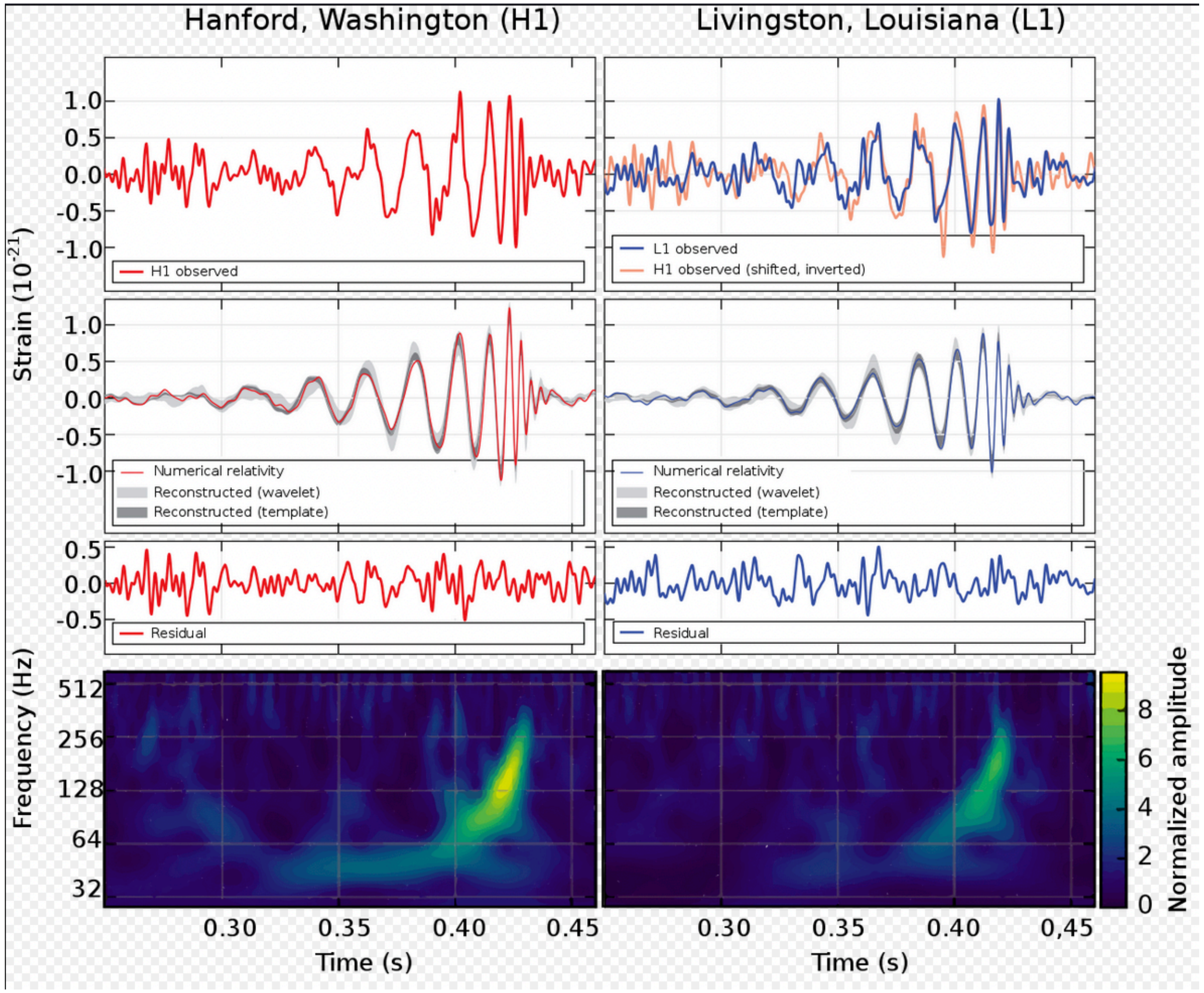
The scientific potential of Gravitational Waves

Chiara Caprini
University of Geneva & CERN (CNRS)



http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.116.061102

Far-reaching scientific potential

- GW direct detection from Earth is a great theoretical and experimental achievement, providing observational access to many new physical phenomena

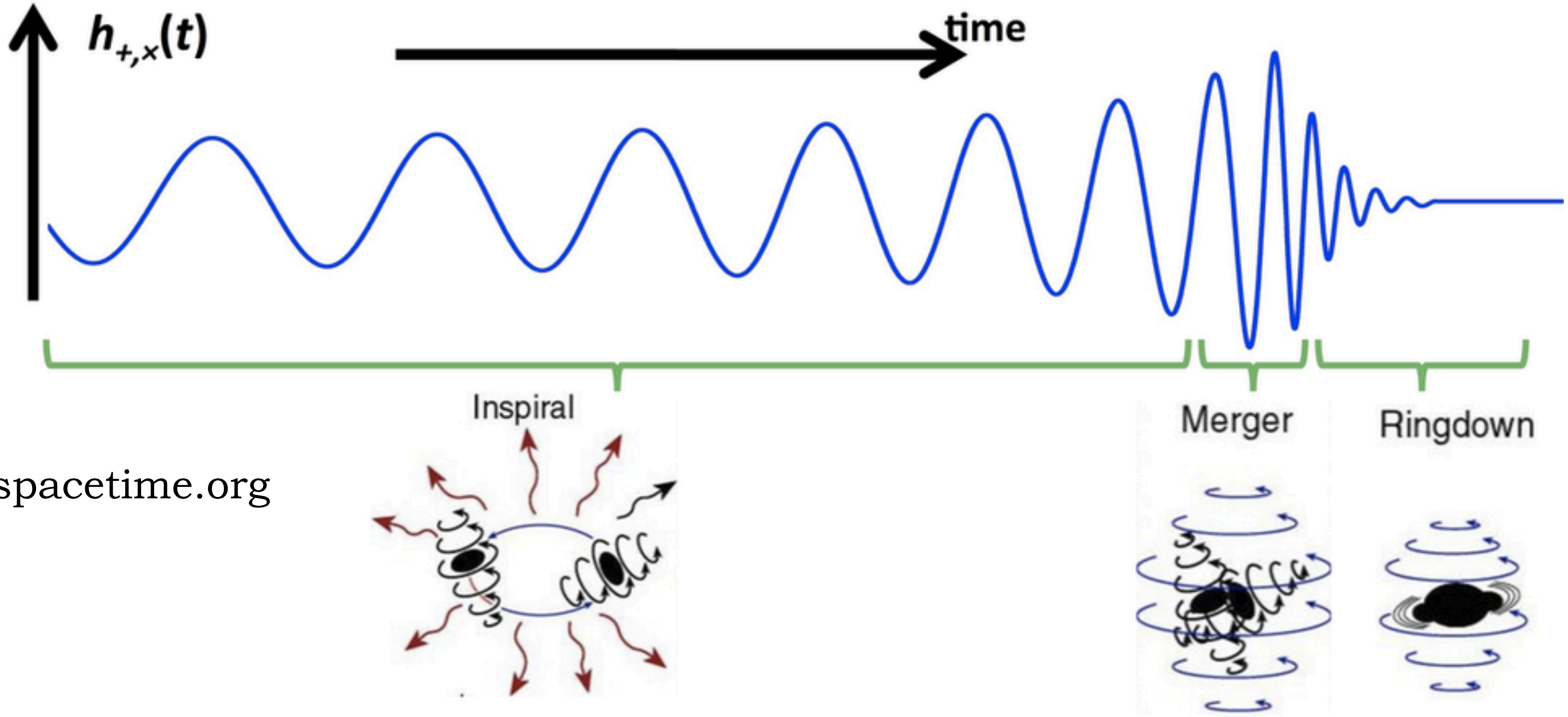
- Astrophysics:
  - Discovery of new astrophysical objects (black hole binaries…)
  - Provide information on their population and characteristics
  - Enlighten astrophysical phenomena (fast gamma-ray bursts, Active Galactic Nuclei, supernovae explosions…)
  - Probe the galaxy and galactic centres environment

- Fundamental physics:
  - Test General Relativity in the strong field regime (Post Newtonian terms, tests of the horizon, GW polarisations, space-time around black holes…)
  - Test of General Relativity at cosmological scales (GW propagation, GW lensing…)
  - High energy and beyond the standard model physics (phase transitions: Electroweak scale, QCD scale, cosmic strings; Inflation…)
  - Matter in extreme conditions (neutron stars equation of state, elements synthesis…)

- Cosmology:
  - Expansion of the universe, dark energy
  - Nature of Dark Matter (Primordial Black Holes, black holes accretion…)
  - Cosmological structure formation, galaxy mergers
  - Early universe before recombination in general

- Data Analysis (Matched filtering, noise and foreground subtraction, machine learning…)
- Detectors (stabilisation, cryogeny, quantum limits, free fall, atom interferometry…)

GW emission from the inspiral of a binary system



soundofspacetime.org

$$M_c = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$f(\tau) = \frac{1}{\pi}\left(\frac{G\, M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}$$

chirp mass

τ time to coalescence

GW emission from the inspiral of a binary system

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 0.2\,\mathrm{sec} \qquad \longrightarrow \qquad f = 37\,\mathrm{Hz}$$

$$M_c = 1.2\,\mathrm{M}_\odot \qquad \tau = 30\,\mathrm{sec} \qquad \longrightarrow \qquad f = 38\,\mathrm{Hz}$$

$$\boxed{f(\tau) = \frac{1}{\pi}\left(\frac{G\,M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}}$$

GW emission from the inspiral of a binary system

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$$M_c = 1.2\,\mathrm{M}_\odot \qquad \tau = 30\,\mathrm{sec} \qquad \longrightarrow \qquad f = 38\,\mathrm{Hz}$$

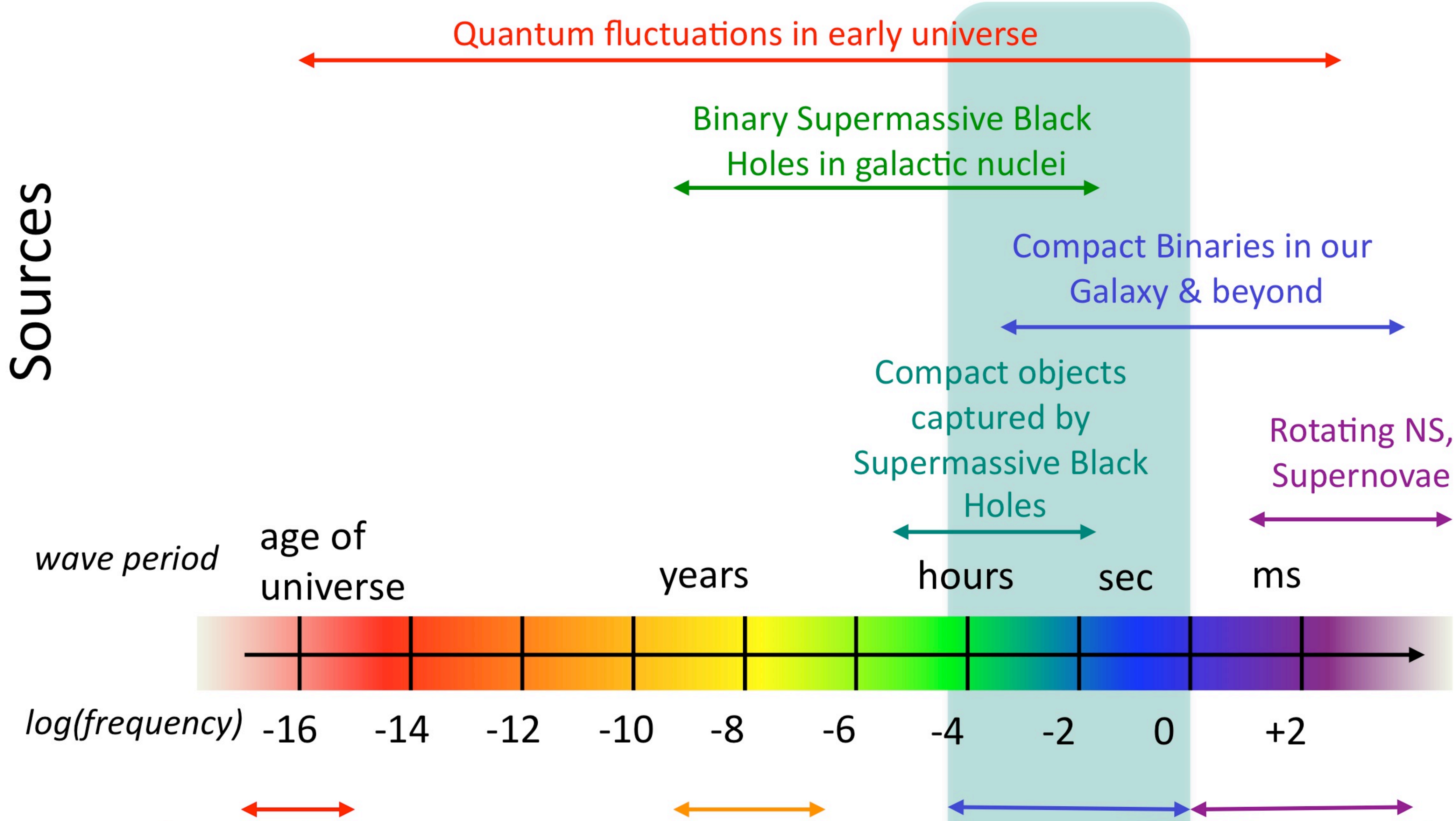
$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 10\,\mathrm{year} \qquad \longrightarrow \qquad f = 0.01\,\mathrm{Hz}$$

$$M_c = 10^6\,\mathrm{M}_\odot \qquad \tau = 1\,\mathrm{hour} \qquad \longrightarrow \qquad f = 1\,\mathrm{mHz}$$

$$M_c = 10^9\,\mathrm{M}_\odot \qquad \tau = 10^5\,\mathrm{year} \qquad \longrightarrow \qquad f = 7 \cdot 10^{-9}\,\mathrm{Hz}$$

$$\boxed{f(\tau) = \frac{1}{\pi}\left(\frac{G\,M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}}$$

The Gravitational Wave Spectrum



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

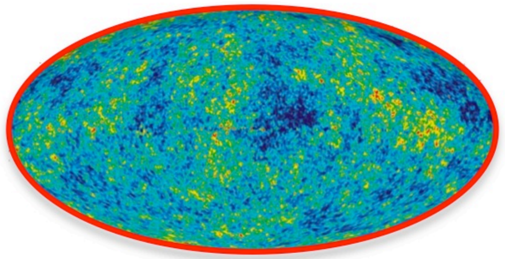
Rotating NS, Supernovae

wave period age of universe years hours sec ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

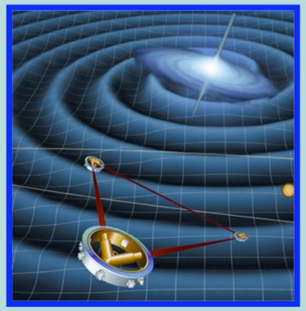
Detectors

Cosmic microwave background polarization



Pulsar Timing

Space Interferometers



Terrestrial interferometers

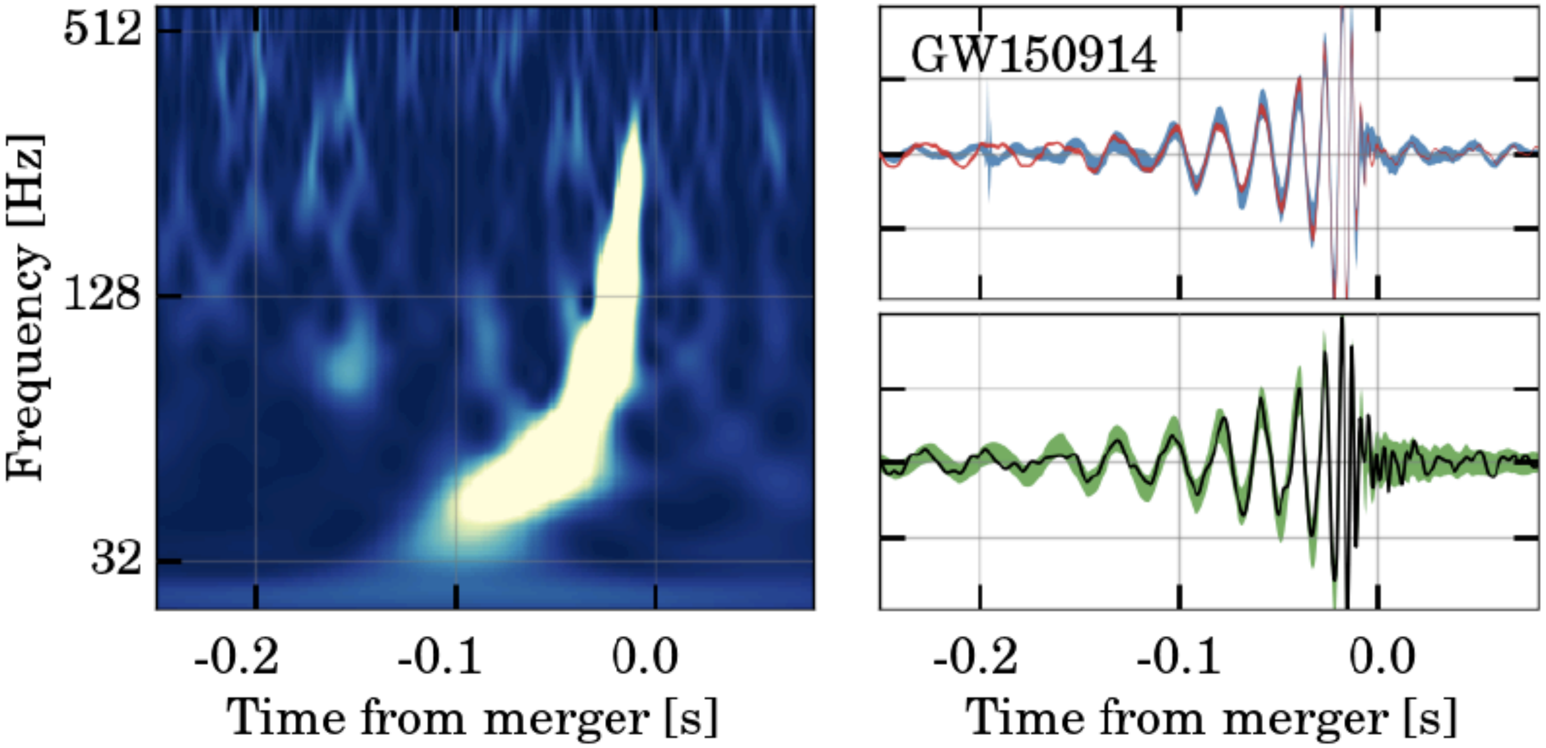
NASA Goddard Space Flight Center

Observables

The gravitational wave strain from the inspiral and merger of compact binaries

$$h(t) \sim \frac{\Delta L}{L}$$

- Compact binaries inspiral, merger (ringdown)
  - Black holes, neutron stars, white dwarfs…
  - In the galaxy or beyond
- Extreme mass ratio inspirals
- Rotating neutron stars
- …



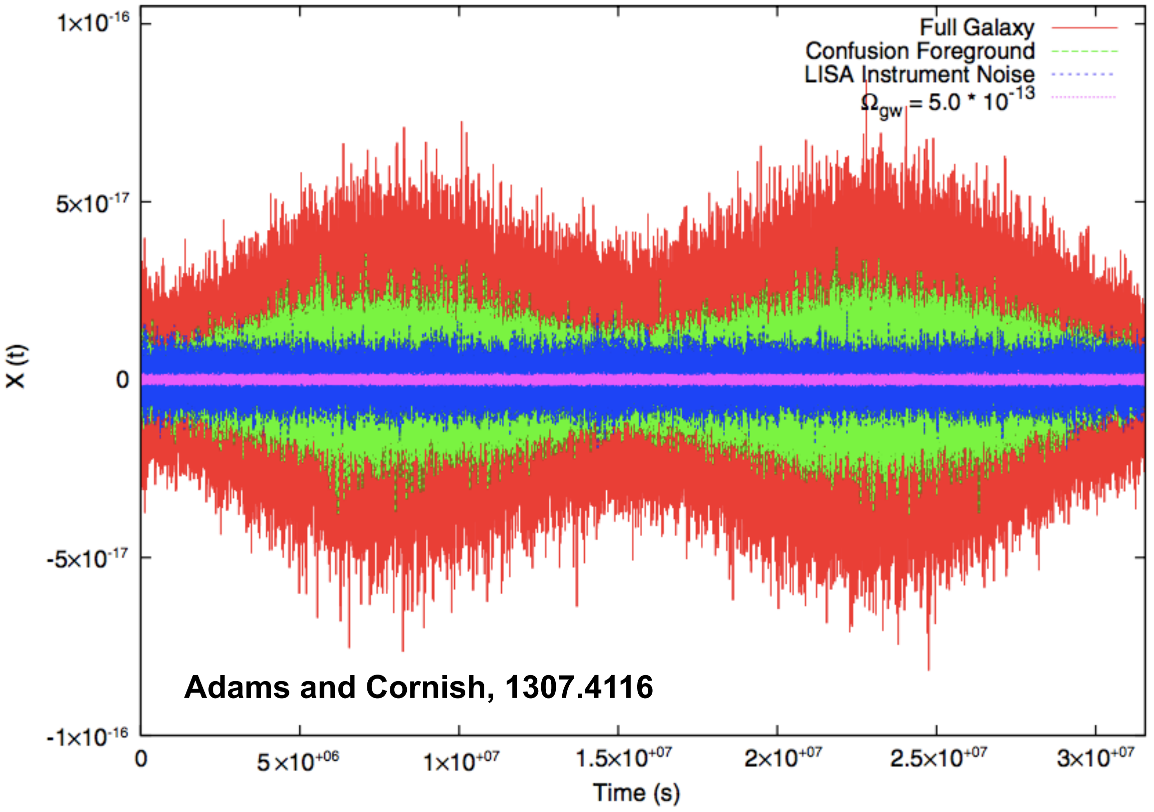
LIGO/Virgo arXiv:1811.12907

Observables

The stochastic gravitational wave background

the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the primordial universe with too small correlation scale (typically horizon at the time of production) with respect to the detector resolution

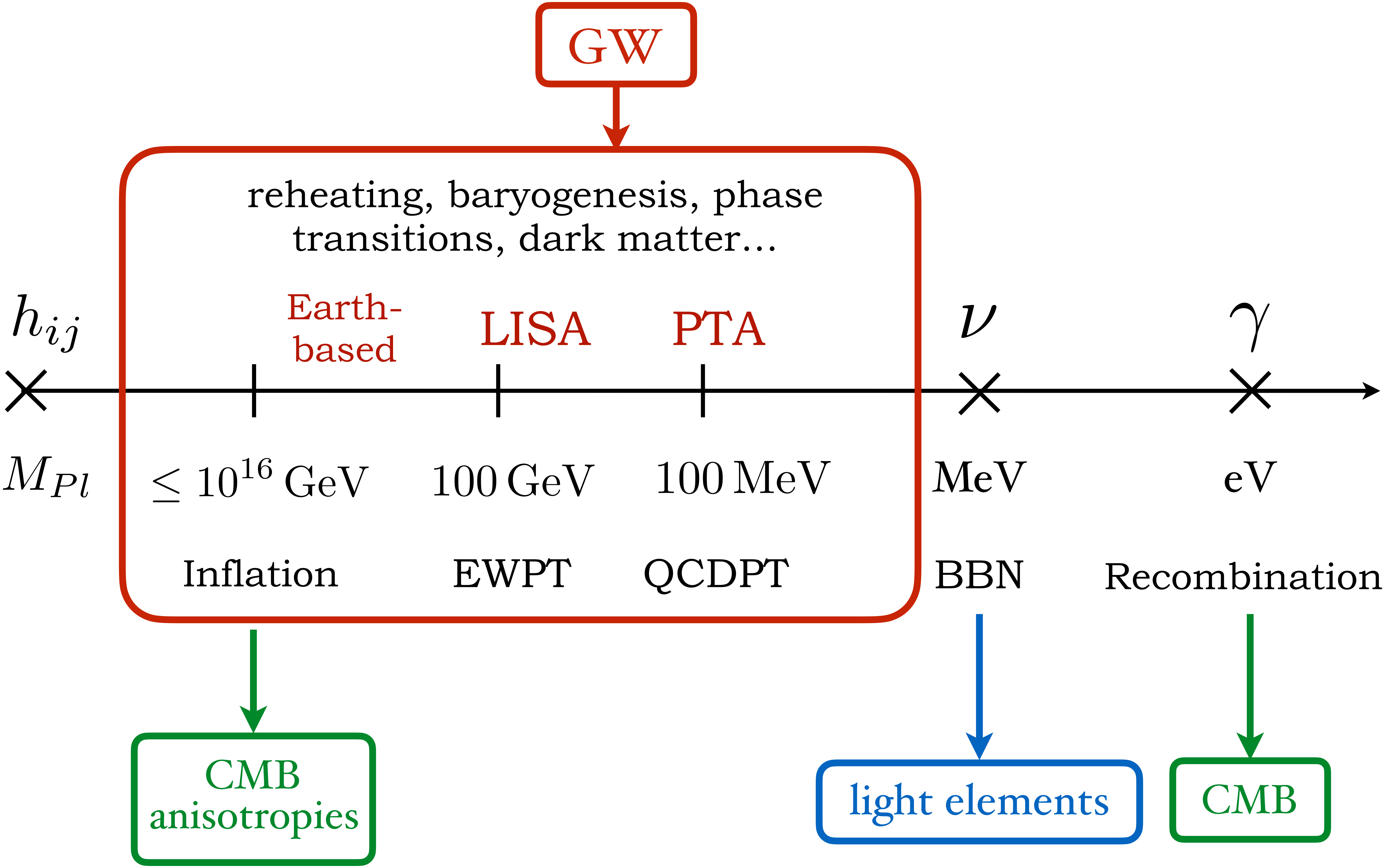


Adams and Cornish, 1307.4116

GWs can bring direct information from very early stages of the universe evolution, to which we have no direct access through em radiation

amazing discovery potential, linked to high energy physics

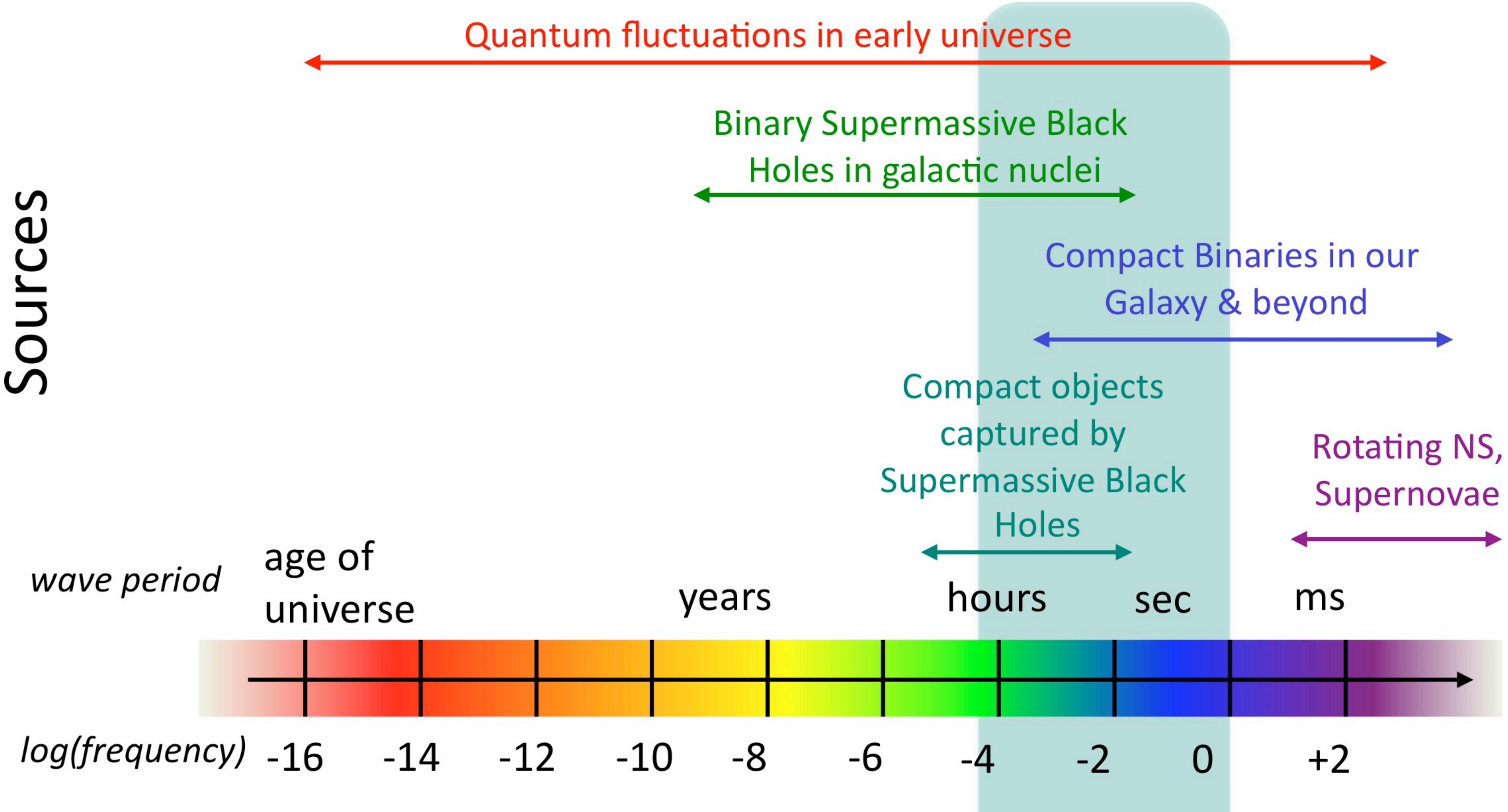
Which energy scales in the universe can we access with GWs compared to usual cosmological observables?



