GW1—Introduction to Gravitational Waves

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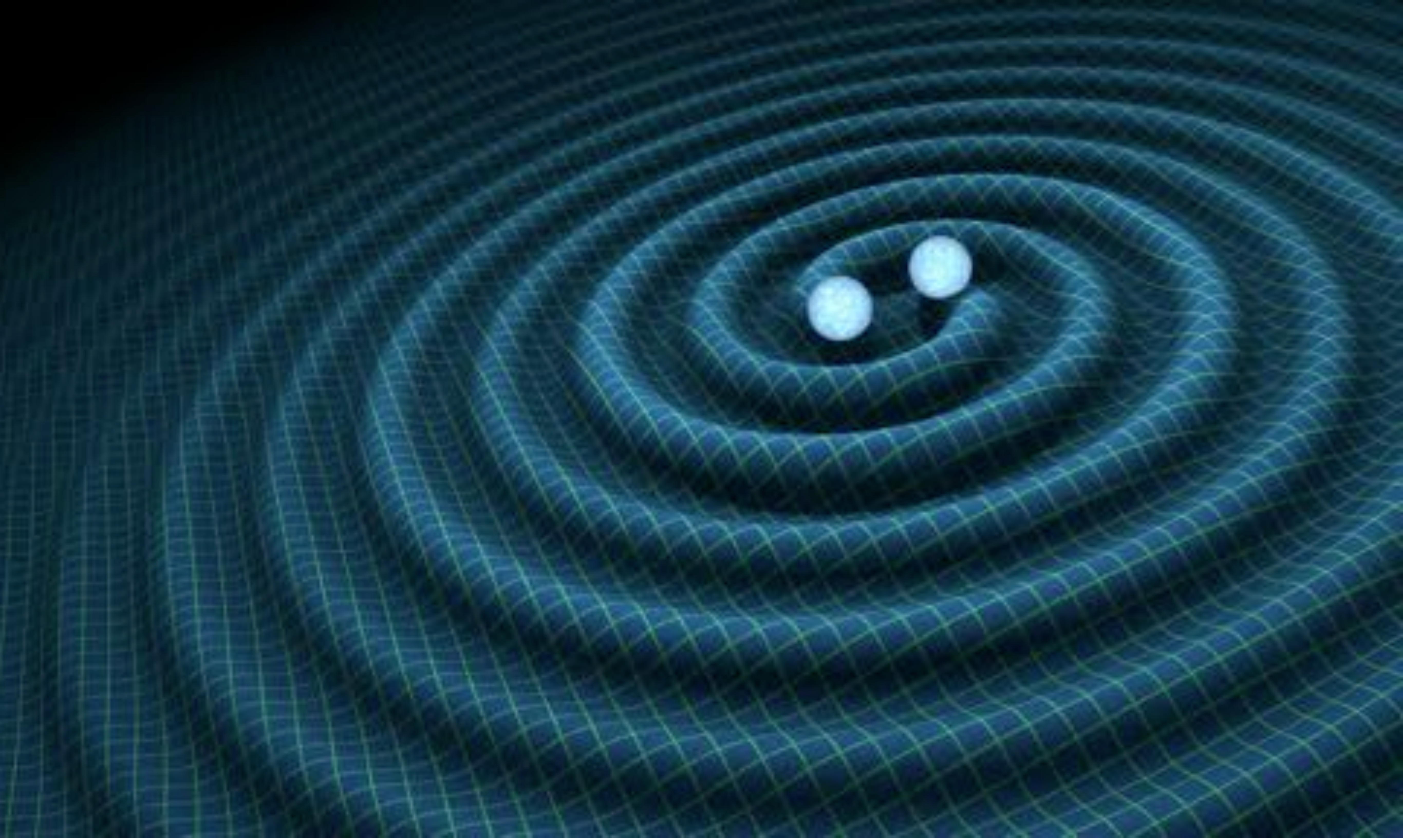
ICTP Summer School on Cosmology 2016

1.1 — GWs in a nutshell



Gravitational waves are propagating ripples in spacetime, produced by the rapid accelerated motion of massive bodies.

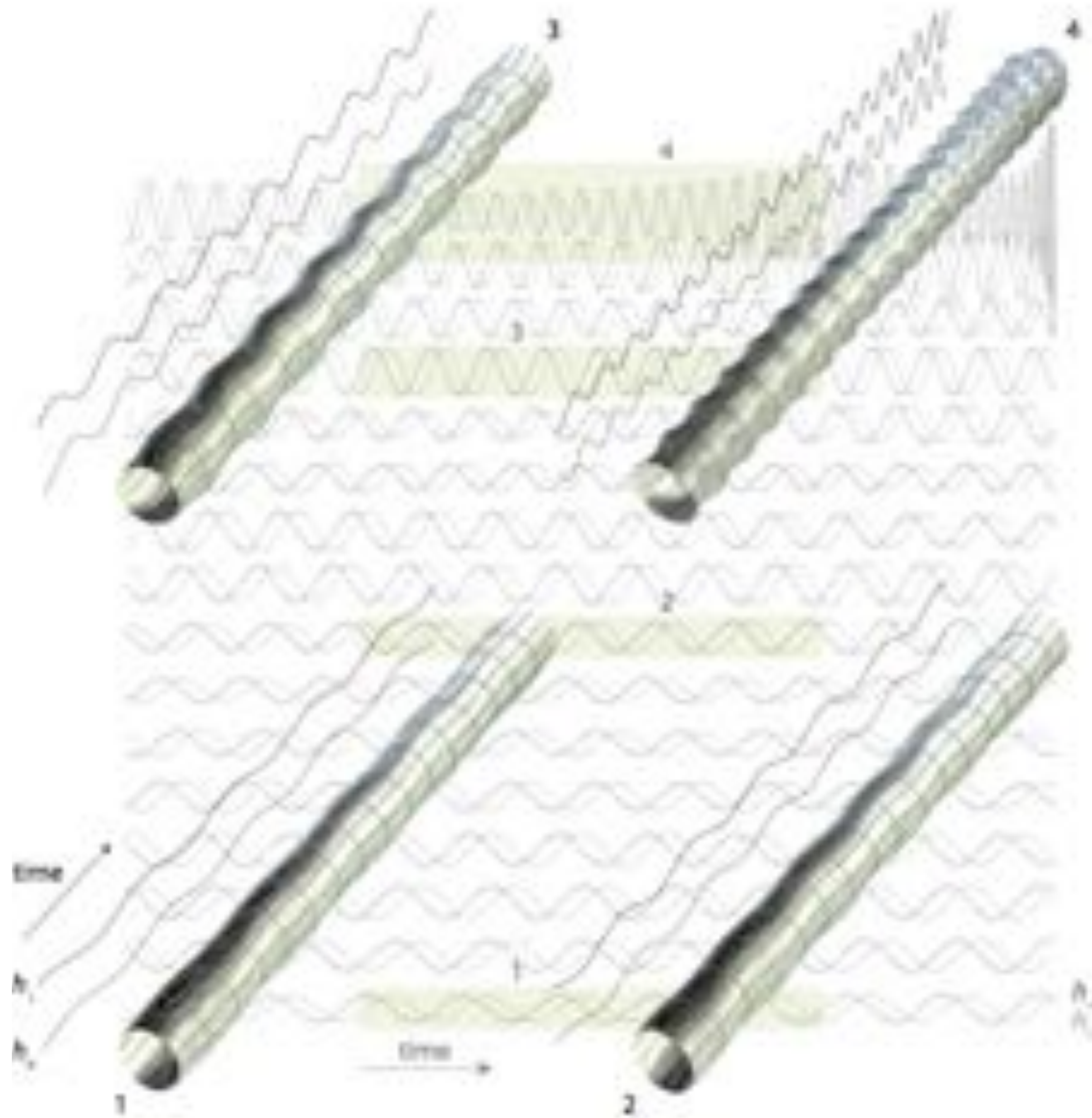
GWs will open many new windows...



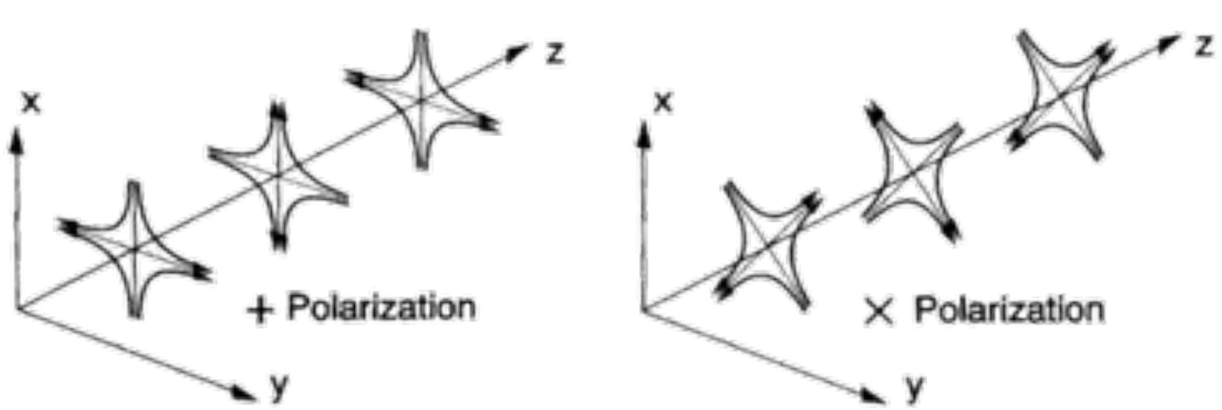
...on the most dramatic
events in the Universe,
the most luminous objects,
the most extreme conditions.

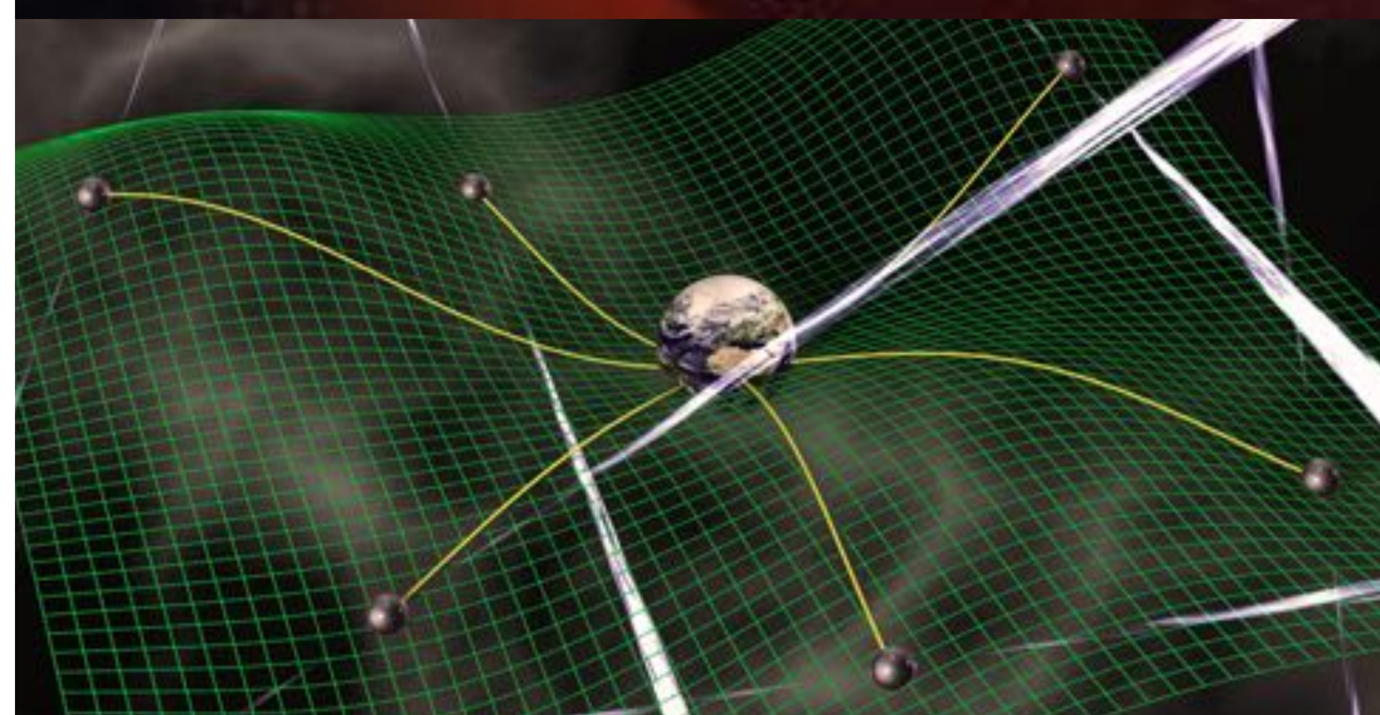
Gravitational waves:

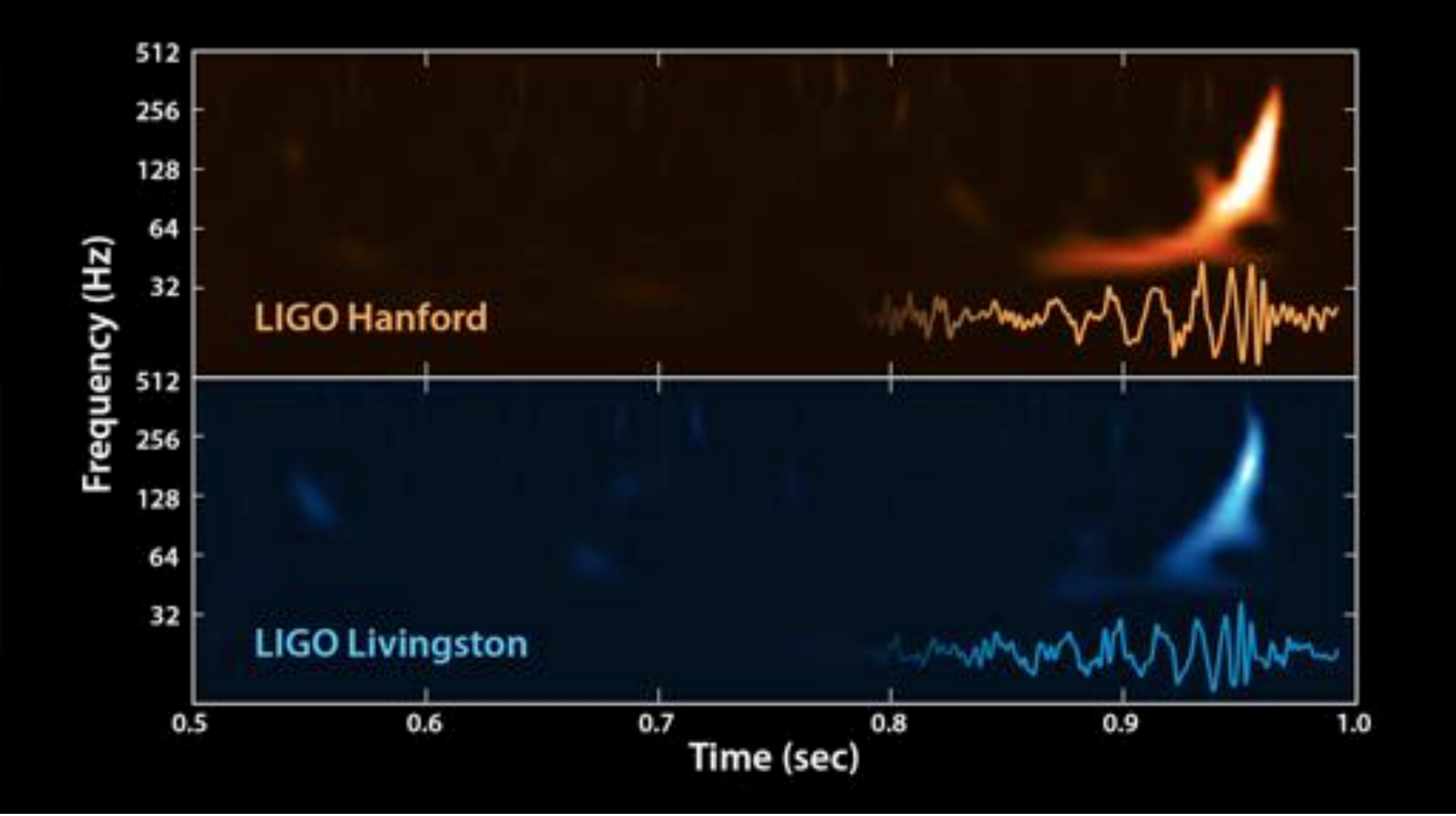
- are emitted by the bulk motion of accelerating masses
- have typical strength 10^{-21}
- interact weakly with matter
- are phase coherent
- are measured by omnidirectional detectors
- do not form images



GWs are detected
across the frequency spectrum
as transverse oscillations
in the distance of test masses.



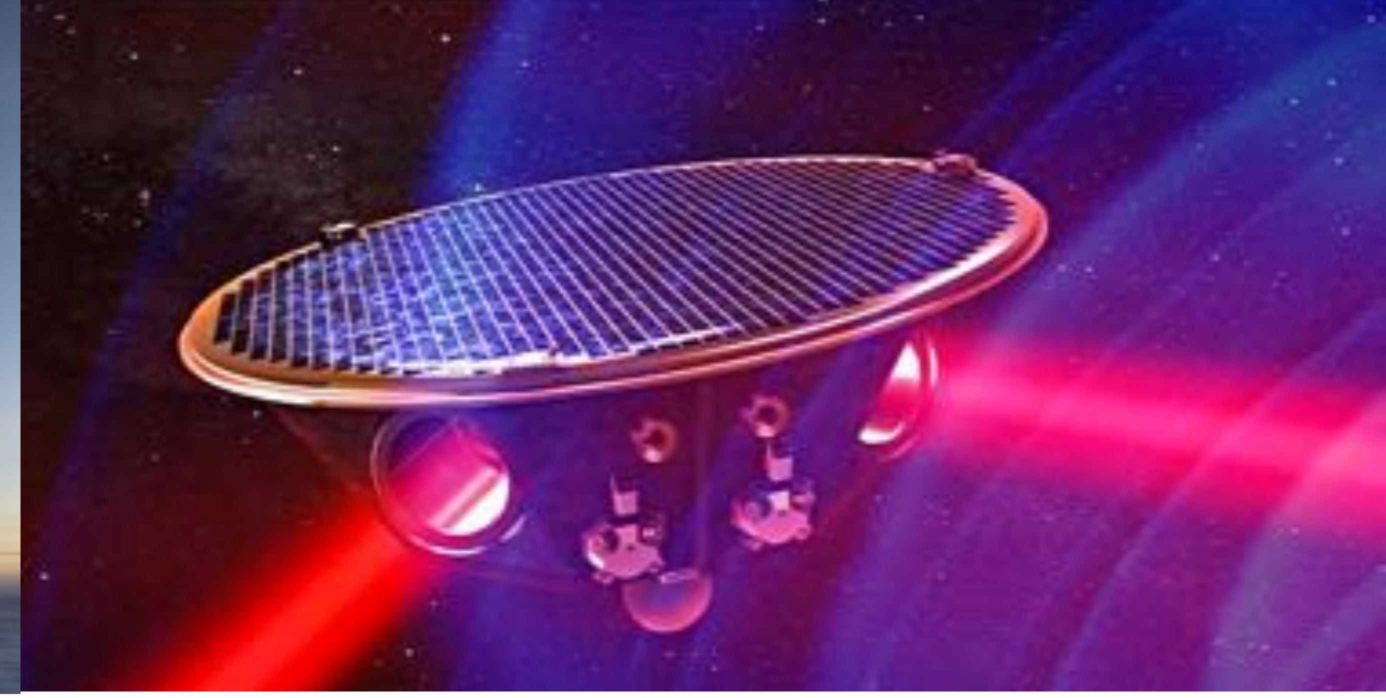




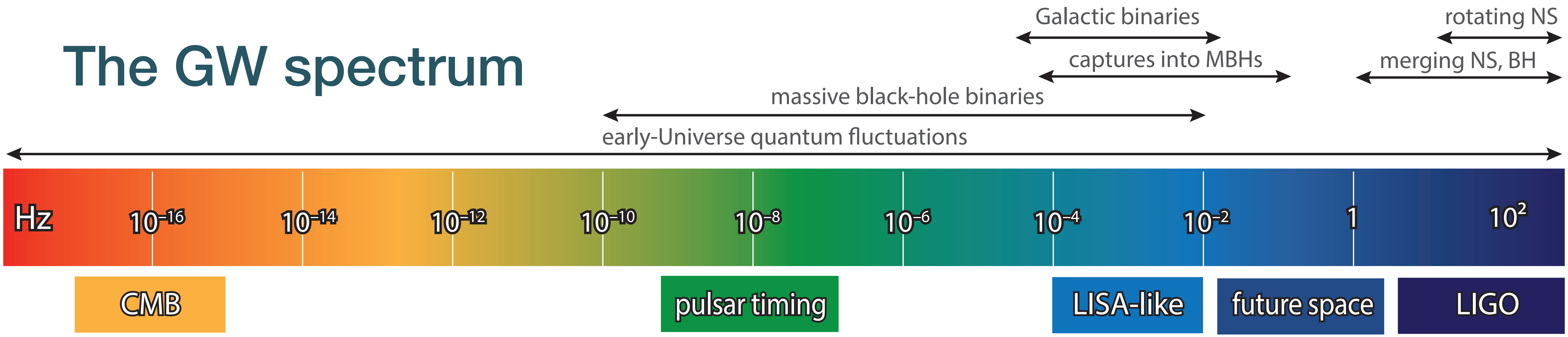
[see this movie at https://youtu.be/QyDcTbR-kEA]

