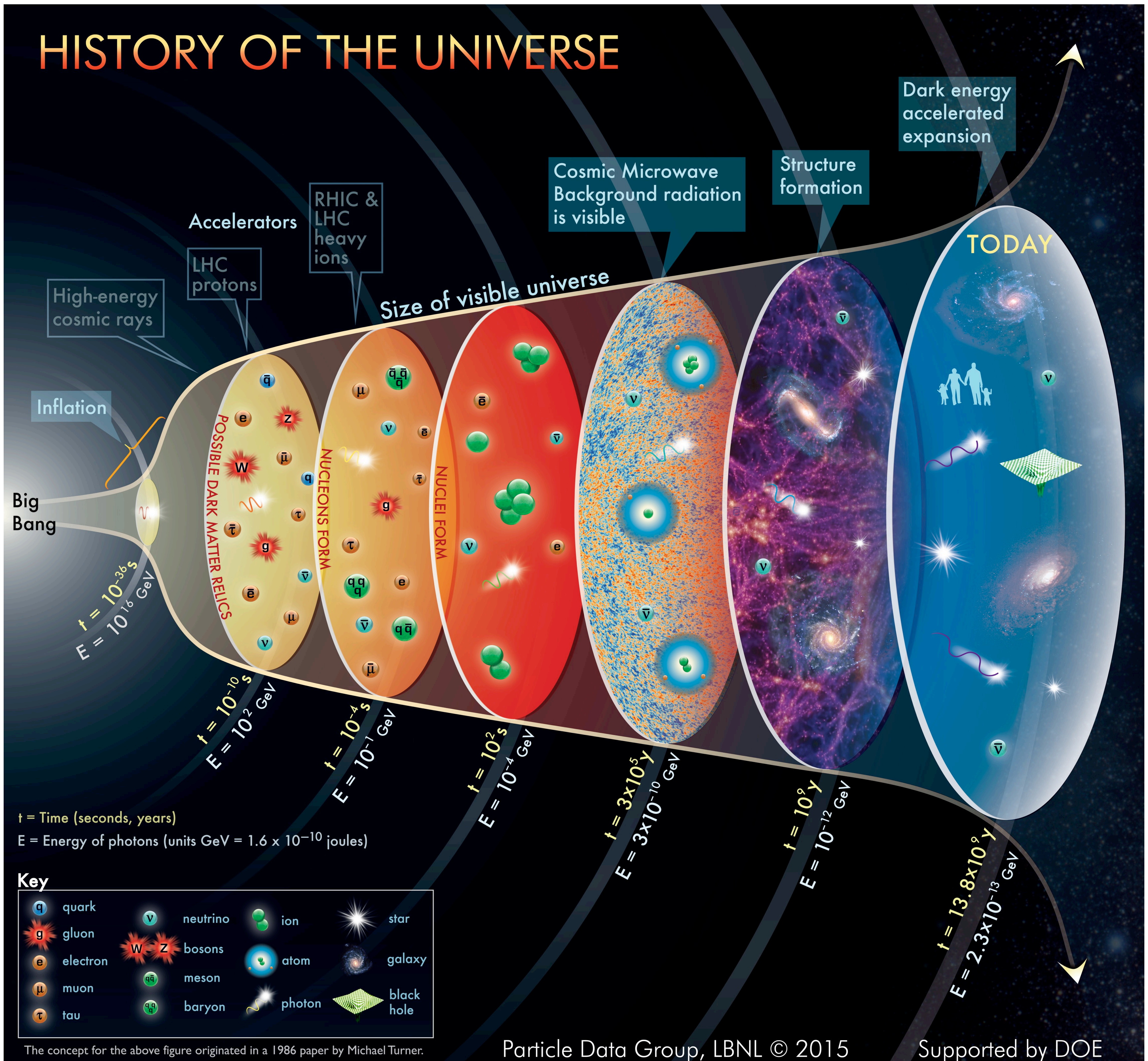
CERN TH Astroparticle/Cosmology



CERN TH Astroparticle/Cosmology

Strong scientific interactions with BSM group

Staff

CAPRINI, Chiara

Welcome!

CAPUTO, Andrea

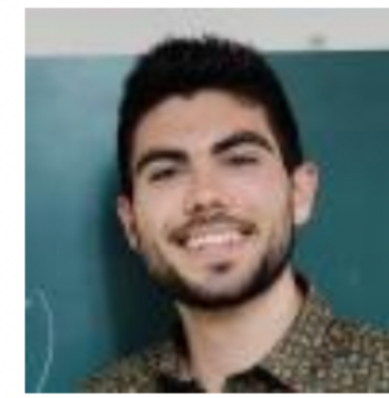
Fellow

DI DIO, Enea

Staff

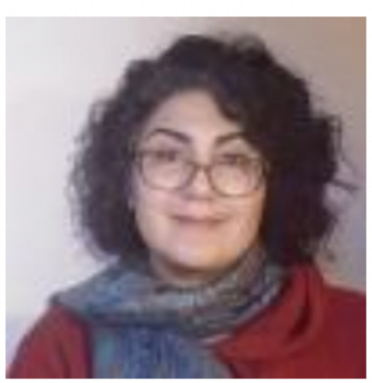
DOMCKE, Valerie

Welcome!



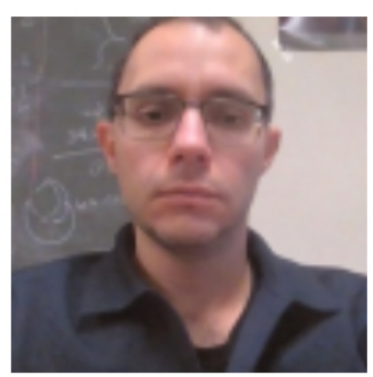
ESCUDERO ABENZA, Miguel

Fellow



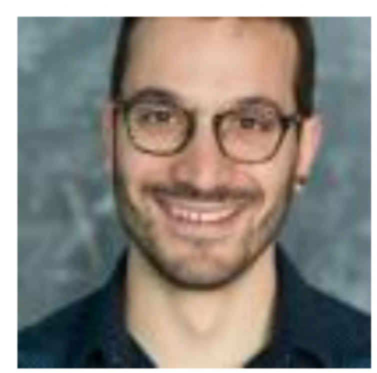
MALEKNEJAD, Azadeh

Welcome!



PIERONI, Mauro

Fellow



ROMPINEVE, Fabrizio

Staff

SIMONOVIC, Marko

CERN TH Astroparticle/Cosmology

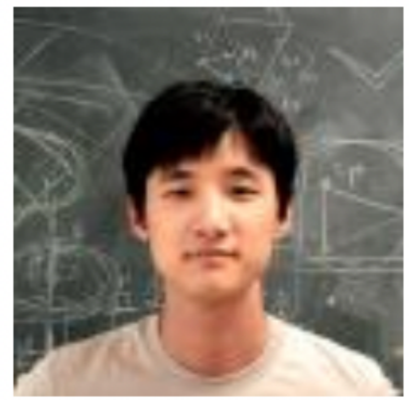
Strong scientific interactions with BSM group

Long term visitor

BRAX,

Philippe

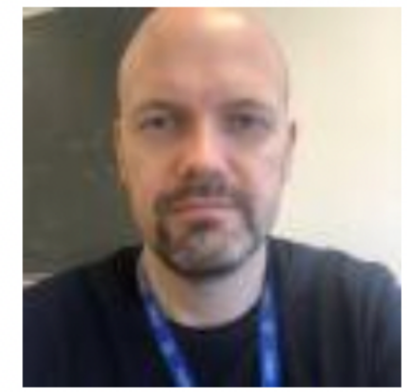
Long term visitor



LEE,

Sung Mook

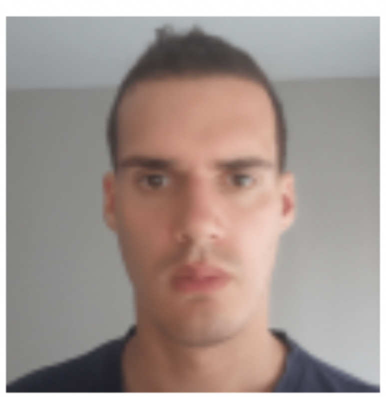
Long term visitor



PRADLER,

Josef

BSM group presentations



BRDAR,

Vedran

CHOI,

Gongjun

KOPP,

Joachim

GEHRLEIN,

Julia

CERN TH Astroparticle/Cosmology

Group meetings

- Mondays at 16:00: cosmo ice cream, ~15 minute black board talk by a group member, in the TH common room
- Tuesdays at 11:30: BSM/cosmo journal club, **new**! Organised by Miguel and Julia, TH common room
- Wednesdays at 11:30: cosmo coffee, weekly seminar by external speakers, TH common room
- Every second Tuesday of each month at 15:00: GW CERN UniGE meeting, zoom
  - Dec 14th, special day at CERN: cosmo coffee by John Ellis on GW searches with atom interferometry; TH Colloquium by Michele Maggiore on the Einstein Telescope; afternoon discussion
- TH Institute: “New physics from galaxy clustering”, 21-25 Nov, Marko Simonovic
- Cosmo skype group

All welcome to join!

