Future prospects for Gravitational waves

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Corfu, May 2024
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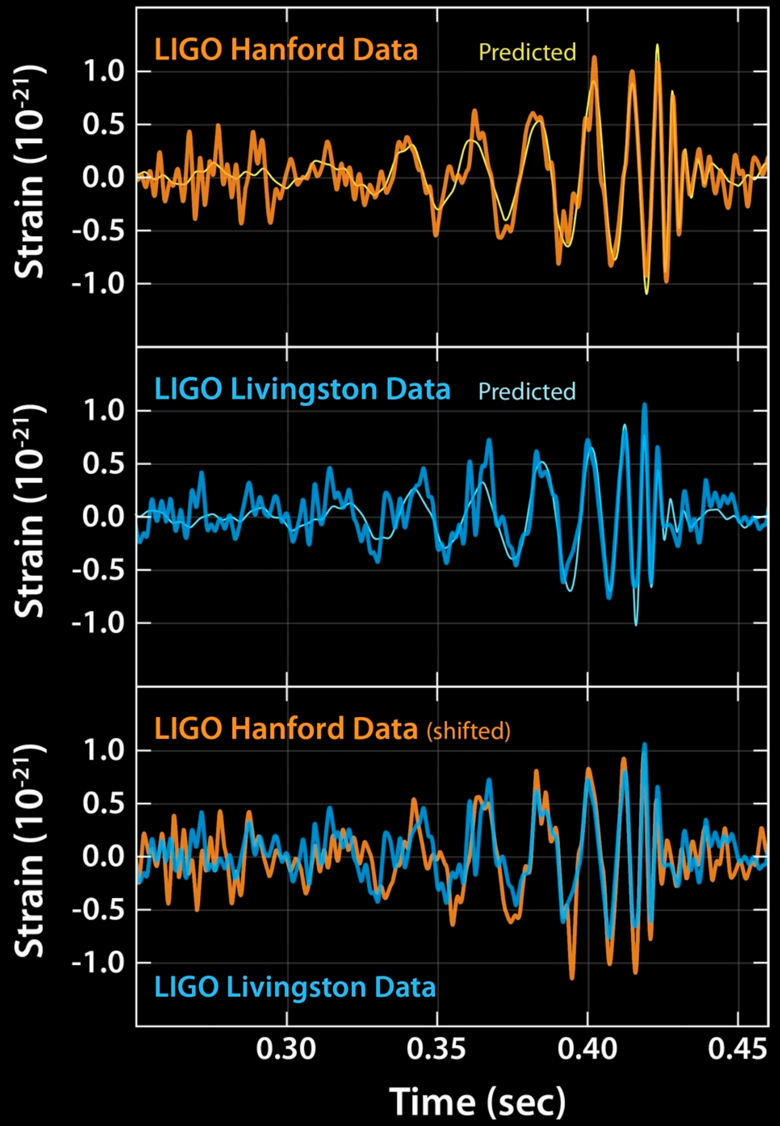
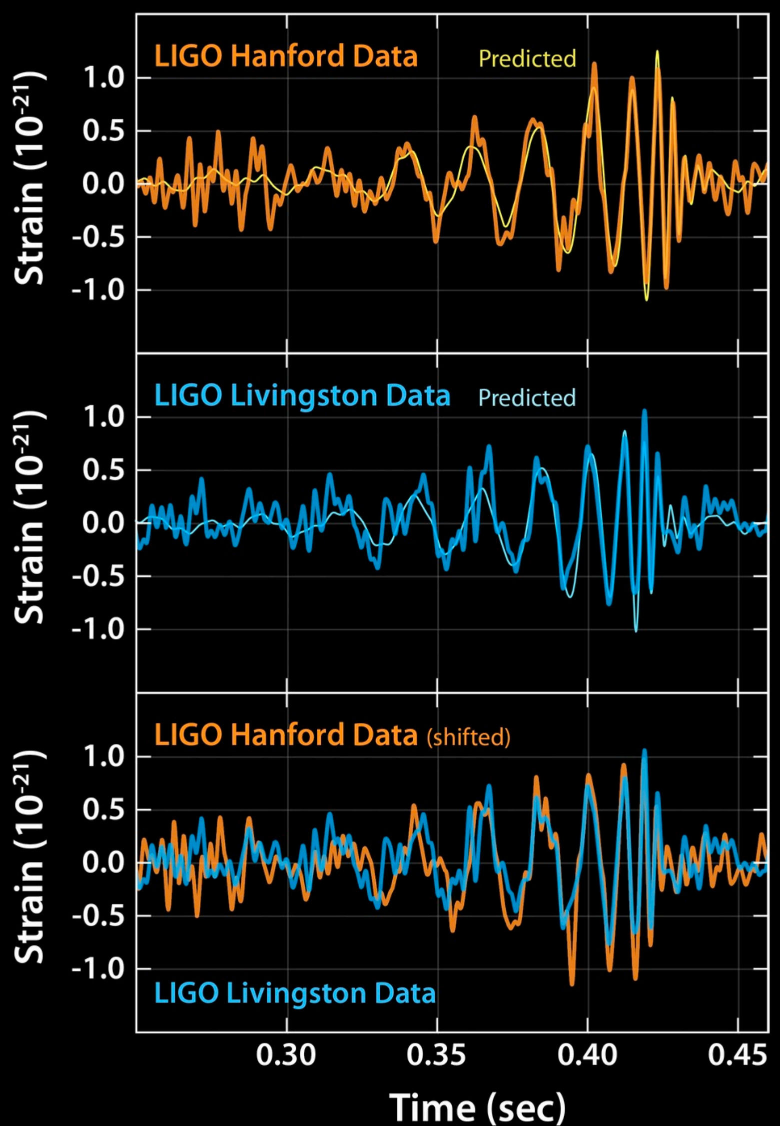
Gravitational wave science



The first event:
GW150914

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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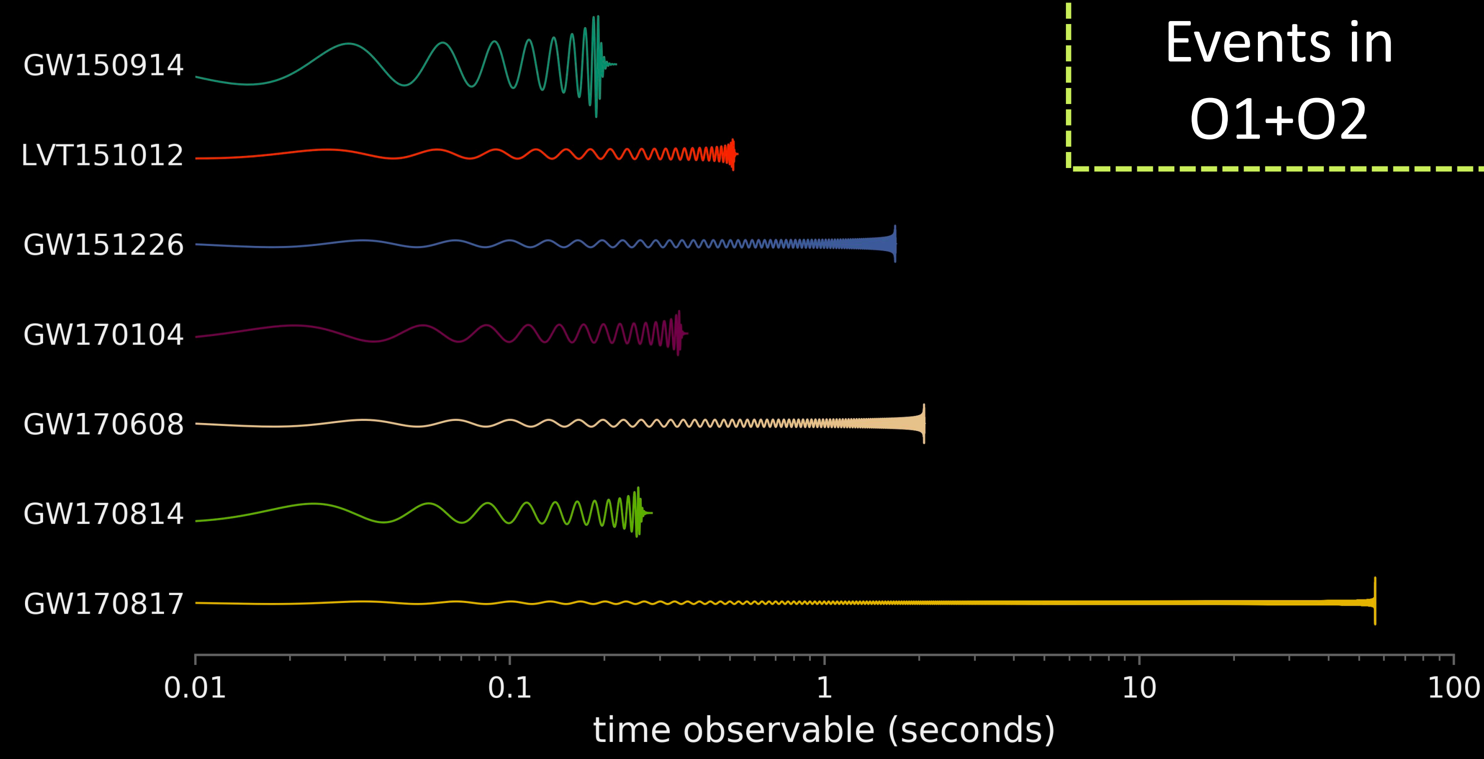
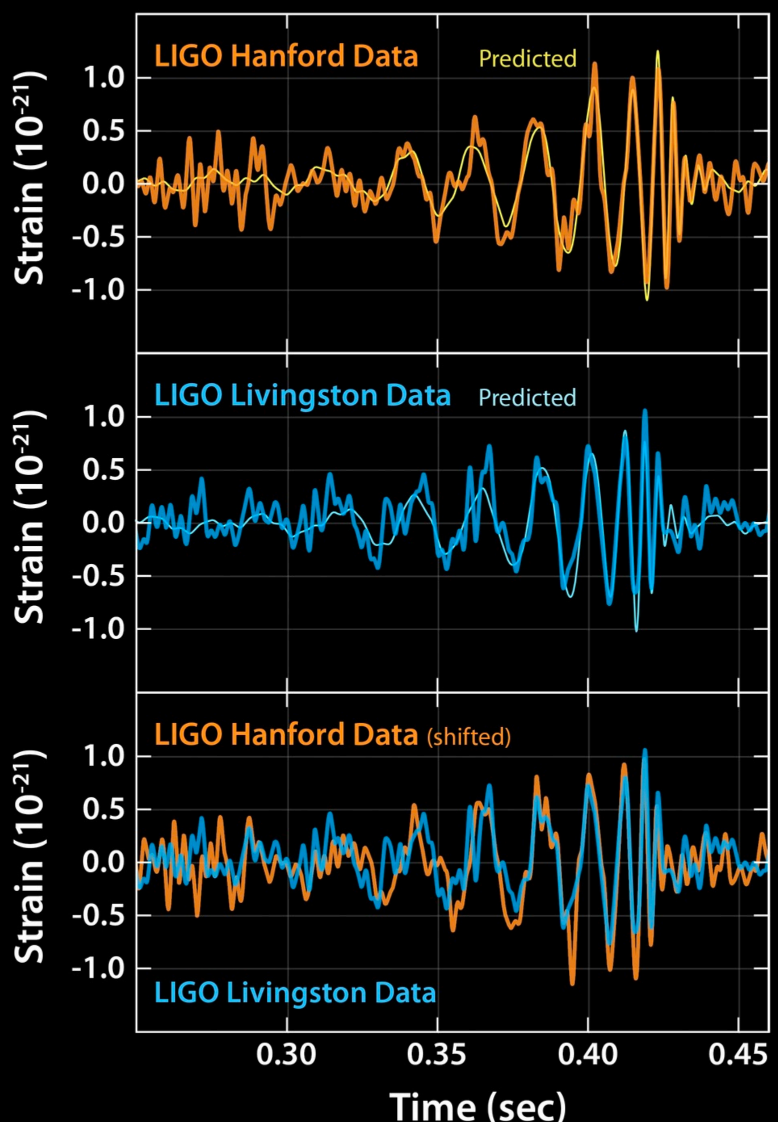


Events in O1+O2

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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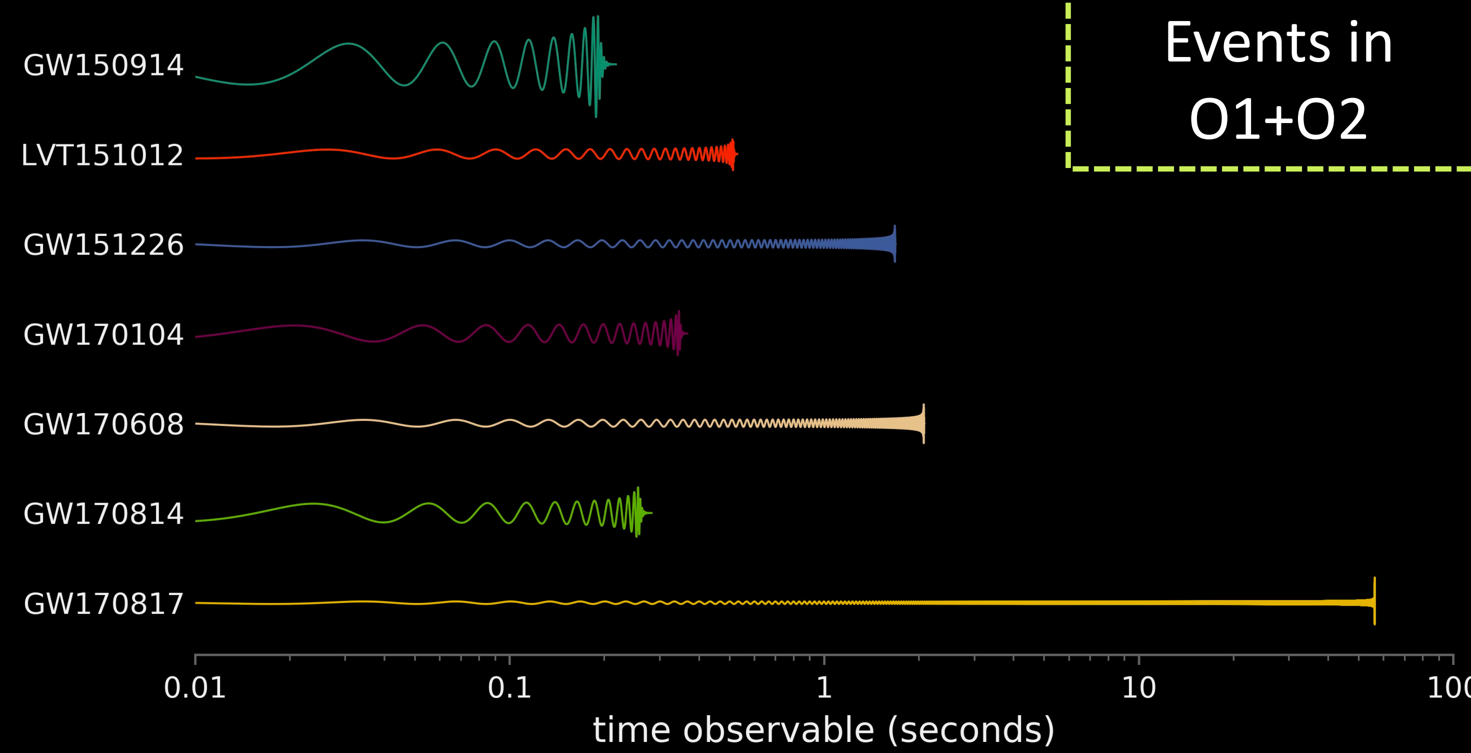

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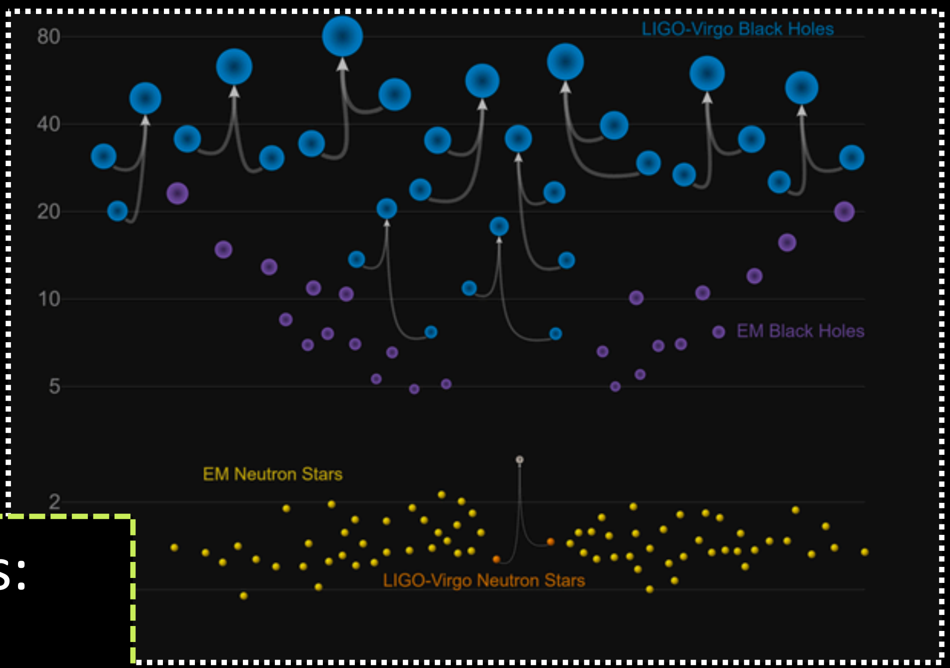
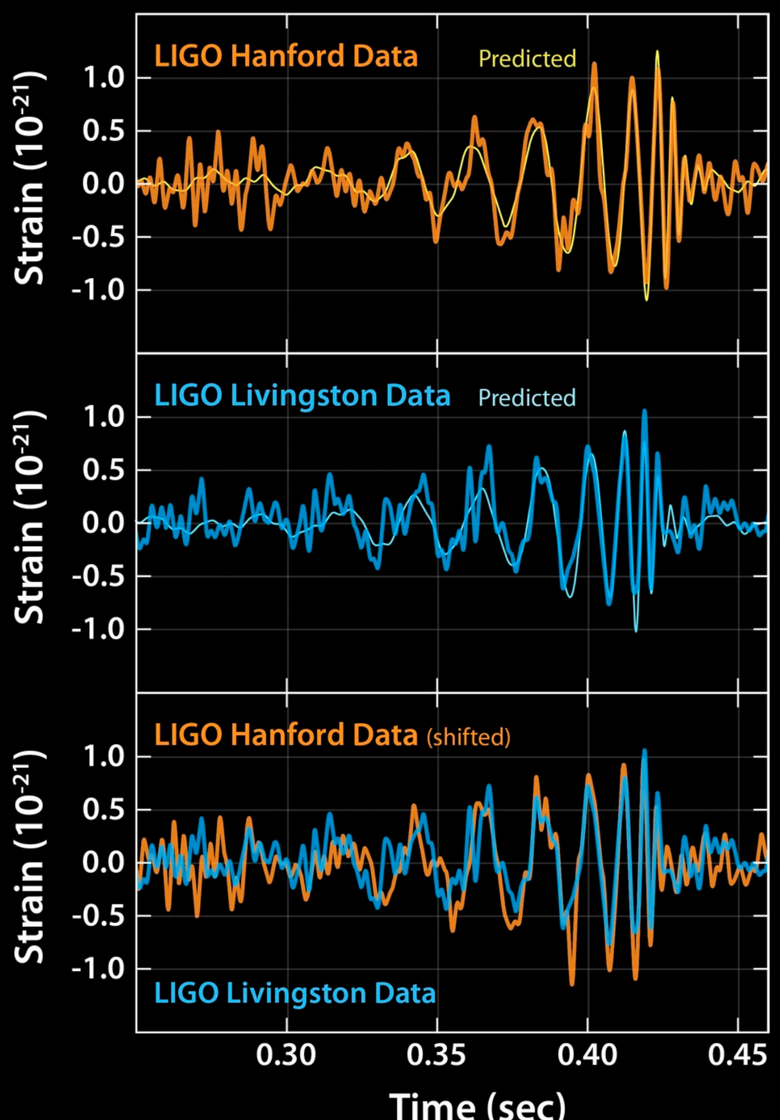


Catalogues: GWTC-1

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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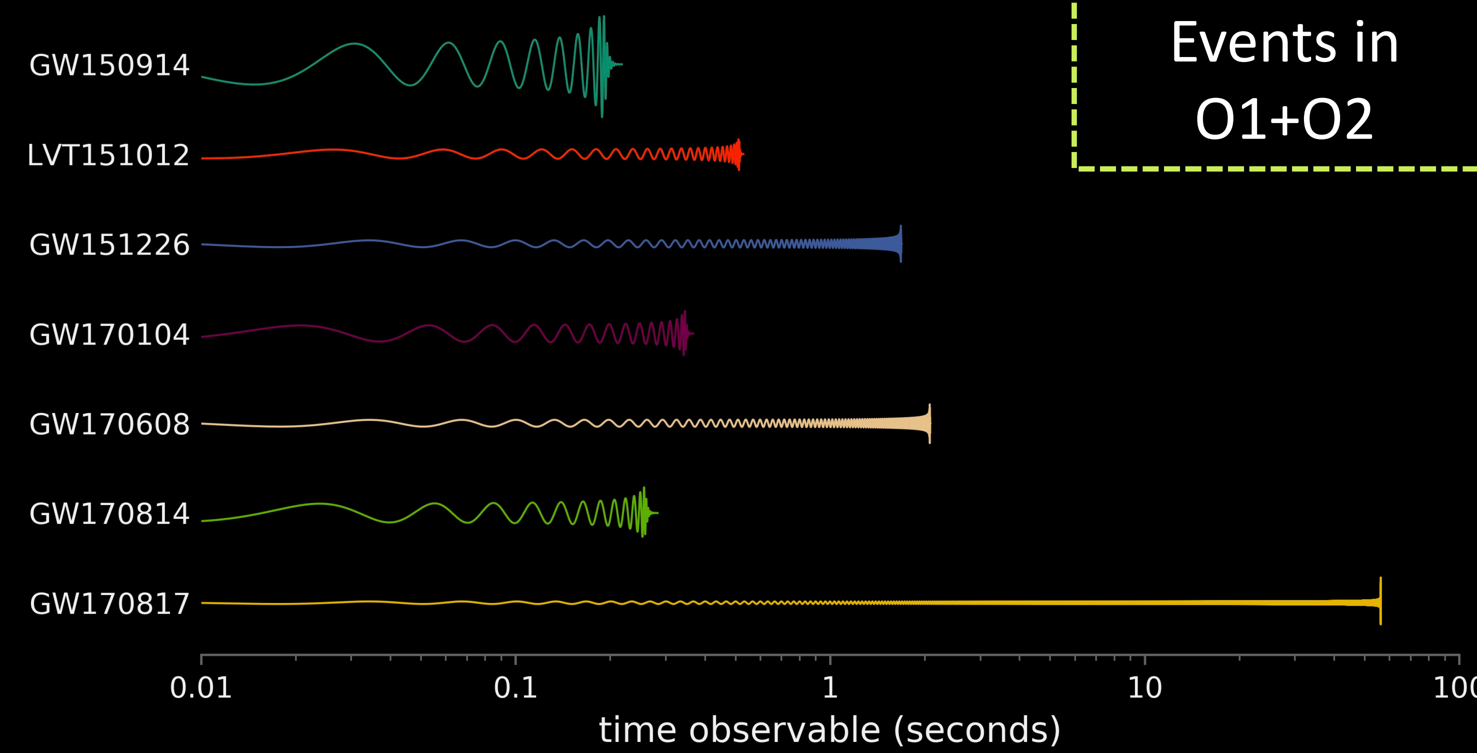

