Gravitational Wave Astronomy

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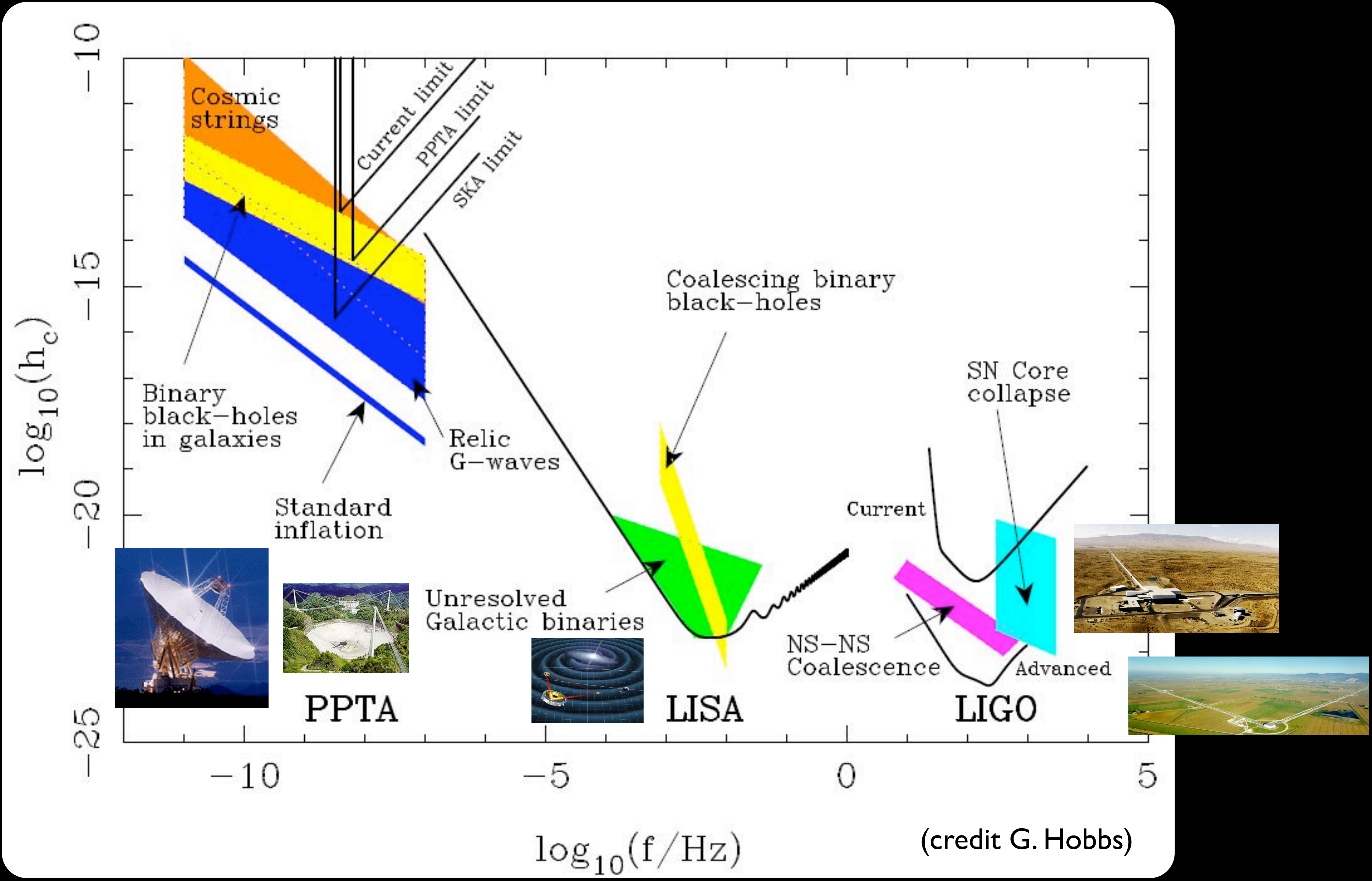
Progress on Old and New Themes in Cosmology
Avignon, 18th - 22nd April 2011

Outline

- Ongoing and future observational avenues:
  - Ground-based gravitational wave laser interferometers (LIGO/Virgo/GEO 600/...)
  - Pulsar Timing Arrays (PTAs)
  - Space-based gravitational wave laser interferometers
- Cosmology in the gravitational-wave observational window:
  - Binary systems: a new class of standard candles
  - Stochastic backgrounds from the early universe

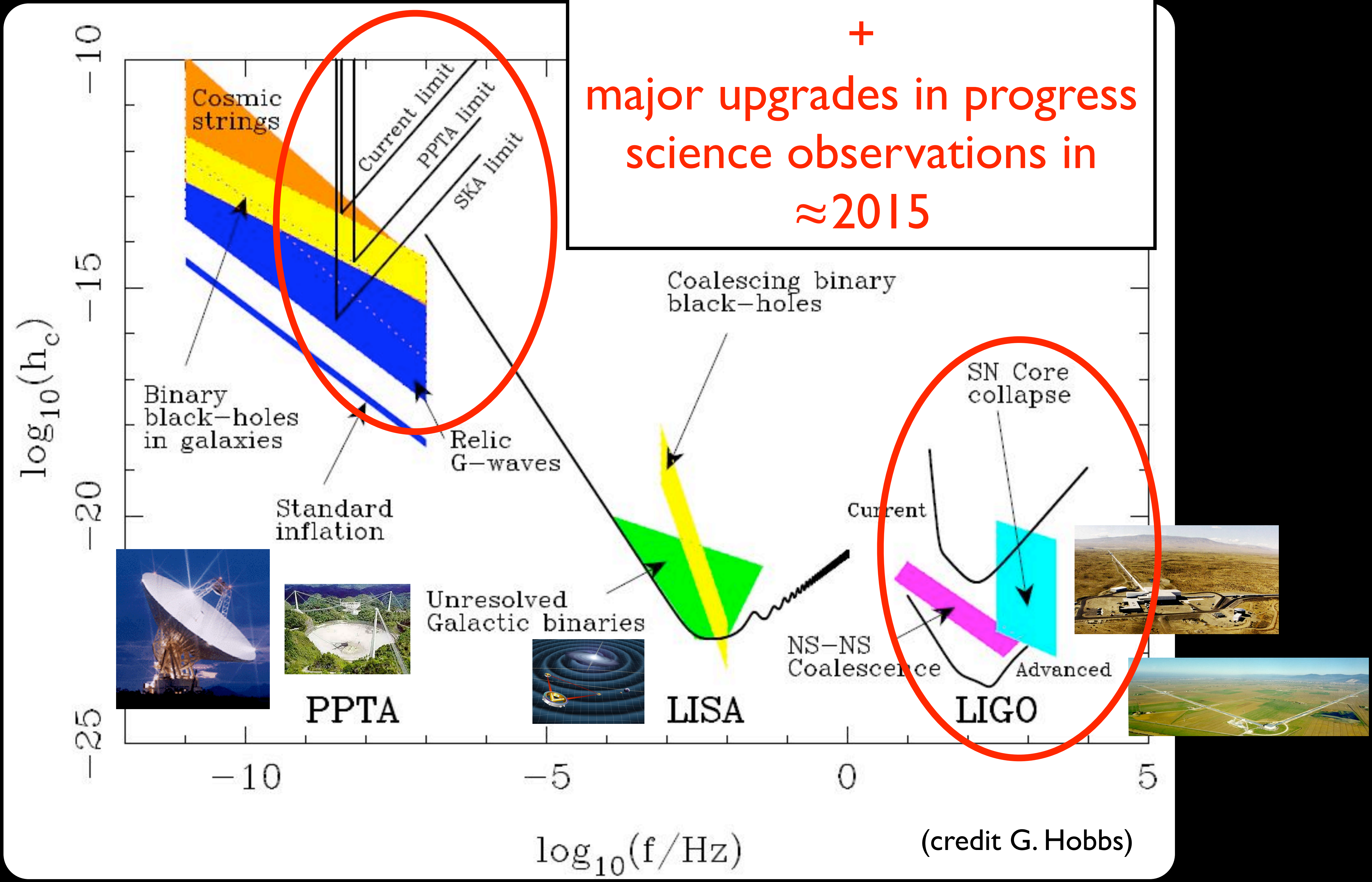
GW spectrum



(credit G. Hobbs)

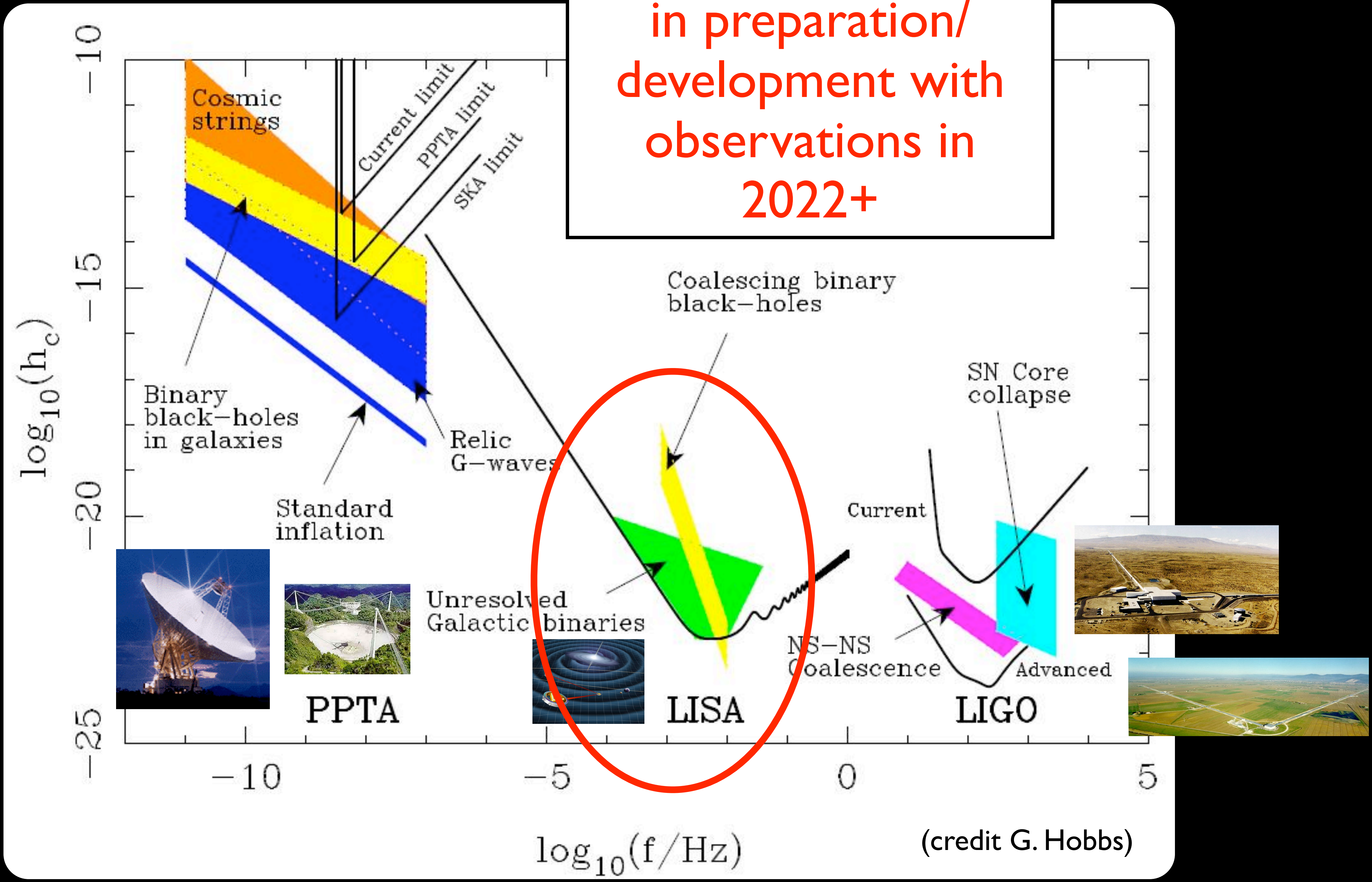
GW spectrum

now
+
major upgrades in progress
science observations in
≈2015



(credit G. Hobbs)

GW spectrum

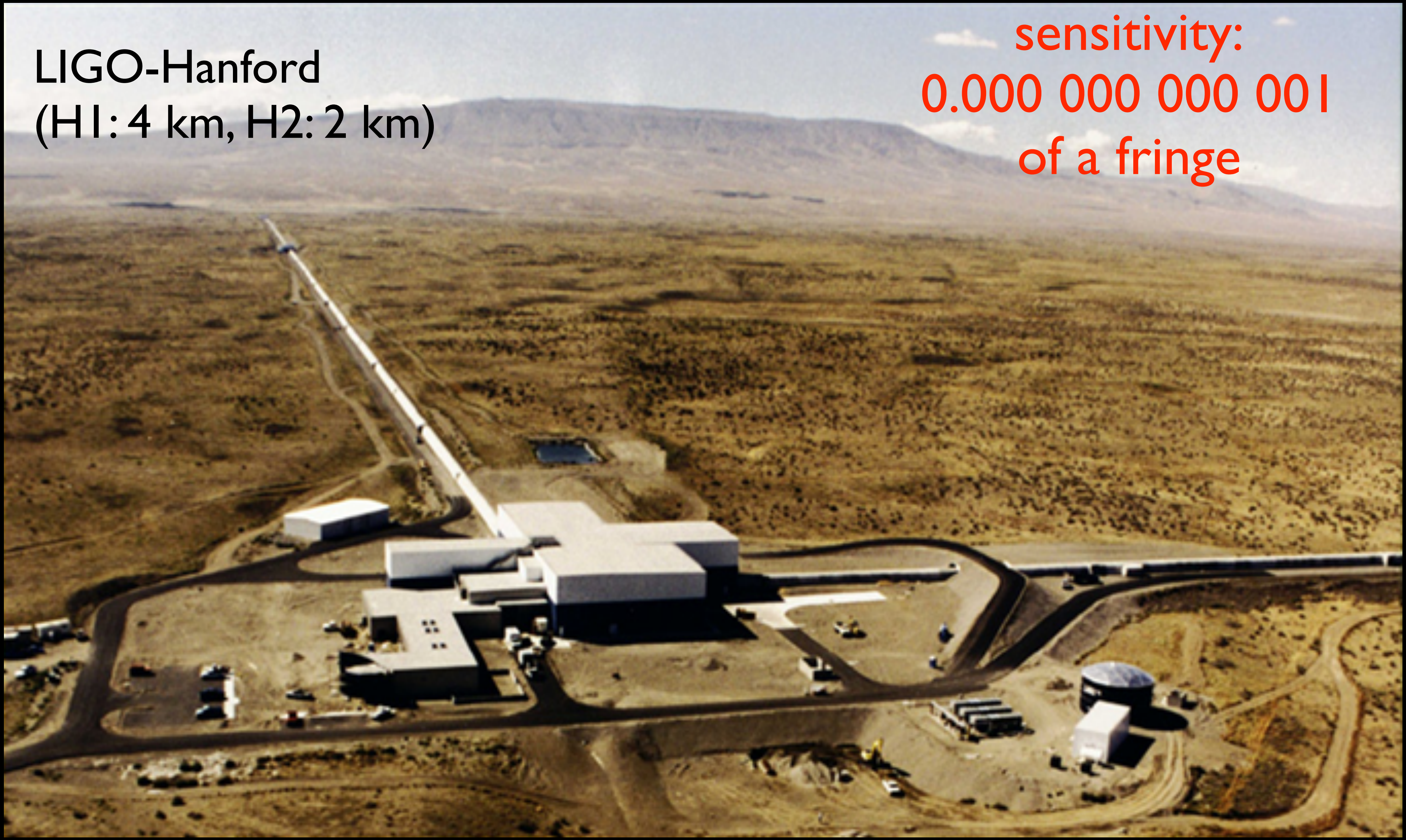


in preparation/ development with observations in 2022+

(credit G. Hobbs)

A.Vecchio - PONT, 19th April 2011

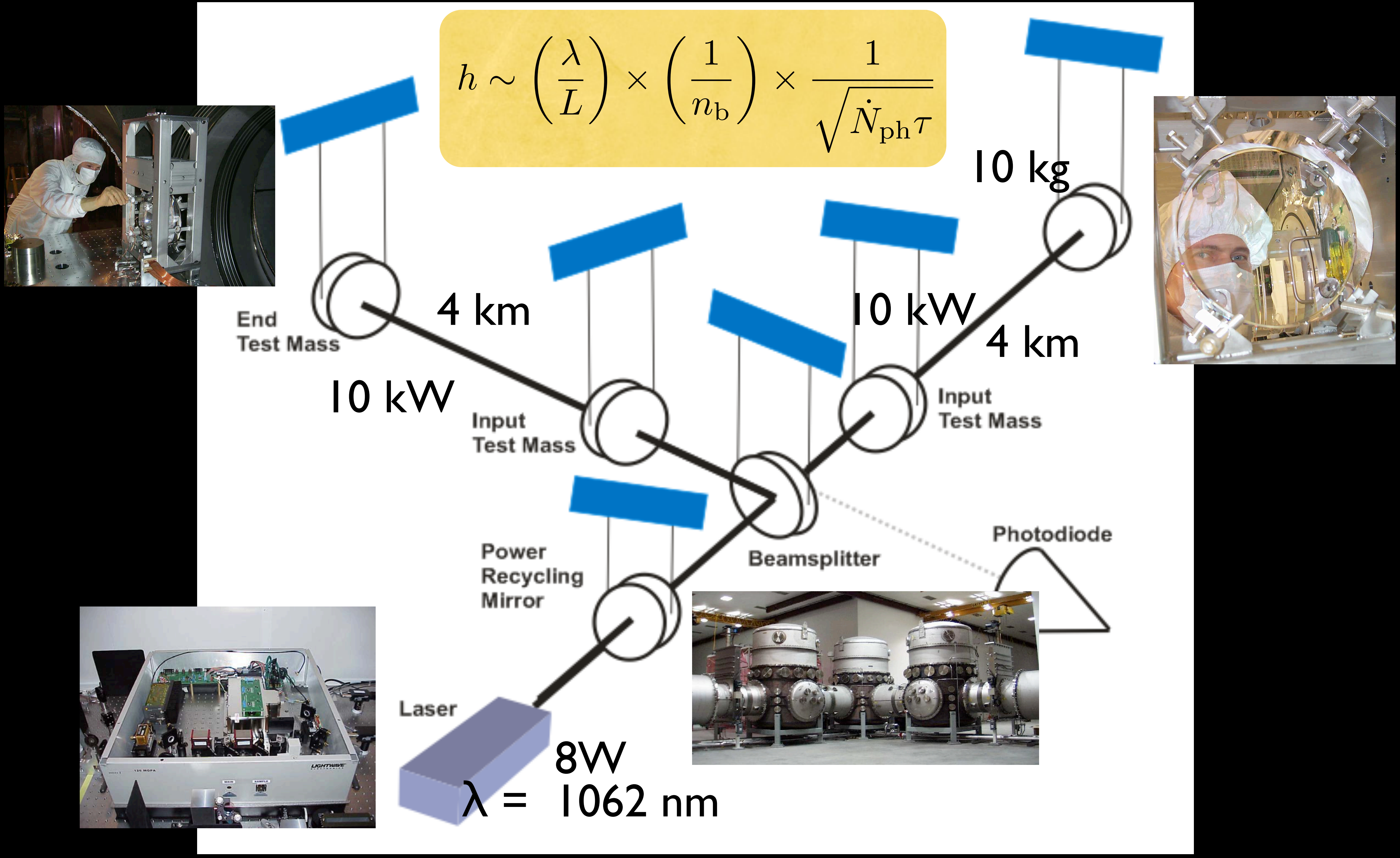
GW laser interferometers



LIGO-Hanford
(H1: 4 km, H2: 2 km)

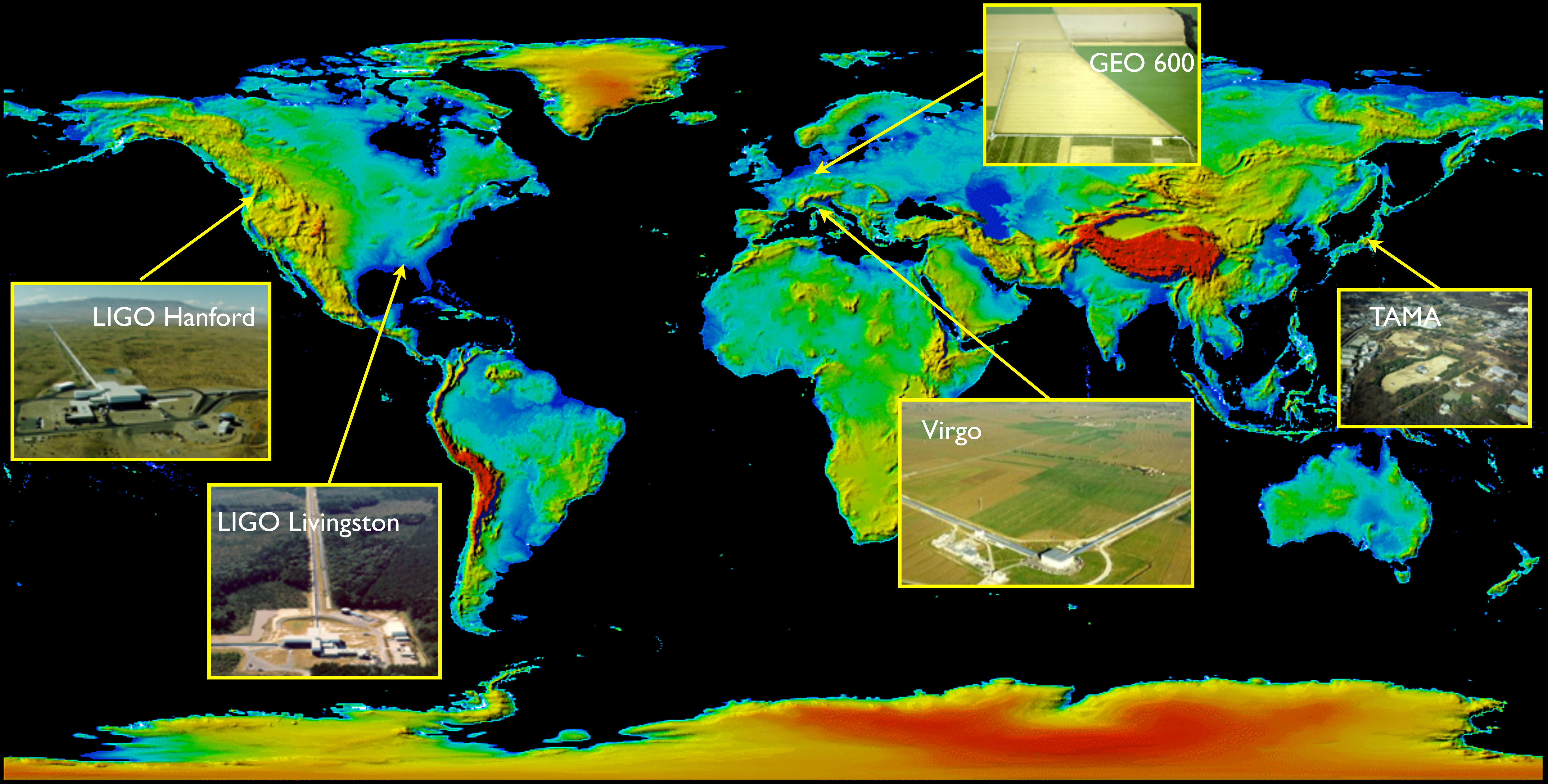
sensitivity:
0.000 000 000 001
of a fringe

GW interferometer in a nutshell

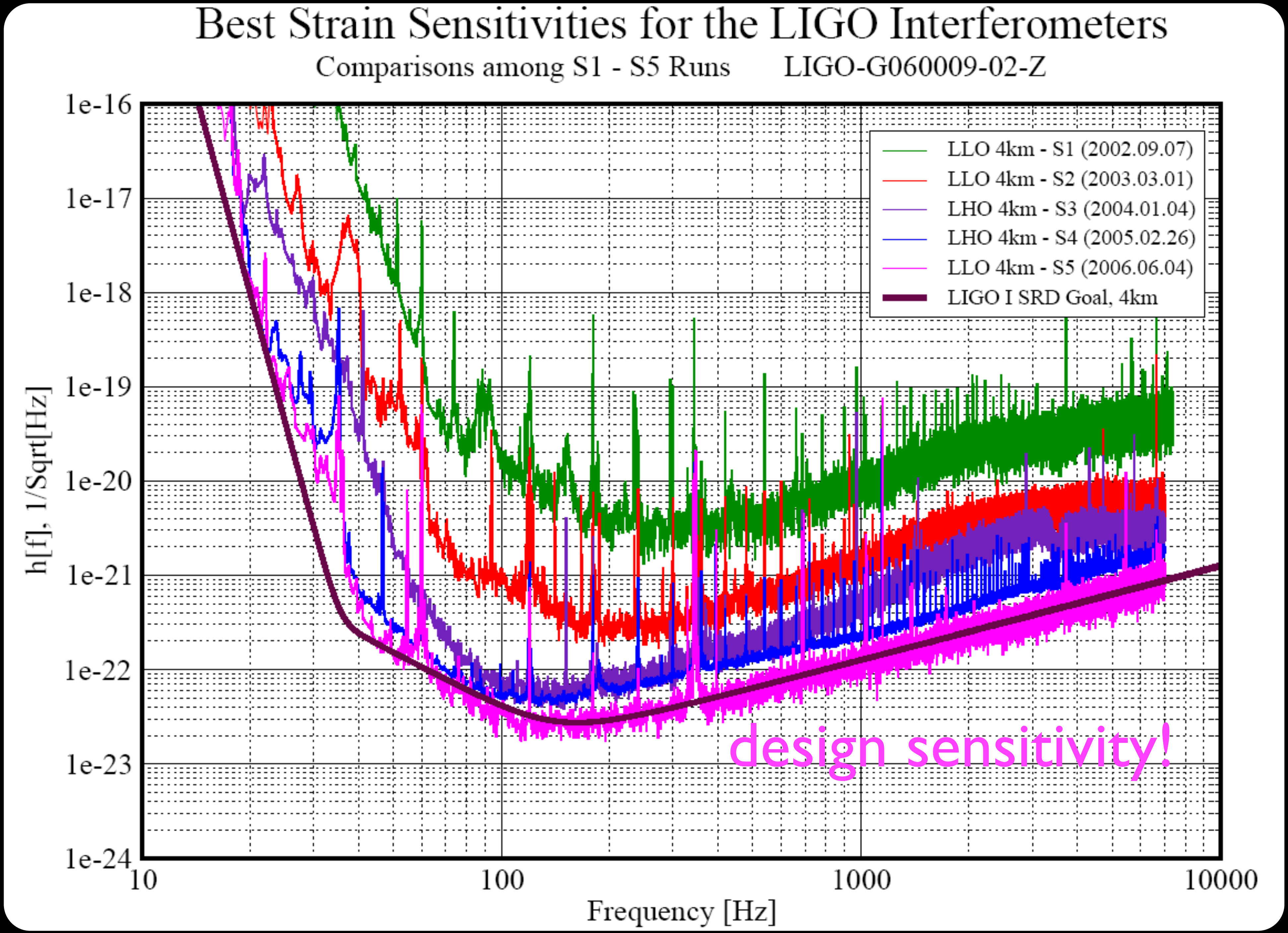


$$h \sim \left(\frac{\lambda}{L}\right) \times \left(\frac{1}{n_{\rm b}}\right) \times \frac{1}{\sqrt{\dot{N}_{\rm ph}\tau}}$$