CERN TH Astroparticle/Cosmology

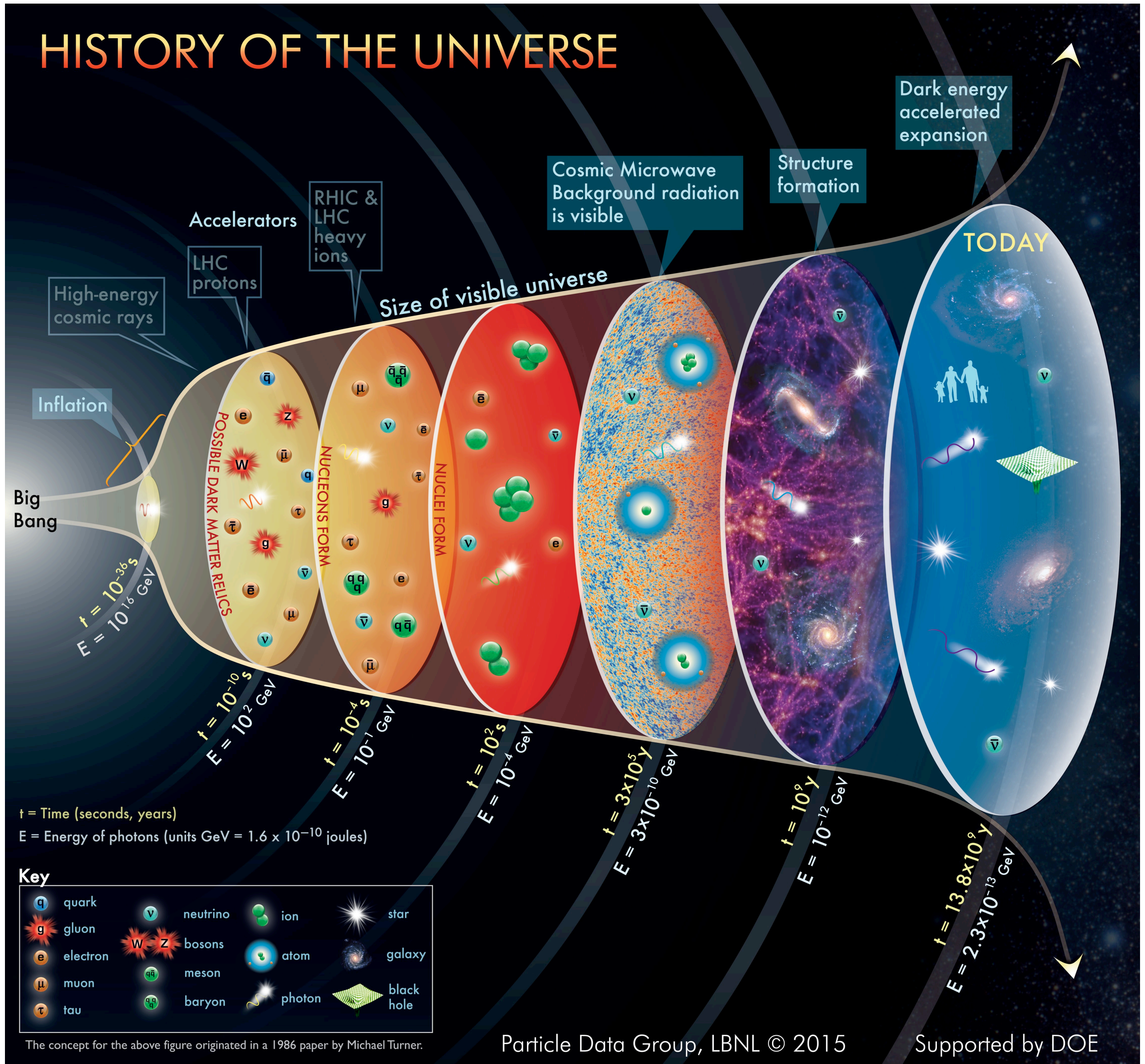
Using astrophysical and cosmological observations
to probe fundamental physics

Recombination and CMB

- confirmation of Big Bang theory, birth of modern cosmology

Primordial universe

- test of high energy phenomena and particle physics
- initial conditions
- unification of forces, Planck scale



Recent universe

- test of gravity at large scales
- late time acceleration
- dark matter
- high energy emissions

CERN TH Astroparticle/Cosmology

- Astrophysical and cosmological observations provide evidence of physics beyond standard theories - standard model, general relativity

  - Late time acceleration: cosmological constant, dark energy, modified gravity - Enea, Marko…

  - Existence and nature of dark matter: mass? interactions? cosmic structure? - Andrea, Fabrizio, Miguel…

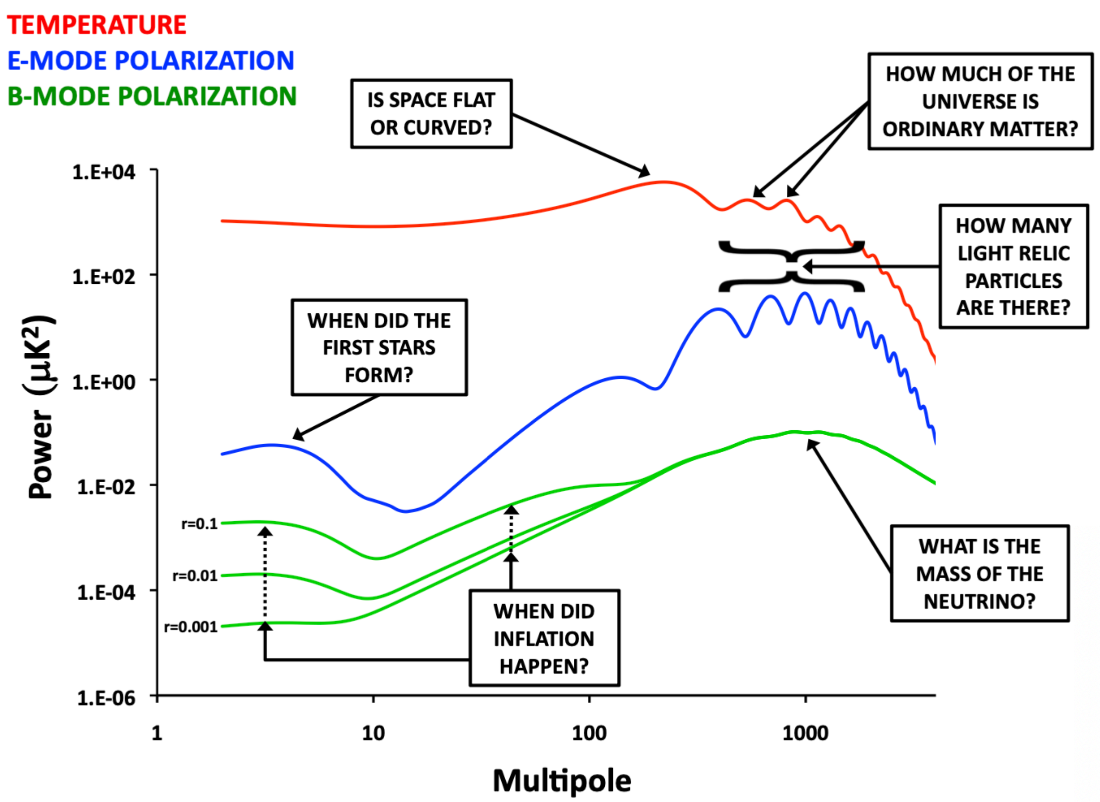
  - Neutrino masses and properties - Miguel…

  - Baryon asymmetry (BSM physics, lepton sector…) - Miguel, Valerie…

  - Inflation (Single field? Interactions? Potential? Observational signatures? Smoking gun?) - Azadeh, Marko, Mauro, Valerie…

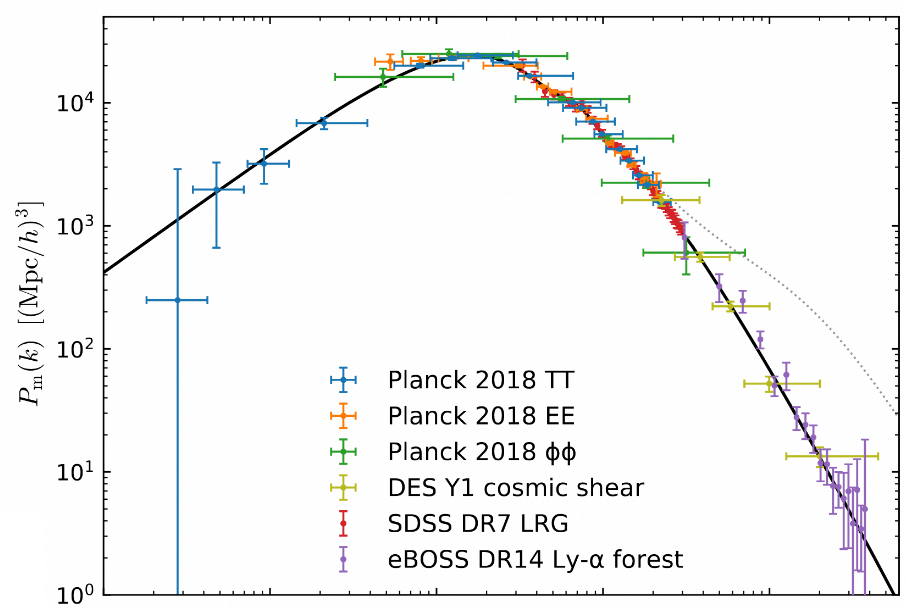
CERN TH Astroparticle/Cosmology

- Astrophysical and cosmological observations provide evidence of physics beyond standard theories - standard model, general relativity
- The evidence is compelling but “indirect”: inferring theories from observations is sometimes challenging

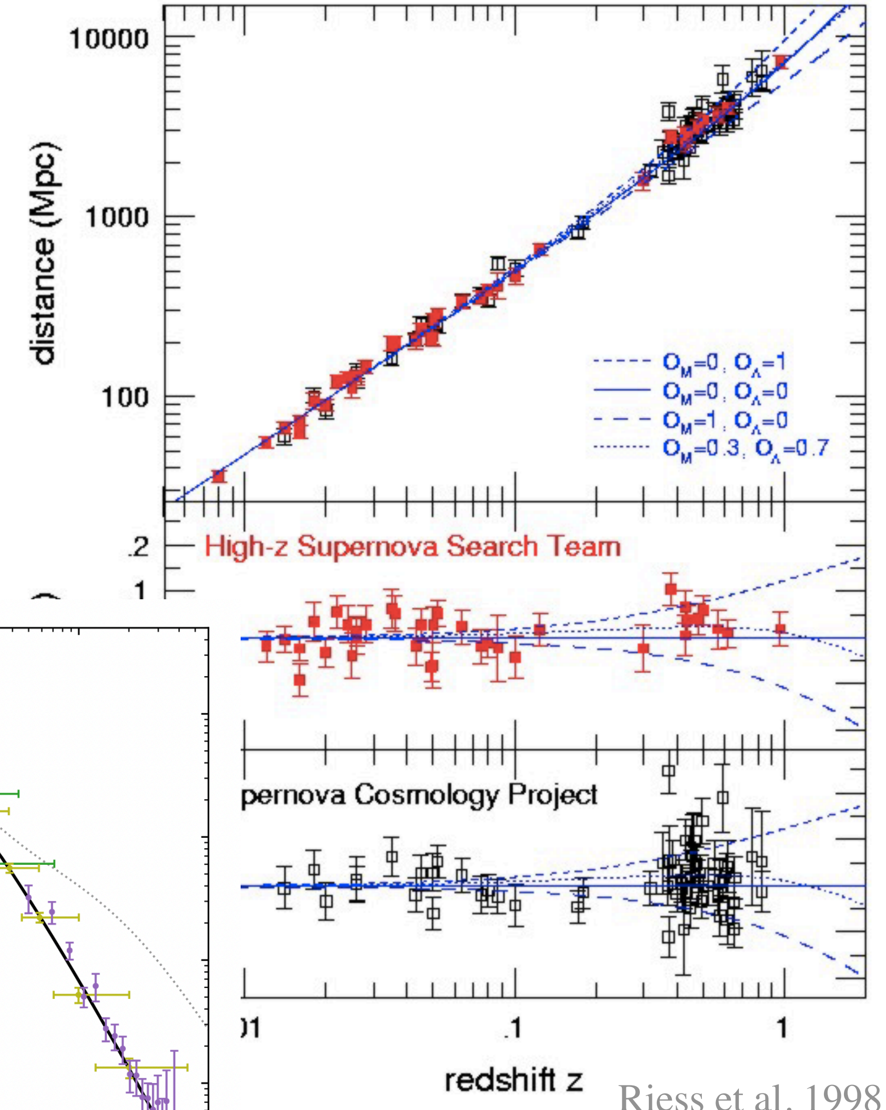


SNOWMASS ArXiv:2203.07638

Do we explain what we observe?