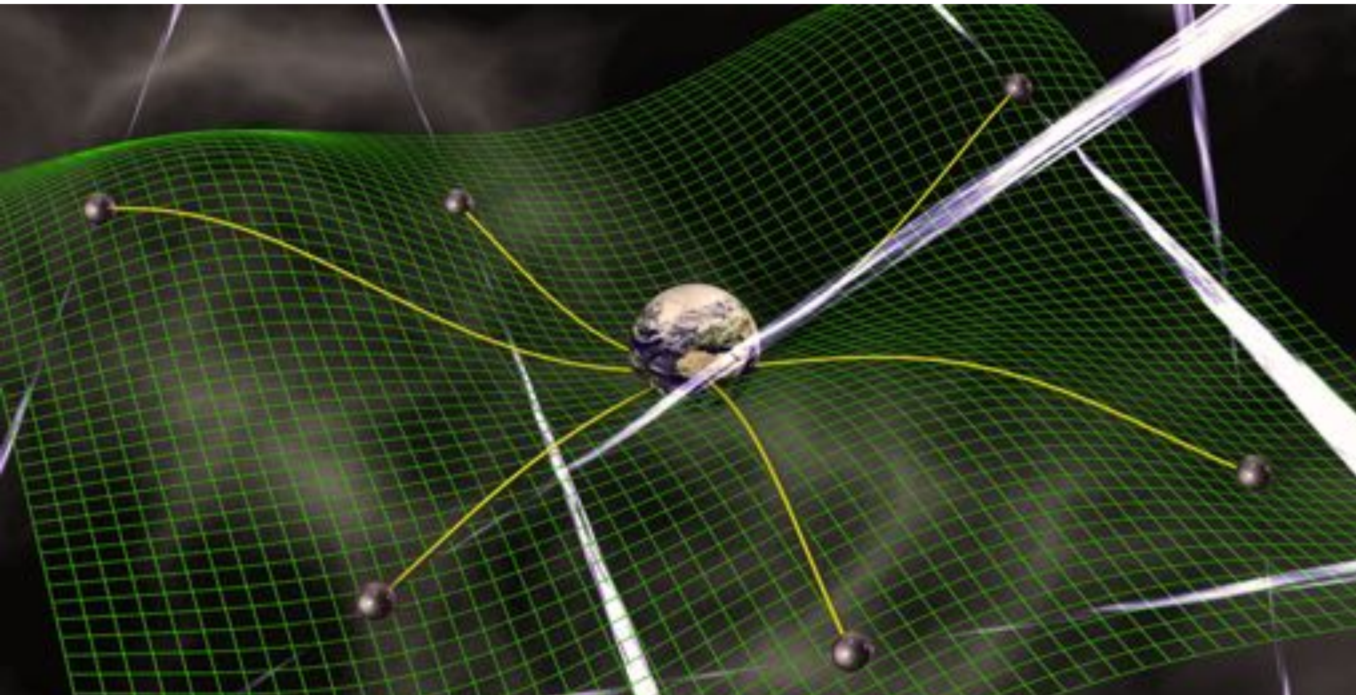
GW150914: the GW era is **now**

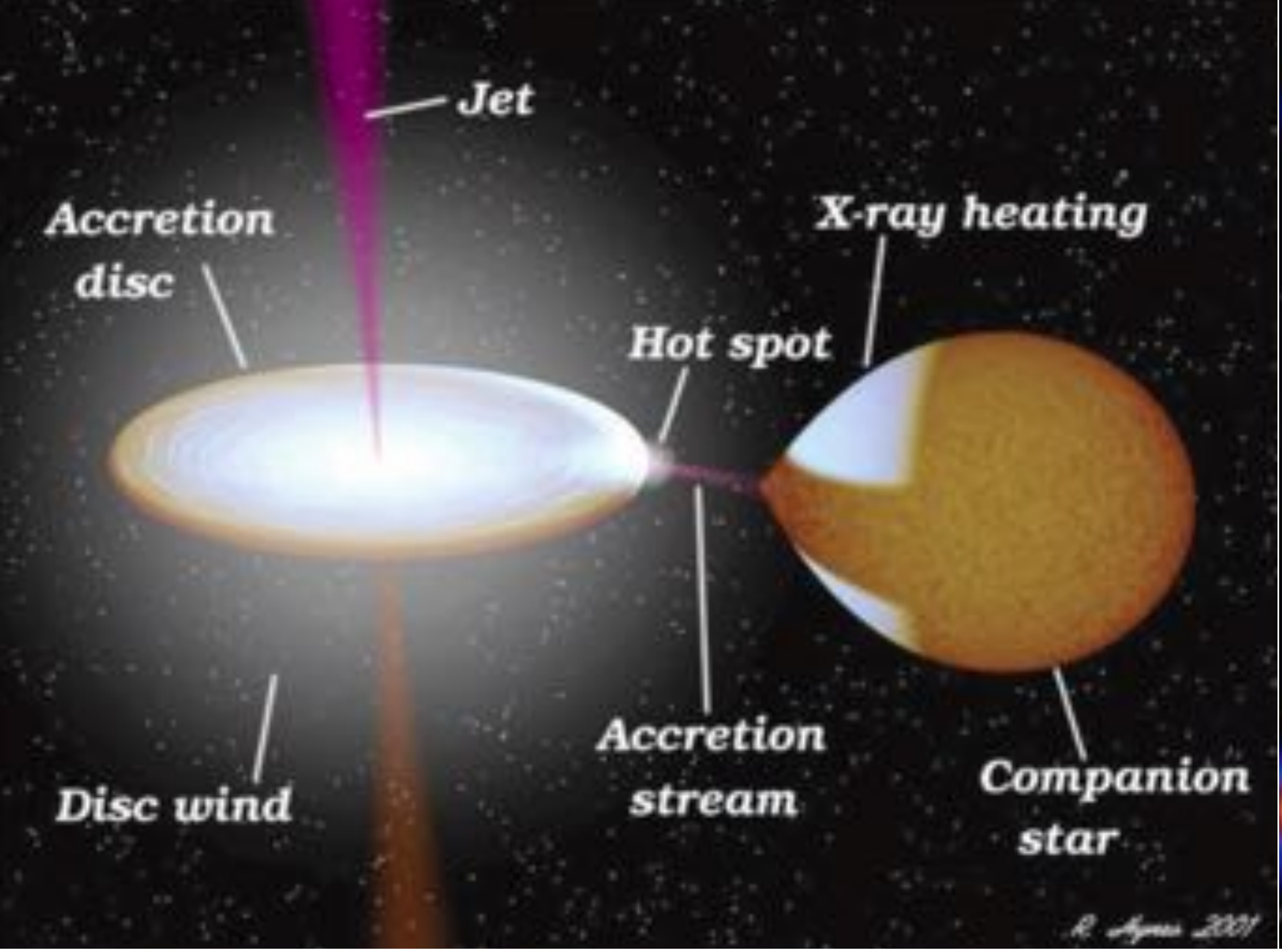
1.2 — sources

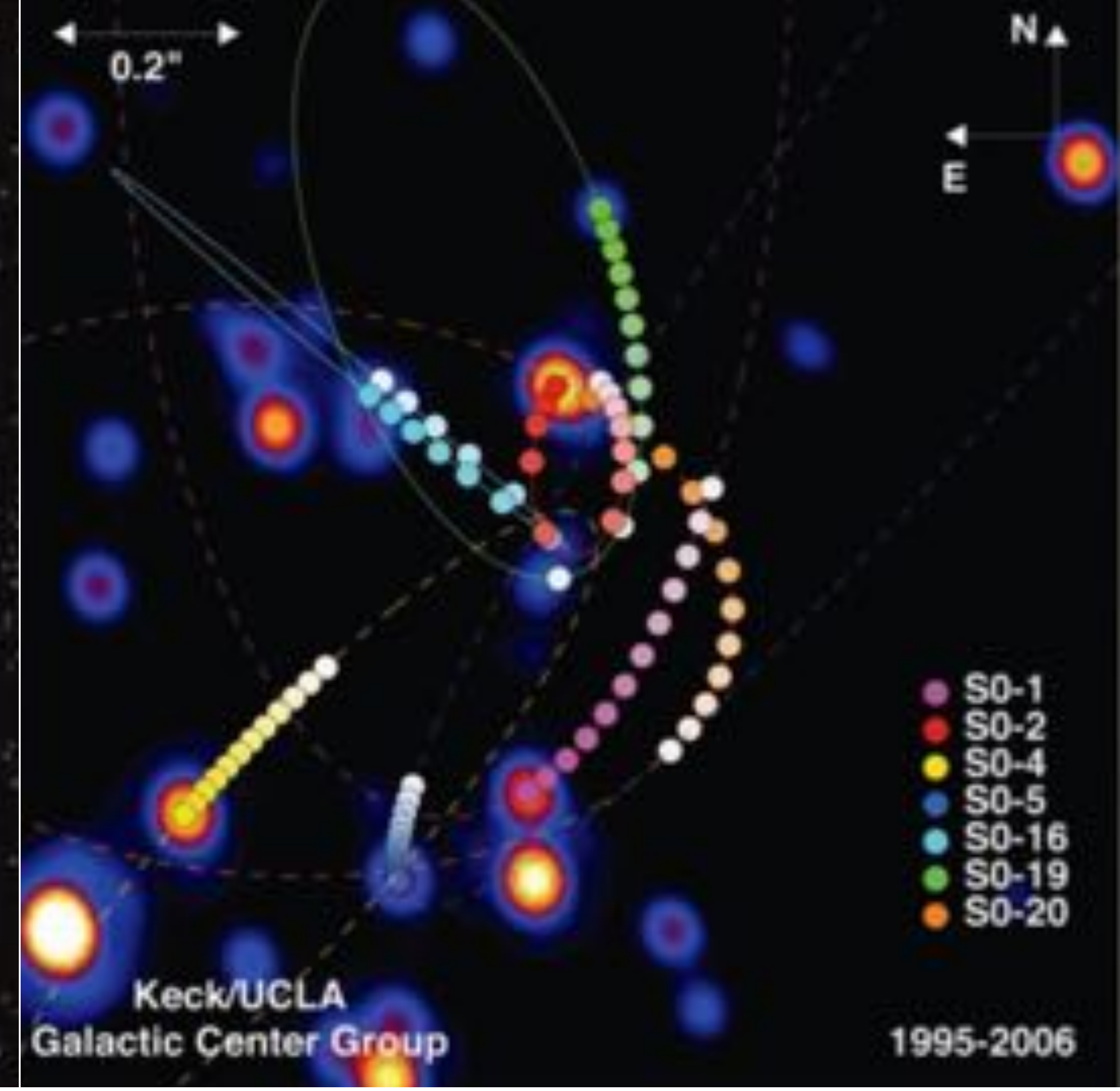


The GW spectrum



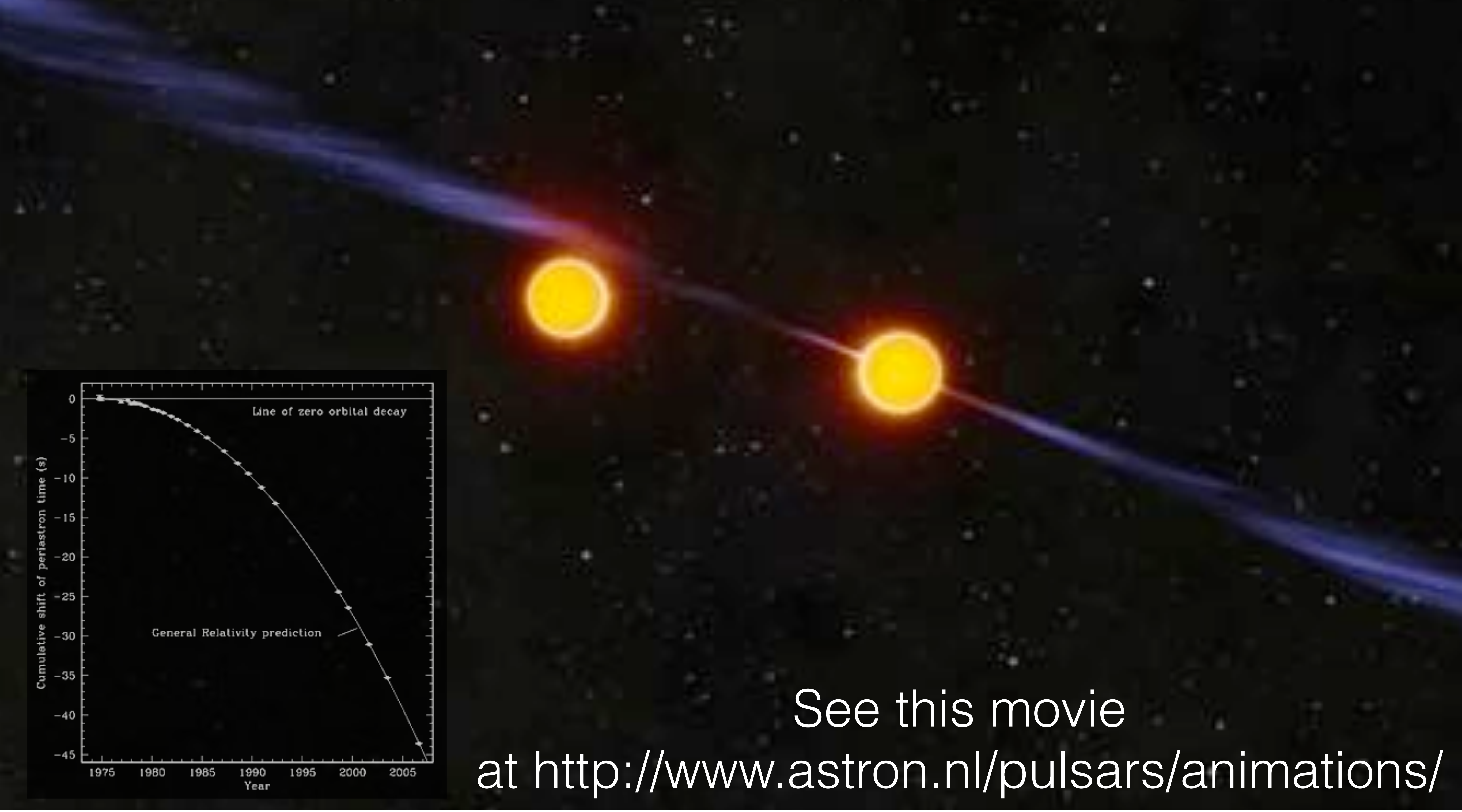




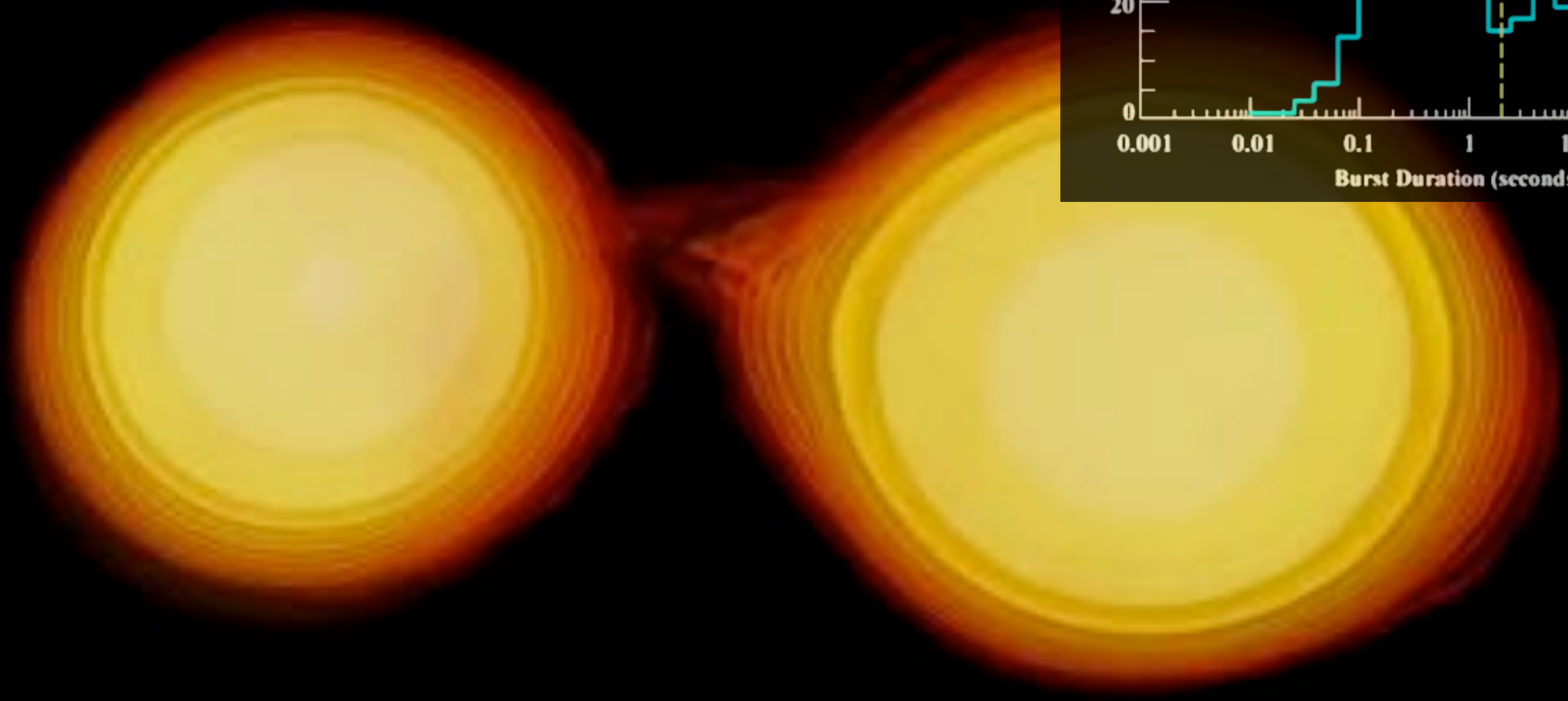


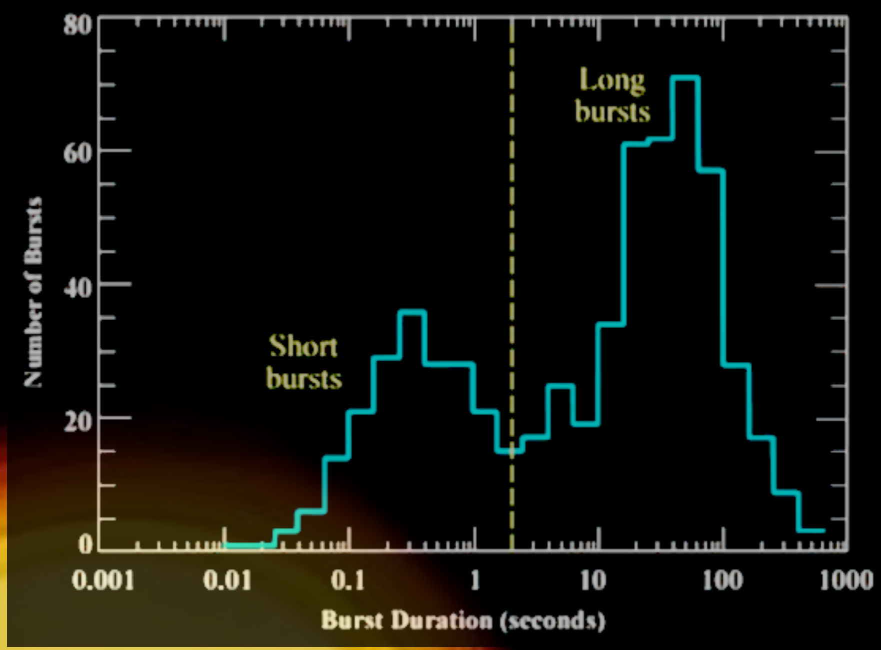
- **black holes** are pure vacuum (and hairless) GR solutions
- they are the endpoint of evolution for massive stars
- stellar-mass black holes are observed in x-ray binaries
- supermassive black holes are inferred at the centers of galaxies

- black-hole binary mergers are non-luminous (in EM!)
- they yield black-hole parameters to constrain population models
- they probe the dynamical, strong-field sector of gravitation
- they are the most luminous transient events in the Universe



- rapidly pulsating radio sources were identified with **neutron stars**
- decreasing orbital period of Hulse-Taylor binary pulsar provided indirect proof of GW emission
- binary pulsars allow precision tests of GR dynamics

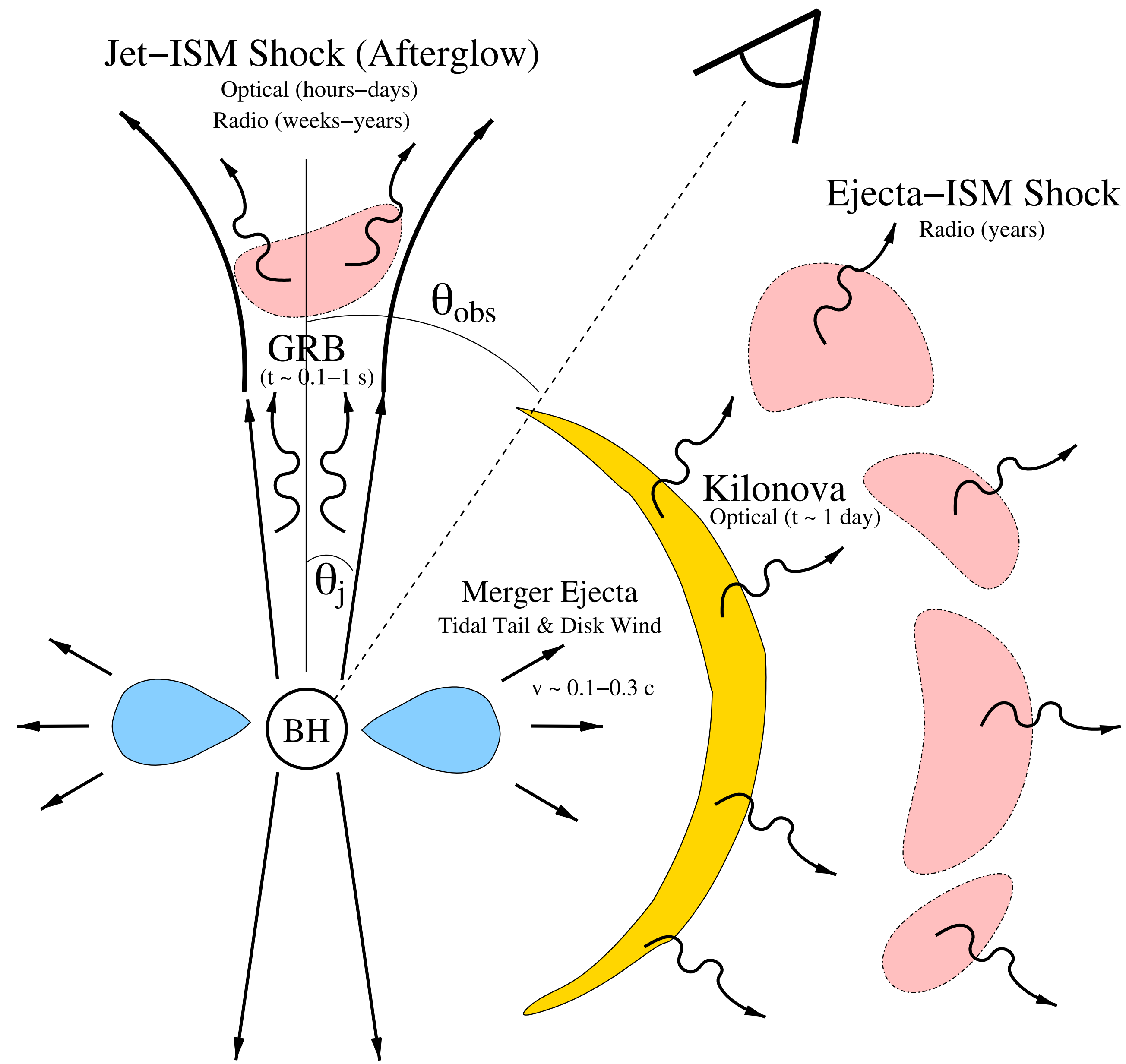




See this movie at https://youtu.be/vw2sLcyV7Vc

- neutron-star binary mergers: well-modeled inspiral, hydro-influenced late-inspiral/merger
- possible engine for short gamma-ray bursts; coincident observations will confirm

a zoo of counterparts
(Metzger & Berger 2011)



