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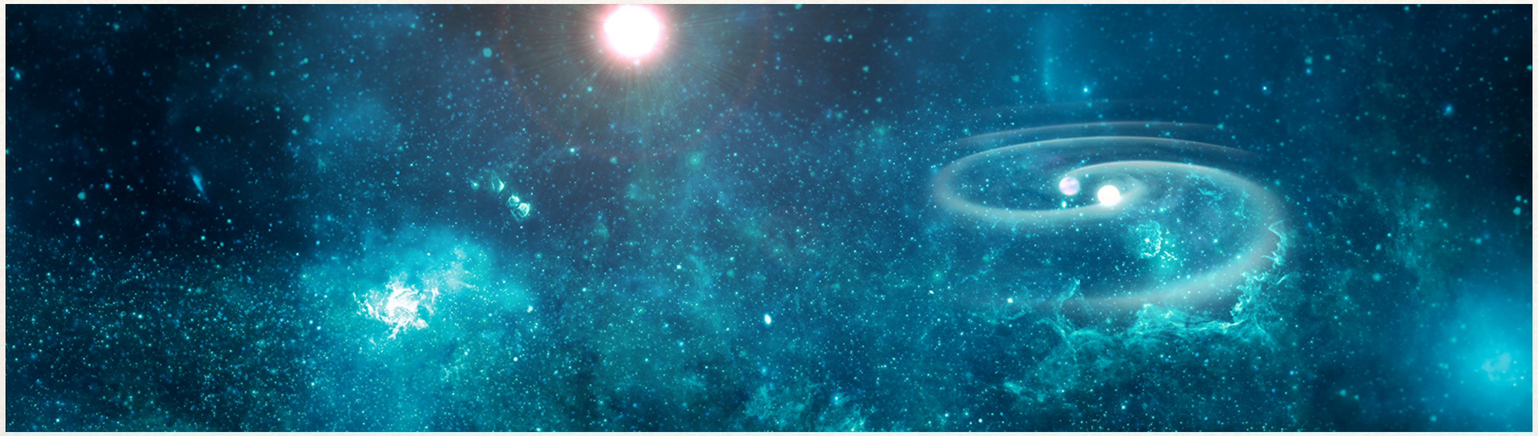
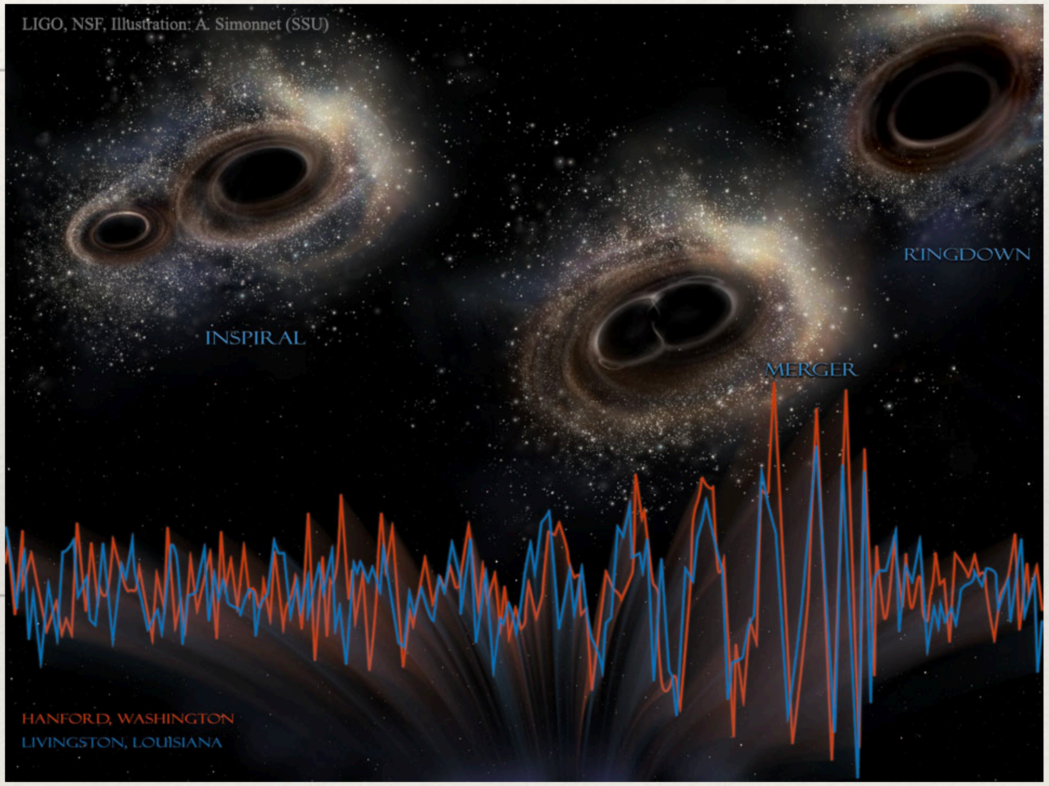
université PARIS DIDEROT PARIS 7



Detecting gravitational waves from kilo-Hz to nano-Hz.

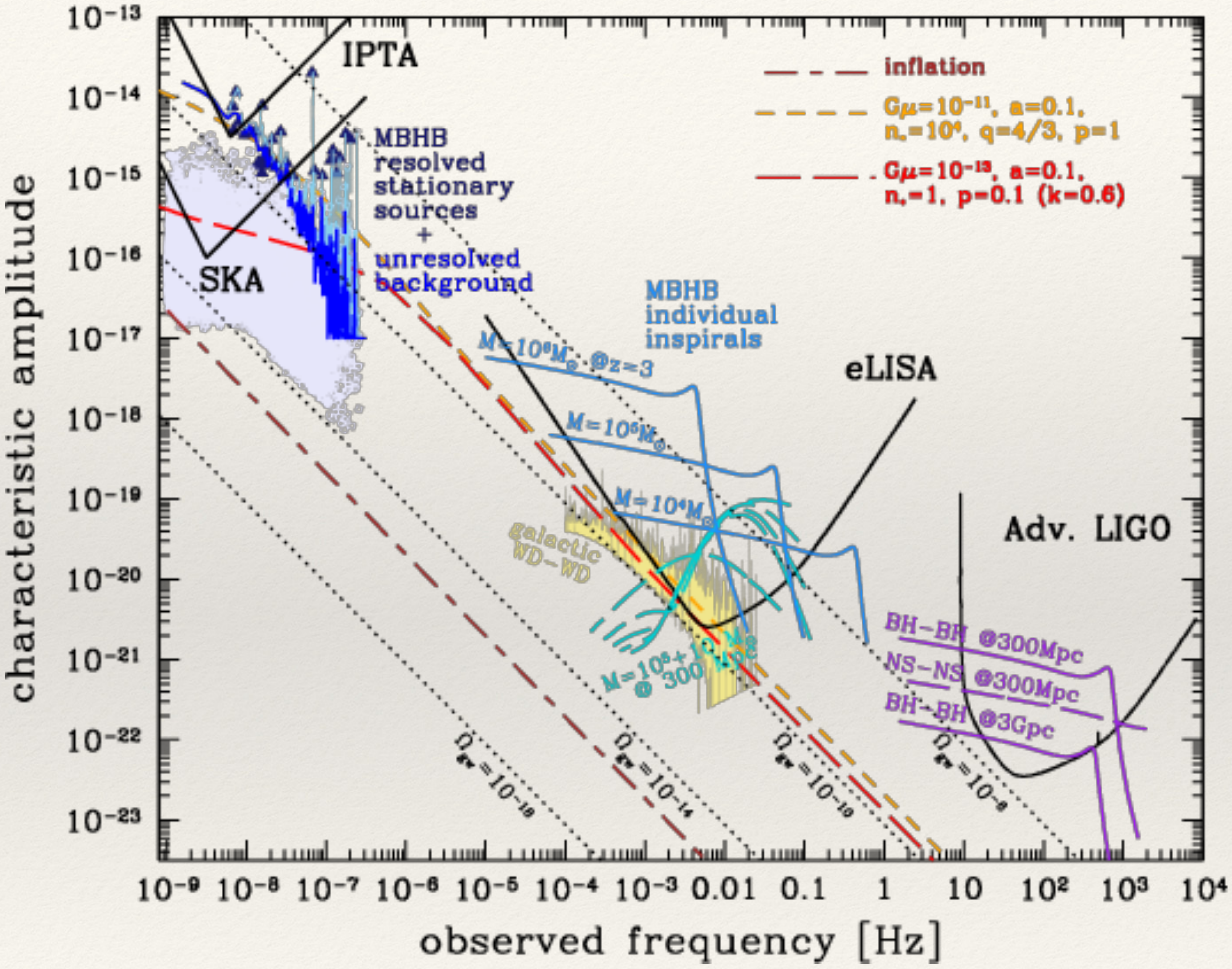

LIGO, NSF, Illustration: A. Simonnet (SSU)

15 October, IPhT

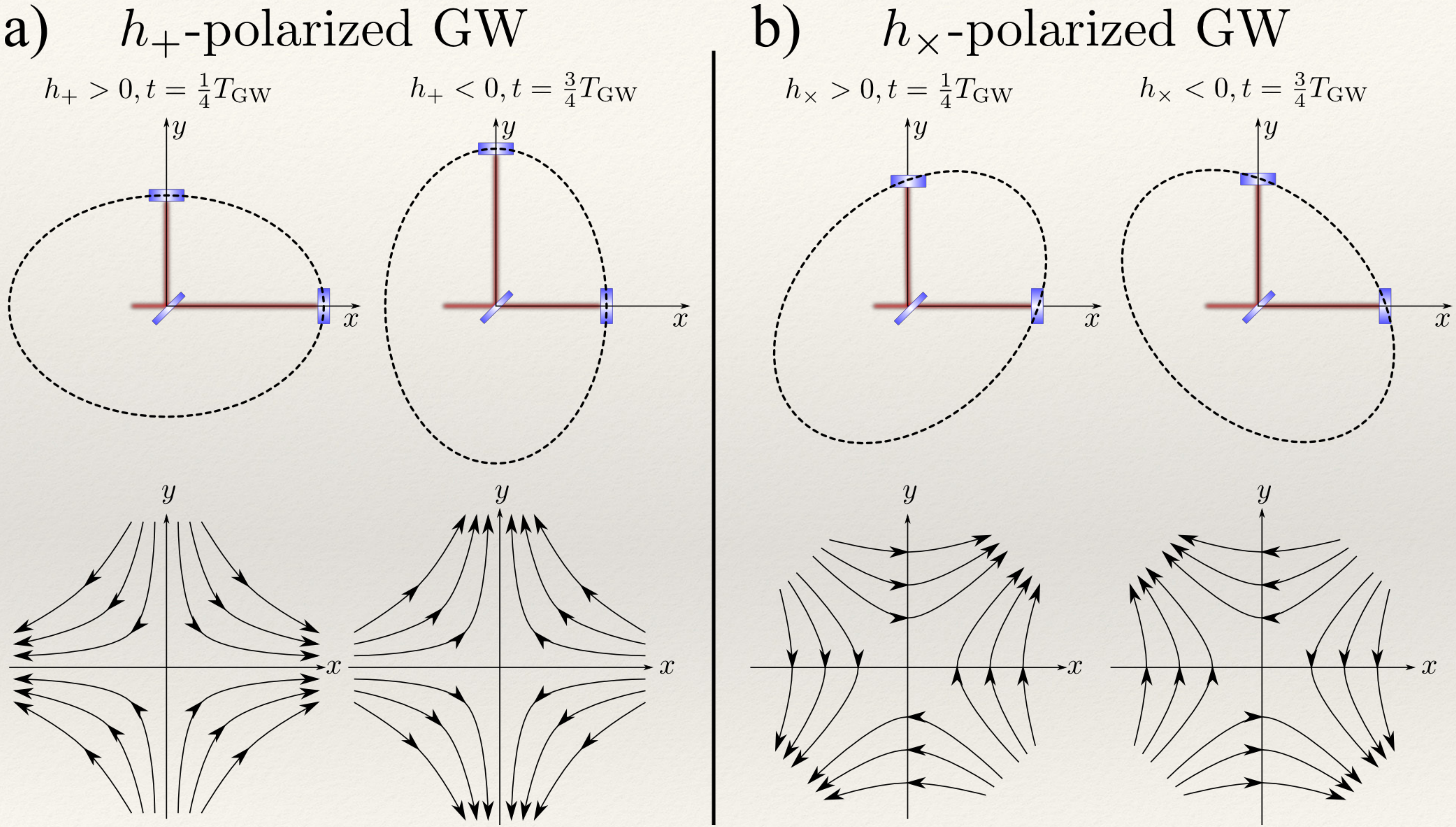
Outline

- LIGO-VIRGO
- LISA: space based GW observatory
- PTA: detecting GWs with Pulsar Timing Array.

Gravitational wave landscape



Basic principle of GW detection



a) h_+-polarized GW

$h_+ > 0, t = \frac{1}{4}T_{\mathrm{GW}}$

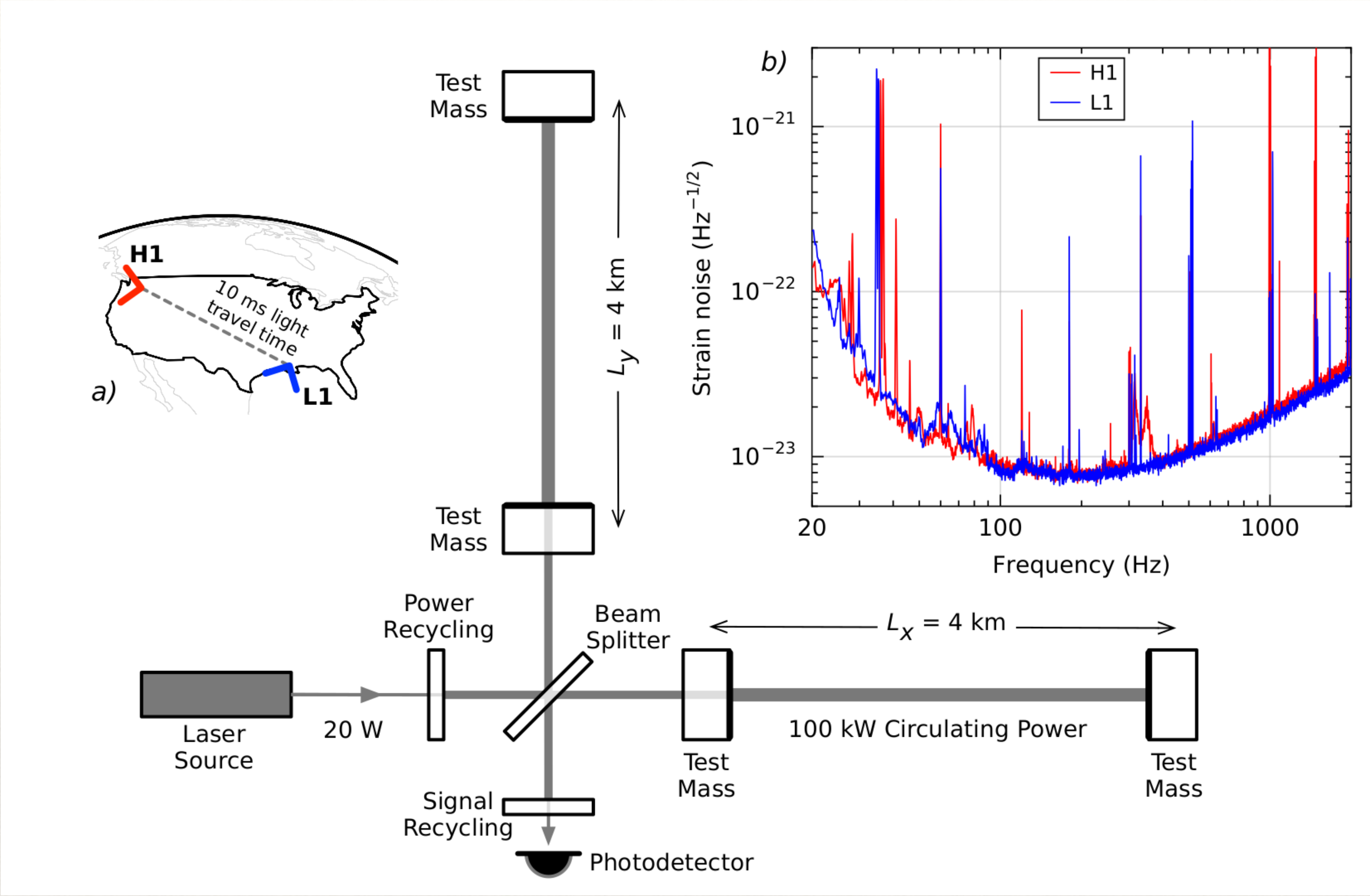
$h_+ < 0, t = \frac{3}{4}T_{\mathrm{GW}}$

