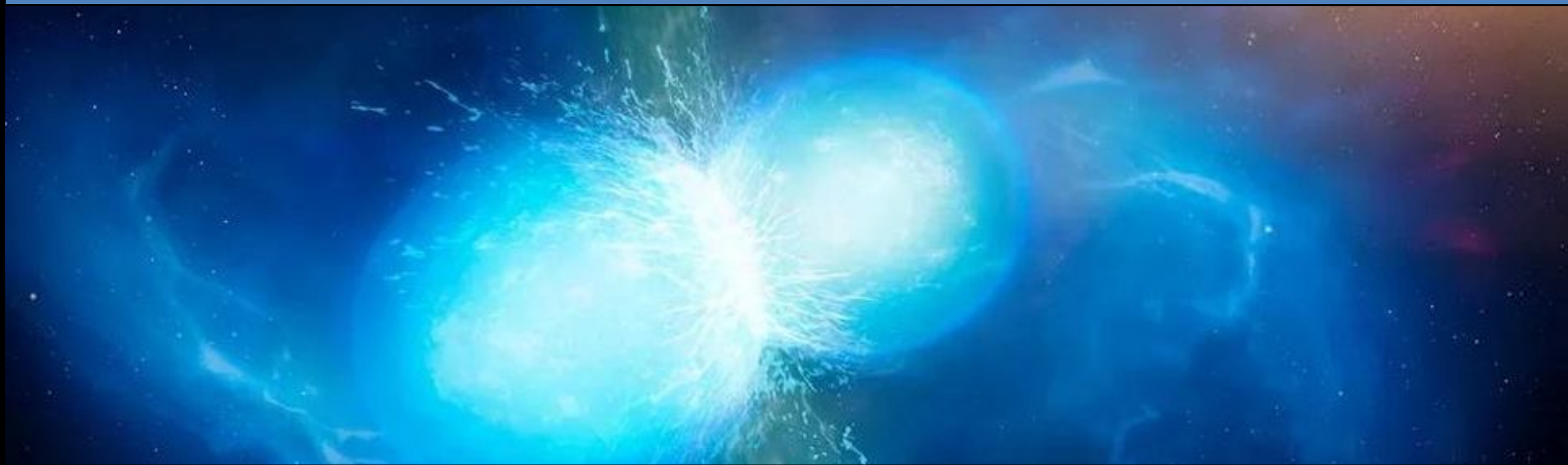


Gravitational Waves: Future Opportunities

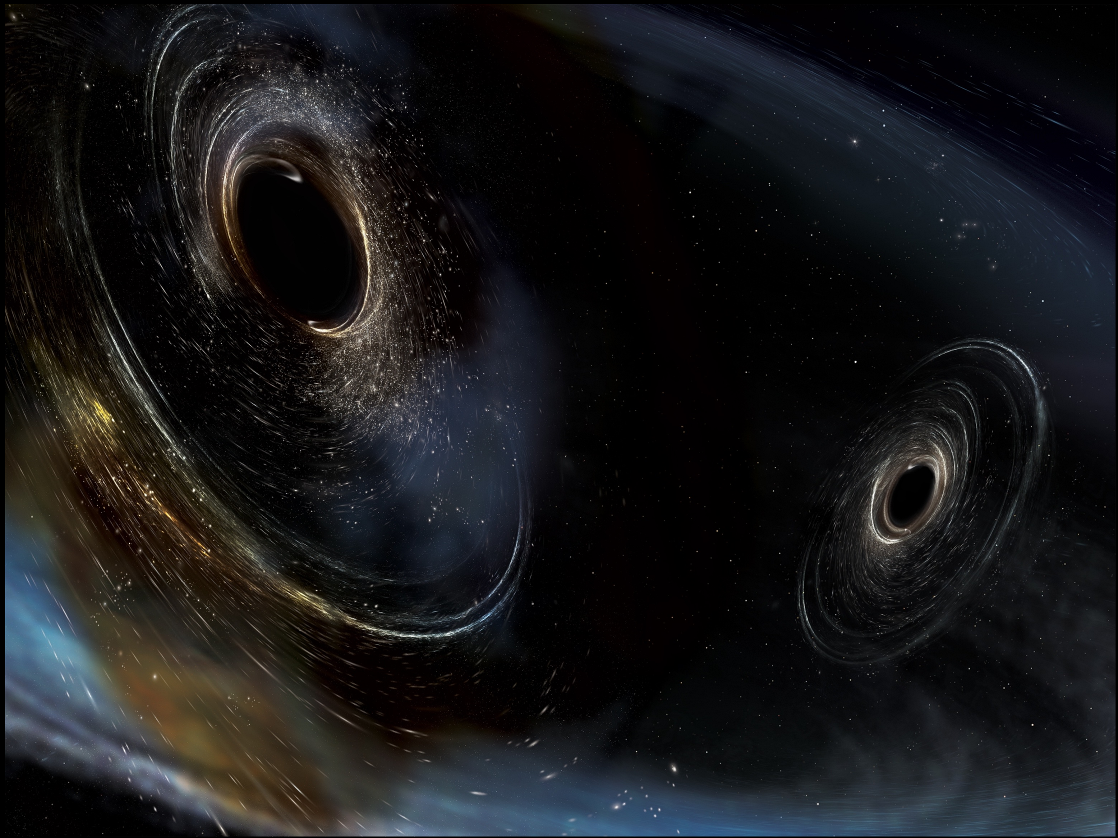
GW science highlights over the next decades

