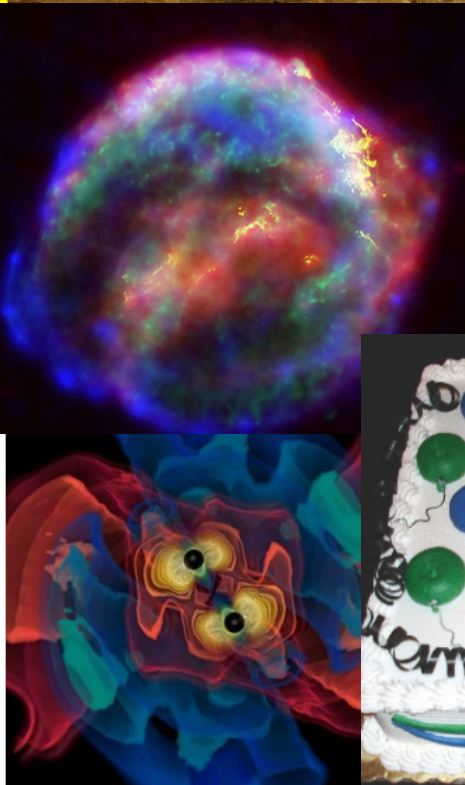


LIGO

LIGO: Gravitational Wave Observatory

O





Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong Fundamental	Strong Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m 3×10^{-17} m for two protons in nucleus	10^{-41} 10^{-41} 10^{-36}	0.8 10^{-4} 10^{-7}	1 1 1	25 60 Not applicable to hadrons	Not applicable to quarks 20

Gravity is “different”:

- by far the weakest
- is manifest in the structure of spacetime itself (according to GR)
- there is no quantum theory of gravity (yet)

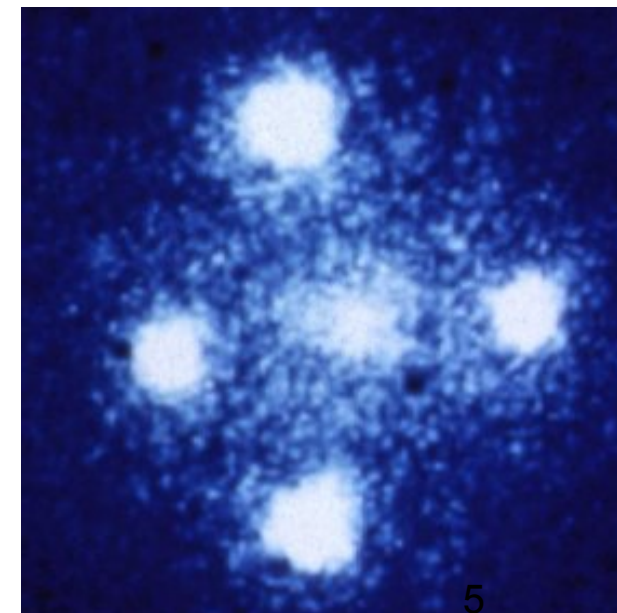
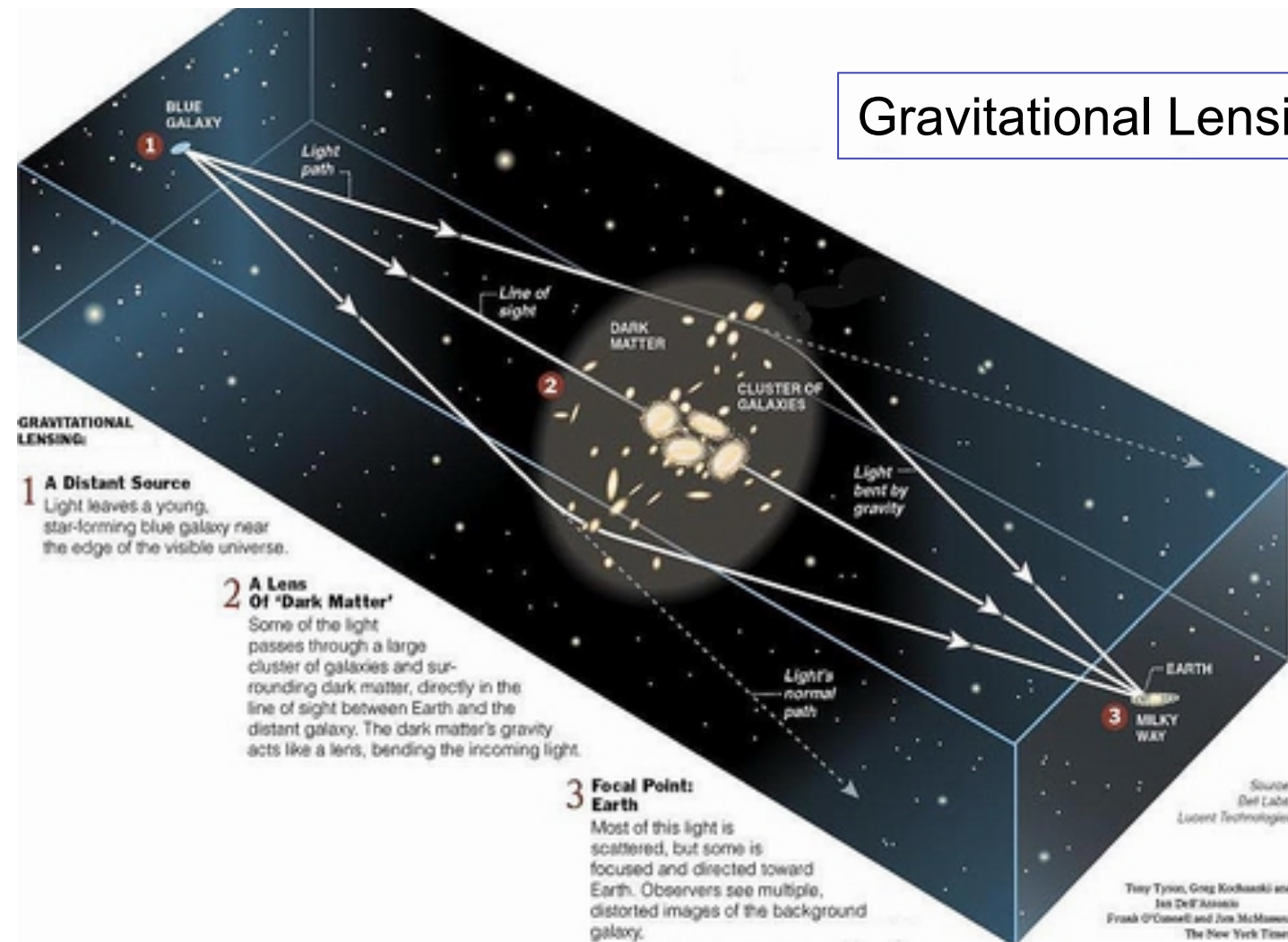
- Gravity as a “fictitious force” ($F \propto m$)
 - Gravity can be “removed” in a special ref. frame -- free fall
- Einstein took this as a clue that gravity is really caused by the structure of spacetime
- Postulates of General Relativity (Einstein *ca.* 1915):
 - Equivalence of inertial and gravitational mass
 - There is no physics experiment which can distinguish between a gravitational field and an accelerating reference frame
 - An elevator at rest in earth’s gravity ($g=9.8 \text{ m/s}^2$)
 - An elevator accelerating upward with $a= 9.8 \text{ m/s}^2$
- What this means
 - extends special relativity to non-zero acceleration
 - Gravity re-described as curvature of spacetime

General Relativity (contd)

Some predictions:

- Gravity influences both mass and energy
 - e.g. bending of light in regions with gravitational field
 - 1919 Eddington; Gravitational lensing: Einstein Cross
- Many small deviations from Newtonian gravity in “weak” fields
 - Gravitational “redshift” (e.g. clocks on satellites are faster)
 - Perihelion advance of mercury
 - Global Positioning System would not work without GR corrections
- Strong field effects
 - Black holes; $R_s = 2GM/c^2$
- Spacetime structure of universe – the cosmological expansion
- And gravitational radiation (gravitational waves)

Gravitational Lensing



In special relativity:

$$ds^2 = (c dt)^2 - (dx^2 + dy^2 + dz^2) = \sum \eta_{\mu\nu} dx_\mu dx_\nu$$

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

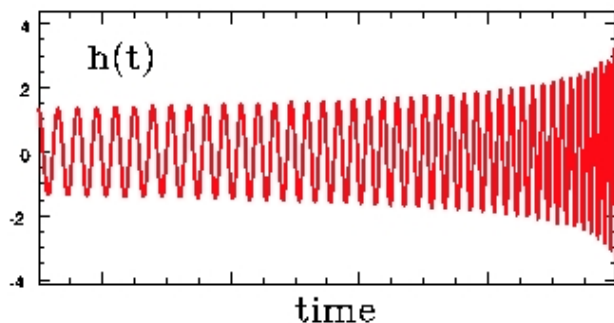
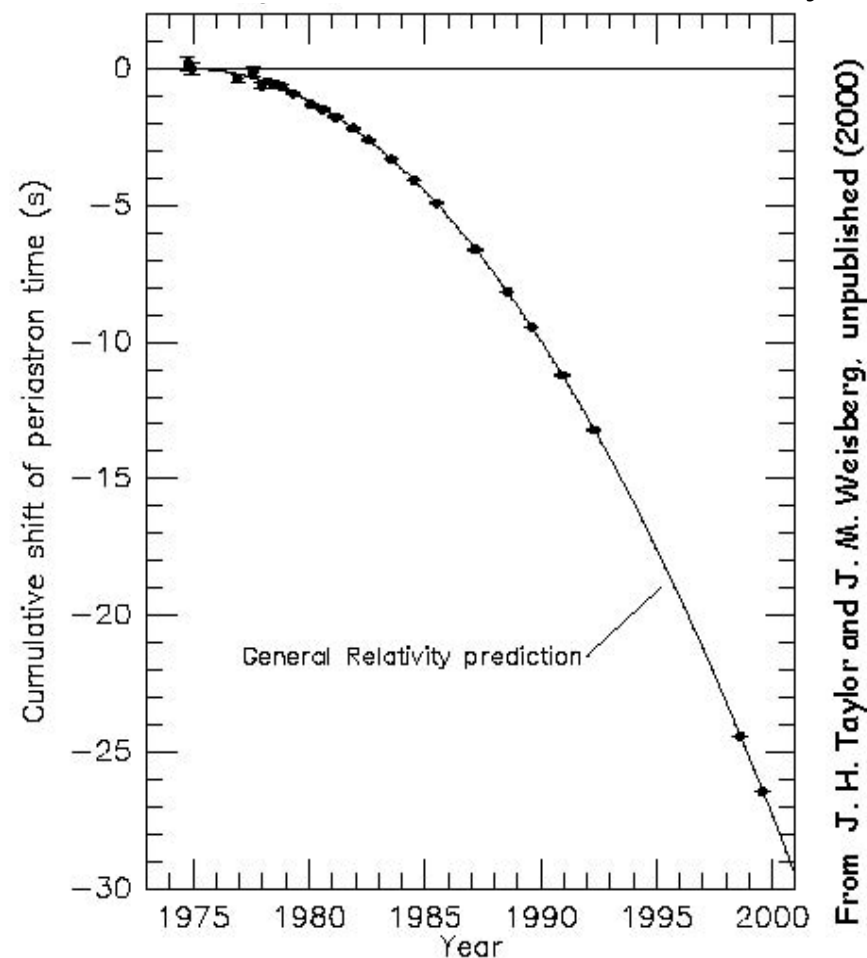
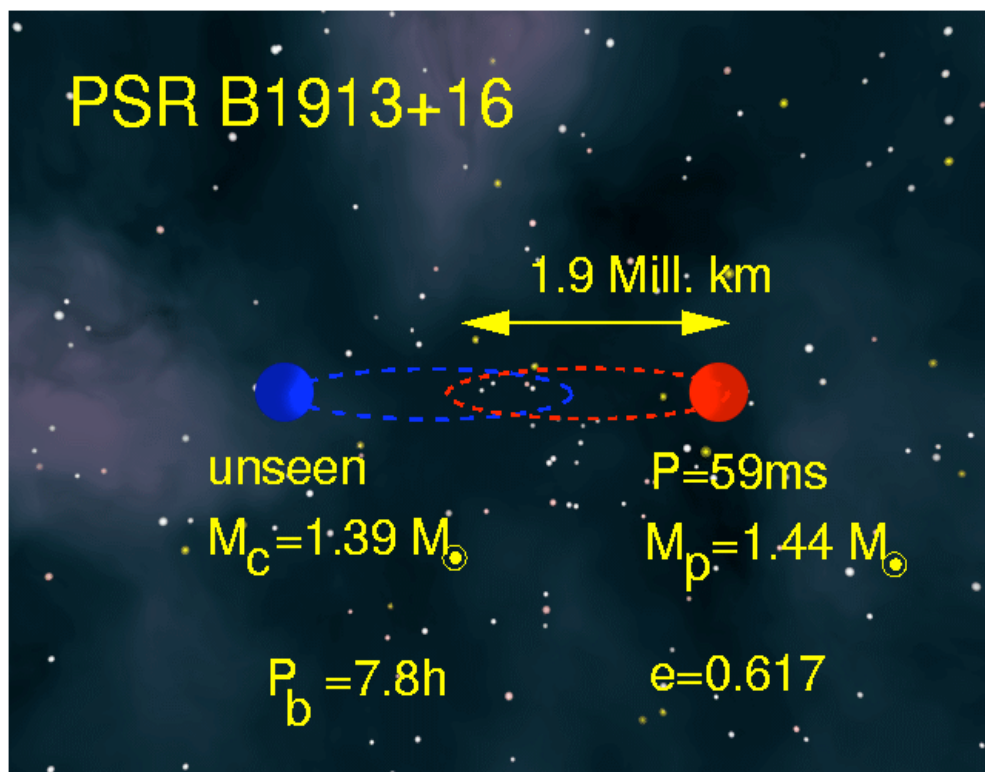
GR:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \quad (+\Lambda\eta_{\mu\nu})$$

$$\eta_{\mu\nu} \rightarrow g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = -16\pi T_{\mu\nu}$$

