CERN Baltic conference
Tallinn 2024

Gravitational Waves

as the key to the Dark Sector

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October 16, 2024

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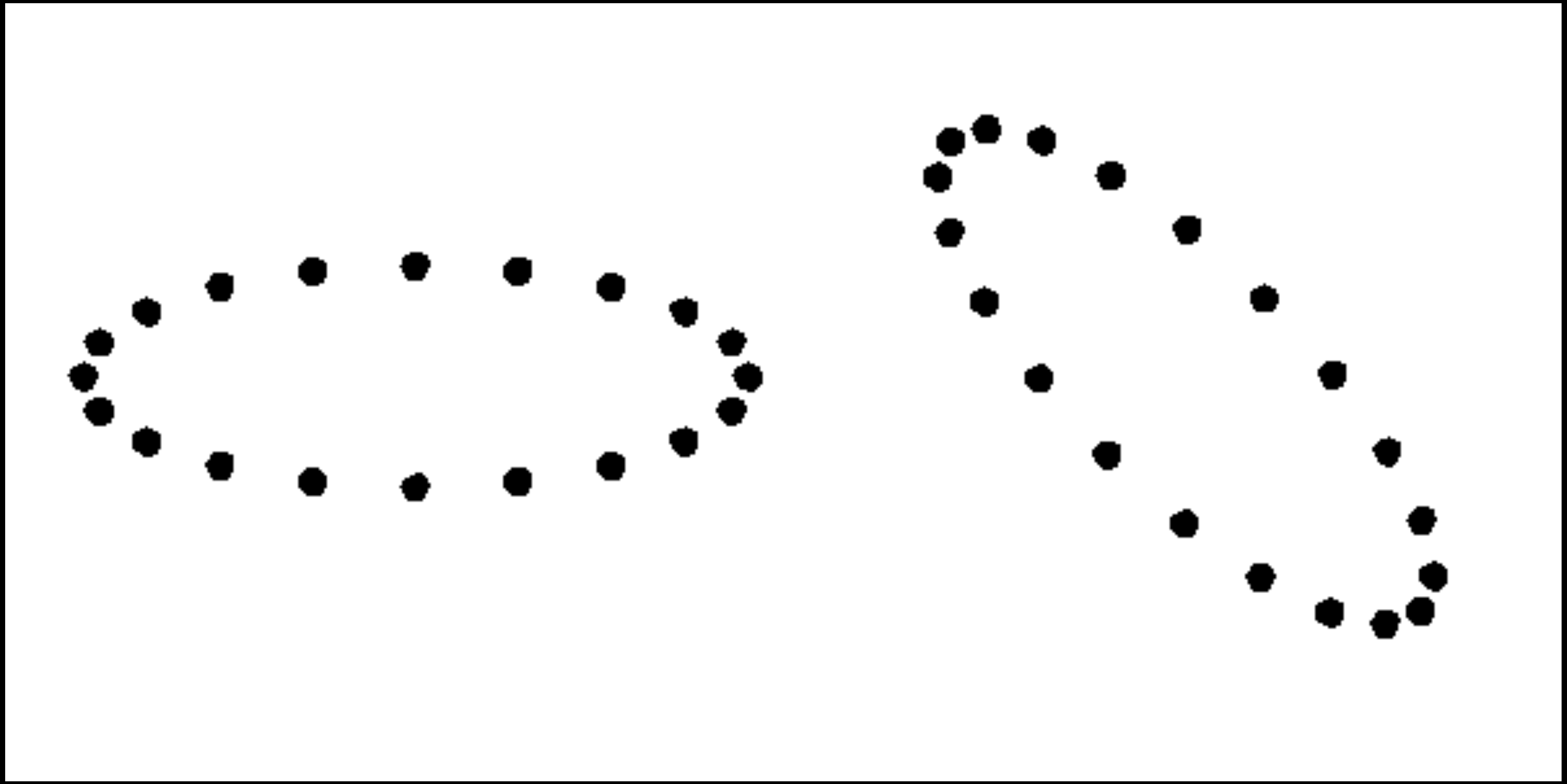
GRAVITATIONAL WAVES

how to detect gravitational waves?



two polarization states:

+
polarization

x
polarization

how to detect gravitational waves?

GRAVITATIONAL WAVES MODULATE LEG LENGTHS

$$\Delta L = \Delta L_x - \Delta L_y = h_+ L_0 cos(\omega t)$$

gravitational wave amplitude: $h \approx 10^{-22}$

leg length: $L = 4km$

↓

leg length fluctuation: $\Delta L \approx 4 \times 10^{-4}\,\mathrm{fm}$

*proton radius $\approx 0.8\,\mathrm{fm}$

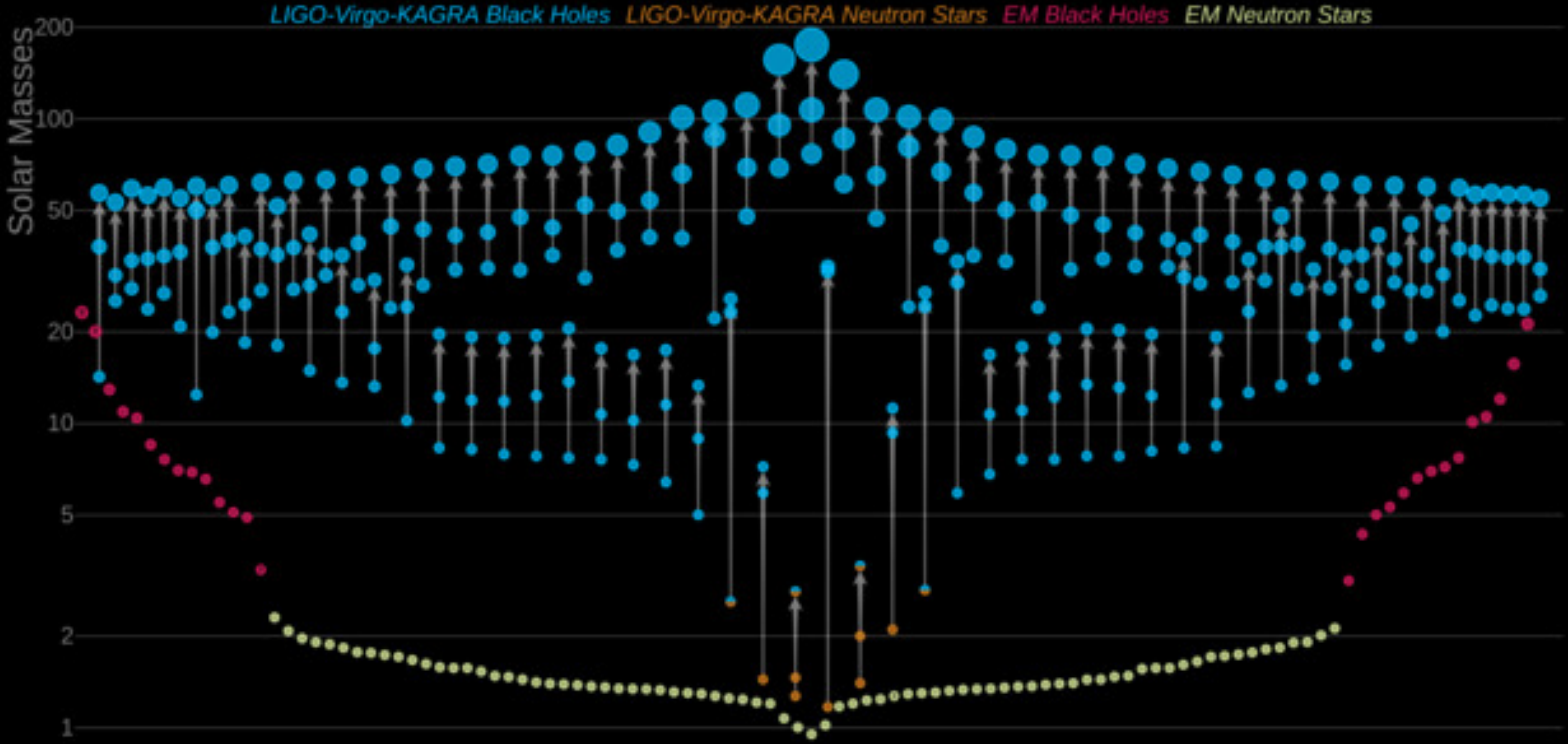
* numbers correspond to the LIGO interferometer setup

World-wide GW detector network

TERRESTIAL GW INTERFEROMETERS

[1304.0670 LIGO-Virgo-KAGRA]

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Pulsar Timing Arrays

1 Pulsars emit radio pulses at periodic intevals

2 Gravitational waves induce tiny differences in the arrival times of these pulses

3 Radio telescope detect GWs by measuring these differences in arrival times in multiple pulsars *(an array of pulsars)* and their correlations

https://nanograv.org/

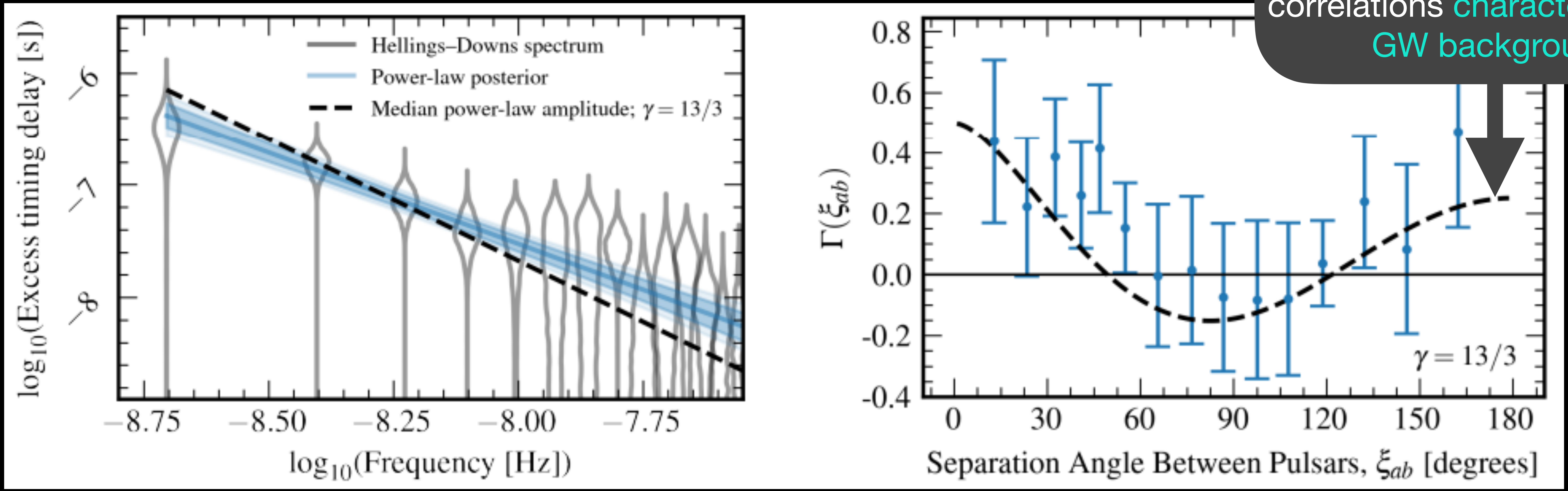
https://nanograv.github.io/optimalobs/

Pulsar Timing Arrays

The IPTA

Radio telescopes of the International Pulsar Timing Array (IPTA)

first detection of a gravitational wave background?

