Future GW Detectors, and Other GW Sources

ACFI Workshop, Oct 2022

Meg Millhouse

Georgia Tech

Outline

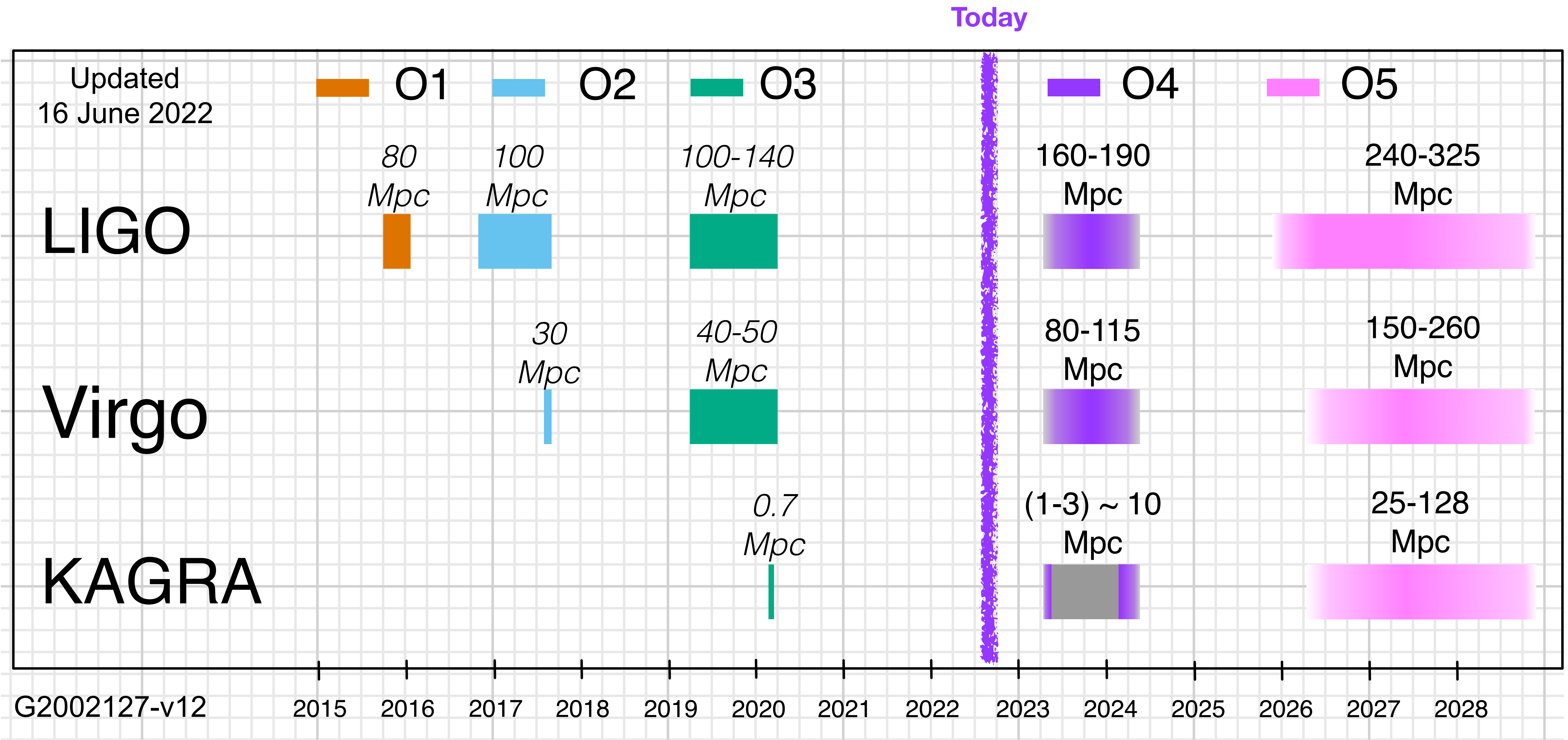
- Near and far(ish) future of ground-based GW detectors
  - A+
  - Cosmic Explorer and Einstein Telescope
  - High frequency detector
- NSs as GW sources beyond inspirals
  - F-modes, continuous gravitational waves

Future of NS GW detections

- Summary of previous talks this week:
  - To learn more about NS interiors, we will need **more** detections, and **higher SNR** detections
  - Upgraded detectors can help solve both of these issues

Near future

O4 BNS
Detections:
~ 7

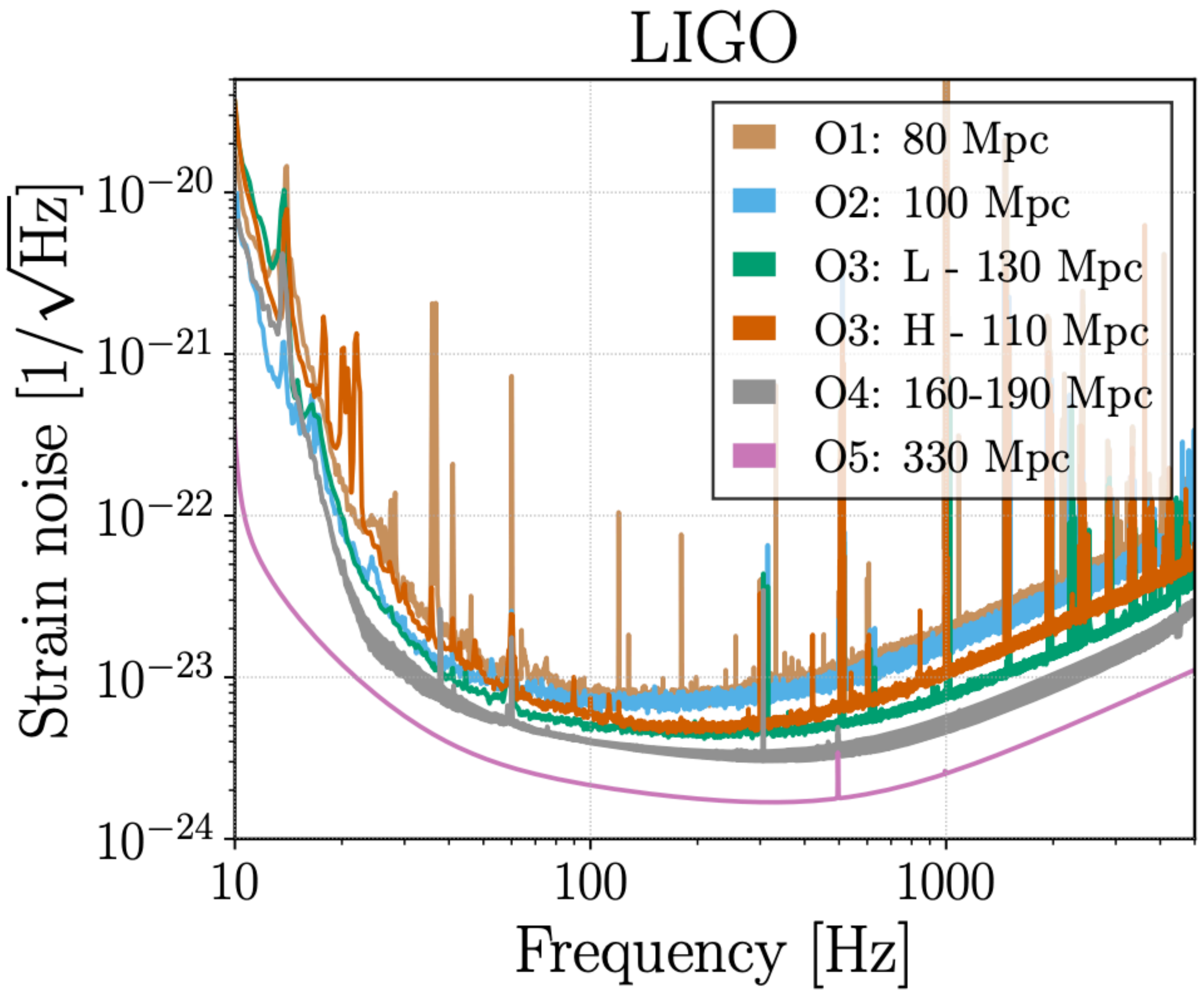


LVK, Living Reviews in Relativity 23, 3 (2020)

Future of current detector sites

LIGO A+ and AdV+

- Upgrades to current LIGO and Virgo sites
- Late 2020s
- Funded, minimal technology risk



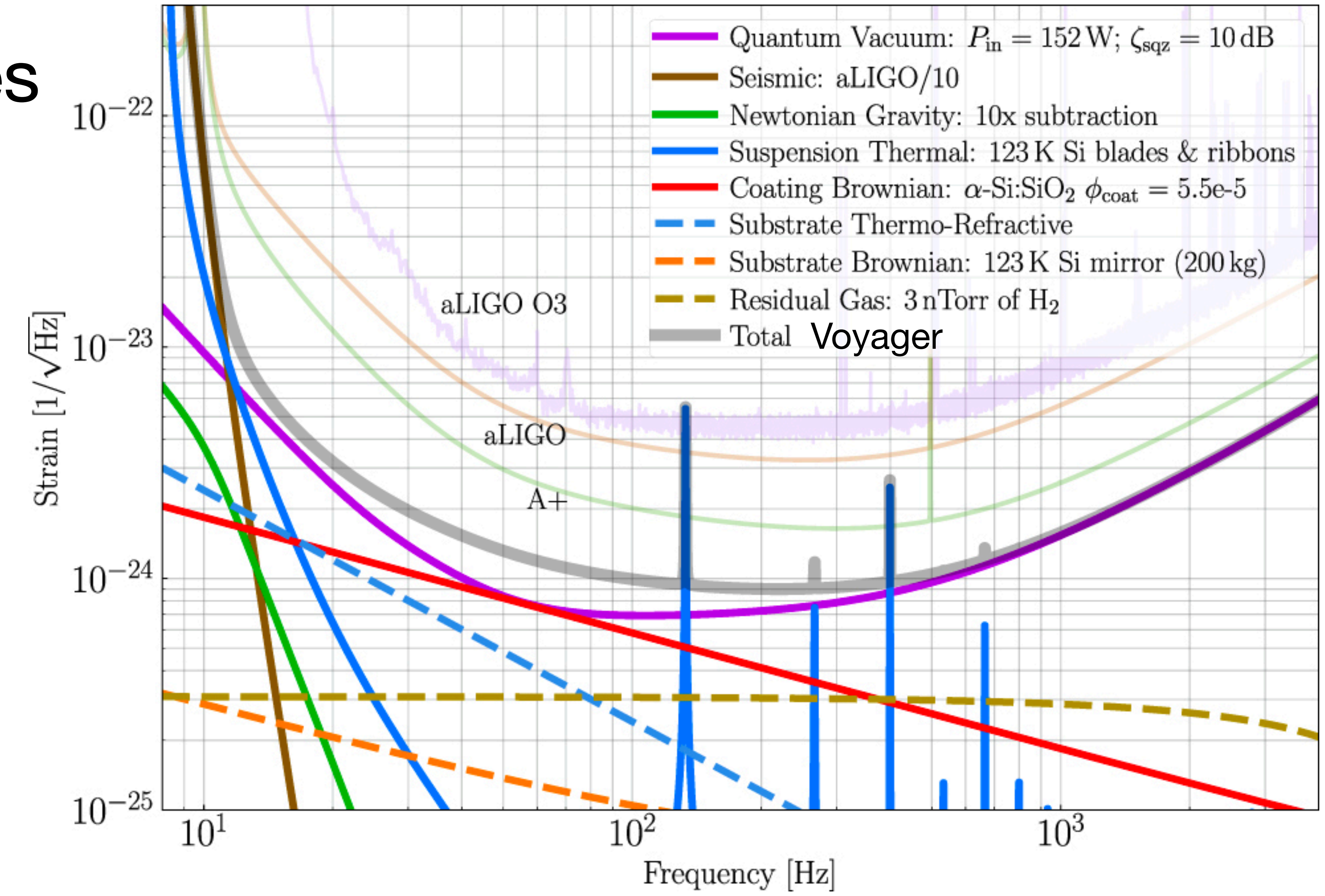
Future of current detector sites

LIGO A+ and AdV+

- Upgrades to current LIGO and Virgo sites
- Late 2020s
- Funded, minimal technology risk

Voyager (Adhikari et al 2020 CQG **37** 165003)

- Possible further upgrades to current LIGO sites post-O5
- Significant technological development

