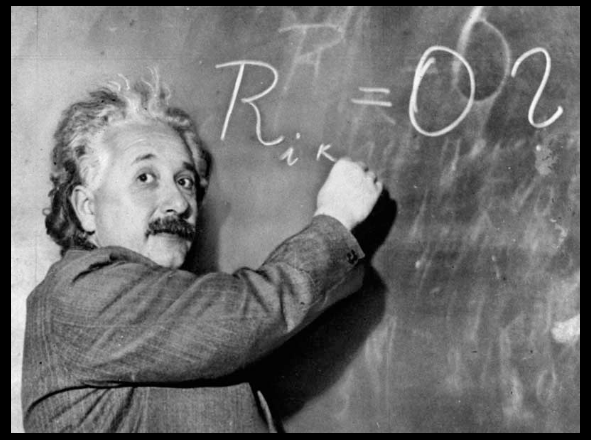
Cosmic Explorer

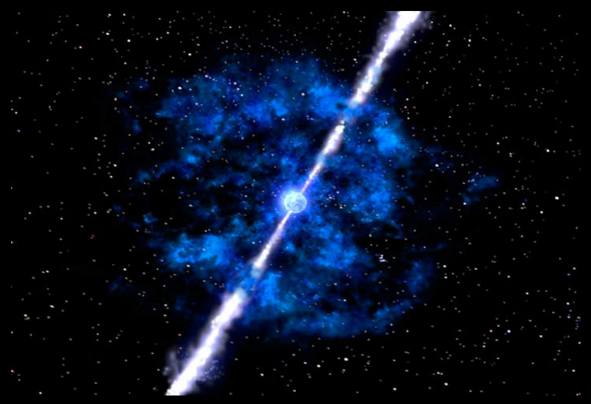
Duncan Brown, Syracuse University

https://cosmicexplorer.org/

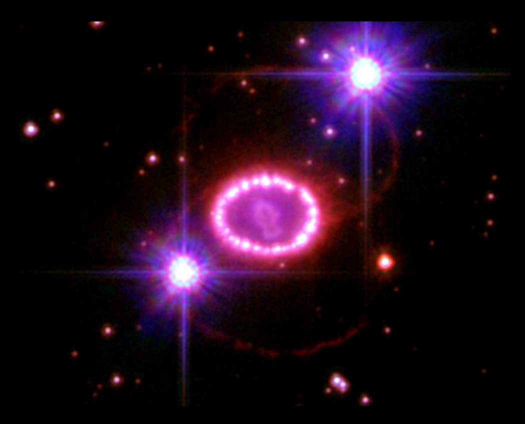


Do gravitational waves exist?
Is general relativity the correct theory of gravity?

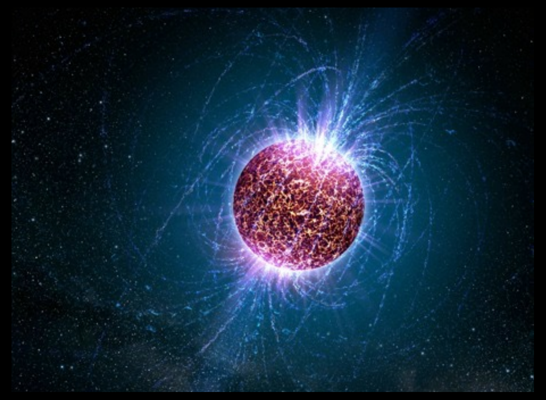
What happens when two black holes collide?
Do black holes really have no hair?



What are the progenitors of short gamma ray bursts?
What is the engine that powers them?



How does core collapse power a supernova?
How does angular momentum transport work in massive stars?



What is the nuclear equation of state at high densities?
Are there phase transitions in neutron stars?

The strength of the gravitational waves radiated is given by their strain h(t) = change in length / length

$$h \sim \frac{G}{c^4}\frac{E_{\rm NS}}{r} \sim 10^{-21}$$

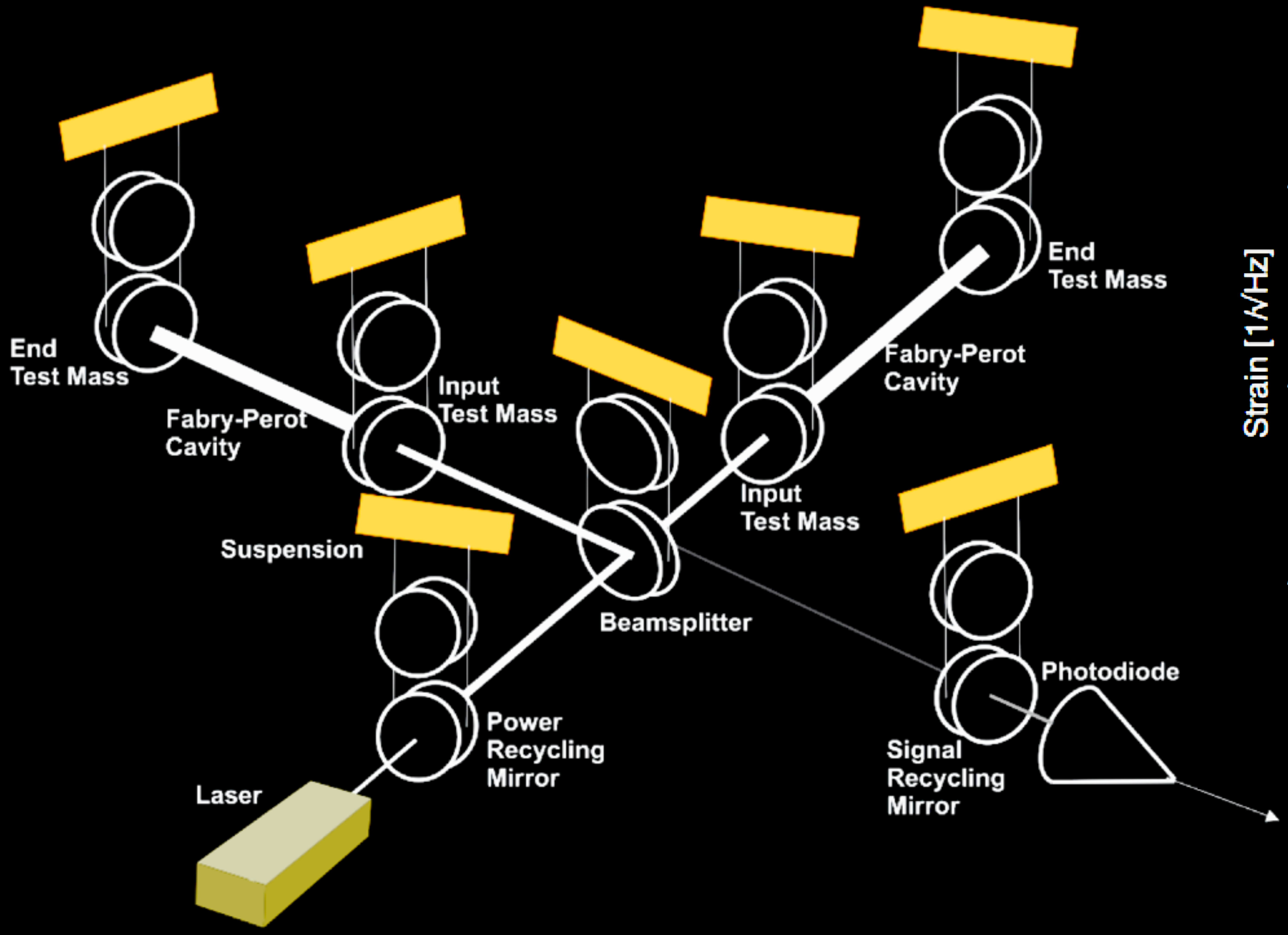
However, the energy radiated is enormous

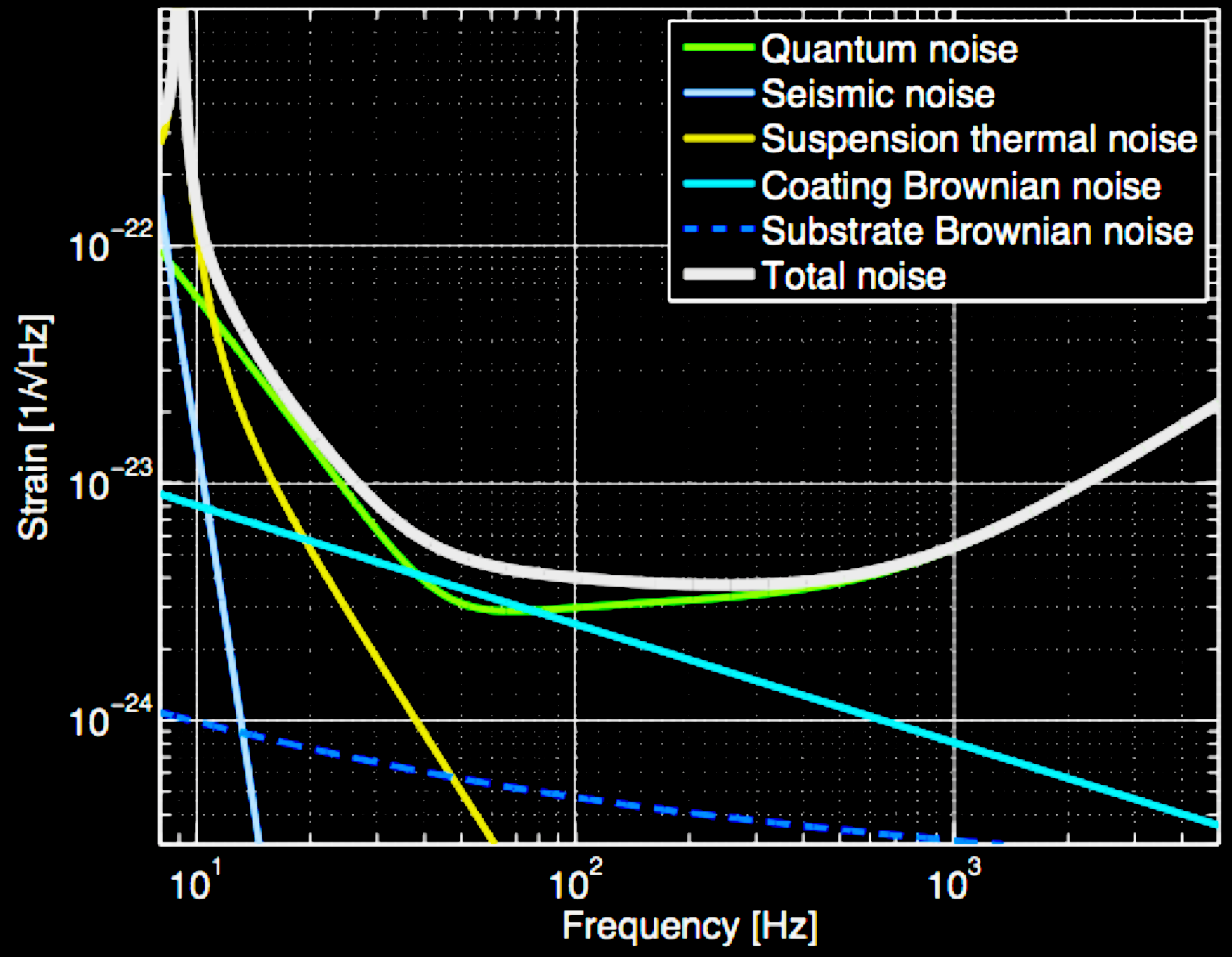
$$L_{\rm GW} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\rm S}}{r}\right)^2 \sim 10^{59}{\rm erg/s}$$

Solar luminosity L ~ 10^{33} erg/s
Gamma Ray Bursts L ~ $10^{49\text{-}52}$ erg/s


Proxima Centauri
Imagine measuring this distance to a precision of ten microns
4.2 light years

Advanced LIGO





Abbott,..., DAB et al. PRL **119** 161101 (2017)

The information about the EOS is encoded in the gravitational-wave phase evolution

$$\Phi_{\mathrm{GW}}(t) = 0\mathrm{pN}(t;\mathcal{M})\,[1 + 1\mathrm{pN}(t;\eta) + \cdots + 3.5\mathrm{pN}(t;\eta) + 5\mathrm{pN}(t;\mathrm{EOS})]$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad \eta = \frac{(m_1 m_2)}{(m_1+m_2)^2}$$

Peters and Mathews Phys. Rev. **131**, 435 (1963),
Blanchet Liv. Rev. Rel. **17**, 2 (2014)

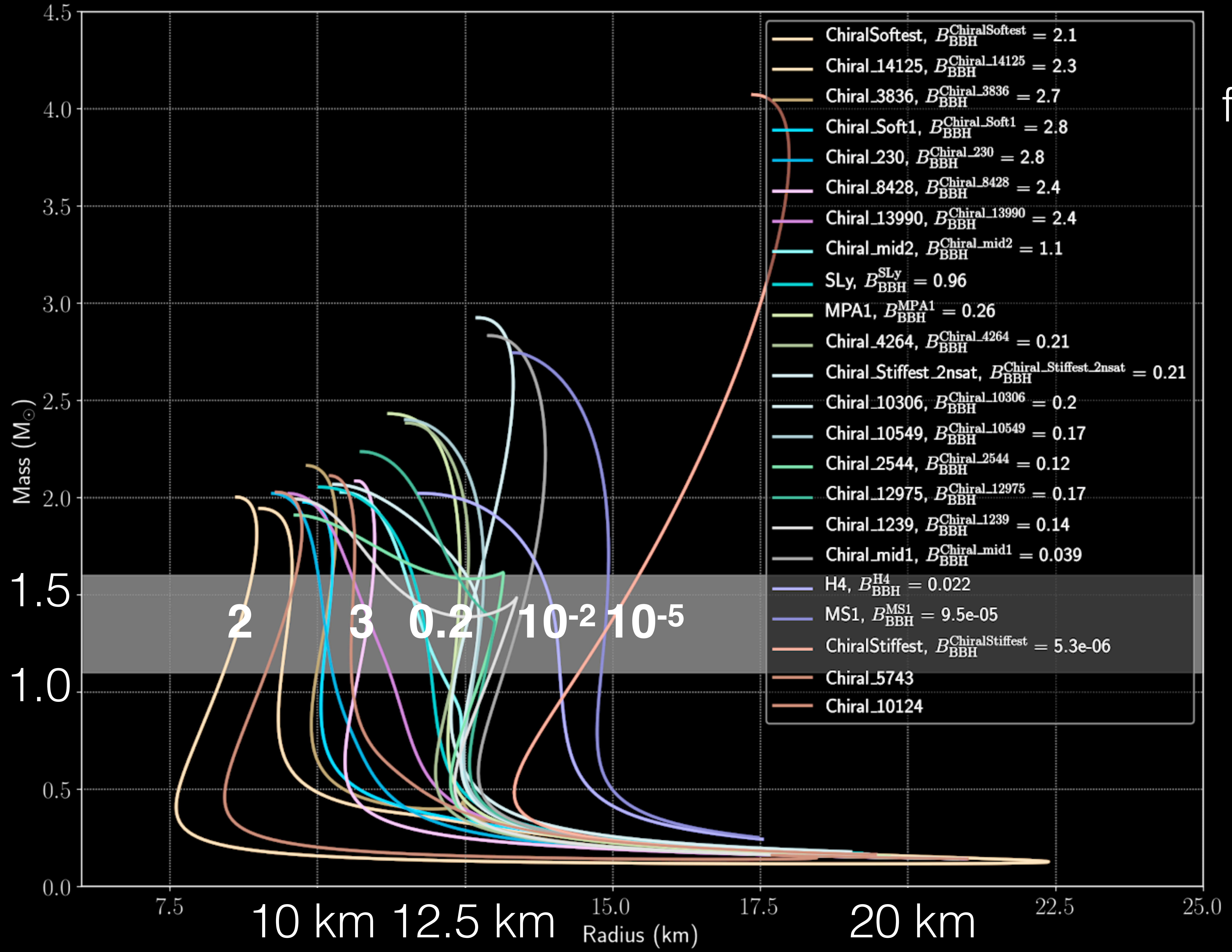
Tidal effects enter the post-Newtonian gravitational-wave phase as

$$\lambda \equiv -\frac{Q_{ij}}{\mathcal{E}_{ij}} \qquad \Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3}k_2\left(\frac{Gm}{Rc^2}\right)^{-5}$$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

$$q = m_2/m_1 \leq 1$$

Flanagan and Hinderer PRD **77** 021502 (2008)



