Title: Gravitational waves as a window on gravity

Speakers: Jocelyn Read

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

Date: March 11, 2025 - 11:15 AM

URL: https://pirsa.org/25030061

Abstract:

Gravitational waves are generally a classical GR phenomenon, carrying the imprint of compact merger sources with strong curvature and dynamic interactions. I will give an overview of current and future gravitational-wave observations, and discuss some areas where gravitational waves astronomy makes contact with the quantum regime.

Gravitational waves as a window on gravity

Emmy Noether Workshop: Quantum Space Time
Perimeter Institute, March 2025

Jocelyn Read, California State University Fullerton
Visitor @ PI to June

NICHOLAS AND LEE BEGOVICH
Center for Gravitational-Wave Physics and Astronomy

Why gravitational waves?

Opportunities for **physical predictions with a theory of gravity**

GW as a gravitational phenomenon

GW Observations:

compact objects with strong curvature, nonperturbative merger physics for black holes and for neutron stars, degenerate QCD matter in a dynamic curved spacetime, sources of both GW and light

Next-generation (XG): observations reach to the early universe

(Gravitational-wave interferometers are quantum optics systems)

What is practically observable?

1916: Not gravitational waves, probably

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

One obtains the radiated energy of the system per unit time…
sees that it must have in all conceivable situations a practically vanishing value.

Image/translation from J. Smith

Gravitational waves

Observations of curved spacetime

- Modern view: Gravitational waves are *obviously* required by a relativistic theory with moving sources
- Historically: hard to disentangle from gauge effects in a purely theoretical analysis;
  needed to consider observational implications

Pirani, 1957

If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (1) becomes

$$\frac{d^2\eta^a}{d\tau^2} + R^a{}_{obo}\,\eta^b = 0 \qquad (a,b = 1,2,3) \qquad (2)$$

Here η^a are the physical components of the infinitesimal displacement and $R^a{}_{obo}$ some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

- $g_{ab} = \eta_{ab} + h_{ab},\ |h_{ab}| \ll 1$

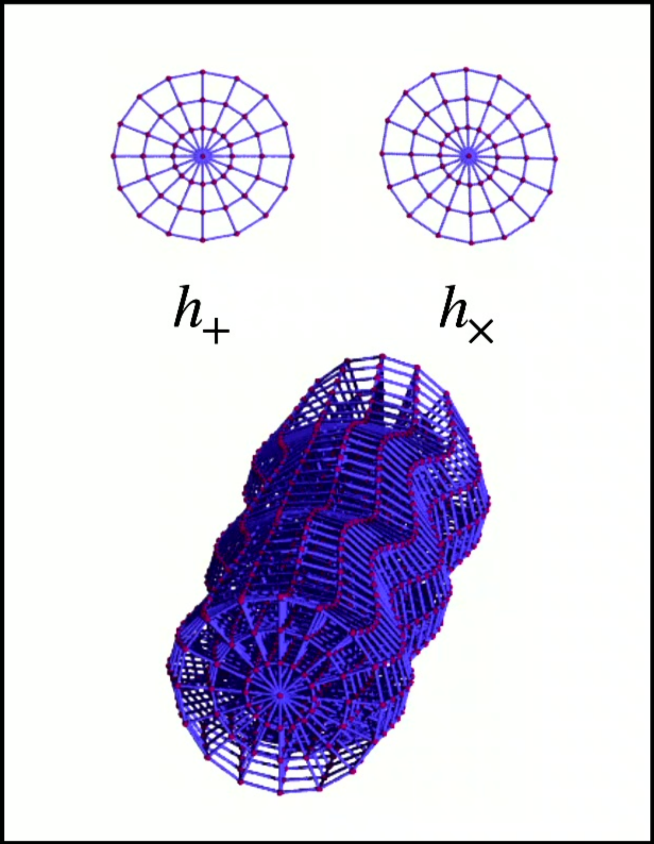
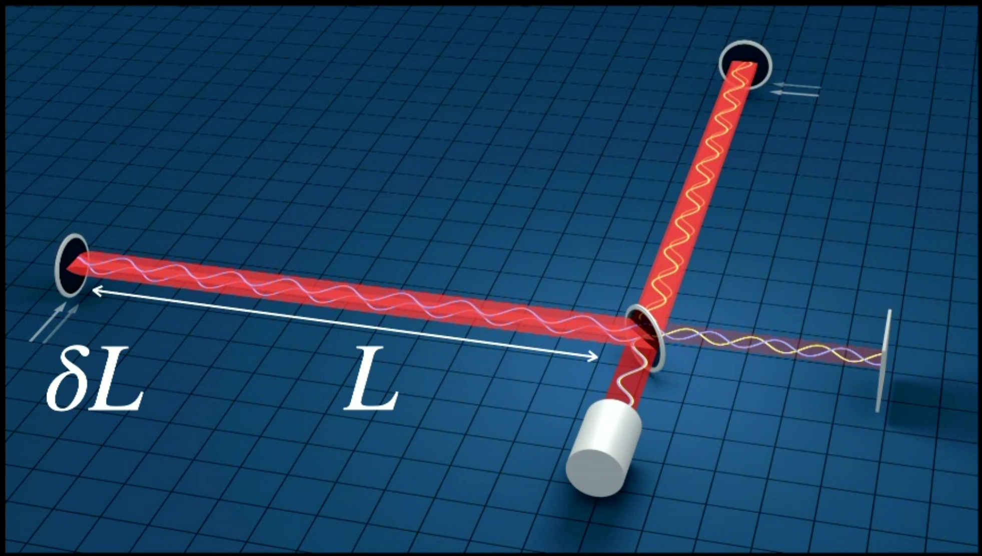


Image from P. Saulson

Measuring gravitational waves



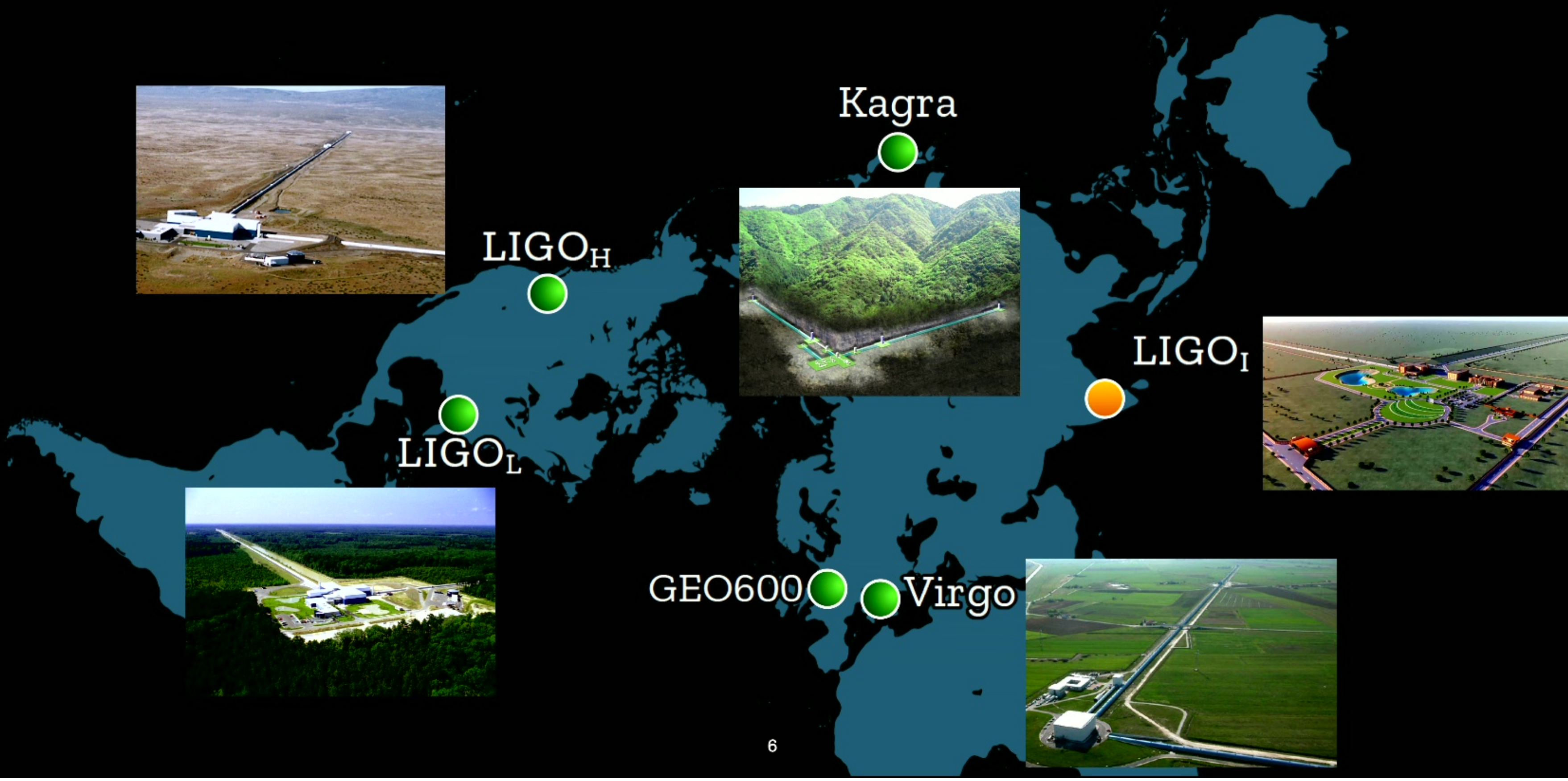
- Amplitude detector (approximately lossless "parametric tranducer")
- Measured strain $h = 2\frac{\delta L}{L}$

- Fractional change from gravitational waves arriving at Earth is $h \sim 10^{-21}$

5

International gravitational-wave network

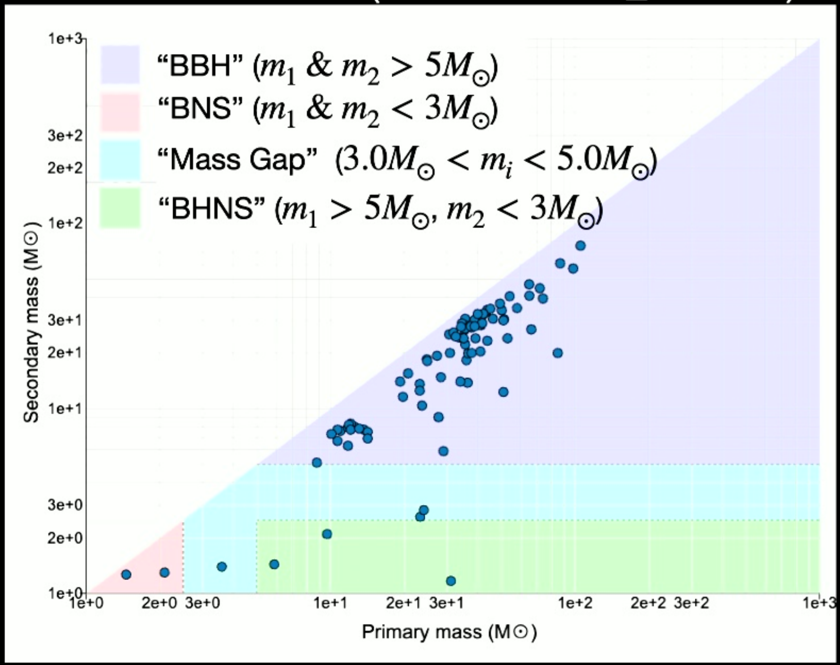
Today's ground-based facilities with $L \sim 3 - 4$ km



Observations

Compact binary mergers

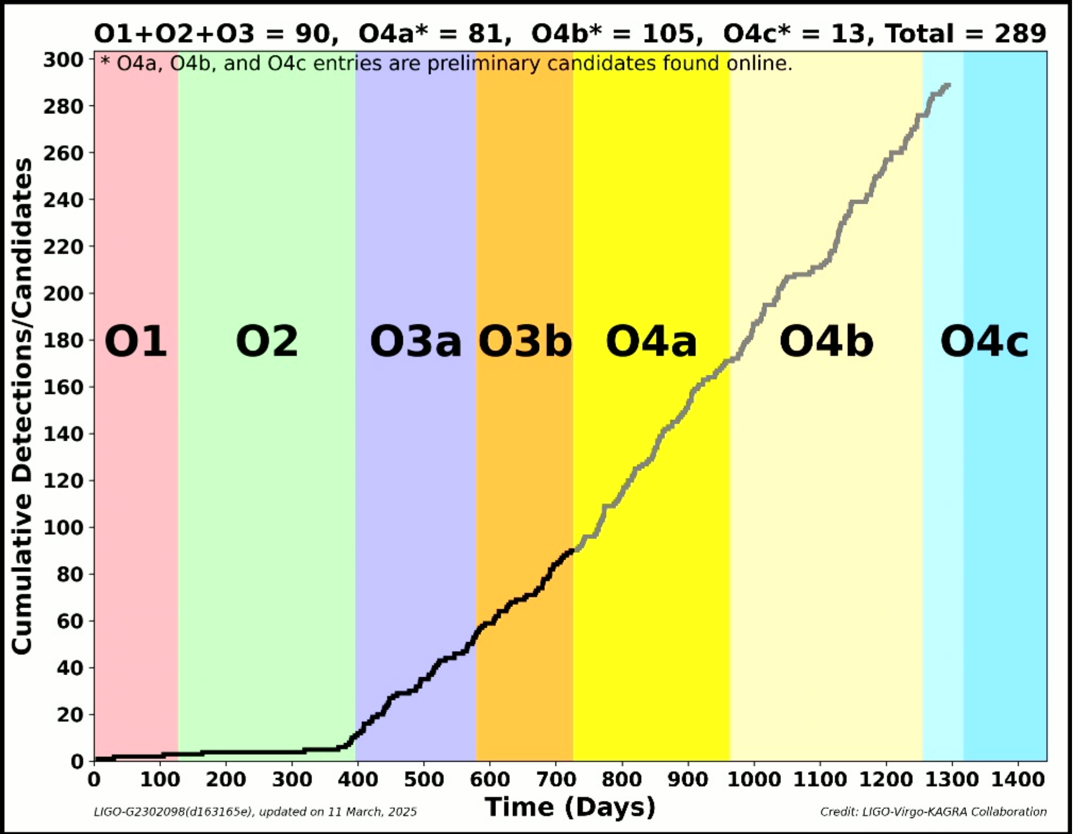
- O1+O2+O3: First 90 published events from 2015-2020 (+ GW230529_181500)



https://catalog.cardiffgravity.org/

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

Additional "significant" alerts in O4 through today
https://gracedb.ligo.org/superevents/public/O4/

