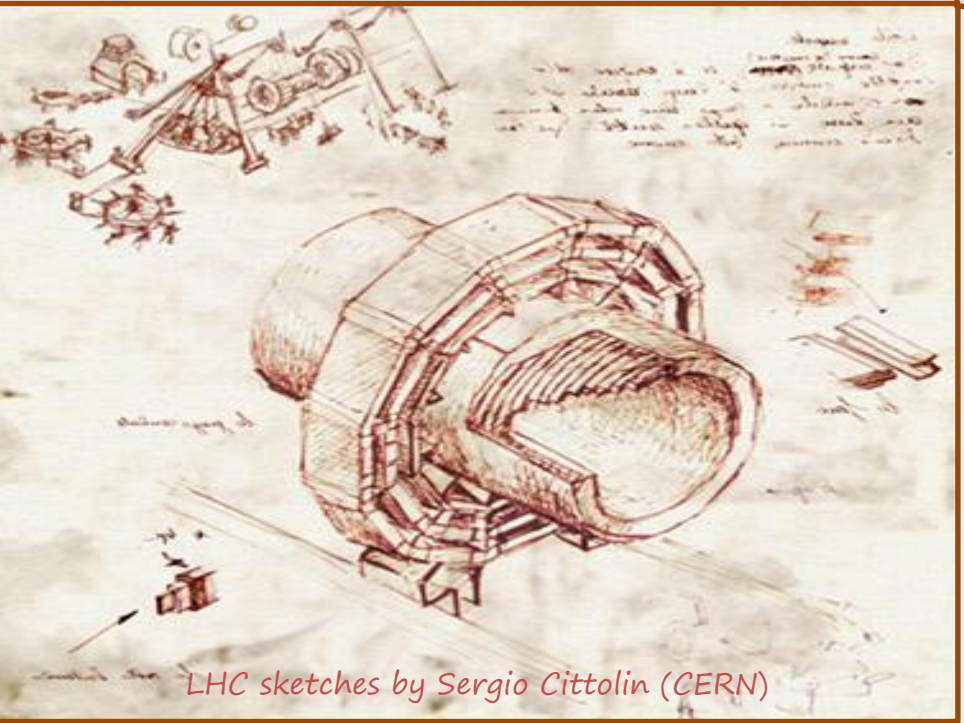
Structured Inventions



LHC sketches by Sergio Cittolin (CERN)

Andrei Seryi
Jefferson Lab and ODU

USPAS

5 February 2025

Scientific revolutions – what drives them?

Two points of view:

Philosopher Thomas Kuhn:

scientific revolutions are concept-driven

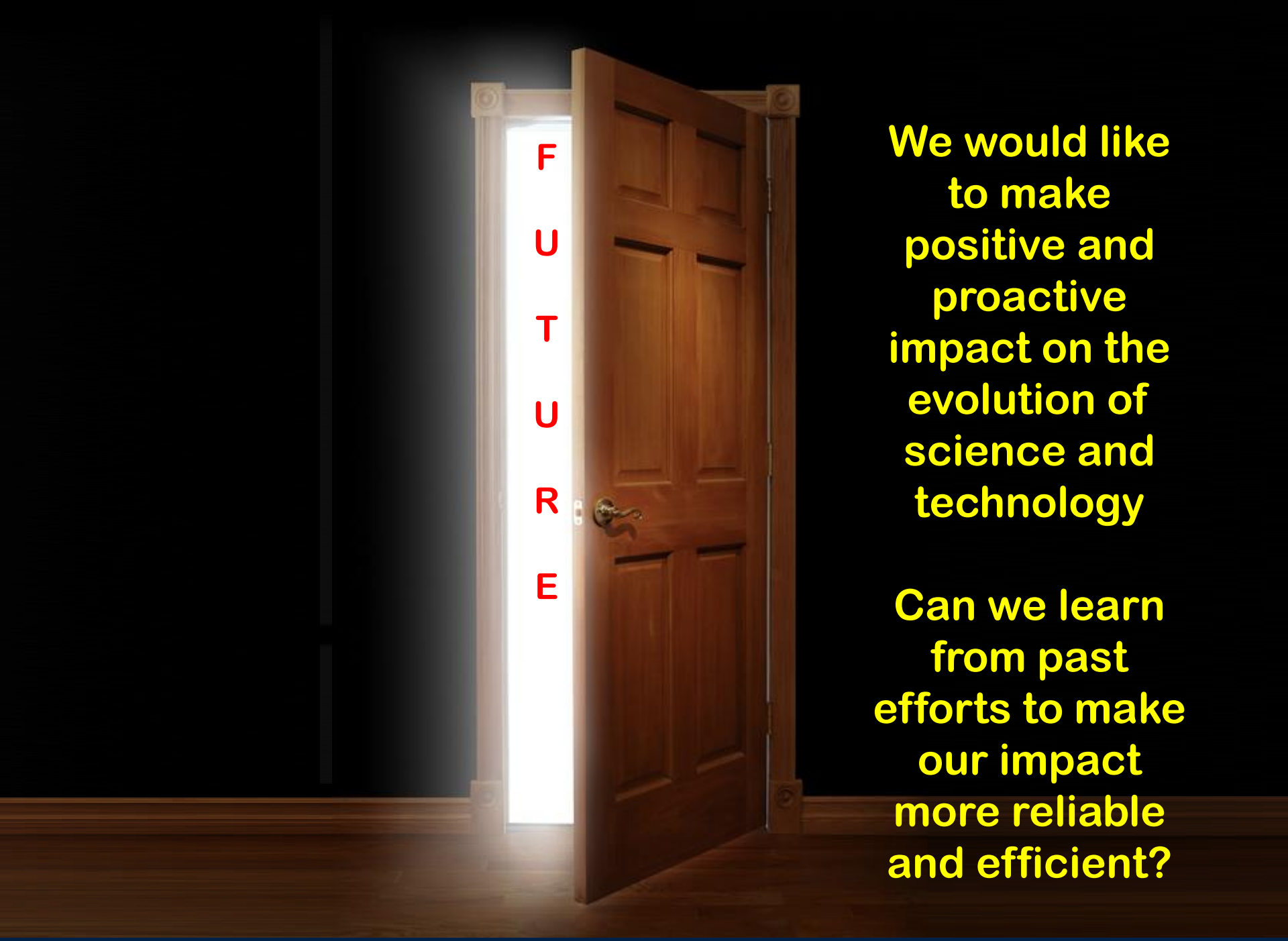
"paradigm shifts"

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….

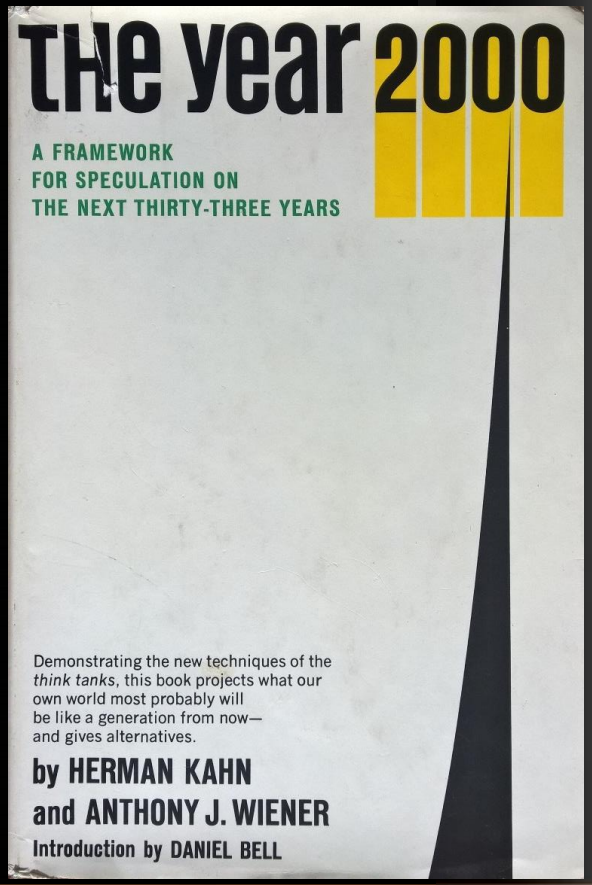
Science will continue to generate unpredictable new ideas and opportunities. And human beings will continue to respond to new ideas and opportunities with new skills and inventions. We remain toolmaking animals, and science will continue to exercise the creativity programmed into our genes."



We would like to make positive and proactive impact on the evolution of science and technology

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

Predictions made in 1968 for the year 2000



"The Year 2000", 1968
K. Herman, A. Wiener
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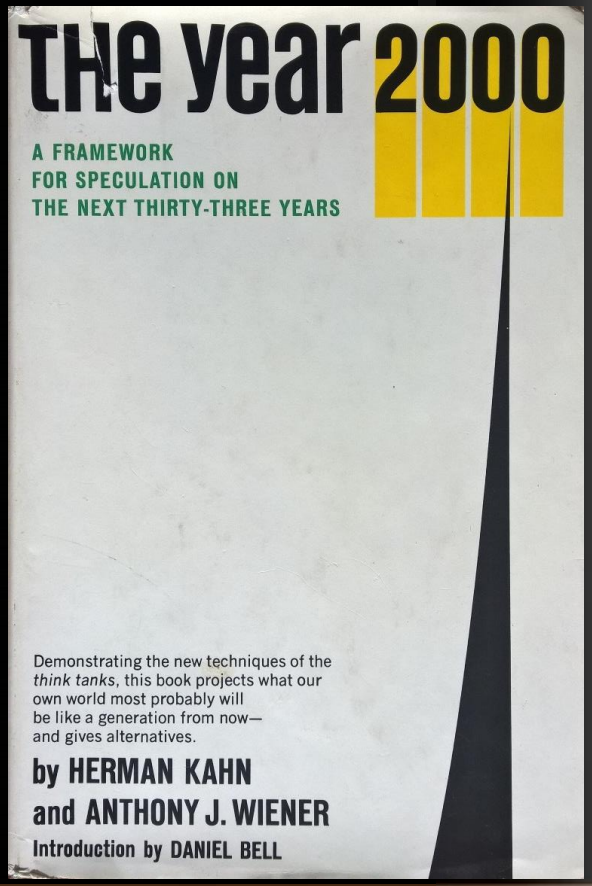

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Can the methodology of predictions be reliable?

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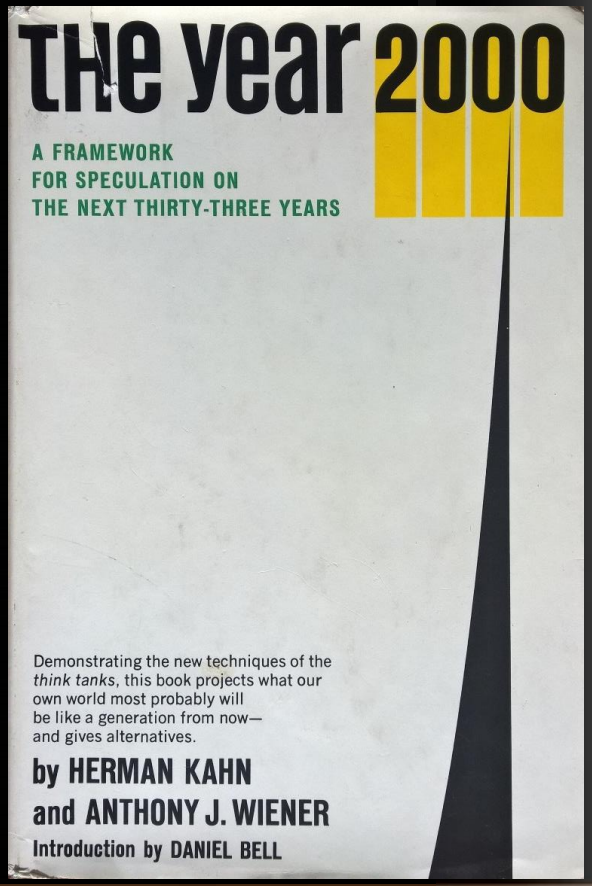

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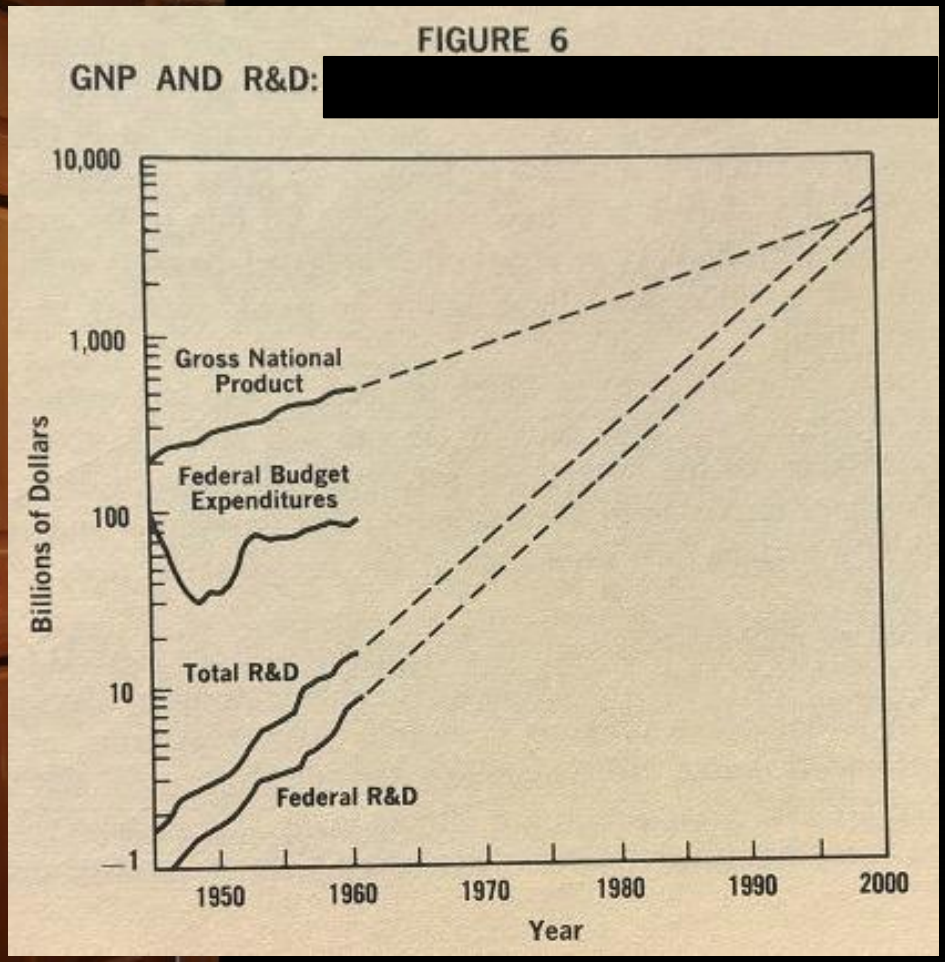
FUTURE



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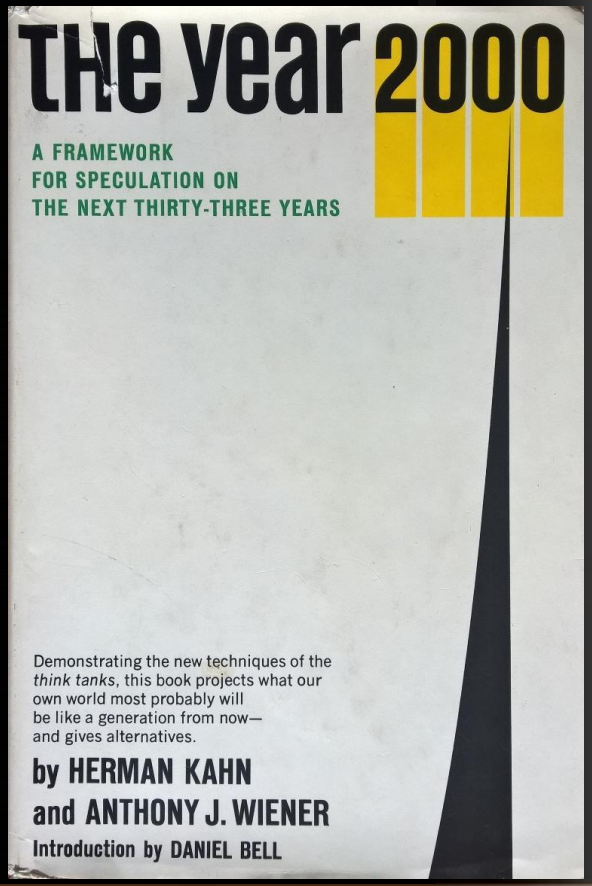

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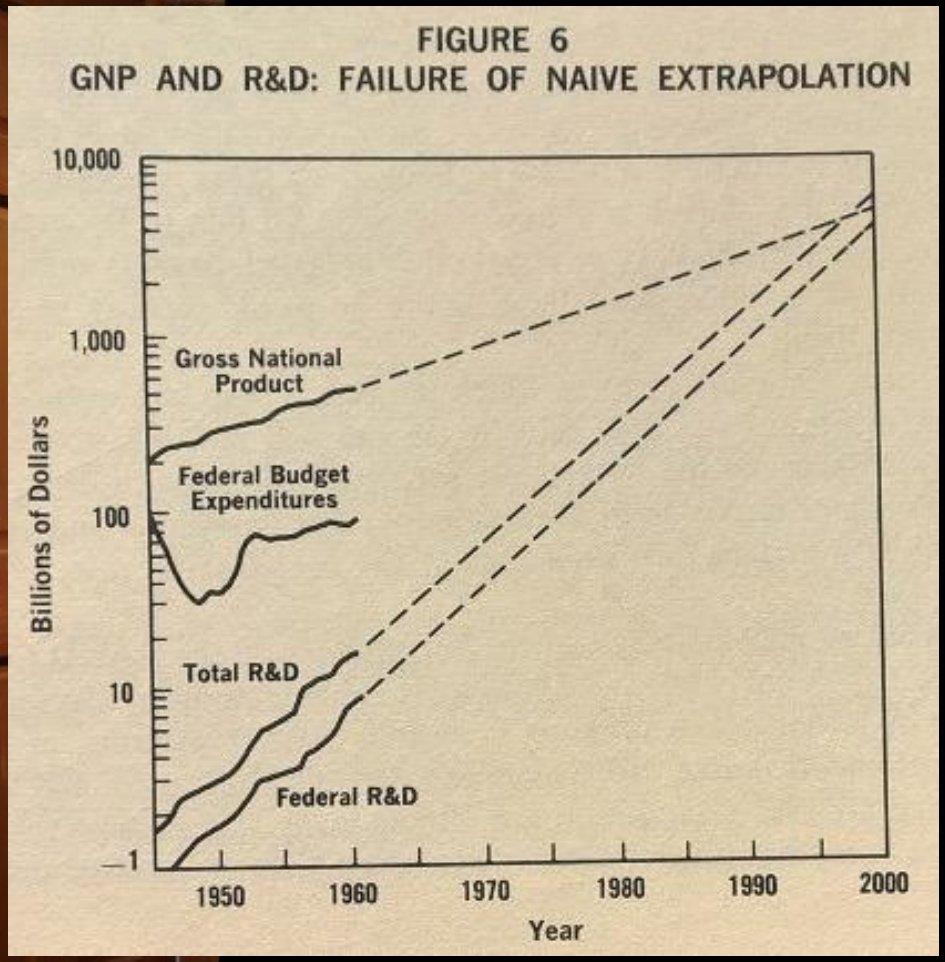


Lesson: avoid naïve extrapolations

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

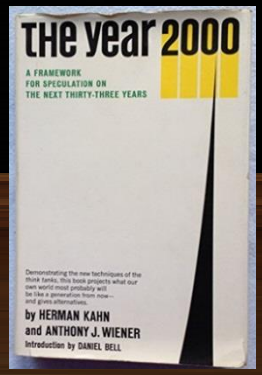
35 – human hibernation for extensive periods (months to years)

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



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Some predictions were accurate, some not

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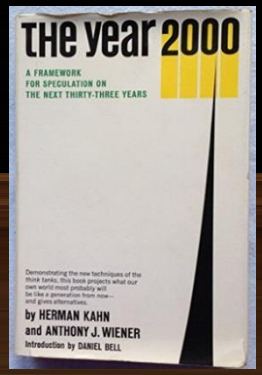

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Some predictions were accurate, some not

Chengdu to launch "artificial moon" in 2020

(People's Daily Online) 09:06, October 16, 2018

“Southwestern China’s city of Chengdu plans to launch its illumination satellite, also known as the “artificial moon”, in 2020, according to Wu Chunfeng, chairman of Chengdu Aerospace Science and Technology Microelectronics System Research Institute Co., Ltd. ... The illumination satellite is designed to complement the moon at night. Wu introduced that the brightness of the “artificial moon” is eight times that of the real moon, and will be bright enough to replace street lights. The satellite will be able to light an area with a diameter of 10 to 80 kilometers, while the precise illumination range can be controlled within a few dozen meters. …The testing of the illumination satellite started years ago, and now the technology has finally matured, explained Wu. Some people expressed concern that the lights reflected from space could have adverse effects on the daily routine of certain animals and astronomical observation. Kang Weimin, director of the Institute of Optics, School of Aerospace, Harbin Institute of Technology, explained that the light of the satellite is similar to a dusk-like glow, so it should not affect animals’ routines.”

http://en.people.cn/n3/2018/1016/c90000-9508748.html

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 "Breakthrough By Design" approach…

…not only for prediction, but for pro-actively shaping the future

Evolution laws and inventive principles

Are there some patterns in evolution of scientific and engineering systems and instruments?

Are there some general inventive principles that connect different instruments/systems in different areas?

Let's look at some examples from a new angle

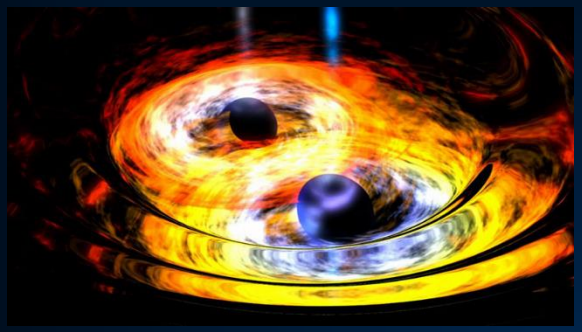
Two scientific instruments

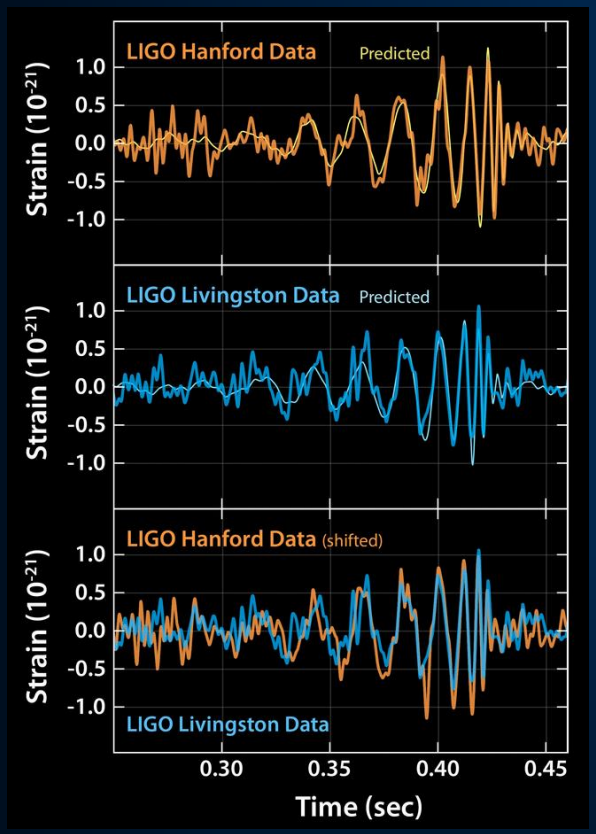
LIGO, Hanford

SLC, Stanford

What is in common?

2017 Nobel Prize in Physics – gravitational waves

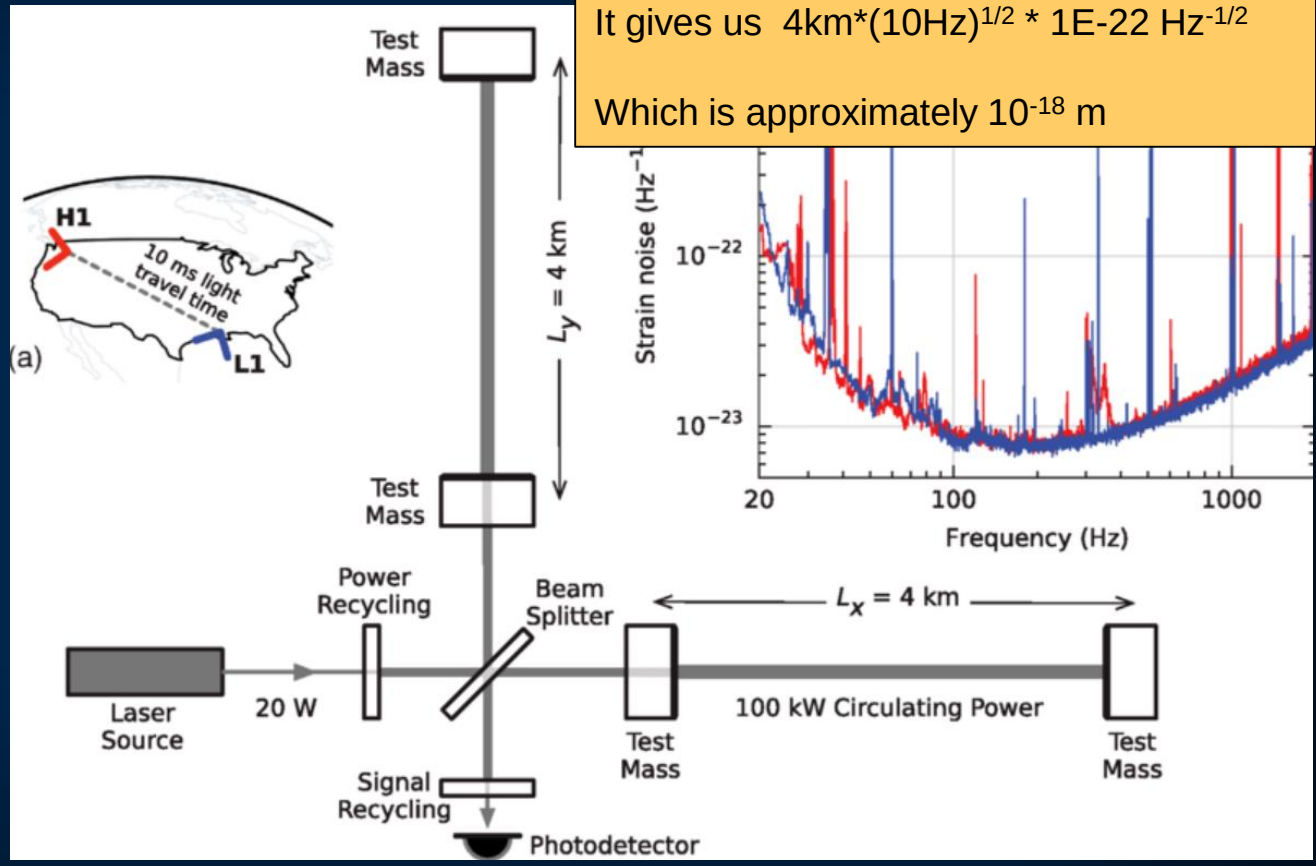




What are these numbers?
Let's say we would like to evaluate noise between 20Hz and 30Hz (i.e. df = 10Hz), where strain noise is about 1E-22 $Hz^{-1/2}$

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

Which is approximately 10^{-18} m



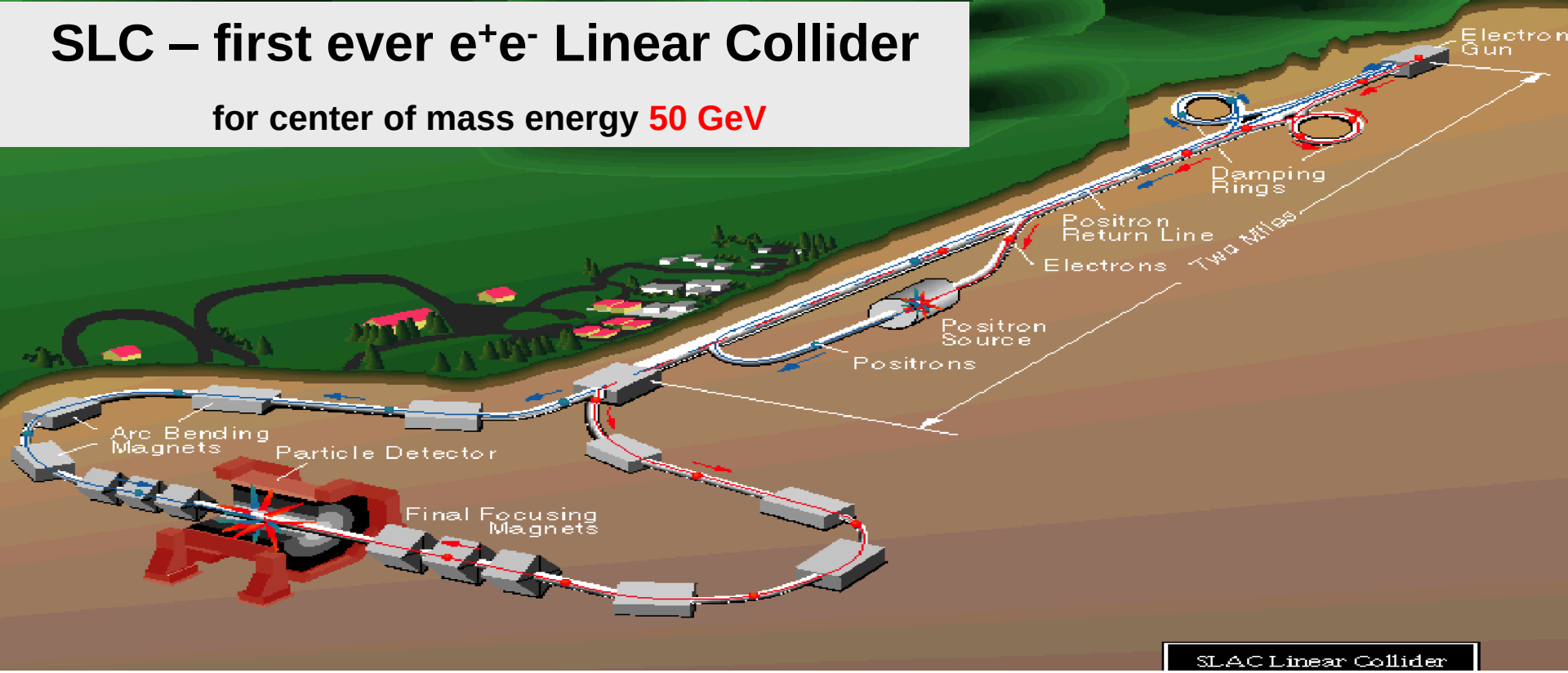
LIGO layout and sensitivity curve

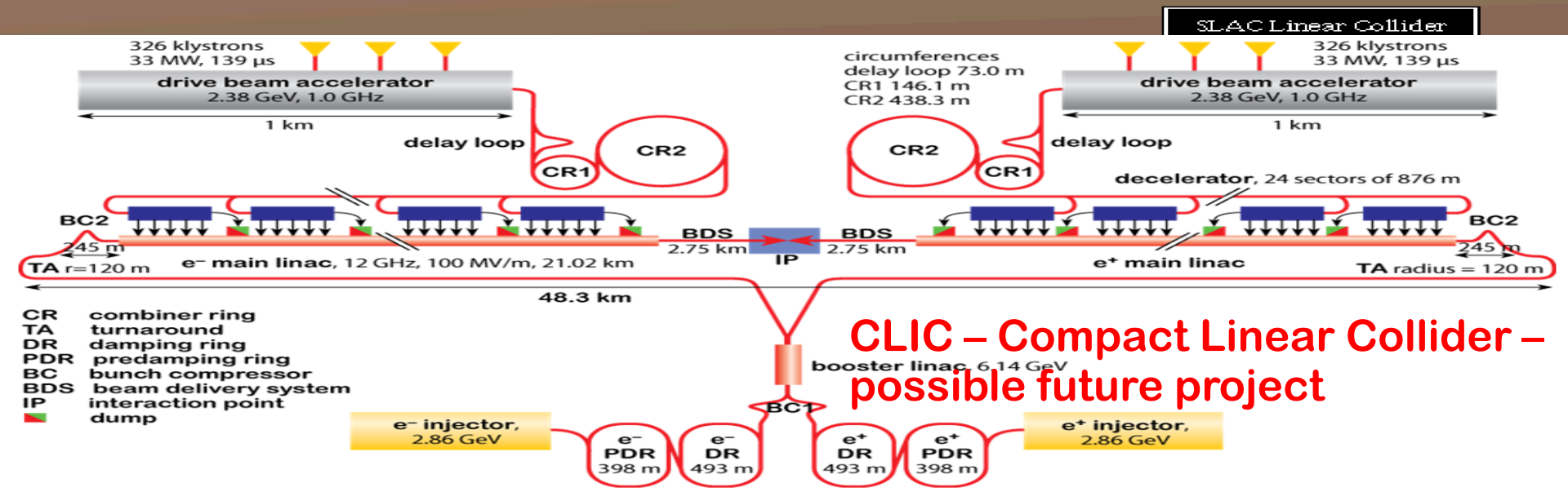
Source: PRL 116, 061102 (2016)