Chabanier et al arXiv:1915.08103



Riess et al. 1998

CERN TH Astroparticle/Cosmology

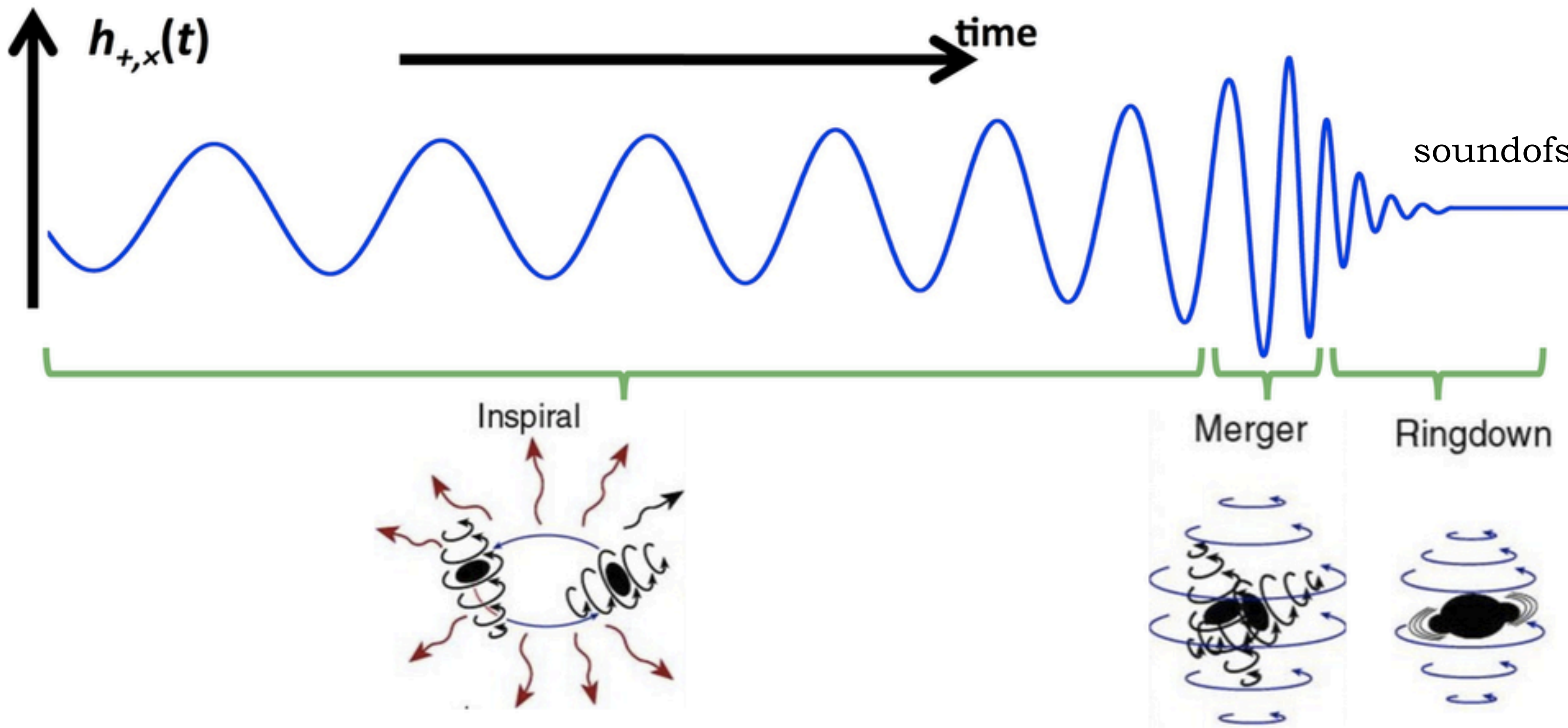
- Astrophysical and cosmological observations provide evidence of physics beyond standard theories - standard model, general relativity

- The evidence is compelling but “indirect”: inferring theories from observations is sometimes challenging

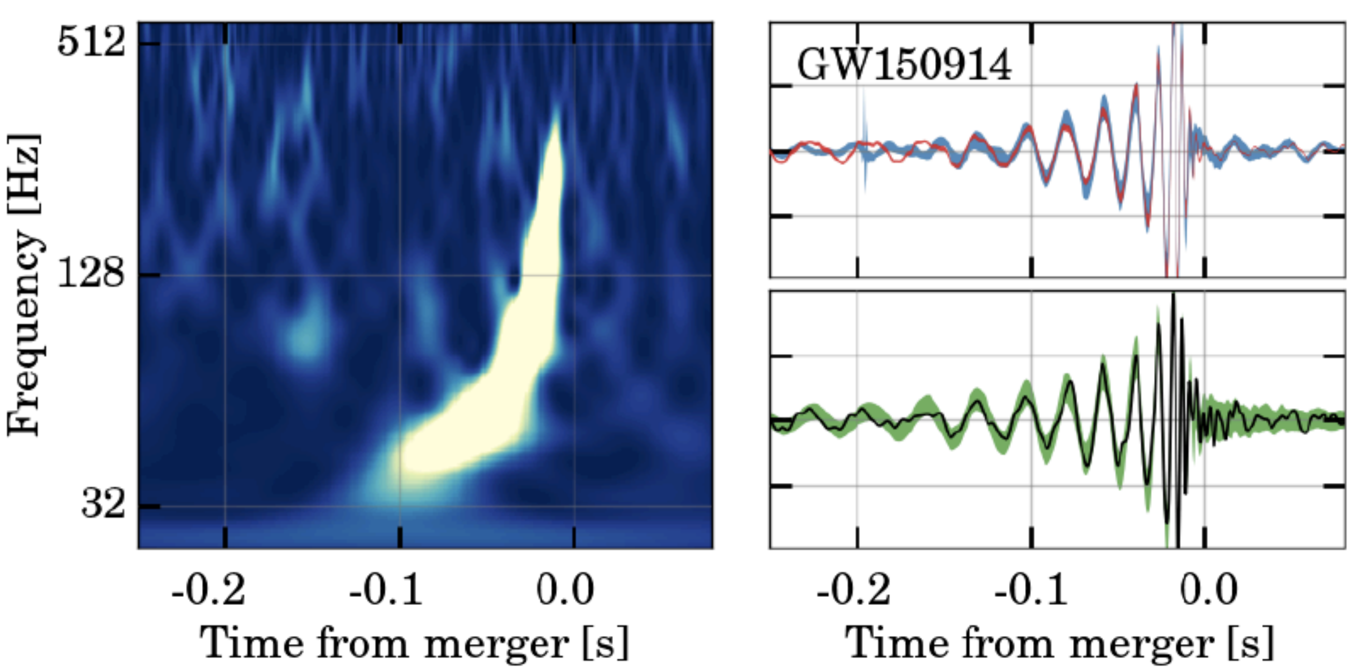
- Good news: the messengers have doubled relatively recently: traditionally electromagnetic waves, cosmic rays; added high energy neutrinos, gravitational waves

Andrea, Azadeh, CC, Fabrizio, Mauro, Valerie…

GW emission from the inspiral of a binary system



soundofspacetime.org



LIGO/Virgo arXiv:1811.12907

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

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

τ time to coalescence

GW emission from the inspiral of a binary system

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

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

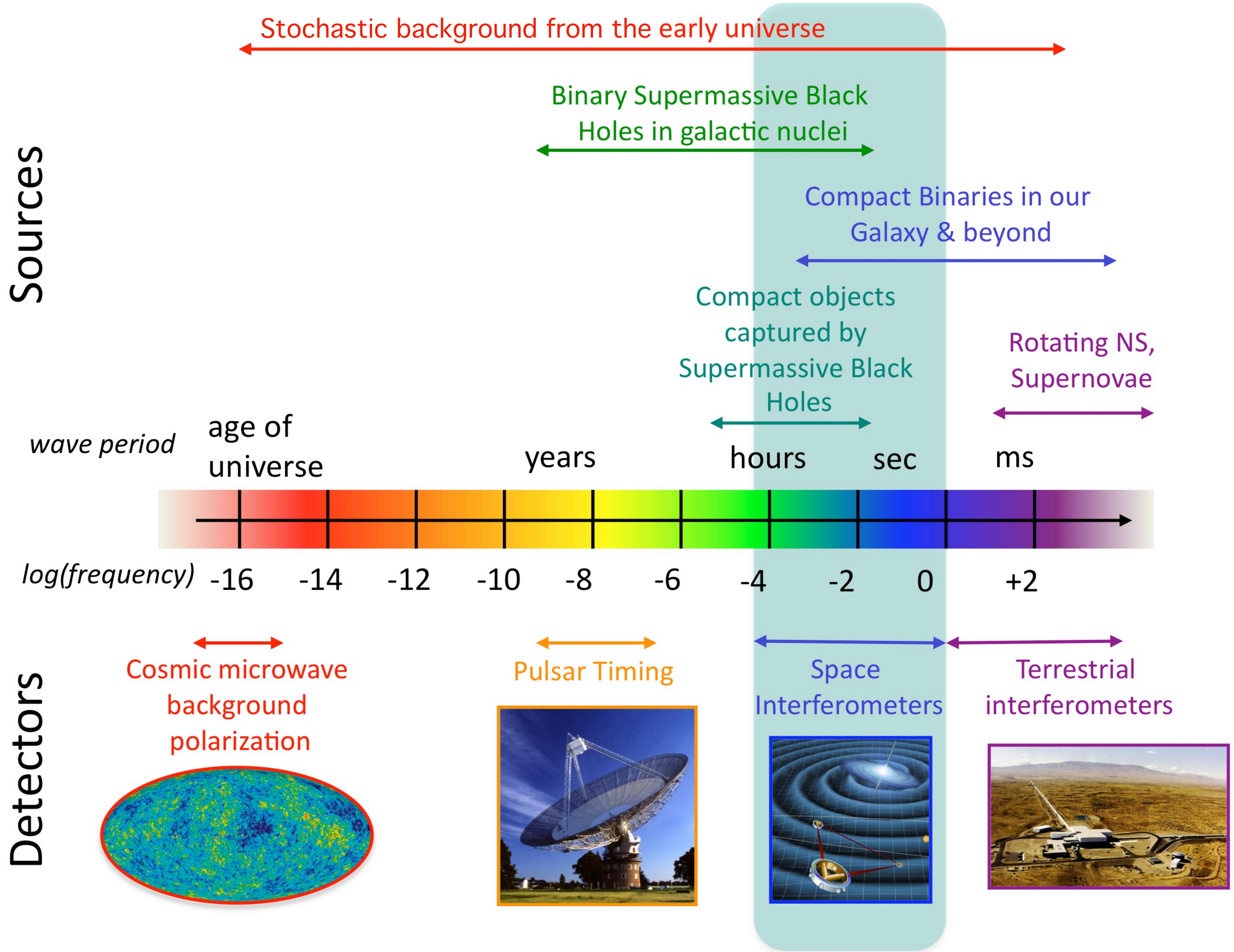
$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 10\,\mathrm{year} \qquad \longrightarrow \qquad f = 0.01\,\mathrm{Hz}$$

