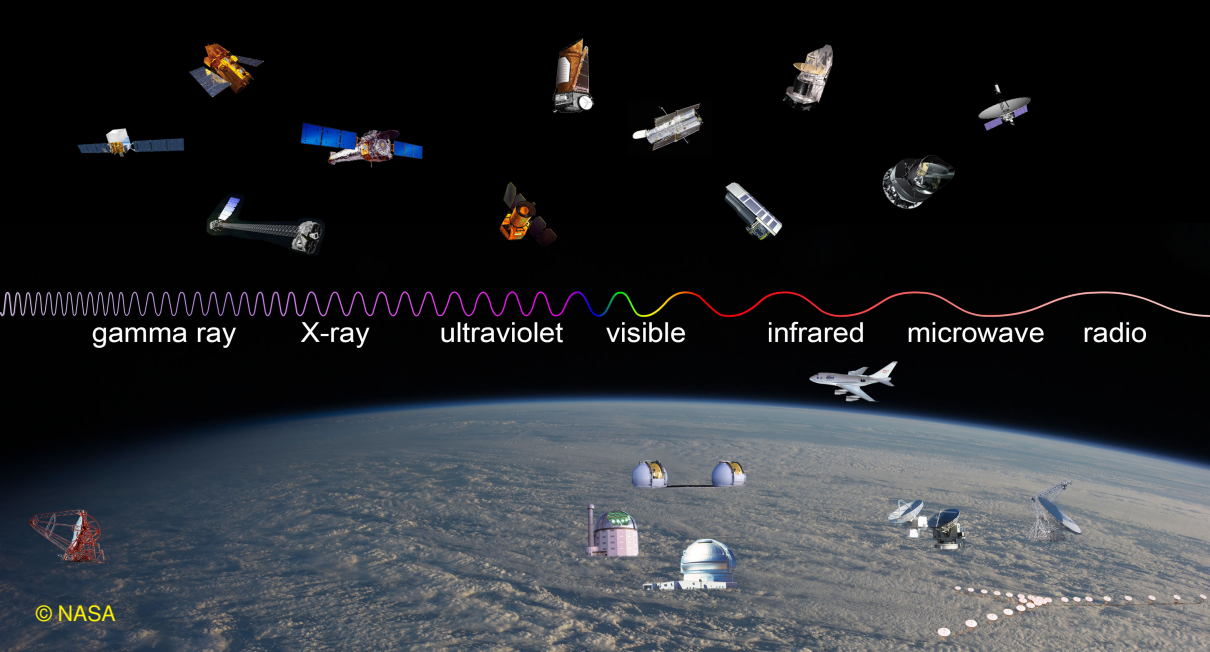


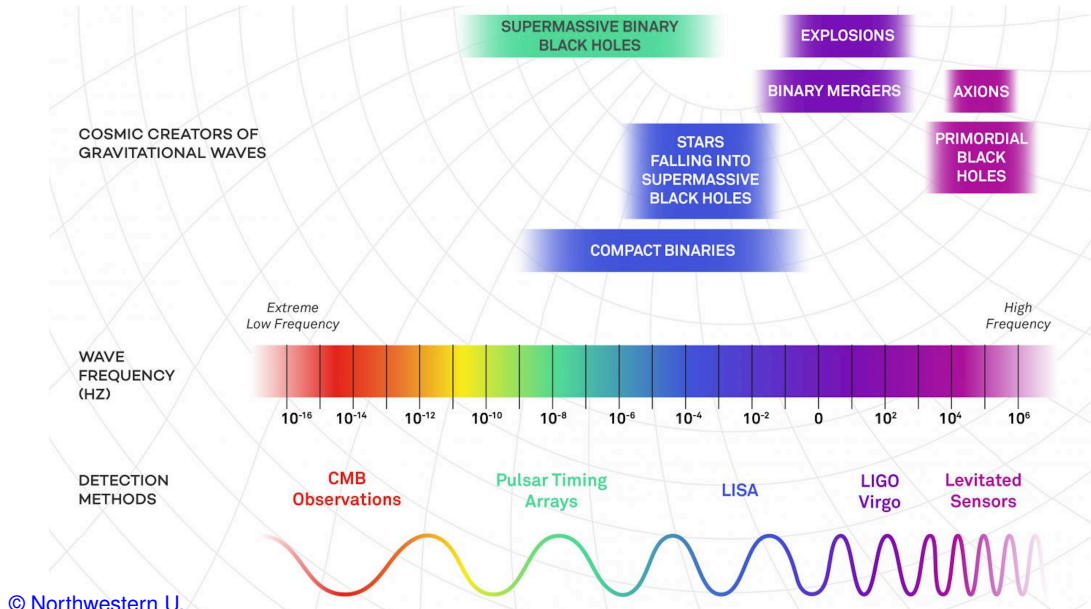
Decihertz GW Detection & Electromagnetic Warnings

Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao (邵立晶)

GW2025 · 千岛湖





© Northwestern U.

Outline



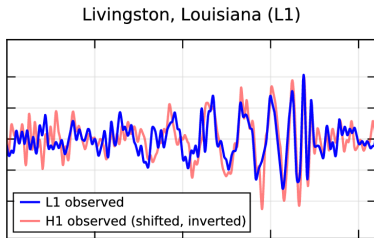
- 1 **Multiband Observation** Liu et al. [[MNRAS:2004.12096](#)]; Song et al. [[npjSE:2502.02995](#)]
- 2 **Parameter Estimation & Early Warnings** Liu & Shao [[ApJ:2108.08490](#)]
- 3 **Population Studies** Liu et al. [[ApJ:2204.06161](#)]
- 4 **EM Followup** Kang et al. [[MNRAS:2205.02104](#)]; Kang et al. [[MNRAS:2309.16991](#)]; Kang et al. [[A&A:2505.10165](#)]
- 5 **Dark Sirens and Cosmology** Liu et al. [[PDU:2205.06991](#)]



Collaborators X. Chen, Y. Gao, Y.-M. Hu ([SYSU](#)), **Y. Kang**, Z. Li, **C. Liu**, M. Liu, Z. Lyu, H. Song, H. Sun ([NAOC](#)), E. Troja ([UniRoma2](#)), M. Wang ([BNU](#)), Z. Wang, H. Yan, Y.-H. Yang ([UniRoma2](#)), Y.-H. Yin ([NJU](#)), B.-B. Zhang ([NJU](#)), B. Zhang ([HKU](#)), F. Zhang ([BNU](#)), J. Zhang ([IGG](#)), J. Zhao, J.-P. Zhu ([HKU](#))

GW Astrophysics

- Detection of GWs opened up a new window to observe **gravitational Universe**, and is revolutionizing **Astrophysics**, **Cosmology**, and **Fundamental Physics**



Abbott et al. [[RPL:1602.03837](#)]

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- **2017 Nobel Prize** to **Rainer Weiss**, **Kip Thorne**, & **Barry Barish** *for decisive contributions to the LIGO detector and the observation of GWs*

Livingston, Louisiana (L1)

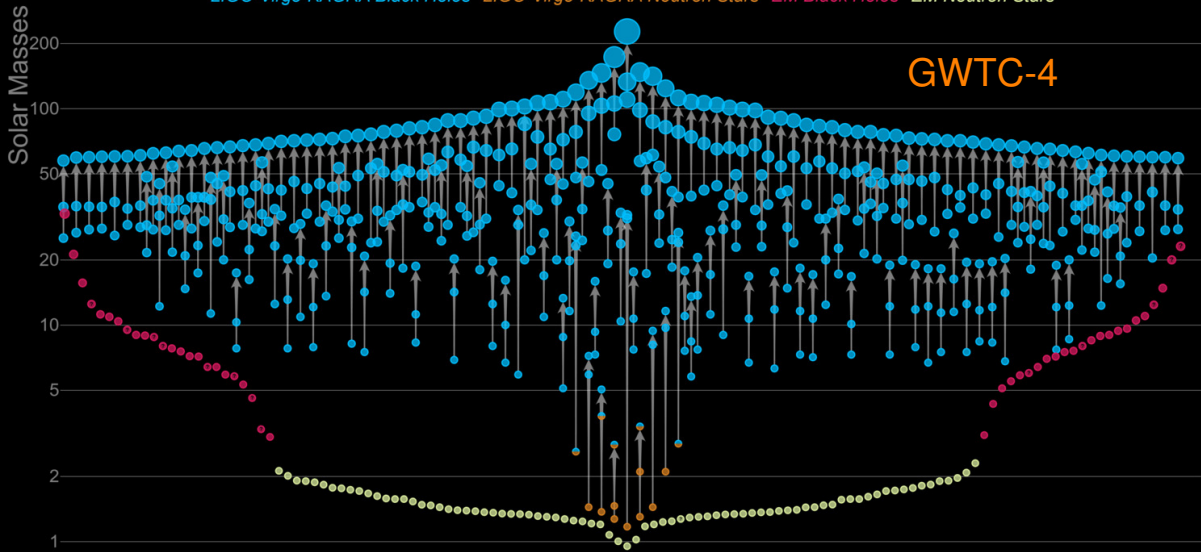


Abbott et al. [[RPL:1602.03837](#)]