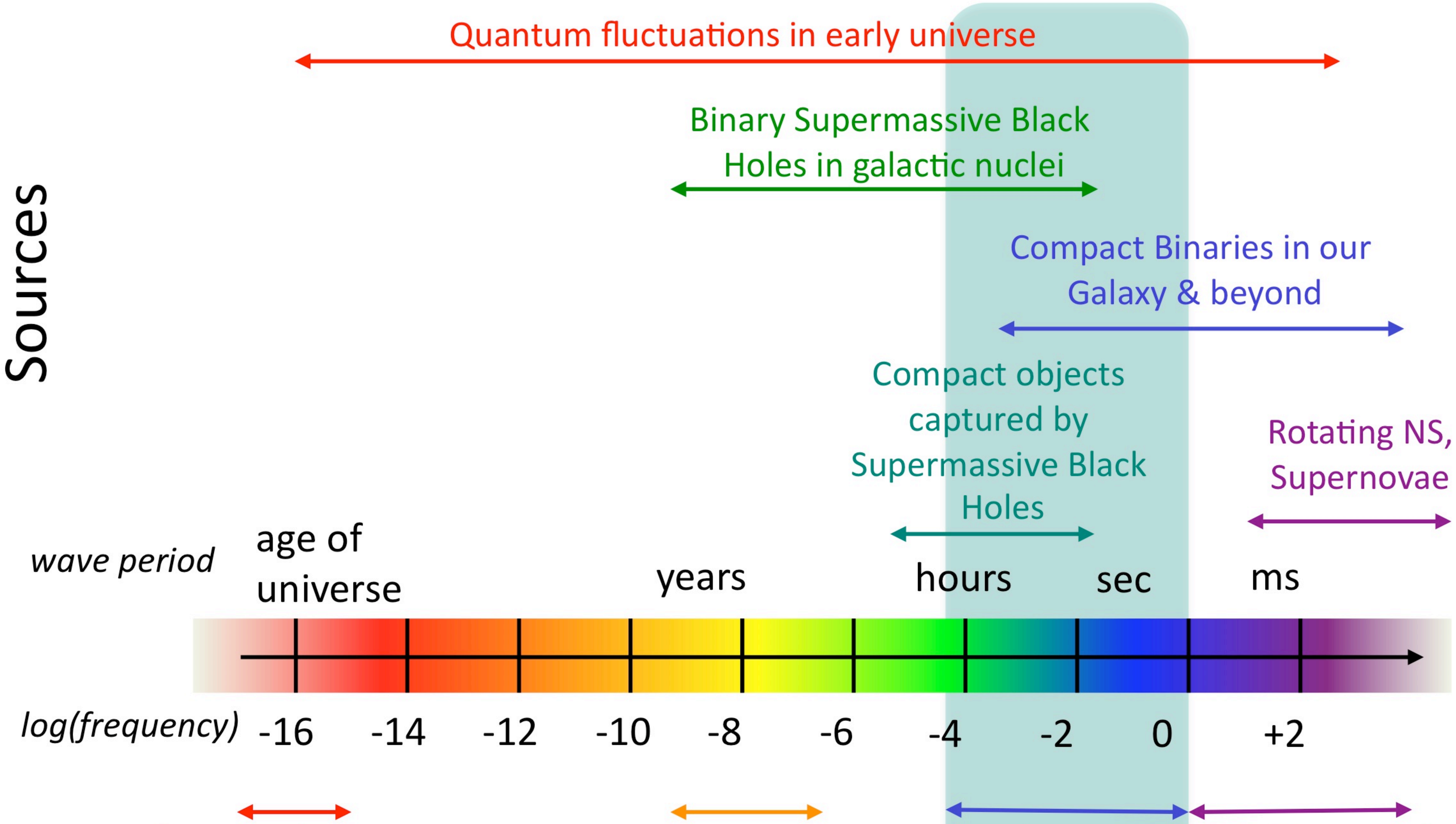


the Hellings-Downs curve describes the angular correlations characteristic to a GW background

spectrum of gravitational waves

[NANOGrav collaboration 2306.16213]

SOURCES OF GRAVITATIONAL WAVES



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

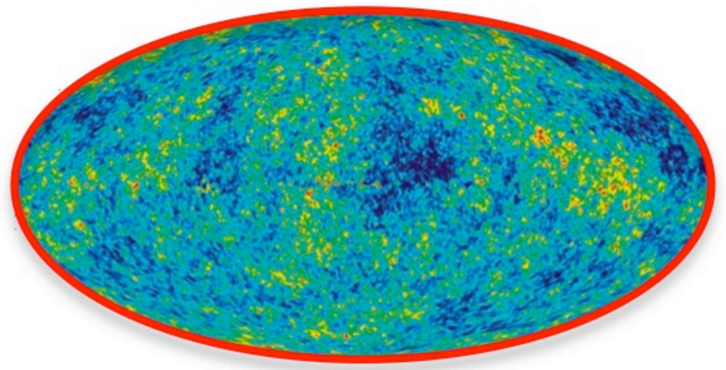
Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