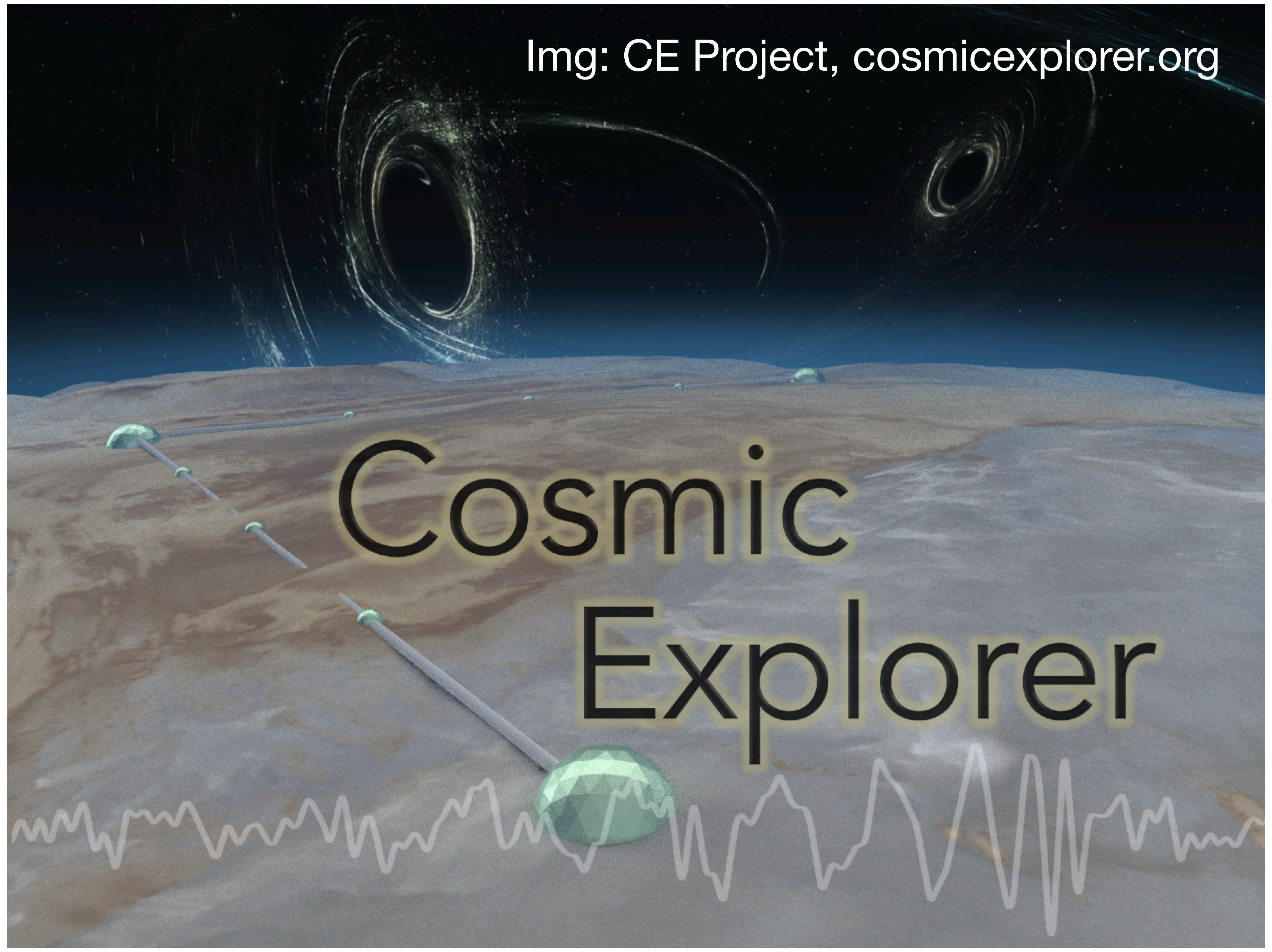


Future Detectors

- 3rd generation detectors, c. 2035

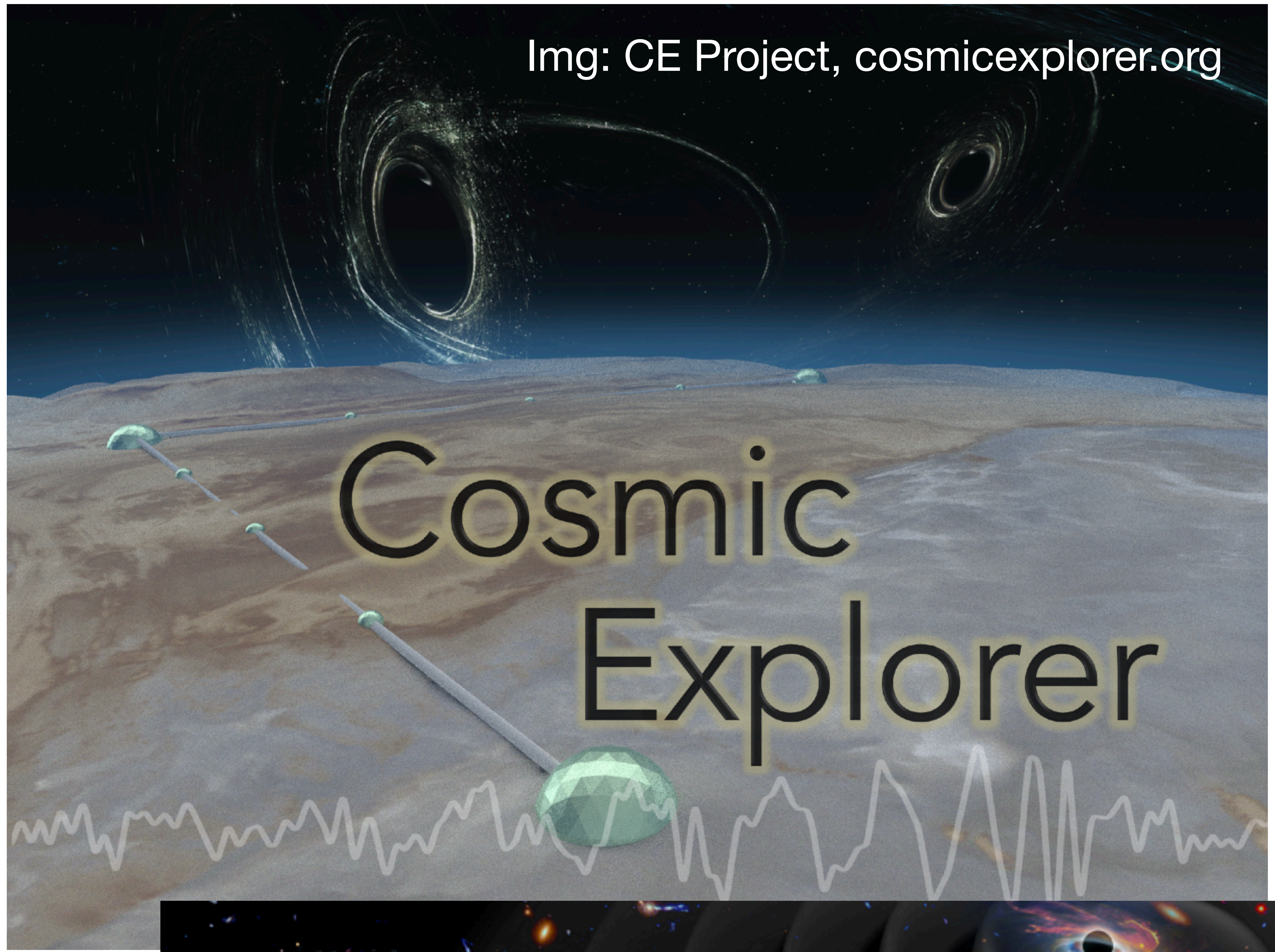
Future Detectors

- 3rd generation detectors, c. 2035
  - Cosmic explorer:
    - 20km or 40km detector, or a combo

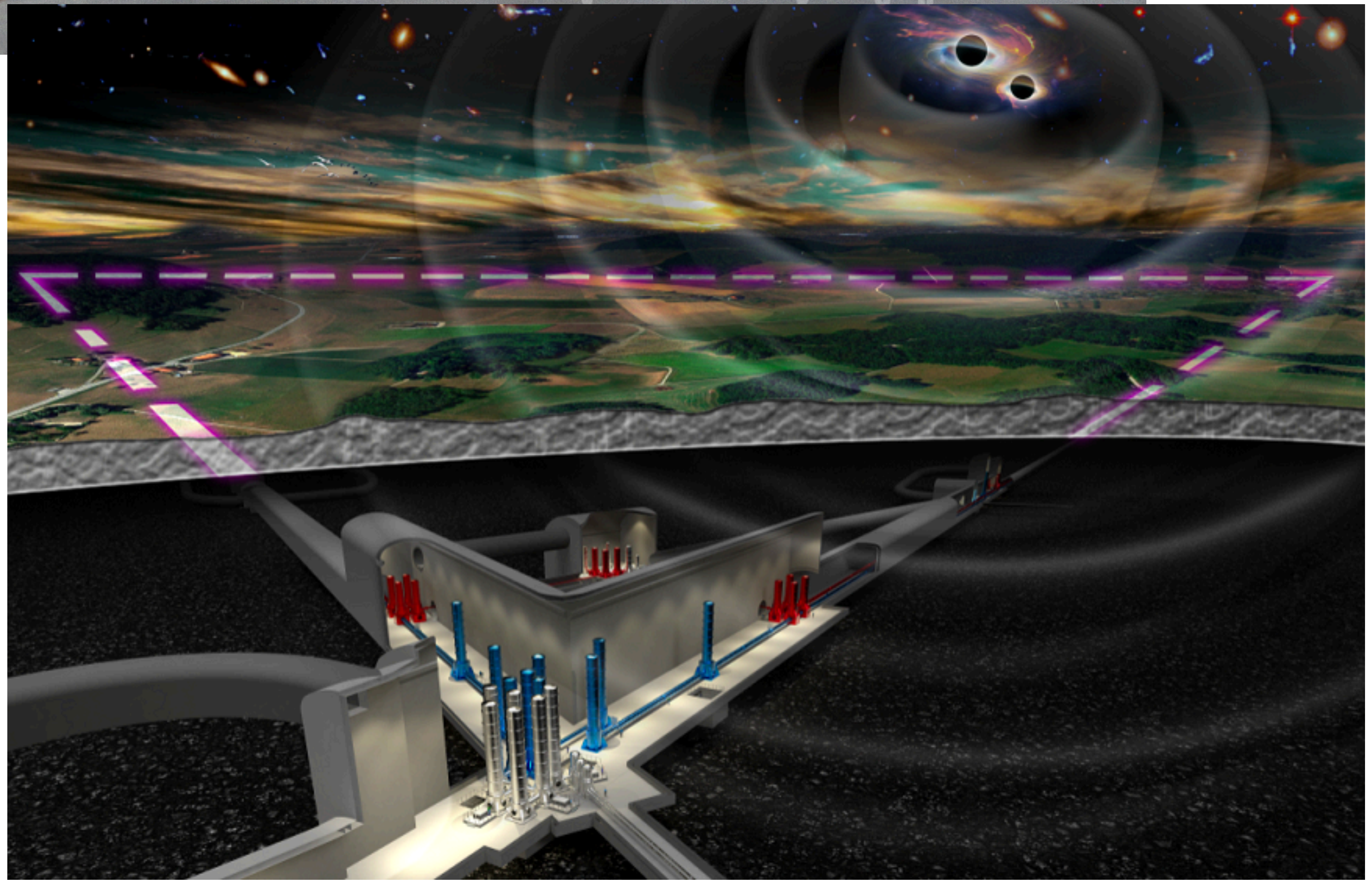


Future Detectors

- 3rd generation detectors, c. 2035
  - Cosmic explorer:
    - 20km or 40km detector, or a combo
  - Einstein Telescope
    - Europe-based
    - 10km triangular configuration, underground