Masses in the Stellar Graveyard

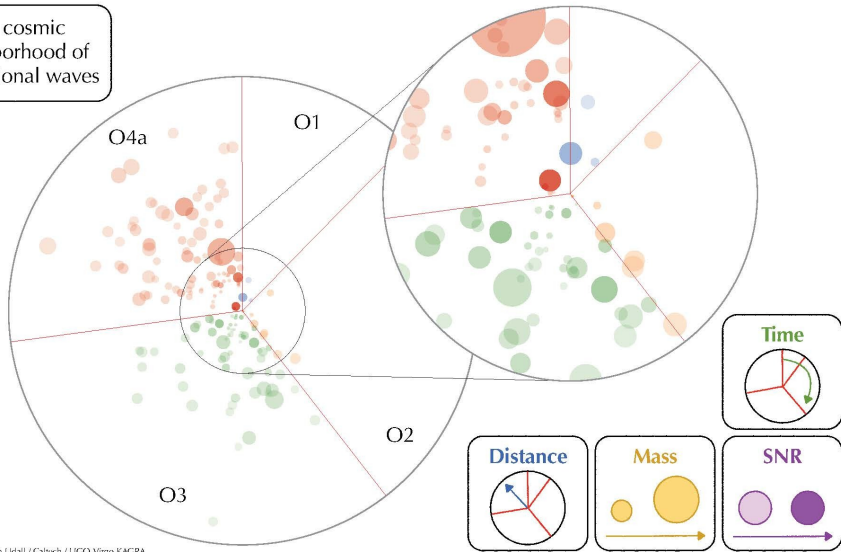
LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



Abac et al. [[arXiv:2508.18082](#)]

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

The cosmic neighborhood of gravitational waves



Derek Davis / Rhiannon Udall / Caltech / LIGO-Virgo-KAGRA

Abac et al. [[arXiv:2508.18082](https://arxiv.org/abs/2508.18082)]

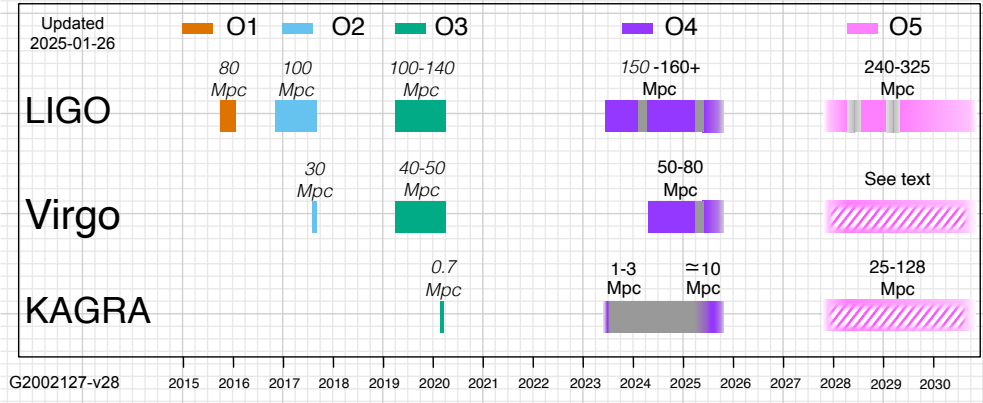
LIGO/Virgo/KAGRA O4 Public Alerts

- O4 Significant Detection Candidates: **243** (271 Total - 28 Retracted)
- O4 Low Significance Detection Candidates: **4906** (Total)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices VOE		1.8411 per year	
S240104bl	BBH (>99%)	Yes	Jan. 4, 2024 16:49:32 UTC	GCN Circular Query Notices VOE		1 per 8.9137e+08 years	
S231231ag	BBH (>99%)	Yes	Dec. 31, 2023 15:40:16 UTC	GCN Circular Query Notices VOE		1 per 3.7932e+06 years	

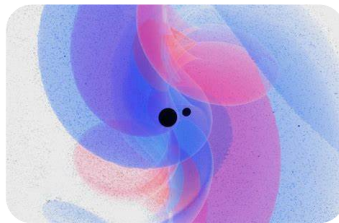
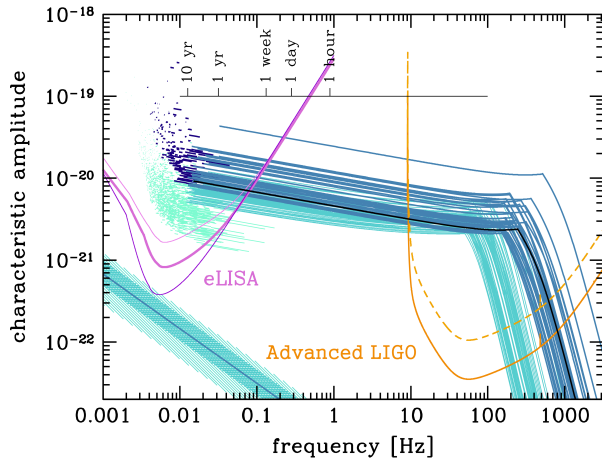
<https://gracedb.ligo.org/superevents/public/O4/>

LIGO/Virgo/KAGRA in the Near Future



LIGO Document G2002127-v28 (Public)

Multiband Observation of BBHs



Sesana [[PRL:1602.06951](#)]

Multiband Observation of BBHs

- **Multiband** observations are benefitted from LIGO/Virgo/KAGRA **heavier BBHs** than (most astrophysicists) previously anticipated

$$f_{\text{GW}} \sim \frac{1}{M}$$

Sesana [[PRL:1602.06951](#)]; Ioyama et al. [[PTEP:1802.06977](#)]; Wong et al. [[PRL:1808.08247](#)]; Gerosa et al. [[PRD:1902.00021](#)]
Moore et al. [[MNRAS:1905.11998](#)]; Robson et al. [[CQG:1803.01944](#)]; Arca Sedda et al. [[CQG:1908.11375](#)]; Toubiana et al. [[PRD:2004.03626](#)]

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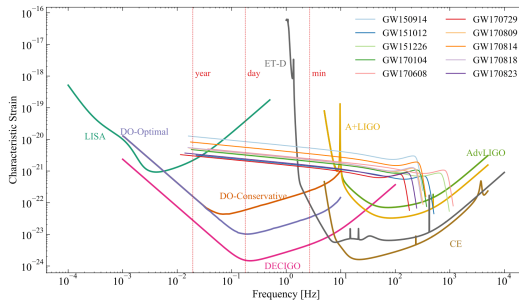
- **Multiband** observations are benefitted from LIGO/Virgo/KAGRA **heavier BBHs** than (most astrophysicists) previously anticipated

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 - Space **predicts** BBH mergers for Ground (and electromagnetic followup, if any)
 - Ground **retraces** (sub-threshold) BBH mergers in Space data
- **Decihertz** observations **boost** the science significantly

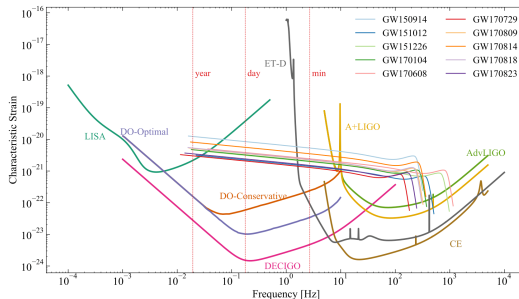
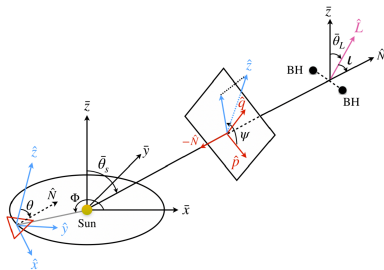
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Parameter Estimation and Joint Analysis



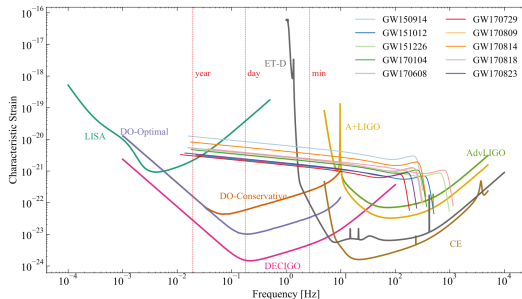
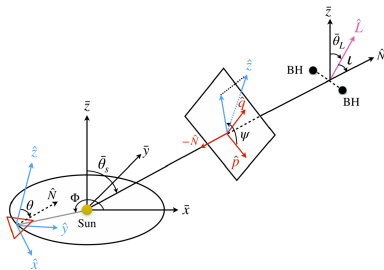
Liu, Shao, Zhao, Gao [MNRAS:2004.12096]

