Unsolved problems in Gravitational Waves

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Unsolved problems in Astrophysics and Cosmology
Centro de Ciencias de Benasque Pedro Pascual 14th - 18th February 2011

1. GW unsolved problems:
No *direct* detection (yet)

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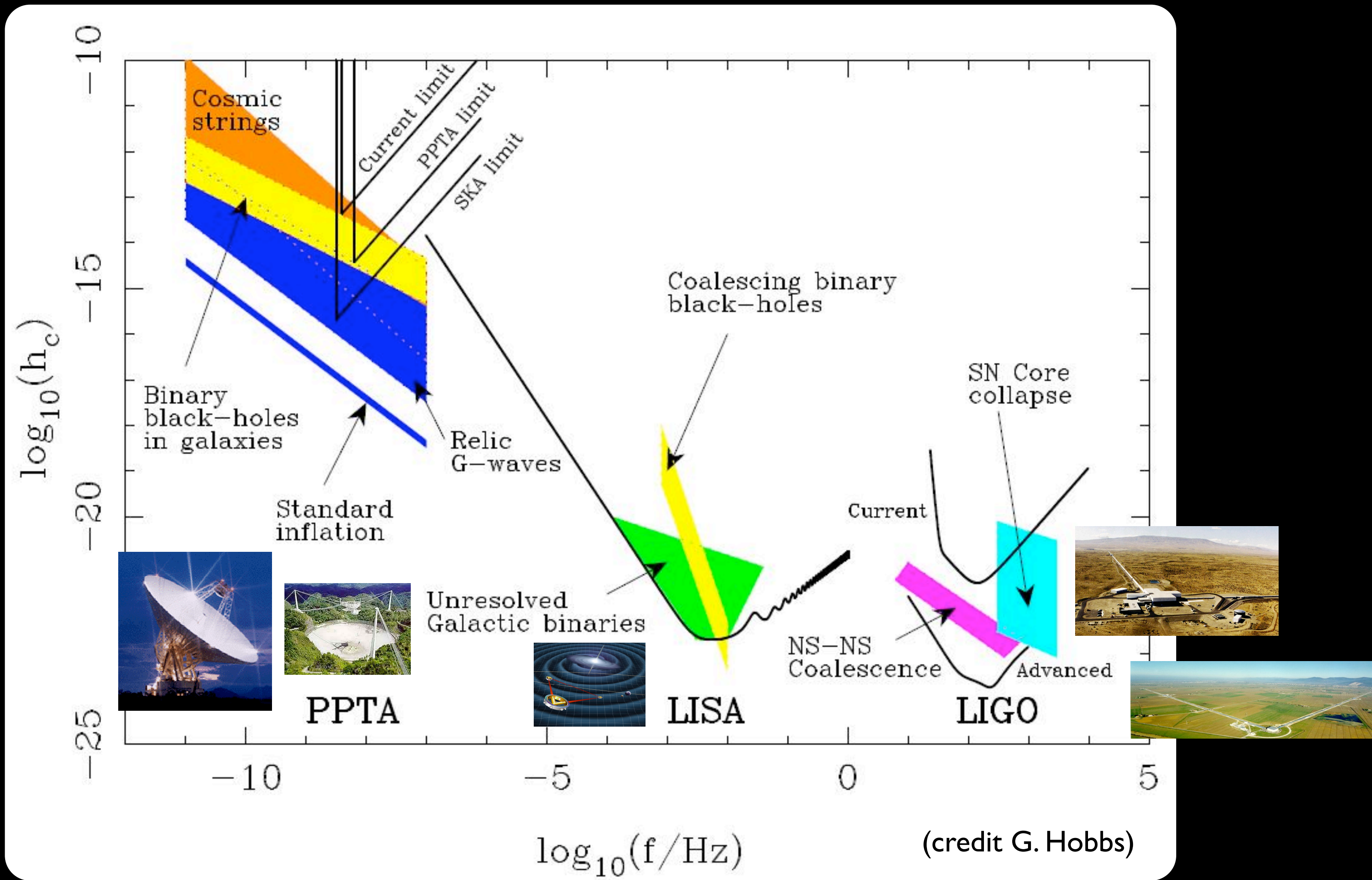
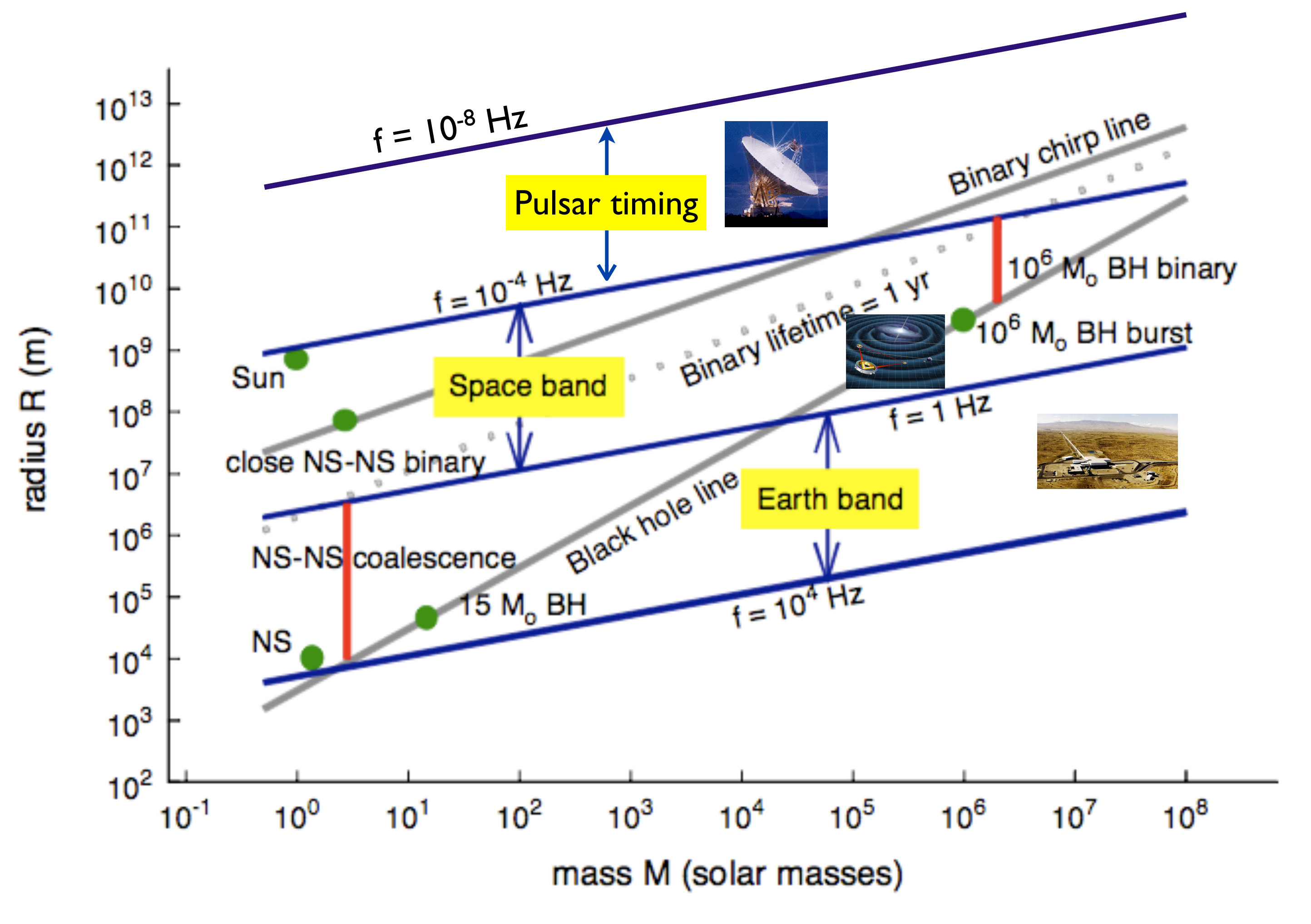
No *direct* detection (yet)
Is it expected?

GW spectrum



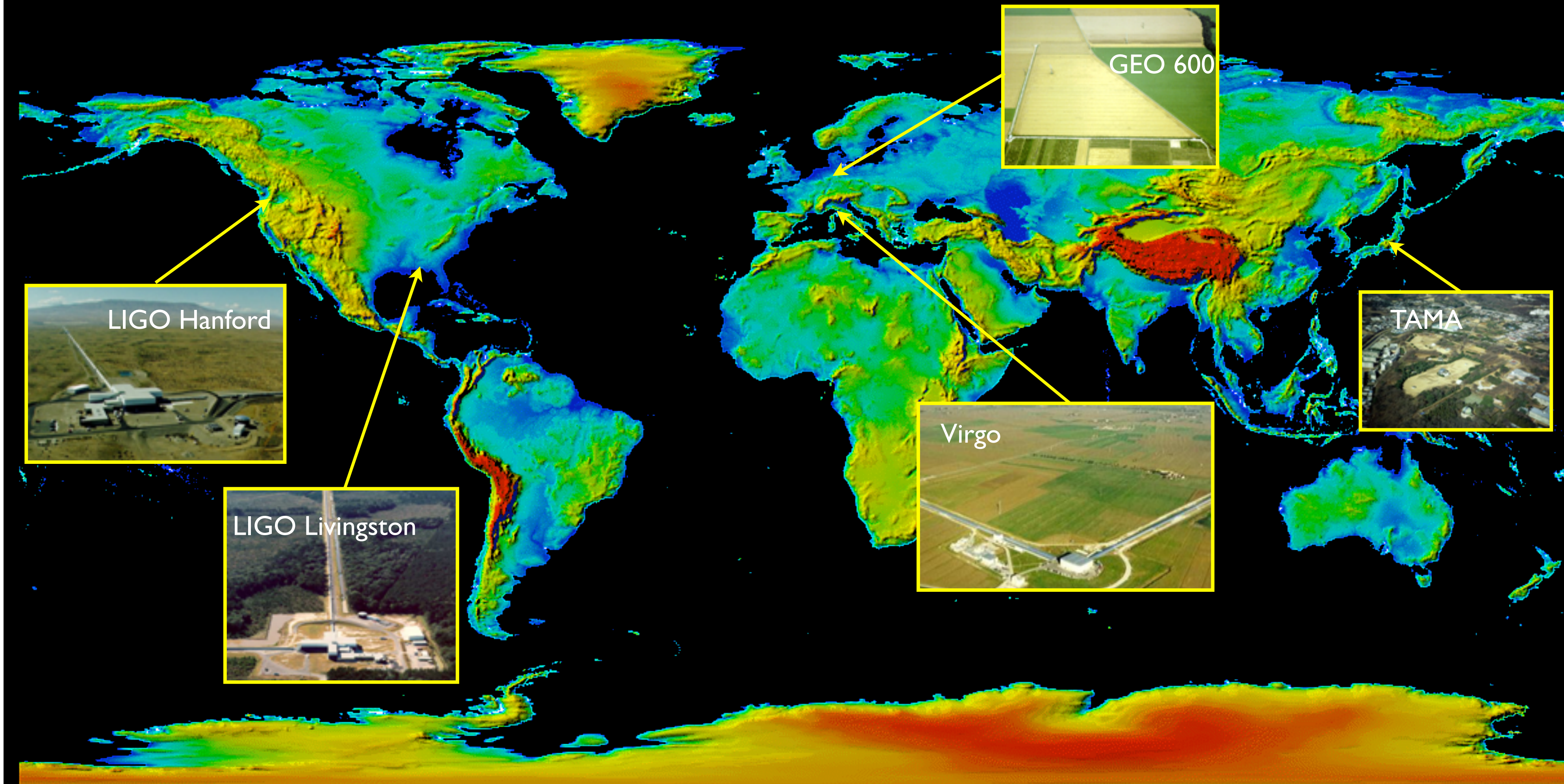
(credit G. Hobbs)

Black holes and GWs

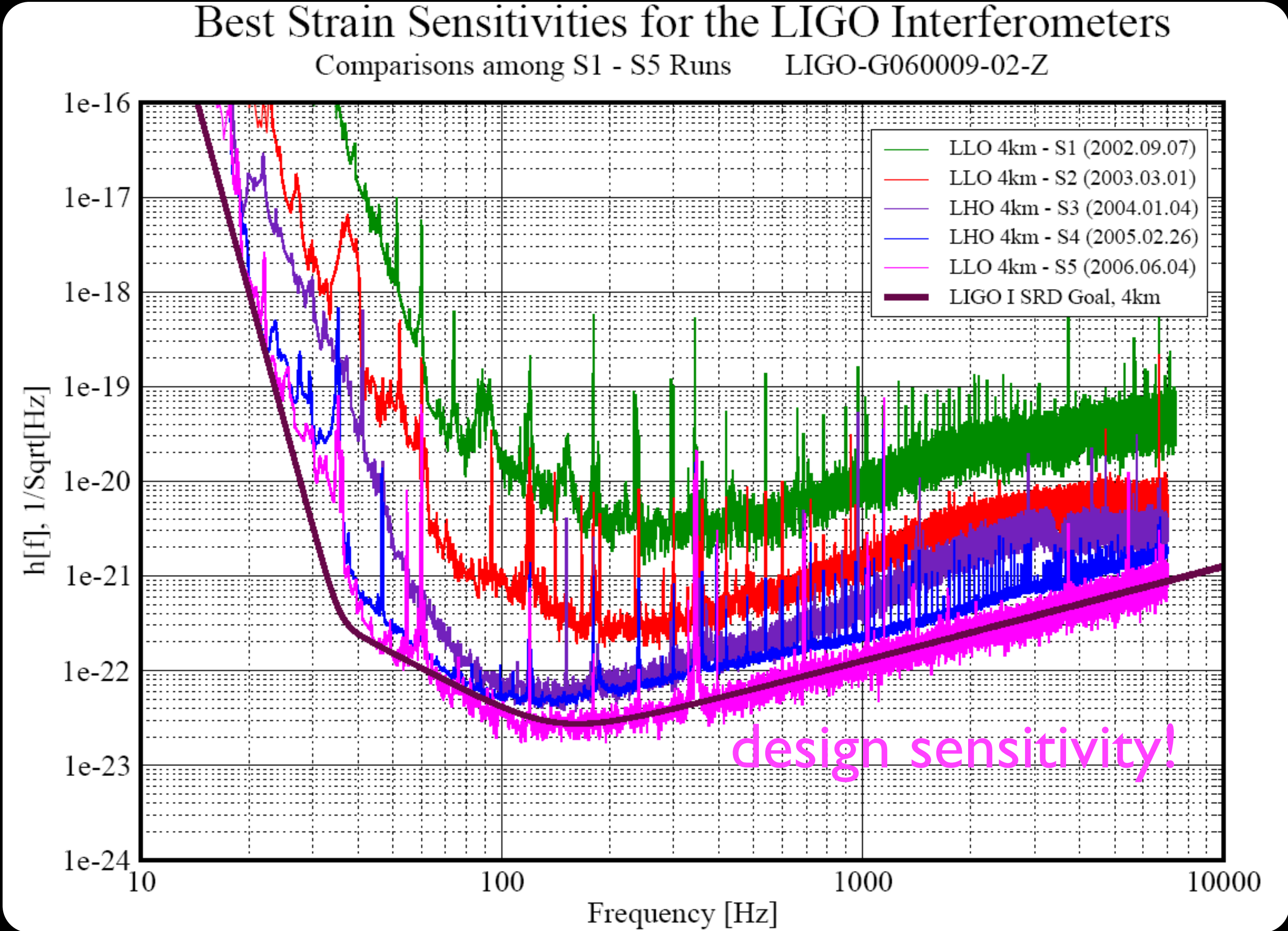


(Schutz)

The global network of laser interferometers

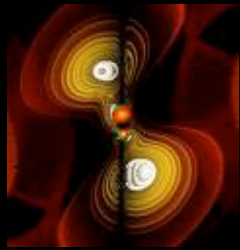


Evolution of LIGO sensitivity



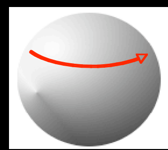
Science targets of on-going searches

- Coalescing binaries
  - NS/BH binary systems

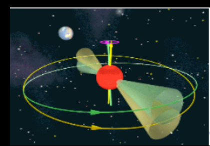


- Un-modeled bursts
  - e.g. supernovae, gamma-ray bursts

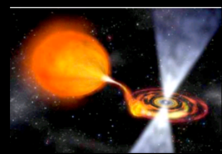
- Continuous waves
  - e.g. rotating neutron stars



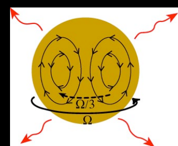
"Mountain" on neutron star



Wobbling neutron star

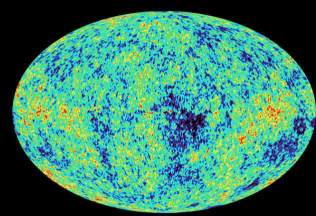


Accreting neutron star



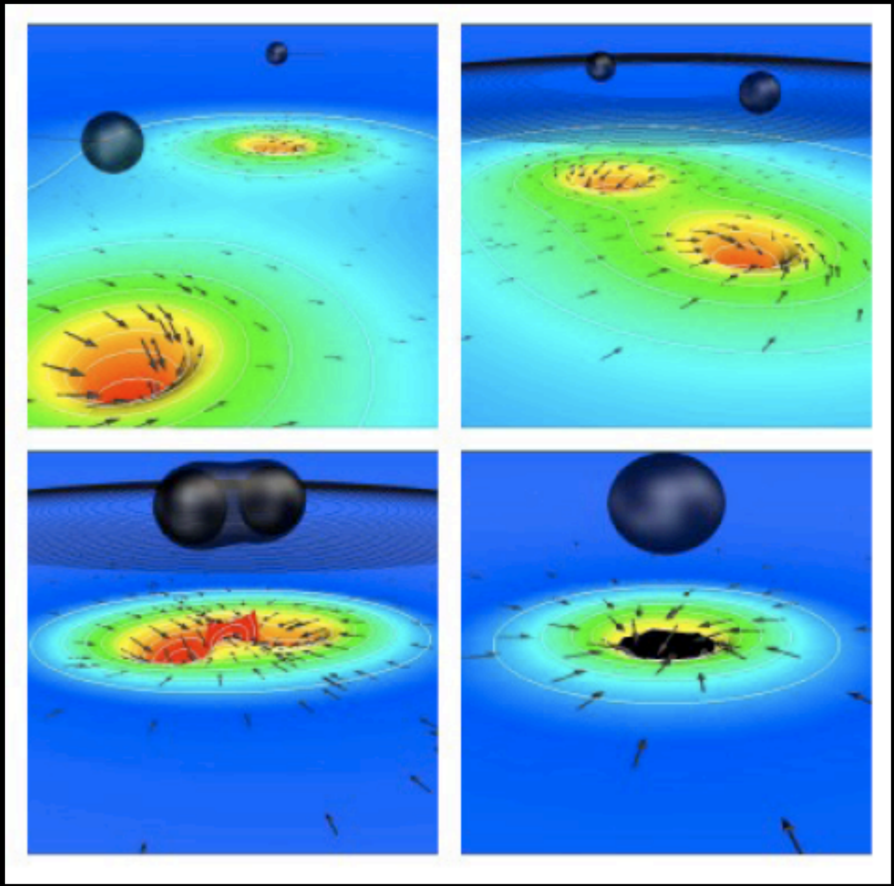
R-modes

- Stochastic signals
  - e.g. backgrounds from the early universe, foreground radiation from astrophysical sources

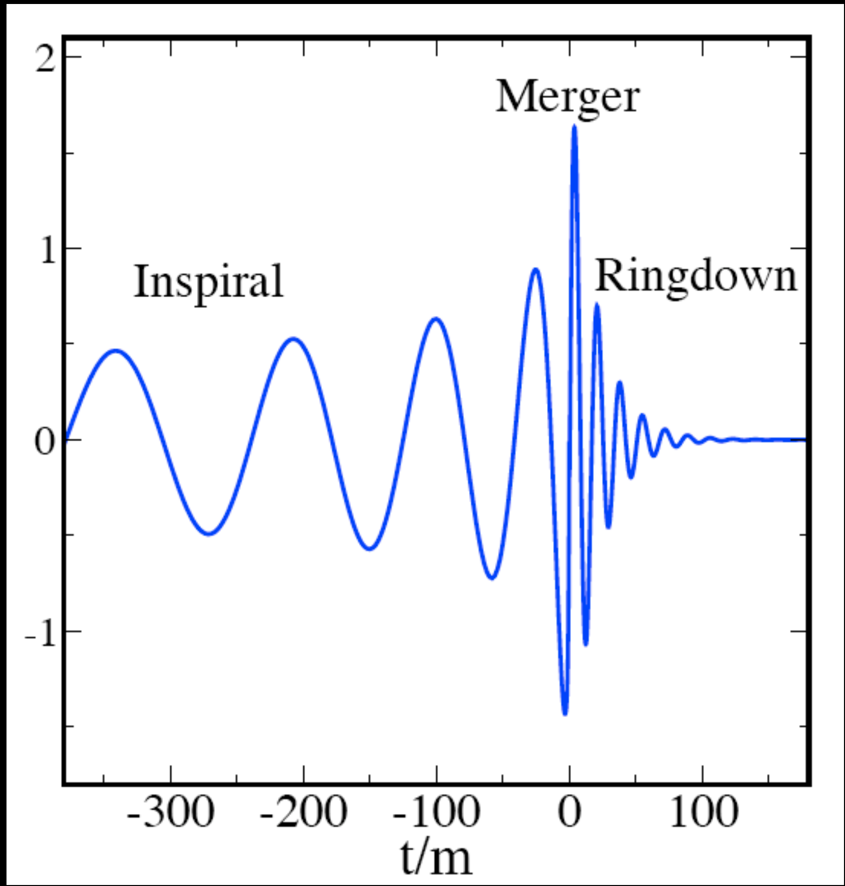


Analog from cosmic microwave background -- WMAP 2003

Coalescing binaries



SpeC code



GWs from binary systems

"chirp" mass
frequency
masses
spins

$$h(t) \sim \text{angles} \times \frac{\mathcal{M}^{5/3} f(t)^{2/3}}{D_L} \cos \Phi(t; m_{1,2}, \mathrm{S}_{1,2})$$

sky location
orbit orientation
luminosity distance

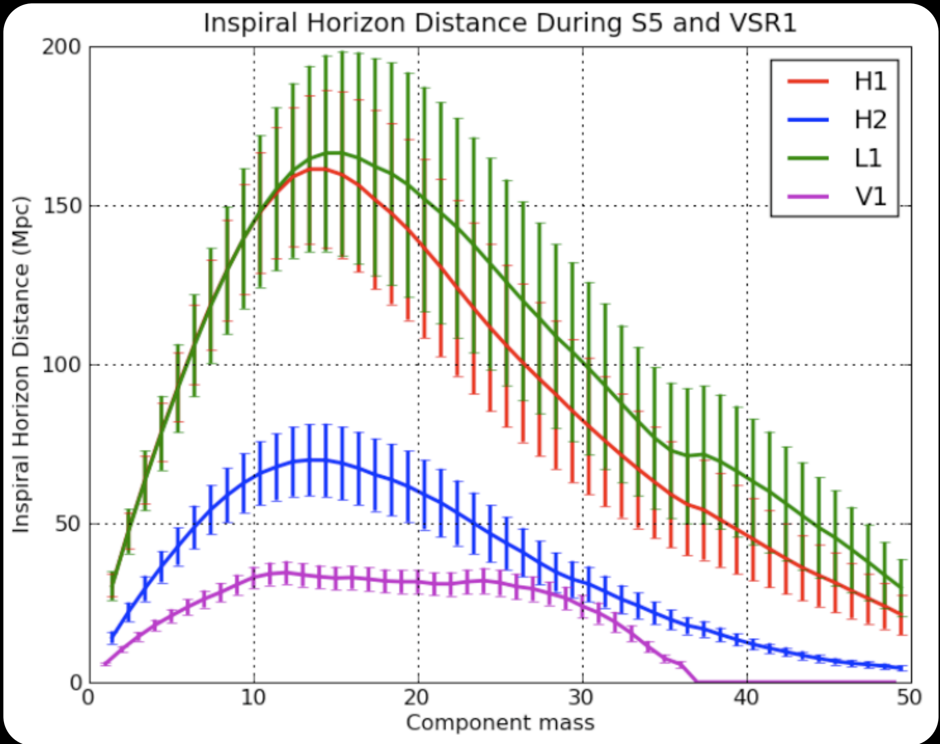
- Demographics of neutron star and black holes: masses, spins, 3D distribution in the universe
- Star formation history, mass function
- Dynamics in star clusters
- Cosmography (binary systems are standard candles): independent measure of luminosity distance, cosmological parameters
- Maps of the strongly non-linear dynamics
- Tests of general relativity
- Joint observations with X/γ-ray, optical, neutrino,... telescopes: full details about the physical processes at work

