Status of Laser Gravitational Wave Antennas

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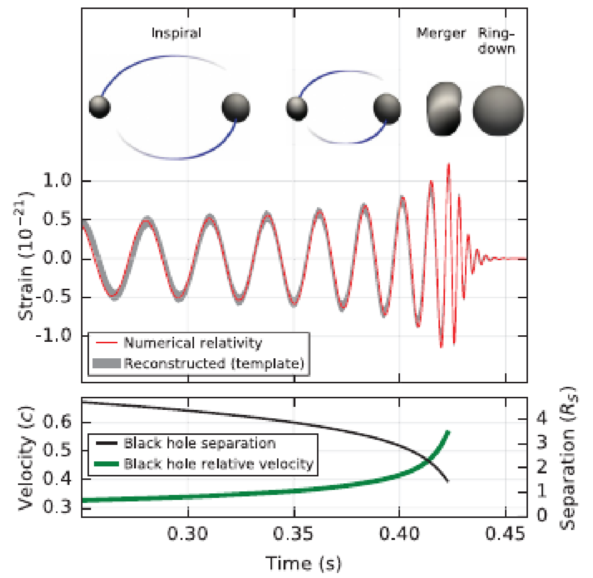
Outline

1. Introduction
2. Scale of displacements
3. Laser GW detectors — what is now?
4. Standard Quantum Limit (SQL) and how to surpass it
5. Quantum variational measurement
6. Squeezed input
7. Conclusion

GW150914: 14 September 2015



Masses of black holes 29 $M_\odot$, 36 $M_\odot$ at distance 1,3 billions of light years

During 100 msec $\simeq 3M_\odot$ transforms to GW

Bottom: The Keplerian eff. black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the eff. relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$,

14 сентября 2015 (GW150914)

Gravitational signal was detected by two detectors of LIGO (Laser Interferometric Gravitational Observatory) in Hanford and Livingston.

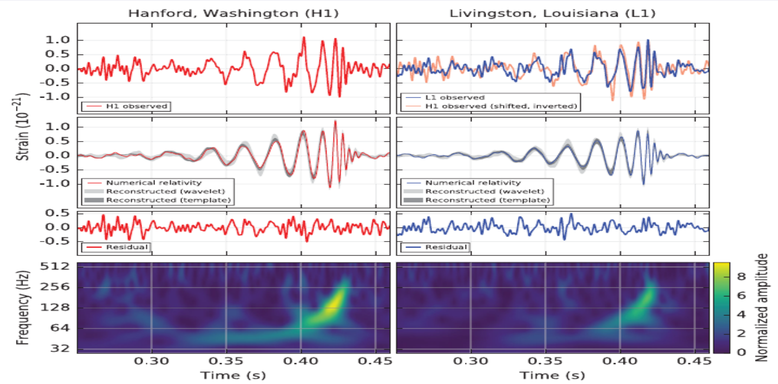


Figure: Lines: 1) Signals in Hanford am Levingston, 2) After filtration in the 35 - 350 Hz band, 3) Residuals after filtration, 4) A time-frequency representation.

Схема антенны aLIGO

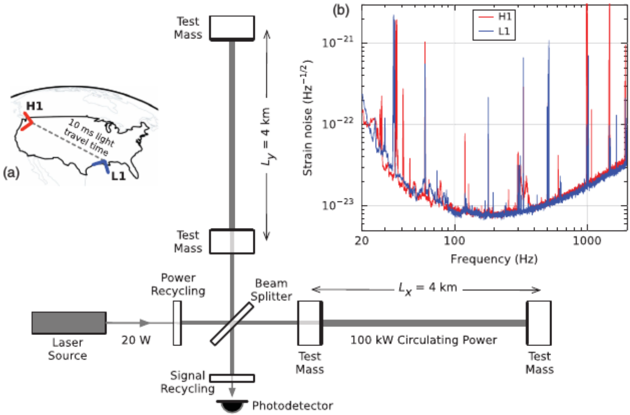
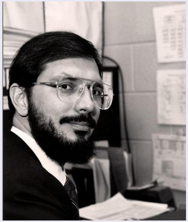


Figure: Схема лазерных интерферометров aLIGO. Узкие пики: калибровка (33–38, 330, and 1080 Гц), моды упругих колебаний нитей подвеса (500 Гц и гармоники), 60 Гц (и гармоники) электропитания.

Нобелевские премии

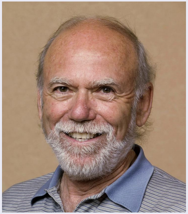
1993 г.

Рассел Халс и Джозеф Тейлор
за открытие гравитационных волн по изменению частоты двойных пульсаров.