Parameter Estimation and Joint Analysis



- Detector motion **verse** static configuration

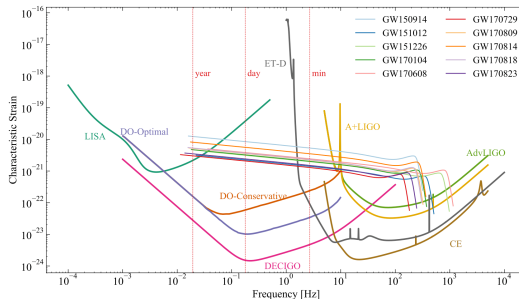
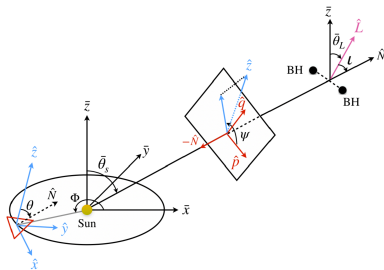
Parameter Estimation and Joint Analysis



- Detector motion **verse** static configuration
- Inspiral-merger-ringdown **verse** post-Newtonian waveform

Liu, Shao, Zhao, Gao [MNRAS:2004.12096]

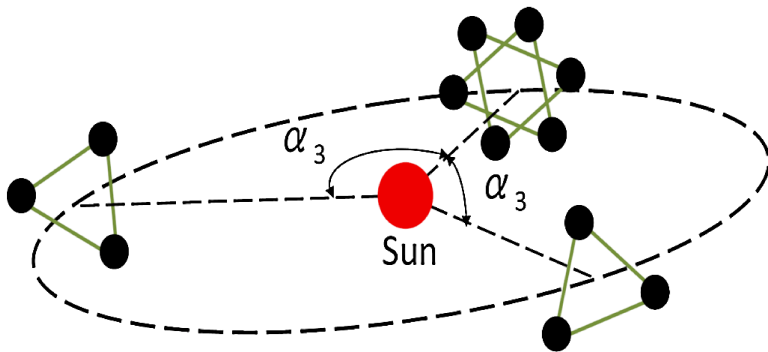
Parameter Estimation and Joint Analysis



- Detector motion **verse** static configuration
- Inspiral-merger-ringdown **verse** post-Newtonian waveform
- Spinning BBHs **verse** nonspinning BBHs

Liu, Shao, Zhao, Gao [MNRAS:2004.12096]

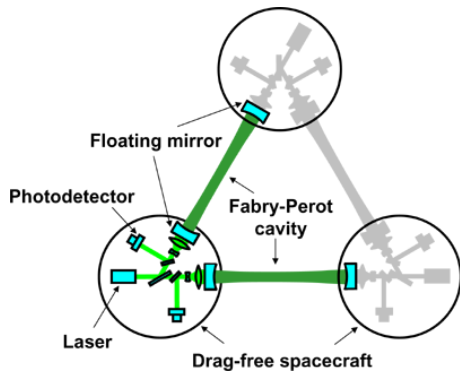
Decihertz GW Detectors



Decihertz Interferometer Gravitational Wave Observatory/Big Bang Observer

Yagi & Seto [PRD:1101.3940]

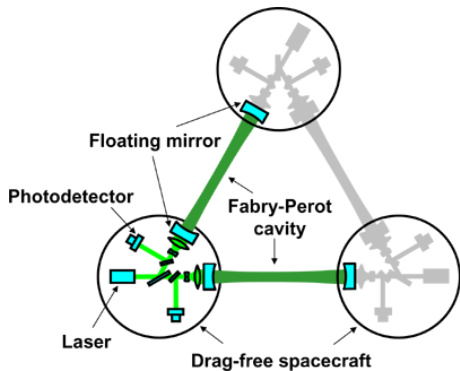
Decihertz GW Detectors



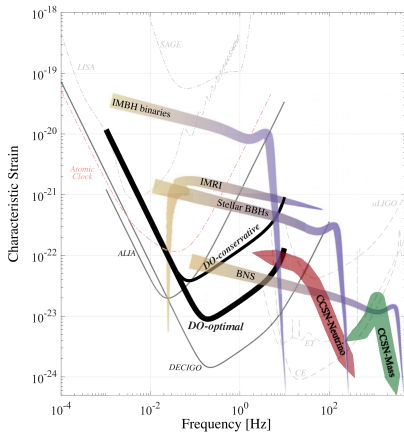
DECIGO & b-DECIGO

Yagi & Seto [[PRD:1101.3940](#)]; Arca Sedda et al. [[CQG:1908.11375](#)]

Decihertz GW Detectors



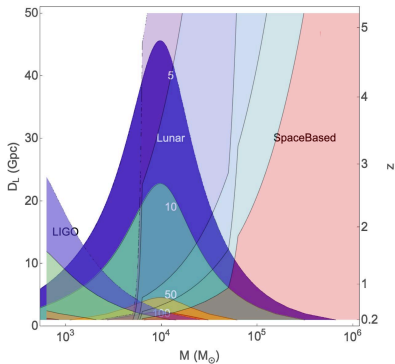
DECIGO & b-DECIGO



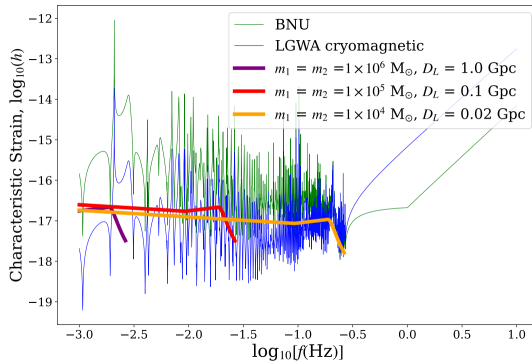
DOs: ESA's Voyage 2050

Yagi & Seto [[PRD:1101.3940](#)]; Arca Sedda et al. [[CQG:1908.11375](#)]

Decihertz GW Detectors



Lunar GW Detector



Li et al. 2023, SCPMA 66:109513; Yan et al. [[PRD:2403.08681](#)]

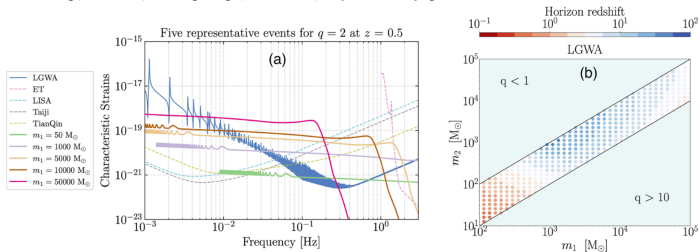


<https://doi.org/10.1038/s44453-025-00002-z>

Probing intermediate-mass black hole binaries with the lunar gravitational-wave antenna

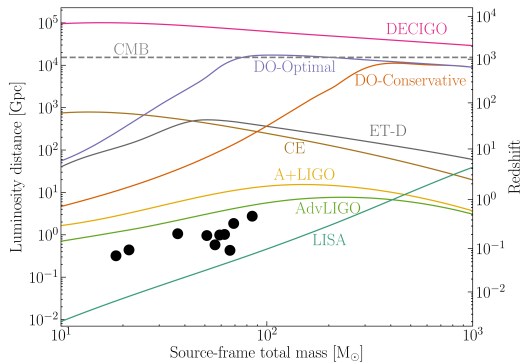
Check for updates

Hanlin Song¹, Han Yan^{2,3}, Yacheng Kang^{2,3}, Xian Chen^{2,3}, Junjie Zhao⁴ & Lijing Shao^{3,5}



Song, Yan, Kang, Chen, Zhao, Shao [npjSE:2502.02995]

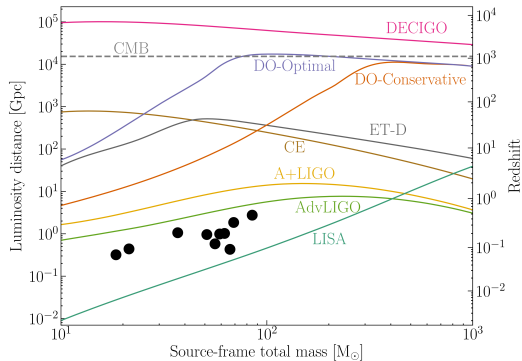
GWTC-1: Horizon Distance & Dipolar Radiation



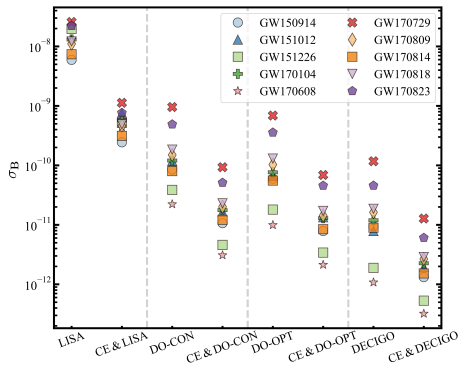
Horizon Distance

Liu, Shao, Zhao, Gao [[MNRAS:2004.12096](#)]

