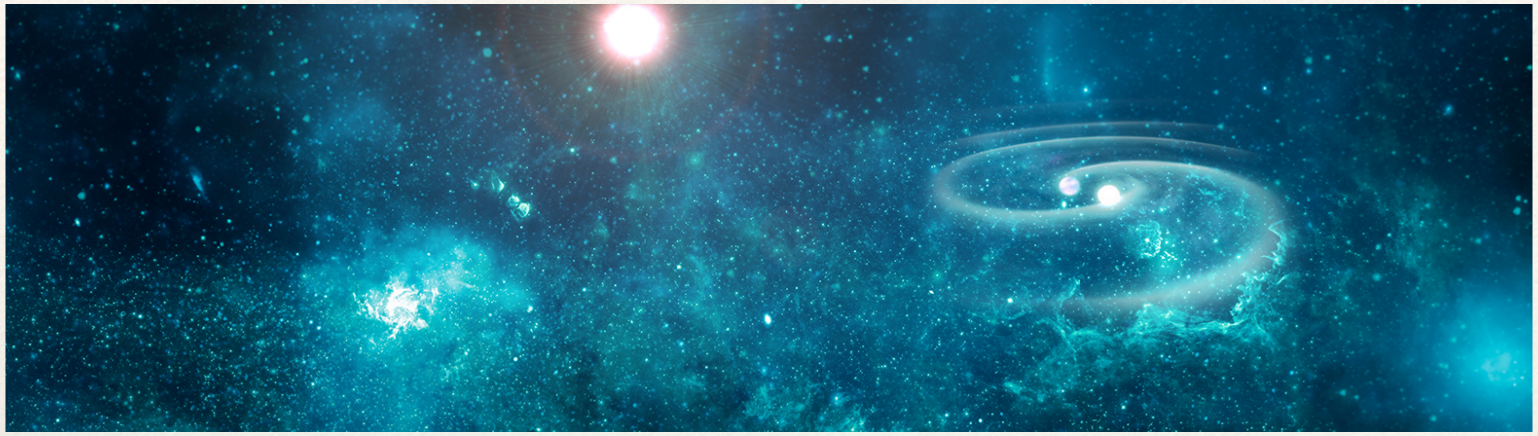
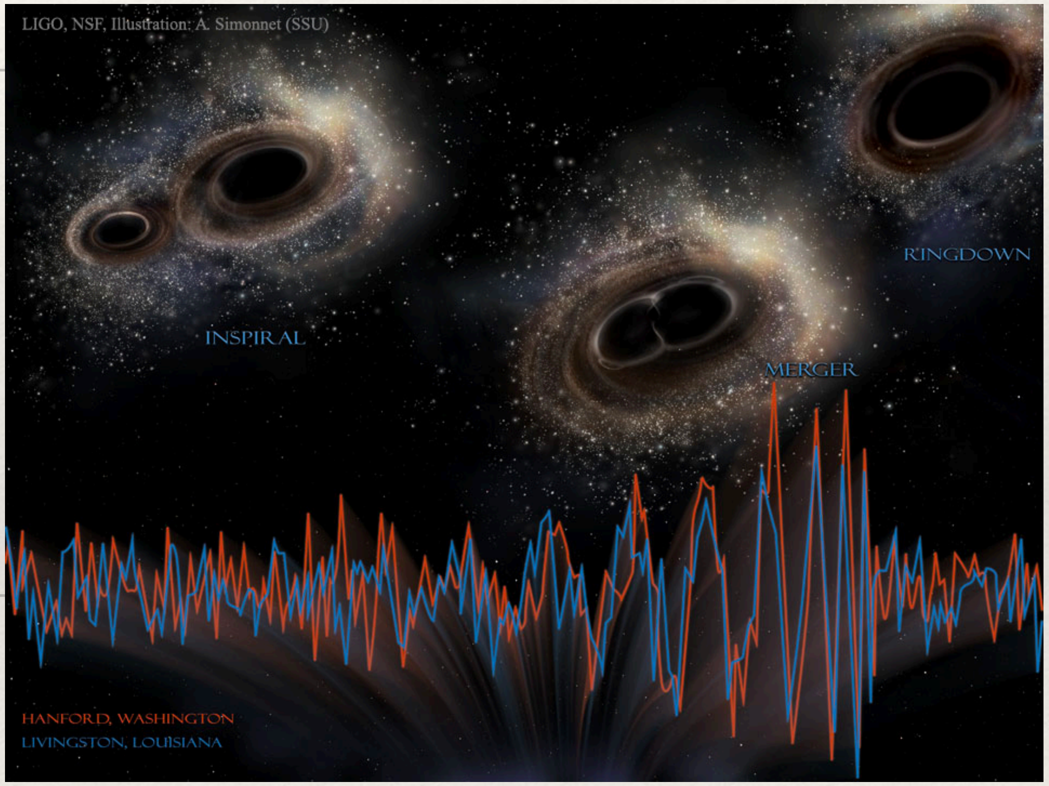
Stanislav Babak.
AstroParticule et Cosmologie, CNRS (Paris)



Detecting low frequency gravitational waves.

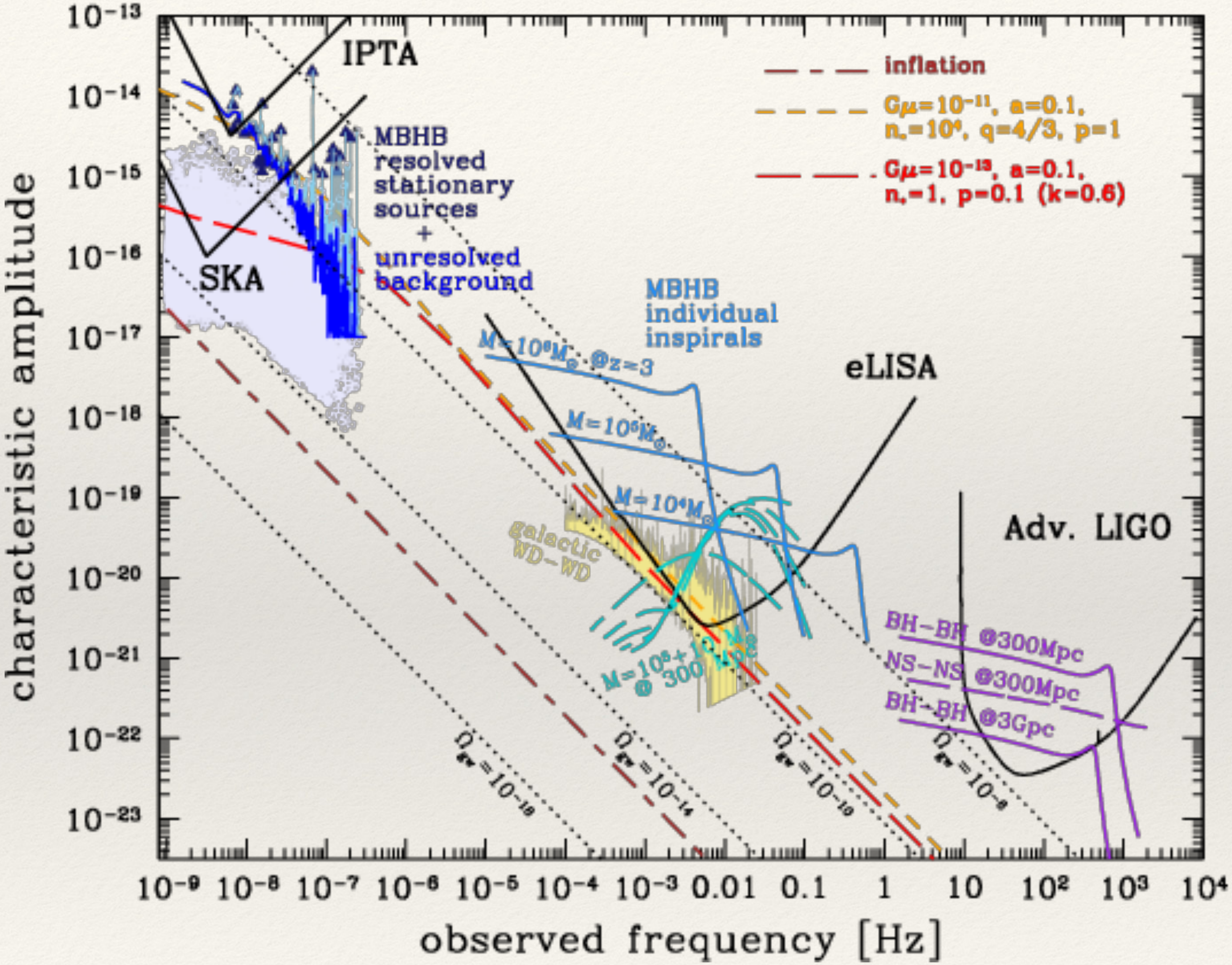

LIGO, NSF, Illustration: A. Simonnet (SSU)

15 January 2019, Rome

Outline

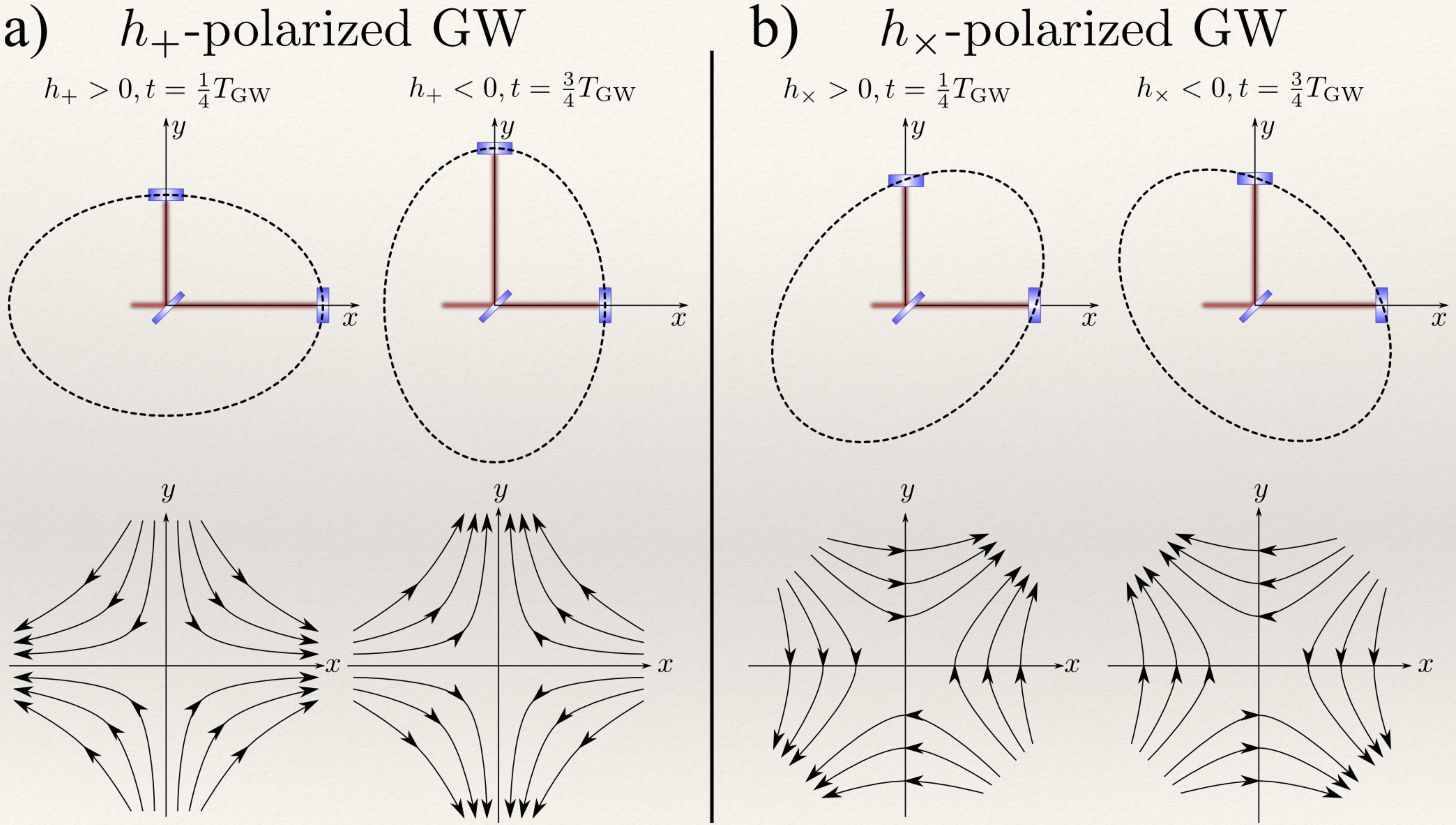
- Gravitational wave (GW) data analysis
- LISA: space based GW observatory
- PTA: detecting GWs with Pulsar Timing Array.

Gravitational wave landscape



[credits: Alberto Sesana]

Basic principle of GW detection



a) h_+-polarized GW

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

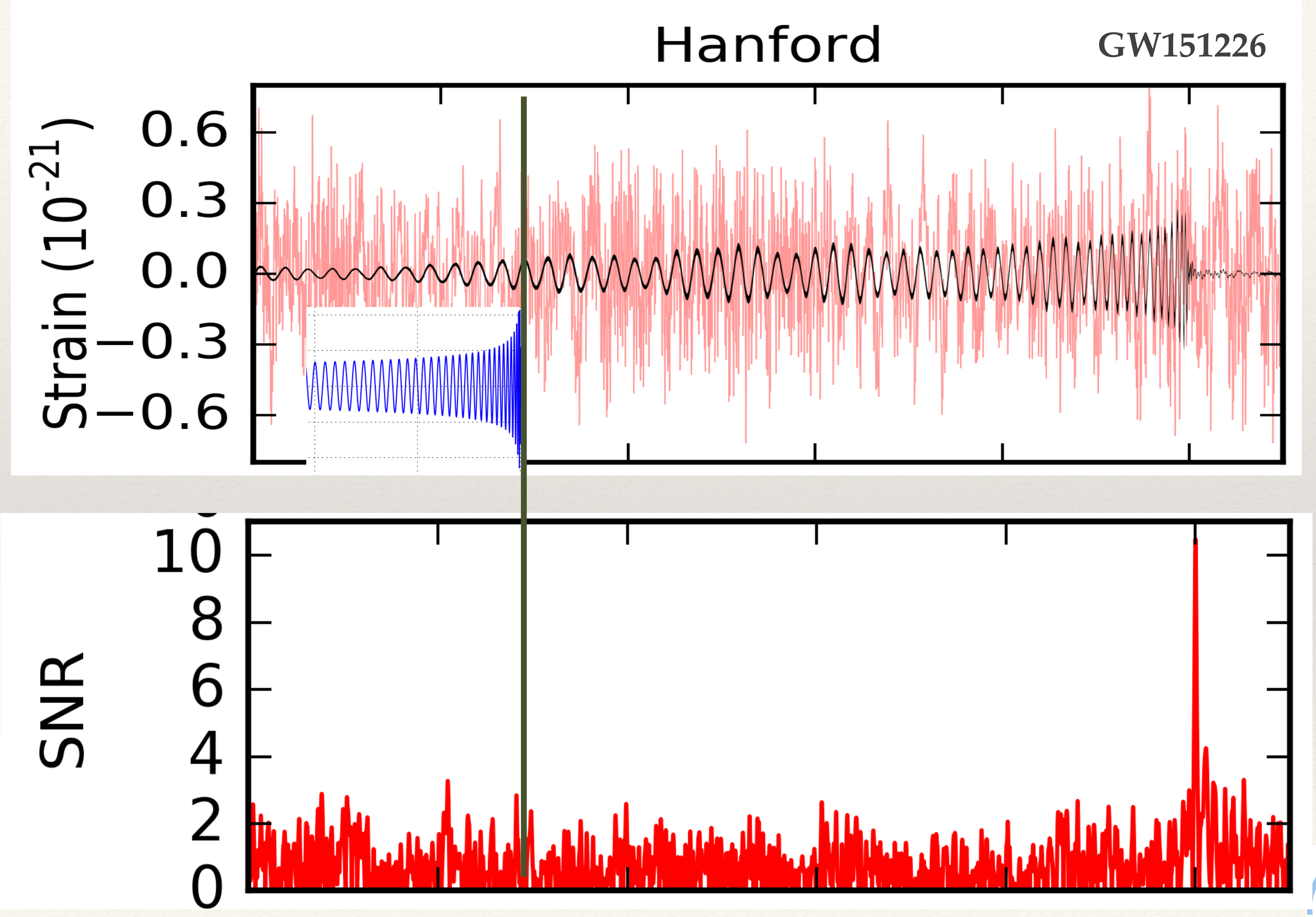
$h_+ < 0, t = \frac{3}{4}T_{\mathrm{GW}}$

b) $h_\times$-polarized GW

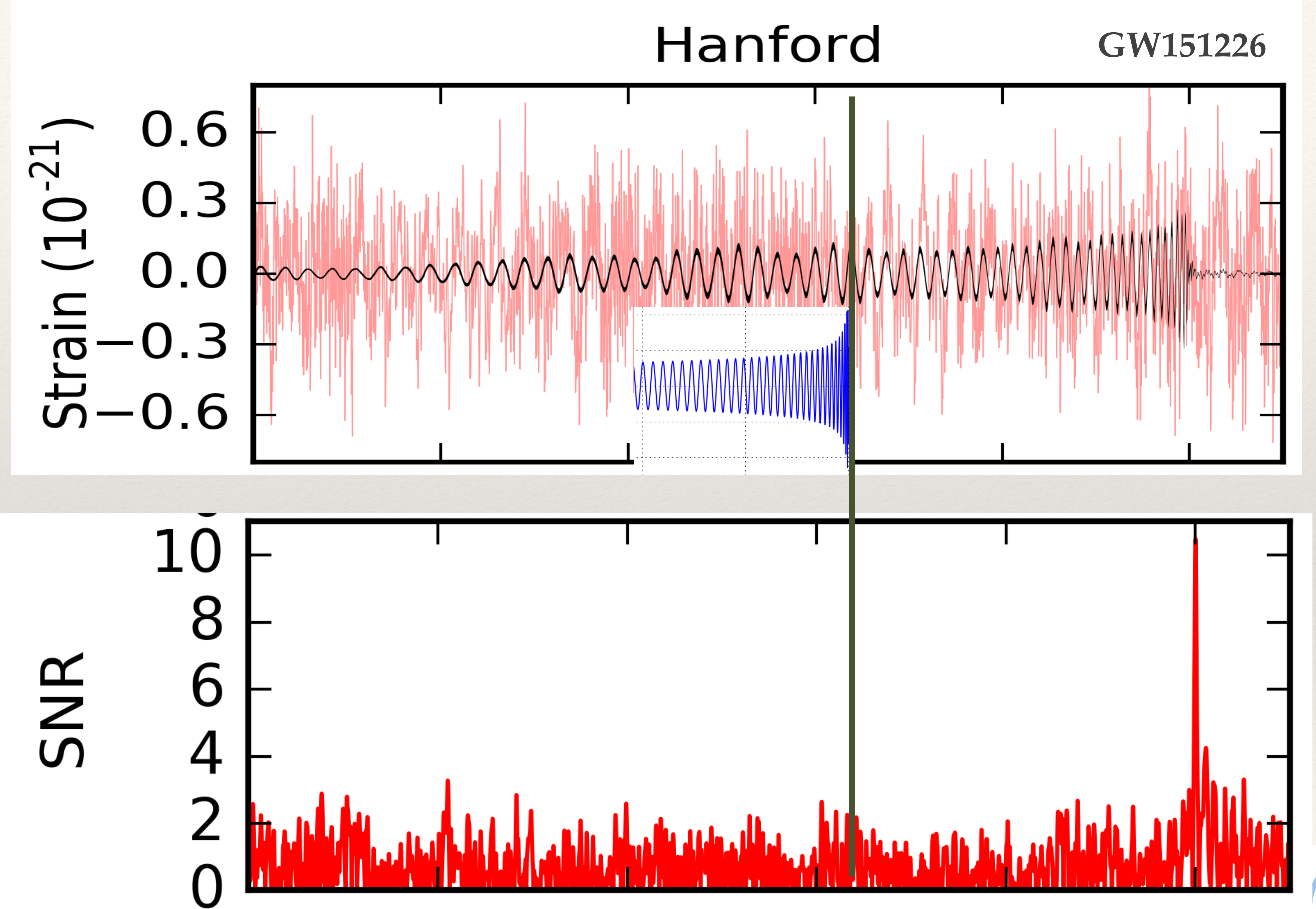
$h_\times > 0, t = \frac{1}{4}T_{\mathrm{GW}}$