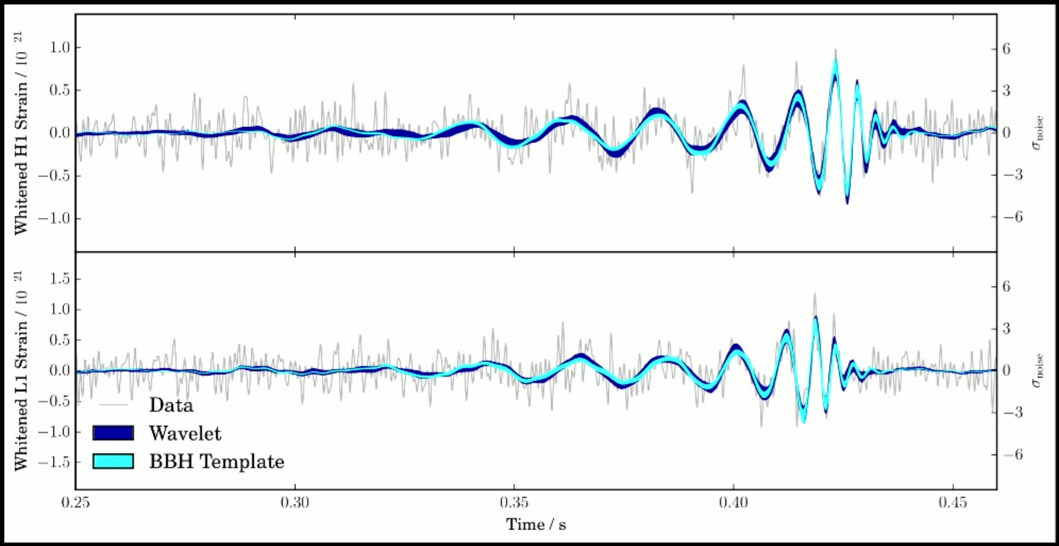


LIGO-G2302098

GW150914

First GW detection; observed in LIGO Livingston and LIGO Hanford

BBH model fit: $m_1 = 36^{+5}_{-4} M_\odot, m_2 = 29^{+4}_{-4} M_\odot$



LIGO/Virgo Properties of the Binary Black Hole Merger GW150914, Phys. Rev. Lett. 116, 241102 (2016)

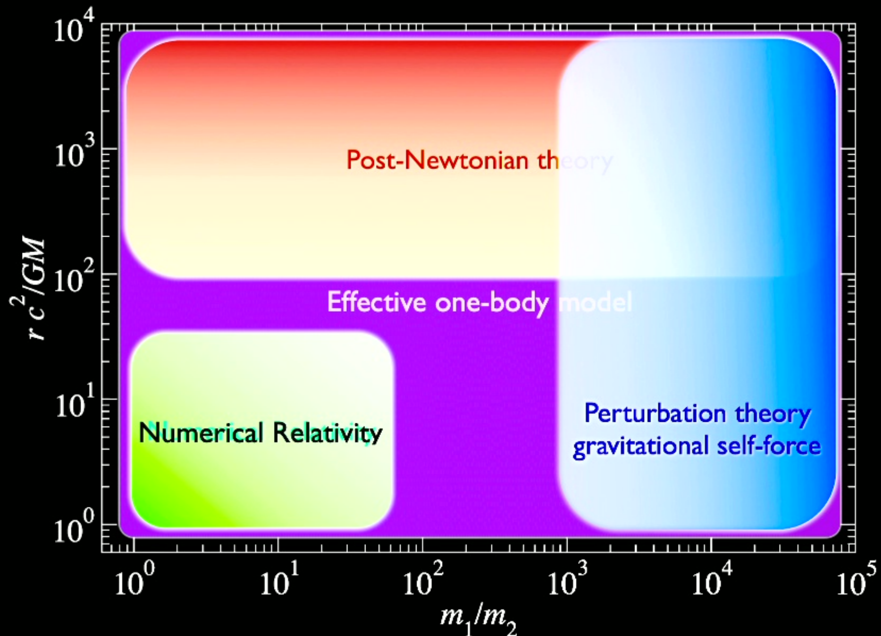


Figure from Buonanno & Sathyaprakash (2014)

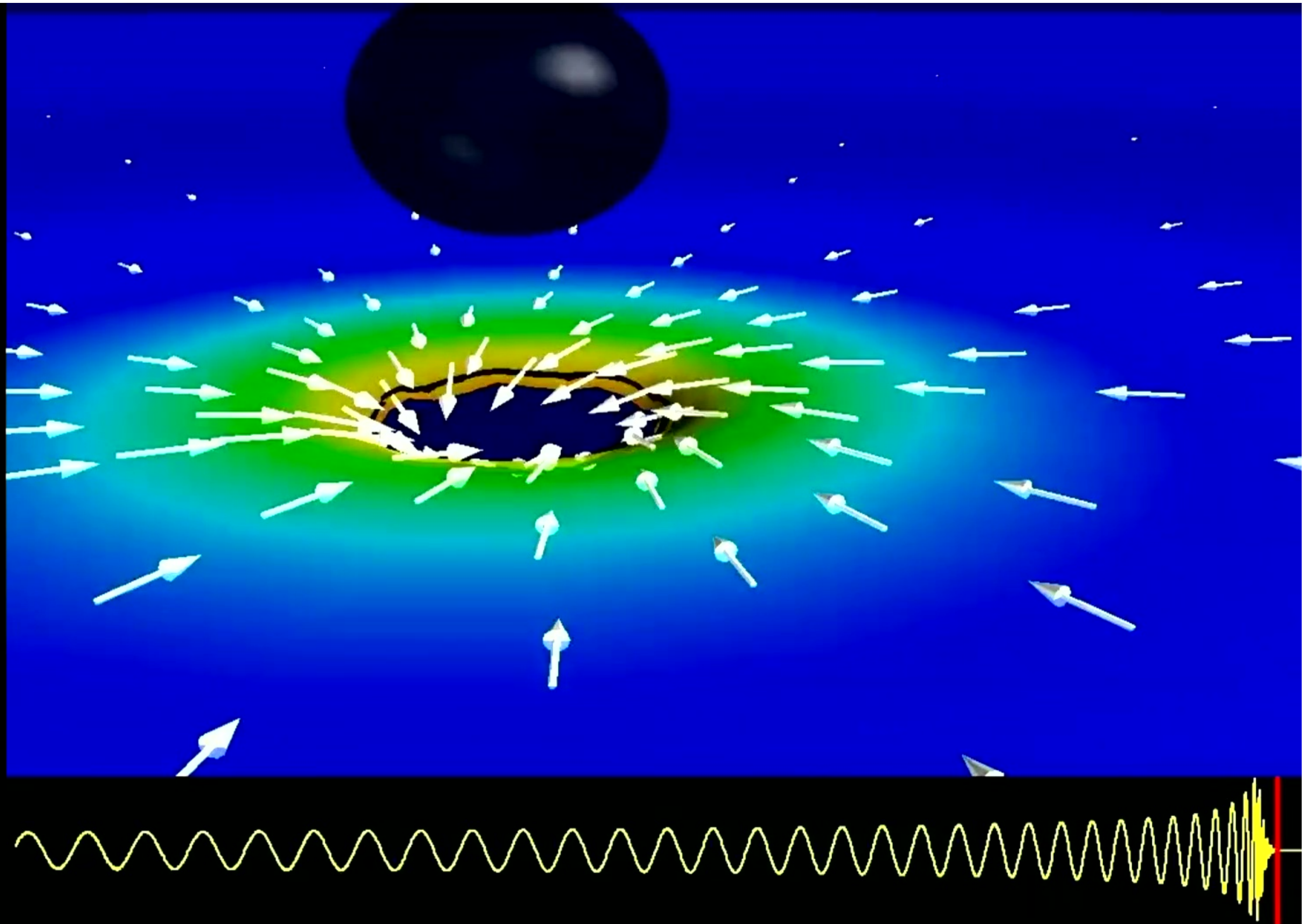
Binary Black Holes:

Numerical simulation

Apparent horizons (local trapping)

3+1 decomposition
depth: curvature
colors: flow of time
arrows: flow of space

GW on future light cone



Movie from Harald Pfeiffer, Geoffrey Lovelace, SXS Collaboration

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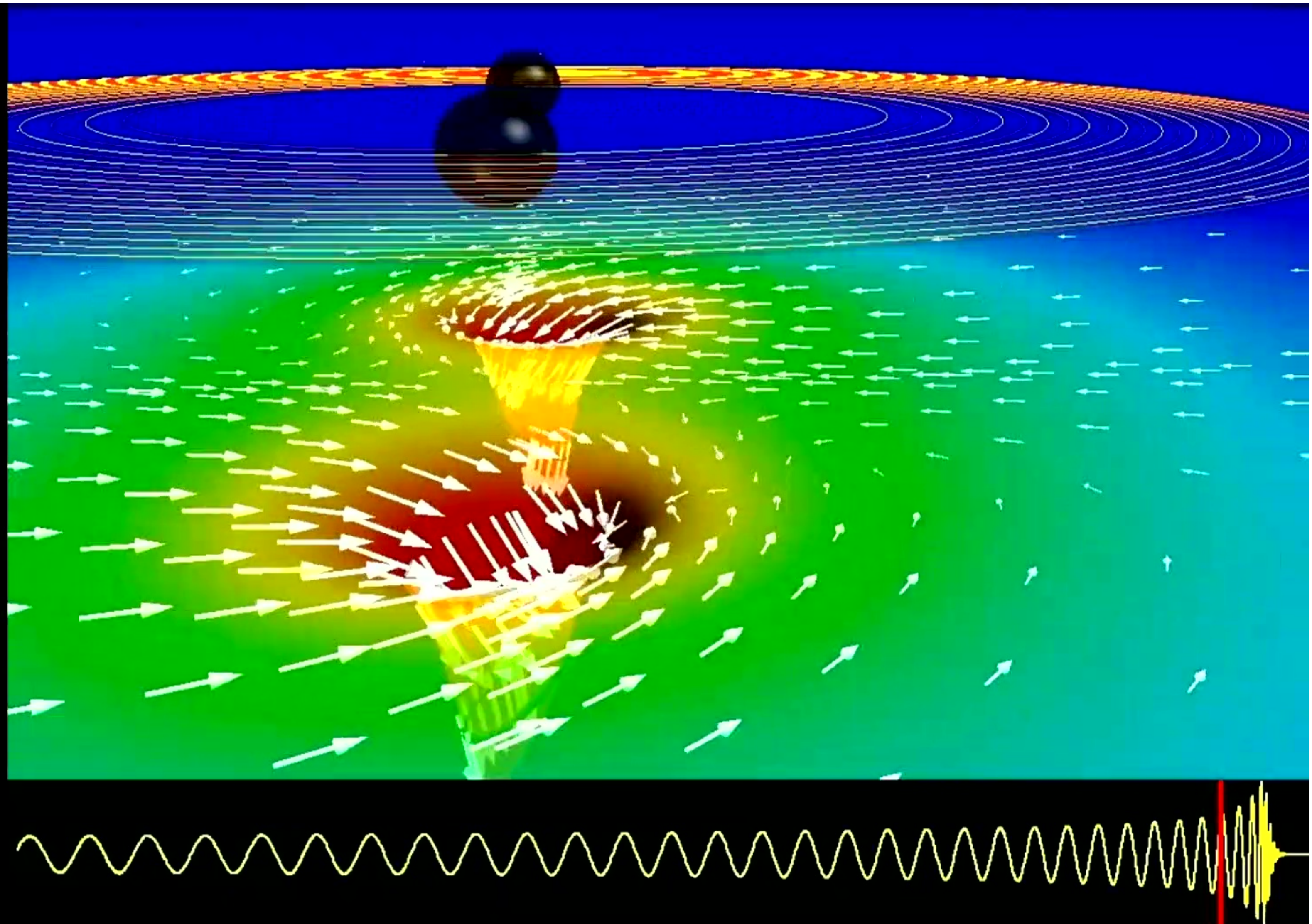
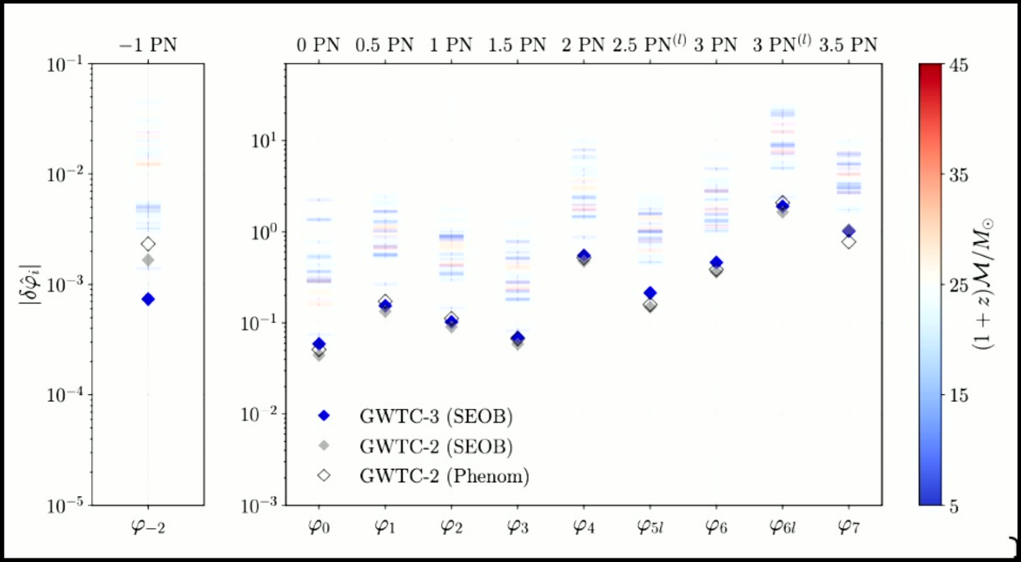
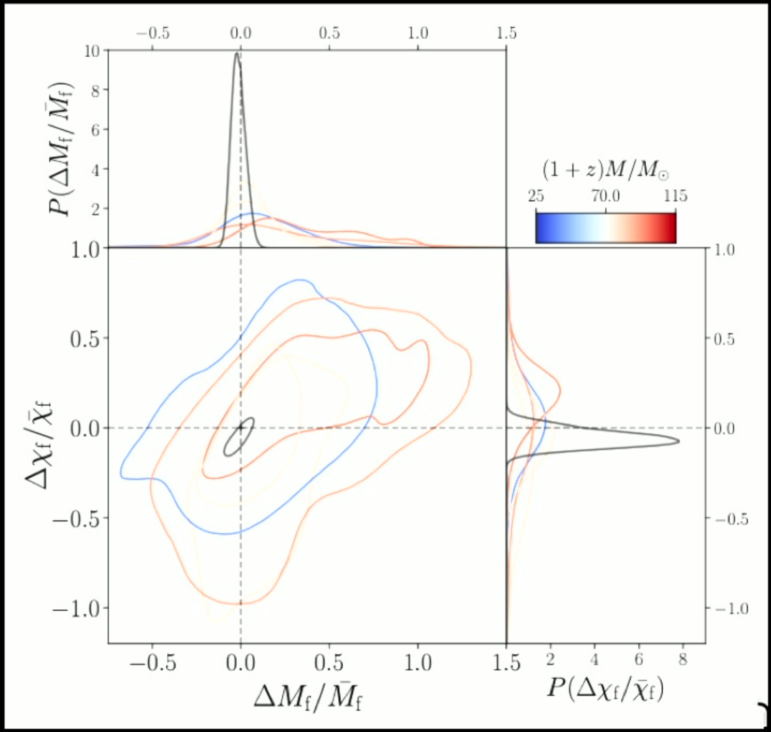


