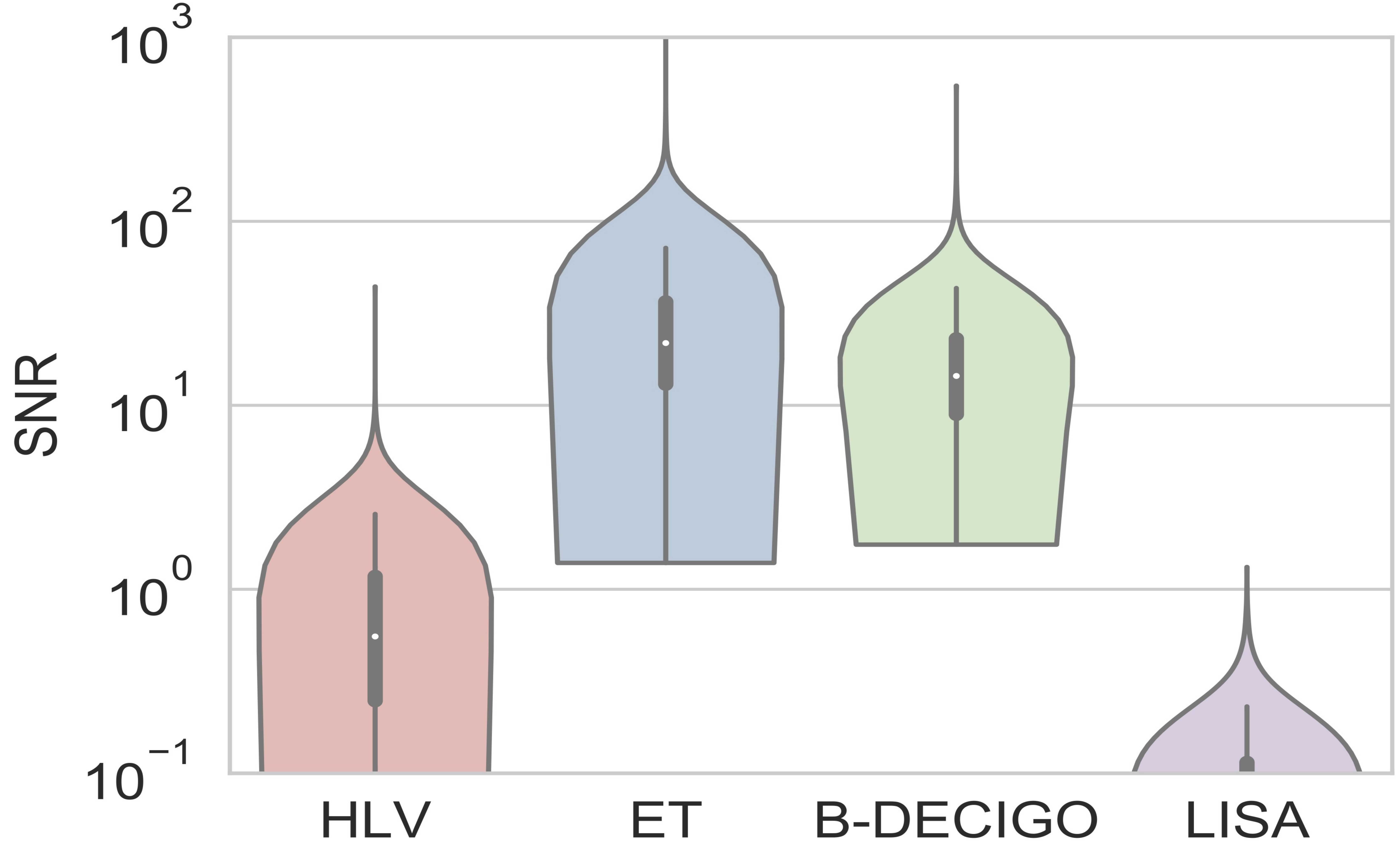
Summary and Outlook

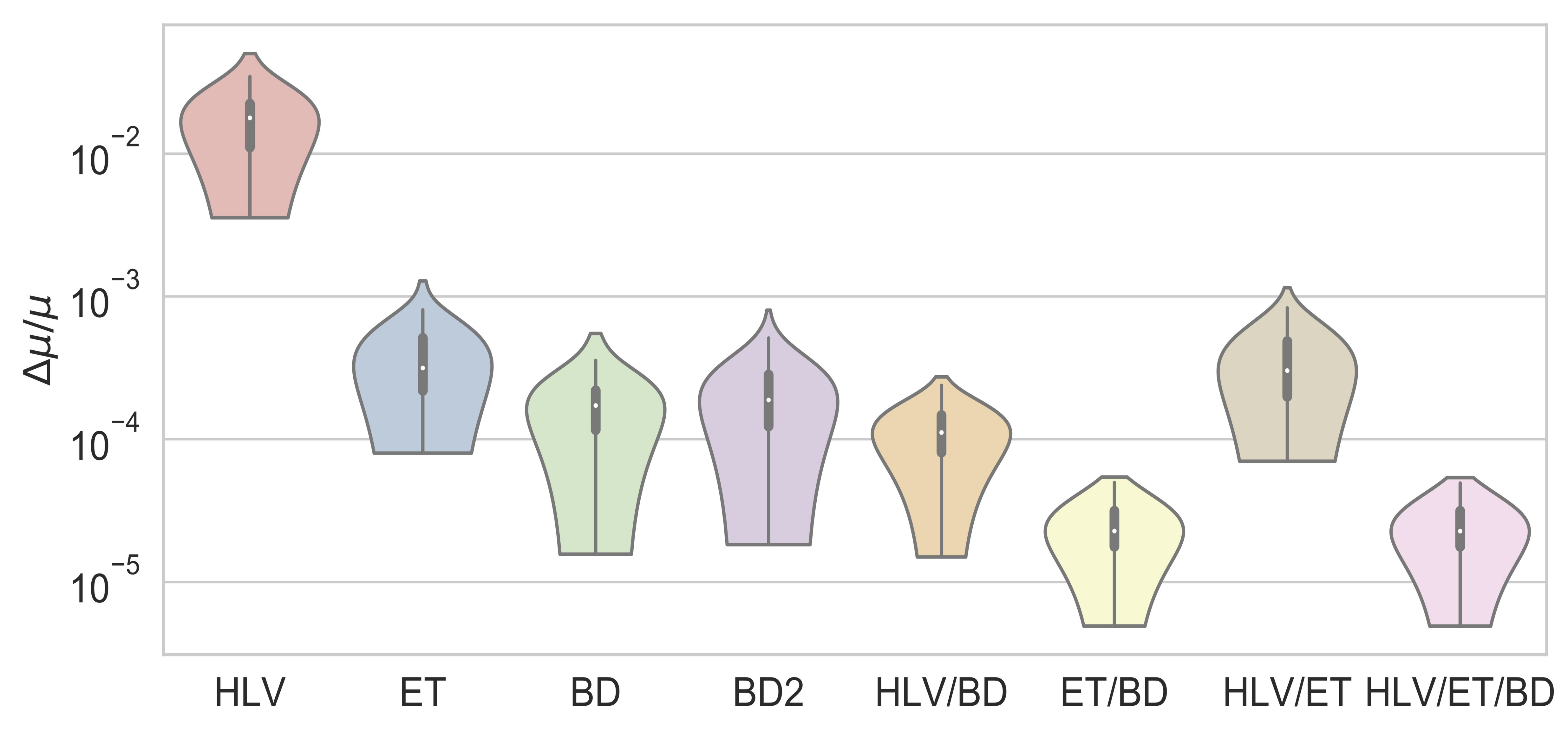
Stellar-mass BBHs: detection capabilities

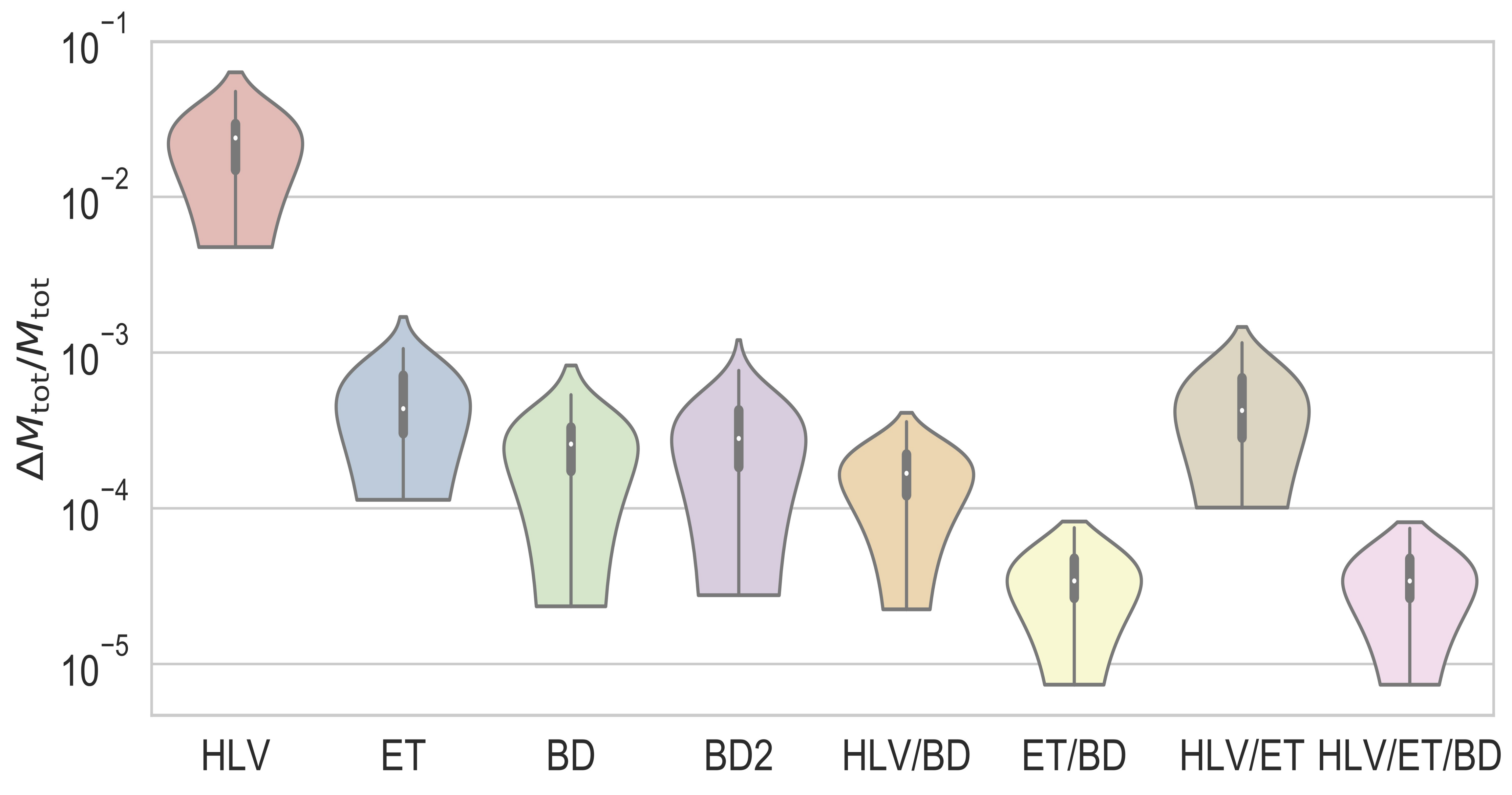


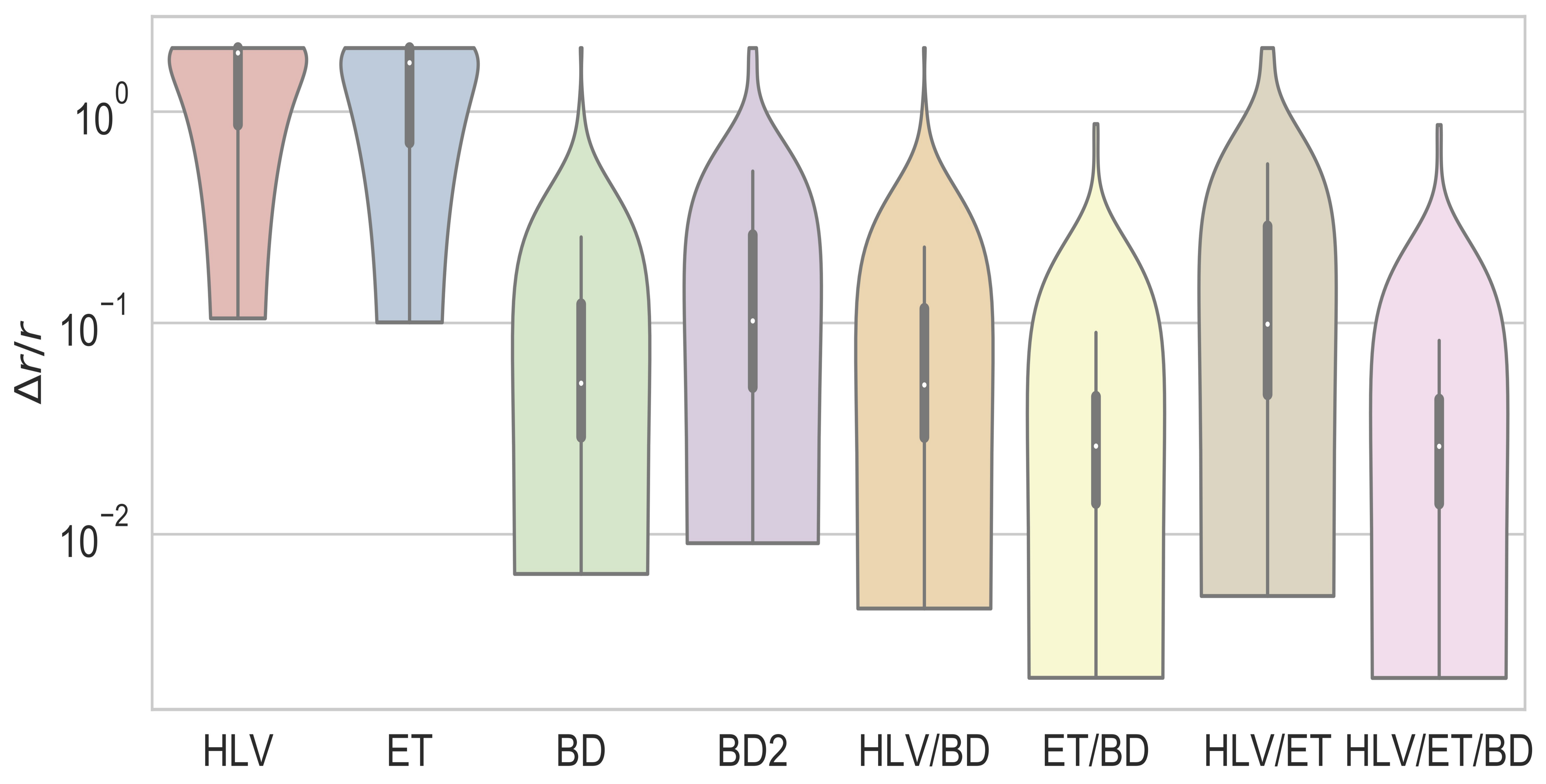
$\mathrm{SNR} > 10$ 1/1000   846/1000   697/1000   0/1000