GWTC-1: Horizon Distance & Dipolar Radiation



Horizon Distance



Dipolar Radiation

Liu, Shao, Zhao, Gao [MNRAS:2004.12096]

Scalarized Black Holes

- **Scalarized BH** solutions were found in scalar-tensor gravity with a **Gauss-Bonnet term** $\mathcal{G} \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$

$$S = \frac{1}{2} \int d^4x \sqrt{-g} \left[R - \frac{1}{2} \nabla_\alpha \varphi \nabla^\alpha \varphi + f(\varphi) \mathcal{G} - V(\varphi) \right] + S_m[\psi_m; g_{\mu\nu}]$$

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- Scalarized binaries have a **dipole flux correction** Barausse et al. [[PRL:1603.04075](#)]

$$\dot{E}_{\text{GW}} = \dot{E}_{\text{GR}} \left[1 + B \left(\frac{M}{r} \right)^{-1} \right]$$

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- In the (restricted) **parametrized post-Einsteinian formalism** Yunes & Pretorius [PRD:0909.3328]

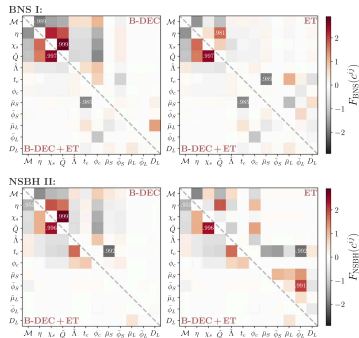
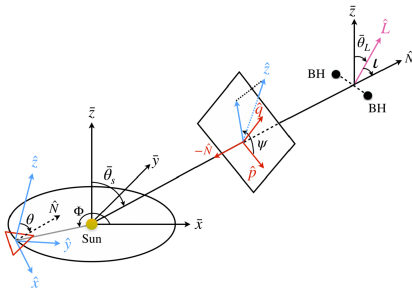
$$\tilde{h}_{\text{ppE}}(f) = A_{\text{GR}}(f) e^{i[\Psi_{\text{GR}}(f) + \beta u^b]} \quad \text{with } b = -7/3 \text{ \& } \beta = -(3/224)\eta^{2/5} B$$

Antoniou et al. [PRL:1711.03390]; Doneva & Yazadjiev [PRL:1711.01187]; Silva et al. [PRL:1711.02080]

Waveform with Matters & Parameter Correlations

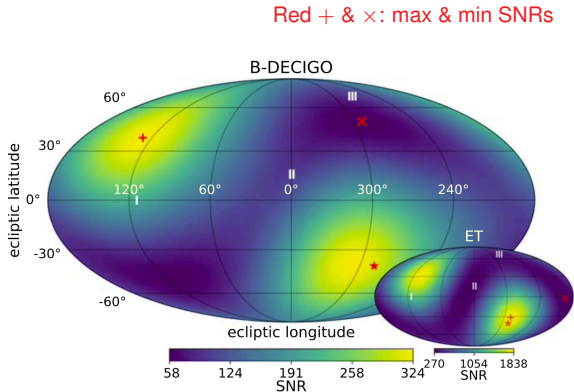
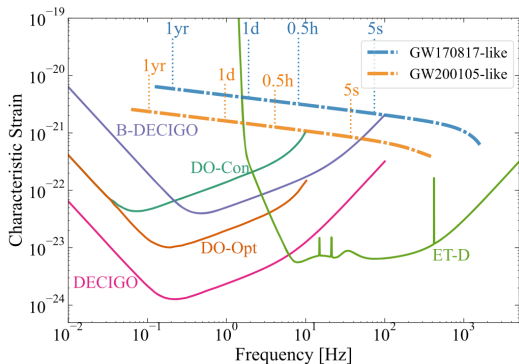
■ Fourier-domain waveform involving NSs

$$\Psi_{\text{NS}}(f) = 2\pi f t_c - 2\varphi_c - \frac{\pi}{4} + \frac{3}{128\eta\nu^5} \left(\Psi_{3.5\text{PN}}^{\text{pp+spin}} + \Psi_{2-3.5\text{PN}}^{\text{QM}} + \Psi_{5-6\text{PN}}^{\text{tidal}} \right)$$



Liu, Shao, Zhao, Gao [MNRAS:2004.12096]; Liu & Shao [ApJ:2108.08490]

Decihertz GWs: SNRs of BNSs & NSBHs



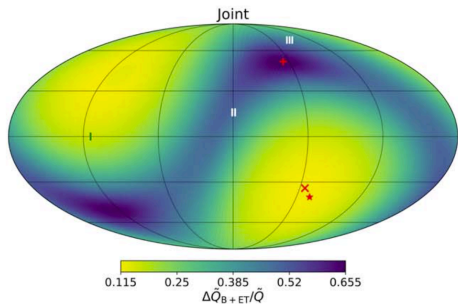
Red star: $\hat{L}$ direction

Liu & Shao [[ApJ:2108.08490](#)]

Decihertz GWs: quadrupole parameter

Measurement Precision

B-DECIGO + ET

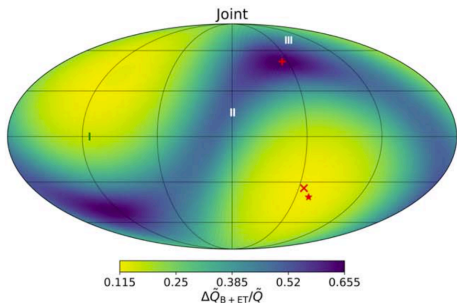


Liu & Shao [[ApJ:2108.08490](#)]

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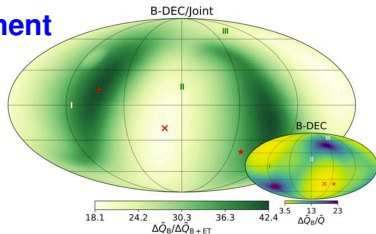
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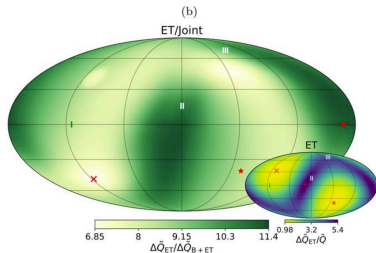


Precision Improvement

$$\frac{\text{B-DECIGO} + \text{ET}}{\text{B-DECIGO}}$$

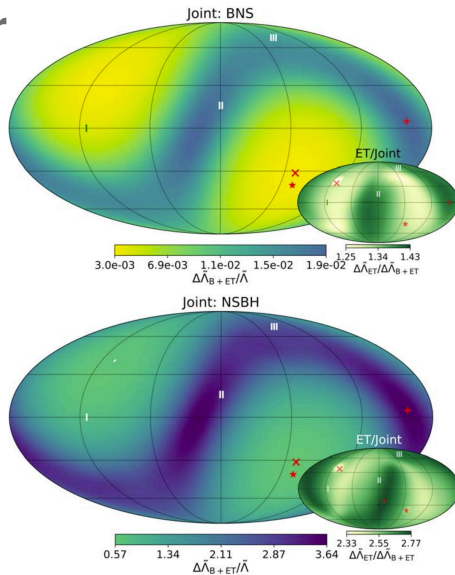


$$\frac{\text{B-DECIGO} + \text{ET}}{\text{ET}}$$



Liu & Shao [[ApJ:2108.08490](#)]

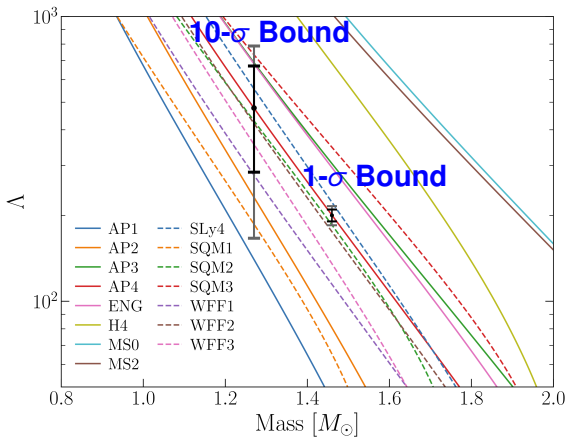
Decihertz GWs: tidal parameter



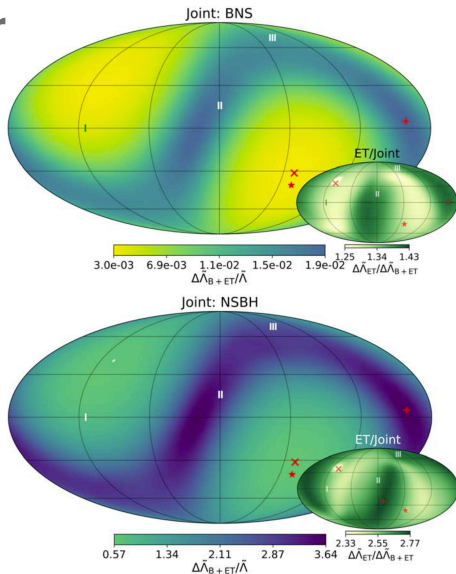
Liu & Shao [[ApJ:2108.08490](#)]