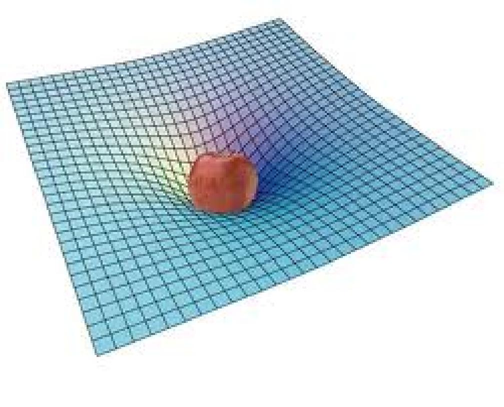


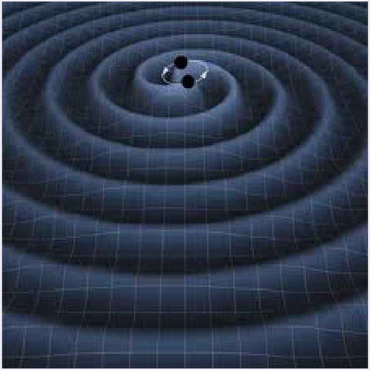

2017 г.

Райнер Вайс, Барри Бариш и Кип Торн
за решающий вклад в детектор LIGO и наблюдение гравитационных волн


Flying pieces of space-time curvature



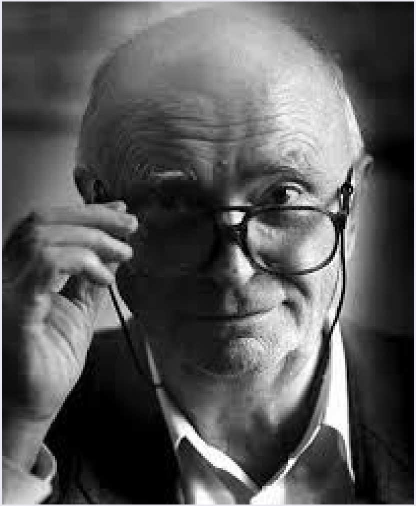


1993 г. Nobel Prize (Russell Hulse and Joseph Taylor) for discovery of GW via change of frequency of double pulsar rotation.

Ты помнишь, как все начиналось...

Твердотельные антенны (1970 – 1990)

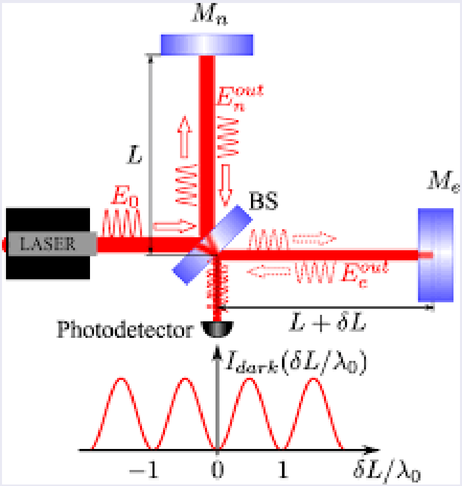
Дж. Вебер в лаборатории



Владимир Борисович Брагинский

Idea of laser GW antenna

M.E. Hertsenshtein and V.I. Pustovoit, Zh.Eks.Ter.Fiz. **43**, 605 (1962)



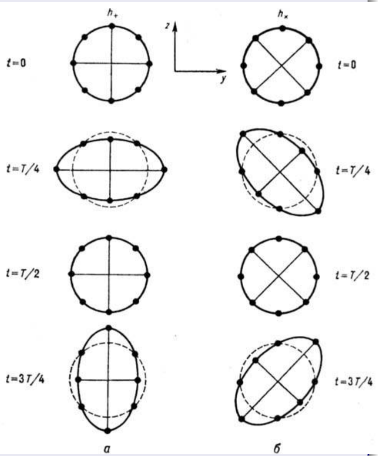
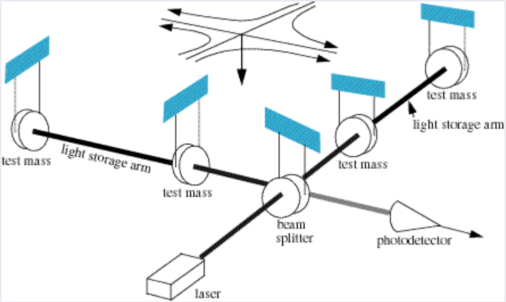


Схема и вид

1992 г. — Kip Thorne, Ronald Driver (CIT) and Rainer Weiss (MIT) предложили LIGO.