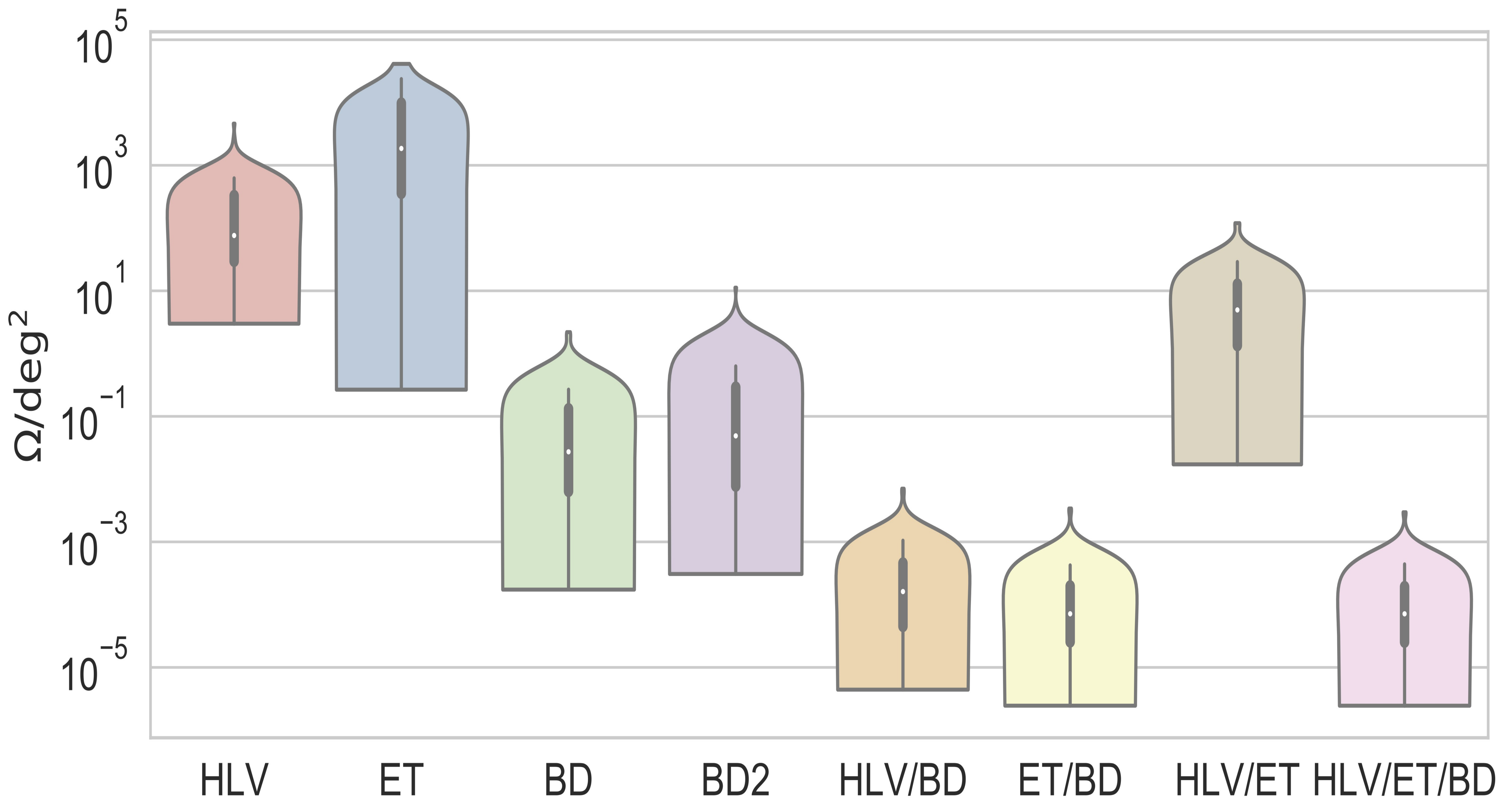
BBH population: mass spectrum is power-law with index -1.6, $\quad 5\,M_{\mathrm{solar}} < M_{\mathrm{BH}} < 60\,M_{\mathrm{solar}}$

Parameter estimates









Results

- B-DECIGO: geostationary orbit is preferable over heliocentric orbit
- Estimate of mass parameters benefits from multiband parameter estimation
- LISA: no good candidate for multiband parameter estimation of stellar-mass BBHs

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3G detector geometries
Multimessenger prospects

→ PE with Triangular ET
→ Geometry comparisons
→ Prospects for multimessenger studies with ET, CE, and 2G

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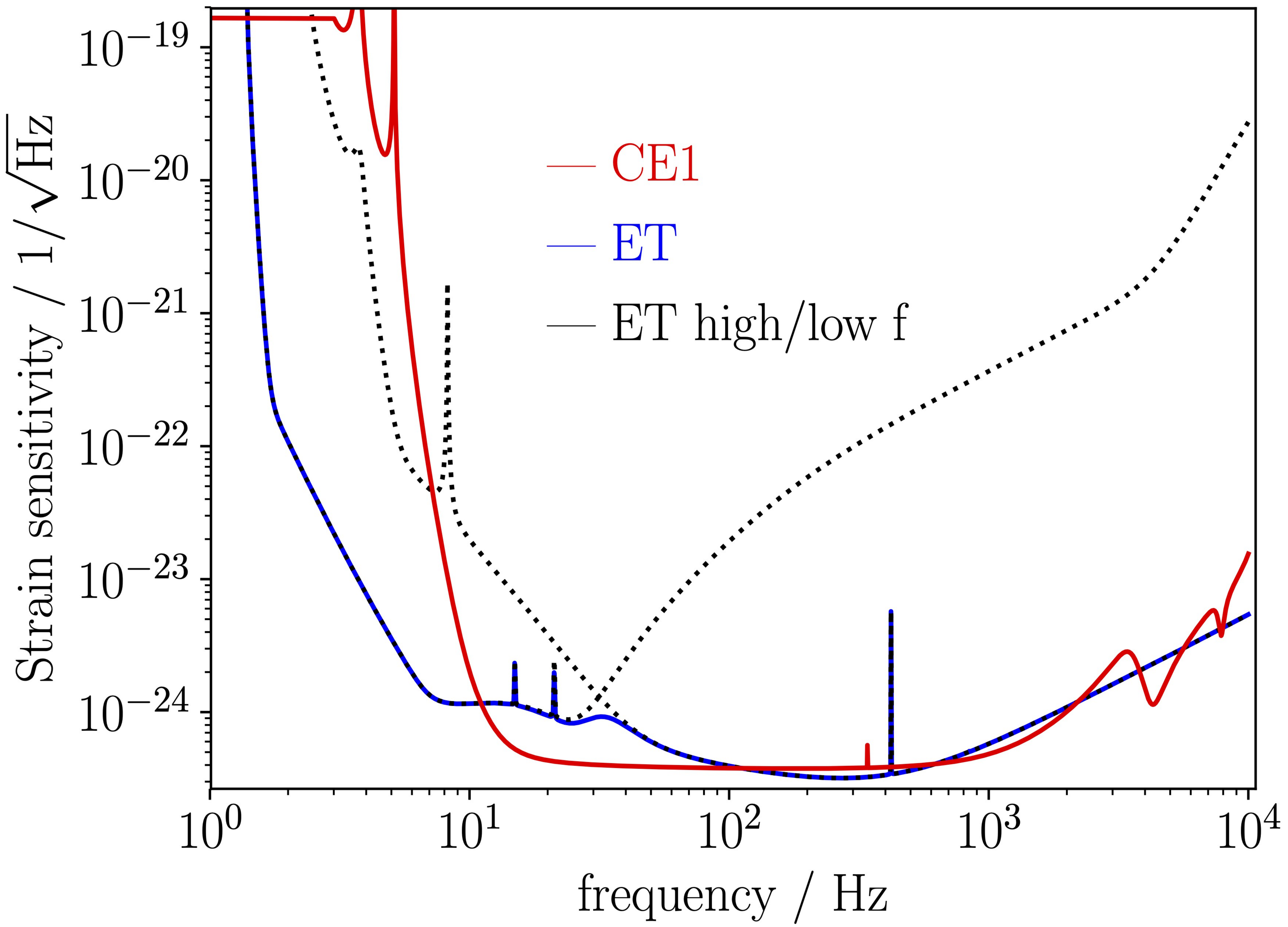
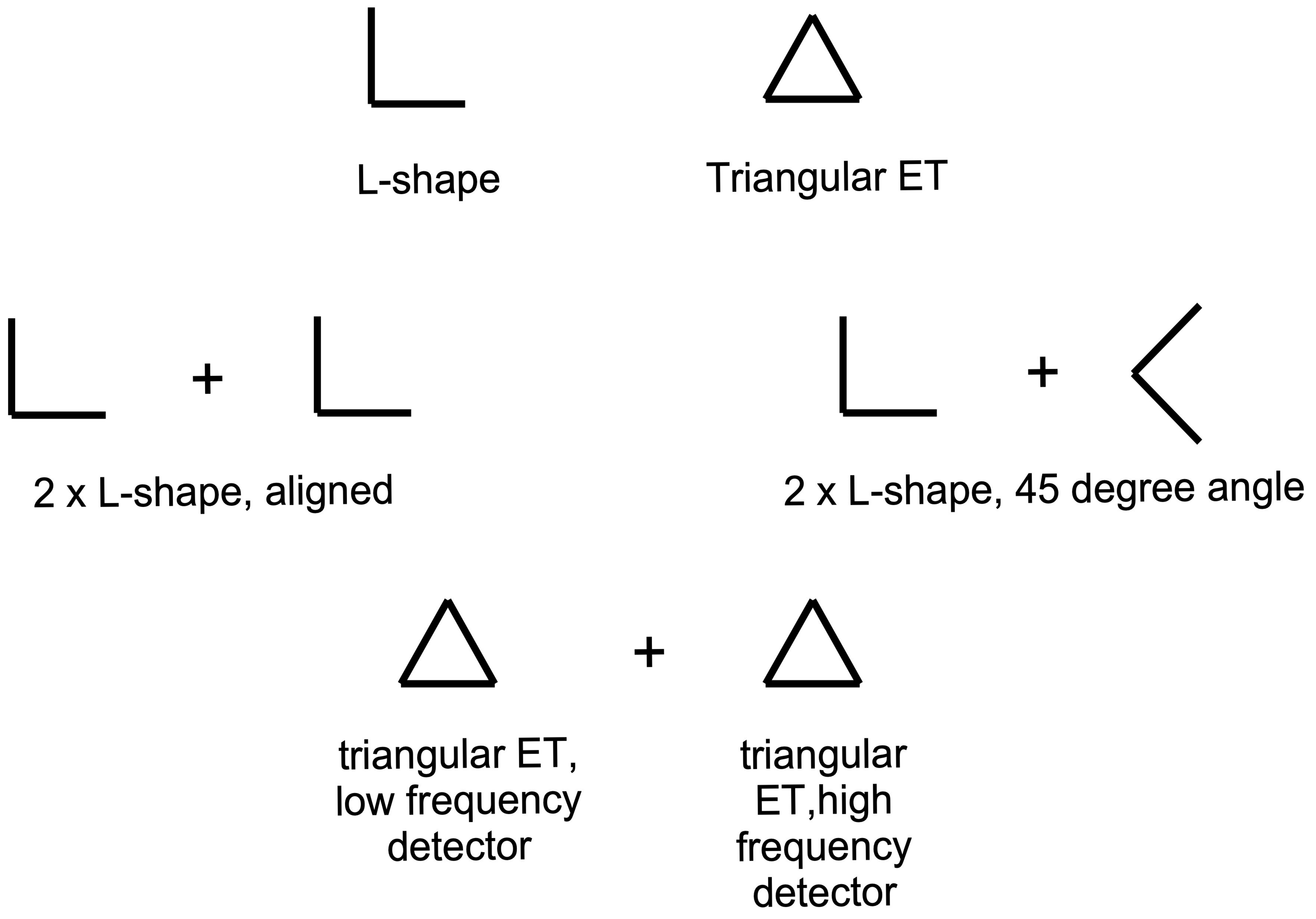
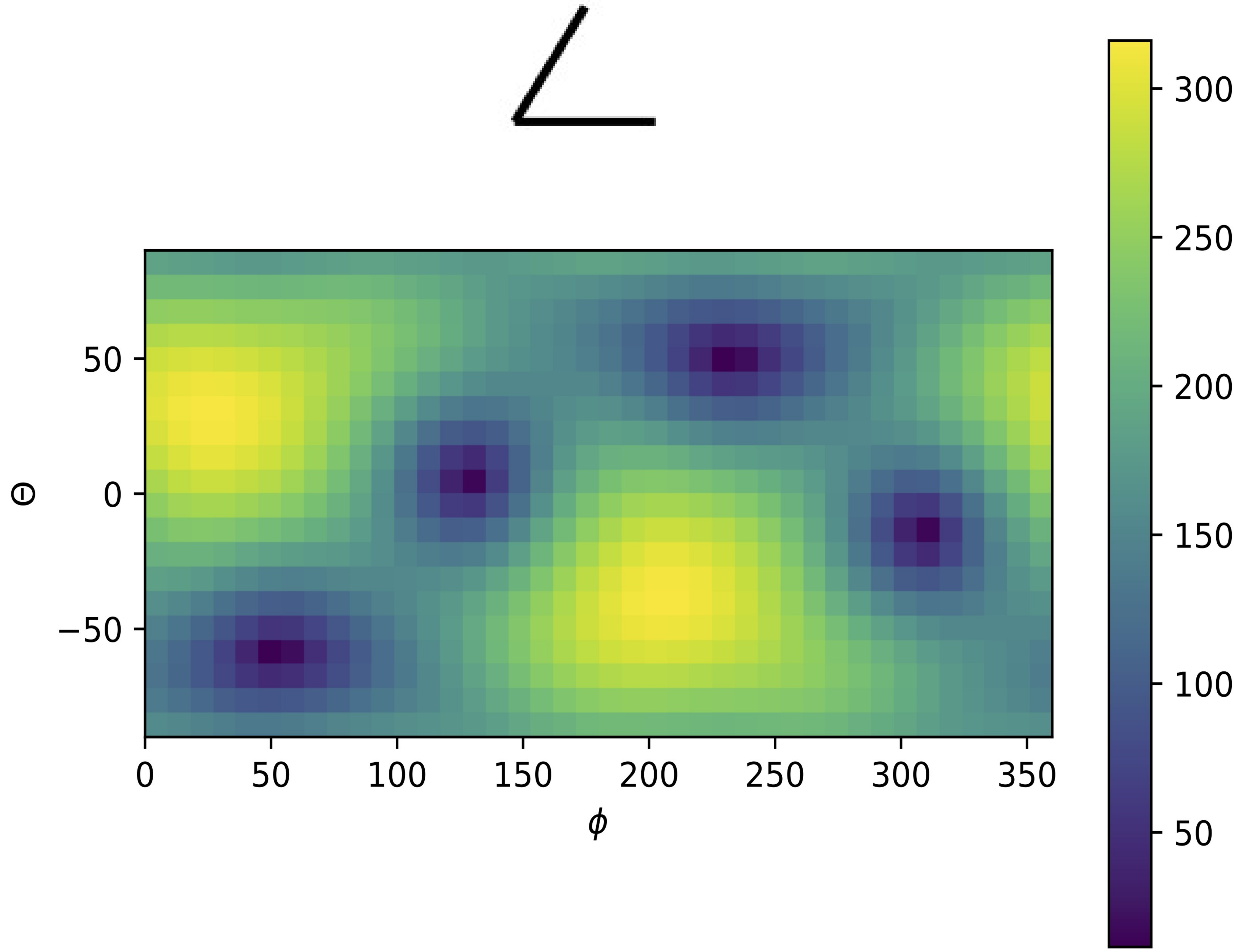
Summary and Outlook