Decihertz GWs: tidal parameter

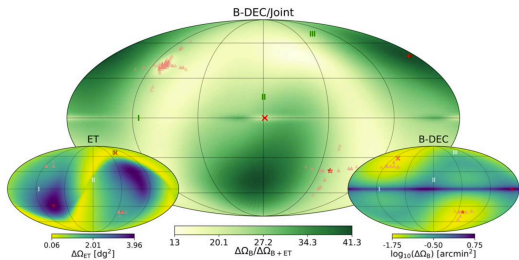
B-DECIGO+ET (black) / ET (gray)



Liu & Shao [ApJ:2108.08490]



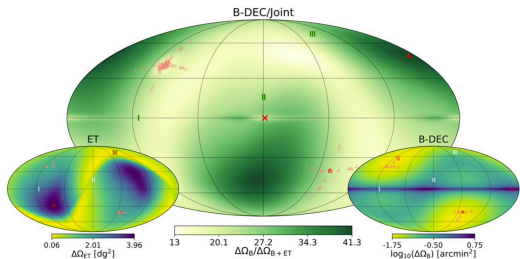
Decihertz GWs: localization



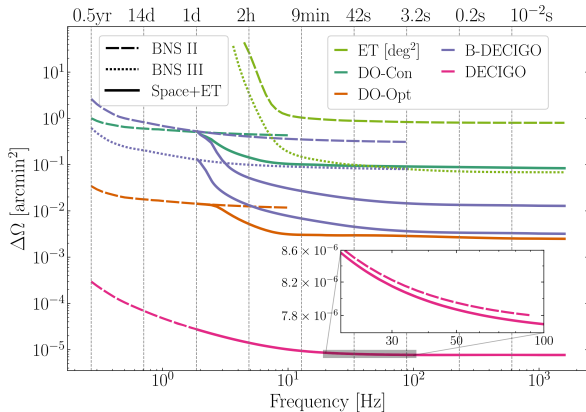
Red triangles have correlation > 0.9995

Liu & Shao [[ApJ:2108.08490](#)]

Decihertz GWs: localization

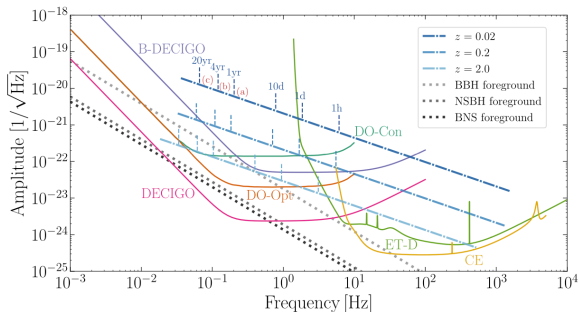
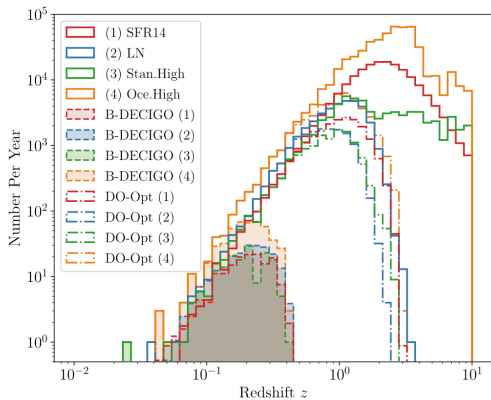


Red triangles have correlation > 0.9995



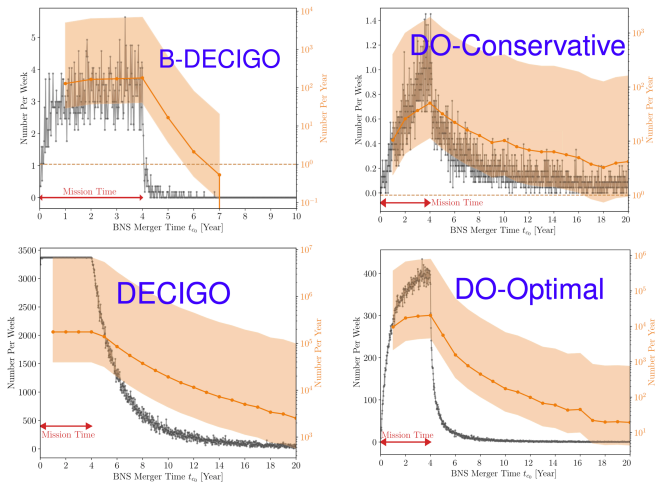
Liu & Shao [ApJ:2108.08490]

BNS: Population & Detection + Signal & Background



Liu, Kang, Shao [[ApJ:2204.06161](#)]

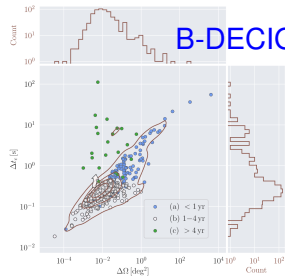
BNS Detections



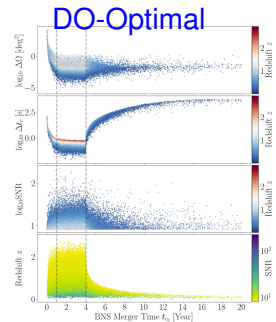
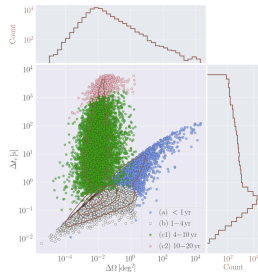
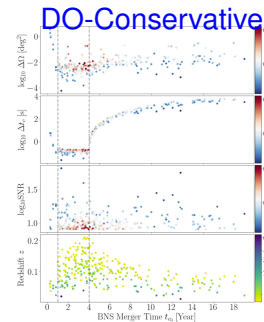
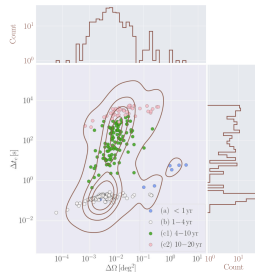
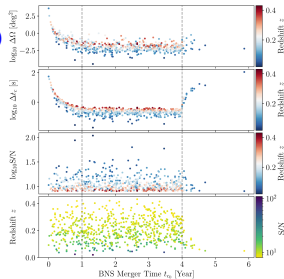
Liu, Kang, Shao [[ApJ:2204.06161](#)]

Three Catalogs

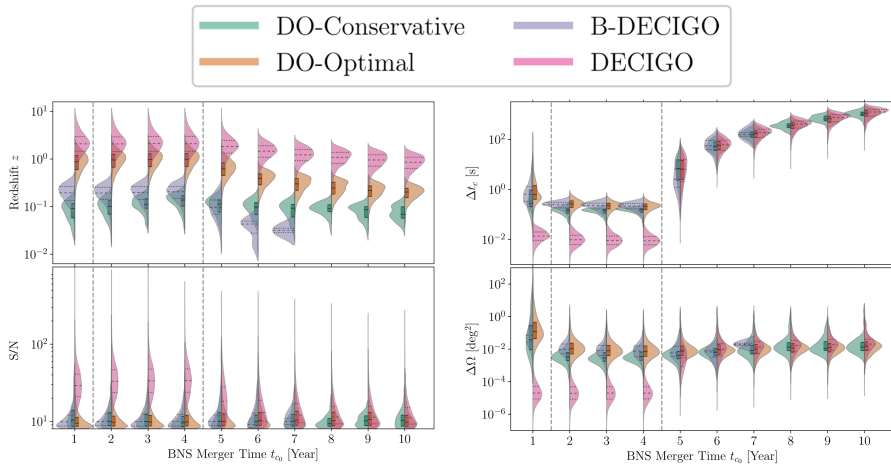
- To merge in < 1 year
- To merge in 1 to 4 years
- To merge in > 4 years