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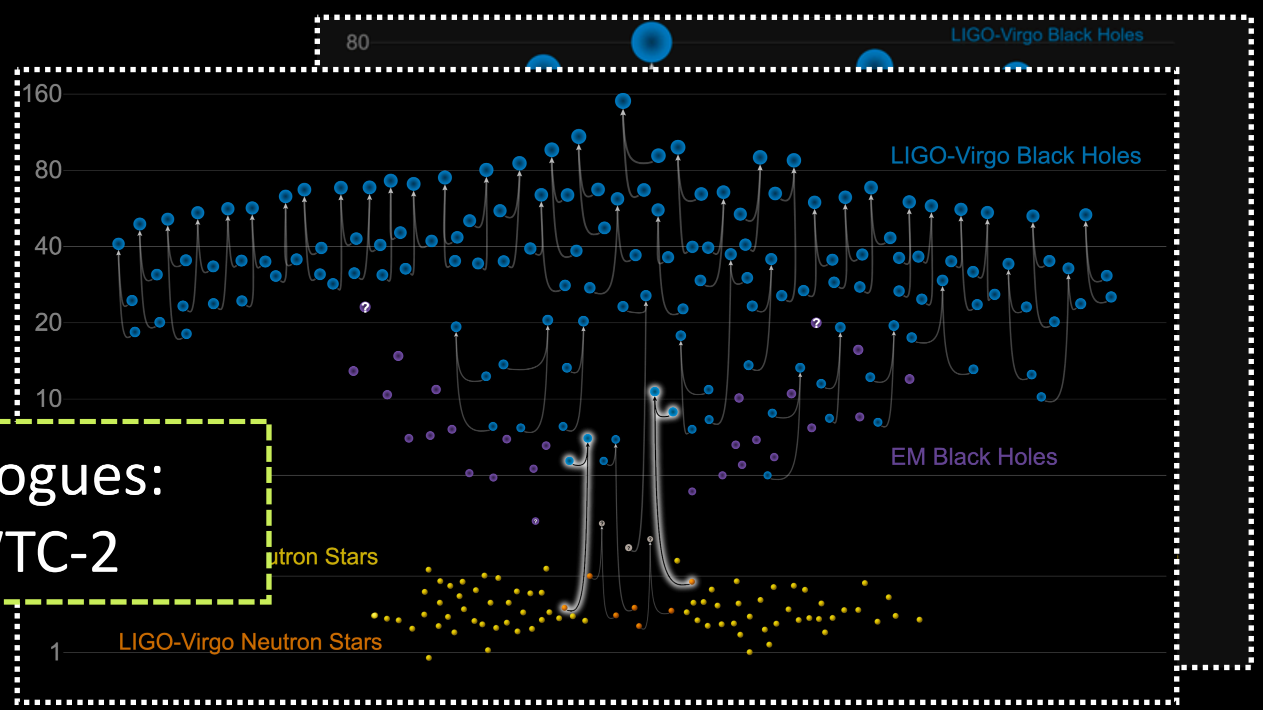
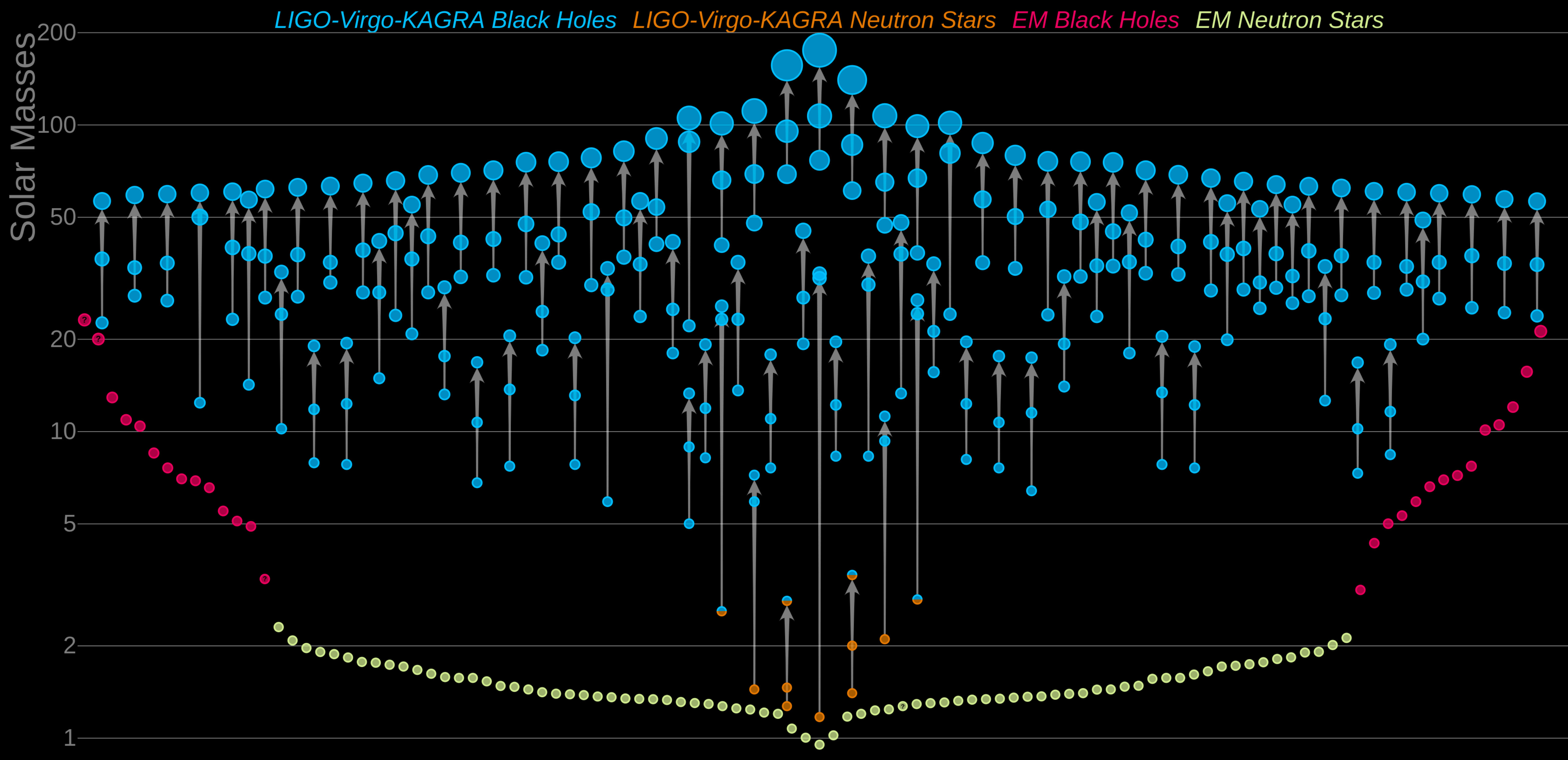


Catalogues: GWTC-2

Images: LIGO/Ben Farr/Aaron Geller

An ever growing catalogue (GWTC-3)



Adapted from LIGO-Virgo-KAGRA, Aaron Geller

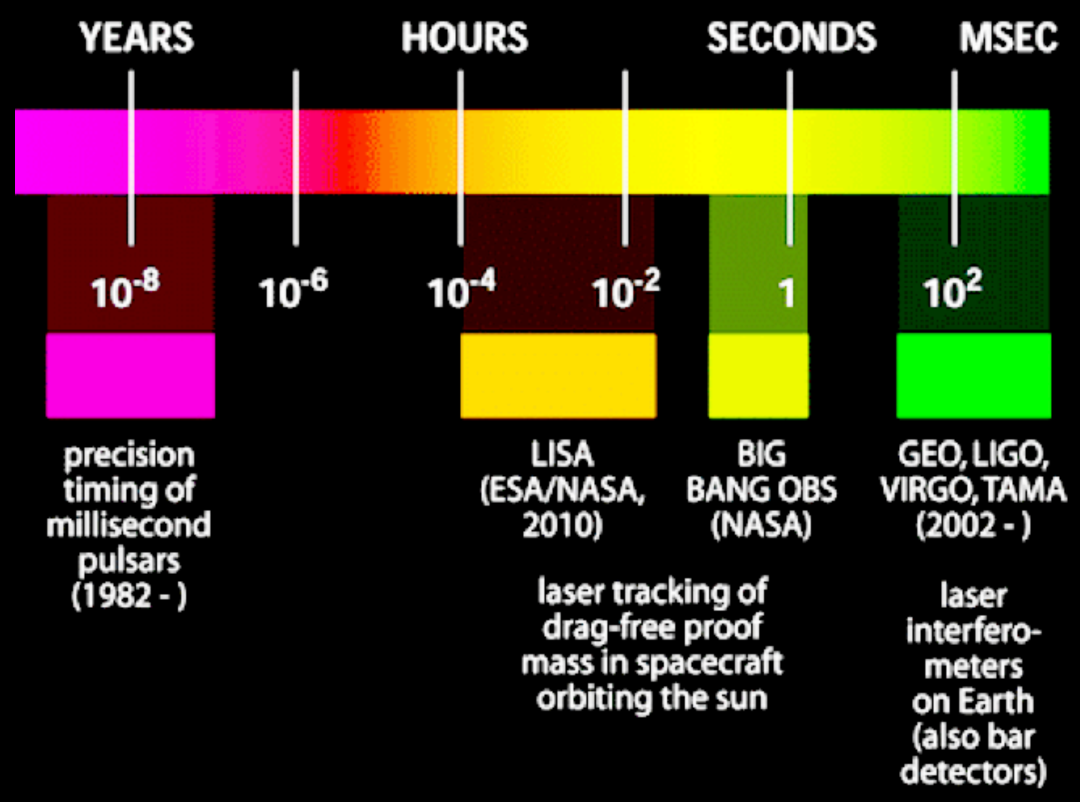
Gravitational wave experiments

running, planned and proposed

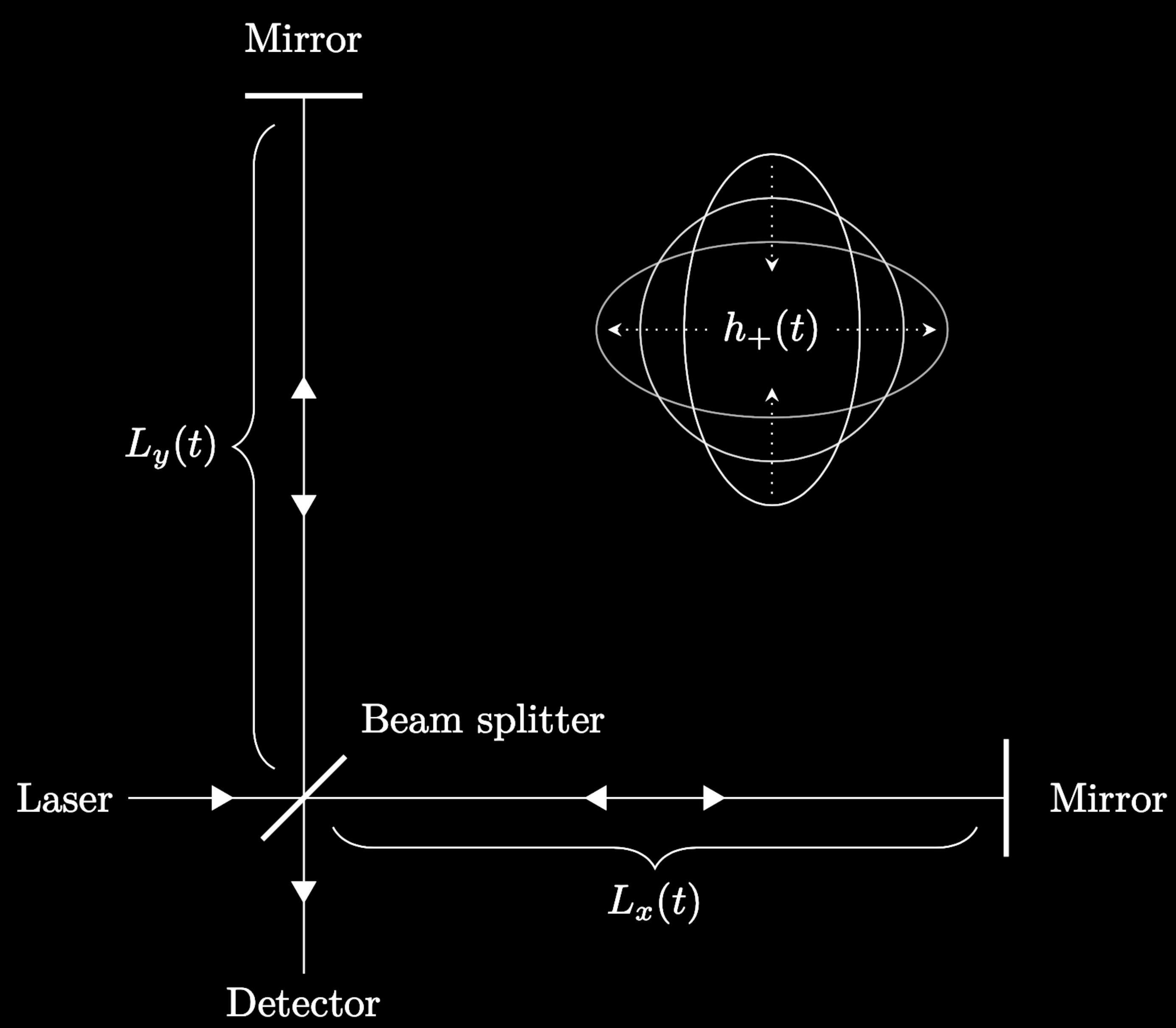
Opportunities in the next decade

- LIGO/Virgo/KAGRA — operational (O4 in progress)
- Pulsar Timing Arrays — operational
- LISA — 2035
- Atom interferometers: AION, Magis — prototypes developed

- Next generation ground-based:
  - Einstein telescope (2030s?)
  - Cosmic Explorer (2030s?)
- Next generation space-based:
  - DECIGO, BBO, …



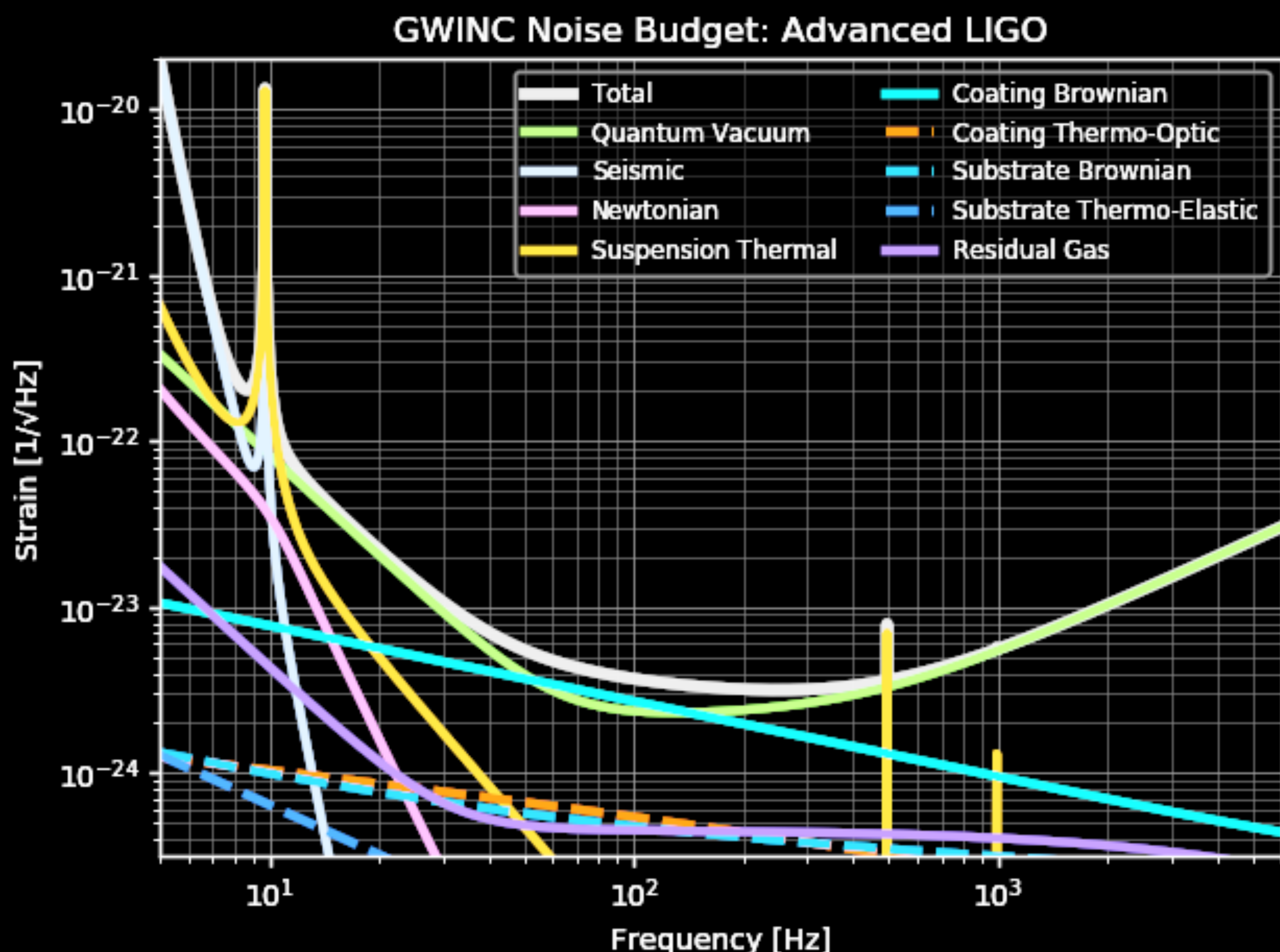
Michelson interferometers



- GW induce changes in path length using interference of a split beam
- Largest interference signal: $$\frac{\omega_{\mathrm{gw}} L}{c} = \frac{\pi}{2} \Rightarrow L = \frac{\lambda_{\mathrm{gw}}}{4}$$
- $100\,\mathrm{Hz} \rightarrow 750\,\mathrm{km}$ detector
- With Fabry-Perot cavities, can increase the effective optical path length without physically lengthening the path
- Arm lengths down to $\mathcal{O}(\mathrm{km})$

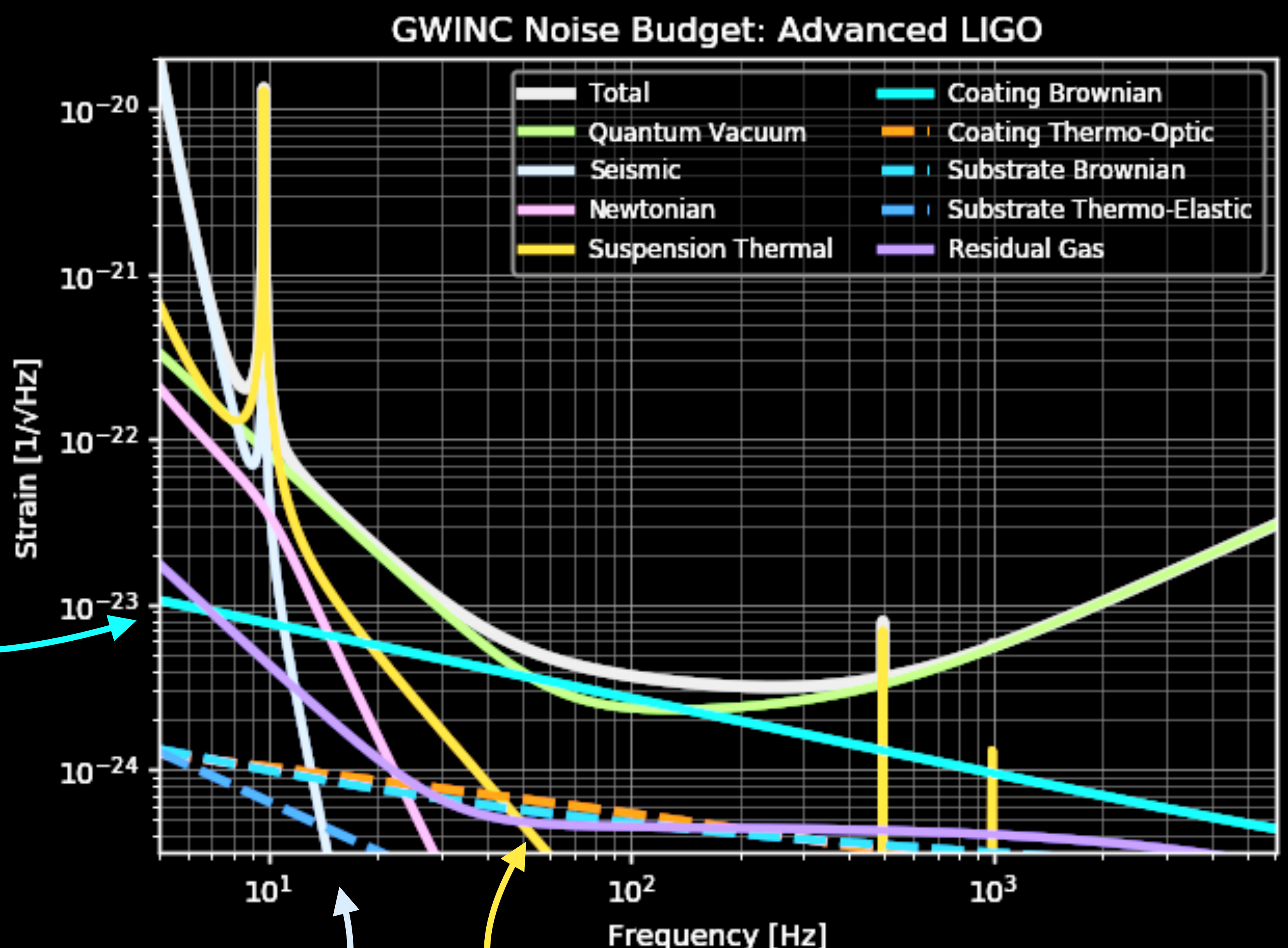
Image by David Weir, DC and Weir, to appear

LIGO/Virgo/KAGRA



Plot from the Python Gravitational Wave Interferometer Noise Calculator (pygwinc)

LIGO/Virgo/KAGRA



molecular motion of atoms within the coatings on the mirrors

Seismic “wall”

thermal motion of atoms and molecules within the suspensions

Shot noise: photons arriving discretely limits the precision with which the mirrors' positions can be measured

Plot from the Python Gravitational Wave Interferometer Noise Calculator (pygwinc)

Future ground-based interferometers

Einstein Telescope (ET):

- European
- Underground triangular setup
- Cryogenic mirrors
- More intense laser beam, squeezed light

Future ground-based interferometers

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Seismic noise

Thermal noise

Quantum noise

Future ground-based interferometers

Einstein Telescope (ET):
- European
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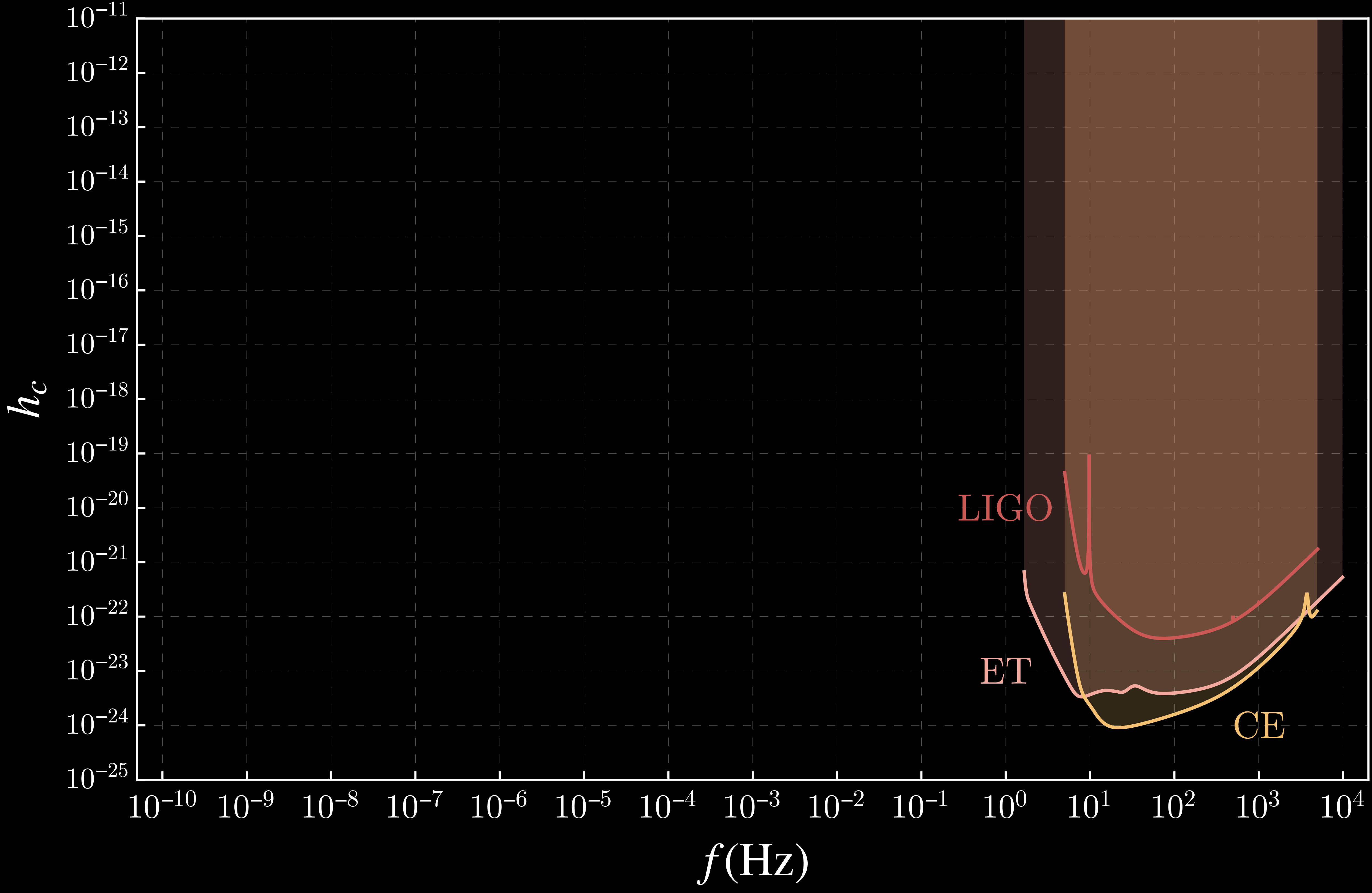
Seismic noise → Underground triangular setup
Thermal noise → Cryogenic mirrors
Quantum noise → More intense laser beam, squeezed light

Voyager:
- **U**pgrade to the existing LIGO
- New technologies such as cryogenically cooled mirrors and improved laser systems
- 2024 white paper