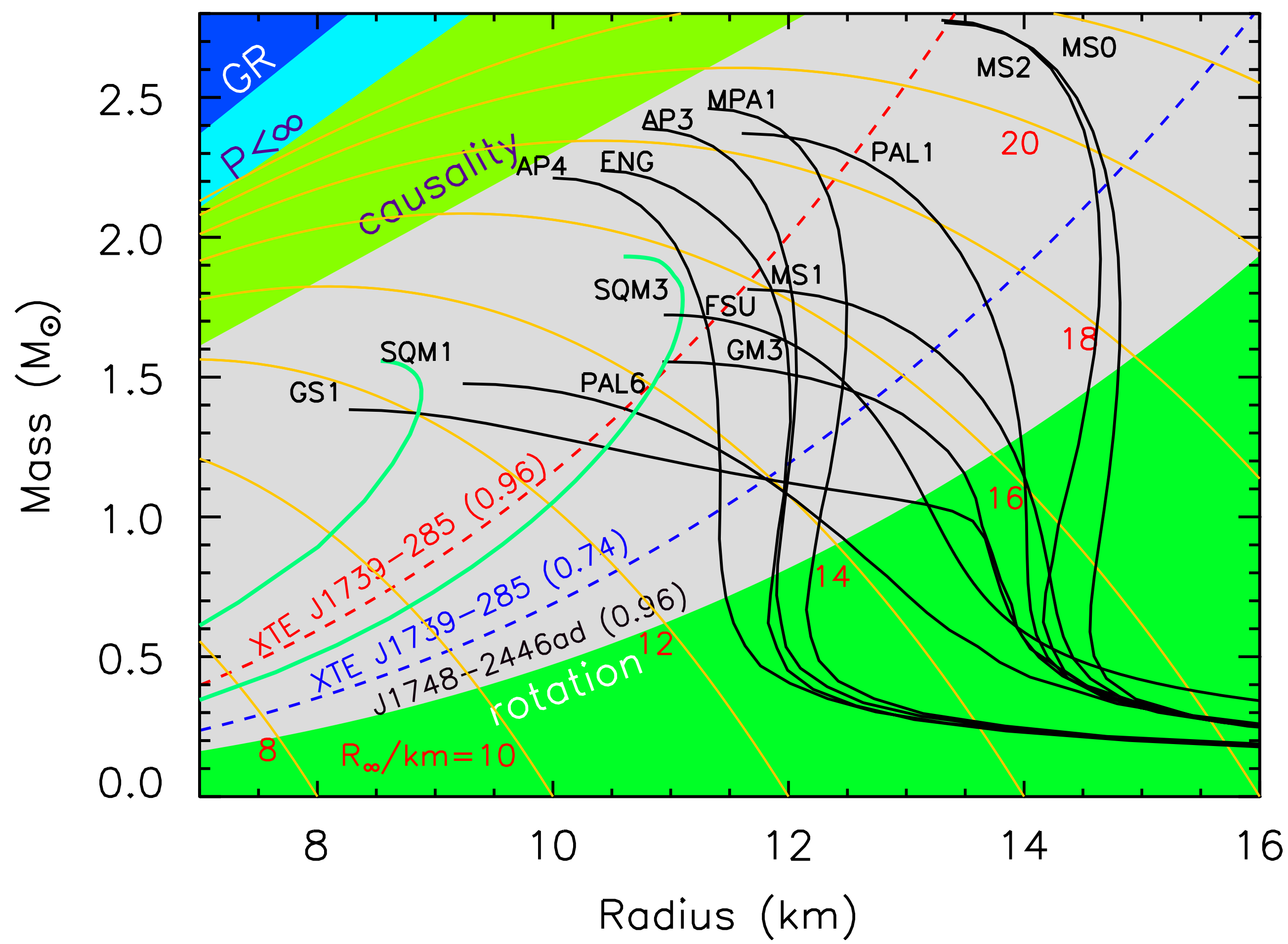
	detectable?	timescale	contamination	detectors
SGRBs	beamed, few/year	seconds	low	Swift/Fermi
orphan afterglows	beamed, 10%	depends on angle	high	LSST
radio	isotropic, weak	months-years	low	wide-field LF higher-sensitivity HF
kilonovae	isotropic, weak	hours-days	high	transient factories, IR? > 6m spectroscopy

neutron stars are unique laboratories for nuclear physics: NS–NS and NS–BH GWs constrain their EOS

- NS maximum mass and radii are poorly known
- maximum mass: EOS stiffness at supernuclear densities
- radius: EOS at nuclear densities (esp. symmetry energy)

- NS–NS GWs: EOS influences tidal deformations in late inspiral, sudden/delayed collapse
- NS–BH GWs: EOS influences NS tidal disruption [MV 2000]

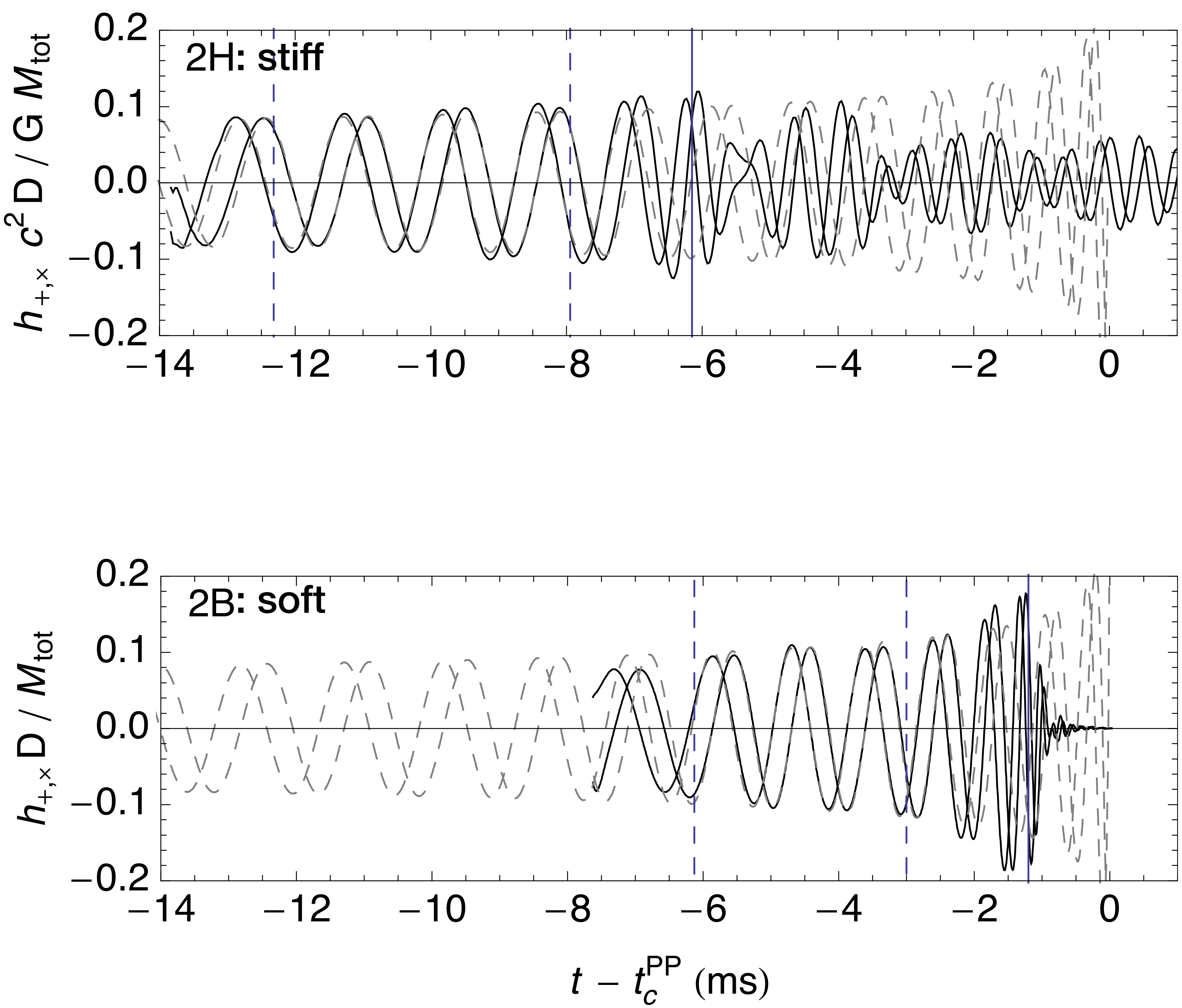
[Lattimer & Prakash 2007]



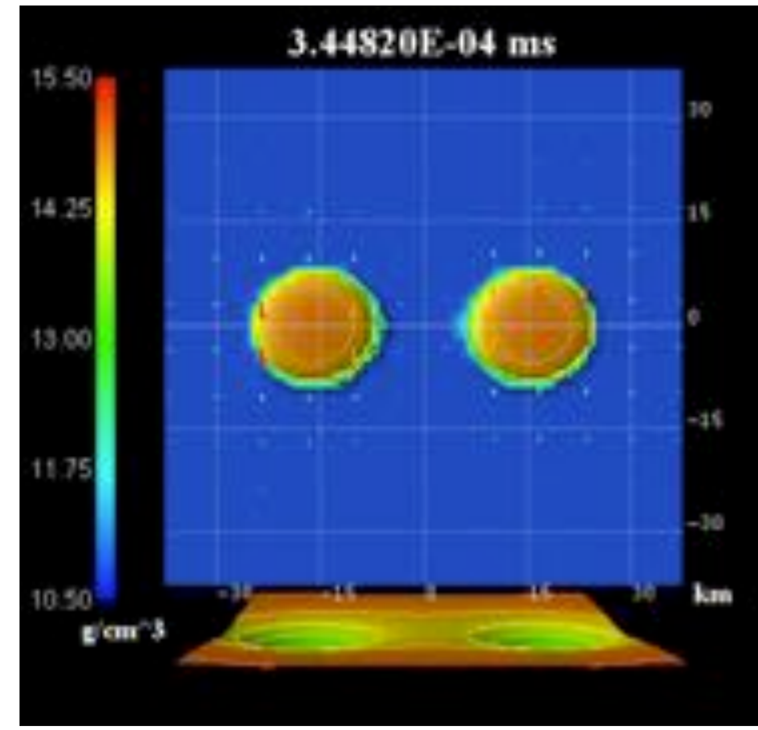
in the late NS–NS inspiral, companions raise quadrupolar tides; inspiral is faster for stiffer EOS

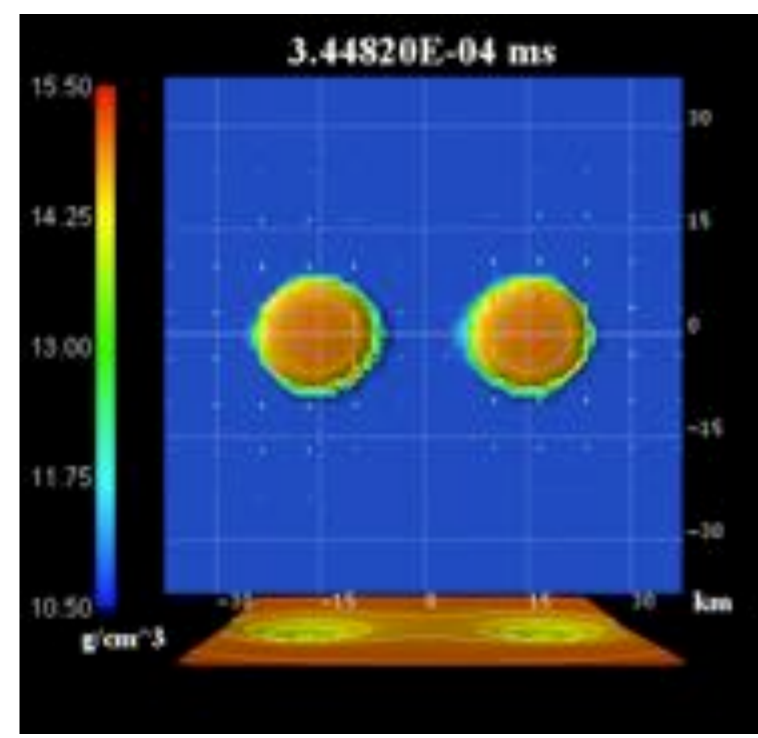
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

$$\lambda = \frac{2}{3} R^5 k_2$$



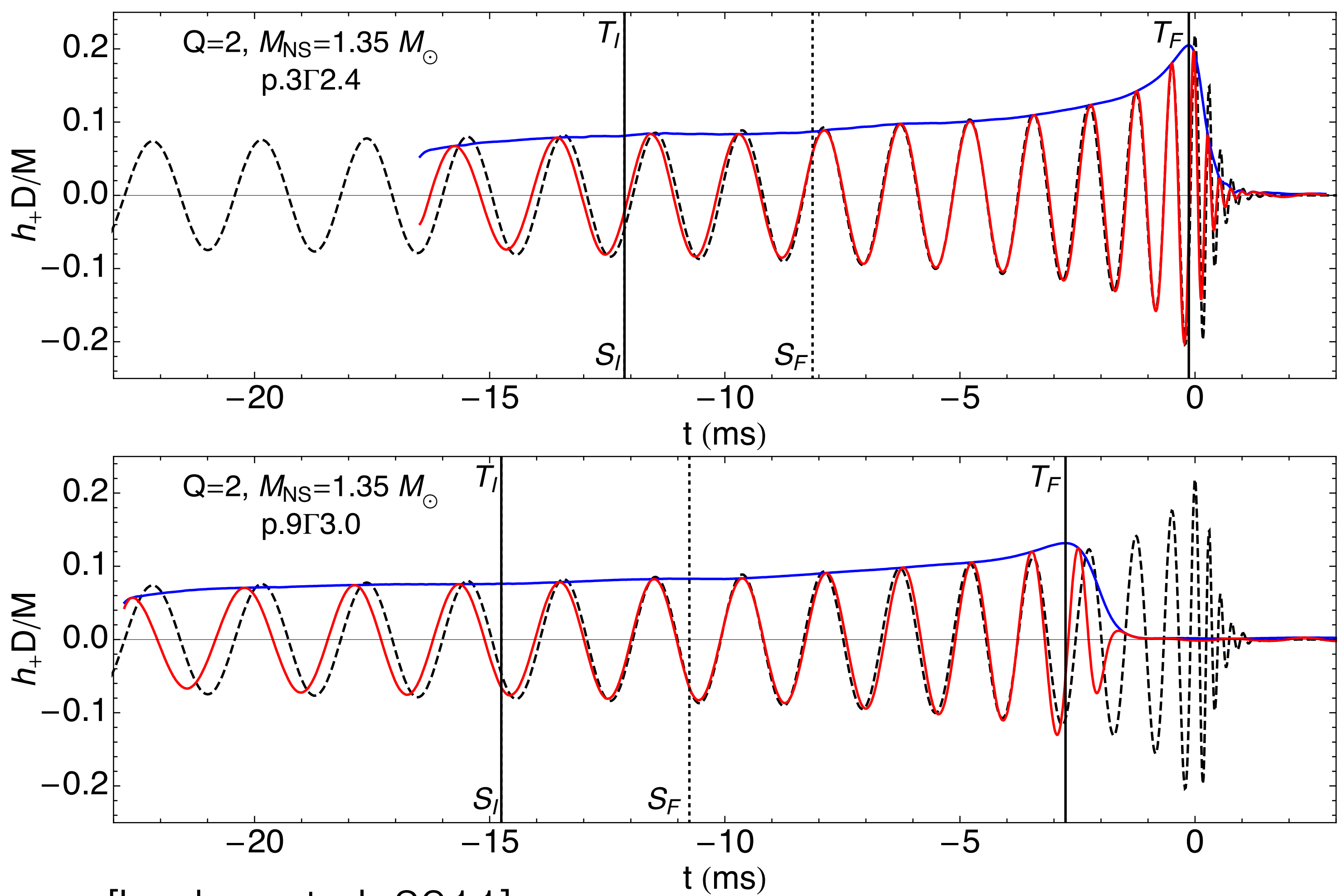
Lackey et al. 2011





Shibata group

in late NS/BH inspiral, larger NS are tidally disrupted, reducing the GW amplitude sharply before merger and suppressing ringdown

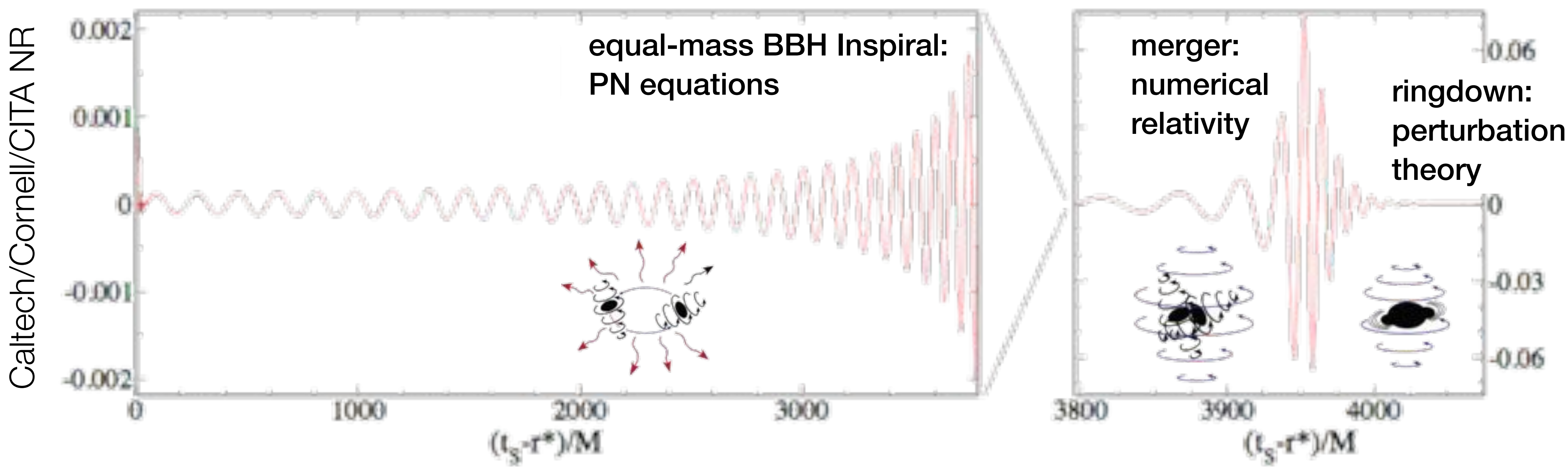


[Lackey et al. 2011]

[Caltech/CITA/Cornell group 2012]

- NS radius can be extracted as well as 10% in aLIGO, a precision comparable to X-ray–burst measurements, but with very different physics
- significant modeling improvements are still needed

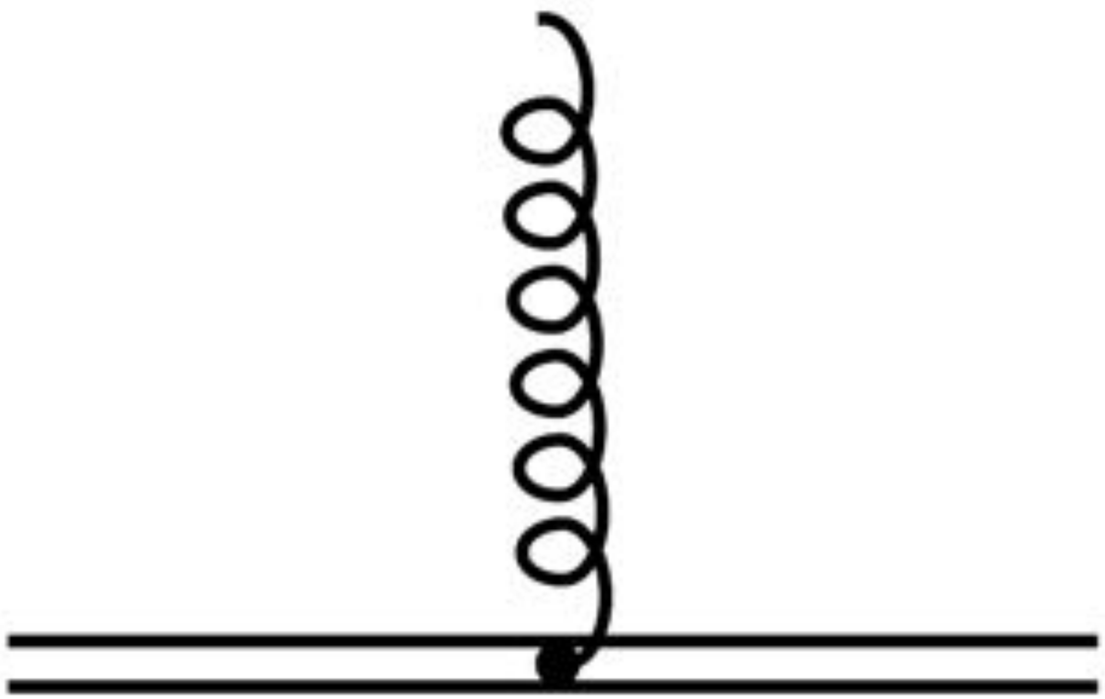
GW science in a nutshell: what's in a binary waveform?



	HF GWs: stellar masses	LF GWs: massive BHs, large separations
astrophysics	populations and histories of compact objects; SN and GRB progenitors*	massive-BH origin and evolution; Galactic WD-binary populations and interactions
nuclear physics	NS EOS, r-mode processes*	
cosmology	standard sirens*	
fundamental gravity	strong-field and radiation-sector dynamics	
black-hole structure		tests of no-hair theorem with EMRIs, ringdowns

