# Measuring Nuclear Physics with Cosmic Explorer

Duncan Brown, Syracuse University

https://cosmicexplorer.org/


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

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

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

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

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

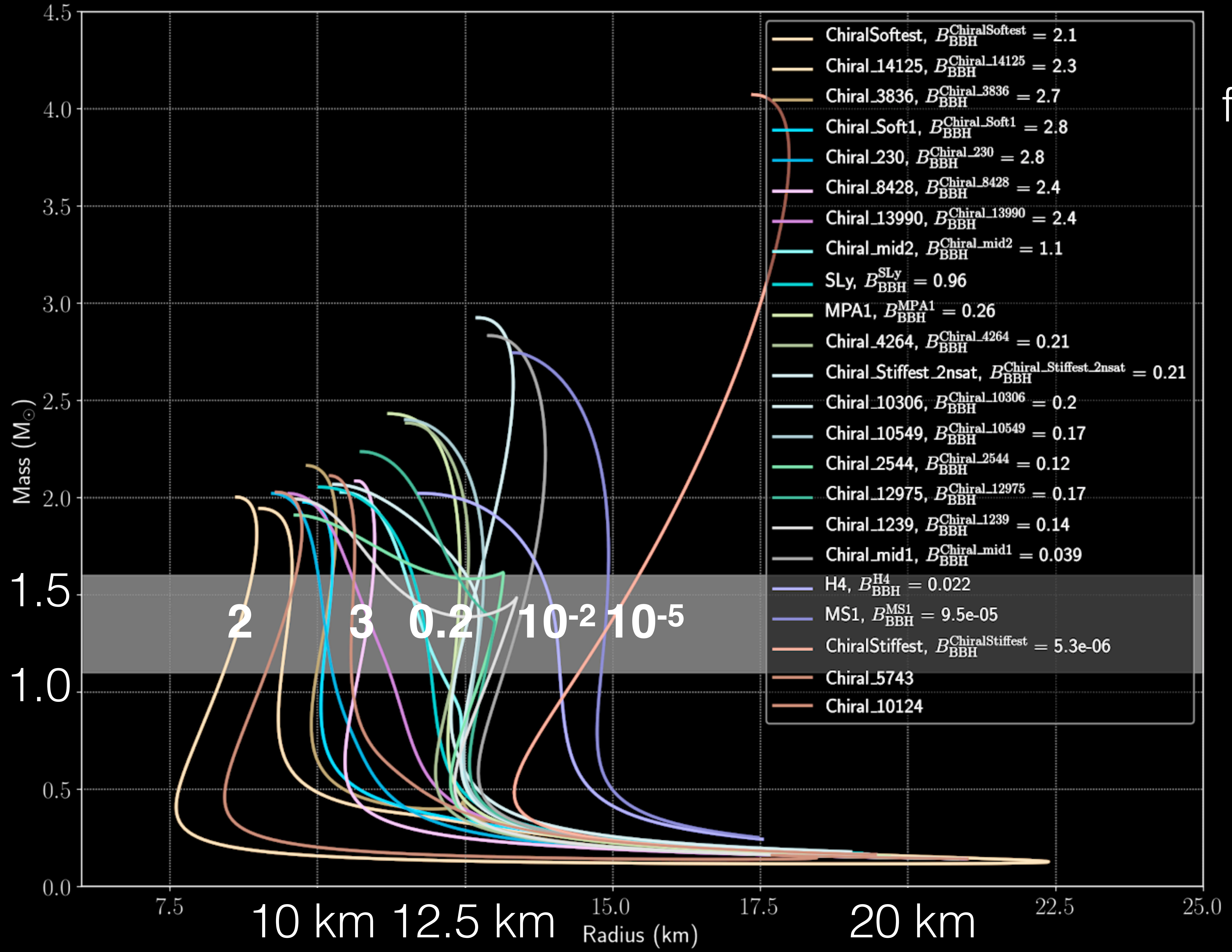
Tidal effects enter the post-Newtonian gravitational-wave phase as