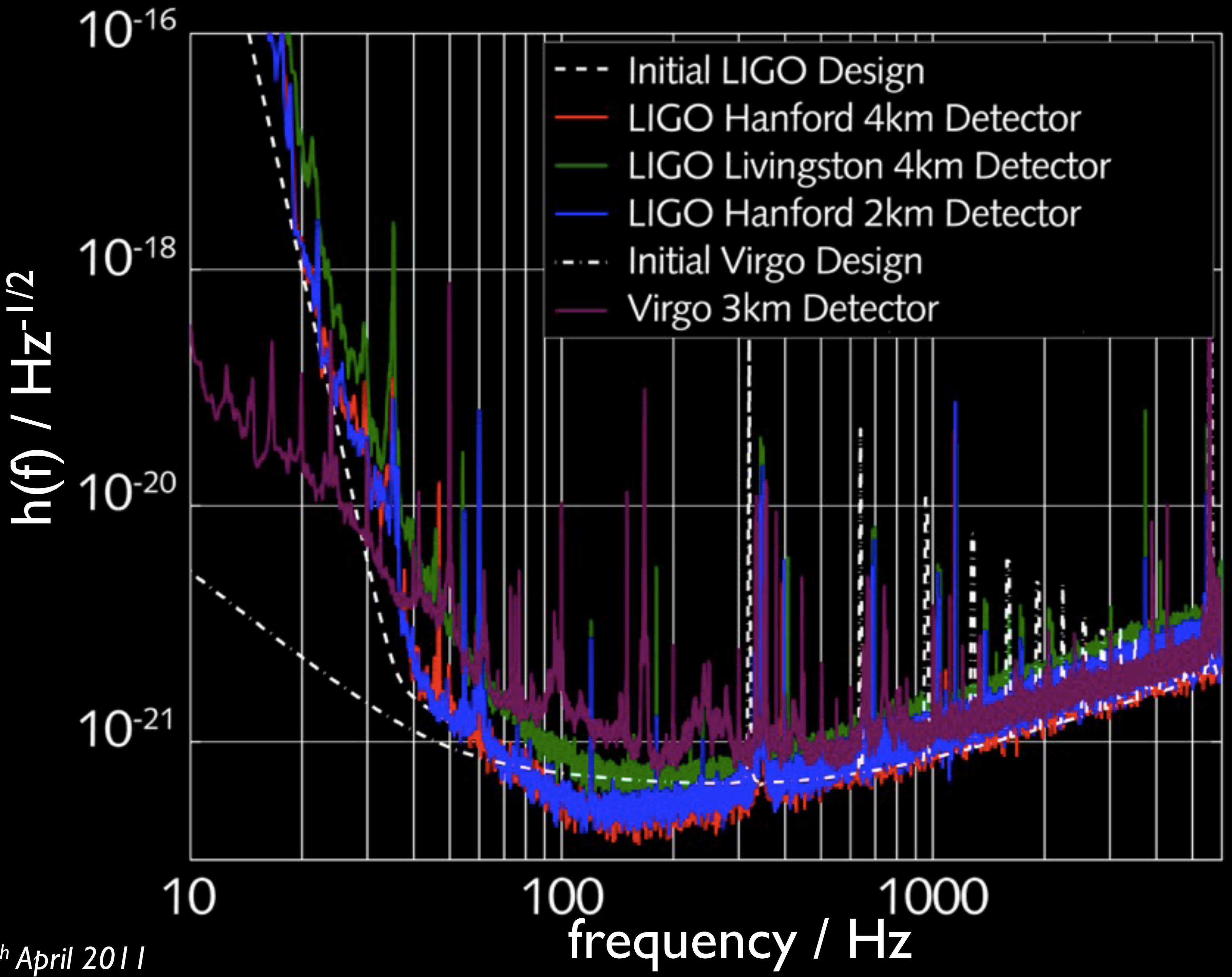
The global network of laser interferometers



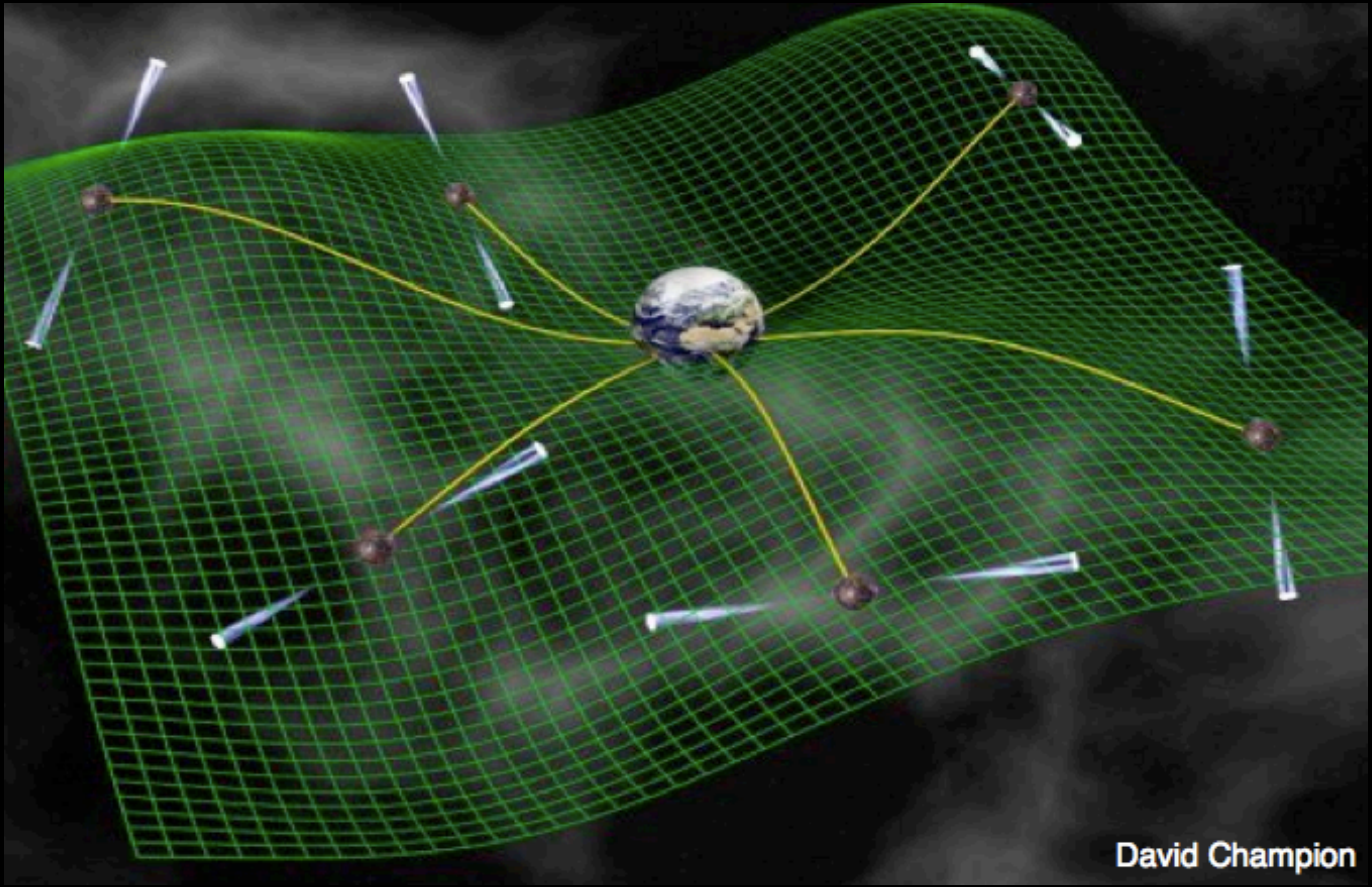
Evolution of LIGO sensitivity



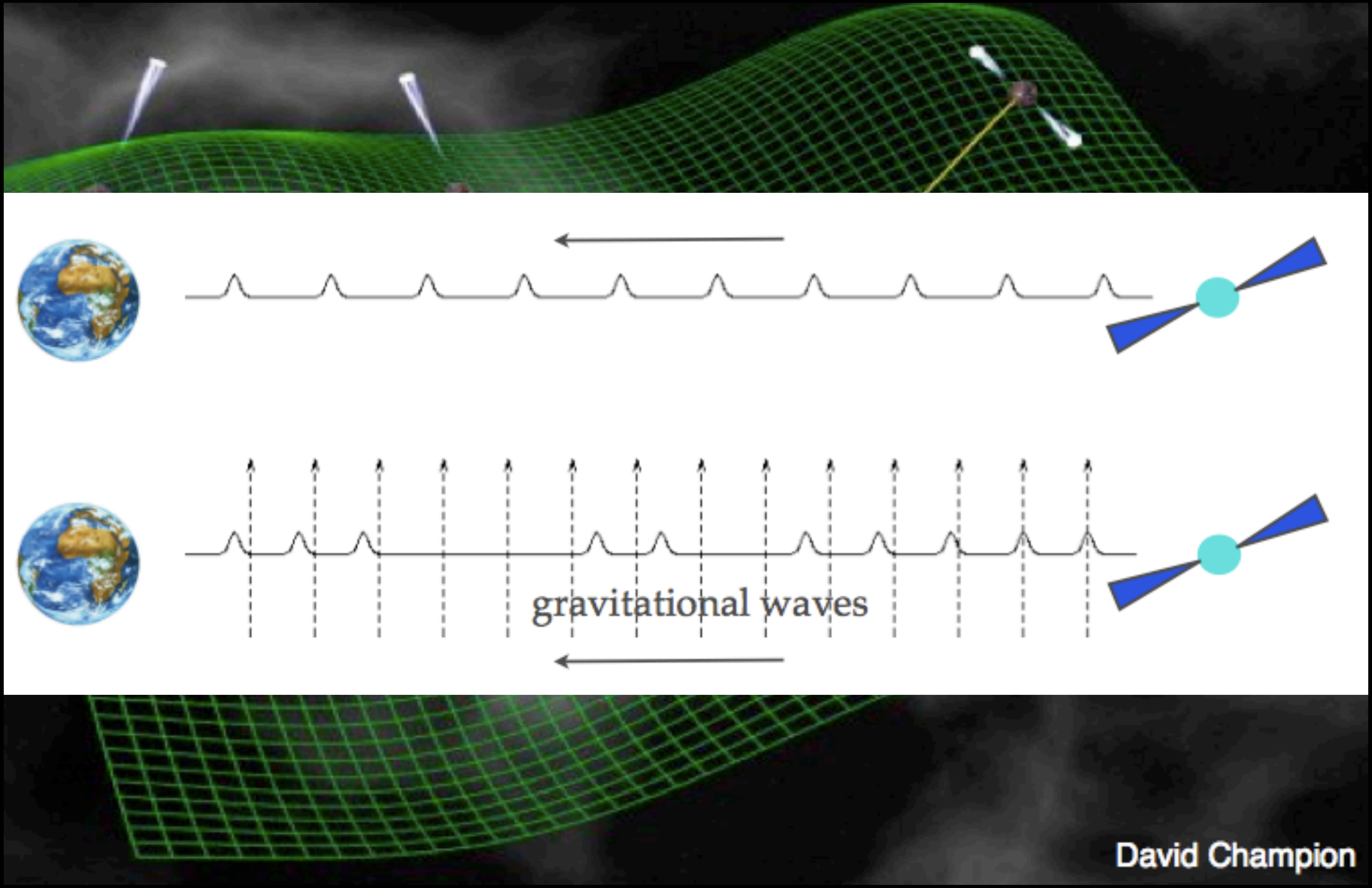
Beyond design sensitivity: eLIGO/Virgo+ (S6/VSR2/3)



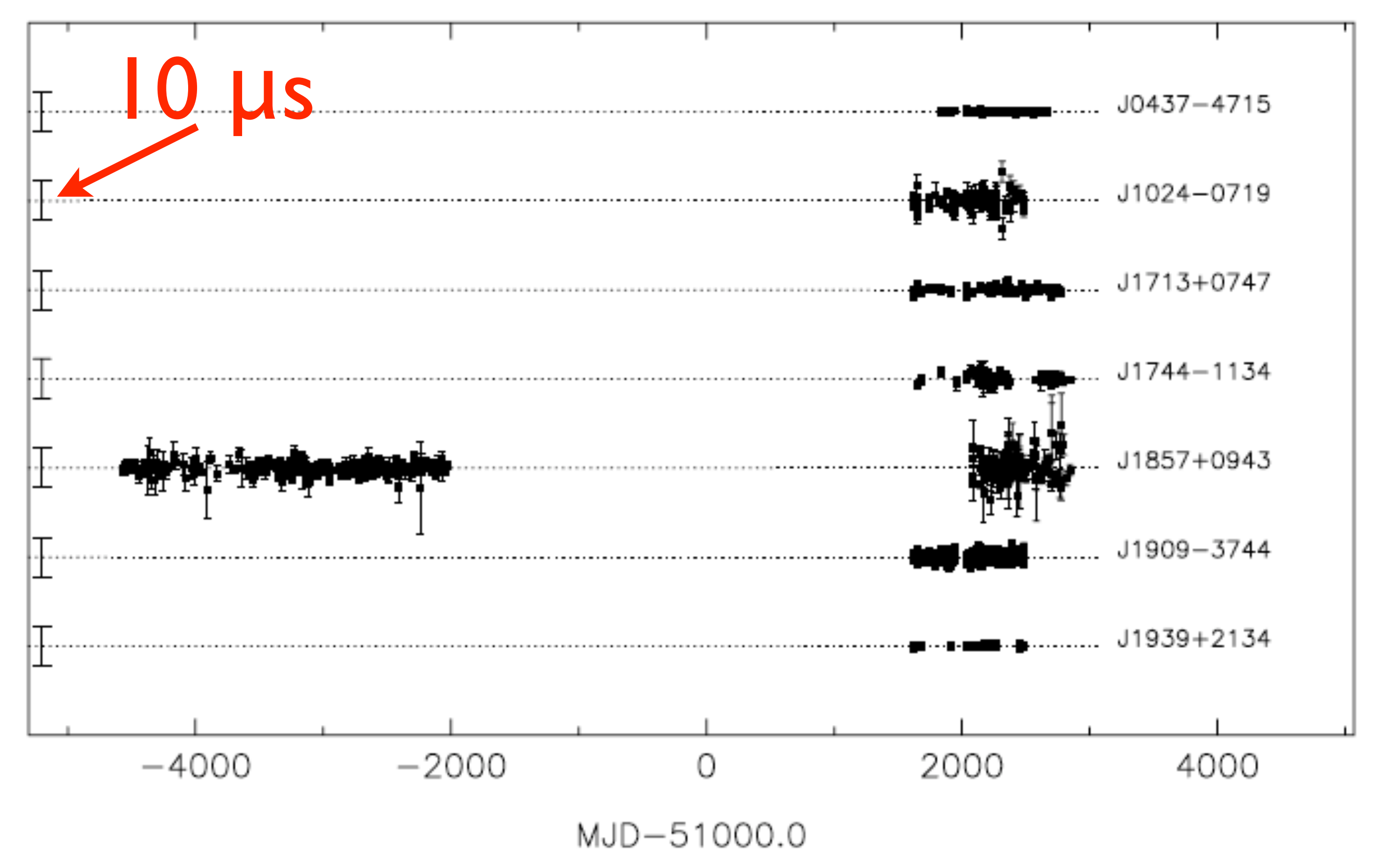
Pulsar Timing Arrays


David Champion

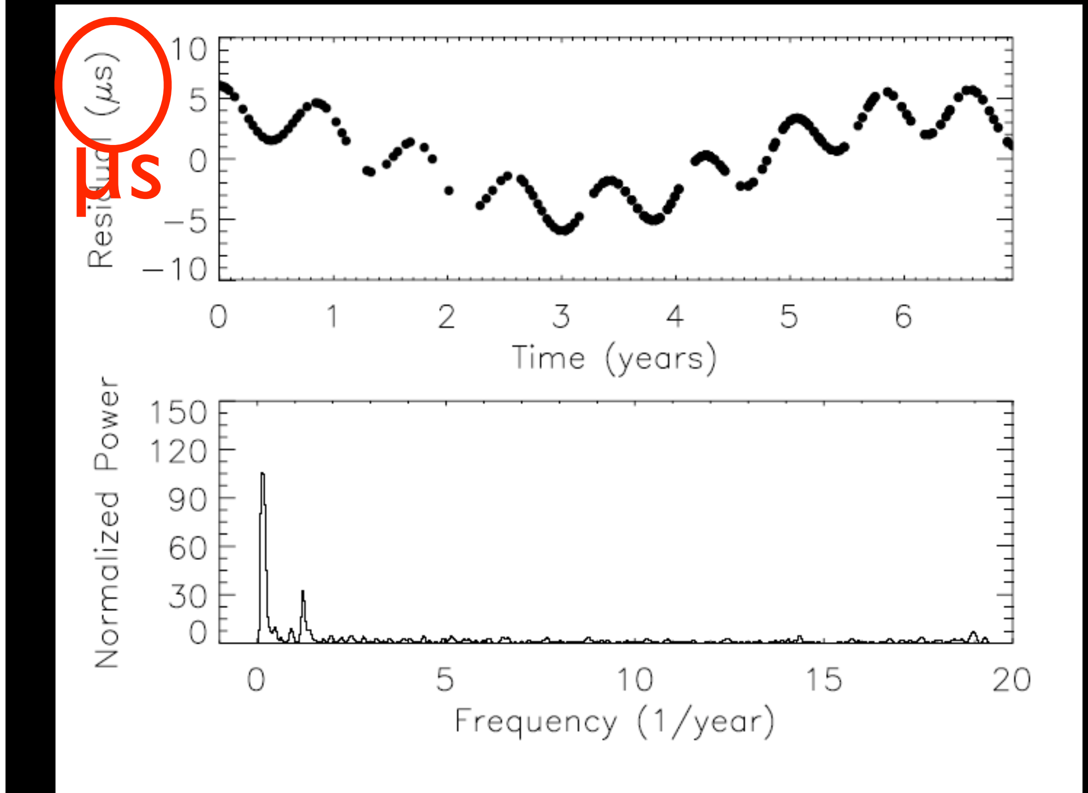
Pulsar Timing Arrays



Observable: timing residuals



10 µs



µs

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.

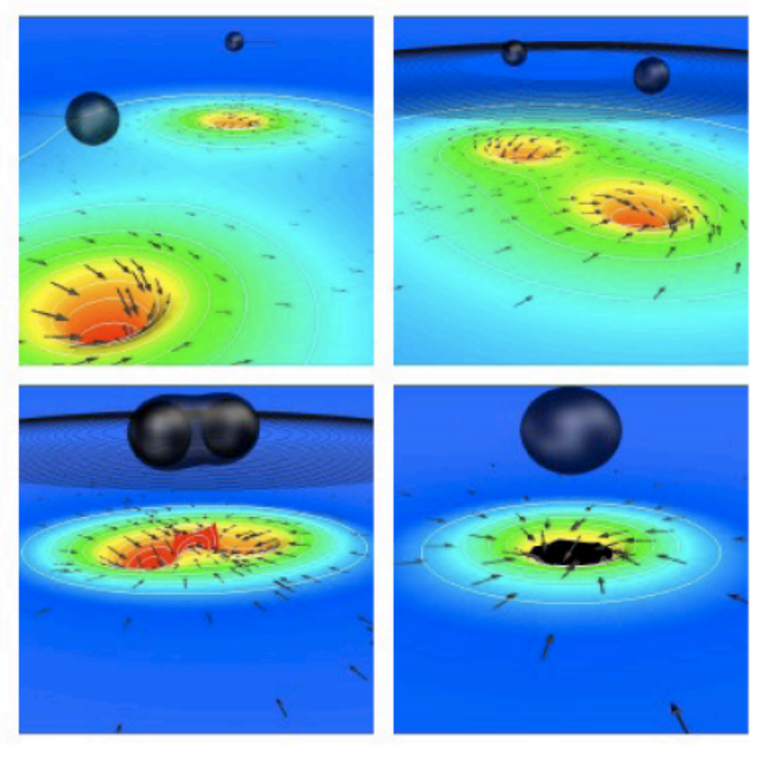
(Jenet et al, 2004, 2006)

$$r(t) \simeq 26 \left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \left(\frac{f}{5\times10^{-8}\,\mathrm{Hz}}\right)^{-1/3} \mathrm{ns}$$

Cosmology with (direct) GW observations

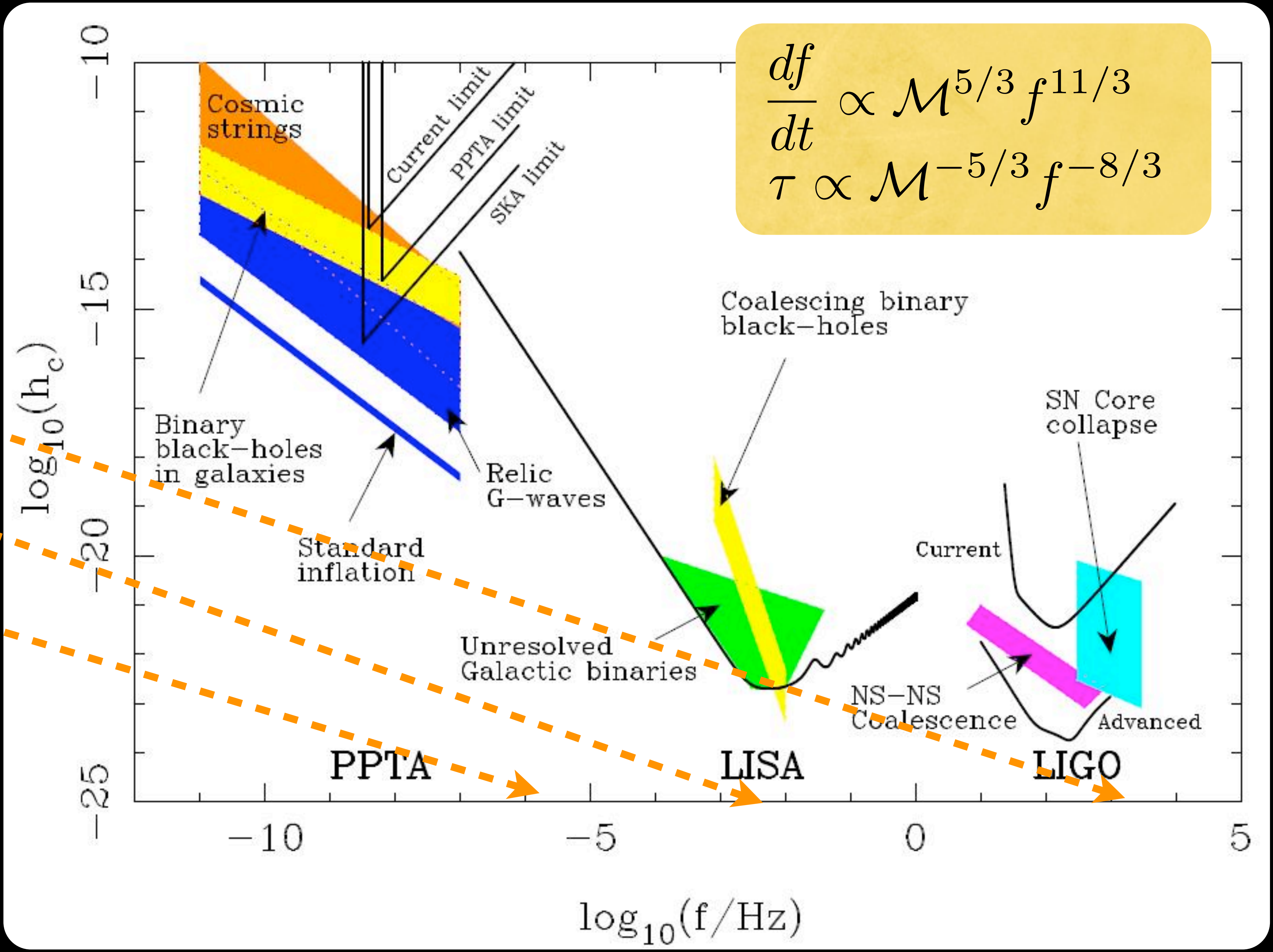
- Binary systems of compact objects (black holes and/or neutron stars): a new class of standard candles (also known as "standard sirens")
- Stochastic background radiation

New class of standard candles: coalescing binaries



Binary systems

$$\begin{aligned} f_{\rm ISCO} &= \frac{1}{6^{3/2}\pi M(1+z)} \\ &= 1.6\left[\frac{M(1+z)}{2.8\,M_\odot}\right]^{-1}\ \mathrm{kHz} \\ &= 4.4\left[\frac{M(1+z)}{10^6\,M_\odot}\right]^{-1}\ \mathrm{mHz} \\ &= 4.4\left[\frac{M(1+z)}{10^9\,M_\odot}\right]^{-1}\ \mu\mathrm{Hz} \end{aligned}$$