b) $h_\times$-polarized GW

$h_\times > 0, t = \frac{1}{4}T_{\mathrm{GW}}$

$h_\times < 0, t = \frac{3}{4}T_{\mathrm{GW}}$

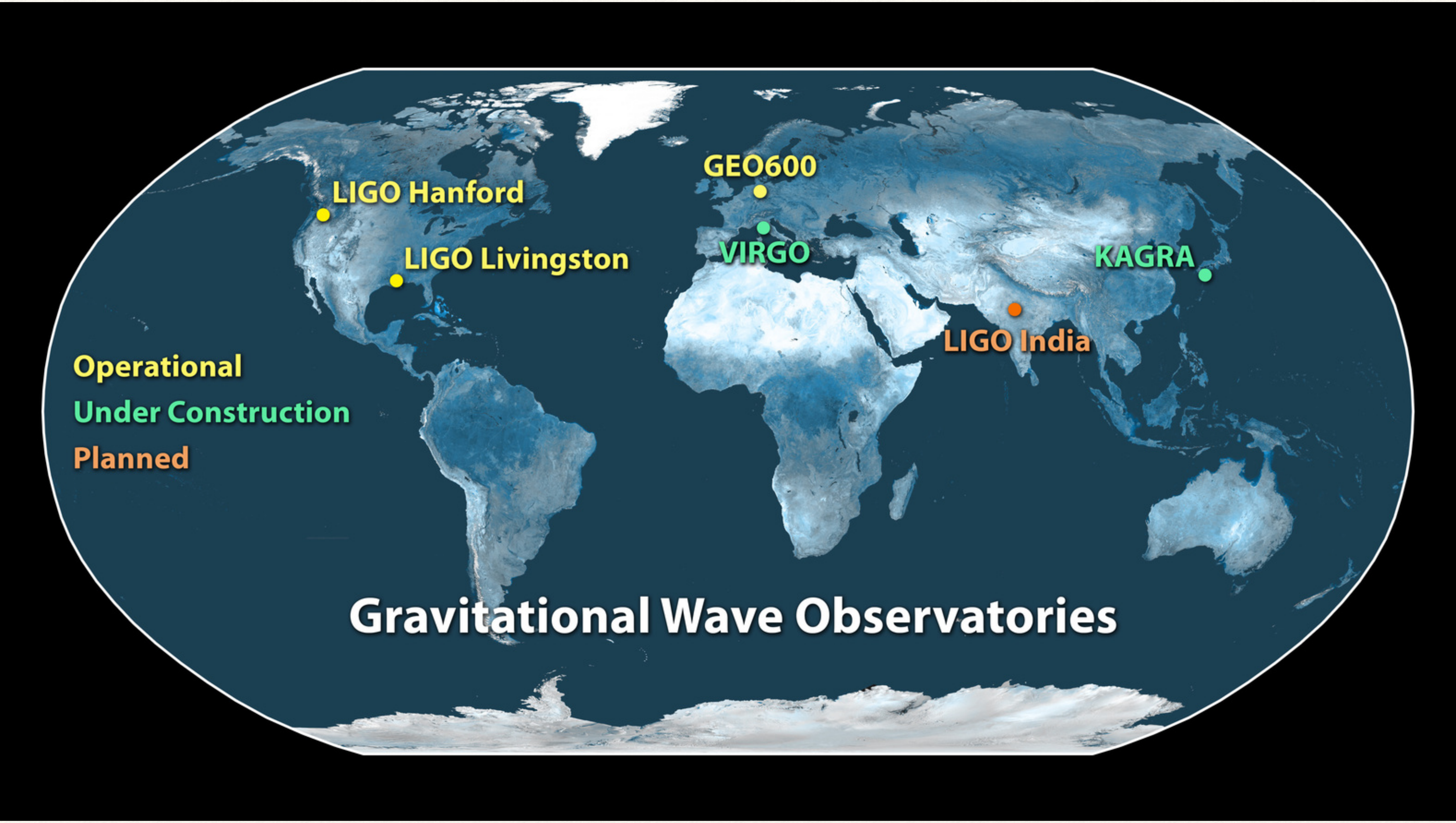
Simplified scheme of ground-based GW detectors



Sensitivity of GW detectors is limites by: seismic noise at low frequencies, thermal noise in mid. freqs and quantum shot noise at high freq.

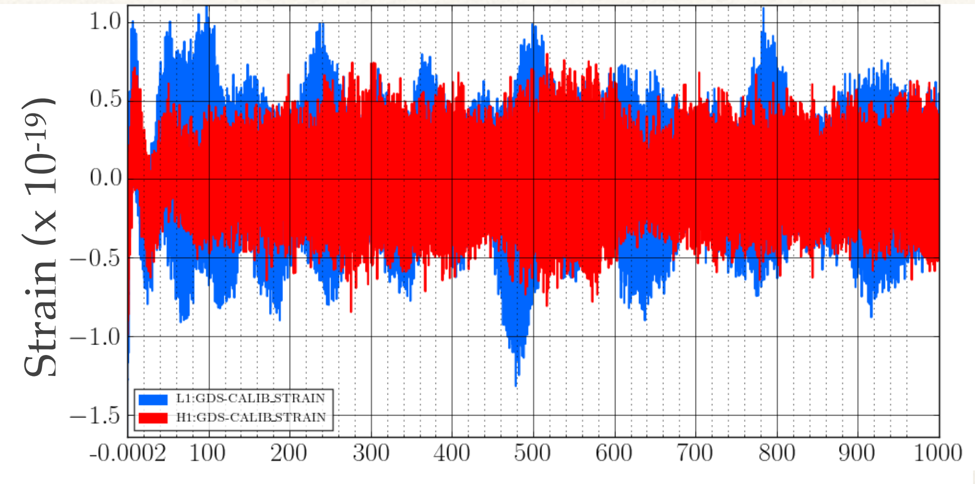
GW amplitude $\longrightarrow$ $h = \dfrac{\delta L_x}{L_x} - \dfrac{\delta L_y}{L_y}$

GW observatories



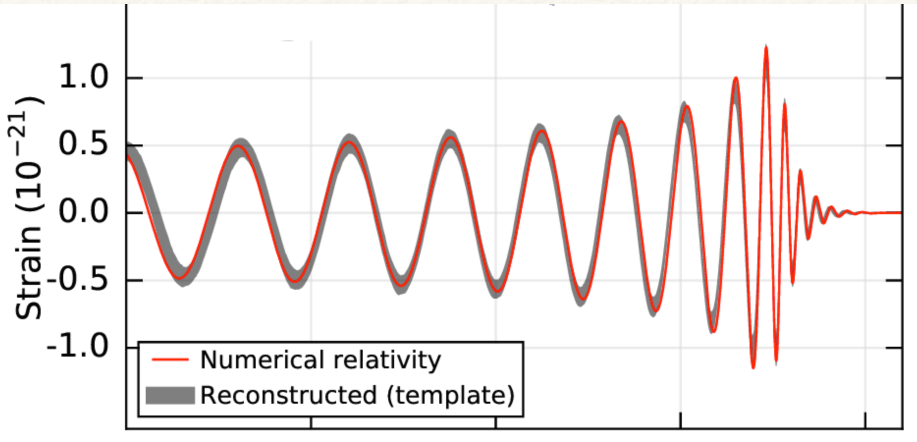
Detecting GW: Matched filtering

GW150914 Raw data



Time (ms) - Event occurs at 390

GW from coalescing BHs



We use matched filtering: searching for a particular pattern in the noisy data: tracking amplitude and phase.

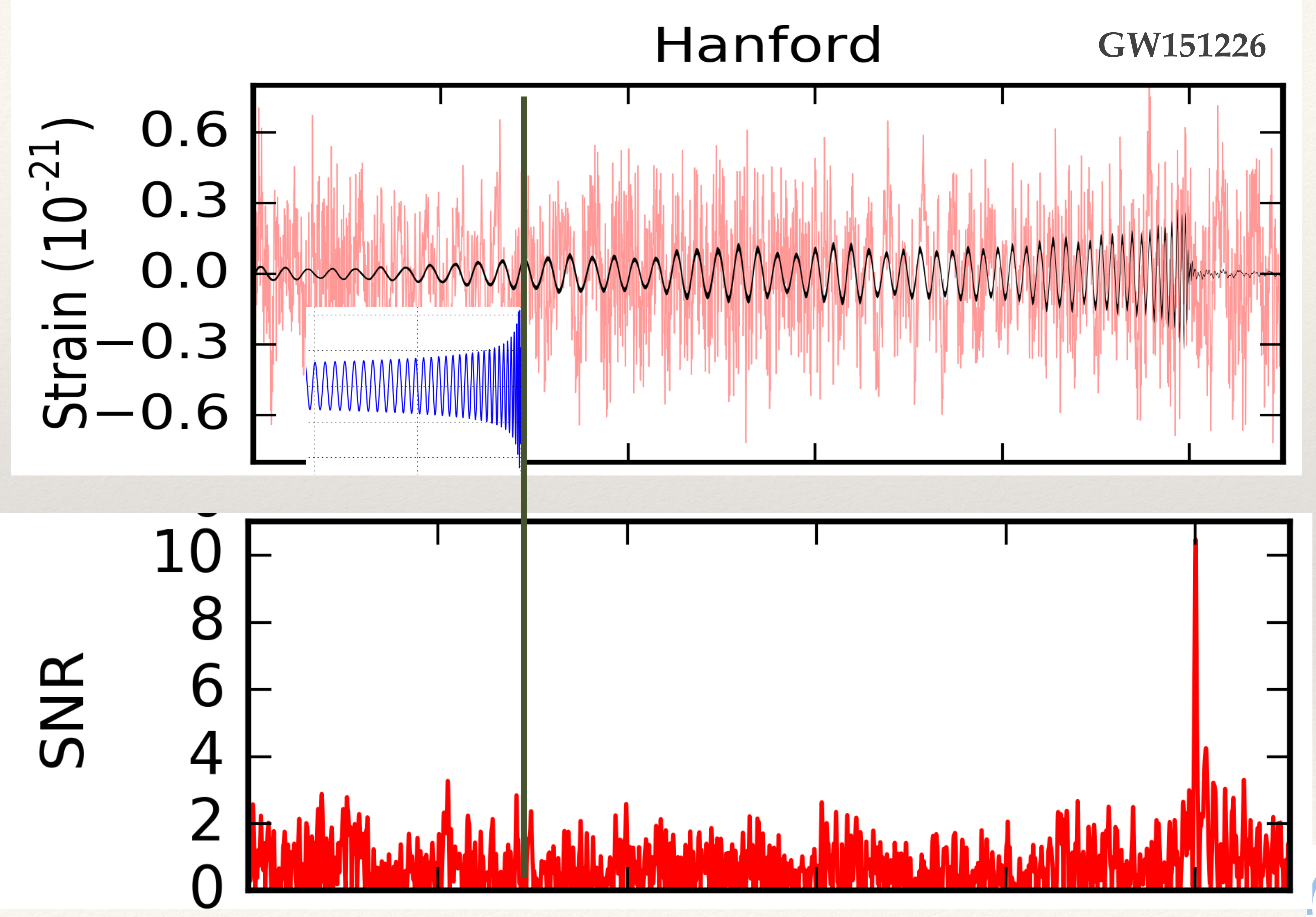
$$\rho \sim 4\Re \int_0^\infty \frac{\tilde{d}(f)\tilde{h}^*(f)}{S(f)} df$$

Signal-to-noise ratio

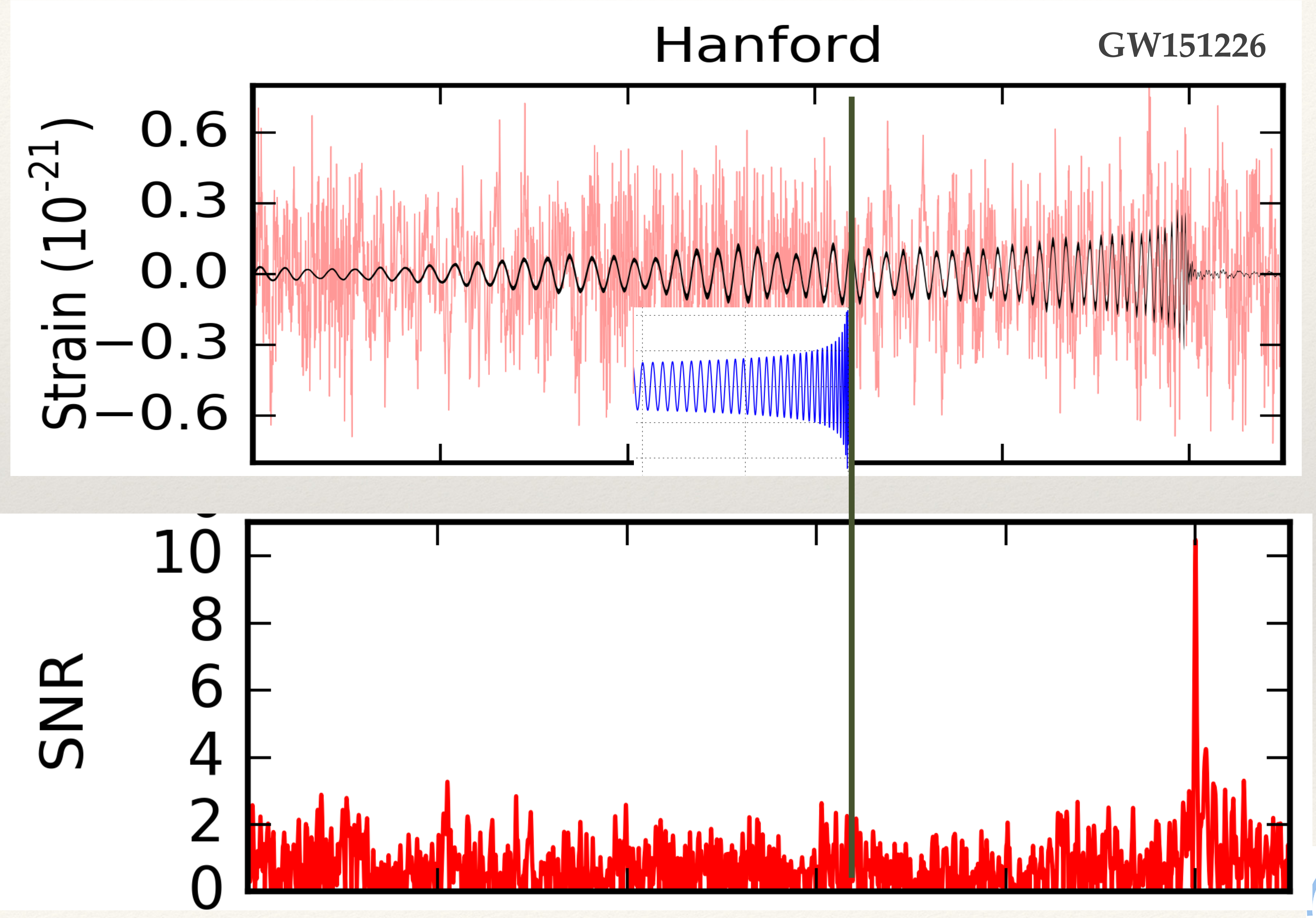
$$L(d|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\sum_k < d_k - h_k(\vec{\theta})|d_k - h_k(\vec{\theta}) >\right]$$