GW

reheating, baryogenesis, phase transitions, dark matter…

The Gravitational Wave Spectrum



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Detectors

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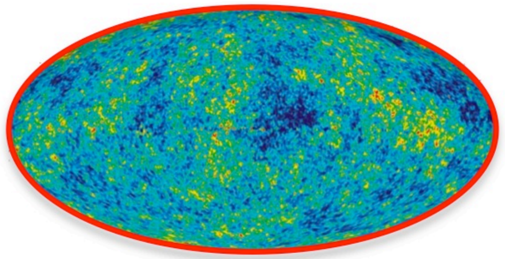
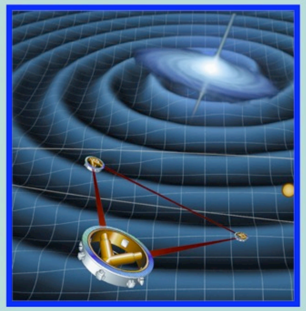


Pulsar Timing

Space Interferometers



Terrestrial interferometers

NASA Goddard Space Flight Center

Earth-based GW detection

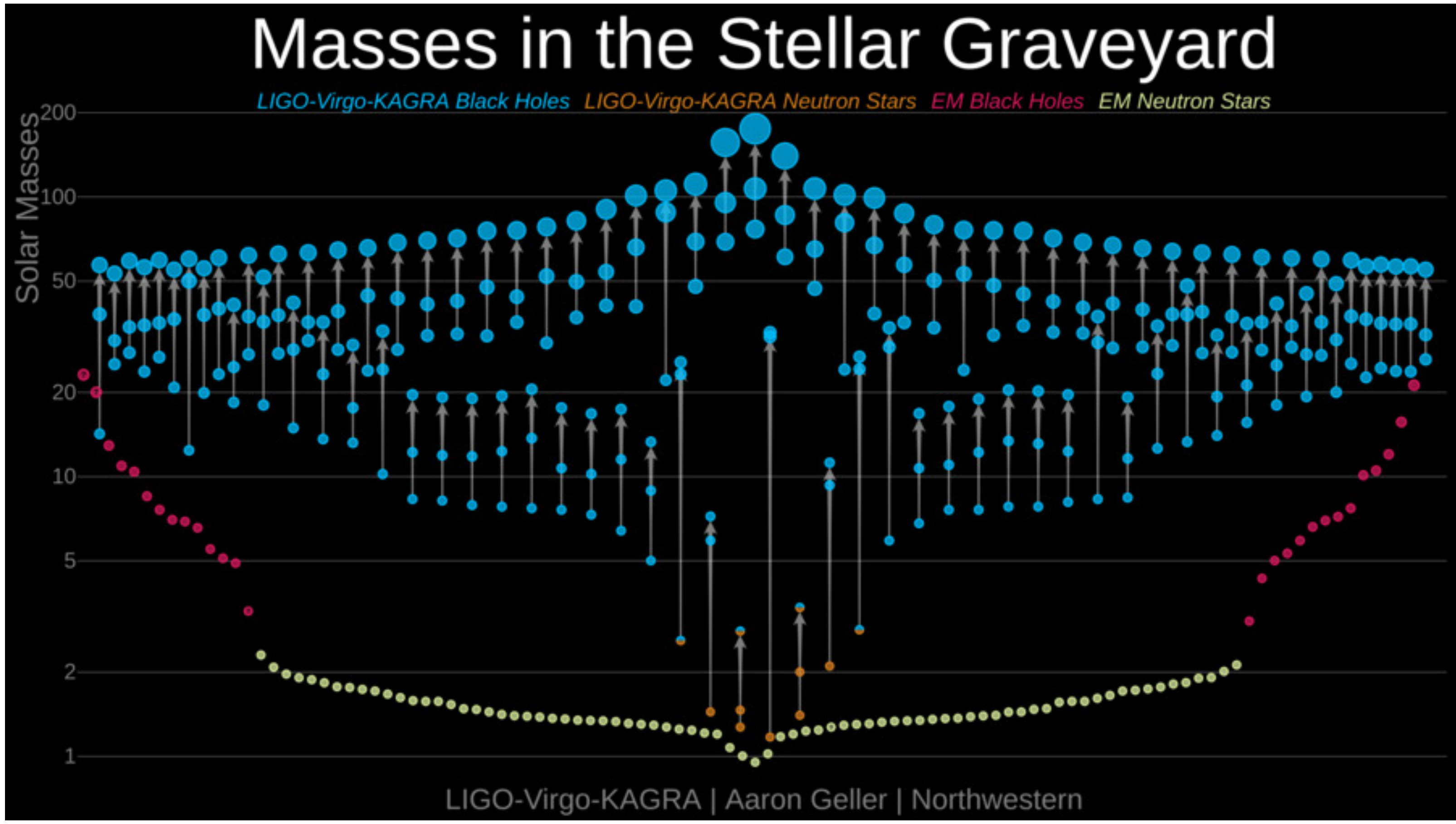
Advanced LIGO/Virgo/KAGRA interferometers +
LIGO India? Einstein Telescope? Cosmic Explorer?

arm length: few km

frequency range of detection: $10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$

TARGET SOURCES:

- Coalescing black hole binaries of few to hundred solar masses
- Neutron Star and NS-BH binaries
- Possibly: SN explosions, rotating NS, stochastic GW background from astrophysical and cosmological sources

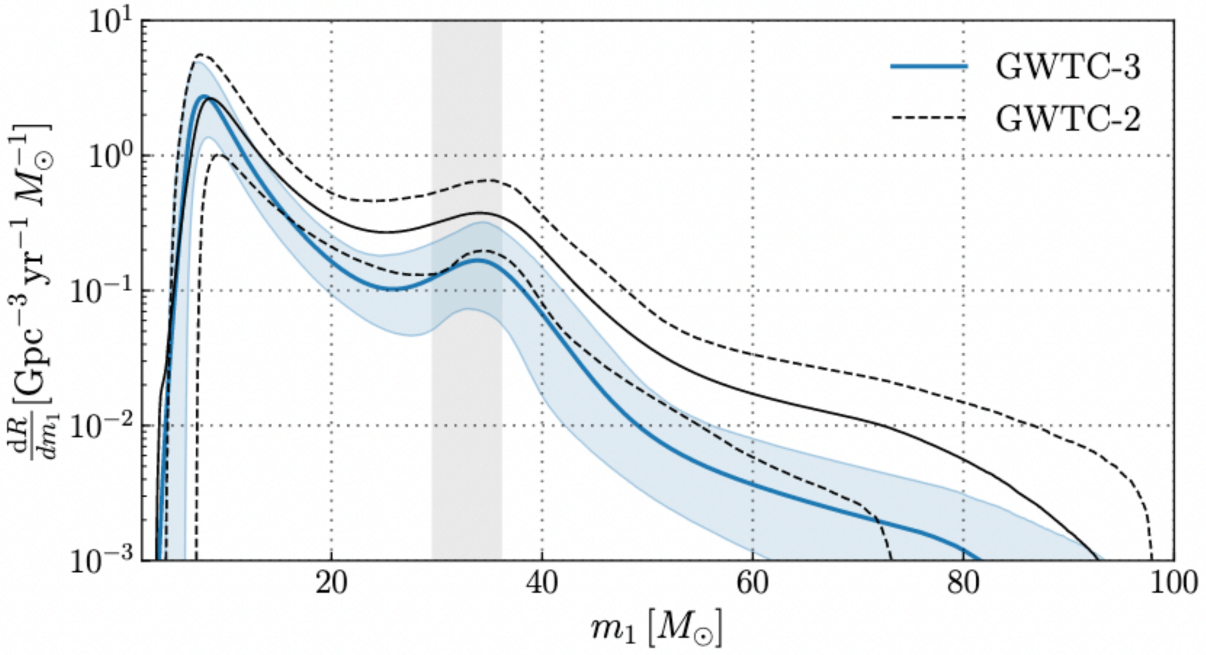


GWTC 3 catalogue, LIGO/Virgo website

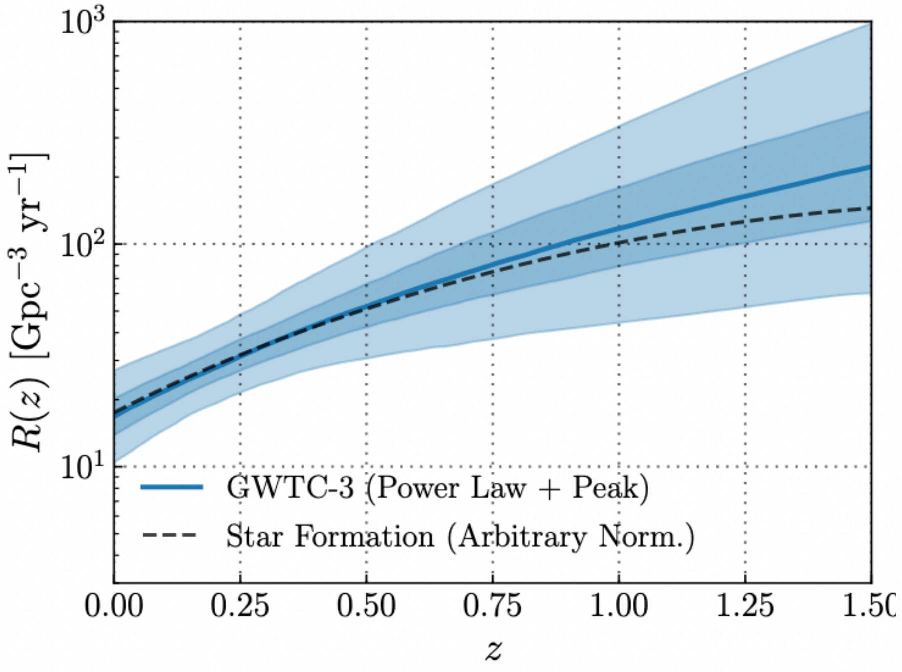
Earth-based GW detection

Properties of the compact binaries:
population, merger rates -> origin, formation channels…

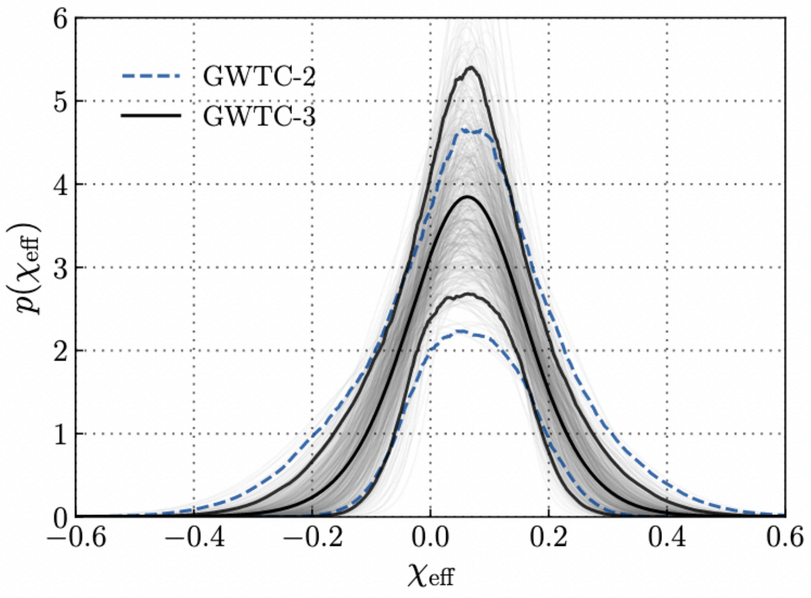
BHBs from GWTC-3
arXiv:2111.03634



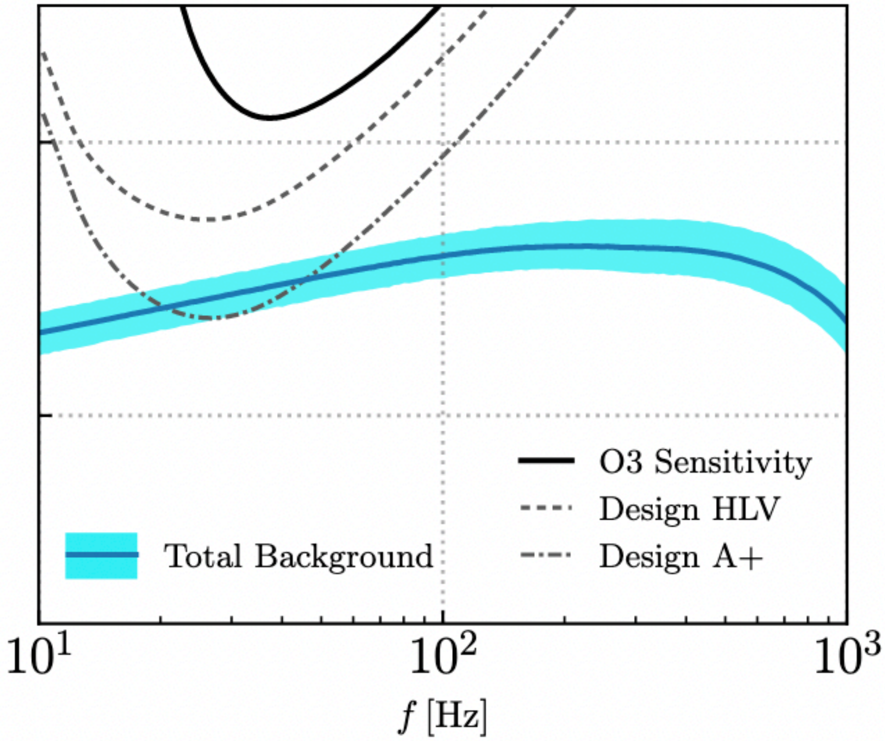
Mass distribution



Merger rate evolution



Spin distribution

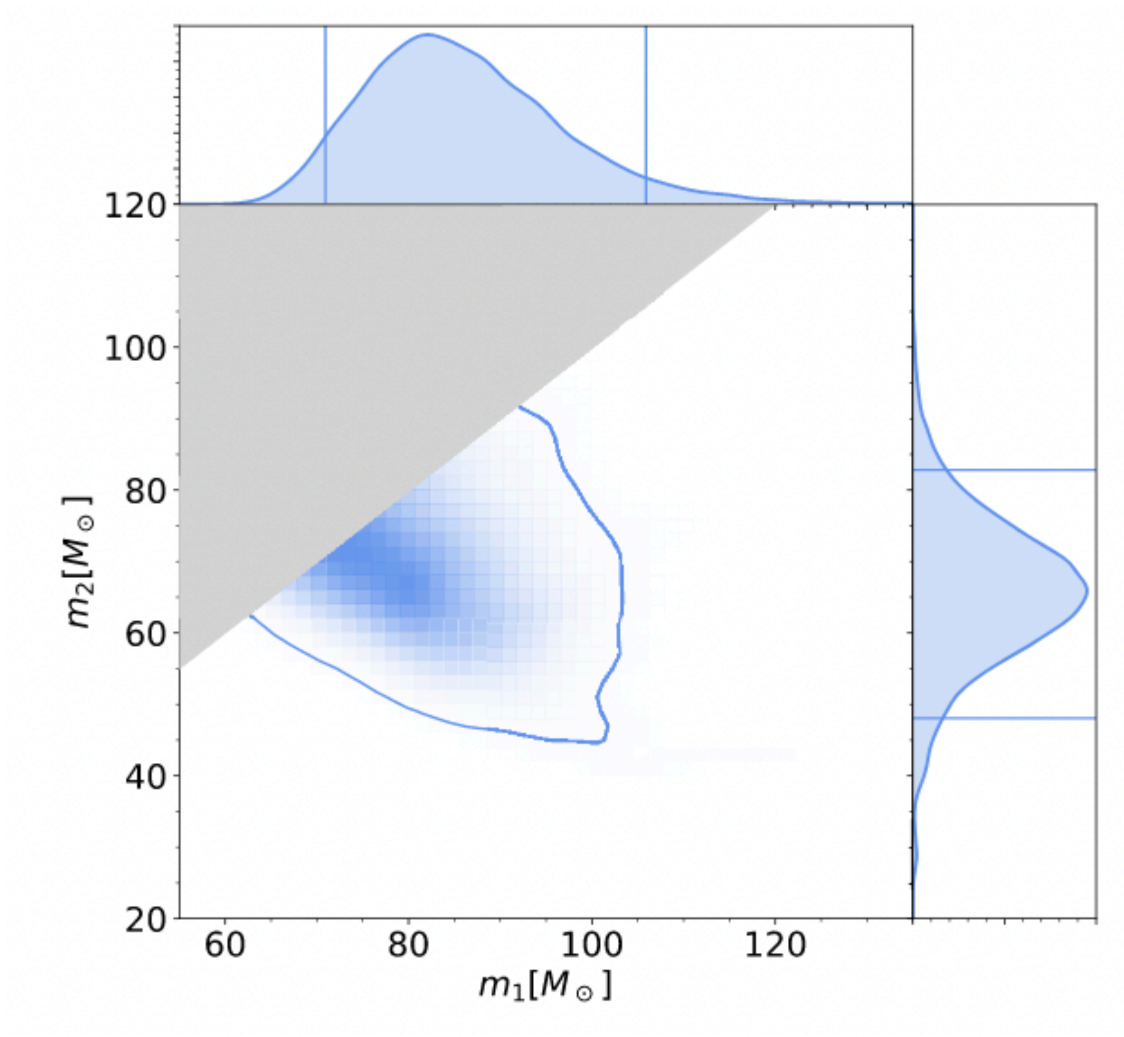


Expected stochastic signal

Earth-based GW detection

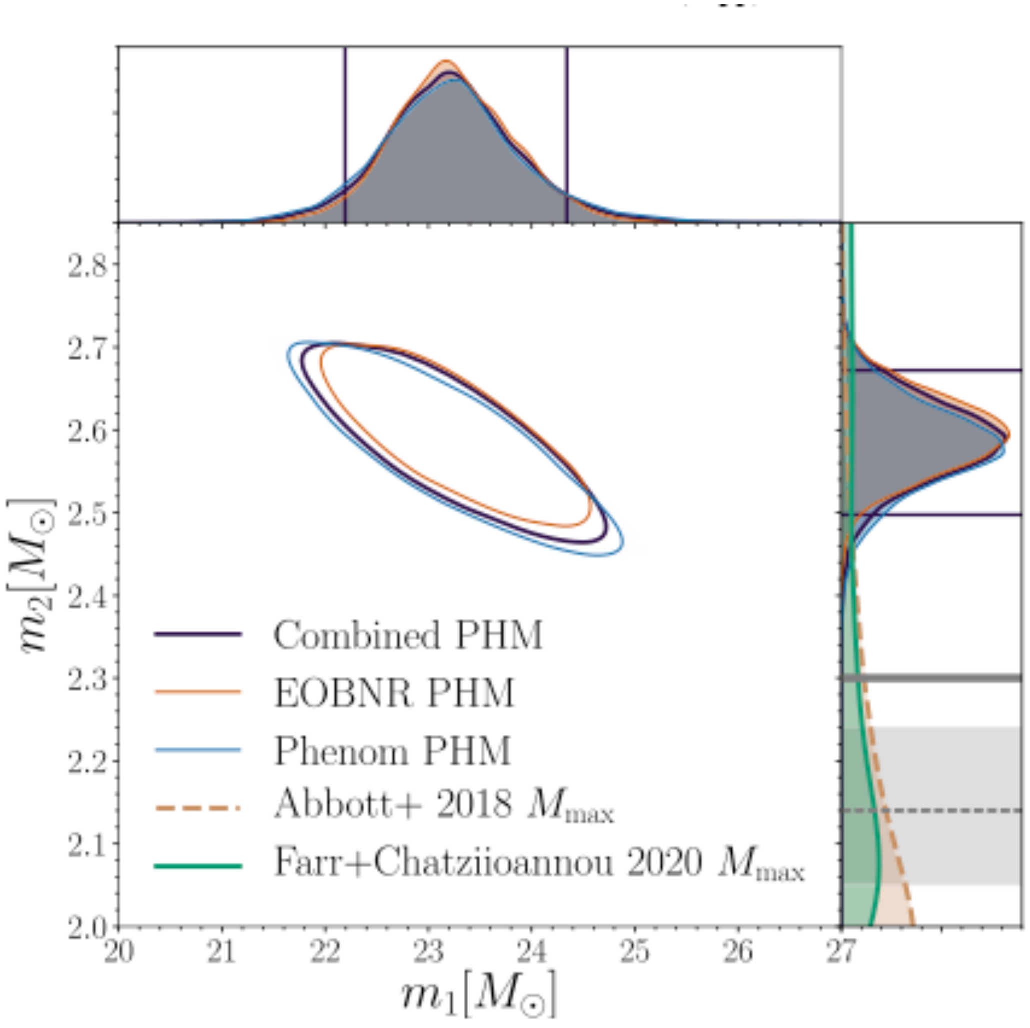
Unusual events, which challenge astrophysical models and/or enlighten them, allowing for new discoveries