Cosmic Explorer (CE):
- US-based
- two detectors, each with arms 40 kilometers long

NEMO (Neutron Star Extreme Matter Observatory):
- Proposed in Australia
- high-frequency gravitational waves



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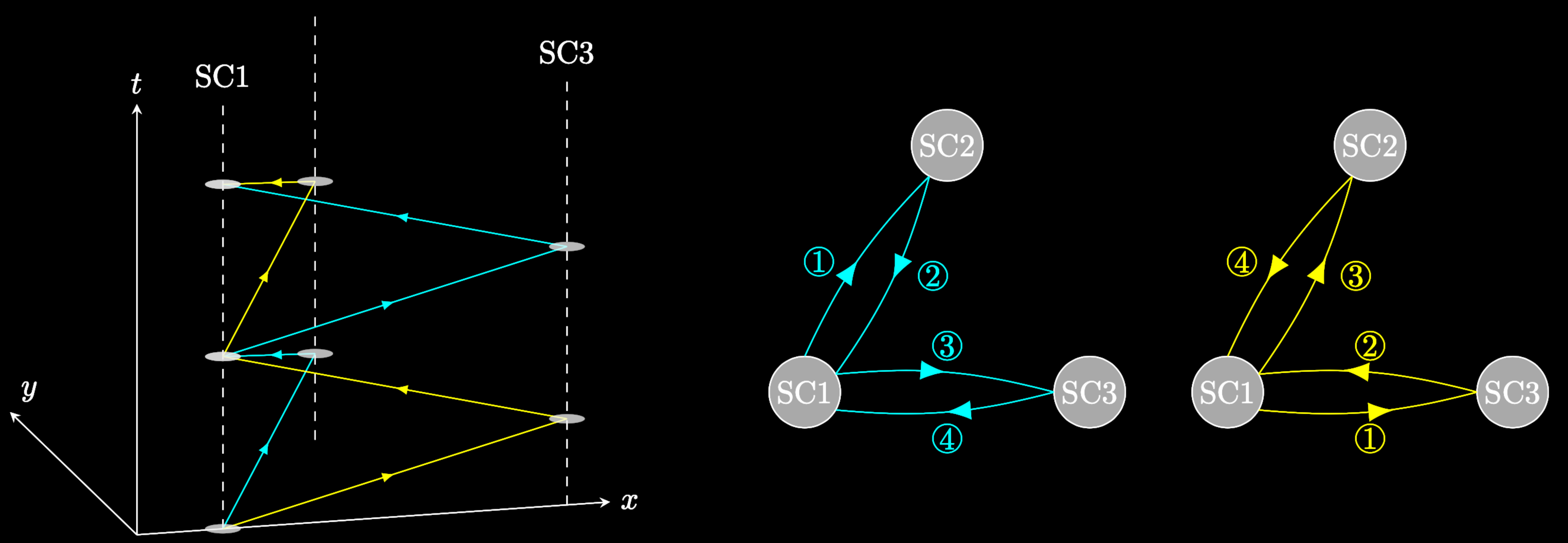
Time-delay interferometry

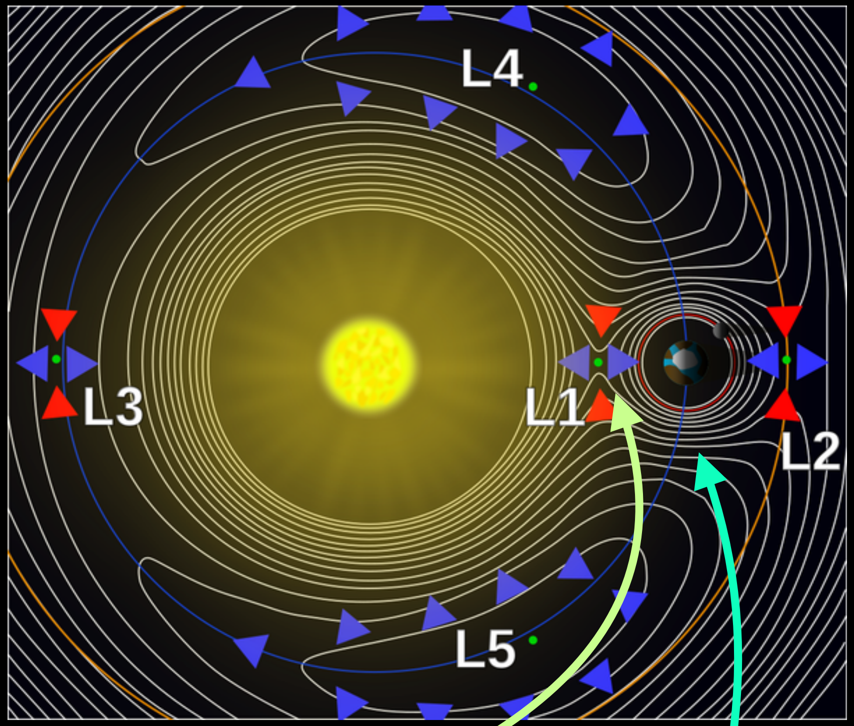
Image by David Weir, DC and Weir, to appear



- Much longer arms, e.g. for LISA $f_{\rm gw} = c/L = \dfrac{3.0 \times 10^5\,{\rm km/s}}{2.5 \times 10^6\,{\rm km}} = 0.12\,{\rm Hz}$
- Impossible to maintain an equal distance between multiple SC in orbit $\rightarrow$ time-delay interferometry
- Each SC receives and transmits laser signals $\rightarrow$ laser noise can be subtracted

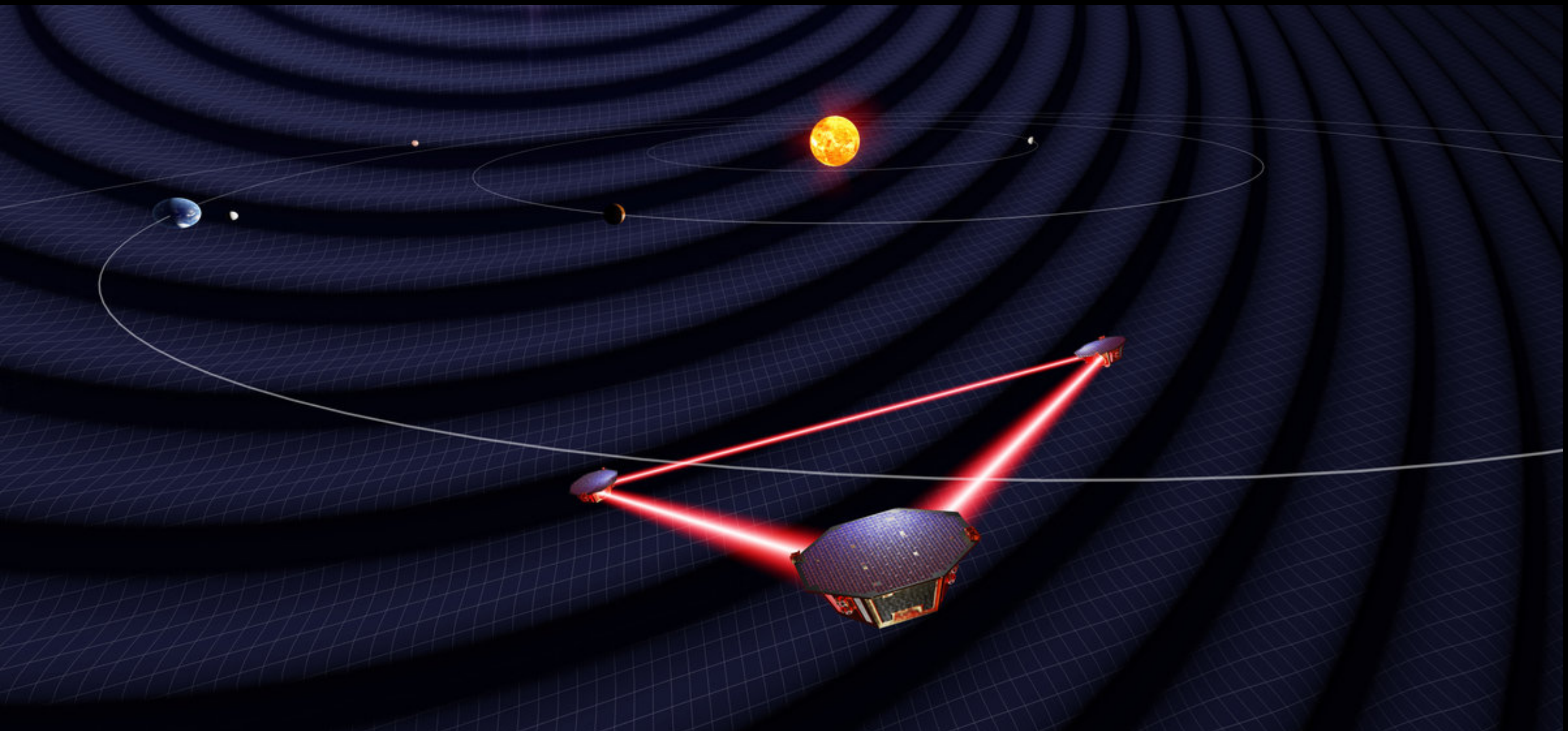
LISA

- ESA & NASA
- Pathfinder mission: 2015
- Launch date: ~ 2035
- LISA Consortium already comprised of $\sim 10^3$ scientists and engineers

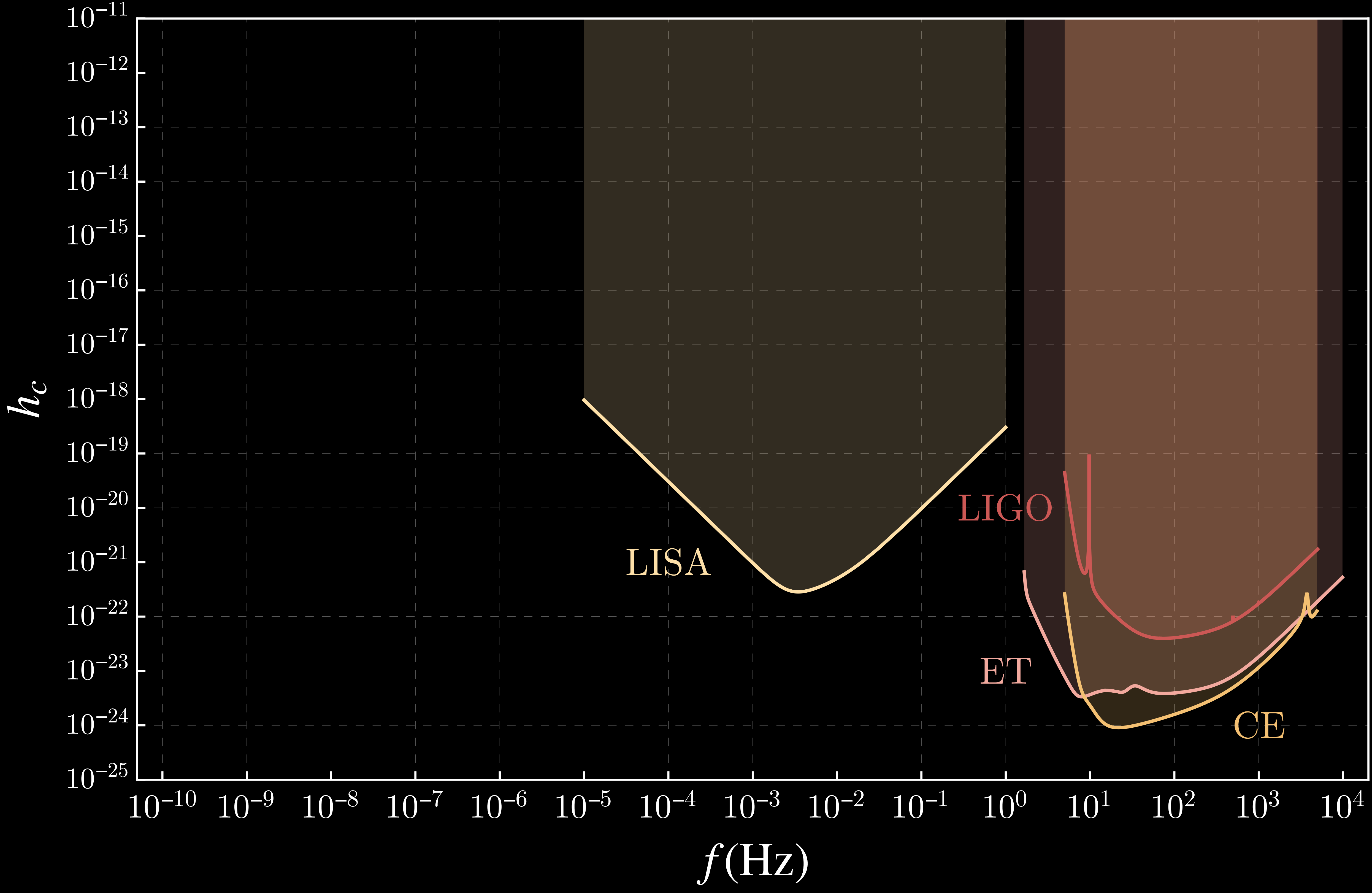


LISA pathfinder
(at L1)

LISA (trailing the earth at
$50\mathrm{M\,km}$ in heliocentric orbit)



LISA
CONSORTIUM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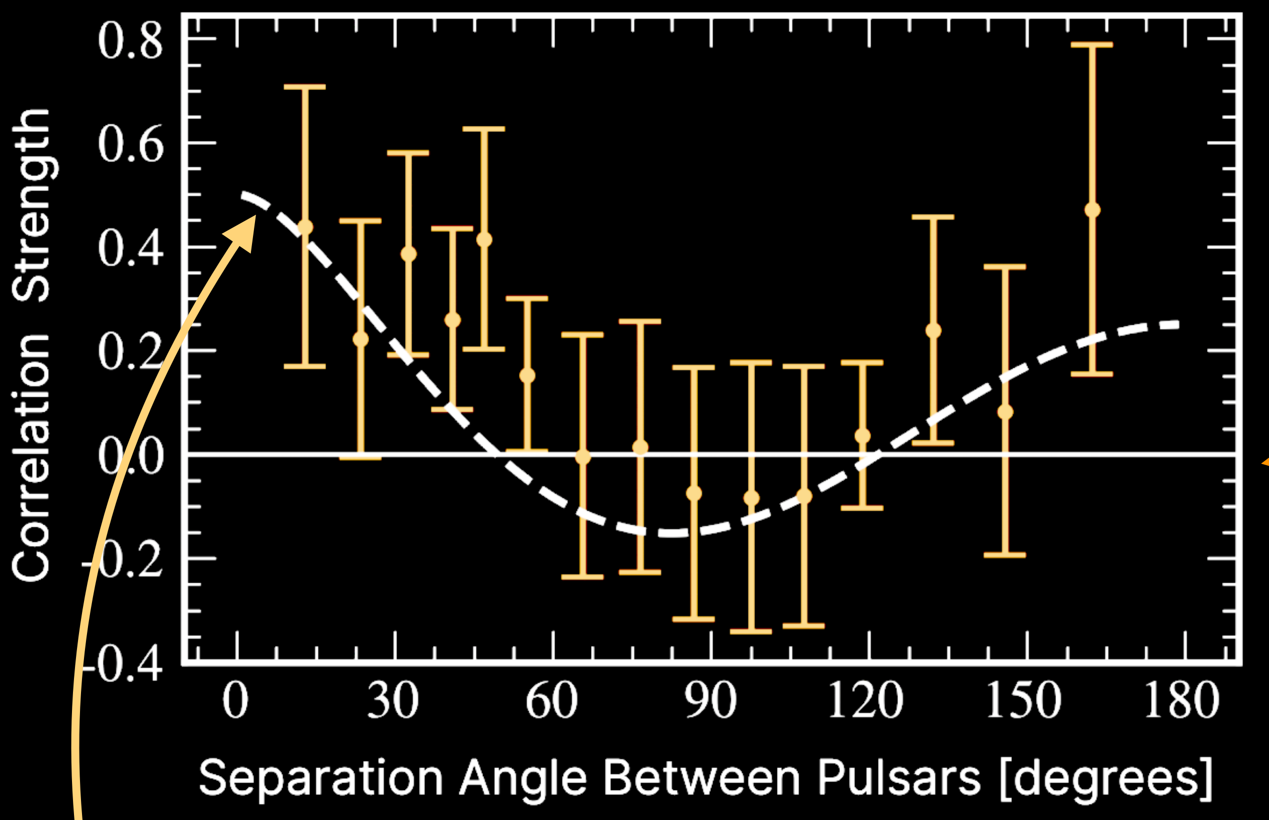
Pulsar timing

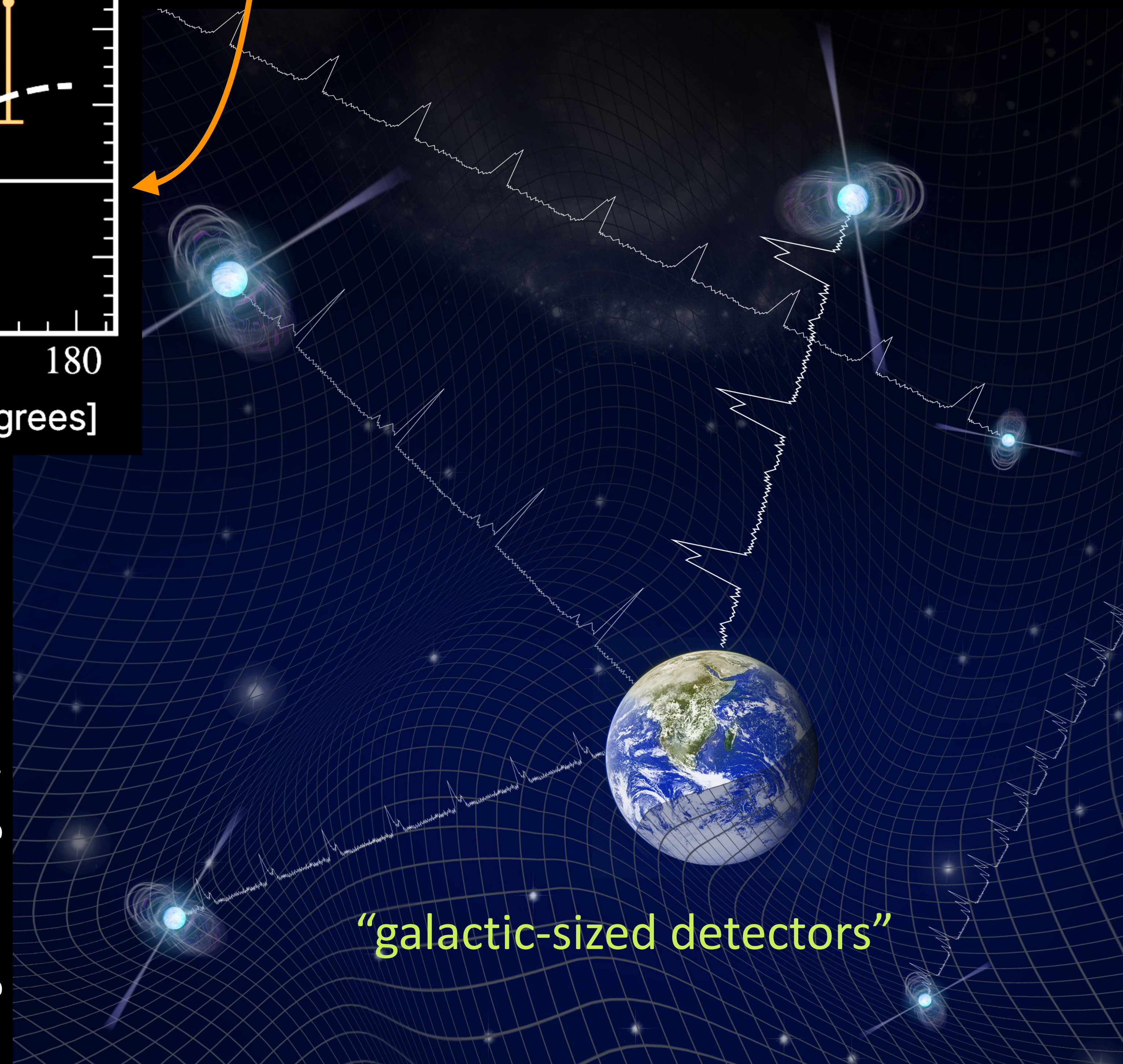
correlations in the arrival times of pulses from multiple millisecond pulsars across the galaxy

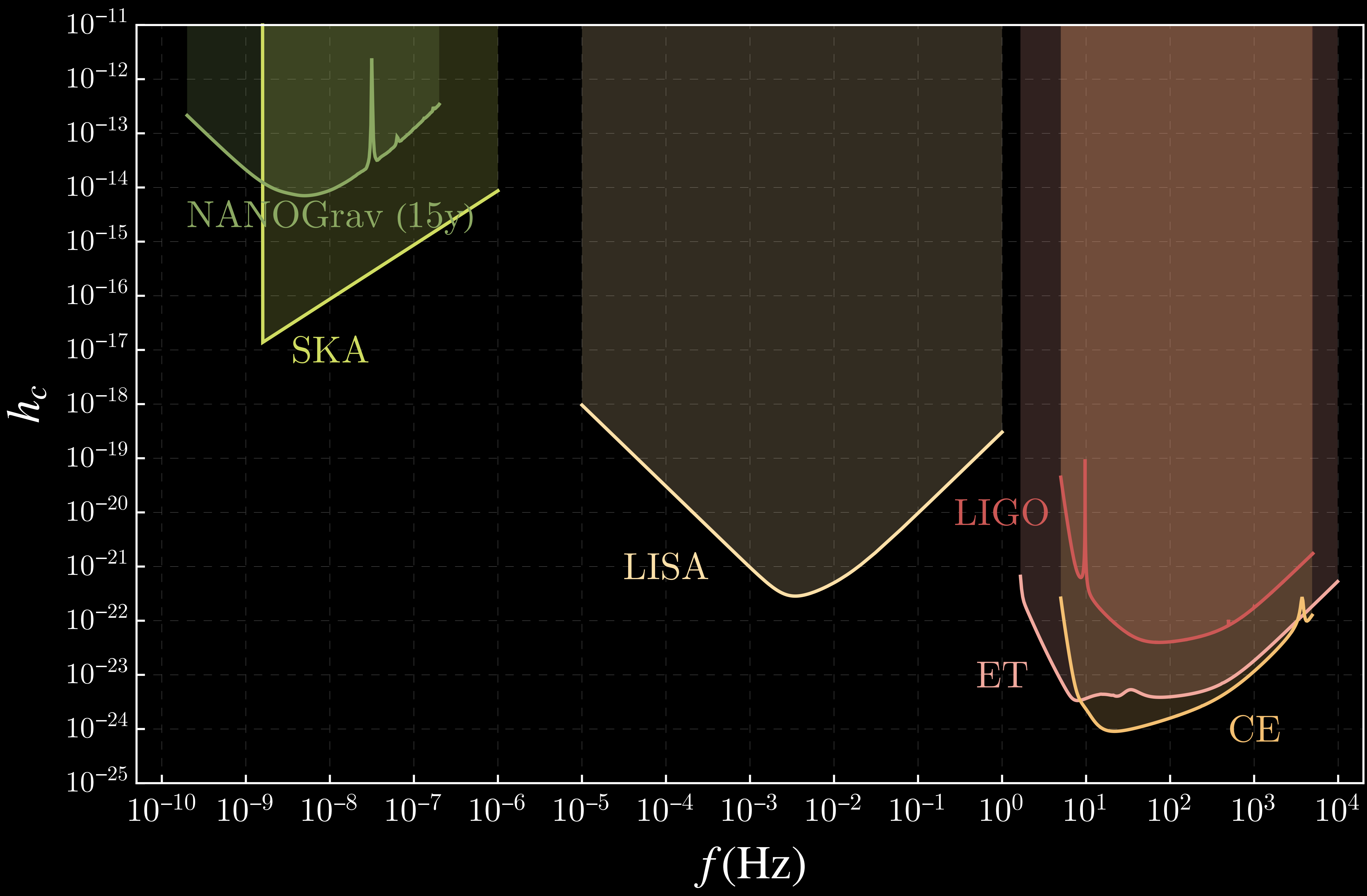
No GW



correlation function assuming
an isotropic and Einsteinian GWB

Image: NANOgrav, Tonia Klein




h_c
$f\,(\mathrm{Hz})$
NANOGrav (15y)
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LISA
LIGO
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NANOGrav (15y)
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What about this gap?
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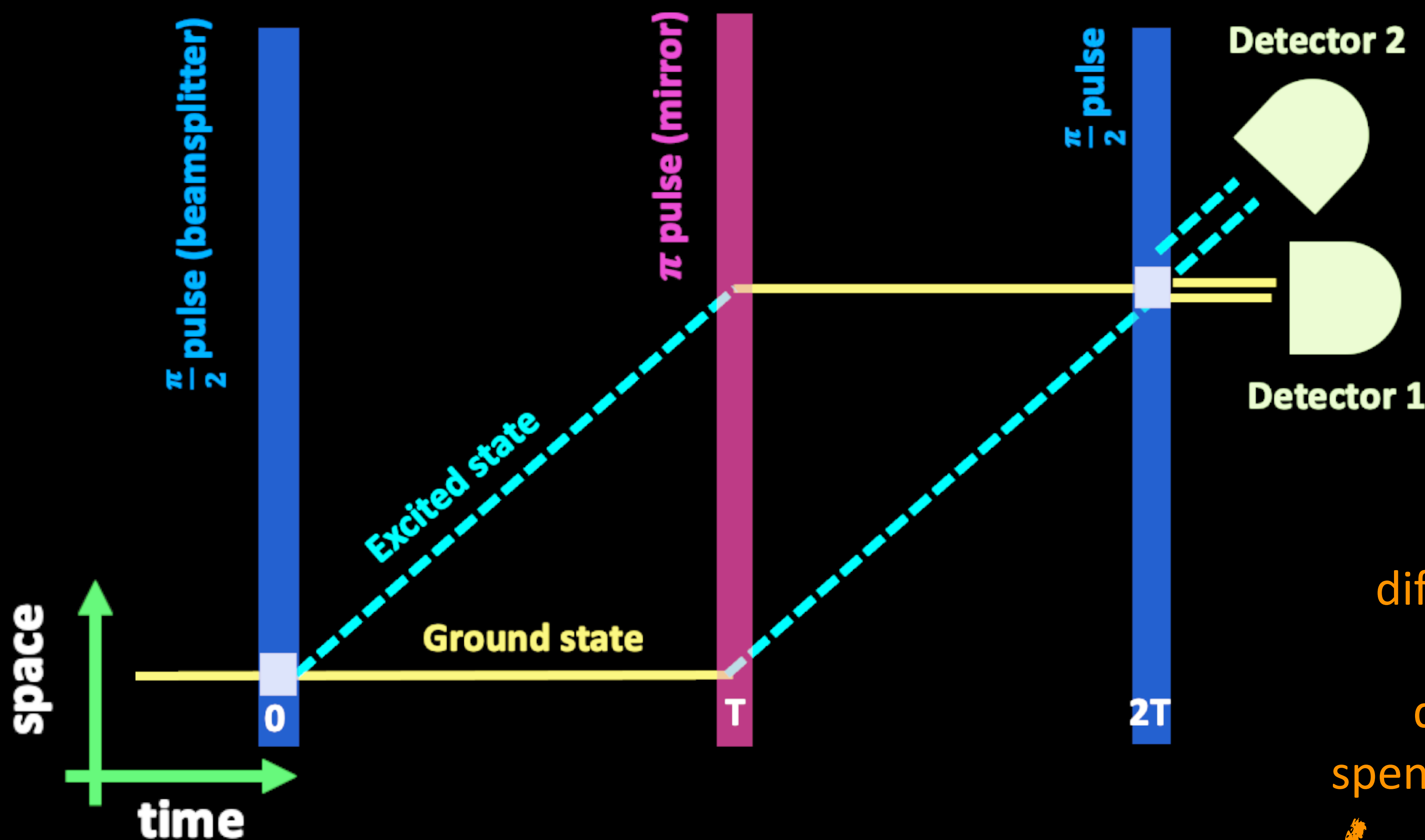
Atom interferometry

