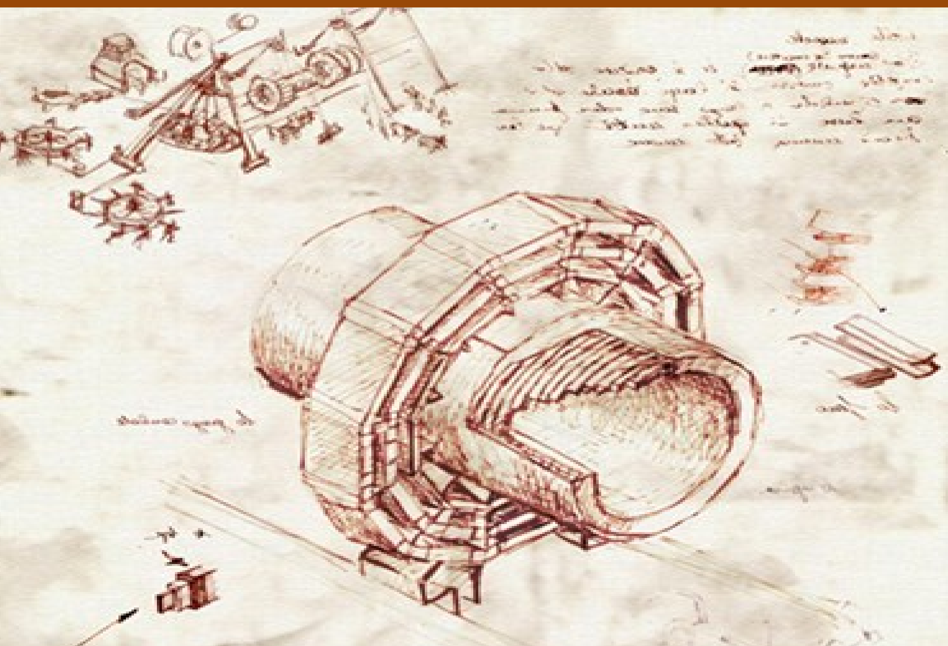
John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

University of Oxford

Views on collider (and other) concepts



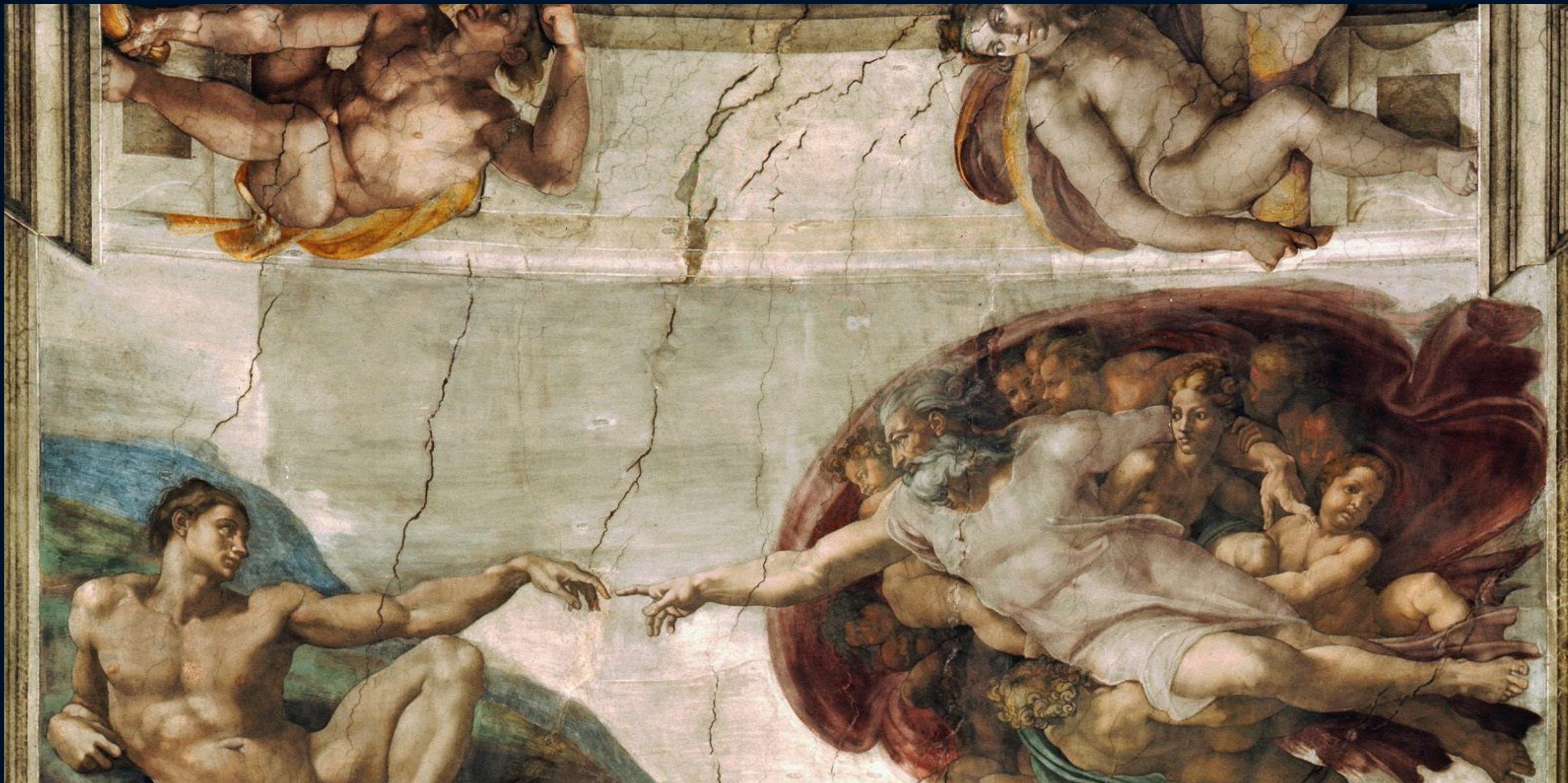
LHC sketches by Sergio Cittolin (CERN) – used with permission

Prof. Andrei A. Seryi

John Adams Institute

F3iA Workshop

December 2016



“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


FUTURE

We would like to predict how our field will look like in the second half of 21 century

For this we need to think out of the box, and…

…and we would like to:

Understand the general laws of evolution of science & technical systems

…and explore where other areas of science and technology are dreaming to be in the second half of 21 century

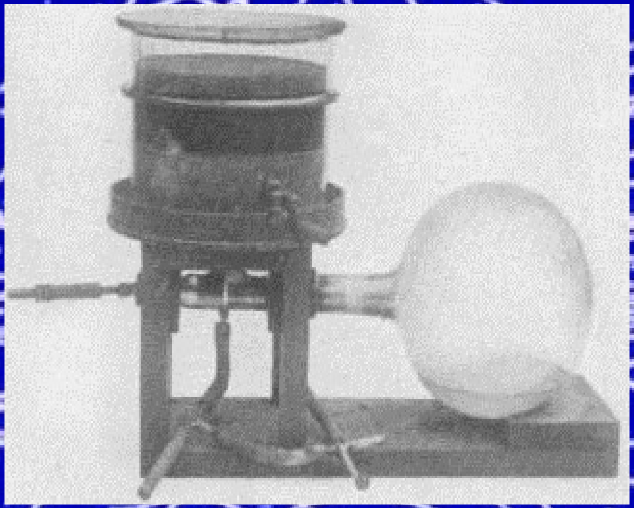
Let me start from a bit far from the main topic

- Half-a-century between similar inventions…
- Inventive principles in science…
- Evolution laws…

- Radars and CPA…
- Molecular machines…
- Fundamental physics prize…

- And then we come to colliders…

Cloud and bubble chambers

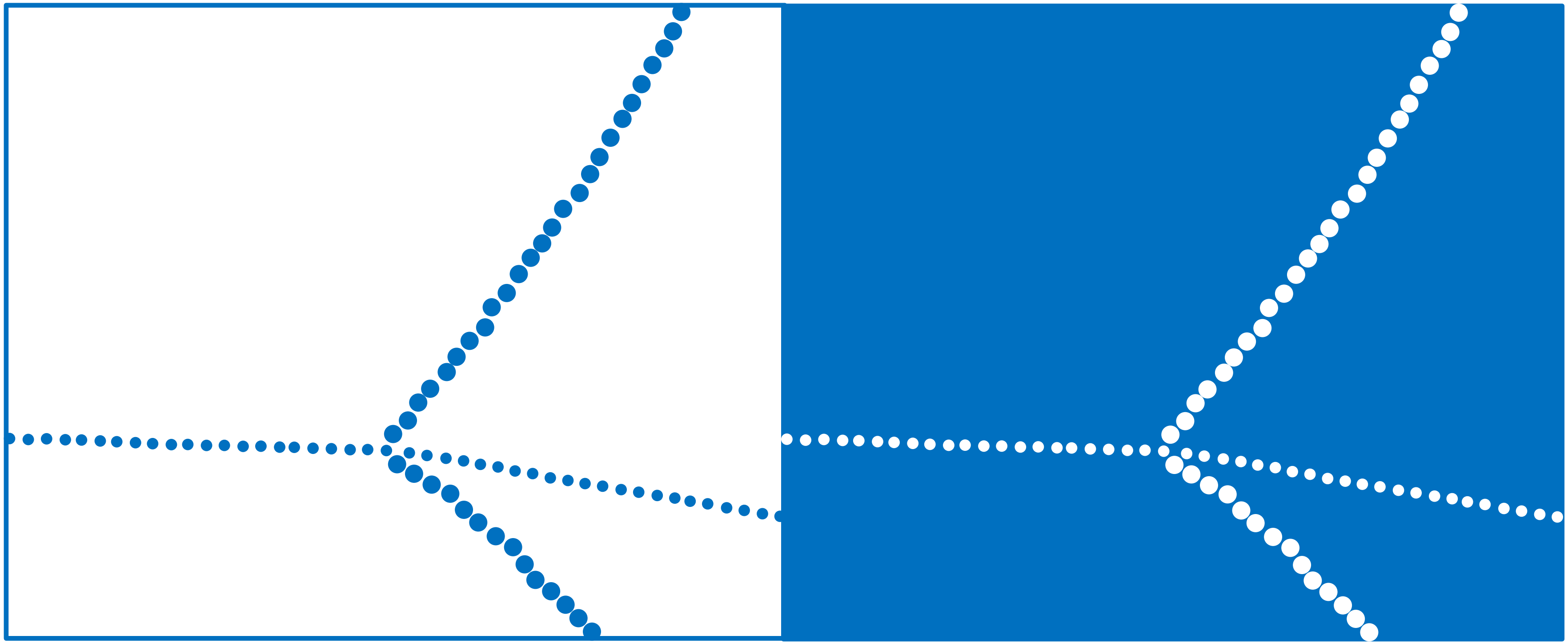


Wilson's Cloud chamber invented in 1911

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

On the photo Bubble chamber being installed near Fermilab

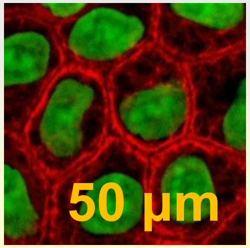
Cloud and bubble chambers



Wilson's Cloud chamber invented in 1911 **Glaser's Bubble chamber, invented in 1952**

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

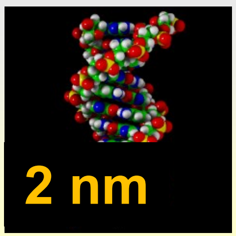
Chemistry Nobel 2014 & inventive principles?



Extra magnification?