1.3 — detection

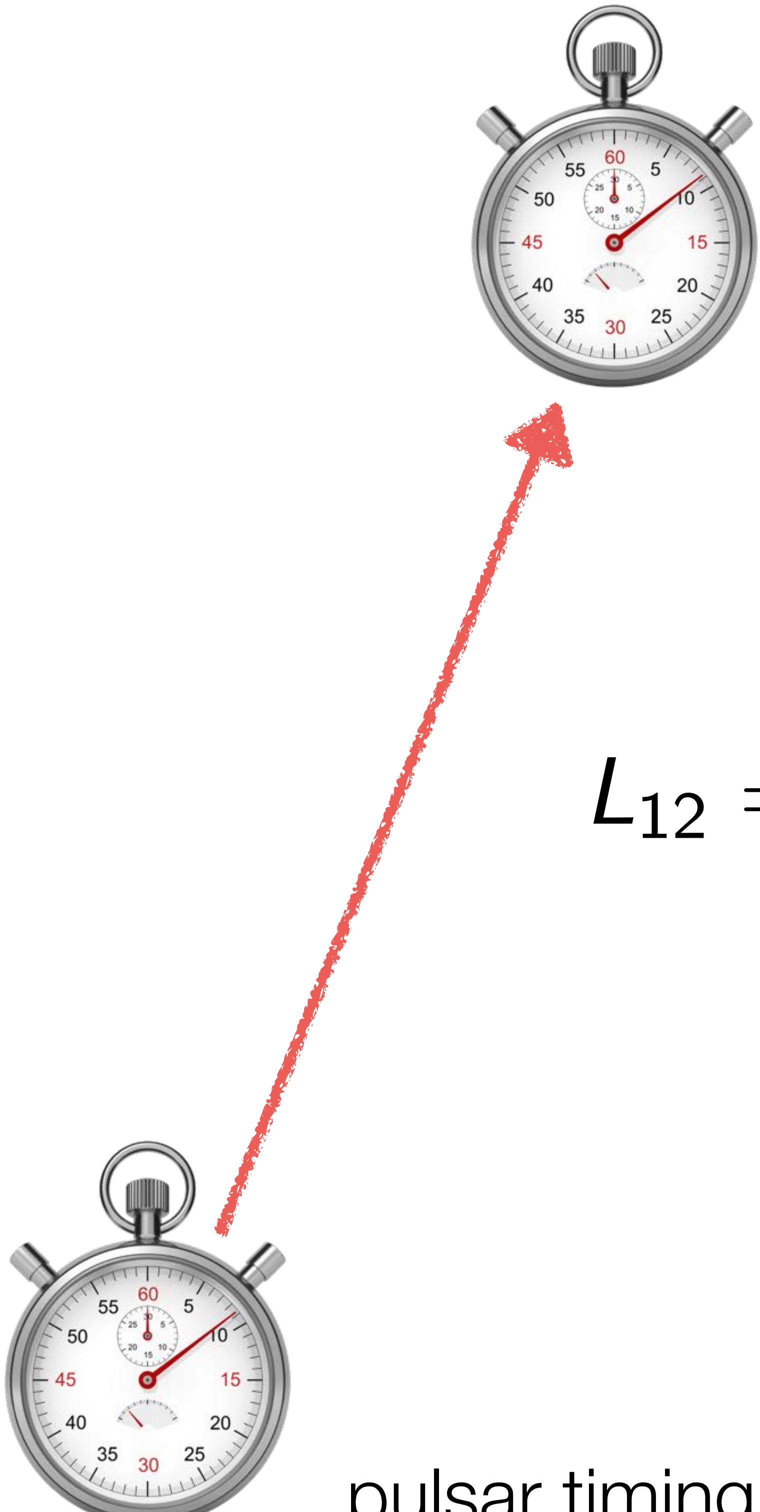
Joseph Weber, 1919-2000



Gravitational wave

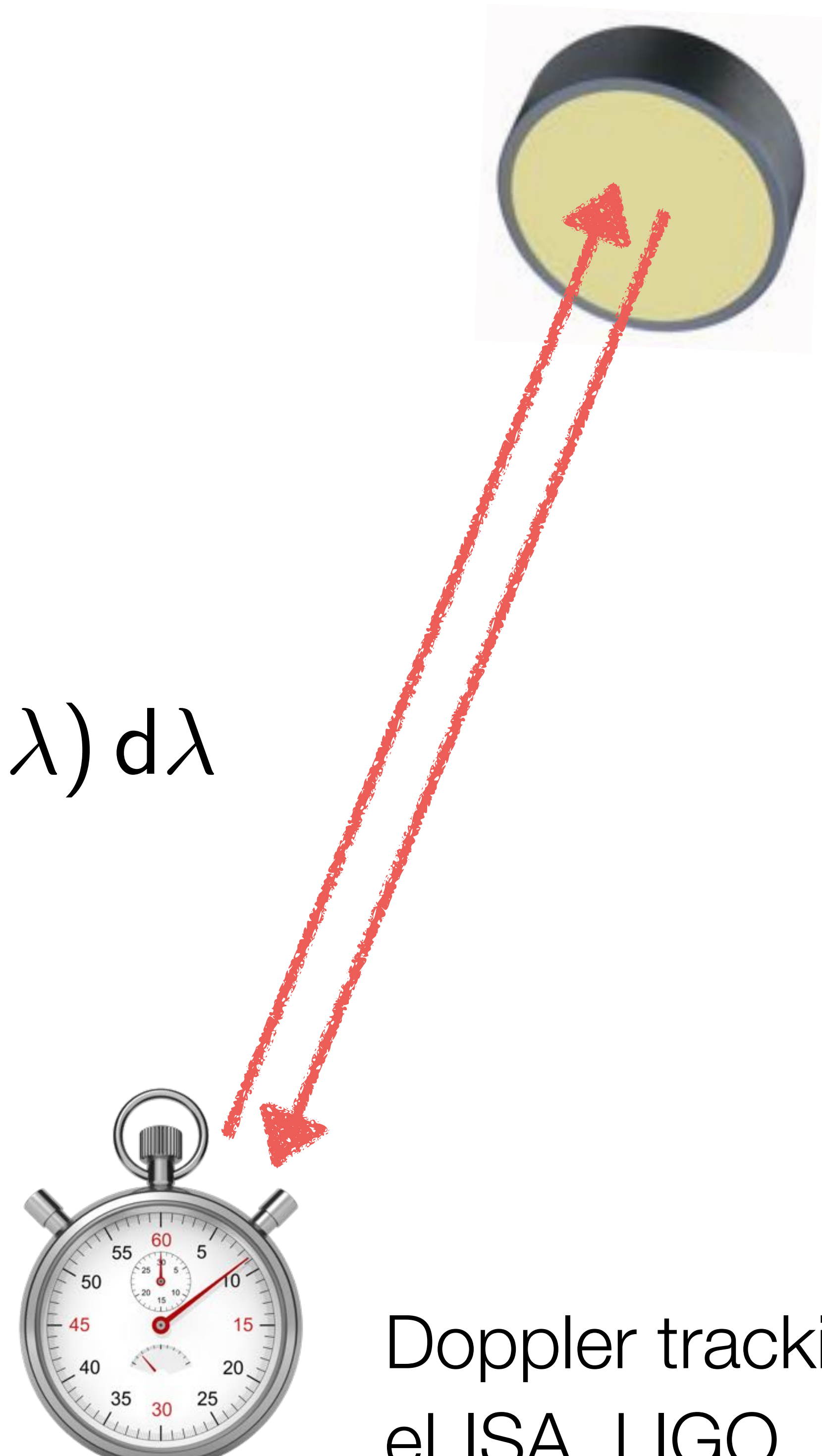
Gravitational-wave detector

Gravitational-wave detector



$$L_{12} = L_{12}^{\text{no gw}} + \frac{1}{2}\int_1^2 h(\lambda)\,\mathrm{d}\lambda$$

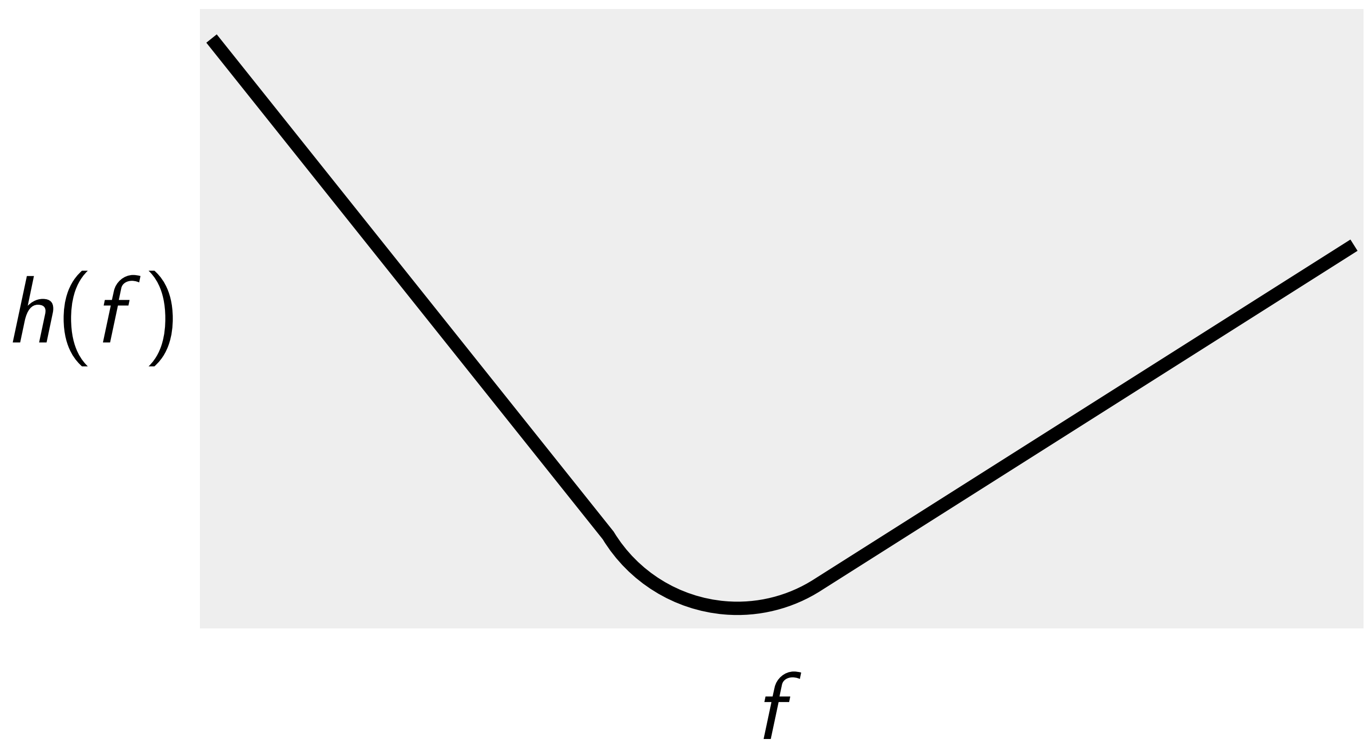
pulsar timing



Doppler tracking,
eLISA, LIGO

Gravitational-wave detector sensitivity

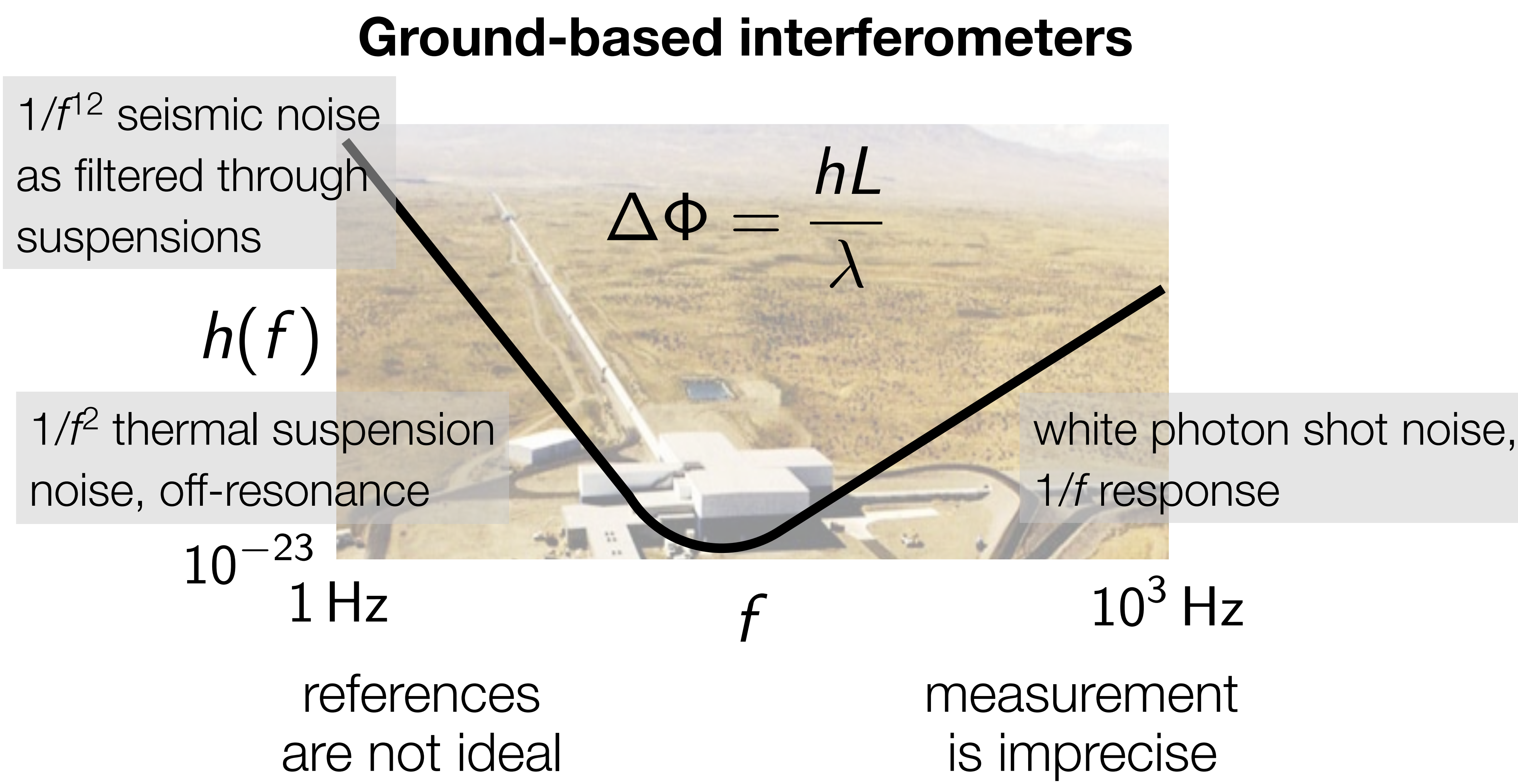
Universal: “it must get better before it gets worse”



references are not ideal

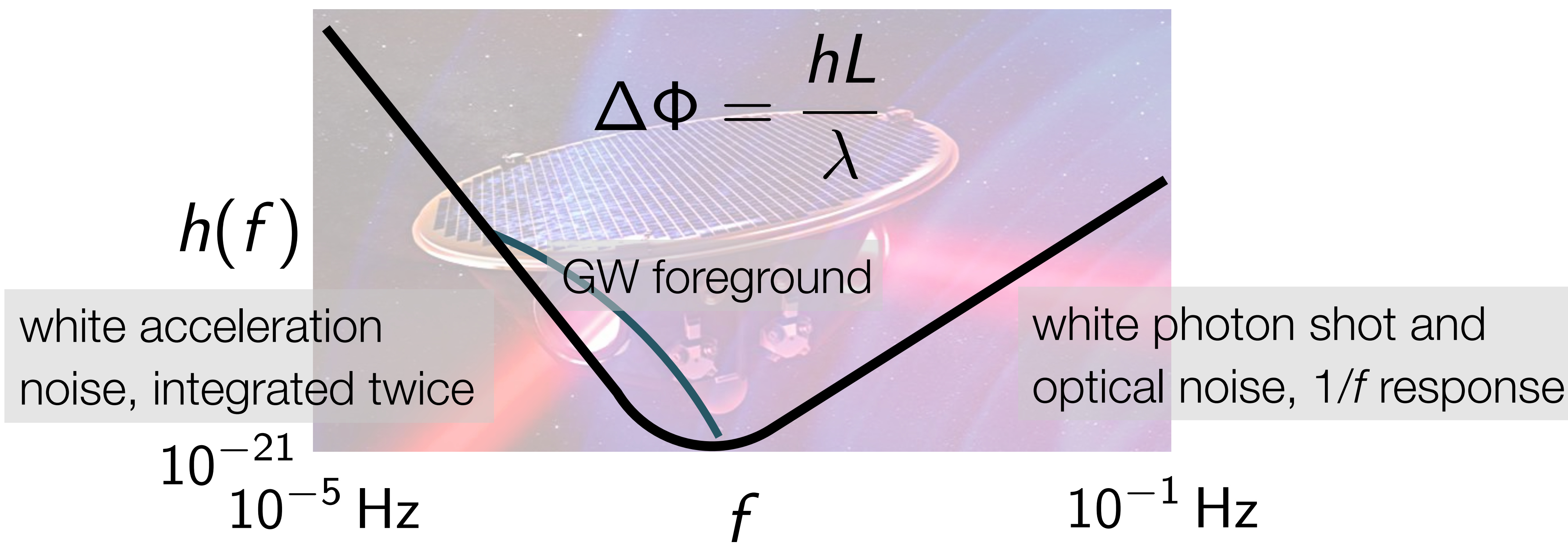
measurement is imprecise

Gravitational-wave detector sensitivity



Gravitational-wave detector sensitivity

Space-based interferometers



references are not ideal

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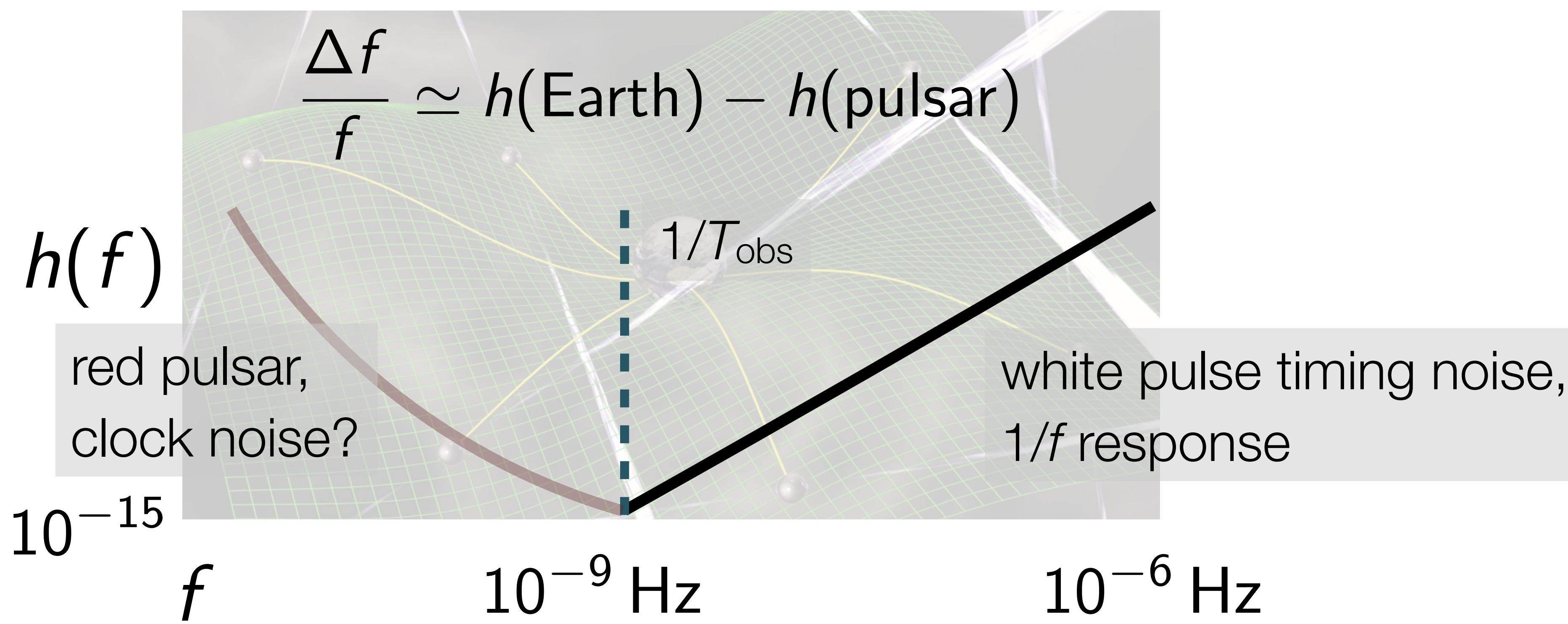
Gravitational-wave detector sensitivity

Pulsar timing



references
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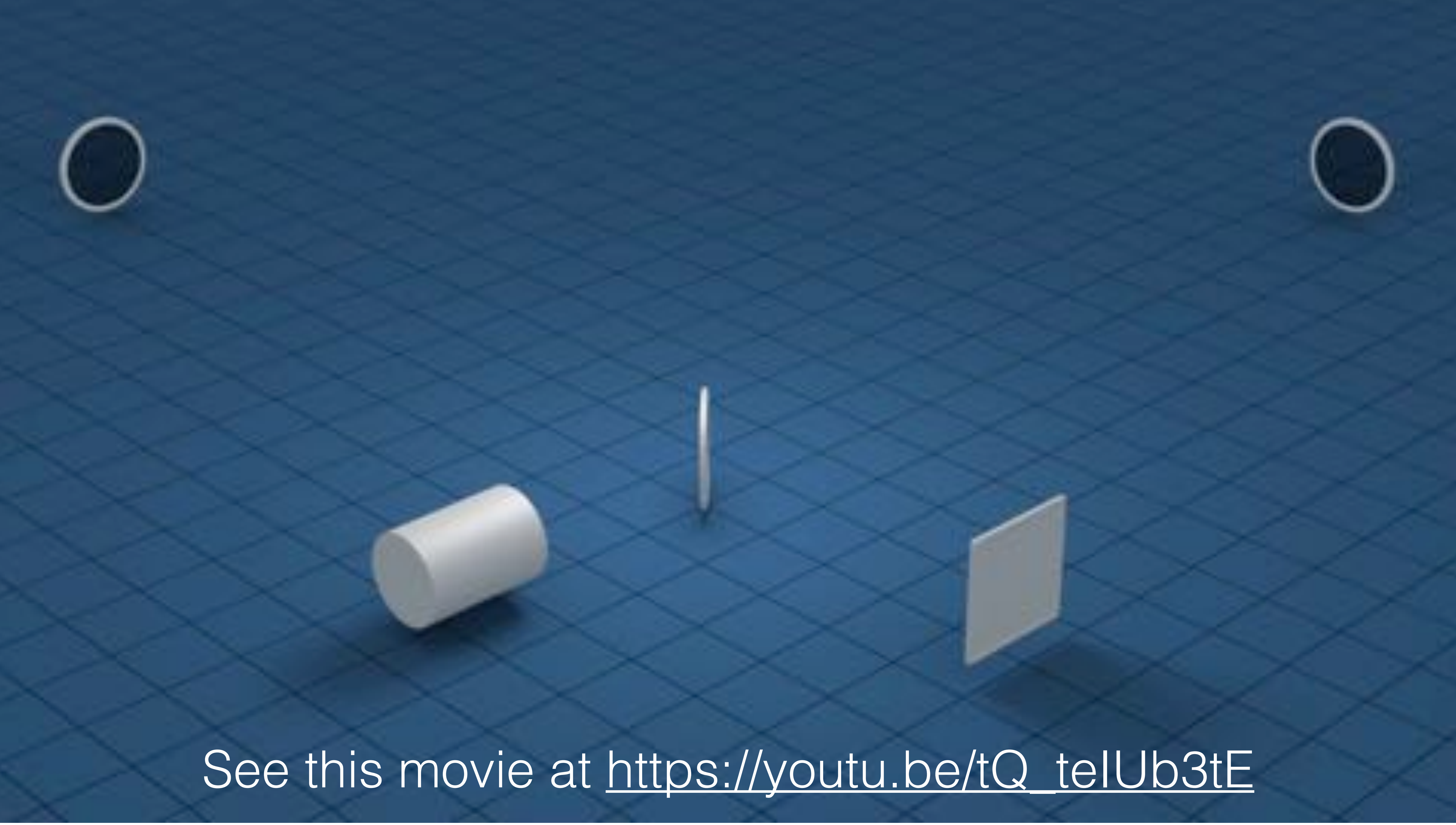
measurement
is imprecise



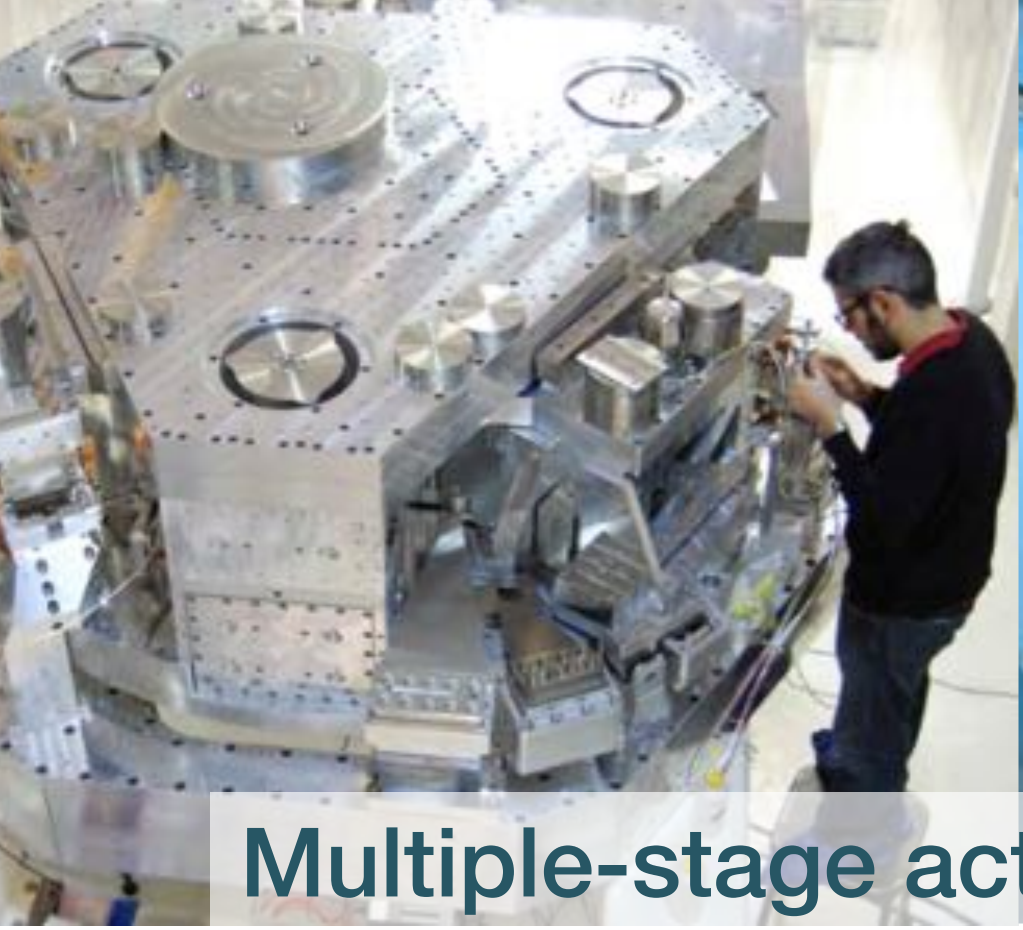
- **ground-based interferometers** use lasers to monitor differential length changes of km-size arms
- sensitive at 10s to 1000s Hz; extremely precise in measuring positions; limited by seismic, thermal, photon noise