Image: Caltech/MIT/LIGO Lab

SLC – first ever e^+e^- Linear Collider

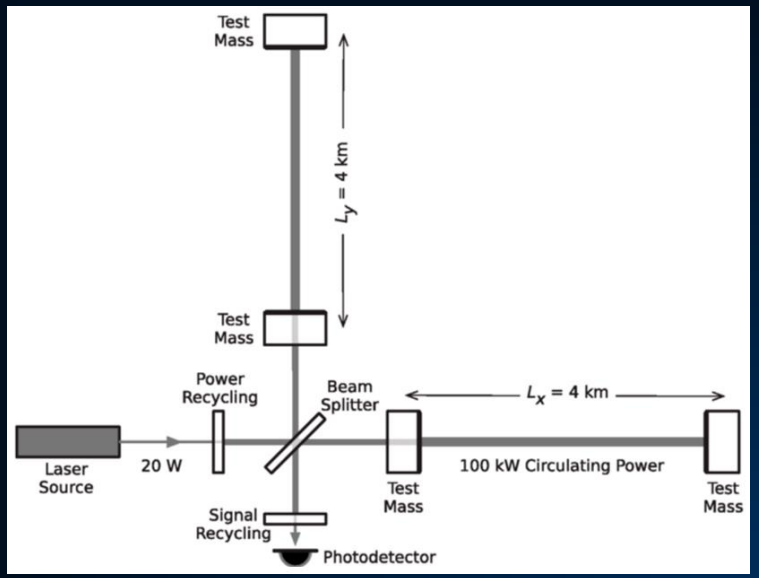
for center of mass energy 50 GeV





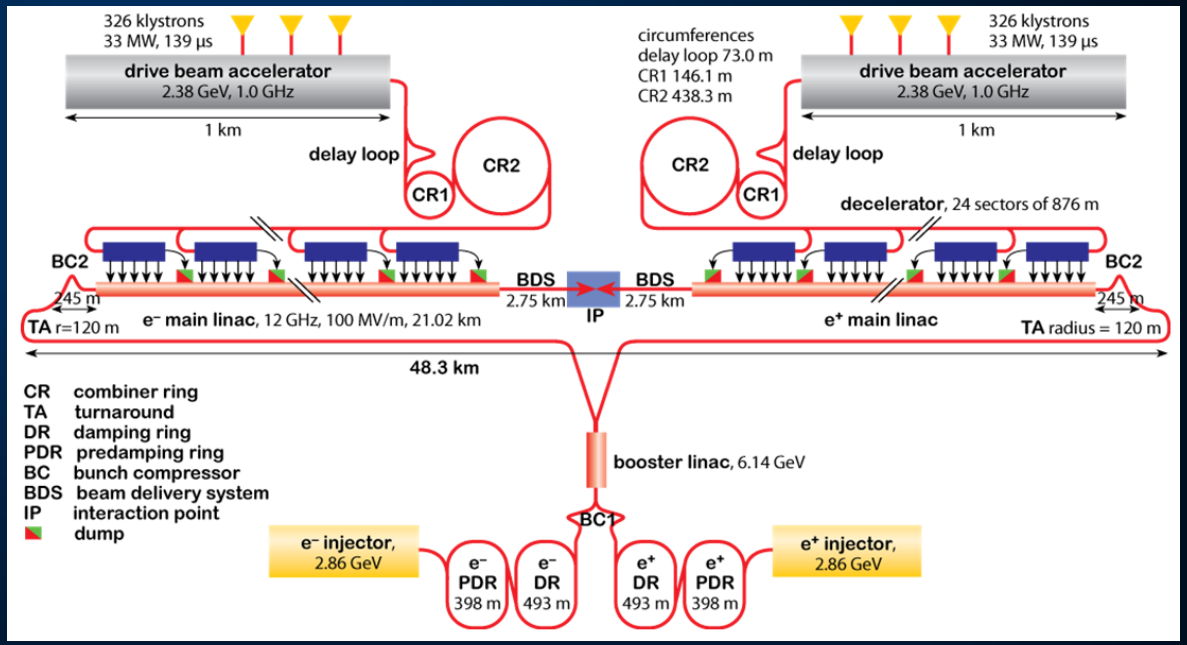
CLIC – Compact Linear Collider – possible future project

These two instruments



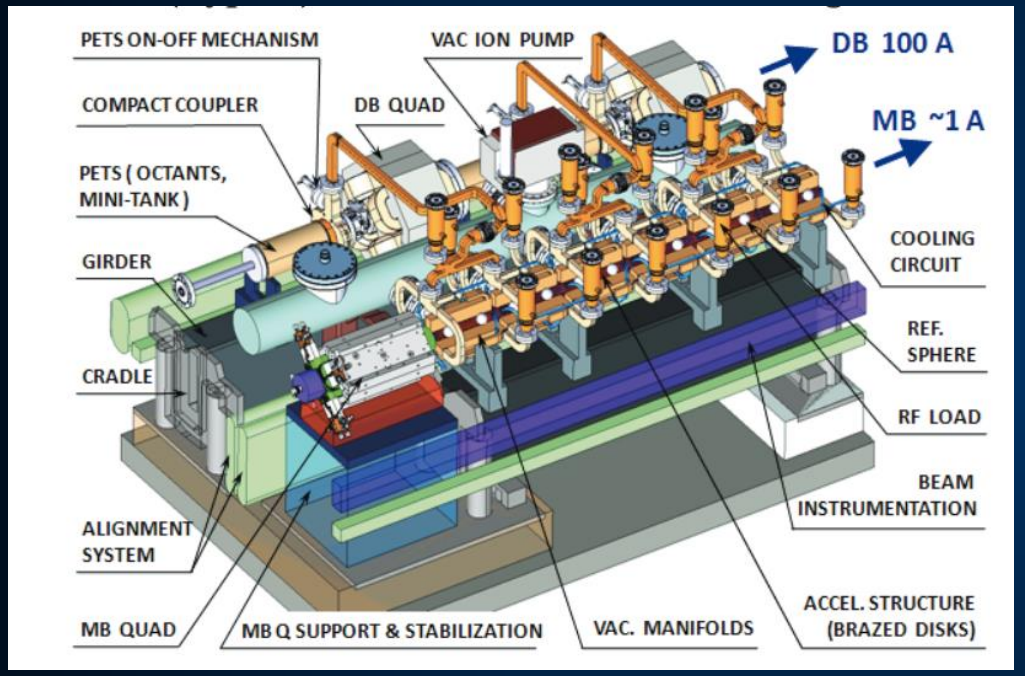
LIGO: keep two objects placed 4km apart stable* to about 1e-9 nm

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

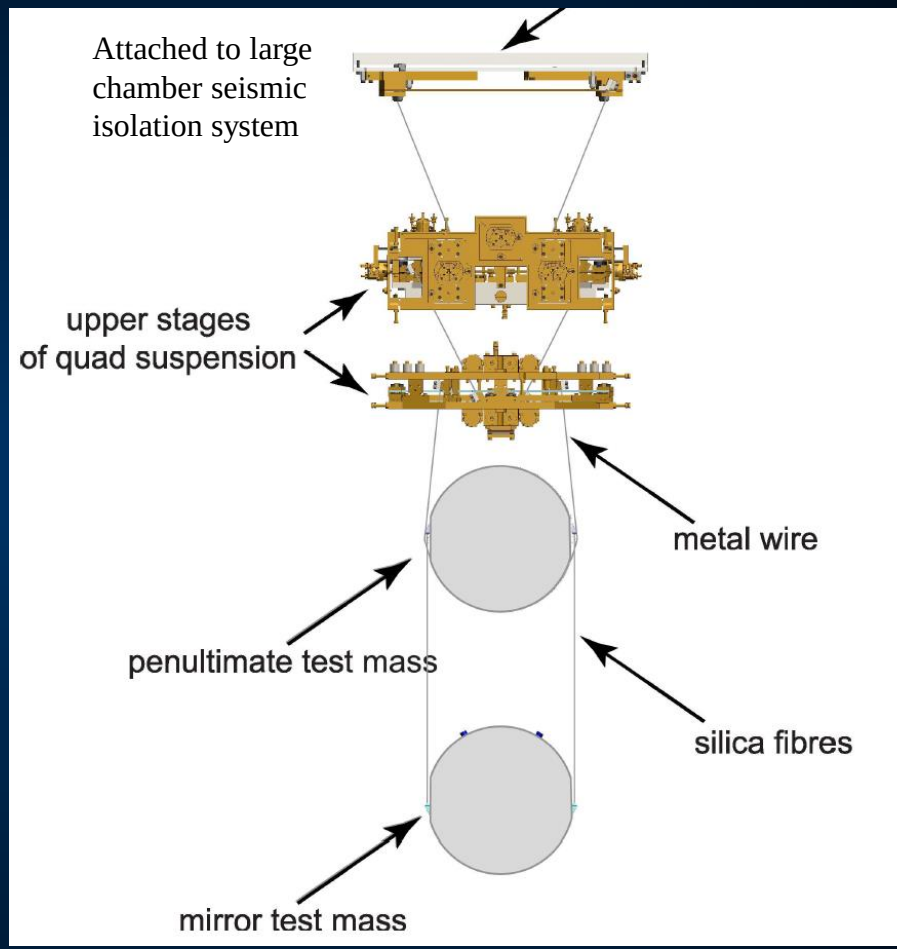


*) approximately, and in certain frequency range

CLIC stability & LIGO test mass isolation



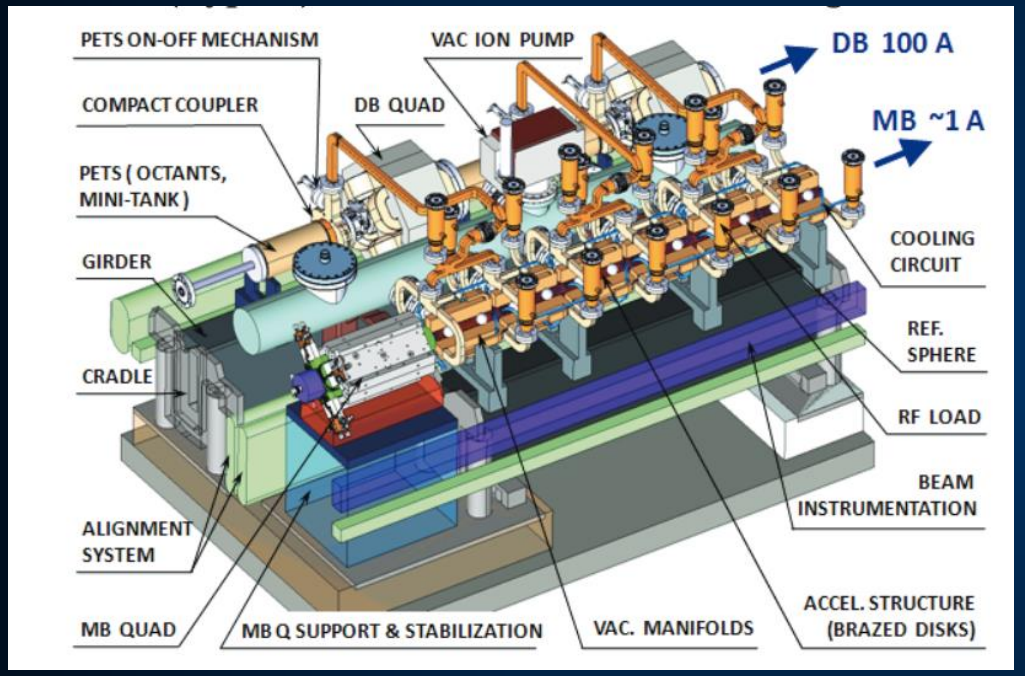
Nested stabilization/alignment systems of CLIC two-beam module

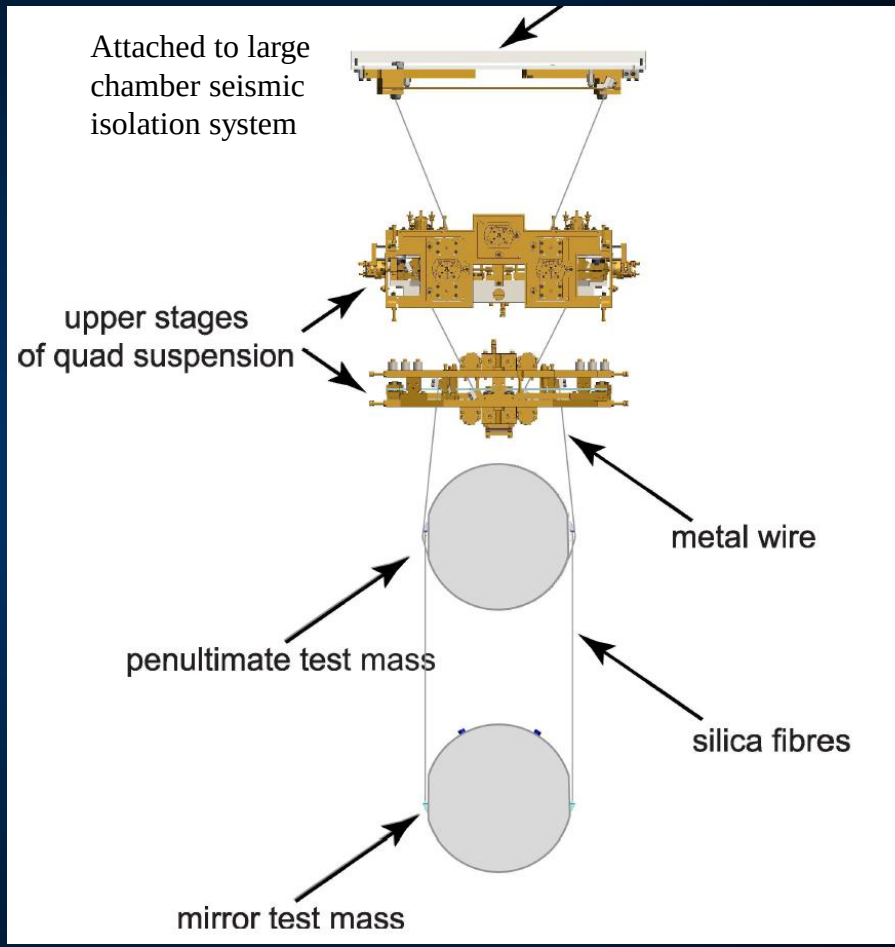


Nested pendulums of LIGO

Source: arXiv:1102.3355

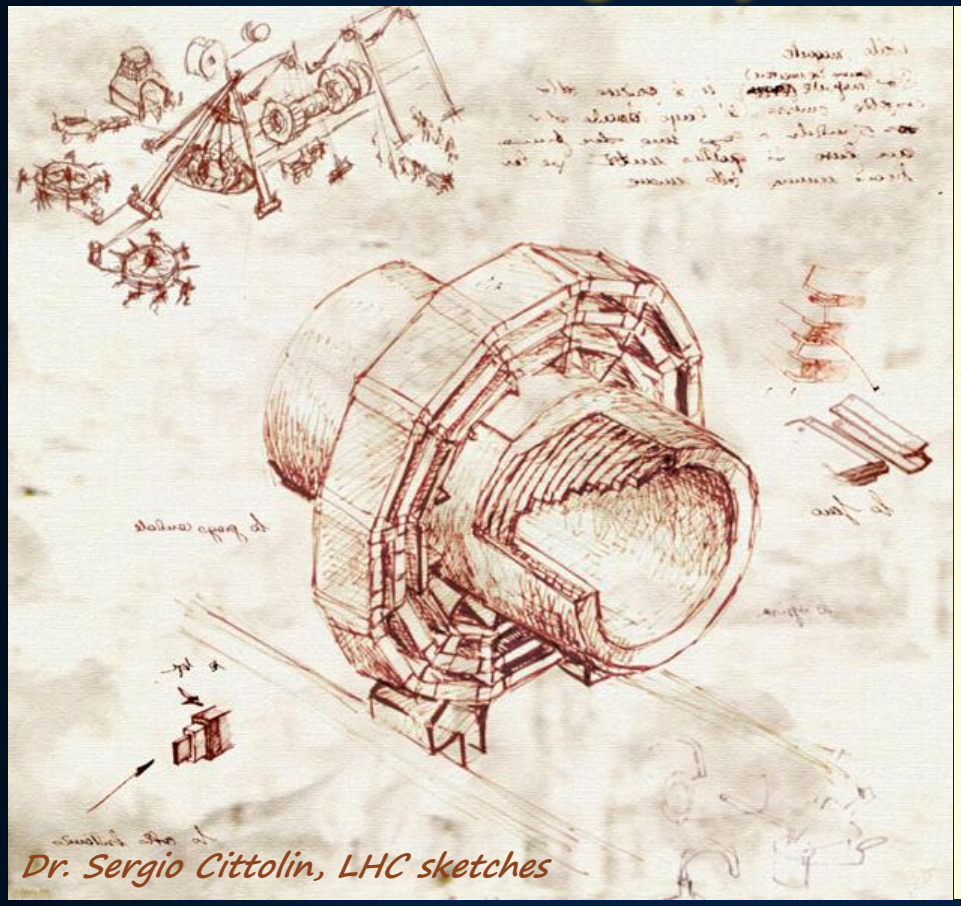
CLIC stability & LIGO test mass isolation

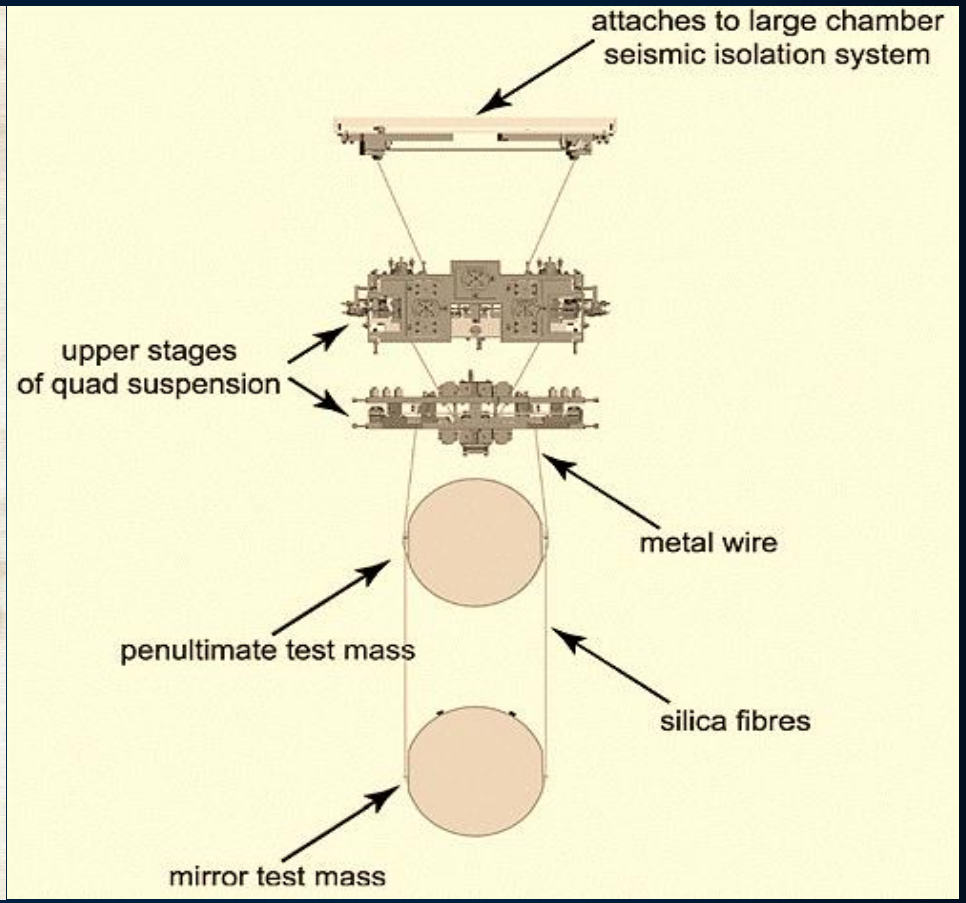




… connected via an inventive principle – let's call it the principle of "nested dolls"

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,
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Mother Goose Rhymes

The principle of “nested dolls” in poetry

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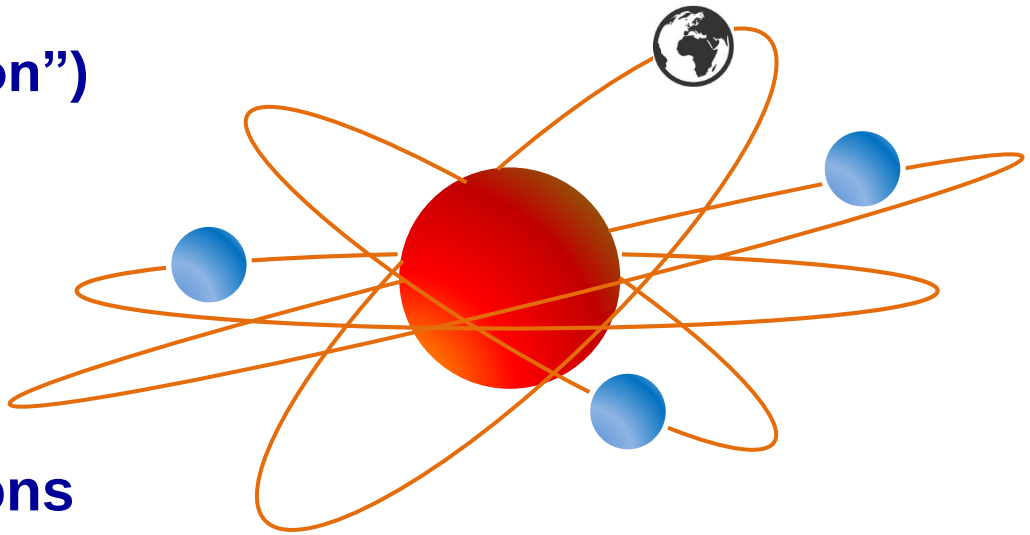
Mother Goose Rhymes

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
…

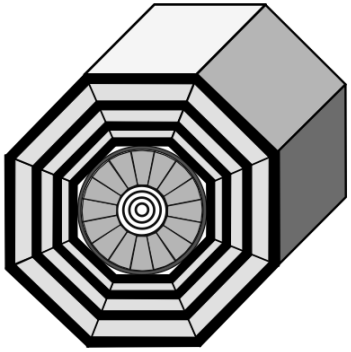
Remake-translation by A.Seryi

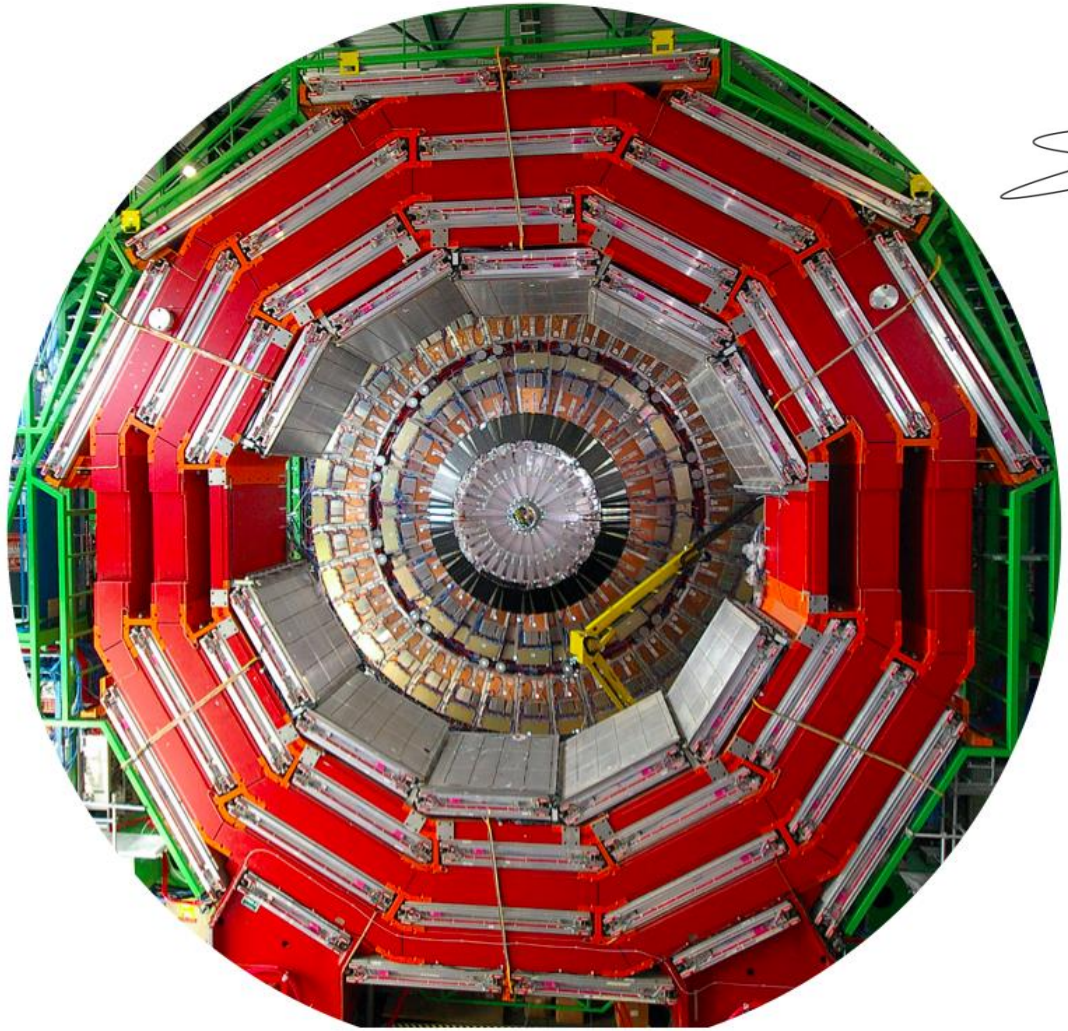
Быть может, эти электроны
Миры, где пять материков,
Искусства, знанья, войны, троны
И память сорока веков!

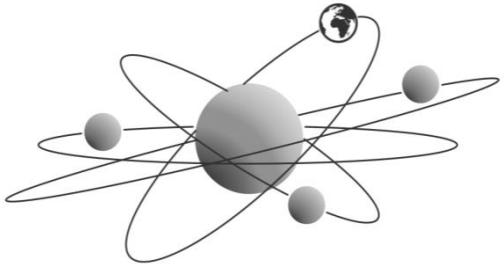
Ещё, быть может, каждый атом —
Вселенная, где сто планет;
Там — всё, что здесь, в объёме сжатом,
Но также то, чего здесь нет.

…

Is there world inside of an electron?