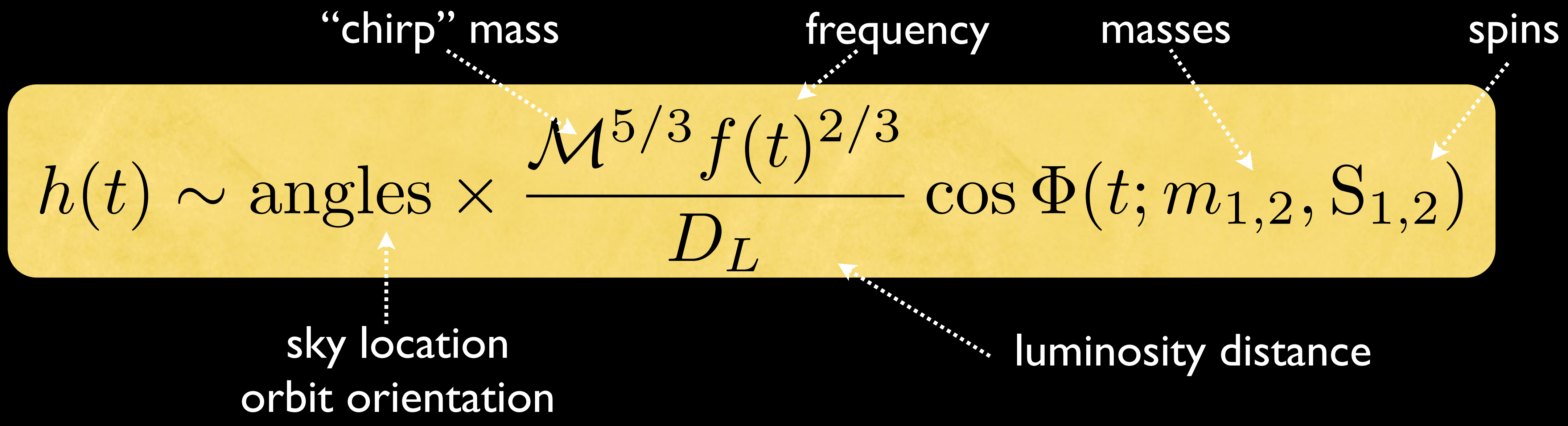


$$\frac{df}{dt} \propto \mathcal{M}^{5/3} f^{11/3}$$

$$\tau \propto \mathcal{M}^{-5/3} f^{-8/3}$$

Measured signal

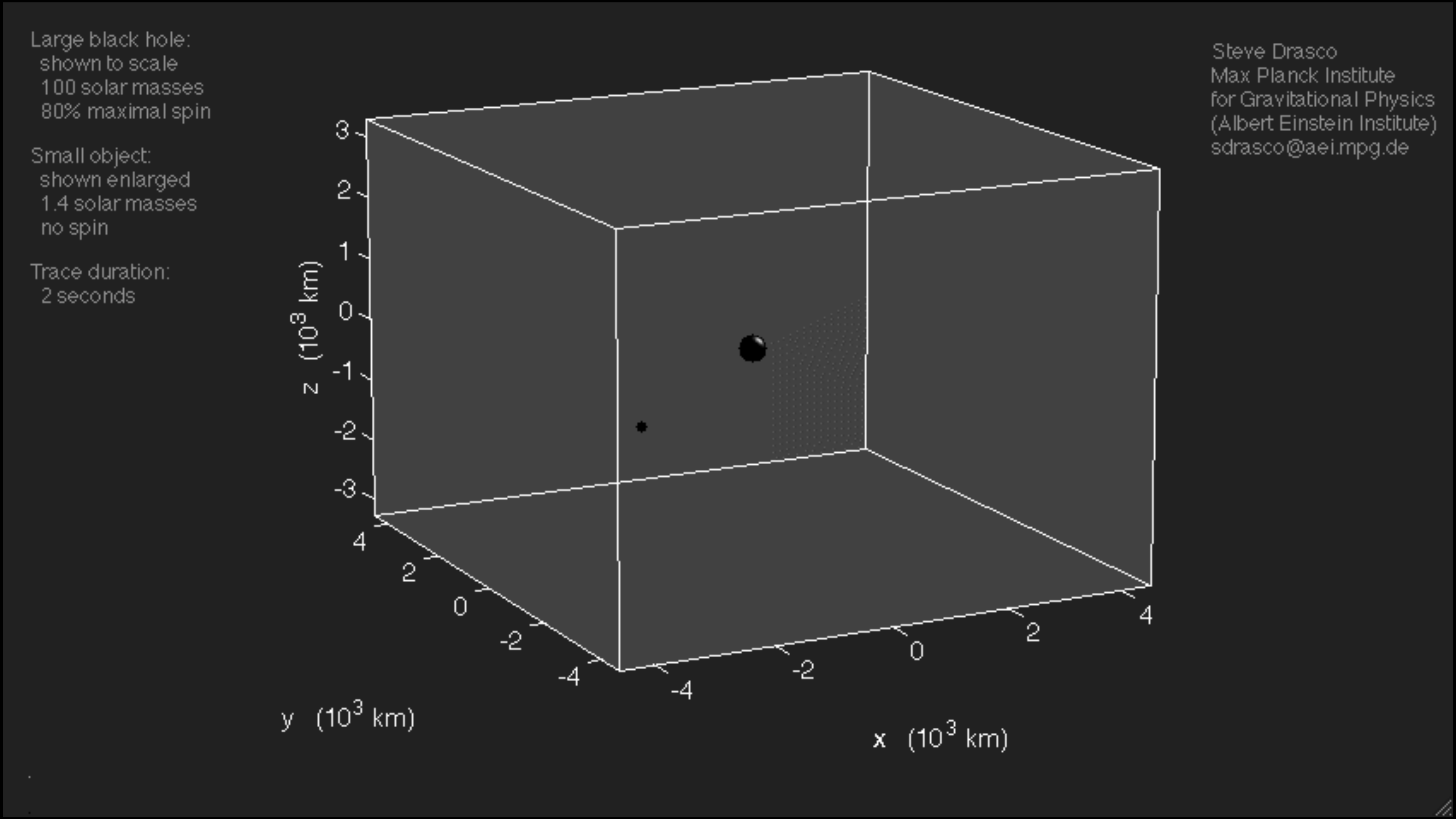
$$h(t) = F_+(\alpha,\delta,\psi)\, h_+(t) + F_\times(\alpha,\delta,\psi)\, h_\times(t)$$



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

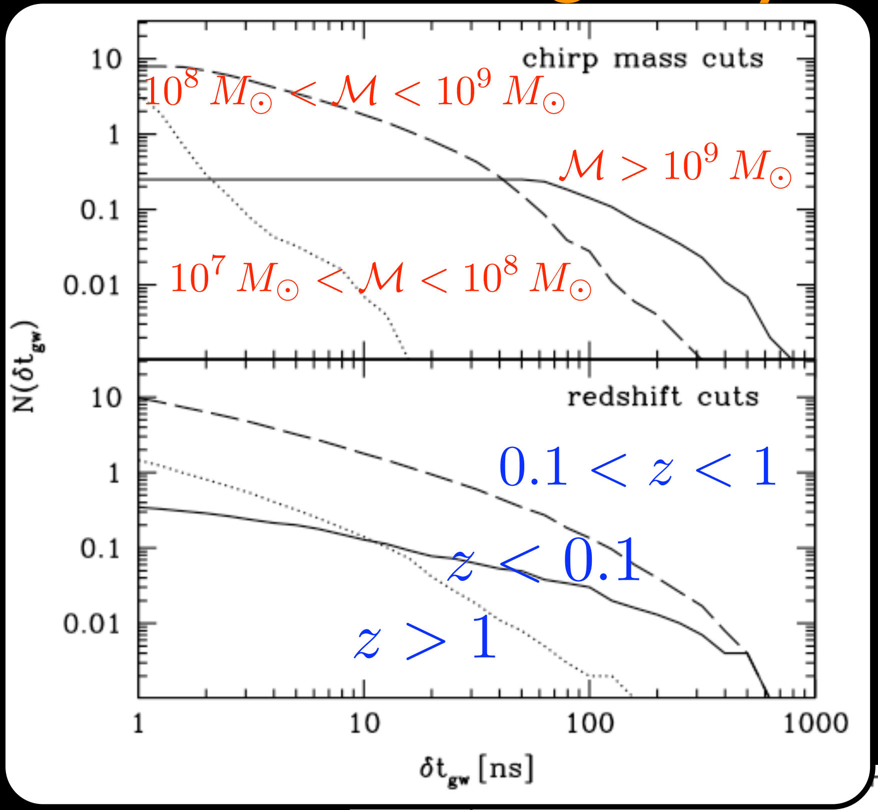
- Polarization amplitudes h_+ (t) and $h_\times$(t) contain full information about the physics
- Unknown parameters (9 for non-spinning binary systems, 15 for general spins, 17 if also eccentricity is present)
  - Physics: masses (2 parameters) & spins (6 parameters)
  - Geometry: luminosity distance (1 parameter), location in the sky (2 parameters) and orbital plane orientation (2 parameters)
  - Time and phase at coalescence (2 parameters)
  - Eccentricity (2 parameters)

Example: 1.4 $M_\odot$ - 100 $M_\odot$

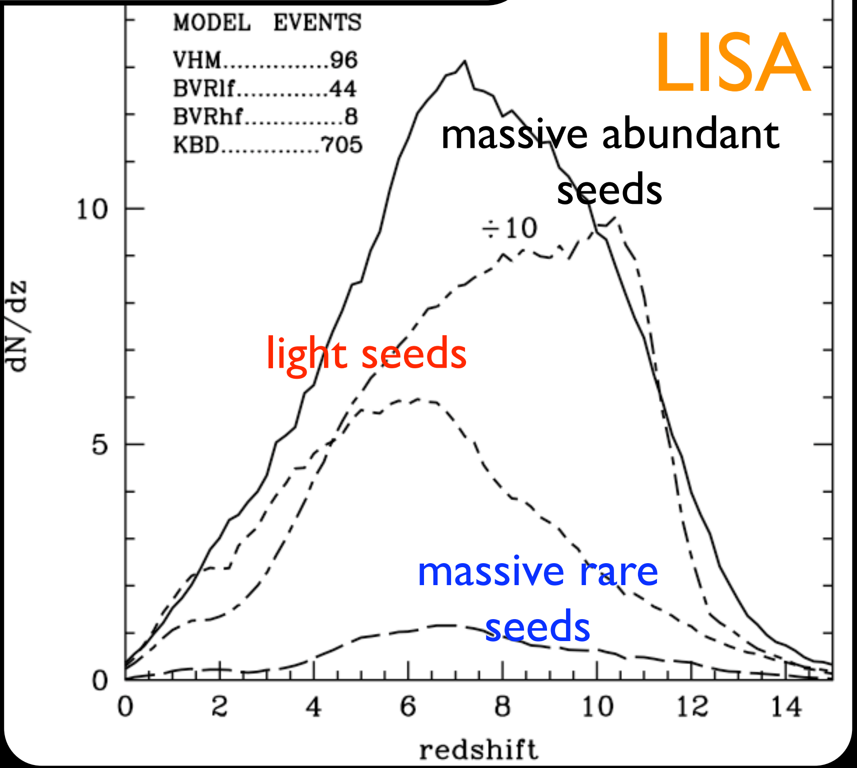


Expected number of detections

Pulsar Timing Arrays

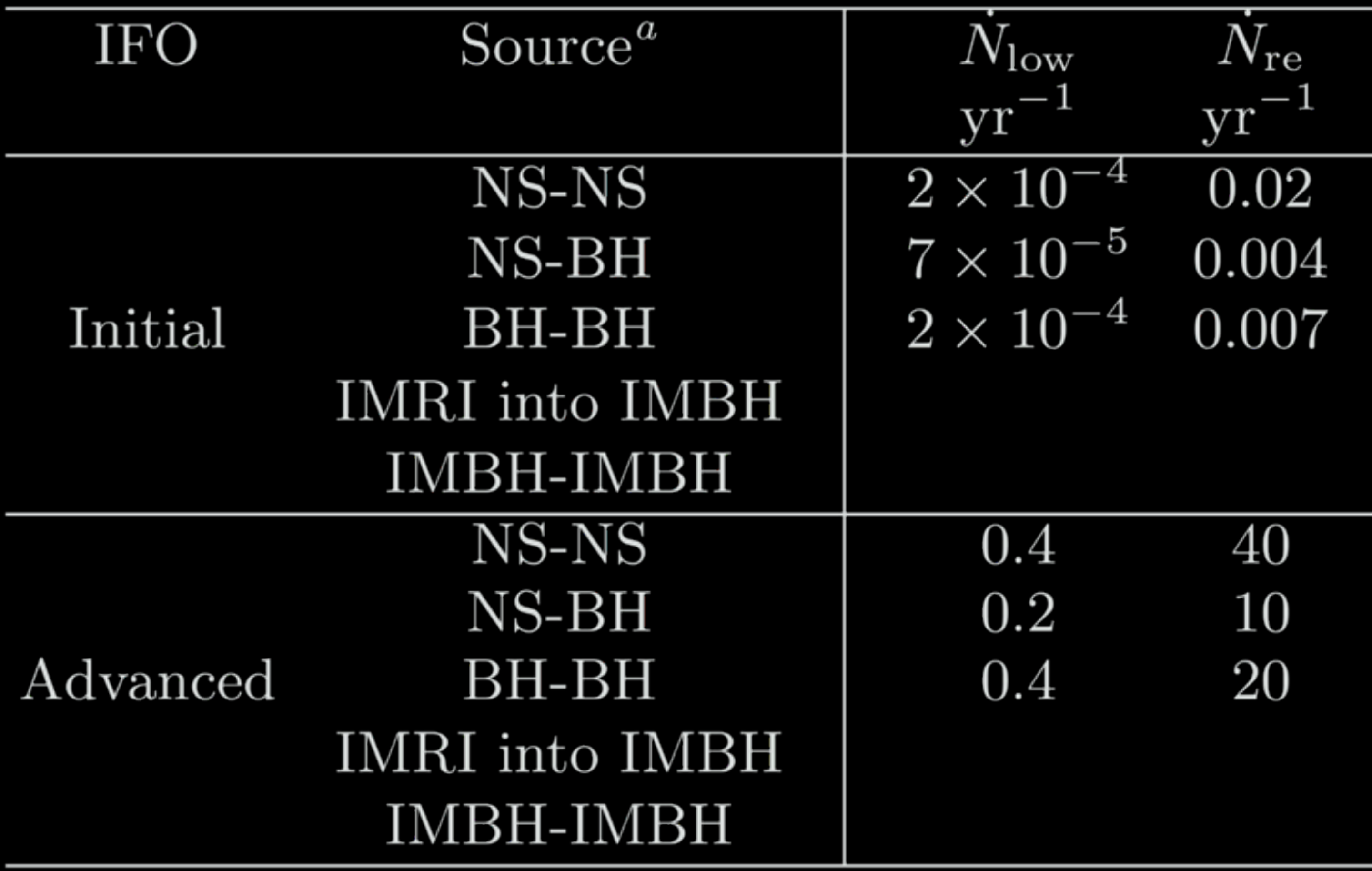


Sesana, AV and Volonteri (2009)



Sesana, Volonteri and Haardt, 2007

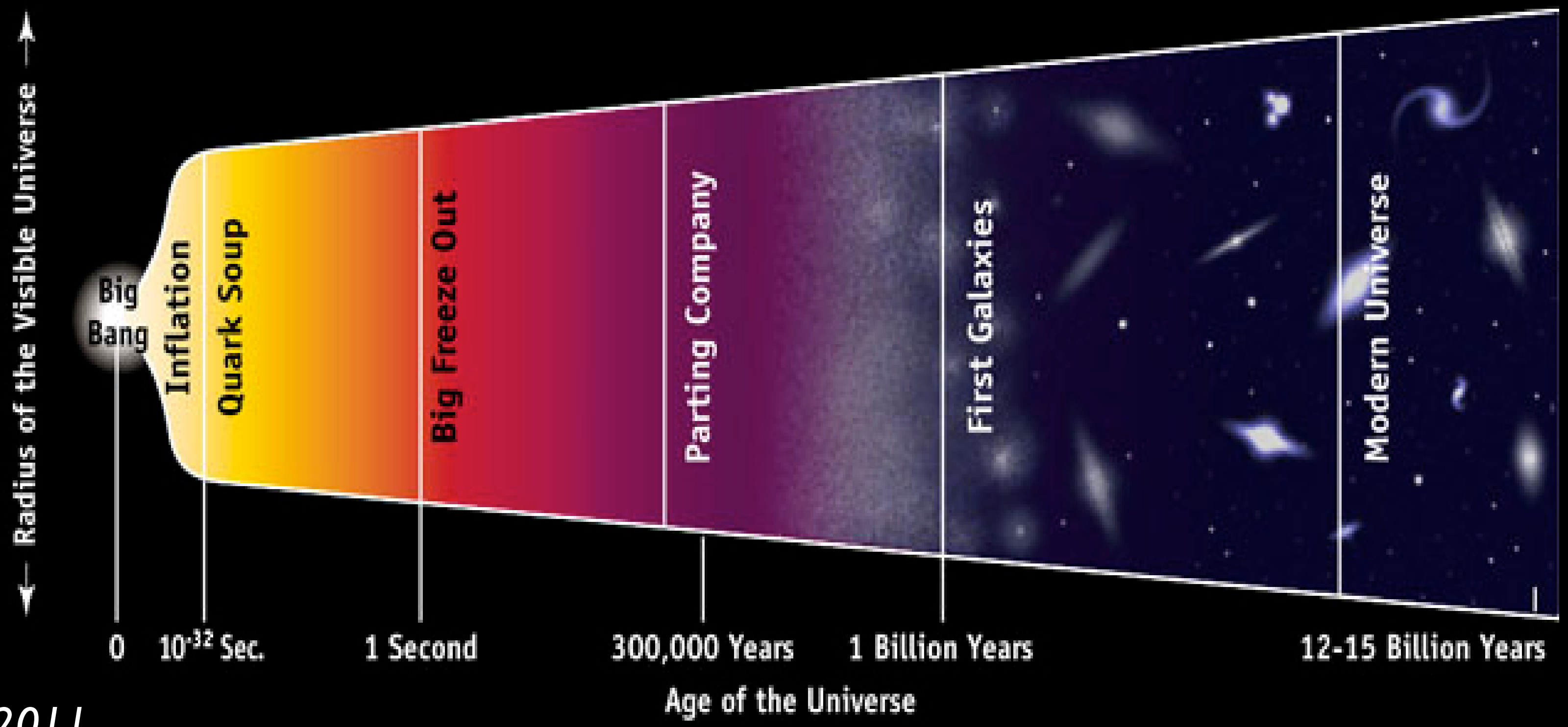
Ground based interferometers



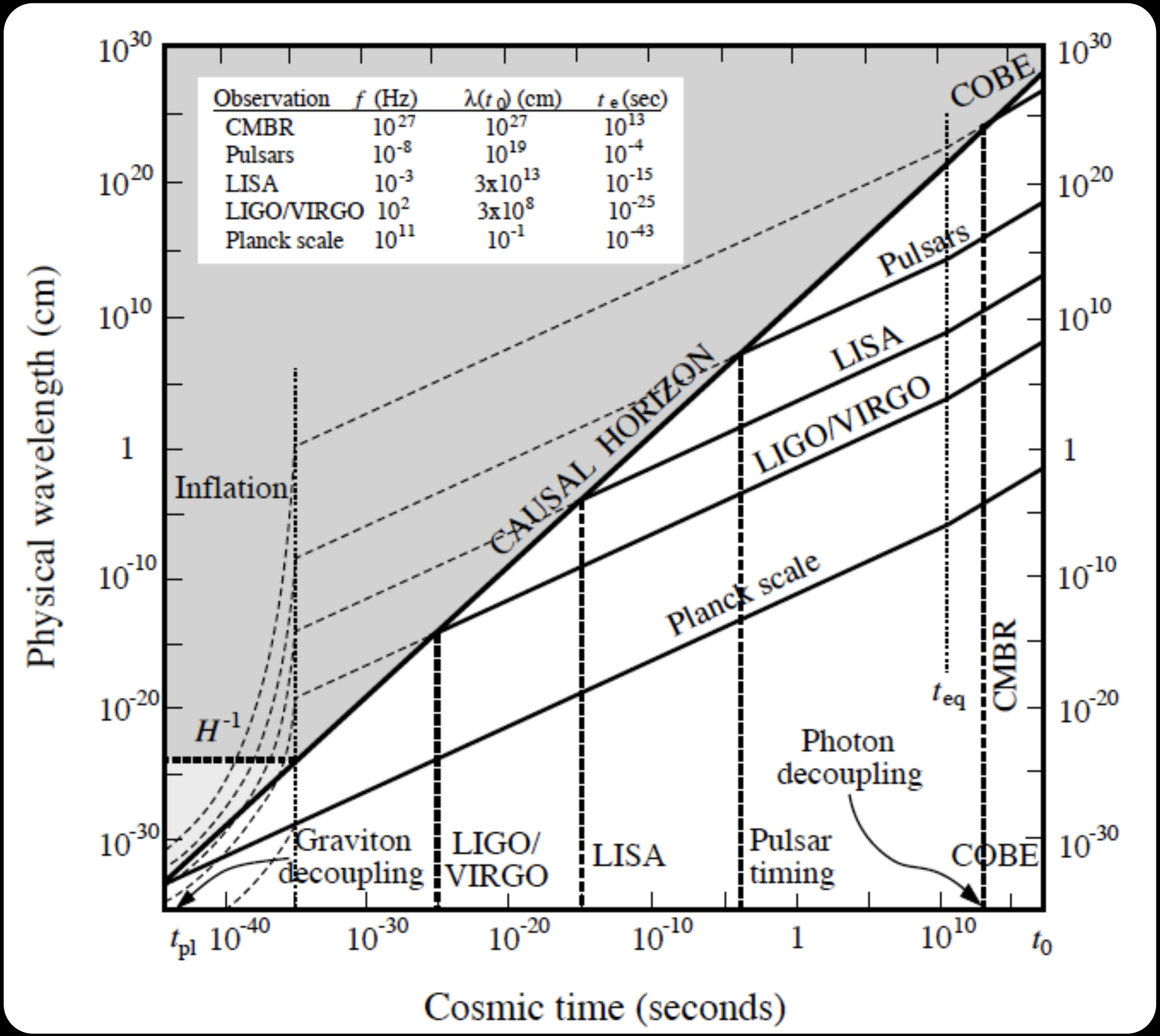
IFO	Source^a	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02
	NS-BH	7×10^{-5}	0.004
	BH-BH	2×10^{-4}	0.007
	IMRI into IMBH		
	IMBH-IMBH		
Advanced	NS-NS	0.4	40
	NS-BH	0.2	10
	BH-BH	0.4	20
	IMRI into IMBH		
	IMBH-IMBH		

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

Stochastic backgrounds from the early universe



GWs and the early universe



Observation	f (Hz)	$\lambda(t_0)$ (cm)	t_e (sec)
CMBR	10^{27}	10^{27}	10^{13}
Pulsars	10^{-8}	10^{19}	10^{-4}
LISA	10^{-3}	$3\text{x}10^{13}$	10^{-15}
LIGO/VIRGO	10^{2}	$3\text{x}10^{8}$	10^{-25}
Planck scale	10^{11}	10^{-1}	10^{-43}

(Battye and Shellard, arXiv:9604059)

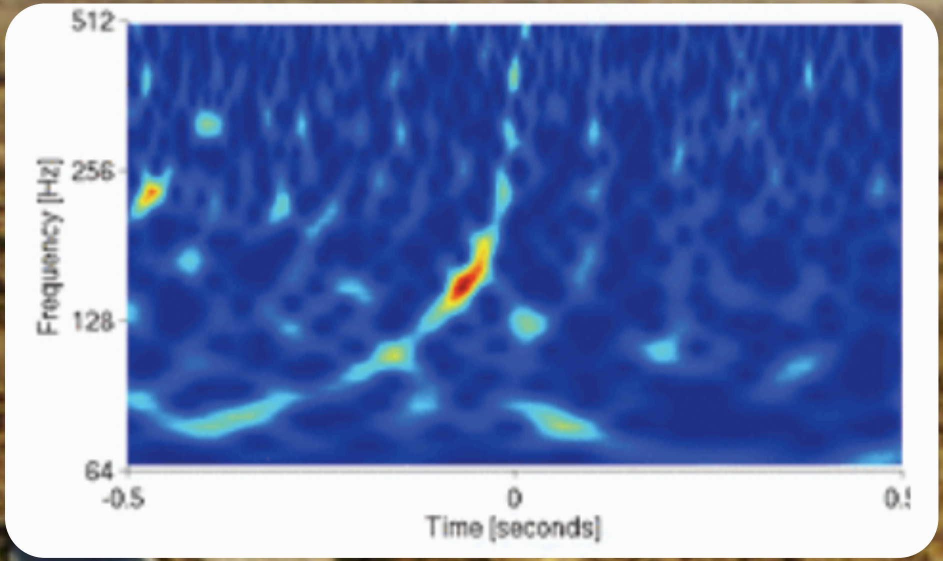
(Very crude) sensitivity estimate for $h^2\ \Omega_{gw}(f)$

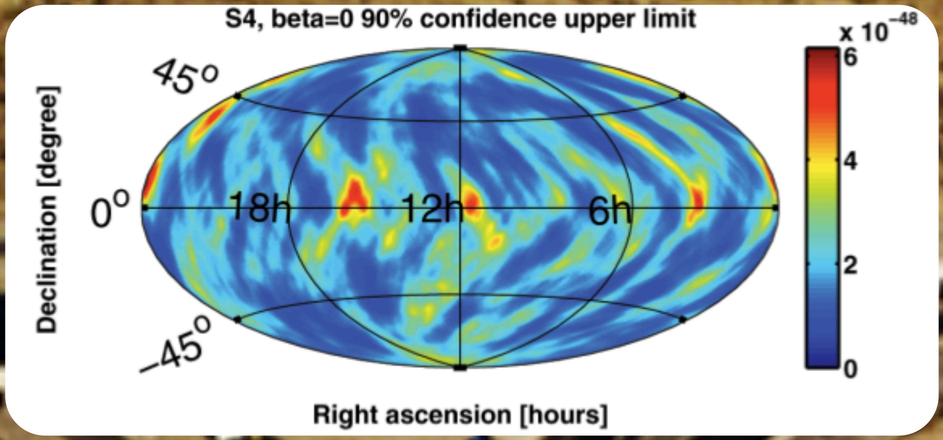
	LIGO/ Virgo	aLIGO/ aVirgo	ET	"LISA"	BBO/ Decigo	PTA	I-PTA	SKA
10-100 Hz	10^{-6}	10^{-8}	10^{-10}					
0.1-1 Hz					10^{-16}			
1-10 mHz				10^{-11}				
1-10 nHz						10^{-8}	10^{-10}	10^{-12}

(Very crude) sensitivity estimate for $h^2\,\Omega_{gw}(f)$

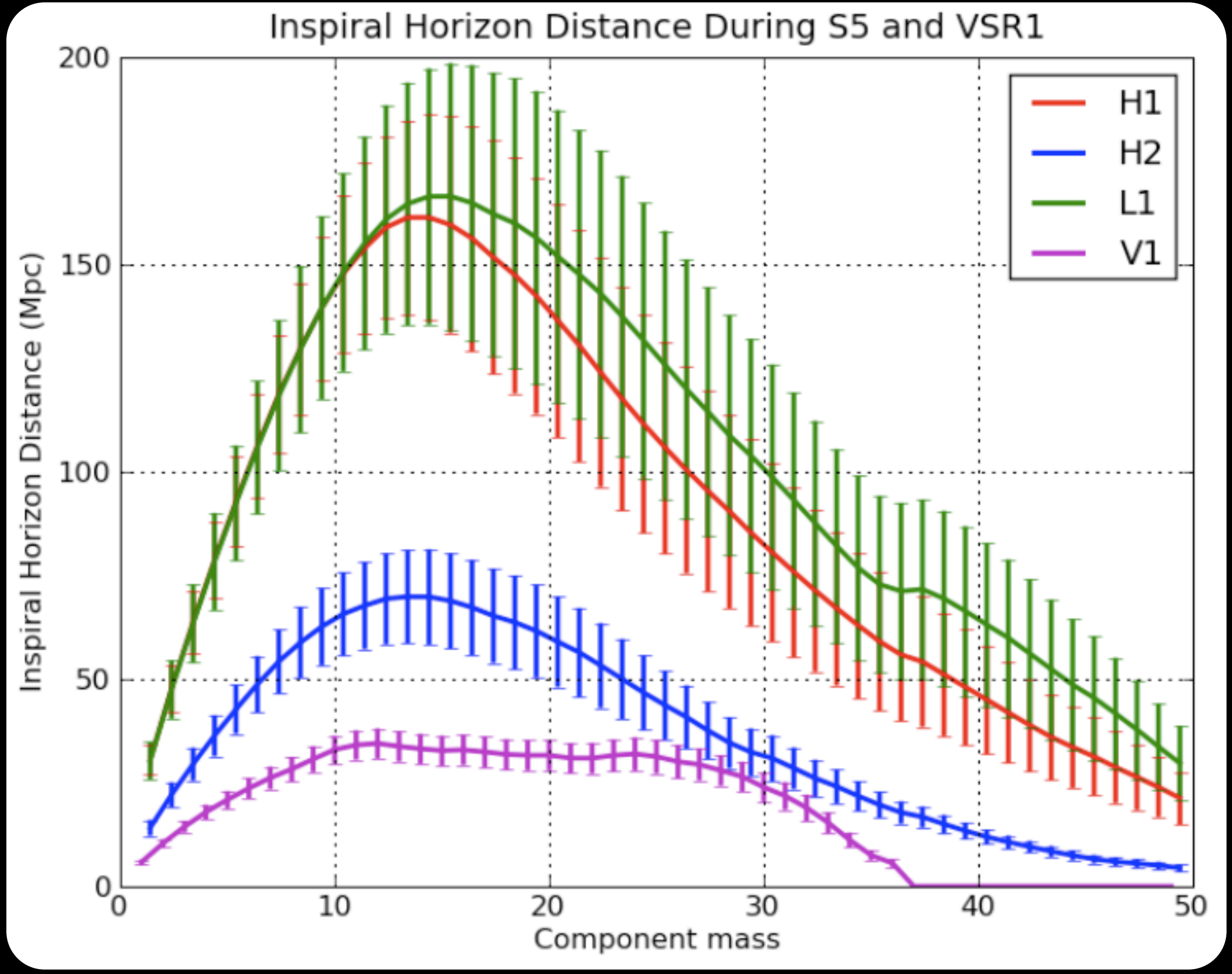
	LIGO/ Virgo	aLIGO/ aVirgo	ET	“LISA”	BBO/ Decigo	PTA	I-PTA	SKA
10-100 Hz	now	2015 -	202?					
0.1-1 Hz					20??			
1-10 mHz				2022+				
1-10 nHz						now	2015 -	202?