GW190521



arXiv:2009.01075

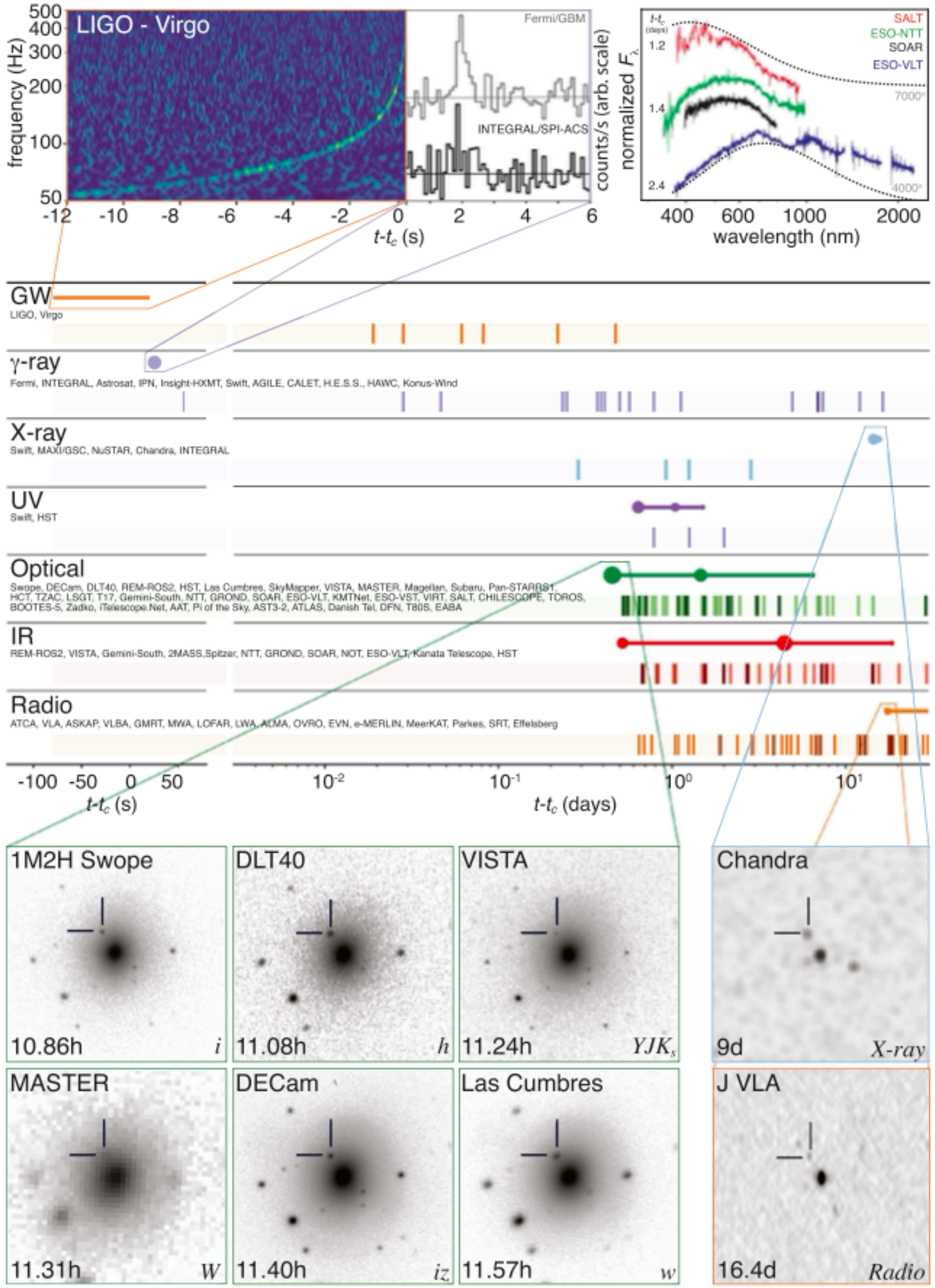
GW190814



arXiv:2006.12611

Earth-based GW detection

Unusual events, which challenge astrophysical models
and/or enlighten them, allowing for new discoveries



GW170817: the birth of
multi messenger astronomy

$$m_1 = 1.36 - 1.60\, M_\odot$$

$$m_2 = 1.17 - 1.36\, M_\odot$$

$$M_c = 1.188^{+0.004}_{-0.002}\, M_\odot$$

$$d_L = 40^{+8}_{-14}\,\mathrm{Mpc}$$

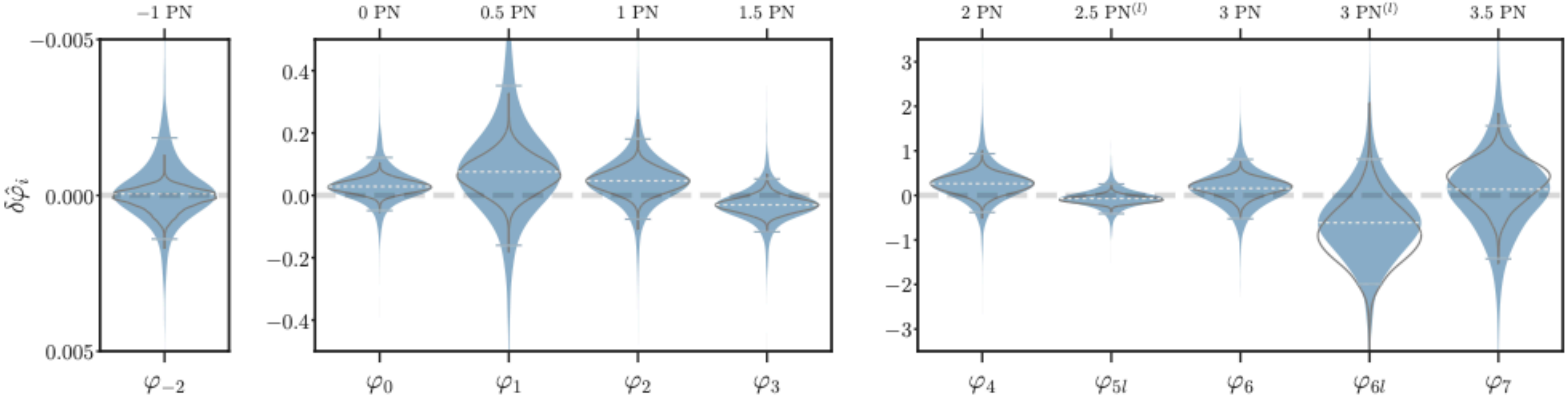
- Associate gamma-ray bursts and neutron star mergers
- Constrain GW propagation speed and in turn modified gravity theories
- Probe the expansion of the universe
- …

arXiv:1710.05833

Earth-based GW detection

Tests of General Relativity

- GW generation: post Newtonian terms
- **GW speed vs speed of light -> constraints on cosmological theories**
- Polarisations
- Dispersion relation
- Ring-down and echoes

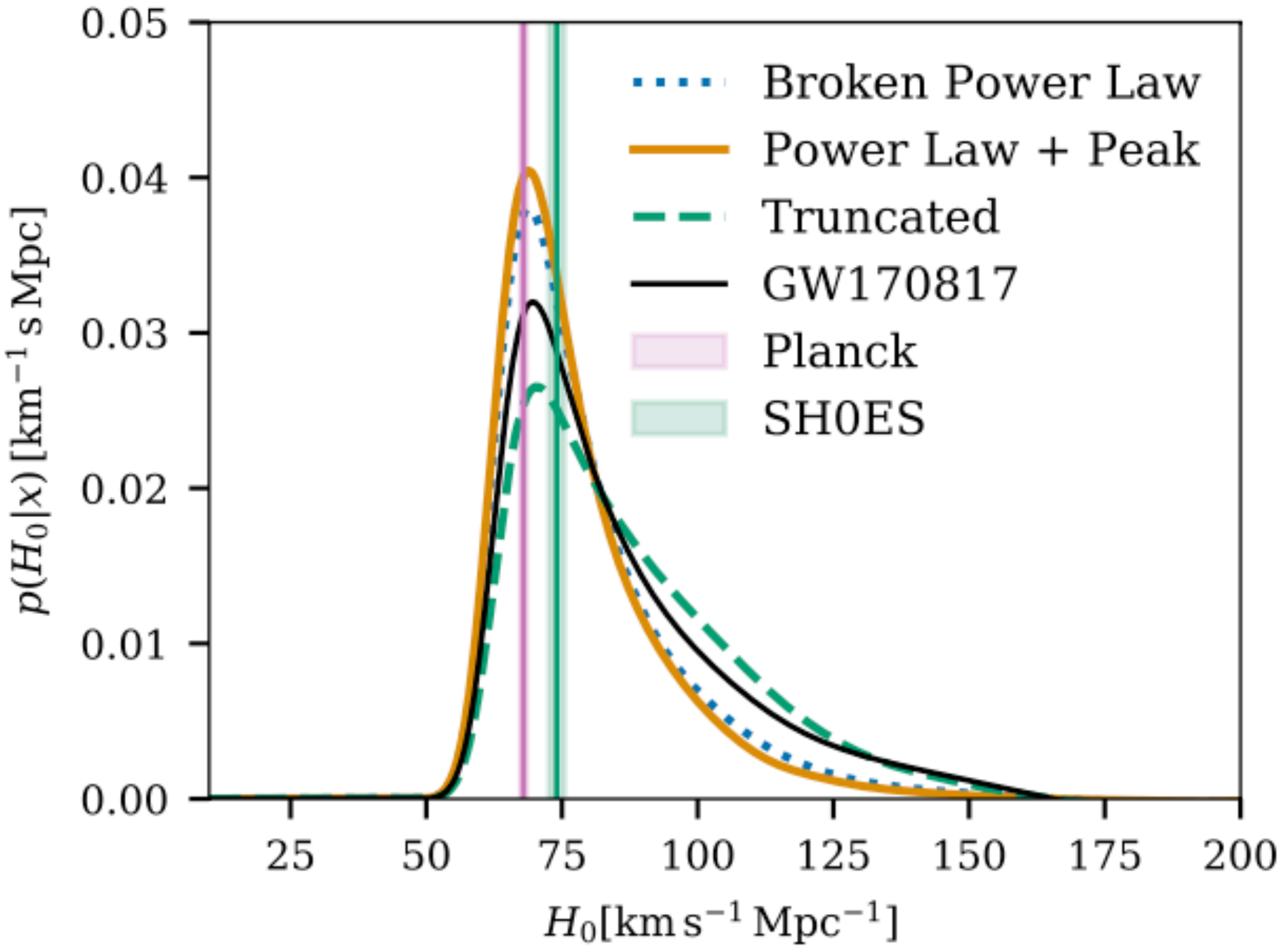


arXiv:2112.06861

Earth-based GW detection

Tests of the expansion of the universe

- GW170817: luminosity distance from GW and redshift from EM counterpart
- Assuming a mass distribution with features -> get the true mass -> get the redshift
- Cross-correlating with galaxy surveys



arXiv:2111.03604

Space-based GW detection

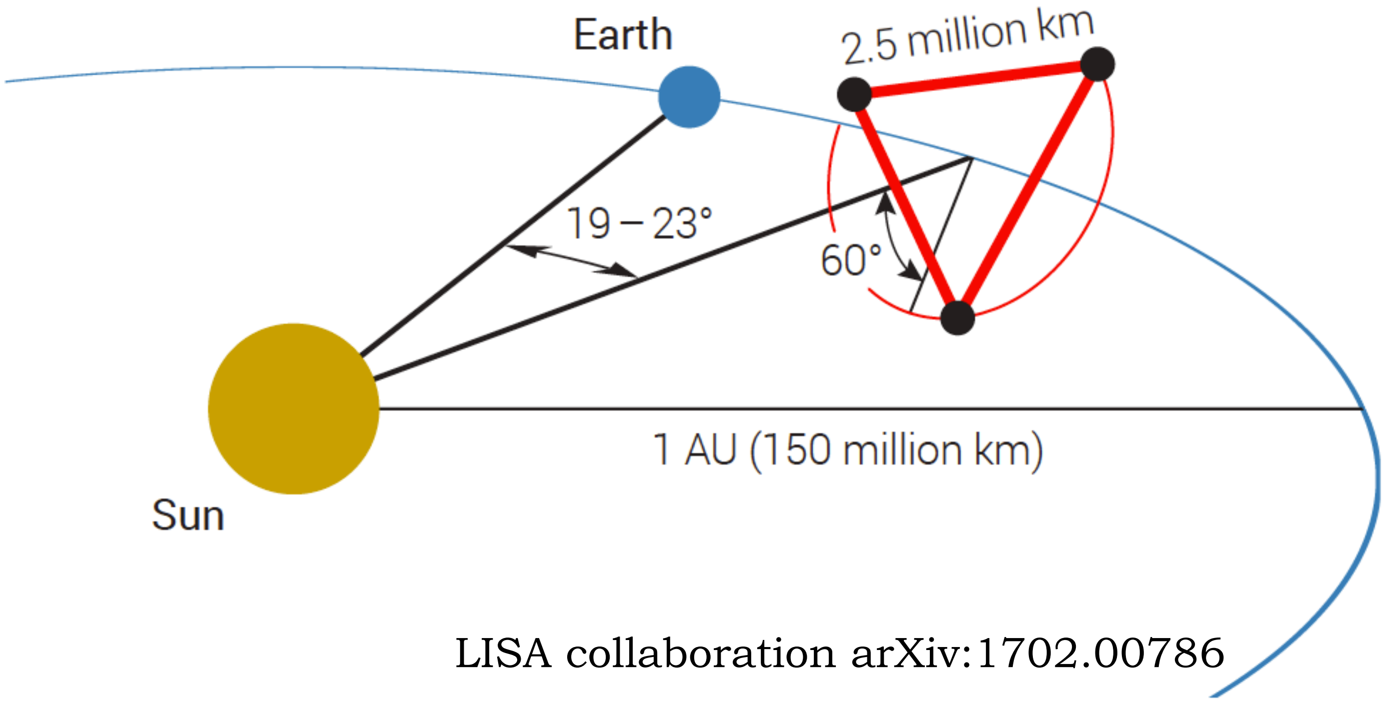
LISA: Laser Interferometer Space Antenna

- no seismic noise
- much longer arms than on Earth: 2.5 million km

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$

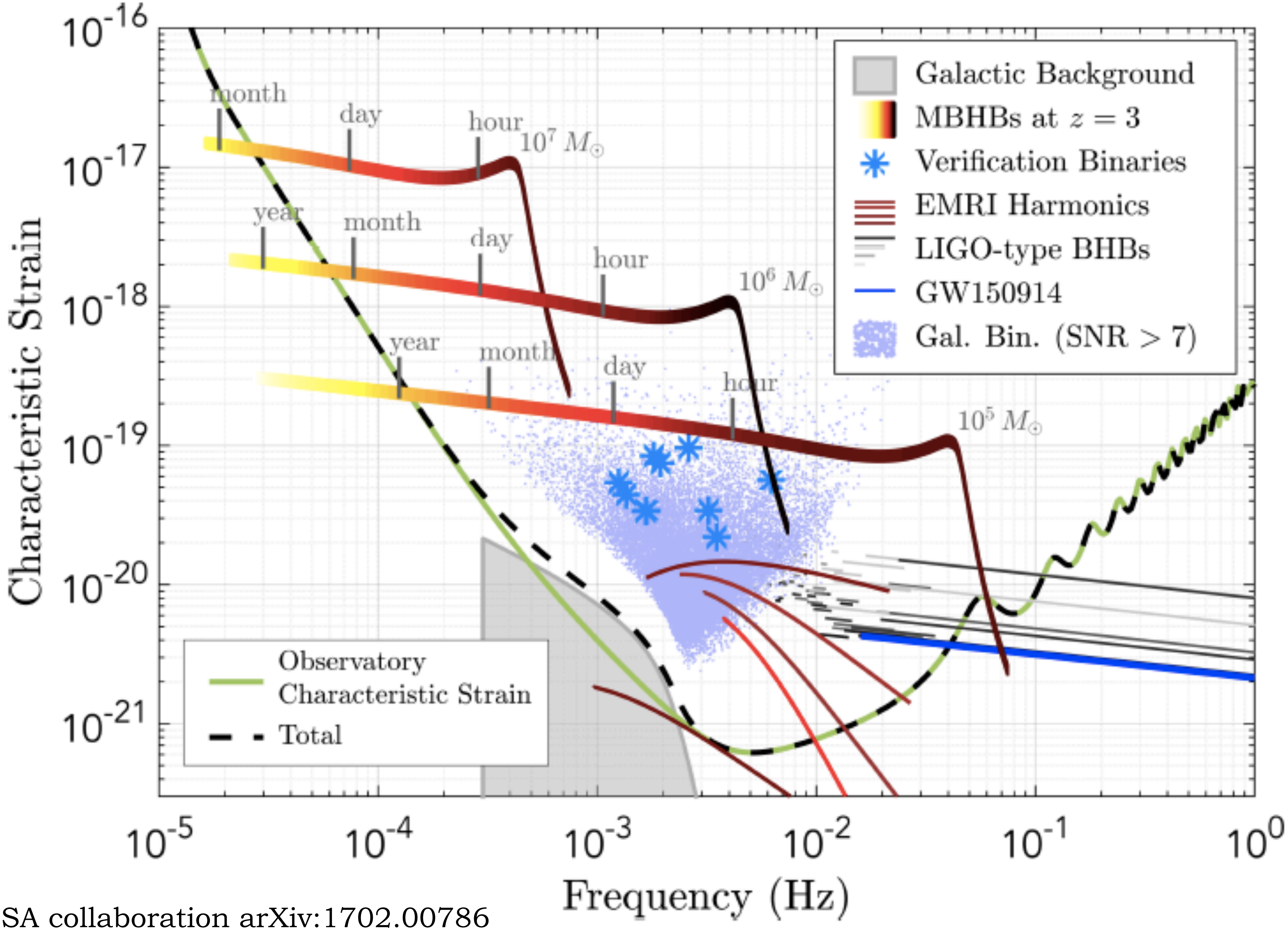
TARGET SOURCES:

- Coalescing massive BH binaries: 10^4 to 10^7 solar masses
- Inspiralling black hole binaries of few to hundred solar masses
- Inspiralling galactic binaries (white dwarfs, neutron stars…)
- Extreme Mass Ratio Inspirals
- Stochastic GW background from astrophysical and cosmological sources



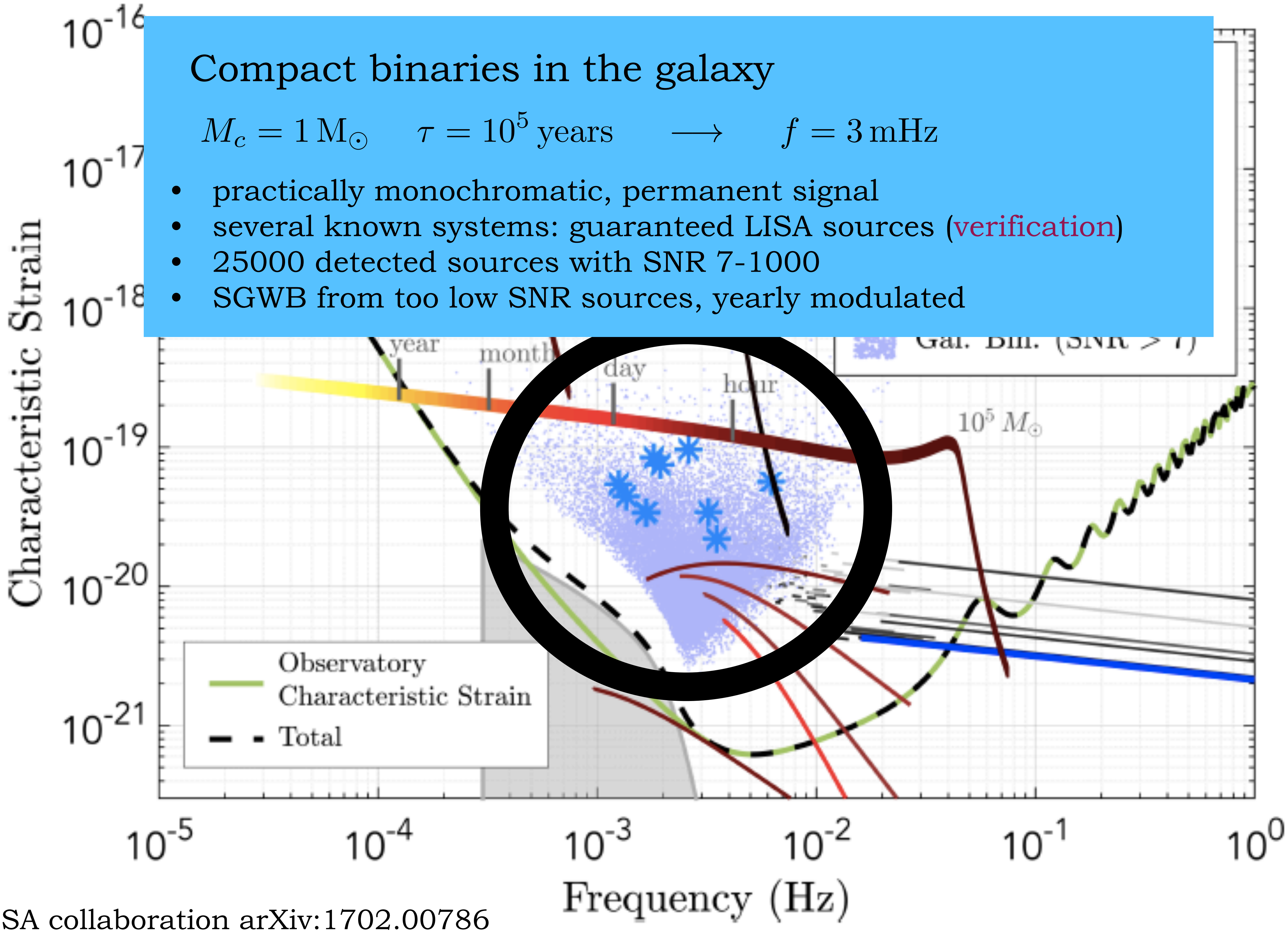
LISA collaboration arXiv:1702.00786

Space-based GW detection



LISA collaboration arXiv:1702.00786

Space-based GW detection



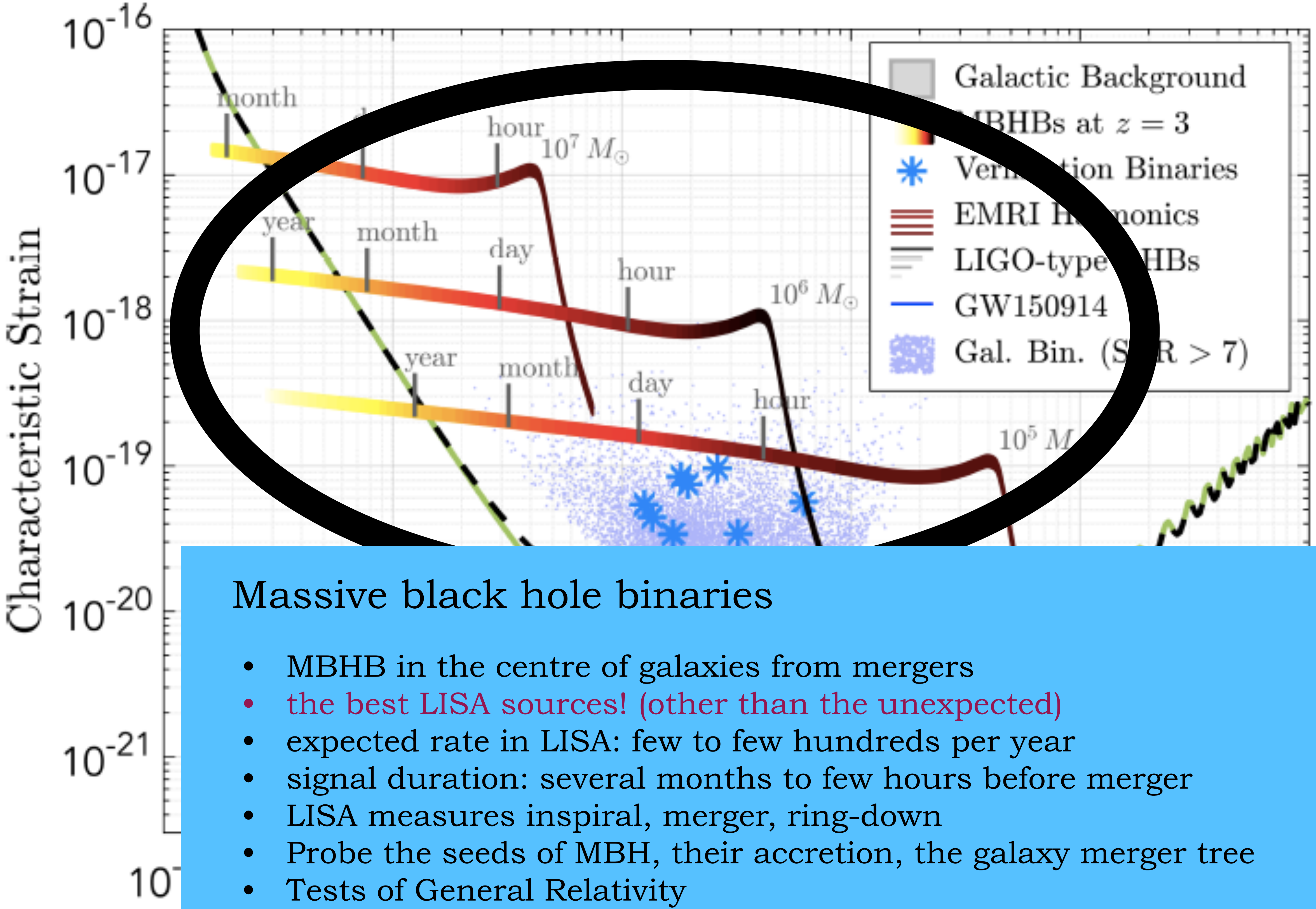
Compact binaries in the galaxy

$$M_c = 1\,\mathrm{M}_\odot \qquad \tau = 10^5\ \text{years} \qquad \longrightarrow \qquad f = 3\,\mathrm{mHz}$$

- practically monochromatic, permanent signal
- several known systems: guaranteed LISA sources (verification)
- 25000 detected sources with SNR 7-1000
- SGWB from too low SNR sources, yearly modulated

LISA collaboration arXiv:1702.00786

Space-based GW detection



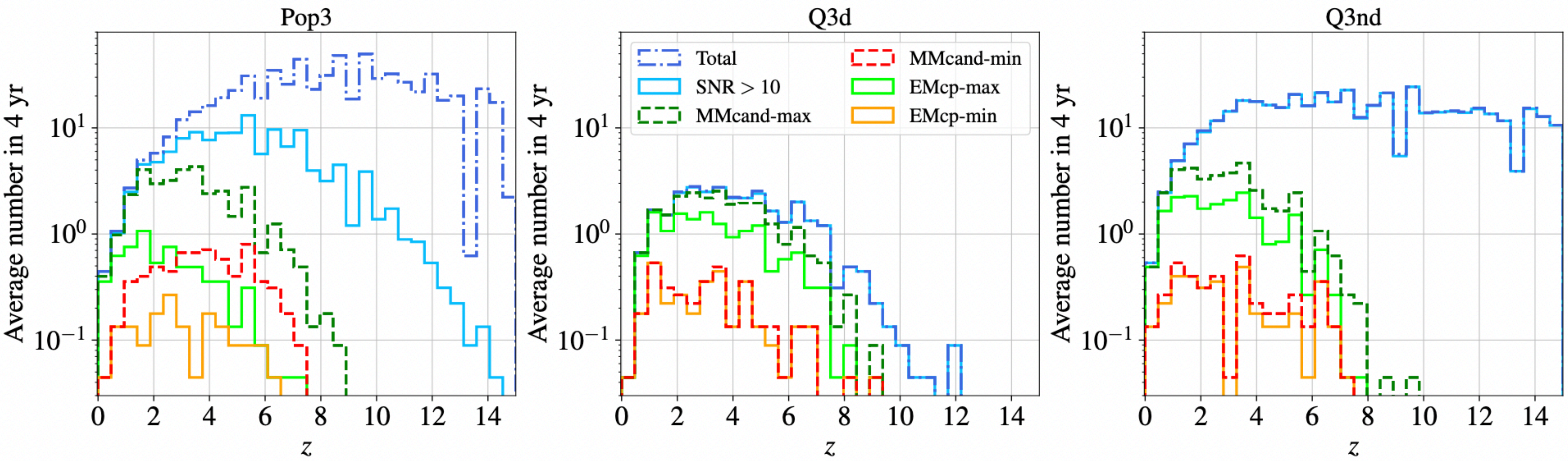
LISA collabora

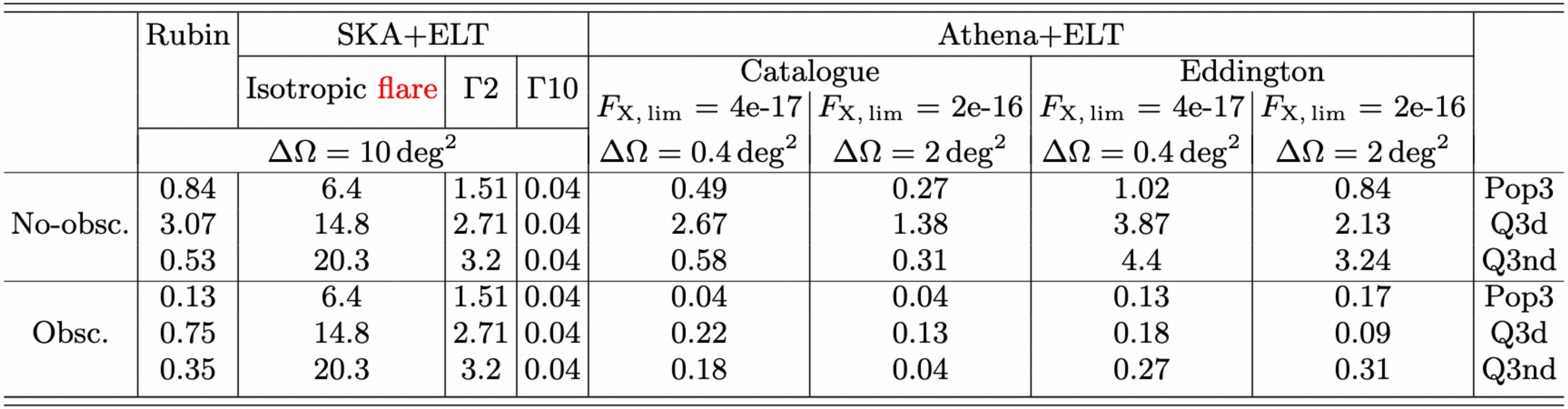
Massive black hole binaries

- MBHB in the centre of galaxies from mergers
- the best LISA sources! (other than the unexpected)
- expected rate in LISA: few to few hundreds per year
- signal duration: several months to few hours before merger
- LISA measures inspiral, merger, ring-down
- Probe the seeds of MBH, their accretion, the galaxy merger tree
- Tests of General Relativity
- EM counterparts?