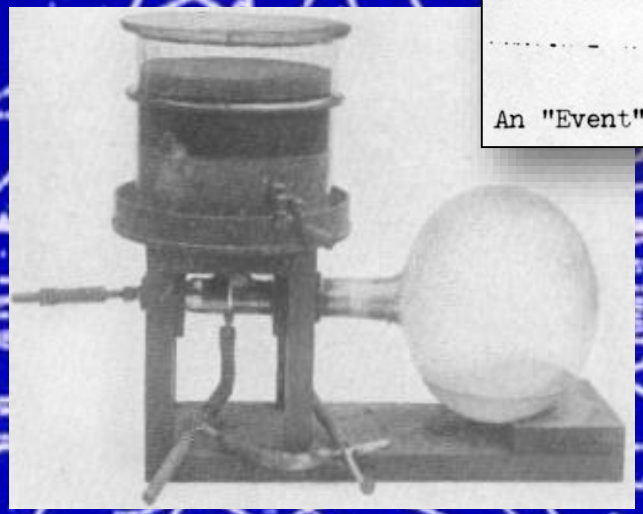


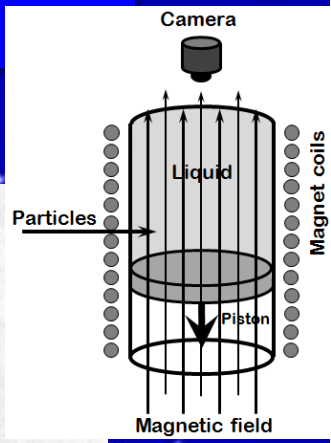


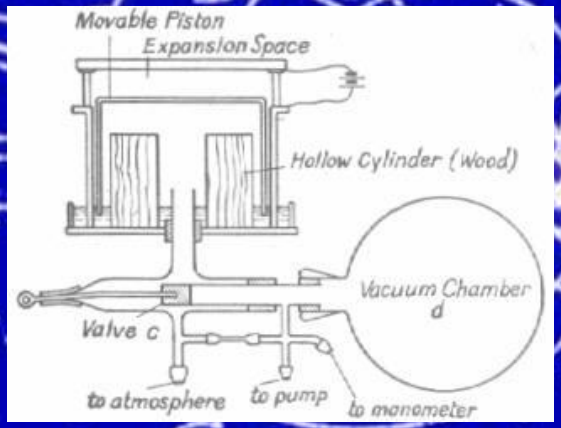


Accelerators and detectors can help to understand whether there is a world inside of an electron

Cloud and bubble chambers





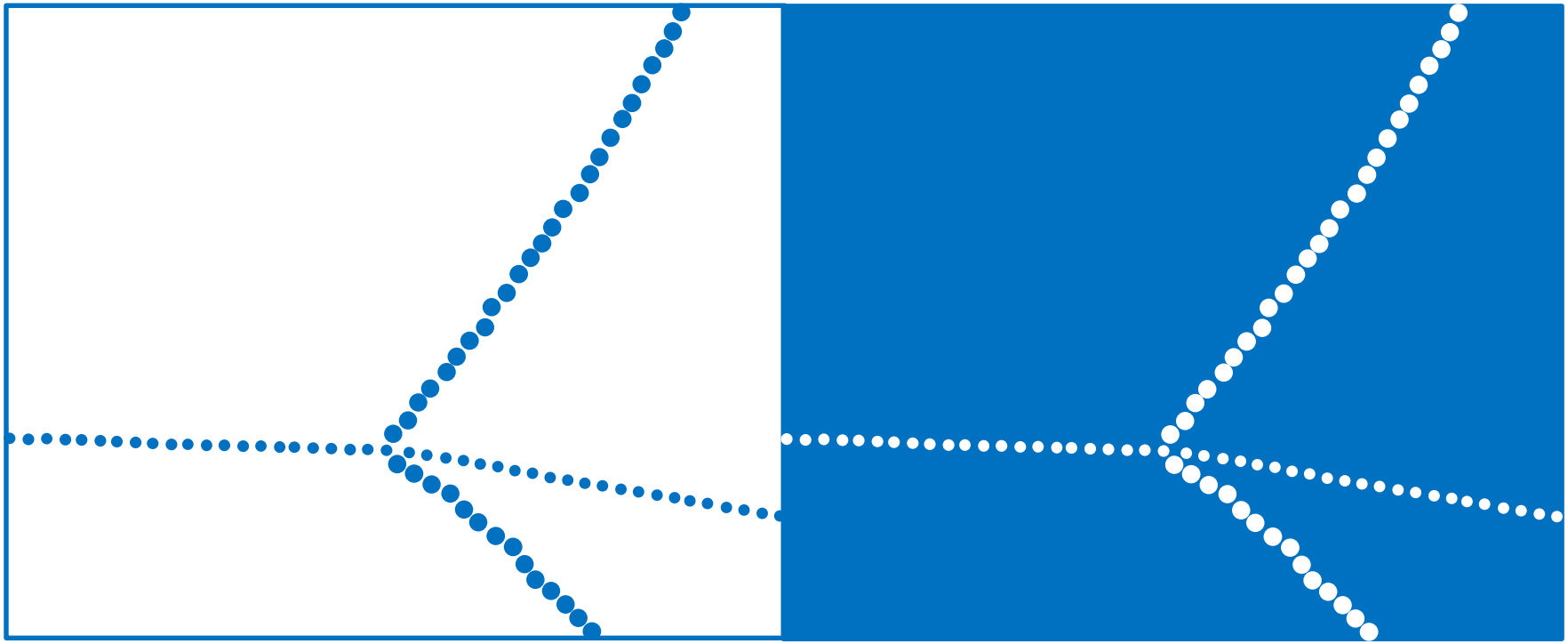


Wilson's Cloud chamber invented in 1911

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

On the photo Bubble chamber being installed near Fermilab

Cloud and bubble chambers

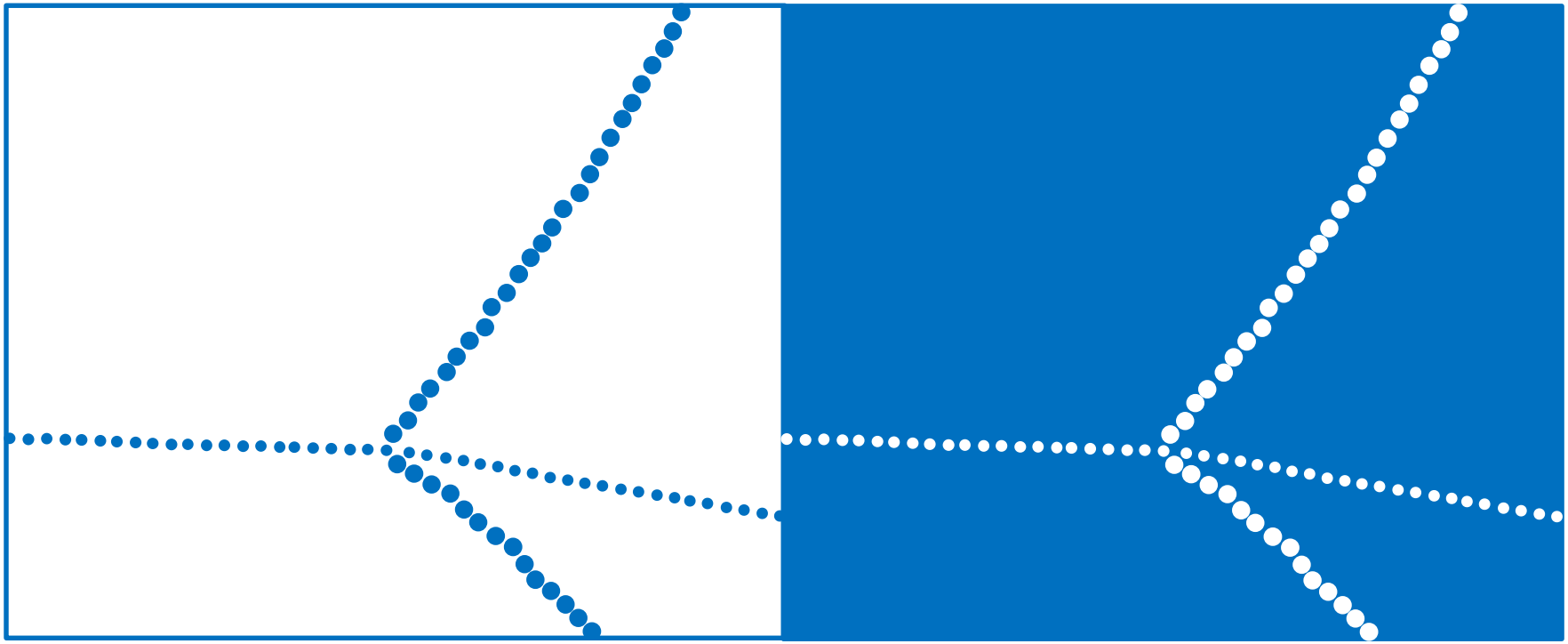


Wilson's Cloud chamber invented in 1911
Bubbles of liquid in a gas

Glaser's Bubble chamber, invented in 1952
Bubbles of gas in a liquid

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
Bubbles of liquid in a gas

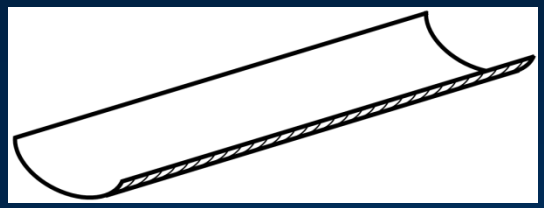
Glaser's Bubble chamber, invented in 1952
Bubbles of gas in a liquid

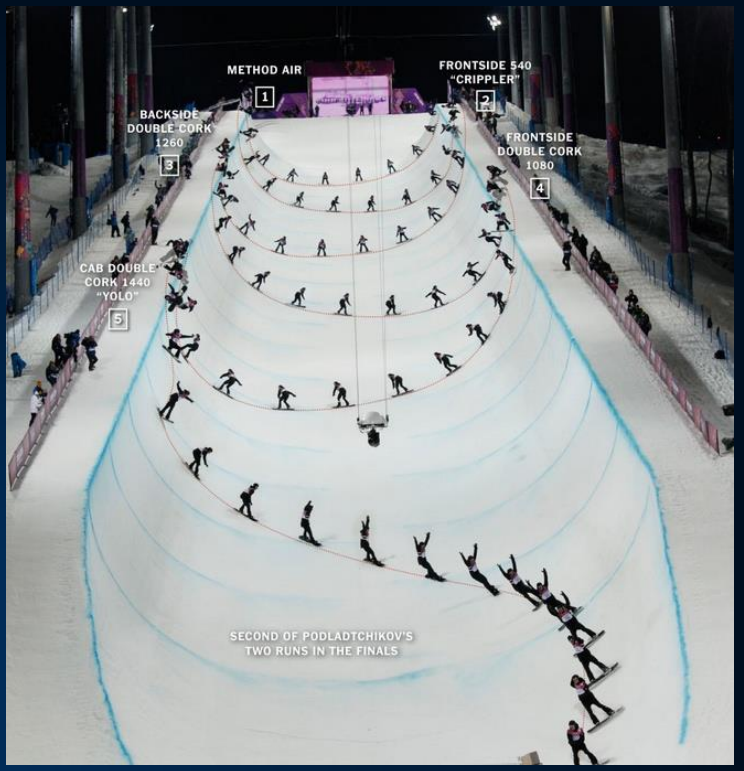
Bubble chamber could have been invented immediately, and not 40 years later after the cloud chamber, if we would have applied the principle of "system and anti-system"

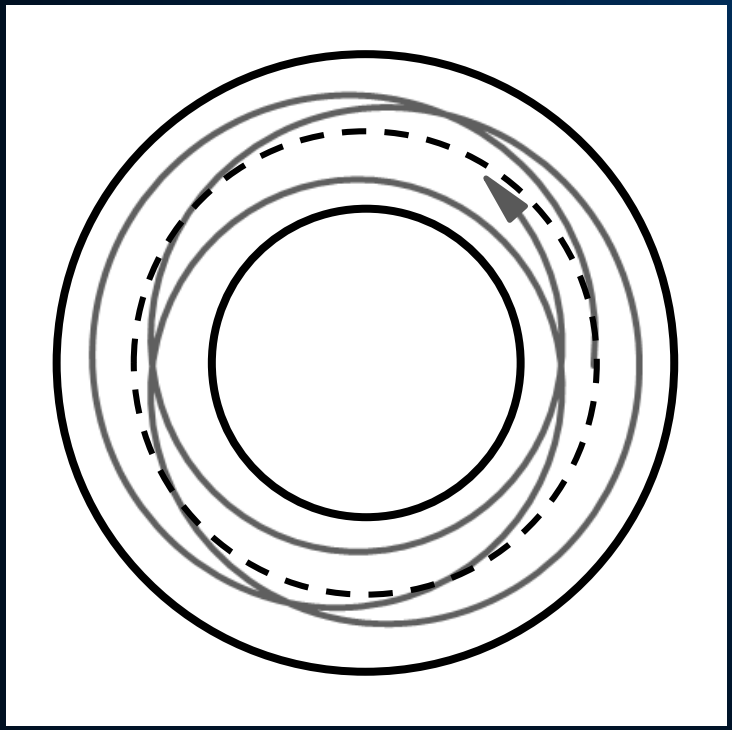
System-anti-system and focusing in accelerators

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter





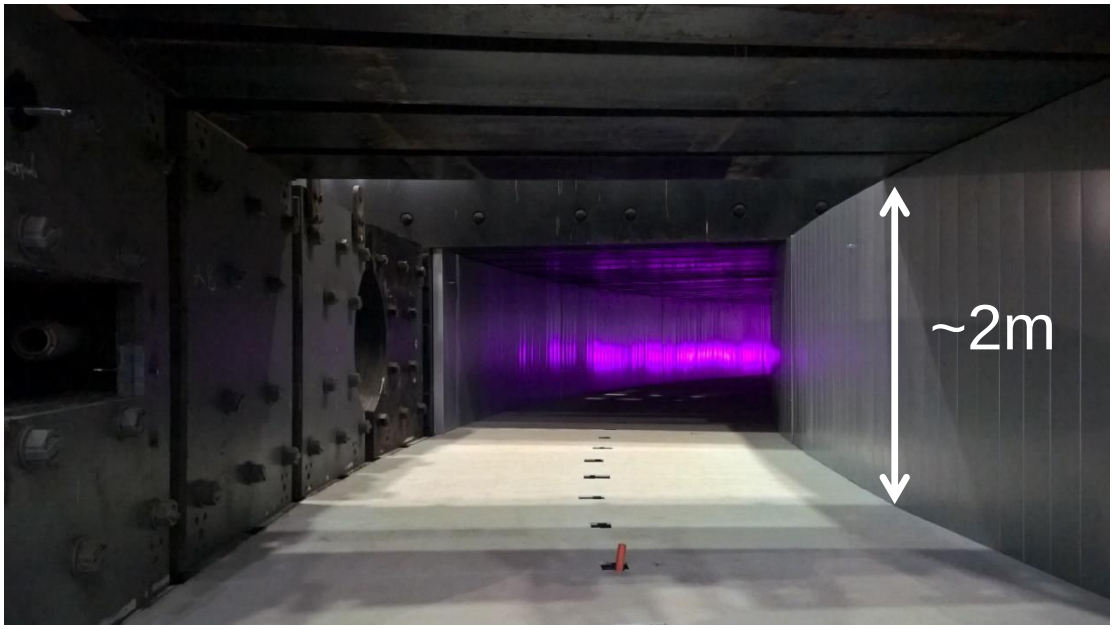


The first accelerators had weak focusing with spatial period greater than the perimeter of the accelerator

The trajectories of particles in an accelerator with weak focusing

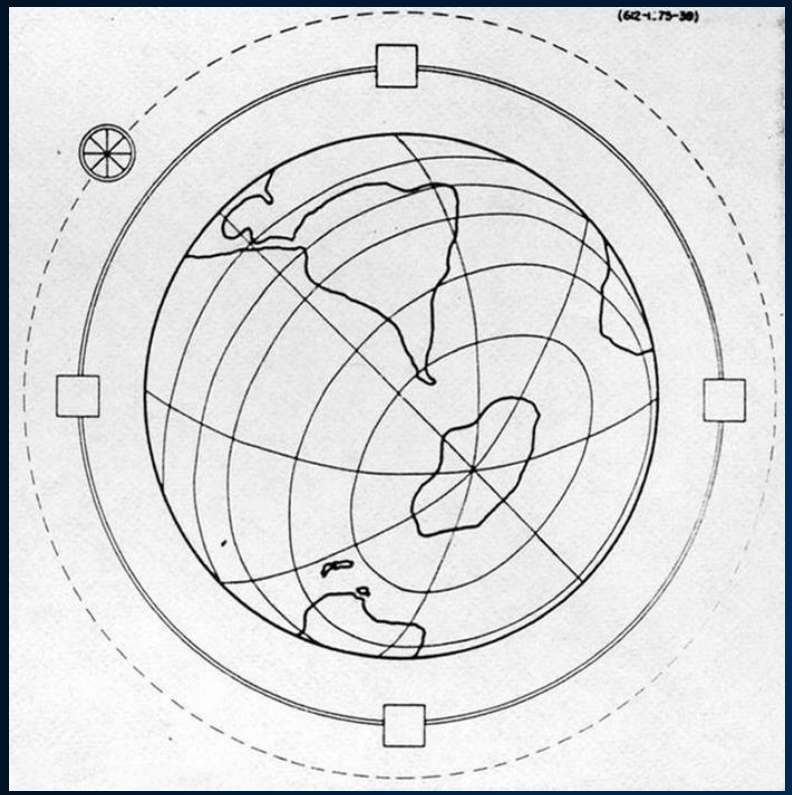
Weak focusing accelerator

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



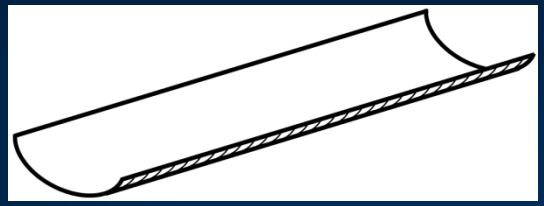
In 1954 Enrico Fermi presented, in his lecture, a vision of an accelerator that would encircle the Earth, and would attain highest possible energies

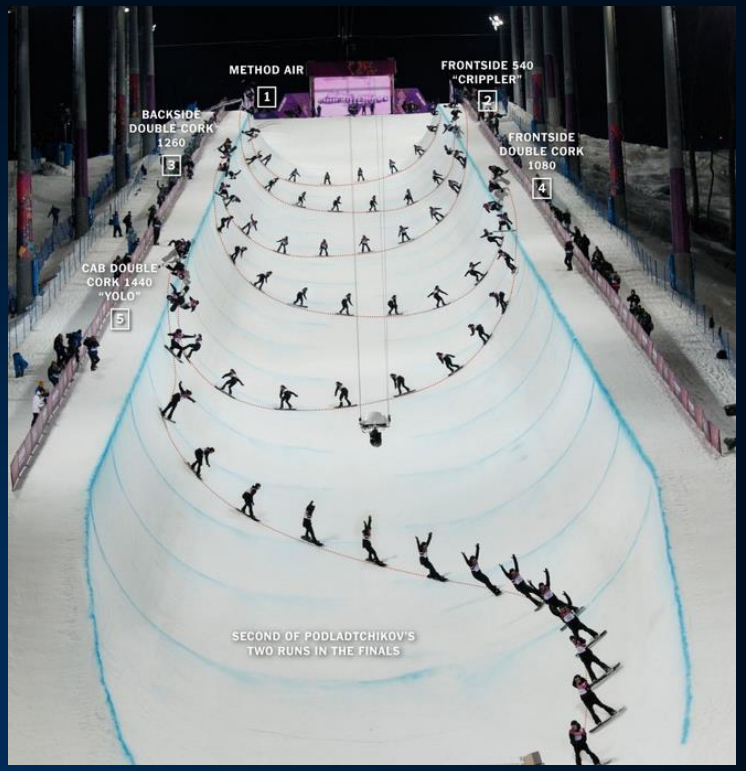
Imagine how humongous it would be if it would be built as a weak focusing machine!

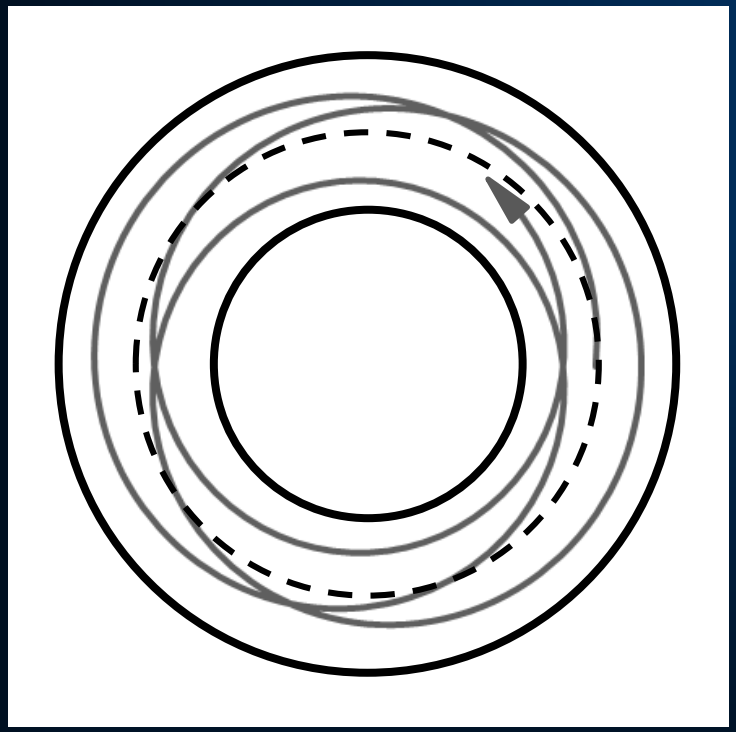
Focusing

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter





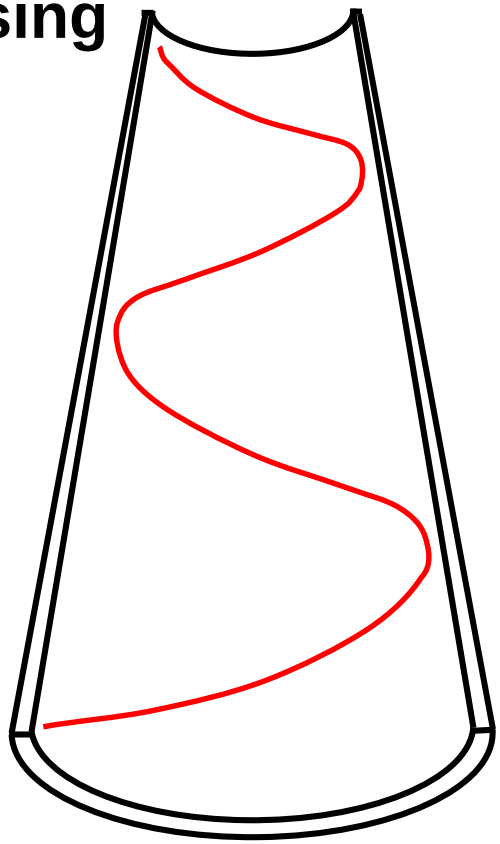


In this analogy, can we bend the gutter stronger, to achieve strong focusing?

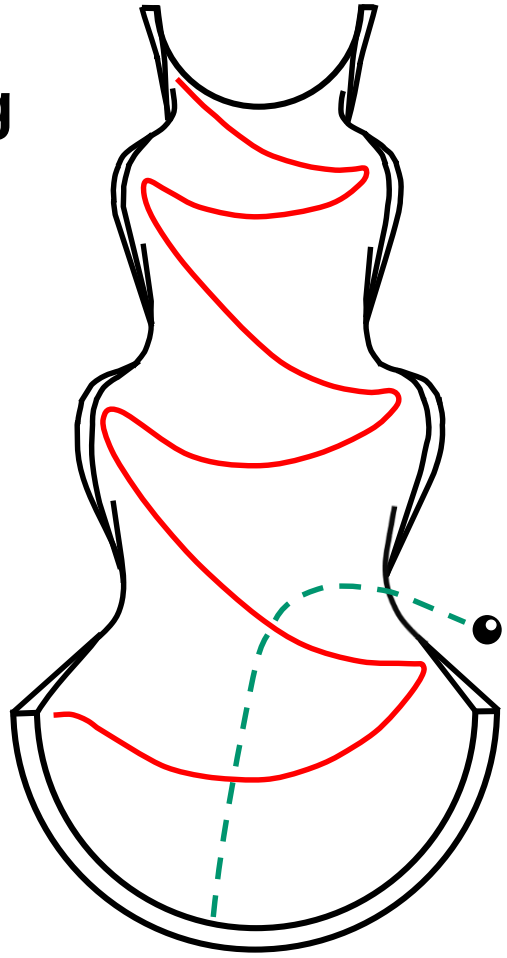
The trajectories of particles in an accelerator with weak focusing

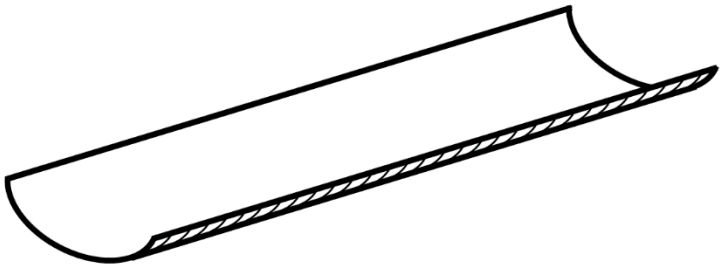
Weak and strong focusing

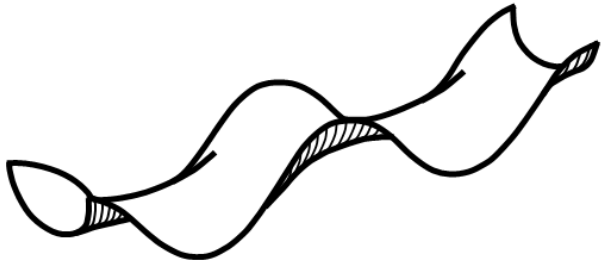
Weak focusing



Strong focusing

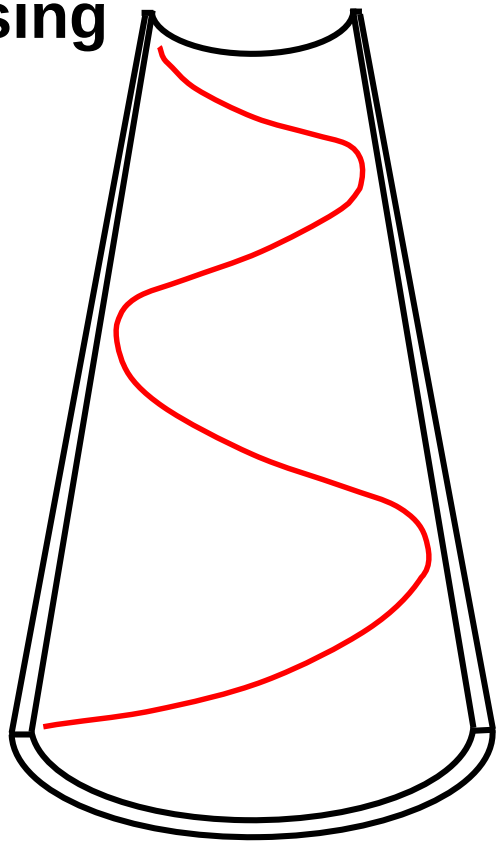




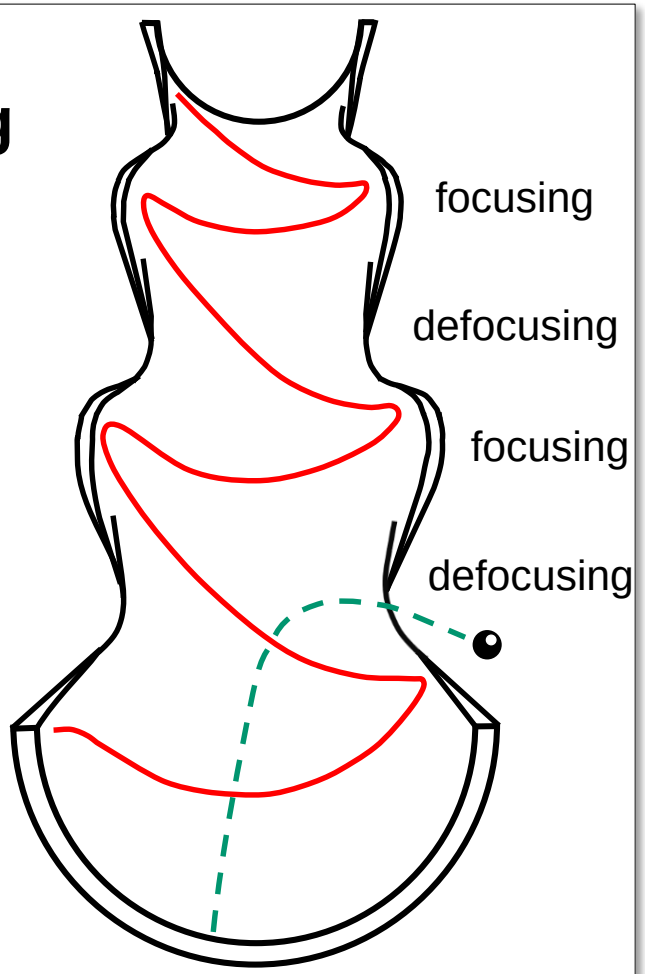


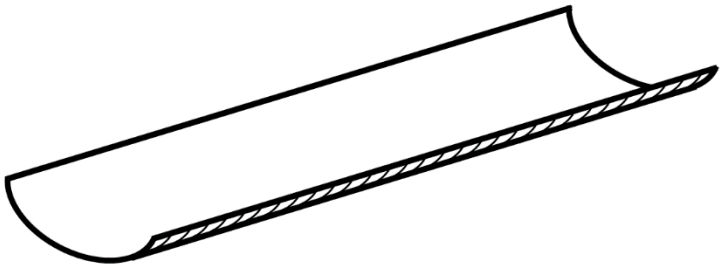
Weak and strong focusing

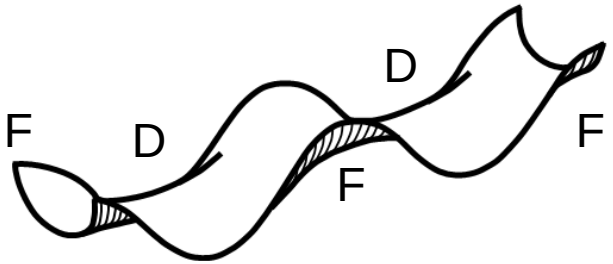
Weak focusing



Strong focusing

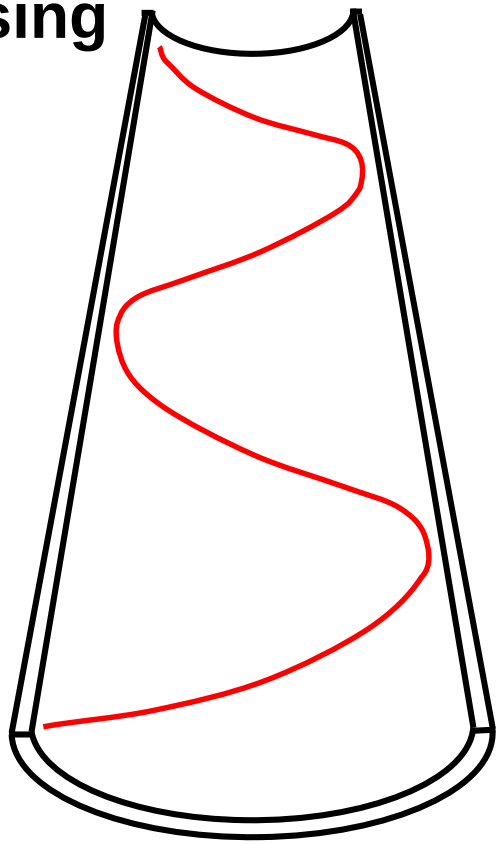






Weak and strong focusing

Weak focusing



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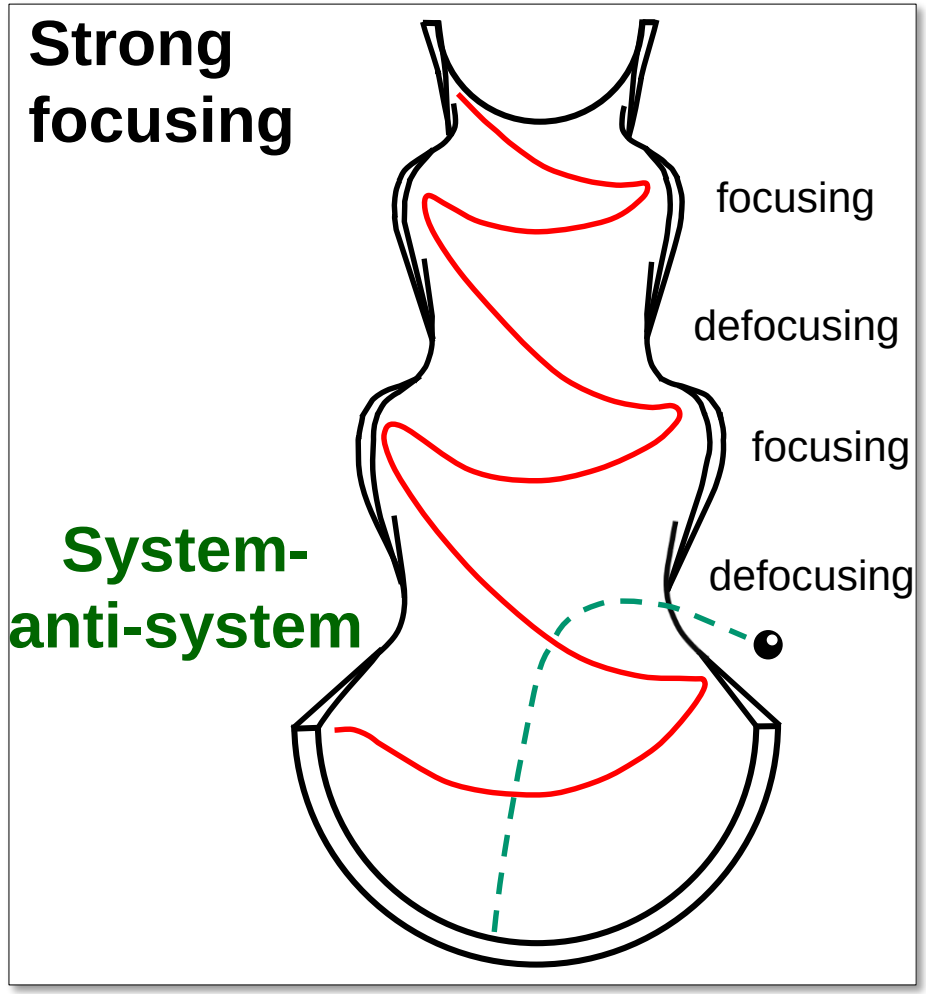
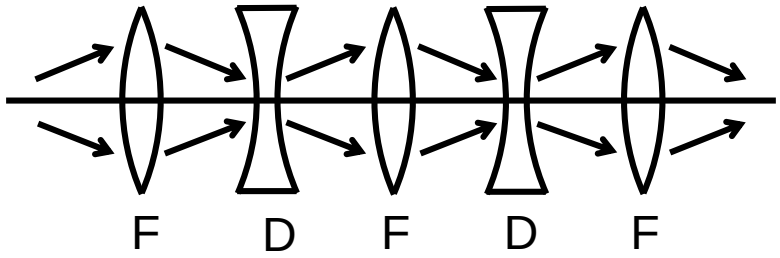
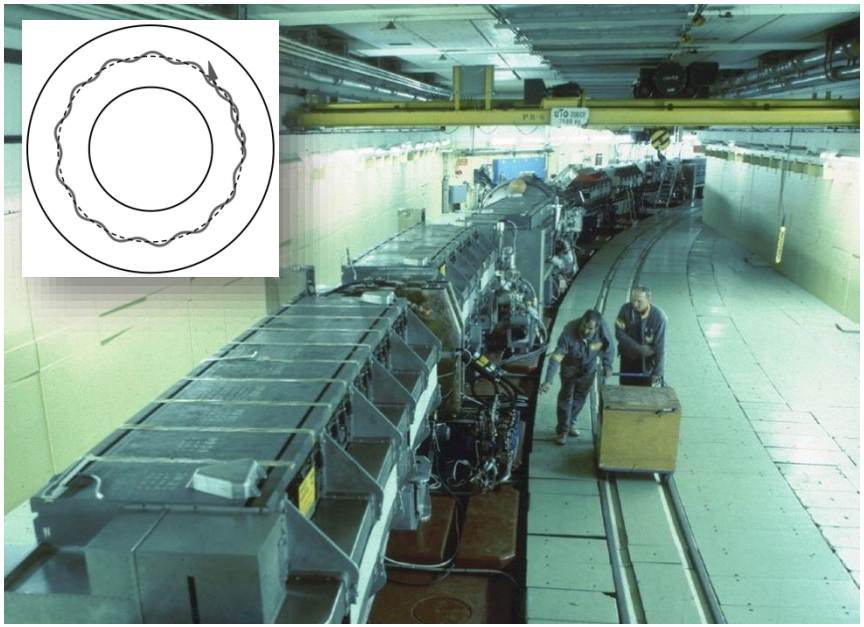




Weak and strong – compare them



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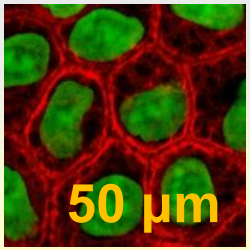
CERN's Proton Synchrotron, the first operating strong-focusing accelerator, reached 24 GeV in 1959. It is a ~200-m diameter ring, weight of magnets 3,800 tons.