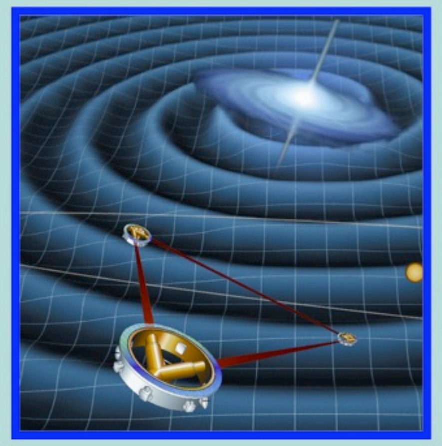
Detectors

Cosmic microwave background polarization



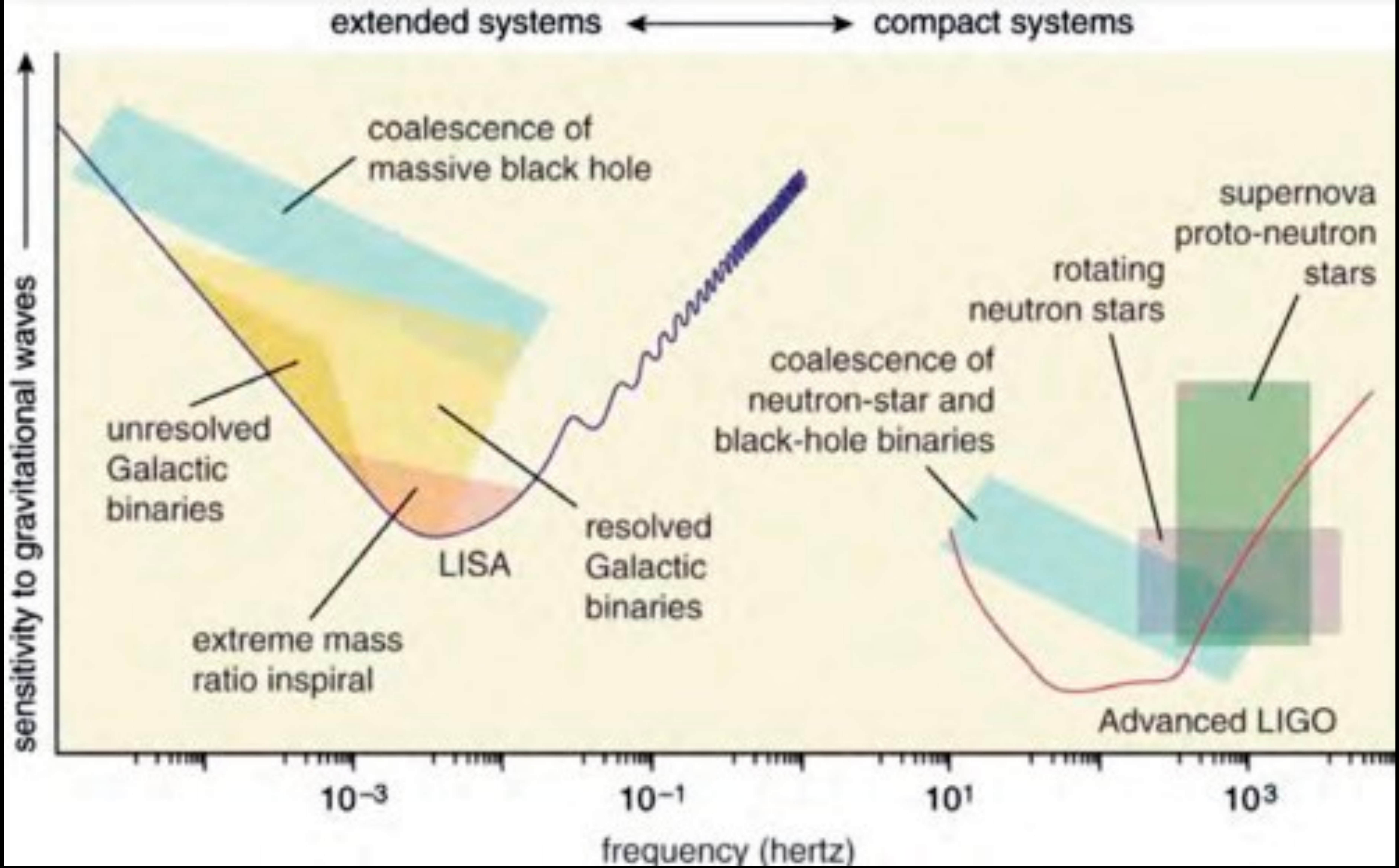
Pulsar Timing

Space Interferometers



Terrestrial interferometers

SOURCES OF GRAVITATIONAL WAVES

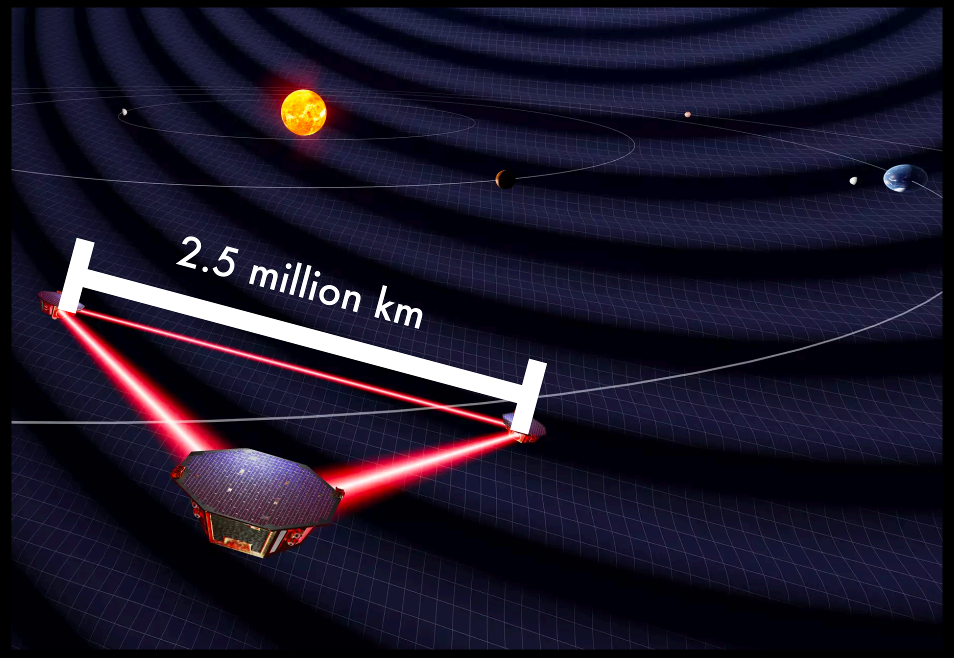


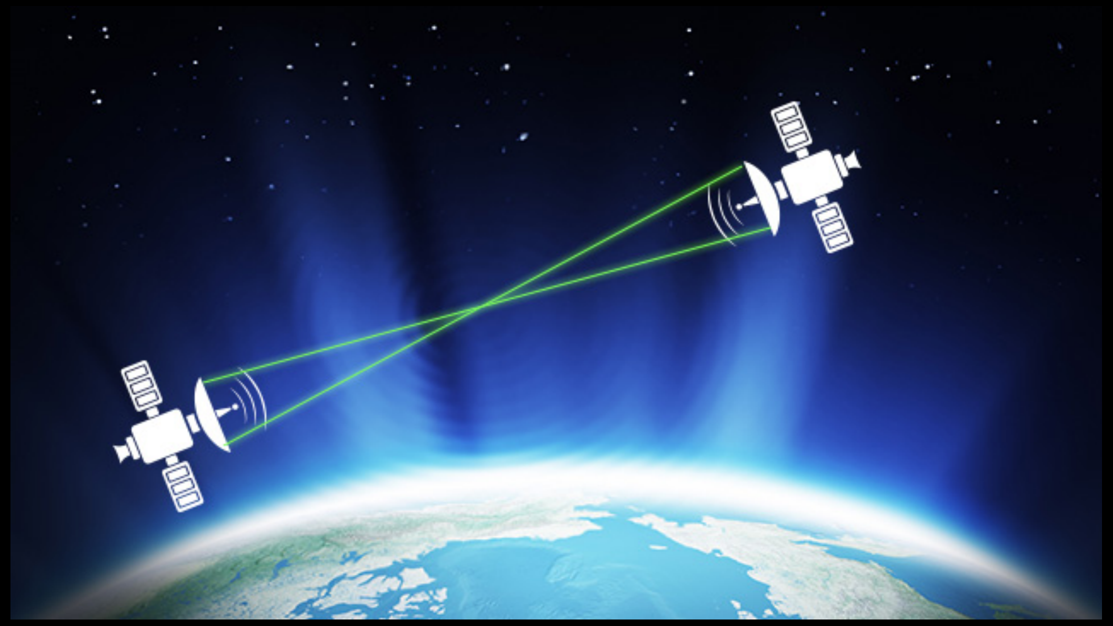
future GW detecors

Laser Interferometer Space Antenna (LISA)

- planned launch in *2037*
- 4+6 years of operation

  4 years with a possible 6 year extension
- probes mHz frequencies



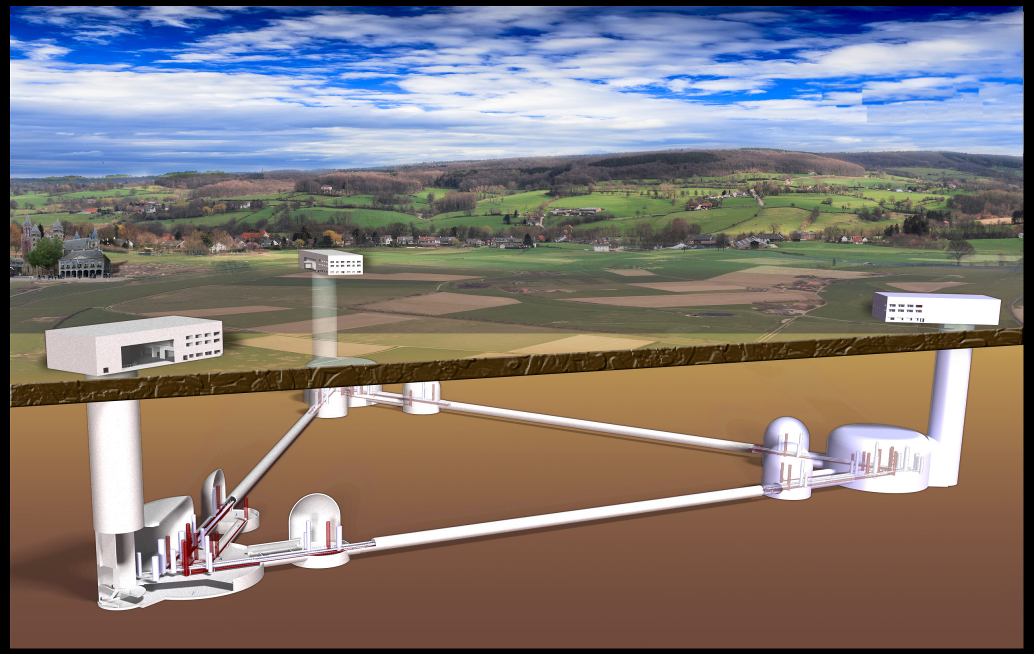


Atomic Interferometric Observatory and Network (AION)

- third. gen GW detector based on atom interferometry
- working prototypes exist
- sensitive to Hz range

Einstein Telescope (ET)

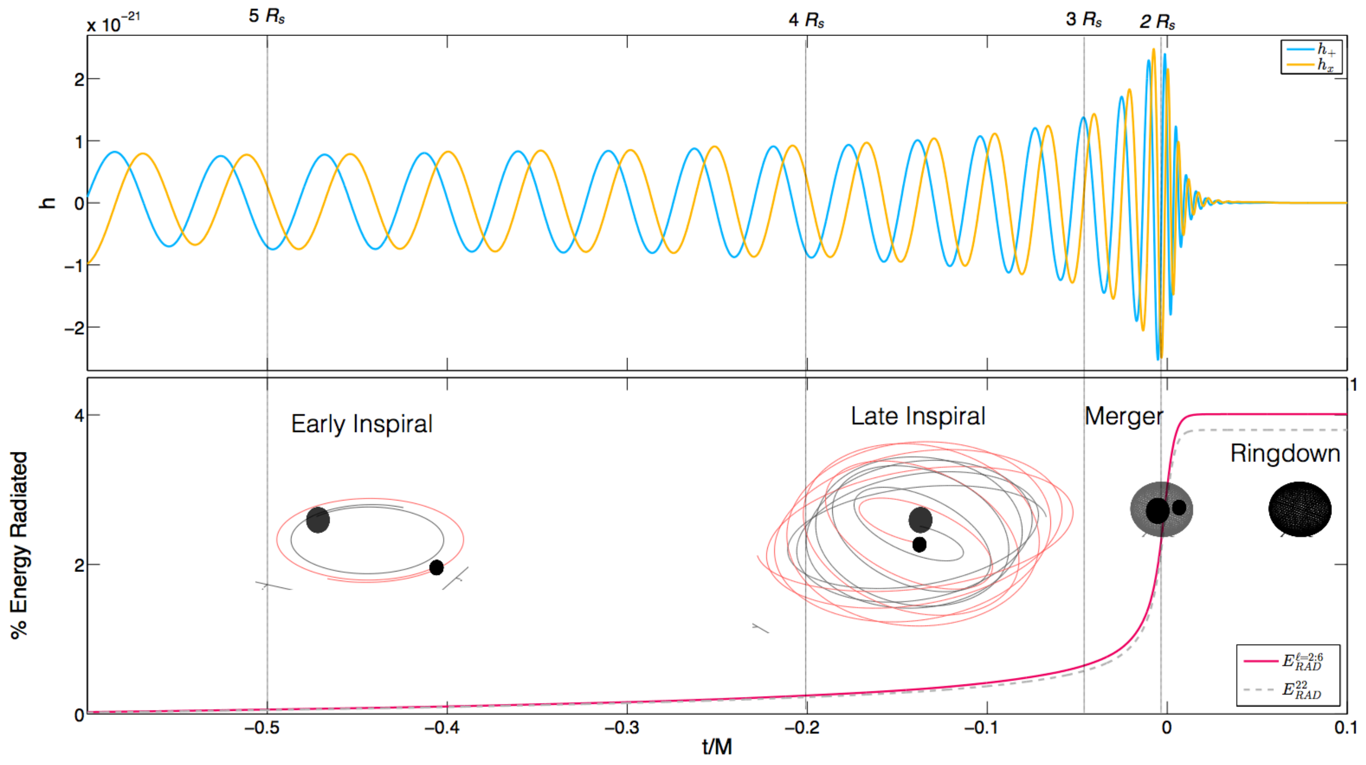
- third gen. terrestial GW interferometer
- planned launch at the end of *30ies*
- probes kHz frequencies



SOURCES OF GRAVITATIONAL WAVES

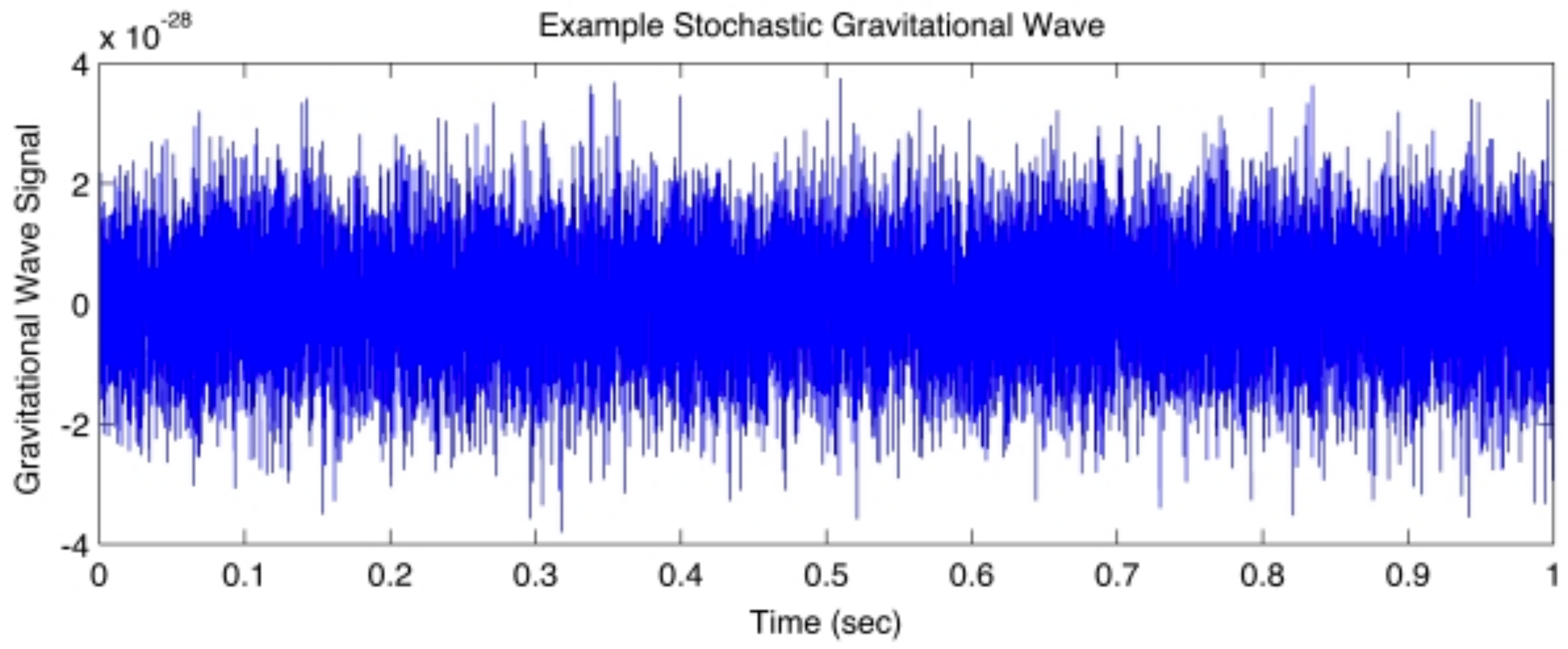
ISOLATED EVENTS

- *mergers of compact objects:*
  - solar mass black holes
  - supermassive black holes
  - neutron stars
  - exotic compact objects
- supernovae