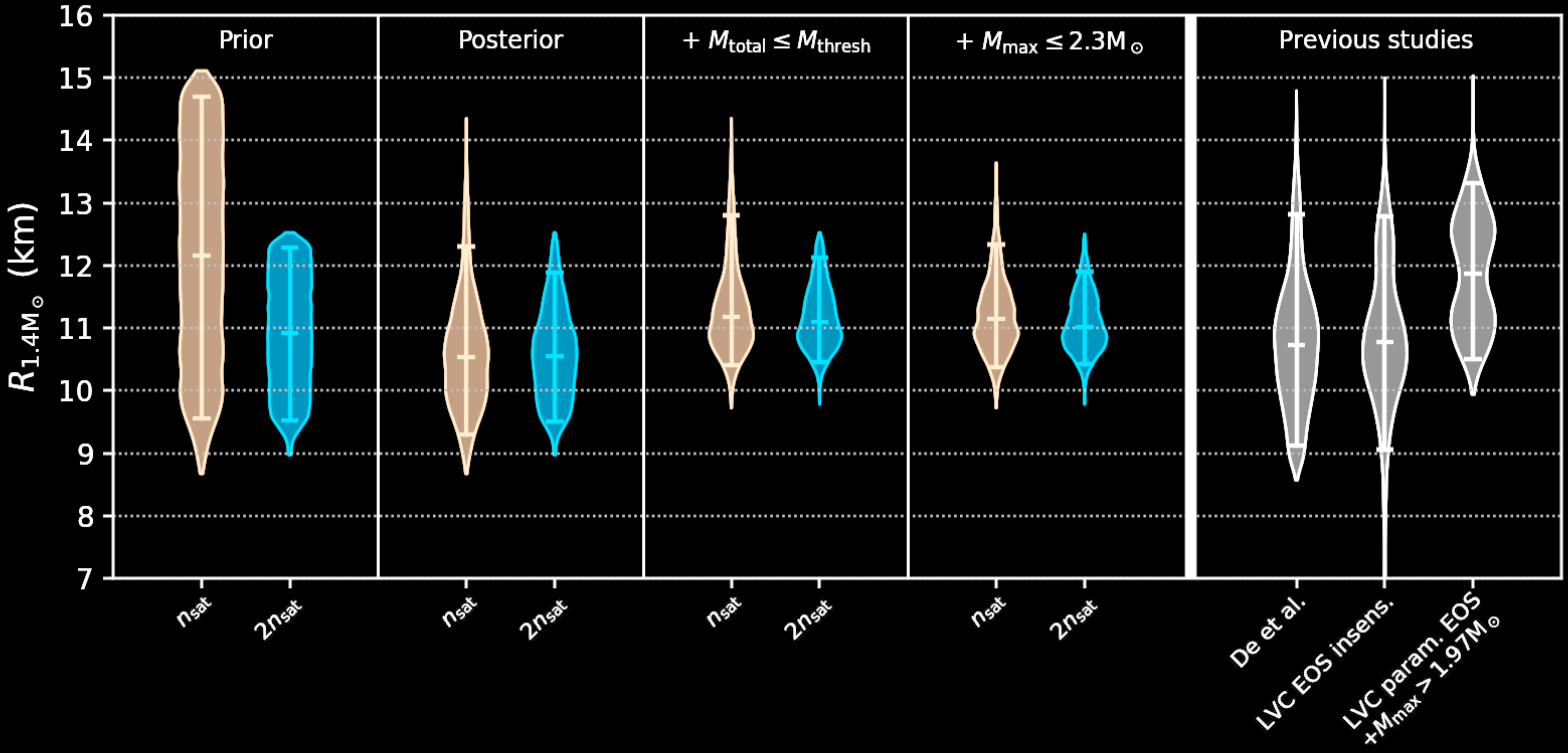
Calculate Bayes factor for specific EOS vs BBH

Only the stiffest EOS are ruled out at high confidence

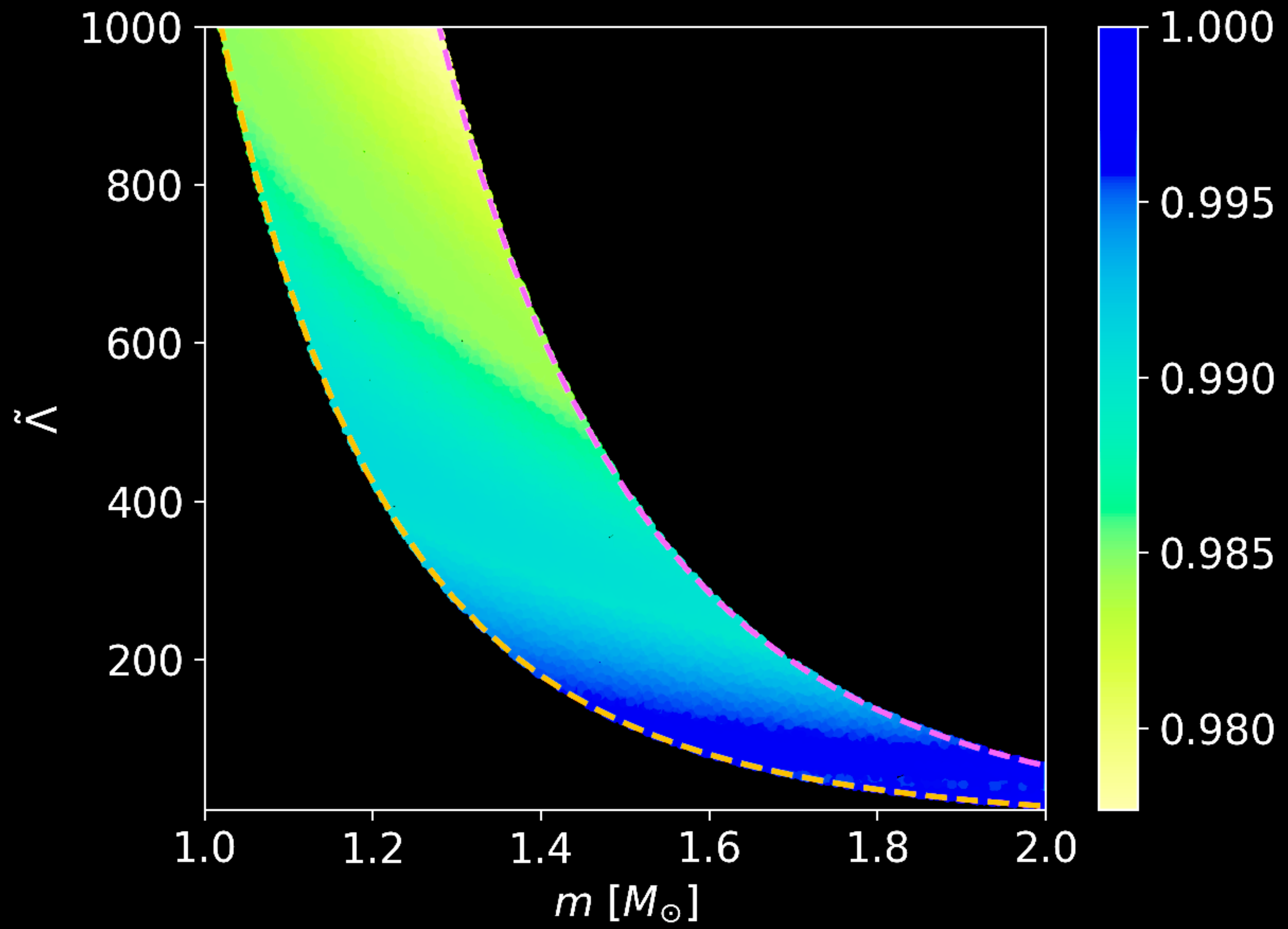
Soft EOSes **and black holes** are all consistent with GW170817

c.f. Abbott et al. CQG **37** 045006 (2020)

Soares-Santos,..., DAB, et al. ApJ **848** L16 (2017)



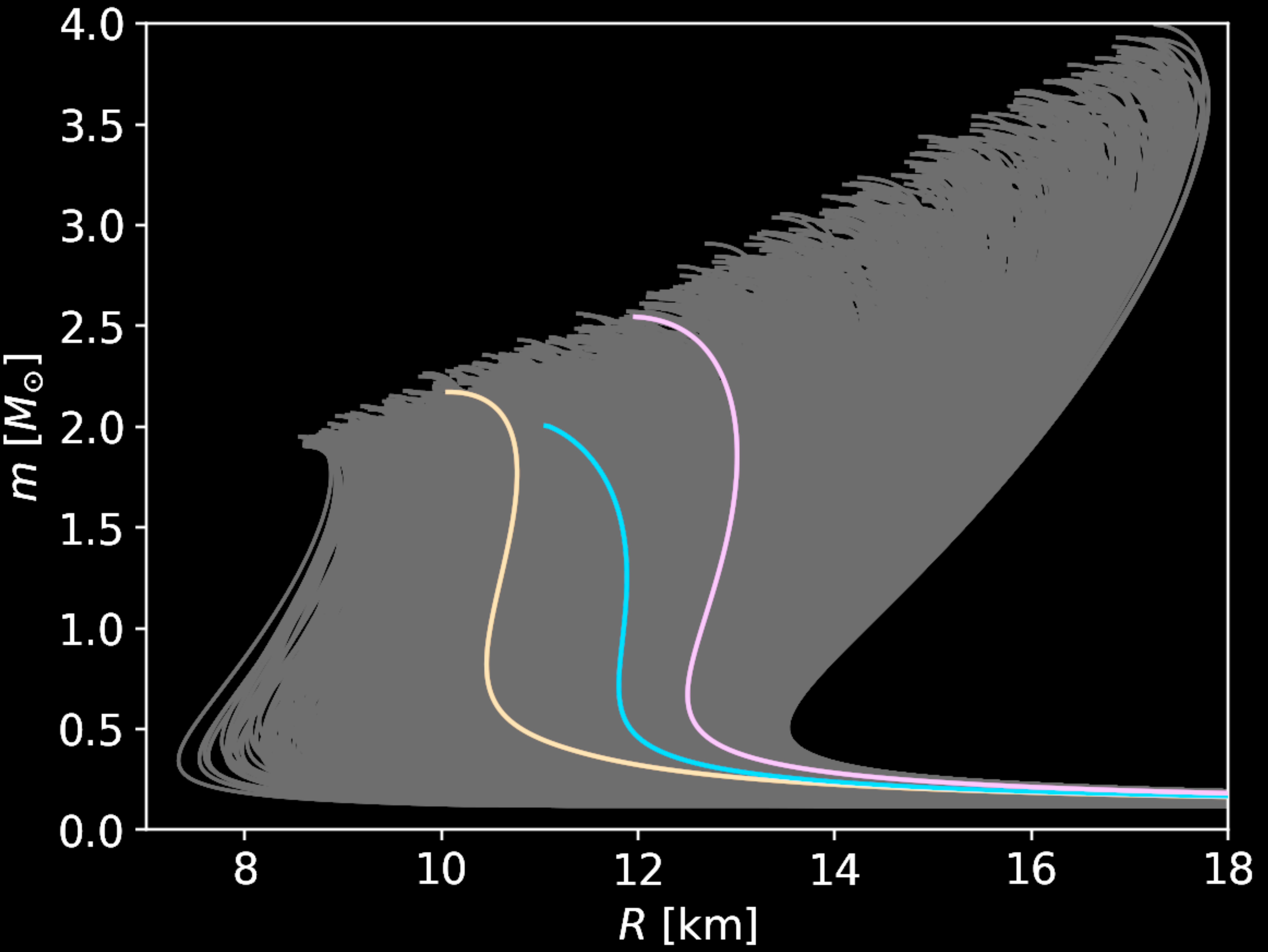
Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)



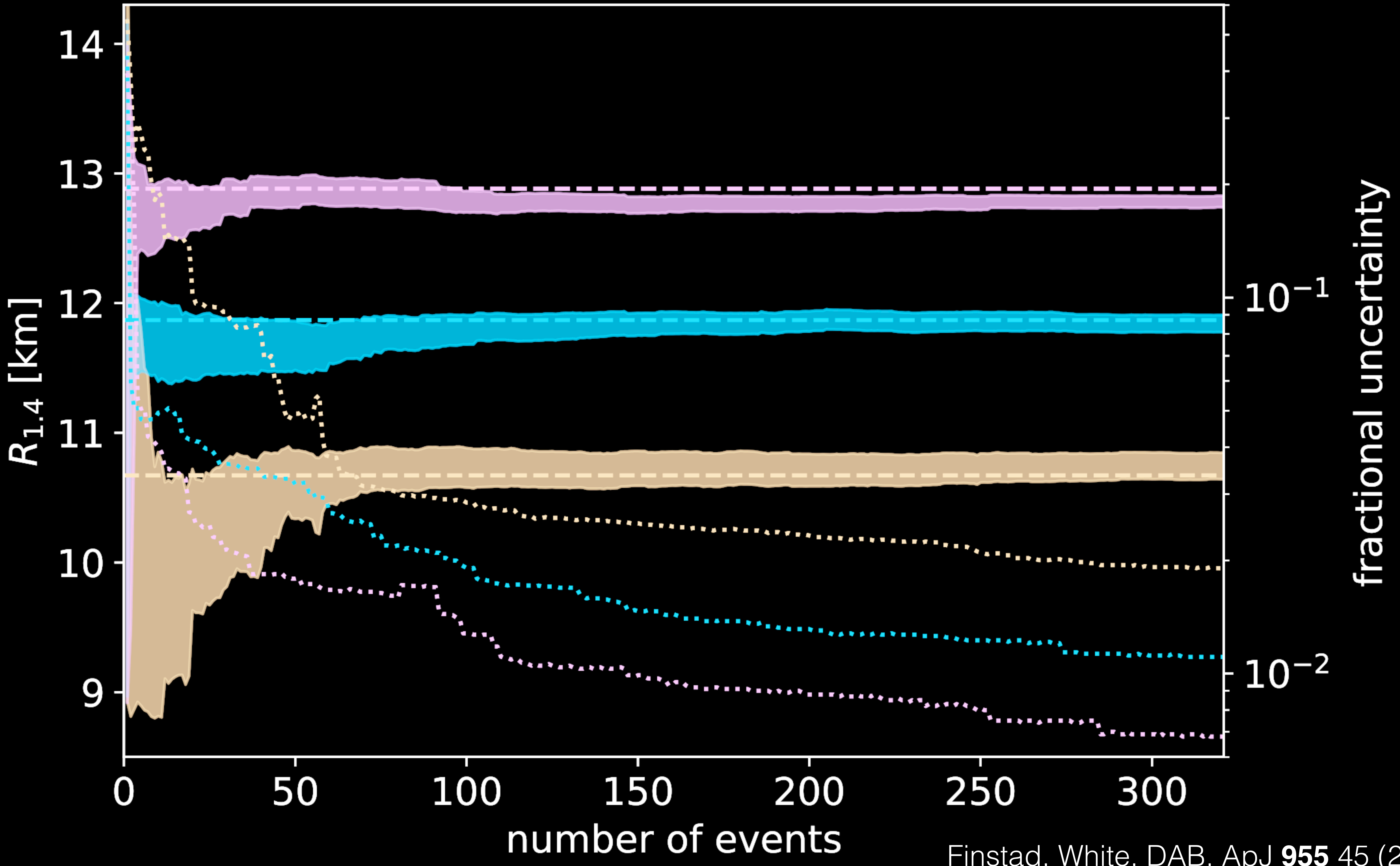
$$\mathcal{O} = \max_{t,\phi} \frac{\langle s|h\rangle}{\sqrt{\langle s|s\rangle\langle h|h\rangle}}$$

$$\langle a|b\rangle = 4\mathrm{Re}\int_{f_{\rm low}}^{f_{\rm high}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\,df$$

