John Adams Institute for Accelerator Science

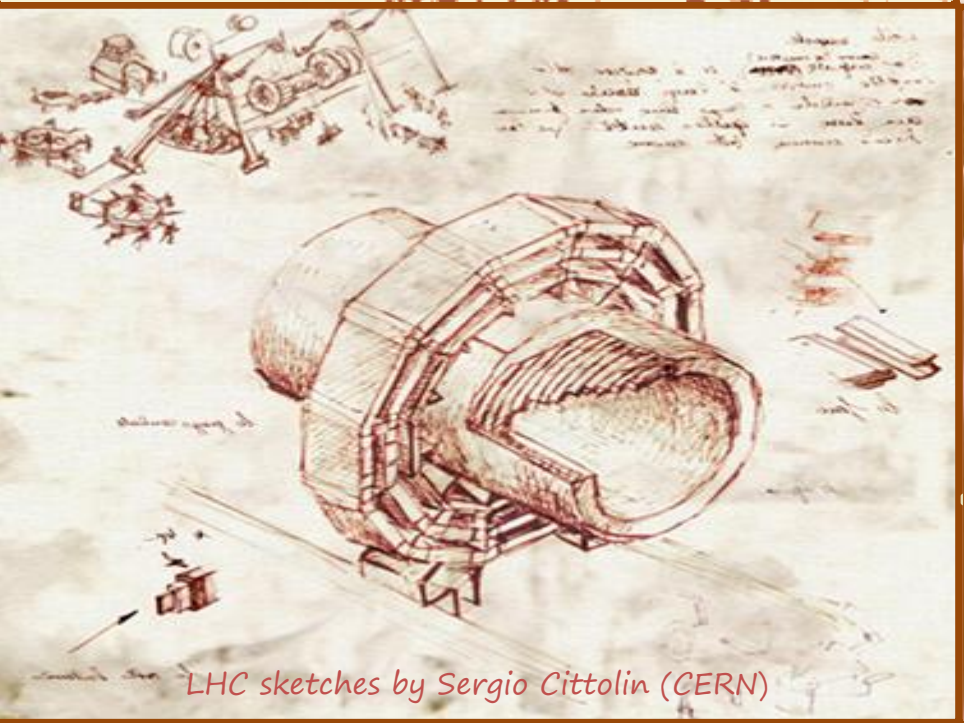
Imperial College London

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF OXFORD

Evolution of scientific instruments

(from methodology of inventiveness TRIZ to applications of plasma acceleration)

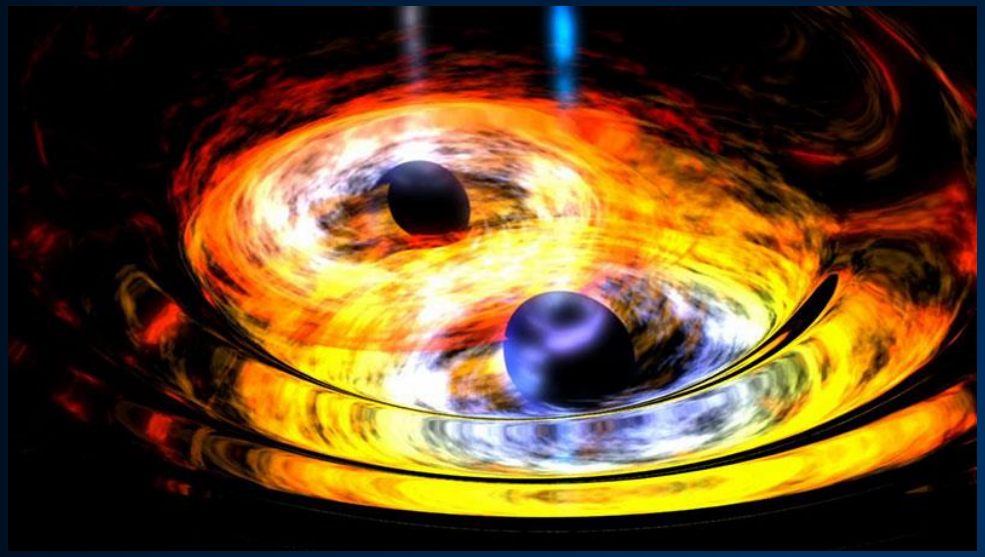


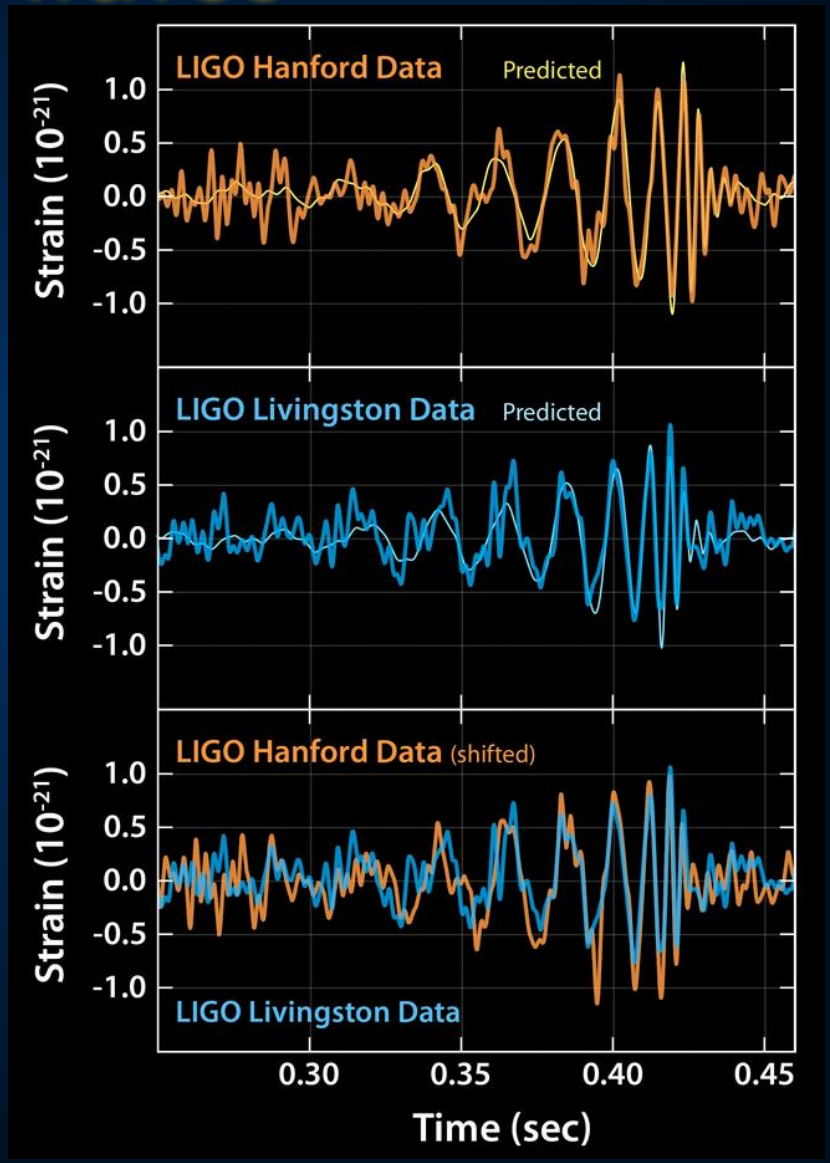
LHC sketches by Sergio Cittolin (CERN)

Prof. Andrei A. Seryi
John Adams Institute

JUAS seminar
5 March 2018

2017 Nobel Prize in Physics – gravitational waves





How this science area will evolve?
What is the next instrument?
Can TRIZ help predicting and building future instruments?
Can TRIZ help to make discoveries in fundamental science?

Image: Caltech/MIT/LIGO Lab

Scientific revolutions – what drives them?

Two points of view:

Philosopher Thomas Kuhn:

scientific revolutions are concept-driven

"paradigm shifts"

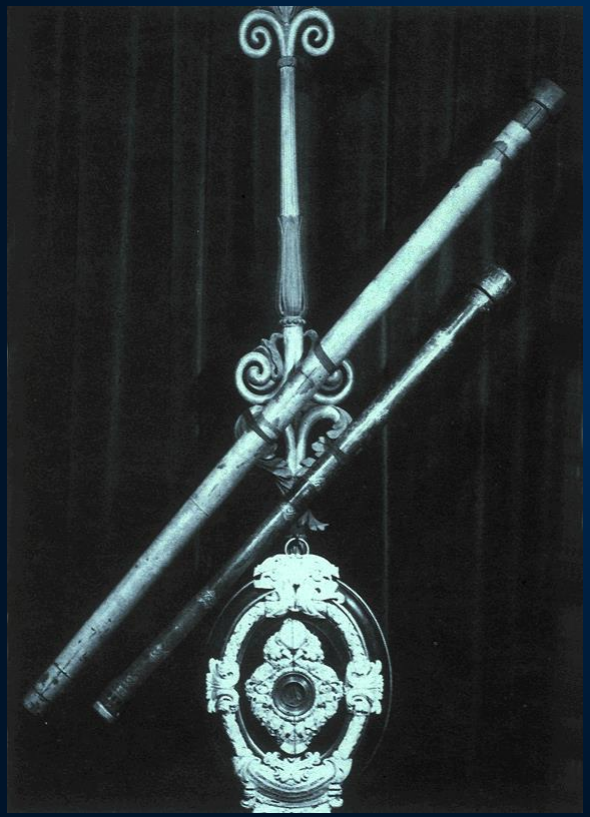
Physicist Freeman Dyson:

scientific revolutions are tool-driven

"The human heritage that gave us toolmaking hands and inquisitive brains did not die. In every human culture, the hand and the brain work together to create the style that makes a civilization….

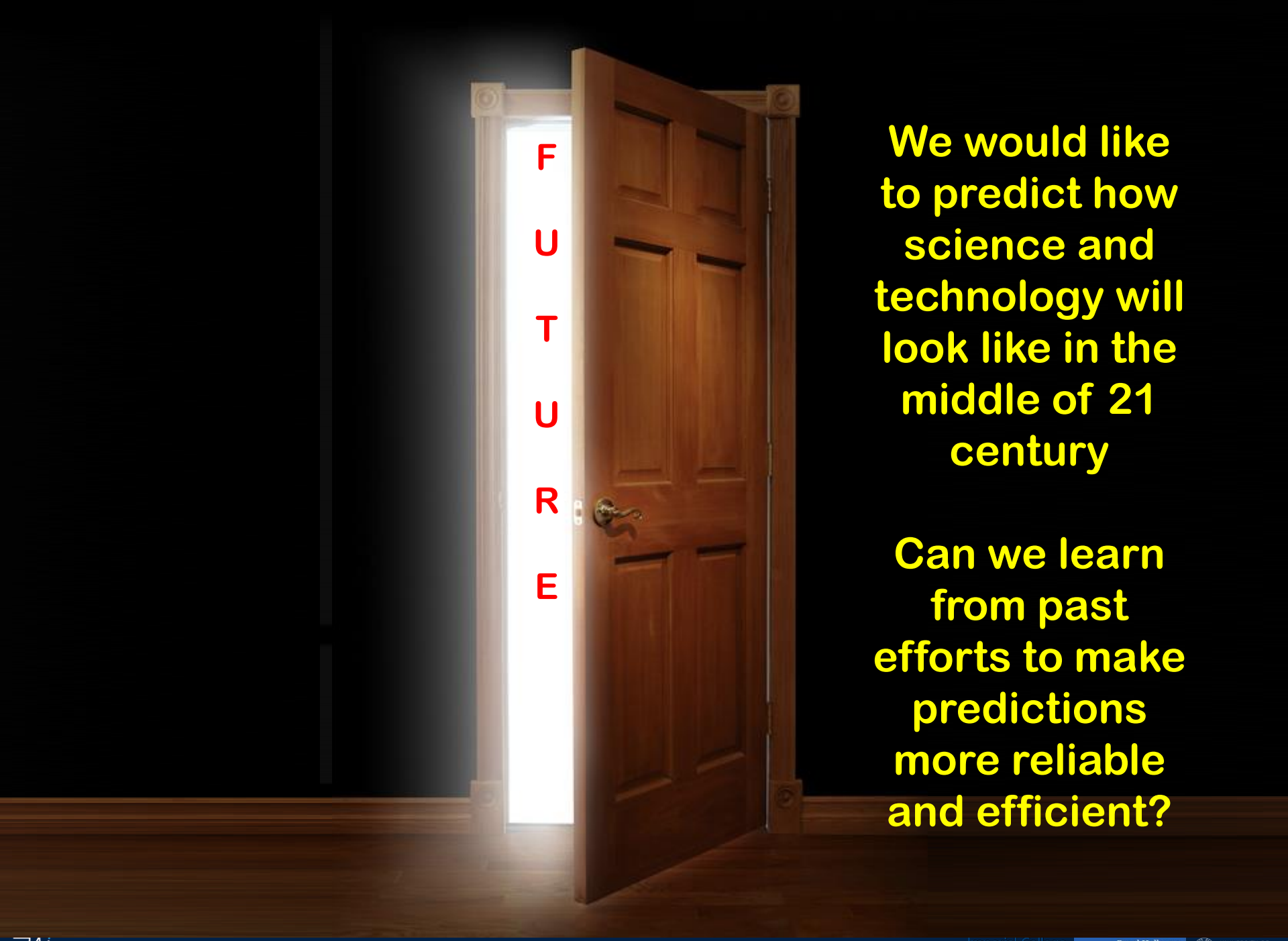
Science will continue to generate unpredictable new ideas and opportunities. And human beings will continue to respond to new ideas and opportunities with new skills and inventions. We remain toolmaking animals, and science will continue to exercise the creativity programmed into our genes."

“Measure what is measurable, and make measurable what is not so”



Galileo Galilei
1564-1642

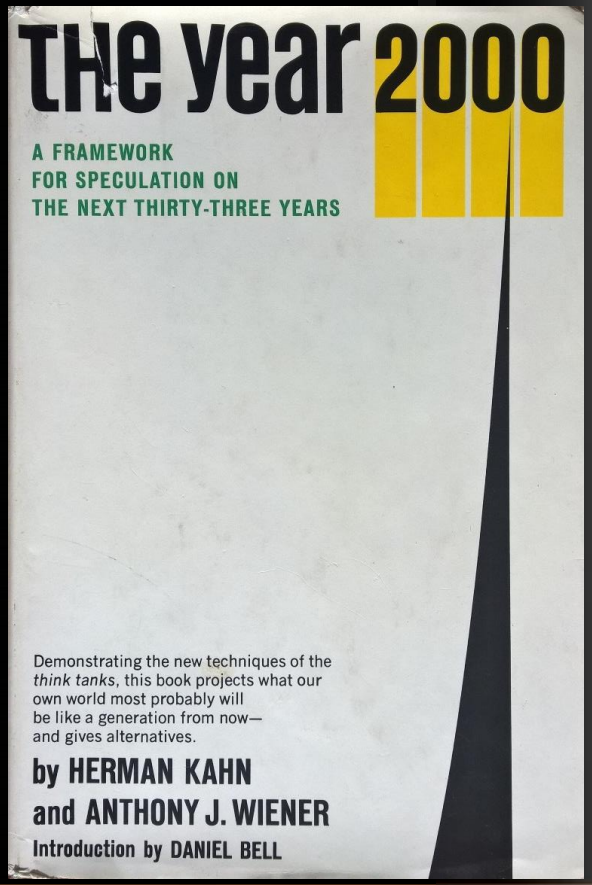

F
U
T
U
R
E



We would like to predict how science and technology will look like in the middle of 21 century

Can we learn from past efforts to make predictions more reliable and efficient?

Predictions made in 1968 for the year 2000

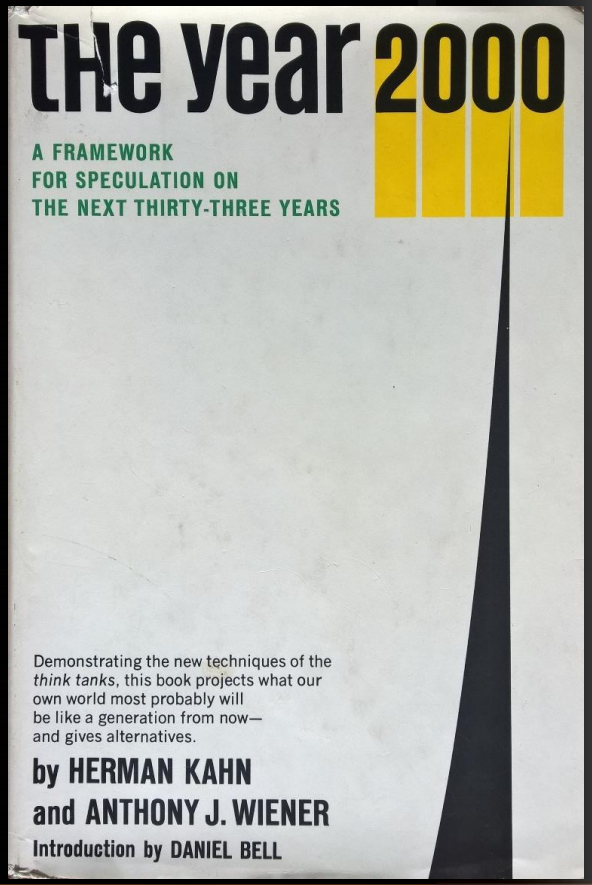


"The Year 2000", 1968
K. Herman, A. Wiener
ISBN 978-0025604407

We would like to predict how science and technology will look like in the middle of 21 century

Can we learn from past efforts to make predictions more reliable and efficient?

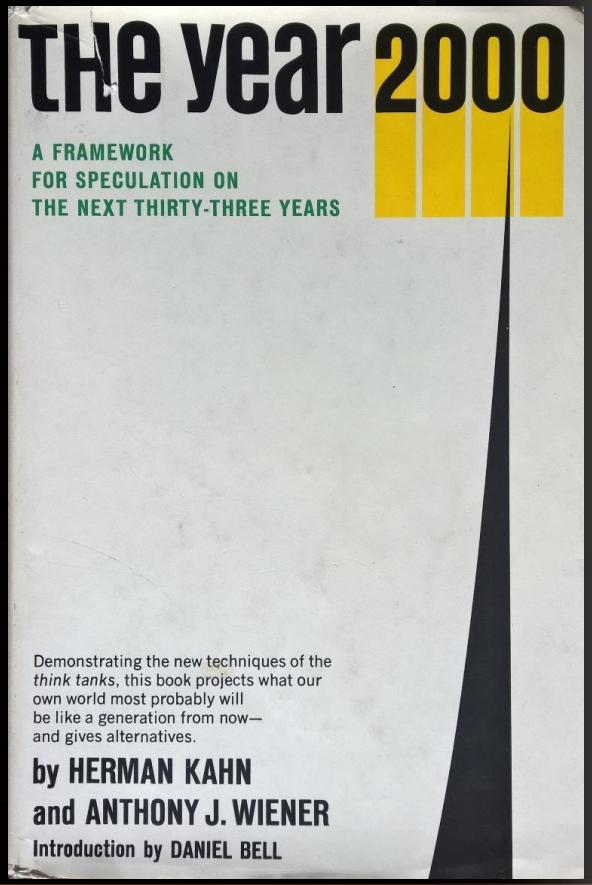
Predictions made in 1968 for the year 2000



"The Year 2000", 1968
K. Herman, A. Wiener
ISBN 978-0025604407

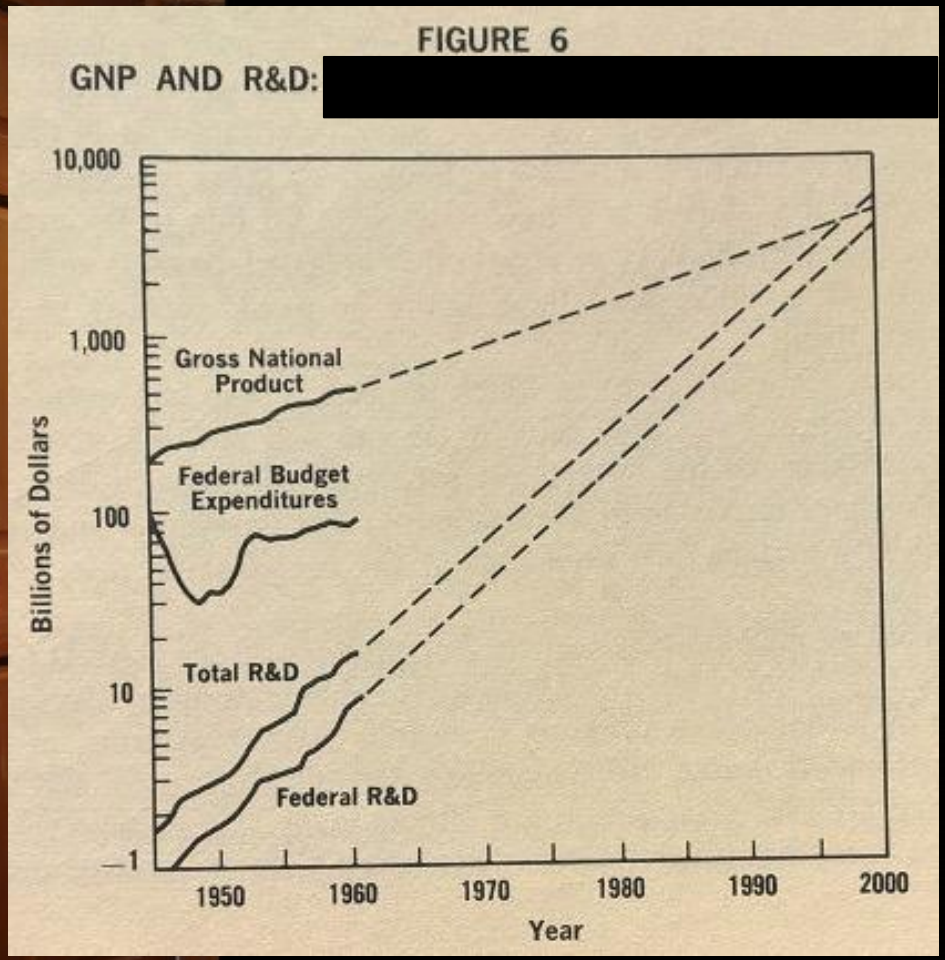
Importance of rigorous methodology of predictions is very important

Predictions made in 1968 for the year 2000

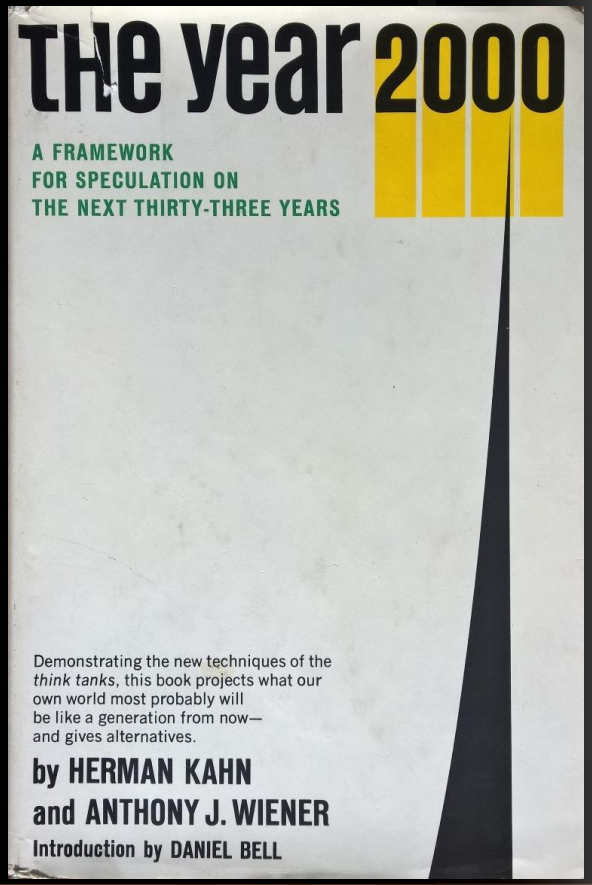


"The Year 2000", 1968
K. Herman, A. Wiener
ISBN 978-0025604407

FUTURE

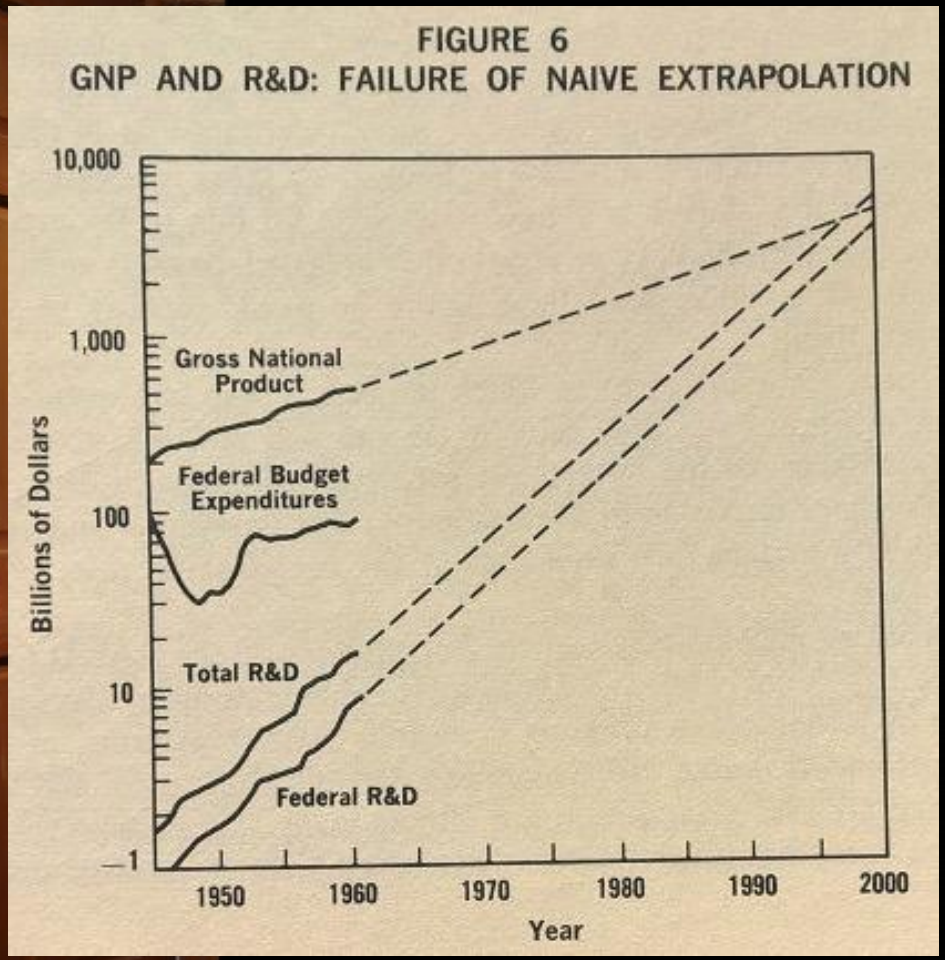


Predictions made in 1968 for the year 2000



"The Year 2000", 1968
K. Herman, A. Wiener
ISBN 978-0025604407

F U T U R E



Lesson: avoid naïve extrapolations

Predictions made in 1968 for the year 2000, examples:

1- Multiple applications of lasers for sensing, communication, cutting, welding… ✓

31- Some control of weather and/or climate

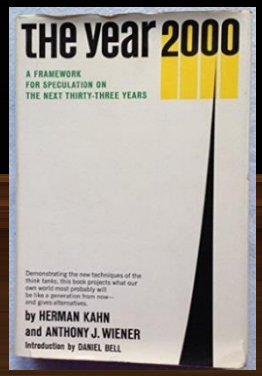
35 – human hibernation for extensive periods (months to years)

58- Chemical methods for improving memory and learning

67- Commercial extraction of oil from shale ✓

81- Personal “pagers” and perhaps even two-way pocket phones ✓

99- Artificial moon for lighting large areas at night



“The Year 2000”, 1968
K. Herman, A. Wiener
ISBN 978-0025604407

Some predictions were accurate, some not

To make viable predictions and efficient research plans:

Learn from the past of this particular area of science…

…but also look around, across different disciplines and areas of science…

And, possibly, use TRIZ laws of evolution

Evolution laws and principles

Are there some patterns in evolution of scientific instruments?

Are there some principles that connect inventions of different scientific instruments?

Let's look at some familiar (for science) examples from a different (TRIZ) angle

Two scientific instruments

What are these two instruments?

What is in common?

Two scientific instruments

LIGO, Hanford

SLC, Stanford

What is in common?

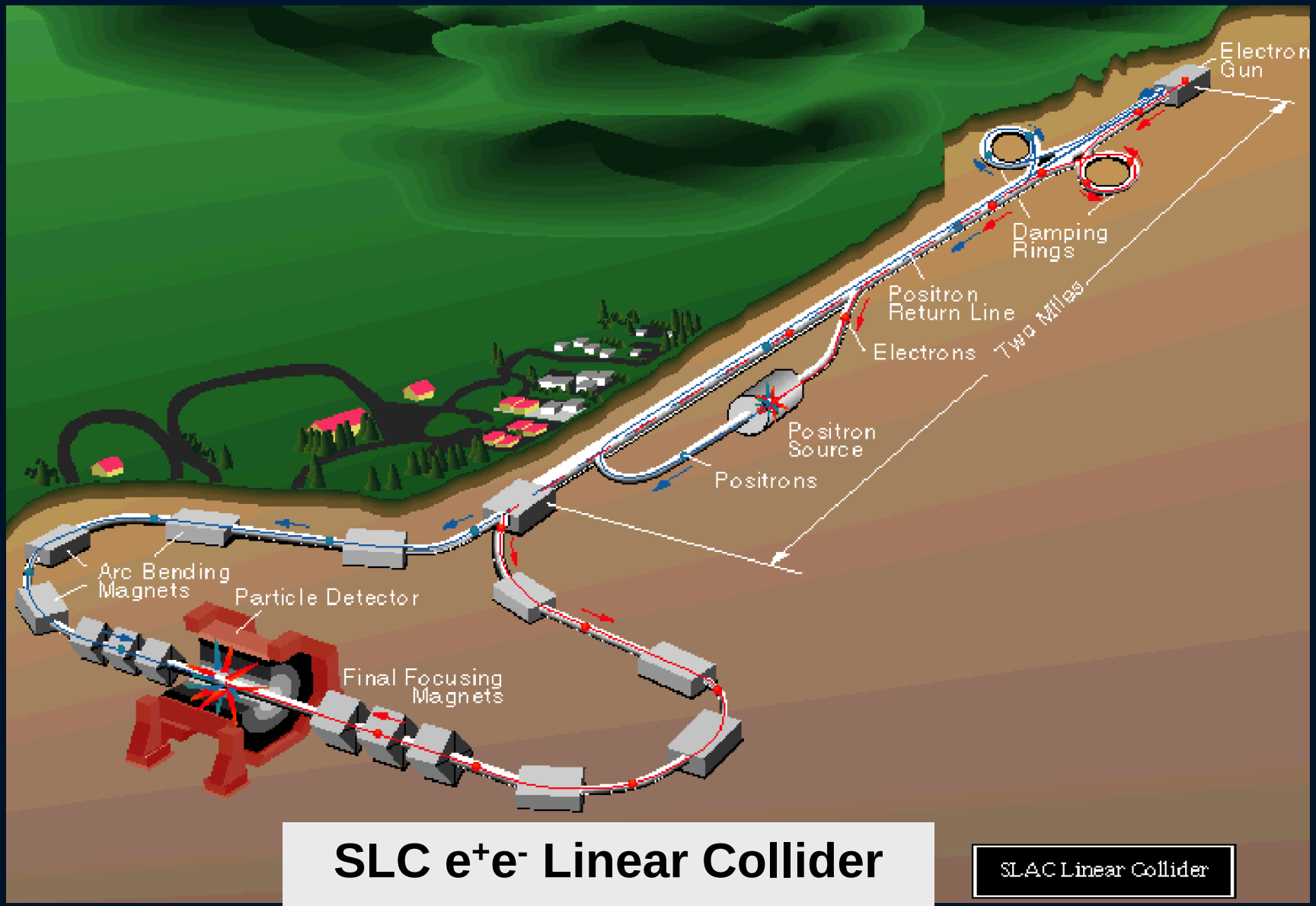
A lot. And also sensitivity to seismic noises.