Detector configurations

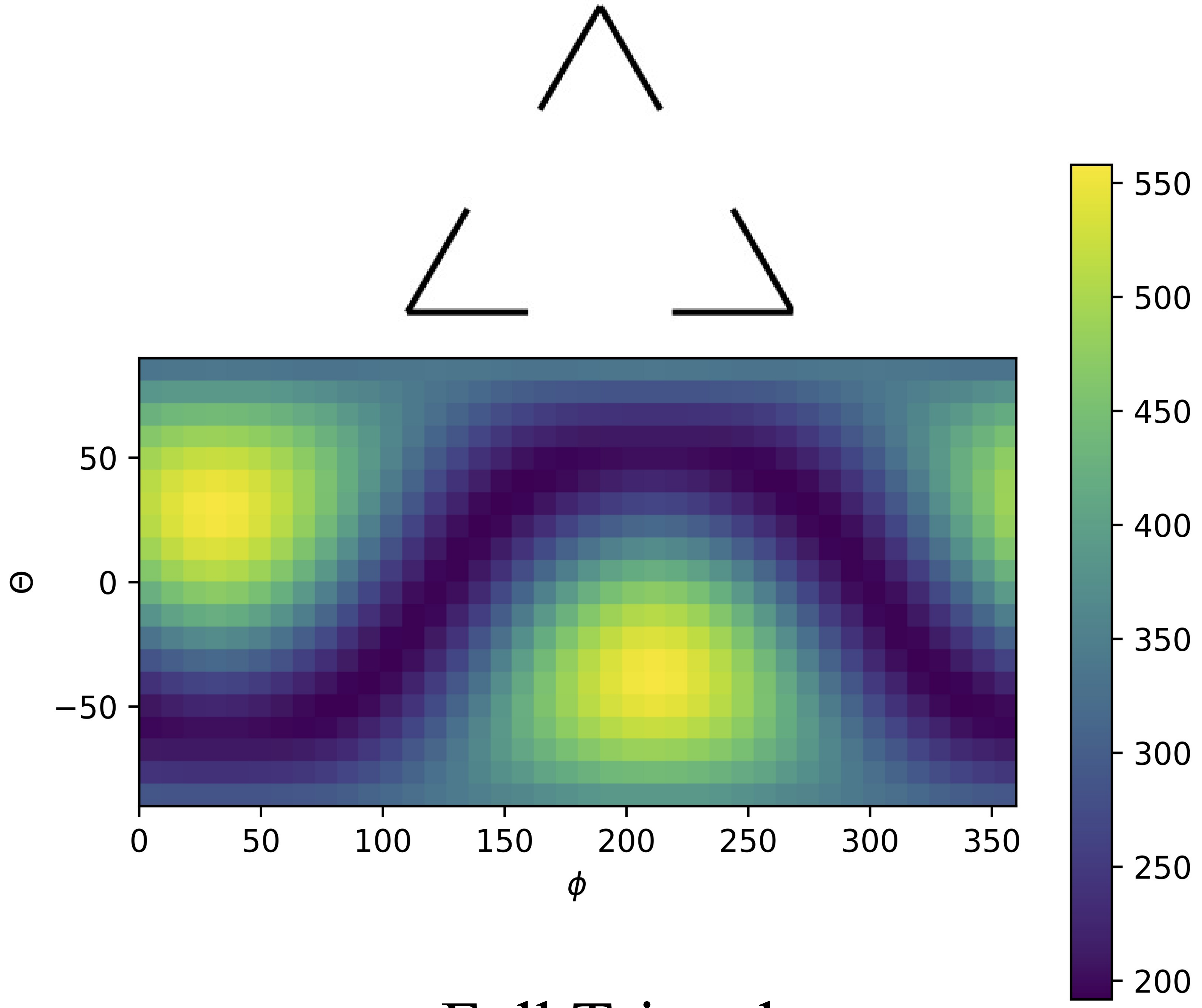




Triangular ET: SNR skymaps



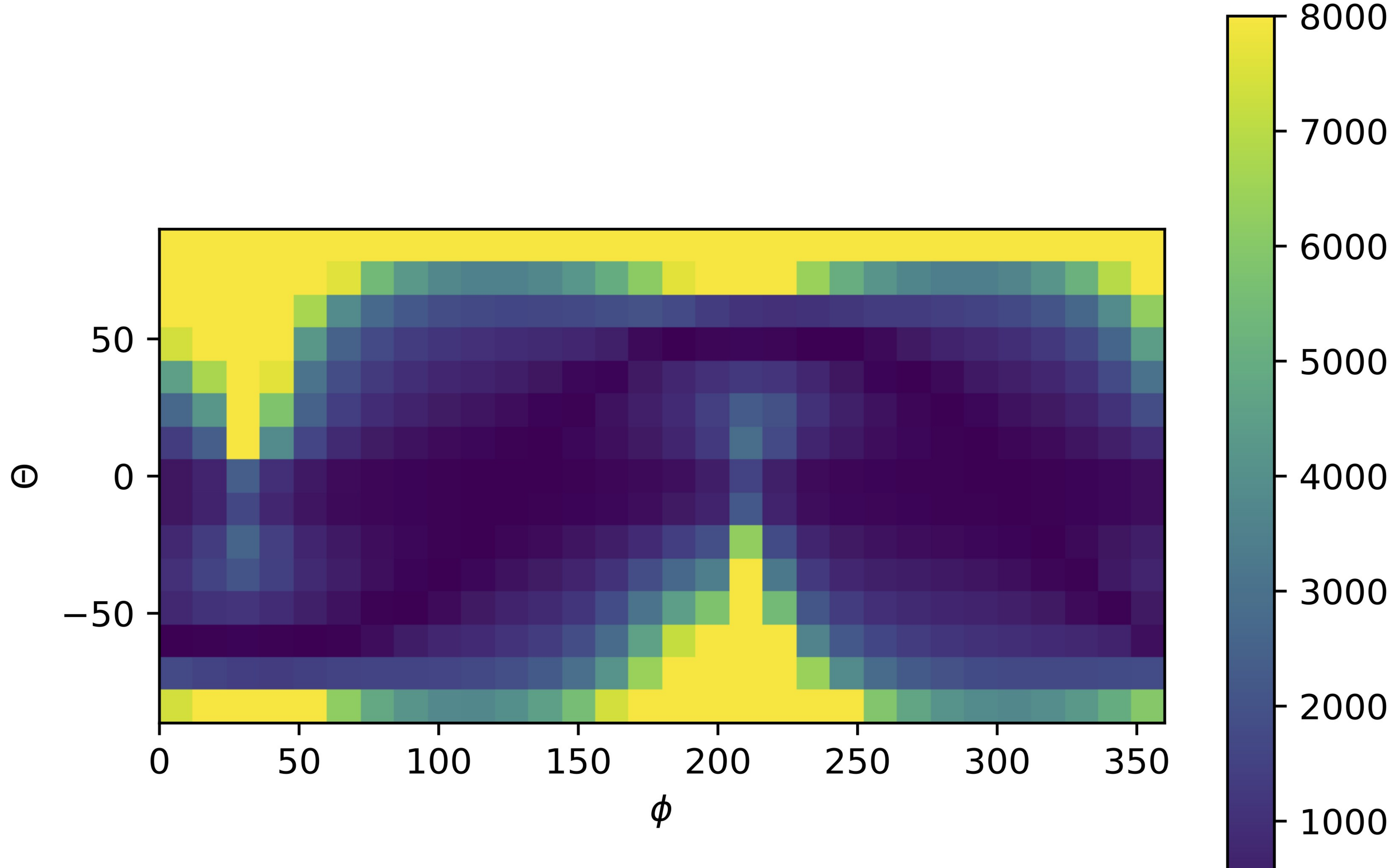
Detector 1



Full Triangle

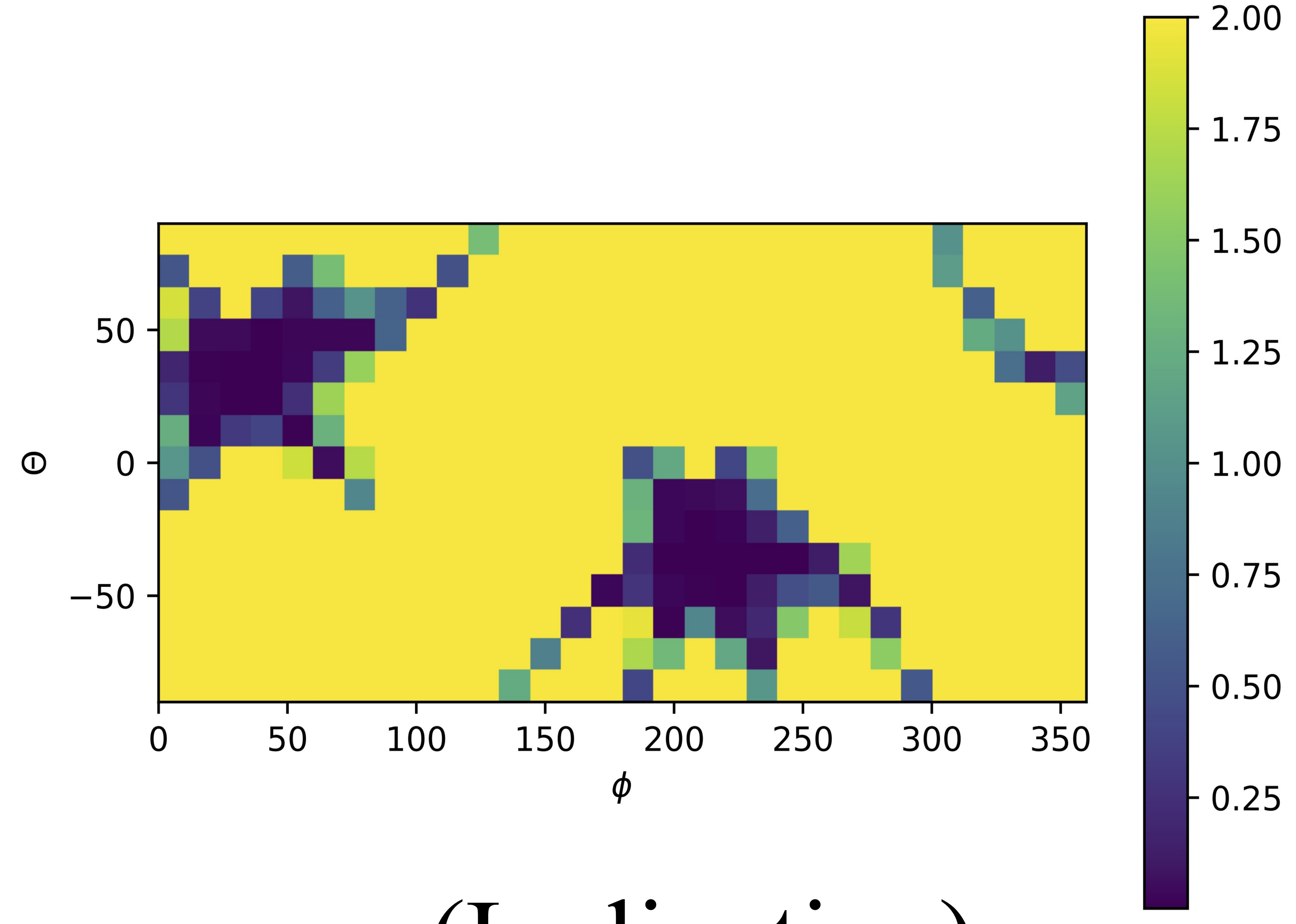
$$M_1 = 16\, M_{solar}, M_2 = 10\, M_{solar}, d = 400\,\mathrm{Mpc}$$