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

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

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

The Gravitational Wave Spectrum

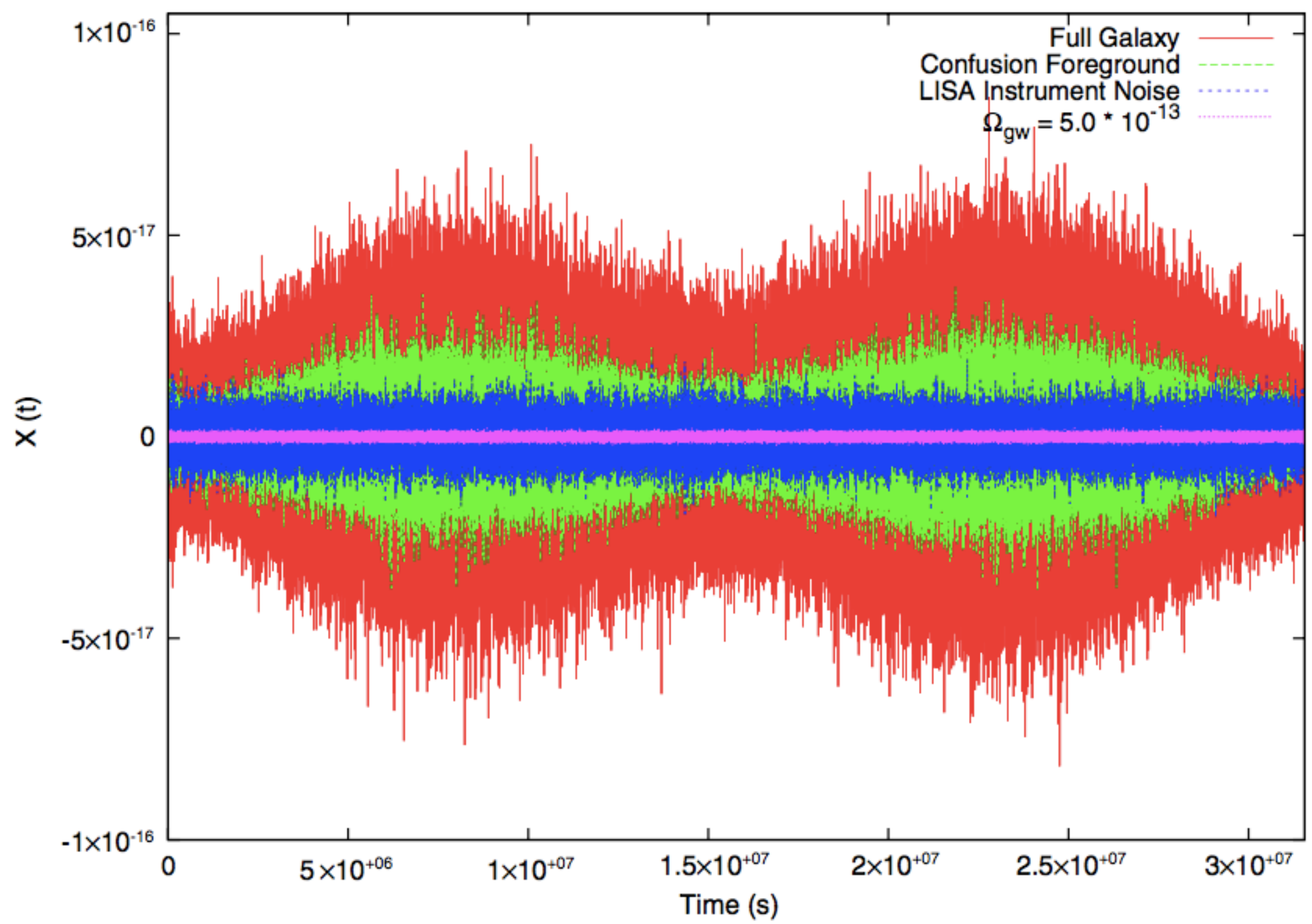


NASA Goddard Space Flight Center

Stochastic gravitational wave background

the superposition of sources that cannot be resolved individually

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

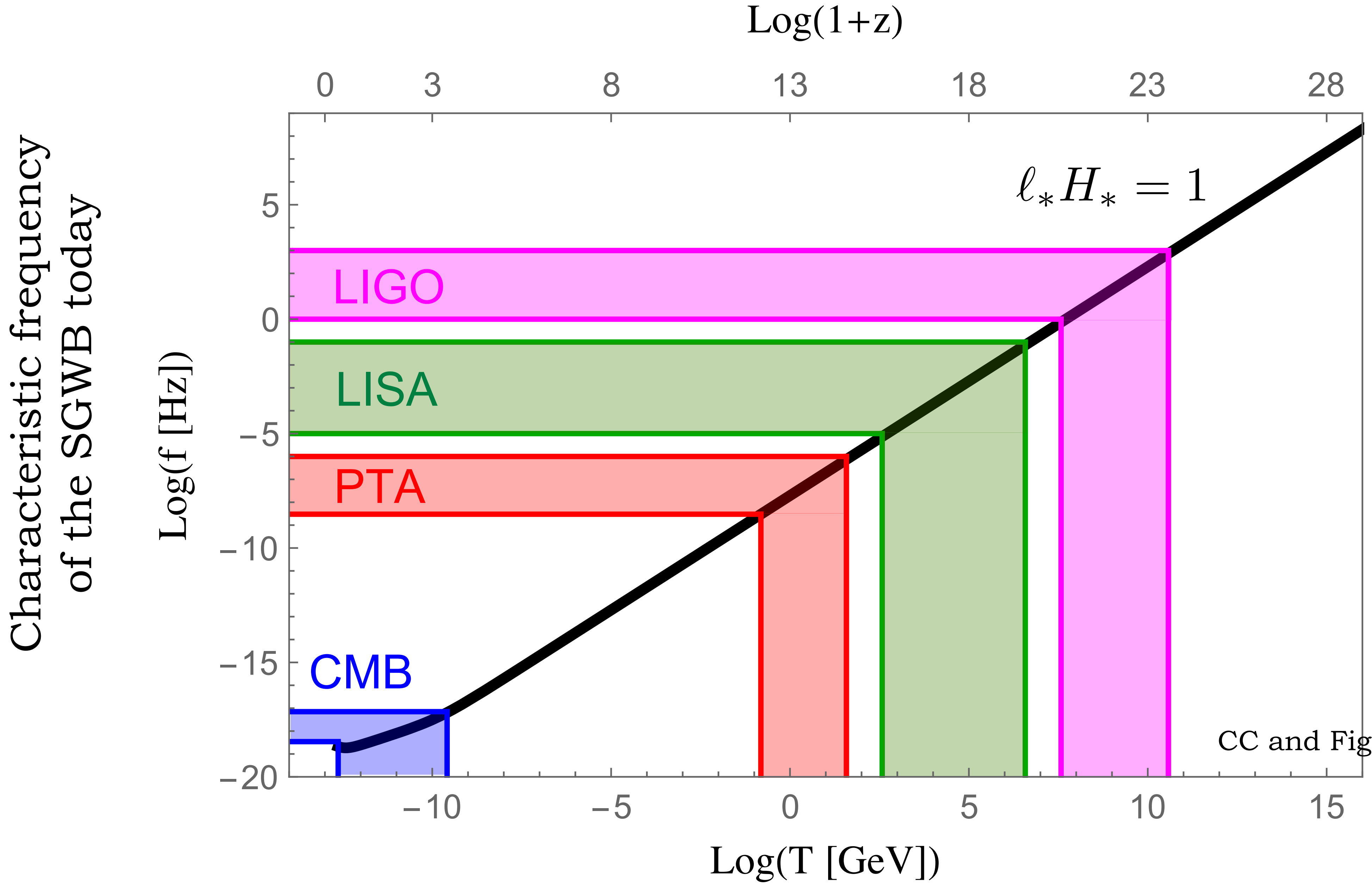


Adams and Cornish, 1307.4116

Potential of GW detectors to probe the primordial universe

Localised source

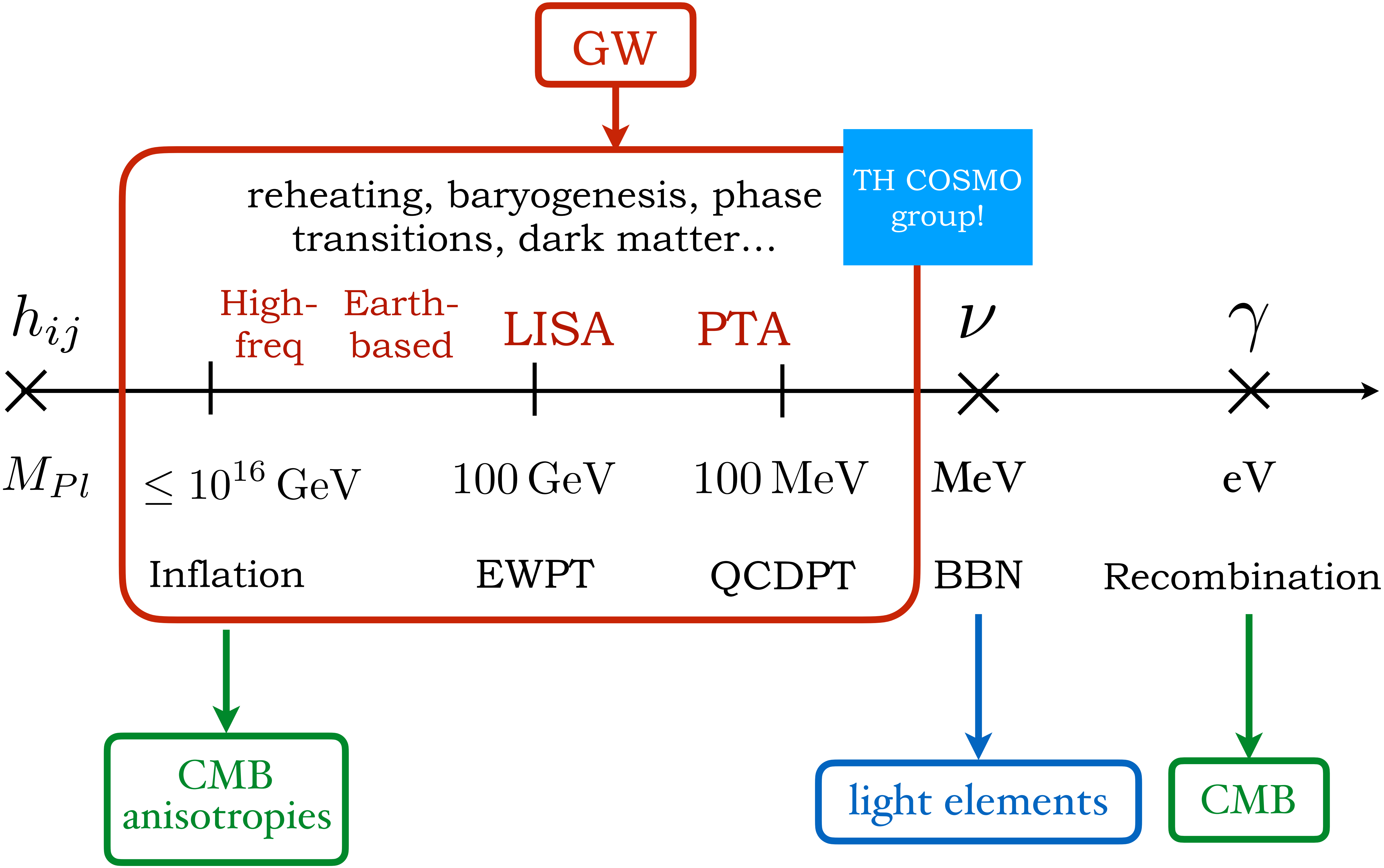
$$f_* = \frac{1}{\ell_*} \geq H_*$$



CC and Figueroa arXiv:1801.04268

Energy scale (temperature) in the early universe

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



The far-reaching scientific potential of GW observations

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

- Astrophysics:
  - Discovery of unexpected 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

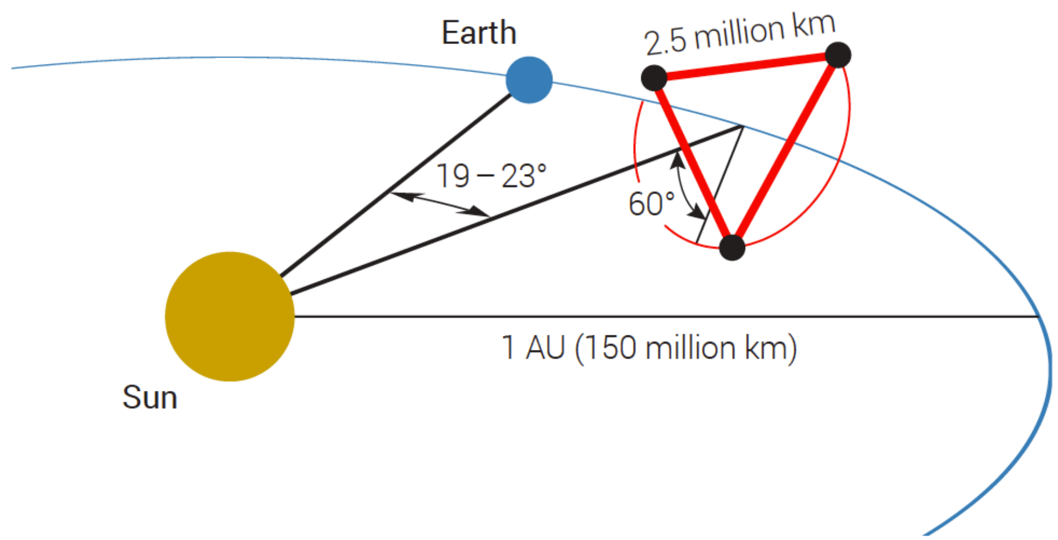
- Fundamental physics:
  - Test General Relativity in the strong field regime (Post Newtonian terms, tests of the horizon, GW polarisations, space-time around black holes…)
  - Test of General Relativity at cosmological scales (GW propagation, GW lensing…)
  - High energy and beyond the standard model 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…)

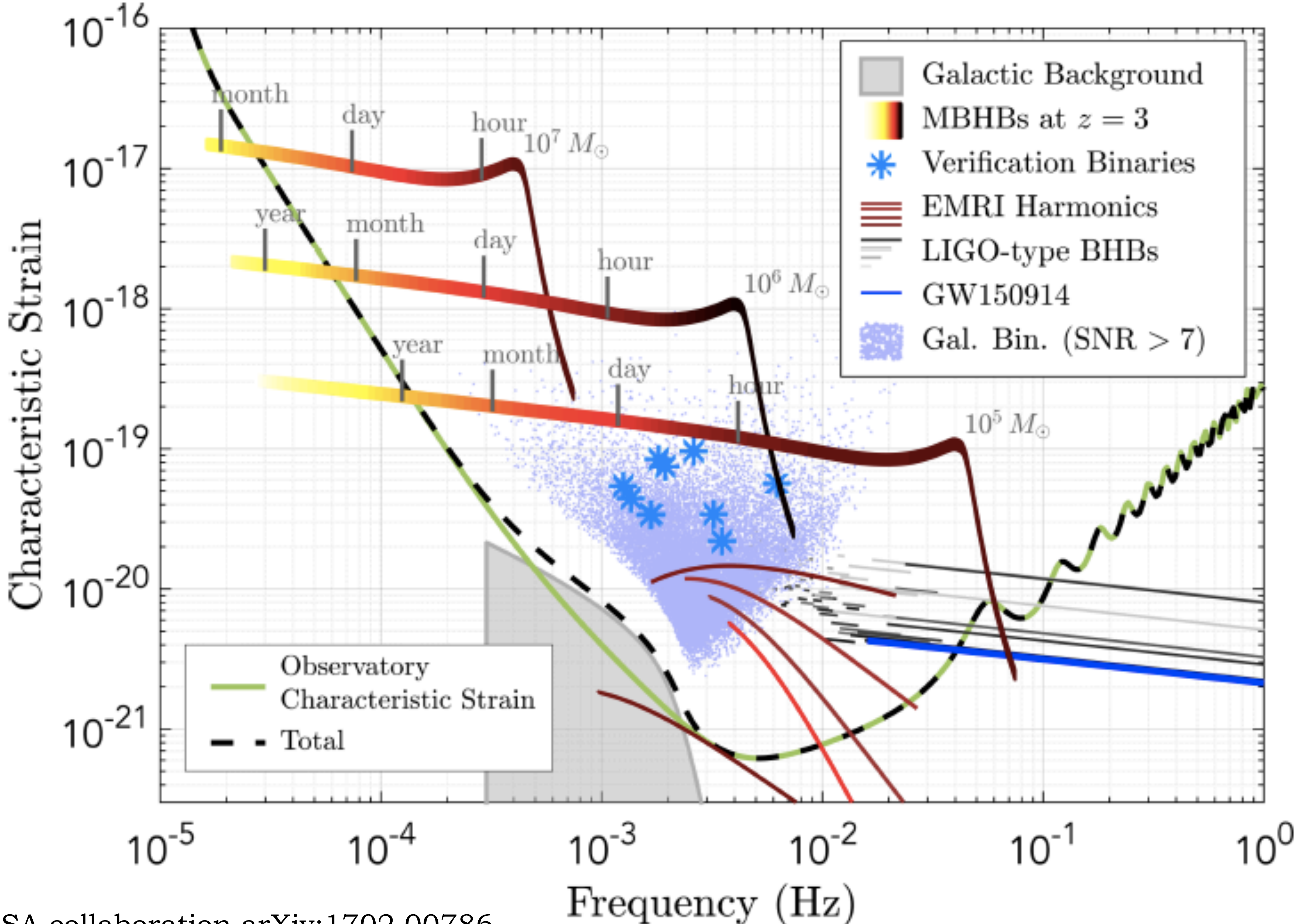
University of Oxford (Ph.D.) -> University of Geneva (postdoc) -> CNRS researcher at CEA Saclay and APC Paris -> shared position CERN/UniGE, on leave from CNRS

Cosmology with Gravitational Waves, in particular with LISA the future space-based interferometer



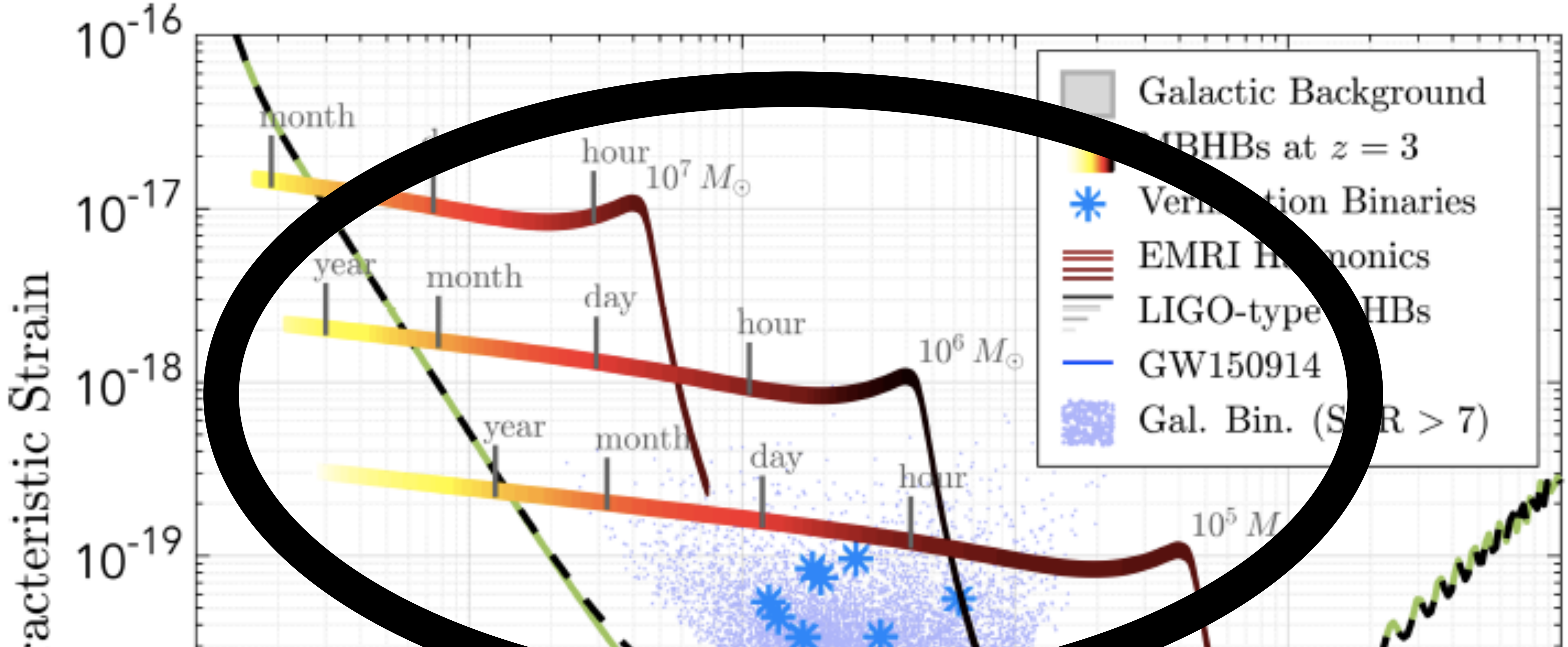
- Coordinator of the Science Investigation Working Group within the LISA Consortium
- Founder of the LISA Cosmology Working Group
- Counselling activity for European Space Agency: Astronomy Working Group, Mission selections (member for M5, coordinator for M/F)
- Co-organiser of TH Colloquium together with Samuel and Sasha
- Co-organiser of GW CERN-UniGE meetings together with Valerie