Likelihood function

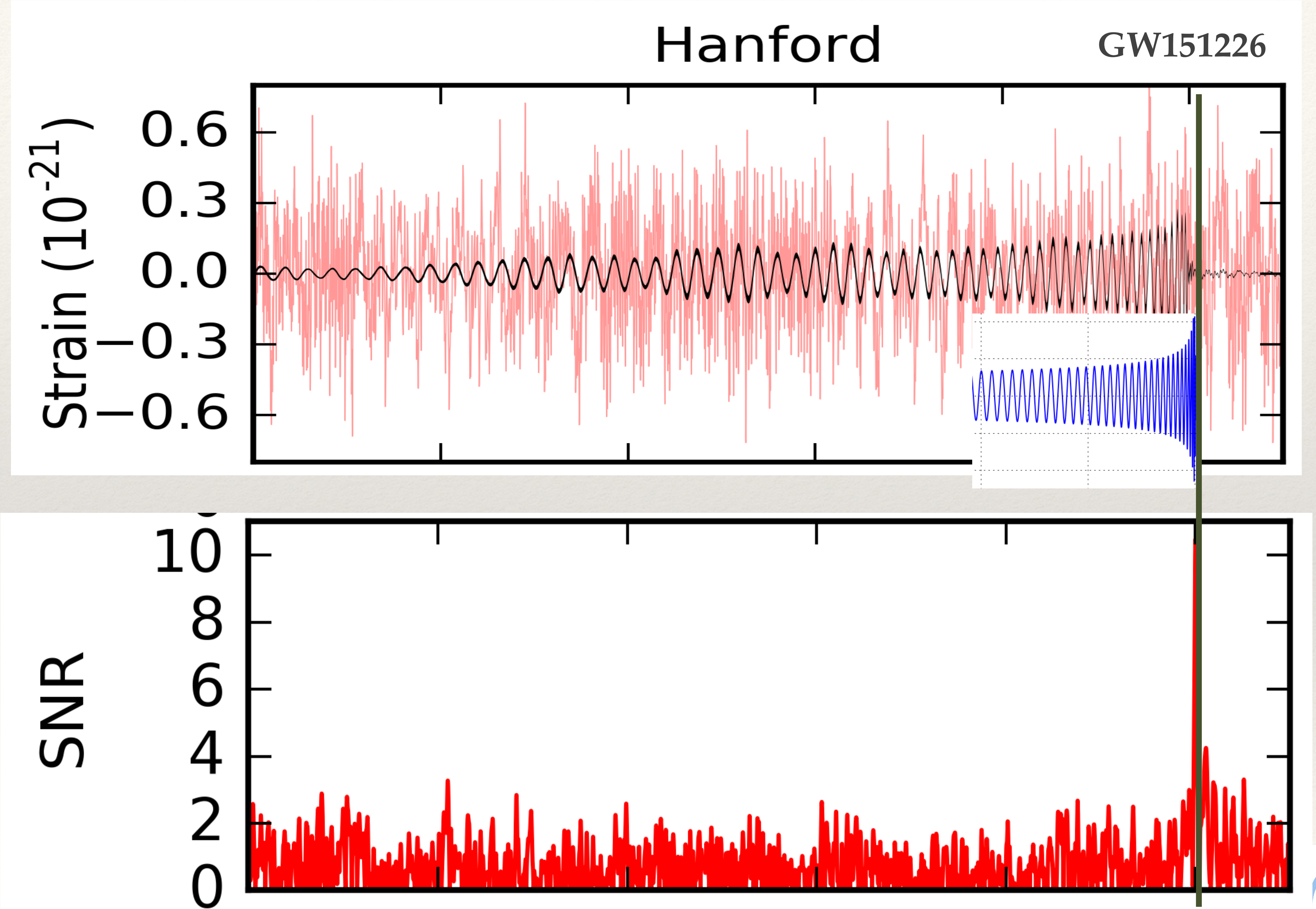
Matched filtering



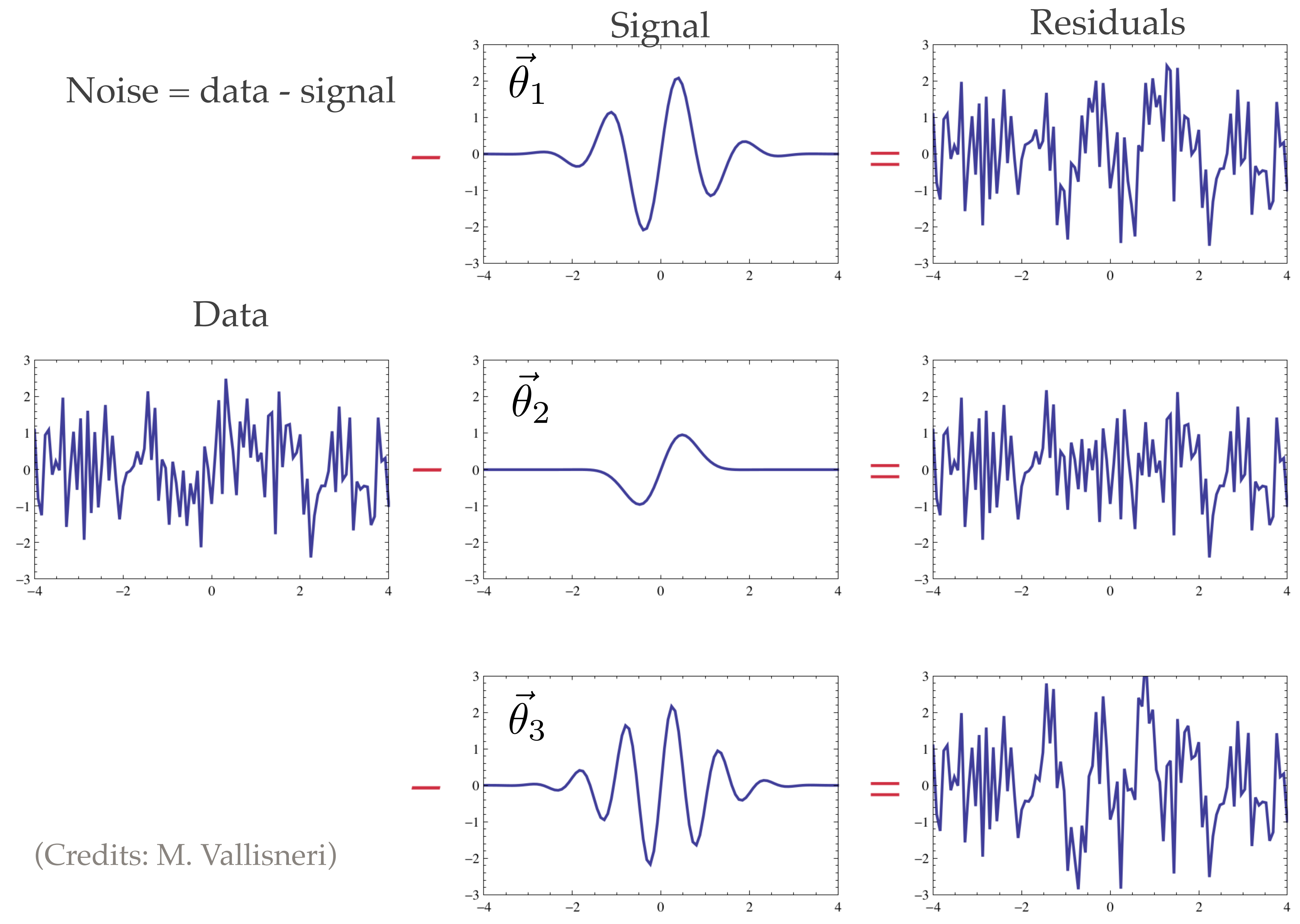
Matched filtering



Matched filtering



Parameter estimation

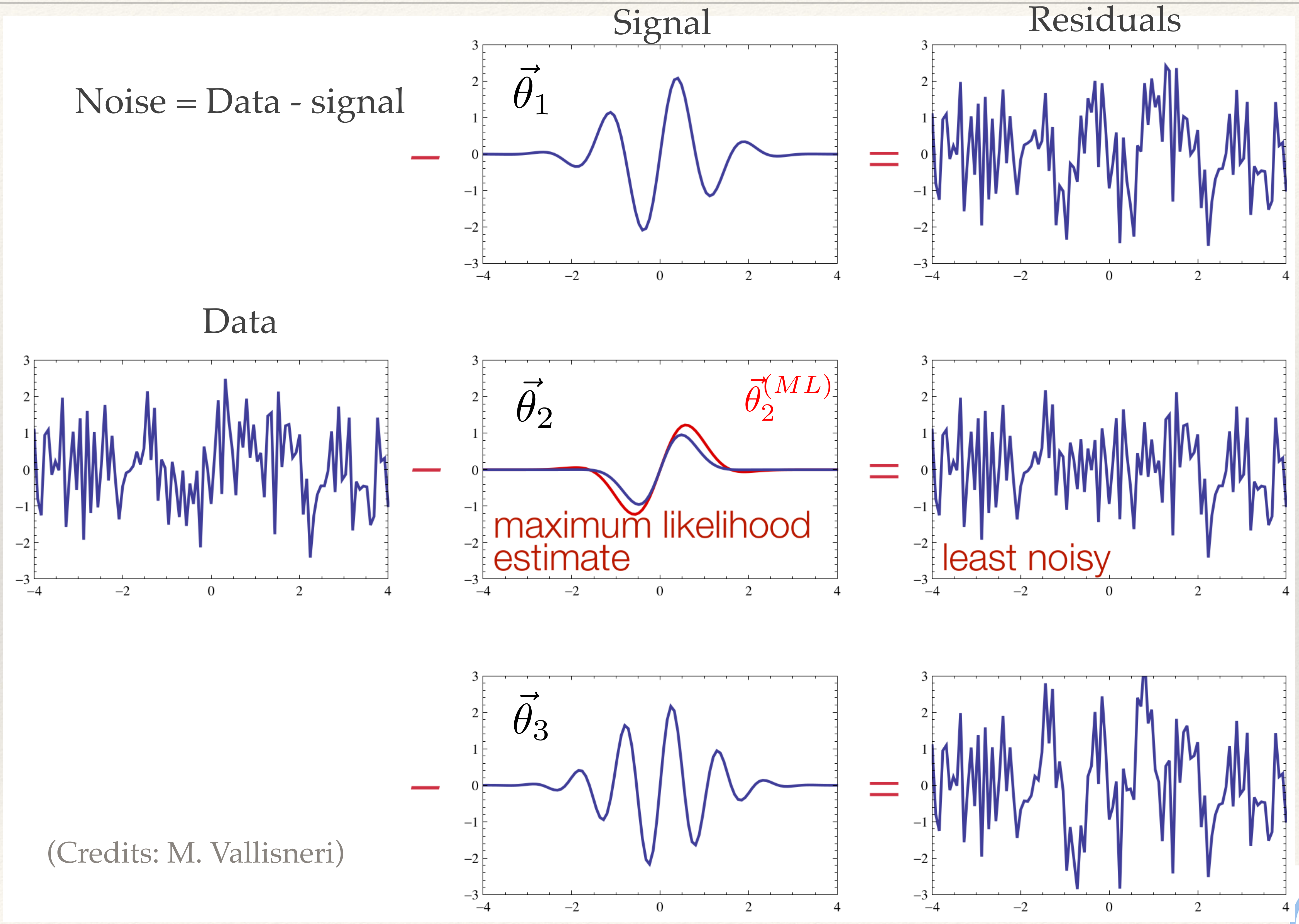


Noise = data - signal

(Credits: M. Vallisneri)

Согласованный фильтр и оценка параметров

Noise = Data - signal

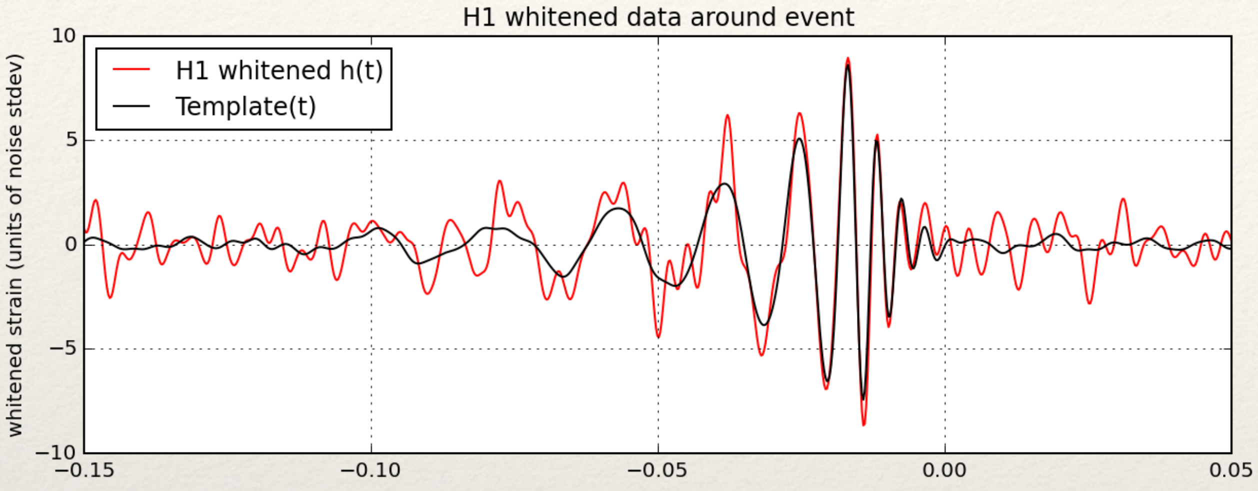


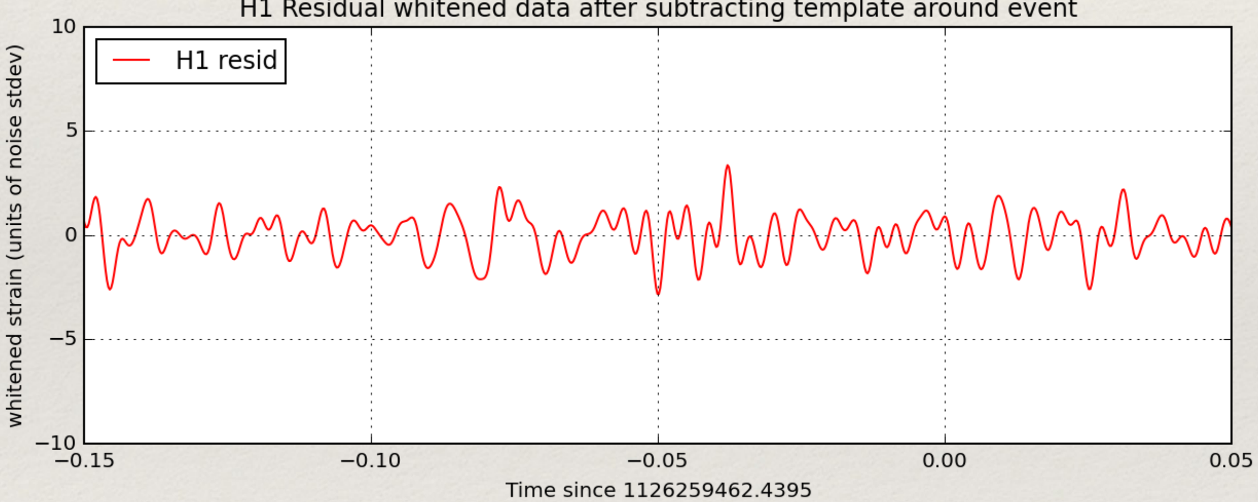
(Credits: M. Vallisneri)