Movie from Harald Pfeiffer, Geoffrey Lovelace, SXS Collaboration

Testing GR
Consistency of GW observations

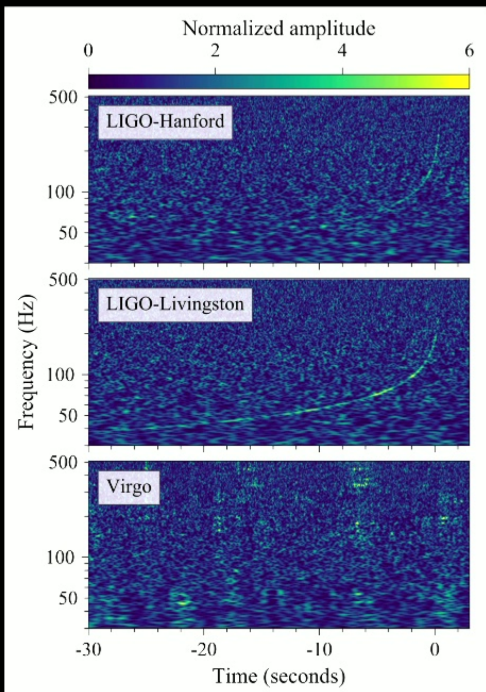
LIGO/Virgo LIGO-P2100275, arXiv:2112.06861, PRD 2024





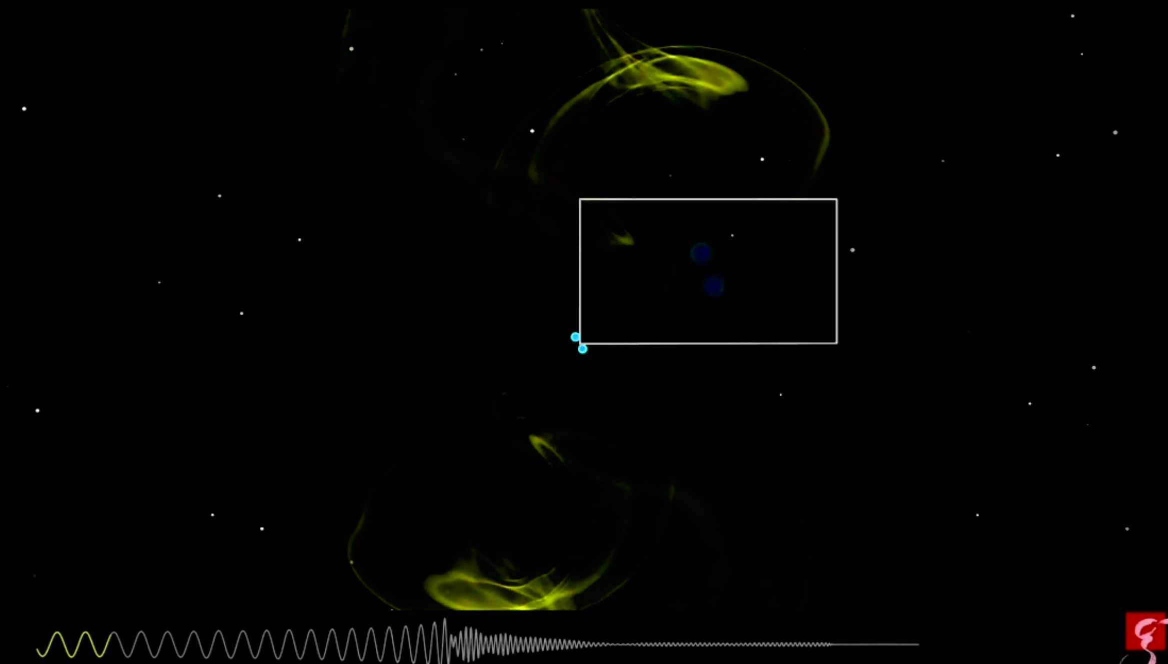
GW170817

First NS detection; three-detector observation



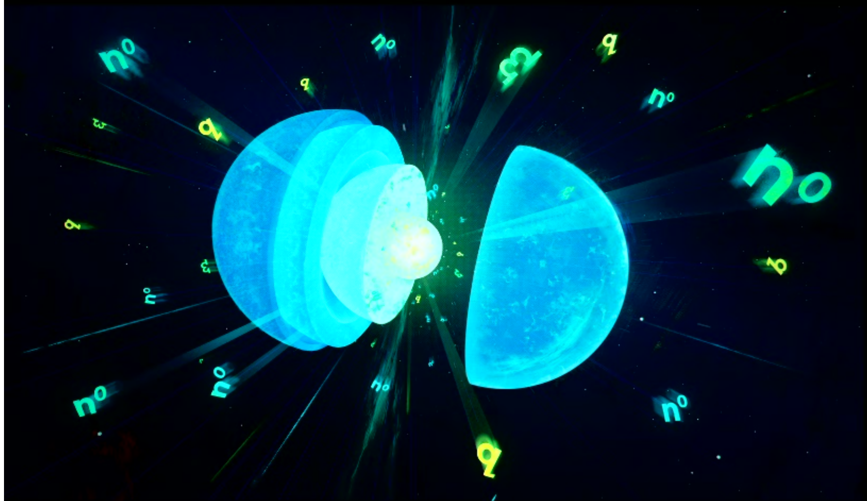
GW170817: Observation
LIGO & Virgo Scientific Collaborations,
Phys. Rev. Lett. 119 161101 (2017)

Simulation: final 40 milliseconds of inspiral

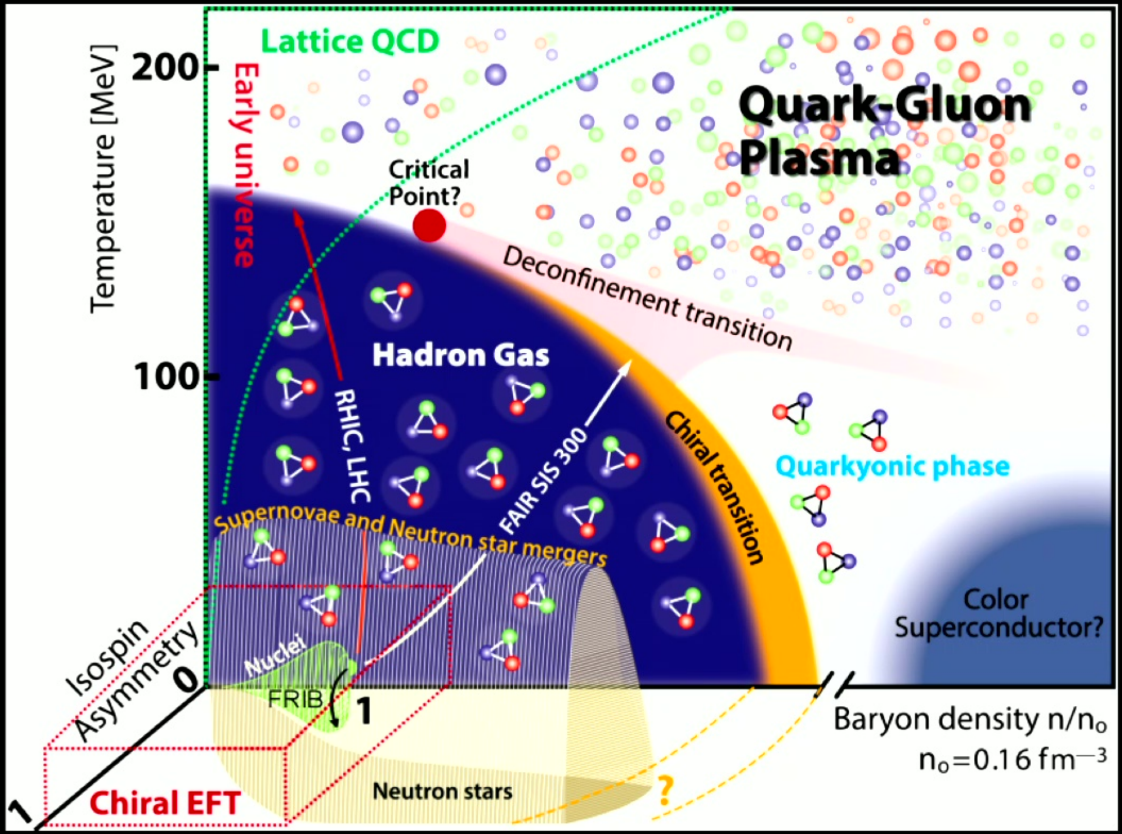


T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)

What is the nature of matter under extreme conditions?



Maciej Rebisz for Quanta Magazine



Drischler, C., Holt, J.W., & Wellenhofer, C. Ann. Rev. Nucl. Part. Sci. 71:403-432 (2021)

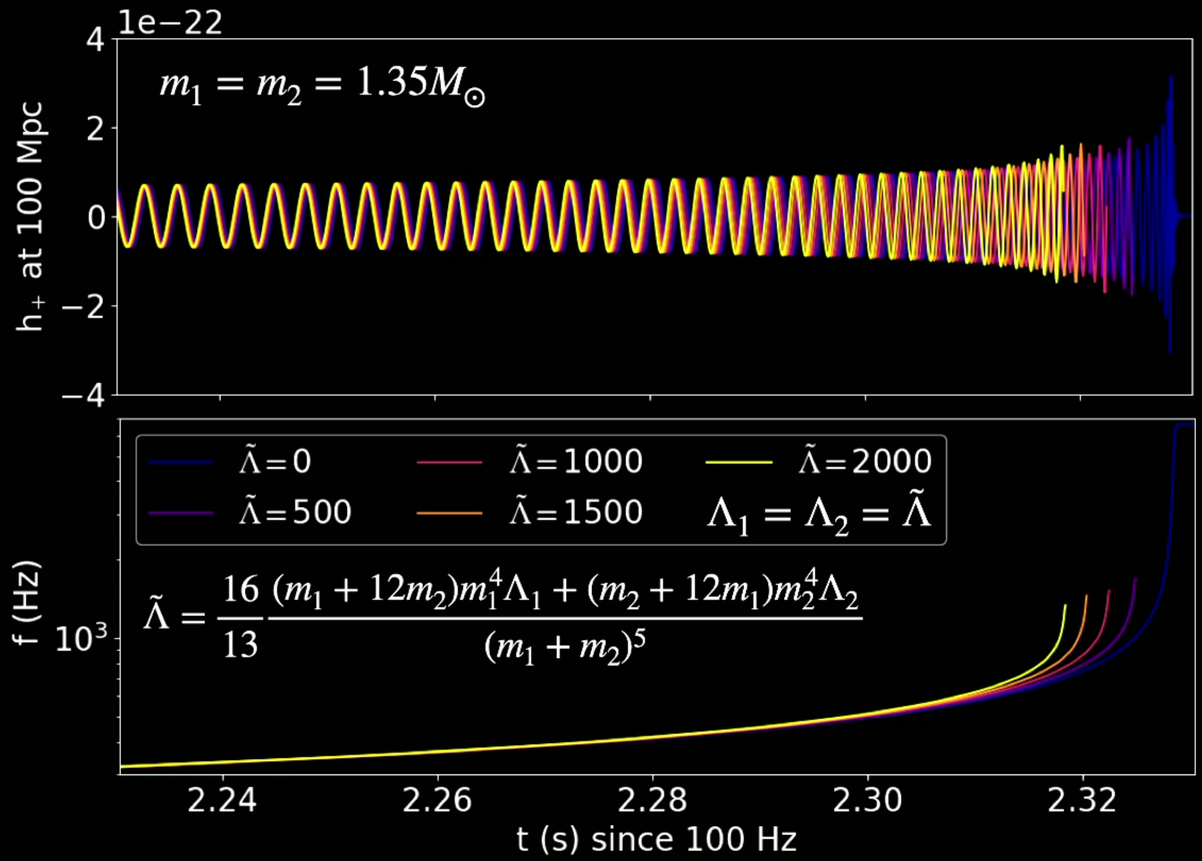
Gravitational-wave imprint of internal structure

Source binary with given $m_1, m_2, \Lambda_1, \Lambda_2$

Leading order coefficient, NR/theory calibrated contributions include higher order effects

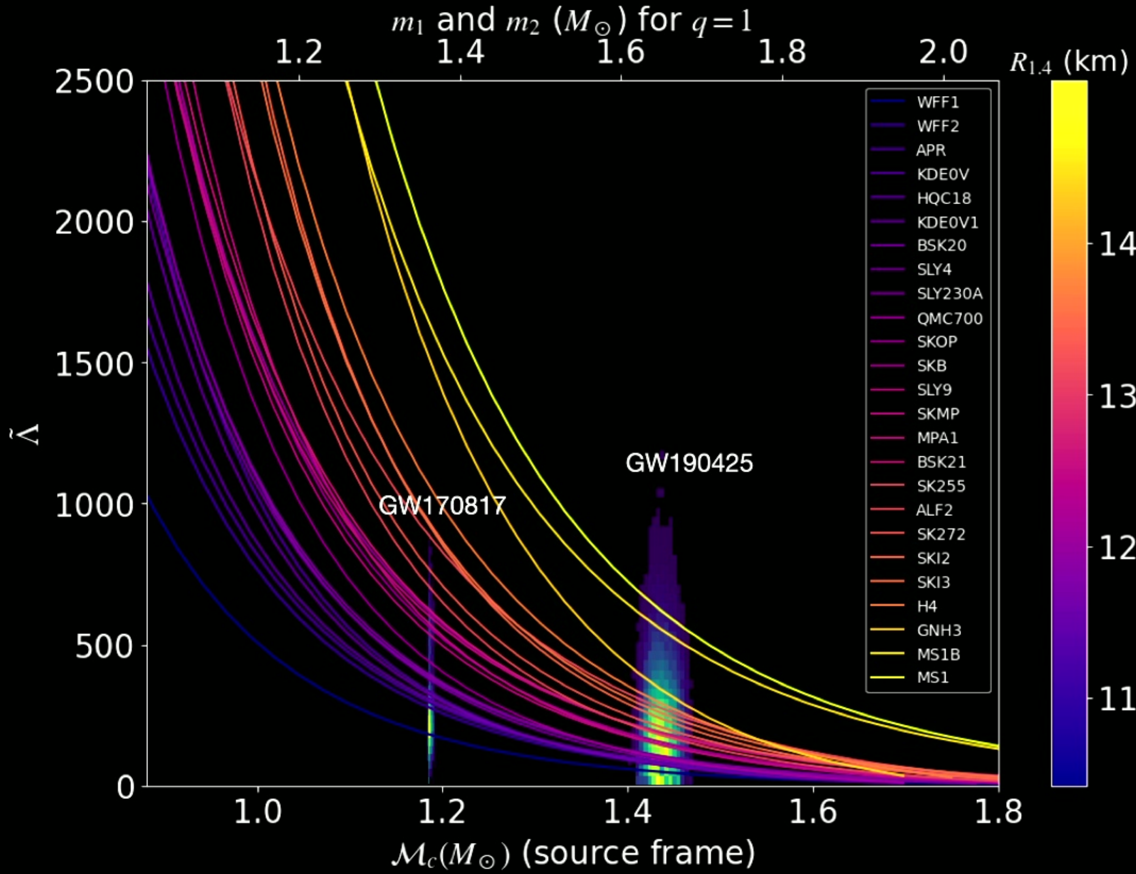
At fixed mass, larger Λ means faster chirp (larger df/dt) as orbital separation approaches NS radius.