Space-based GW detection

EM counterparts are few and cluster at redshift $2 < z < 5$
their number depends heavily on the astrophysical generation model
and on the possible EM detection channel

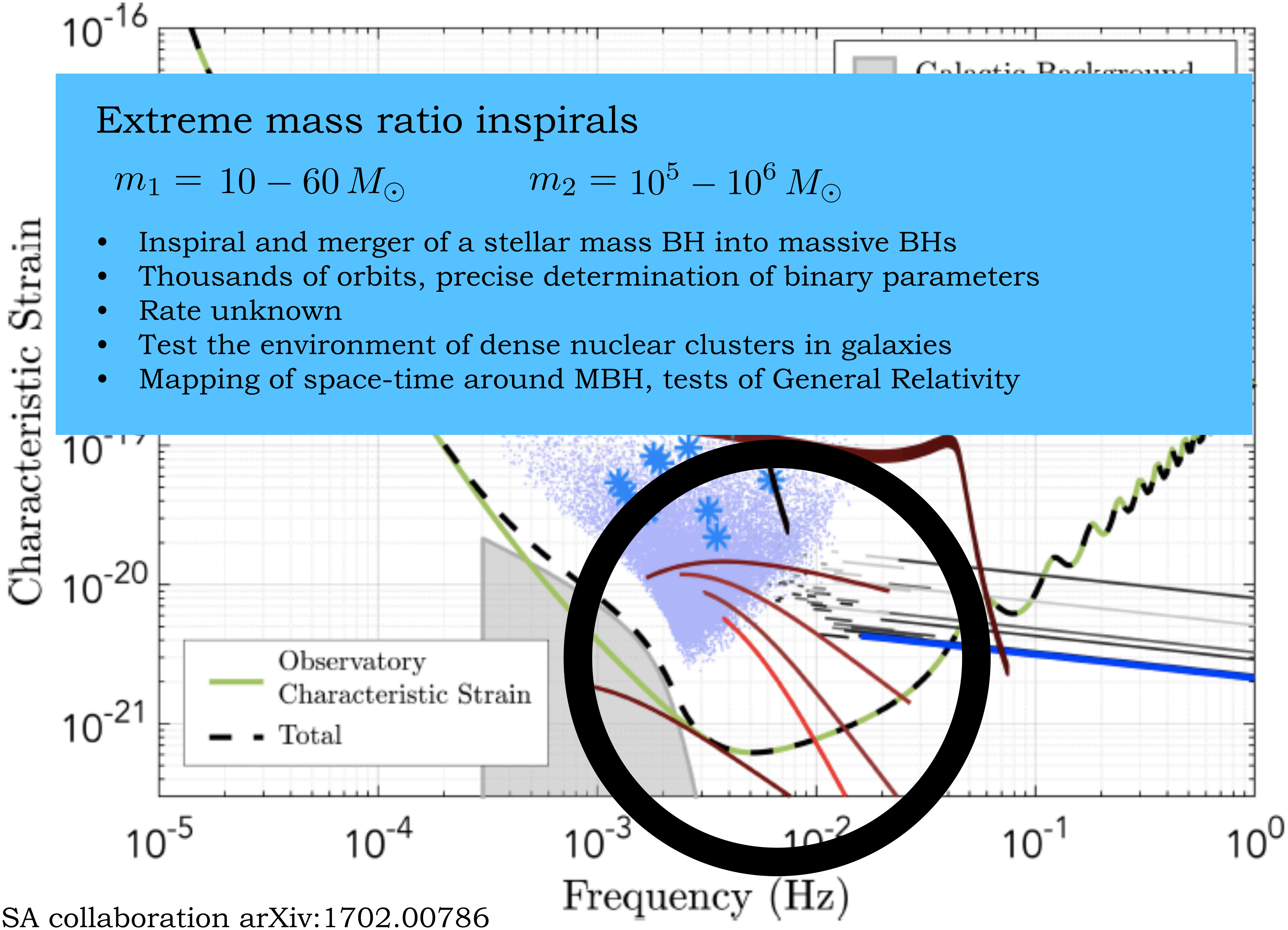




	Rubin	SKA+ELT			Athena+ELT				
					Catalogue		Eddington		
		Isotropic flare	Γ2	Γ10	$F_{\mathrm{X,\,lim}} = 4\text{e-}17$	$F_{\mathrm{X,\,lim}} = 2\text{e-}16$	$F_{\mathrm{X,\,lim}} = 4\text{e-}17$	$F_{\mathrm{X,\,lim}} = 2\text{e-}16$	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	
No-obsc.	0.84	6.4	1.51	0.04	0.49	0.27	1.02	0.84	Pop3
	3.07	14.8	2.71	0.04	2.67	1.38	3.87	2.13	Q3d
	0.53	20.3	3.2	0.04	0.58	0.31	4.4	3.24	Q3nd
Obsc.	0.13	6.4	1.51	0.04	0.04	0.04	0.13	0.17	Pop3
	0.75	14.8	2.71	0.04	0.22	0.13	0.18	0.09	Q3d
	0.35	20.3	3.2	0.04	0.18	0.04	0.27	0.31	Q3nd

Tamanini et al, arXiv:1601.07112; Mangiagli et al, arXiv:2207.10678

Space-based GW detection



Extreme mass ratio inspirals

$m_1 = 10 - 60\, M_\odot \qquad m_2 = 10^5 - 10^6\, M_\odot$

- Inspiral and merger of a stellar mass BH into massive BHs
- Thousands of orbits, precise determination of binary parameters
- Rate unknown
- Test the environment of dense nuclear clusters in galaxies
- Mapping of space-time around MBH, tests of General Relativity

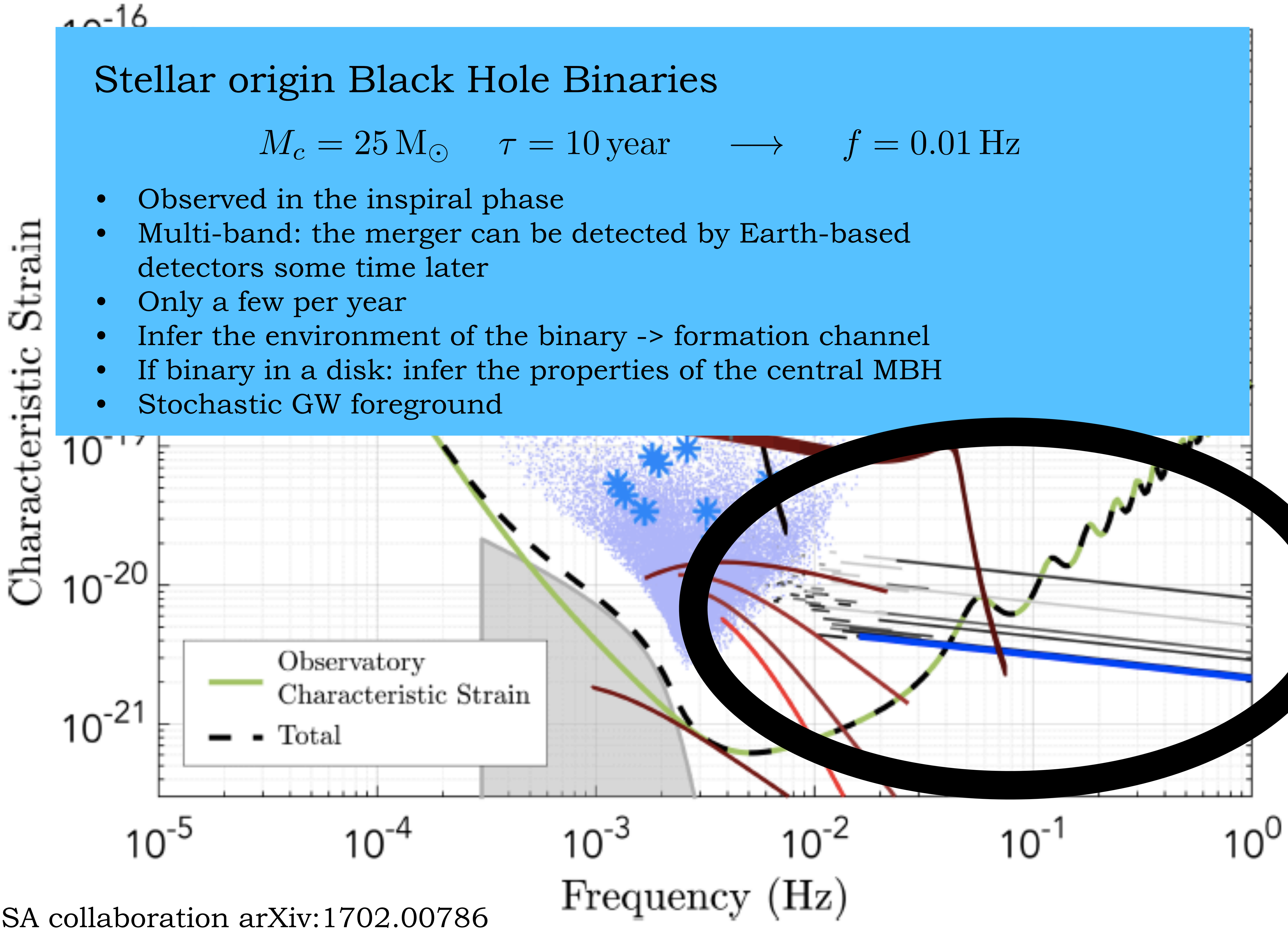
LISA collaboration arXiv:1702.00786

Space-based GW detection

Stellar origin Black Hole Binaries

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 10\,\mathrm{year} \qquad \longrightarrow \qquad f = 0.01\,\mathrm{Hz}$$

- Observed in the inspiral phase
- Multi-band: the merger can be detected by Earth-based detectors some time later
- Only a few per year
- Infer the environment of the binary -> formation channel
- If binary in a disk: infer the properties of the central MBH
- Stochastic GW foreground

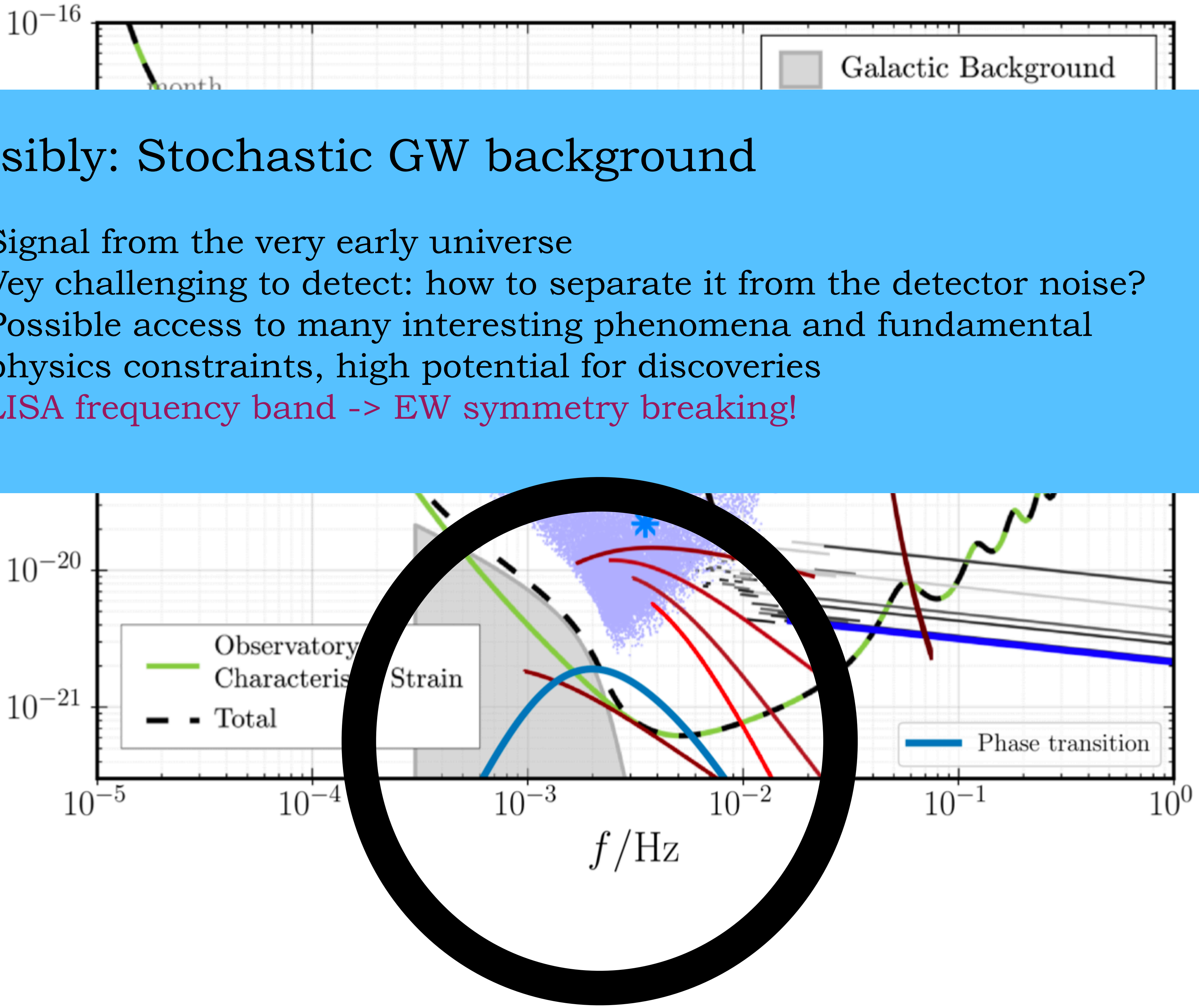


LISA collaboration arXiv:1702.00786

Space-based GW detection

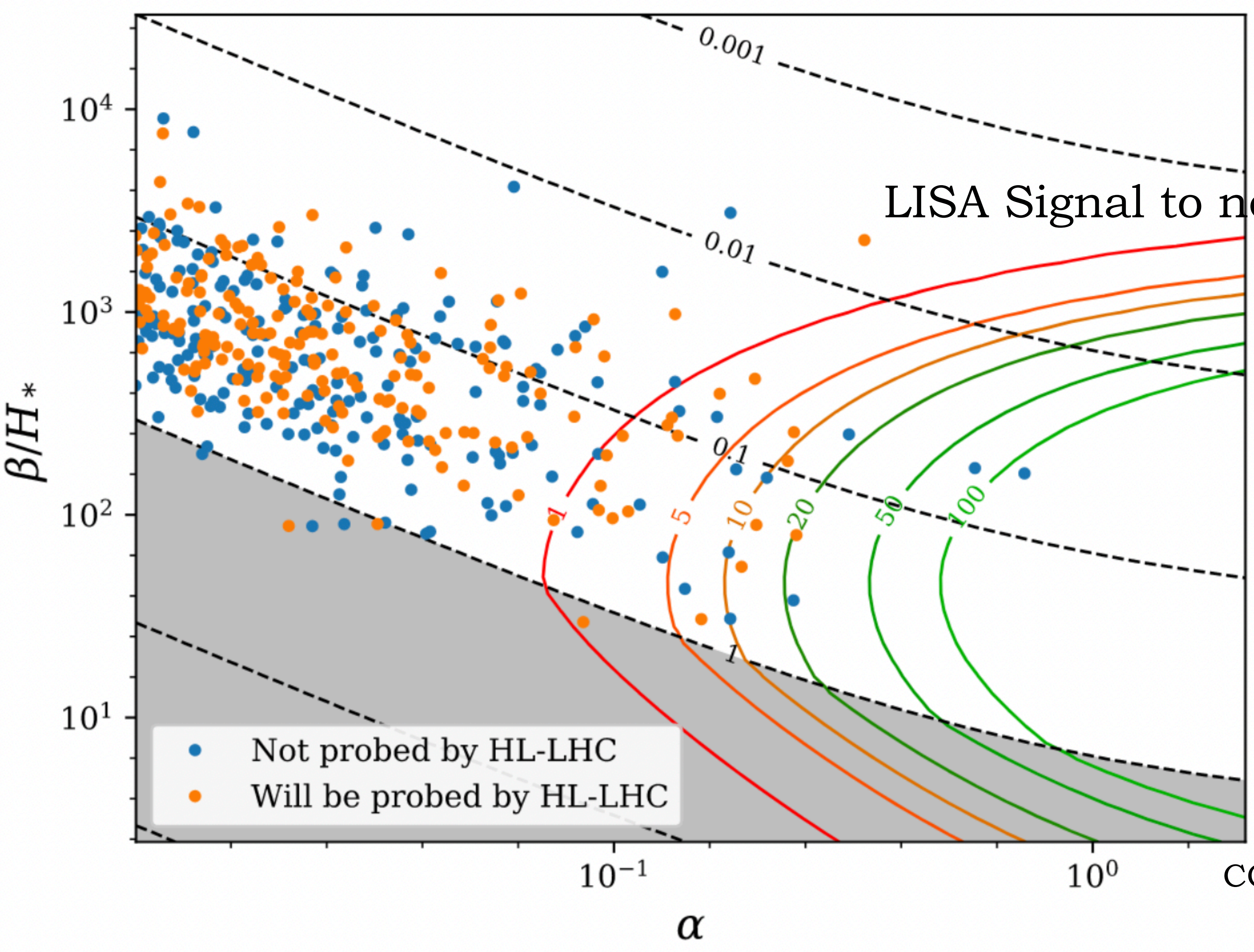
Possibly: Stochastic GW background

- Signal from the very early universe
- Vey challenging to detect: how to separate it from the detector noise?
- Possible access to many interesting phenomena and fundamental physics constraints, high potential for discoveries
- LISA frequency band -> EW symmetry breaking!



One example of GW signal from the EW phase transition
“Higgs portal” scenario
Can be probed both at LISA and at the High Luminosity LHC

Inverse duration of the first order EW phase transition



LISA Signal to noise ratio curves

CC et al, arXiv:1910.13125

Strength of the first order EW phase transition

Space-based GW detection

Pulsar timing array

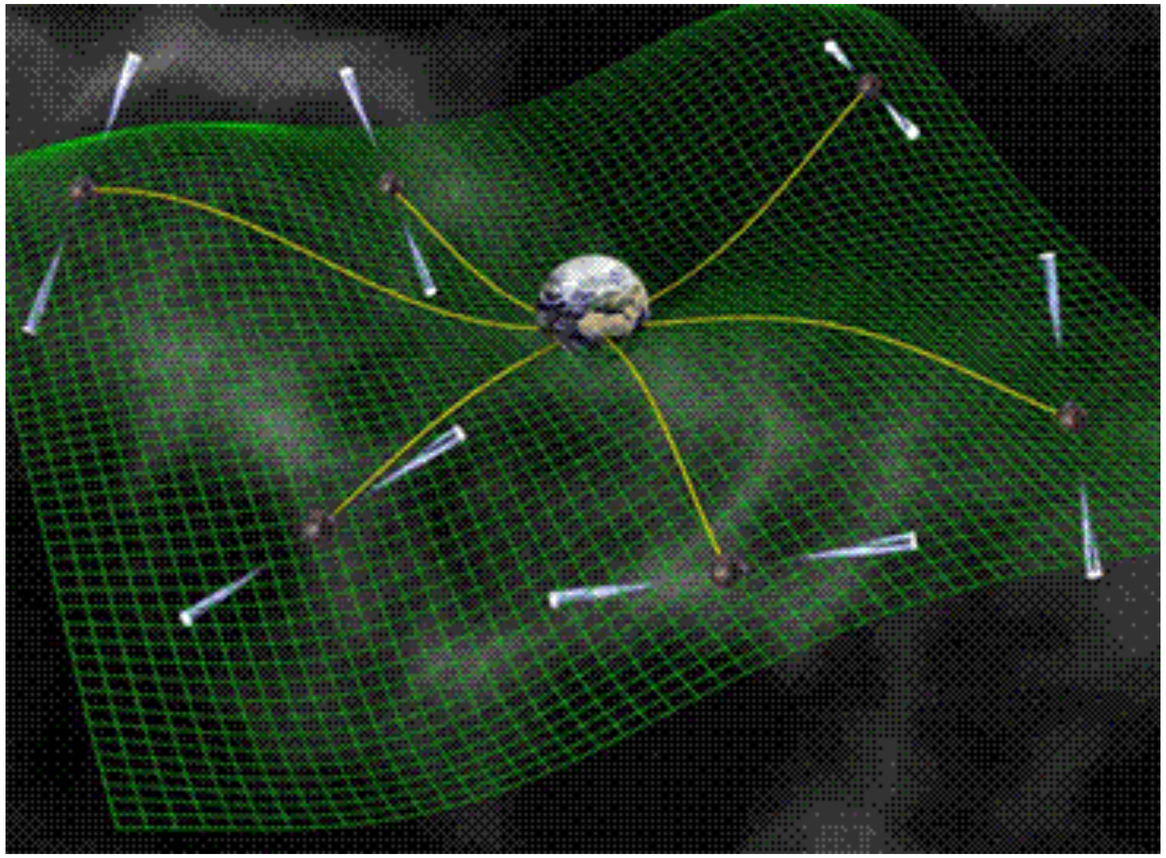
frequency range of detection: $10^{-9}\,\mathrm{Hz} < f < 10^{-7}\,\mathrm{Hz}$

OBSERVABLE:
correlated shifts in time of arrivals of radio pulses due to GW propagation between Pulsar and Earth

TARGET SOURCE:
Super Massive BH binaries (masses of order 10^9 solar masses):
stochastic background from inspirals and/or resolved signals

Recent discovery of correlated noise in all Pulsar networks!
(NanoGrav, Parkes, European, International)

Z. Arzoumanian et al, arXvi: 2009.04496, B. Goncharov et al, arXiv:2107.12112, S. Chen et al, arXiv:2110.13184



Space-based GW detection

Pulsar timing array

- There is a strong statistical support for the presence of a common red noise
- There is no evidence yet for a quadrupolar signal
- Possible explanation: background from SMBHBs