Современная лазерная гравитационная антенна

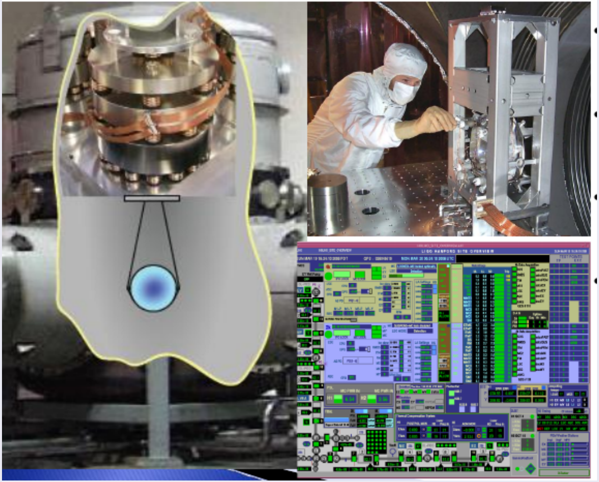
LIGO: две антенны (4 км)

1992 г. — Kip Thorne, Ronald Driver (CIT) and Rainer Weiss (MIT) предложили LIGO (Laser Inteferometric Gravitational Observatory).
1992 г. — гр. В.Б.Брагинского начала сотрудничать с LIGO.

2002 г. — Initial LIGO: S1 (scientific run), начаты записи сигнала.
2010 г. — остановка Initial LIGO, начат переход на Advanced LIGO.
2015 г. — инженерный и научный запуск Advanced LIGO,

Initial LIGO

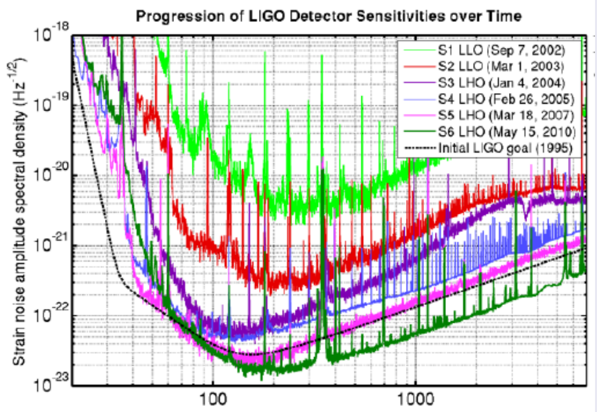
Сложнейшая инженерная установка



- $>$ 1000 систем автоподстройки
- $>$ 500 контрольных каналов (0.5 Тб в сутки, около 300 специалистов + всп. персонал)
- \$ 30 млн в год на управление

Initial LIGO

Пройден тяжелый путь (2002 – 2010)



- S6, 2010 г. – Запланированная чувствительность достигнута и превышена
- Более 2 лет непрерывной записи
- **Гравитационные волны не были обнаружены . . .**

LIGO Scientific Collaboration

VIRGO, GEO600

Virgo (Италия, Франция)
Антенна (3 км) в Кошине (Италия)

GEO (Великобритания, Германия)
Антенна (600 м) в Ганновере

Cryogenic

KAGRA (Japan) — зеркала при криогенной температуре.

International G.-W. Observatory Network (IGWN)

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Scale of displacements

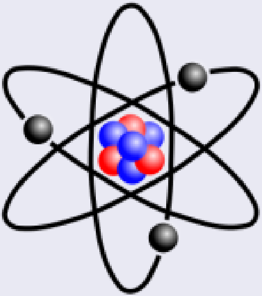
From Earth to atom

$\sim$ $1.3 \cdot 10^7$ m $=$ 13000 km

$\Rightarrow$

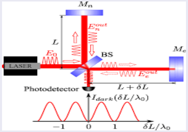
$\sim 10^{-1}$ m

$\Rightarrow$



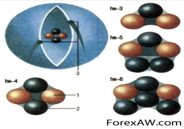
$\sim 7 \cdot 10^{-10}$ m $= 7$ A

From atom to LIGO: $d_{LIGO} \simeq 10^{-4} d_n$



d_{LIGO} 10^{-19} m

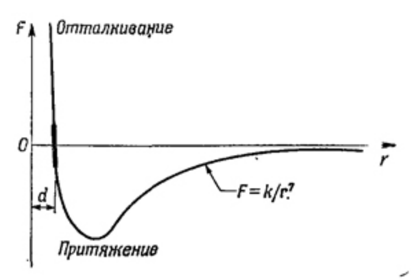
$\simeq$



$\sim 2 \cdot 10^{-15}$ m $=$ $5 \cdot 10^{-5}$ A

Atoms on surface

Surface fluctuations (rough estimate)



At room temperature $\Delta x \simeq 10^{-10}$ m.
On spot 10 cm $\times$10 cm — about $N = 10^{18}$ atoms.
Surface fluctuations ("breathing")

$$\Delta X \simeq \frac{\Delta x}{\sqrt{N}} \simeq 10^{-19}\ \text{m} \qquad (1)$$

More accurate calculations

LIGO: mean position of spot $D = 10$ cm fluctuates for $\tau \simeq 0.01$ c
$\Delta X_{\text{therm}} \simeq 10^{-19}$ m
It is about в 10 *billions (!) times smaller* than atom,
or в *10 thousands (!) times smaller* than nucleus
Is it possible to measure?