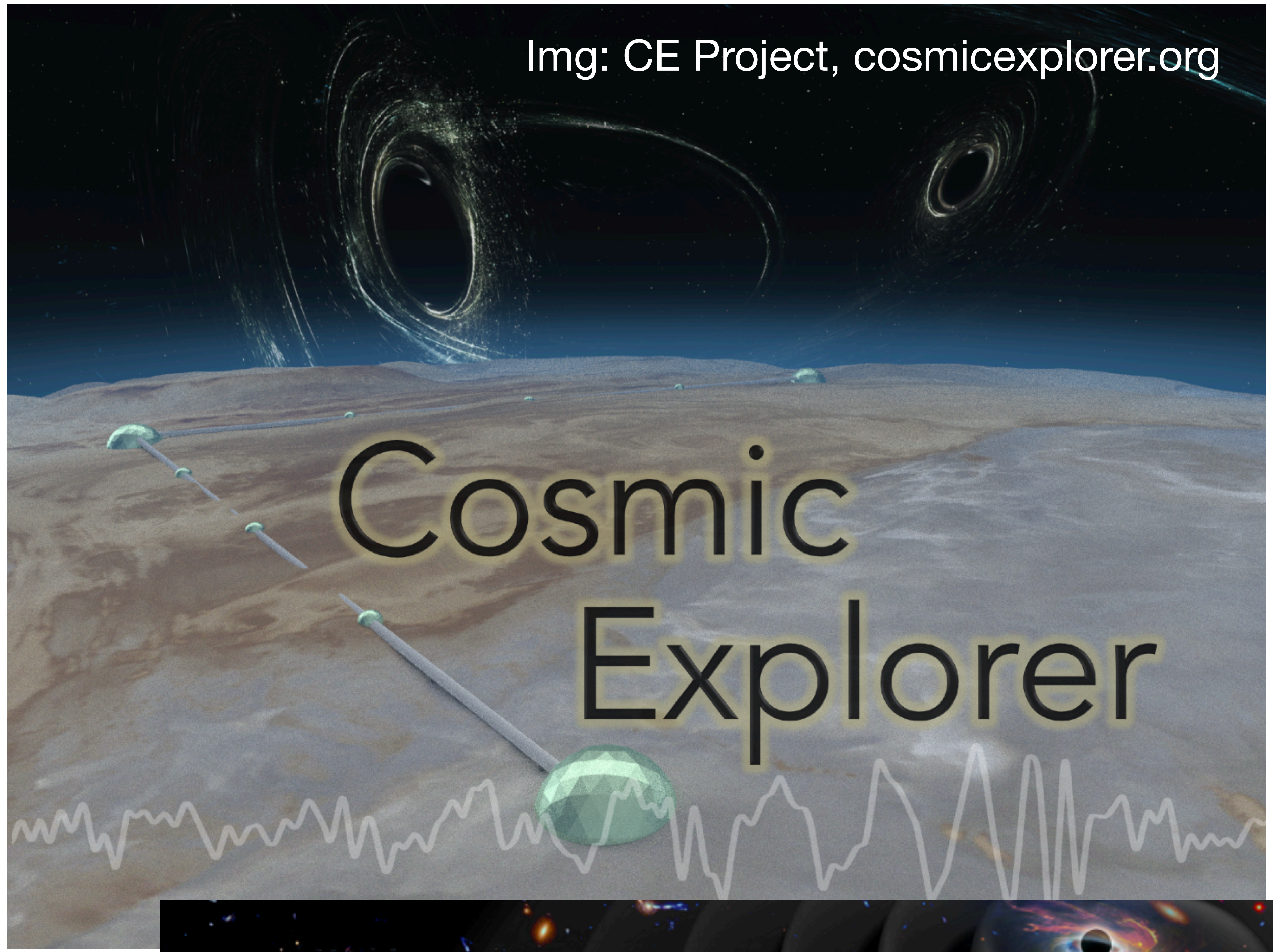


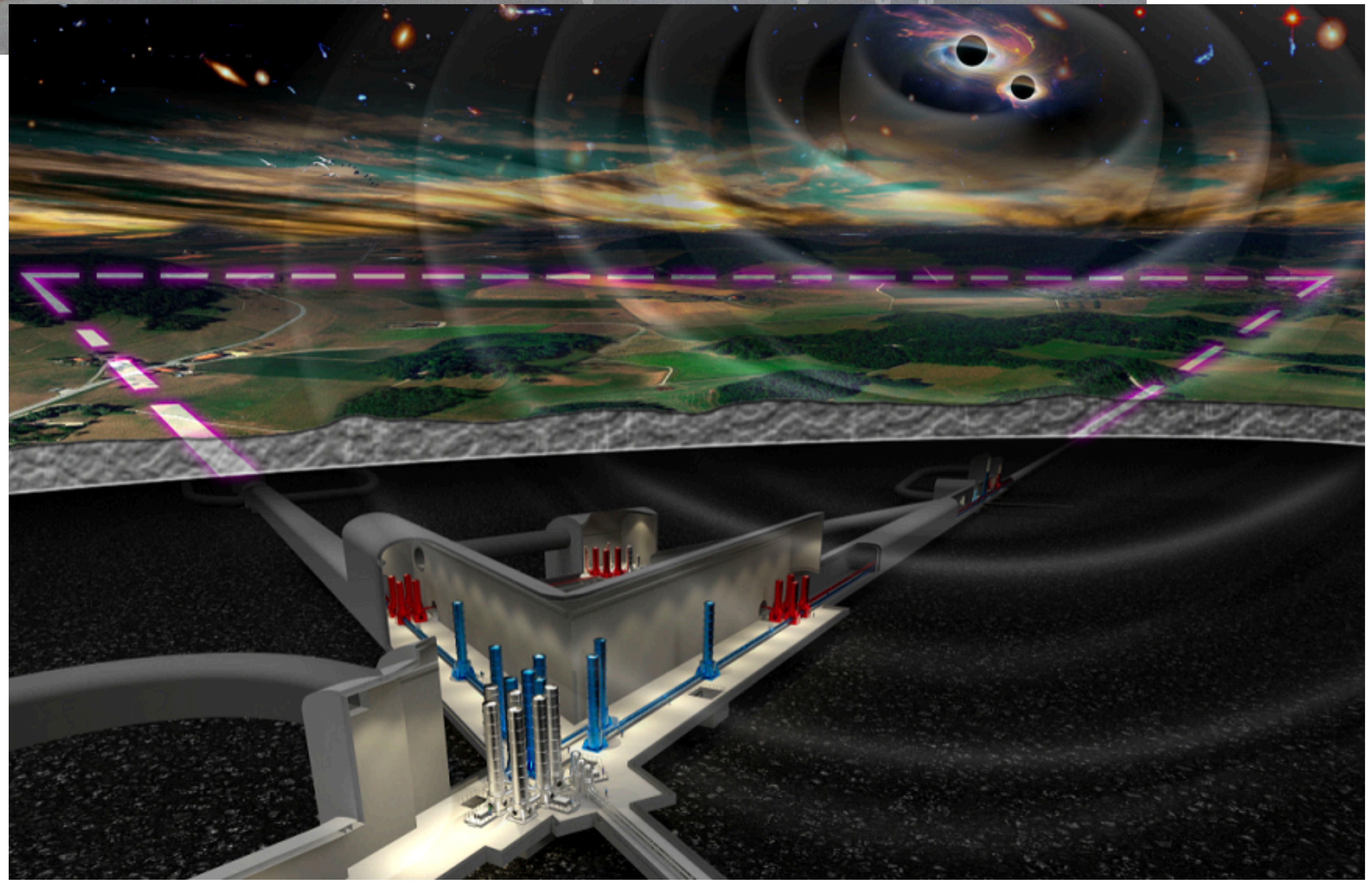
Img: CE Project, cosmicexplorer.org


Img: ET collaboration, et-gw.eu

Future Detectors

- 3rd generation detectors, c. 2035
    - Cosmic explorer:
        - 20km or 40km detector, or a combo
    - Einstein Telescope
        - Europe-based
        - 10km triangular configuration, underground
- Still some uncertainty in funding (need >$1B), technology, timeline

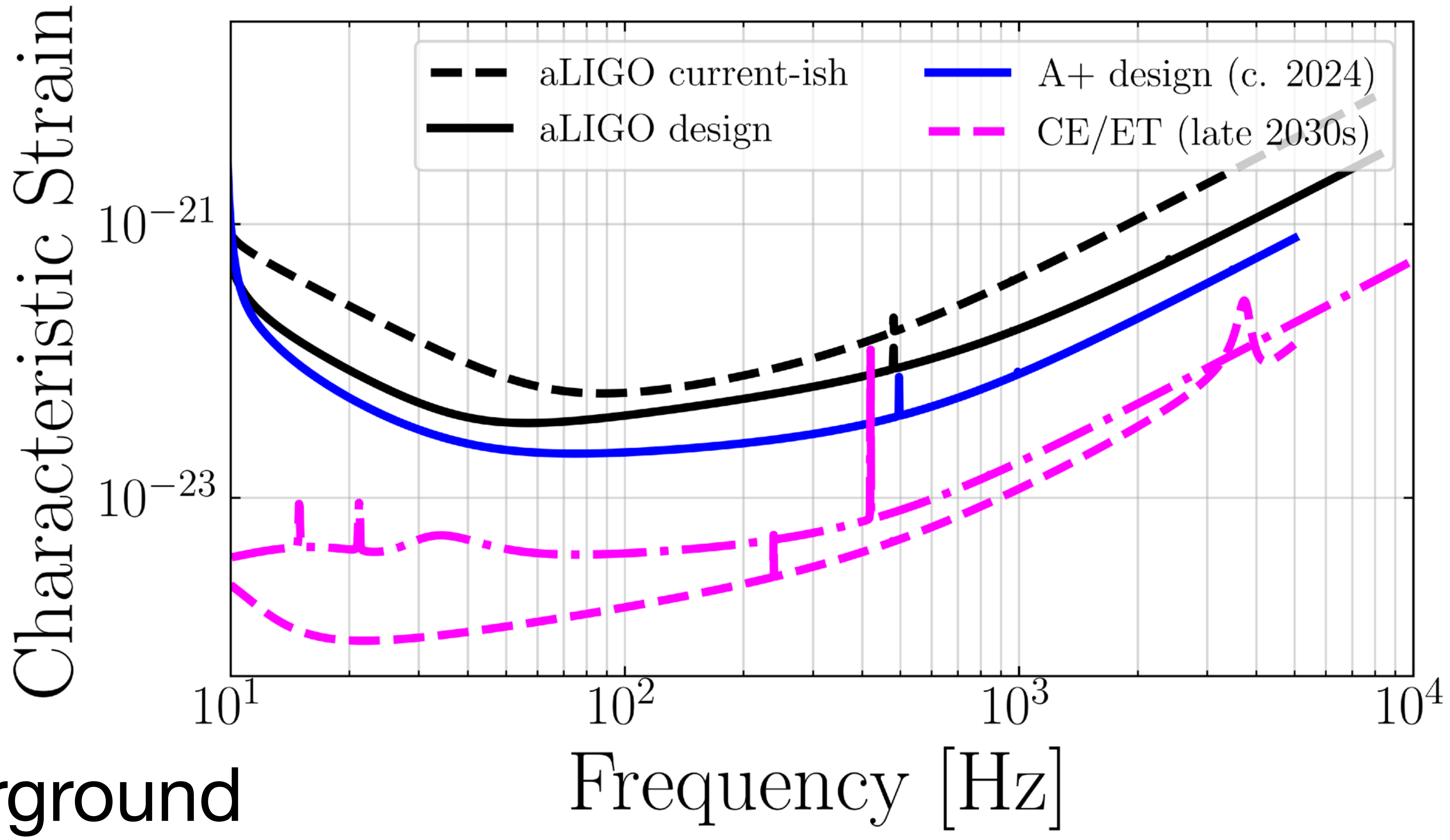




Img: ET collaboration, et-gw.eu

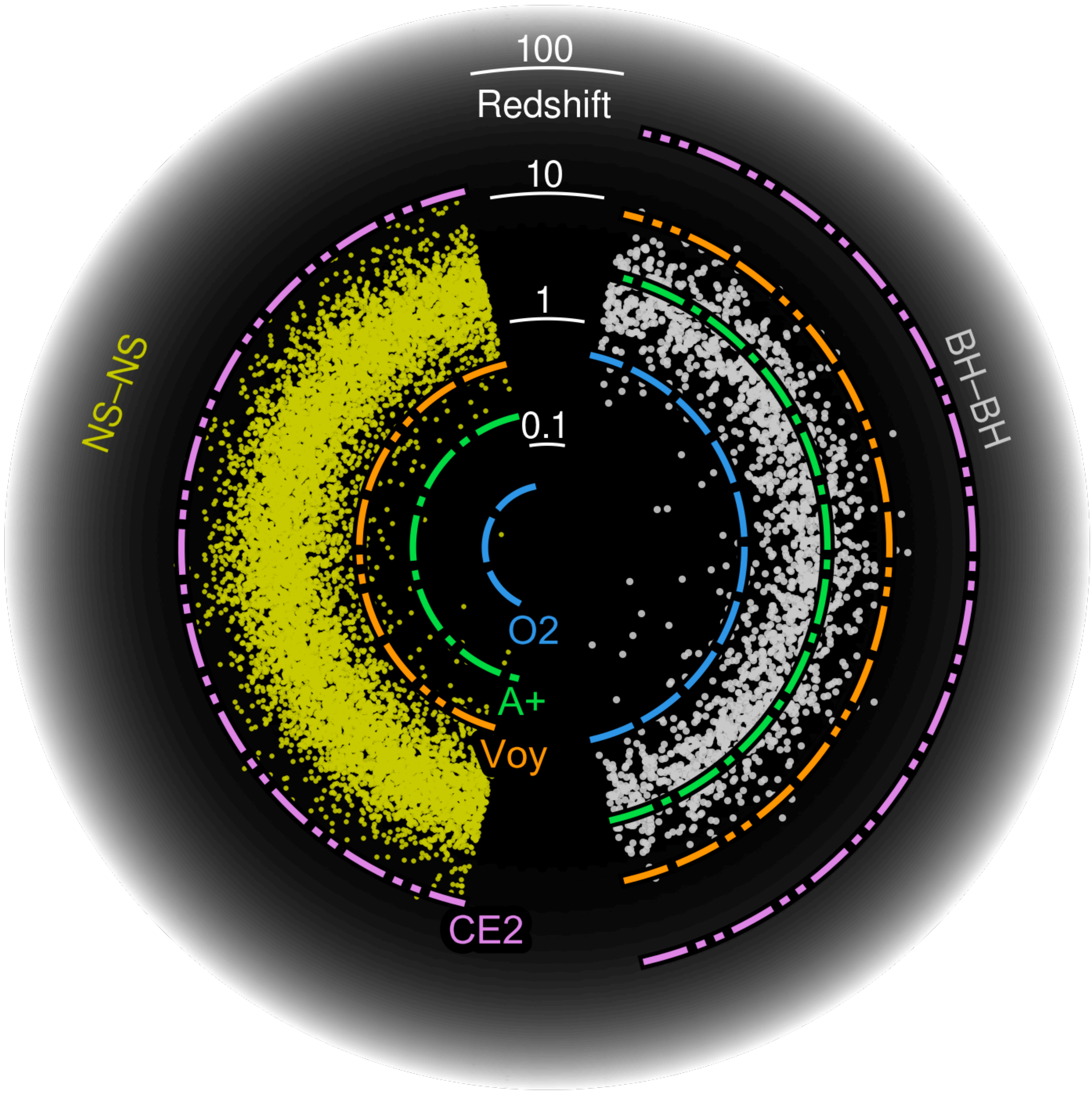
Future Detectors

- 3rd generation detectors, c. 2035
  - Cosmic explorer:
    - 20km or 40km detector, or a combo
  - Einstein Telescope
    - Europe-based
    - 10km triangular configuration, underground
- Still some uncertainty in funding (need >$1B), technology, timeline



3G Landscape

- CE a “neutron star machine”
- Lots of multi messenger opportunity
- Also comes with data analysis challenges:
  - Need accurate waveforms, ability to handle lots of events in searches/PE