$\Lambda = 0$ for BH



Plots made using pycbc, TEOBResumS
https://github.com/jsread/APSPlots2024

EOS from binary neutron star gravitational-wave observations



Chirp mass $\mathscr{M}$, Combined tidal parameter $\tilde{\Lambda}$: coefficients of leading-order waveform effects

Cold NS EOS:

$$\Lambda_i(m_i) \rightarrow \tilde{\Lambda}(\mathscr{M}, q)$$

GW170817 from LIGO/Virgo GWTC-1, Phys. Rev. X 9, 031040 (2019)

GW190425 from LIGO/Virgo GWTC-2, Phys. Rev. X 11, 021053 (2021)

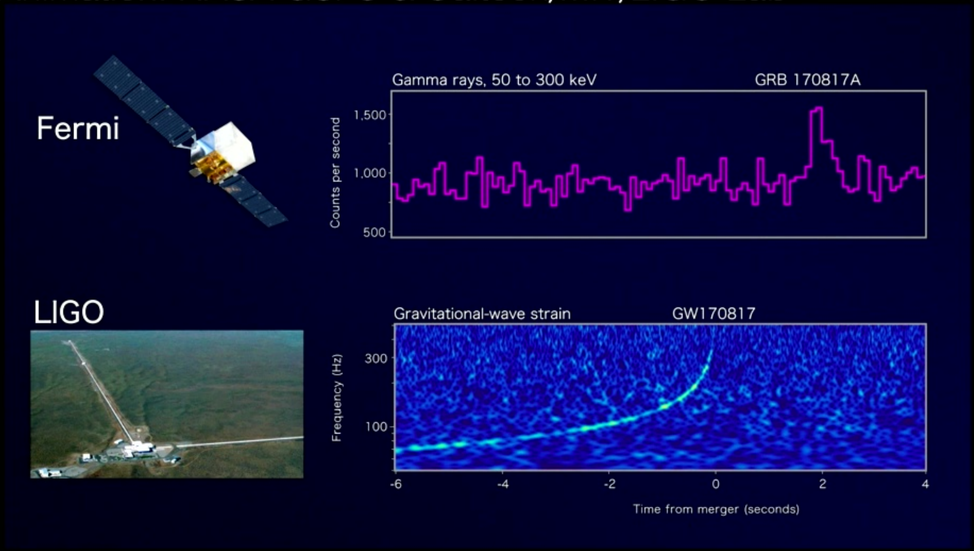
Reweight to prior flat in $\tilde{\Lambda}$ following method of LIGO/ Virgo GW190425 ApjL 892 L3 (2020)

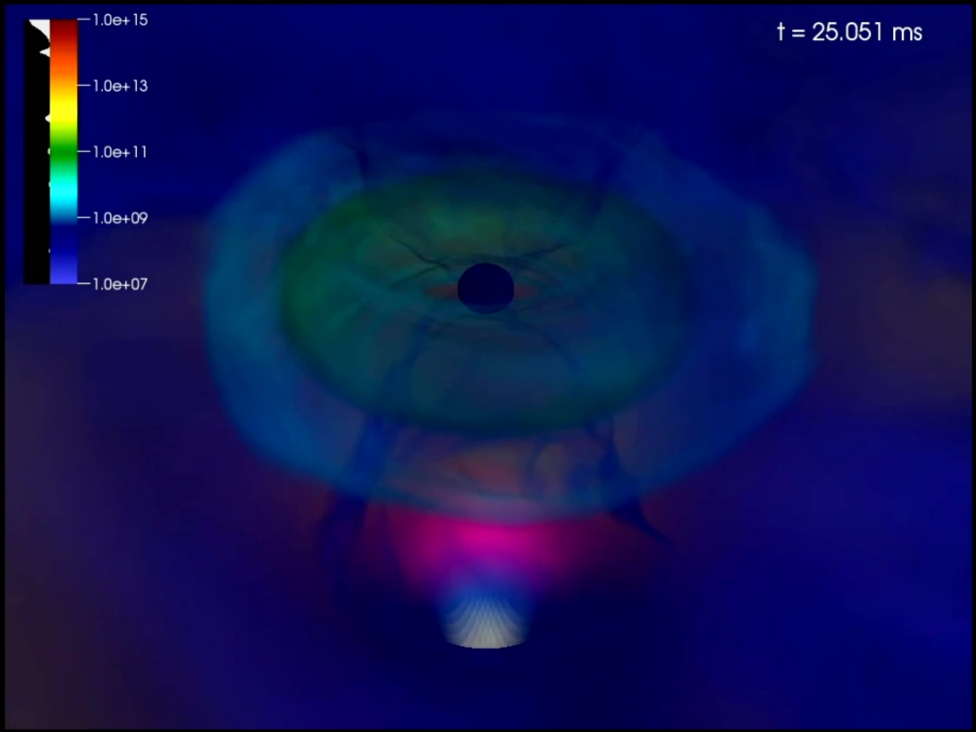
Formal EOS likelihood calculation: LIGO /Virgo Class. Quant. Gravity 37 4, 045006 (2020)

Plots made using public release data, LALSuite
https://github.com/jsread/APSPlots2024

GW + light
GW170817, GRB170817A

Animation: NASA GSFC & Caltech/MIT/LIGO Lab





simulation from D. Radice (Penn State) ApJ 869:130 (2018)

- Speed of light/speed of GW = 1 ($\pm 10^{-15}$) LVC et al ApJL 848 L13 2017

GW + light

GW170817, GRB170817A

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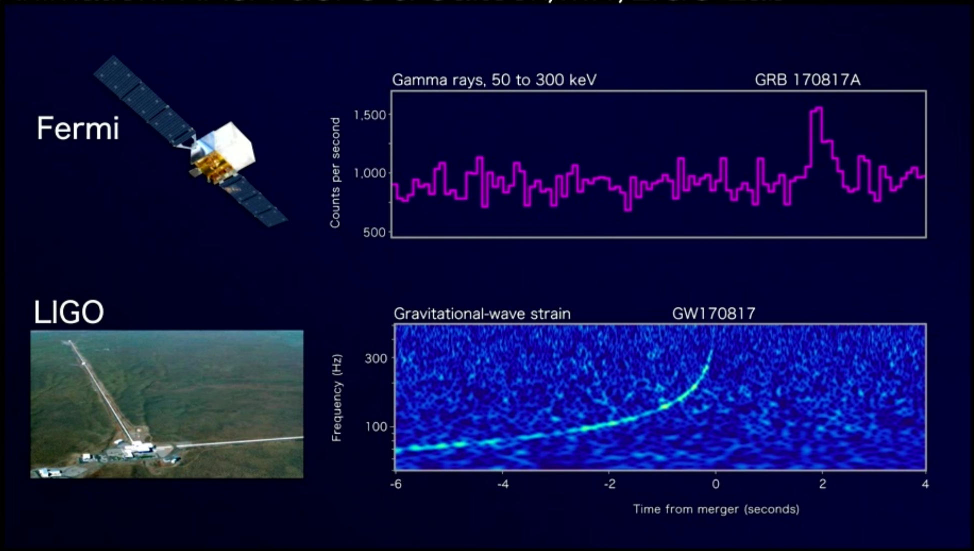

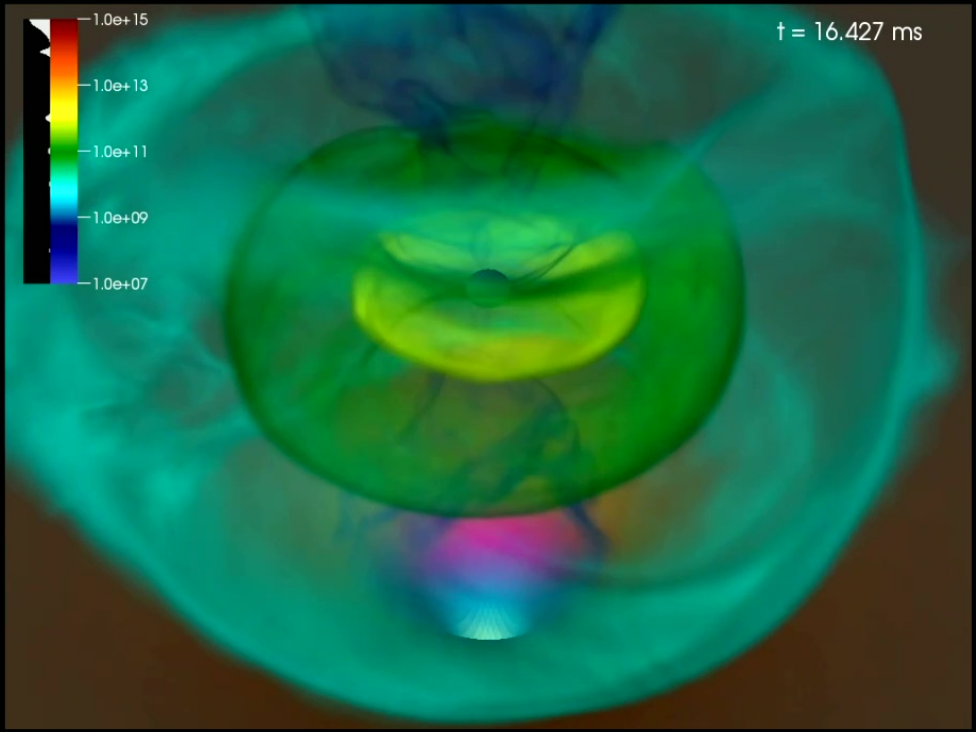

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Gravitational-wave localization

"Bright sirens": redshift from light, luminosity distance from GW

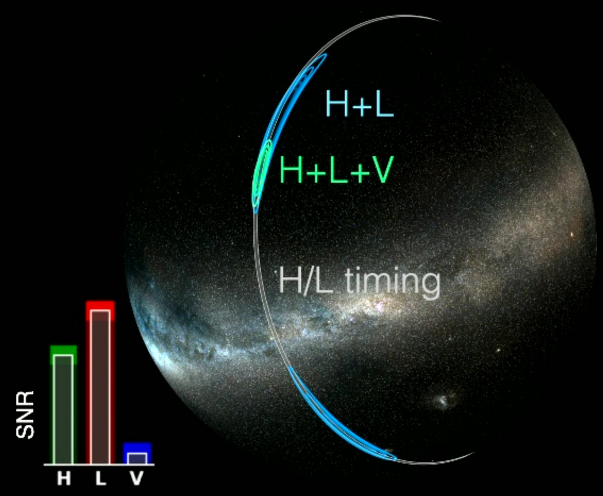
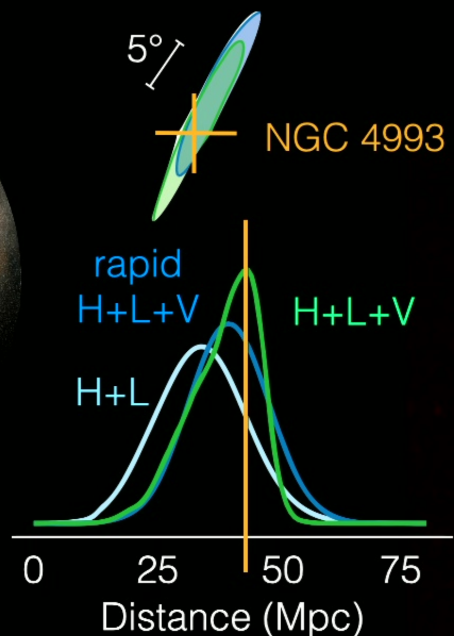


Image LIGO/Virgo/Leo Singer
(Milky Way image: Axel Mellinger)



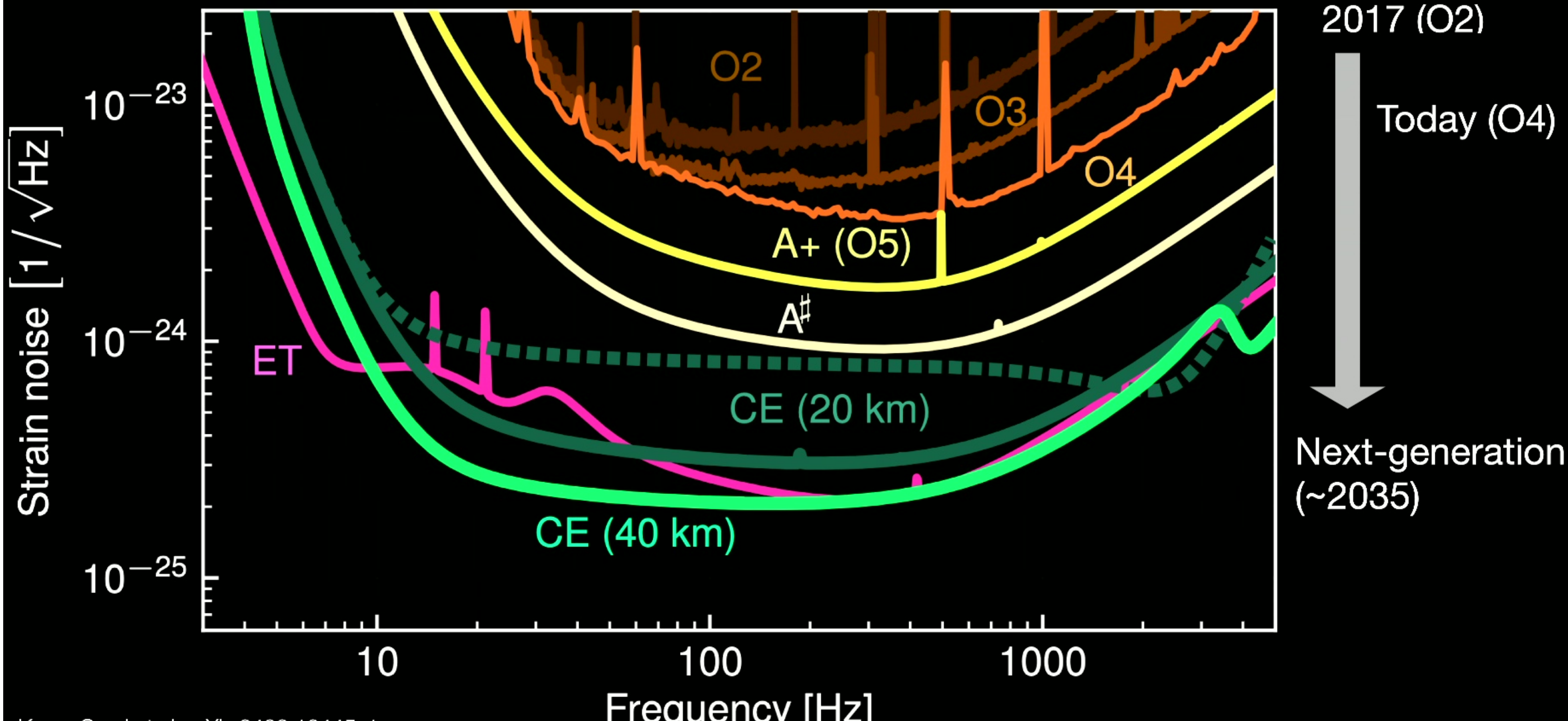
GW170817: Observation,
LIGO & Virgo Scientific Collaborations,
Phys. Rev. Lett. 119 161101 (2017)

Source is galaxy NGC 4993,
redshift z=0.009727

Abbott et al ApJL 848 2 (2017)