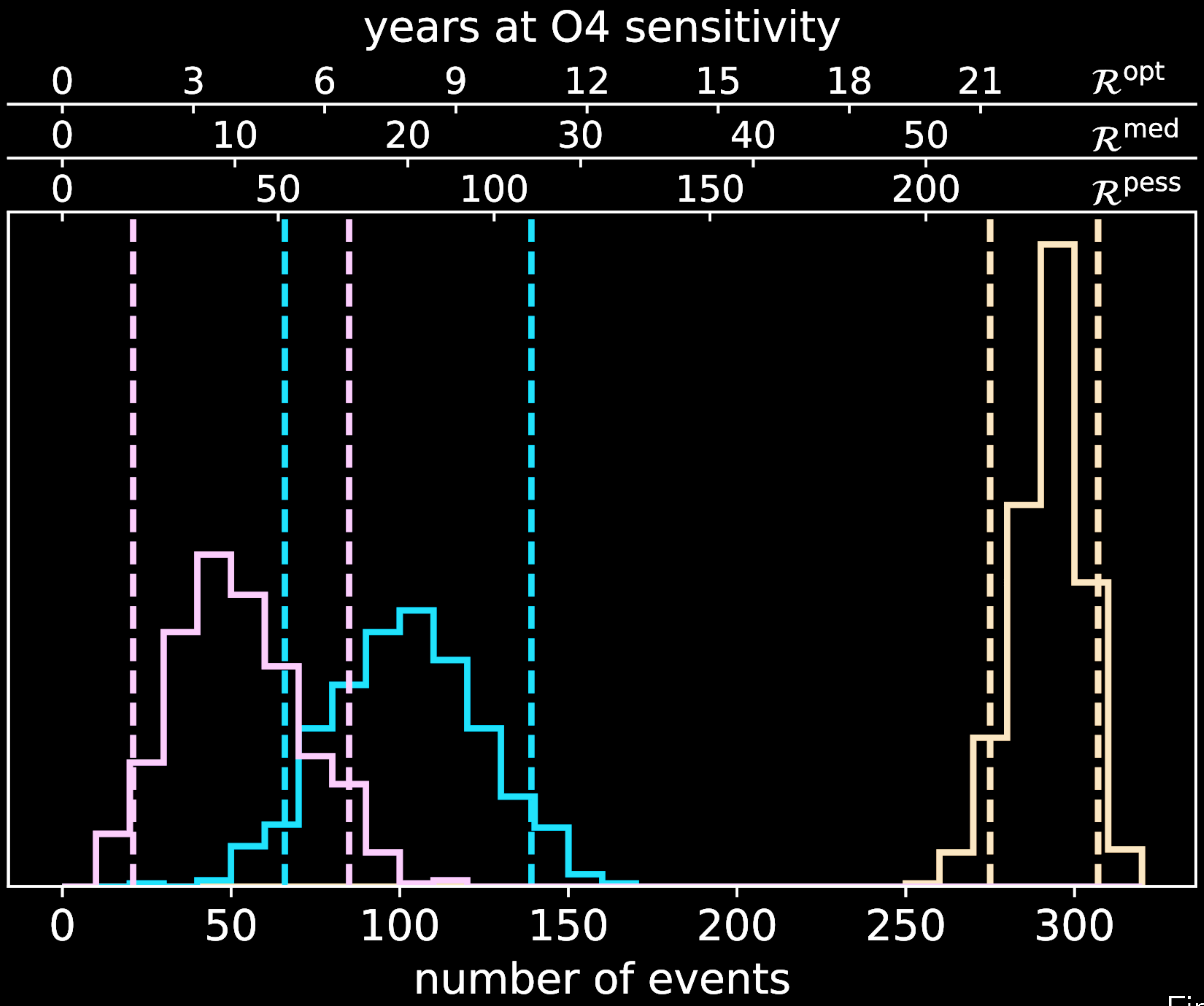
Finstad, White, DAB, ApJ **955** 45 (2023)



Finstad, White, DAB, ApJ **955** 45 (2023)

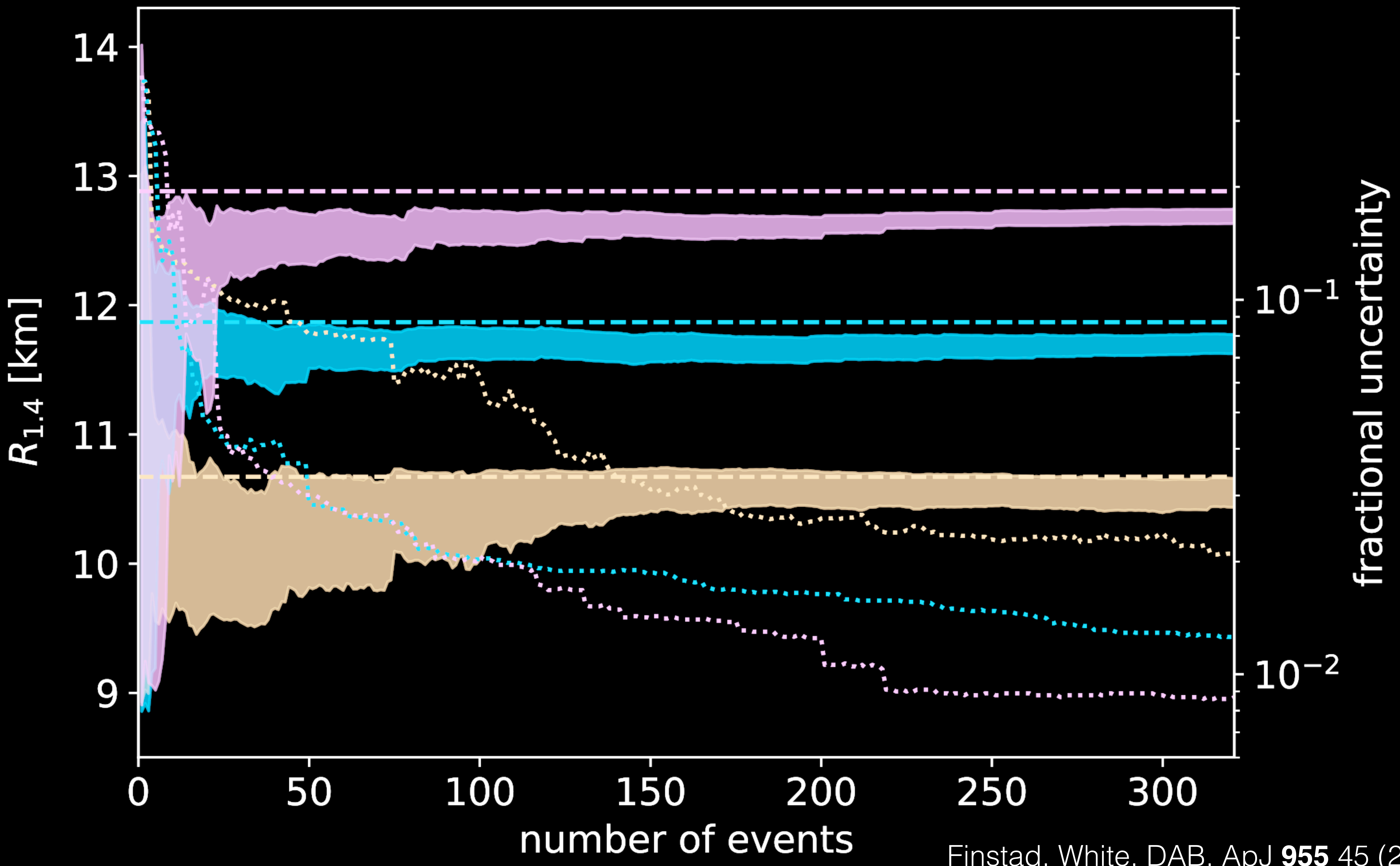


Finstad, White, DAB, ApJ **955** 45 (2023)



Distribution of number of events required to reach 2% precision in the neutron star radius

Finstad, White, DAB, ApJ **955** 45 (2023)

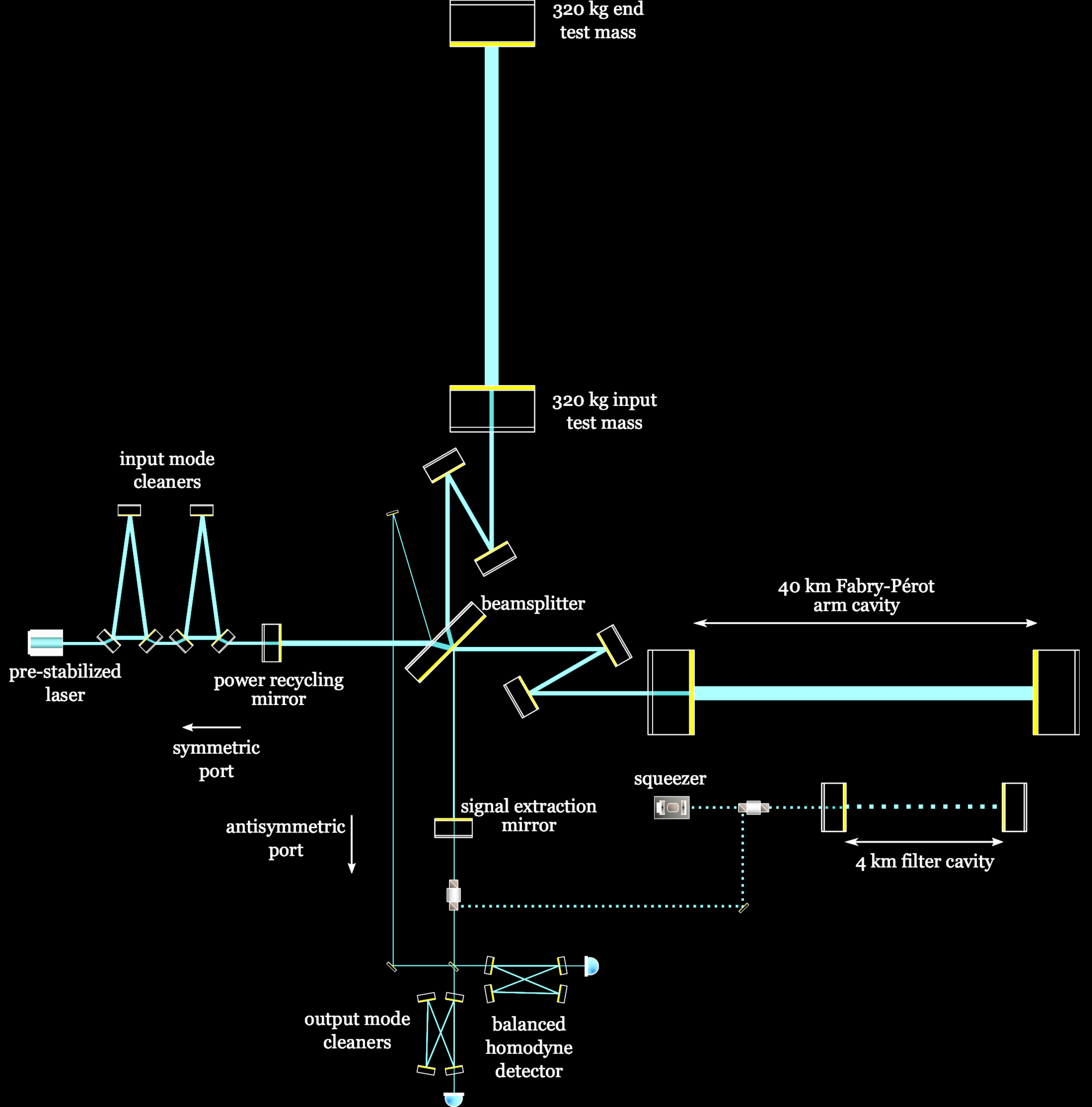


Finstad, White, DAB, ApJ **955** 45 (2023)

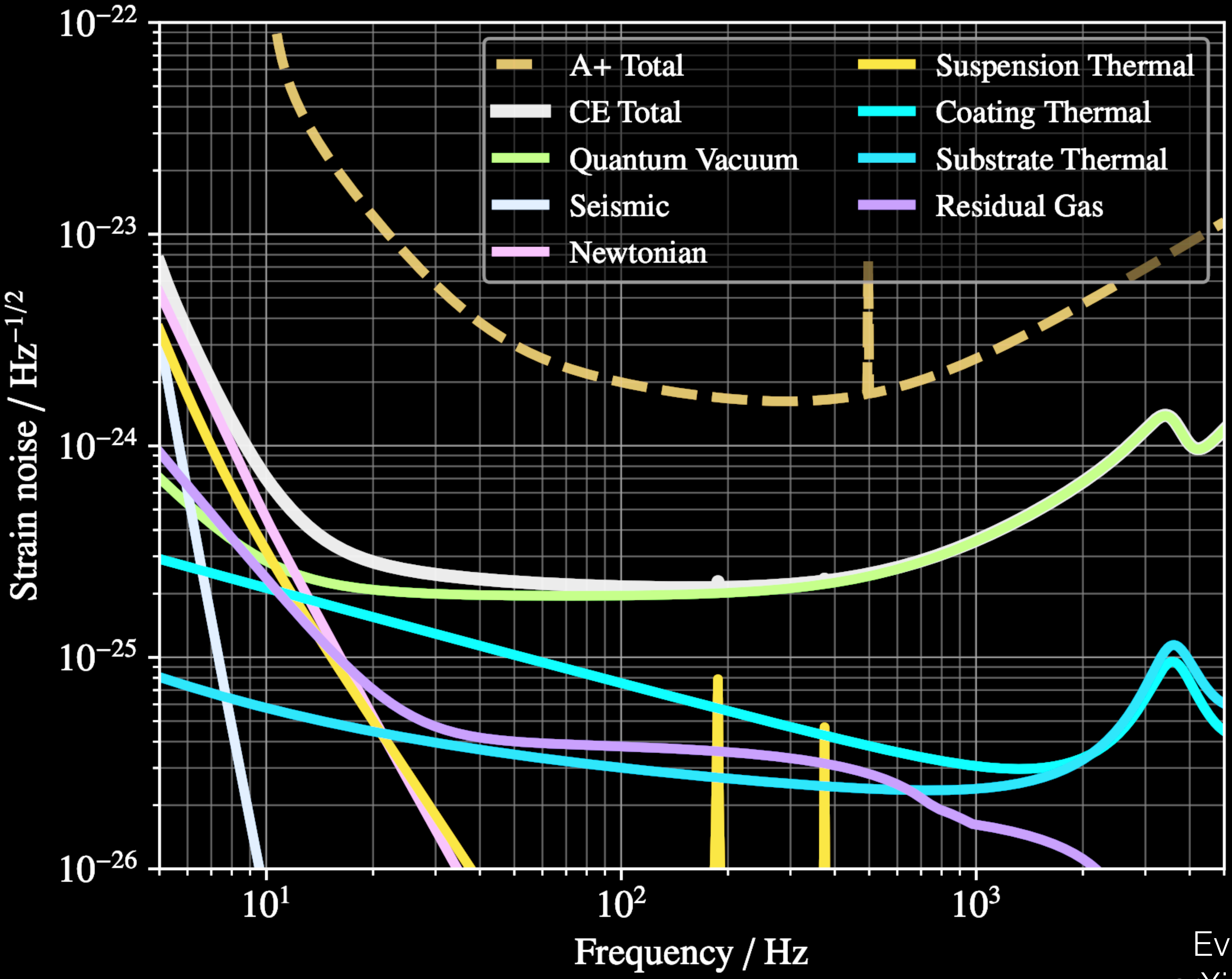
What is the future of gravitational-wave astronomy beyond LIGO?