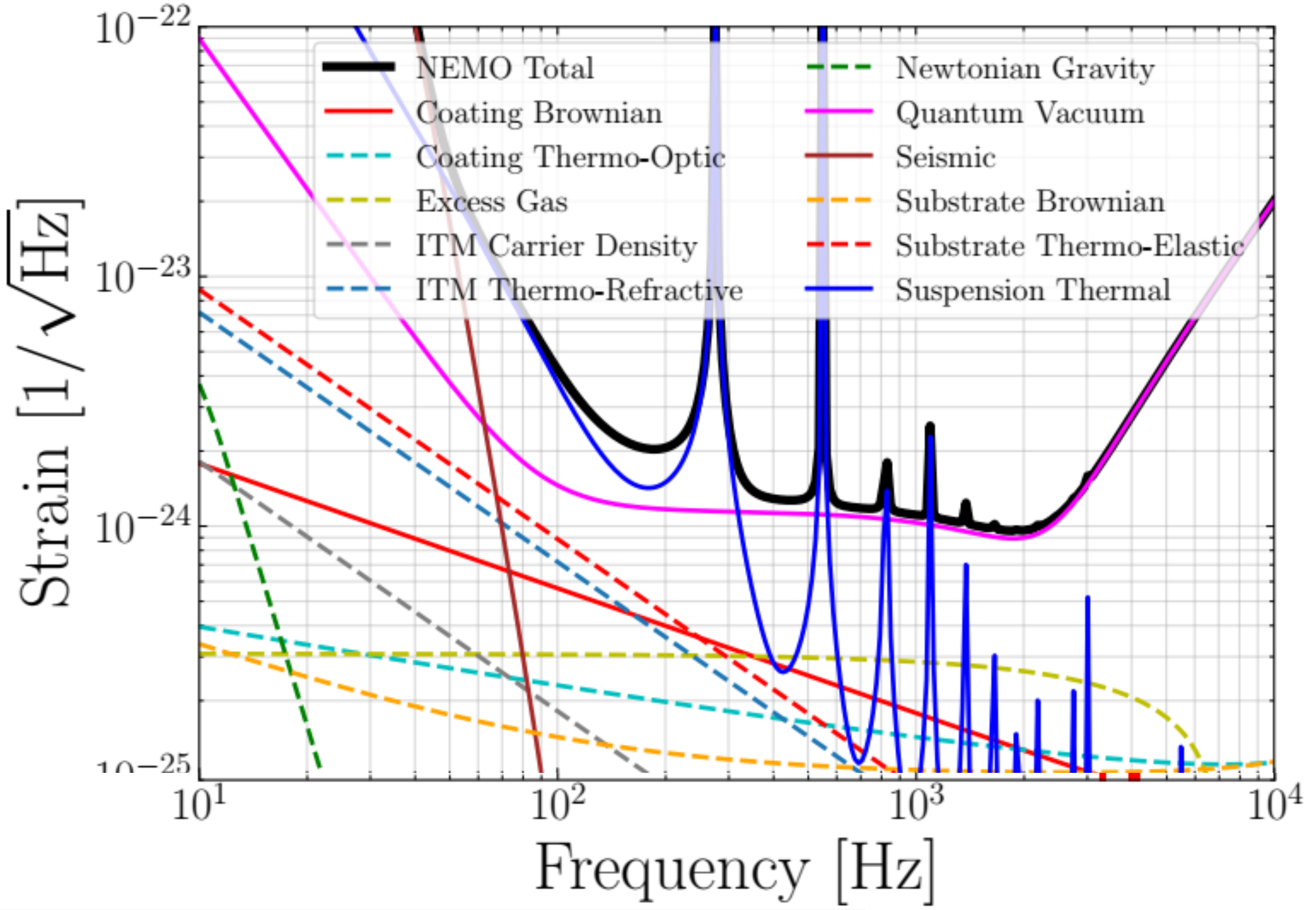


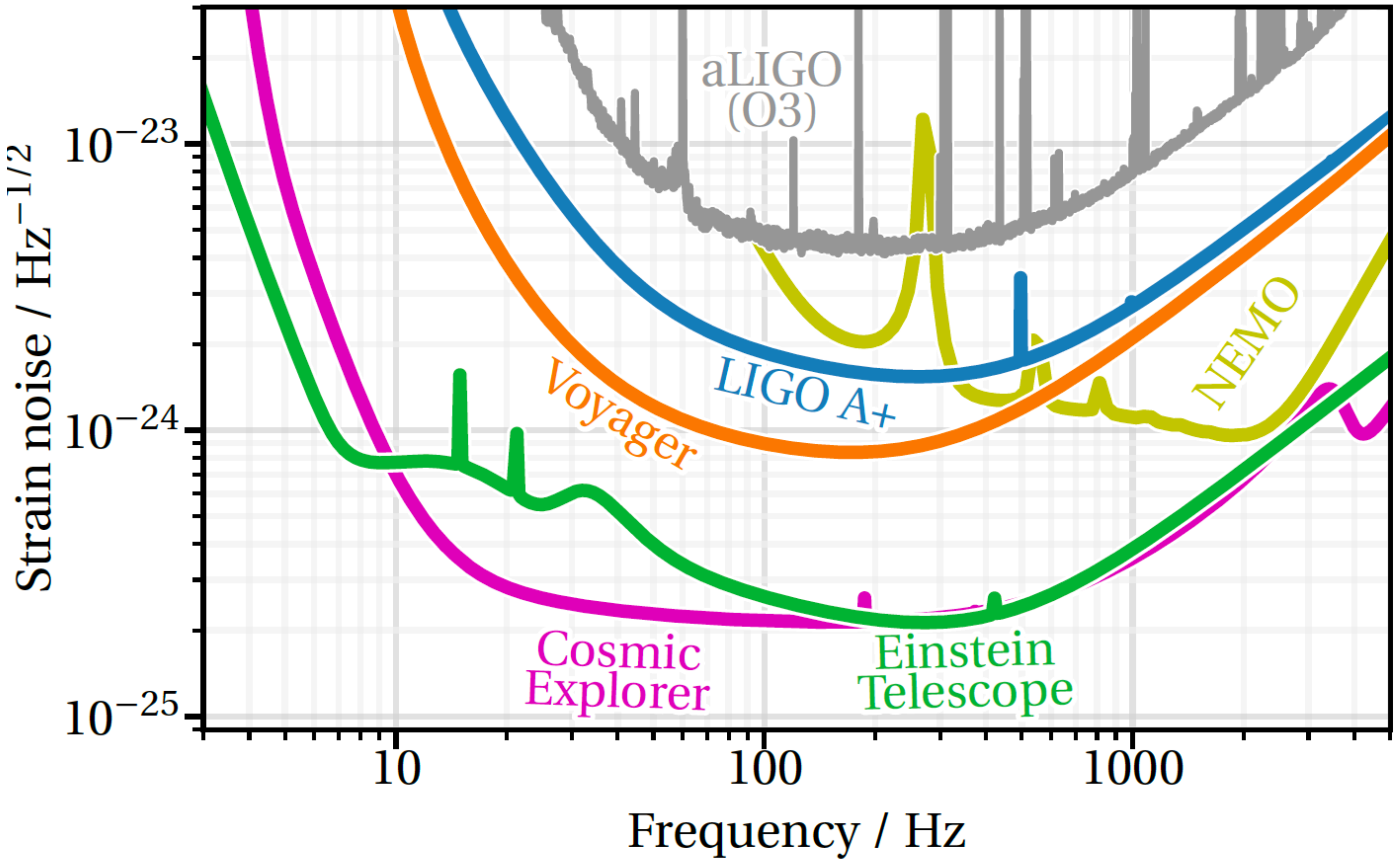
Hall and Vitale, LIGO DCC: G1900803

Neutron Star Extreme Matter Observatory (NEMO)

Ackley et al. PASA (2020) 37, e047

- High frequency detector
- A “matter machine” — targeting BNS systems
- Relatively cheap: $200M
- Small technology risk
  - Can serve as technological development for 3G detectors



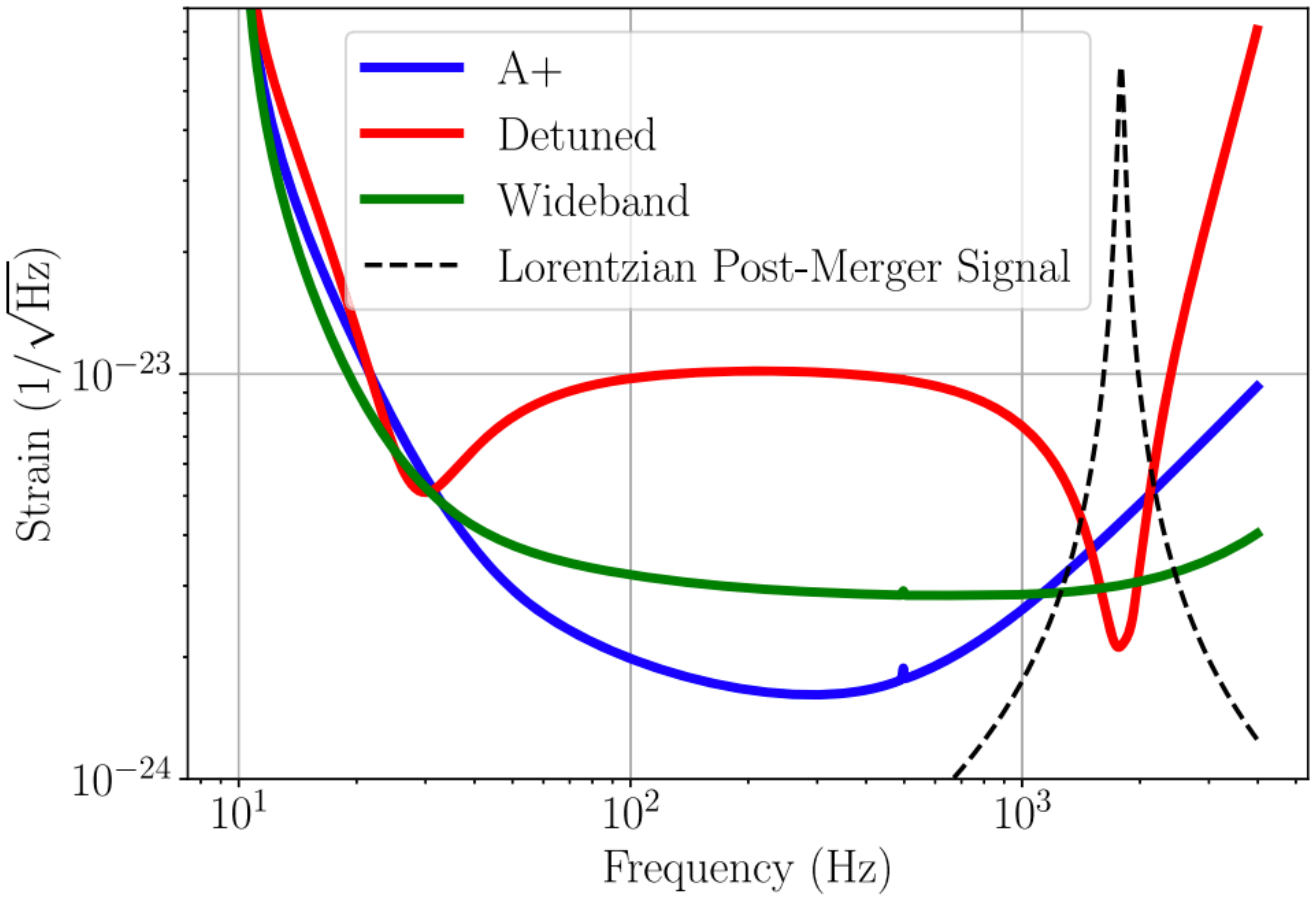


Thank you Paul Lasky for help with this slide!

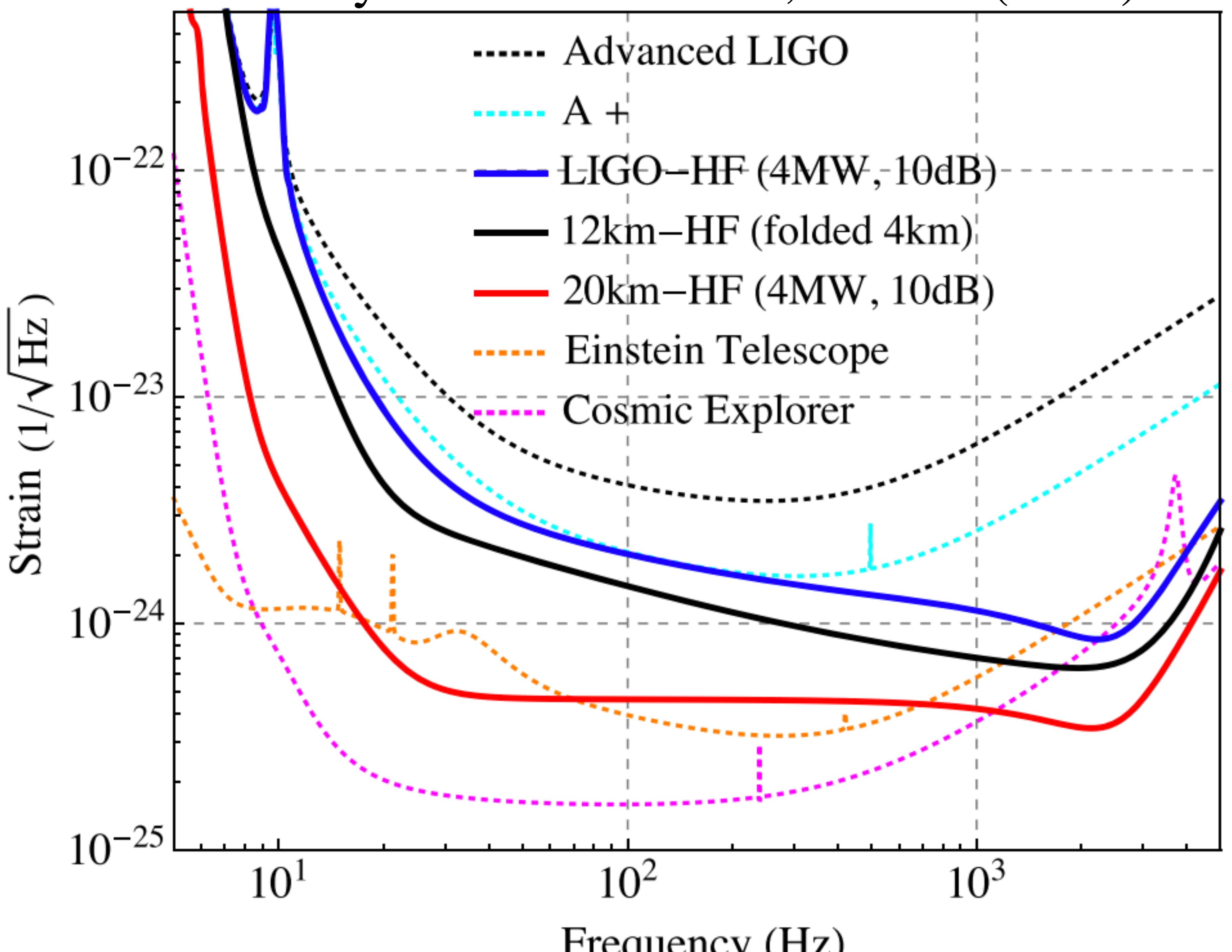
Other high frequency prospects

Could tune current detectors for high frequency specifically

Ganapathy et al. PRD 103, 022002 (2021)



Martynov et al. PRD 99, 102004 (2019)

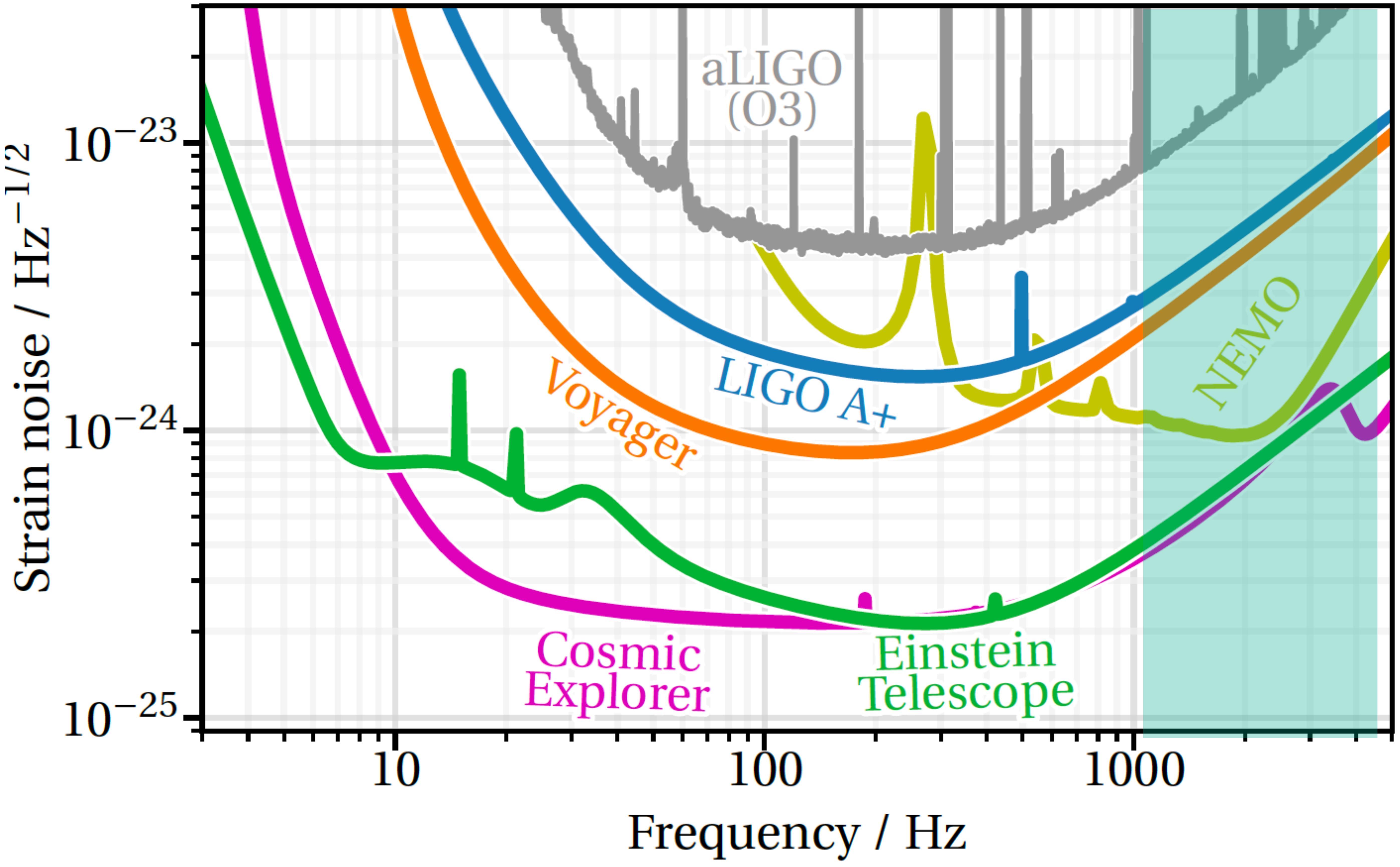


Other observing prospects

BNS inspirals not the only possible source of GWs from NSs

- Fundamental mode excitation/post-merger
- Quasiperiodic GWs from isolated neutron stars
- Plus surprises?