The potential of space-based GW detection: LISA



LISA collaboration arXiv:1702.00786

The potential of space-based GW detection: LISA



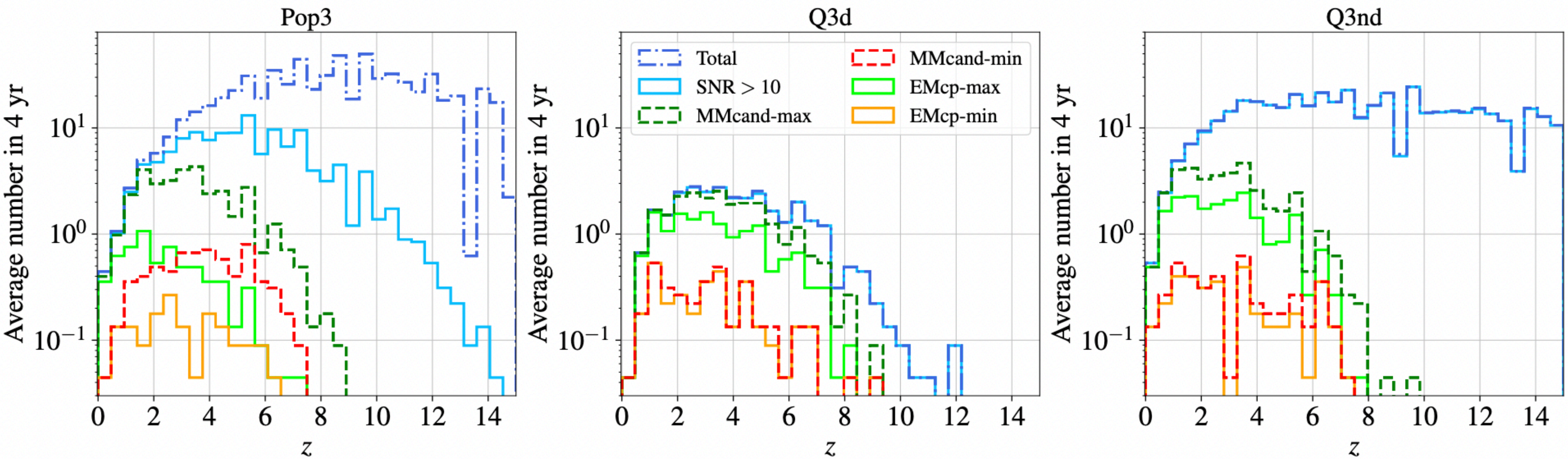
LISA collabora

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? Test of the universe acceleration?**

Example of my contribution: EM counterparts to MBHB in LISA

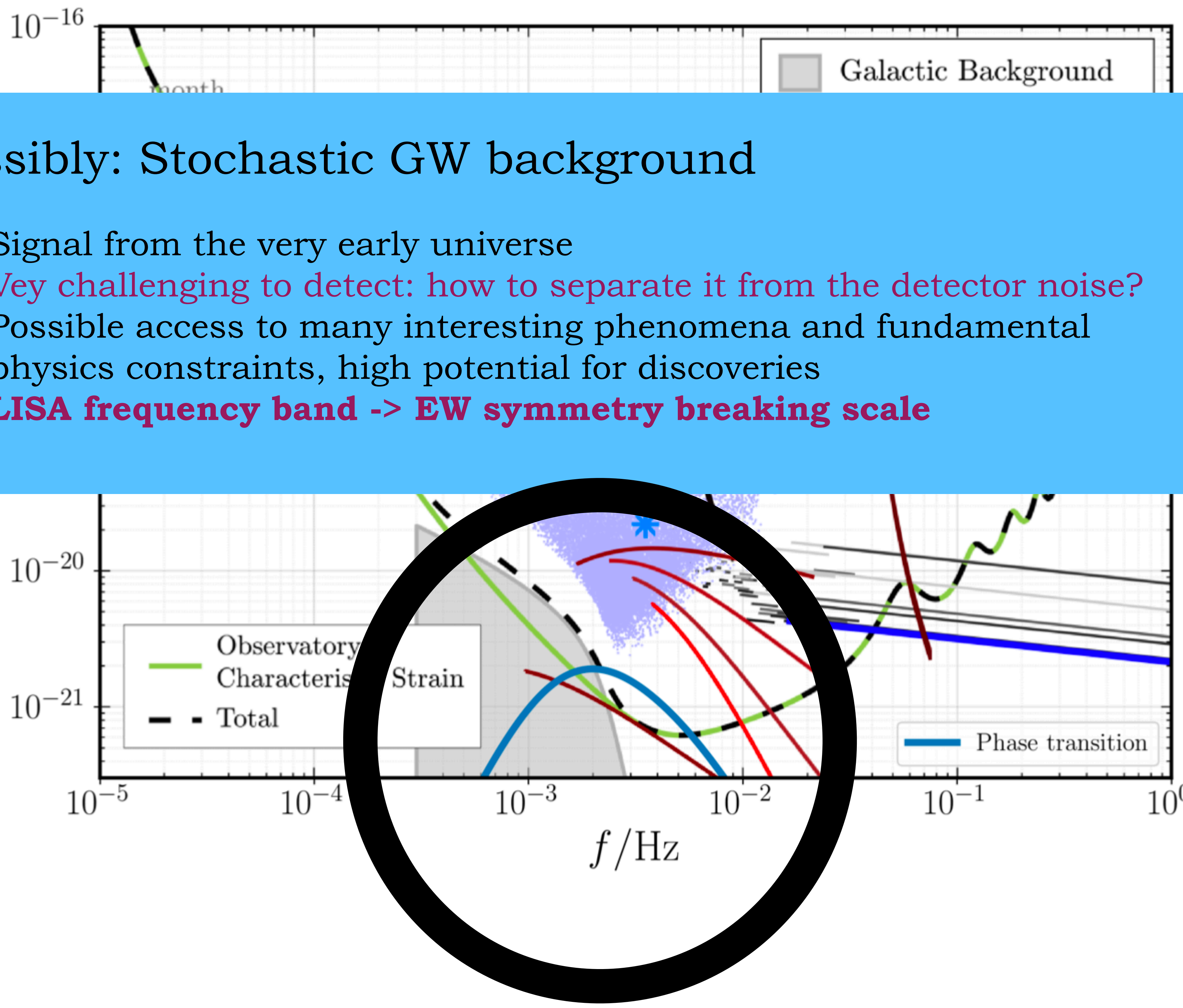
EM counterparts are few and cluster at redshift 2 < z < 5
their number depends heavily on the astrophysical generation model
and on the possible EM detection channel



	Rubin	SKA+ELT Isotropic flare	SKA+ELT $\Gamma 2$	SKA+ELT $\Gamma 10$	Athena+ELT Catalogue $F_{\mathrm{X,\,lim}} = 4\text{e-}17$	Athena+ELT Catalogue $F_{\mathrm{X,\,lim}} = 2\text{e-}16$	Athena+ELT Eddington $F_{\mathrm{X,\,lim}} = 4\text{e-}17$	Athena+ELT Eddington $F_{\mathrm{X,\,lim}} = 2\text{e-}16$	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	
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

