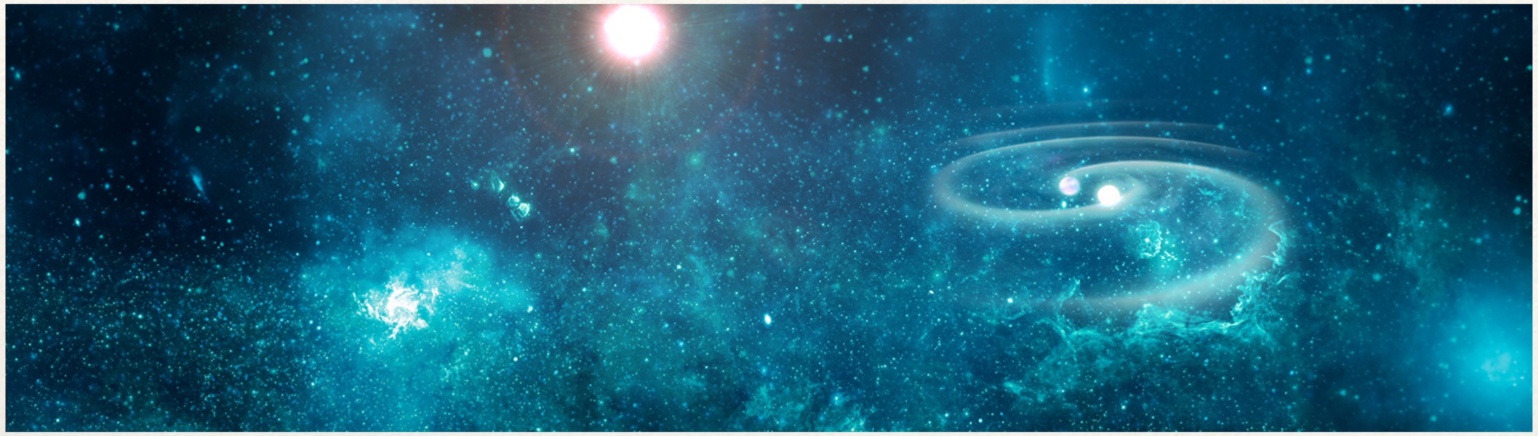
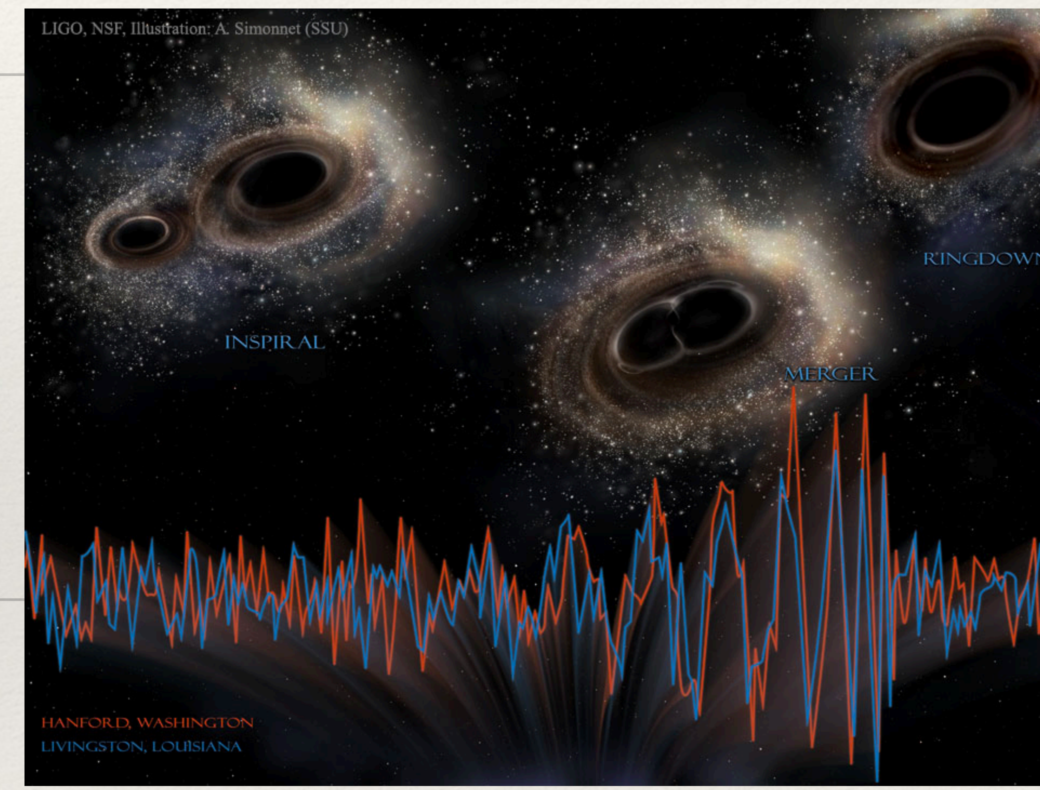
Stanislav Babak.
AstroParticule et Cosmologie, CNRS (Paris)