CELLS
Twenty per mm

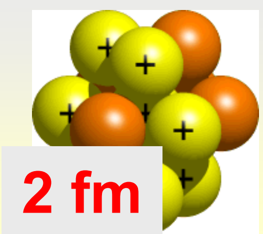
Microscope



x 25 thousand

DNA
Five hundred thousand per mm

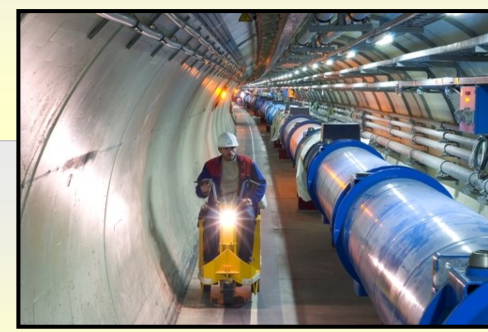
Electron microscope

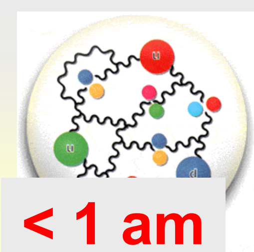


x 1 million

Nucleus
Five hundred billion per mm

Particle Accelerators



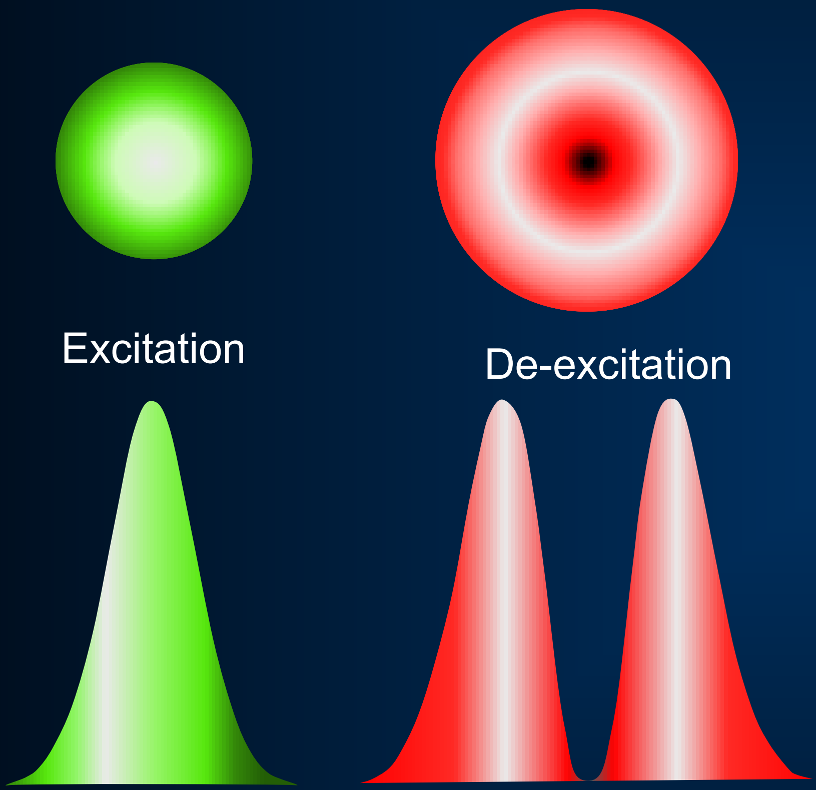


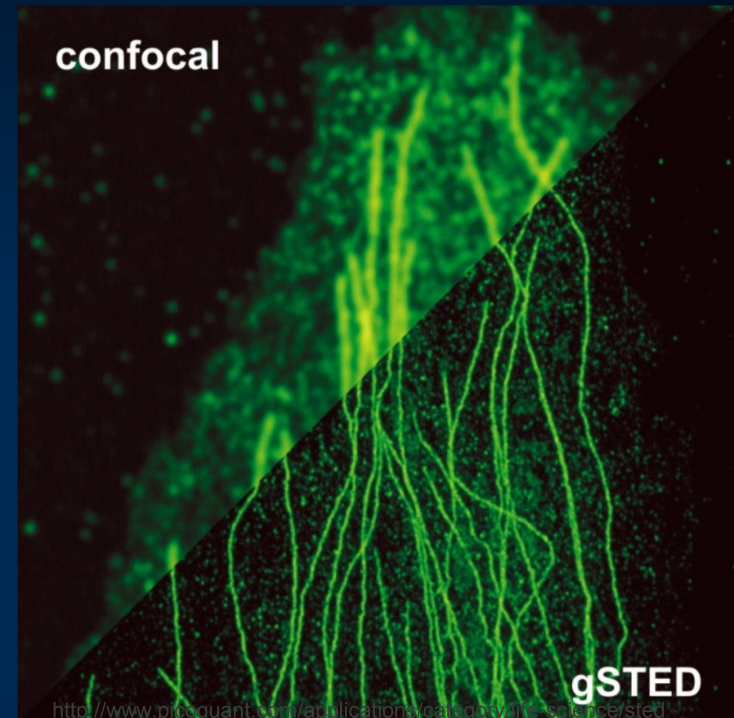
x 2 thousand

Quarks
More than one million billion per mm

Chemistry Nobel 2014 …

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell



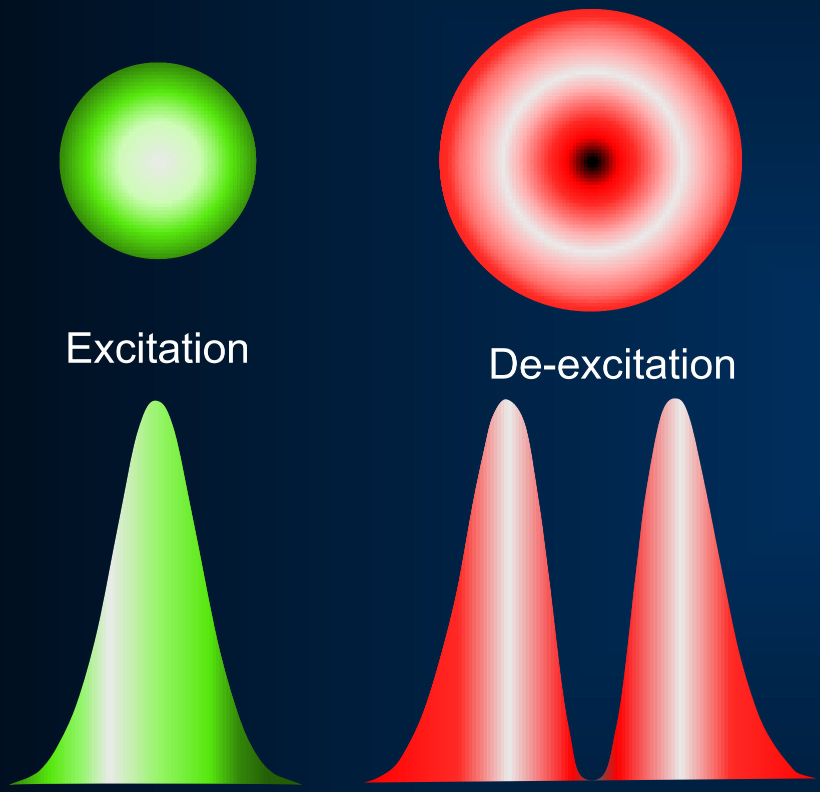


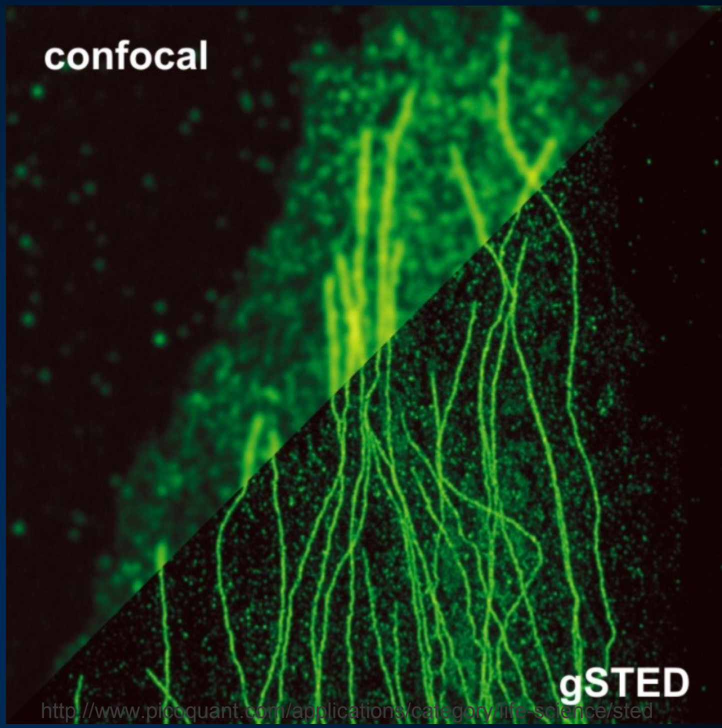
(gated) STED image of Tubulin vs standard confocal image

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

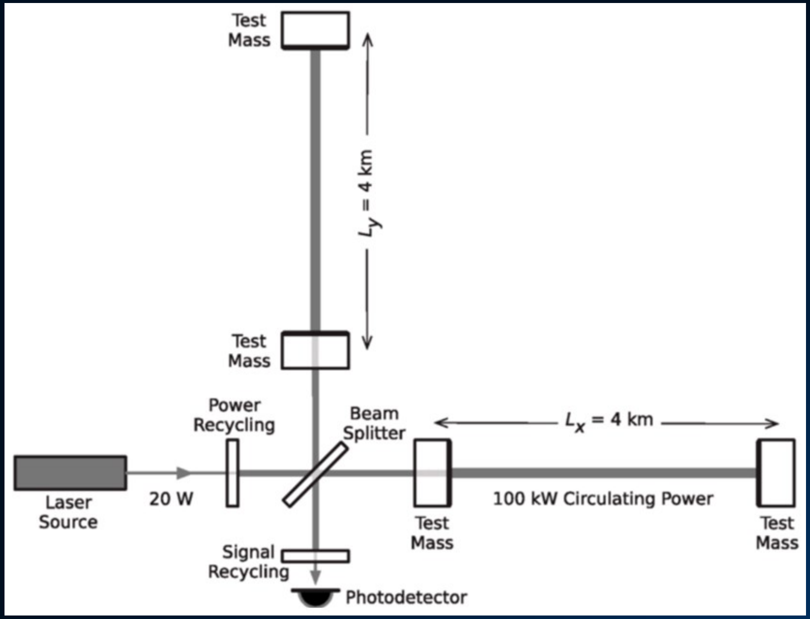
And this can be viewed as a combination of the inventive principles "system and anti-system" and "nested dolls"

Two scientific instruments

LIGO, Hanford

SLC, Stanford

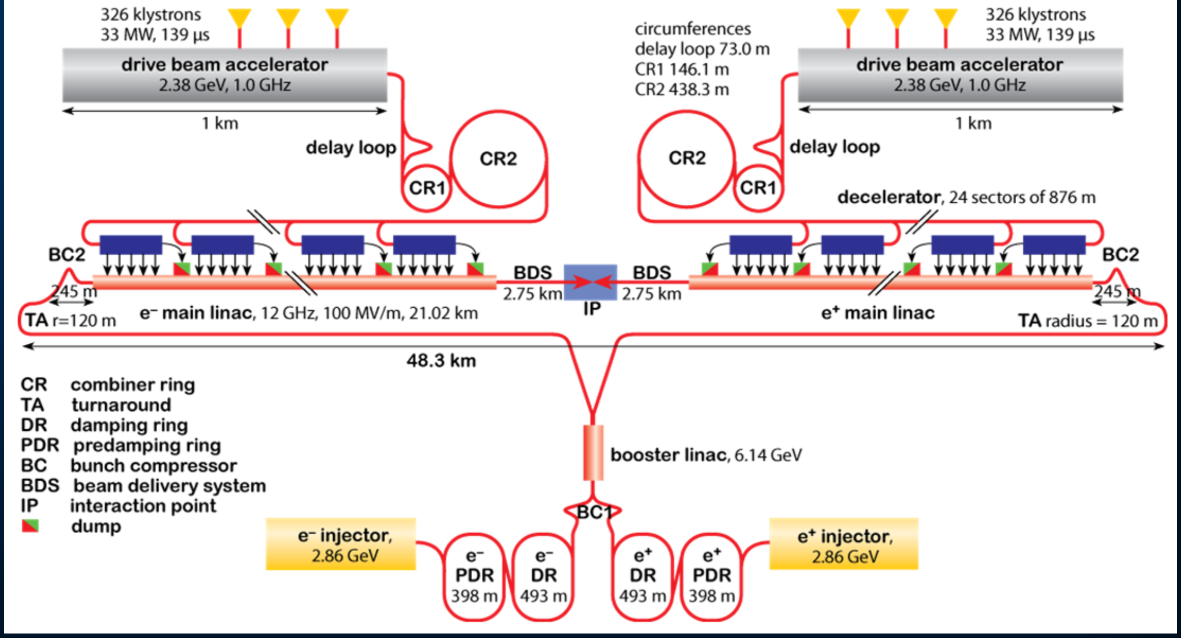
There is a lot in common



One of the common things of two instruments

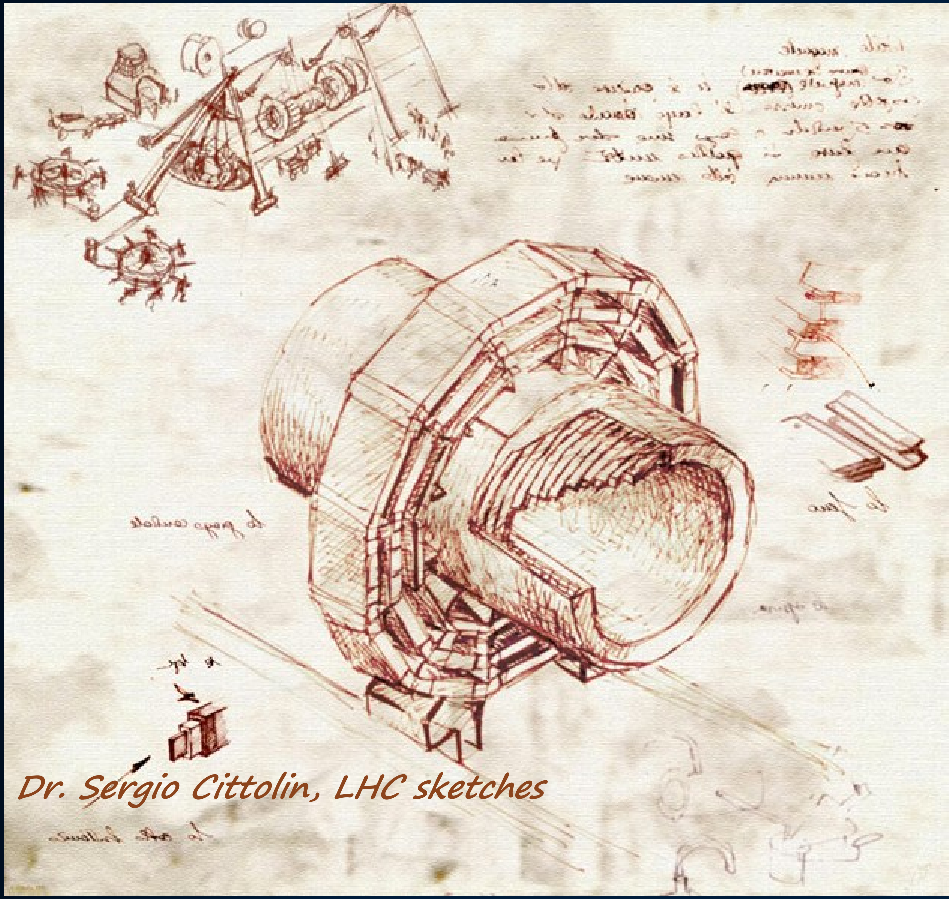
LIGO: keep two objects placed 4km apart stable* to about 1e-9 nm