What displacement we can measure?

V.B. Braginsky, V.I. Panov and V.D. Popelnyuk, 1981

Superconducting capacity meter, gap 4 microns:

$$\Delta X \simeq 10^{-19}\ \text{m},\quad \text{gap 4 microns},\quad \text{for } \tau = 10\ \text{c}$$

"Initial" LIGO, 2011

Laser beam measures coordinate averaged over spot $D = 6$ cm

$$\Delta X \simeq 4\times 10^{-18}\ \text{m},\quad \text{distance } \mathrm{L} = 4\ \text{km},\quad \text{for time } \tau \simeq 0.01\ \text{c}$$

Advanced LIGO, 2023

$$\Delta X \simeq 0.5\times 10^{-19}\ \text{м},\quad \text{distance } \mathrm{L} = 4\ \text{km},\quad \text{for time } \tau \simeq 0.01\ \text{c (!)}$$

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Advanced LIGO A+

A+ status for O4 (March 2023)

- ✓ ***O4 A+ systems delivered, installed, tested; commissioning in progress***
  - ✓ Improved squeezed light injection
    - ✓ OPO Upgrade
    - ✓ High-T Faraday isolators
    - ✓ Adaptive mode matching
  - ✓ Frequency-Dependent Squeezing (FDS)
    - ✓ Squeezed light injection, Civil + Vacuum
    - ✓ Filter cavity optics, seismic isolation, suspensions, baffles, sensing, control/data system
  - ✓ Civil construction
  - ✓ Vacuum system expansion

- ➤ *Up to 5.4 dB squeezing achieved! (LLO, 10 Feb 2023)*
- ➤ *Quantum noise suppressed throughout signal band!*

(excerpted from M. Zucker NSF talk)

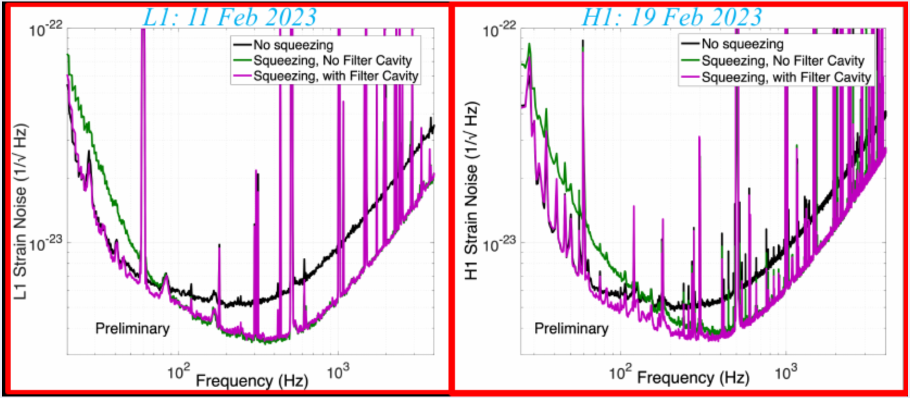
3

Now O4 operates.

Current sensitivity of Advanced LIGO A+

Sensitivity and squeezing improvement

Frequency Dependent Squeezing Achieved in Lousiana and Hanford Interferometers

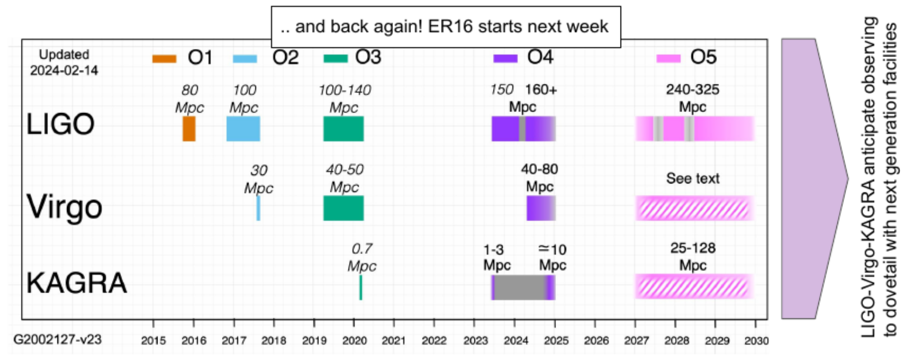


Squeezing is about 5 dB. Filter cavity (300 m) — frequency squeezing.