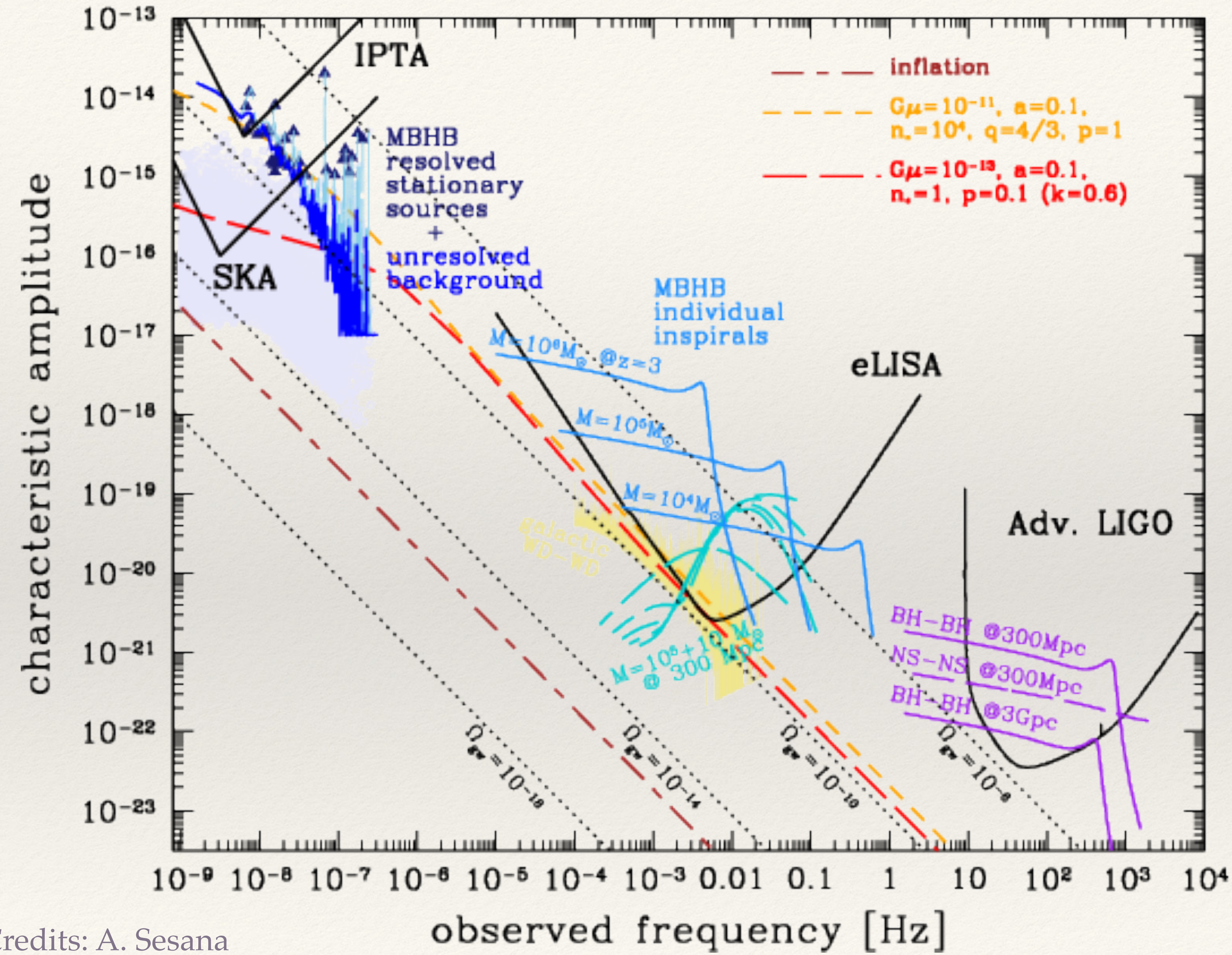


Fundamental physics with gravitational waves



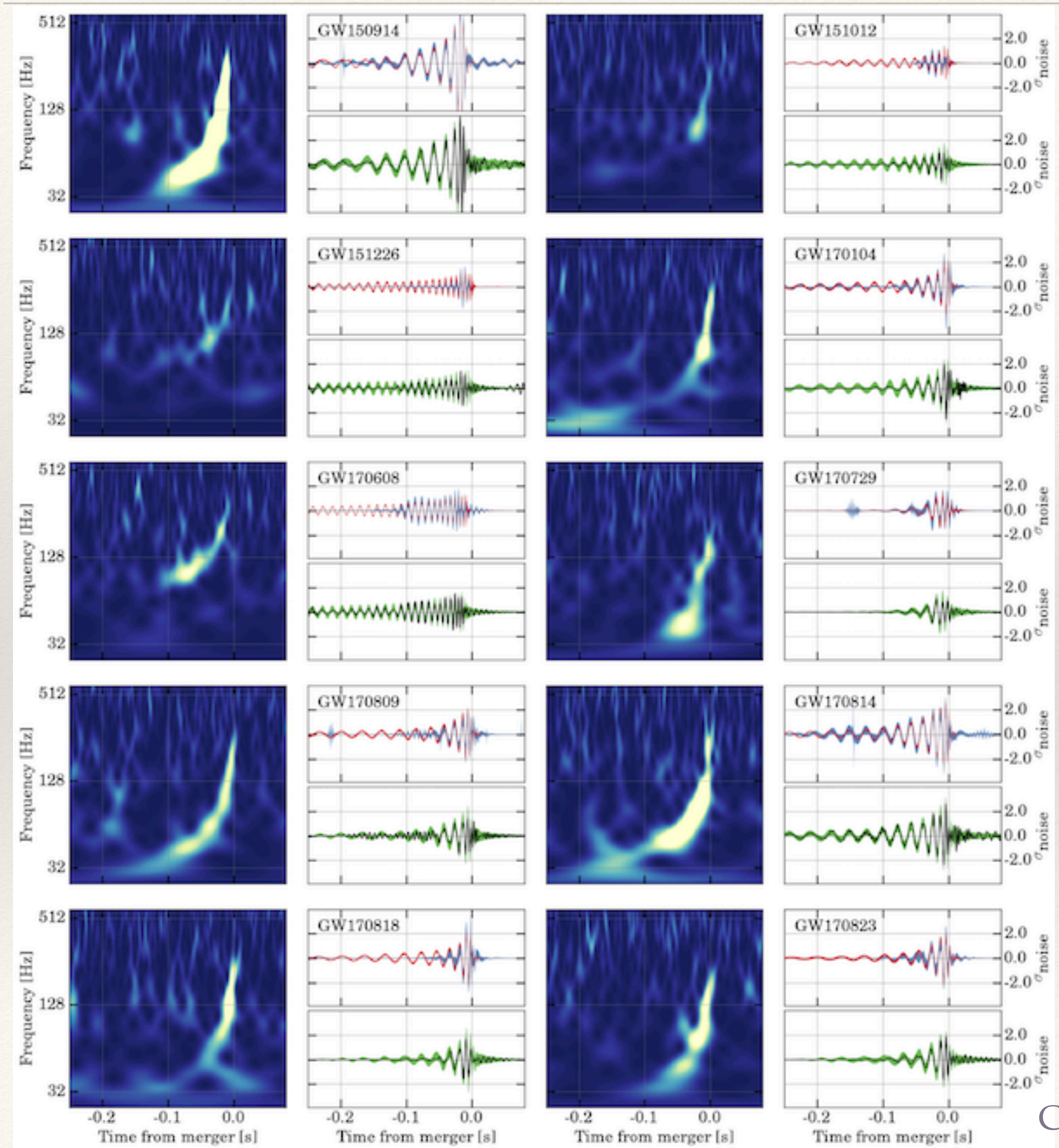
Annecy, 12-13 November

GW landscape



Credits: A. Sesana

Results from O1-O2 runs



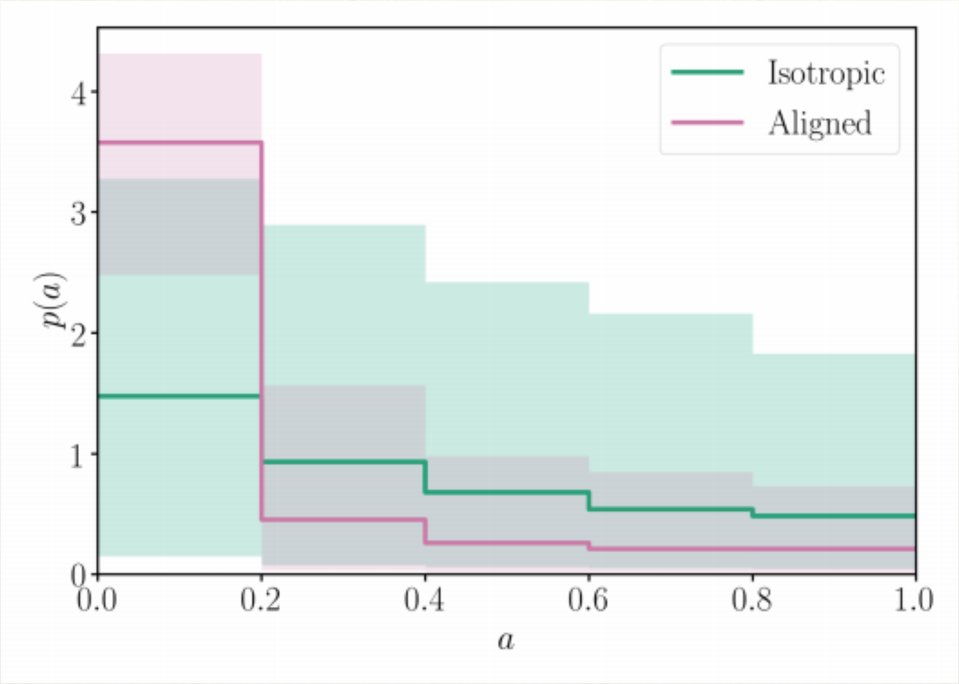
- The first GW catalogue:
  - 10 GW signals from black hole binaries and
  - 1 binary neutron star merger
- The e/m counterpart was associated with the BNS merger

- Discovery of BHs M> 20 solar
- Binary systems merge t<t_hubble
- SGRB - kilonovae - BNS

Credits: LVC

Astrophysical population of BHs

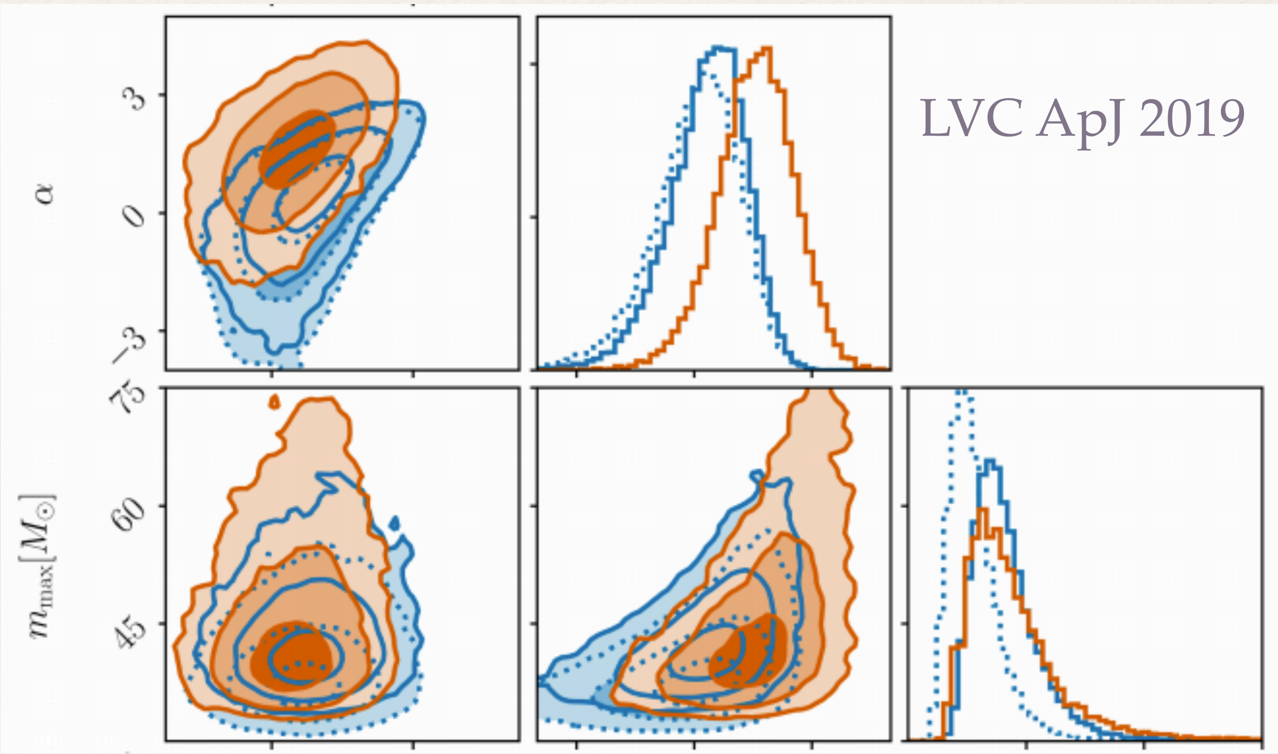
- **How black hole binaries were formed**?
- **What is origin of black holes**: stellar collaps vs primordial BHs, 1st vs 2nd generaiton of BHs



distribution of spin amplitude

Mass distribution

$$p(m_1, m_2|m_{min}, m_{max}, \alpha, \beta) \propto C(m_1) m_1^{-\alpha} \left(\frac{m_1}{m_2}\right)^{\beta}, \text{ if } m_{min} \leq m_2 \leq m_1 \leq m_{max}$$

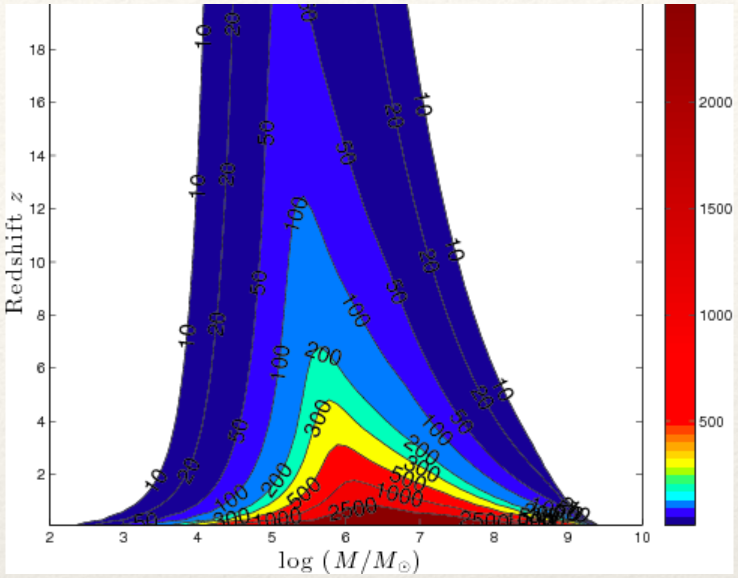


- **We need more events: on-going O3 (~35 public events)**
- **We need high SNR events: better determination of parameters (1/SNR), especially spins: Einstein Telescope**

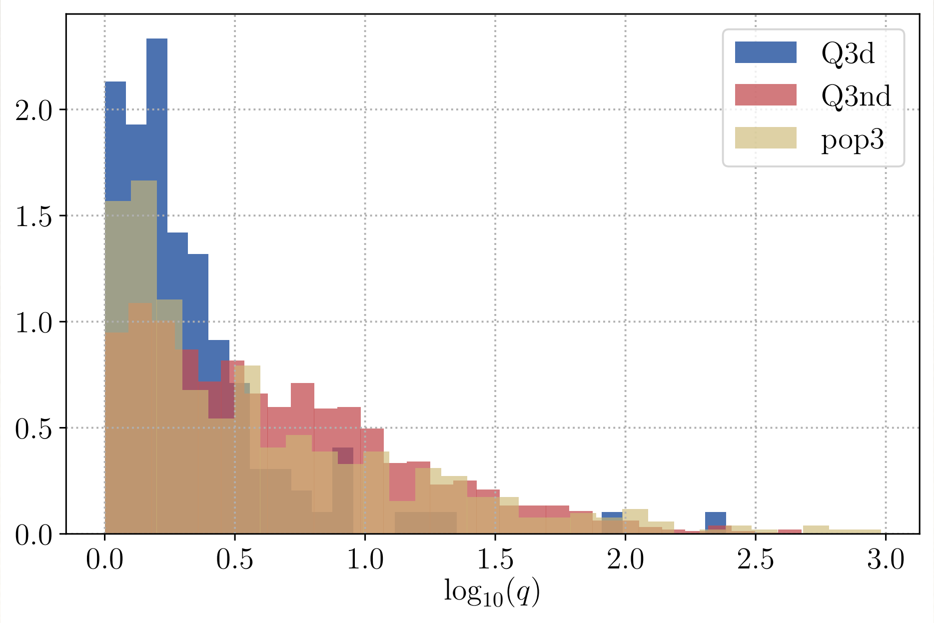
Super-massive black holes

Prime sources for LISA (merging MBH binaries) and PTA (inspiral)