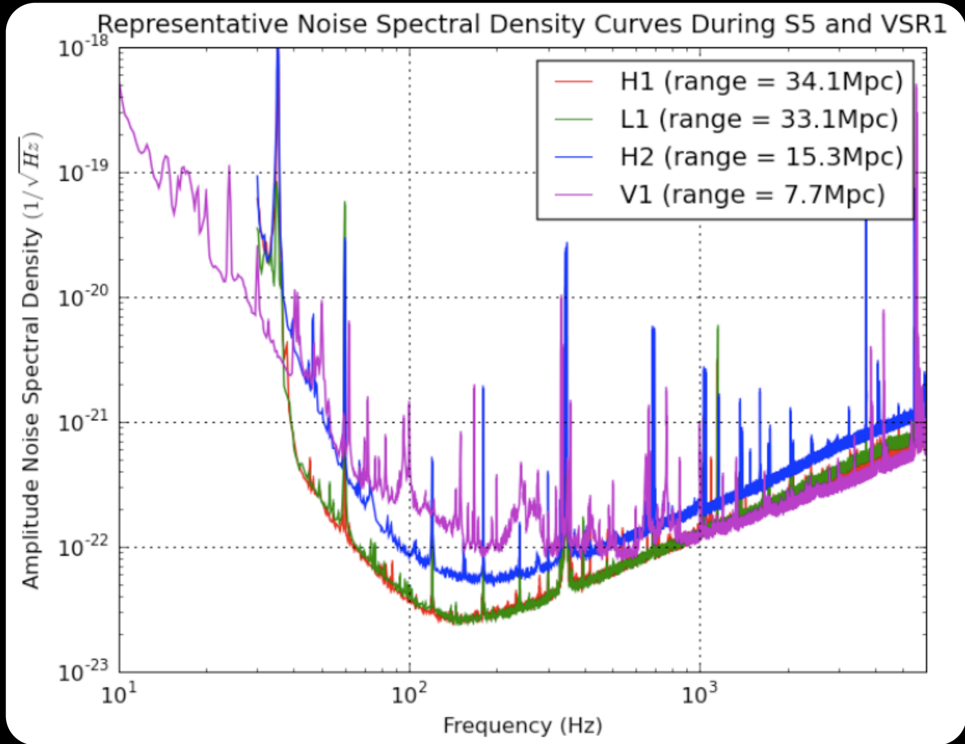
Measured signal: strain

$$h(t) = F_+(\alpha,\delta,\psi)\, h_+(t) + F_\times(\alpha,\delta,\psi)\, h_\times(t)$$

- Polarization amplitudes $h_+(t)$ and $h_\times(t)$ contain full information about the physics
- Unknown parameters (9 for non-spinning binary systems, 15 for general spins, 17 if also eccentricity is present)
  - Masses (2 parameters)
  - Source location in the sky (2 parameters)
  - Orbital plane orientation (2 parameters)
  - Luminosity distance
  - Time and phase at coalescence (2 parameters)
  - Spins (6 parameters)
  - Eccentricity (2 parameters)

How far could LIGO/Virgo see during S5/VSR1?





- LIGO S5: November 2005 - October 2007
- One year of data at design sensitivity in triple coincidence
- VIRGO VSR1: last 5 months of the run

Detection rate

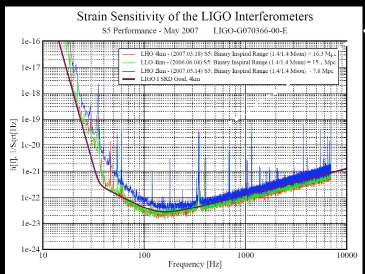
Detection Rate

$$\dot{N} = R \times N_{\rm G}$$

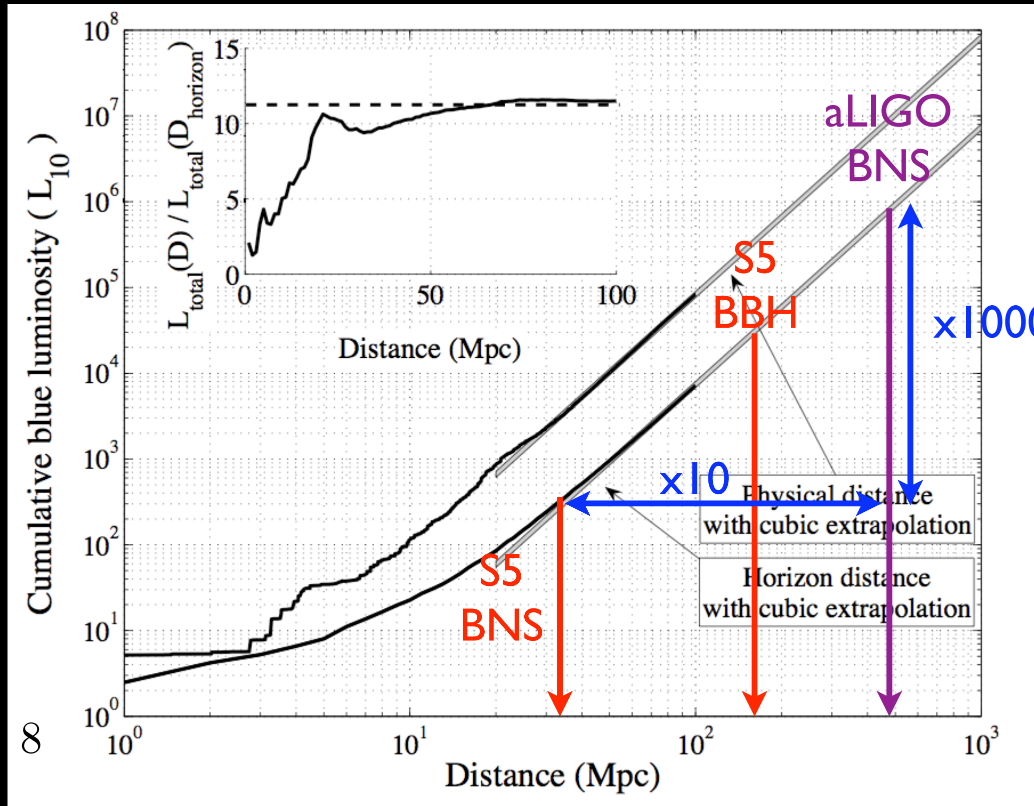
number of galaxies accessible by a search in L_{10}'s

coalescence rate per galaxy

$$\mathrm{SNR}^2 = \int_{f_{\rm low}}^{f_{\rm isco}} \frac{|\tilde{h}(f)|^2}{S_n(f)} df$$



$$\tilde{h}(f) \propto \frac{\mathcal{M}^{5/6}}{D_L} f^{-7/6}$$



$$N_{\rm G}(L_{10}) = \frac{4\pi}{3} D^3_{\rm hor} \times \left(\frac{1}{2.26}\right)^3 \times 0.02$$

L_{10} / Mpc^3

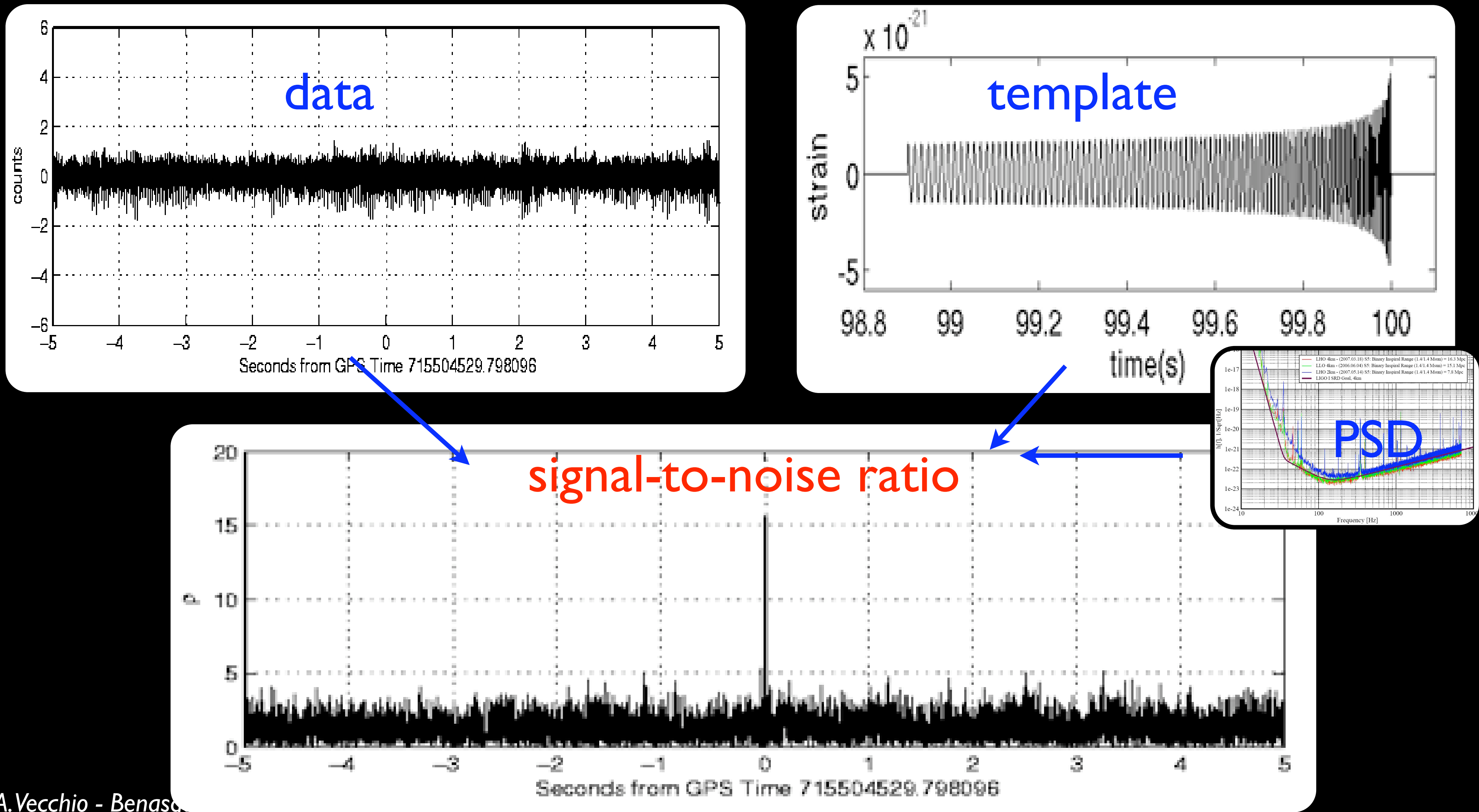
average over sky and orientation

Expected detection rates

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

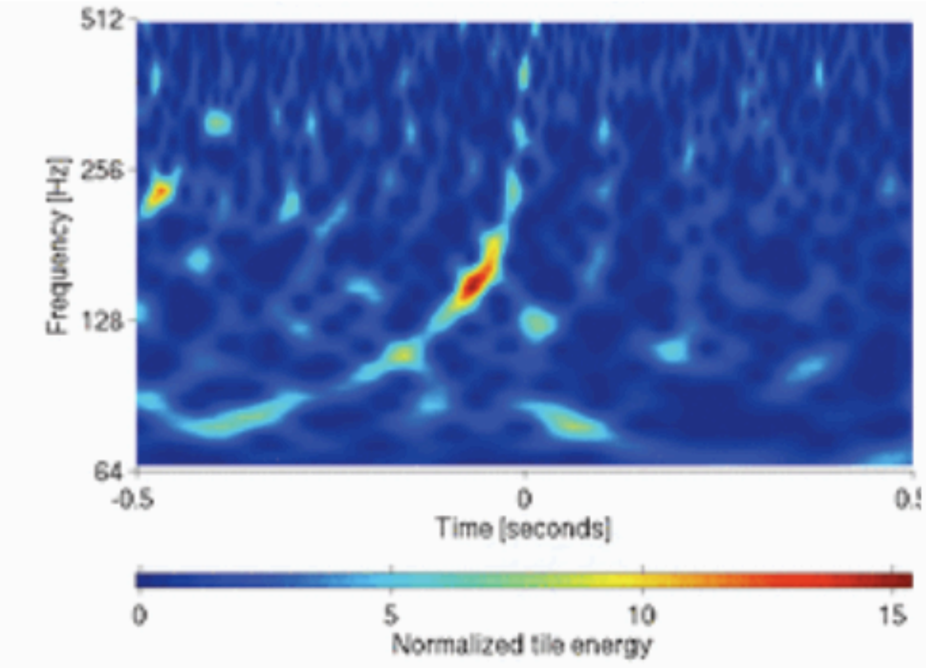
Abadie et al. (LSC and Virgo), CQG 27, 173001 (2010)

Searching for binaries: matched-filtering

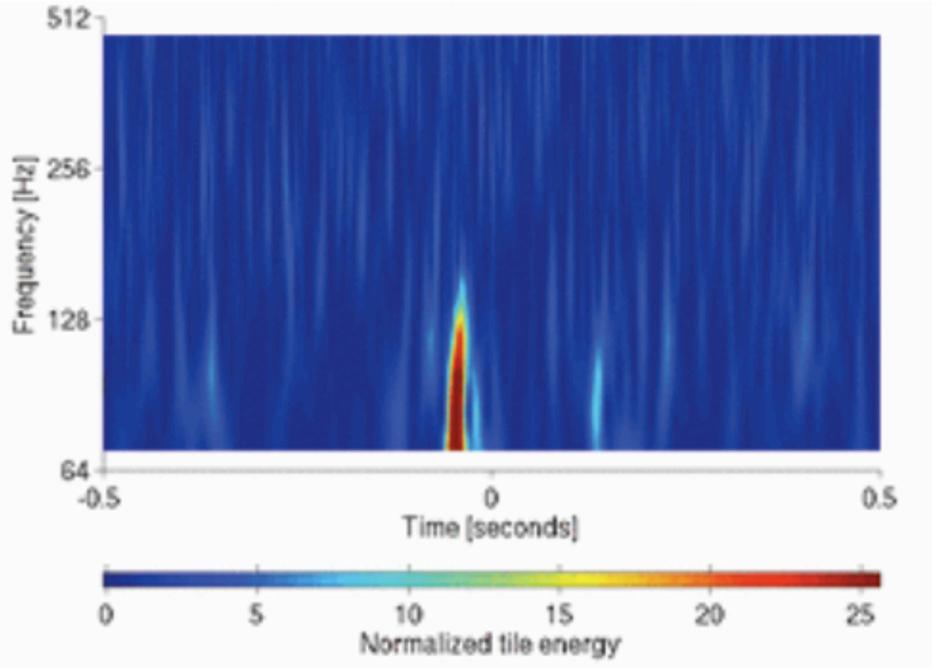


Examples of “signals”

