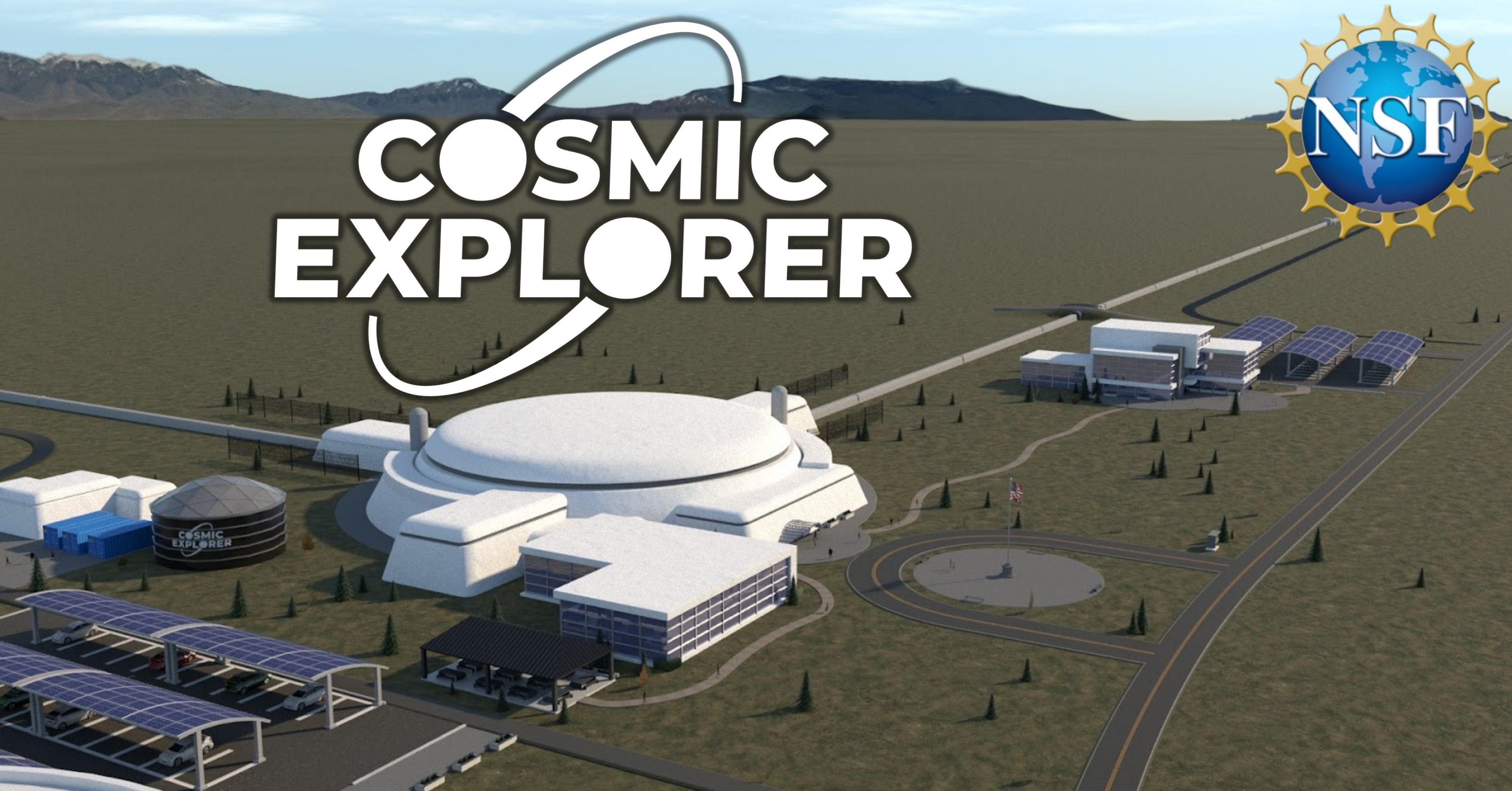

THE ONASSIS FOUNDATION
SCIENCE LECTURE SERIES

The 2022 Lectures in Physics

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ONASSIS EDUCATION

Cosmic Explorer

- LIGO has been very successful, but the next big step in gravitational-wave science will require new facilities
- Cosmic Explorer is a larger, and more technically advanced version of the current LIGO observatories
  - Two observatories: one 40km (25 miles) and the other 20km on a side

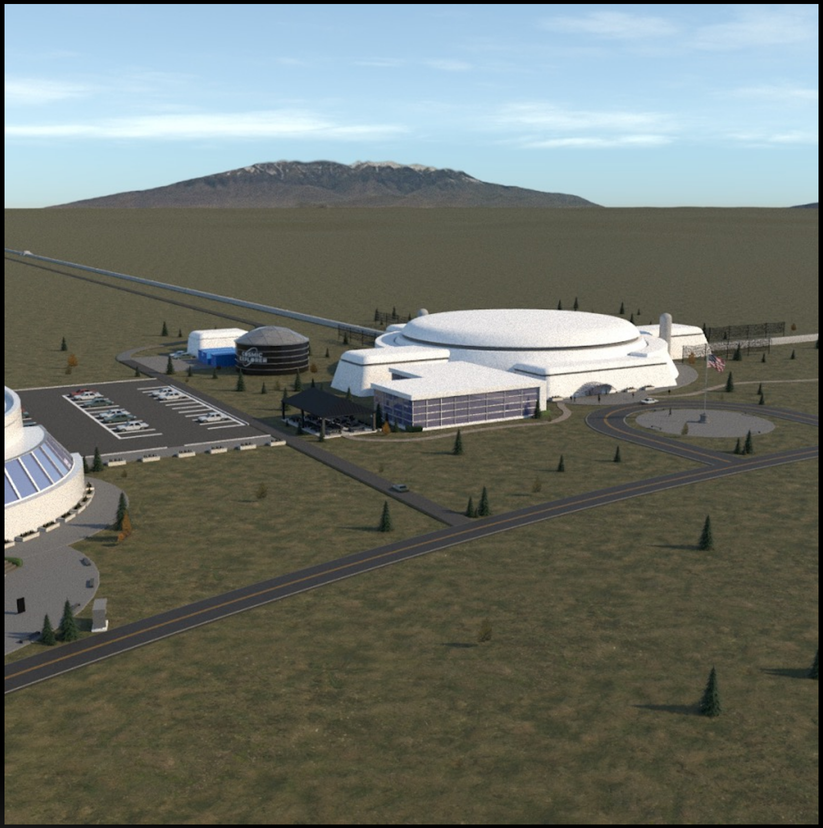
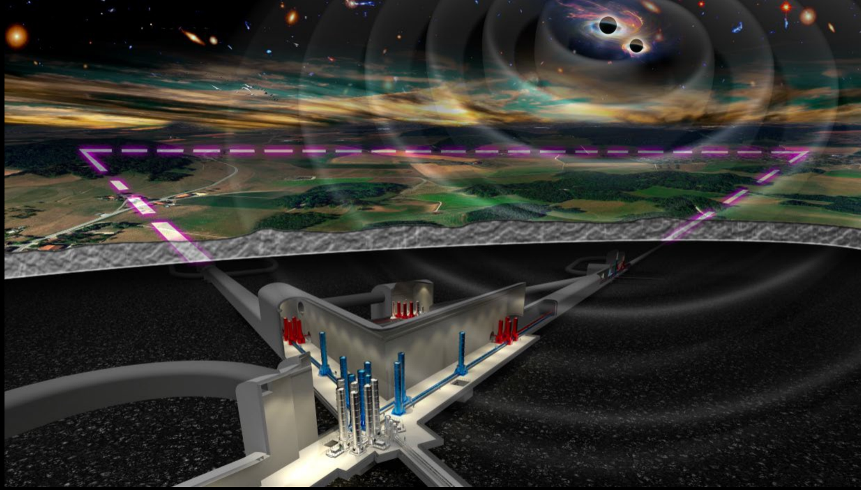


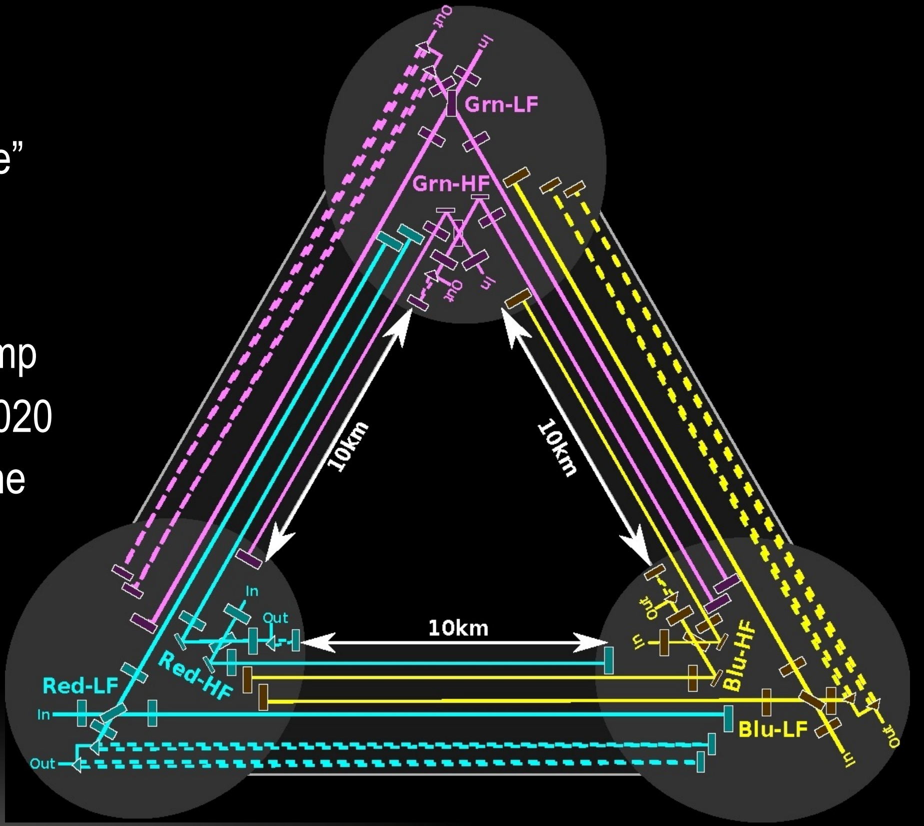
Image: Eddie Anaya (Cal State Fullerton)

COSMIC EXPLORER

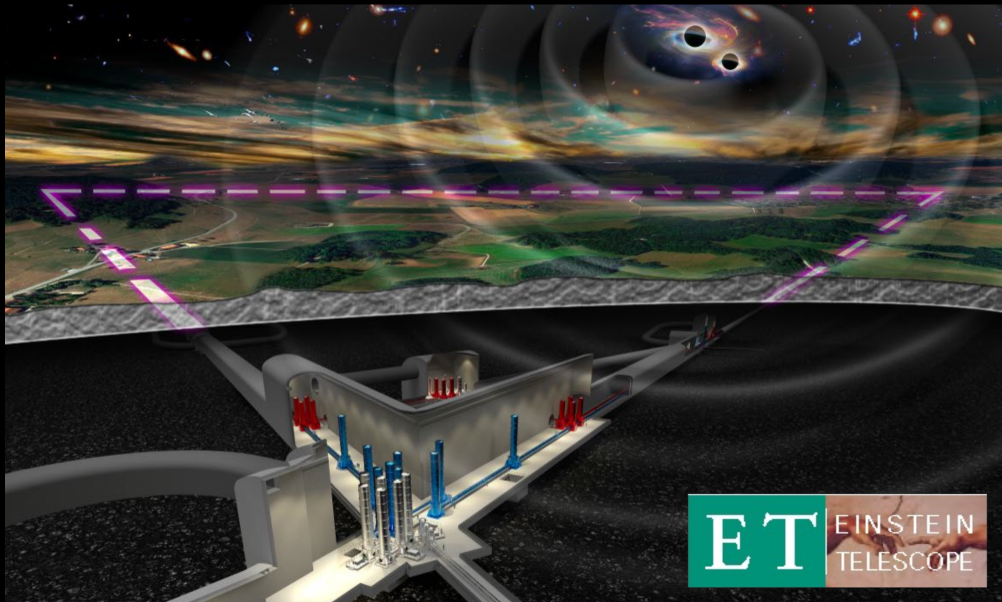
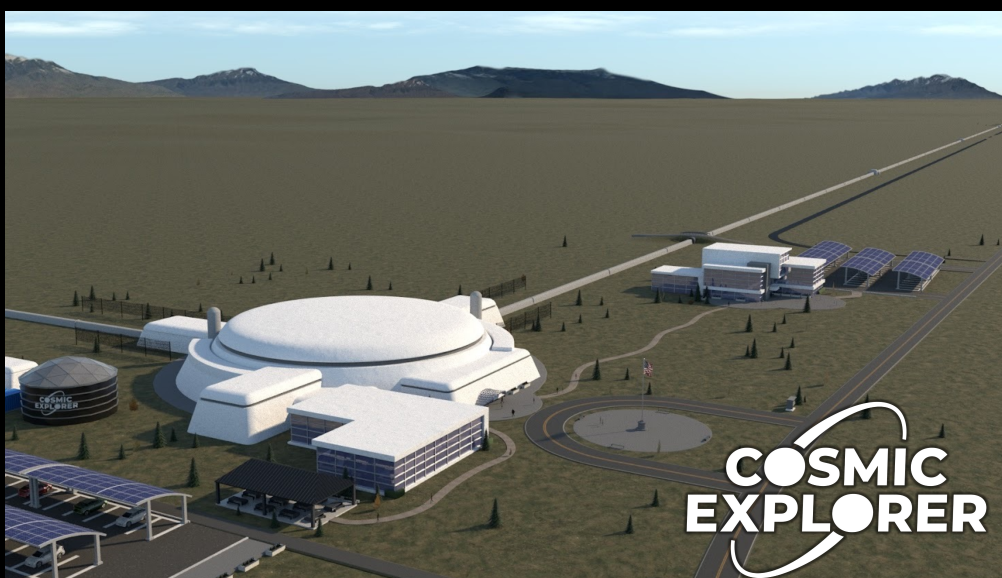
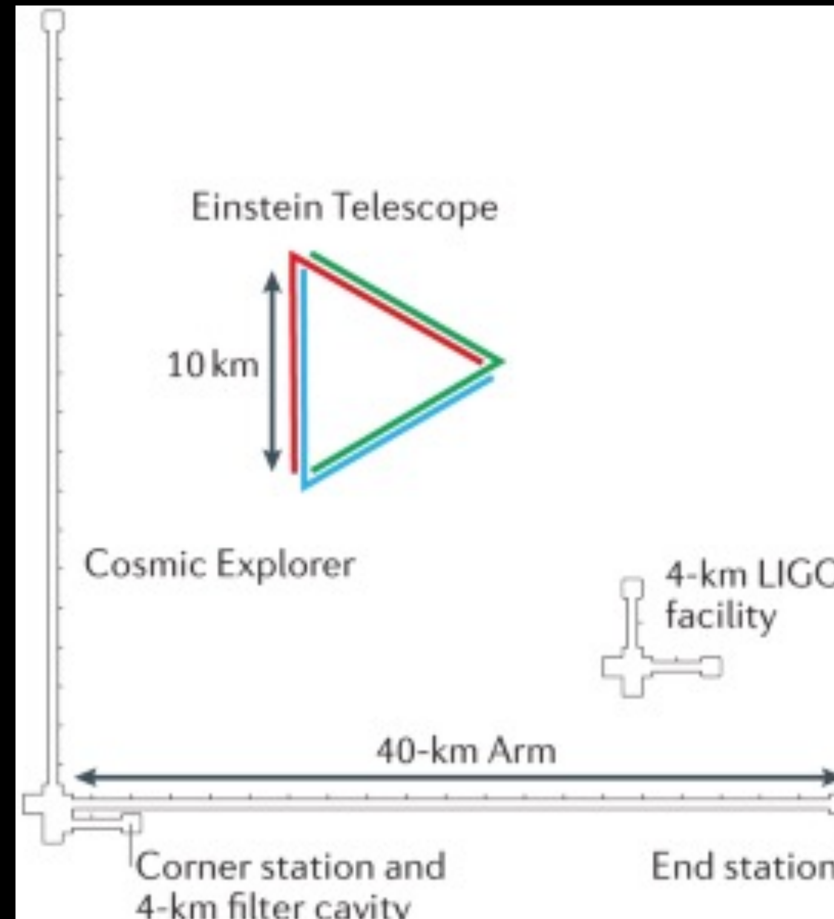
Einstein Telescope (ET)

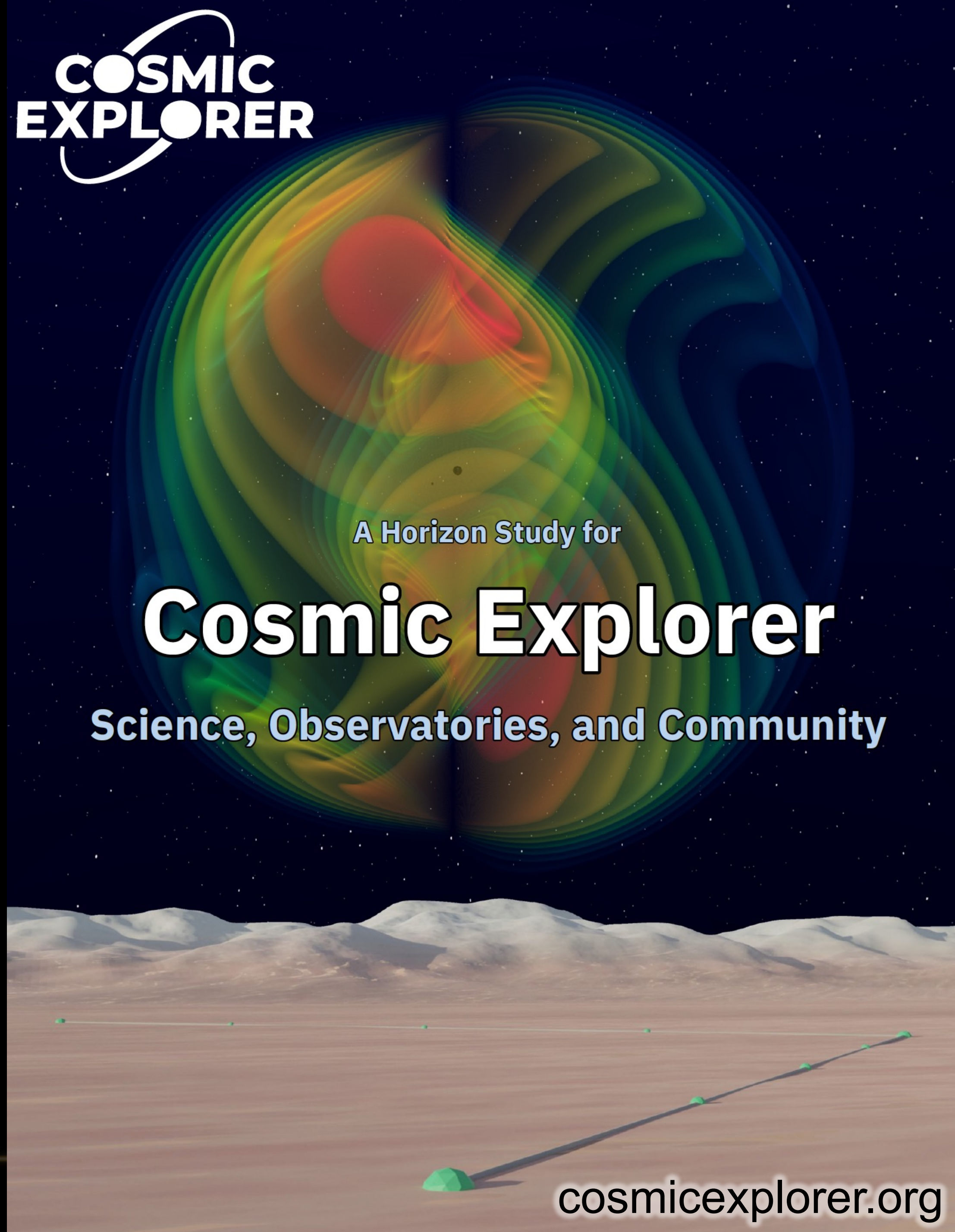
- Underground; in Eurome
- Six detectors arranged in a triangle
  - ⇒ sense both GW polarizations
  - ⇒ “null stream” for consistency checks
- Observe down to a few hertz using “xylophone” detectors approach
  - ⇒ low frequency: cryogenic silicon
  - ⇒ high frequency: high power, room temp
- ET Design Report published 2011, updated 2020
- In 2021, ET was included in the roadmap of the European Strategic Forum for Research Infrastructures (ESFRI).