The potential of space-based GW detection: LISA

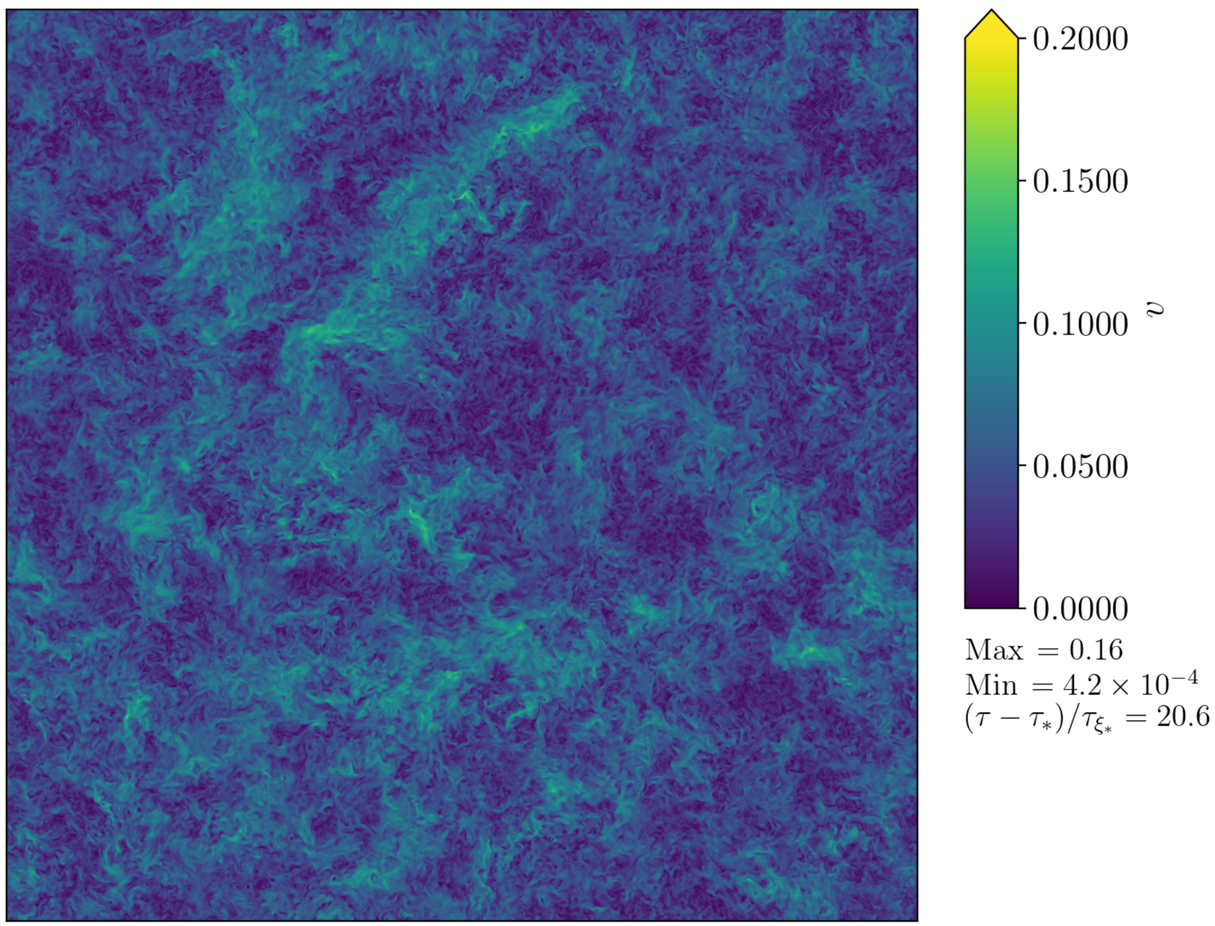


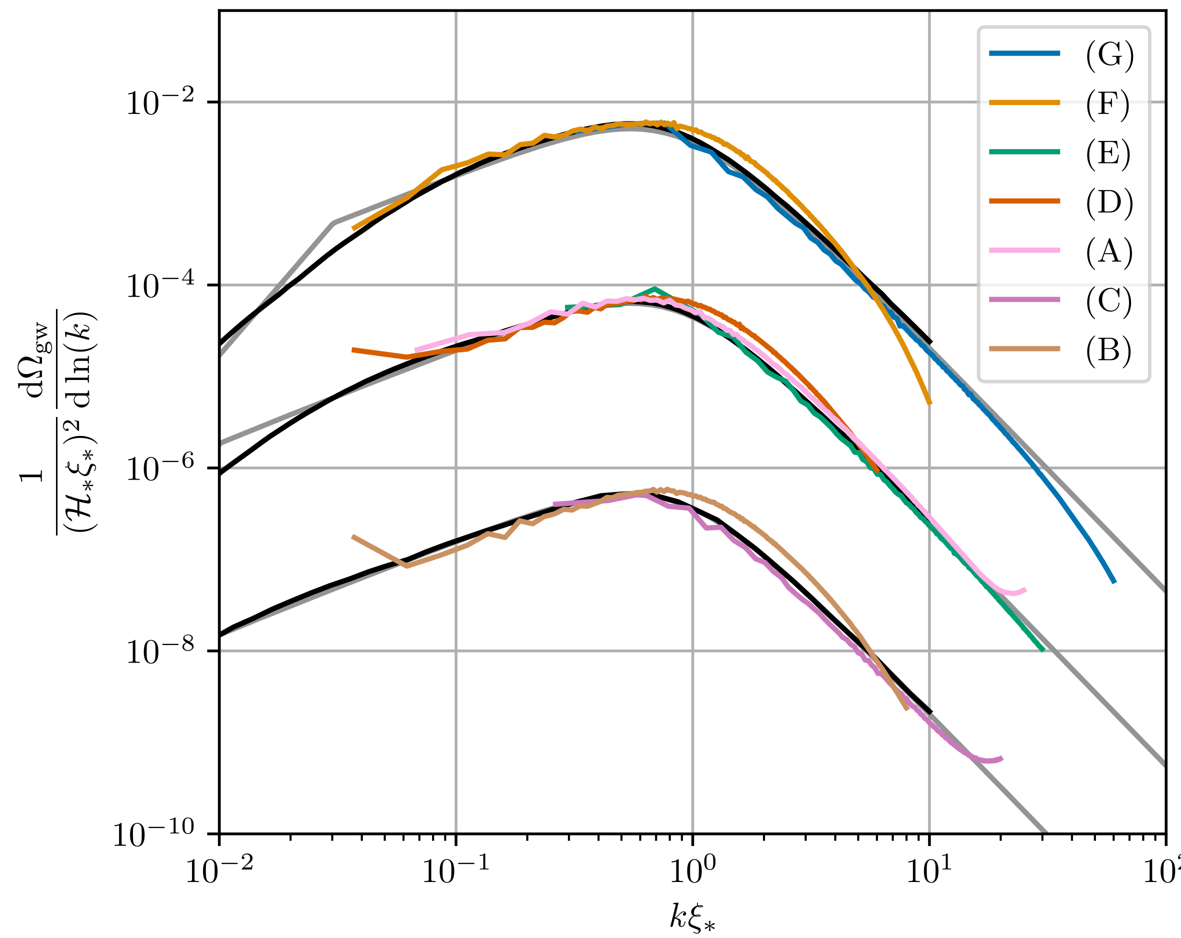
Possibly: Stochastic GW background

- 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 scale**

The potential of space-based GW detection: LISA

Example of my contribution:
GWs from (magneto)hydrodynamic turbulence simulations





CC et al, arXiv:2205.02588

How to define vorticity in the relativistic regime?

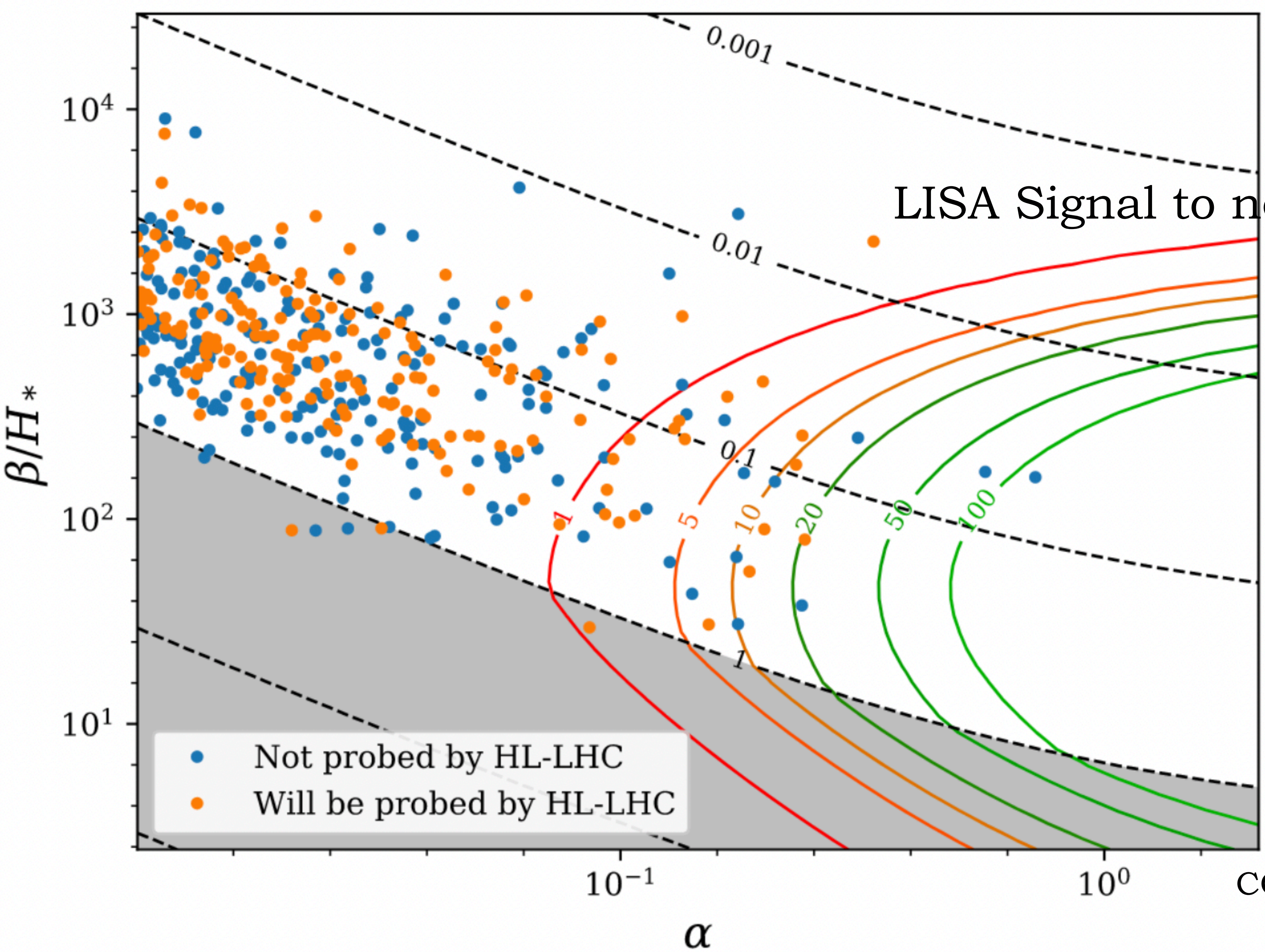
P. Auclair, D. Cutting, M. Hindmarsh, A. Roper Pol, K. Rummukainen, D. Steer, D. Weir

The potential of space-based GW detection: LISA

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

Attention! Old plot!