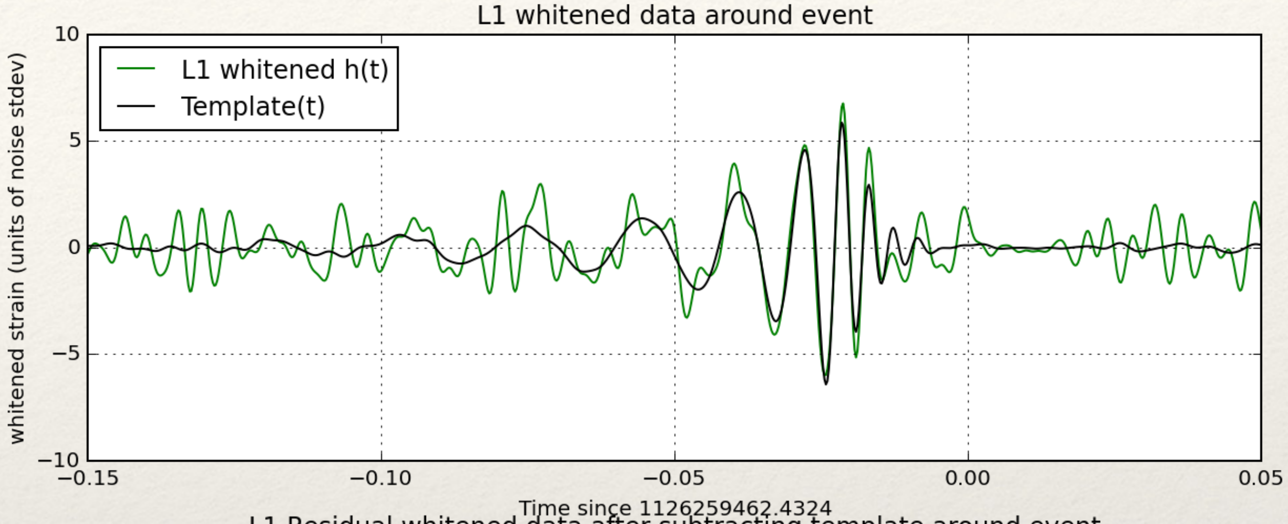
Matched filtering: GW150914

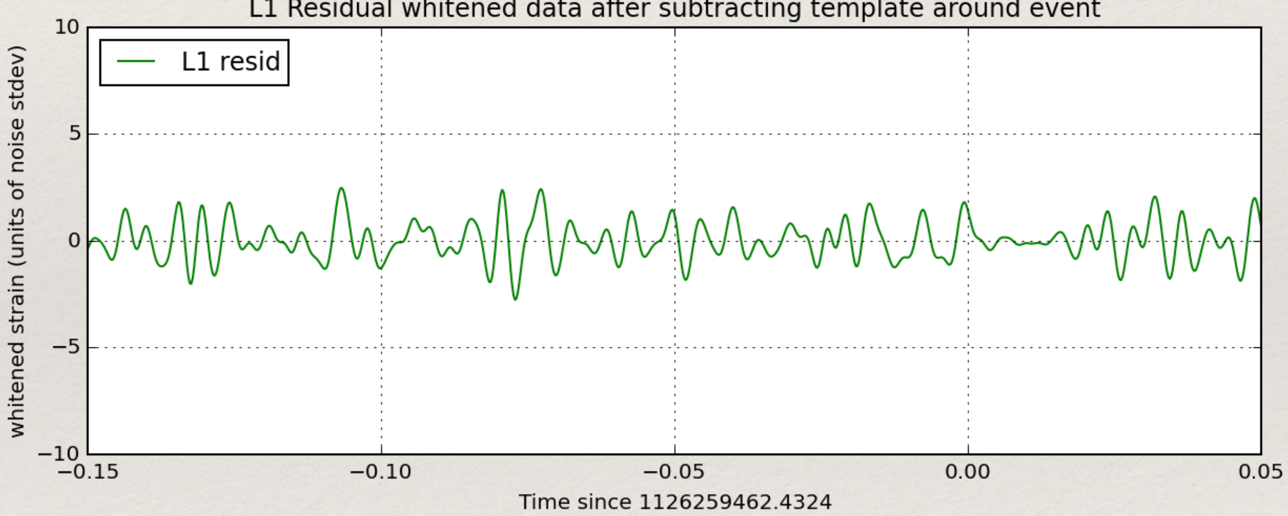
H1

L1


H1 whitened data around event

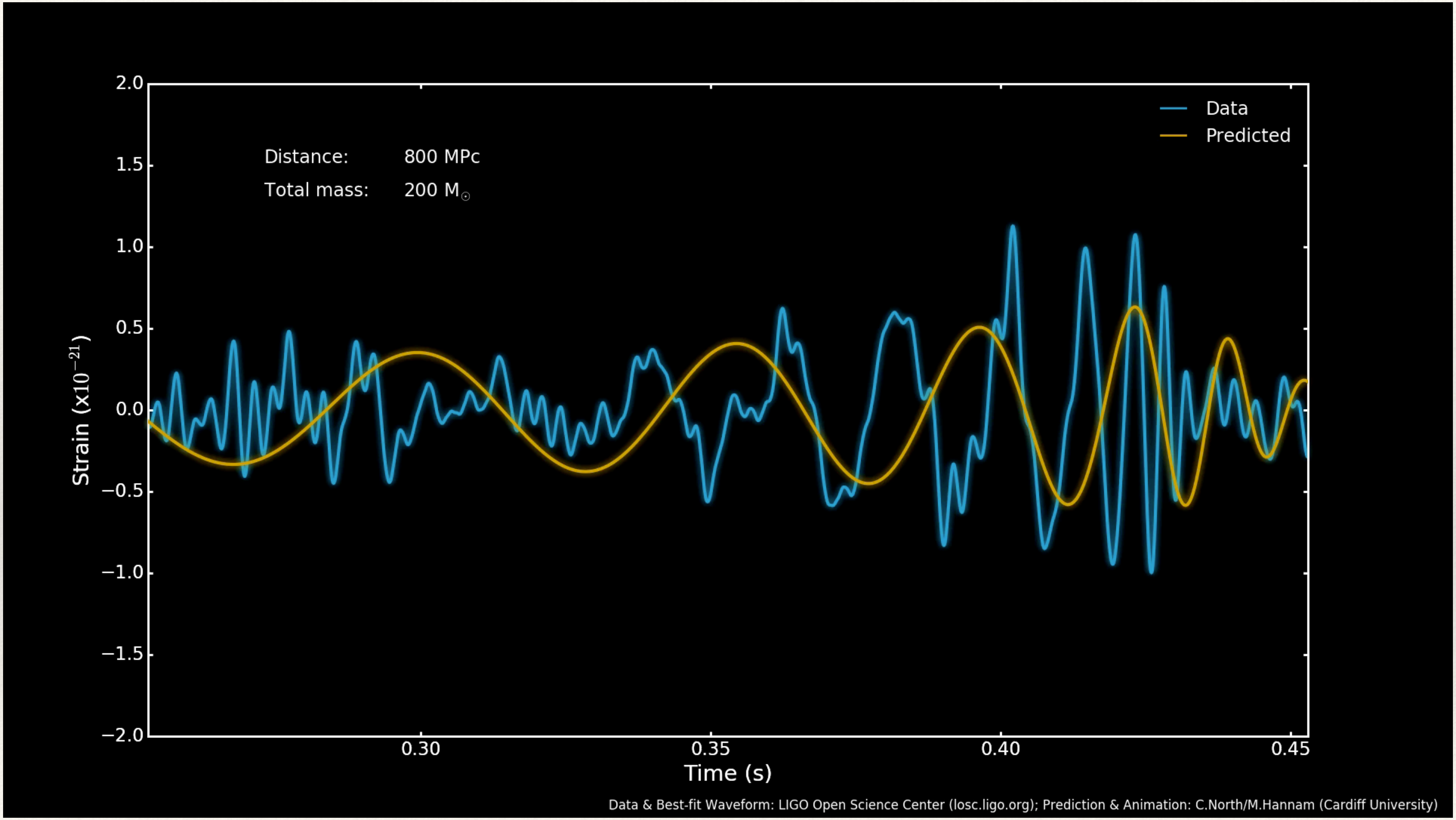

H1 Residual whitened data after subtracting template around event


L1 whitened data around event


L1 Residual whitened data after subtracting template around event

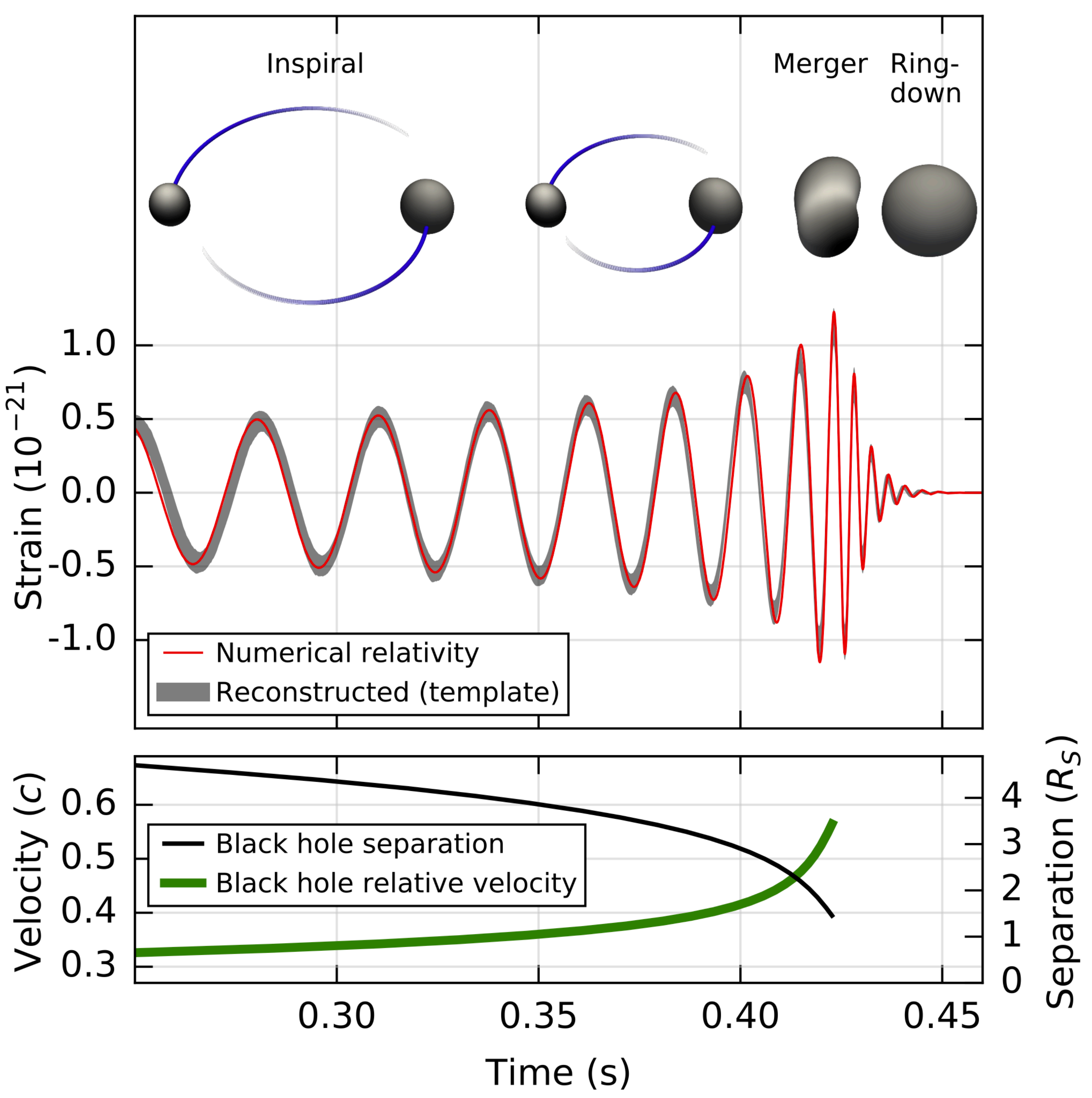
[LOSC: https://losc.ligo.org/tutorials/]

Parameter estimation



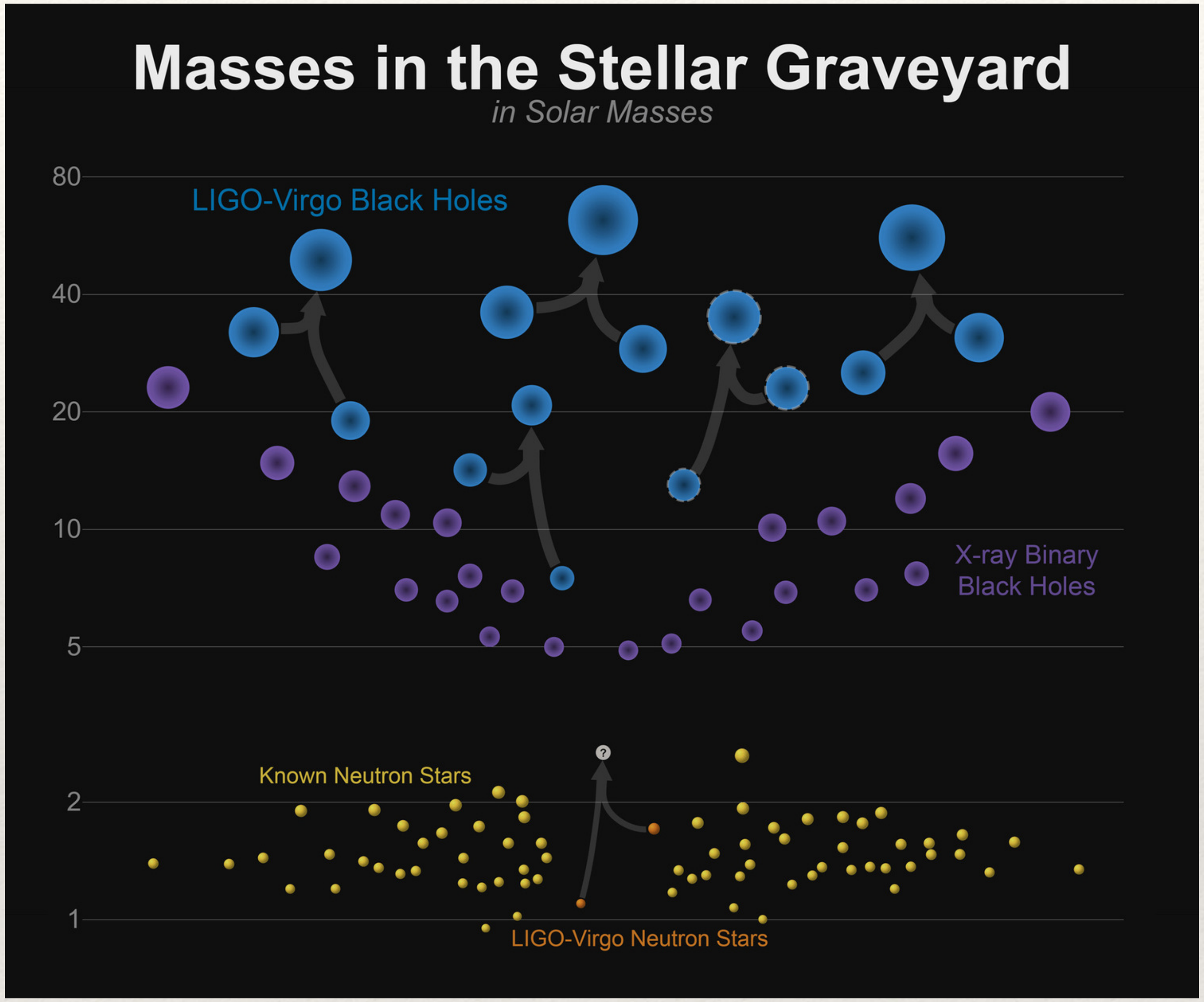
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