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

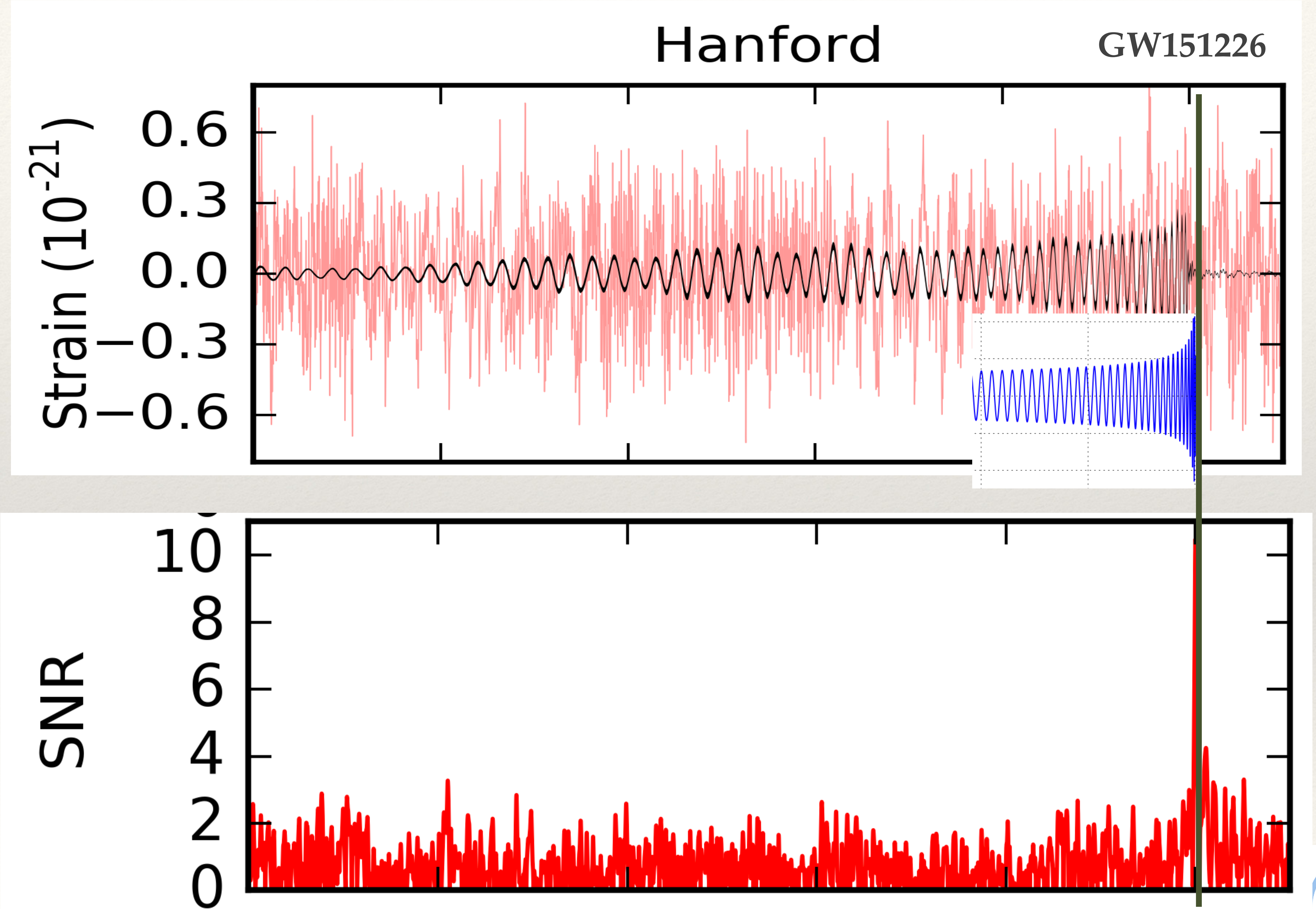
Matched filtering



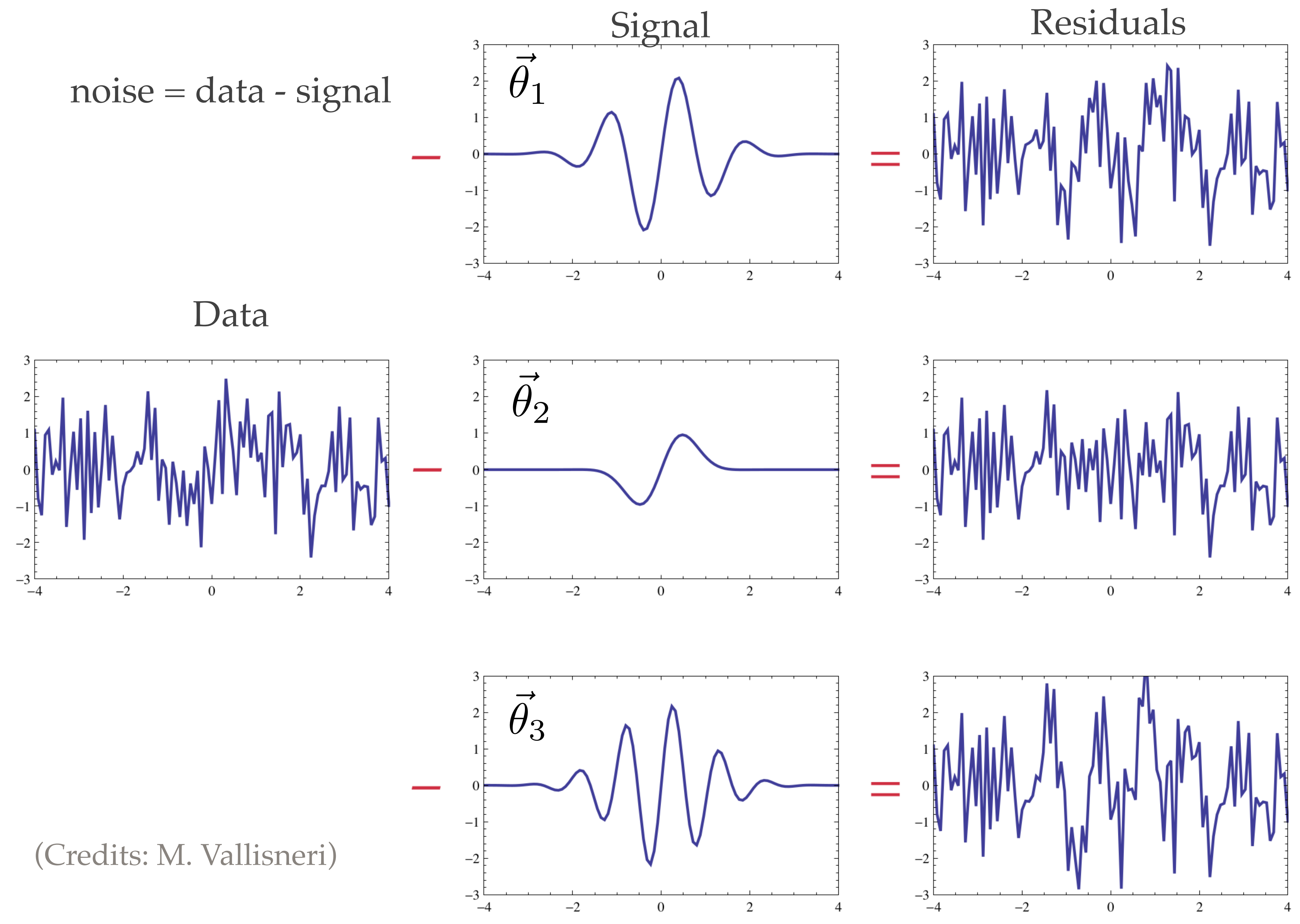
Matched filtering



Matched filtering



Parameter estimation

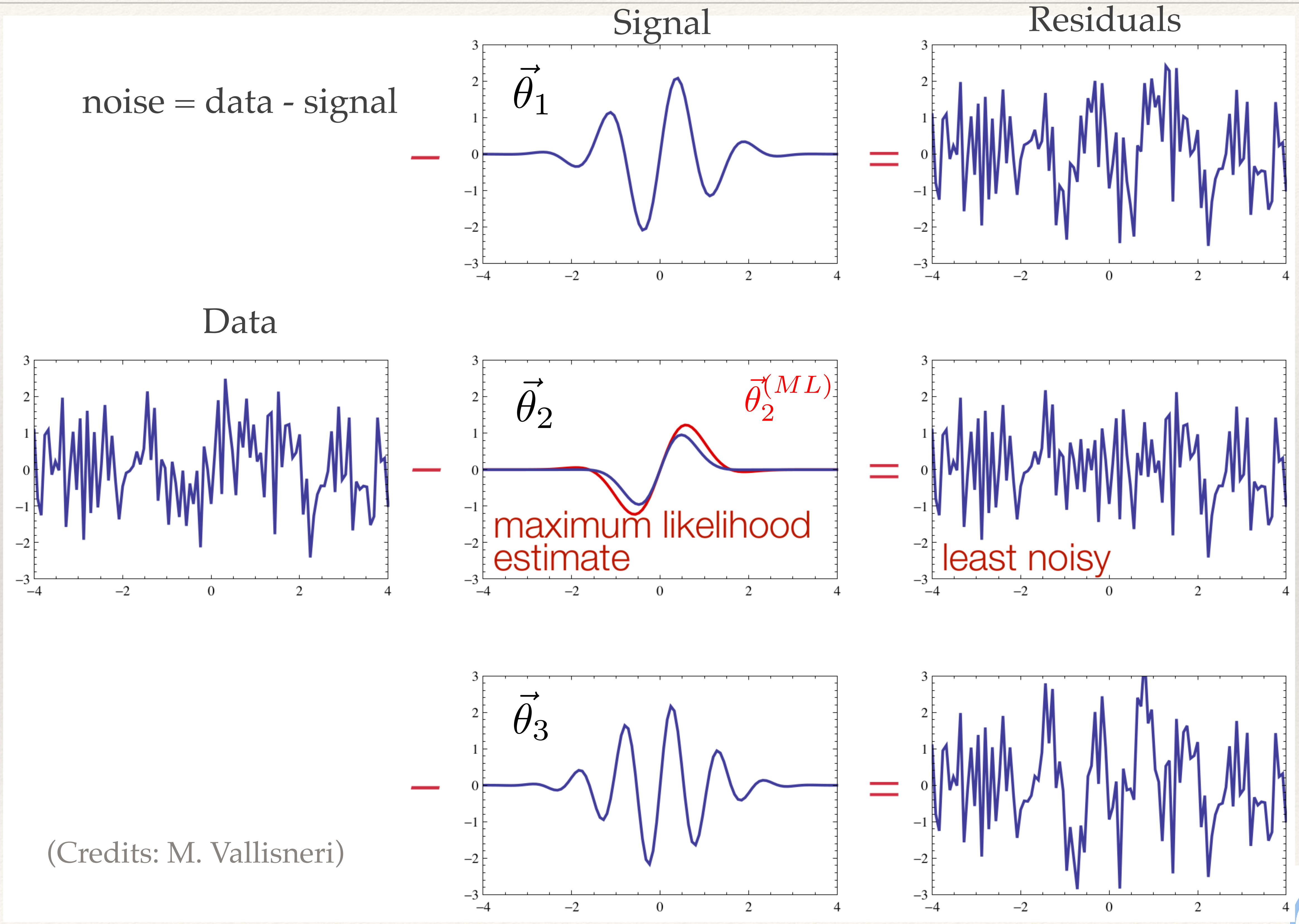


noise = data - signal

(Credits: M. Vallisneri)

Согласованный фильтр и оценка параметров

noise = data - signal

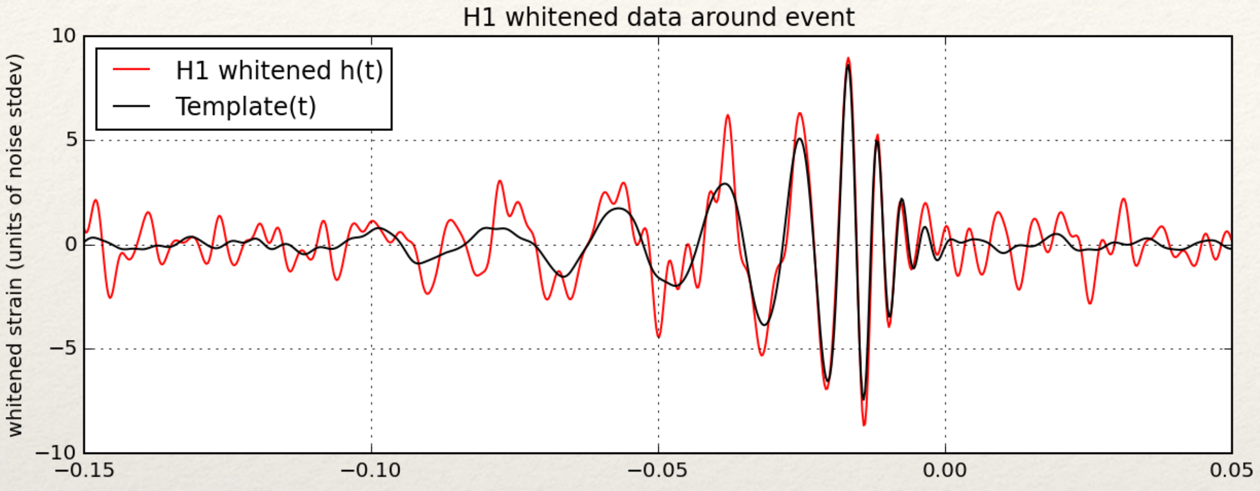


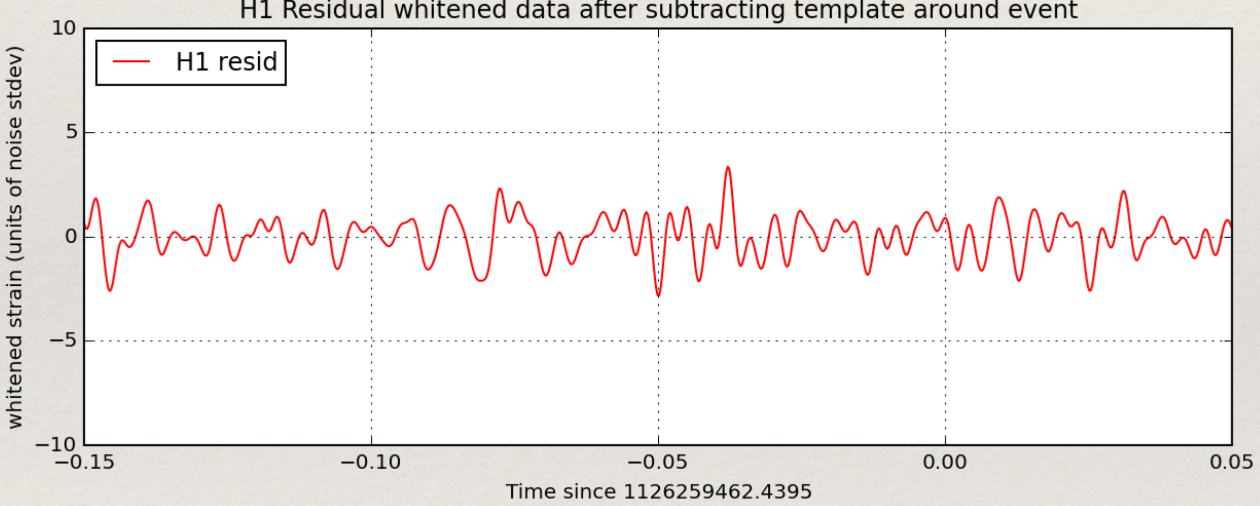
(Credits: M. Vallisneri)

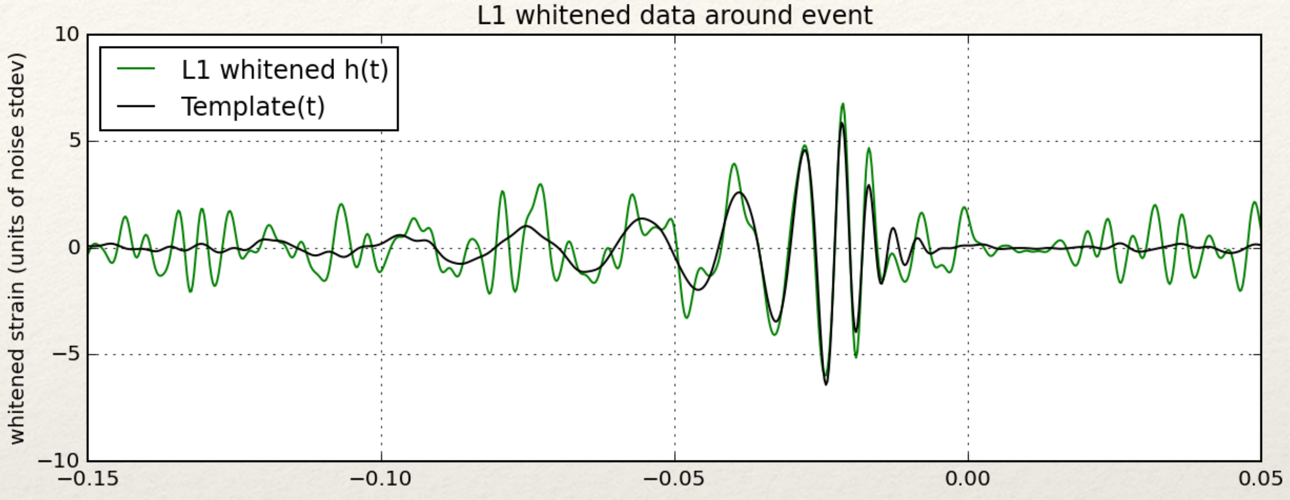
Matched filtering: GW150914

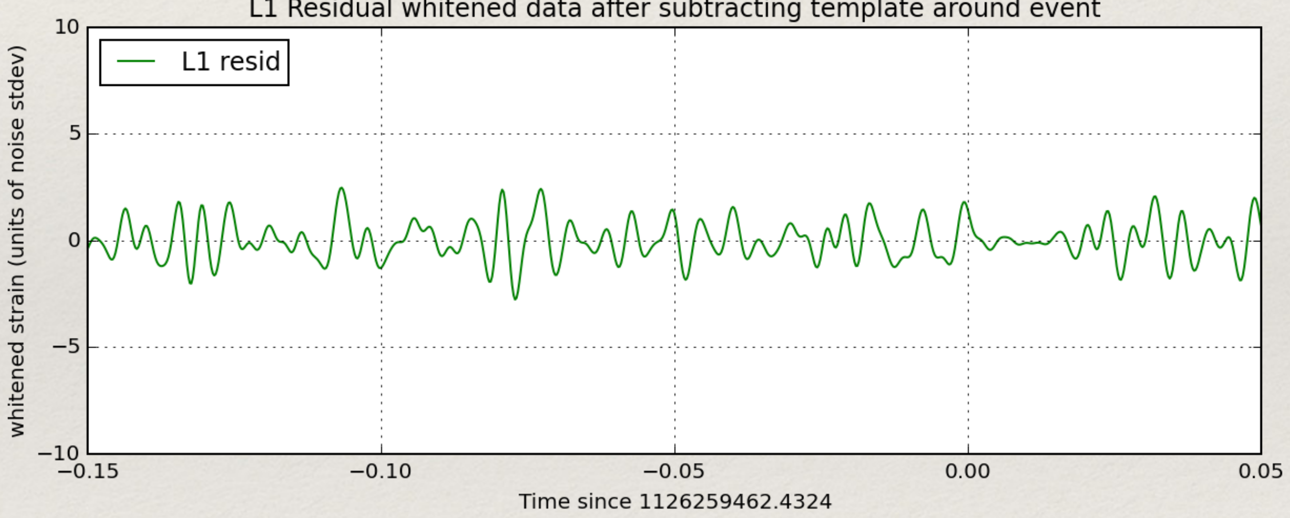
H1

L1



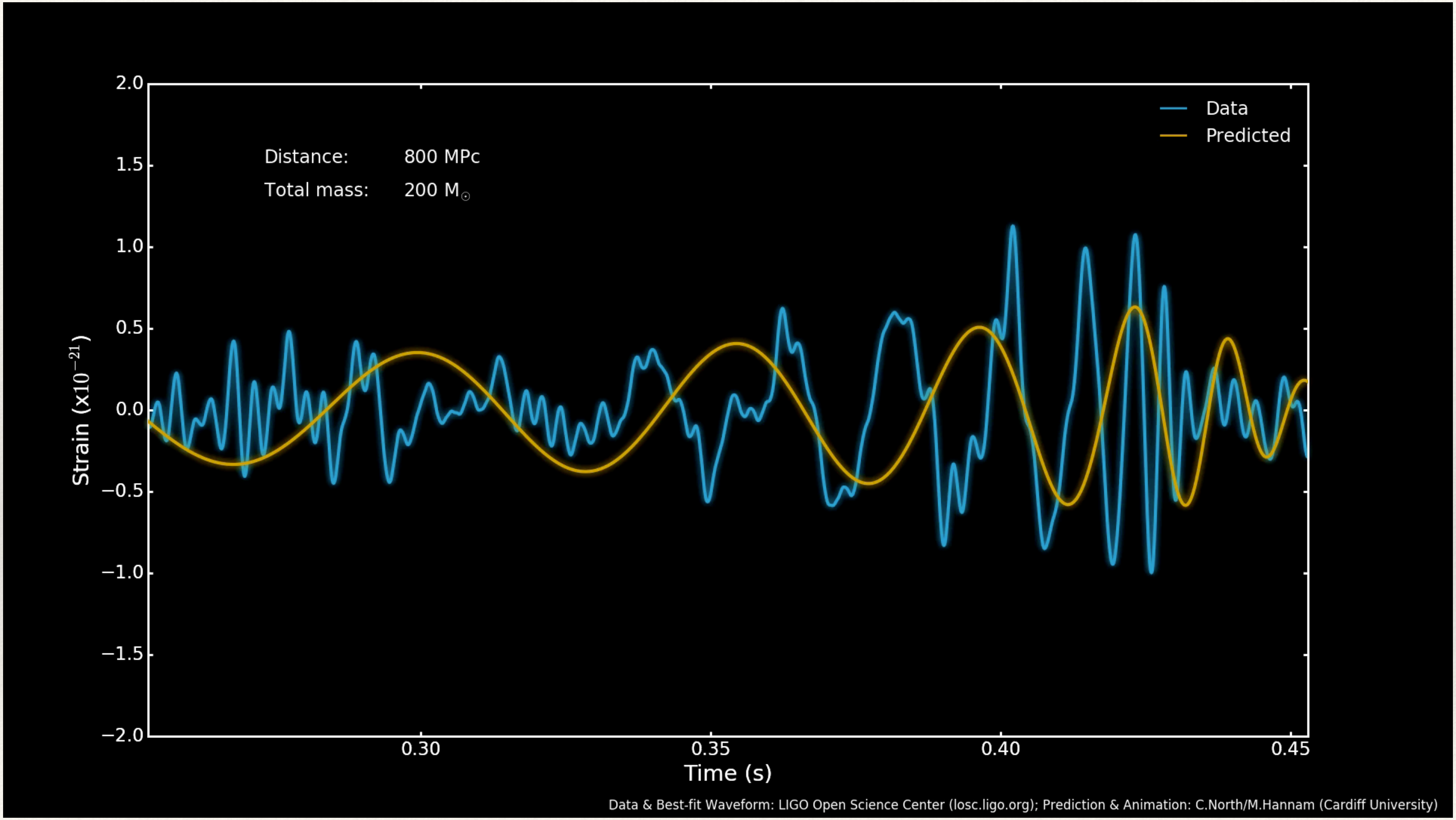






[LOSC: https://losc.ligo.org/tutorials/]