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

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

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

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

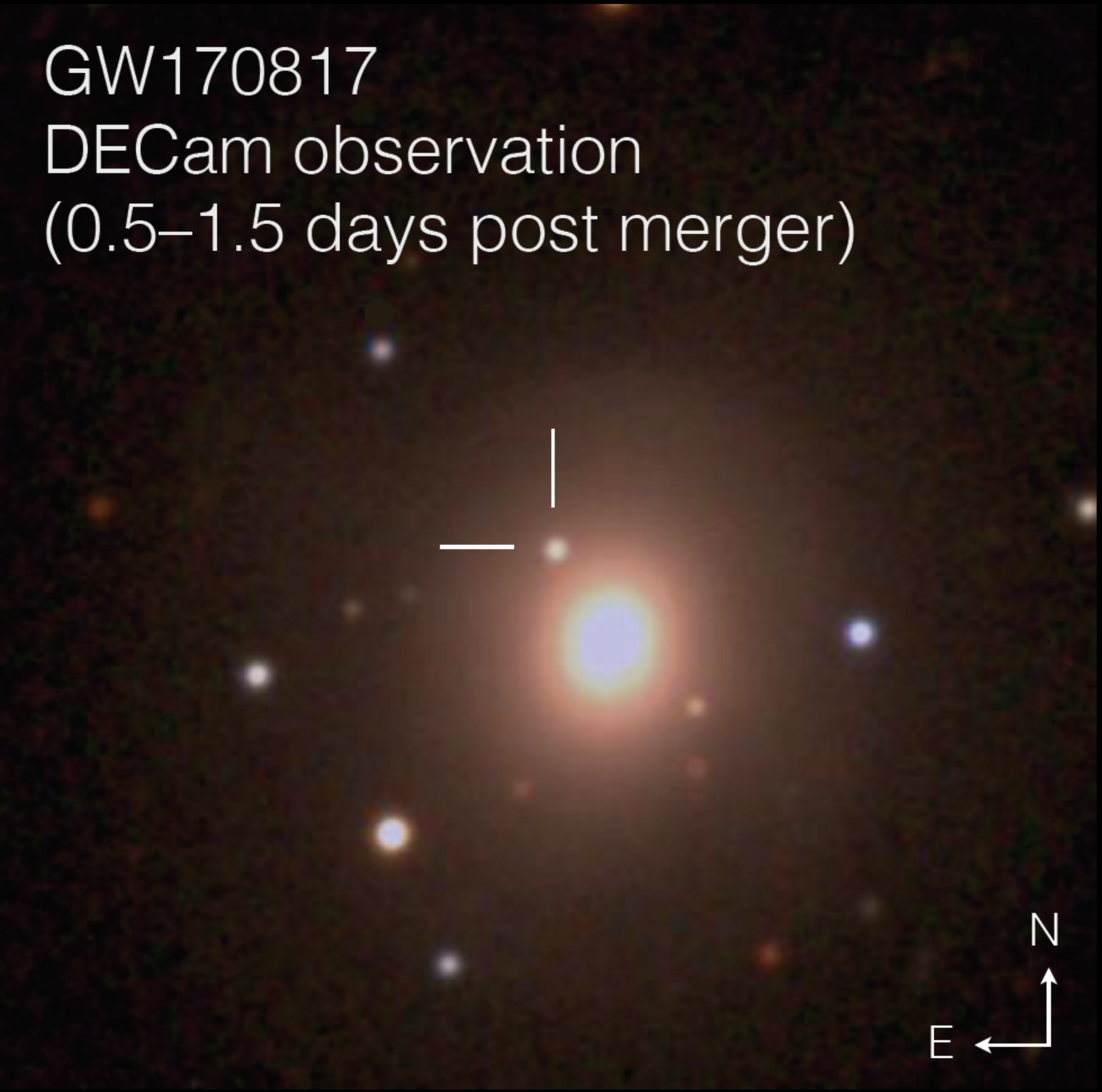


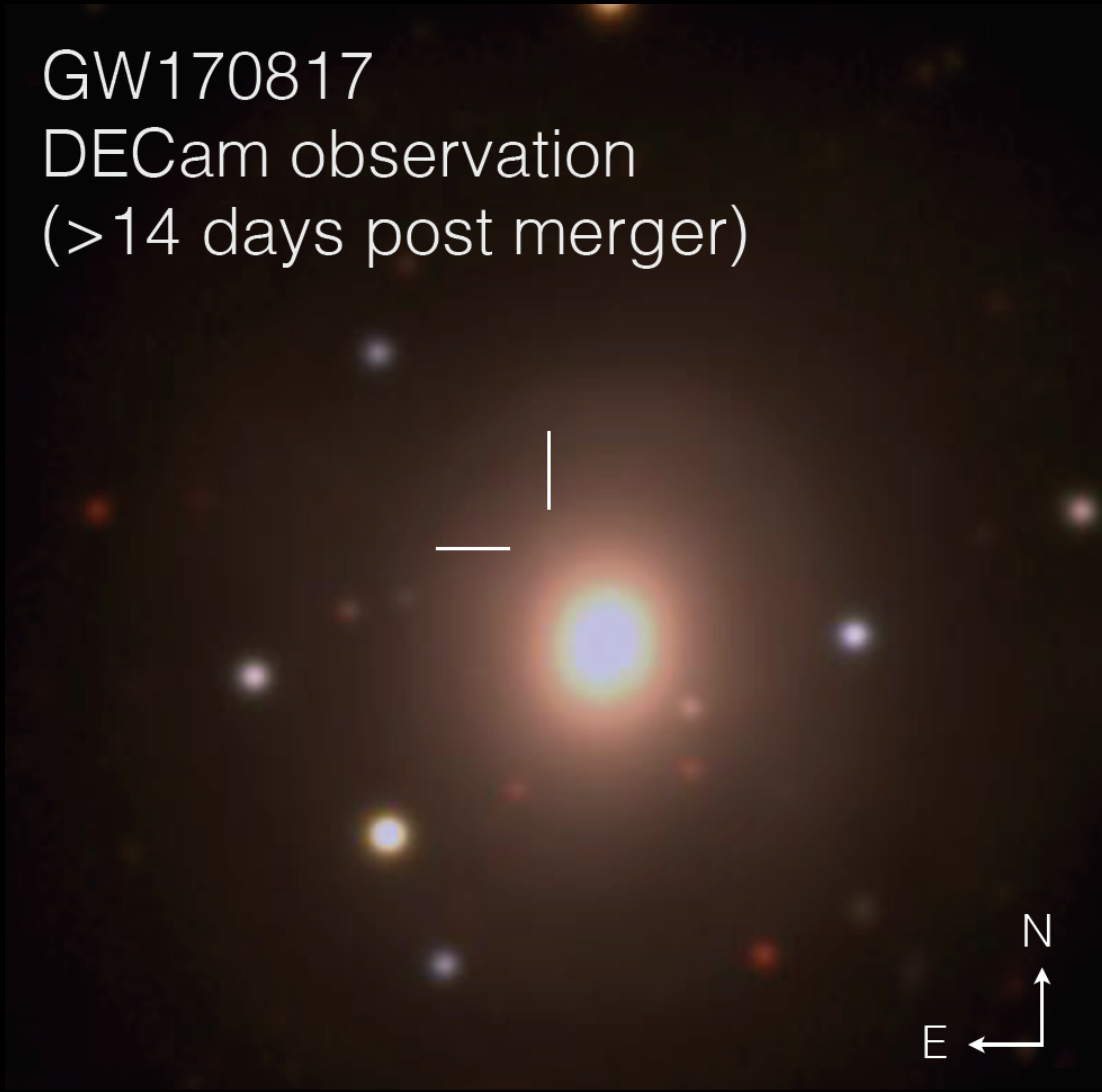

Calculate Bayes factor for specific EOS vs BBH

Only the stiffest EOS are ruled out at high confidence

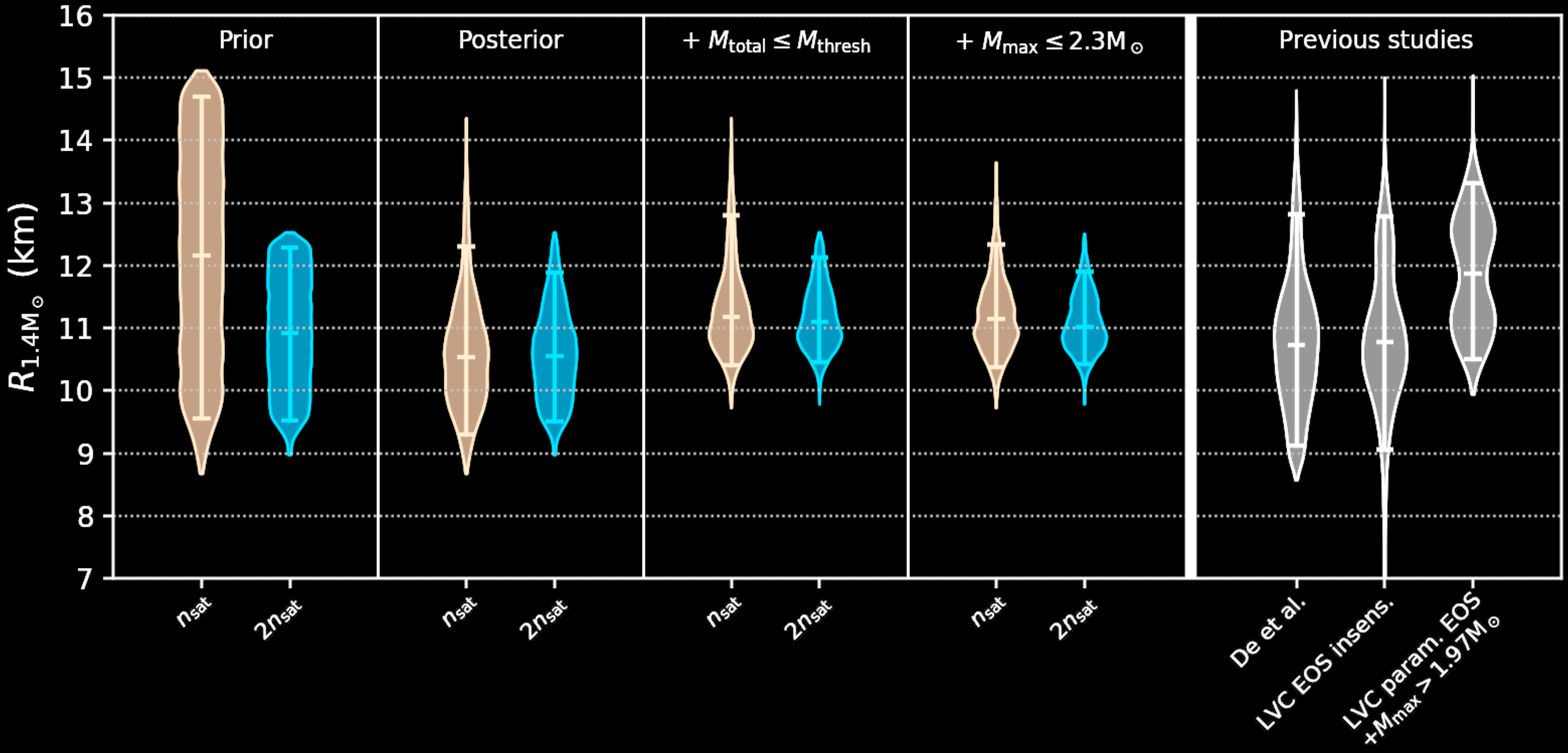
Soft EOSes **and black holes** are all consistent with GW170817

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

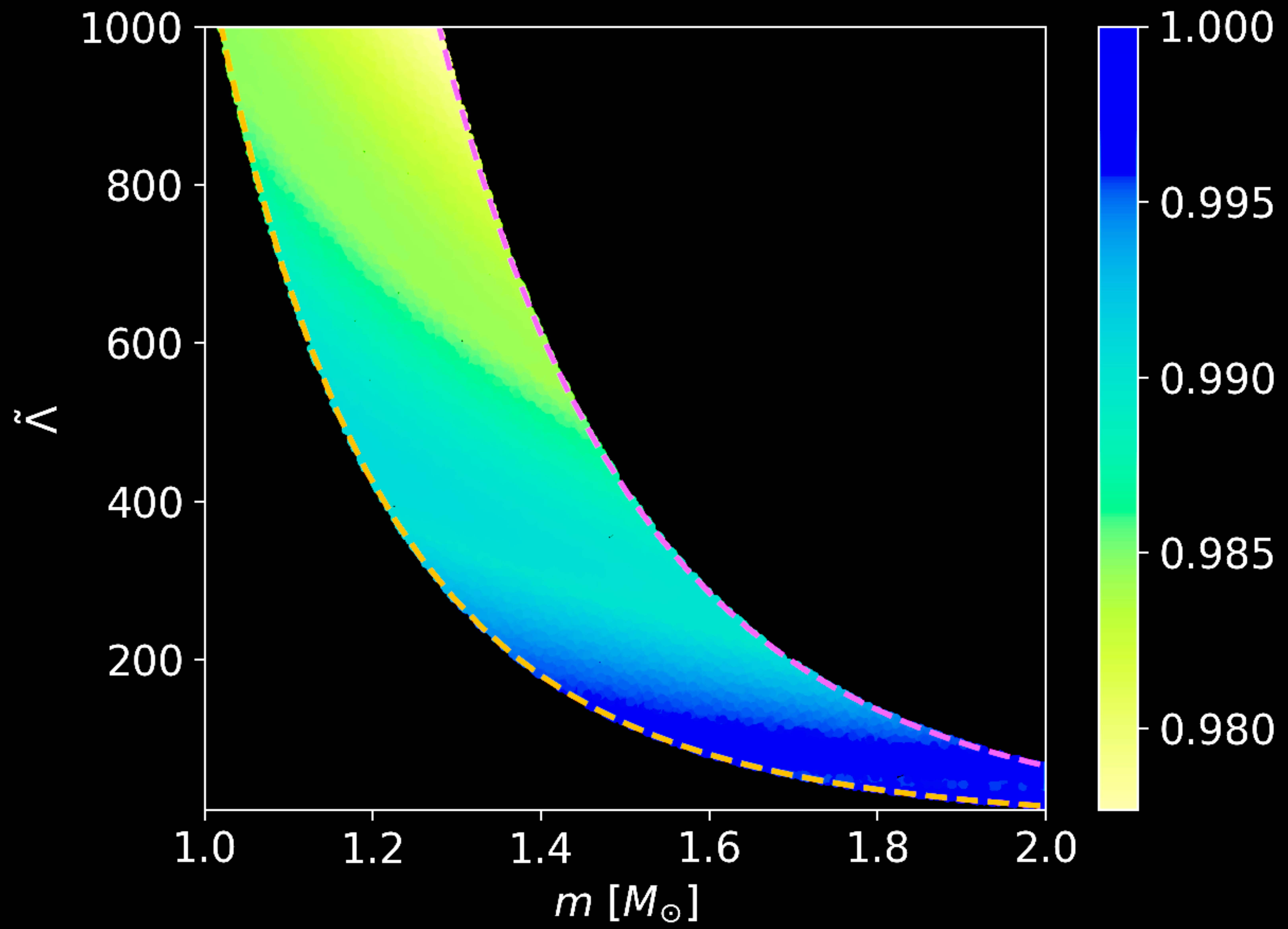



Soares-Santos,..., DAB, et al. ApJ **848** L16 (2017)



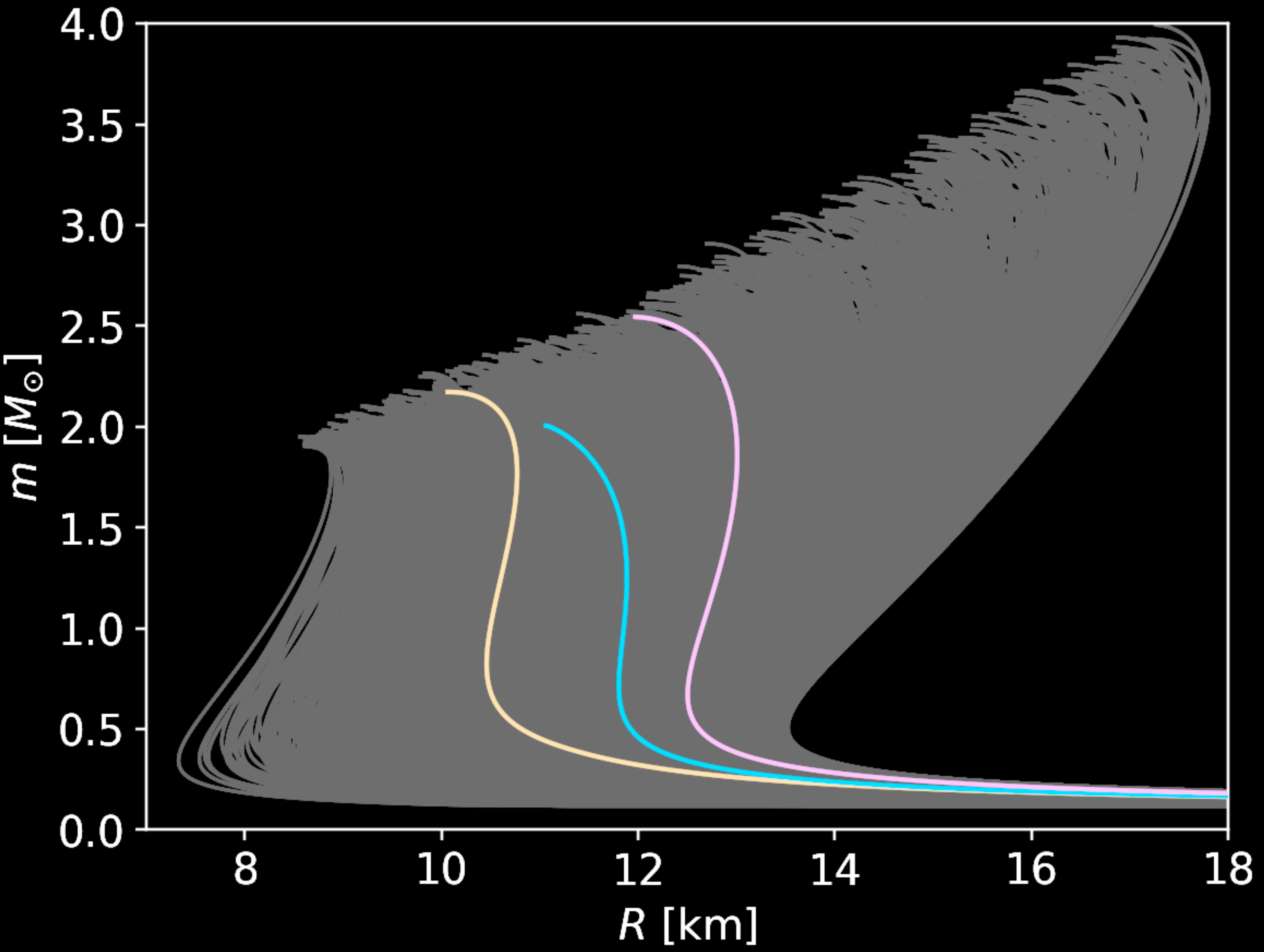

Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)