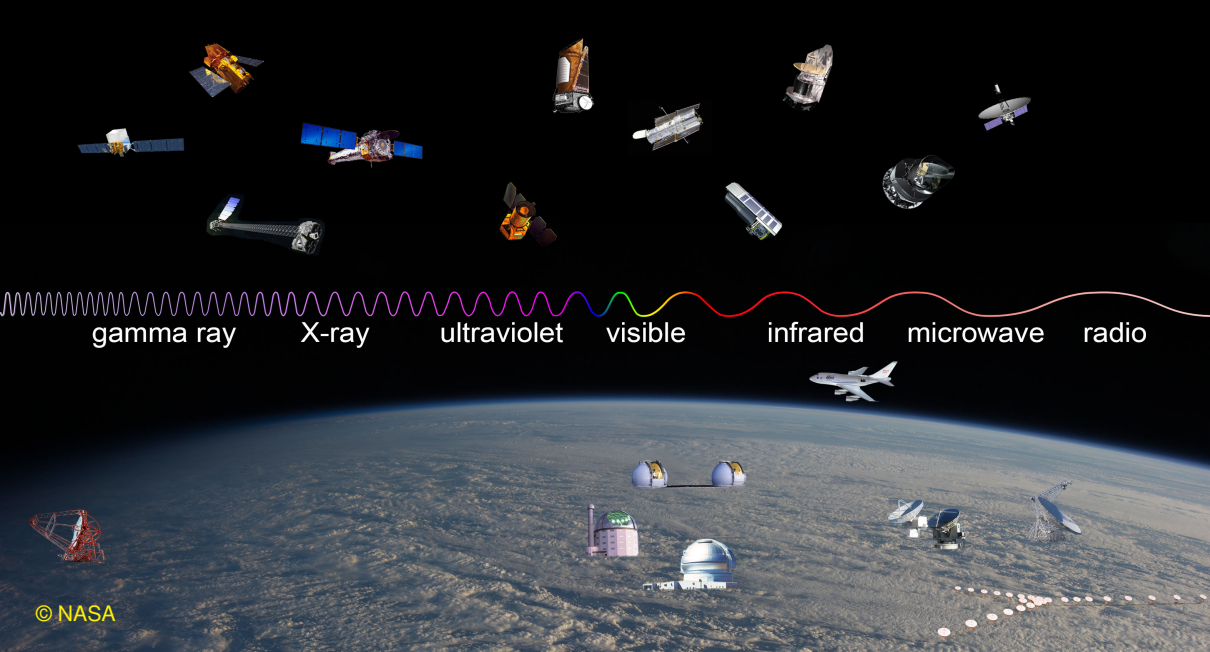
Liu, Kang, Shao [ApJ:2204.06161]



Parameter Estimation



Liu, Kang, Shao [[ApJ:2204.06161](#)]

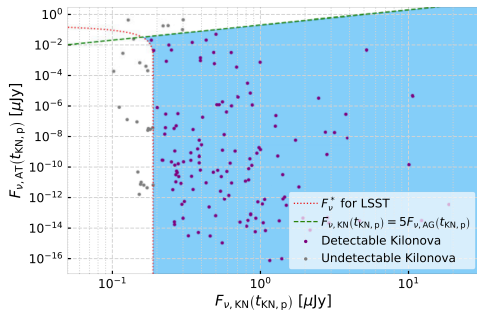


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Kilonova Detection in g , r , i Bands

$$F_{\nu,\text{KN}}(t_{\text{KN},p}) + F_{\nu,\text{AG}}(t_{\text{KN},p}) > F_{\nu}^*$$

$$F_{\nu,\text{KN}}(t_{\text{KN},p}) > 5F_{\nu,\text{AG}}(t_{\text{KN},p})$$



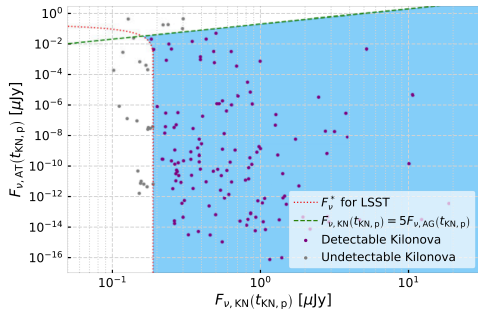
r -band of LSST

Kang, Liu, Shao [[MNRAS:2205.02104](#)]

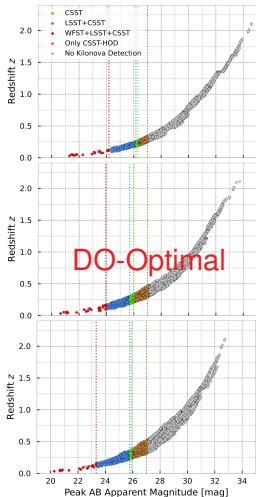
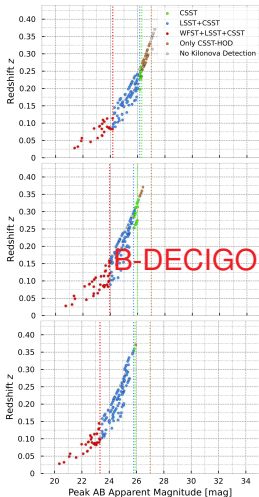
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r -band of LSST

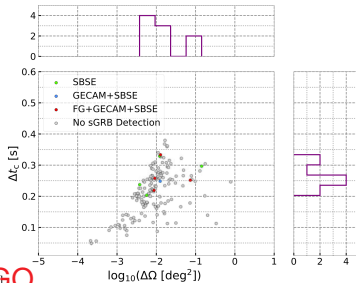


Kang, Liu, Shao [MNRAS:2205.02104]

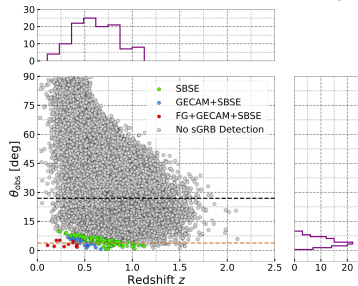
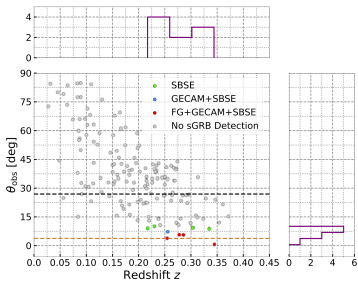
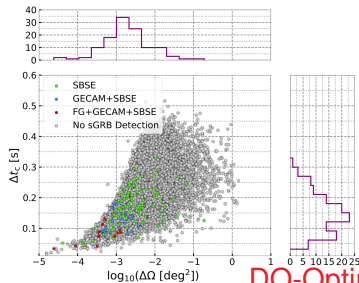
GRB Detection



B-DECIGO



DO-Optimal



Kang, Liu, Shao [MNRAS:2205.02104]

GRB 211211A: possibly a NS-WD merger?

THE ASTROPHYSICAL JOURNAL LETTERS, 954:L17 (7pp), 2023 September 1

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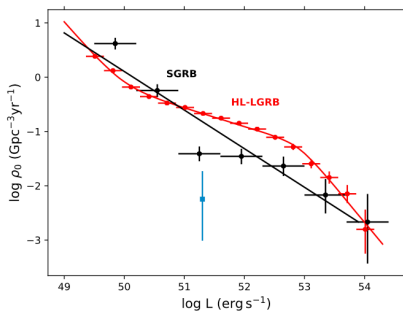
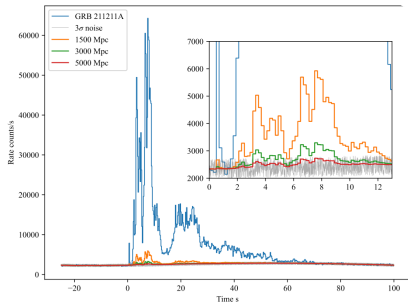
OPEN ACCESS

<https://doi.org/10.3847/2041-8213/acf04a>



GRB 211211A-like Events and How Gravitational Waves May Tell Their Origins

Yi-Han Iris Yin^{1,2} , Bin-Bin Zhang^{1,3,4} , Hui Sun⁵ , Jun Yang^{1,3} , Yacheng Kang^{6,7} , Lijing Shao^{7,8} ,
Yu-Han Yang⁹ , and Bing Zhang^{10,11} 



Shared Properties of merger-driven long GRBs

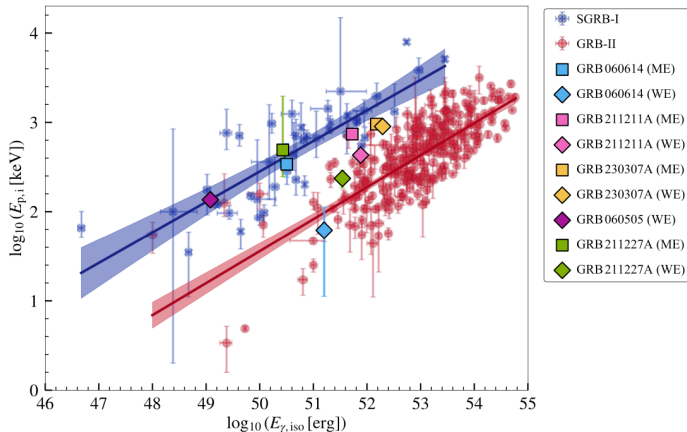


Fig. 1. $E_{p,i}-E_{\gamma,iso}$ relations for GRBs with known redshifts. All error bars correspond to 1σ confidence intervals. The solid lines and shaded areas represent the best-fit correlations and the 90% credible intervals, respectively, for SGRB-IIs (blue) and GRB-IIIs (red). Solid squares and diamonds represent the properties of ME and WE phases for our LGRB-I sample, respectively.