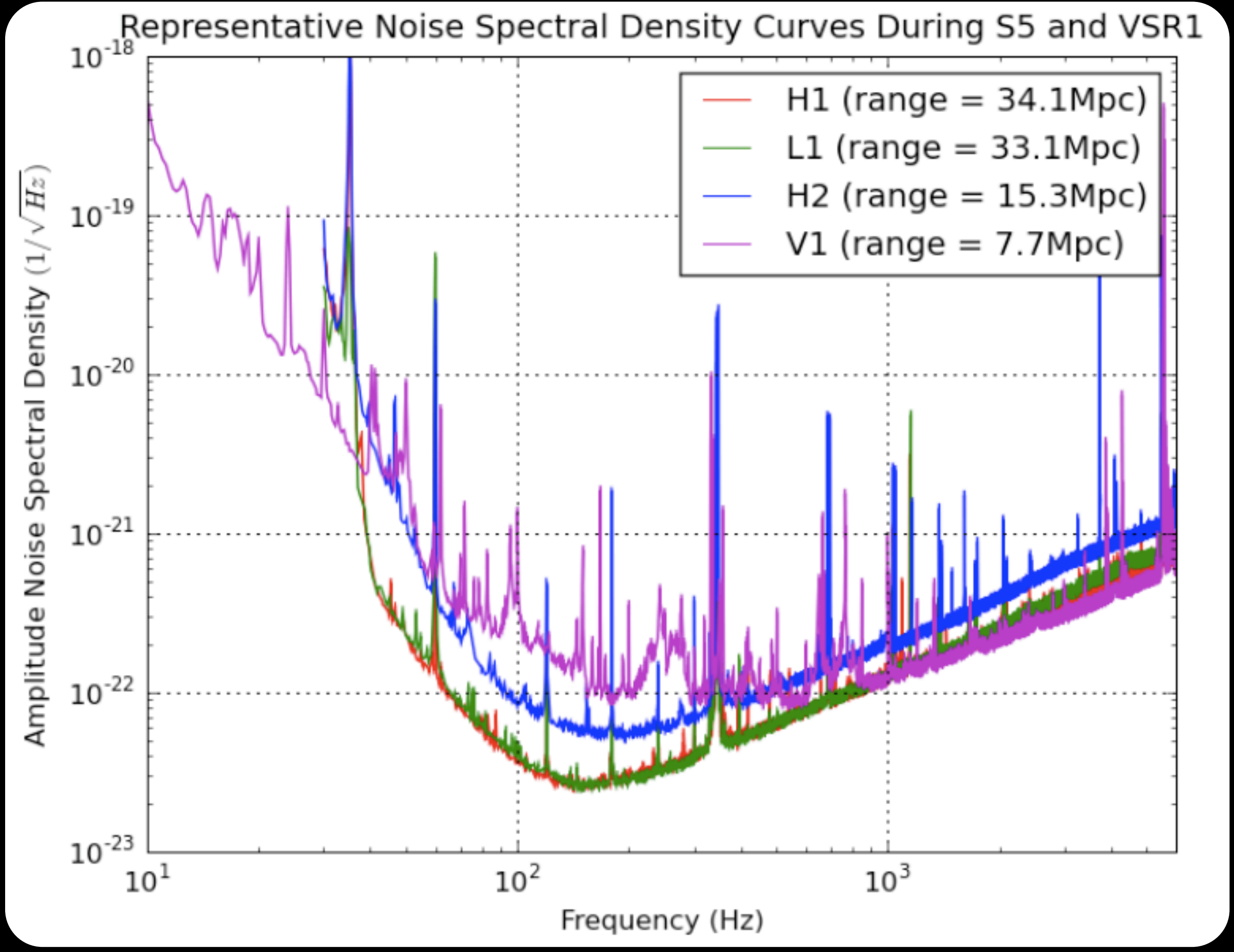
Ground based observations





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

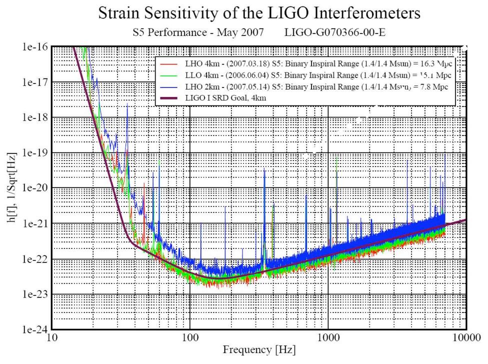
Detection Rate

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

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

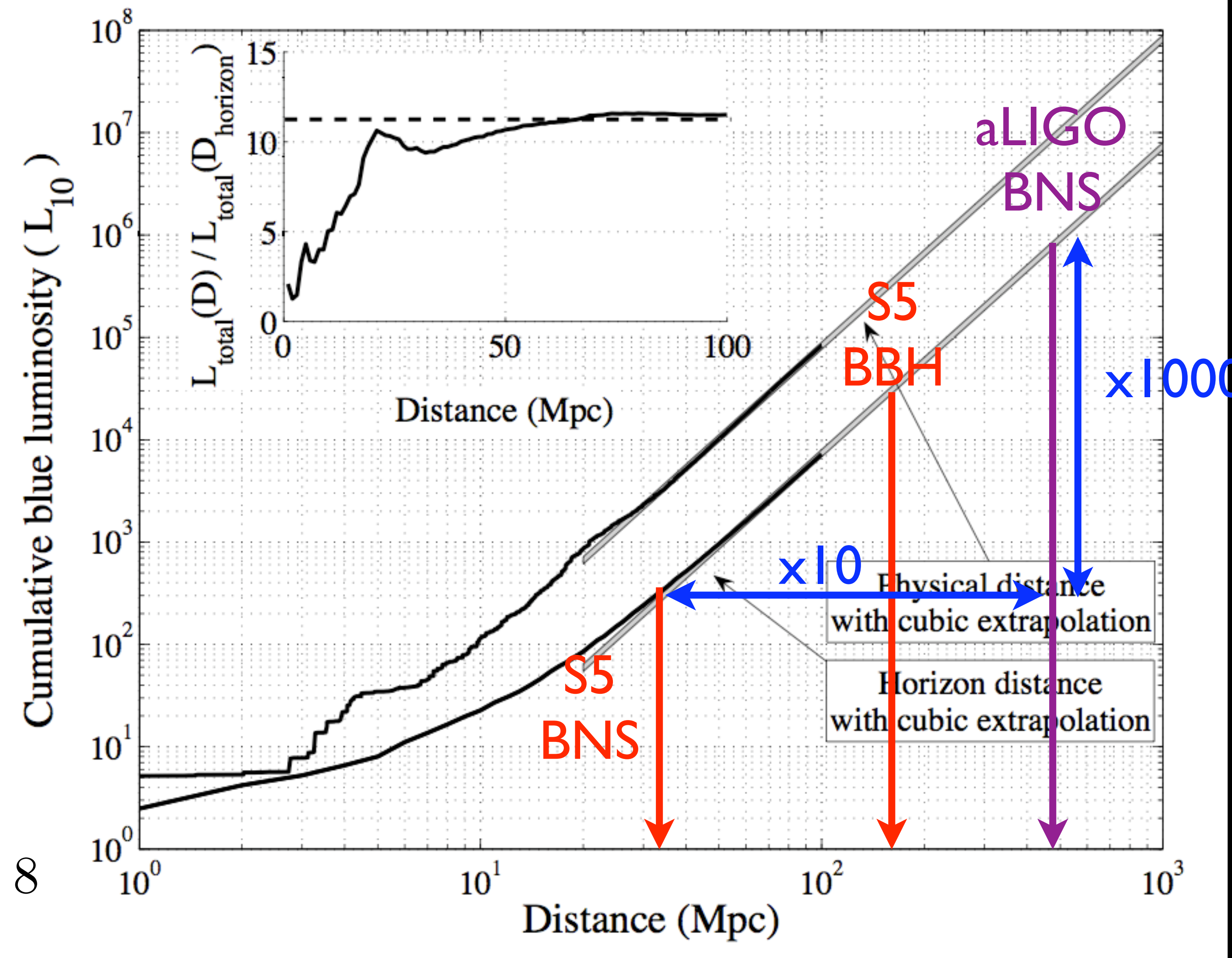
coalescence rate per galaxy

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


Strain Sensitivity of the LIGO Interferometers

S5 Performance - May 2007 LIGO-G070366-00-E

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



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

L_{10} / Mpc^3

average over sky and orientation

Expected detection rates

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ 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)

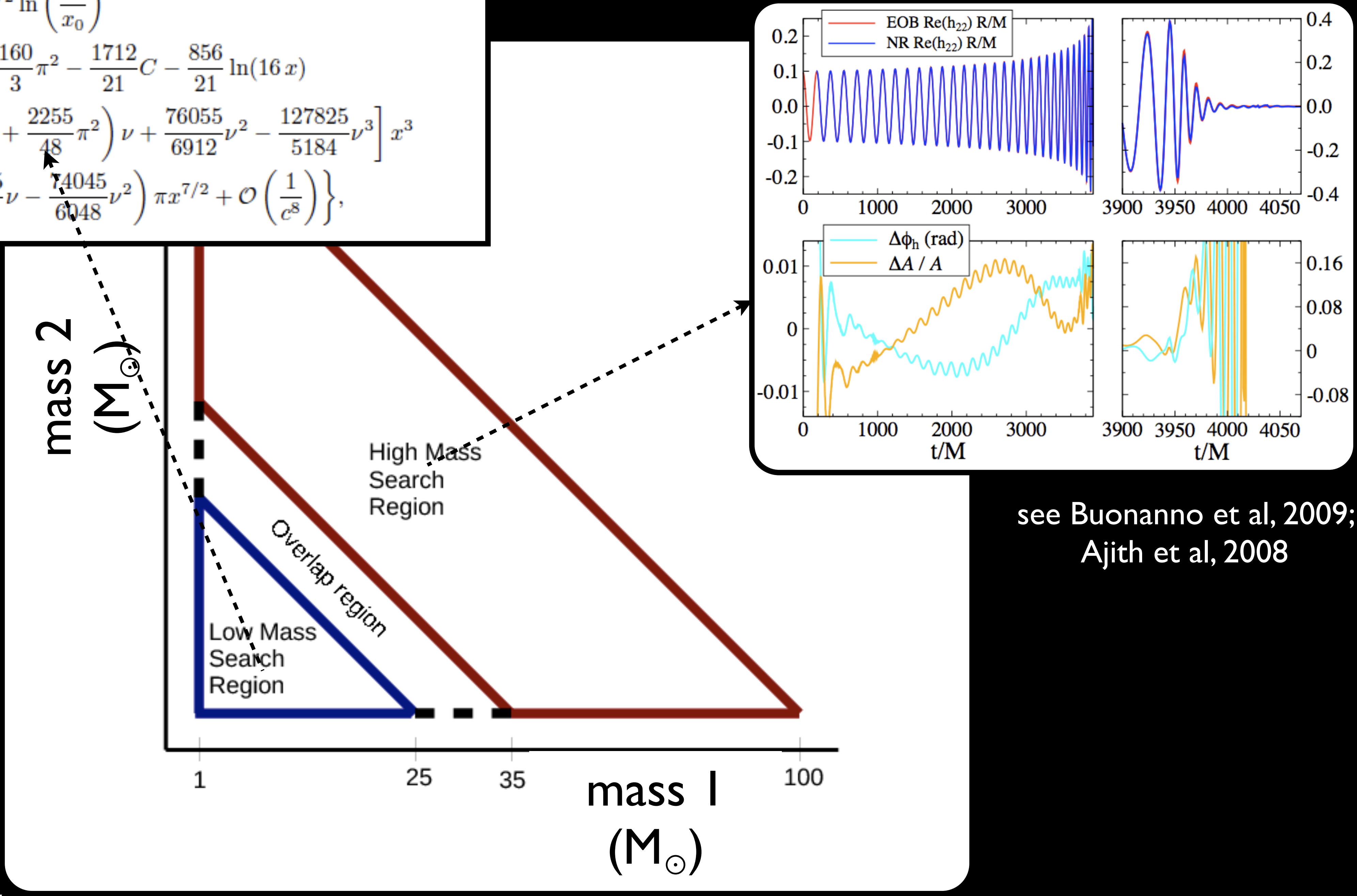
Mass search area

post-Newtonian approx. of inspiral

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

Blanchet LLR 2006

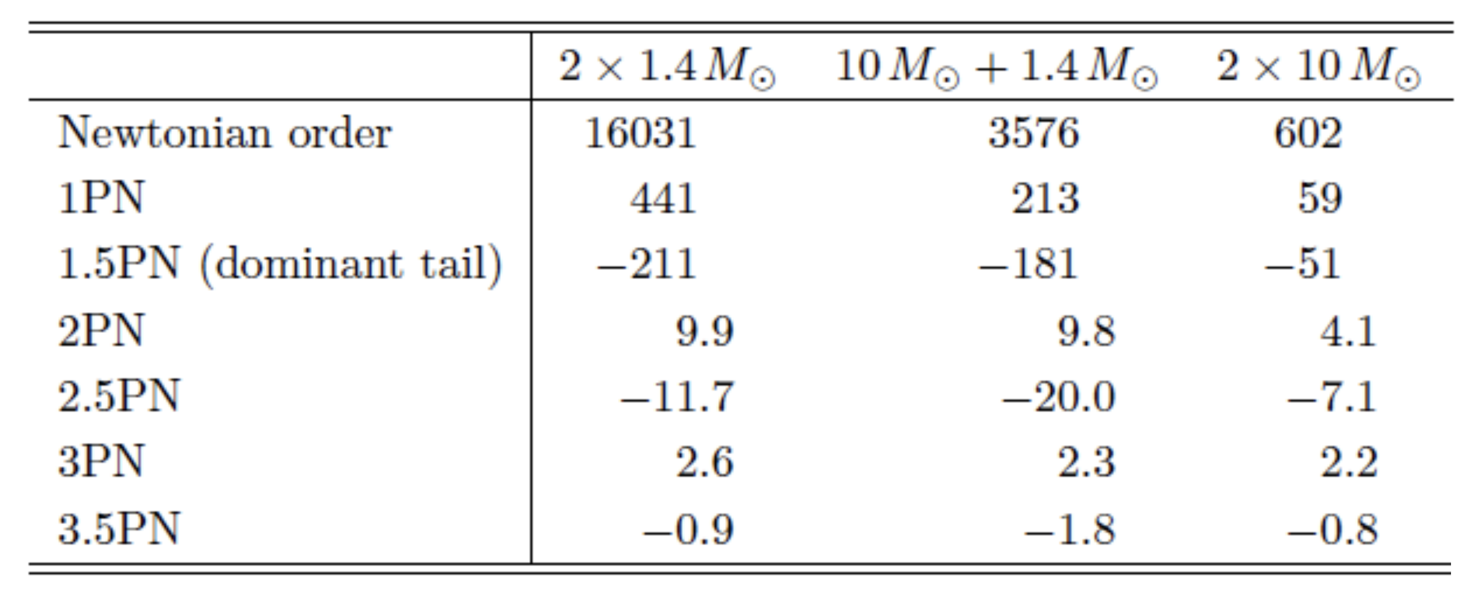
full inspiral-merger-ringdown waveforms



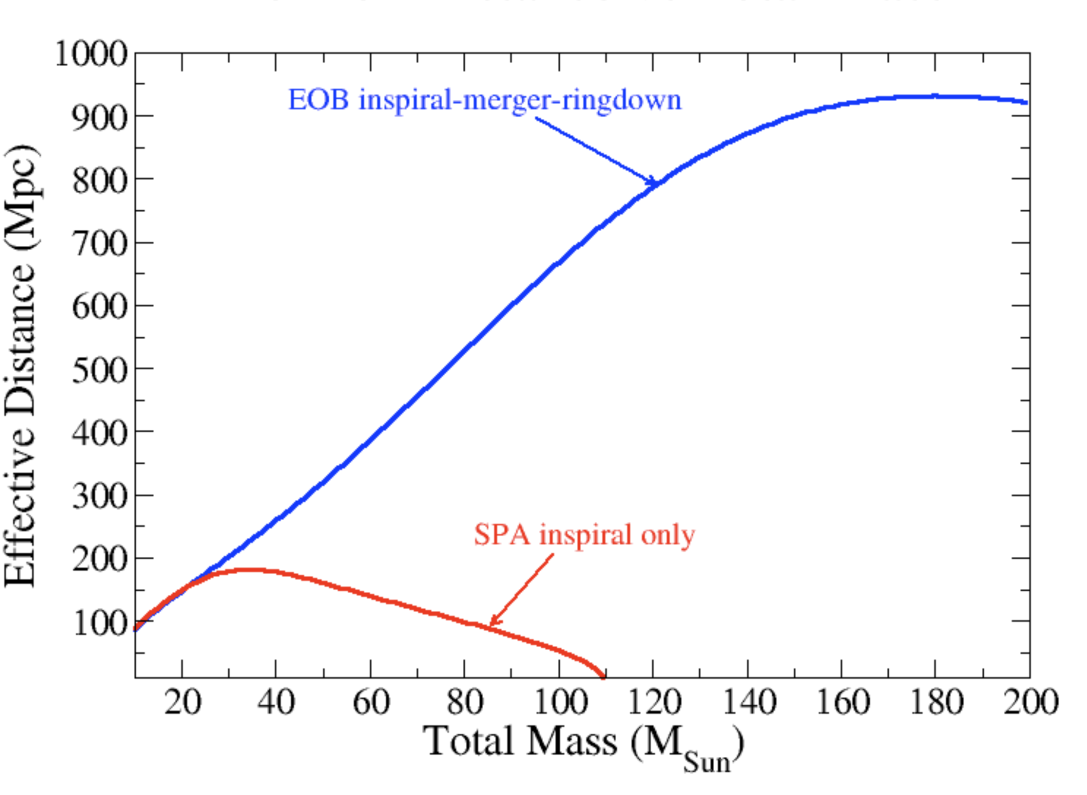
see Buonanno et al, 2009; Ajith et al, 2008

The two body problem

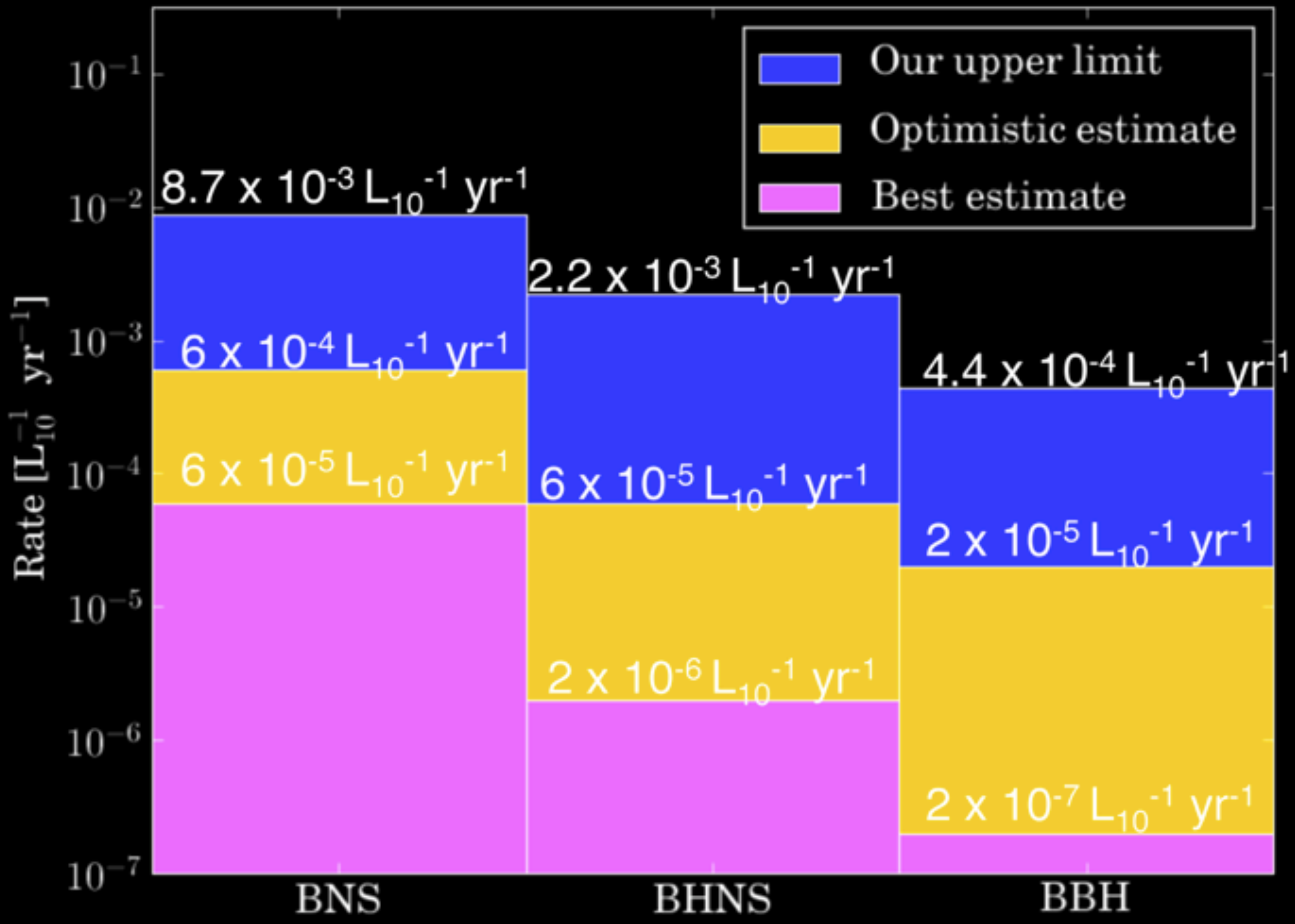
Number of inspiral wave cycles (f>10Hz)



	$2 \times 1.4\,M_\odot$	$10\,M_\odot + 1.4\,M_\odot$	$2 \times 10\,M_\odot$
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



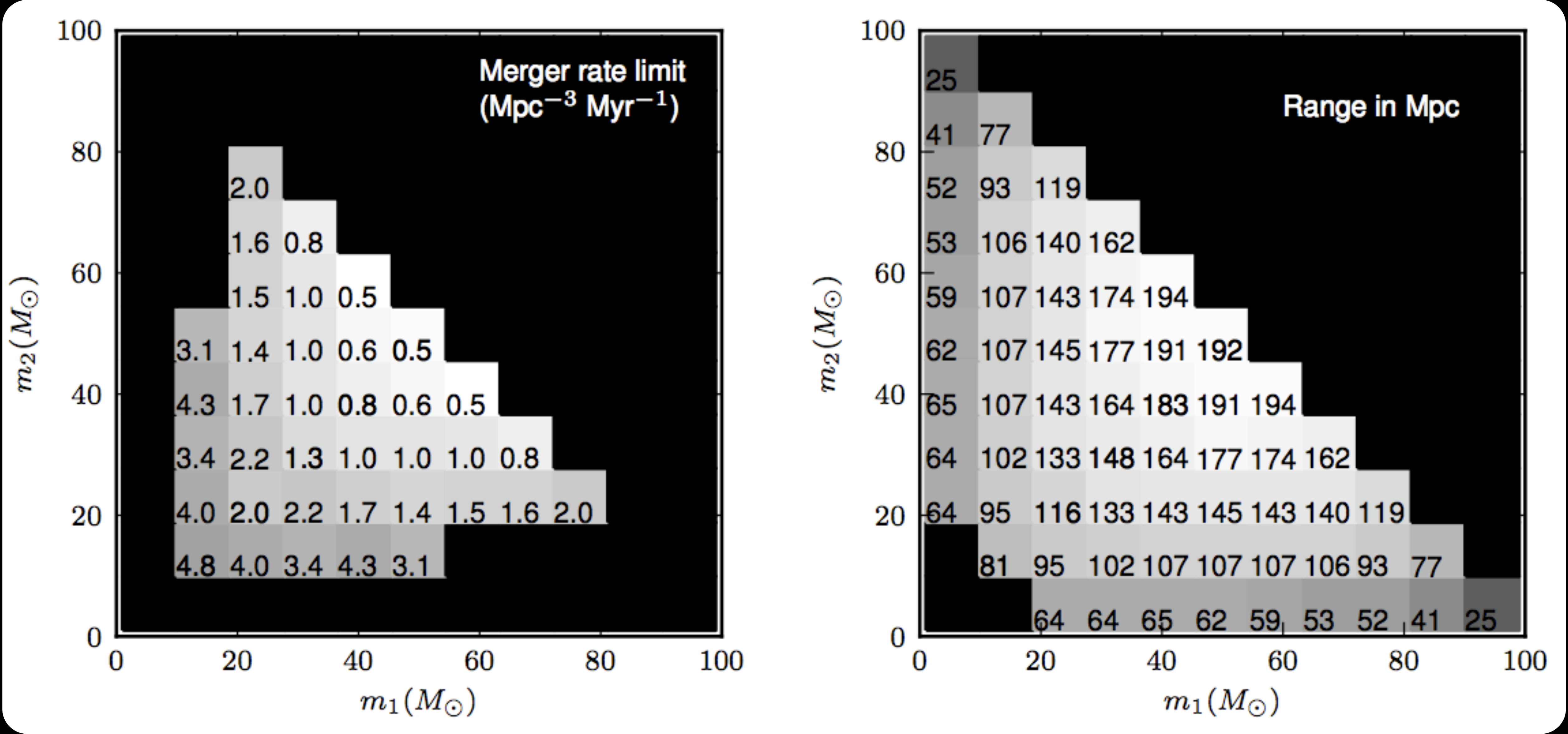
S5 “low-mass”: Upper-limits



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

S5 “high-mass”: Upper-limits

Upper-limit a factor ~ 10 higher than optimistic rate



Merger rate limit (Mpc^{-3} Myr^{-1})