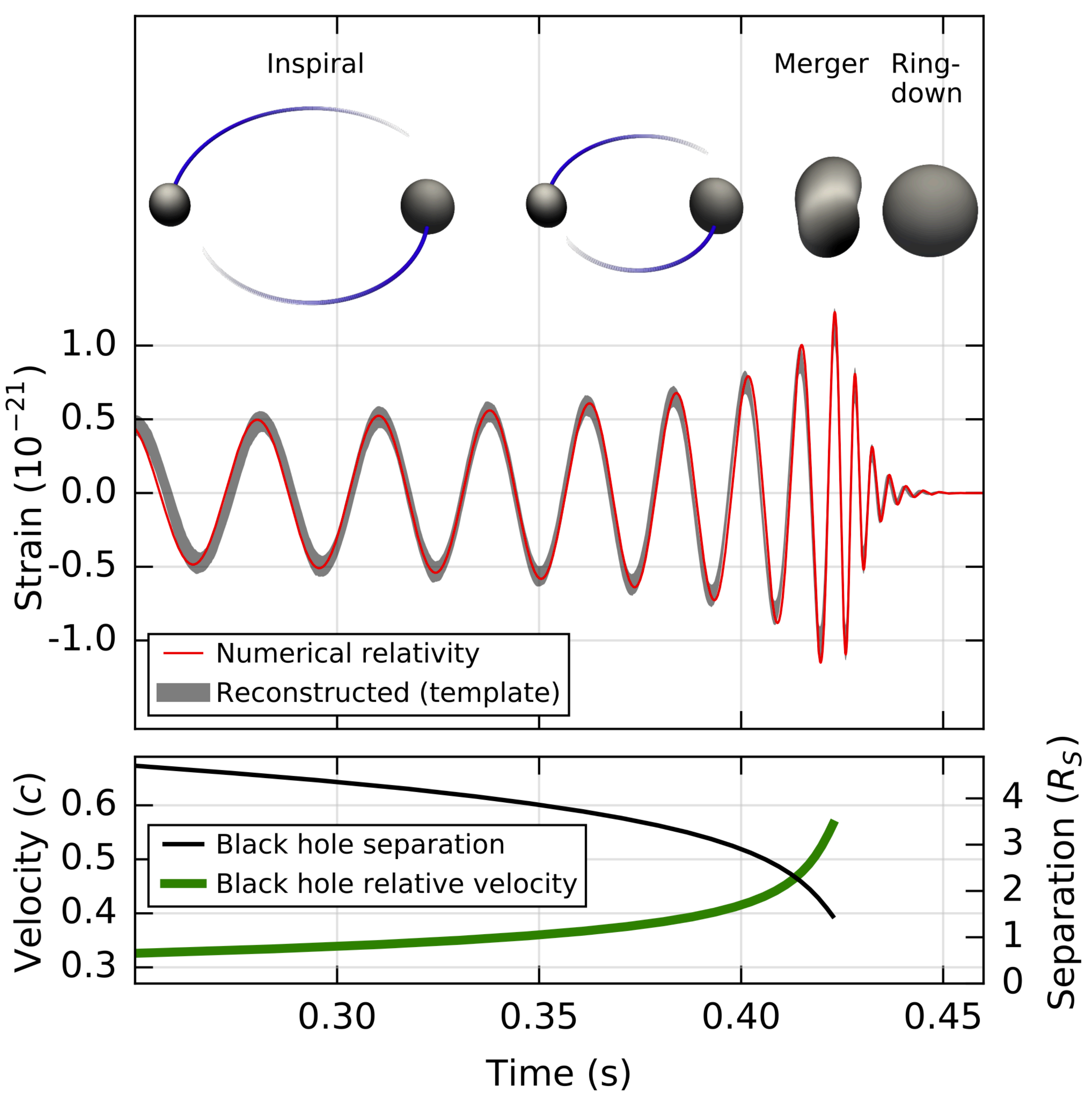
Parameter estimation



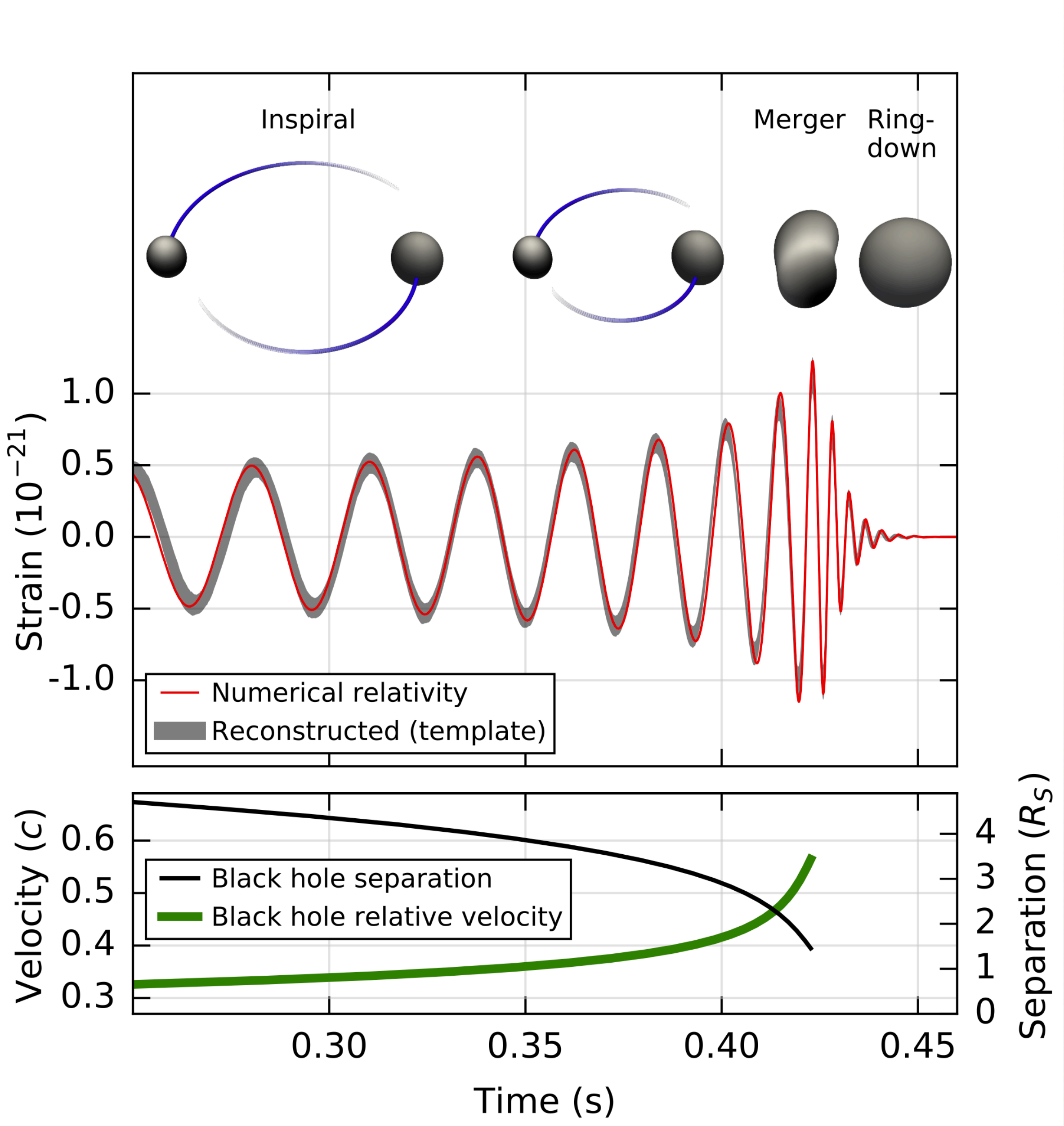
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

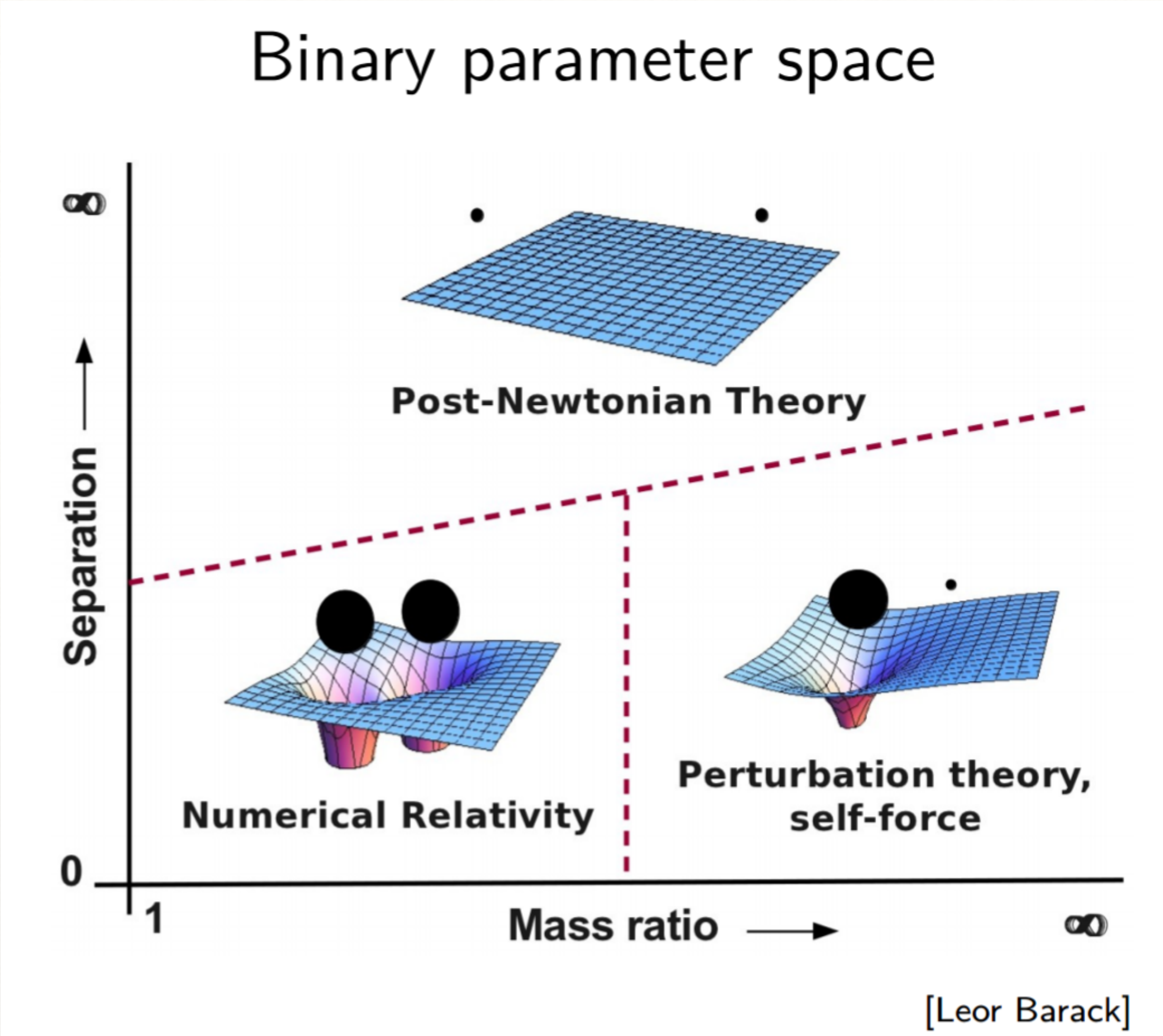
[credits: LIGO/VIRGO scientific collaboration]

GW signal from merging BHs



Modelling GW signal from coalescing BH binaries





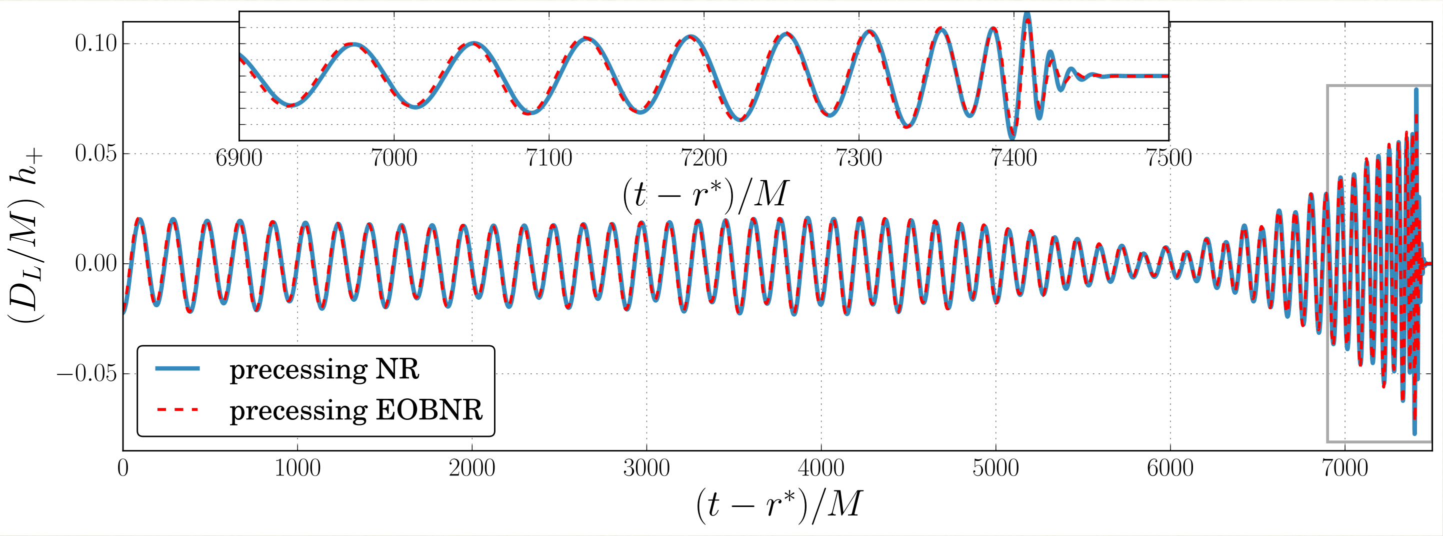
[Leor Barack]

- 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)

Waveform models

- MBH binaries: spinning, precessing , important to include merger and ringdown

$$m_1/m_2 = 5, \quad |\mathbf{S_1}/m_1^2| = 0.5, \quad \theta_1 = 90^\circ, \quad \mathbf{S_2} = 0$$

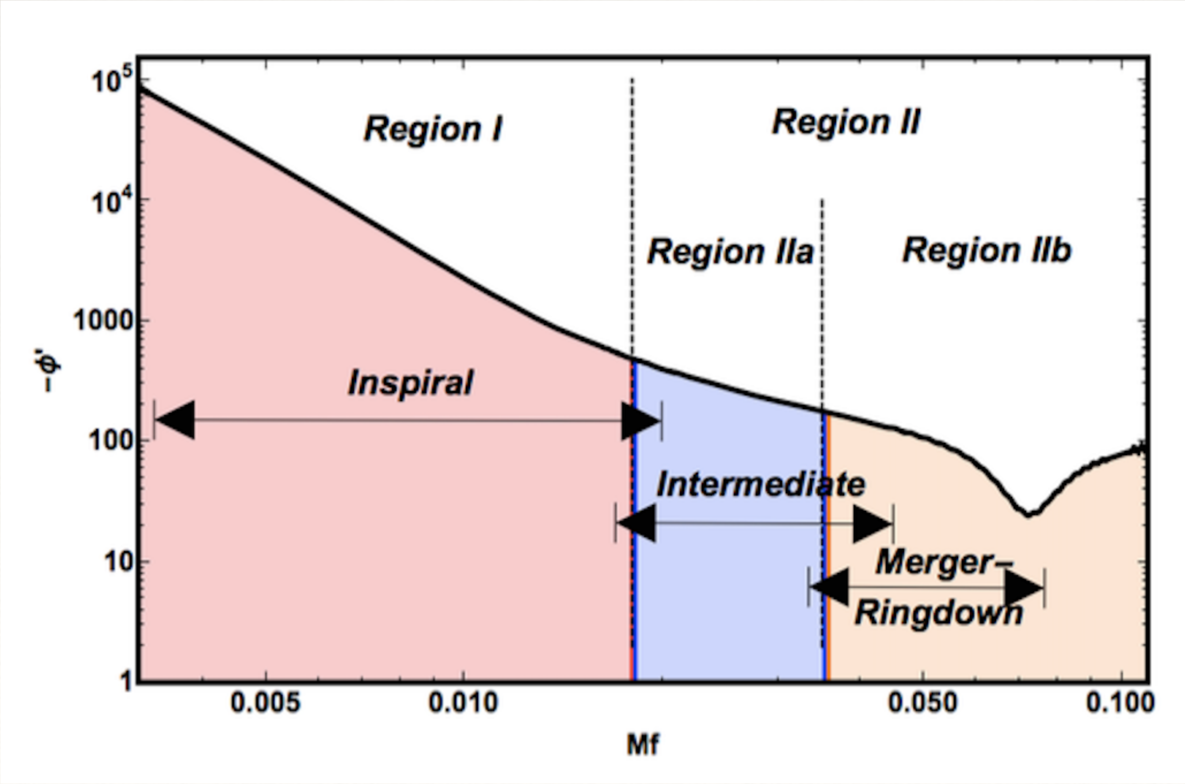


precessing SEOBNR model

- Constructed in time domain
- Tuned to match NR data
- Full 3-d spin dynamics
- Slow to generate

[Babak, Taracchini, Buonanno 2016]

Phenomenological model



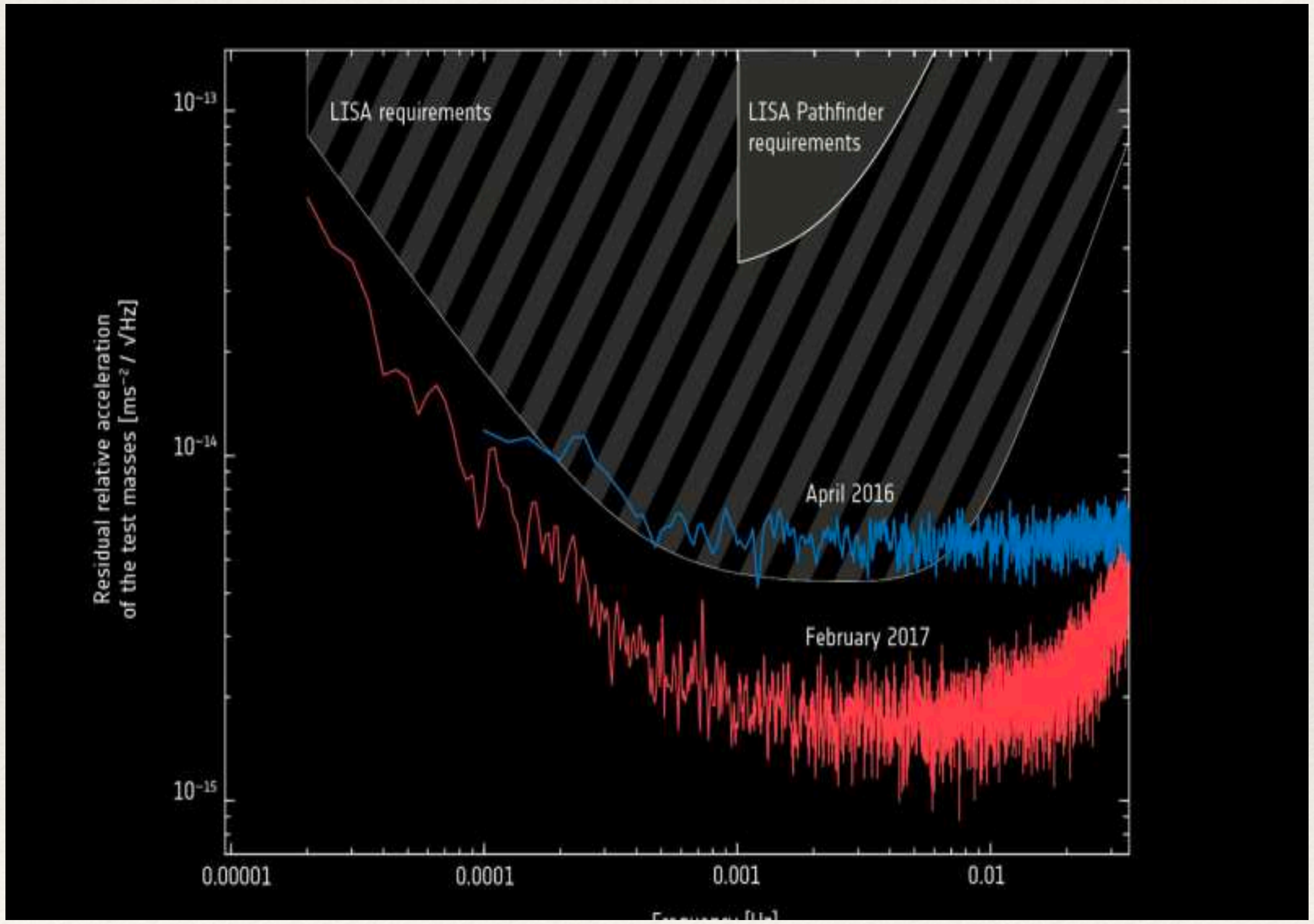
- Waveform constructed in the frequency domain
- Uses Post-Newtonian results for the early evolution (inspiral) of a binary
- For merger-ringdown part: there is an analytical expression with free parameters which are calibrated to fit the NR data
- Precession is added by rotation taken from the Post-Newtonian evolution
- Very fast to generate

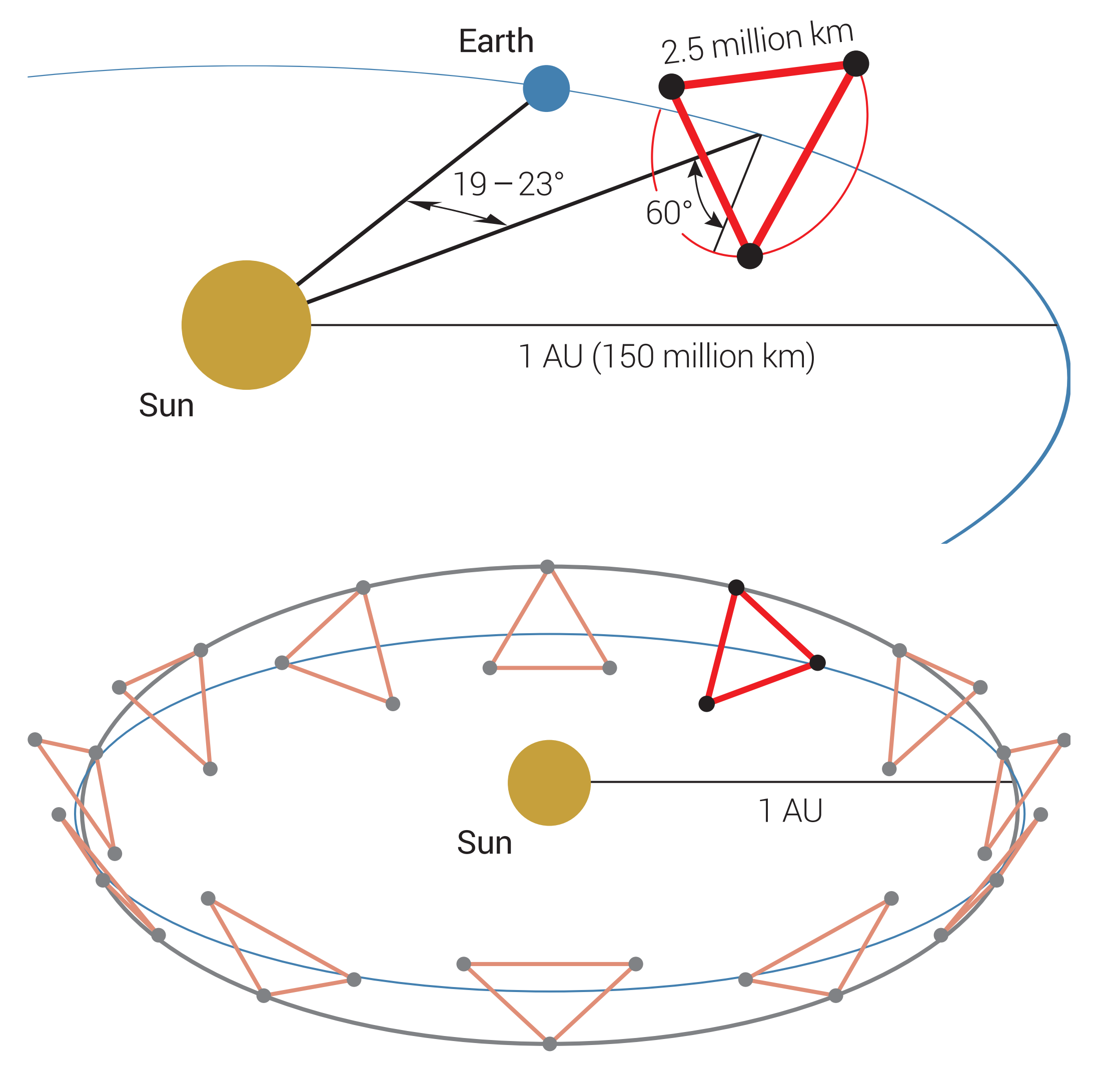
[Khan+ 2015]

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.