What sets the detector sensitivity?

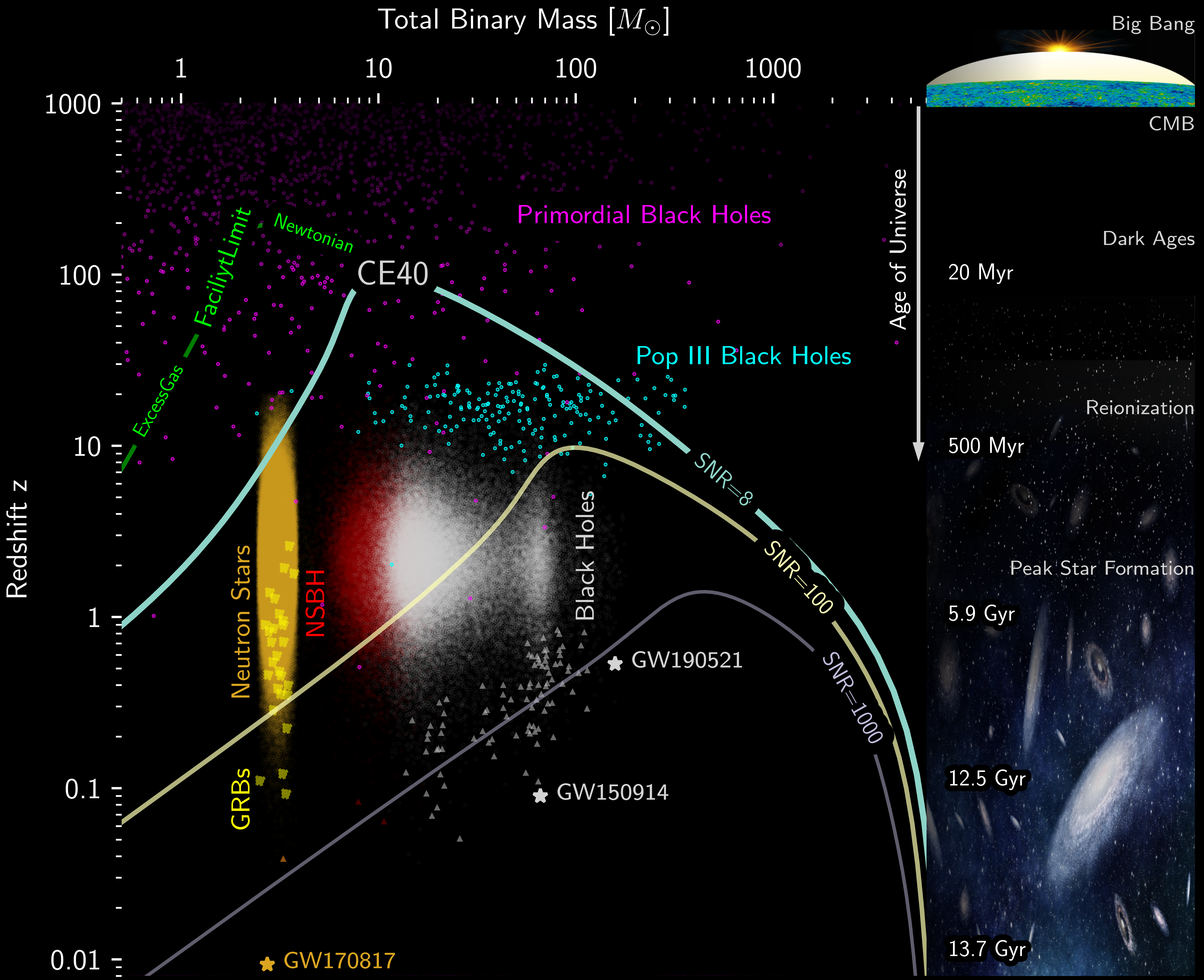
- Gravitational-wave detectors are essentially antennas
- The highest frequency of interest sets the ideal scale of the antenna
- For neutron star mergers, this is ~ few kHz
- Detector length should be ~ few x 10 km
- About ten times the size of Advanced LIGO
- Scaling up arm length gains sensitivity with only modest technology improvements



Evans, …, DAB, et al.
arXiv:2306.13745 (2023)



Evans, …, DAB, et al.
arXiv:2306.13745 (2023)



Evans, ..., DAB, et al.
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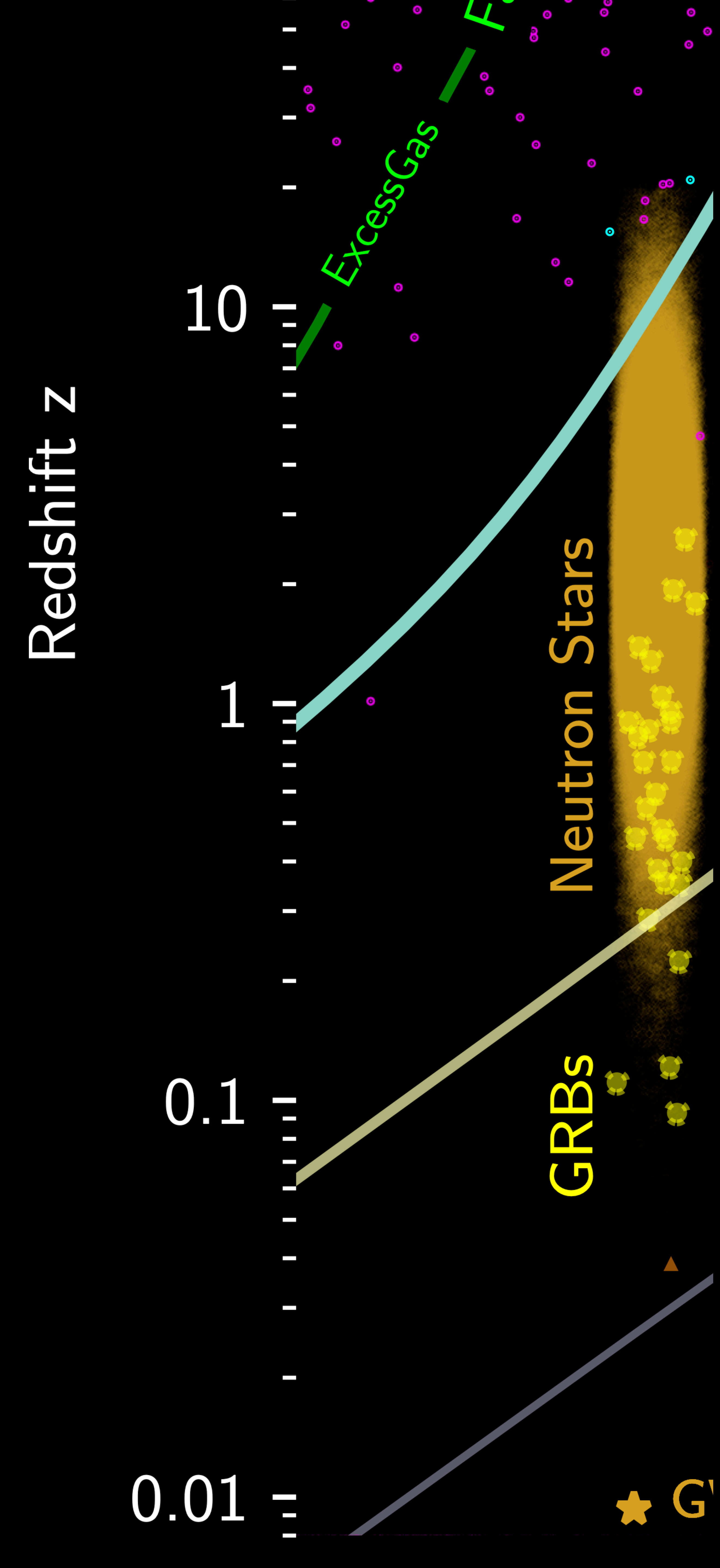
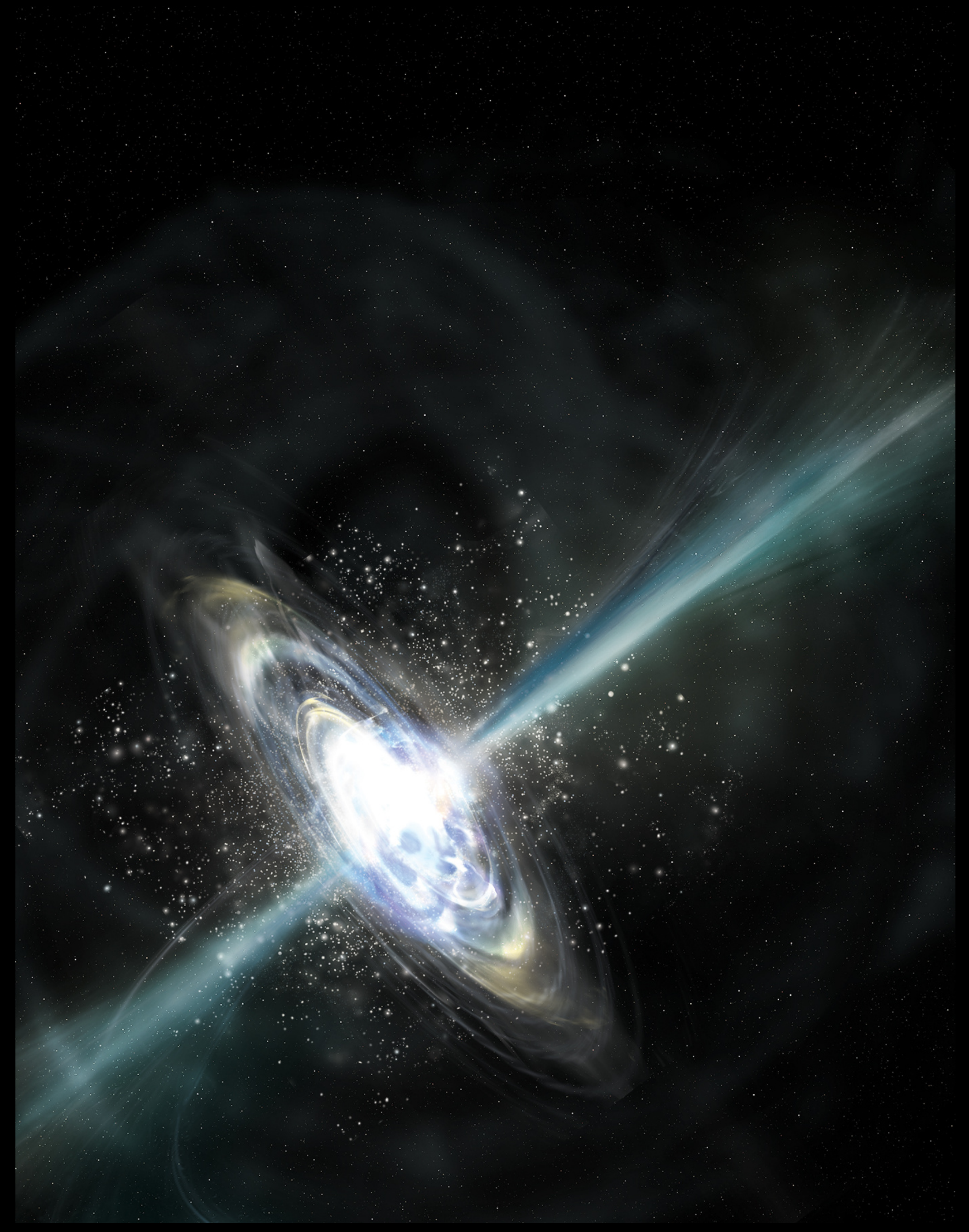
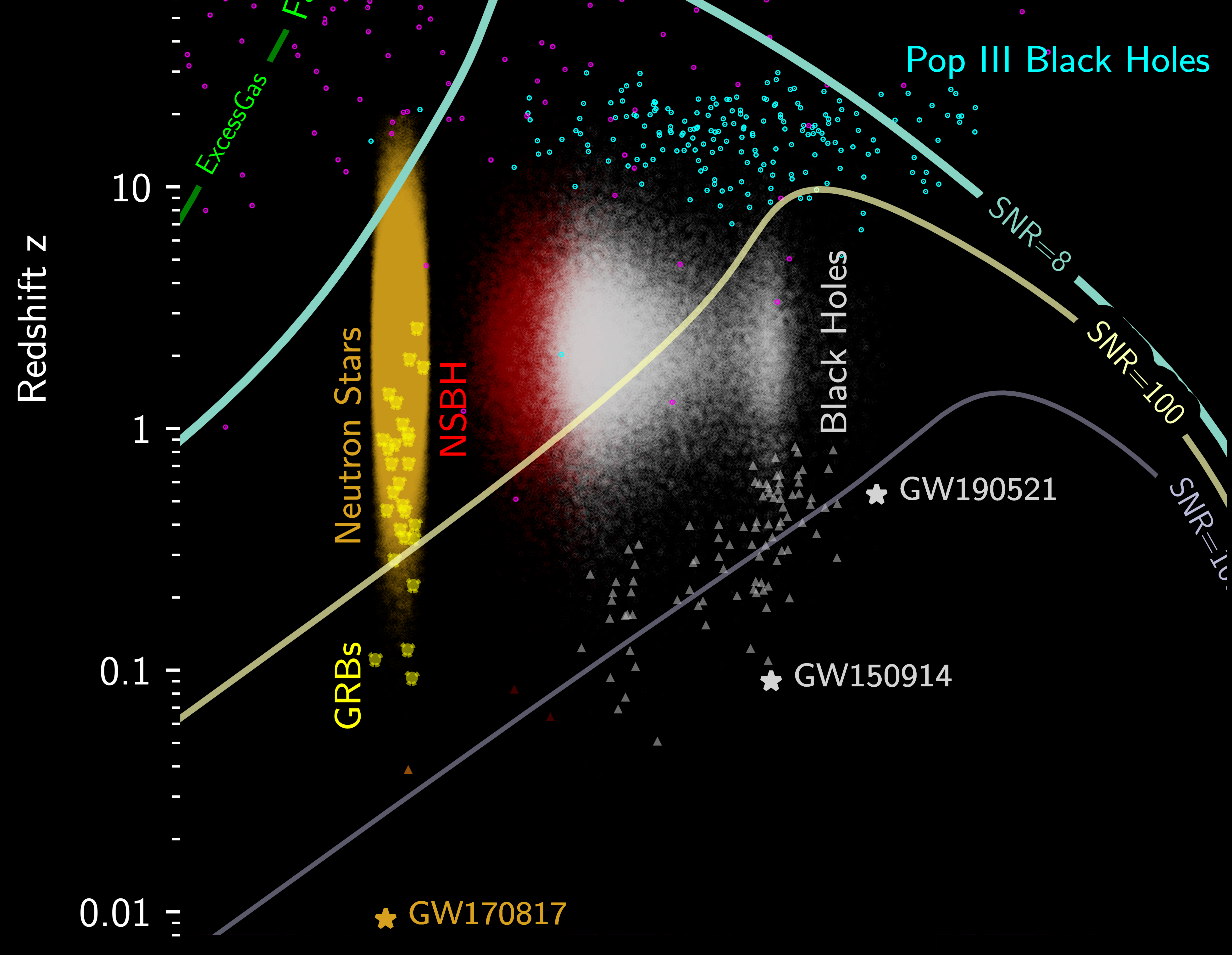


Detect the majority of neutron star mergers in the universe!