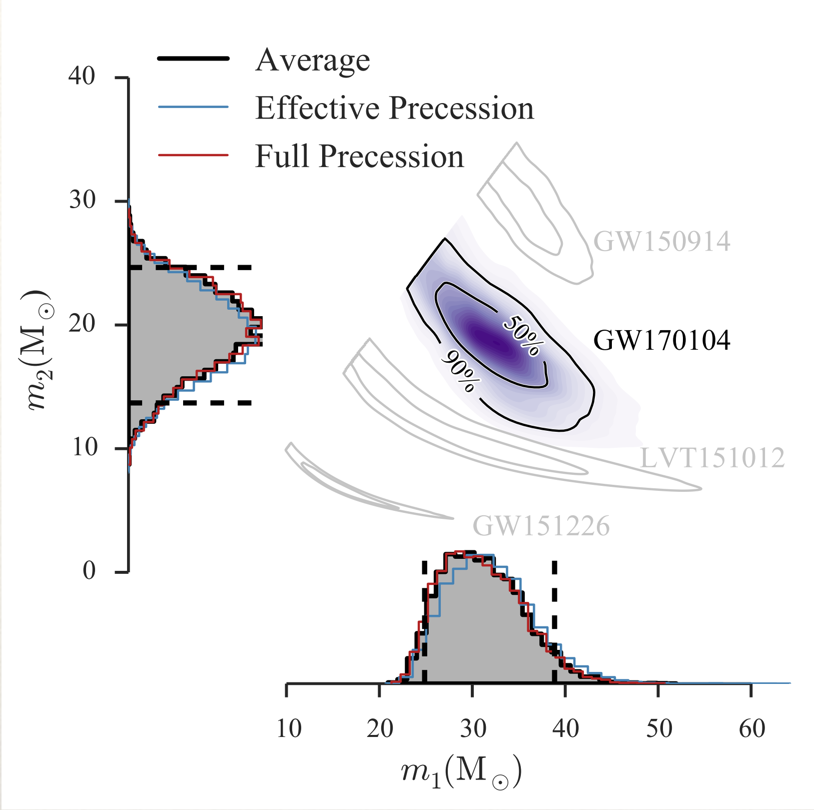
GW signal from merging BHs



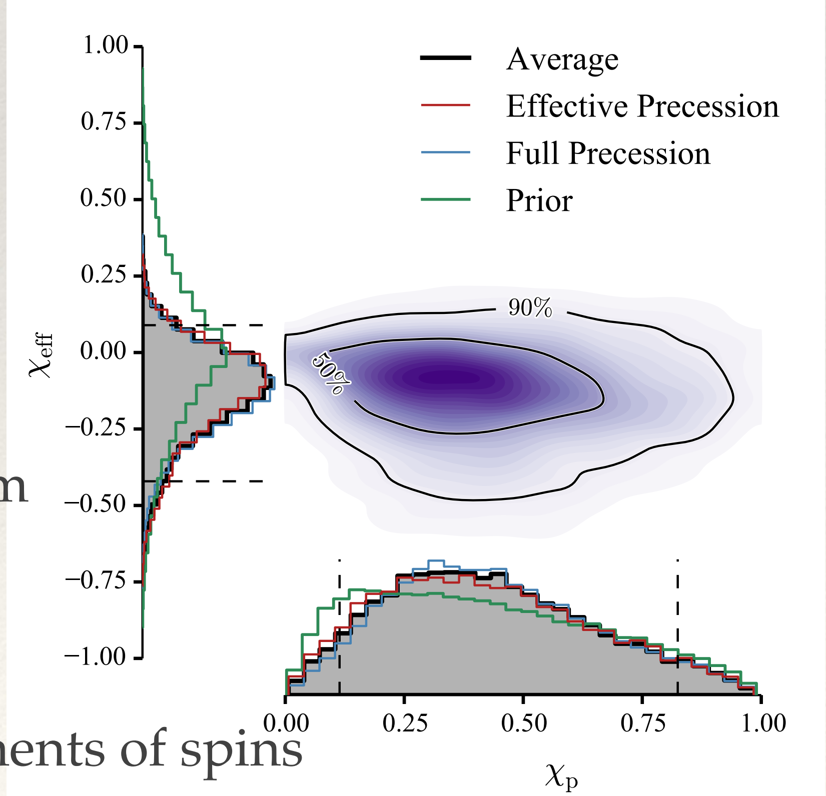
Parameter estimation

Detected binary systems



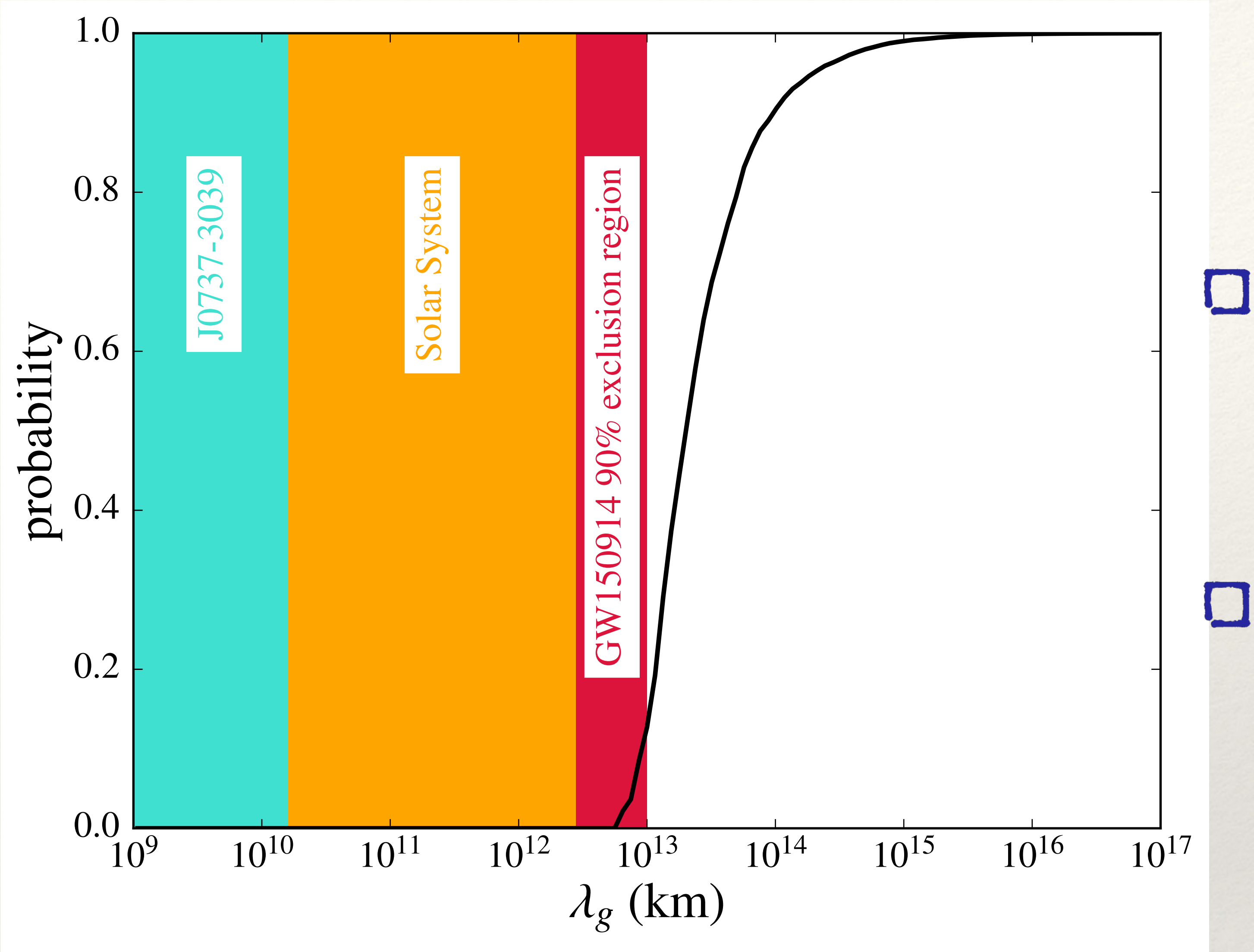


Component of spins along orbital momentum



Components of spins in orbital plane

Testing GR



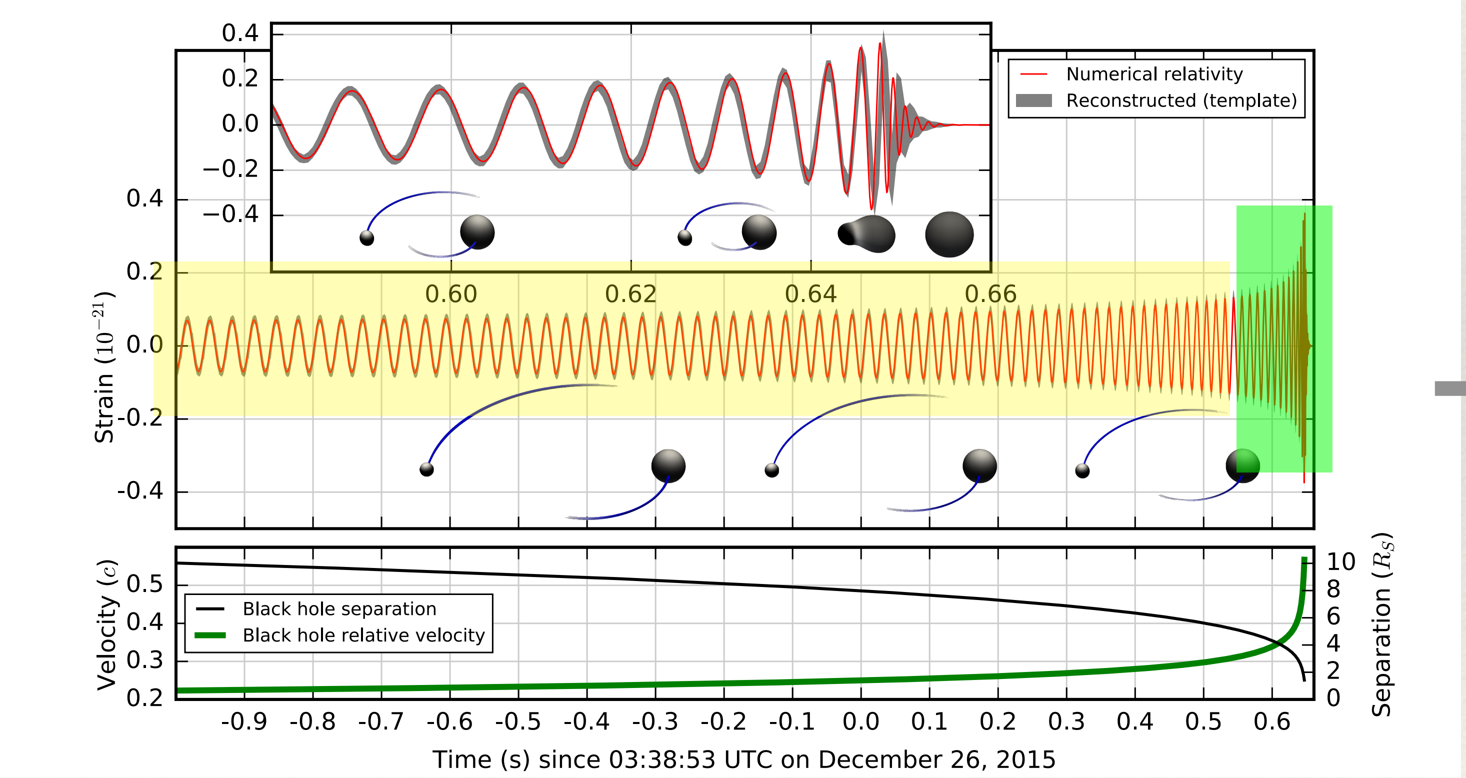
- If graviton has a mass (m_g) then we should observe dispersion of the GW
- The data is consistent with GR: can set an upper limit on the mass/ lower limit on the corresponding Compton wavelength:

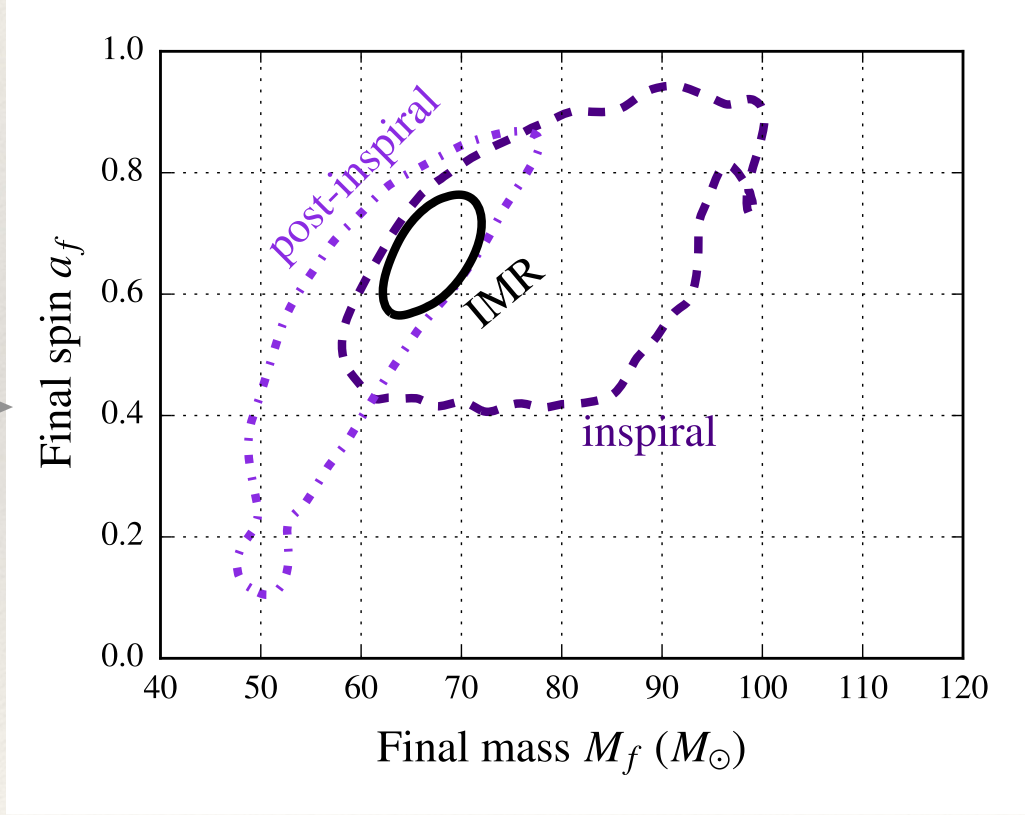
$$\lambda_g = h/(cm_g)$$

[LVC PRL (2016)]

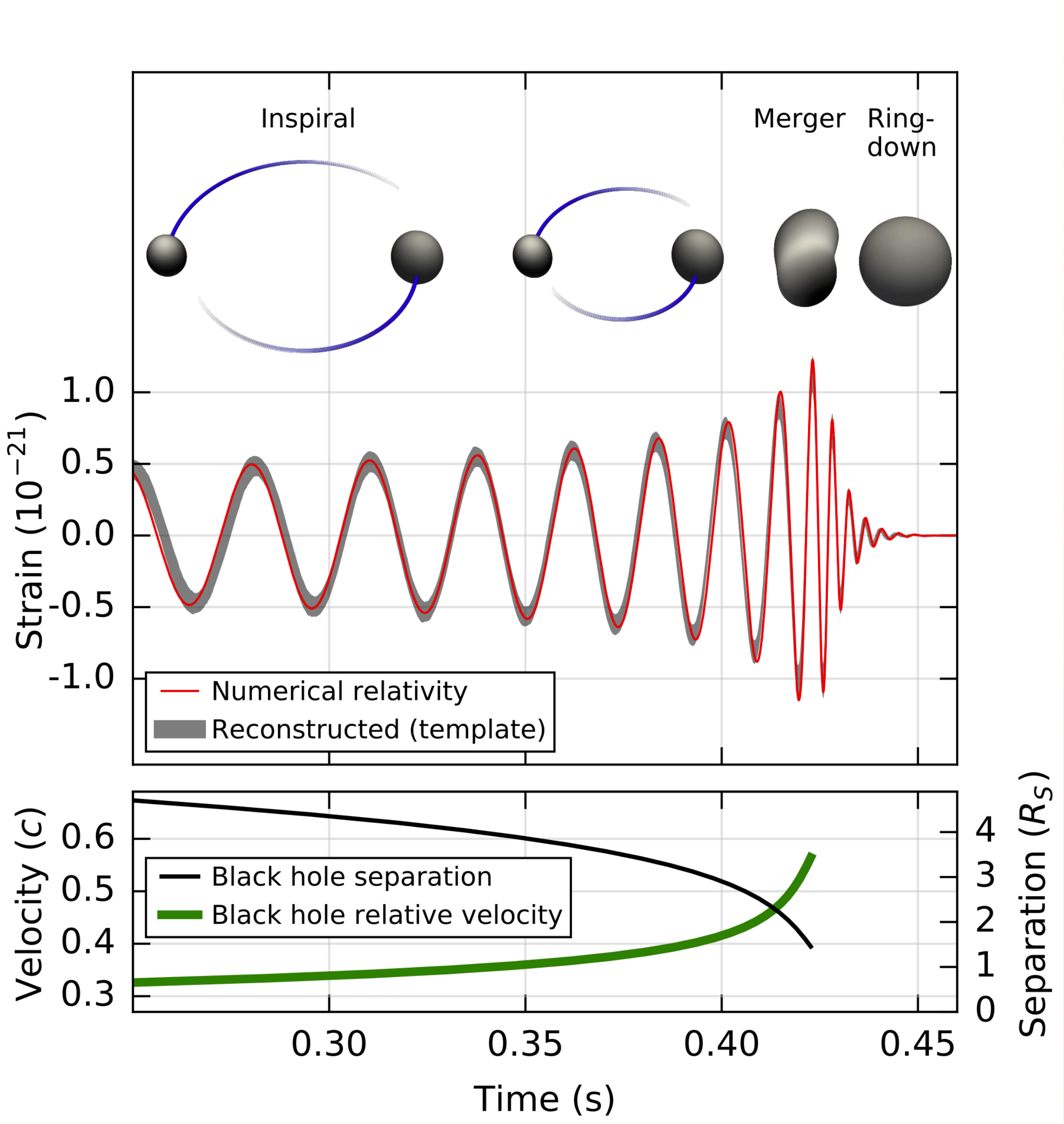
Testing GR

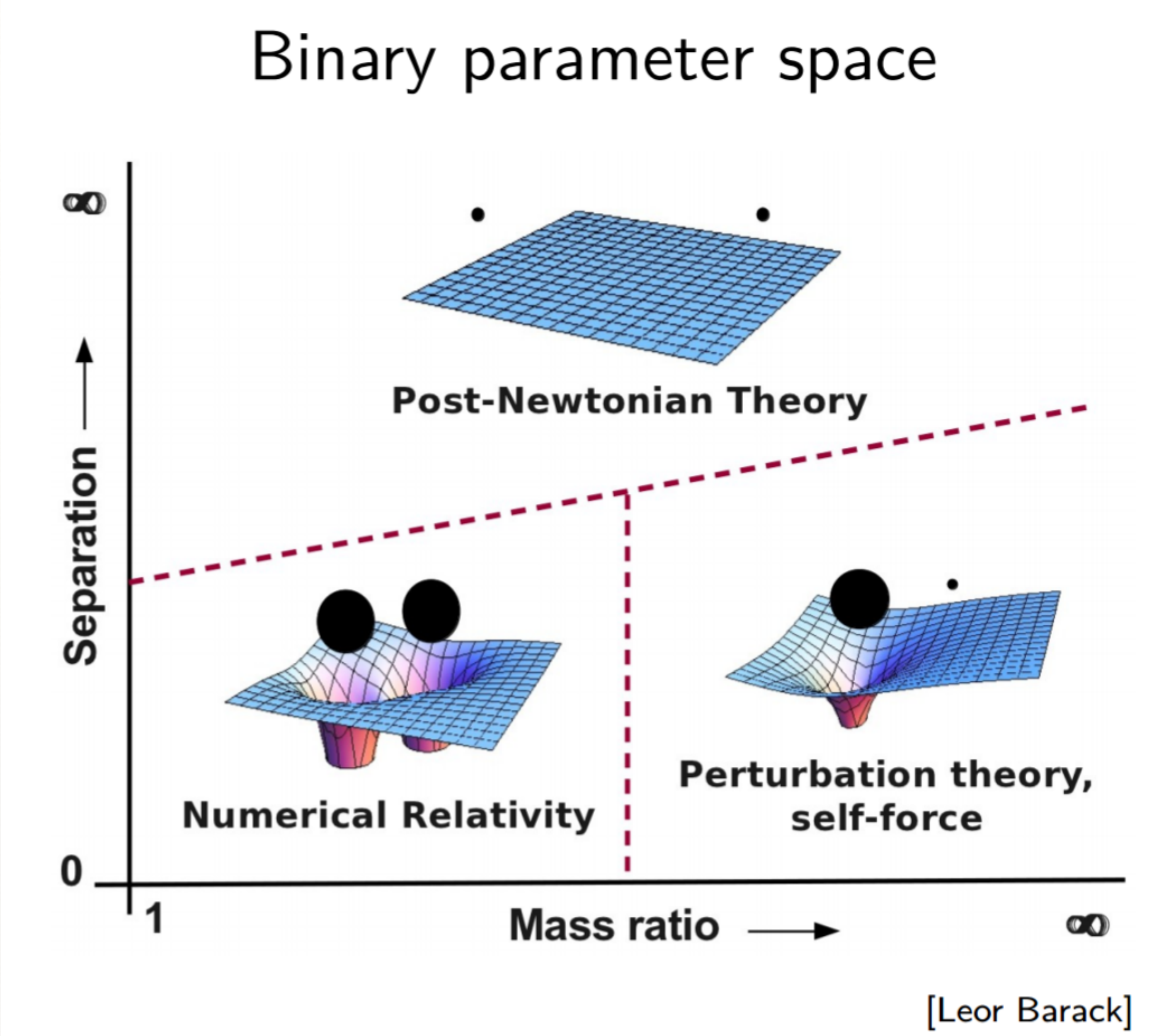
- We can check self consistency of GR: analyze two parts of the same signal independently and check if estimated parameters overlap





Modelling GW signal from coalescing BH binaries

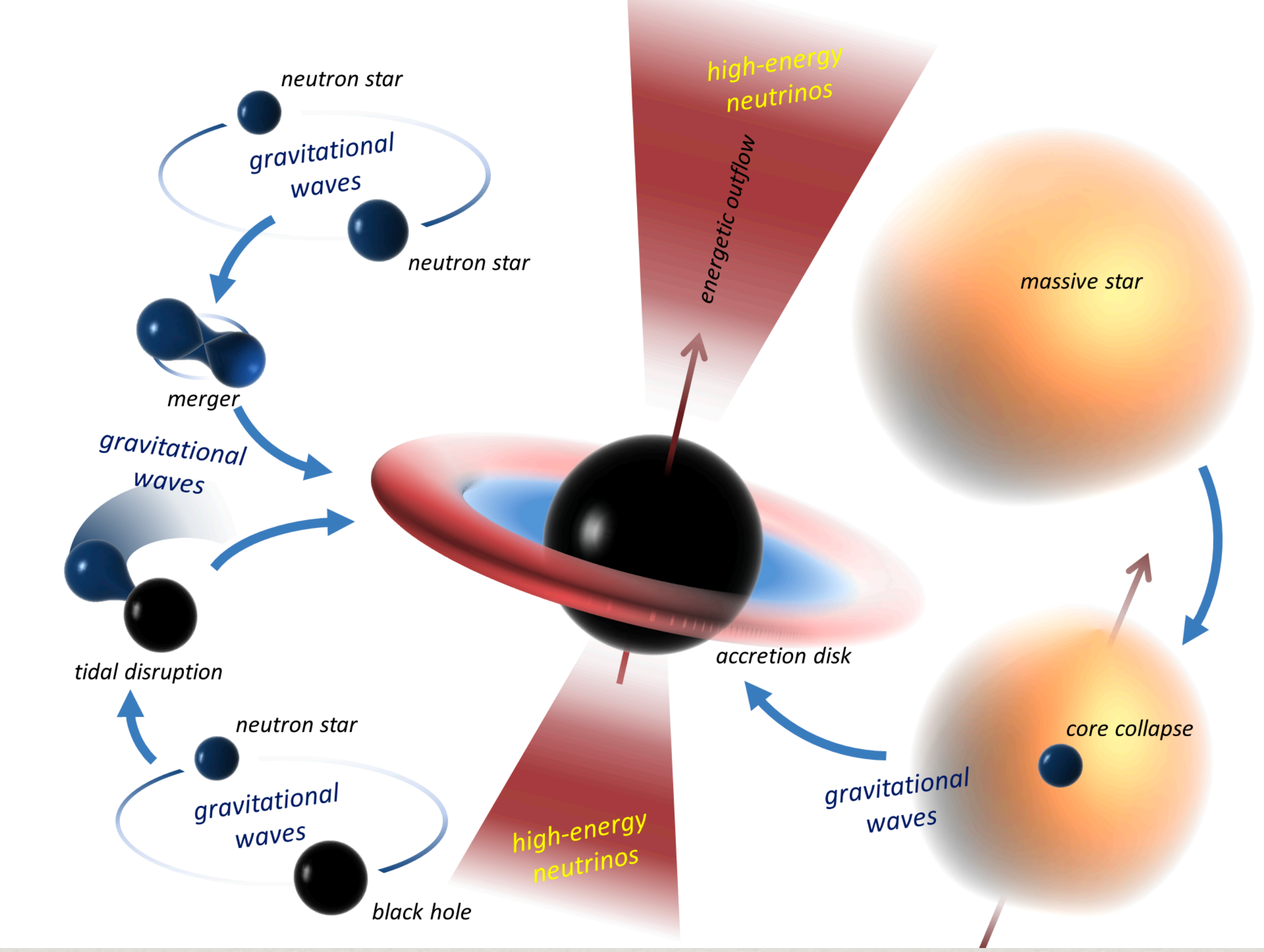




[Leor Barack]

- GW signal can be conditionally split into 3 parts: inspiral (slow orbital evolution under radiation reaction, merger, and ringdown (remnant BH releases excitations as quasinormal oscillations)