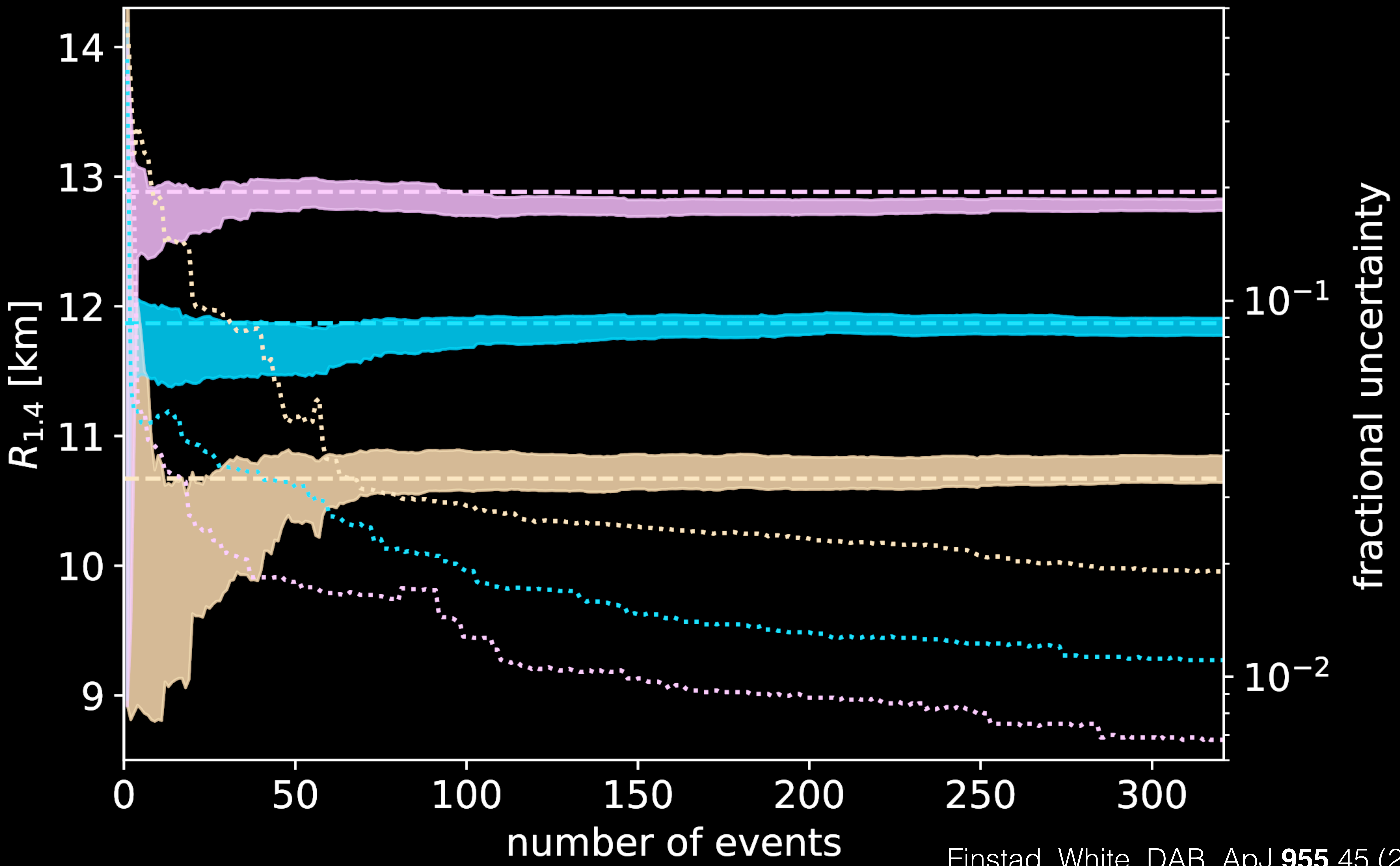

$$\mathcal{O} = \max_{t,\phi} \frac{\langle s|h\rangle}{\sqrt{\langle s|s\rangle\langle h|h\rangle}}$$

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

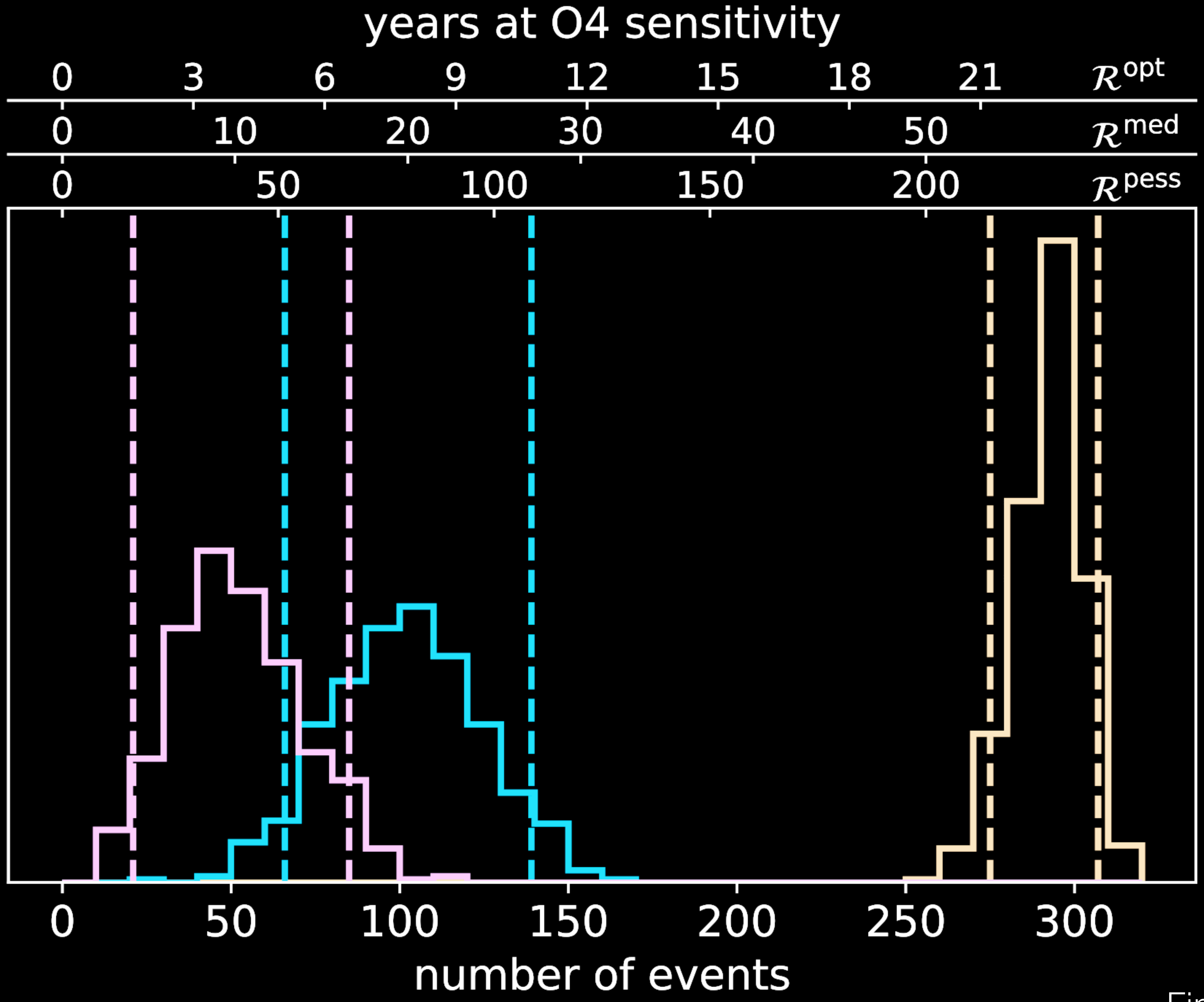
Finstad, White, DAB, ApJ **955** 45 (2023)




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

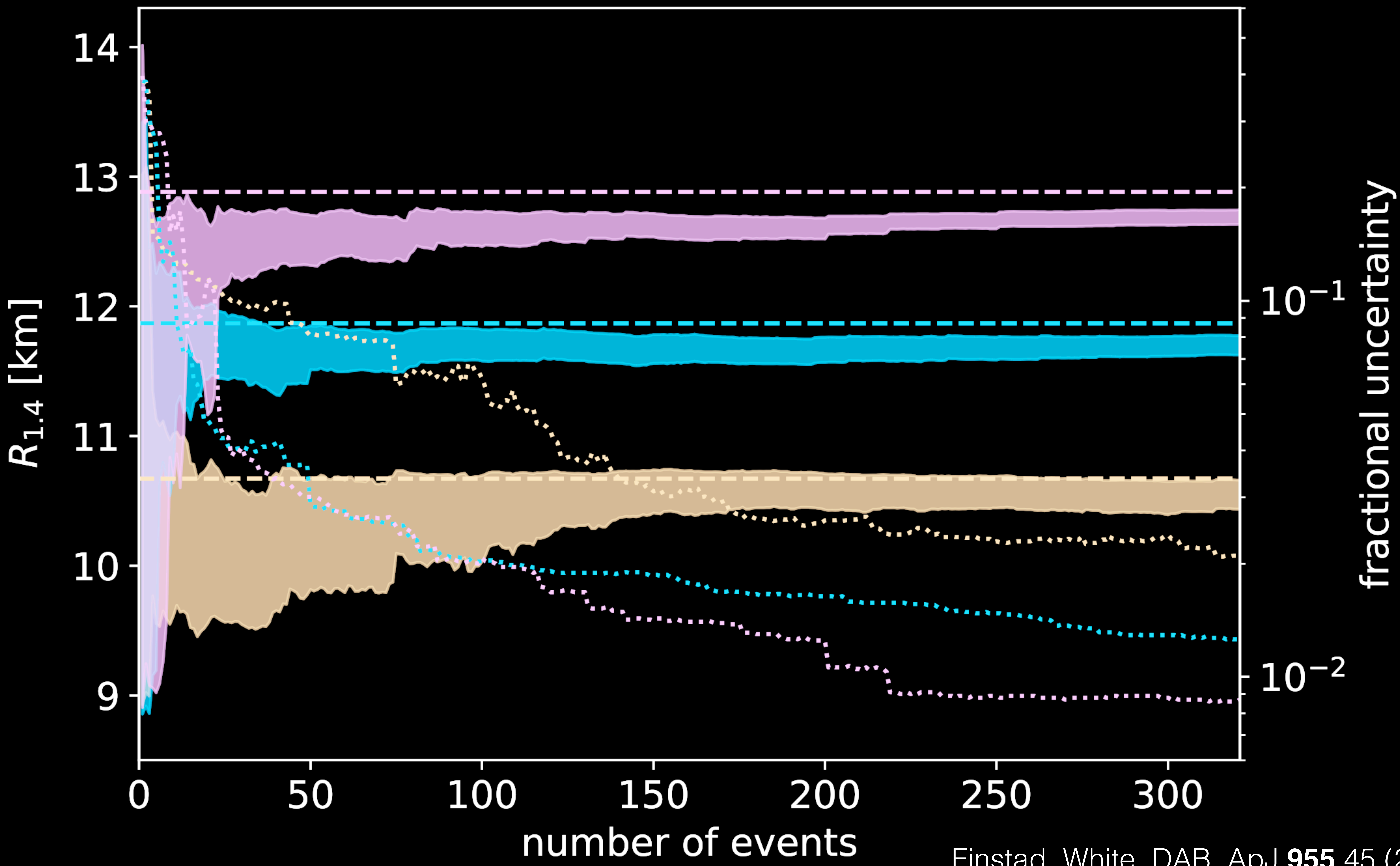



Finstad, White, DAB, ApJ **955** 45 (2023)