All-sky coverage for GRBs in the Cosmic Explorer era will maximize the science output

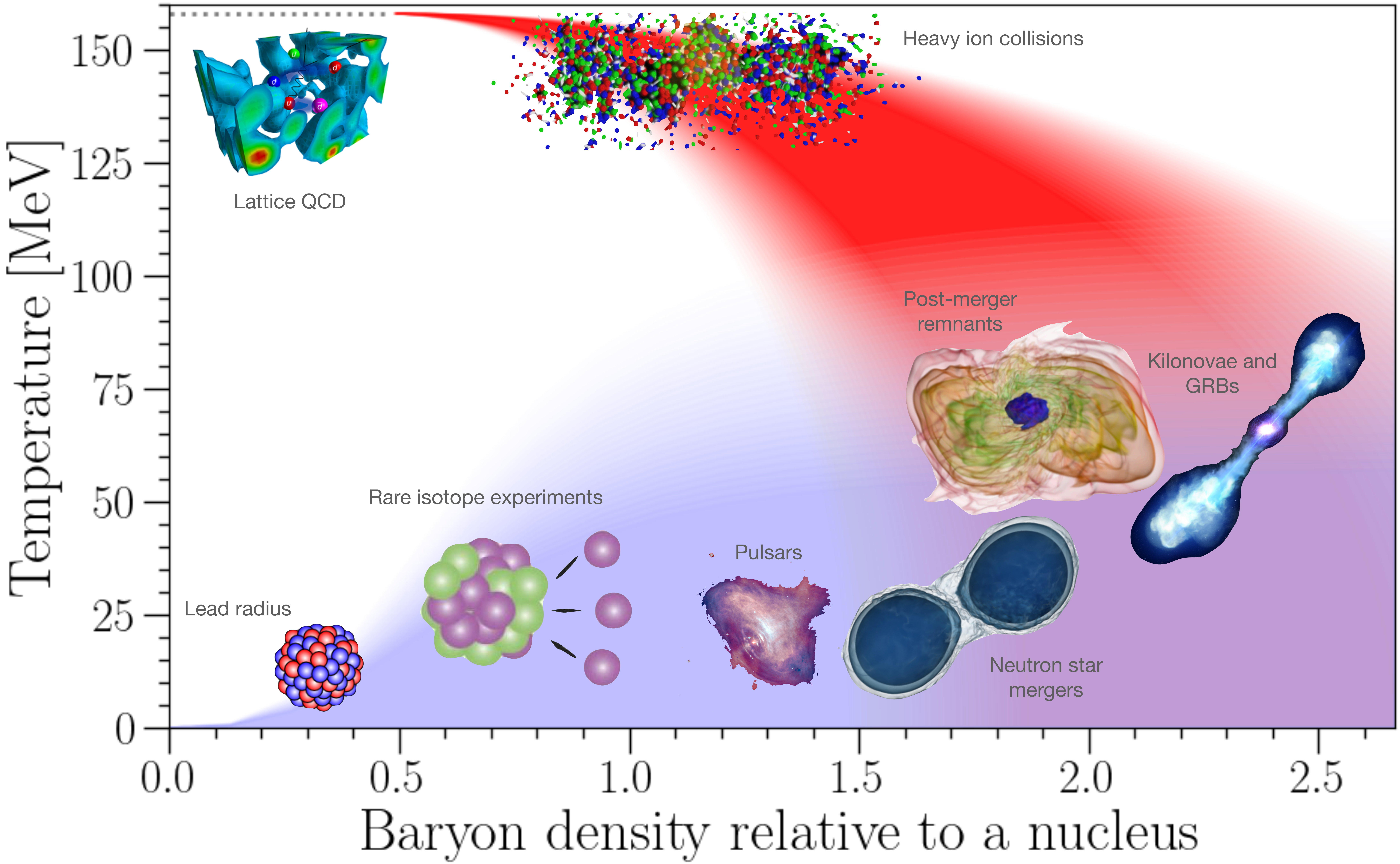


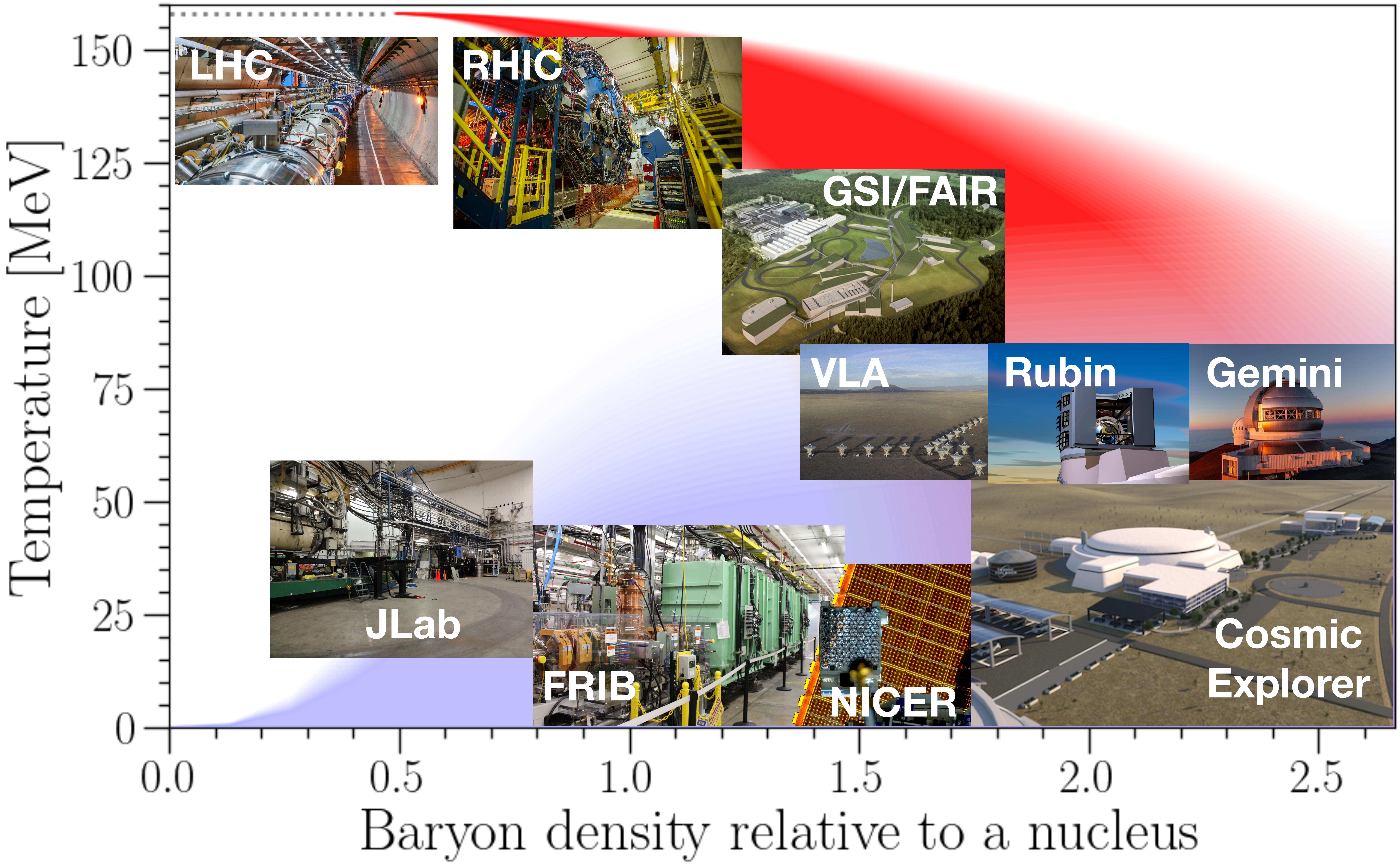


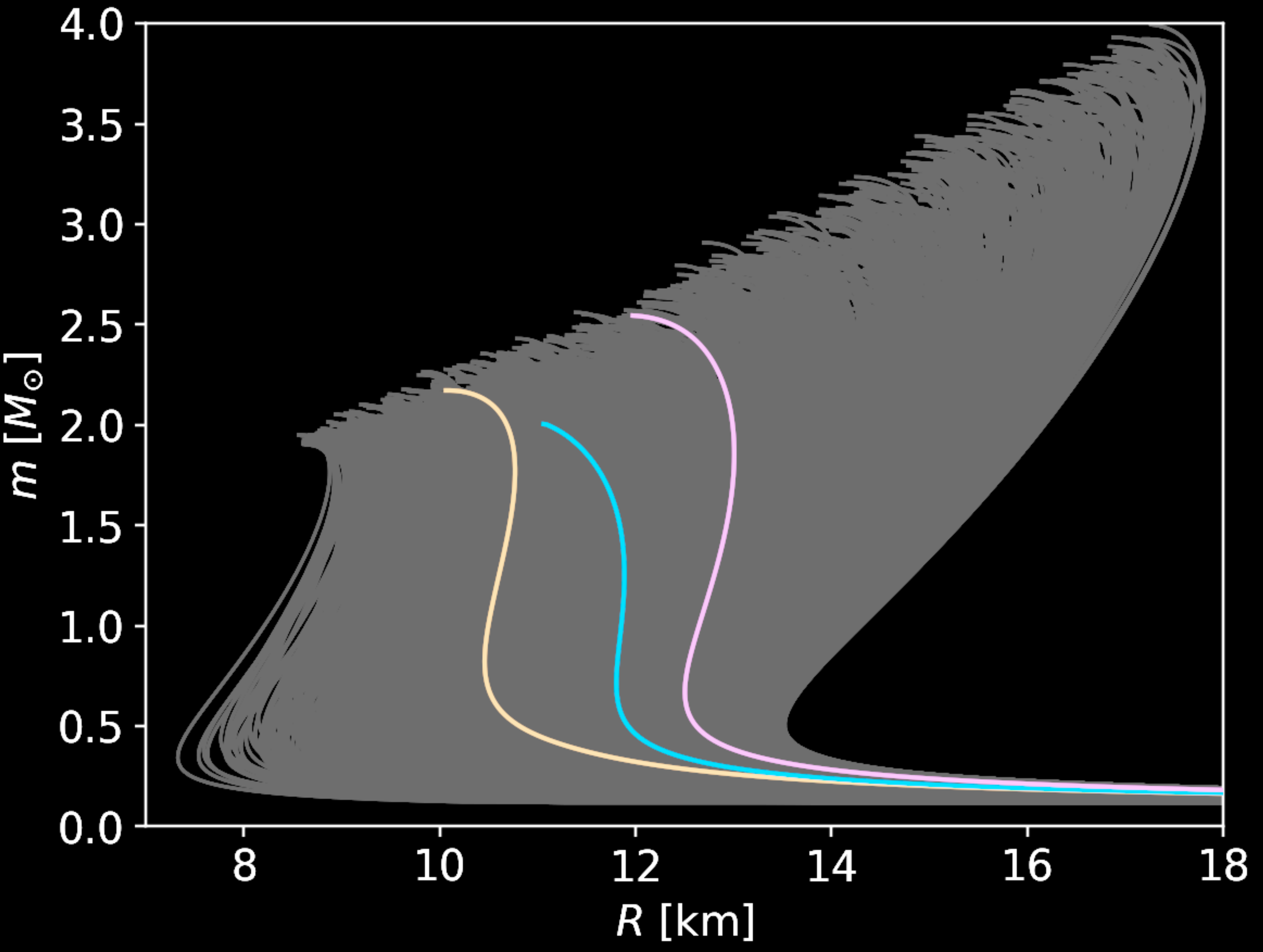
Precision measurement of the masses and spins of **large** numbers of compact objects

Explore the core collapse mechanism and angular momentum transport in massive stars

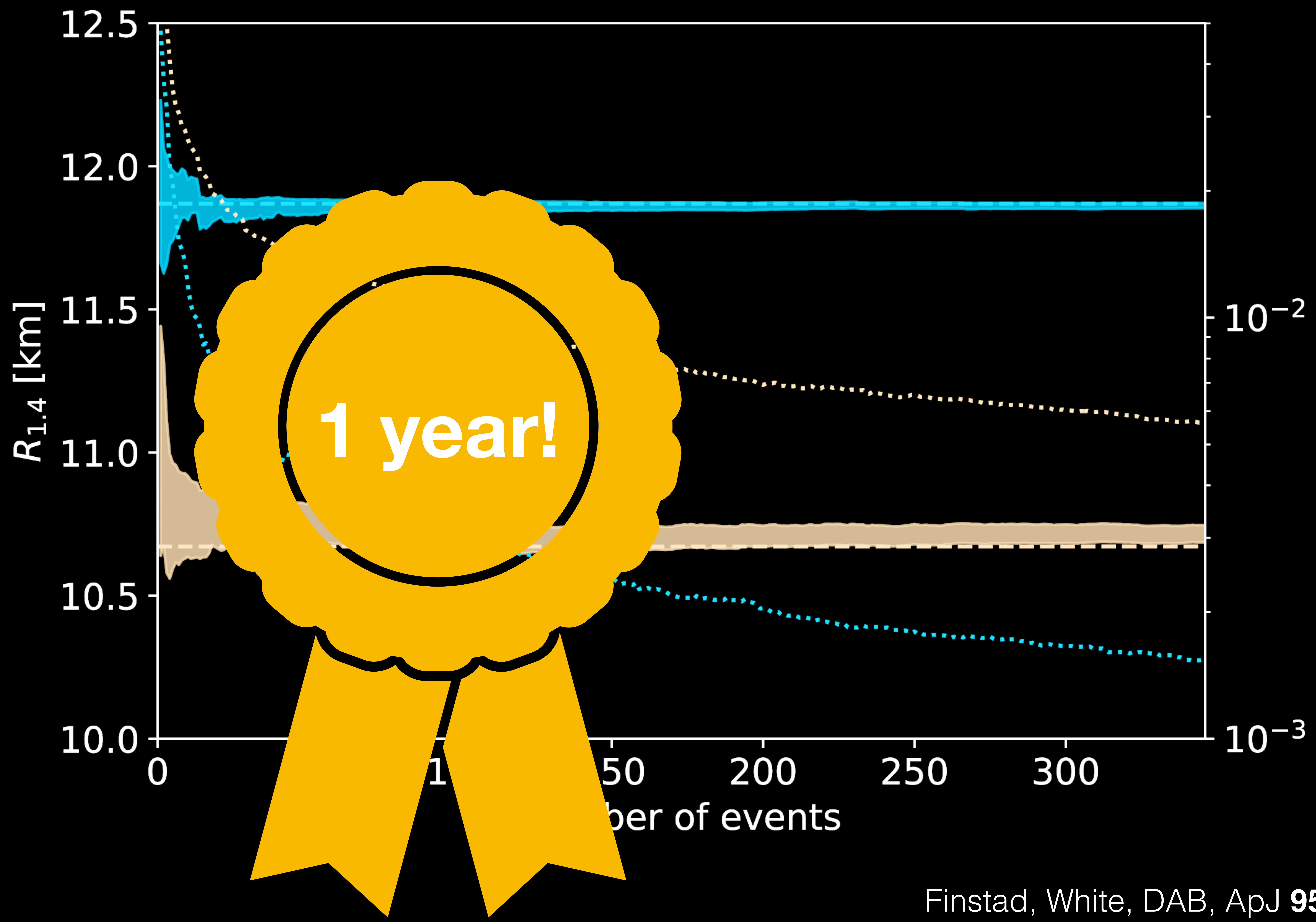
Connect remnant physics to EM observations of progenitors