Patrick Sutton

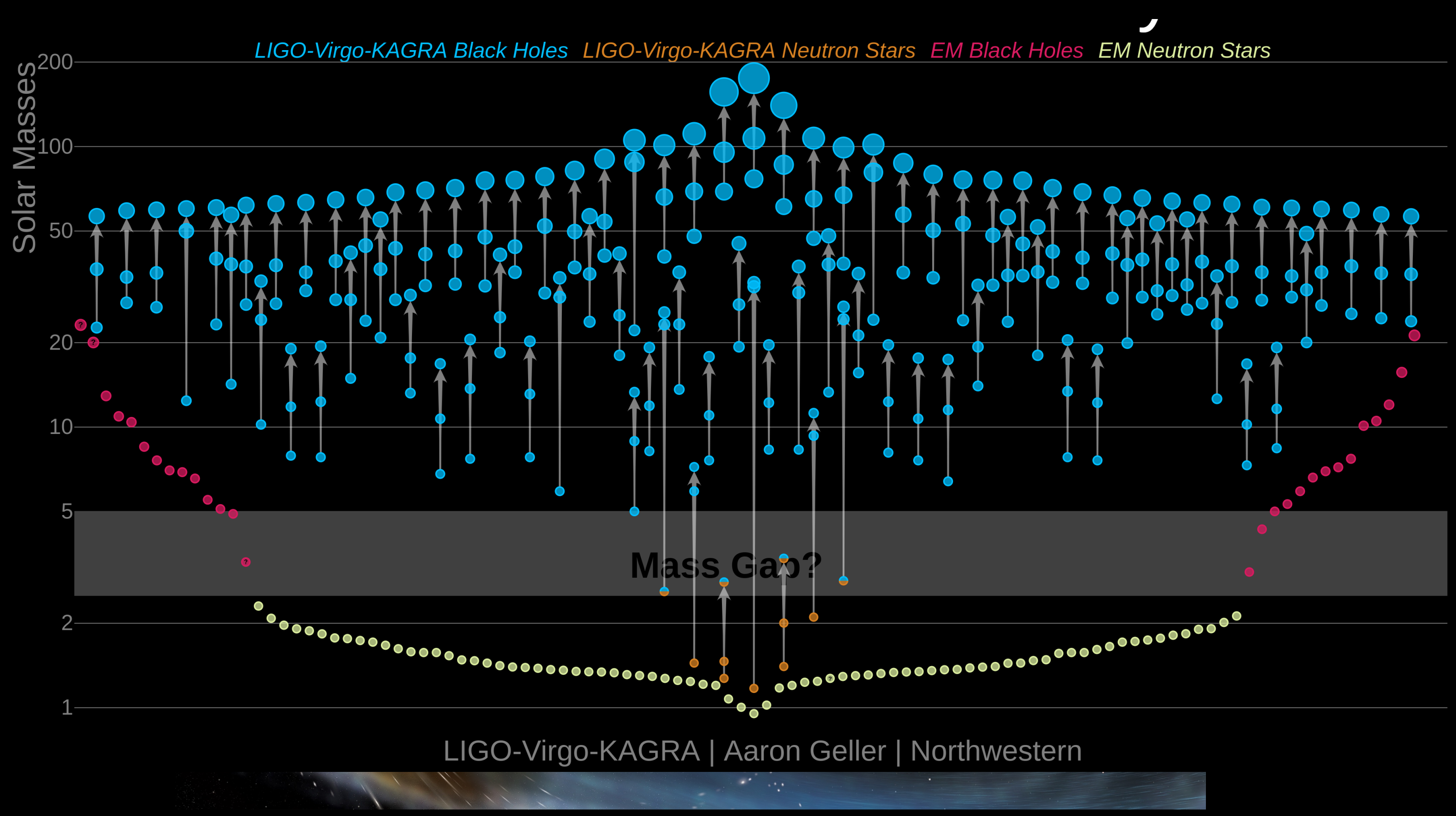
Cardiff University

The ONASSIS FOUNDATION
Science Lecture Series

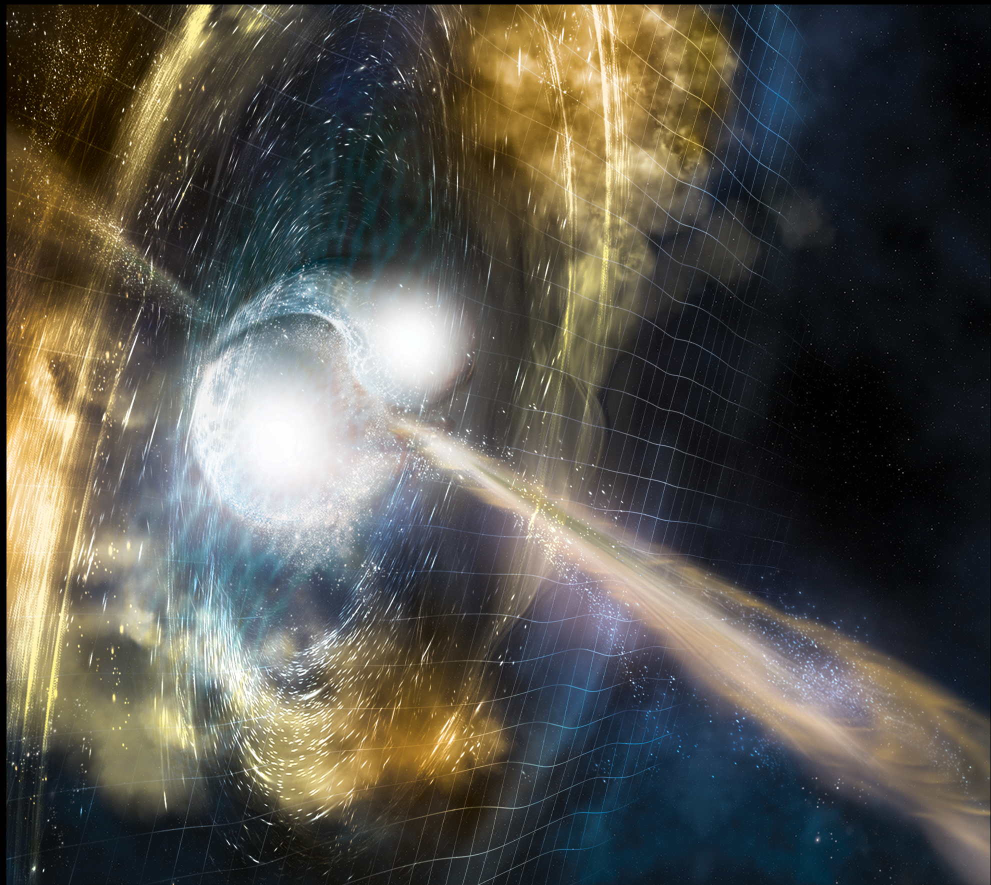
Highlights so far



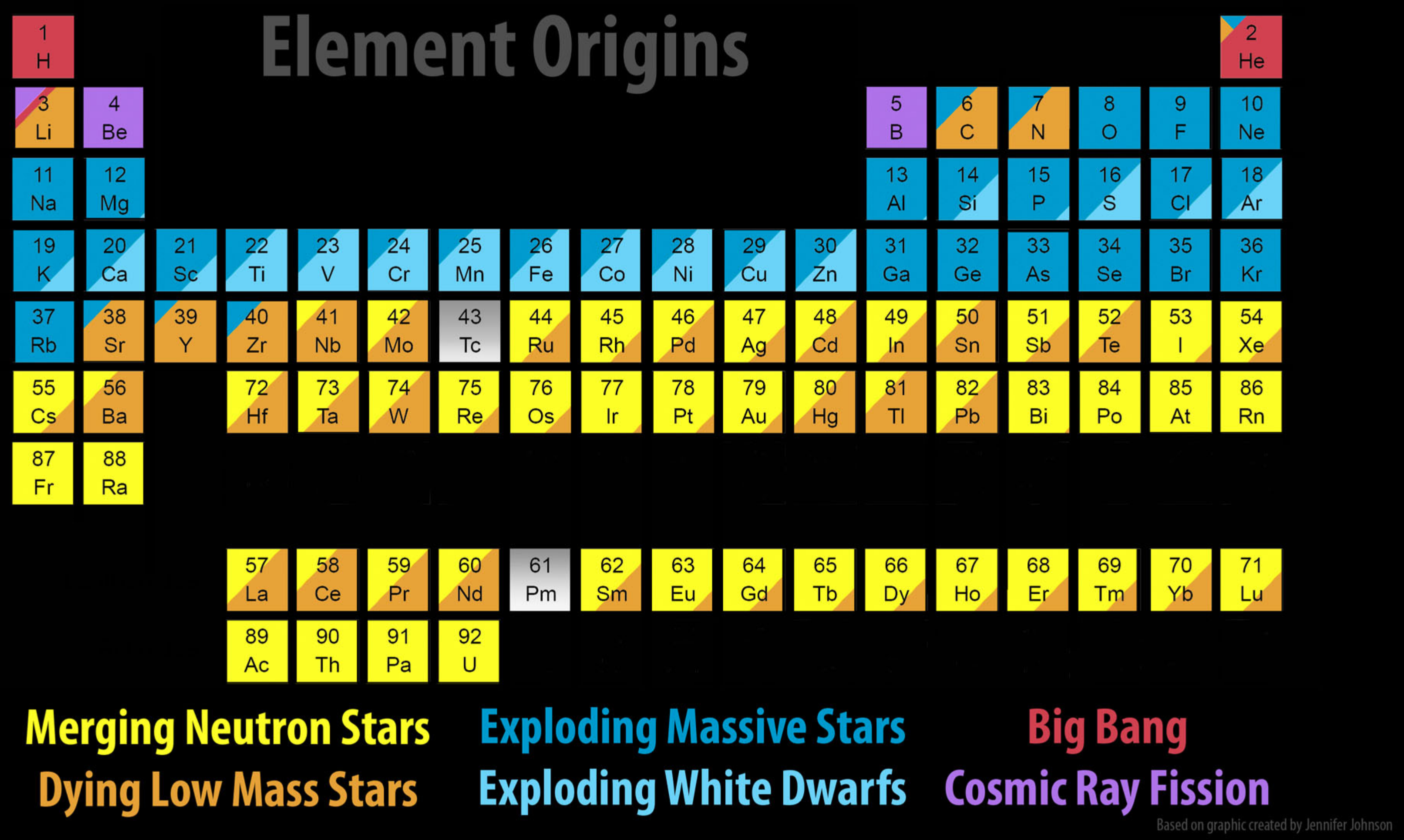
Highlights so far



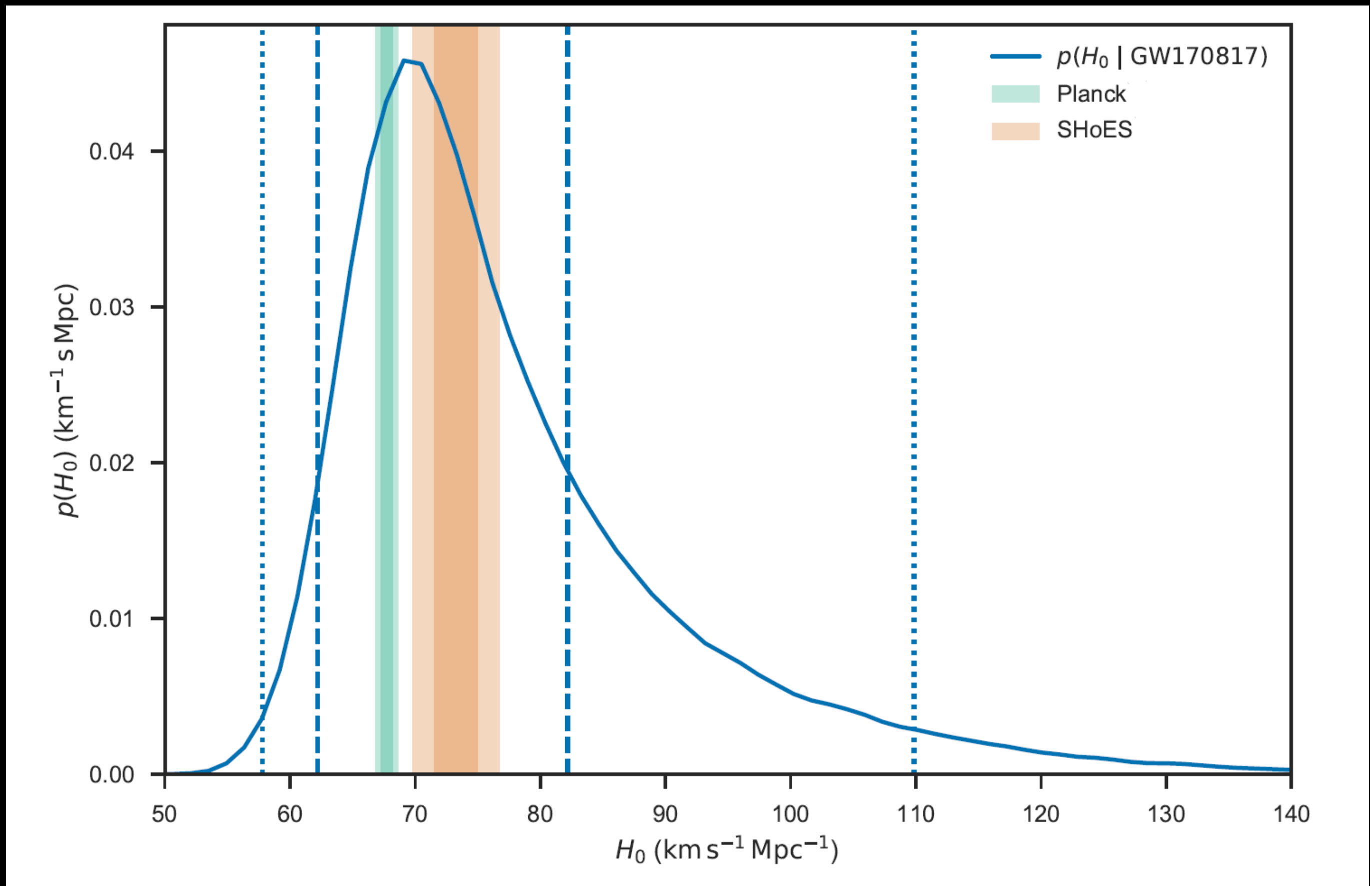
Highlights so far



Highlights so far



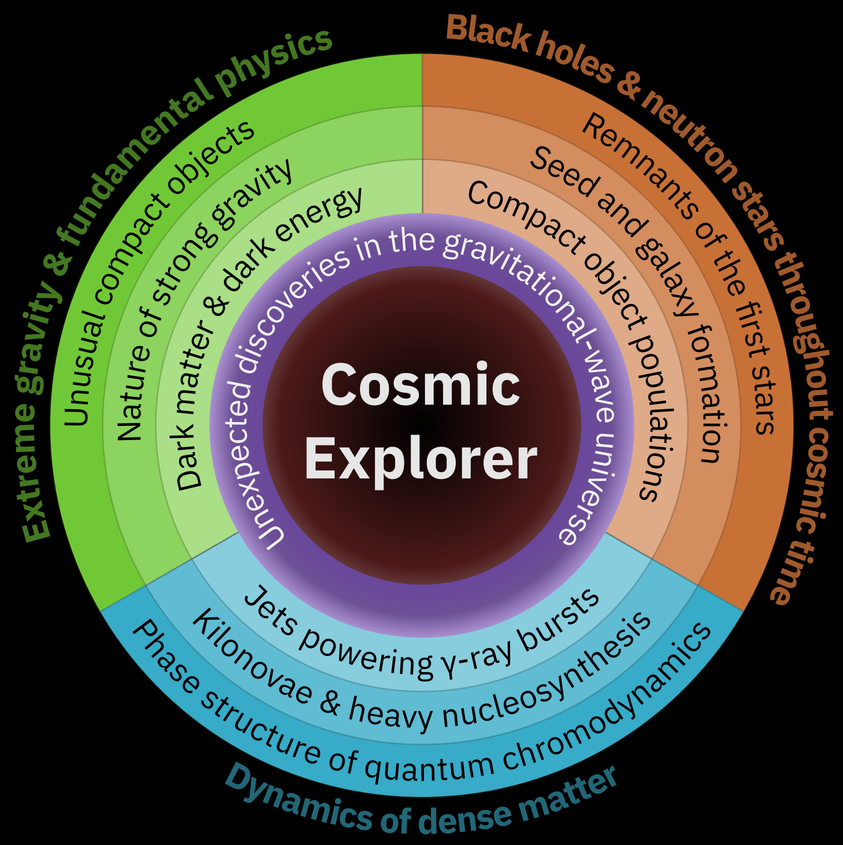
Highlights so far



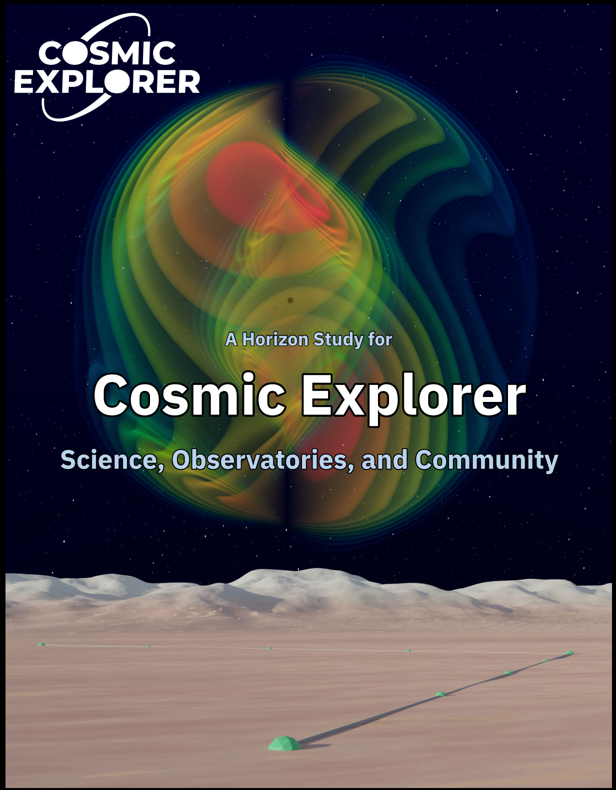
Abbott et al. Nature 551, 85 (2017)

Future Opportunities: Many topics!

- Multi-messenger astronomy
  - sites of r-process heavy element production, BNS vs NSBH, etc.
- Equation of state of dense nuclear matter
  - size of neutron stars; are there phase transitions beyond nucleons?
- Cosmology with standard sirens
  - Hubble parameter, dark energy equation of state and its variation with redshift
- Strong field tests of general relativity
  - binary black hole orbital dynamics
- Testing the black hole hypothesis
  - BH no-hair theorem, horizon structure, echoes, ...
- New fields and novel compact objects
  - ultra-light bosonic fields, axions, boson stars, extremely compact objects
- Primordial stochastic backgrounds
  - early universe phase transitions, cosmic strings, etc.



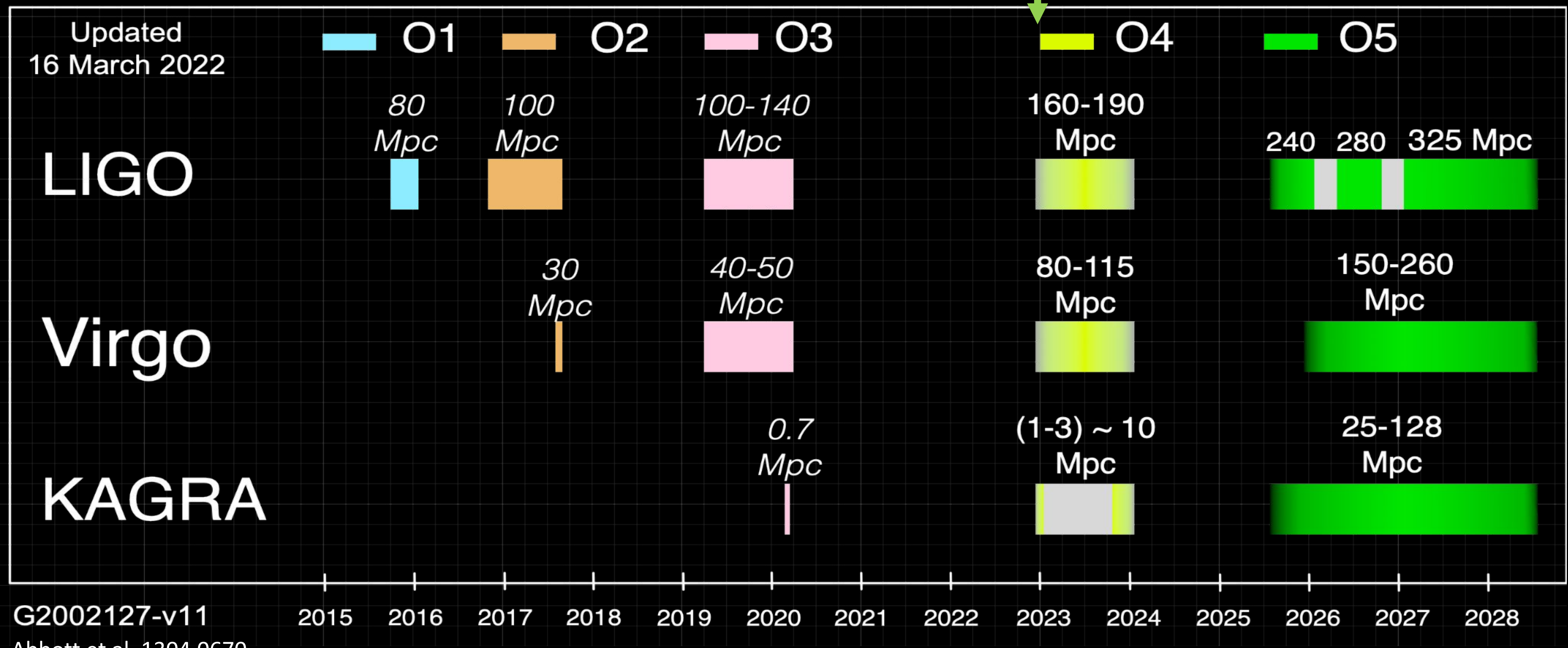
Some Key References



https://dcc.cosmicexplorer.org/
https://apps.et-gw.eu/tds/ql/?c=15418
V. Kalgera et al., 2111.06990
M. Maggiore et al. 1912.02622
B. P. Abbott et al., 1304.0670