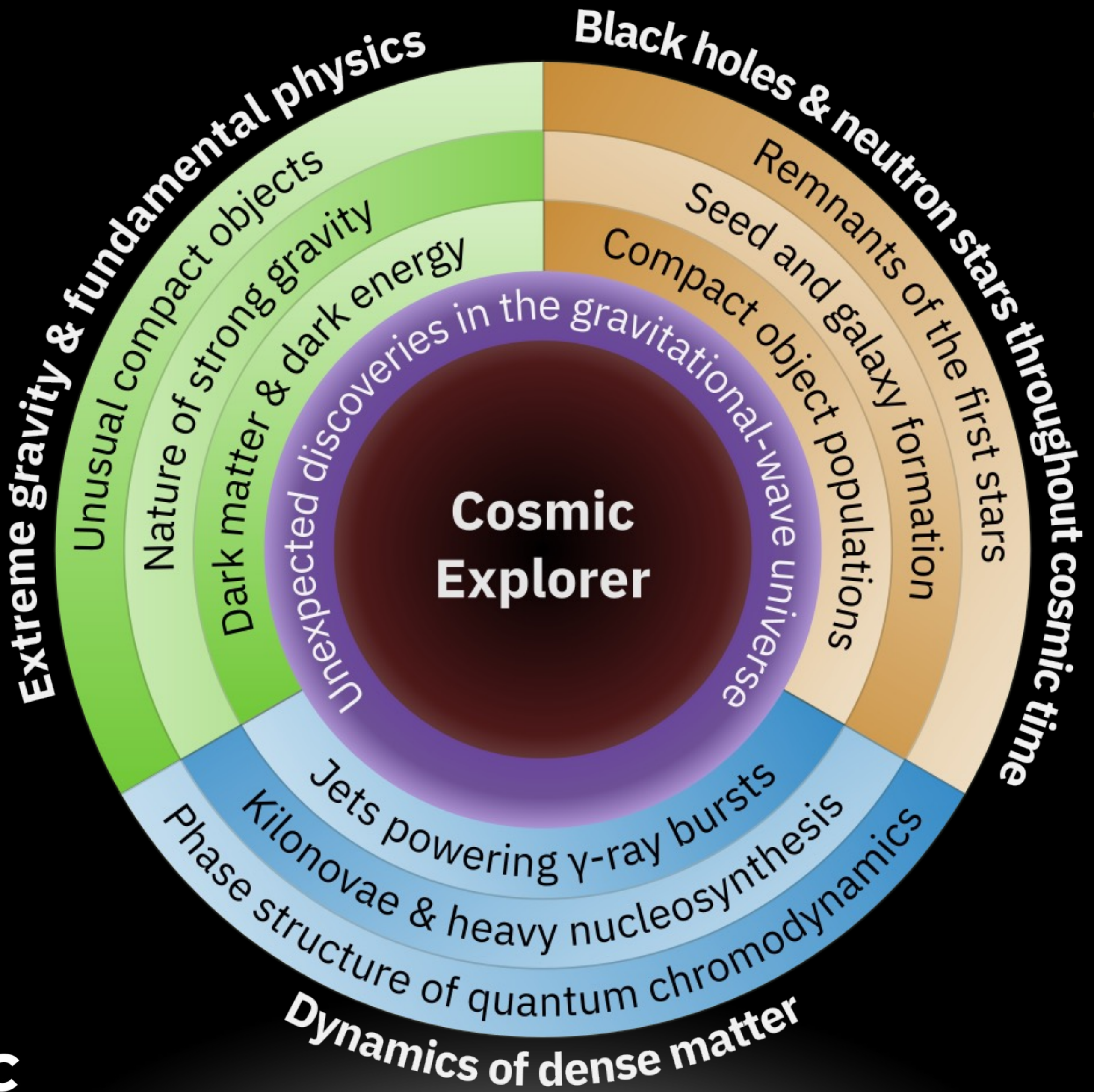




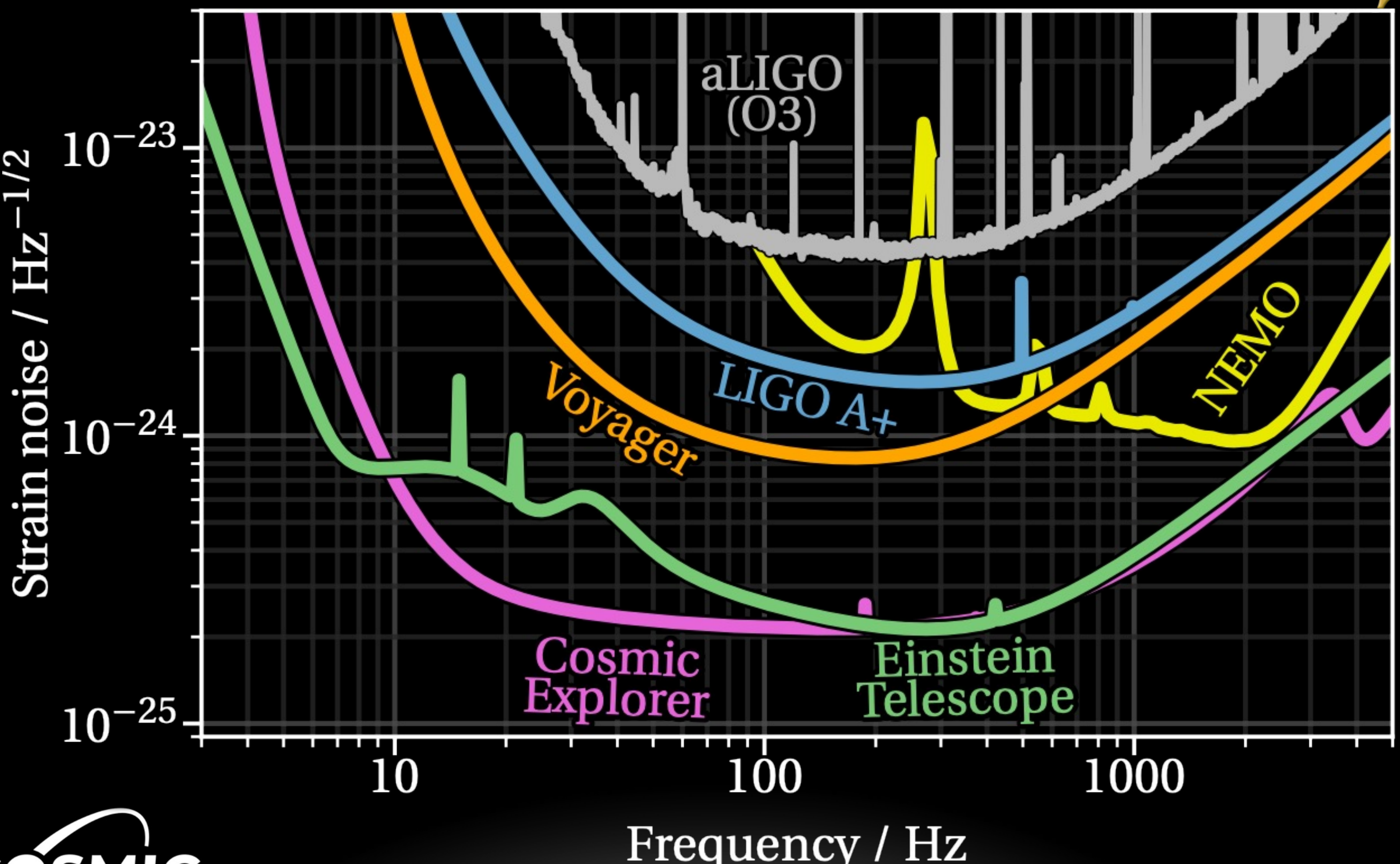
COSMIC EXPLORER

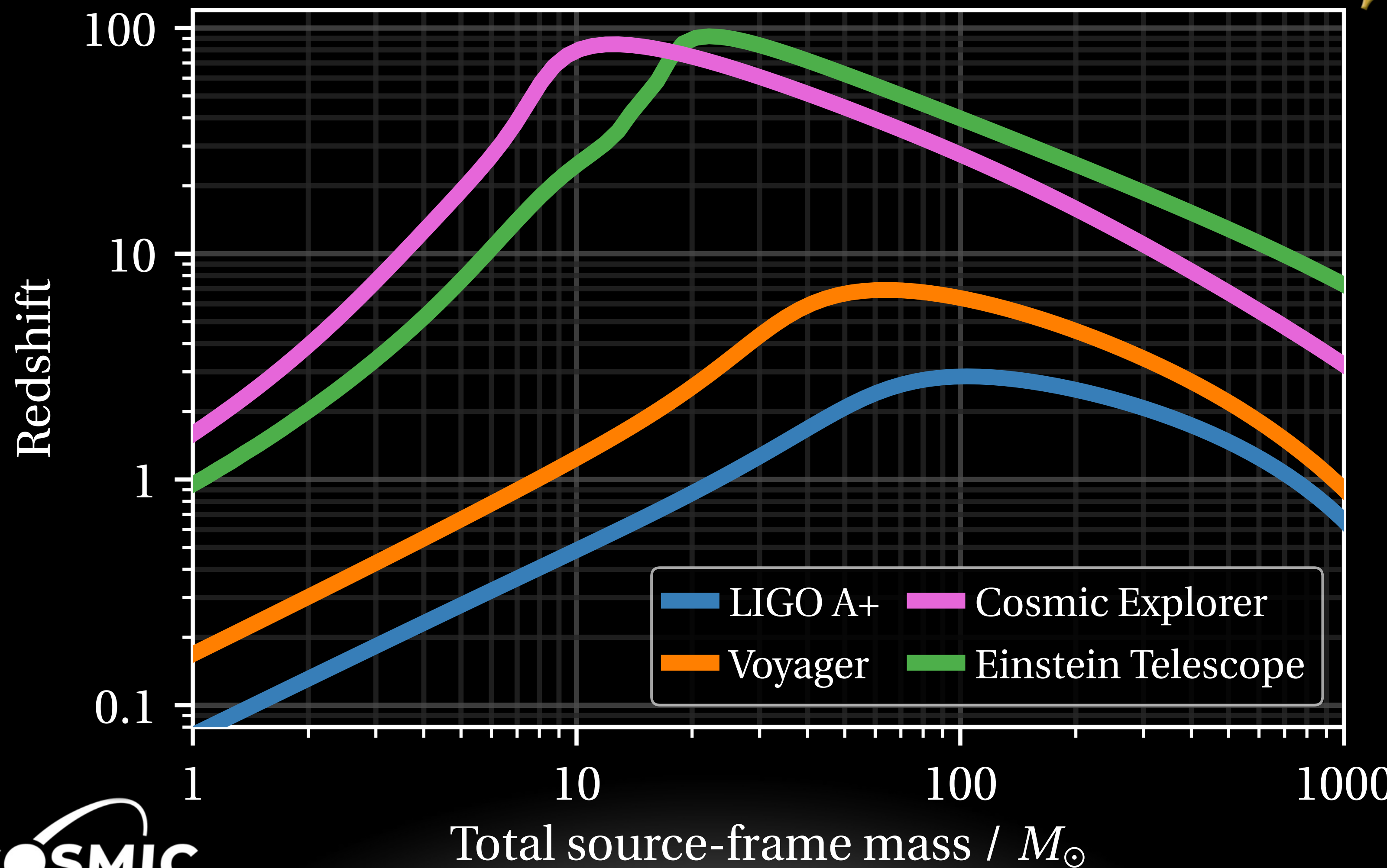

ET
EINSTEIN
TELESCOPE

COSMIC
EXPLORER

Einstein Telescope
10 km
Cosmic Explorer
4-km LIGO facility
40-km Arm
Corner station and 4-km filter cavity
End station


COSMIC EXPLORER
A Horizon Study for
Cosmic Explorer
Science, Observatories, and Community
cosmicexplorer.org

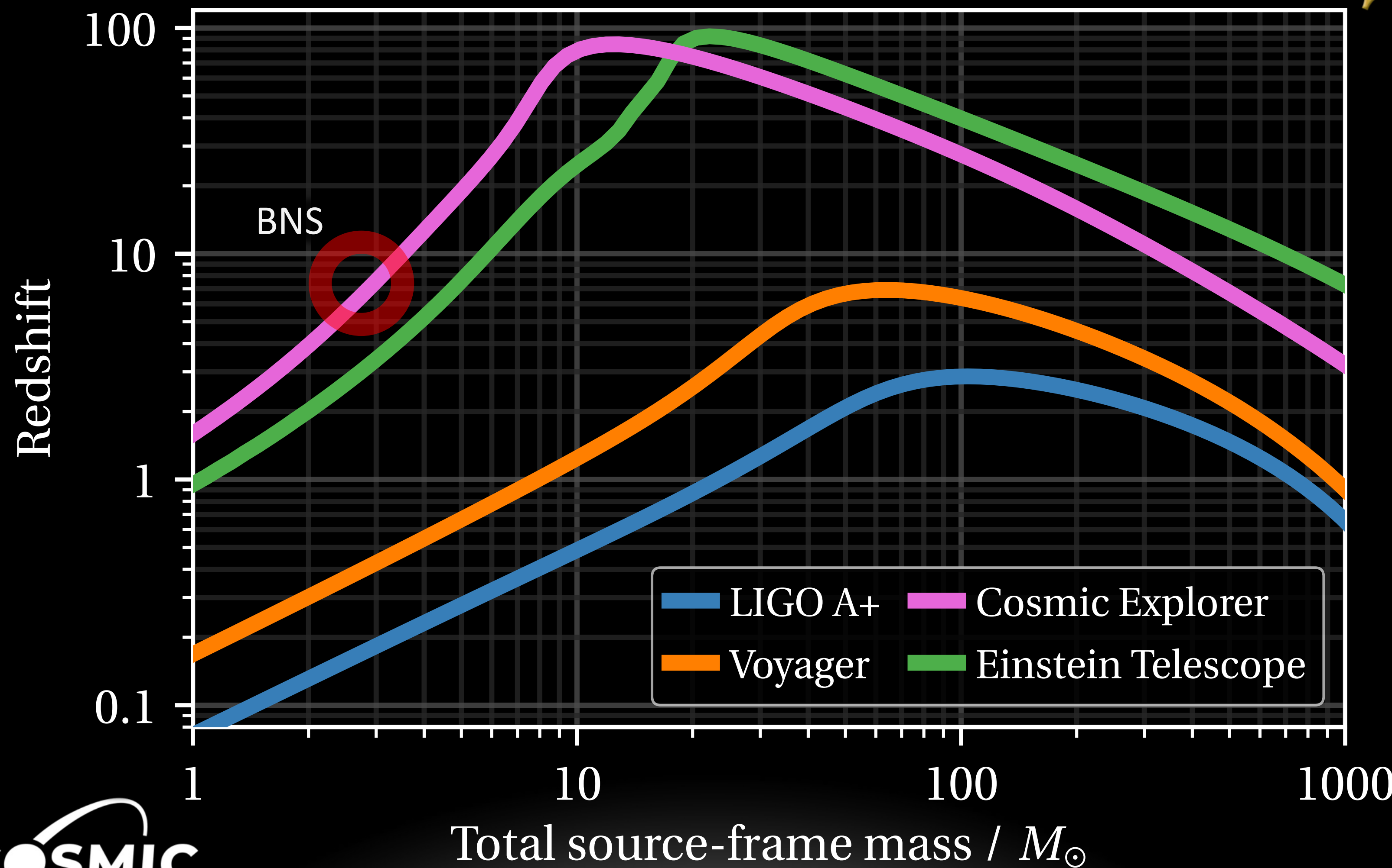


COSMIC EXPLORER

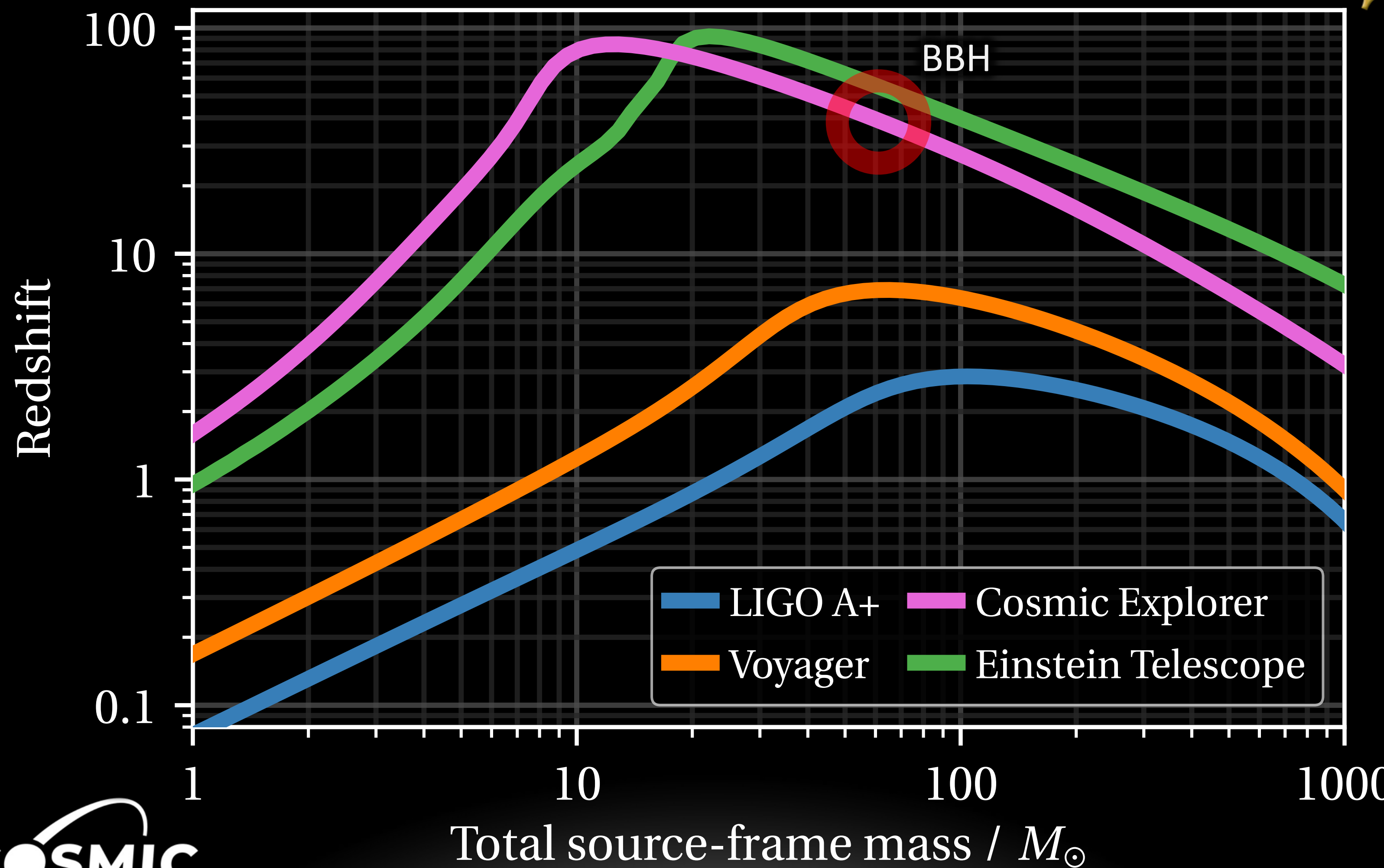

aLIGO (O3)
LIGO A+
Voyager
NEMO
Cosmic Explorer
Einstein Telescope
10^{-23}
10^{-24}
10^{-25}
Strain noise / $Hz^{-1/2}$
10
100
1000
Frequency / Hz



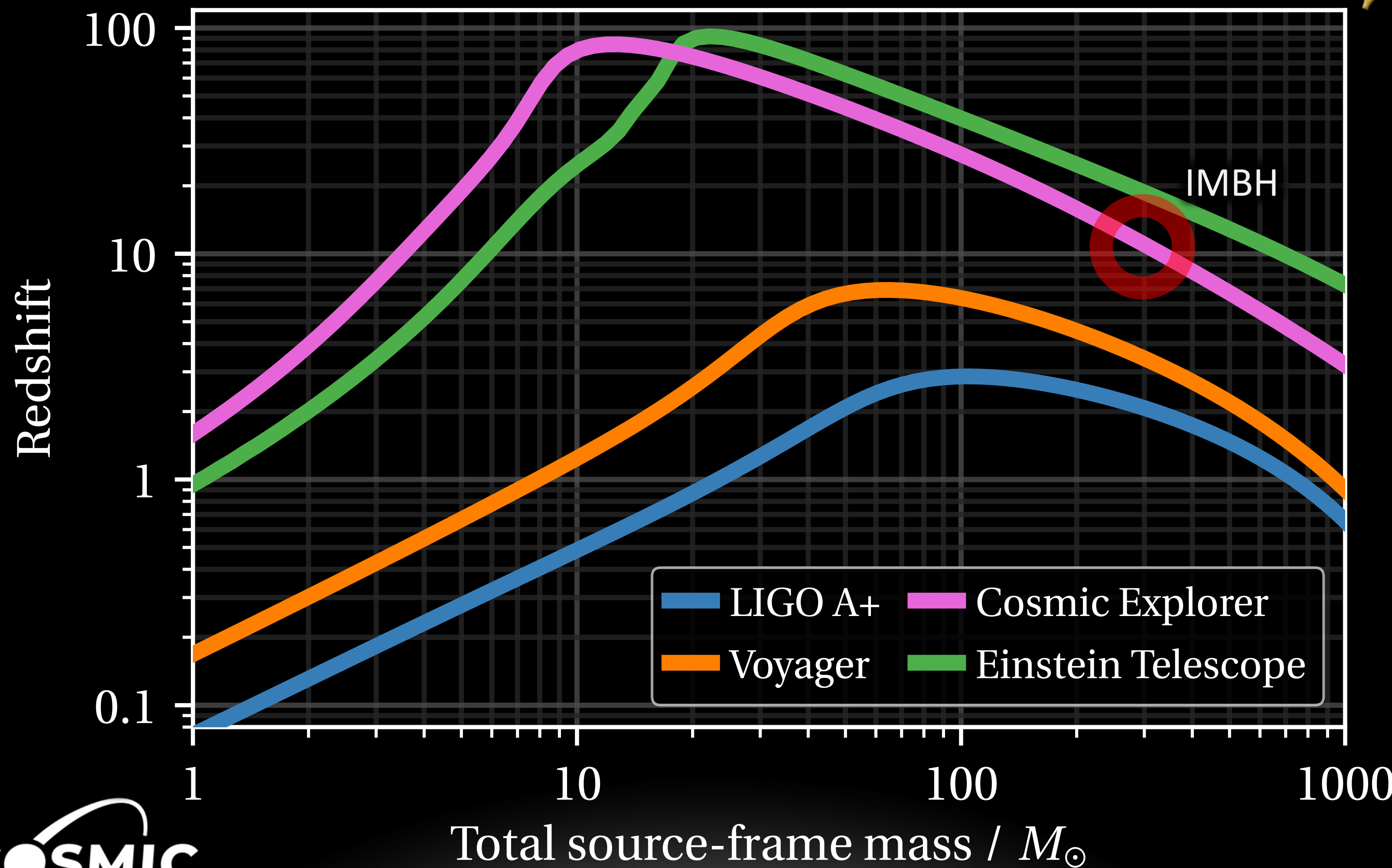
100
10
1
0.1
Redshift
1
10
100
1000
Total source-frame mass / $M_\odot$
LIGO A+
Cosmic Explorer
Voyager
Einstein Telescope