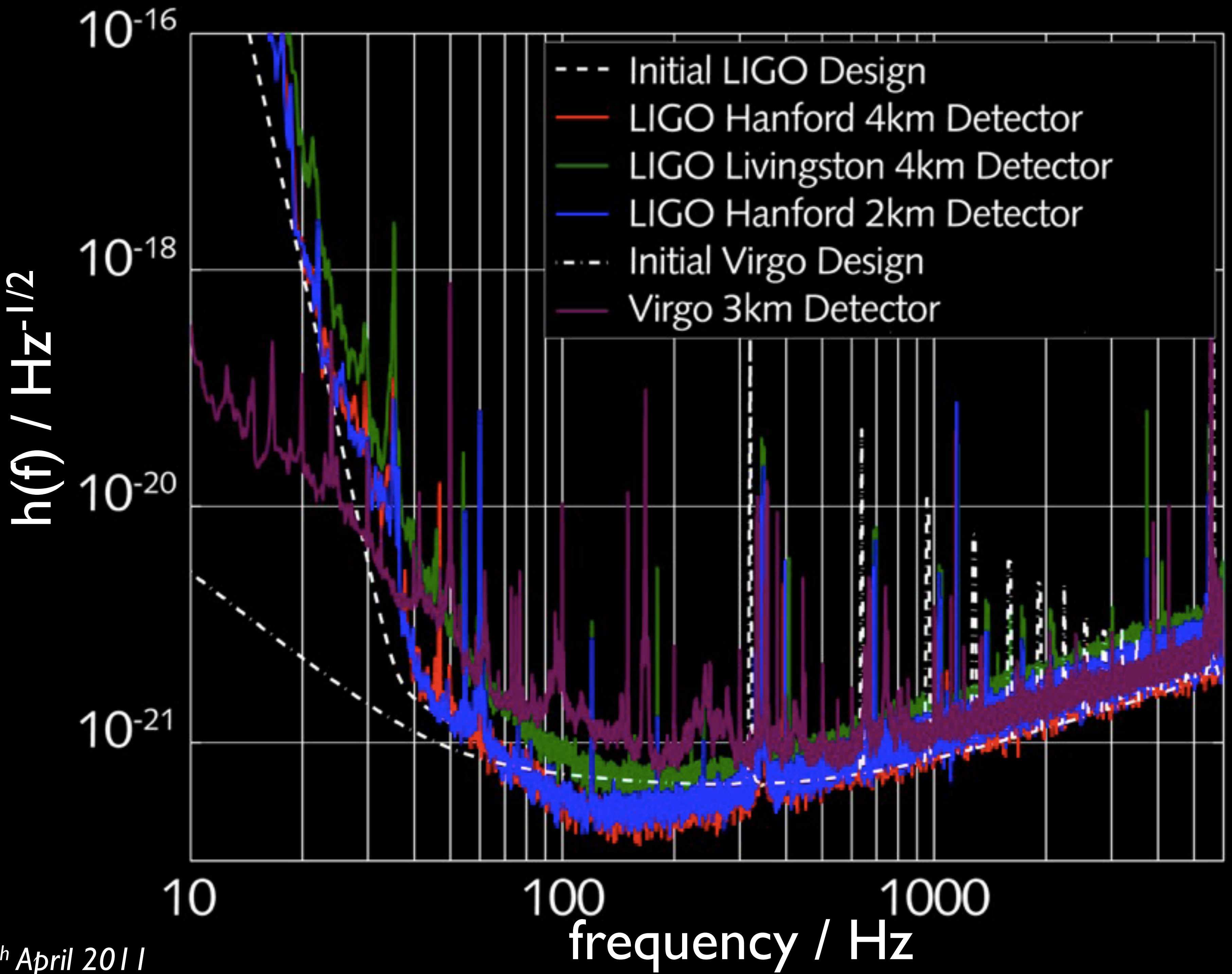
	2.0						
	1.6	0.8					
	1.5	1.0	0.5				
3.1	1.4	1.0	0.6	0.5			
4.3	1.7	1.0	0.8	0.6	0.5		
3.4	2.2	1.3	1.0	1.0	1.0	0.8	
4.0	2.0	2.2	1.7	1.4	1.5	1.6	2.0
4.8	4.0	3.4	4.3	3.1			

Range in Mpc

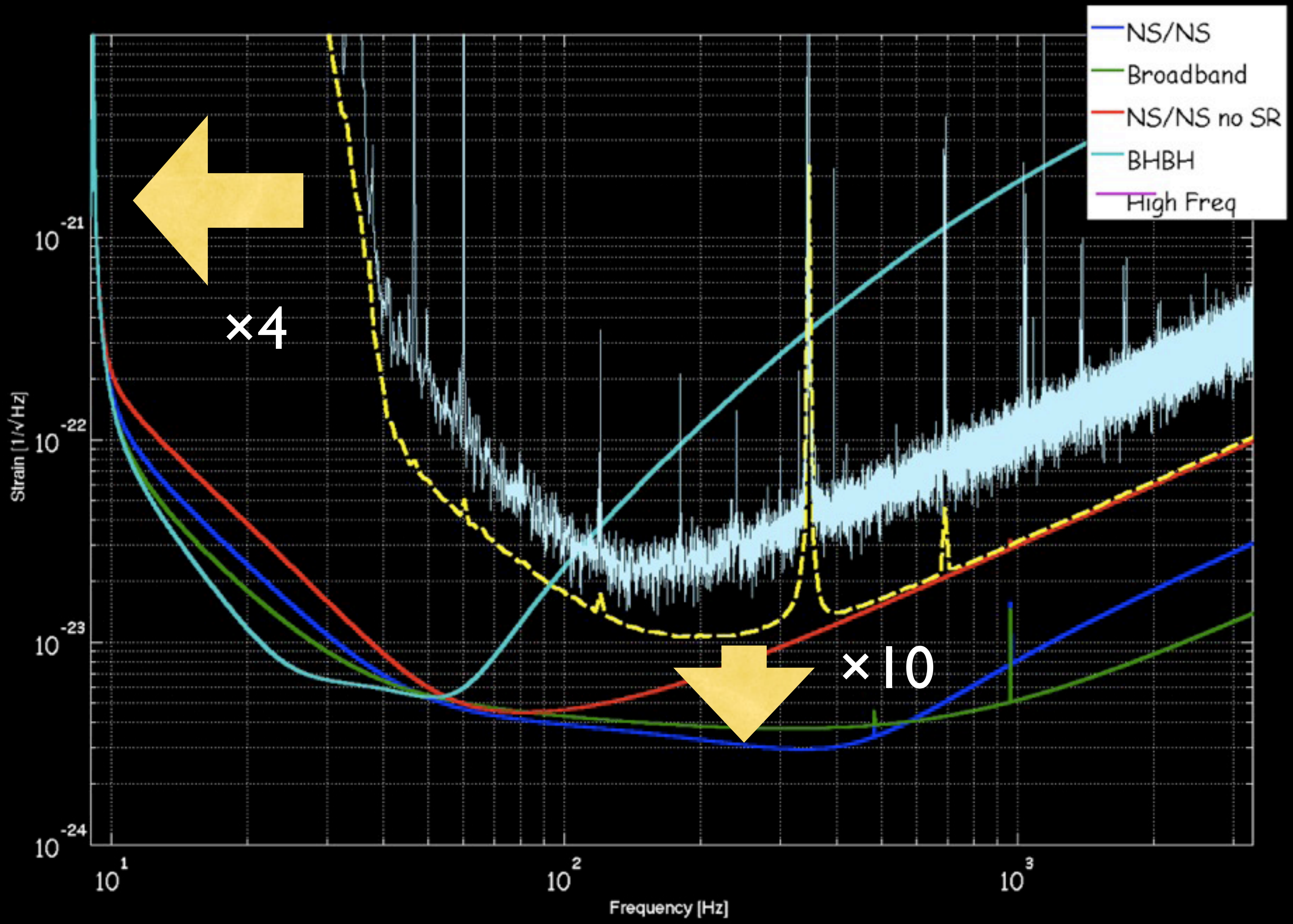
25										
41	77									
52	93	119								
53	106	140	162							
59	107	143	174	194						
62	107	145	177	191	192					
65	107	143	164	183	191	194				
64	102	133	148	164	177	174	162			
64	95	116	133	143	145	143	140	119		
	81	95	102	107	107	107	106	93	77	
		64	64	65	62	59	53	52	41	25

Abadie et al. (LSC and Virgo), arXiv:1102.3781

eLIGO/Virgo+
Analysis in progress



Advanced LIGO



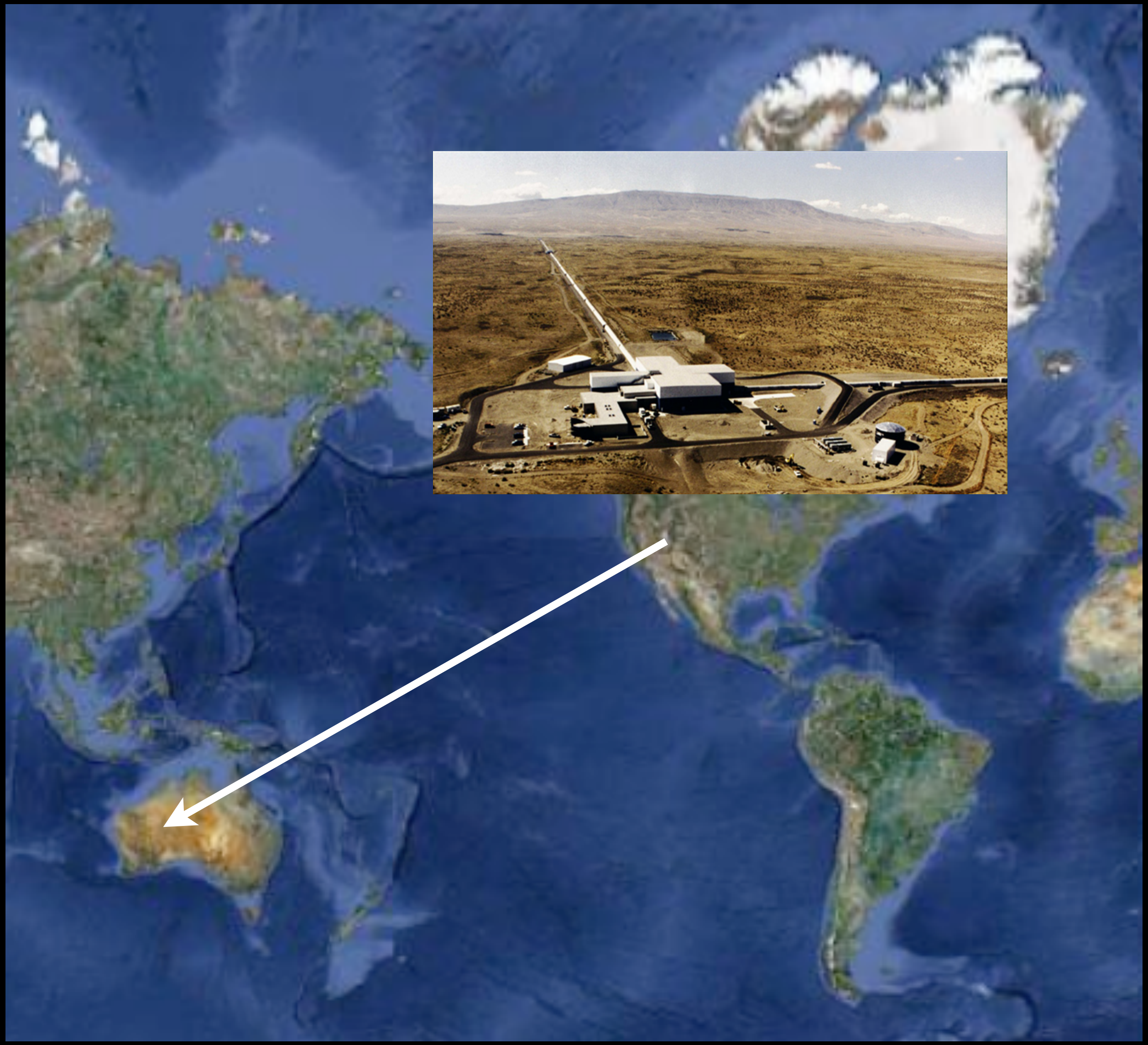
Expected detection rates

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ 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)

LIGO Australia?

Gingin facility



Decision will be made by Oct 2011

LCGT

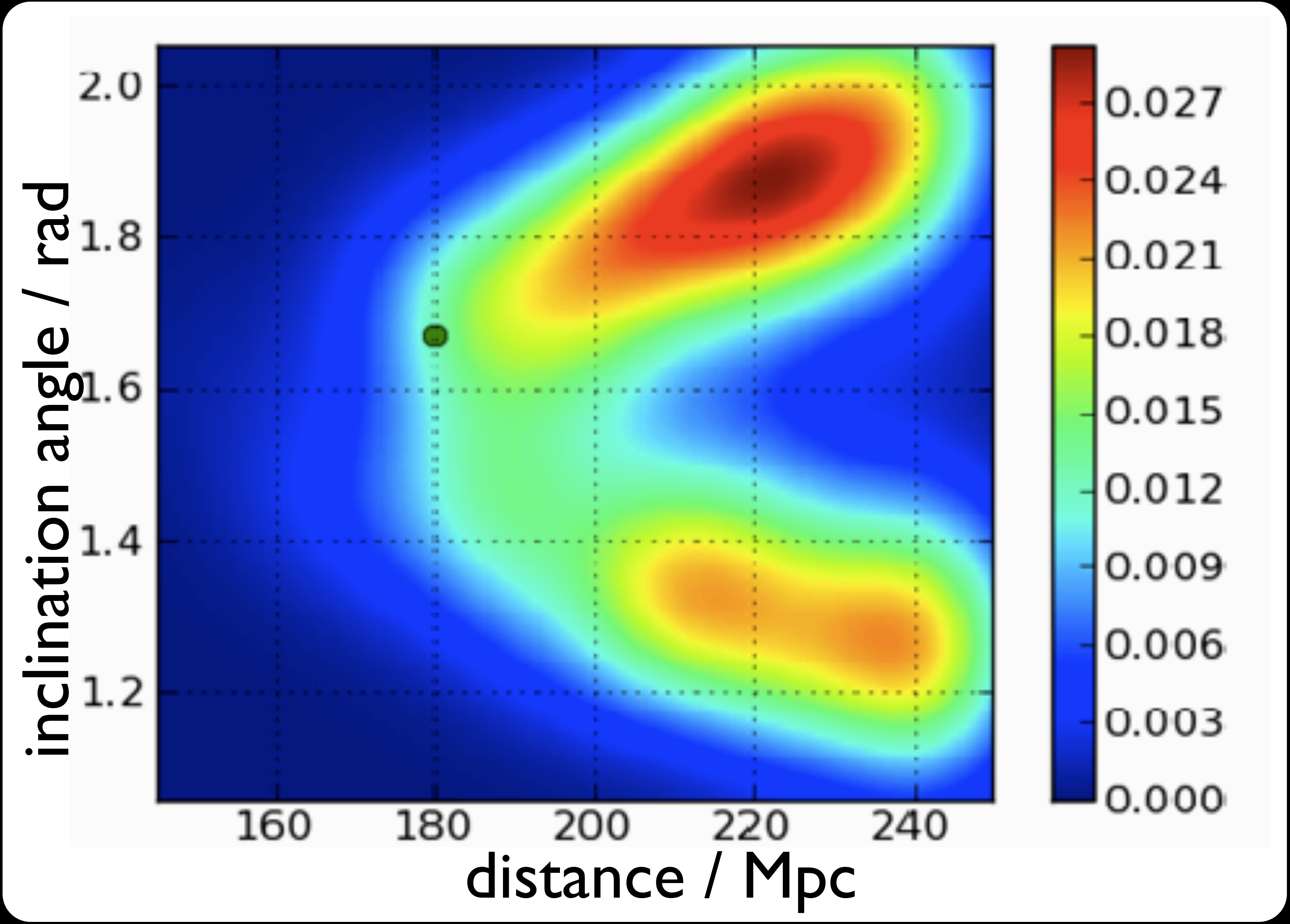

LCGT
Feel the Universe in Underground
- Detect Gravitational Waves from 200 Mpc Away -
37km from the Nippon Sea
Ikenoyama Mt.
1000m Underground
Mozumi area
XMASS
Kamland
SG
Super Kamiokande
CLIO
3km
LCGT project
358m Altitude
to Tateyama
LCGT
Image
Atotsu river
to Toyama
Takahara river
41
to Takayama
Atotsu
Entrance
Detect 3 / 100,000,000,000,000,000,000 meter changes
GEO600-HF
(Germany・England)
Advanced-LIGO
(USA)
Advanced-VIRGO
(France・Italy)
Next Generation
Gravitational Wave
Detector Network
Large-scale Cryogenic
Gravitational wave Telescope
(LCGT) (Japan)
4km
Washington : Desert
4km
Louisiana : Forest
600m
Hanover
3km
Pisa
ACIGA
(Australia)

Binaries as standard candles

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

- The luminosity distance $D_L(z; H_0, \Omega_M, \Omega_\Lambda, \Omega_k, ..)$ is a direct observable
- However, the redshift z cannot be measured directly
- One needs z from an electro-magnetic counterpart (e.g. gamma-ray burst?) or from the association with the host galaxy
- The key idea was put forward over 20 years ago (Schutz 1986)

Distance measurements

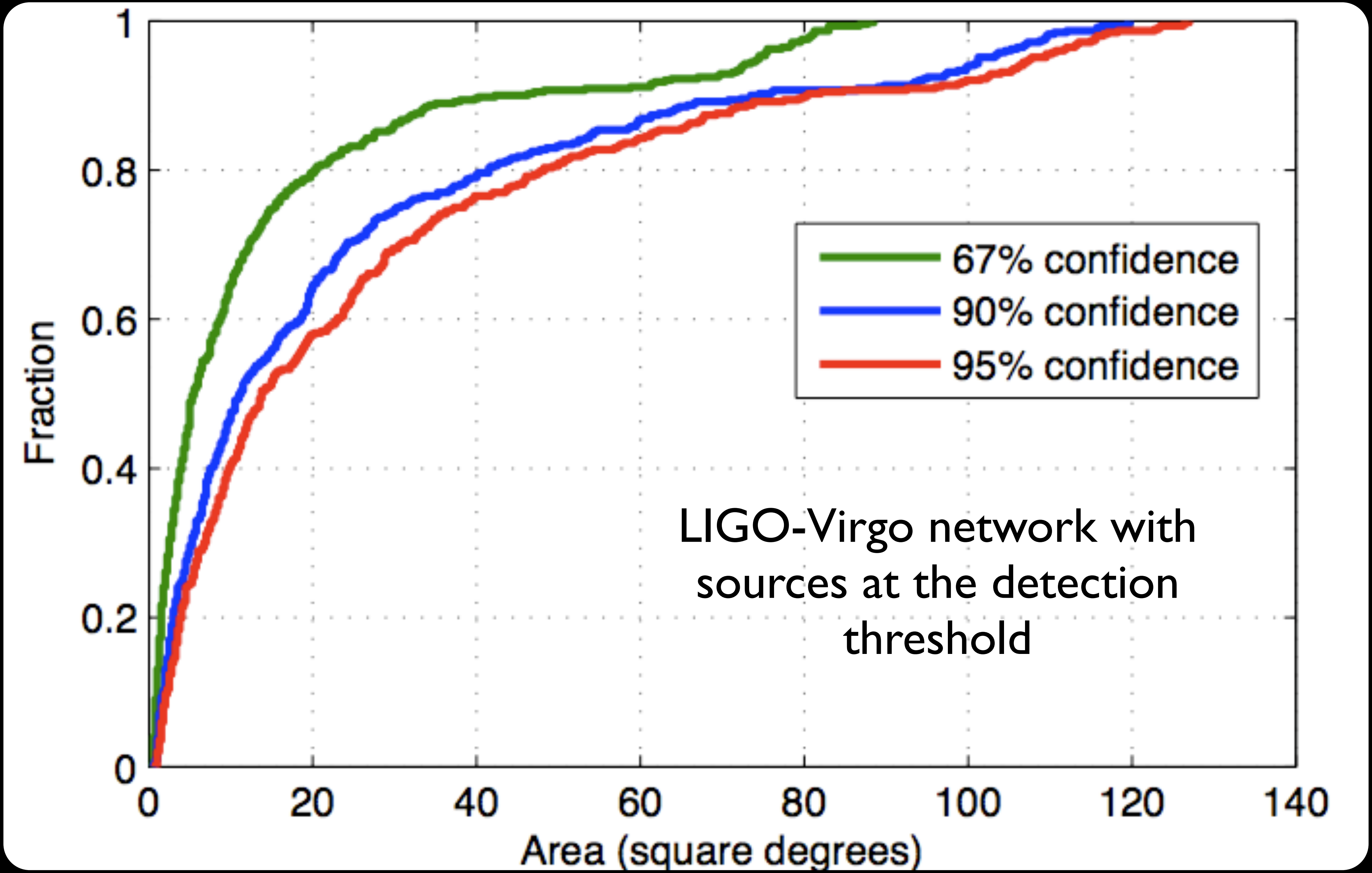


$$h_+ = \# \frac{(1 + \cos^2 \iota)}{D}$$

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

Veitch and AV (2010)

Error box in the sky



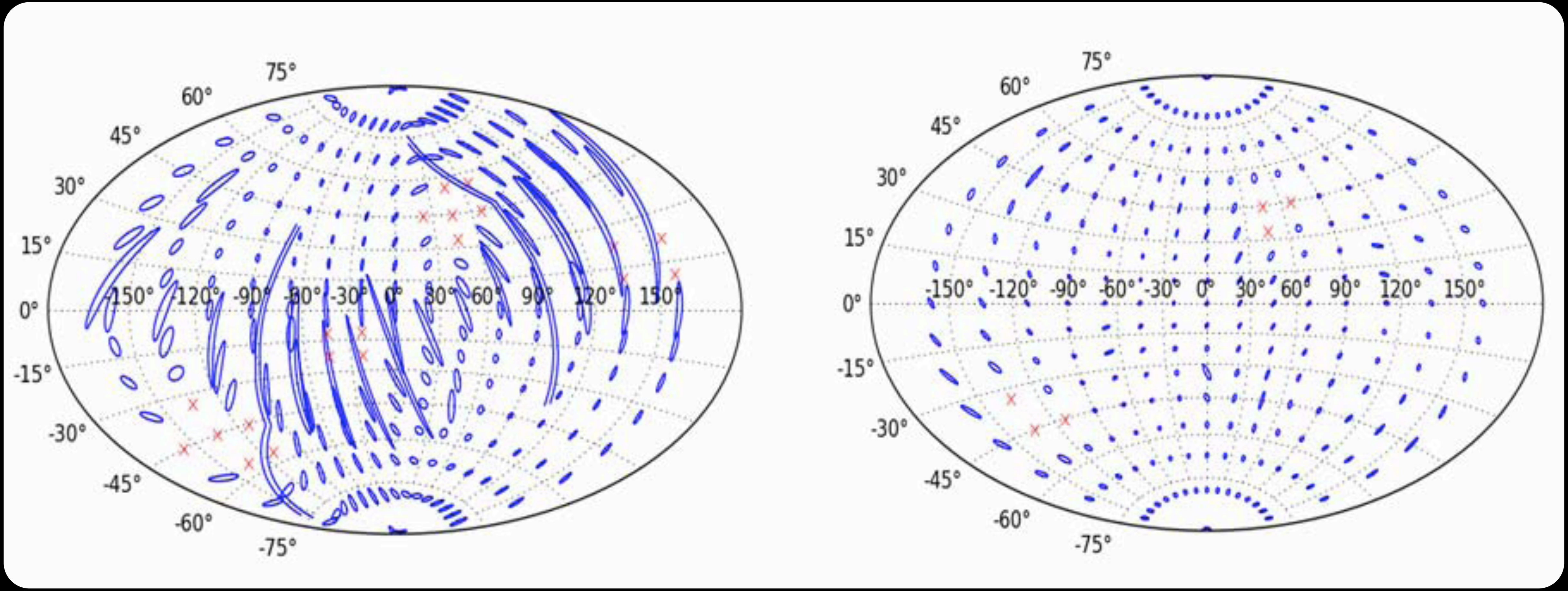
LIGO-Virgo network with sources at the detection threshold

this is just an example run, systematic studies are needed (and are in progress)