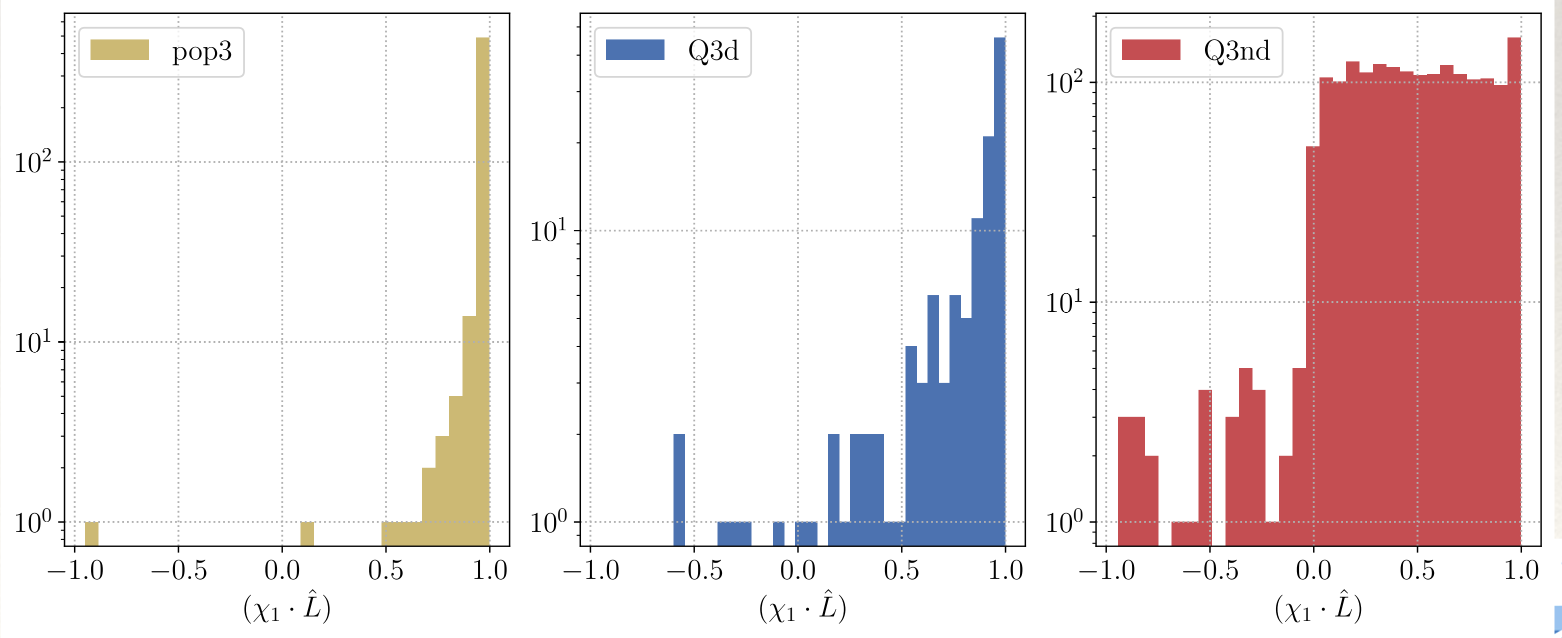
- LISA will observe merging MBHBs to very high redhsift



- **pop3** model: light seeds, remnants of pop3 stellar population
- **Q3d** model: heavy seeds, (direct collapse of gigantic clouds) + delay between galactic and MBH merger
- **Q3Nd** model: heavy seeds, (direct collapse of gigantic clouds) + **NO** delay between galactic and MBH merger



Antonini+, Aph.J. 2015



Figures from: Marsat+ in prep.

Cosmography with GWs

Rate of expansion of the Universe?

More than 4-sigma discrepancy in Hubble constant

$H_0 = 66.93 \pm 0.62 \text{ kmMpc}^{-1}\text{s}^{-1}$ CMB-based result (Planck collaboration)

$H_0 = 73.5 \pm 1.4 \text{ kmMpc}^{-1}\text{s}^{-1}$ SN Ia measurements

Late-time acceleration of the Universe

- Dark energy
  - Cosmological constant? (fluid with energy density independent of space and time)
  - Early dark energy: DE evolves with redshift and contributes to rate of expansion at z>1
- Dark matter
- Modification of GR on large scale

Cosmography with GWs

Standard sirens: GWs deliver information about the luminosity distance to the colaescing binaries. We need information about the redshift to the GW sources then we can infer cosmological parameters

$$D_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

We can obtain redshift

1. directly if we associate GW with a host galaxy: requires e/m counterpart
2. statistically if have enough of GW events

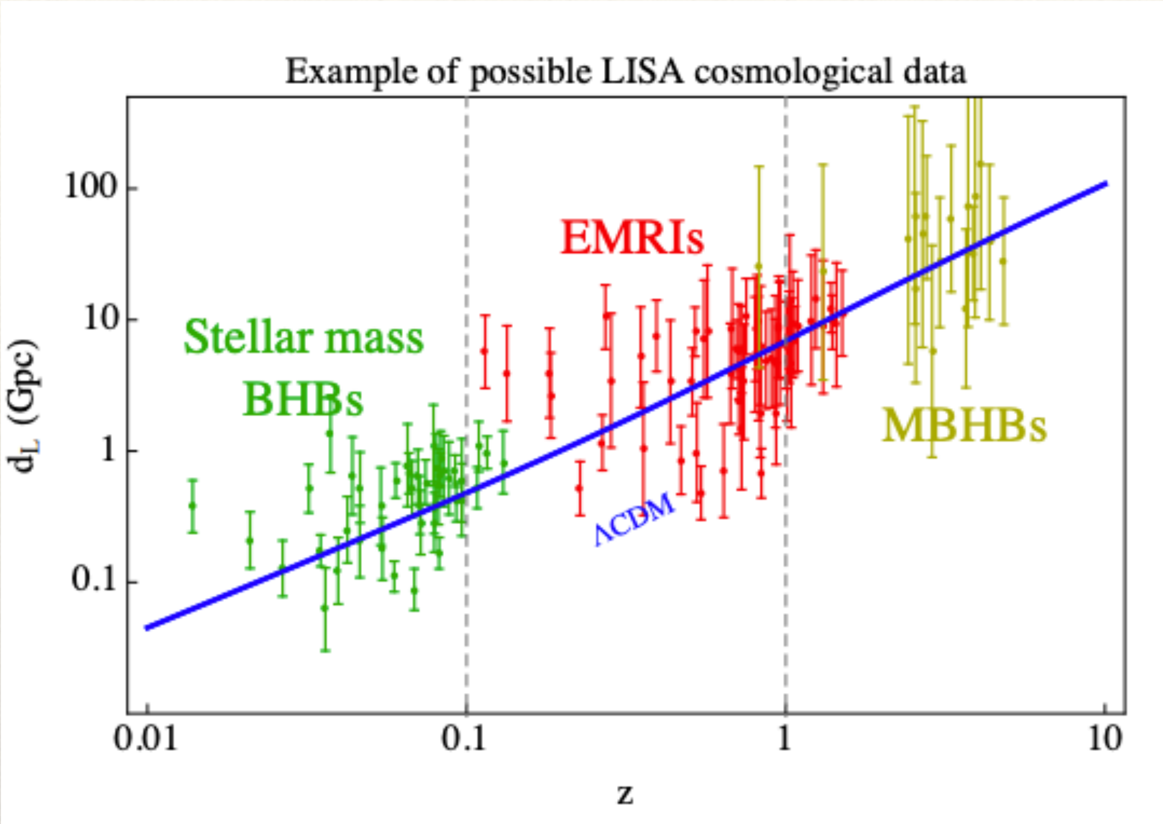
Ground based detectors

BNS event (GW170817): inferring Hublle constants using (1.) $H_0 = 70.0^{+12}_{-8}\ \mathrm{kmMpc^{-1}s^{-1}}$

- Require about 100 BNS events with e/m counterpart to constrain Hubble constants to 2%
  - **Long-term observations** with Ad-(LIGO/Virgo) GW detectors
  - **Einstein Telescope**: 10^5 BNS mergers/year
- We can measure the redshift directly from GW from merging BNS if
  - we know EoS and we observe the merger in GW
  - Requires significant improvement at high frequency: next generation like **Einstein Telescope**

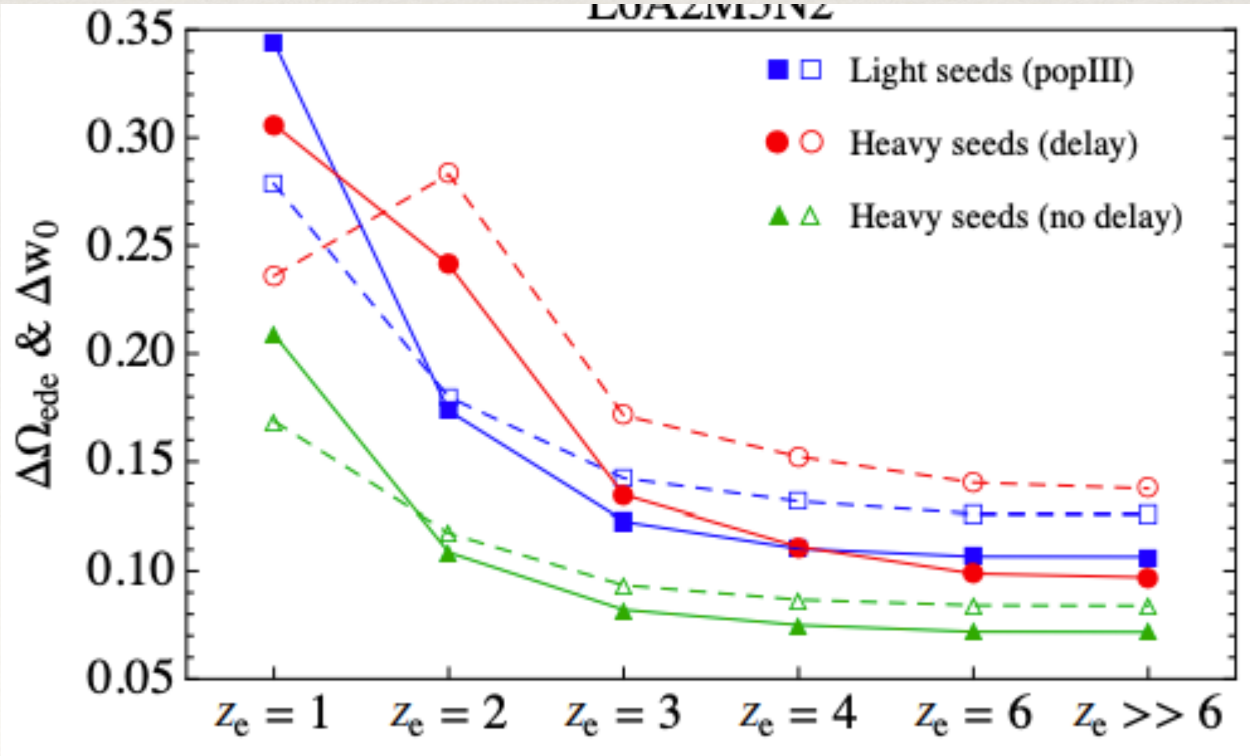
Cosmography with GWs

LISA can probe the expansion of Universe at several scales



N. Tamanini J. Phys. CF 2016

We might be able to constrain not only the Hubble constant but also the dark energy