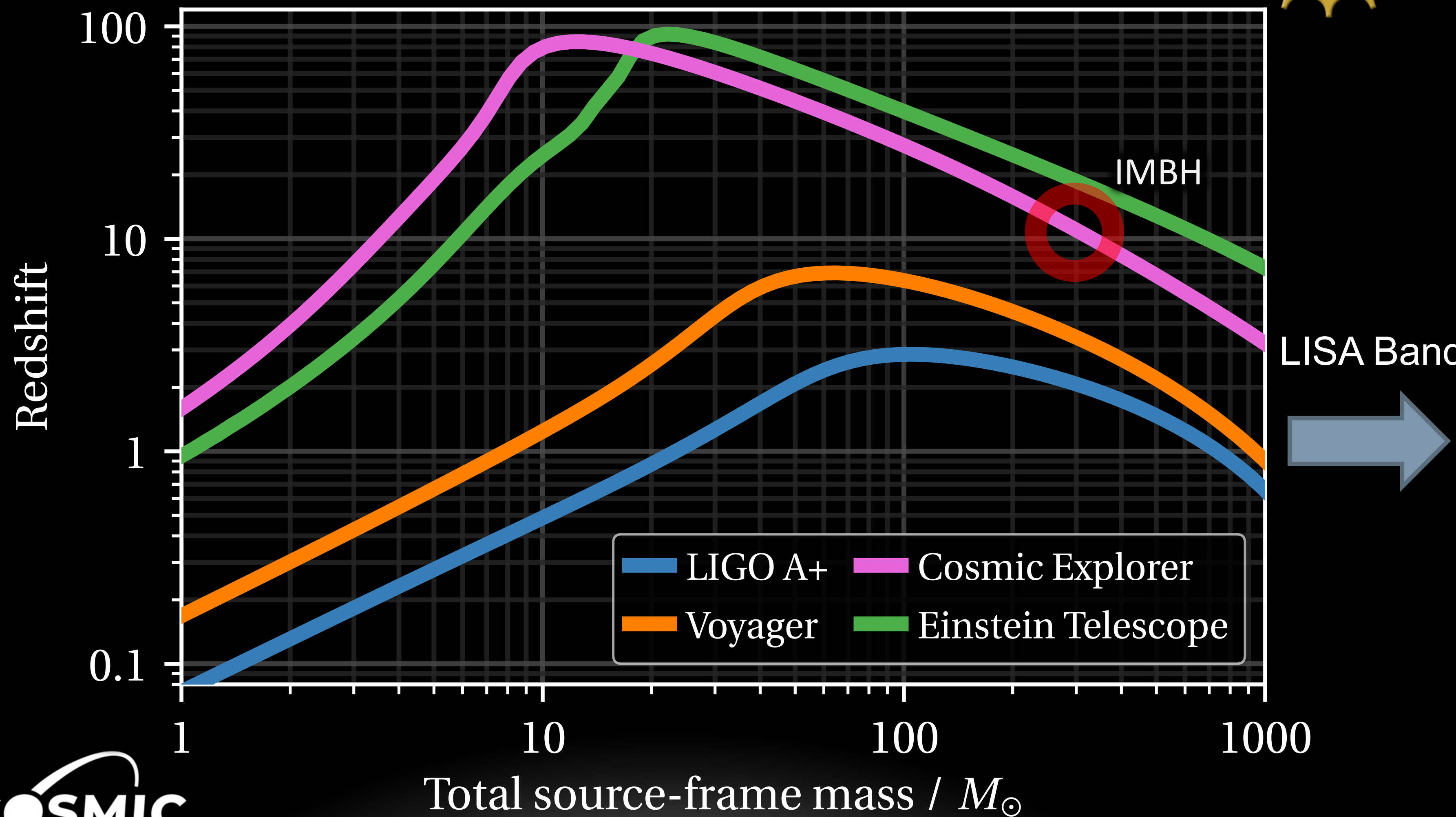
100
10
1
0.1
Redshift
BNS
1
10
100
1000
Total source-frame mass / $M_\odot$
LIGO A+
Cosmic Explorer
Voyager
Einstein Telescope



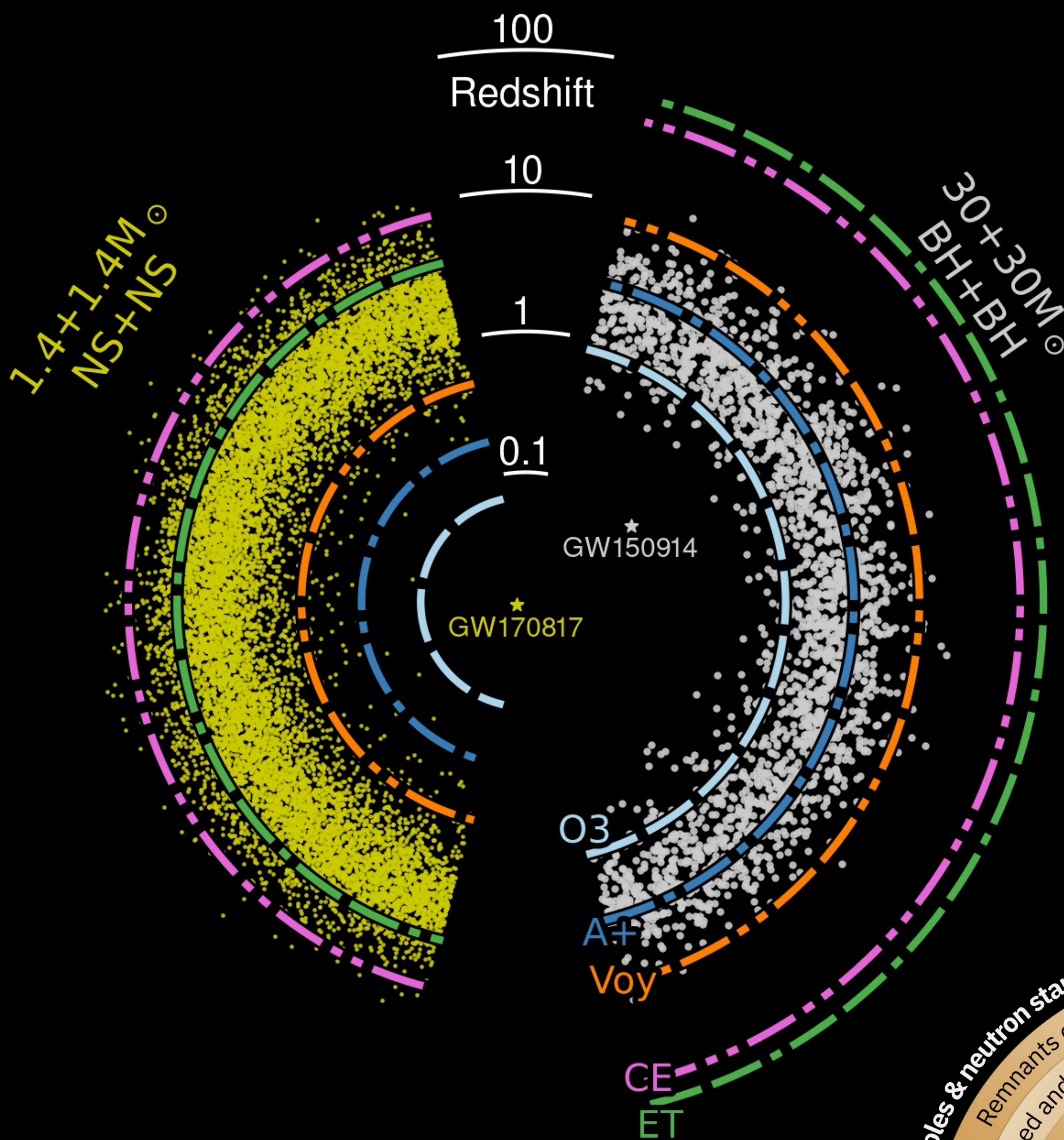
100
10
1
0.1
Redshift
BBH
1
10
100
1000
Total source-frame mass / $M_\odot$
LIGO A+
Cosmic Explorer
Voyager
Einstein Telescope

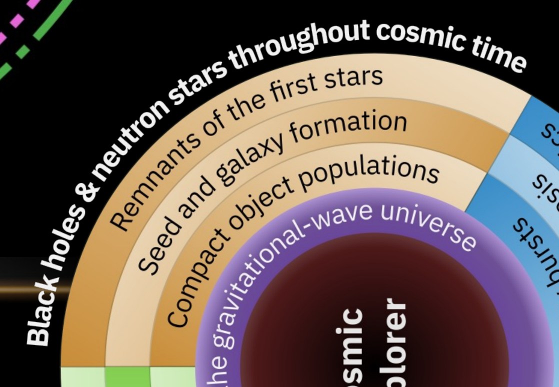


100
10
1
0.1
Redshift
1
10
100
1000
Total source-frame mass / $M_\odot$
IMBH
LIGO A+
Cosmic Explorer
Voyager
Einstein Telescope


100
10
1
0.1
Redshift
1
10
100
1000
Total source-frame mass / $M_{\odot}$
IMBH
LISA Band
LIGO A+
Cosmic Explorer
Voyager
Einstein Telescope

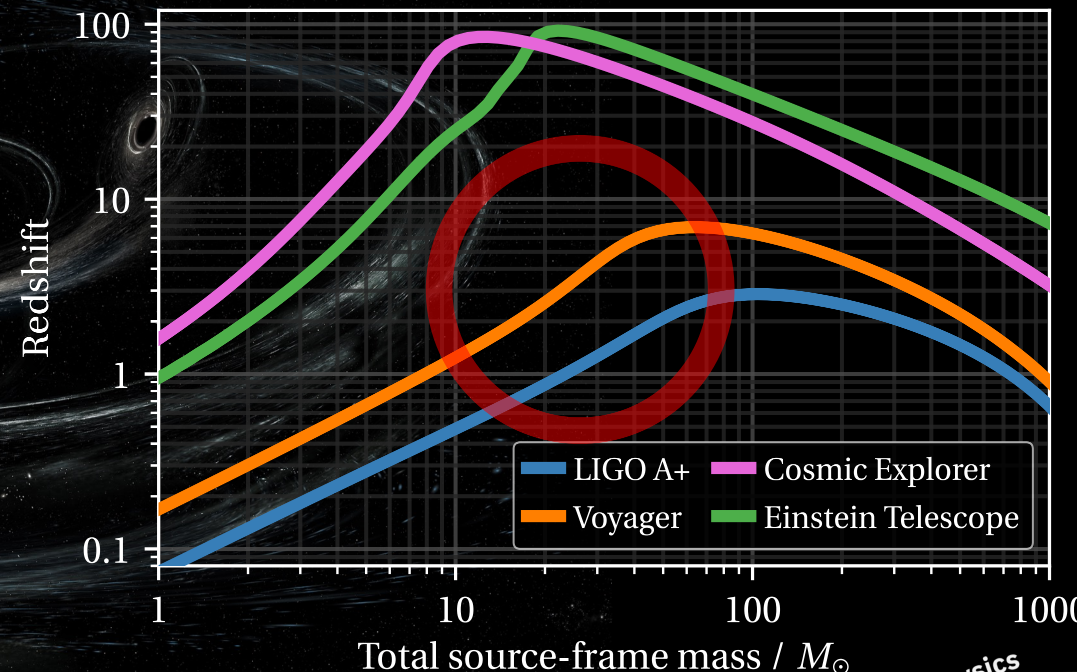
Black Holes & Neutron Stars Throughout Cosmic Time





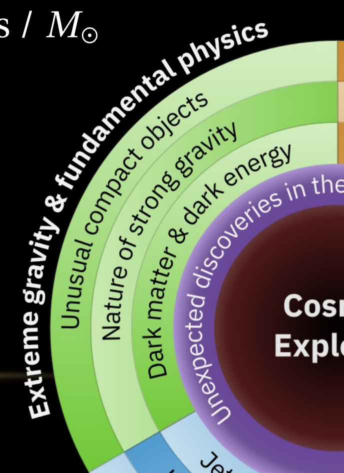
Precision tests will be enabled by black hole mergers like those seen now (~30 solar mass, at z ~ 0.3), which will have an SNR ~ 1000 in CE.

Extreme Gravity & Fundamental Physics



With thousands of BBH events per day, we will be able to cherry pick the most telling events (high spins, large kicks, edge-on, high ellipticity, etc.).

COSMIC EXPLORER



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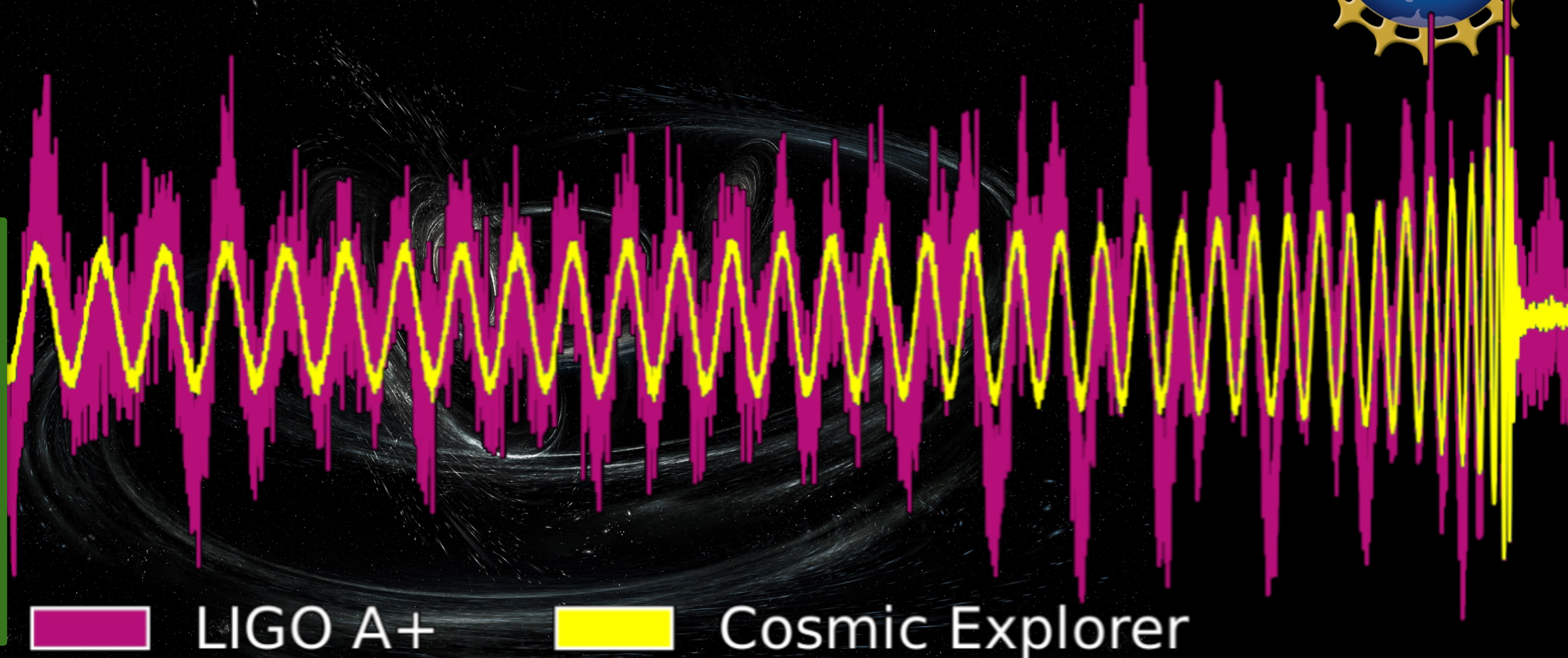
Extreme Gravity & Fundamental Physics



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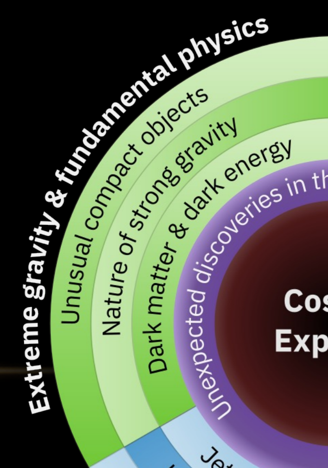
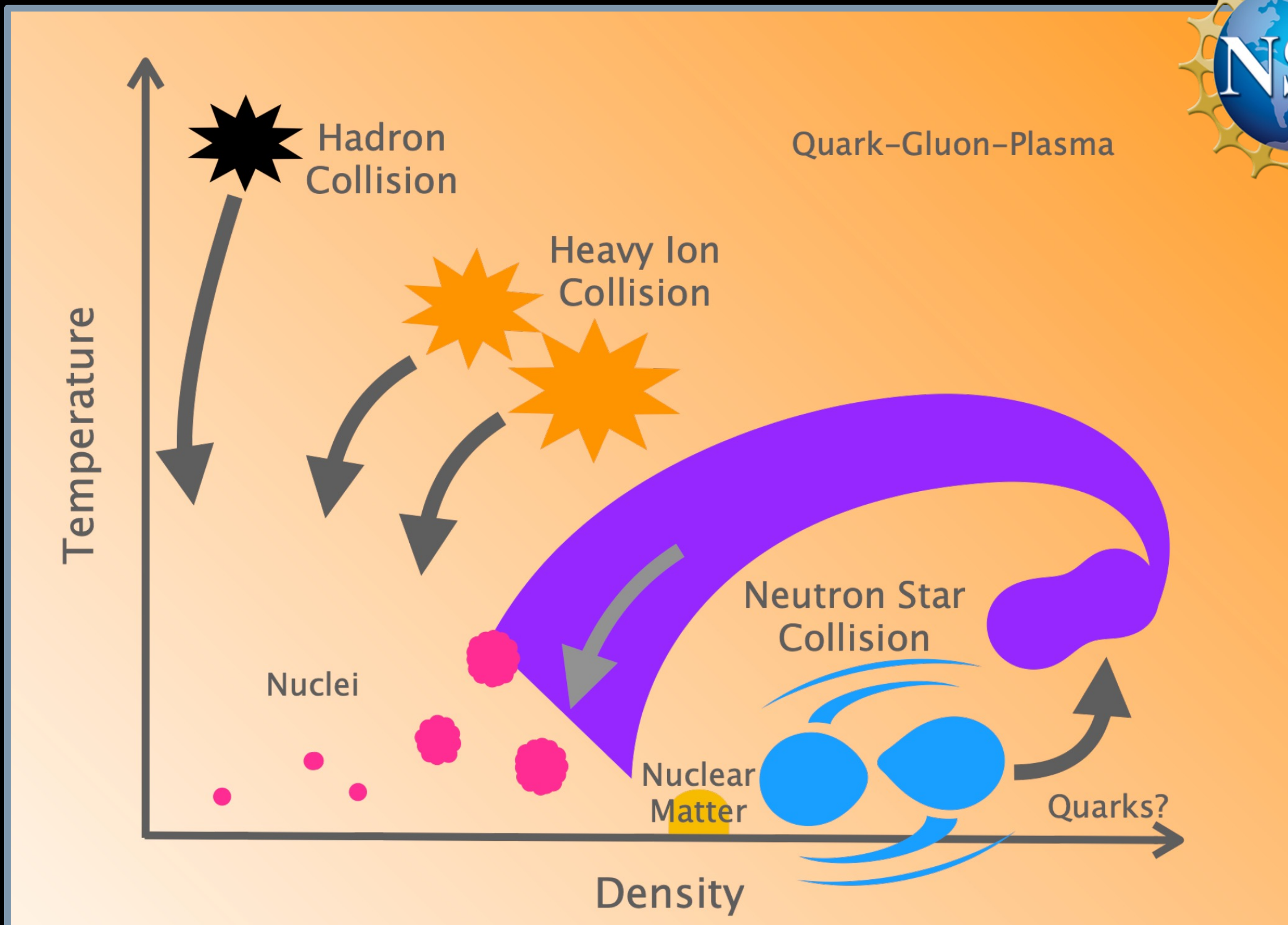
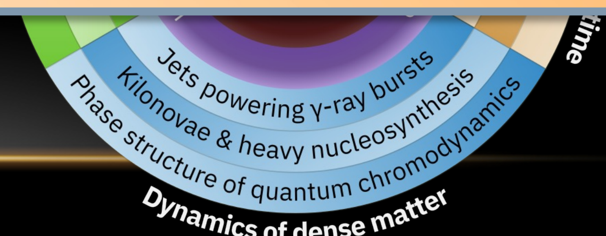


COSMIC EXPLORER

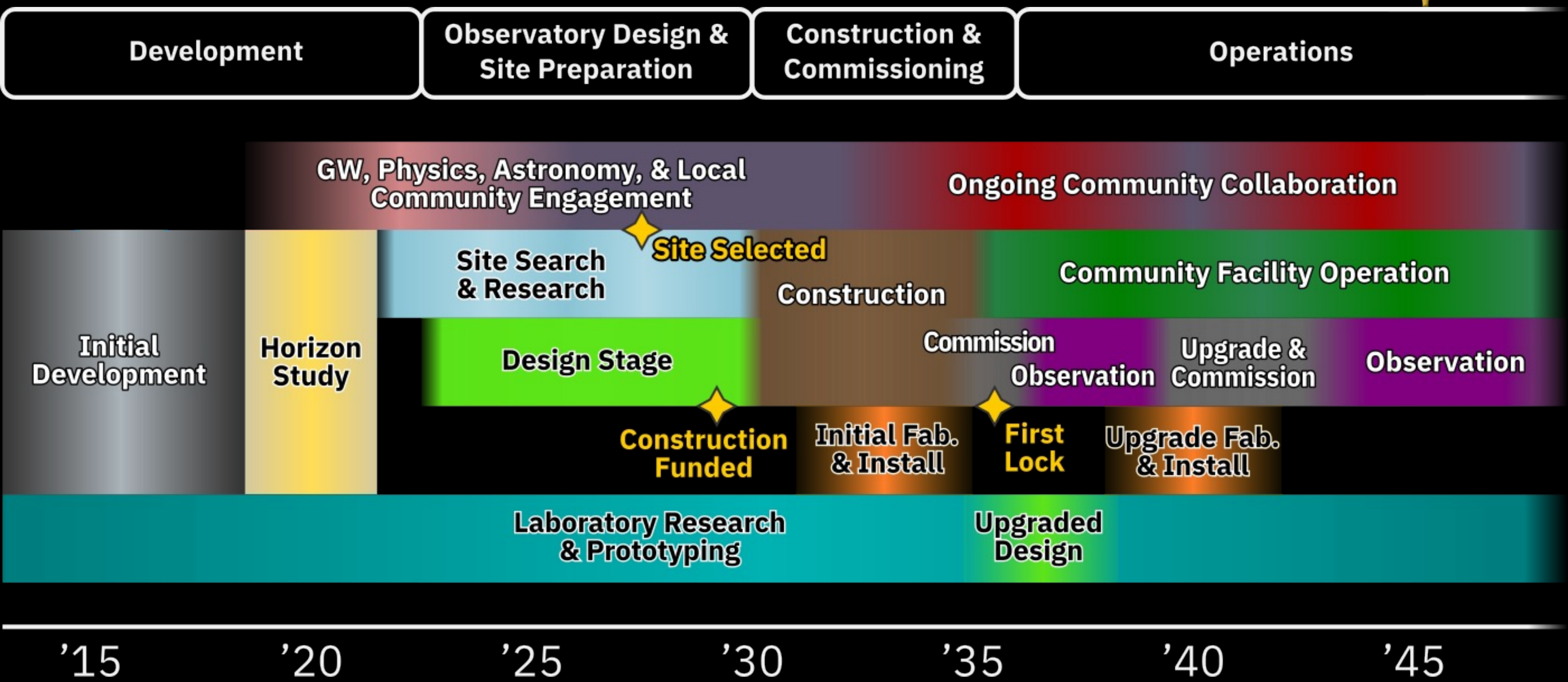
Dynamics of Dense Matter & Extreme Environments