The first ever linear collider

SLC e^+e^- Linear Collider

for center of mass energy 50 GeV

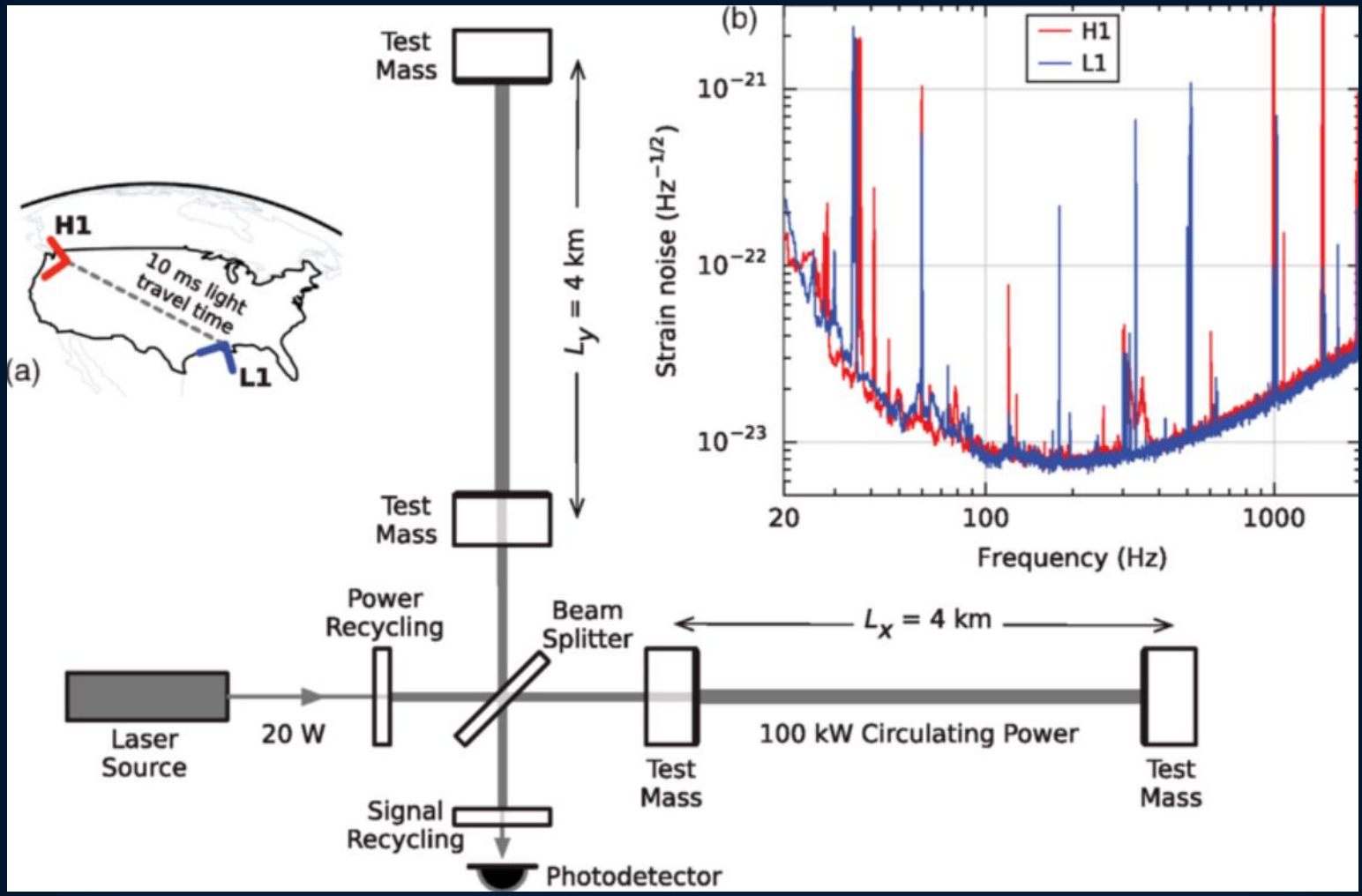
The first ever linear collider



SLC e^+e^- Linear Collider

for center of mass energy 50 GeV

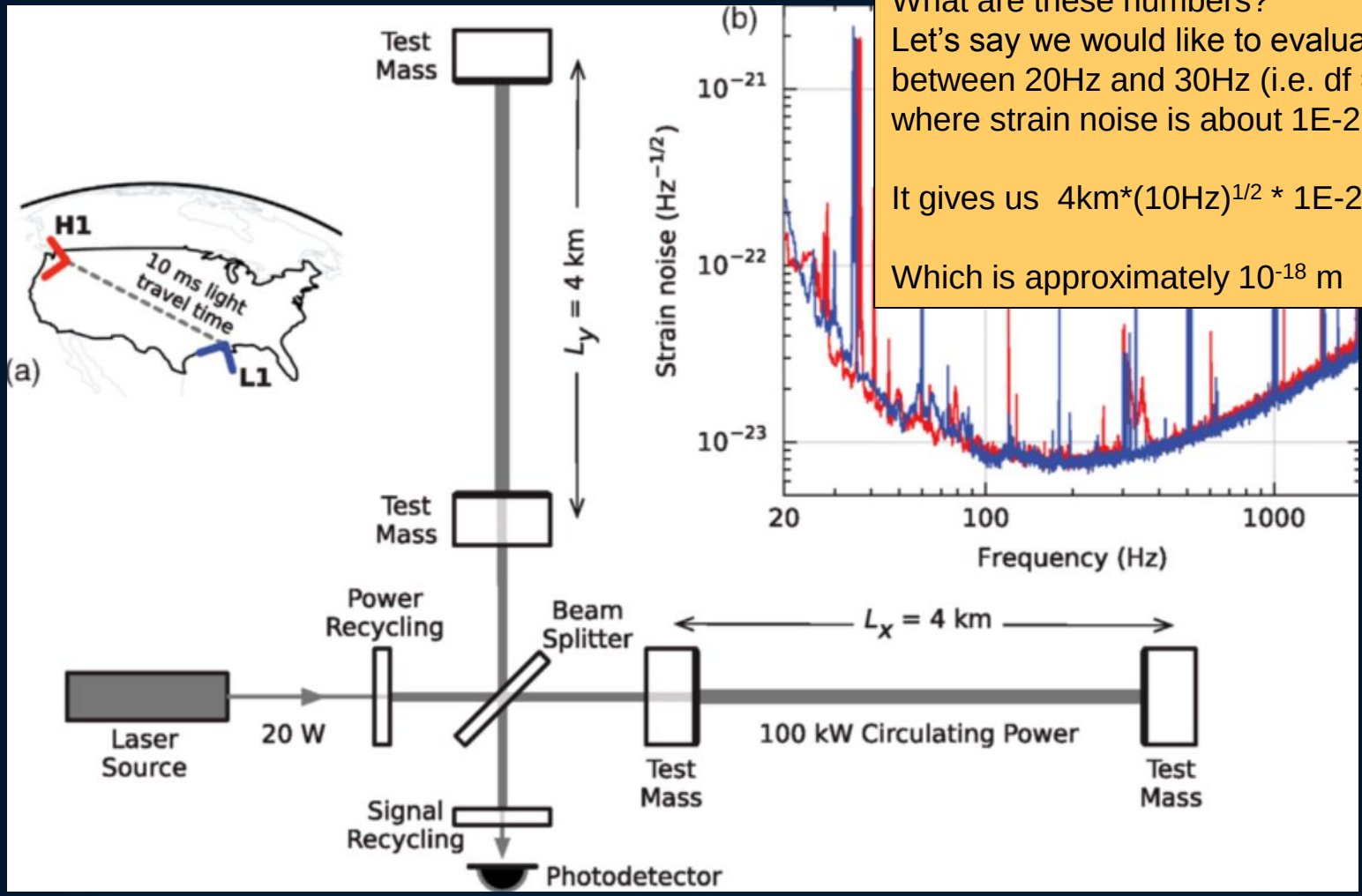
LIGO



LIGO layout and sensitivity curve

Source: PRL 116, 061102 (2016)

LIGO



What are these numbers?
Let's say we would like to evaluate noise between 20Hz and 30Hz (i.e. df = 10Hz), where strain noise is about 1E-22 $Hz^{-1/2}$

It gives us 4km*$(10Hz)^{1/2}$ * 1E-22 $Hz^{-1/2}$

Which is approximately 10^{-18} m

LIGO layout and sensitivity curve

Source: PRL 116, 061102 (2016)

LIGO seismic sensitivity

Gravity gradients, caused by direct gravitational coupling of mass density fluctuations to the suspended mirrors, were identified as a potential source of noise in ground-based gravitational-wave detectors in 1972 [312]. The noise associated with gravity gradients was first formulated by Saulson [274] and Spero [290], with later developments by Hughes and Thorne [183] and Cella and Cuoco [93]. These studies suggest that the dominant source of gravity gradients arise from seismic surface waves, where density fluctuations of the Earth's surface are produced near the location of the individual interferometer test masses, as shown in Figure 7.

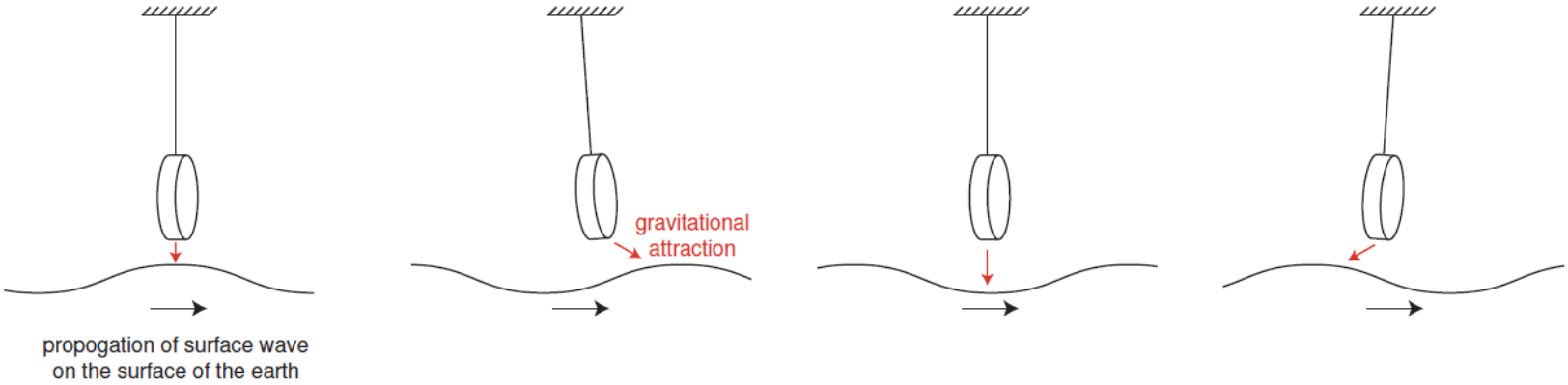


Figure 7: Time-lapsed schematic illustrating the fluctuating gravitational force on a suspended mass by the propagation of a surface wave through the ground.

Source: arXiv:1102.3355

PHYSICAL REVIEW D, VOLUME 58, 122002

Seismic gravity-gradient noise in interferometric gravitational-wave detectors

Scott A. Hughes
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
and Max-Planck-Institut für Gravitationsphysik, Schlatzweg 1, 14473 Potsdam, Germany
(Received 4 June 1998; published 18 November 1998)

When ambient seismic waves pass near and under an interferometric gravitational-wave detector, they induce density perturbations in the Earth, which in turn produce fluctuating gravitational forces on the interferometer's test masses. These forces mimic a stochastic background of gravitational waves and thus constitute a noise source. This *seismic gravity-gradient noise* has been estimated and discussed previously by Saulson

at noisy times, and (iii) a corresponding estimate of the magnitude of $\beta'(f)$ at quiet and noisy times. We conclude that *at quiet times* $\beta' \simeq 0.35-0.6$ at the LIGO sites, and *at noisy times* $\beta' \simeq 0.15-1.4$. (For comparison, Saulson's simple model gave $\beta=\beta'=1/\sqrt{3}=0.58$.) By folding our resulting transfer function into the ''standard LIGO seismic spectrum,'' which approximates $\tilde{W}(f)$ at typical times, we obtain the gravity-gradient noise spectra. At quiet times this noise is below the benchmark noise level of ''advanced LIGO interferometers'' at all frequencies (though not by much at ~ 10 Hz); at noisy times it may significantly exceed the advanced noise level near 10 Hz. The lower edge of our quiet-time noise constitutes a limit, beyond which

Source for portrait: Nobel Media

PHYSICAL REVIEW D, VOLUME 60, 082001

Human gravity-gradient noise in interferometric gravitational-wave detectors

Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125 and Max-Planck-Institut für GravitationsPhysik, Schlatzweg 1, 14473 Potsdam, Germany

Carolee J. Winstein
Department of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, Califor

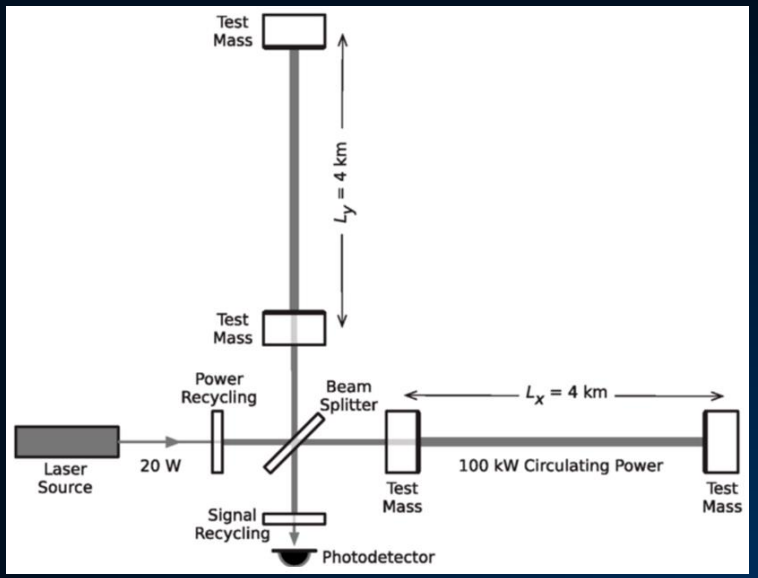
(Received 5 October 1998; published 24 September 1999)

Among all forms of routine human activity, the one which produces the strongest gravity-gradient noise in interferometric gravitational-wave detectors (e.g. LIGO) is the beginning and end of weight transfer from one foot to the other during walking. The beginning and end of weight transfer entail sharp changes (time scale

test mass, and we estimate this formula to be accurate to within a factor 3. To ensure that this noise is negligible in advanced LIGO interferometers, people should be prevented from coming nearer to the test masses than $r \simeq 10$ m. A $r \simeq 10$ m exclusion zone will also reduce to an acceptable level gravity gradient noise from the slamming of a door and the striking of a fist against a wall. The dominant gravity-gradient noise from automobiles and other vehicles is probably that from decelerating to rest. To keep this below the sensitivity of advanced LIGO interferometers will require keeping vehicles at least 30 m from all test masses.

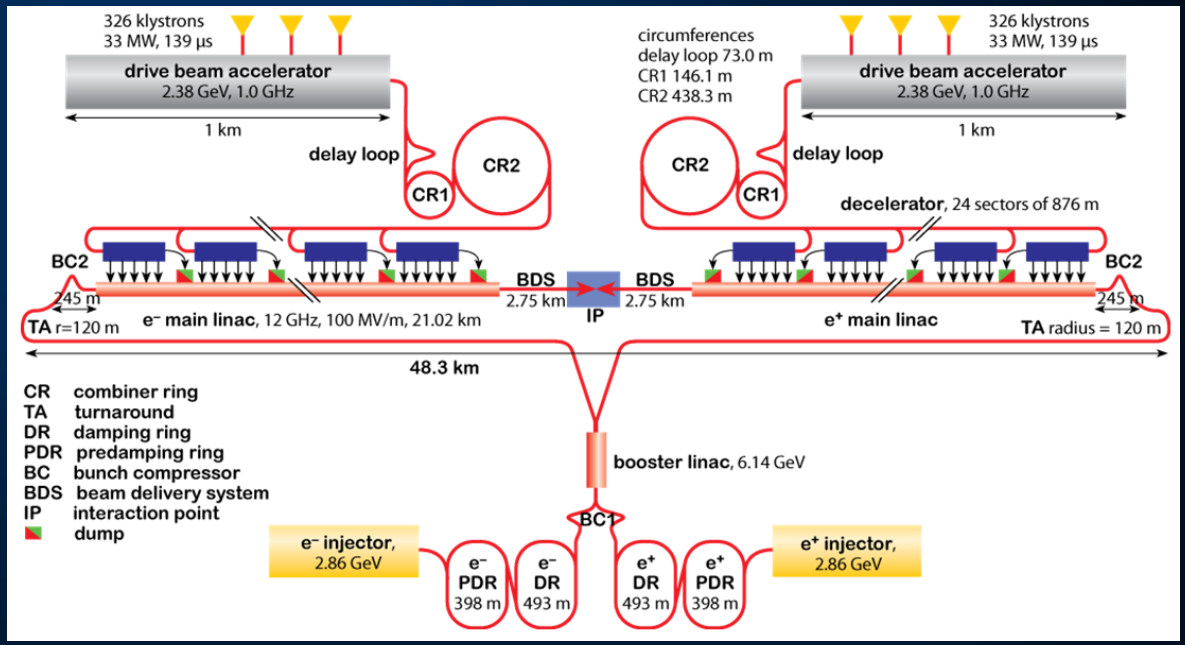
Source for portrait: Nobel Media

These two instruments



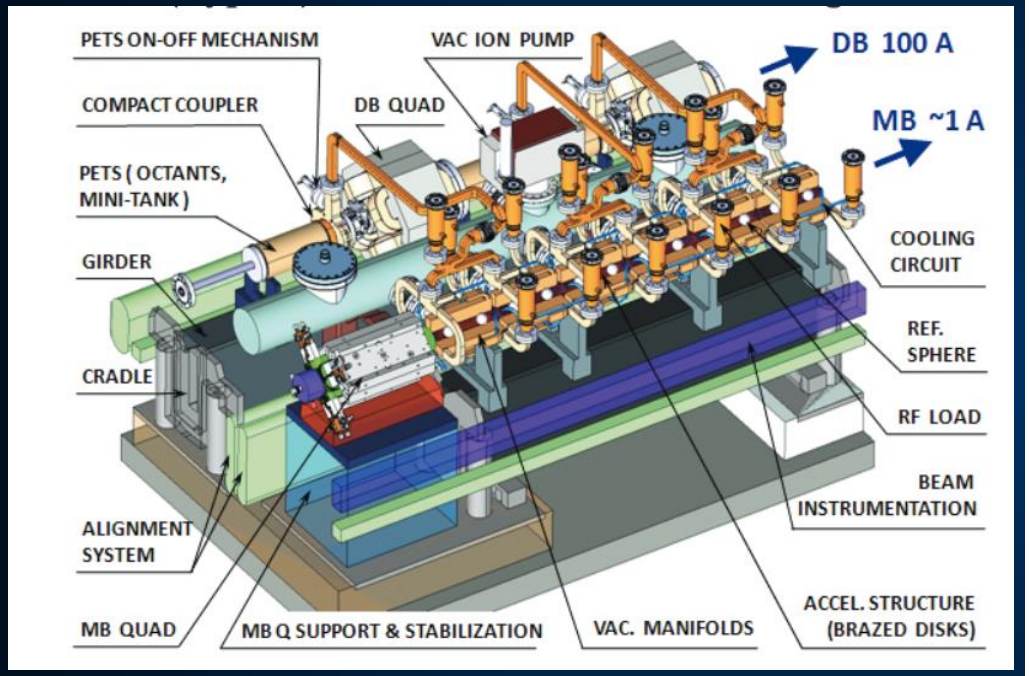
LIGO: keep two objects placed 4km apart stable* to about 1e-9 nm

CLIC – Compact Linear Collider: keep 100,000 objects distributed over 50km stable* to about 10 nm

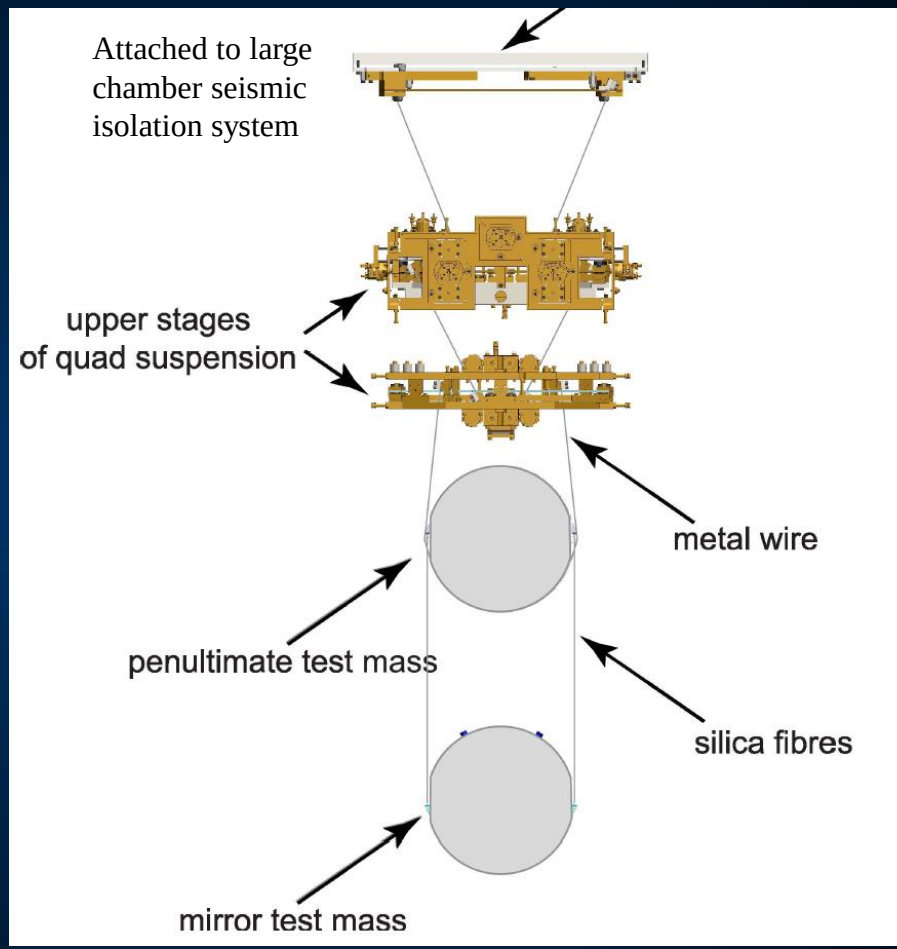


*) approximately, and in certain frequency range

CLIC stability & LIGO test mass isolation



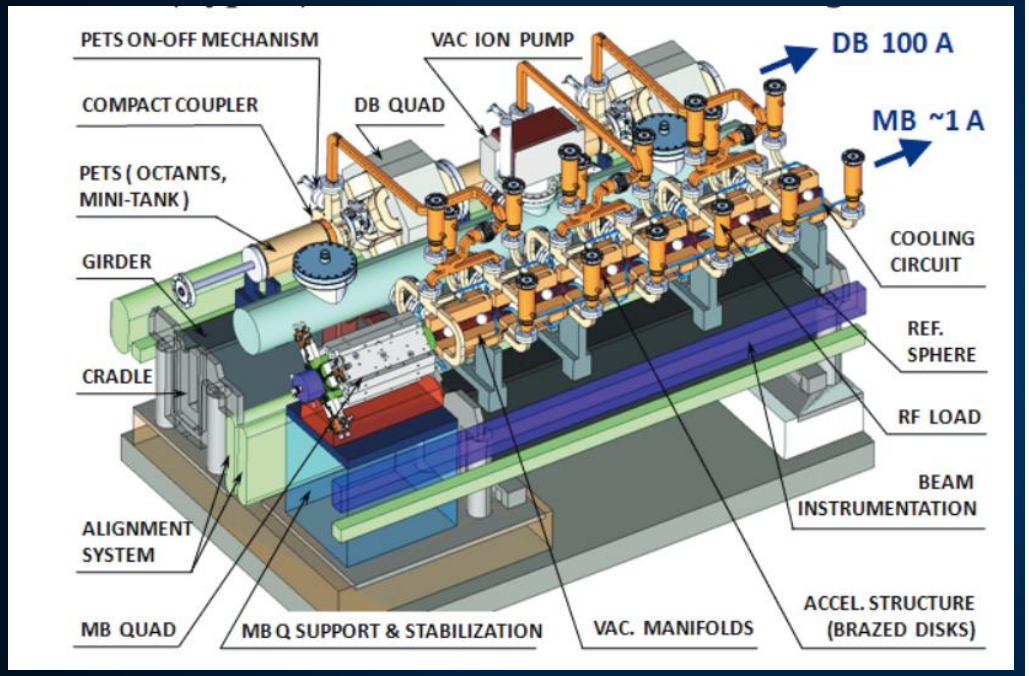
Nested stabilization/alignment systems of CLIC two-beam module

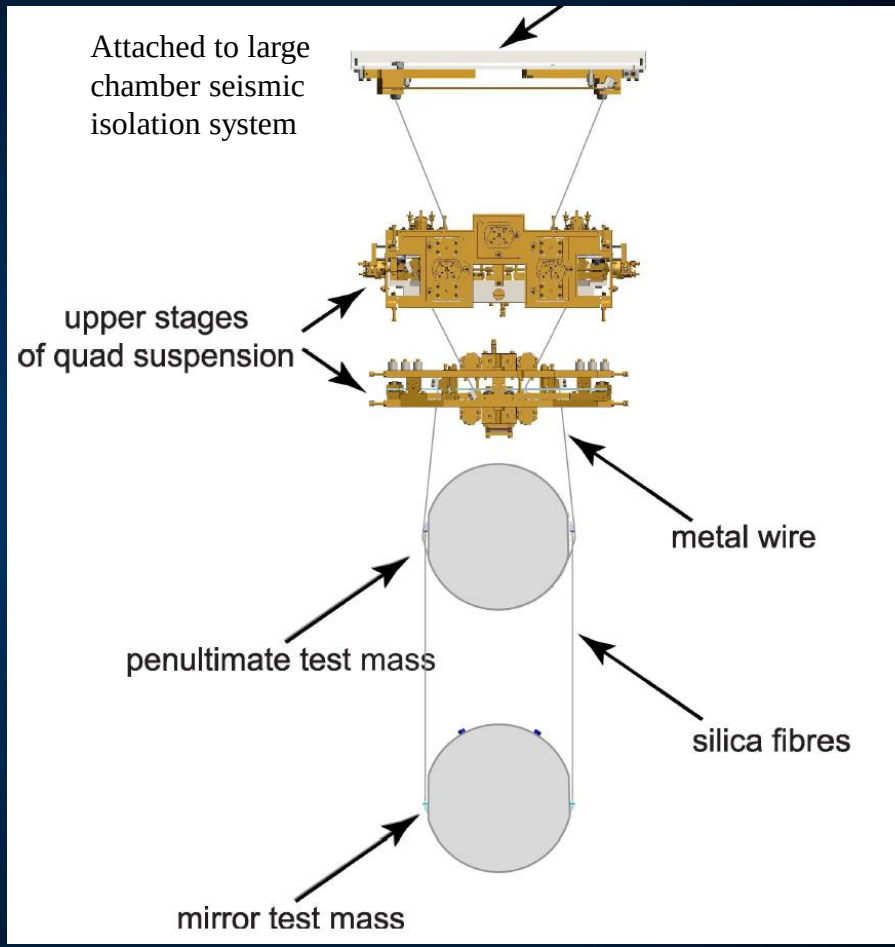


Nested pendulums of LIGO

Source: arXiv:1102.3355

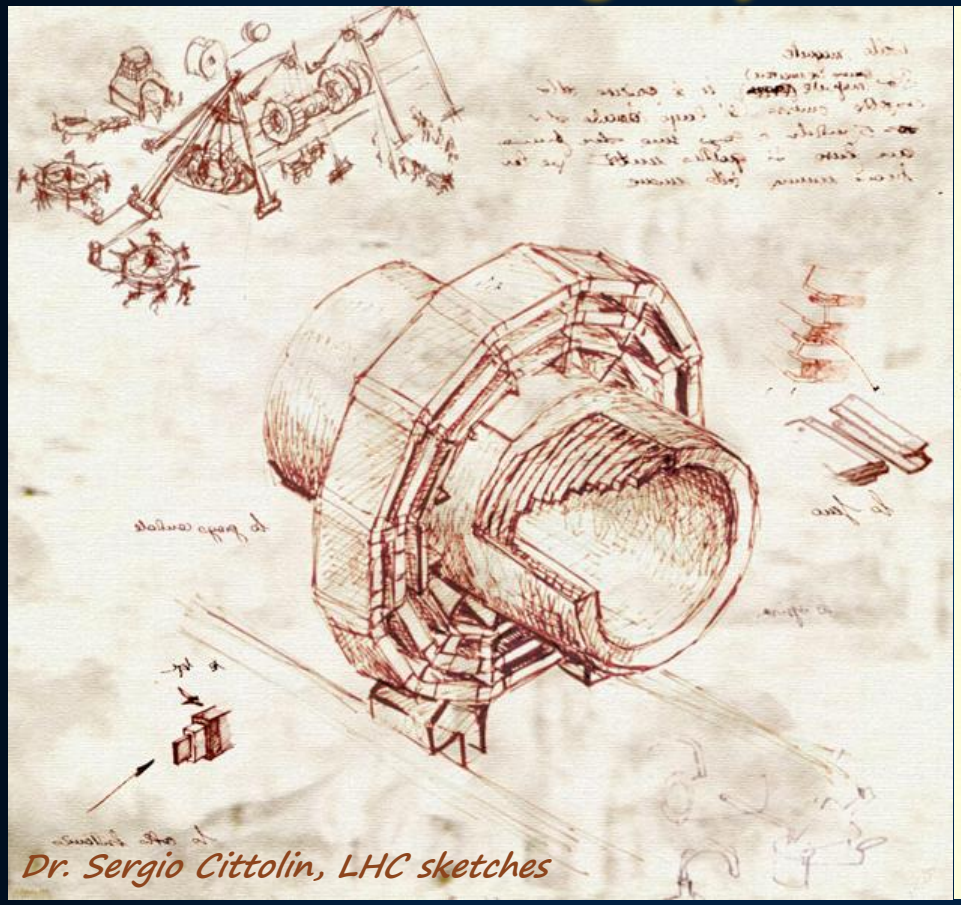
CLIC stability & LIGO test mass isolation

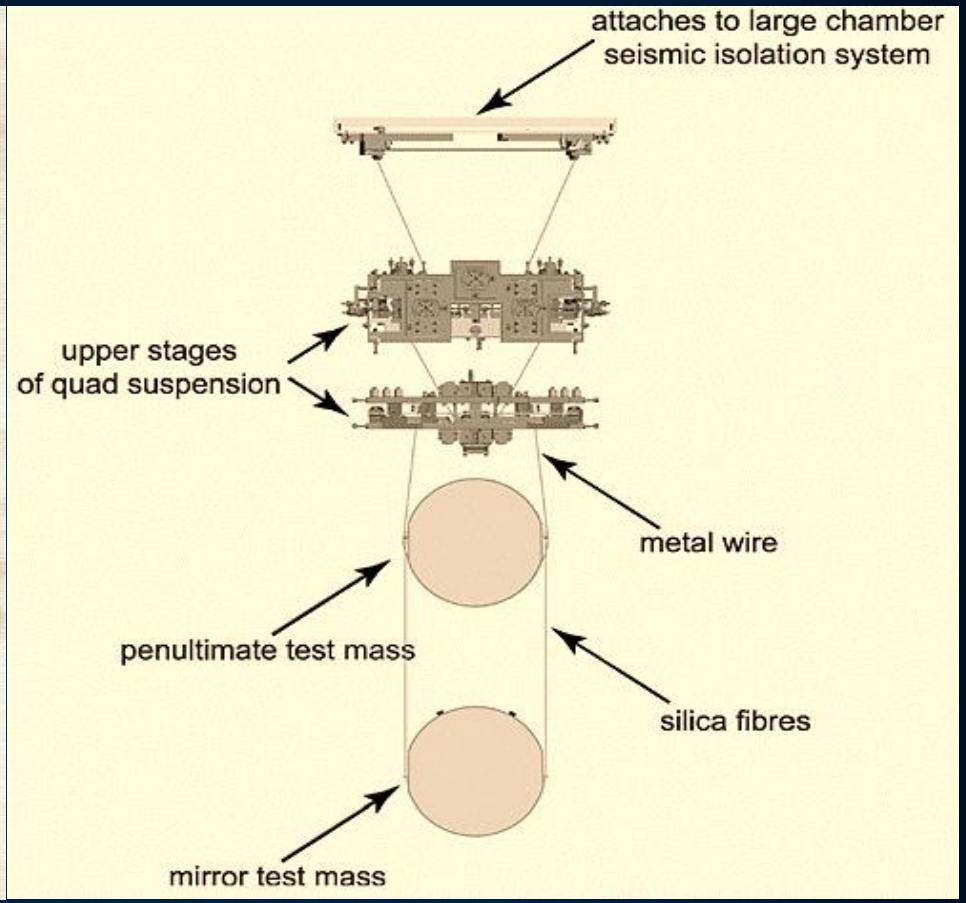




… connected via an inventive principle – let's call it the principle of "nested dolls"

Particle or gravitational waves detectors are arranged just as nested dolls…





Examples of “nested dolls” *inventive principle* can be found in various areas

The principle of “nested dolls” in poetry

“This is the house that Jack built”

This is the house that Jack built.