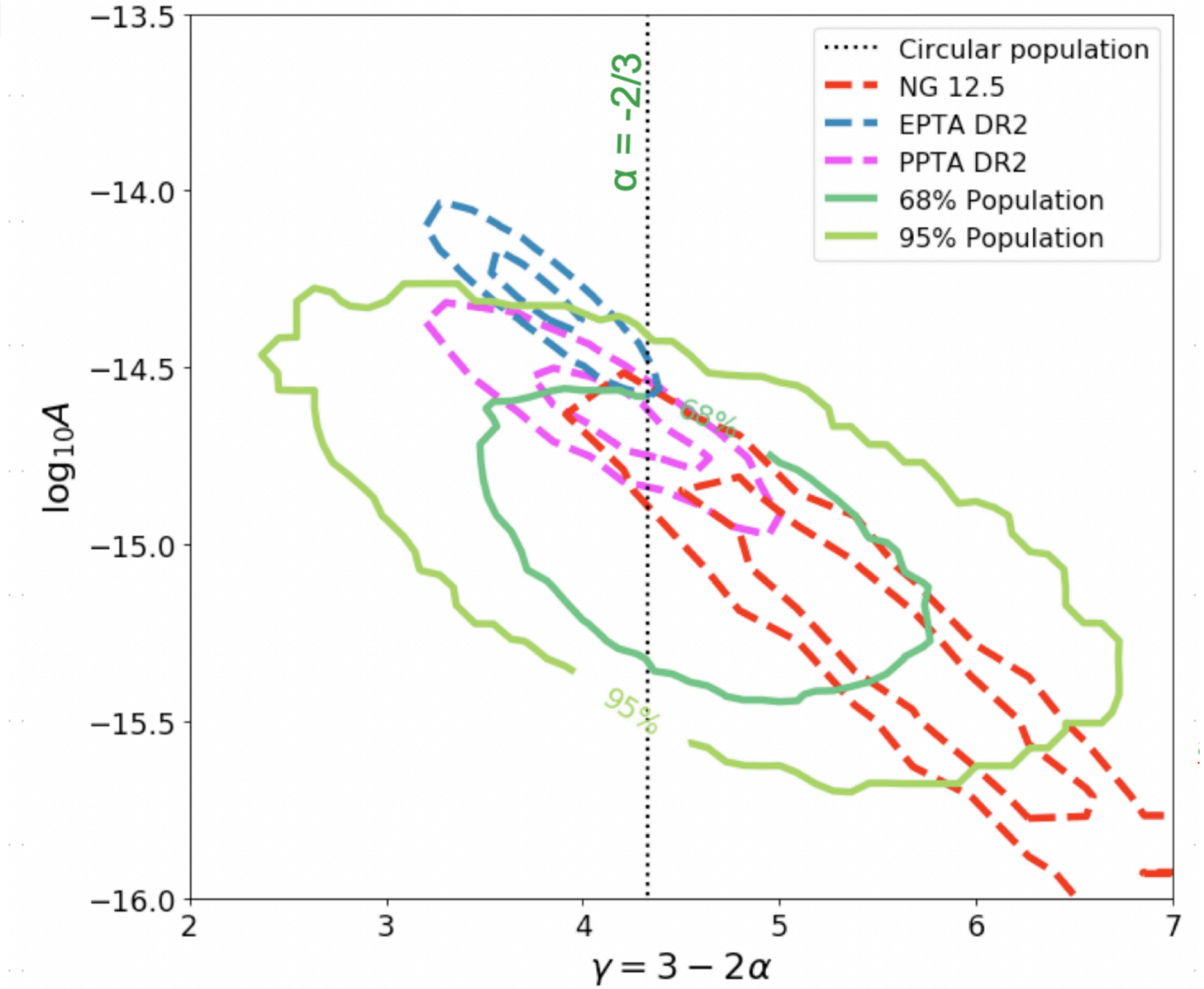


Figure from:
S. Babak & S. Chen, 2021

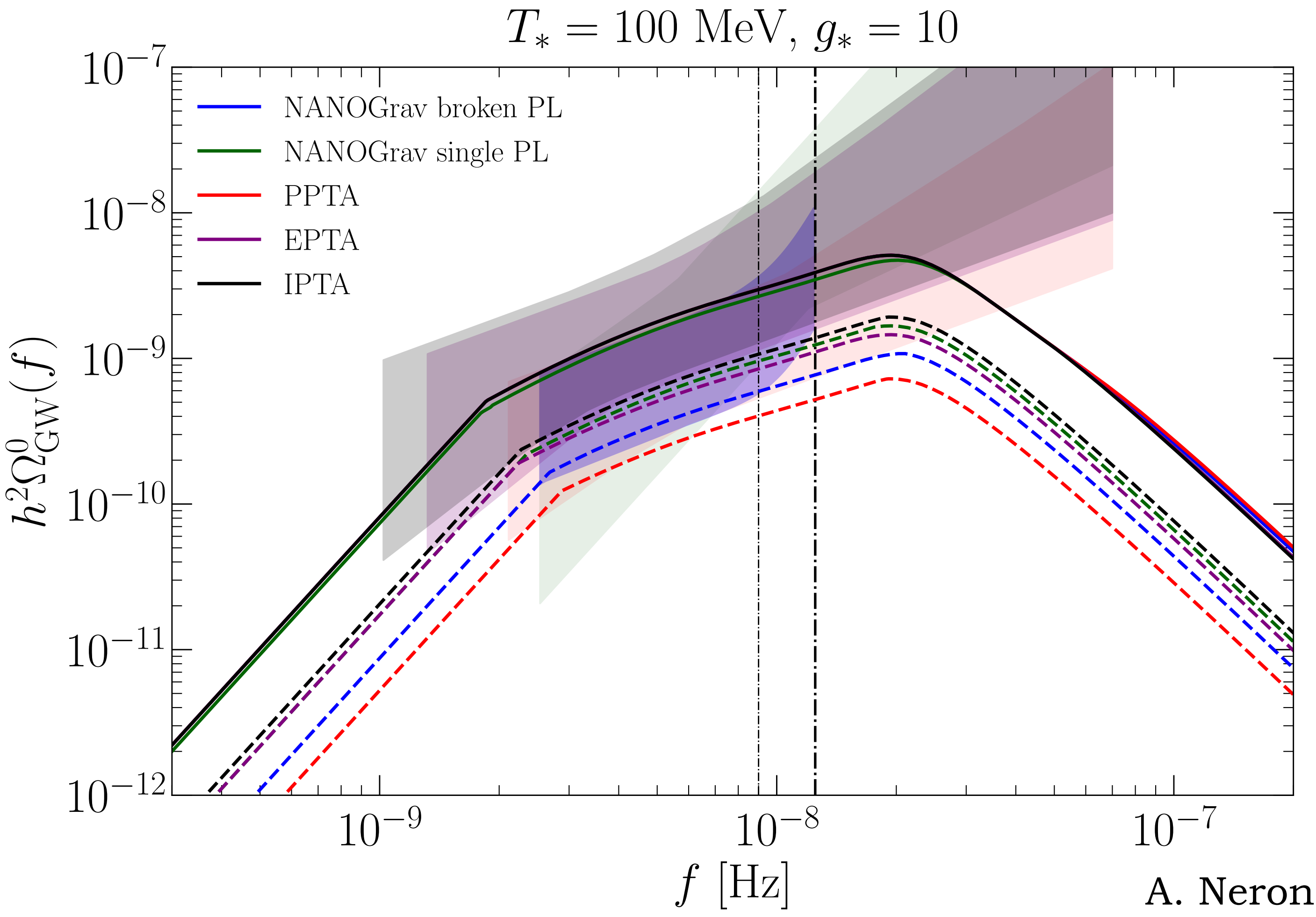
Z. Arzoumanian et al, arXvi: 2009.04496, B. Goncharov et al, arXiv:2107.12112, S. Chen et al, arXiv:2110.13184

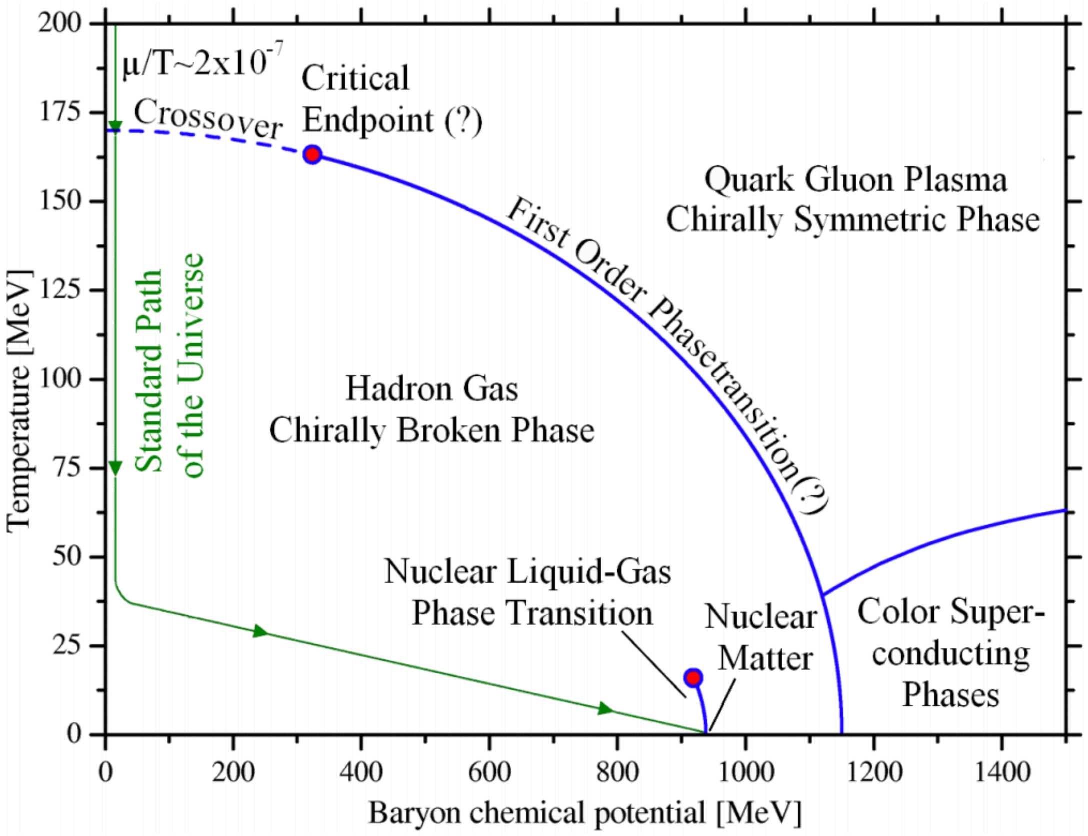
Space-based GW detection

Pulsar timing array

PTA (nHz) are sensitive to energy scales around the **QCD scale**, so they can probe physical processes connected to the QCDPT IF it is first order

It is compatible with the GW generated by fully developed MHD turbulence at the QCD scale


$T_* = 100$ MeV, $g_* = 10$



T. Boekel and J. Schaffner-Bielich, arXiv:1105.0832
D. Schwarz and Stuke, arXiv:0906.3434
M. Middeldorf-Wygas et al, arXiv:2009.00036

A. Neronov et al, arXiv:2009.14174

“Indirect” GW detection with the CMB

frequency range of detection: $10^{-18}\,\mathrm{Hz} < f < 10^{-16}\,\mathrm{Hz}$

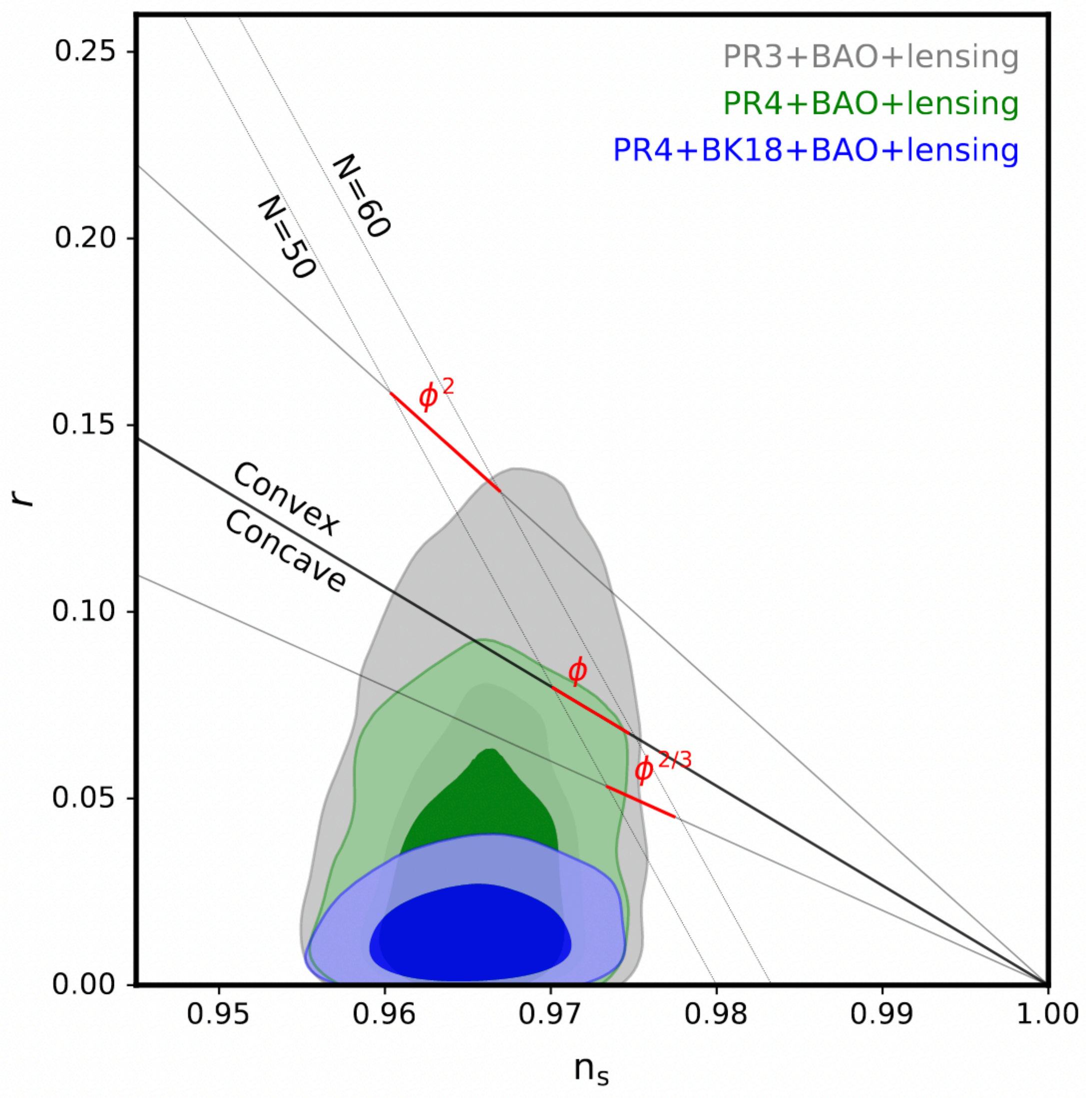
OBSERVABLE:
Temperature anisotropies and B-polarisation in CMB spectrum

$$\frac{\delta T}{T} = -\int_{t_{\rm dec}}^{t_0} \dot{h}_{ij}\, n^i n^j\, dt$$

TARGET SOURCE:
GW generated by quantum metric fluctuations during Inflation

PRESENT SITUATION:
Upper bound on the tensor to scalar ratio

$$r = \mathcal{P}_h/\mathcal{P}_{\mathcal{R}} < 0.032$$

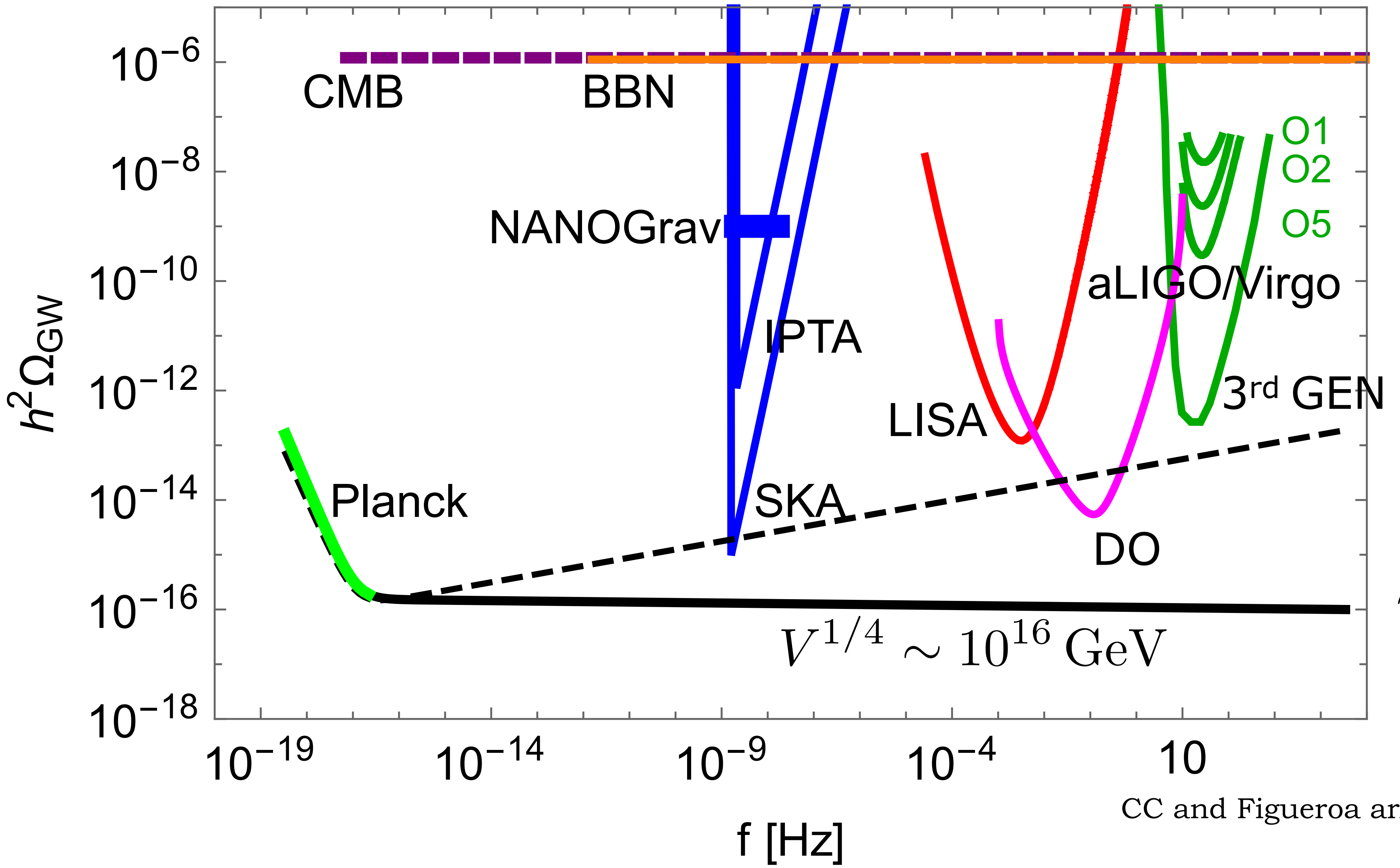


Tristram et al 2112.07961

"Indirect" GW detection with the CMB

The signal in the standard slow roll scenario is too low for direct GW detection

There is the possibility to **enhance the signal going beyond the standard scenario**: adding extra fields, modifying the inflaton potential, modifying the gravitational interaction, adding a phase with stiff equation of state...



$n_T \simeq -2\epsilon$

CC and Figueroa arXiv:1801.04268

Thank you for your attention

Backup

Characteristic frequency of the GW signal

A GW source acting at time t* in the early universe cannot produce a signal correlated on length/time scales larger than the causal horizon at that time

$$\ell_* \leq H_*^{-1}$$

ℓ_* characteristic length/time-scale of the source, i.e. typical size/time of the tensor anisotropic stresses

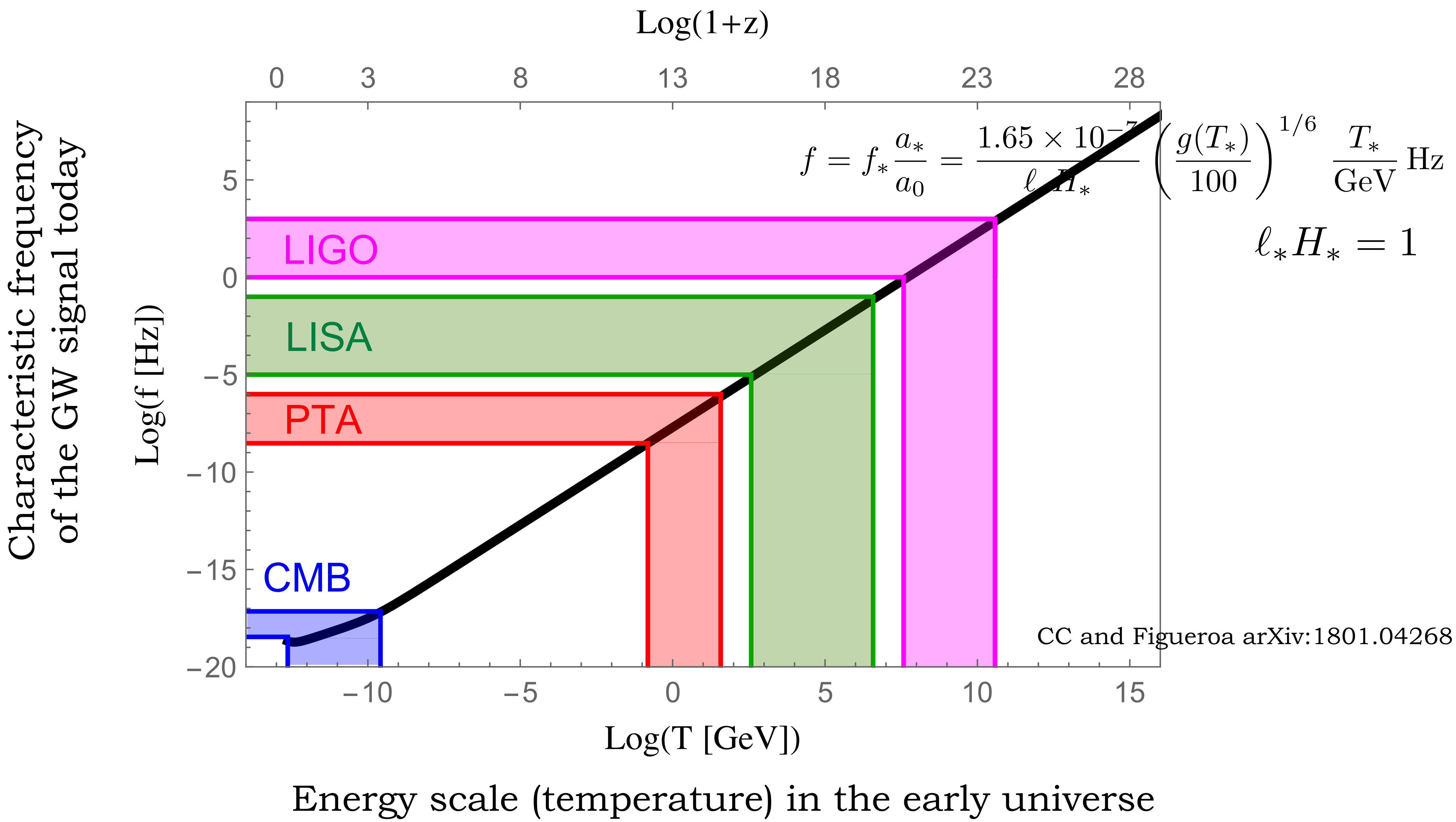
characteristic frequency of the GW signal $f_* = \frac{1}{\ell_*} \geq H_*$

$\ell_* H_*$ Ratio of the typical length/time-scale of the GW sourcing process to the Hubble scale at the generation time

characteristic frequency today

$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\ell_* H_*} \left(\frac{g(T_*)}{100} \right)^{1/6} \frac{T_*}{\mathrm{GeV}} \, \mathrm{Hz}$$

Potential of GW detectors to probe the very early universe



$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\ell_* H_*} \left(\frac{g(T_*)}{100}\right)^{1/6} \frac{T_*}{\mathrm{GeV}}\,\mathrm{Hz}$$

$$\ell_* H_* = 1$$

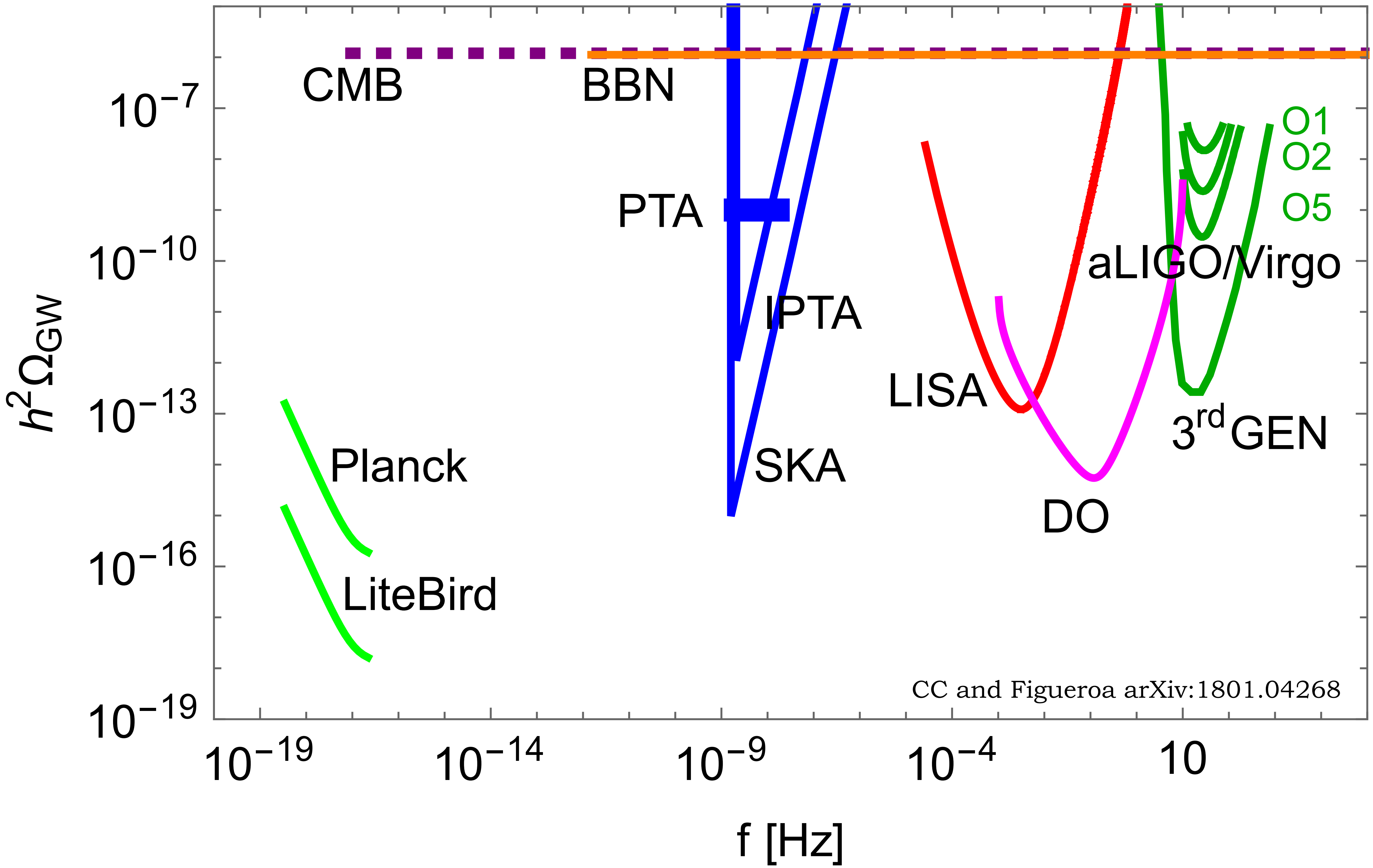
CC and Figueroa arXiv:1801.04268

$T_{\rm QCD} \sim 100\,\mathrm{MeV}$ $\ell_* H_* \sim 0.1$ → $f \sim 10\,\mathrm{nHz}$ PTA

$T_{\rm EW} \sim 100\,\mathrm{GeV}$ $\ell_* H_* \sim 0.01$ → $f \sim \mathrm{mHz}$ LISA

Observational landscape:
what is/will be known about a stochastic GW background

Normalised GW energy density



CC and Figueroa arXiv:1801.04268

Characteristic frequency of the GW signal today

Can we populate the previous diagram with signals?