Sky resolution

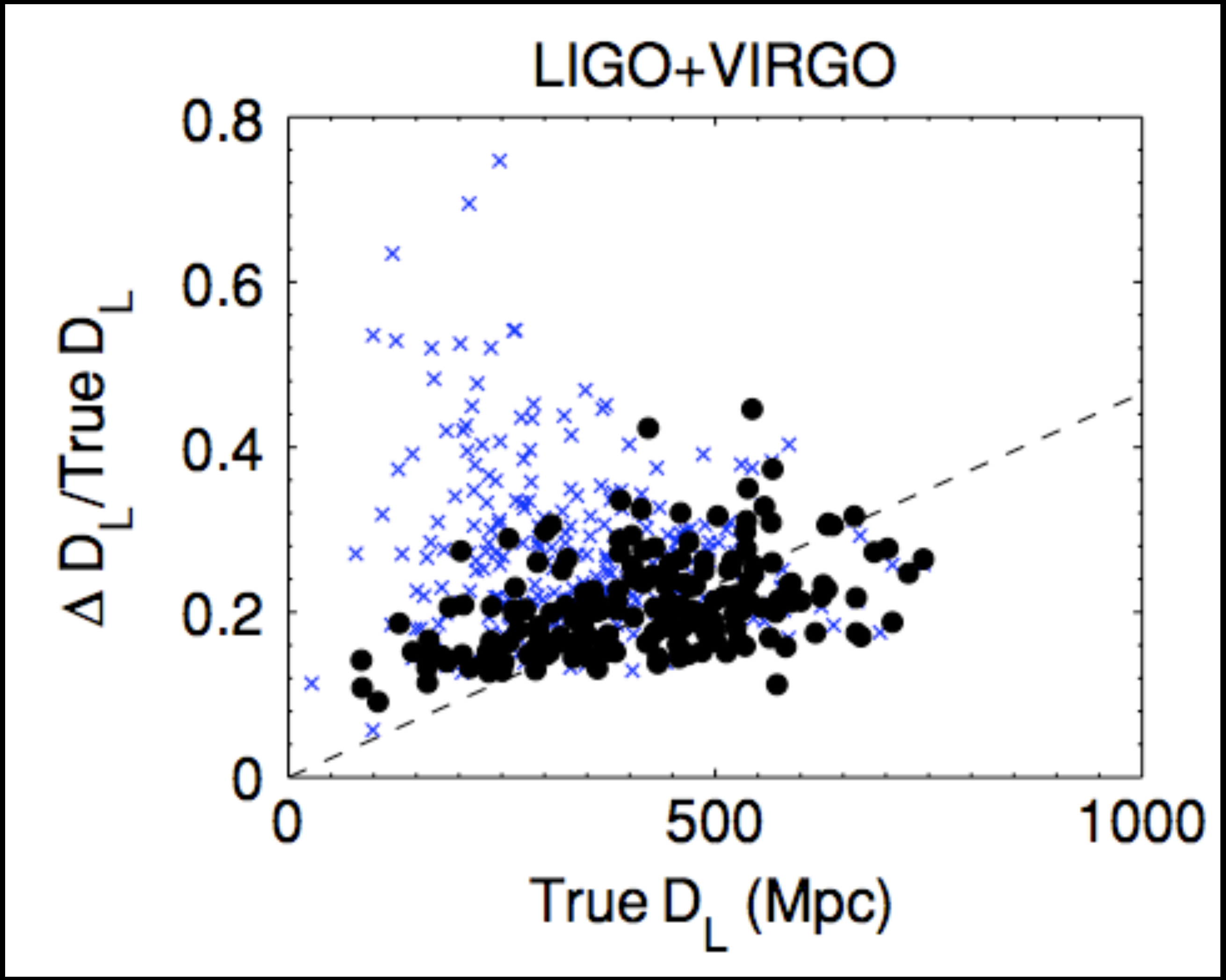
Current network

Current network
+
instrument in Australia



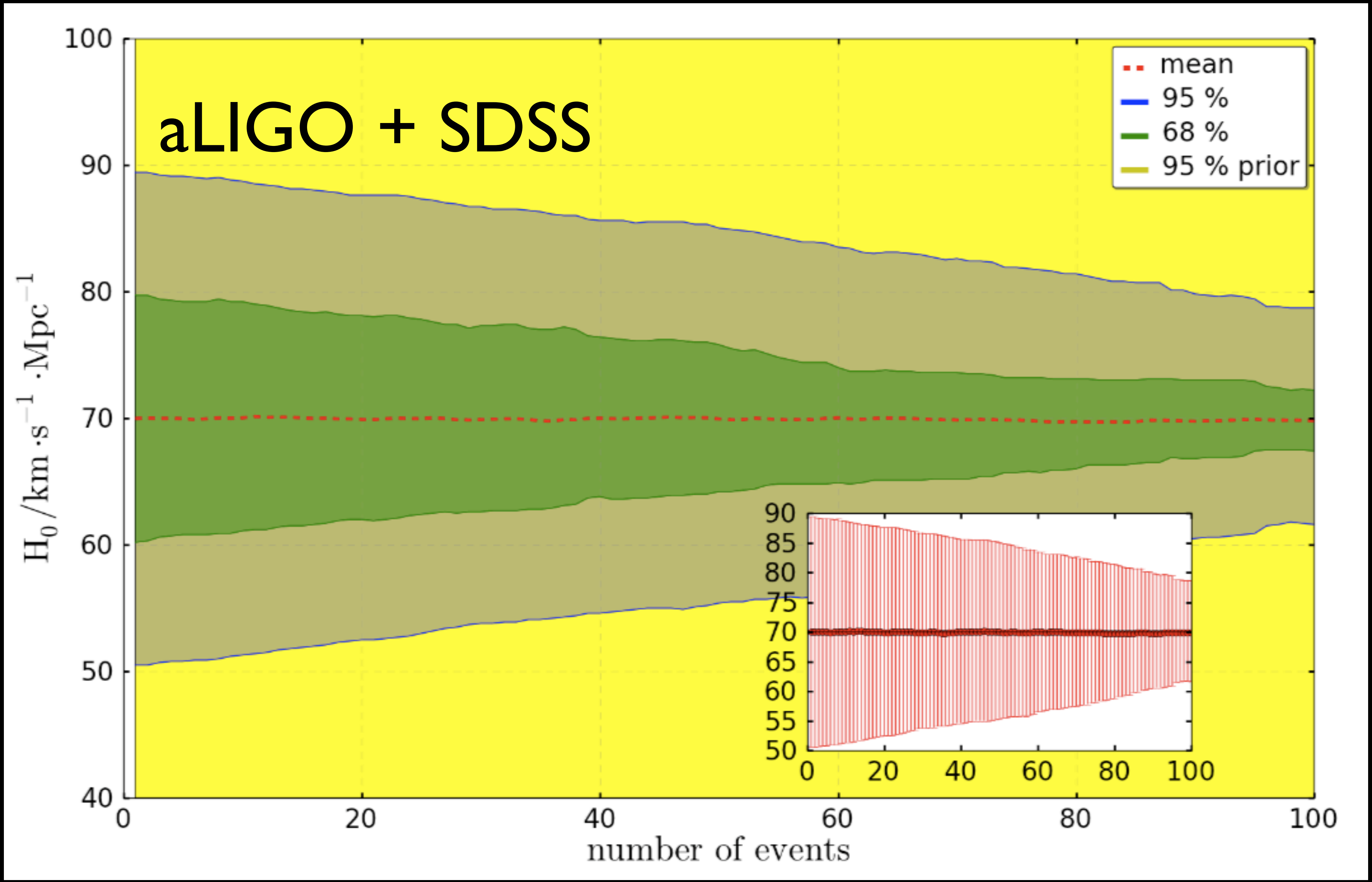
Measuring cosmological parameters

- “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



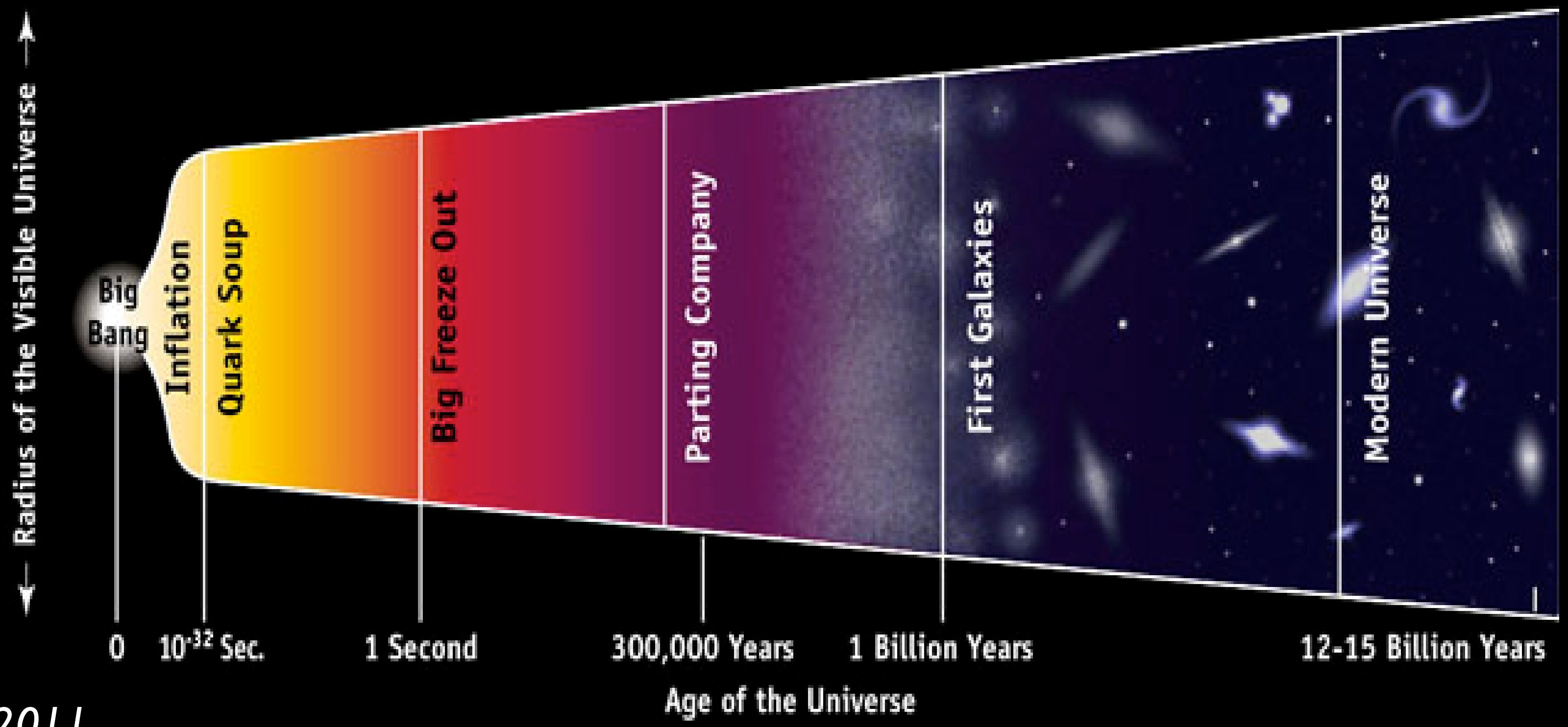
Nissanke et al, 2010

Example: Measuring H_0



Del Pozzo and AV, in preparation

Stochastic backgrounds from the early universe



Stochastic backgrounds

Spectrum:

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

Amplitude:

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

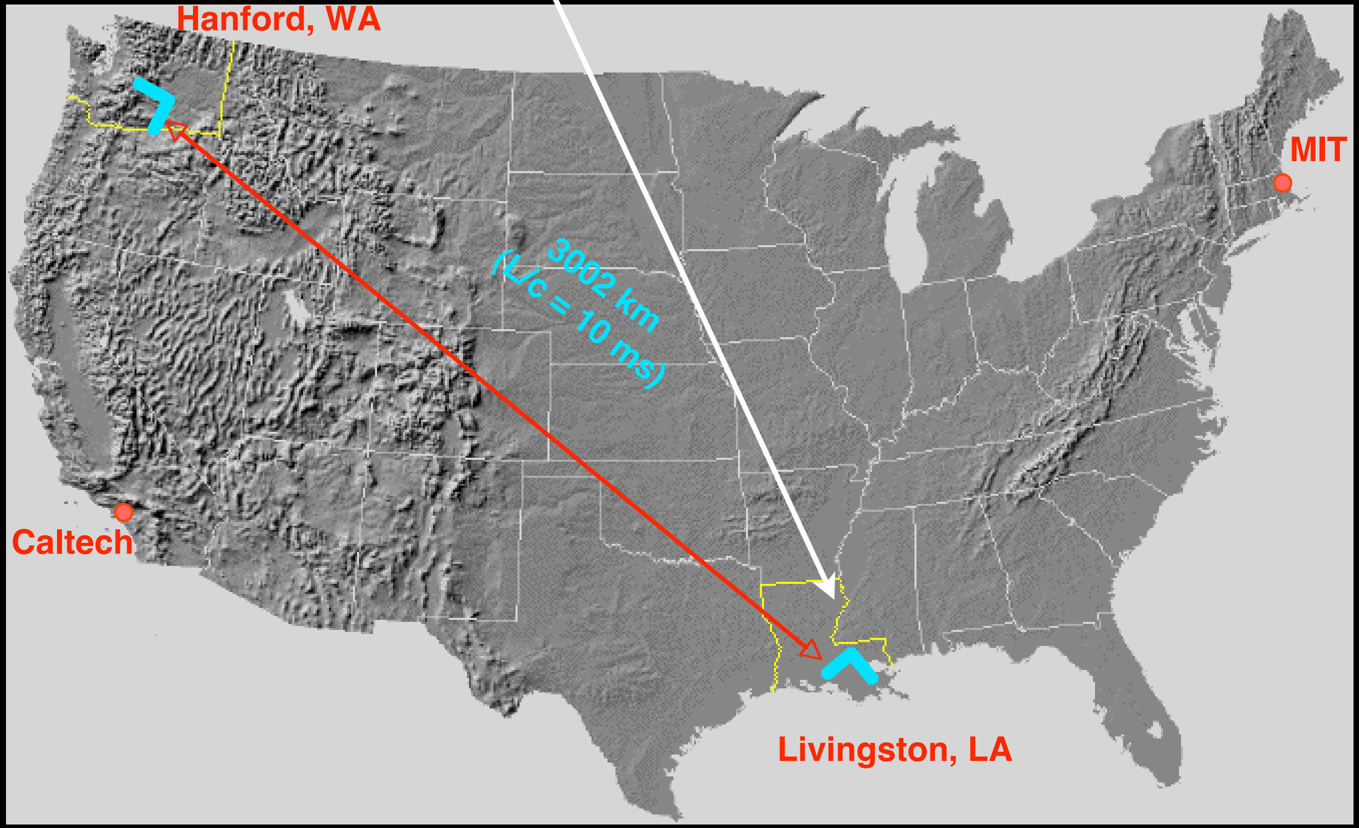
Search approach

- 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

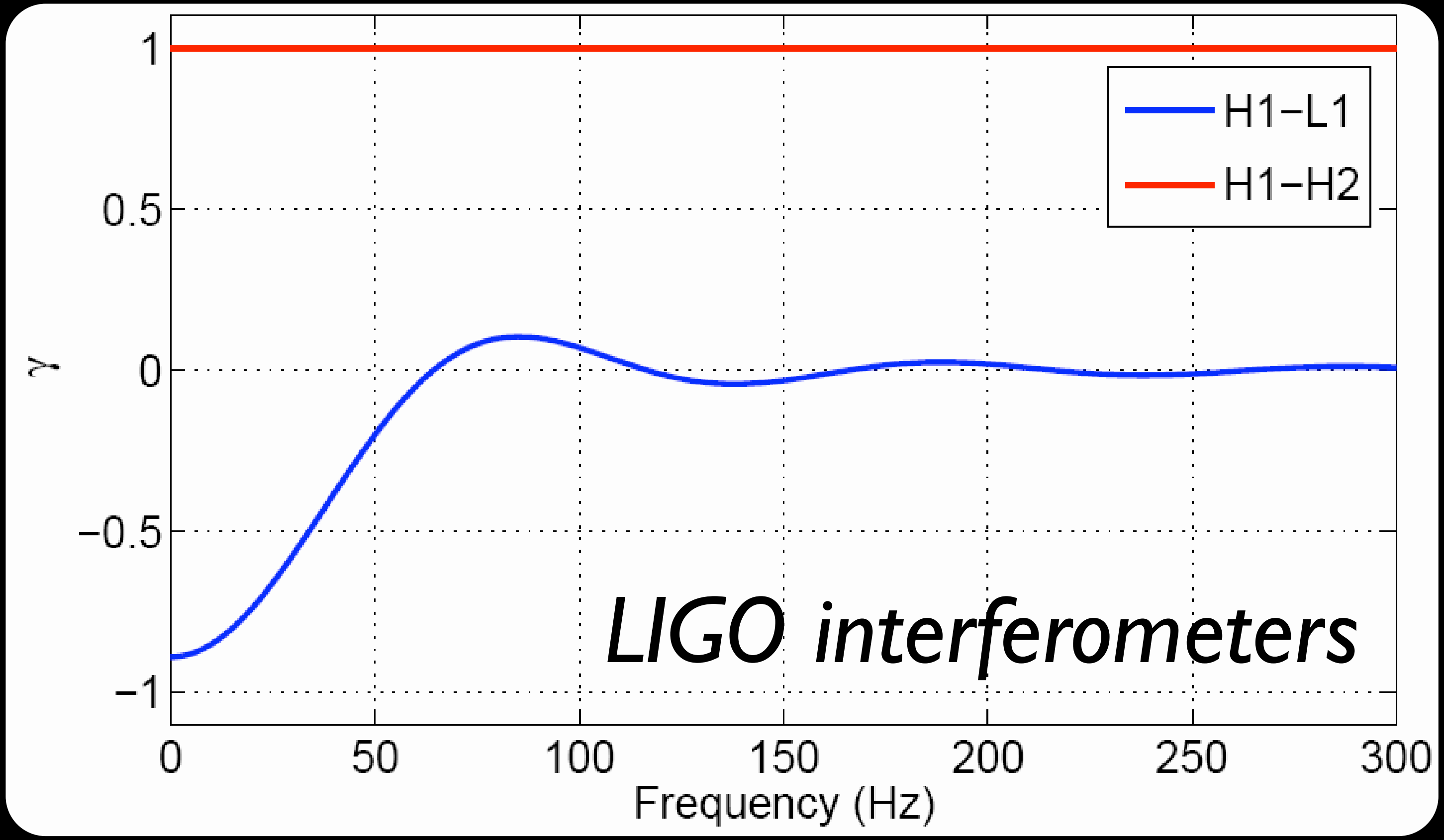
$$s_1 = n_1 + h_1$$
$$s_2 = n_2 + h_2$$

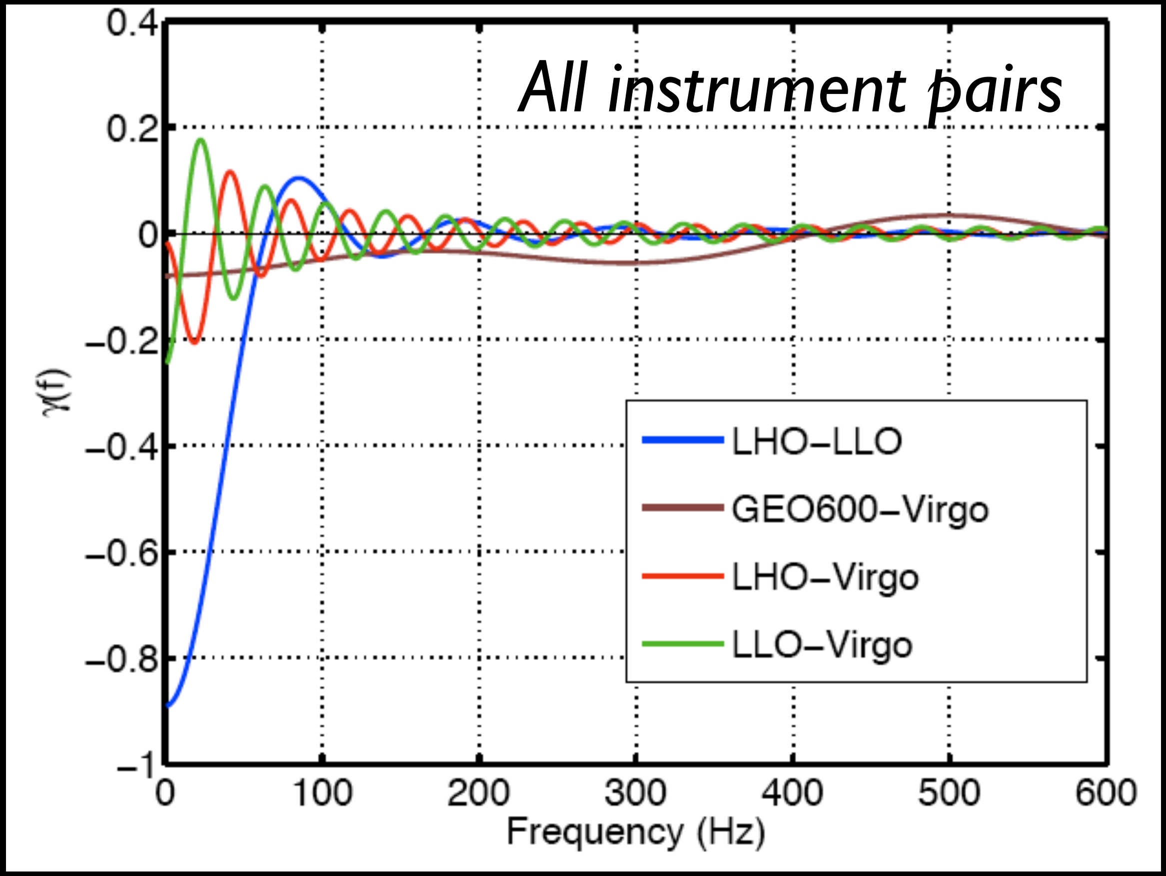


Geometry: overlap reduction function

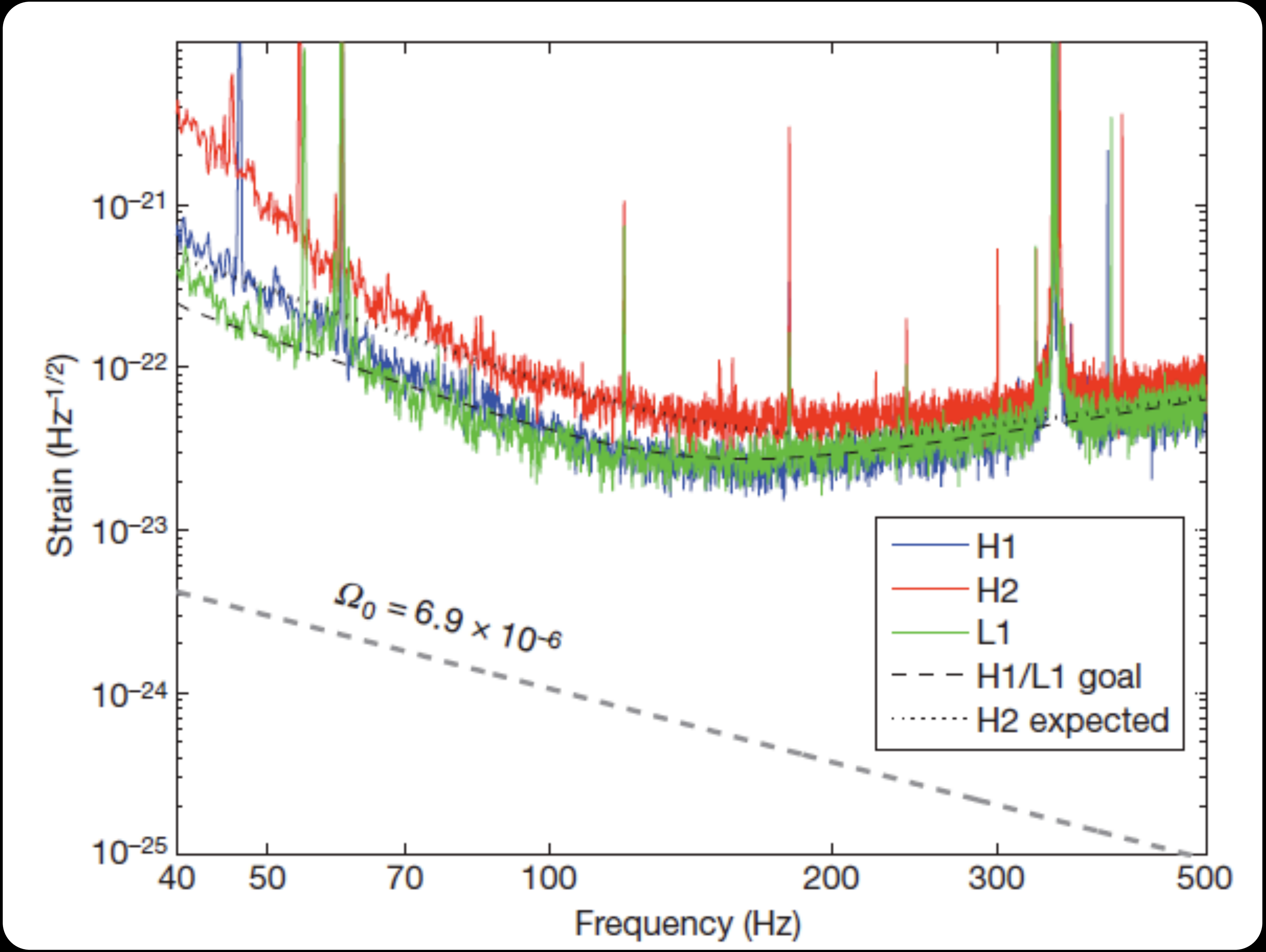
$$\gamma(f) \equiv \frac{5}{8\pi} \sum_{A=+,\times} \int_{S^2} d\hat{n}\, e^{i2\pi f \hat{n}\cdot\Delta\vec{x}/c}\, F_1^A(\hat{n}) F_2^A(\hat{n})$$

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

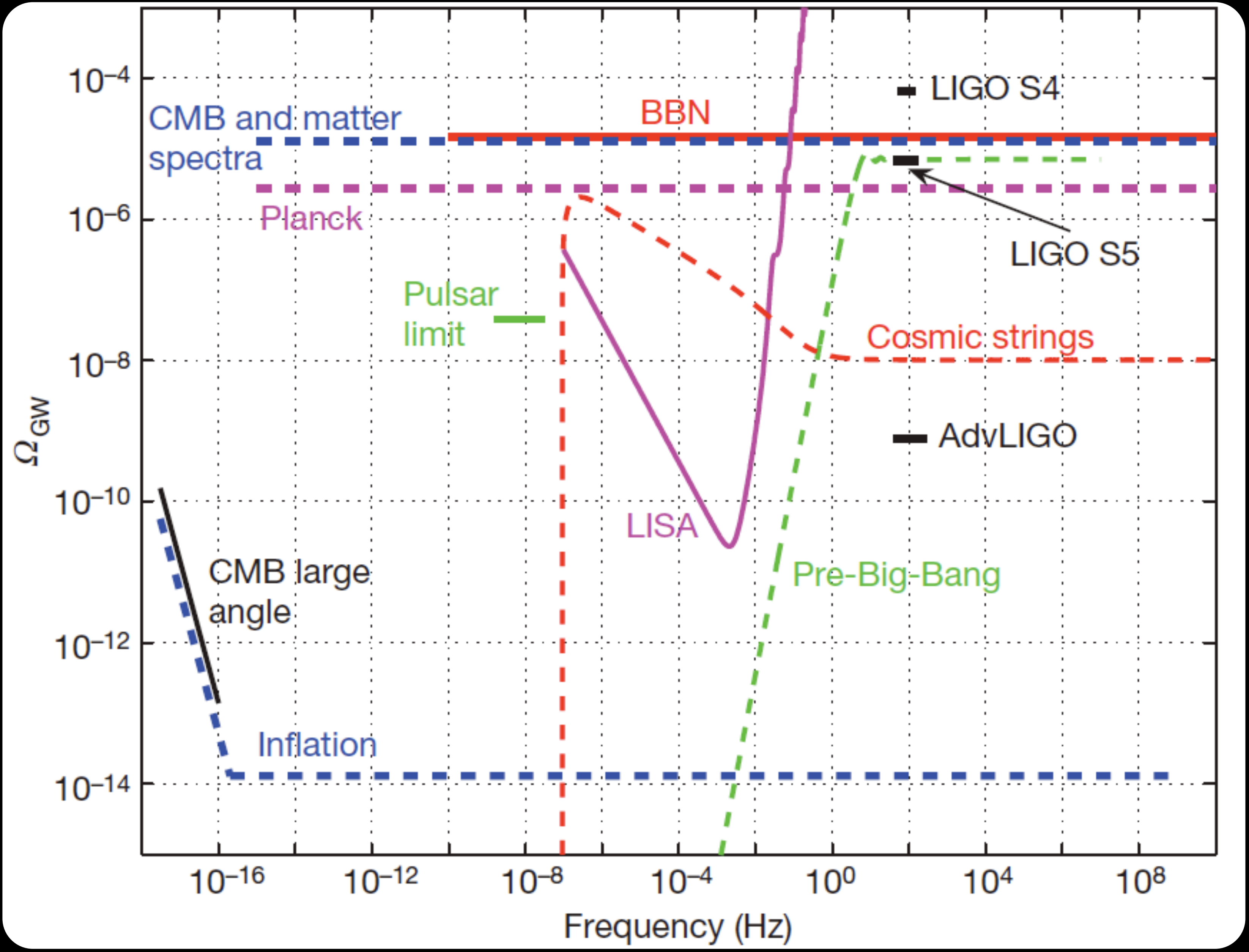




S5 LIGO sensitivity



LIGO upper-limit vs nucleosynthesis bound



Upper-limit

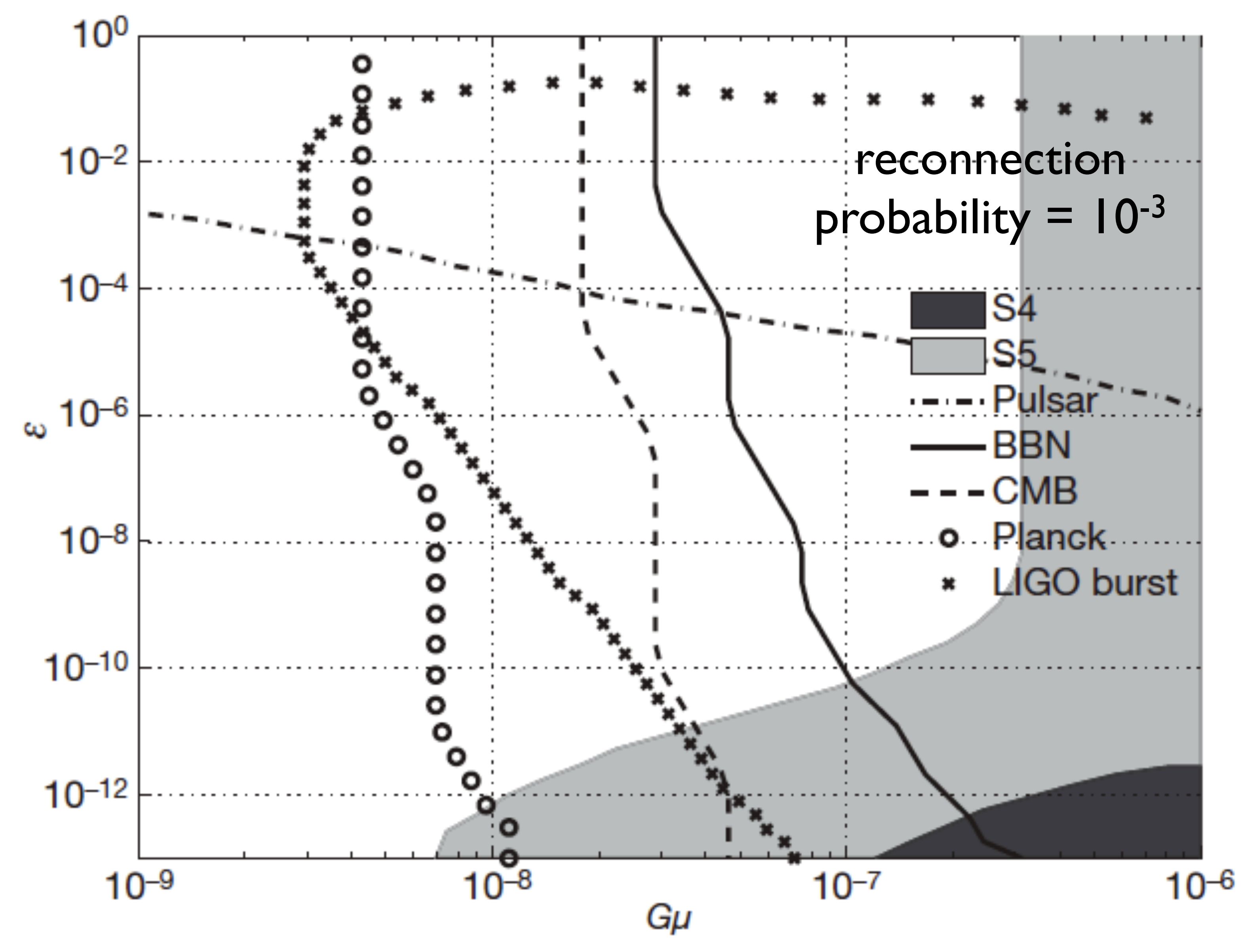
$$41.5\text{Hz} \leq f \leq 161.25\text{Hz}$$