Taylor and Hulse: Pulsar observed for 25 years:



← 300 million years from
now

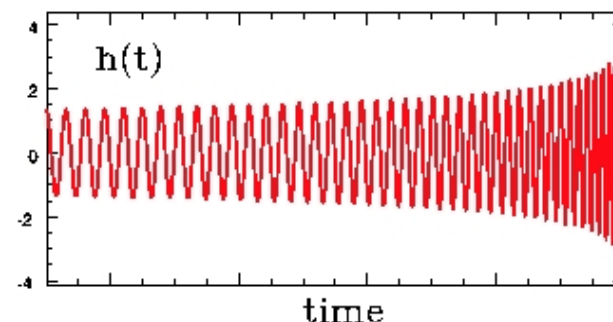
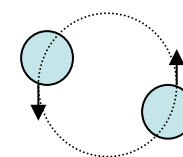
- GW emission requires time varying quadrupole moment of mass distribution, $\ddot{I}_{\mu\nu}$
→ gravitational-wave strain, $h = \delta L / L$, is the analog of the radiation field E in E&M
- Strain estimate:

$$h \sim \left(\frac{GM}{c^2} \right) \left(\frac{v^2}{c^2} \right) \frac{1}{r}$$

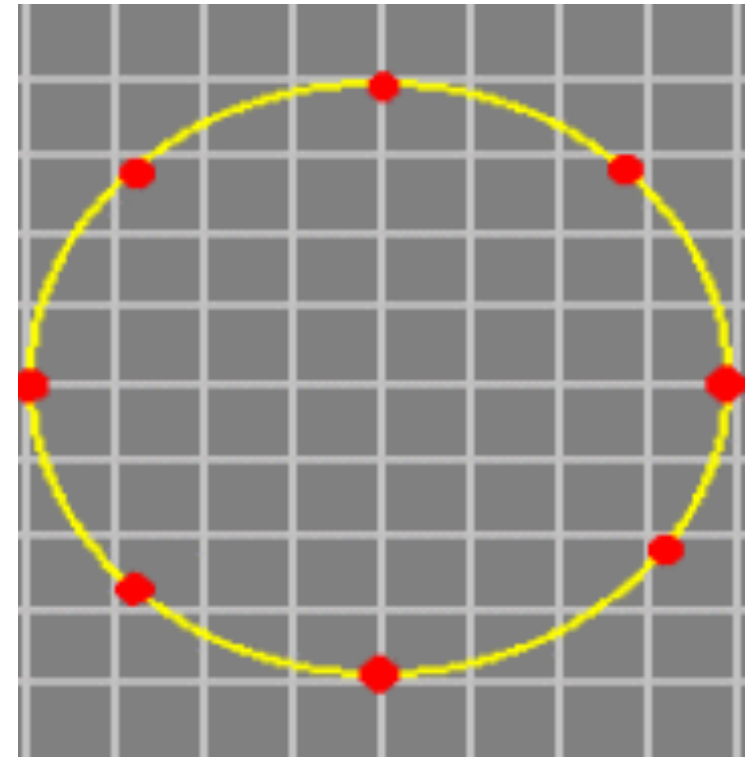
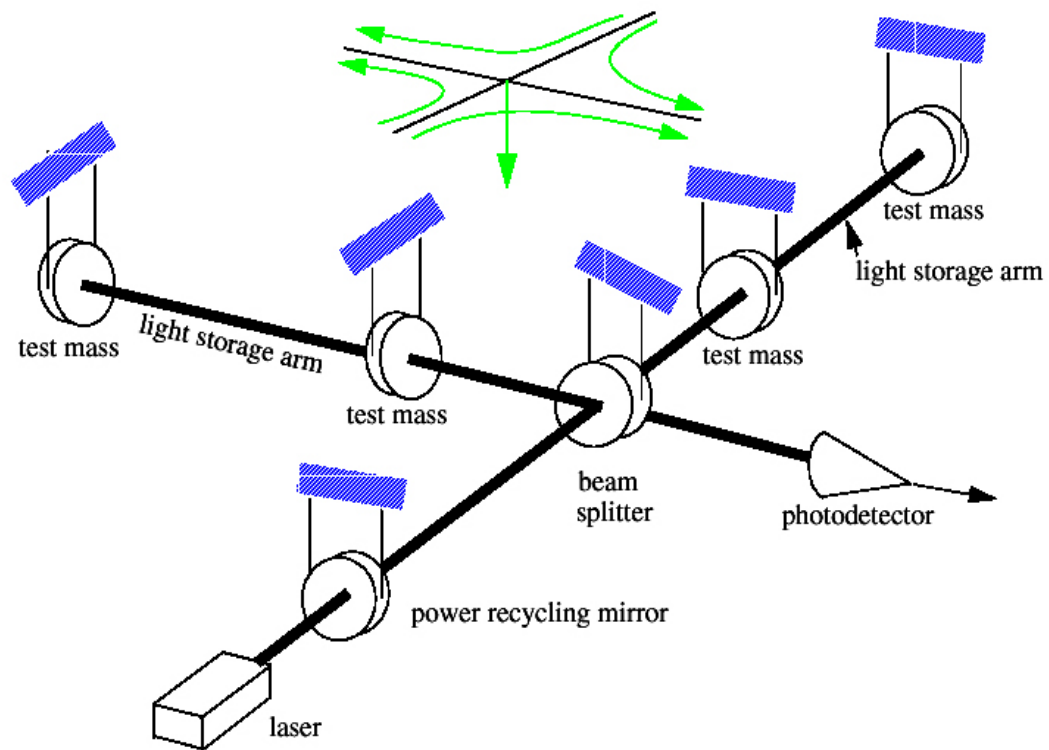
For $1M_{\odot} \Rightarrow R_s = 2GM_{\odot}/c^2 = 3 \text{ km}$

If $v \approx c$, then at $r = 15 \text{ Mpc}$:

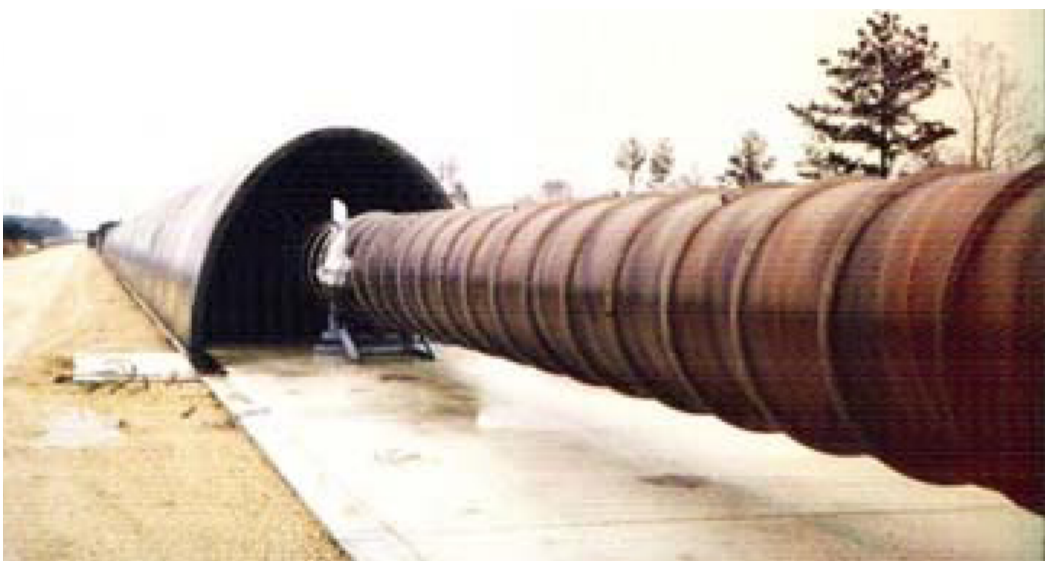
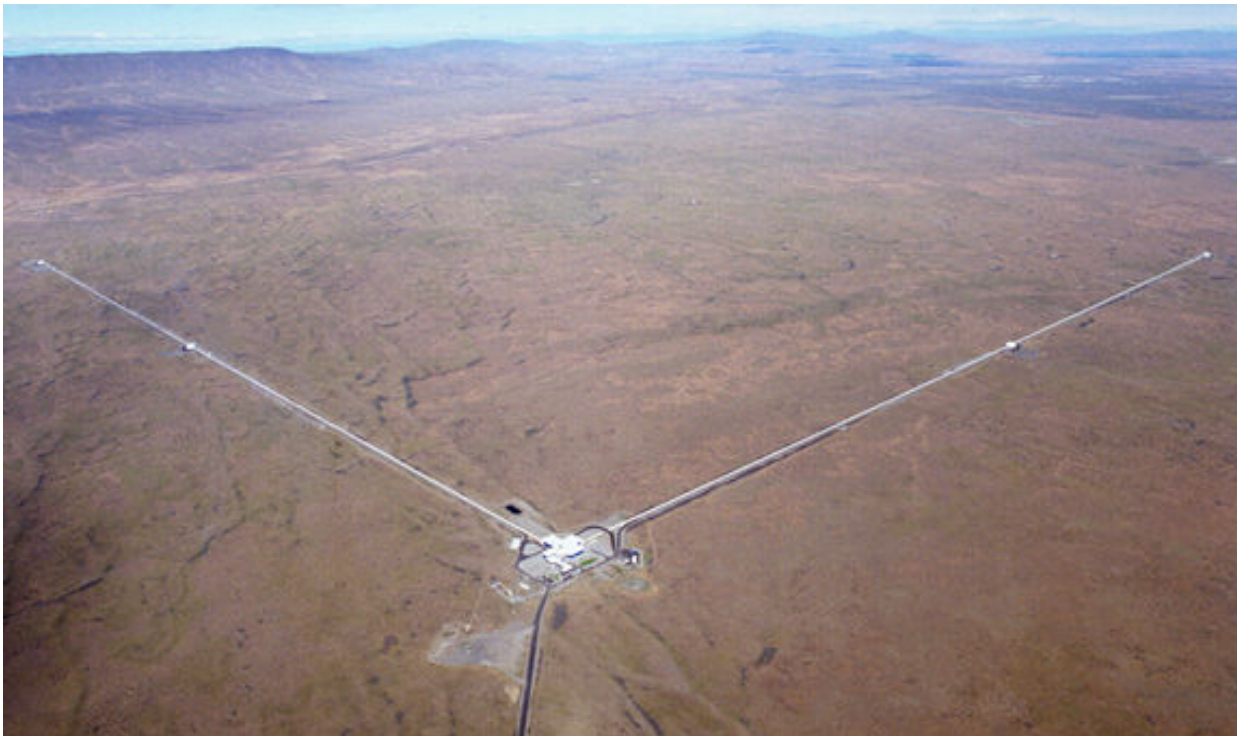
$$h \sim 3 \times 10^{-21}$$