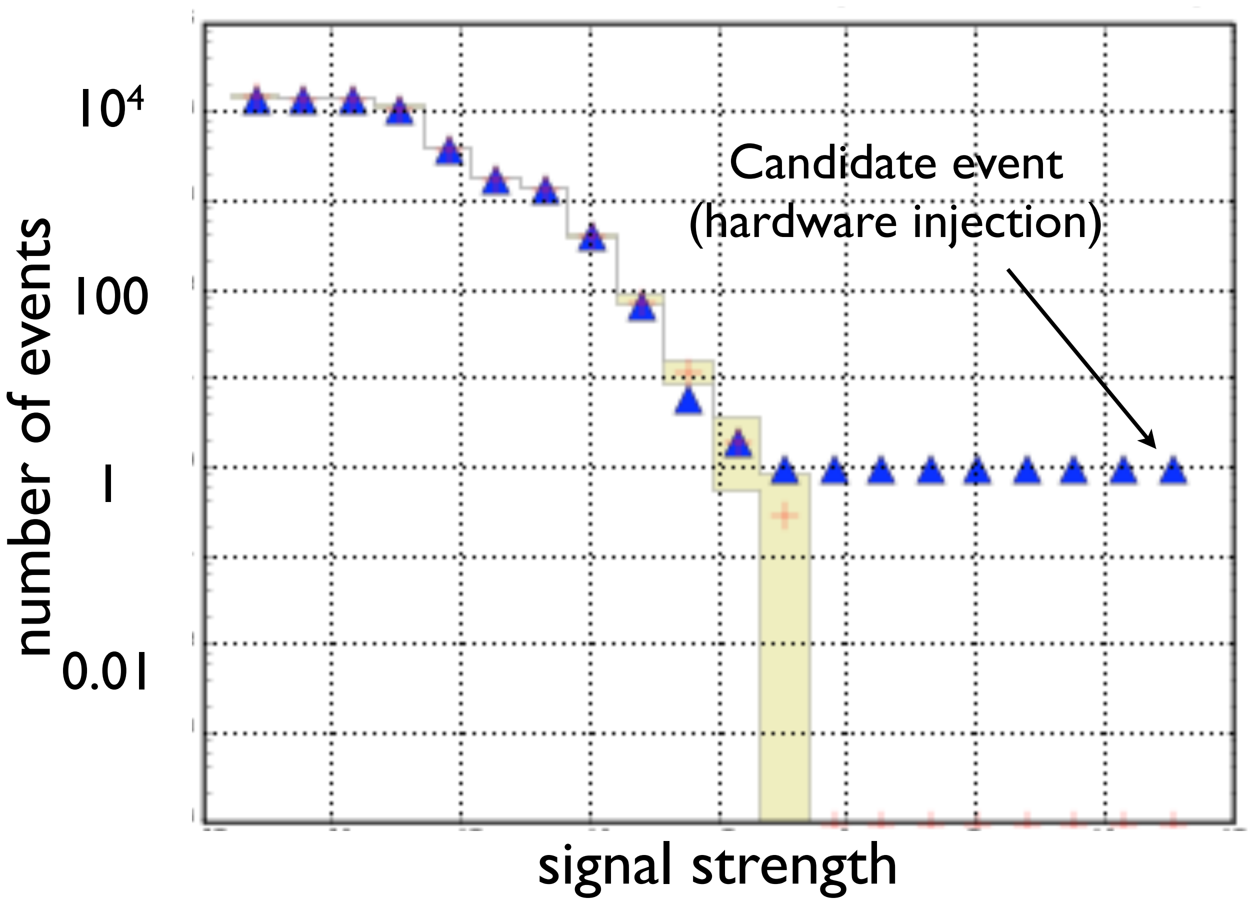
Hardware injection



Instrumental artifact



How a detection candidate shows up

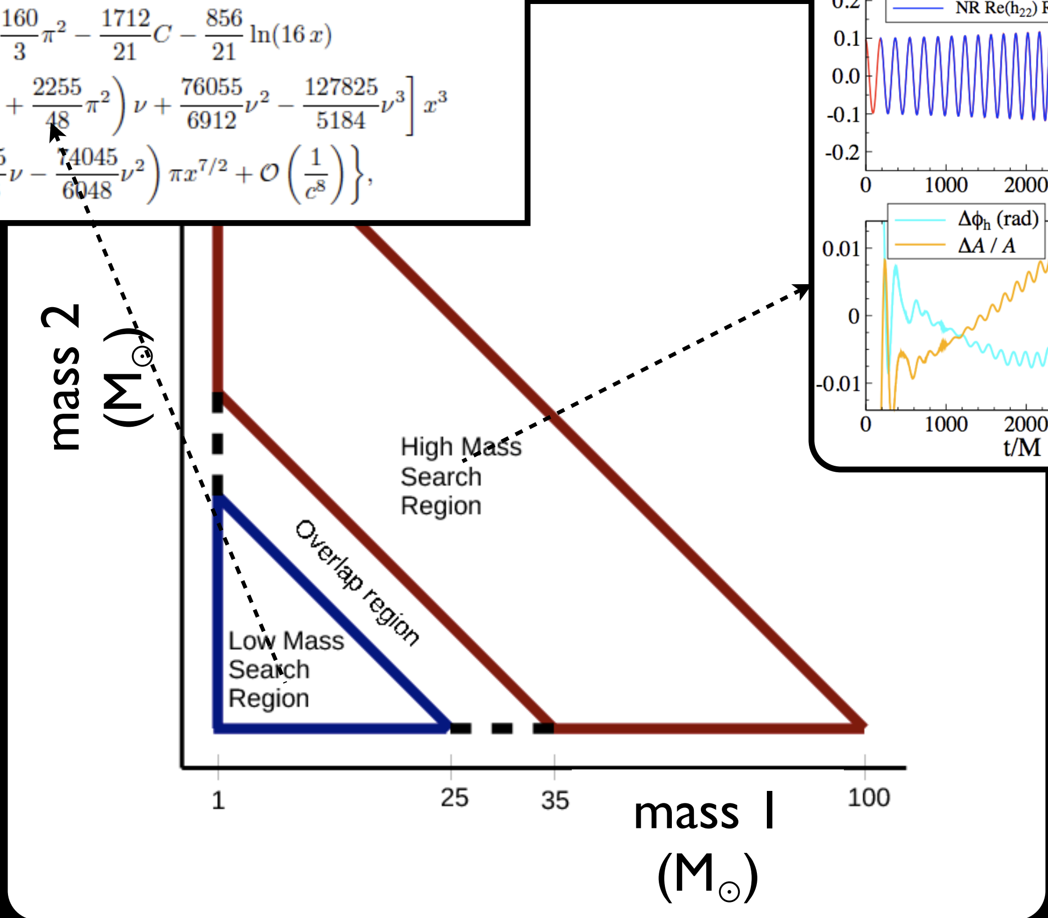


Mass search area

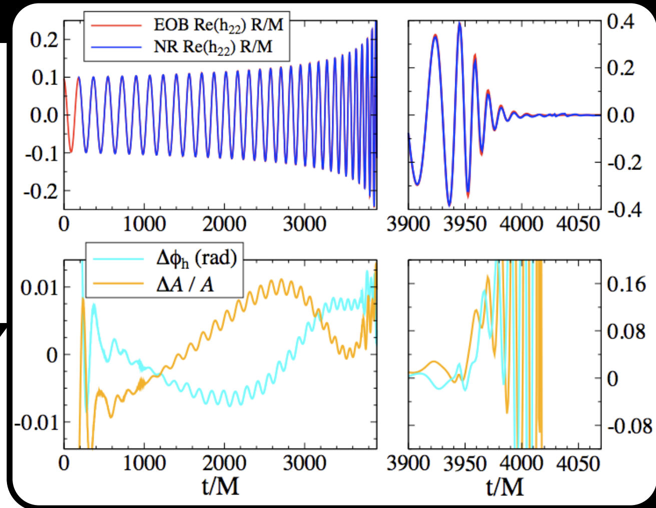
post-Newtonian approx. of inspiral

$$\phi = -\frac{x^{-5/2}}{32\nu}\Bigg\{1 + \left(\frac{3715}{1008} + \frac{55}{12}\nu\right)x - 10\pi x^{3/2} + \left(\frac{15293365}{1016064} + \frac{27145}{1008}\nu + \frac{3085}{144}\nu^2\right)x^2 + \left(\frac{38645}{1344} - \frac{65}{16}\nu\right)\pi x^{5/2}\ln\left(\frac{x}{x_0}\right) + \Bigg[\frac{12348611926451}{18776862720} - \frac{160}{3}\pi^2 - \frac{1712}{21}C - \frac{856}{21}\ln(16\,x) + \left(-\frac{15737765635}{12192768} + \frac{2255}{48}\pi^2\right)\nu + \frac{76055}{6912}\nu^2 - \frac{127825}{5184}\nu^3\Bigg]x^3 + \left(\frac{77096675}{2032128} + \frac{378515}{12096}\nu - \frac{74045}{6048}\nu^2\right)\pi x^{7/2} + \mathcal{O}\left(\frac{1}{c^8}\right)\Bigg\},$$

Blanchet LLR 2006



full inspiral-merger-ringdown waveforms

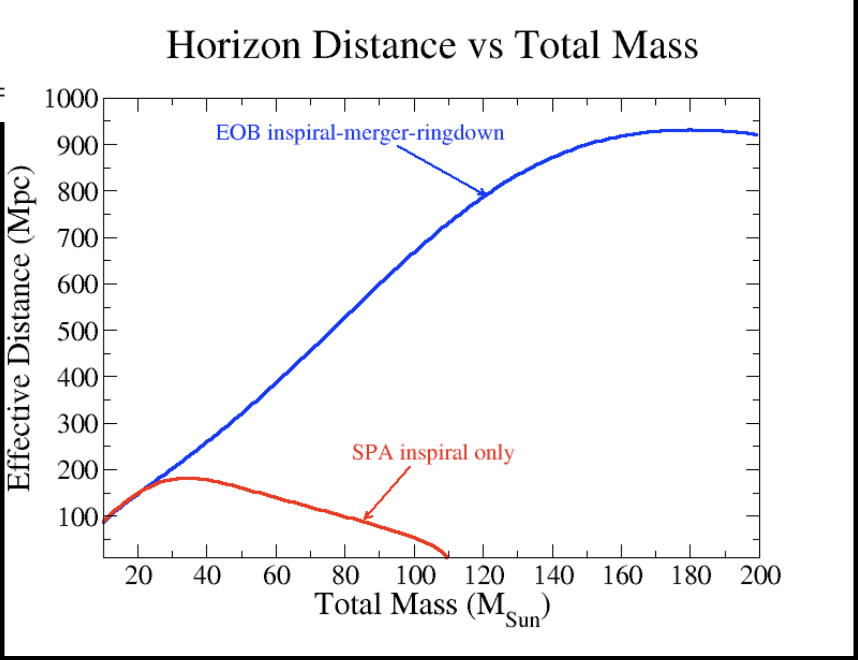


see Buonanno et al, 2009; Ajith et al, 2008

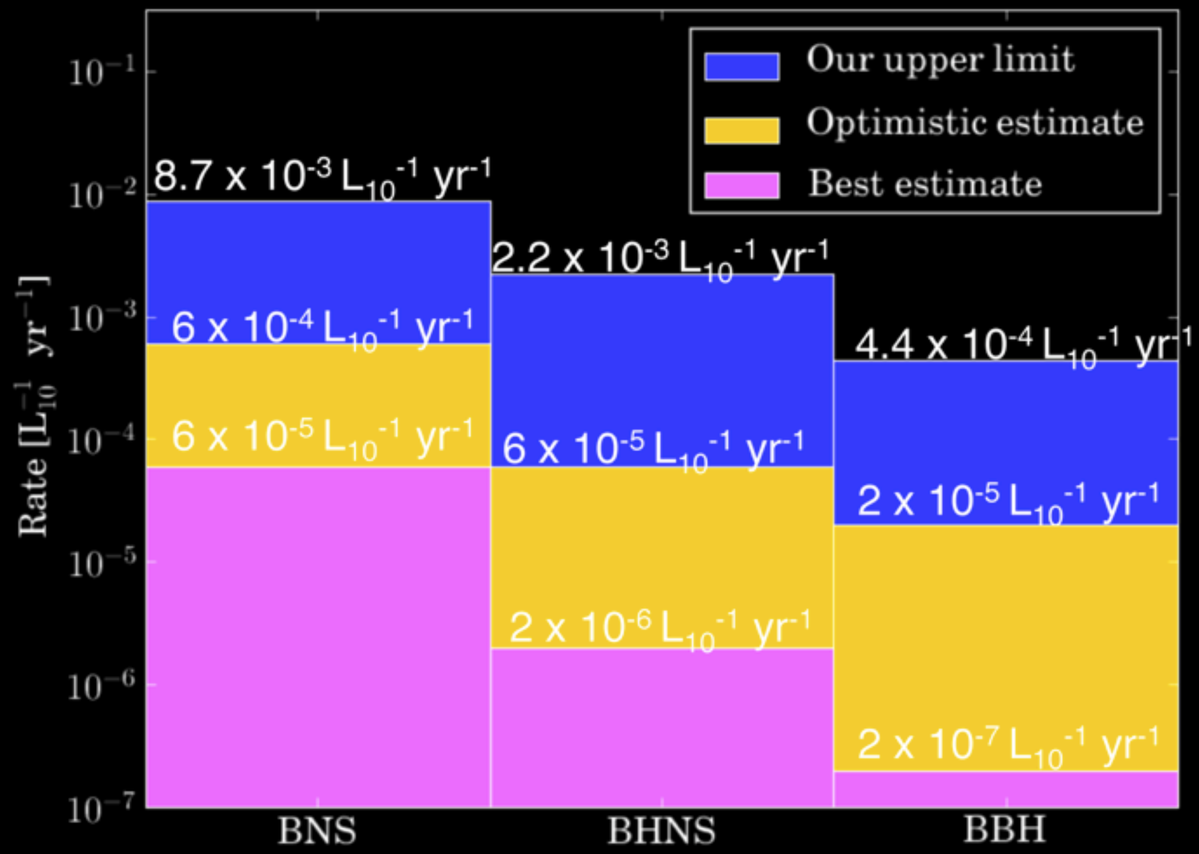
The two body problem

Number of inspiral wave cycles (f>10Hz)

	$2 \times 1.4\, M_\odot$	$10\, M_\odot + 1.4\, M_\odot$	$2 \times 10\, M_\odot$
Newtonian order	16031	3576	602
1PN	441	213	59
1.5PN (dominant tail)	-211	-181	-51
2PN	9.9	9.8	4.1
2.5PN	-11.7	-20.0	-7.1
3PN	2.6	2.3	2.2
3.5PN	-0.9	-1.8	-0.8

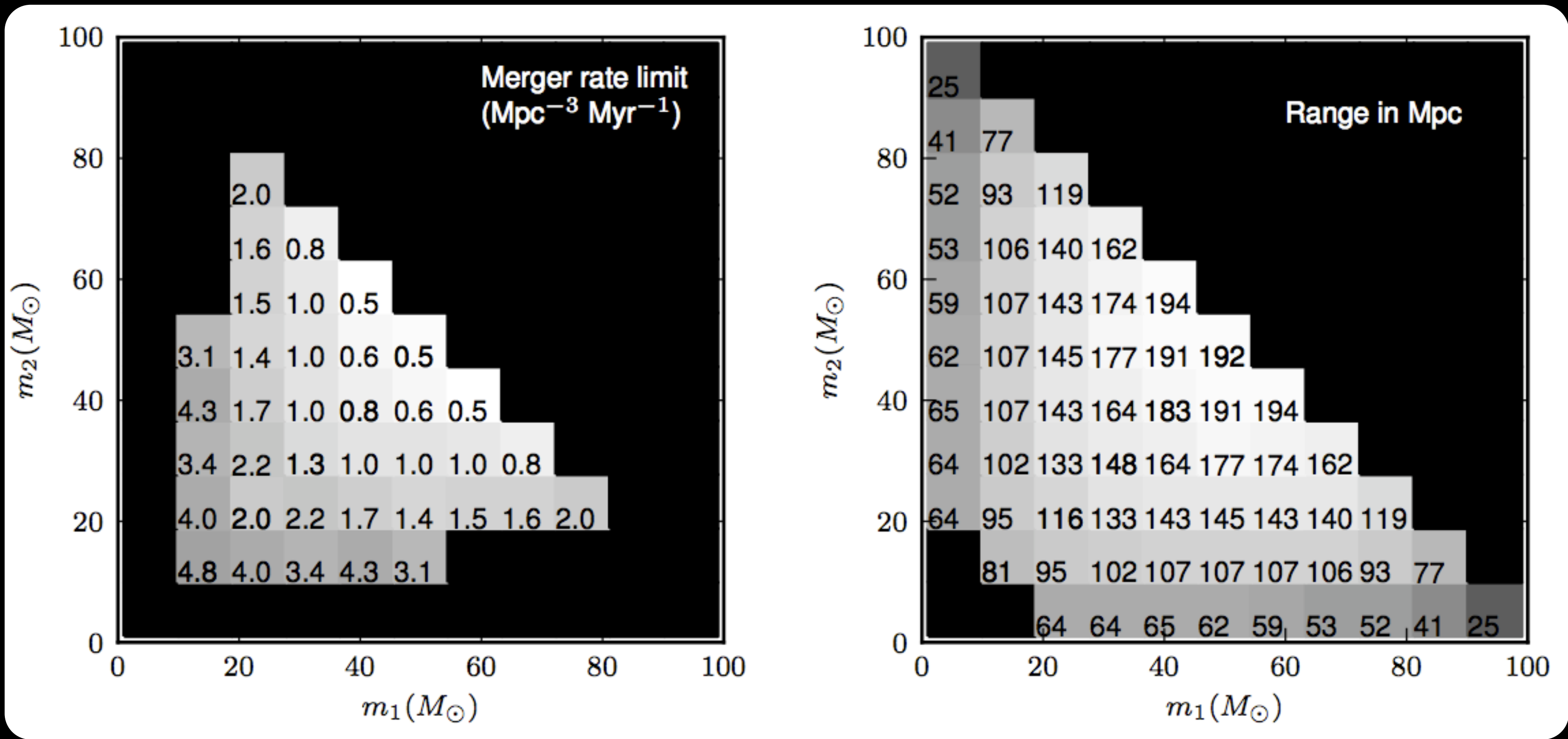


S5 "low-mass": Upper-limits



Abadie et al. (LSC and Virgo), PRD 82, 102001 (2010)

S5 “high-mass”: Upper-limits



Upper-limit a factor ~ 10 higher than optimistic rate

1. GW unsolved problems:

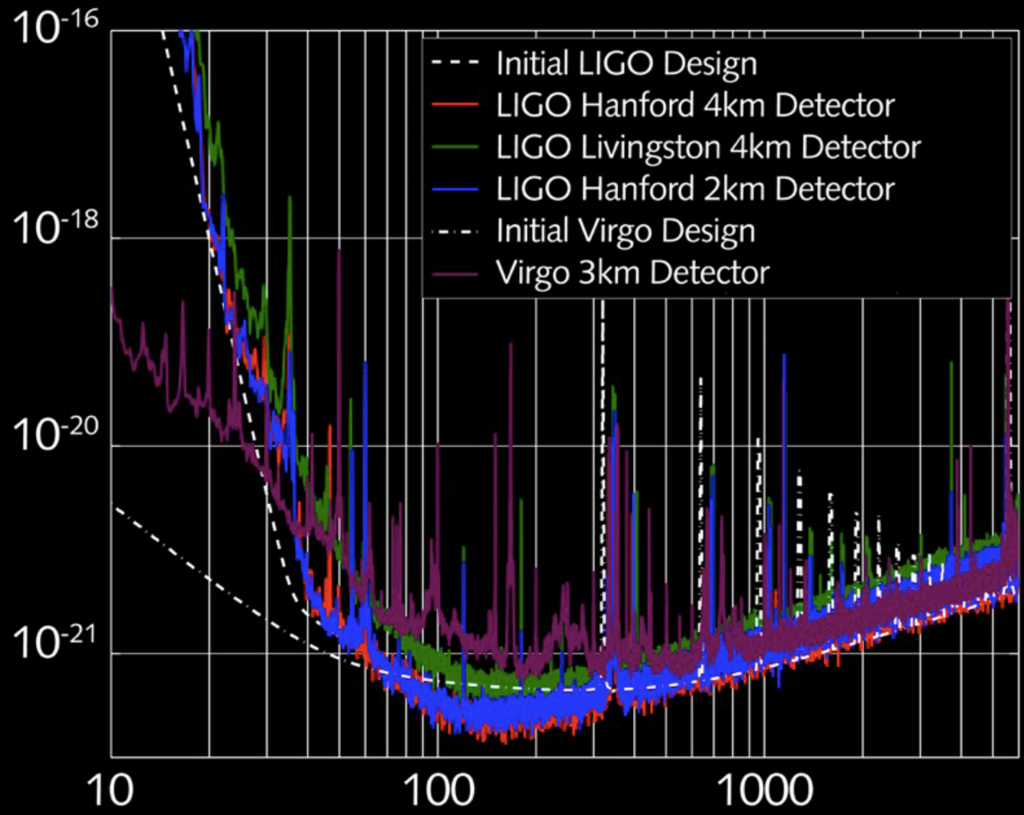
No *direct* detection (yet)

Is it expected?

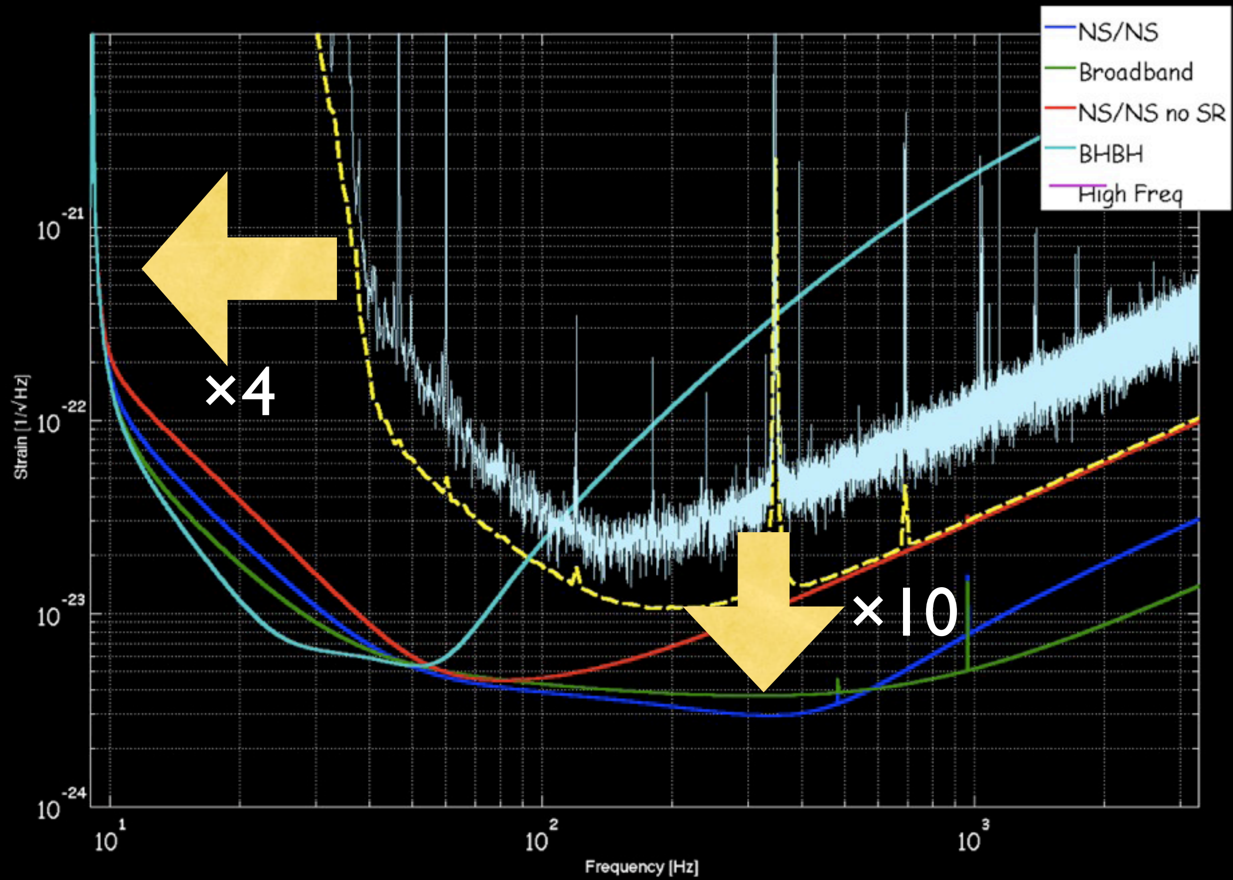
(Unfortunately) yes

2. Any chance of a detection "soon"?

Beyond design sensitivity: eLIGO/Virgo+ (S6/VSR2/3)



Advanced LIGO



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	IMBH-IMBH			0.1[d]	1[e]

Abadie et al. (LSC and Virgo), CQG 27, 173001 (2010)

LIGO Australia?