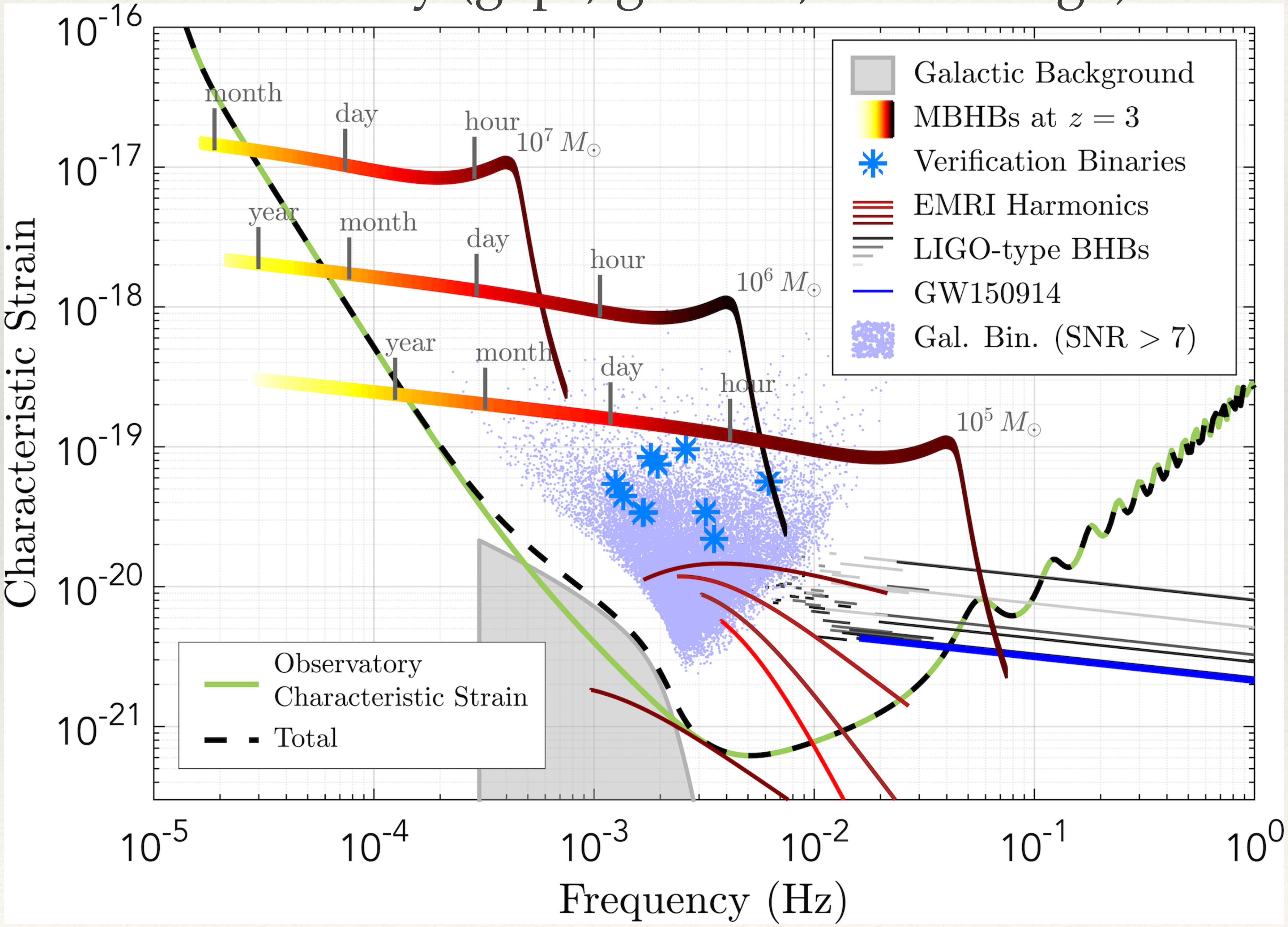


LISA (cartoon)

[credits: credits AEI/Milde marketing]

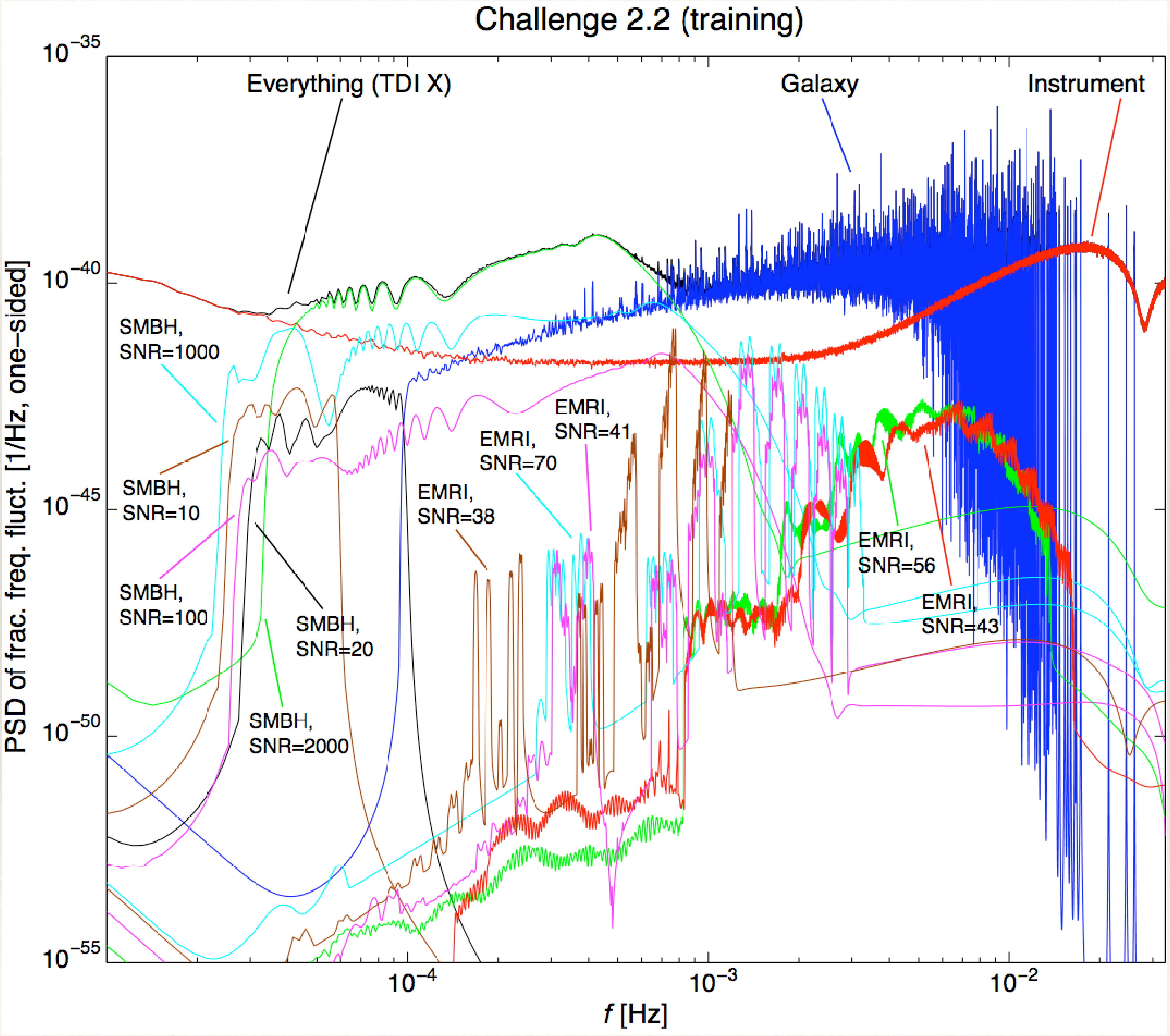
What is special about LISA data

- GW signals are long lived (months-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”)



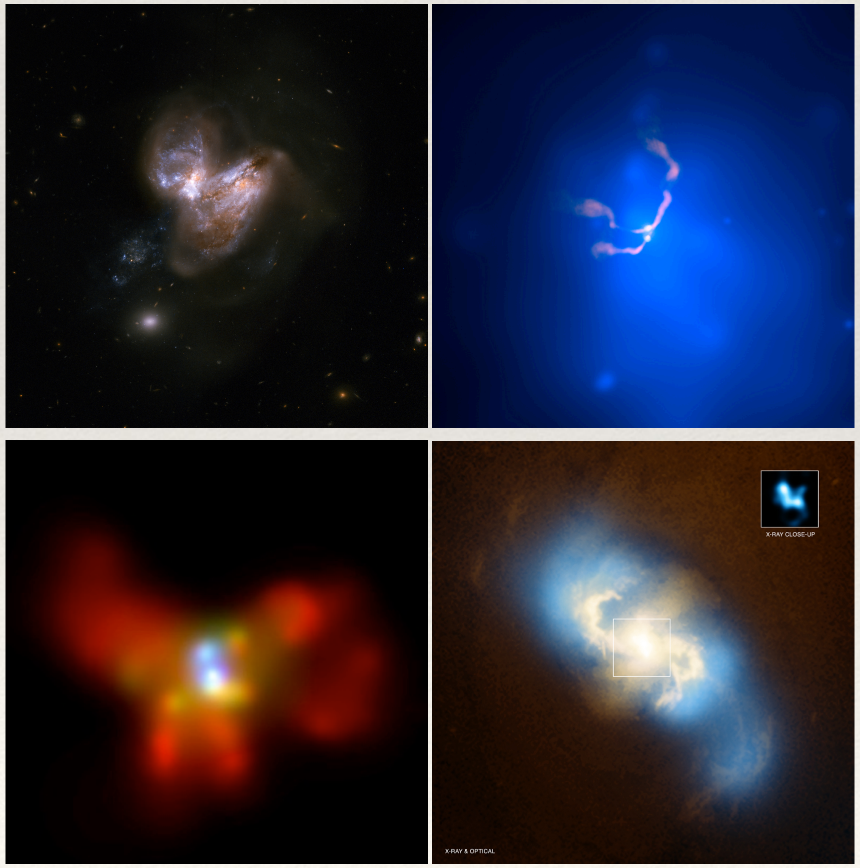
Mock LISA Data Challenge

Simulated LISA data used in MLDC: power spectral density of X



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

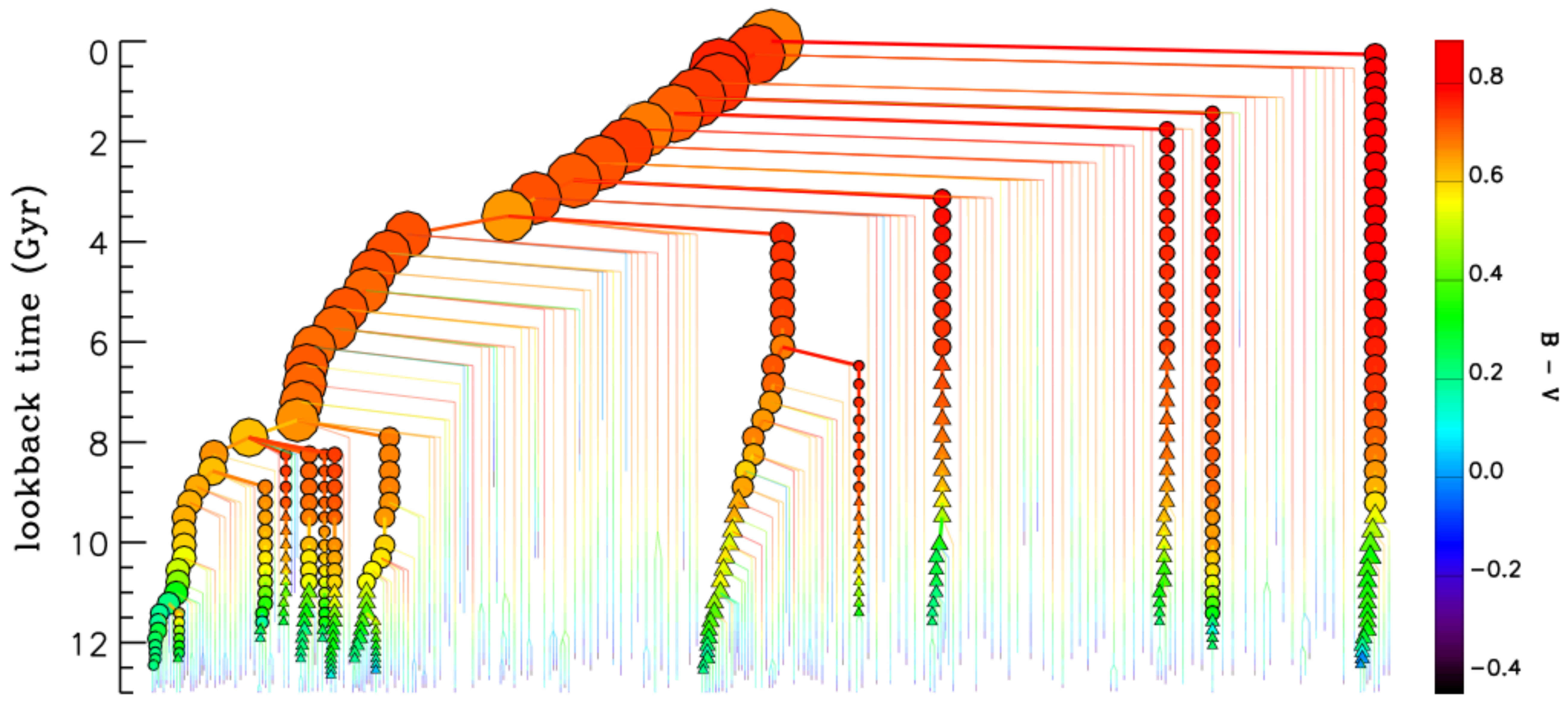


Credits: Hassinger+, VLA, Chandra , NASA

Image: Hubble telescope

MBH formation and evolution

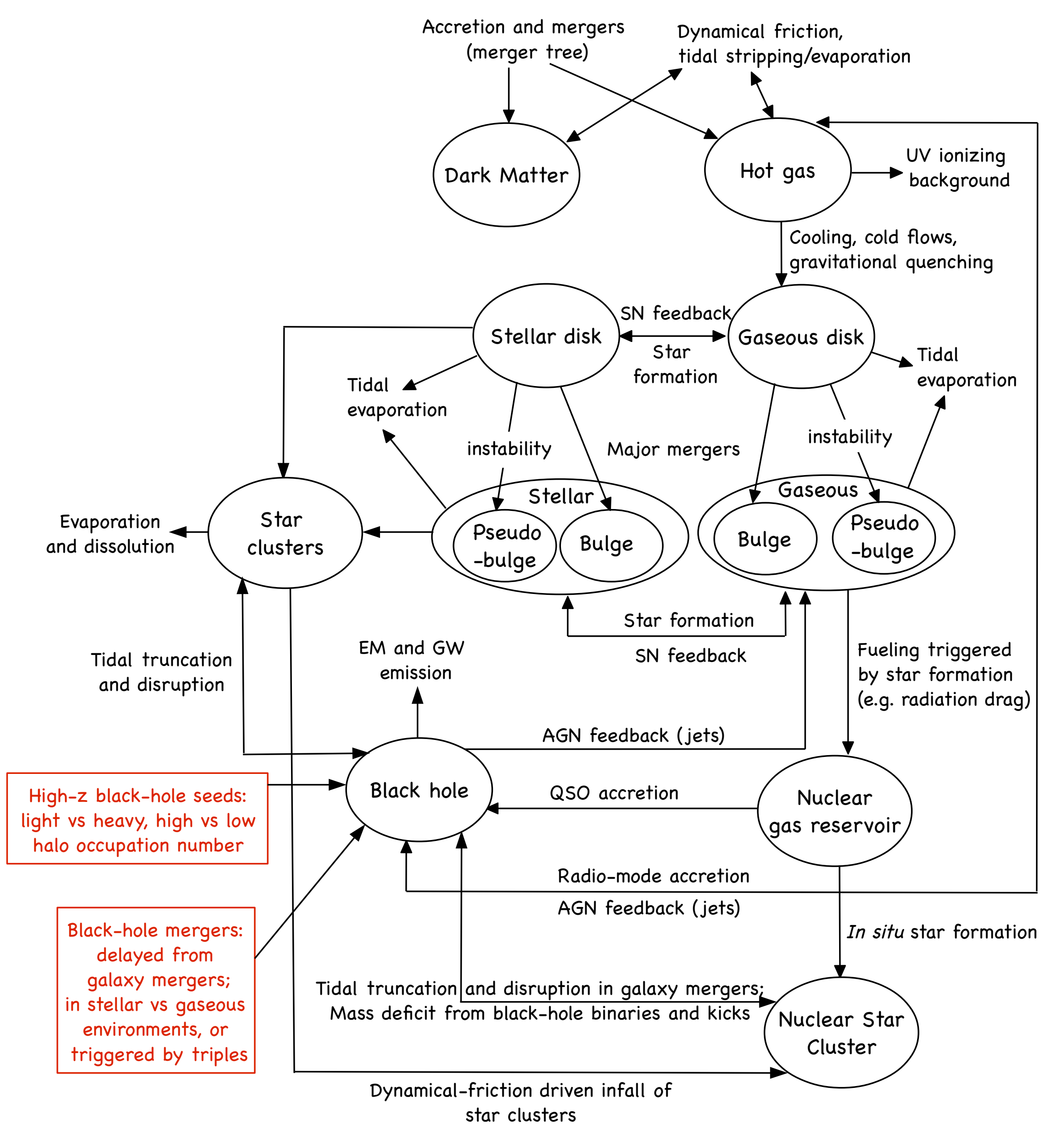
MBHs are formed from initial seeds (large or small) and accumulate the mass by accreting gas and major mergers



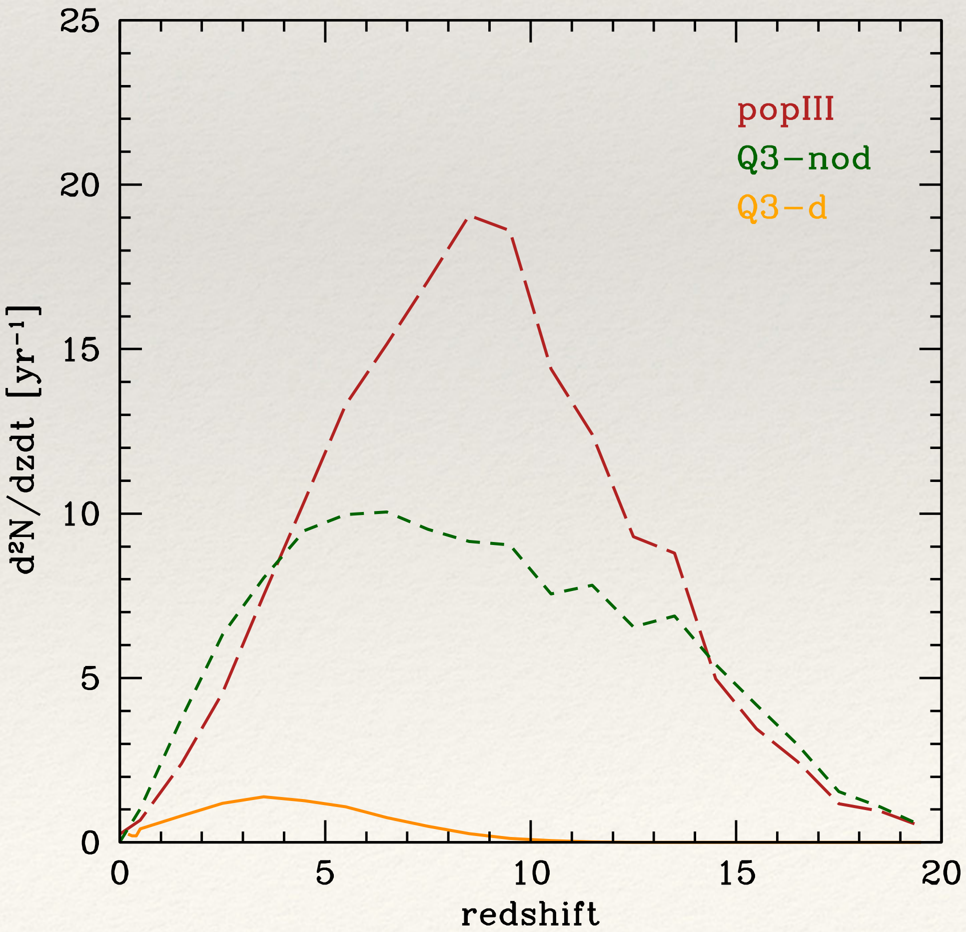
[credits: Gabriella De Lucia]

Catalogue of binary MBHs

Klein et al. (2016)