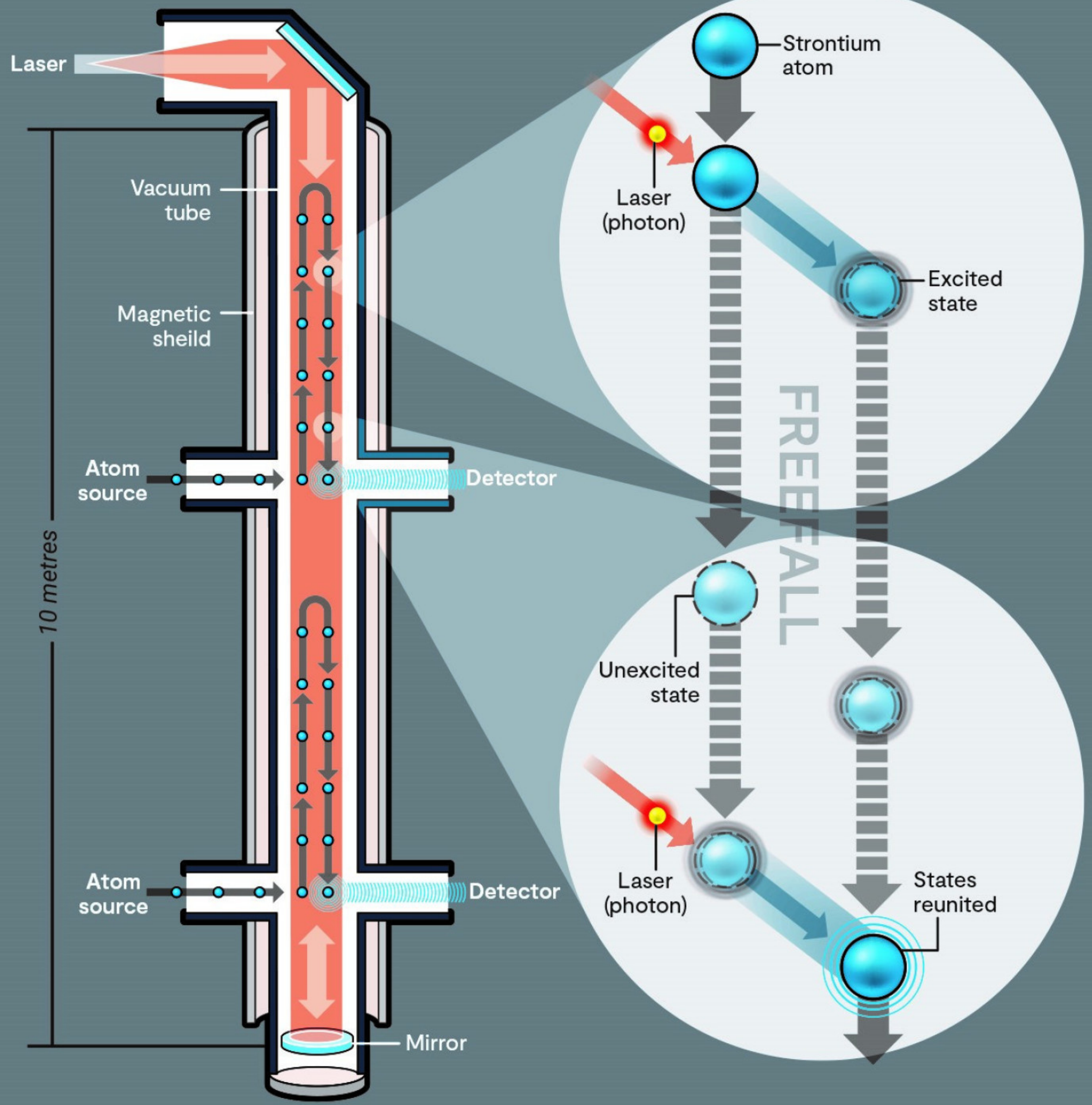


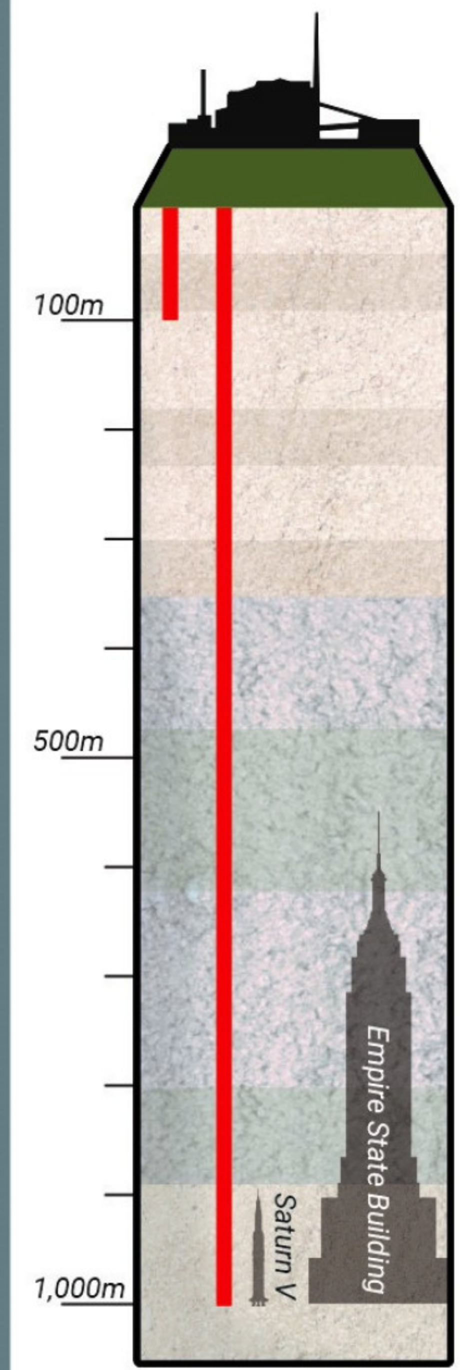
$\Delta\phi(2T)$ phase difference between the arms due to difference in time spend in excited state

- In the detectors, $P_g = \cos^2\left(\frac{\Delta\phi(2T)}{2}\right)$, $P_e = \sin^2\left(\frac{\Delta\phi(2T)}{2}\right)$
- Two atom interferometers $\Delta\Phi \equiv \Delta\phi_1 - \Delta\phi_2$ ← Cancel laser noise
- GW modify the light travel time → times that the arms spend in excited state different between two interferometers → $\Delta\Phi \neq 0$ → phase shift depends on GW strain

Image from Hannah Banks, BeyondWimps meeting at Durham University, 2024

AION Atom Interferometer Observatory and Network





Once the technique is proven at the 10 metre scale, the project will be scaled up to a 100 metre facility that will be constructed within an existing mineshaft at the Boulby Underground Laboratory. The hope is that the project can then be scaled up to 1,000 metres, which will require a new underground facility.

Infographic: Ben Gilliland, STFC

Atom interferometry timeline

Prototypes

- AION-10/AION-100
- MAGIS-100
- MIGA
- VLBAI
- ZAIGA

in development now

km-scale

- AION-km
- MAGIA-advanced
- ELGAR
- MAGIS-km
- advanced ZAIGA

2030s

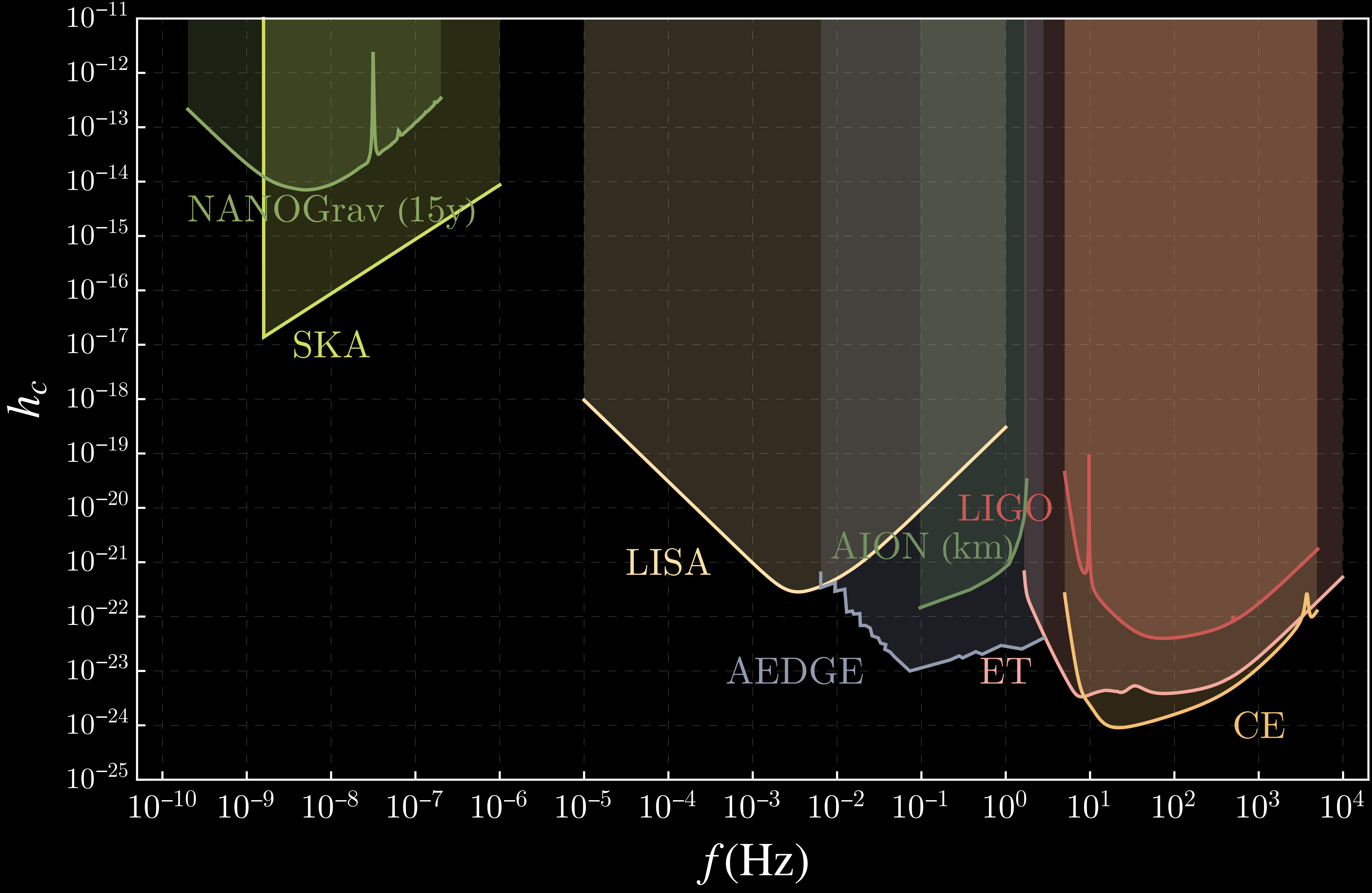
space

- AEDGE

?

GW science

Ultralight DM searches


NANOGrav (15y)
SKA
LISA
AION (km)
LIGO
AEDGE
ET
CE
h_c
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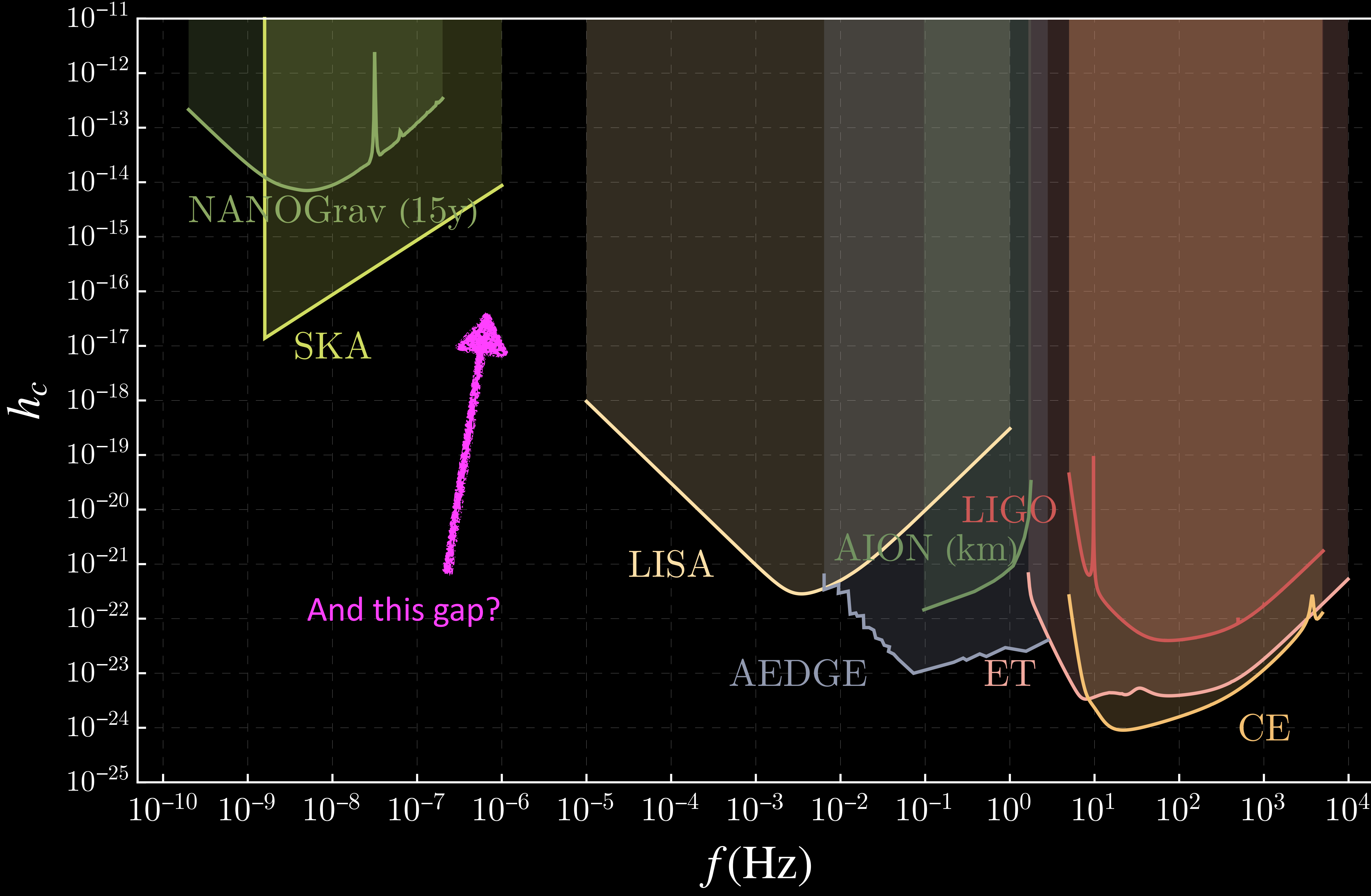
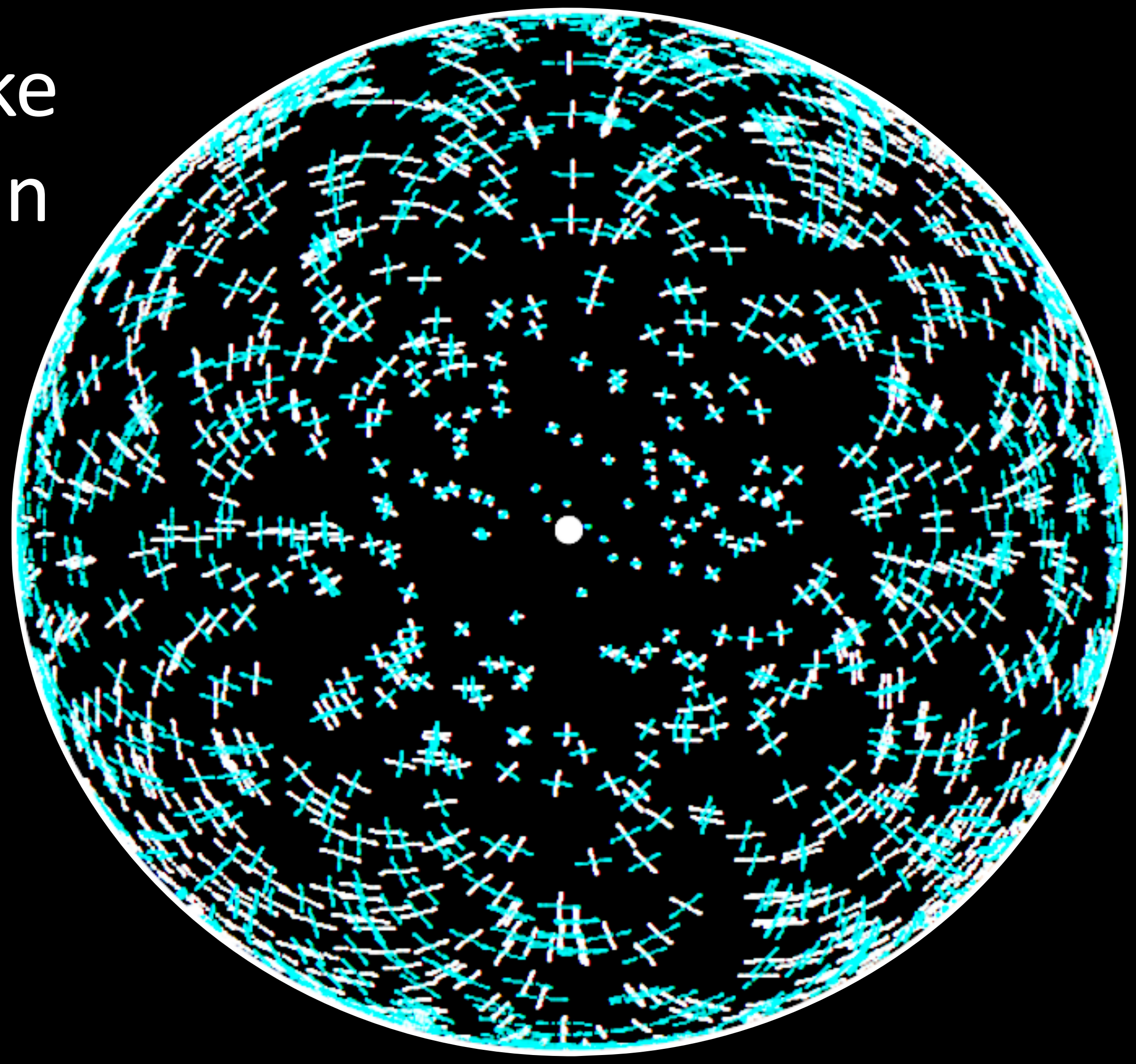


h_c
$f\,(\mathrm{Hz})$
NANOGrav (15y)
SKA
LISA
AION (km)
LIGO
AEDGE
ET
CE
And this gap?