Other GW sources (LIGO-VIRGO)



Credit: I. Bartos/Based on arXiv:1212.2289

- Core collapse of a massive star
- Merging Neutron stars
- Merging Neutron star - Black hole
- Monochrtomatic GW from defform single NS
- Stochastic GW signal from processes in the early Universe

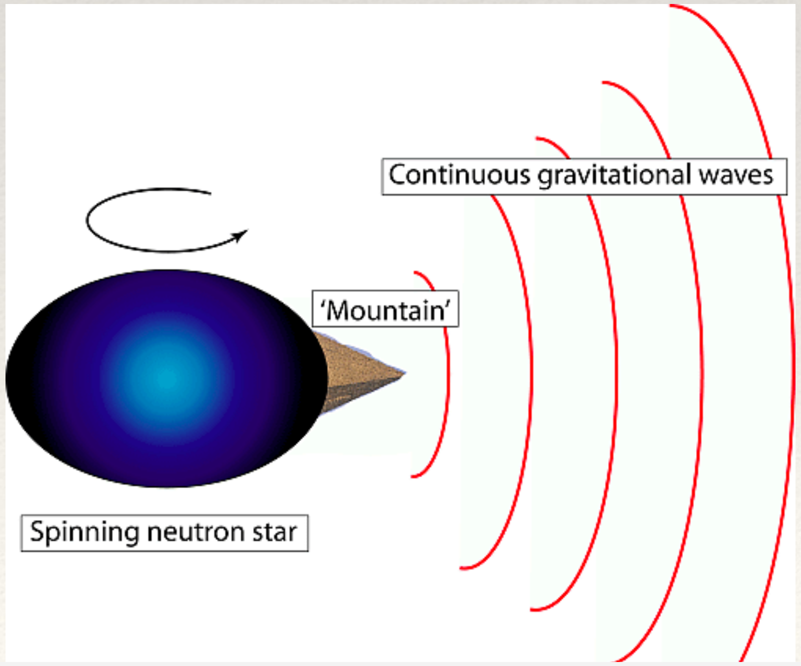
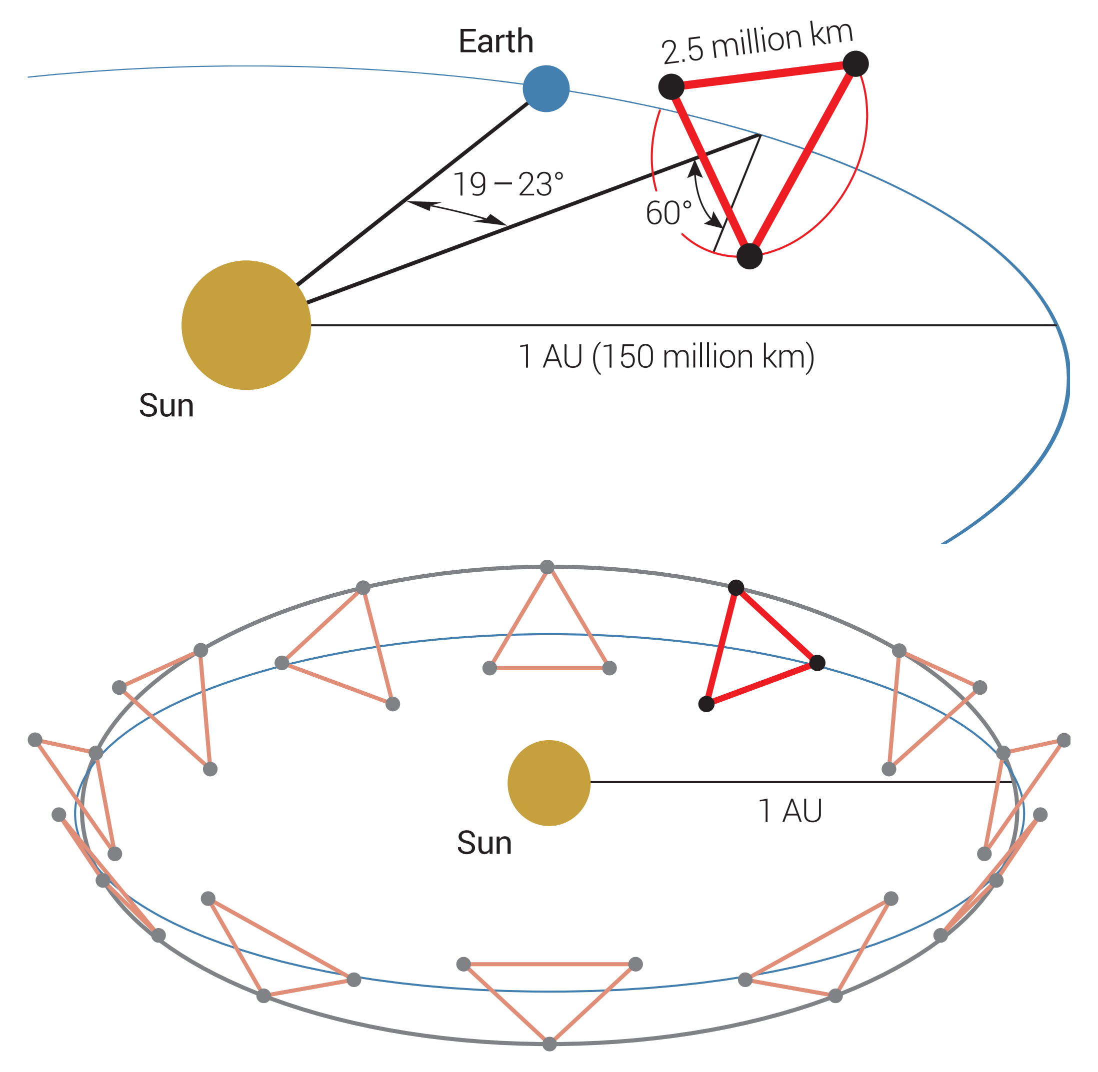


Image from https://physics.anu.edu.au/quantum/cgp/research/datatheory/neutronstars.php

Laser Interferometer Space Antenna (LISA)

- LISA: GW observatory in space. Launch data 2032-2034

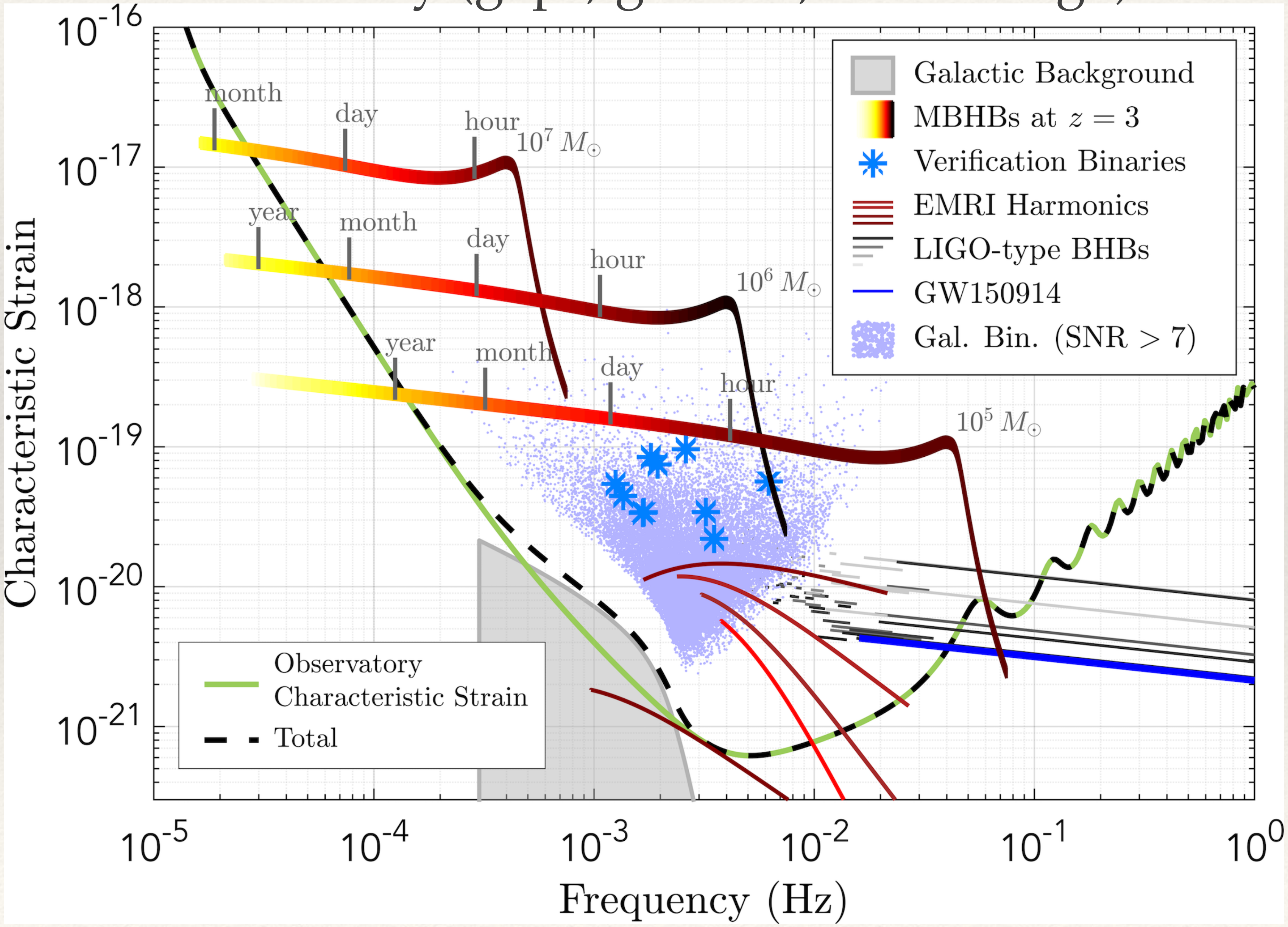
- LISAPathfinder - Technology mission to demonstrate technical readiness of LISA - one of the most successful ESA mission.



LISA (cartoon)

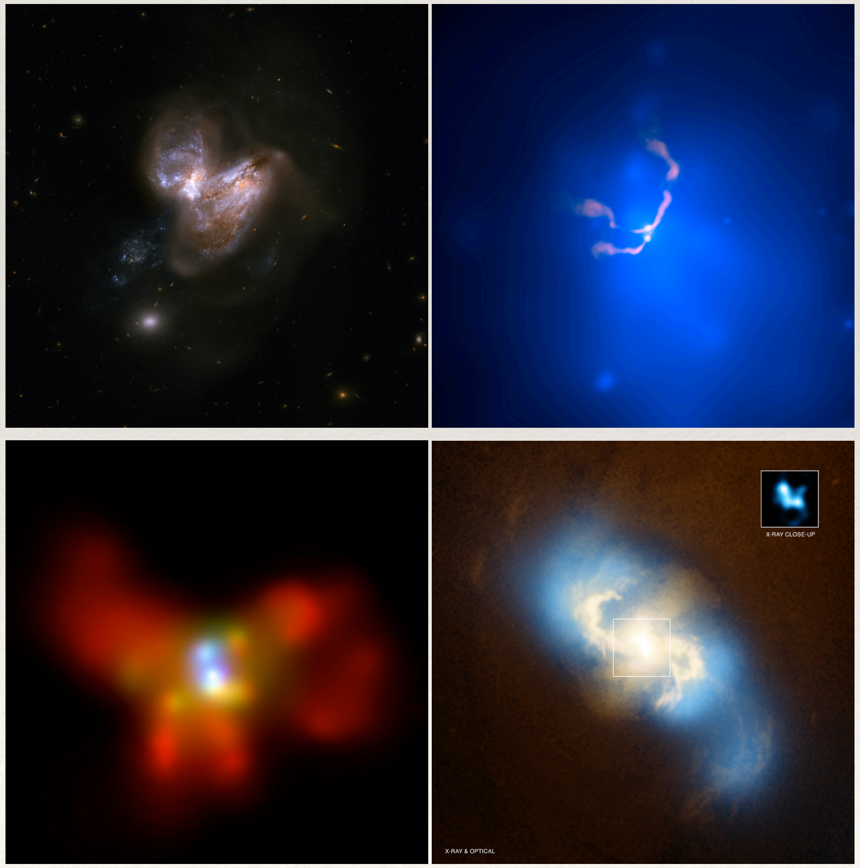
What is special about LISA data

- GW signals are long lived (monts-years) and strong
- LISA data will contain thousands of GW signals simultaneously present in the data (overlapping in time and in frequency). We need to separate and characterize each signal.
- The noise is non-stationary (gaps, glitches, “breathing”)



Massive BH binaries

- We think the all galaxies contain massive BHs in their nuclei: MBH with mass 4mln. solar mass is in the centre of our Galaxy
- MBHs are formed together with galaxies and accumulate mass by accreting a gas and through merging with other MBHs
- Galaxies merge (observations), as result we could have a MBH binary which could merge in a reasonable time
- Stars and/or gas are required to dissipate orbital momentum from MBH binary and bring it in GW driven regime



Credits: Hassinger+, VLA, Chandra , NASA

Image: Hubble telescope

EMRIs (extreme mass ratio inspirals)

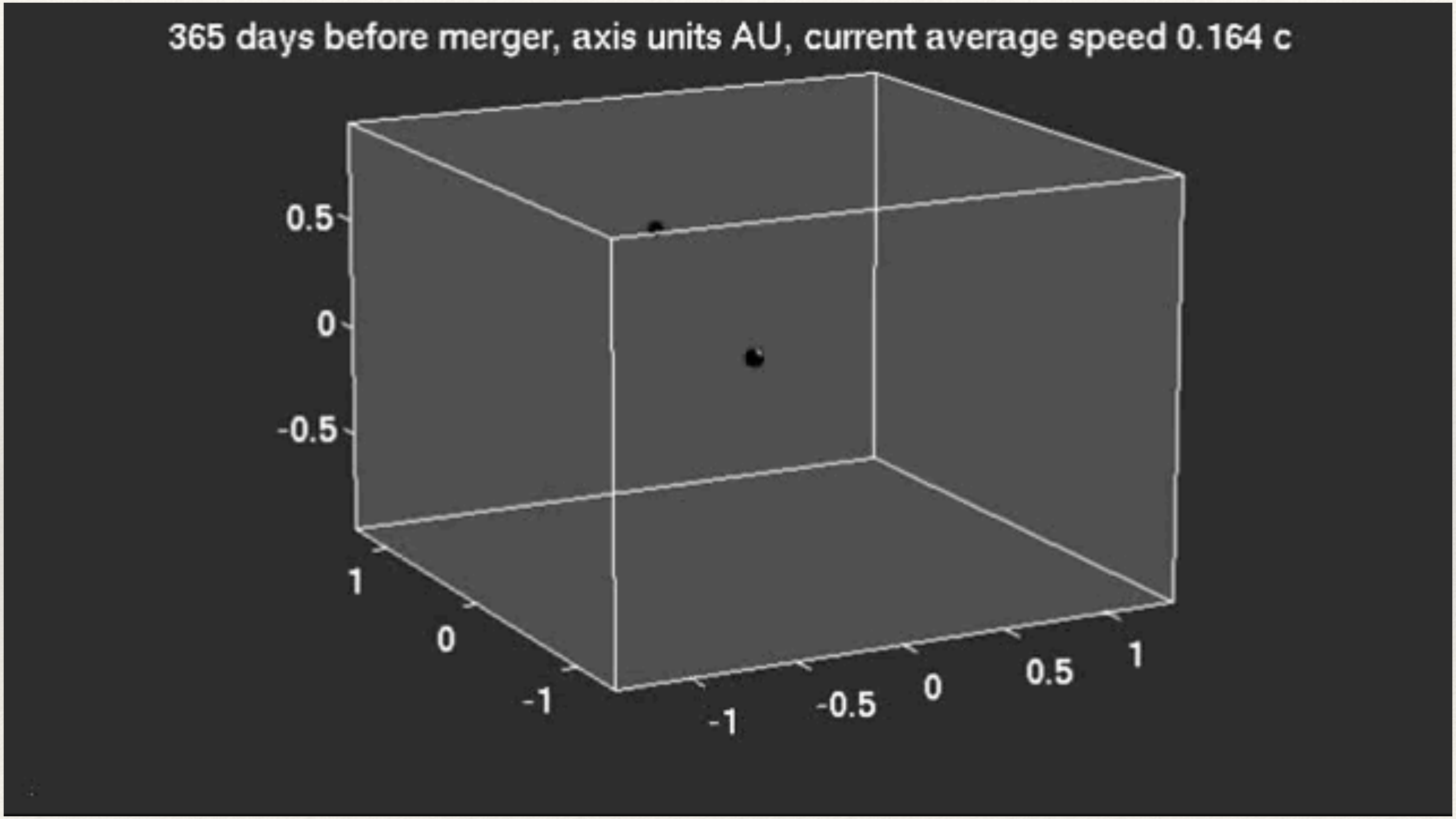
- Massive BHs could be embeded in the stellar cusps (high density stellar environment)

- Massive BH could capture a compact object (NS, stellar mass BH) which starts moving in a very eccentric orbit which shrinks under GW radiation

- EMRI: Binary system with an extreme mass ratio: 10^{-7} - 10^{-5}

- Compact object completes ~ 10^{6} orbits in the close vicinity of a MBH before plunge