Ch. Caprini, N. Tamanini JCAP 2016

Early Universe in GWs

The violent processes in the early Universe produce stochastic GW background (SGWB)

- *First order phase transition*: collision of true vacuum bubbles and conversion to the symmetry-broken phase accompanied with snisotropic stresses.
  - The LISA band (10^{-4} - 0.1 Hz) corresponds to the energy scale of the EW (electroweak) phase transition (up to 10^4 TeV).
  - Formation of sound wave, shocks and turbulence in the plasma

- *Cosmic strings*: a network of strings formed in the early Universe generates SGWB (as superposition of many uncorrelated sources) and (possibly) individual bursts

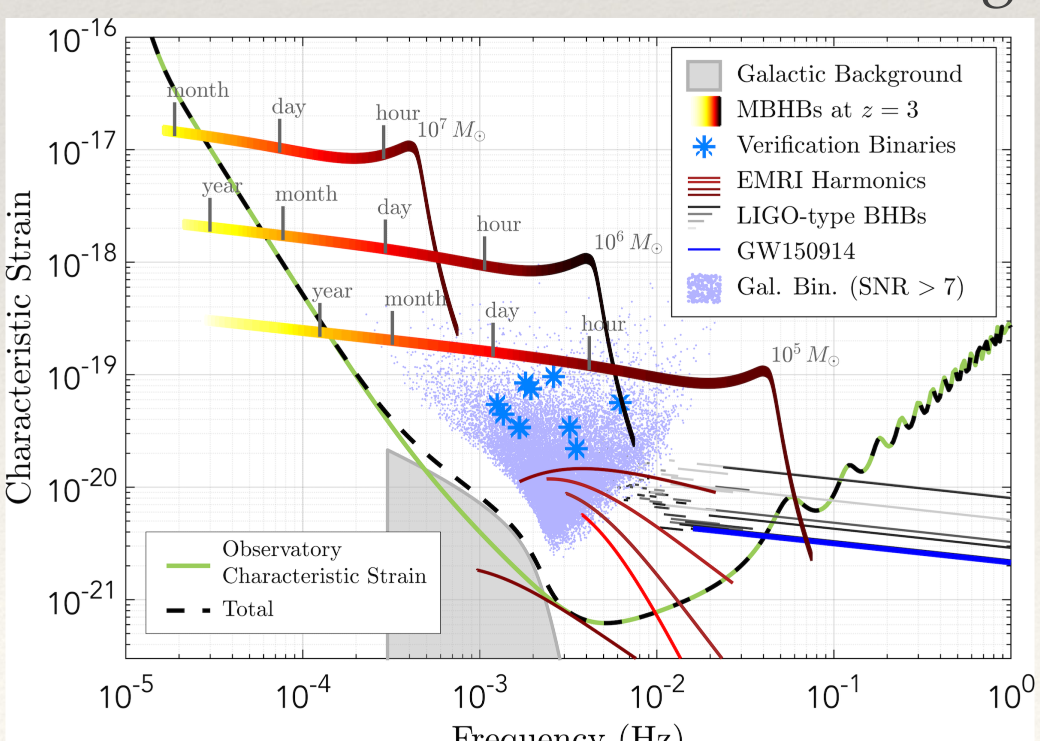
Astro stochastic GW signal

Population of unresolved (and subthreshold) GW signals will also create SGW signal

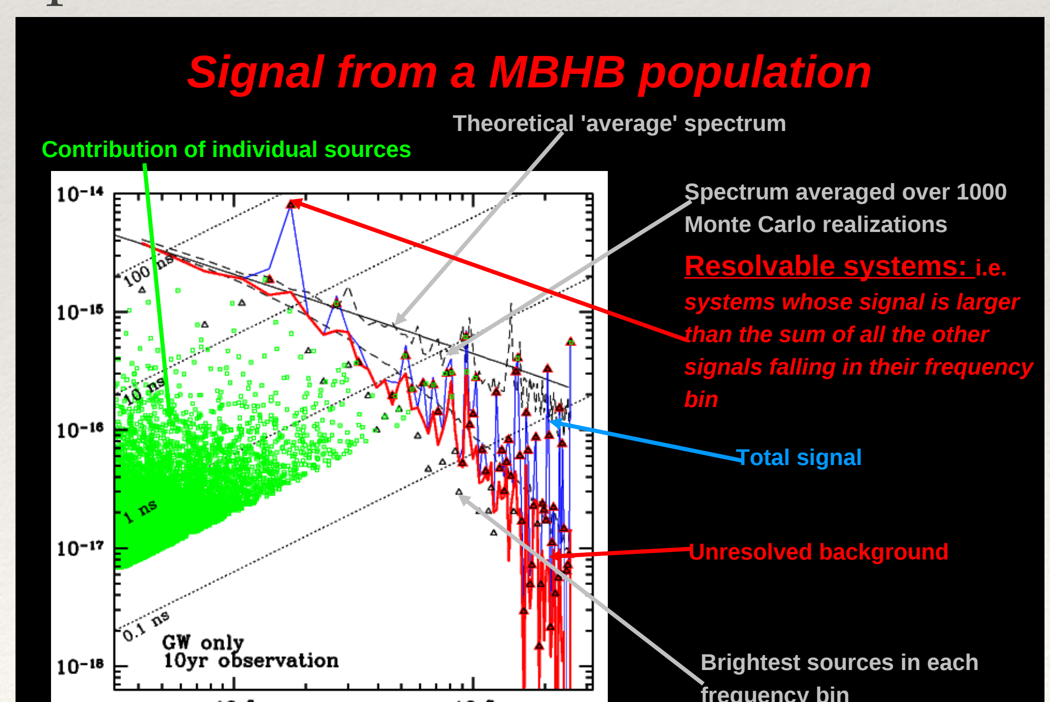
- In LIGO/Virgo frequency band: population of inspiralling binaries (BH-BH, BH-NS, NS-NS).
  - might be limiting noise/foreground in Einstein Telescope

- In LISA band:
  - Galactic binaries (white dwarfs) are numerous and will create unresolved foreground
  - Event rate for other sources is uncertain, with the most optimistic astro models we might have detectable stochastic signal from EMRIs, stellar mass BH binaries

- In PTA band we should have SGW signal from population of MBHB in the local Universe