Neutron star *f*-modes



(Plot from P. Lasky)

- Bursts of GW radiation from excitation of the fundamental quadrupole moment
  - Short duration (~milliseconds)
  - High frequency (~ 1-4kHz)
  - Frequency related to NS radius

Neutron star *f*-modes

- Model GW signal as damped sinusoid: $h(t) = h_0 e^{-t/\tau_{\mathrm{GW}}} \sin\left(\omega_{\mathrm{GW}} t\right)^{\dagger}$
  - Damping time τ_{GW} and frequency ω_{GW} depend on mass and radius of NS
- Potential mechanism: pulsar glitches
  - Sizes in range $\Delta\nu \approx 10^{-9} - 10^{-5}\ \mathrm{Hz}^{*}$
  - Possible causes: Starquakes, momentum transfer between crust and core

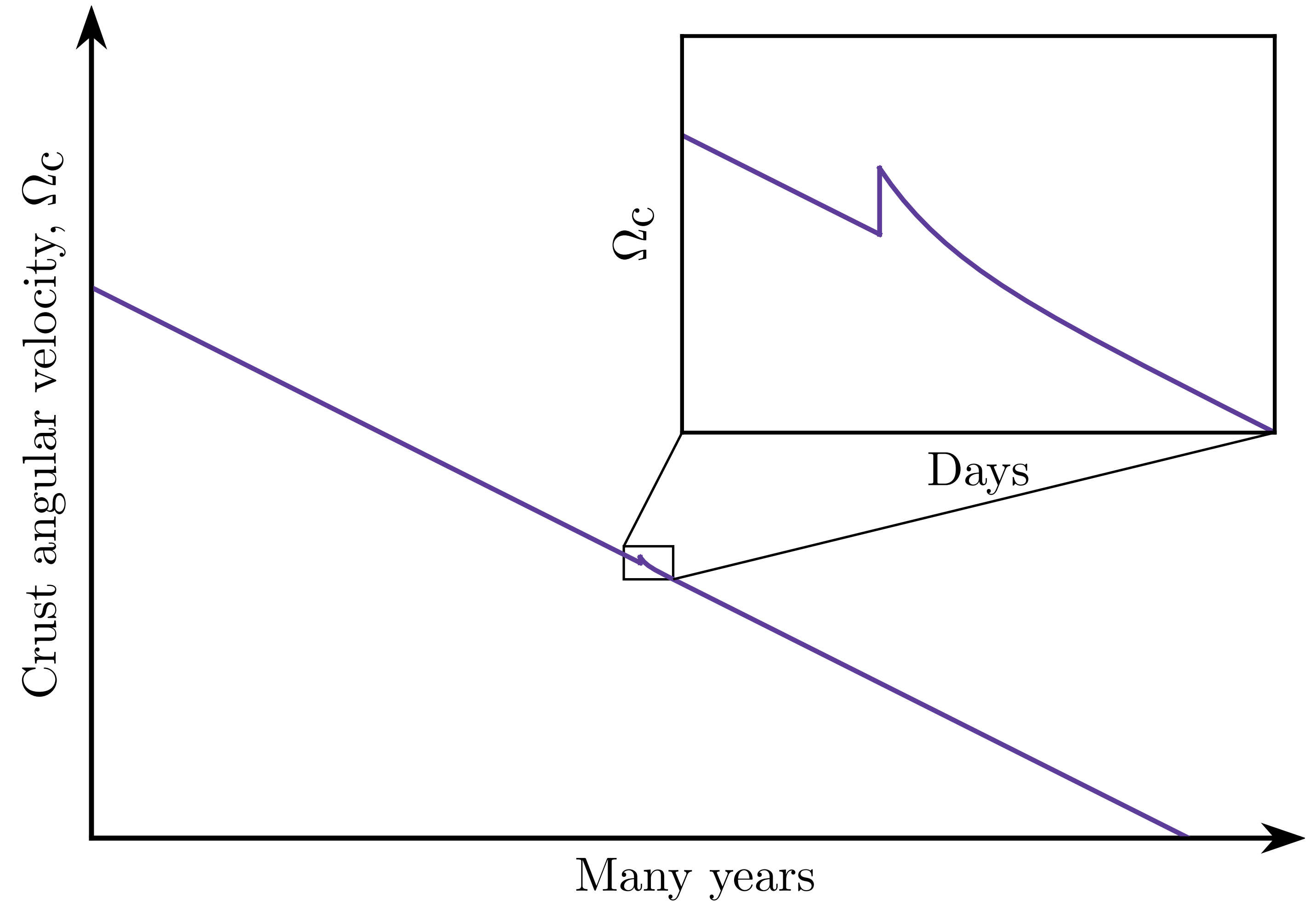


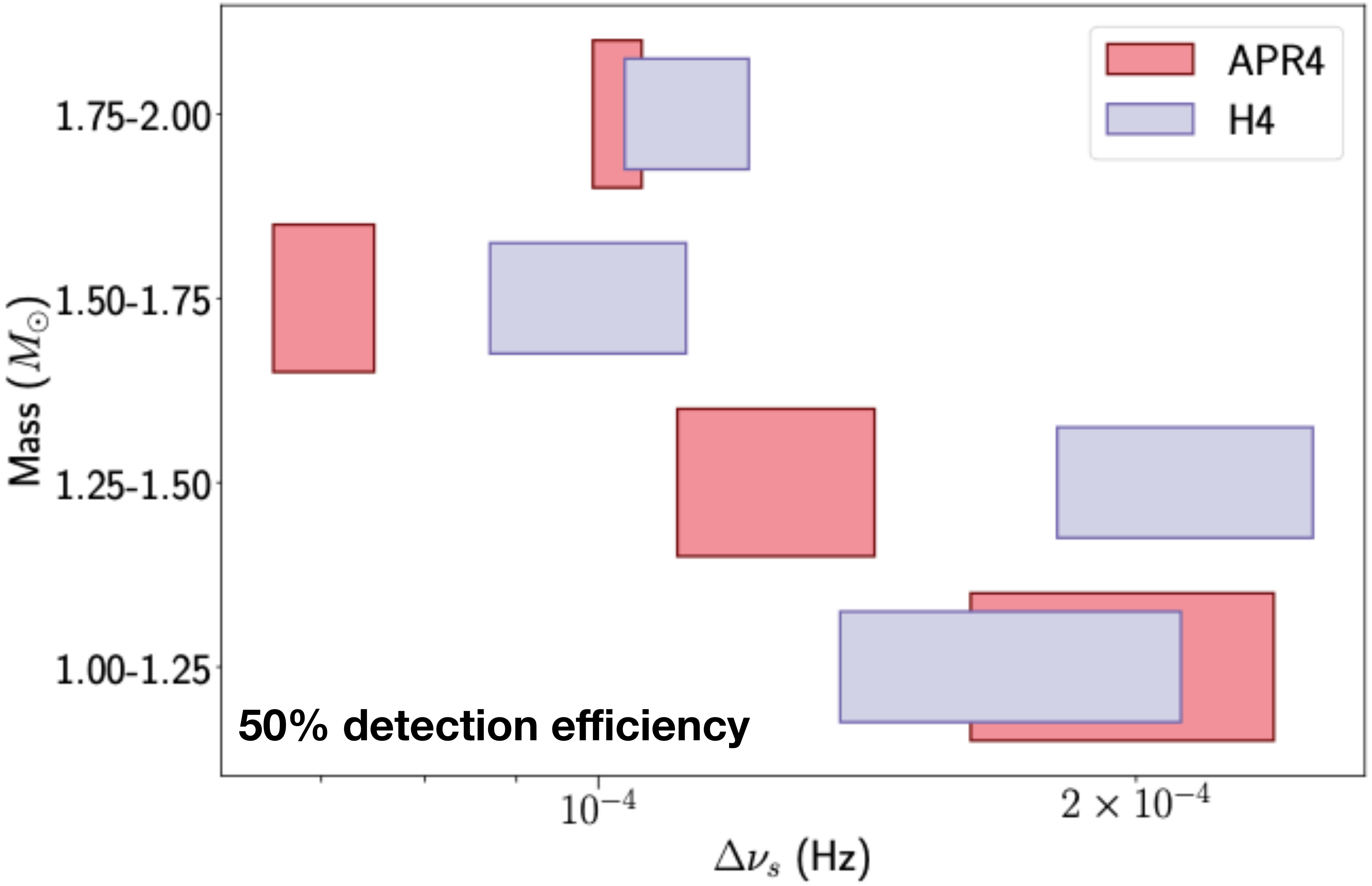
Image from J.B. Carlin

*Basu et al., MNR 414, 1679 (2011); Shaw et al., Jodrell Bank Glitch Catalogue; Hobbs et al. ATNF Pulsar Catalogue

† Kokkotas & Andersson 2002

Neutron star *f*-modes: Pulsar glitches

Recent LVK results



(Glitch size)

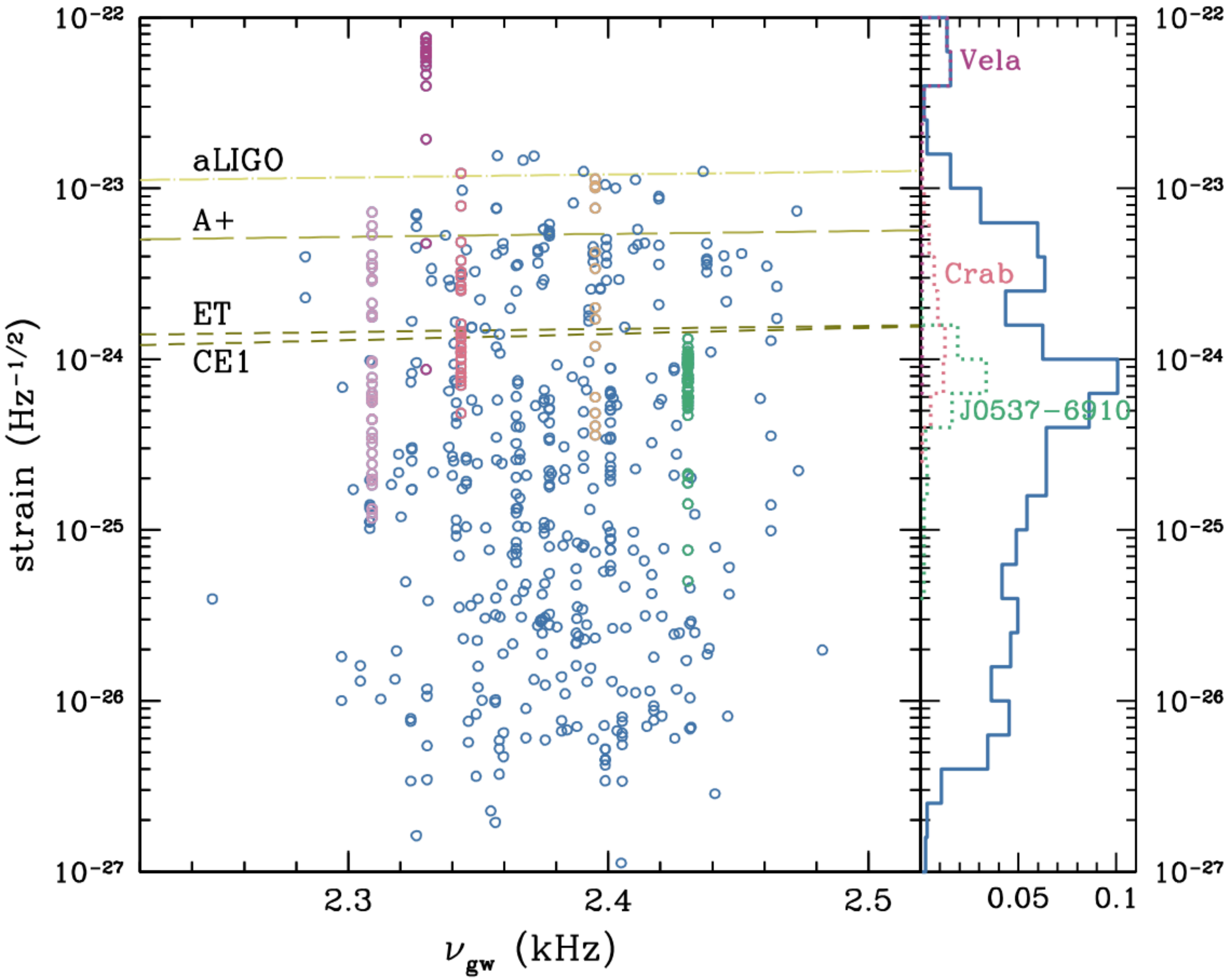
Abbott et al., arXiv:2107.03701

Injection study for the all-sky search

- Distribute sources uniformly across sky, masses between $1 - 2\ M_\odot$
- Use Vela as standard candle for distance ($287\ \mathrm{pc}$) and spin ($\nu_s = 11.2\ \mathrm{Hz}$)