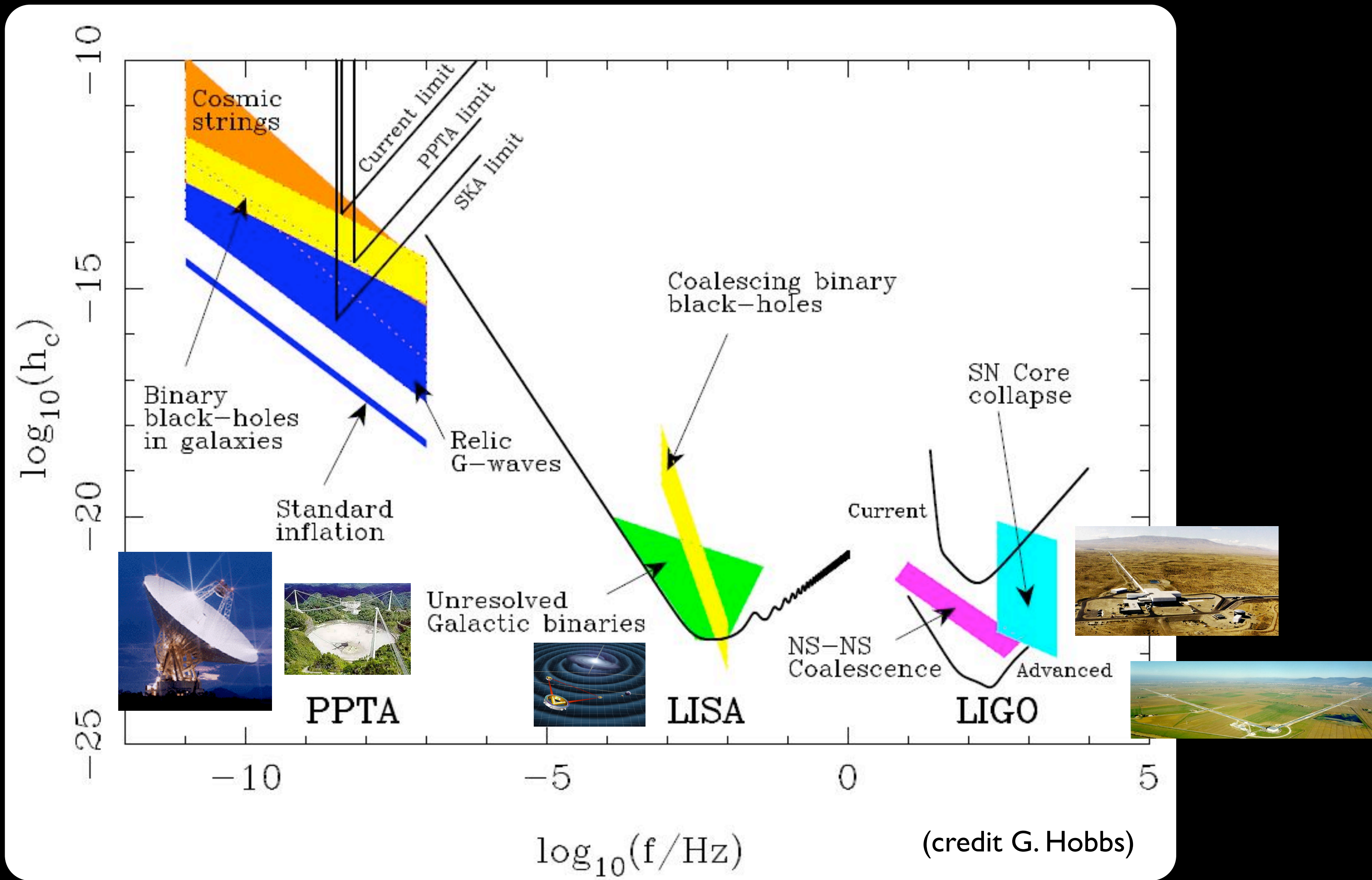
Gingin facility

Decision will be made by Oct 2011

LCGT

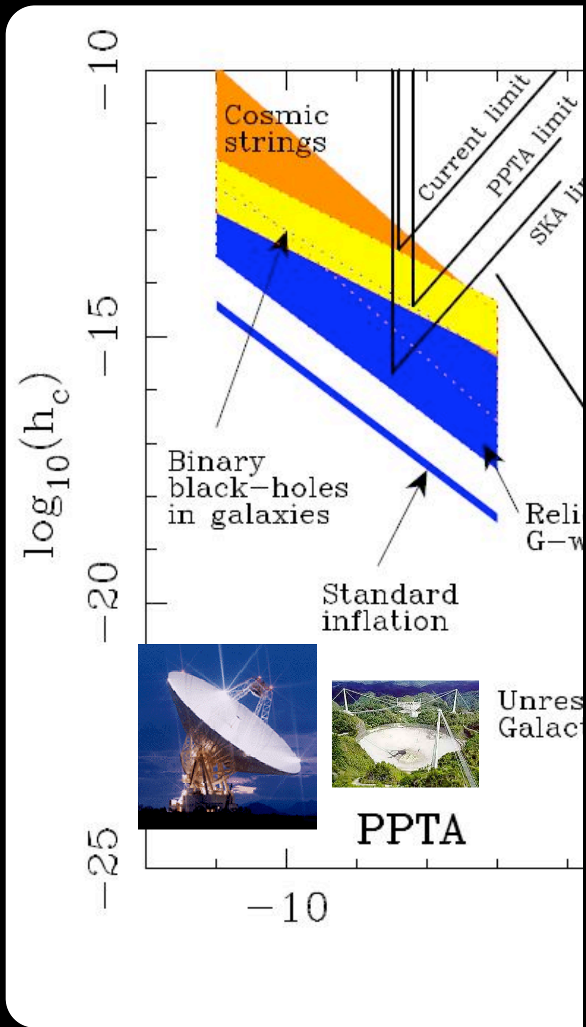

LCGT
Feel the Universe in Underground
- Detect Gravitational Waves from 200 Mpc Away -
37km from the Nippon Sea
Ikenoyama Mt.
1000m Underground
Mozumi area
XMASS
Kamland
SG
Super Kamiokande
CLIO
3 km
358m Altitude
LCGT project
to Tateyama
LCGT
Image
to Toyama
Takahara river
Atotsu river
Atotsu
Entrance
to Takayama
Detect
3
100,000,000,000,000,000,000
meter changes
GEO600-HF
(Germany・England)
Advanced-LIGO
(USA)
Advanced-VIRGO
(france・Italy)
Large-scale Cryogenic
Gravitational wave Telescope
(LCGT) (Japan)
Next Generation
Gravitational Wave
Detector Network
4km
Washington : Desert
4km
Louisiana : Forest
600m
Hanover
3km
Pisa
ACIGA
(Australia)

GW spectrum



(credit G. Hobbs)

Pulsar Timing Arrays

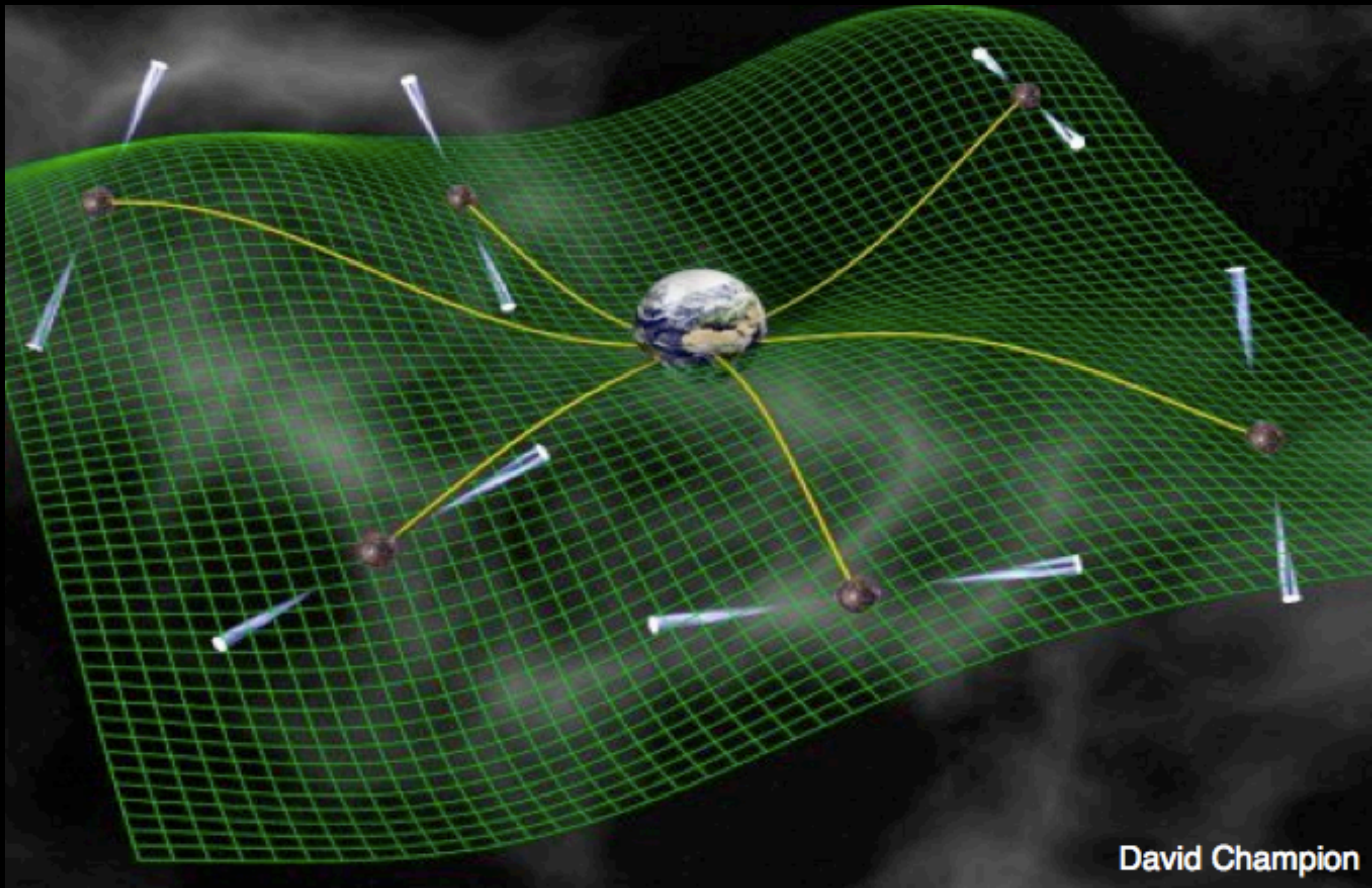


In operation:

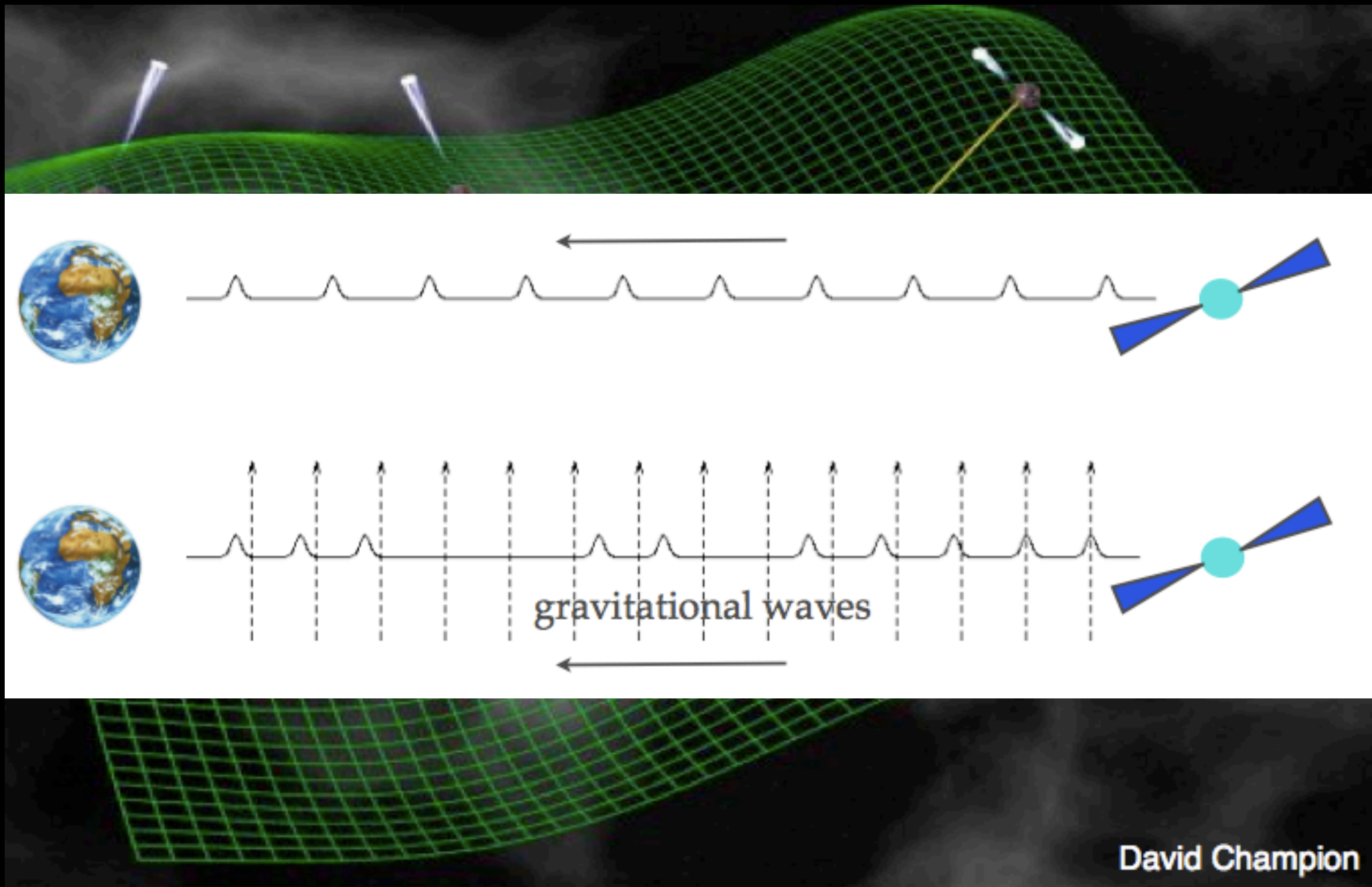
- Parkes PTA
- European Pulsar Timing Array (EPTA/LEAP)
- Nanograv

A. Vecchio - Benasque, 15th February 2011

Pulsar Timing Arrays



Pulsar Timing Arrays



PTA and 3C 66B

- VLBI measurements of motion of radio core 3C 66B (Sudou et al, 2002). Consistent with super-massive black hole binary with:

$$\begin{aligned} P &= 1.05 \pm 0.03\,\mathrm{yr} \\ M &\approx 5 \times 10^{10}\, M_\odot \\ z &= 0.02 \end{aligned}$$

- Analysis of timing data from a single pulsar (B1855+09) rules out the system at 95% confidence (Jenet et al, 2004)

- See also Lommen and Backer (2001) for proof-of-concept analysis

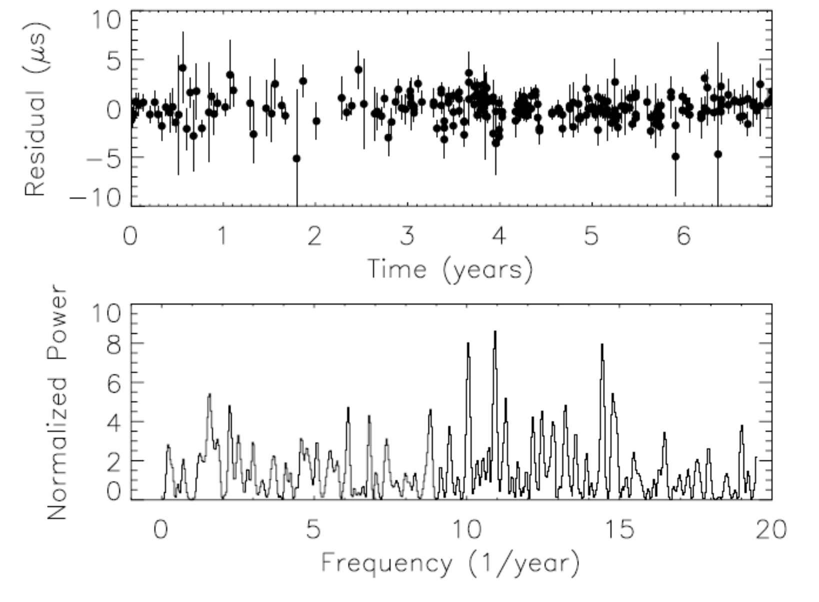


FIG. 2.—*Top*: Timing residuals for PSR B1855+09. *Bottom*: The corresponding normalized Lomb periodogram.

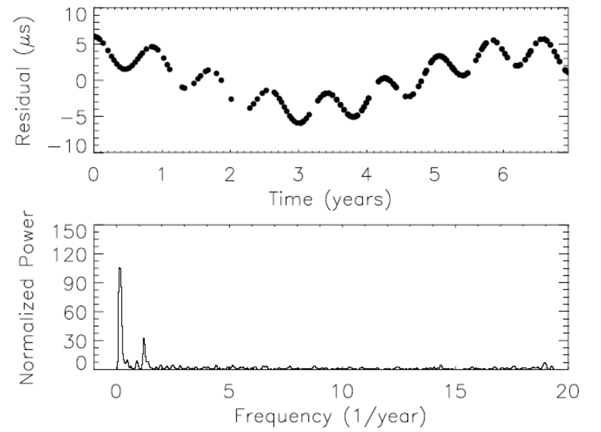
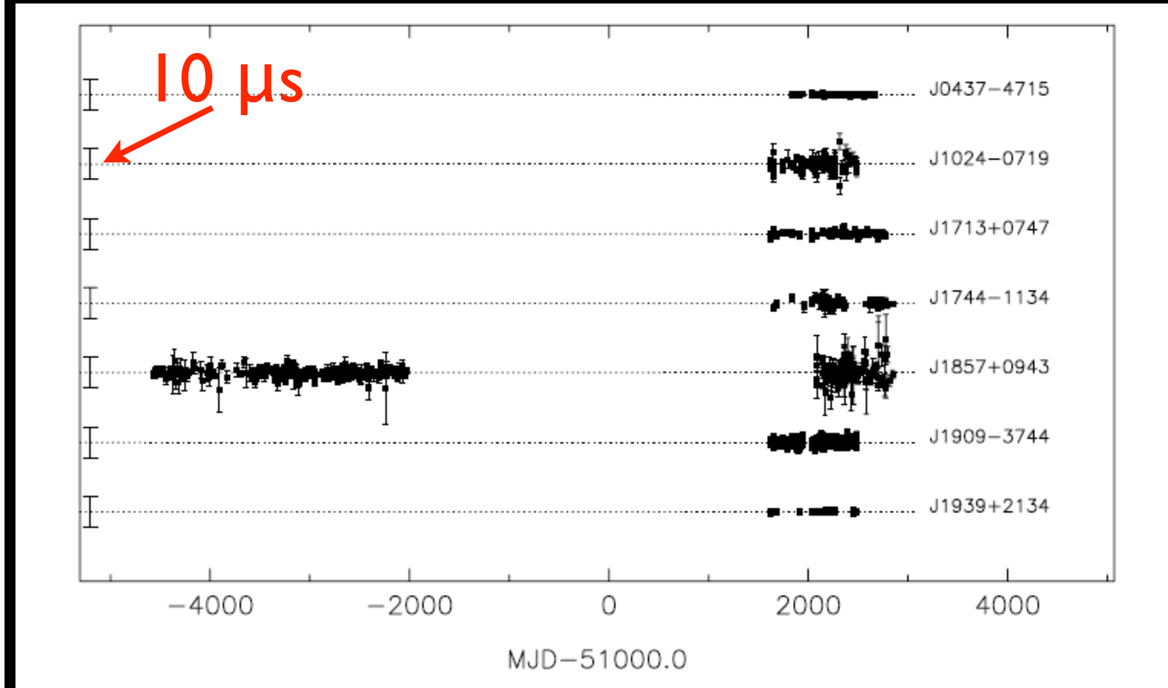


FIG. 1.—*Top*: Theoretical timing residuals induced by G-waves from 3C 66B. The timing points are chosen to coincide with the actual timing residuals of PSR B1855+09. *Bottom*: The corresponding normalized Lomb periodogram.

What is the sensitivity needed?



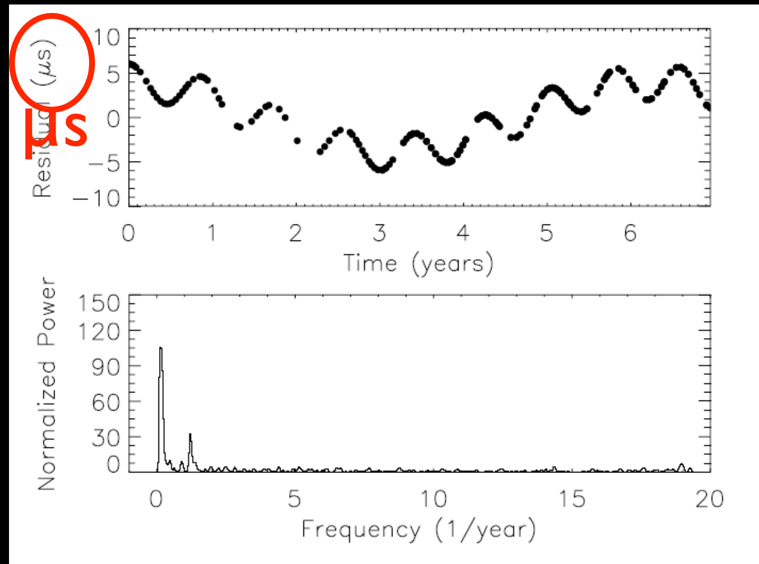


FIG. 1.—*Top*: Theoretical timing residuals induced by G-waves from 3C 66B. The timing points are chosen to coincide with the actual timing residuals of PSR B1855+09. *Bottom*: The corresponding normalized Lomb periodogram.