Possible sources of a stochastic GW background

- Foreground from astrophysical sources (galactic binaries, stellar origin BHB…)

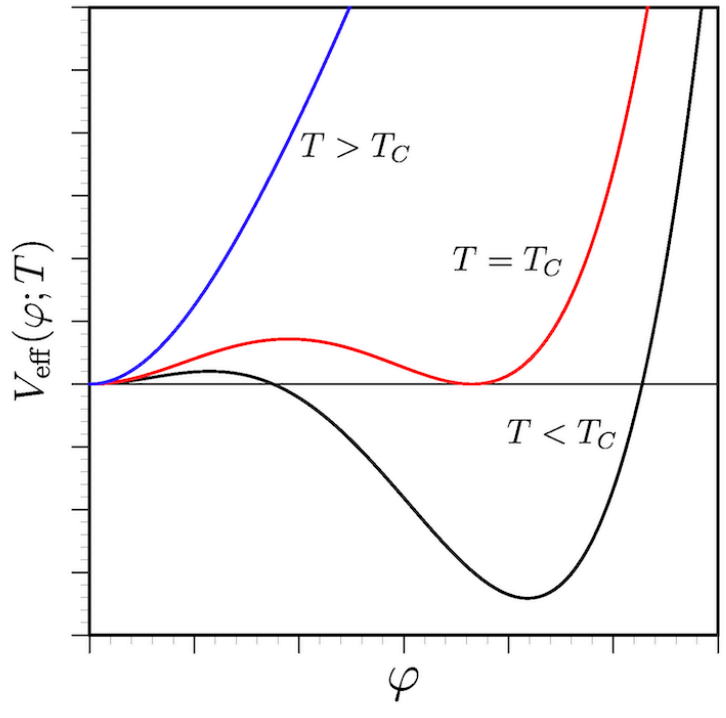
- Background from the very early universe

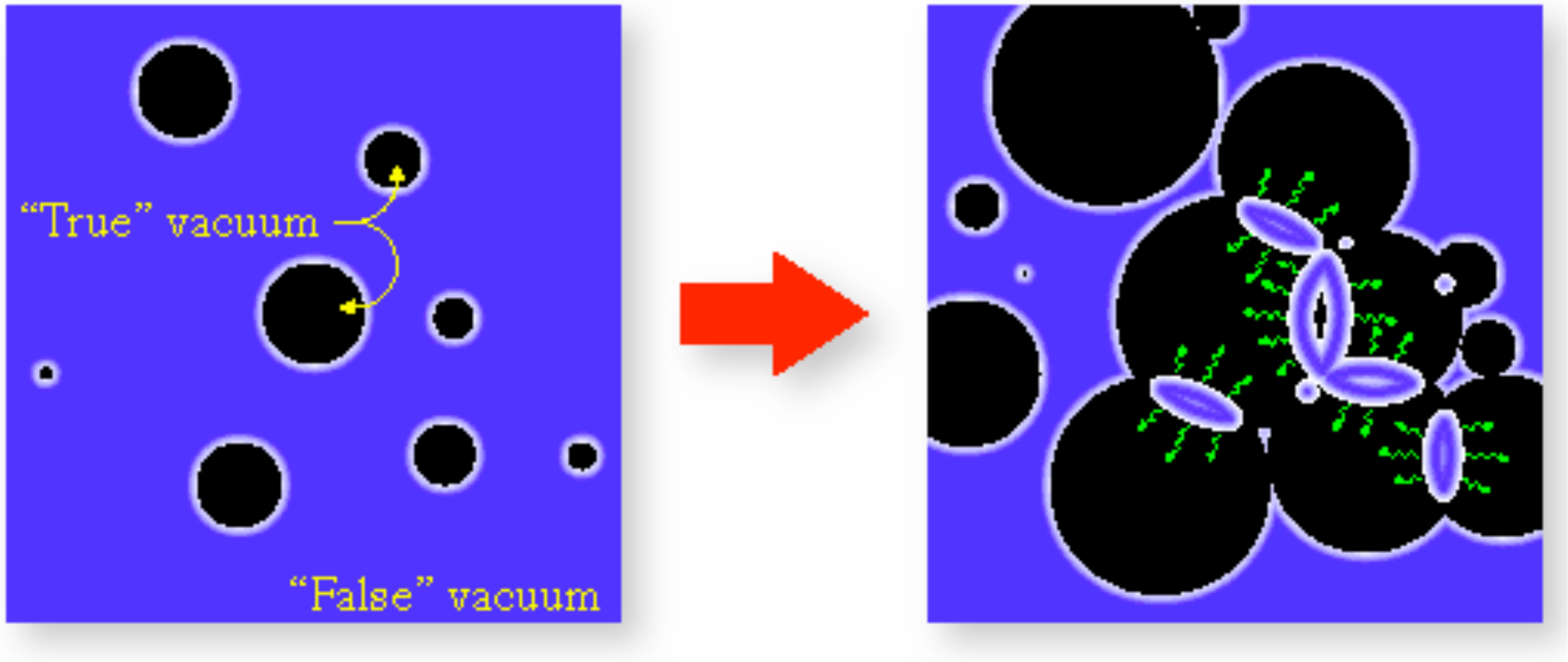
- Inflation:
    - quantum tensor fluctuations (at first and second order)
    - tensor modes from additional fields (scalar, gauge…)
    - GWs linked to primordial BHs
    - preheating
    - modifications of gravity
    - …

- Other phase transitions:
    - stable topological defects (in particular strings)
    - *first order* phase transitions
        - bubble wall collisions
        - bulk fluid motion (compressional and vortical)
        - magnetic fields

Sources of tensor anisotropic stress at a first order phase transition:

GW sourcing process $$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

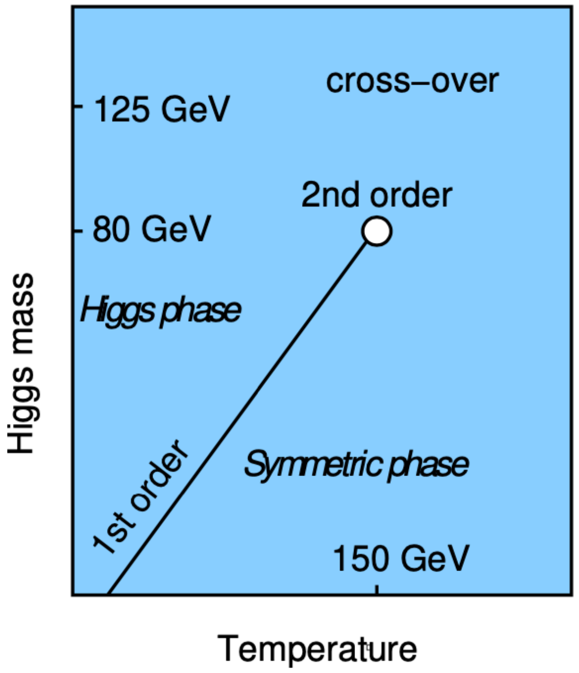




- Bubble collision (scalar field gradients) $\Pi_{ij}^{TT} \sim [\partial_i\phi\partial_j\phi]^{TT}$
- Bulk fluid motion $\Pi_{ij}^{TT} \sim [\gamma^2(\rho+p)v_i v_j]^{TT}$
- Electromagnetic fields $\Pi_{ij}^{TT} \sim [-E_iE_j - B_iB_j]^{TT}$

Electroweak phase transition: phase transition of the Higgs field, driven by the temperature decrease as the universe expands

Standard Model
of particle physics:
Cross-over
Negligible GW production



M. Hindmarsh et al,
arXiv:2008.09136

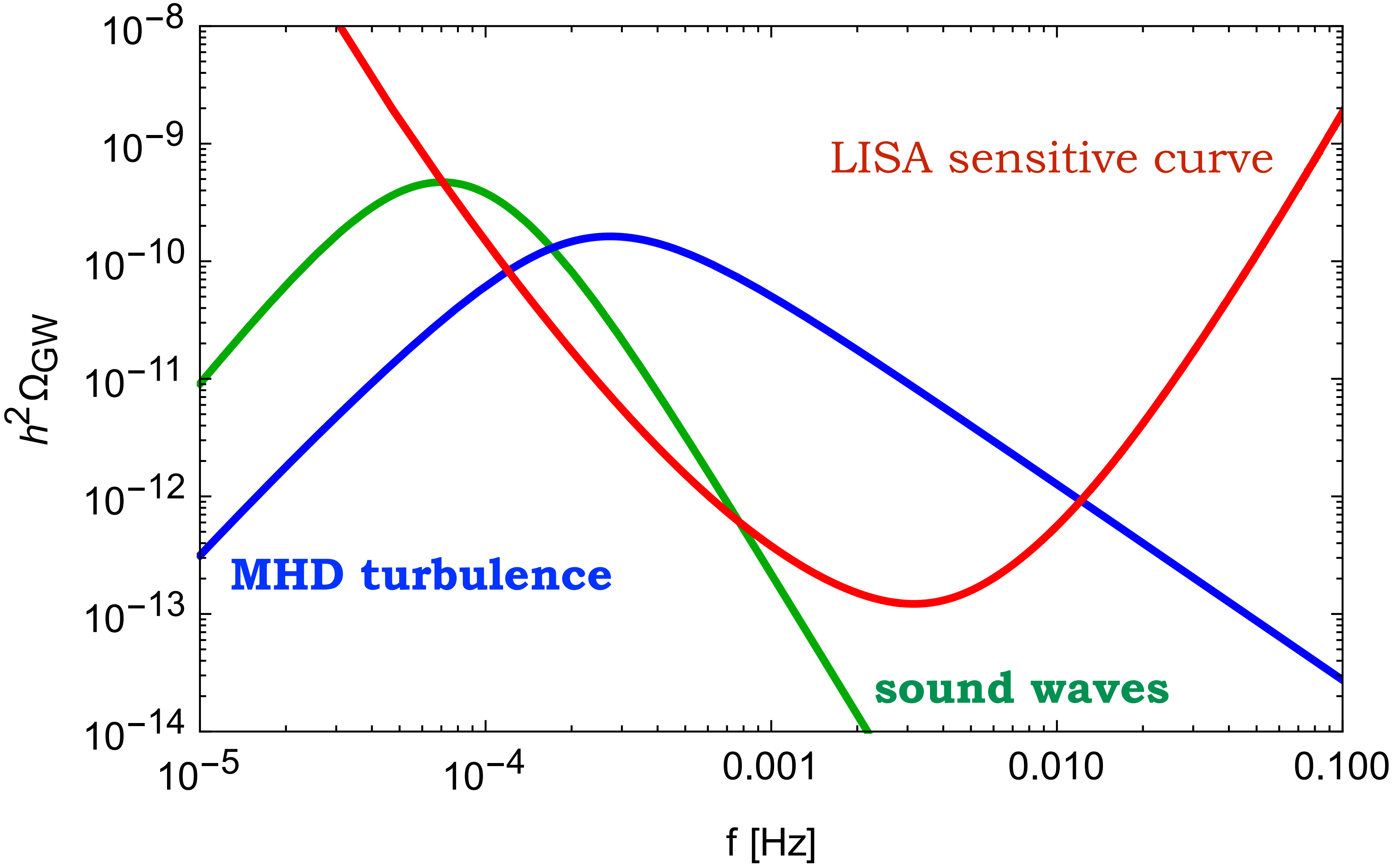
Beyond the Standard Model:
First order phase transition
Possibly observable GW production

Examples of scenarios leading to observable signals:

- singlet/multiplet extensions of SM or MSSM (SUSY motivated or not)
- SM plus dimension six operator (EFT approach)
- Dark Matter sector uncoupled to the SM
- Warped extra dimensions
- …

One example of GW signal from the EW phase transition
“Higgs portal” scenario

$$\tau_{\rm nl} \sim \frac{\ell_*}{v_{\rm rms}} = \frac{0.54}{\mathcal{H}_*}$$



T_*=59.6 GeV, α=0.17, β/H_*=12.5

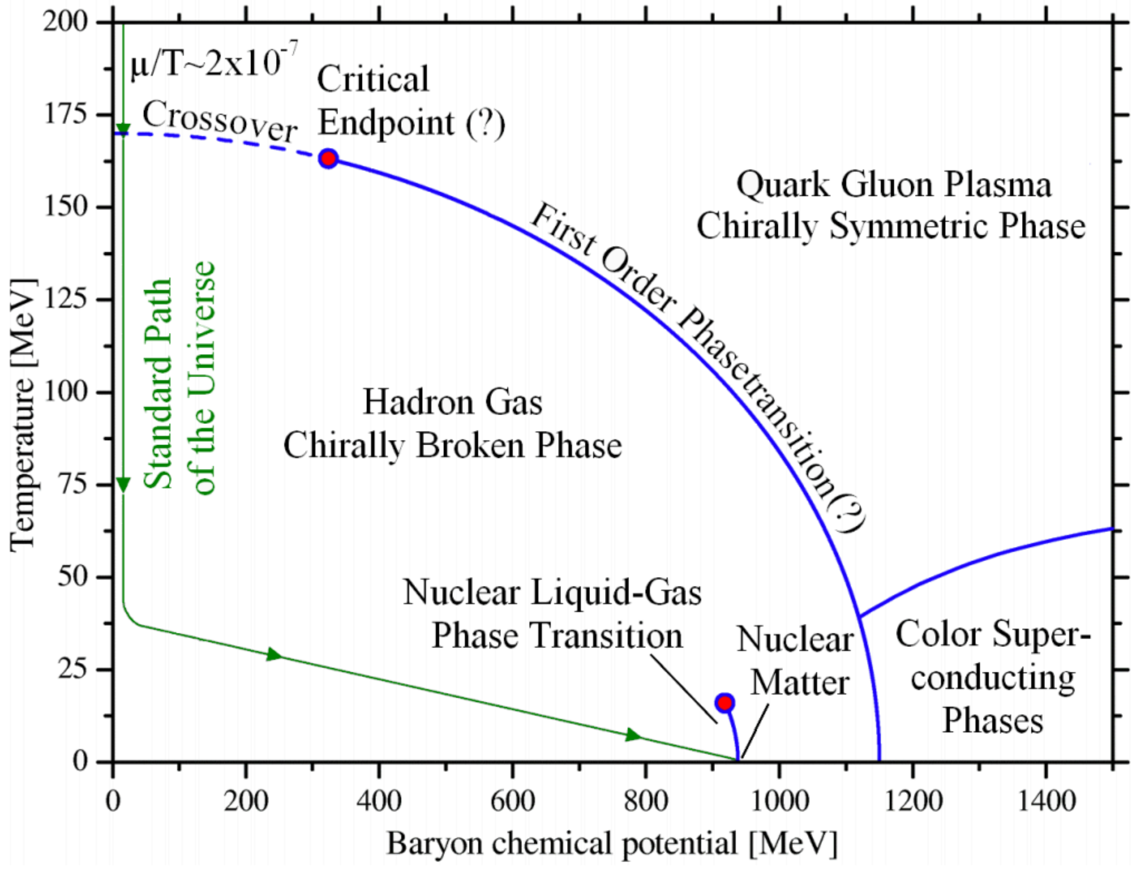
$$\langle v^2\rangle_{\rm turb} = 0.25\,\langle v^2\rangle_{\rm sound} \qquad\qquad \delta t_{\rm fin} = 5\,\delta t_e$$

QCD phase transition and Pulsar Timing Array noise excess?

- In the Standard Model at zero baryon chemical potential it is a cross-over, negligible GW production

- It depends on the (uncertain) conditions of the early universe

D. Schwarz and Stuke, arXiv:0906.3434
M. Middeldorf-Wygas et al, arXiv:2009.00036



T. Boekel and J. Schaffner-Bielich, arXiv:1105.0832

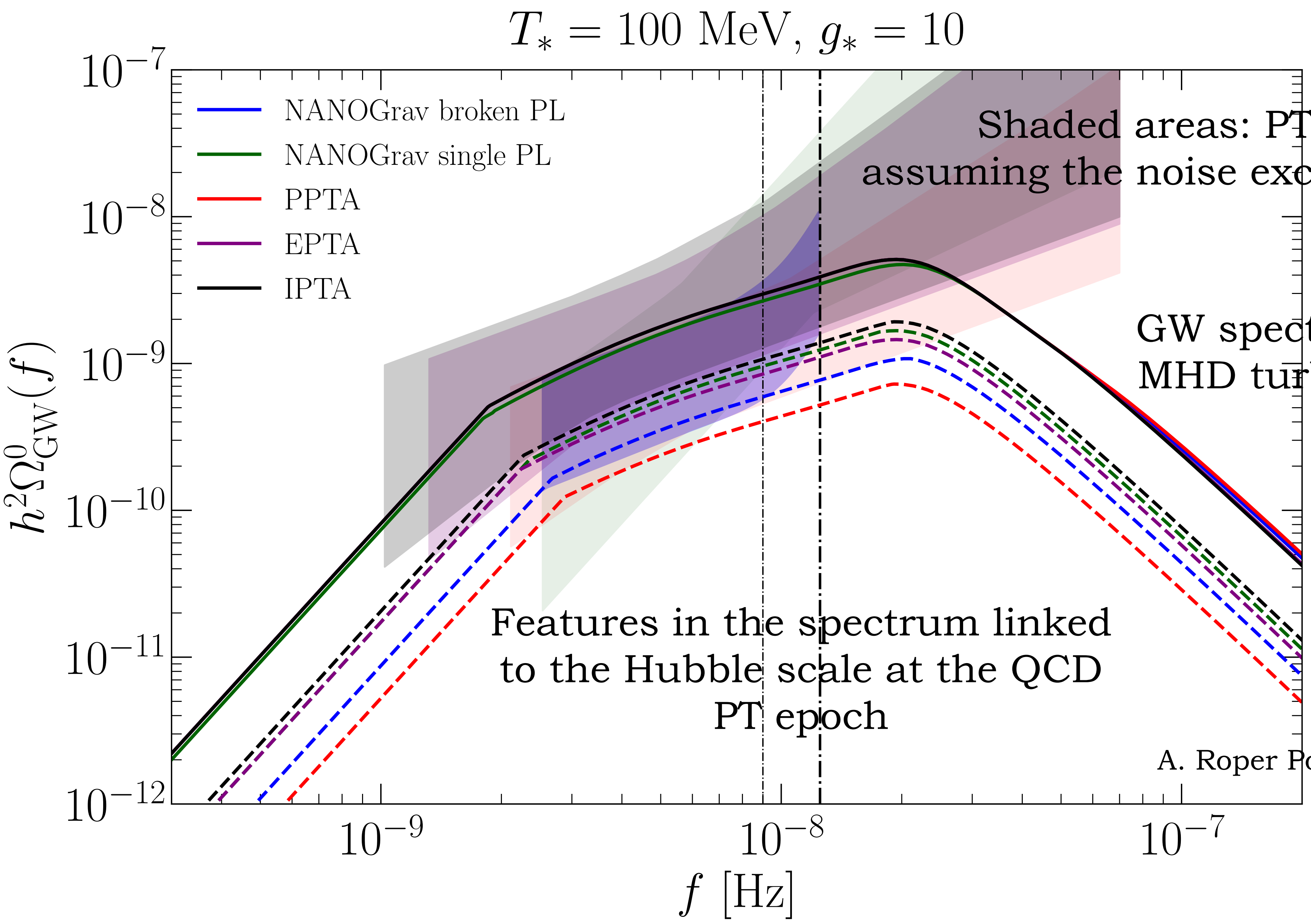
PTA (nHz) are sensitive to energy scales around the **QCD scale**, so they can probe physical processes connected to the QCDPT IF it is first order

- PTA observatories (NANOGrav, Parkes, European) have recently measured common noise excess

- It is compatible with the GW generated by fully developed MHD turbulence at the QCD scale

A. Neronov et al, arXiv:2009.14174

QCD phase transition and Pulsar Timing Array noise excess?



Shaded areas: PTA detections assuming the noise excess is a GW signal

GW spectra from MHD turbulence

Features in the spectrum linked to the Hubble scale at the QCD PT epoch

A. Roper Pol et al, arXiv:2201.05630

- The noise excess can be explained by MHD turbulence at the QCD scale if the PT temperature scale is 2 MeV < T_* < 200 MeV, the magnetic field energy density is close to 10% of the radiation energy density and the magnetic correlation scale is close to the horizon

Overview of GW detection

- cosmic microwave background (indirect)

frequency range of detection: $10^{-18}\,\mathrm{Hz} < f < 10^{-16}\,\mathrm{Hz}$

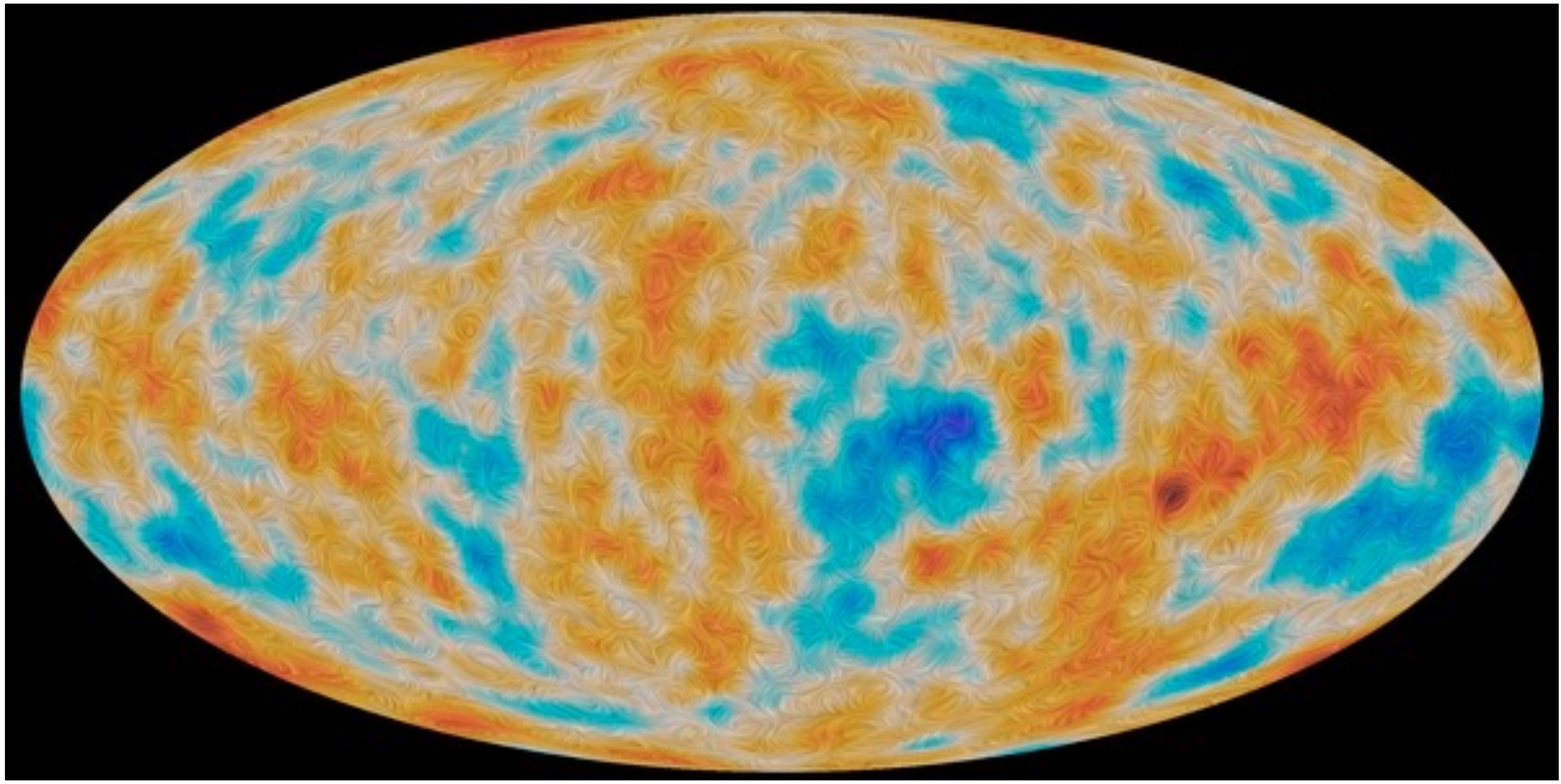
- target: temperature fluctuations and B polarisation