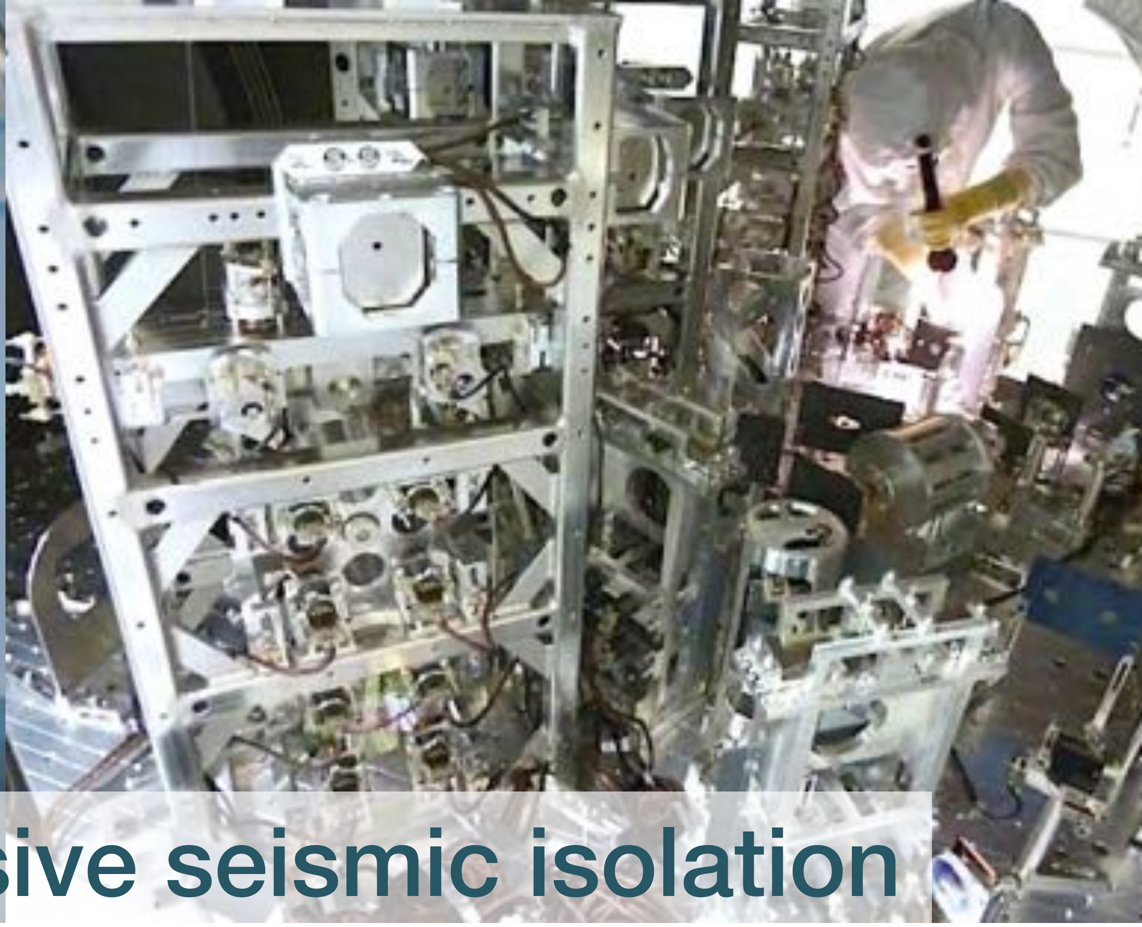


Advanced LIGO & Advanced Virgo

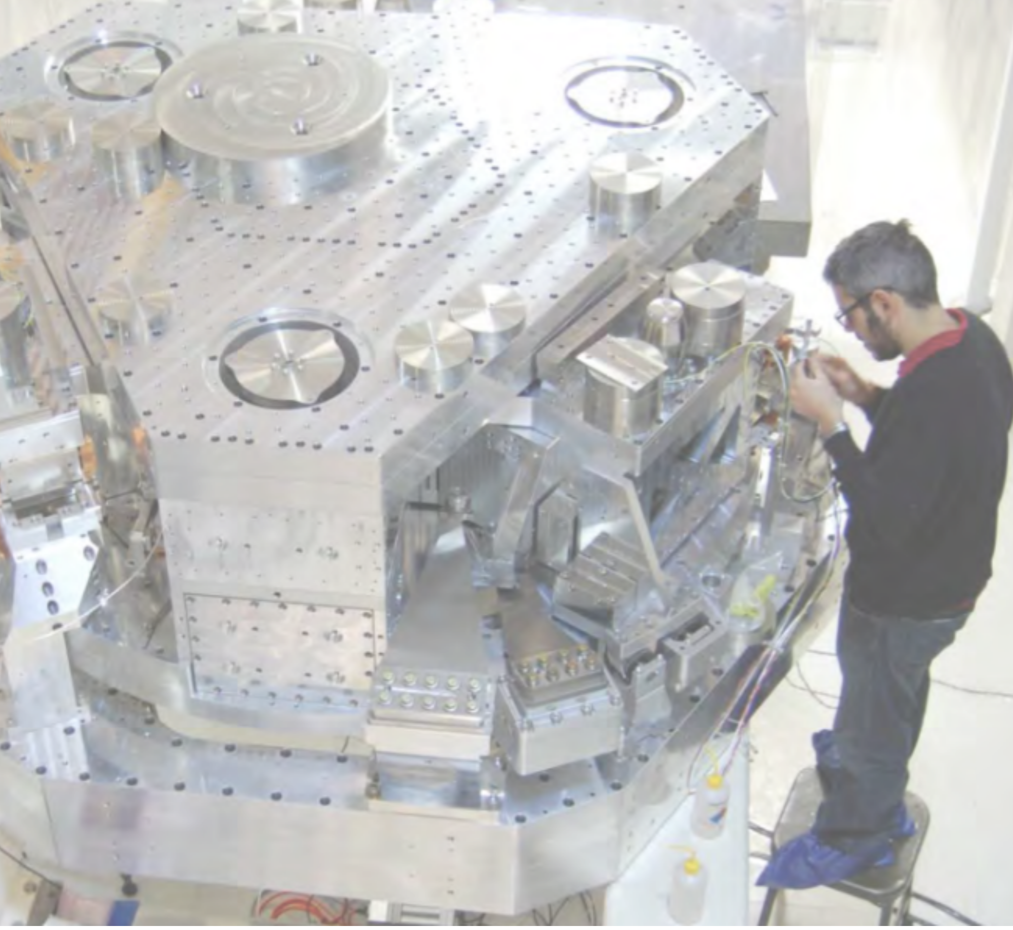


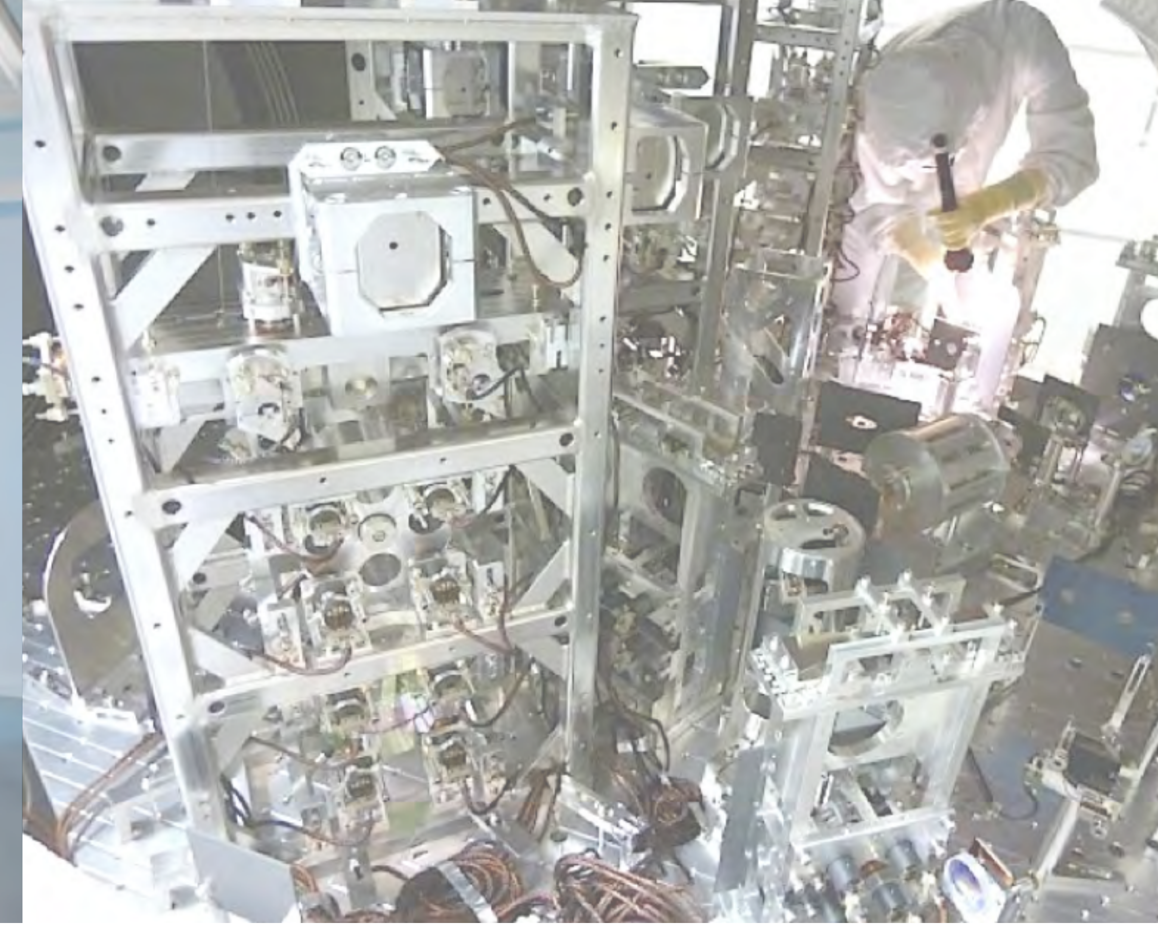
High-vacuum tubes and chambers

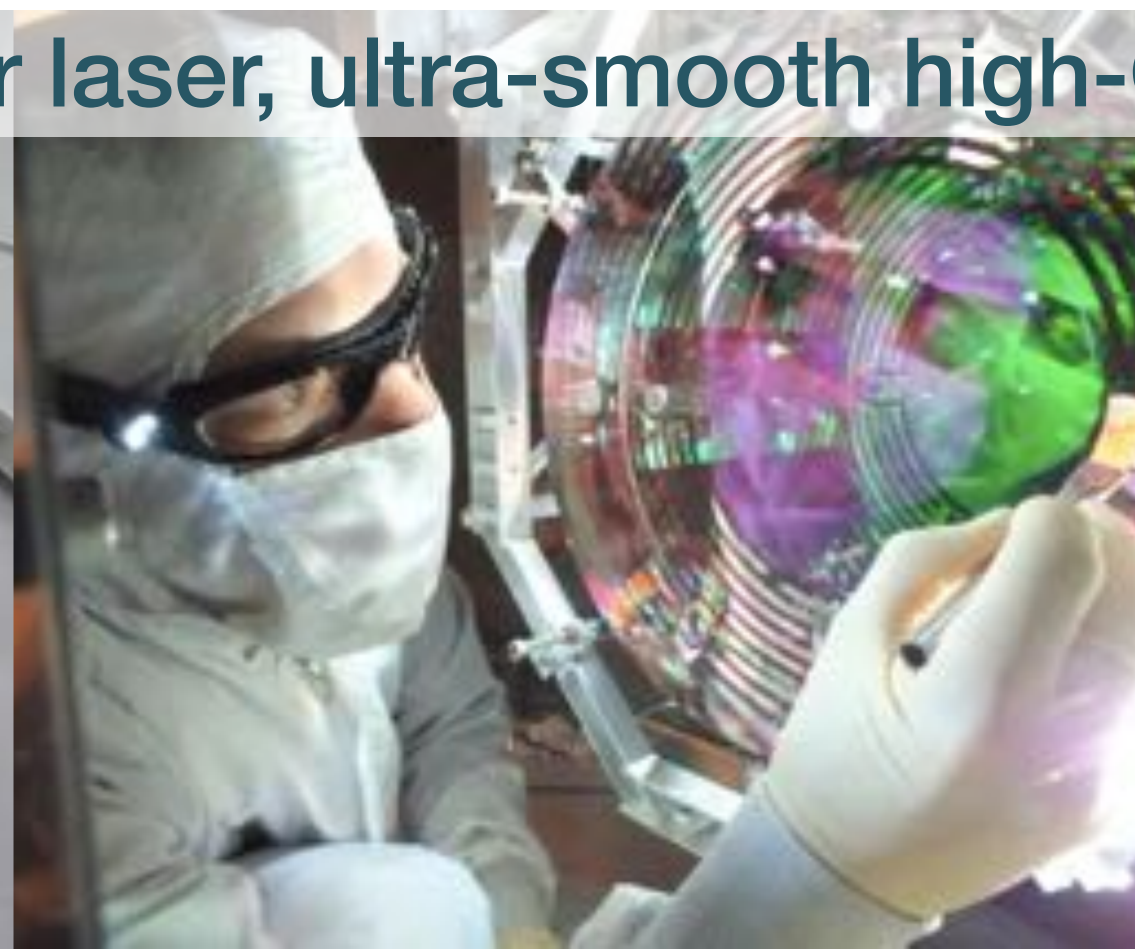
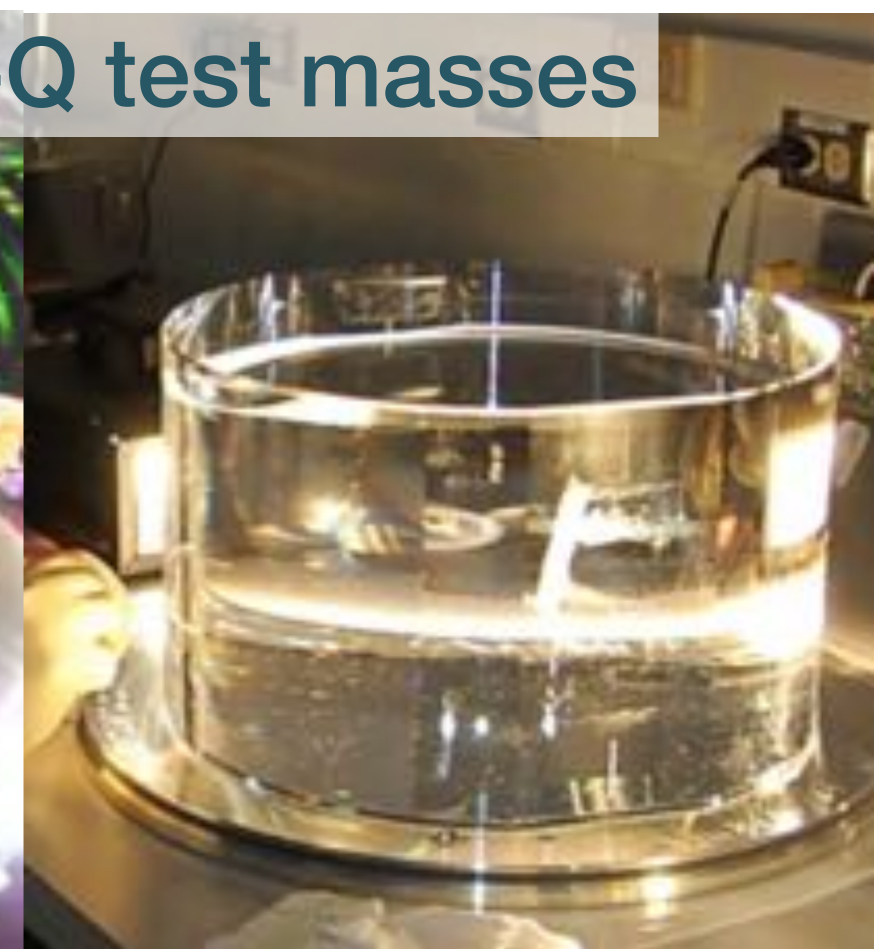


Multiple-stage active and passive seismic isolation

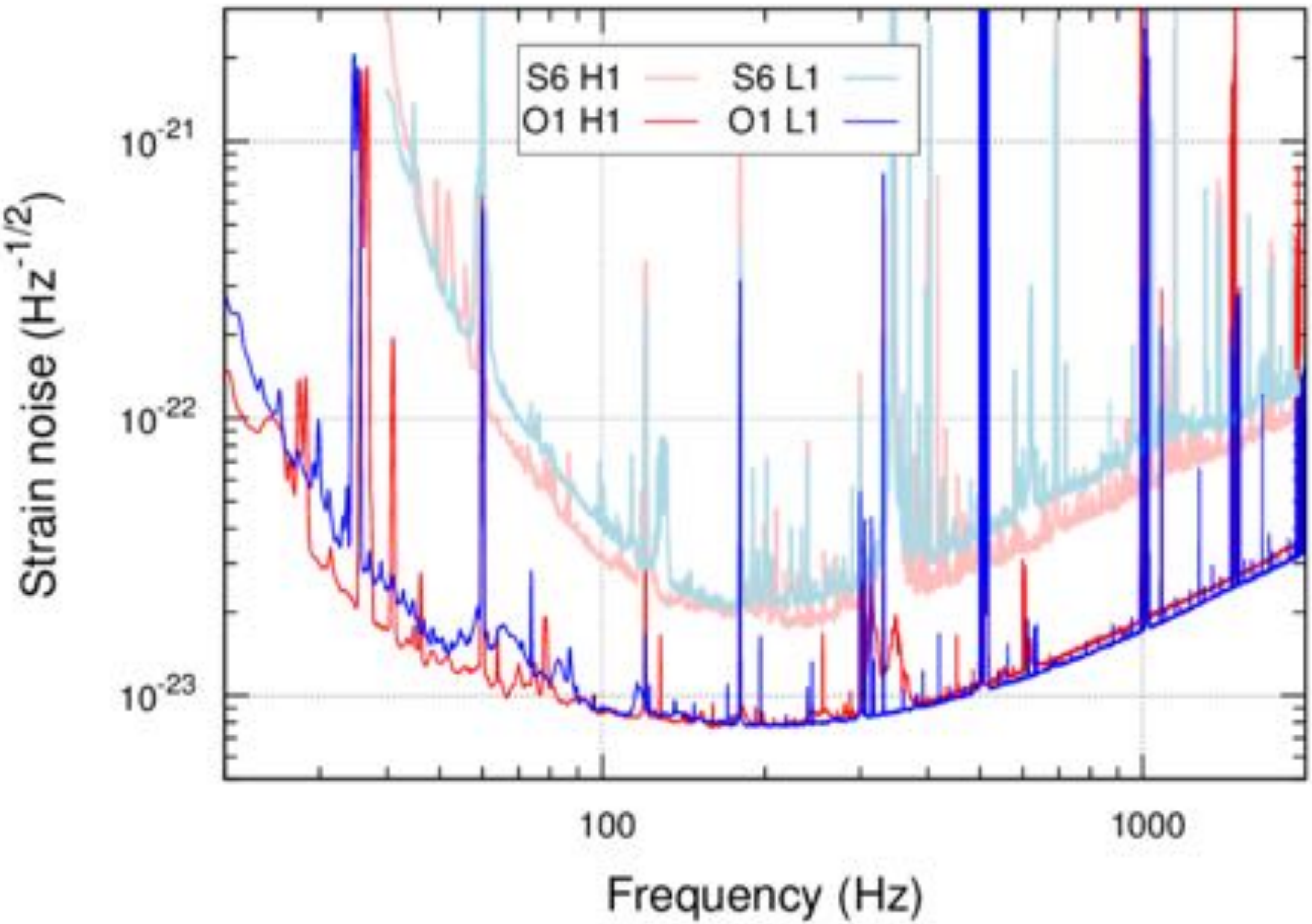



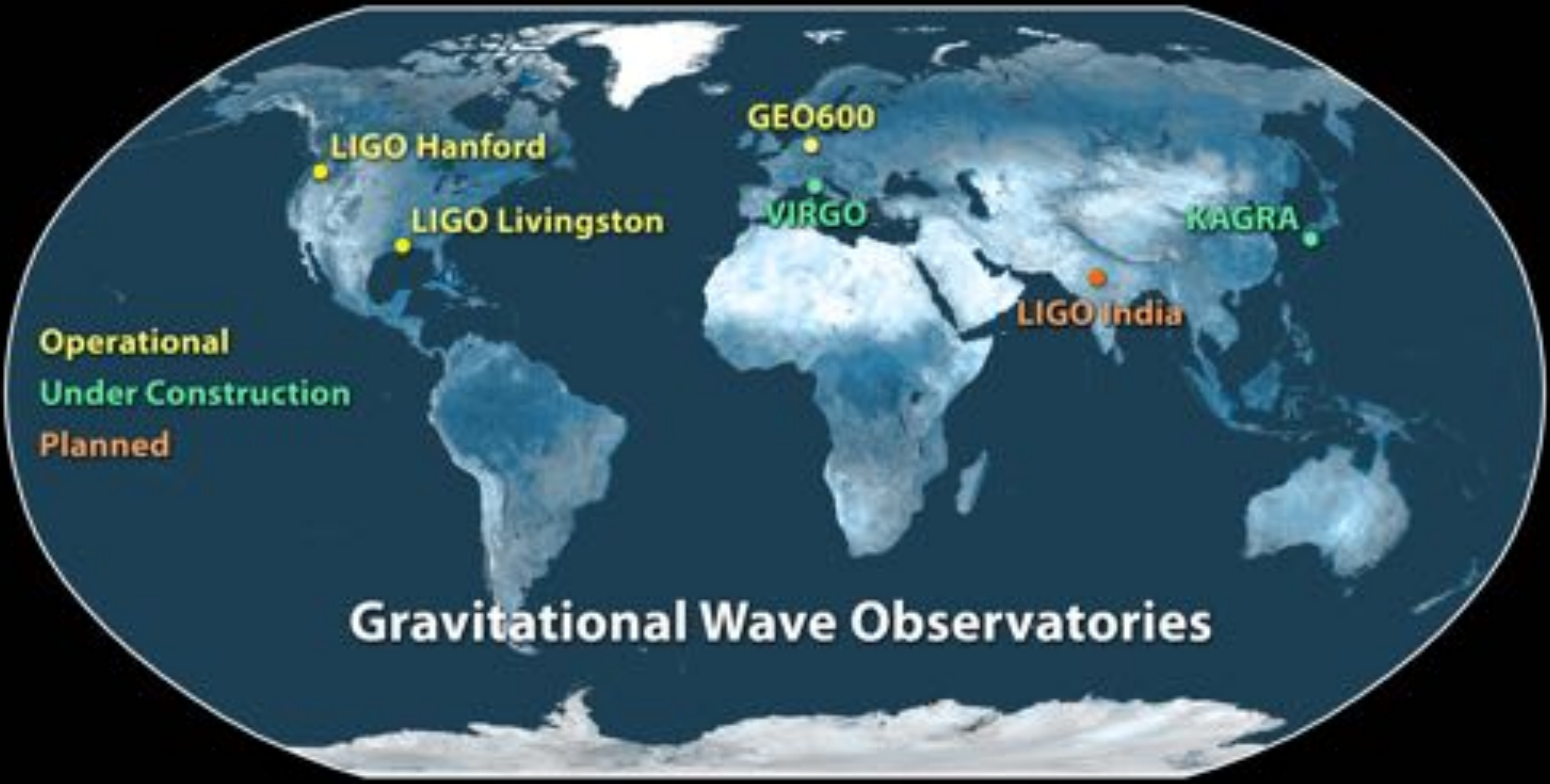


High-power laser, ultra-smooth high-Q test masses

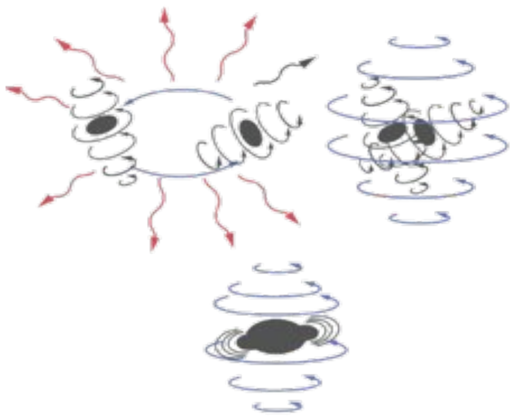




Advanced LIGO sensitivity, September 2016



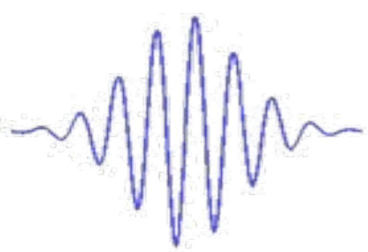

GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

LIGO–Virgo science goals…



Inspiral/merger/ringdown GWs from NS and BH binaries

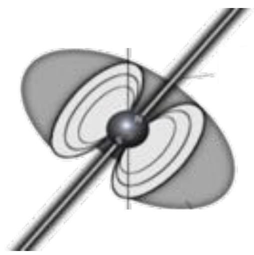
- determine rate of mergers and parameter distributions
- establish GRB link to NS–NS mergers
- probe NS equation of state
- test strong-field GR and alternative theories