Triangular ET: Parameter estimation skymaps (BBH)

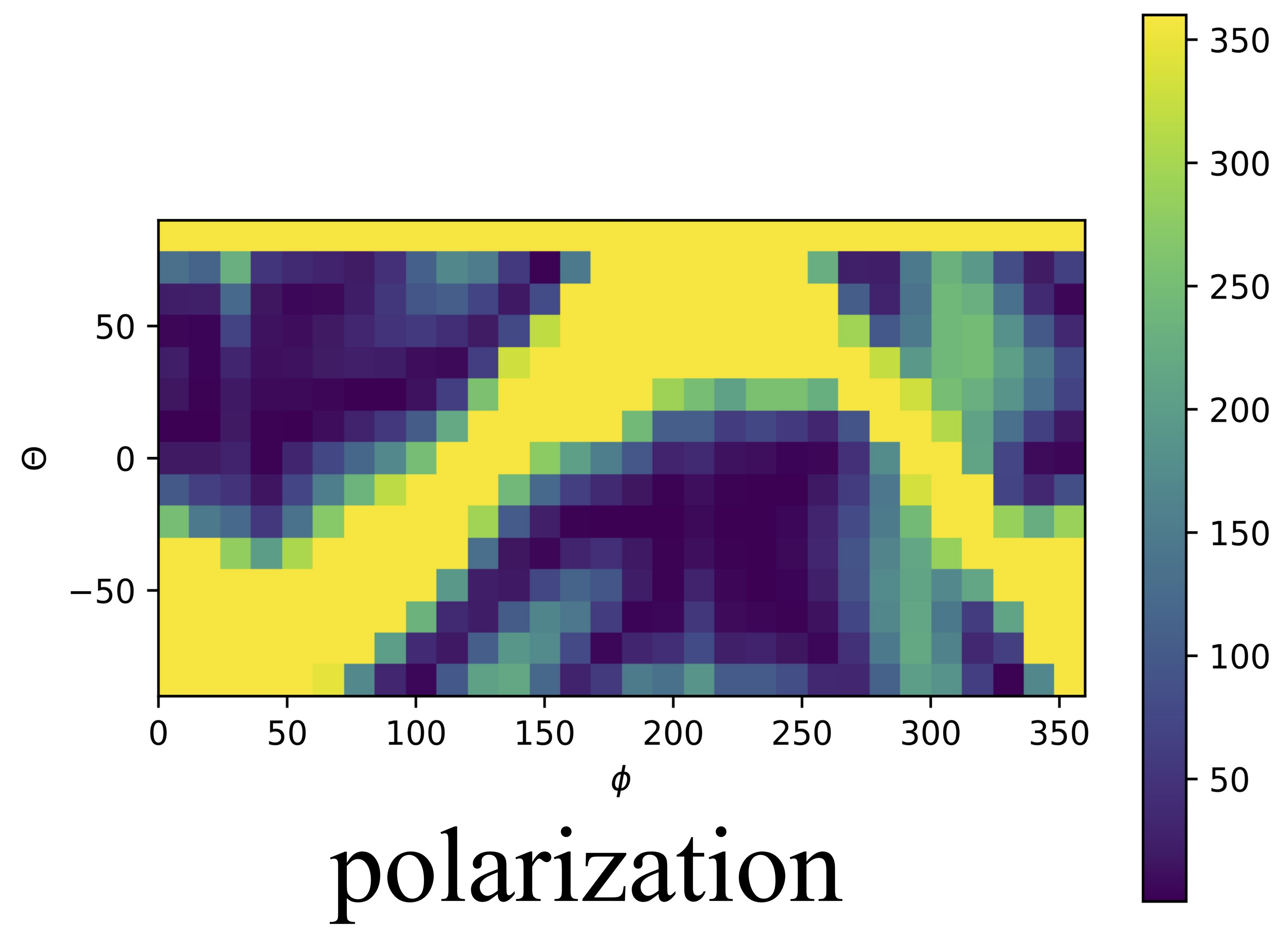


Sky localization

$$M_1 = 16\, M_{\text{solar}}\,,\ M_2 = 10\ M_{\text{solar}}\,,\ d = 400\,\text{Mpc}$$



cos(Inclination)



polarization

Number of detections for BBH&BNS

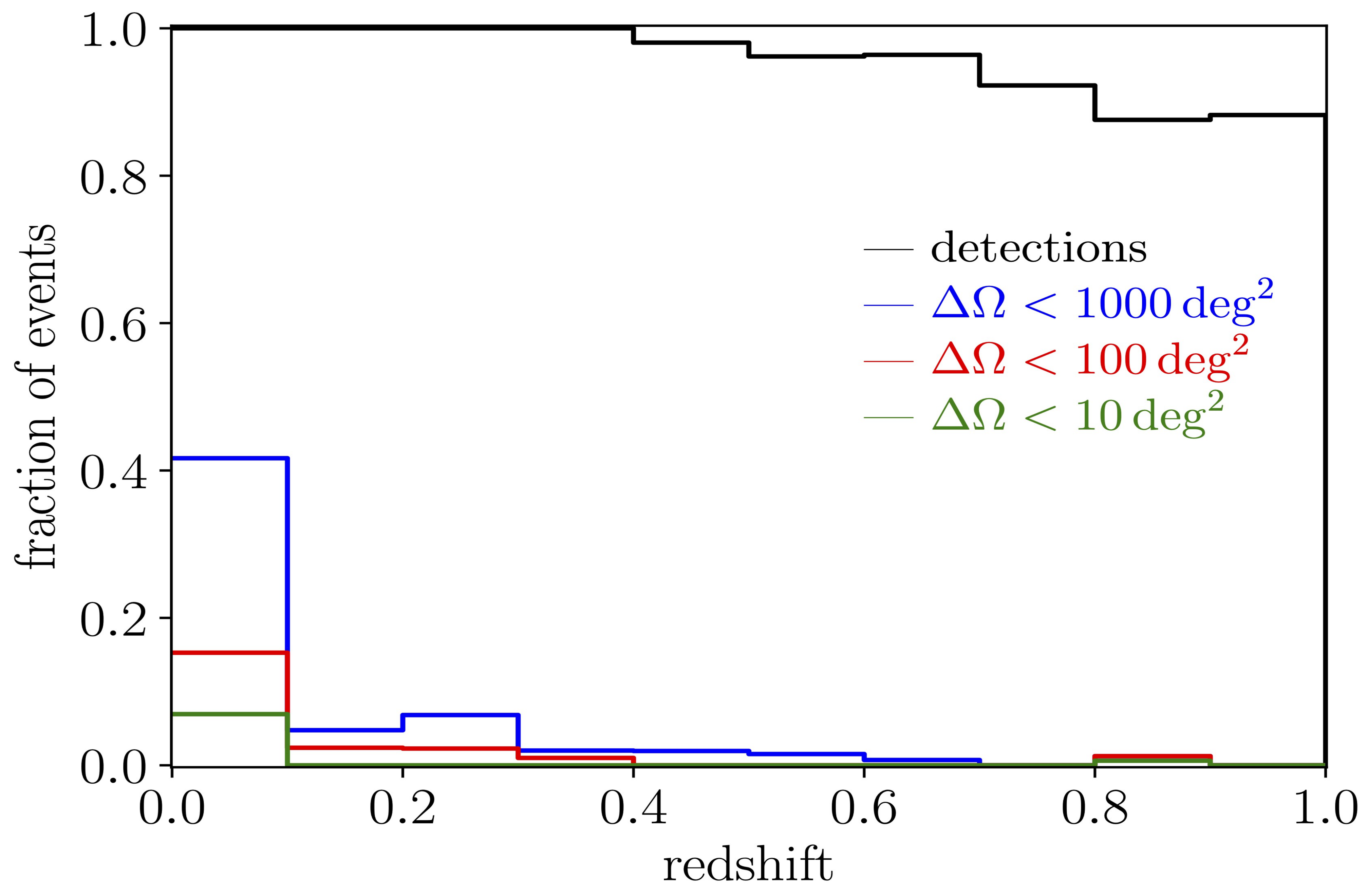
BBH

SNR > 10 events	ET	ET (L)	2xET (L aligned)	2xET (L 45 deg)	ET (low)	ET (high)	2 ET high+low	CE
out of 1000 events	846	731	781	834	842	149	848	660

BNS

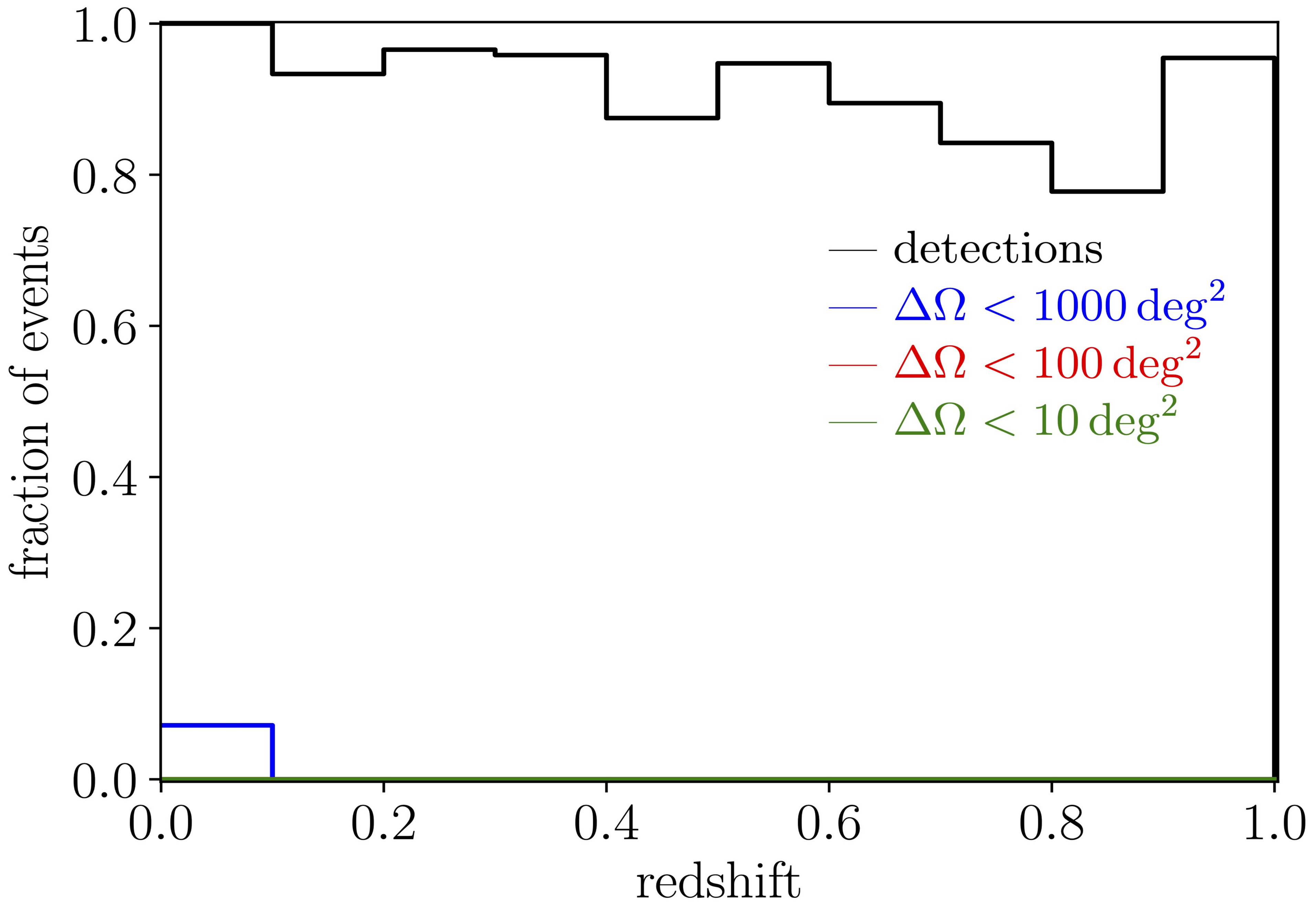
SNR > 10 events	ET	ET (L)	2xET (L aligned)	2xET (L 45 deg)	ET (low)	ET (high)	2 ET high+low	CE
out of 1000 events with all z	109	70	101	97	65	38	115	96
out of 1000 events with $z < 1.5$	390	268	343	348	237	132	375	329
out of 469 events with $z < 1.0$	267	204	241	245	186	120	262	228
out of 81 events with $z < 0.5$	80	65	68	77	70	55	78	67