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

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

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

Constraining string models

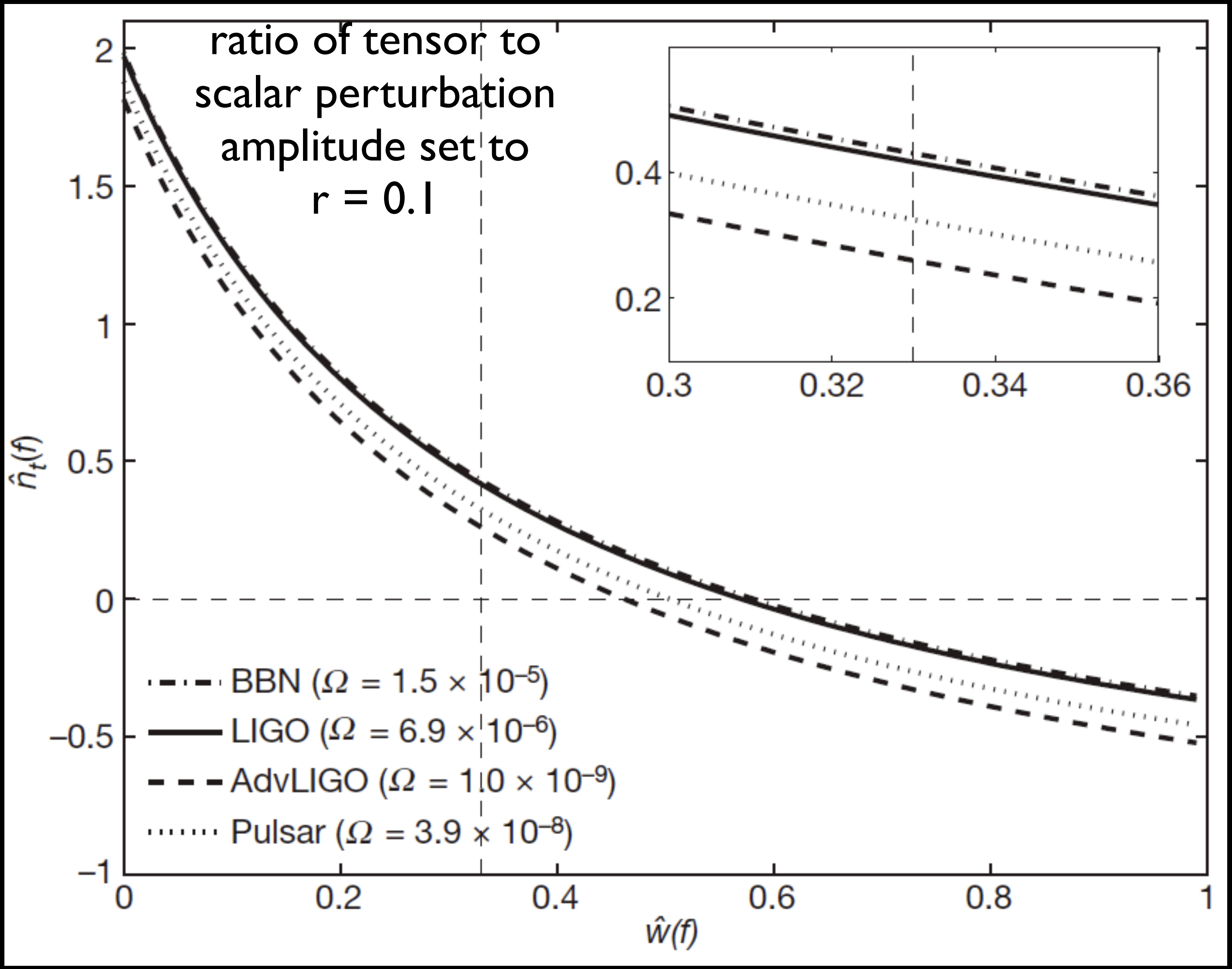


Abbott et al, Nature **460**, 990 (2009)

Constraining the early universe evolution

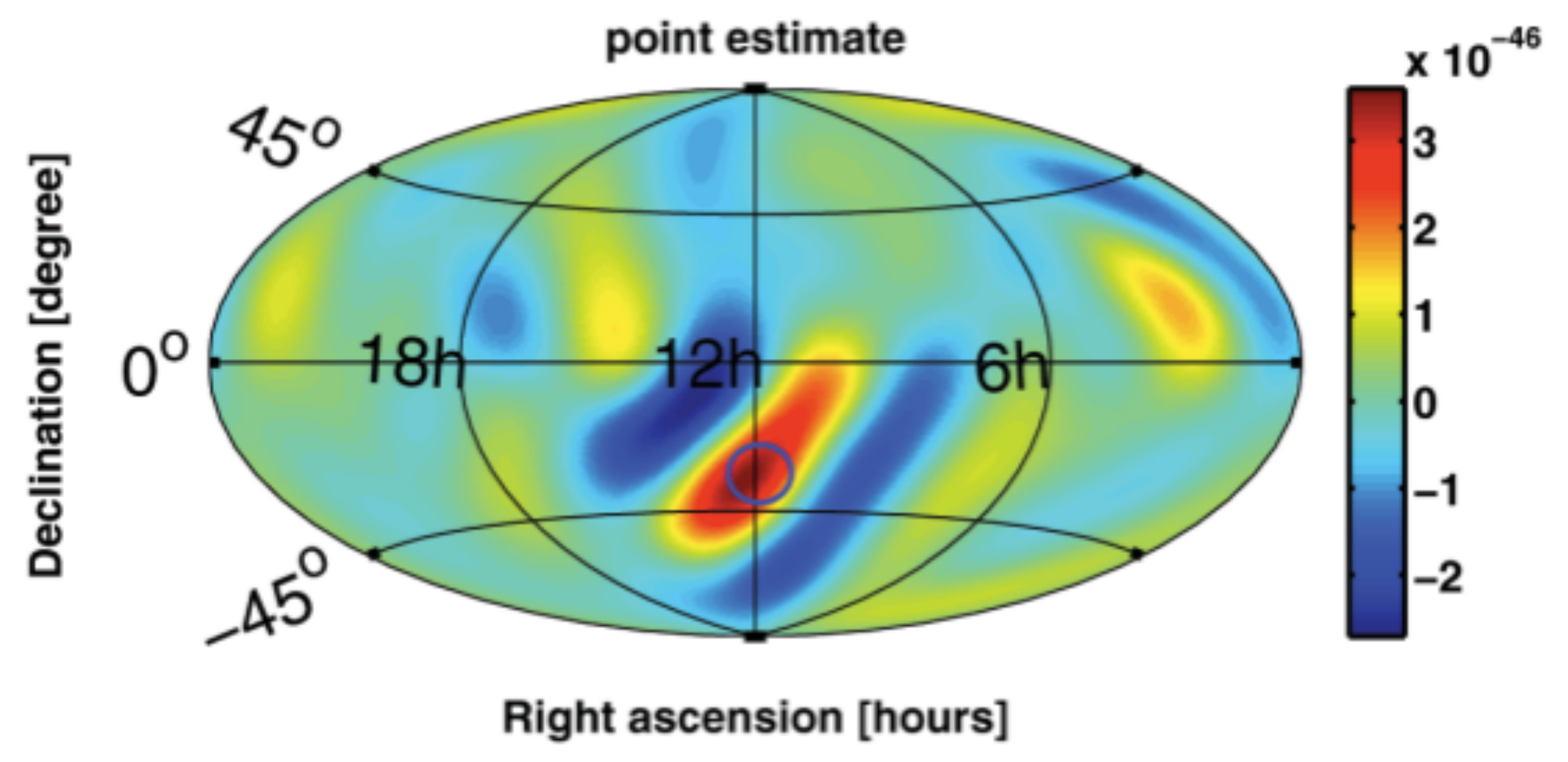
$$\Omega_{\rm GW}(f) = A f^{\hat{\alpha}(f)} f^{\hat{n}_t(f)} r$$

$$\hat{\alpha}(f) = 2\,\frac{3\hat{w}(f)-1}{3\hat{w}(f)+1}$$



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

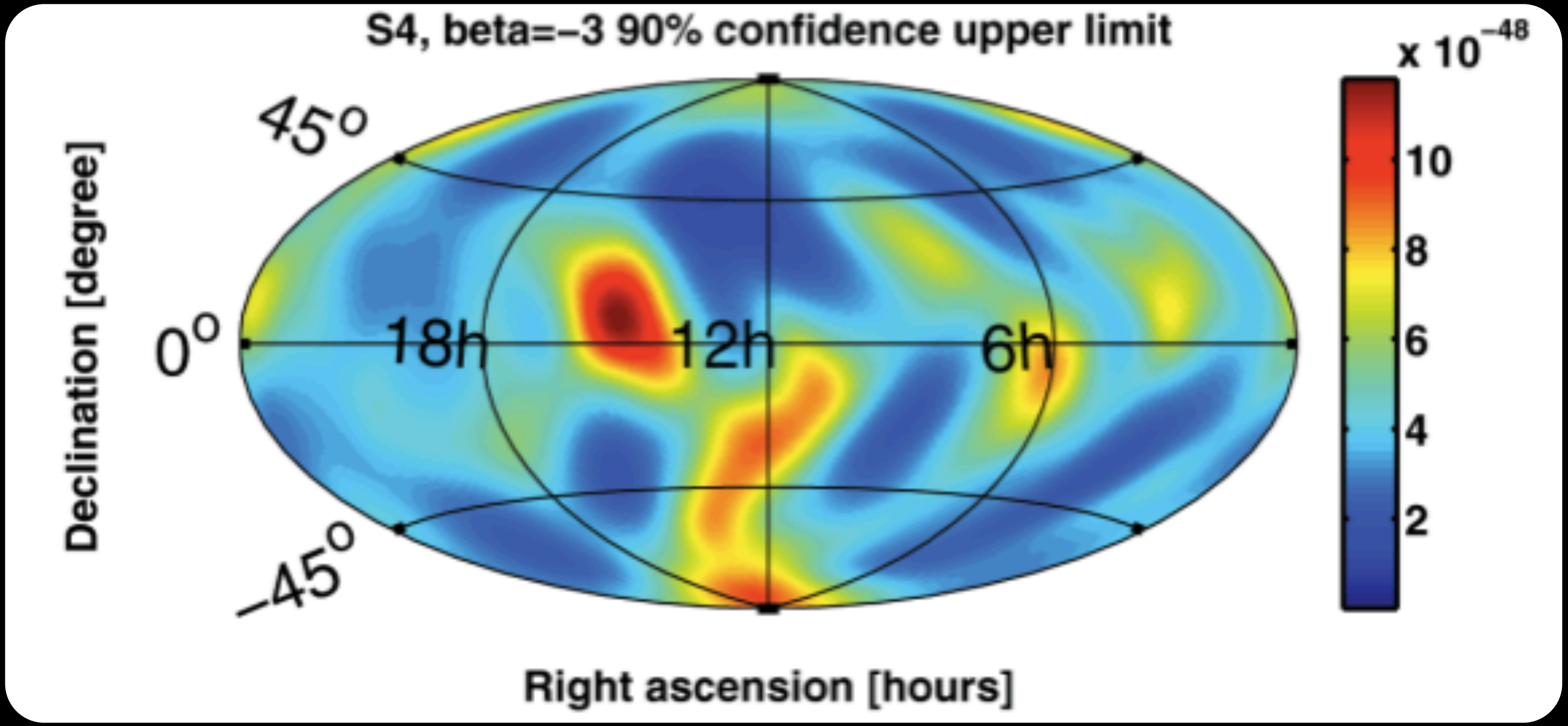
Beyond isotropy



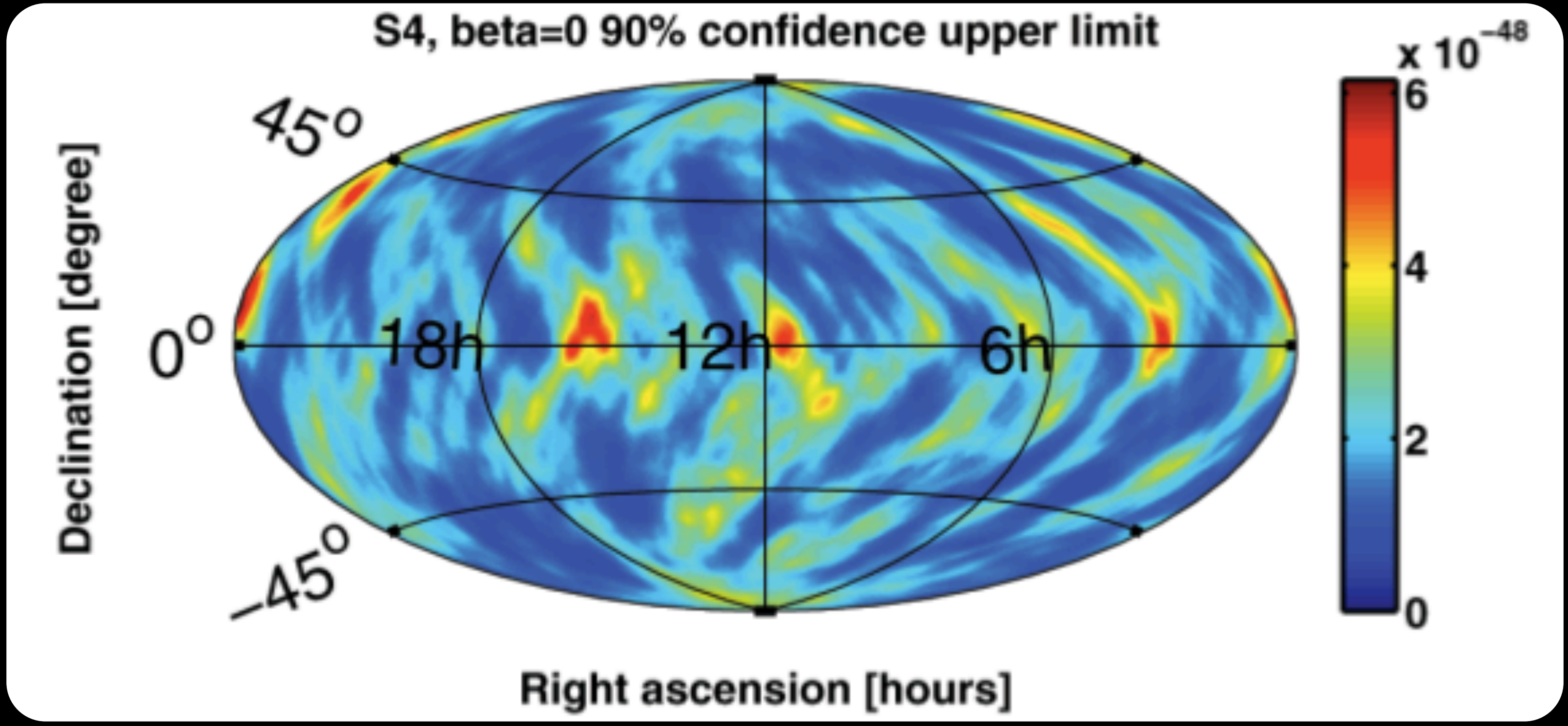
Abbott et al (LSC & Virgo Collaboration),
PRD **76**, 082003 (2007)

Anisotropy: (S4) upper-limit

$\Omega_{gw} = \text{const}$

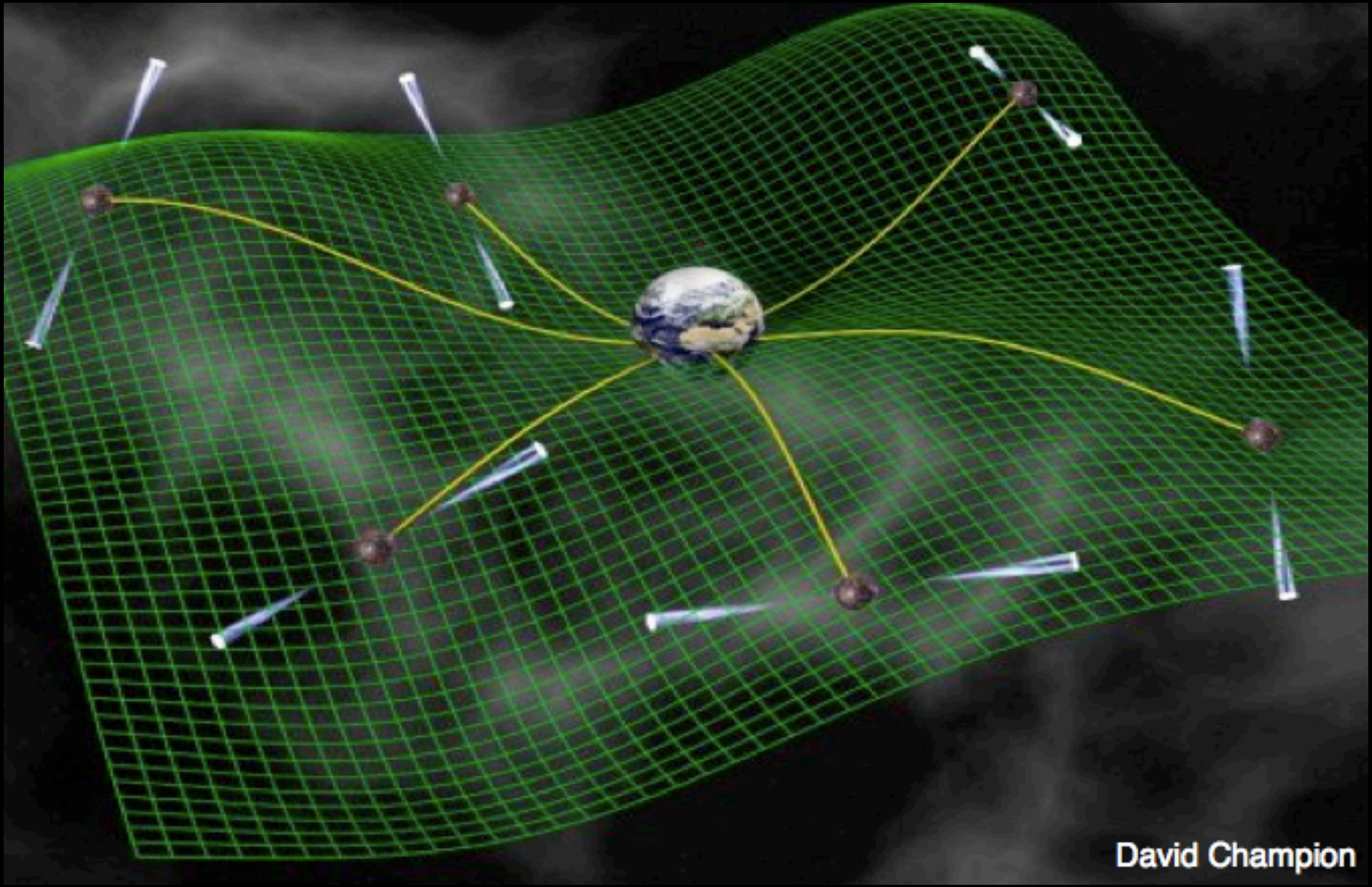


$\Omega_{gw}(f) \propto f^3$

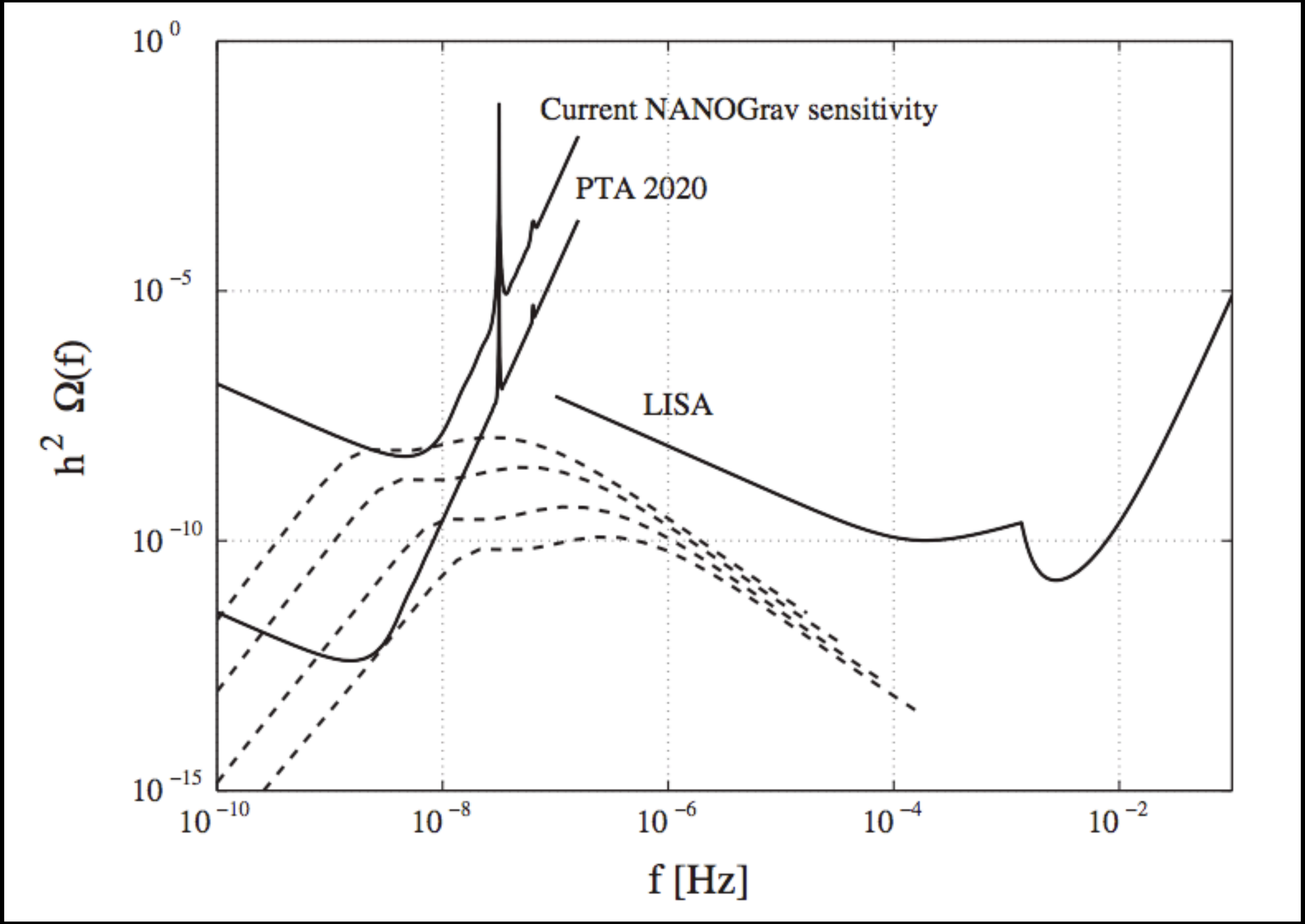


Abbott et al (LSC & Virgo Collaboration), PRD **76**, 082003 (2007)