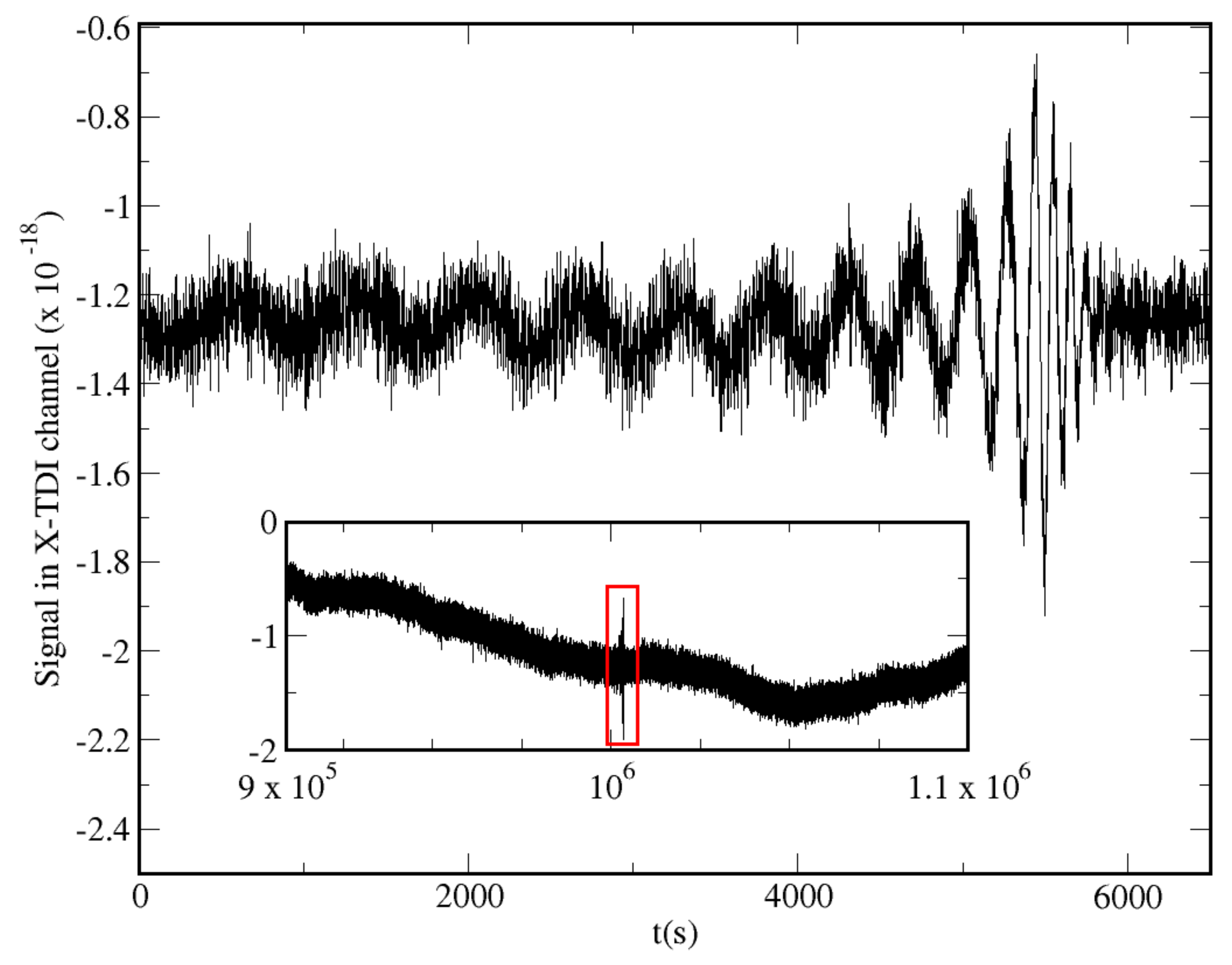


- Models for MBH evolution are described in [Barausse+ 2010, Sesana+2014, Antonini+ 2015].
- Key ingredients: “initial seeds” -> light/heavy
- Delays: delay between time of galaxy merger and MBH merger
  - Catalogues: popIII, Q3-d, Q3-nod

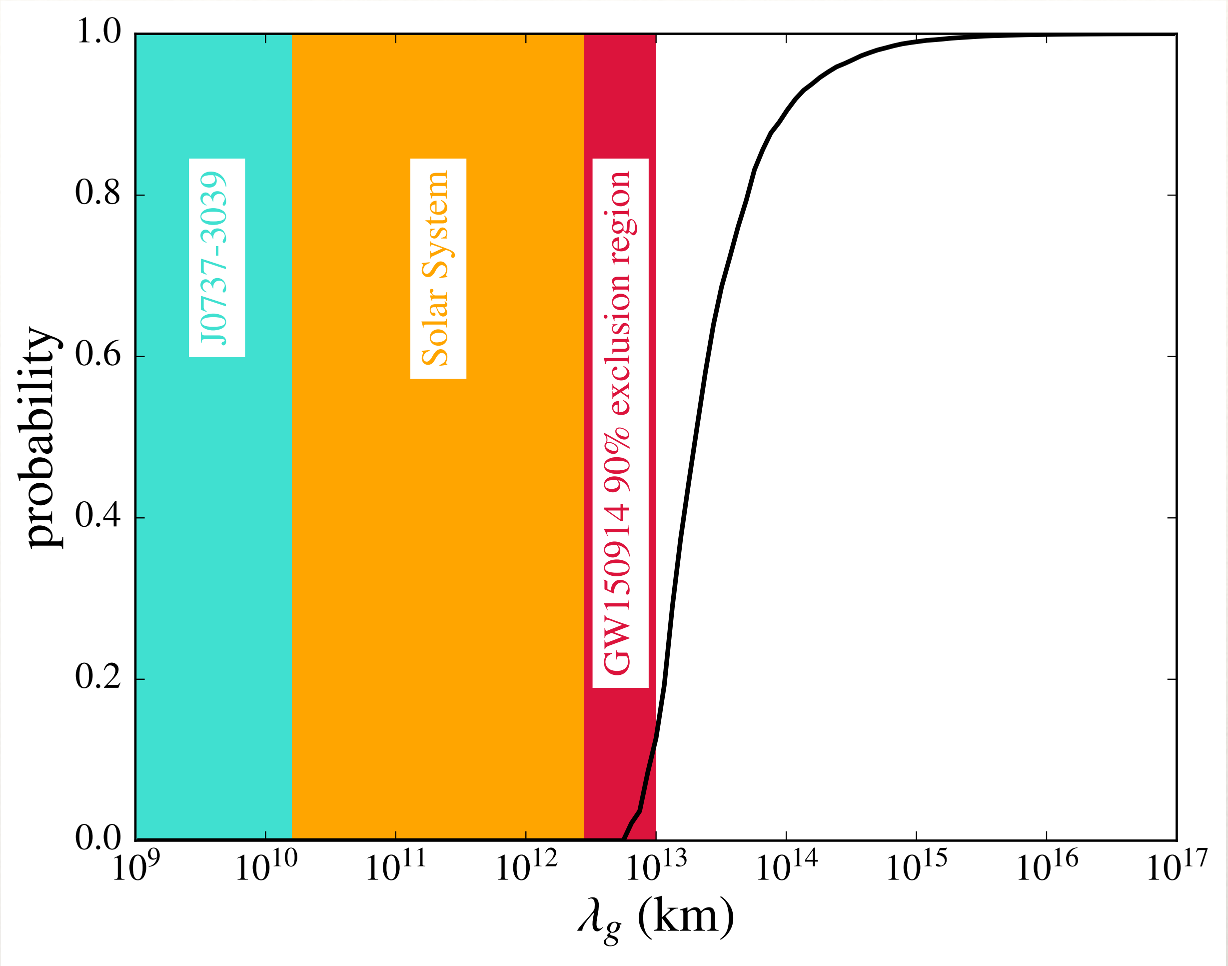


GW signal from merging MBHB

Simulated LISA data with GW signal from merging MBHB at redshift 3

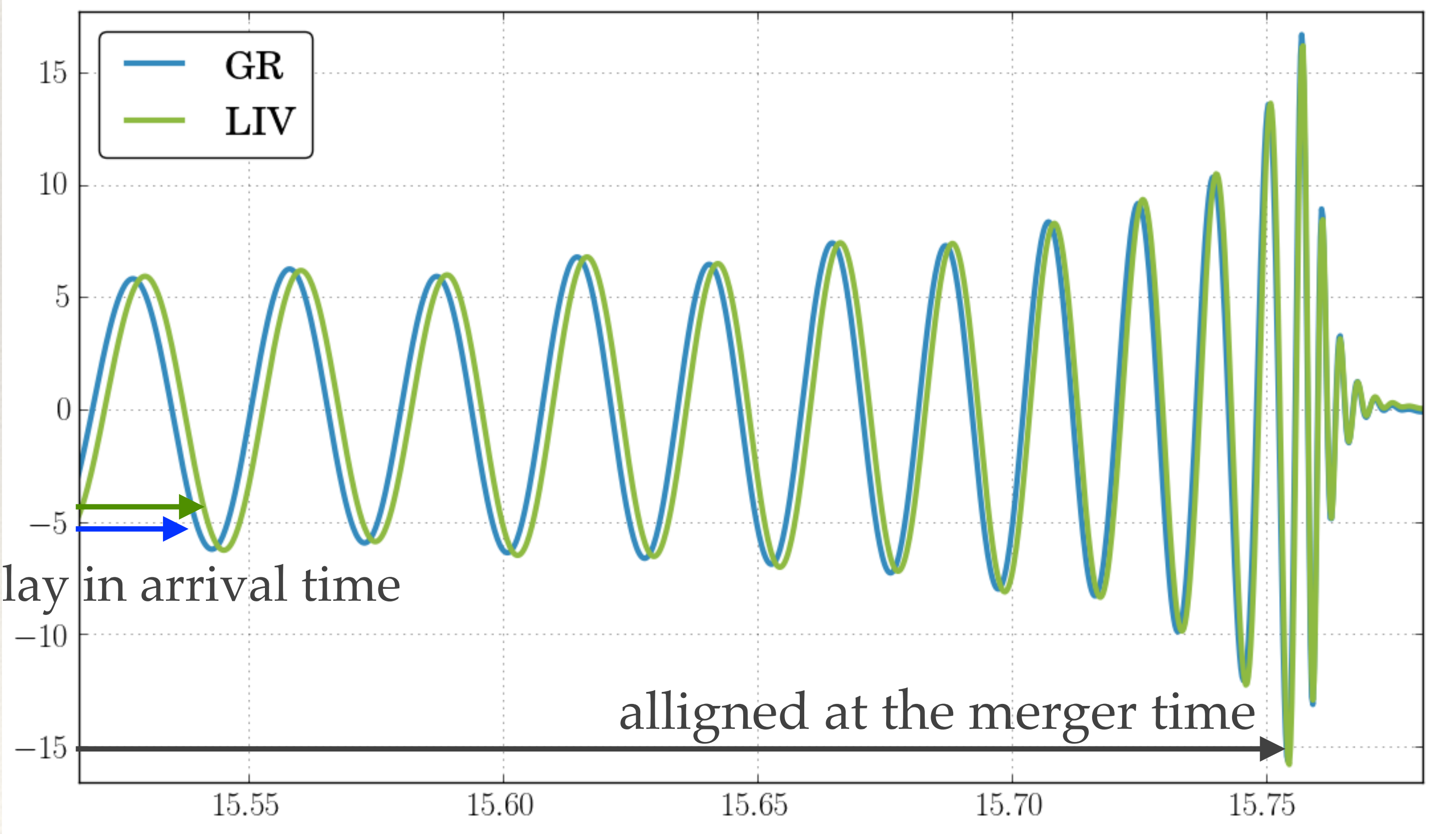


Testing GR



[LVC PRL (2016)]

- If graviton has a mass (m_g) then we should observe dispersion of the GW
- The LIGO/VIRGO data is consistent with GR: can set an upper limit on the mass/ lower limit on Compton wavelength: $\lambda_g = h/(cm_g)$

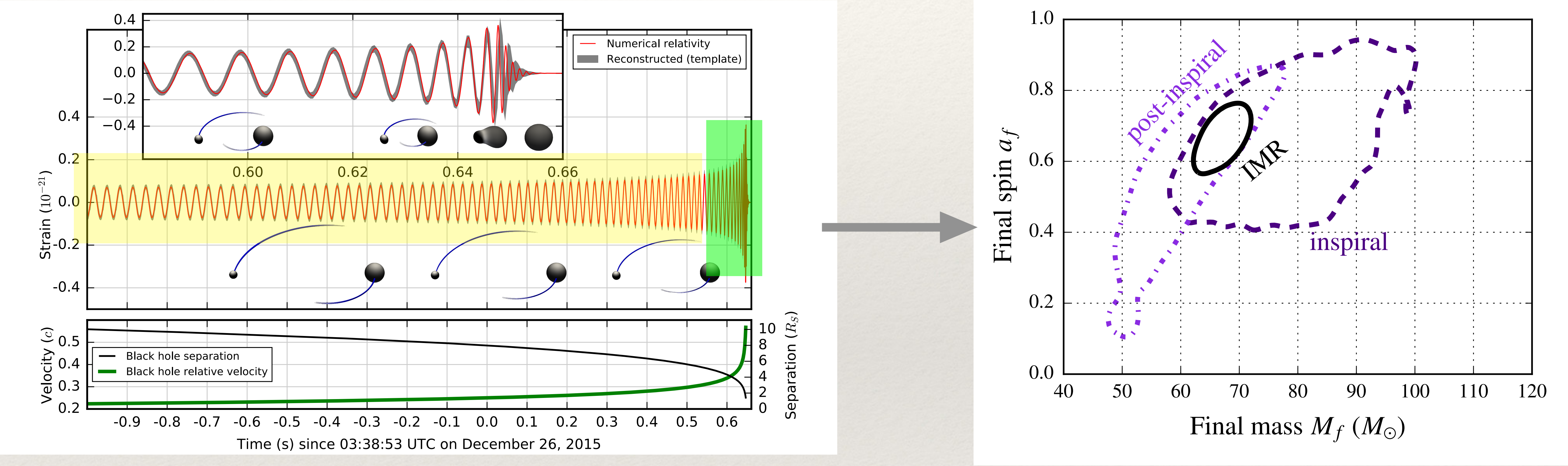


delay in arrival time

alligned at the merger time

Testing GR

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



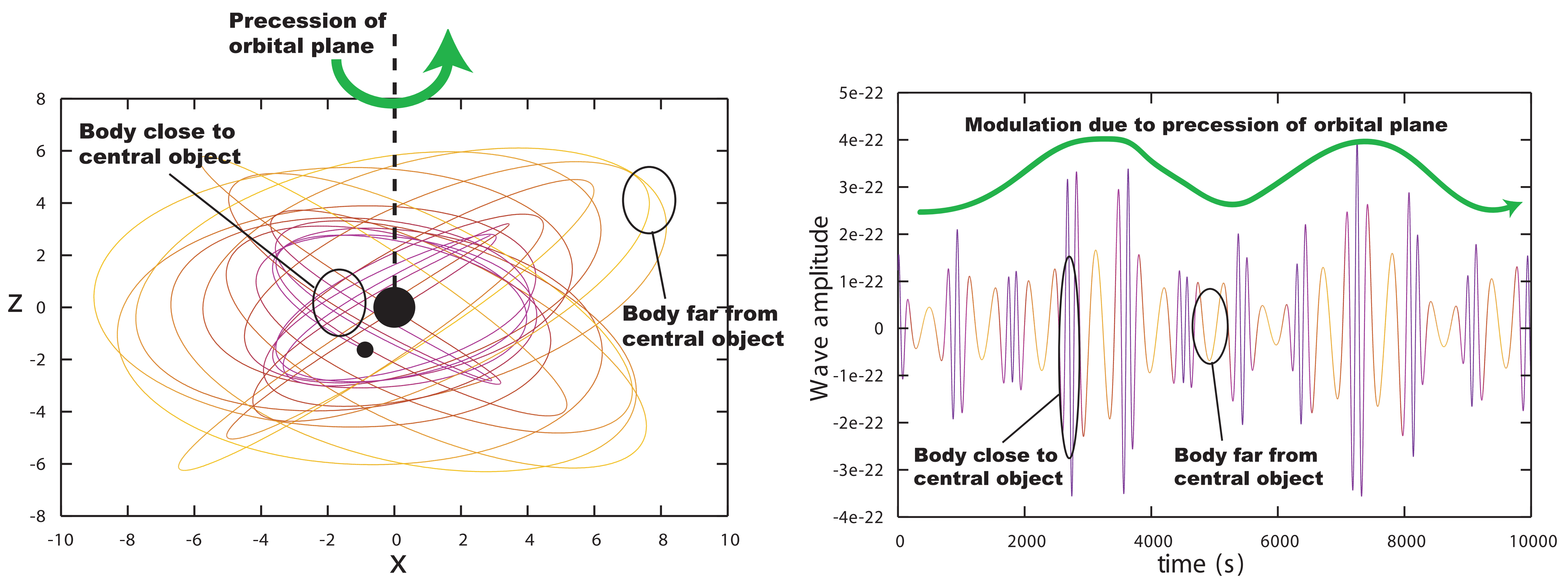
- LISA can detect ringdown directly with significant SNR: can test no-hair theorem
  - Detection of the dominant quasi-normal mode gives M, a of a remnant
  - Detection of subdominant modes - consistency with recovered mass and spin

EMRIs (extreme mass ratio inspirals)

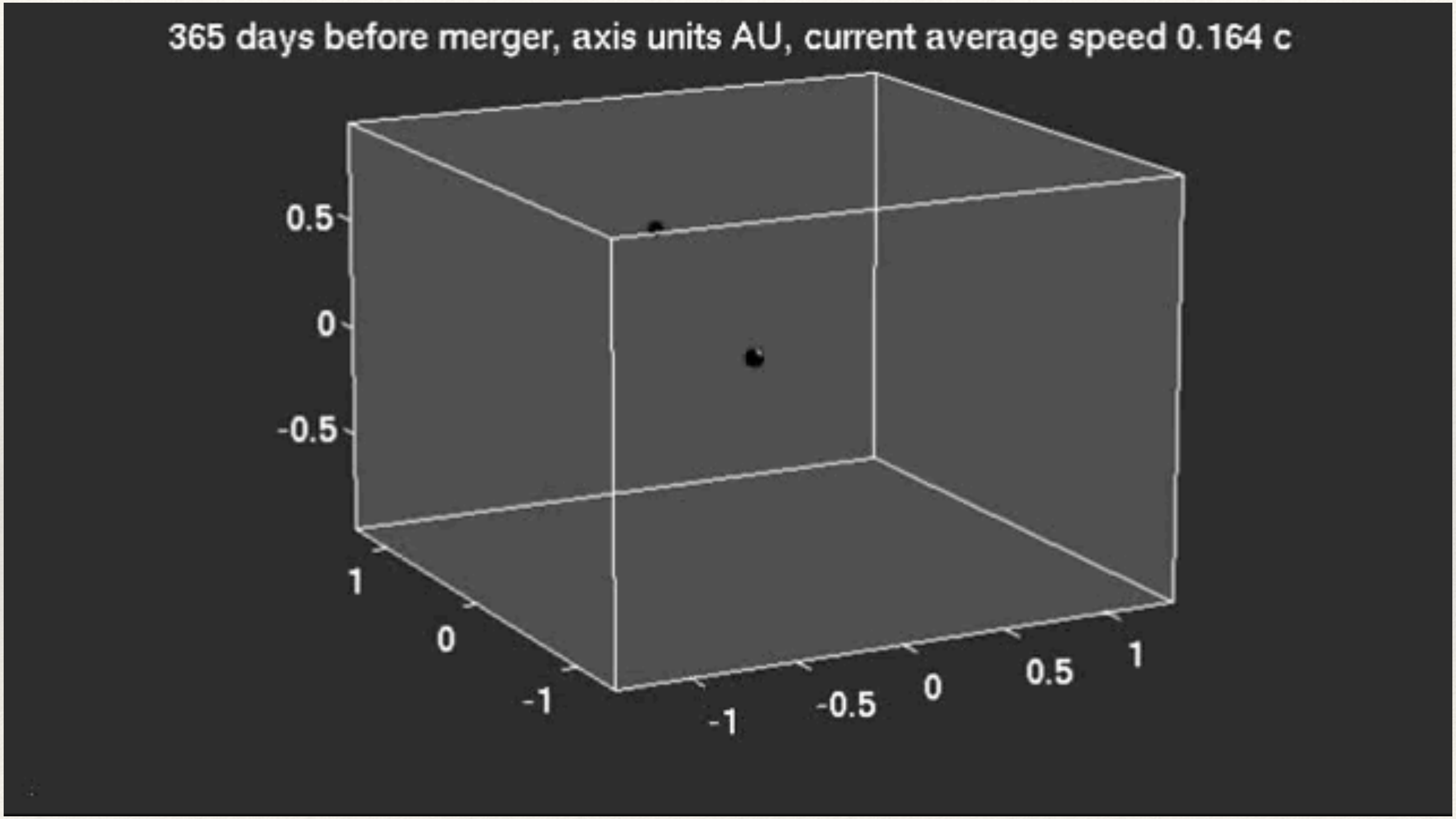
- Massive BHs could be embeded in the stellar cusps (high density stellar environment)
- Massive BH could capture a compact object (NS, stellar mass BH) which starts moving in a very eccentric orbit which shrinks under GW radiation
- EMRI: Binary system with an extreme mass ratio: 10^{-7} - 10^{-5}
- Compact object completes ~ 10^{6} orbits in the close vicinity of a MBH before plunge

EMRIs: orbital evolution and GW signal

The orbital motion can be seen as three-periodic: radial, zimuthal and polar motion with non-commensurate frequencies. Frequencies are slowly change in time as small body spirals toward the massive BH.