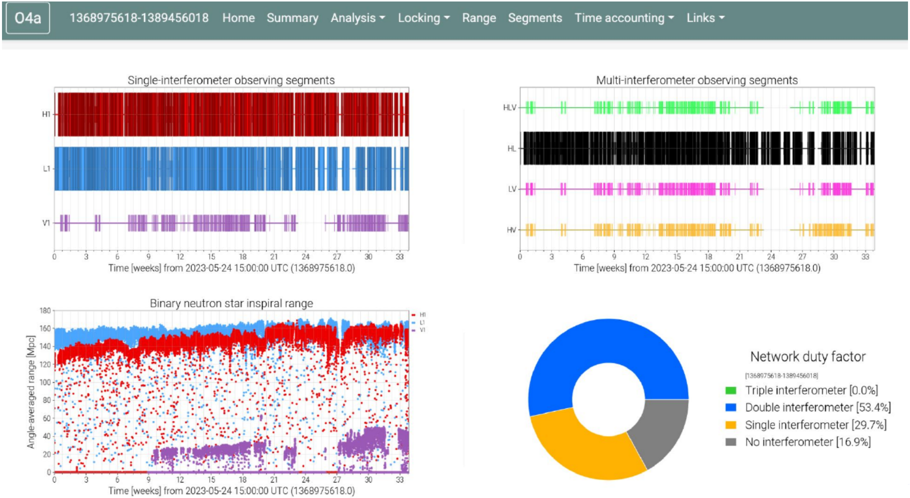
Advanced LIGO A+: schedule for the period 2024 – 2028

Past and future Observation Runs

Expect to be observing 50% of the time



O4a Summary


O4a
1368975618-1389456018
Home
Summary
Analysis
Locking
Range
Segments
Time accounting
Links
Single-interferometer observing segments
H1
L1
V1
Time [weeks] from 2023-05-24 15:00:00 UTC (1368975618.0)
Multi-interferometer observing segments
HLV
HL
LV
HV
Time [weeks] from 2023-05-24 15:00:00 UTC (1368975618.0)
Binary neutron star inspiral range
Angle-averaged range [Mpc]
H1
L1
V1
Time [weeks] from 2023-05-24 15:00:00 UTC (1368975618.0)
Network duty factor
[1368975618-1389456018]
Triple interferometer [0.0%]
Double interferometer [53.4%]
Single interferometer [29.7%]
No interferometer [16.9%]

O4a Summary (cont.)

O4a (more than 1/2 year) — 81 significant candidates

Significant alerts:
- False alarm rate less than ~1/month
- ~ 1 BBH per 3 days **actual**
- ~ 1 BNS per 3-6 months **predicted**

Other alerts:
- Not significant and false alarm rate less than few per day.

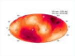
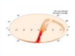
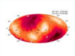
O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

O4 Low Significance Detection Candidates: **1610** (Total)

Show All Public Events

Page 1 of 7. next last »

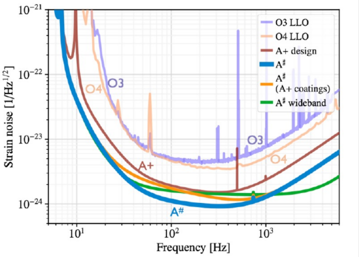
SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices | VOE		1 per 4.3136 years
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices | VOE		1.8411 per year
S240104bl	BBH (>99%)	Yes	Jan. 4, 2024 16:49:32 UTC	GCN Circular Query Notices | VOE		1 per 8.9137e+08 years

BBH — 81 events. BNS — 0 events.

A+ Status and Plans

- The LSC "Post-O5" report recommends pursuing a series of upgrades for the LIGO detectors collectively known as A#



Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Mass of test-mass	40 kg	100 kg	320 kg
Test-mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian suppression	0 db	6 db	20 db

- We are aiming to have a mature conceptual design and costing to be able to submit a proposal by mid-2025 frame.