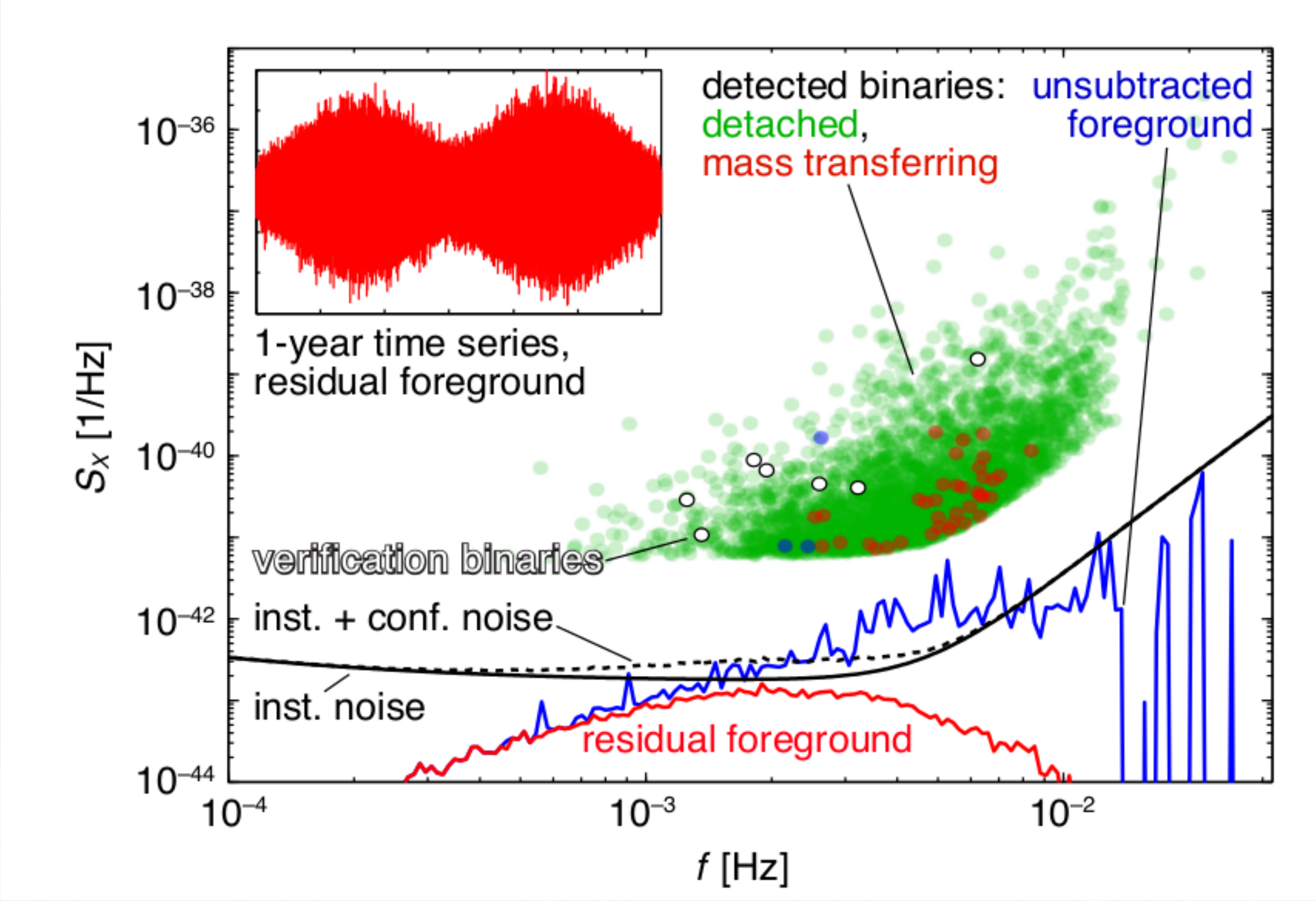
EMRI



Credits: S Draco, CalTech

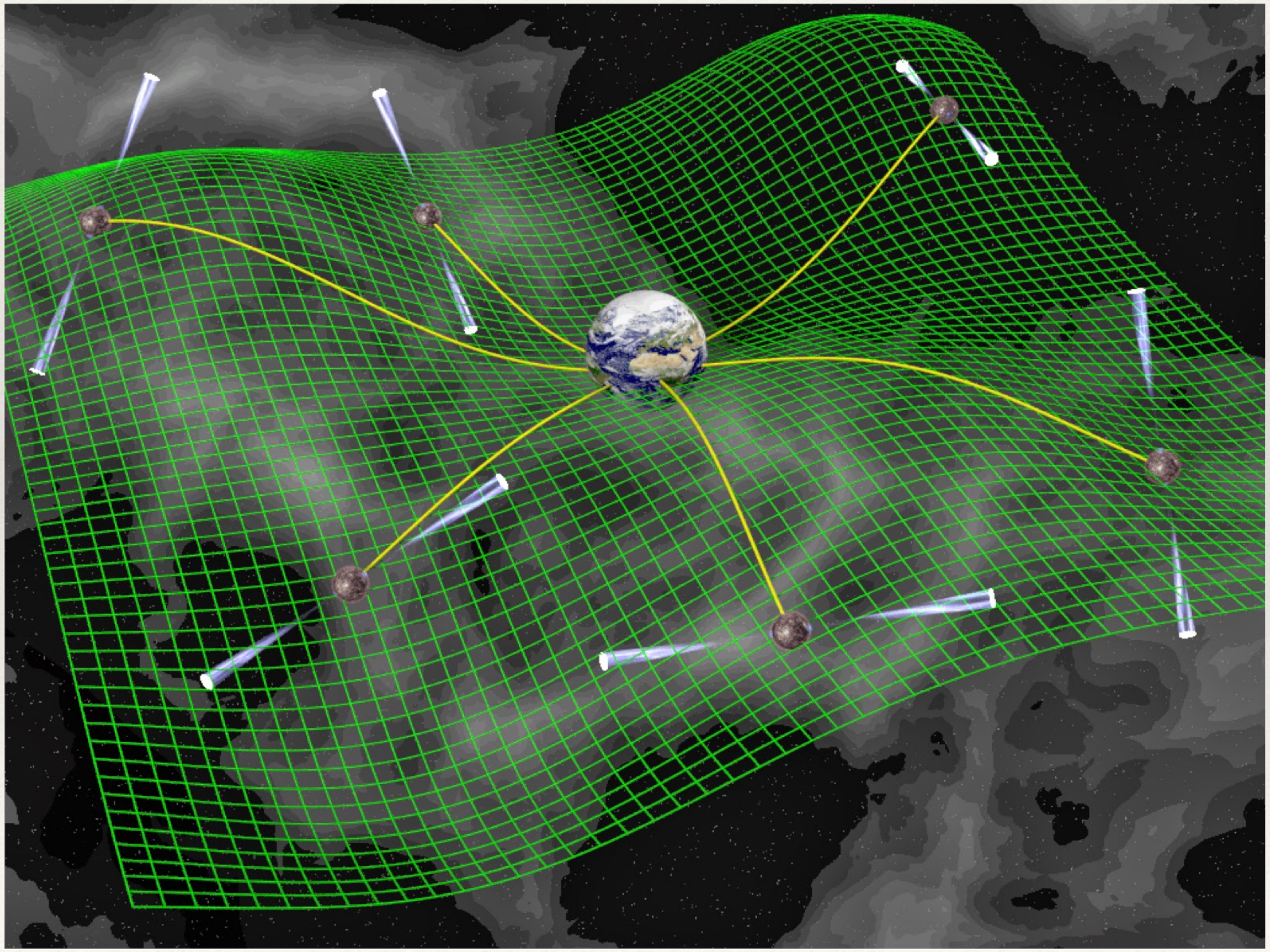
White dwarf binaries in our Galaxy

- We expect to have ~10^7 white dwarf binaries in the LISA band, and about 10 be indiviually detected, other form stochastic GW signal (foreground)
- GW signal is almost monochromatic
- We have guaranteed (verification) binaries observed in e/m (GAIA, LSST)



Pulsar Timing Array: PTA

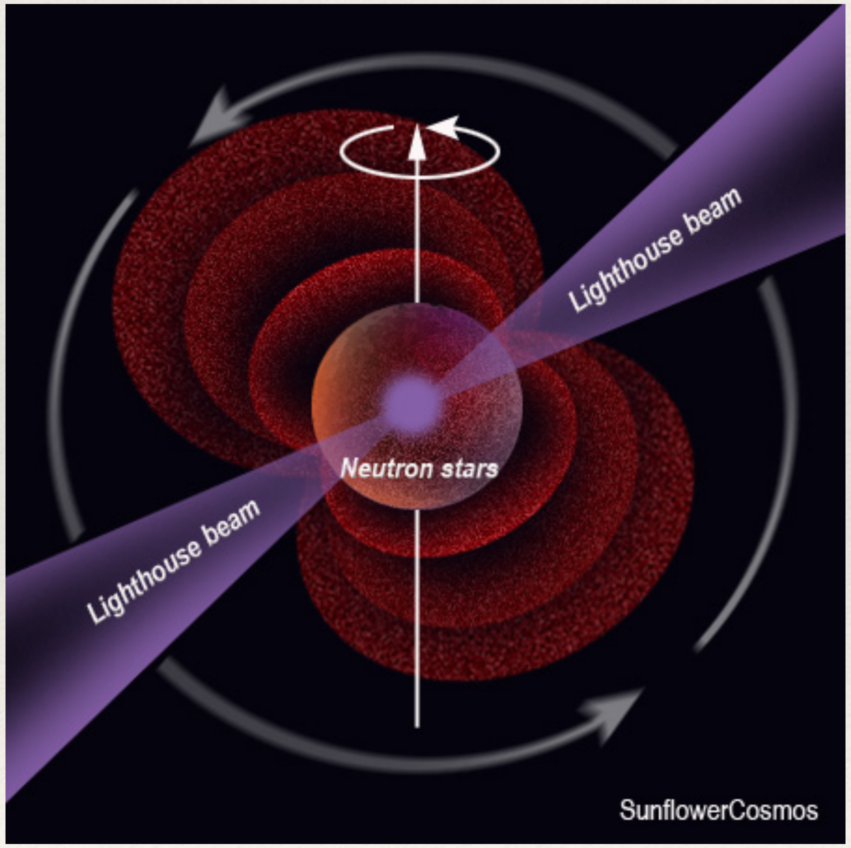
The main idea behind pulsar timing array (PTA) is to use ultra-stable millisecond pulsars as beacons for detecting GW in the nano-Hz range 10^{-9} - 10^{-7} Hz

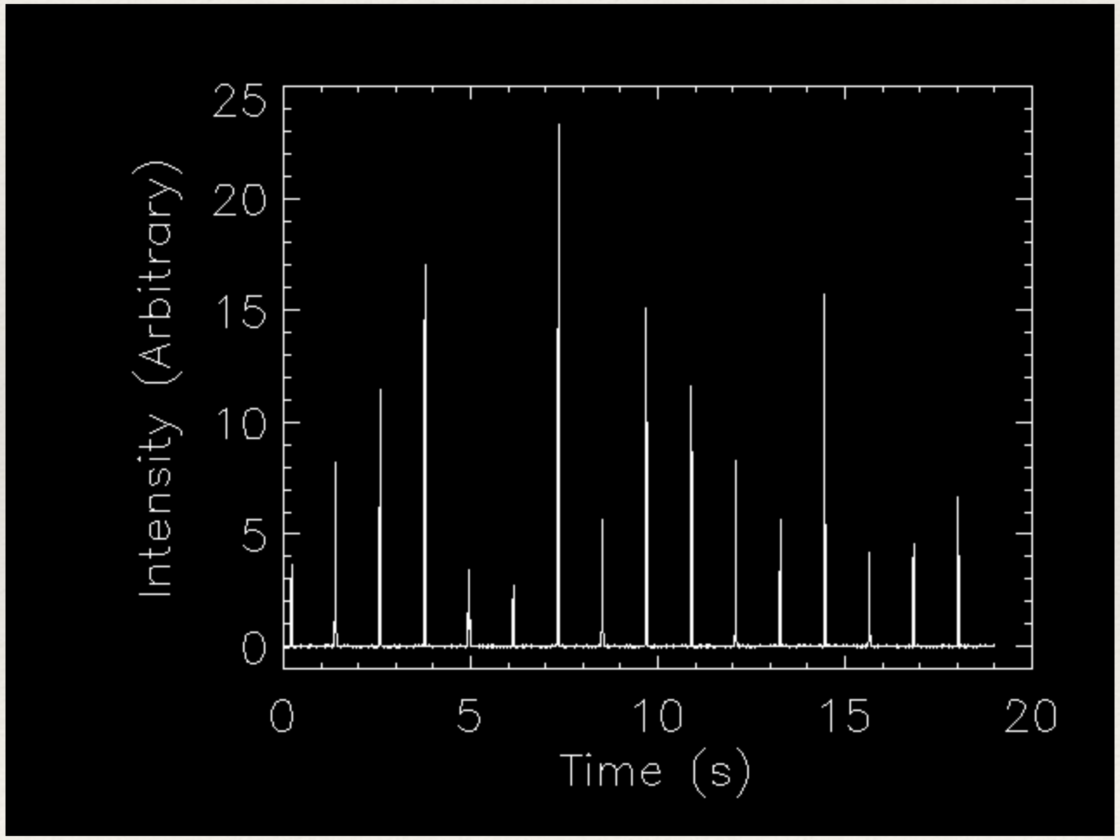


Credits: D. Champion

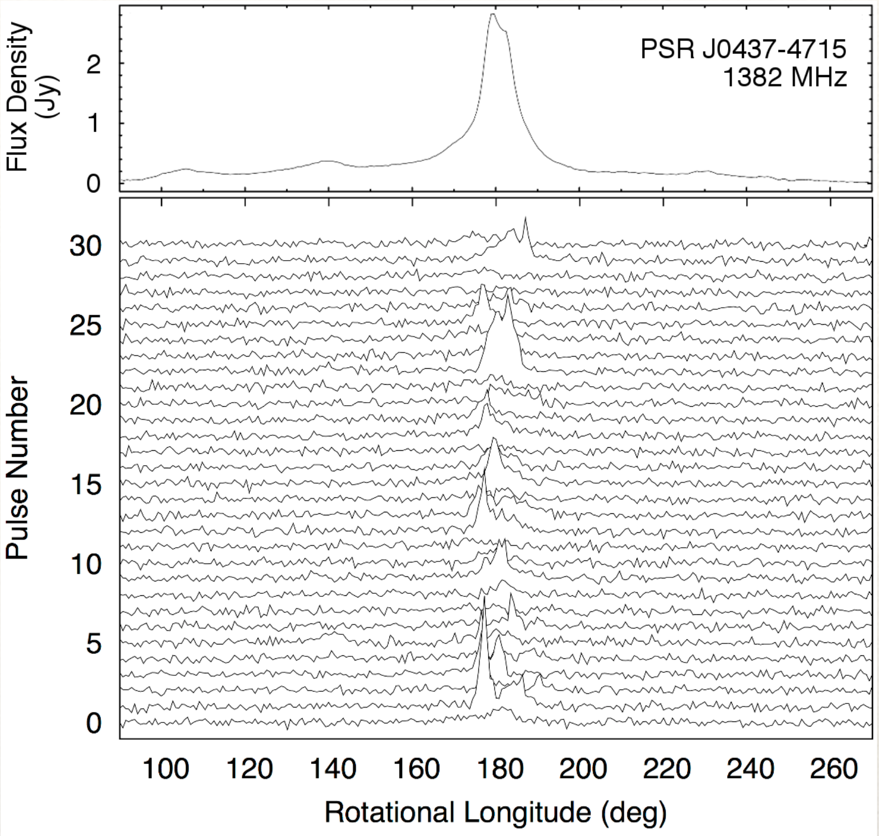
Millisecond pulsars

Pulsars are neutron stars with rapid rotation and strong magnetic field. Period from few seconds to few milliseconds (MSP). MSP - usually old, recycled pulsars, often in binaries.

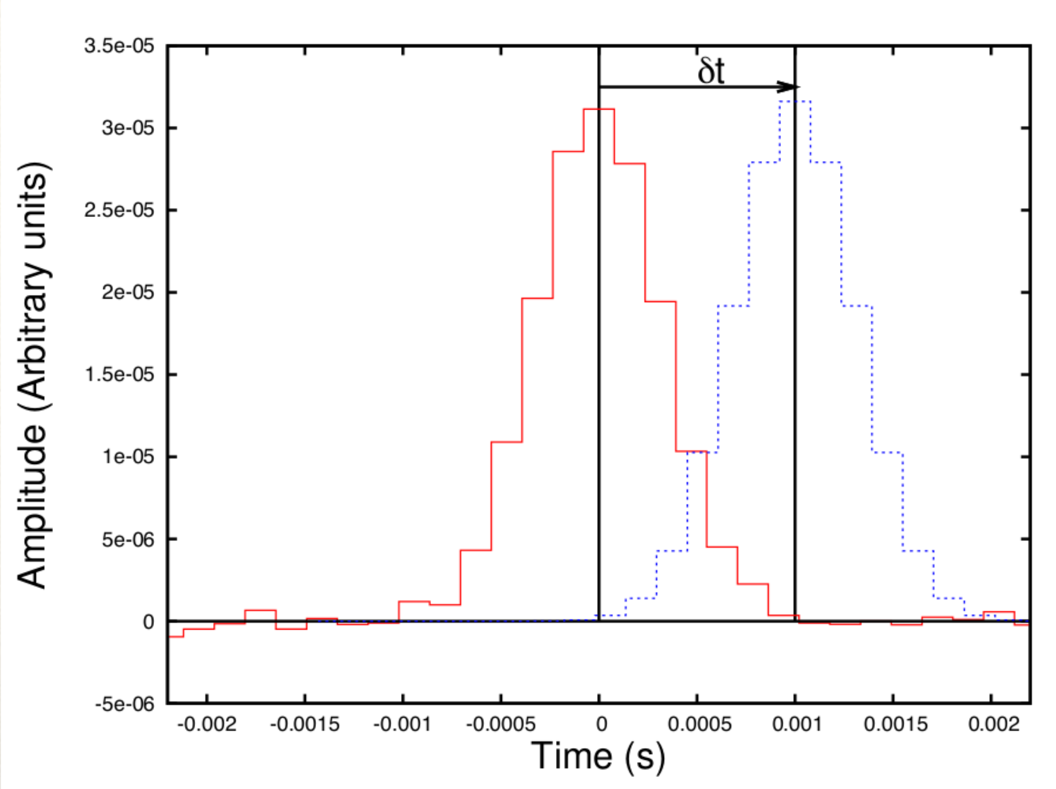




Pulsar timing



Figs: credits
S. Burke-Spolar & L. Lentati



- Each pulse has a lot of micro-structure but stable is averaged over hour.
- We use average pulse profile to get *time-of-arrival* (TOA) for the pulses
- We know well the pin of pulsars: can predict TOAs and subtract from measured: *residuals*