Temperature [MeV]
150
125
100
75
50
25
0
0.0
0.5
1.0
1.5
2.0
2.5
Baryon density relative to a nucleus
Heavy ion collisions
Lattice QCD
Post-merger
remnants
Kilonovae and
GRBs
Rare isotope experiments
Pulsars
Lead radius
Neutron star
mergers


LHC
RHIC
GSI/FAIR
VLA
Rubin
Gemini
JLab
FRIB
NICER
Cosmic Explorer
Temperature [MeV]
150
125
100
75
50
25
0
0.0
0.5
1.0
1.5
2.0
2.5
Baryon density relative to a nucleus

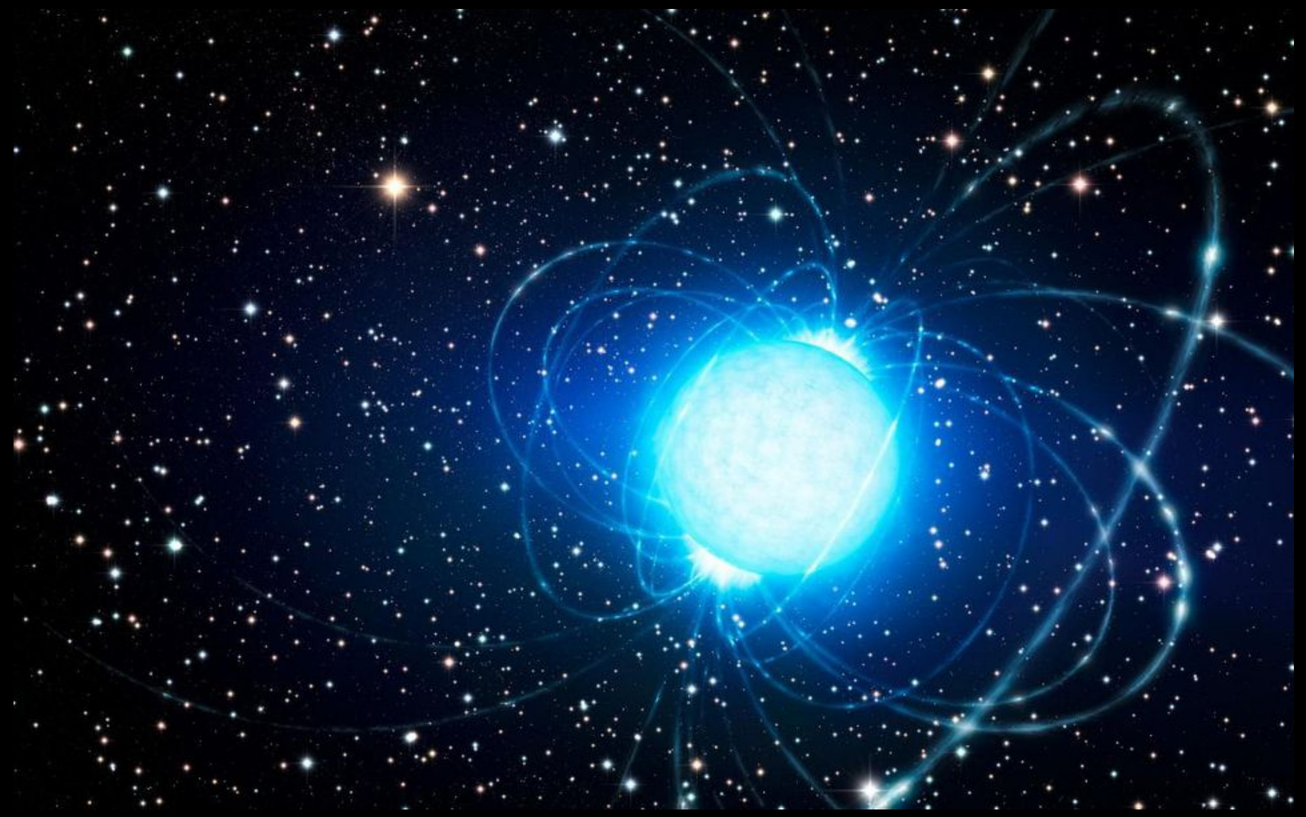


Finstad, White, DAB, ApJ **955** 45 (2023)

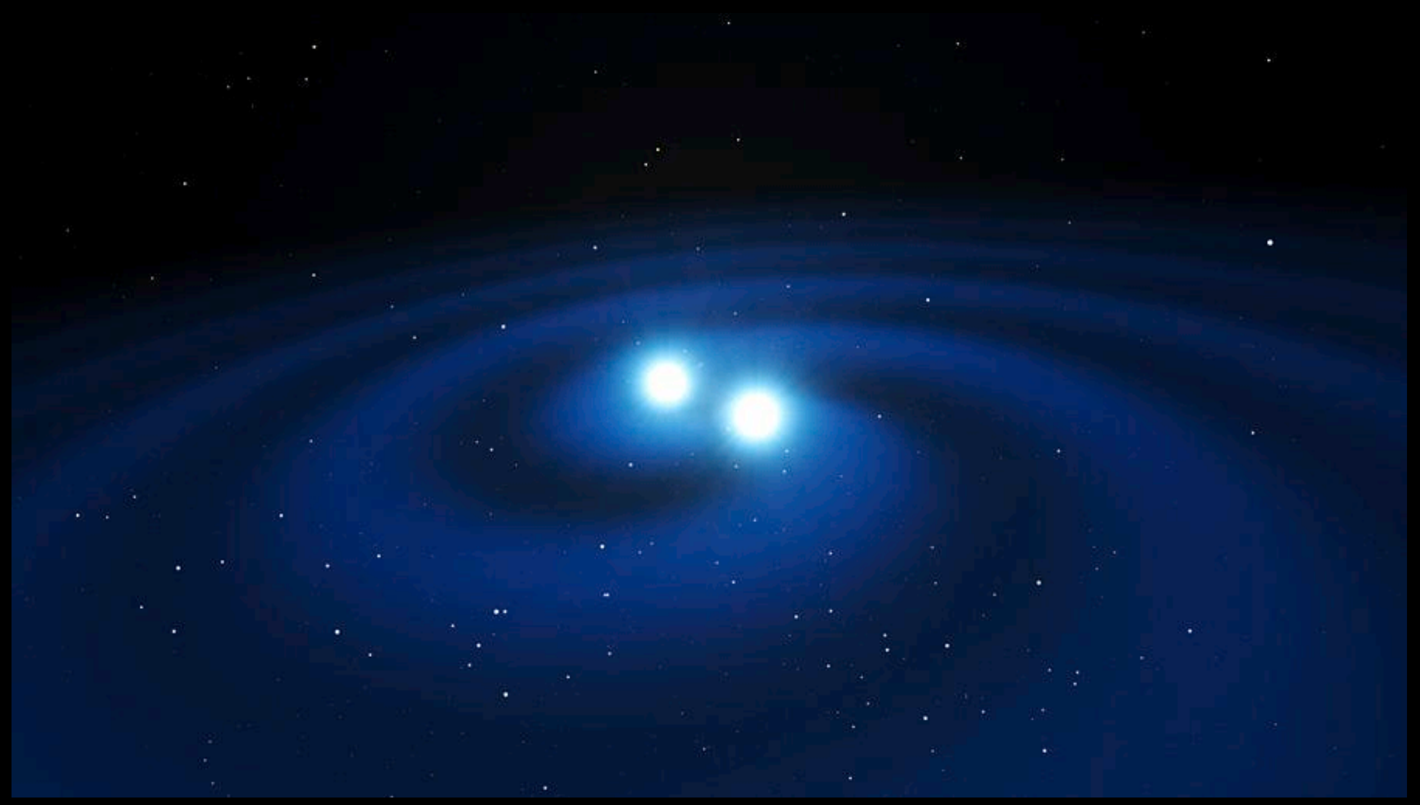


Finstad, White, DAB, ApJ **955** 45 (2023)

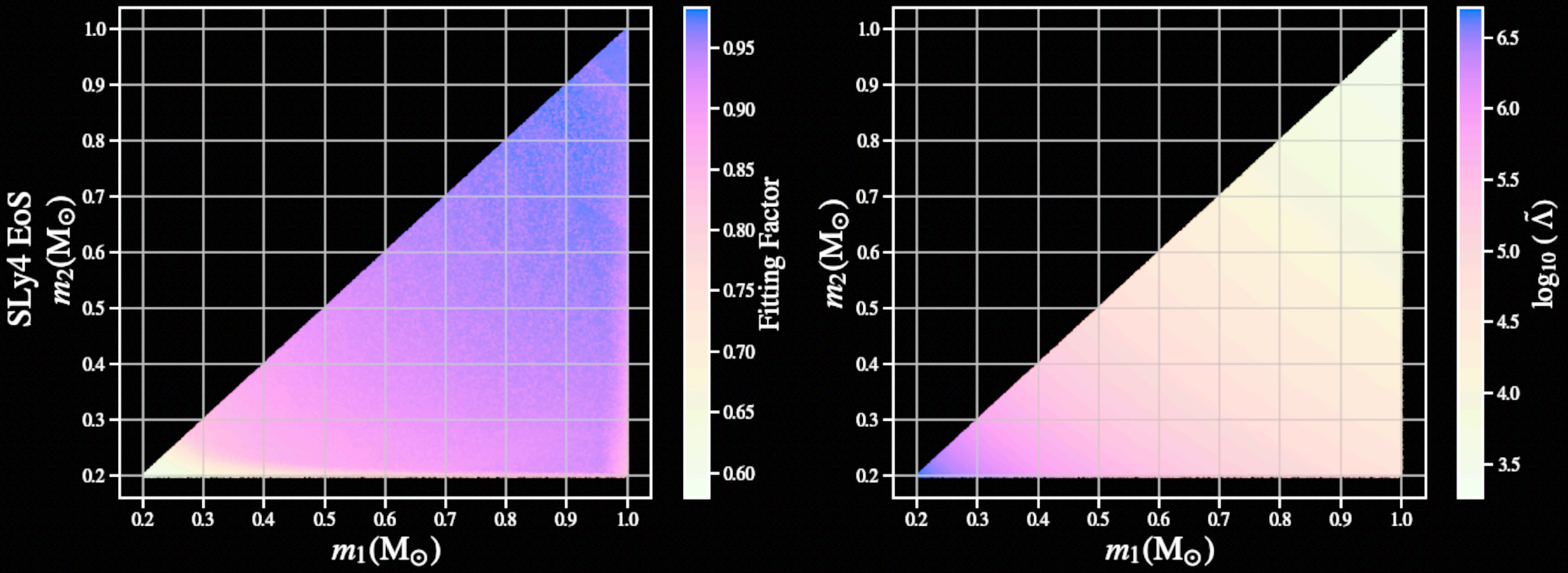
Fundamental Physics and Exotic Sources



Is dark matter hiding in the cores of neutron stars?



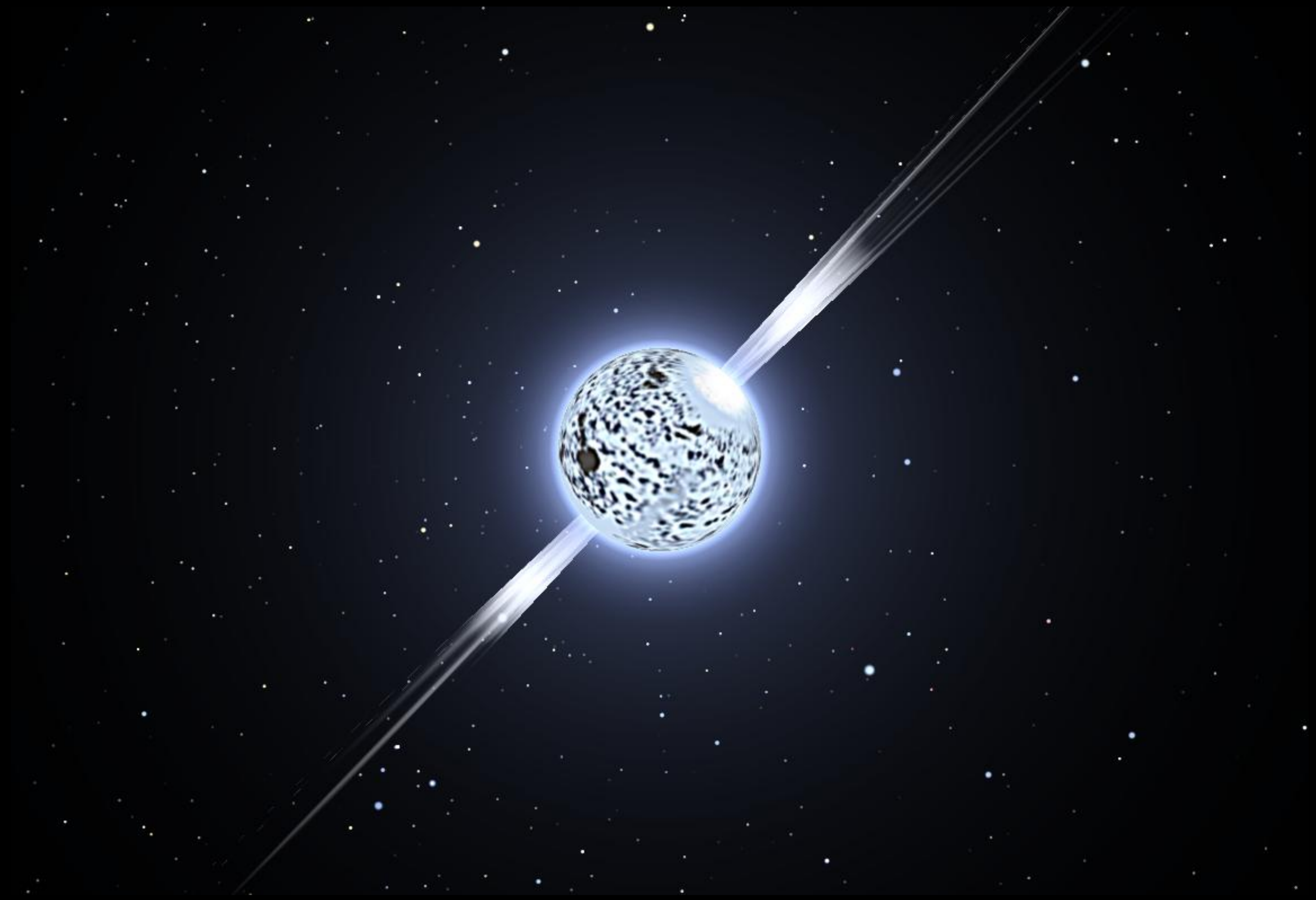
Do sub-solar mass neutron stars exist?