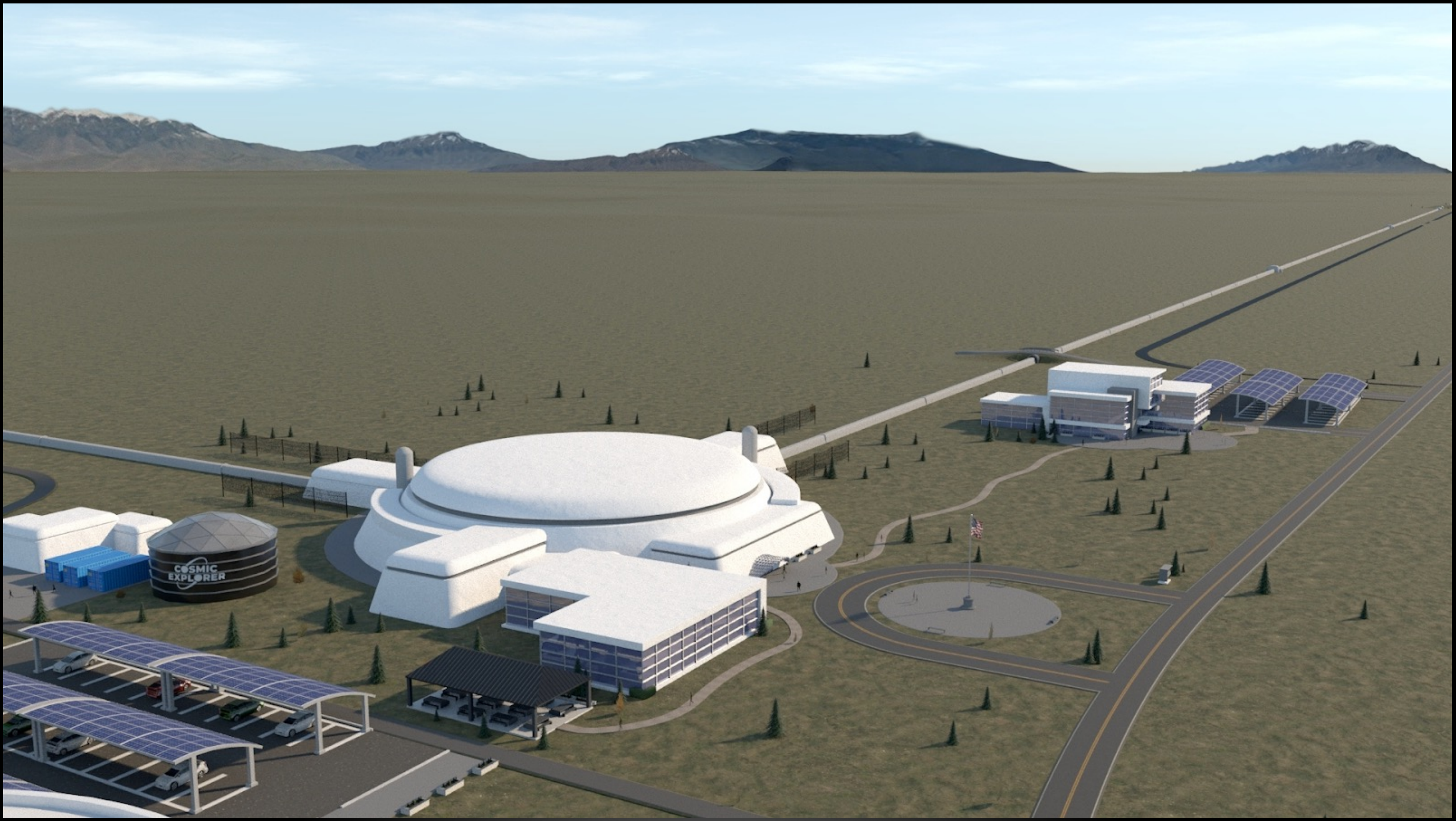
COSMIC EXPLORER

Cosmic Explorer Timeline

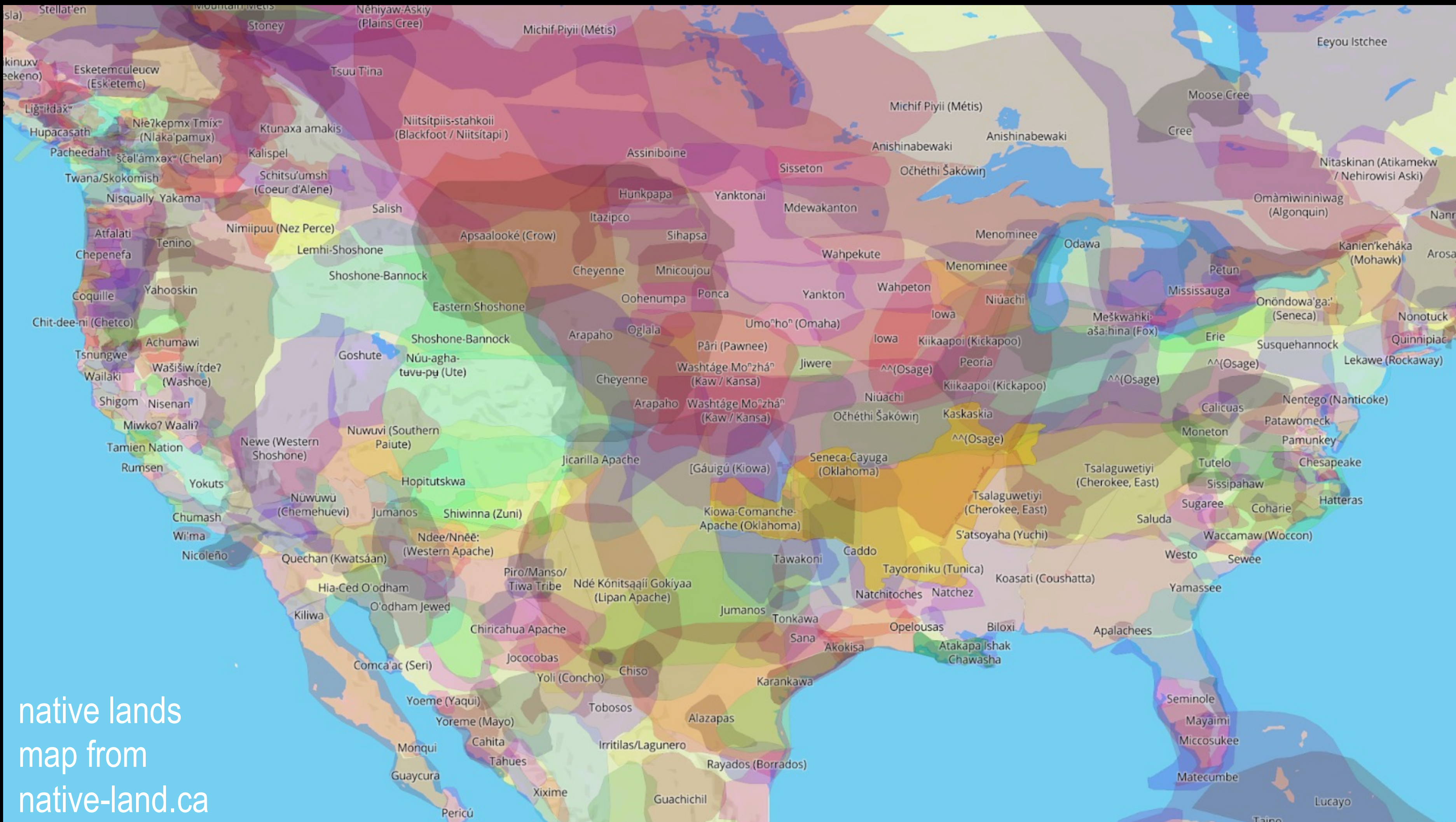


COSMIC EXPLORER

Cosmic Explorer



Cosmic Explorer



native lands map from native-land.ca

Cosmic Explorer

We live and work on the unceded ancestral lands of Indigenous peoples.

I, together with the Cosmic Explorer team, acknowledge these Indigenous communities and their stewardship of the land, past, present and future.

The Cosmic Explorer team is committed to building long-lasting synergistic relationships with Indigenous communities in order to align our goals while building trust and mutual respect.

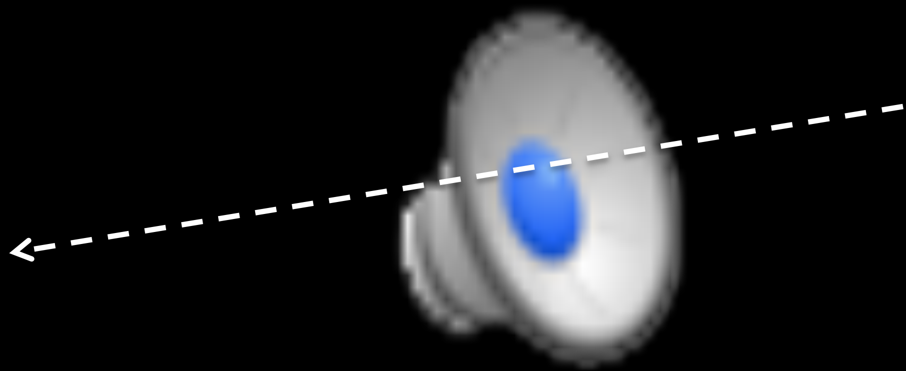
native lands map from native-land.ca

learn more about land acknowledgements at nativegov.org

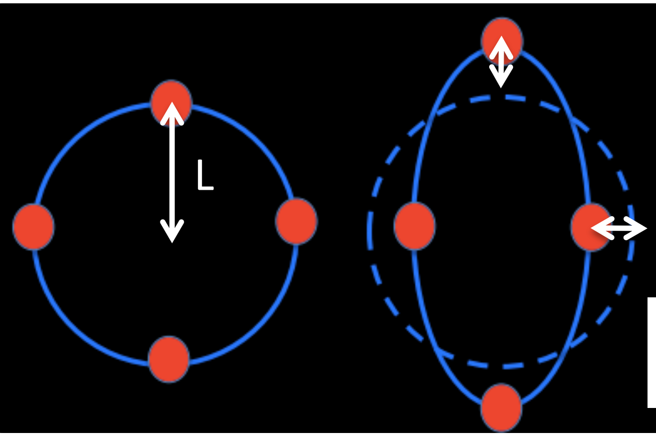
Origin of CE in 2013

- **L**ong
  Uncomplicated
  Next-generation
  Gravitational-wave
  Observatory (LUNGO)
- As a counterpoint to the complicated schemes being contemplated at the time

Gravitational Wave Strain



If you have masses that are free to move, you can (at least in principle) measure the space-time distortion produced by the gravitational wave



Amplitude of the gravitational wave

$$h \sim 10^{-21}$$

$$\Delta L = h \times L = 10^{-21} \times 1000 = 10^{-18} m$$

Why 40km?

- Broadly speaking, the sensitivity of these instruments improves with length
- The bandwidth is, however, limited to roughly

$$\frac{c}{2L} = \frac{3\times 10^5 \frac{km}{s}}{2 \times 40\ km} \simeq 4\ kHz$$

so making a detector longer than 40km would compromise its access to interesting astrophysics (i.e., post-merger signals and supernovae).

Bandwidth vs. Length

- Buonanno: $f_{merger} \sim 4.4\ \mathrm{kHz} \left(\frac{M_\odot}{M}\right)$
  - lightest black hole binaries will merge below $\sim 2\ \mathrm{kHz}$
- Binary Neutron Stars expected to produce post-merger signals around 2-3kHz
- Supernovae may produce significant signal amplitudes up to few kHz
- Detector response (Sutton: "antenna pattern") becomes complicated, and gets smaller, as $f \rightarrow \frac{c}{2L}$

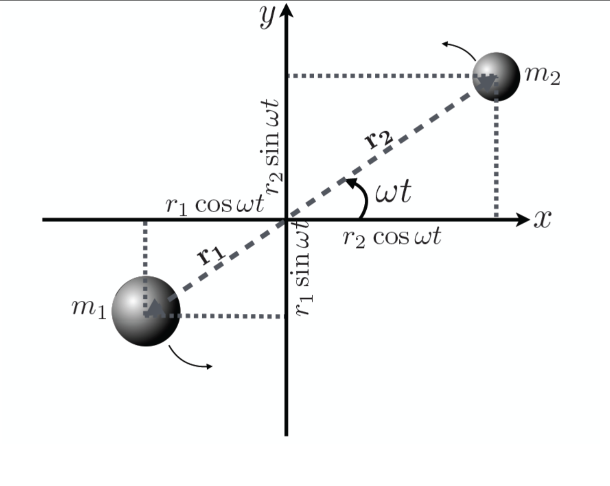
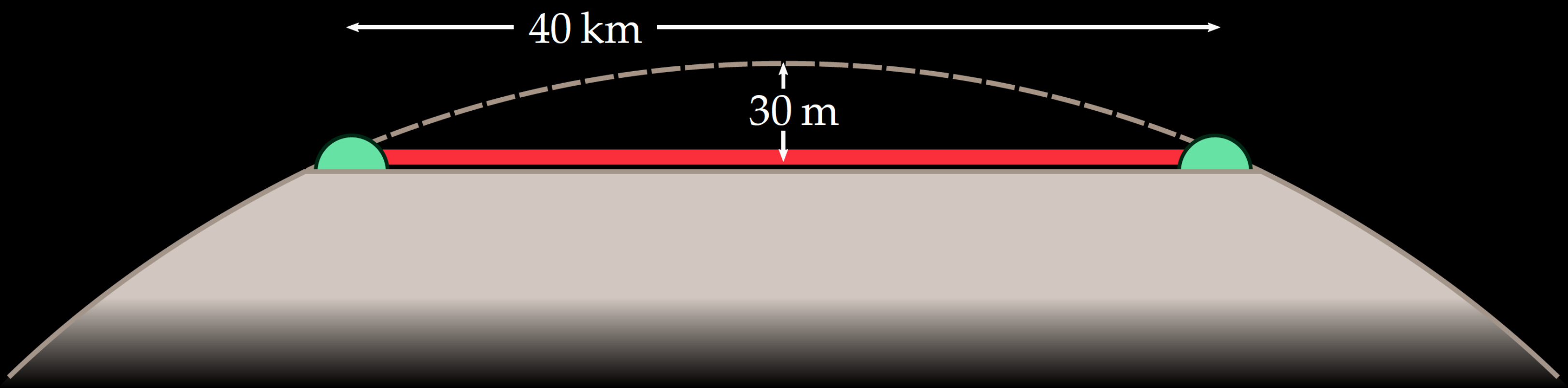
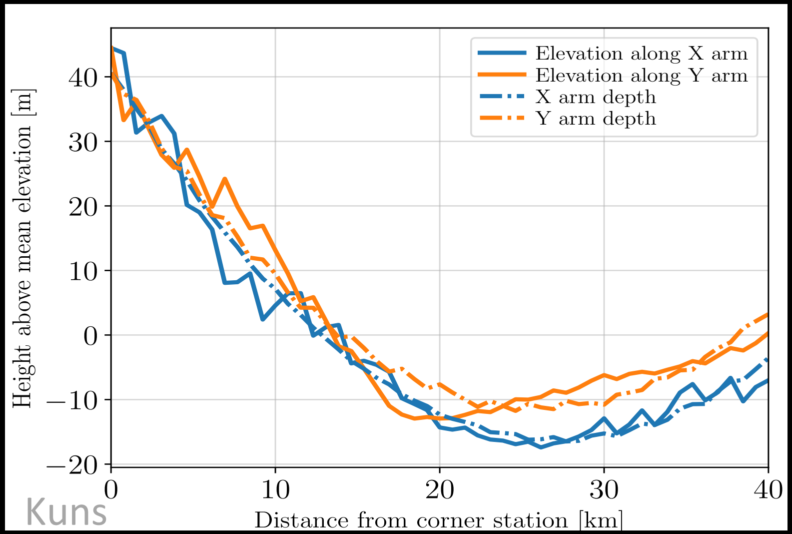


Figure 6 A two-body system, m_1 and m_2 orbiting in the xy-plane around their C.O.M.

40km CE


40 km
30 m


Elevation along X arm
Elevation along Y arm
X arm depth
Y arm depth
Height above mean elevation [m]
Distance from corner station [km]
40
30
20
10
0
−10
−20
0
10
20
30
40
Kuns

How do fundamental noises scale? Just 1/L, right? Nope…

Shot Noise
while maintaining bandwidth

$$\frac{h_{\text{shot}}}{h_{0\,\text{shot}}} = \sqrt{\frac{2\ \text{MW}}{P_{\text{arm}}}} \sqrt{\frac{\lambda}{1.5\ \mu\text{m}}} \left(\frac{3}{r_{\text{sqz}}}\right) \sqrt{\frac{40\ \text{km}}{L_{\text{arm}}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\,\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2\ \text{MW}}} \sqrt{\frac{1.5\ \mu\text{m}}{\lambda}} \left(\frac{3}{r_{\text{sqz}}}\right) \left(\frac{320\ \text{kg}}{m_{\text{TM}}}\right) \left(\frac{40\ \text{km}}{L_{\text{arm}}}\right)^{3/2}$$

B P Abbott *et al* 2017 *CQG* **34** 044001

Coating Thermal Noise
constant loss angle…

$$\frac{h_{\text{CTN}}}{h_{0\,\text{CTN}}} = \sqrt{\frac{T}{123\ \text{K}}} \sqrt{\frac{\phi_{\text{eff}}}{5 \times 10^{-5}}} \left(\frac{14\ \text{cm}}{r_{\text{beam}}}\right) \left(\frac{40\ \text{km}}{L_{\text{arm}}}\right)$$

Residual Gas Noise
facility limit…

$$\frac{h_{\text{gas}}}{h_{0\,\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4 \times 10^{-7}\ \text{Pa}}} \sqrt{\frac{14\ \text{cm}}{r_{\text{beam}}}} \sqrt{\frac{40\ \text{km}}{L_{\text{arm}}}}$$

How do fundamental noises scale? Just 1/L, right? Nope…

Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}}\sqrt{\frac{\lambda}{1.5\ \mu\rm m}}\left(\frac{3}{r_{\rm sqz}}\right)\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{320\ \rm kg}{m_{\rm TM}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

B P Abbott *et al* 2017 *CQG* **34** 044001

Coating Thermal Noise
constant loss angle…

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}}\sqrt{\frac{\phi_{\rm eff}}{5\times10^{-5}}}\left(\frac{14\ \rm cm}{r_{\rm beam}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)$$

Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times10^{-7}\ \rm Pa}}\sqrt{\frac{14\ \rm cm}{r_{\rm beam}}}\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

How do fundamental noises scale? Just 1/L, right? Nope…

longer wavelength?
need more power…

Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}}\sqrt{\frac{\lambda}{1.5\ \mu\rm m}}\left(\frac{3}{r_{\rm sqz}}\right)\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{320\ \rm kg}{m_{\rm TM}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

B P Abbott *et al* 2017 *CQG* **34** 044001

Coating Thermal Noise
constant loss angle…

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}}\sqrt{\frac{\phi_{\rm eff}}{5\times10^{-5}}}\left(\frac{14\ \rm cm}{r_{\rm beam}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)$$

Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times10^{-7}\ \rm Pa}}\sqrt{\frac{14\ \rm cm}{r_{\rm beam}}}\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

How do fundamental noises scale? Just 1/L, right? Nope…

Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}} \sqrt{\frac{\lambda}{1.5\ \mu\rm m}} \left(\frac{3}{r_{\rm sqz}}\right) \sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}} \sqrt{\frac{1.5\ \mu\rm m}{\lambda}} \left(\frac{3}{r_{\rm sqz}}\right) \left(\frac{320\ \rm kg}{m_{\rm TM}}\right) \left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

B P Abbott *et al* 2017 *CQG* **34** 044001

Coating Thermal Noise
constant loss angle…

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}} \sqrt{\frac{\phi_{\rm eff}}{5\times10^{-5}}} \left(\frac{14\ \rm cm}{r_{\rm beam}}\right) \left(\frac{40\ \rm km}{L_{\rm arm}}\right)$$

Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times10^{-7}\ \rm Pa}} \sqrt{\frac{14\ \rm cm}{r_{\rm beam}}} \sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

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Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}}\sqrt{\frac{\lambda}{1.5\ \mu\rm m}}\left(\frac{3}{r_{\rm sqz}}\right)\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^3$$

B P Abbott *et al* 2017 *CQG* **34** 044001

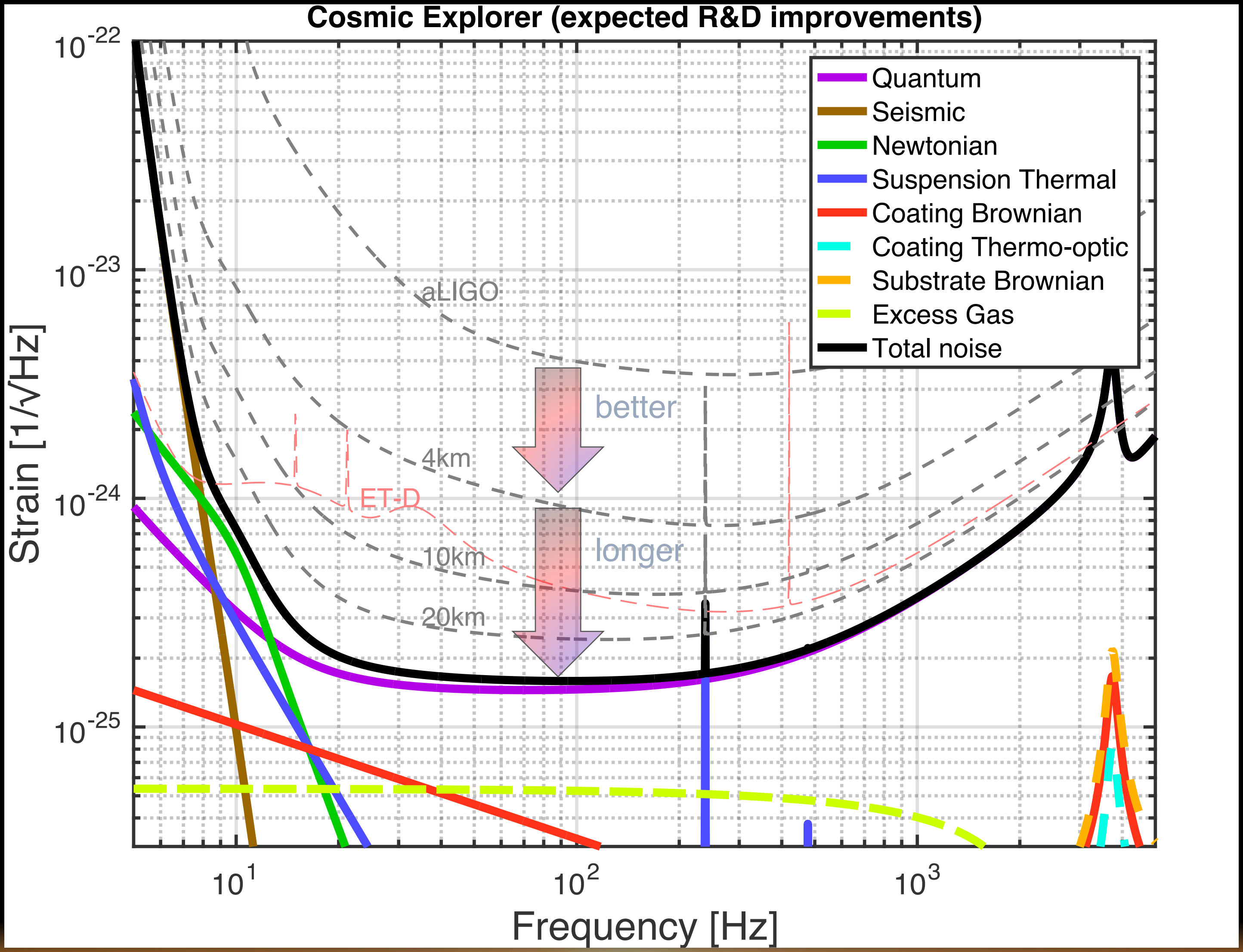
Coating Thermal Noise
loss angle dependence?