Radio observations show glitch sizes ~3 orders of magnitude smaller than what GW search is capable of

Neutron star *f*-modes



Ho et al, PRD 101, 103009 (2020)

For *f*-modes excited to similar levels of known pulsar glitches, could see quite a few with 3G detectors

BNS post-merger

- BNS merger could result in hypermassive neutron star
- Probe “hot” EoS
- Again, GW peak frequency related to NS mass and radius
    - Plus more structure, like subdominant peak
- Could also see evidence of phase transition [see Bauswein et al Phys. Rev. Lett; Phys. Rev. Lett. 122, 061102 (2019)]

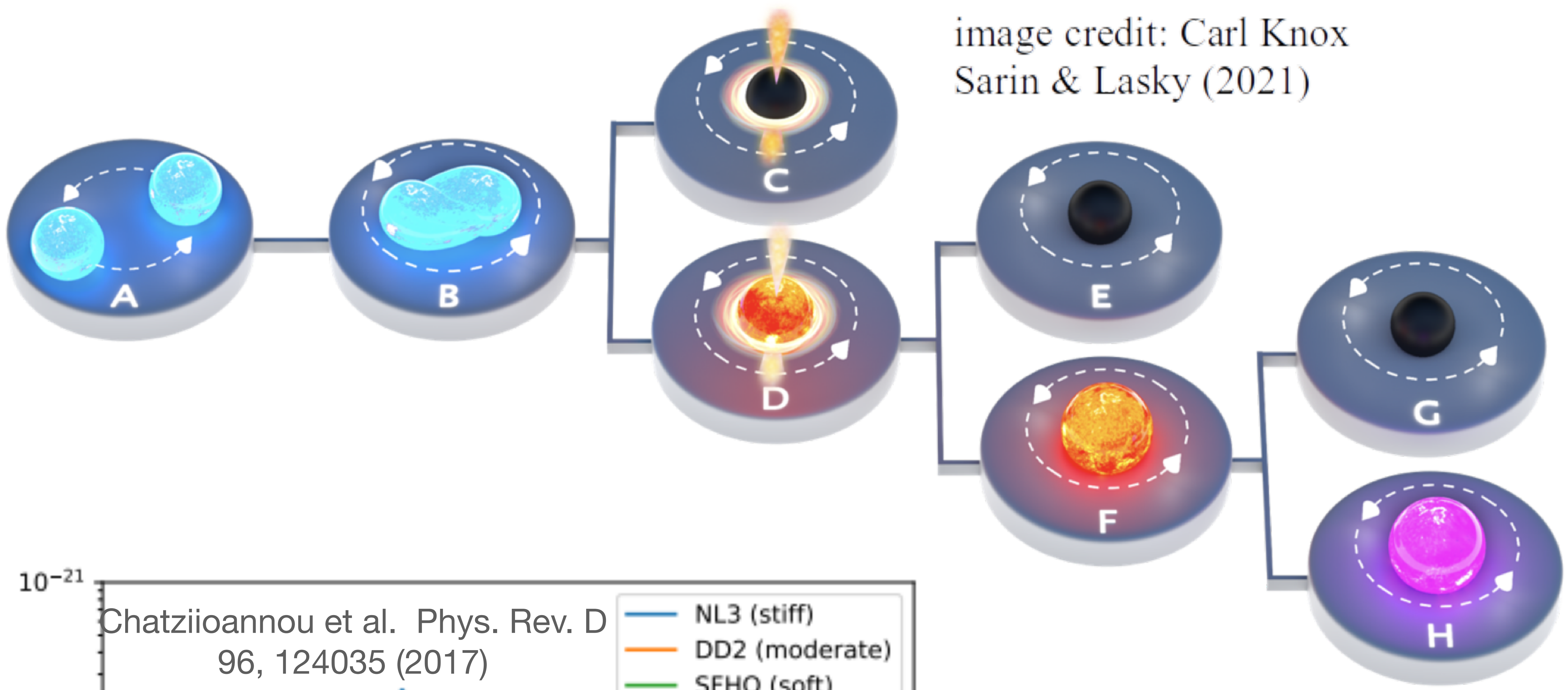
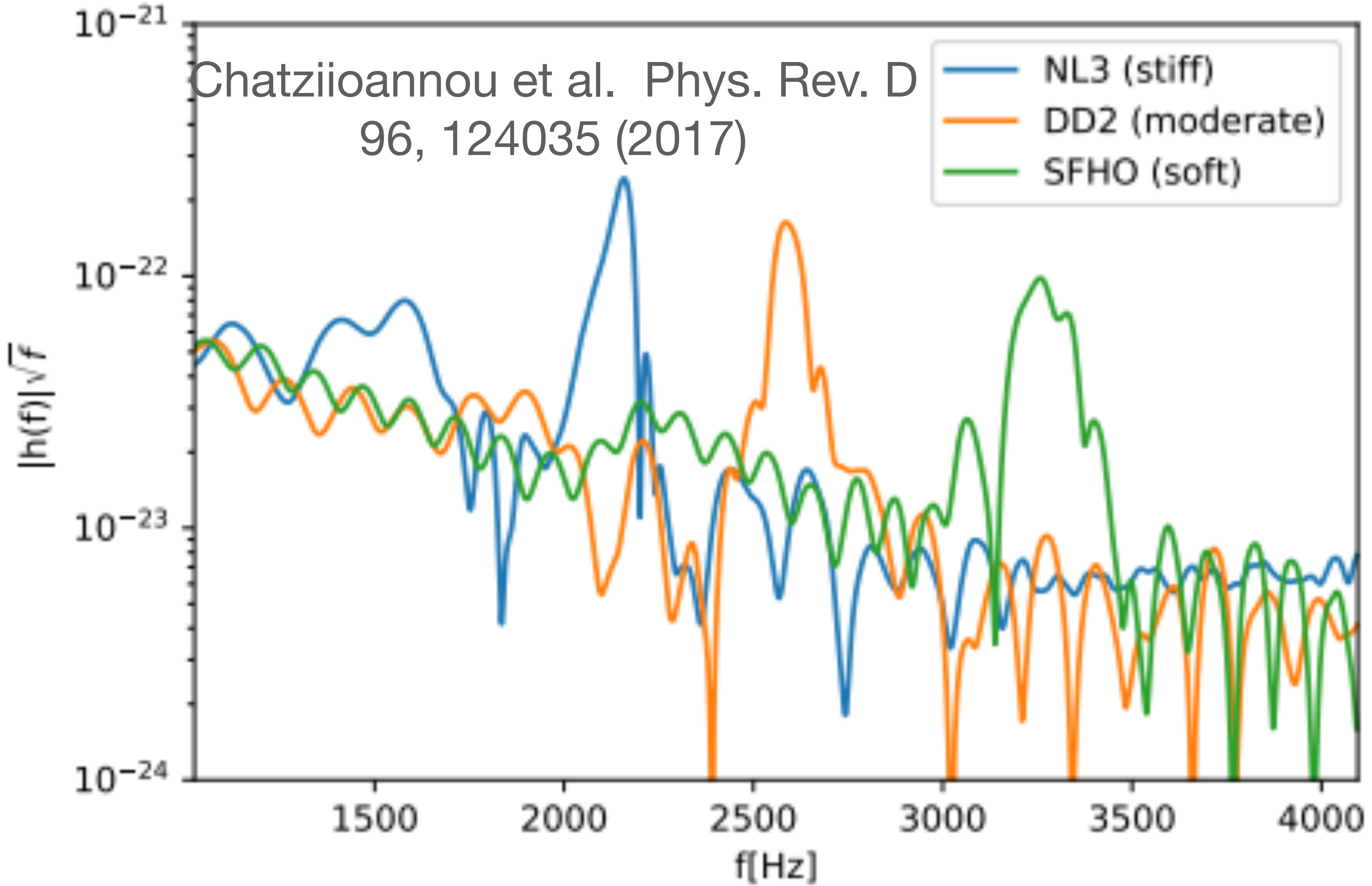
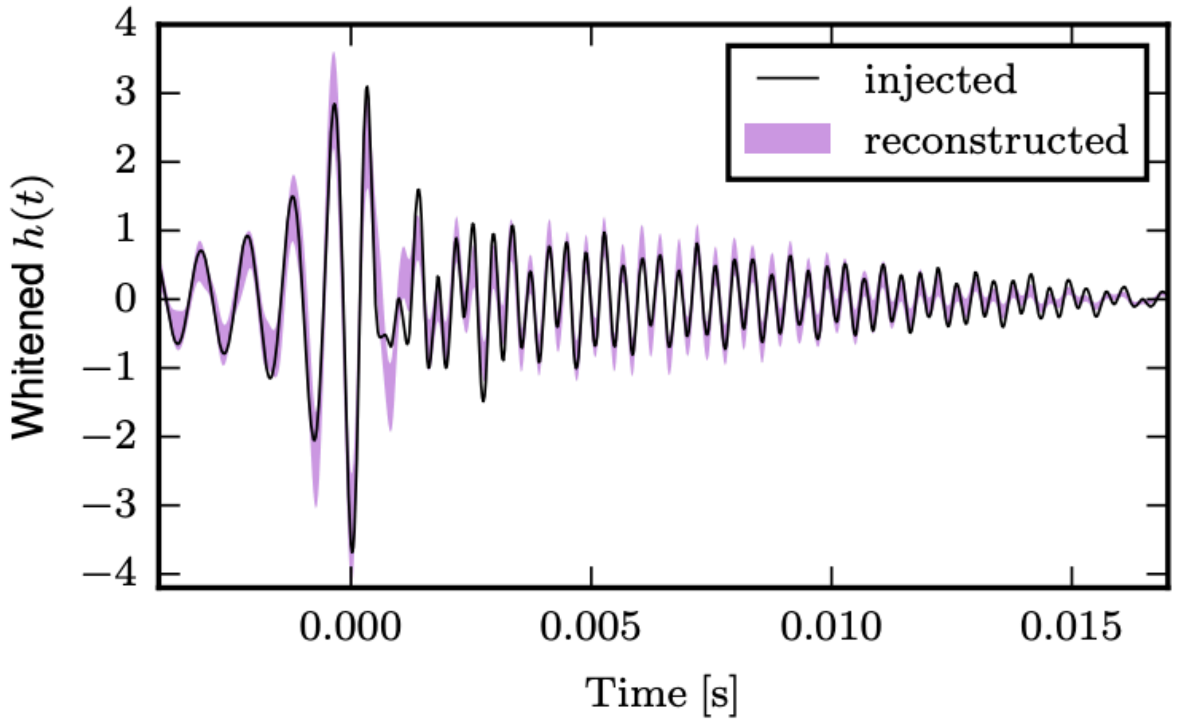


image credit: Carl Knox
Sarin & Lasky (2021)



Chatziioannou et al. Phys. Rev. D 96, 124035 (2017)