Future observing runs

mid-December
2022 -> March 2023



G2002127-v11
Abbott et al. 1304.0670

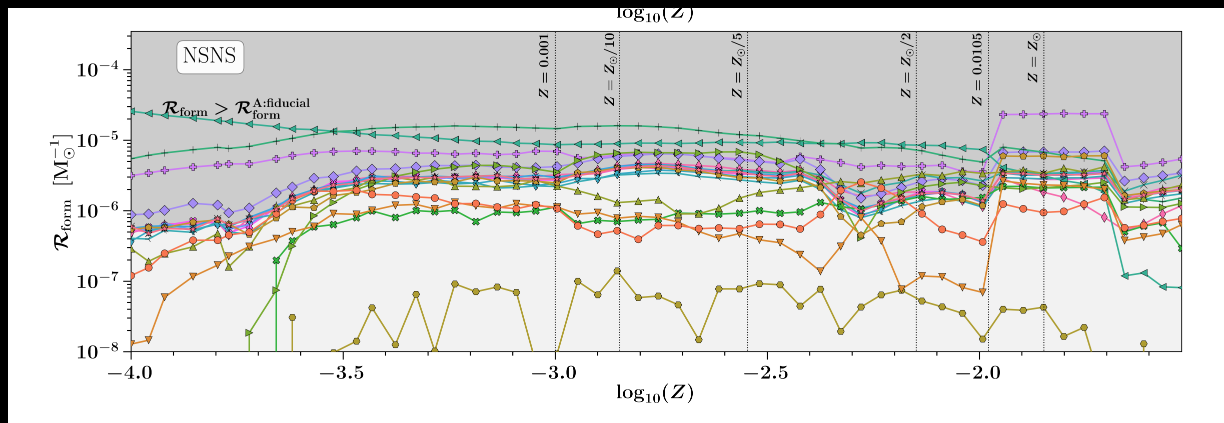
11

Exploring Binary Evolution

F. Broekgaarden et al. 2112.05763

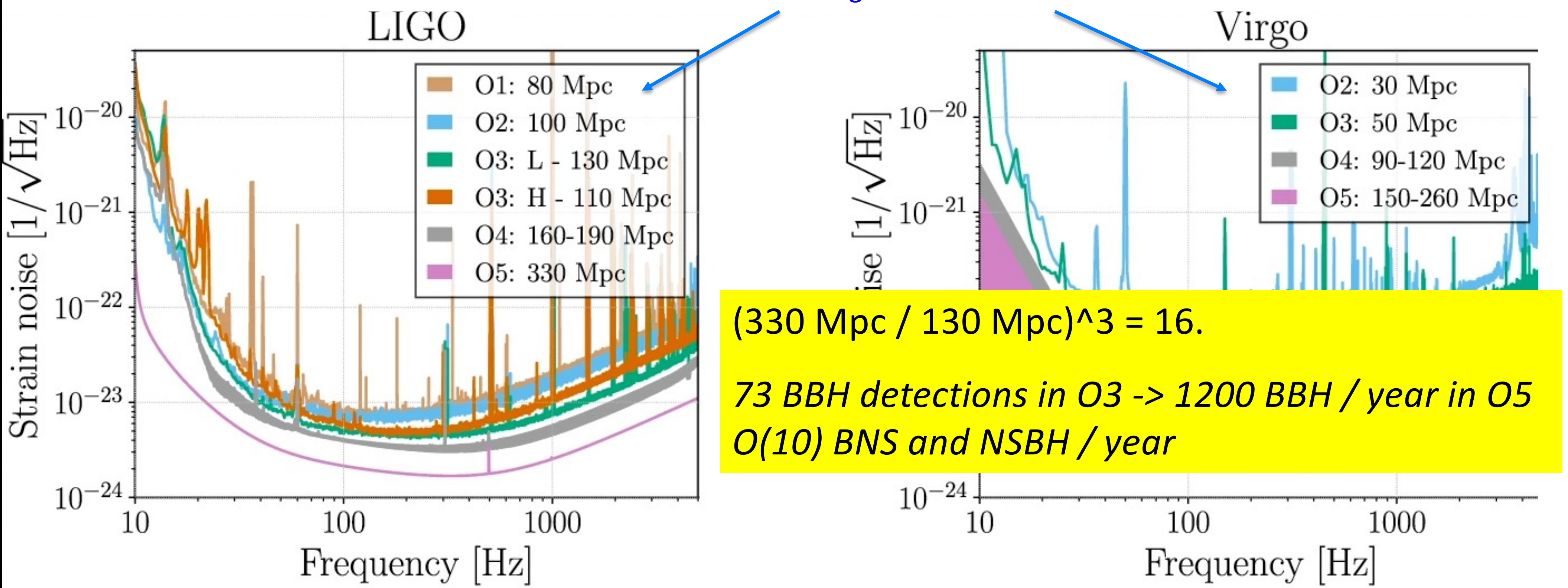
μ	Label	Variation
A	fiducial	–
B	$\beta = 0.25$	fixed mass transfer efficiency of $\beta = 0.25$
C	$\beta = 0.5$	fixed mass transfer efficiency of $\beta = 0.5$
D	$\beta = 0.75$	fixed mass transfer efficiency of $\beta = 0.75$
E	unstable/no case BB	case BB mass transfer is always unstable
F	E + K	case BB mass transfer is always unstable & HG donor stars initiating a CE may survive
G	$\alpha = 0.1$	CE efficiency parameter $\alpha = 0.1$
H	$\alpha = 0.5$	CE efficiency parameter $\alpha = 0.5$
I	$\alpha = 2$	CE efficiency parameter $\alpha = 2$
J	$\alpha = 10$	CE efficiency parameter $\alpha = 10$
K	optimistic CE	HG donor stars initiating a CE may survive
L	rapid SN	Fryer rapid SN remnant mass model
M	$m_{NS} = 2\,M_\odot$	maximum NS mass is fixed to $2\,M_\odot$
N	$m_{NS} = 3\,M_\odot$	maximum NS mass is fixed to $3\,M_\odot$
O	no PISN	no PISN and pulsational-PISN
P	$\sigma^{1D}_{rms} = 100\,km\,s^{-1}$	$\sigma^{1D}_{rms} = 100\,km\,s^{-1}$ for core-collapse SNe
Q	$\sigma^{1D}_{rms} = 30\,km\,s^{-1}$	$\sigma^{1D}_{rms} = 30\,km\,s^{-1}$ for core-collapse SNe
R	$v_{k,BH} = 0$	we assume BHs receive no natal kick
S	$f_{WR} = 0.1$	Wolf-Rayet wind factor $f_{WR} = 0.1$
T	$f_{WR} = 5$	Wolf-Rayet wind factor $f_{WR} = 5$

(20 binary stellar evolution models) ×
(metallicity-dependent star formation rate densities)
= 560 Universe realisations



Outlook for LIGO/Virgo/KAGRA/LIGO-India

average distance to which we can
detect a NS-NS merger with SNR>8

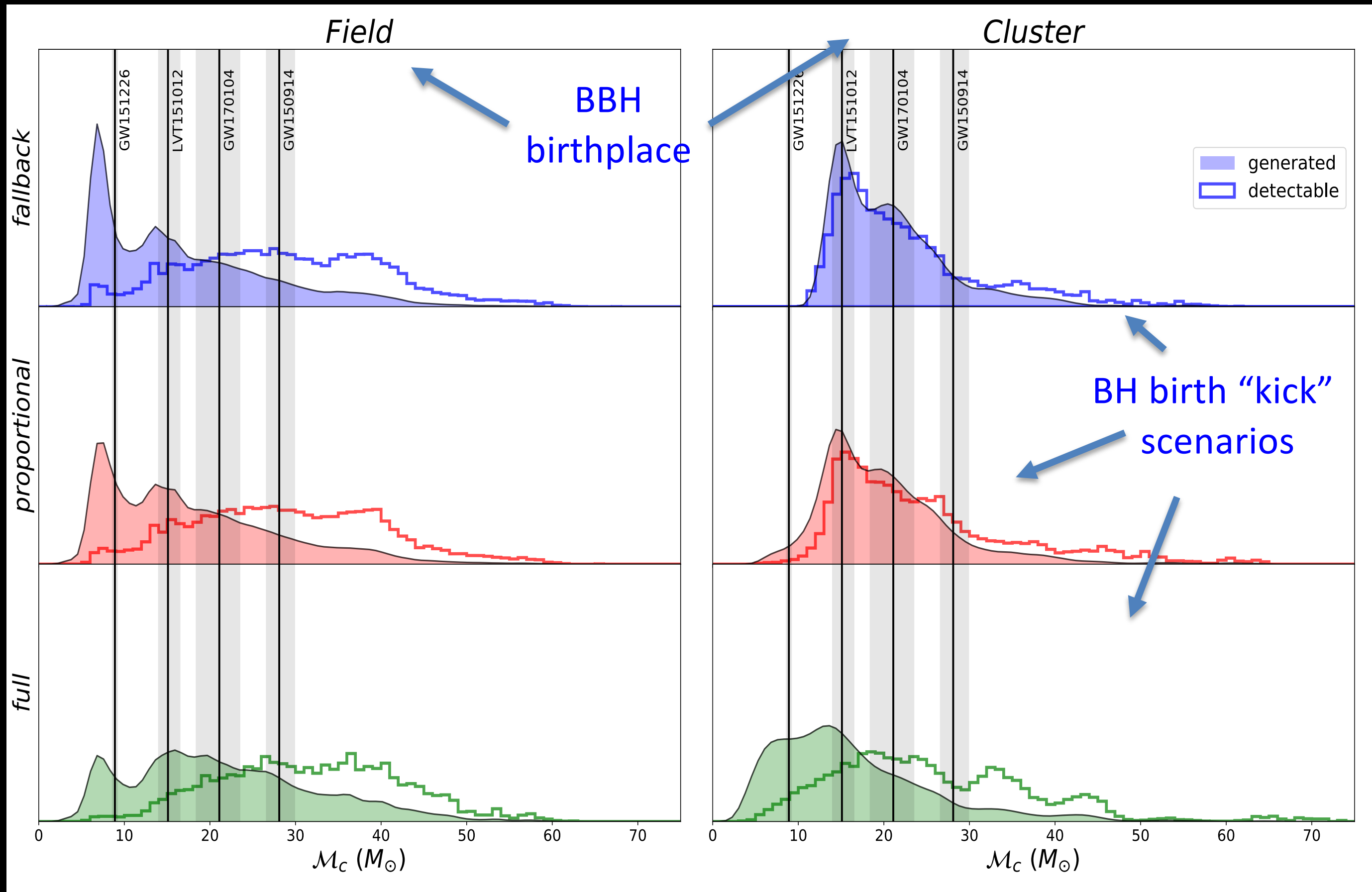


(330 Mpc / 130 Mpc)^3 = 16.

73 BBH detections in O3 -> 1200 BBH / year in O5
O(10) BNS and NSBH / year

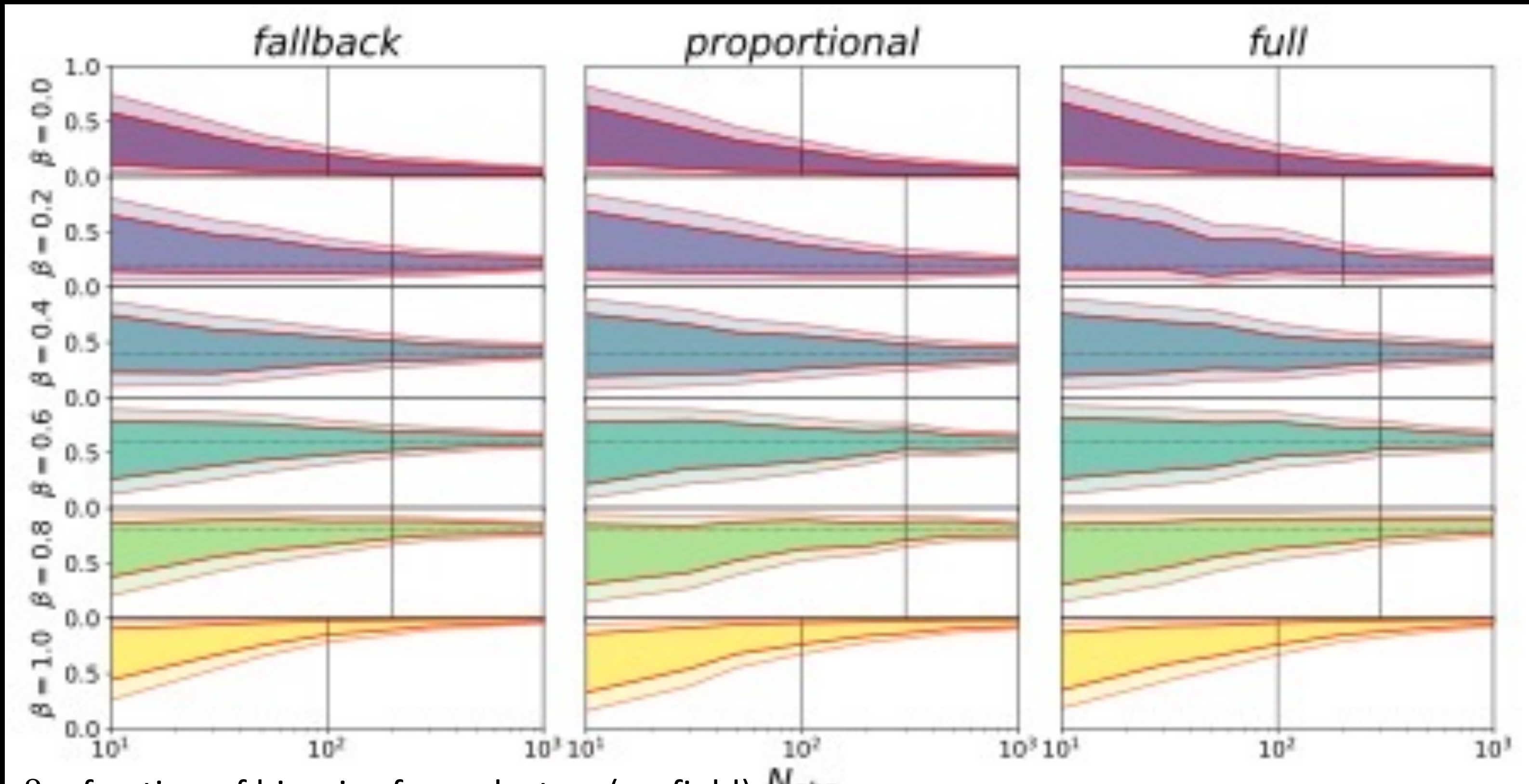
Abbott et al. 1304.0670

Constraining Binary Evolution Models



M. Zevin et al.,
Ap 846:82 (2017)

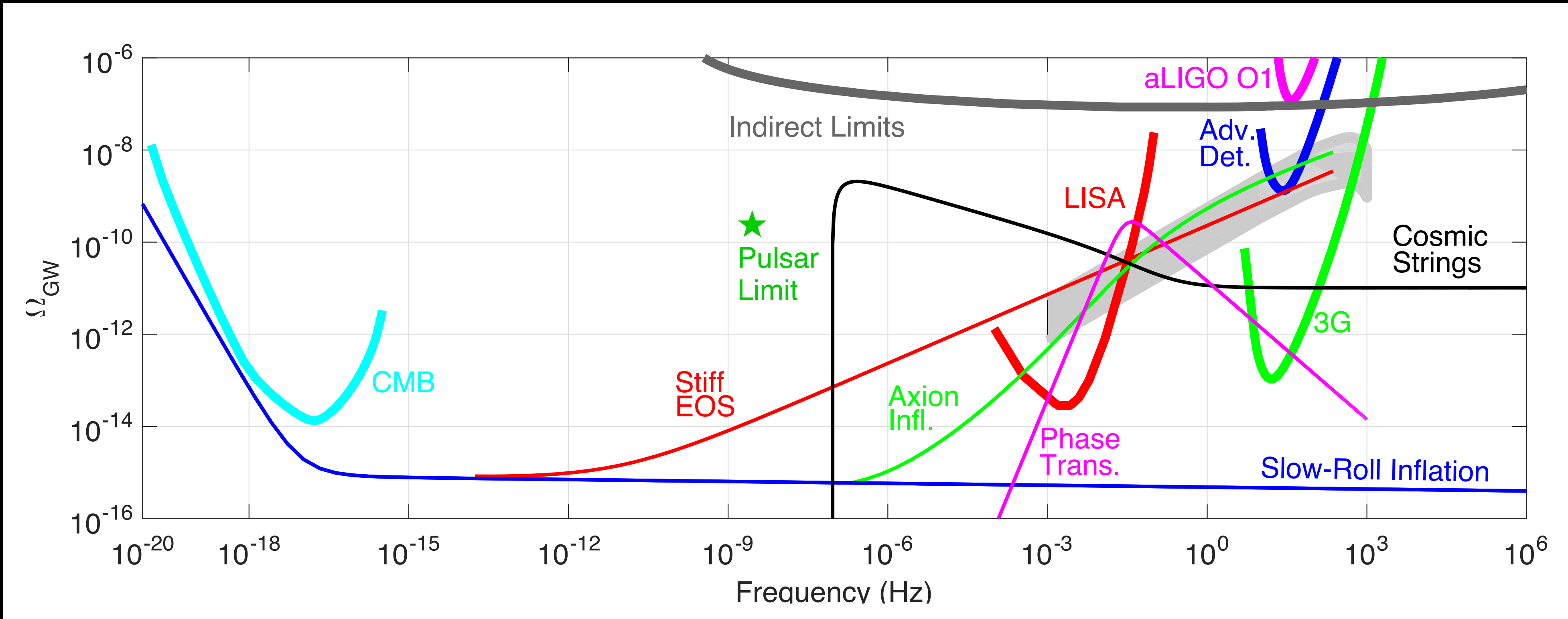
Constraining Binary Evolution Models



β = fraction of binaries from clusters (vs. field)