ESO/N.R. Tanvir, A.J. Levan, VIN-ROUGE collaboration

Future capabilities on Earth

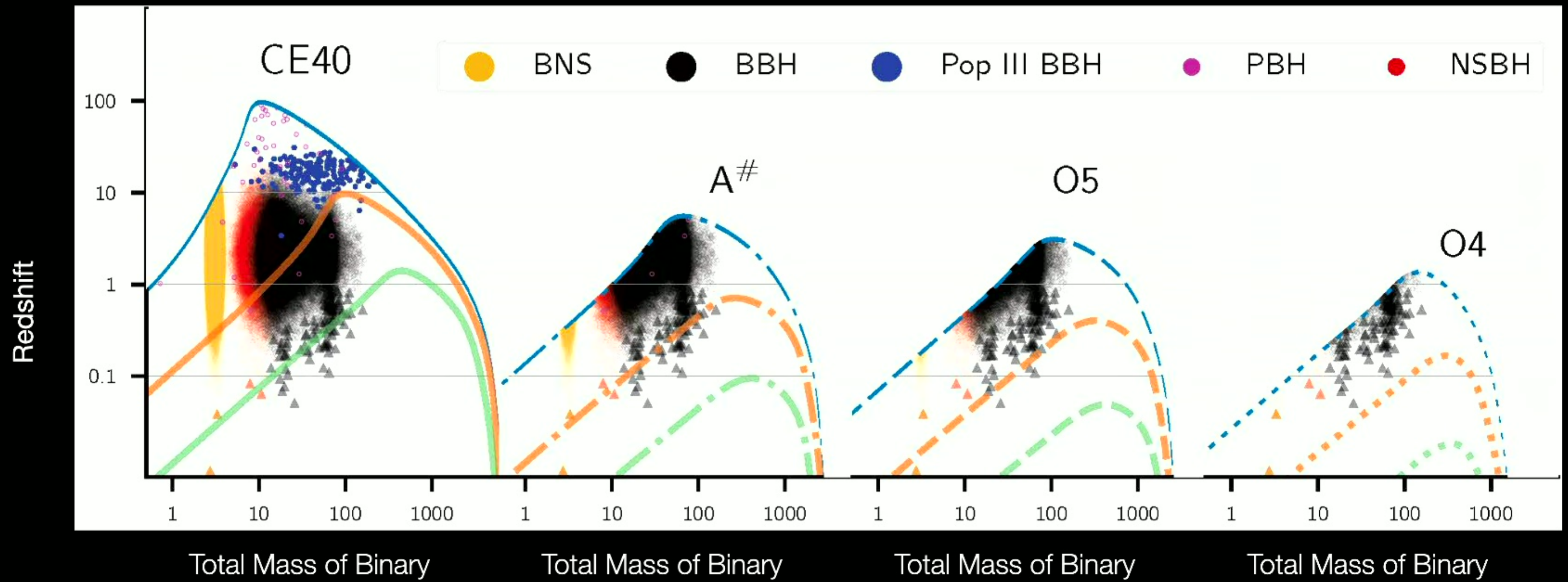


Kuns; Corsi et al. arXiv:2402.13445v1

Unveiling the GW Universe

Binary mergers across cosmic time

— — range to SNR 8
— — range to SNR 100
— — range to SNR 1000



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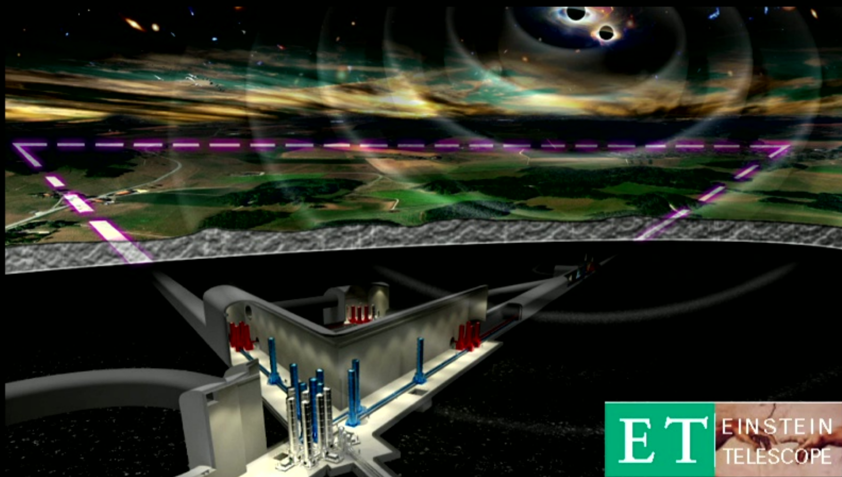
White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745

"XG": new facilities for ground-based GW



Einstein Telescope (ET)

- 10 km underground triangle
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- Site procedure in progress, decision 2025/26
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NSF

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Images courtesy Einstein Telescope, Cosmic Explorer

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GW across the universe

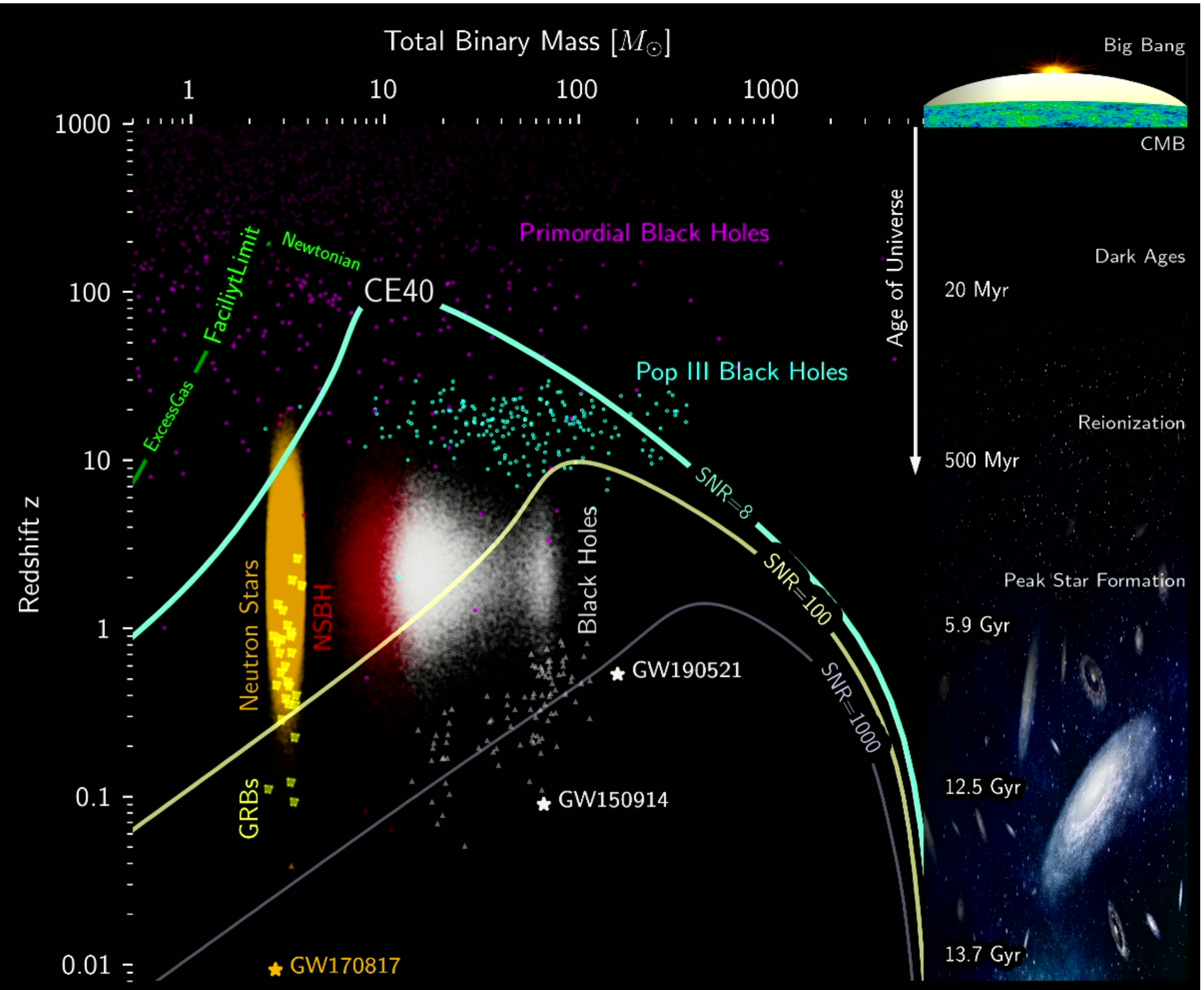
Current sGRB distances
z~0.01-1.5

Independent kilonova identification
to z~0.02-0.5 for LSST
to z~1 for Roman

Chase et al 2022 ApJ 927 163

FRB distances ~100-1000 Mpc
O3 CBC Exclusions ~ 60-600 Mpc

R. Abbott et al 2023 ApJ 955 155



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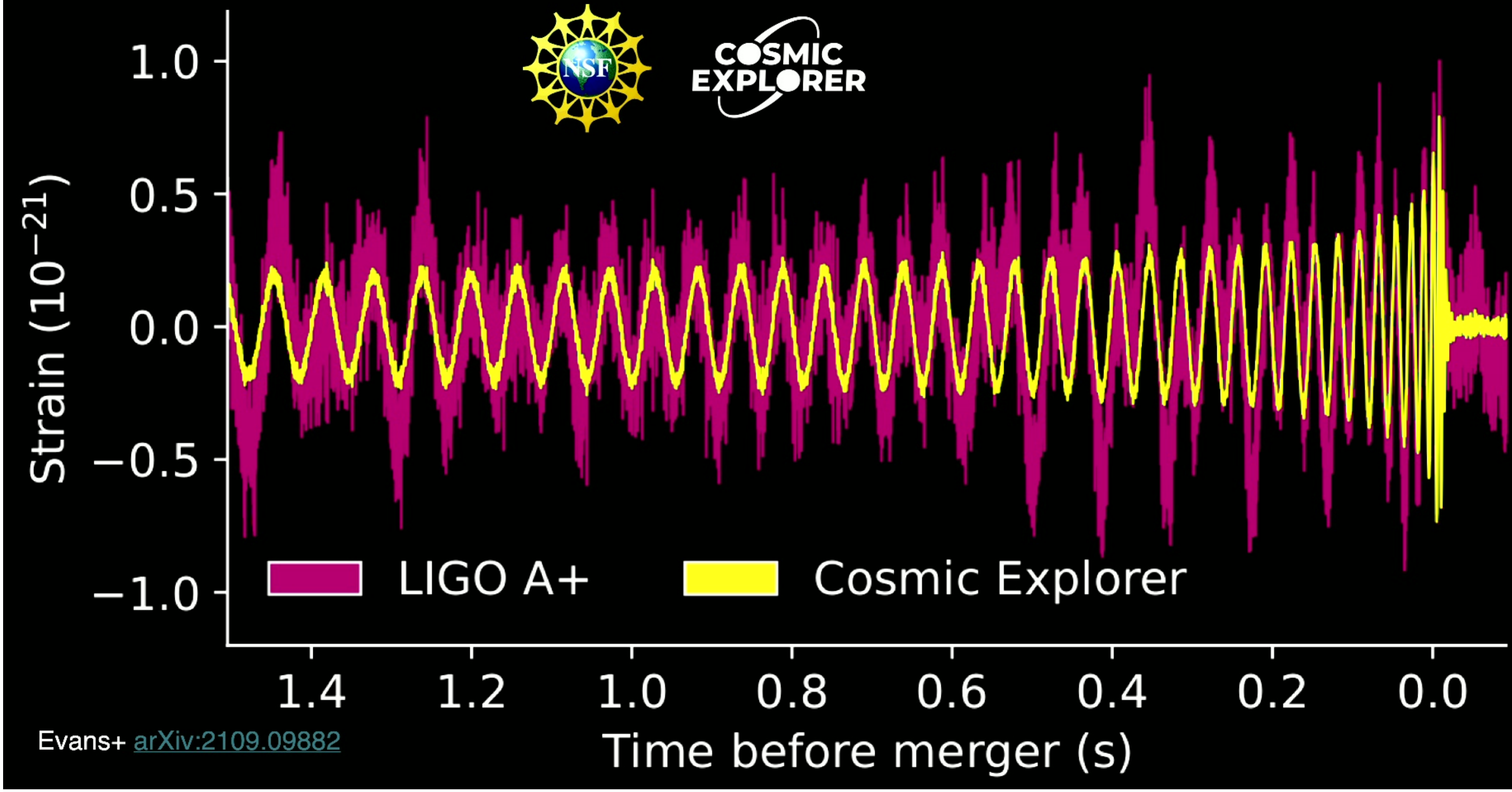
GW150914 as Cosmic Explorer would see it