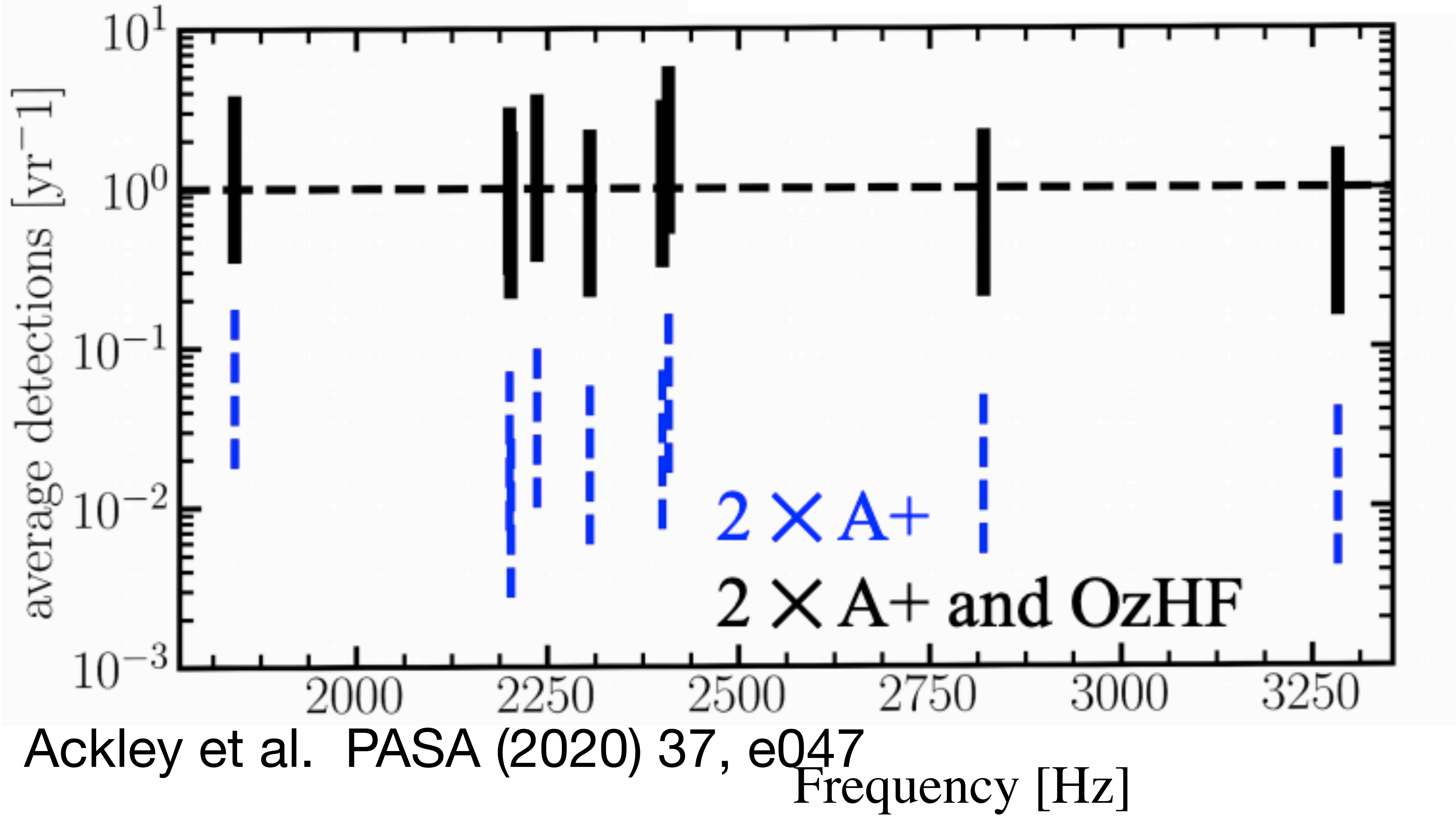
BNS post-merger

- Likely need next gen detectors for a post-merger detection

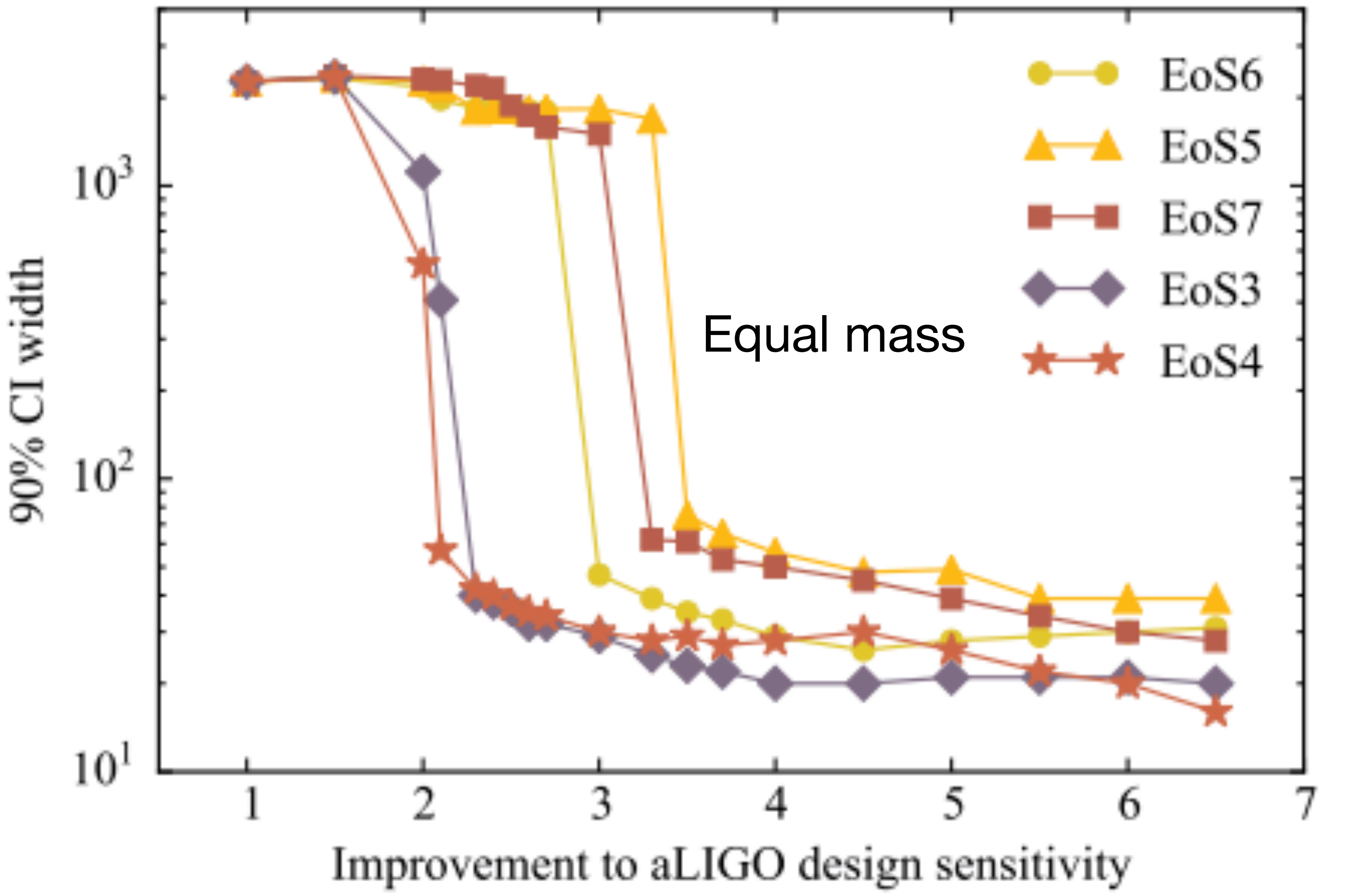
Martynov et al. PRD 99, 102004 (2019)

	SLY/APR4	SLY/SFHo	APR4/SFHo
LIGO-HF	$0.53^{+1.4}_{-0.41}$	$2.22^{+4.22}_{-1.82}$	$1.21^{+3.5}_{-1}$
Einstein Telescope	$0.15^{+0.13}_{-0.12}$	$0.42^{+0.8}_{-0.37}$	$0.27^{+0.65}_{-0.2}$
Cosmic Explorer	$1.44^{+3}_{-1.18}$	$4.84^{+10.01}_{-3.88}$	$3.94^{+8.17}_{-3.15}$
20 km-HF	$9.18^{+18.22}_{-7.24}$	$31.37^{+65.25}_{-24.39}$	$22.27^{+45.13}_{-17.71}$

BNS post-merger rates with A+ and NEMO



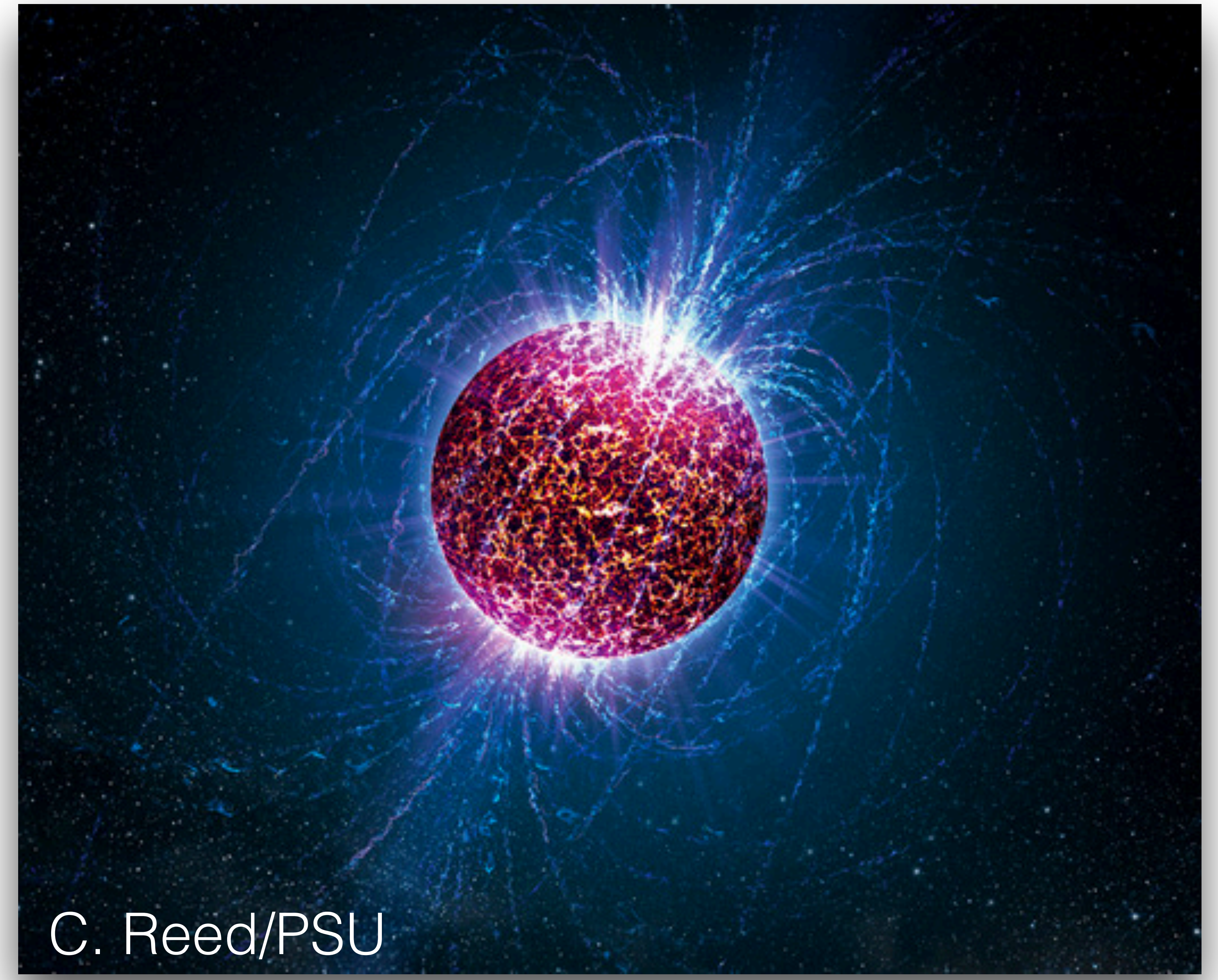
Ackley et al. PASA (2020) 37, e047



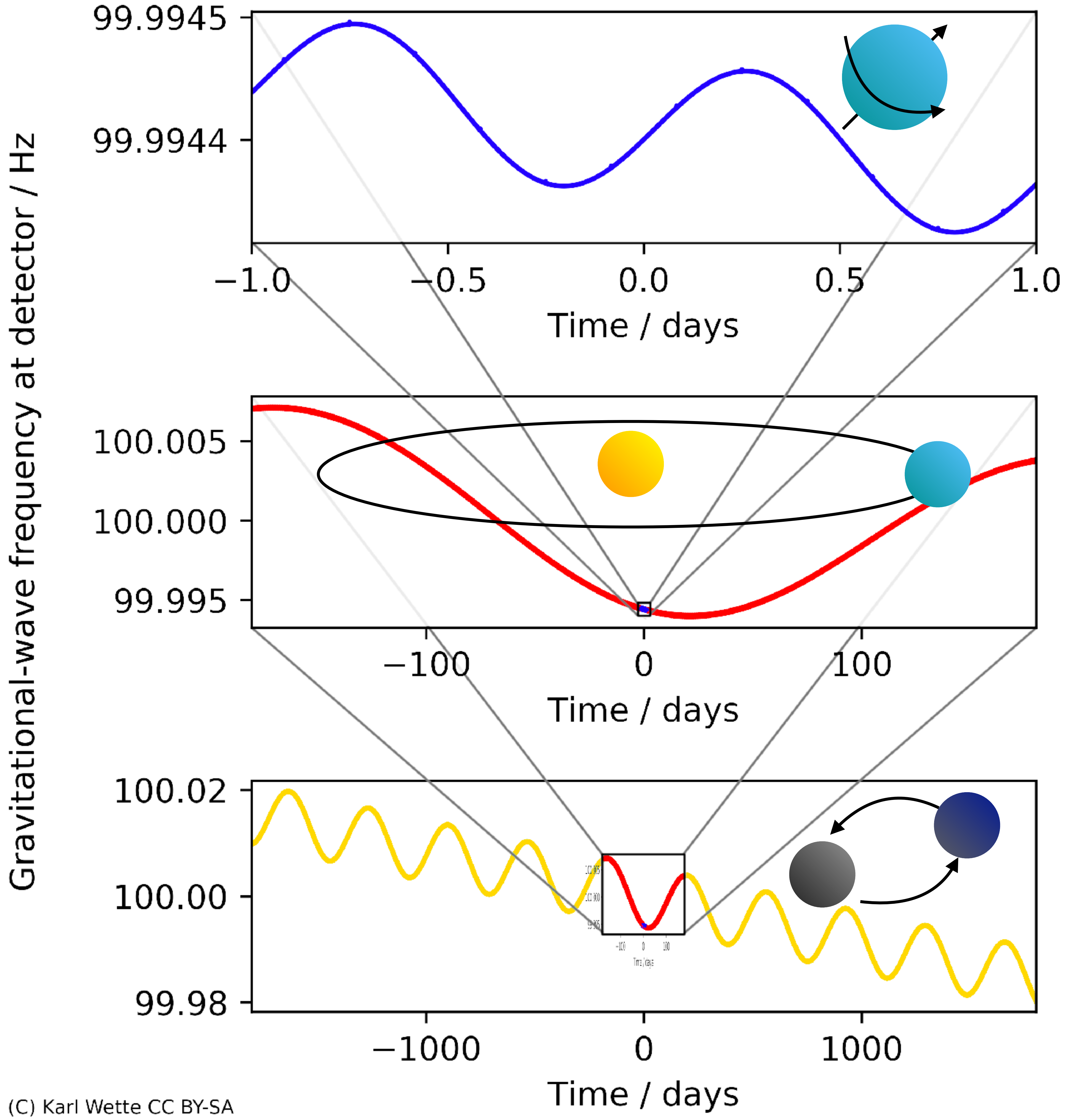
Torres-Rivas et al. Phys. Rev. D 99, 044014 (2019)

GWs from isolated NSs

- Long lasting, quasi-monochromatic gravitational waves from non-axisymmetric neutron stars
- Signals can be present in detector data for ~years
- Smaller amplitude than compact binaries, but signal evidence can accumulate



GWs from isolated NSs



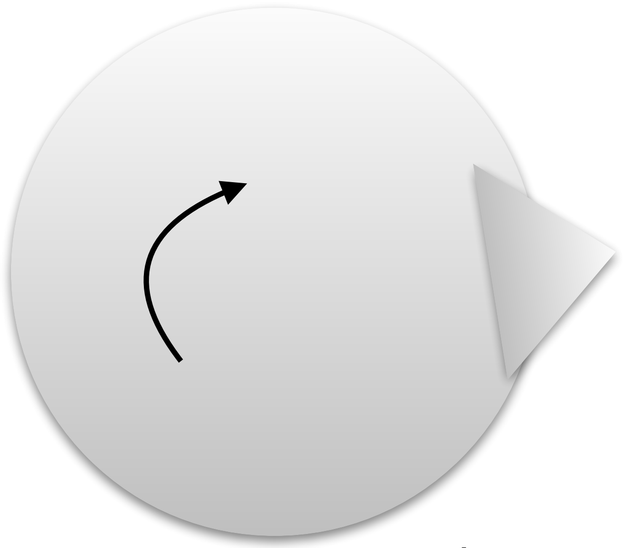
Img: Karl Wette

- Long signals will appear doppler shifter in the detectors
  - Good sky localization
  - Can discern overlapping signals

GWs from isolated NSs

Emission mechanisms

Equatorial bulge
(Or “mountains on neutron stars”)



(not to scale)

$$f_{\mathrm{GW}} = 2 f_{\mathrm{rotation}}$$

$$h_0 \propto \frac{f_{\mathrm{GW}} I_{zz}}{r} \epsilon \qquad \epsilon \equiv \frac{I_{xx} - I_{yy}}{I_{zz}}$$

Predicted maximum ellipticity: $10^{-5} - 10^{-1}$

Johnson-McDaniel + B.J. Owen, PRD 88 044004 (2013)