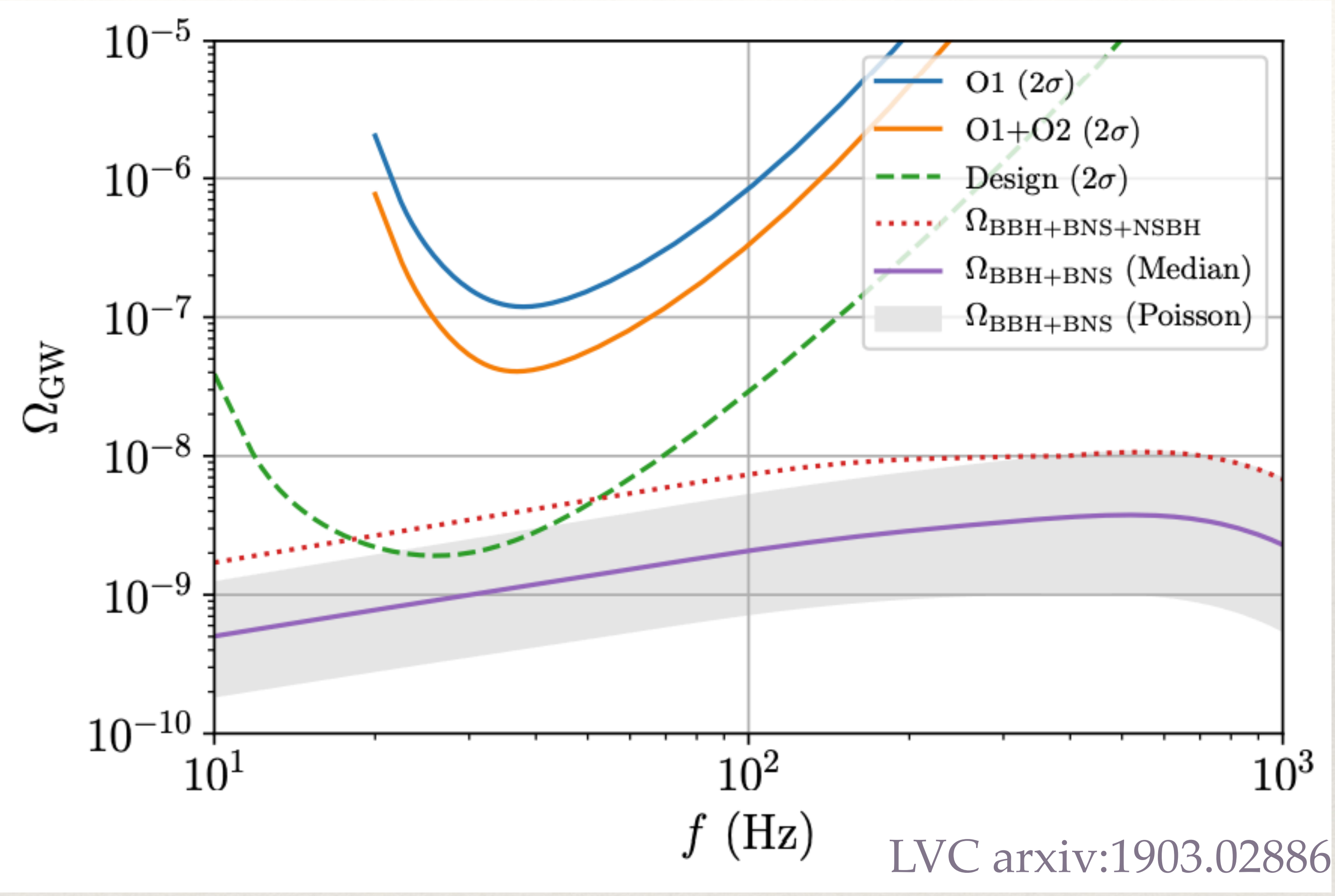
Credits: LISA consortium



Credit: A. Sesana

Search for stochastic GW signal

Current result from O1 and O1+O2 LVC data

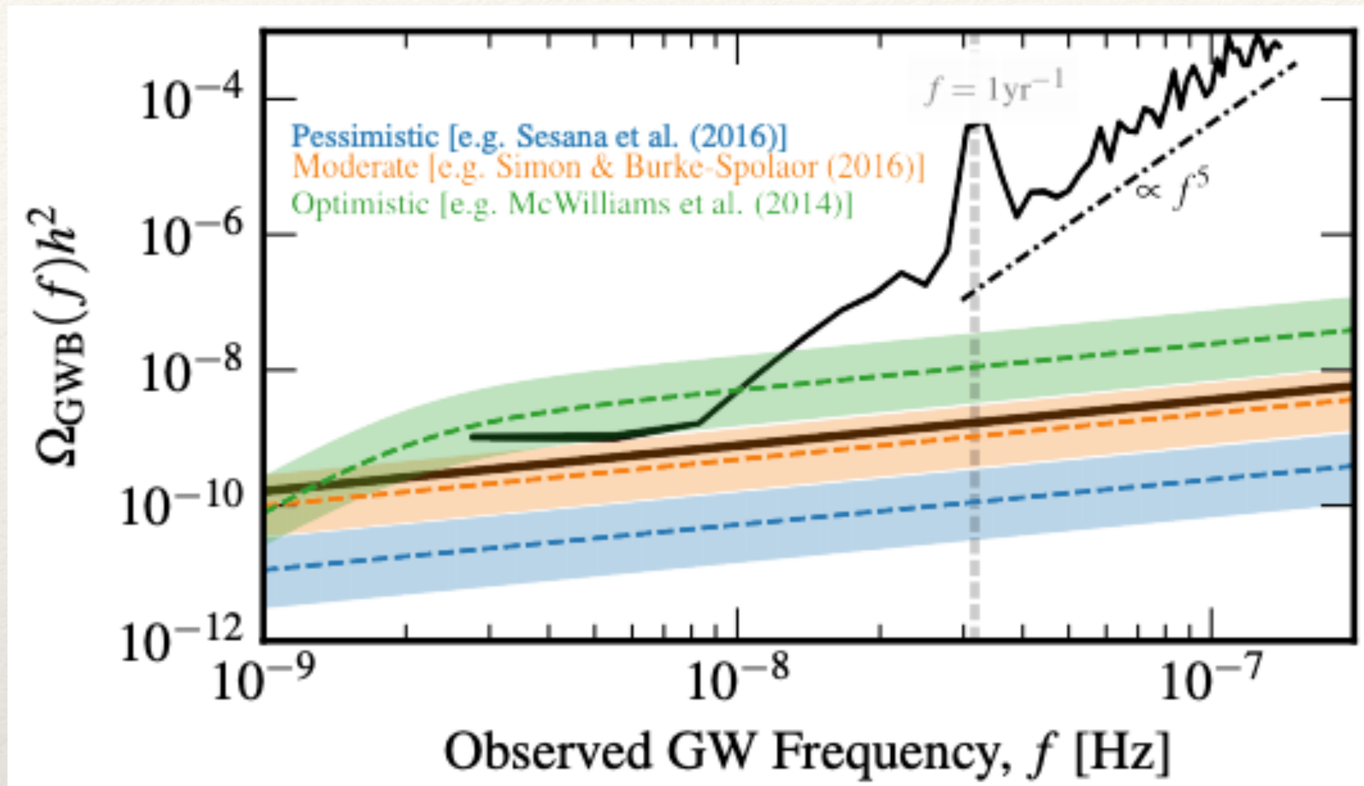


LVC arxiv:1903.02886

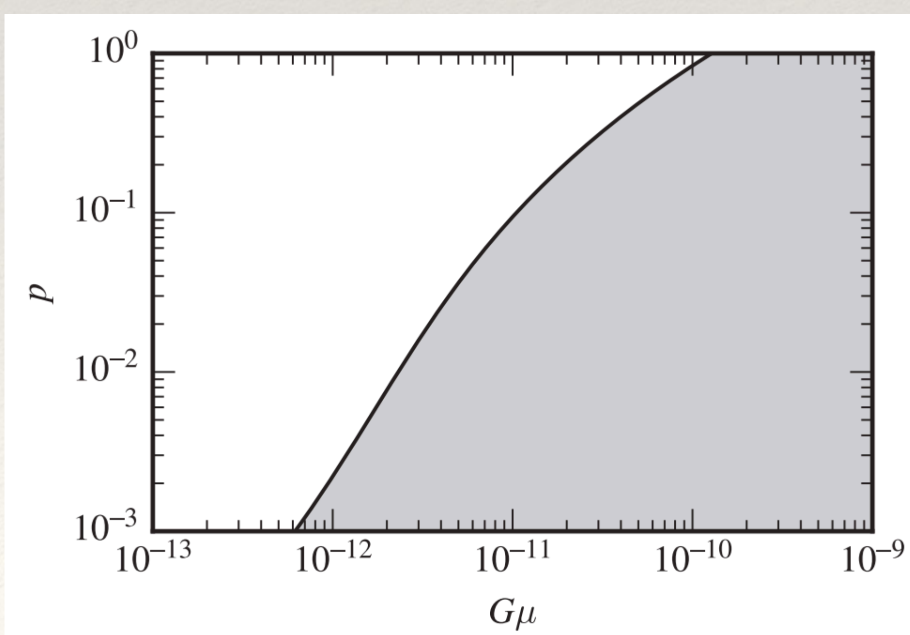
Constrain on the string's tension parameter $G\mu \leq 10^{-9}$

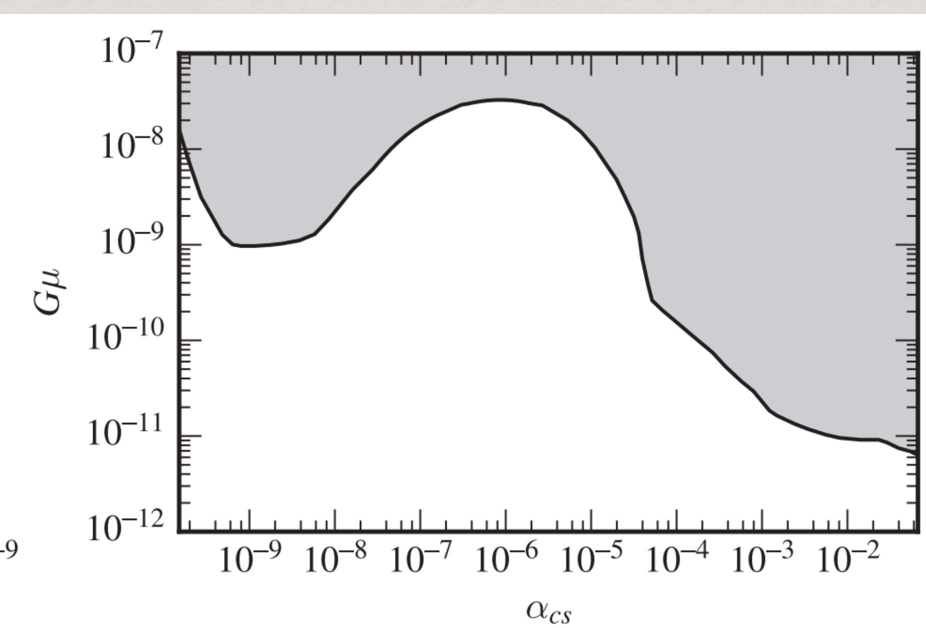
Search for stochastic GW signal

Upper limit in the PTA frequency band (Nanograv data)



Constraining string's parameters, grey area is excluded region

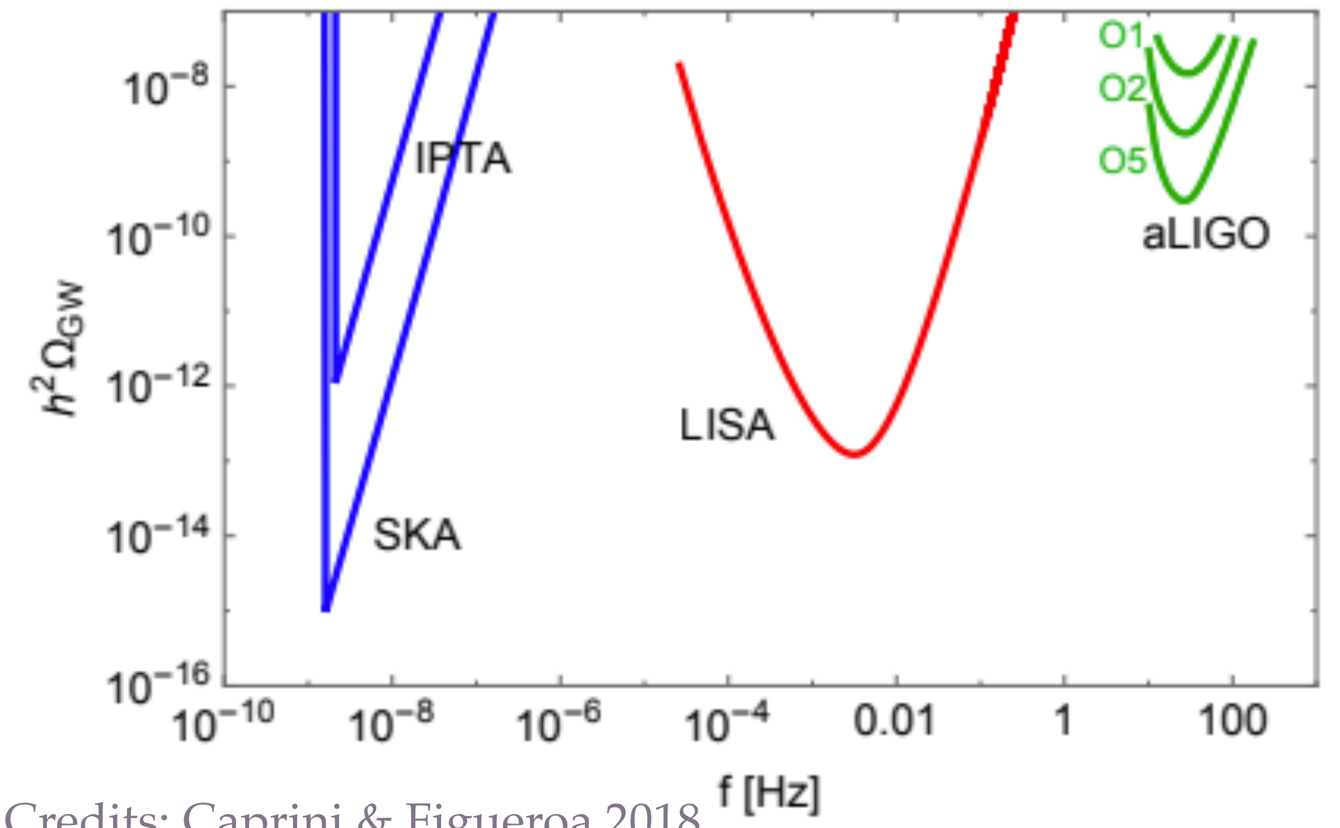




Nanograv. ApJ 2016, 2018

Search for stochastic GW signal

Expected sensitivity to SGWB in LISA band



Credits: Caprini & Figueroa 2018

LISA will constrain the cosmic string tension down to the level $G\mu \leq 10^{-17}$

- For detecting GWB, it is important to
  - understand instrumental and environmental noise (magnetic field in LIGO-Virgo, pulsar and dispersion variation in PTA, noise coupling and estimation in LISA)
  - model the GWB: astro population should produce characteristic (broken) power-law spectrum, deviation in spectral shape from the expected instrumental noise is a huge advantage

Testing GR

Why we need to modify GR? What can GW tell us?