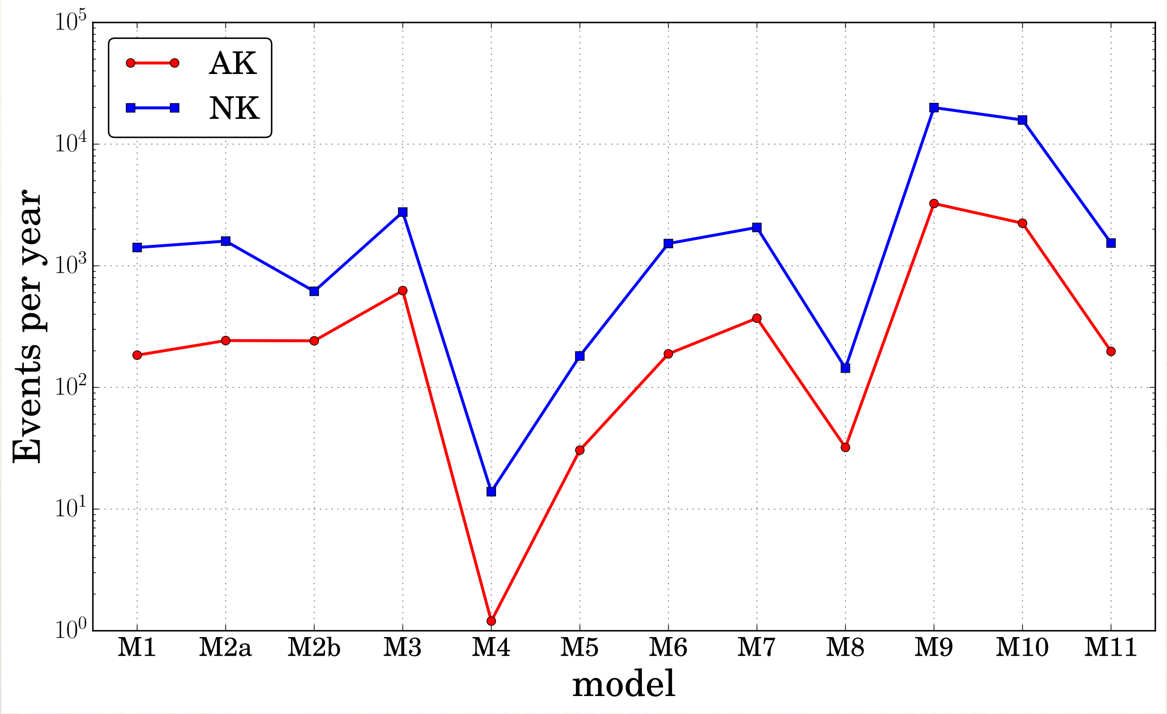
EMRI



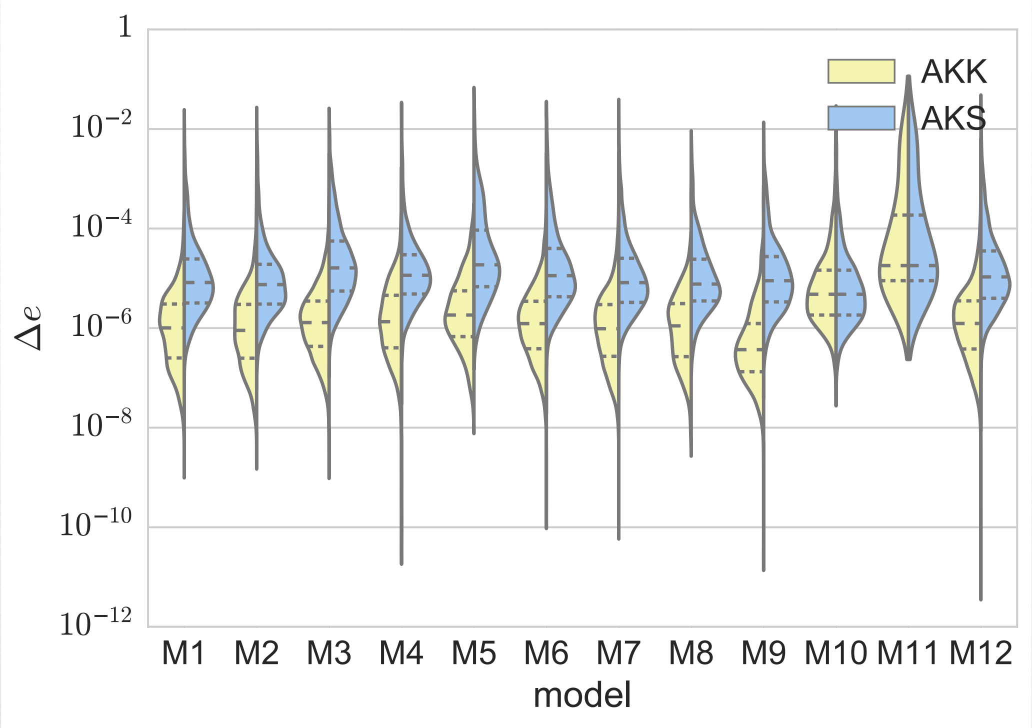
Credits: S Draco, CalTech

EMRIs: event rate and parameter estimation

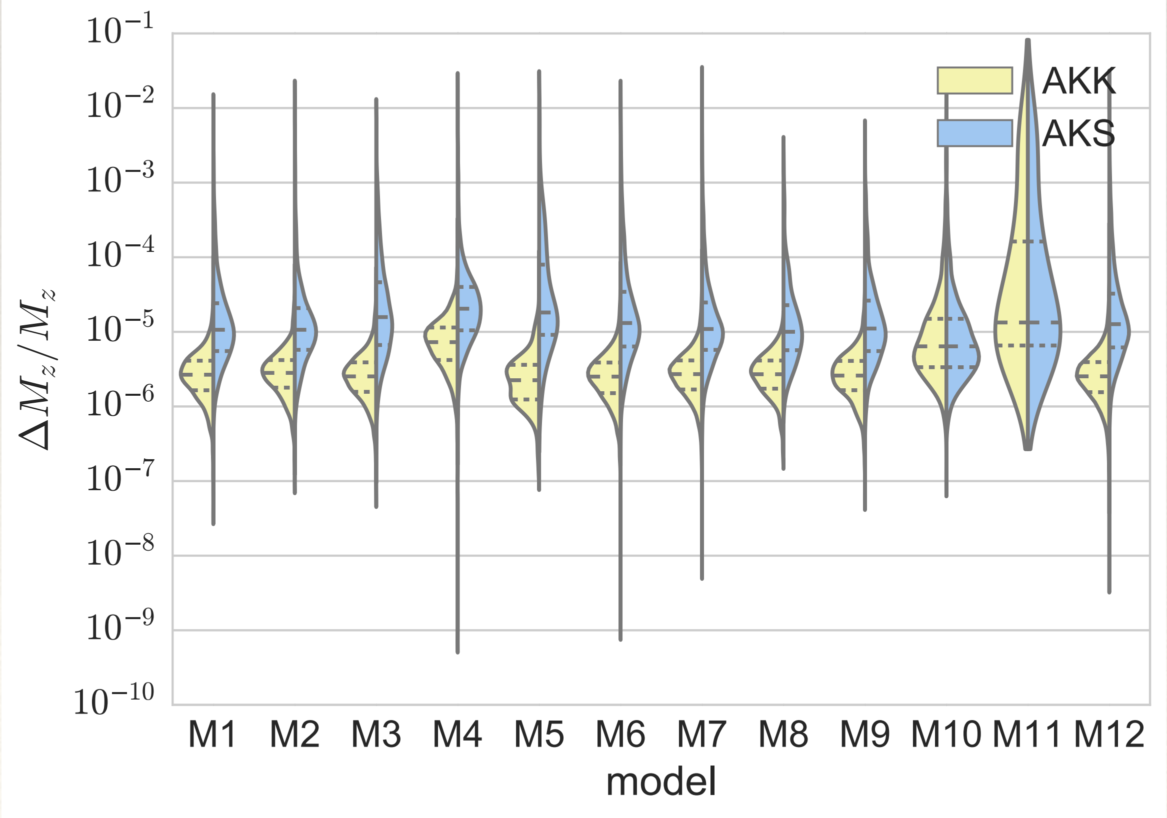
Event rate (detection)



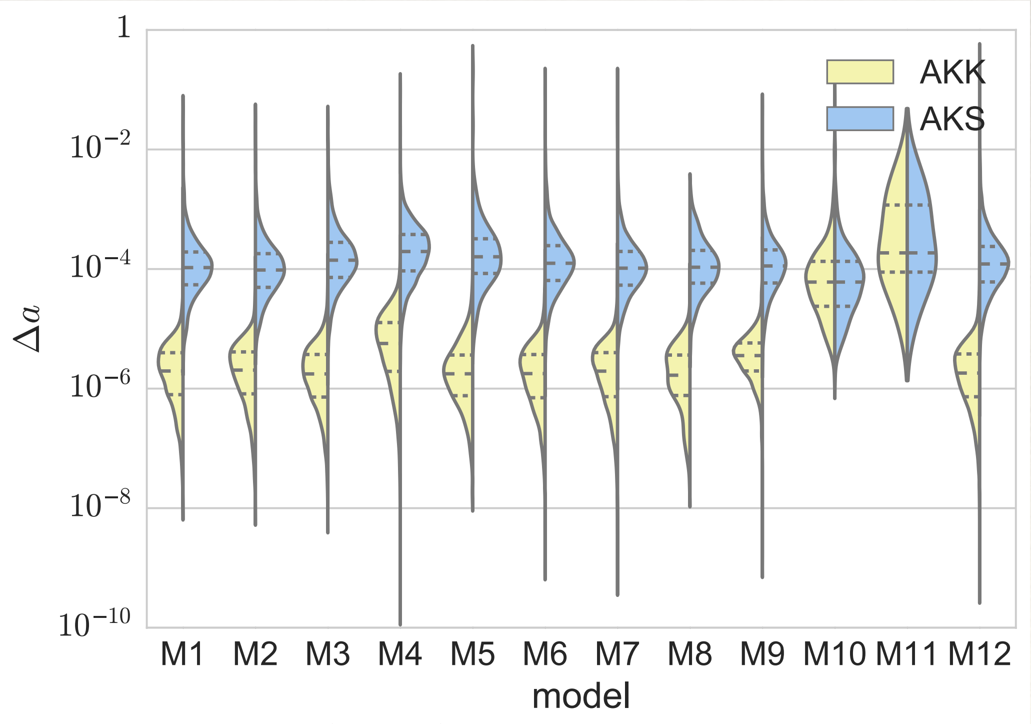
Measurement accuracy: eccentricity



Measurement accuracy: Mass



Measurement accuracy: spin



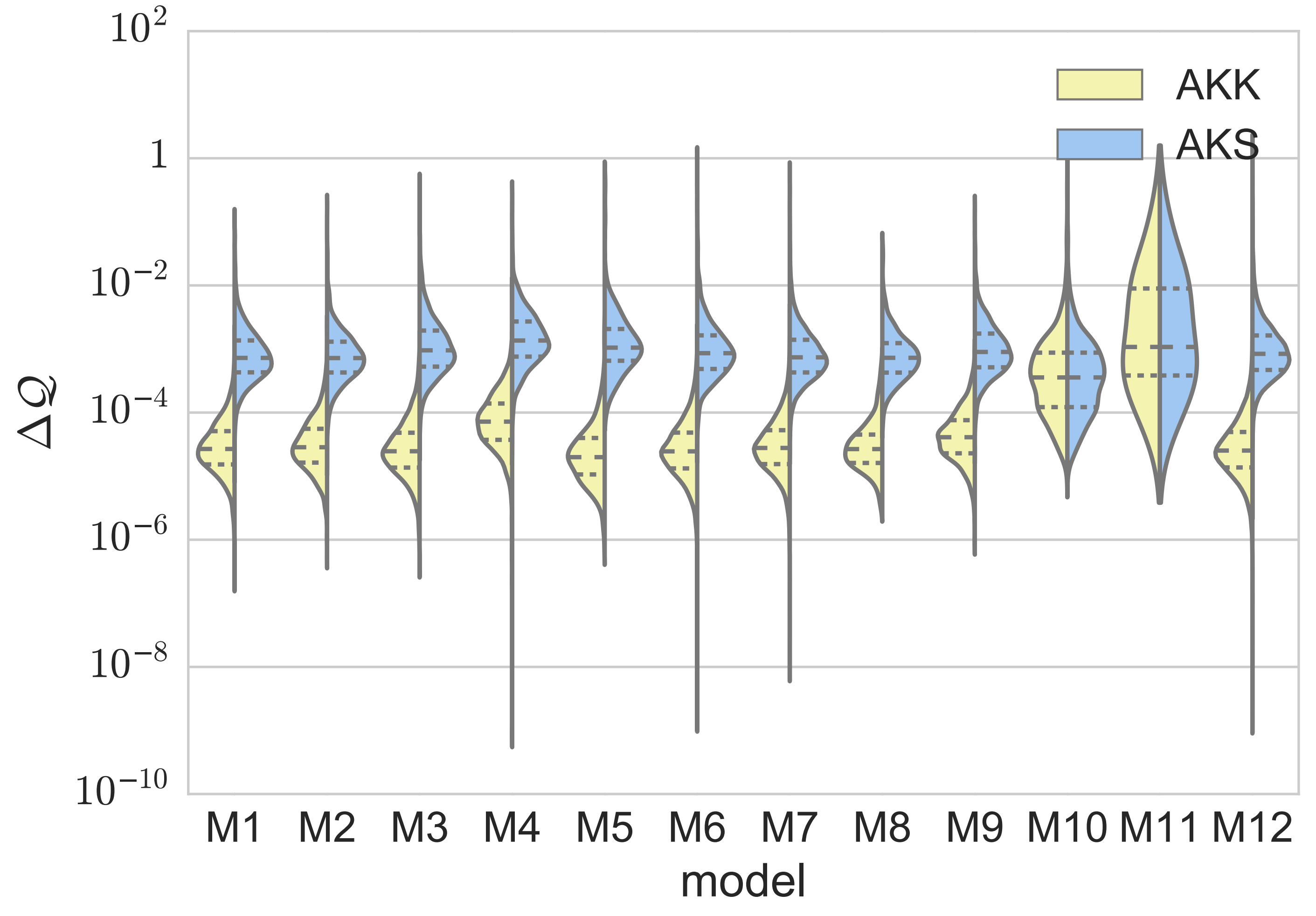
[Babak+ PRD (2017)]

Fundamental physics with EMRIs

Extreme mass ratio ensures that the inspiralling object acts like a test particle. Use emitted GWs to map out the spacetime structure (geodesy -> holiodesy). Deviations from Kerr:

- Astrophysical perturbations (i.e. not clean two body system)
- Exotic central object consistent with GR (e.g. massive Boson star)
- One of the assumptions of uniqueness theorem violated (axisymmetry, no horizon)
- Breakdown of GR in strong field limit

Deviation in qusdrupole moment from Kerr value



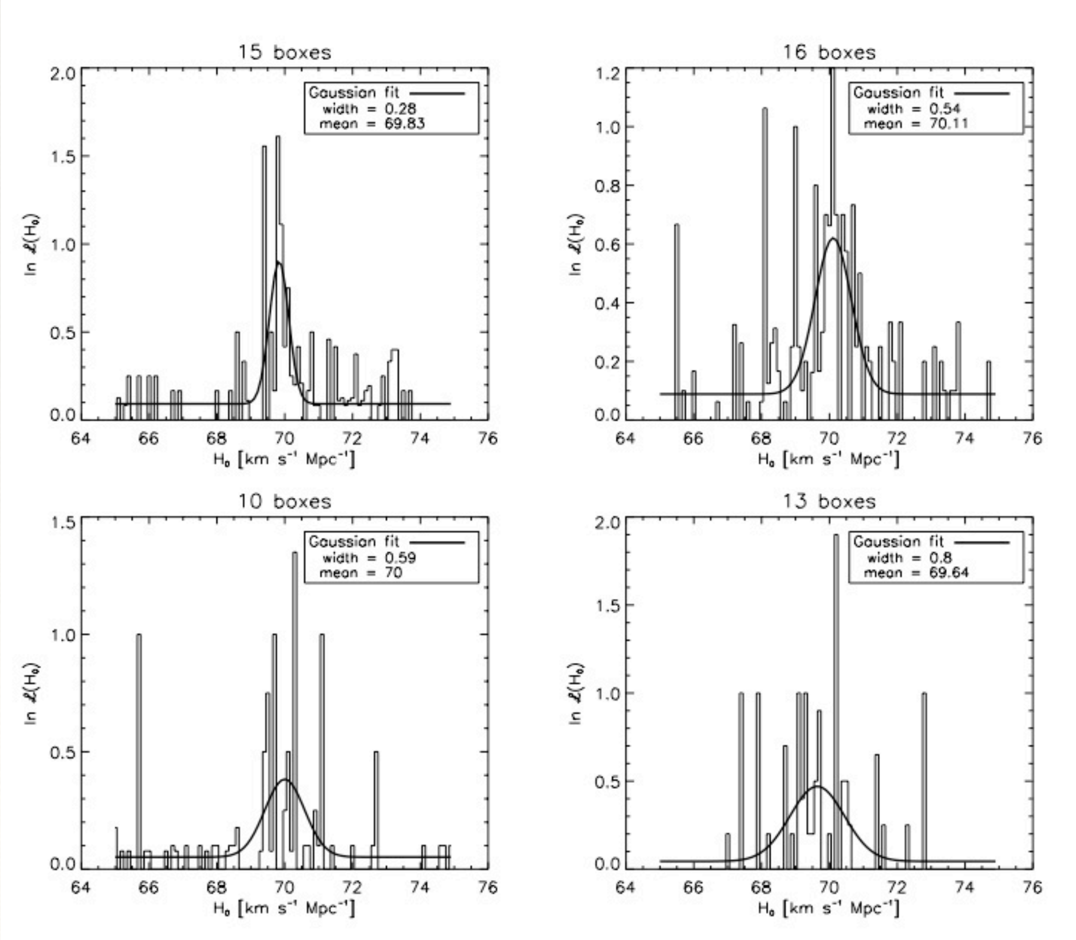
Kerr solution: axisymmetric, vacuum.
two free parameters: mass (M), spin (a).
Multipolar structure:

$$M_l + iS_l = M(ia)^l$$

[Babak+ PRD (2017)]

Cosmography with EMRIs

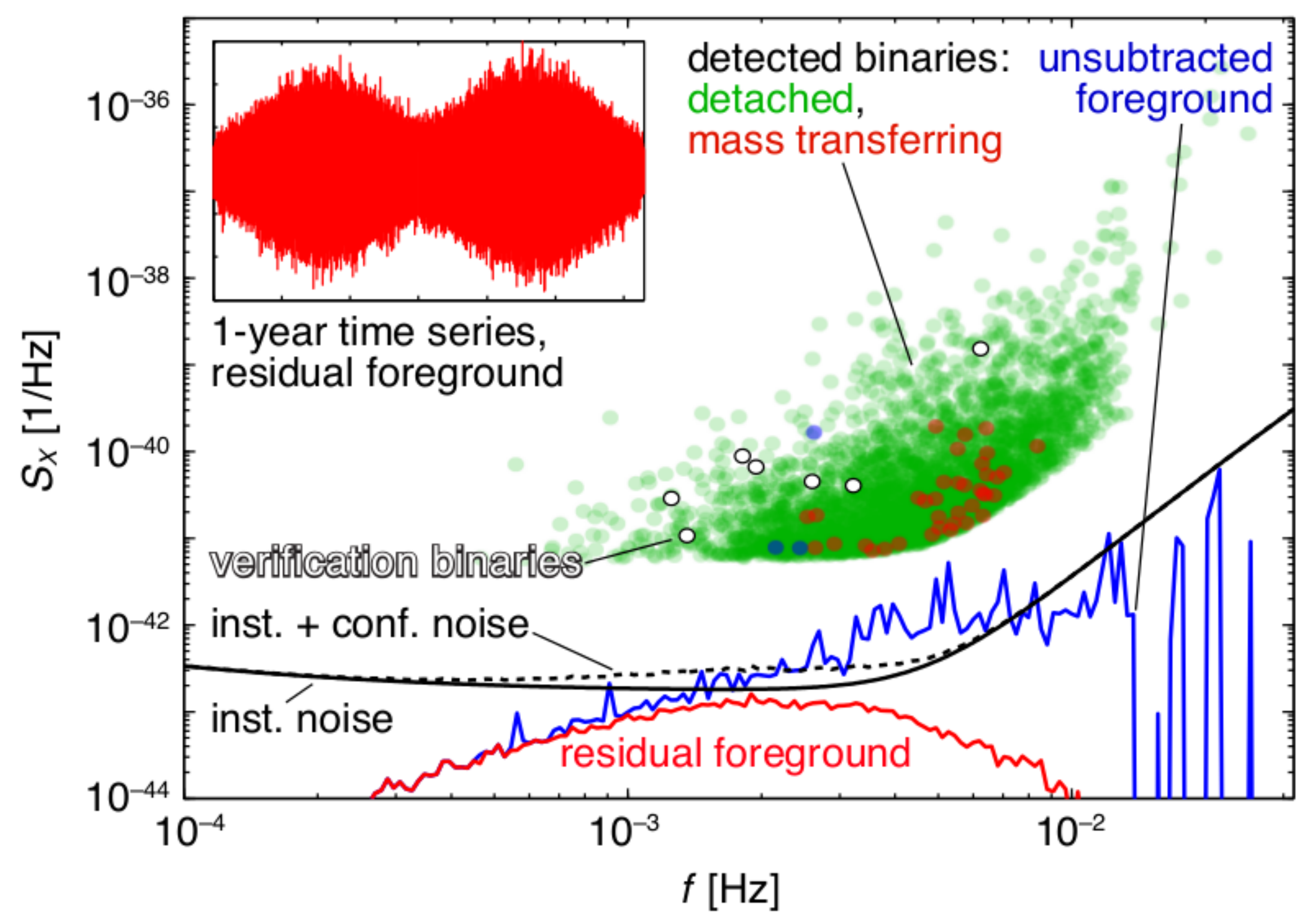
- GW gives us measurement of luminosity distance, if we have e/m counterpart we can get the redshift information: GW sources can be used as “standard sirens” to estimate cosmological parameters
- EMRI with e/m counterpart -> measurement of H (Hubble constants) with 3% accuracy
- No e/m counterpart -> can estimate Hubble constant statistically [McLeod&Hogan PRD (2008)]
  - Let every galaxy in the LISA error box “vote” on the Hubble constant and check consistency across all detected EMRIs
  - If 20 EMRIs are detected at z<0.5, we will determine the Hubble constant to 1% accuracy
  - Determination of the redshift of all galaxies in a typical EMRI error box at z<0.5 is already possible



[McLeod&Hogan PRD (2008)]

White dwarf binaries in our Galaxy

- We expect to have $\sim 10^7$ white dwarf binaries in the LISA band, and about 10^4 will 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)