(Jenet et al, 2004, 2006)

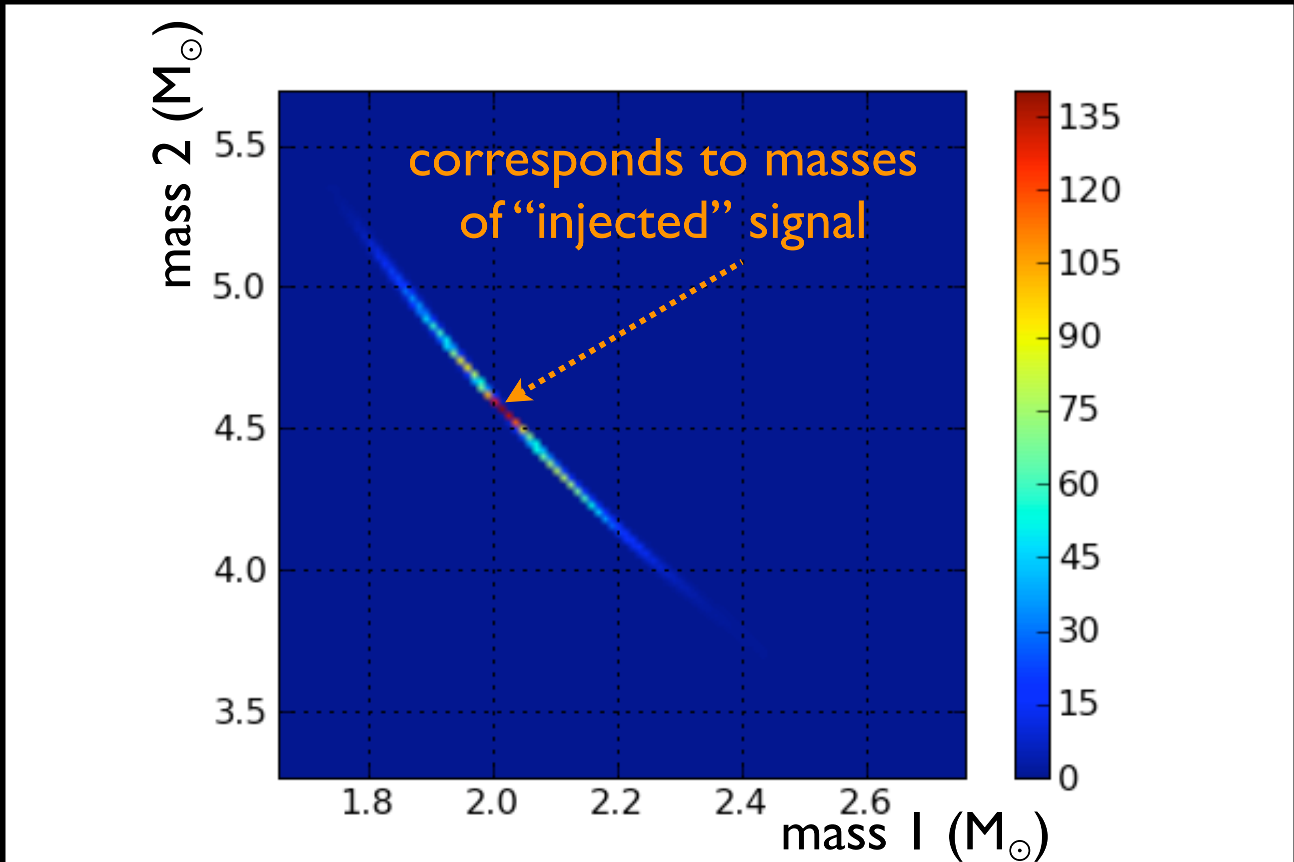
$$r(t) \simeq 26 \left(\frac{\mathcal{M}}{10^9\, M_\odot}\right)^{5/3} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \left(\frac{f}{5\times 10^{-8}\,\mathrm{Hz}}\right)^{-1/3} \mathrm{ns}$$

3. Can we do precise astronomy?

3a. Are coalescing binaries a new class of standard candles? (do we need a new class?)

e.g.: Measuring masses

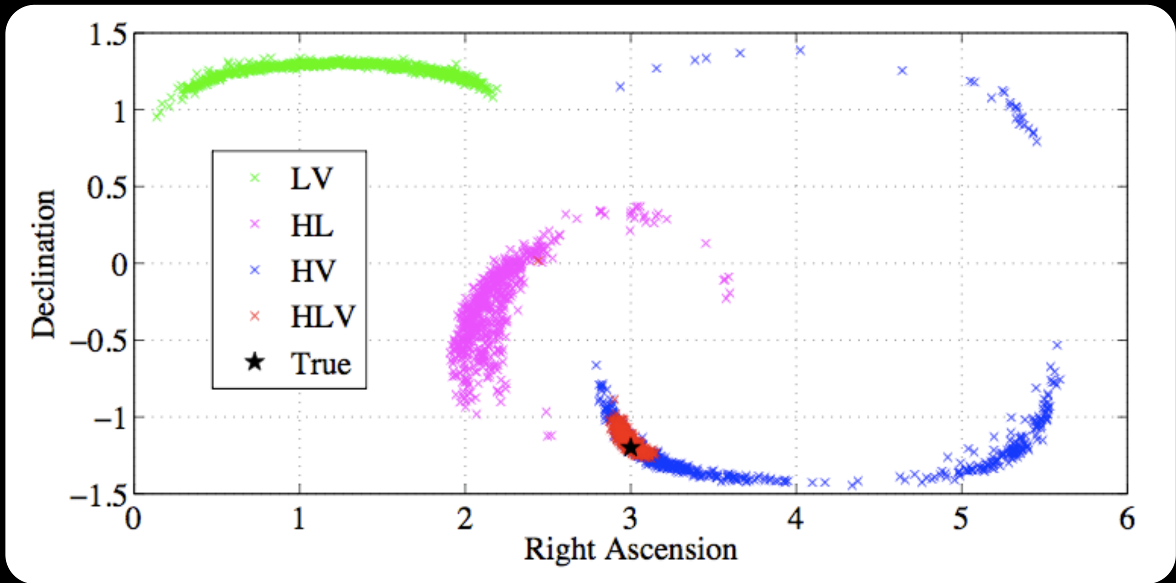
Marginalised PDFs over a 9-dimensional parameter space
(non-spinning inspiral)



(see e.g. Roever et al, 2007, van der Sluys et al 2008, Veitch and AV 2009)

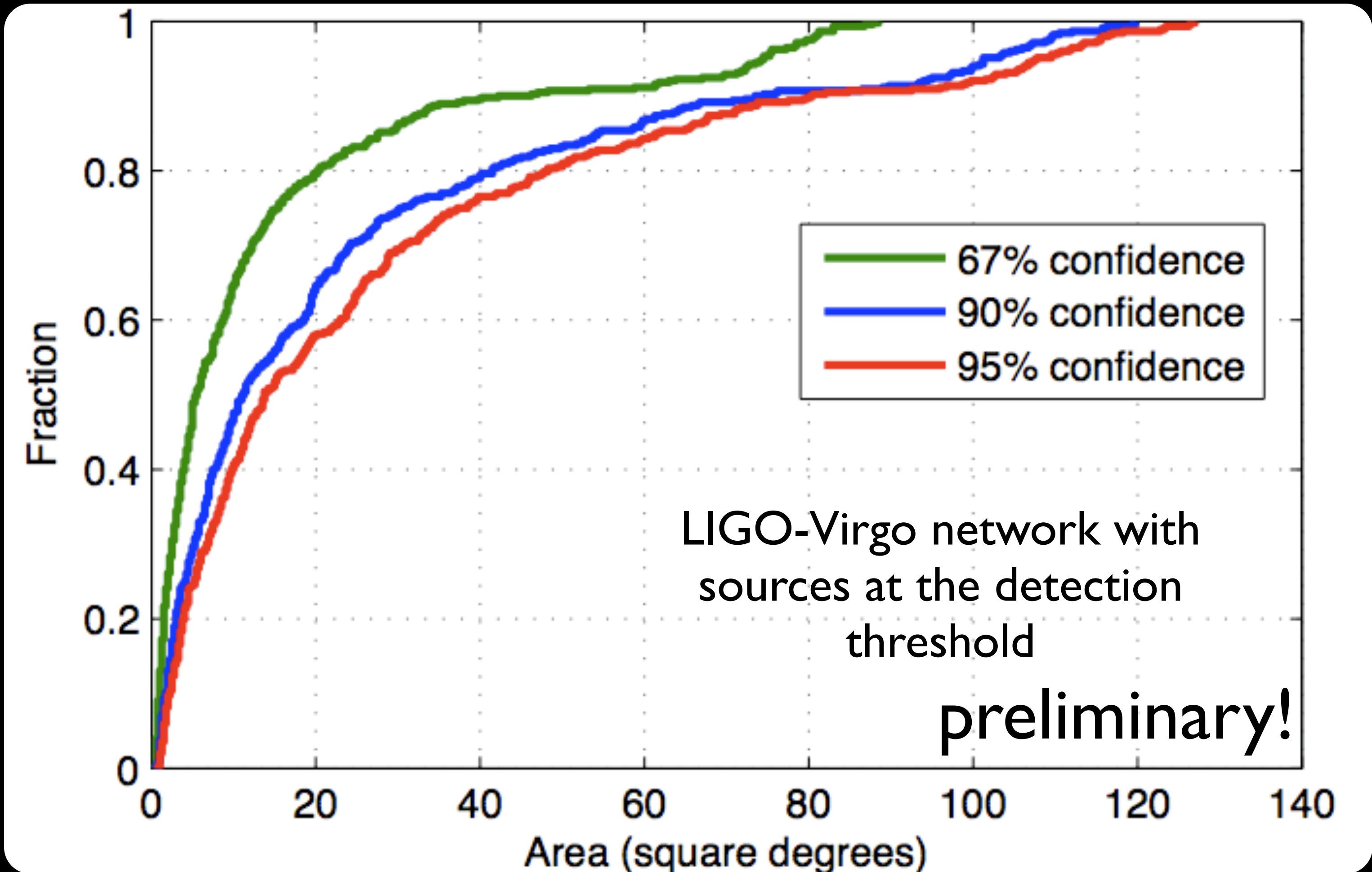
Sampling rings in the sky

$$h(t) = F_+(\alpha,\delta,\psi)\, h_+(t) + F_\times(\alpha,\delta,\psi)\, h_\times(t)$$

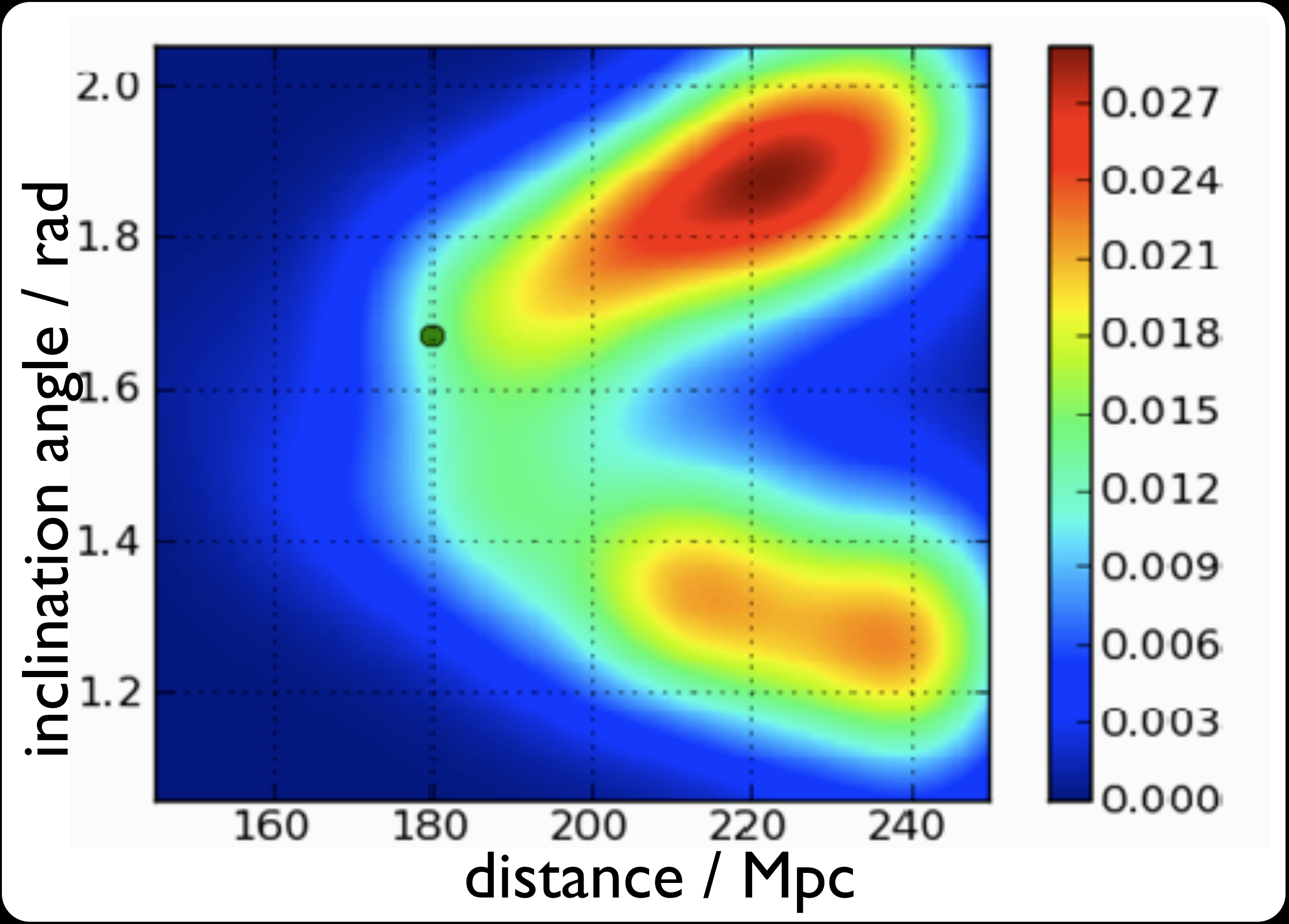


(Veitch & AV 2010)

Locating a source in the sky



Distance measurements



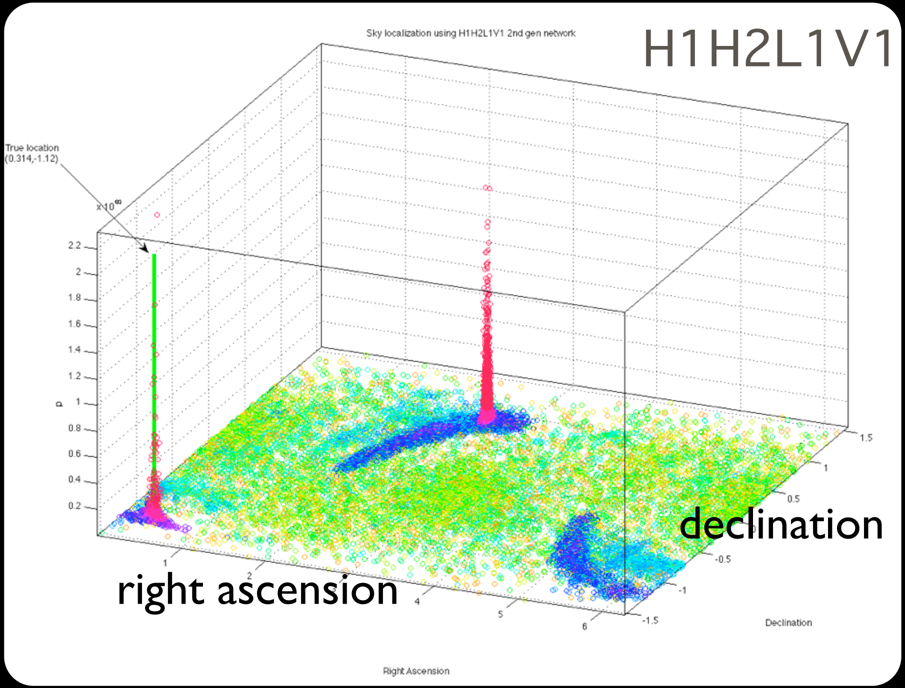
$$h_+ = \# \frac{(1+\cos^2 \iota)}{D}$$

$$h_\times = \# \frac{\cos \iota}{D}$$

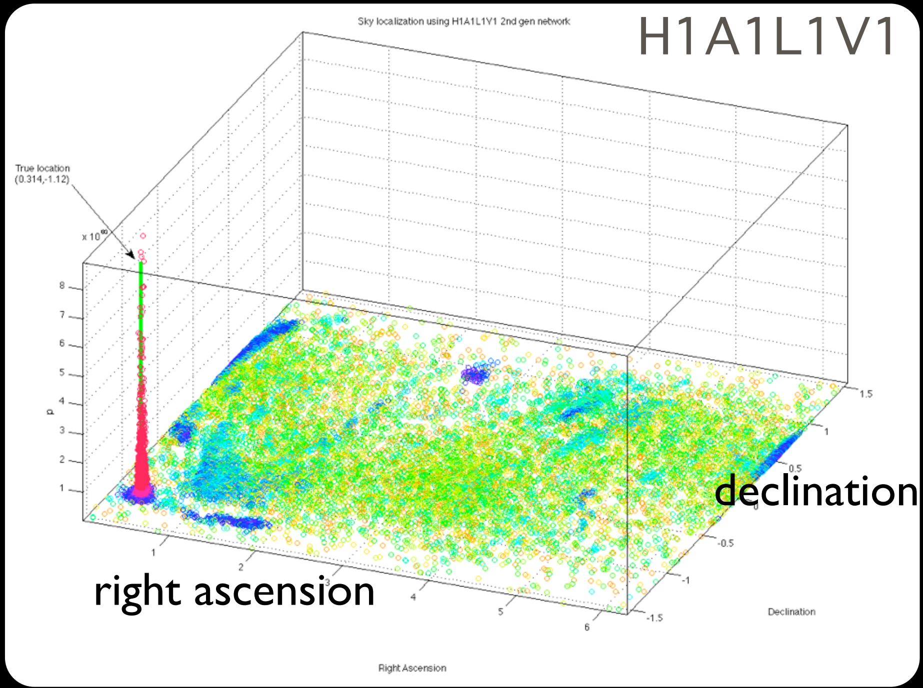
credit J.Veitch

(One of the) benefits of LIGO Australia

Current network



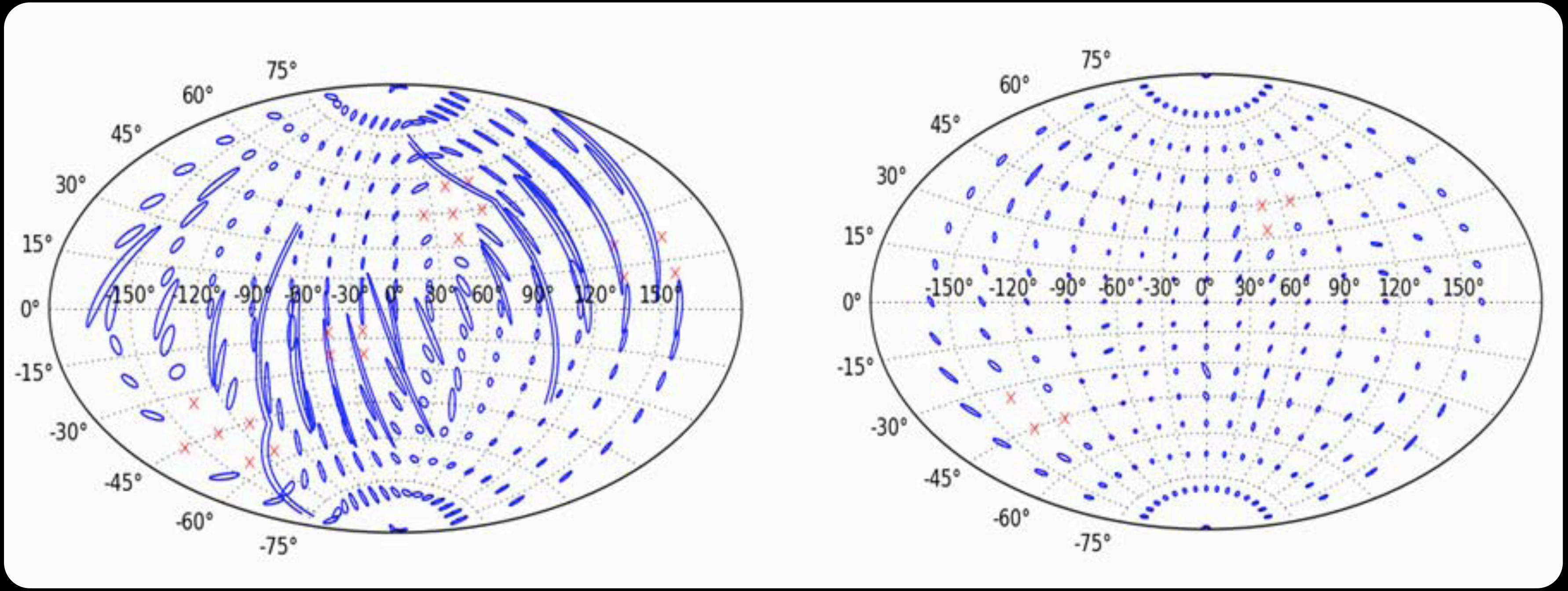
Current network + instrument in Australia



Sky resolution

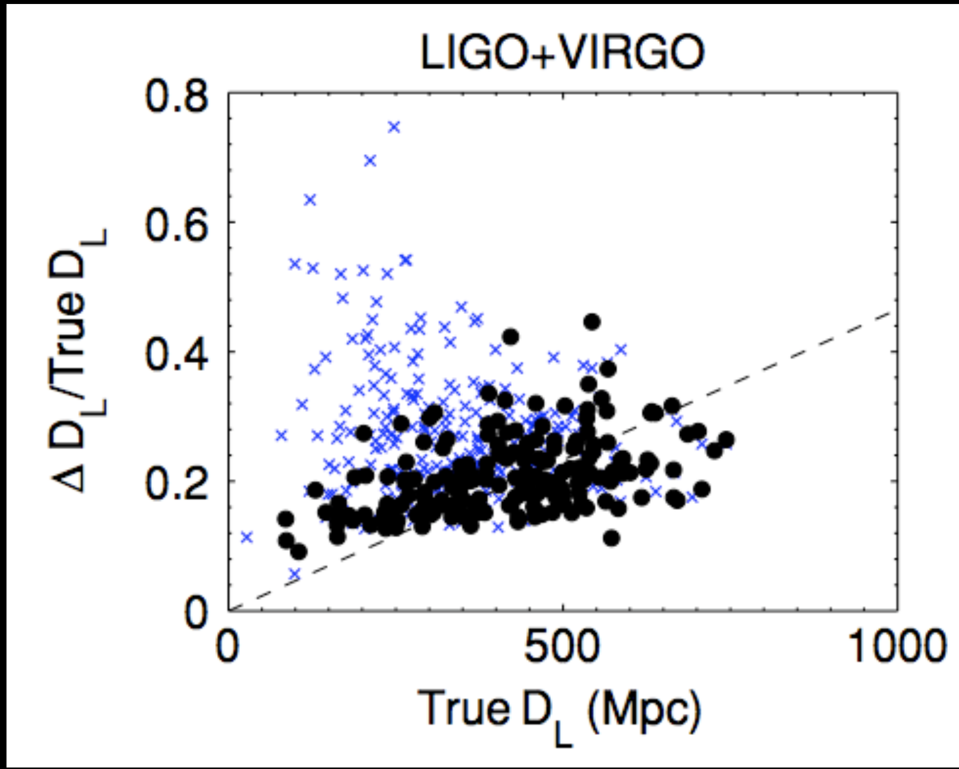
Current network

Current network
+
instrument in Australia



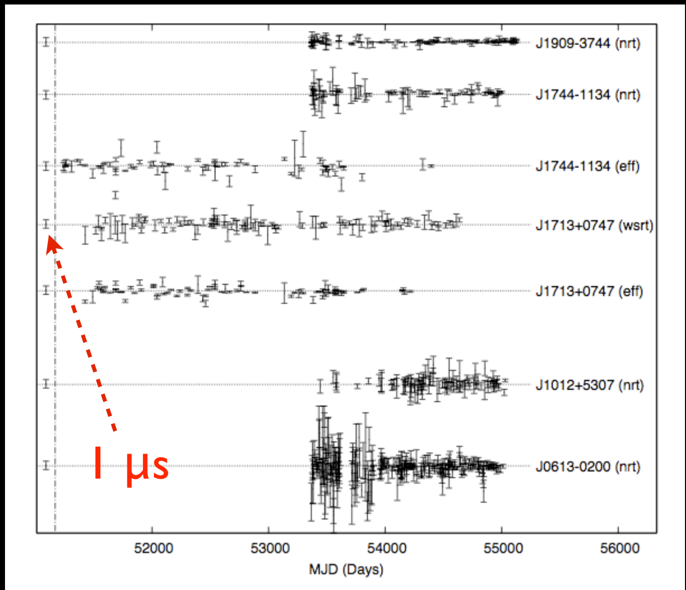
Measuring cosmological parameters

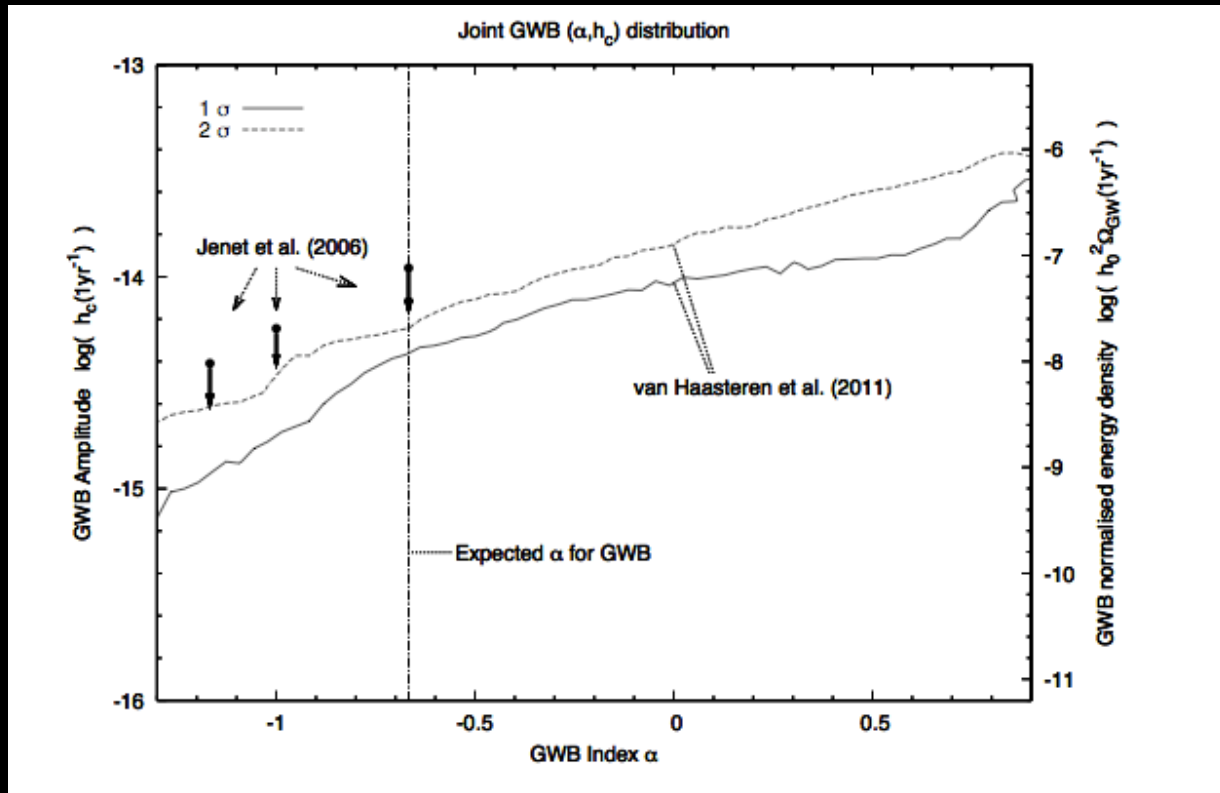
- "Poor" angular resolution may prevent optical identification (i.e. redshift)
- Degeneracies in parameter space my limit accuracy in distance measurements
- Weak lensing may be the ultimate limitation if there is a small number of detections
- Many papers (Hughes, Holz & Co), the issue is not settled