Shared Properties of merger-driven long GRBs

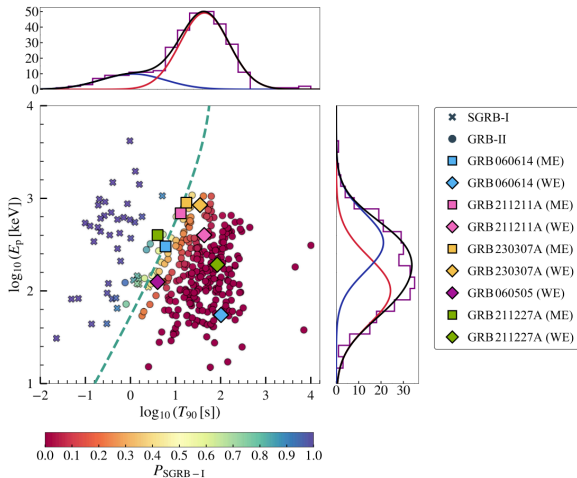
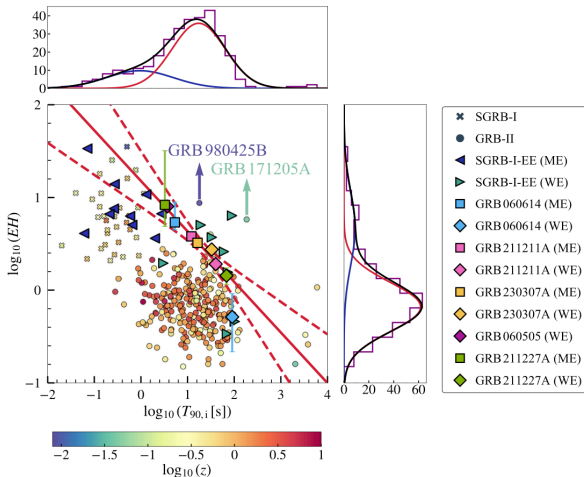


Fig. 2. GRB classification diagram in the $E_p - T_{90}$ domain. The crosses and circles represent the known classification of SGRB-I and GRB-IIs in the MP sample. The different colors indicate the probability of a GRB event being a SGRB-I ($P_{\text{SGRB-I}}$) based on two independent two-dimensional Gaussian components. The dashed cyan line indicates the dividing line with $P_{\text{SGRB-I}} = 0.5$. In the top and right projected histograms, the blue and red lines represent the contributions from SGRB-I candidates (smaller T_{90} , larger E_p) and GRB-II candidates (larger T_{90} , smaller E_p), while the black lines are the combined distributions of two Gaussian components.

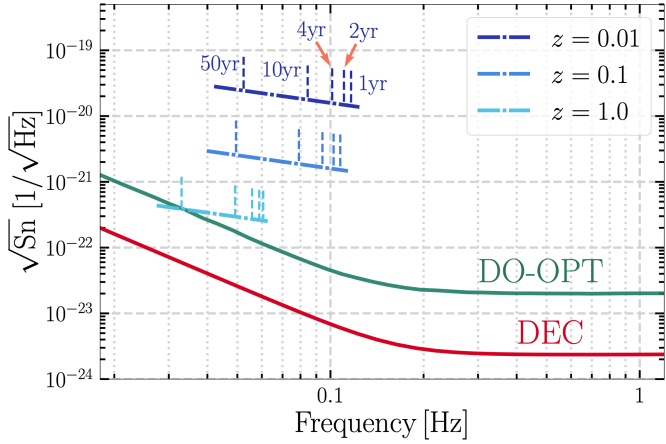
Shared Properties of merger-driven long GRBs



$$EH \equiv \frac{(E_{p,i}/100 \text{ keV})}{(E_{\gamma,\text{iso}}/10^{51} \text{ erg})^{0.4}}$$

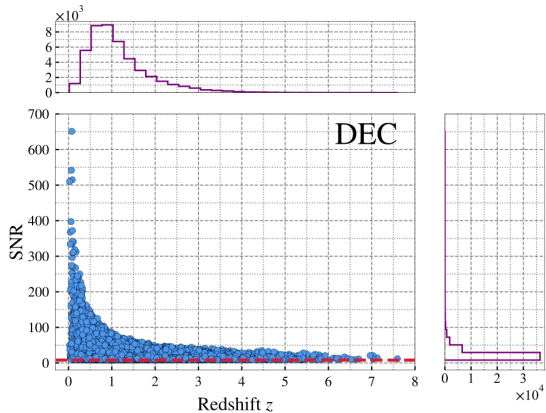
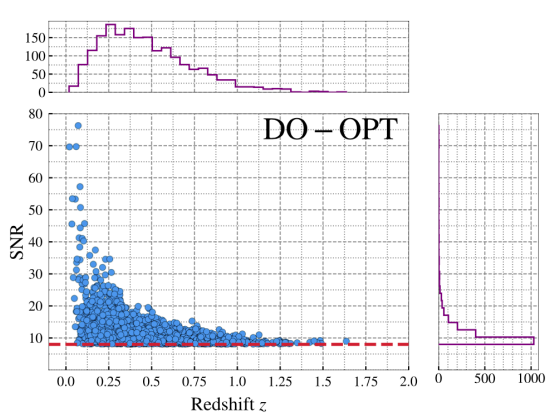
Fig. 3. GRB classification diagram in the $EH-T_{90,i}$ domain. The colorbar now indicates the redshift. The ME and WE components of SGRB-I-EE events are denoted by the left- and right-pointing triangles, respectively. The best-fit $EH-T_{90,i}$ correlation is shown as a solid line, with the 90% credible intervals indicated by dashed lines. GRB 980425B ($EH = 8.72$) and GRB 171205A ($EH = 5.78$) are labeled.

Decihertz's Arena



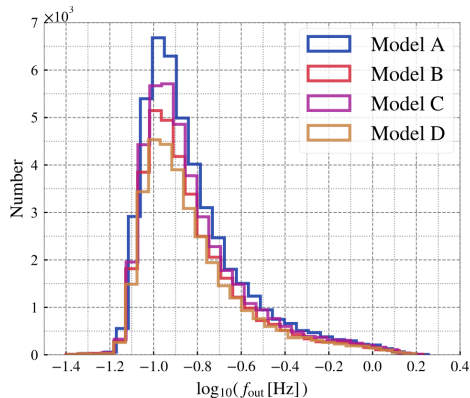
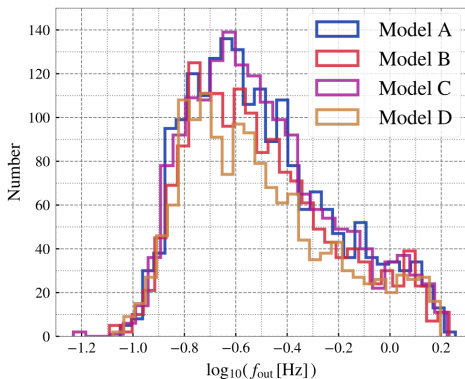
Kang et al. [[MNRAS:2309.16991](#)]

NS-WD Binaries



Kang et al. [[MNRAS:2309.16991](#)]

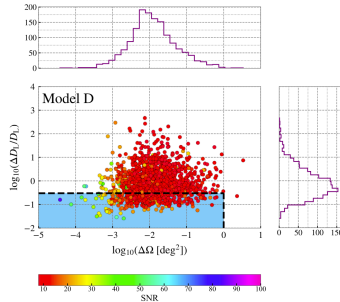
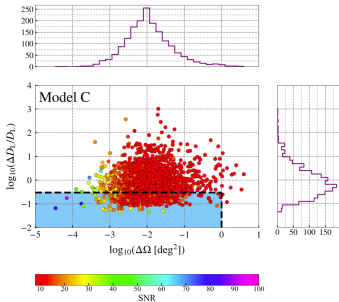
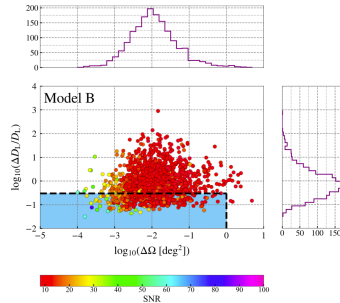
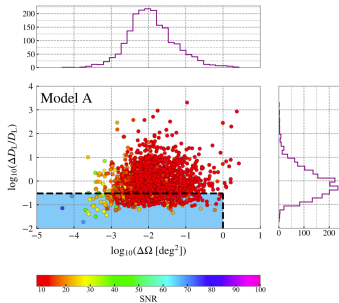
NS-WD Binaries



Kang et al. [[MNRAS:2309.16991](#)]