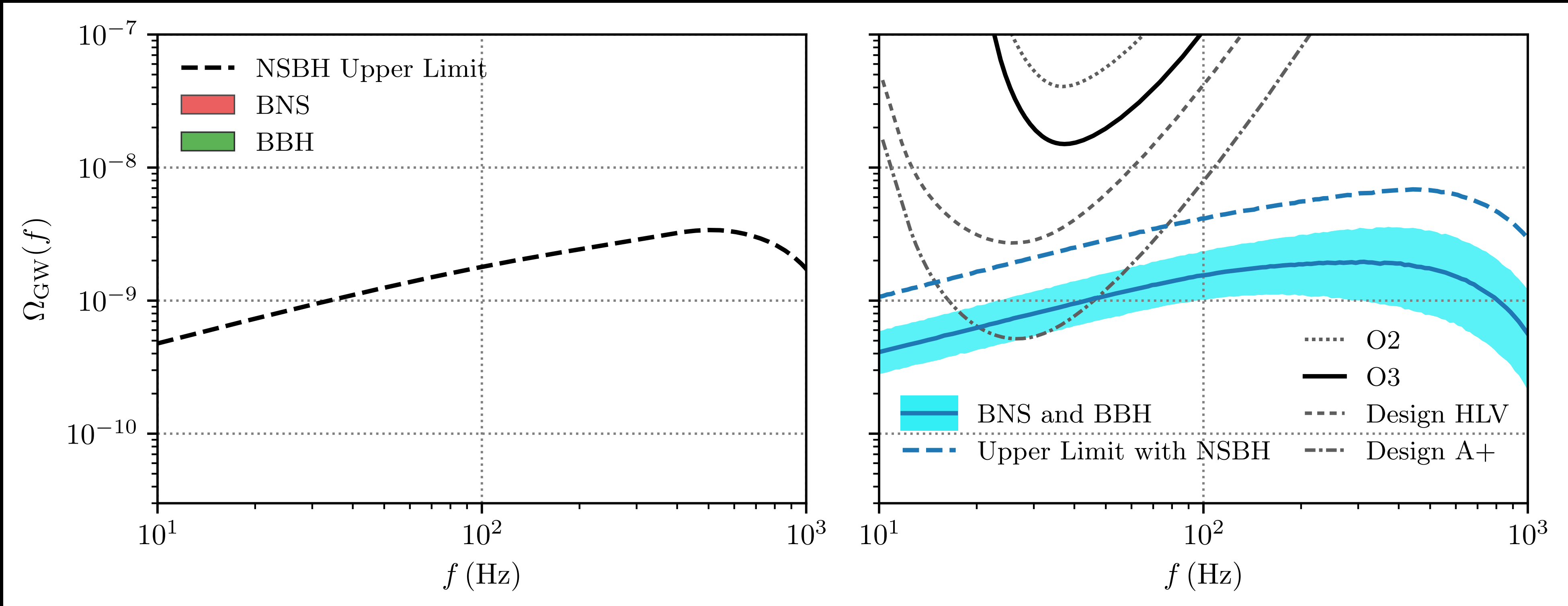
M. Zevin et al., Ap 846:82 (2017)

Stochastic Gravitational-Wave Backgrounds

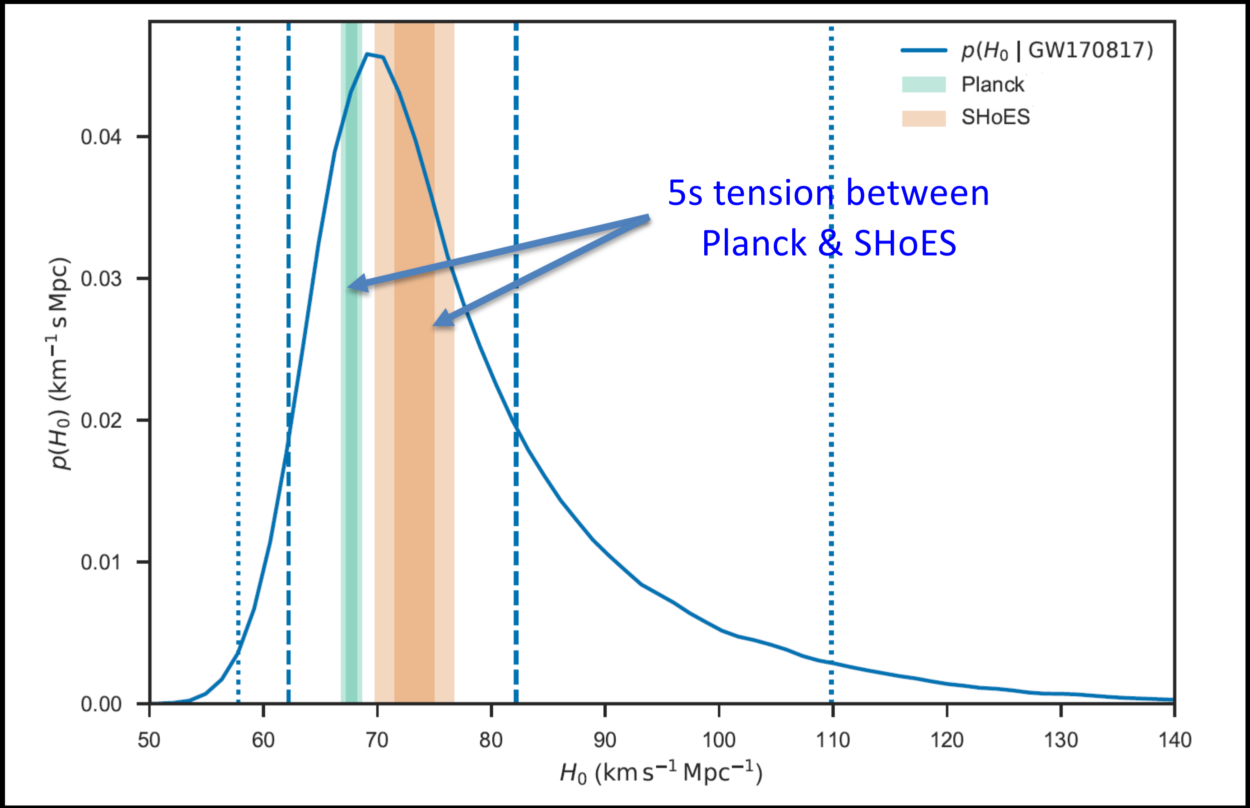


A Detectable Astrophysical Background

B. Abbott et al. Phys. Rev. D 104, 022004 (2021)

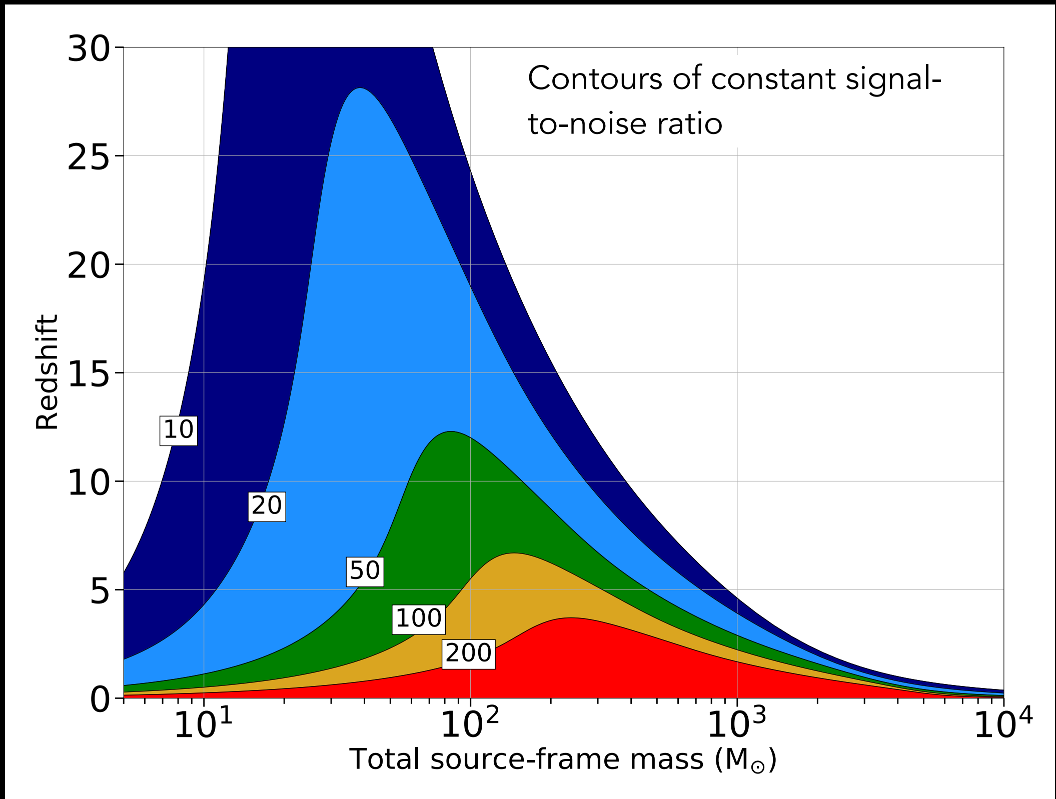


Cosmology from Third Generation Instruments

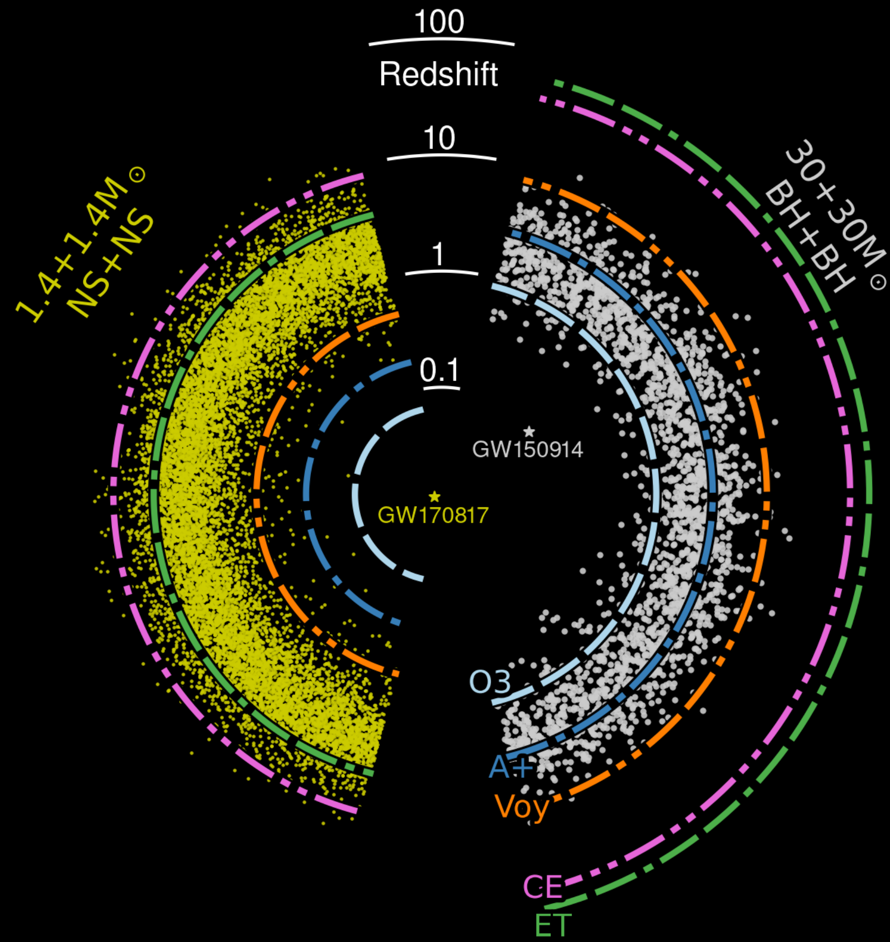


Abbott et al. Nature 551, 85 (2017)

