PHY 554
Fundamentals of Accelerator Physics
Lectures 25-26
Scientific and Societal Applications of Accelerators

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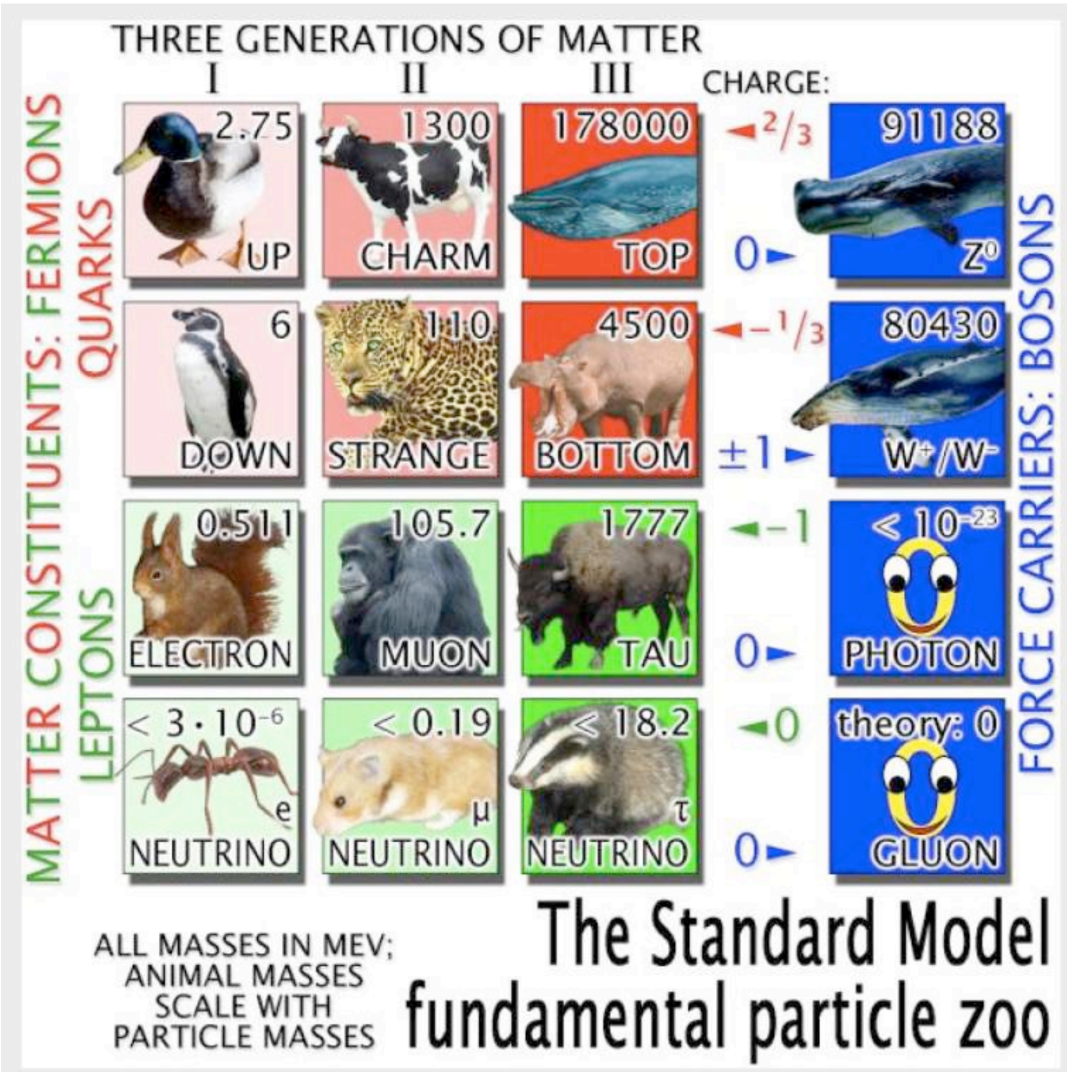
Fist lecture: Scientific Applications
Second lecture: Societal Applications

Scientific Applications

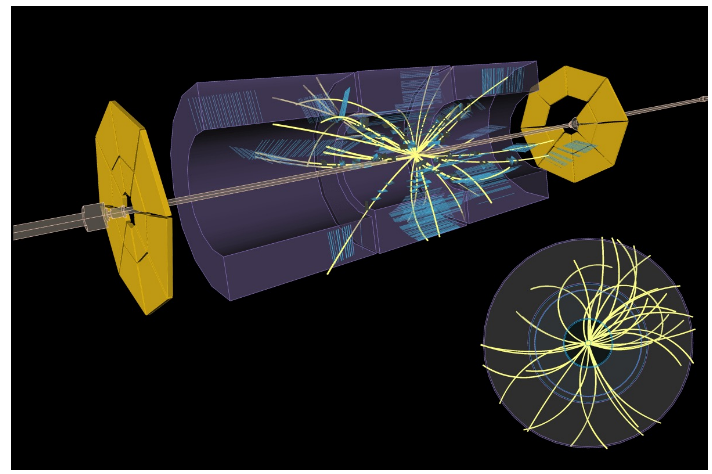
- **High energy and Nuclear Physics** – colliders
- **Neutron sciences** – neutron spallation sources
- **Photon Sciences** – light sources
  - **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
  - **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- http://www.acceleratorsamerica.org/resources/applications/index.html

Why we need Colliders?

Accelerator allowed us to discover the entire zoo of the Standard Model particles

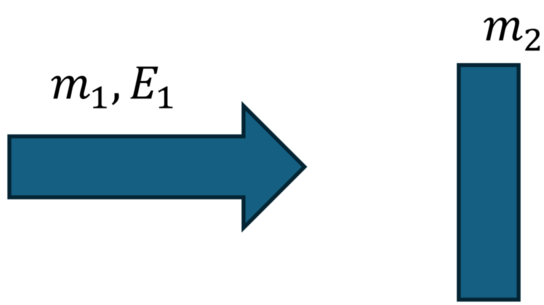


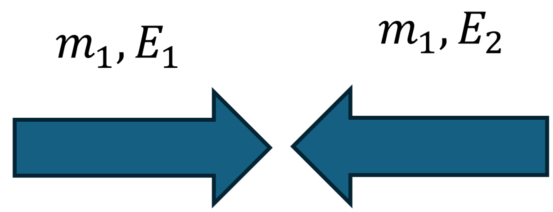
HIGS 125,180 MeV



ATLAS detector at LHC

Fix target vs colliders





Fixed target: $E_{cm} = \sqrt{m_1^2 + m_2^2 + 2m_2E_1} \sim \sqrt{2m_2E_1}$

Collider: $E_{cm} = 2\sqrt{\mathrm{E}_2E_1}$

For high energies, the difference can be orders of magnitude!
Protons at 7 TeV LHC energy: $E_{cm,fixed} = 114$ GeV, $E_{cm,collider} = 14$ TeV! >100x bigger

High Energy and Nuclear Physics

- Colliders – world's most powerful microscopes
- Hence, they allow to look into the matter on smaller and smaller scale, and, sometimes, discover new states of mater or new particles

$$\delta x \cdot \delta p \geq \hbar \qquad \delta p \leq \frac{E_{cm}}{c}; \ \delta x \geq c\frac{\hbar}{E_{cm}}$$

or for new particles

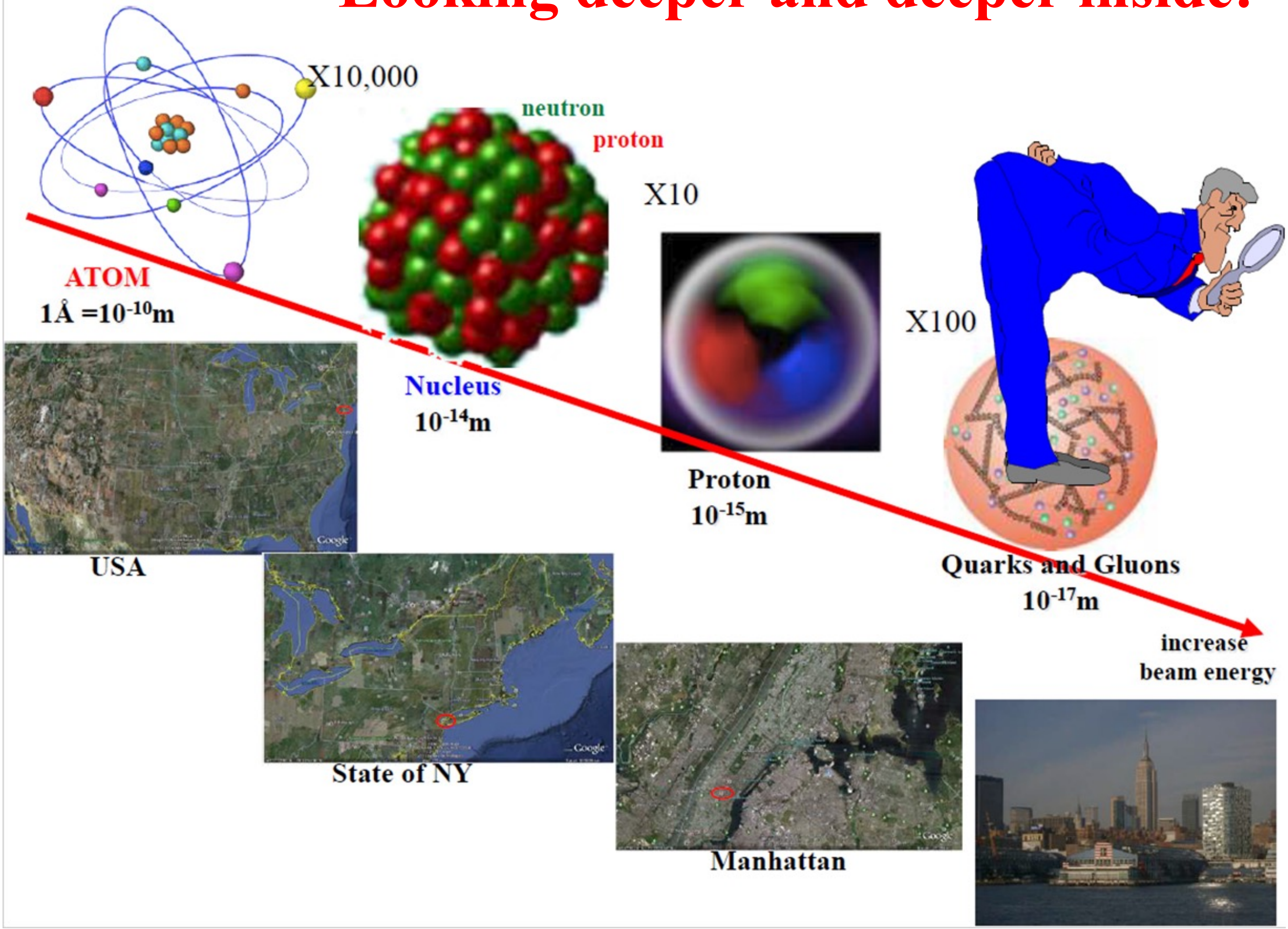
$$M_{part} \leq \frac{E_{cm}}{c^2}$$

- For ultra-relativistic particles the c.m. energy is a simply twice the geometrical average of the colliding particles

$$E_{cm} \cong 2\sqrt{E_1 E_2}$$

Collider	E_1, GeV	E_2, GeV	E_{cm}, GeV
RHIC	250 p	250 p	500.0
eRHIC	250 p	21.2 e-	145.6
LHC	6500 p	6500 p	13,000
B-factory	3.5 e-	10.58 e+	12.2
Fixed target	E_1, GeV	E_2, GeV	E_{cm}, GeV
CEBAF	6 e-	0.938 p	4.7
	12 e-	0.938 p	6.7
	6 e-	0.00051 e-	0.1
	12 e-	0.00051 e-	0.2

Looking deeper and deeper inside!



Productivity of colliders

- Luminosity

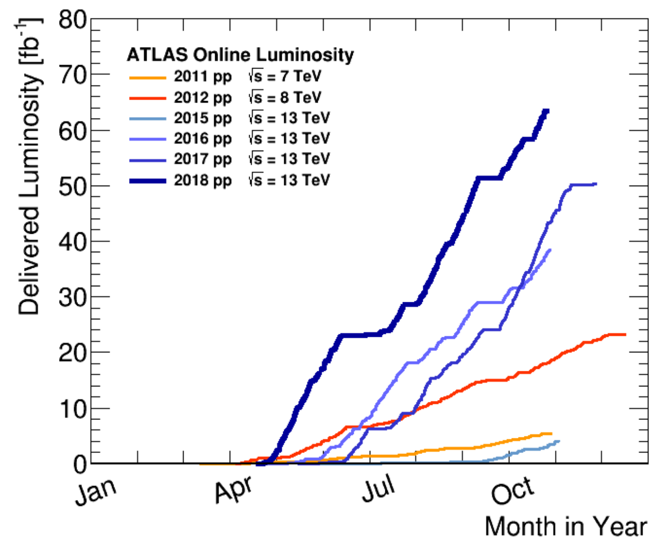
$$L = f_c \frac{N_1 N_2}{A} \cong f_c \frac{N_1 N_2}{2\pi\sqrt{\beta_{x1}\varepsilon_{x1} + \beta_{x2}\varepsilon_{x2}}\sqrt{\beta_{y1}\varepsilon_{y1} + \beta_{y2}\varepsilon_{y2}}}$$

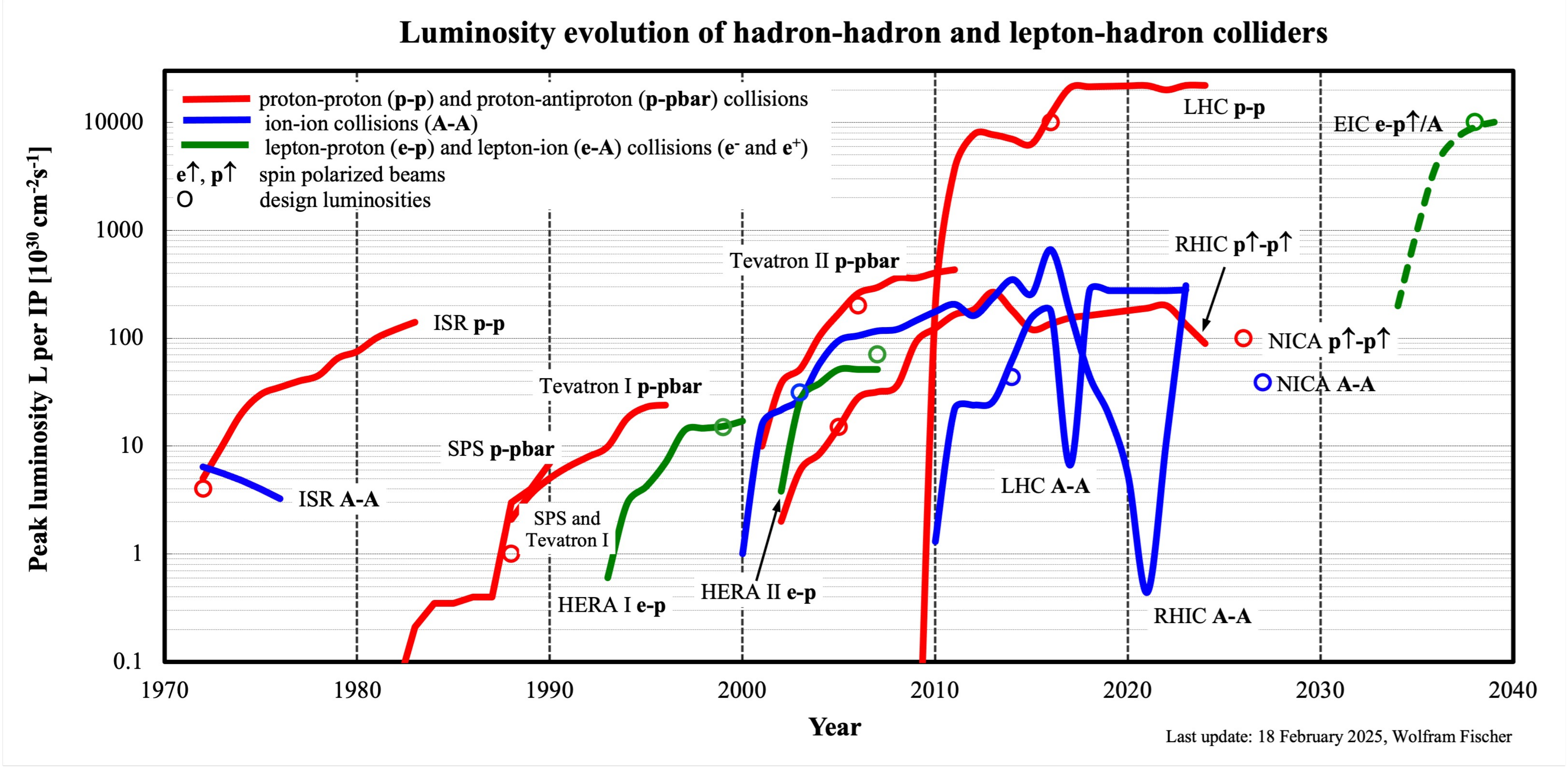
- Number of events generated over a unit time with unit cross-section (~probability)
- Luminosity is measured in $cm^{-2}sec^{-1}$
- Delivered or Integrated luminosity is measured in invers femtobarns [fb^{-1}]
- Determines probability of seeing rare events

If an event A->B has a cross-section $\sigma_{A\to B}$ (for example generating Higgs particle), then numbers of interested events per second:

$$\dot{N}_{A\to B} = \sigma_{A\to B} \cdot L$$

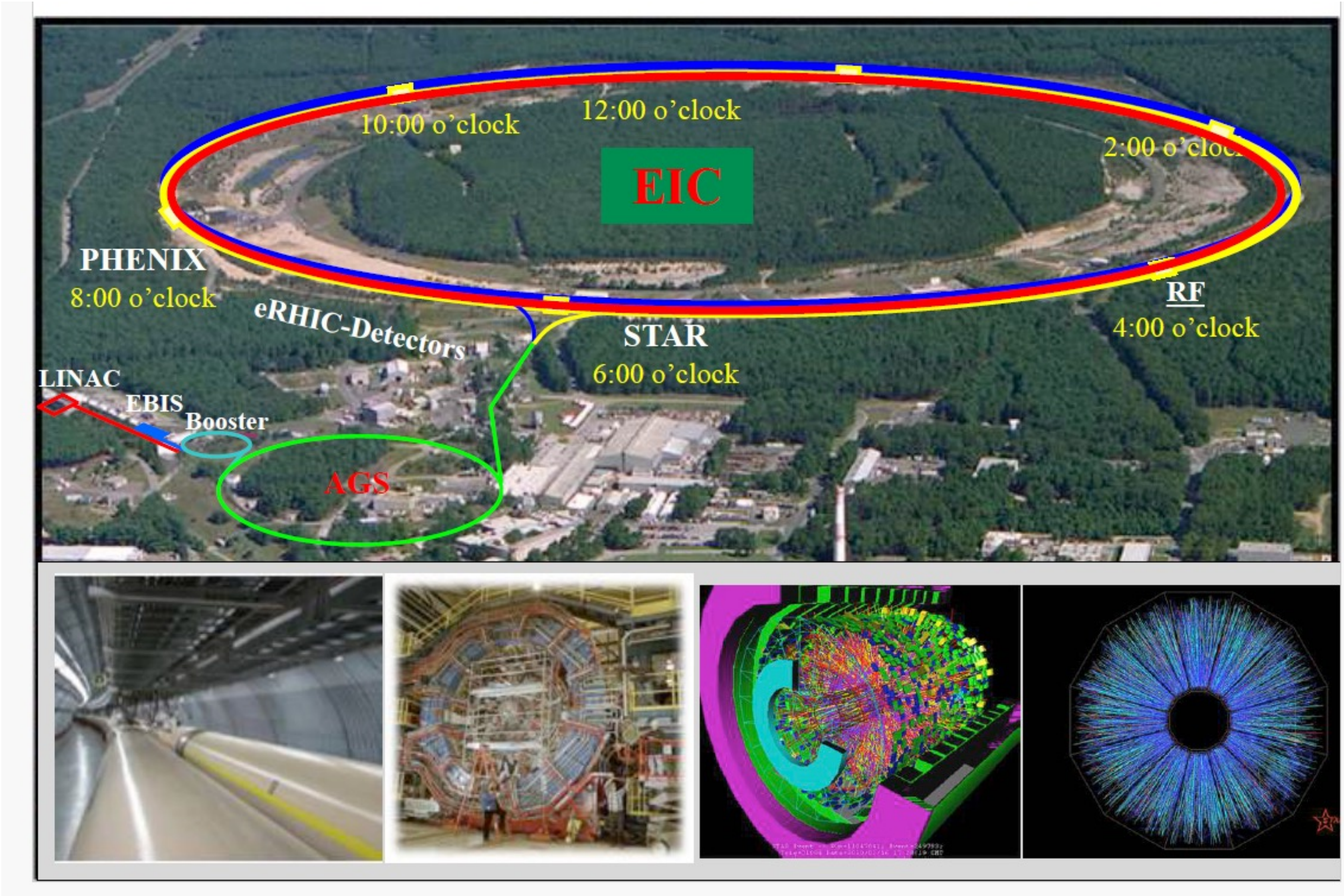
Collider	L
RHIC	10^{32}
EIC	10^{33} - 10^{34}
LHC	10^{34}
B-factory	10^{34}
Fixed target	L
CEBAF	10^{35}