Modeled and unmodeled bursts

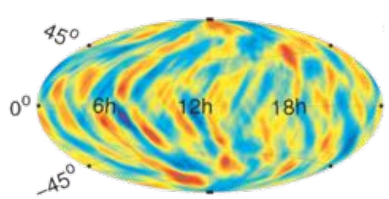
- observe core collapse of massive stars; determine blow-up mechanism (neutrino, MHD, acoustic)
- discover IMBHs (mergers, ringdowns, eccentric encounters)
- look for cosmic (super-)string cusps
- search in coincidence with EM and neutrino events (GRBs, SGRs, pulsar glitches, supernovae), compare energetics

...LIGO–Virgo science goals



Continuous waves from rapidly rotating NSs

- detect elastic or magnetic deformations; unstable mode oscillations; free precession
- understand properties of solid and fluid NS phases (inertia tensor, magnetic field, viscosity, internal structure)
- discover accretion-powered GW emission in LMXBs



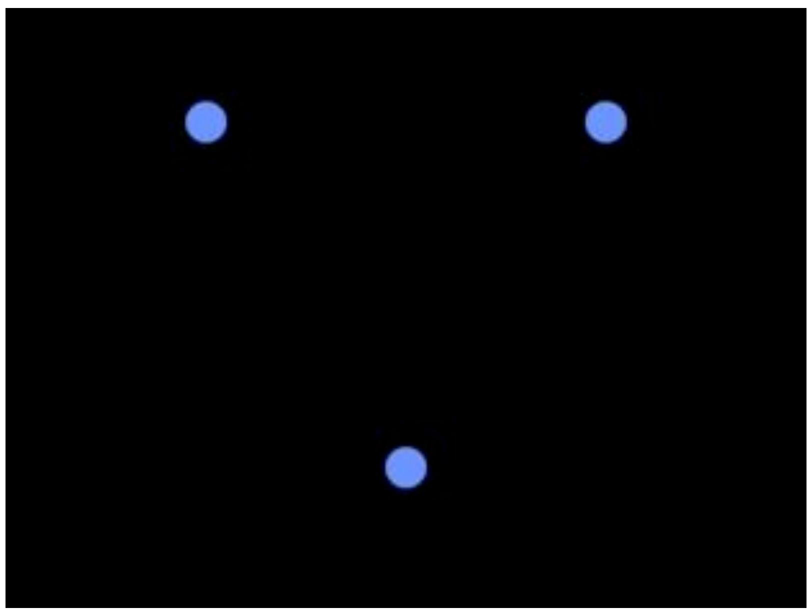
Cosmological and astrophysical stochastic backgrounds

- constrain inflationary, superstring, pre-Big Bang models
- look for cosmic strings
- constrain source populations in the Galactic neighborhood

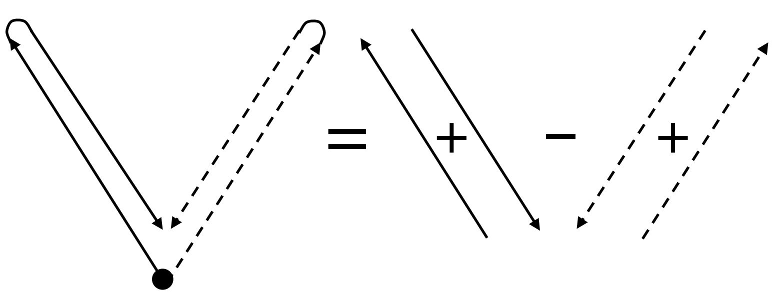
- **LISA**: a 2030s ESA mission with NASA participation, will use laser interferometer to monitor picometer fluctuations in the Mkm distance between freely-falling test masses protected by the spacecraft

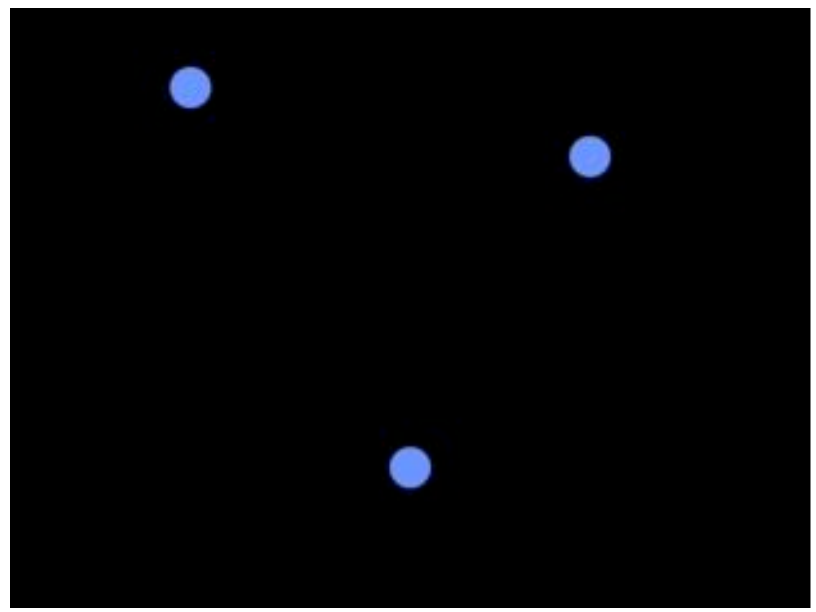
To remove clock (laser-frequency) noise 160 dB louder than GWs we combine one-way measurements in the interferometers synthesized with Time Delay Interferometry

(D. Shaddock)

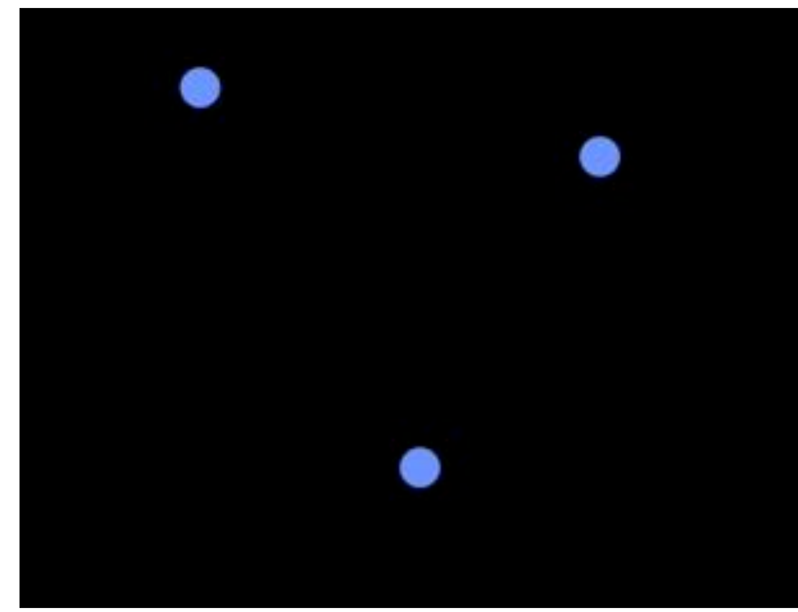


- Equal arms

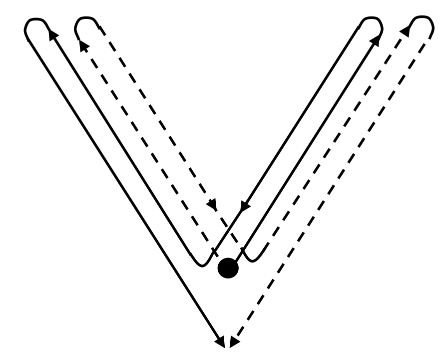




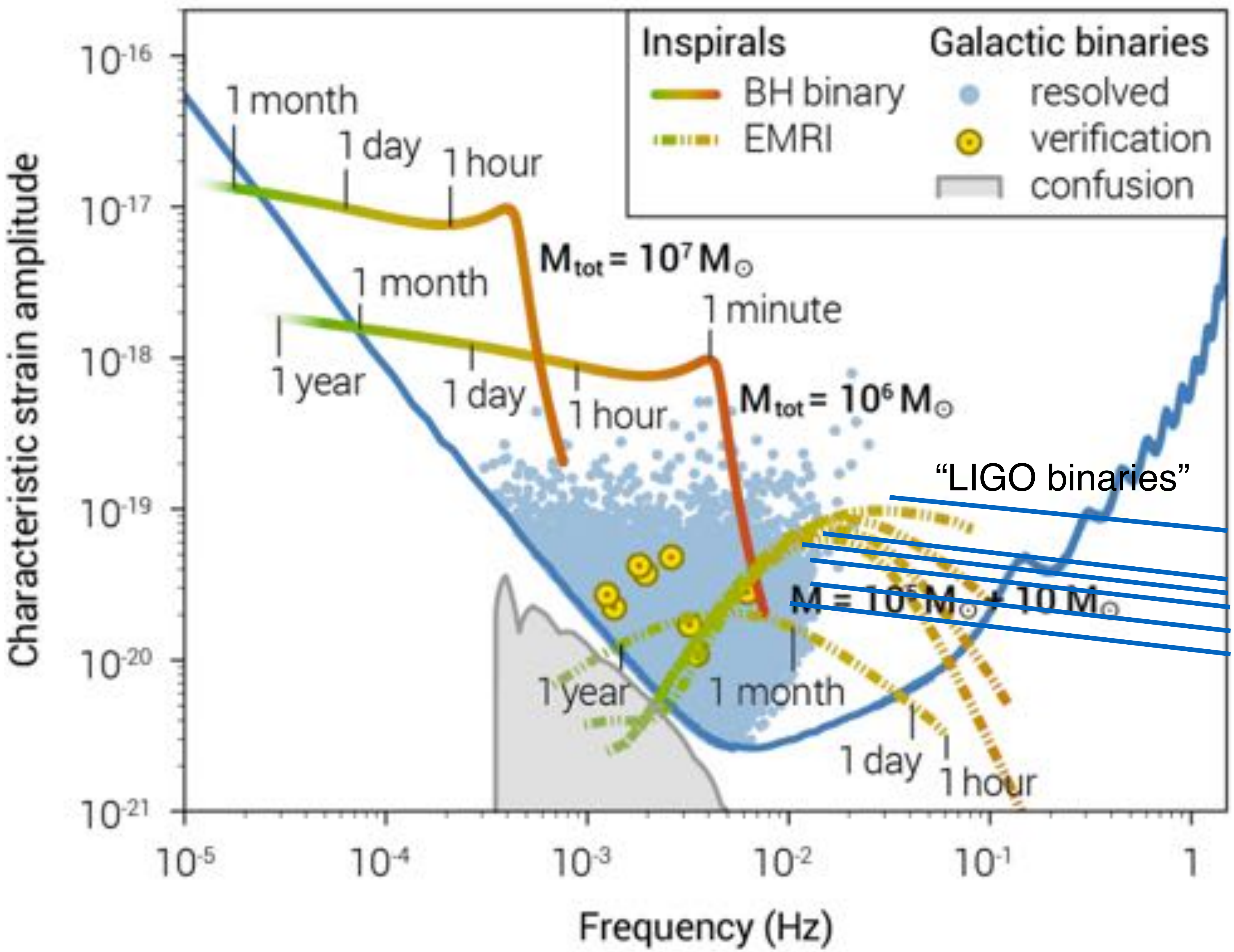
- Unequal arms



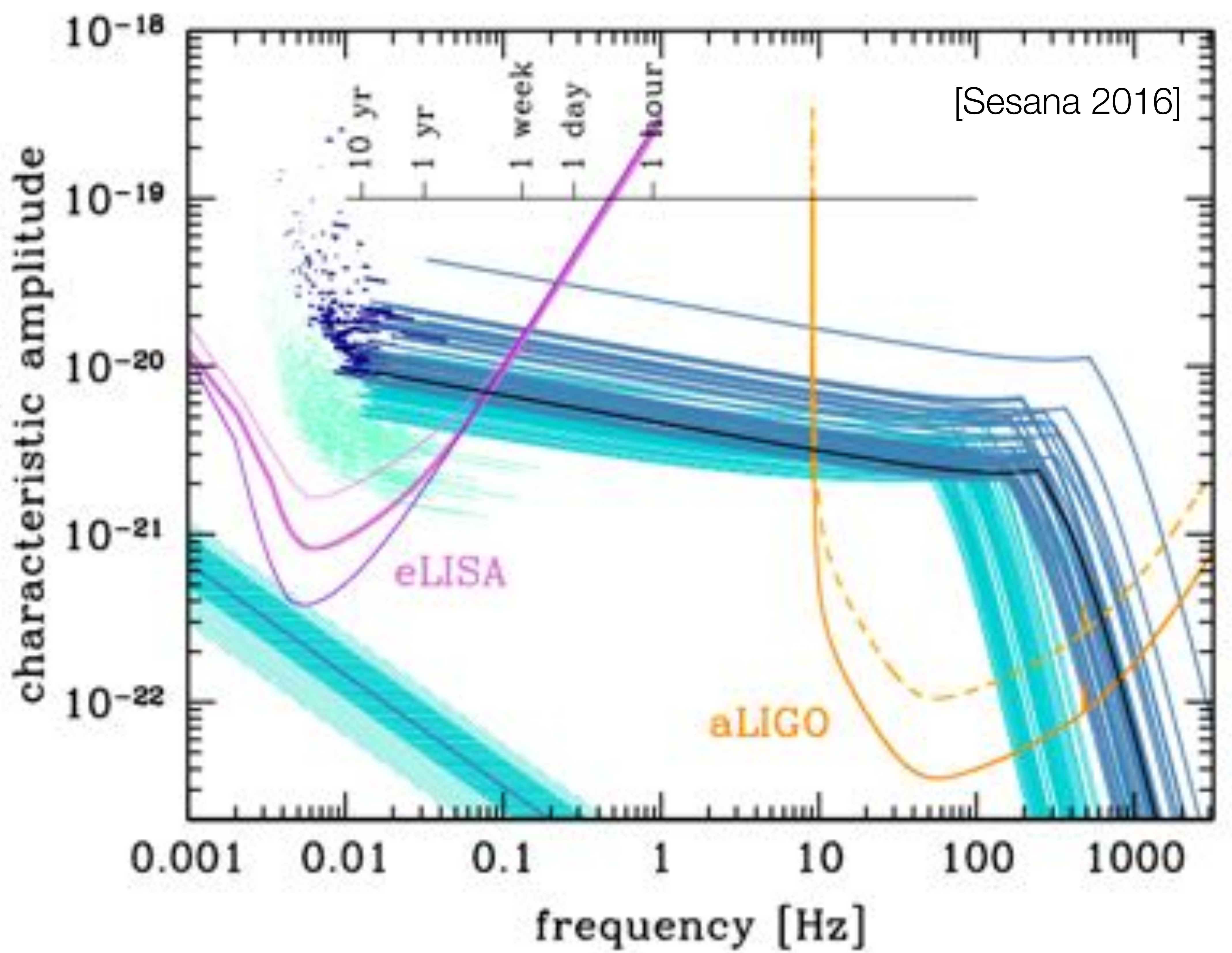
- TDI



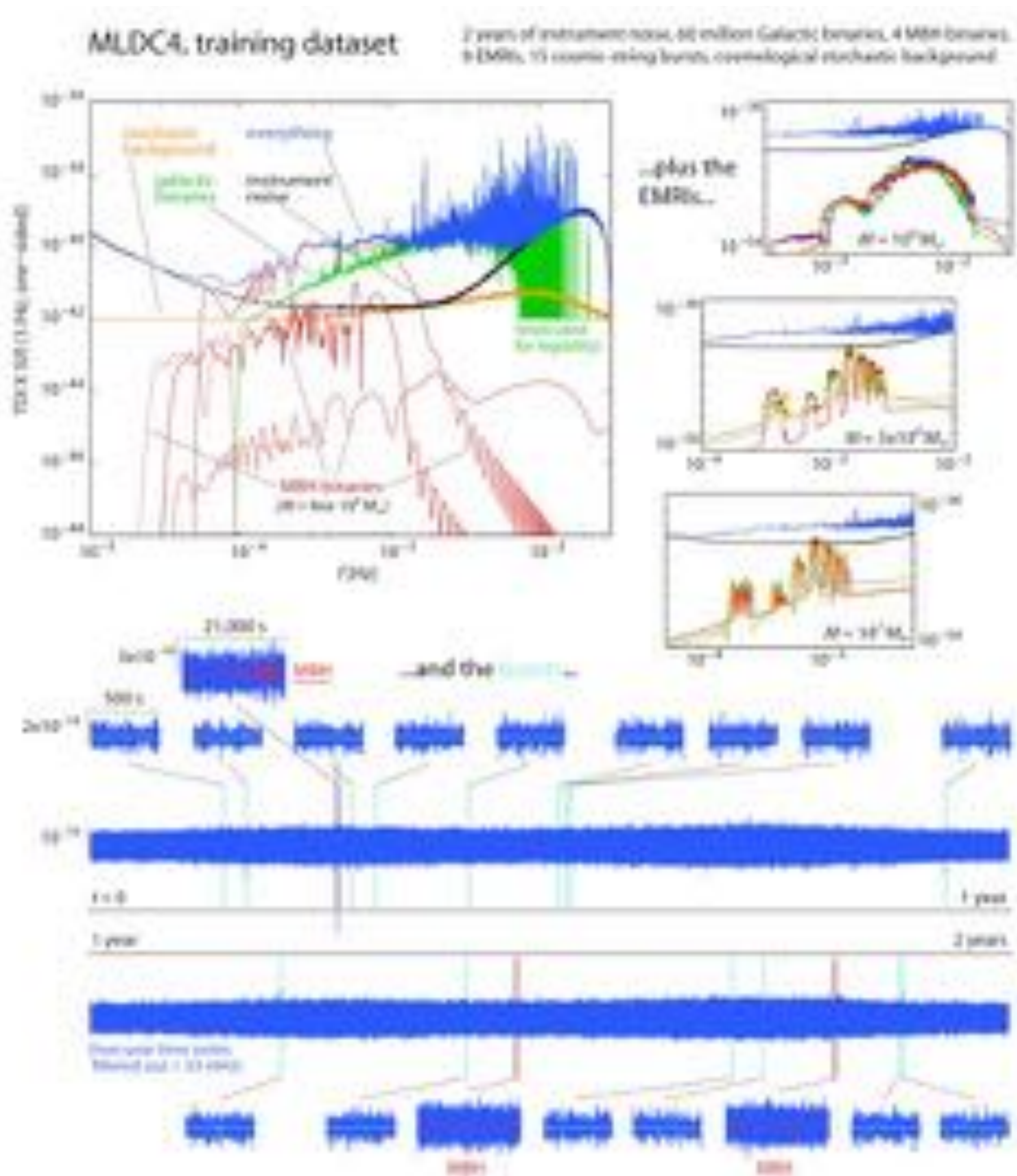
LISA science goals (classic)



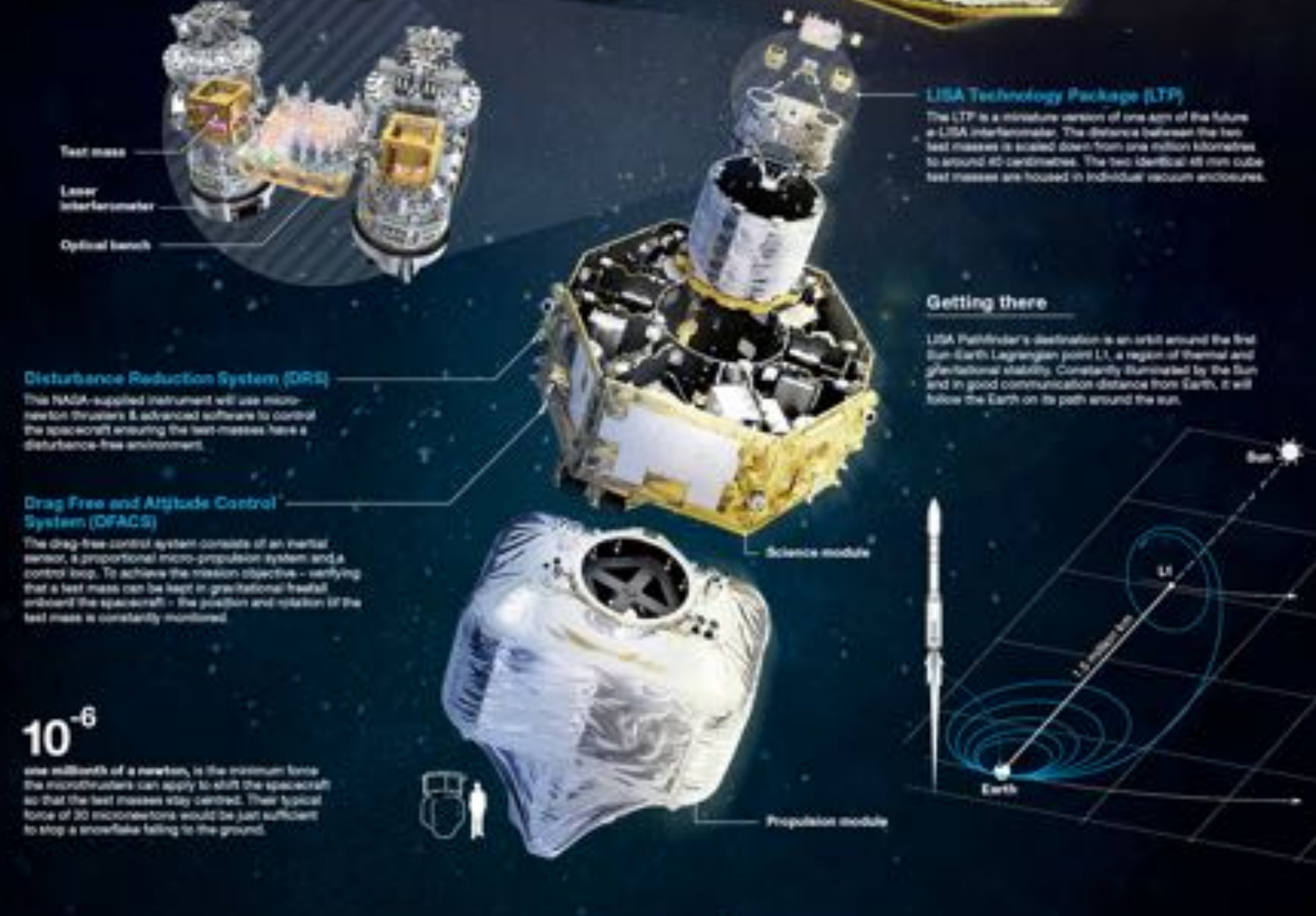
LISA science goals (new)