The structure of matter…



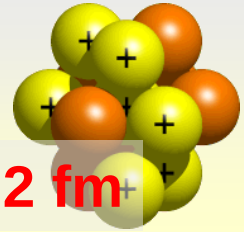
Extra magnification?

CELLS
Twenty per mm

Microscope

x 25 thousand

DNA
Five hundred thousand per mm



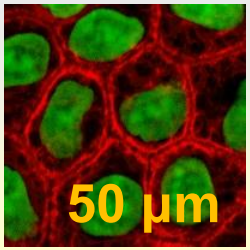
x 1 million

Nucleus
Five hundred billion per mm

x 2 thousand

Quarks
More than one million billion per mm

…use particles



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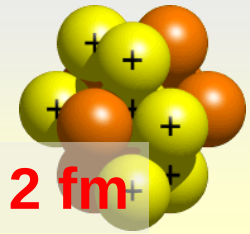

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Particles & their wave properties

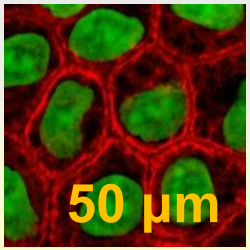
Wavelength corresponding to the particle:

$$\lambda = h / p$$

De Broglie Wavelength — Planck Constant — Momentum

See small? Use particles and increase their energy

…use particle accelerators



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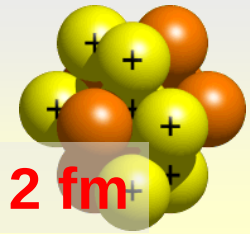
Electron microscope



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Particle Accelerators

x 2 thousand

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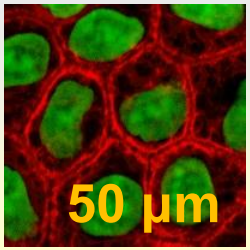
Chemistry Nobel 2014 & inventive principles?



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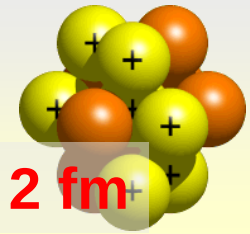

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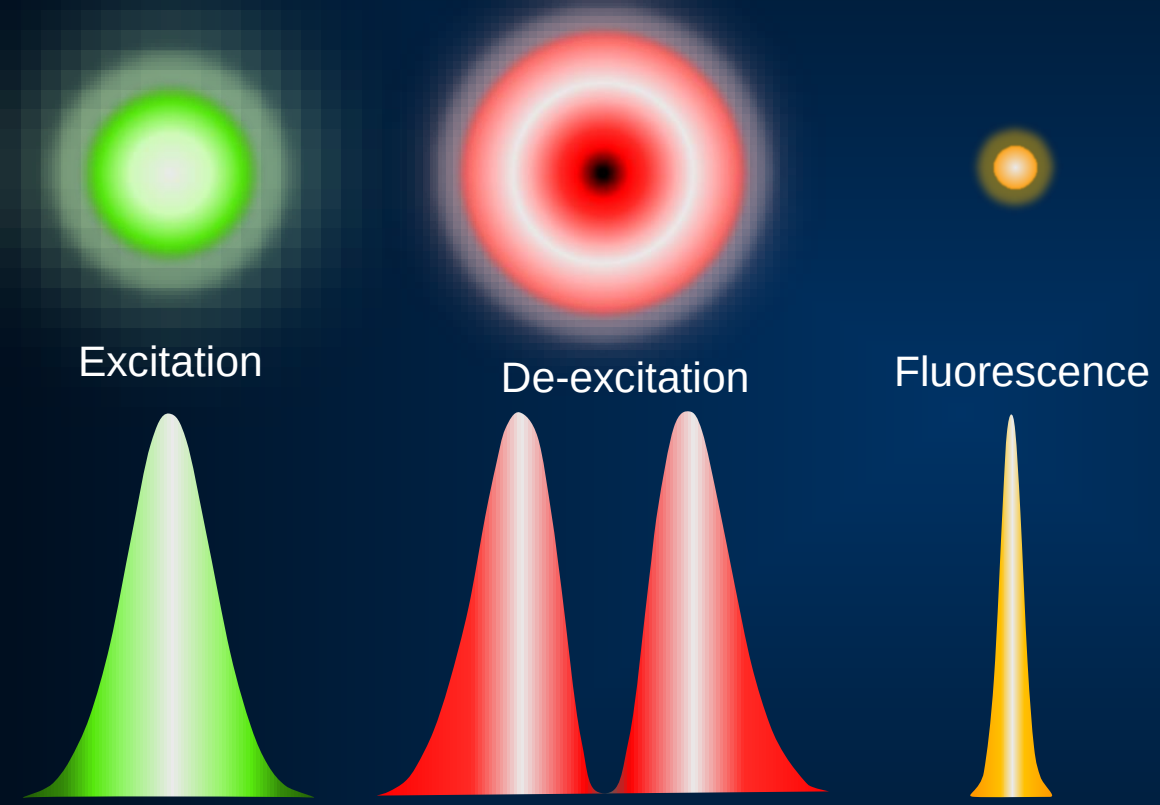
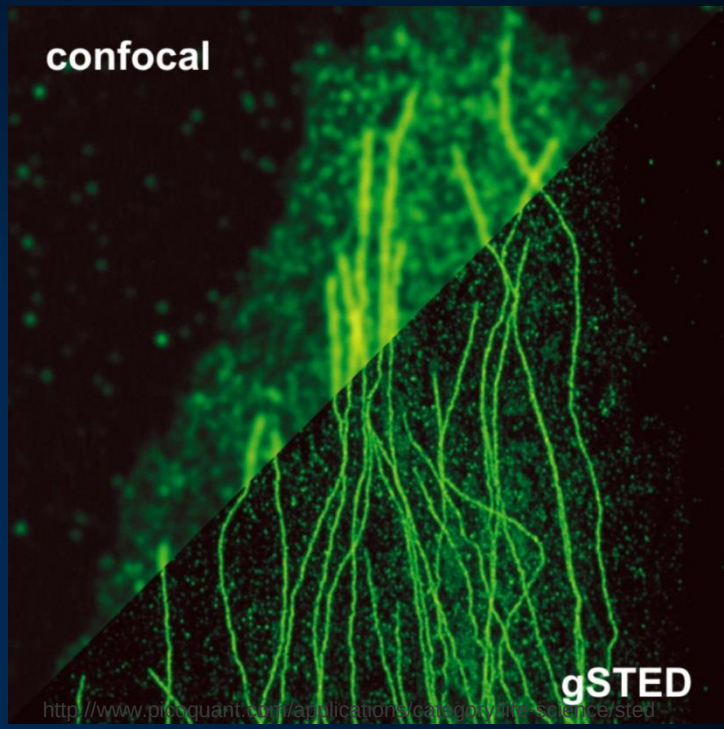
Chemistry Nobel 2014 …

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)
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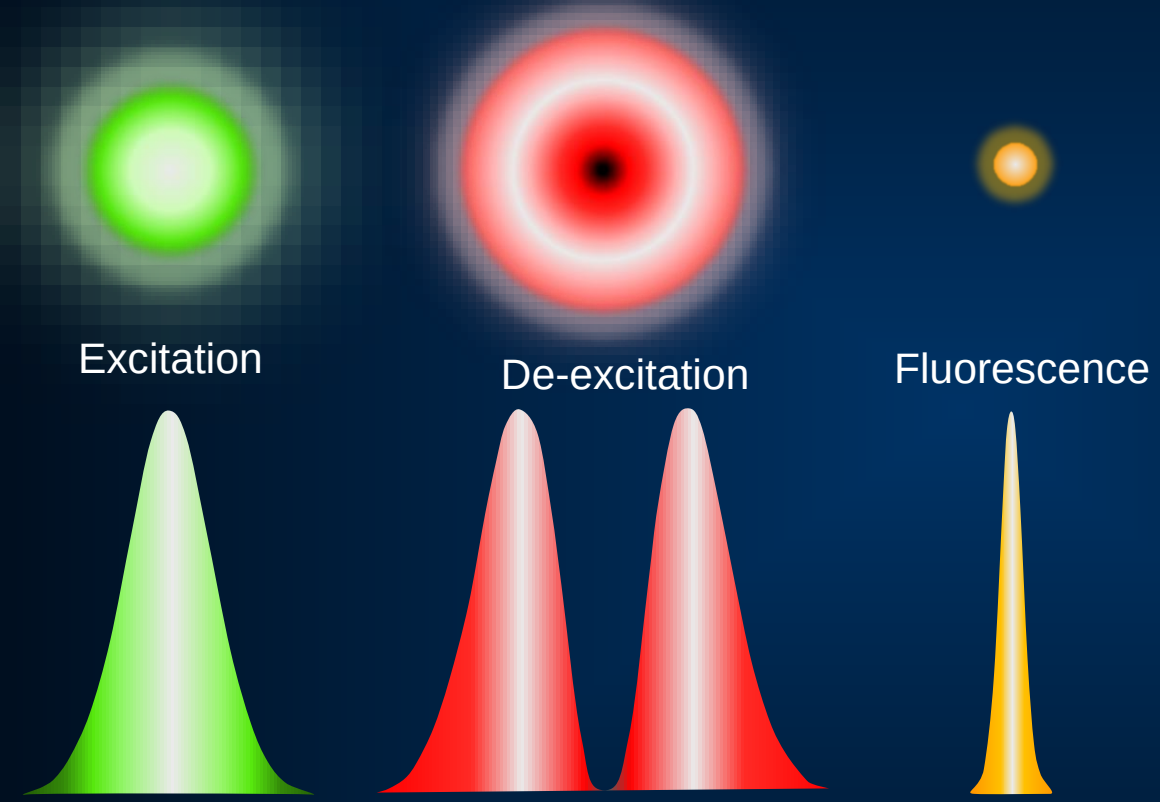
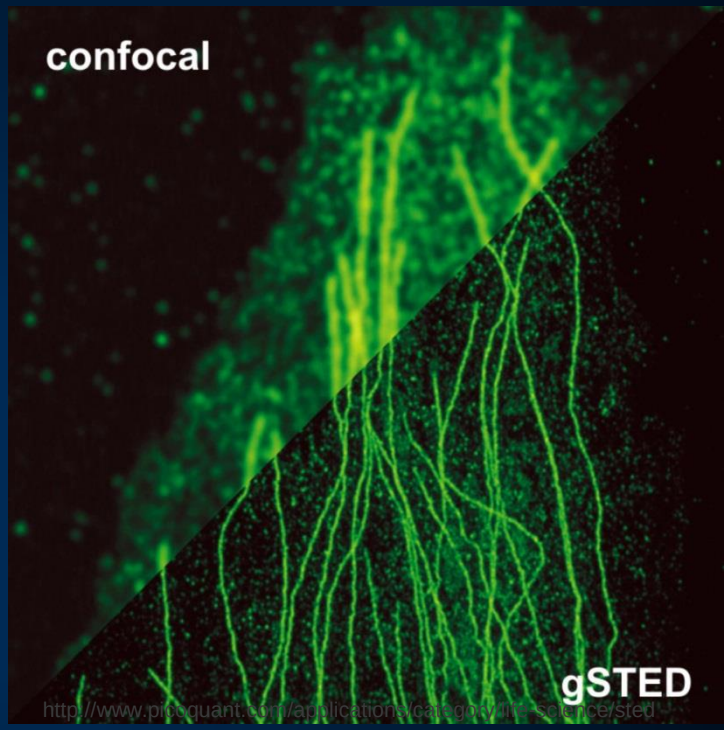




(gated) STED image of Tubulin vs standard confocal image

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

Nobel prize 2018 – CPA

Arthur Ashkin, Gérard Mourou and Donna Strickland

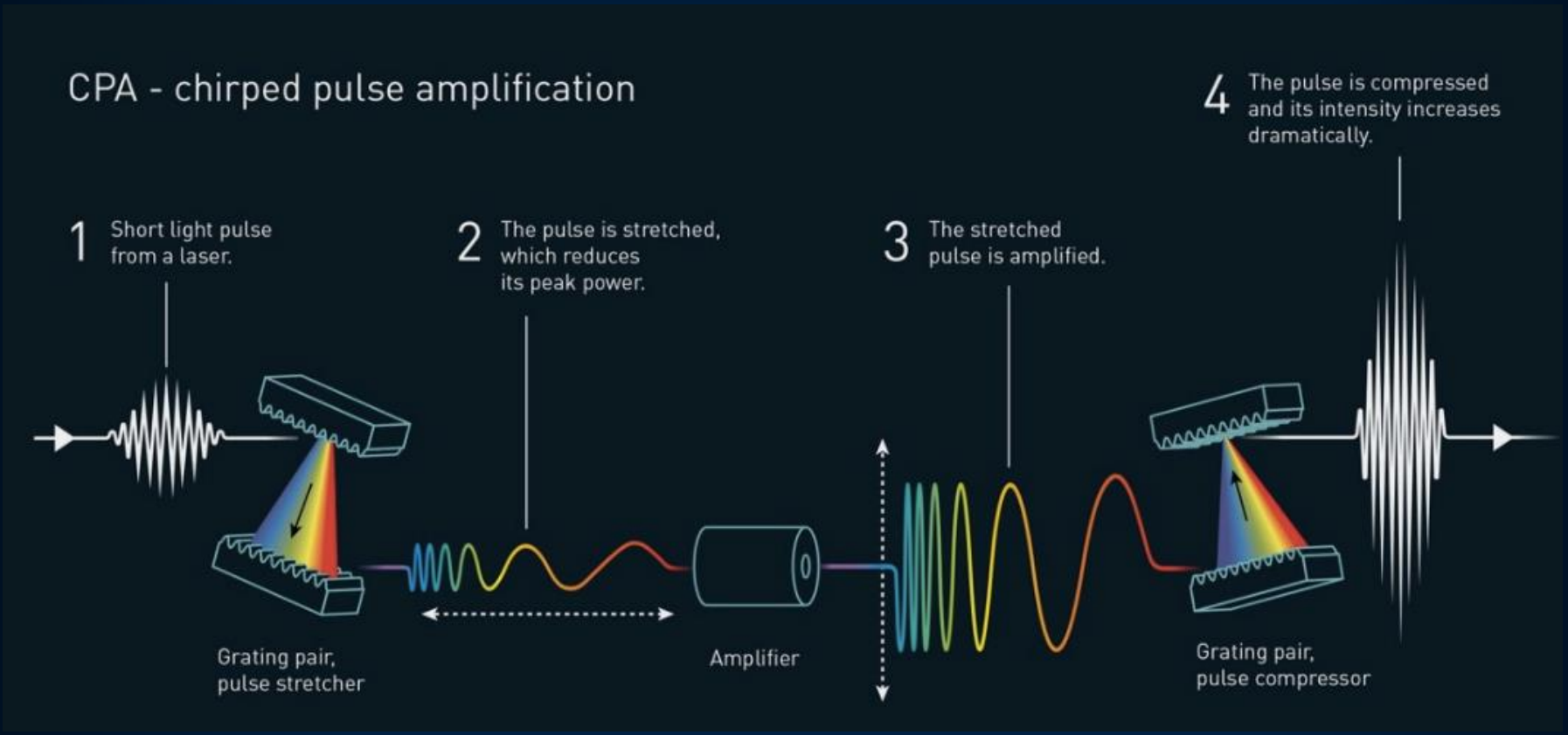


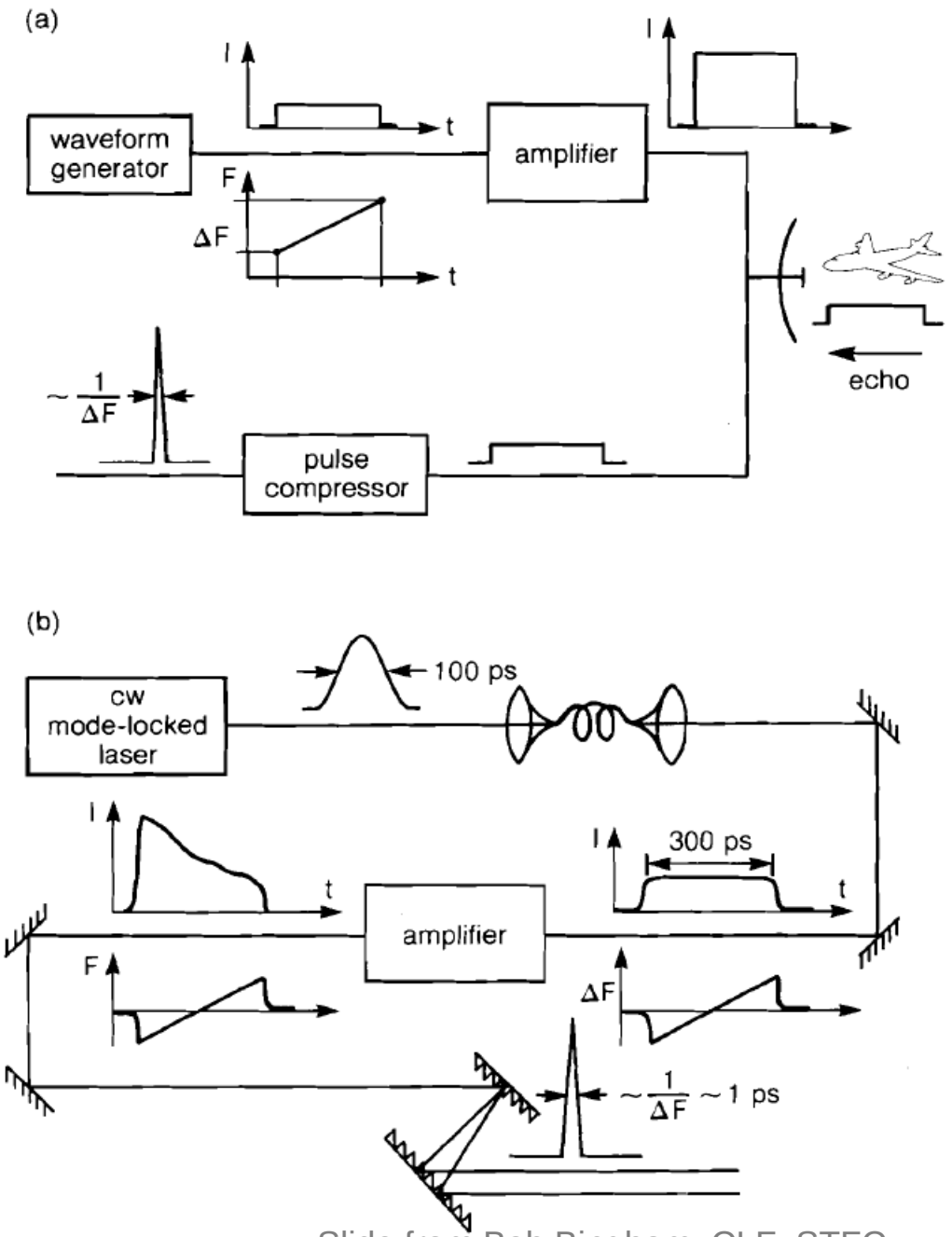
Image: Johan Jarnestad/Royal Swedish Academy of Sciences

Is there an inventive principle here that is used in other areas?

Chirped pulse amplification from Radar to Lasers (CPA)

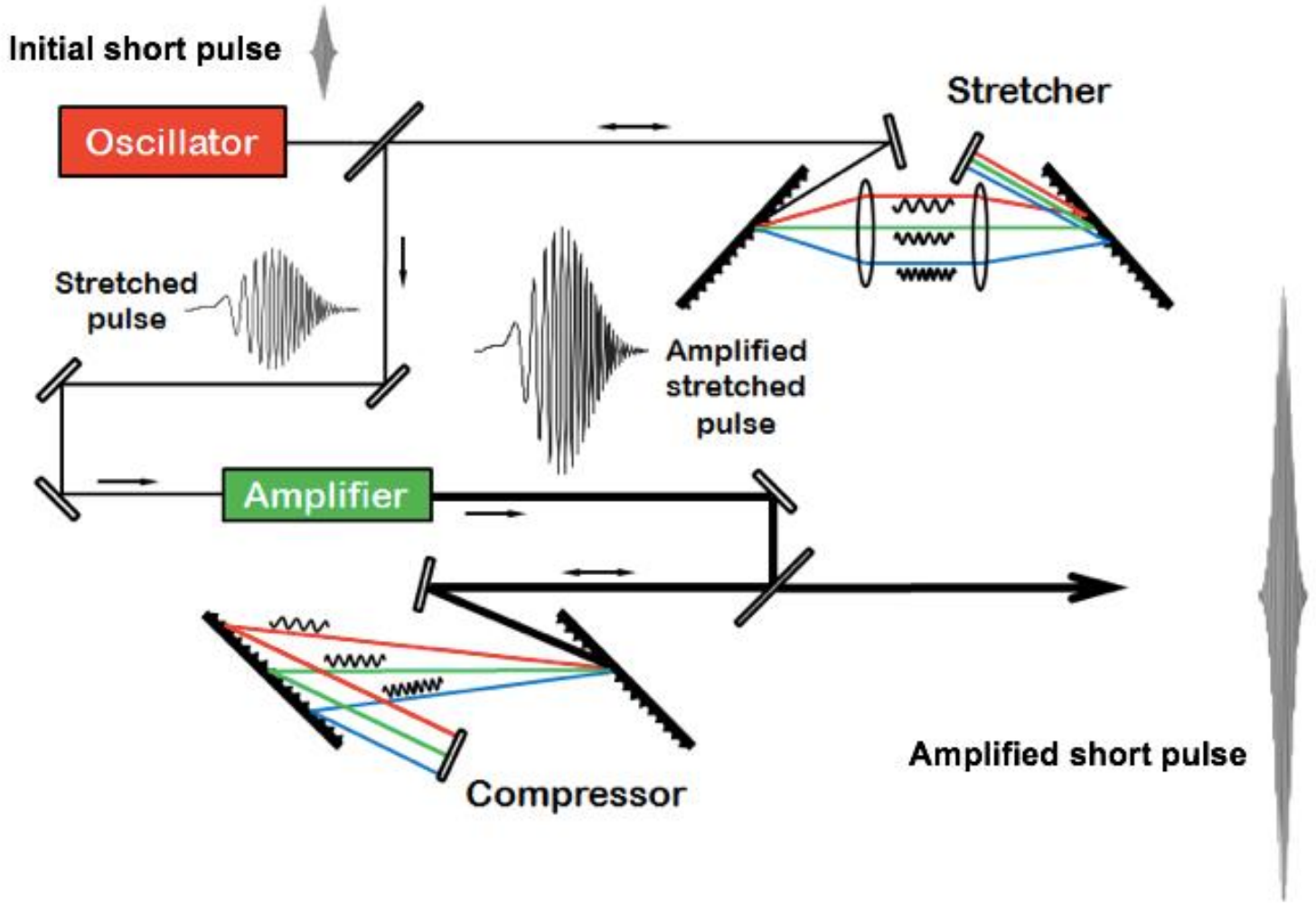
Diagrams taken from early LLE review On the comparison between RADAR chirped pulse amplification from the 1940 onwards upper diagram and laser chirped pulse amplification bottom diagram carried out at the LLE Rochester.

LLE Review 25 3B 1985.



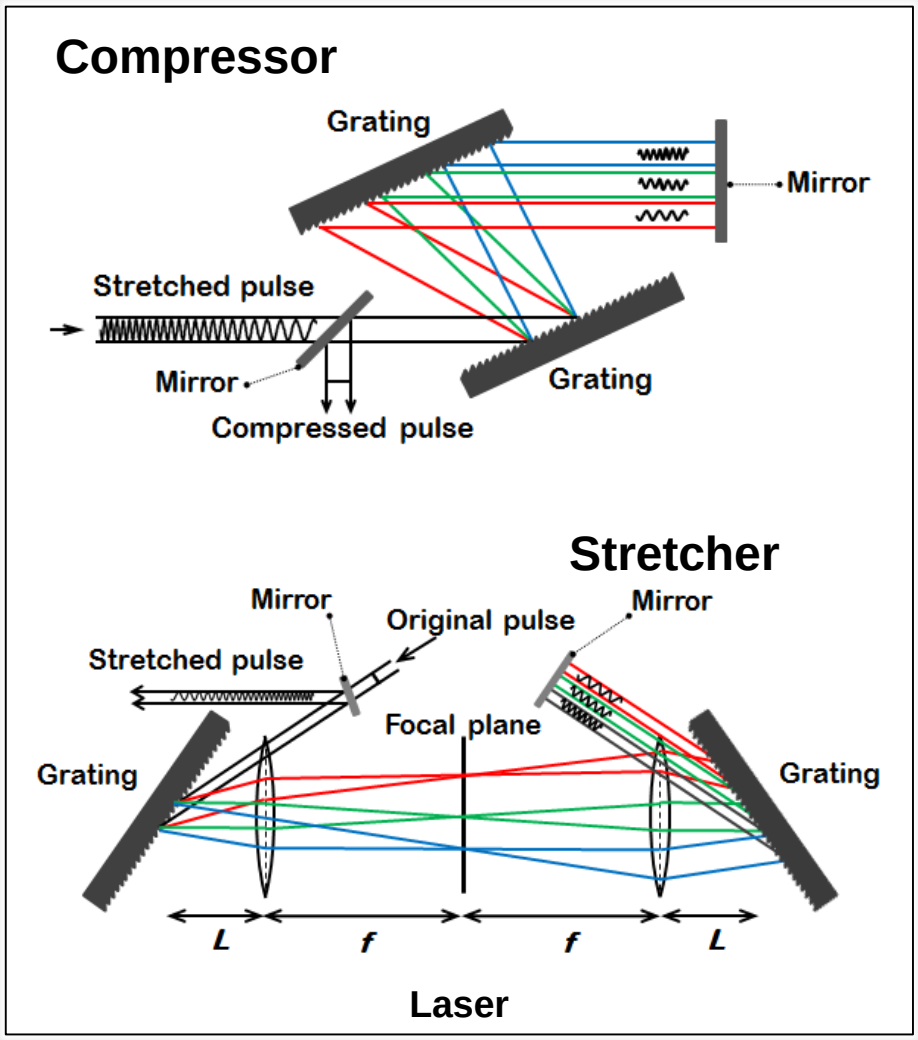
Slide from Bob Bingham, CLF, STFC

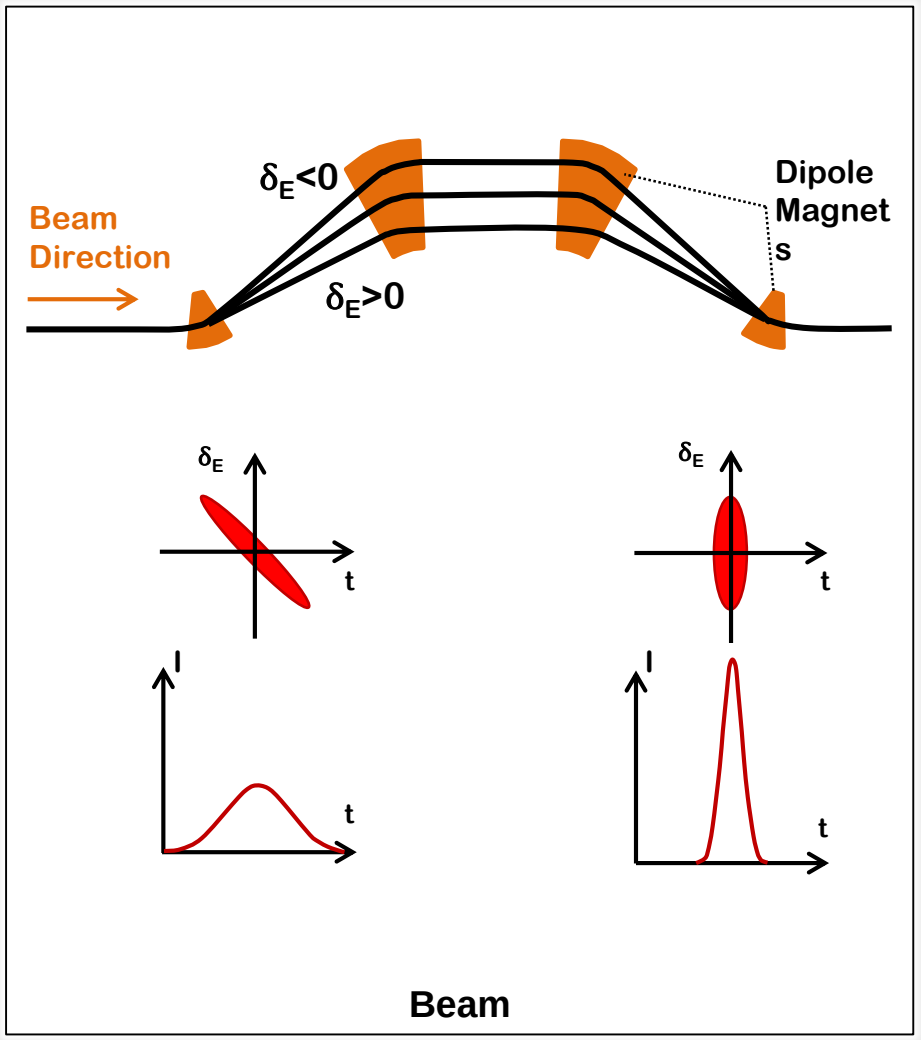
CPA – Chirped Pulse Amplification



- **CPA: pulse stretching and compressing using time-energy correlation**

Beam and laser bunch/pulse compression





Both in laser and beam use z-Energy correlation to compress/stretch the pulse – this seem to be one more general inventive principle – connecting laser CPA and particle accelerators

Radar and CPA

Evolution from chirped pulse amplification in radars to lasers, and connection of CPA with bunch compression in accelerators, seem to demonstrate that …

The same Problems and Inventions appear again and again but in different areas of science and technology

Let's now talk about inventiveness

We have seen several examples of what seem to be some general inventive principles and evolution laws

It happens that many of such inventive principles and evolution laws are known for half a century and widely used…
…but so far not in science

Let's discuss methodologies of inventiveness

How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company?

What was that magic bullet?
…wait a few slides…

But it was [redacted] that became the bedrock of innovation at Samsung. And it was introduced at Samsung by [redacted] whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 [redacted] led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. [redacted] is now an obligatory skill set if you want to advance within Samsung.