Astrometry

- Galaxy surveys such as GAIA make precise observations of 10^9 stars in our galaxy
- Gravitational wave signals interfere with the light of those stars as it travels towards the Earth, which would register as very small wiggles in their apparent position
- Compression of the dataset is necessary and possible
- For shifts of about a pc, frequency is similar to that of PTAs:

$$f_{\mathrm{GW}} \sim c/\mathrm{pc} \sim 10^{-9}\mathrm{Hz}$$



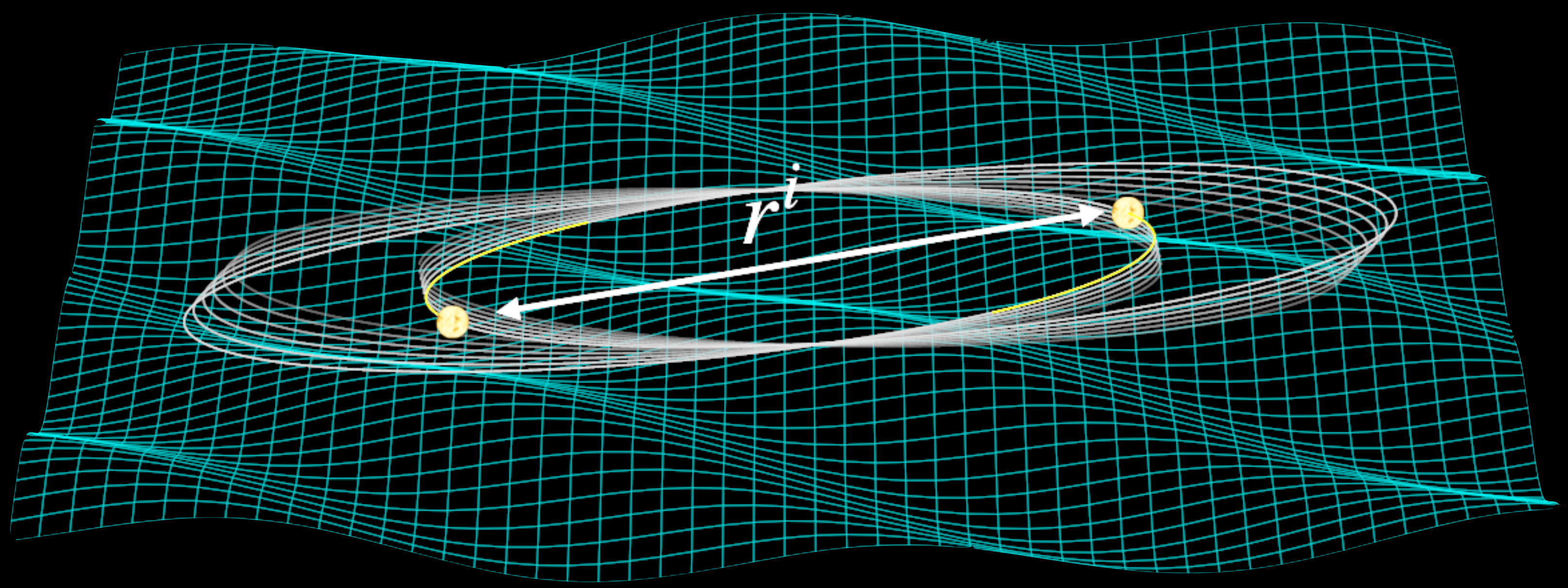
Moore, Mihaylov, Lasenby, Gilmore, PRL, arXiv:1707.06239

$$h_c = 10^{-14}\left(\frac{5\mathrm{years}}{t_m}\right) \forall f < \frac{1}{t_m}$$

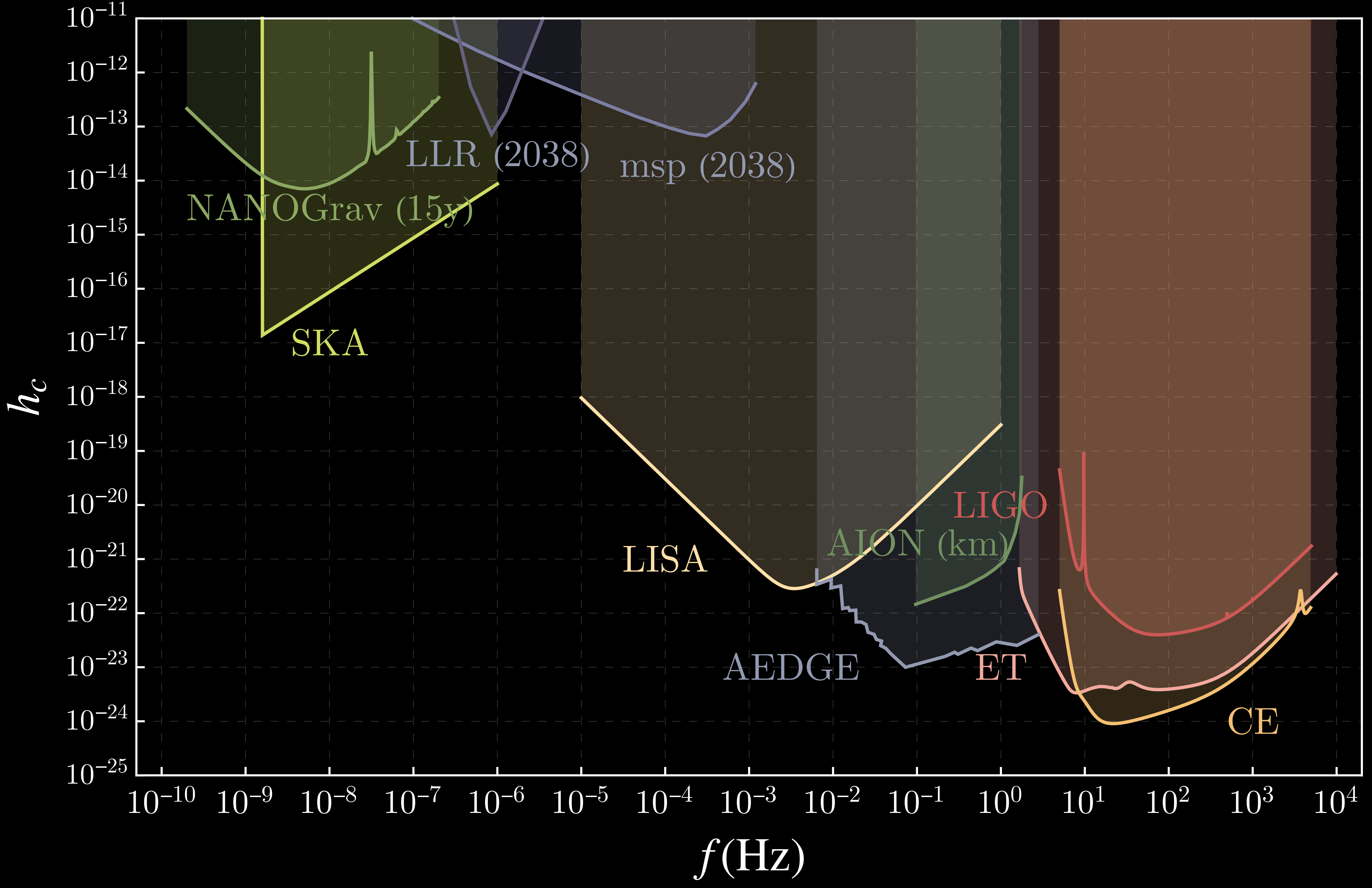
Absorption by binaries

Blas & Jenkins, PRL (2022) 10, 101103

- In the presence of GW, $\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$



- Can probe via: binary pulsar timing, lunar and satellite ranging



h_c
f(Hz)
NANOGrav (15y)
SKA
LLR (2038)
msp (2038)
LISA
AEDGE
AION (km)
LIGO
ET
CE

Gravitational wave opportunities

for fundamental physics

Phenomenological opportunities

(not exhaustive!)

Compact object histories
Populations of black holes and neutron stars at high redshift

Cosmology
Independent probe of H_0

Tests of GR
Space-time near the horizon

Nuclear physics
The dynamics of dense matter
Multi-Messenger Astrophysics

Dark matter
Dark object binaries
Space-time near a black hole
Environmental effects
Early Universe signatures
Black hole superradiance
Direct searches for ultralight particles

Early Universe physics
Cosmological phase transitions
Cosmic strings

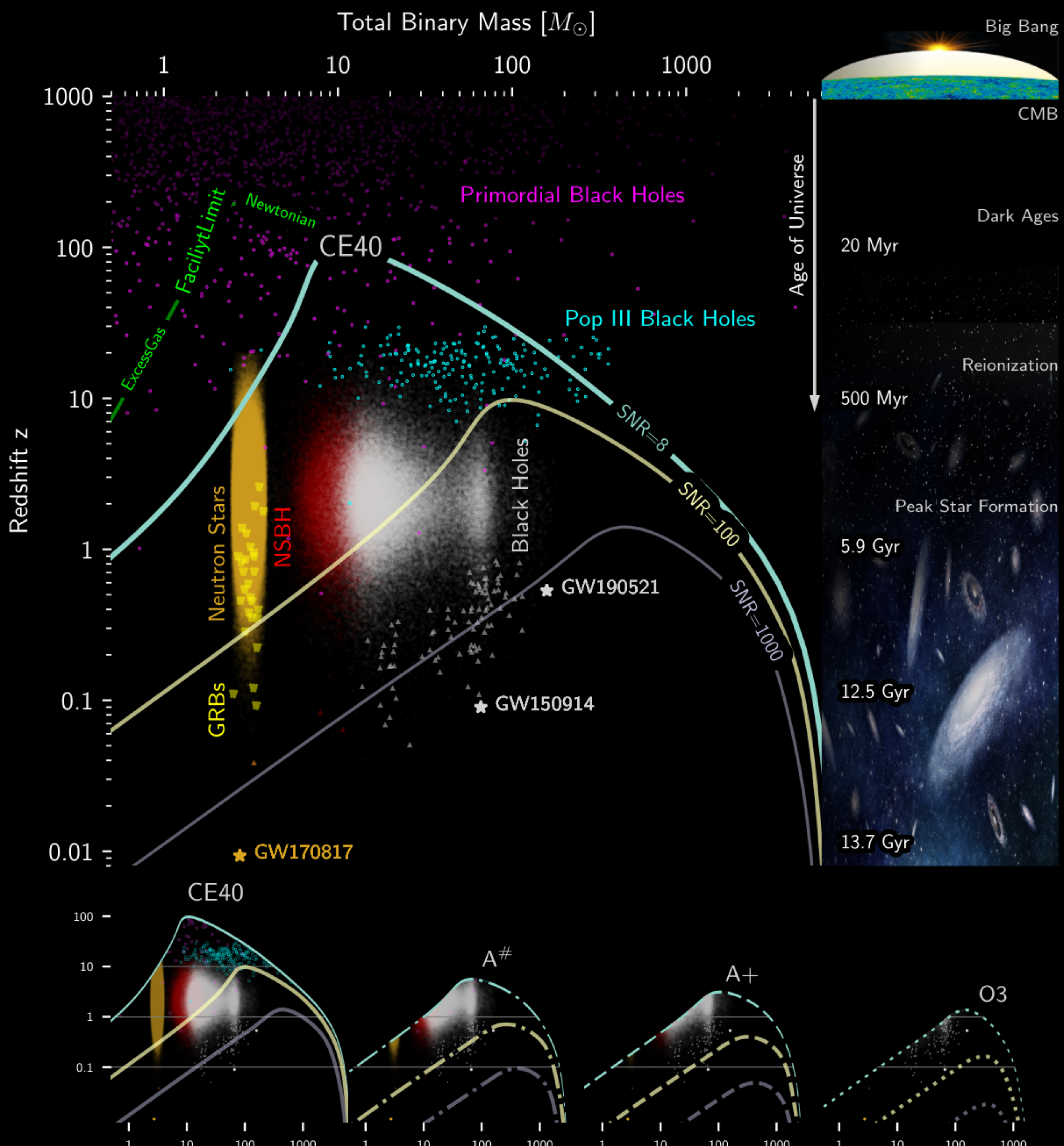
Histories

GW detectors measure the displacement of test masses: strain amplitude scales with $\propto 1/r$

(The total *energy* of the quadrupole radiation would fall off with $1/r^2$)

→ Can probe very high redshifts! E.g. mergers BHs from the very first (pop-III) stars, PBHs…

Image: Cosmic Explorer white paper, arXiv:2306.13745



Nuclear physics

- BNS mergers probe the EoS of nuclear matter under extreme densities (exceeding atomic nuclei)

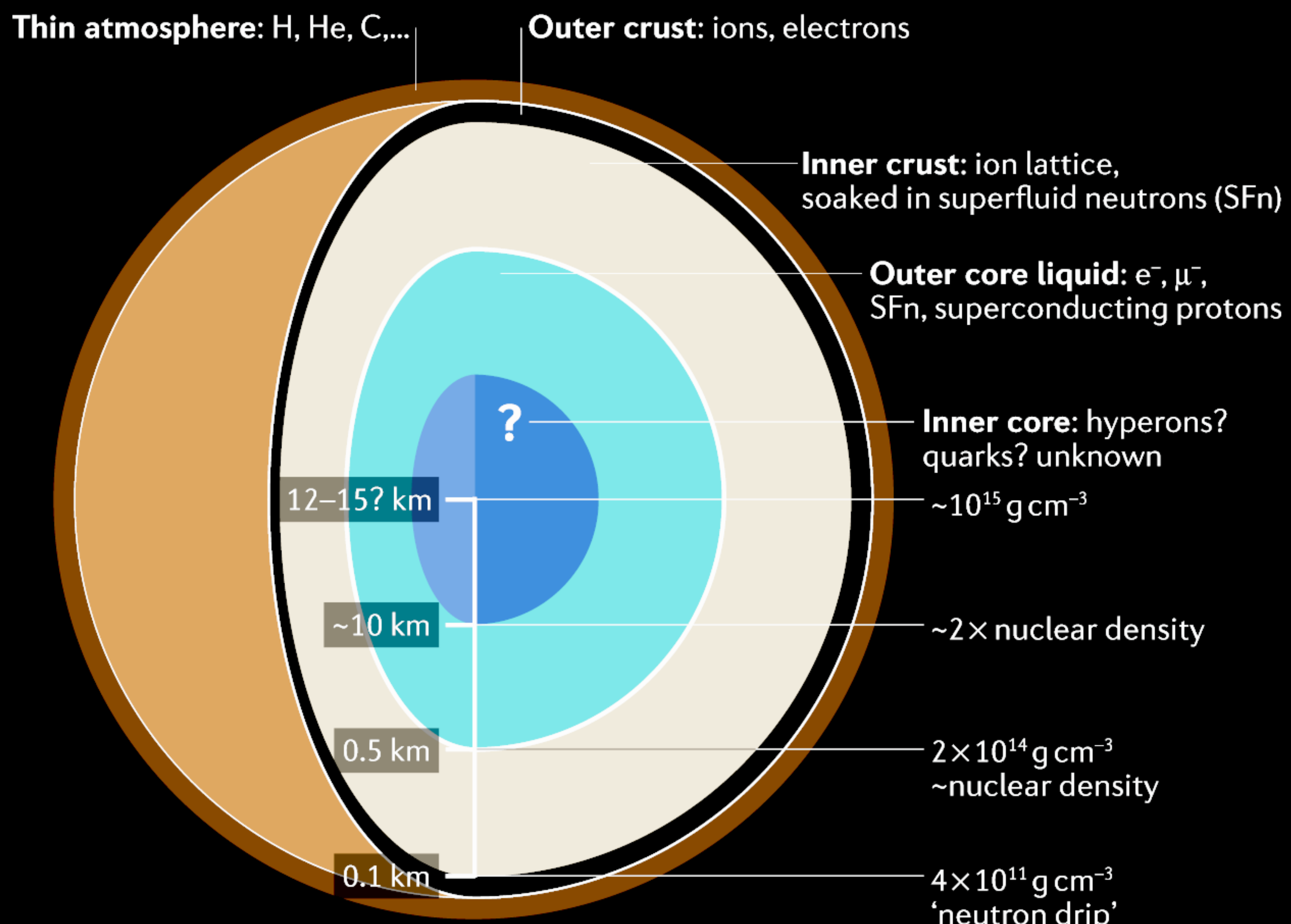


Image: Yunes, Miller, Yagi, Nature Review of Physics, arXiv:2202.04117

Nuclear physics

- BNS mergers probe the EoS of nuclear matter under extreme densities (exceeding atomic nuclei)
- Inspiral regime
  - Tidal Deformability imprints on the waveform
- Post-merger/ringdown
  - Ringdown oscillations (frequency/damping time) can tell us about nuclear EOS under extreme conditions
  - Can also show signals of the presence of a phase transition (sudden changes)

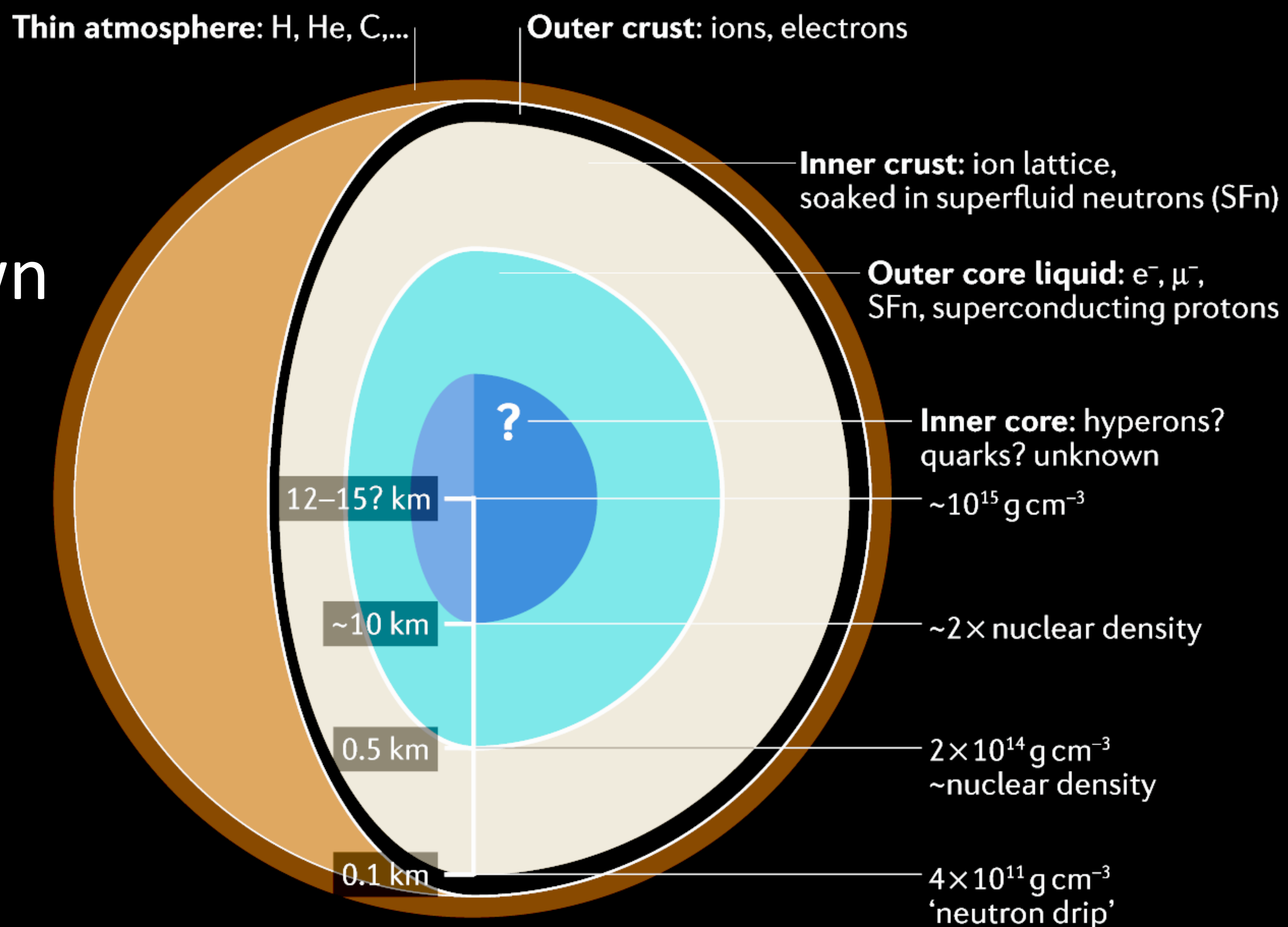
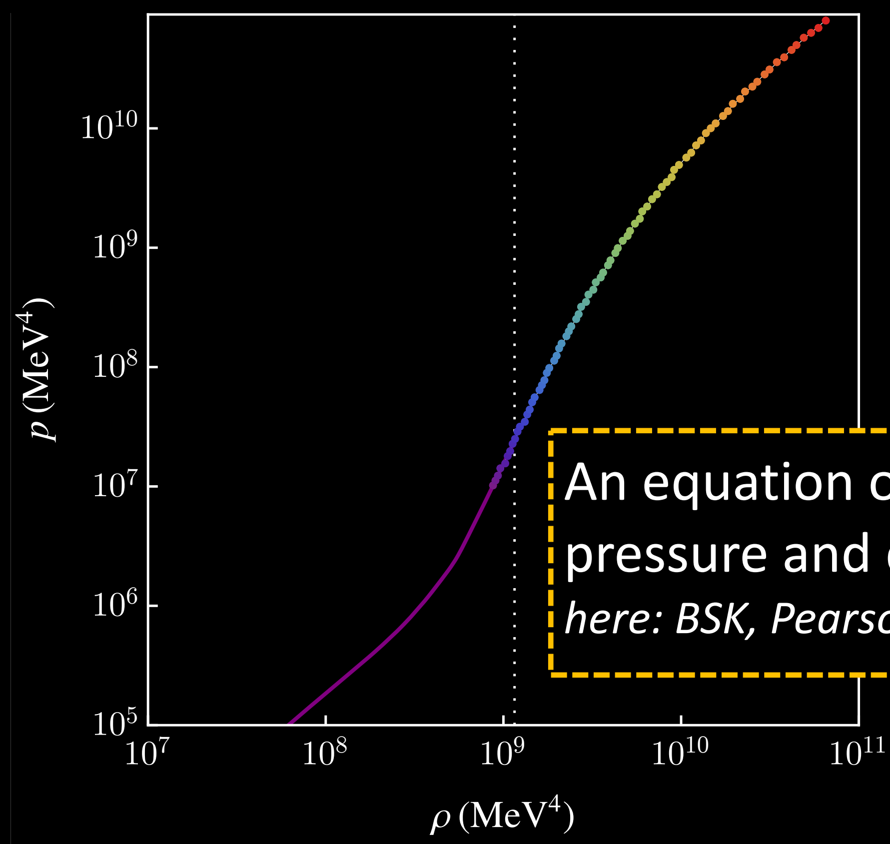


Image: Yunes, Miller, Yagi, Nature Review of Physics, arXiv:2202.04117

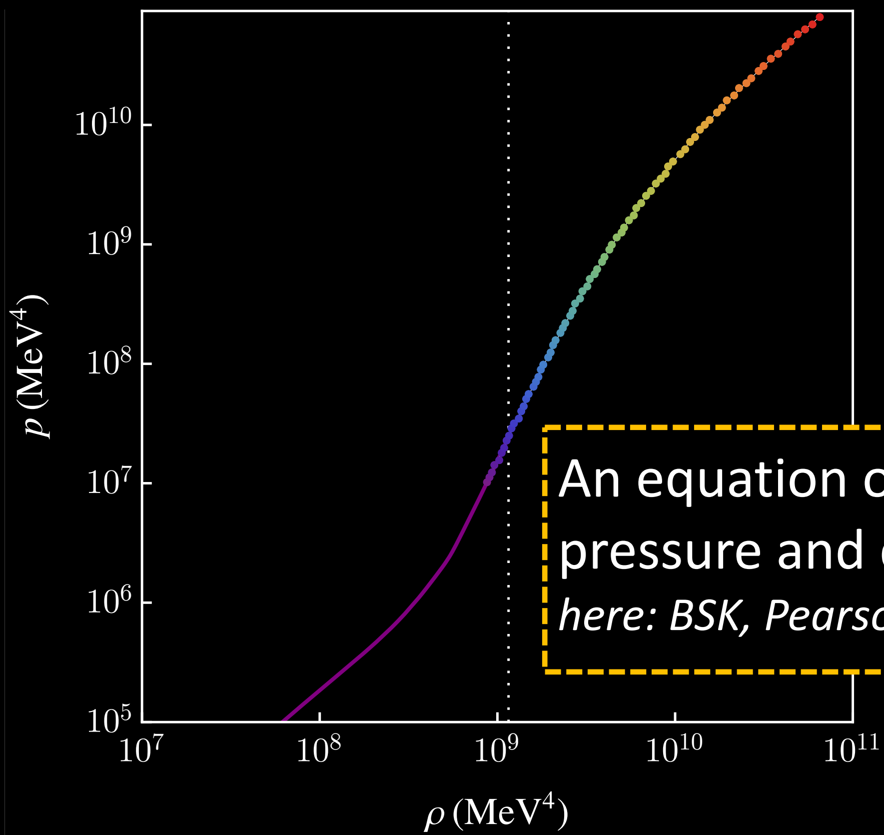
Nuclear physics



An equation of state relates pressure and density

here: BSK, Pearson et al, PRC (2020)

Nuclear physics



An equation of state relates pressure and density
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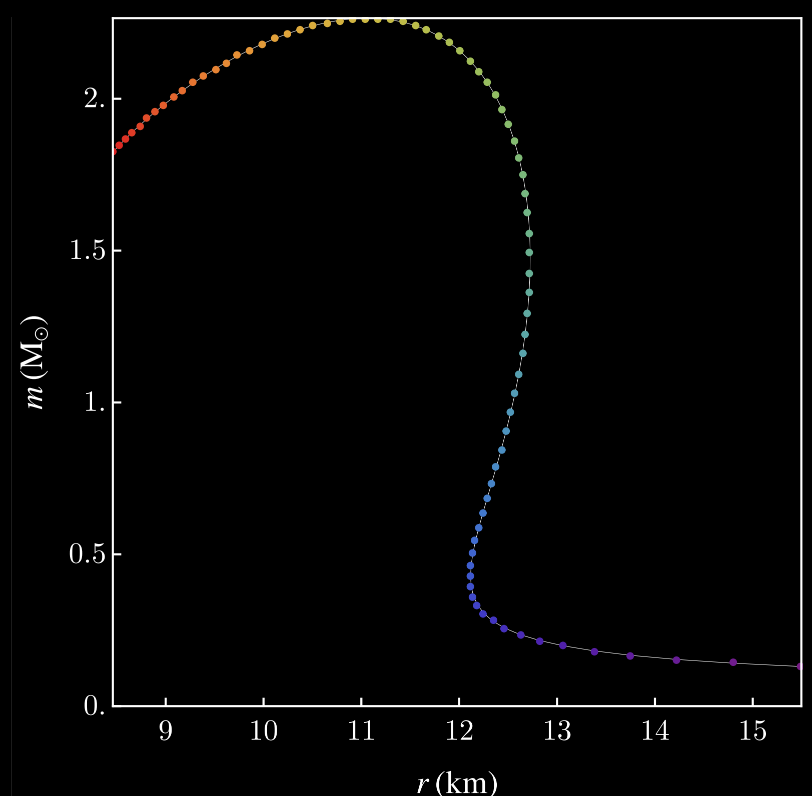
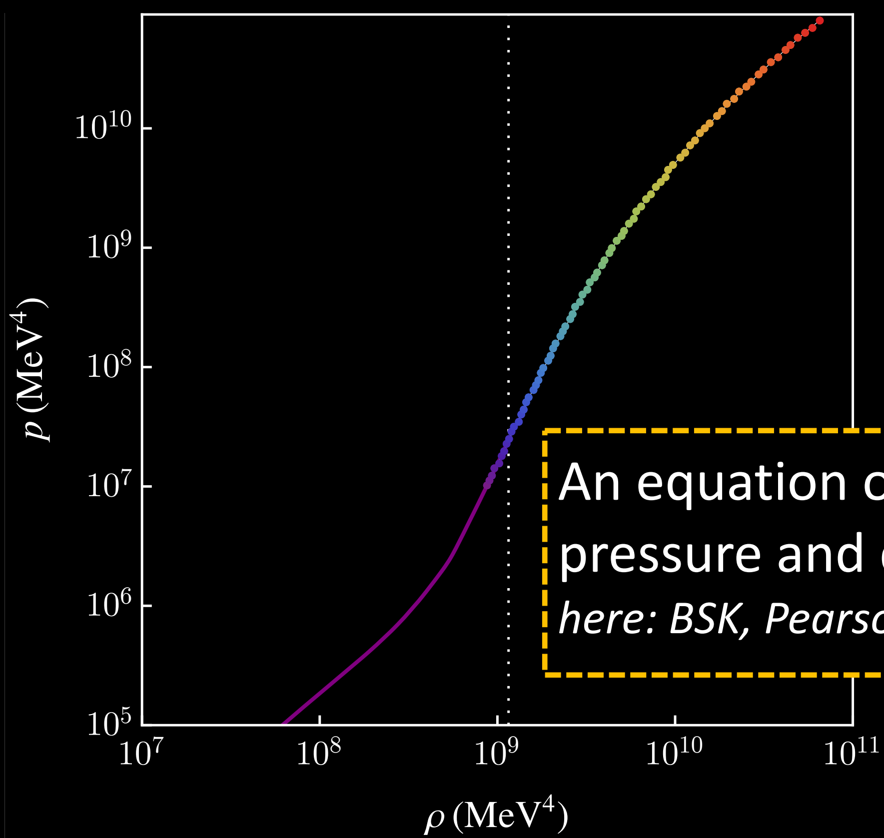
Solving the TOV equations, $m(r)$ (and $\rho(r)$) can be found