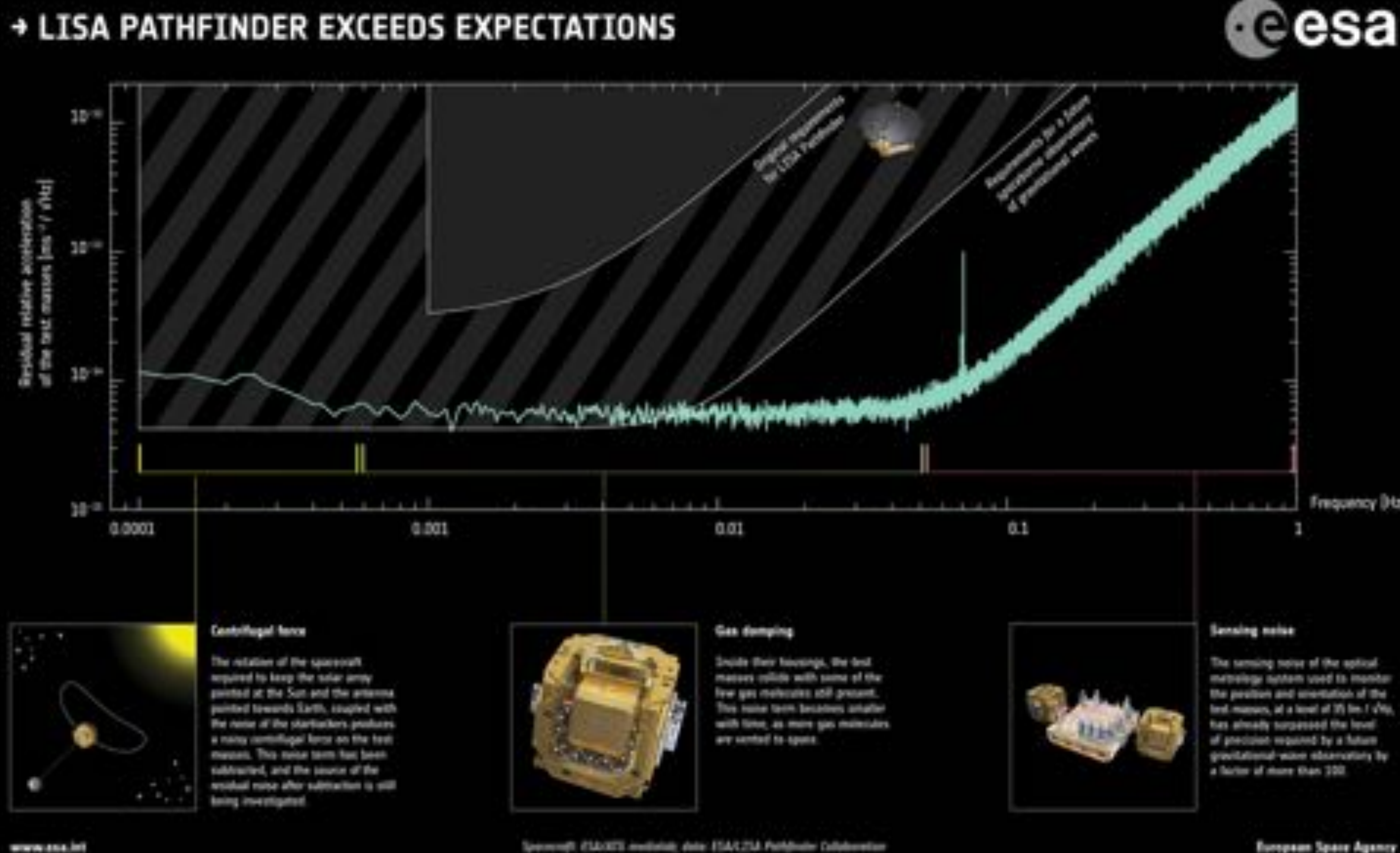
Proving data analysis: the Mock LISA Data Challenges

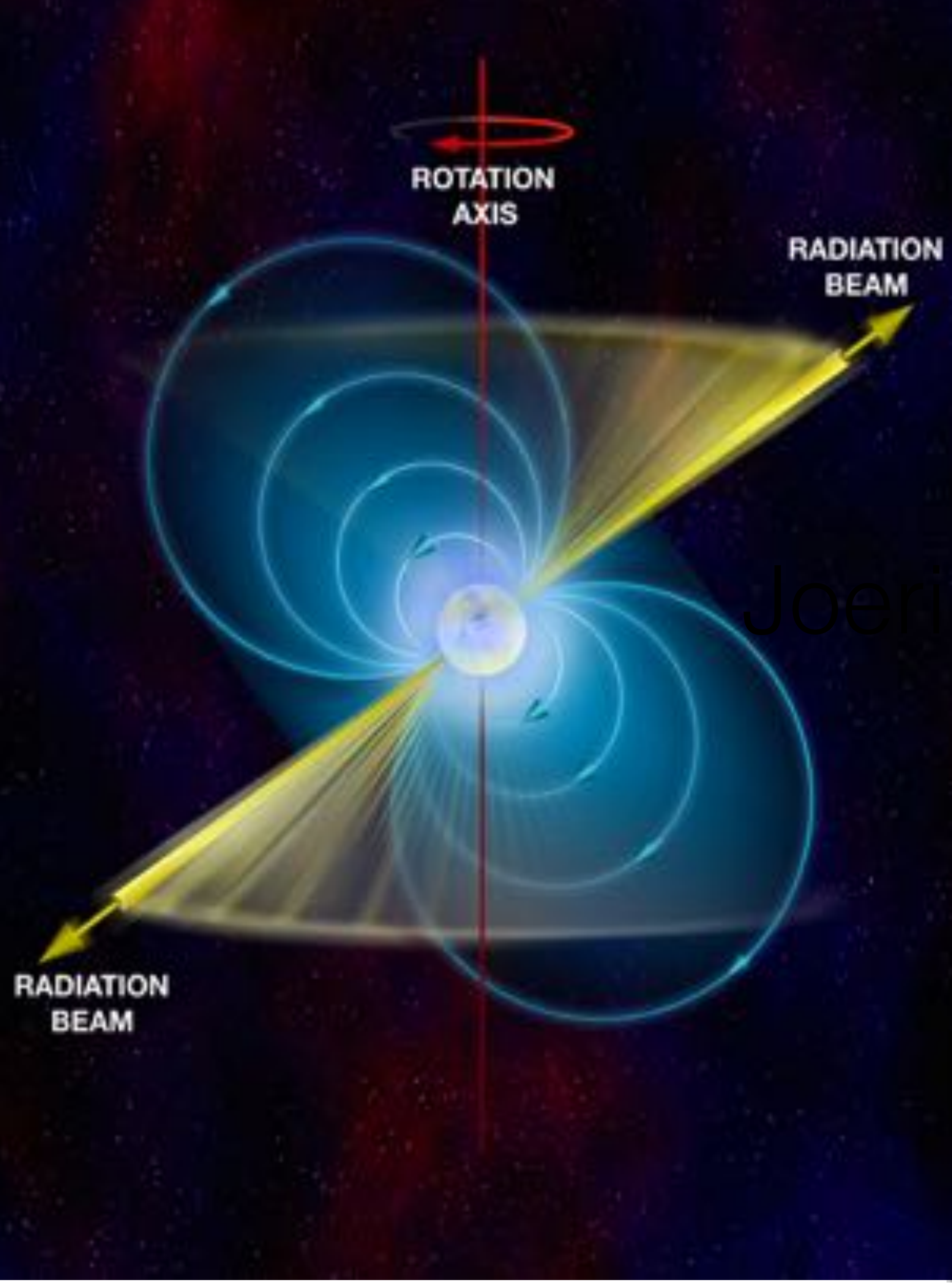


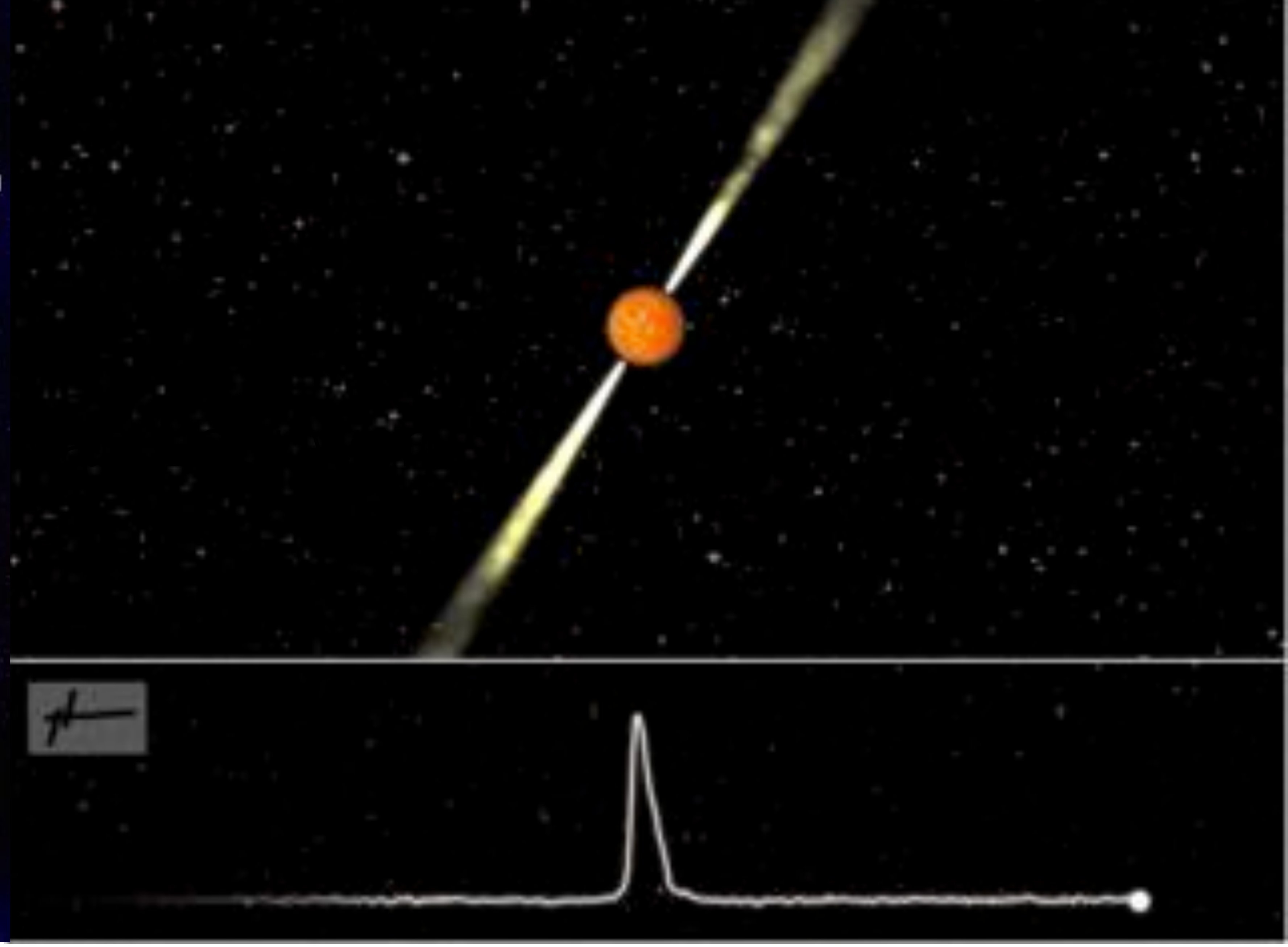
Testing technology: LISA Pathfinder/ST7



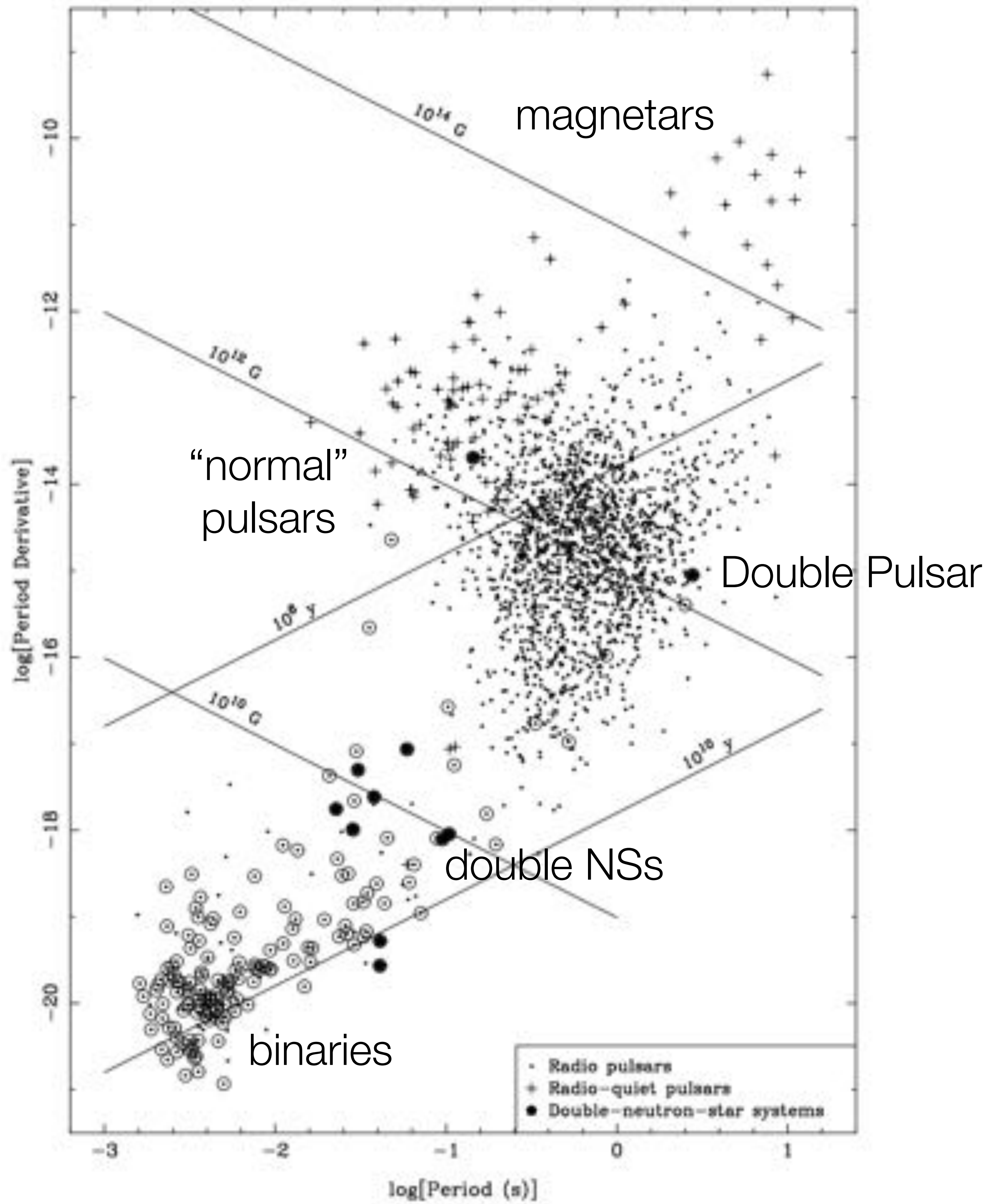
Testing technology: LISA Pathfinder/ST7





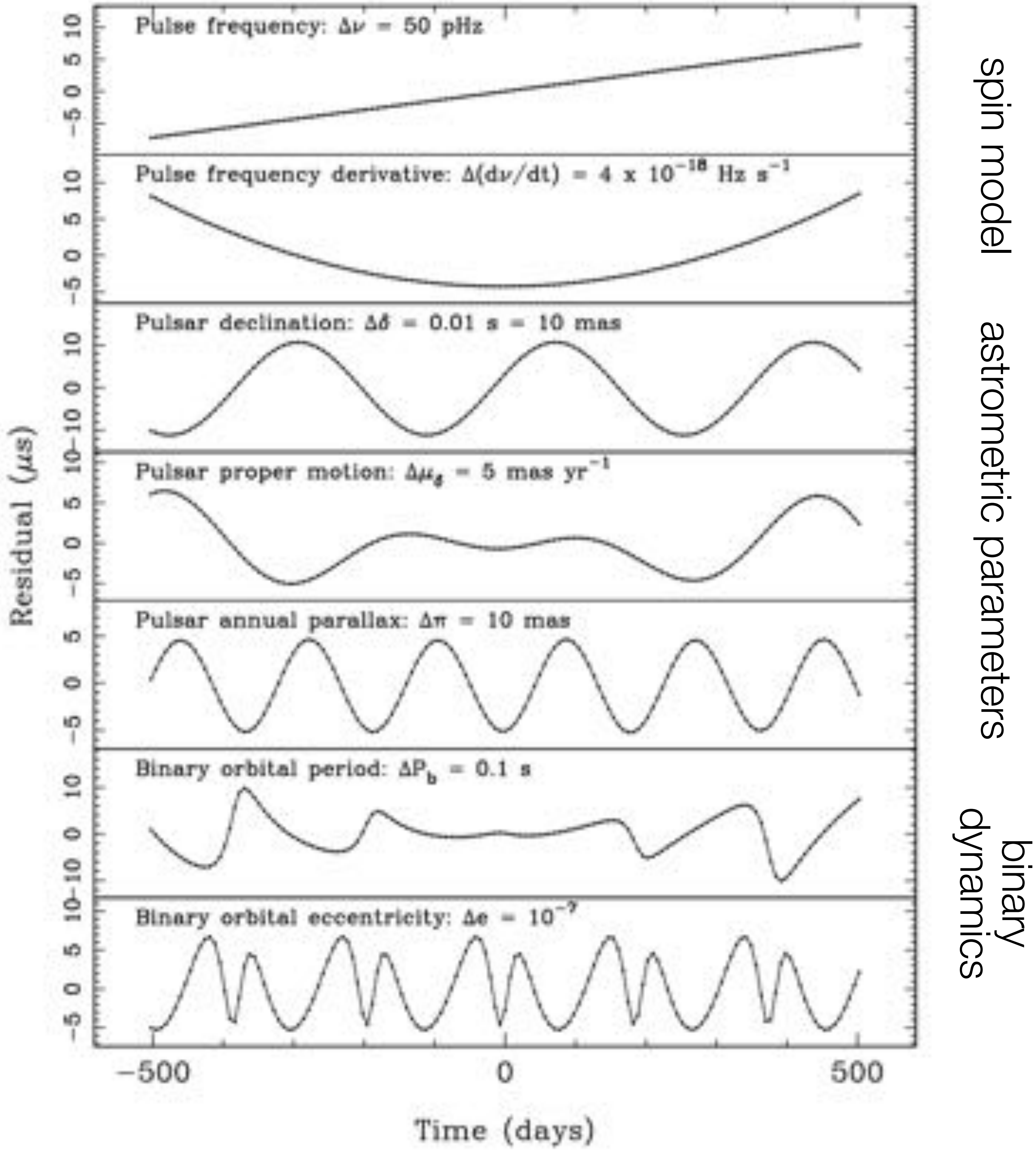


- **Pulsar-Timing Arrays**: using pulsars as fundamental clocks for GW measurement
- Pulsars have rapid, **regular** rotation (ms to s)
- Radio emission along magnetic field axis; misalignment of rotation and magnetic field axes creates “lighthouse” behavior



Pulsars: Nature's precision clocks

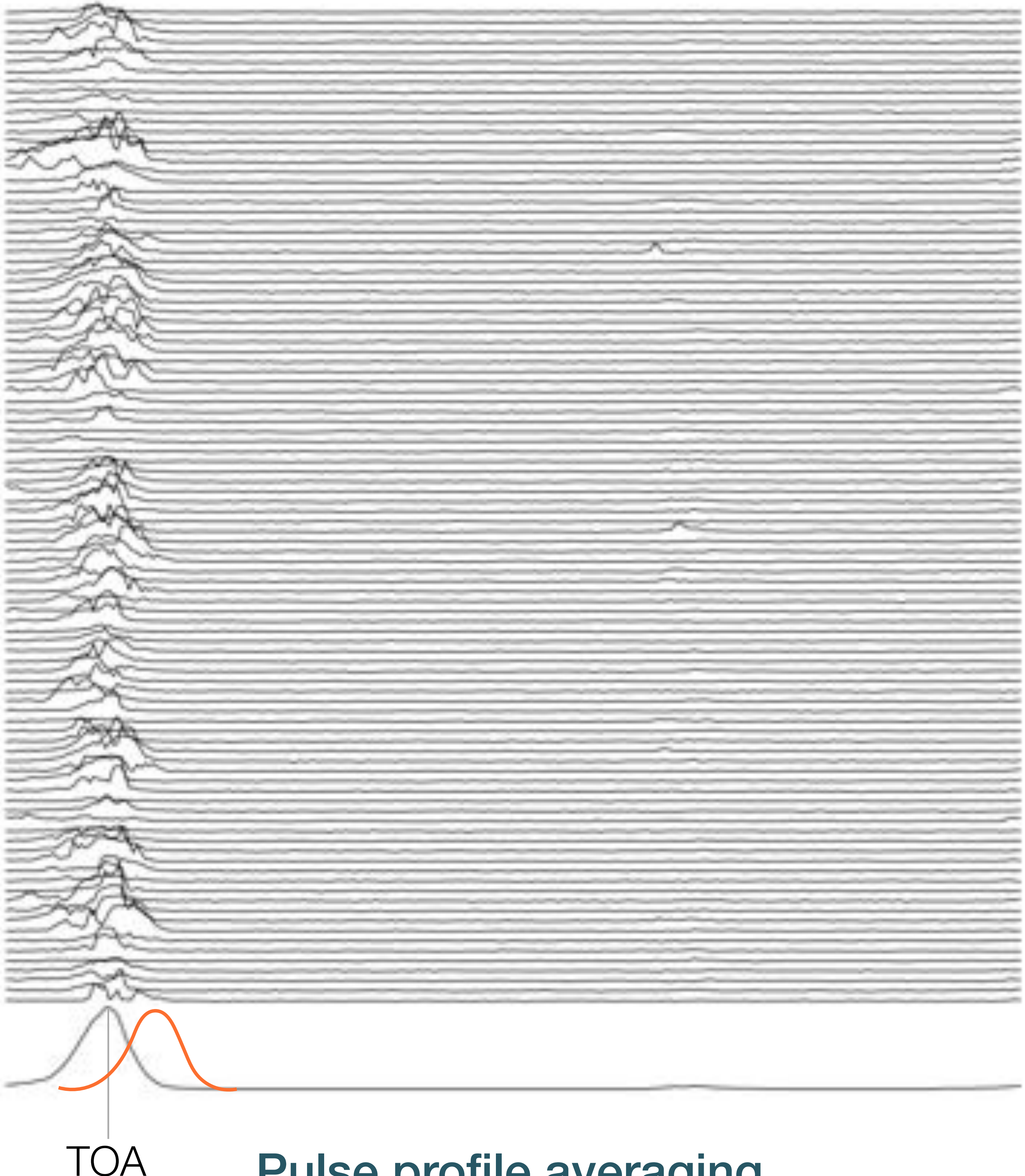
[Manchester 2015]