How to invent – evolution of the methods

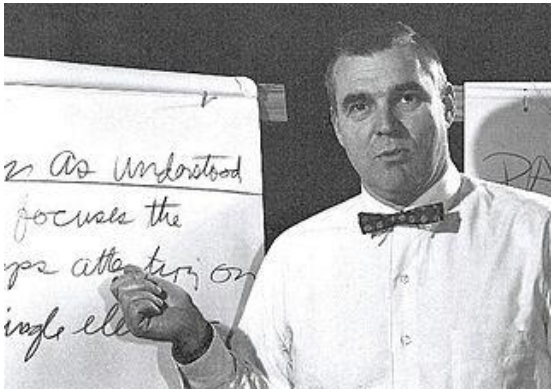
- **Brute-force or exhaustive search**
  - consider any possible ideas
- **Brainstorming**
  - psychological method which helps to solve problems and to invent
  - The main feature of brainstorming – separate the process of idea generation from the process of their critical analysis
  - The method of brainstorming did not meet expectations
    - the absence of feedback, which is the power of the method, is simultaneously its handicap, as feedback is needed for development and adjusting of an idea

Alex Osborn
(1888 – 1966)

The author of brainstorming Alex Osborn introduced the method around 1950s

How to invent – evolution of the methods

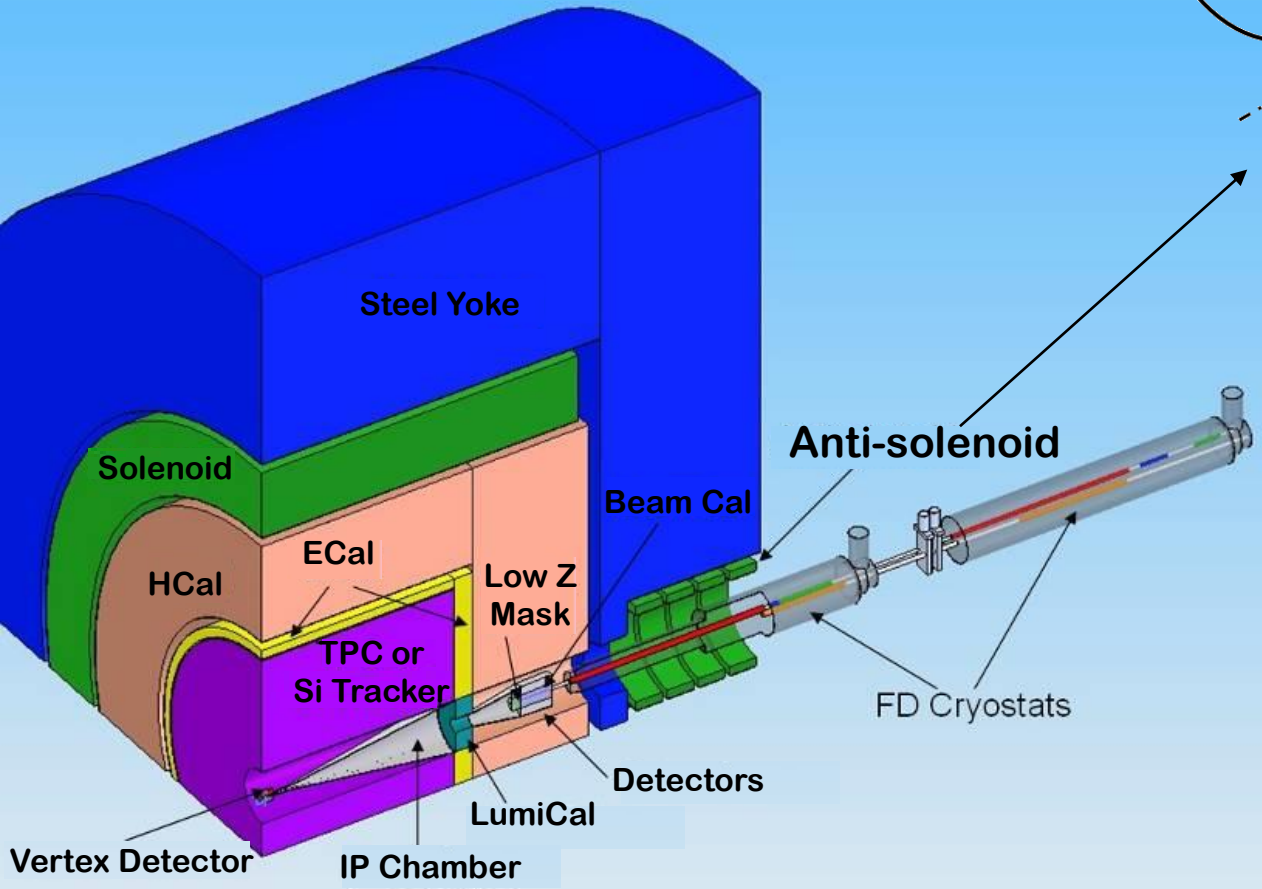
- **Synectics – improved Brainstorming**
- **Features of Synectics:**
  - **Permanent groups for problem solving**
    - **whose members with time become less sensitive to critics and more efficient in problem solving**
  - **Emphasis on the importance to see familiar behind unknown and vice versa**
    - **which should help to solve a new and unfamiliar problem with known methods**
  - **Importance of a fresh view at a problem**
  - **Use of analogies to generate fresh view**
    - **direct (any analogy, e.g. from nature);**
    - **empathic (attempting to look at the problem identifying yourself with the object);**
    - **symbolic (finding a short symbolic description of the problem and the object);**
    - **metaphorical (describing the problem in terms of fairy-tales and legends);**

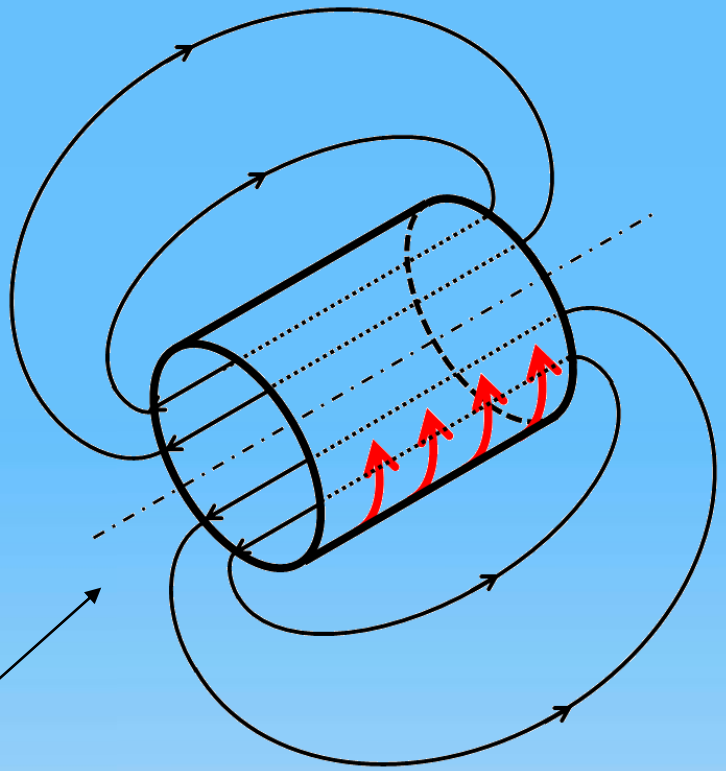


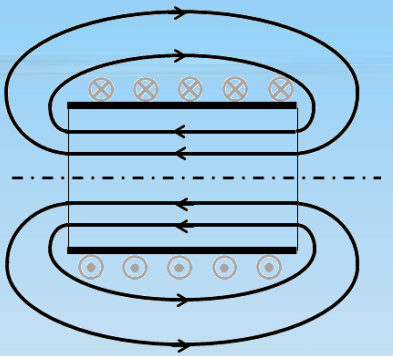
Attempting to improve brainstorming, George Prince (on the photo) and William Gordon introduced the method of Synectics

ILC Interaction Region…

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

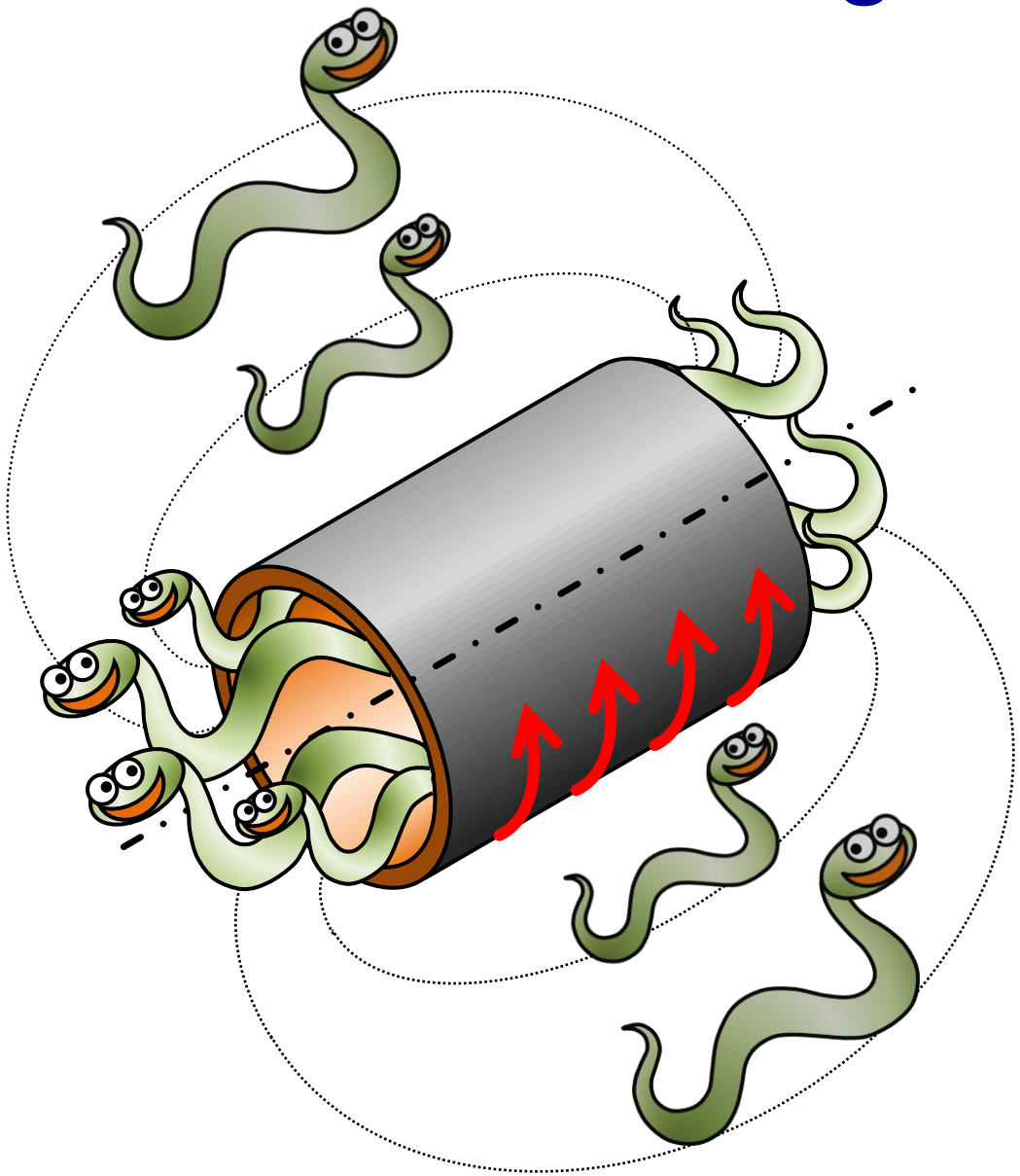






Synectics : use of analogies

- **Use of analogies to generate fresh view**
  - **…**
  - **empathic (attempting to look at the problem identifying yourself with the object);**
  - **…**
  - **metaphorical (describing the problem in terms of fairy-tales and legends);**

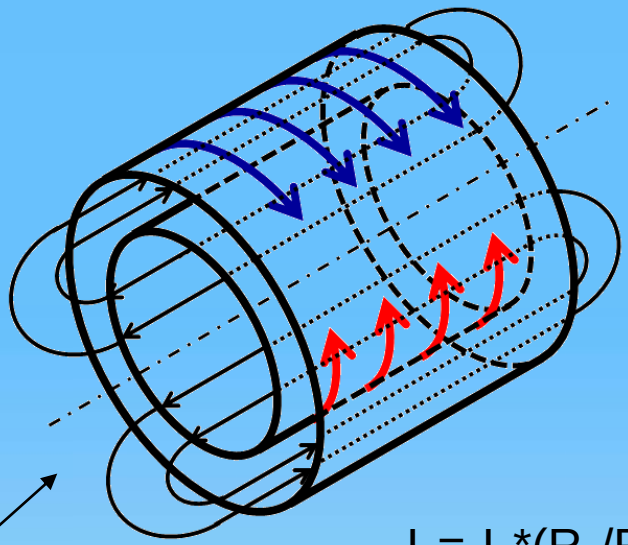


How to contain the magnetic flux?

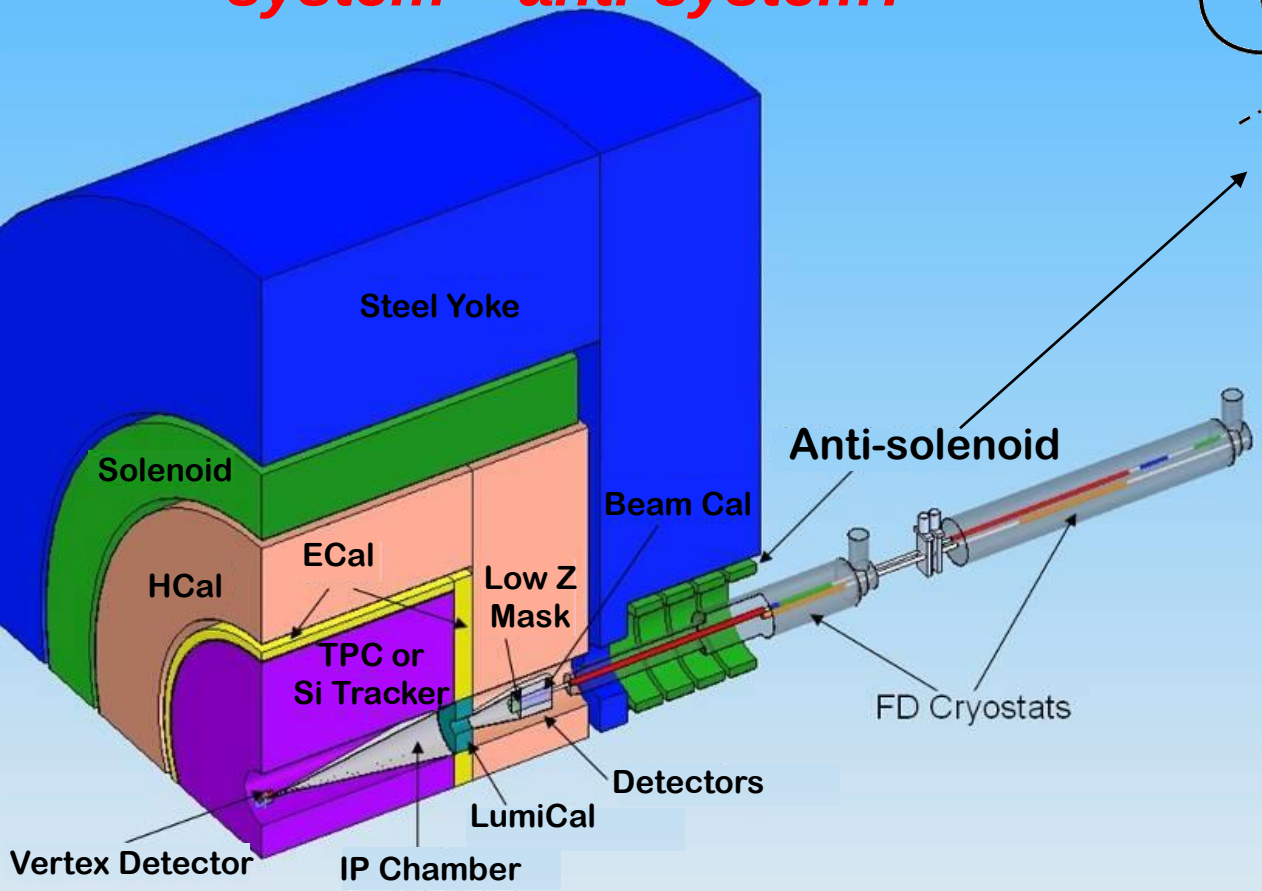
ILC Interaction Region…

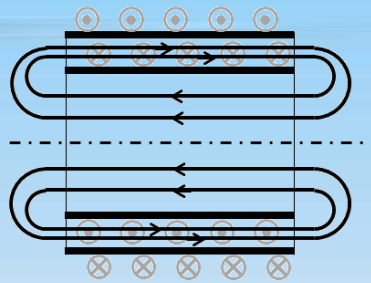
Dual anti-solenoid is used, to cancel its external field – this makes it force-neutral

What if we try nested doll & system – anti-system?



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





Synectics and use of analogies

- **Use of analogies to generate fresh view**
  - **…**
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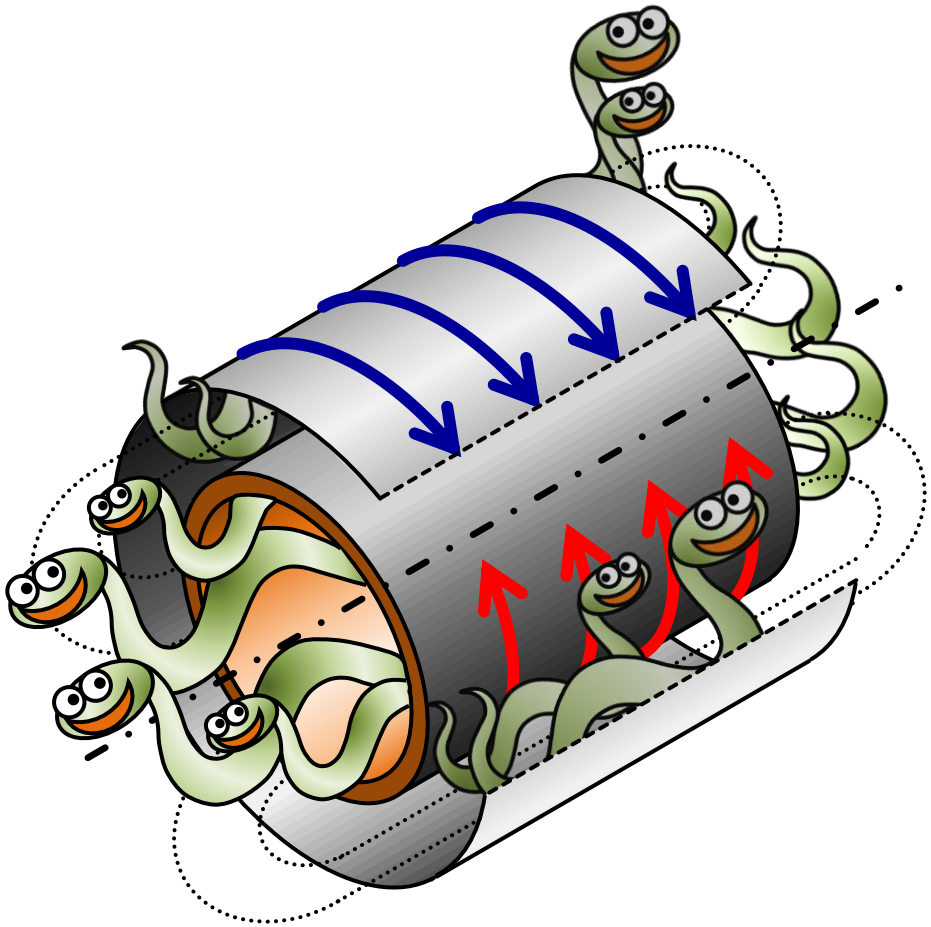


Synectics does not help

How to invent – evolution of the methods

- **Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search**
  - **Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself", ideally using resources already existing in the system**

How to invent – evolution of the methods

- **Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search**
  - **Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself", ideally using resources already existing in the system**
  - **One should aim at such formula in any invention, armed with precise identification of physical contradiction – essence of TRIZ**

Illustration by Sasha Seraia

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**
  - **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**

How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

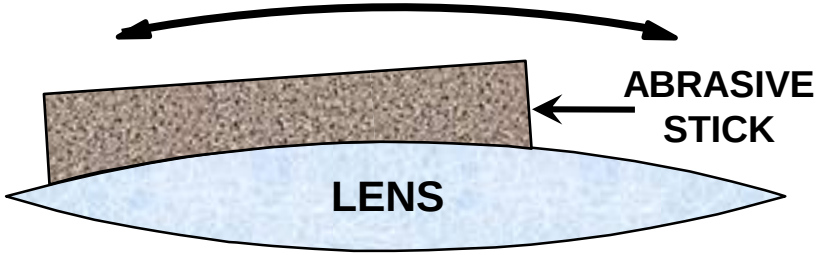
What Makes Samsung Such An Innovative Company?

Why are we interested in this in relation to science?
…wait a few more slides…

But it was TRIZ that became the bedrock of innovation at Samsung. And it was introduced at Samsung by Russian engineers whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 TRIZ led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. TRIZ is now an obligatory skill set if you want to advance within Samsung.

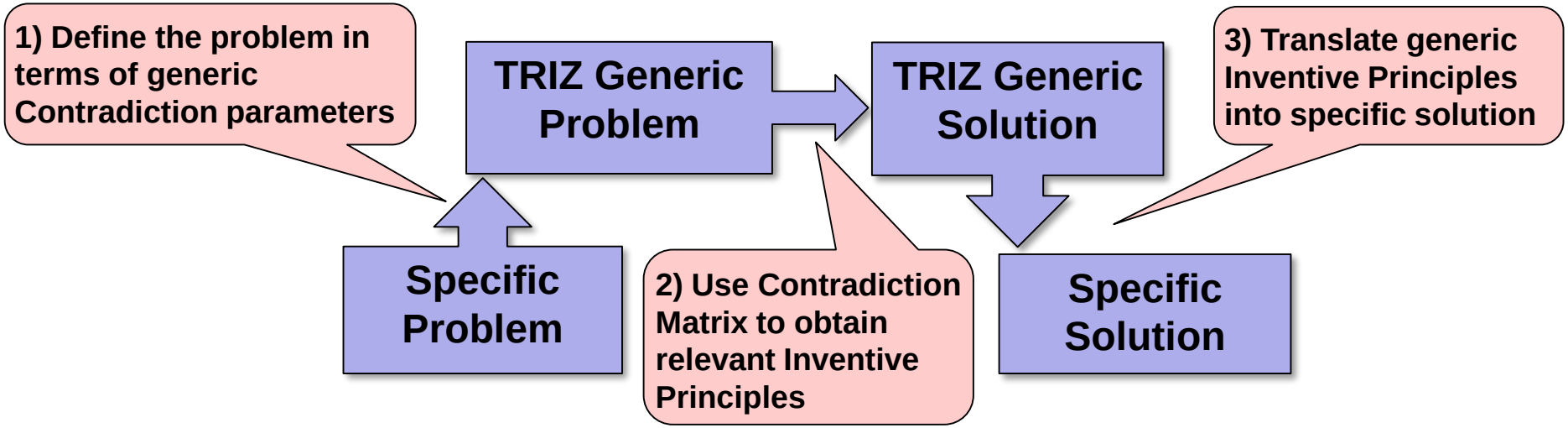
TRIZ in action - example



Problem: Lens polished – heat generated. Heat degrades optical properties. Existing cooling methods ineffective, as cannot achieve uniform cooling at each abrasive particle

To be improved: SPEED, What gets worse: TEMPERATURE

Has anyone else solved such contradiction?



Example: following J.Scanlan, School of Engineering Sciences, Univ. of Southampton

Elements of TRIZ contradiction matrix

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object
14. Strength
15. Durability of moving object
16. Durability of non moving object
17. Temperature
18. Illumination intensity
19. Use of energy by moving object
20. Use of energy by stationary object

21. Power
22. Loss of Energy
23. Loss of substance
24. Loss of Information
25. Loss of Time
26. Quantity of substance/the
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful
31. Object-generated harmful
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Difficulty of detecting
38. Extent of automation
39. Productivity

Only 39 Matrix parameters!!!

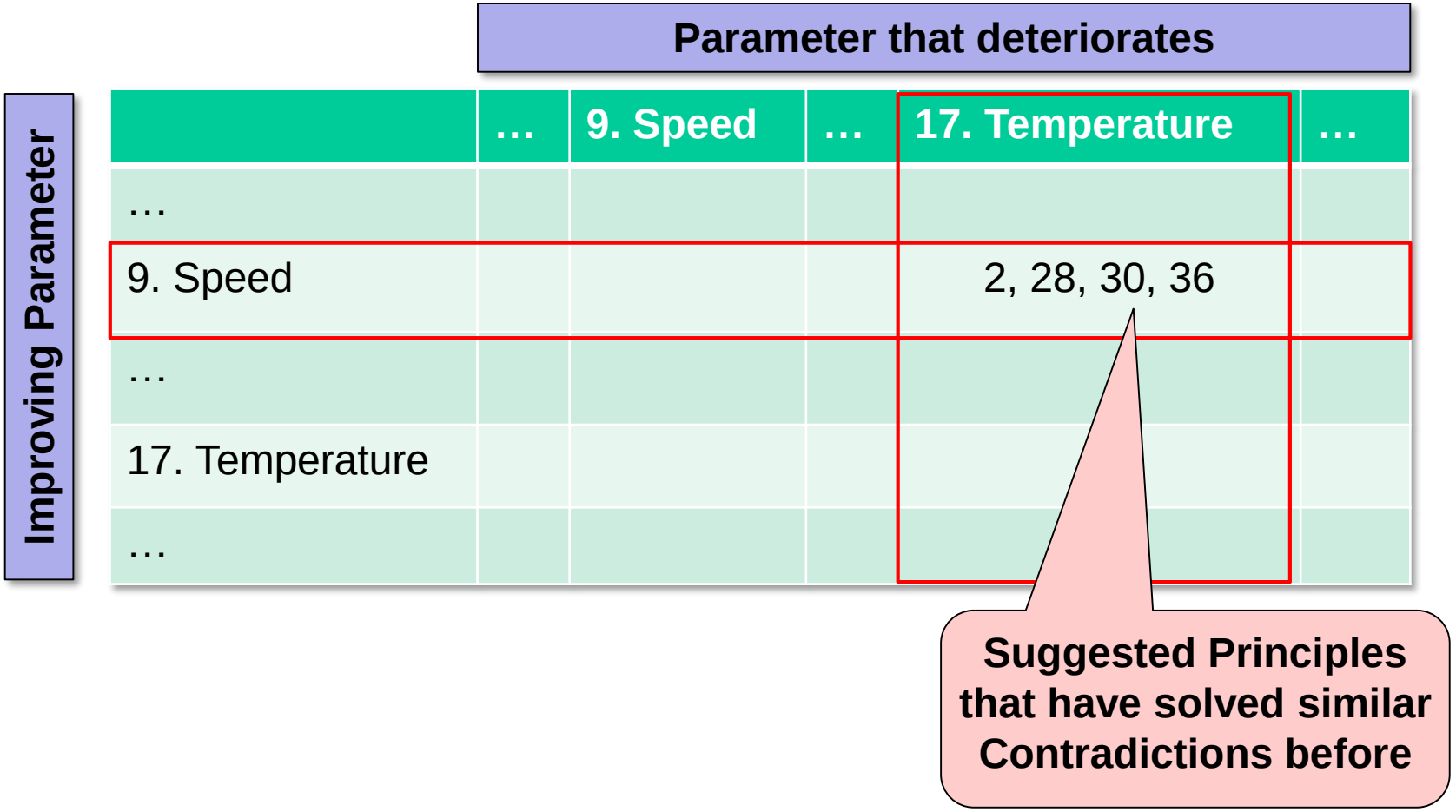
TRIZ Inventive Principles

1. Segmentation
2. Taking out
3. Local quality
4. Asymmetry
5. Merging
6. Universality
7. Russian dolls
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action
11. Beforehand cushioning
12. Equipotentiality
13. "The other way round"
14. Spheroidality - Curvature
15. Dynamics
16. Partial or excessive actions
17. Another dimension
18. Mechanical vibration
19. Periodic action
20. Continuity of useful action
21. Skipping
22. Blessing in disguise
23. Feedback
24. Intermediary
25. Self-service
26. Copying
27. Cheap short-lived objects
28. Mechanics substitution
29. Pneumatics and hydraulics
30. Flexible shells and thin films
31. Porous materials
32. Colour changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions
37. Thermal expansion
38. Strong oxidants
39. Inert atmosphere
40. Composite materials

Only 40 Principles !!!

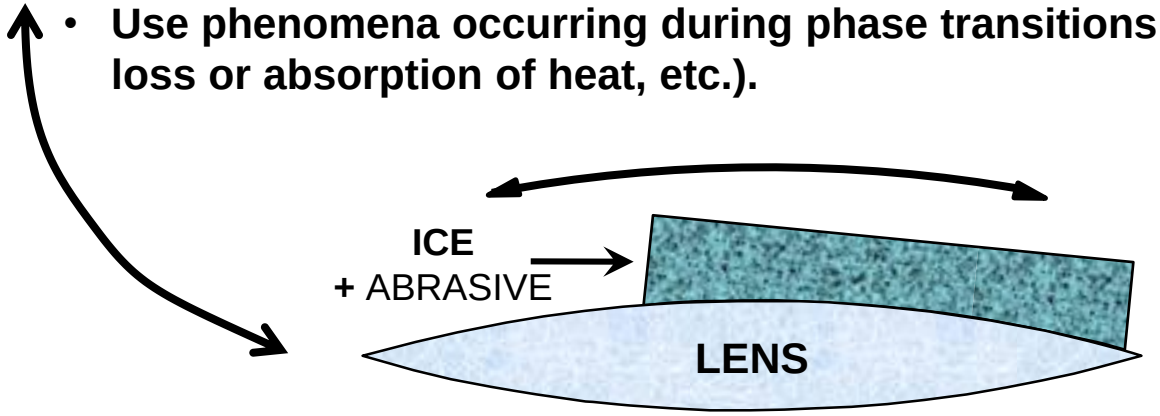
TRIZ Principles and Contradiction matrix

For our example with the lens:



TRIZ in action - example

- **Perform lookup* of TRIZ Matrix for this contradiction:**
  - **Improving 9: SPEED without damaging 17: TEMPERATURE**
- **Find Principles to solve this contradiction:**
  - **2. Taking out**
  - **28. Mechanics substitution**
  - **30. Flexible shells and thin films**
  - **36. Phase transitions**
    - **Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).**



Abrasive + Ice - Inventive Principle ‘Phase Transition’

*) E.g. at http://www.triz40.com/

TRIZ for Universities

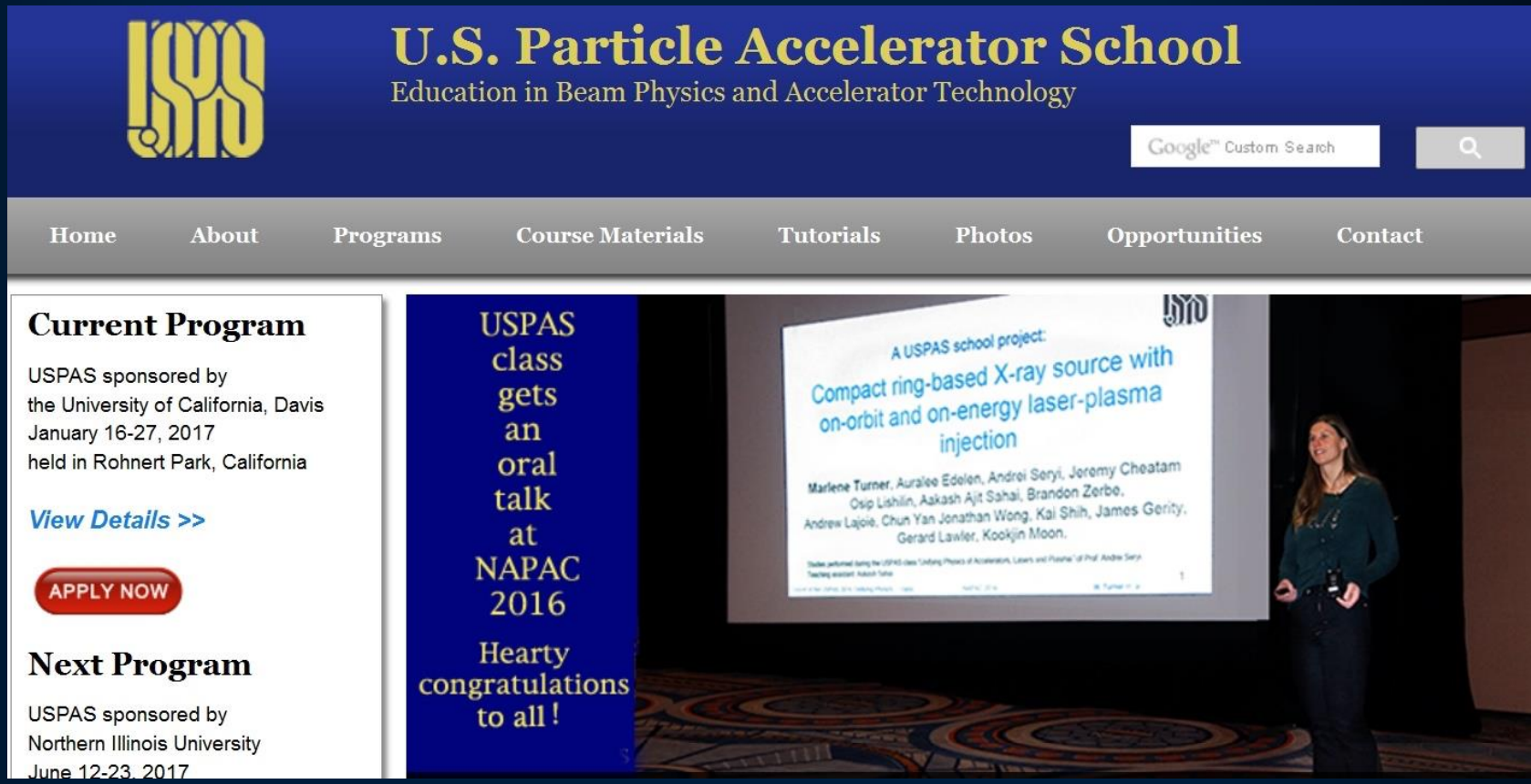
Can TRIZ be useful in university education?