Nuclear physics



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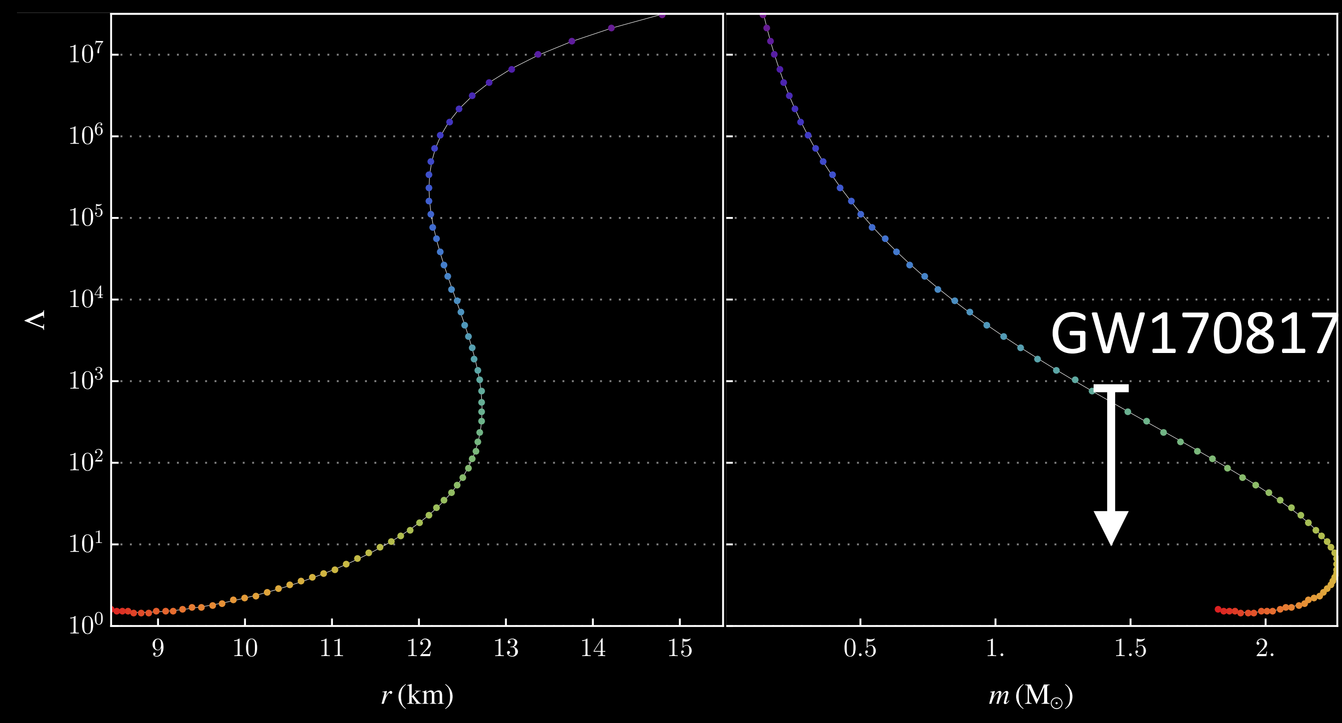

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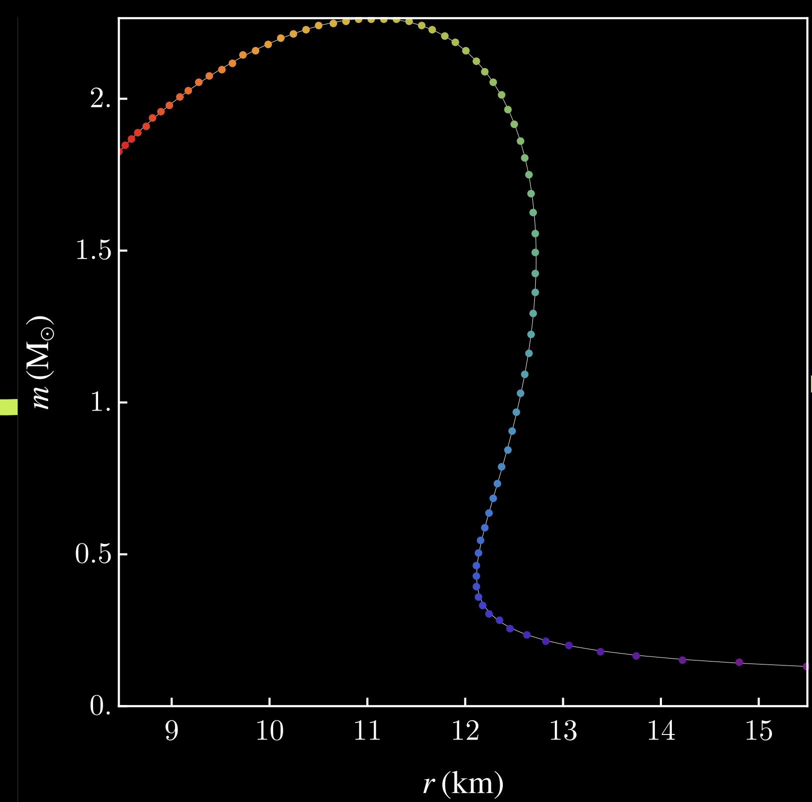


The tidal love number Λ imprints on the waveform as a phase $\delta\Psi$ at 5PN
Flanagan & Hinderer, PRD (2007)

Cosmology / expansion history

- GW amplitude depends on luminosity distance:

$$A = \frac{\tilde{M}_c}{d_L} f(\tilde{M}_c, t) \text{ where } \tilde{M}_c = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

Break the mass-distance degeneracy

Bright sirens
EM counterparts

Host galaxy redshift can be obtained from EM counterpart

Dark sirens
Galaxy catalogues

Galaxy surveys are used to provide redshift estimates

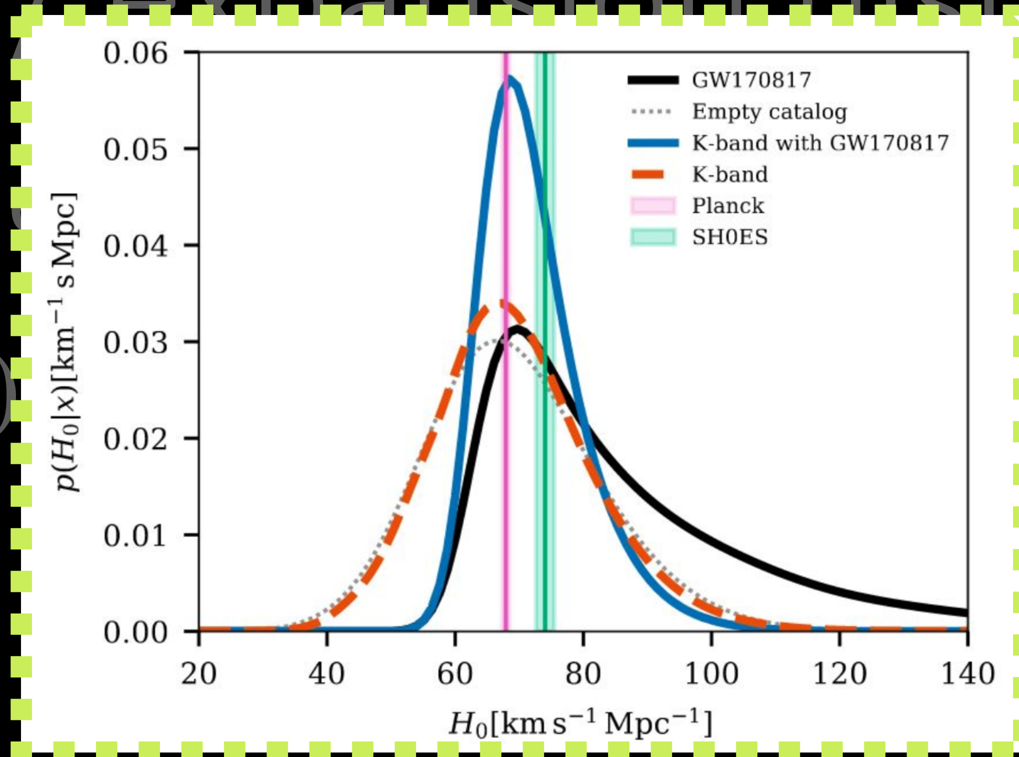
Spectral sirens
Redshifted masses

Features in the mass distribution break the mass-redshift degeneracy

Cosmology / expansion history

- GW amplitude d… ta…

$$A = \frac{\tilde{M}_c}{d_L} f(\tilde{M}_c, t) \ldots$$



However: changing population parameters leads to a significant shift in posterior

→ Cannot separate this analysis from spectral sirens

image from LVK, ApJ, arXiv:2111.03604

Bright sirens
EM counterparts

Host galaxy redshift can be obtained from EM counterpart

Dark sirens
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Spectral sirens
Redshifted masses

Features in the mass distribution break the mass-redshift degeneracy

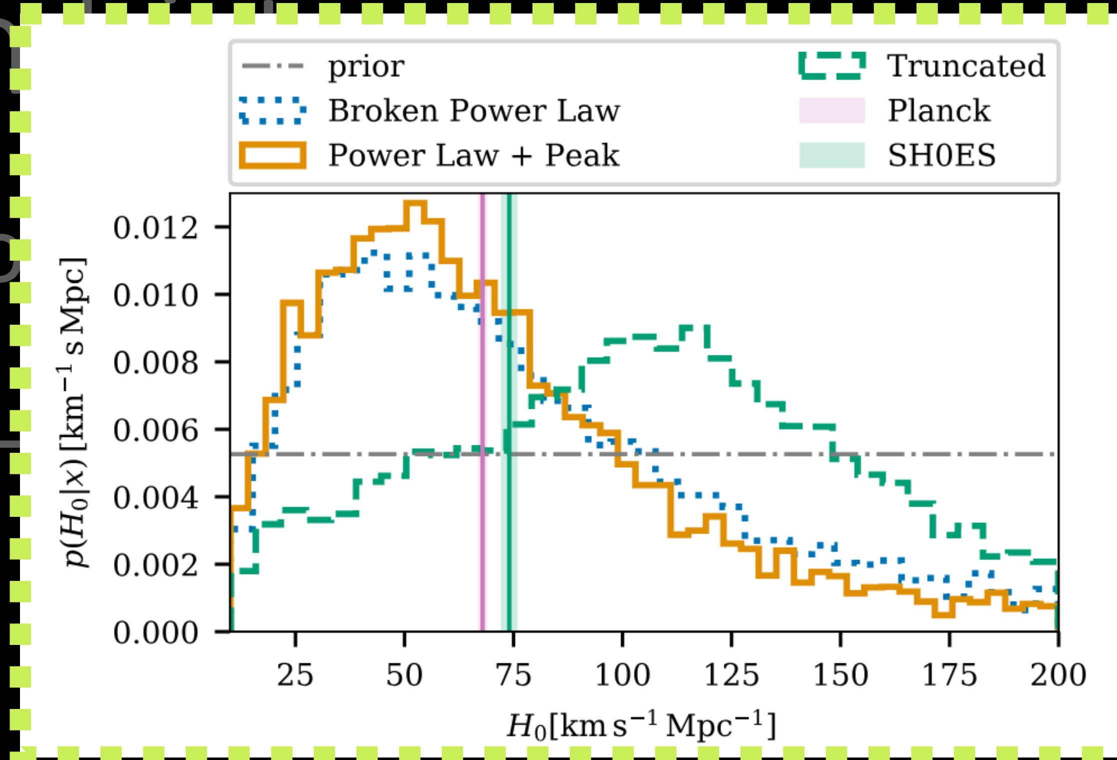
Cosmology / expansion

- GW amplitude depends on lumino

$$A = \frac{\tilde{M}_c}{d_L}$$

(Very) sensitive to assumed population model(shown in numerous other works)

image from LVK, ApJ, arXiv:2111.03604



Bright sirens
EM counterparts

Host galaxy redshift can be obtained from EM counterpart

Dark sirens
Galaxy catalogues

Galaxy surveys are used to provide redshift estimates

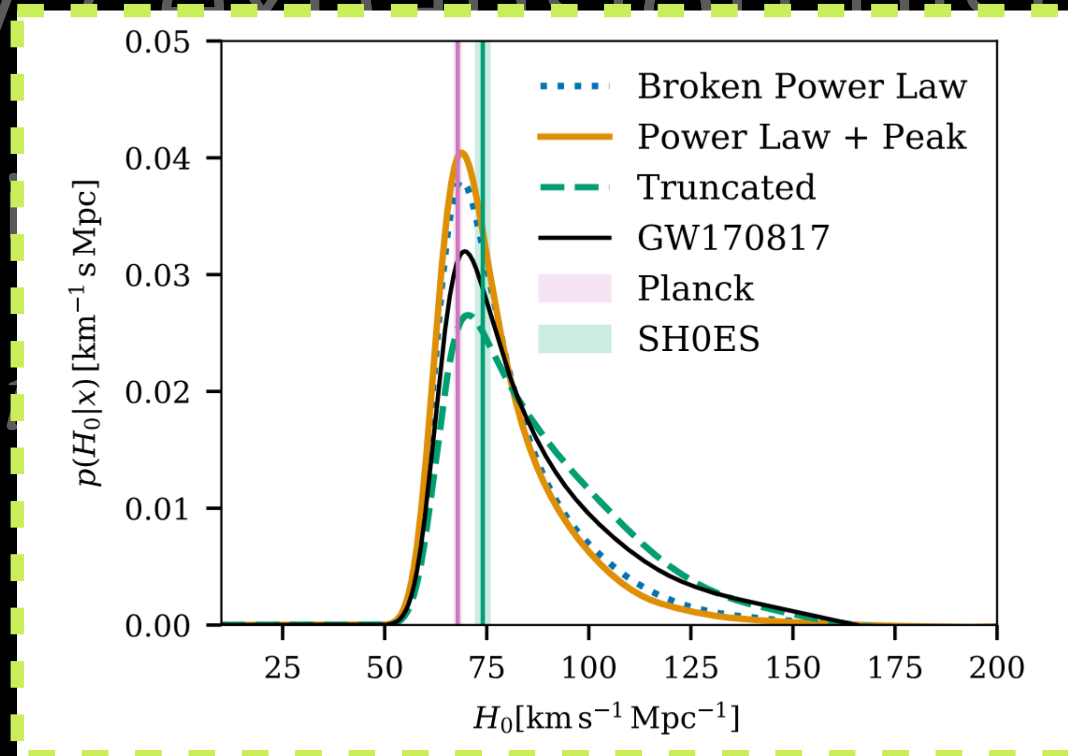
Spectral sirens
Redshifted masses

Features in the mass distribution break the mass-redshift degeneracy

Cosmology / expansion history

- GW amplitude

$$A = \frac{\tilde{M}_c}{d_L} f(\tilde{M}_c,$$



Spectral sirens + bright siren GW170817

image from LVK, ApJ, arXiv:2111.03604

Bright sirens
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Spectral sirens
Redshifted masses

Features in the mass distribution break the mass-redshift degeneracy

Early Universe physics

- Inflation

- First order phase transitions

- Cosmic strings

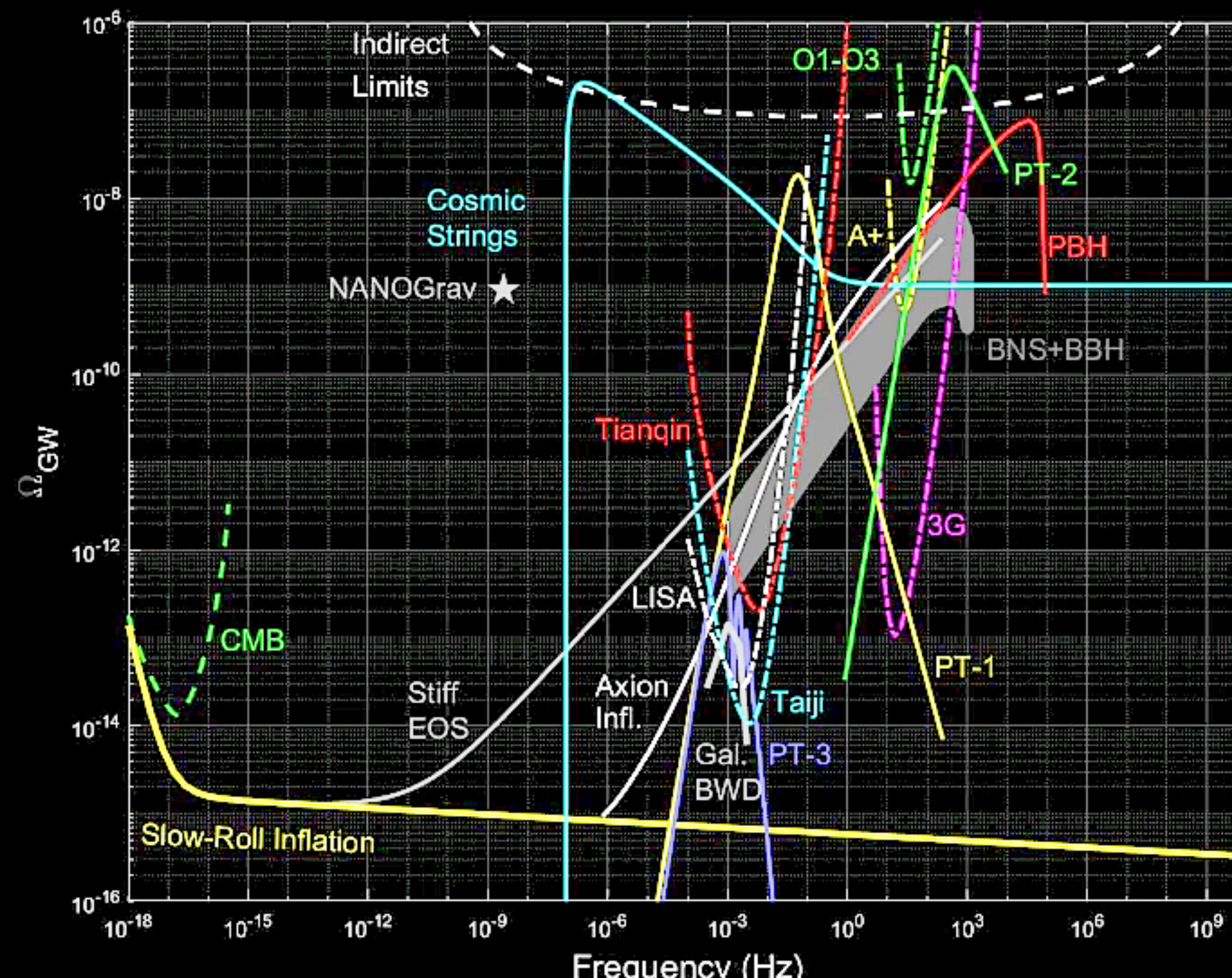
… among other mechanisms

Early Universe physics

- Inflation
  - Imprint as B- modes on the CMB, $f \sim 10^{-16}\,\mathrm{Hz}$
  - GW experiments are only competitive with current CMB constraints for blue-shifted spectra
  - Such spectra may occur in non-standard scenarios
  - Examples are nonlinear (p)reheating dynamics, features in the inflation potential, non-standard cosmologies…

- First order phase transitions
- Cosmic strings

$$\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

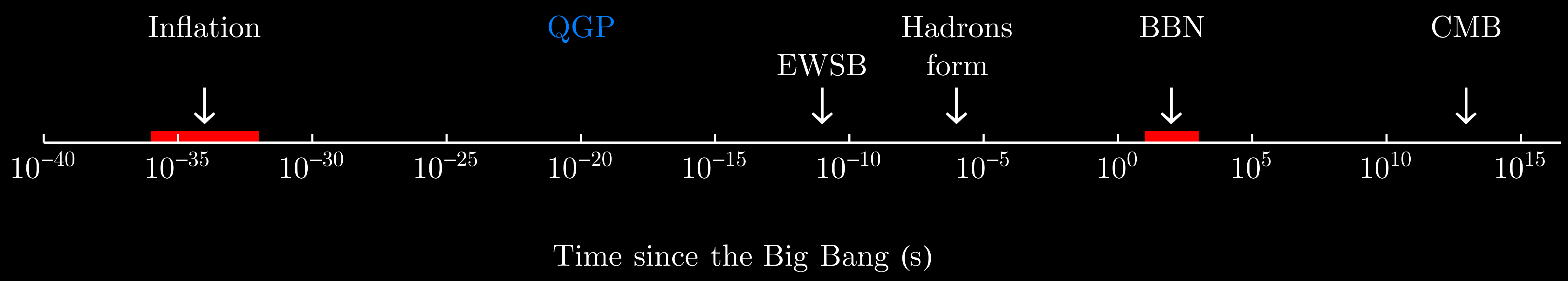


… among other mechanisms

Image from Caldwell et al, GR and gravitation, arXiv:2203.07972

Early Universe physics

Our cosmic timeline



Early Universe physics

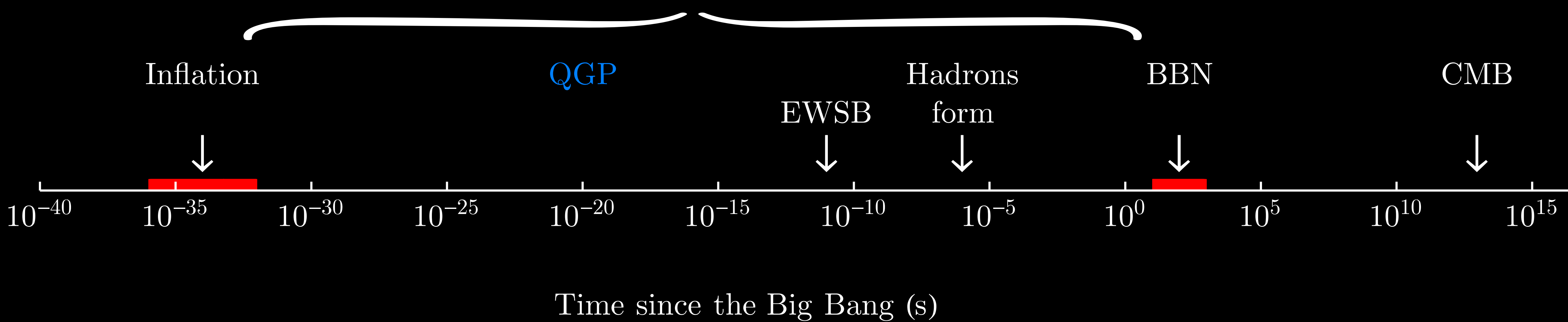
Our cosmic timeline

Grand Unification of gauge forces?

Dark Matter production, mass mechanism, and abundance?

Solution to the strong-CP problem?

Explanation of the matter-antimatter asymmetry?