GW Interferometer Principle

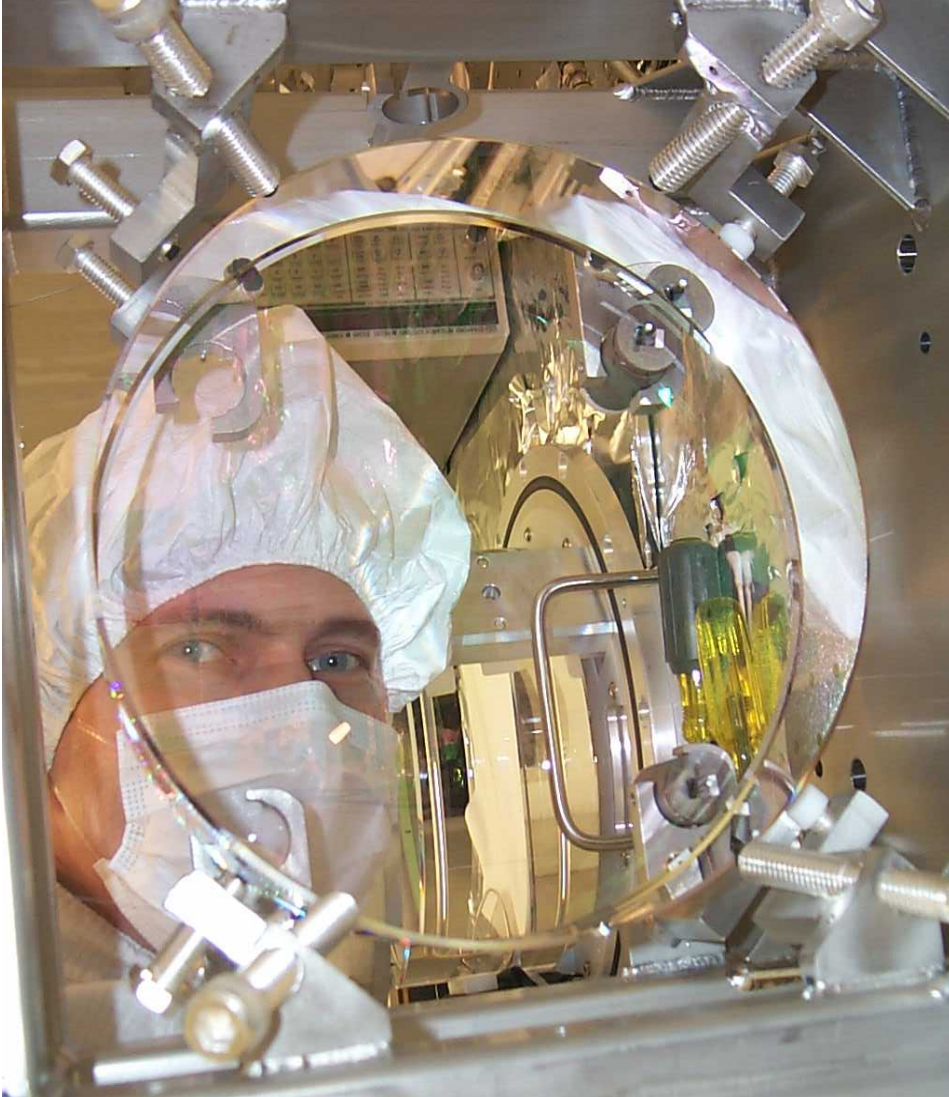


$$\text{GW strain: } h = \delta L / L$$



- 1.2 m diameter beam pipe
- aligned to a mm
- Total of 16km -- no leaks
- 1 nTorr (!)
- few, remote pumps





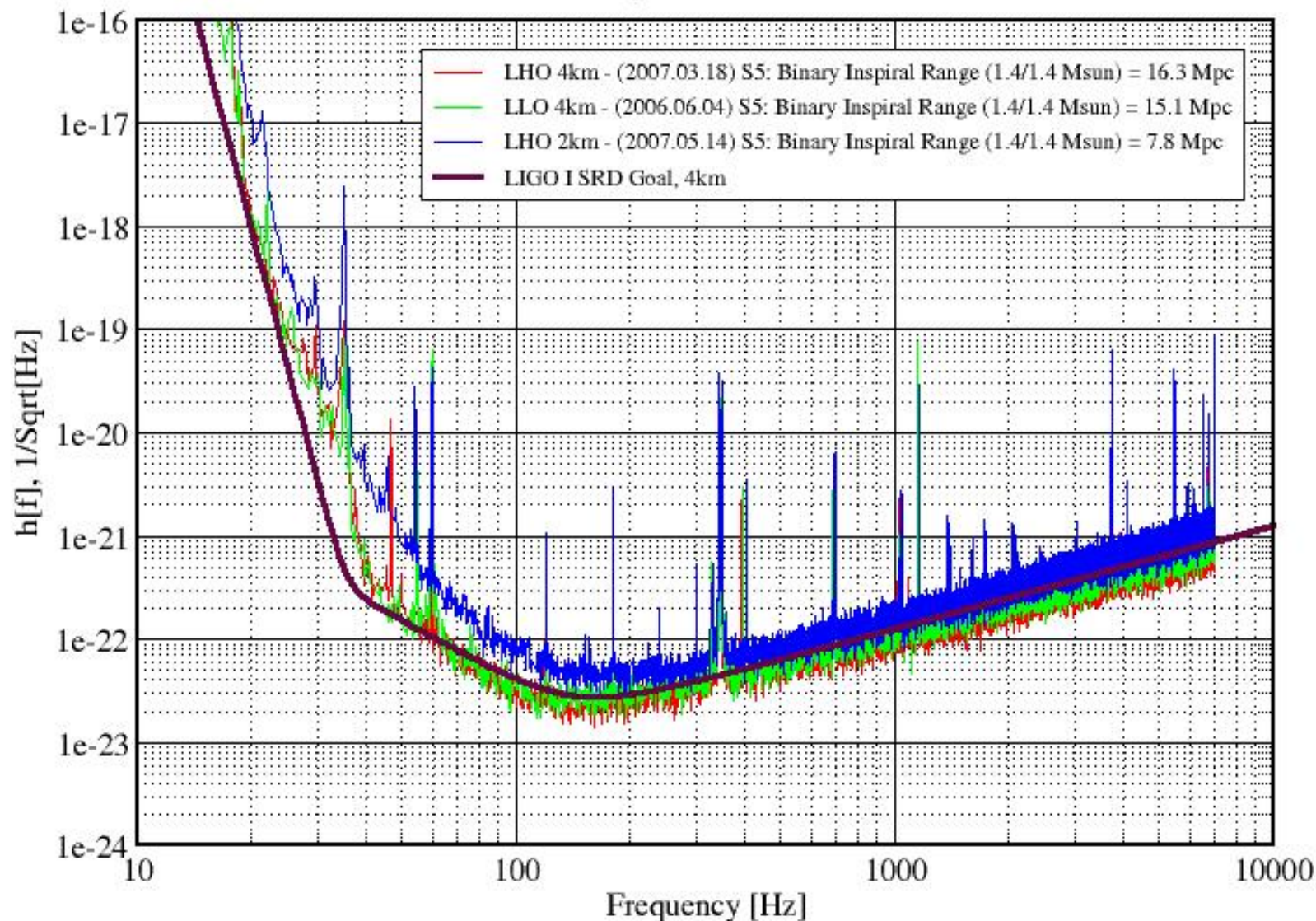
Fused Silica, 10 kg, 25 cm diameter
and 10 cm thick
Polished to $\lambda/1000$ (1 nm)



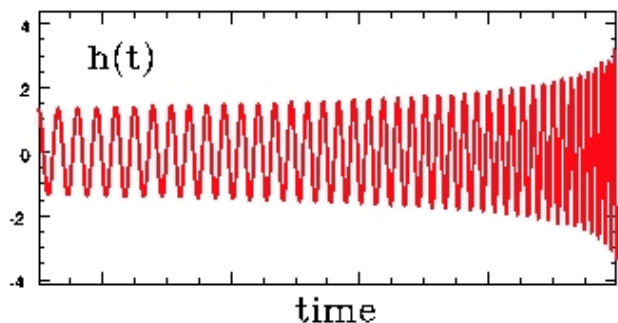
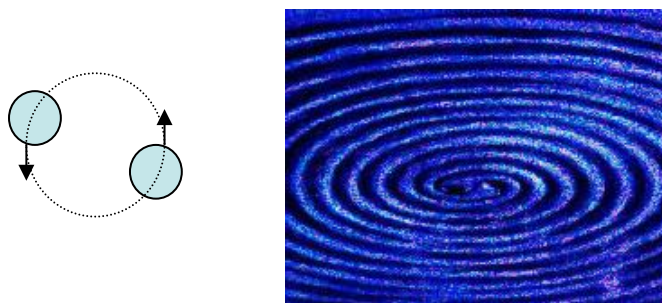
Strain Sensitivity of the LIGO Interferometers

S5 Performance - May 2007

LIGO-G070366-00-E



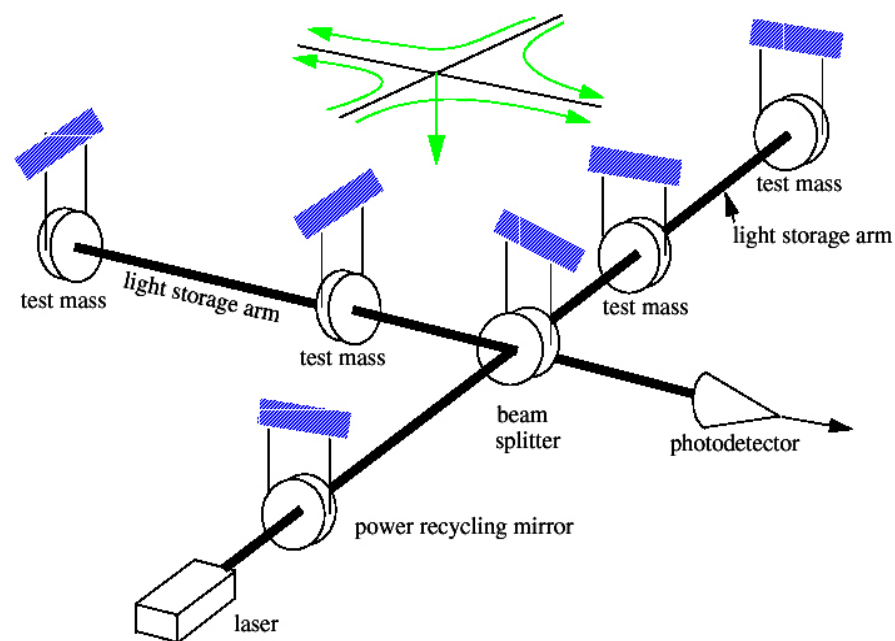
Binary neutron star system in Virgo according to General Relativity



$$h \sim \left(\frac{GM}{c^2} \right) \left(\frac{v^2}{c^2} \right) \frac{1}{r}$$