Wolfram Fischer at COOL'25 workshop Oct26-31, 2025 Stony Brook, NY

Close to Home: From RHIC to EIC



25 Years of RHIC

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BROOKHAVEN BULLETIN
Vol. 54 - No. 21 June 16, 2000
BROOKHAVEN NATIONAL LABORATORY

RHIC Begins World's Highest Energy Heavy-Ion Collisions

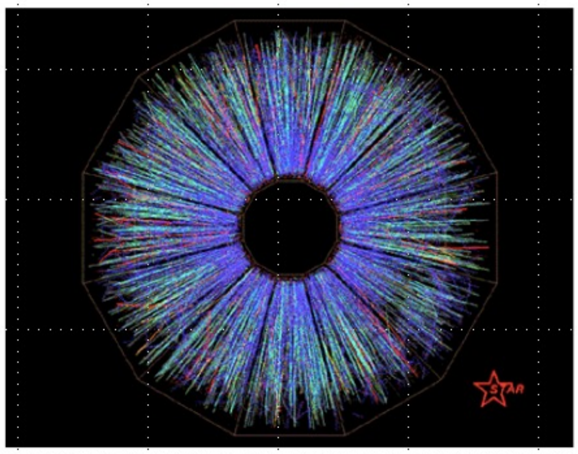
On the evening of Monday, June 12, operators in the main control room of the Relativistic Heavy Ion Collider (RHIC) watched control displays anxiously as the beams circulating in the collider's twin rings appeared to be colliding.

"The atmosphere was tense and very exciting," said Thomas Roser, head of the Accelerator Division and run coordinator for RHIC's first collision run. "We were operating at nearly 30 billion electron volts (GeV) per nucleon, our target energy for first collisions,

"We are crossing into a new frontier of scientific inquiry."

and we knew the beams were crossing at the collider's intersection points. But we couldn't say for sure that we'd had collisions until we got definitive, corroborative evidence from the detectors."

All four of RHIC's detectors — BRAHMS, PHENIX, PHOBOS and STAR — were poised and ready to take data as the accelerator physicists began to steer the beams into colli-



A view of a RHIC collision seen in the STAR detector. "We knew immediately that we'd seen a true, beam-on-beam collision because all the particle tracks clearly originated at the center of the beam tube and sprayed out in all directions," said John Harris of Yale University and head of the STAR team. The symmetric pattern of particle tracks contrasts dramatically with so-called background events the team had witnessed, where collisions between ions and gas particles in the beam tube produce tracks going in only one direction.

est and biggest particle a
studies in nuclear phy
crossing into a new fron
tific inquiry," said Ener
Bill Richardson upon h
first collisions. "Scientist
the world will use this
swer some of the most ba
about the properties of m
evolution of our univers
The collider aims to
conditions of the early un
insights into the fundan
of matter — and exten
aries of scientific un
through the 21st century
Scientists will use d
during the collisions to
particles known as quar

*The high tem
tures and den
should allow
soup-like plas
a state of mat
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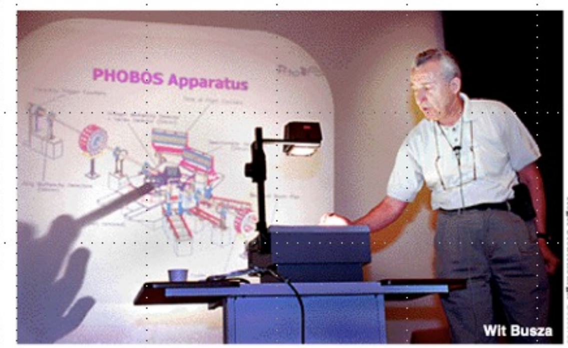
existed millionths of
a second after the*

PHOBOS Collaboration Presents First Physics Results From RHIC

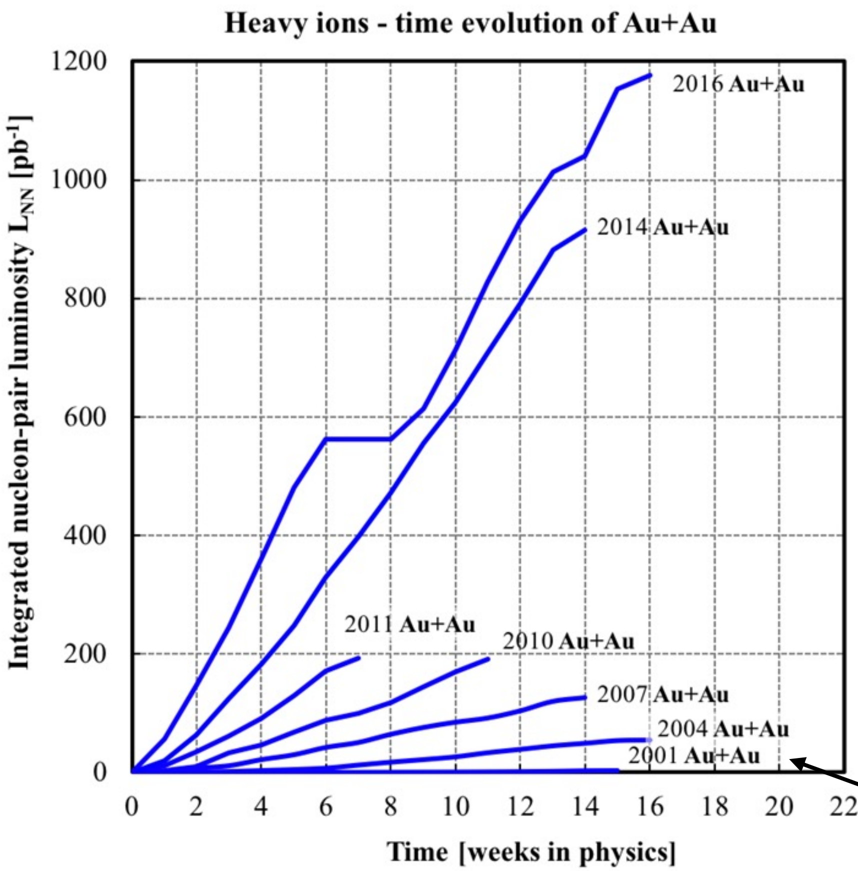


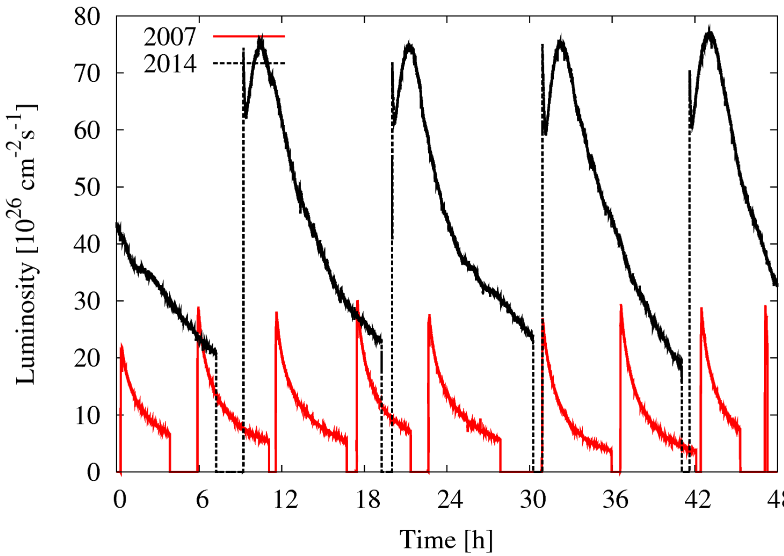
The first physics results from the initial collisions at BNL's Relativistic Heavy Ion Collider (RHIC) were presented by the PHOBOS collaboration to a full house at Berkner Hall on July 19.

collisions. At the higher energy, the collisions achieved an energy density 50 percent higher than that observed for lead-lead collisions at CERN, the European particle physics laboratory."

As Busza explained, data for the

Ramping up luminosity





can now be done in 1/2 day
(200x faster)

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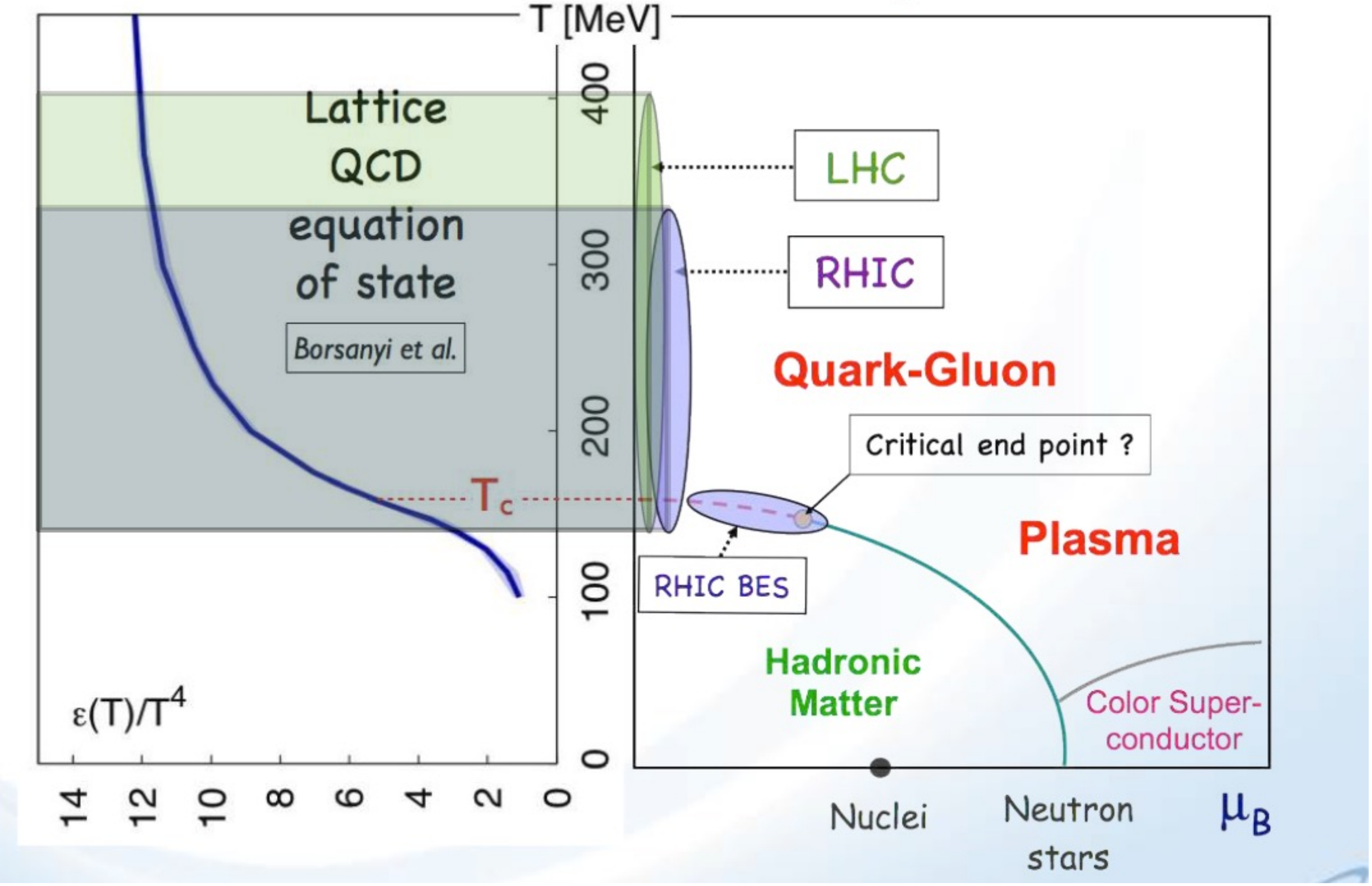
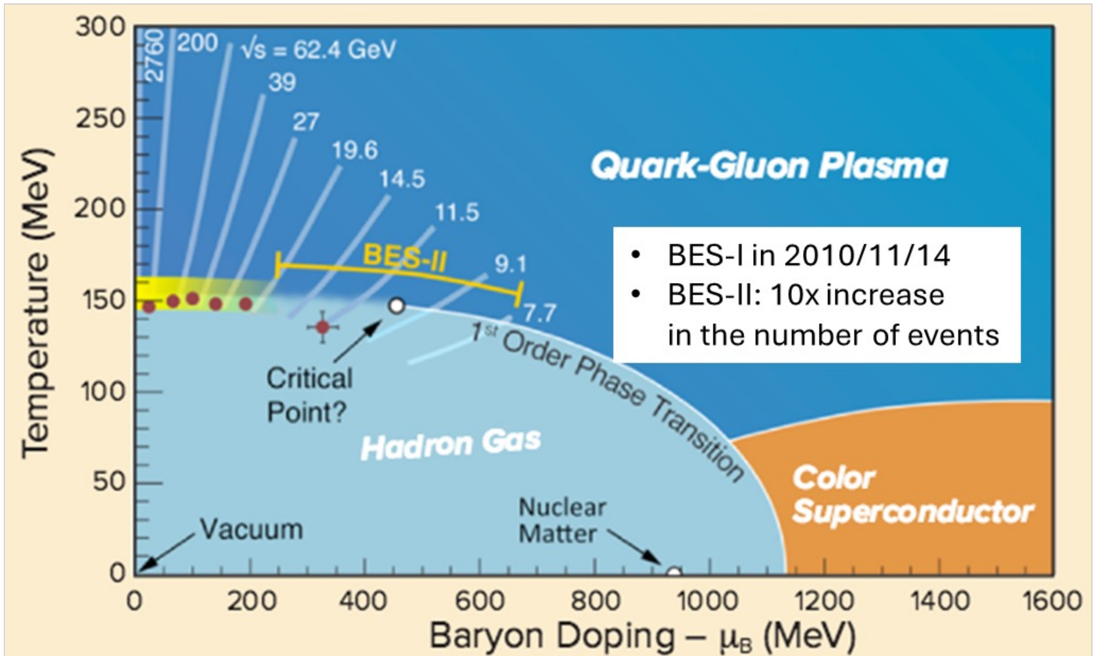
QCD Phase Diagram



Explore operation beyond RHIC designed parameters (colliding hadrons at low energy)

Low-Energy RHIC electron Cooling (LEReC) for the Beam Energy Scan I and II (BES-I, II)



[2015 NSAC Long Range Plan for Nuclear Science]

Au+Au collisions down to 3.85 GeV/n
(40% of CoM energy at nominal injection)

Luminosity really low
- Space charge
- Intrabeam scattering
- Magnetic field errors (also time dependent)
- Large beam with losses

BES-II goal of 4x luminosity over 3.85 – 9.8 GeV/n
(highest energy is nominal injection)

Designed cooler for 2 lowest energies

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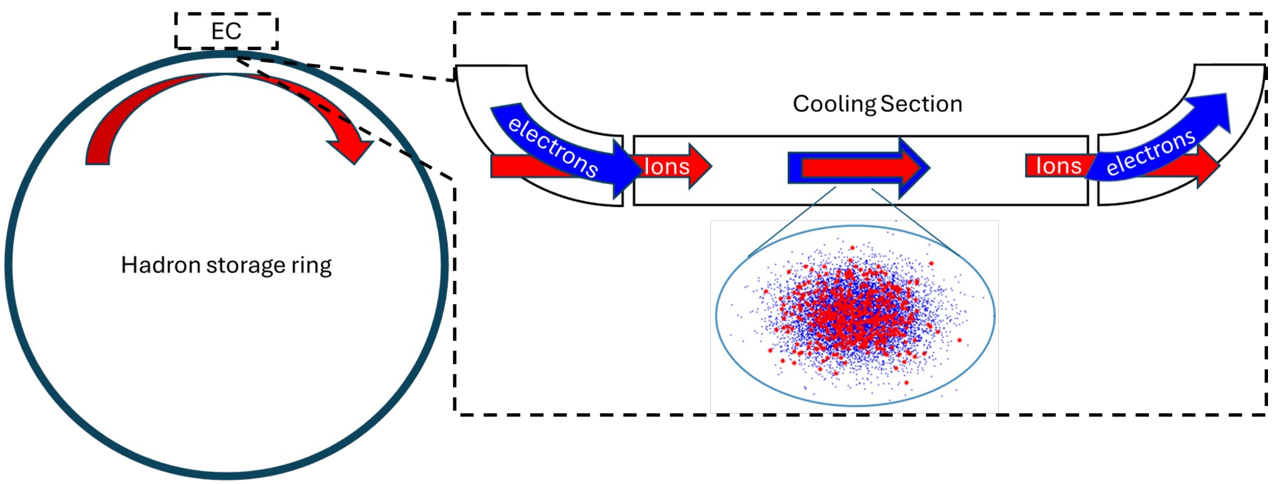
Use electron accelerators to hadrons

- Modern accelerators are very complex systems
- Sometimes one needs build smaller accelerator to help the main accelerator achieve required performance

What is Electron Cooling? Basic.