Early Universe physics

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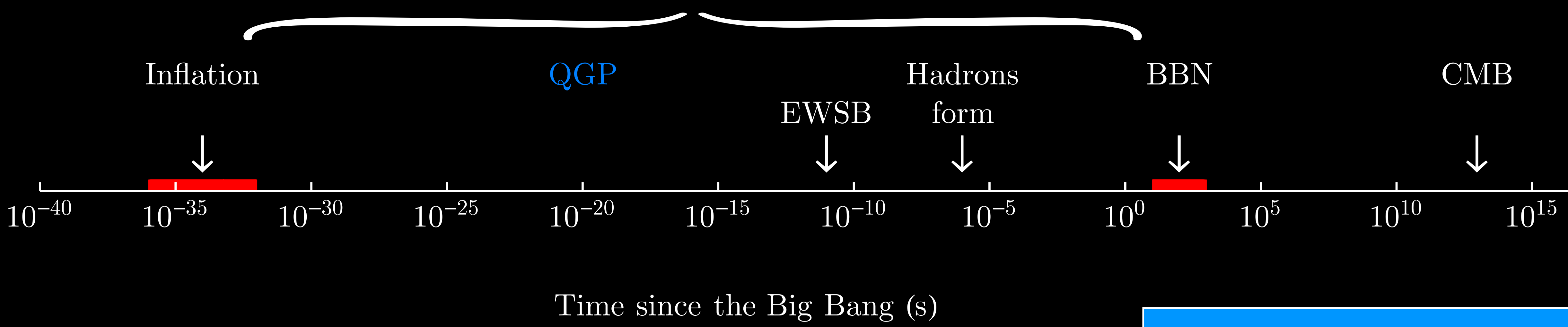


Before recombination, the Universe was opaque to photons

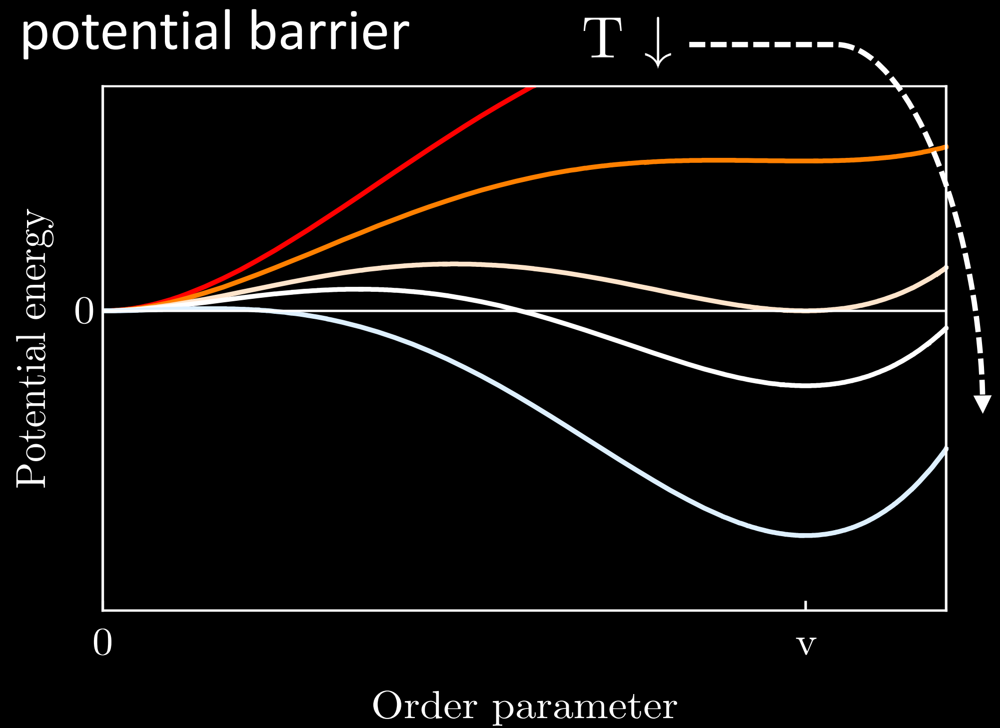
The CMB photons currently constitute our earliest *direct* cosmological probe

Gravitational radiation released in the early Universe travels (nearly) unimpeded until today

Early Universe physics

First order phase transitions

First order phase transitions are described by tunnelling through a potential barrier



Early Universe physics

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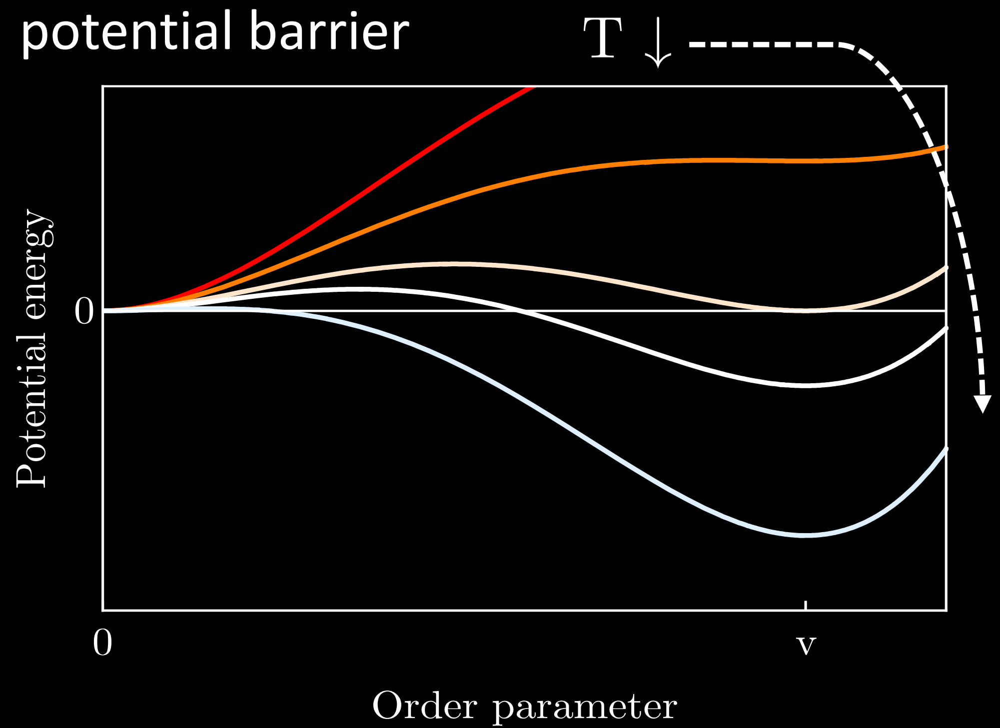
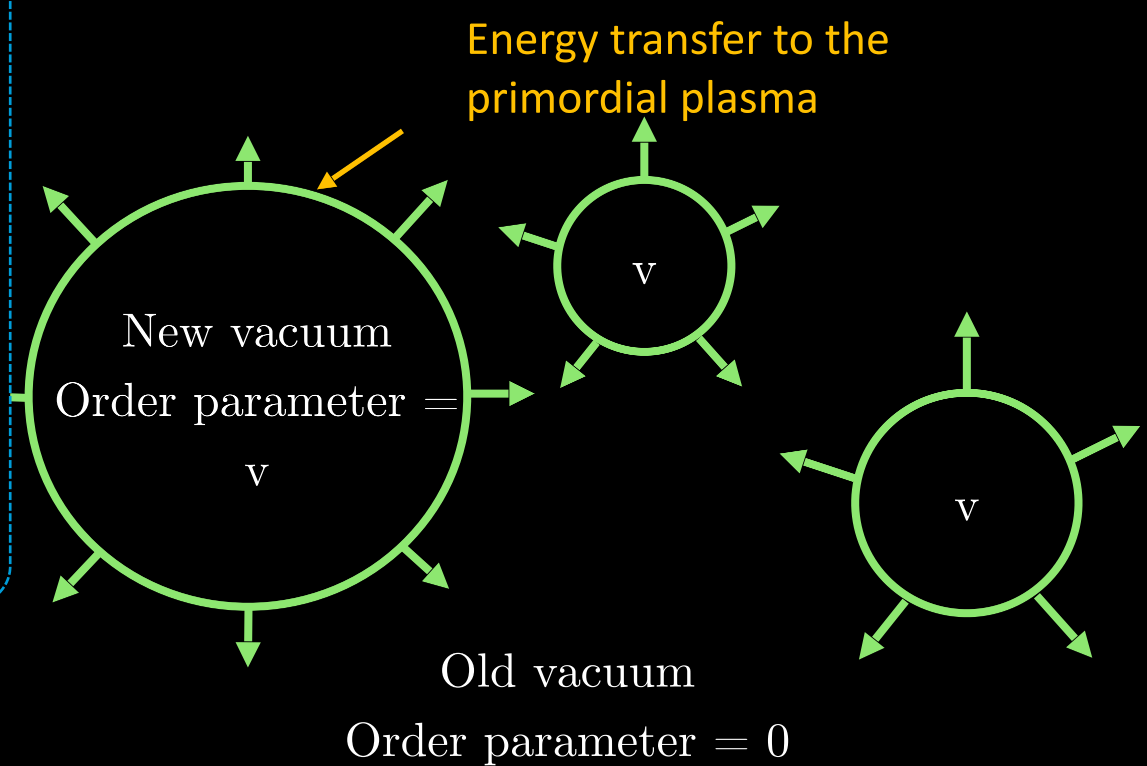


Bubbles nucleate, expand, and interact with the plasma; Bubble and plasma shell collisions source GWs



Early Universe physics

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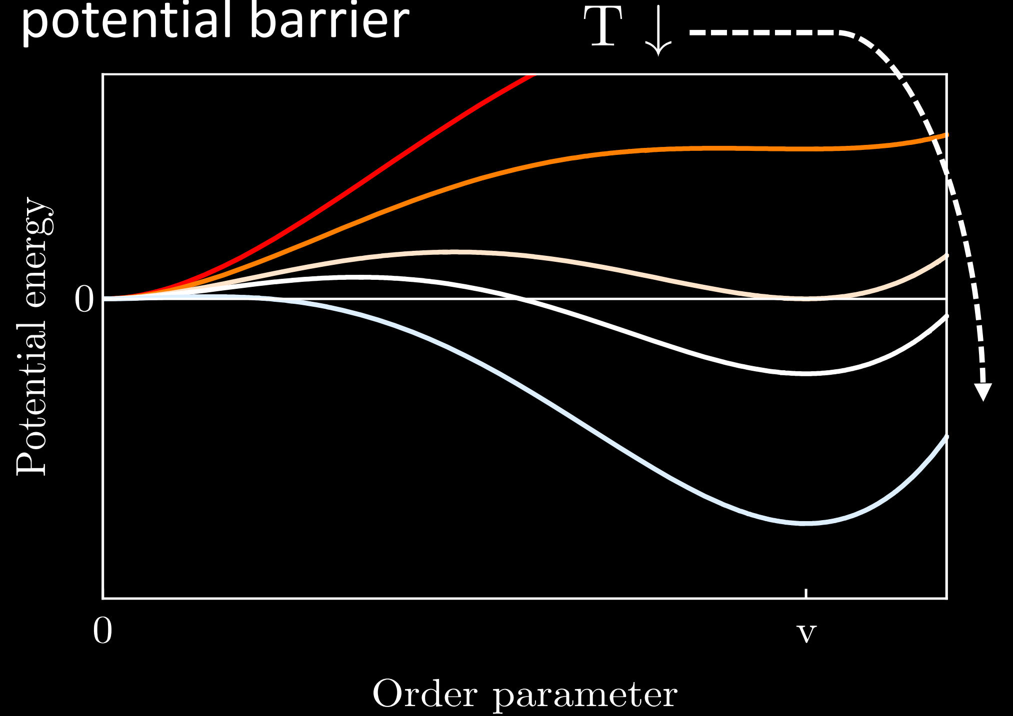

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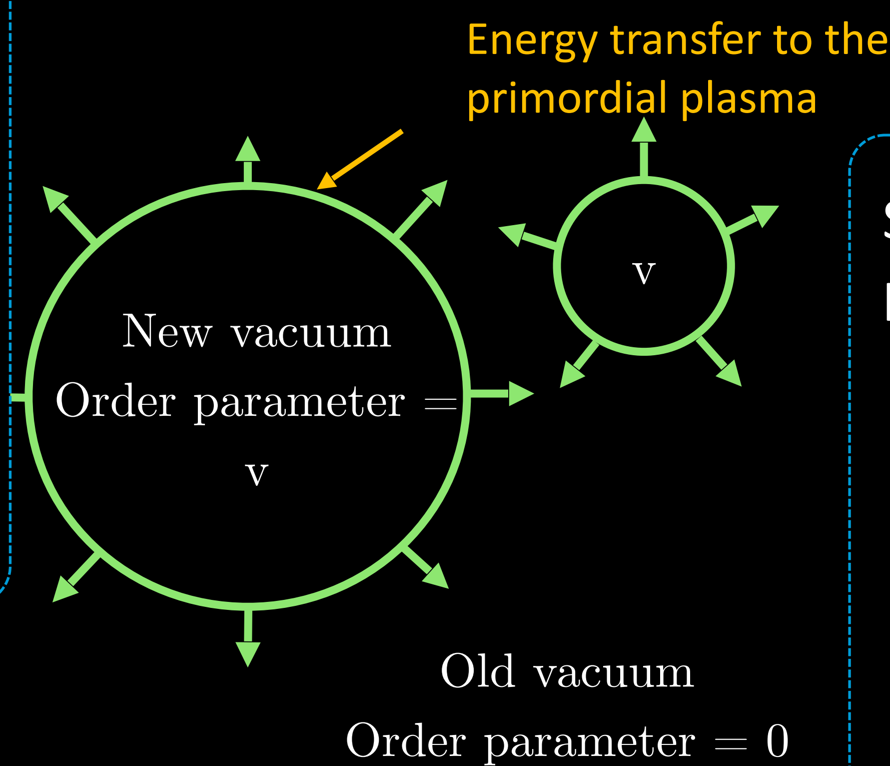


Simulations relate thermal parameters to GW spectra

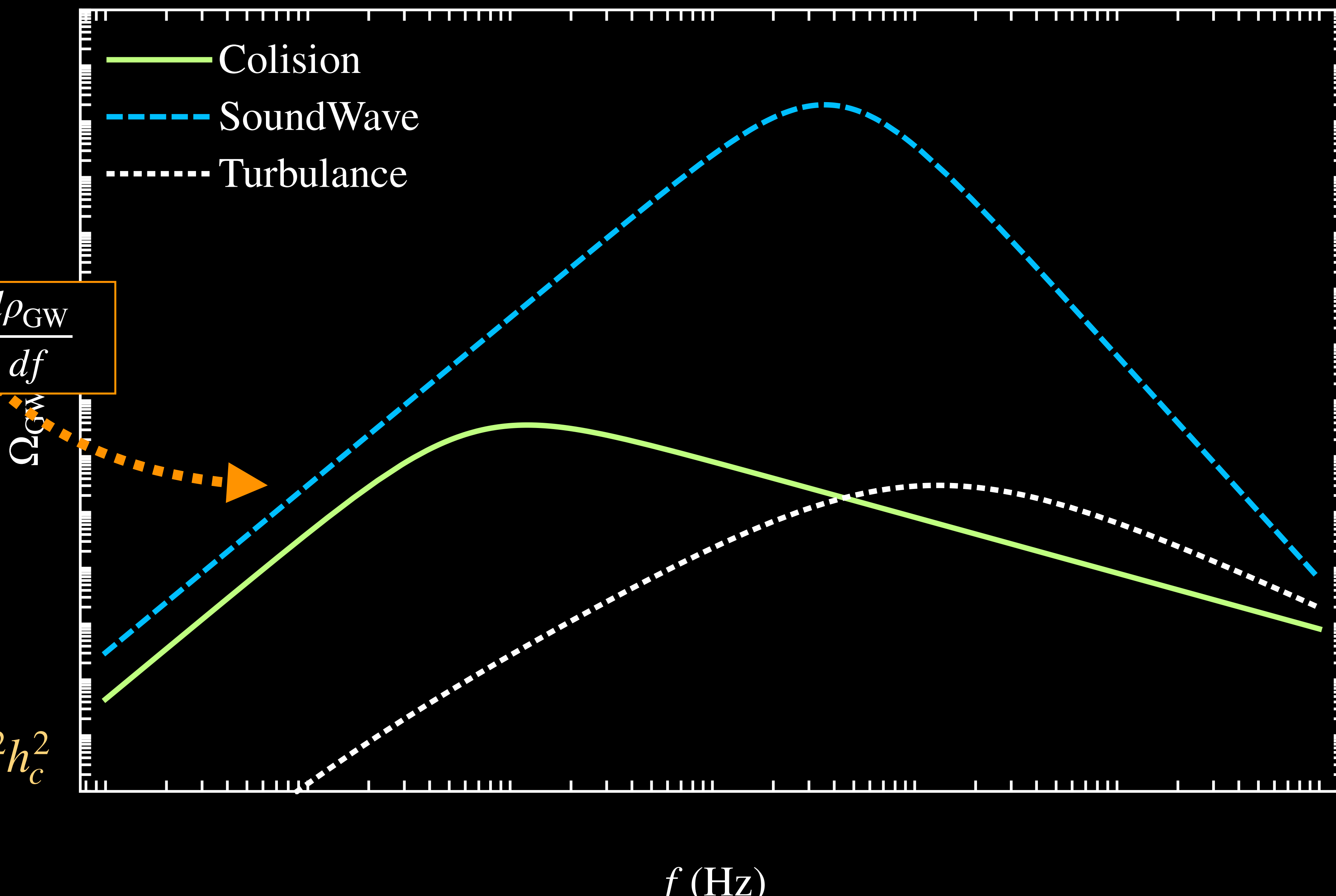
Snapshot from simulation: Daniel Cutting, private communication

Early Universe physics

Phase transitions and GW spectra

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$

$$\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

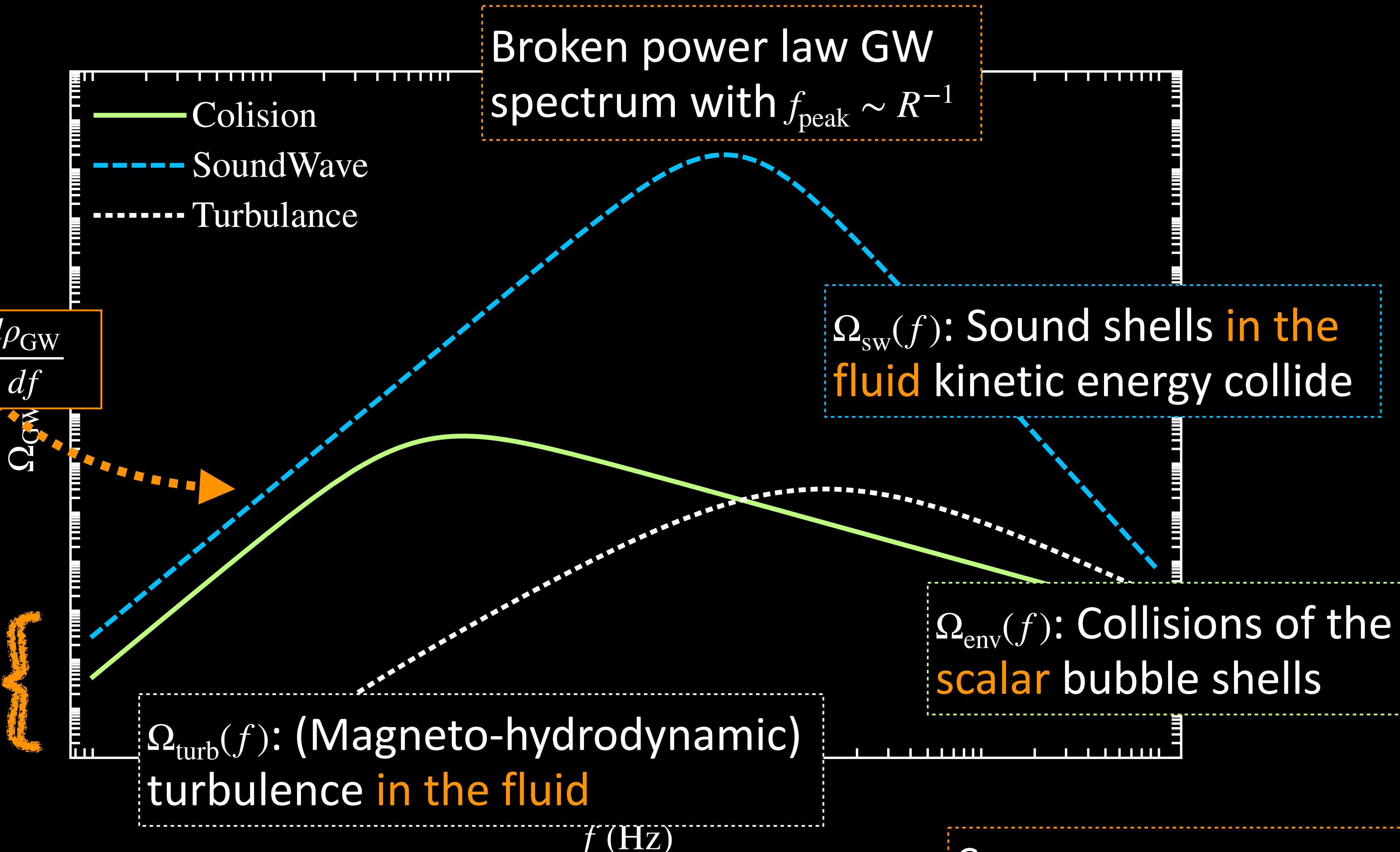


Early Universe physics

Phase transitions and GW spectra

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$

$\propto f^3$

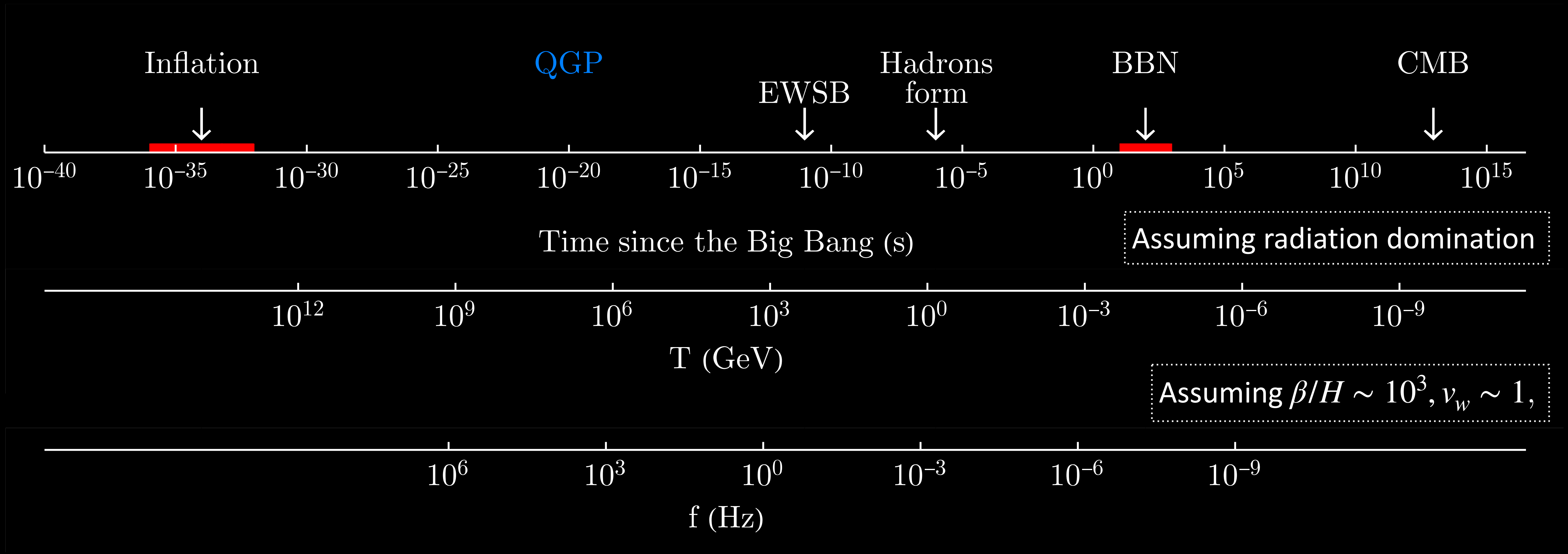


Compare:

- Binary inspirals $\Omega \sim f^{2/3}$
- Cosmic strings $\Omega \sim f^0$

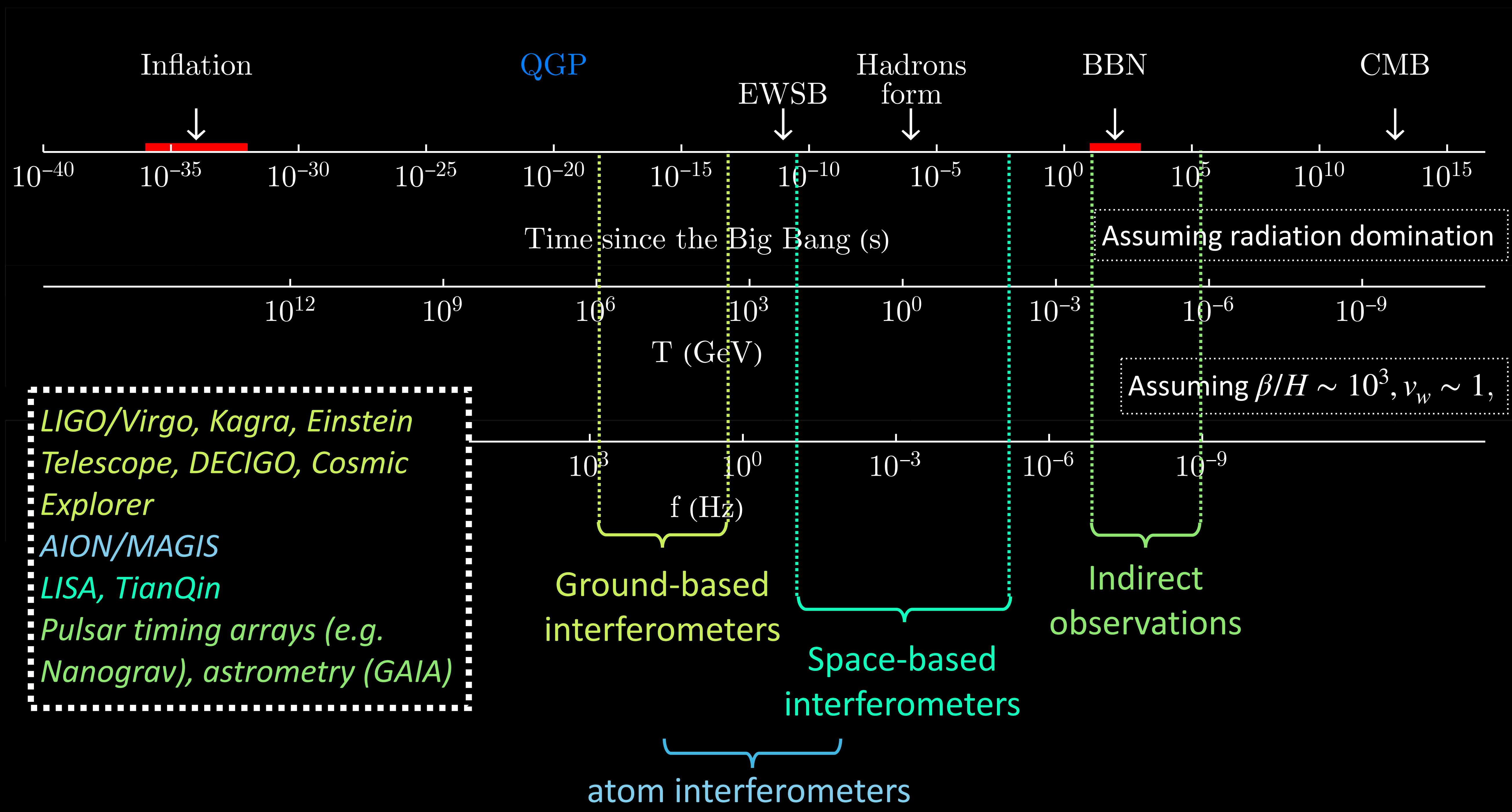
Early Universe physics

Phase transitions and our cosmic timeline



Early Universe physics

Phase transitions and our cosmic timeline



Early Universe physics

Cosmic strings

- 1d defects formed during phase transitions
  - Extremely thin (about a proton width), very long
  - Large mass per unit length (tension μ)