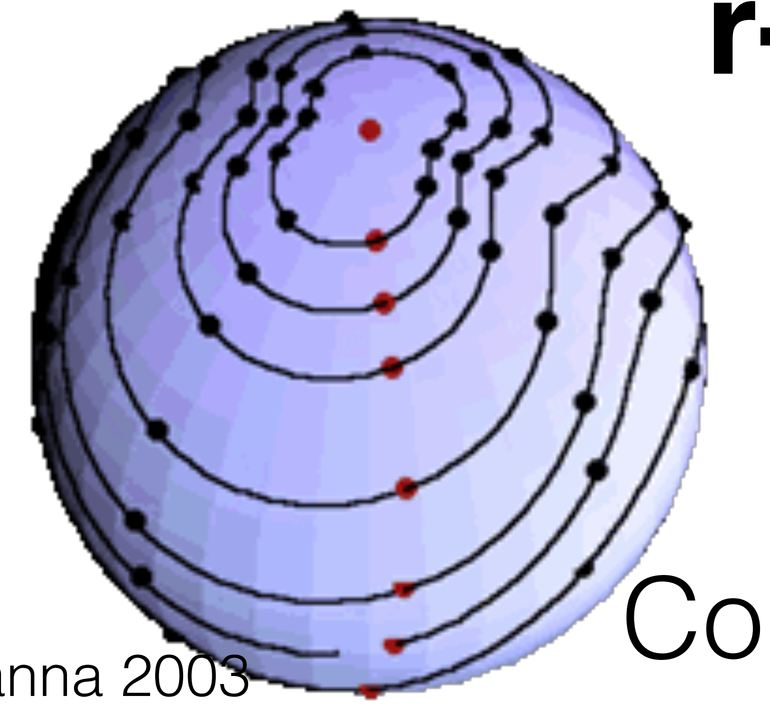
Normal neutron matter   Strange quark star

Constraining maximum ellipticity can constrain NS interior

GWs from isolated NSs

Emission mechanisms

r-modes



C. Hanna 2003

Coriolis restoring force

r-modes unstable to GW emission

Could be main mechanism by which young NSs are spun down

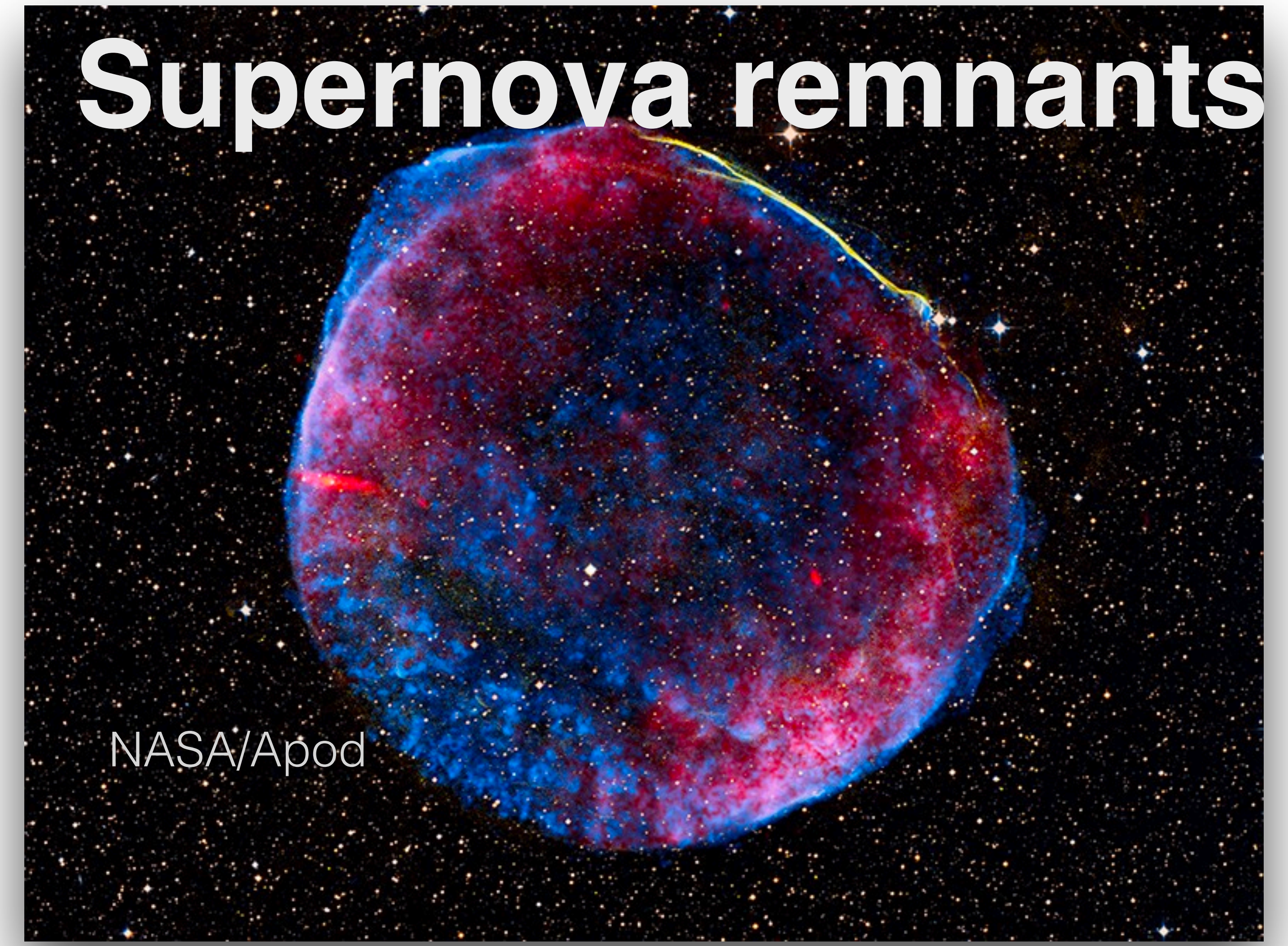
Lindblom et al., PRD **80**, 4843 (1998)
Andersson, ApJ 502, 2 (1998)
Haskell, IJMP E 24 (2015)

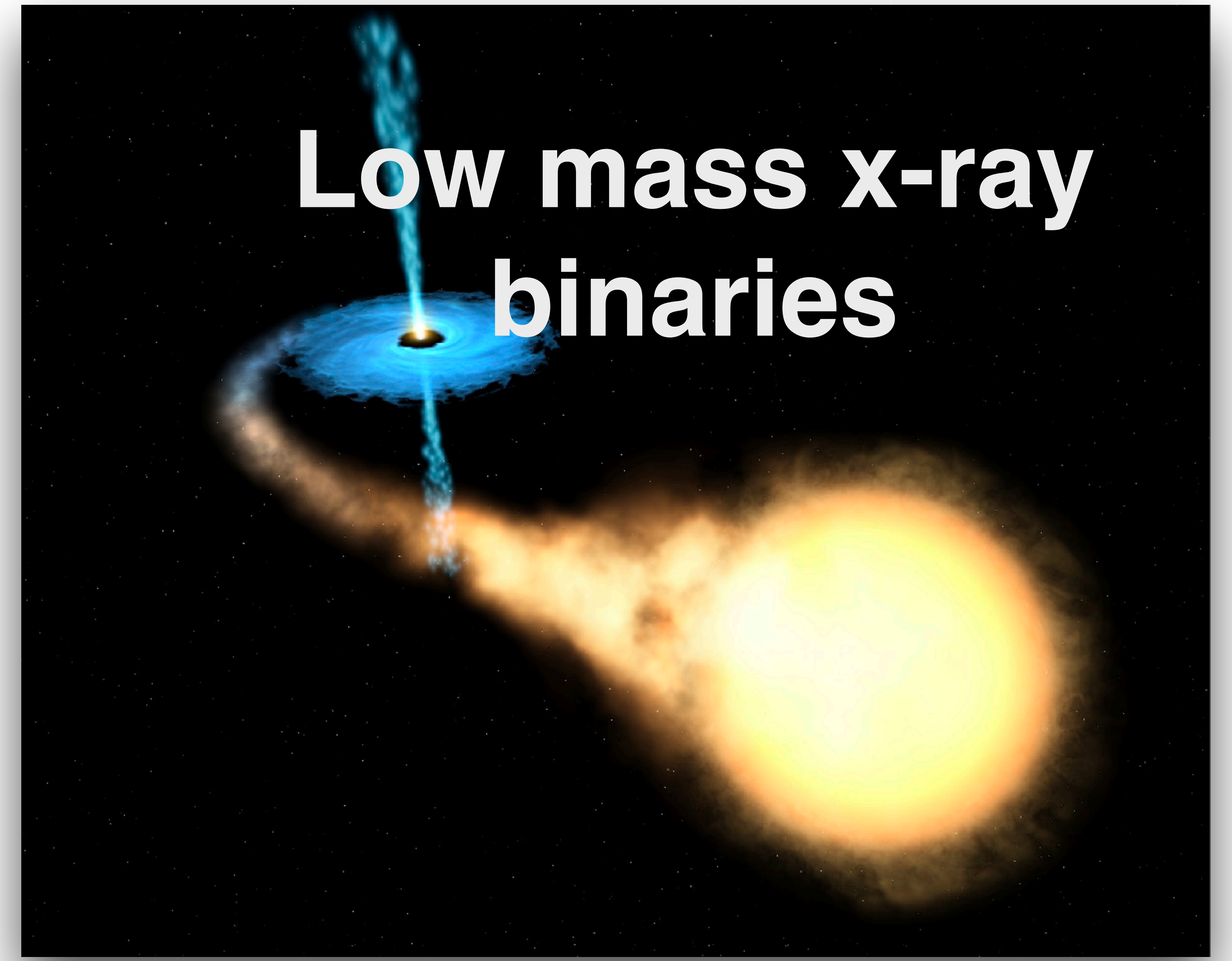
GWs from isolated NSs

Sources

- Very good frequency information vi EM counterparts
- Or, useful to test relation between crust & core rotation

-Youngest known NSs
- Possible r-mode source





- NS accreting
- Possibly in torque balance

GWs from isolated NSs

Recent search results & prospects

- No detection yet, but beginning to beat indirect spin-down limit
  - Known pulsars: LVK, *ApJ* **935** 1 (2022)
  - Constraints on r-mode emission: LVK, *ApJ* **922** 71 (2021)
- Future prospects:
  - Detection prospects scale with detector sensitivity and observation time

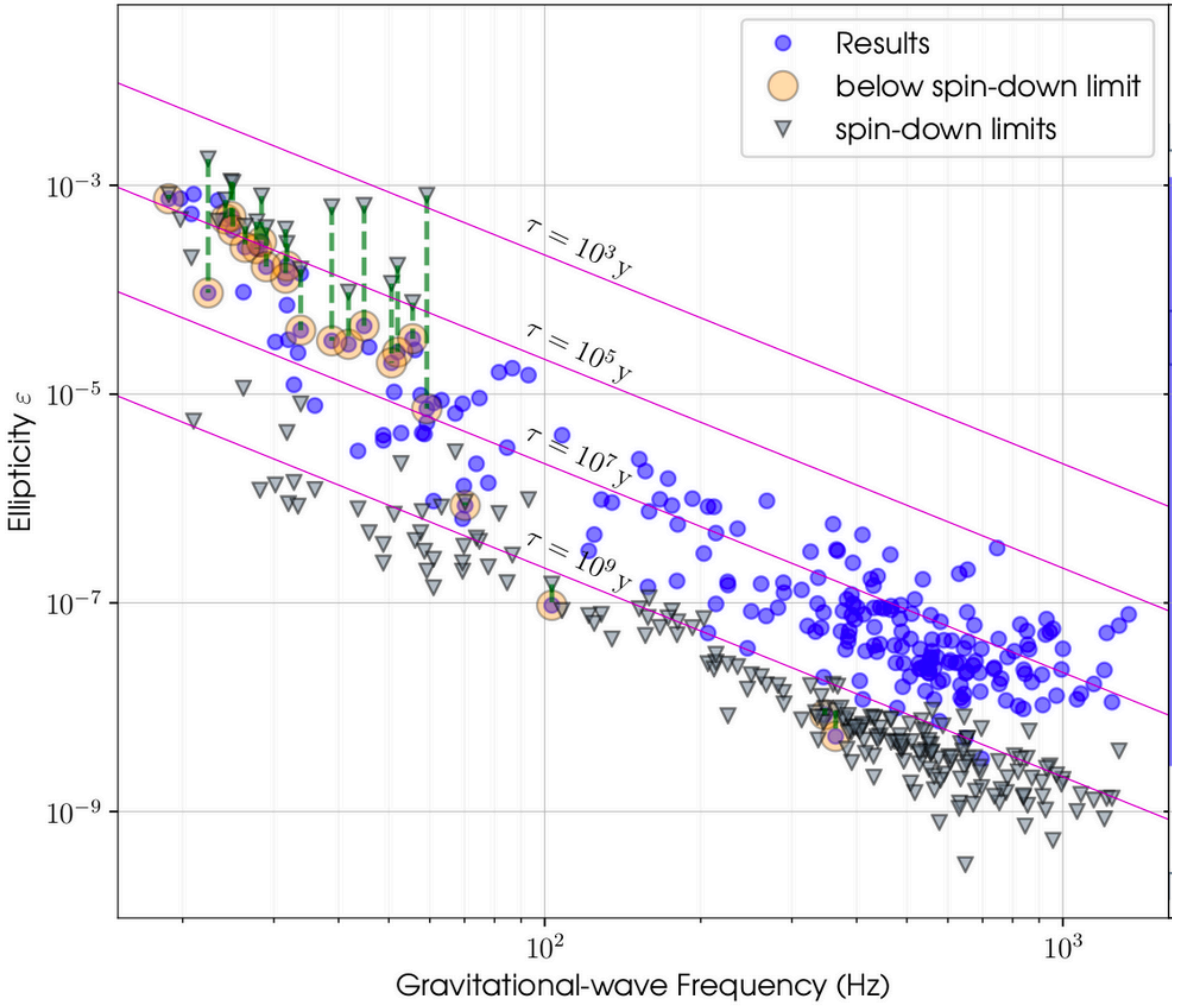
$$\rho^2 \sim h_0^2 \frac{T}{S_n}$$

Observation time

S/N

Noise

  - Better detectors will help, but so will longer observing campaigns — but keep in mind computing cost!



arXiv:2111.13106

Summary

- Improved detectors crucial for understanding NS matter
    - Detectors sensitive at high frequency extra important to make inferences about NSs in pre- and post-merger phase
- Think beyond binary mergers!
    - Continuous gravitational waves could give info on maximum ellipticity, or presence of *r*-modes