BNS at $r = 15$ Mpc: $h \sim 10^{-21}$

As detected by LIGO:



$$h = \Delta L / L \Rightarrow \Delta L \sim 10^{-18} \text{ m required}$$

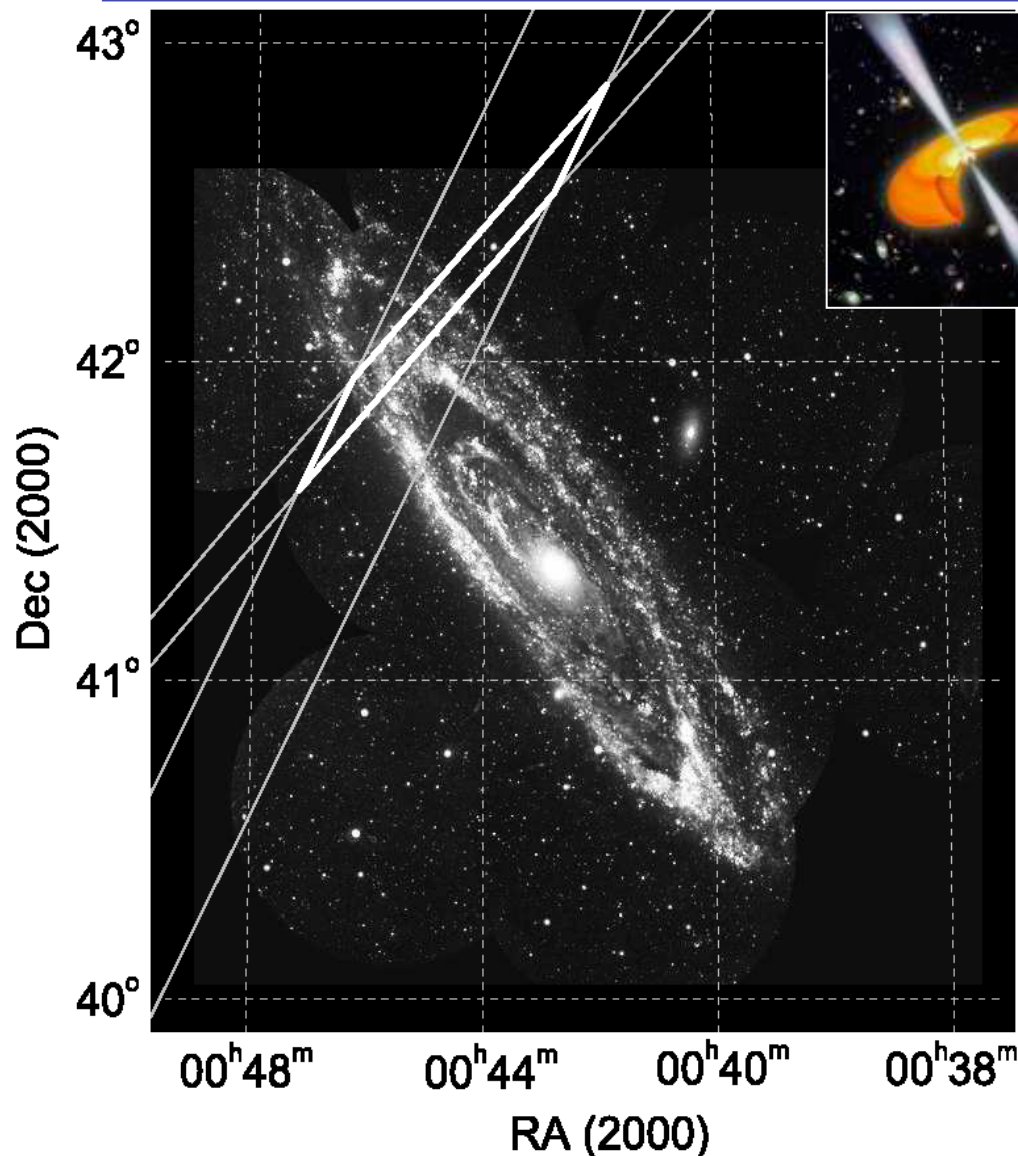
Has this sensitivity been achieved?

Yes!

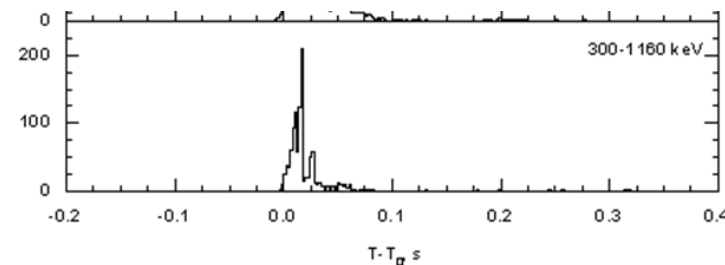
Have GWs been detected??

No!!





Revised error box: arXiv:0712.1502

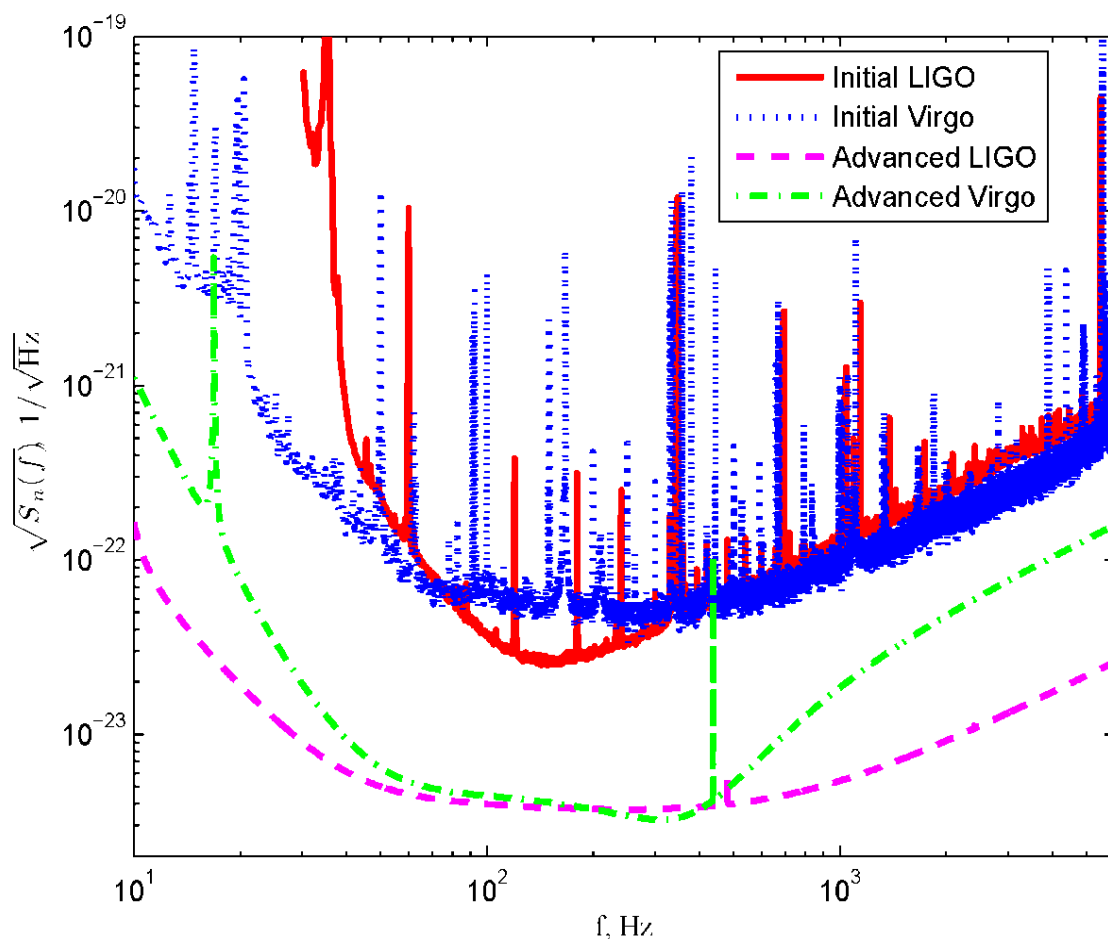
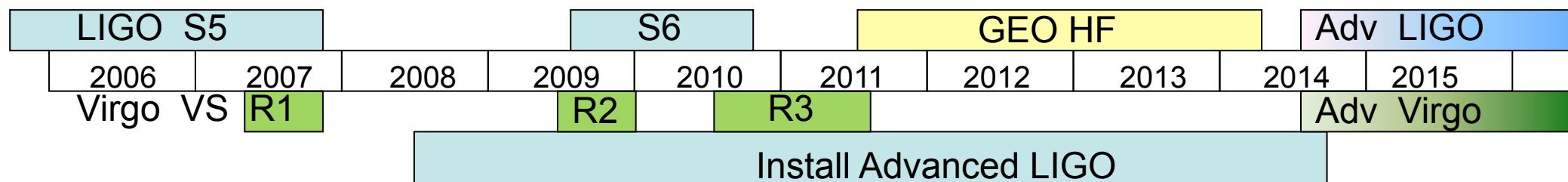


- GRB 070201 – a short-duration gamma-ray burst with position consistent with Andromeda at a distance of 0.7 Mpc
- BNS hypothesis ruled out at ~99% CL (Astrophys. J. 681 (2008) 1419)

Multi-messenger astronomy:

Optical, Gamma-rays, radio, ...
neutrinos, gravitational waves

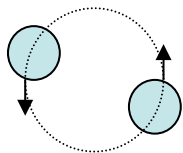
- Detection confidence
- Source localization and identity



Advanced LIGO and Virgo

- Major upgrades
 - Lasers, optics, suspensions
 - Limited by Quantum noise
- 10x better sensitivity
- 1000x bigger search volume

Compact binary coalescence: expected rates



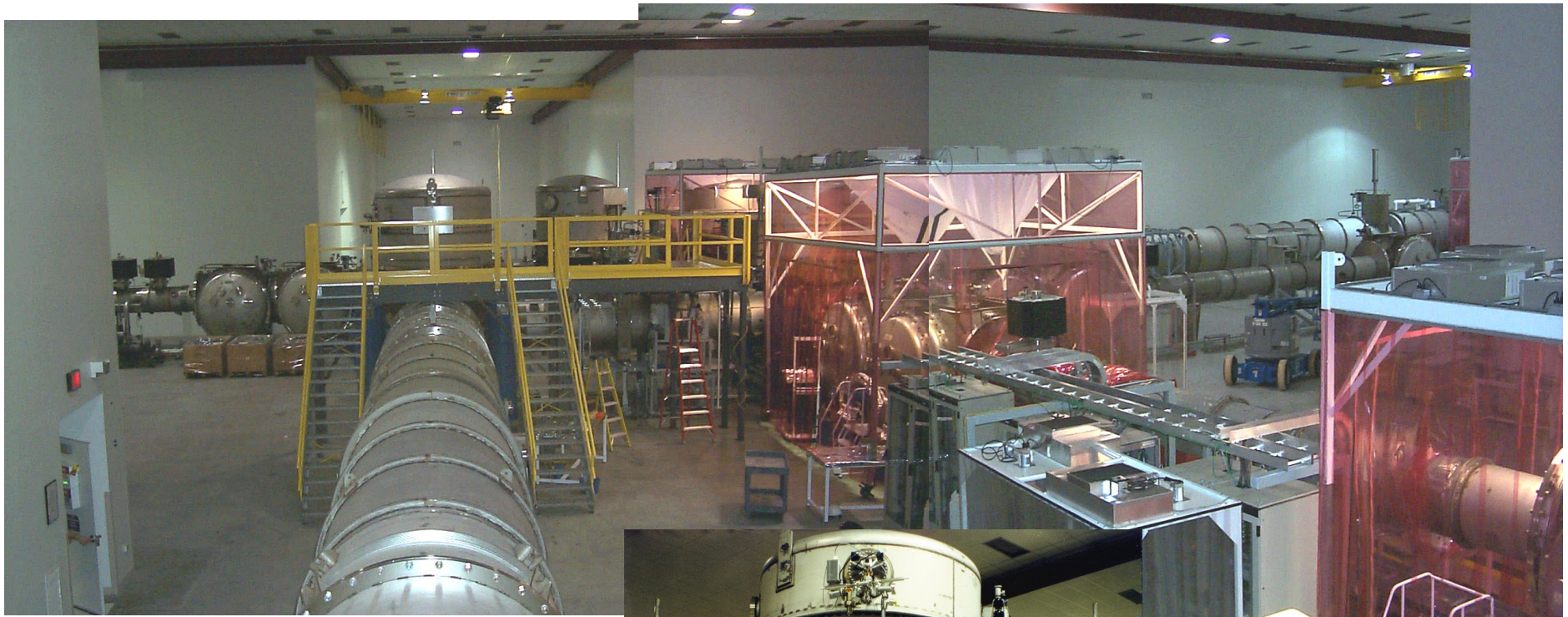
arXiv: 1003.2480 ,
CQG, (LSC, Virgo)

TABLE V: Detection rates for compact binary coalescence sources.