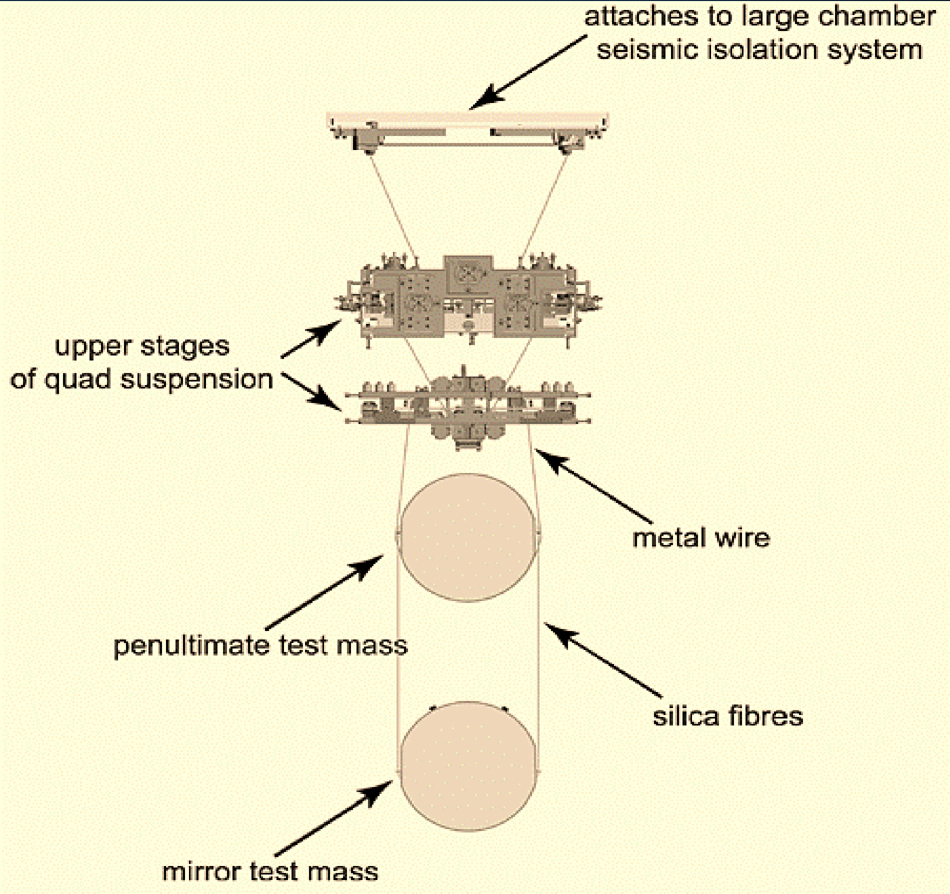
CLIC – Compact Linear Collider: keep 100,000 objects distributed over 50km stable* to about 10 nm



*) approximately, and in certain frequency range

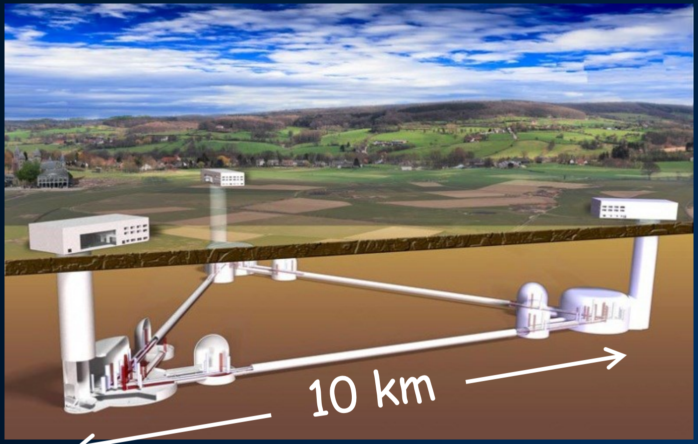
Particle or gravitational waves detectors are arranged just as nested dolls…



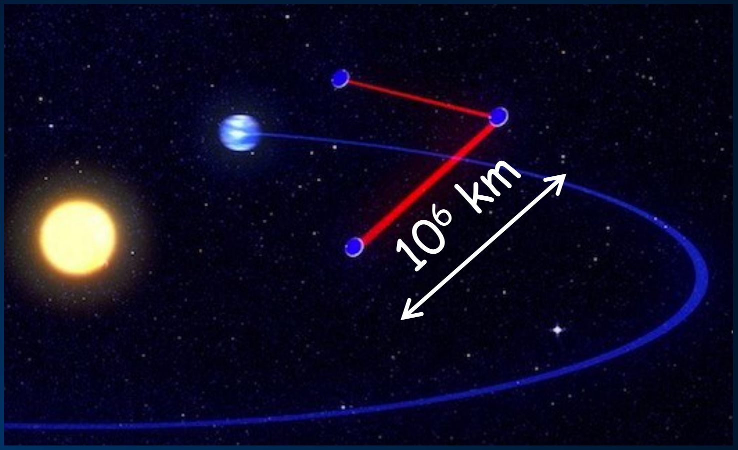


This is another common thing

Next generation of gravitational wave detectors



Einstein telescope



eLISA

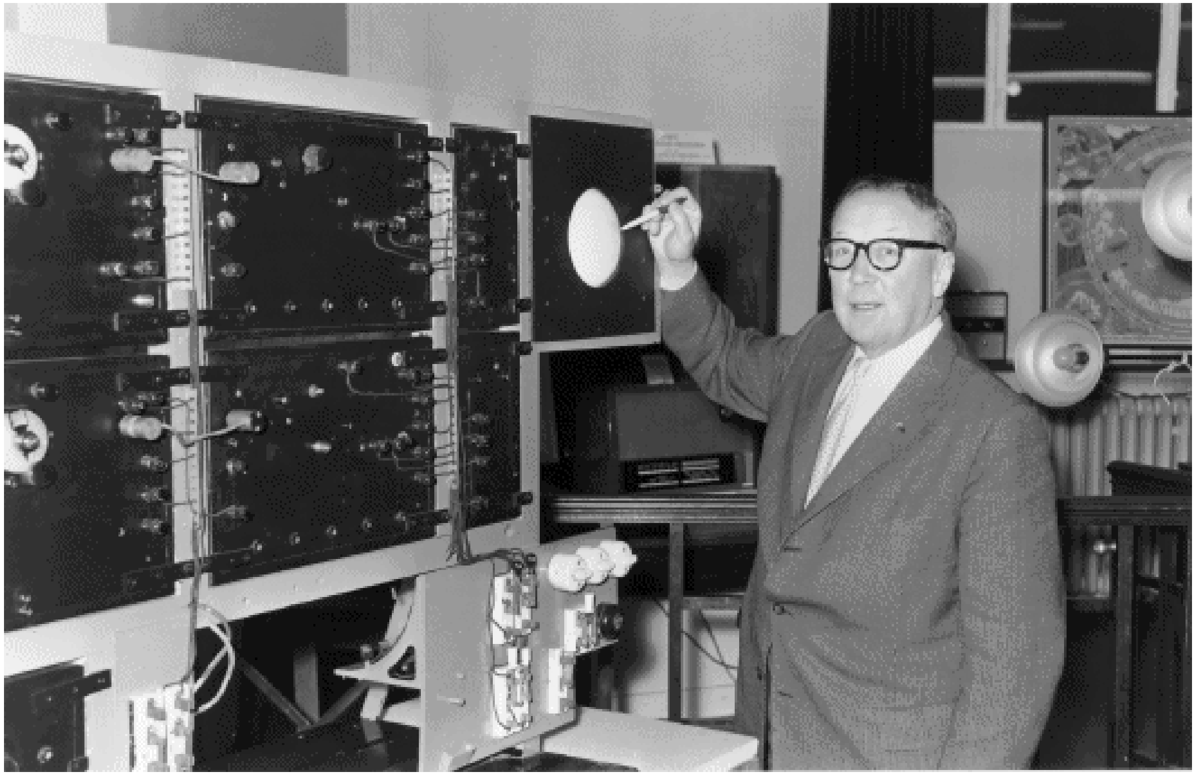
Increasing size three times is demonstration of “naturalness” in science-societal way

Looking at space is natural (but for accelerators much more difficult – I would not consider it for 21 Century)

Development of Radar

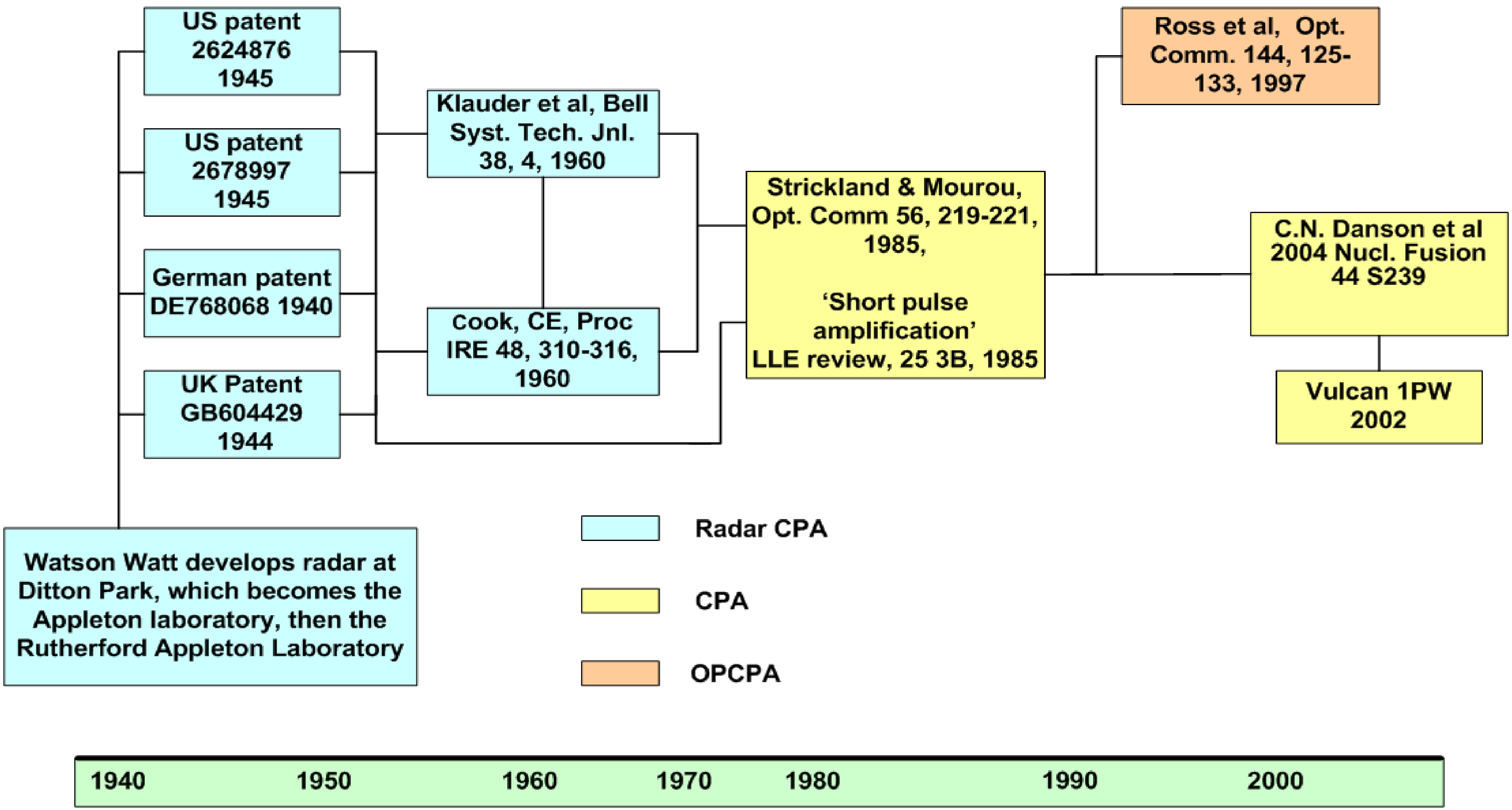
Sir Robert Watson-Watt with the original British Radar Apparatus made at Ditton Park in 1935 this became the Appleton Laboratory Merged with the Rutherford Laboratory to become Rutherford Appleton Laboratory.

This apparatus is now in the London Science Museum.



Slide from Bob Bingham, CLF, STFC

Radar and Laser Amplification

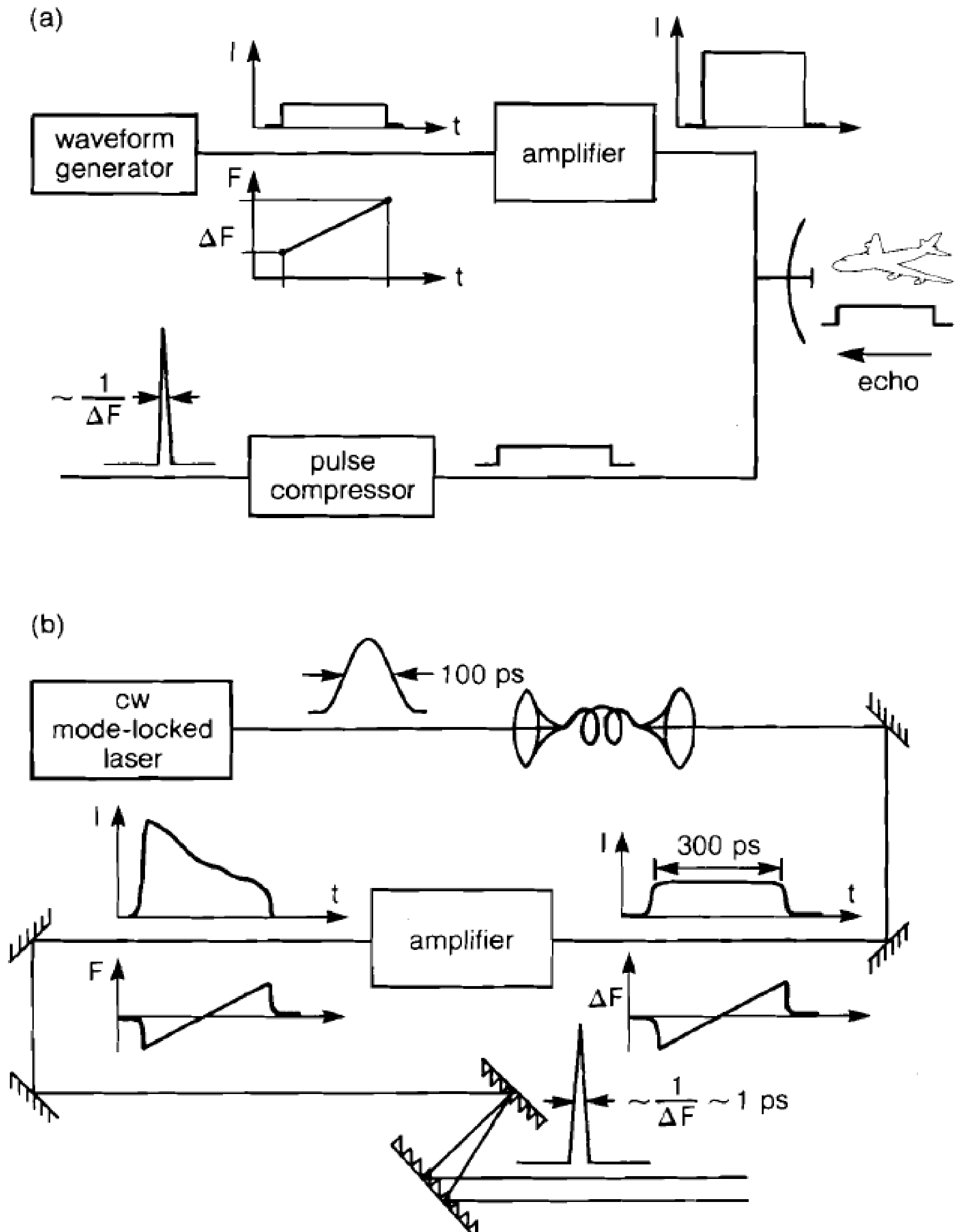


Slide from Bob Bingham, CLF, STFC

Chirped pulse amplification from Radar to Lasers (CPA)