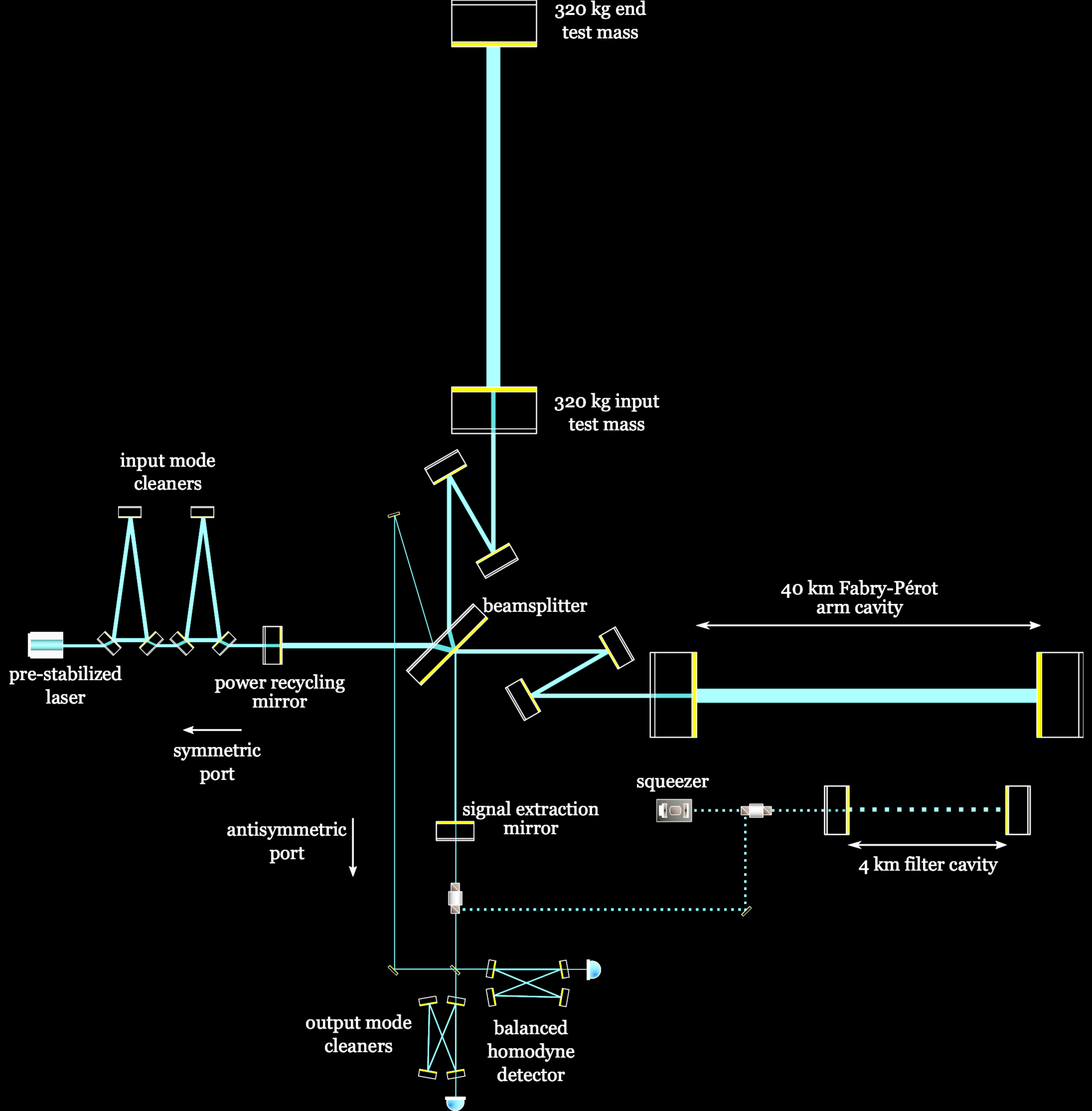



Distribution of number of events required to reach 2% precision in the neutron star radius

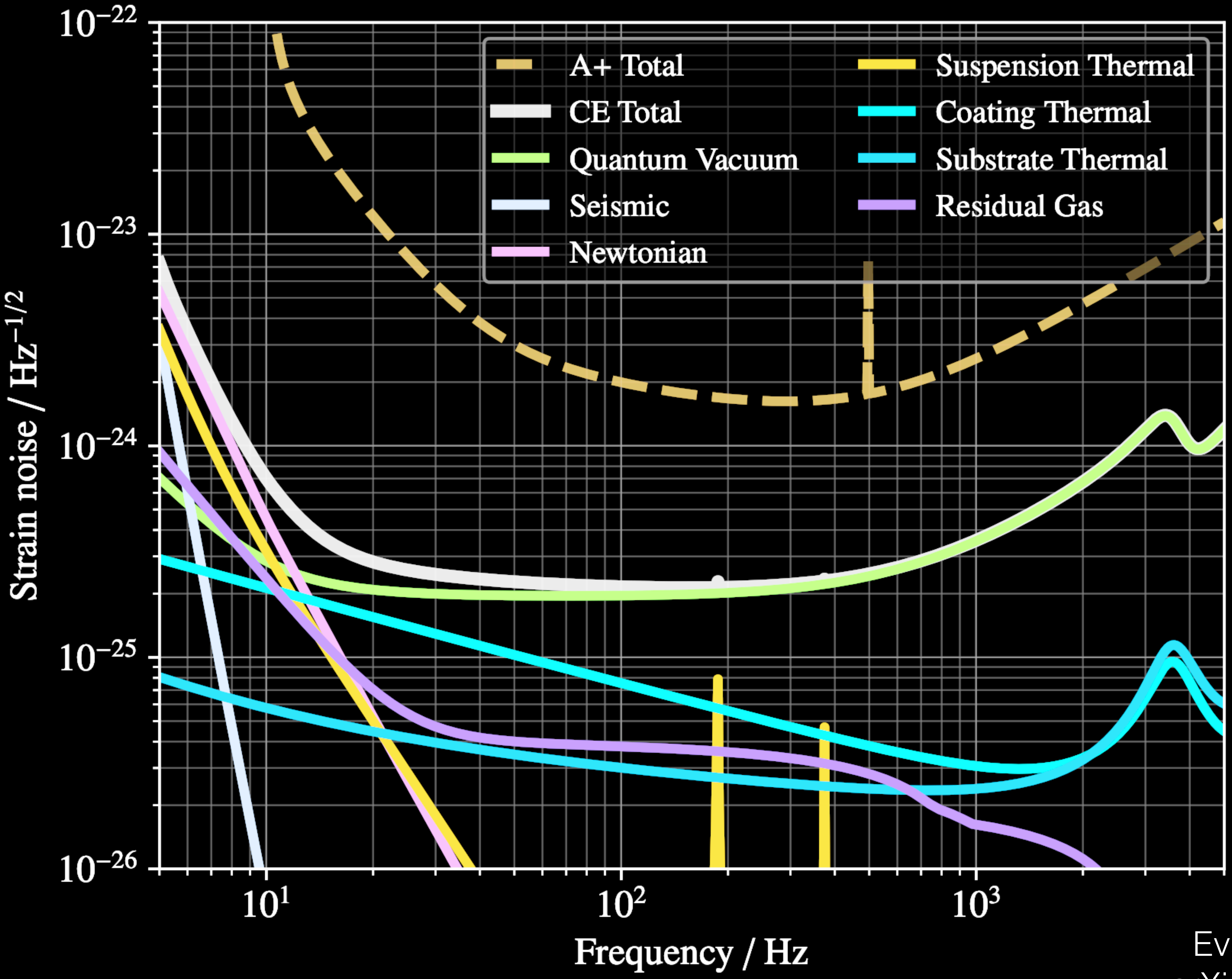
Finstad, White, DAB, ApJ **955** 45 (2023)



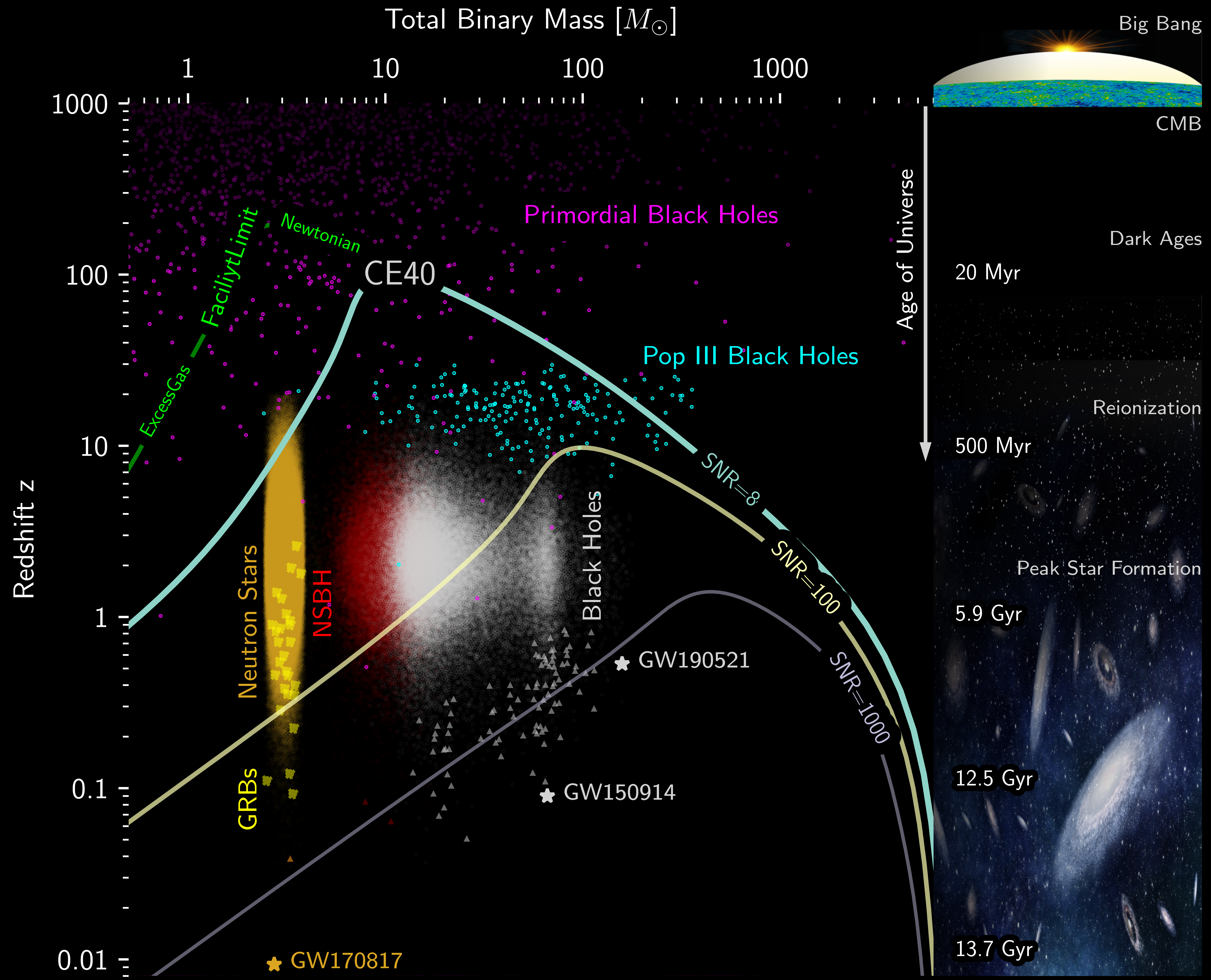

Finstad, White, DAB, ApJ **955** 45 (2023)