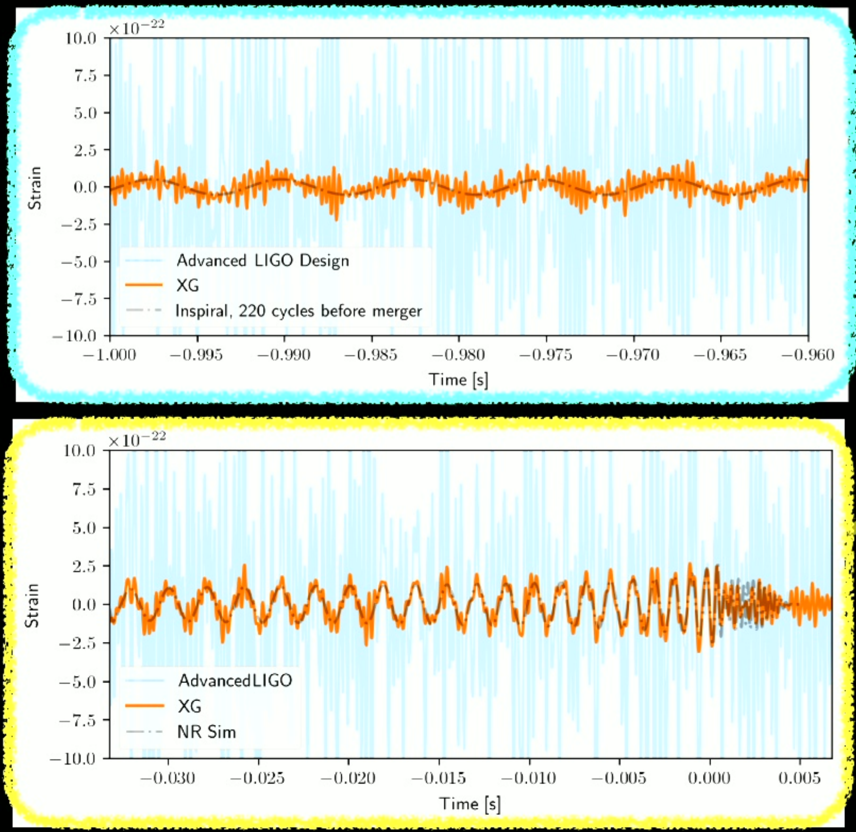


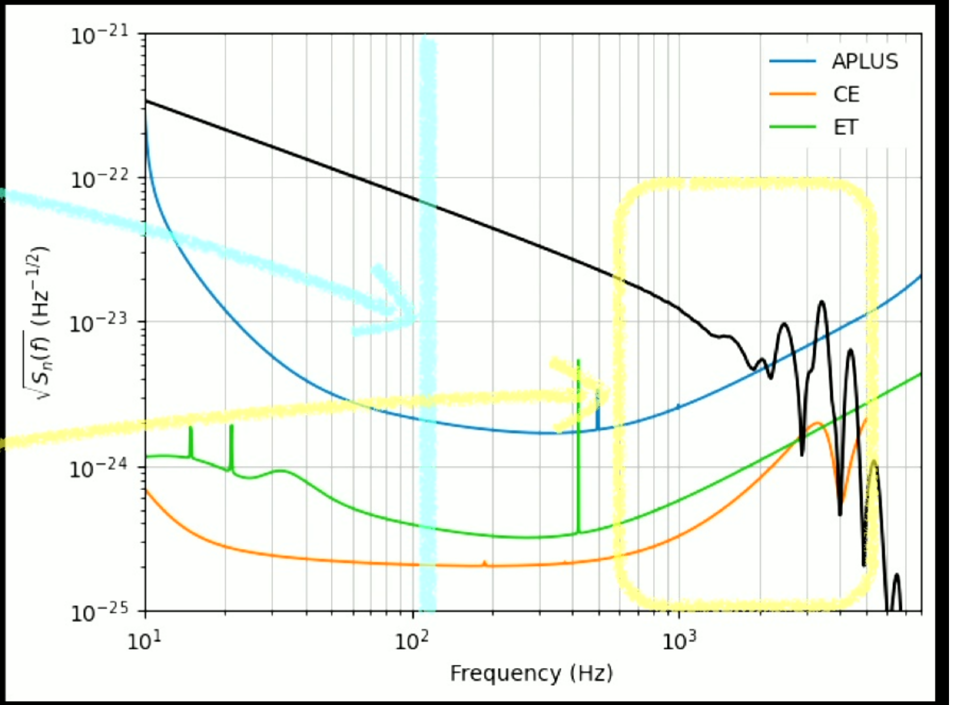
Evans+ arXiv:2109.09882

21

GW170817 as Cosmic Explorer would see it

Hundreds of individually resolvable cycles





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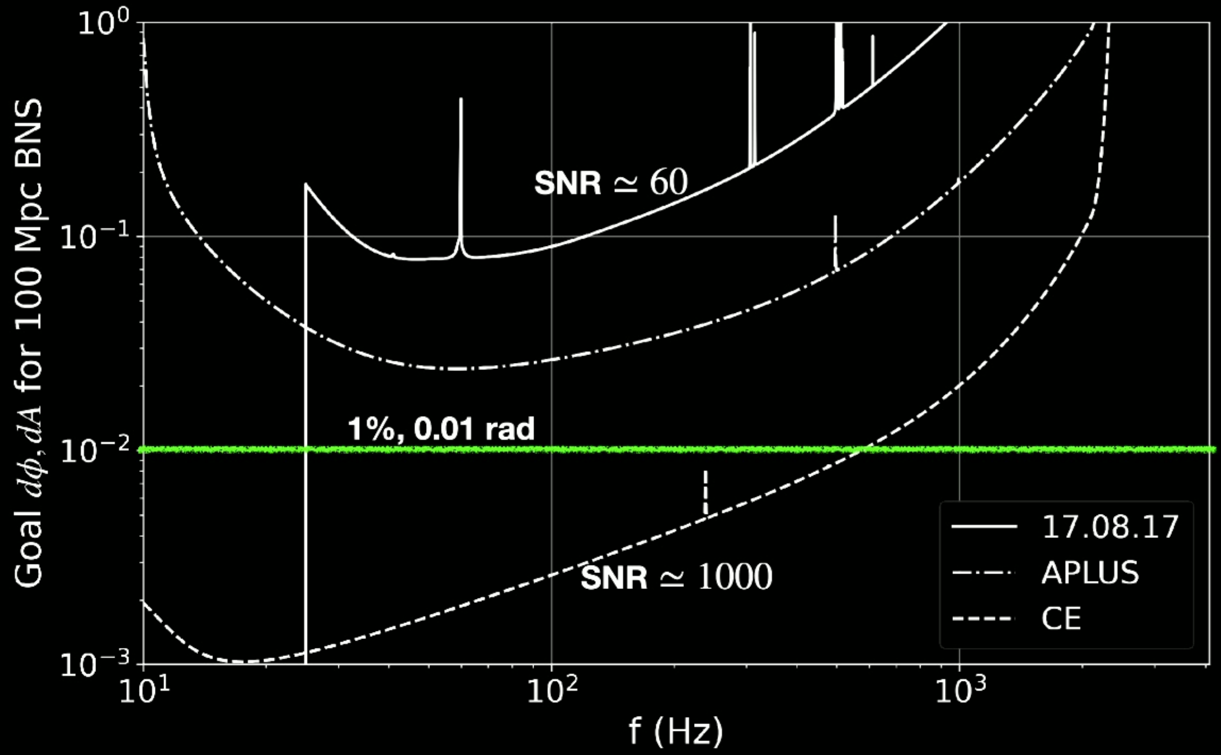
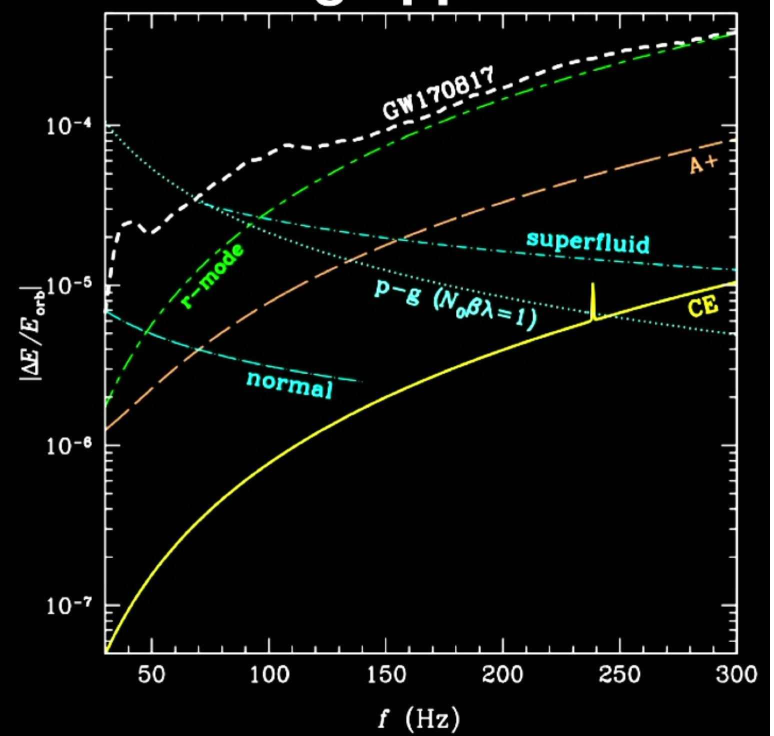
JS Read

Precision requirements for calibration & waveforms



Modeling opportunities

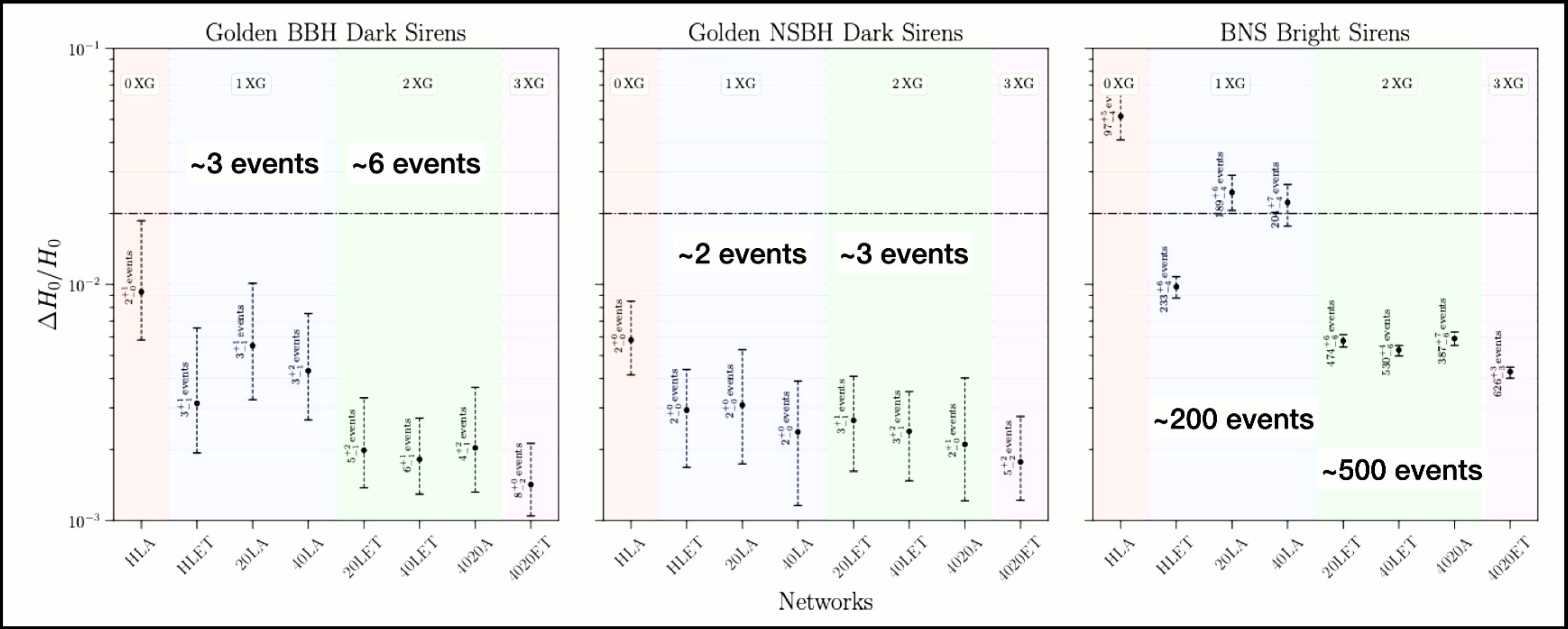


Jocelyn Read 2023 Class. Quantum Grav. 40 135002

Ho and Andersson Phys. Rev. D 108, 043003 (2023)

Nearby cosmology: EM association

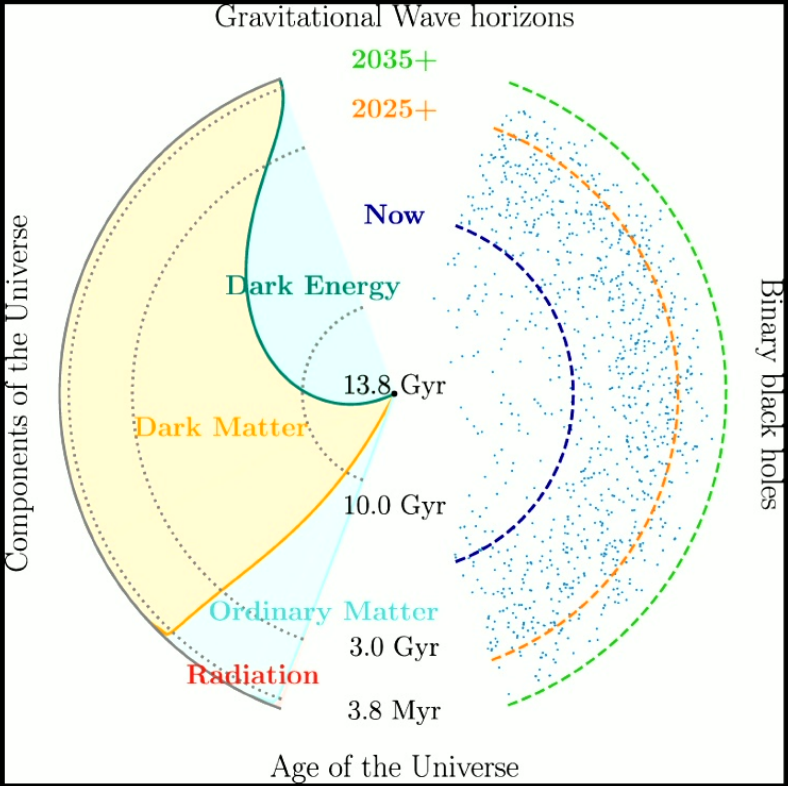
Gupta et al Class.Quant.Grav. 41 (2024)
HLA: A# Sensitivity at Hanford, Livingston and Aundha (India)



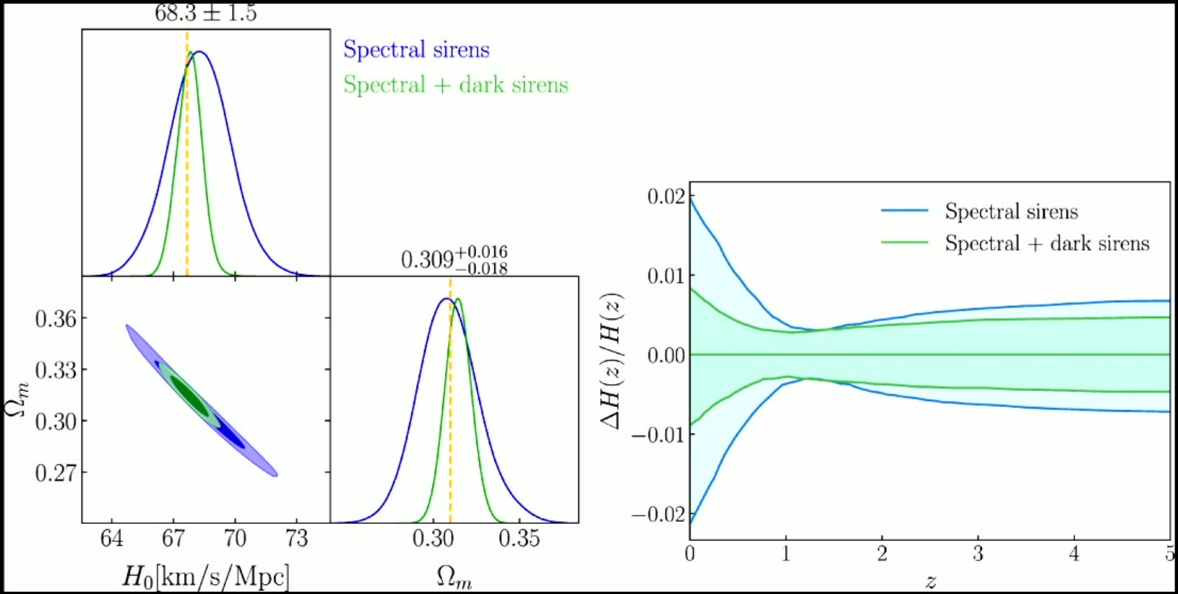
“Golden” BBH/NSBH with galactic identification: $z \leq 0.1$ and $\Delta\Omega \leq 0.04$ deg^2
“Bright” BNS with $z \leq 0.3$ and $\Delta\Omega \leq 10$ deg^2