Bandopadhyay, …, DAB, et al. Phys. Rev. D 107, 103012 (2023)

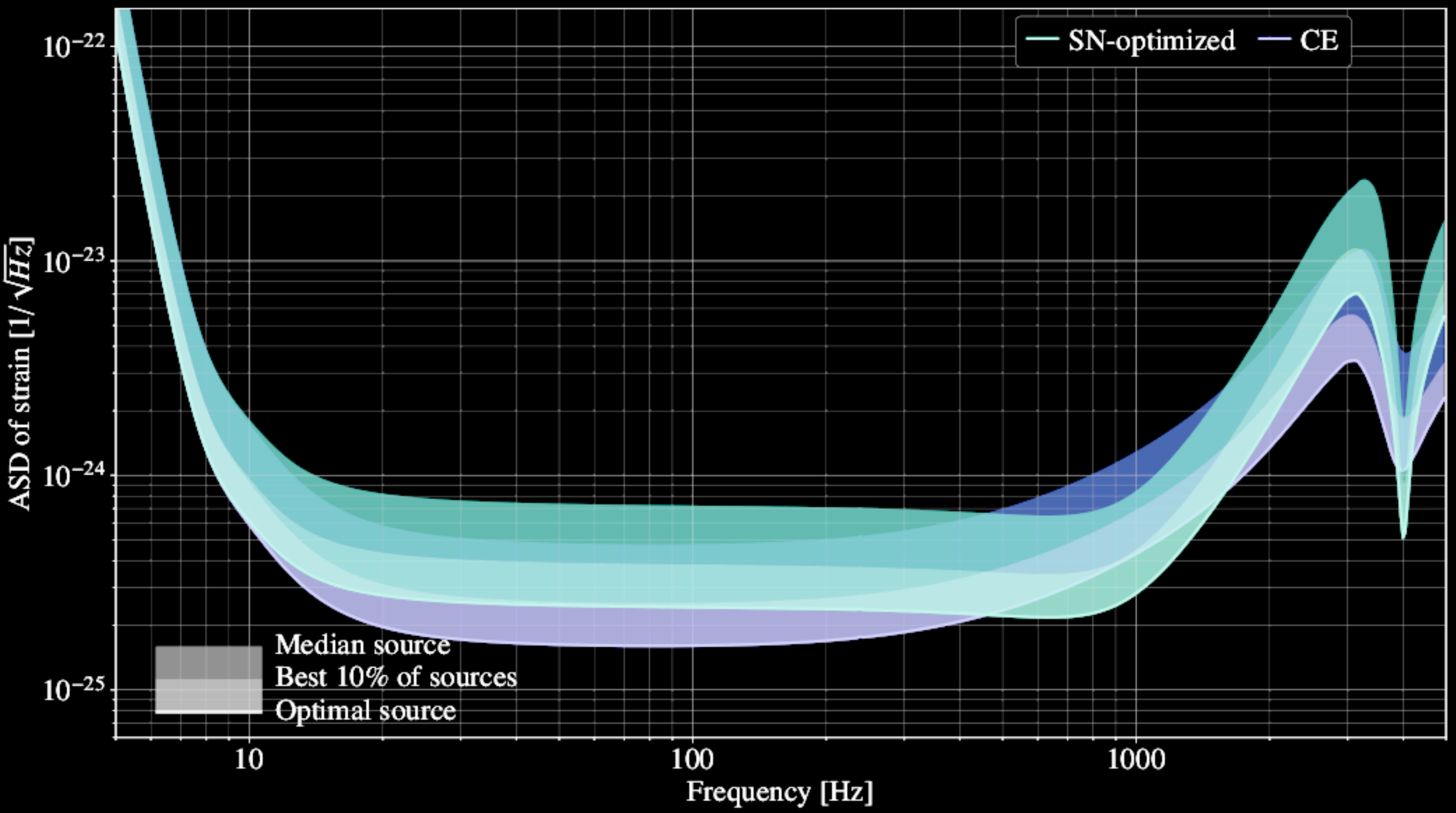
Potential for New Discoveries

Core collapse supernovae



Gravitational Waves from Pulsars

Supernovae in Cosmic Explorer

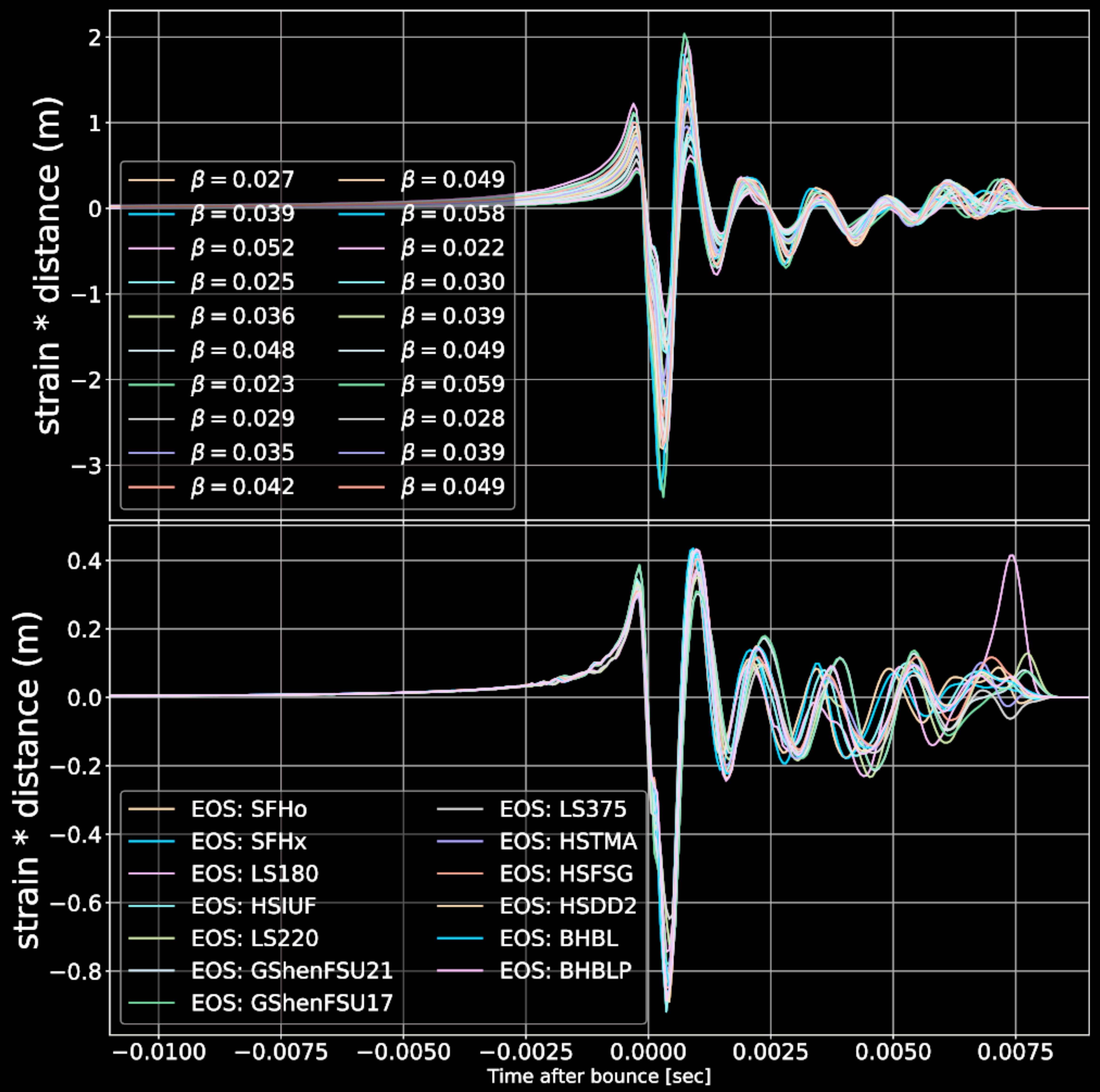


70 kpc at SNR 8

95 kpc at SNR 8

c.f. DUNE

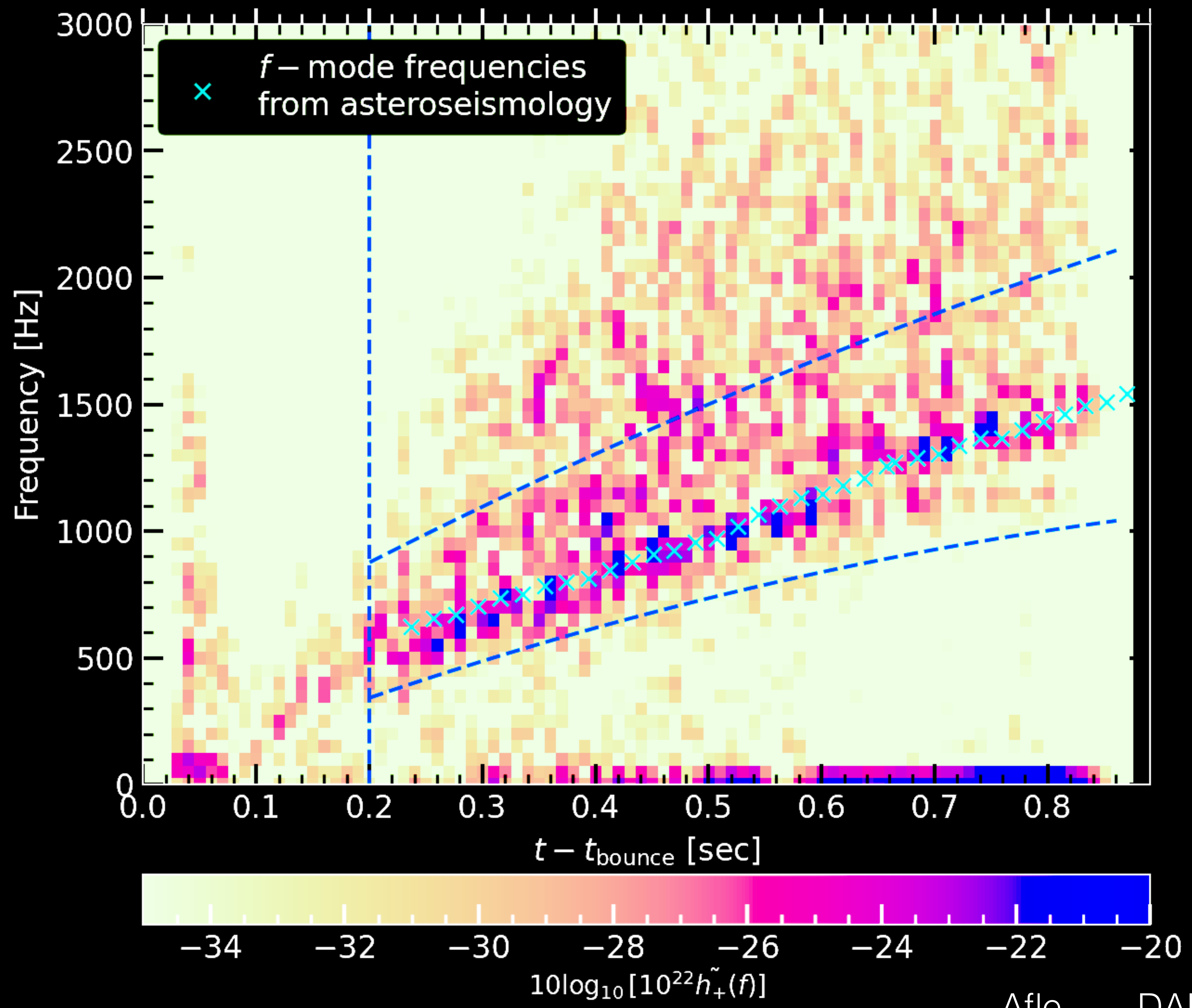
Srivastava, Ballmer, DAB, Afle, Burrows, Radice, Vartanyan PRD **100**, 043026 (2019)



For a galactic progenitor with β = 0.02, 90 % credible interval is 0.02 (aLIGO), 0.002 (CE)

A galactic supernova observed by Cosmic Explorer could constrain f_{peak} to within 10 Hz

Afle and DAB Phys. Rev. D **103**, 023005 (2021)

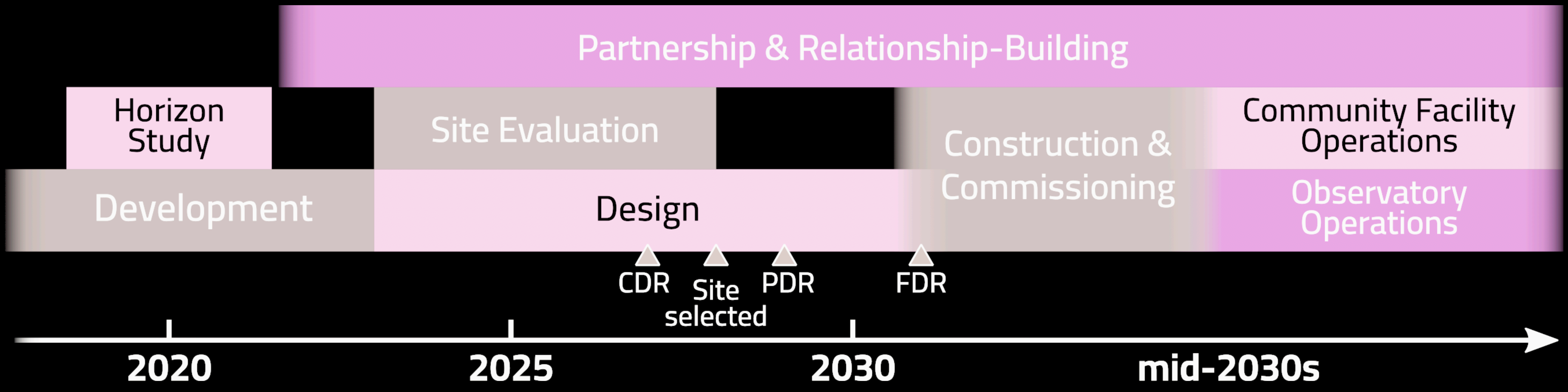


Around 400 ms after the bounce, most of the energy is in the f-mode of the protoneutron star

For supernova < 10 kpc Cosmic Explorer can measure the energy in the f-mode of the protoneutron star to within 20%

Afle, …, DAB, et al. Phys. Rev. D **107,** 123005 (2023)

Where is Cosmic Explorer today?