See Monday afternoon SUS/SEI session talk by Edgard Bonilla

Voyager: comparison with aLIGO A+

What is the same

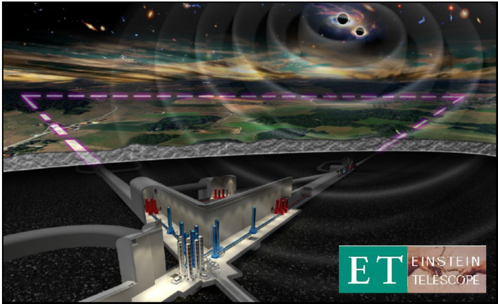
The same vacuum tubes, arms 4 km

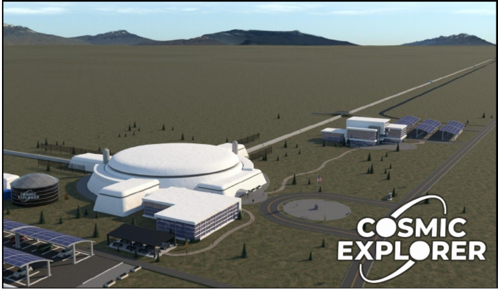
Difference

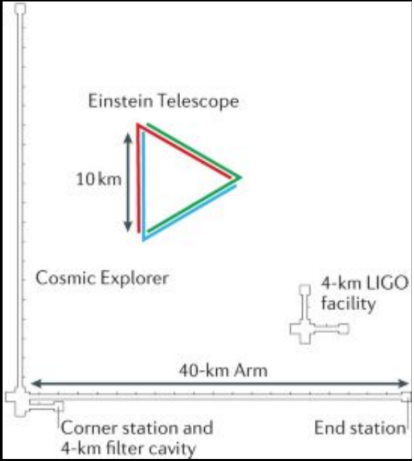
- Mirror' mass is 200 kg
- Material — crystal silicon
- Support: ribbons from crystal silicon
- Temperature of masses: 123 K
  - Lower mechanical losses
  - At 123 K thermal expansion coefficient $\to 0$
  - Large thermal conductivity of silicon

Problem: there is commercial available silicon with mass about 50 kg, not more.

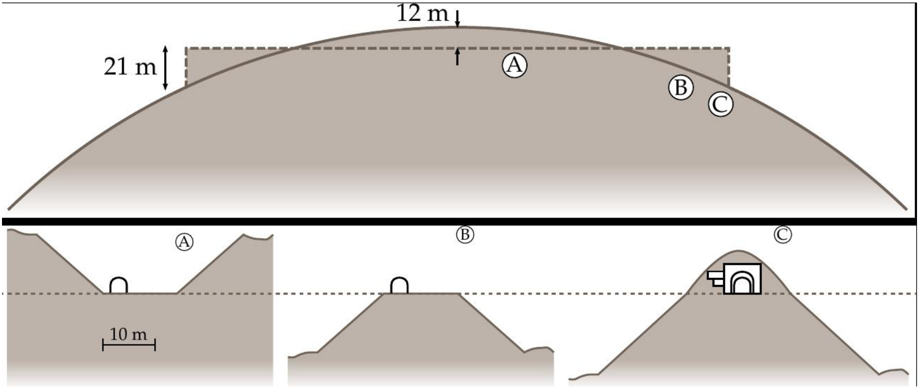
Future plans







CE — 40 rm



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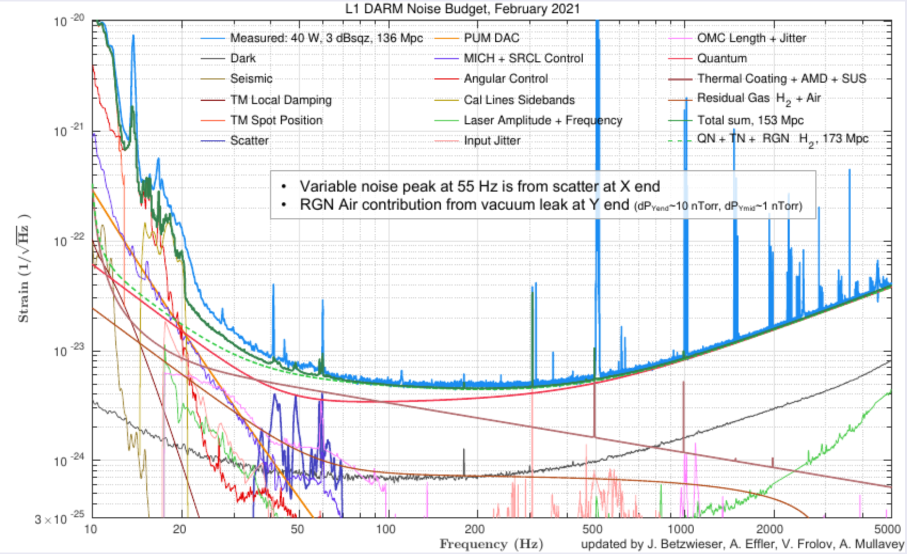
Noise budget: L1GO Louisiana, 2021

Sensitivity is close to SQL. What is it?