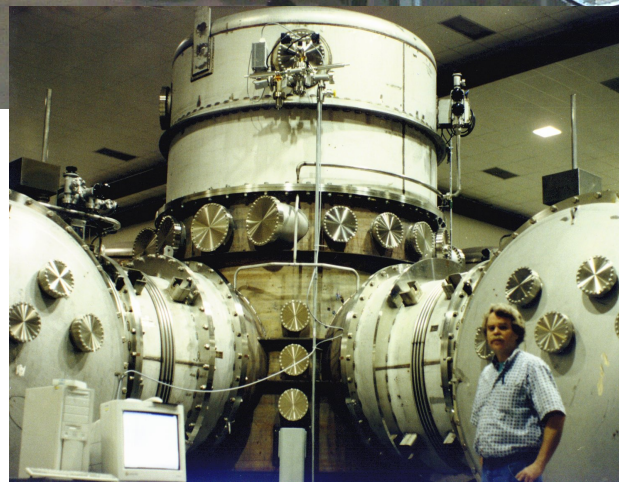
IFO	Source ^a	$\dot{N}_{\text{low}}$ yr ⁻¹	$\dot{N}_{\text{re}}$ yr ⁻¹	$\dot{N}_{\text{high}}$ yr ⁻¹	$\dot{N}_{\text{max}}$ yr ⁻¹
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			10^{-4}^d	10^{-3}^e
Advanced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

Short GRB rates consistent with this.
But also uncertain (due to beaming angle)
Fong and Berger, arXiv:1204.5475

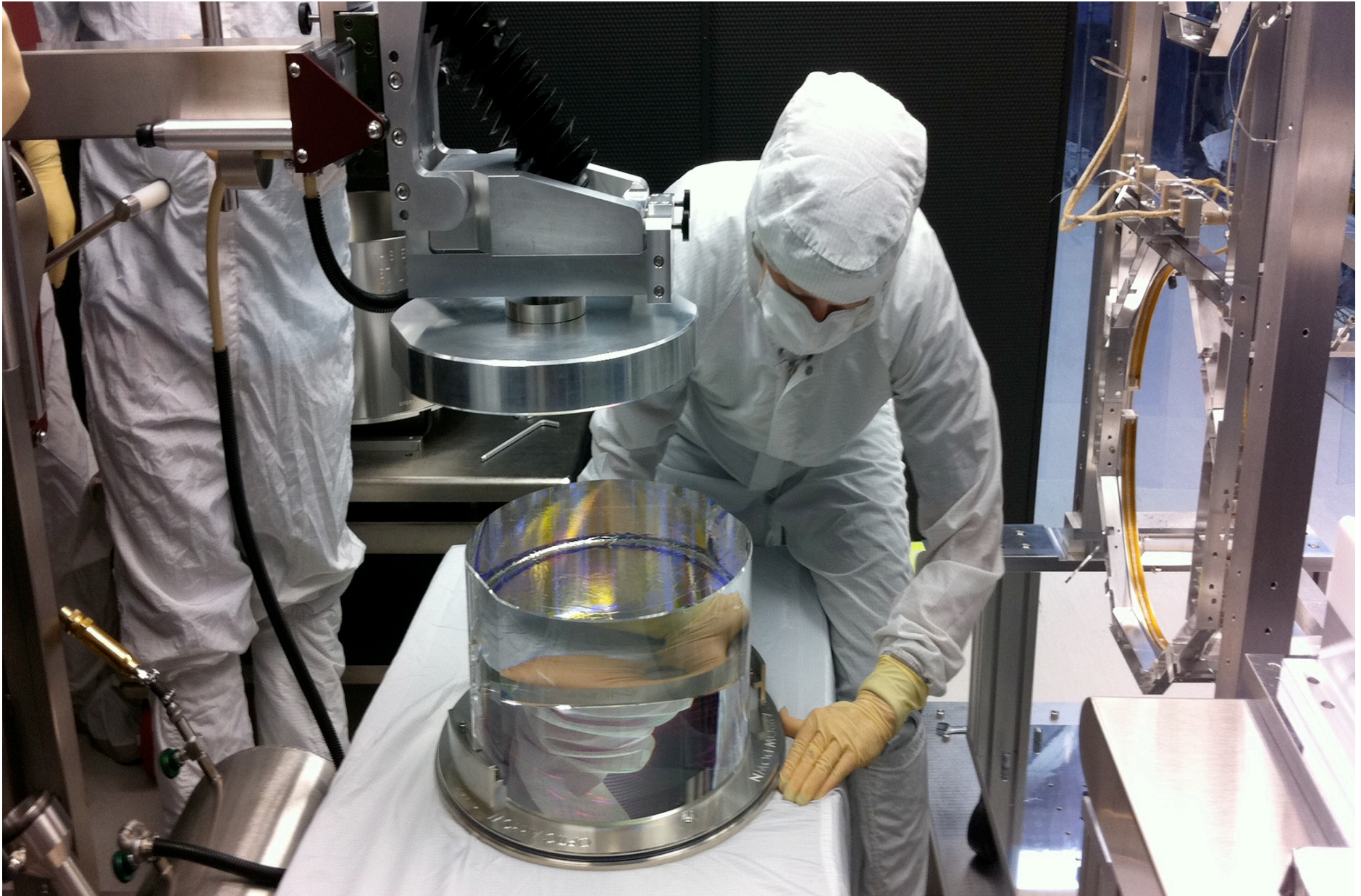
Upgrade activity at Hanford

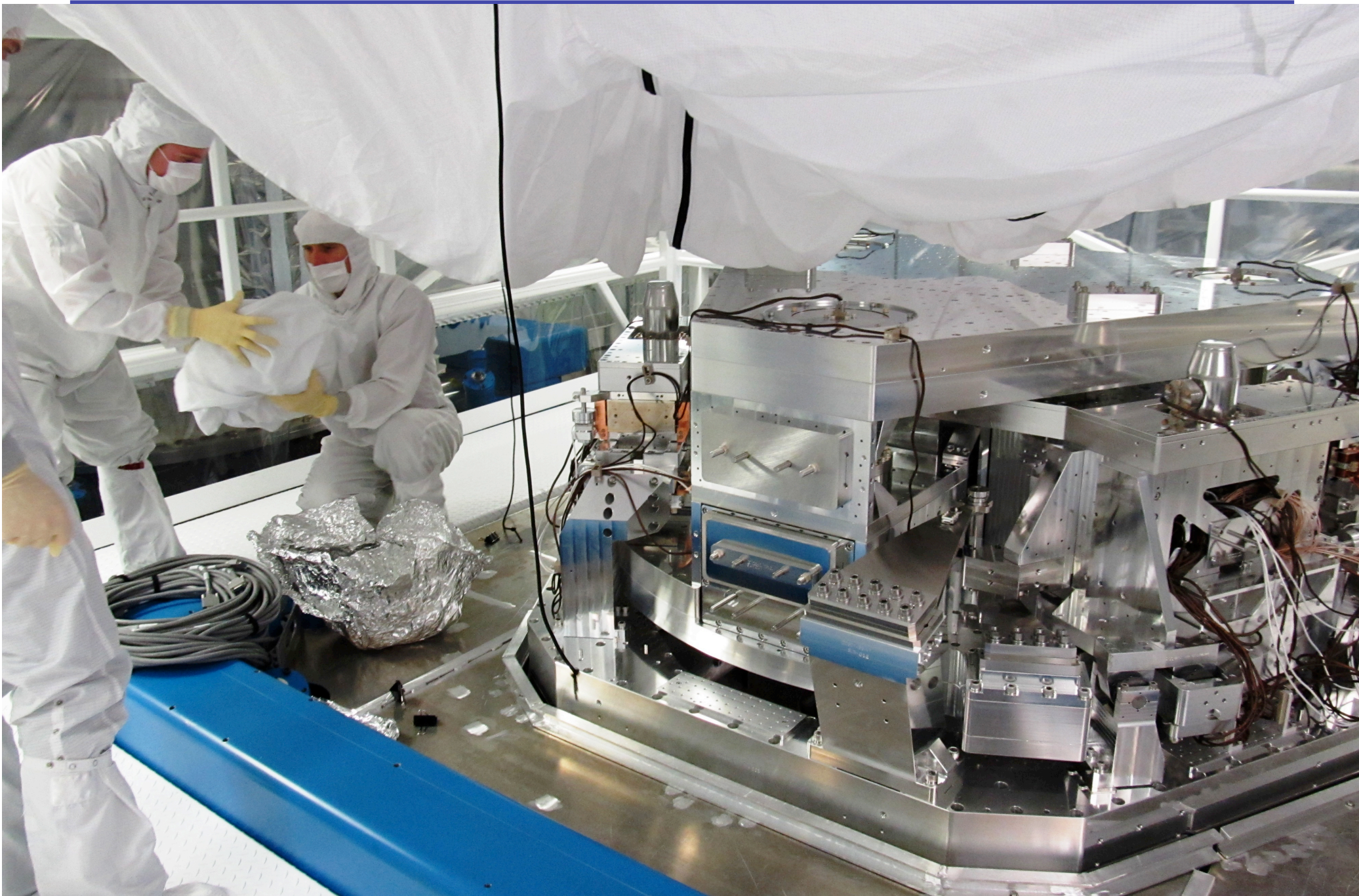


View inside Corner Station

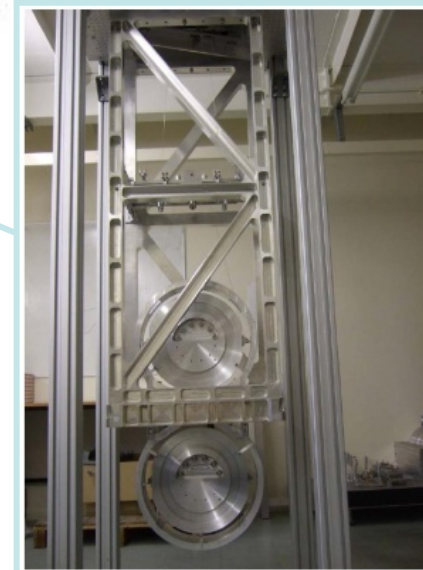
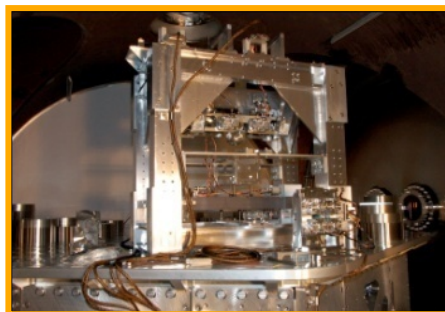
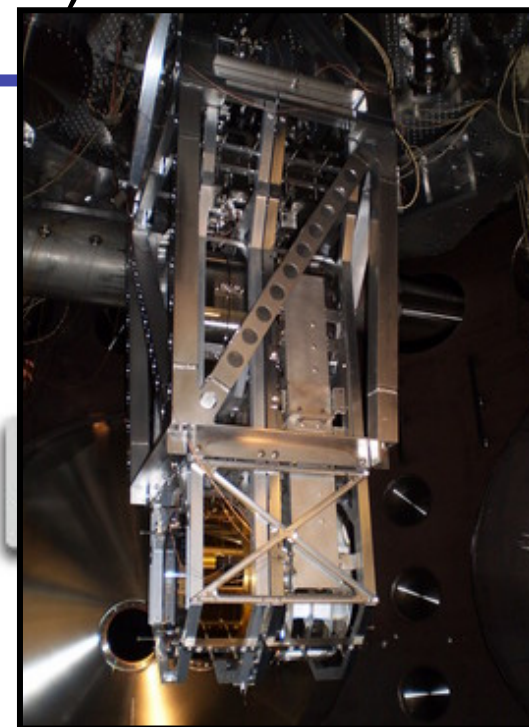
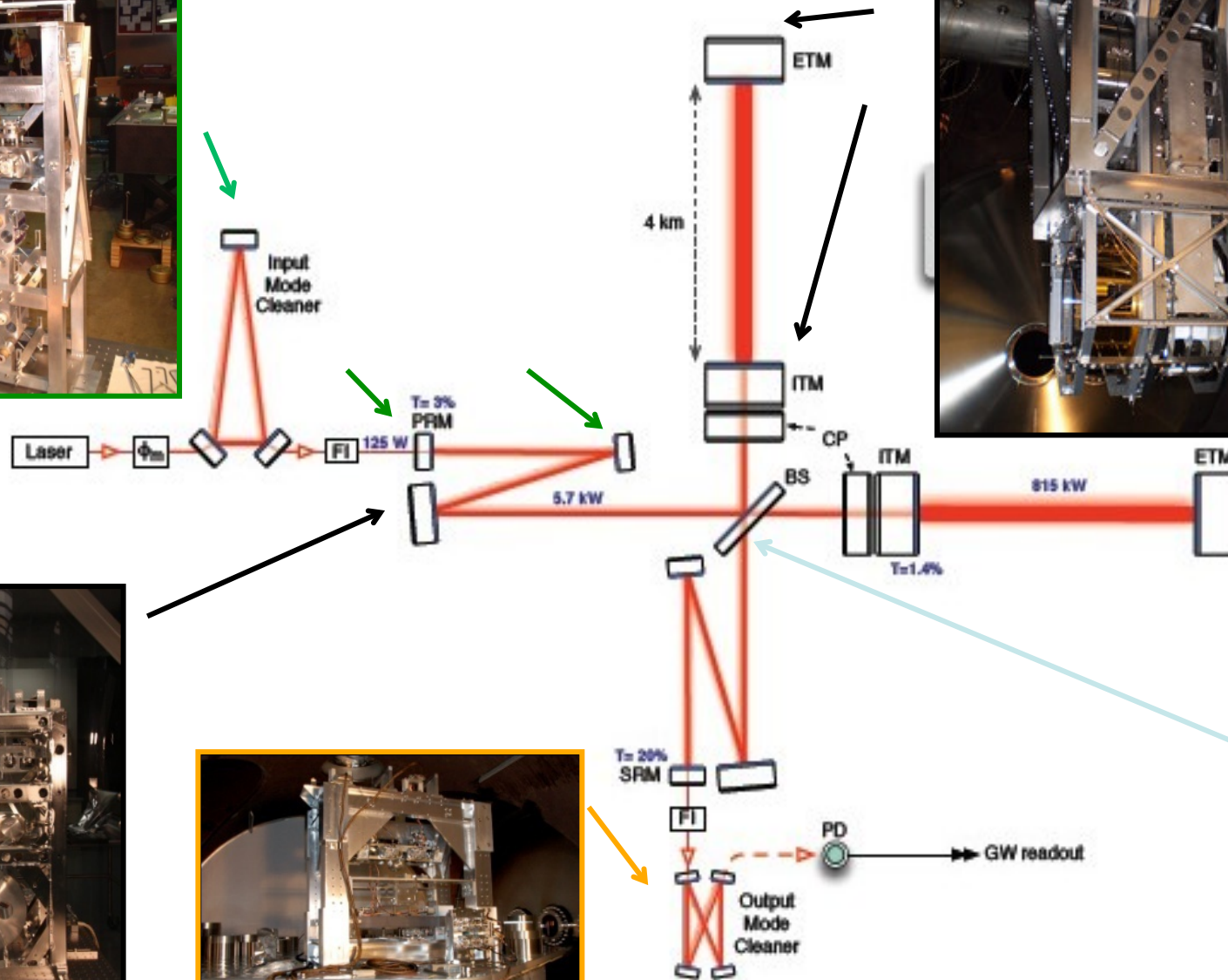