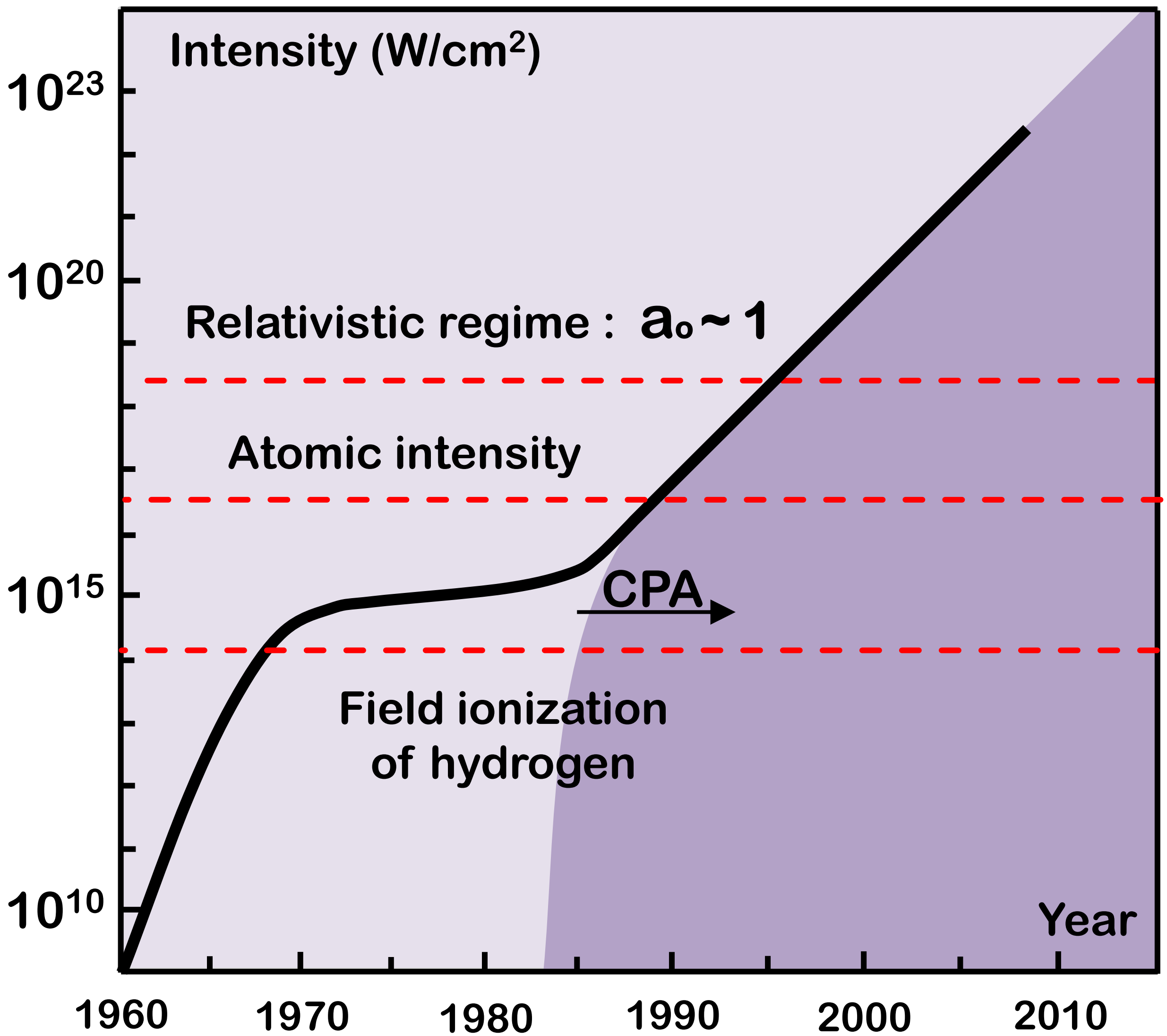
Diagrams taken from early LLE review On the comparison between RADAR chirped pulse amplification from the 1940 onwards upper diagram and laser chirped pulse amplification bottom diagram carried out at the LLE Rochester.

LLE Review 25 3B 1985.



Slide from Bob Bingham, CLF, STFC

CPA invention: exponential growth of laser power



Progress in peak intensity since laser invention in 1960

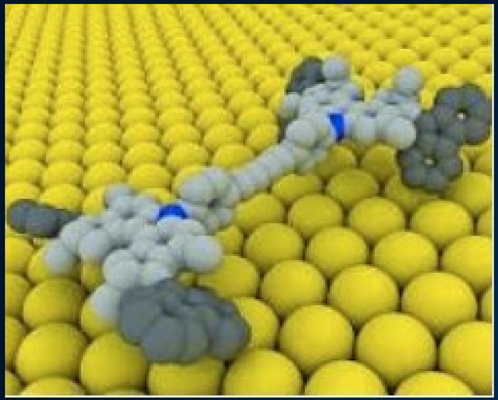
Radar and CPA

Evolution from radar to chirped pulse amplification in lasers demonstrate one of general trends in science and technology:

From mechanical oscillations to EM, and within EM from microwave to optical frequencies

Let's note this trend as we will discuss evolution of accelerator designs in the next slides (or during the entire workshop)

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

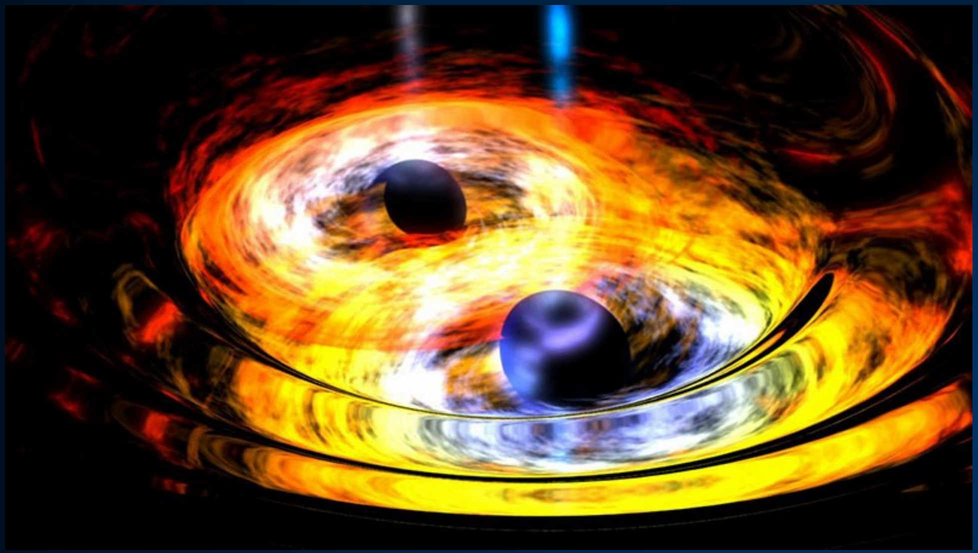
that were developed in 20^{th} century

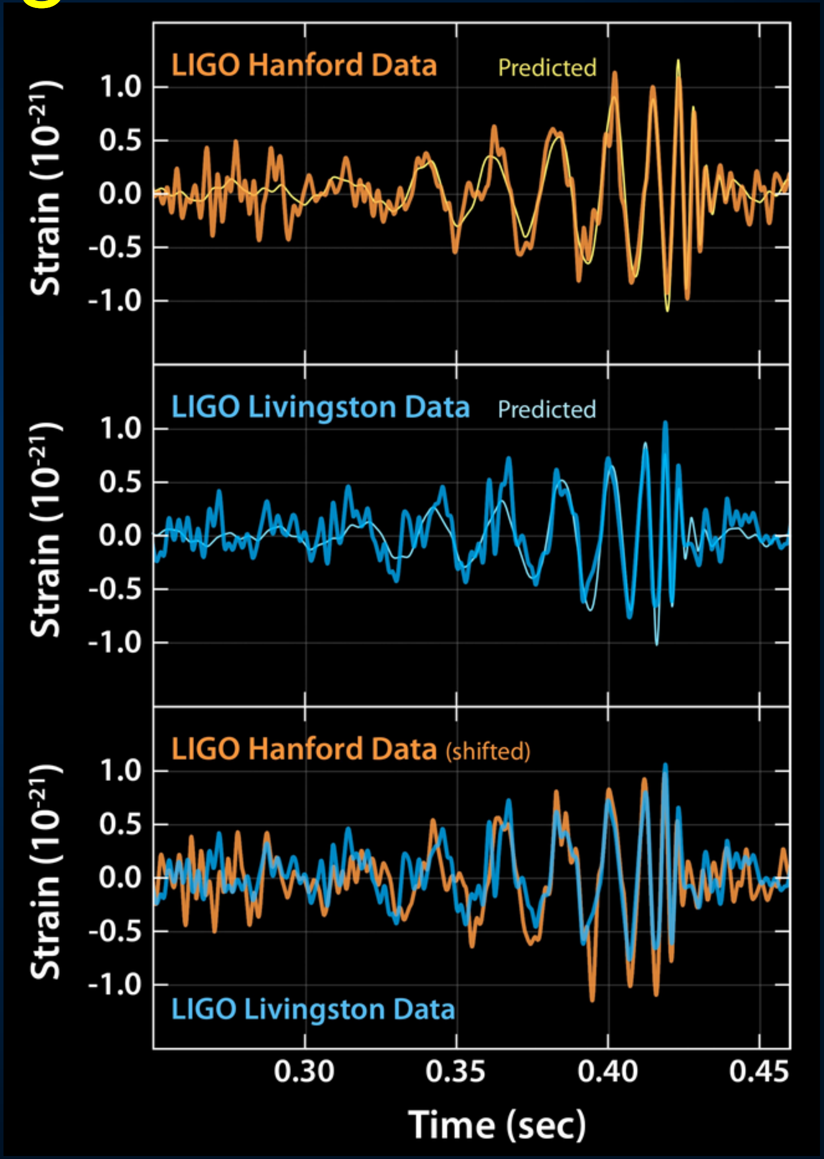
- Static Laws
  - The law of the completeness of the parts of the system
    - 4 parts: engine, transmission, working unit, control element
  - The law of energy conductivity of the system
    - every technical system is a transformer of energy and it should circulate freely and efficiently through its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

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

(For accelerators, we can at least assume that our devices (e.g. targets) can be assembled atom by atom)

2016 Special Breakthrough Prize in Fundamental Physics – gravitational waves





And now let's recall the breakthrough challenge, established by the same people who established the prize

Image: Caltech/MIT/LIGO Lab

Breakthrough challenge 3 - Starshot

Nano-space-ship with light-sail (2g total mass) propelled by laser to 20% of speed of light, to reach Alfa Centauri within a generation (and to take photos and send them back)

Enormous number of challenges!
Multi-year R&D is funded (M100$)

Board of
Breakthrough Starshot:

Stephen Hawking
Yuri Milner
Mark Zuckerberg

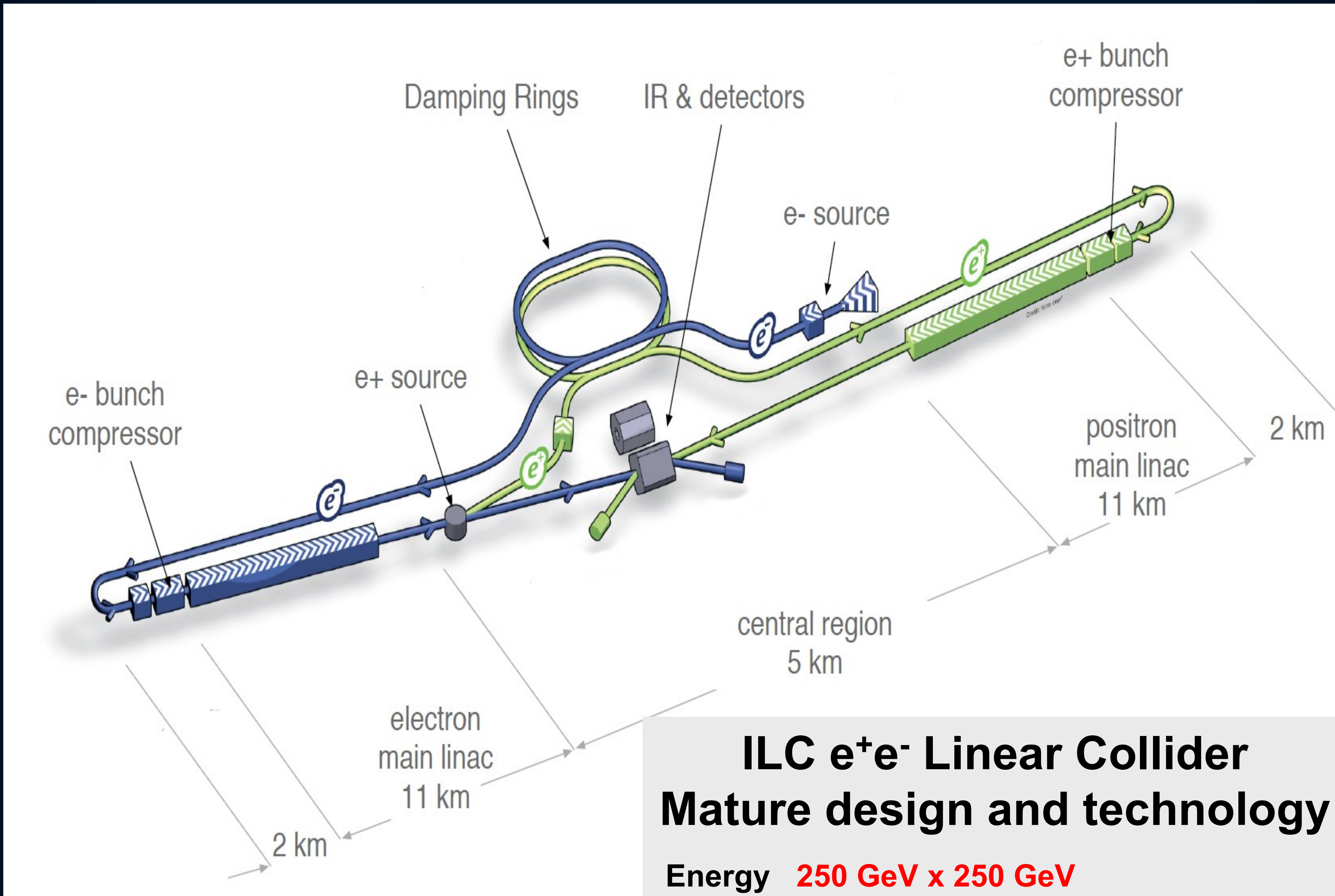
(For accelerators, we should note where, in particular, this R&D will push lasers, in terms of their power, controllability, stability)

https://breakthroughinitiatives.org/Challenges/3

Road to a collider

We of course do not know what is between our present location and the desired goal, what else we will find on the way and where exactly we will end up…