- Mix a hadron bunch with an electron bunch traveling with the same velocity and let the two bunches travel together over some length. ➡ The velocity spread of hadrons will get reduced. Why?
- In the co-moving frame, the mixture of an ion bunch and an electron bunch looks like a mixture of two gases – a gas of ions and a gas of electrons
- Electrons are much lighter; hence, the gas of electrons is much colder than the gas of ions. ➡ Heat transfer ≡ Electron Cooling



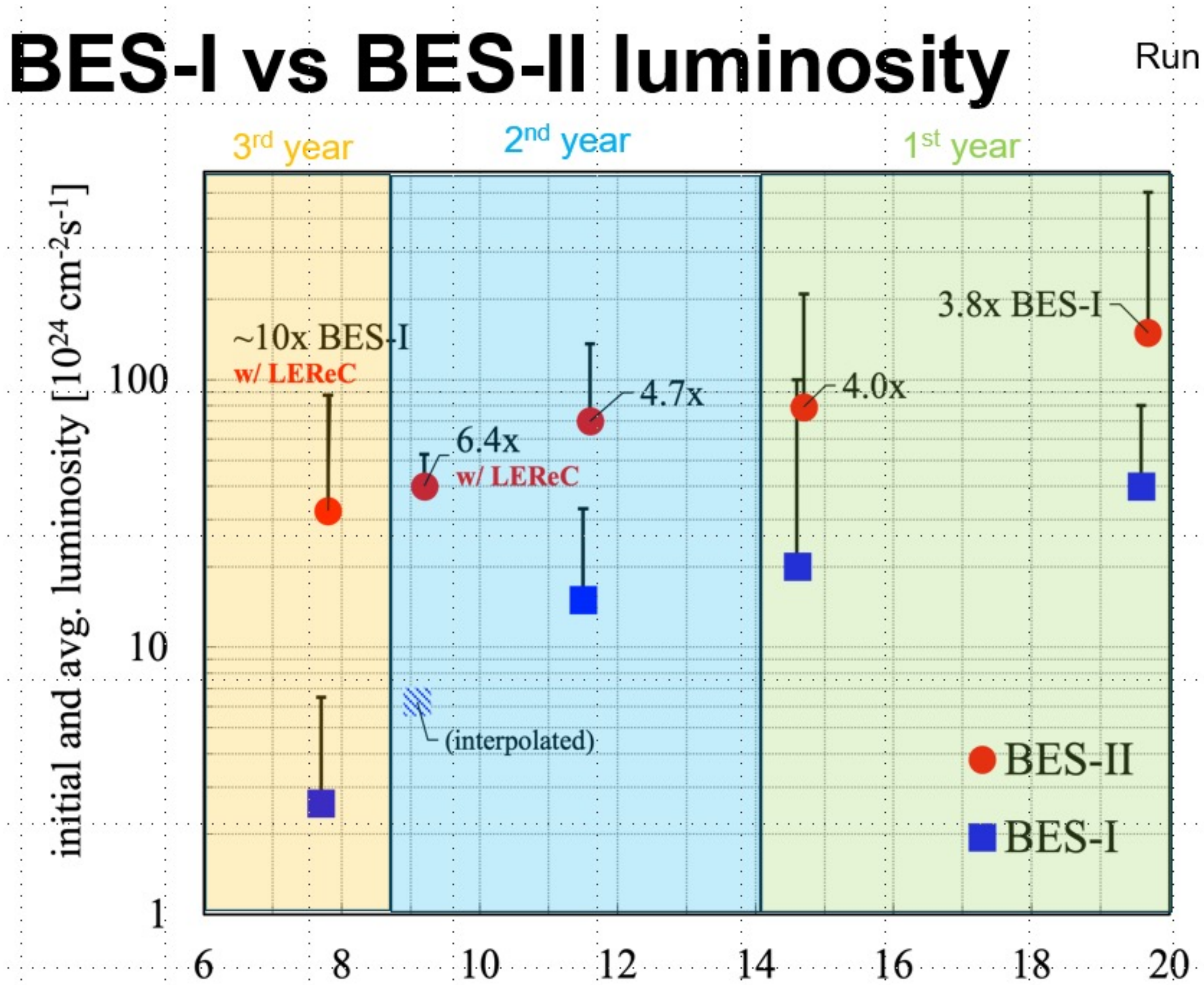
$$m_e \ll m_i$$

$$T = \frac{m\bar{v}^2}{3k_B}$$

$$T_e \ll T_i$$

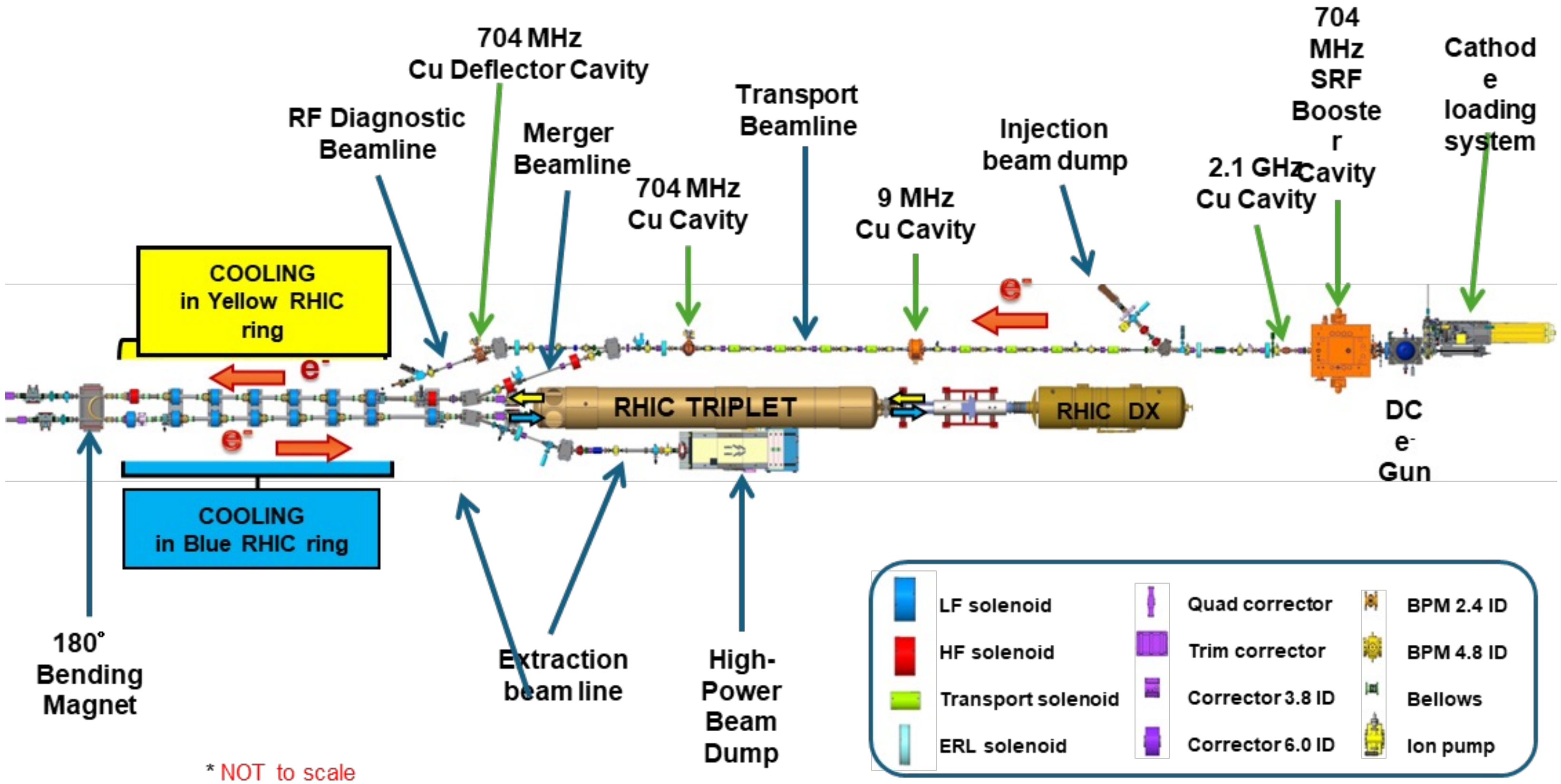
RHIC luminosity at lowest energy of operation

With introducing electron cooling we were able to increase luminosity 10 times at the lowest energy



LEReC Accelerator

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



LEReC parameters

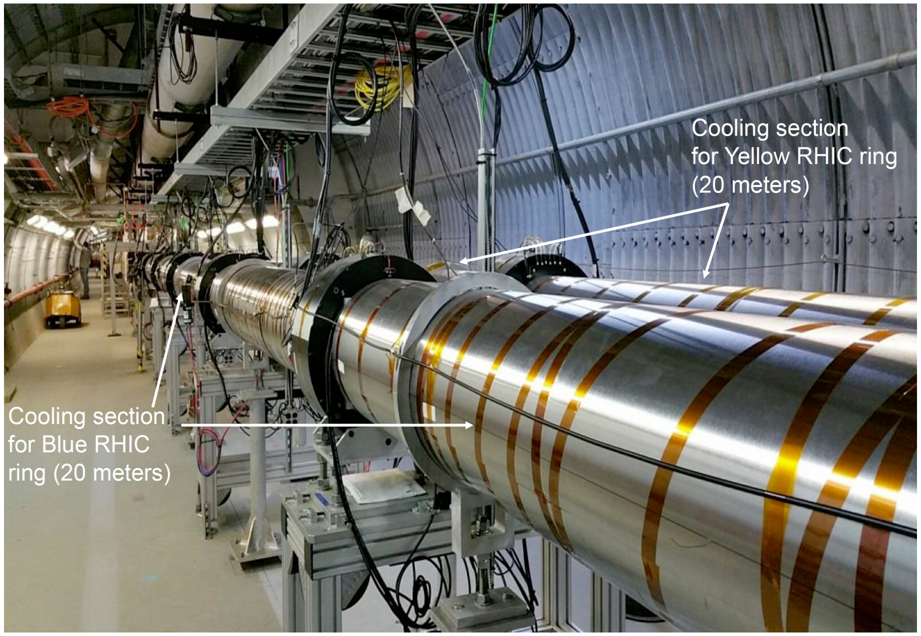
Operation kinetic energy: 1.6-2 MeV,

Average current: 30 mA,

Normalized emittance < 2 um

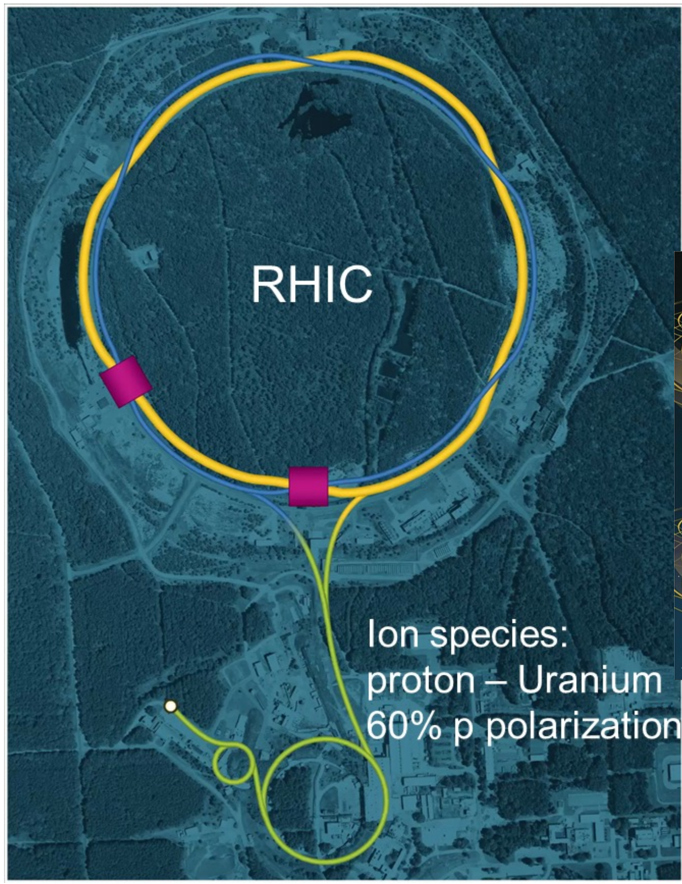
Low Energy RHIC electron Cooler

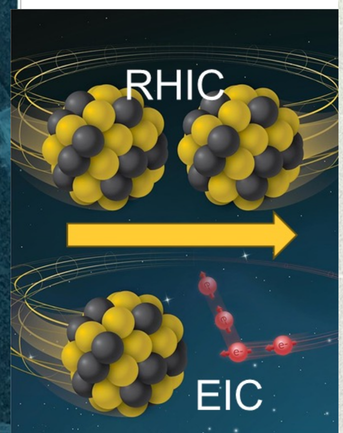
- LEReC operational electron cooler:
  - utilizes RF-accelerated electron bunches
  - uses non-magnetized electron beam (no magnetization at the cathode and no continuous solenoidal field in cooling section)
- LEReC approach to cooling is directly scalable to high-energies – pre-cooler in EIC at injection

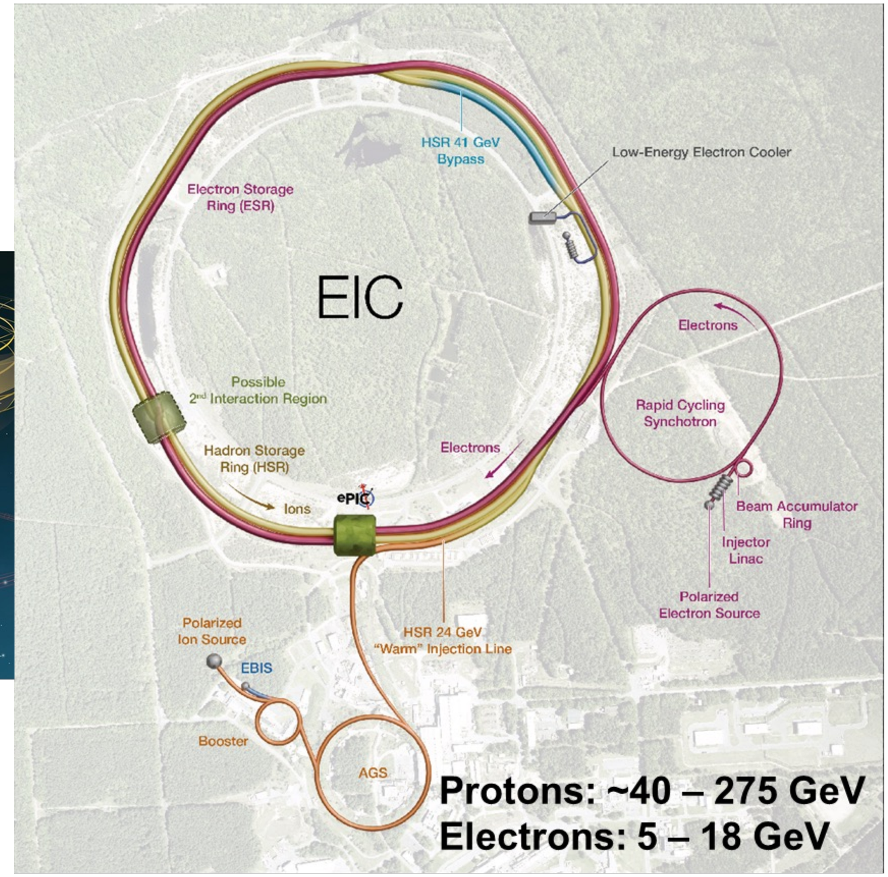


A.V. Fedotov et al., "Experimental demonstration of hadron beam … ", PRL 124, 084801 (2020)]

From RHIC to EIC







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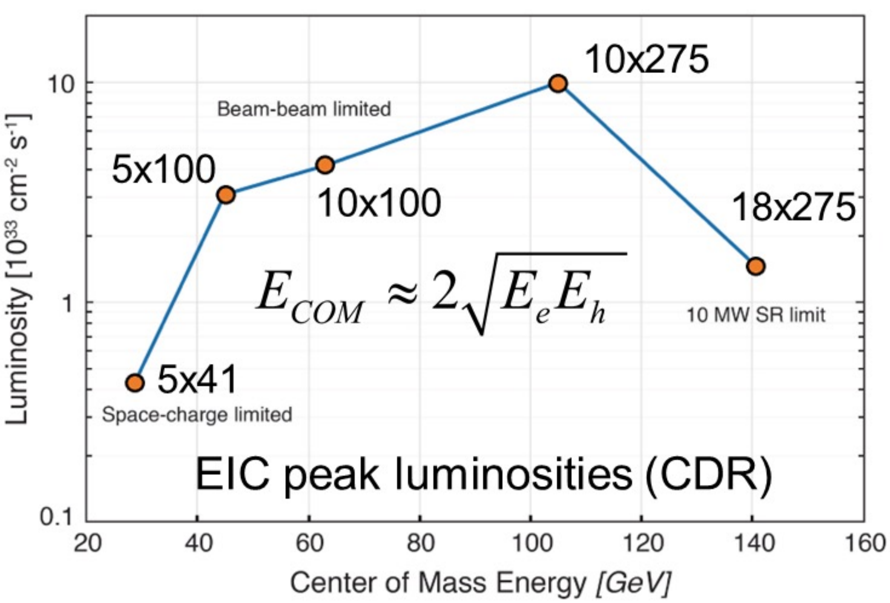
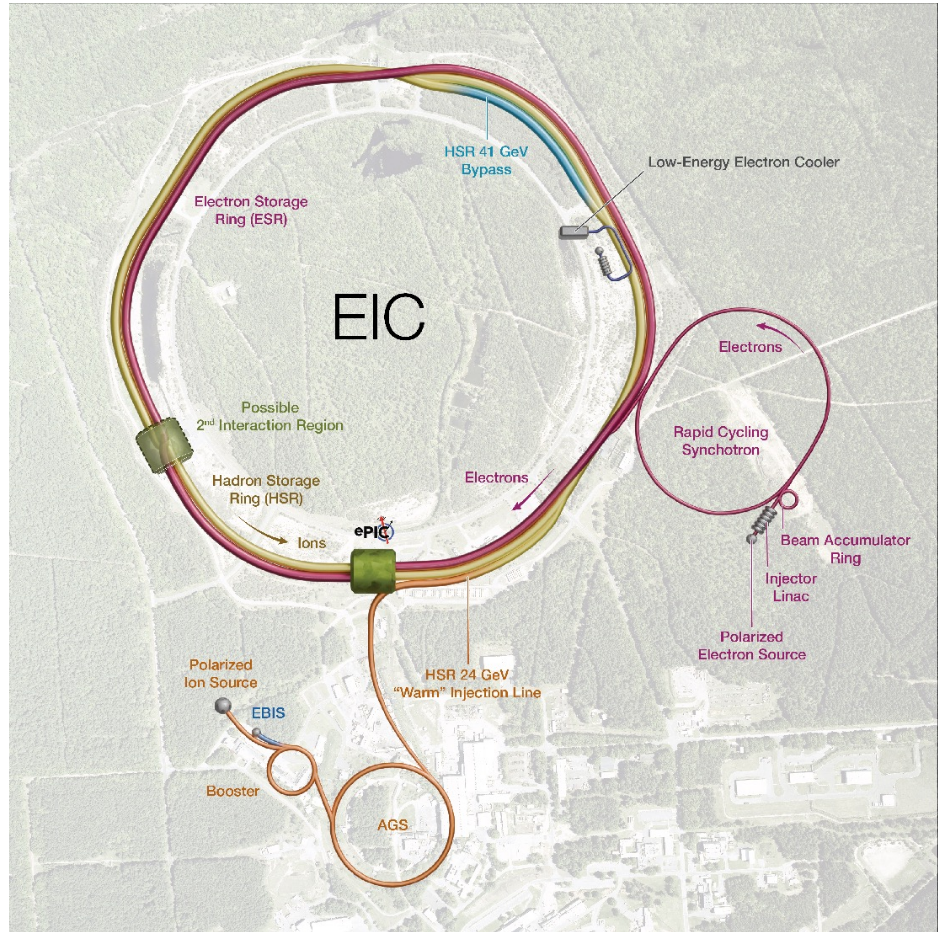
EIC at Brookhaven National Lab

- Center-of-mass energies: ~20 to ~140 GeV (e-p)
- High degree of beam polarization: ~70%
- Availability of ion beams: from proton to Pb
- Luminosity: $10^{33} – 10^{34}$ $cm^{-2}sec^{-1}$
- Possibly more than one IR





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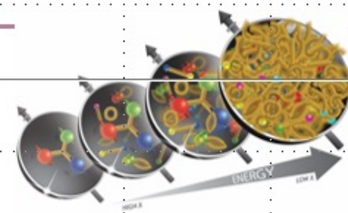
EIC Accelerator Performance

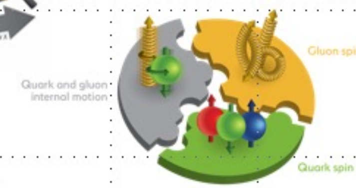
wide center-of-mass energy $\sqrt{s}$: 20 – 140 GeV :

- map the out nucleon and nuclei structure from high to low x



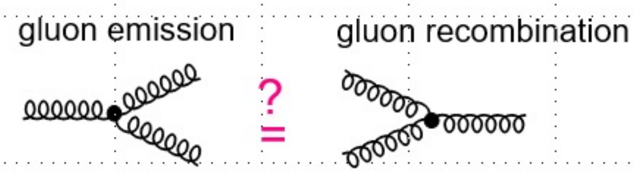
polarized electron and hadron (p, He-3) beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the spatial and momentum structure of the nucleon in 3d
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei



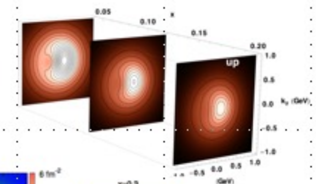
nuclear beams: d to Pb

- accessing the highest gluon densities → saturation
- quark and gluon interact with a nuclear medium



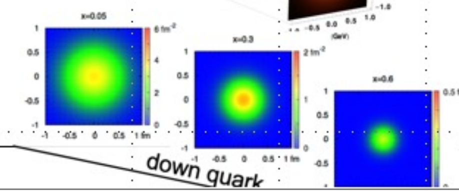
high luminosity 10^{33}-10^{34} $cm^{-2}s^{-1}$:

- mapping the spatial and momentum structure of nucleons and nuclei in 3d
- access to rare probes, i.e. Ws



large acceptance (0.2 – 1.3 GeV) through forward focusing IR magnets

- spatial imaging of nucleons and nuclei



Electron-Ion Collider

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EIC hadron beam cooling

- **Low-energy cooling (LEC):**

The goal of cooling at proton injection energy is to obtain initial proton parameters by cooling the vertical emittance from ~2 um to 0.3-0.5 um (rms normalized).