- Already mentioned discrepancy in the Hubble constant, dark matter, dark energy
- Singularity (even though it is covered by an event horizon)
- Need for a quantum version of gravitation
- Gravity might be emergent: it is a low-energy manifestation of more fundamental, non-gravitational degree of freedom
- Just fun to do it: children approach “let’s break it and see what is inside”

What are possible manifestations of deviations from GR in GWs ?

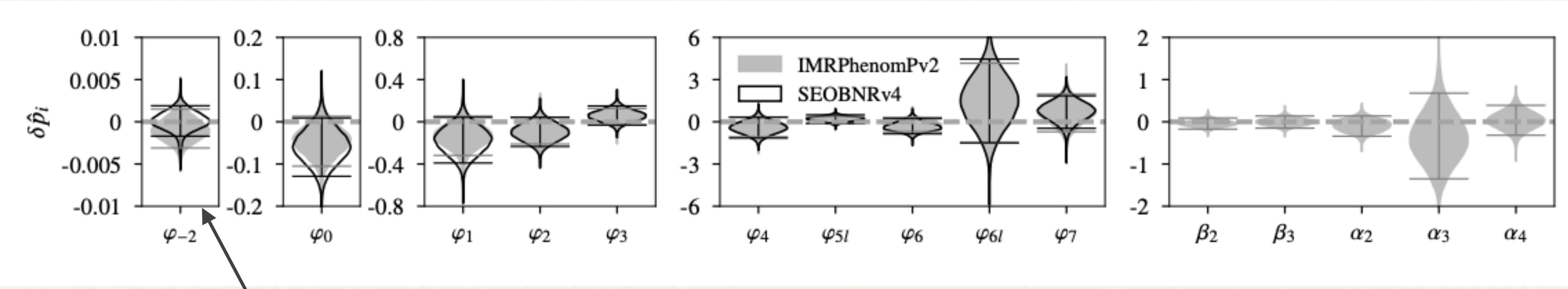
- In the radiation sector: the dissipation of energy from the system is not consistent with GR (for example dipolar radiation)
- In the polarization: GR predicts 2 tensorial polarization, there could be in addition two scalar and two vectorial
- In the propagation: dispesion, graviton vs photon speed
- Do we test GR or astrophysical environment?
- BH mimickers: boson stars, gravastars

Testing GR with binaries

- It is important to **understand the noise**, especially if it is non-stationary (glitches)
- It is important to **model accurately the GW signal in GR**: testing GR will be limited by accuracy of GW model (very much true for LISA and ET)
- GW from coalescing binaries are modelled only within GR (already challenging). Deviations are introduced in a **phenomenological** way to reflect the plausible deviations

O1-O2 results

Parametrized test: the GW phase presented (in FD) as sum of terms (Post-Newtoian expansion). We can introduce deviations in numerical coefficients and infer those deviations from the data (consistency test)



LVC arxiv 1903.04467

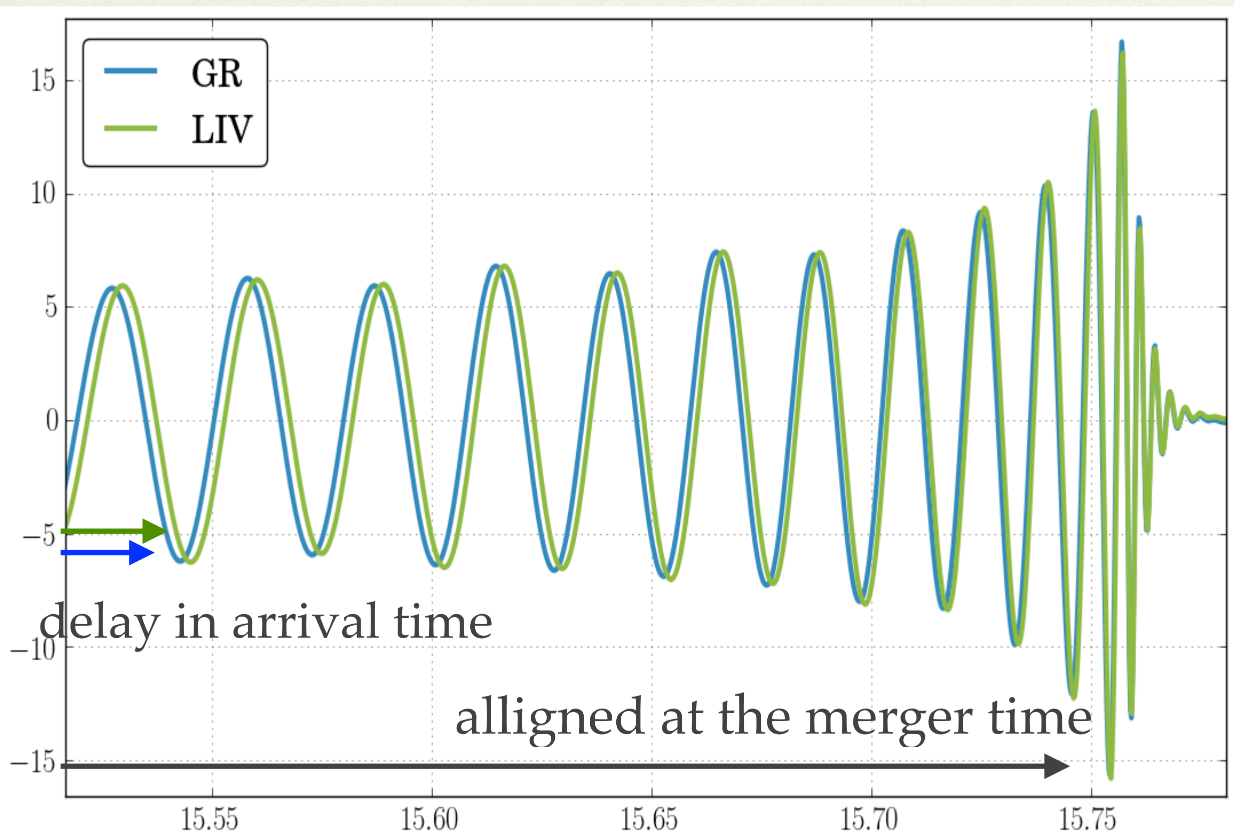
Dipolar radition

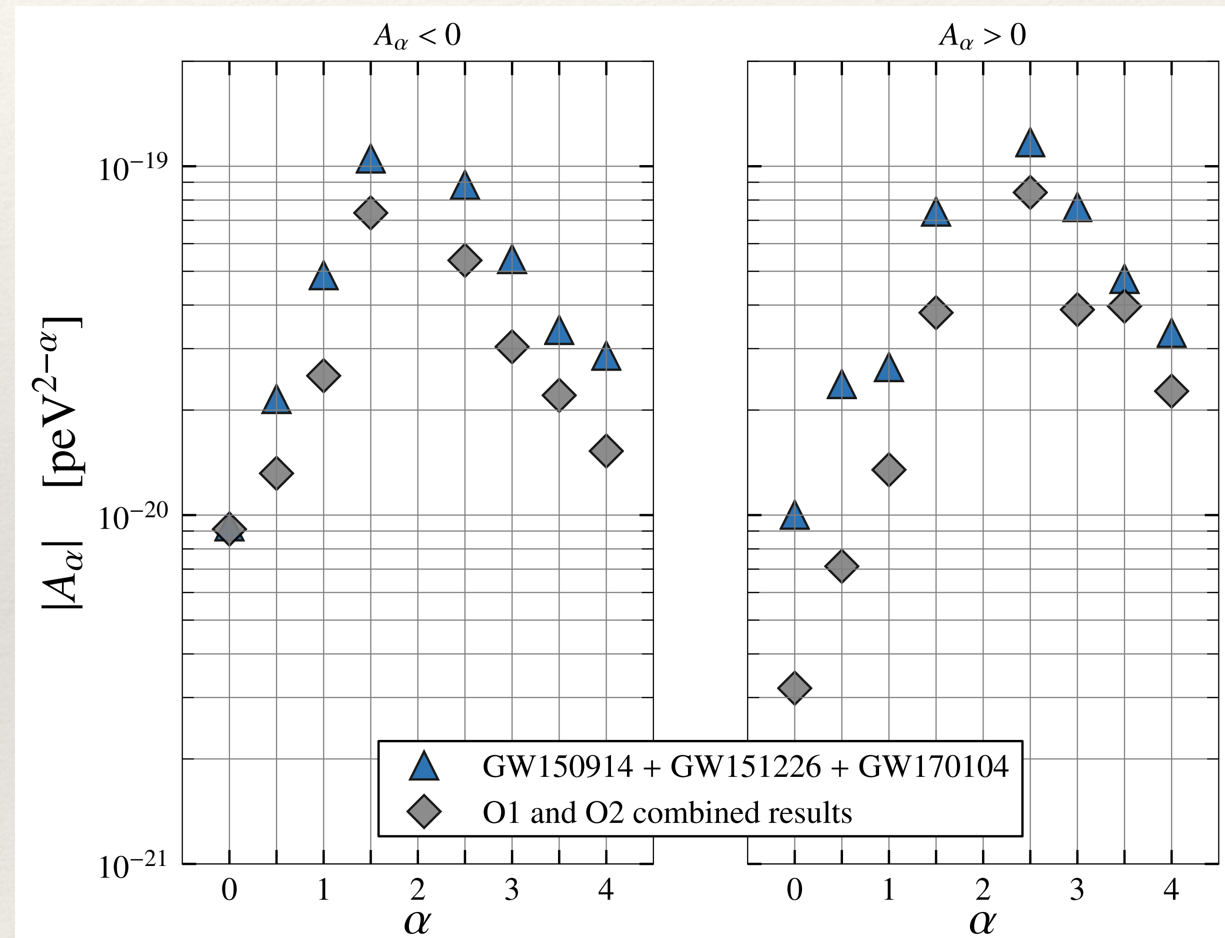
Testing GR with binaries

Propagation test: some modifications of GR lead to dispersion of GWs (massive graviton, theories with violation of the Lorentz invarainace (Horjava-Lifshitz, extra-dimensional))

The generic energy-momentum relation which leads to dispersion:

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$





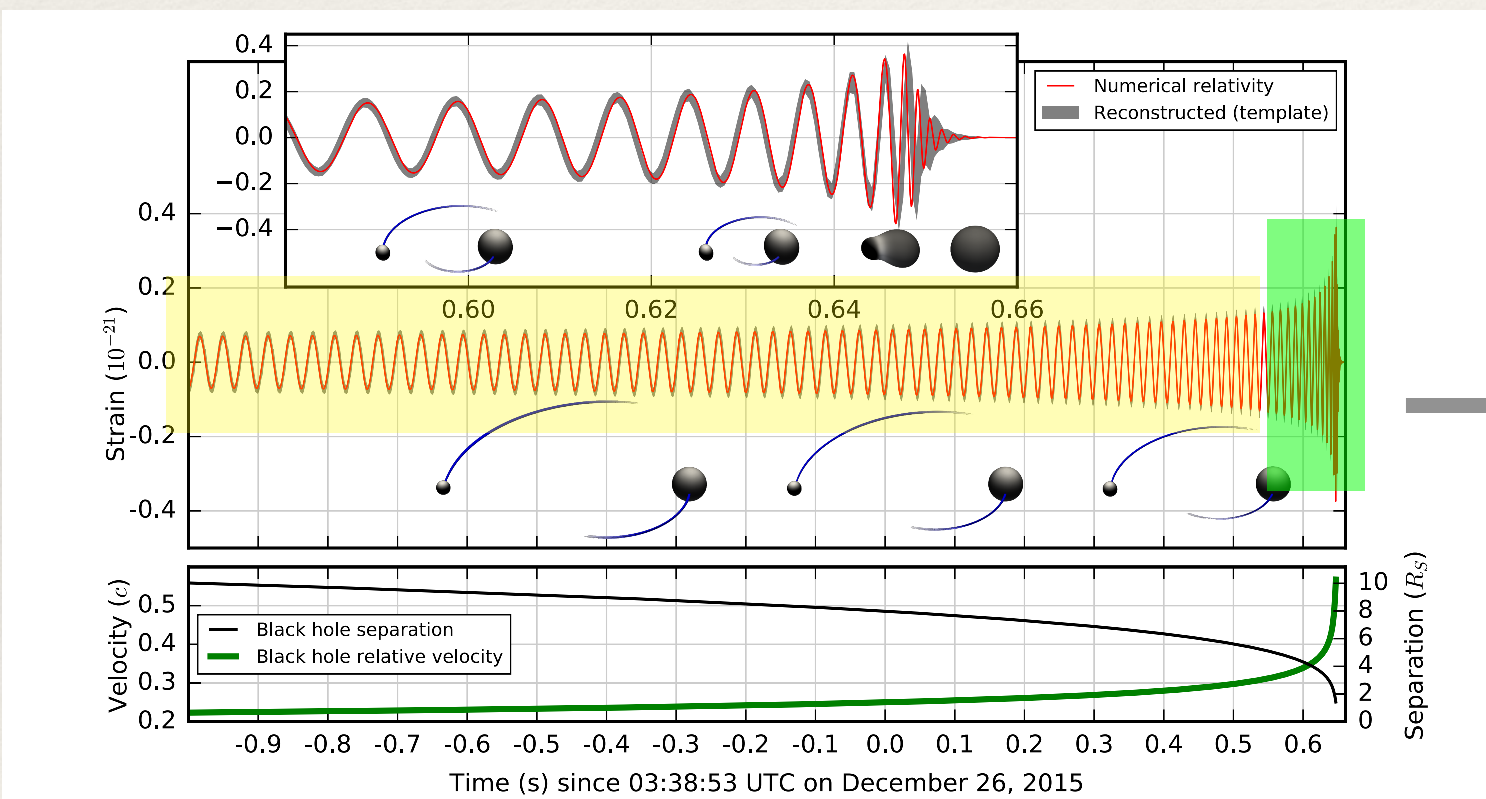
$$m_g \leq 6.76 \times 10^{-23} \mathrm{eV/c^2}$$

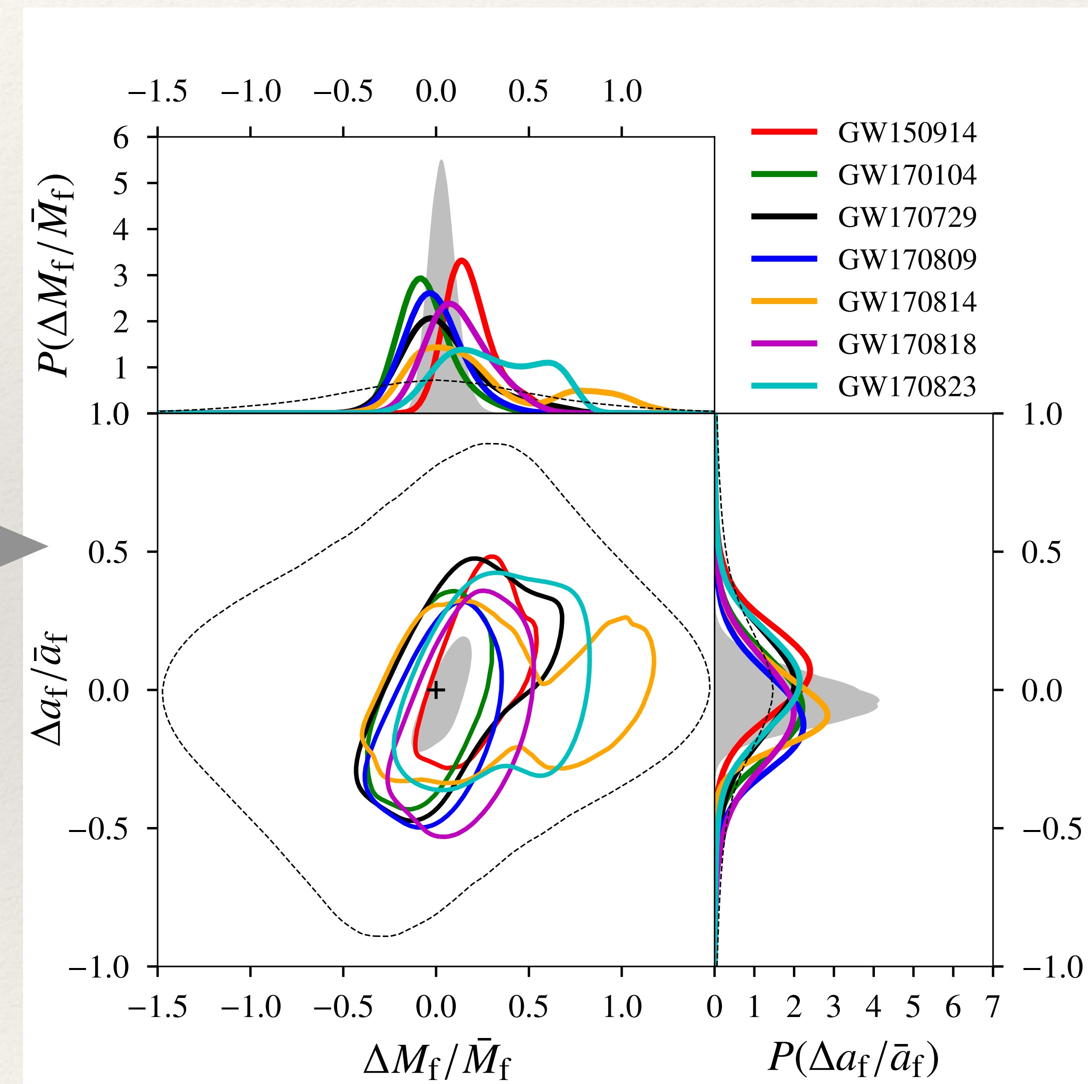
LVC arxiv 1903.04467

BNS merger: speed of propagation GW vs e/m: $(c_T - c)/c \leq 10^{-15}$
constraints and elimination of some modified gravity theories

Inspiral-merger-ringdown consistency test

We can check if early and late parts of the signal agree with each other (within GR):
consistency test