Cosmology from Third Generation Instruments

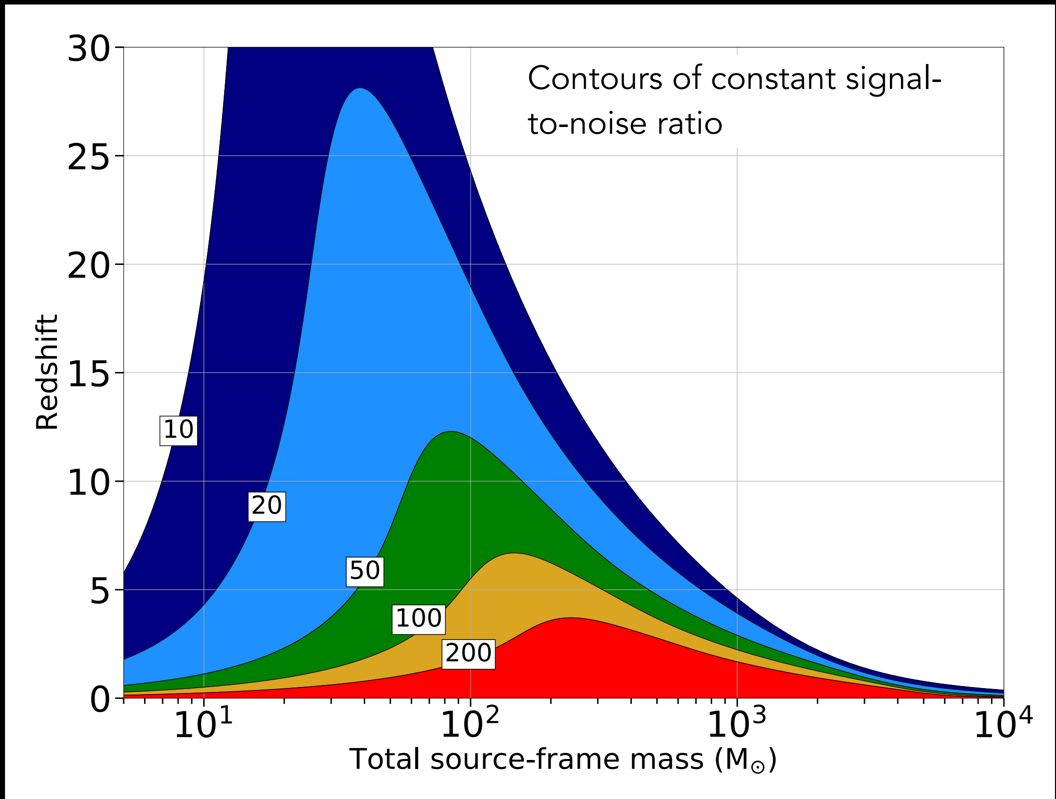


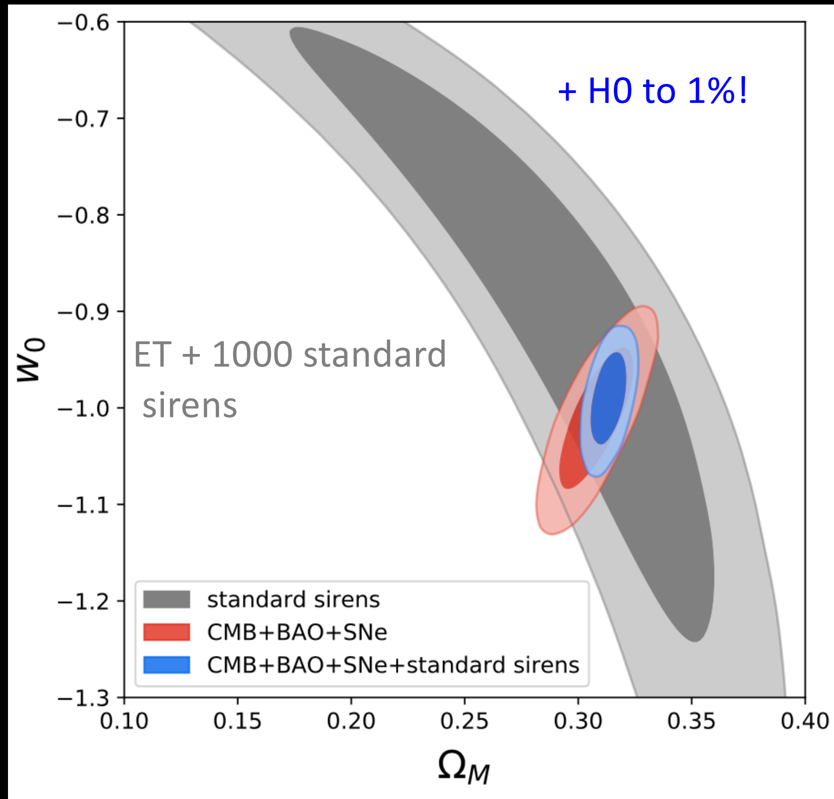
V. Kalgera et al., 2111.06990



https://dcc.cosmicexplorer.org/

Cosmology from Third Generation Instruments

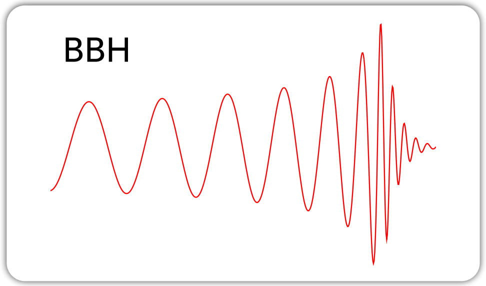




V. Kalgera et al., 2111.06990

E. Belgacem, et al., Phys. Rev. D98 (2018) 023510

Determining the Neutron Star EOS



- inspiral phase: well described by post-Newtonian approximation + tides
- post-merger bar-deformed hyper-massive neutron star

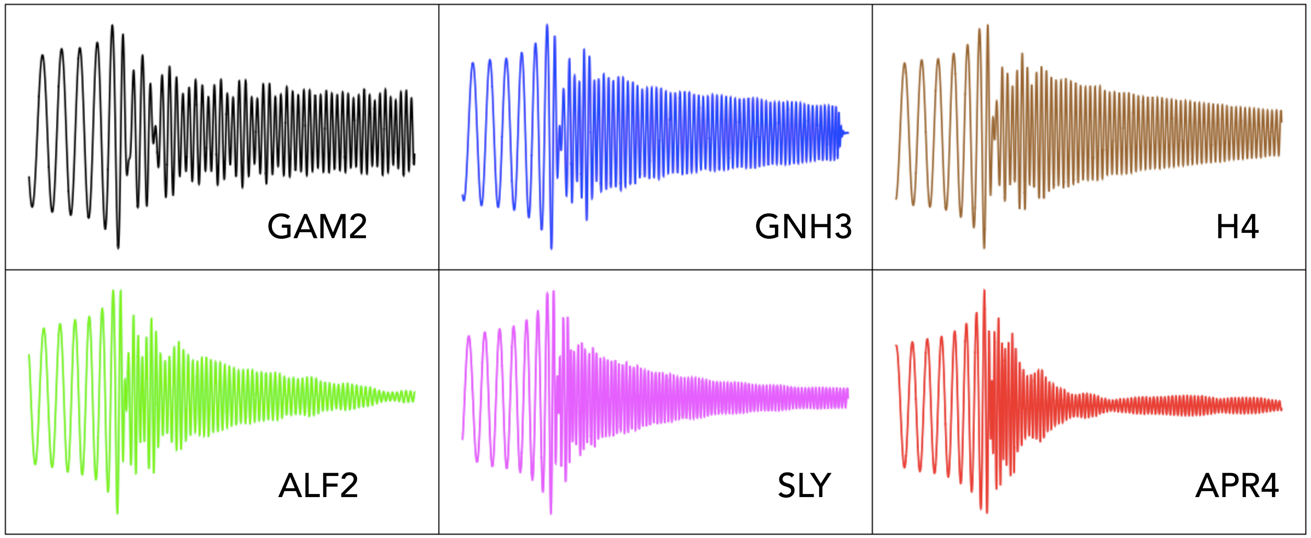
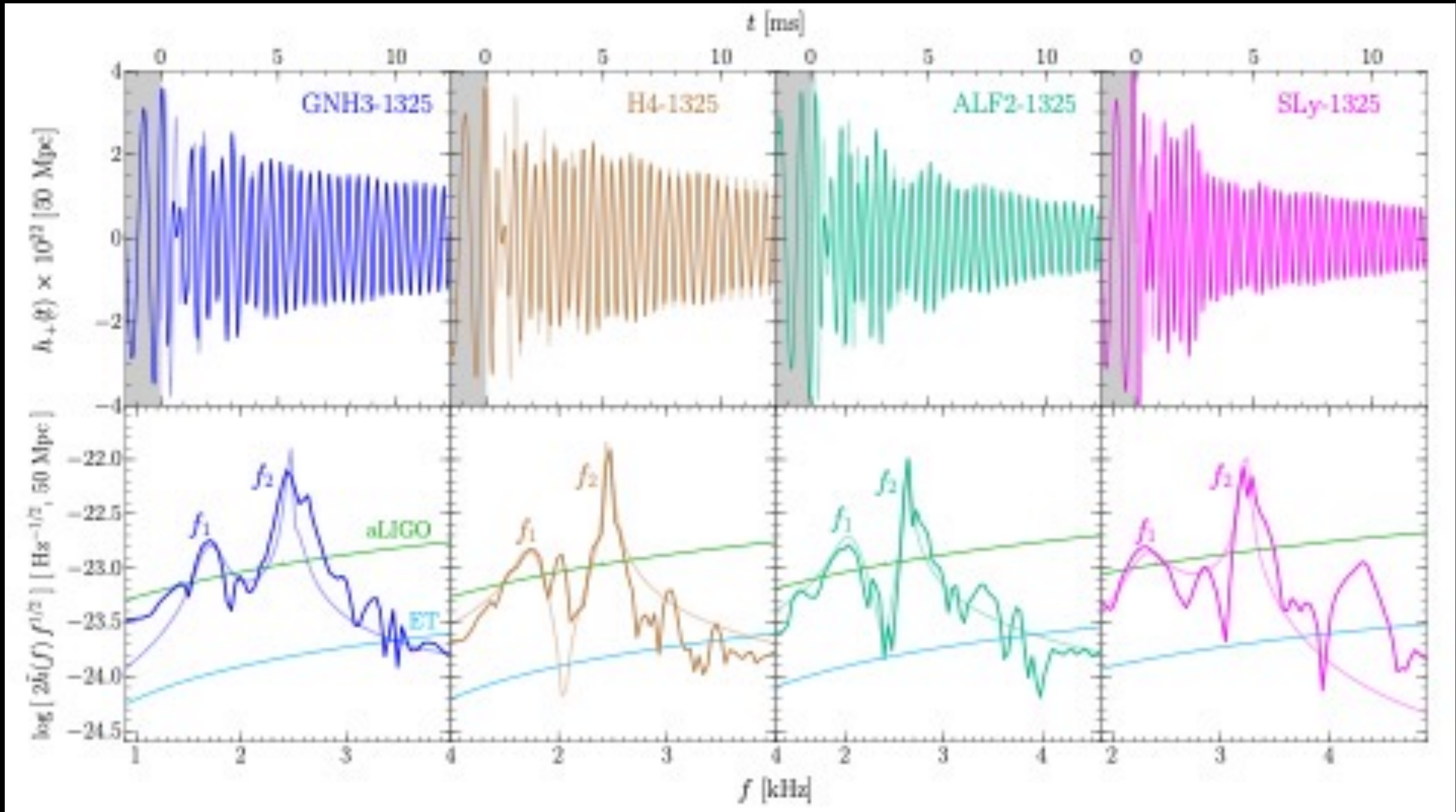


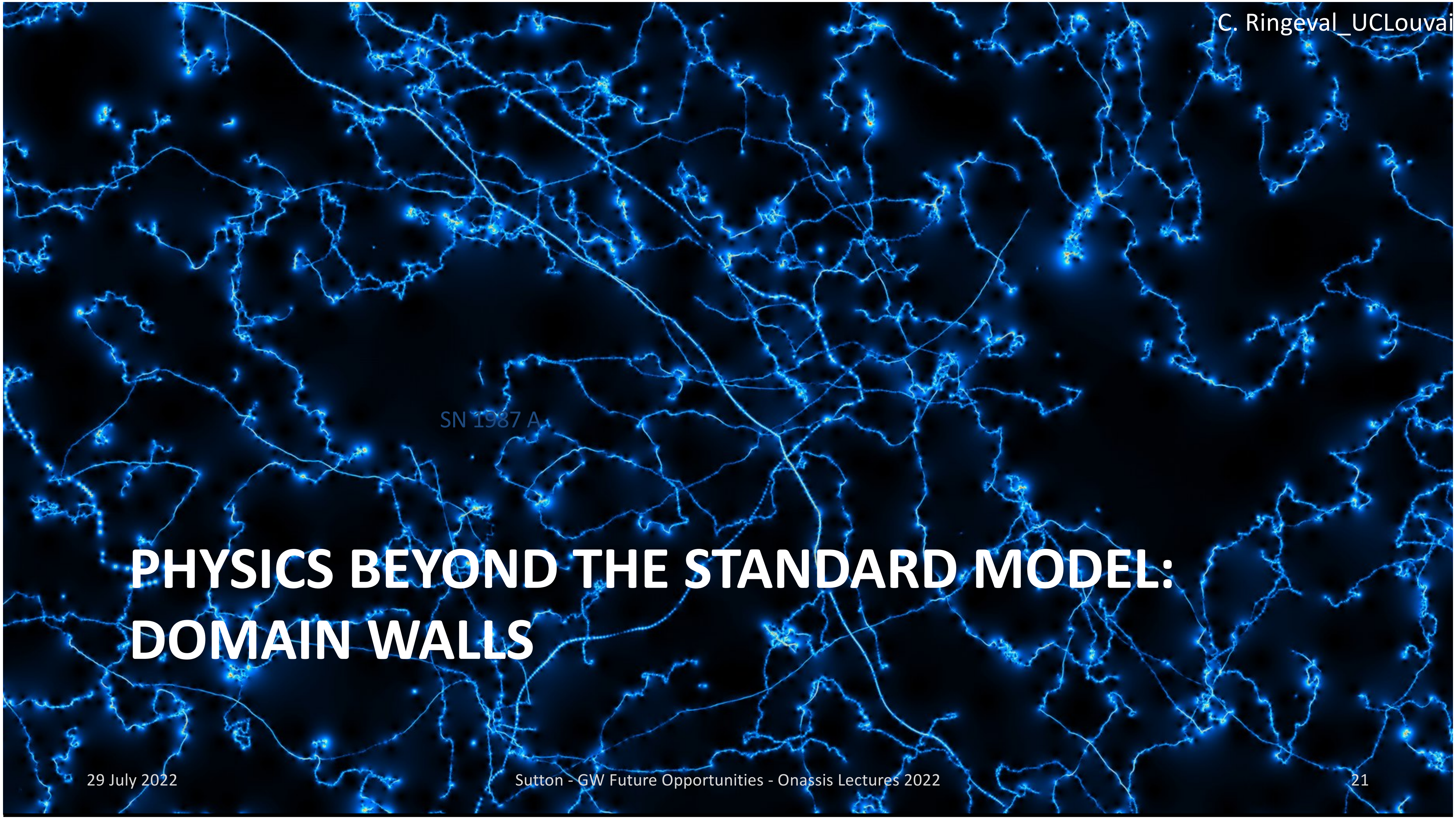
image: B. Sathyaprakash

Determining the Neutron Star EOS



Post-merger
SNR at 100 Mpc
~1 (LIGO/Virgo)
~10 (ET/CE)

S. Bose et al., Phys. Rev. Lett. 120, 031102 (2018)



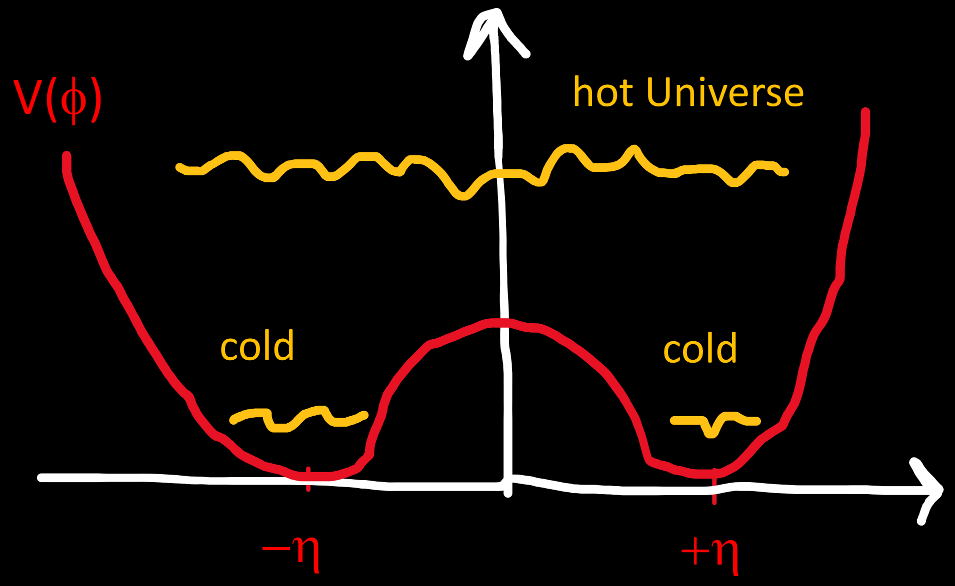
PHYSICS BEYOND THE STANDARD MODEL: DOMAIN WALLS

Searching for Domain Walls

- Assumption: there exists an undetected scalar field ϕ with "Mexican hat" like potential .

