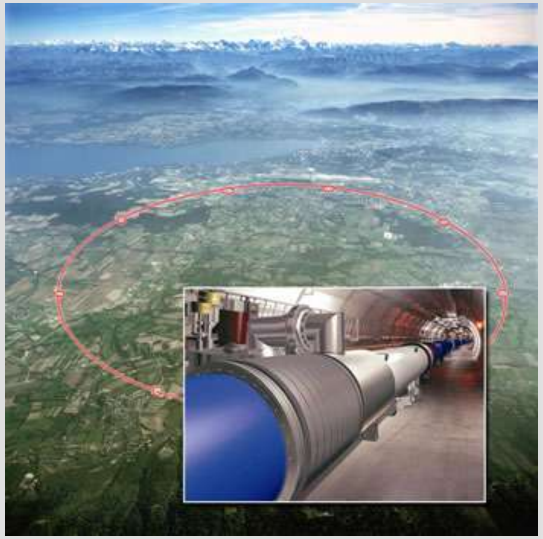


1920s 1970s 2020s 2070s ?

Particle Beams and Accelerators:

Pushing the Frontiers of Science

Vladimir SHILTSEV (NIU / MAE / FAPS / FAAAS / FIEEE / FMBAS)

University of Hawai'i at Mānoa, February 13, 2025


SCIENCE AND TECHNOLOGY
ENGINEERING AND TECHNOLOGY
MECHANICAL ENGINEERING
MEDICAL ENGINEERING
ENVIRONMENTAL ENGINEERING
ENVIRONMENTAL BIOTECHNOLOGY
INDUSTRIAL BIOTECHNOLOGY
NANO TECHNOLOGY
HEALTH SCIENCES
MEDICAL BIOTECHNOLOGY
PHYSICAL SCIENCES
BIOLOGICAL SCIENCES
AND RELATED ENVIRONMENTAL SCIENCES
SOCIAL SCIENCES
HELLO!
PSYCHOLOGY
ECONOMICS AND BUSINESS
LAW
SOCIOLOGY
EDUCATIONAL SCIENCES
POLITICAL SCIENCE
MEDIA AND COMMUNICATIONS
HUMANITIES
HISTORY AND ARCHAEOLOGY
LANGUAGES AND LITERATURE
ANIMAL AND DAIRY SCIENCE
AGRICULTURE, FORESTRY AND FISHERIES
AGRICULTURAL

Subfields of Physics

APS125

"Classical"

- Atomic, Molecular and Optical Physics (DAMOP)
- Condensed Matter Physics (DCMP)
- Fluid Dynamics (DFD)
- Materials Physics (DMP)

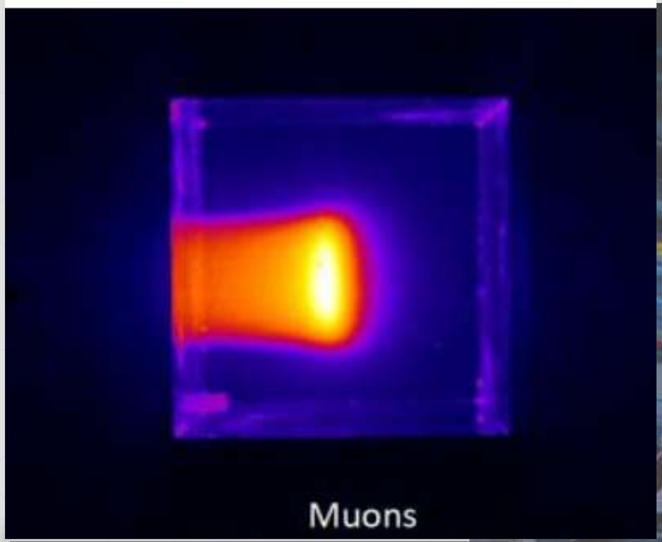
"Modern"