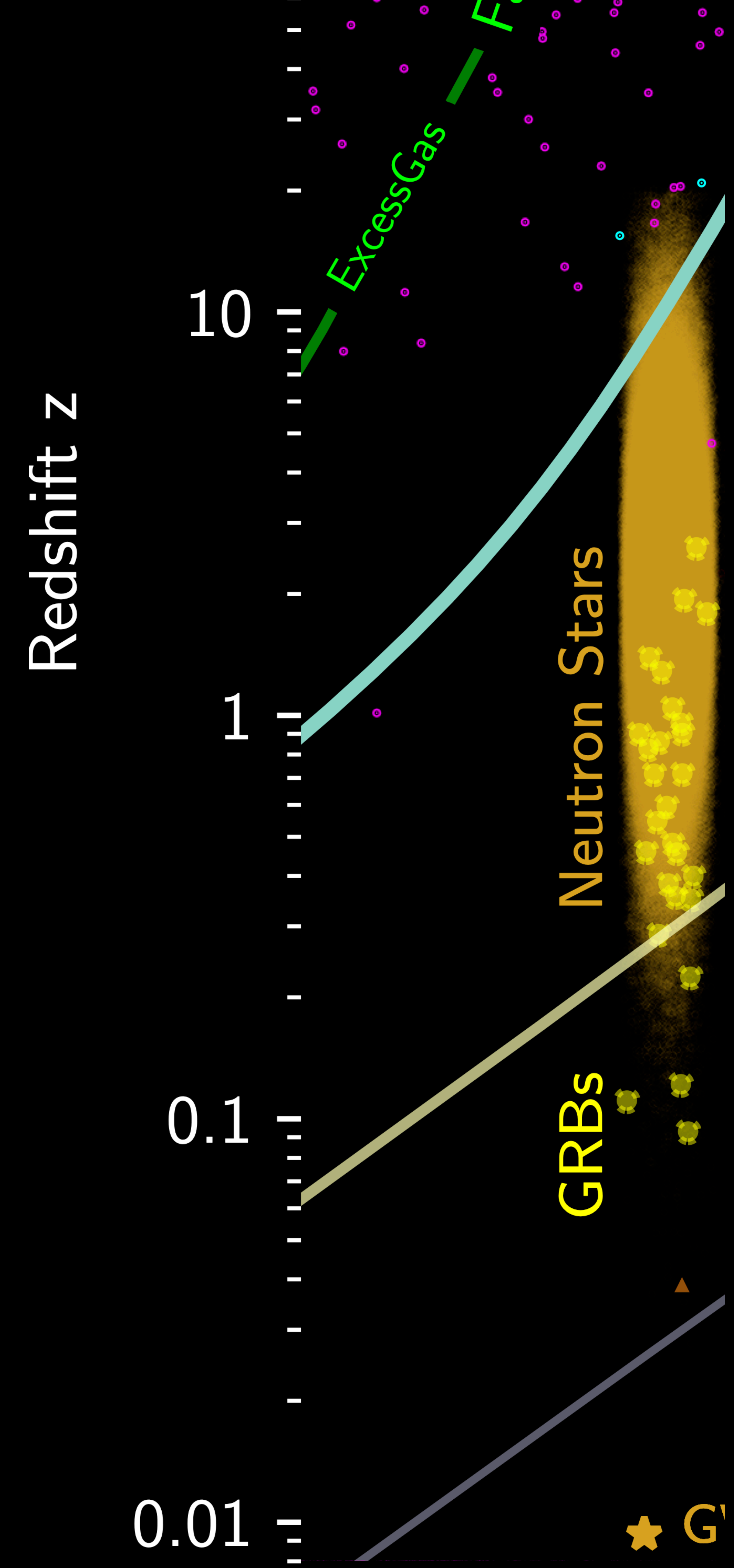

Evans, …, DAB, et al.
arXiv:2306.13745 (2023)




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

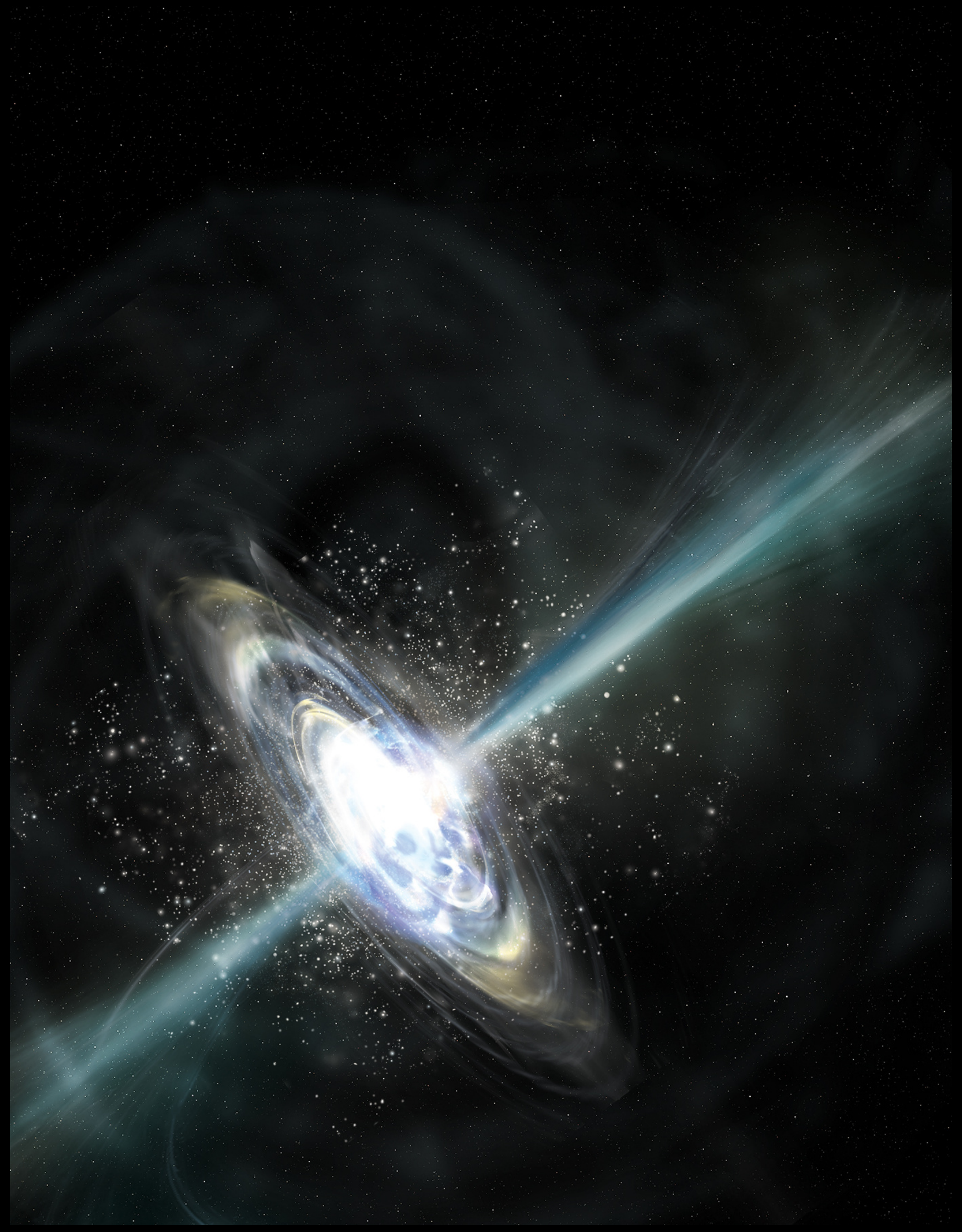


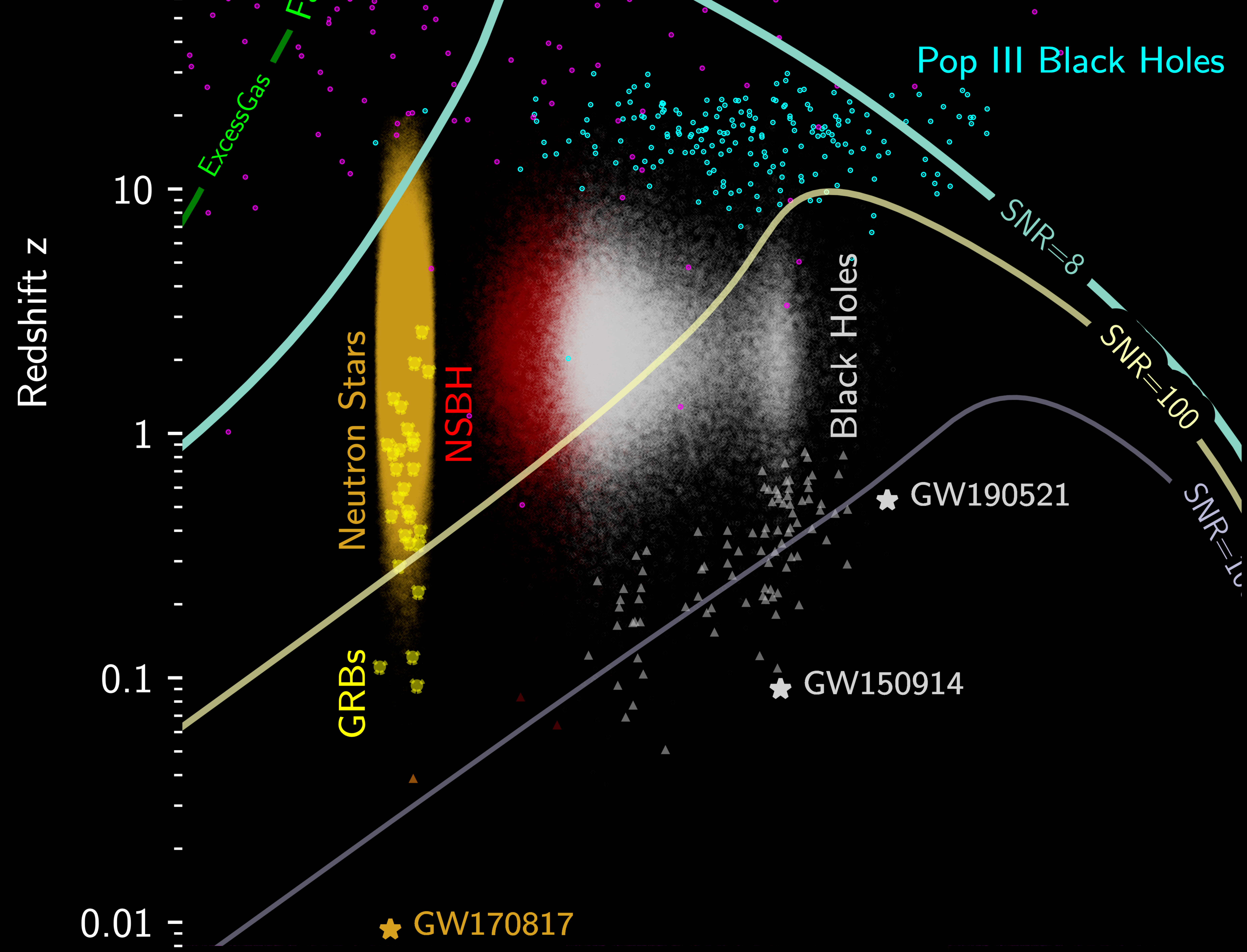

Evans, …, DAB, et al.
arXiv:2306.13745 (2023)