STOCHASTIC BACKGROUNDS

- *GWs from the early universe:*
  - inflationary fluctuations
  - cosmic phase transitions
  - cosmic strings
- stochastic GWs from unresolvable binaries, supermassive black holes



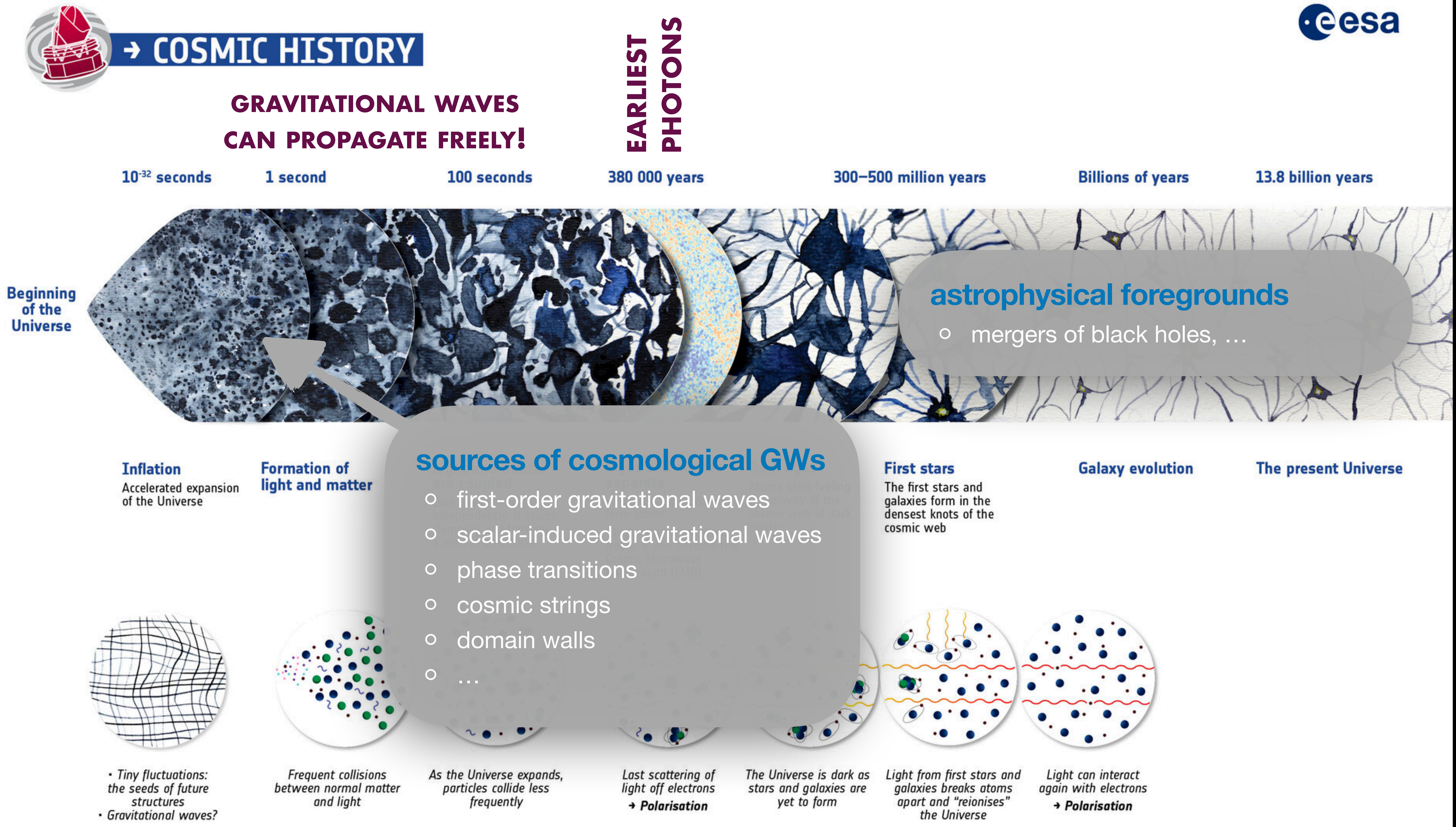
THE EARLY UNIVERSE

AND

GRAVITATIONAL WAVES

GRAVITATIONAL WAVES CAN PROPAGATE FREELY!

EARLIEST PHOTONS



astrophysical foregrounds

- mergers of black holes, …

sources of cosmological GWs

- first-order gravitational waves
- scalar-induced gravitational waves
- phase transitions
- cosmic strings
- domain walls
- …

cosmic history

temperature of the primordial plasma

frequency of (horizon sized) gravitational waves

the GW frequency can be higher

comoving size of cosmic horizon

$$\frac{T}{\mathrm{TeV}} \approx \frac{f}{0.2\mathrm{mHz}} \approx \frac{k}{(60\mathrm{pc})^{-1}}$$

For example, in the Standard Model....

- *QCD phase transition:* $T \approx 130\,\mathrm{MeV},\ f \approx 20\,\mathrm{nHz}$ (**PTA frequencies**)
- *electroweak phase transition:* $T \approx 160\,\mathrm{GeV},\ f \approx 0.03\,\mathrm{mHz}$ (**LISA frequencies**)

cosmic phase transitons

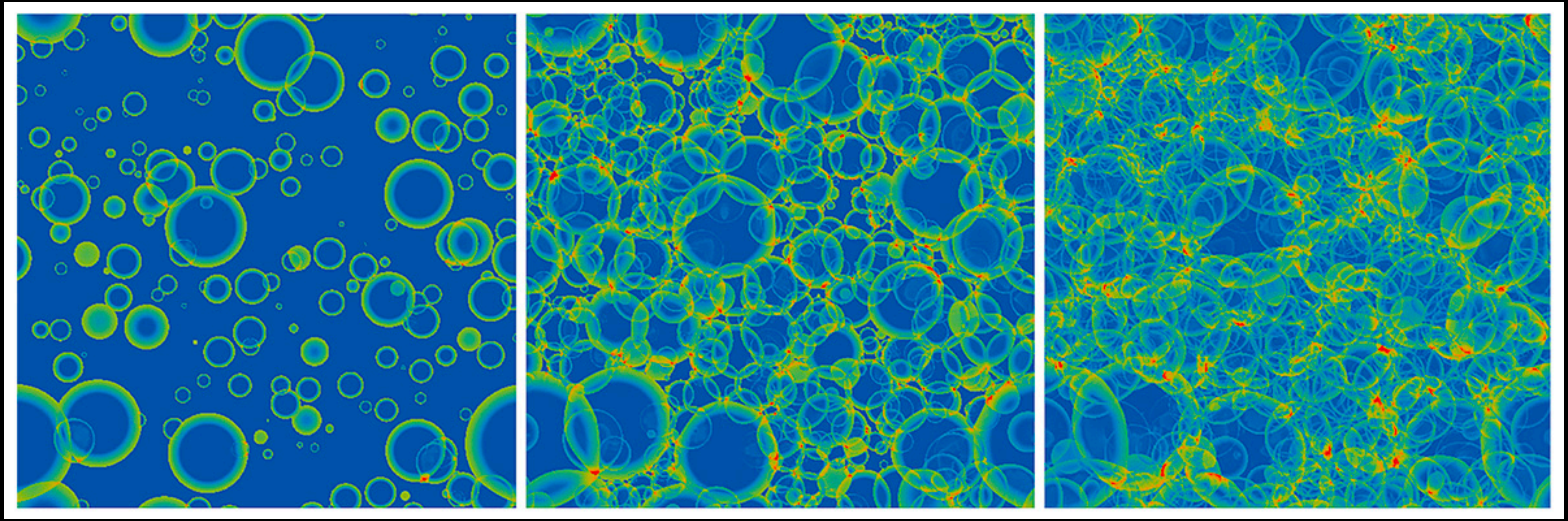
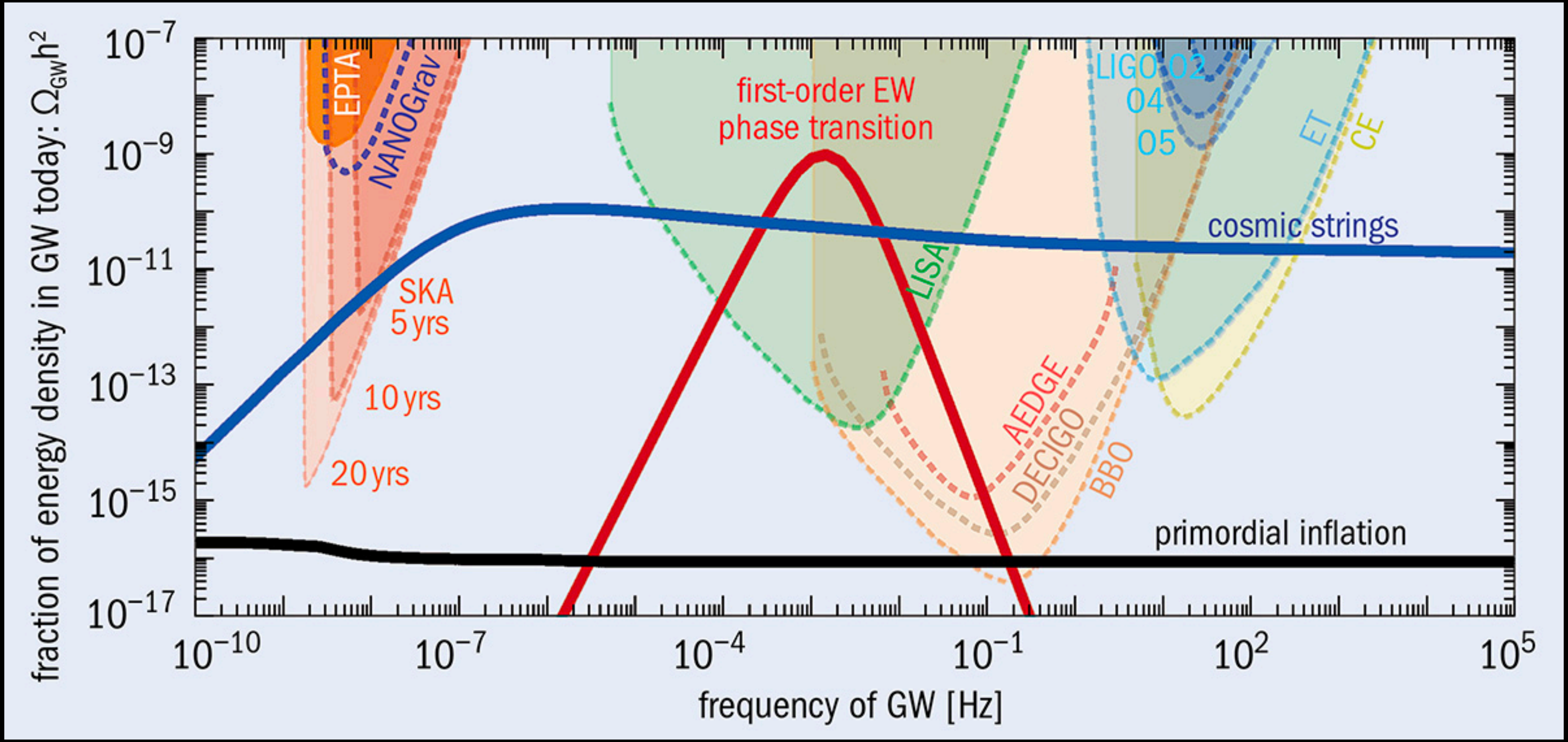