Nissanke et al, 2010

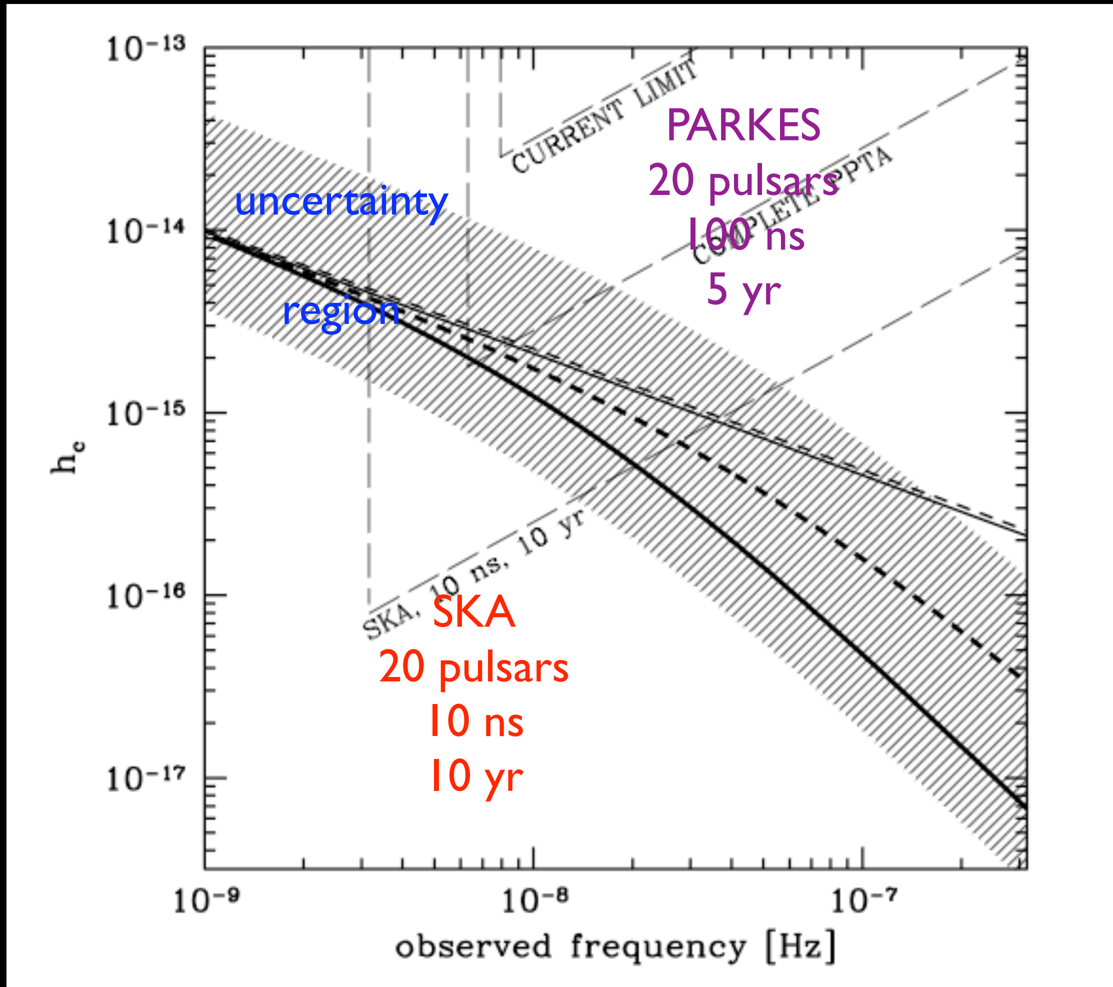
New upper-limit from EPTA





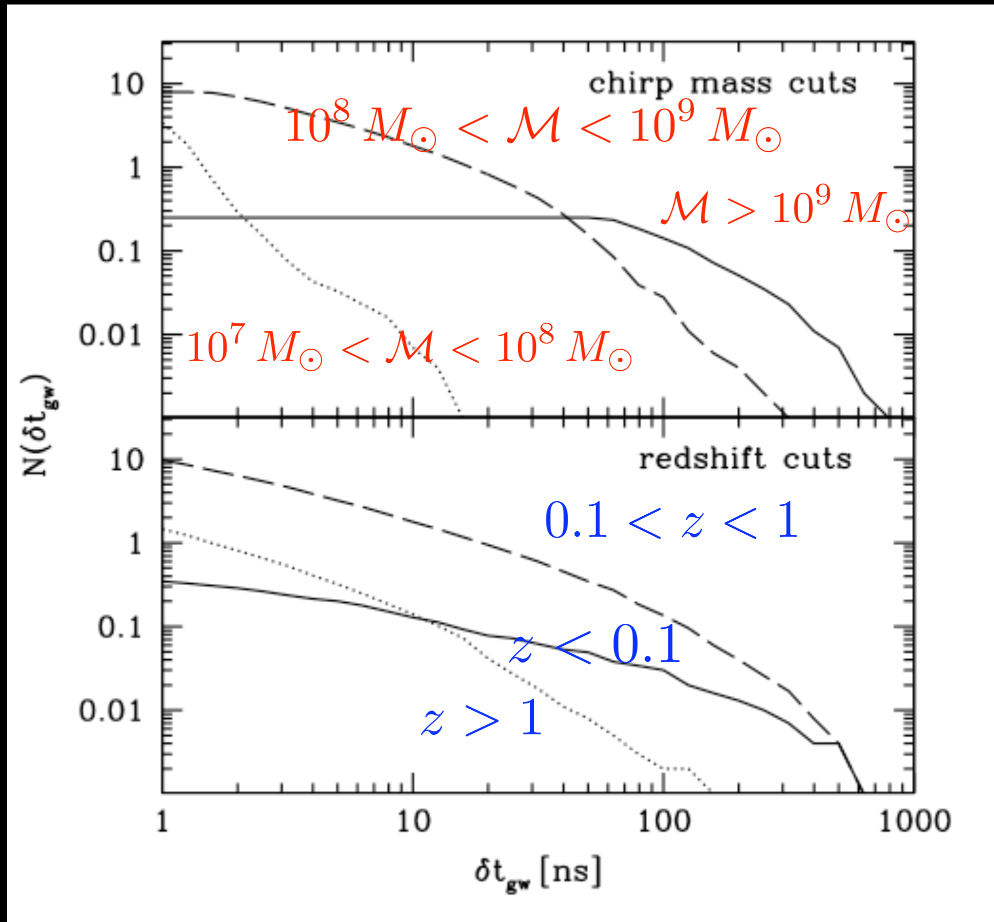
van Haasteren et al (EPTA), 2010 submitted

Observing the foreground form SMBH binaries



Sesana, AV and Colacino (2008)

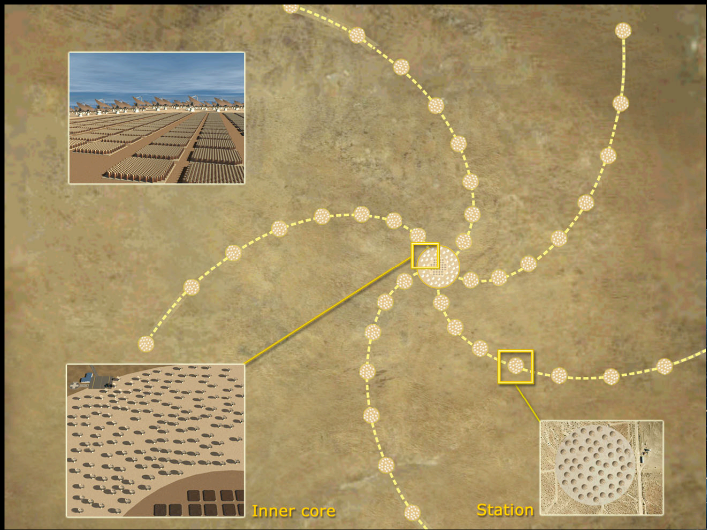
Resolving SMBH binaries



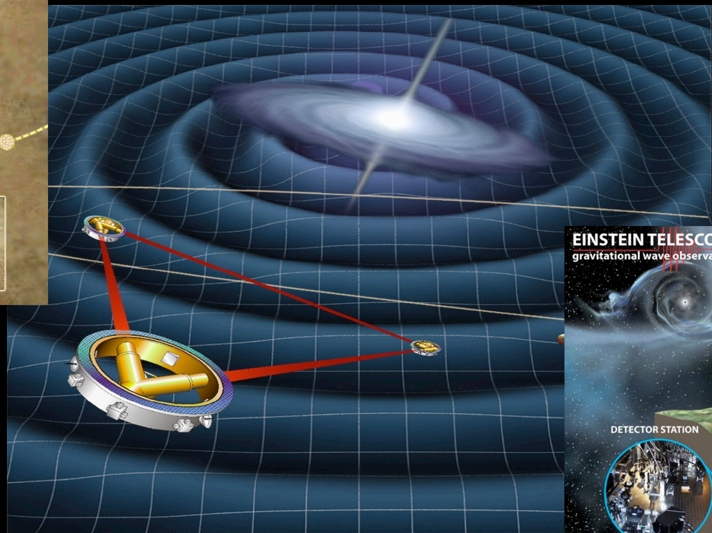
Sesana, AV and Volonteri (2009)

2020 - 2030+

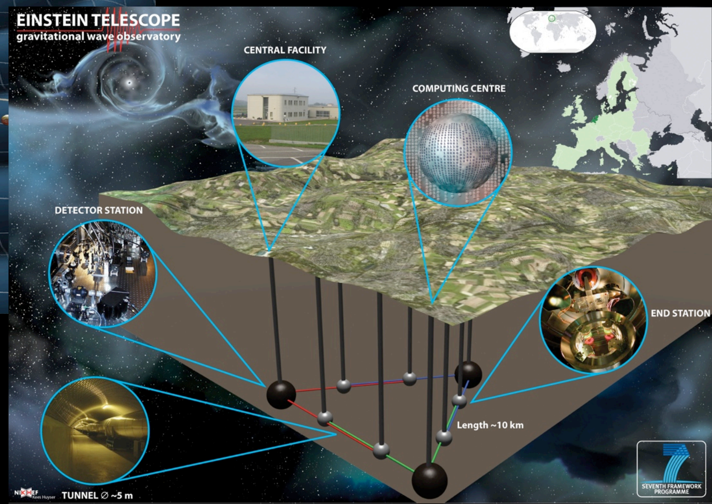
Square Kilometre Array (SKA)

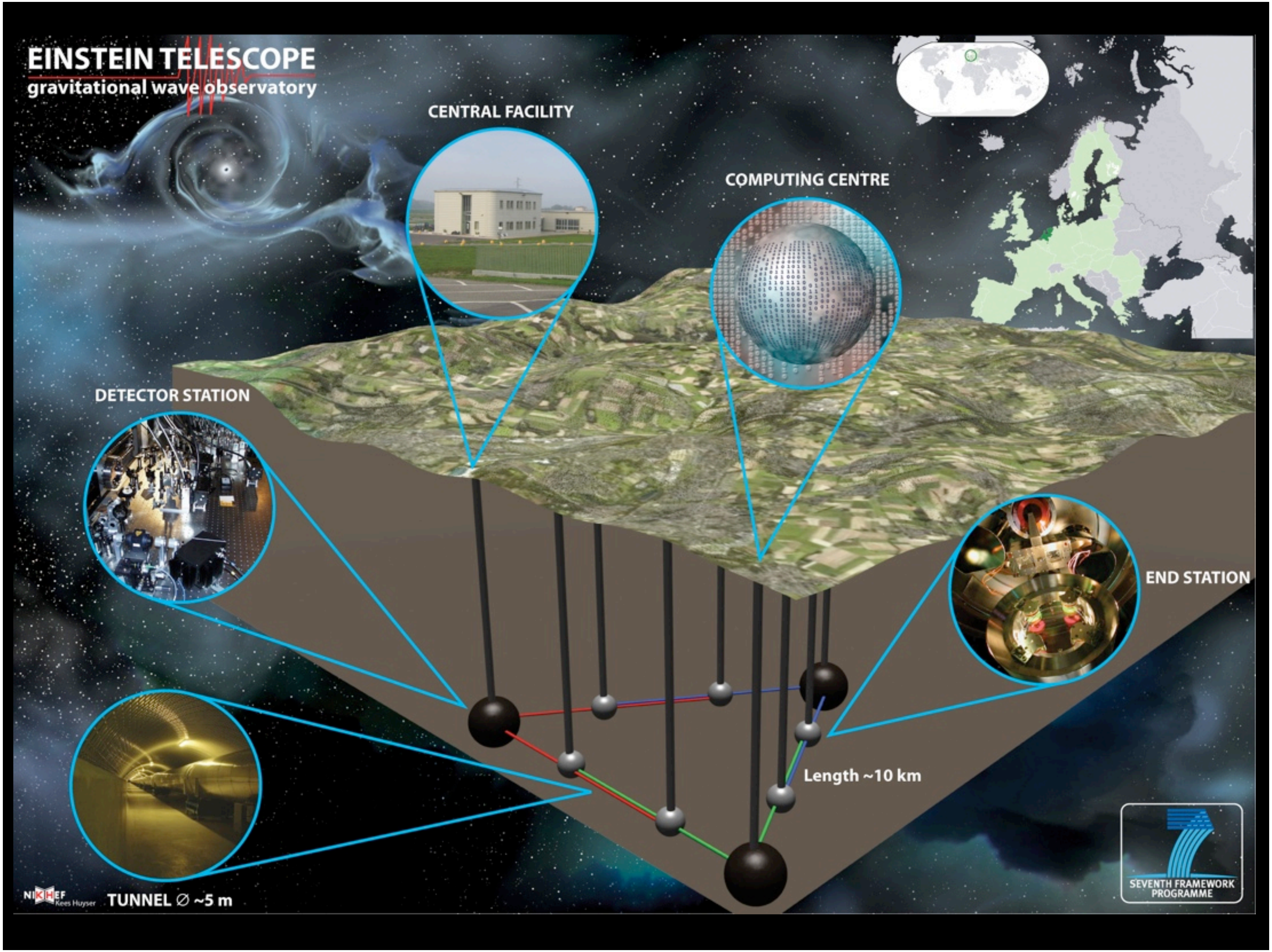


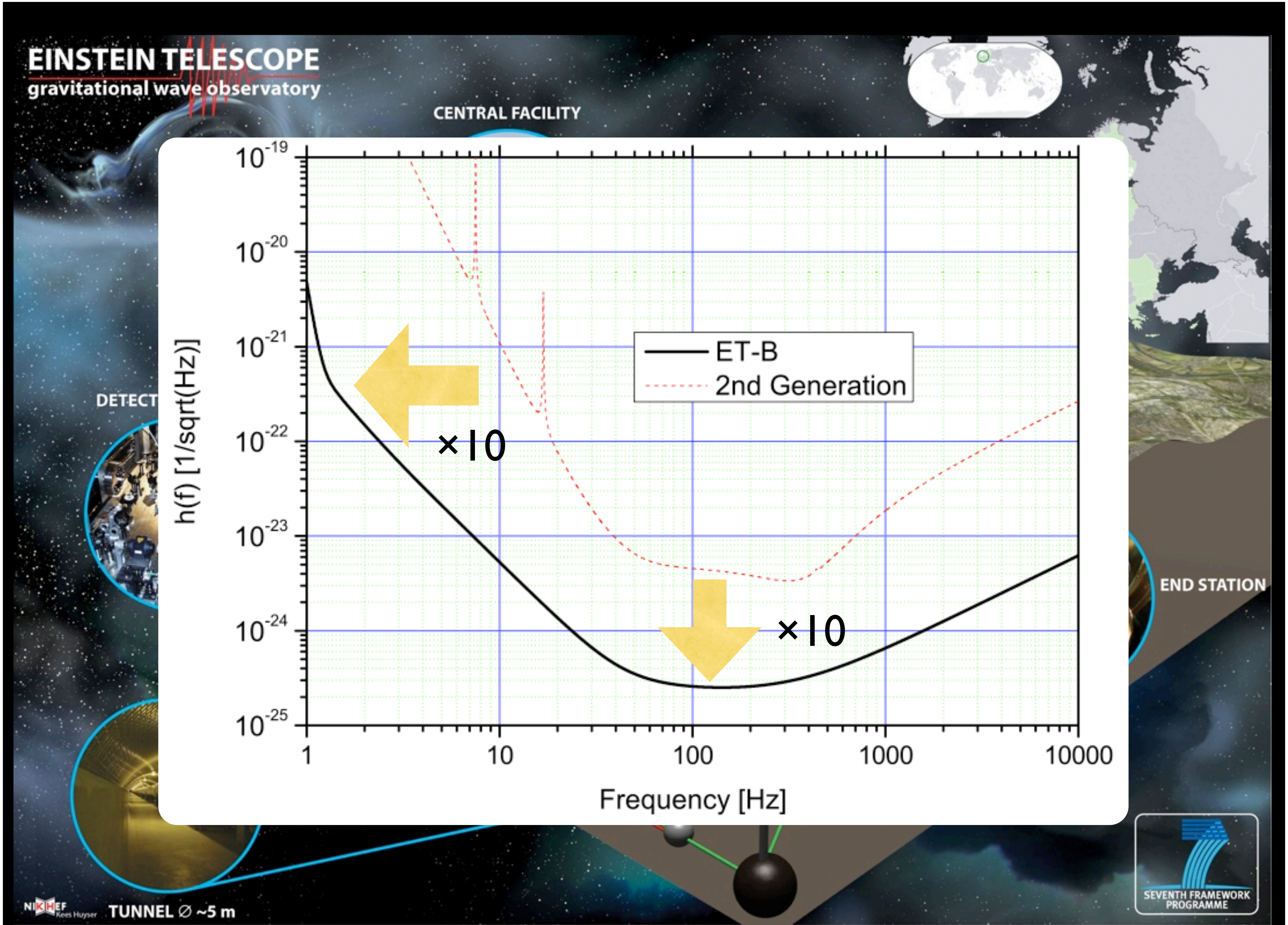
Laser Interferometer Space Antenna (LISA)