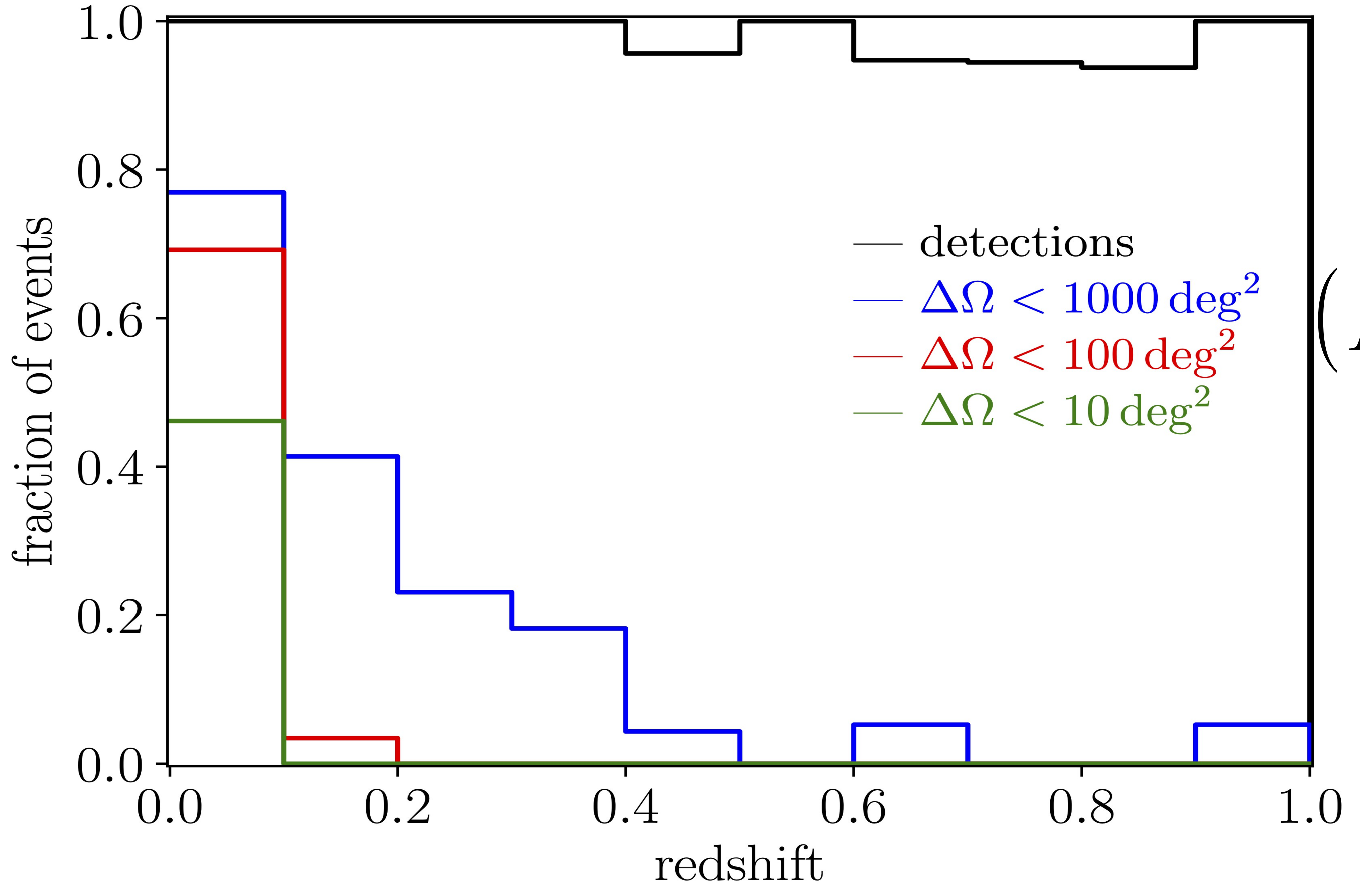
Sky localization estimates (BBH)



ET (triangular)

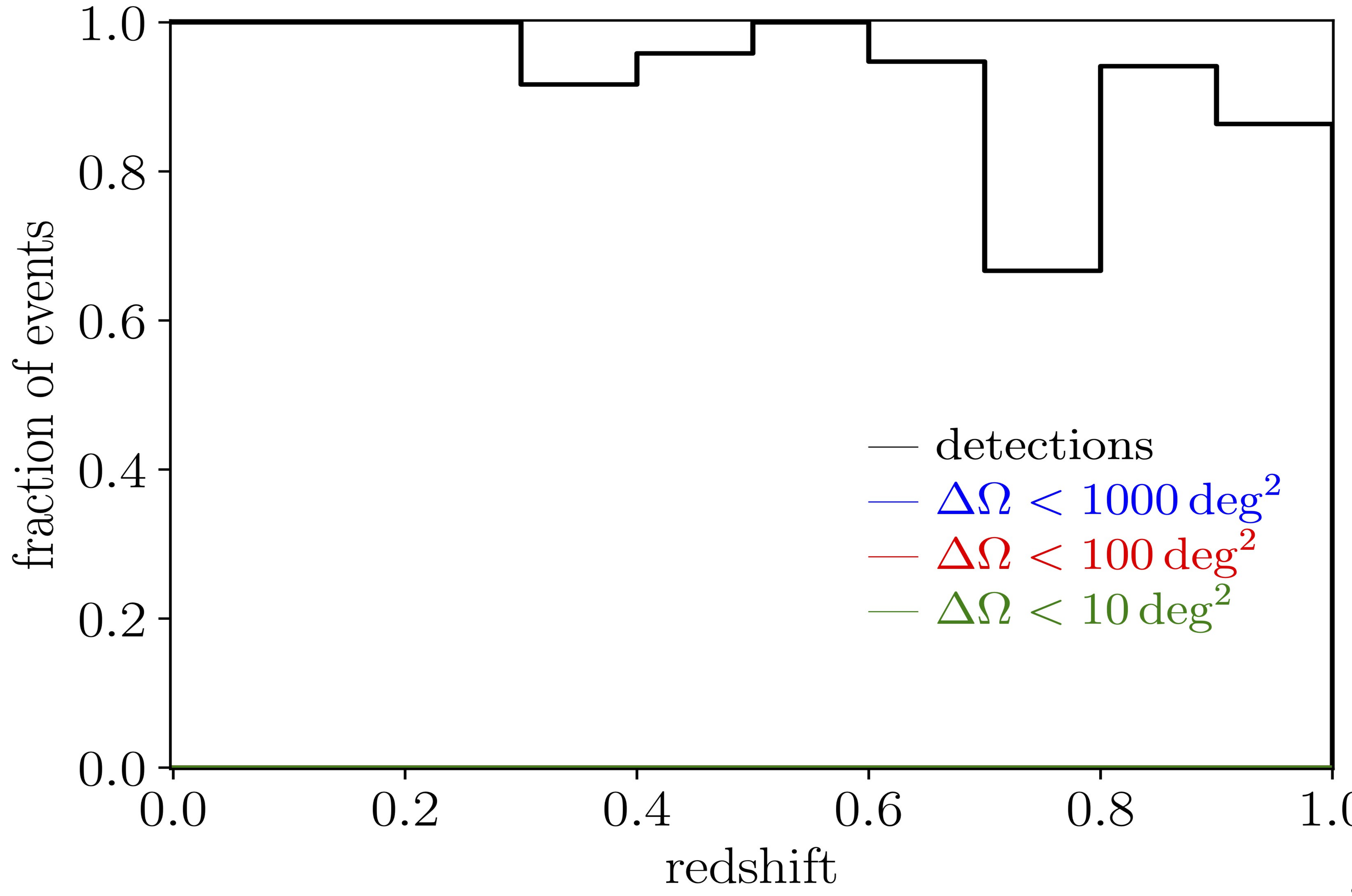
L − shape (ET sensitivity)



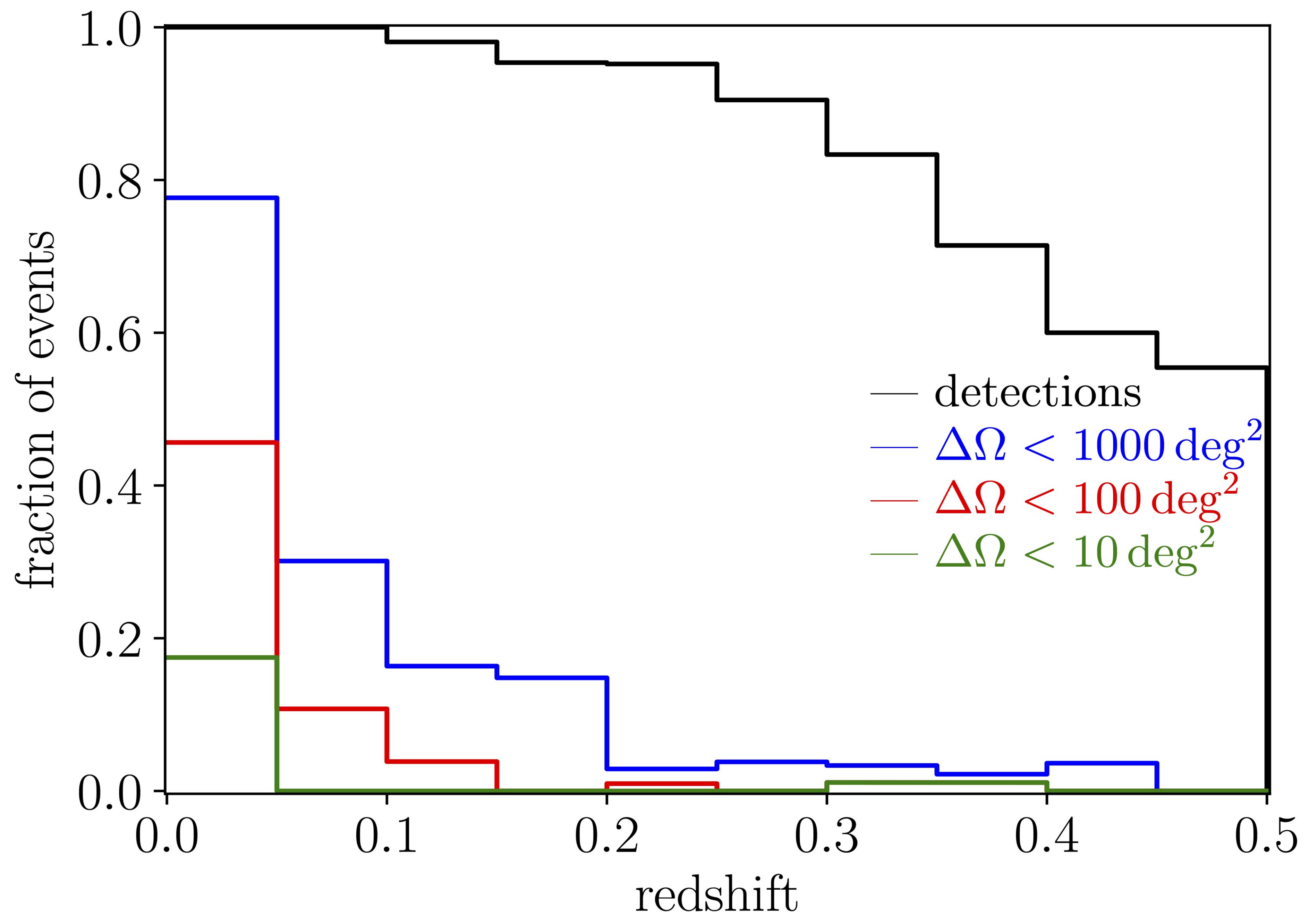


2x *L − shape (ET sensitivity)*

L − shape (CE sensitivity)