Timing residuals

The complete timing model for TOAs depend on many parameters

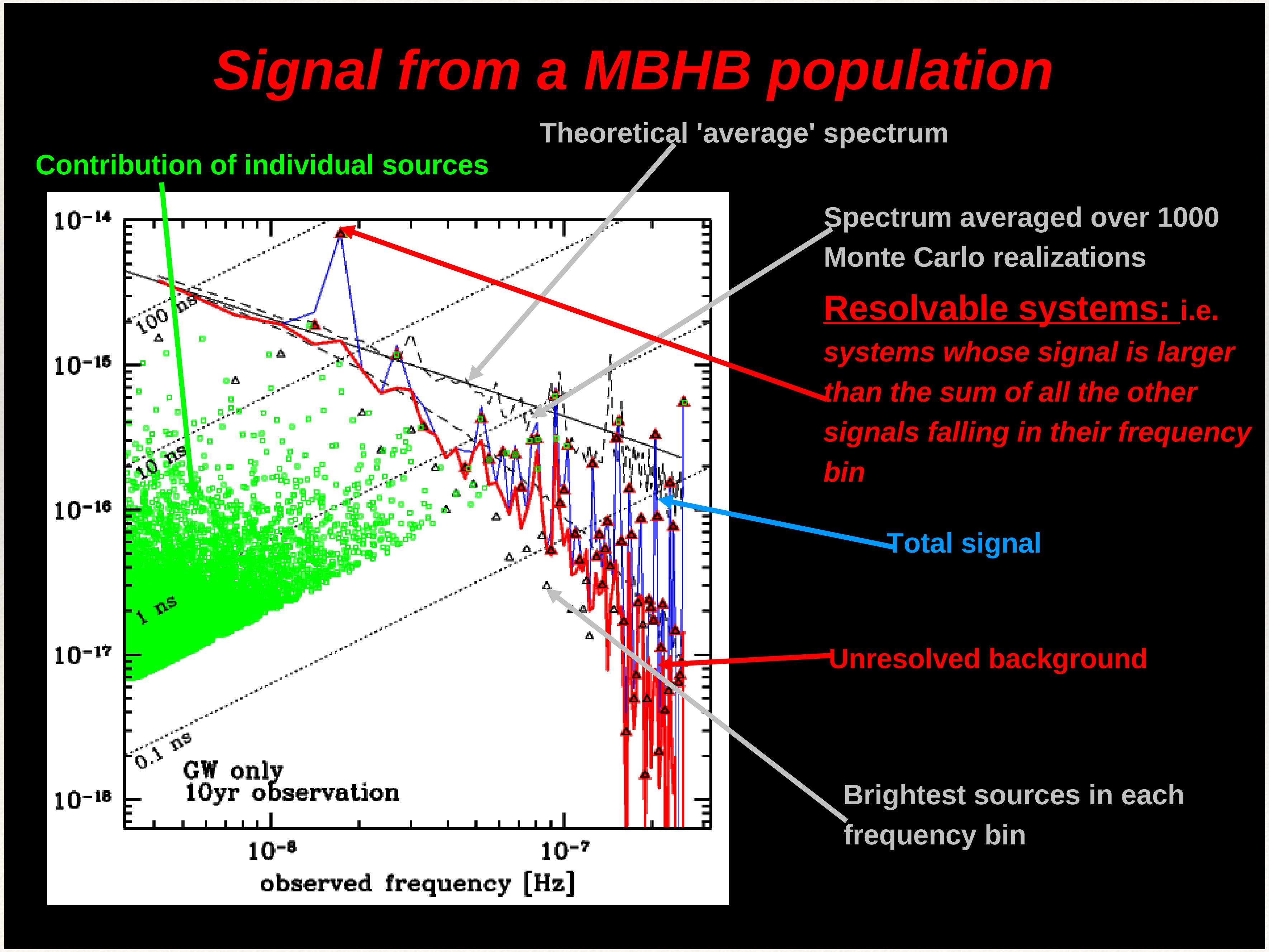
$$t_{toa} = t_{toa}(P, \dot{P}, \ddot{P}, \Delta_{clock}, \Delta_{DM}(L), \Delta_{\odot-\oplus}, \Delta_E, \Delta_S)$$

$P, \dot{P}, \ddot{P}$	period of pulsar, its spin-down, glitches.
Δ_{clock}	difference in local clock and terrestrial
$\Delta_{DM}(L)$	delay caused by interstellar medium
$\Delta_{\odot-\oplus}$	translation from observatory frame to SSB
Δ_E	accounts for the time dilation from oving pulsar and grav. redshift caused by Sun, planets or binary component
Δ_S	(Shapiro delay) extra time required by the pulse to travel through the curved space-time

$$dt = t^p_{toa} - t^o_{toa} = dt_{errors} + \delta\tau_{GW} + noise$$

Supermassive BH binaries

- The main GW source in PTA: population of supermassive BH binaries (mass 10^7 - 10^{10} solar) on the broad orbits (period ~ year)
- GW is monochromatic over decades: many signals form stochastic GW signal at low frequencies



Signal from a MBHB population

Theoretical 'average' spectrum

Contribution of individual sources

Spectrum averaged over 1000 Monte Carlo realizations

Resolvable systems: i.e. *systems whose signal is larger than the sum of all the other signals falling in their frequency bin*

Total signal

Unresolved background

Brightest sources in each frequency bin

Correlation

The key feature of stochastic GW signal: it is correlated across pulsars in the array with characteristic quadrupolar pattern given by Hellings-Downs curve: the correlation depends only on the angular separation of pair of pulsars

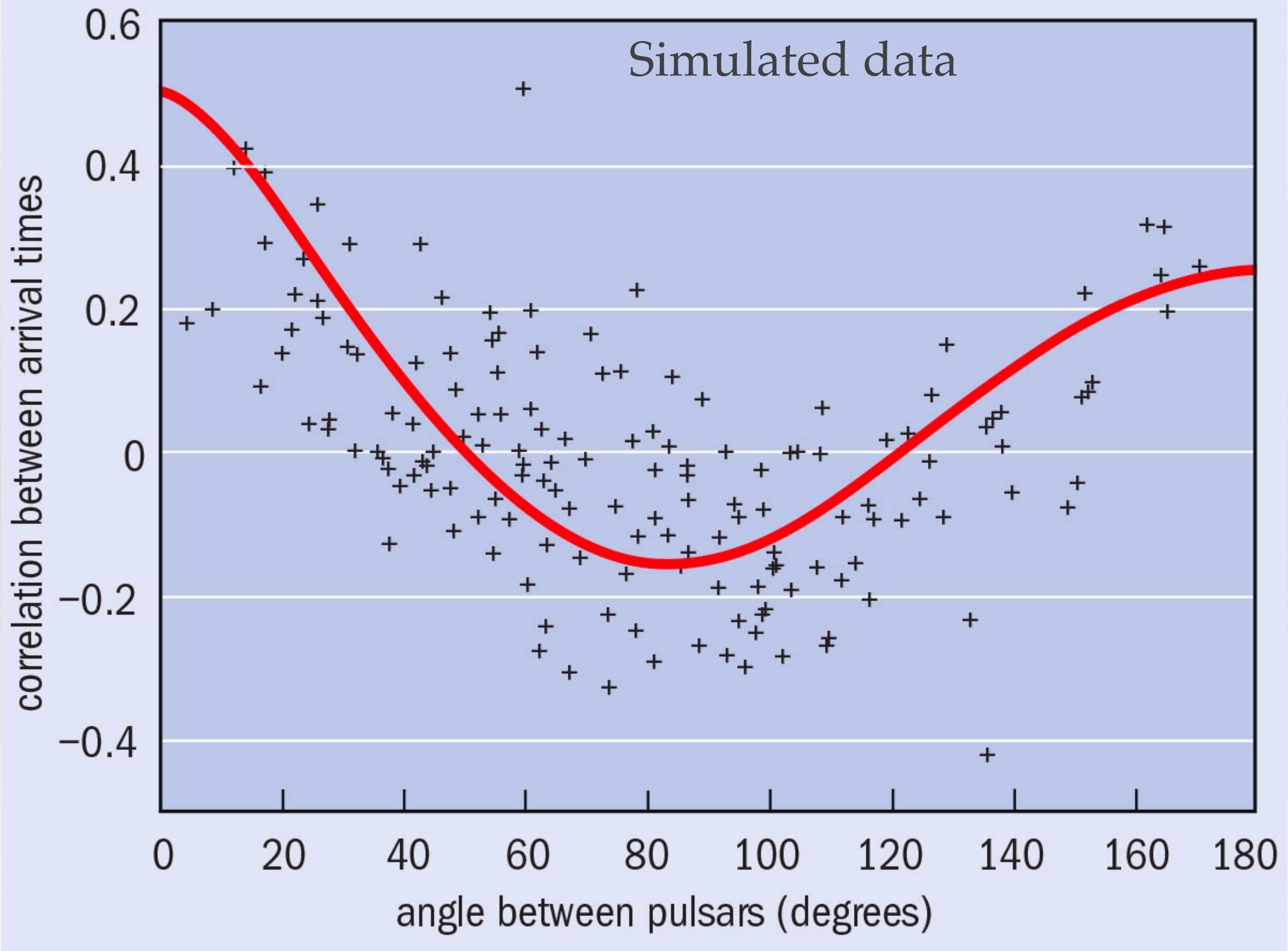
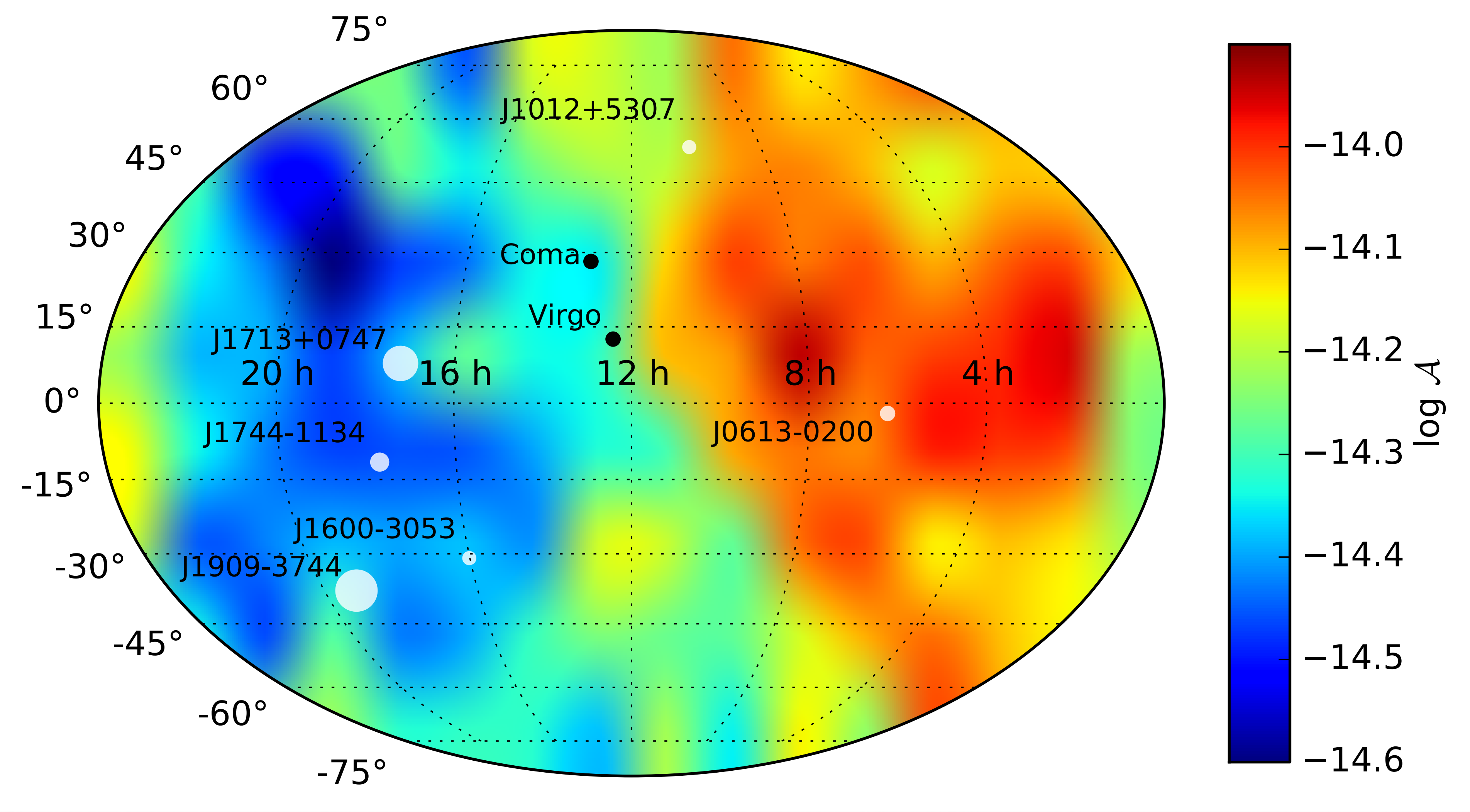


Fig. from IOP, Physics World

Upper limit on GW in nano-Hz band

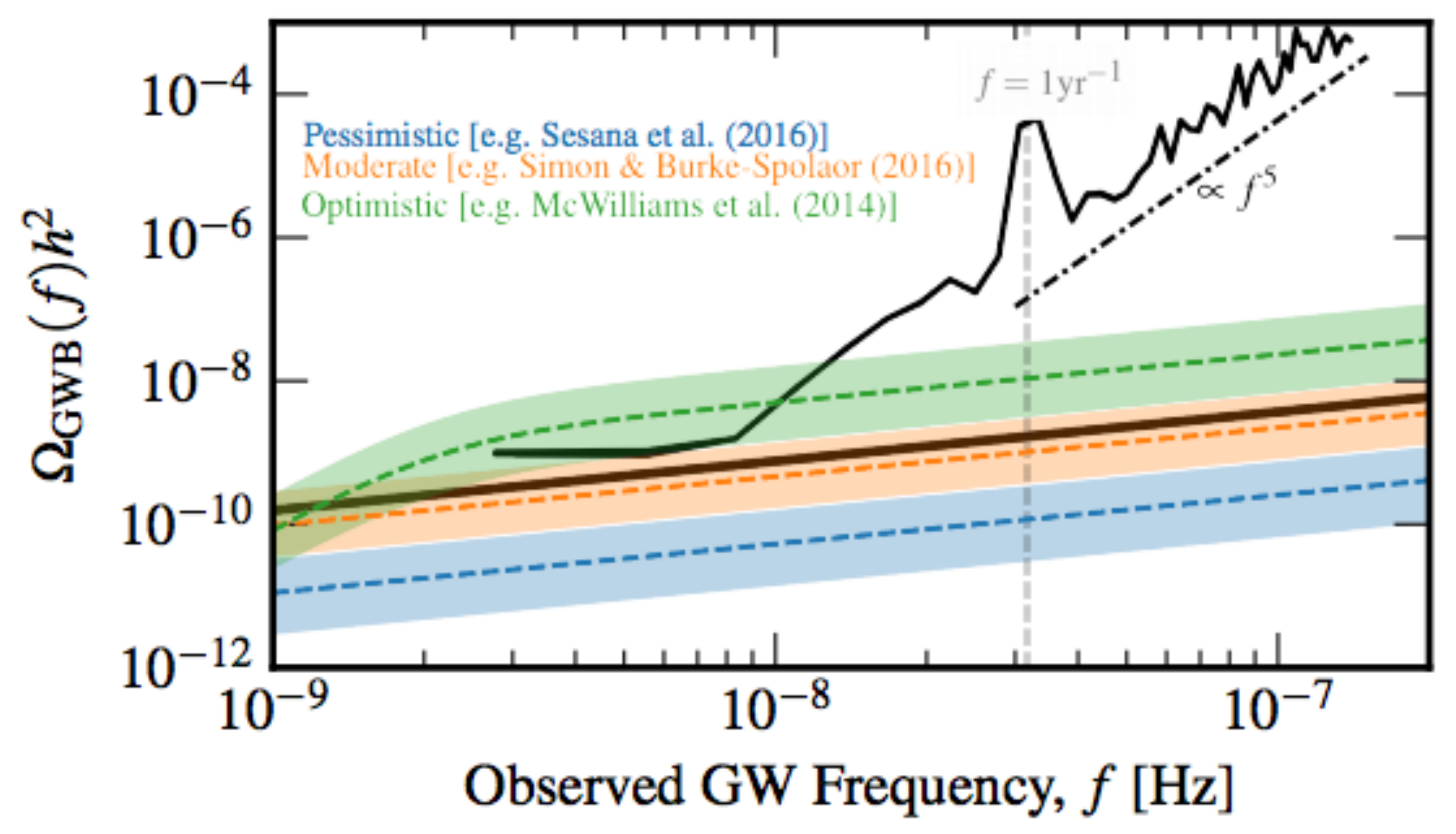
- GW are not yet detected by PTA: require long monitoring of pulsars (decades) to integrate the signal oput of noise + more stable pulsars.
- We can set un upper limit on the strength of GWs in the nano-Hz band: upper limit on the strain of individual signals.



[Babak+ MNRAS (2015), EPTA]

Upper limit on the stochastic GW signal

We can rule out some over-optimistic astrophysical models.



[Nanograv, arXiv: 1801.02617]

Conclusion

- LIGO-VIRGO completed two observational runs: detected handful of GW signals from colaesing binaries. Next run will start next year with (hopefully) improved sensitivity. More signals (surprises?)

- LISA is in the phase "A": it will deliver info on evolution of MBHs and their environment, structure of Galaxy, fundamental physics, cosmography.

- PTA: detection of GWs in the nano-Hz band is inevitable: we need long integration time. New large radiotelescopes (FAST, SKA) will discover new pulsars and improve on the existing.