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

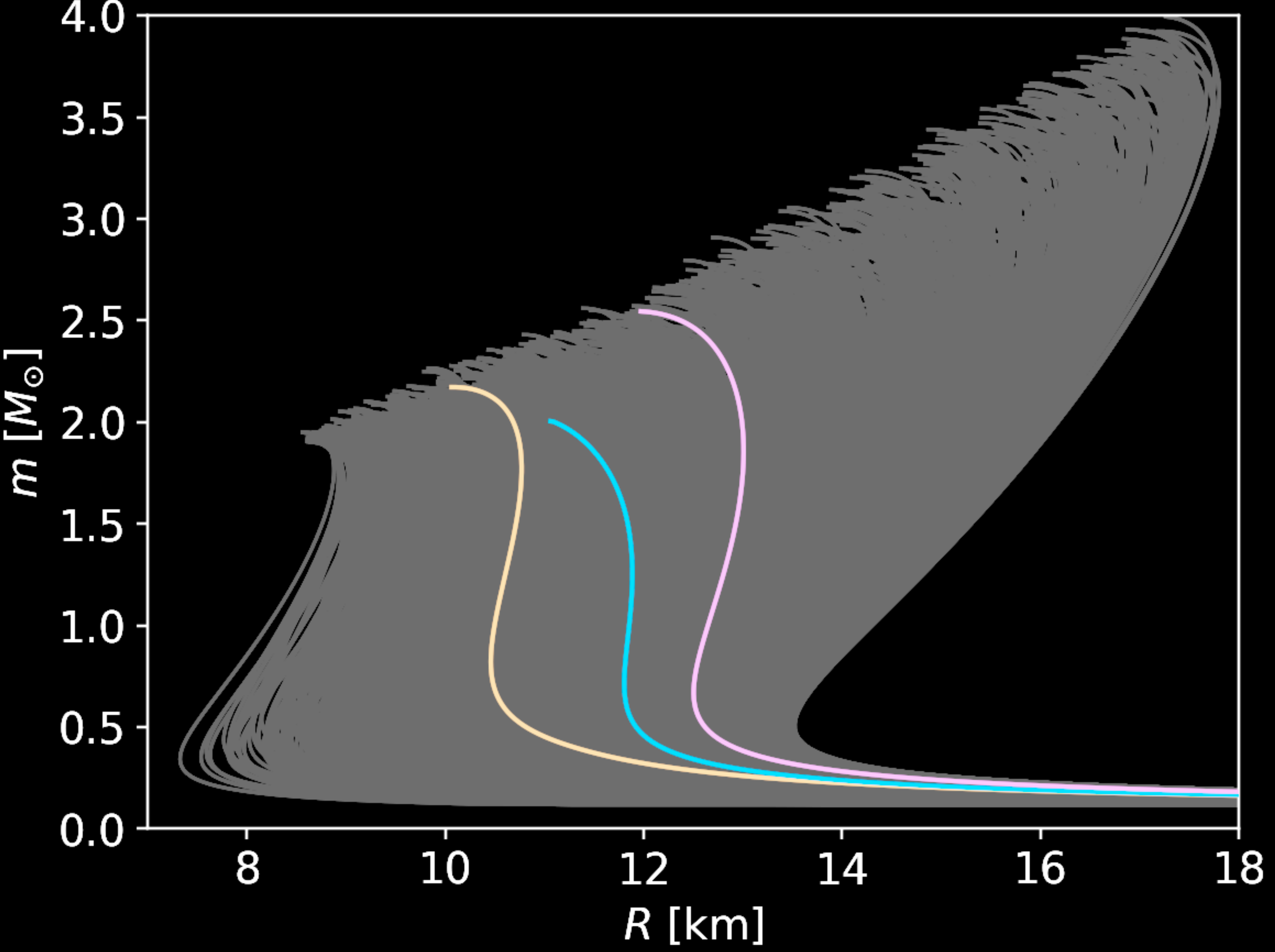




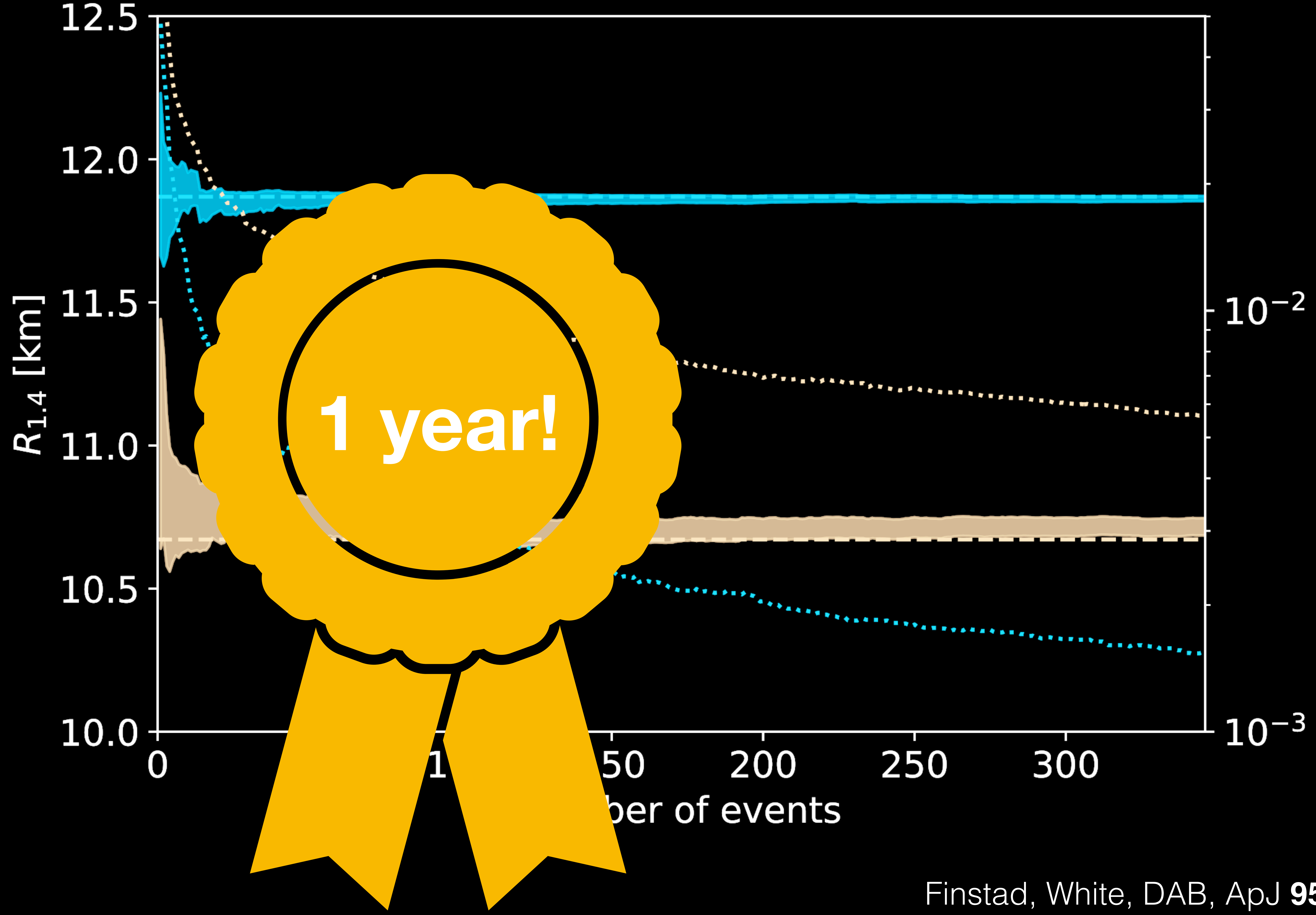

Precision measurement of the masses and spins of **large** numbers of compact objects

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

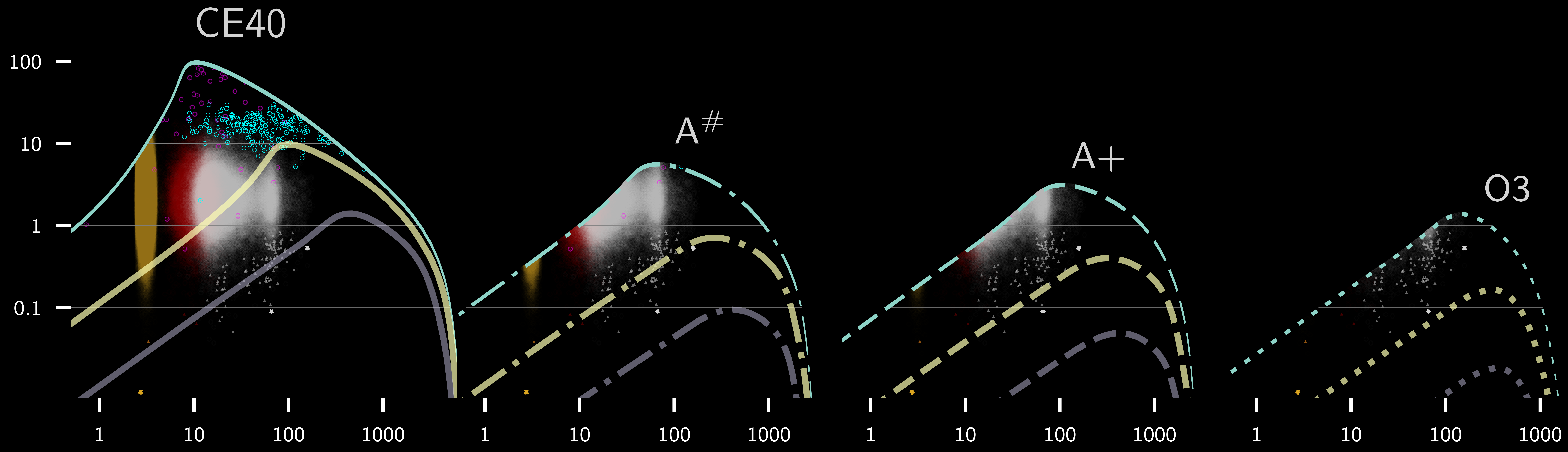
Connect remnant physics to EM observations of progenitors