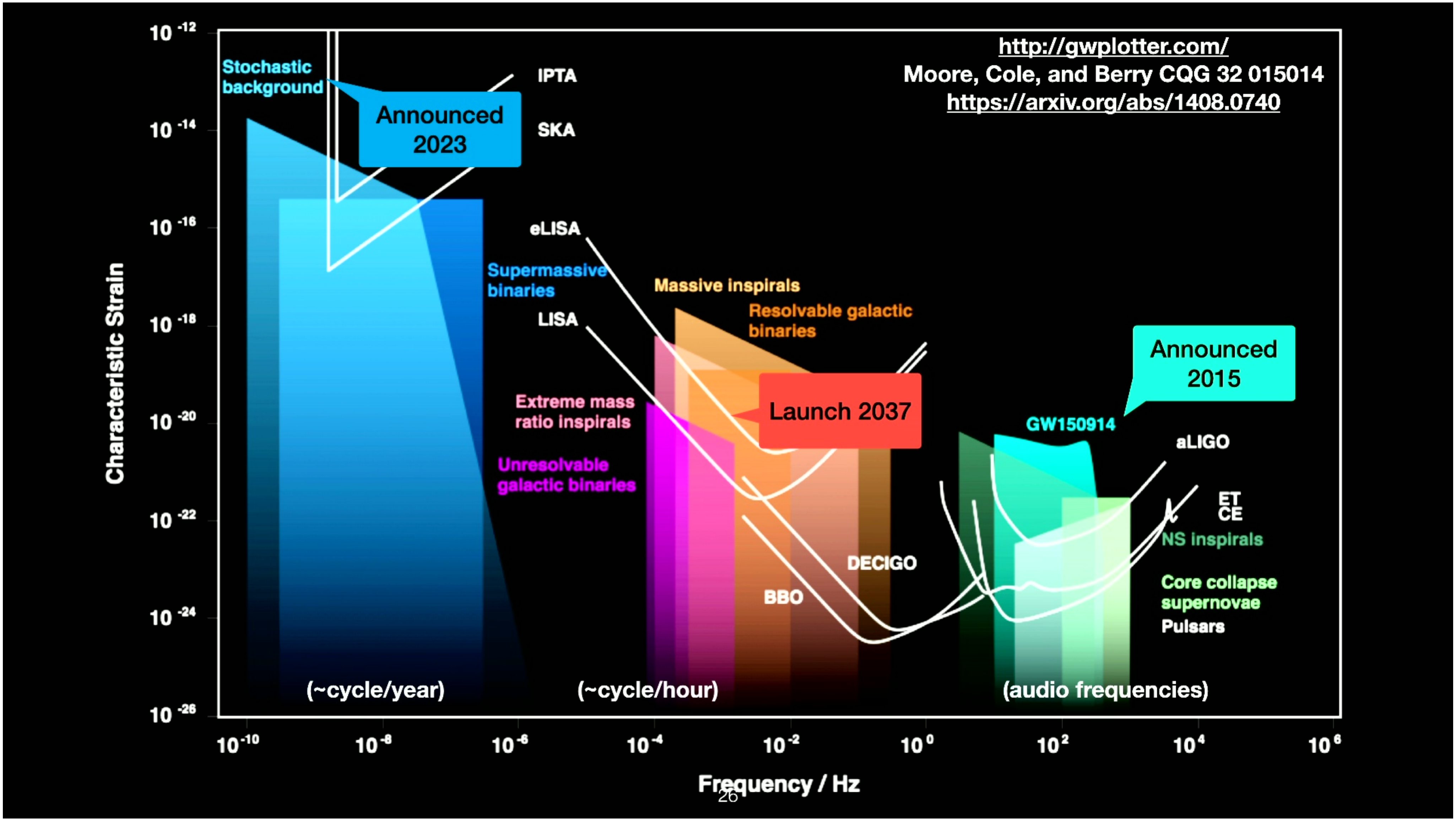
XG: Dark Sirens and Spectral sirens

Hsin-Yu Chen et al 2024 Class. Quantum Grav. 41 125004



Spectral sirens require a robust feature in mass distributions to break mass-redshift degeneracy



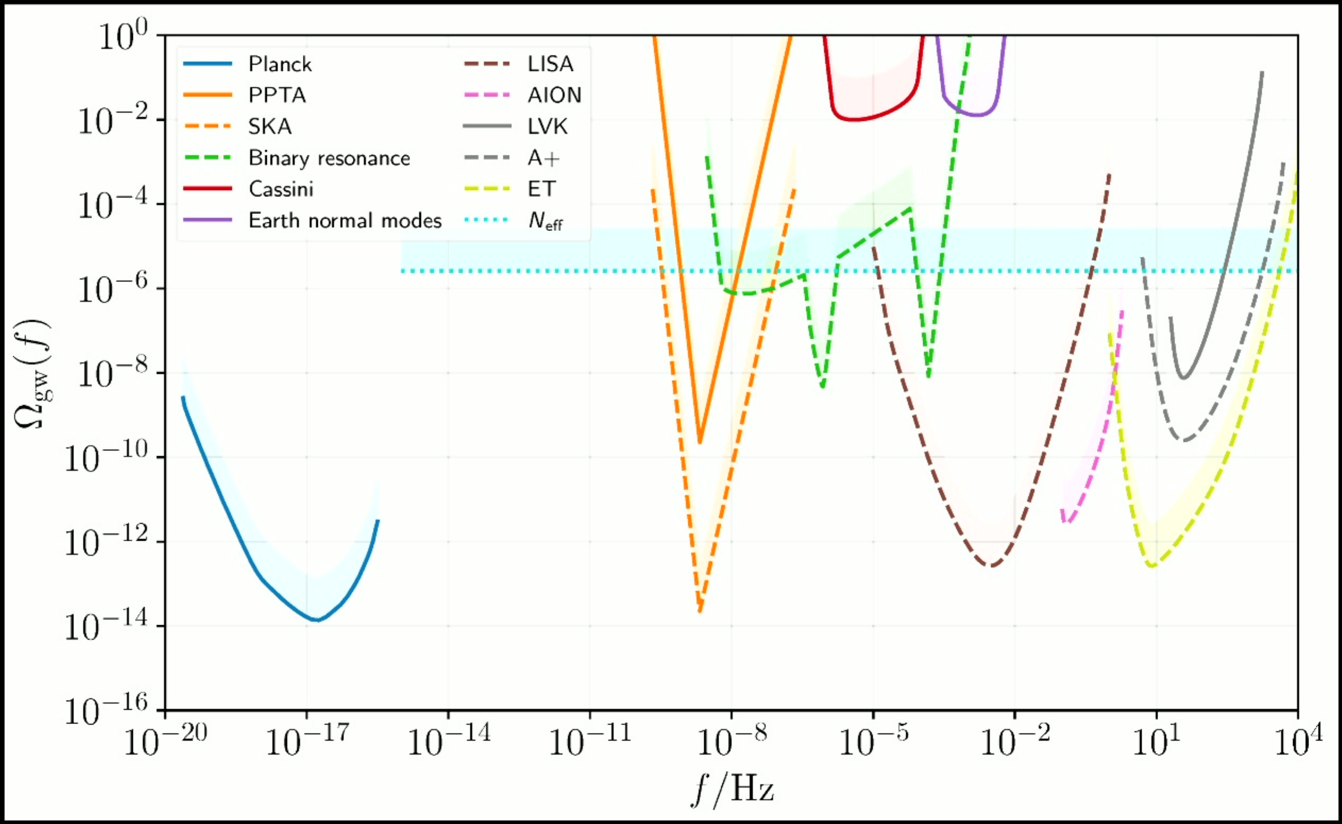


http://gwplotter.com/
Moore, Cole, and Berry CQG 32 015014
https://arxiv.org/abs/1408.0740
Stochastic background
Announced 2023
IPTA
SKA
eLISA
Supermassive binaries
LISA
Massive inspirals
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Launch 2037
Announced 2015
GW150914
aLIGO
ET
CE
NS inspirals
Core collapse supernovae
Pulsars
DECIGO
BBO
(~cycle/year)
(~cycle/hour)
(audio frequencies)
Characteristic Strain
Frequency / Hz

26

Stochastic gravitational-wave background

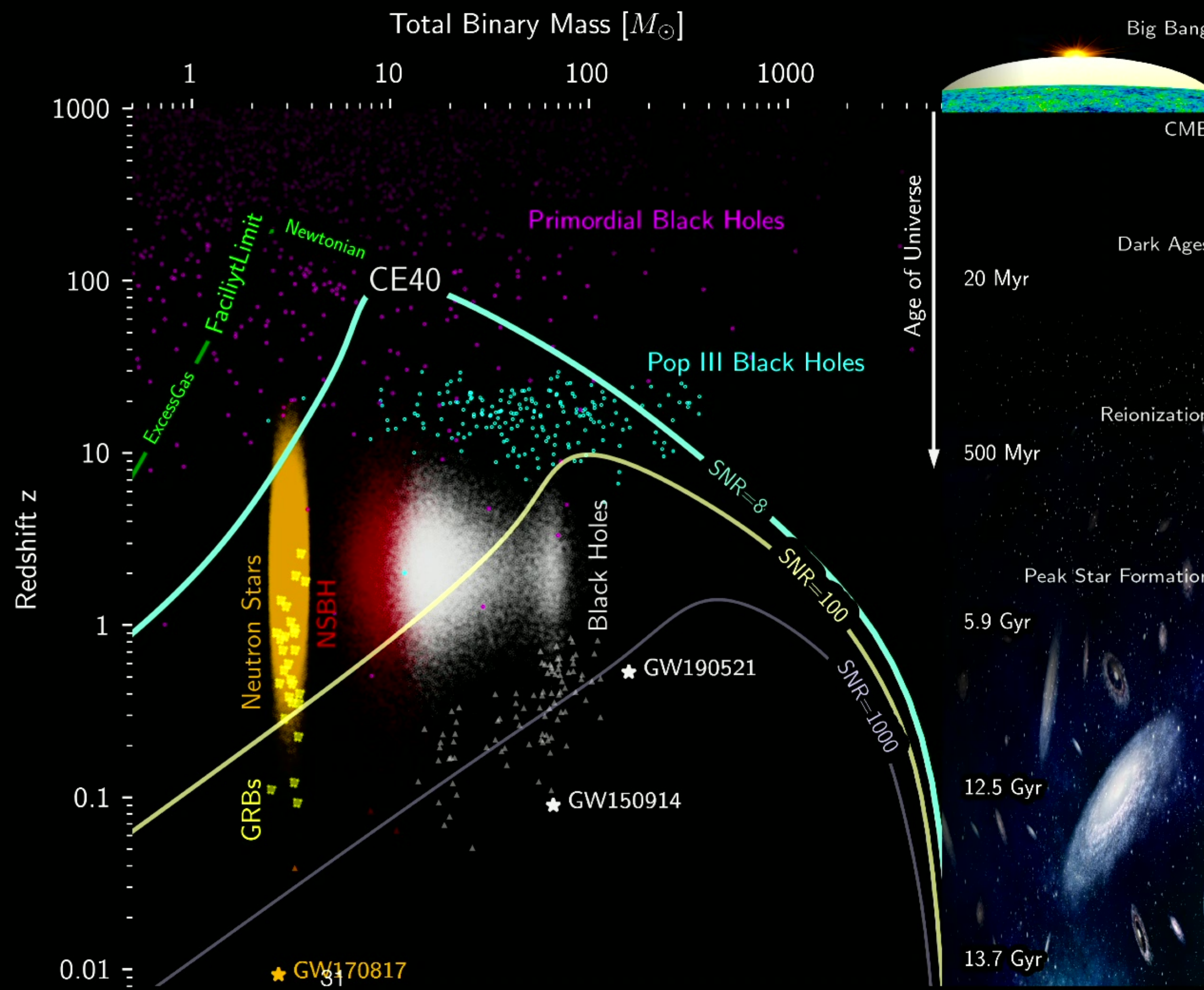
Current and future constraints



Renzini, A.I. et. al. Galaxies 2022, 10, 34.

COSMIC EXPLORER

Thank you!



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Site evaluation and design funded by NSF starting 2023

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Gupta et al Class.Quant.Grav. 41 (2024)
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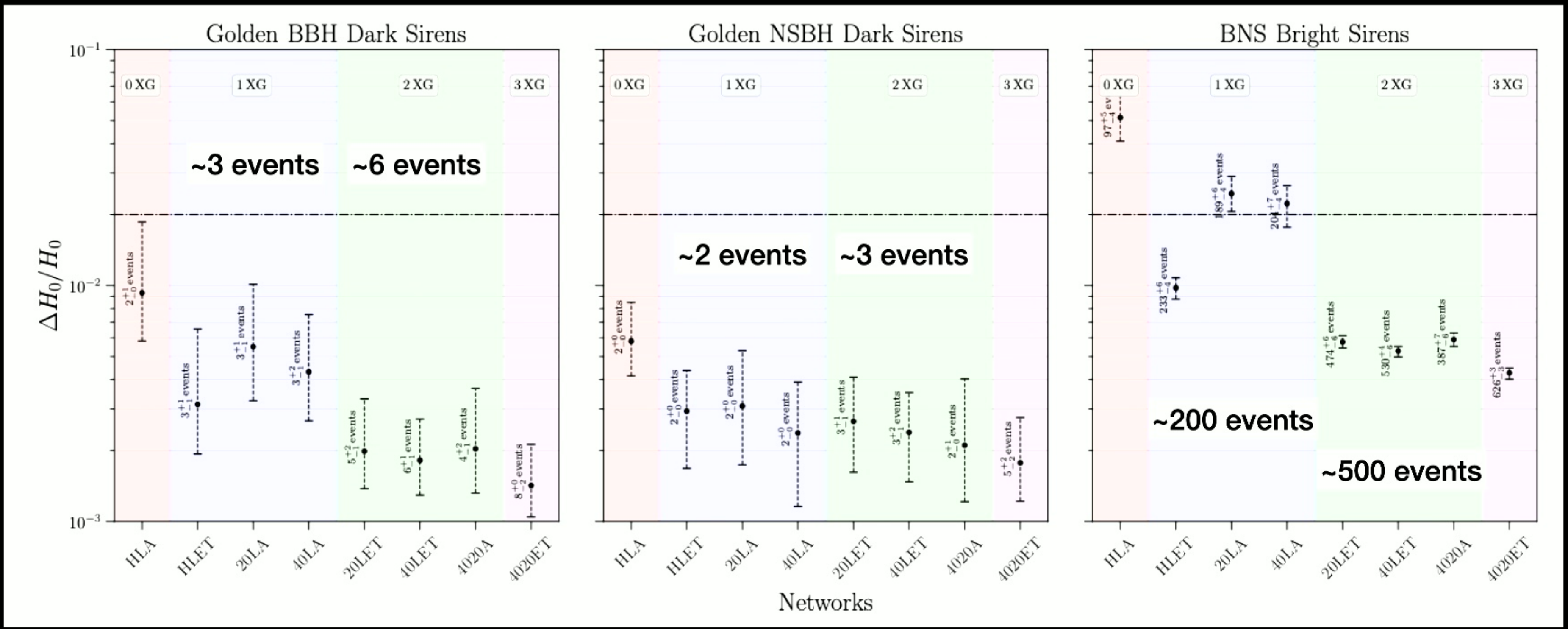