Don't drop the test mass

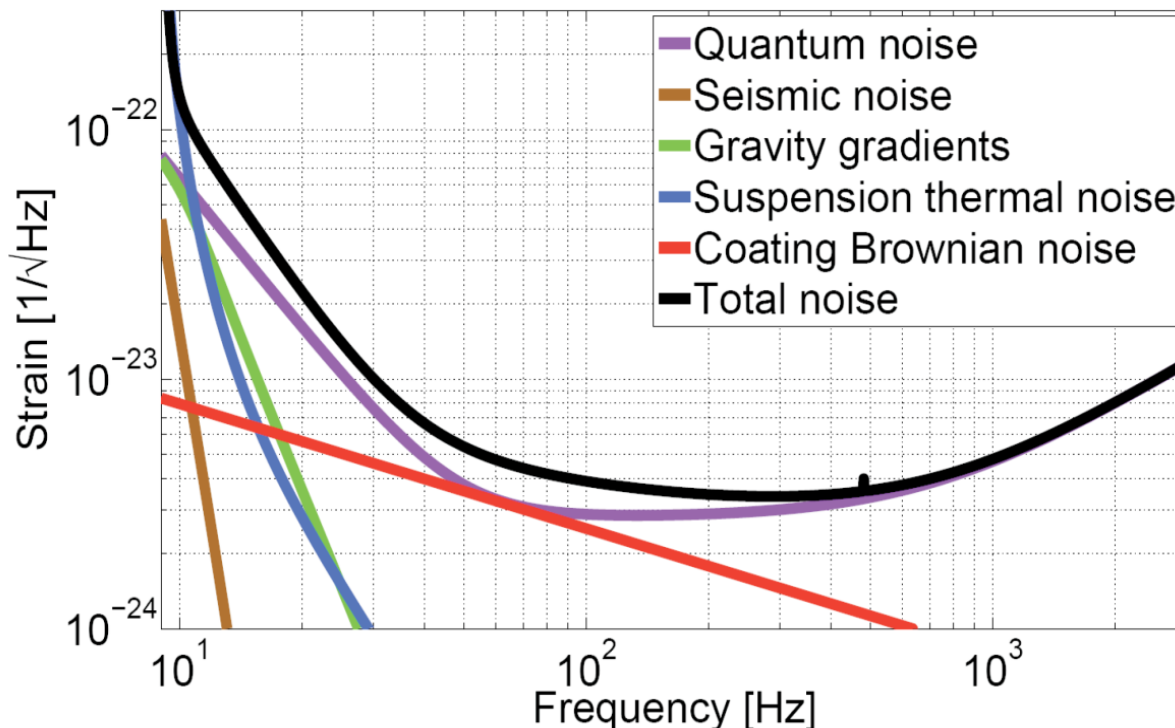
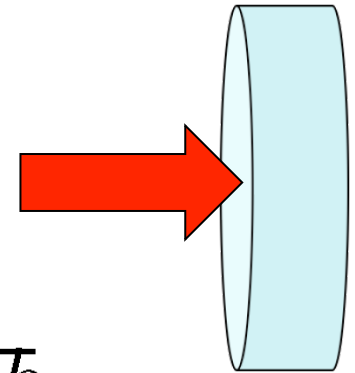




New hardware going in
(shown here: suspensions)



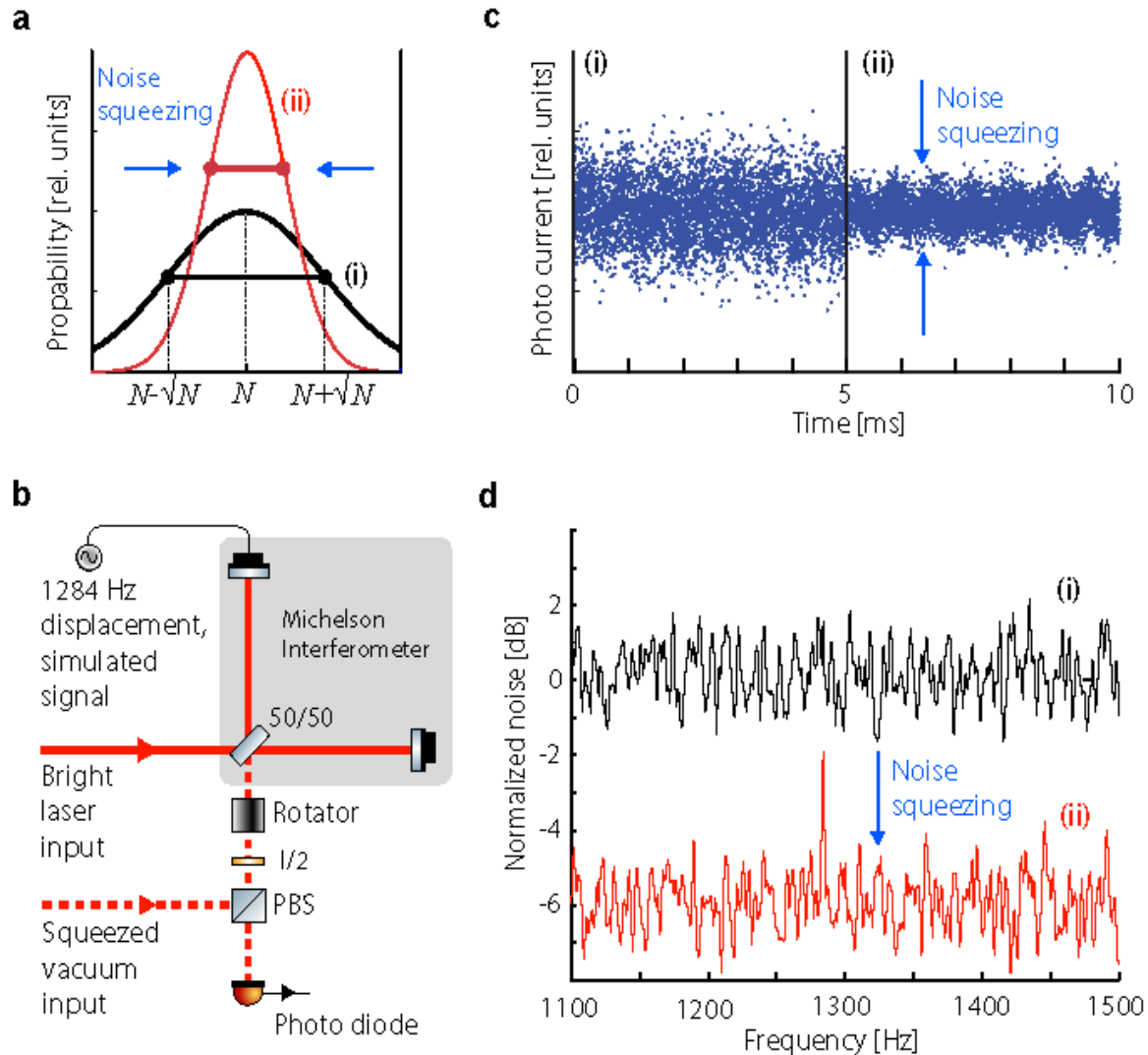
- LIGO is a Heisenberg microscope
- Mirror position (x) – given by the E field *phase* and the momentum kick of the mirror (p) due to *radiation pressure* are fundamentally connected by quantum mechanics: $[x, p_x] = i\hbar$



In the quantum optics description:

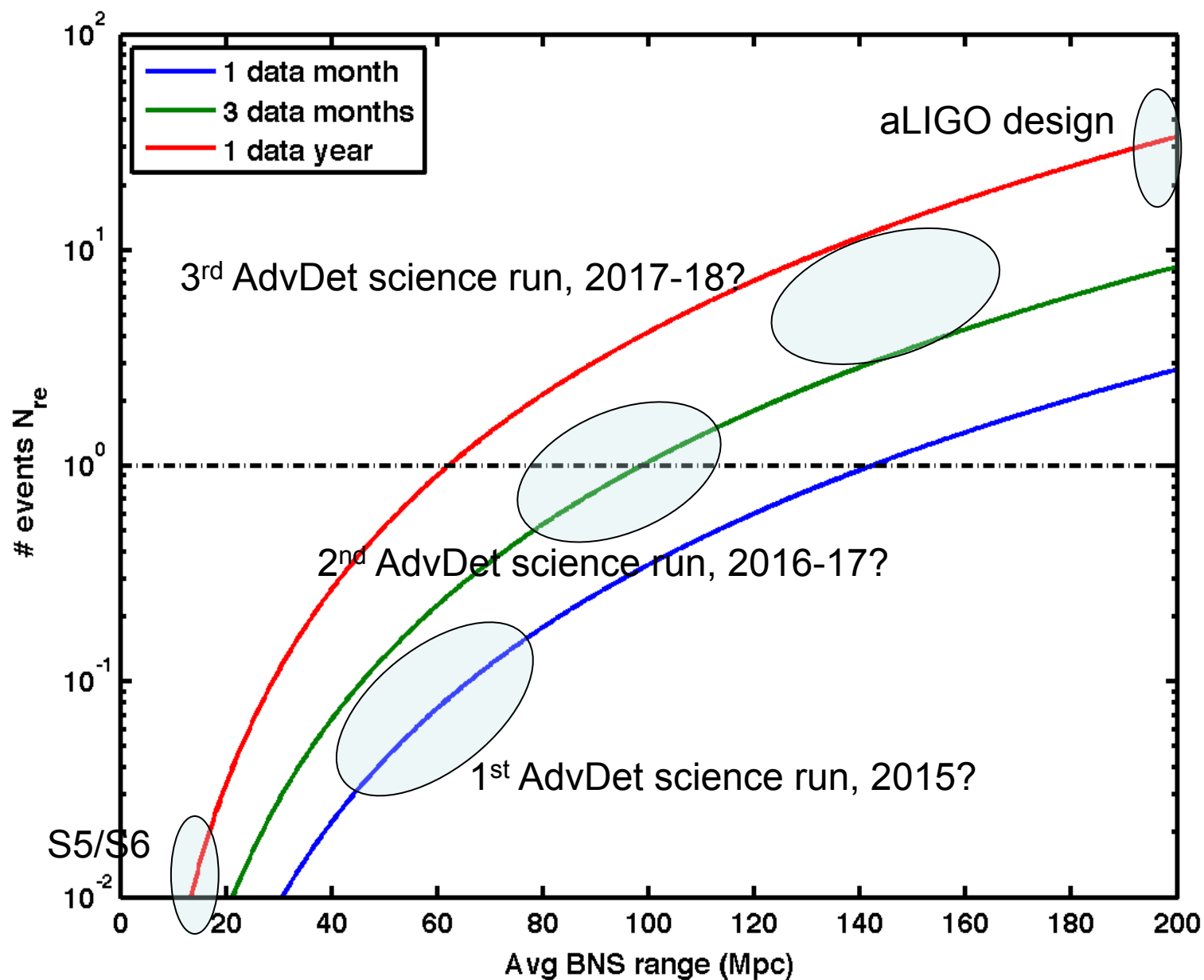
- $x \rightarrow$ phase (shot) noise
- $p \rightarrow$ amplitude (radiation pressure) noise