figure source: https://cerncourier.com/a/electroweak-baryogenesis/

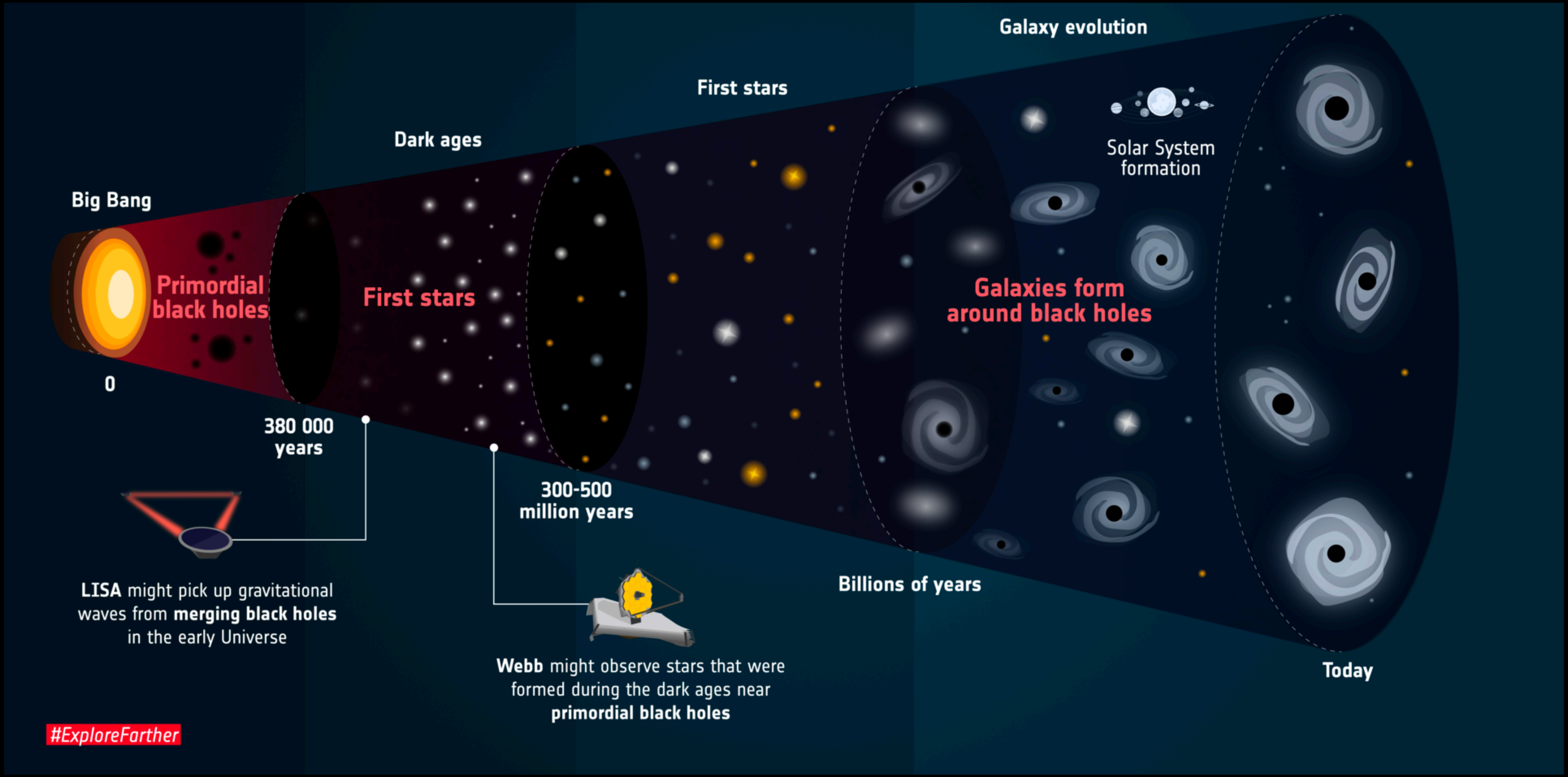
cosmic phase transitons



1st order EW phase transitions testable with LISA!

figure source: https://cerncourier.com/a/electroweak-baryogenesis/

cosmic inflation and primordial black holes



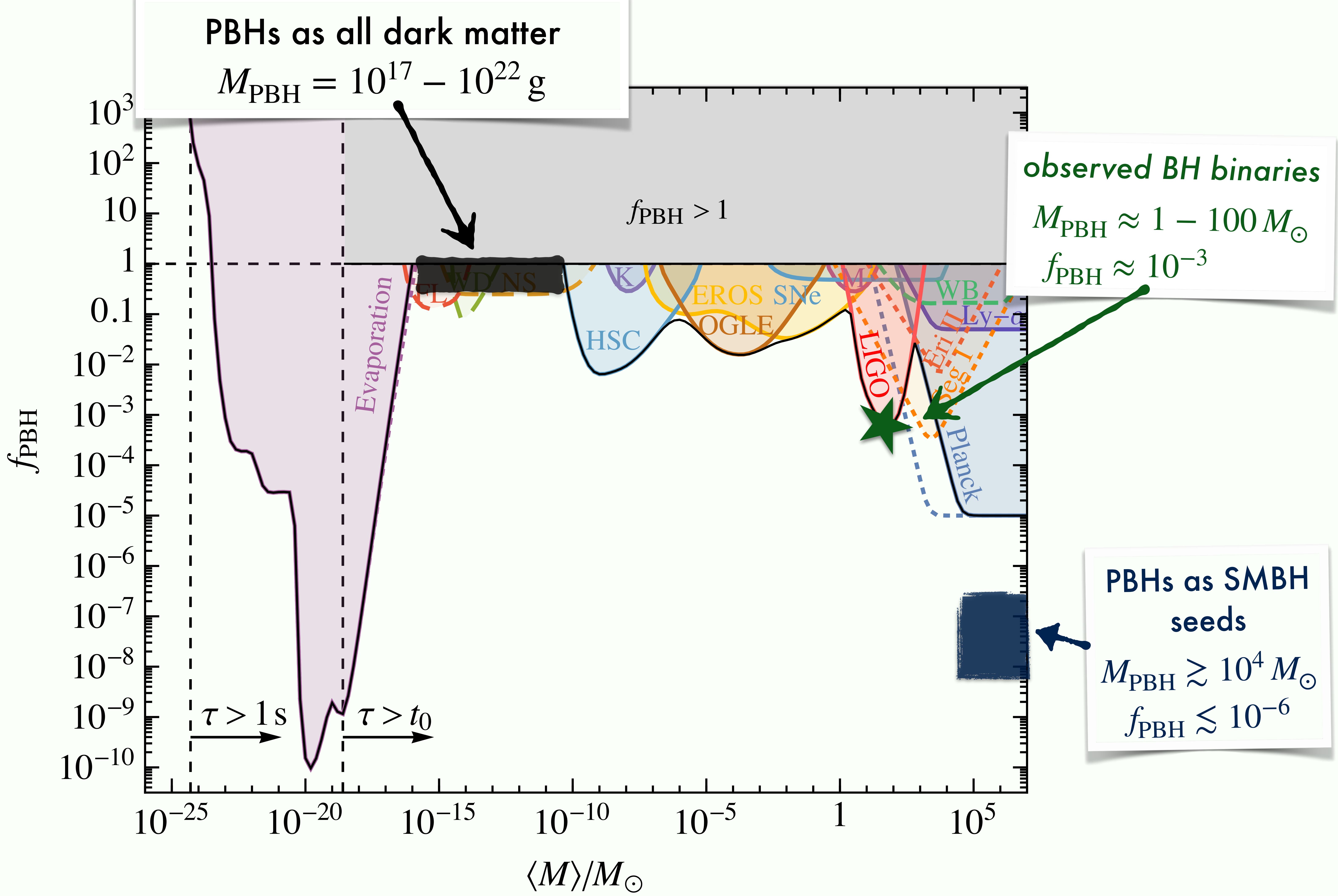
LISA might pick up gravitational waves from **merging black holes** in the early Universe

Webb might observe stars that were formed during the dark ages near **primordial black holes**