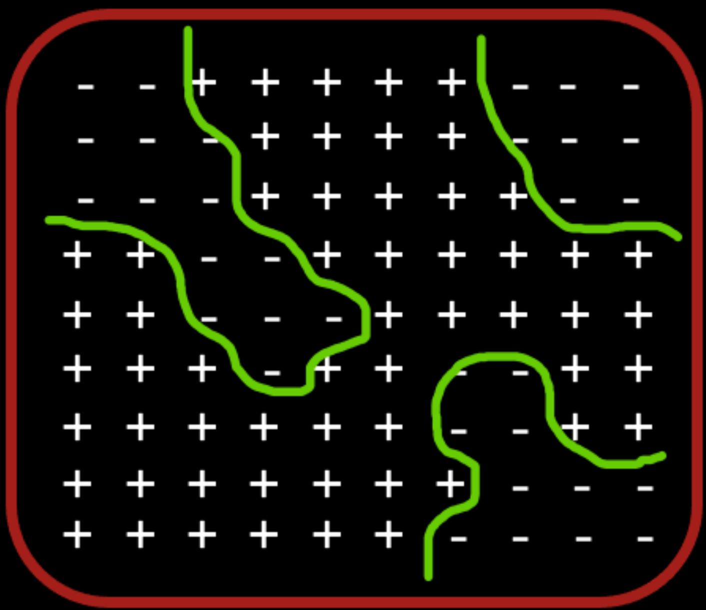
e.g.: $V \sim a - b\,\phi^2 + c\,\phi^4$

- As the early Universe cools, different regions settle into the $+\eta$ and $-\eta$ vacuum states.



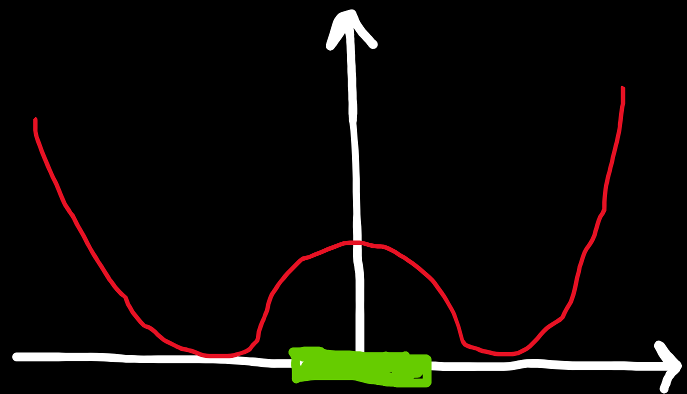
e.g. A. Vilenkin, Phys. Rep. 121, 263 (1985).

Domain Walls



“domain walls”

- The boundaries between the $+\eta$ and $-\eta$ regions have non-zero energy density: ”domain walls”.



- Proposed solution for dark matter ...

Physical effect

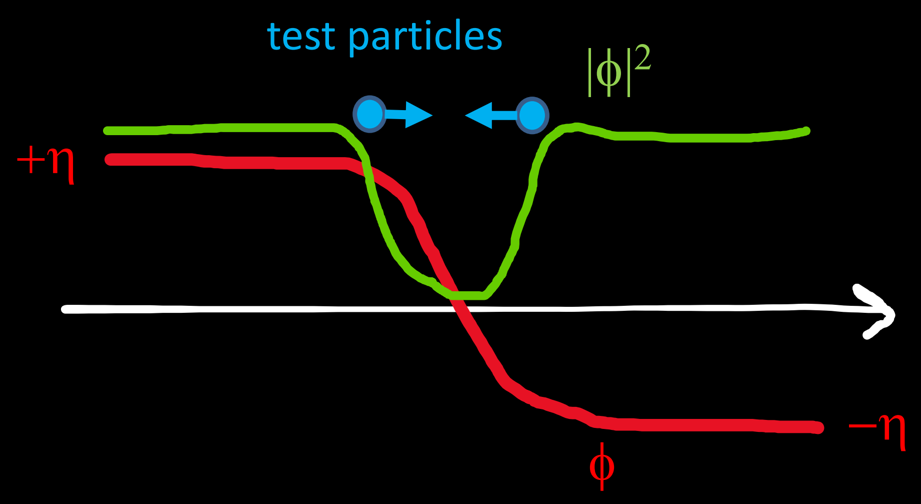
- Simplest case: scalar field affects masses of fermion particles as

$$m_f \to m_f \left[1 + \left(\frac{\phi}{\Lambda'_f}\right)^2\right]$$

coupling constant

- Test particles will "fall into" the wall as

$$\delta \boldsymbol{a}_{\text{test}} = -\frac{\boldsymbol{\nabla} M_{\text{test}}}{M_{\text{test}}}$$

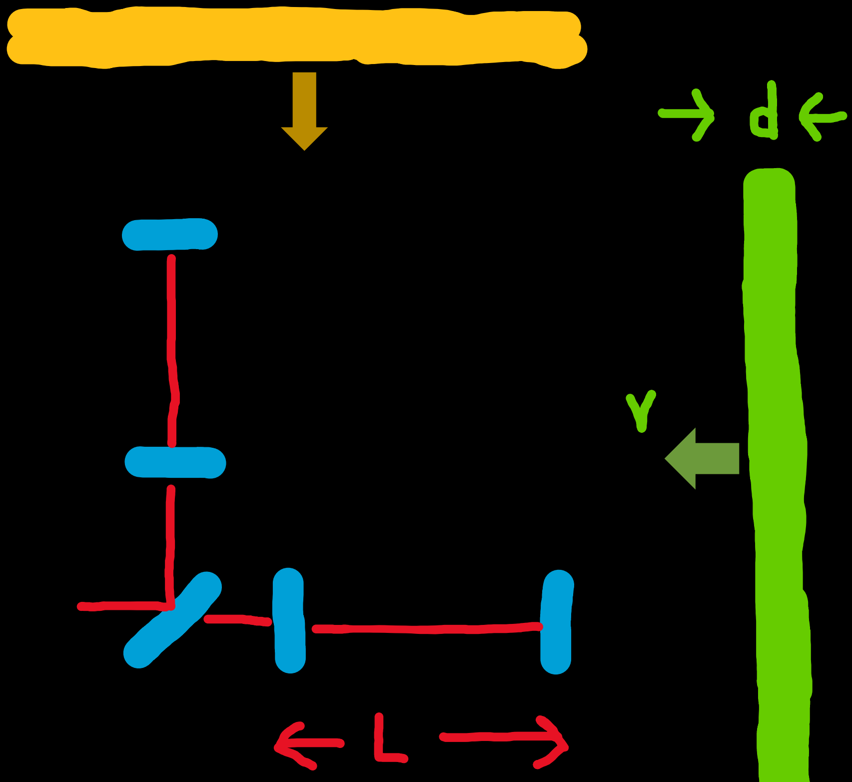


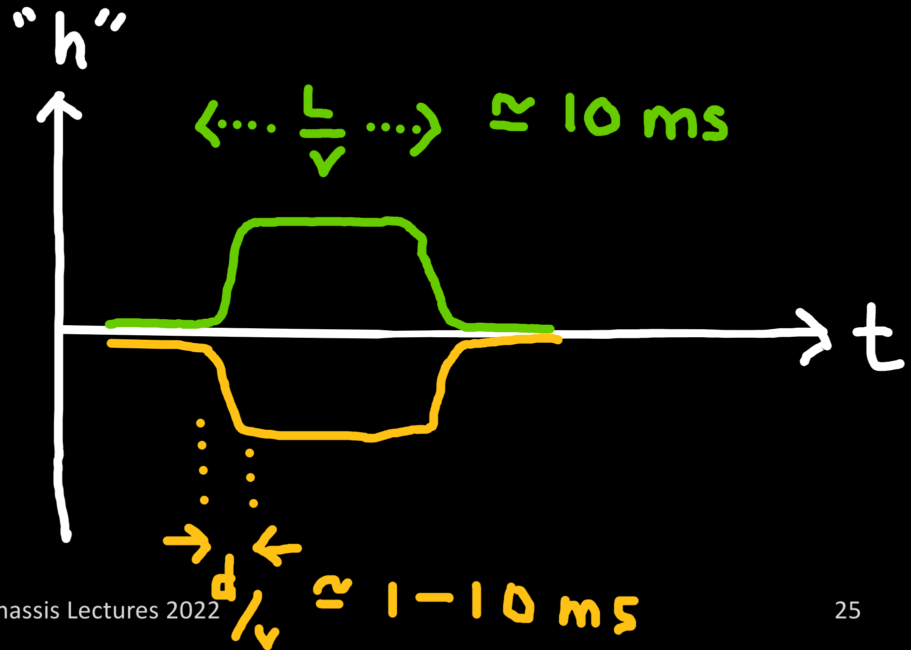
H. Grote & Y. Stadnik, Phys. Rev. Research 1, 033187 (2019)

Signal in an interferometer

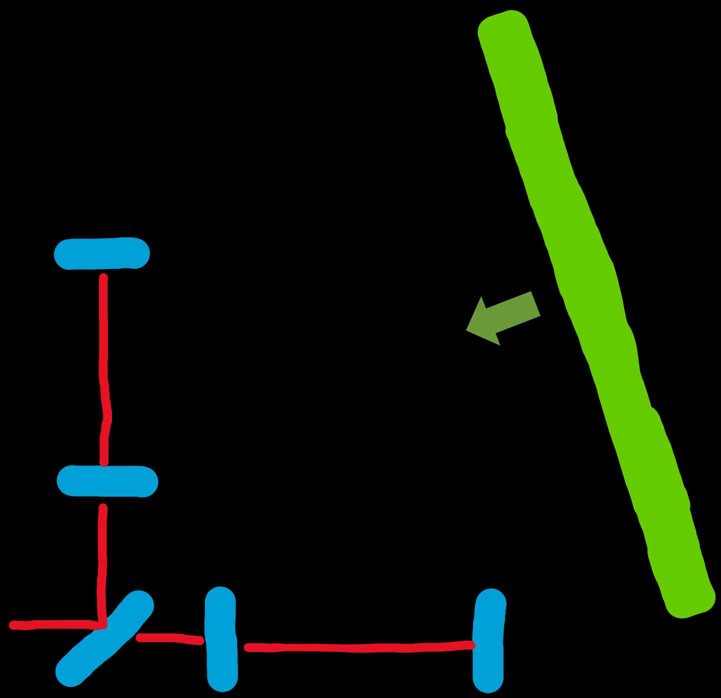
d ≲ 1 km
v ~ 300 km/s

- Typical speed ~ 300km/s (dark matter halo).
- Signal strength and morphology both depend on incident direction.





Signal in an interferometer



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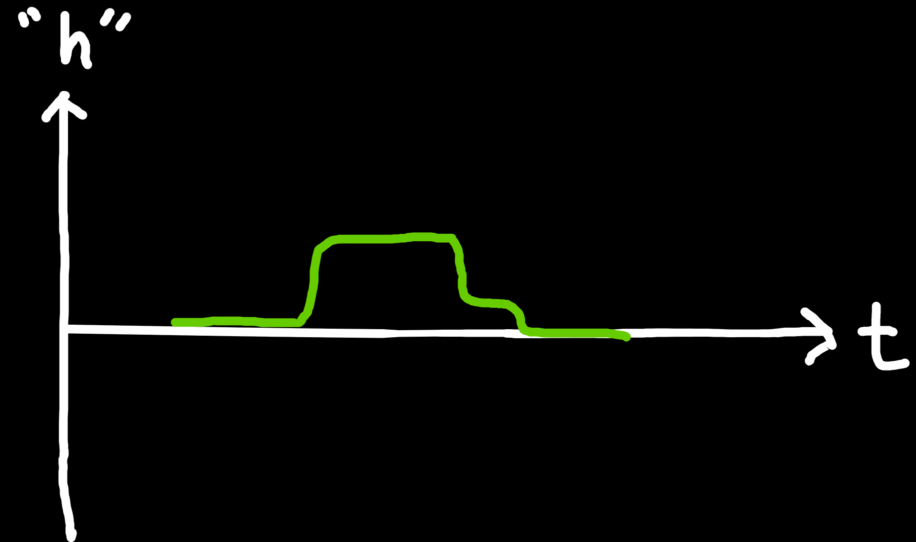
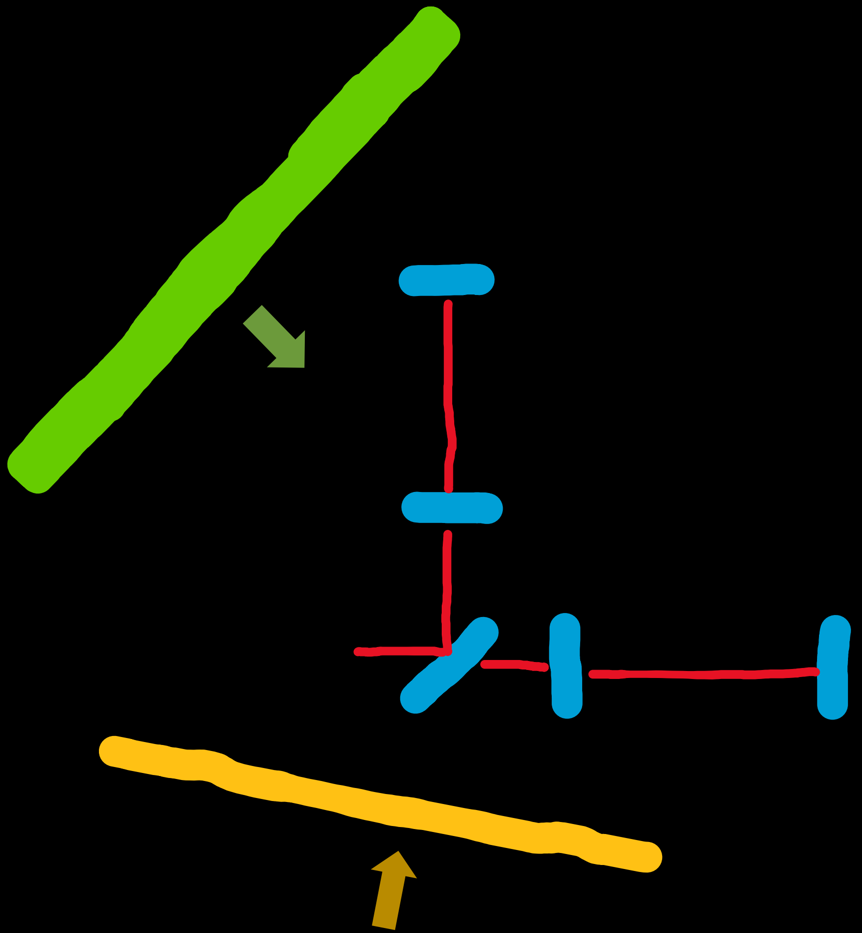