International Linear Collider ILC



ILC e^+e^- Linear Collider
Mature design and technology

Energy **250 GeV x 250 GeV**

ILC - considered by Japan

The final decision will be made by the Government of Japan in the coming years

Some (possibly wrong 😉) ideas we thought about on the way

Re-optimize ILC parameters in such a way, that the beam will have, after IP, large disruption, but much lower dE/E

Then, such beam can be collected after IP and decelerated – energy recovery

Estimations [1] shown that 92% of beam can be decelerated down to 10 GeV

[1] Future prospects of accelerator science for particle physics, A. Seryi, 2010, NIM A 623 (2010)

Deceleration can be done in separate SC RF structures in dual-aperture criomodules **(like LHC dual aperture magnets)**

Interestingly, this idea lead to something quite different =>

Compact SCRF X-ray and THz light source

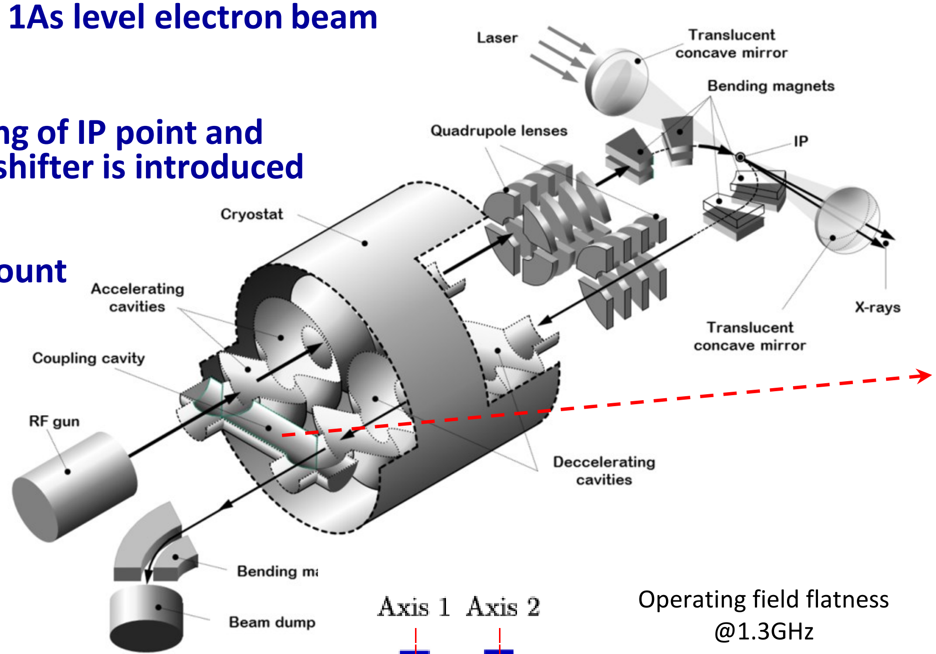
Asymmetric Energy Recovery Linac

Advantages:

a) capability to drive 1As level electron beam average current

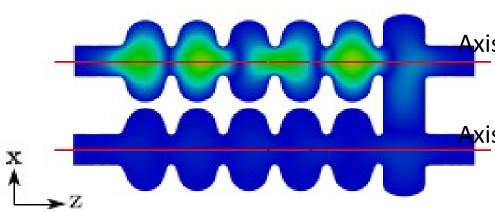
b) independent tuning of IP point and accelerator if phase shifter is introduced in the coupling cell

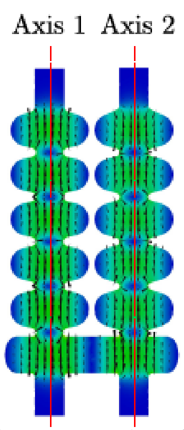
c) field tuning to account for beam change at interaction point



Al prototype for low-level RF measurements

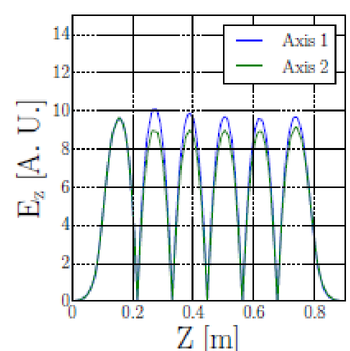
Electric field contour plot of dipole partial eigenmode at 1.73GHz





Electric field contour plot of operating eigenmode at 1.3GHz

Operating field flatness @1.3GHz



Some other (certainly wrong😉) ideas we thought about on the way

Accelerate e+- and p in ILC together. Use many dual sailboat chicanes to control relative timing. Then use p-beam to boost E of e+ and e-

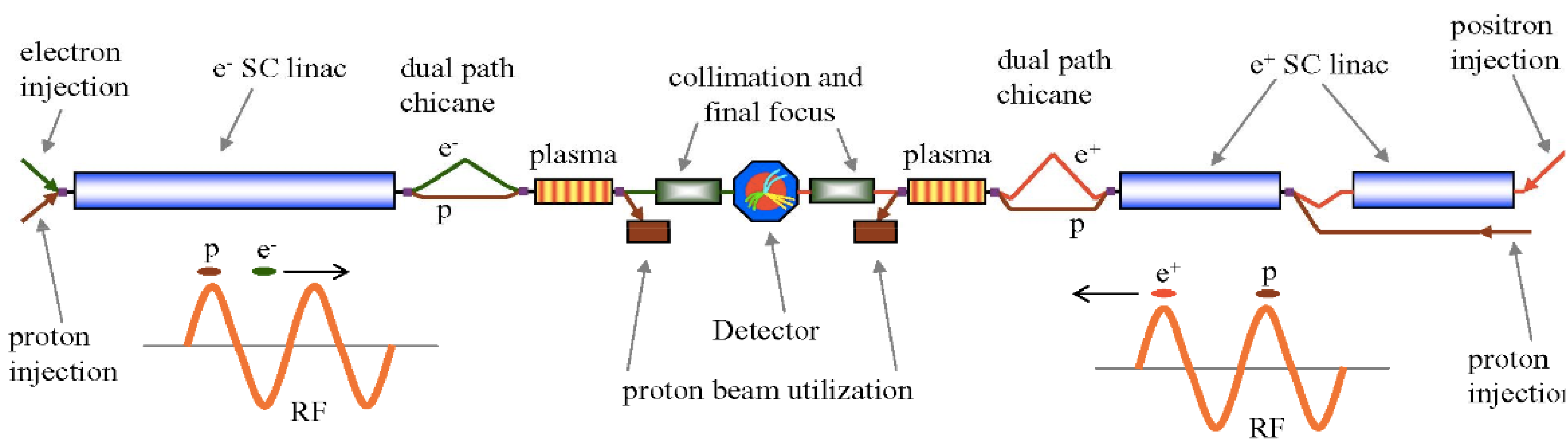
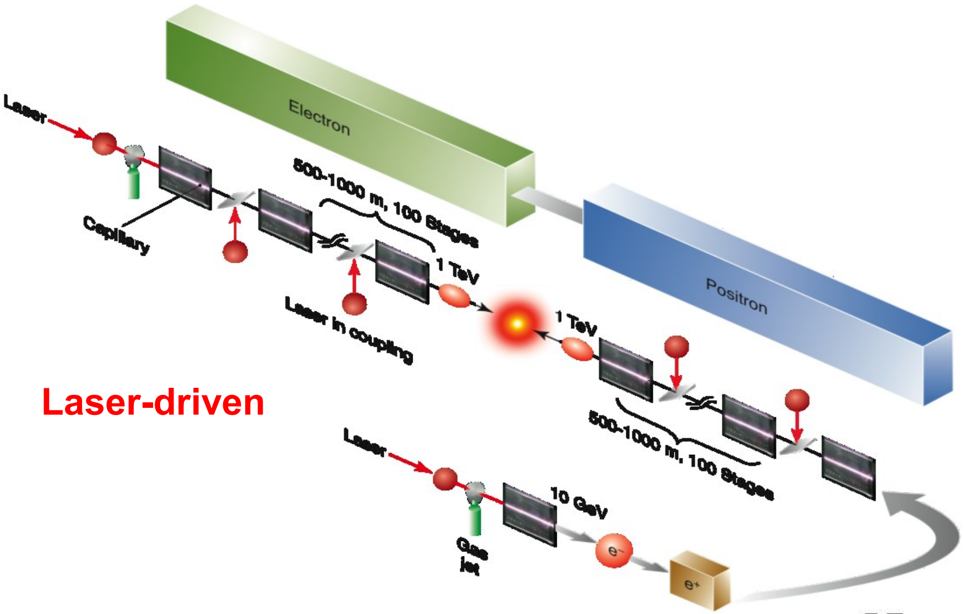


Figure 1: Concept for a multi-TeV upgrade of the International Linear Collider based on proton-driven plasma acceleration. The phase slippage controlling chicanes within the linacs are not shown. Not to scale.

Multi-TeV Upgrade Concept for International Linear Collider Based on Proton Driven Plasma Acceleration, A. Seryi, ILC-NOTE-2010-052.

sed colliders



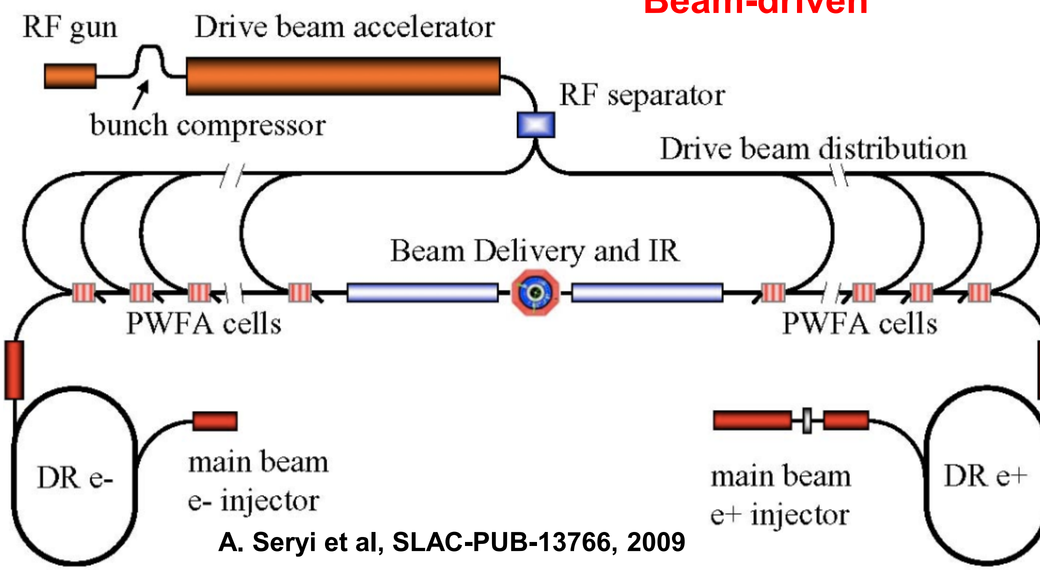
Laser-driven

E. Esarey et al, Rev. Mod. Phys. (2009)

One of the main difficulties of both of these concepts:

Combination of traditional technology with new

Beam-driven



A. Seryi et al, SLAC-PUB-13766, 2009

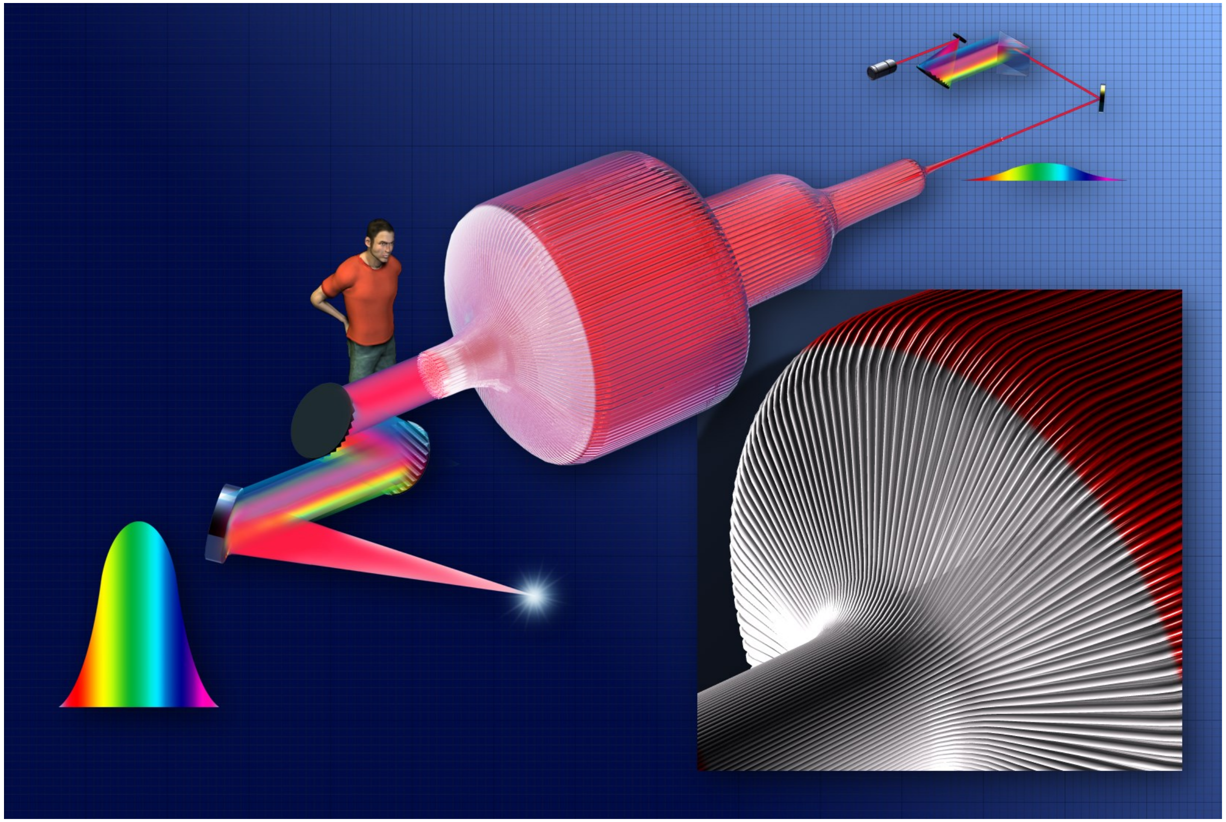
The approaches should be modified – only new technology should be used

A bit more about lasers…

- Commercial fiber lasers reach 100 kW in CW
- Wall plug efficiency > 40%
- Photo below is from IPG Photonics

Laser combination

Research on combining many fibre lasers (short pulses!) together for high rep rate, high energy laser systems.