Cooling at injection energy of protons (24 GeV) requires a 13 MeV electron beam.

Our present design concept is similar to the existing RHIC LEReC system

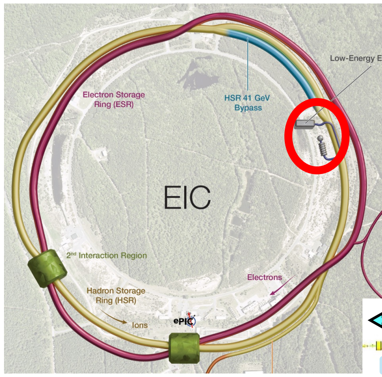
A. V. Fedotov et al. "Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches", Phys. Rev. Lett. 124, 084801 (2020)

- **High-energy proton cooling at collisions** (possible future upgrade)

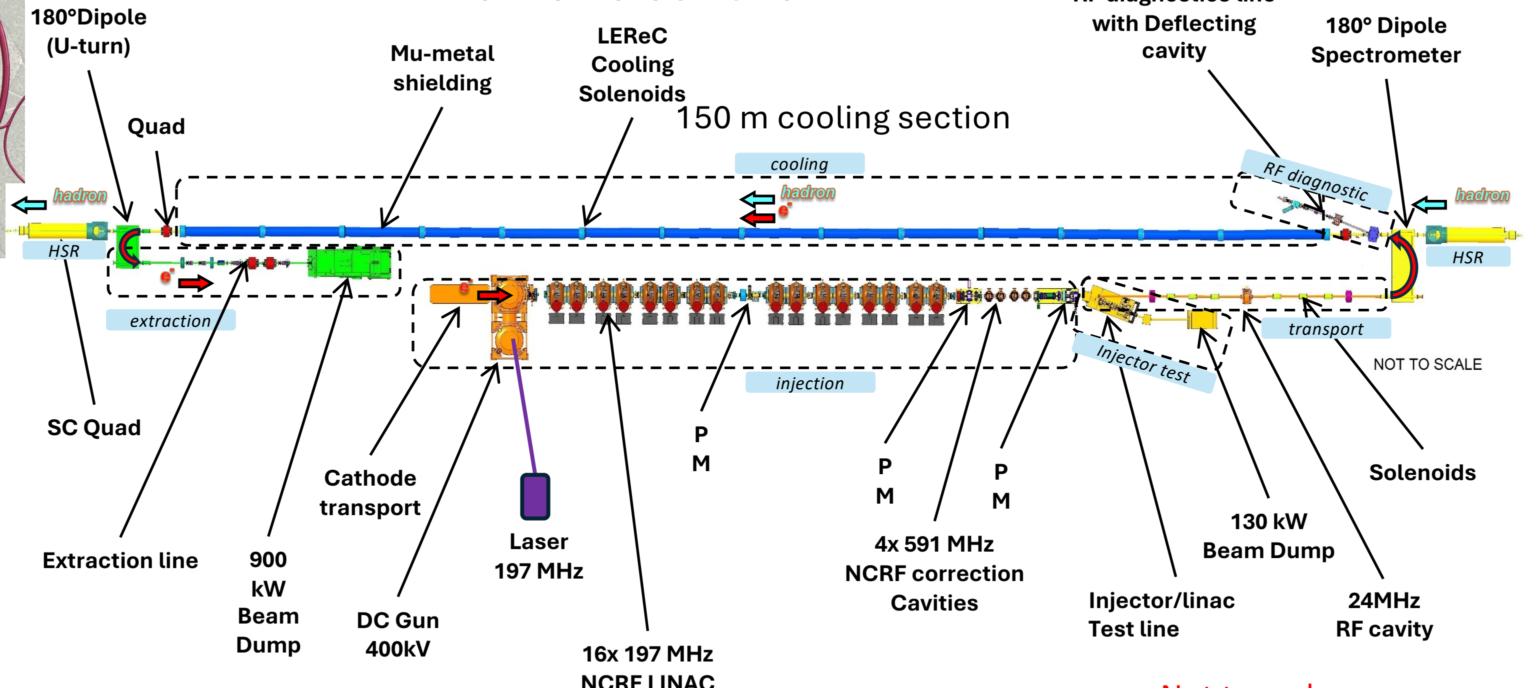
The goal of cooling at EIC proton collision energies of 41, 100 -- 275 GeV is to counteract the longitudinal and transverse emittance growth and to maintain the 'flat' proton beam. Several candidate concepts are being considered.

- **Ion beam cooling at collisions:** Conventional microwave stochastic cooling

Low-energy Cooler Concept



24 GeV protons
12.5 MeV electrons



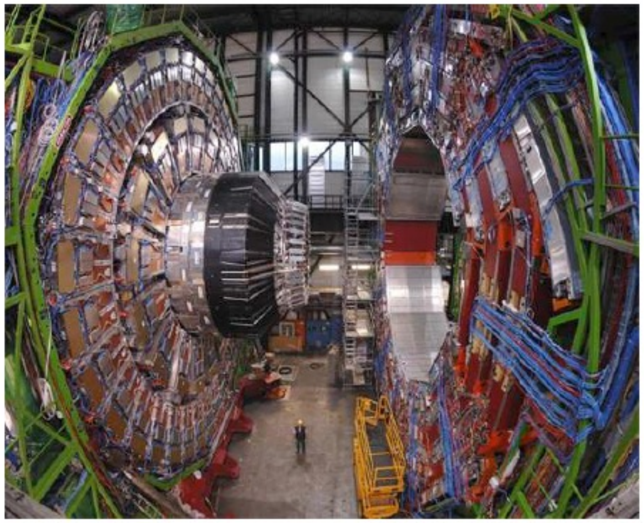
IR2 layout (all within the existing RHIC Tunnel)

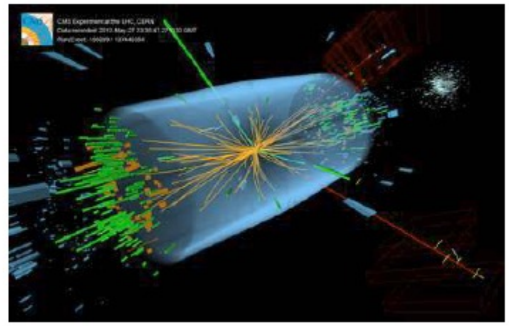
Compatible with future beam cooling upgrades at the collision energies

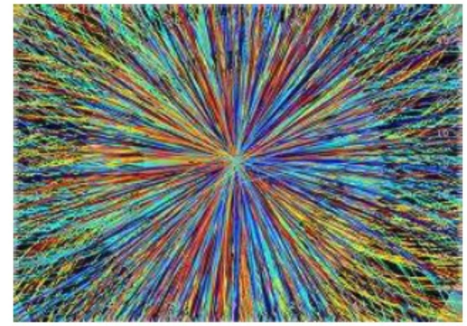
Not to scale

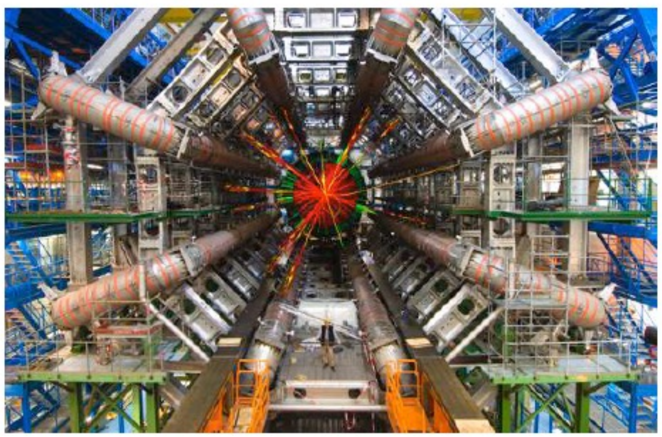
LEC parameters
Operation kinetic energy: 12.5 MeV,
Average current: 70 mA,
Normalized emittance < 1.5 um

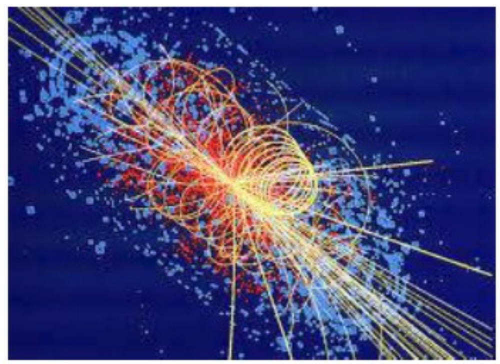
LHC – energy frontier

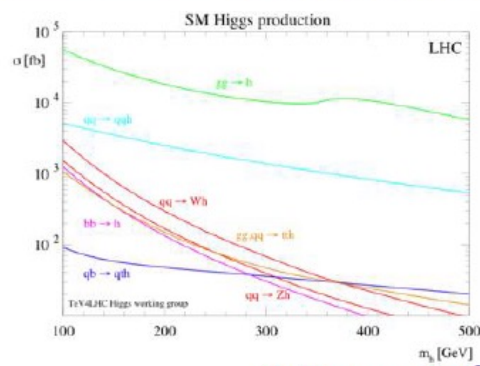


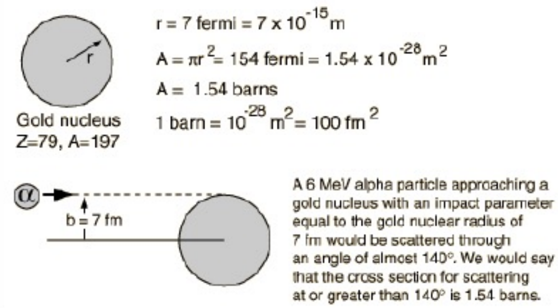






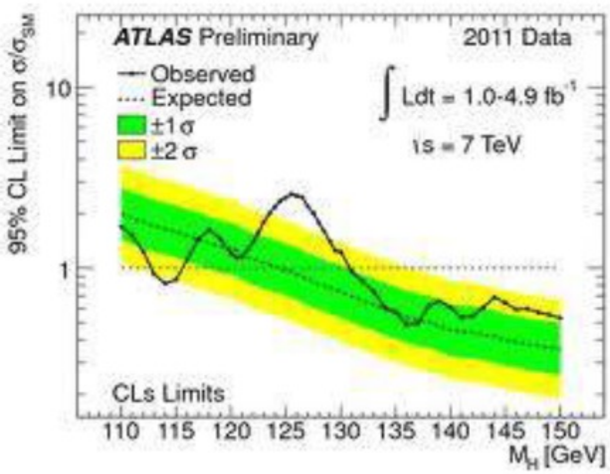


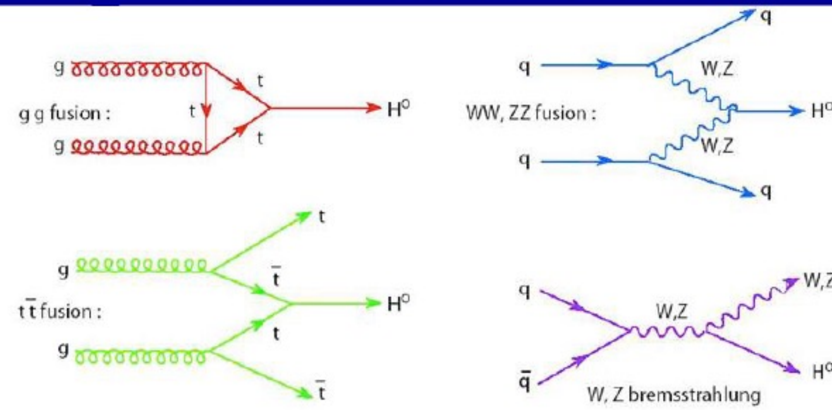


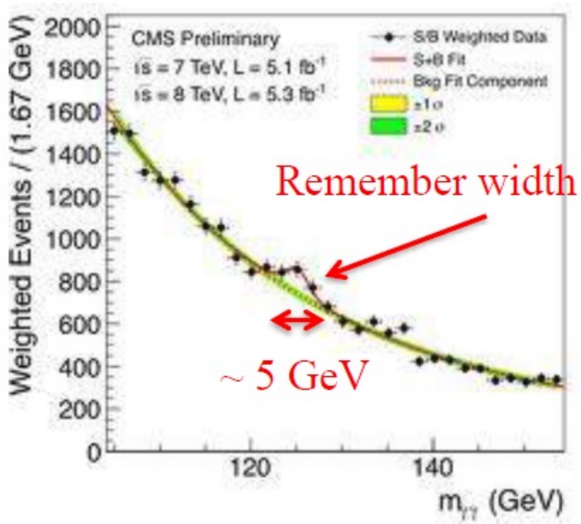


1 Barn=10^{-28} cm^2, 1 fb=10^{-43} cm^2

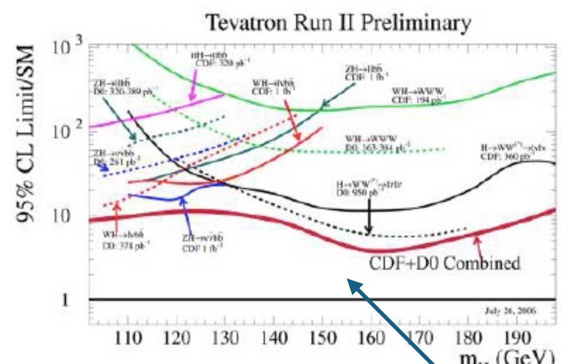
Higgs at LHC: blip in cross-section







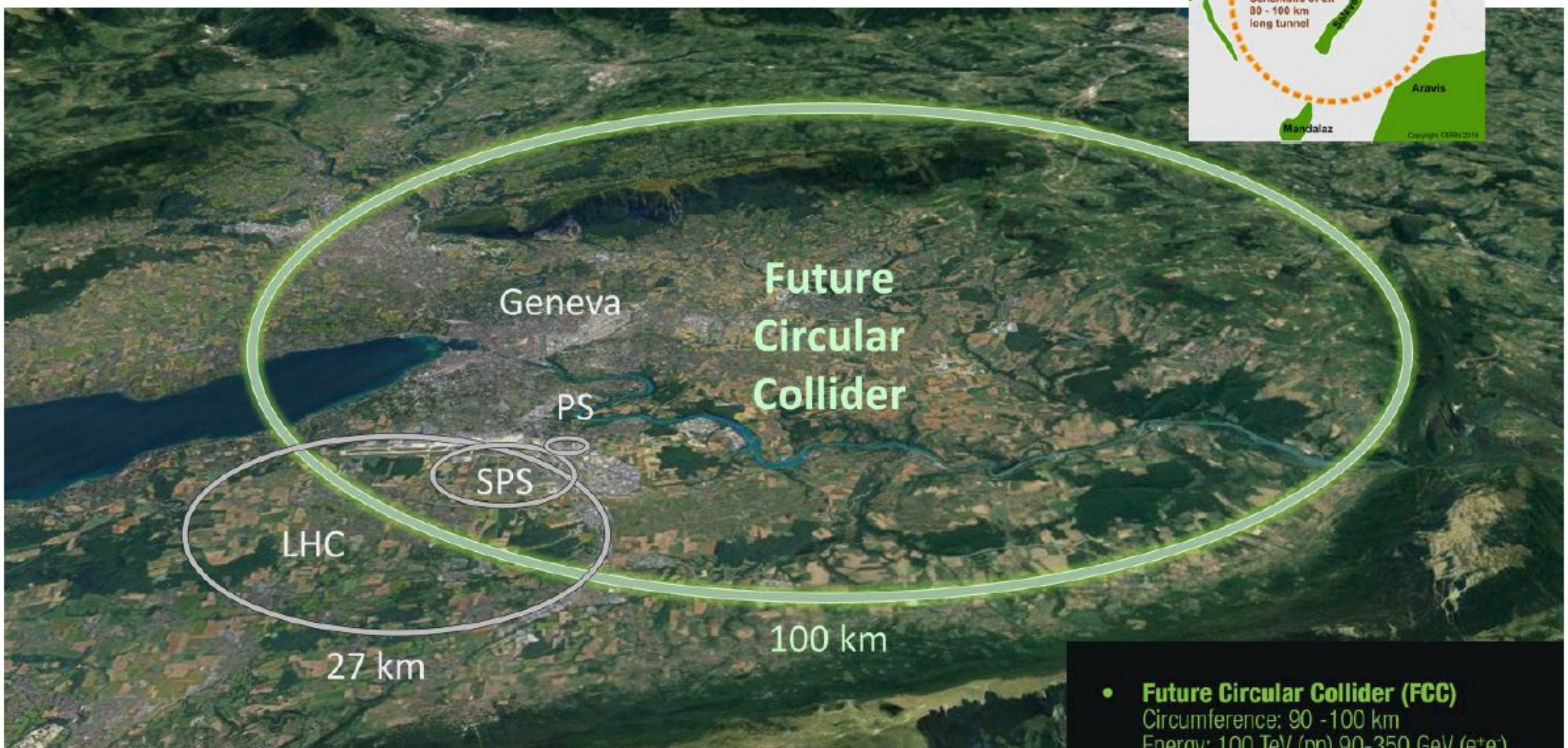
Tevatron at FERMILAB has necessary energy reach but did not had enough luminosity to find
Higgs – it only had "hints"



Tevatron might be able to detect HIGGS earlier

Proposal for Future Circular Collider (FCC) at CERN

C.M. Energy: 365 GeV e^+e^-, 100 TeV pp,

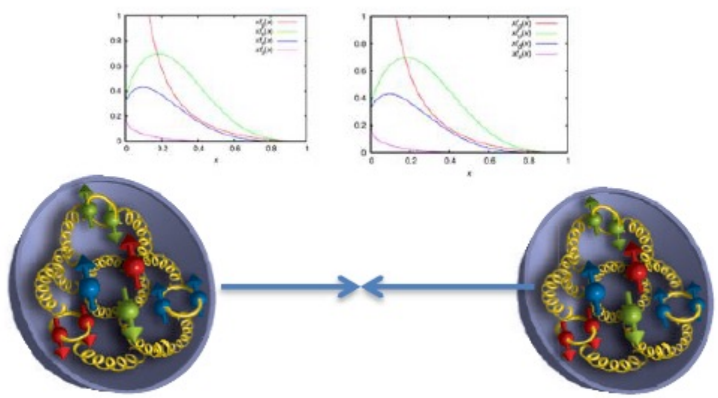


- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)
- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)
- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV (pp)

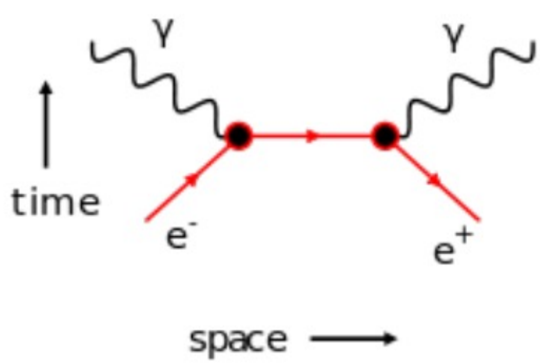
New challenge: SR power of proton beam is large and has to be evacuated from inside 4K SC magnets…

Why e^+e^- or e^-h colliders?