Early Universe physics

Cosmic strings

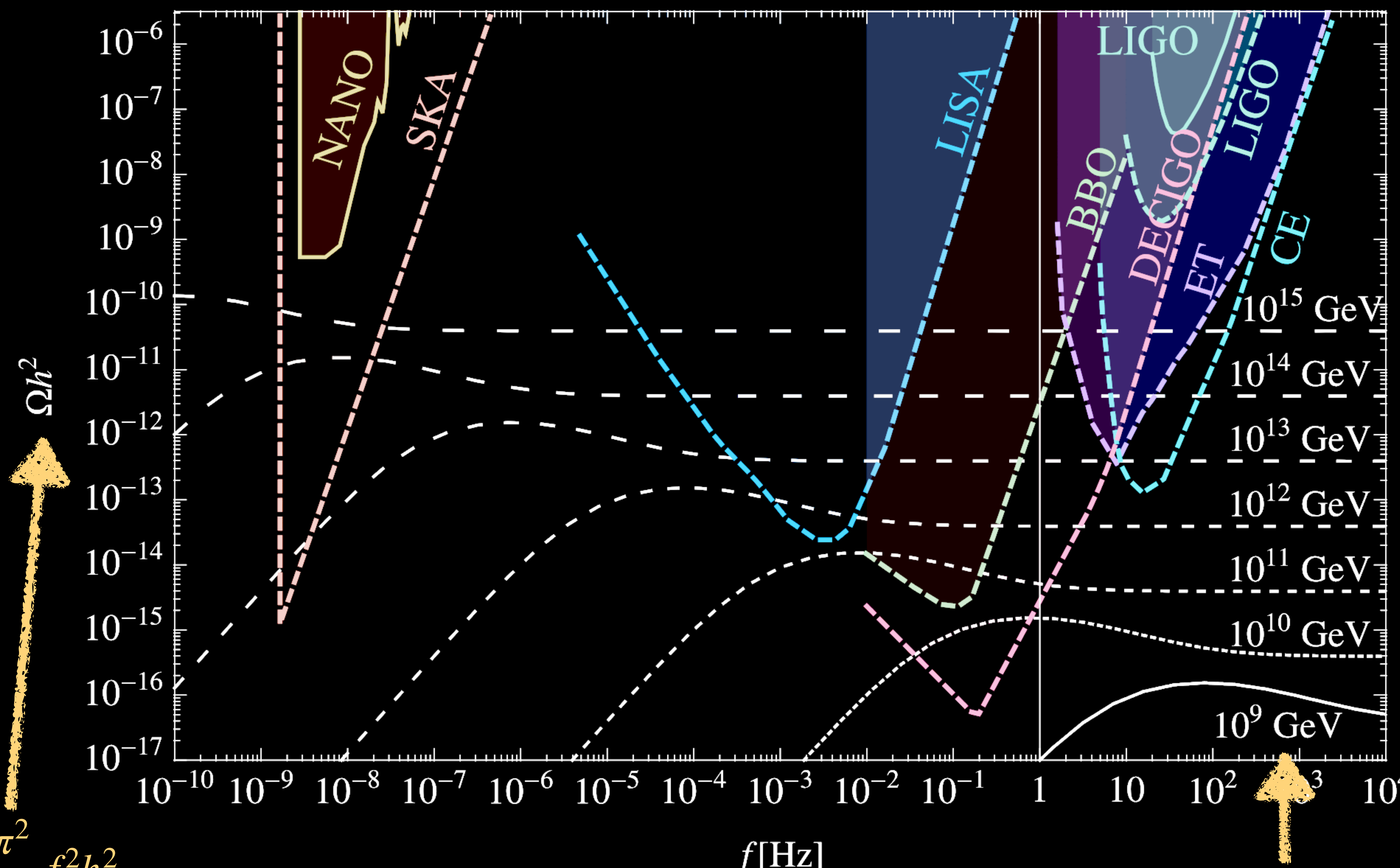
- 1d defects formed during phase transitions
  - Extremely thin (about a proton width), very long
  - Large mass per unit length (tension μ)

- Must lose energy
  - Energy density redshifts as $\rho / a^2 \rightarrow$ would lead to cosmic string domination
  - Emit GW through dynamics such as loop formation, cusps, and kinks
  - Typically reach a scaling solution where the number of long strings and loops remains proportional to the volume of the universe.

- SGWB depends primarily on the string tension $G\mu$

Early Universe physics

Cosmic strings

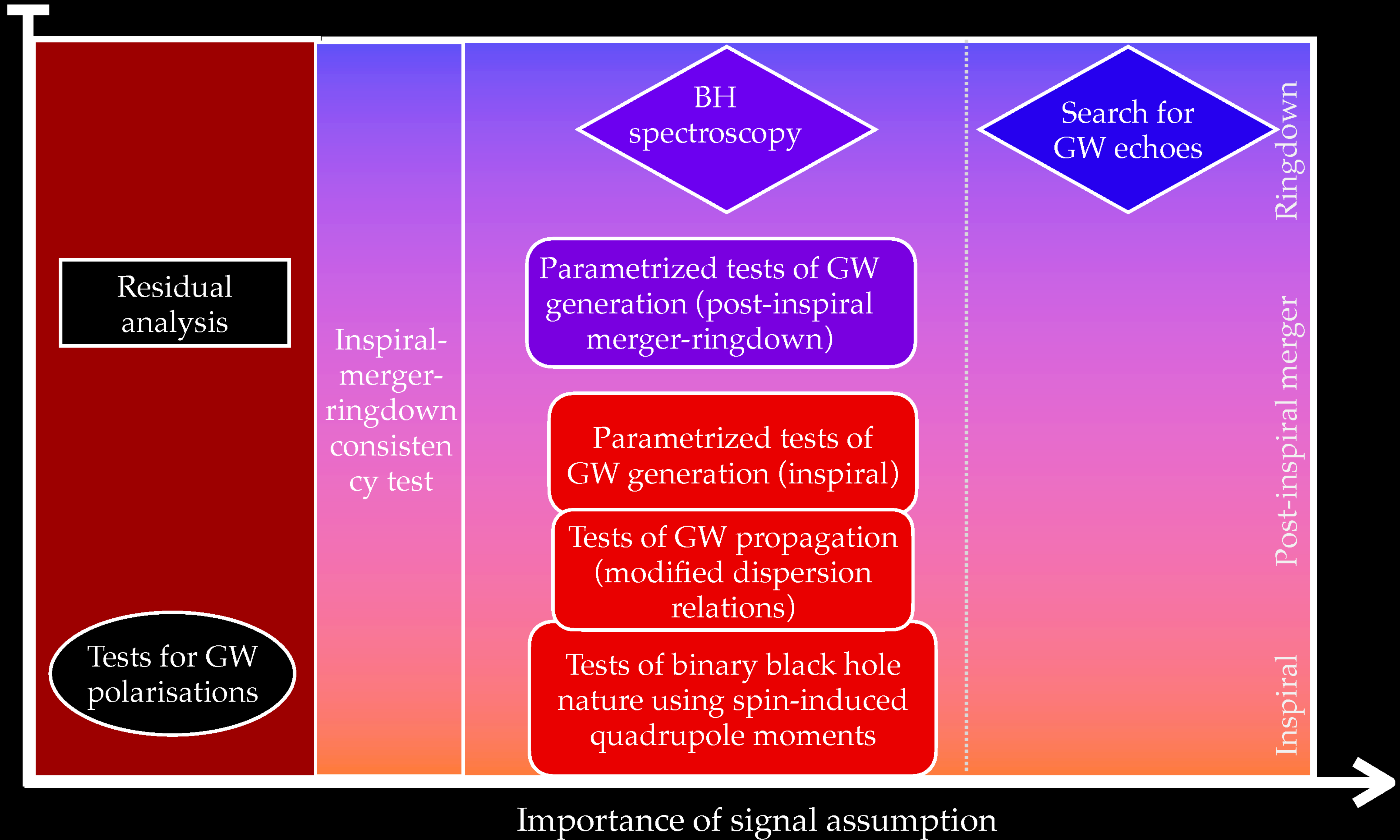


$$\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

$$\mu^2 = \Lambda$$

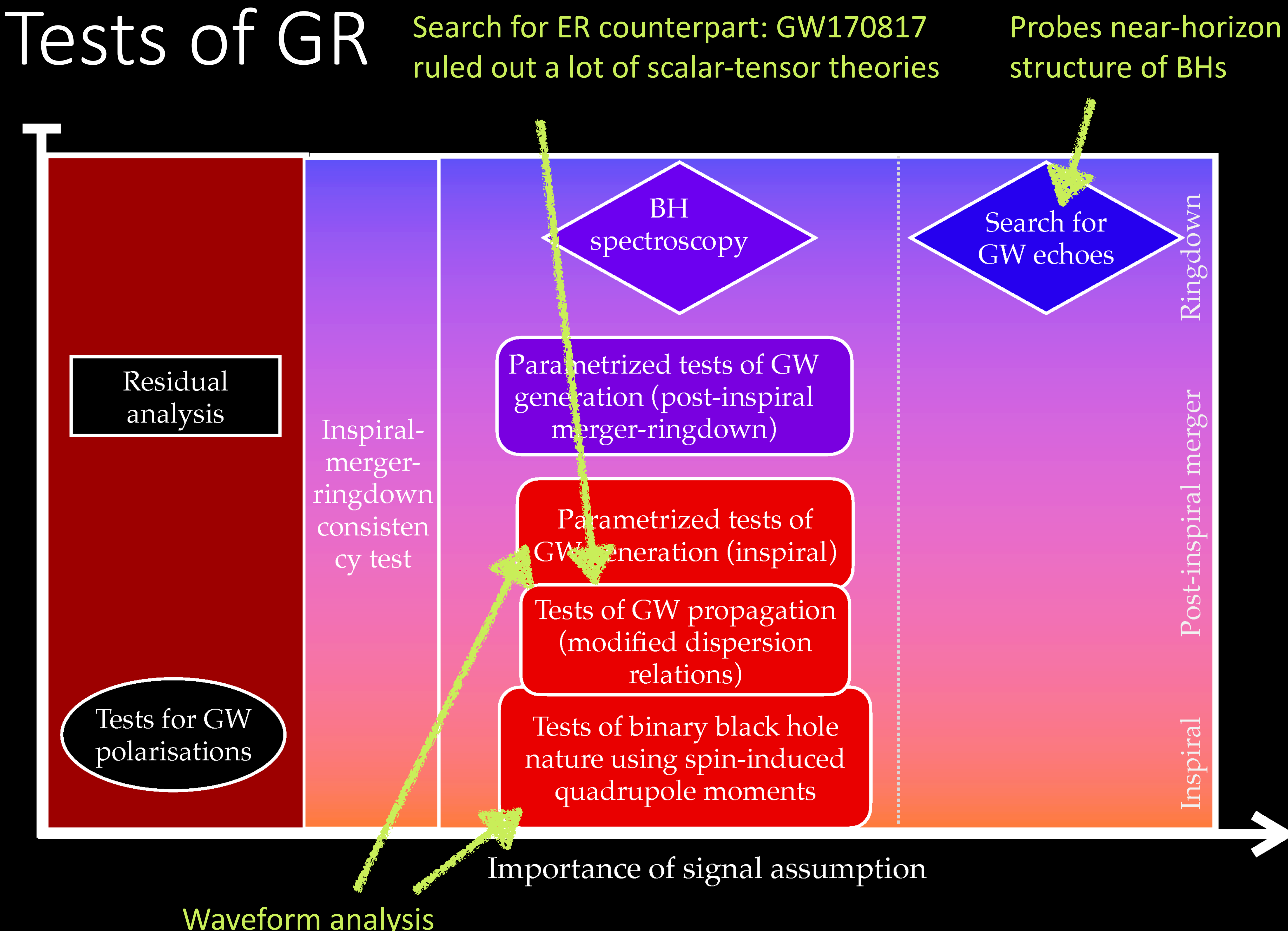
Image from Dror, Hiramatsu, Kori, Murayama, White, PRL, arXiv:1908.03227

Tests of GR



Ohme and Krishnendu, Universe, arXiv:2201.05418

Tests of GR

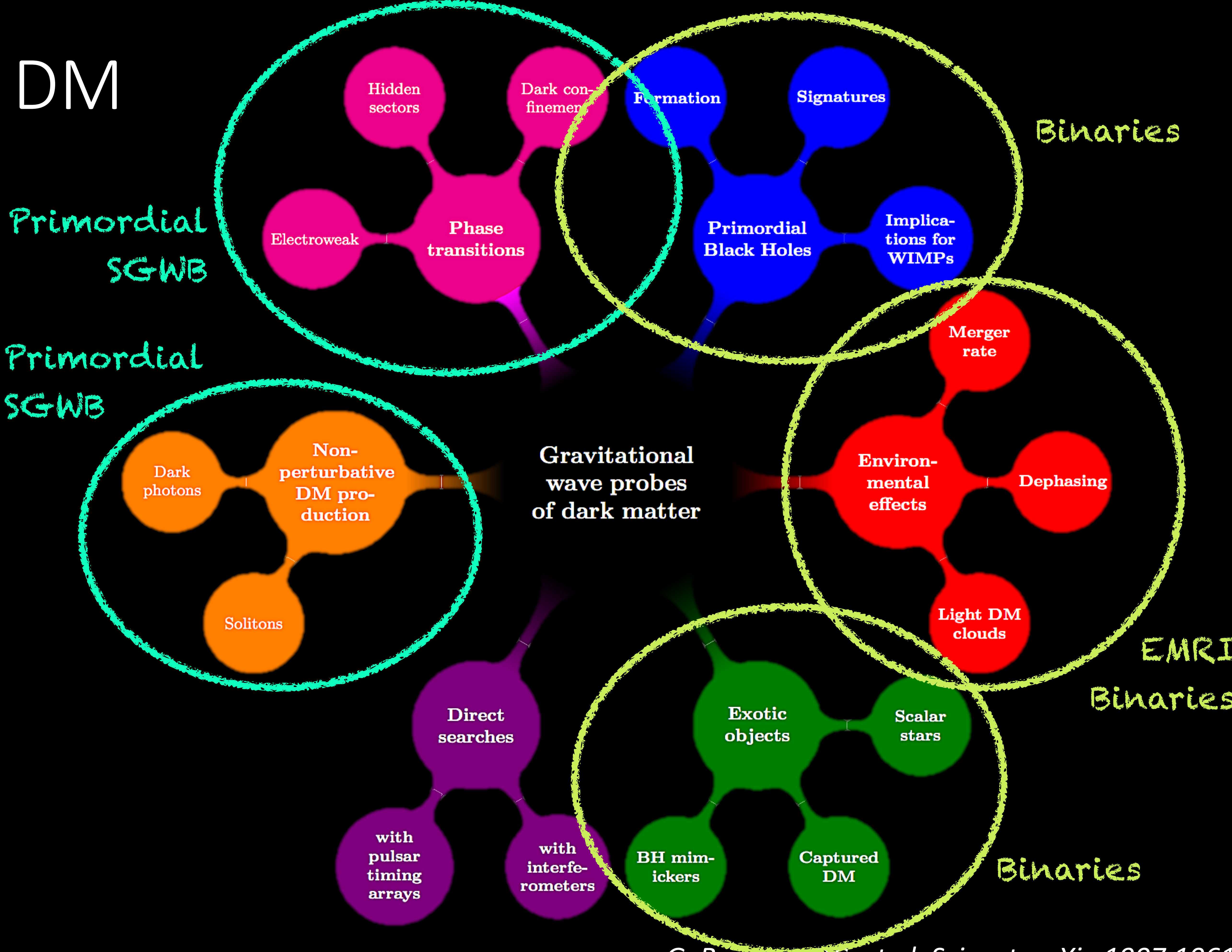


Ohme and Krishnendu, Universe, arXiv:2201.05418

DM

G. Bertone, DC, et al. Scipost, arXiv:1907.10610

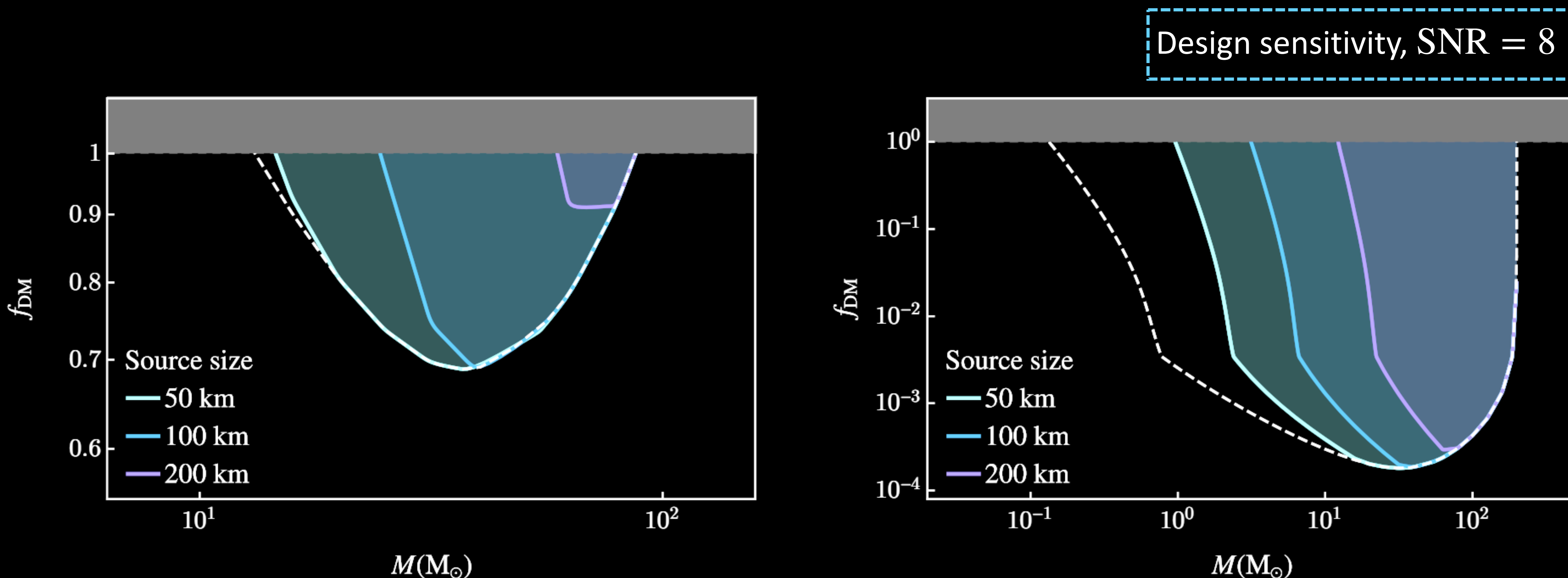
DM



G. Bertone, DC, et al. Scipost, arXiv:1907.10610

Dark binary observation with LVK

...Very sensitive to the assumed formation mechanism



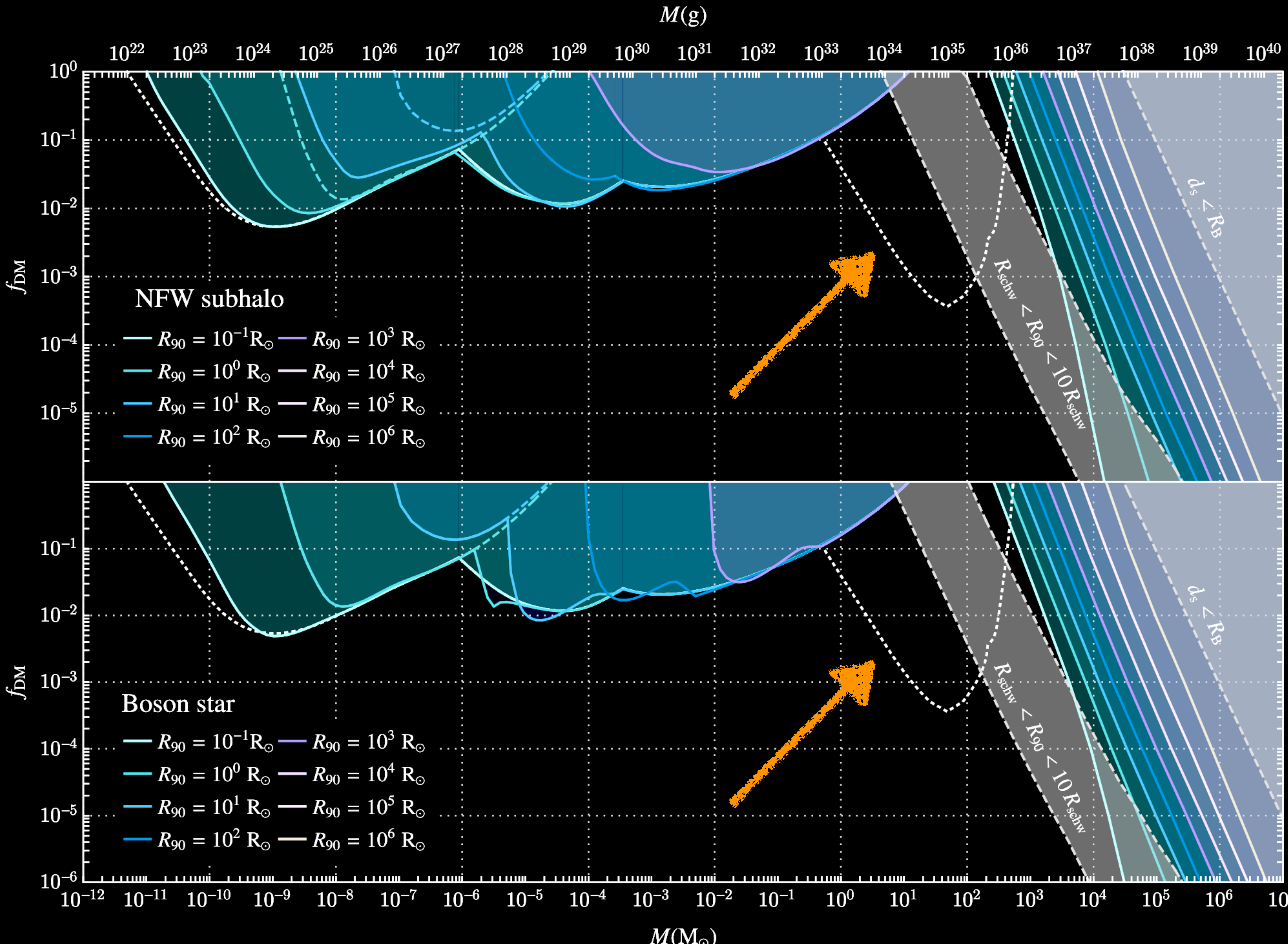
Late Universe formation (optimistic estimate)

S. Bird et al., PRL, arXiv:1603.00464

Early universe formation

Jedamzik, JCAP, arXiv:2006.11172
Vaskonen Veermae, PRD, arXiv:1908.09752.
Hutsi, Raidal, Vaskonen, Veermae, JCAP, arXiv:2012.02786

See also Giudice, McCullough, Urbano, JCAP, arXiv:1605.01209



Complementary to other constraints on dark objects

DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962,
DC, D. McKeen, N. Raj, Z. Wang, PRD, arXiv:2007.12697,
DC, Sevillano Muñoz arXiv:2403.13072

To conclude

- Currently running and future experiments will probe GW across many decades in frequency
  - Ground-based interferometers probe $1 - 10^3\,\mathrm{Hz}$
  - Space-based interferometers will probe $10^{-6} - 10^{-1}\,\mathrm{Hz}$
  - Pulsar-timing arrays probe $10^{-9} - 10^{-7}\,\mathrm{Hz}$
  - Further proposals include atom interferometry, lunar lensing, astrometry…

- This brings great opportunities in astrophysics, nuclear physics, and particle physics

- Not mentioned: other GW detection proposals in the nano-mHz band, detecting high frequency GW, superradiance, …

Thank you!

…ask me anything you like!

djuna.l.croon@durham.ac.uk | djunacroon.com