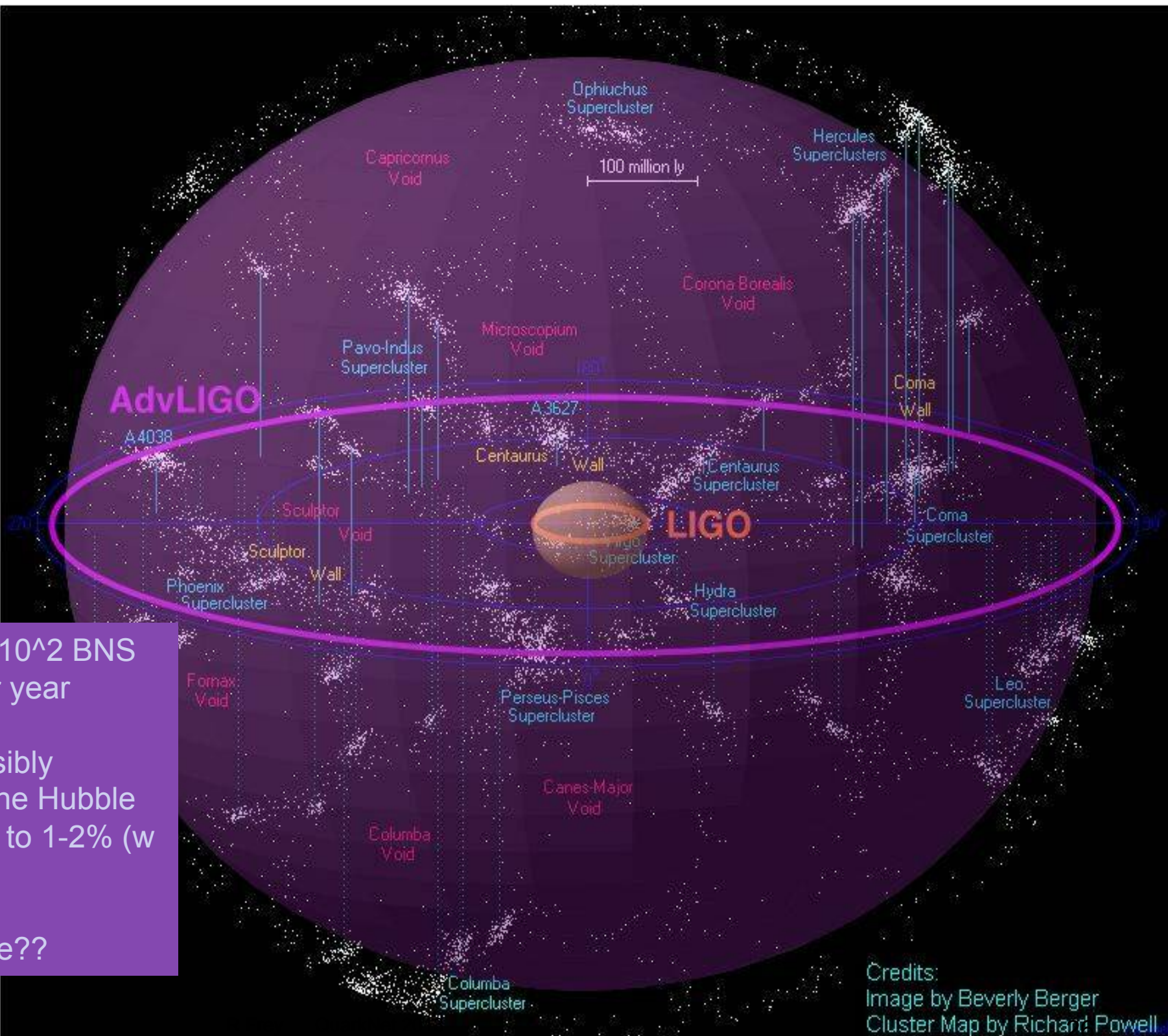
• Squeezed light (or squeezed



- A non-linear “squeezer” introduces a correlation between photons.
- This “squeezed vacuum” is injected.
- This correlates the photons in the main arms and entangles the noise in the two arms

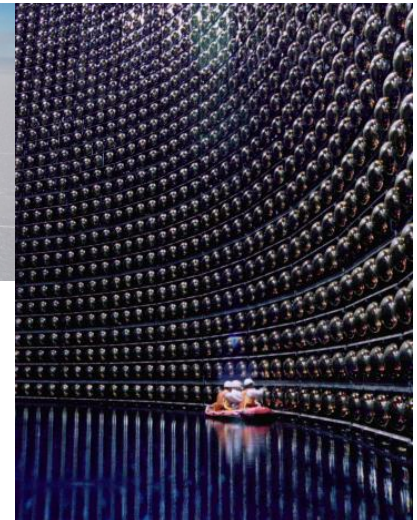
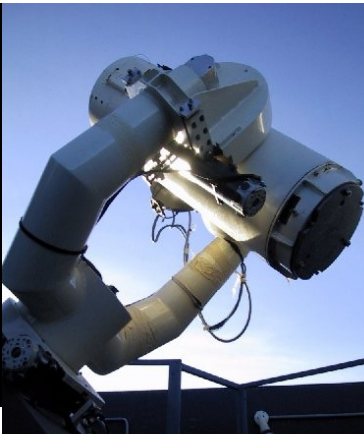
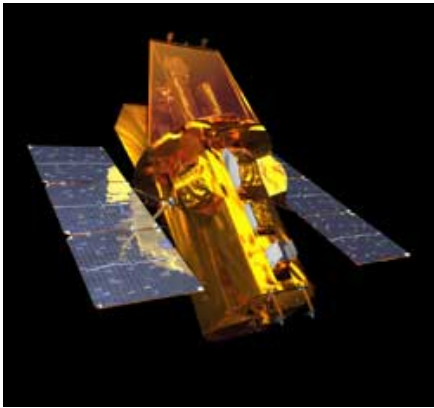
**Demonstrated in
GEO and in LIGO
(H1) in 2012 (paper in
prep)**





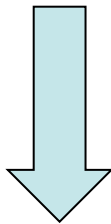
- Expect $\sim 10^2$ BNS events per year
- Can possibly measure the Hubble parameter to 1-2% (w to 10%)
- What else??

Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

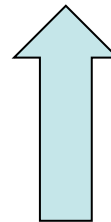


EM , neutrinos

External
Triggers



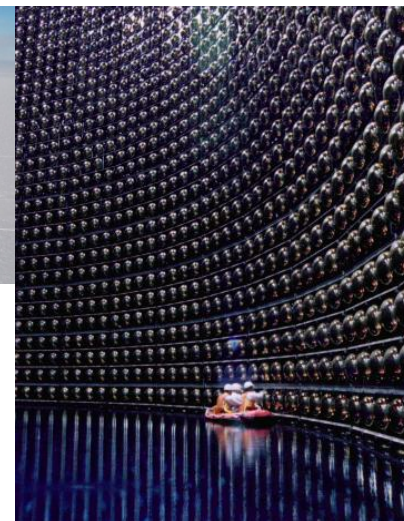
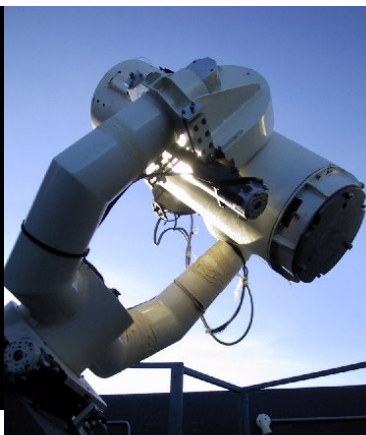
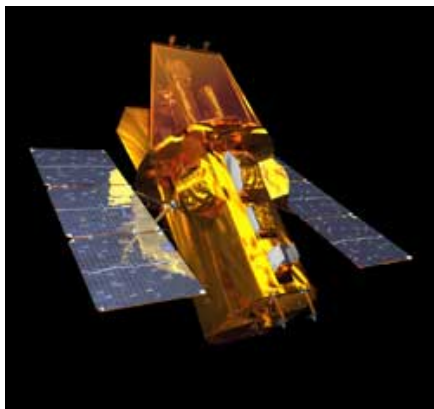
Follow
Ups



GW

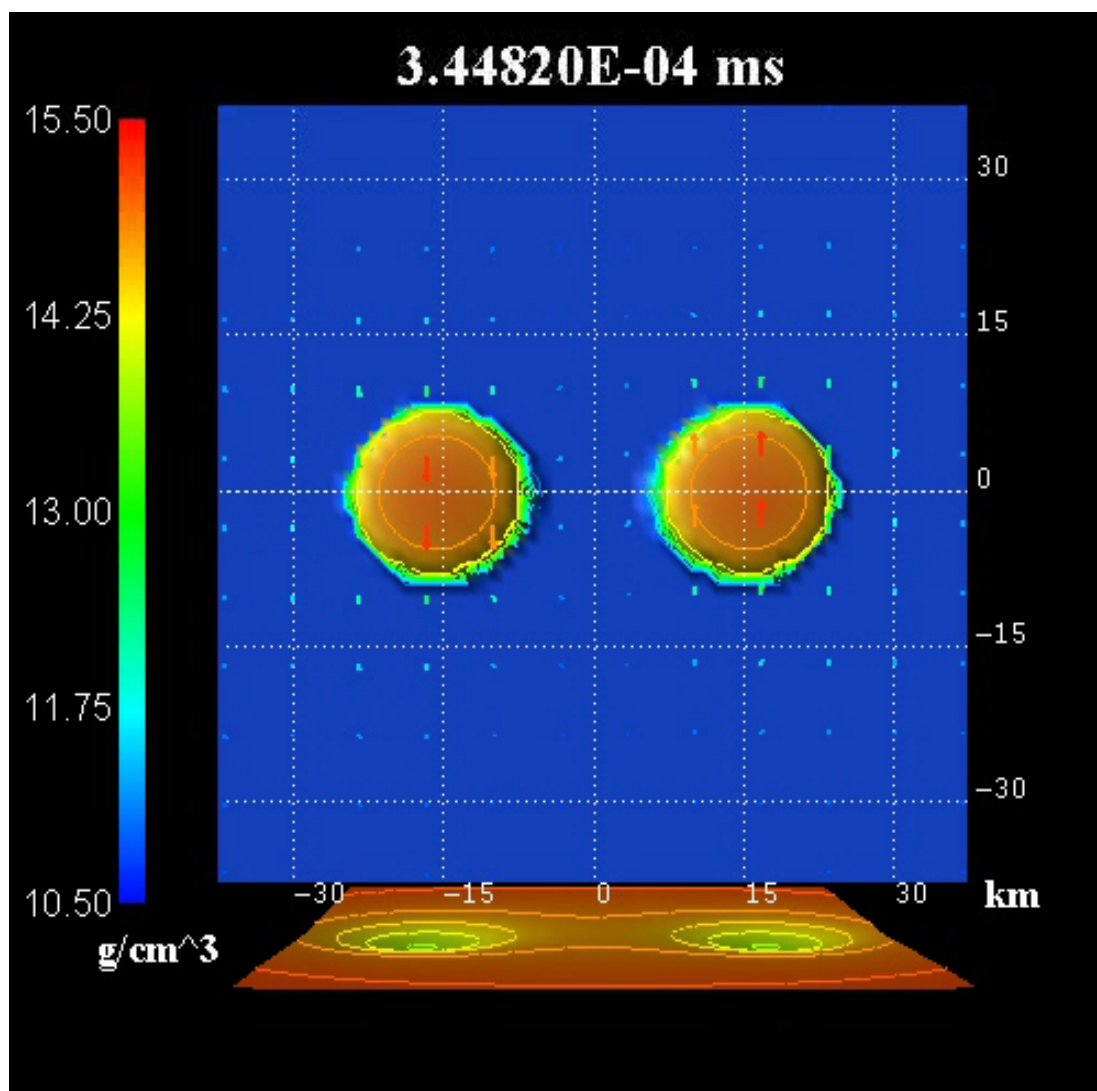


Multi-messenger astronomy with GWs



- Detection confidence
- Event time
- Sky position
- Improved search sensitivity
- Redshift
- Progenitor information





- NS-NS merger remnant accretion disk powers short GRB
- Bombarded by neutron-rich ejecta from the merger
- synthesizes heavy nuclei (competes with supernovae)
- decay makes EM afterglow (an target for EM followup obs)