To the best of our knowledge electrons and positions (or muons) do not have internal structure



Colliding hadron is as colliding
two caps of quark-gluon soup
(+ sea quarks): energies and polarization
are varying and initial state is unknown



Pure initial state (energy of annihilated electron-positron pair)

Very precise knowledge of the energy and polarization

B-factories

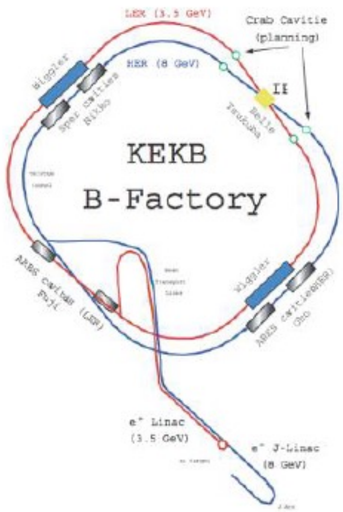
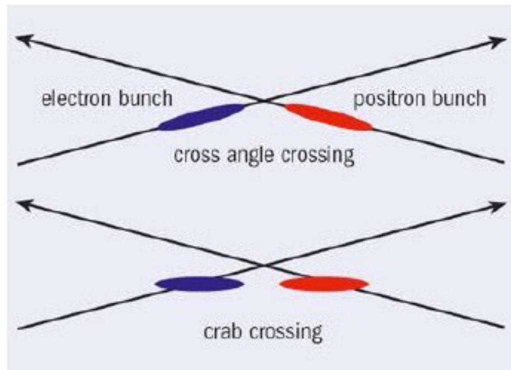
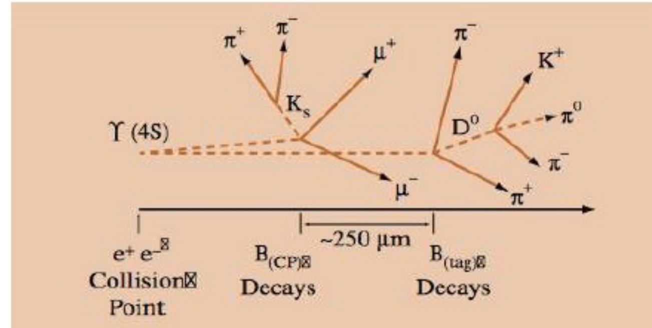


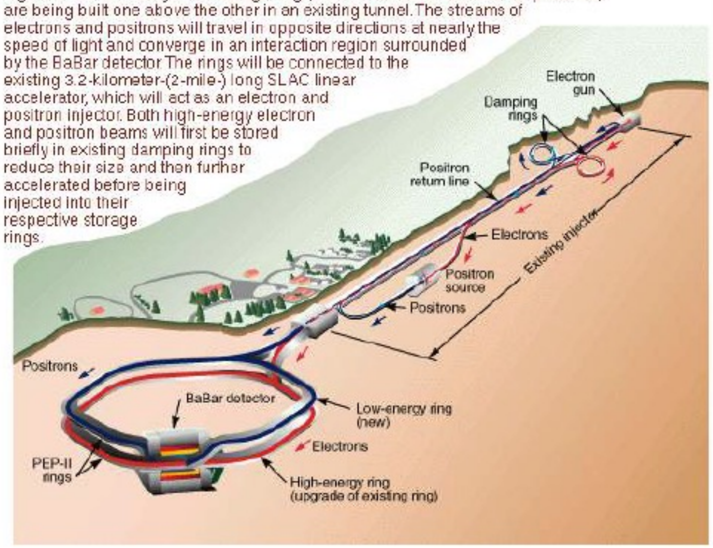
Figure 1: A schematic view of the KEKB.

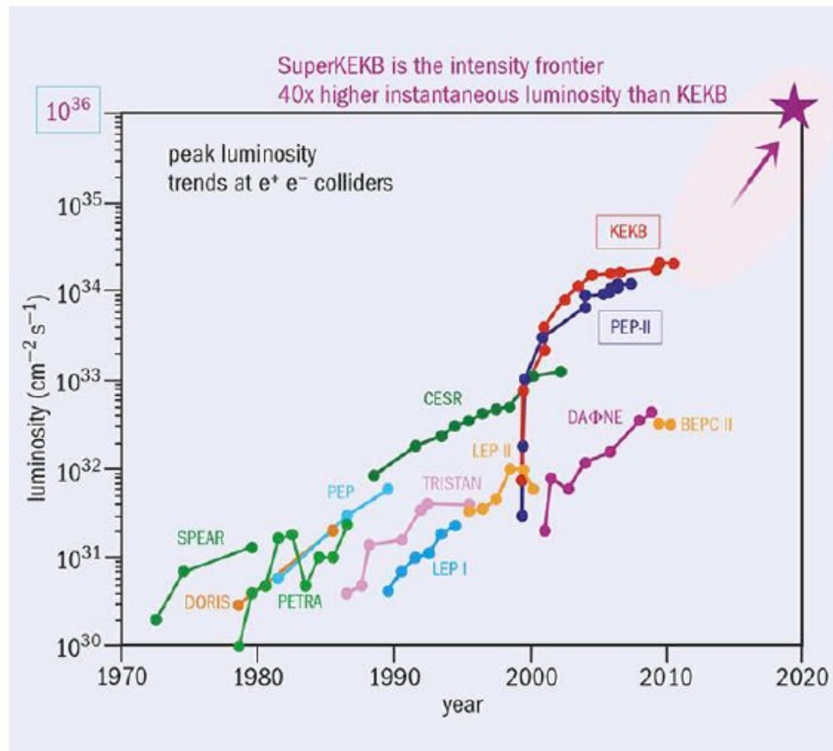




A typical "golden event" at an asymmetric B factory. The first B meson decays into a J/ψ (which immediately decays to $\mu^+\mu^-$) and a K_S, while the second B yields a clear tag.

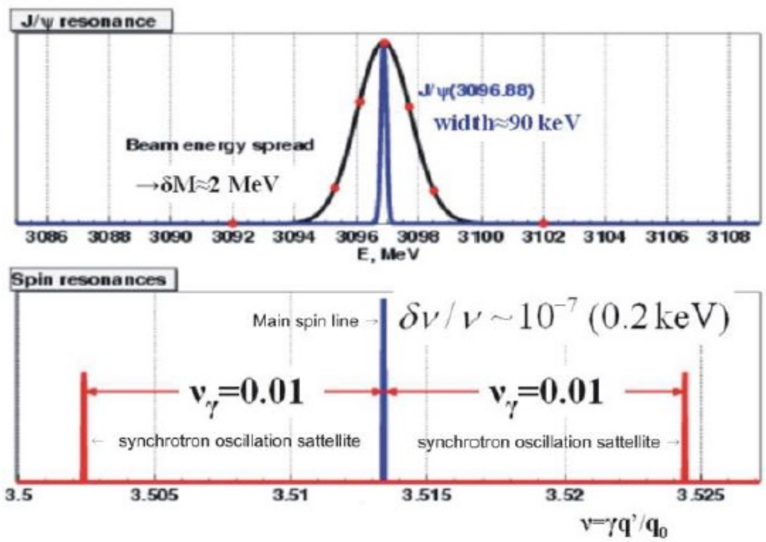
Figure 2. The B-Factory's two storage rings, one for electrons and one for positrons, are being built one above the other in an existing tunnel. The streams of electrons and positrons will travel in opposite directions at nearly the speed of light and converge in an interaction region surrounded by the BaBar detector. The rings will be connected to the existing 3.2-kilometer-(2-mile-) long SLAC linear accelerator, which will act as an electron and positron injector. Both high-energy electron and positron beams will first be stored briefly in existing damping rings to reduce their size and then further accelerated before being injected into their respective storage rings.

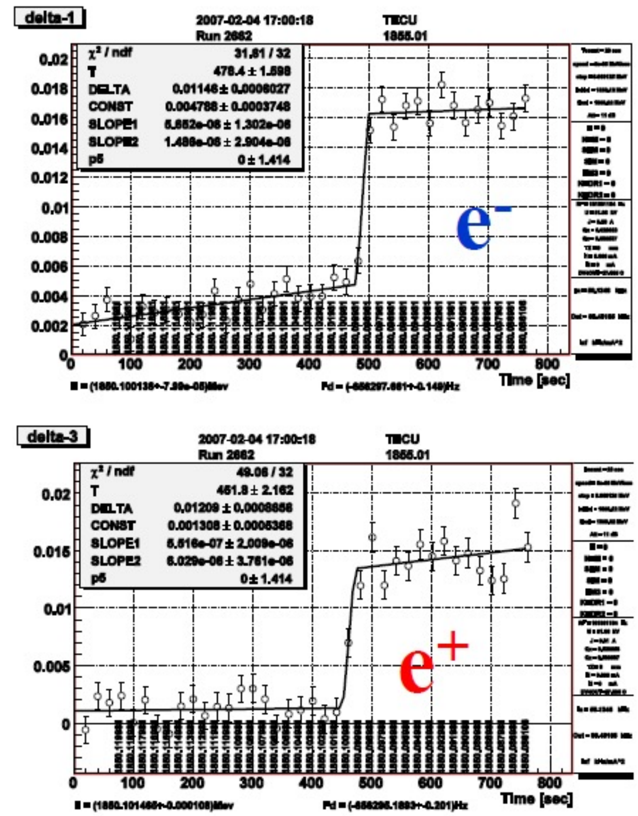




Reaching extreme resolution of measurements

BEAM ENERGY SPREAD AND SPIN SPECTRA at VEPP-4M





In homogeneous magnetic field a width of the spin spectra is ~10^{-9} !
In real storage ring it is ~10^{-7} due to betatron oscillations and nonlinearity of magnetic field and noise in magnet system

E_p - E_e =(1.32±0.14) keV: 0.4 p.p.m. energy accuracy

Compare this with 1% scale resolution in p-p collisions

Largest e^+e^- collider - LEP

PR04.00 23.06.00

The LEP machine at CERN is the largest particle collider in the world. In a ring 27 km in circumference, buried about 100 m underground, bunches of electrons and positrons race round in opposite directions...

Last sprint for LEP

The Director General, Prof. Luciano Maiani, began his report with the performance of the Laboratory's flagship accelerator, the Large Electron-Positron collider, LEP, during its final year. LEP is achieving its highest energy collisions ever with beams of over 104 GeV, well exceeding its design energy and giving experiments a final chance of discovering the still-elusive Higgs particles before the end of it's experimental programme in September. Thanks to precision data from LEP and elsewhere, scientists already know that Higgs particles, if they exist, must be within range of LEP's successor, the LHC.

Before LHC

Under discussions

CERN

Future Circular Colliders (FCC)

	√s	Ring(km)
FCC-ee	90-365 GeV	100
FCC-hh	100 TeV	100

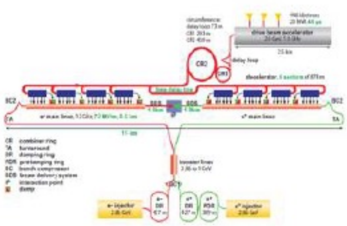
Integrated FCC program: FCC-ee as a first step, then FCC-hh

Options		
FCC-eh	3.5 TeV	Needs FCC-hh
HE-LHC	27 TeV	LHC tunnel
LE-FCC	37.5 TeV	100km

Conceptual Design Report in 2018

Common layout for FCC ee and hh

CLIC Collider at CERN



- CLIC is a linear e^+e^- collider based on "warm" RF technology with 70+ MV/m acceleration
  - The only way to get to multi-TeV e^+e^-
- 11km long for 380 GeV in the center of mass
- Under active design development

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

Japan

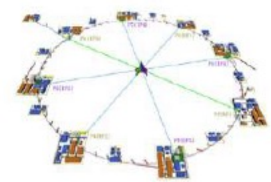
International Linear Collider

- ILC or International Linear Collider is e^+e^- linear collider with the following main parameters
  - Center of mass energy 250 GeV (upgradeable to higher energies)
  - Luminosity $>10^{34}$ $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible

China

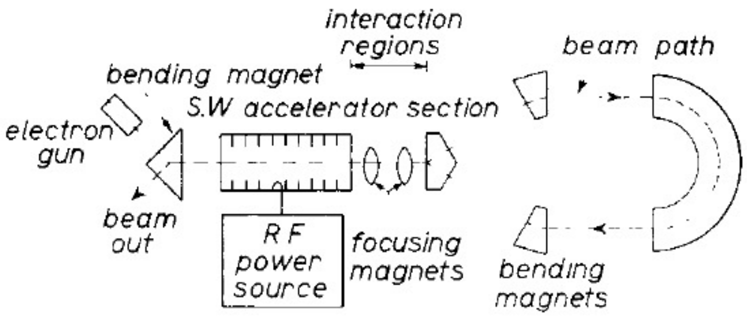
Proposals for Colliders in China: CepC and SppC

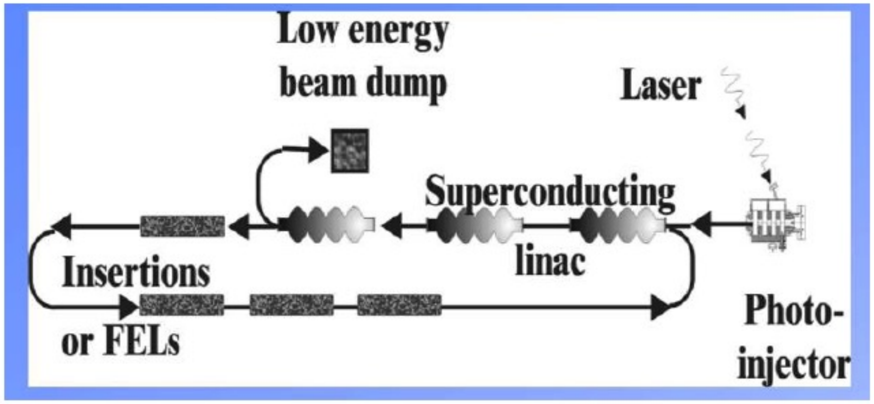
- CepC – Circular Electron Positron Collider
  - ~100 km long ring
  - 90-250 GeV in the center of mass
  - Z boson and Higgs factory
- SppC – Super Proton Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets



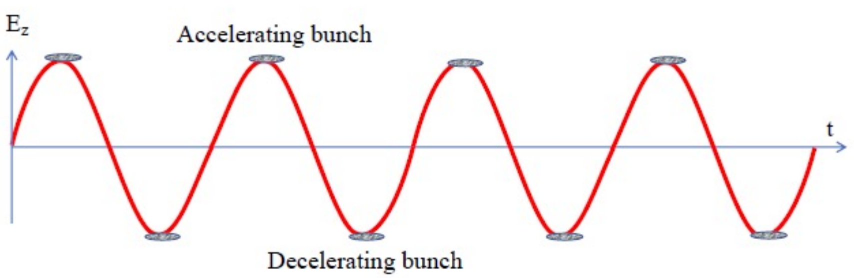
Superconducting RF Energy Recovery Linac

- Invented by M. Tigner, Nuovo Cimento **37** 1228 (1965)





- followed by Stanford, BINP, Jefferson Lab, JAERI, BNL, Cornell, LBNL, Daresbury *and more …*



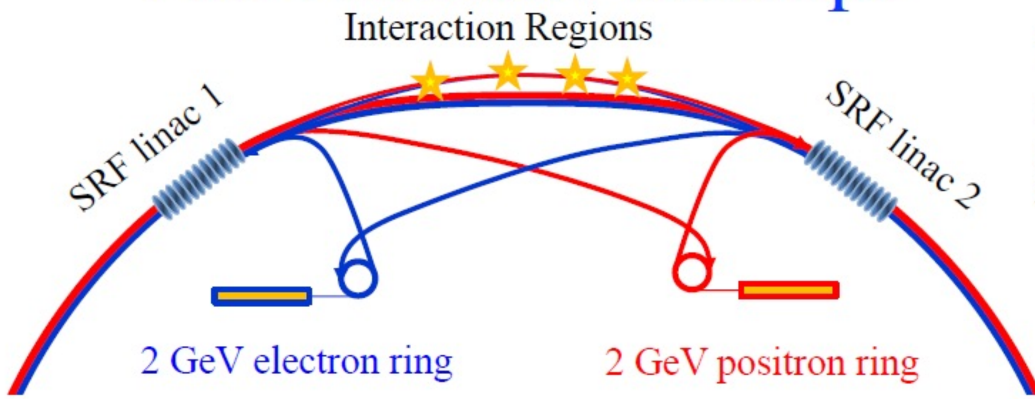
ERLs - path to the future

As compared to a ring, the beam properties are largely determined by the injector system:

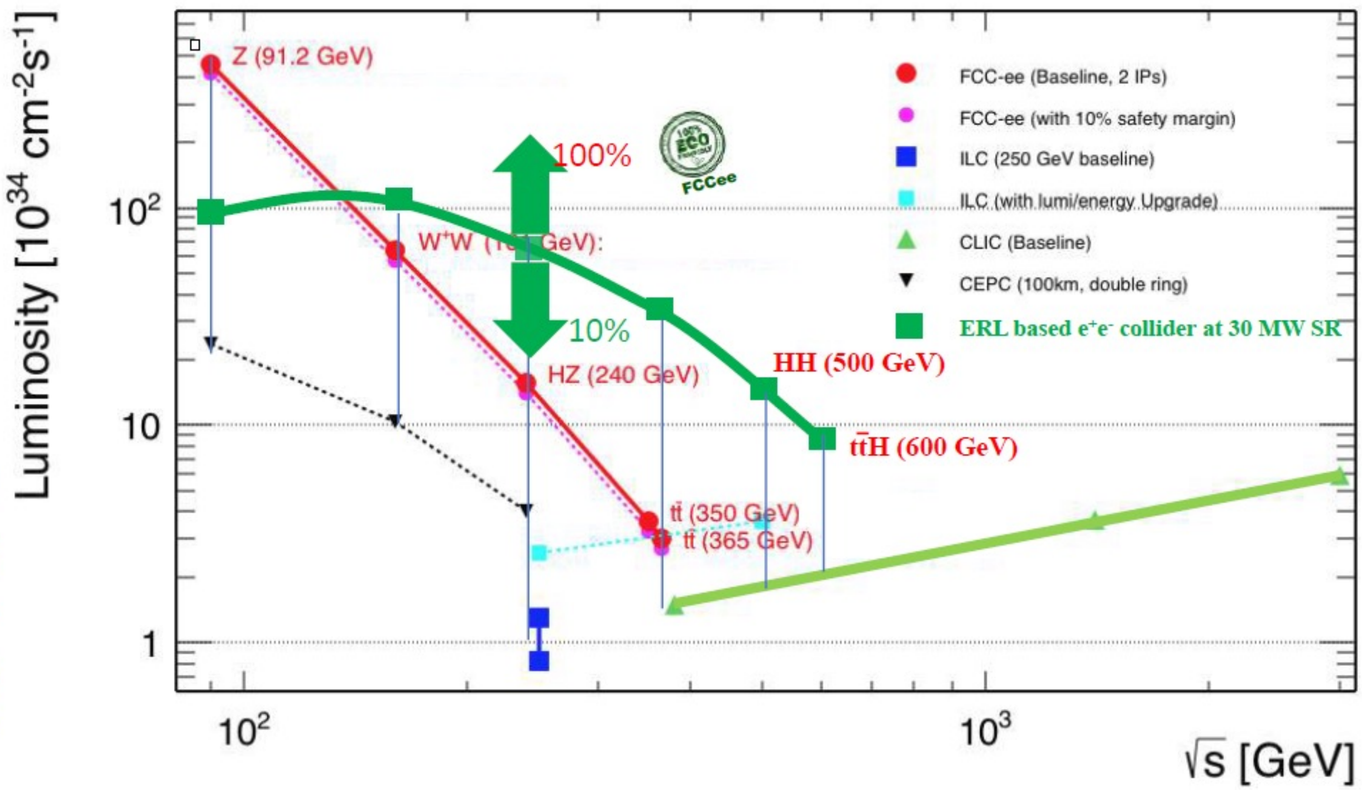
- The bunch length can be in fsec range
- Smaller emittances
- Higher coherence fraction

Current of 0.1 A and energy of 200 GeV leads to a beam power of 20 GW !!!
The energy of the spent beam has to be recaptured for the new beam.