Illustration by Sasha Seraia

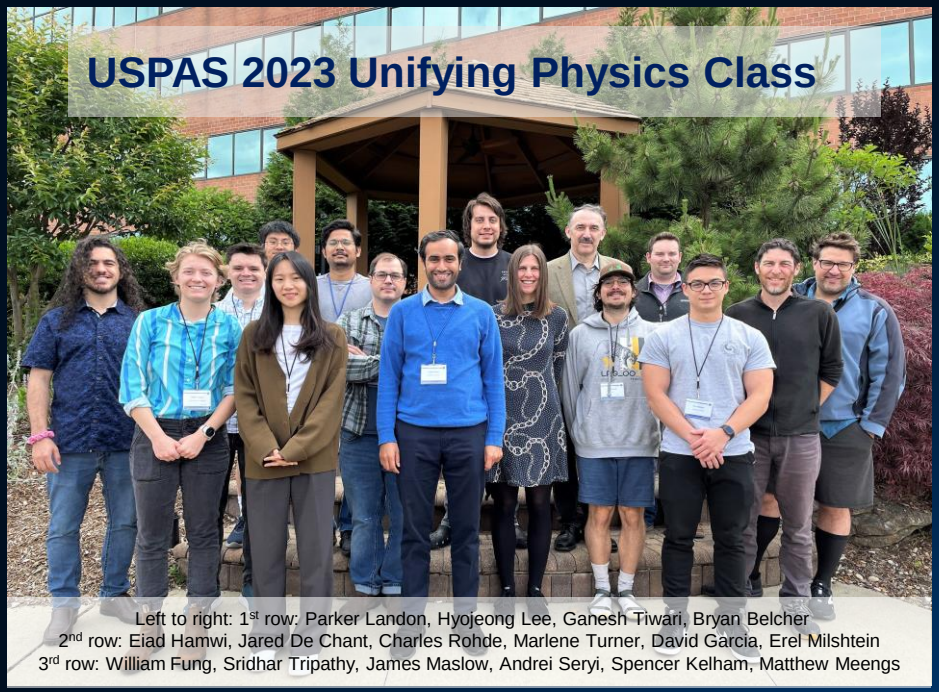
Looking at the world "through the prism of TRIZ"

Can TRIZ be used in university education?

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!

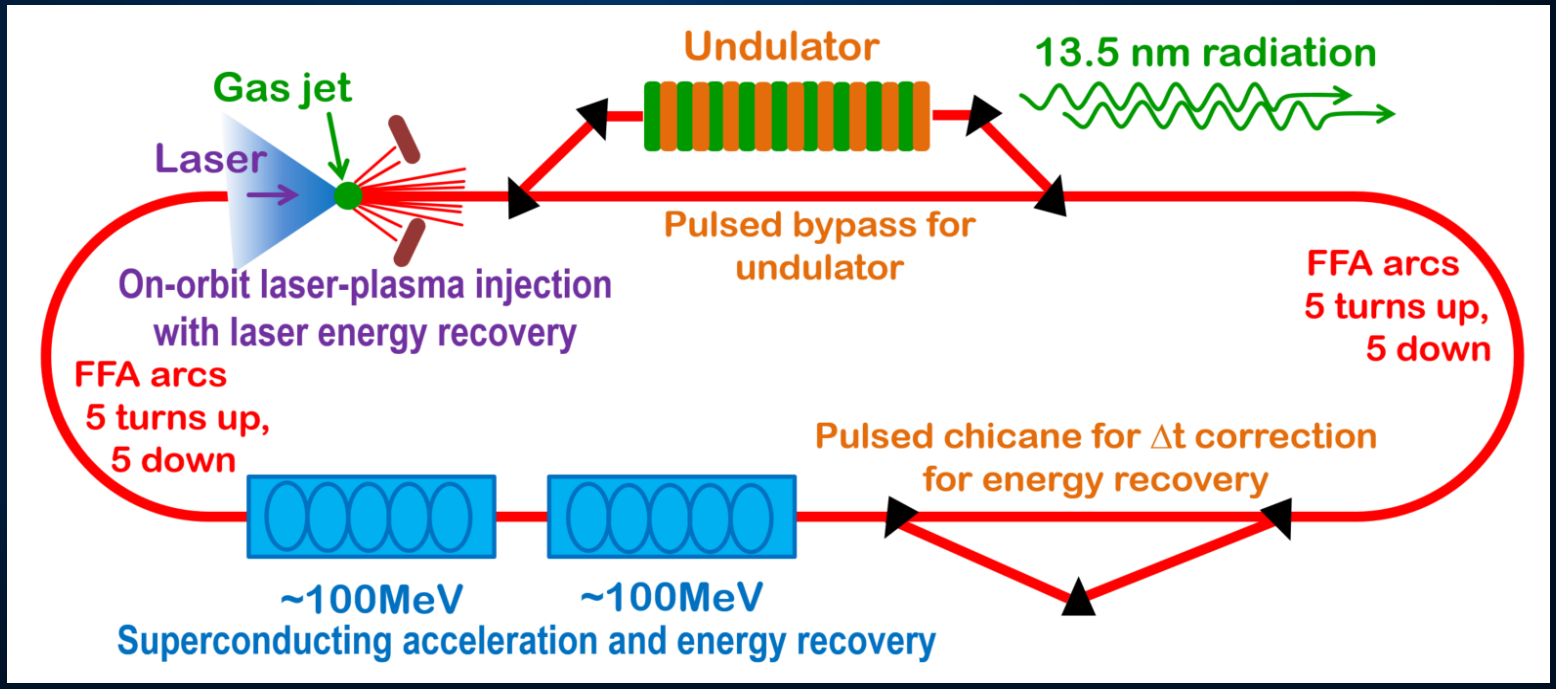


Left to right: 1st row: Parker Landon, Hyojeong Lee, Ganesh Tiwari, Bryan Belcher
2nd row: Eiad Hamwi, Jared De Chant, Charles Rohde, Marlene Turner, David Garcia, Erel Milshtein
3rd row: William Fung, Sridhar Tripathy, James Maslow, Andrei Seryi, Spencer Kelham, Matthew Meengs

Mini-Project 3 - Compact recirculation-FFA-ERL-based 13.5 nm FEL with on-orbit laser-plasma injection with energy recovery

During one-week course, students were able to define main parameters of this conceptual design, making several improvements and inventions on the way

IPAC 2024 https://doi.org/10.18429/jacow-ipac2024-mopg66



Can TRIZ be used in university education?

Yes. However, some critics:

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

Expected critics: 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 universities should be different than in industrial companies…

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

TRIZ for universities

Can be very useful

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

However, this was just the first small step…

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 university education (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

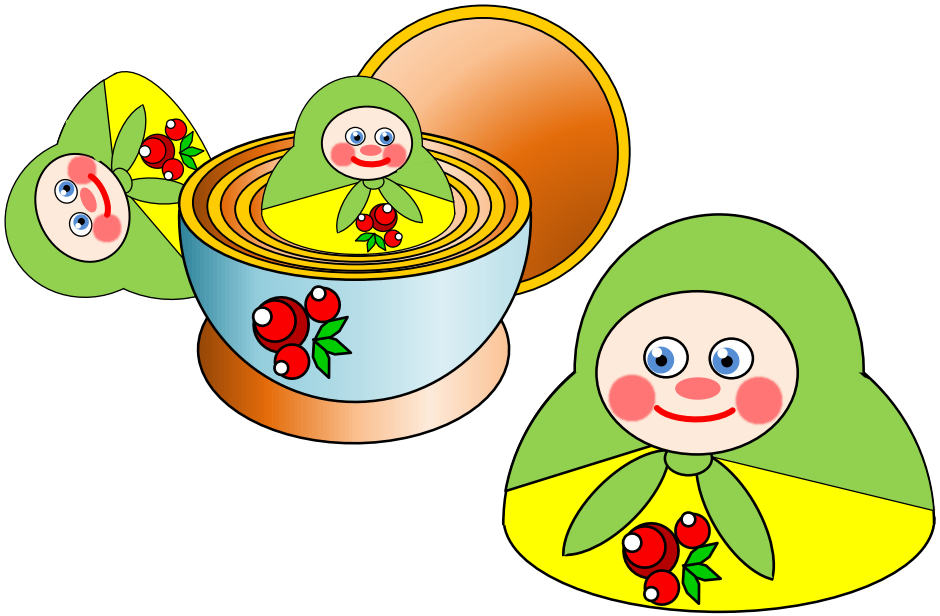
See more details in:

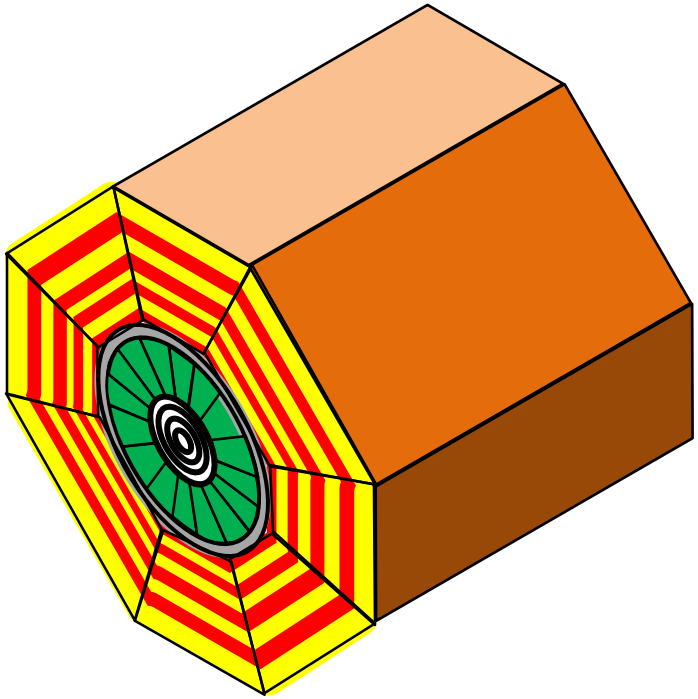
Accelerating Science TRIZ inventive methodology in illustrations
Elena Seraia, Andrei Seryi

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

7. Nested doll

- Place one object inside another; place each object, in turn, inside the other.
- Make one part pass through a cavity in the other.

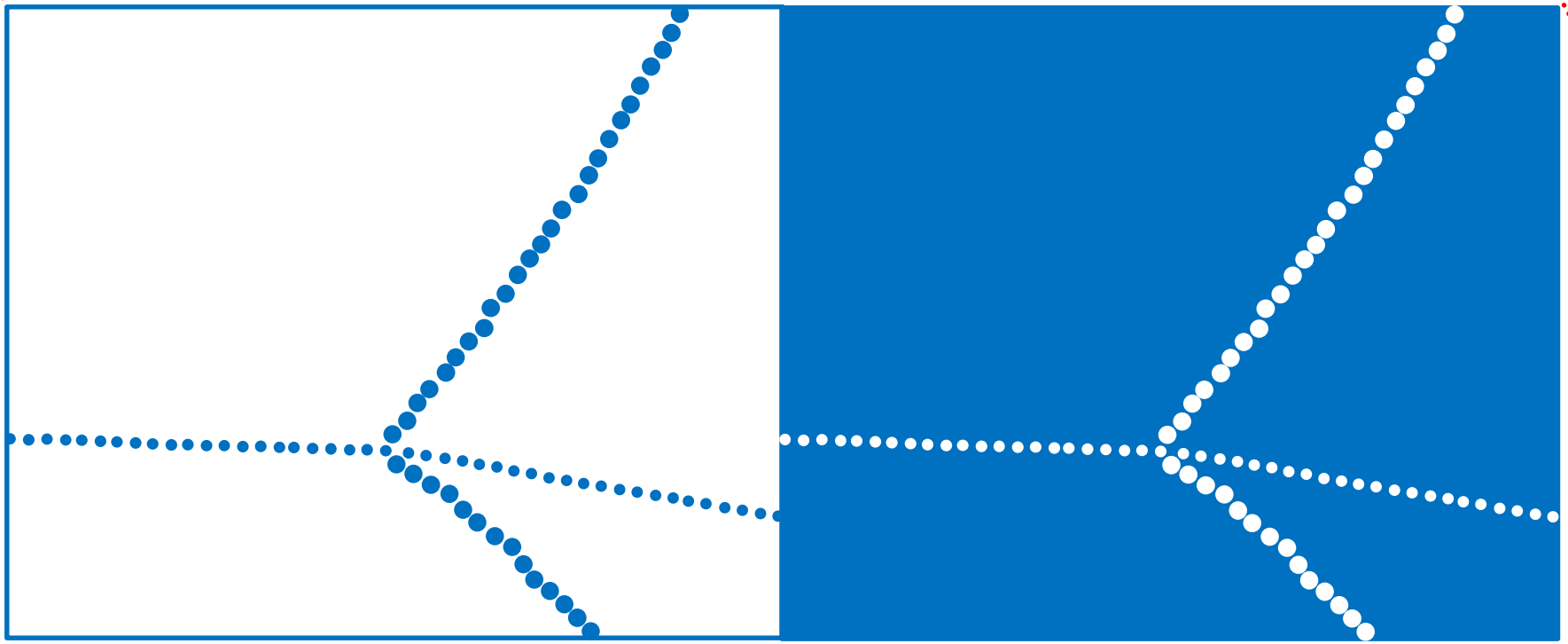




High energy physics detectors

13. The other way round

- Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
- Make movable parts (or the external environment) fixed, and fixed parts movable.
- Turn the object (or process) “upside down”.

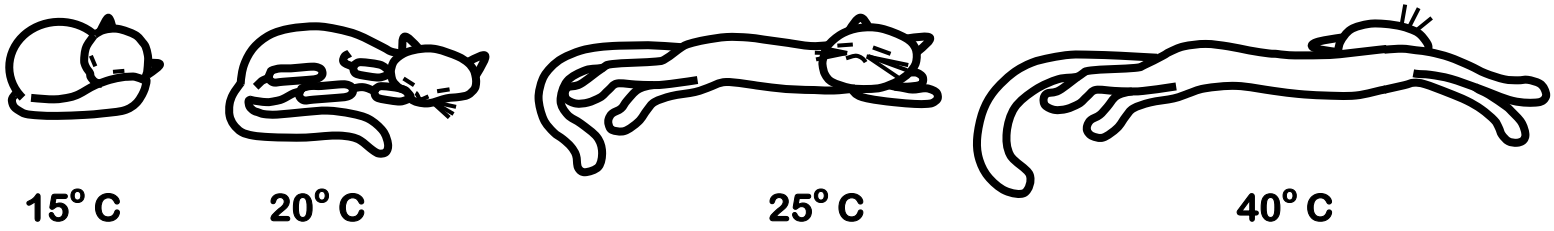


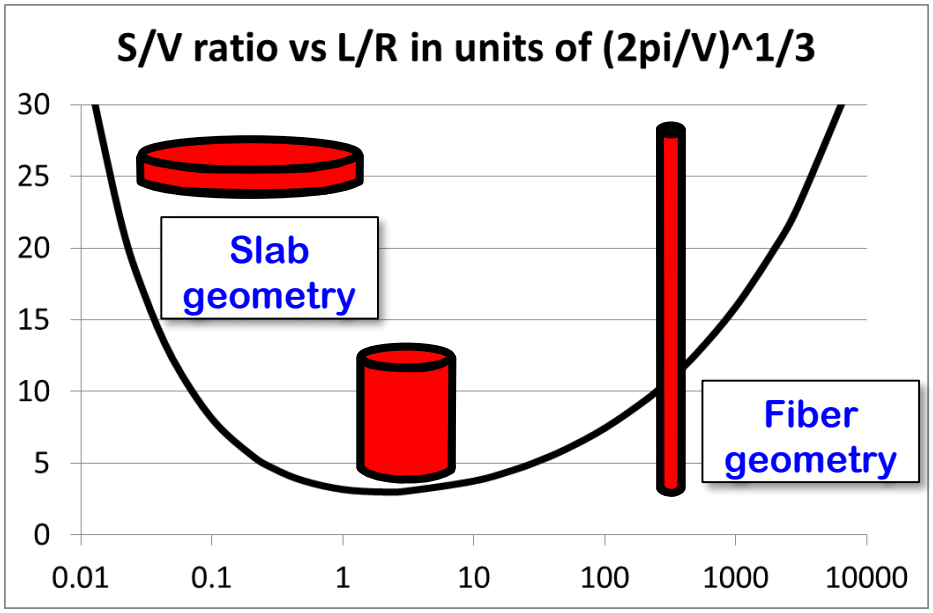
Cloud and bubble chambers

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.





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

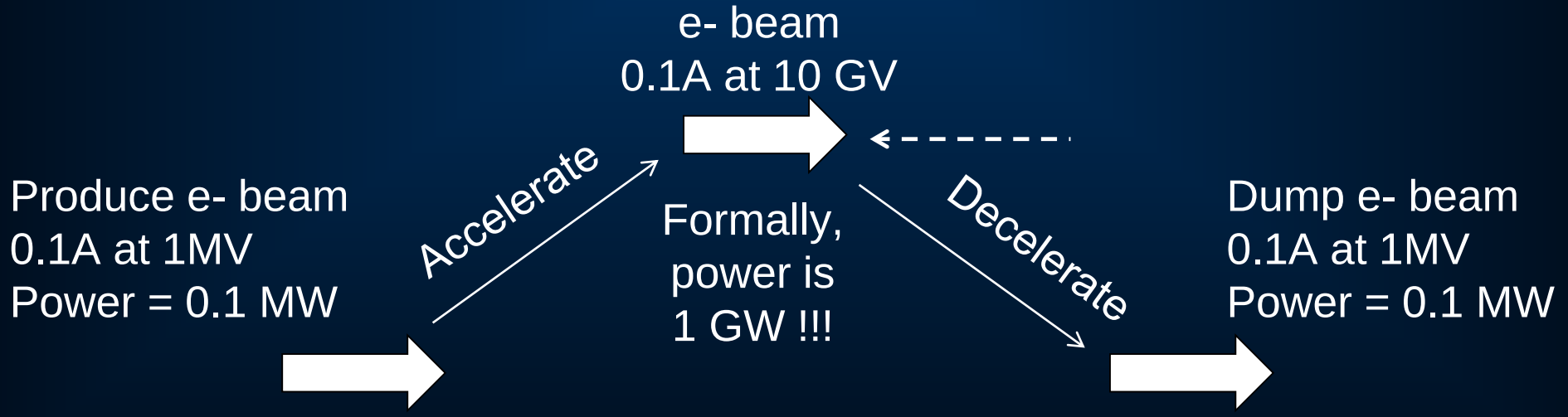
Further adjustments

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



Inventing sci. instruments

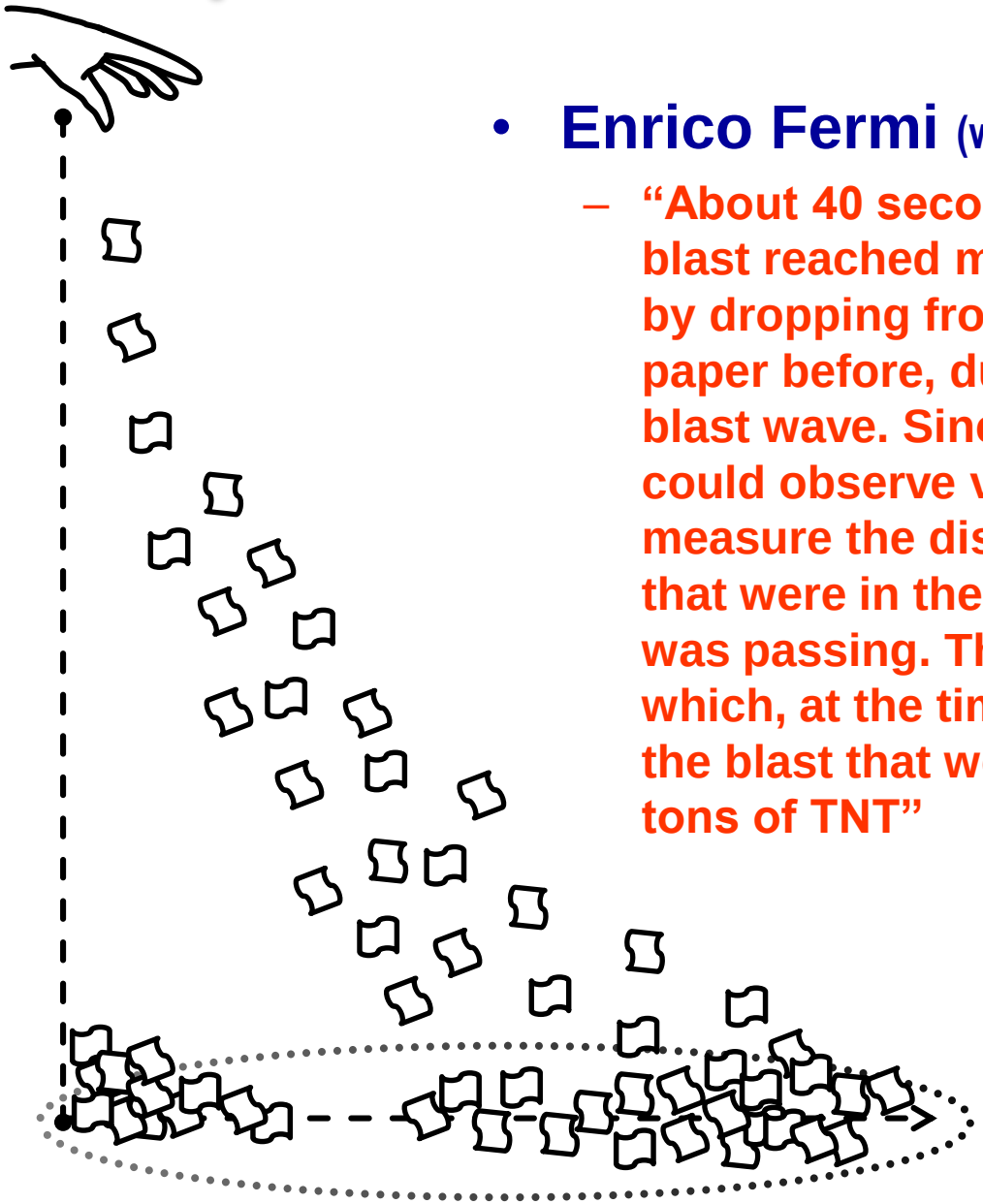
Even if one would define a set of TRIZ inventive principles that would include many approaches used in science, would it be sufficient?

No

What would be missing?

Most importantly – the art of estimations

Example of back-of-the-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-the-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**

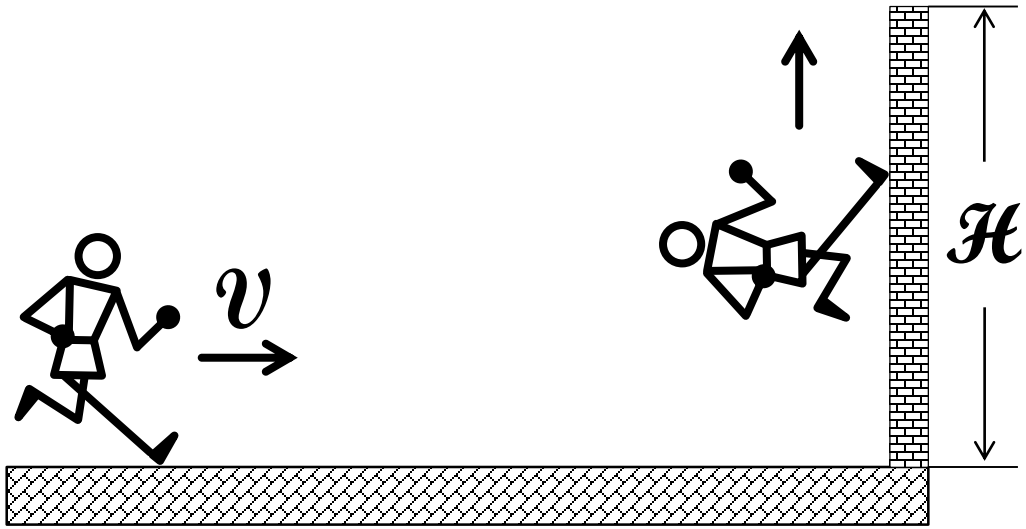
- **To train yourself on back-of-envelope estimations one can consider various questions**
- **They do not have to be necessarily serious ;-)**
- **But the estimates should be based on a physical effect that is considered most important for a given question**
- **Making an estimate would also allow us to make invention how to improve a system**

Importance of back-of-the-envelope estimations

- **They are important because**
  - **they help to understand things better - obvious**
  - **but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics**

- **What speed V is needed to reach height H and get to other side of the wall?**

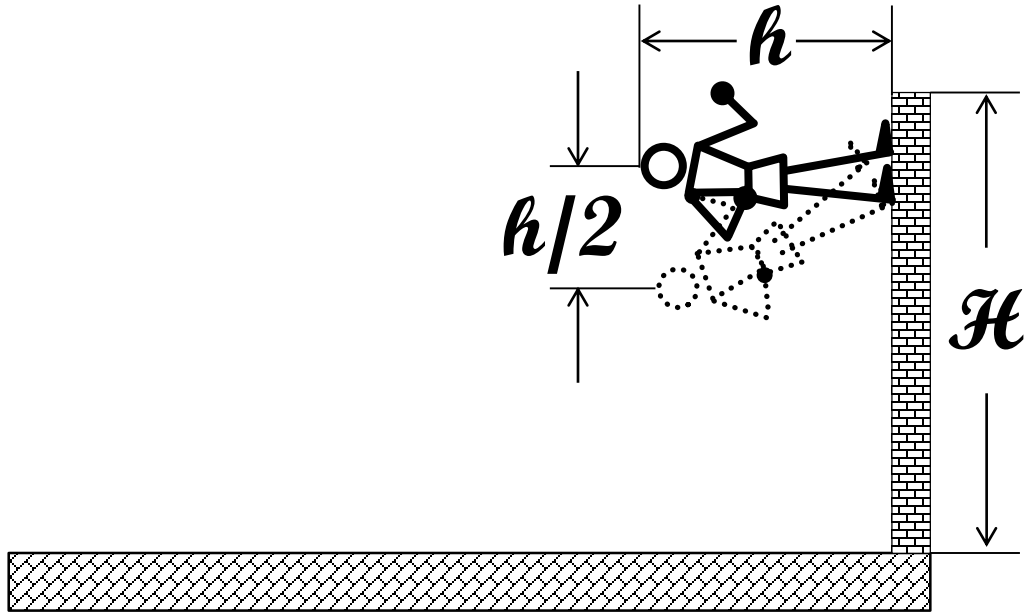
;-)



Importance of back-of-the-envelope estimations

- **Estimate by requiring that during run along the wall the head would not fall to lower than half the height of the person…**

;-)



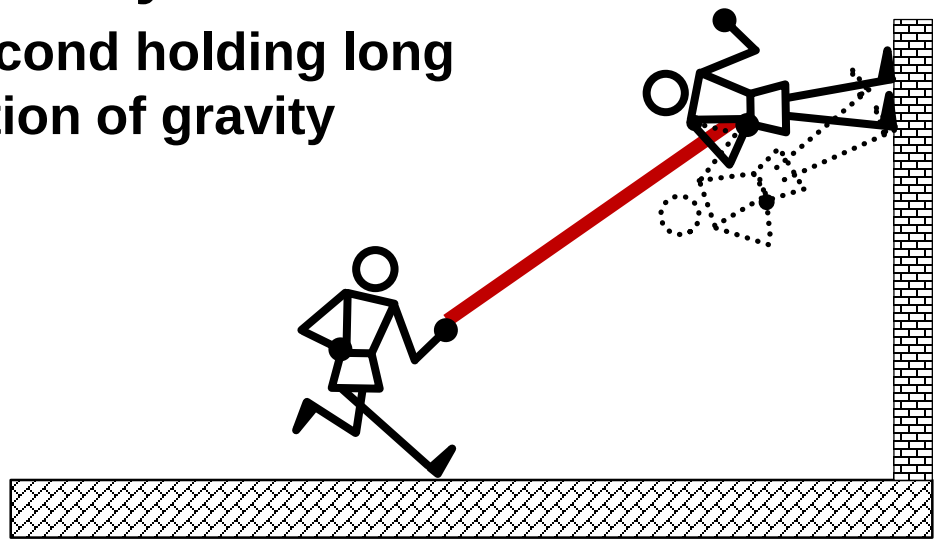
You will then find
$V=H\,(g/h)^{1/2}$

or, for H=2m

V~4.7 m/s

Applying an inventive principle

- **Once we made the estimation and understood the main challenge, we can solve the problem**
- **Apply inventive principle**
- **In this case – #9 Preliminary anti-action**
  - **Two people running, second holding long stick to compensate action of gravity**



The art of estimating

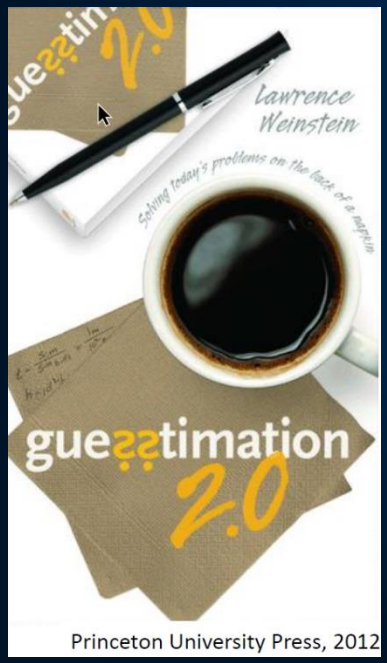
Enrico Fermi was known for his ability to back-of-envelope estimations

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

Image credits (clockwise from top): Phys-Math School; Phys-Math School; V Parkhomchuk

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

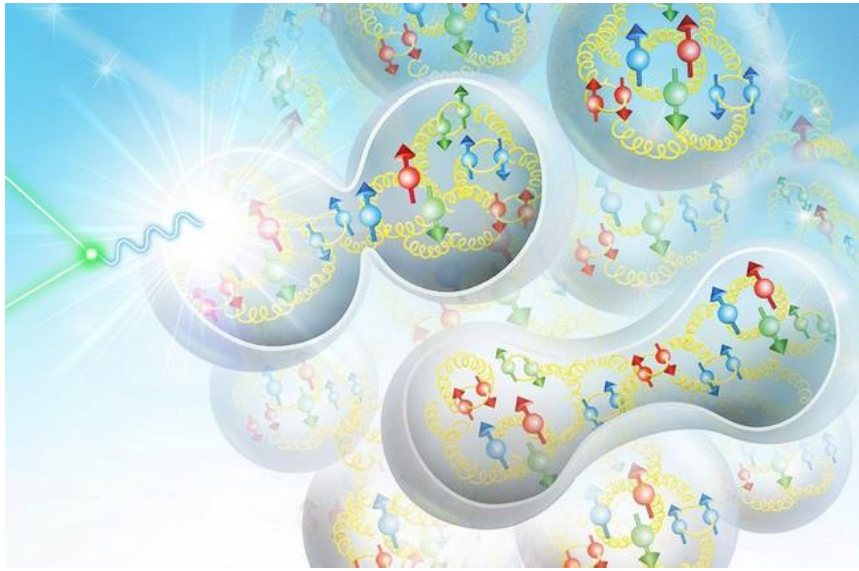
http://cerncourier.com/cws/article/cern/69910



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

Estimate how to study AI-Proton

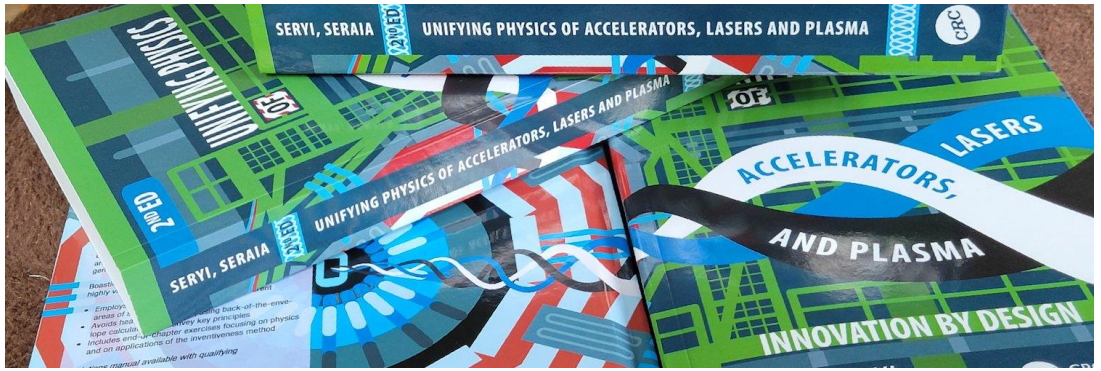
In the book "The Three body problem" by Liu Cixin, civilisation of Alpha Centauri sent to Earth protons with embedded Artificial Intelligence, which penetrated high-energy physics experiments at LHC to spoil the results and stop science progress on Earth.