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}}\sqrt{\frac{\phi_{\rm eff}(T)}{5\times10^{-5}}}\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

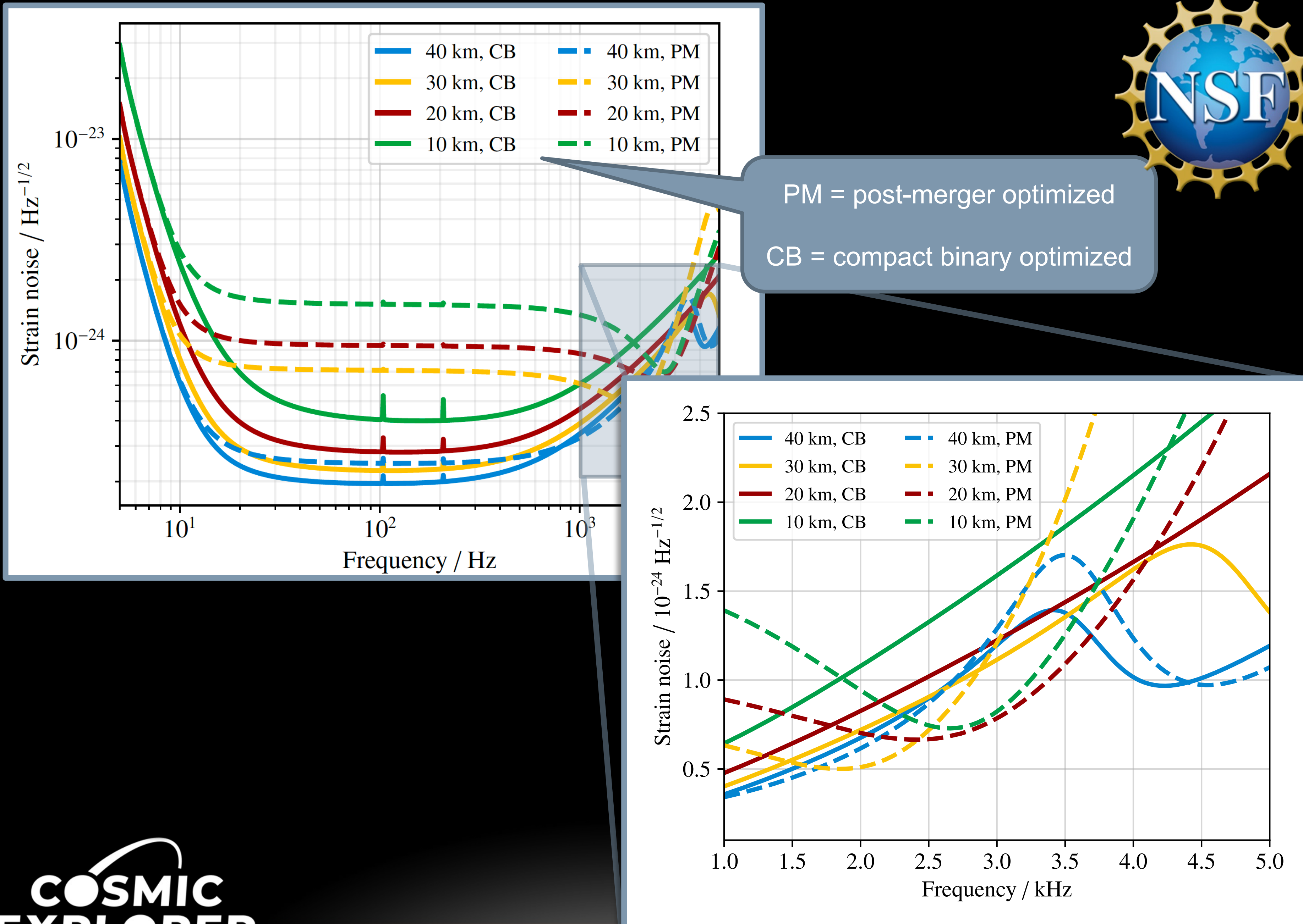
Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times10^{-7}\ \rm Pa}}\sqrt{\frac{40\ \rm km}{L_{\rm arm}^{3/2}}}$$

Scaling Up… an example



Exploring the sensitivity of next generation gravitational wave detectors
(2017) CQG 34, 044001

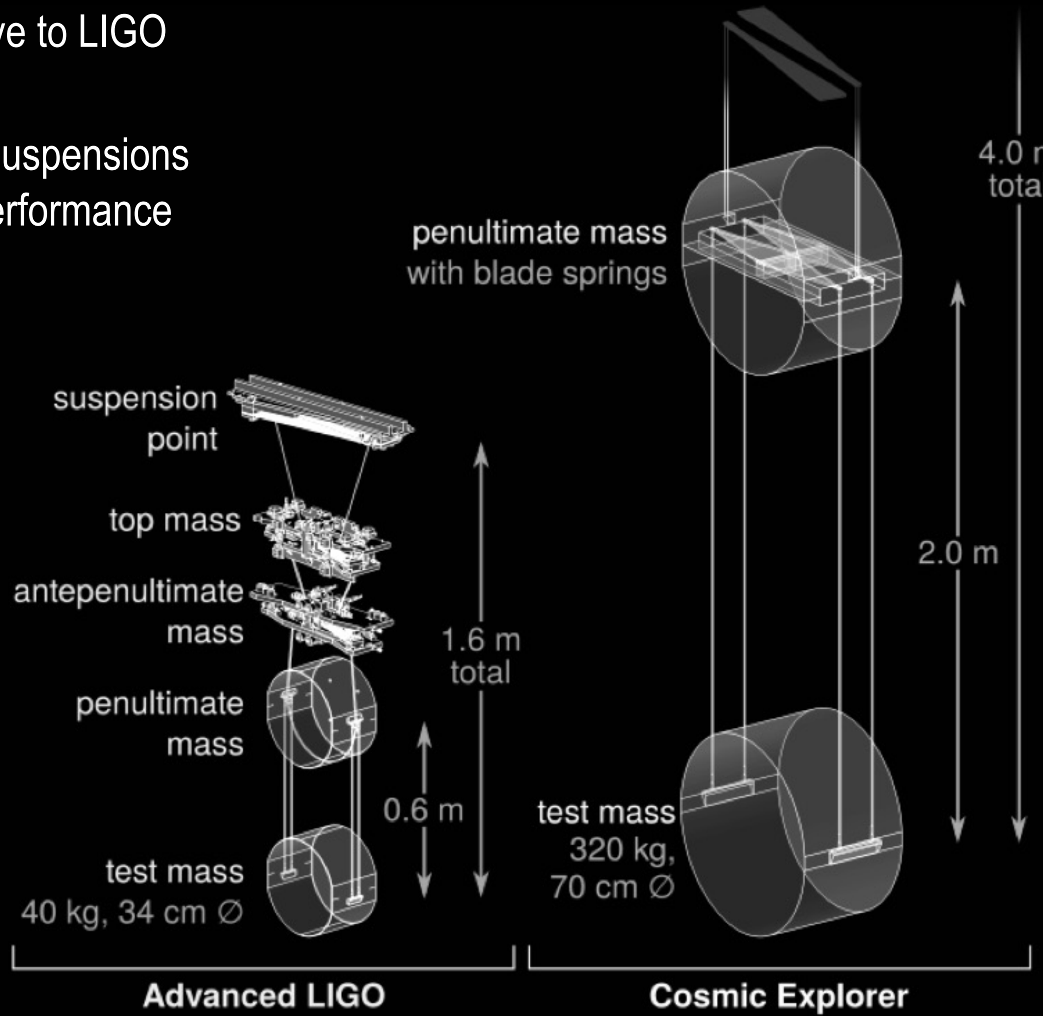


NSF

COSMIC EXPLORER

Technical Readiness of Cosmic Explorer

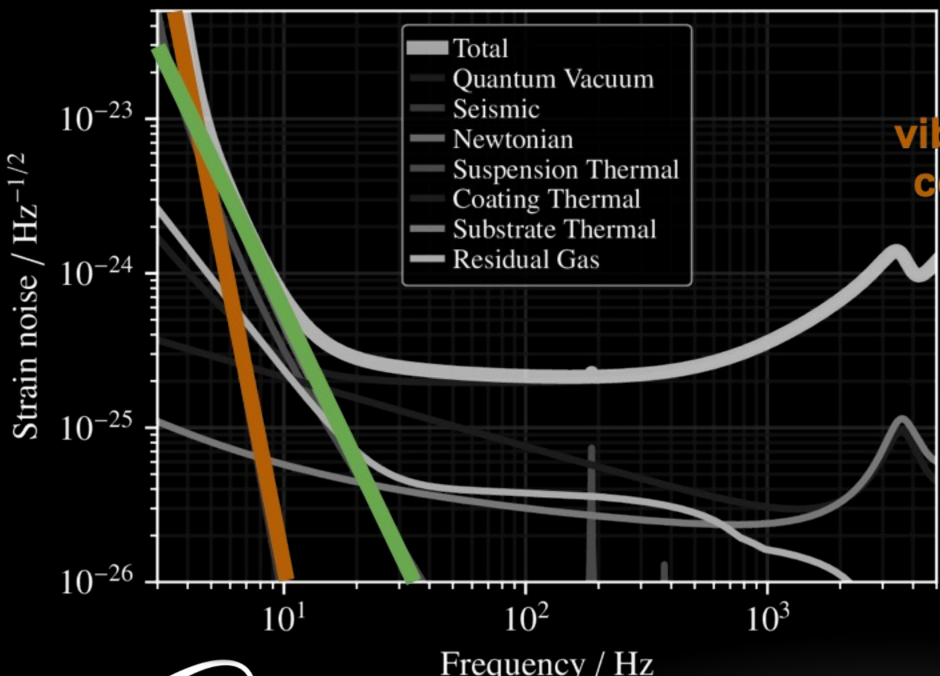
- Mostly "incremental" changes relative to LIGO
- The mirrors will be bigger, and the suspensions longer to help with low-frequency performance
- We expect somewhat better coatings for the mirrors (lower thermal noise, few or no point absorbers)
- While challenging, we are targeting a plausible improvement in quantum performance (10dB of squeezing)

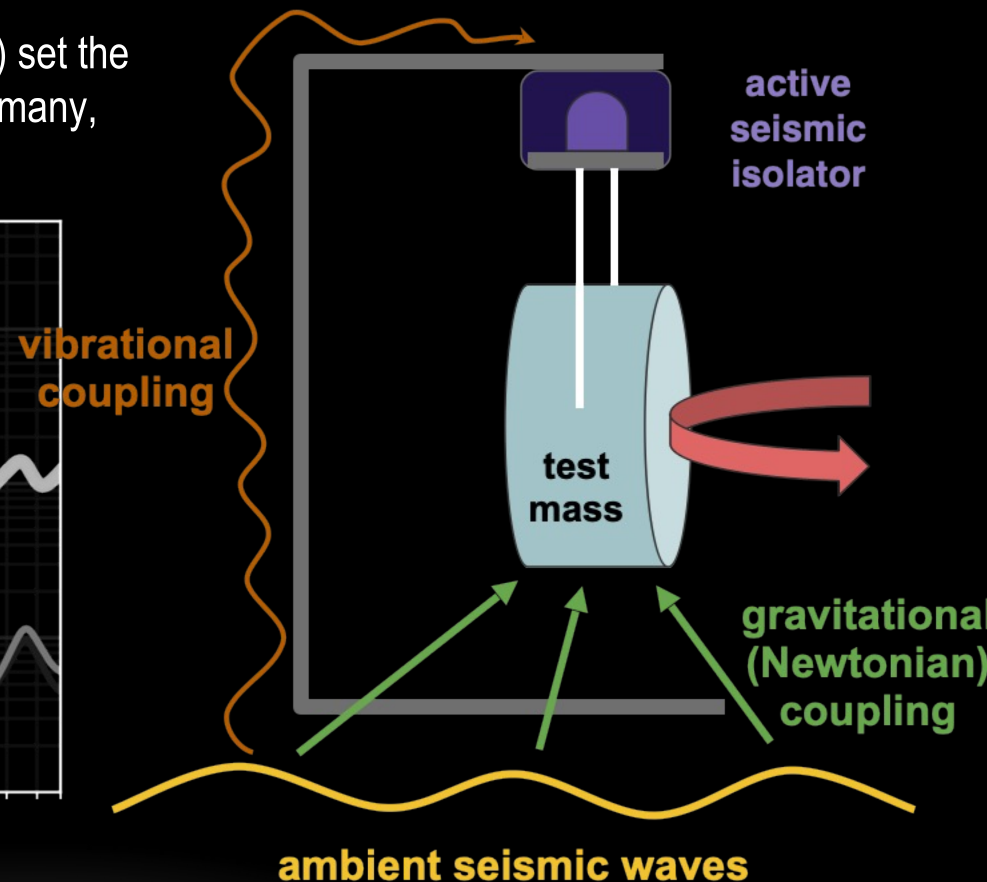


Hall+ PRD 103 122004 (2021)

Newtonian Noise (local gravity)

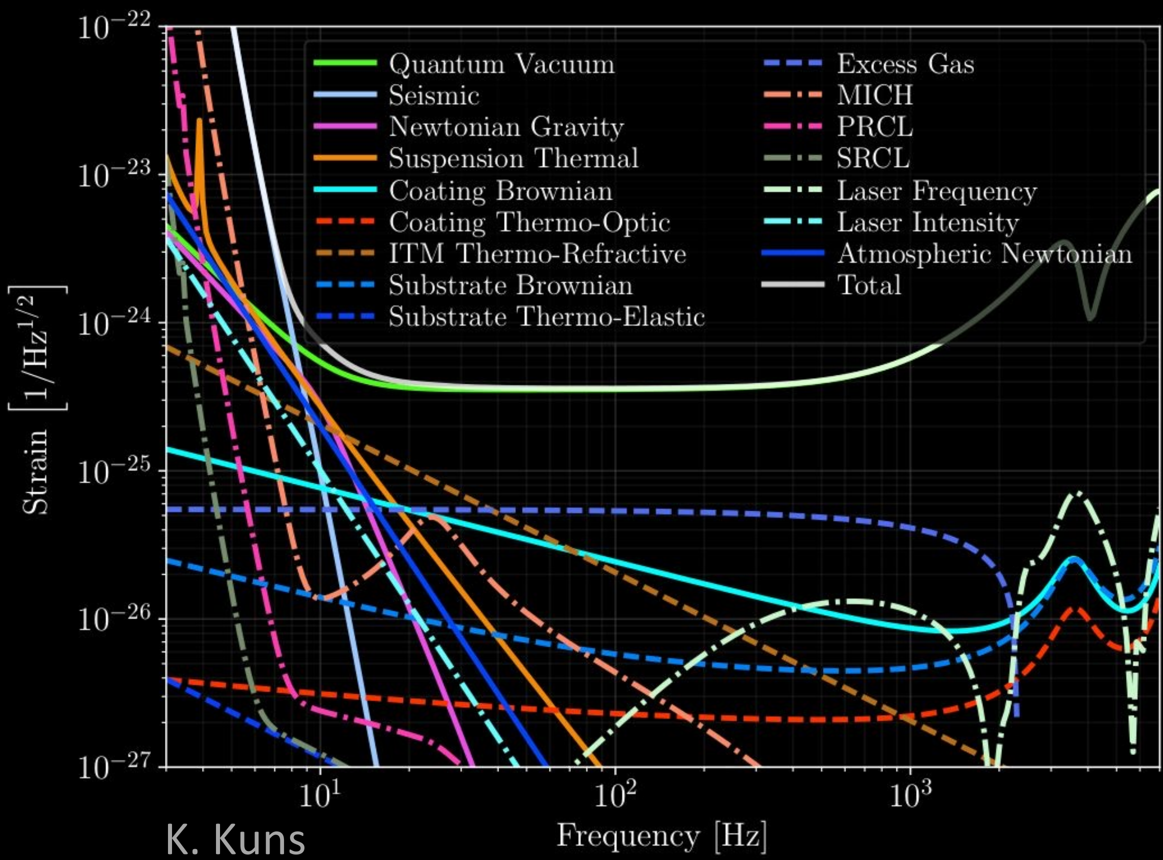
- Variations in local gravity (Vitale, Harms) set the limit at low frequency (along with many, many, technical noises…)

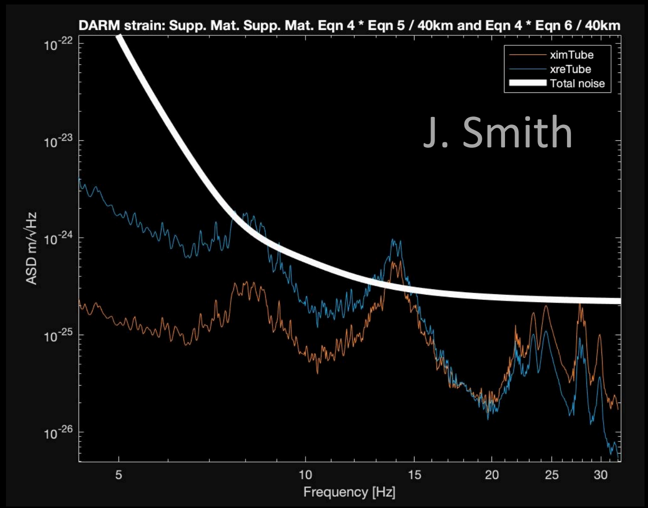


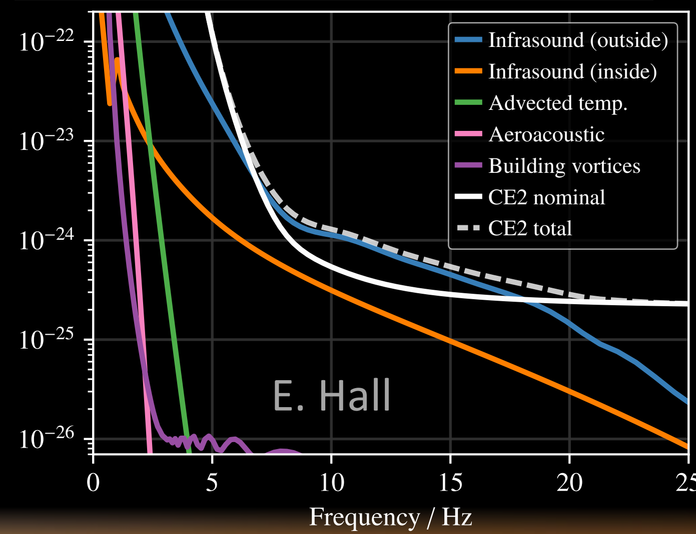


COSMIC EXPLORER

Low frequencies are hard





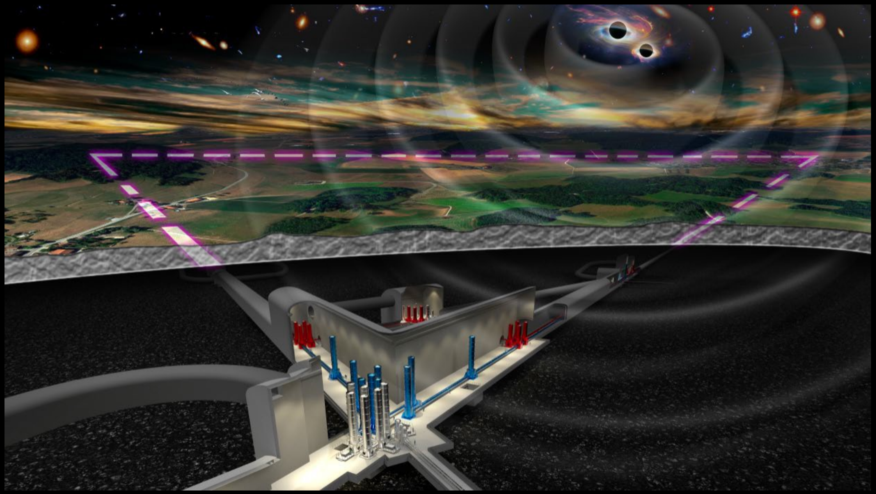


Some Context...