ERL collider concept



CERN Courier News:
"US proposal teases FCC-ee energy boost"
https://cerncourier.com/a/us-proposal-teases-fcc-ee-energy-boost/



- F
- B
- B
- A … RF linac
- D … epeats

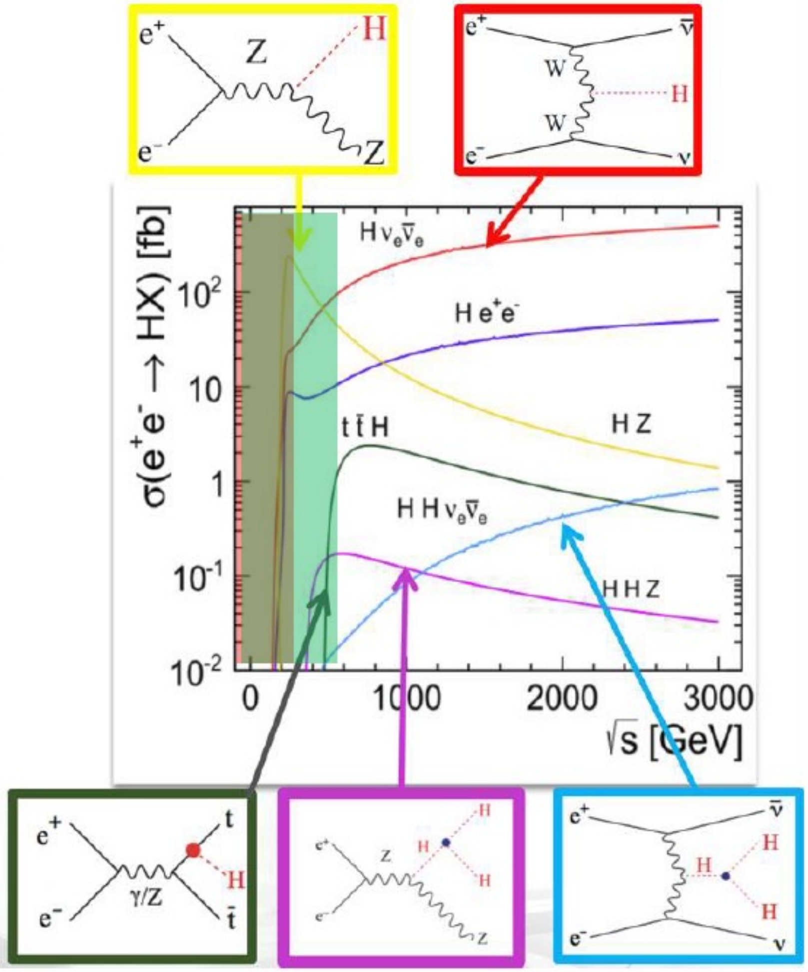
e^+e^- colliders

$\sqrt{s}$ [GeV]	Science Drivers
90-200	EW precision physics, Z, WW
250	Single Higgs physics (HZ), Hνν
365	tt
500-600	HHZ, ttH direct access to Higgs self-couplings, top Yukawa couplings
1000-3000	HH$\nu\nu$ Higgs self-couplings in VBF

Precision measurement and search for new physics studying deviations from the SM

→ Need high luminosity (and energy)

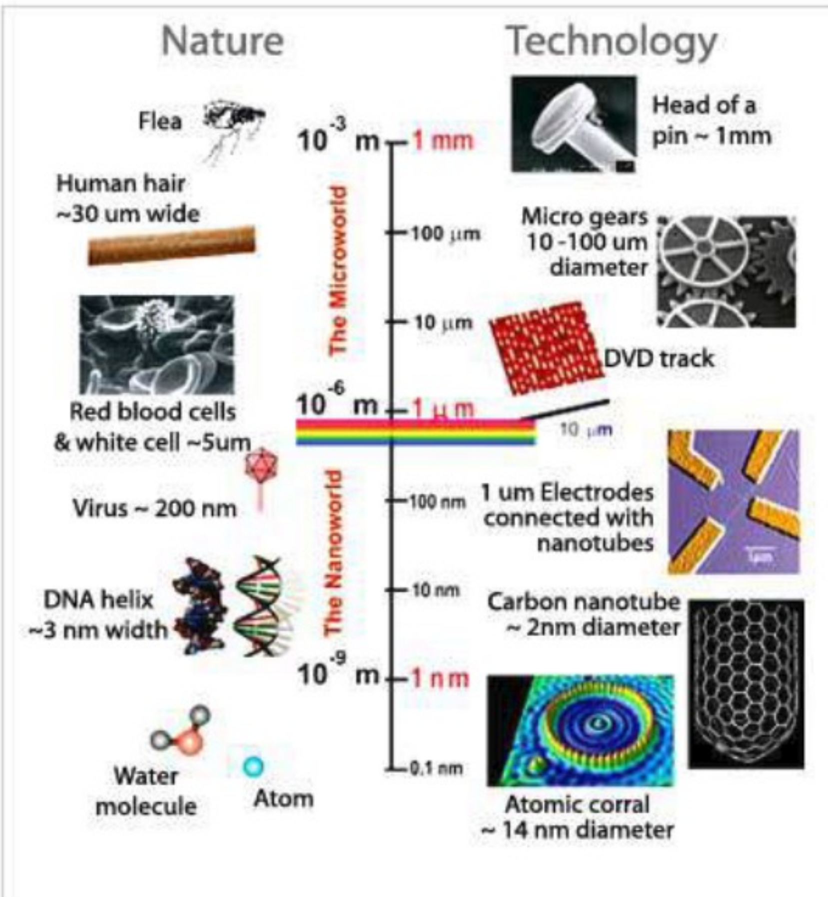
U.S. DEPARTMENT OF ENERGY



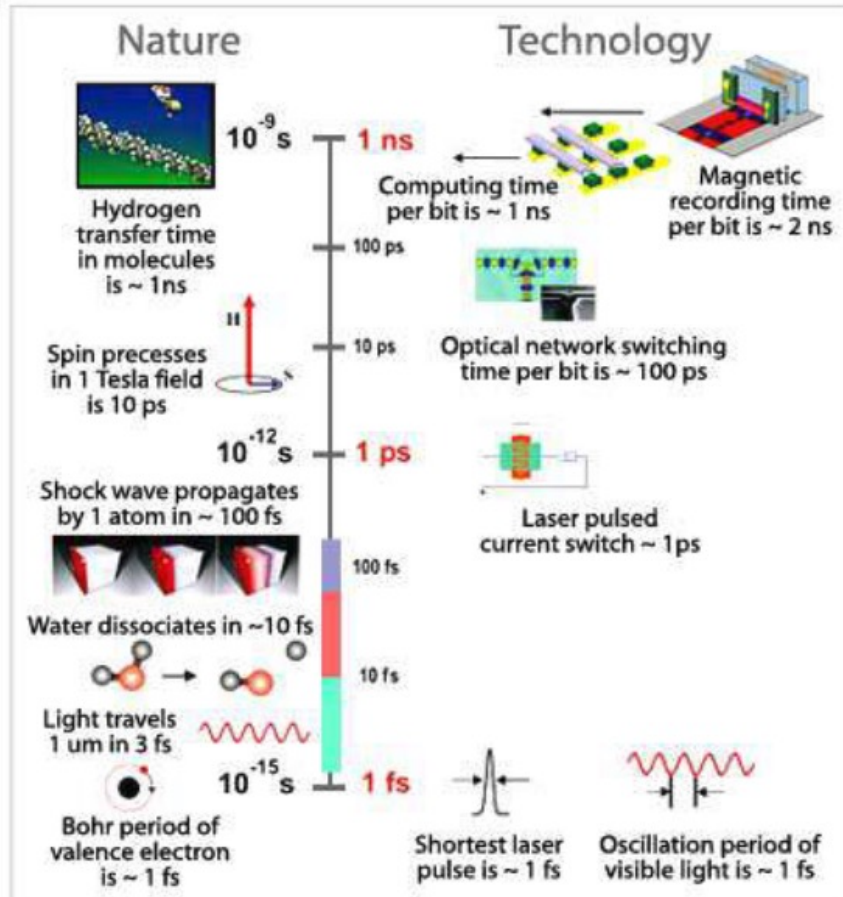
An ERL e^+e^- collider would provide higher luminosity and high-energy up to c.m. energy of 500 or 600 GeV to enable double-Higgs and $t\bar{t}H$ production

What Light Sources Are For?

Ultra-Small



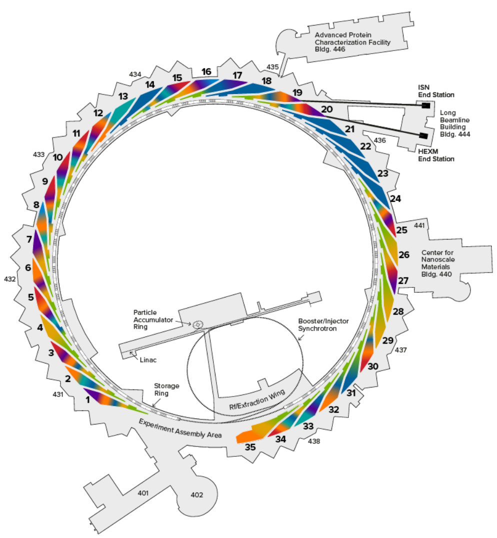
Ultra-Fast



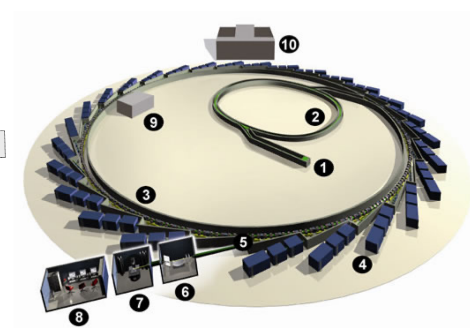
http://www.sc.doe.gov/bes/scale_of_things.html

Synchrotron light sources

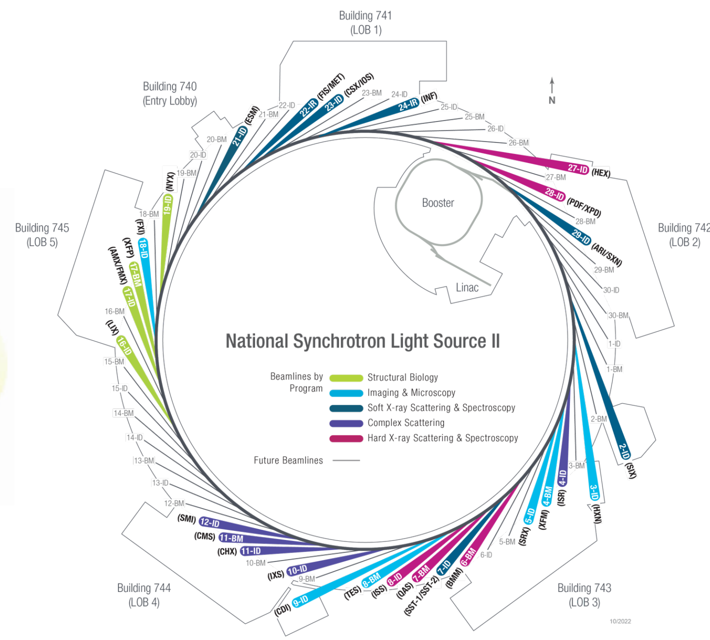
- Remember the synchrotron radiation that limited our electron energy?
- Turns out: it can be useful!
- Source of bright, short X-ray pulses



Advanced Photon Source,
Argonne National Laboratory

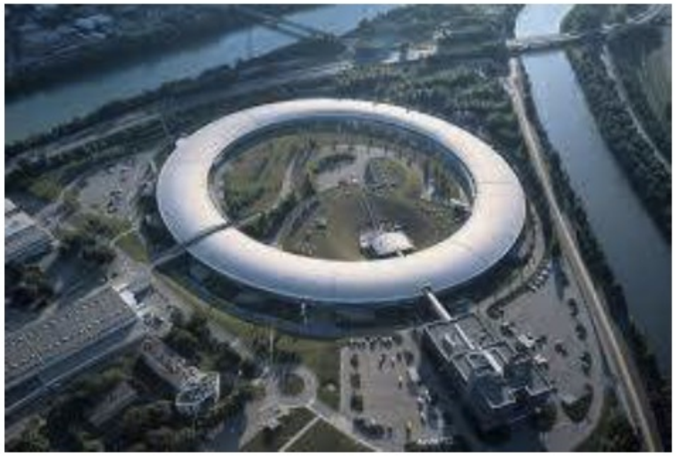


Diamond Light Source,
Oxfordshire, UK



NSLS-II,
Brookhaven National
Laboratory

SR Light Source Worldwide: 4 out of few dozens



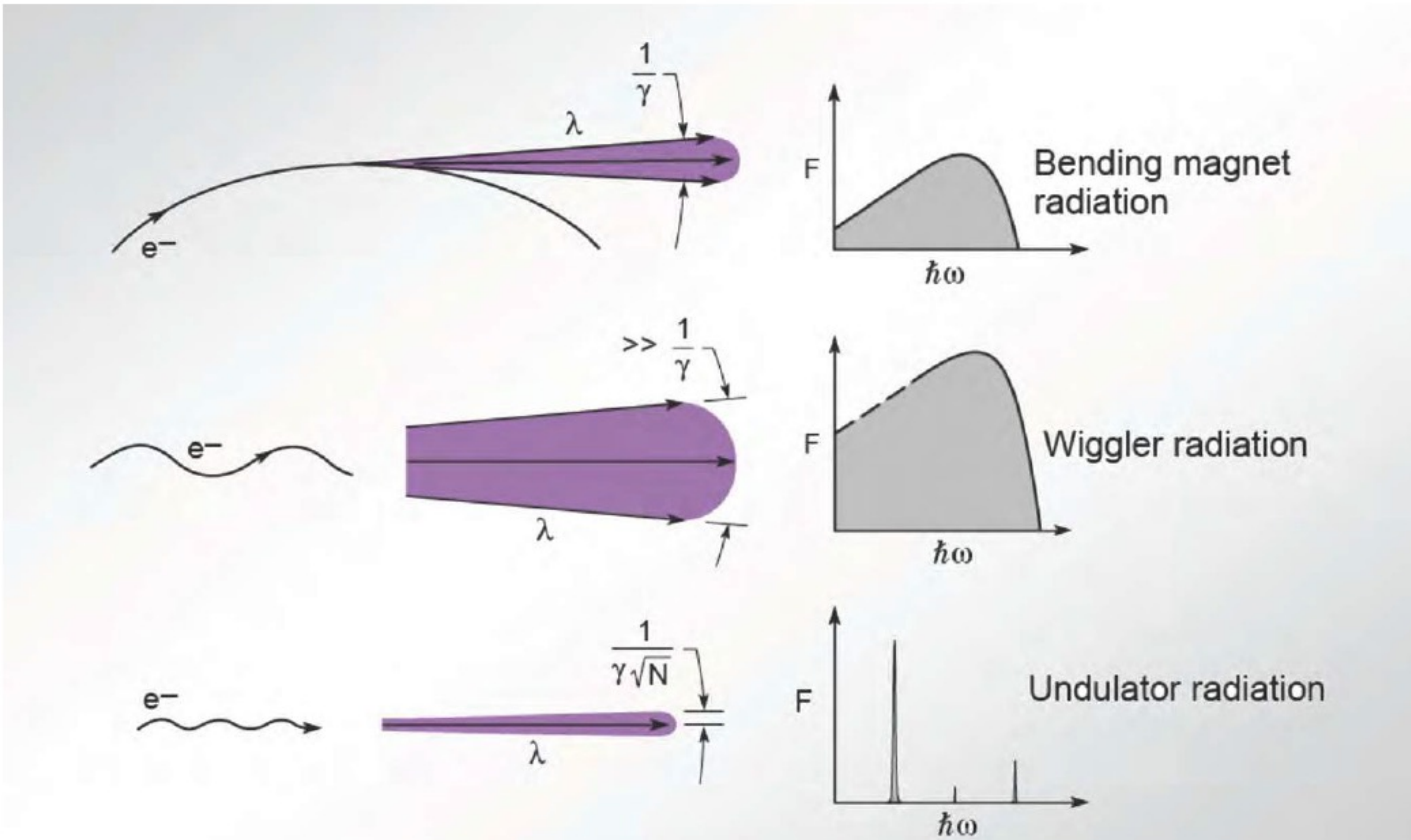
ESRF, 6 GeV

SPring-8, 8 GeV

NSLS II, 3 GeV

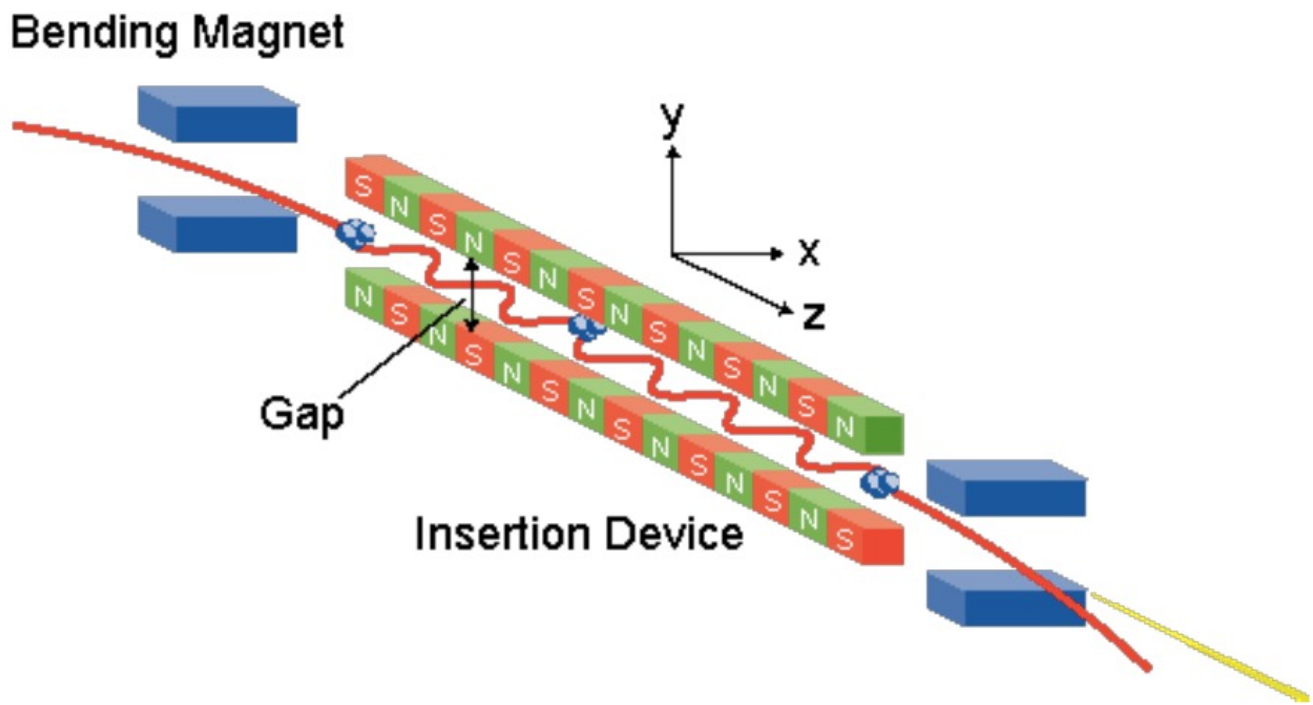
SSRF, 3.5 GeV

Difference between bending magnet and Undulator/Wiggler radaition



Courtesy of W. Barletta

SR from Undulator/Wiggler



They are called 'insertion devices' in straight sections.
Modern accelerators provides many long straight sections.