Imagine that some of AI-Protons were captured, trapped, and Earth scientists wanted to study them.

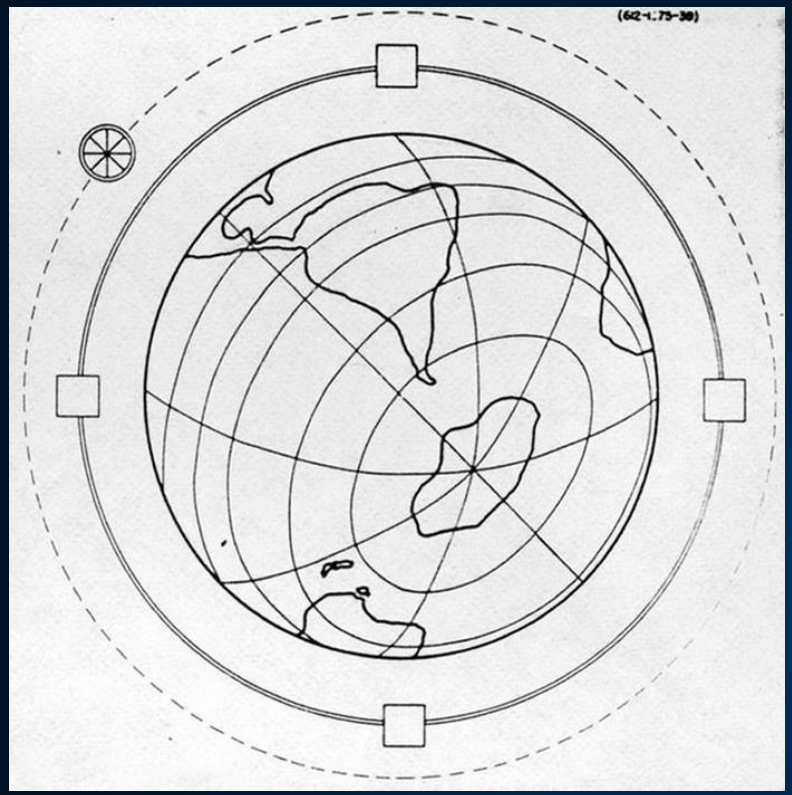
They assumed that AI is encoded into interaction of gluons in the AI-Protons, and used fixed-target experiment similar to CEBAF, to study the AI-Protons.

Estimate the energy of electron beam that Earth scientist needed to use to study the AI-Protons



See the solution guidance for this and many other examples in the 2nd edition of "Unifying Physics of Accelerators, Lasers and Plasma"

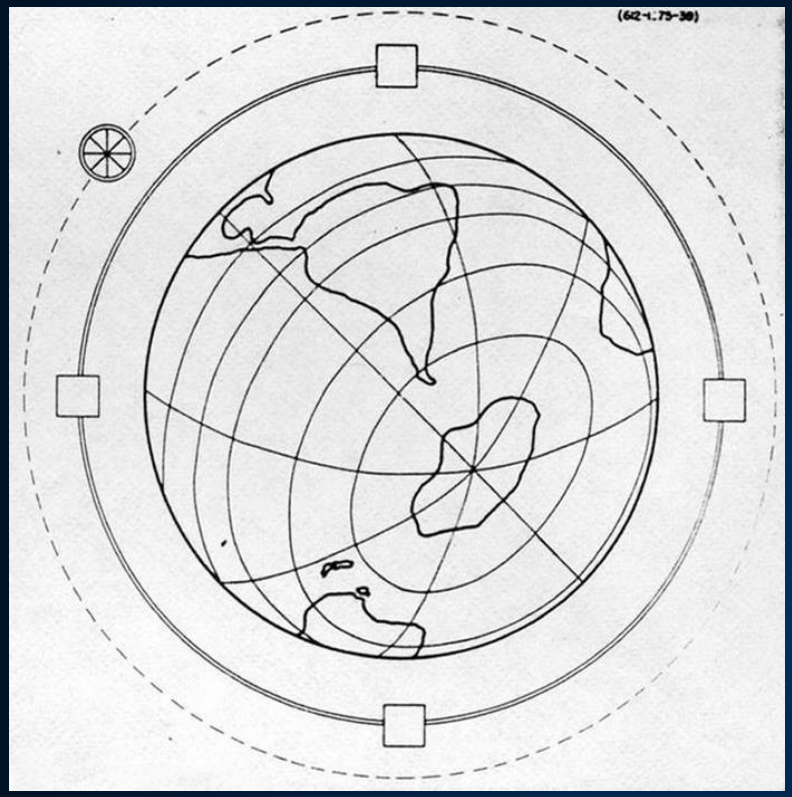
Evolution of accelerators



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

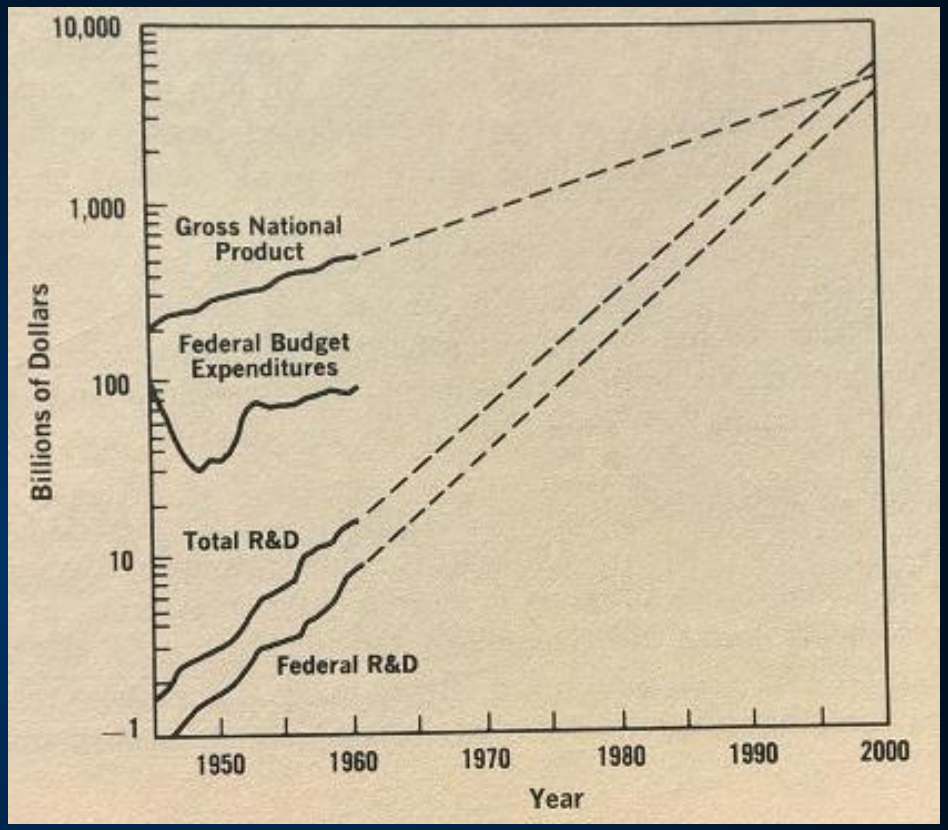
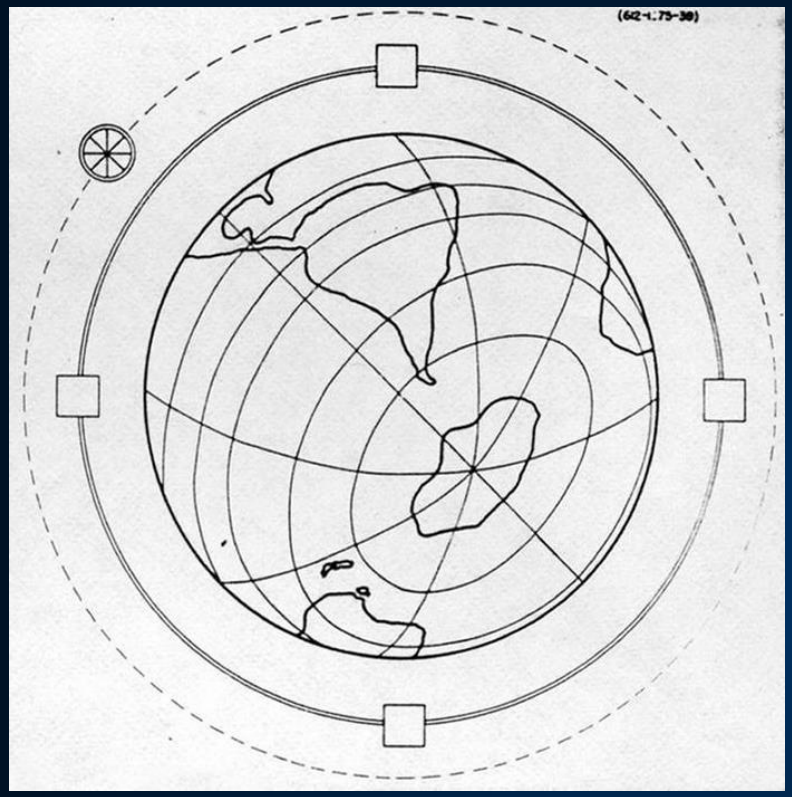


Fig 6, GNP and R&D: Failure of naïve extrapolation.
"The Year 2000", 1968, K. Herman, A. Wiener

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



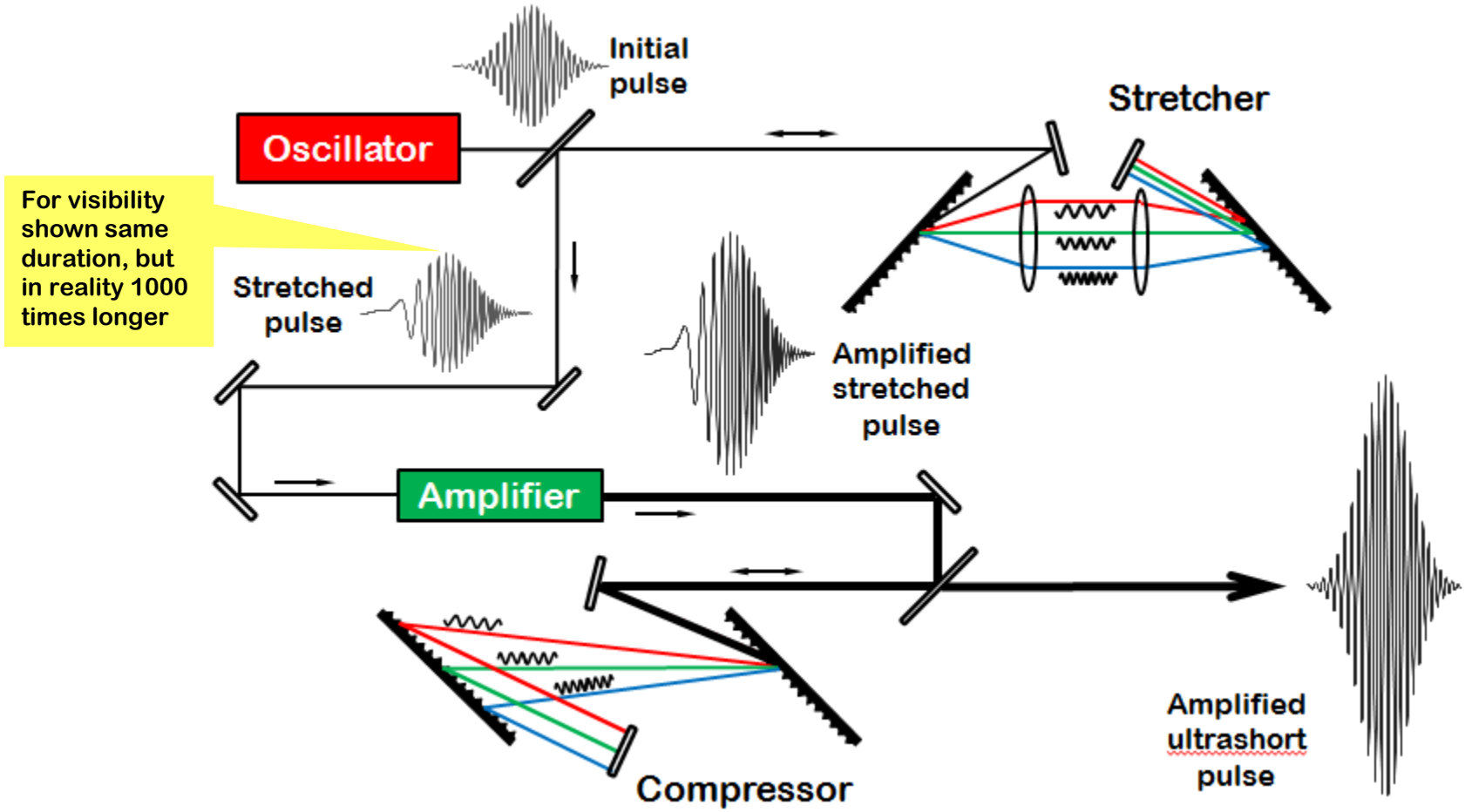
Enrico Fermi Earth accelerator, 1954

Would this be indeed a natural evolution of accelerators?

No.

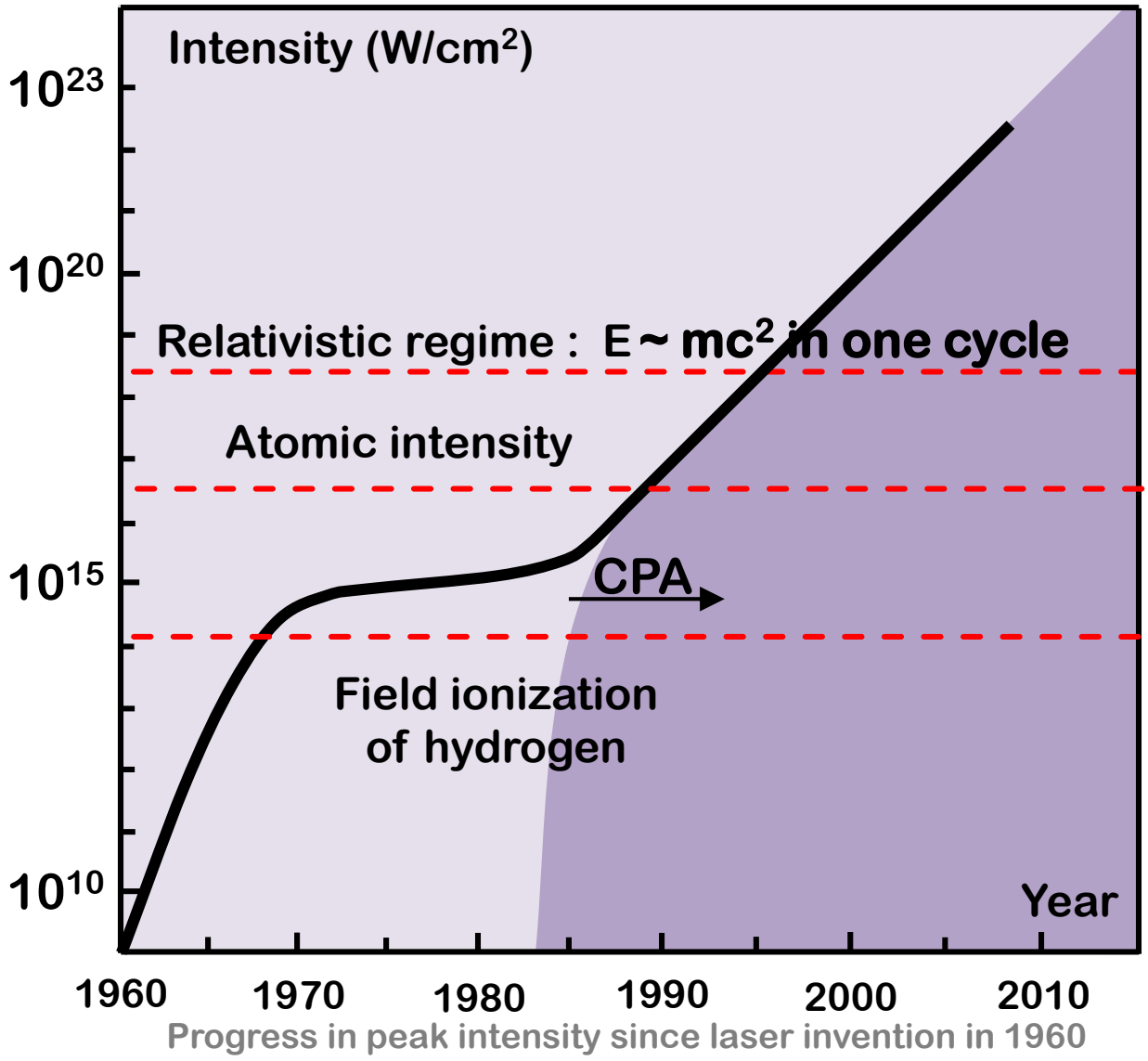
Increasing the size or base of the experiment, to increase precision, with proportional or event faster increase of the cost, would unlikely be accepted by governments and society

CPA – Chirped Pulse Amplification



- **CPA: pulse stretching and compressing using time-energy correlation**

CPA invention: exponential growth of laser power

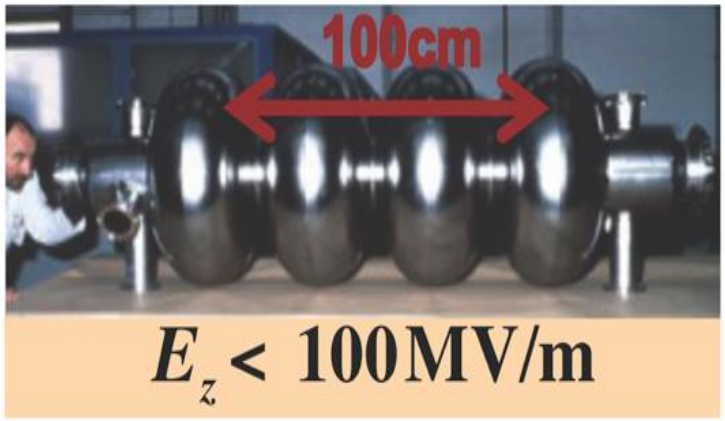


Progress in peak intensity since laser invention in 1960

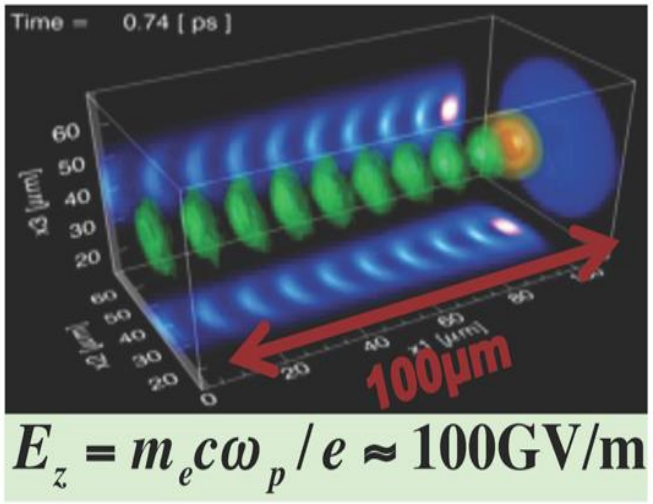
One of 40 inventive principles of TRIZ

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

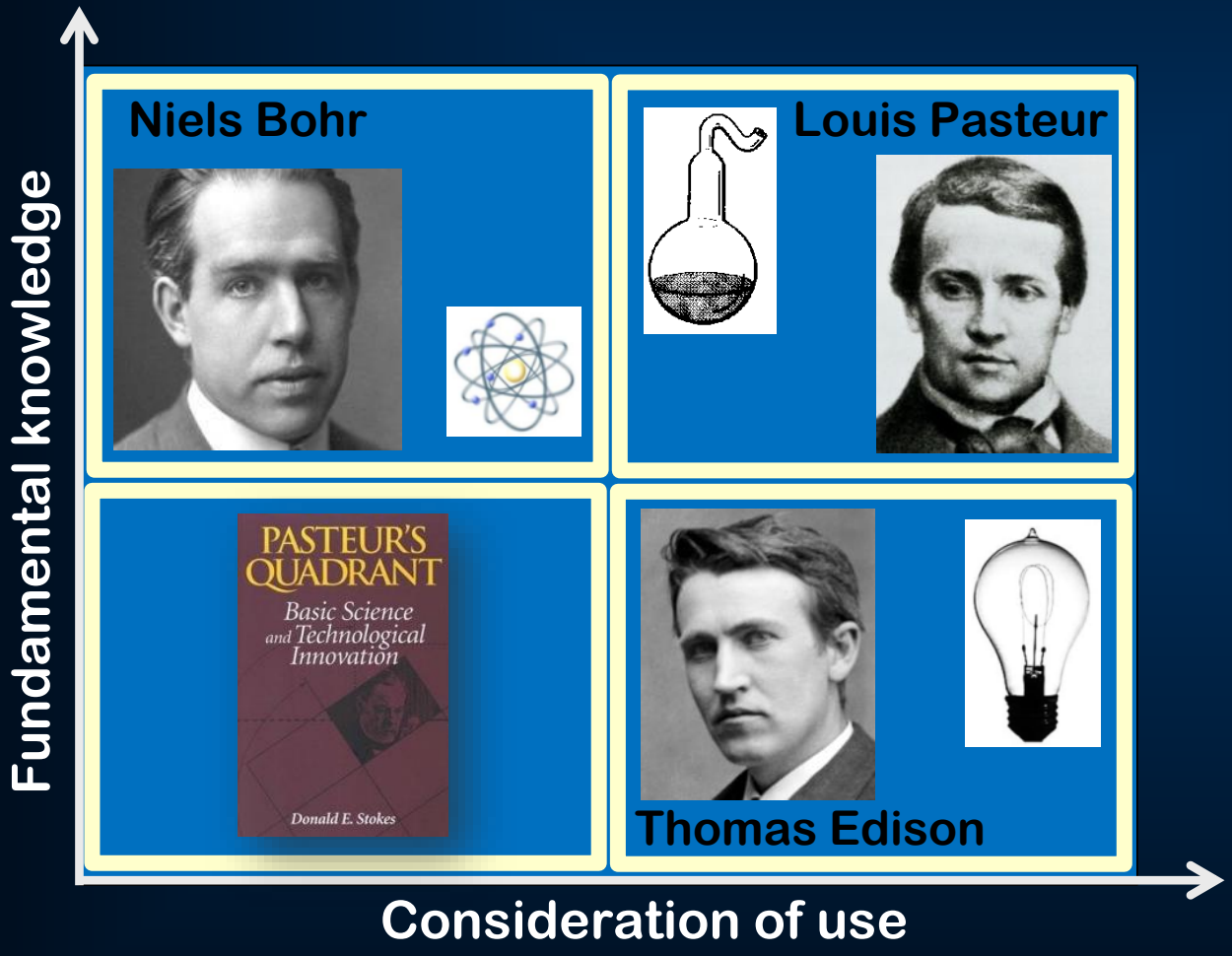
Plasma acceleration

Let's now talk about evolution of synchrotron light sources and FELs

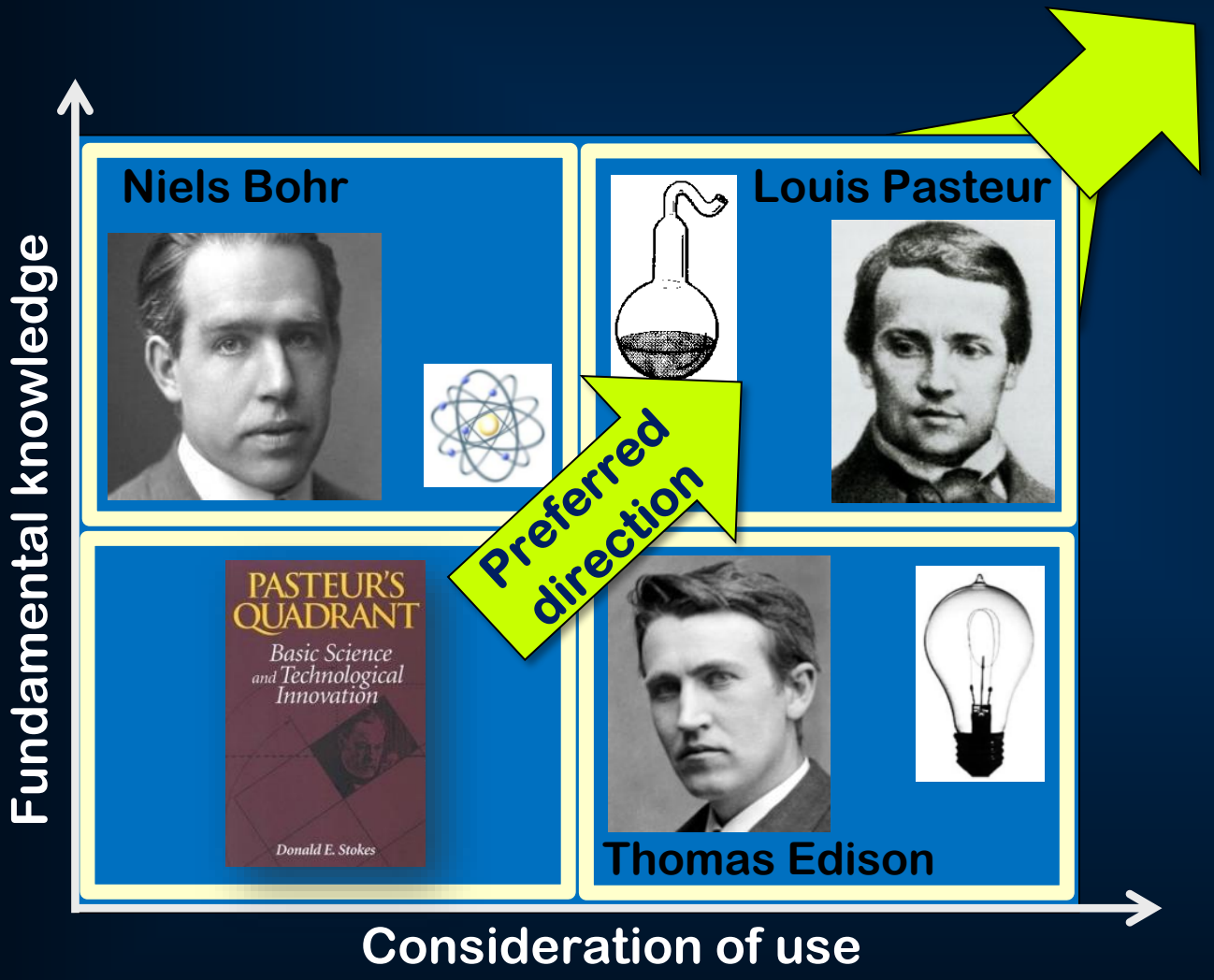
including those based on plasma acceleration

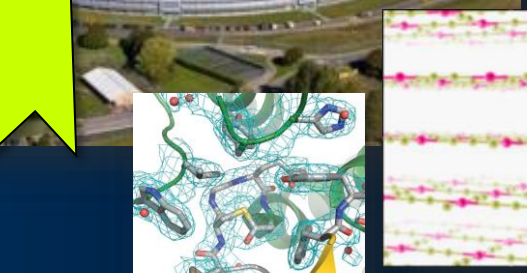
But first, let's define some metric which allow us to evaluate and compare the importance of different directions of research

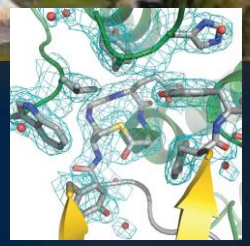
Why SR sources are so important?

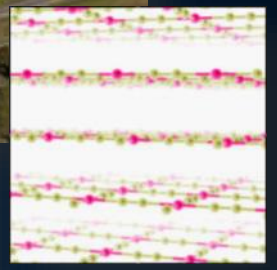


Why SR sources are so important?