The Next-Gen GW Network

Einstein Telescope (ET) is a similar project underway in Europe

- Planning to operate together
- On the European Strategy for Research Infrastructures (ESFRI) Roadmap
- Different design (underground triangle, 6 interferometers, 3 of them cryogenic)



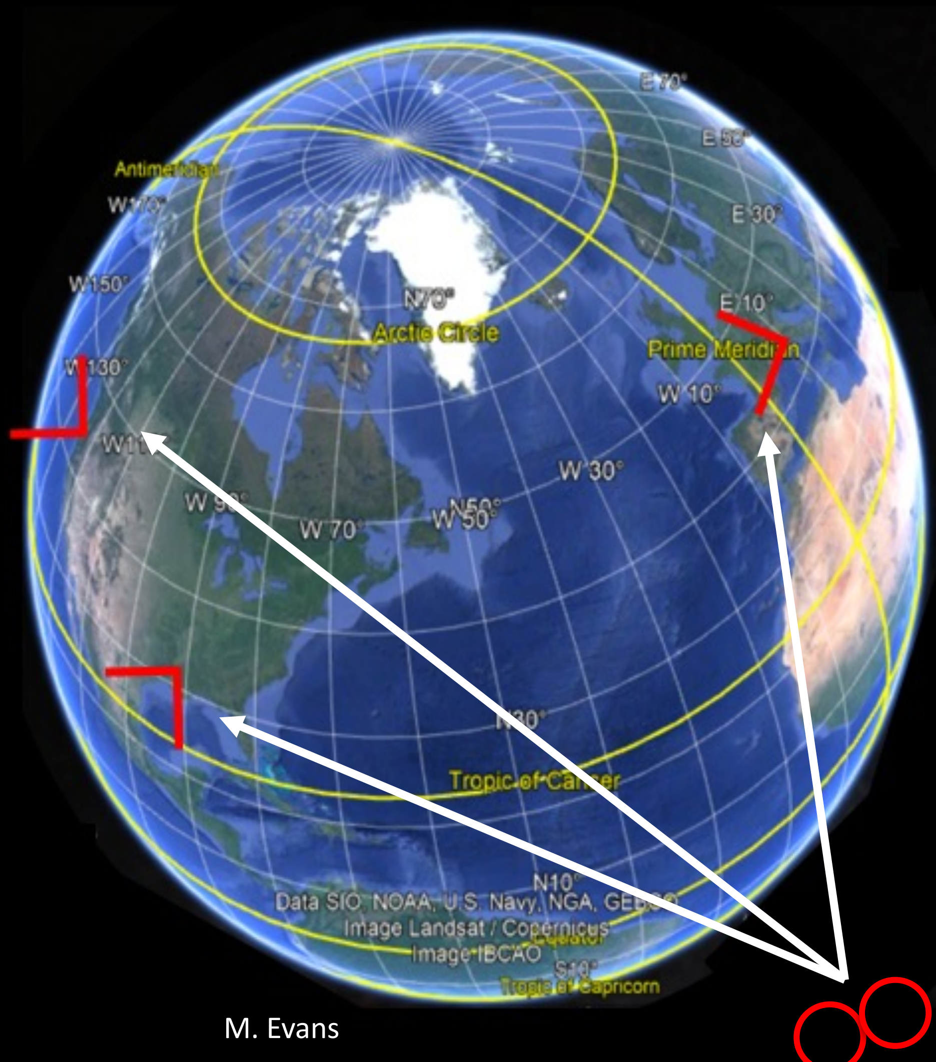
Laser Interferometer Space Antenna (LISA)

- An ESA-led space observatory with a small NASA contribution
- Expected to be launched in 2034 and take data concurrently with CE and ET

Neutron-star Extreme Matter Observatory (NEMO)

- An Australian observatory but a smaller observatory focused on specific science
- Aspire to build a CE-like detector in the future

As previously mentioned (Katsavounidis, Sutton), networks are important for GW science



Binary black hole system merging here

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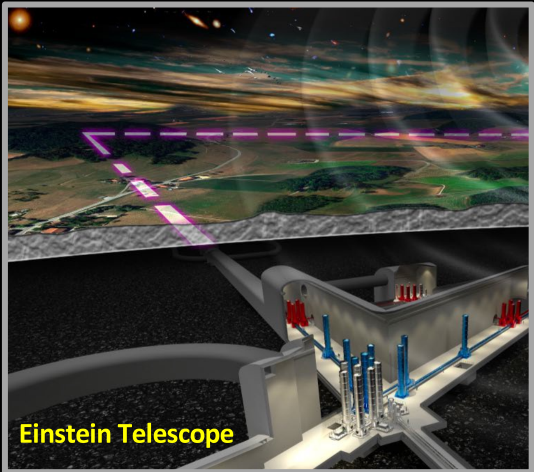

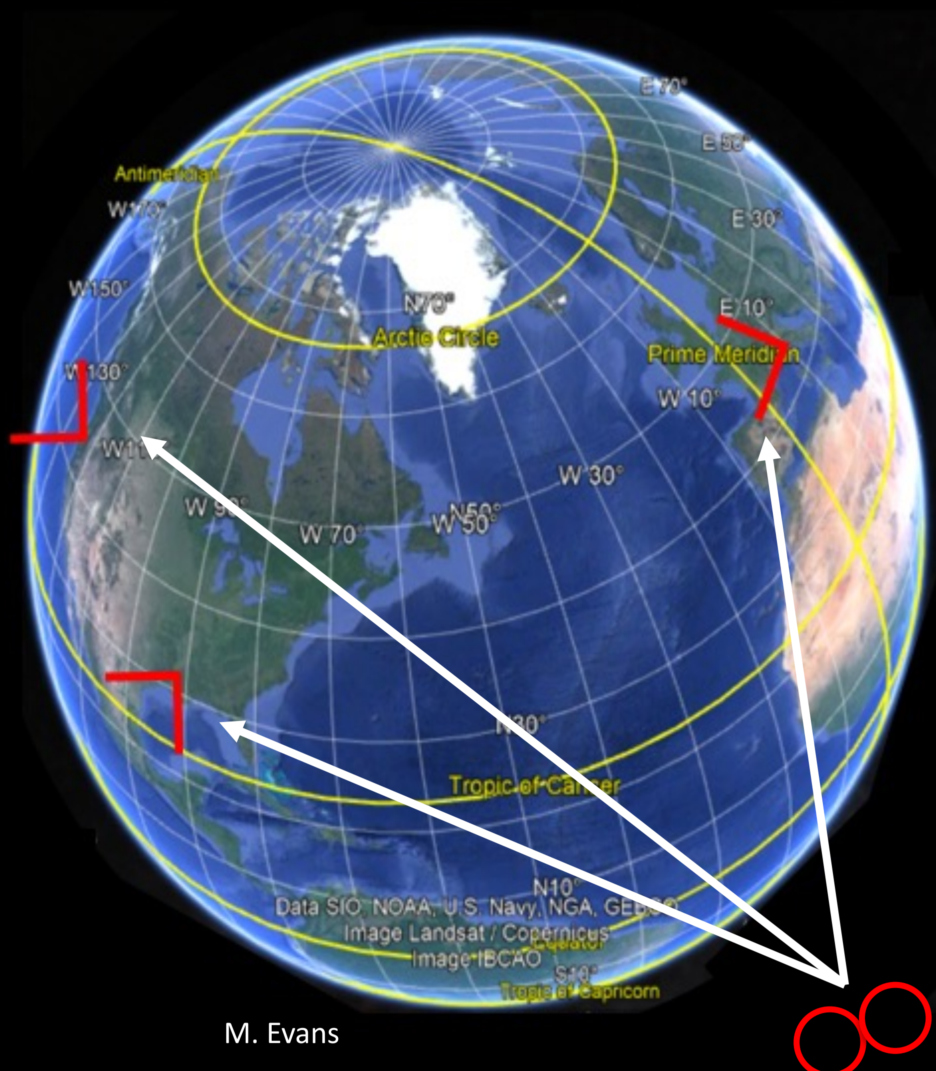

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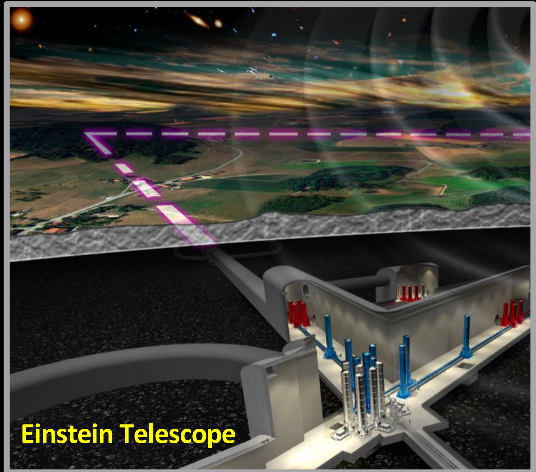
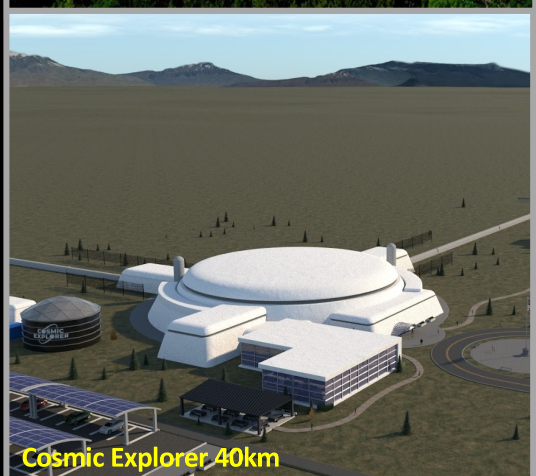
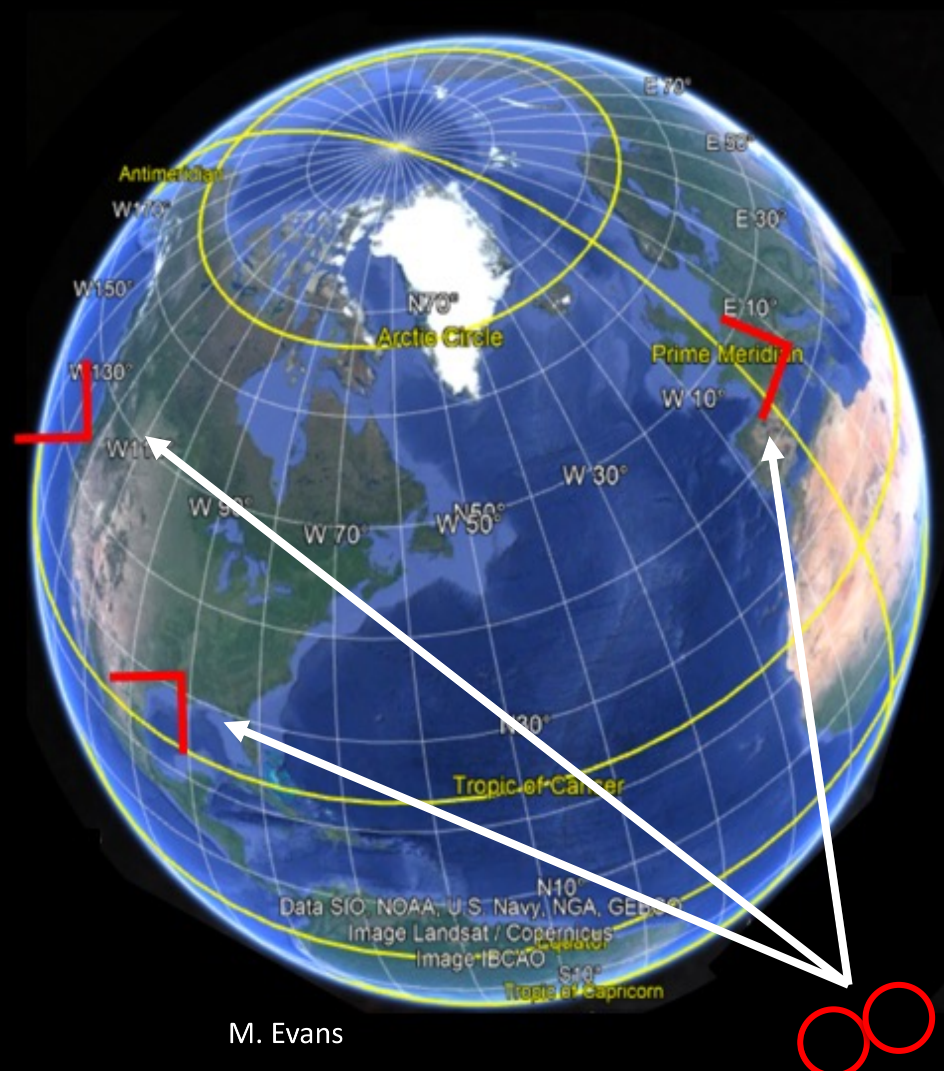
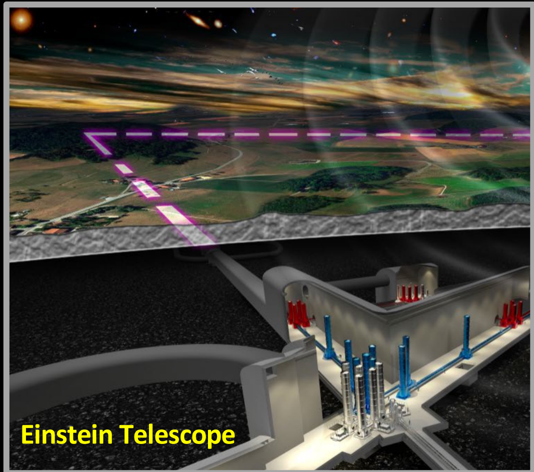
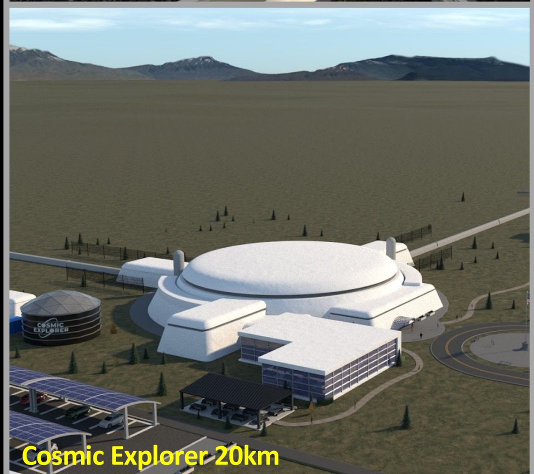






M. Evans





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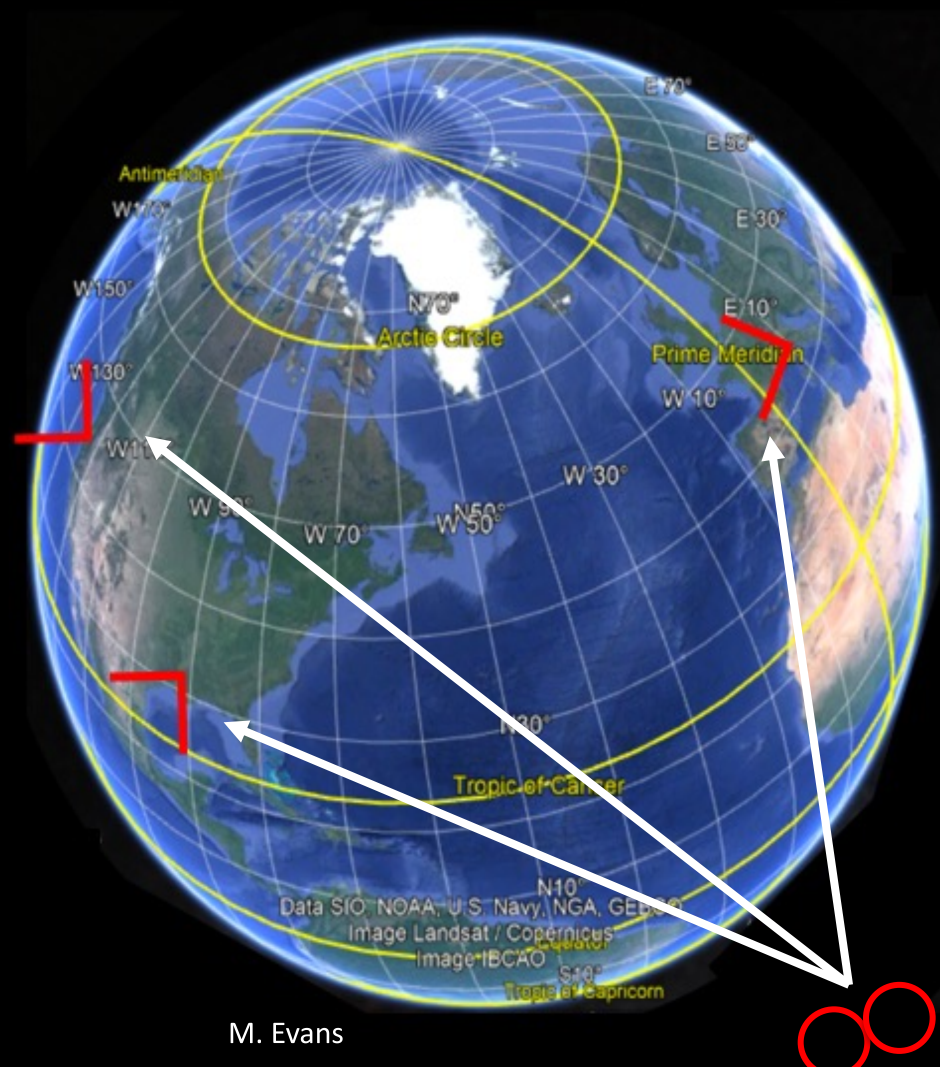
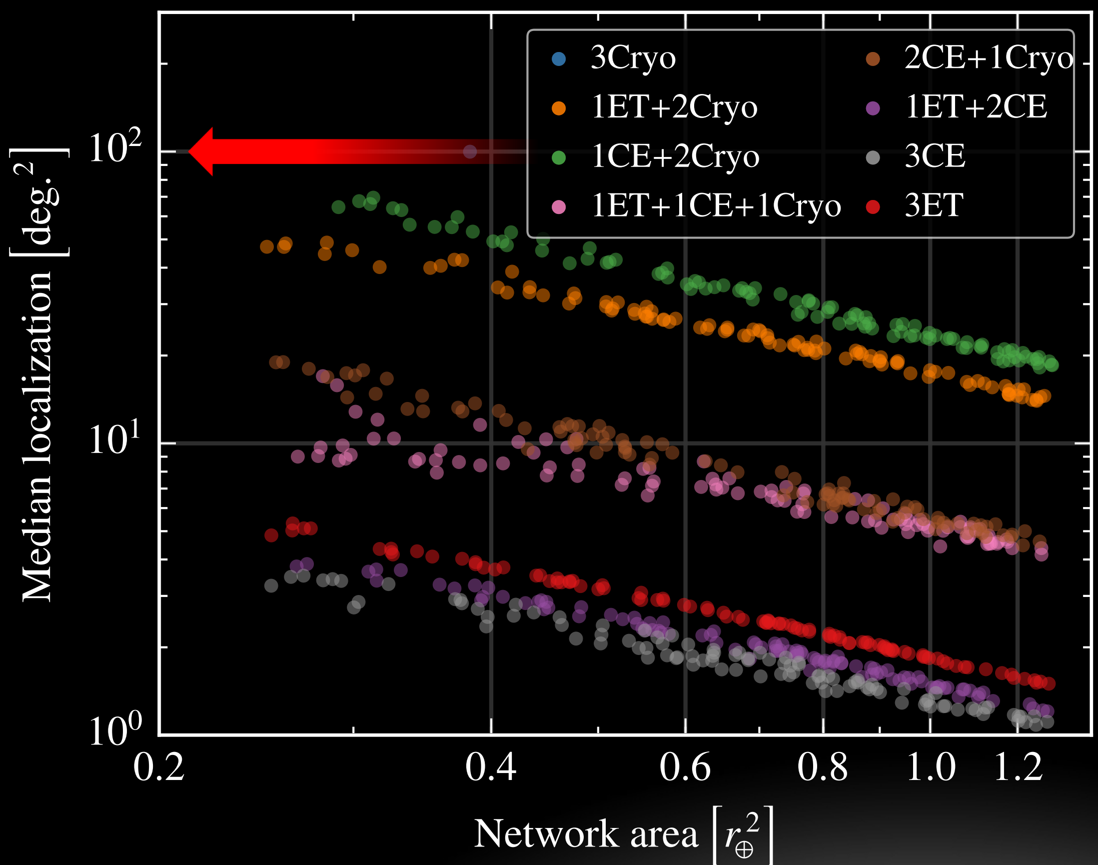
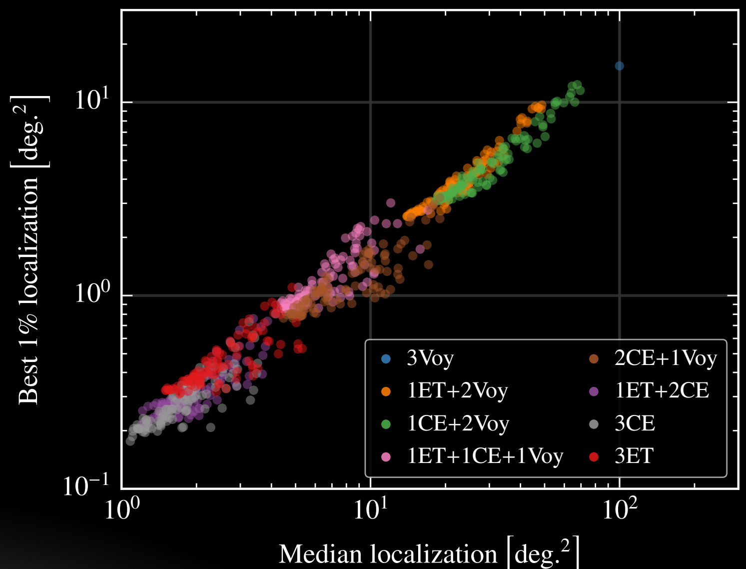