Undulator: Power scales an N_e

Brilliance

- Quality of synchrotron source is given by "brilliance"
- Number of photons per second, per photon energy bandwidth, per solid angle, per unit source size
- $Br. \propto \frac{\mathrm{I}}{\varepsilon_x \varepsilon_y}$, I is the beam current

Close to home: NSLS II

Discovery-Class Science

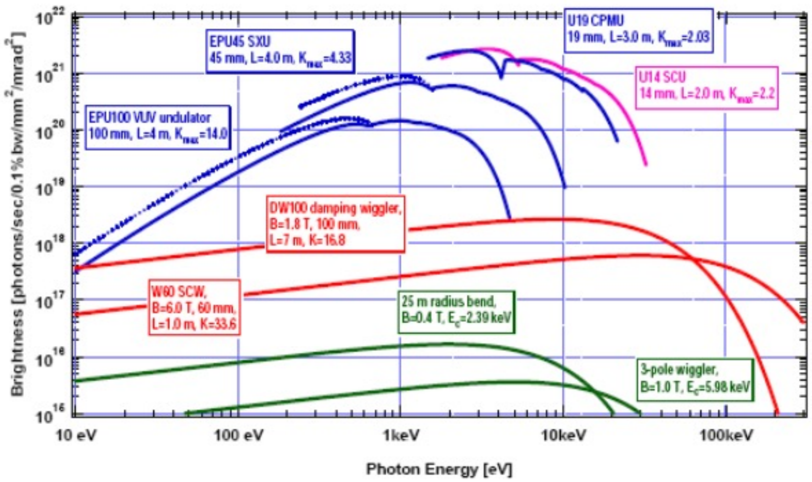
Clean and Affordable Energy: new materials that use sunlight to split water for hydrogen production and harvest solar energy with high efficiency and low cost.

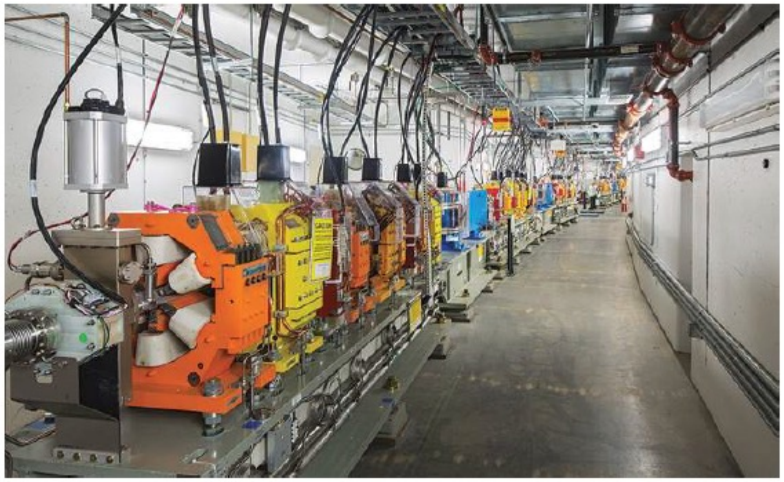
Molecular Electronics: new electronic materials that scale beyond silicon could be used to make faster, less expensive, energy-efficient electronics.

Self-assembly: hierarchical structures from nanometer-scale building blocks, mimicking nature to assemble nanomaterials into useful devices more simply and economically.

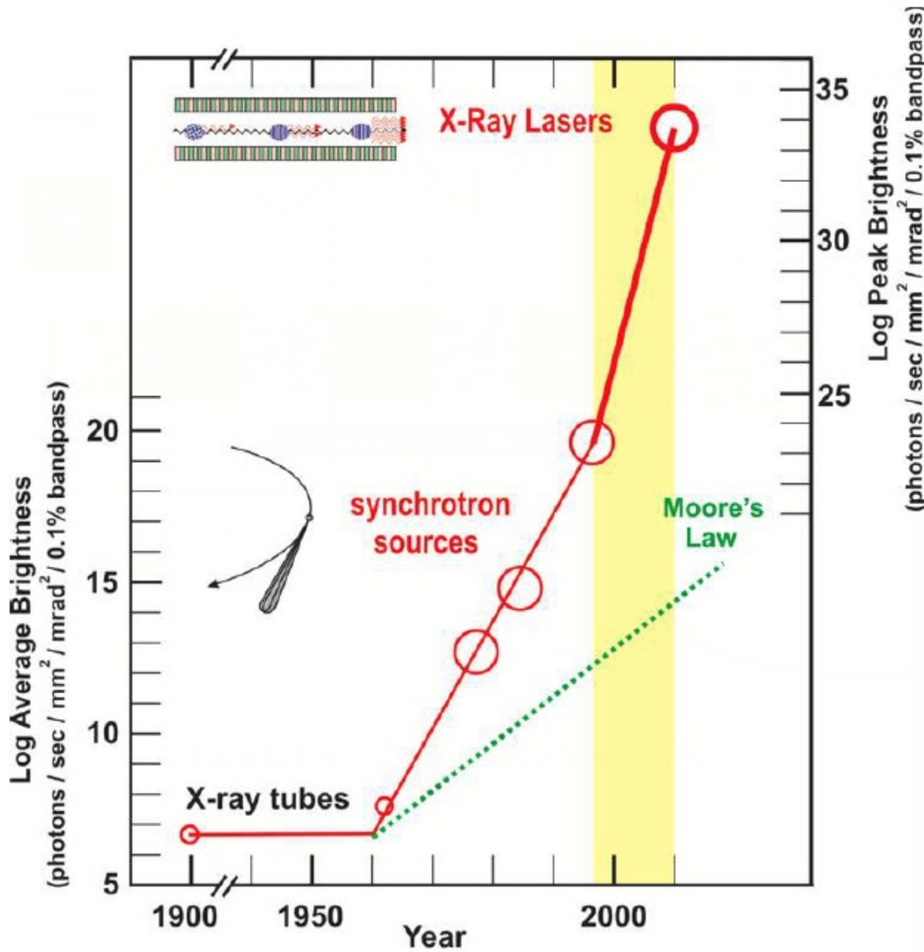
High-Temperature Superconductors may lead to materials that allow super-efficient electricity transmission at room temperature.

50-fold brighter than other state-of-the-art light sources in USA

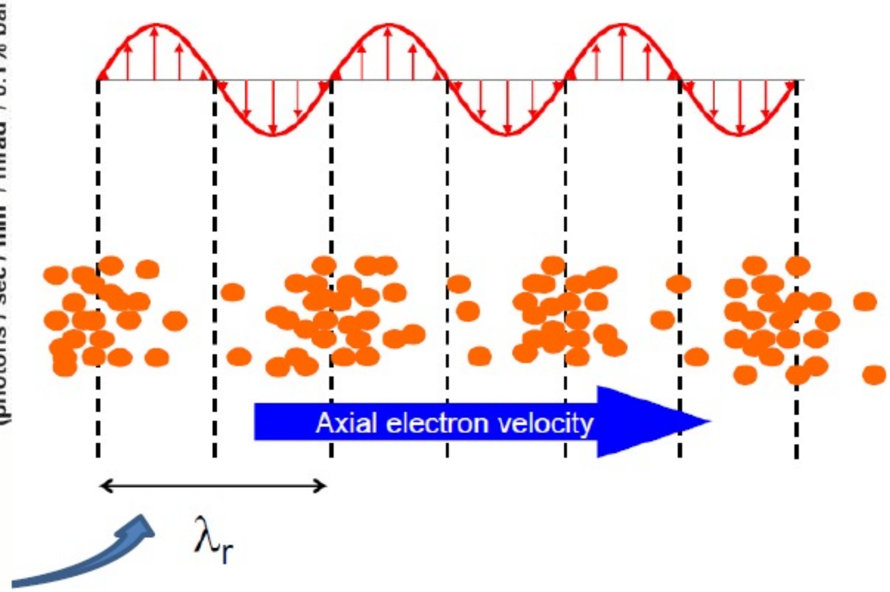




FEL: Micro-Bunching and Coherent Radiation
Inventor: John Madey



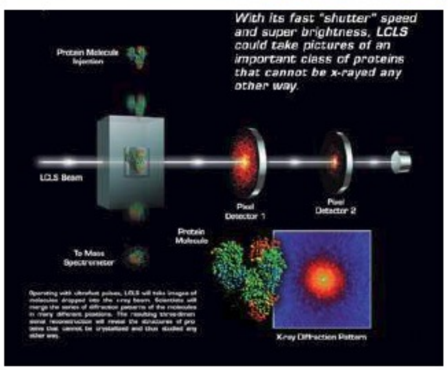
FEL: Power scales as N_e^2



X-ray Free Electron lasers

https://lcls.slac.stanford.edu/overview

LCLS at SLAC
First X-ray laser



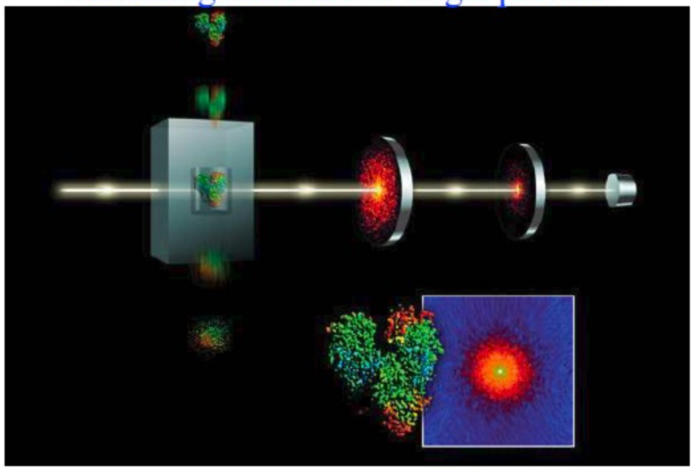
SACLA X-ray FEL
Japan

PAL X-ray FEL
South Korea

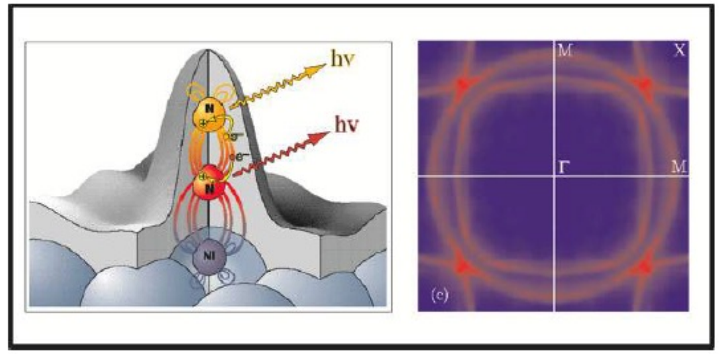
The European X-ray FEL with SRF linac

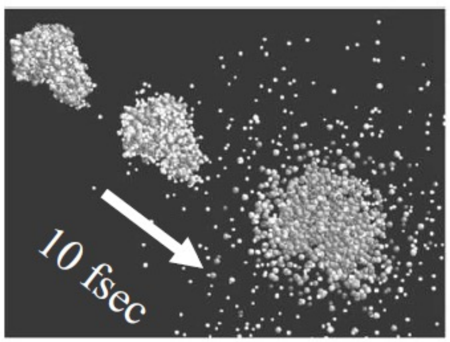
Some applications

Single shot X-ray diffraction:
Restoring structure of single protein

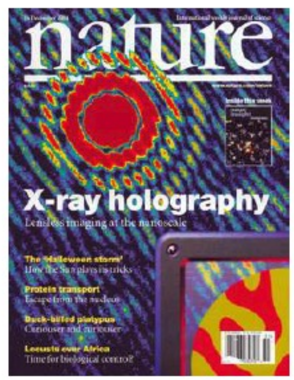


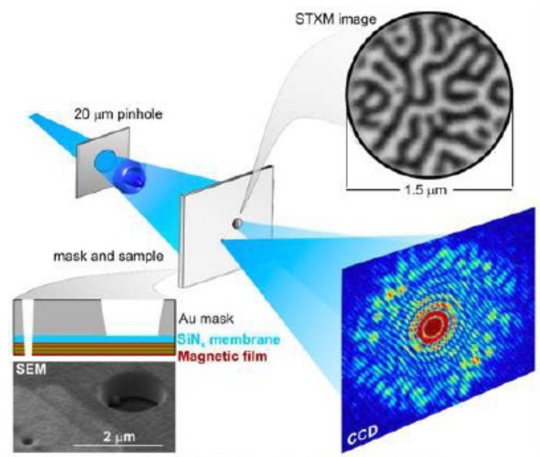
Locating electrons





To decipher a single protein or a cell one needs a single shot fsec pulse with lot of X-ray photons

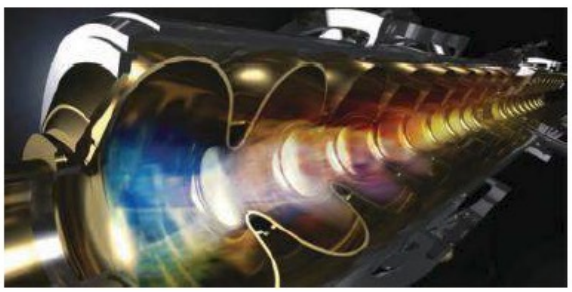


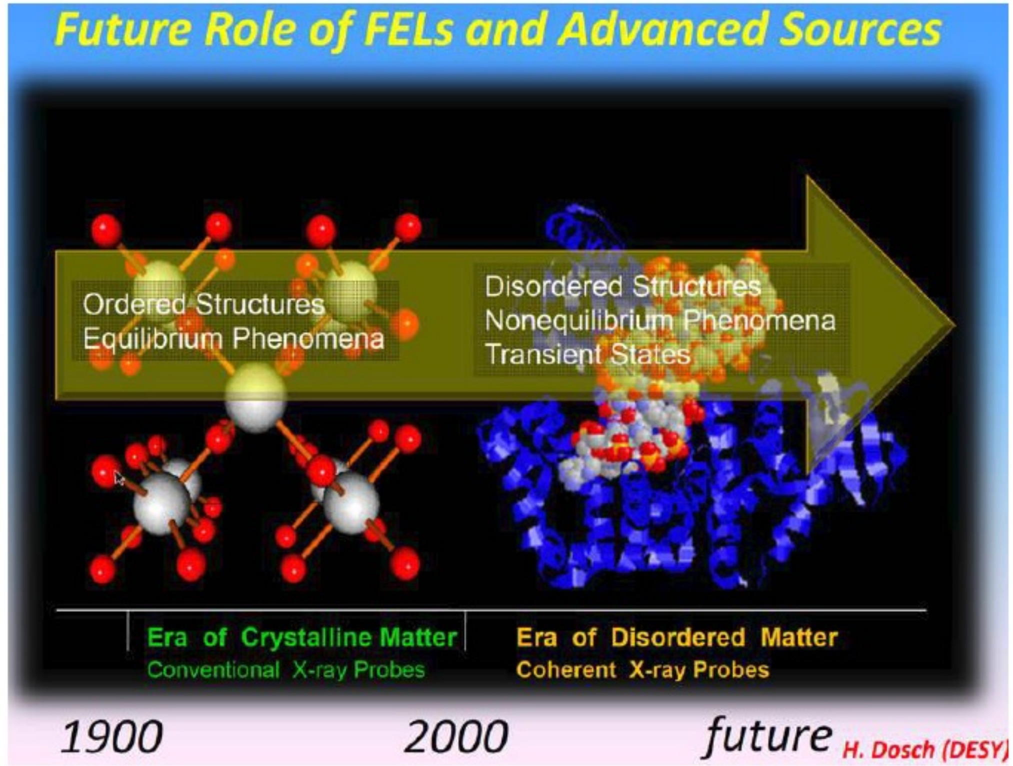


S. Eisebitt, J. Lüning, W.F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt & J. Stöhr / *Nature*, 16 Dec 2004

Future FELs - 1000 brighter

LCLS II – CW FEL
with SRF linac



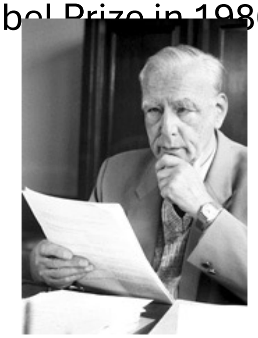


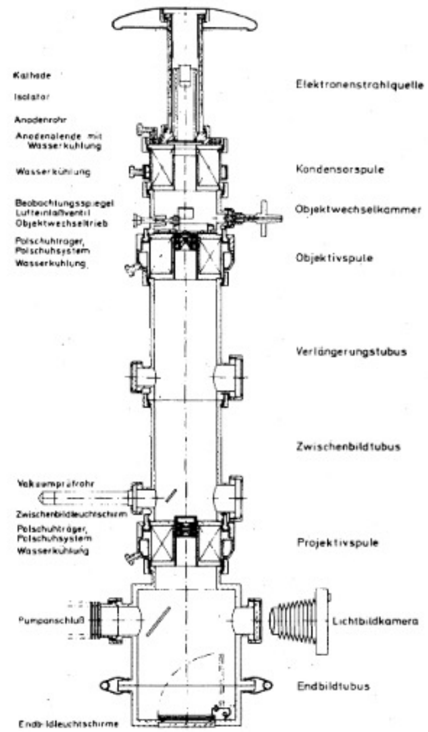
and X-ray FEL oscillators…..