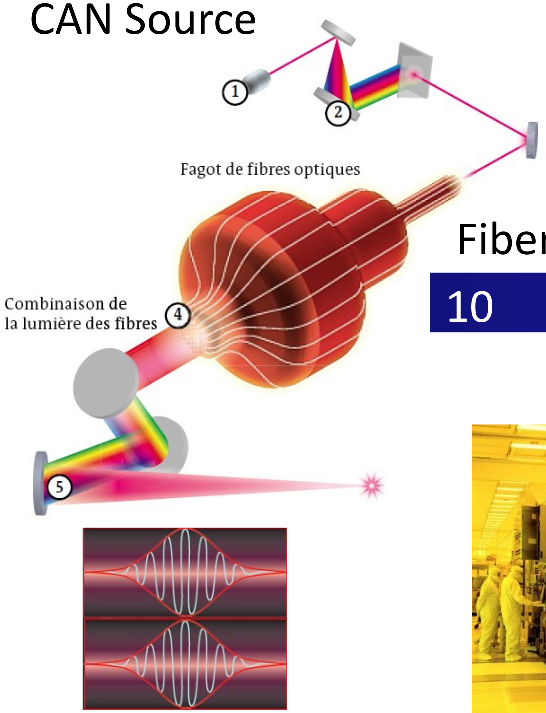


Phase control and combine 100s – 1000s fibres

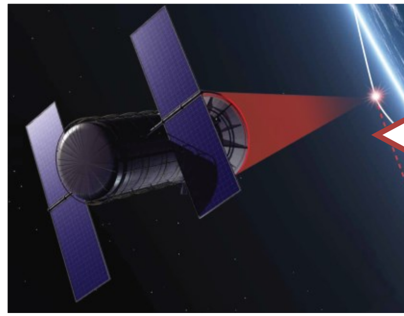
"The future is fibre accelerators", Gerard Mourou, Bill Brocklesby,Toshiki Tajima & Jens Limpert, Nature Photonics 7, 258–261 (2013)

CAN laser potential Applications

CAN Source



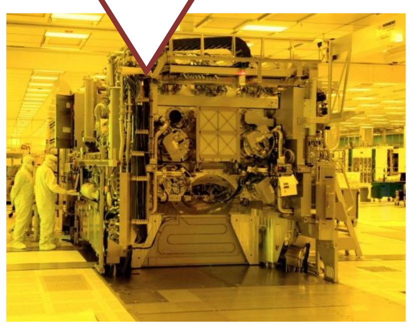
Orbital debris removal



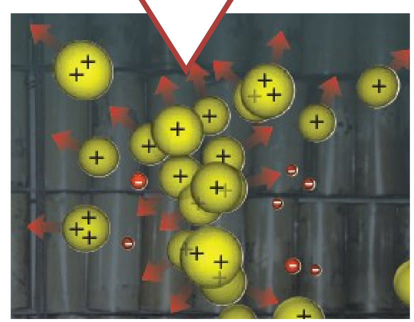
Particles Acceleration

Fiber number

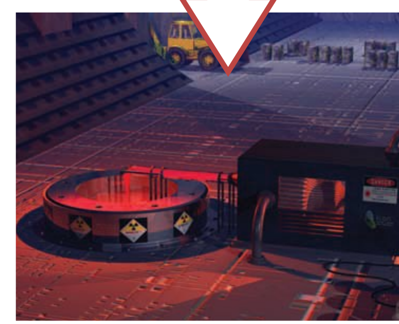
10 100 1 000 10 000 100 000



XUV Photolithography



Chemical agent Neutralization



Nuclear waste transmutation

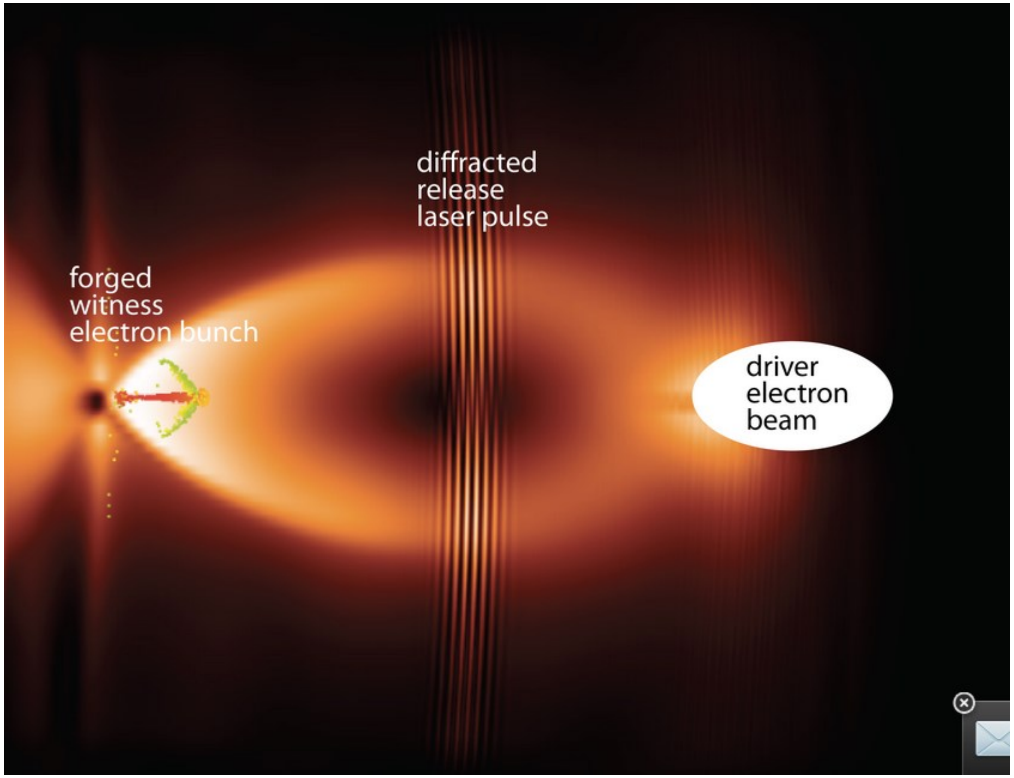
Gérard MOUROU ICAN

Even more about lasers – & acceleration

"Proton acceleration by single-cycle laser pulses offers a novel monoenergetic and stable operating regime"
ML Zhou, XQ Yan, G Mourou, JA Wheeler, JH Bin, J Schreiber, T Tajima
Physics of Plasmas 23 (4), 043112 1 (2016)

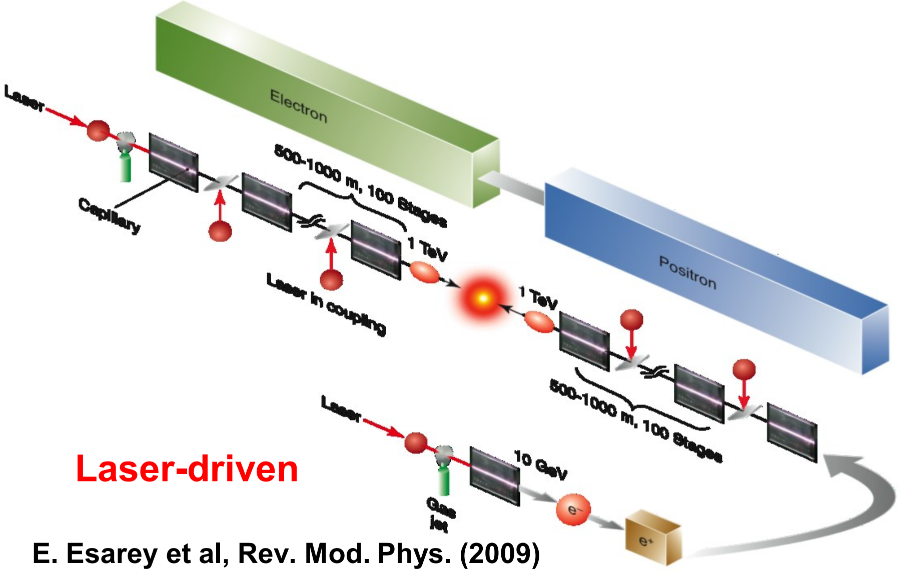
"Instability-free regime for ion production was revealed leading to the efficient coherent generation of short femtosecond monoenergetic ion bunches with a peak energy greater than GeV"

Laser-plasma – Trojan horse



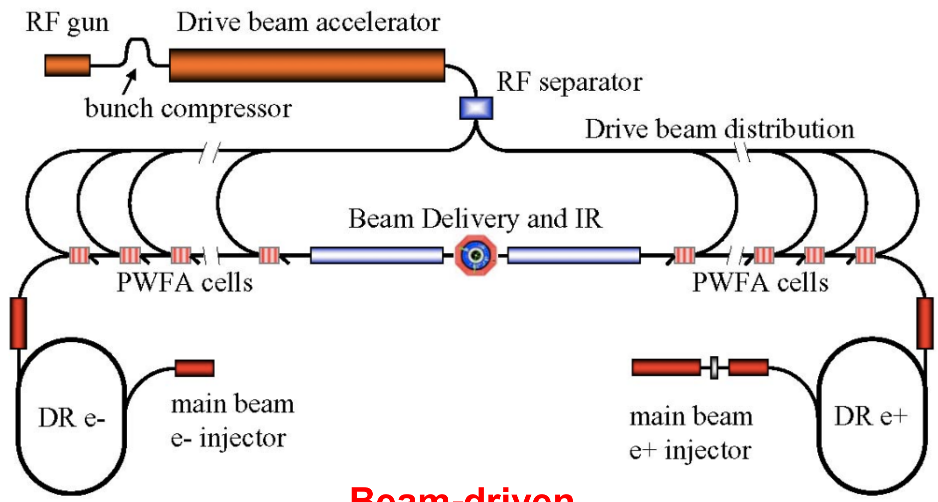
Bernhard Hidding et al

- Can we consider:
  - using solenoidal field in the bubble (special shape of e-drive or laser) for emittance compensation
  - Creating target inside so that emitting region is even much smaller



Laser-driven

E. Esarey et al, Rev. Mod. Phys. (2009)

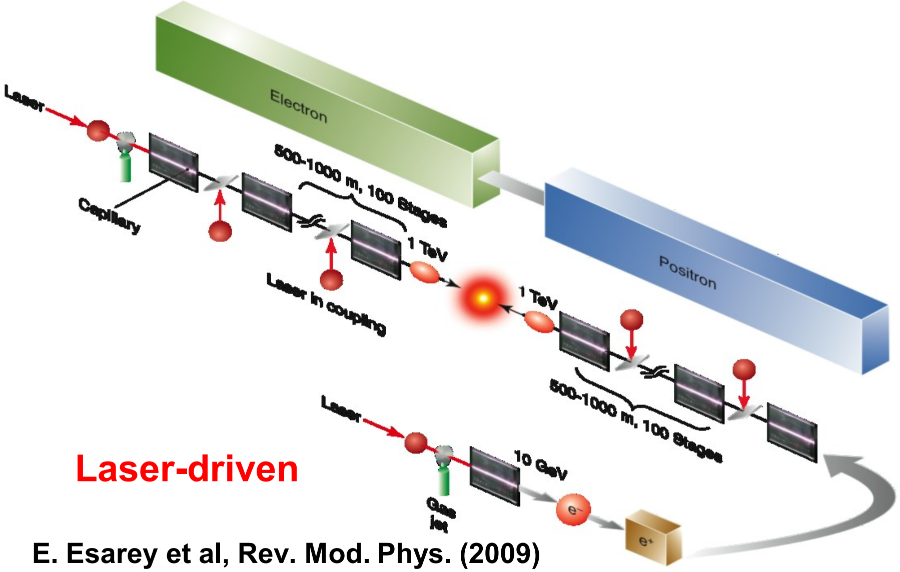


Beam-driven

A. Seryi et al, SLAC-PUB-13766, 2009

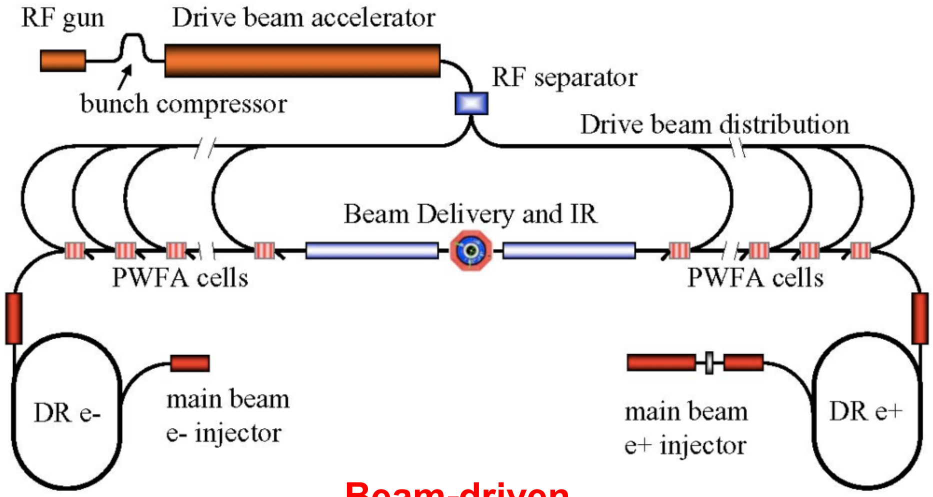
Taking all the above into account – how should these concepts evolve, aiming at second half of 21 century?