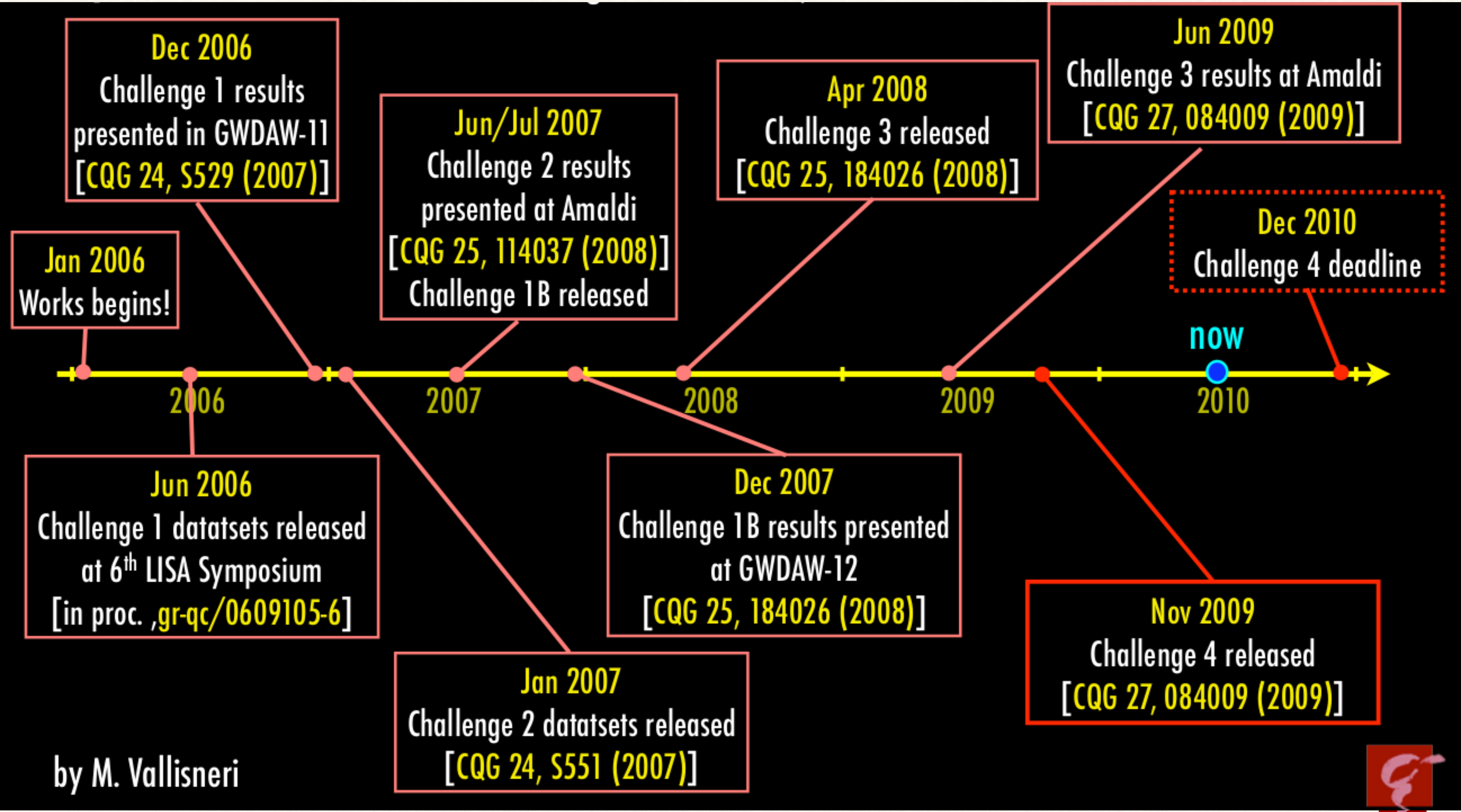


Mock LISA Data Challenge (Past)

- Goal#1: Demonstrate that we can meet LISA's scientific requirements
- Goal#2: Develop common framework which allows comparison of various data analysis methods
- Goal#3: Push for development and improvement of DA techniques
- Goal#4: Build experienced LISA community

- It was coordinated and organised by a small group.
- The software for generating the data was/is(?) public.
- MLDCs were produced (roughly) once a year and increasing in complexity
- Data contained the training data set (open challenge) and actual mock data (blind search)
- Results were collected after a deadline and assessed

Timeline



Jan 2006
Works begins!

Jun 2006
Challenge 1 datatsets released
at 6th LISA Symposium
[in proc. ,gr-qc/0609105-6]

Dec 2006
Challenge 1 results
presented in GWDAW-11
[CQG 24, S529 (2007)]

Jan 2007
Challenge 2 datatsets released
[CQG 24, S551 (2007)]

Jun/Jul 2007
Challenge 2 results
presented at Amaldi
[CQG 25, 114037 (2008)]
Challenge 1B released

Dec 2007
Challenge 1B results presented
at GWDAW-12
[CQG 25, 184026 (2008)]

Apr 2008
Challenge 3 released
[CQG 25, 184026 (2008)]

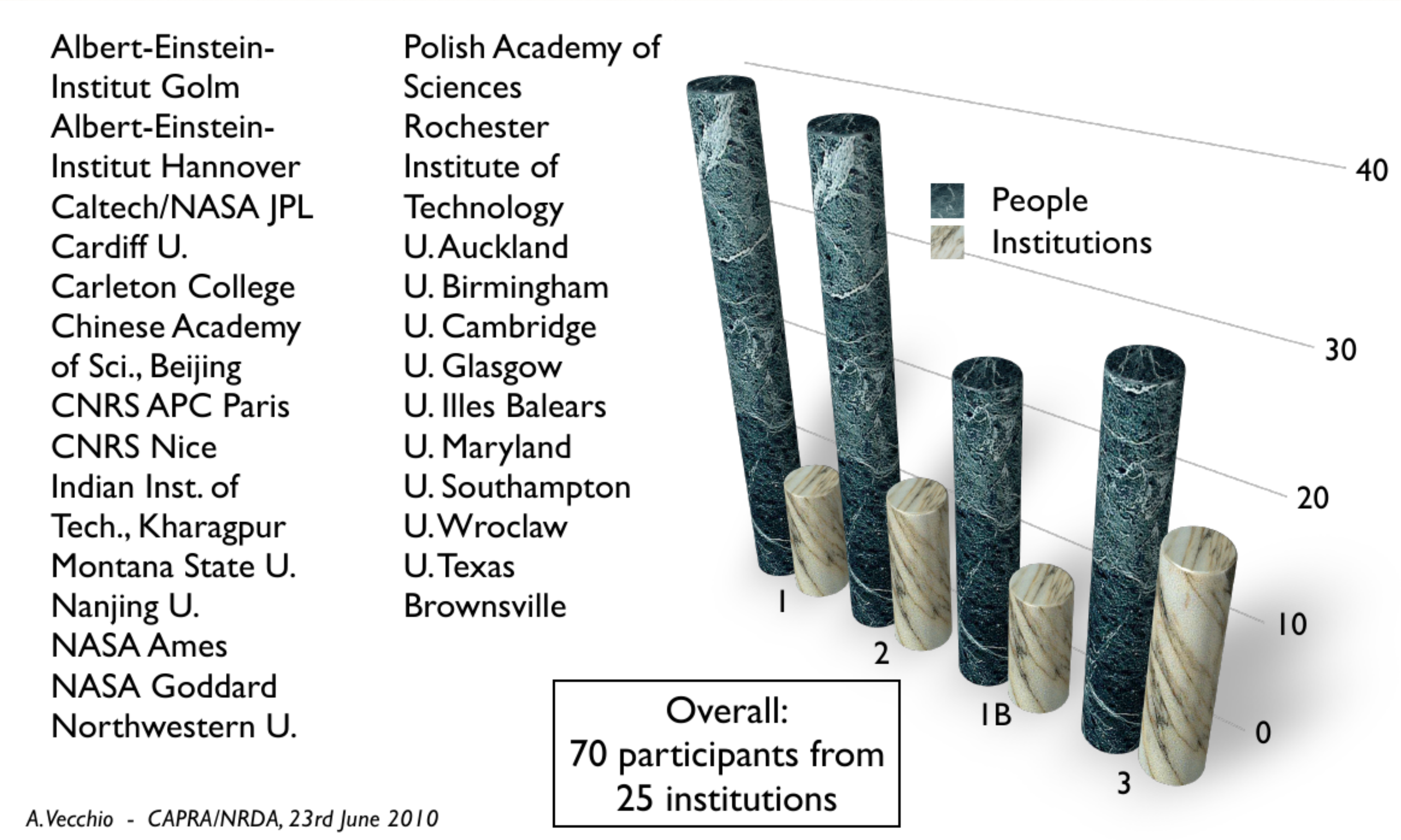
Jun 2009
Challenge 3 results at Amaldi
[CQG 27, 084009 (2009)]

Nov 2009
Challenge 4 released
[CQG 27, 084009 (2009)]

Dec 2010
Challenge 4 deadline

by M. Vallisneri

Participation

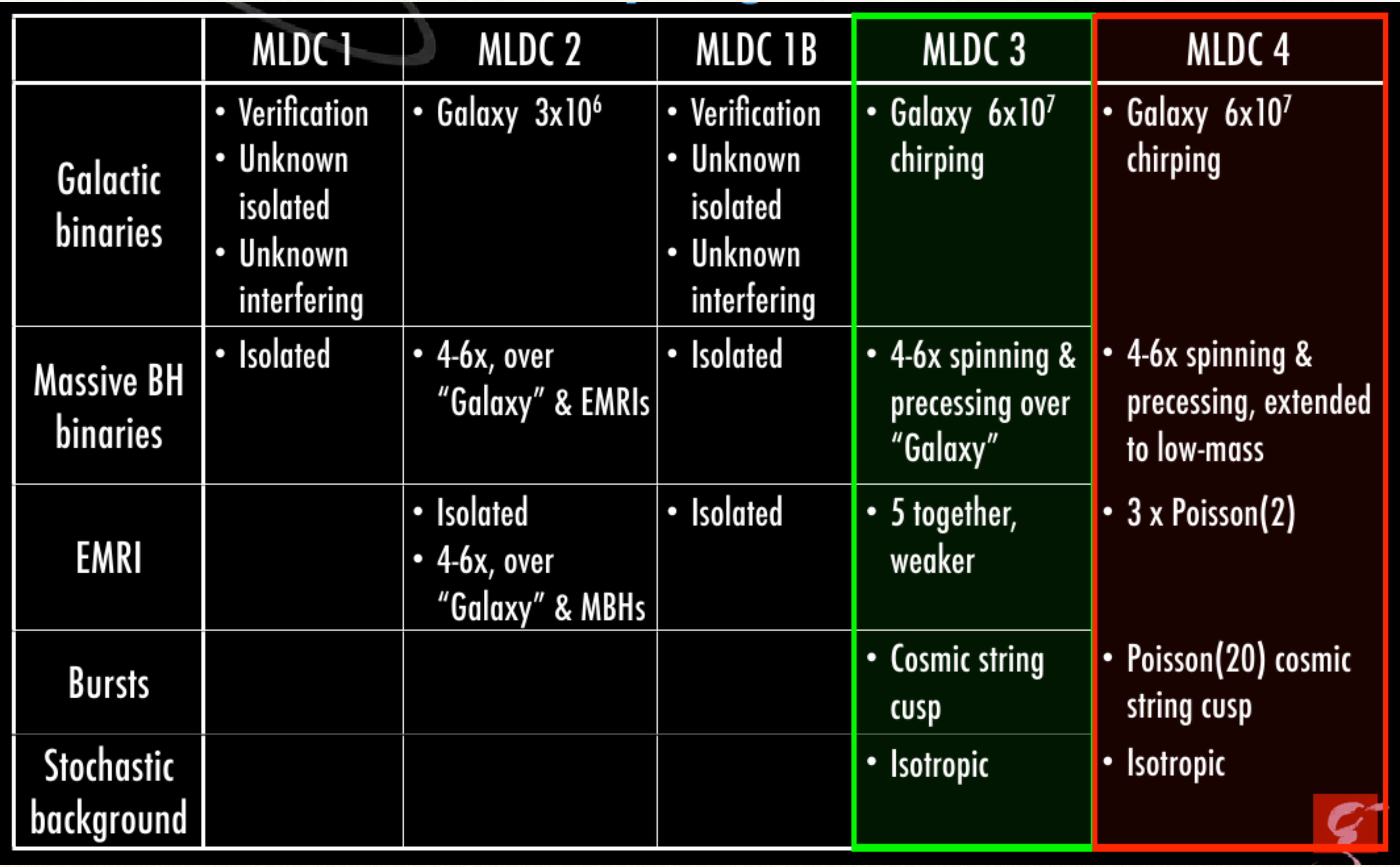


Albert-Einstein-Institut Golm
Albert-Einstein-Institut Hannover
Caltech/NASA JPL
Cardiff U.
Carleton College
Chinese Academy of Sci., Beijing
CNRS APC Paris
CNRS Nice
Indian Inst. of Tech., Kharagpur
Montana State U.
Nanjing U.
NASA Ames
NASA Goddard
Northwestern U.
Polish Academy of Sciences
Rochester Institute of Technology
U. Auckland
U. Birmingham
U. Cambridge
U. Glasgow
U. Illes Balears
U. Maryland
U. Southampton
U. Wroclaw
U. Texas Brownsville

Overall:
70 participants from
25 institutions

A. Vecchio - CAPRA/NRDA, 23rd June 2010

Content



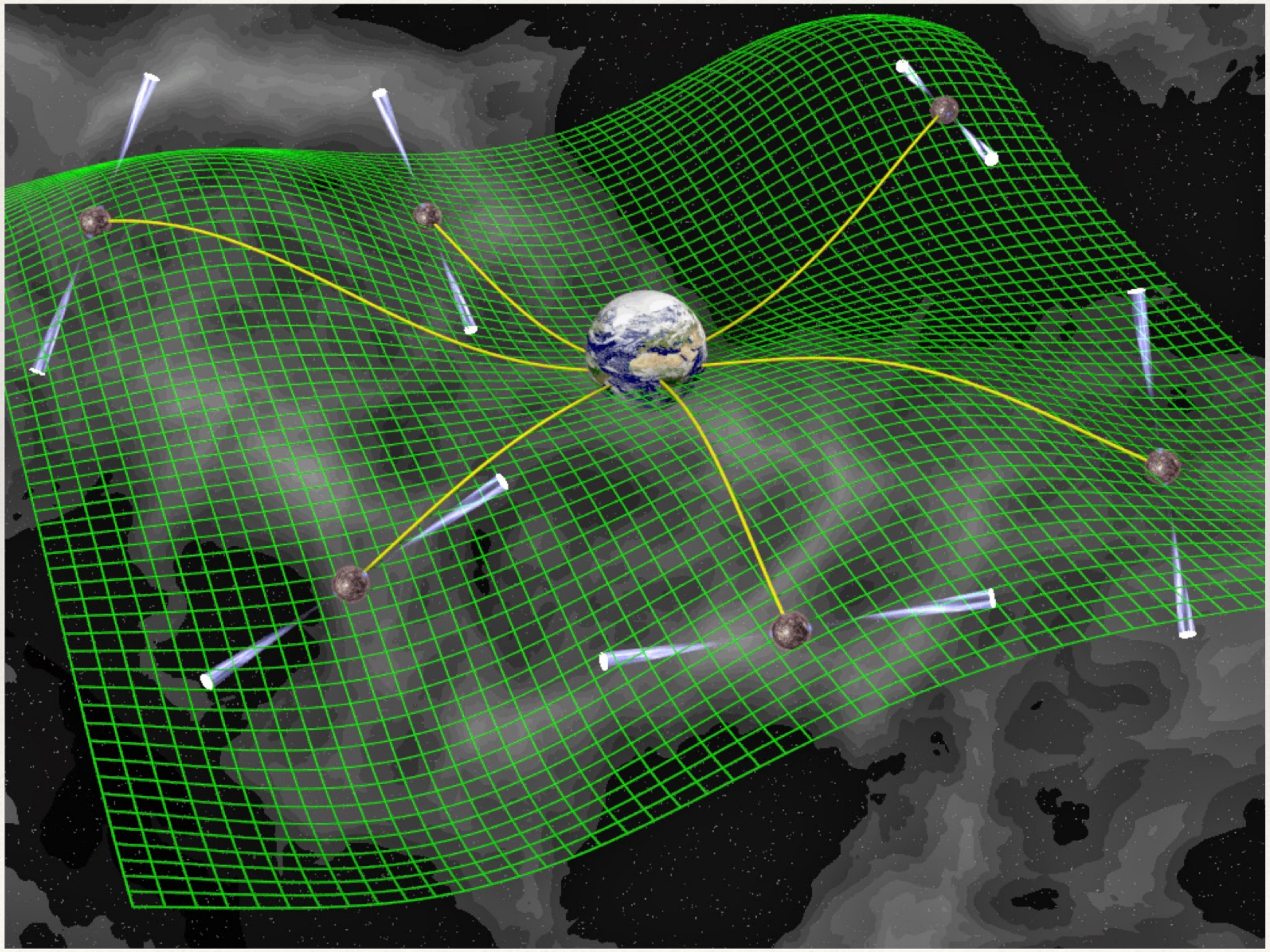
	MLDC 1	MLDC 2	MLDC 1B	MLDC 3	MLDC 4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	• Galaxy 3×10^6	• Verification • Unknown isolated • Unknown interfering	• Galaxy 6×10^7 chirping	• Galaxy 6×10^7 chirping
Massive BH binaries	• Isolated	• 4-6x, over "Galaxy" & EMRIs	• Isolated	• 4-6x spinning & precessing over "Galaxy"	• 4-6x spinning & precessing, extended to low-mass
EMRI		• Isolated • 4-6x, over "Galaxy" & MBHs	• Isolated	• 5 together, weaker	• 3 x Poisson(2)
Bursts				• Cosmic string cusp	• Poisson(20) cosmic string cusp
Stochastic background				• Isotropic	• Isotropic

Current LISA Data Challenge: Radler

Source	Model	# of sources	data description
Galactic binaries	Approximate response Generated in FD (Cornish/ Littenberg/Robson)	1.Verification binaries: 10 2. Galaxy: ~26 mln.	Detached WD binaries, frequency evolution, 2 years long. 15 sec cadence.
MBHB	Inspiral-merger-ringdown, circular, non-precessing. Generated in FD (PhenomD).	1. Using approximate FD response (Marsat/Baker) 2. Using LISACode	1 GW source/dataset. SNR 100-500, taken from astrophysical catalogue. 1 year long, 10 sec cadence
EMRIs	Analitic kludge (Barack/ Cutler 2004) . Generated in TD.	1 GW source/dataset	SNR 30-80, taken from astrophysical catalogue. 2 years long data, cadence 15 sec
SOBBH	Inpiral only, circular non-precessing, Generated in FD (PhenomD)	1. Bright source: ~160 (SNR>5) 2. Catalogue: ~21000	2 years long datasets, 5 sec cadence
Stochastic GW	Superposition of pixels uniform in the sky. LISACode	2 datasets	Signal is powerlaw in PSD. (2 different powerlaws). 2 years long data

Pulsar Timing Array: PTA

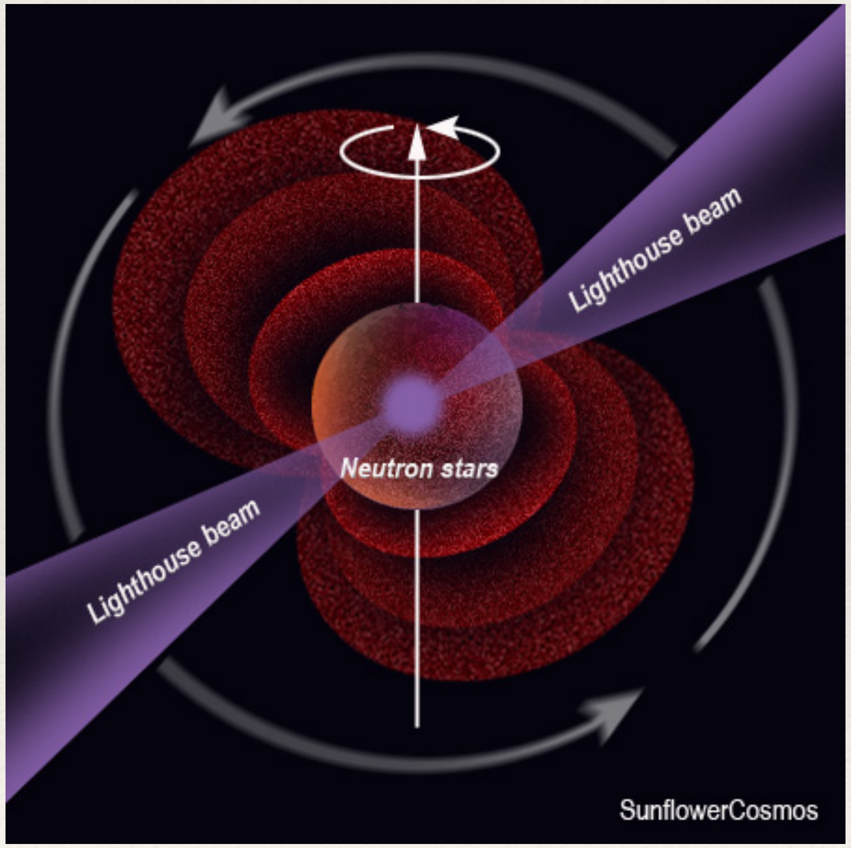
The main idea behind pulsar timing array (PTA) is to use ultra-stable millisecond pulsars as beacons for detecting GW in the nano-Hz range 10^{-9} - 10^{-7} Hz