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

Maybe a new discovery: Pulsar Timing Arrays

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

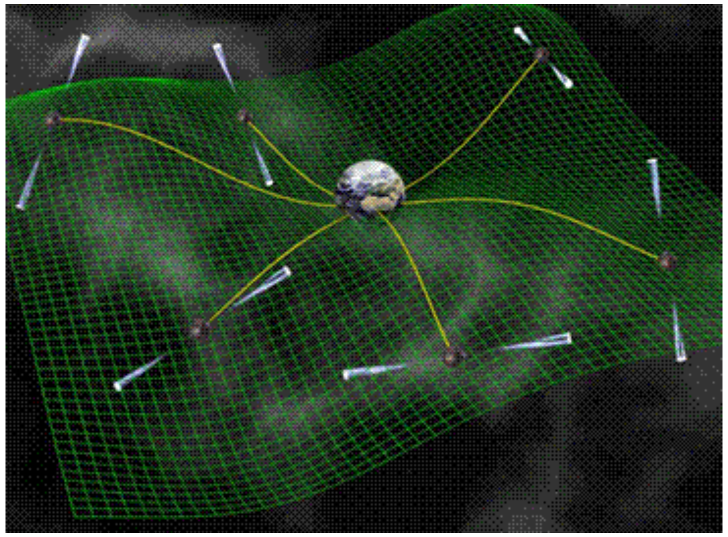
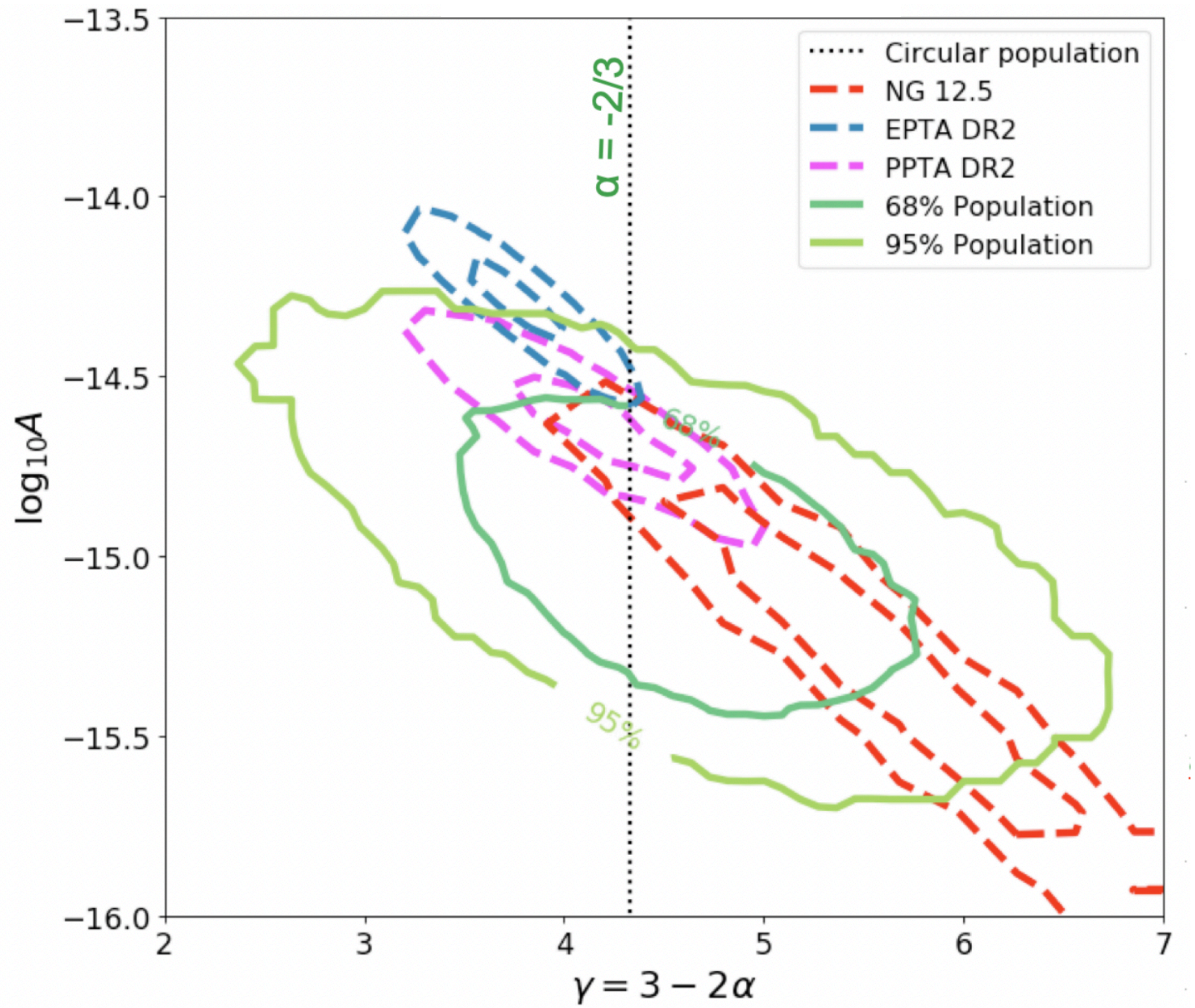


Figure from: S. Babak & S. Chen, 2021

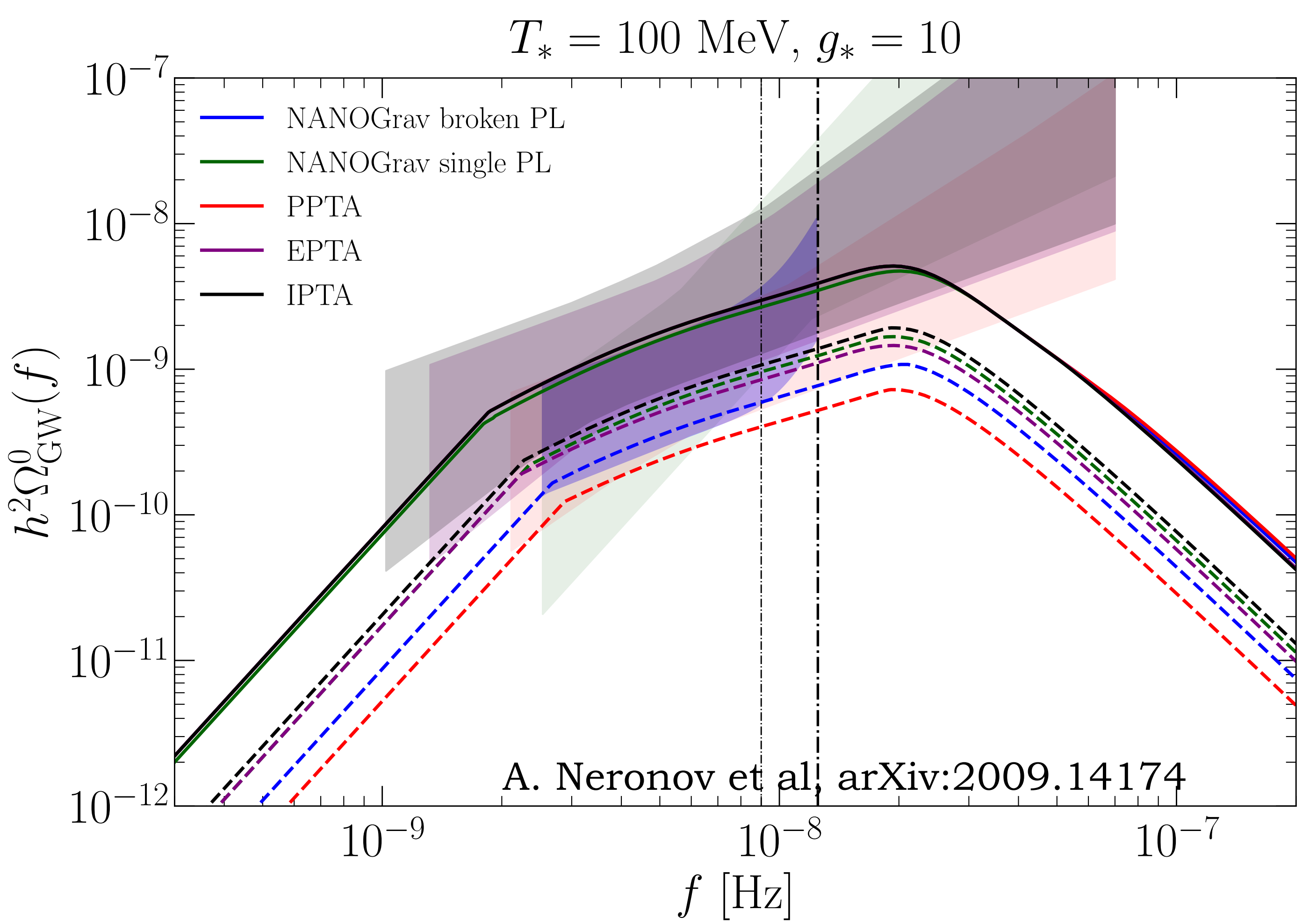


Z. Arzoumanian et al, arXvi: 2009.04496, B. Goncharov et al, arXiv:2107.12112, S. Chen et al, arXiv:2110.13184

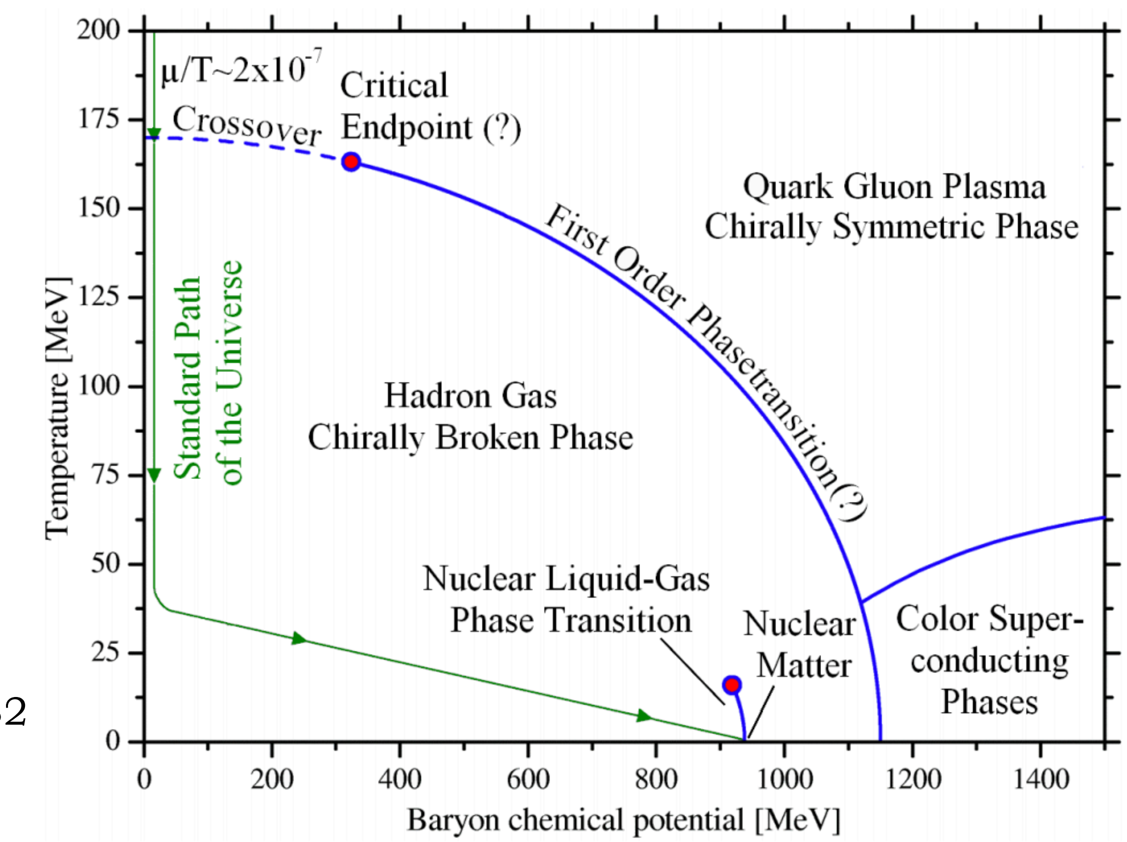
Maybe a new discovery: Pulsar Timing Arrays

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

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



Please, give me a motivation!



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

Thank you for your attention