- **Remove conventional systems**
  - **Remove 4km final focus, assume emittance so small that strong focusing at IP not needed**
  - **Cooling (if needed for e+) is in linear system**
  - **Could p-drive beam be useful, as a driver, produced by a single-cycle laser pulse?**



Laser-driven

E. Esarey et al, Rev. Mod. Phys. (2009)



Beam-driven

A. Seryi et al, SLAC-PUB-13766, 2009

Taking all the above into account – how should these concepts evolve, aiming at second half of 21 century?

- **Rely on progress in lasers**
  - **Progress driven by commercial applications**
  - **Progress driven by XCAN**
  - **Progress driven by Starshot challenge**

    - **And proactively help this progress!**

Natural scale of projects and goals

- **LHC to FCC**
  - LHC – mostly Europe funded – natural scale project (affordable)
  - FCC (~3 times LHC) – natural scale project funded by 3 regions (Europe, Asia, Americas)

    - FCC is ~2035 timescale
    - In the second half of 21 century we will hopefully have some plasma colliders

Physics & societal case for projects

- **Case for collider project**
  - We often hear that physics case for ~nTeV collider not that strong, and the physics case may be at Plank's scale…
- **Let's compare this with mission to Mars**
  - Science case of Mars mission is not that strong in comparison with mission to Alpha Centauri
  - But we cannot go immediately to Alpha Centauri
  - But this does not mean we would not go to Mars!

- **In addition to physics/science case, there is societal case of continuing scientific pursuit and technology development**

Colliders or…

JAI research directions

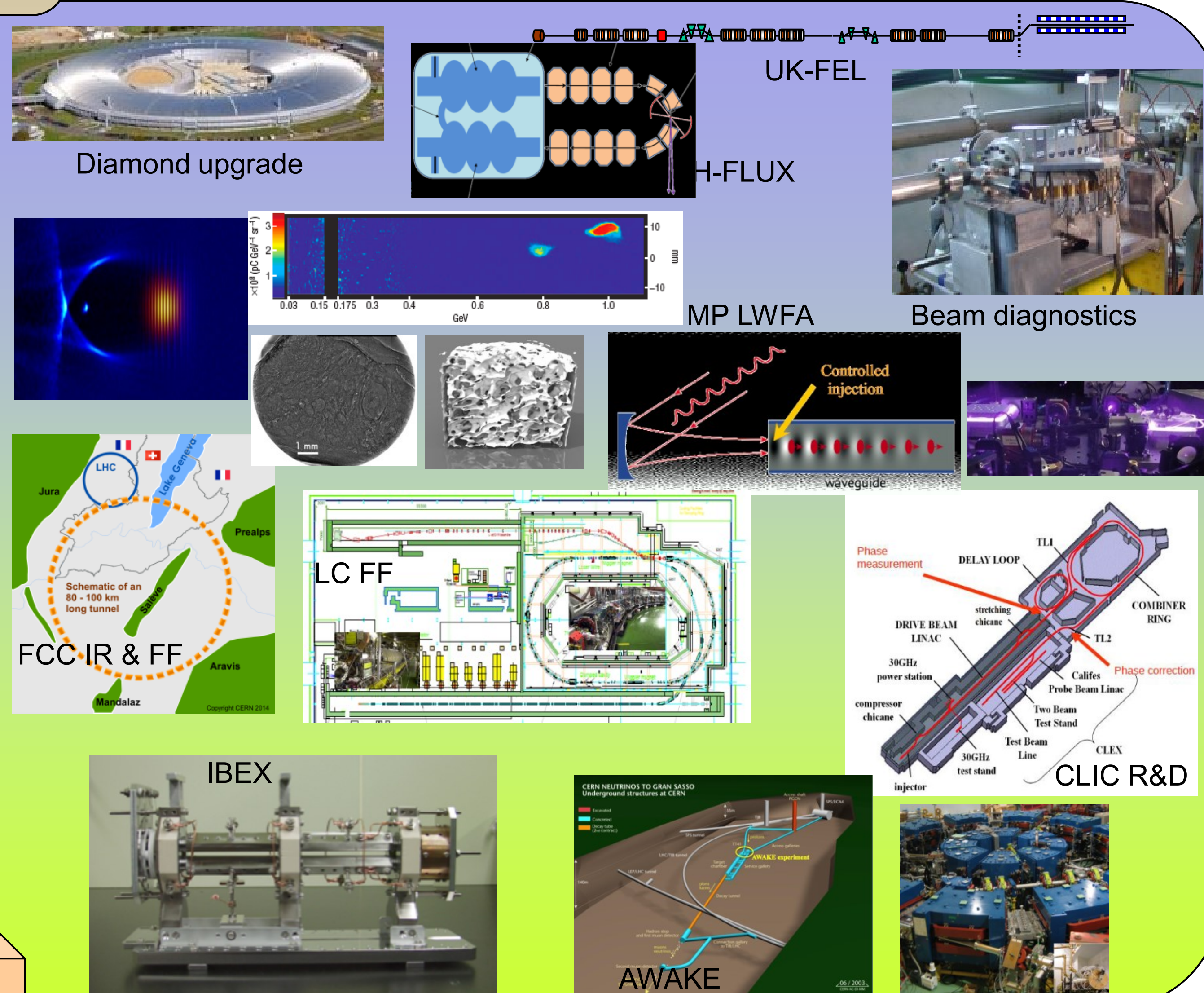
FEL and novel light sources

Plasma acceleration

Future colliders and particle physics facilities

Intense hadron beams

Training



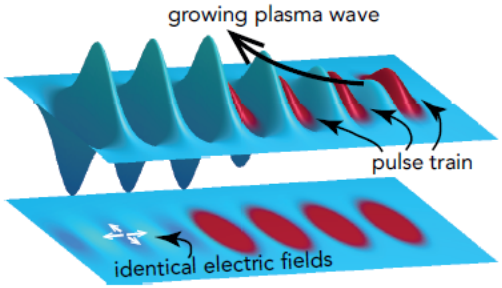
John Adams
lerator Science
Imperial College London
Royal Holloway University of London
UNIVERSITY OF OXFORD
PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Niels Bohr
Louis Pasteur
Accelerator Science & Technology
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Protons/Ions
Patent
Fundamental knowledge
Consideration of use

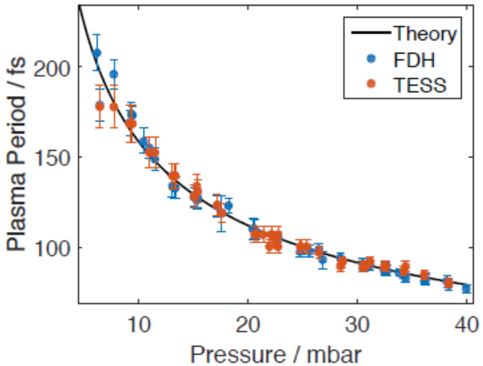
Development of wakefield accelerators

Development of efficient high rep-rate LWFA

- Multi-pulse laser wakefield acceleration may offer route to high repetition rate plasma accelerators driven by trains of low-energy laser pulses
- Proof-of-principle experiments
  - Ti:sapphire laser
  - FDH and TESS to measure wakefield
- Two-pulse expts
  - Wakefield interference clearly observed
  - Cancellation of wakefield by second pulse is first step to “energy recovery”
- Multi-Pulse expts (N = 7):
  - Strong resonance when pulse separation matches plasma period
  - Excellent agreement with linear theory

Cartoon of MP-LWFA scheme

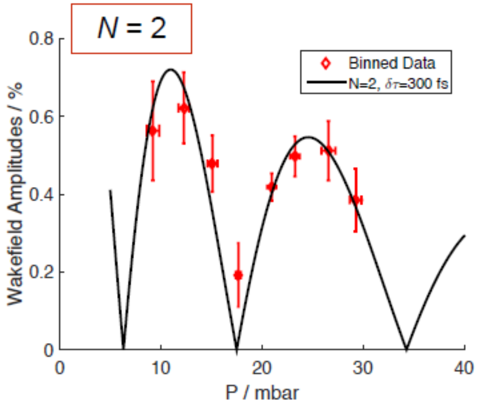


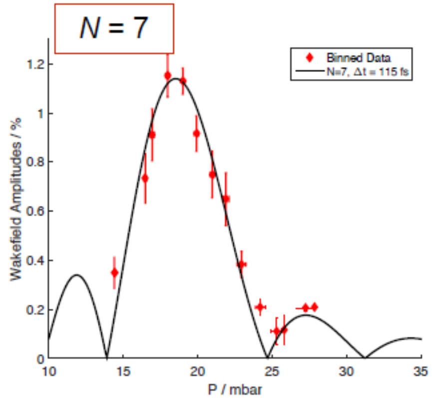


FDH and TESS are in excellent agreement with each other and expected plasma period

Expected wake amplitude:

$$\frac{\delta n_e}{n_{e0}} \propto \left(\frac{\delta n_e}{n_{e0}}\right)_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$



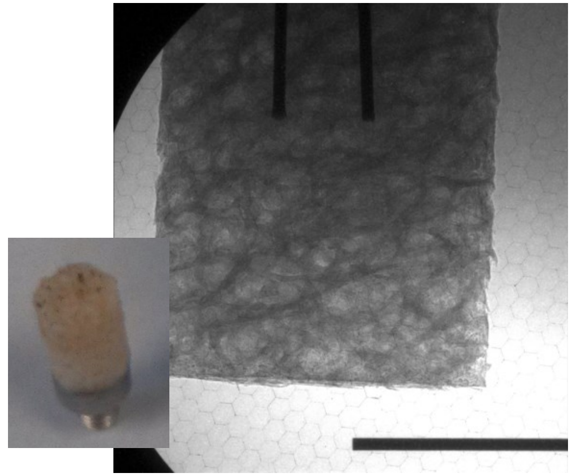


Preliminary analysis!

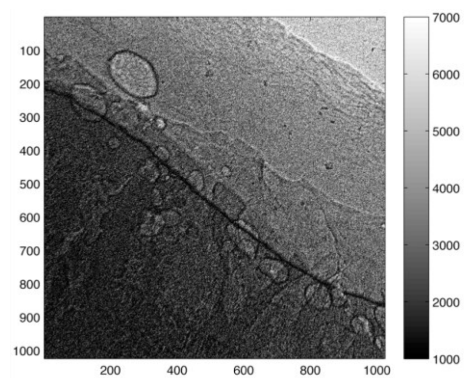
Simon Hooker at al

Medical application of laser-acc. particles

- **Betatron radiation could prove to be an interesting source for medical radiography**
  - **Small source size and collimated beam allows for high resolution phase contrast imaging of soft tissue, e.g. breast, prostate…**
  - **Hard photon energy with small source size allows for high resolution imaging of bone, biological samples**



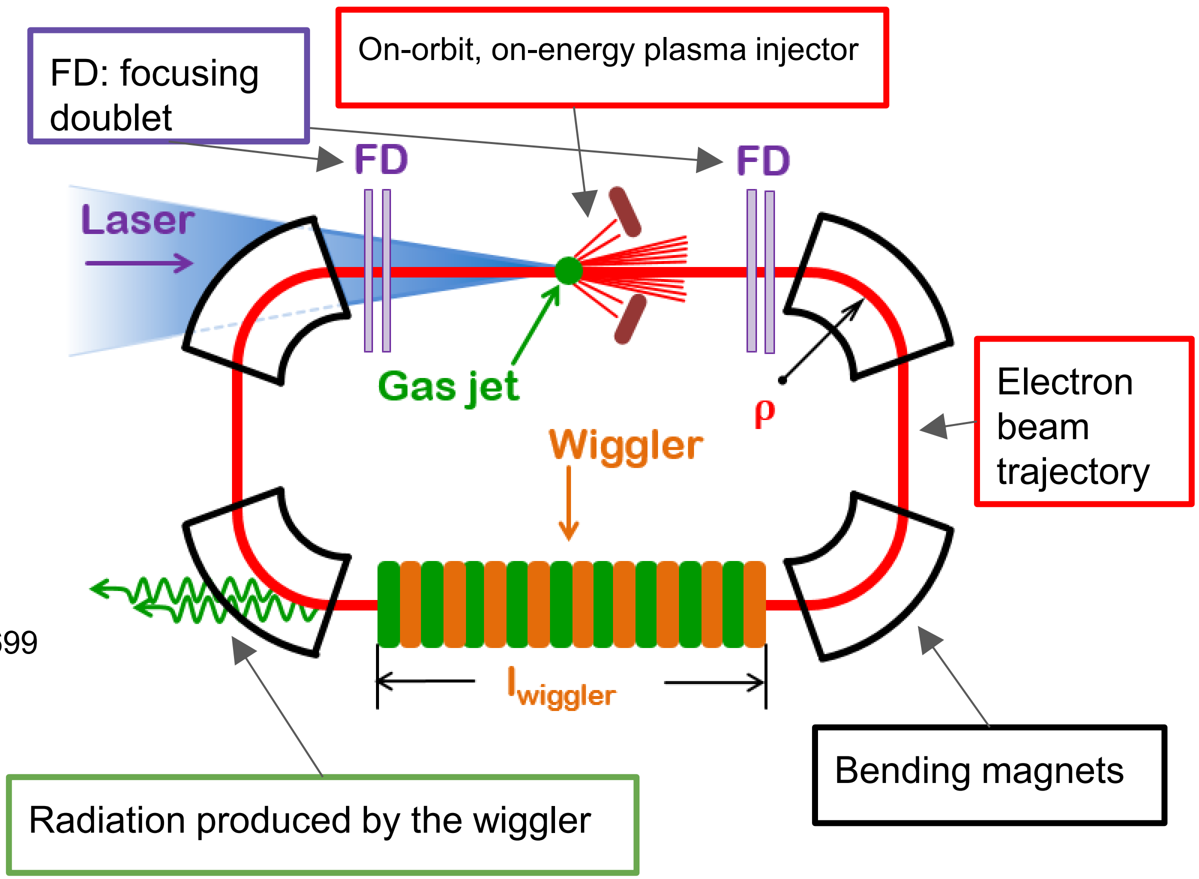
X-ray radiograph of femural bone sample (left, and photo inset) tomographically reconstructed (right)



Phase-contrast imaging of prostate (left) and tomograph of pre-natal mouse (right)