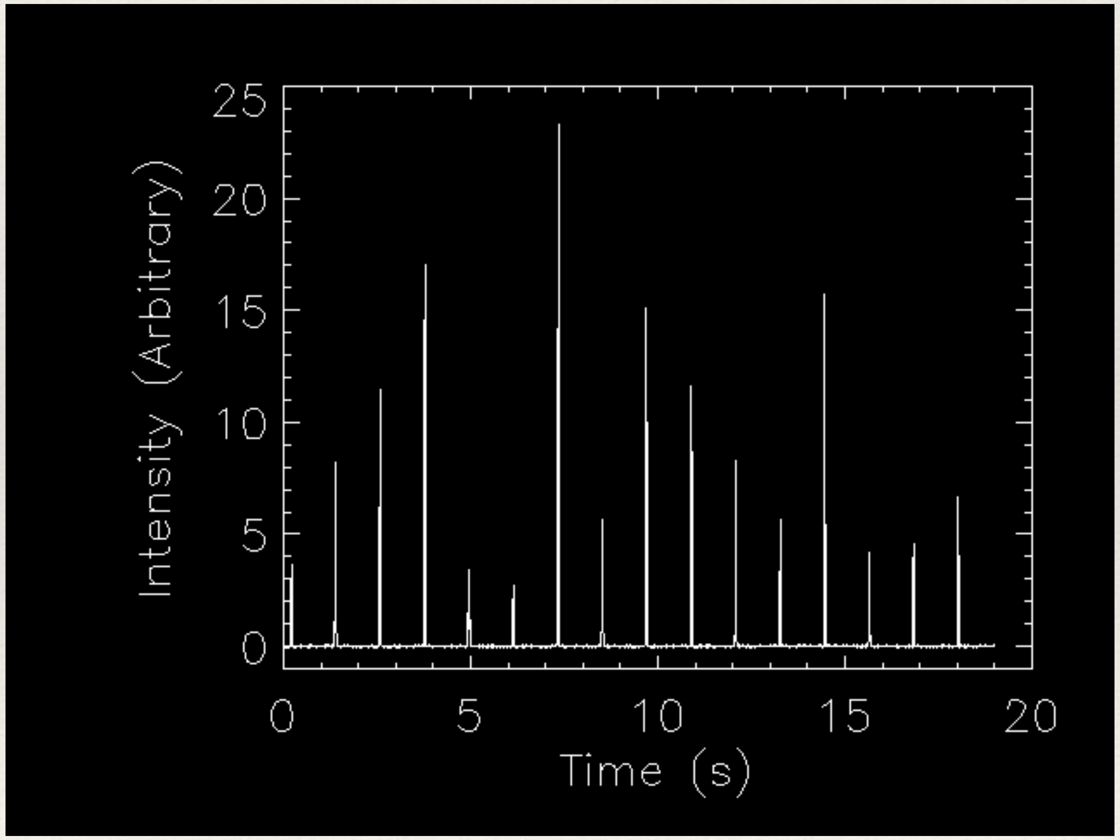


Credits: D. Champion

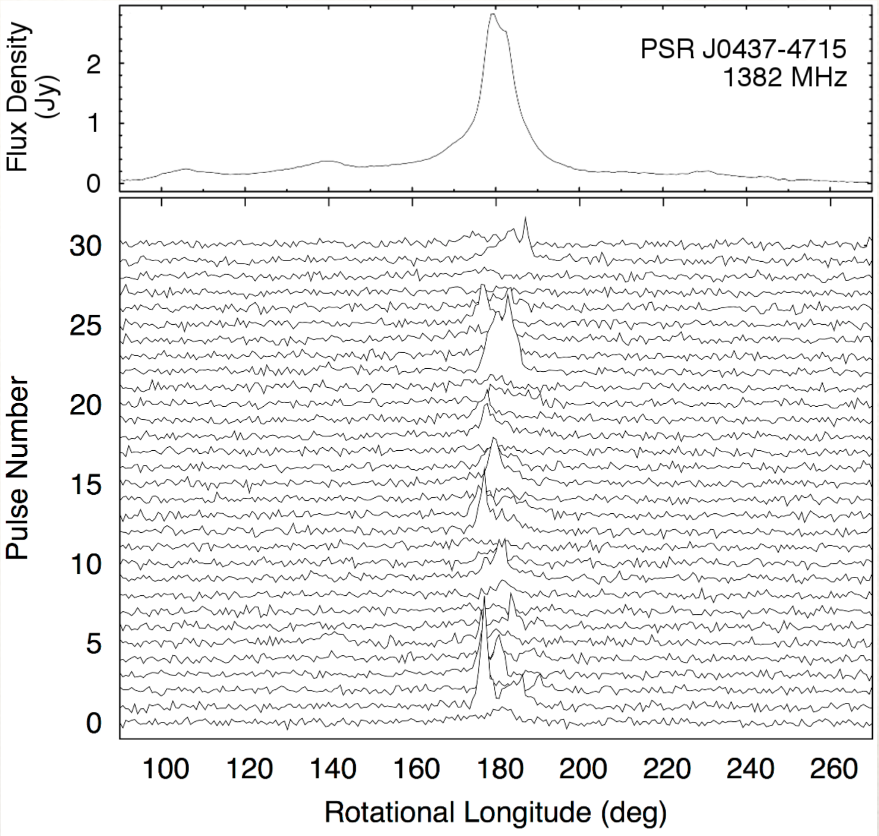
Millisecond pulsars

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.

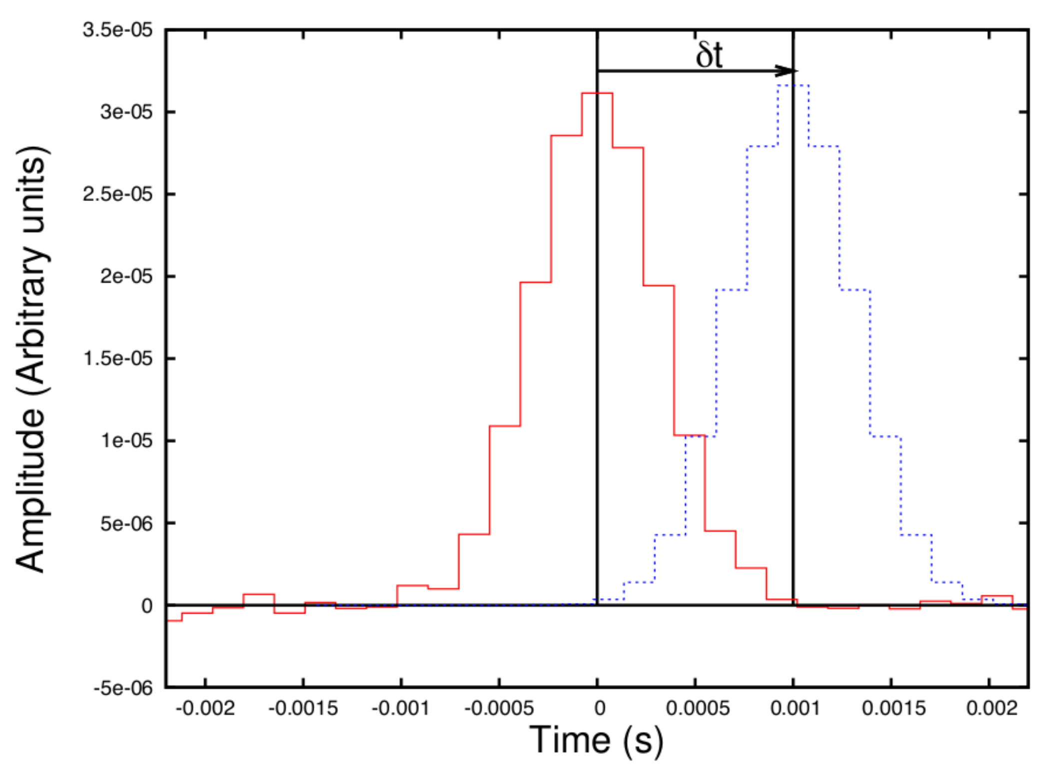




Pulsar timing



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

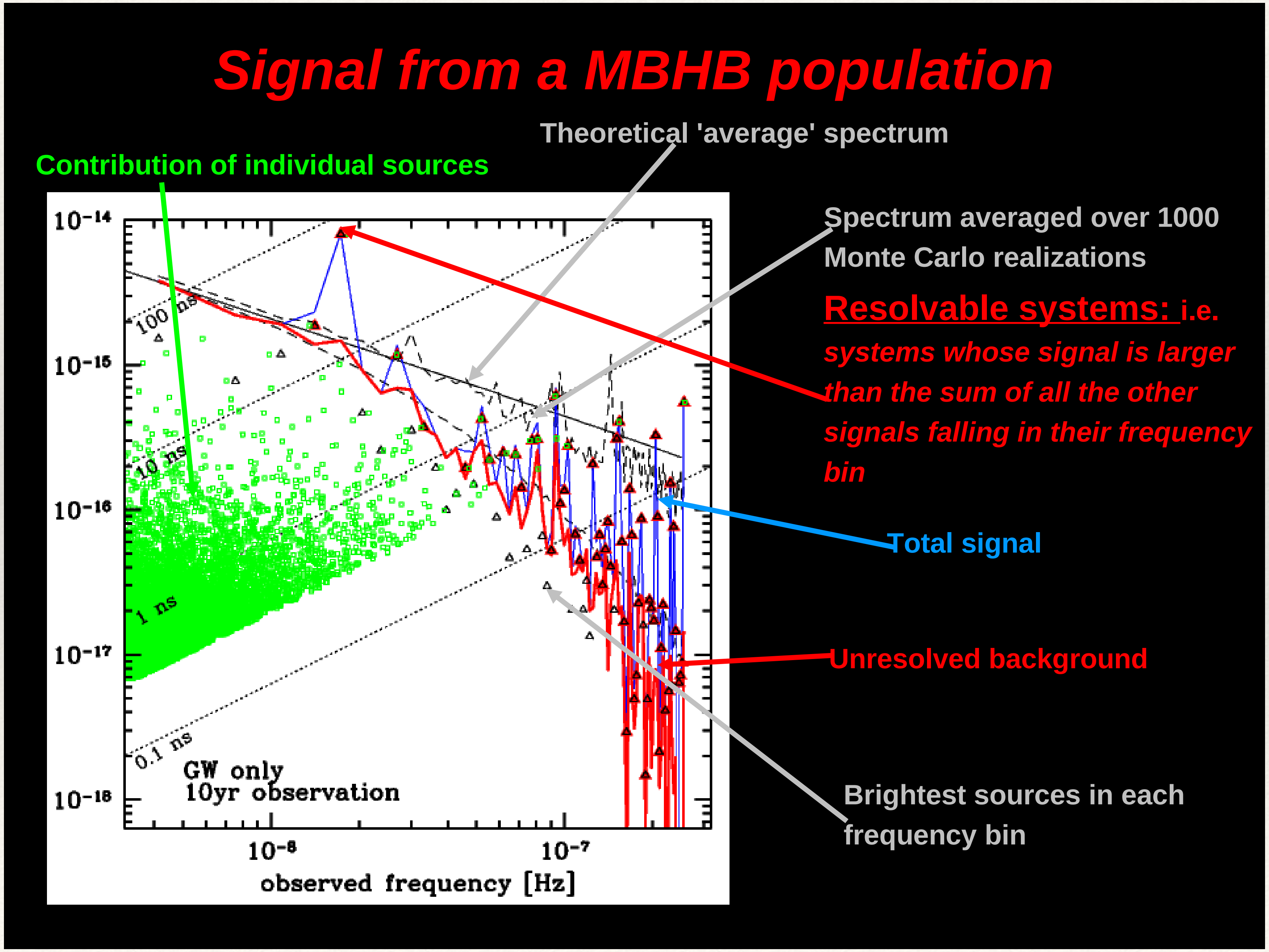
$$t_{toa} = t_{toa}(P, \dot{P}, \ddot{P}, \Delta_{clock}, \Delta_{DM}(L), \Delta_{\odot-\oplus}, \Delta_{E}, \Delta_{S})$$

$P, \dot{P}, \ddot{P}$	period of pulsar, its spin-down, glitches.
Δ_{clock}	difference in local clock and terrestrial standard
$\Delta_{DM}(L)$	delay caused by interstellar medium
$\Delta_{\odot-\oplus}$	translation from observatory frame to SSB
Δ_{E}	accounts for the time dilation from moving 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

Contribution of individual sources

Theoretical 'average' spectrum

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

[credits: Alberto Sesana]

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

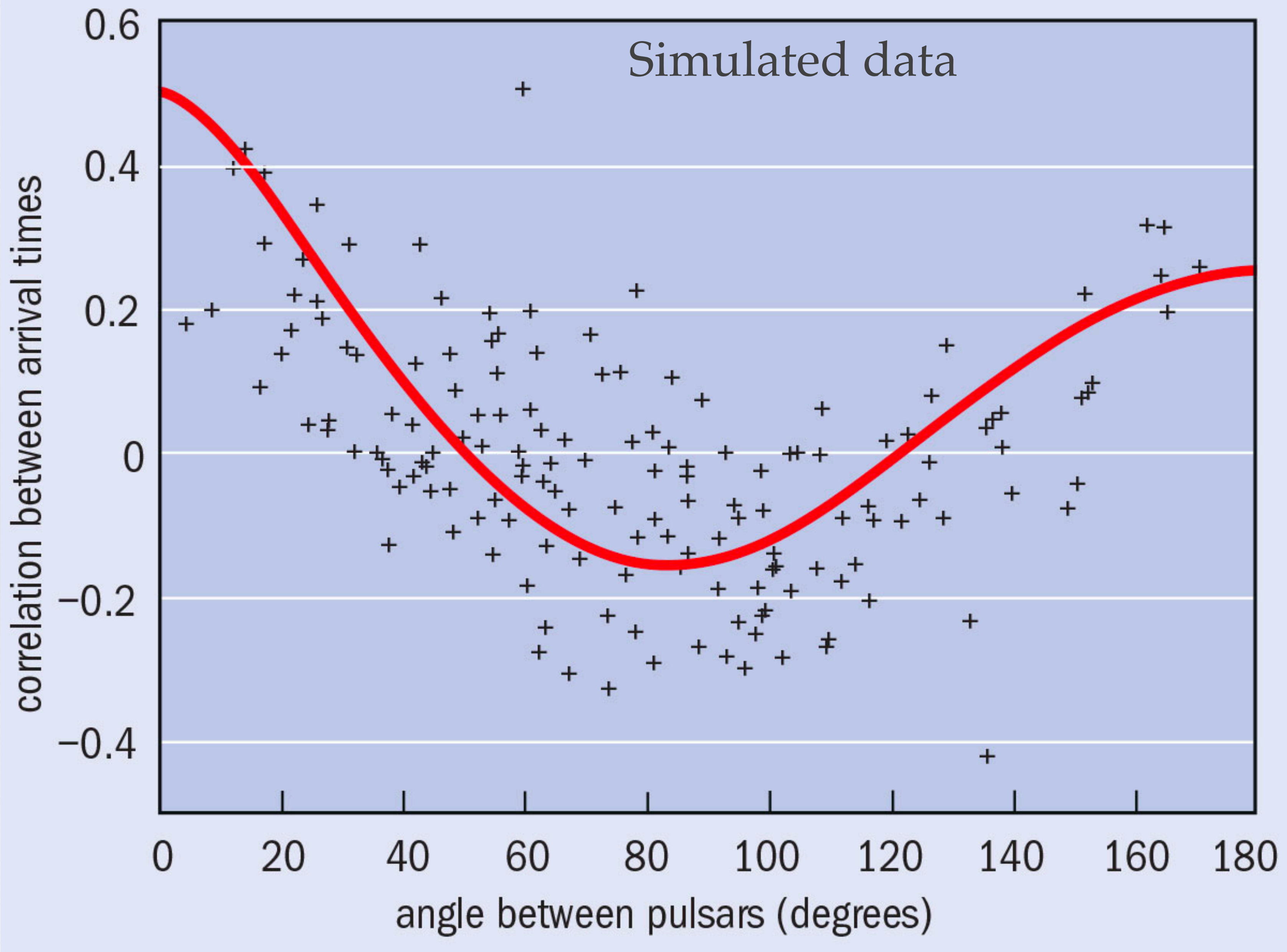
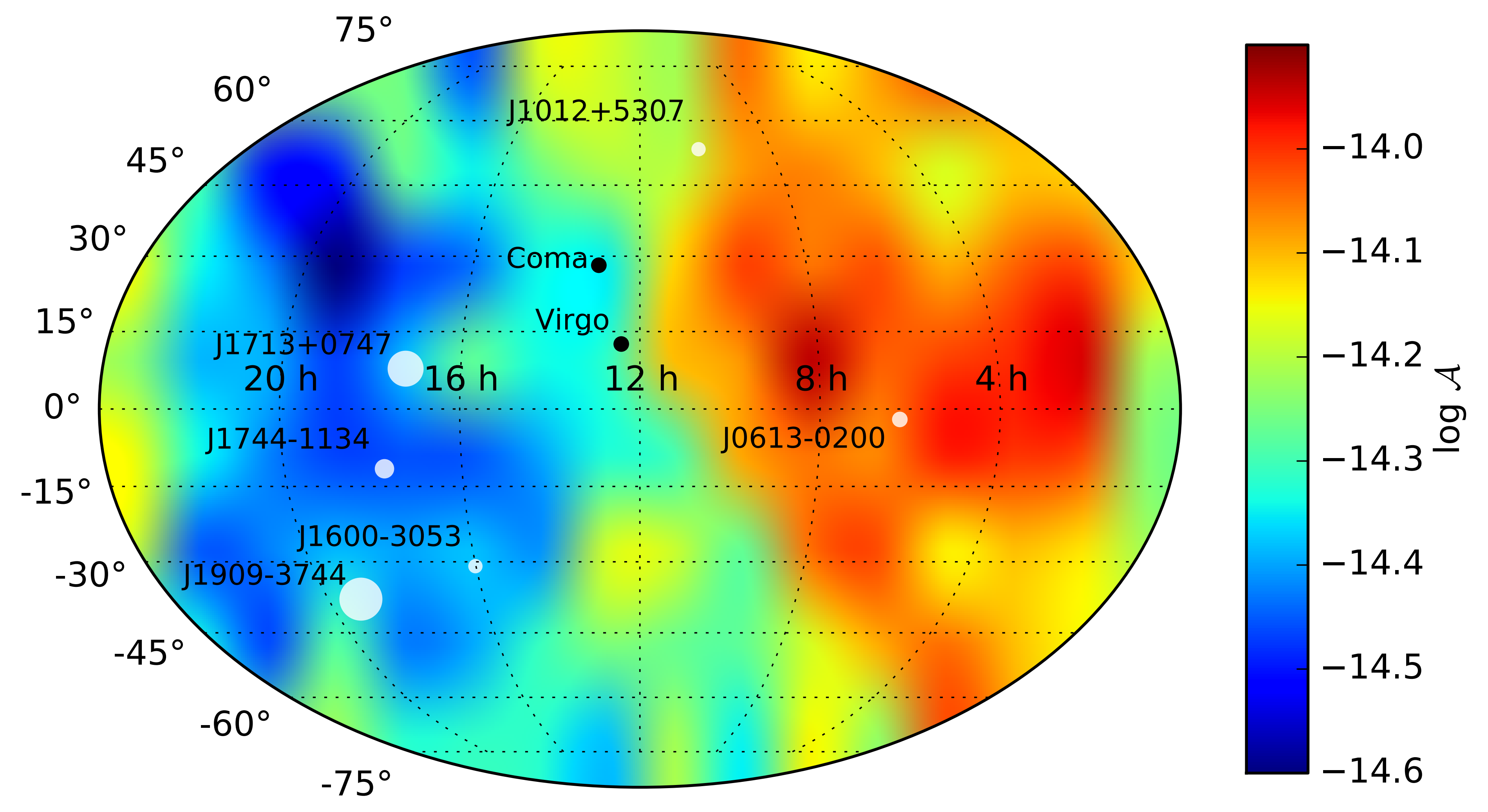


Fig. from IOP, Physics World

Upper limit on GW in nano-Hz band

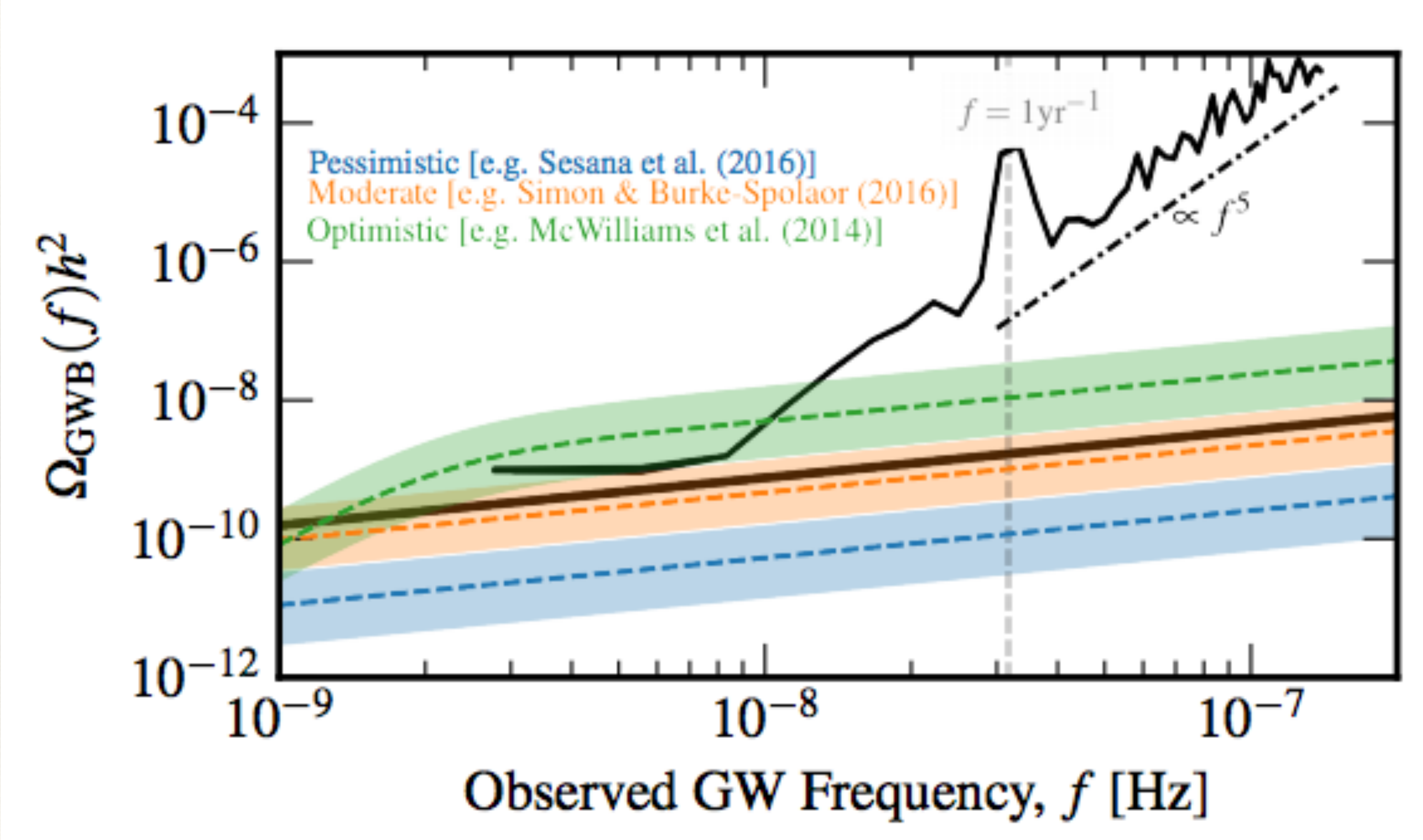
- GW are not yet detected by PTA: require long monitoring of pulsars (decades) to integrate the signal oput of noise + more stable pulsars.
- We can set un upper limit on the strength of GWs in the nano-Hz band: upper limit on the strain of individual signals.



[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

- LISA is in the phase “A”. It will be launched ~2034 and it will deliver info on evolution of MBHs and their environment, structure of Galaxy, fundamental physics, cosmography.
- LISA is not “LIGO in space”: different GW source, different data, different measurements and (somewhat) different data analysis techniques

- 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.