-- BD Metzger, et al

H																	He				
Li	Be															B	C	N	O	F	Ne
Na	Mg															Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
Fr	Ra																				
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu					
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr					

Big Bang

Supernovae

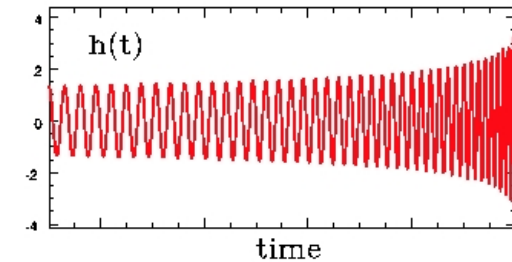
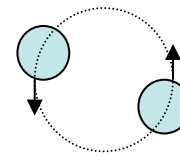
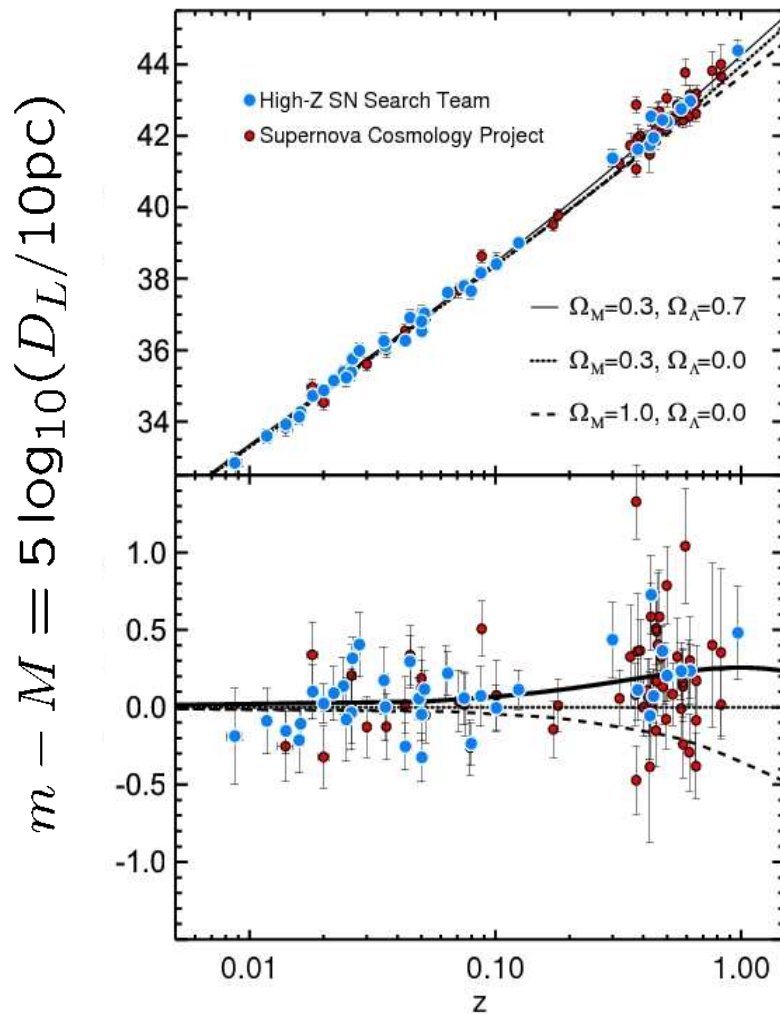
Large Stars

Small Stars

Cosmic Rays

Shibata

Hubble plots with SNe Ia
(the 2011 Physics Nobel Prize)

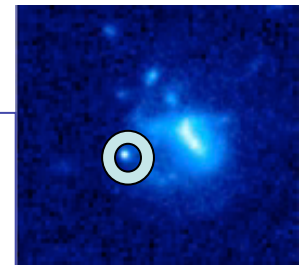


Binary NS/BH system GW waveforms are functions of:

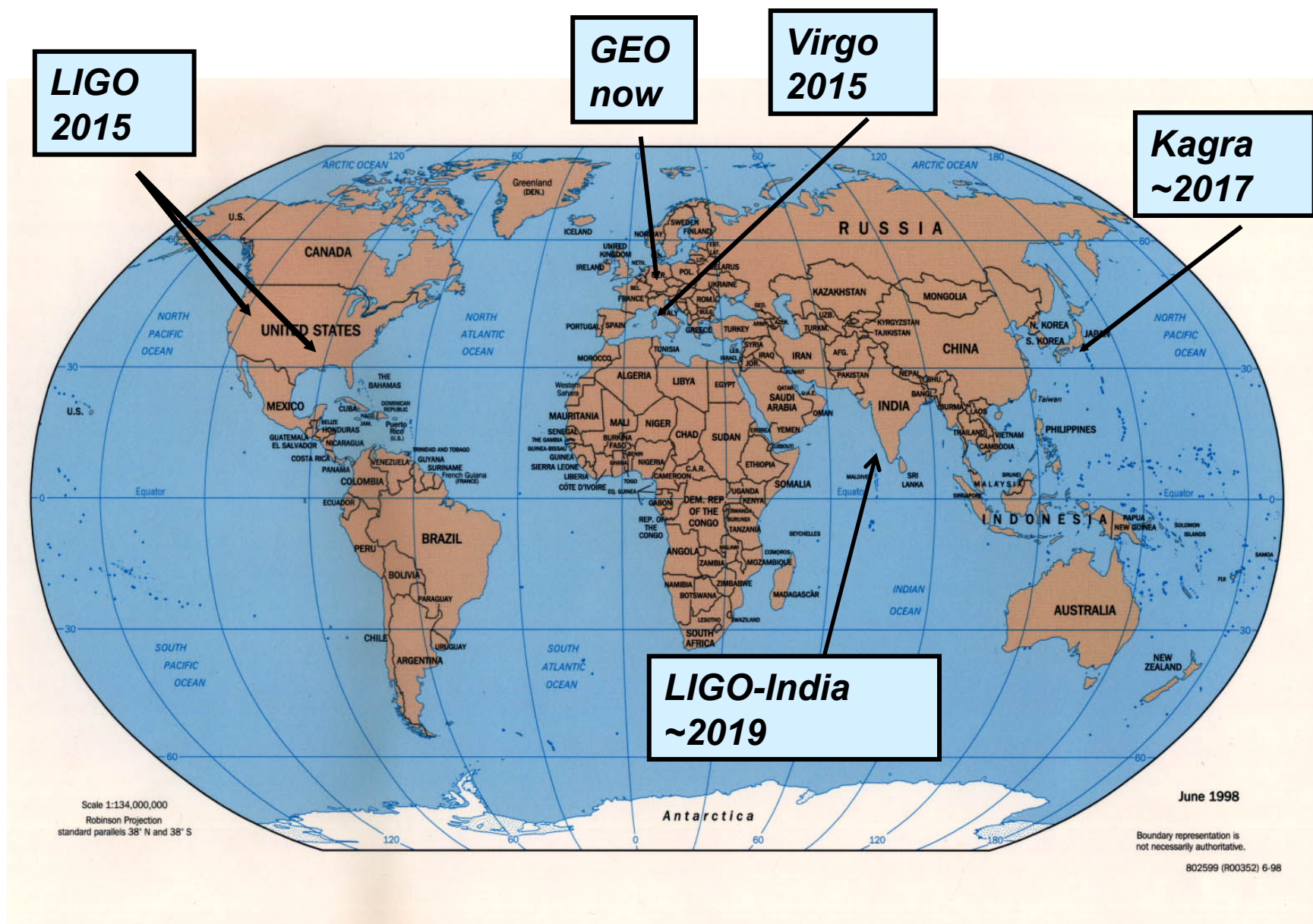
$$(1+z)\mathcal{M}, D_L, \iota, \theta, \phi, \psi$$

allow extraction of Distance (D_L) which is *independent of EM distance ladder*

10 short GRBs observed by LIGO could determine the Hubble parameter to $\sim 3\%$ and the dark energy parameter to $\sim 10\%$

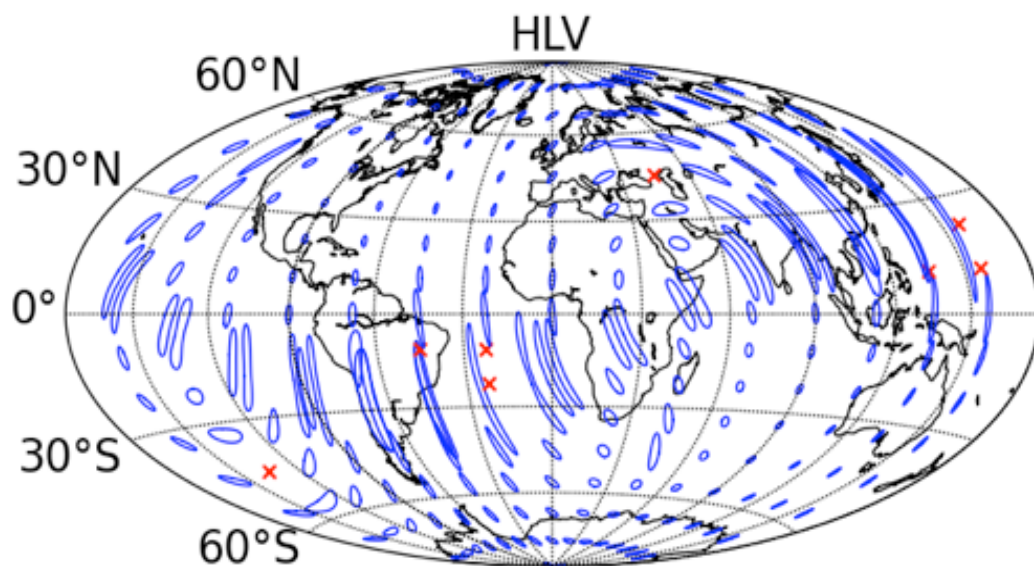


The 2nd generation GW detector network

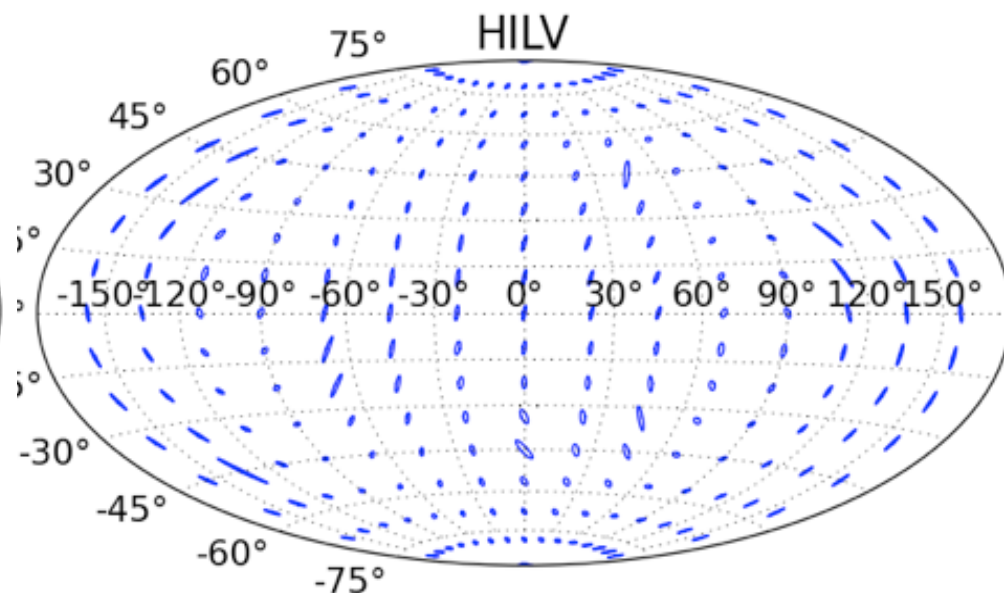


Moving one LIGO detector to India

Determination of source sky position: NS-NS binary inspirals



LIGO-Virgo



LIGO-Virgo + LIGO India



Fairhurst et al., arXiv:0908.2356; 1010.6192; 1205.6611

-
- A new era of GW astronomy/ astrophysics is beginning
 - No GW detections with initial LIGO, but much progress
 - Learned how to improve detectors
 - Learned how to analyze GW data and say a little about astrophysics
 - Forged partnerships and collaborations (ongoing)
 - Era of GW observations with advanced detectors begins ~2015
 - To take full advantage of likely GW detections and the full science opportunity presented by these sensitive instruments, an emerging field of GW astronomy has spun up
 - Fun and excitement! UO is an important player in LIGO.