Pulsar Timing Arrays

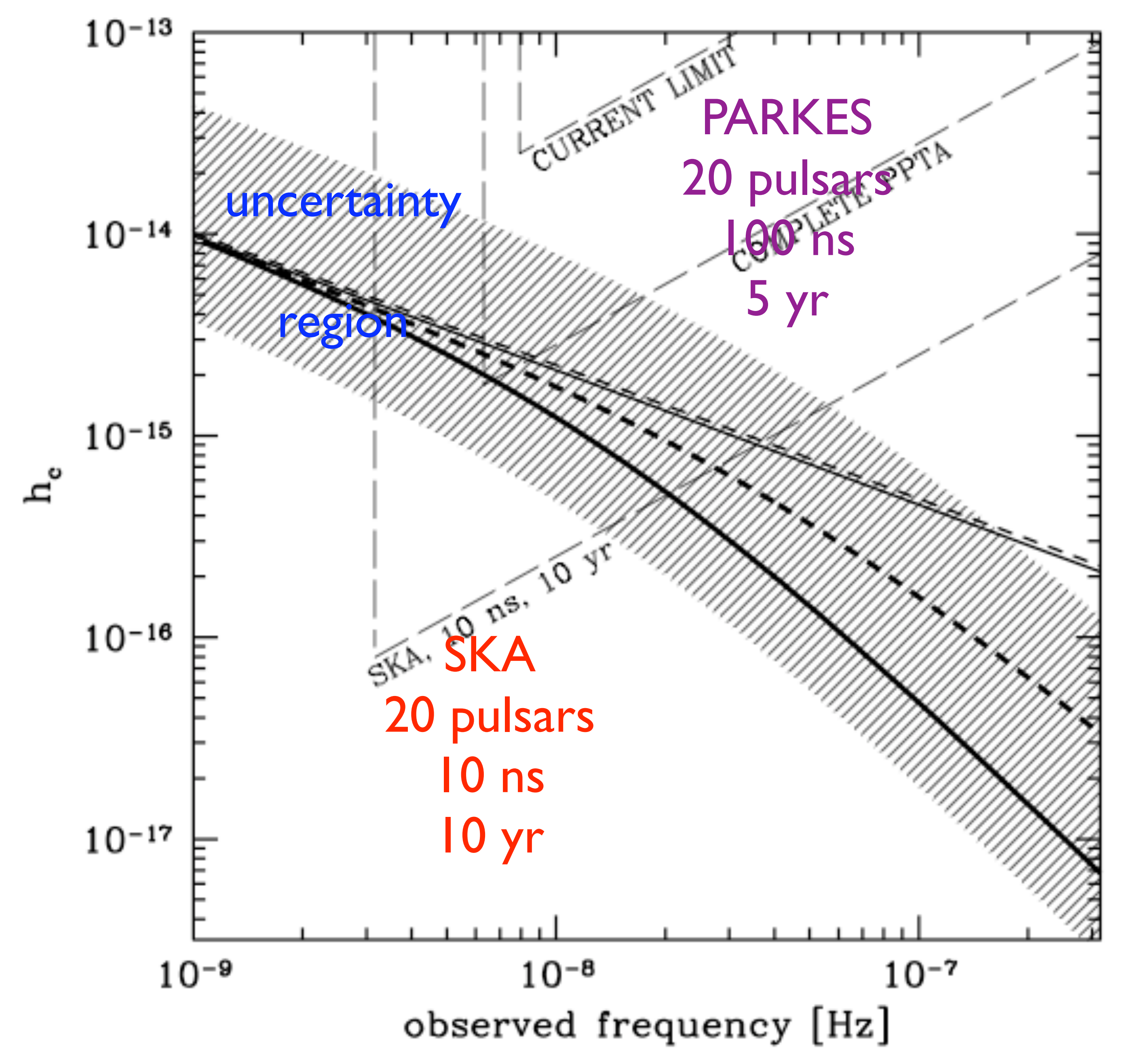

David Champion

Example: background from QCD phase transitions



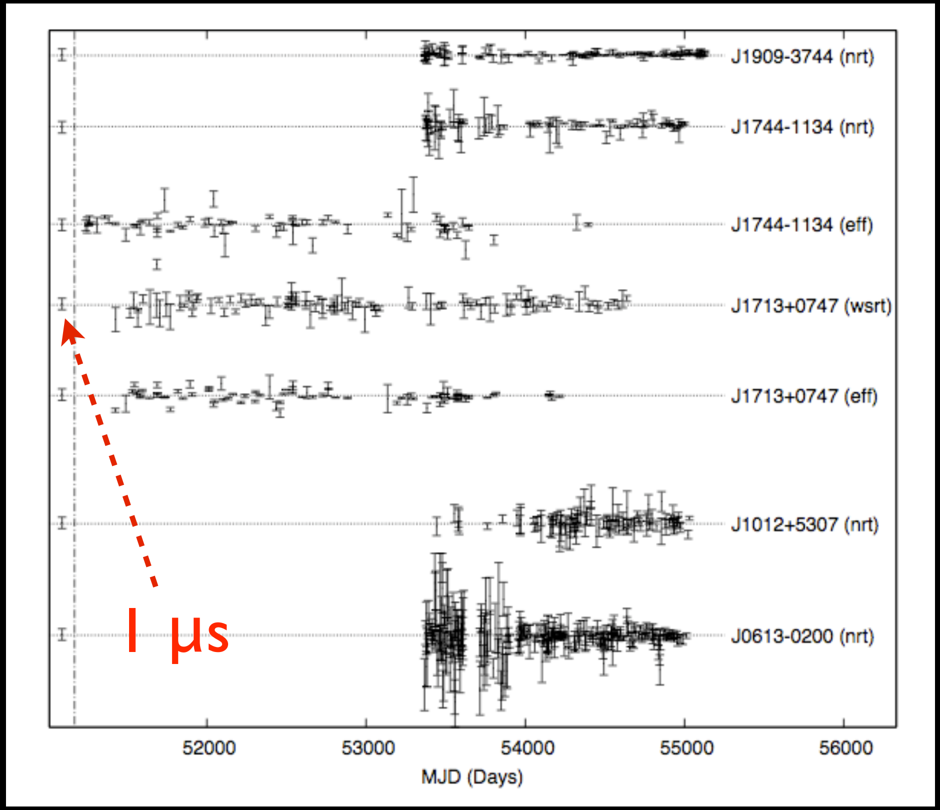
Carpini, Durrer and Siemens (2010)

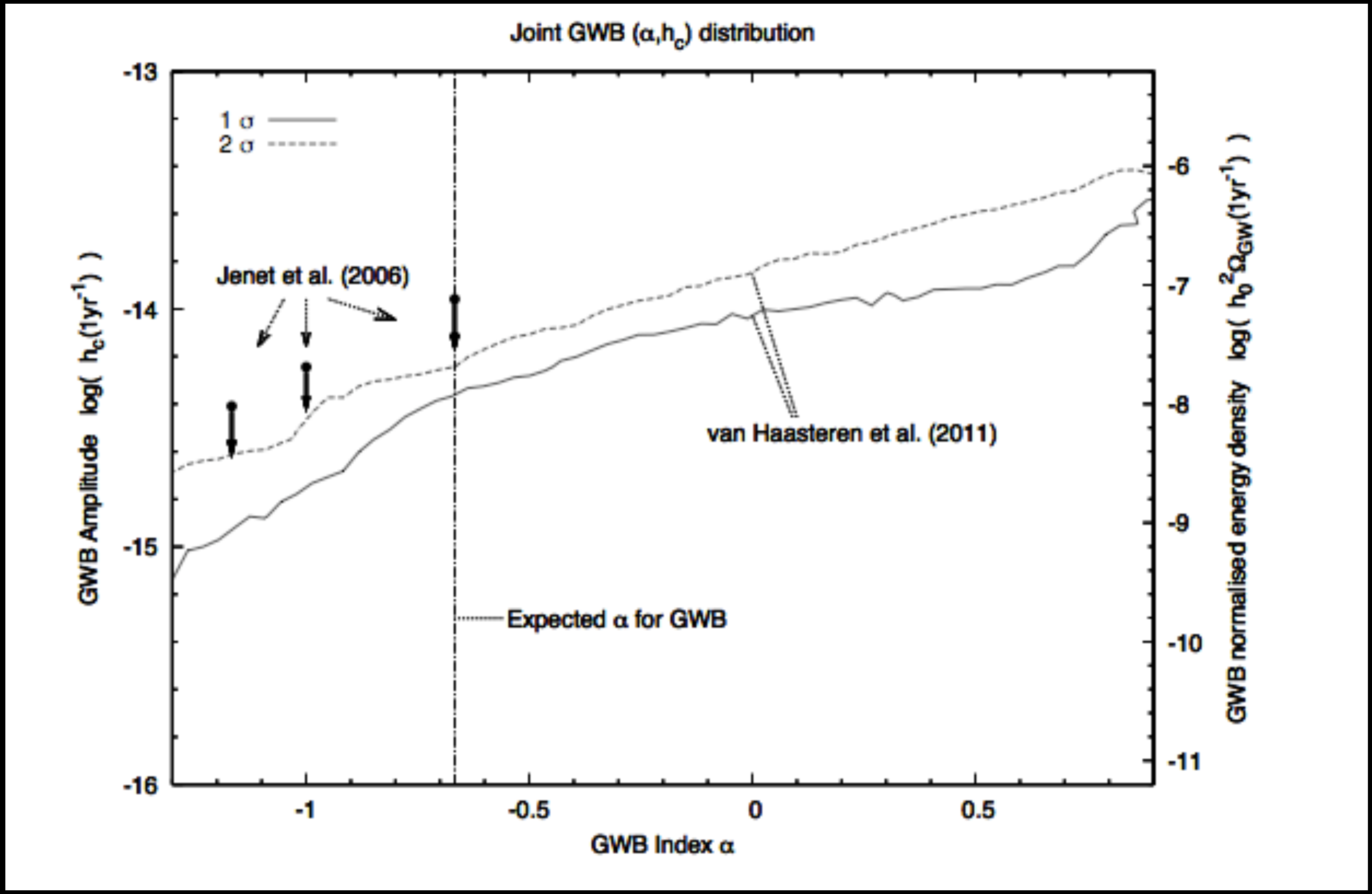
Foreground from SMBH binaries



Sesana, AV and Colacino (2008)

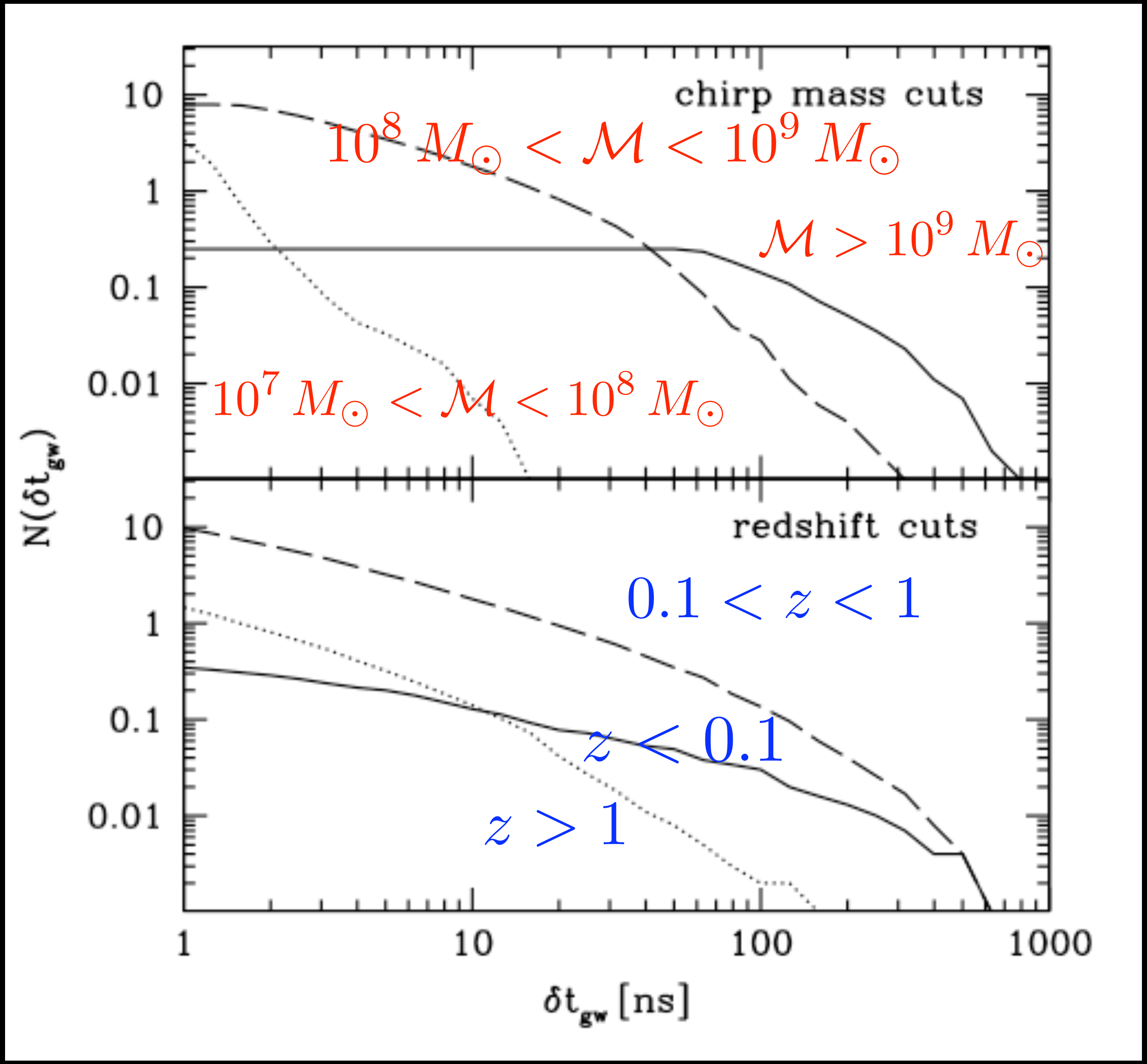
New upper-limit from EPTA





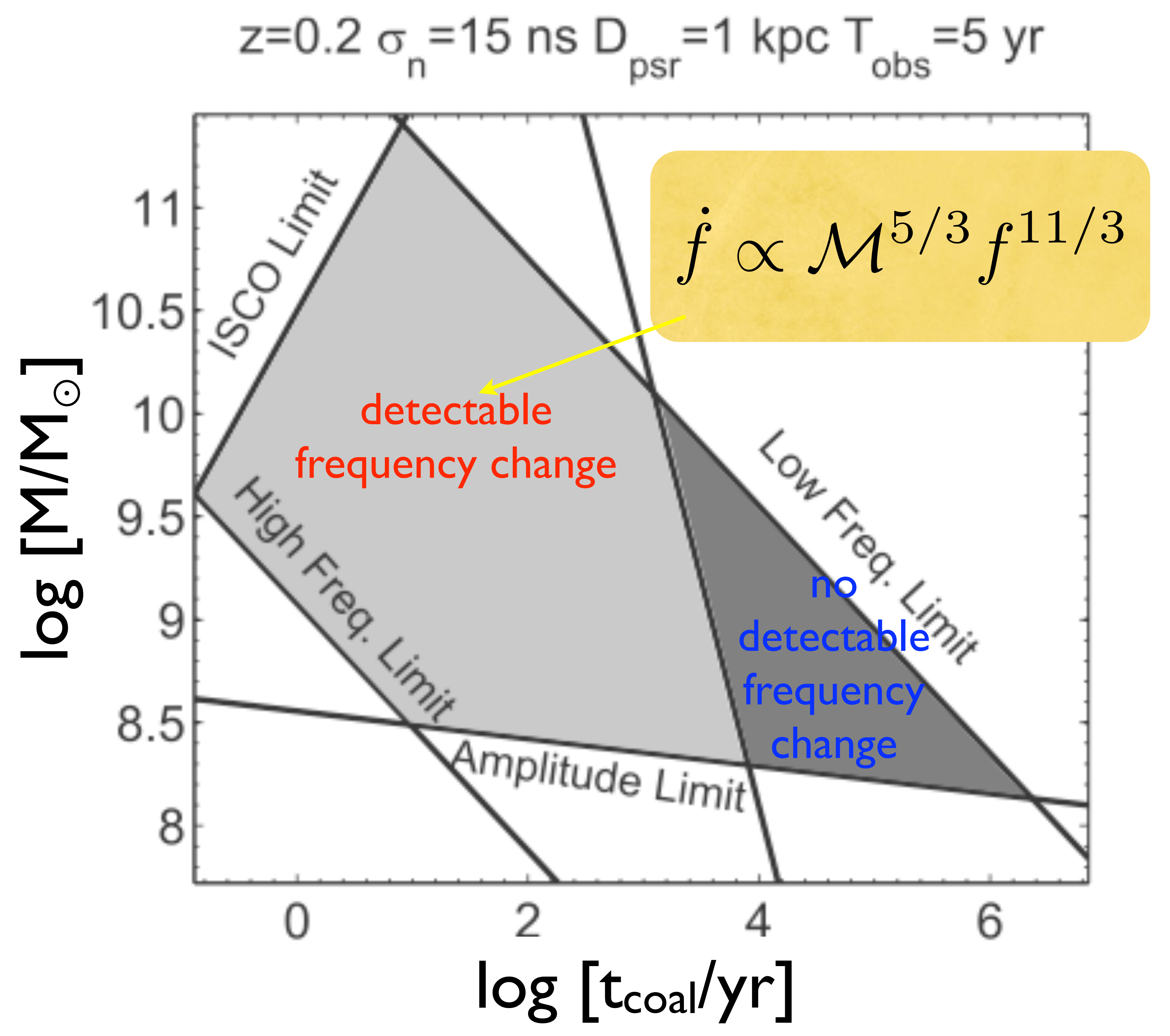
van Haasteren et al (EPTA), 2010 submitted

Resolving SMBH binaries



Sesana, AV and Volonteri (2009)

Parameter space



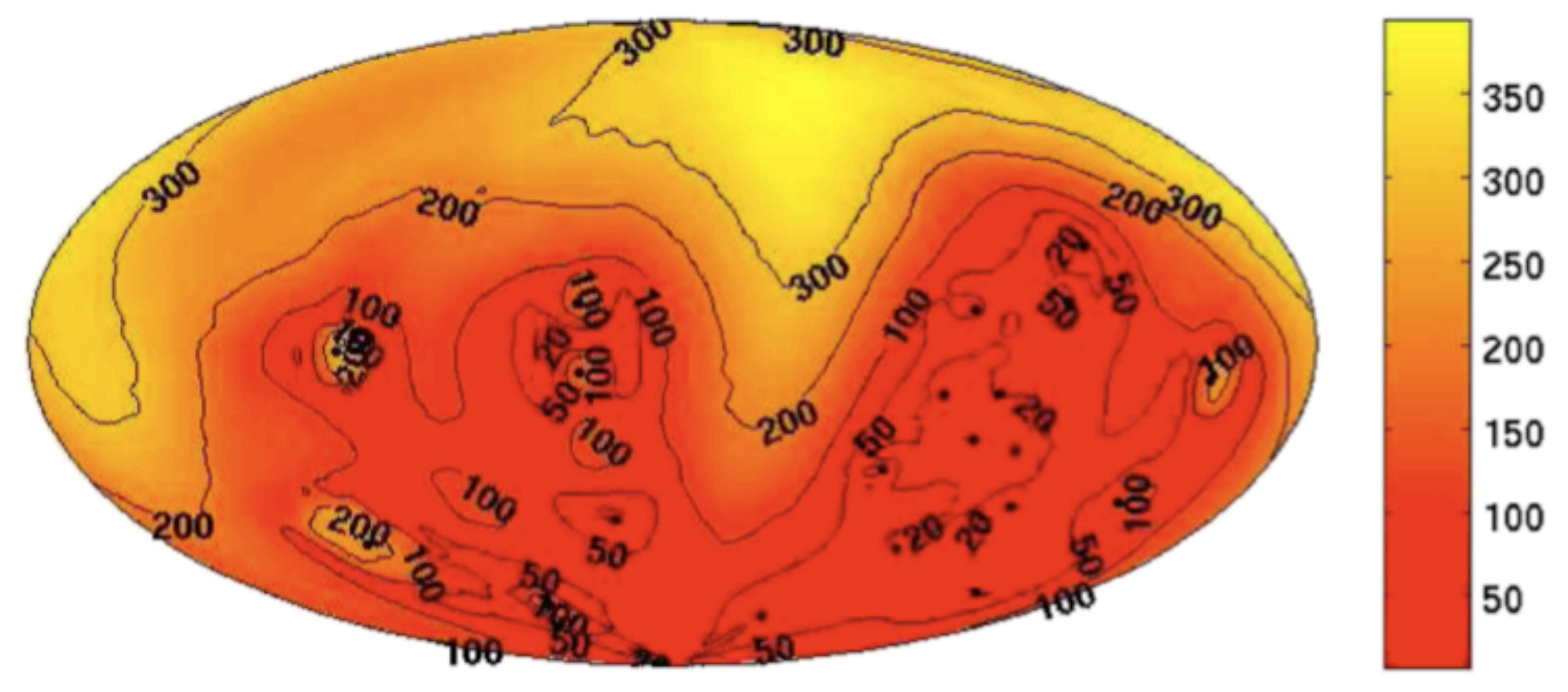
$$\dot{f} \propto \mathcal{M}^{5/3} f^{11/3}$$

detectable frequency change

no detectable frequency change

Lee et al, arXiv:1103.0115

PTA sky resolution

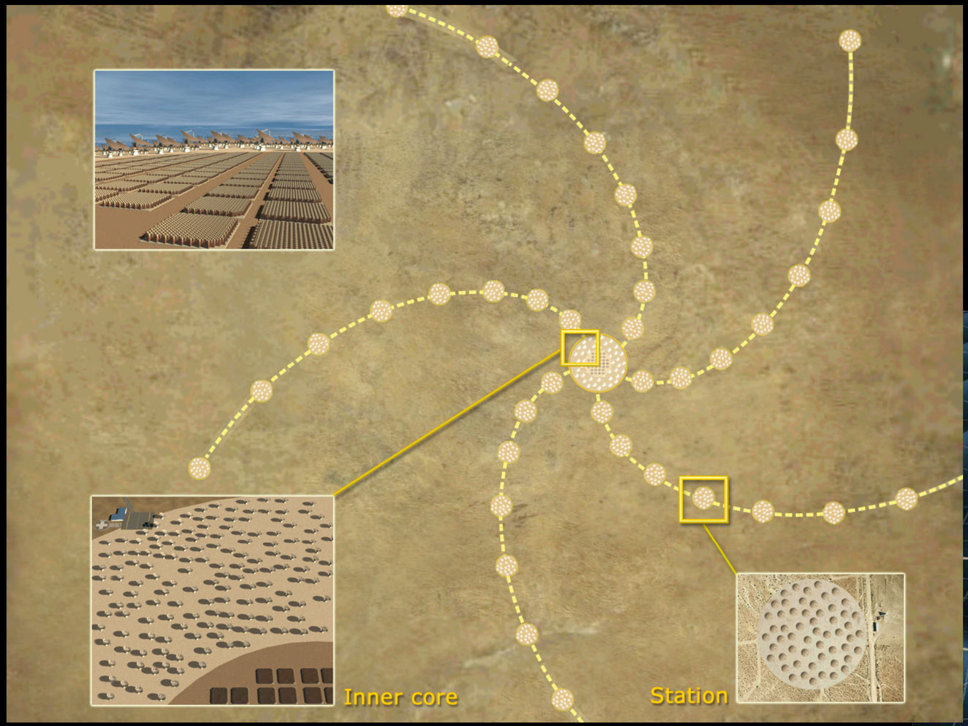


Distance error measurements:
$\Delta D_L/D_L \sim 1/\mathrm{SNR}$

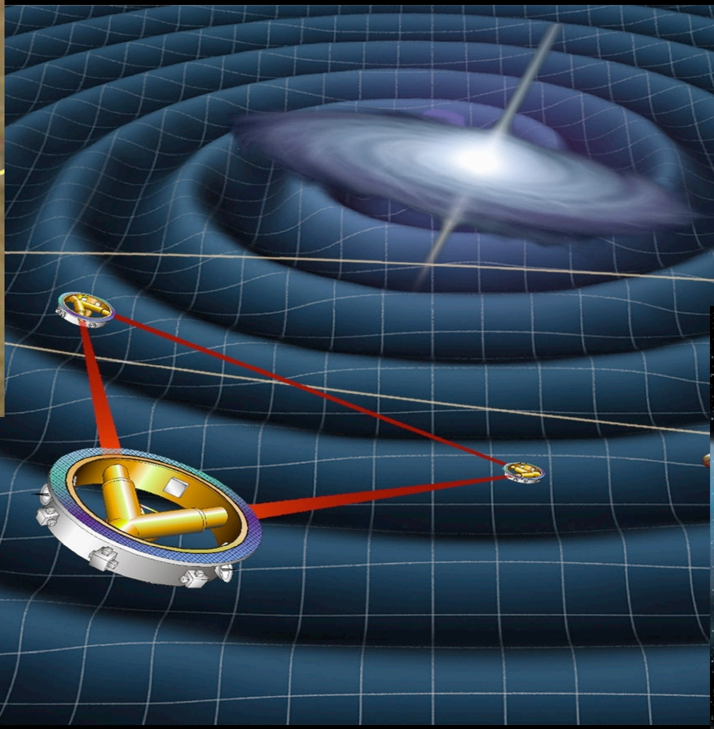
Sesana and AV, 2010;
see also Corbin & Cornish arXiv:1008.1782;
Lee et al, arXiv:1103.0115

Long(er) term future

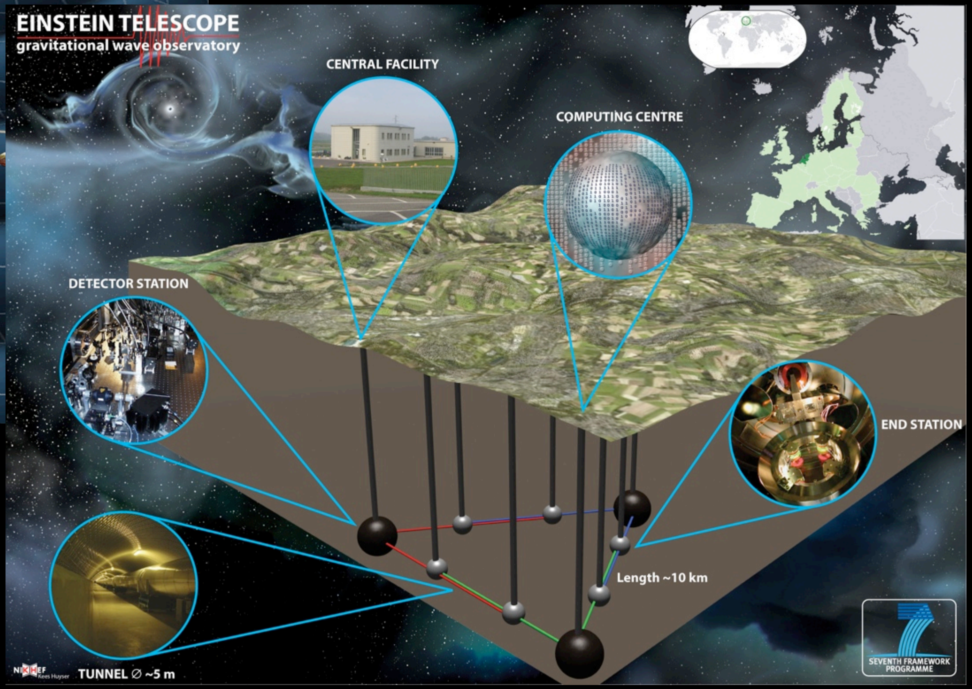
Square Kilometre Array (SKA)



Space based laser interferometer



Einstein gravitational-wave Telescope (ET)



Conclusions

- It is highly likely (though not totally guaranteed) that in the next 5-to-10 years gravitational waves will be directly observed (by LIGO/Virgo/GEO/etc. and/or PTAs)

- Gravitational wave observations will provide an entirely new arena to test ideas in cosmology (and astrophysics, fundamental physics, ...)

- (In my opinion) gravitational wave cosmology won't happen any time soon, but when it does it may well provide one of biggest payoffs of gravitational-wave science