JAI / Imperial College

USPAS 2016 students' design project – compact ring-based X-ray source with on-orbit and on energy laser-plasma injection



https://arxiv.org/abs/1610.05699

In this project looked at producing 0.4 keV or 10 keV photons from wiggler, with 1 GeV electrons (NC or SC magnets); or 10 keV photons with 3 GeV electrons and SC magnets

Conceptual design of this project started this summer at one-week-long USPAS class taught by A.Seryi and A.Sahai

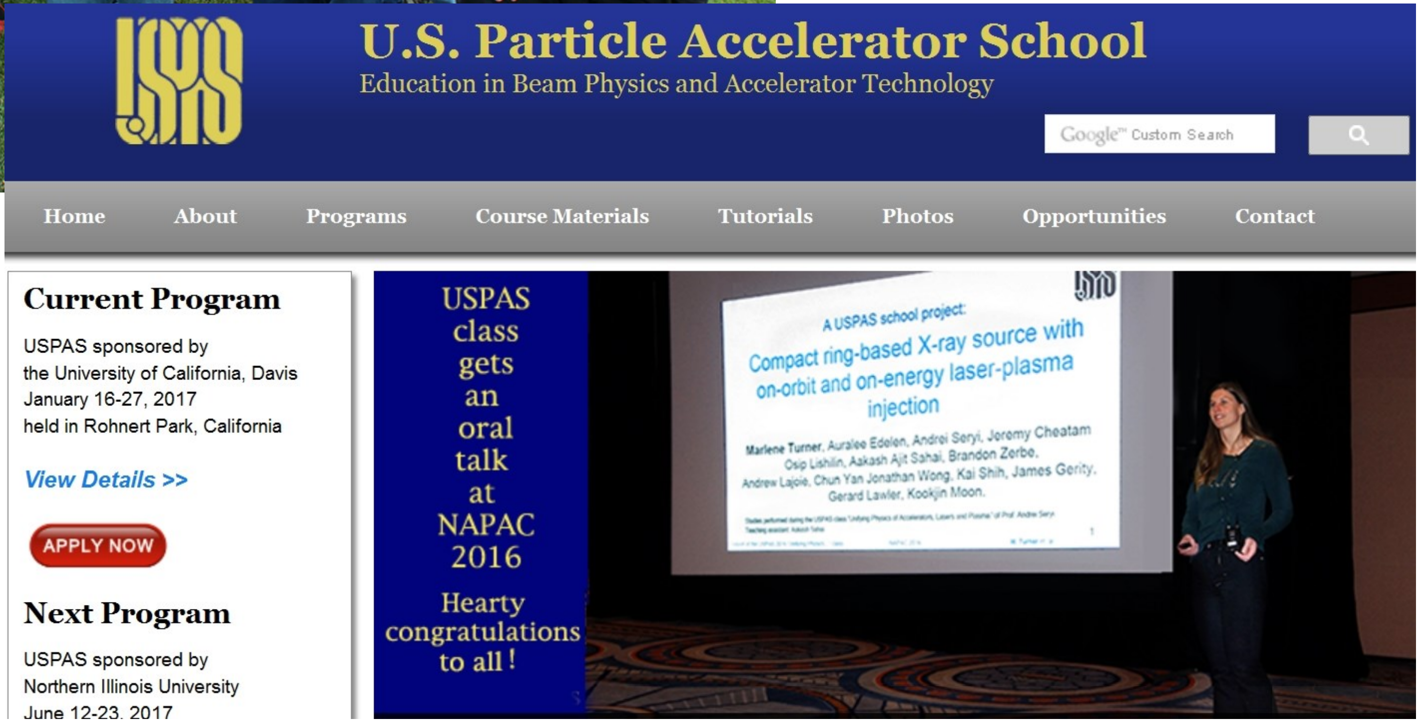
USPAS 2016 “Unifying Physics...” Class

The 1 week long “**Unifying Physics of Accelerators, Lasers and Plasma**” class was held in June 2016.

The class was taught by Prof. Andrei Seryi and Dr Aakash Sahai following book “Unifying Physics of Accelerators, Lasers and Plasma.”

After the USPAS class, the team wrote a paper for NA-PAC 2016 conference

The paper was selected as contributing oral presentation at NA-PAC 2016 (Oct 2016)



One more collider…
(low energy)

LETTERS
PUBLISHED ONLINE: 18 MAY 2014 | DOI: 10.1038/NPHOTON.2014.95
nature photonics

A photon–photon collider in a vacuum hohlraum

O. J. Pike[1]*, F. Mackenroth[1,2], E. G. Hill[1] and S. J. Rose[1]

The ability to create matter from light is amongst the most striking predictions of quantum electrodynamics. Experimental signatures of this have been reported in the scattering of ultra-relativistic electron beams with laser beams[1,2], intense laser–plasma interactions[3] and laser-driven solid target scattering[4]. However, all such routes involve massive particles. The simplest mechanism by which pure light can be transformed into matter, Breit–Wheeler pair production ($\gamma\gamma' \rightarrow e^+e^-$)[5], has never been observed in the laboratory. Here, we present the design of a new class of photon–photon collider in which a gamma-ray beam is fired into the high-temperature radiation field of a laser-heated hohlraum. Matching experimental parameters to current-generation facilities, Monte Carlo simulations suggest that this scheme is capable of producing of the order of 10^5 Breit–Wheeler pairs in a single shot. This would provide the first realization of a pure photon–photon collider, representing the advent of a new type of high-energy physics experiment.

Ranked 1st in Altmetrics of all papers published in Nature Photonics
Picked up by 54 news outlets around the world
On of the 10 biggest Science and Technology stories in 2014 in Phys.Org
One of top 10 Imperial College news stories of all time (website hits)

Slides from Steve Rose

On searching for Breit-Wheeler pair production: three different approaches

Slides from Steve Rose

Threshold for Breit-Wheeler: product of two photon energies > 511^2 keV^2

Beam + Laser

Gamma-ray (100 GeV)

Optical laser photon (eV)

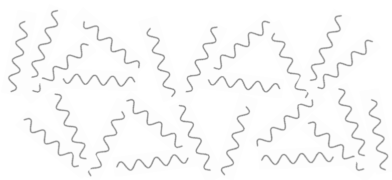
Beam + Beam

Gamma-ray (MeV)

Gamma-ray (MeV)

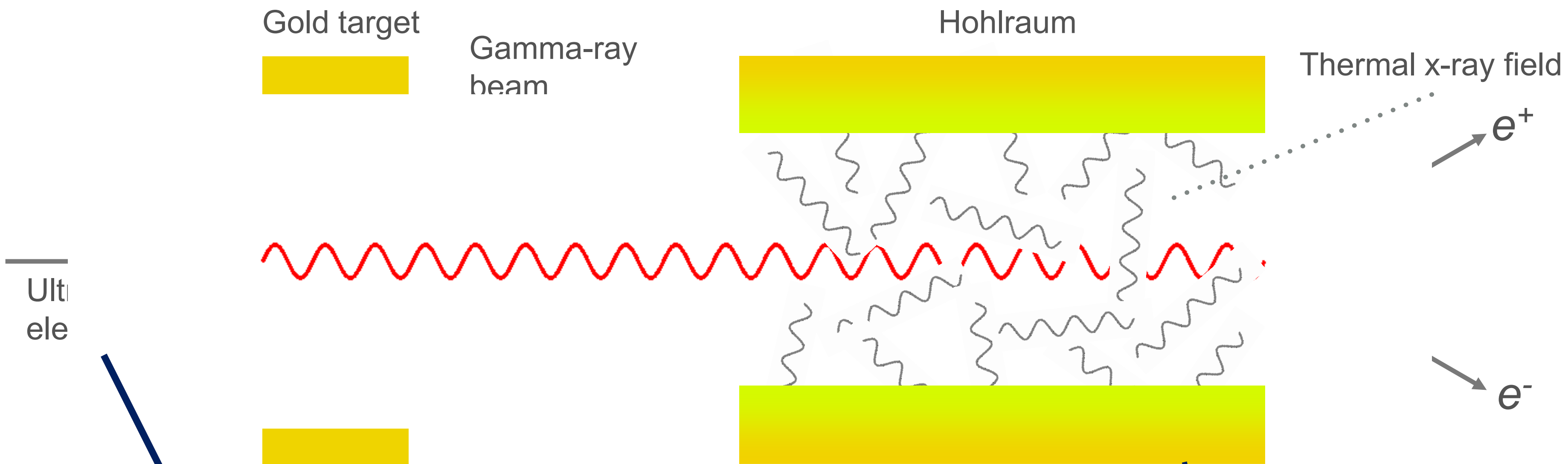
Beam + Target

Gamma-ray (GeV)



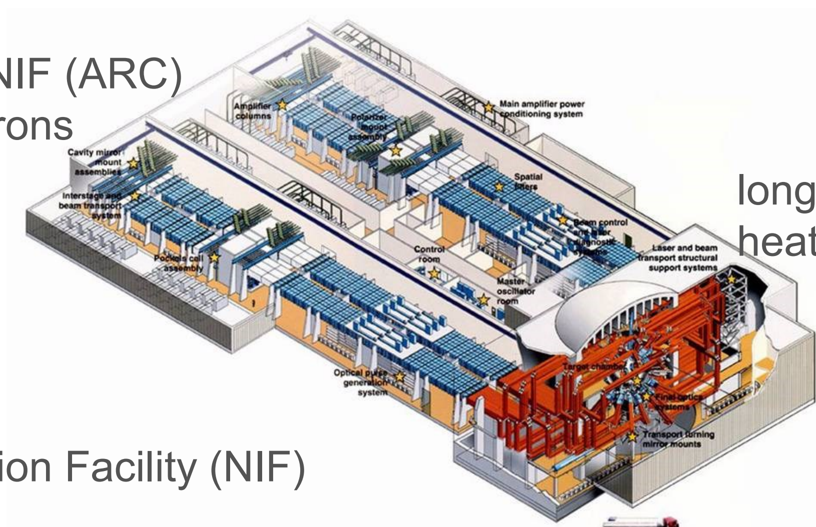
Thermal x-ray field (100 eV)

A photon-photon collider in a vacuum hohlraum: new HEP experiment using HEDP (High Energy Density Physics) facilities such as the US National Ignition Facility



short-pulse laser on NIF (ARC) accelerates the electrons

long-pulse laser on NIIF heats hohlraum



National Ignition Facility (NIF)

Slides from Steve Rose

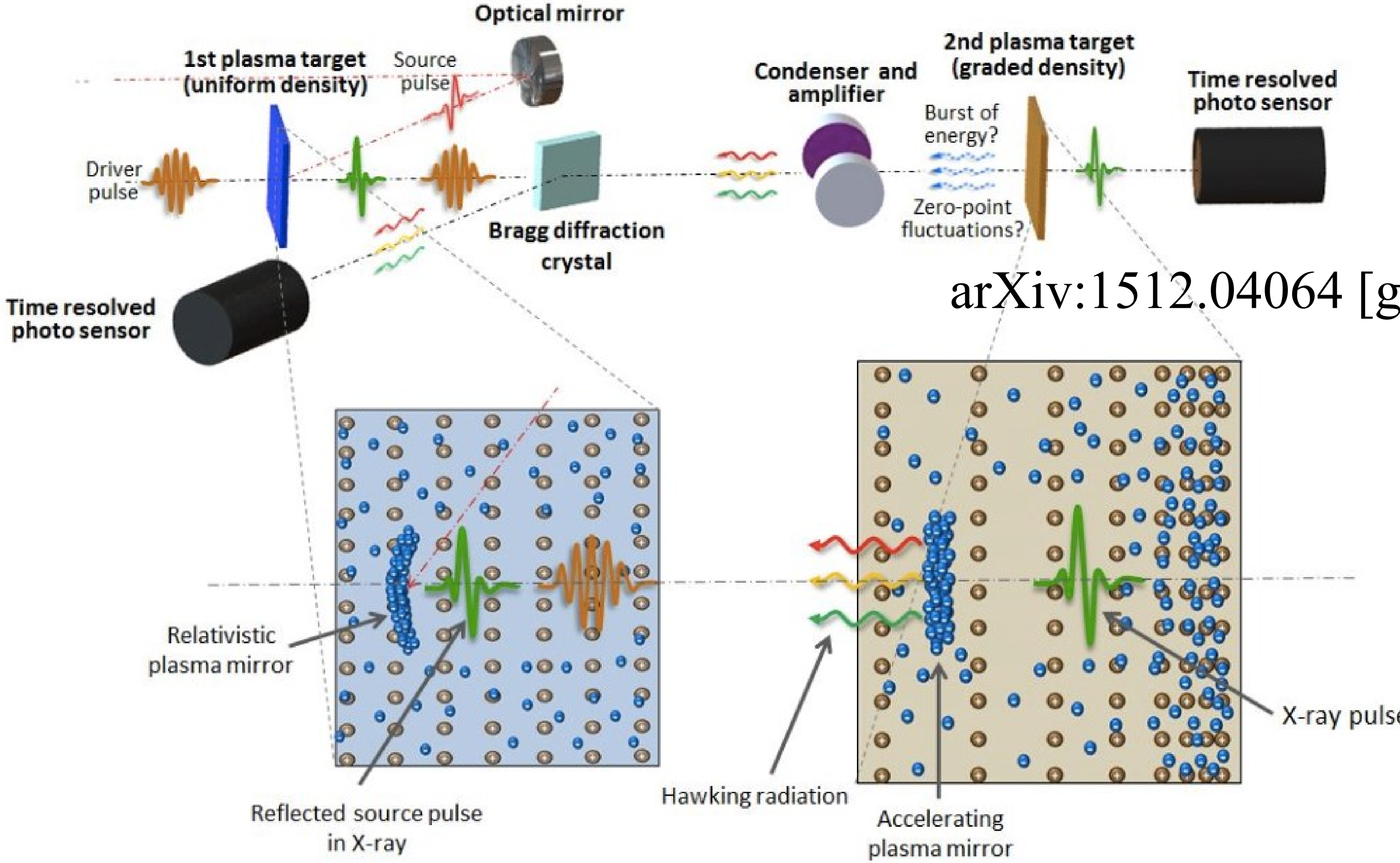
Pike, Mackenroth, Hill and Rose, Nature Photonics 2014

And one more "collider"…

(of accelerating mirrors with…)

Accelerating Plasma Mirrors to Investigate Black Hole Information Loss Paradox

Pisin Chen, Gerard Mourou, 2015



arXiv:1512.04064 [gr-qc]

Creation of the needed target with density gradient can rely on technology similar to the one used for creation of molecular machines

Thank you for your attention!

Let's discuss