Coherent state of quantum oscillator

Zero state $|0\rangle$

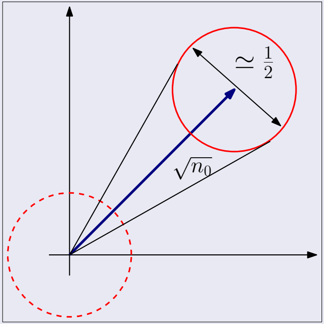
$$\sqrt{\langle \Delta x^2\rangle} = \sqrt{\frac{\hbar}{2m\omega}},\quad \sqrt{\langle \Delta p^2\rangle} = \sqrt{\frac{\hbar m\omega}{2}} \quad \Rightarrow \quad \langle \mathcal{E}\rangle = \frac{\hbar\omega}{2}$$

Cohherent state $\alpha\rangle$

α — mean amplitude,
$n_0 = \alpha^2$ — mean qaunta number

$$\langle \mathcal{E}\rangle = \hbar\omega_0\alpha^2 + \frac{\hbar\omega}{2},$$

$$\Delta n = \sqrt{n_0},\quad \Delta\phi = \frac{1}{2\sqrt{n_0}}$$



Standard Quantum Limit (SQL)

Coherent state of light

Uncertainty of phase ϕ и quanta number n in laser pulse (N — mean quanta number):

$$\Delta n = \sqrt{N}, \quad \Delta\phi = \frac{1}{2\sqrt{N}}$$

SQL — V.B. Braginsky idea (1968)

Reason of SQL[a]:
continious measurement and Heisenberg principle:

$$\Delta X_{\text{meas}}\, \Delta P_{\text{BA}} \geq \hbar/2\,.$$

[a] V.B. Braginsky, Sov. Phys. JETP, **26**, 831, 1968.
V.B. Braginsky and F.Ya. Khalili, Quantum measurement, 1992.

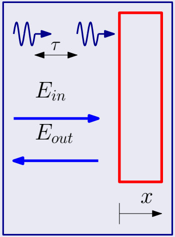
Simple optic meter

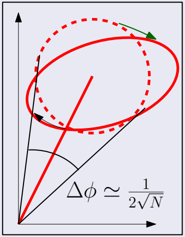
Measurement error — phase fluctuations

$$2k\delta X_{\text{meas}} = \Delta\phi, \qquad k = \frac{\omega_0}{c}$$

$$\Delta\phi = \frac{1}{2\sqrt{N}}$$

$$\Rightarrow \quad \delta X_{\text{meas}} = \frac{1}{4k\sqrt{N}}.$$





Back action

Back action: amplitude fluctuations (fluctuations of light pressure force)

$$\delta P_{\text{BA}} = 2\hbar k\sqrt{N}\,, \quad \delta X_{\text{BA}} = \frac{\delta P_{\text{BA}}\tau}{m},$$

SQL

Total error of coordinate

$$\Delta x_{\rm total} = \sqrt{\delta X_{\rm meas}^2 + \delta X_{\rm BA}^2} = \sqrt{\left[\frac{1}{4k\sqrt{N}}\right]^2 + \left[\frac{2\hbar k\sqrt{N}\cdot\tau}{m}\right]^2}$$

$$\Delta x_{\rm total}\Big|_{\rm min} = \Delta X_{SQL} = \sqrt{\frac{\hbar\tau}{m}}, \quad N_{\rm opt} = \frac{m}{8\hbar k^2\tau}$$

How to surpass SQL

Quantum Non-Demolition Measurement (QND)

To measure integral of movement — back action cancellation[a].

For example, invariant for free mass — speed (momentum).
But it should be *direct* measurement — difficulty.

[a] V.B. Braginsky and F.Ya. Khalili, Quantum measurement, Cambridge Univ. Press, 1992

Not QND measurement

- Quantum variational measurement
- Squeezed input
- Optical rigidity

Realization — more easy.

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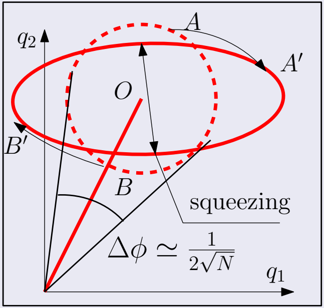
Quantum variational measurement

What will be at $N > N_{opt}$?

SQL — at $N = N_{opt}$.
At $N > N_{opt}$ quasi-classically:
LP force is larger in point A, it transforms to A'
In B LP force is smaller, it it transforms to B'
Phase disturbance.
It means — *squeezing*
$\Rightarrow$ we have to measure squeezed quadrature
SQL can be surpassed[a]



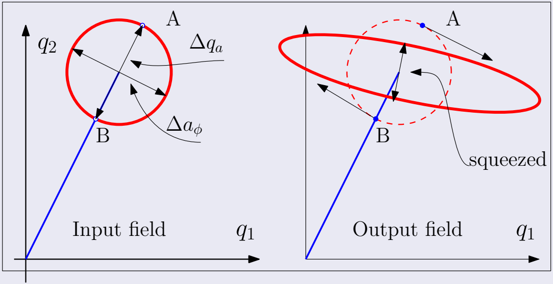
[a] S.P. Vyatchanin, ZhETF, **109**, 1873, 1996

Example: Squeezing in nonlinear media

Refraction index n depends on intensity P:

$$n = n_0(1 - \alpha P) \qquad (2)$$

Input field is in coherent state,
output one — squeezed.