This is the malt
That lay in the house that Jack built.

This is the rat,
That ate the malt
That lay in the house that Jack built.

This is the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

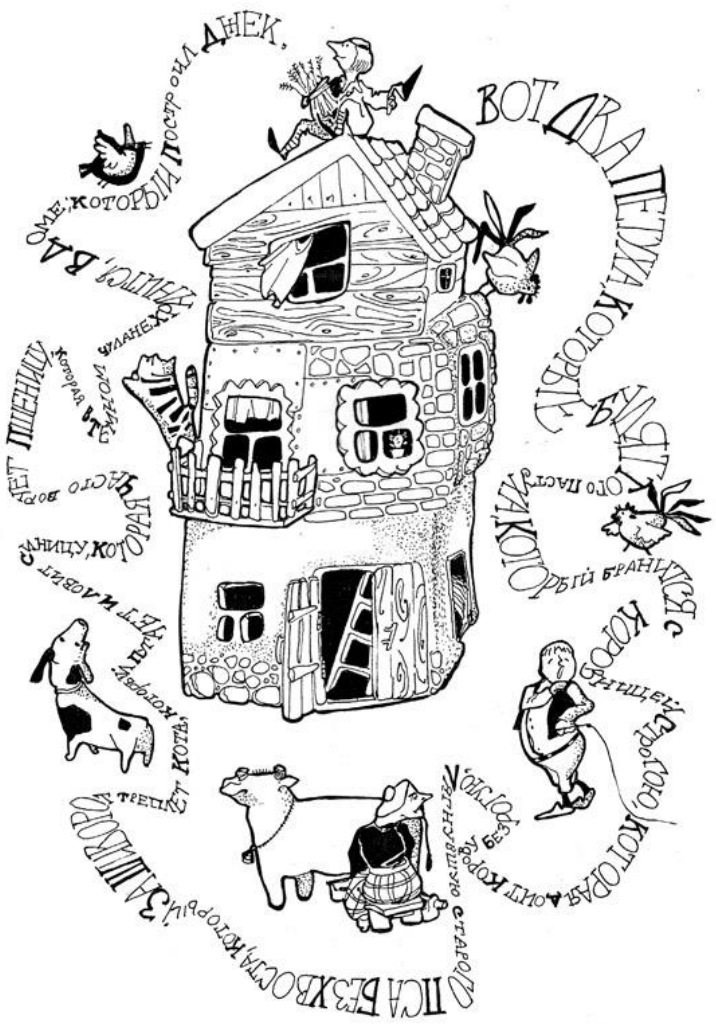


Illustration by Olga Rubtsova (Atroshenko)

This is the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the farmer sowing his corn,
That kept the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

Mother Goose Rhymes

The principle of “nested dolls” in poetry

“This is the house that Jack built”

This is the house that Jack built.

This is the malt
That lay in the house that Jack built.

This is the rat,
That ate the malt
That lay in the house that Jack built.

This is the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

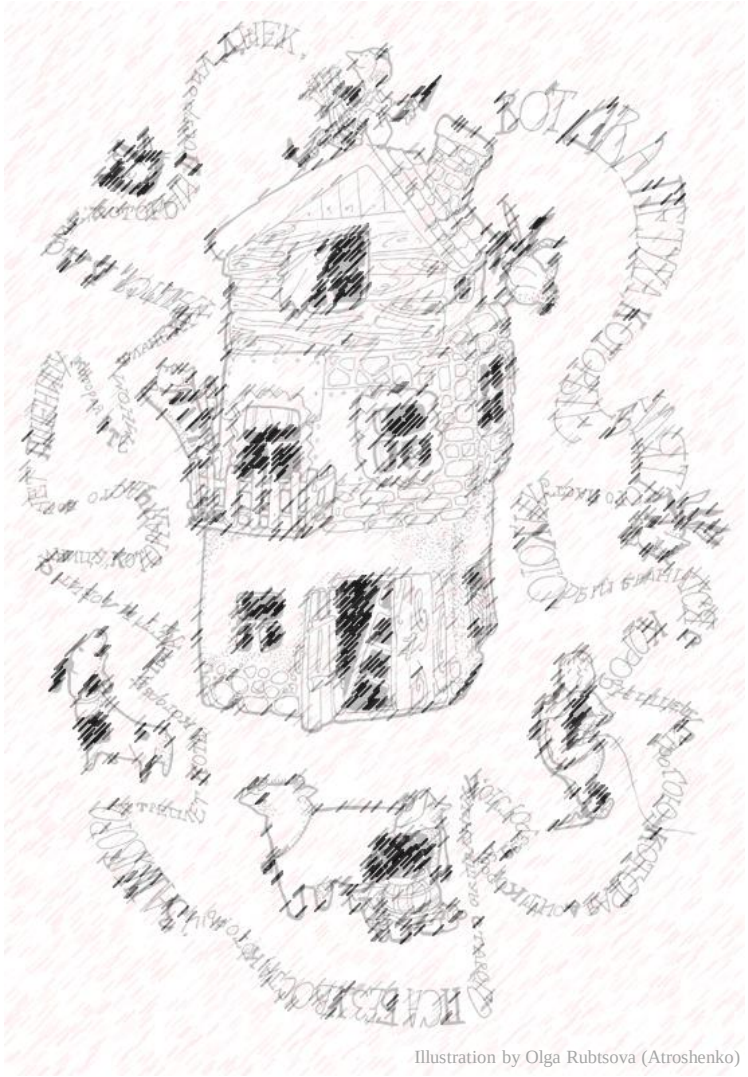


Illustration by Olga Rubtsova (Atroshenko)

This is the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

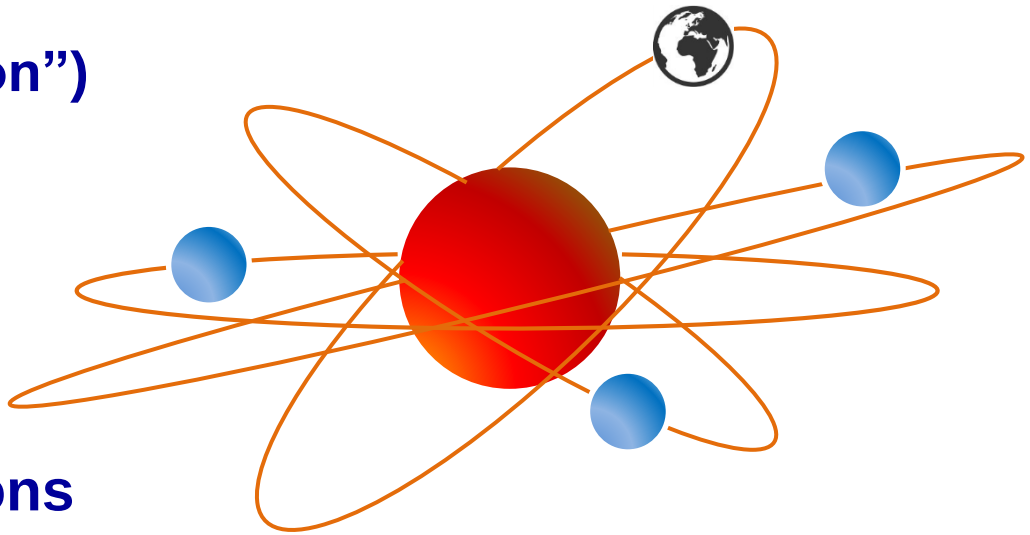
This is the farmer sowing his corn,
That kept the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

Mother Goose Rhymes

Is there any example of this principle in science fiction?

The principle of “nested dolls” in sci-fi poetry

Valery Bryusov – 1920 poem
“Atom” (“The World of Electron”)



Can you imagine that electrons
Are planets circling their Suns?
Space exploration, wars, elections
And hundreds of computer tongues
…

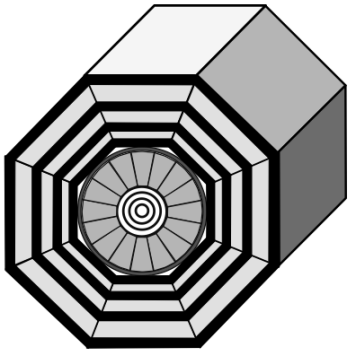
Remake-translation by A.Seryi

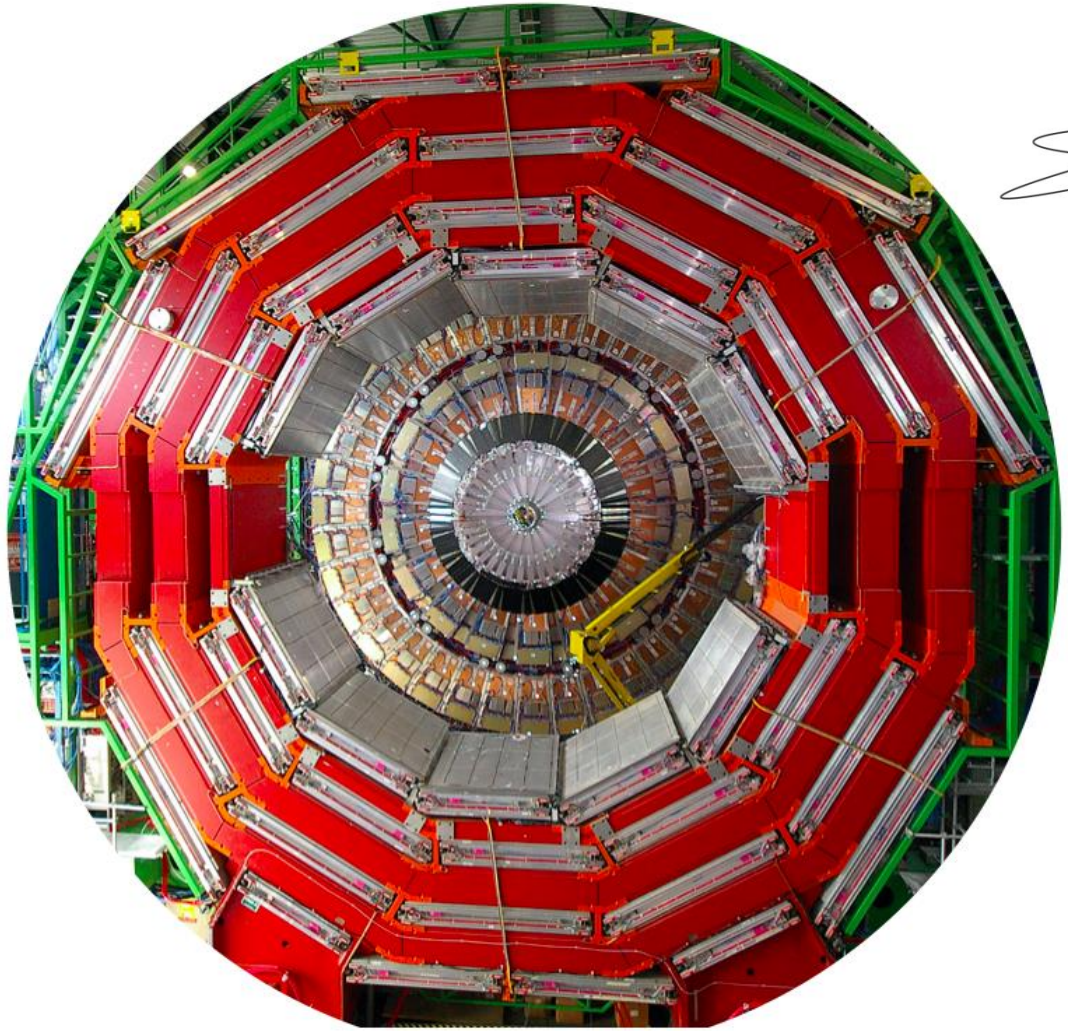
Быть может, эти электроны
Миры, где пять материков,
Искусства, знанья, войны, троны
И память сорока веков!

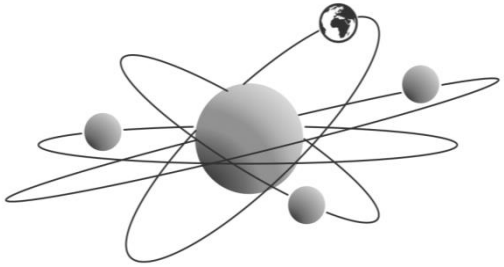
Ещё, быть может, каждый атом —
Вселенная, где сто планет;
Там — всё, что здесь, в объёме сжатом,
Но также то, чего здесь нет.

…

Is there world inside of an electron?

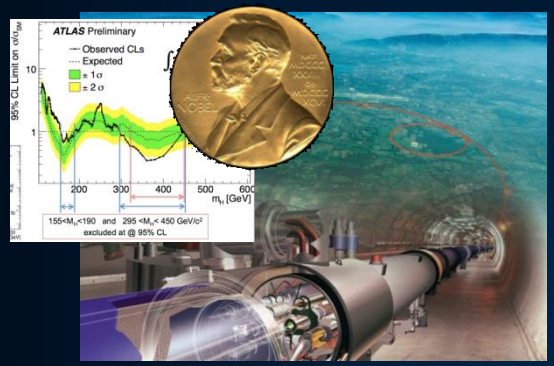


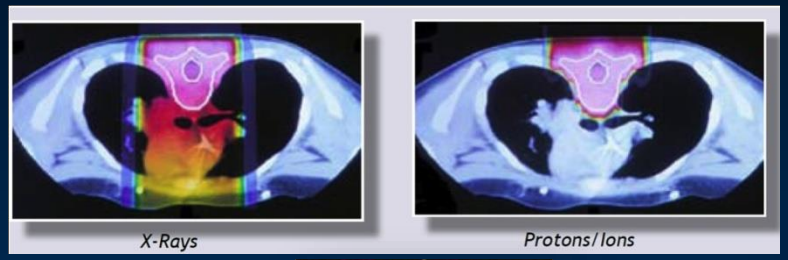


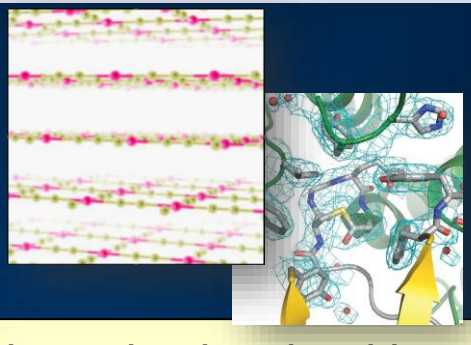


Accelerators and detectors can help to understand whether there is a world inside of an electron

Accelerators for science and society







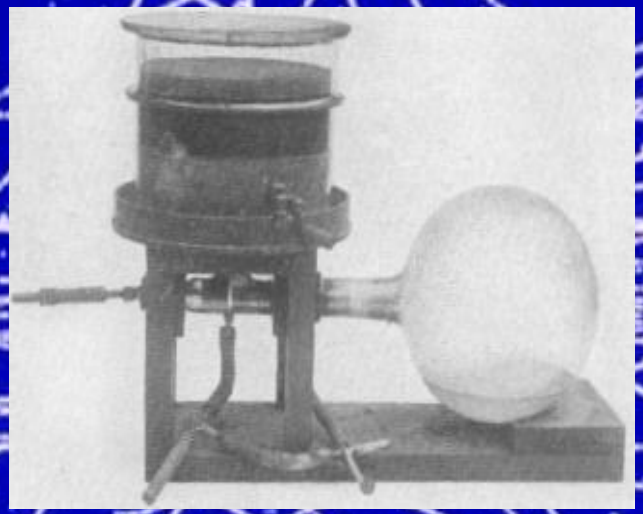
Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry…

Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

Cloud and bubble chambers

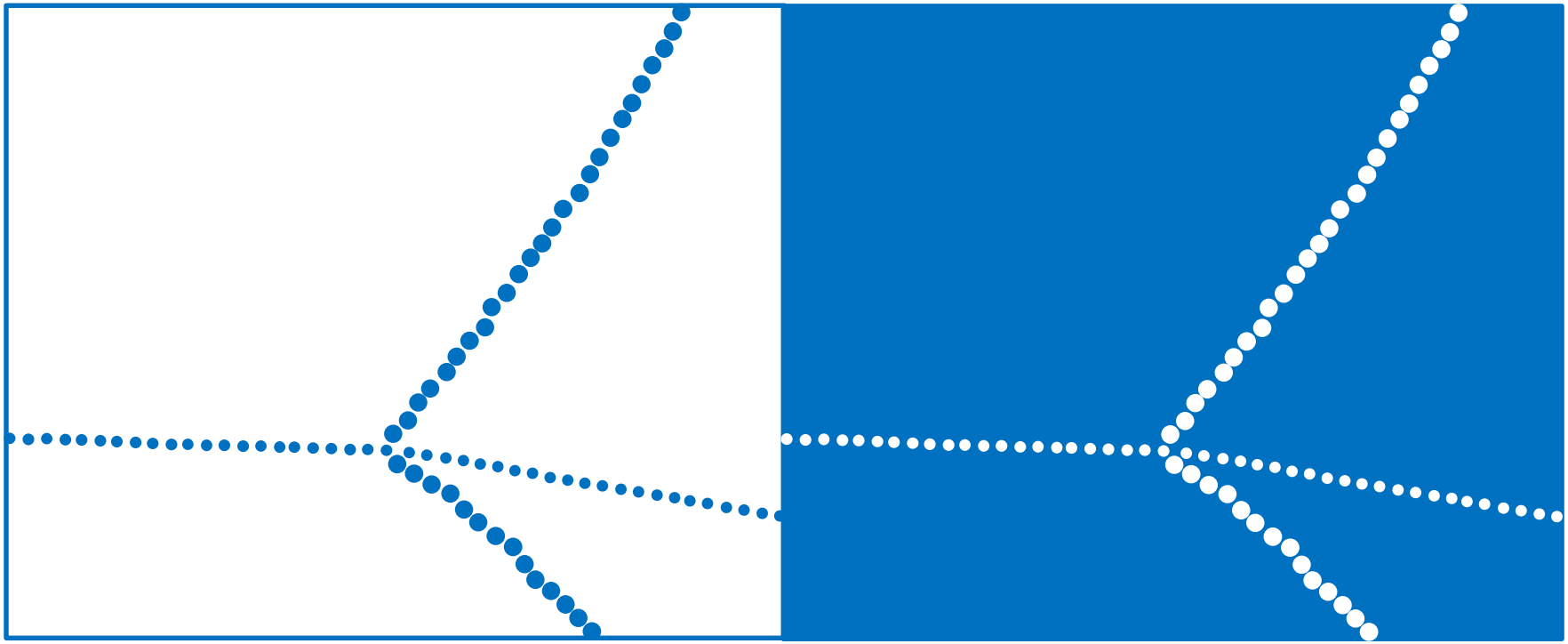


Wilson's Cloud chamber invented in 1911

Bubble Chamber (invented in 1952 by D. Glaser – Nobel prize 1960)

On the photo Bubble chamber being installed near Fermilab

Cloud and bubble chambers

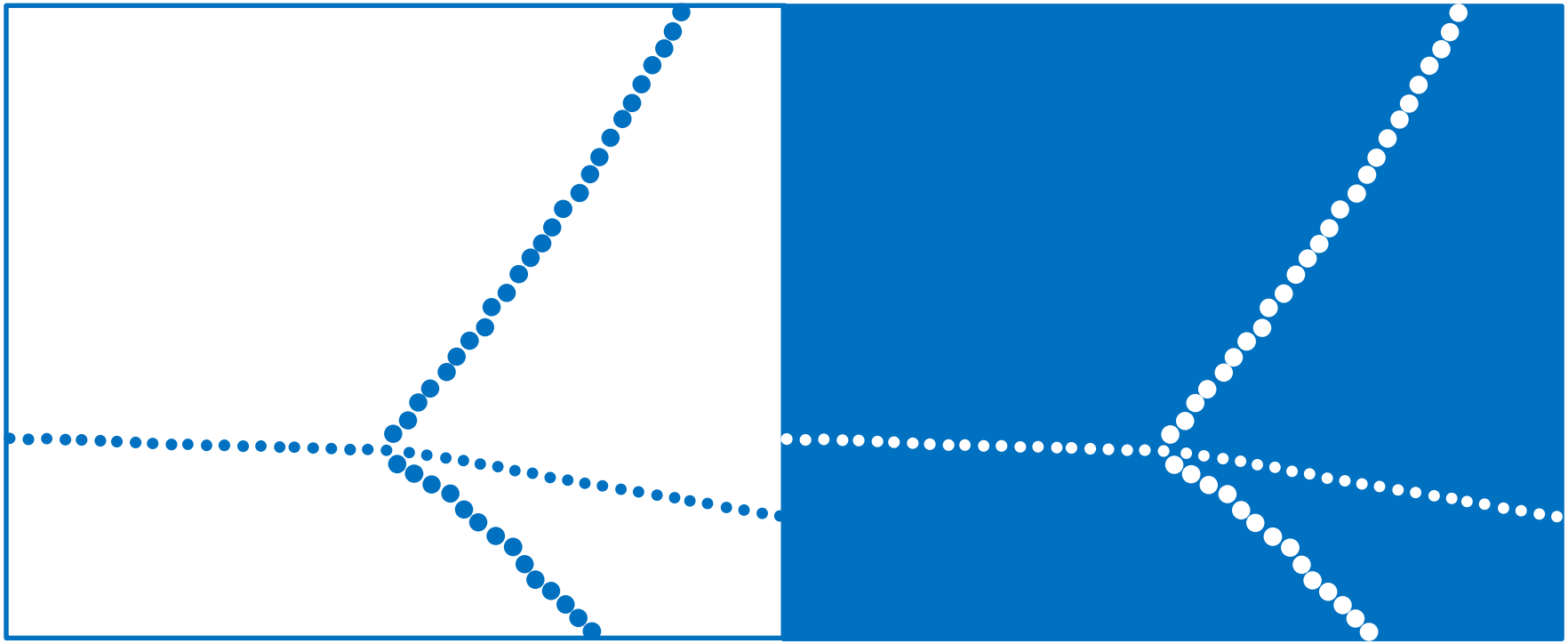


Wilson's Cloud chamber invented in 1911

Glaser's Bubble chamber, invented in 1952

These two instruments are connected via another inventive principle – "the other way around" or "system and anti-system"

Cloud and bubble chambers



Wilson's Cloud chamber invented in 1911

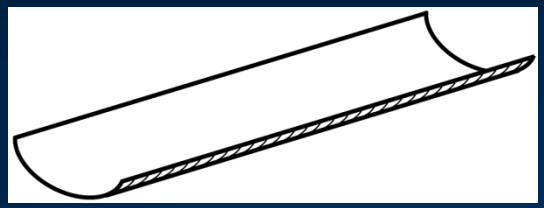
Glaser's Bubble chamber, invented in 1952

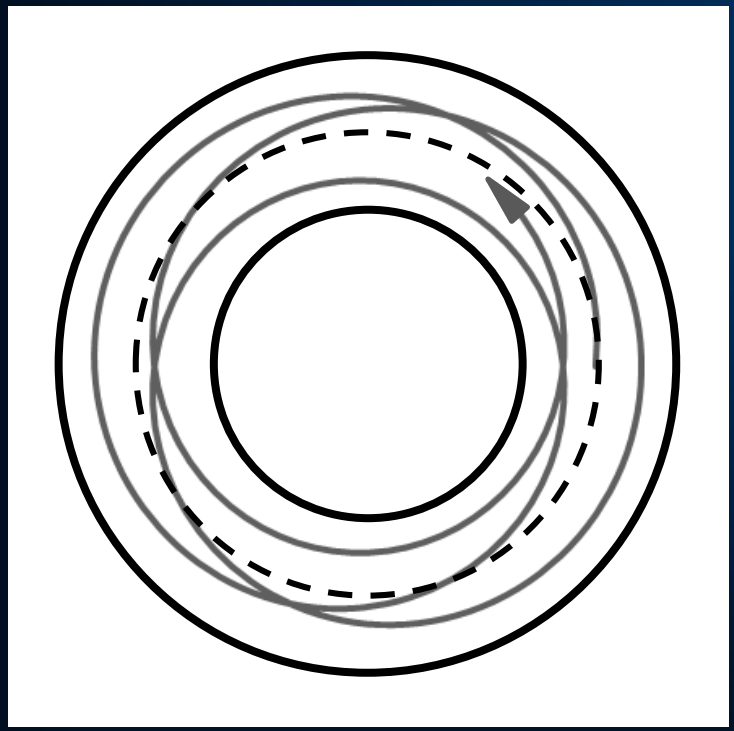
Bubble chamber could have been invented immediately, and not 40 years later after the cloud chamber, if we would have applied the principle of "system and anti-system"

System-anti-system and focusing in accelerators

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter





The first accelerators had weak focusing with spatial period greater than the perimeter of the accelerator

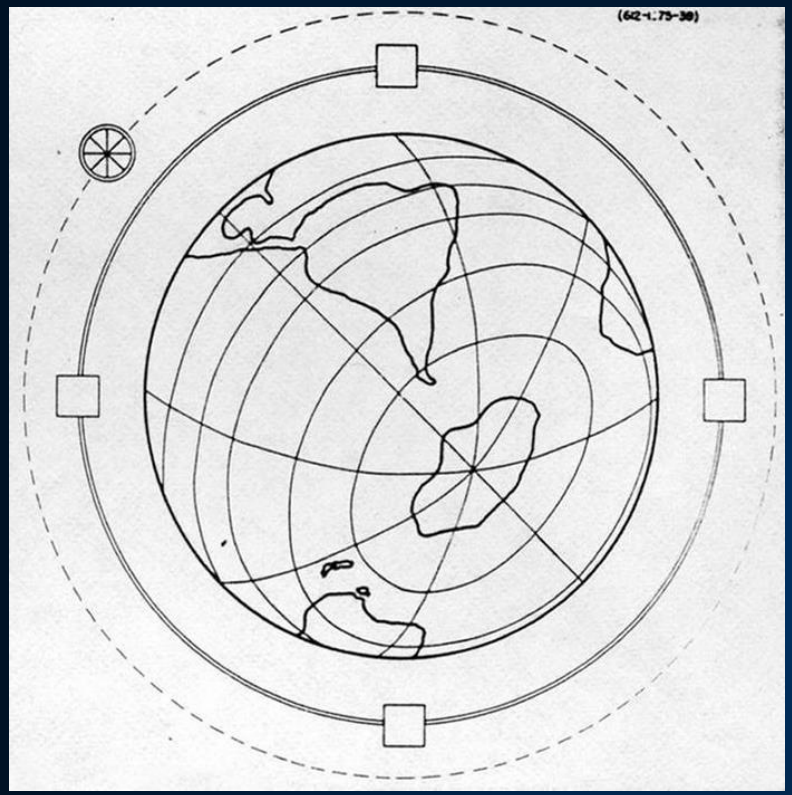
The trajectories of particles in an accelerator with weak focusing

Weak focusing accelerator

10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for its time. It is ~60m diameter ring, and its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

View inside of the magnets. Vacuum chamber, which occupied all this space, now removed.

Dreaming big



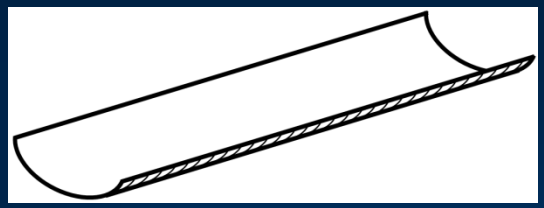
In 1954 Enrico Fermi presented, in his lecture, a vision of an accelerator that would encircle the Earth, and would attain highest possible energies

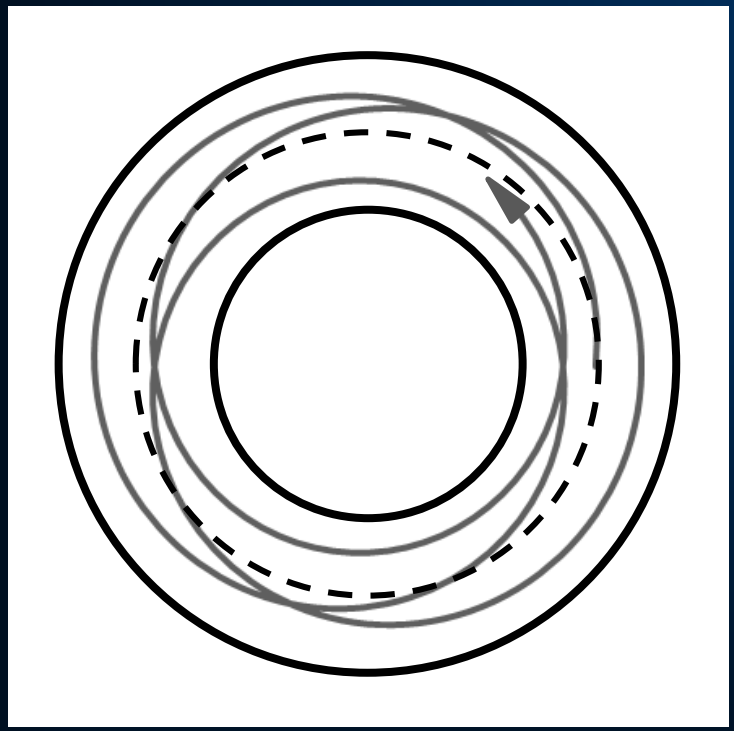
Imagine how humongous it would be if it would be built as a weak focusing machine!

Focusing

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter



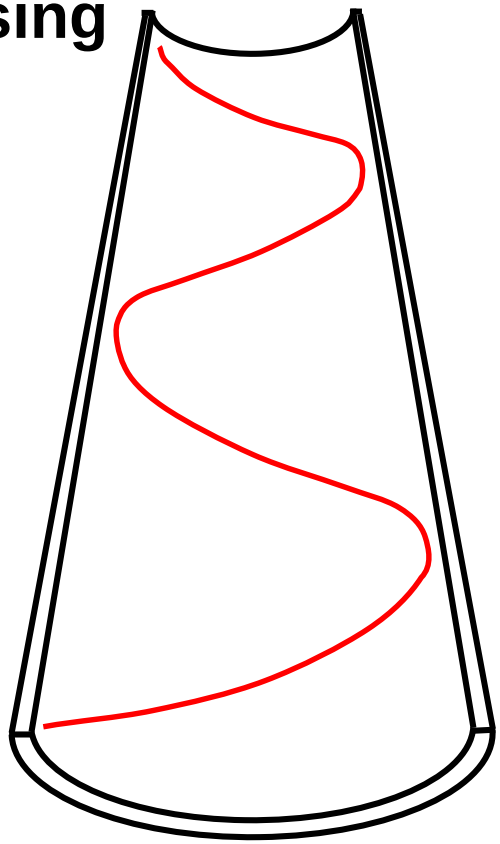


In this analogy, can we bend the gutter stronger, to achieve strong focusing?