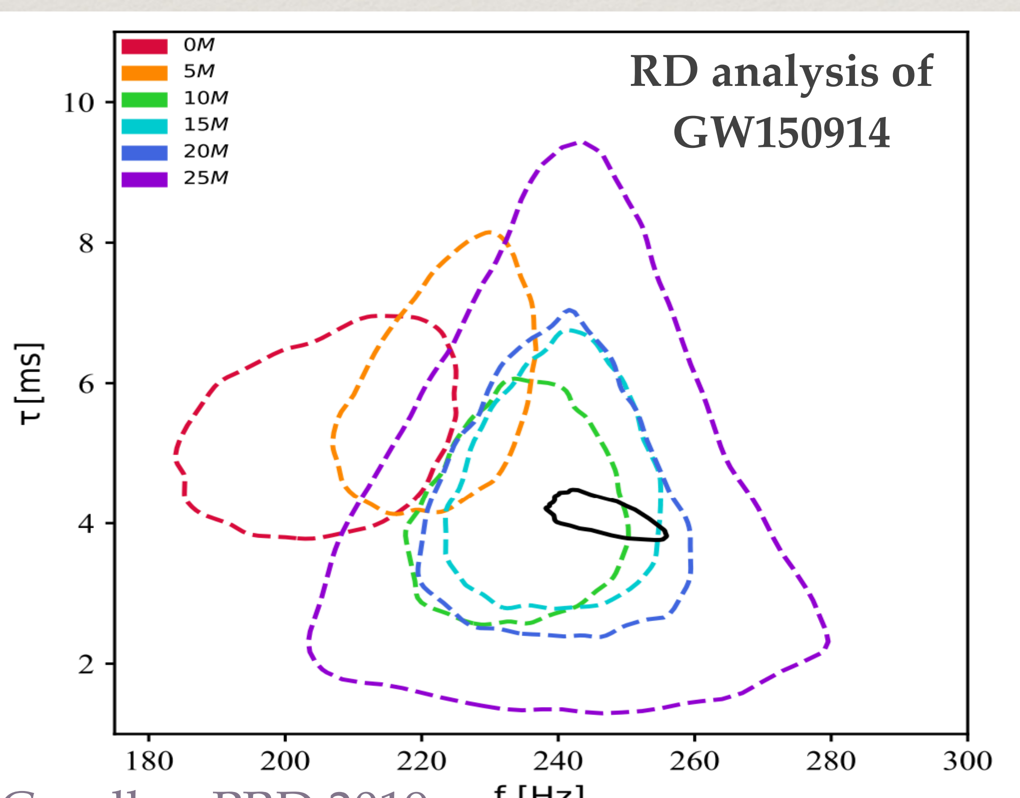
LVC arxiv 1903.04467

No-hair (No Kerr BH) test

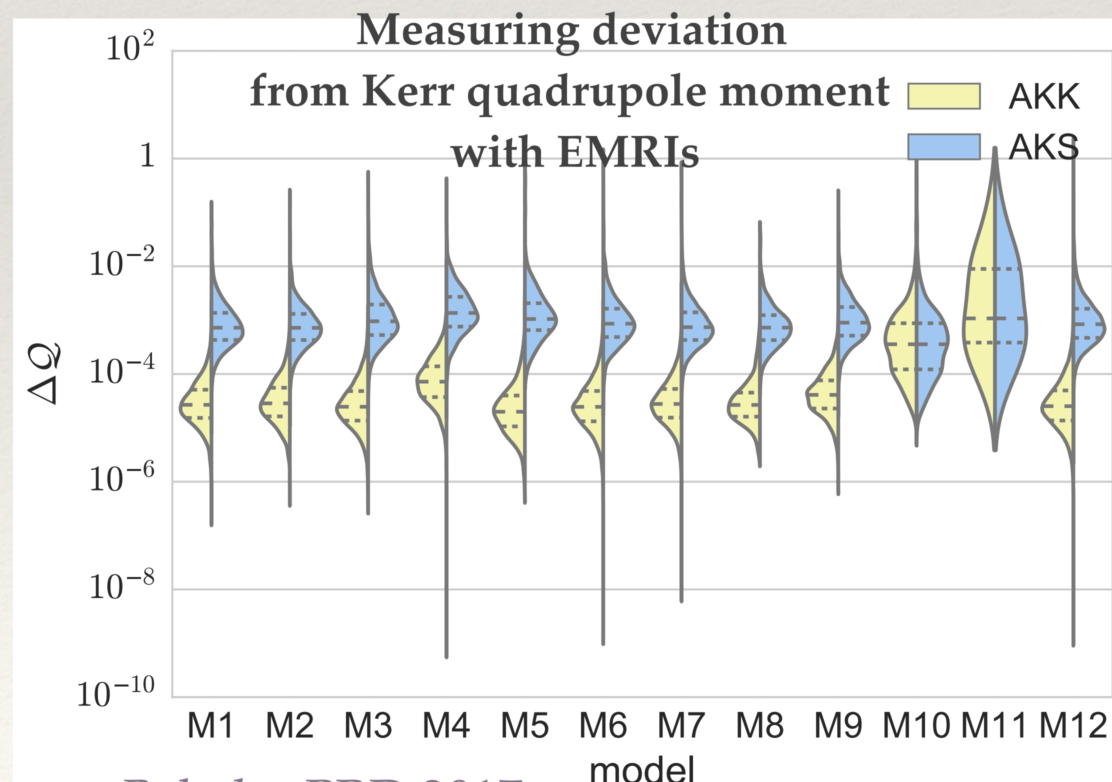
BH in GR (vacuum) is described by two parameters: its mass and spin

- Measuring ring-down (quasinormal modes), each mode is described by 2 params: freq and decay time
  - Identifying and characterizing a single mode: gives mass and spin
  - Identification and characterization of two modes: test no-hair theorem
- Requires high SNR (and several signals): Einstein Telescope and LISA

- Extreme mass ratio inspirals (LISA): compact object (NS, BH) orbiting MBH in galactic nuclei, spends 10^5-10^6 cycles in close vicinity of a horizon: mapping spacetime (holiodesy)



Carullo+ PRD 2019

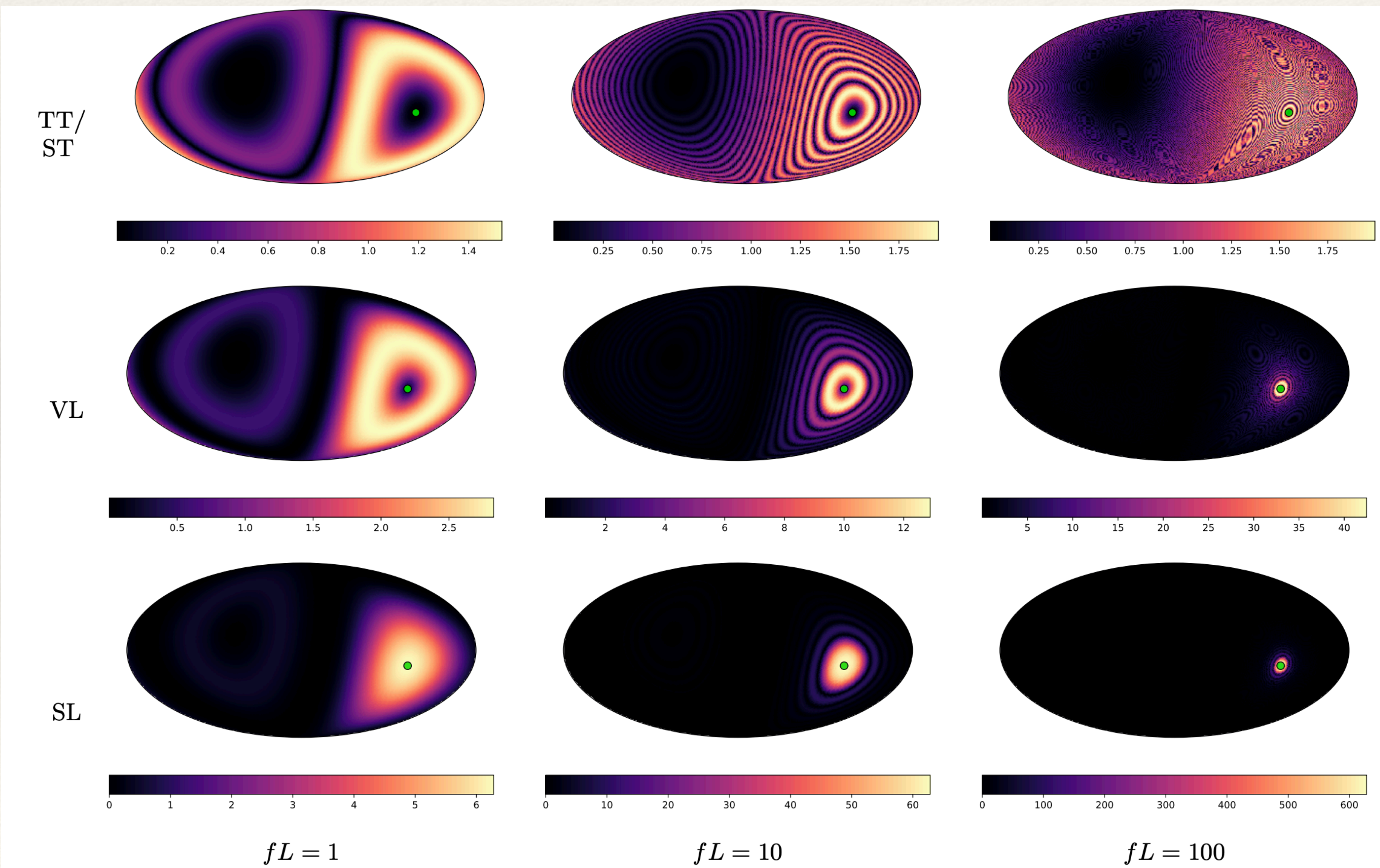


Babak+ PRD 2017

Measuring polarization

- To measure the extra polarizations:
  - Use stochastic GW signal
  - Use PTA (multi-arm): $h_{95\%}^{TT} < 2.0 \times 10^{-14}, \quad h_{95\%}^{ST} < 1.3 \times 10^{-14}, \quad h_{95\%}^{VL} < 8.6 \times 10^{-15}, \quad h_{95\%}^{SL} < 4.0 \times 10^{-14}$

Antenna response function in PTA to GW polarizations



Tensorial and common mode

Vectorial modes

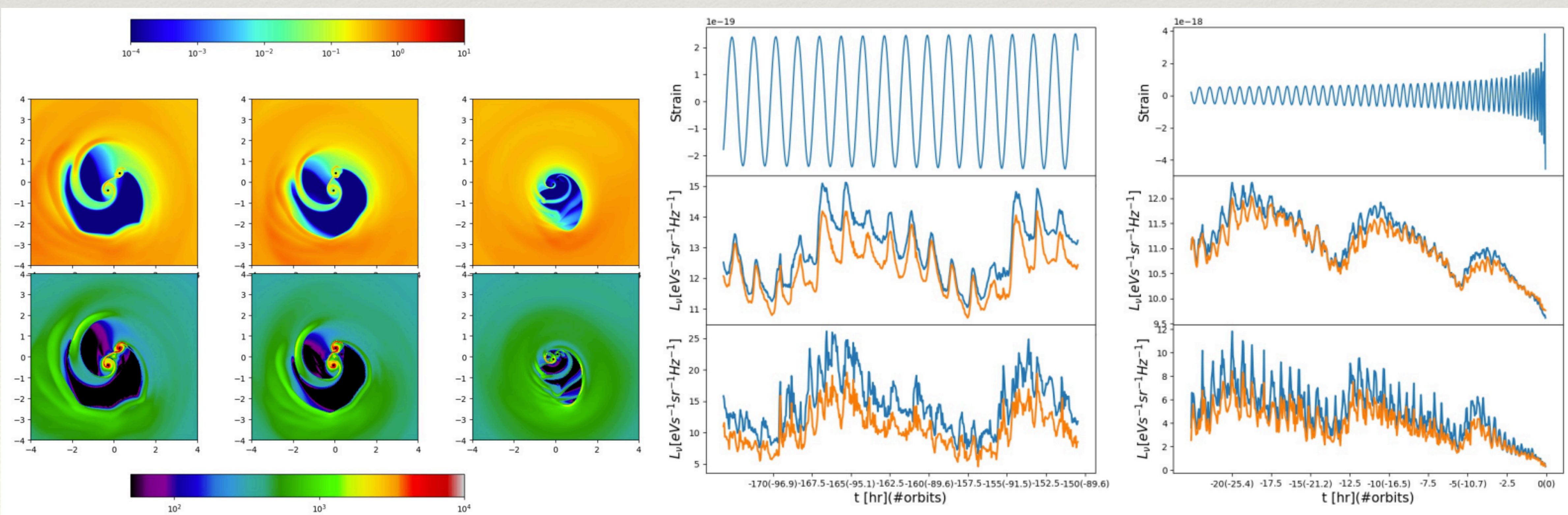
Longitudinal mode

O'Beirne+ PRD 2019

Multi-messenger

- **Merging BNS** could be also observed through e/m and neutrino observations
  - Unique (nature provided) nuclear physics laboratory: need to decript the messages it sends
  - During inspiral the NSs behave (almost) like point masses: need merger
    - **Einstein Telescope + Cosmic Explorer**

- **LISA**: Unique opportunity to **see**``live” merging massive BHs if we identify a host galaxy in advance. Possible if MBHB are embedded in circumbinary gaseous disk



Y. Tang+, MNRAS 2018

Very short summary

- GWs provide a new channel to explore the Universe. GWs curry completely **new and vast** information.
- We have learned a lot already. To do (much) more we need:
  - More GW events (long-term observations): O3-O4
  - More high SNR events: **Einstein Telescope, LISA**
- The future is multi-band multi-particle observations