#ExploreFarther

esa

scenarios for
primordial black holes

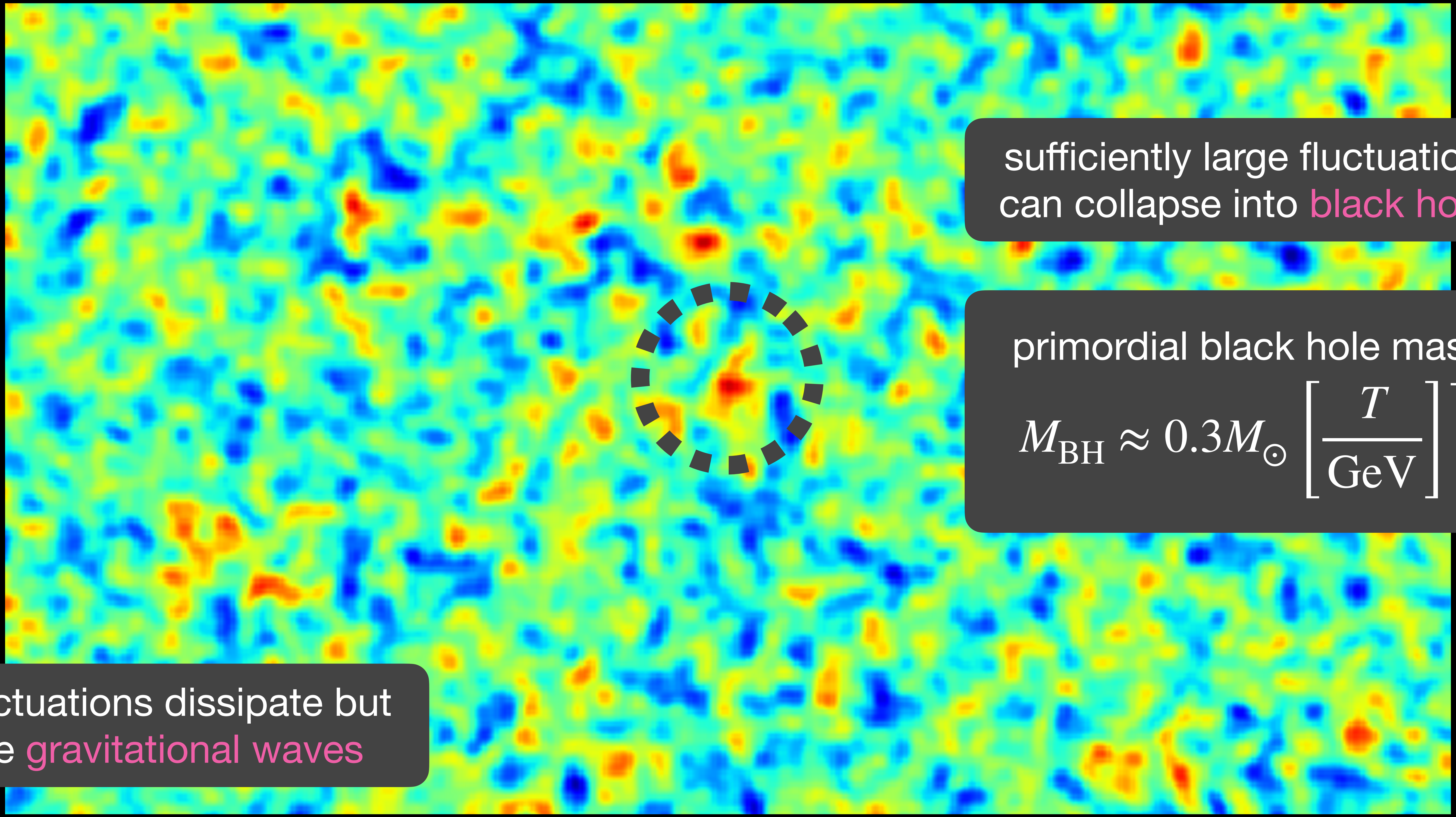


PBHs as all dark matter
$M_{\rm PBH} = 10^{17} - 10^{22}\,{\rm g}$

observed BH binaries
$M_{\rm PBH} \approx 1 - 100\, M_\odot$
$f_{\rm PBH} \approx 10^{-3}$

PBHs as SMBH seeds
$M_{\rm PBH} \gtrsim 10^4\, M_\odot$
$f_{\rm PBH} \lesssim 10^{-6}$

evolution of primordial density fluctuations



sufficiently large fluctuations can collapse into black holes

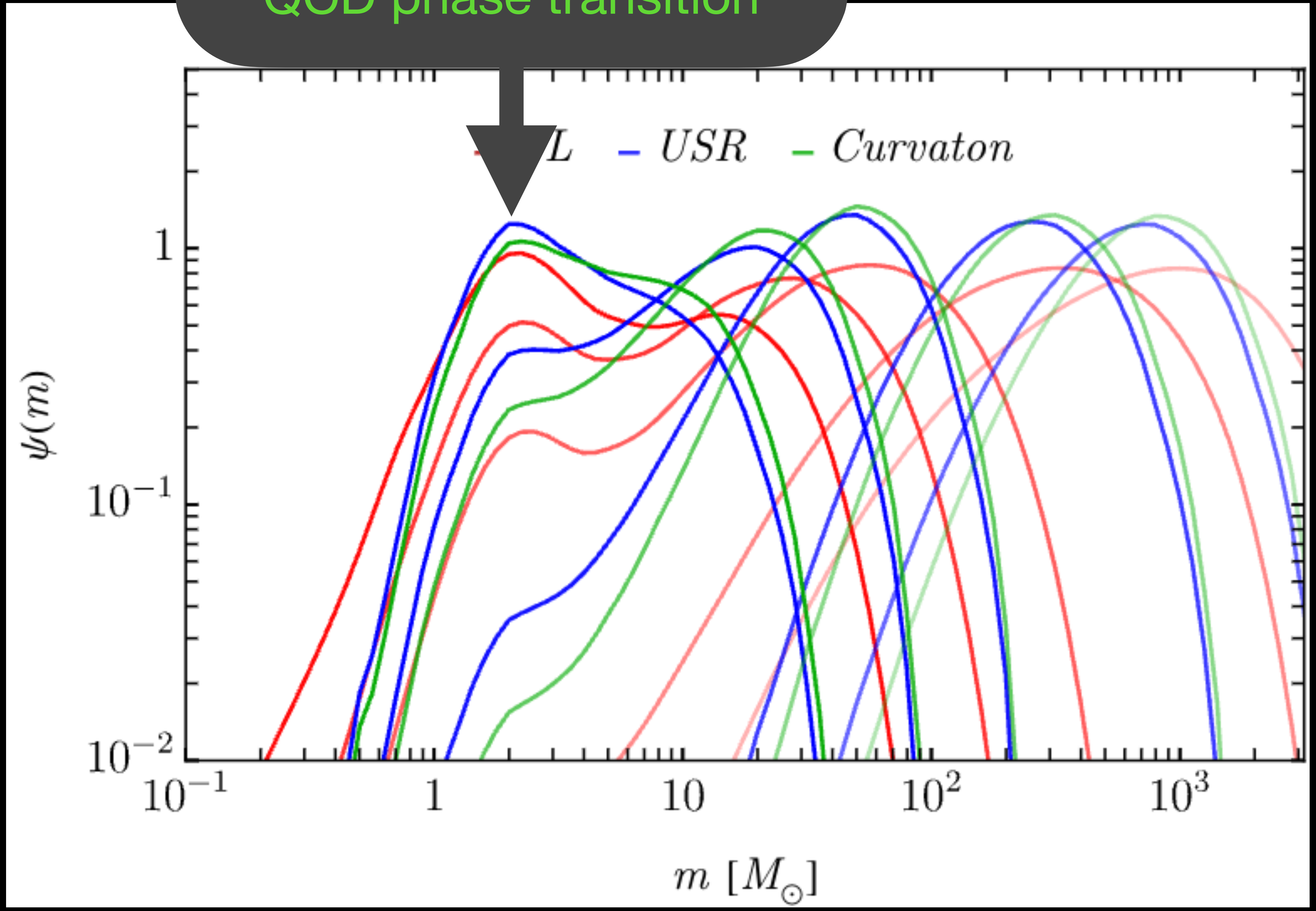
primordial black hole mass:

$$M_{\rm BH} \approx 0.3 M_\odot \left[\frac{T}{\rm GeV}\right]^{-2}$$

remaining fluctuations dissipate but can produce gravitational waves

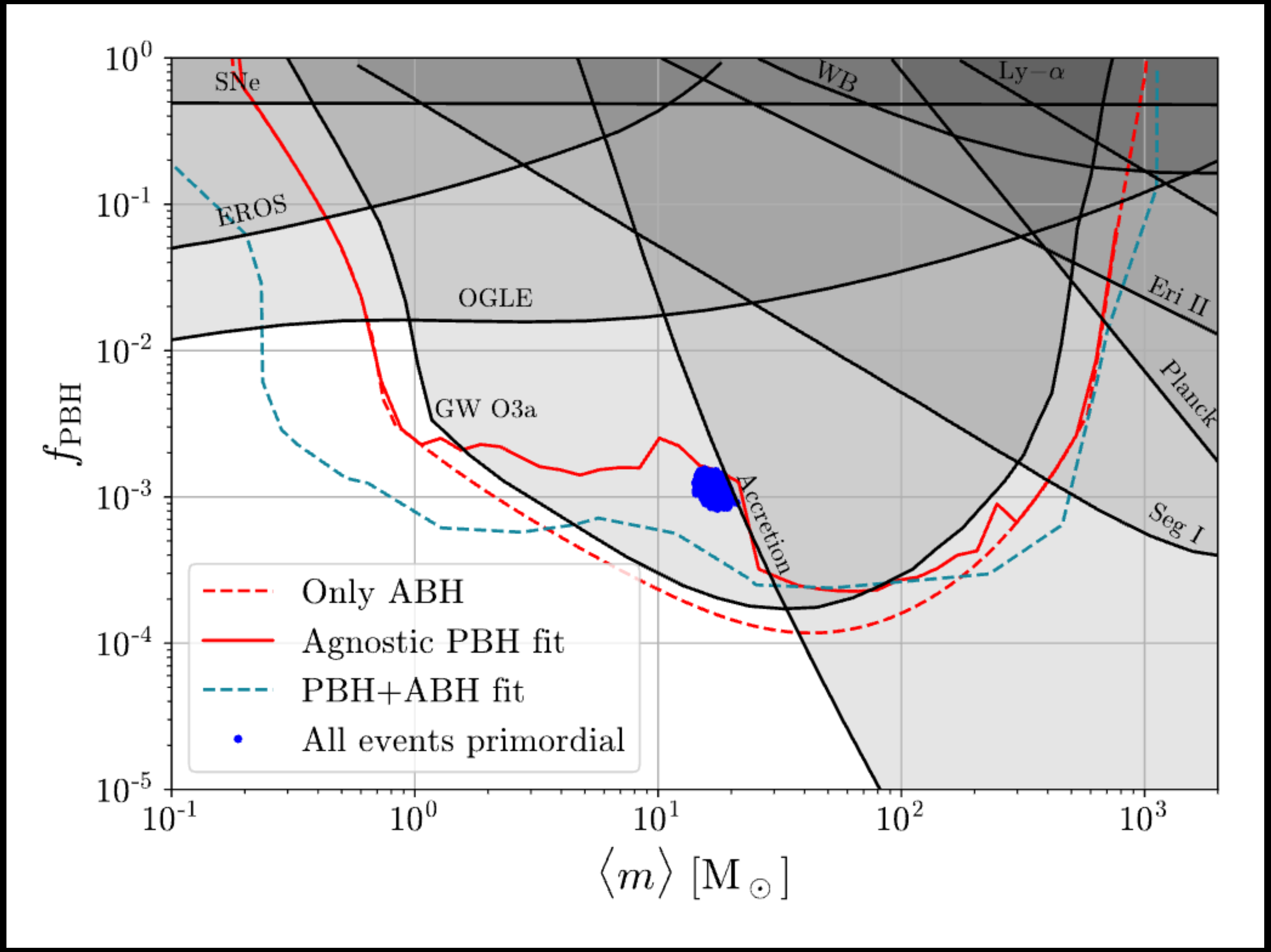
density fluctuations in the primordial plasma

have we seen primordial black holes?