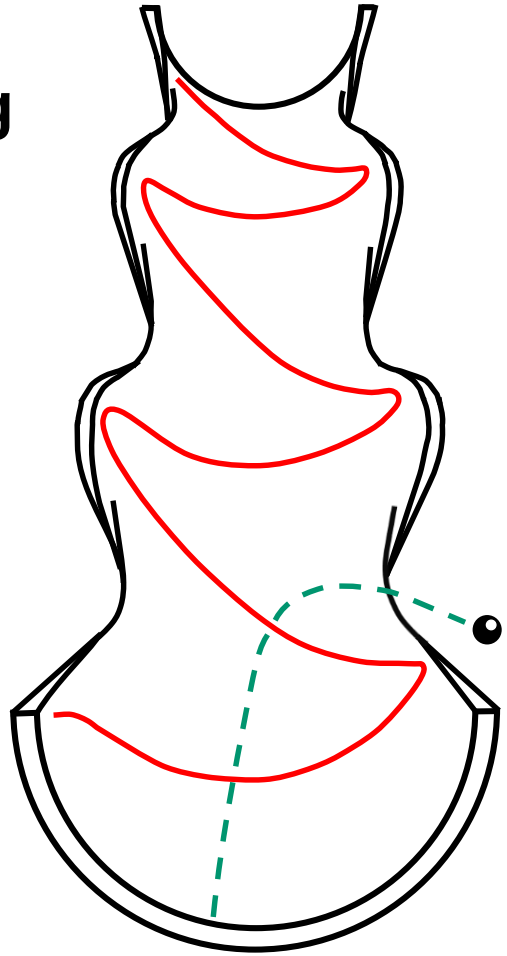
The trajectories of particles in an accelerator with weak focusing

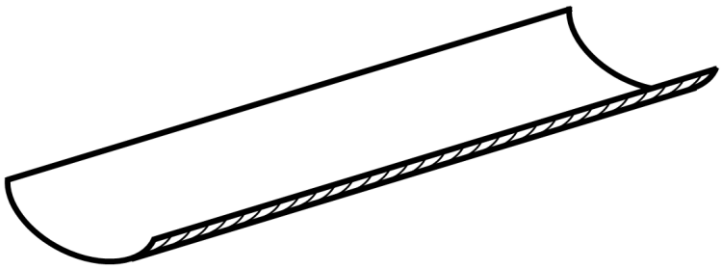
Weak and strong focusing

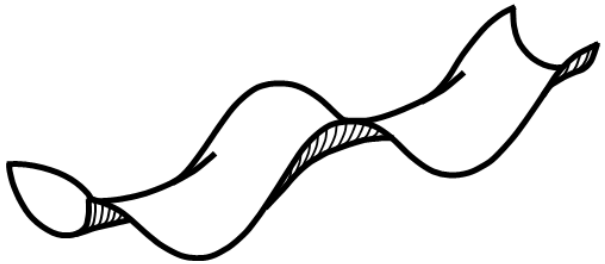
Weak focusing



Strong focusing

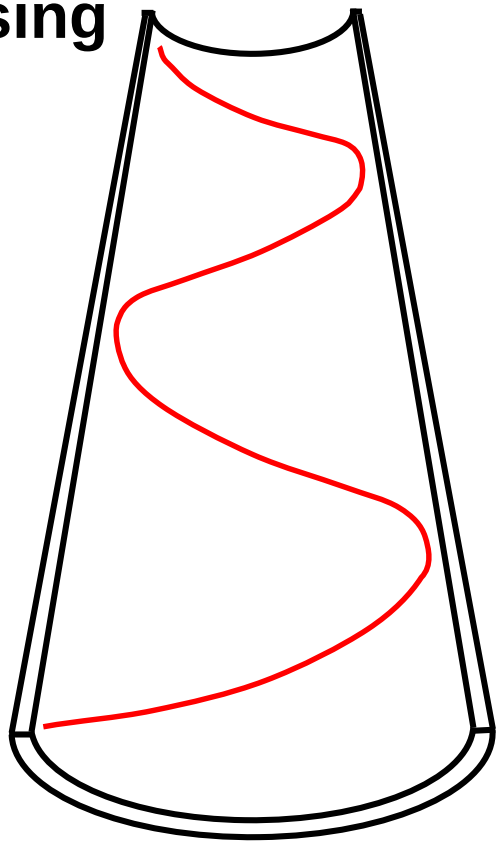




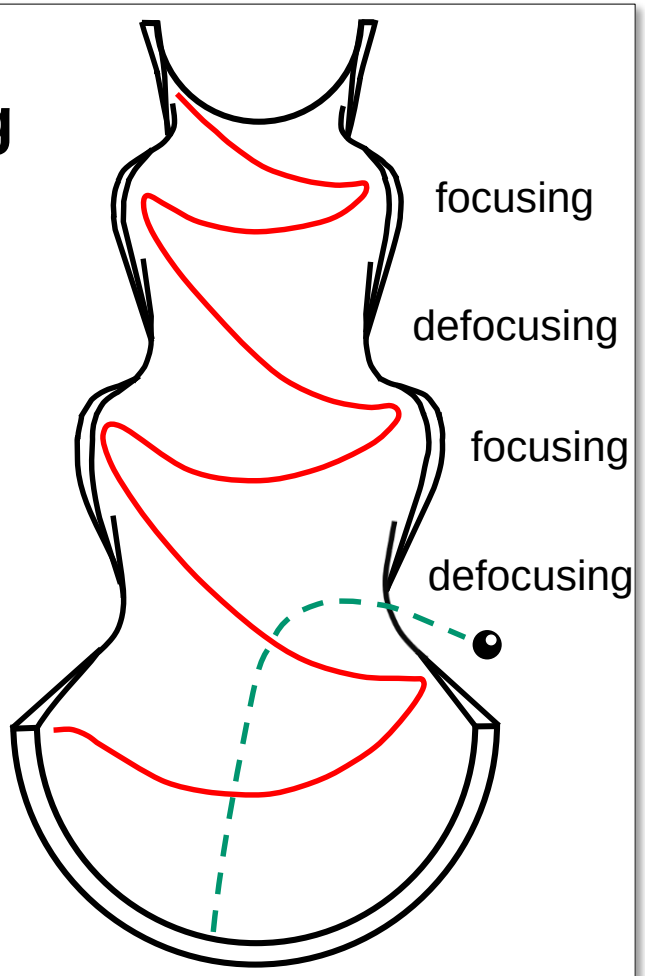


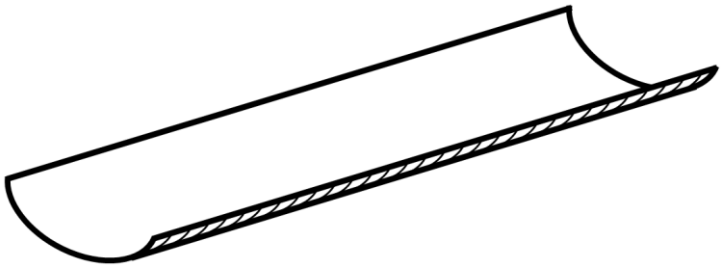
Weak and strong focusing

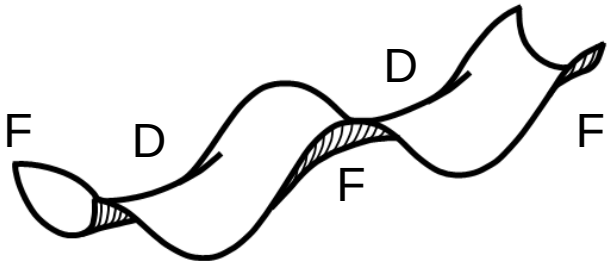
Weak focusing



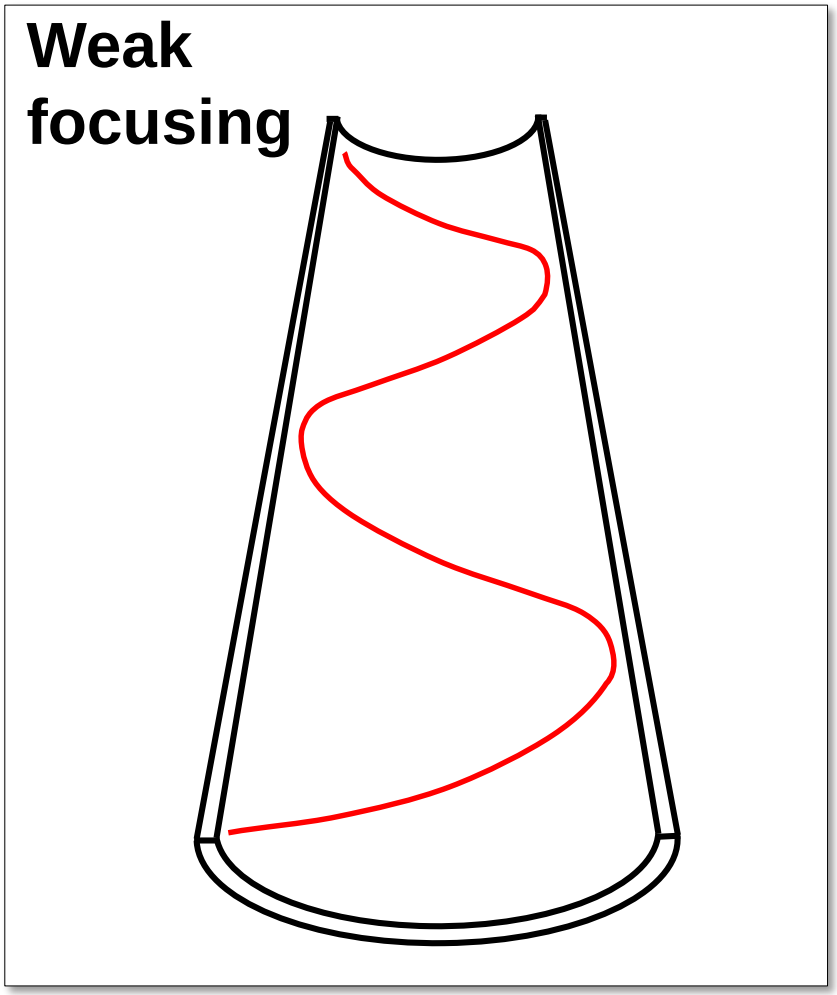
Strong focusing

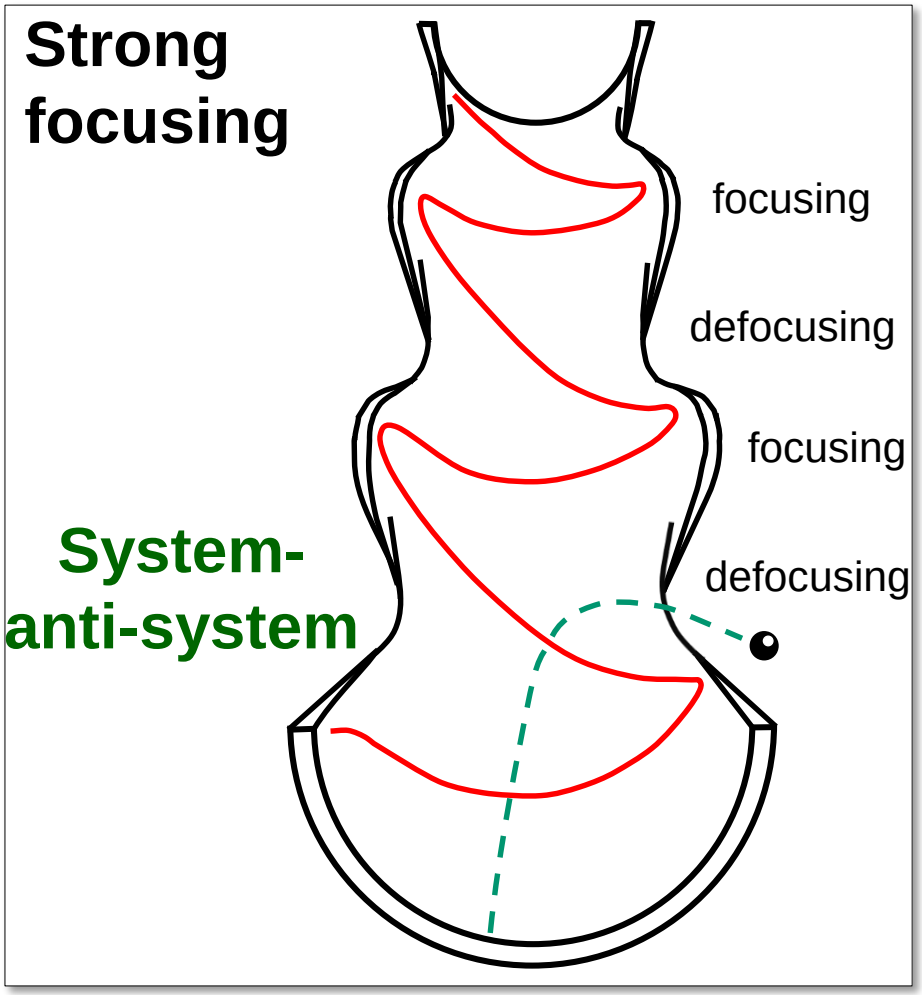


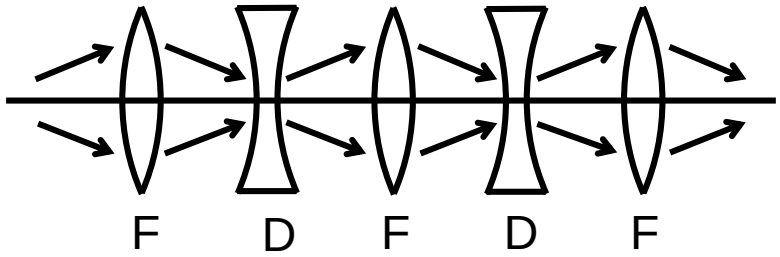




Weak and strong focusing



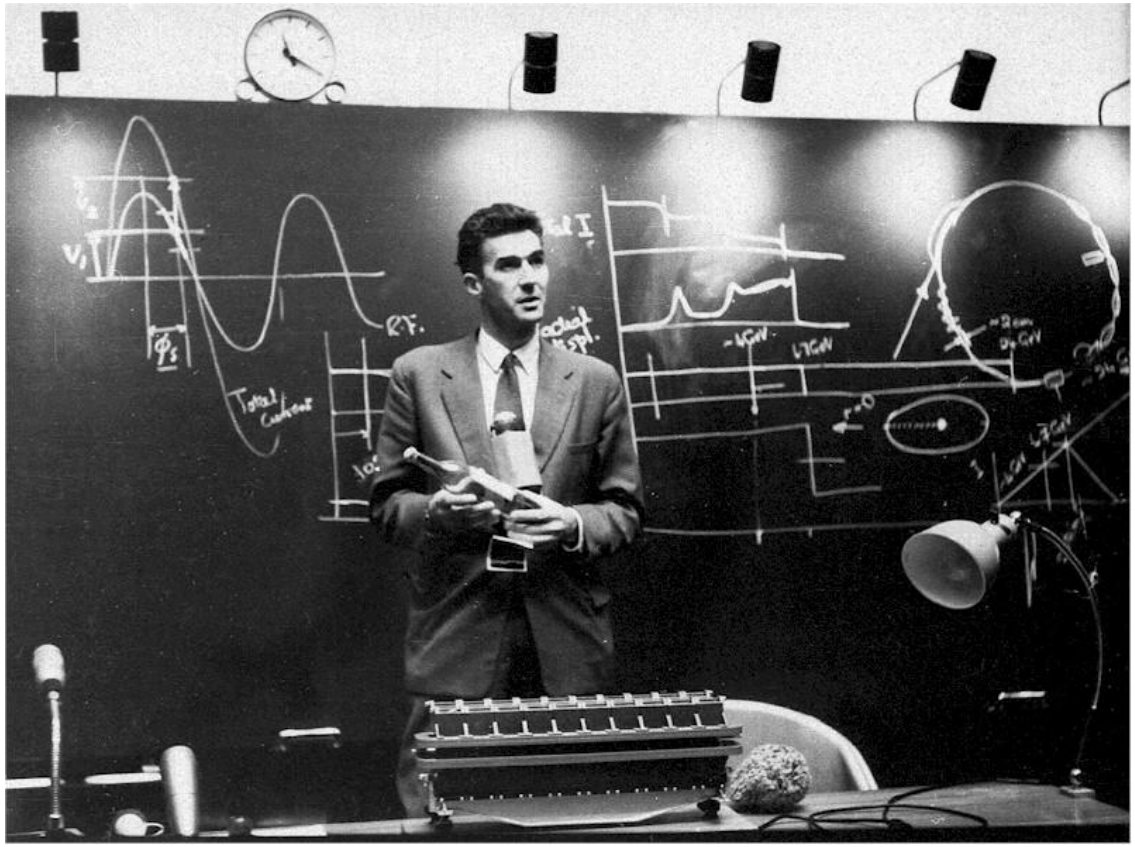




Strong focusing and JA history

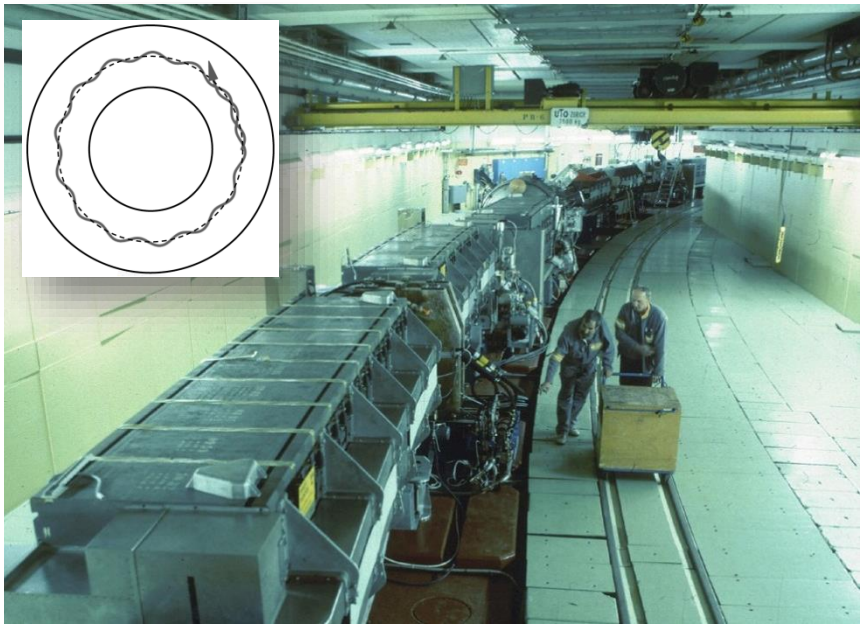
John Bertram Adams led the realization of the first strong-focusing proton accelerator.

He was part of the team who had the courage to cancel (in Oct 1952) the already approved 10 GeV weak focusing accelerator for a totally innovative 25 GeV Proton Synchrotron.



On the photo above Sir John Adams is announcing (on 25 Nov 1959) that CERN's PS just reached 24GeV and passed the Dubna's Synchrophasotron world record of 10GeV. This image shows Adams addressing the audience with a token of the victory – a bottled polaroid photograph showing the 24 GeV pulse in the machine ready to be sent back to the Joint Institute for Nuclear Research at Dubna as a sign that CERN had broken Dubna's record of 10 GeV.

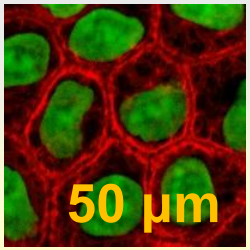
Weak and strong – compare them



10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for his time. It is ~60m diameter ring, and its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

CERN's Proton Synchrotron, the first operating strong-focusing accelerator, reached 24 GeV in 1959. It is a ~200-m diameter ring, weight of magnets 3,800 tons.

Chemistry Nobel 2014 & inventive principles?



Extra magnification?

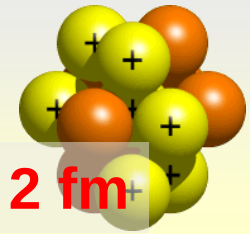
CELLS
Twenty per mm

Microscope

x 25 thousand

DNA
Five hundred thousand per mm

Electron microscope



x 1 million

Nucleus
Five hundred billion per mm

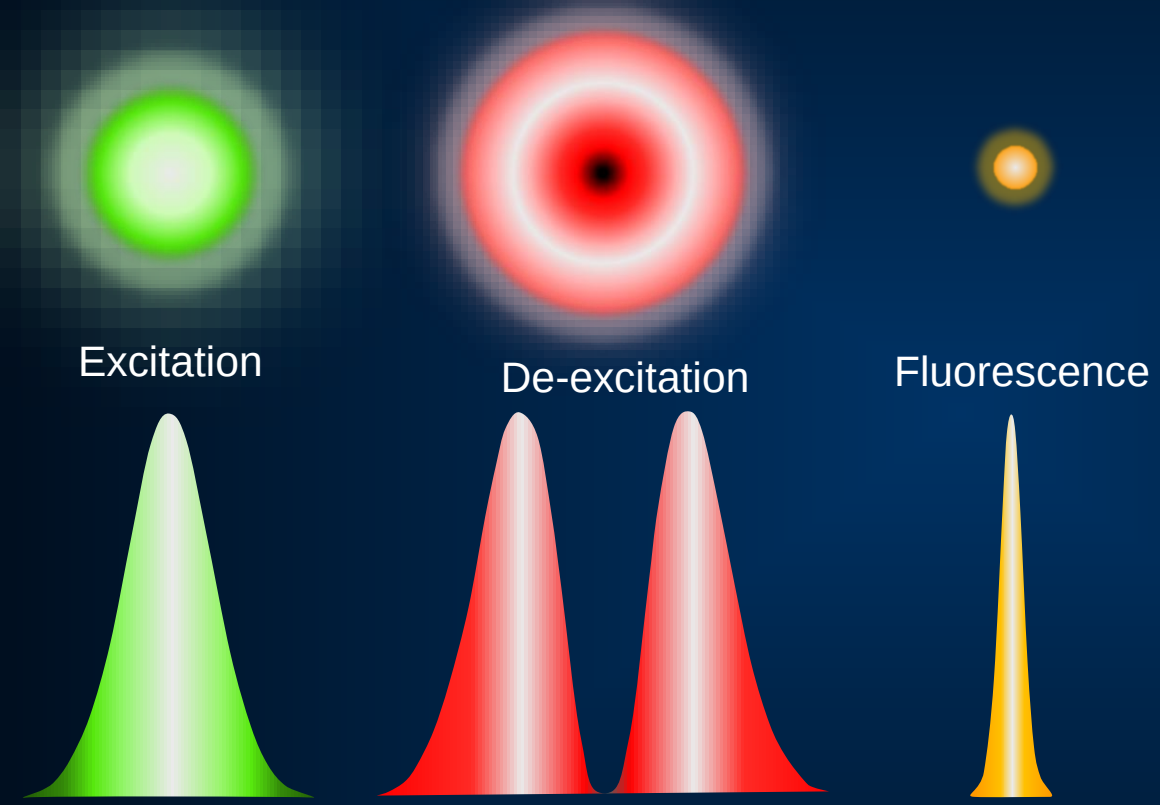
Particle Accelerators

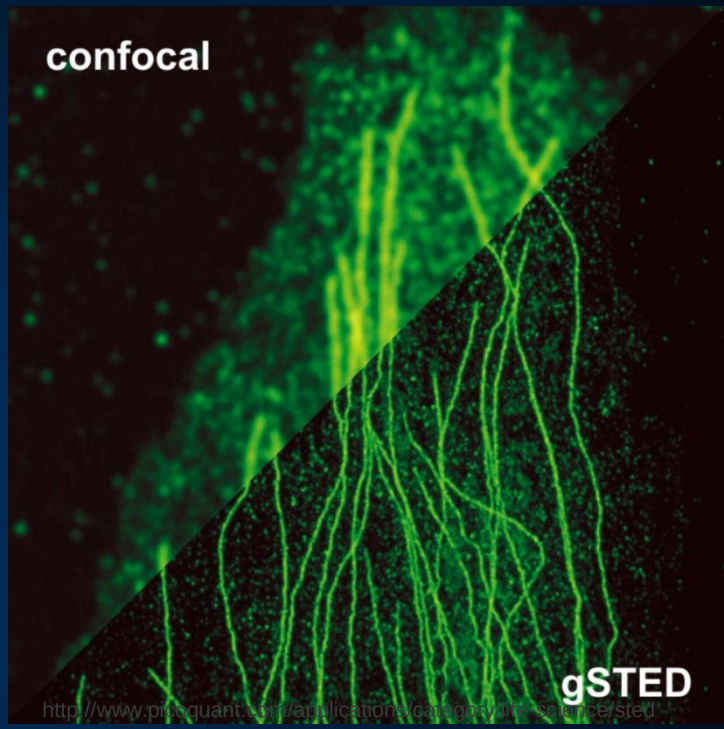
x 2 thousand

Quarks
More than one million billion per mm

Chemistry Nobel 2014 …

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell



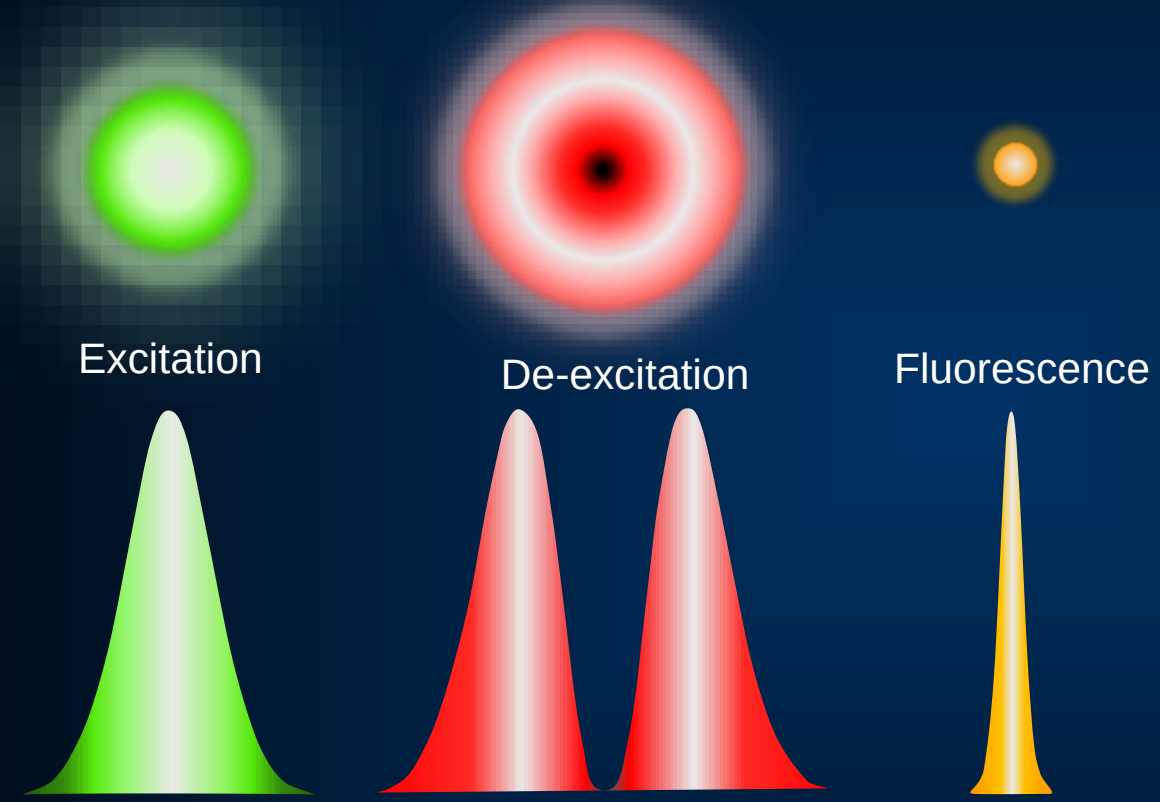


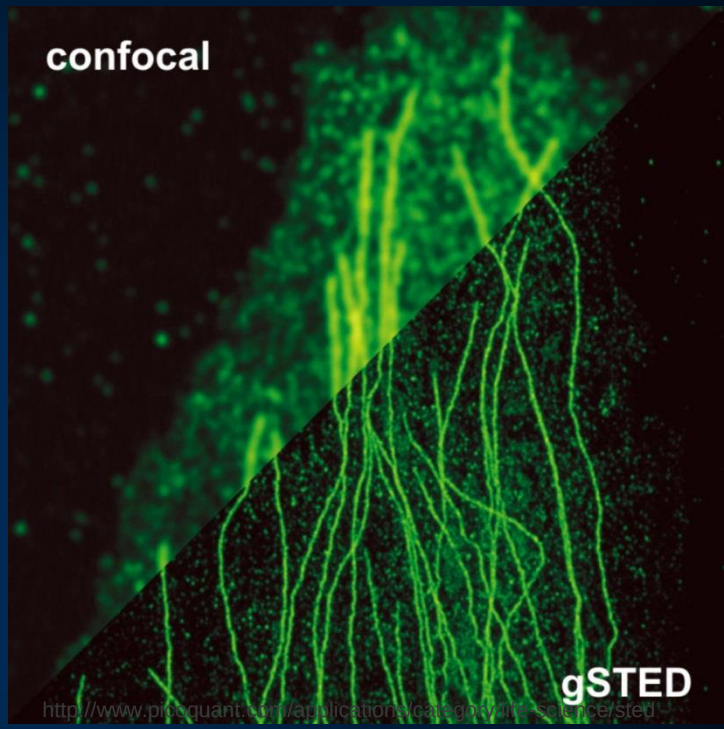
(gated) STED image of Tubulin vs standard confocal image

This can improve the resolution to be a factor of several below the wavelength of light

Chemistry Nobel 2014 & inventive principles

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell



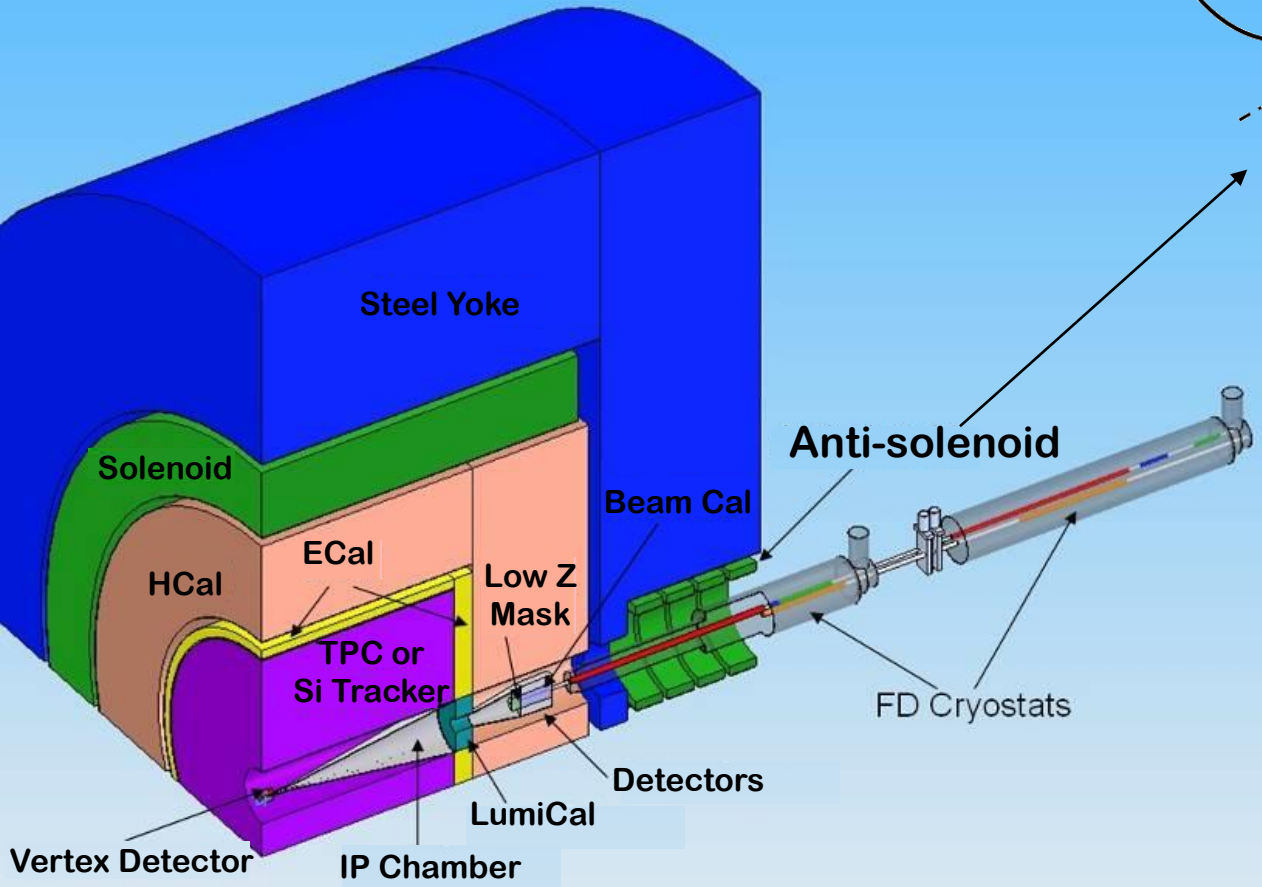


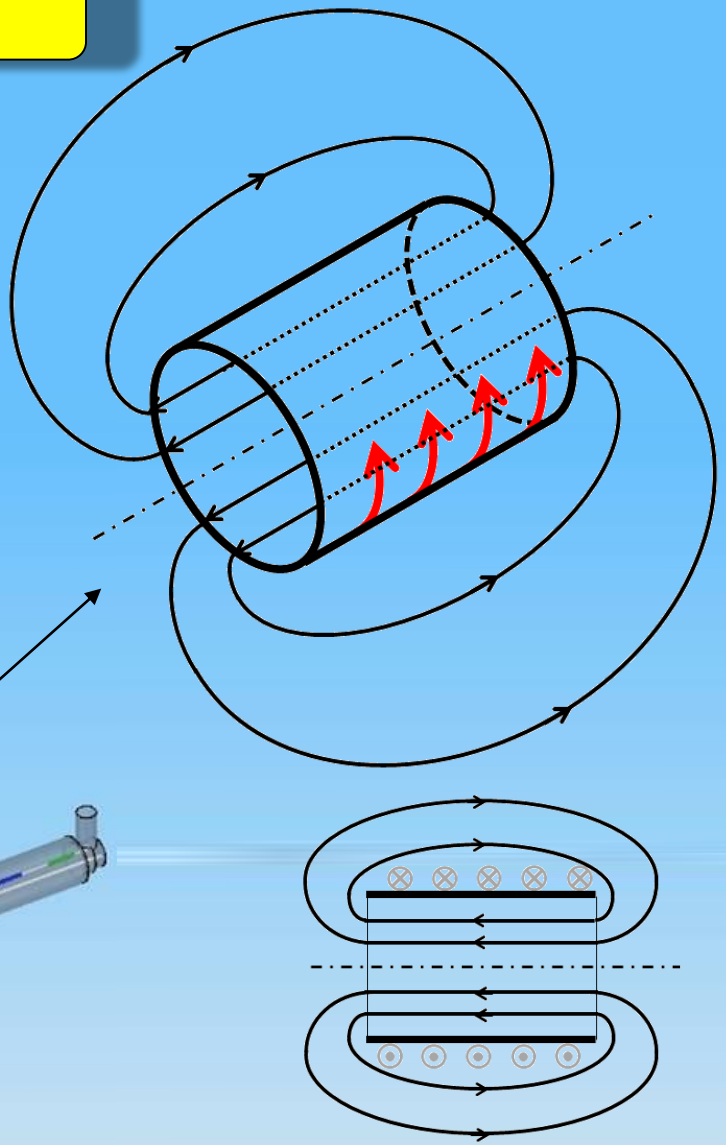
(gated) STED image of Tubulin vs standard confocal image