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




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

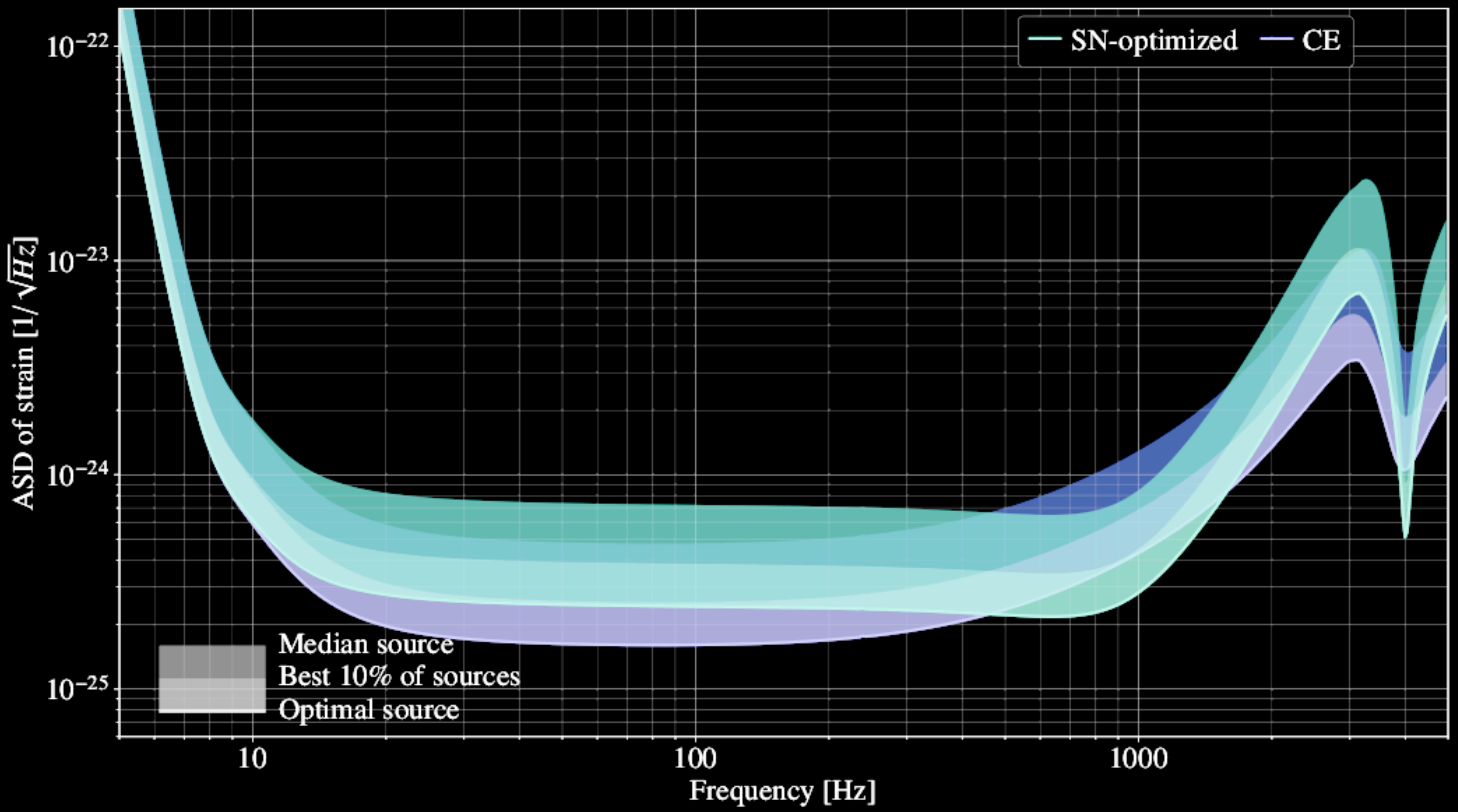



| Detector network | Soft EoS | Medium EoS | Stiff EoS |
|---|---|---|---|
| LIGO-Virgo | $2e5^{+4e4}_{-4e4}$ | $5e4^{+1e4}_{-1e4}$ | $7000^{+900}_{-900}$ |
| 3 A$^\sharp$ | $300^{+50}_{-50}$ | $100^{+40}_{-40}$ | $20^{+4}_{-4}$ |
| CE20 | $21^{+10}_{-10}$ | $15^{+7}_{-7}$ | $3^{+1}_{-1}$ |
| CE40 | $12^{+3}_{-3}$ | $8^{+1}_{-1}$ | $1^{+0.6}_{-0.6}$ |
| CE40+2 A$^\sharp$ | $9^{+4}_{-4}$ | $6^{+2}_{-2}$ | $0.4^{+0.2}_{-0.2}$ |
| CE40+CE20+A$^\sharp$ | $5^{+2}_{-2}$ | $3^{+1}_{-1}$ | $0.2^{+0.07}_{-0.07}$ |