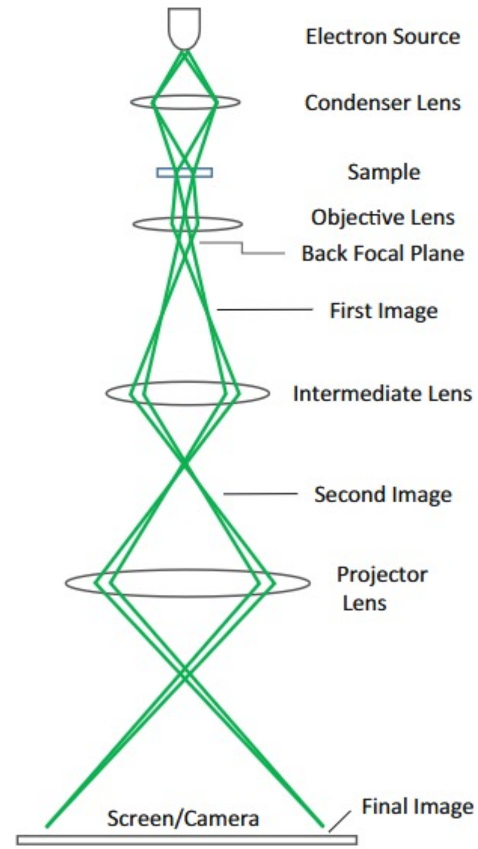
https://lcls.slac.stanford.edu/lcls-ii

How electron microscopes work

- Instrument resolution set by wavelength
- Electron microscope energy: 20-400 keV: 8.6-1.6 pm
- Basic principle like an optical microscope
- Invented by Ernst Ruska in 1933
- Nobel Prize in 1986



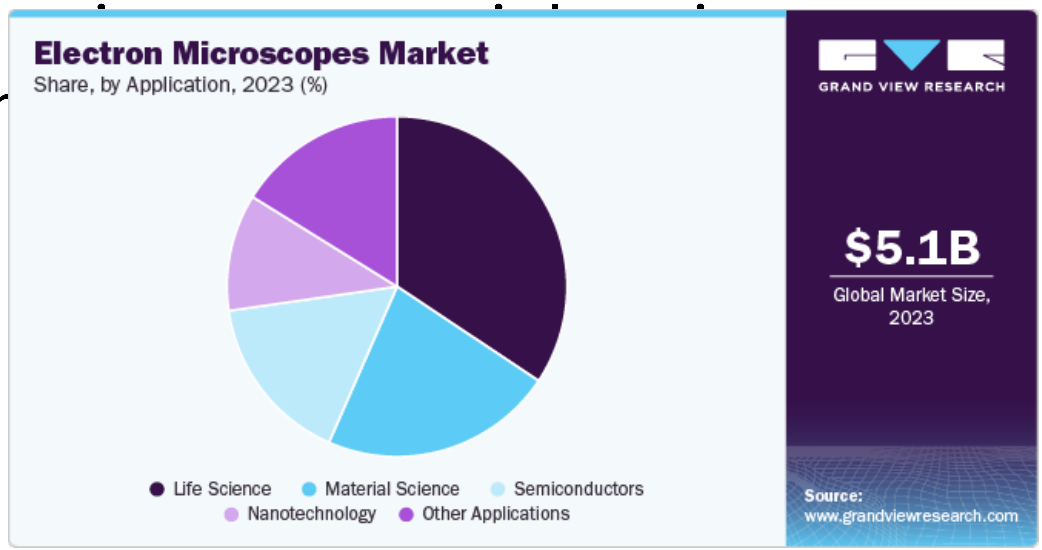




First transmission electron microscope with super-optical resolution

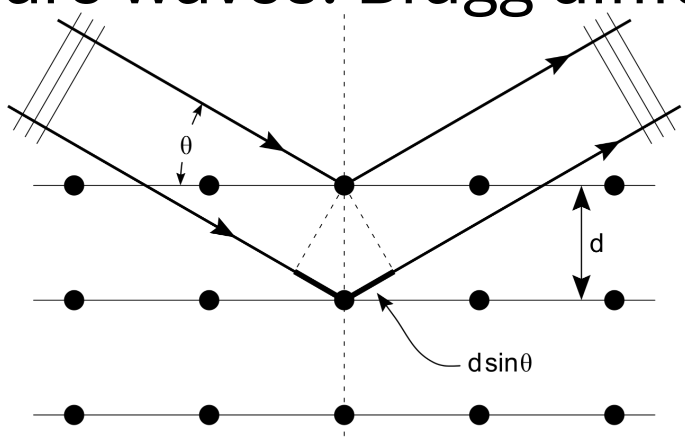
Electron microscopes in industry

- Large manufacturers: JEOL, ThermoFisher, Hitachi, Zeiss, etc.
- $5B industry in 2023
- Life
  sem



Electron diffraction

- Closely related field
- Use electrons to probe crystal structure
- Electrons are waves: Bragg diffraction



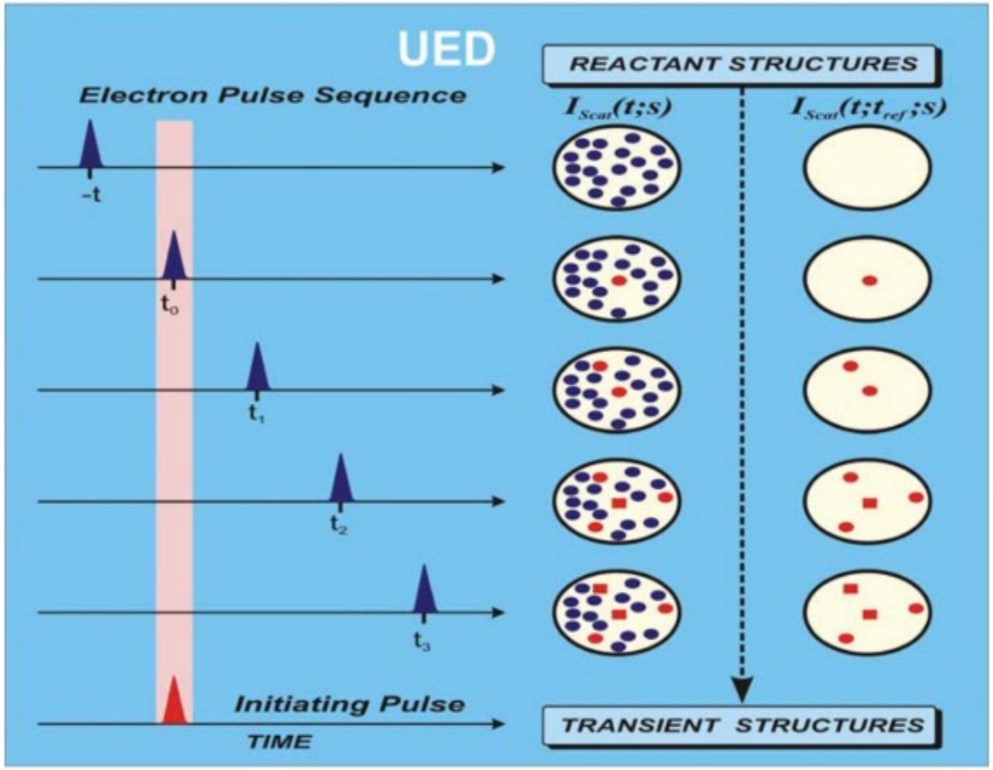
Picture credit: Wikipedia

Ultrafast electron diffraction

- Electron microscopes and diffraction give you a picture
- What if we want to make molecular movies?

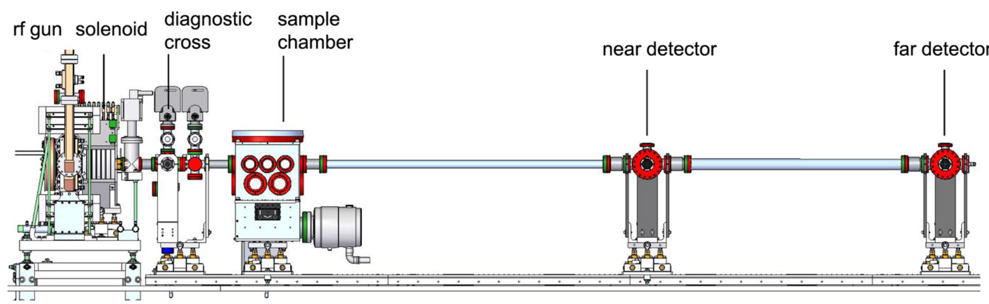
Principles of UED

- Concept of UED developed by Ahmed Zewail, “father of femtochemistry”
- Nobel Prize awarded in 1999 "for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

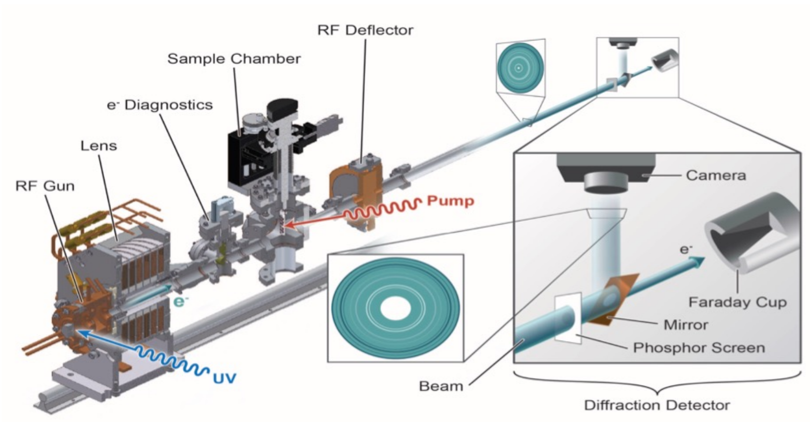


A. Zewail, *Annu. Rev. Phys. Chem.* **57**, 65-103 (2006)

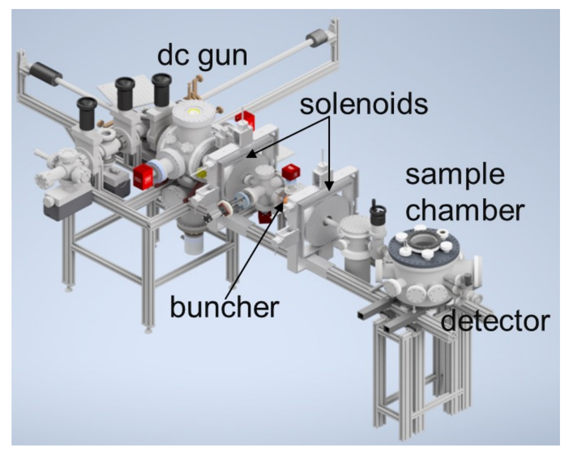
Some UED machines



MeV UED at SLAC



MeV UED at BNL

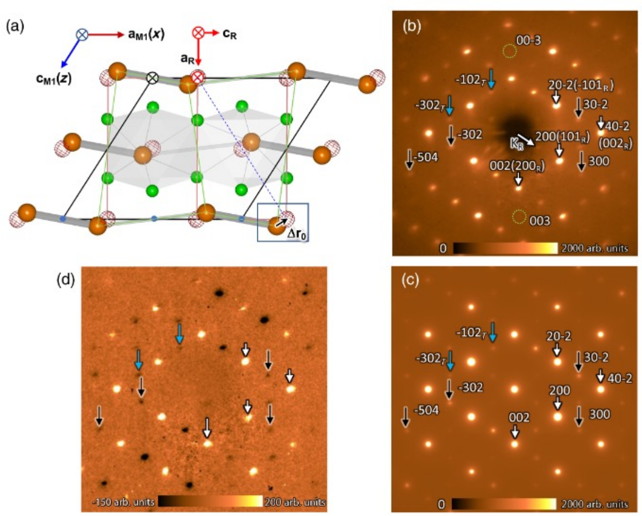


MEDUSA at Cornell

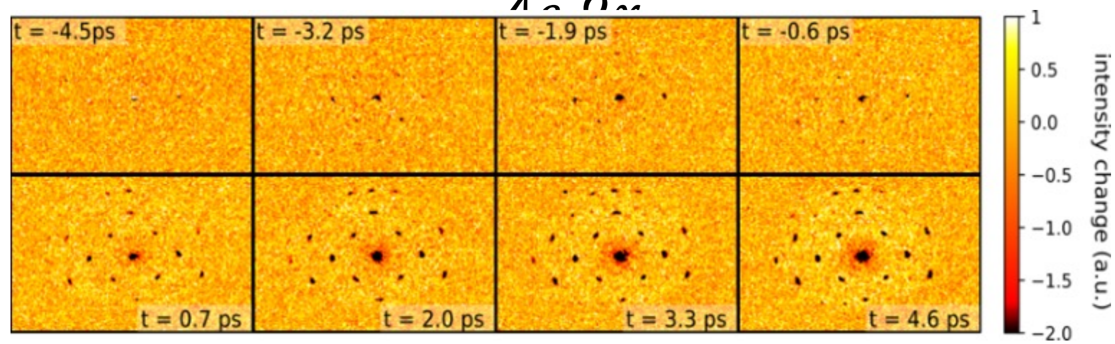
UED resolution

- Time resolution set by bunch length of electron beam (<200 fs)

resolution: $\Delta s = \frac{2\pi}{\lambda_e}\frac{\varepsilon_n}{\sigma_x}$ often



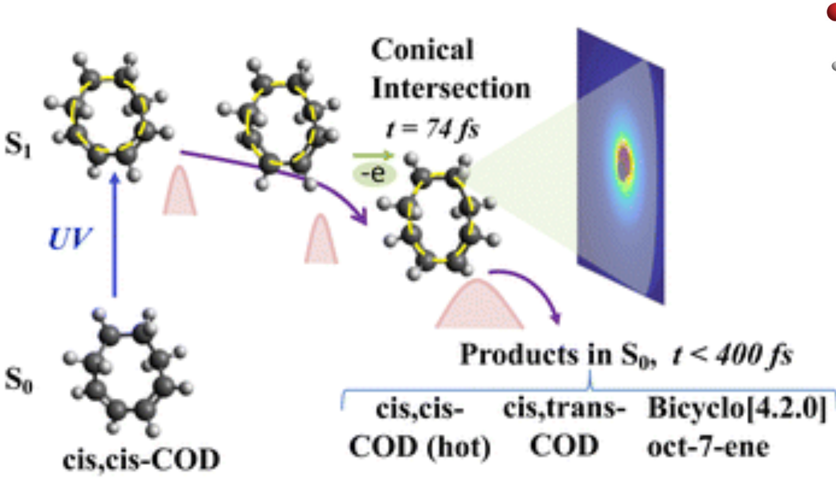
J. Li, *et al.*, *Phys. Rev. X* **12**, 021032 (2022)



W. Li, *Struct. Dyn.* **9**, 024302 (2022)

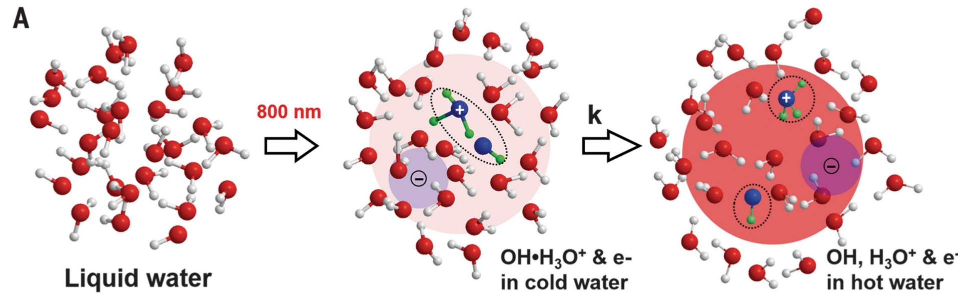
UED highlights

Studying conical intersections

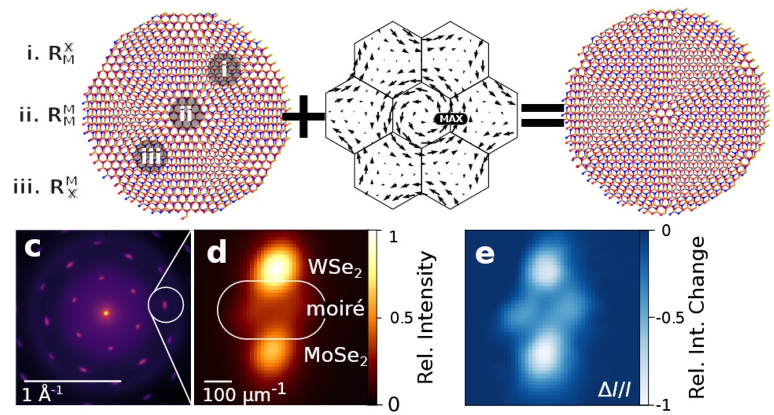


S. Muvva, *Phys. Chem. Chem. Phys* **27**, 471-480 (2025)

Structural changes in photoionized water



M. Lin, *Science* **374**, 92-95 (2021)



C. Duncan, arXiv:2502.11452 (2025)

End of first lecture

Societal Applications of Accelerators

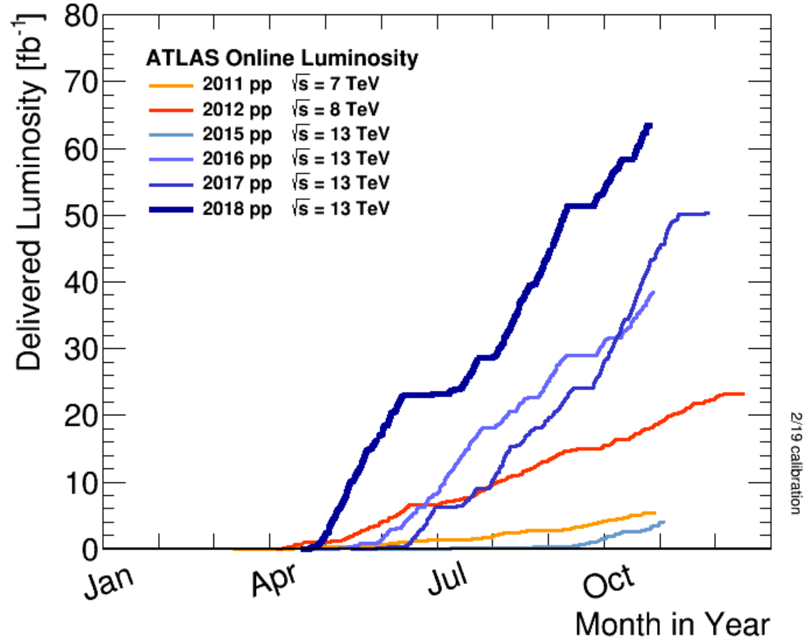
- **Semiconductors:** The semi-conductor industry relies on accelerator technology to implant ions in silicon chips, making them more effective in consumer electronic products such as computers, smart phones and MP3 players.
- **Clean air and water:** Studies show that blasts of electrons from a particle accelerator are an effective way to clean up dirty water, sewage sludge and polluted gases from smokestacks.
- **Cancer therapy:** When it comes to treating certain kinds of cancer, the best tool may be a particle beam. Hospitals use particle accelerator technology to treat thousands of patients per year, with fewer side effects than traditional treatments.
- **Medical diagnostics:** Accelerators are needed to produce a range of radioisotopes for medical diagnostics and treatments that are routinely applied at hospitals worldwide in millions of procedures annually.
- **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
- **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- **Nuclear energy:** Particle accelerators have the potential to treat nuclear waste and enable the use of an alternative fuel, thorium, for the production of nuclear energy.

http://www.acceleratorsamerica.org/resources/applications/index.html

Homework

- Based on the LHC delivered luminosity plot *)

1. How much luminosity has been changed from RUN1 (2011-2012) to RUN2 (2015-2018)?
2. What was most likely the main cause of this change?
3. Estimate how many Higgs bosons were generated during the 2016-2018 years of operation?



Assuming that Higgs production cross-section: $=10^{-35}$ cm^2

*) https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2