And this can be viewed as a combination of the inventive principles “system and anti-system” and “nested dolls”

Linear collider Interaction Region…

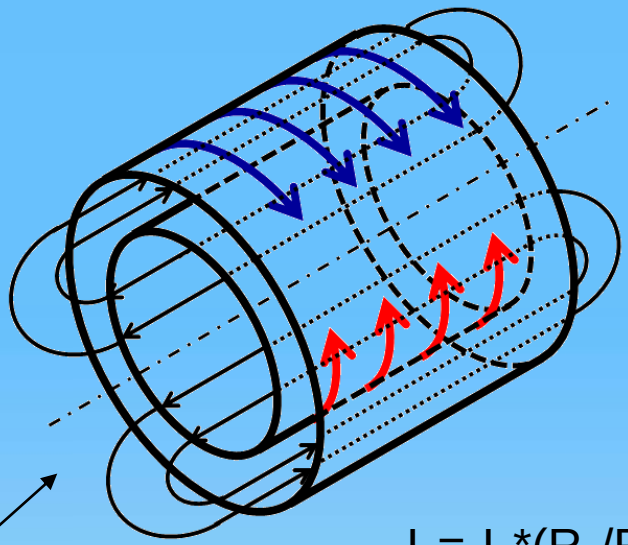
Anti-solenoid is needed, but it would be pulled into the main solenoid with humongous force



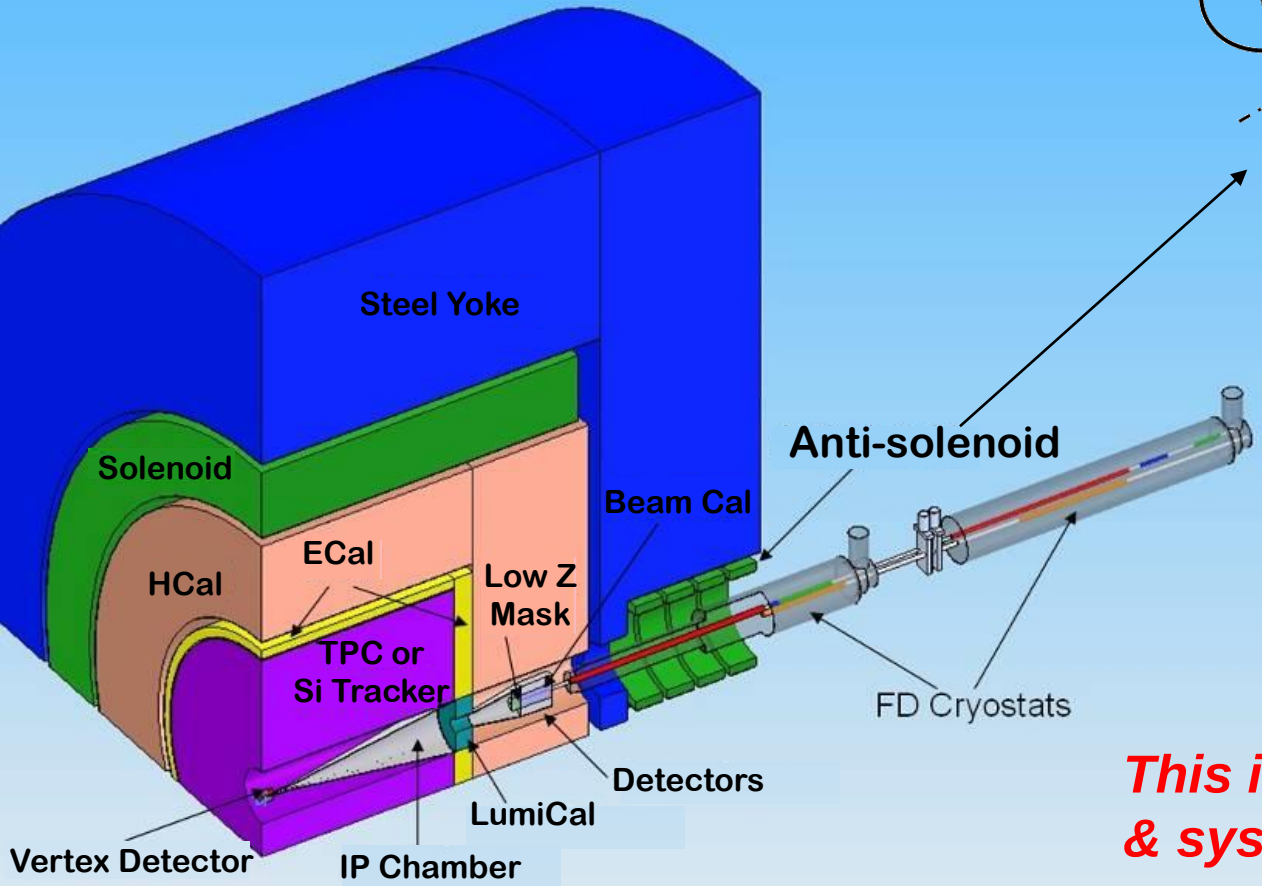


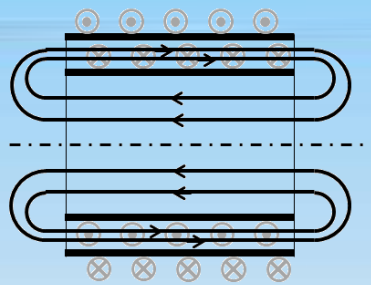
Linear collider Interaction Region…

Dual anti-solenoid is used, to cancel its external field – this makes it force-neutral



$I_2 = -I_1 * (R_1/R_2)^2$





This is again the nested doll & system – anti-system!

How to invent – TRIZ

- **TRIZ – *T*eoria *R*eshenia *I*zobretatelskikh *Z*adach**

= Theory of Inventive Problem Solving

- **Developed by Genrikh Altshuller in SU**
  - **Work in patent office in 1946**
  - **Analysed many patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**

Genrikh Altshuller (aka Altov)1926-1998

How to invent – TRIZ

- **TRIZ – *T*eoria *R*eshenia *I*zobretatelskikh *Z*adach**

  = Theory of Inventive Problem Solving
- **Developed by Genrikh Altshuller in SU**

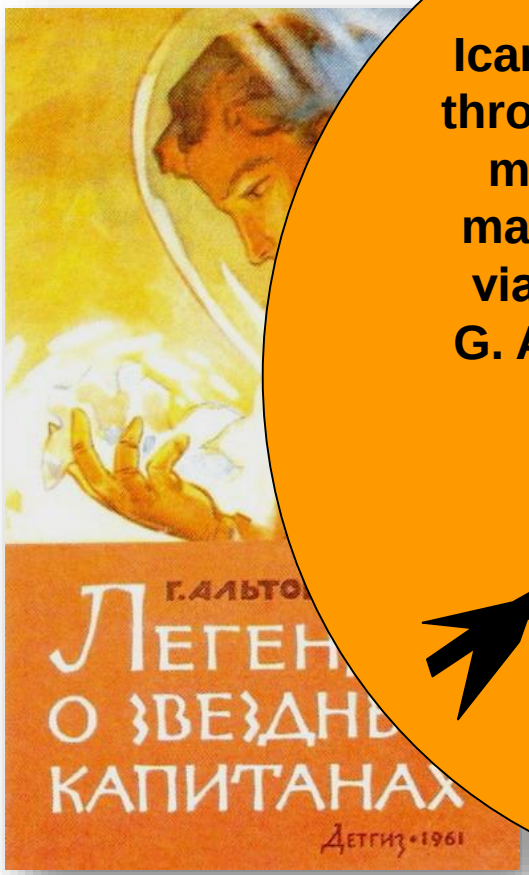
Genrikh Altshuller (aka Altov)1926-1998

How to invent – TRIZ

- **TRIZ – *T*eoria *R*eshenia *I*zobretatelskikh *Z*adach**
  = Theory of Inventive Problem Solving
- **Developed by G… r in SU**

Genrikh Altshuller (aka Altov)1926-1998

Icarus and Daedalus flying through Sun on spaceships made from neutron star materials, communicating via gravitational waves…
G. Altov, "Legend of space captains"



How to invent – TRIZ

- **TRIZ – *T*eoria *R*eshenia *I*zobretatelskikh *Z*adach**

= Theory of Inventive Problem Solving

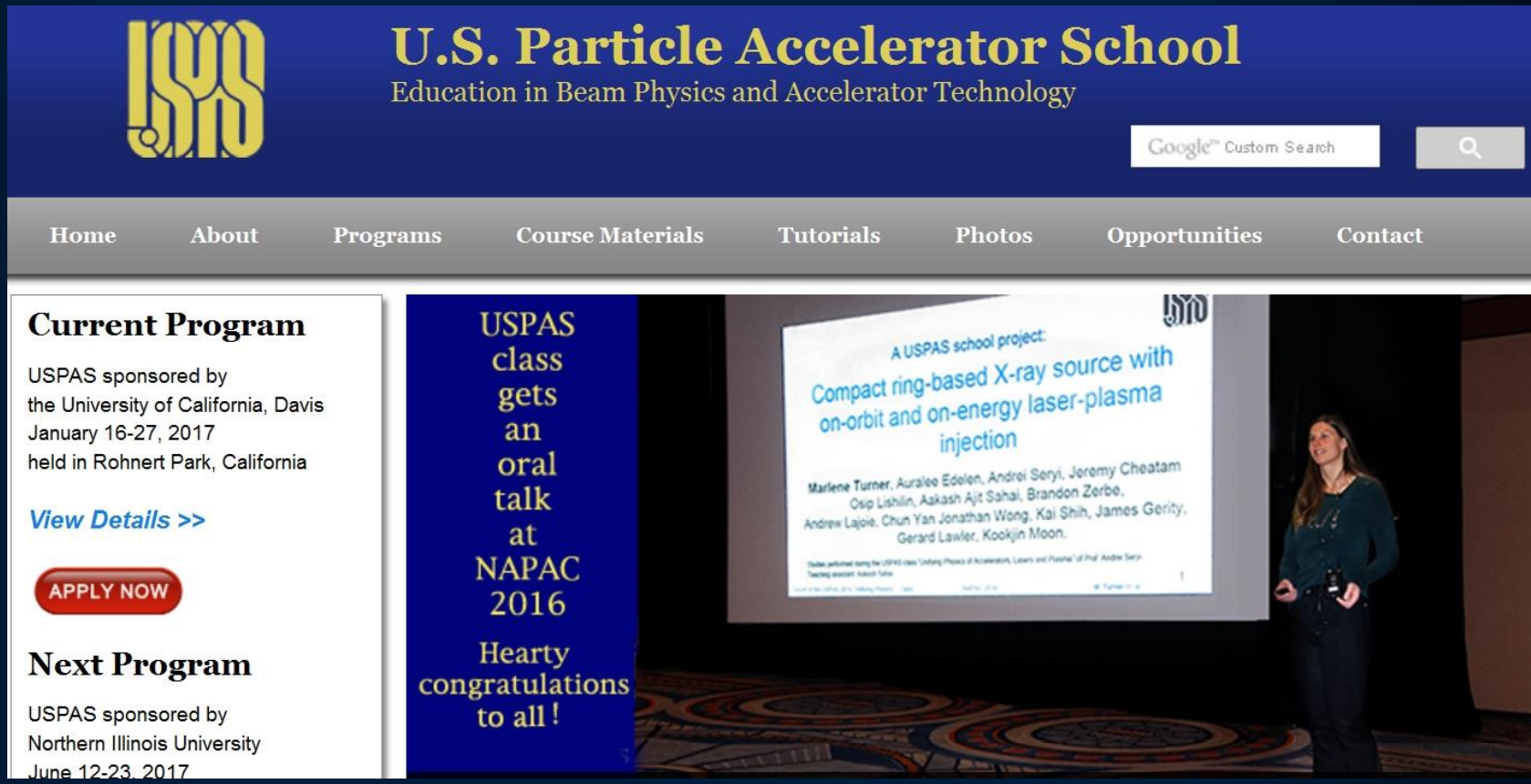
- **Developed by Genrikh Altshuller in SU**
  - **Work in patent office in 1946**
  - **Analysed many patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**

Genrikh Altshuller (aka Altov)1926-1998

- **Four key discoveries of TRIZ:**
  - **The same Problems and Solutions appear again and again but in different industries**
  - **There is a recognisable Technological Evolution path for all industries**
  - **Innovative patents (23% of total) used science/engineering theories outside their own area/industry**
  - **An Innovative Patent uncovers and solves contradictions**

Can TRIZ be used in science?

Yes, and very successfully



Class of graduate students, after one-week course on accelerators, lasers and plasma, and TRIZ, created a novel design and were invited to make a plenary invited presentation at the North American Particle Accelerator conference!

Can TRIZ be used in science?

Yes. However, some comments:

In science it is not always possible to use prescriptive step-by-step methods with pre-defined tables of contradictions…

Critics expected from scientists: why only the first contradiction is addressed? Is it just a linear order correction? How can TRIZ help to come to breakthrough ideas like theory of relativity? Etc…

Arguably, the way to teach TRIZ in science schools should be different than in engineering schools and companies…

Maybe, the best way to introduce TRIZ to science is via the process of pro-active re-creation of TRIZ for science

TRIZ for science

Can be very useful

Pro-active re-creation of TRIZ for science is attempted in this book:
- helps to connect different areas
- helps to learn inventiveness methods

The re-interpreted and extended TRIZ is called in this book Accelerating Science TRIZ (AS-TRIZ)
(hinting that any area of science can be accelerated using TRIZ)

Creating TRIZ for science through the process of analysing and re-building TRIZ will also help us to study it proactively

Major components of TRIZ that should be kept for applications to science (in extended & re-defined shape) are, to start with:

- **inventive principles**
- **laws of evolution of systems**

40 inventive principles in illustrations

- **One can find many illustrations of inventive principles based on engineering examples**
- **On the next pages you will find illustrations based on accelerator science and some other areas of science**
  - You will notice that some of the standard definitions of TRIZ principles are re-defined
  - Selected principles will be shown

See more details in:

Accelerating Science TRIZ inventive methodology in illustrations
Elena Seraia, Andrei Seryi

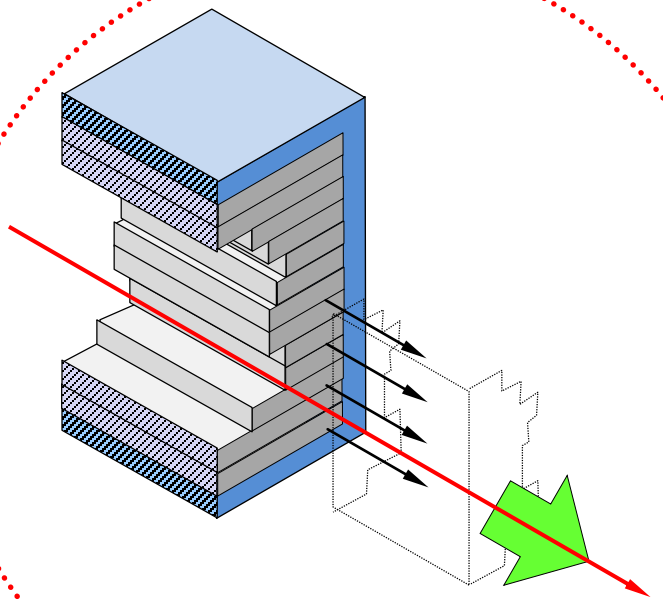
arXiv:1608.00536 [physics.ed-ph]
https://arxiv.org/abs/1608.00536

One of 40 inventive principles of TRIZ

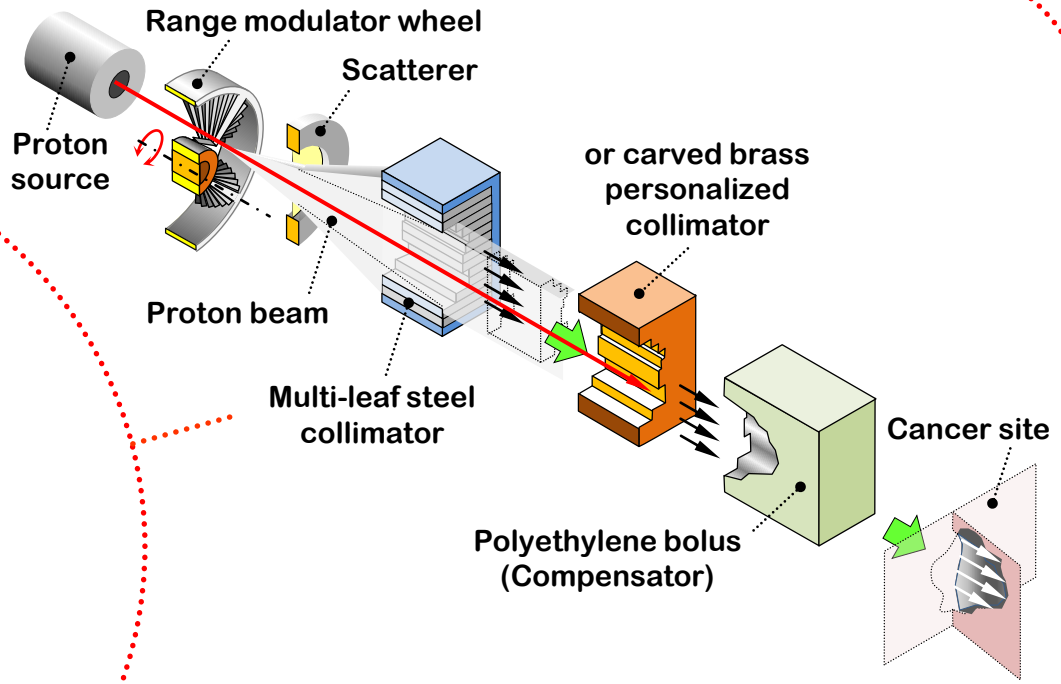
1. Segmentation

- Divide an object into independent parts.
- Make an object easy to disassemble.
- Increase the degree of fragmentation or segmentation.

See more illustrations at arXiv:1608.00536



Multi-leaf steel collimator

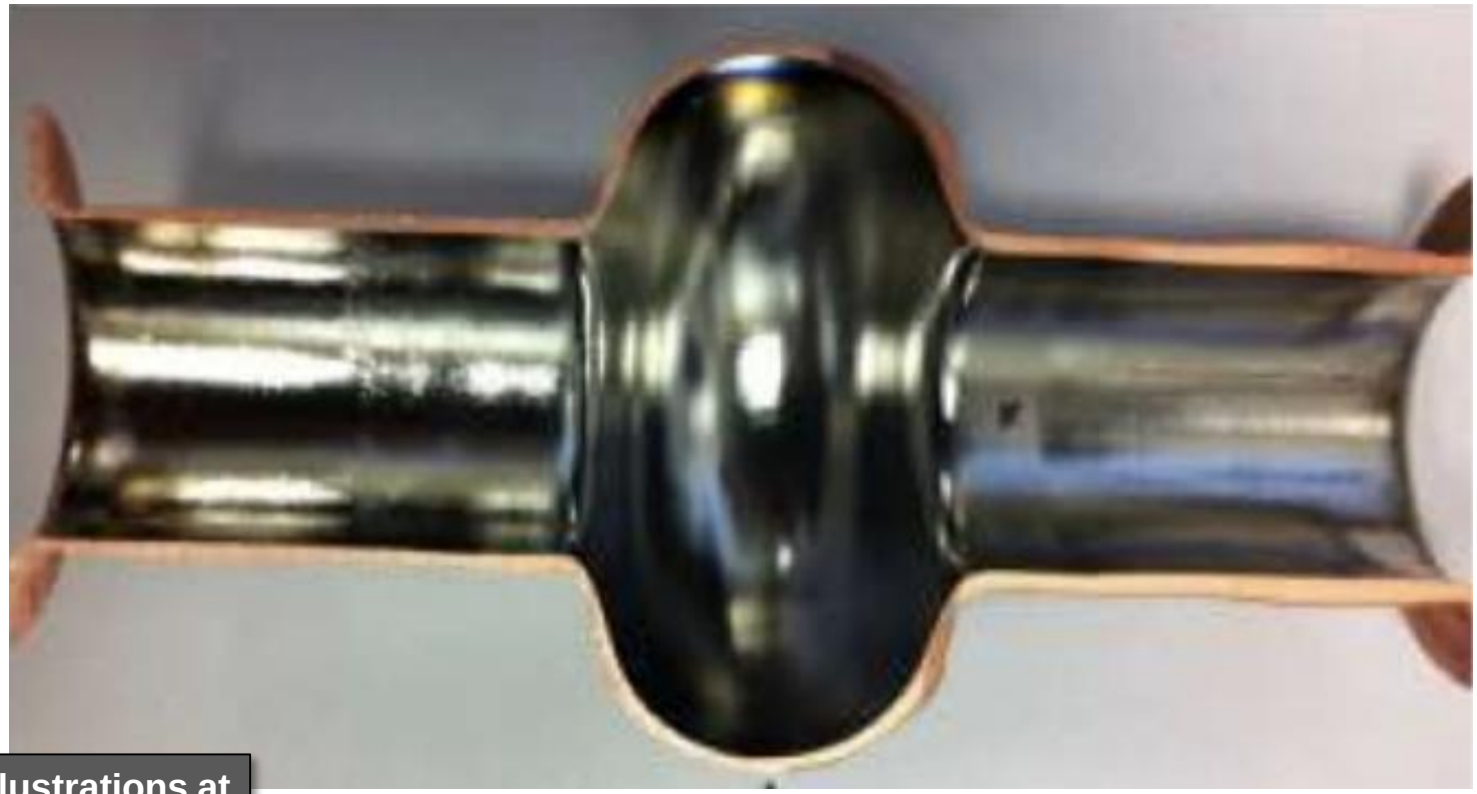


Proton therapy

One of 40 inventive principles of TRIZ

3. Local quality

- Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.
- Make each part of an object function in conditions most suitable for its operation.
- Make each part of an object fulfill a different and useful function.



Nb coated copper cavity

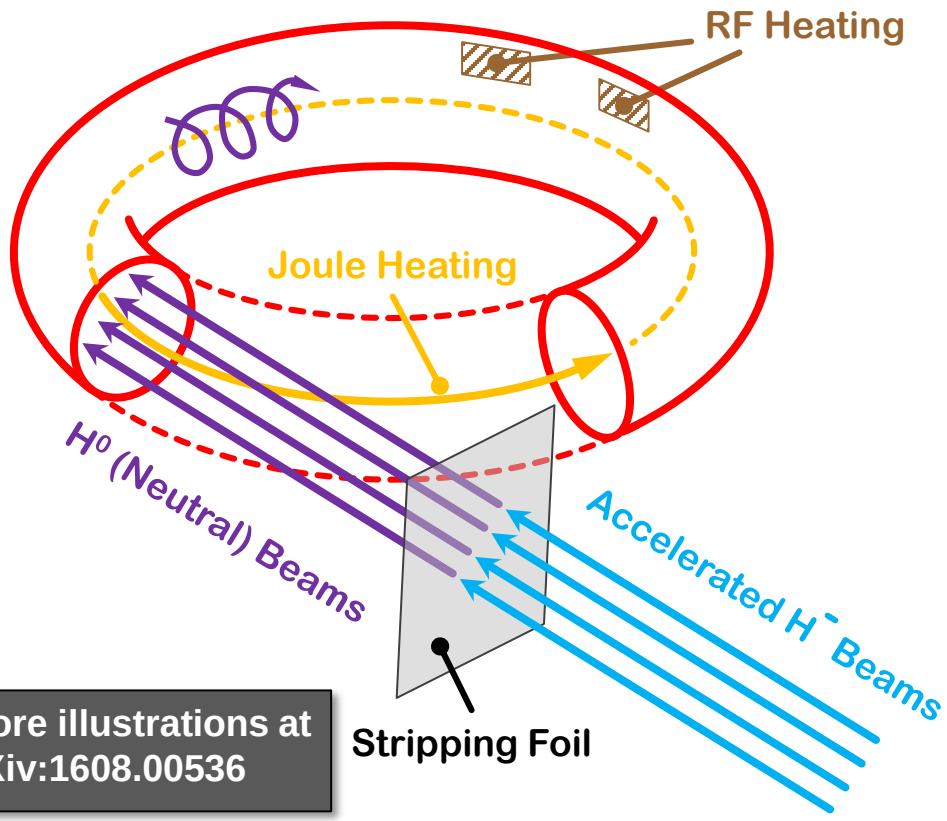
See more illustrations at arXiv:1608.00536

Enzo Palmieri, A.A.Rossi, R. Vaglio, "Experimental Results on Thermal Boundary Resistance for Nb and Nb/Cu", Science, Oct 2014

One of 40 inventive principles of TRIZ

8. Anti-~~weight~~ force

- To compensate for the ~~weight of~~ force on an object, merge it with other objects that provide compensating force.
- To compensate for the ~~weight of~~ force on an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).



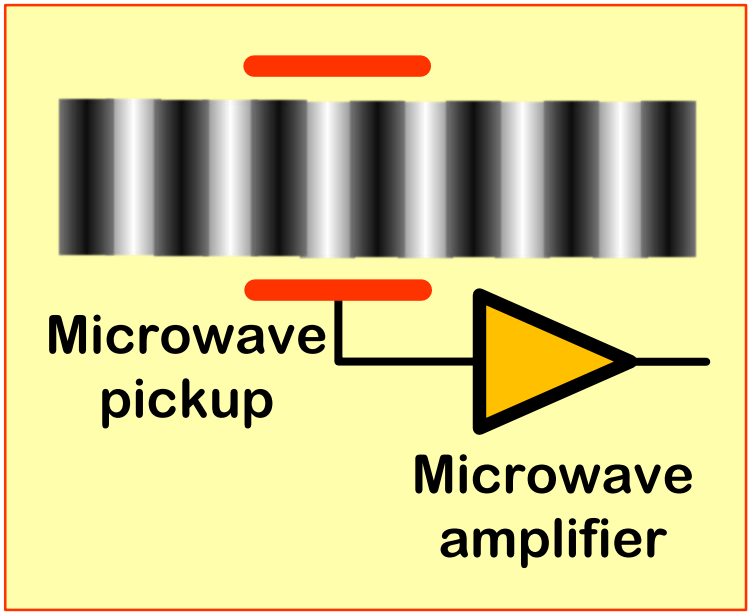
See more illustrations at arXiv:1608.00536

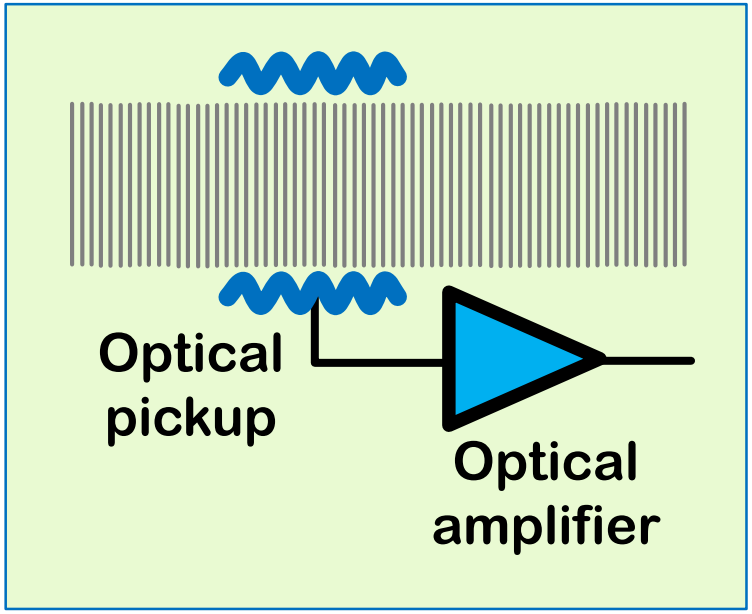
Heating of plasma with neutral beams

One of 40 inventive principles of TRIZ

18. ~~Mechanical vibration~~ Oscillations and resonances

- Cause an object to oscillate or vibrate.
- Increase its frequency (~~even up to the ultrasonic~~ from microwave to optical).
- Use an object's resonant frequency.
- Use piezoelectric vibrators instead of mechanical ones.
- Use combined ultrasonic and electromagnetic field oscillations.





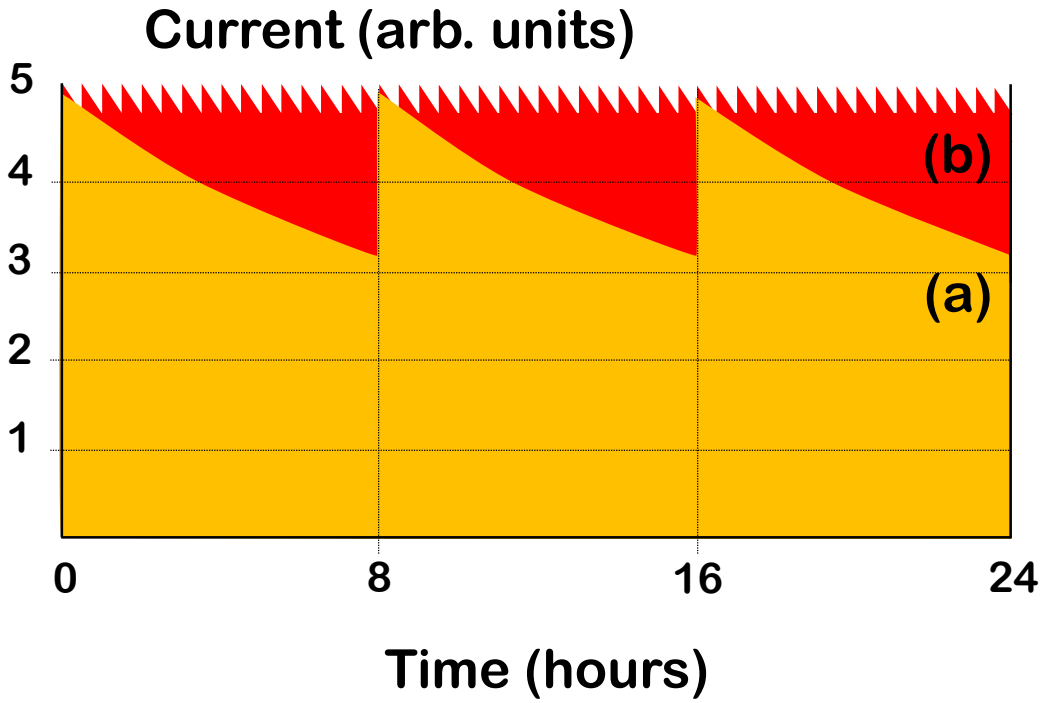
Stochastic cooling => optical stochastic cooling

See more illustrations at arXiv:1608.00536

One of 40 inventive principles of TRIZ

20. Continuity of useful action

- Carry on work continuously; make all parts of an object work at full load, all the time.
- Eliminate all idle or intermittent actions or work.