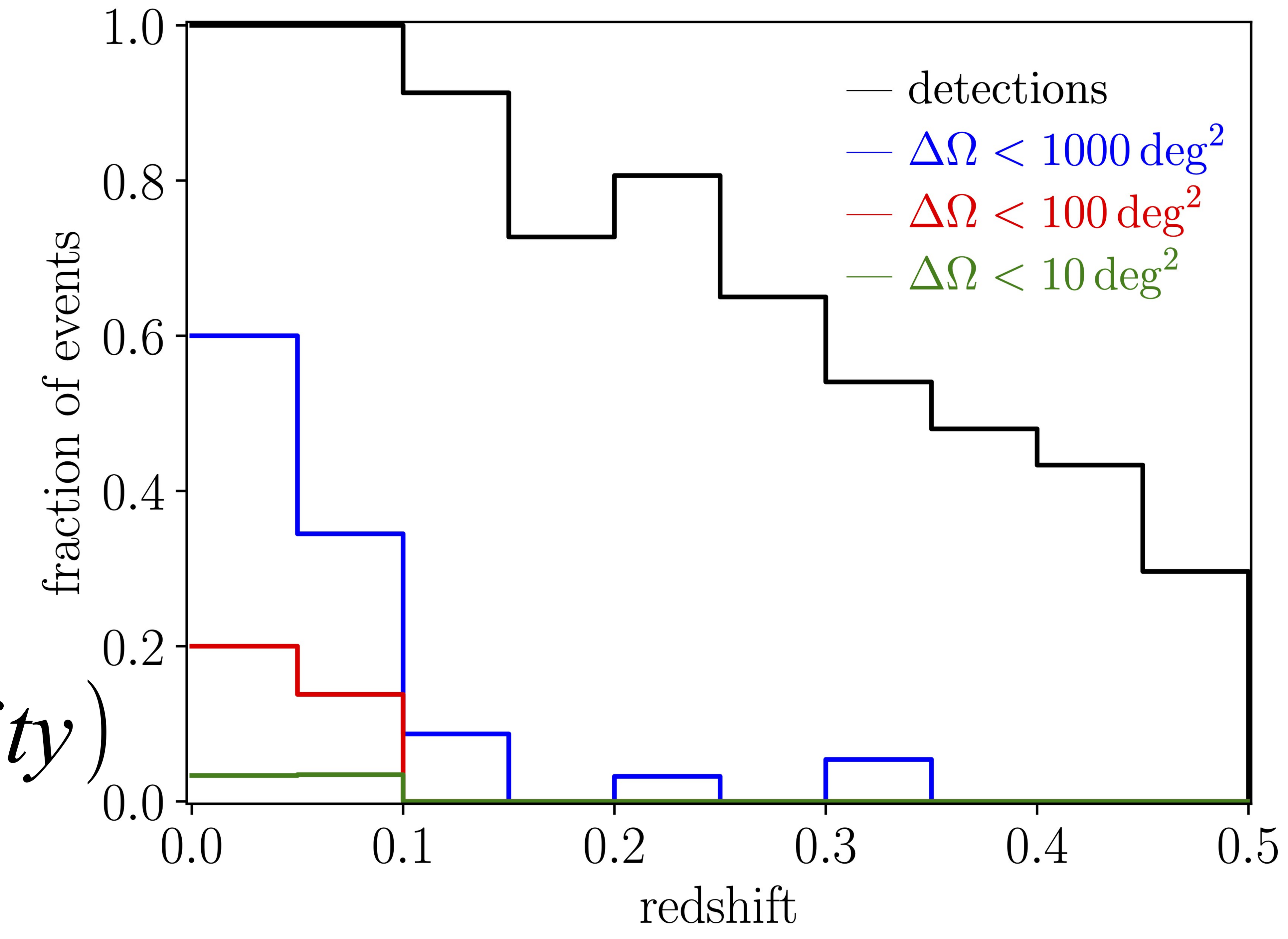


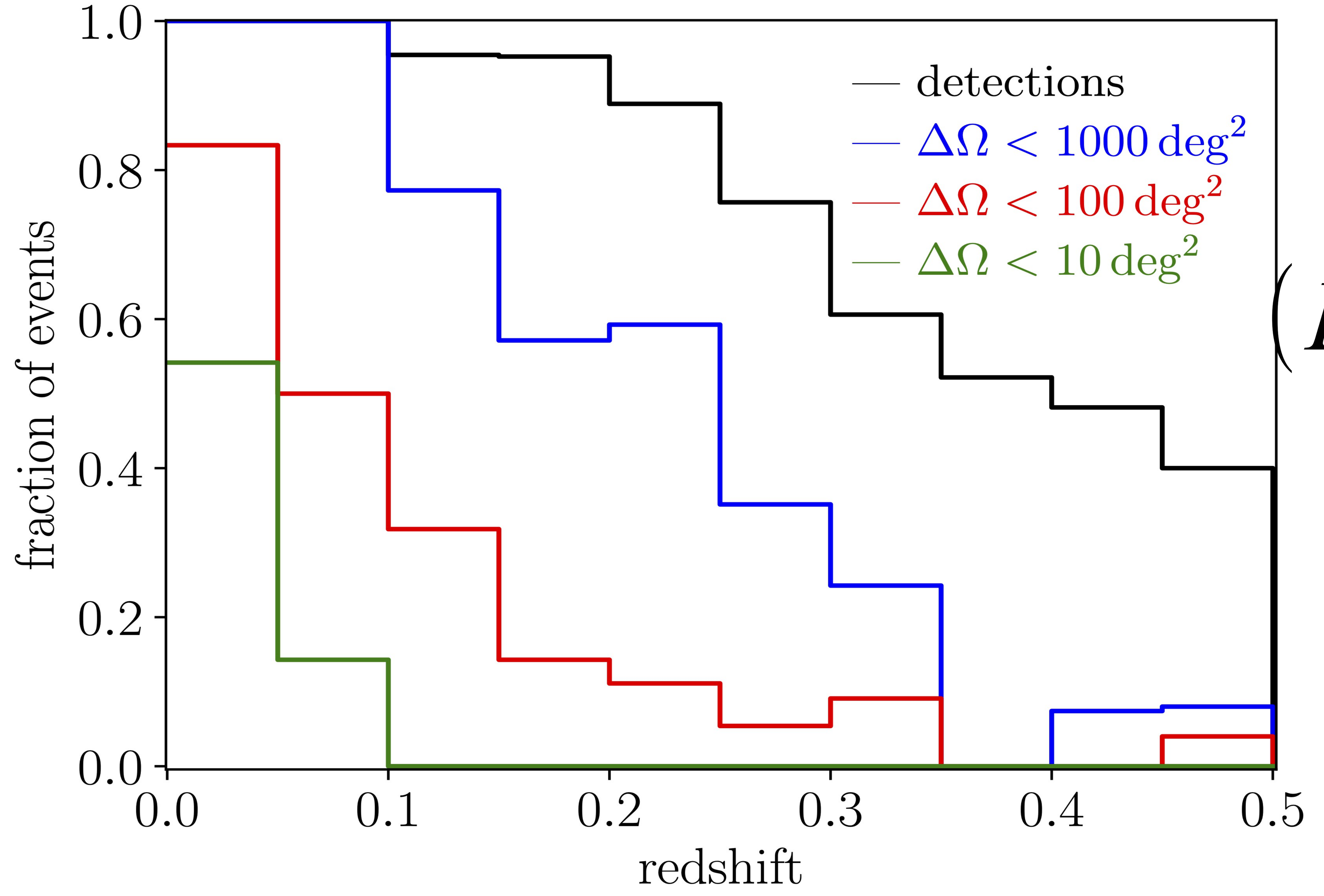
Sky localization estimates (BNS)