Deterministic effects in timing residuals

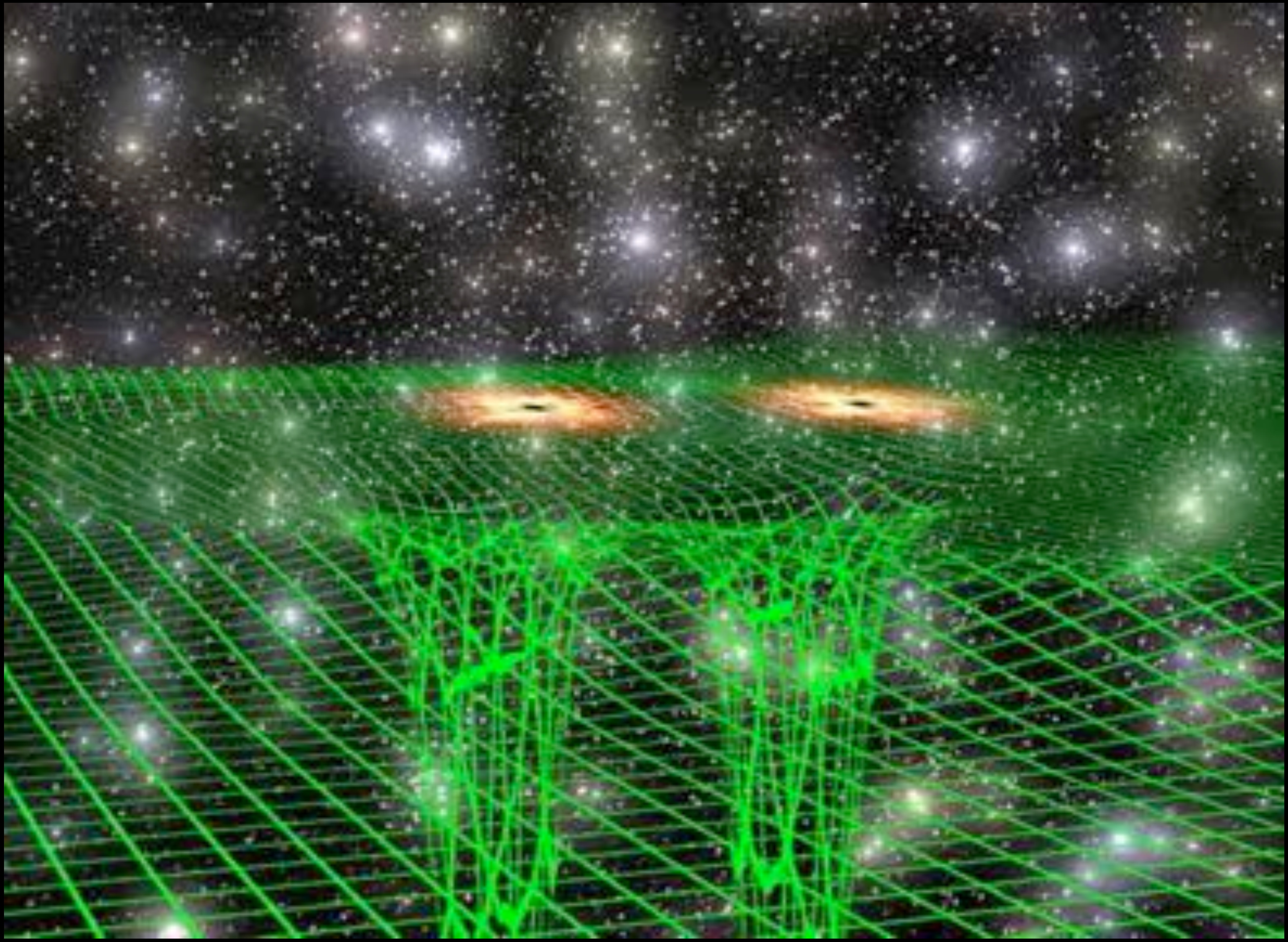
f = 300 Hz [Manchester 2015]

$$\sigma_{\mathrm{TOA}} = \frac{W}{\mathrm{SNR}\sqrt{N_\phi}}$$

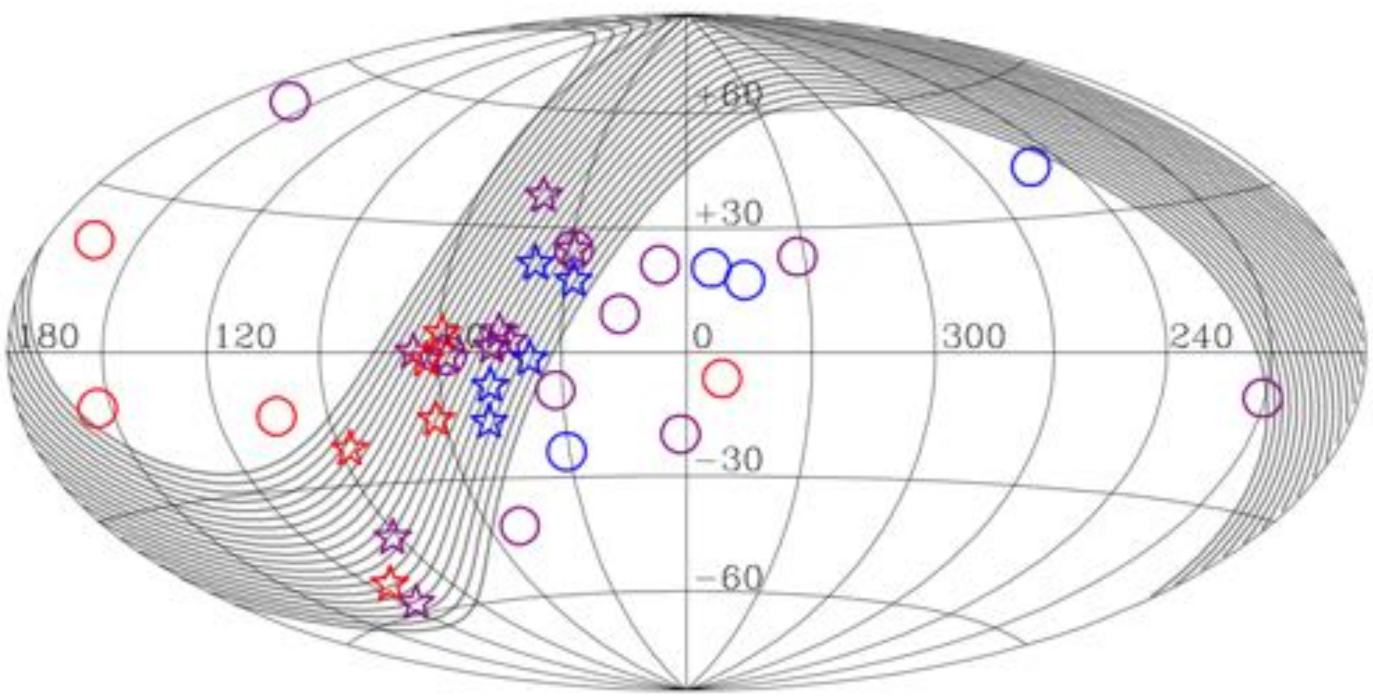


Pulse profile averaging

B0950 (P = 253 ms), 100 top pulses in 5-min integration [Stairs 2003]

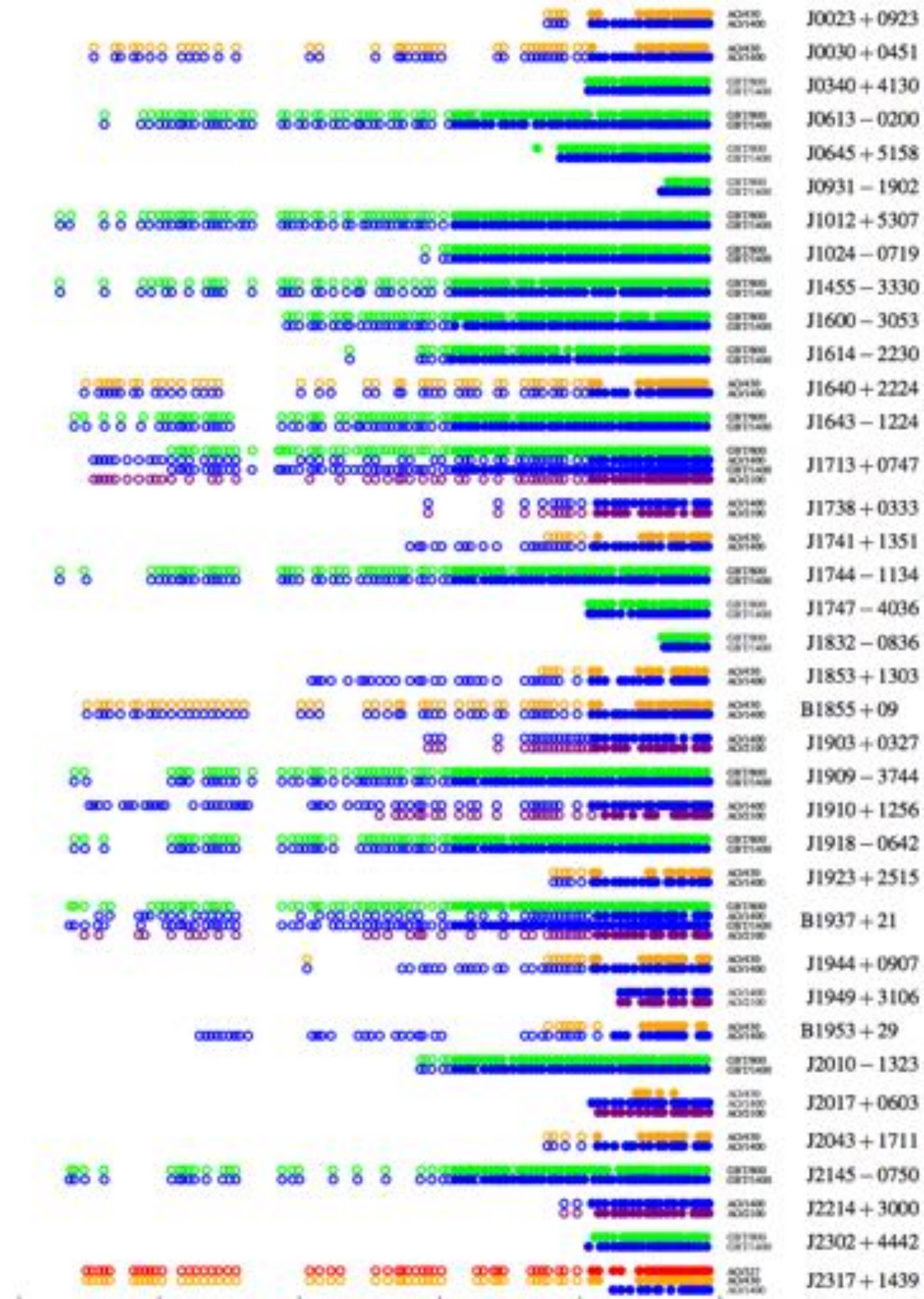


See this movie
at http://www.astron.nl/pulsars/animations/



The NANOGrav pulsars

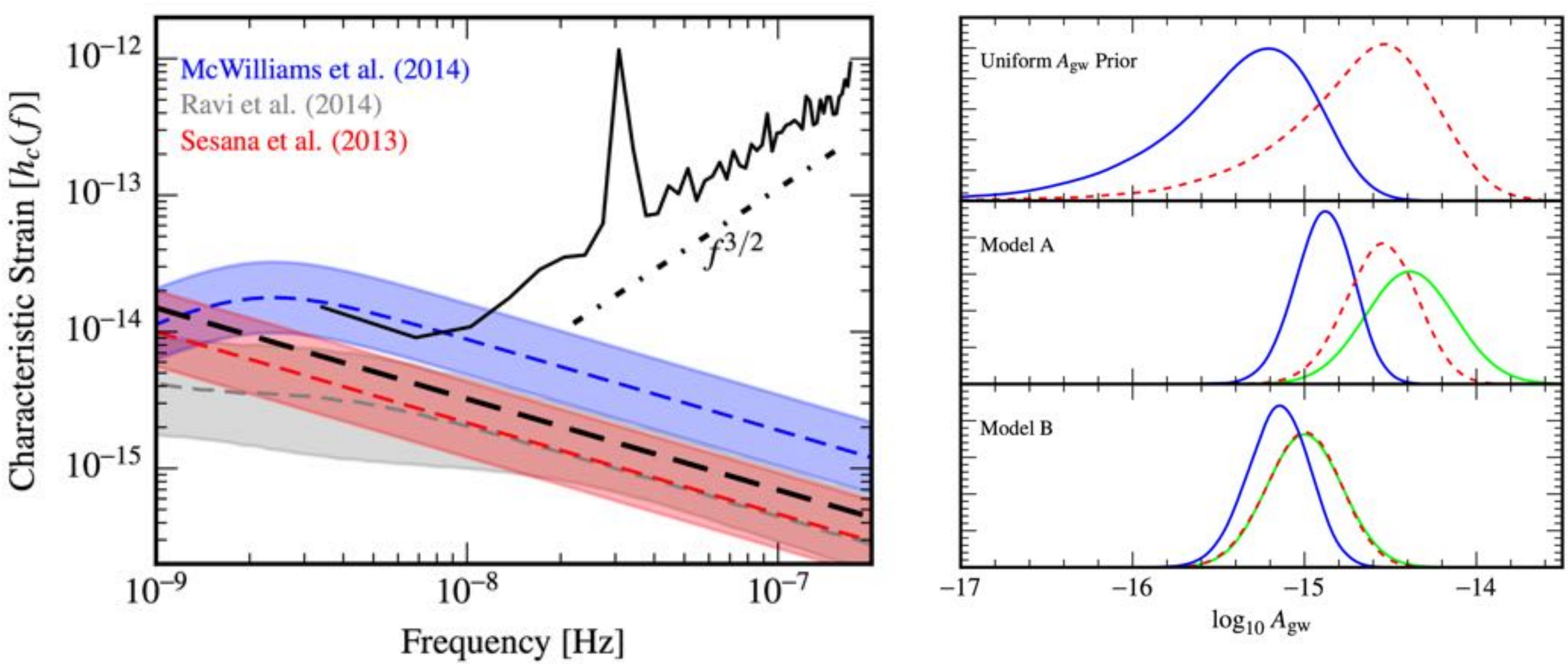
[McLaughlin 2013]



The NANOGrav 9-year dataset

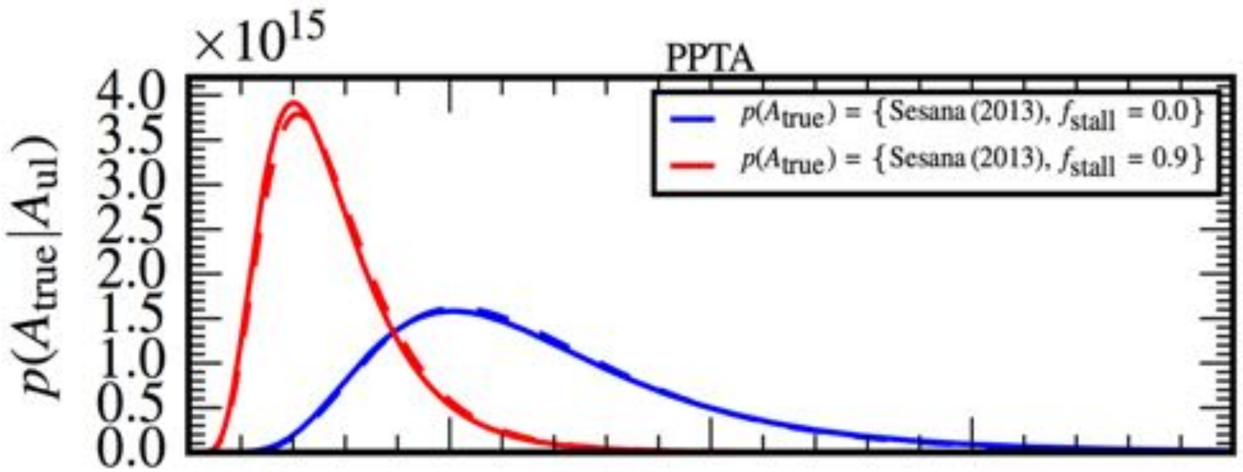
[NANOGrav 2015]

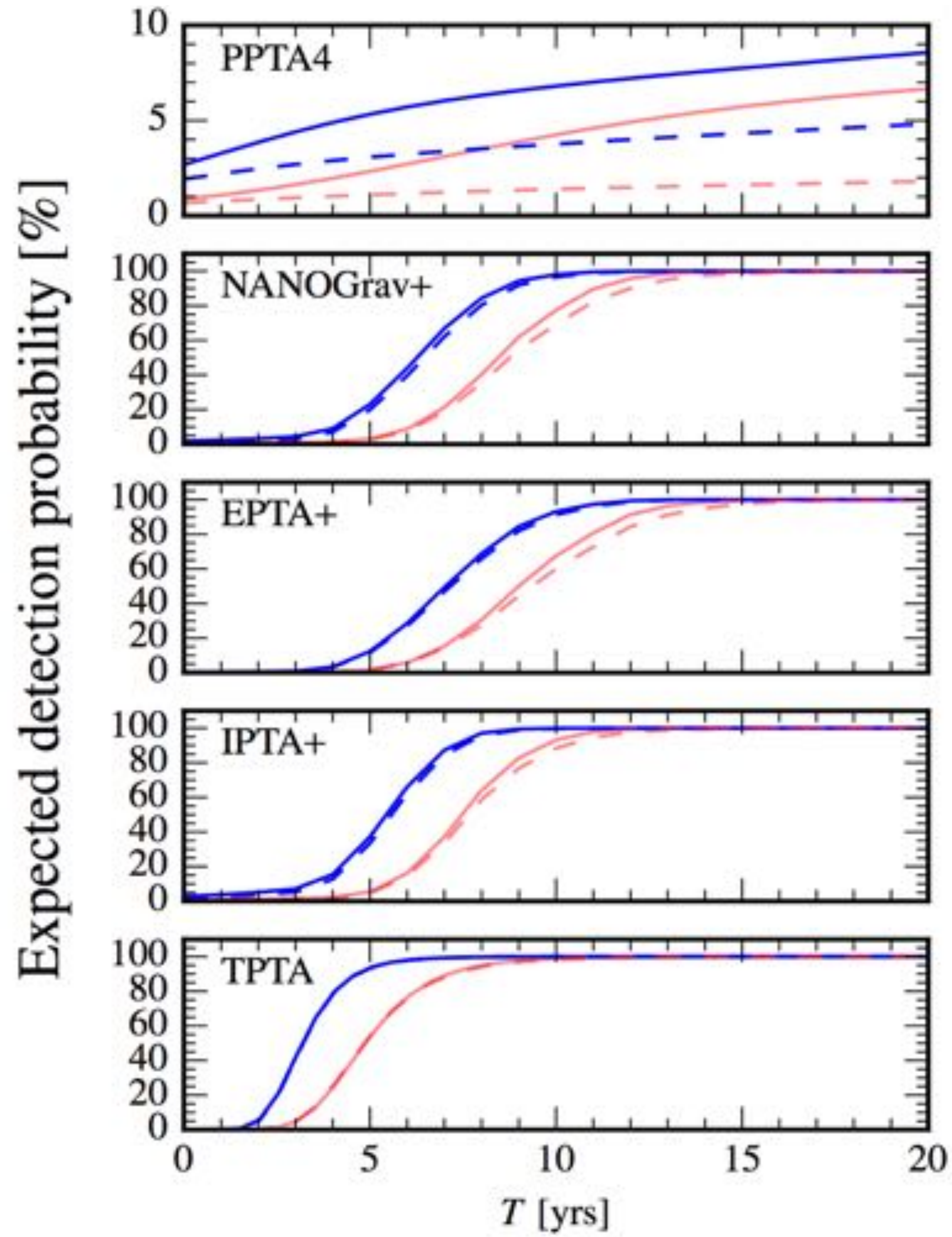

INTERNATIONAL PULSAR TIMING ARRAY
IPTA
EPTA
NANOGrav
PPTA
Green Bank Telescope, WV, US
Arecibo Observatory, PR, US
Nancay Radio Telescope, Nancay, France
Lovell Telescope, Cheshire, UK
Parkes Observatory, Parkes, Australia
LOFAR, Exloo, Netherlands
GMRT, Pune, India
WSRT, Westerbork, Netherlands
Effelsberg 100-m Radio Telescope, Effelsberg, Germany



isotropic SMBH background 9-year analysis

[NANOGrav 2015]

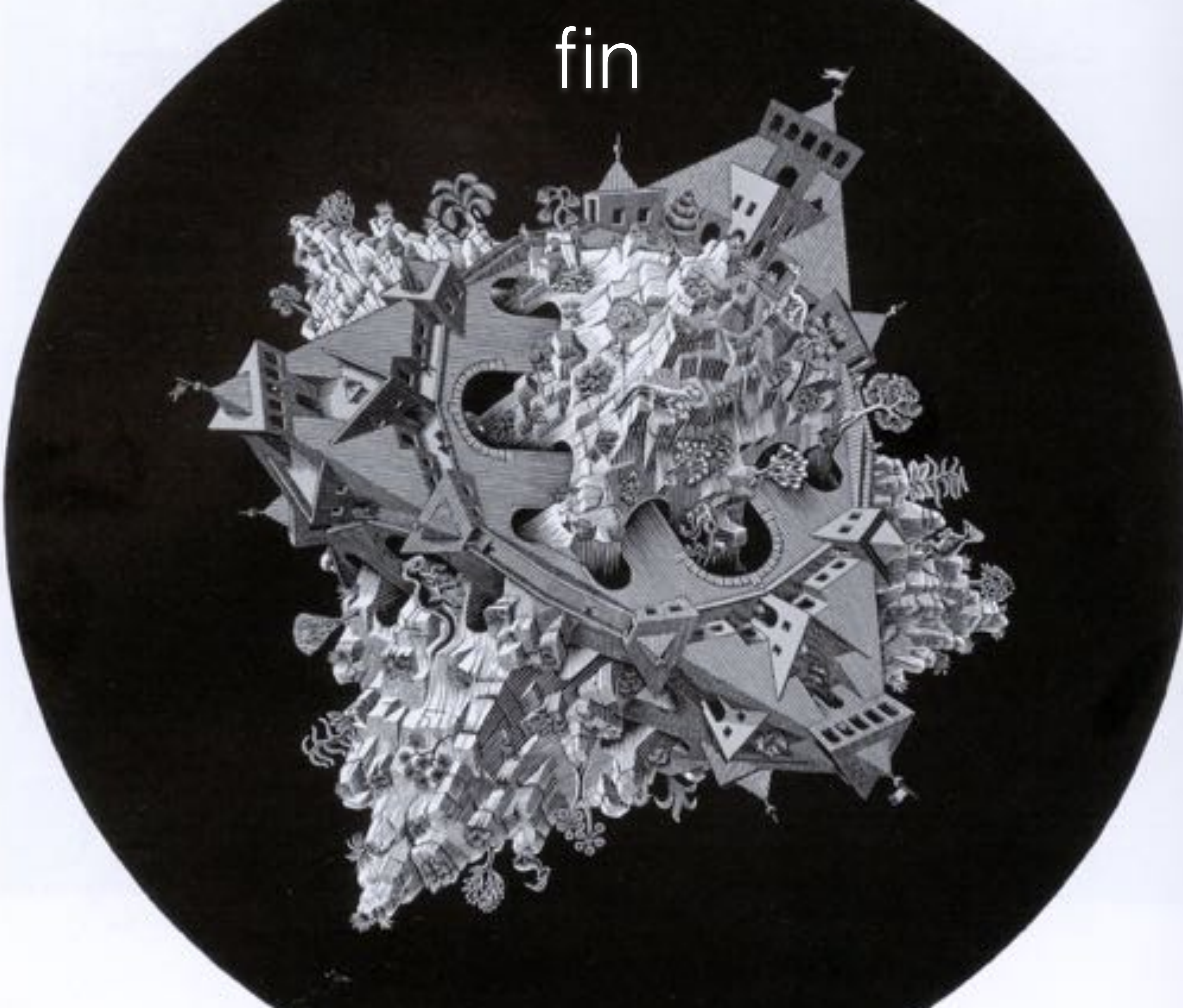




detection probability given the PPTA limit

[Taylor, Vallisneri, et al. 2015]

fin



…to follow, on this screen…

2: GW theory

3: GW150914 (colloquium)

4: data analysis

5: cosmology and testing GR