Source Localization



arXiv 1902.09485



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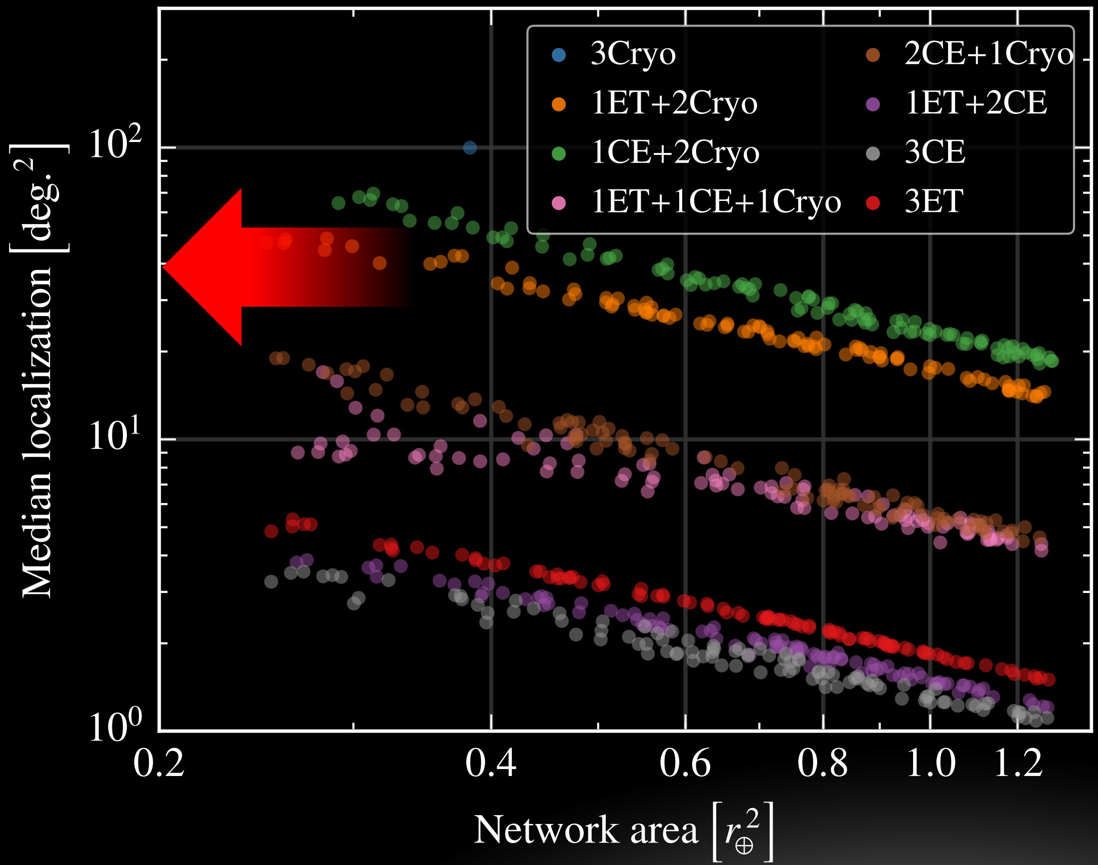

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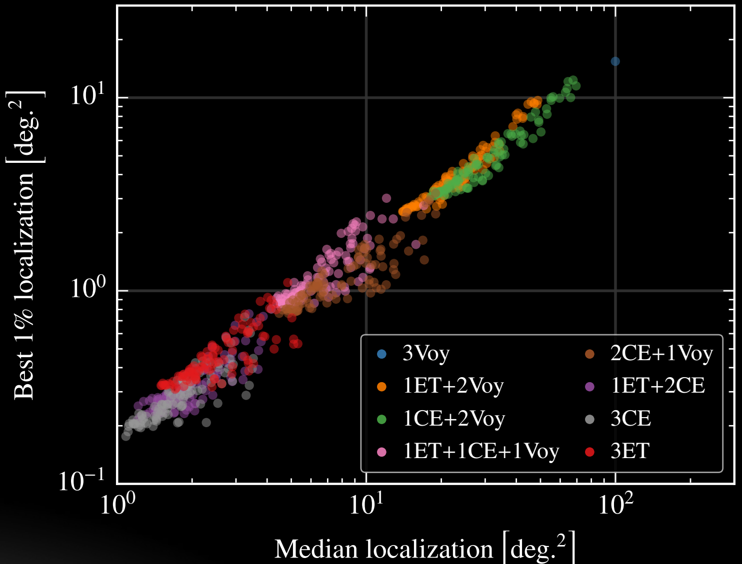

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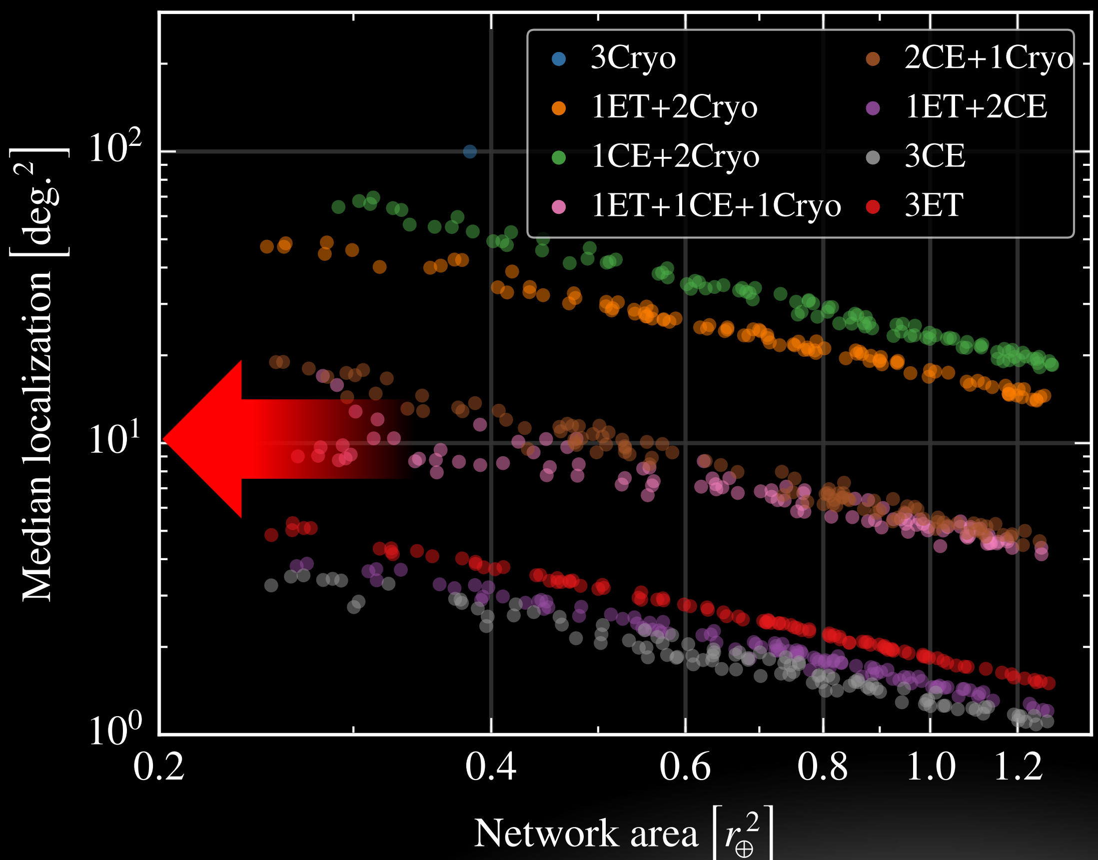

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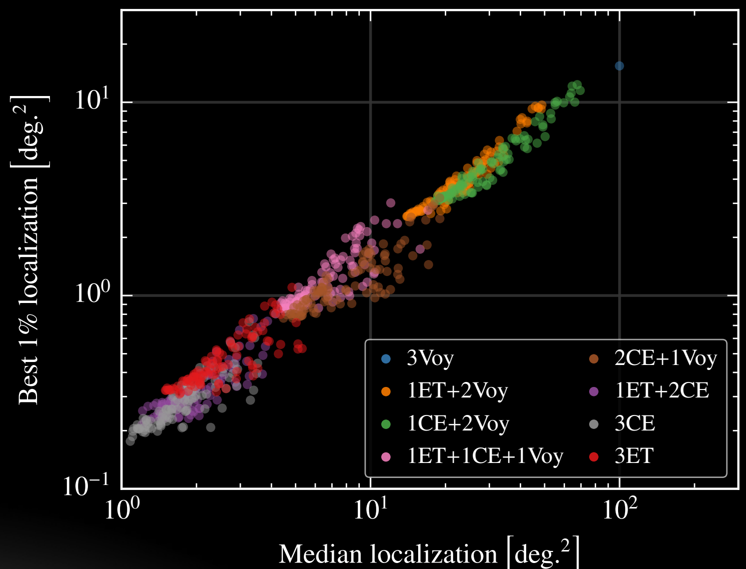

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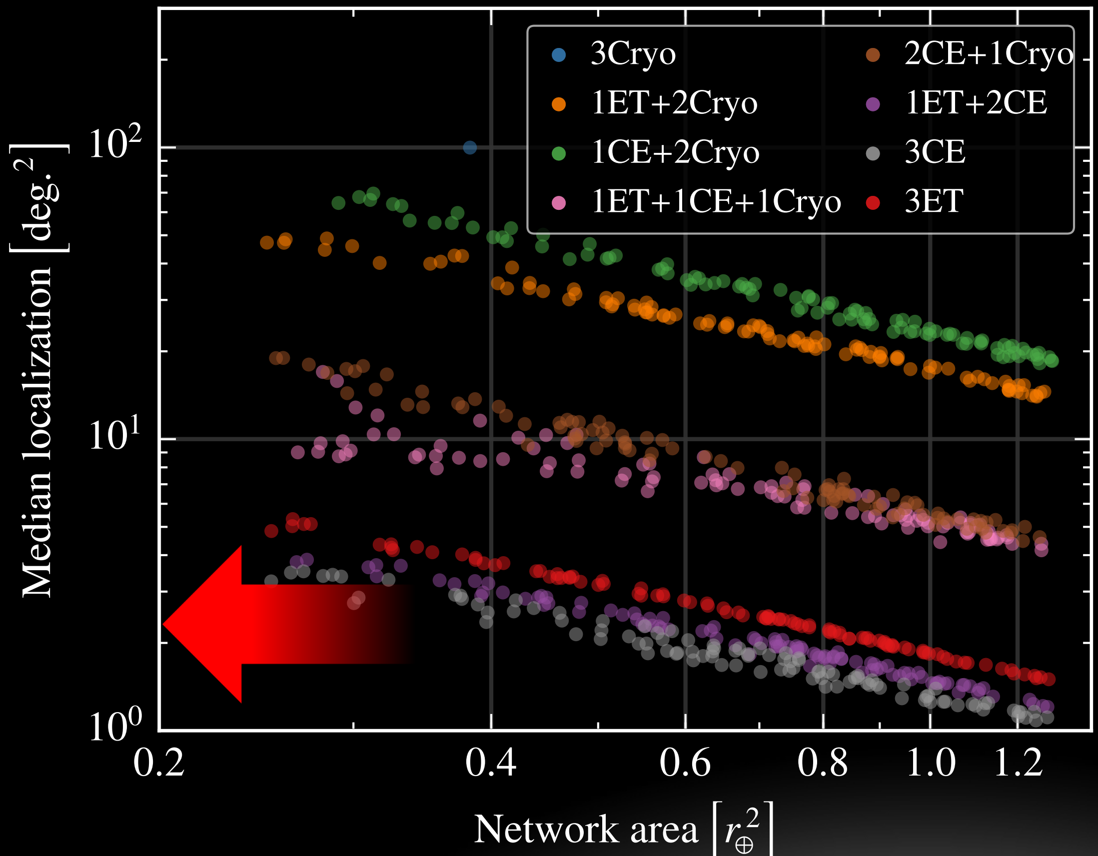

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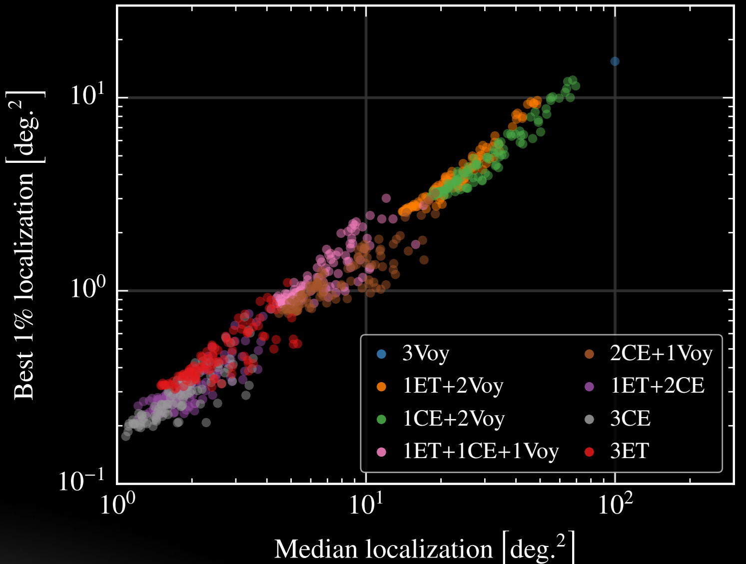

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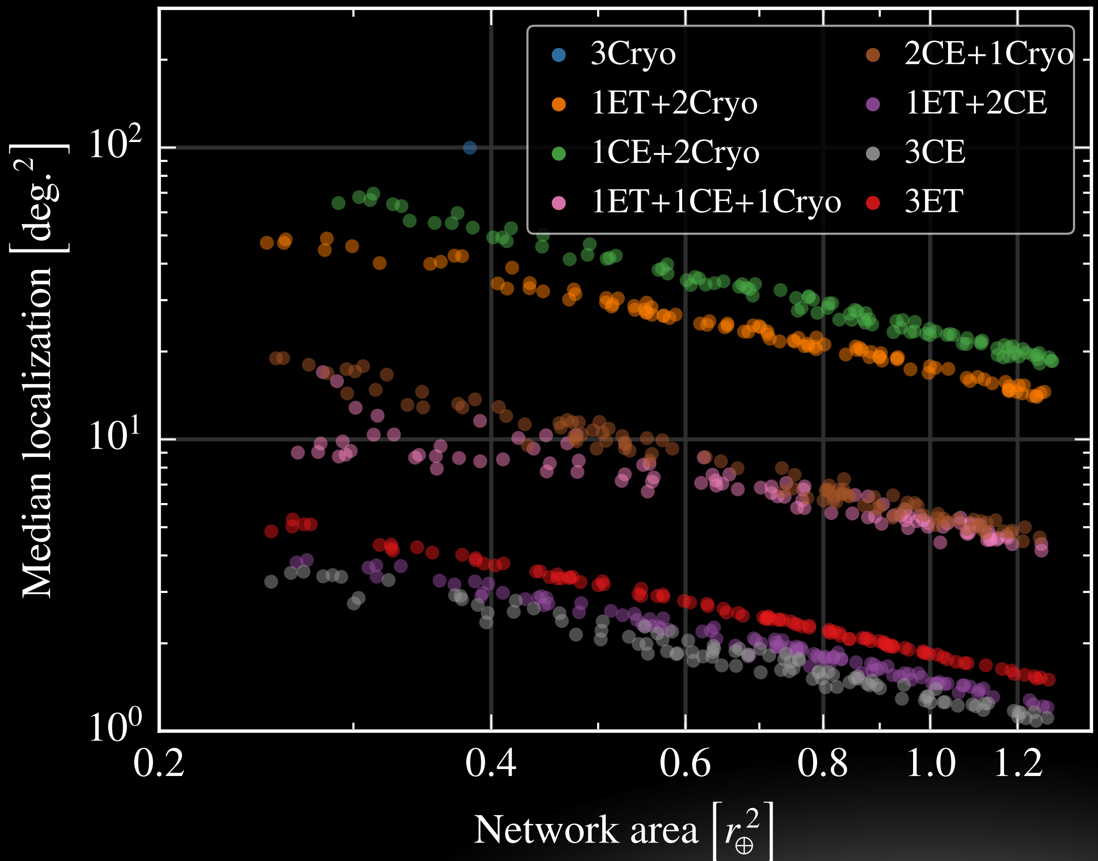

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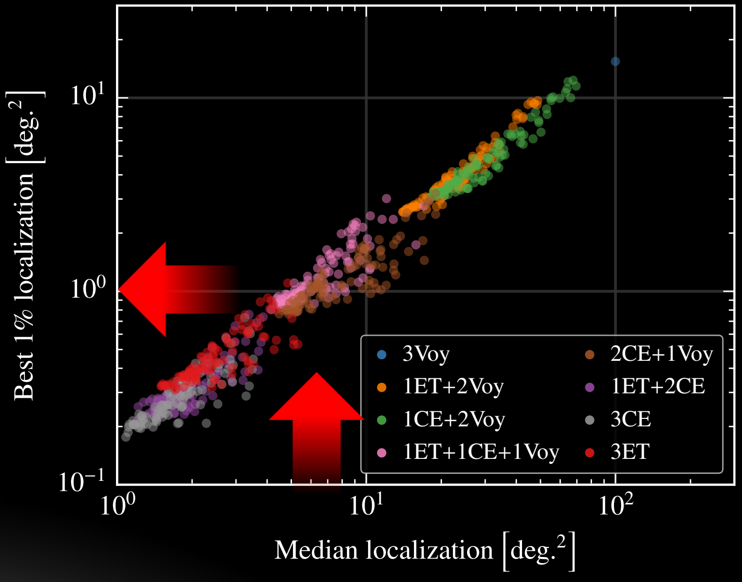
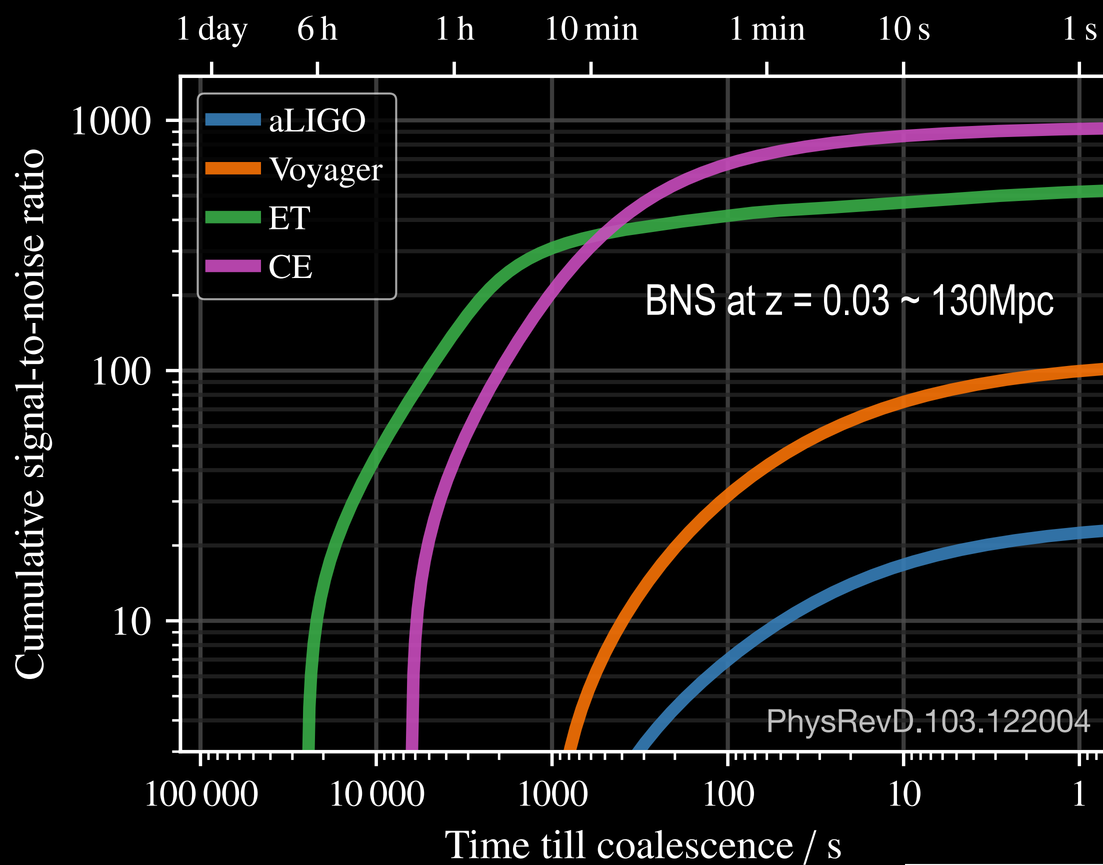
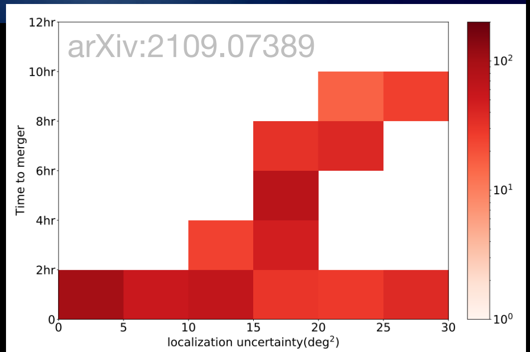


Localization and Early Warning





(c) 1ET2CE

EW time	τ_{EW} = 120 s				τ_{EW} = 300 s				τ_{EW} = 600 s			
Ω_{90} (deg^2)	≤ 100	≤ 20	≤ 10	≤ 1	≤ 100	≤ 20	≤ 10	≤ 1	≤ 100	≤ 20	≤ 10	≤ 1
HLKI+E	66	7	4	1	47	7	3	1	1	0	0	0
VKI+C	2	1	0	0	1	0	0	0	0	0	0	0
KI+EC	2,100	310	100	5	1,700	200	63	3	21	2	1	0
ECS	6,000	950	400	16	3,600	500	170	6	110	4	2	0