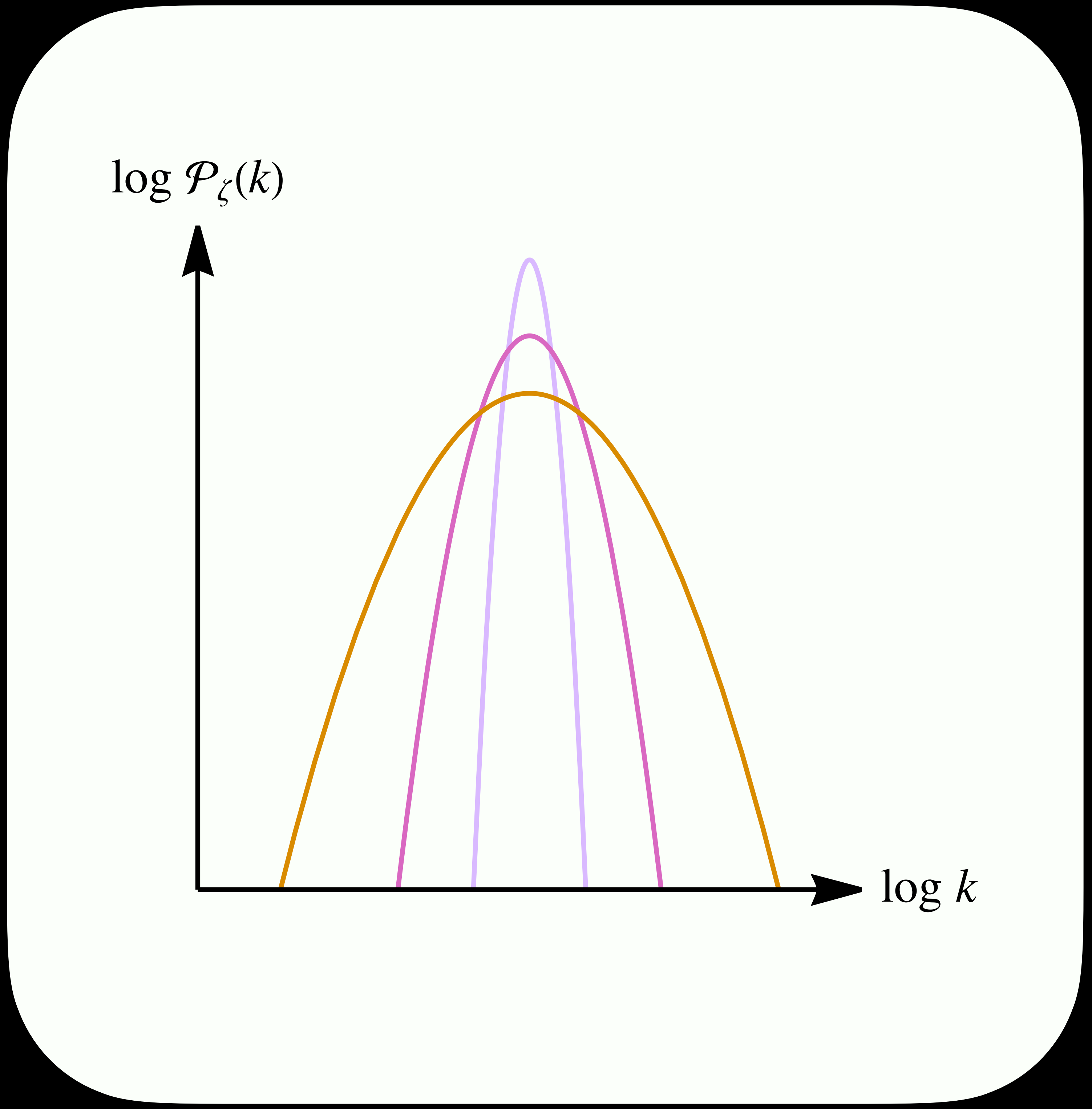
this feature depends on the QCD phase transition

possible mass distributions of priordial black holes

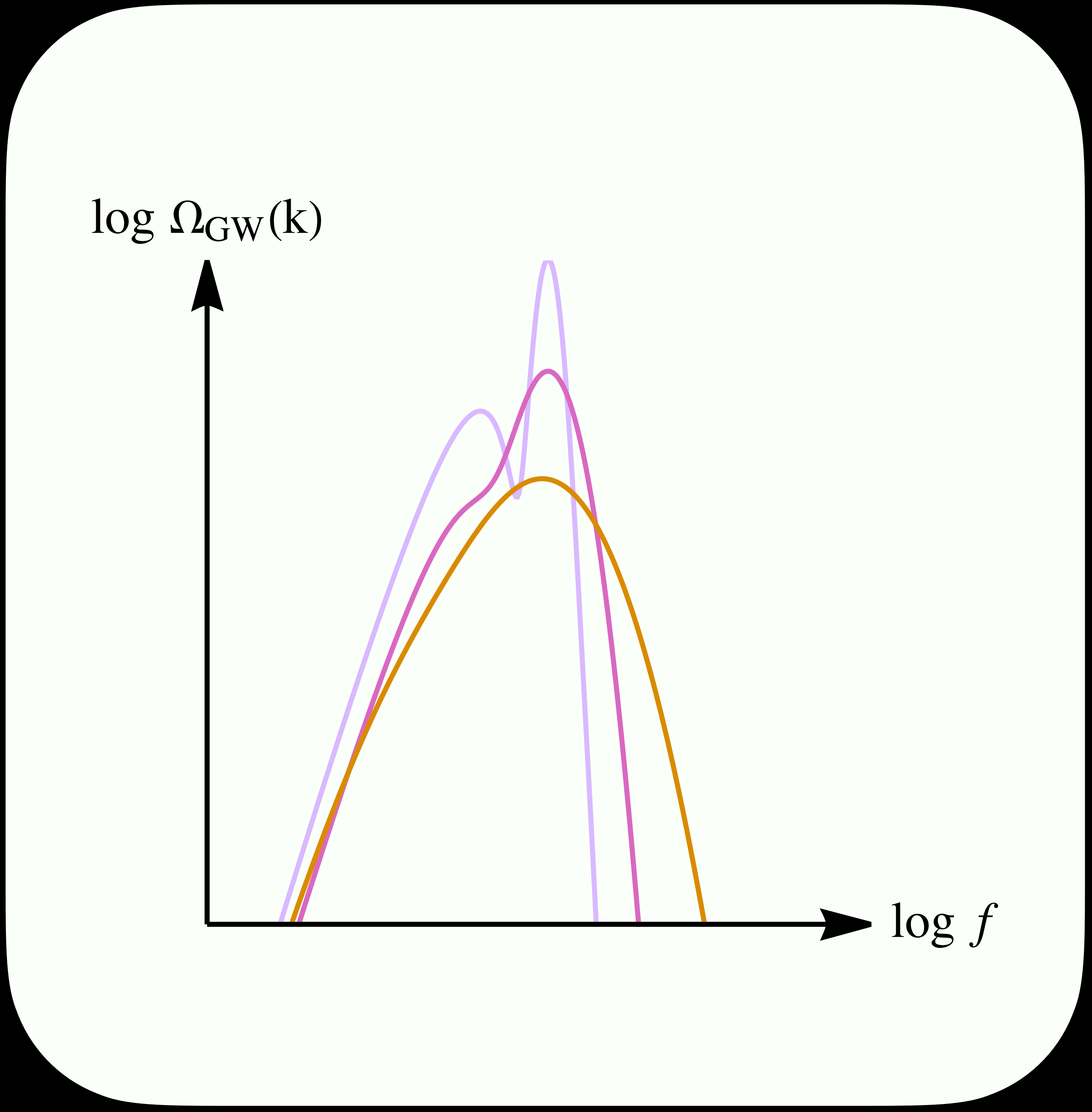


constraints on primordial black holes from LIGO-Virgo-Kagra 3rd observational run