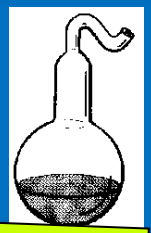


Fundamental knowledge

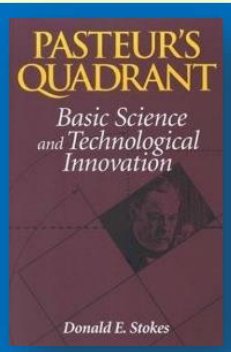
Consideration of use

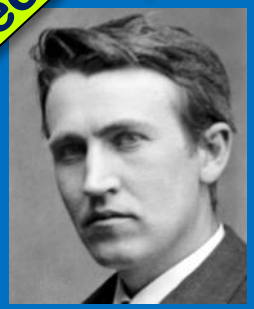
Niels Bohr

Louis Pasteur

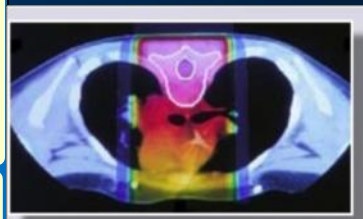


Preferred direction





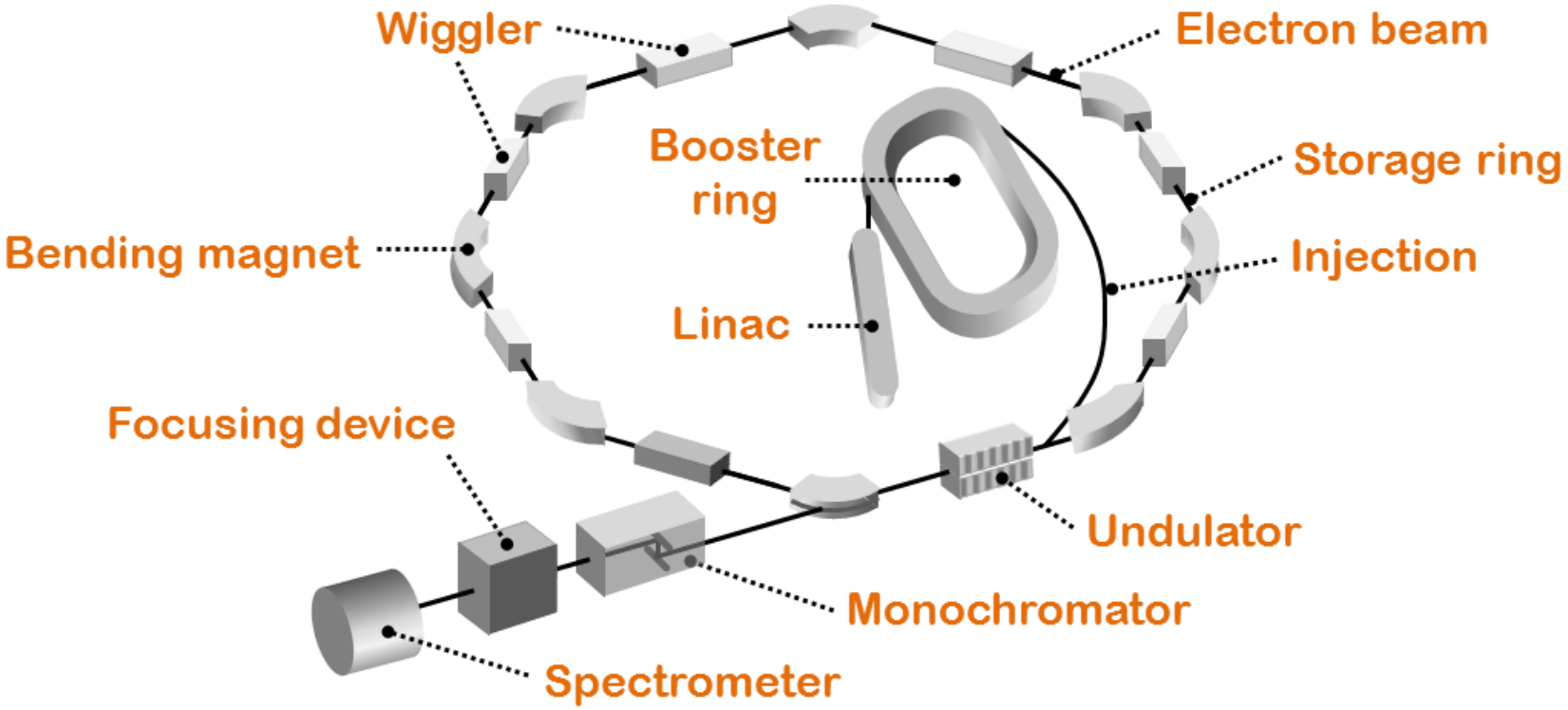
Thomas Edison



X-Rays

Protons/Ions

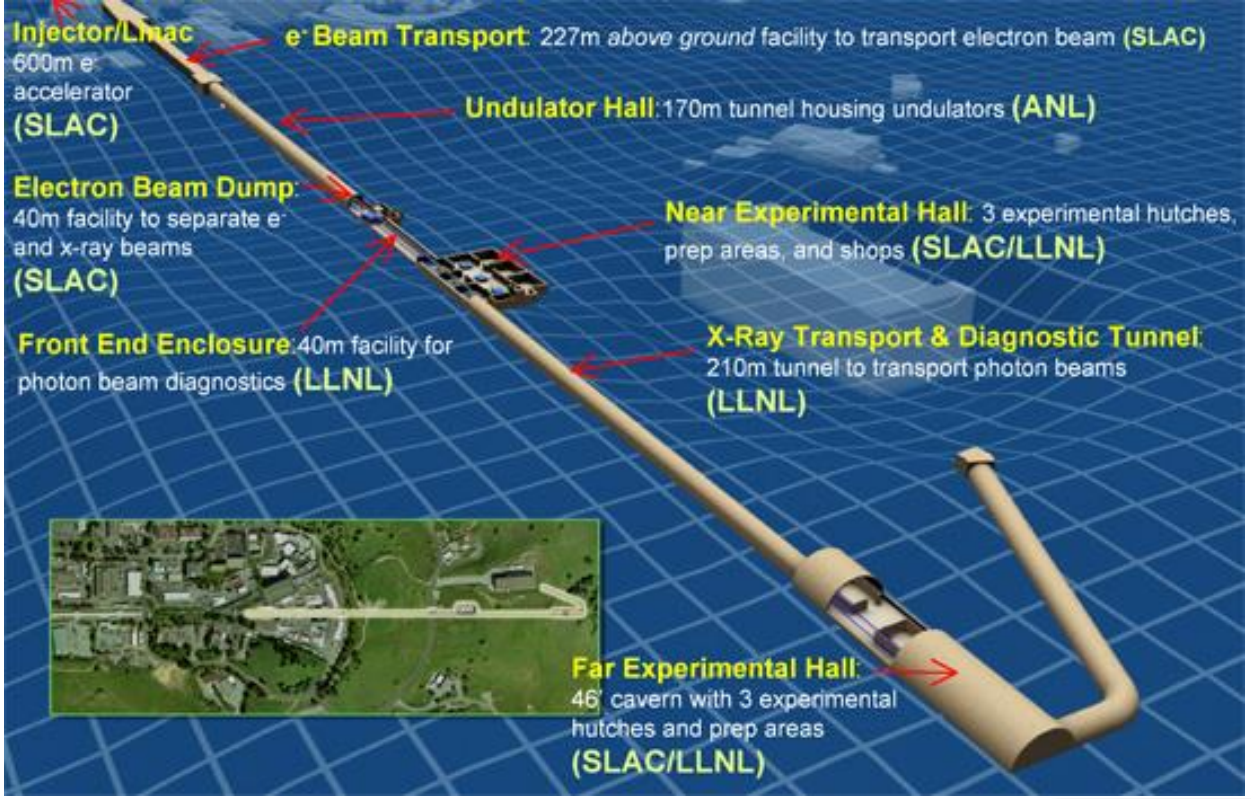
Synchrotron light source

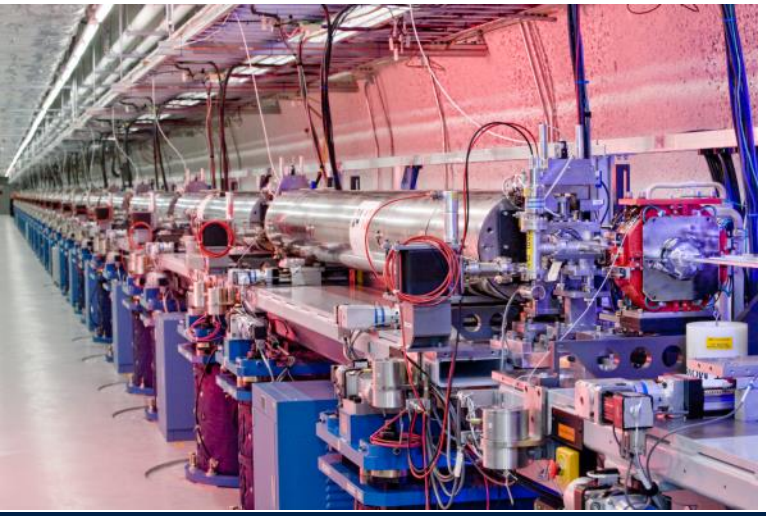


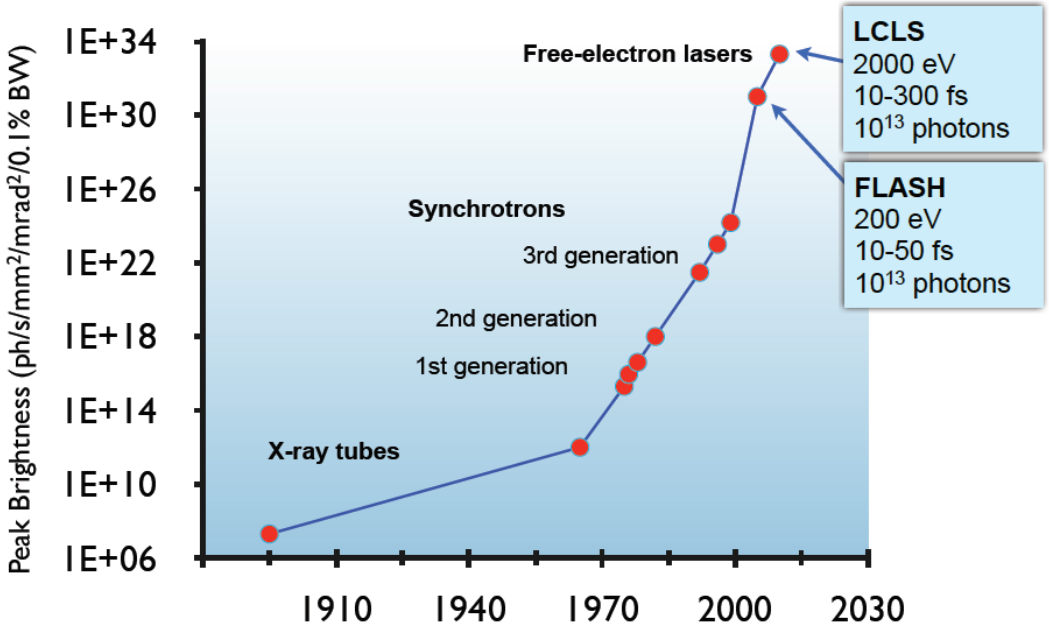
4th generation light source – example

X-ray FEL-

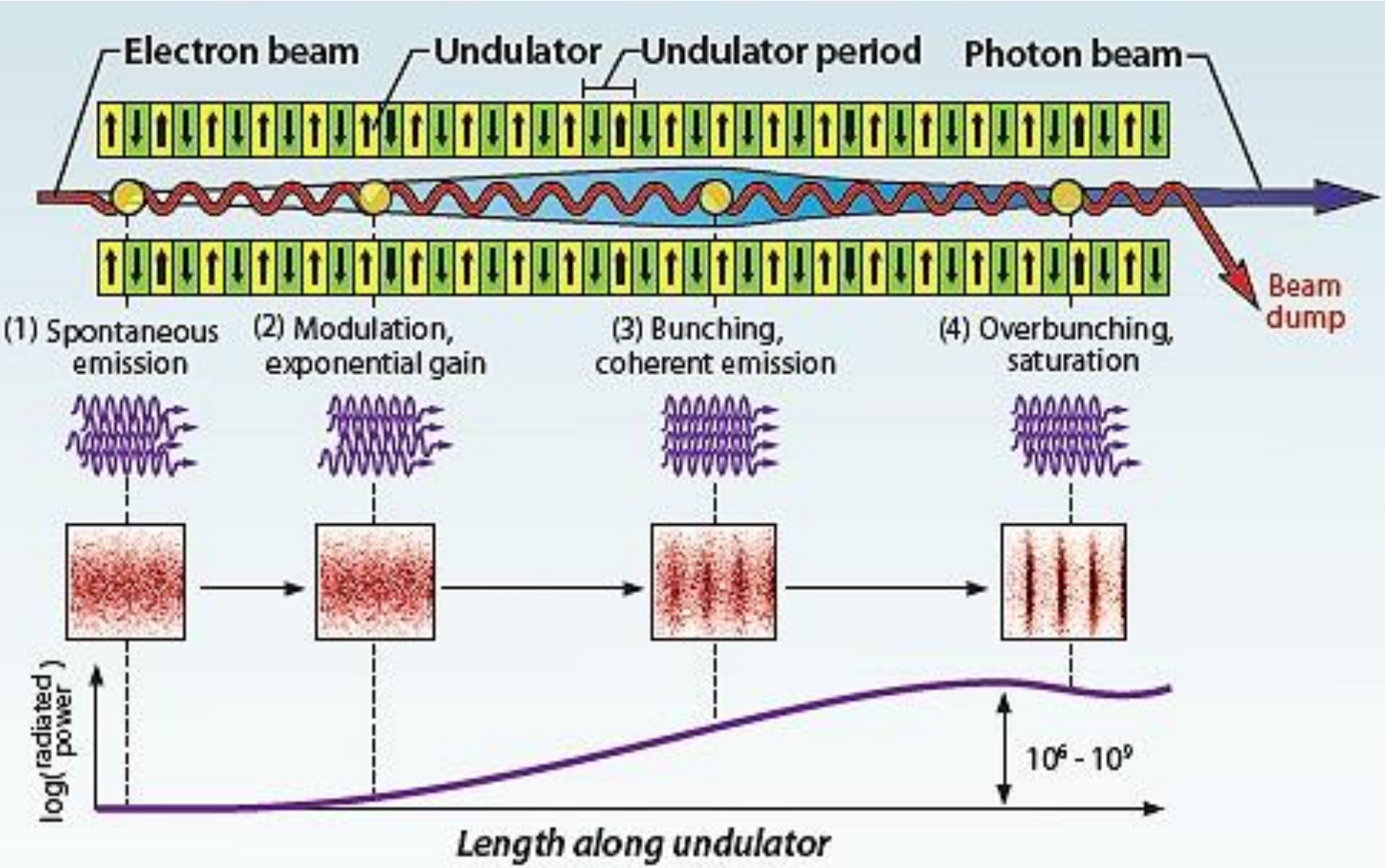
LCLS at SLAC



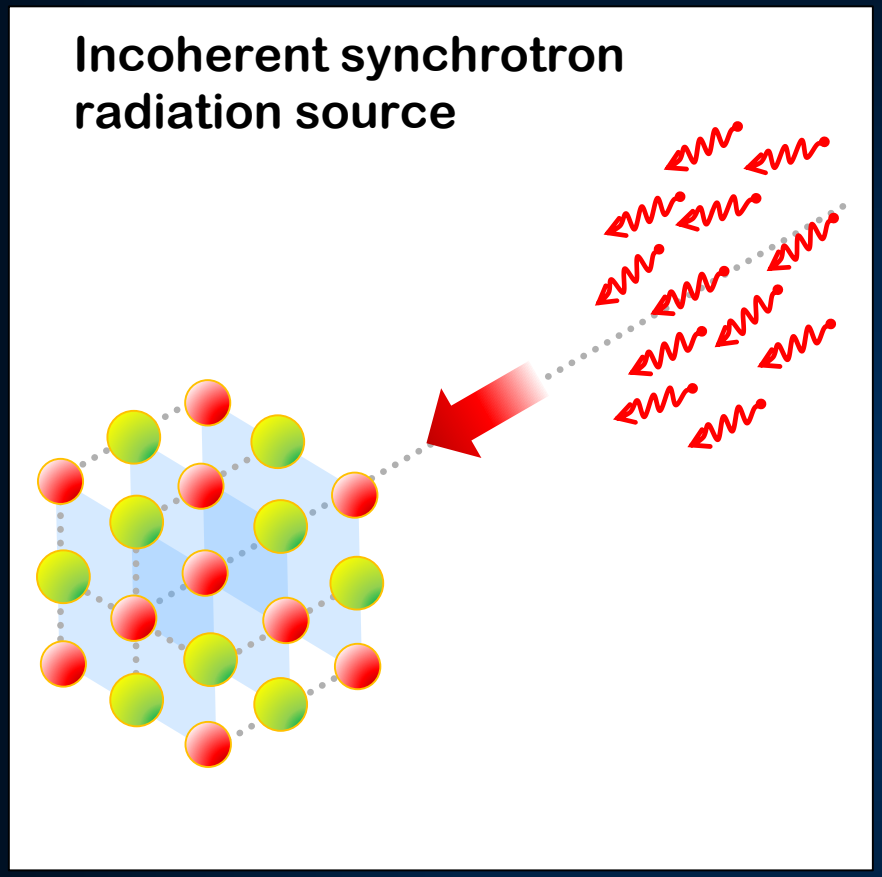


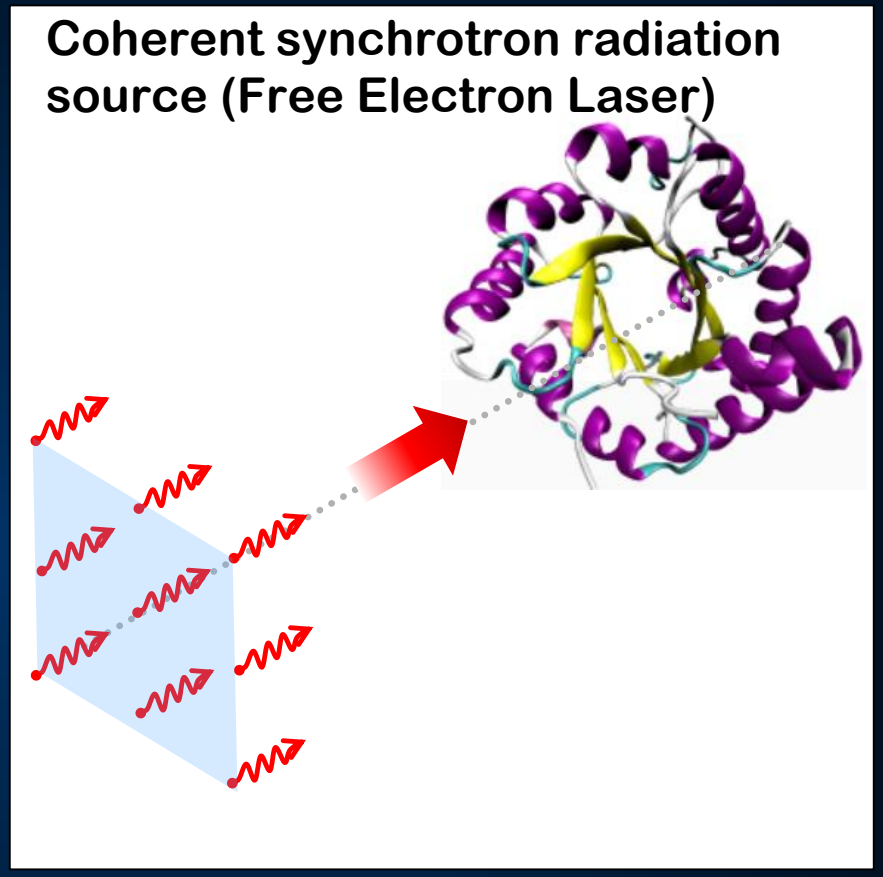


4th generation light source – Free Electron Laser Overview



Incoherent SR => coherent





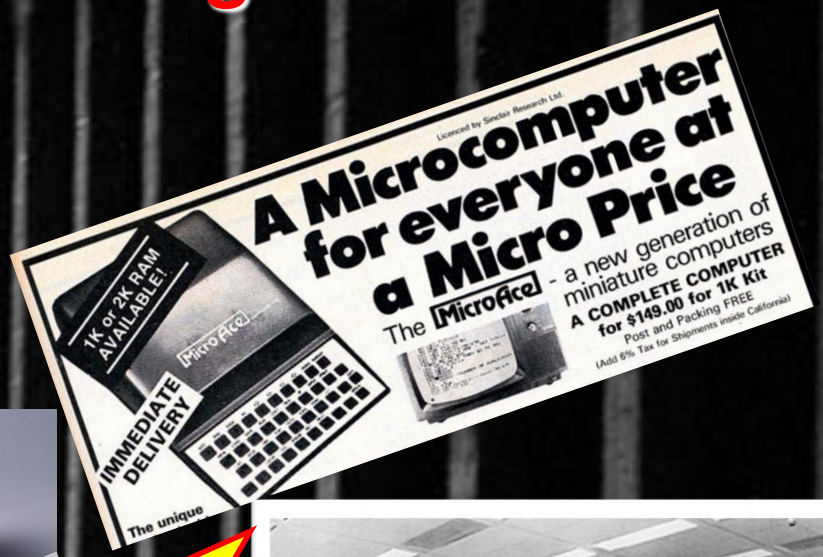
Era of studies of crystal structures by incoherent sources of X-rays

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

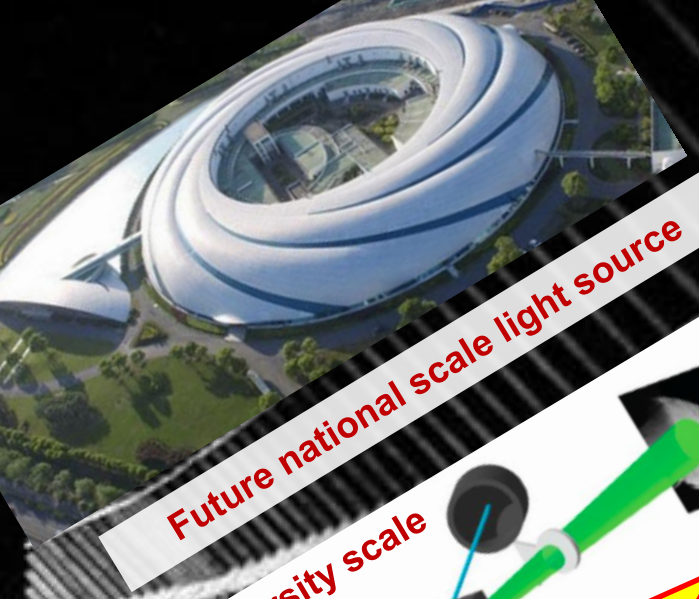
…and also this is an inventive principle “the other way around”

Evolution of computers and light sources

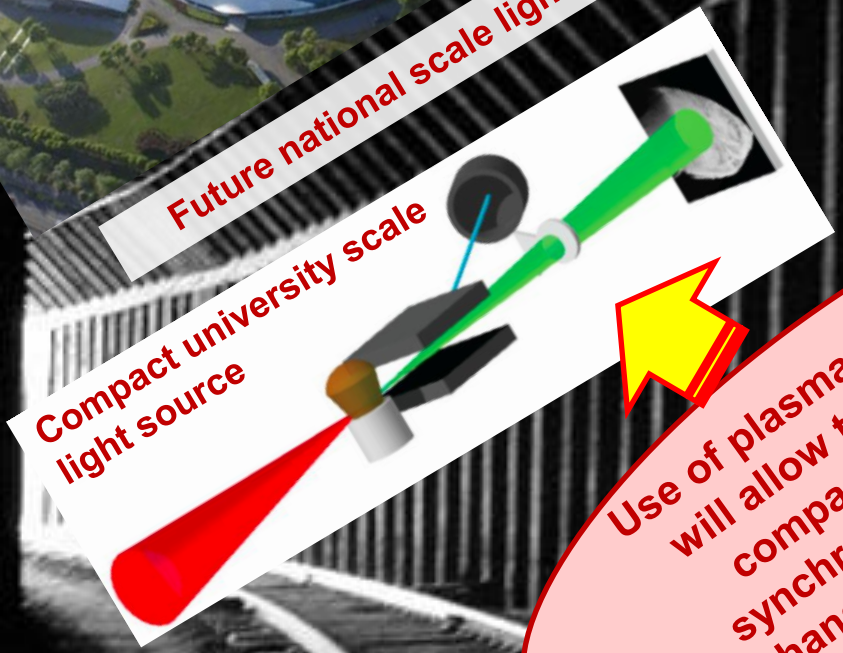
"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981



Evolution of computers and light sources



Future national scale light source



Compact university scale light source

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

Further evolution of light sources

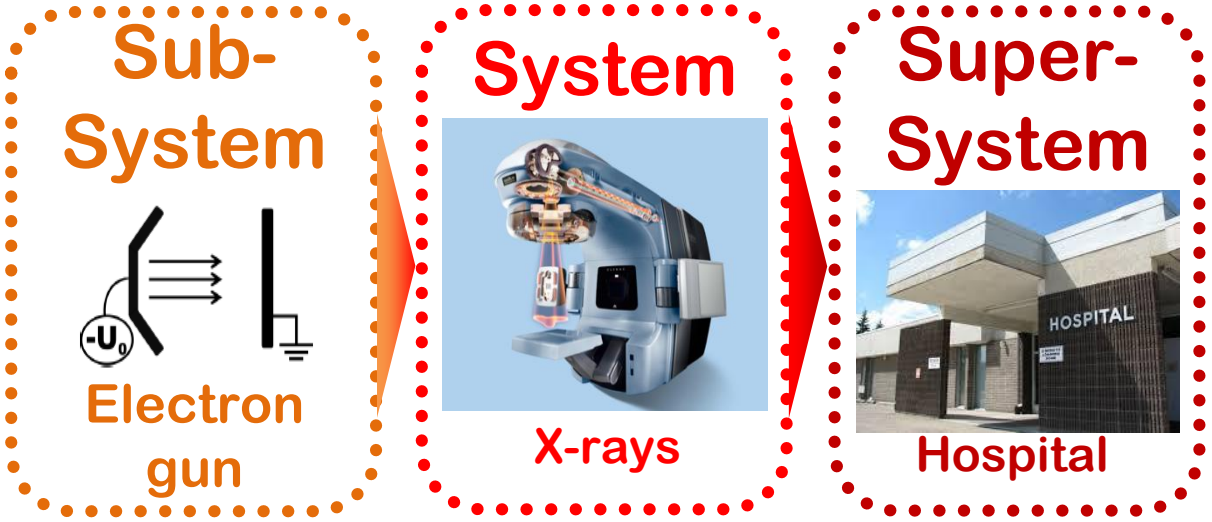
Let's assume that laser-plasma FEL is working

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

Let's apply the TRIZ general laws of evolution

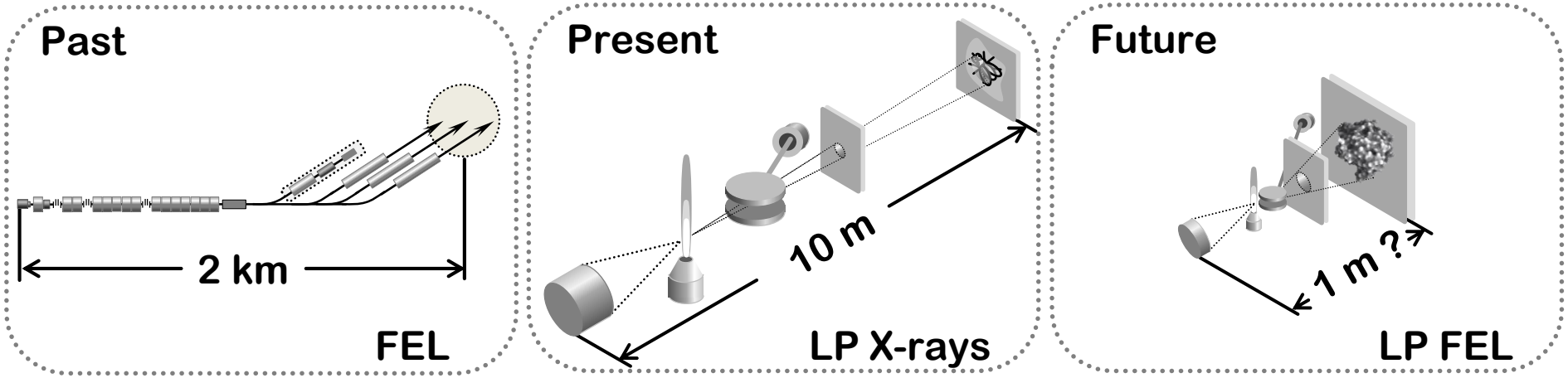
Transition to a super-system

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



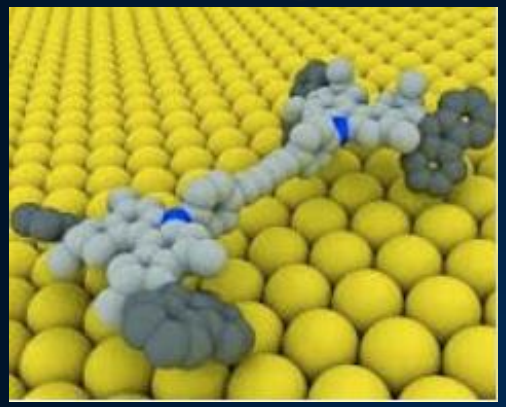
“a system exhausting possibilities of further significant improvement is included in a super-system as one of its parts”

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

TRIZ evolution laws allow to predict what parts of molecular machine would be invented next:

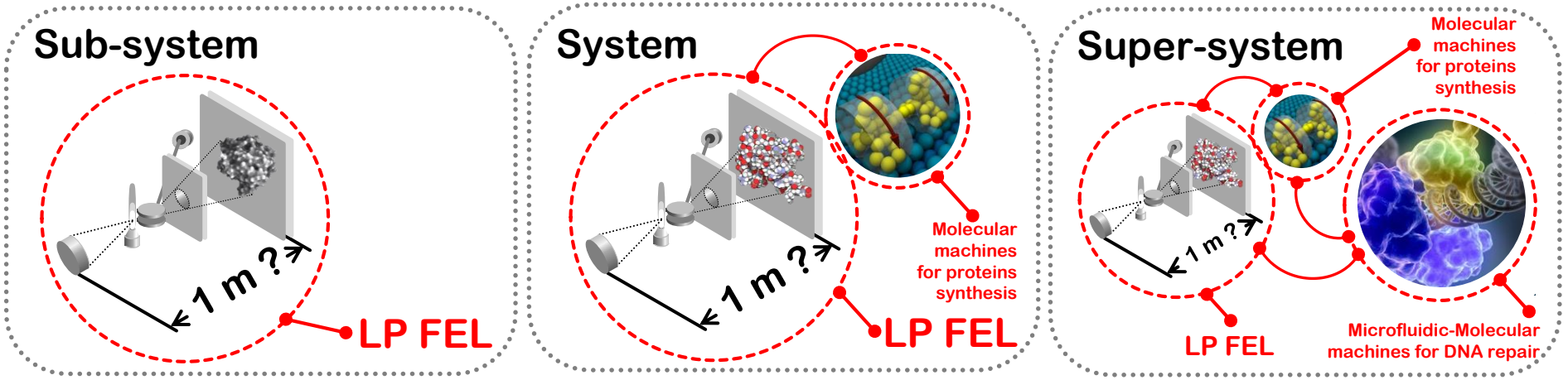
- Static Laws
  - The law of the completeness of the parts of the system
    - 4 parts: engine, transmission, working unit, control element
  - The law of energy conductivity of the system
    - every technical system is a transformer of energy and it should circulate freely and efficiently through its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

Most importantly –
these machines can become part of another super-system

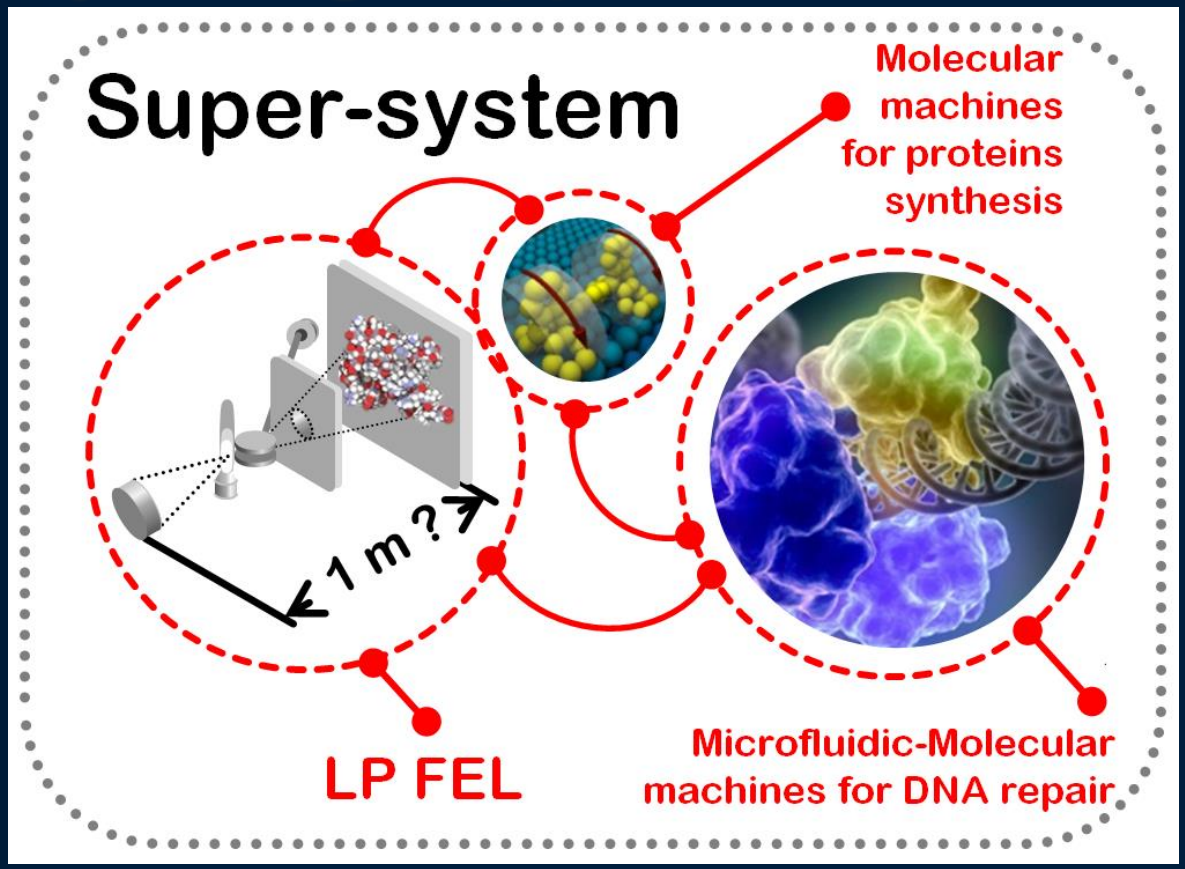
FEL and molecular machine becomes part of another system

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 this dream – with help of Breakthrough By Design approach – 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

“The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark”

Michelangelo

In combination with the art of estimations, TRIZ can be very useful for university education and research

As an inspiration, as a very efficient toolbox, as a way to connect different disciplines, as a new way to see the world – **Breakthrough By Design approach**

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  - **Continuing support of graduate educational program**
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  - https://www.unifyingphysics.com/
- **CERN for "eBook for all!" program that enabled conversion of the 1st edition of "Unifying Physics…" to Open Access**
- **And thanks to USPAS and Bill Barletta for opportunity to present this lecture**

Lecture materials

- **Slides and video will be available at**
  - https://www.unifyingphysics.com/

  - **See section Resources**
  - **You can also access the 1st edition of the book which is now Open Access**

Thank you for your attention!

And thanks to all colleagues for materials used in these slides