Results

- upper bound on stochastic background:

$$r \leq 0.12$$

Ade et al 1502.00612



Cosmic microwave background

frequency range of detection: 10^{-18} Hz < f < 10^{-16} HZ

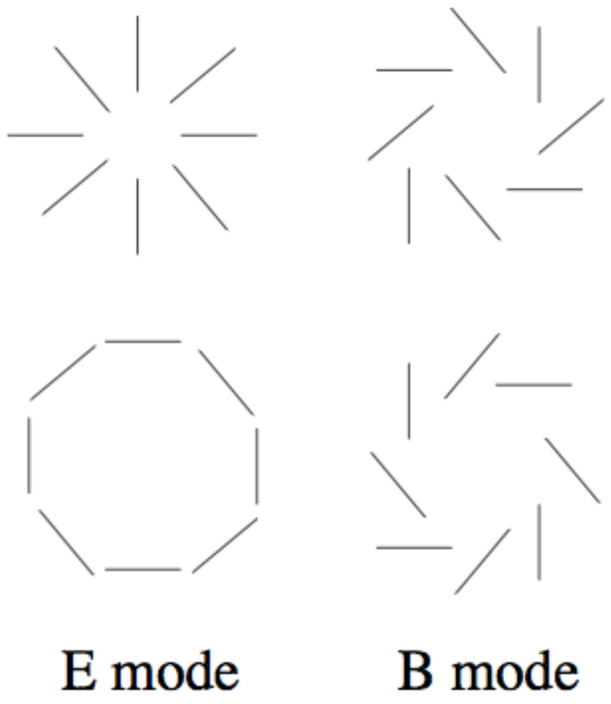
- temperature : limit by Planck

$$\frac{\delta T}{T} = -\int_{t_{\rm dec}}^{t_0} \dot{h}_{ij}\, n^i n^j \, dt$$

- polarisation: BB spectrum measured by BICEP2 and Planck generated at photon decoupling time, from Thomson scattering of electrons by a quadrupole temperature anisotropy in the photons

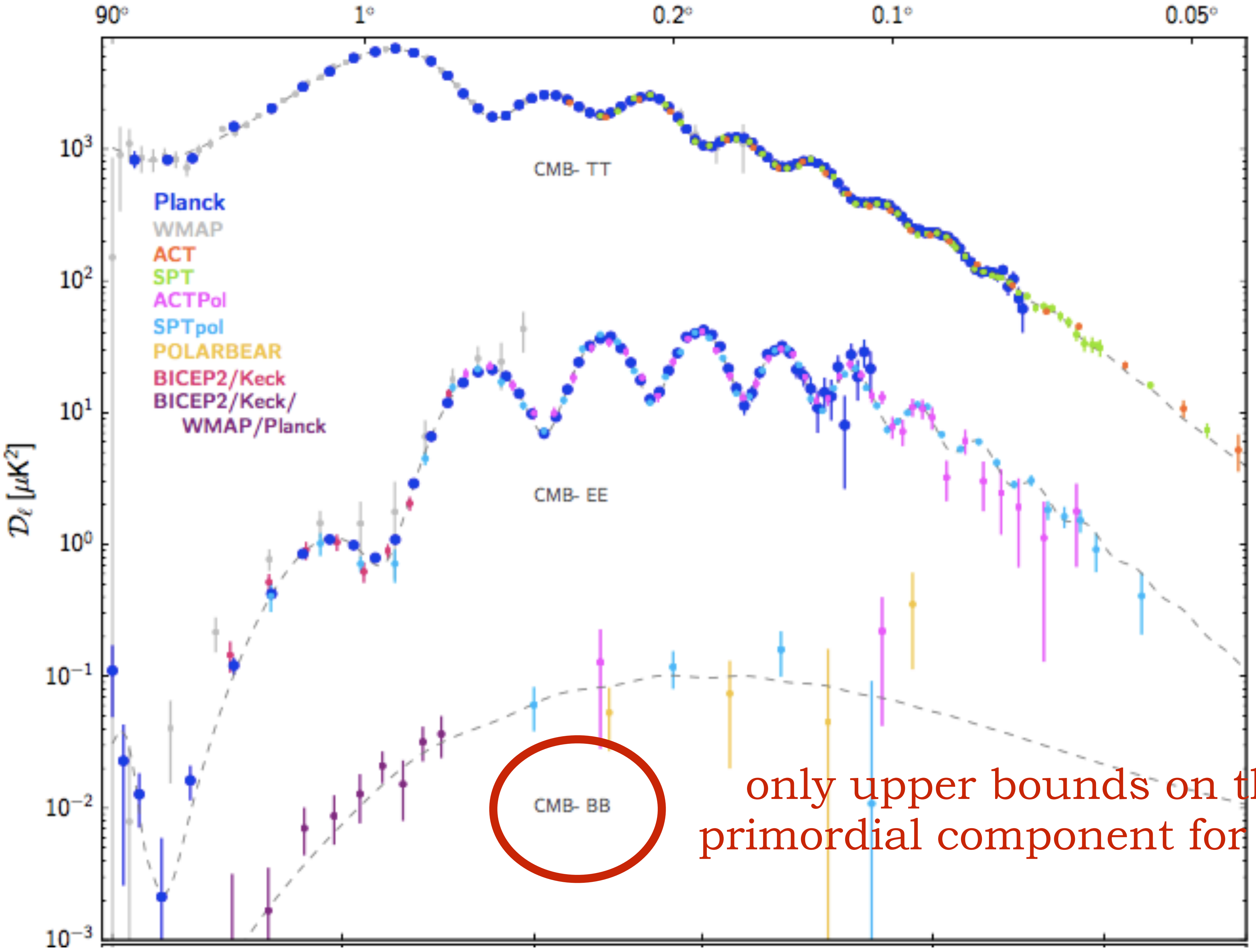
polarisation patterns

generated by primordial scalar and tensor perturbations



generated only by primordial tensor perturbations or by foregrounds

Cosmic microwave background



only upper bounds on the primordial component for now

Planck collaboration: arXiv:1807.06205

GW signal from inflation

Amplification of tensor metric vacuum fluctuations by the exponential expansion

$$h_r''(\mathbf{k},\eta) + 2\,\mathcal{H}\,h_r'(\mathbf{k},\eta) + k^2\,h_r(\mathbf{k},\eta) = 16\pi G\,a^2\,\xcancel{\Pi_r(\mathbf{k},\eta)}$$

- ✓ canonically normalised free field $v_\pm = a\,M_{Pl}\,h_\pm$
- ✓ quantisation
- ✓ homogeneous wave equation: harmonic oscillator with *time dependent* frequency

$$v_\pm''(t) + (k^2 - a^2 H^2)v_\pm(t) = 0$$

$k \gg a\,H$ sub-Hubble modes

$$\omega^2(t) = k^2$$

free field in vacuum
zero occupation number

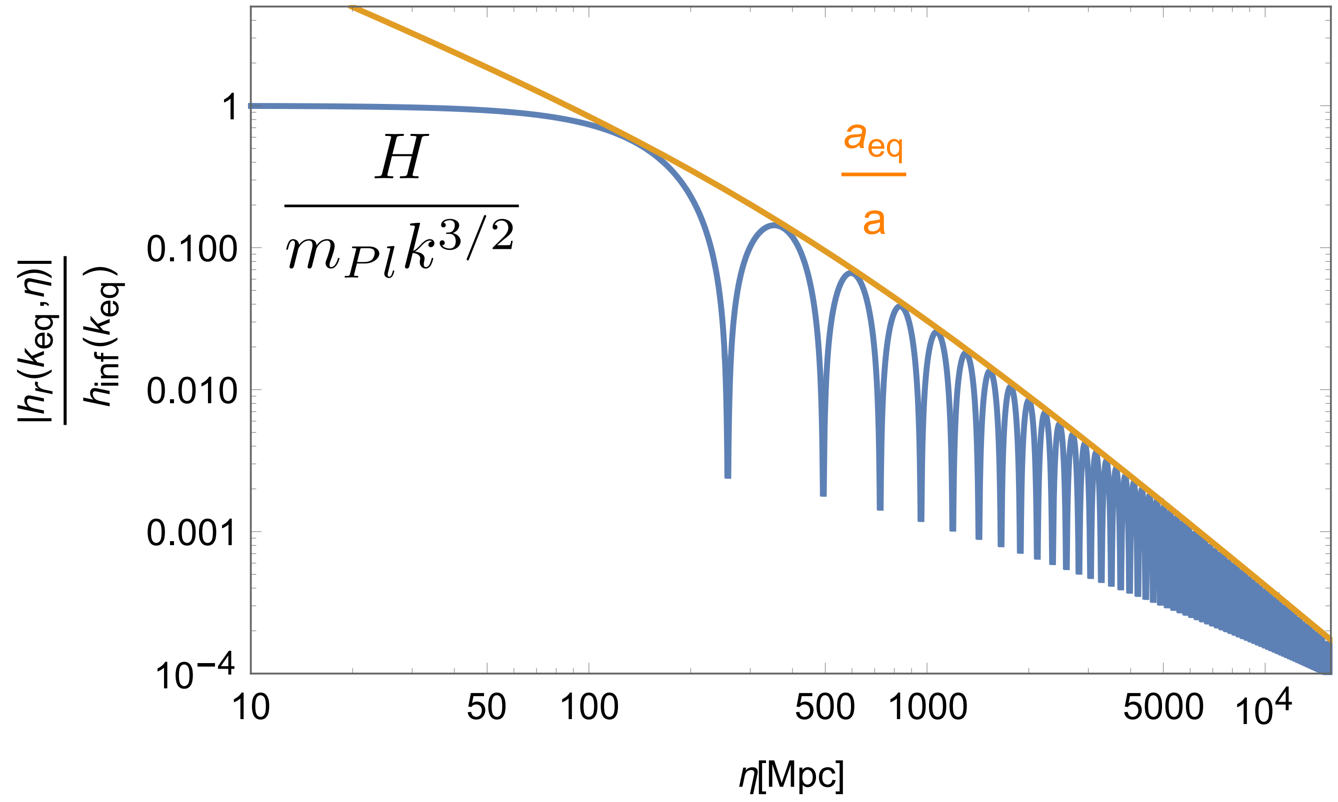
$k \ll a\,H$ super-Hubble modes

$$\omega^2(t) = -a^2 H^2$$

super-Hubble modes have very large occupation number

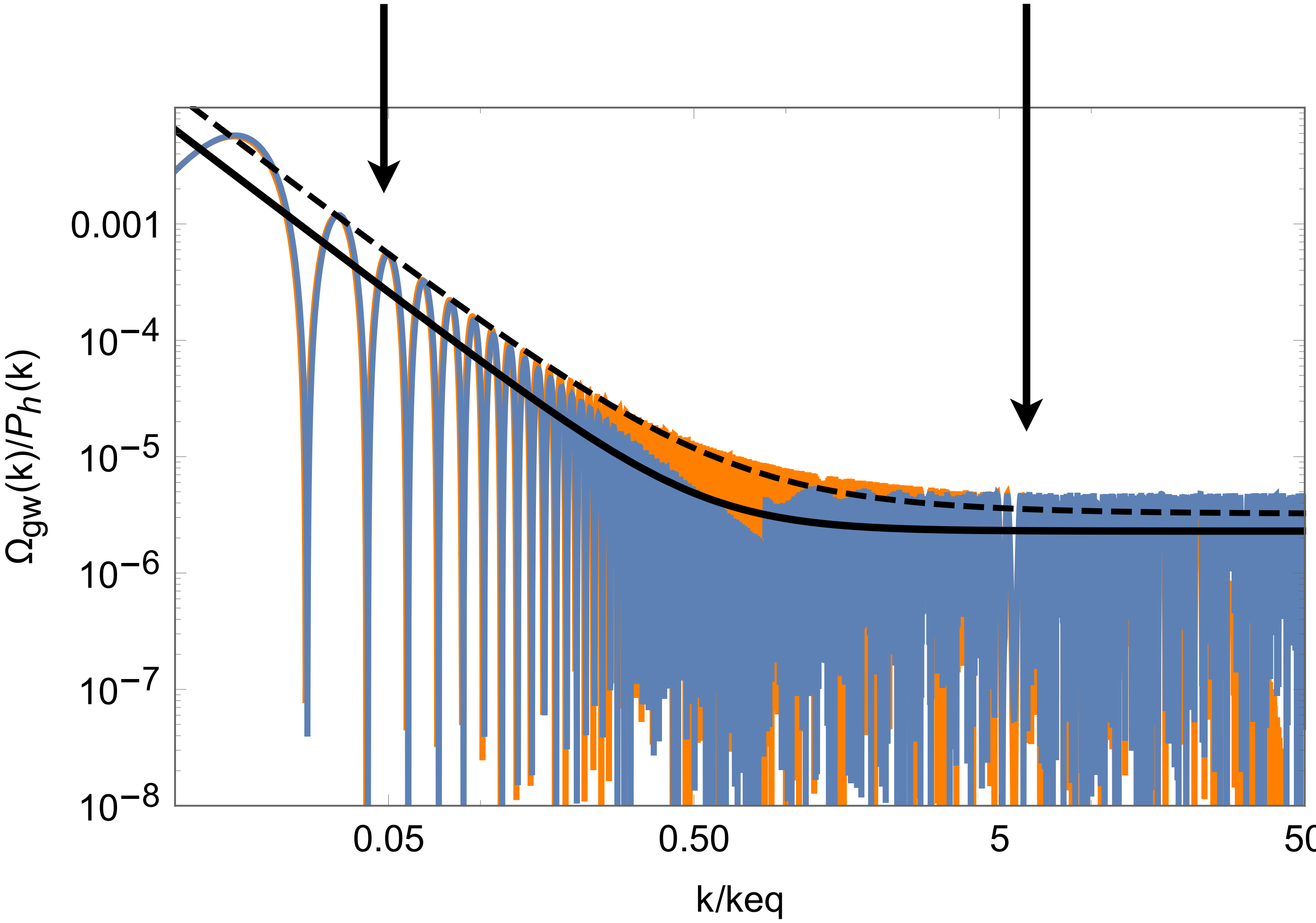
GW signal from (slow roll) inflation

- tensor spectrum $$\mathcal{P}_h = \frac{2}{\pi}\frac{H^2}{m_{Pl}^2}\left(\frac{k}{aH}\right)^{-2\epsilon} \qquad \epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$
- transfer function from inflation to today, as modes re-enter the Hubble horizon



Modes entering the Hubble horizon in the matter era

Modes entering the Hubble horizon in the radiation era



$$\Omega_{\rm GW}(k,\eta_0) = \frac{[T'(k,\eta_0)]^2}{12a_0^2H_0^2}\mathcal{P}_h(k)$$

GW signal from (slow roll) inflation

- tensor spectrum $\mathcal{P}_h = \frac{2}{\pi}\frac{H^2}{m_{Pl}^2}\left(\frac{k}{aH}\right)^{-2\epsilon}$ $\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$

$$\boxed{\Omega_{\rm GW}(f) = \frac{3}{128}\,\Omega_{\rm rad}\, r\, \mathcal{P}_{\mathcal{R}}^{*}\left(\frac{f}{f_*}\right)^{n_T}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]}$$

- tensor to scalar ratio $r = \mathcal{P}_h/\mathcal{P}_{\mathcal{R}}$

- scalar amplitude at CMB pivot scale $\mathcal{P}_{\mathcal{R}}^{*} \simeq 2\cdot 10^{-9}$ $k_* = \frac{0.05}{\rm Mpc}$

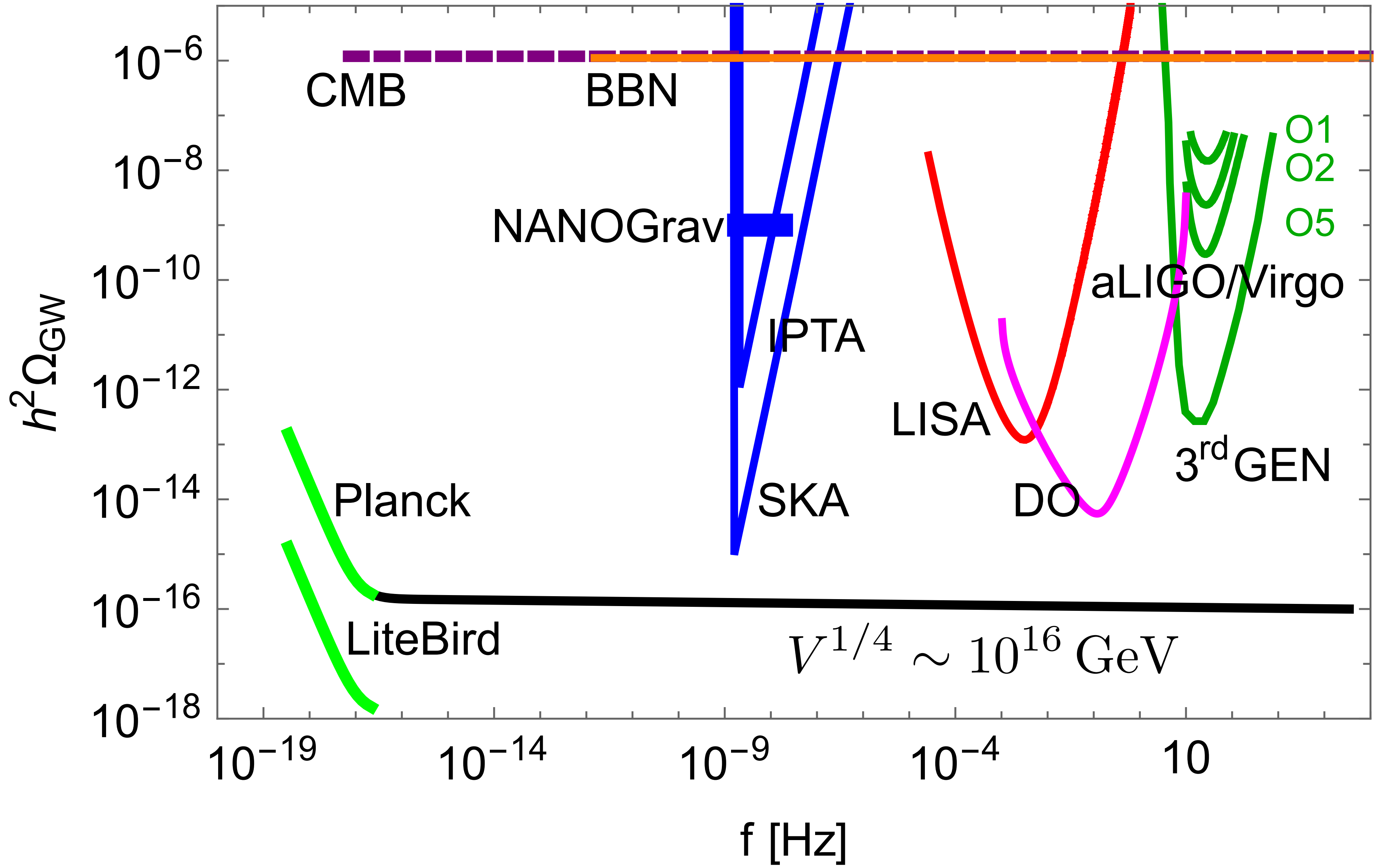
- GW signal extended in frequency: $H_0 \leq f \leq H_{\rm inf}$

continuous sourcing of GW as modes re-enter the Hubble horizon

GW signal from (slow roll) inflation

Gw detectors offer the amazing opportunity to probe the inflationary power spectrum (and the model of inflation) down to the tiniest scales

BUT! The signal in the standard slow roll scenario is too low

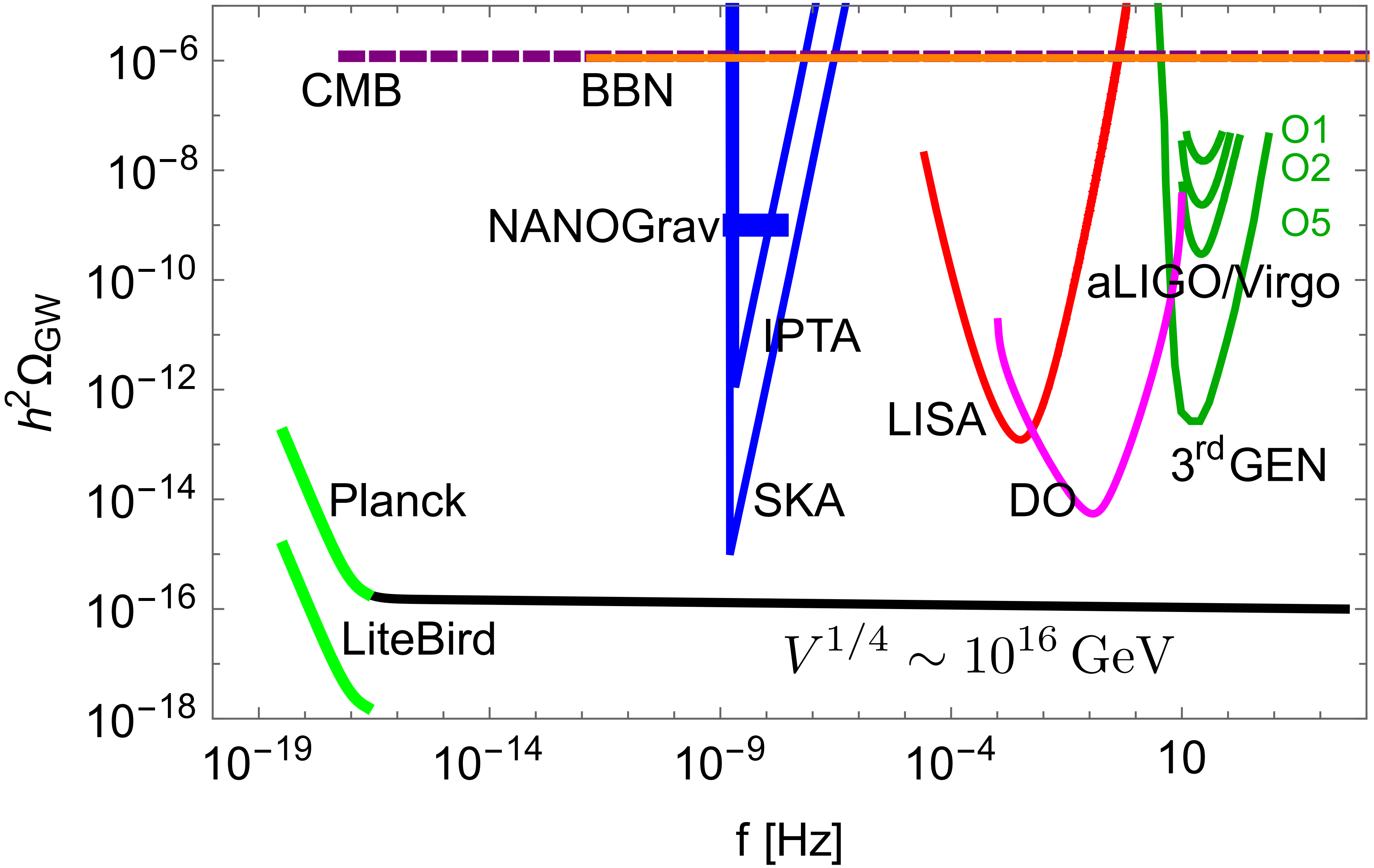


$n_T \simeq -2\epsilon$

GW signal from (slow roll) inflation

Gw detectors offer the amazing opportunity to probe the inflationary power spectrum (and the model of inflation) down to the tiniest scales

(P)reheating generates a signal, but unfortunately at very high frequencies

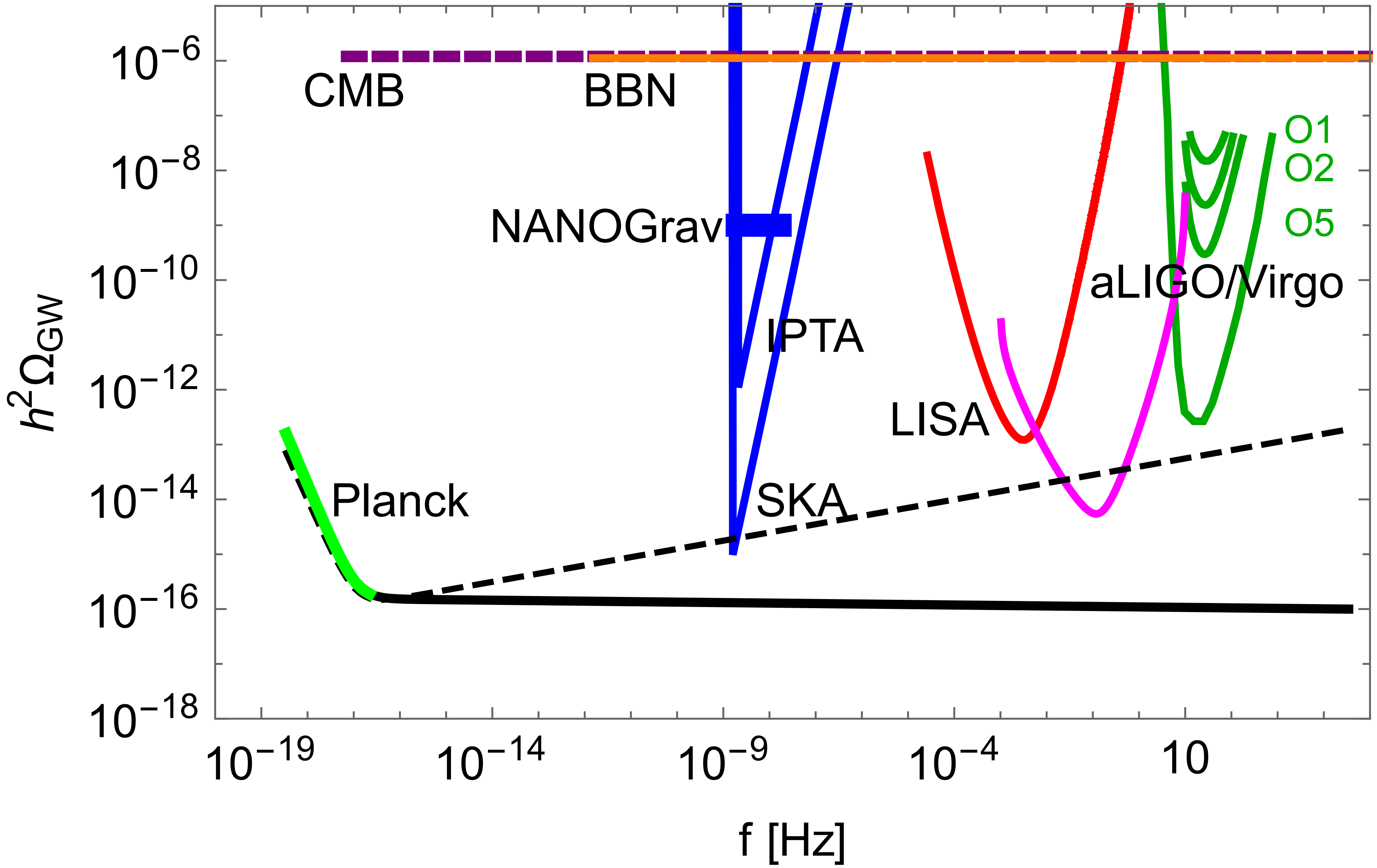


$n_T \simeq -2\epsilon$

GW signal from (non-standard) inflation

There is the possibility to enhance the signal going beyond the standard inflationary scenario: adding extra fields, modifying the inflaton potential, modifying the gravitational interaction, adding a phase with stiff equation of state…