Years to measure $R_{1.4}$ to 10 m

Bandopadhyay, ..., DAB, et al.
arXiv:2402.05056

# Supernovae in Cosmic Explorer

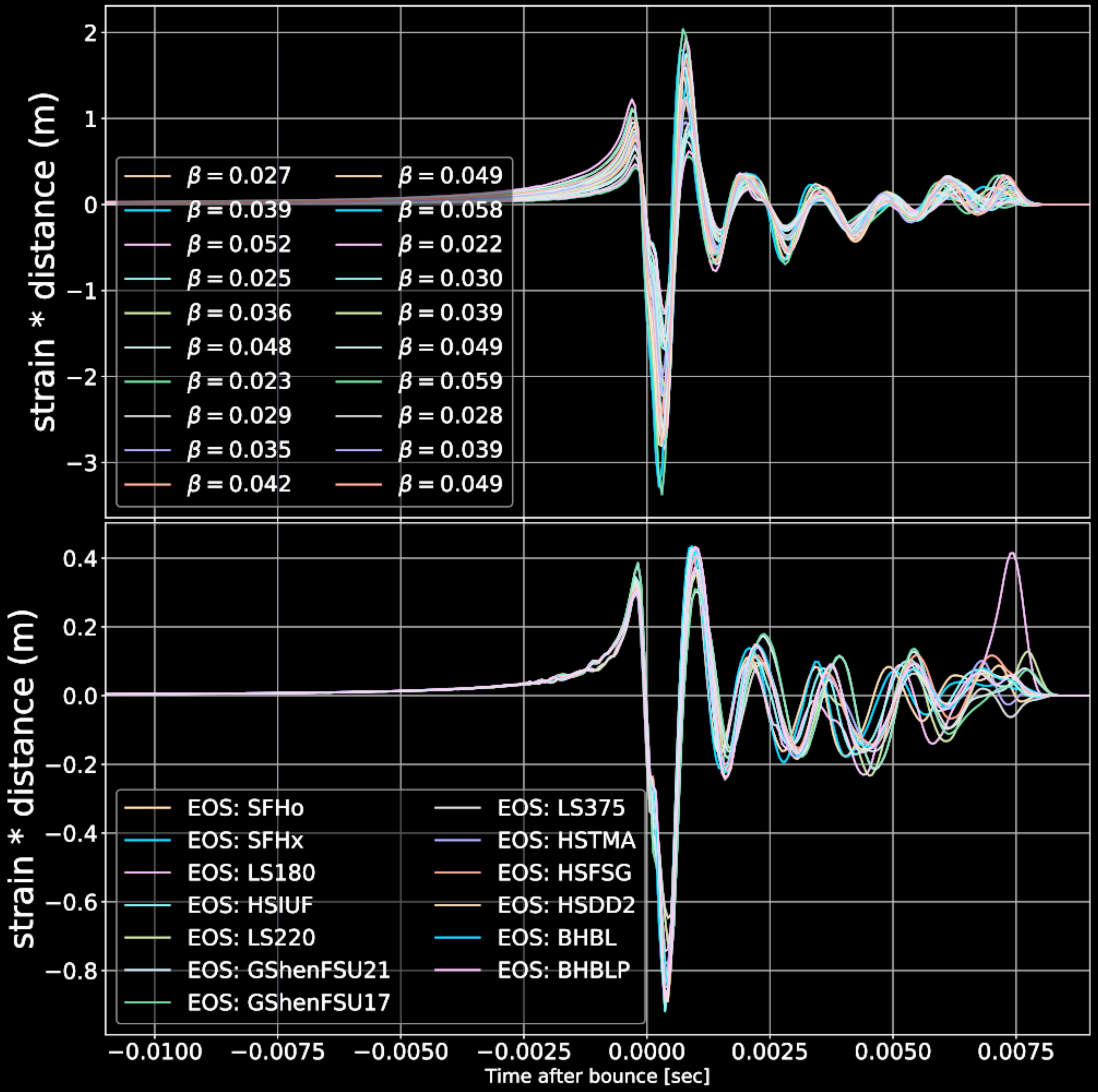


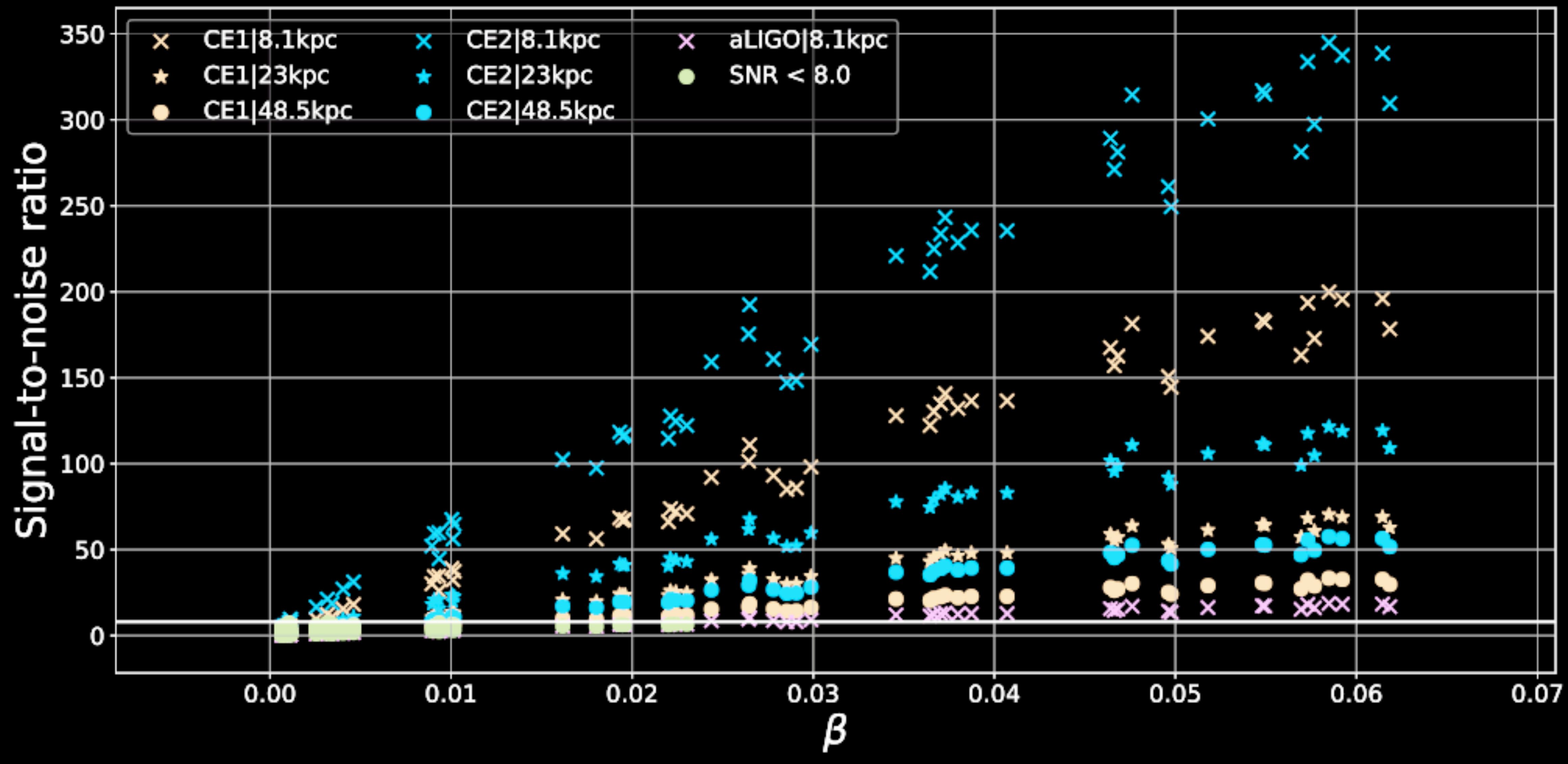

70 kpc at SNR 8

95 kpc at SNR 8

c.f. DUNE

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

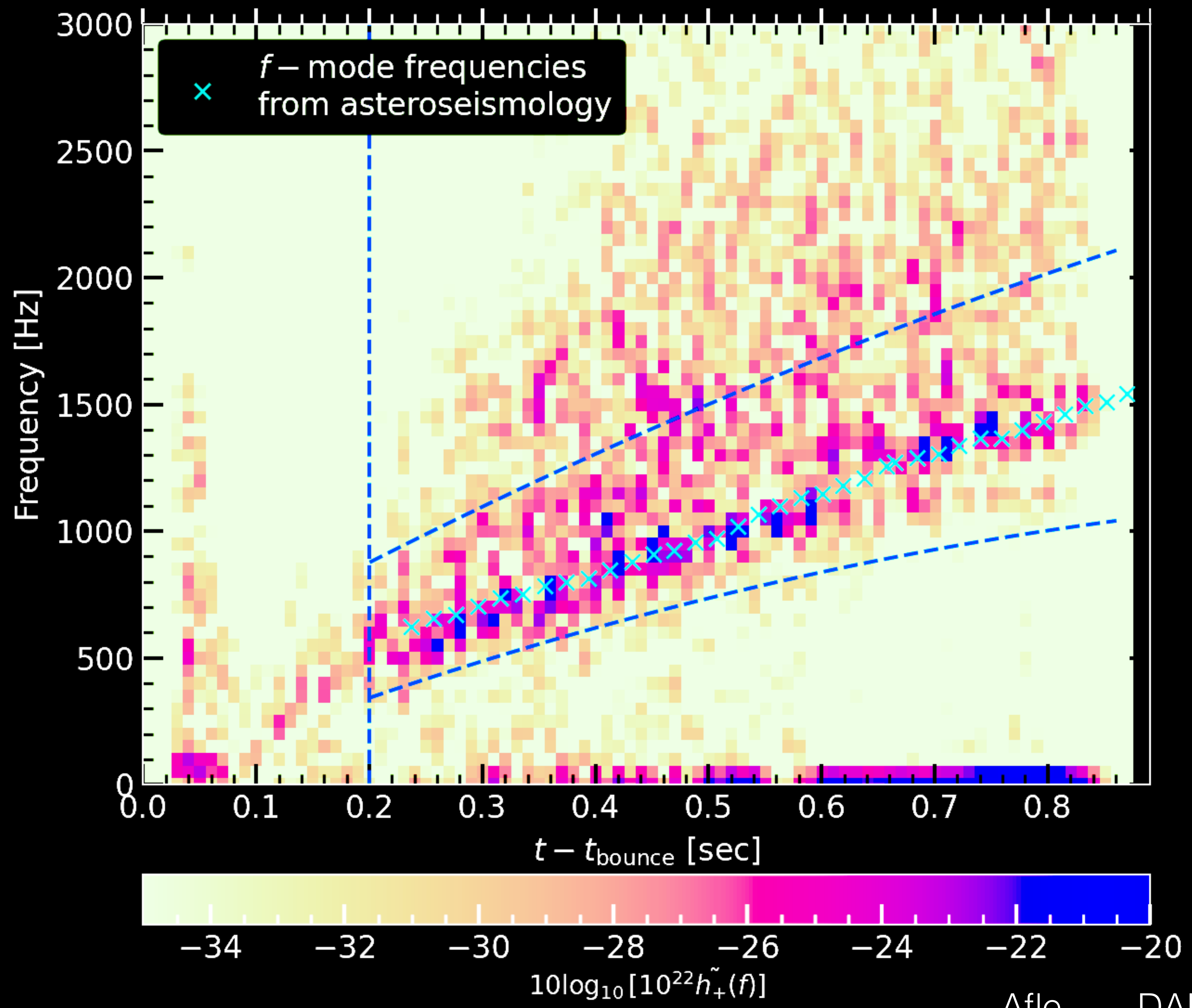



For a galactic progenitor with β = 0.02,
90 % credible interval is
0.02 (aLIGO), 0.002 (CE)

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

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

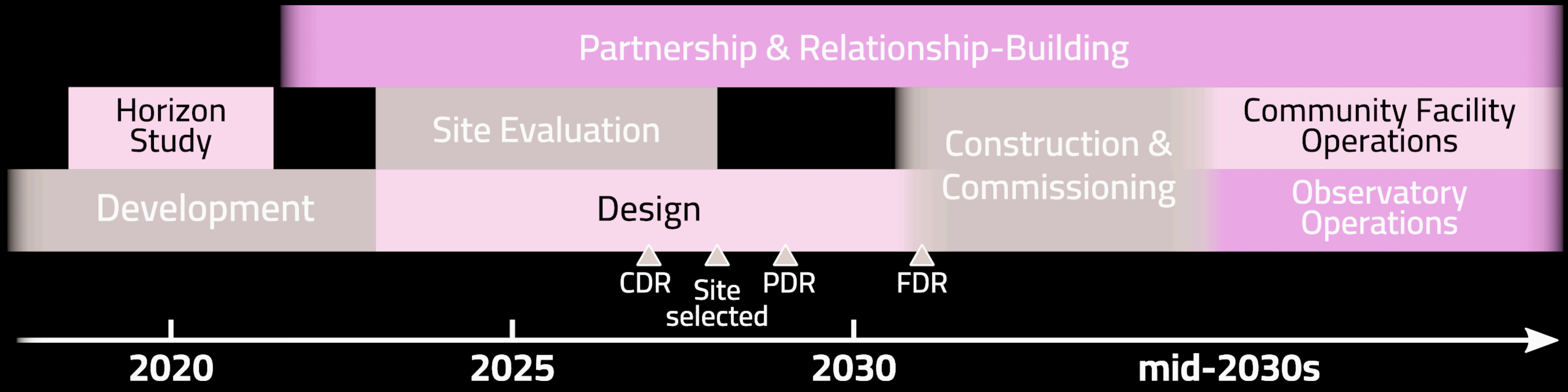



Around 400 ms after the bounce, most of the energy is in the f-mode of the protoneutron star

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?


Partnership & Relationship-Building
Horizon Study
Site Evaluation
Construction & Commissioning
Community Facility Operations
Development
Design
Observatory Operations
CDR
Site selected
PDR
FDR
2020
2025
2030
mid-2030s

$2M $10M

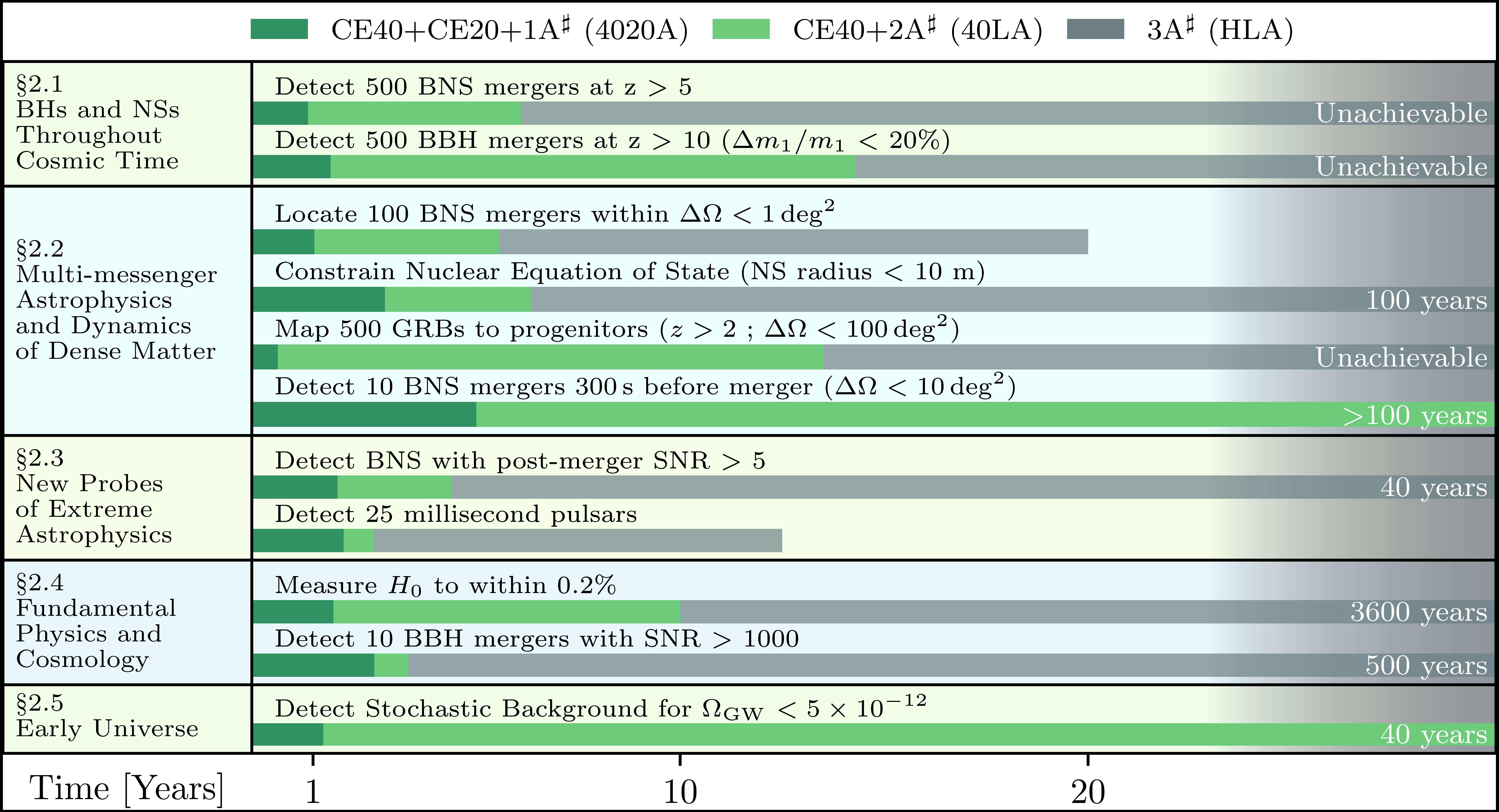
# Cosmic Explorer Horizon Study

## 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



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

COSMIC EXPLORER

Home Overview Science News The CE Consortium For Researchers NSF Funding


cosmicexplorer.org