$ET\,(triangular)$

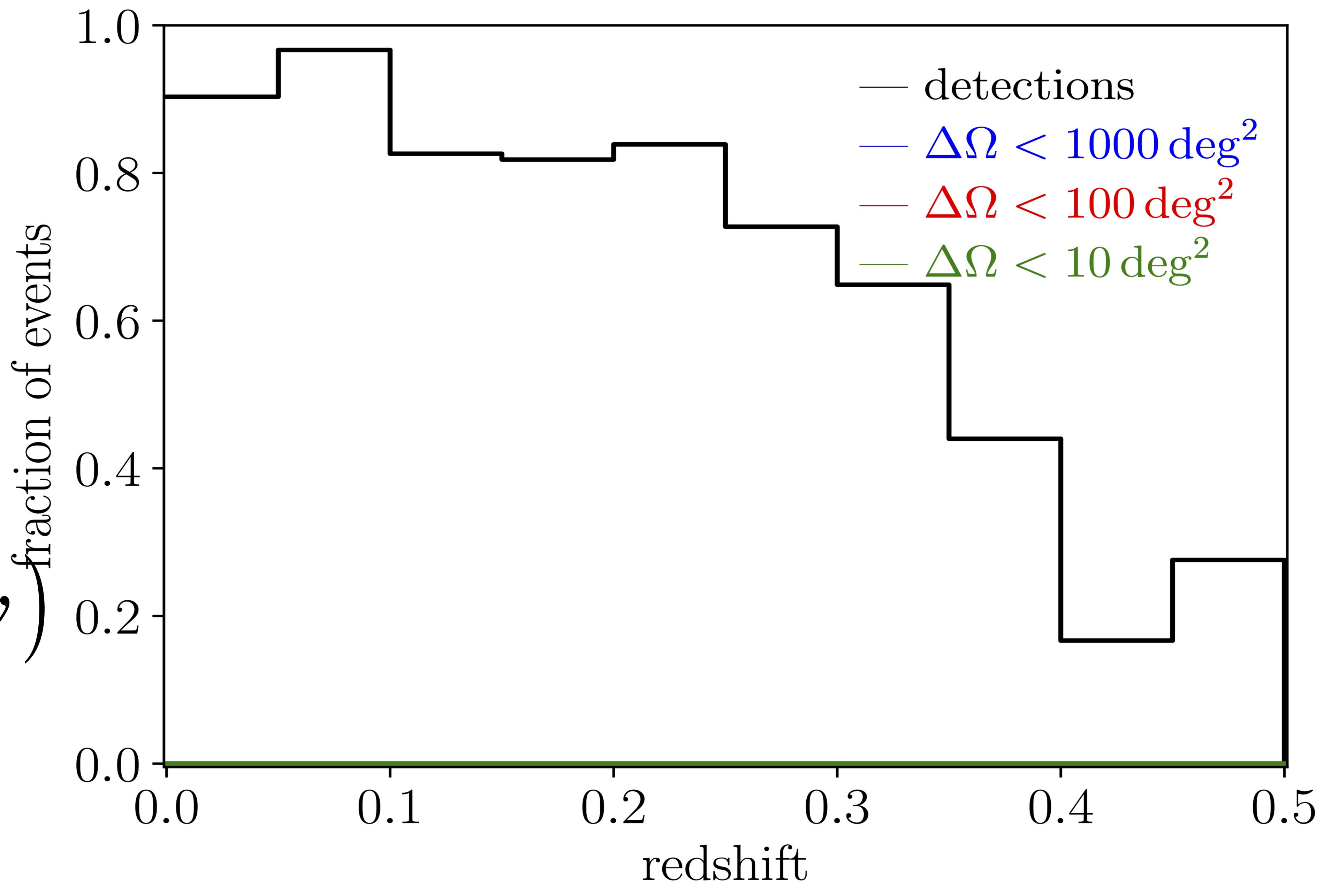
$L-shape$
$(ET\ sensitivity)$



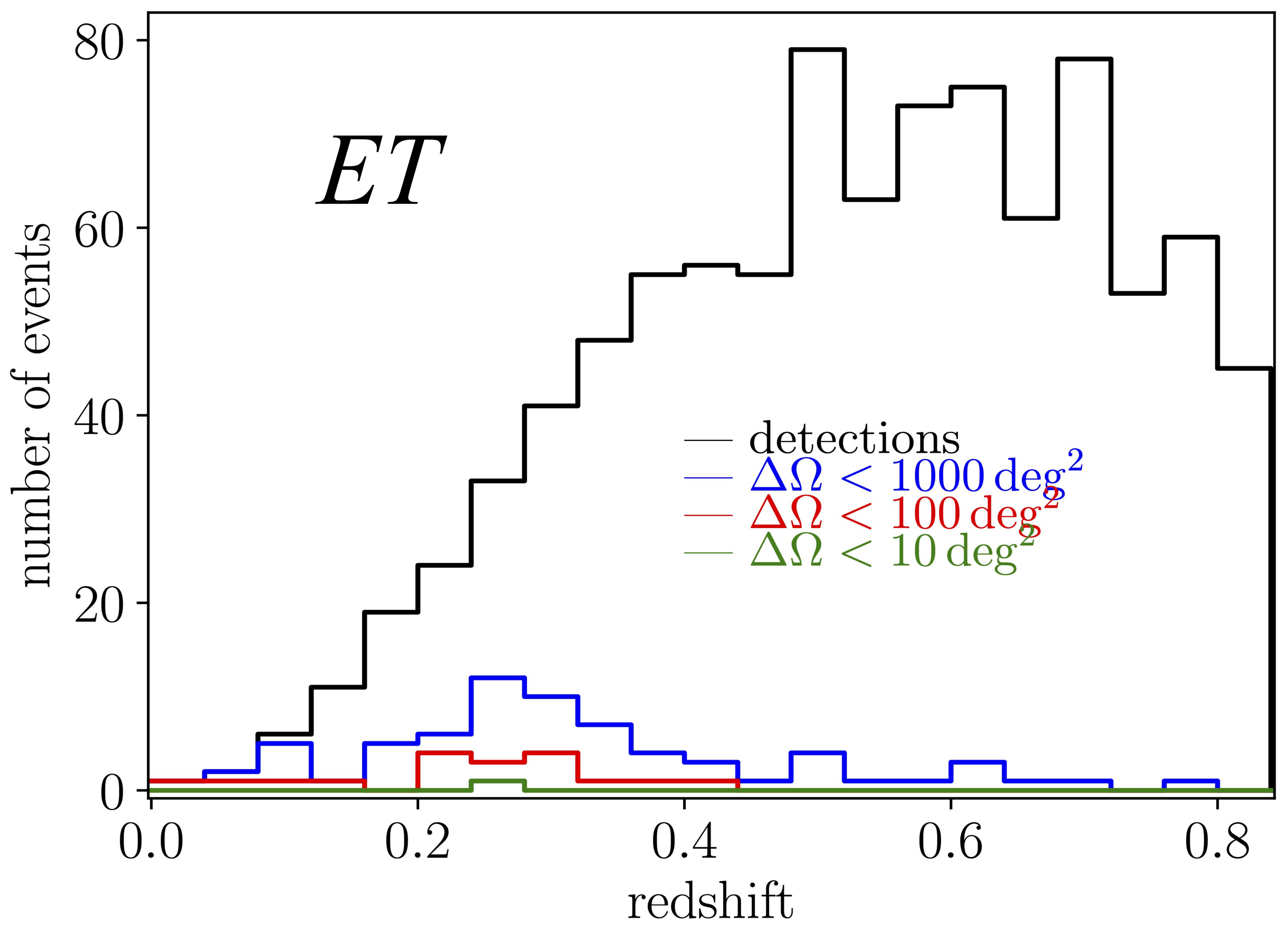


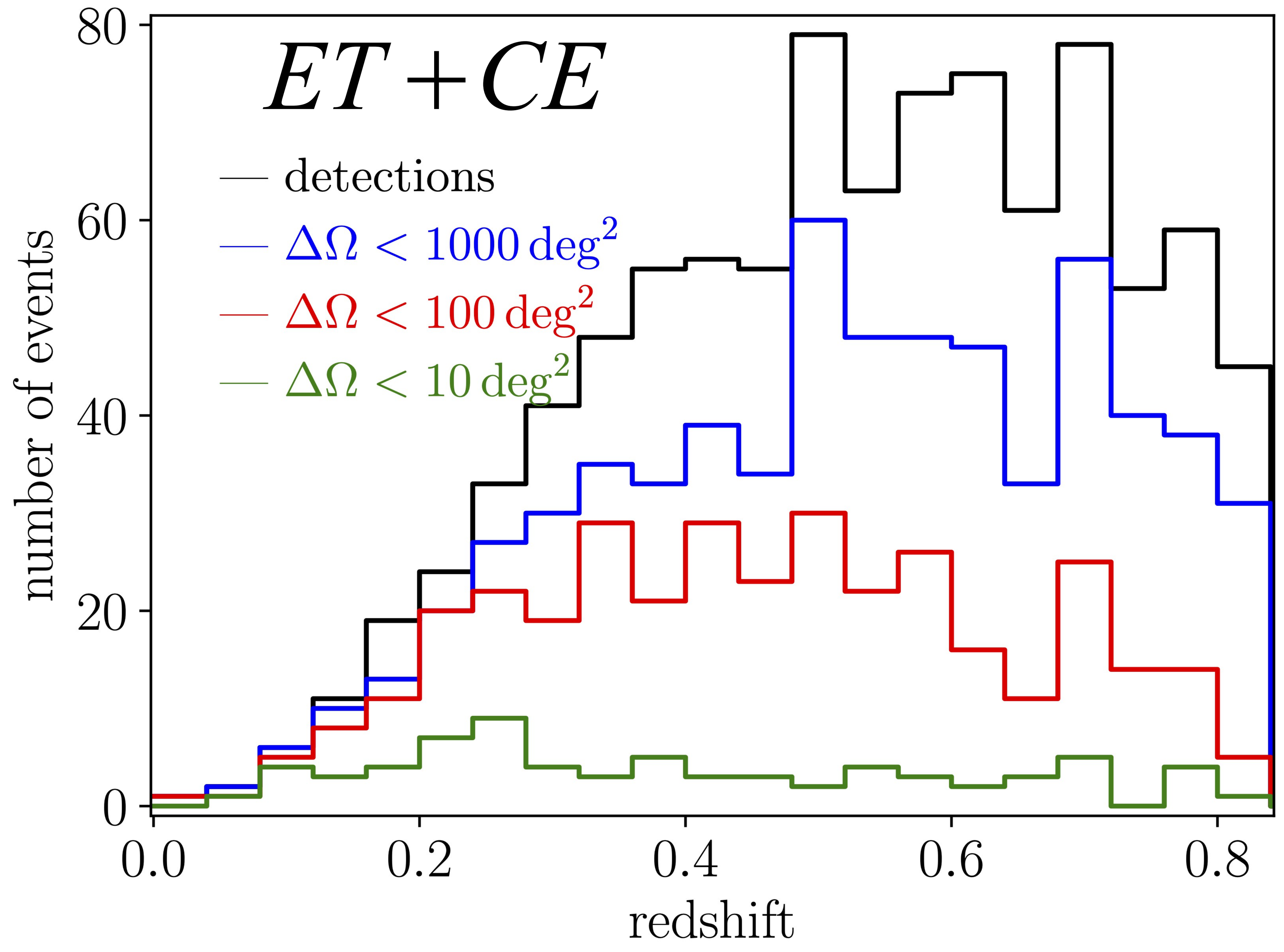
2x $L-shape$
$(ET\ sensitivity)$

$L-shape$
$(CE\ sensitivity)$

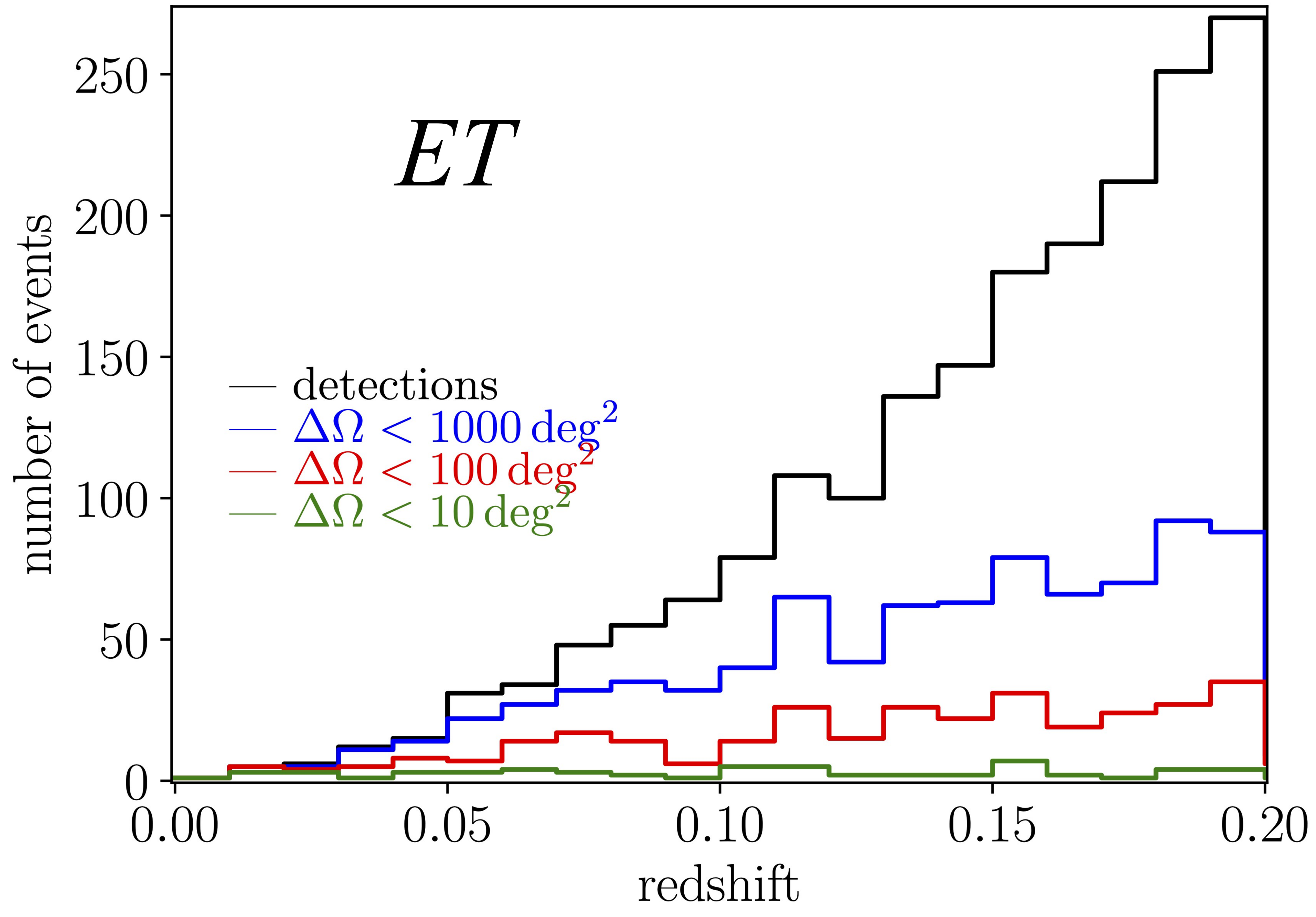


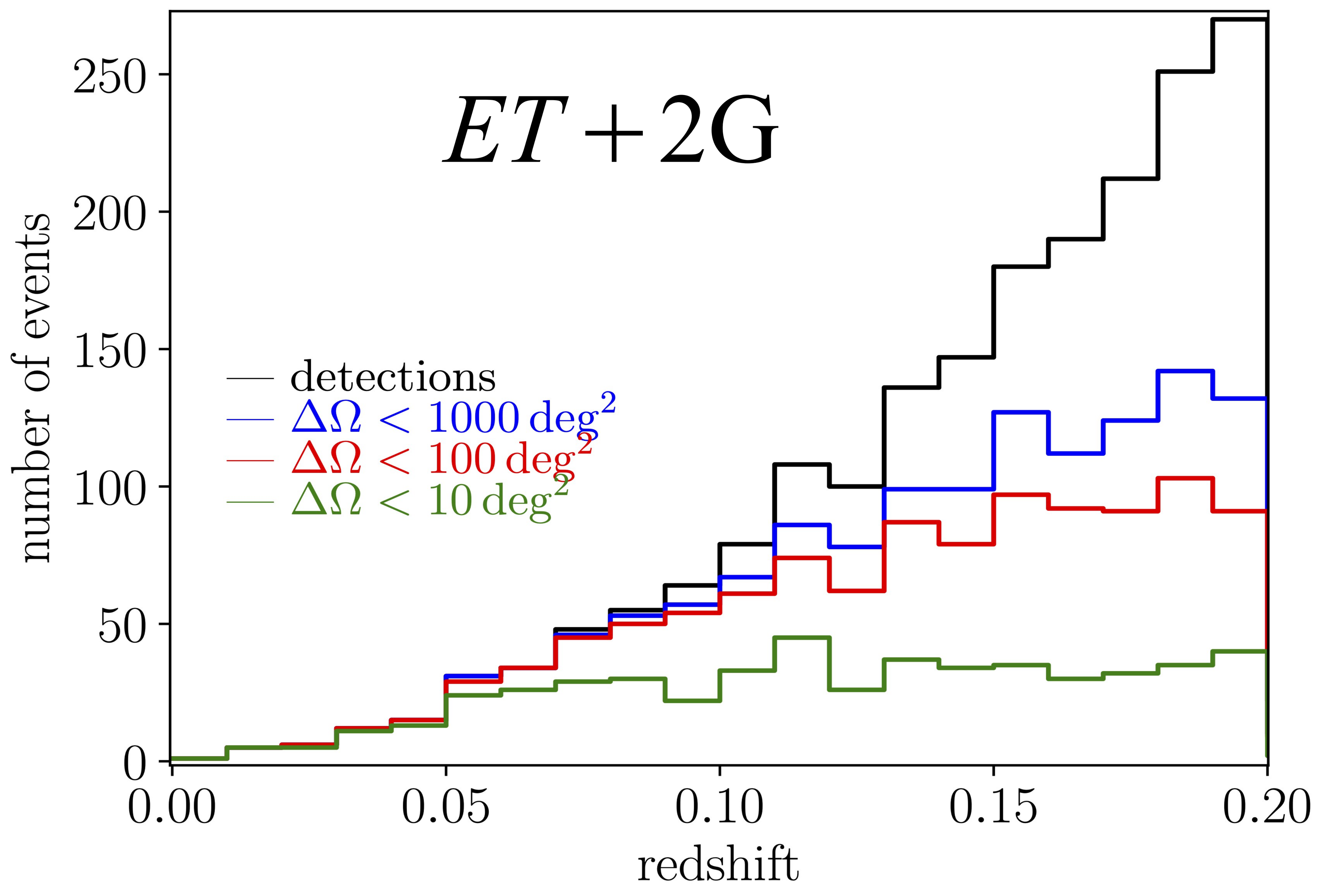
3G+2G detectors: Astrophysical studies





1 *week observation time*





1 *year observation time*

Results

- Triangular shape has advantages for parameter estimation
- Low-frequency sensitivity is crucial for sky localization estimate of BNS
- CE: better sensitivity for detecting BNS, but unable to obtain sky localization
- 2 detector networks give better sky localization estimates (time triangulation)
- For 2 detector networks aligned detectors are better for detecting BNS, not aligned detectors are better for detecting BBH

Introduction/Motivation

Analysis framework

Detector performances
Multiband parameter estimation

3G detector geometries
Multimessenger prospects

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Posteriors
Influence of Priors
Influence of waveforms

Summary and Outlook

S19XXXX: PE results

- Subthreshold event, SNR 9.68
- m1 large, approx. 90 M_solar
- m2 42 M_solar
- Distance 4080 Mpc
- Sky localization approx. 3000 square degrees (90% area)