Borhanian and Sathyaprakash, in preparation

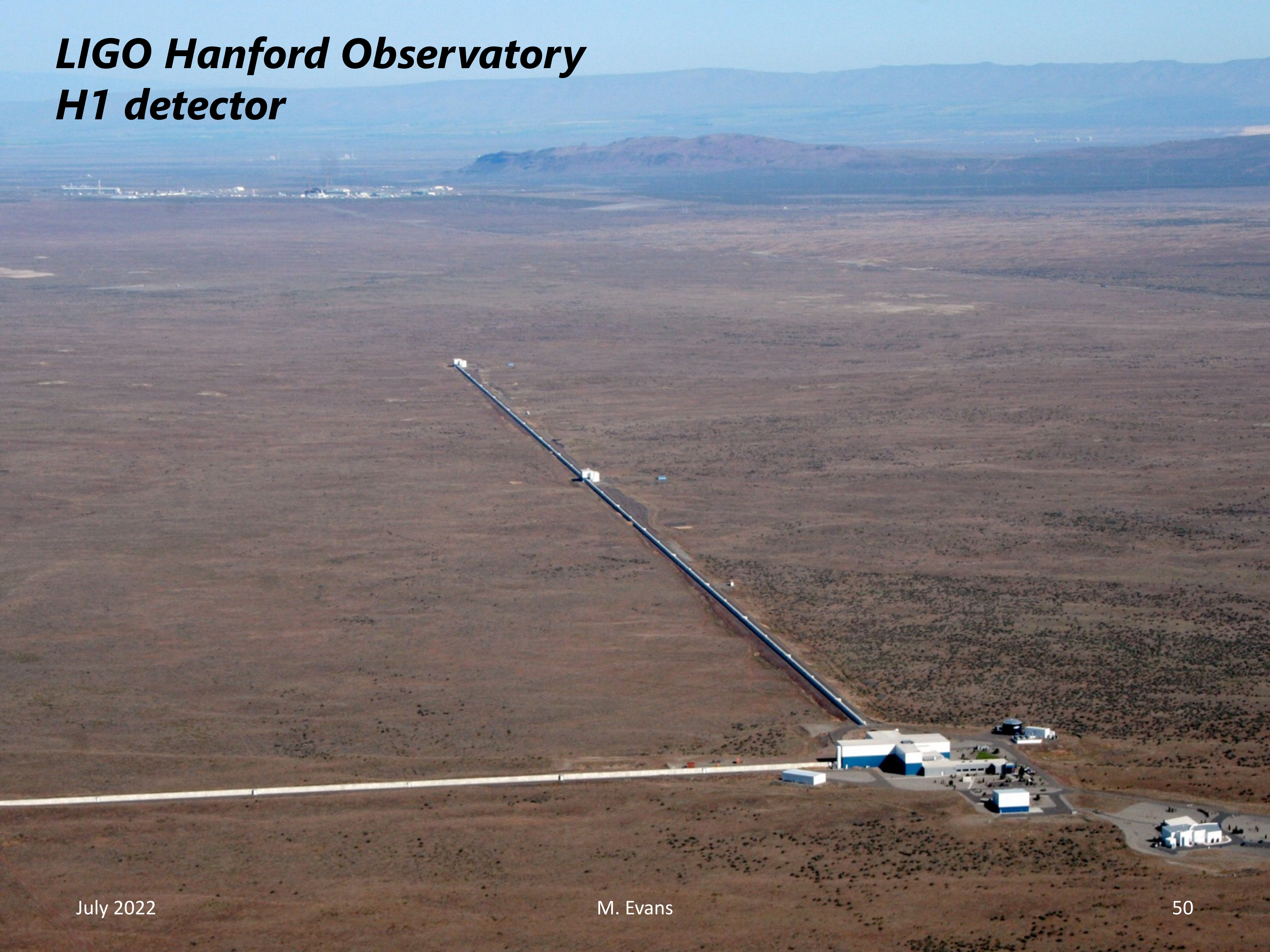
Conclusion

- Gravitational-wave science is still in its infancy
- We are at the dawn of a new age of exploration
- Cosmic Explorer is the US concept for a next-generation gravitational-wave detector
- We are very excited about the future!

COSMIC EXPLORER

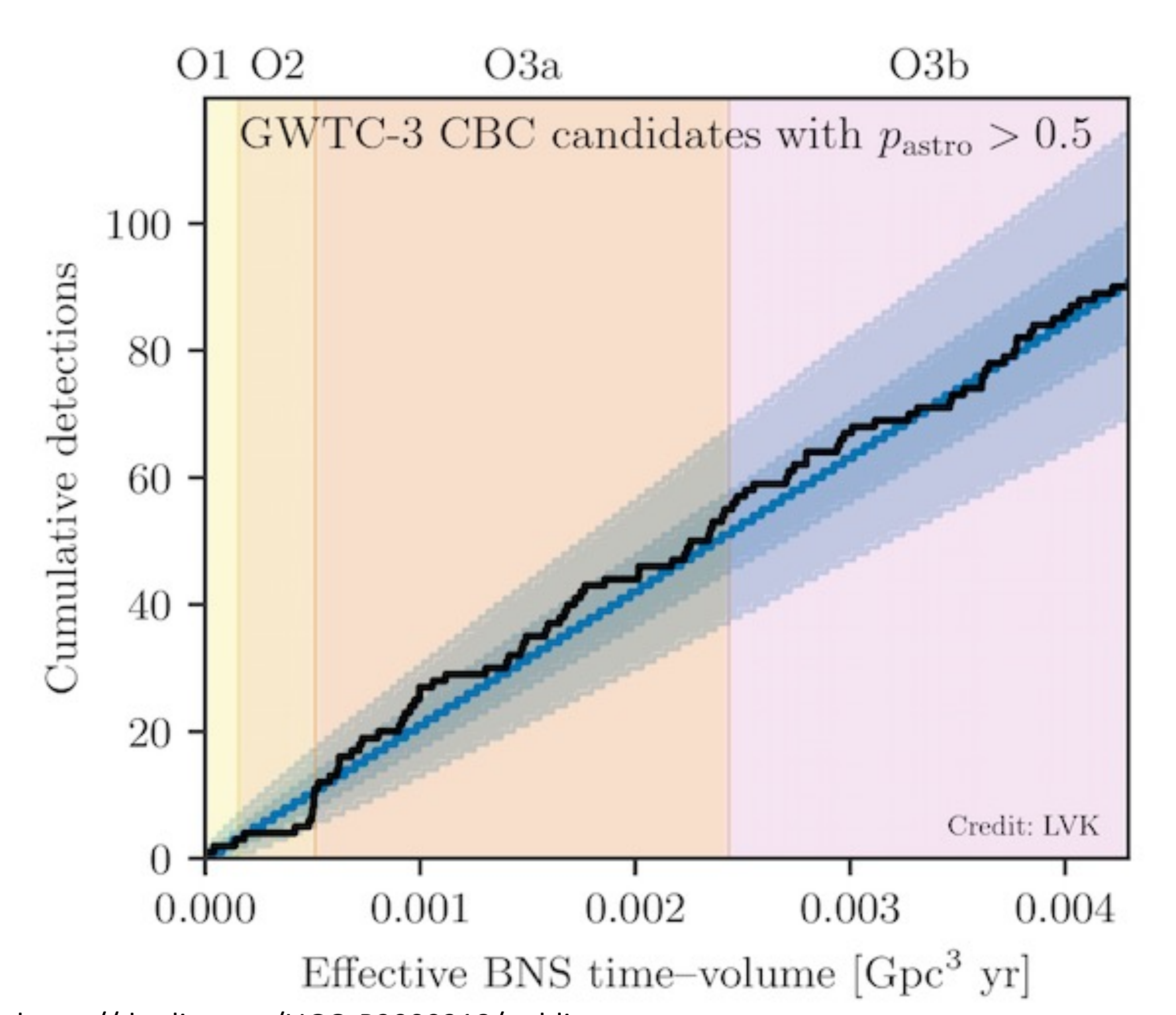
spares

LIGO Hanford Observatory H1 detector



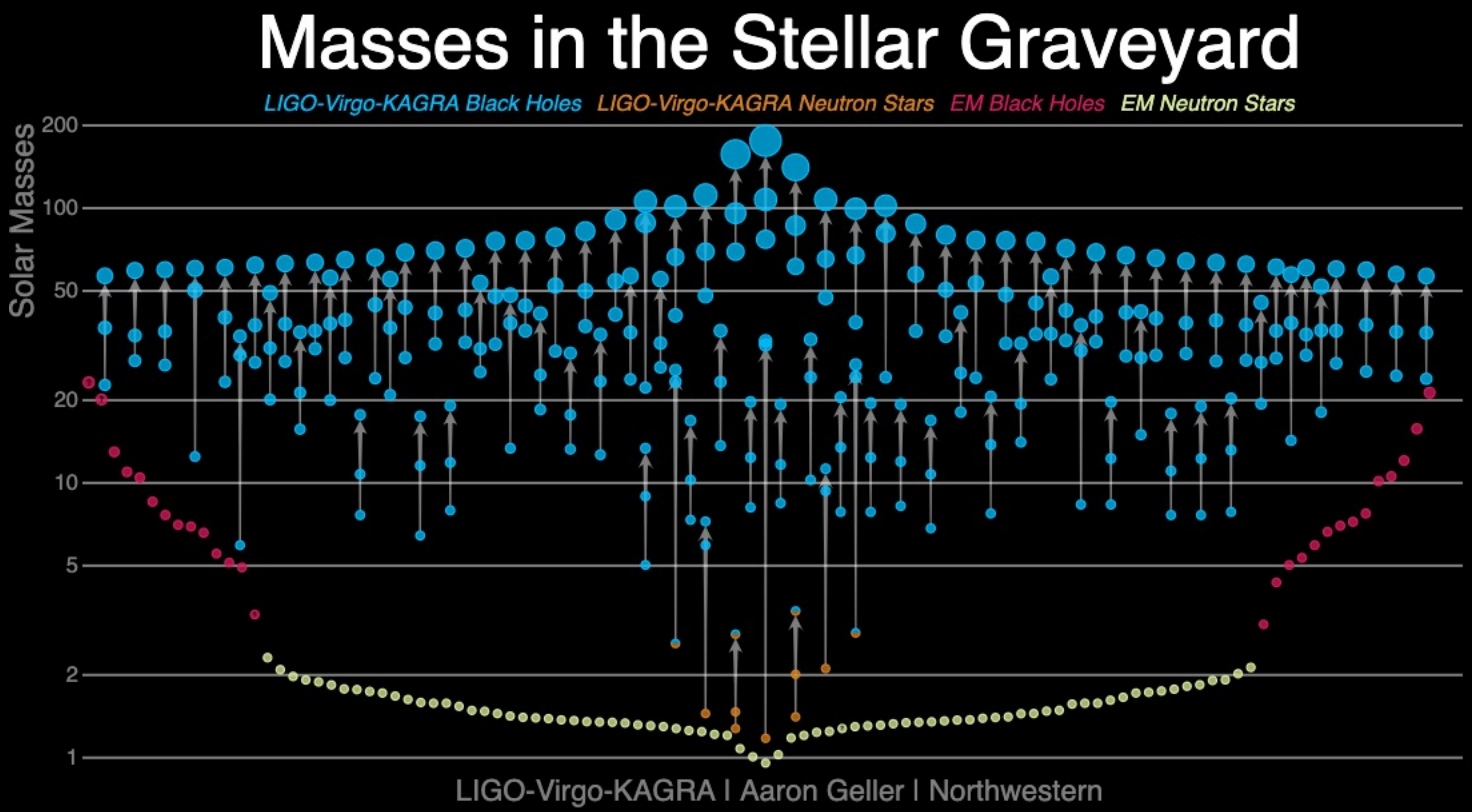
LIGO Livingston Observatory L1 detector

Now approaching 100 events!



https://dcc.ligo.org/LIGO-P2000318/public

Now approaching 100 events!



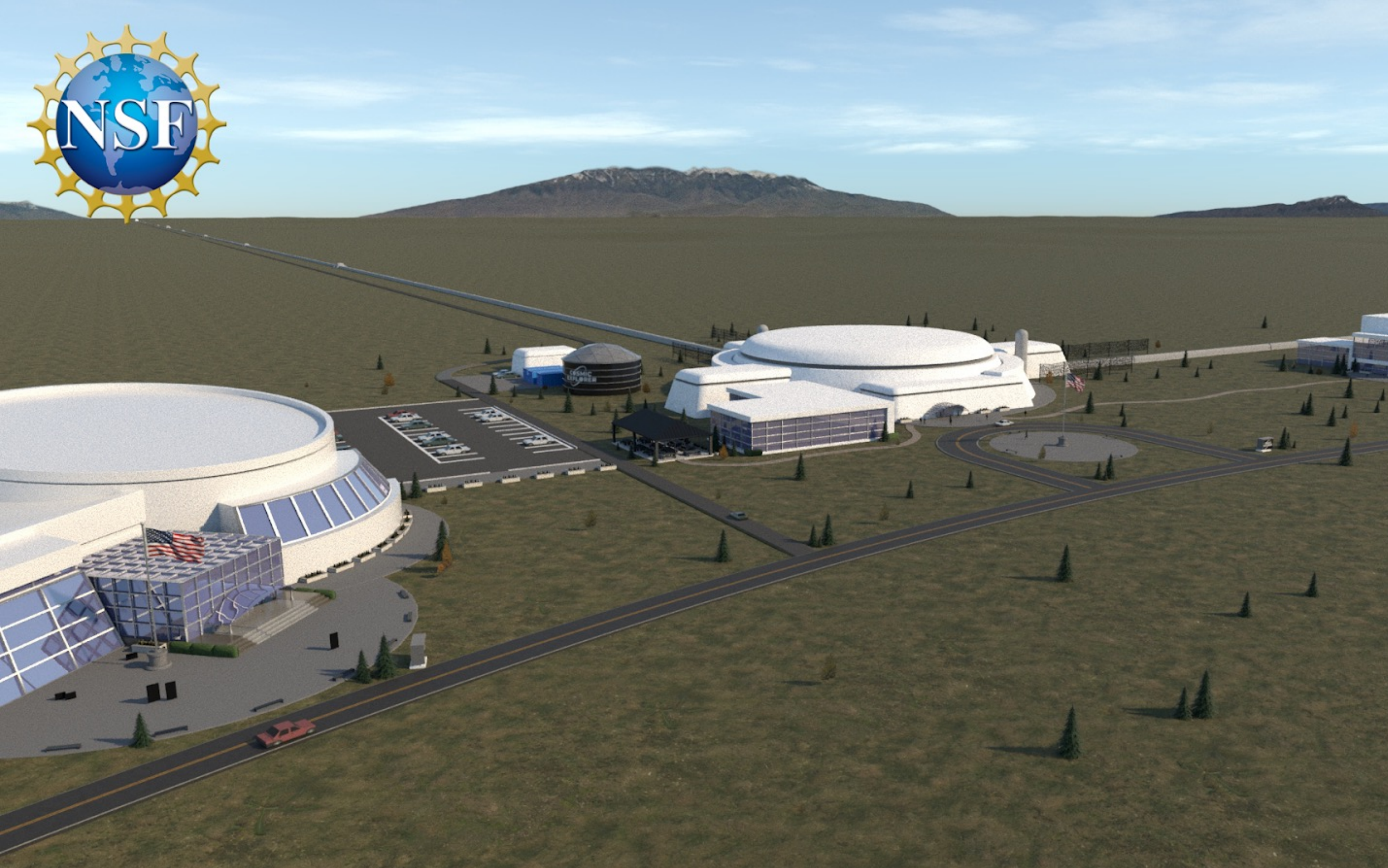


Image: Eddie Anaya
(Undergrad, Art, Cal State Fullerton)

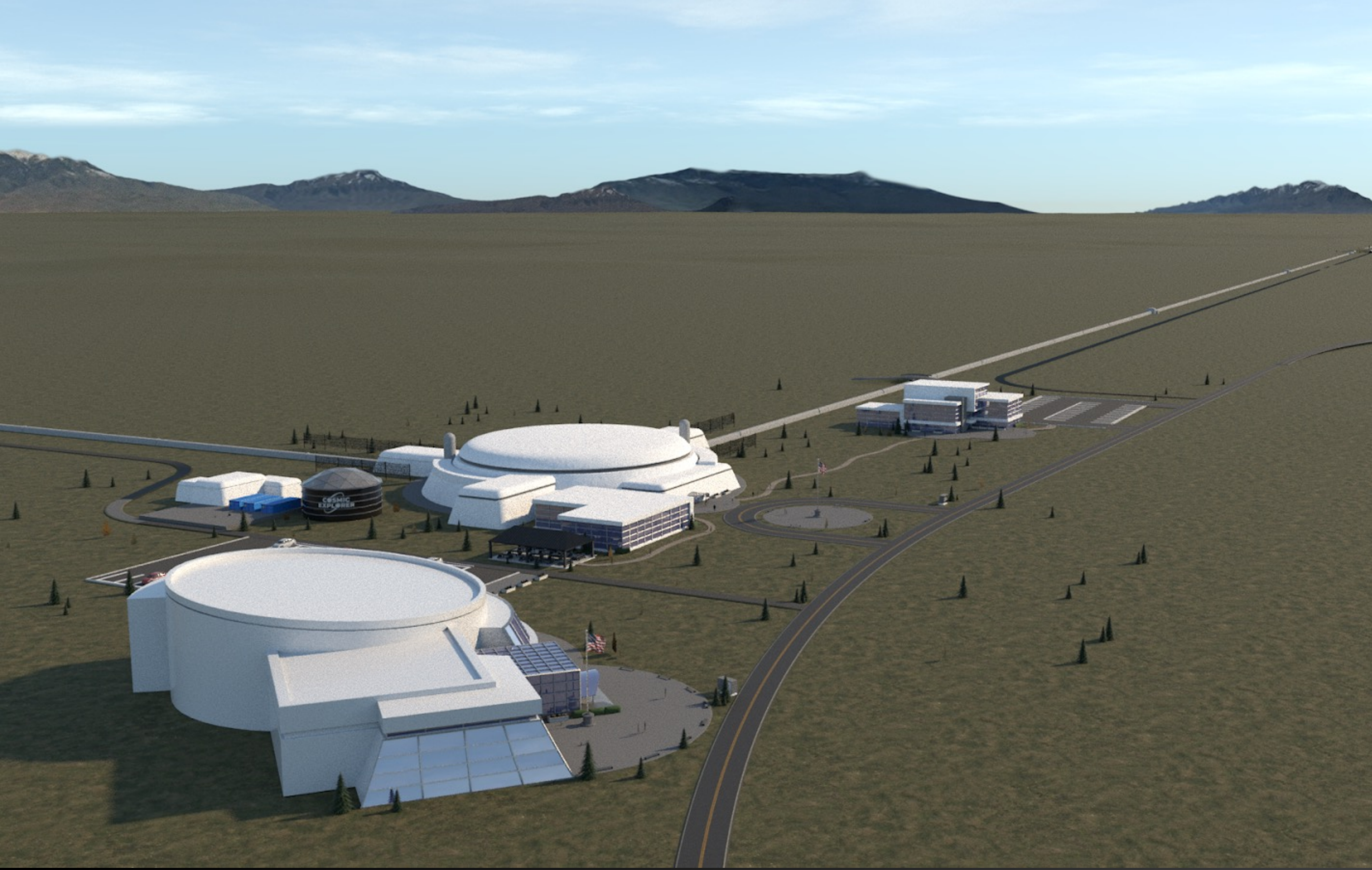


Image: Eddie Anaya
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COSMIC EXPLORER

Signal Frequency and Black Hole Mass

<u>Estimate Period of Last Orbit</u>

For 30 $M_\odot$, R_s ~ 90km
take $r_1 = r_2 = 2\ R_s$ so that $v = c / 2$

T_{orb} = (4 π) 90 km / (c / 2)
~ 7.5 ms
$f_{orb} = 1 / T_{orb}$ ~ 125 Hz
$f_{GW} = 2\ f_{orb}$ ~ 250 Hz

(actual value for GW150914 was ~200 Hz)

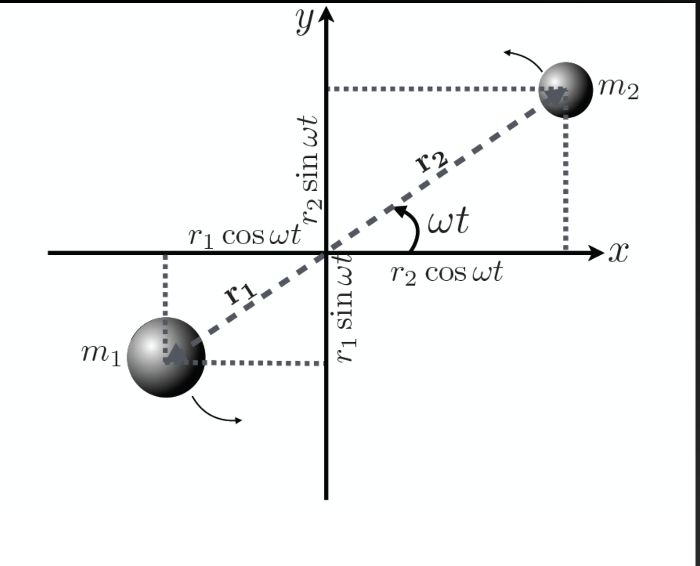


Figure 6 A two-body system, m_1 and m_2 orbiting in the xy-plane around their C.O.M.

"The basic physics of the binary black hole merger GW150914" (arXiv:1608.01940)

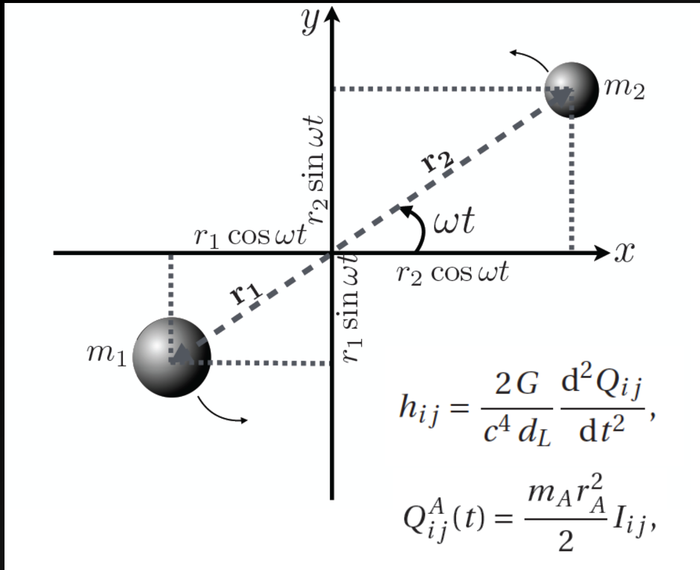
Signal Amplitude and Distance

<u>Estimate Distance to Source</u>

For 30 M⊙ , R_s ~ 90km
take GW strain at the source
h = ¼ (since v / c = ½)

$d_L \sim R_s / (4\, h_{obs}) \sim 2.5$ G light-years

(actual value for GW150914 was 1.3 Gly)



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