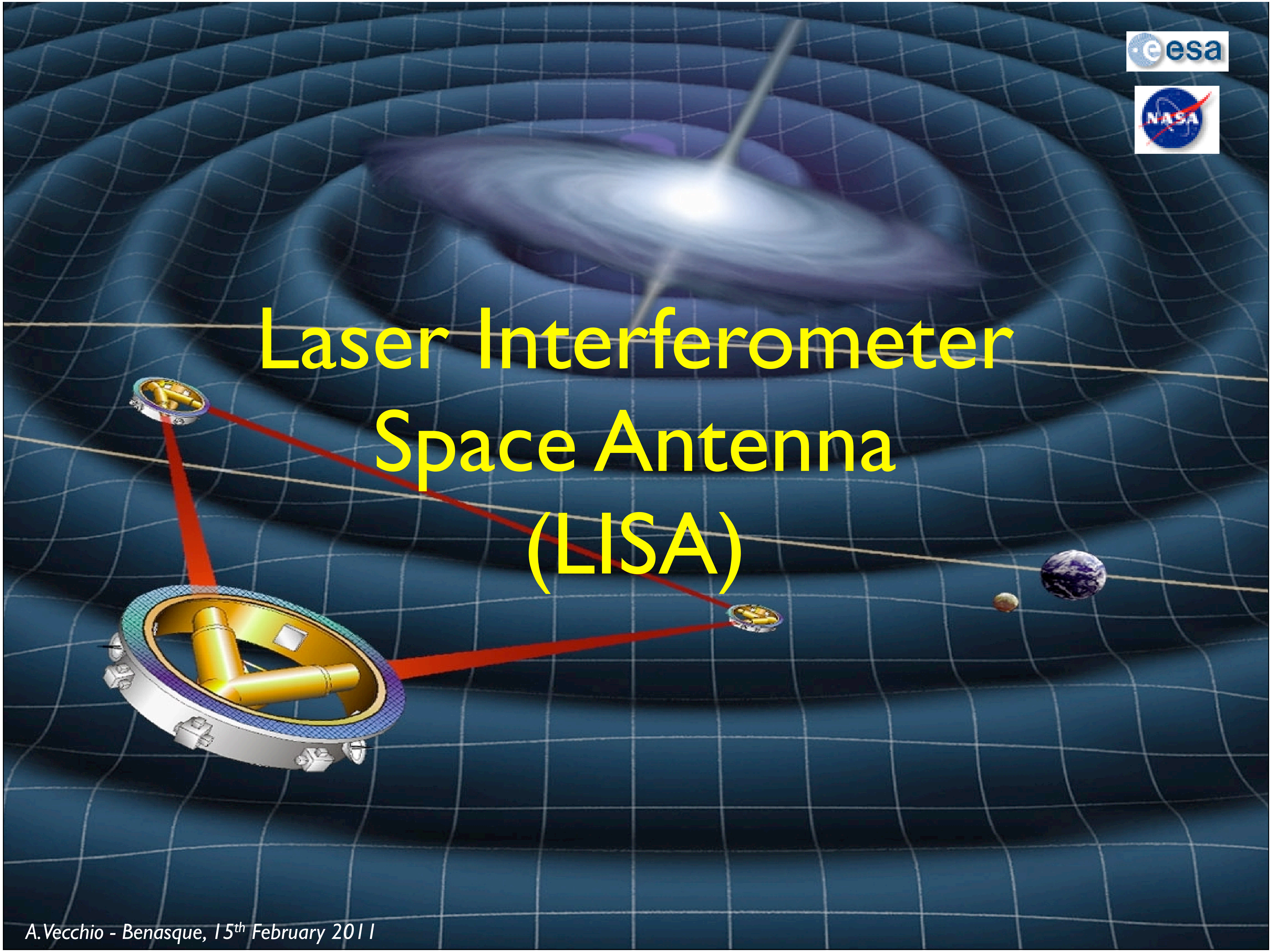
Einstein gravitational-wave Telescope (ET)

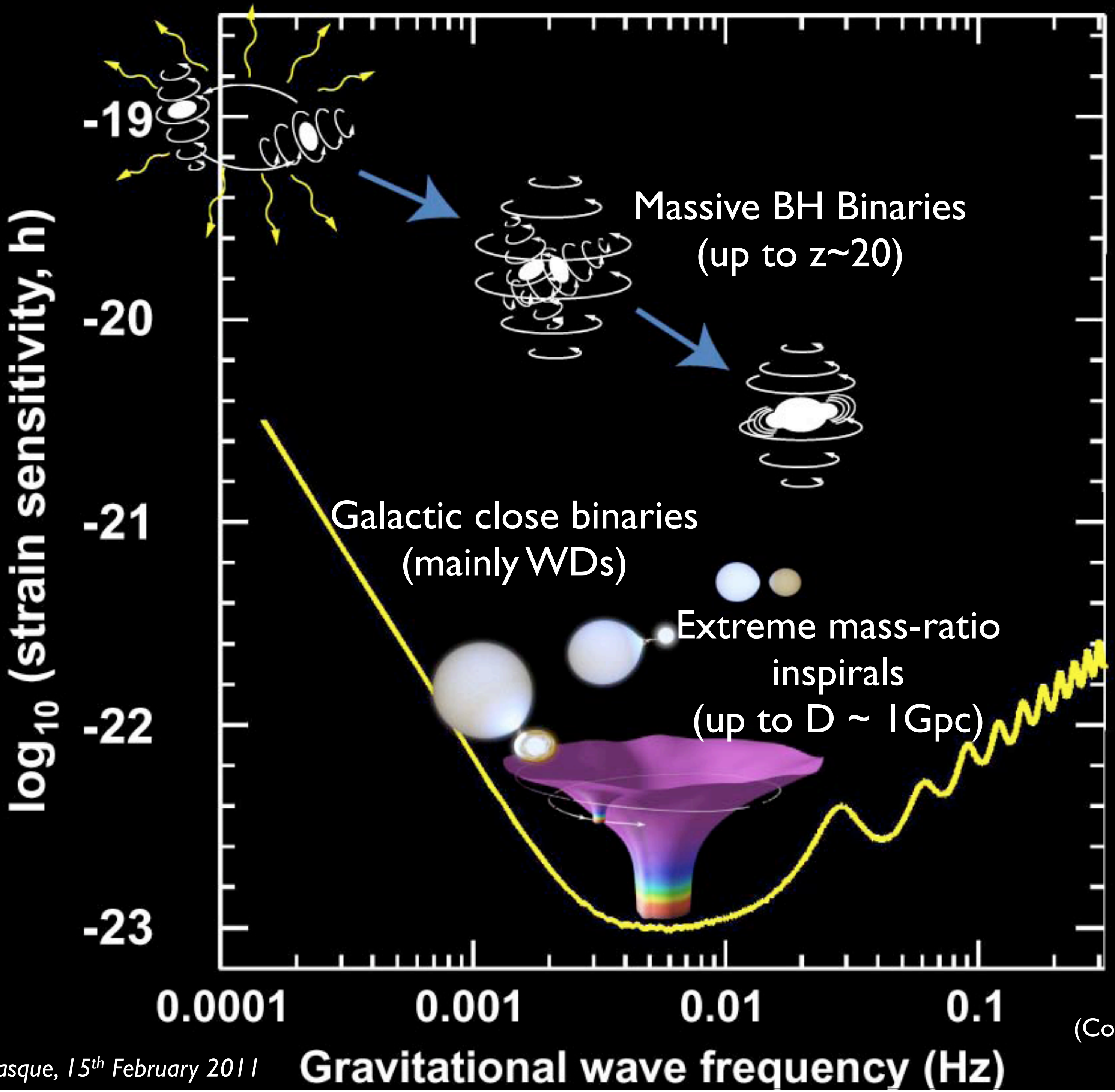



EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
NIKHEF
Kees Huyser
SEVENTH FRAMEWORK PROGRAMME


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
DETECT
END STATION
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME
h(f) [1/sqrt(Hz)]
Frequency [Hz]
ET-B
2nd Generation
×10
×10
1
10
100
1000
10000
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25

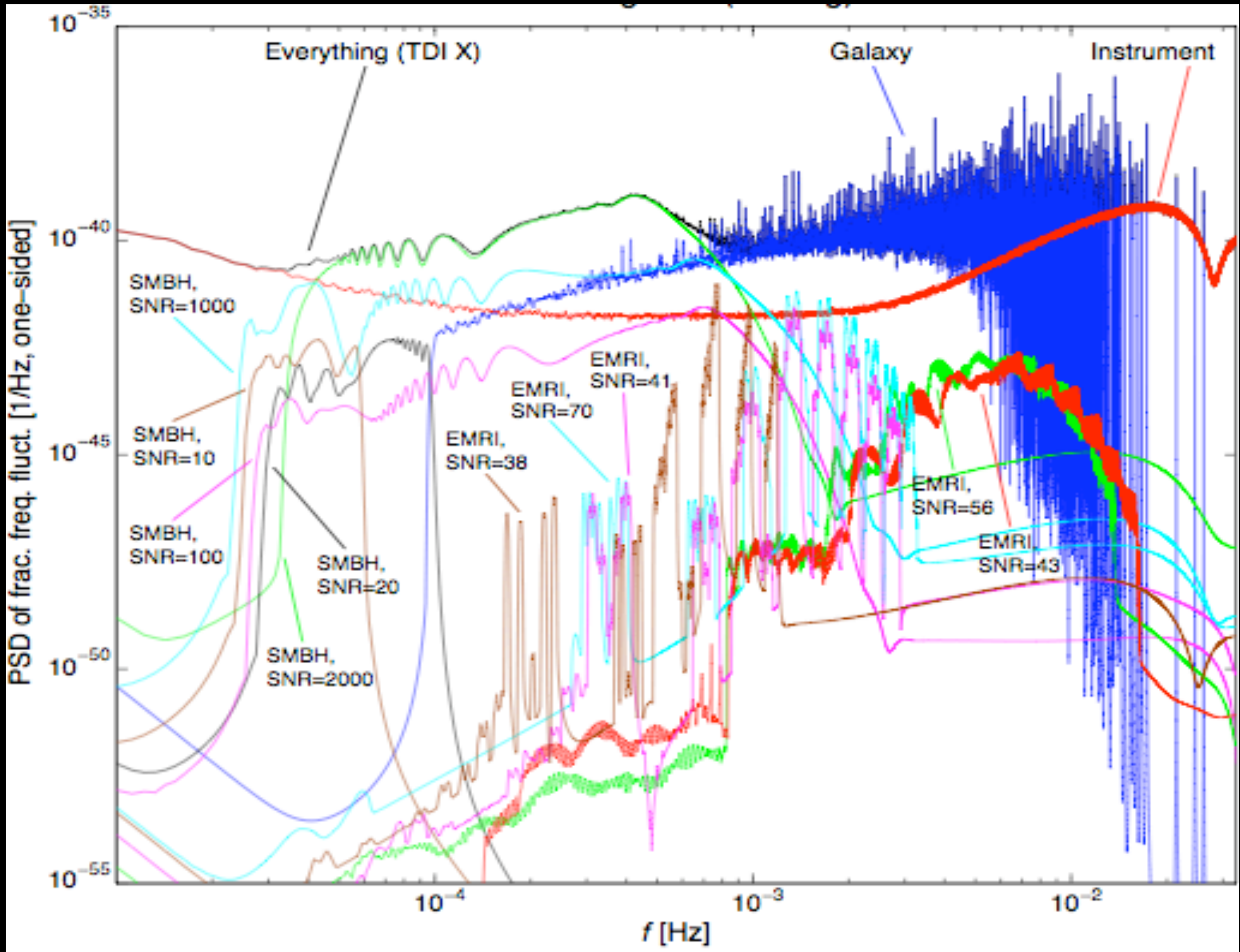
Laser Interferometer Space Antenna (LISA)





(Courtesy S. Phinney)

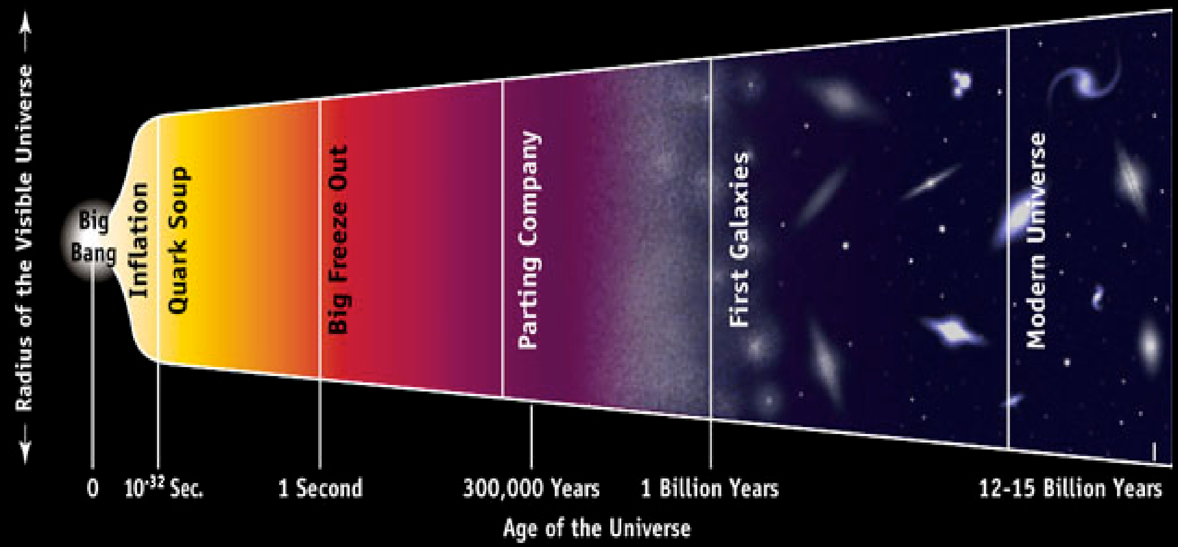
The embarrassment of richness



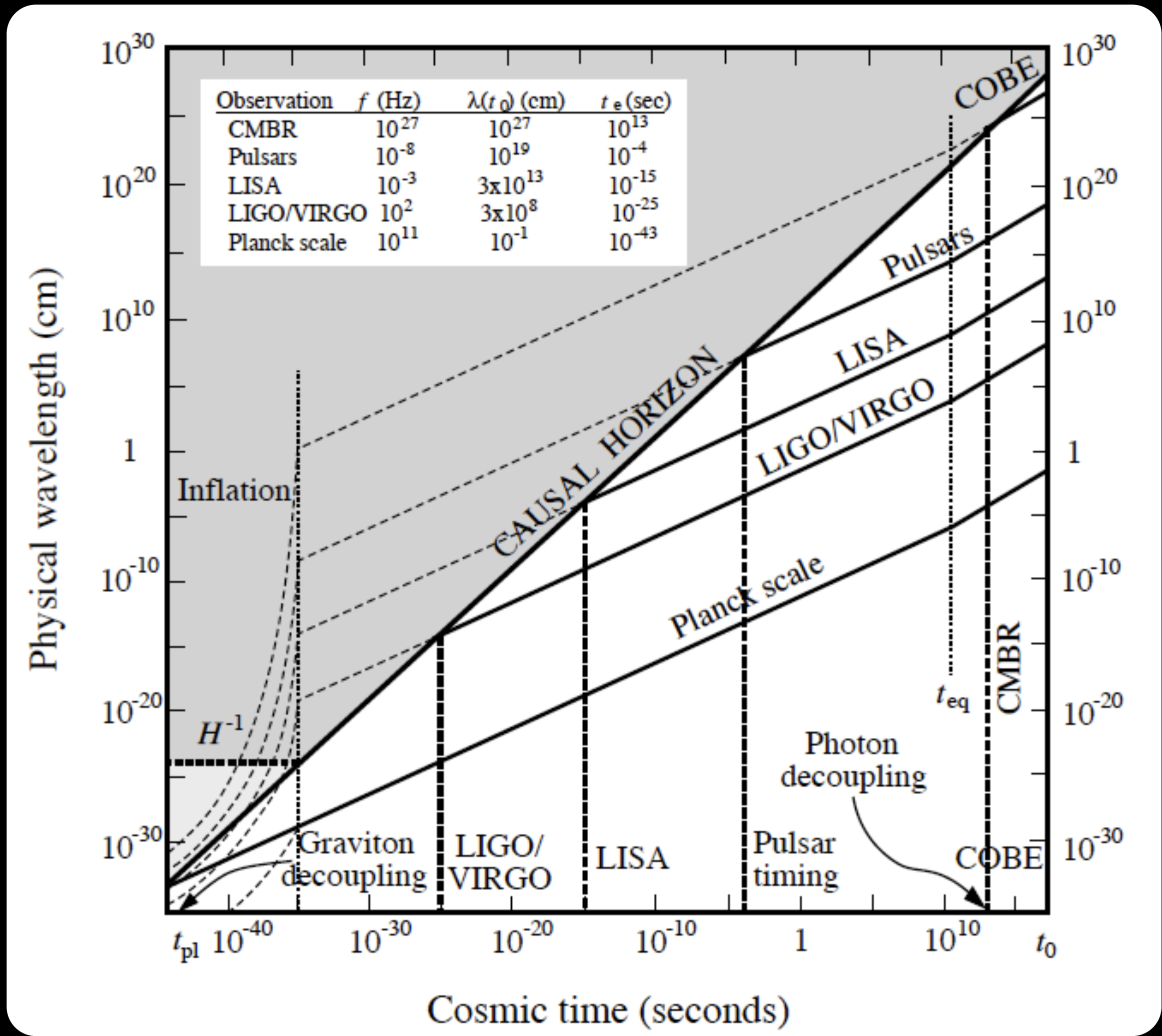
(Courtesy M.Vallisneri)

4. Any chance of *directly* observing relic gravitons?
(possibly all the way back to an inflationary epoch)

GW stochastic backgrounds



GWs and the early universe



(Battye and Shellard, arXiv:9604059)

Stochastic backgrounds

Spectrum:

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm c}} \frac{d\rho_{\rm gw}(f)}{d\ln f}$$

Amplitude:

$$S^{1/2}(f) = 5.6 \times 10^{-22} \left[h_{100}^2 \Omega_{\rm gw}(f)\right]^{1/2} \left(\frac{f}{100\,{\rm Hz}}\right)^{-3/2} \,{\rm Hz}^{-1/2}$$

Search approach

- Cross-correlation between outputs from pairs of instruments

$$\langle \tilde{s}_1^*(f)\tilde{s}_2(f)\rangle = \gamma(f) S_{\rm gw}(f)$$

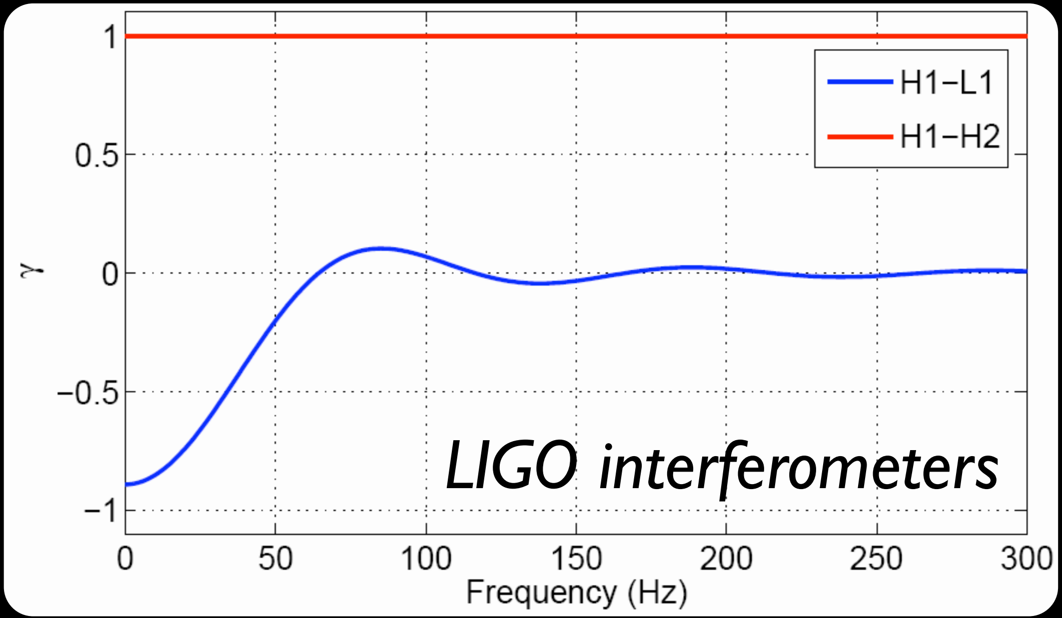
- The geometry enters via the overlap reduction function that depends on orientation and separation of the instruments

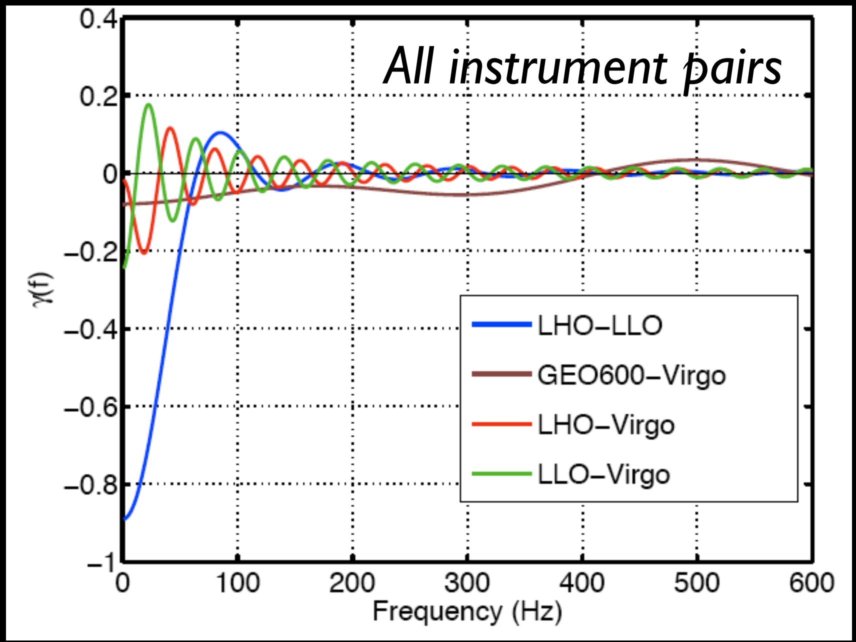
$$s_1 = n_1 + h_1$$
$$s_2 = n_2 + h_2$$

Geometry: overlap reduction function

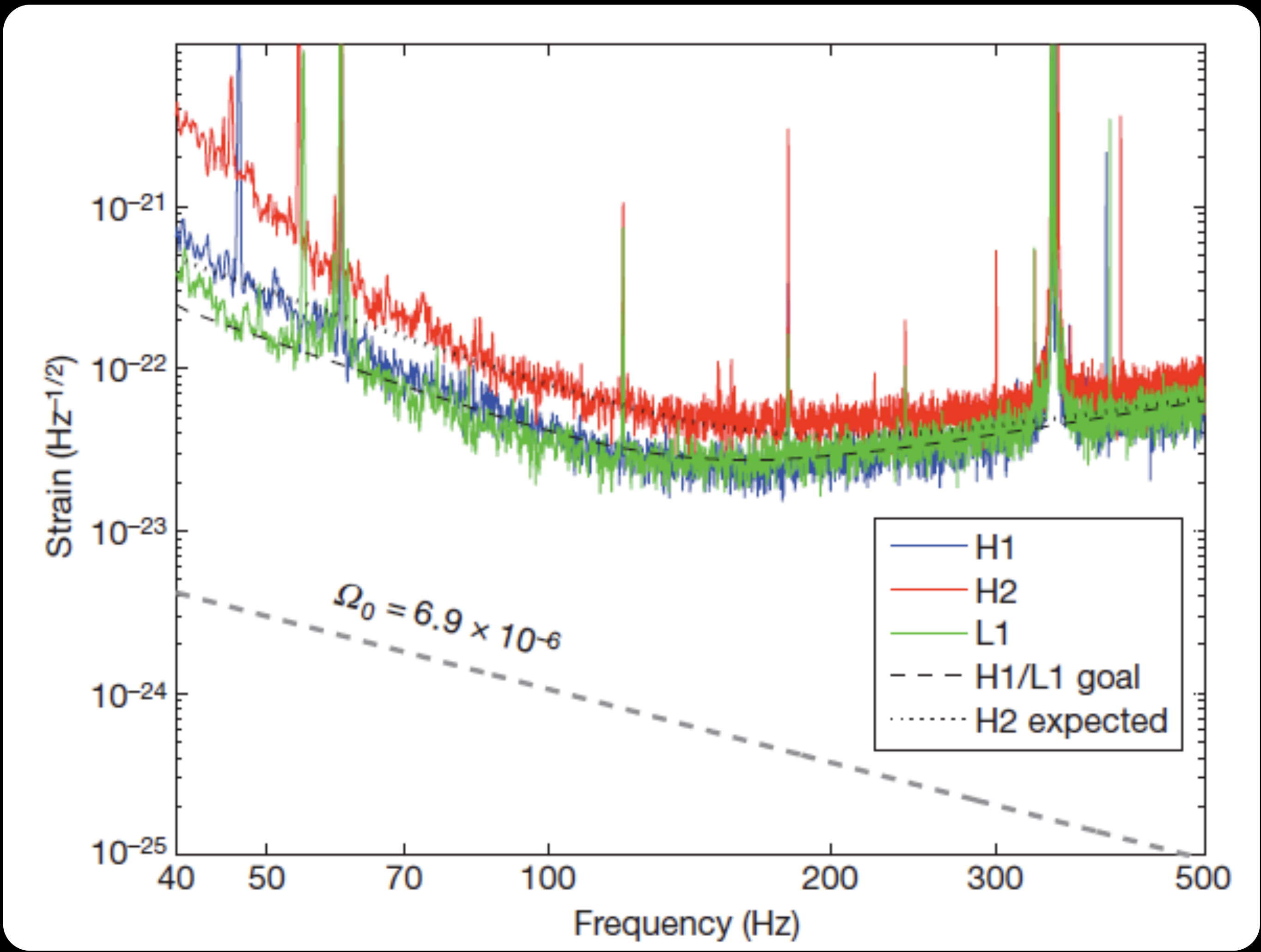
$$\gamma(f) \equiv \frac{5}{8\pi} \sum_{A=+,\times} \int_{S^2} d\hat{n}\, e^{i2\pi f \hat{n}\cdot\Delta\vec{x}/c}\, F_1^A(\hat{n}) F_2^A(\hat{n})$$

$$F^A(\hat{n}) \equiv \frac{1}{2}\, e^A_{ab}(\hat{n})\, \left[\hat{l}_1^a \hat{l}_1^b - \hat{l}_2^a \hat{l}_2^b\right]$$