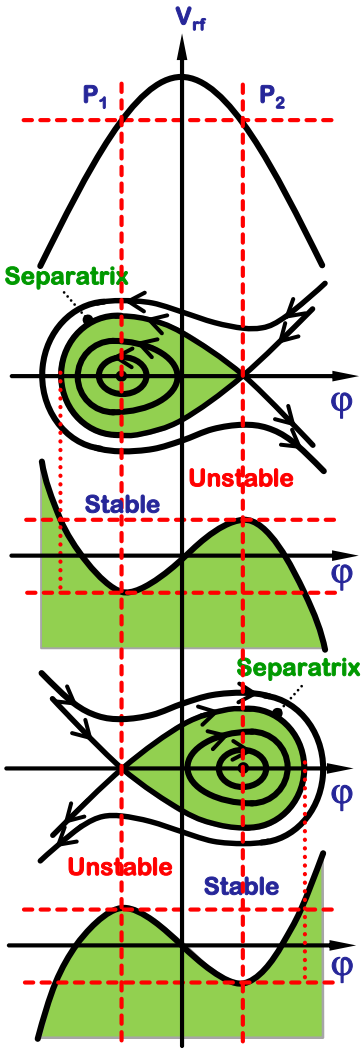
See more illustrations at arXiv:1608.00536

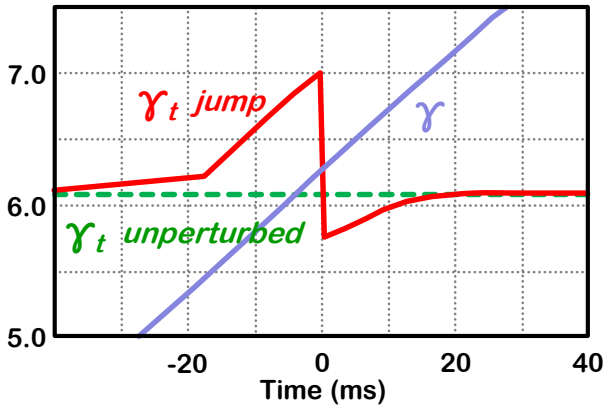
Top off injection

One of 40 inventive principles of TRIZ

21. Skipping

- Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.





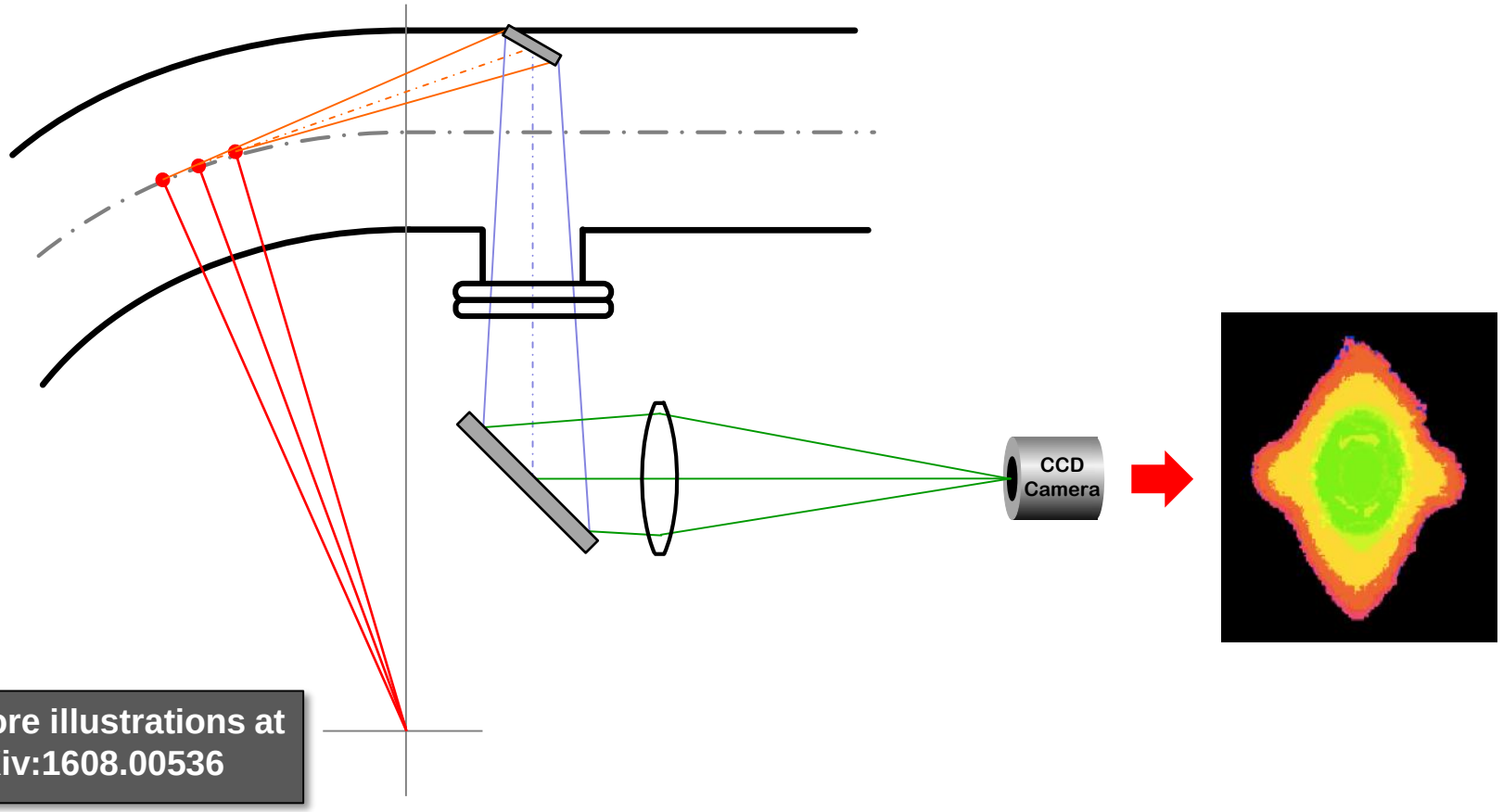
Crossing transition energy with γ_t jump technique

See more illustrations at arXiv:1608.00536

One of 40 inventive principles of TRIZ

26. Copying

- Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.
- Replace an object, or process with optical copies.
- If visible optical copies are already used, move to infrared or ultraviolet copies.



See more illustrations at arXiv:1608.00536

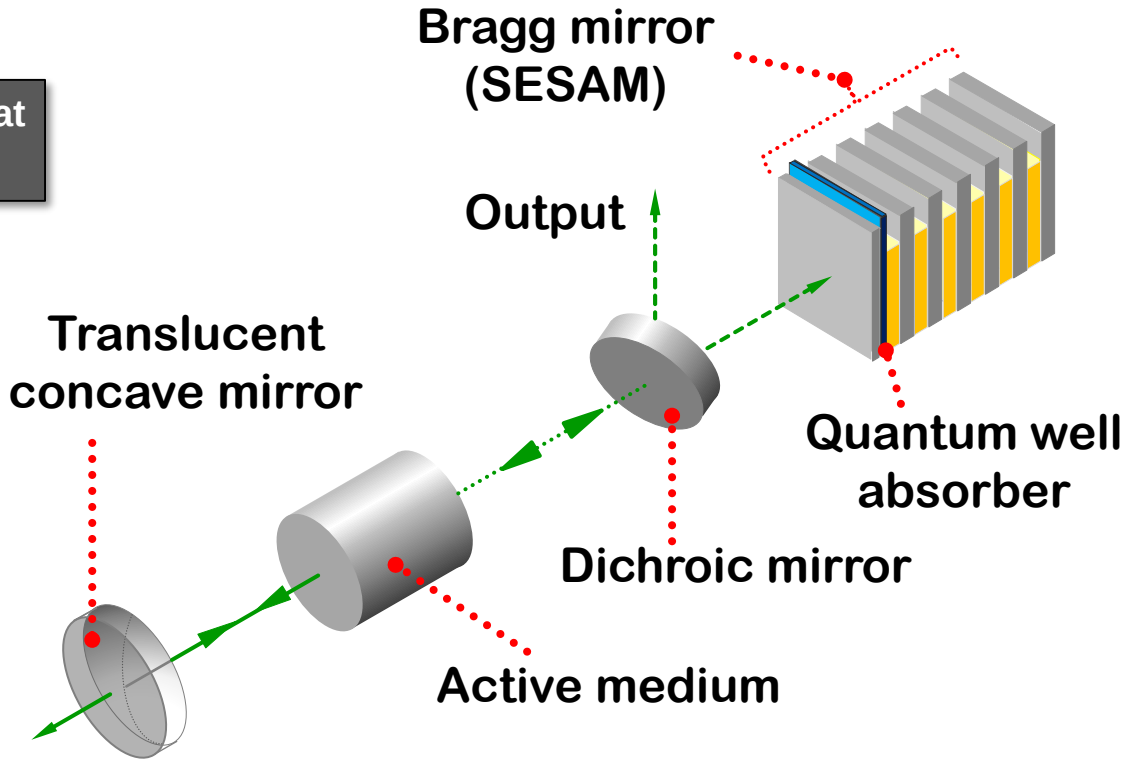
Synchrotron radiation profile monitor

One of 40 inventive principles of TRIZ

34. Discarding and recovering

- Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
- Conversely, restore consumable parts of an object directly in operation.

See more illustrations at arXiv:1608.00536



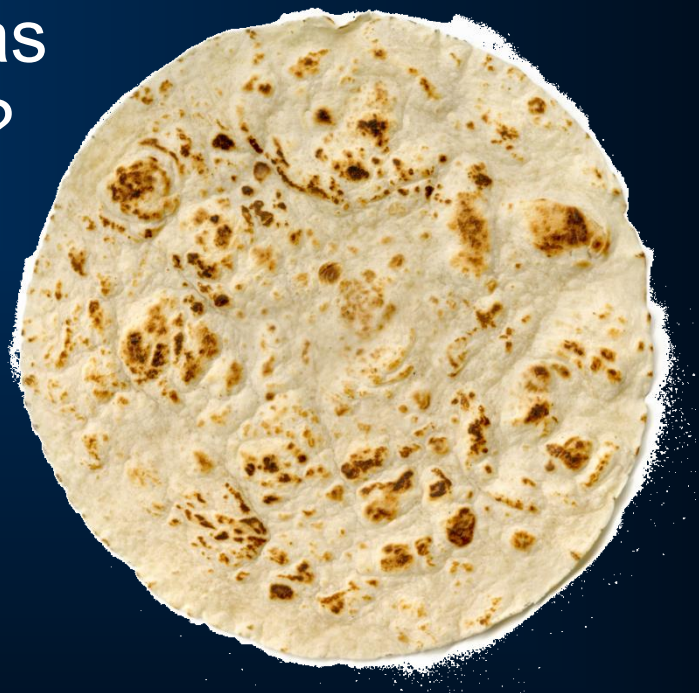
Semiconductor Saturable Absorber Mirror - SESAM

A bit more suggestions

… on how to make TRIZ more suitable for science

The principle "parameter change" can be interpreted very widely, and thus be very applicable to science

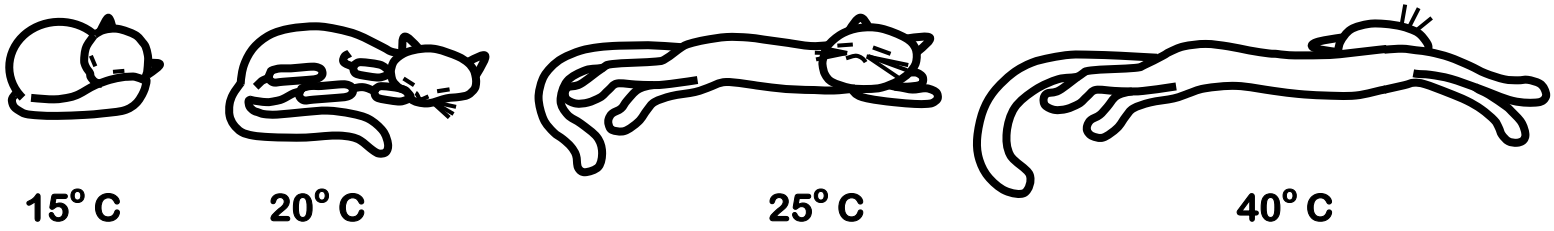
What if we define the "parameter" as the ratio of volume to surface area?

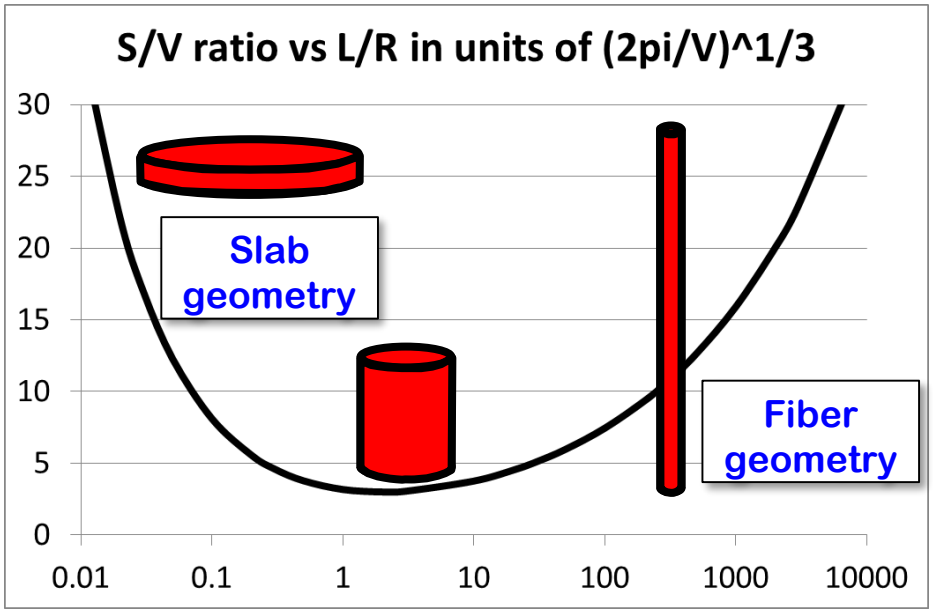


One of 40 inventive principles of TRIZ

35. Parameter changes

- Change an object's physical state (e.g. to a gas, liquid, or solid.)
- Change the concentration or consistency.
- Change the degree of flexibility. Change the temperature.
- Change volume to surface ratio, etc.





See more illustrations at arXiv:1608.00536

Fiber lasers

Inventive principles and fundamental symmetries

Including change of V/S into the principle “parameter change” connects it to fundamental symmetries, i.e. conservation laws of physics

$$\int_{\Delta V} d^3x \nabla \cdot \mathbf{A} = \oint_{\Delta S} \mathbf{A} \cdot d\mathbf{S}$$

Gauss theorem (divergence theorem): the total sources and sinks of a vectorial quantity, or the integral volume of its divergence, is equal to the net flux of this vectorial quantiry across the volume boundary

Further suggestions

Also, hopefully, constructive

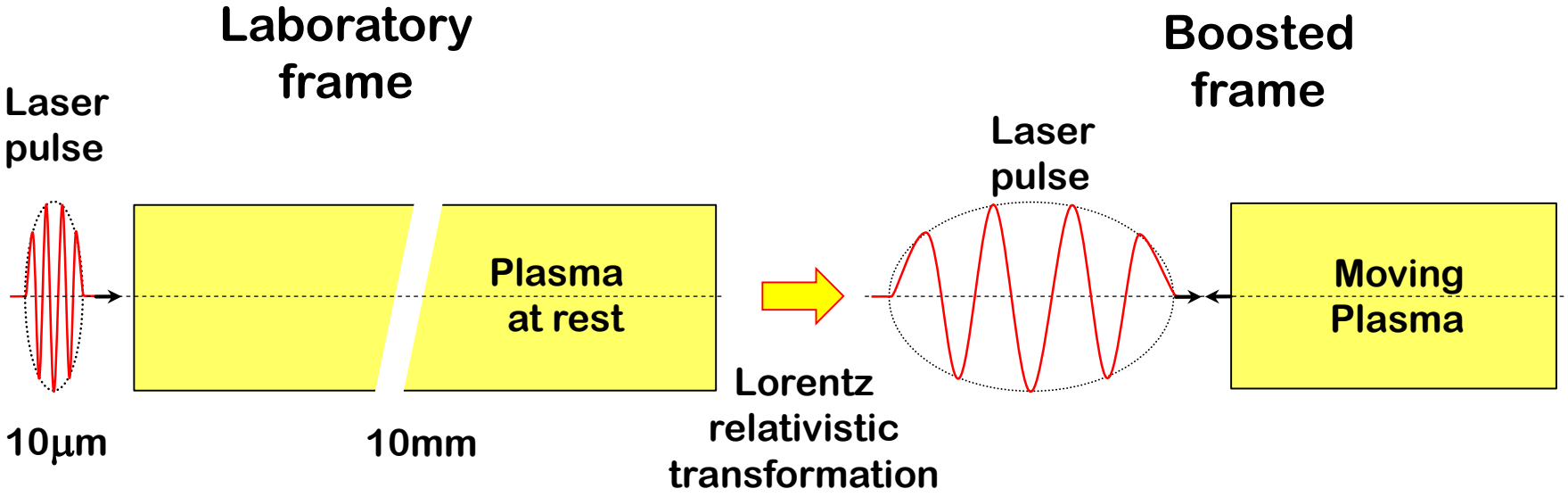
The principle "parameter change" can be interpreted very widely, and thus be very applicable to science

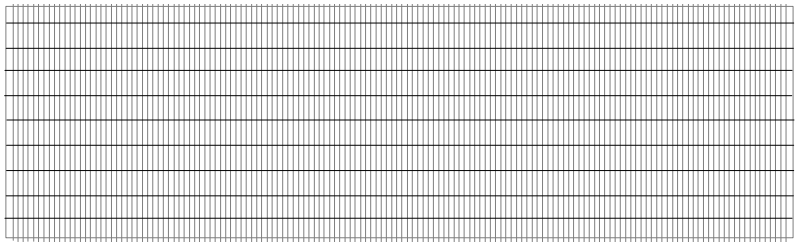
What if "parameter change" include change of the reference frame?

And not just in a conventional sense, but in relativistic?

“Parameter change” & ref frame transformation

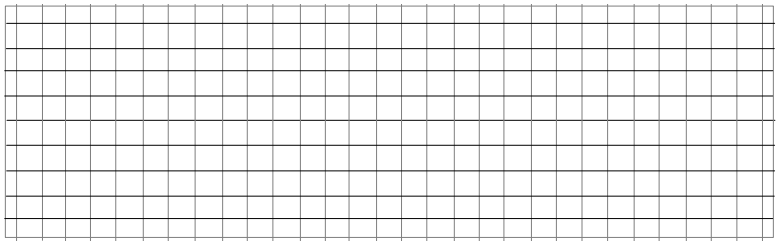
- In physics change of reference frame is a common trick. But…





Grid for numerical calculations

Accurate computation very hard even at supercomputers



Grid for numerical calculations

Accurate computation now much more feasible

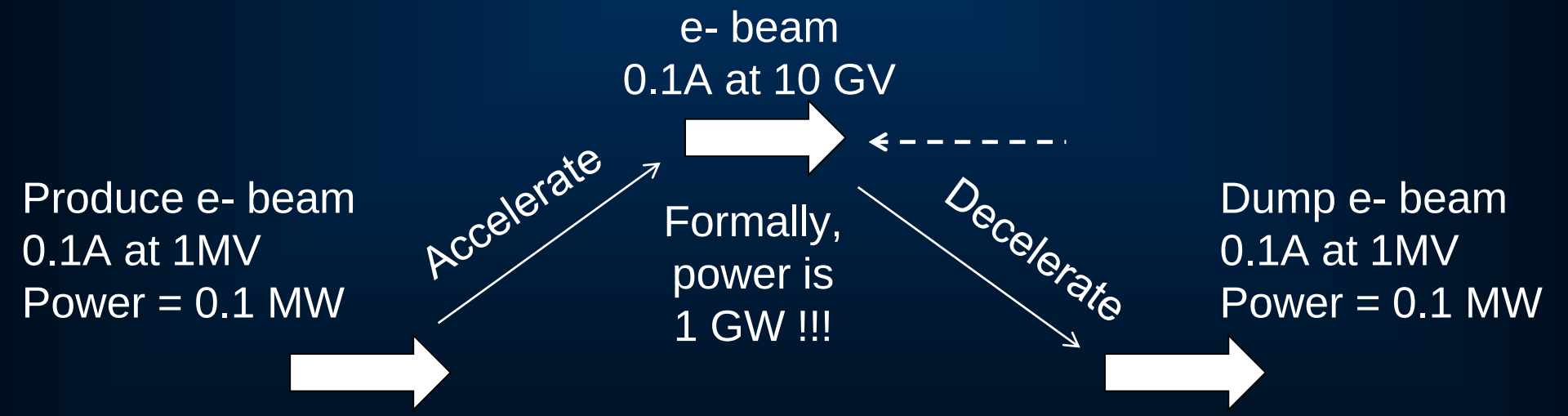
Further questions

What about quantum effects?

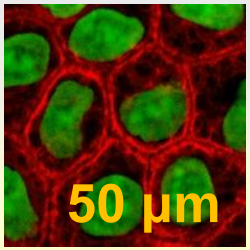
Can we (should we) include some inventive principles related to uncertainty principle, quantum entanglement, etc.?

Or what about energy recovery?

The method which enables many modern scientific instruments



Colliders & principles of TRIZ



Extra magnification?

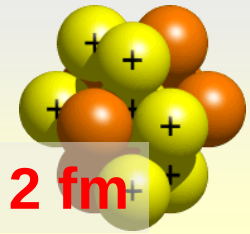
CELLS
Twenty per mm

Microscope

x 25 thousand

DNA
Five hundred thousand per mm

Electron microscope



x 1 million

Nucleus
Five hundred billion per mm

Particle Accelerators

& Colliders

x 2 thousand

Quarks
More than one million billion per mm

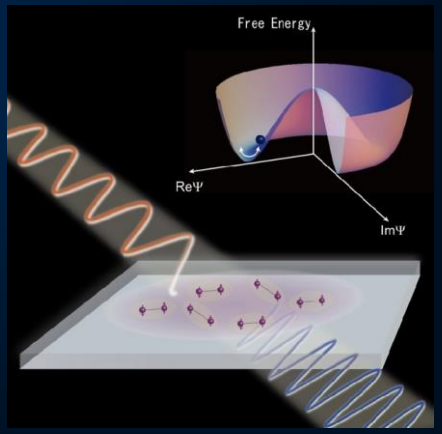
Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Higgs and Superconductivity

"The recent discovery of the Higgs boson has created a lot of excitement … the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics … In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry... *On page 1145 of this issue, Matsunaga et al. report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients*."

Particle physics in a superconductor, A Pashkin & A Leitenstorfer Science 345, 1121 (2014)



Higgs and Superconductivity

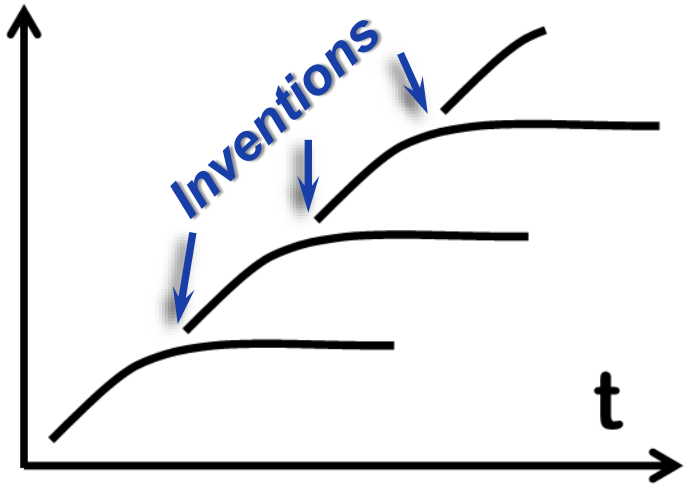
"The recent discovery of the Higgs boson has created a lot of excitement … the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics … In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry... *On page 1145 of this issue, Matsunaga et al. report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients*."

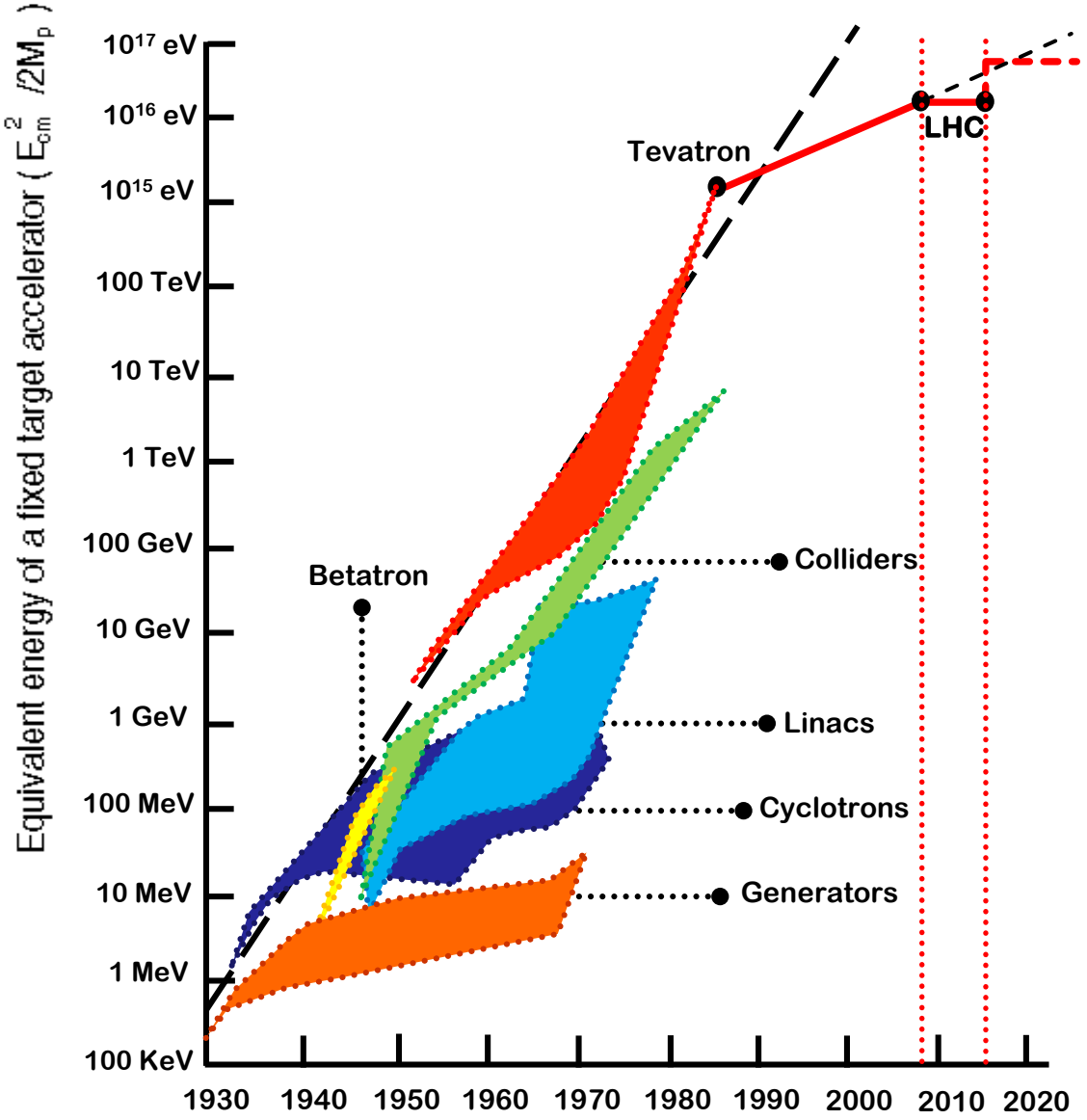
Particle physics in a superconductor, A Pashkin & A Leitenstorfer Science 345, 1121 (2014)

- This shows us that a general conclusion of TRIZ
  - ***"The same Problems and Solutions appear again and again but in different disciplines"***
- is applicable to science too

Evolution of accelerators

- History of accelerators…
- …and evolution *(and saturation)* of particular technologies of acceleration, and birth of the new technologies *via inventions*





Inventing sci. instruments

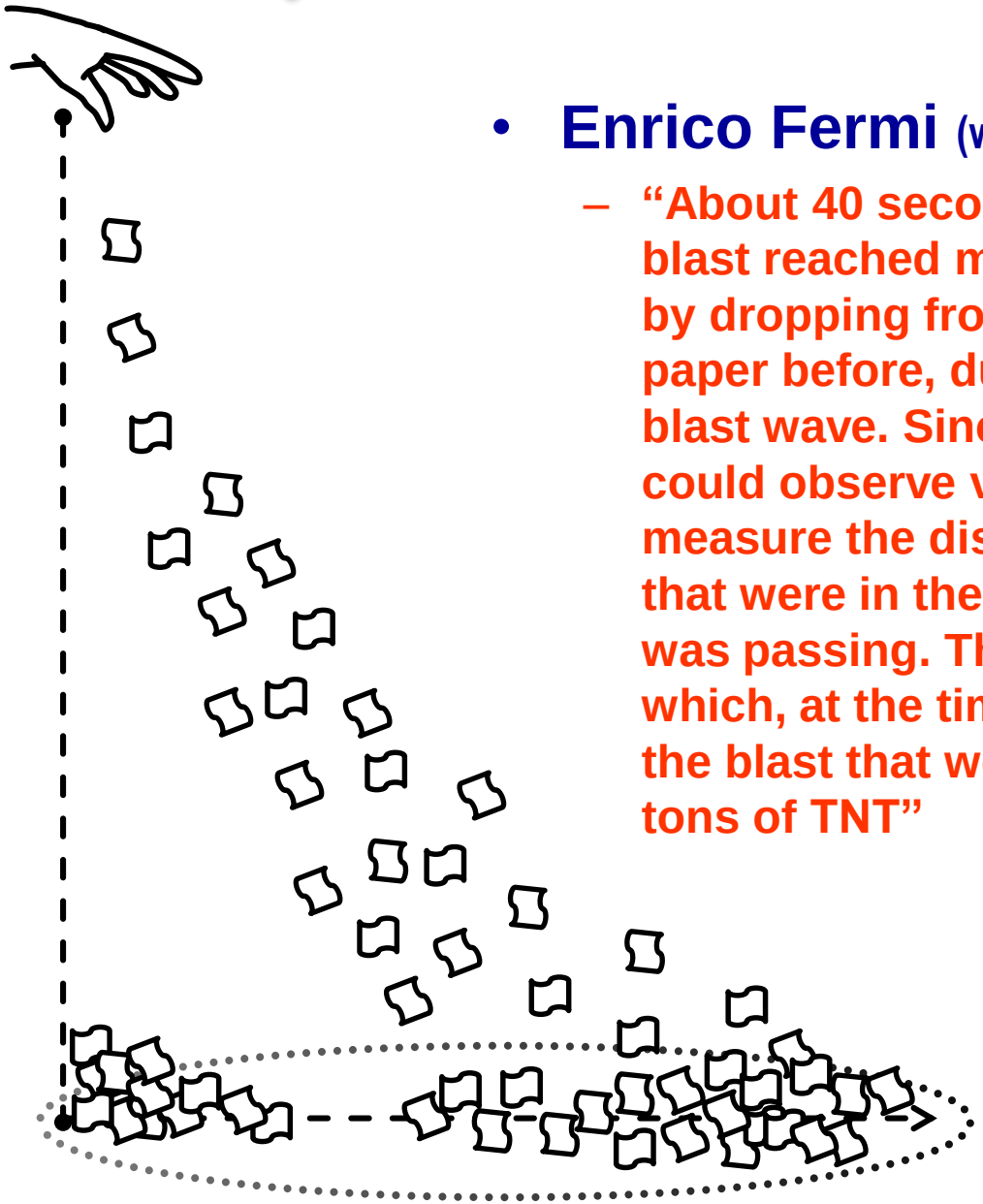
Even if one would define a set of TRIZ inventive principles that would include many approaches used in science, would it be sufficient?

No

What would be missing?