Signal in an interferometer



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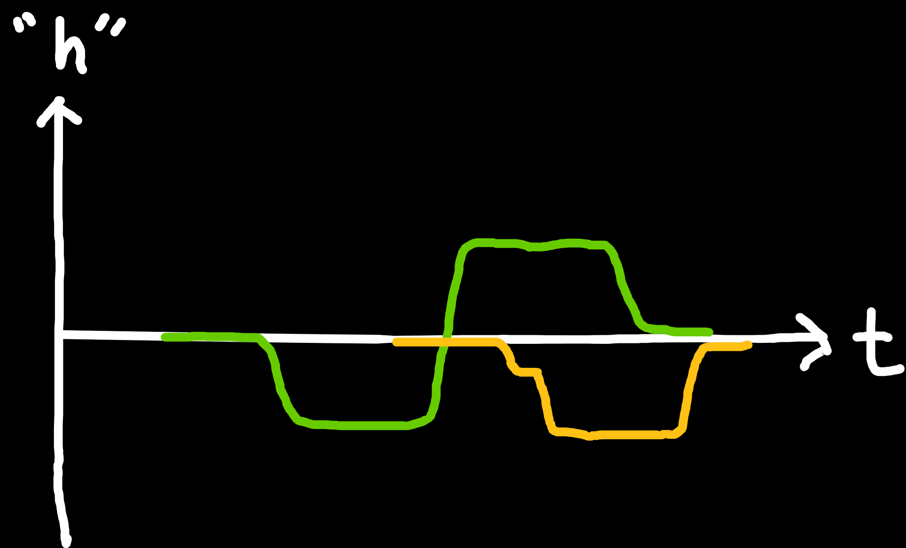
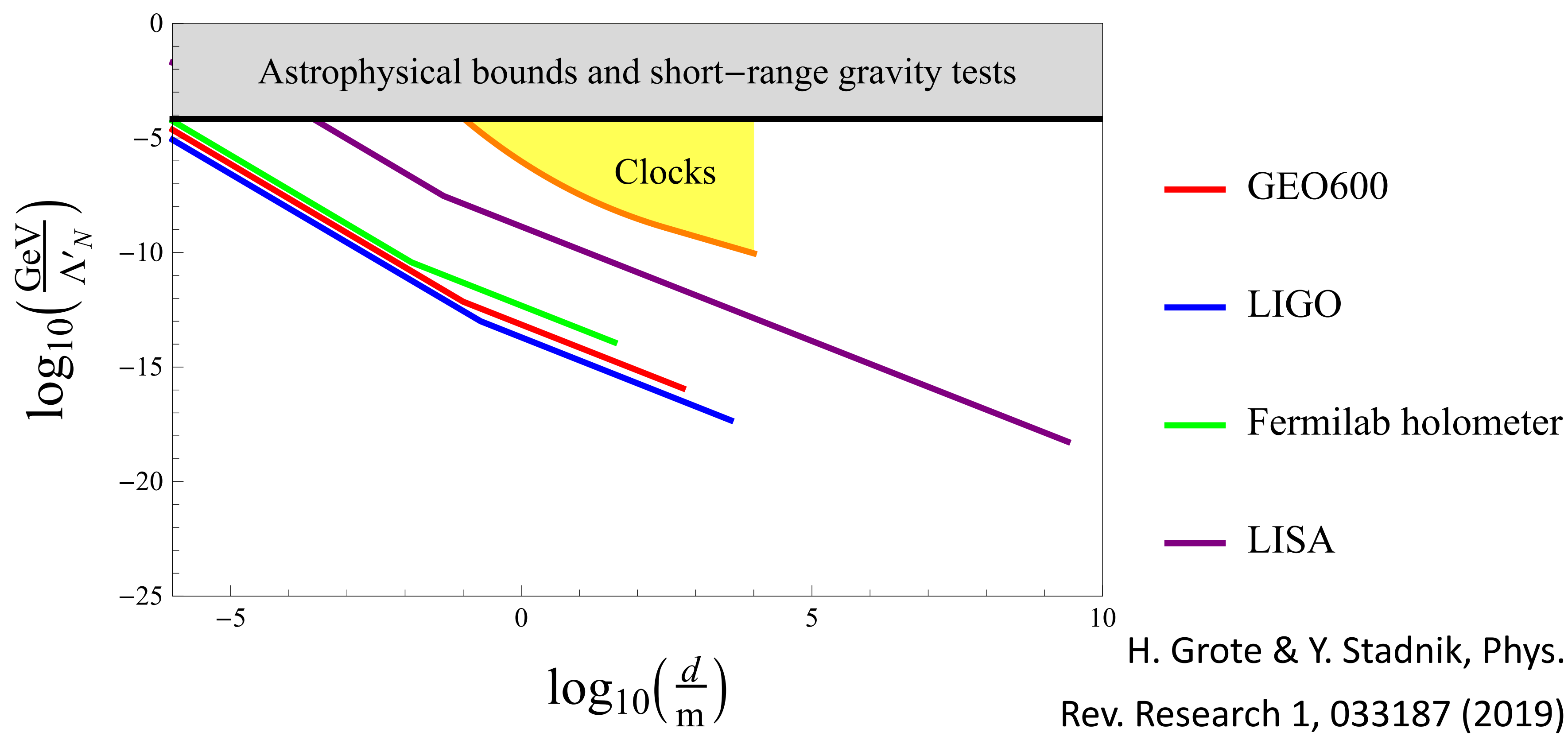


Projected Bounds



H. Grote & Y. Stadnik, Phys. Rev. Research 1, 033187 (2019)

Signal in a Network

- Typical wall speed:

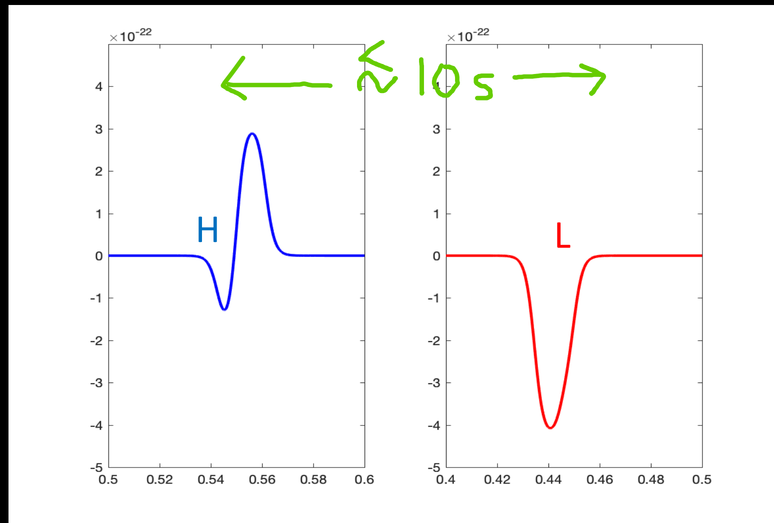
  v ~ 300 km/s ~ 0.001 c

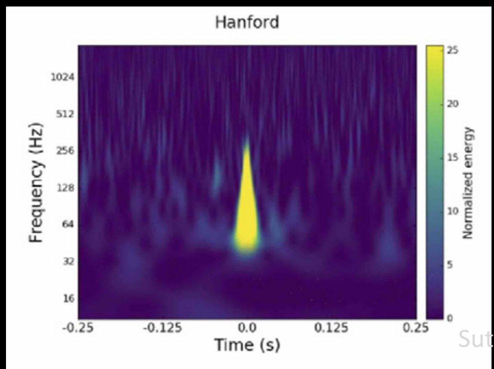
- Coincidence window:

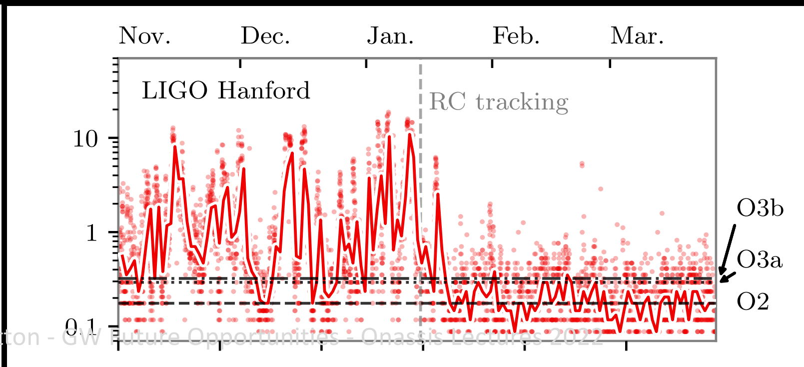
  T ~ 10 s (HL)

  T ~ 30 s (HLV)

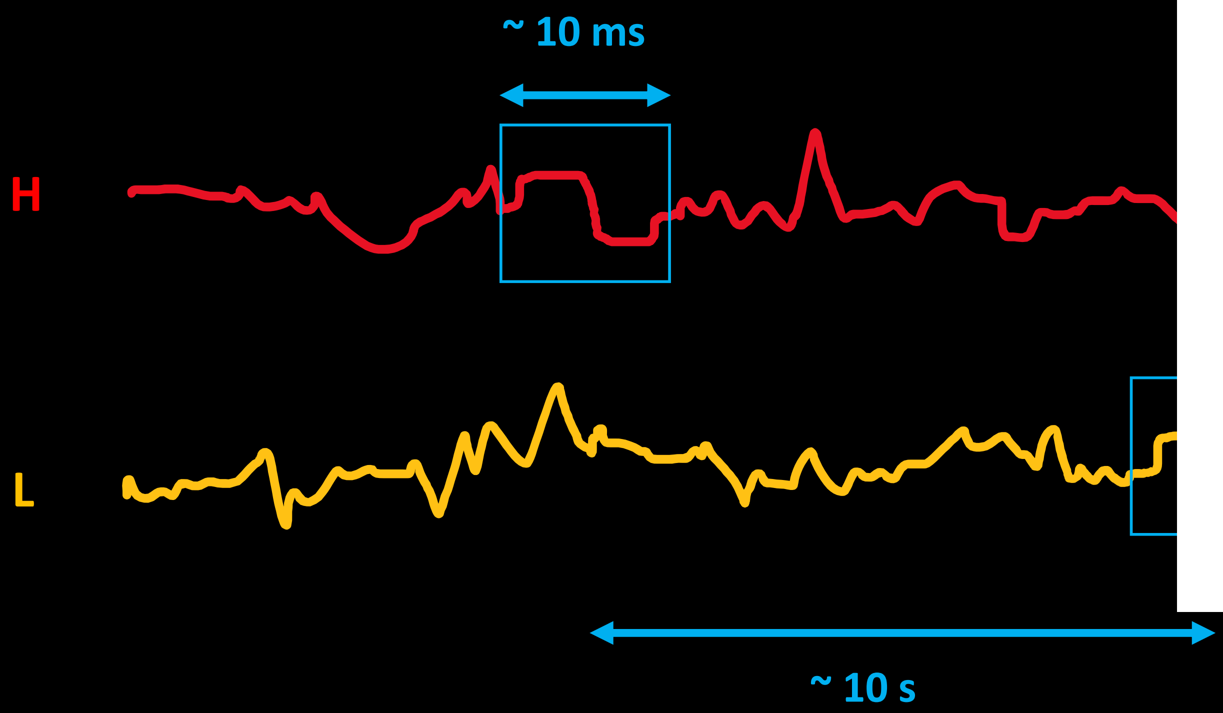
- Expect *many* coincident glitches …

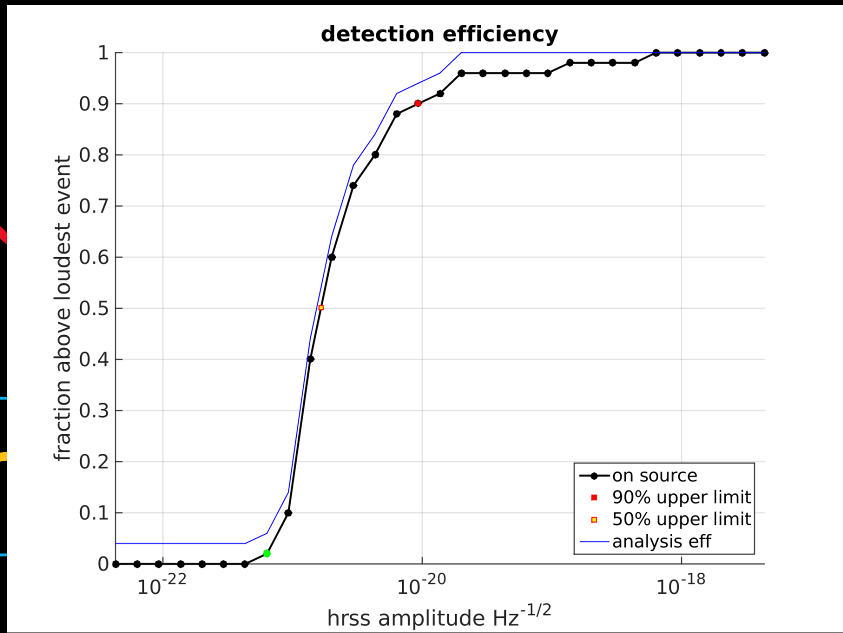






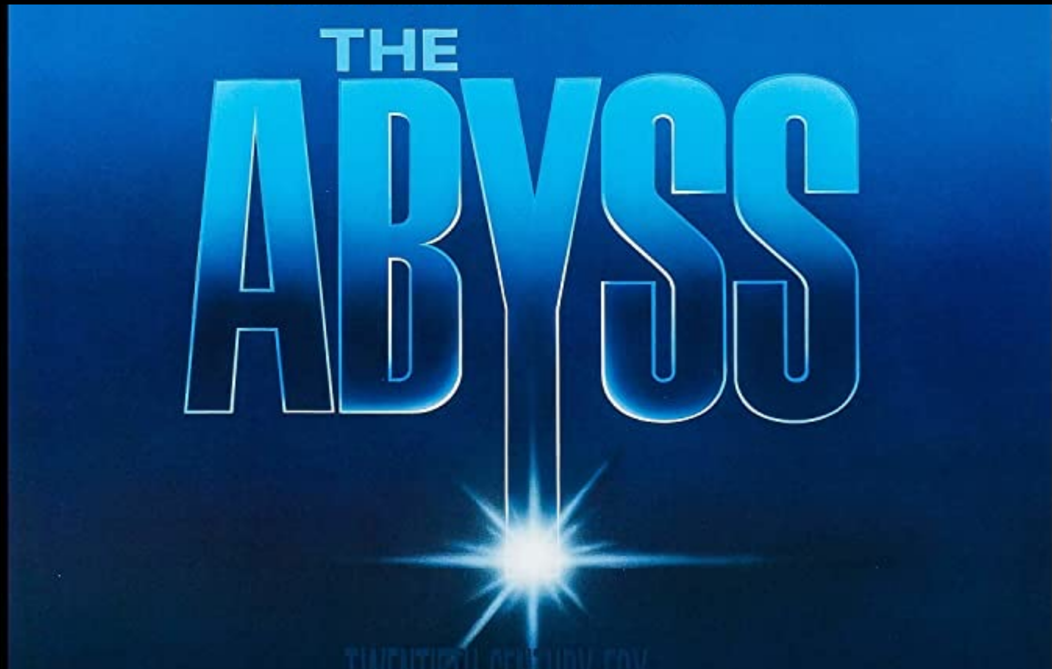
Simplest approach: cross-correlation search