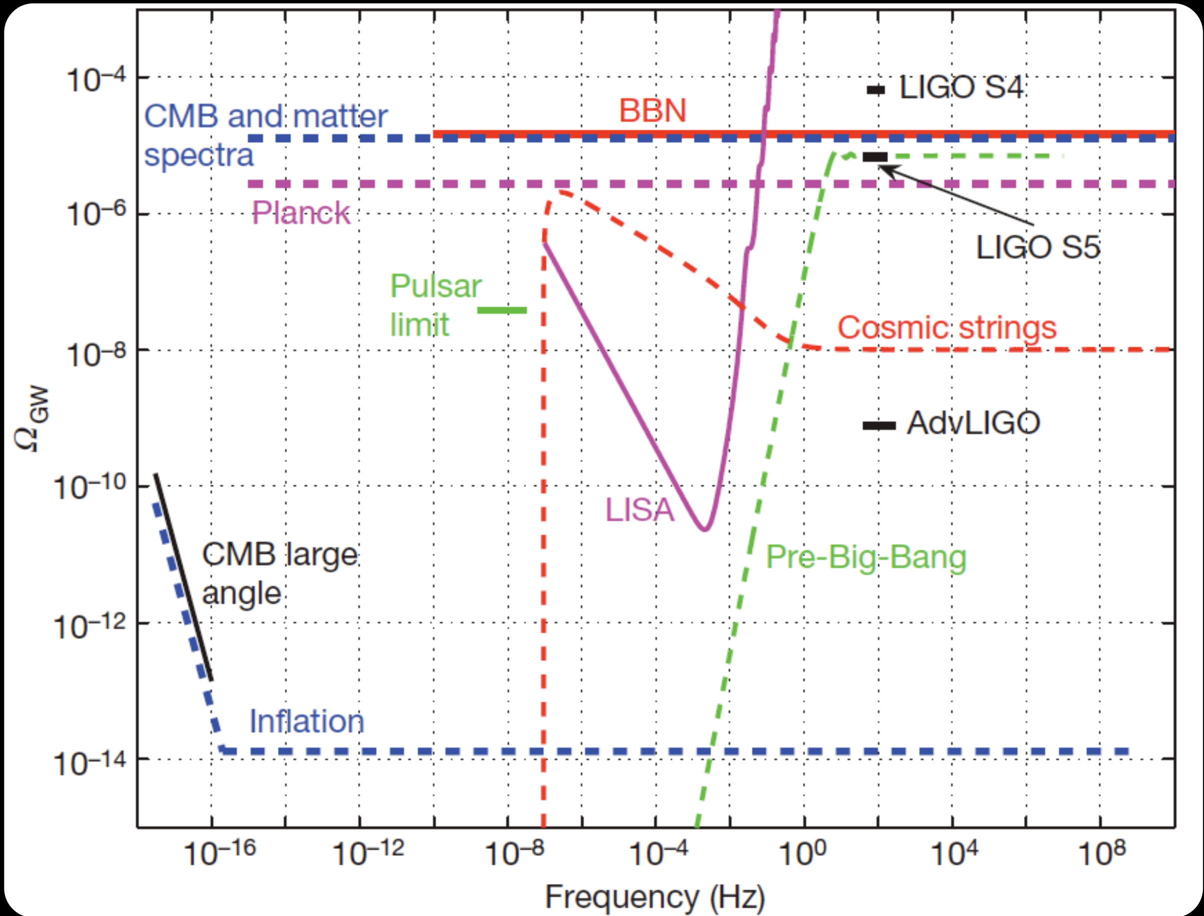




S5 LIGO sensitivity



LIGO upper-limit vs nucleosynthesis bound



Upper-limit

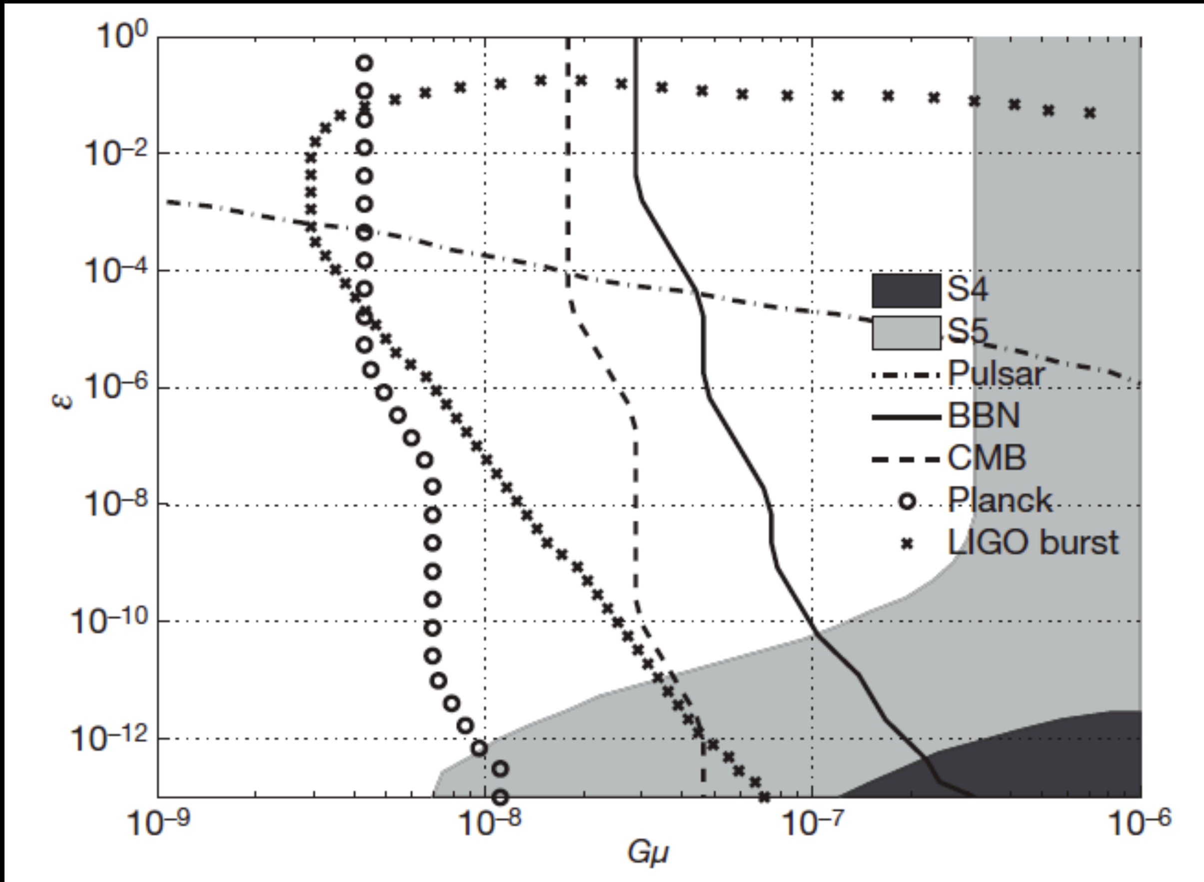
$$41.5\text{Hz} \leq f \leq 161.25\text{Hz}$$

$$\Omega_{\rm GW}(f) = \Omega_0$$

$$\Omega_0^{95\%} = 6.9 \times 10^{-6}$$

Abbott et al (LSC & Virgo Collaboration), Nature **460**, 990 (2009)

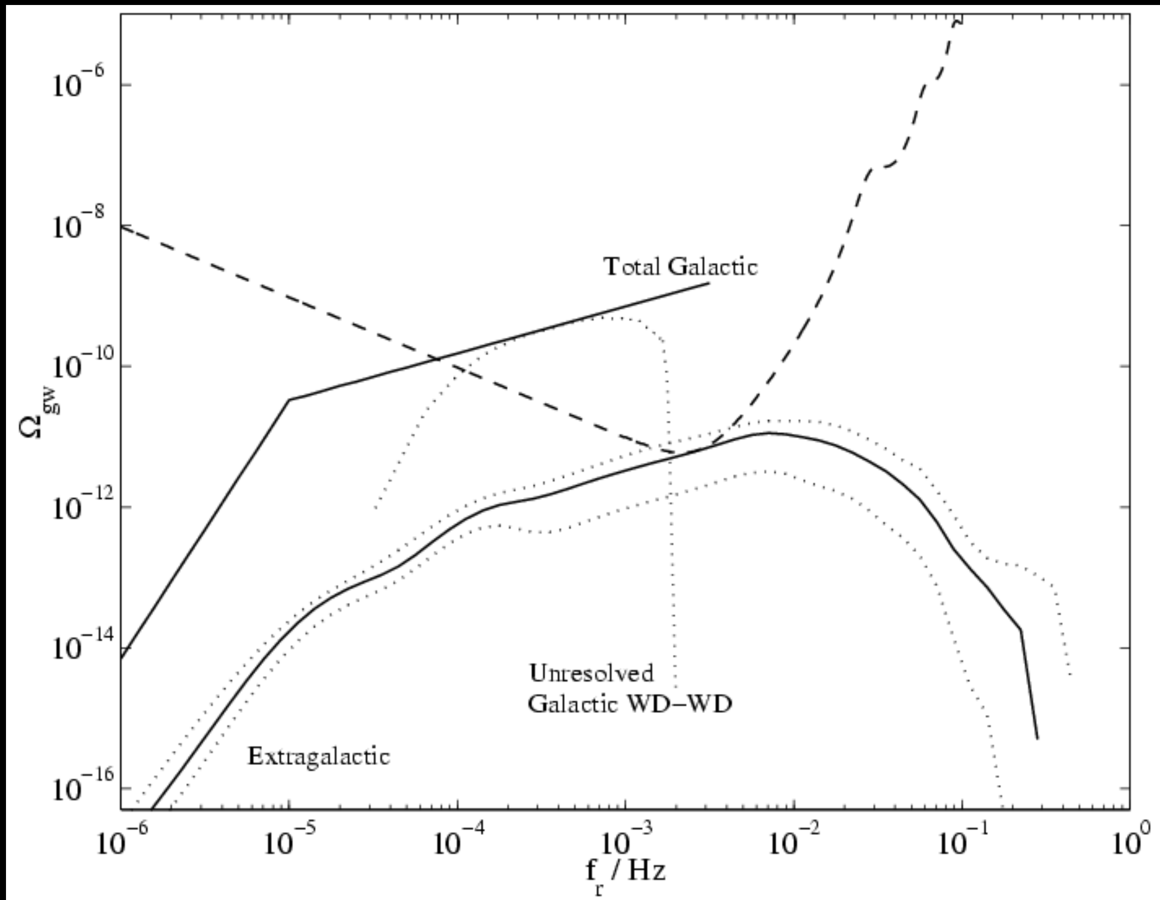
Constraining e.g. string models



Abbott et al, Nature **460**, 990 (2009)

Foregrounds

$$S^{1/2}(f) = 5.6 \times 10^{-22} \left[h_{100}^2 \Omega_{\rm gw}(f)\right]^{1/2} \left(\frac{f}{100\,{\rm Hz}}\right)^{-3/2} \,{\rm Hz}^{-1/2}$$



Farmer and Phinney, 2003

The Big Bang Observer:
Direct detection of gravitational waves from the birth of the Universe to the present

P.I.: E. S. Phinney

US Co-Is: Peter Bender, Saps Buchman, Robert Byer, Neil Cornish, Peter Fritschel, William Folkner, Stephen Merkowitz

Foreign Co-P/Is: Karsten Danzmann, Luciano DiFiore, Seiji Kawamura, Bernard Schutz, Alberto Vecchio, Stefano Vitale

Collaborators: John Armstrong, Fabrizio Barone, Charles Bennett, Jordan Camp, Joan Centrella, David Chernoff, Adrian Cruise, Curt Cutler, Frank Estabrook, Jens Gundlach, Gerhard Heinzel, Ronald Hellings, Craig Hogan, James Hough, Scott Hughes, Andrew Jaffe, Barry Kent, William Kinney, Alberto Lobo, Nergis Mavalvala, Thomas Prince, Michael Sandford, Bangalore Sathyaprakash, David Shoemaker, Steinn Sigurdsson, Clive Speake, David Spergel, Robin Stebbins, Timothy Sumner, Kip Thorne, Massimo Tinto, Carlo Ungarelli, Henry Ward.

NASA OSS Vision Missions Program, Proposal VM03-0021-0021

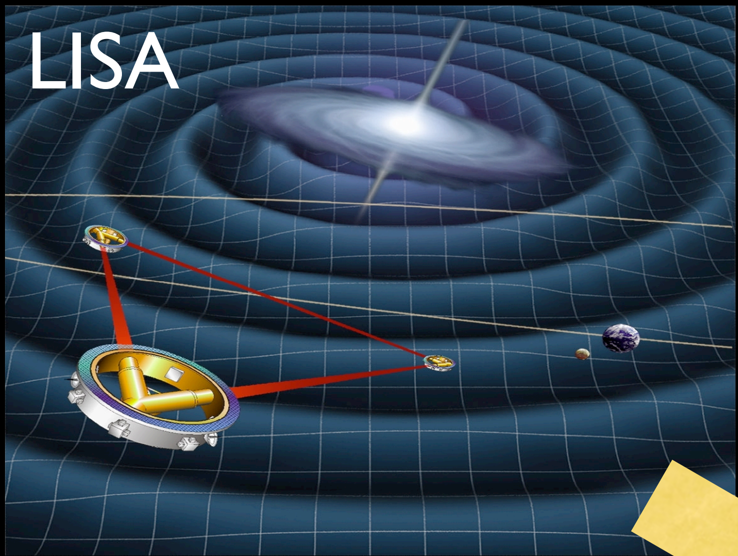
I. Introduction: Primary and Secondary Science Objectives

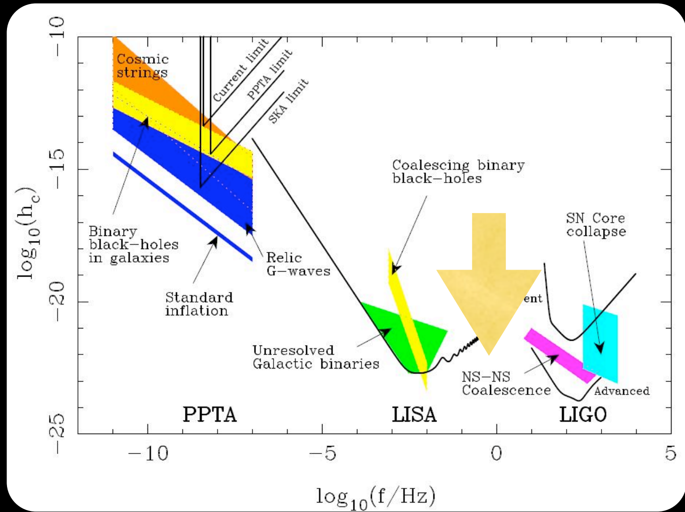
NASA's 2002 SEU Roadmap *Beyond Einstein* highlights three major unanswered questions raised by Einstein's general theory of relativity:

1. *What powered the Big Bang?*
2. *What happens to space, time and matter at the edge of a black hole?*
3. *What is the mysterious dark energy pulling the Universe apart?*

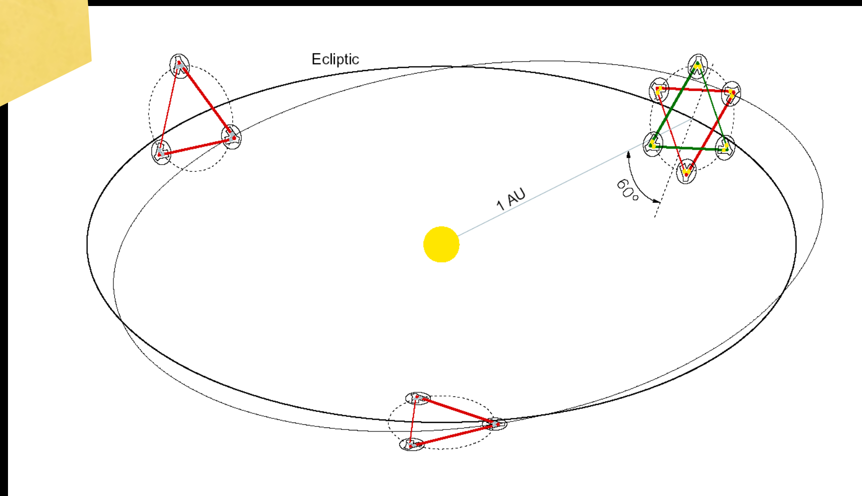
The prime scientific objective of the Big Bang Observer (BBO) mission is the direct detection of relic gravitational waves from inflation. When combined with cosmic microwave background inferences about gravitational waves 17 orders of magnitude lower in frequency,

Big Bang Observer & DECIGO



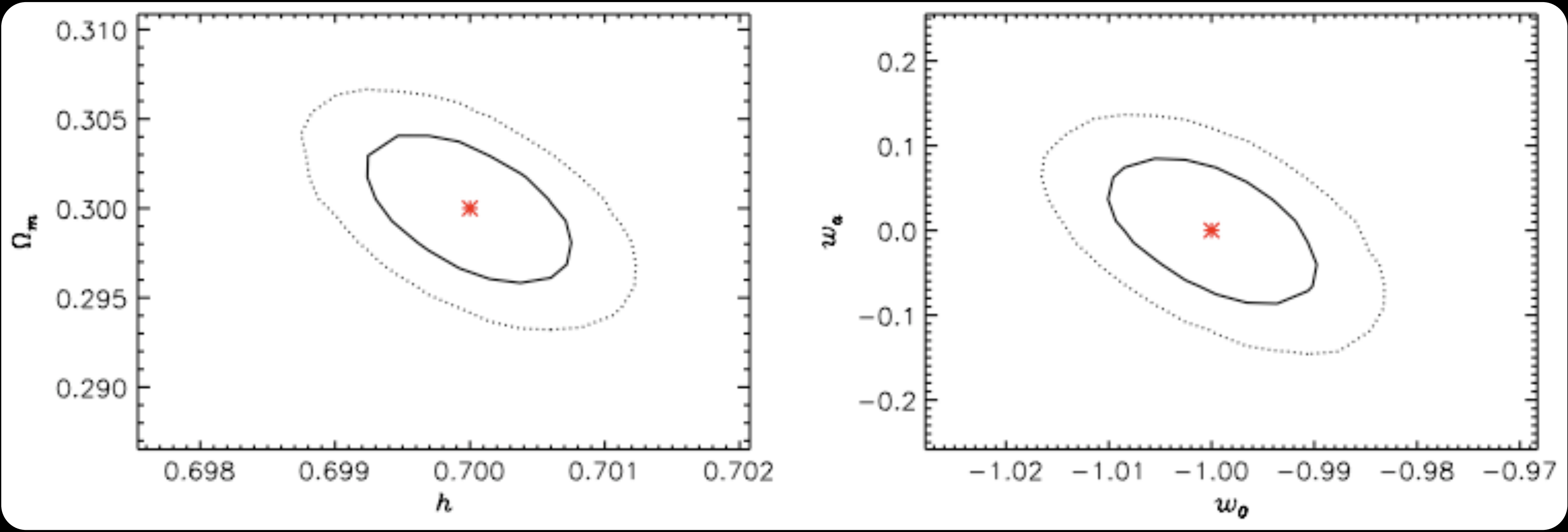


BBO/DECIGO



- arm-length shorter by ~ x100
- peak sensitivity ~ 0.1-1 Hz

The ultimate dark energy mission?



Cutler and Holz 2009

To summarise

1. No *direct* detection (yet)
2. Prospects for detecting soon-ish (both from ground and with pulsar timing arrays)?
3. High precision astronomy and cosmography?
4. Is it on the cards to detect gravitational waves emitted by processes in the early universe?