Most importantly – the art of estimations

Example of back-of-envelope estimations



- **Enrico Fermi** (who was ~10 miles from the Trinity test):
  - **"About 40 seconds after the explosion the air blast reached me. I tried to estimate its strength by dropping from about six feet small pieces of paper before, during, and after the passage of the blast wave. Since, at the time, there was no wind I could observe very distinctly and actually measure the displacement of the pieces of paper that were in the process of falling while the blast was passing. The shift was about 2 1/2 meters, which, at the time, I estimated to correspond to the blast that would be produced by ten thousand tons of TNT"**

Importance of back-of-envelope estimations

- **They are important because**
  - **they help to quickly check if your idea is viable - obvious**
  - **but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics**

- **To train yourself on back-of-envelope estimations one can consider various questions**
- **They do not have to be necessarily serious ;-)**
- **But the estimates should be based on a physical effect that is considered most important for a given question**

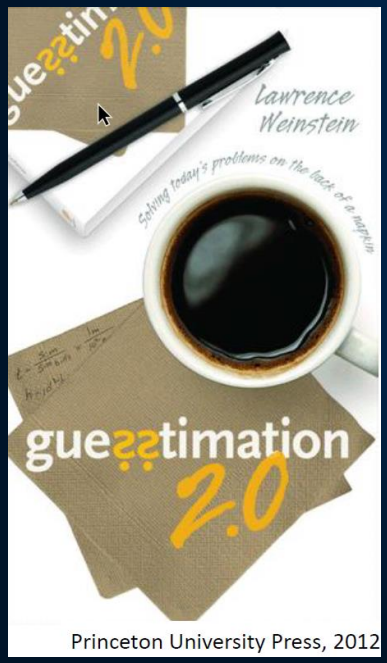
The art of estimating

Enrico Fermi was known for his ability to back-of-envelope estimations

Many leading centers teach the art of estimating from school – e.g. the unique Phys-Math school in Novosibirsk

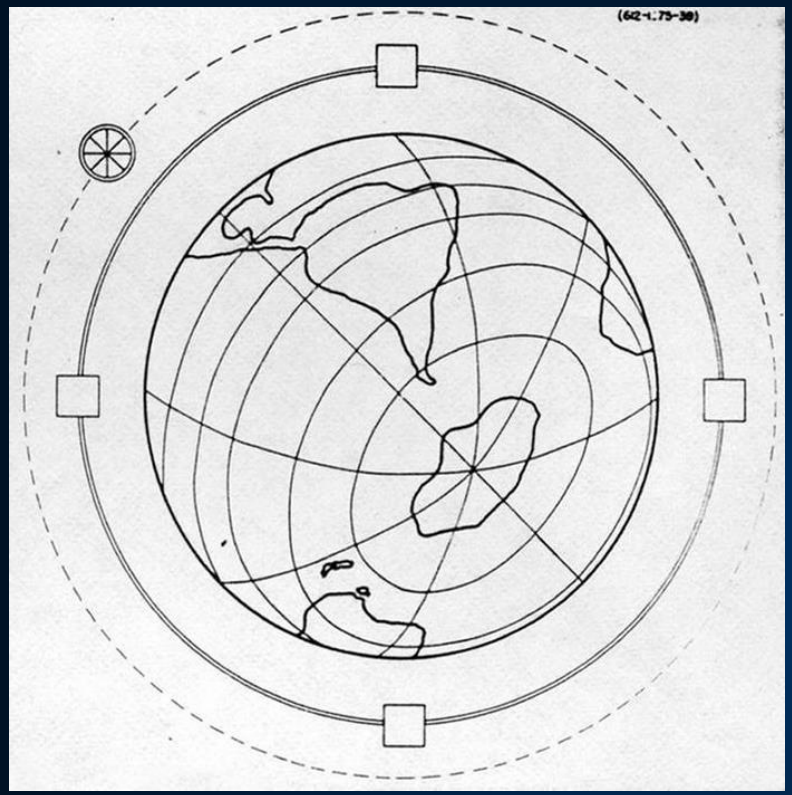
(Clockwise from top left) The Phys–Math School in Novosibirsk, Russia. Students deriving formulae during a class. Graduates of the 1963 class.

http://cerncourier.com/cws/article/cern/69910



There are books that can help to master the art of estimations, e.g. “Guesstimation 2.0” by Lawrence Weinstein (Old Dominion University)

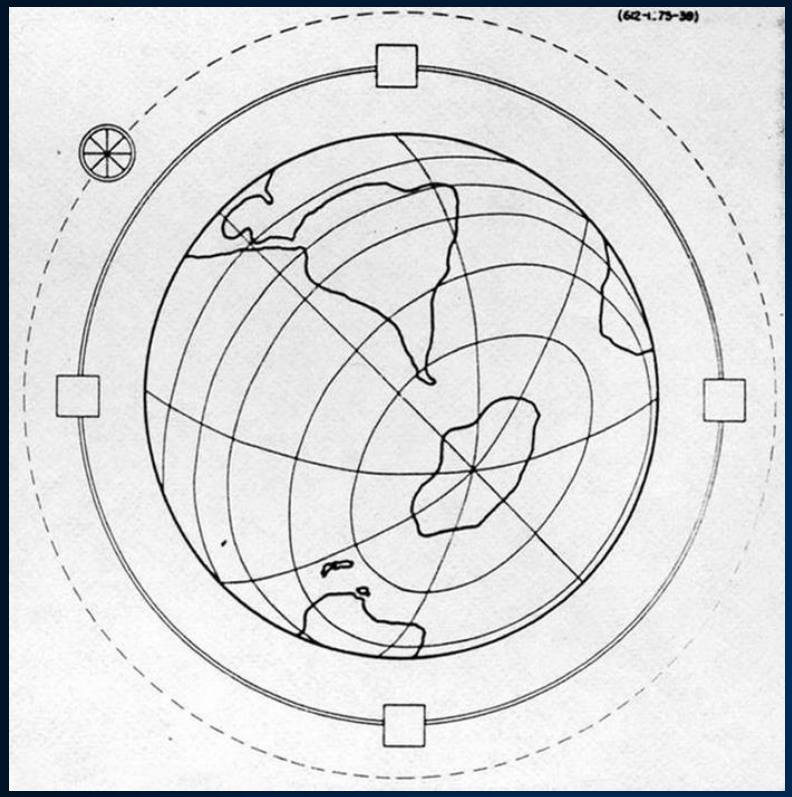
Evolution of accelerators



In 1954 Enrico Fermi presented, in his lecture, a vision of an accelerator that would encircle the Earth, and would attain highest possible energies

Would this be indeed a natural evolution of accelerators?

Evolution of accelerators



Enrico Fermi Earth accelerator, 1954

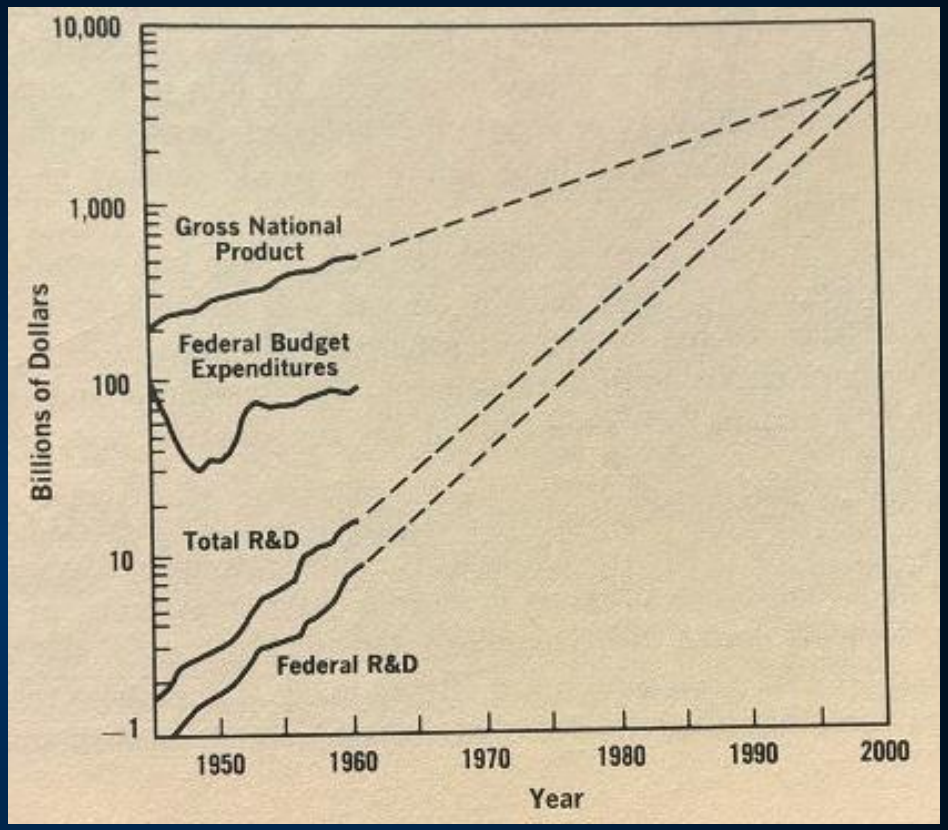
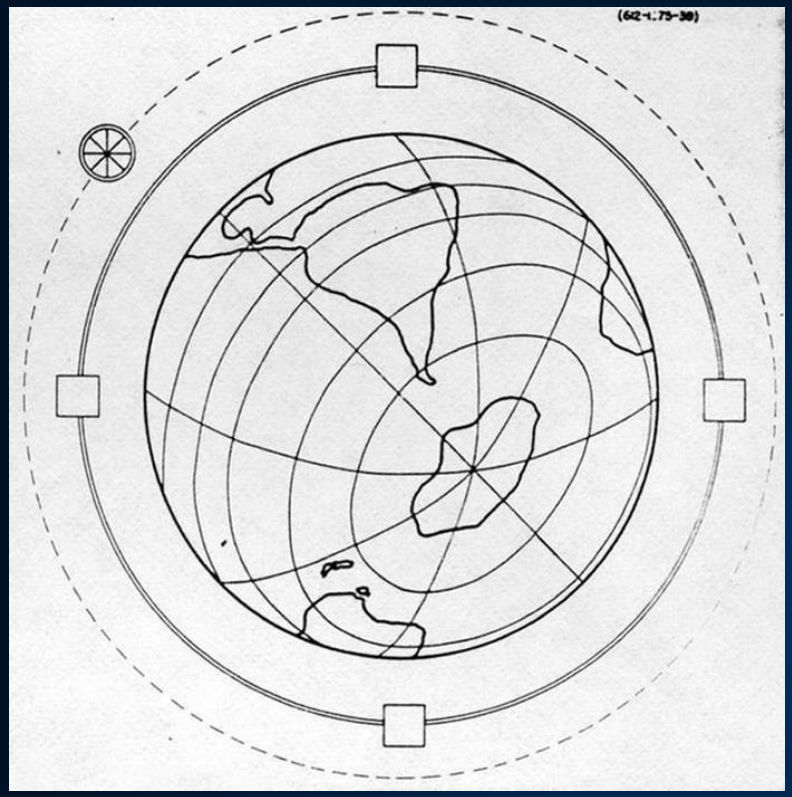


Fig 6, GNP and R&D: Failure of naïve extrapolation. "The Year 2000", 1968, K. Herman, A. Wiener

Would this be indeed a natural evolution of accelerators?

No. And not only because R&D budget is now not growing faster than GDP

Evolution of accelerators



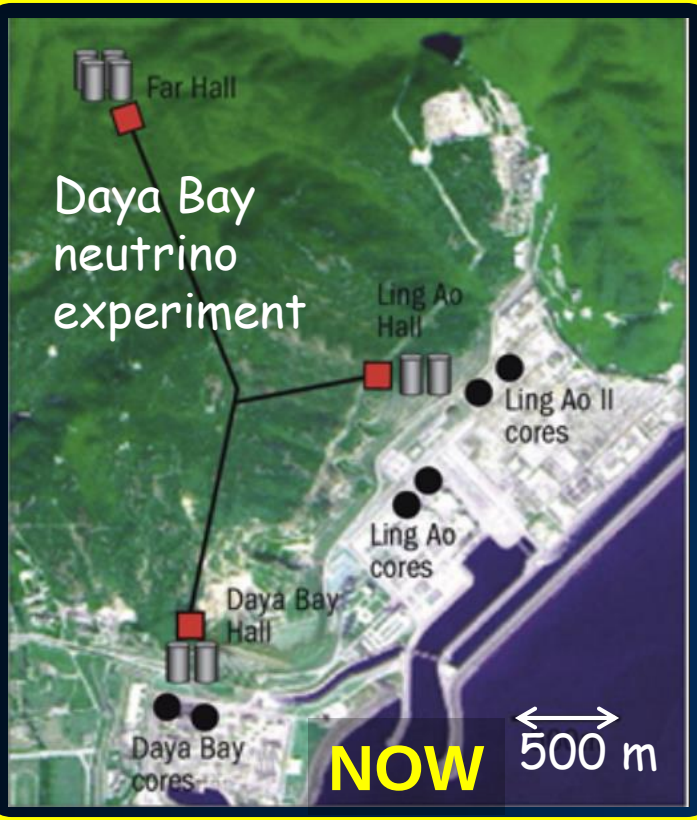
Enrico Fermi Earth accelerator, 1954

Would this be indeed a natural evolution of accelerators?

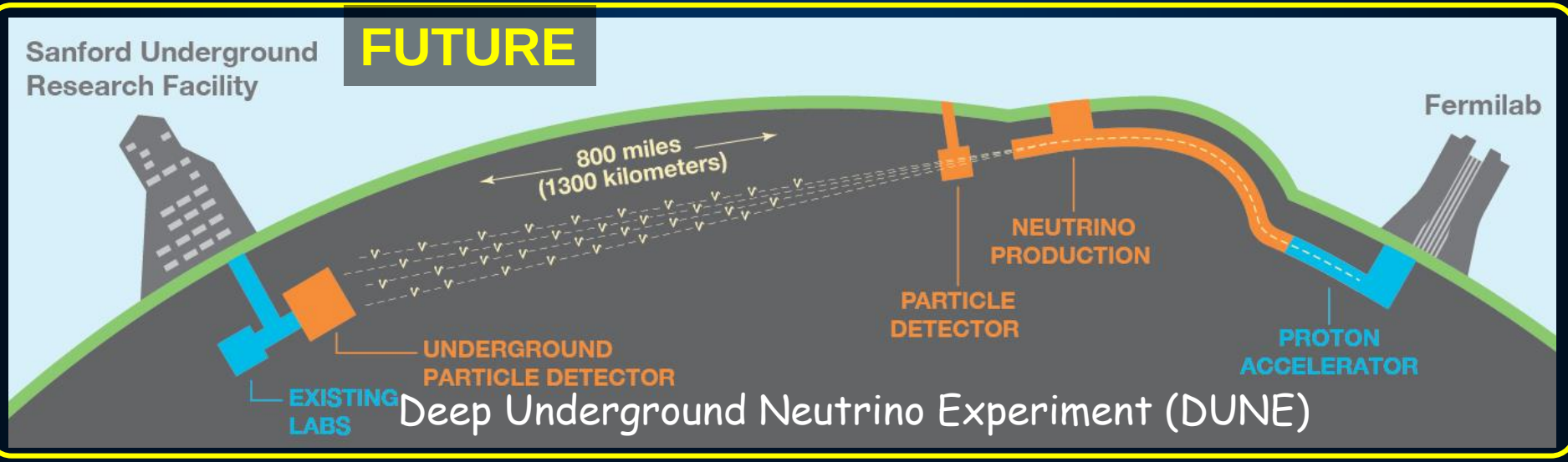
No.

Increasing the size or base of the experiment, to increase precision, with proportional or event faster increase of the cost, would unlikely be accepted by governments and society

Evolution of neutrino experiments



Increasing the size or base of the experiment, to increase precision, <u>without</u> proportional increase of the cost – good chance to be accepted by society & governments



Evolution of neutrino

UK signs £65m science partnership agreement with US

20 September 2017

The UK is investing £65million in a flagship global science project based in the United States that could change our understanding of the universe. The investment, made under a new UK-US Science and Technology agreement, further secures the UK's position as the international research partner of choice.

Today, UK Universities and Science Minister Jo Johnson signed the agreement with the US Energy Department to invest the sum in the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE). DUNE will study the properties of mysterious particles called neutrinos, which could help explain more about how the universe works and why matter exists at all.

This latest investment is part of a long history of UK research collaboration with the US, and is the first major project of the wider UK-US Science and Technology agreement.

Jo Johnson (UK Minister of State for Universities, Science, Research and Innovation) and Judith G. Garber (U.S. Acting Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs) signed the U.S.-UK Science and Technology Agreement on Sept. 20 in Washington, D.C.
(Credit: FCO)

EXISTING LABS PARTICLE DETECTOR ACCELERATOR

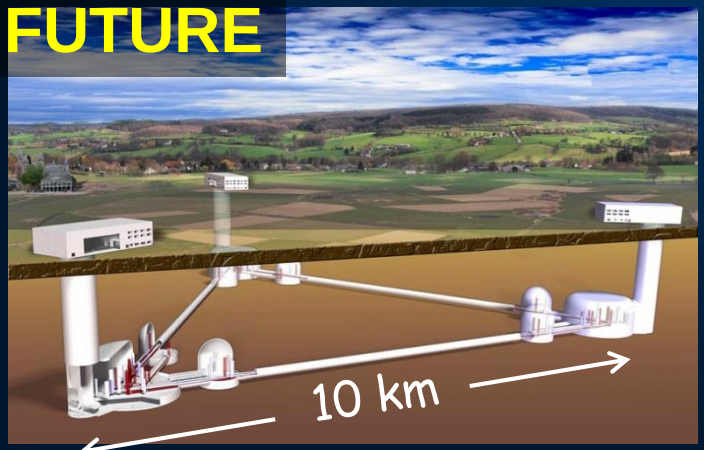
Deep Underground Neutrino Experiment (DUNE)

Evolution of gravitational wave detectors

NOW

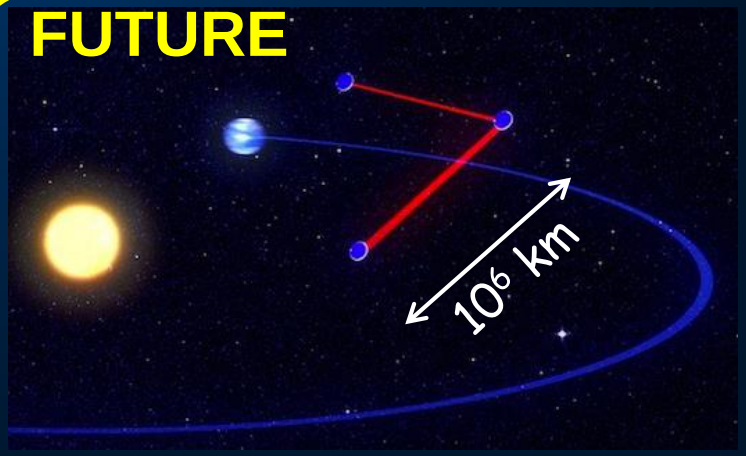
Increasing the size or base of the experiment, to increase precision, without proportional increase of the cost – good chance to be accepted by society & governments

FUTURE



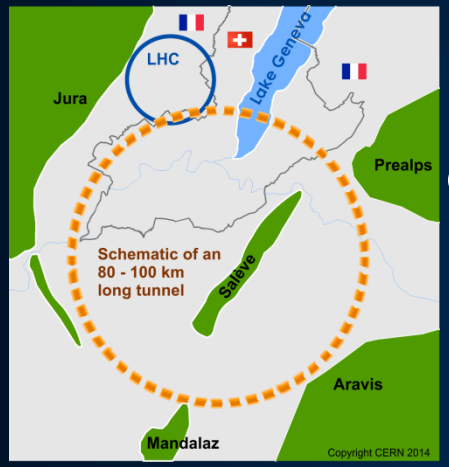
Einstein telescope

FUTURE



eLISA

From that point of view – can next big conventional collider be built (accepted by government & society)?

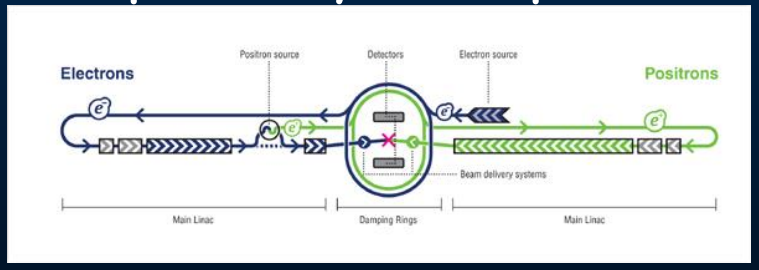


Circular collider FCC (CERN)

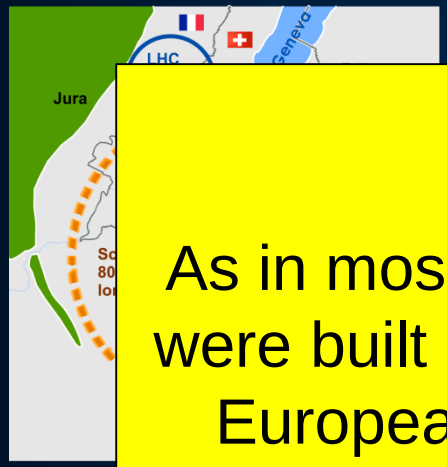
Circular collider CEPC (China)

Size of each of this is ~30-100km (in length or perimeter), i.e. ~3 times larger than LHC

Linear collider ILC (possibly in Japan)



From that point of view – can next big conventional collider be built (accepted by government & society)?



Yes.

But:

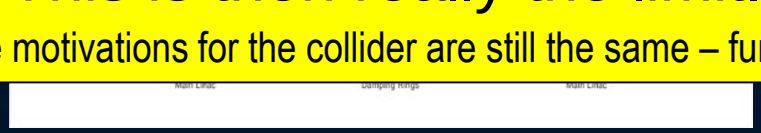
As in most of previous cases the largest colliders were built as mostly regional efforts (e.g. primarily European funding for LHC), building ~3 times larger and more expensive collider perhaps can be done but only with all world efforts combined.

I.e. only once more.

This is then really the limit.

(Assuming that the motivations for the collider are still the same – fundamental science)

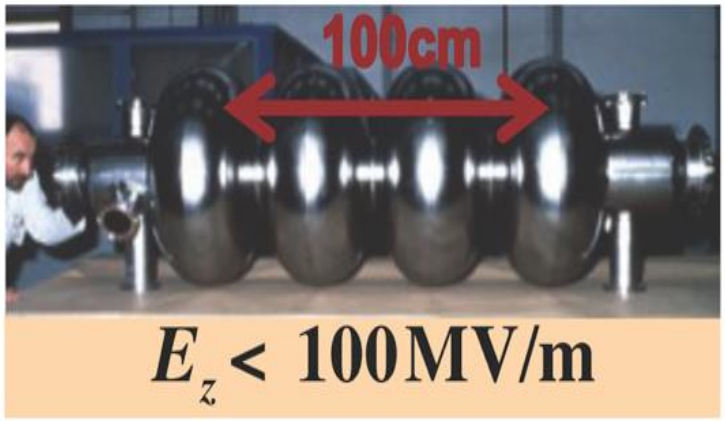
Size of this is ~ 100km or peri i.e. ~3 t larger than LHC



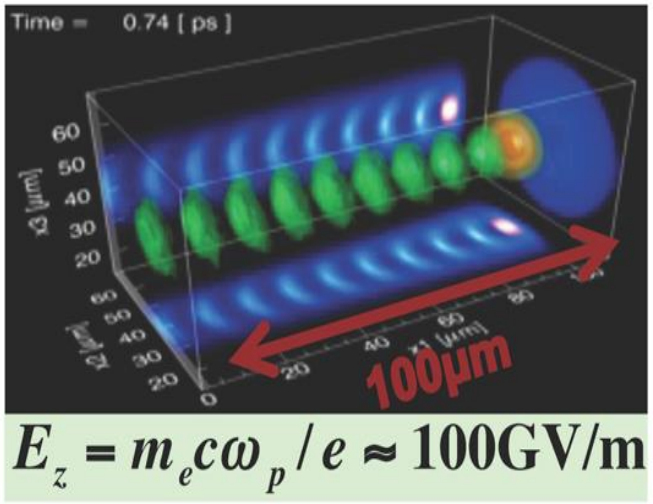
One of 40 inventive principles of TRIZ

27. Cheap short-living objects

- Replace an expensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).



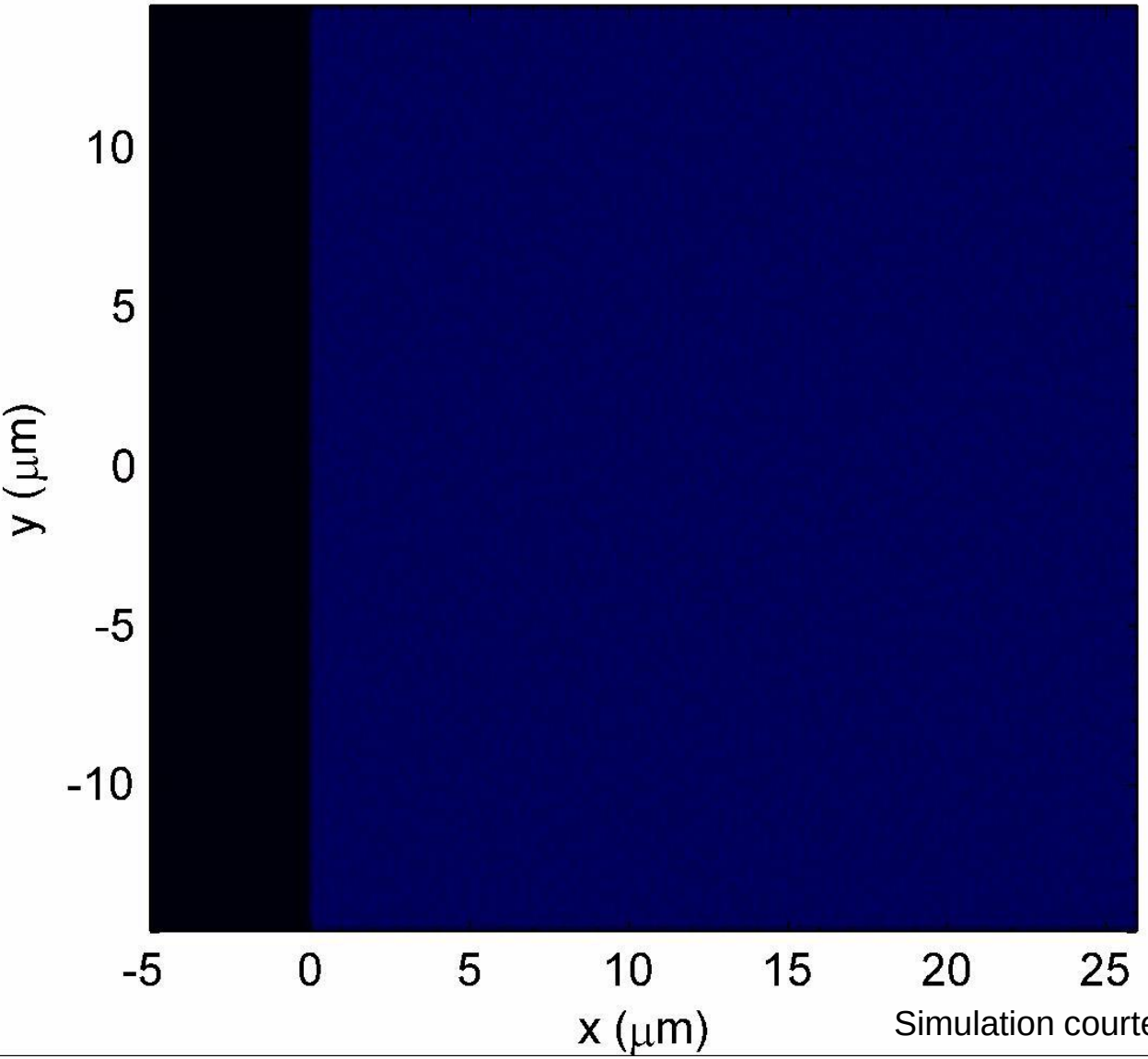
Accelerating structure, metal (normal conductive or super-conductive)



"Accelerating structure" produced on-the-fly in plasma by laser pulse

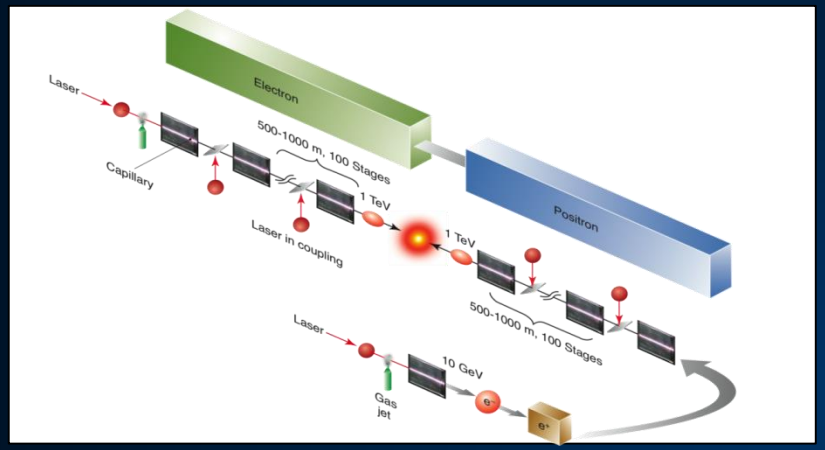
See more illustrations at arXiv:1608.00536

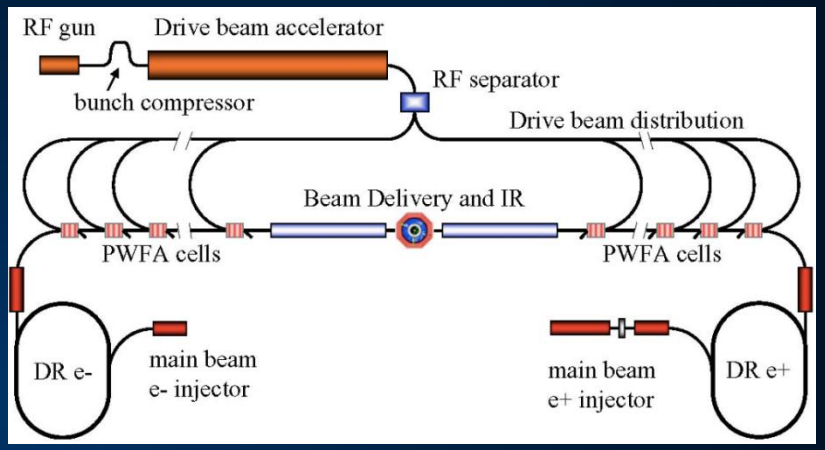
Plasma acceleration



Simulation courtesy Prof Simon Hooker

Can the next collider be based on plasma acceleration?