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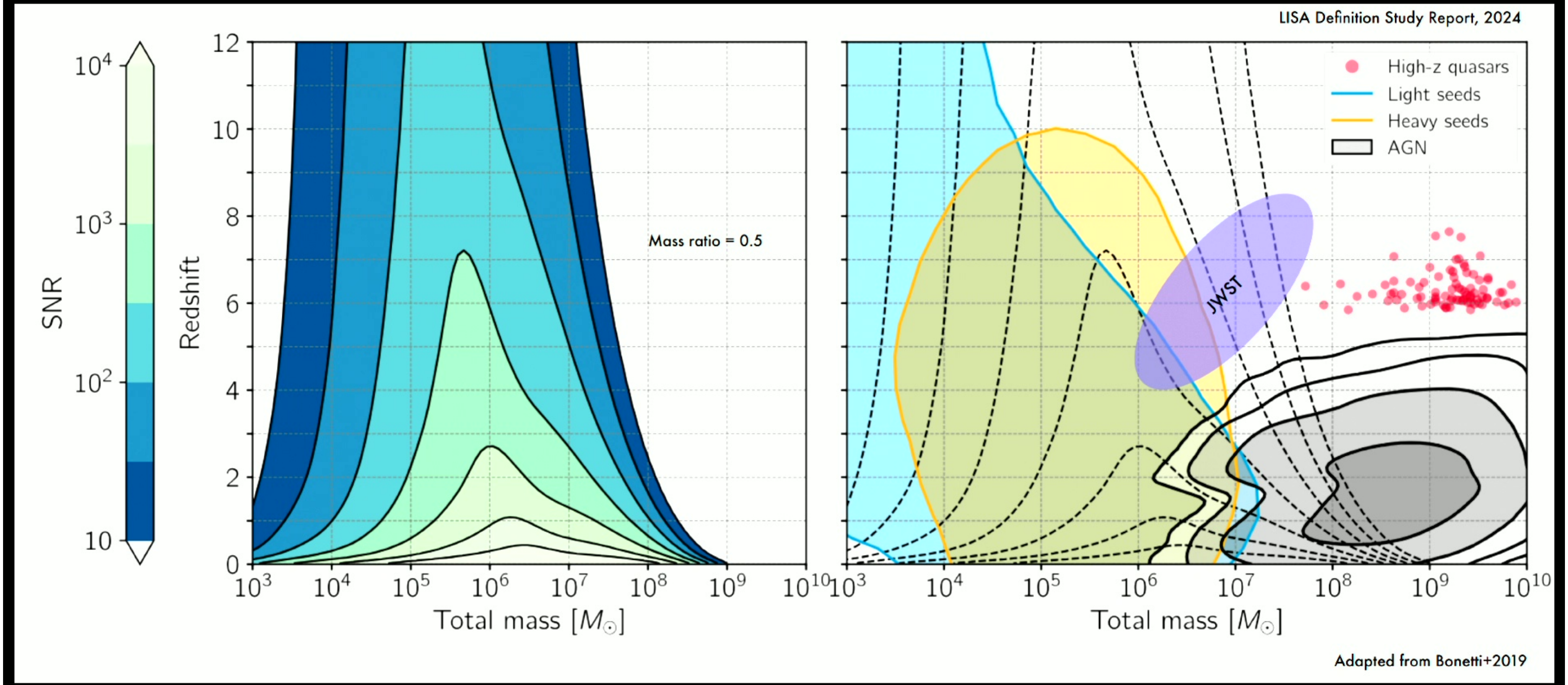
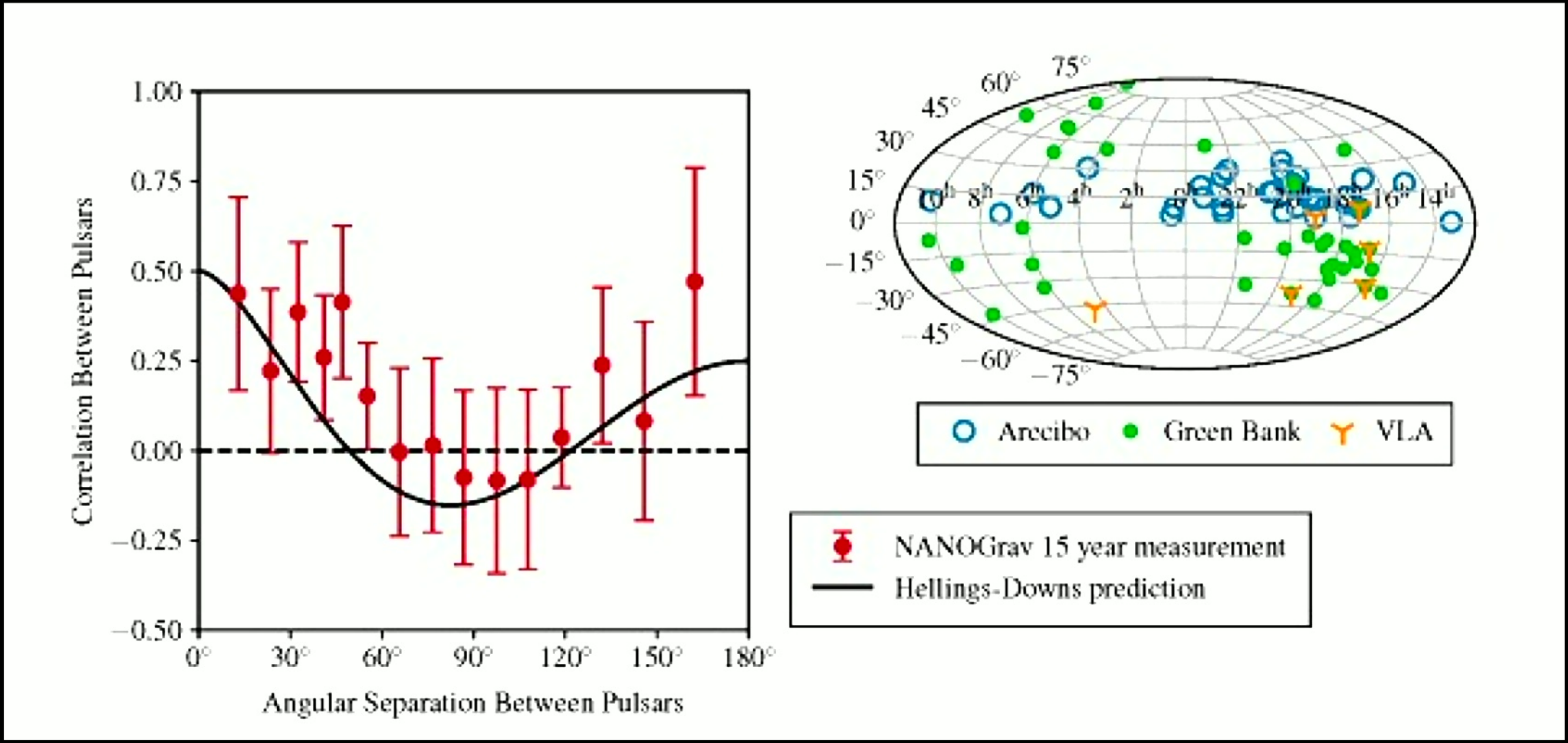
LISA: Observational Reach (launch 2037)



Slide from Kelly Holley-Bockelmann

Red noise with GW angular correlation

e.g. NANOGrav's 15 yr Data Set and the Gravitational Wave Background



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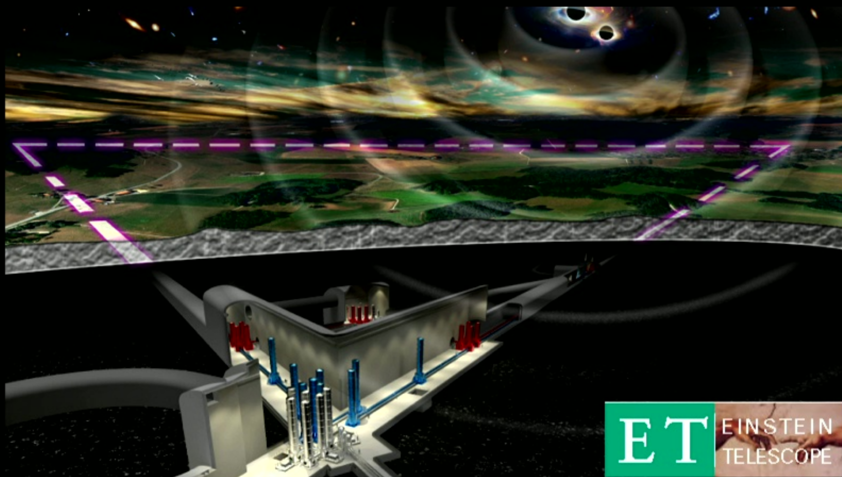

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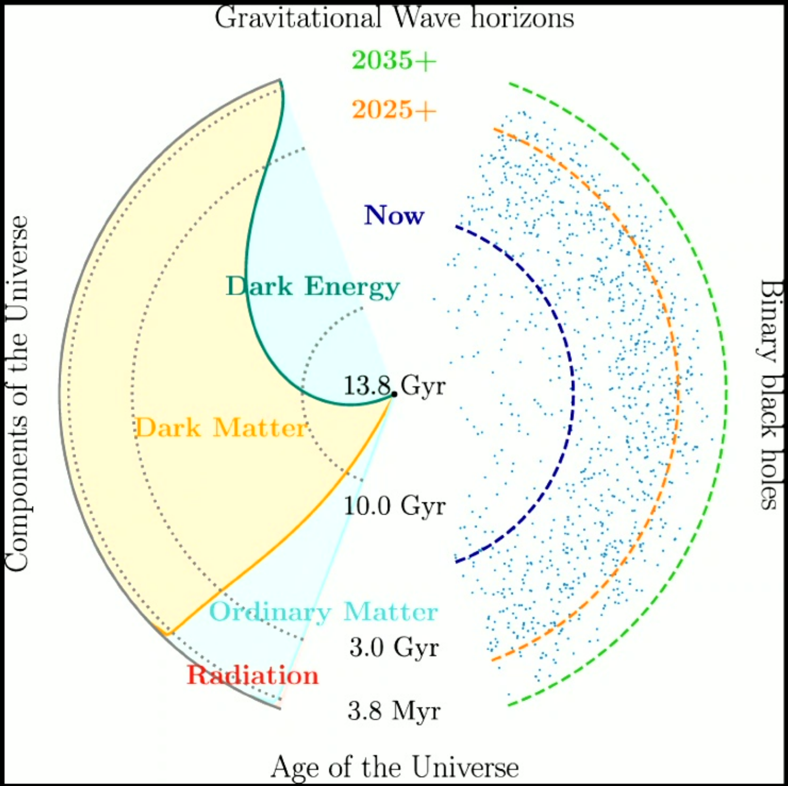

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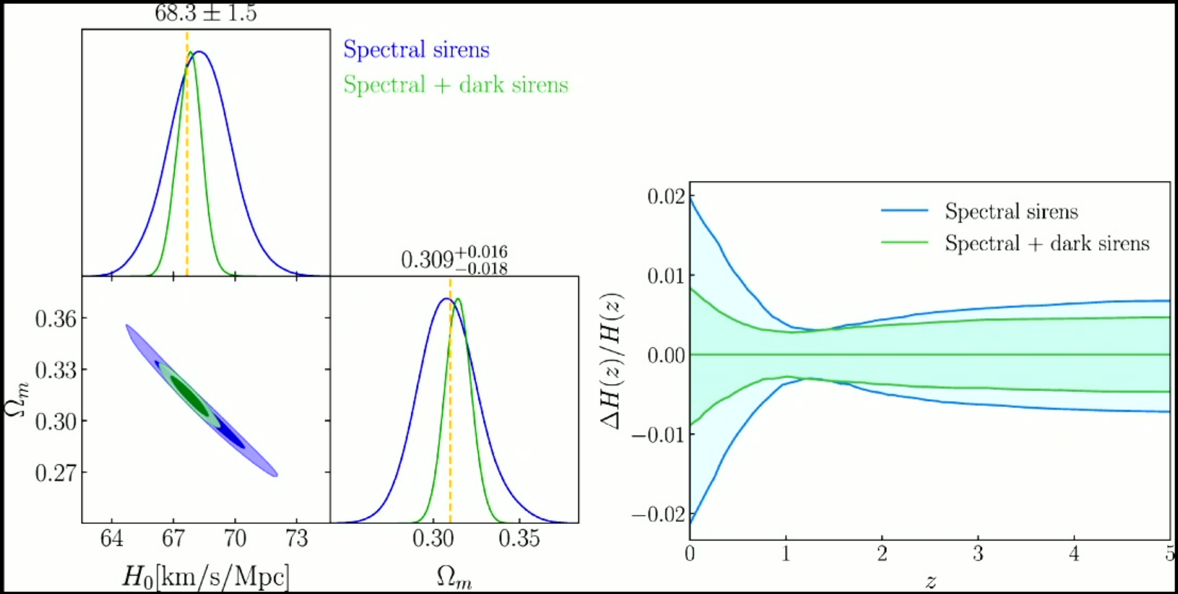

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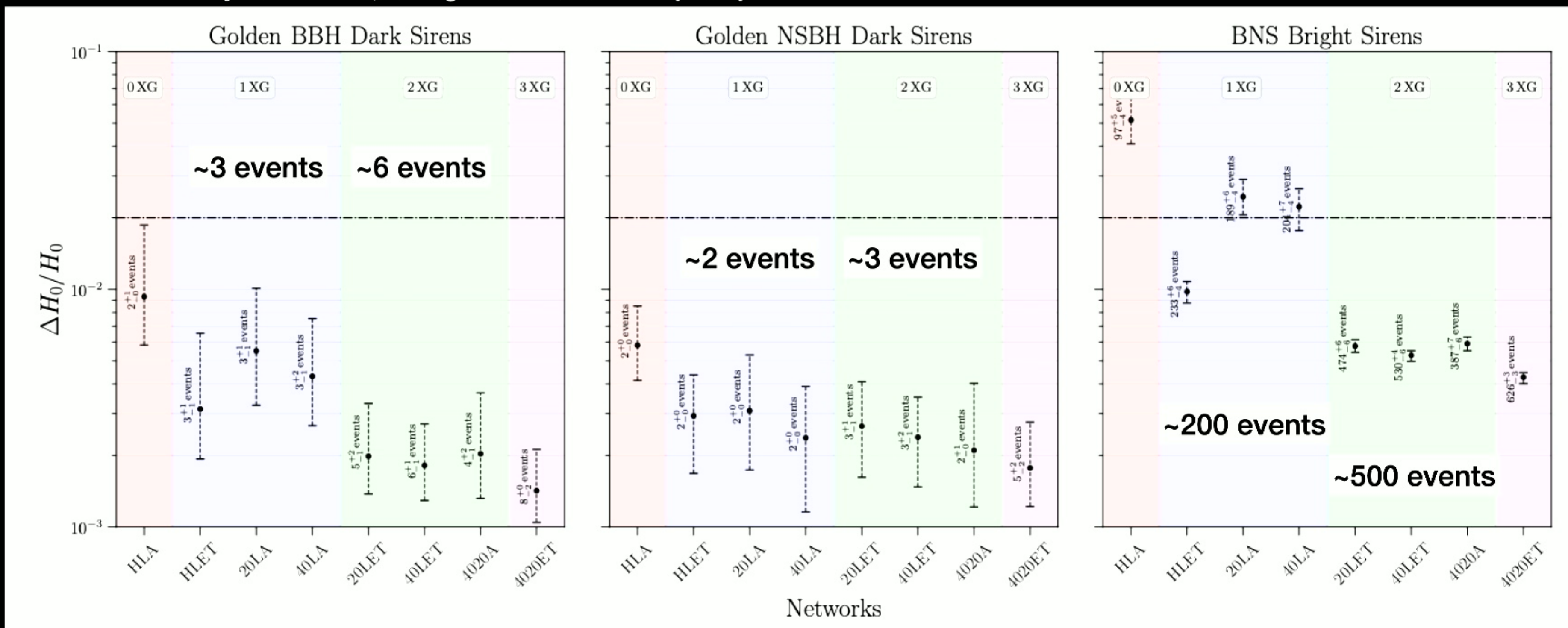
Gupta et al Class.Quant.Grav. 41 (2024)
HLA: A# Sensitivity at Hanford, Livingston and Aundha (India)



“Golden” BBH/NSBH with galactic identification: $z \leq 0.1$ and $\Delta\Omega \leq 0.04$ deg^2
“Bright” BNS with $z \leq 0.3$ and $\Delta\Omega \leq 10$ deg^2

Science Traceability for Cosmic Explorer

Cosmic Explorer Consortium contribution to Design process

- Identify *measurement objectives* that set *instrument requirements* to answer *key science questions* from:
  - Pathways to Discovery in Astronomy and Astrophysics for the 2020s, NSAC 2023 Long Range Plan for Nuclear Science, ASTRONET Science Vision and Roadmap 2022-2035, Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics (P5) 2023
- Working groups: Compact binary mergers, Dense matter, Multi-messenger observations, Cosmology, Dark sector physics, Tests of GR
- Meetings announced to Cosmic Explorer Consortium, join at https://cosmicexplorer.org/consortium.html