$2M $9M

Launching the Cosmic Explorer Conceptual Design

Identifying and Evaluating Sites for Cosmic Explorer

Cosmic Explorer Optical Design

Enabling Megawatt Optical Power in Cosmic Explorer

Local Gravity Disturbances and Scattered-Light Mitigation

Cosmic Explorer Horizon Study

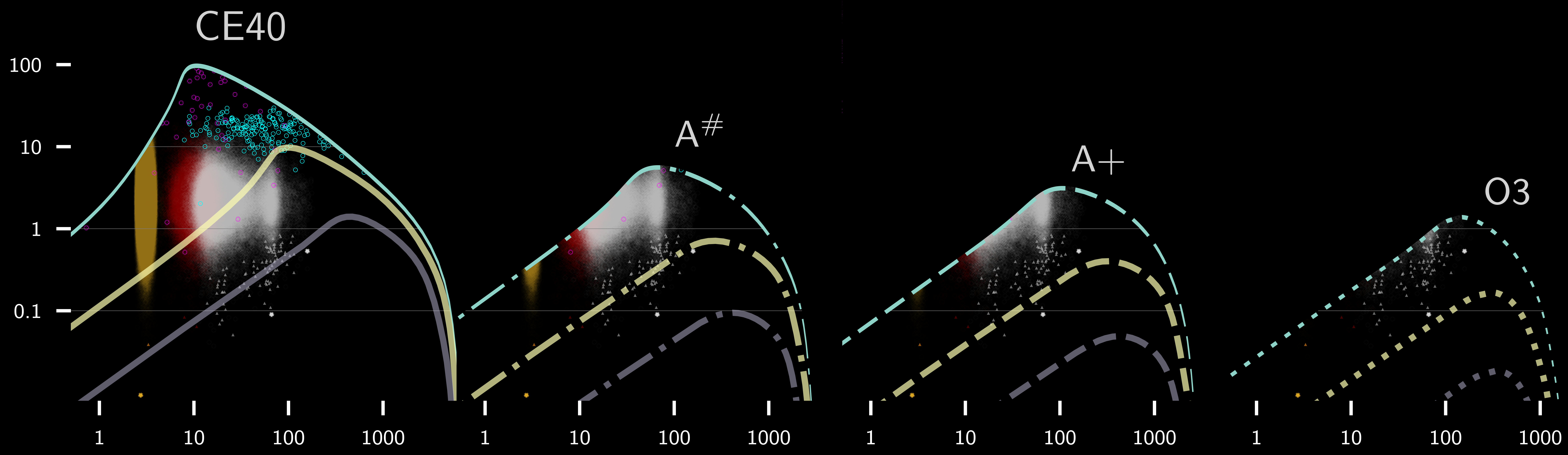
Summarizes the roadmap for US third-generation detectors

- https://dcc.cosmicexplorer.org/CE-P2100003/public
- For the next few years, we (including you!) will be
  - Deepening our understanding of the next-generation science case,
  - Developing instrument science to pave the wave for new detectors
  - Creating theoretical frameworks and data analysis algorithms for CE science
- Join the consortium!
- https://cosmicexplorer.org/consortium.html

Cosmic Explorer NSF White Paper

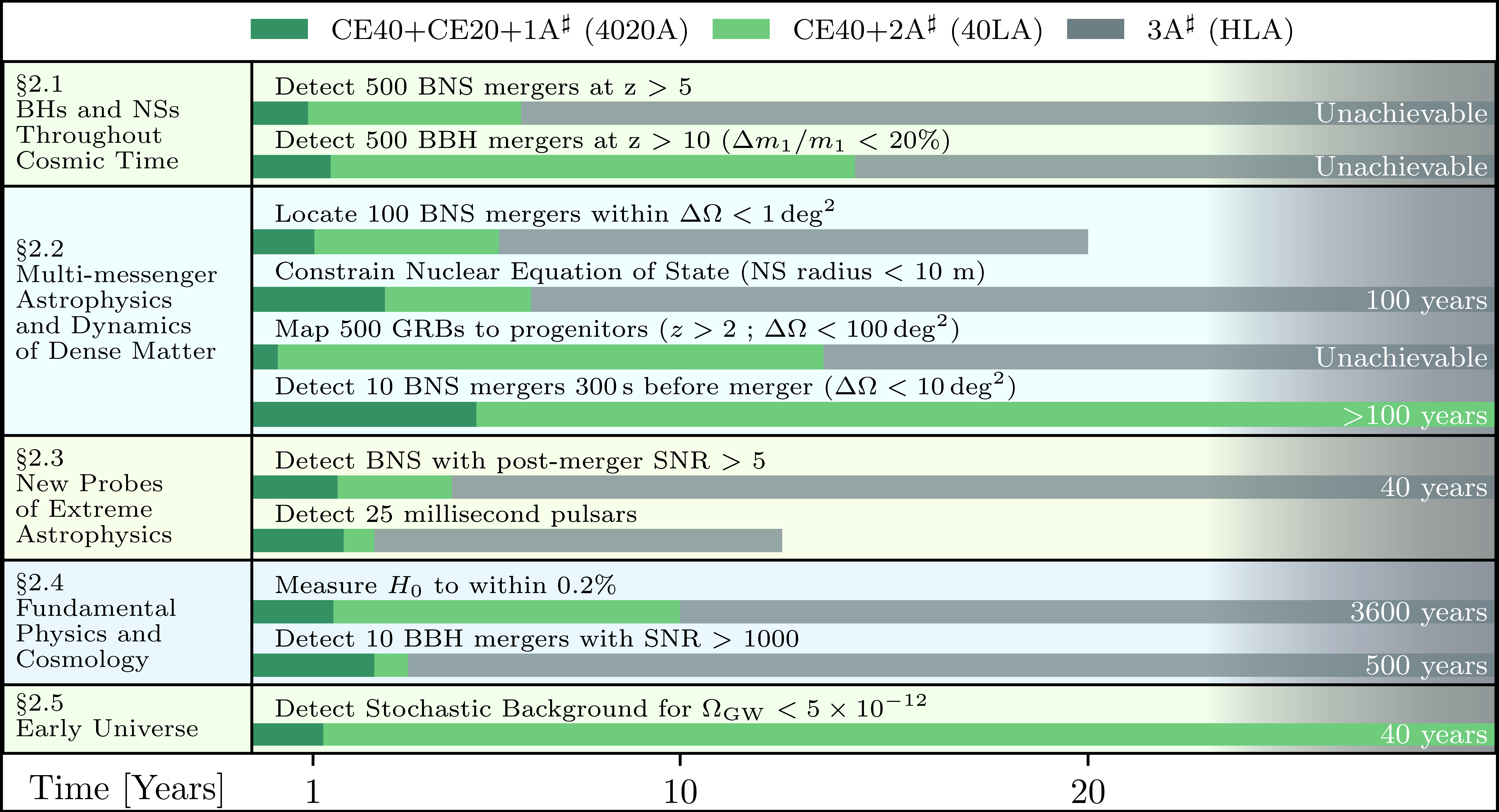
Responds to the NSF MPS Advisory Committee request

- arXiv:2306.13745
- Updates Horizon Study
- Incorporates new community input from consortium science letters
- https://dcc.cosmicexplorer.org/cgi-bin/private/DocDB/DisplayMeeting?conferenceid=1053
- Begins detailed comparison of possible detector configurations



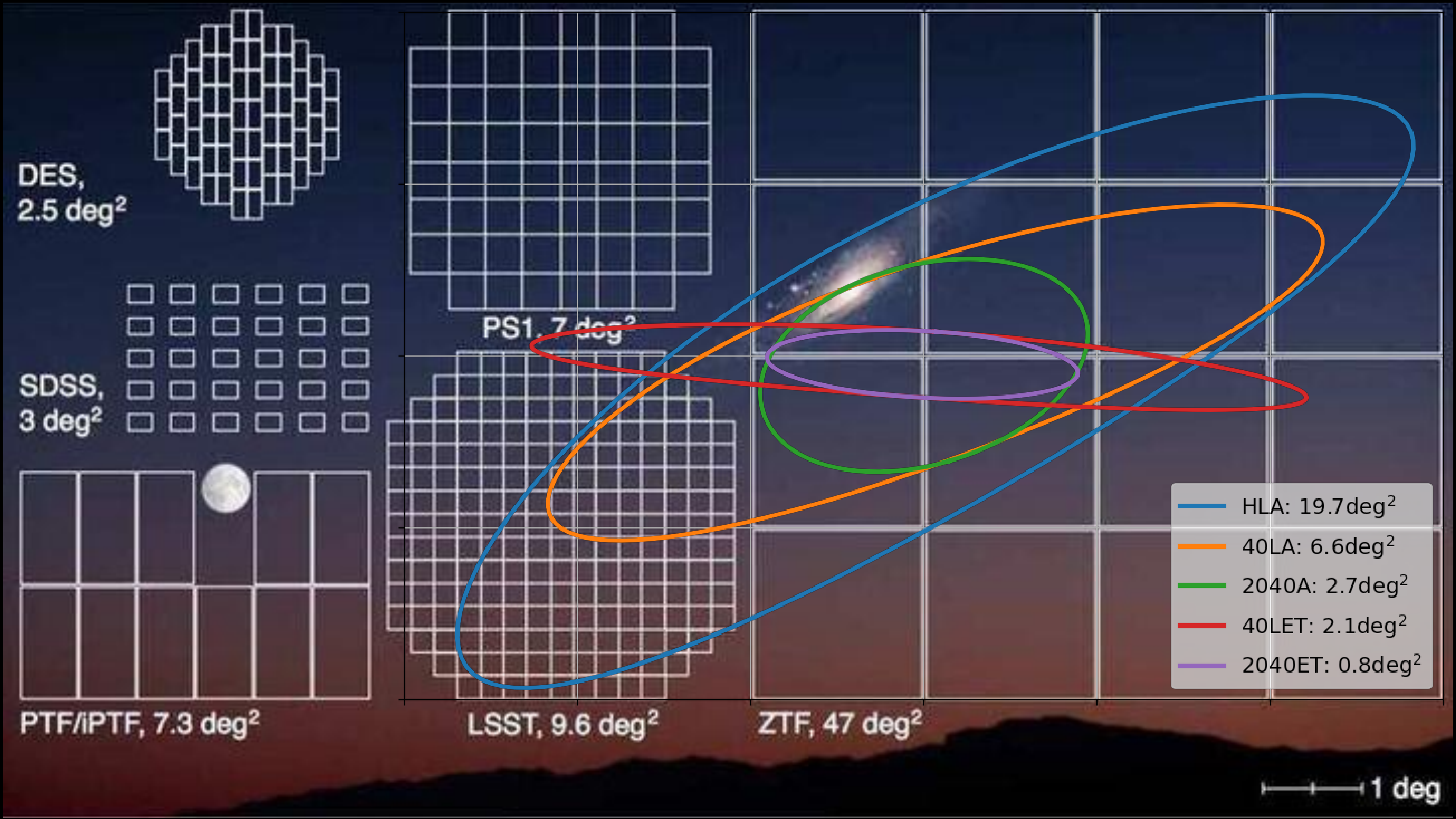
Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian mitigation	0 dB	6 dB	20 dB

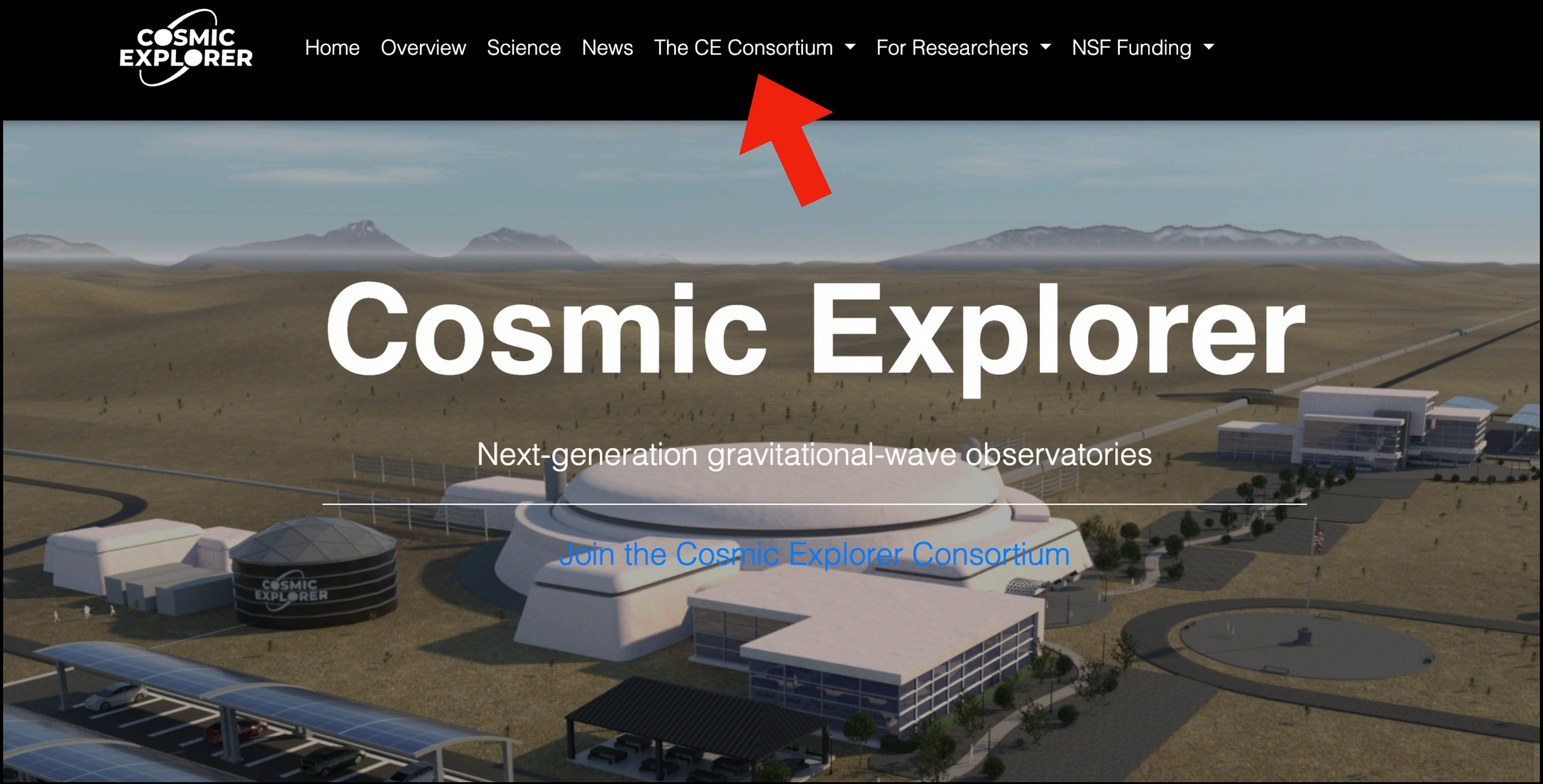
Evans, …, DAB, et al.
arXiv:2306.13745 (2023)



CE40+CE20+1A♯ (4020A)
CE40+2A♯ (40LA)
3A♯ (HLA)
§2.1 BHs and NSs Throughout Cosmic Time
Detect 500 BNS mergers at z > 5
Unachievable
Detect 500 BBH mergers at z > 10 (Δm1/m1 < 20%)
Unachievable
§2.2 Multi-messenger Astrophysics and Dynamics of Dense Matter
Locate 100 BNS mergers within ΔΩ < 1 deg2
Constrain Nuclear Equation of State (NS radius < 10 m)
100 years
Map 500 GRBs to progenitors (z > 2 ; ΔΩ < 100 deg2)
Unachievable
Detect 10 BNS mergers 300 s before merger (ΔΩ < 10 deg2)
>100 years
§2.3 New Probes of Extreme Astrophysics
Detect BNS with post-merger SNR > 5
40 years
Detect 25 millisecond pulsars
§2.4 Fundamental Physics and Cosmology
Measure H0 to within 0.2%
3600 years
Detect 10 BBH mergers with SNR > 1000
500 years
§2.5 Early Universe
Detect Stochastic Background for ΩGW < 5 × 10−12
40 years
Time [Years]
1
10
20

Einstein Telescope


DES, 2.5 deg²
SDSS, 3 deg²
PTF/iPTF, 7.3 deg²
PS1, 7 deg²
LSST, 9.6 deg²
ZTF, 47 deg²
HLA: 19.7deg²
40LA: 6.6deg²
2040A: 2.7deg²
40LET: 2.1deg²
2040ET: 0.8deg²
1 deg



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