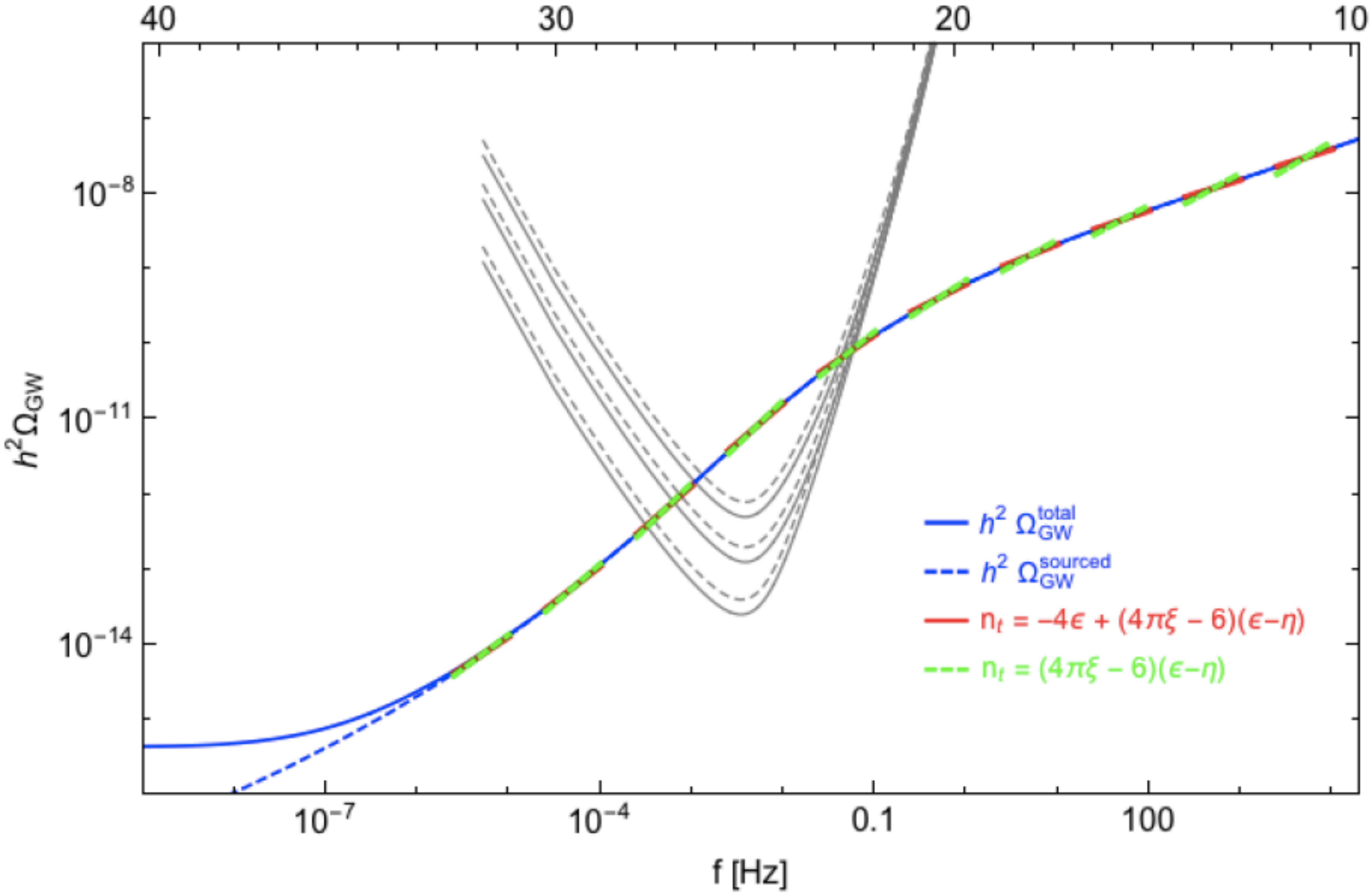
$$H_r''(\mathbf{k},\eta) + \left(k^2 - \frac{a''}{a}\right) H_r(\mathbf{k},\eta) = \boxed{16\pi G\, a^3\, \Pi_r(\mathbf{k},\eta)}$$



just one example: inflaton-gauge field coupling

$$\Delta\mathcal{L} = -\frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Pi_{ij} \sim [-E_iE_j - B_iB_j]^{TT}$$



$$\Lambda = \frac{M_{Pl}}{35}$$

quadratic
inflaton
potential

OTHER SIGNATURES:
non-gaussianity, chirality

N. Bartolo et al, arXiv:1610.06481
N. Bartolo et al, arXiv:1806.02819

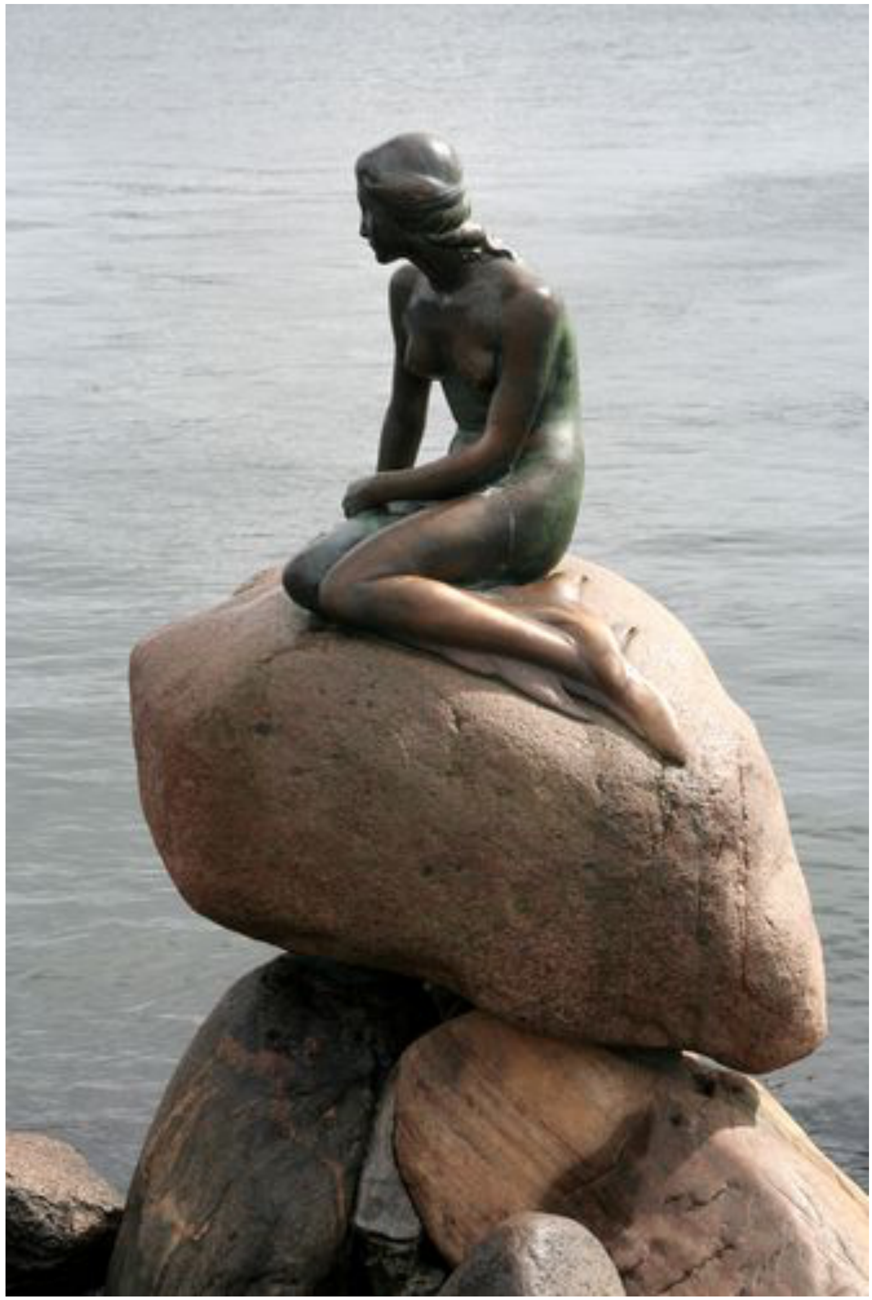
Using GW emission by compact binaries to test the background expansion of the universe

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

Measurement of d_L: standard sirens

- Measurement of the luminosity distance: no calibration needed, EASY AND DIRECT

- Measurement of the redshift: IMPOSSIBLE!



B. Schutz, Nature 323, 310 (1986)

Inspiral of compact binaries at cosmological distance

$$h_+(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\left(\frac{1+\cos^2\theta}{2}\right)\cos(2\Phi(\tau))$$

$$h_\times(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\,\cos\theta\,\sin(2\Phi(\tau))$$

$$\mathcal{M}_c = (1+z)M_c$$

Redshifted chirp mass
degeneracy among the redshift and the true chirp mass

Assuming that the redshift is constant

$$\dot{f}_O = \frac{96\pi^{8/3}}{5}(G\,\mathcal{M}_c)^{5/3}{f_O}^{11/3}$$

Measurement of $d_L(z)$

$$\mathcal{M}_c = (1+z)M_c$$

How can we break this degeneracy and use GW emission to build the Hubble diagram $d_L(z)$?

There are a few methods to obtain the redshift information, depending on the nature of the source and on the detector

- Direct method: directly identify the galaxy hosting the event, via the measurement of a (transient) electromagnetic counterpart
- Statistical method: cross-correlate the sky position given by the GW measurement with galaxy catalogues
- Assume that one knows or constrains the intrinsic mass of the object

Direct method with LISA: massive BH binaries

- Massive BH binaries mergers are expected to have counterparts if they occur in gaseous disks at the centre of galaxies (the rate of these events is uncertain)
- One must select events with good sky localisation (few!)
- Weak lensing (and peculiar velocity) error affect the measurement of d_L

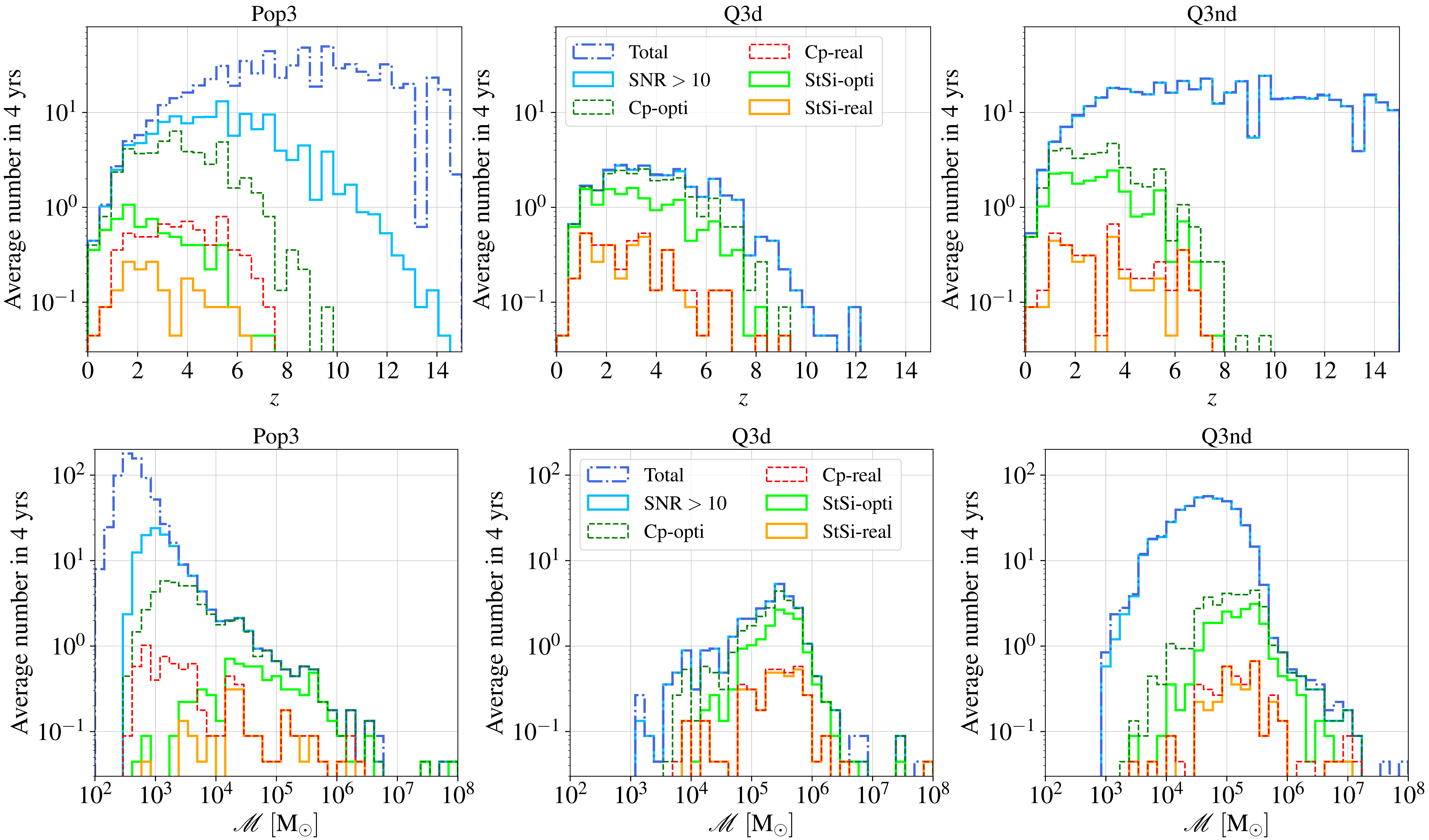
Our approach

- Step 0: simulated catalogues of massive BH binaries (E. Barausse)
- Step 1: LISA parameter estimation (error on sky localisation and d_L)
  - Bayesian code LISAbeta (S. Marsat)
- Step 2: model of the EM counterpart and detection strategy (redshift error)
  - Detection of the host galaxy with LSST
  - Localisation of a radio counterpart with SKA and detection of the host galaxy with ELT
  - Localisation of a X-ray counterpart with Athena and detection of the host galaxy with ELT
- Step 3: construction of the Hubble diagram

Tamanini et al, arXiv:1601.07112
Mangiagli et al, in preparation

Direct method with LISA: massive BH binaries

- The number of standard sirens is quite low
- The events cluster at high redshift 2 < z < 5

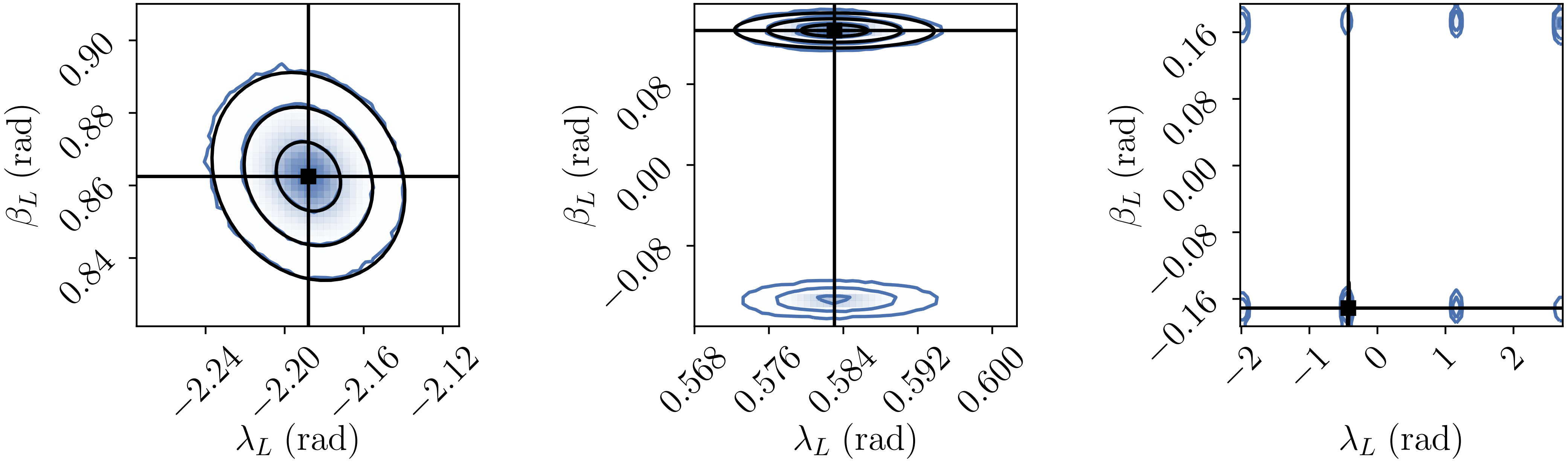


Direct method with LISA: massive BH binaries

The number of standard sirens depends heavily
on the astrophysical generation model and on the EM detection channel

	LSST	SKA+ELT			Athena+ELT				
					Catalog		Eddington		
		Isotropic	$\Gamma 2$	$\Gamma 10$	$F_{\mathrm{X,\,lim}} = $ 4e-17	$F_{\mathrm{X,\,lim}} = $ 2e-16	$F_{\mathrm{X,\,lim}} = $ 4e-17	$F_{\mathrm{X,\,lim}} = $ 2e-16	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	
No-obsc.	0.84	6.8	1.51	0.04	0.49	0.27	1.02	0.84	Pop3
	3.07	14.84	2.71	0.04	2.67	1.38	3.87	2.09	Q3d
	0.53	20.0	3.07	0.04	0.58	0.31	4.22	2.98	Q3nd
Obsc.	0.4	6.8	1.51	0.04	0.18	0.04	0.31	0.18	Pop3
	0.89	14.84	2.71	0.04	0.18	0.09	0.18	0.09	Q3d
	0.27	20.0	3.07	0.04	0.09	0.04	0.27	0.18	Q3nd

Some events are multi-modal in the sky position and need to be treated separately



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$$\mathcal{M}_c = (1+z)M_c$$

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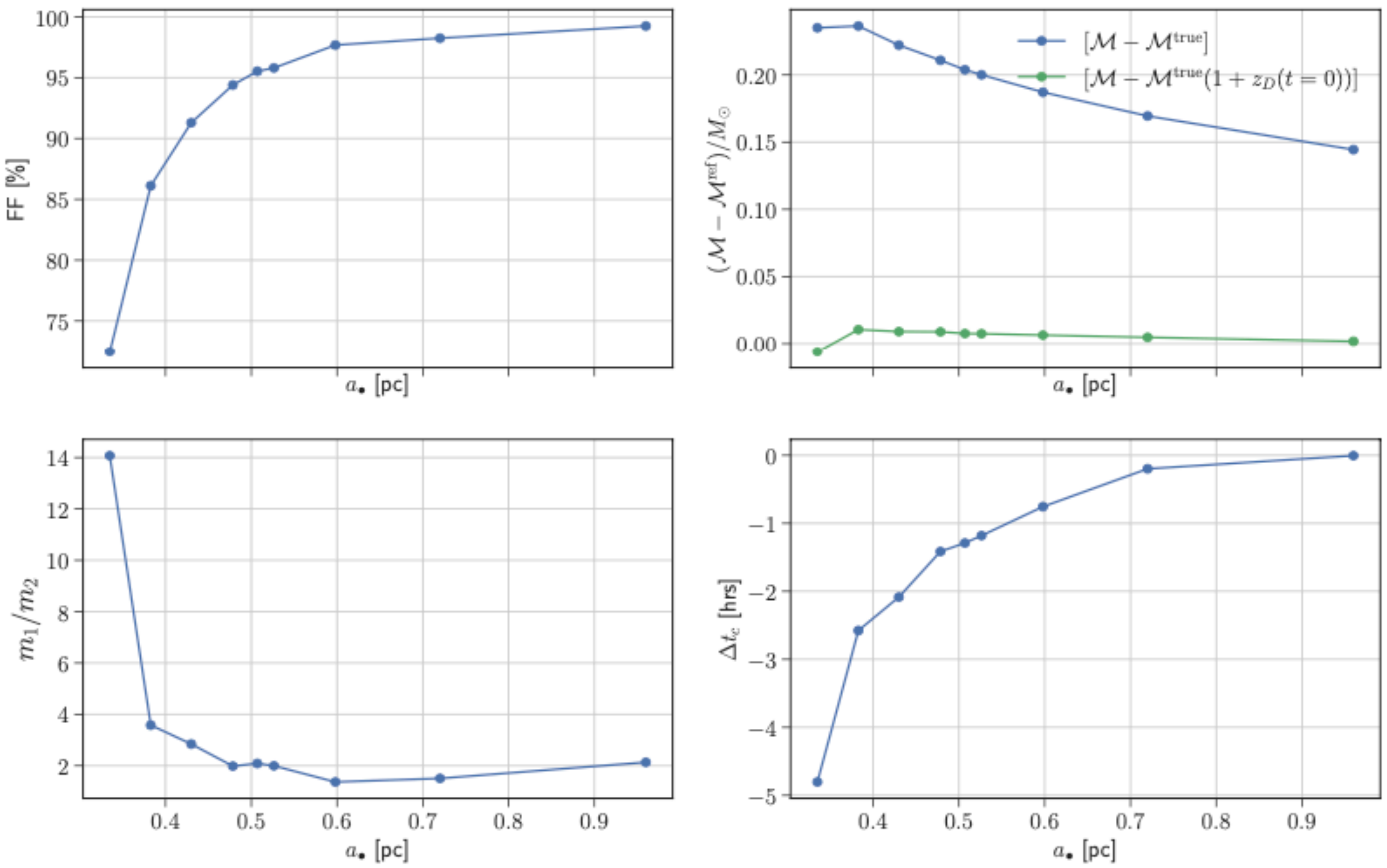
degeneracy among the redshift and the true chirp mass

Assuming that the redshift is constant

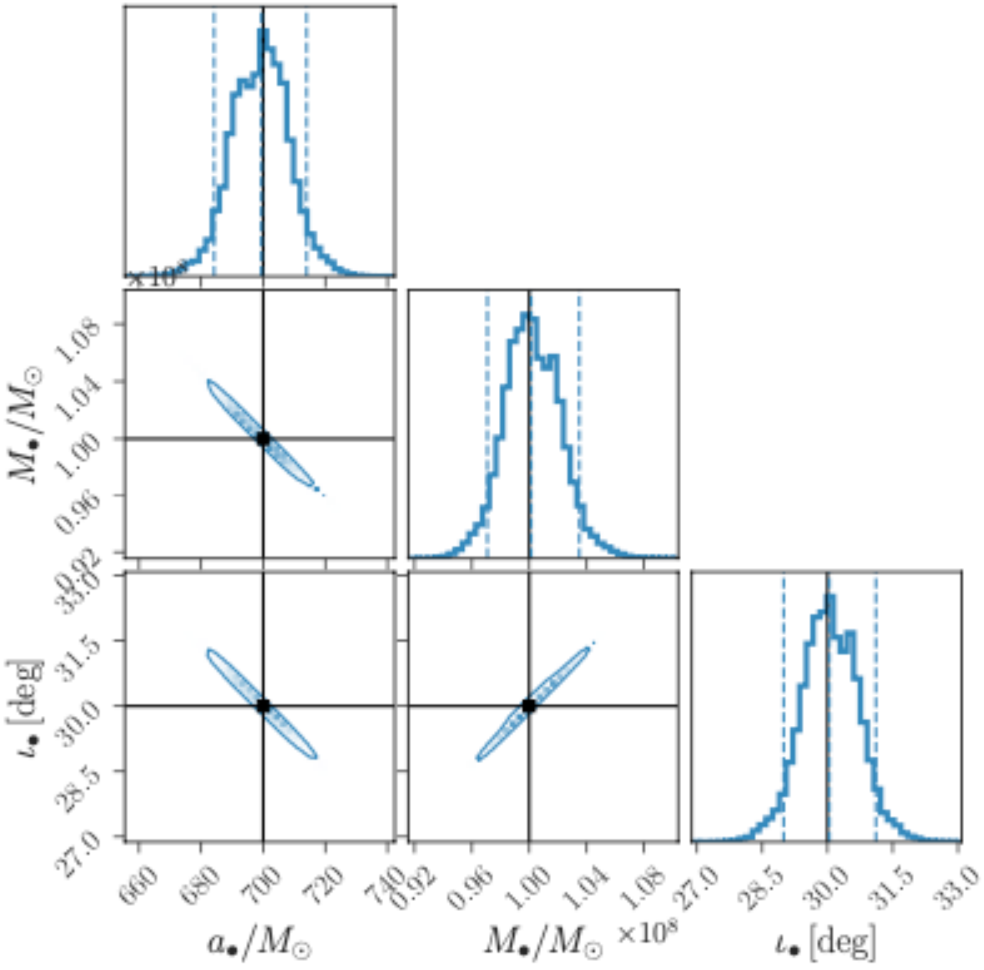
$$\dot{f}_O = \frac{96\pi^{8/3}}{5}(G\,\mathcal{M}_c)^{5/3}{f_O}^{11/3}$$

Environmental effects on waveforms of SOBHBs in LISA

LISA can measure the dephasing in SOBHBs waveforms due to Doppler modulation and Shapiro time delay if the binary orbits a MBH



This can provide access to the central MBH parameters



Sberna et al, arXiv:2205.08550