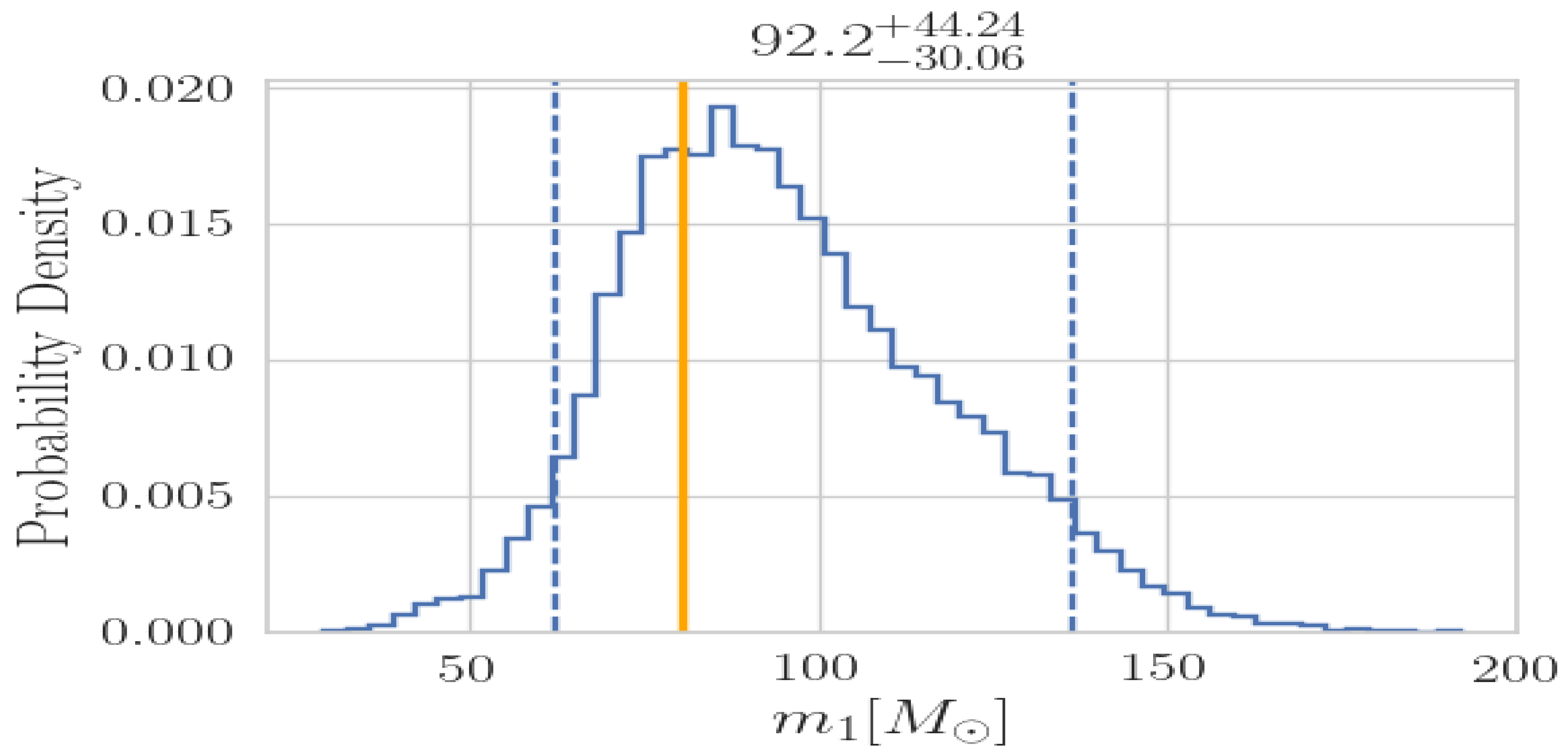
Final IMRPhenomPv2 run

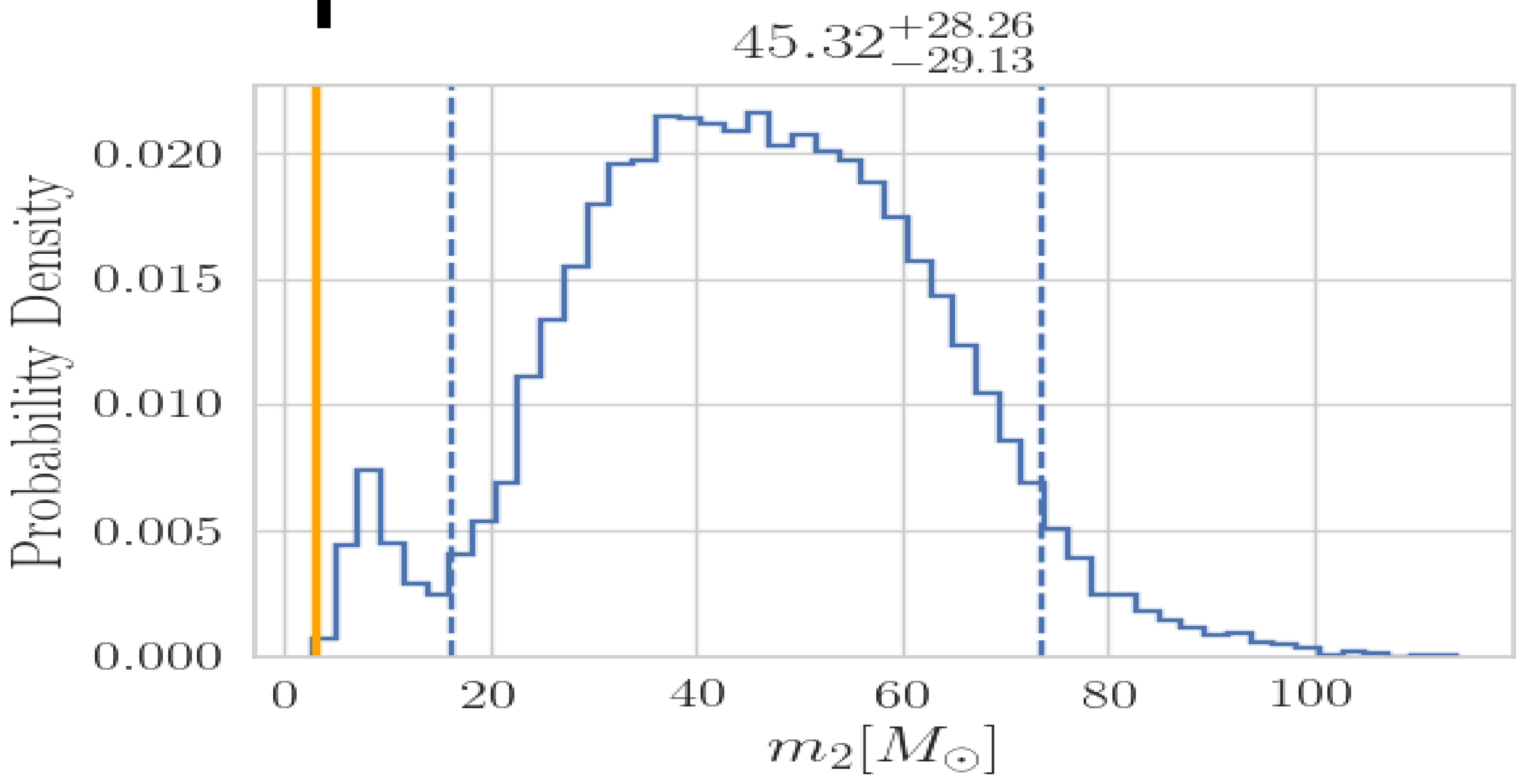
3

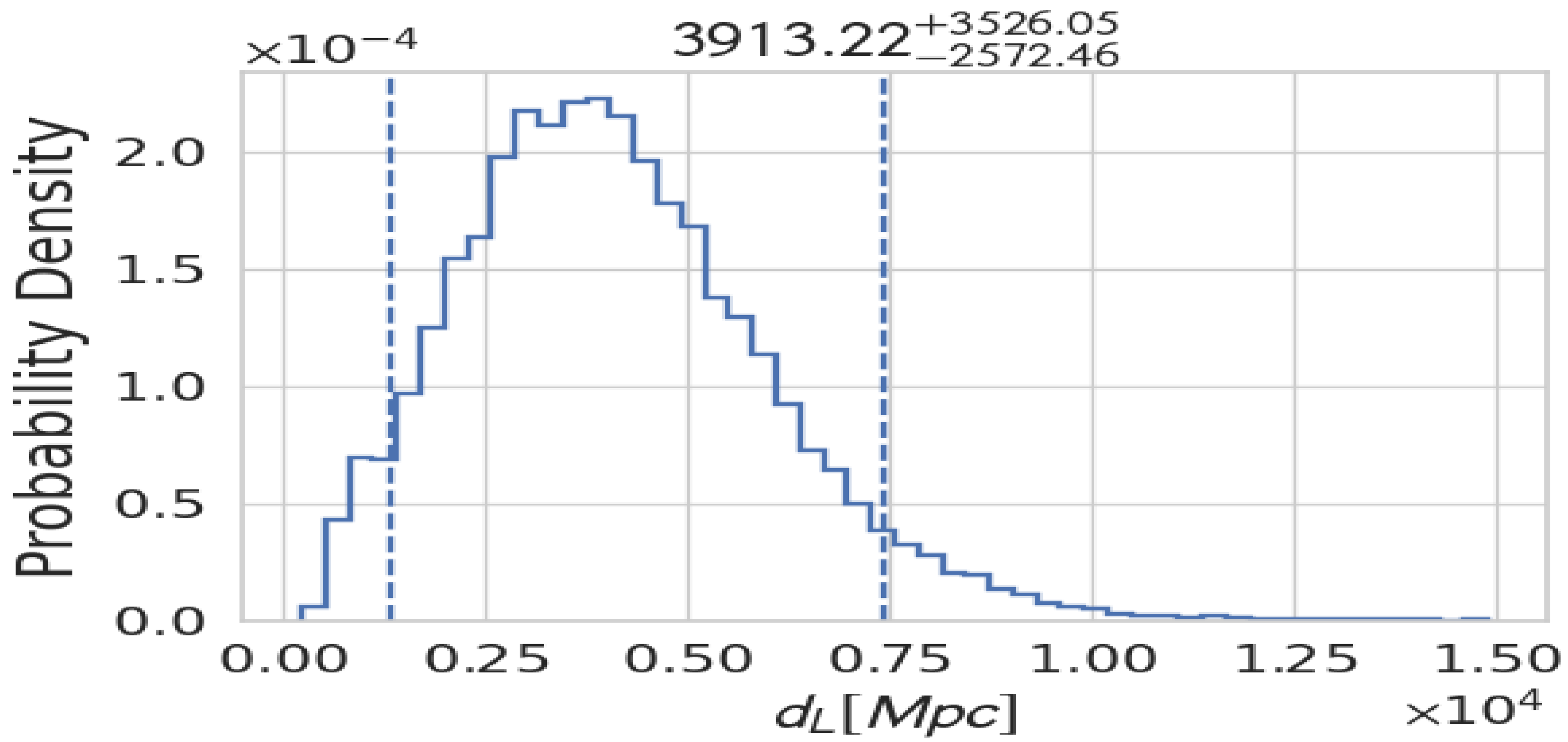
IMRPhenomXHM
Default distance prior

6

IMRPhenomXHM
Uniform distance prior







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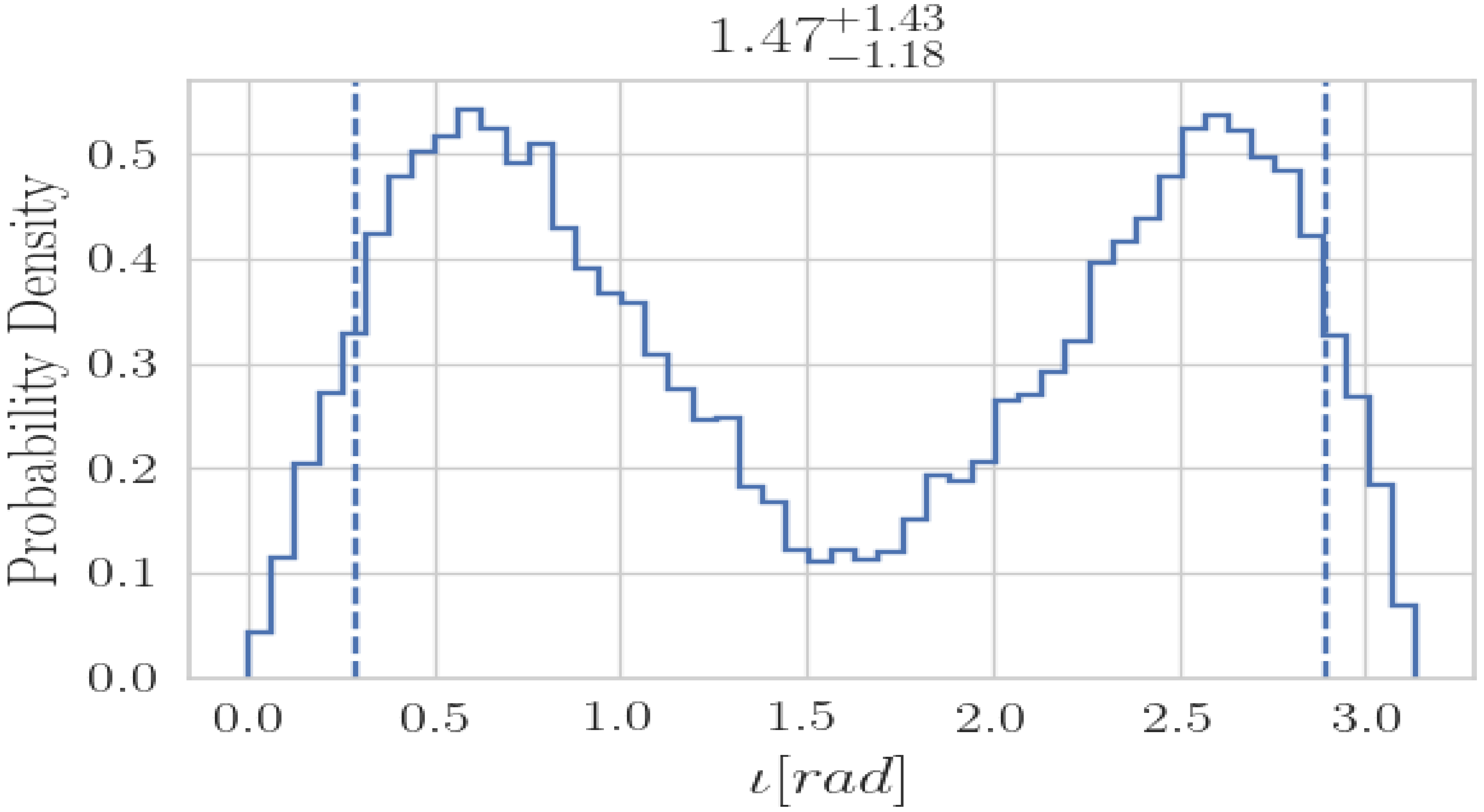

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Summary and Outlook

Summary

- Comprehensive picture of the capabilities of the next generation of gravitational wave detectors
- Benefits of multiband parameter estimation
- Investigation of different detector geometries and networks for 3G detectors
- Prospects for multimessenger studies involving 3G+2G detectors
- Outlook: Full Bayesian approach, deeper understanding of PE with ET&LISA, how do Fisher estimates relate to data analysis for actual events?