Size ~2-3km (i.e. ~10 times smaller)

Many inventions still to be done to make them feasible – active R&D by many teams worldwide

To finish up, let's talk about evolution of synchrotron light sources and FELs

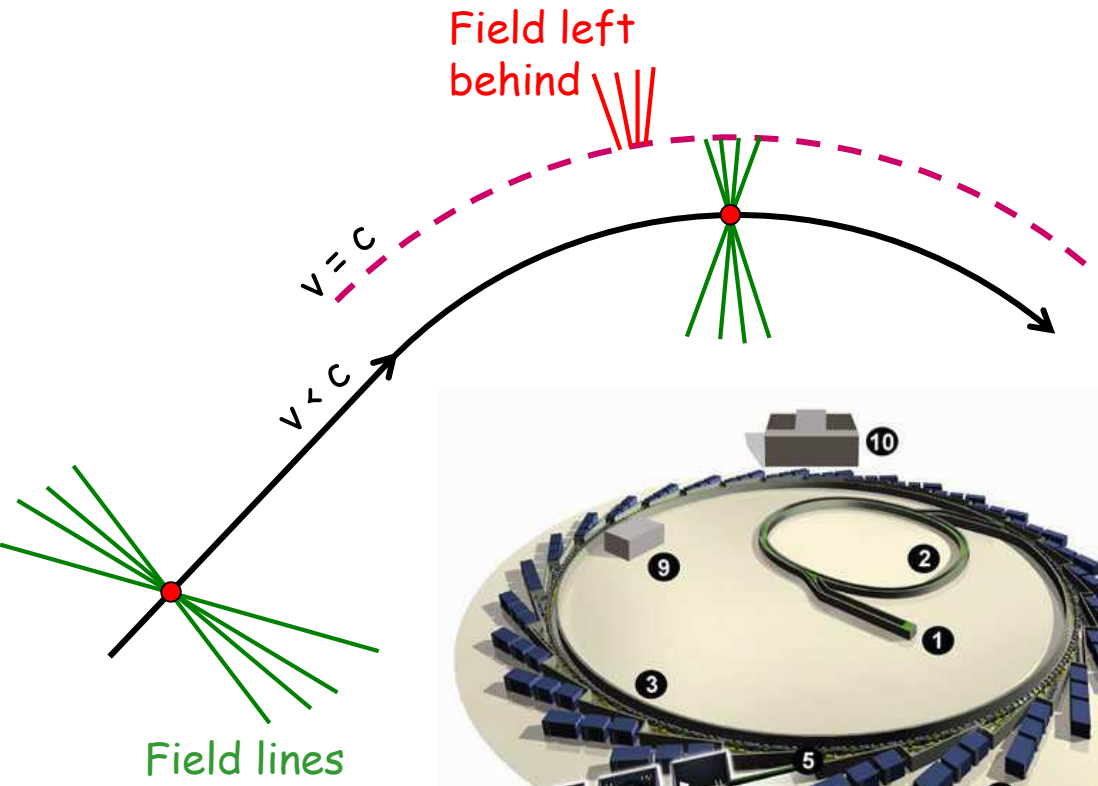
including those based on plasma acceleration

But first, let's define some metric which allow us to evaluate and compare the importance of different directions of research

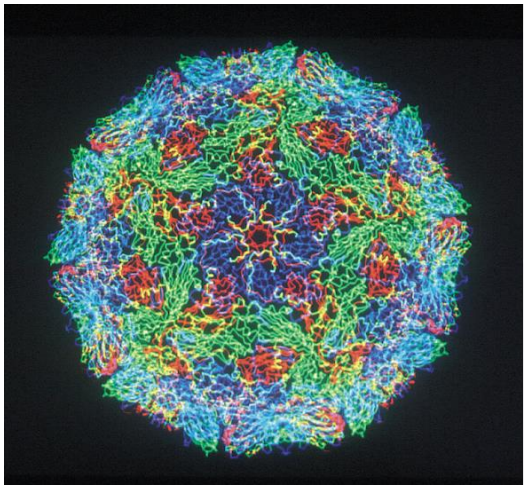

Physical Review Letters
Physical Review Letters
Patent
Niels Bohr
Louis Pasteur
Accelerator Science & Technology
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Protons/Ions
Patent
Fundamental knowledge
Consideration of use

Synchrotron radiation light sources

Synchrotron Radiation (SR) caused by leaving part of fields behind when the beam moves along the curve



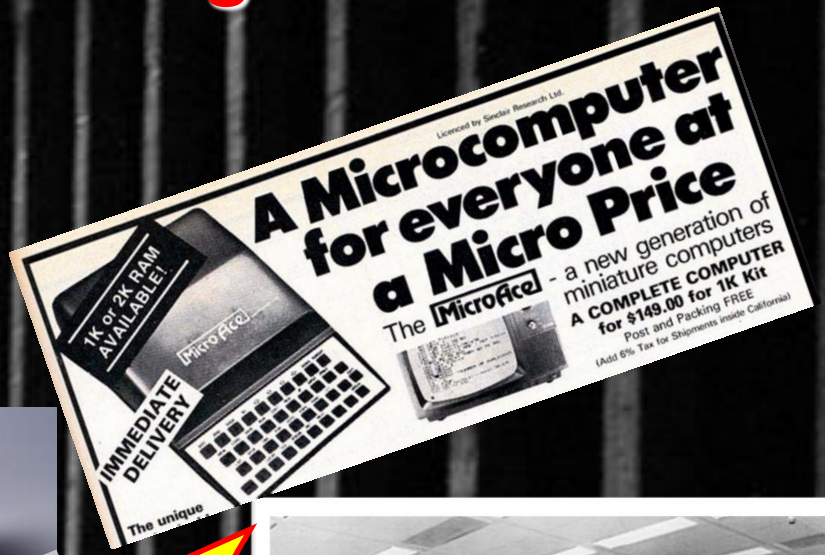
Synchrotron radiation can be useful



Example of a structure of a virus decoded using SR

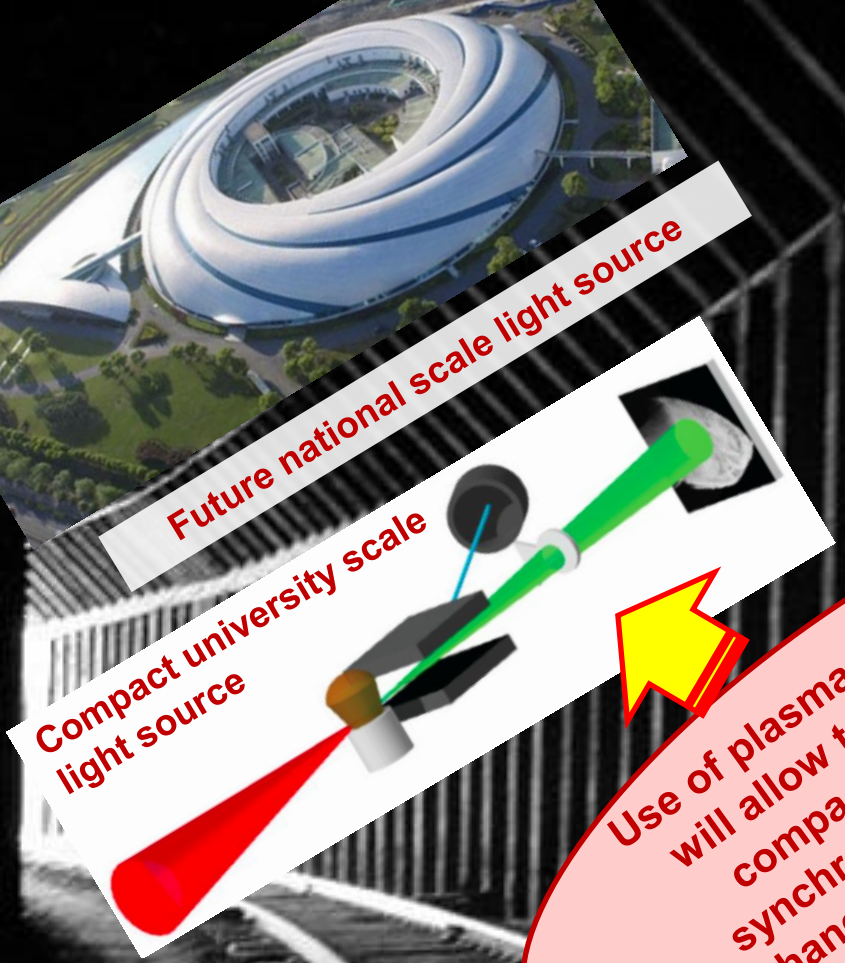
Diamond SR source at Harwell, UK

Evolution of computers and light sources



"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981

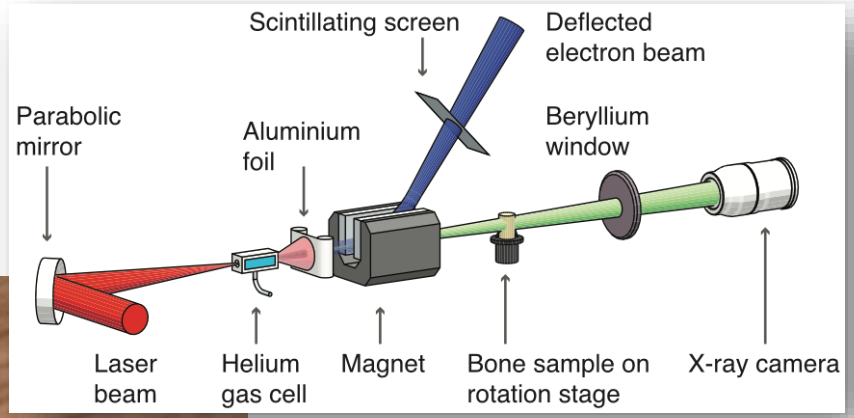
Evolution of computers and light sources



Use of plasma acceleration will allow to create very compact sources of synchrotron radiation – change of the paradigm

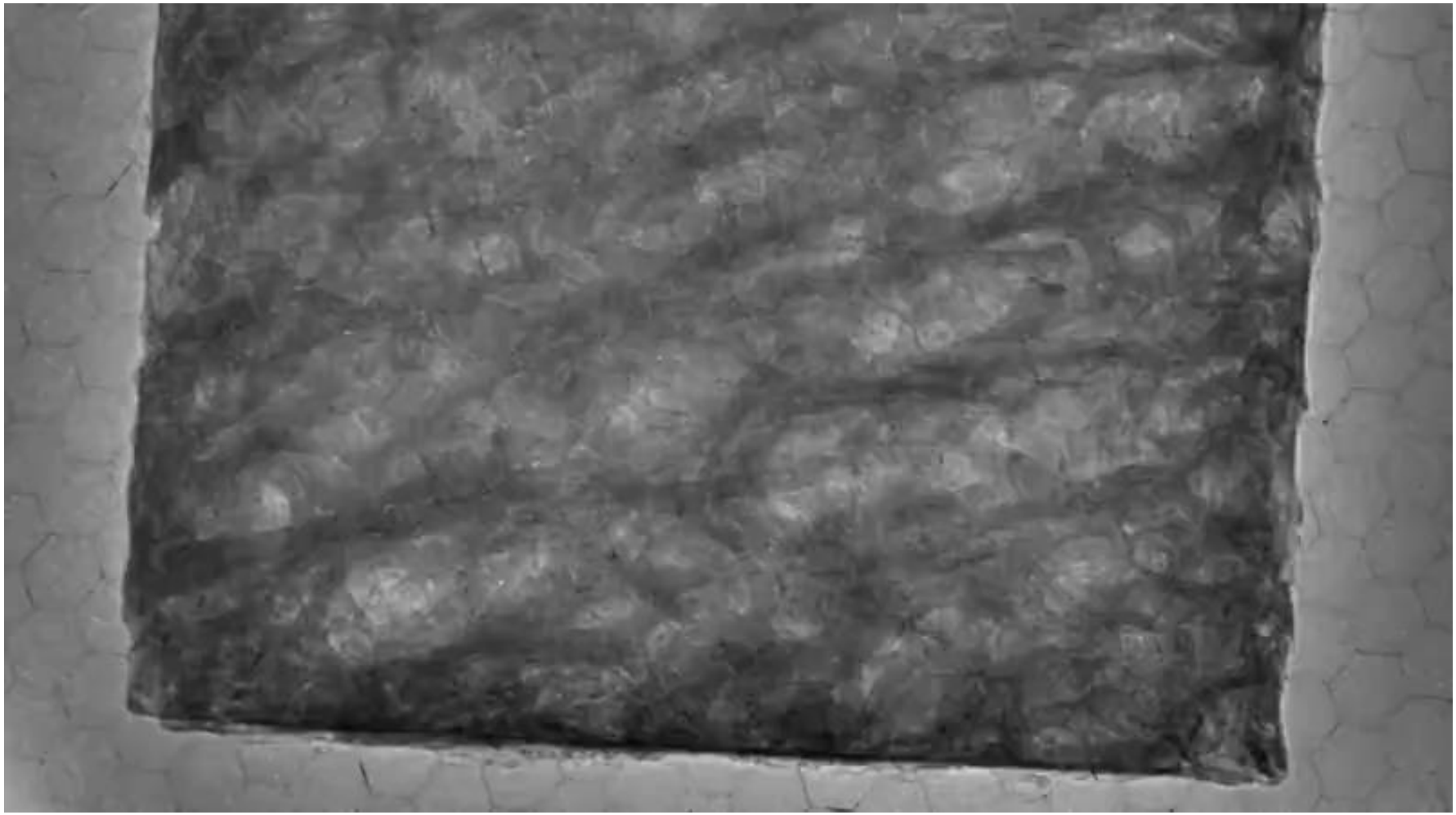
Imaging with laser-plasma accelerated beams

Roentgen 1896



Bone sample

Imaging with laser-plasma accelerated beams

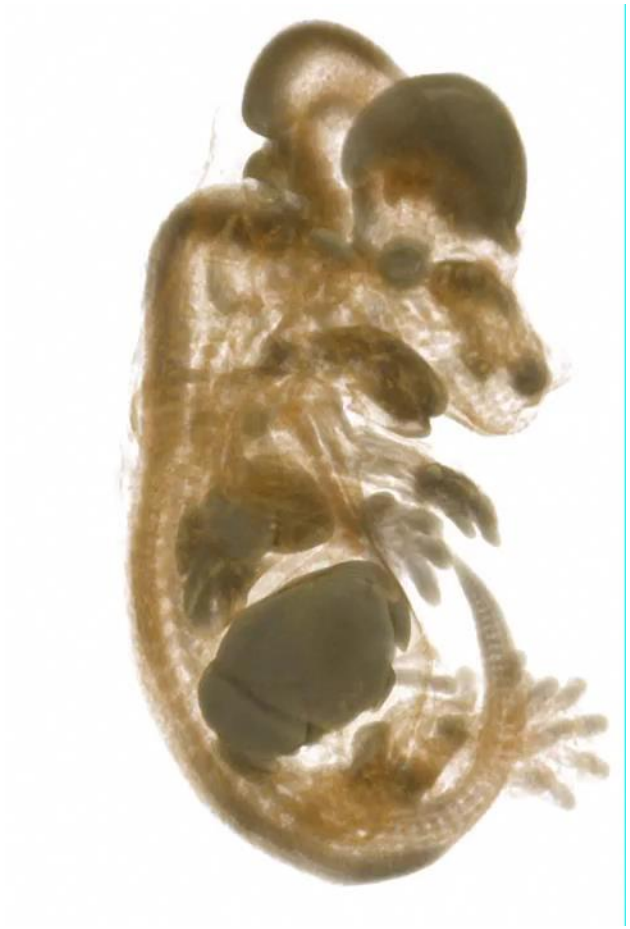


Bone tomography

Voxel size 5×5×5 µm

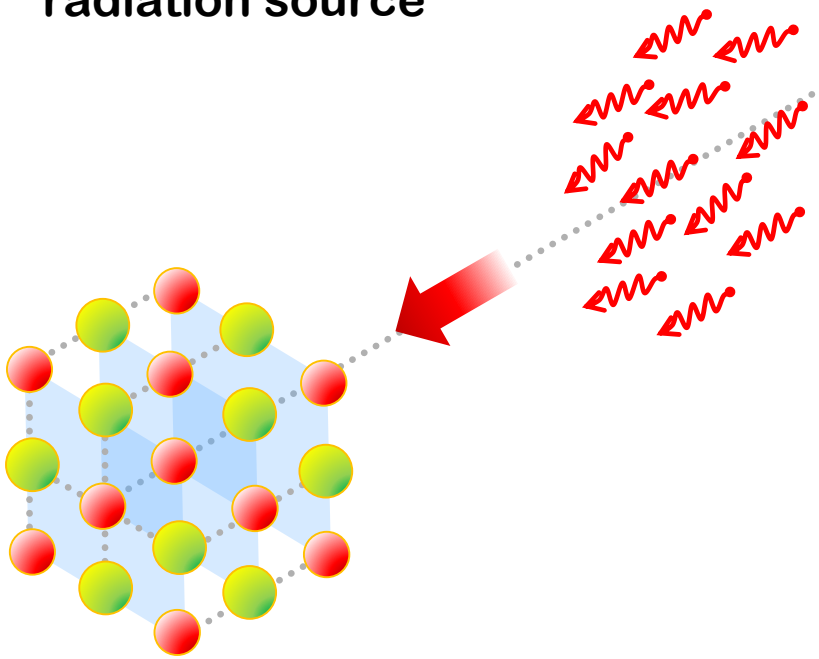
Cole, J. et al. Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone. Sci. Reports 5:13244 (2015).

Mouse 14.5day tomography

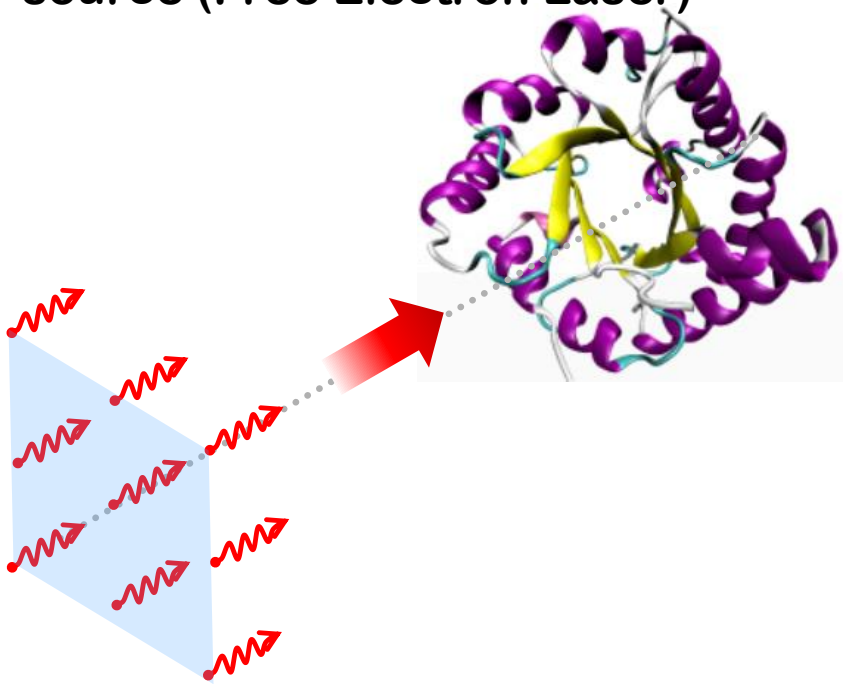


Incoherent SR => coherent

Incoherent synchrotron radiation source



Coherent synchrotron radiation source (Free Electron Laser)



Era of studies of crystal structures by incoherent sources of X-rays

Era of studies of non-crystalline structures by coherent sources of X-rays

…and also this is an inventive principle “the other way around”

Further evolution of light sources

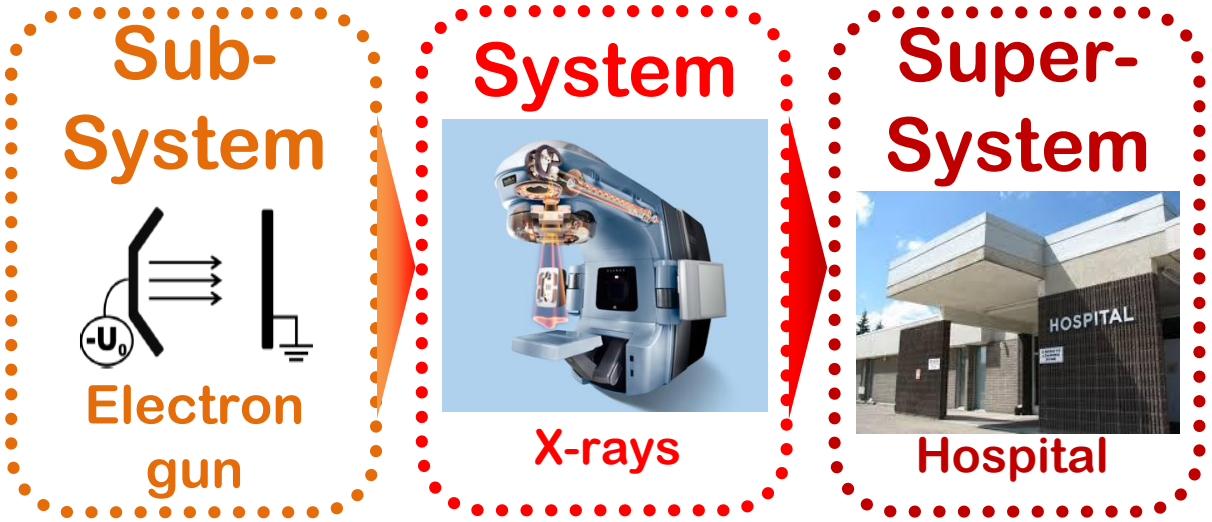
Let's assume that laser-plasma FEL is working

What are long-terms perspectives and evolution of light sources then?

Let's apply the TRIZ general laws of evolution

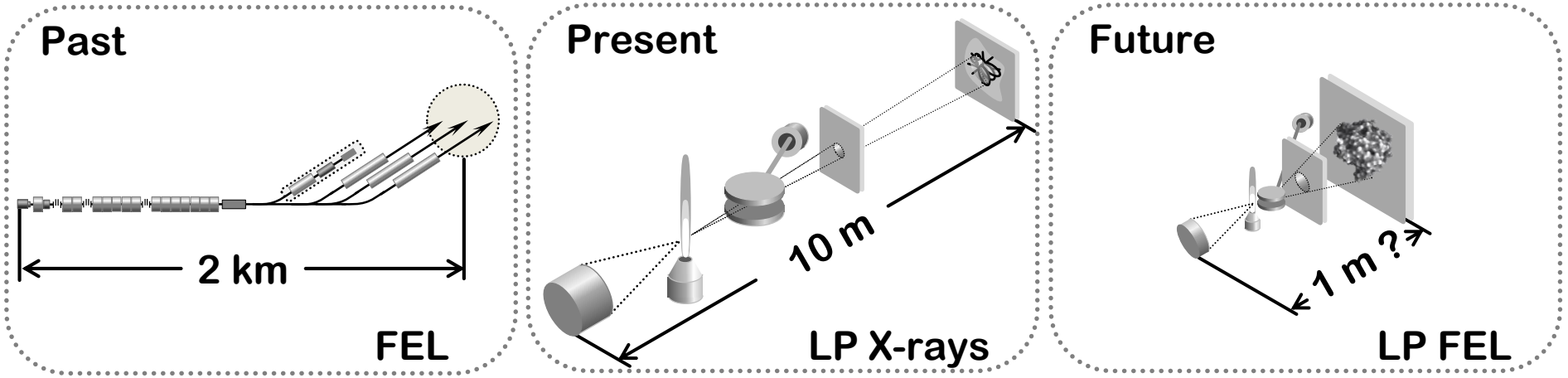
Transition to a super-system

- **Kinematic laws (standard TRIZ)**
  - **The law of transition to a super-system**



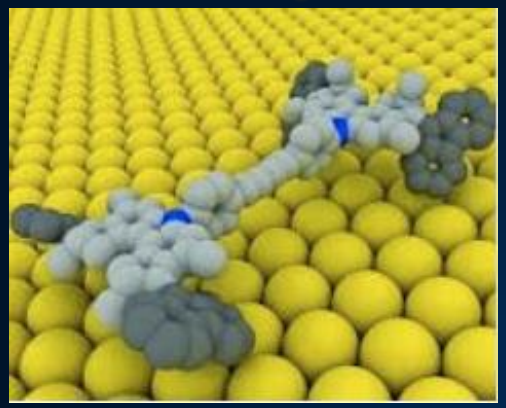
“a system exhausting possibilities of further significant improvement is included in a super-system as one of its parts”

FEL evolution forecast



FEL will be so compact and developed that it can become part of another system, and that system in turn part of super-system

Nobel prize 2016 – molecular machines



Pierre Sauvage, J. Fraser Stoddart, and Ben L. Feringa, Chemistry Nobel Prize 2016

Compare this with laws of technical system evolution

that were developed for TRIZ in 20th century

- Static Laws
  - The law of the completeness of the parts of the system
    - 4 parts: engine, transmission, working unit, control element
  - The law of energy conductivity of the system
    - every technical system is a transformer of energy and it should circulate freely and efficiently through its 4 main parts

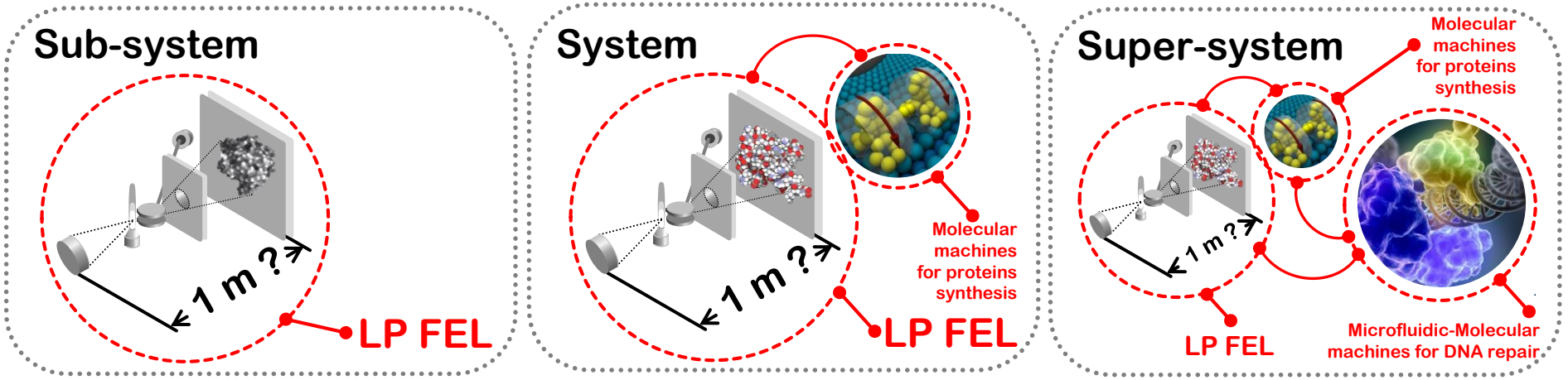
These laws allow to predict what parts of molecular machine would be invented next

These machines can become part of another super-system

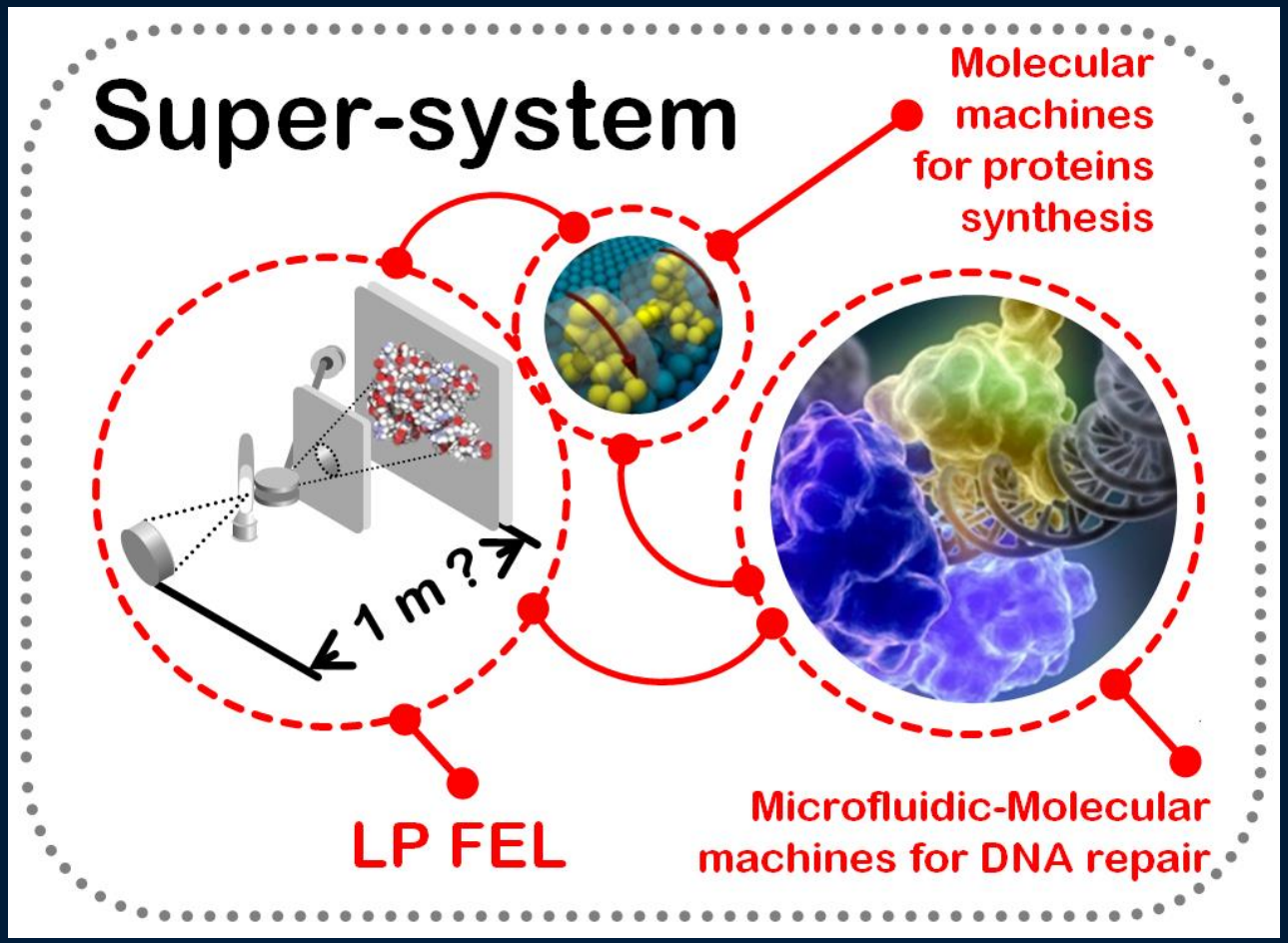
FEL and molecular machine becomes part of another system

FEL is part of system where it analyses proteins synthesized by molecular machine

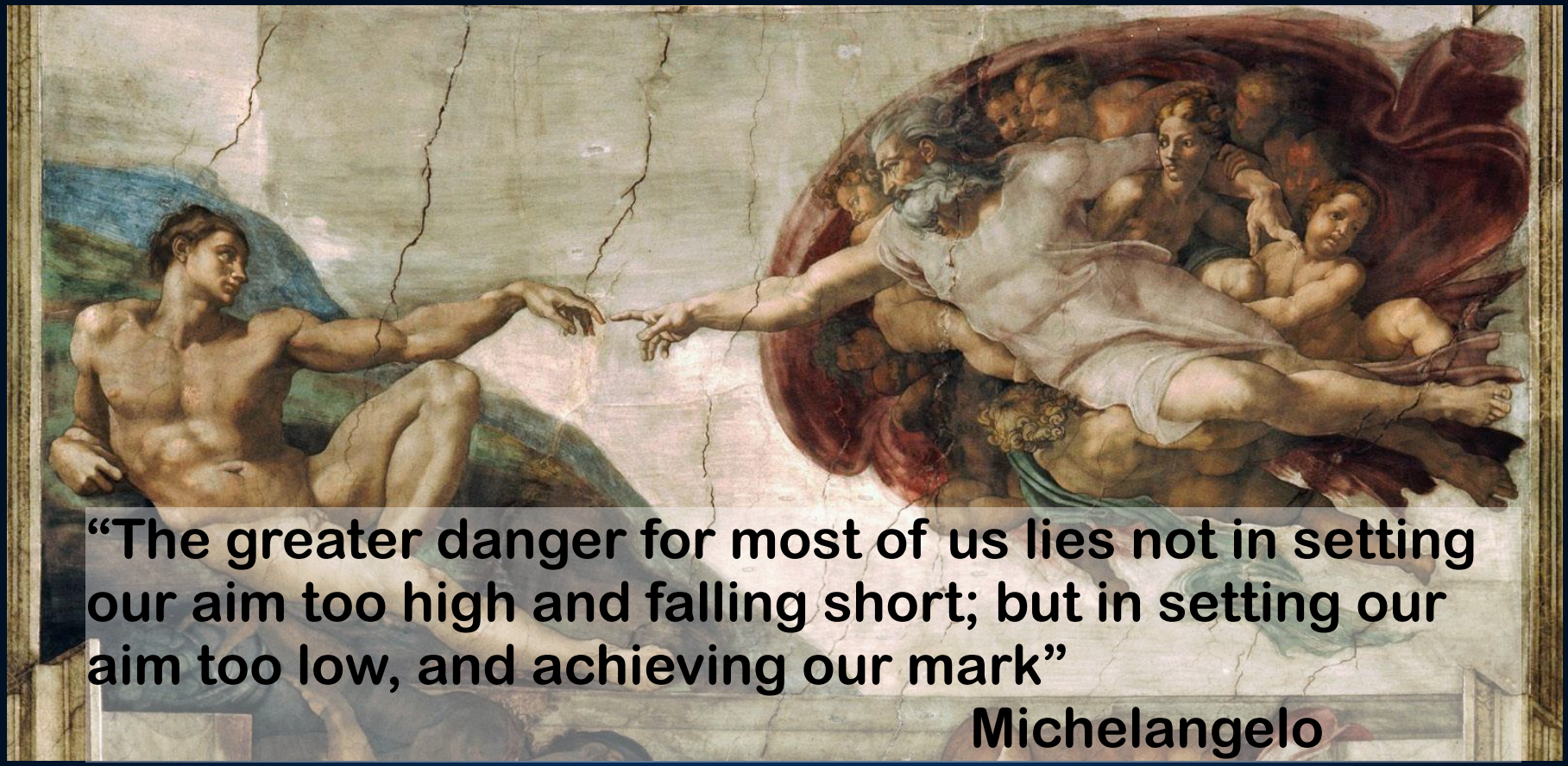
FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair



Make (with help of TRIZ) this dream a reality!



Laser plasma FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair



TRIZ can be very useful for science

As an inspiration, as a very efficient toolbox, as a way to connect different disciplines, as a new way to see the world

Thank you for your attention!

Thanks to my colleagues for materials used in these slides