Quasi-classical explanation:
point A moves slightly faster, point B — slower.

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Idea of squeezed input

Phase diagrams

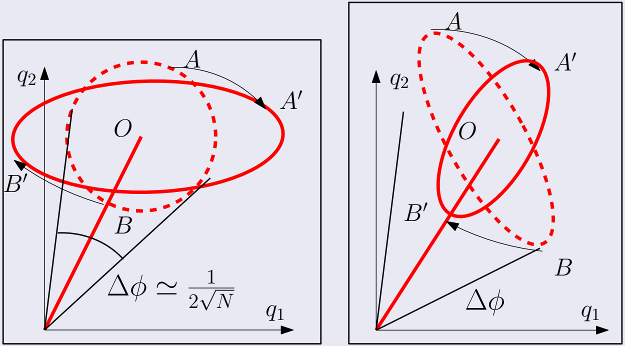


Figure: *Left:* input wave is in coherent state (dashed), phase of output wave is disturbed due to LP pressure ($A \to A'$, $B \to B/$). *Right:* input wave is in squeezed state (dashed), initial squeezing is chosen in optimal way so that after reflection — phase squeezing.

Frequency dependence

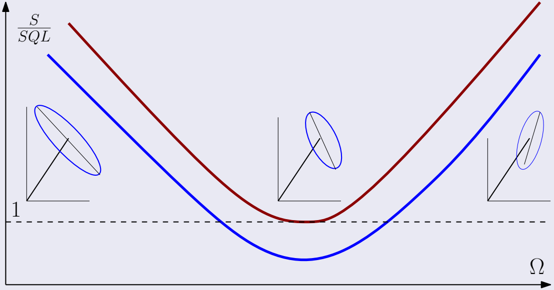
Squeezing should depend on spectral frequency

Recall

$$q_\phi(\Omega) = \beta \left\{ d_\phi(\Omega) - \mathcal{K}\, d_a \right\} - \sqrt{2\beta\mathcal{K}}\, \frac{F_s(\Omega)}{\sqrt{2\hbar m \Omega^2}}\,,$$

$$q_a(\Omega) = \beta\, d_a(\Omega), \quad \boxed{\mathcal{K} \equiv \frac{2\hbar\kappa_0\omega_0^2 A^2}{mL^2\Omega^2 \left|\frac{\kappa_0}{2} - i\Omega\right|^2}, \quad \beta \equiv \frac{\frac{\kappa_0}{2} + i\Omega}{\frac{\kappa_0}{2} - i\Omega}}\,.$$

Power parameter $\mathcal{K}$ defines the value of ponderomotive squeezing. It depends on frequency ($\mathcal{K} \sim 1/\Omega^2$).

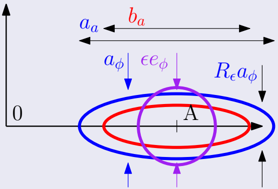


Frequency dependent squeezing

Experimental difficulties

- Relatively easy to obtain squeezing on high frequencies in range 100 kHz and larger. For GW detectors we need squeezing in band 10 Hz – 1 kHz.
- Frequency dependent squeezing on low frequencies — difficult task.
- Loss factor: squeezing is very vulnerable to optical losses ("problem of waist").

$$b_a = R_\epsilon\, a_a + \epsilon\, e_a = R_\epsilon\, e^r a_{a\,\mathrm{vac}} + \epsilon\, e_a,$$
$$b_\phi = R_\epsilon\, a_\phi + \epsilon\, e_\phi = R_\epsilon\, e^{-r} a_{\phi\,\mathrm{vac}} + \epsilon\, e_\phi,$$



Plan and reality

A+ LIGO plan: to inject 12 dB squeezing.
Now — 5.4 dB frequency dependent squeezing is realized (!)
5 dB $\Rightarrow$ $\Delta q_{vac}/\Delta q_{sq} \simeq 1.8$, 10 dB $\Rightarrow$ $\Delta q_{vac}/\Delta q_{sq} \simeq 3.1$

1 Introduction

2 Scale of displacements

3 Laser GW detectors — what is now?

4 Standard Quantum Limit (SQL) and how to surpass it

5 Quantum variational measurement

6 Squeezed input

7 Conclusion

Conclusion

- Accuracy of GW detectors are about 160 Mp.
- During O4a about 81 BBH (binary black holes) coalescences are detected.
- No BNS (binary neutron stars) coalescences are detected.
- Accuracy of GW detectors are close to SQL
  $\Rightarrow$ surpassing SQL is an actual problem.
- Practical methods to overcome SQL for free mass
  - Quantum variational measurement
  - Squeezing input

Long Live Gravitational Waves!
Long Live Quantum measurements!

Thank you for attention!