scalar induced gravitational waves



the spectrum of
primordial density fluctuations

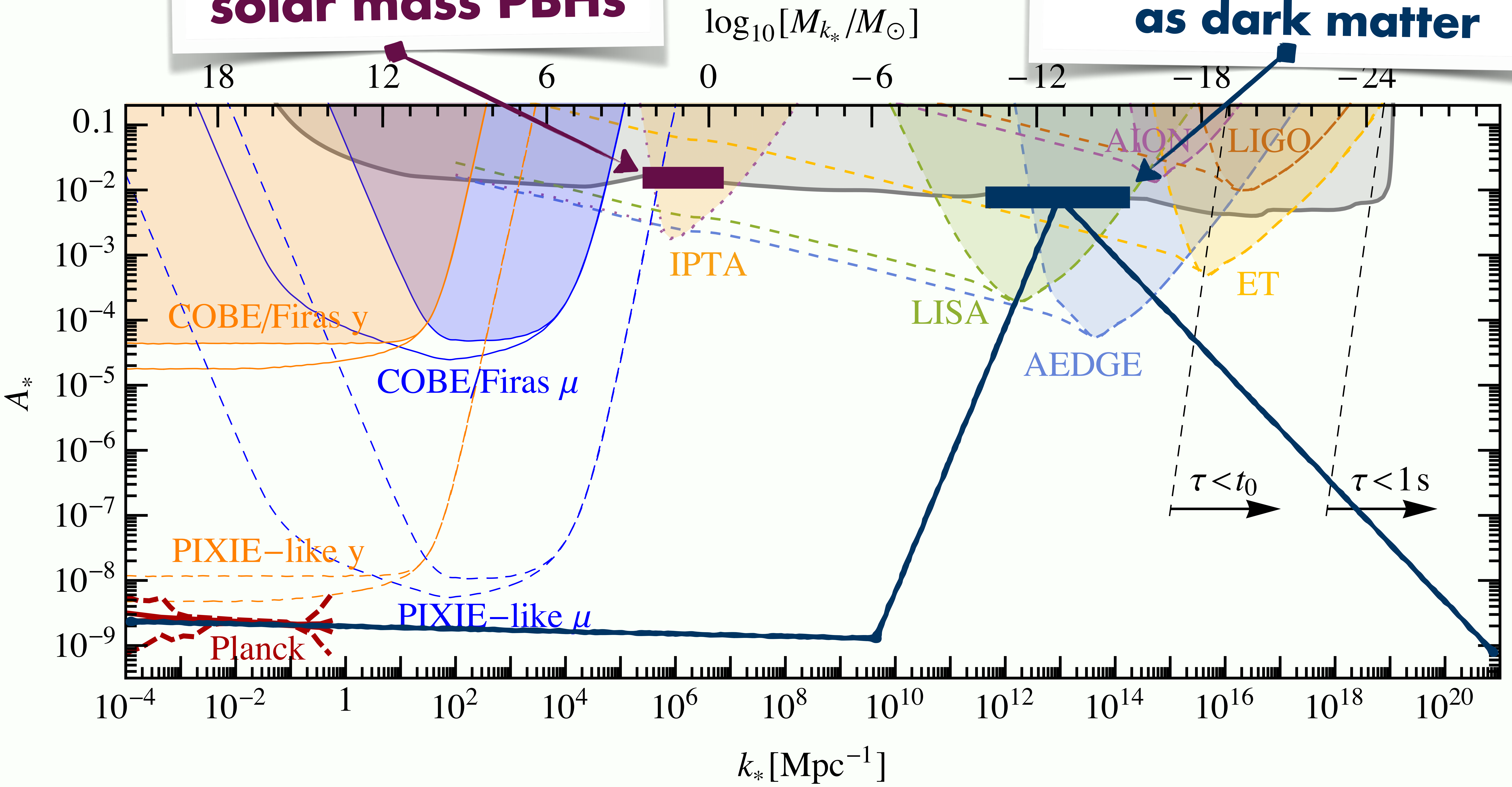


the spectrum of the induced
gravitational waves

probing primordial density fluctuations through scalar induced GWs

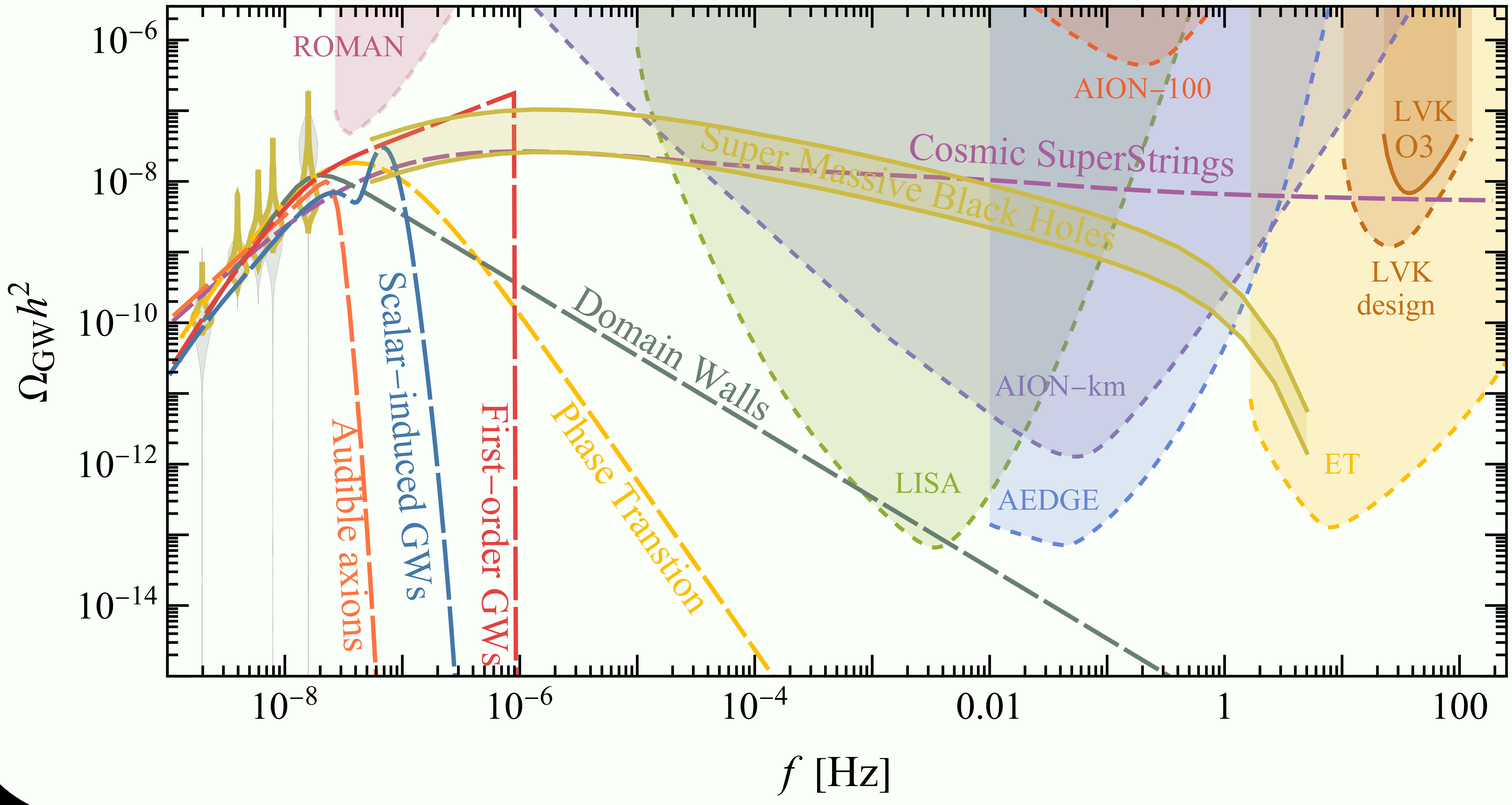
solar mass PBHs

primordial black holes as dark matter

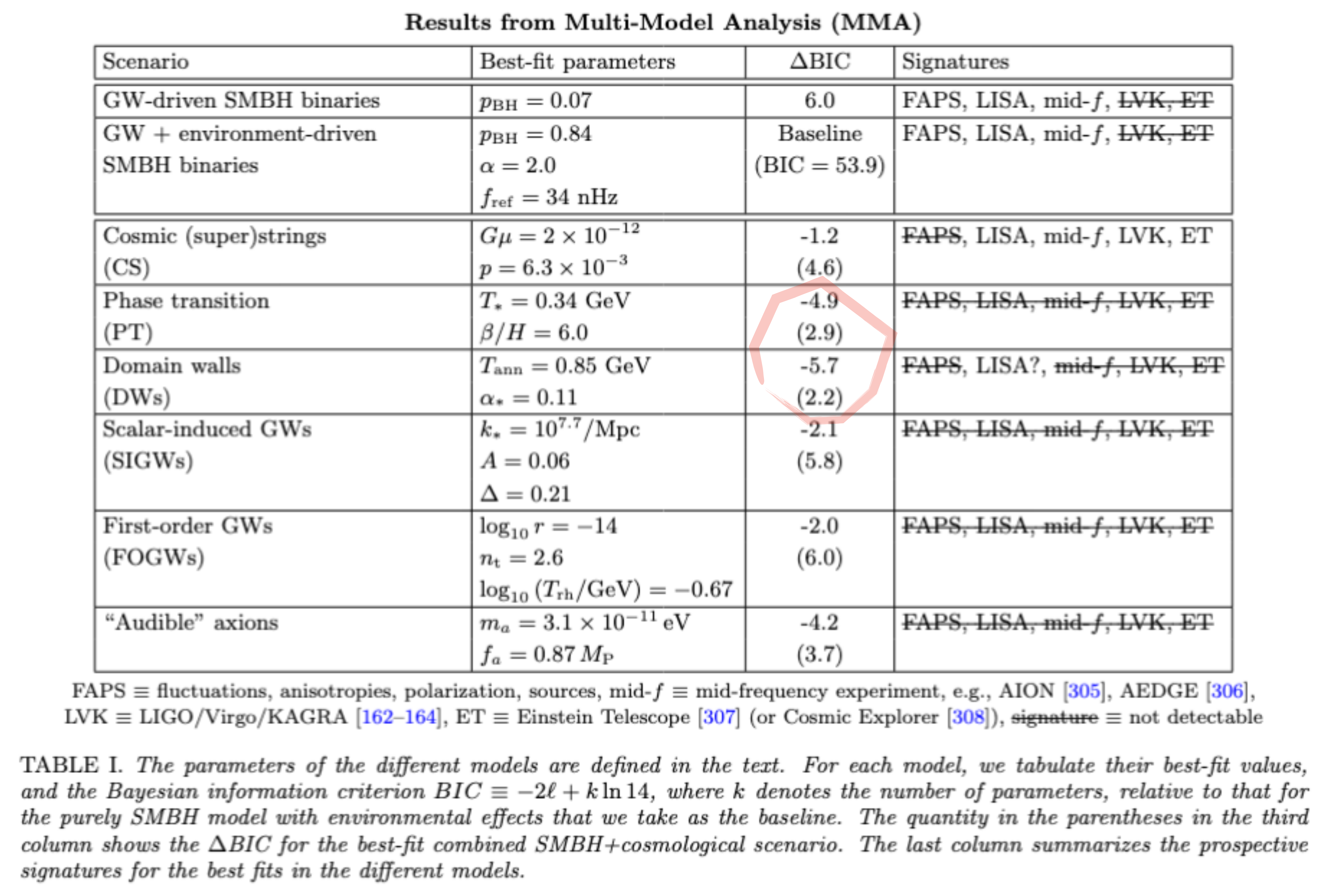


[2205.13540 Karam et al]

interpreting the GW signal from PTAs



[2308.08546 Ellis et al]



Results from Multi-Model Analysis (MMA)

Scenario	Best-fit parameters	ΔBIC	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.07$	6.0	FAPS, LISA, mid-f, ~~LVK, ET~~
GW + environment-driven SMBH binaries	$p_{\rm BH} = 0.84$ $\alpha = 2.0$ $f_{\rm ref} = 34$ nHz	Baseline (BIC = 53.9)	FAPS, LISA, mid-f, ~~LVK, ET~~
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.2 (4.6)	~~FAPS~~, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.34$ GeV $\beta/H = 6.0$	-4.9 (2.9)	~~FAPS, LISA, mid-f, LVK, ET~~
Domain walls (DWs)	$T_{\rm ann} = 0.85$ GeV $\alpha_* = 0.11$	-5.7 (2.2)	~~FAPS~~, LISA?, ~~mid-f, LVK, ET~~
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.7}/{\rm Mpc}$ $A = 0.06$ $\Delta = 0.21$	-2.1 (5.8)	~~FAPS, LISA, mid-f, LVK, ET~~
First-order GWs (FOGWs)	$\log_{10} r = -14$ $n_{\rm t} = 2.6$ $\log_{10}(T_{\rm rh}/{\rm GeV}) = -0.67$	-2.0 (6.0)	~~FAPS, LISA, mid-f, LVK, ET~~
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\rm P}$	-4.2 (3.7)	~~FAPS, LISA, mid-f, LVK, ET~~

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [305], AEDGE [306], LVK ≡ LIGO/Virgo/KAGRA [162–164], ET ≡ Einstein Telescope [307] (or Cosmic Explorer [308]), ~~signature~~ ≡ not detectable

TABLE I. *The parameters of the different models are defined in the text. For each model, we tabulate their best-fit values, and the Bayesian information criterion* $BIC \equiv -2\ell + k \ln 14$, *where* k *denotes the number of parameters, relative to that for the purely SMBH model with environmental effects that we take as the baseline. The quantity in the parentheses in the third column shows the* ΔBIC *for the best-fit combined SMBH+cosmological scenario. The last column summarizes the prospective signatures for the best fits in the different models.*

[2308.08546 Ellis et al]

summary

- gravitational wave astronomy is still a new field and has a lot of potential for discovering new physics
- GWs can give us unprecedented direct access to very high energy processes in the early universe
- future GW experiments can probe a wide range of new physics scenarios
- GW observations can confirm or rule out the window for PBH dark matter

* *and there are many other unmentioned possibilities for probing new physics with gravitational waves, like tests of general relativity, structure formation, probes of the expansion history of the (late) universe ….*