Early Warning

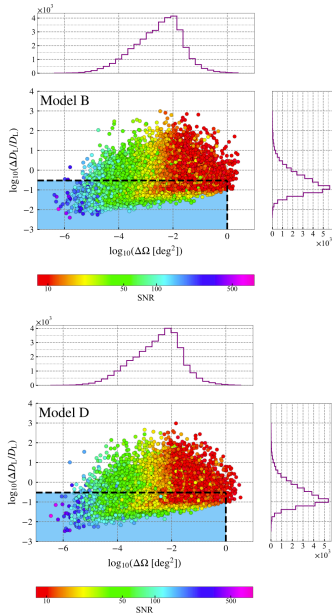
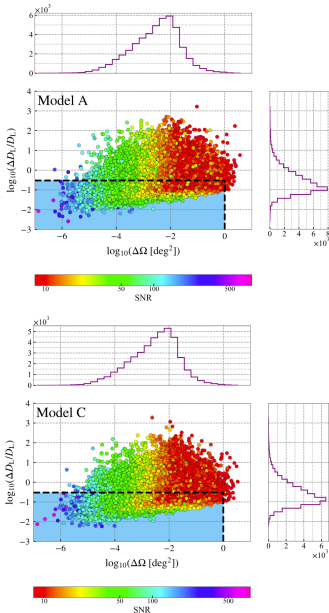
DO-OPT



Kang et al. 2024 [[MNRAS:2309.16991](#)]

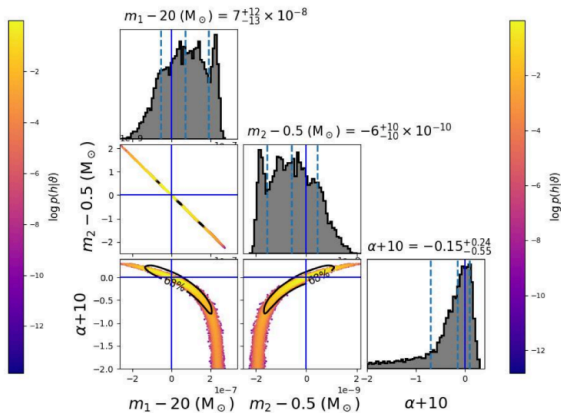
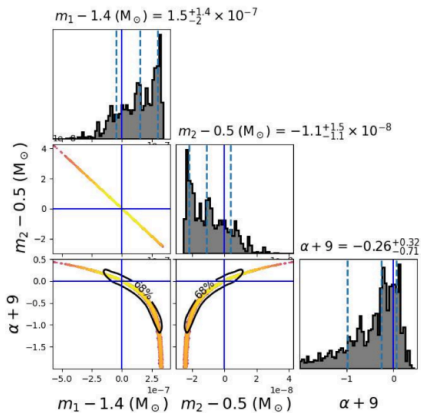
Early Warning

DECIGO



Kang et al. [[MNRAS:2309.16991](#)]

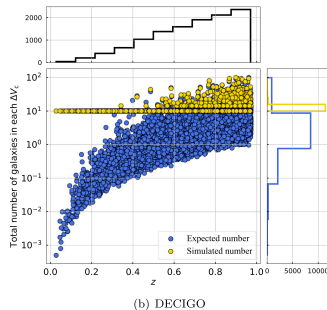
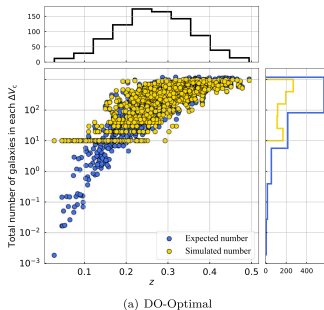
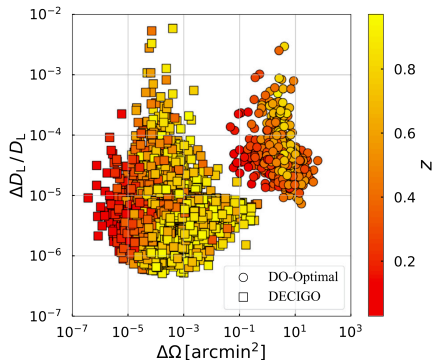
Mass Transfer Rate



$$\dot{m} = 10^{-\alpha} M_\odot \text{ yr}^{-1}$$

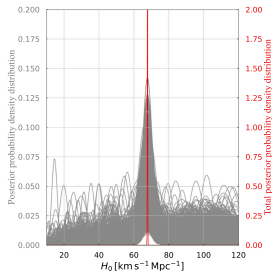
Lyu & Shao [arXiv:2402.16612]

Dark Siren: localization & host galaxies for BBHs

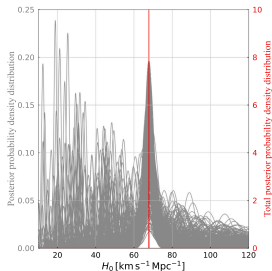


Liu, Liu, Hu, Shao, Kang [PDU:2205.06991]

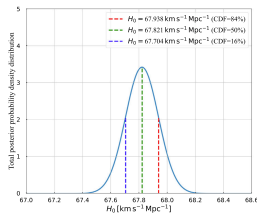
Dark Siren: Hubble parameter



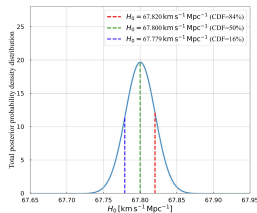
(a) DO-Optimal



(b) DECIGO



(a) DO-Optimal



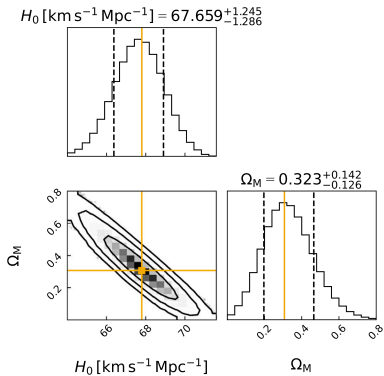
(b) DECIGO

Measurements from individual BBHs

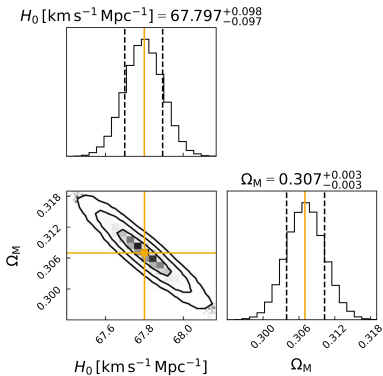
All BBHs Combined

Liu, Liu, Hu, Shao, Kang [PDU:2205.06991]

Dark Siren: H_0 and Ω_M



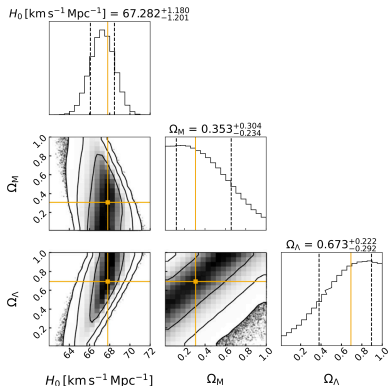
(a) DO-Optimal



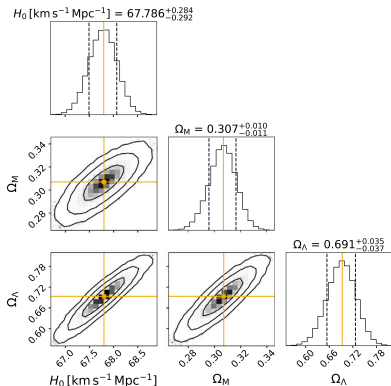
(b) DECIGO

Liu, Liu, Hu, Shao, Kang [PDU:2205.06991]

Dark Siren: H_0 , Ω_M , and Ω_Λ



(a) DO-Optimal

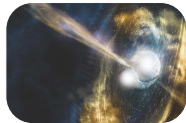


(b) DECIGO

Liu, Liu, Hu, Shao, Kang [PDU:2205.06991]

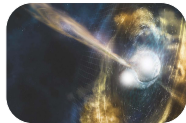
Summary

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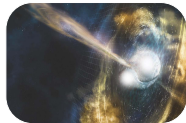
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- **Decihertz GWs** will provide extraordinary information about stellar-mass BBHs, BNSs, NS-BHs, and NS-WD binaries
- We studied in great details the **parameter estimation** in decihertz GW detections, also for **source populations**



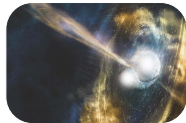
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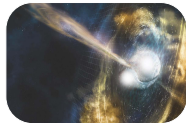
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- Decihertz GWs will provide excellent **early warning** for **electromagnetic followups**: kilonova and (merger-driven long-duration) GRBs
- Mass transfer rates involving WDs are precisely measured
- It makes use of “**dark sirens**” to tightly constrain cosmology



Thank you!