H. Qi, P. Sutton, & H. Grote, in preparation

PHYSICS BEYOND THE STANDARD MODEL:
BLACK-HOLE ECHOES



THE ORIGIN OF ECHOES

Images from Abedi+ 1612.00266

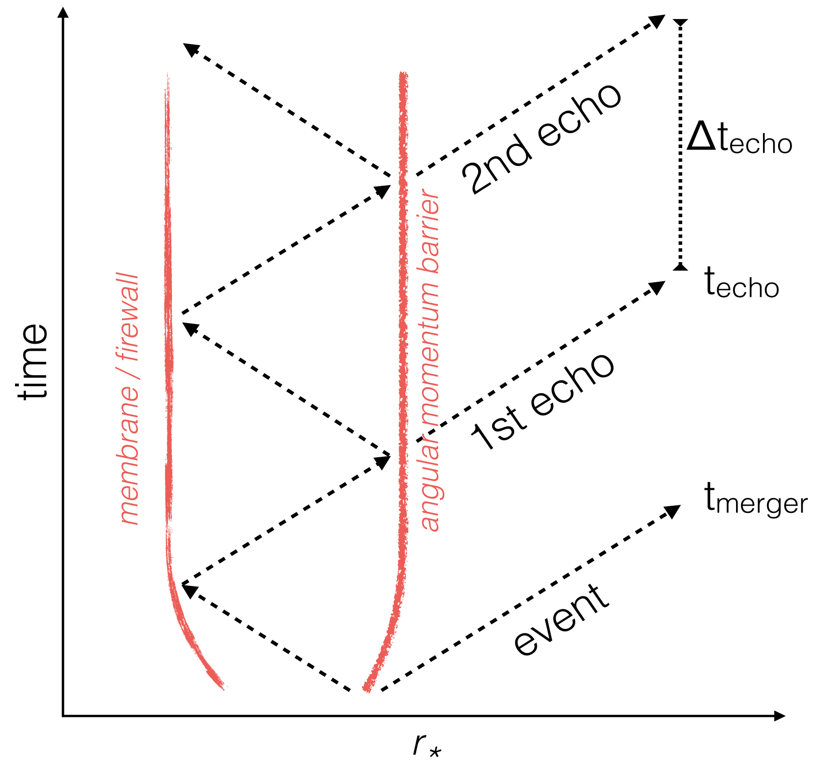
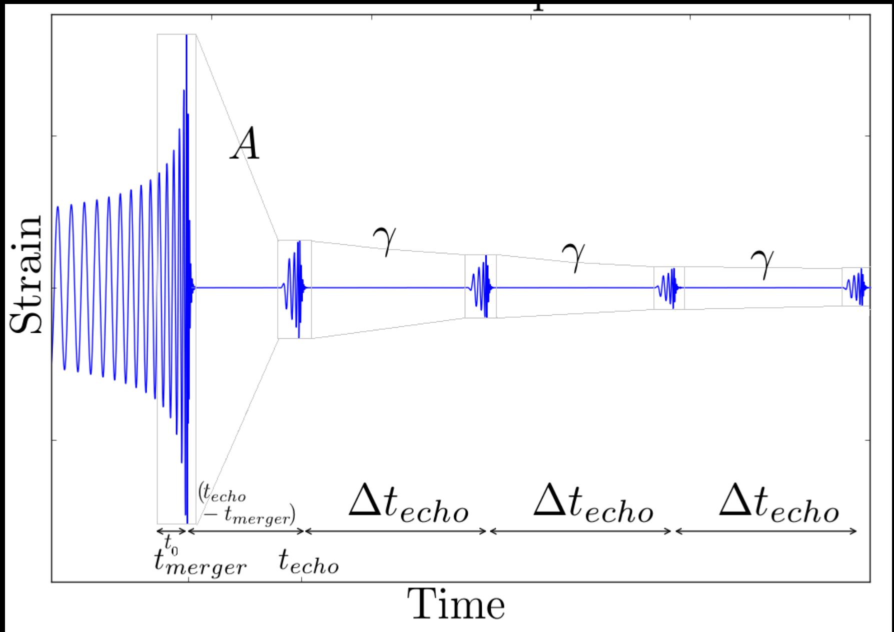


FIG. 1: Spacetime depiction of gravitational wave echoes from a membrane/firewall on the stretched horizon, following a black hole merger event.

- *"Ordinary" black holes may be replaced by Exotic Compact Objects (ECOs*
  - *fuzzballs, gravastars, fireballs …*
  - *Cardoso & Pani, Living Rev Relativ (2019) 22:4*
- *The ECO acts as a **cavity**, temporarily trapping waves between the near-horizon membrane barrier and the angular momentum barrier ("photon sphere") that exists further out.*
  - *Cardoso+ arXiv:1602.07309, Cardoso+ arXiv:1608.08637*

THE ECHO SIGNAL

Image from Westerweck+ 1712.09966



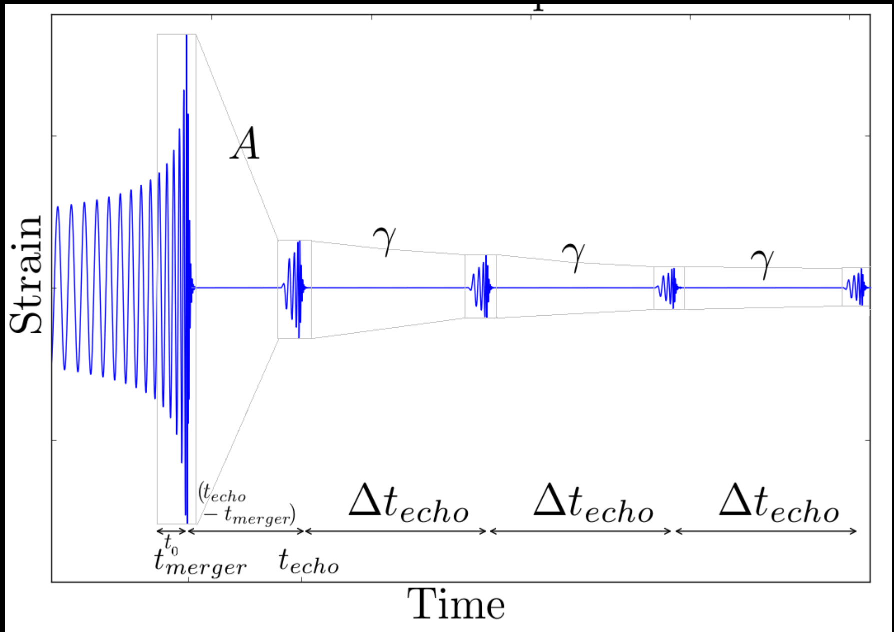
- Echoes of the late merger-ringdown
- Key parameters:
  - Amplitude A (unconstrained).
  - Decay parameter: $0 < \gamma < 1$. Expect γ <~ 1
Wang+ 1803.02845, Correia+ 1802.07735
  - Echo repeat time Δt_{echo}:

$$\Delta t_{echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a^2}}\right) \times \ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right)$$

$$\simeq 0.126 \text{ sec} \left(\frac{M_{\rm BH}}{67\ M_\odot}\right)\left(1+\frac{1}{\sqrt{1-a^2}}\right),$$

THE ECHO REPEAT TIME

Image from Westerweck+ 1712.09966



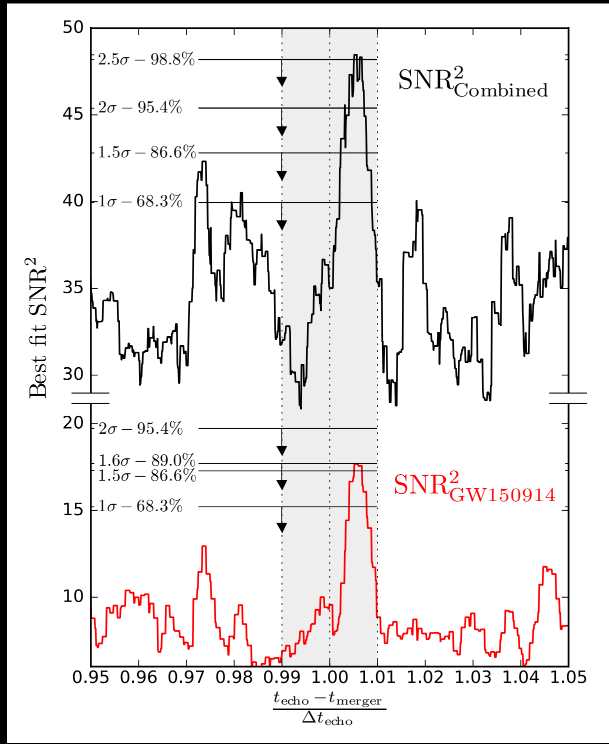
- Uncertainties:
  - Moving barrier from L_{Planck} outside horizon to x10 changes Δt_{echo} by < 1%
  - t_{echo}-t_{merger} = Δt_{echo} +/- ~ 1%
  - *QNM content uncertain but temporal (repeating) structure well-constrained.*

$$\Delta t_{echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a^2}}\right)\times \ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right)$$
$$\simeq 0.126 \text{ sec}\left(\frac{M_{\rm BH}}{67\ M_\odot}\right)\left(1+\frac{1}{\sqrt{1-a^2}}\right),$$

TENTATIVE DETECTIONS OF ECHOES

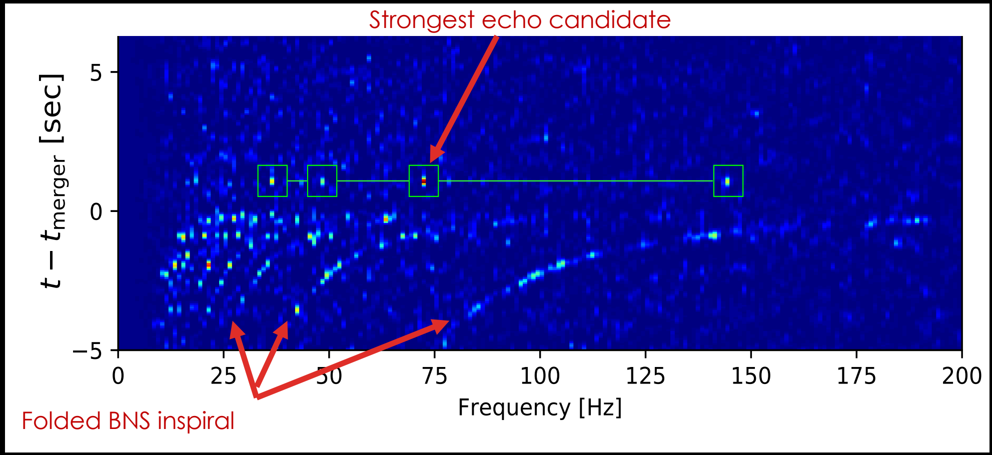
- First evidence: **Abedi+ 1612.00266**
  - Analysed O1 BBHs with a matched-filter search
  - Combined analysis found signal with false-alarm probability **p=0.011**
  - **Caveats:** see Westerweck+ 1712.09966

- **Conklin+ 1712.06517**: Model ~agnostic approach: using folded spectograms multiplied across detectors.
  - Found echoes for 5 BBHs with p ~ 0.2% -- 4%.
  - Δt_{echo} values shorter than Abedi+.



THE BNS EVENT GW170817

- Abedi & Afshordi 1803.10454 adapted the model-agnotic approach of Conklin+ 1712.06517 (folded spectograms multiplied across detectors).
- Results:
  - Δt_{echo} = 0.014s (f_{peak} = 72Hz)
  - p = 1.6e-5 (4.2σ)
  - Contrast with Conklin+: Δt_{echo} = 0.007s, p ~ 1%



Folded correlation spectrogram from 1803.10454

CONTRA-INDICATIONS

- Uchikata+ 1906.00838: More sophisticated matched-filter search using templates constructed from numerical solutions to the Teukolsky equations.
  - No significant events were found.
- Tsang 1906.11168: Apply BayesWave signal-reconstruction algorithm to O1 & O2 events.
  - No significant events were found.

Uchikata+ p values

	Data version	
Event	C01	C02
GW150914	0.992	0.984
GW151012	0.646	0.882
GW151226	0.276	-
GW170104	0.717	0.677
GW170608	-	0.488
GW170729	-	0.575
GW170814	-	0.472
GW170818	-	0.976
GW170823	-	0.315
Total	0.976	0.921

FUTURE OPPORTUNITIES: MANY TOPICS!

- Multi-messenger astronomy
  - sites of r-process heavy element production, BNS vs NSBH, etc.
- Equation of state of dense nuclear matter
  - size of neutron stars; are there phase transitions beyond nucleons?
- Cosmology with standard sirens
  - Hubble parameter, dark energy equation of state and its variation with redshift
- Strong field tests of general relativity
  - binary black hole orbital dynamics
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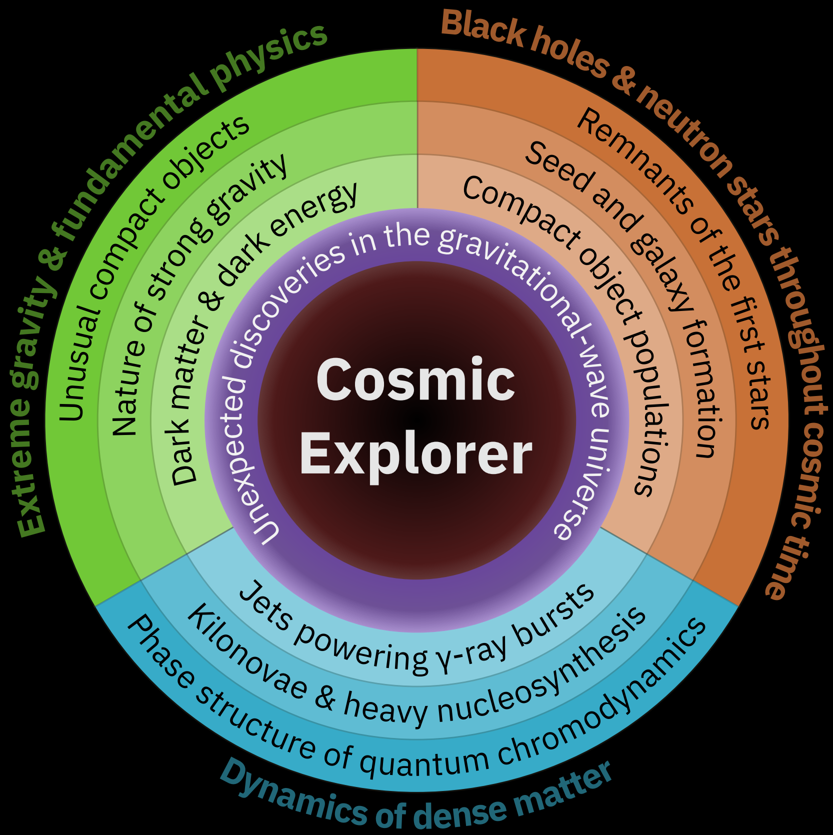

Thank You!!

- Prof. Barry Barish
- Prof. Yannis Papamastorakis
- & Eleftheria!