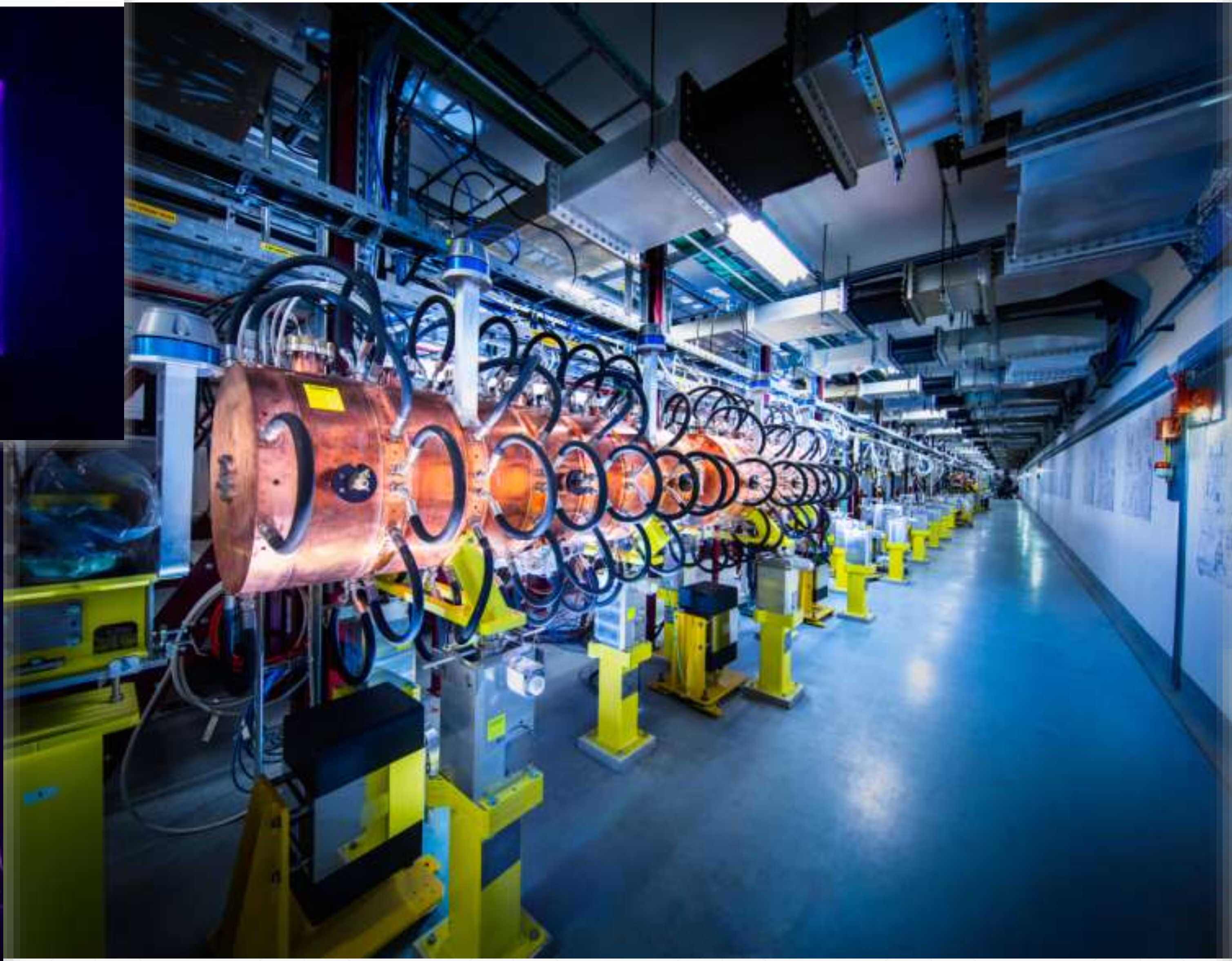
- Astrophysics (DAP)
- Biological Physics (DBIO)
- Polymer Physics (DPOLY)
- Laser Science (DLS)
- Plasma Physics (DPP)
- Nuclear Physics (DNP)
- Particles and Fields (DPF)
- Soft Matter (DSOFT)
- Computational Physics (DCOMP)

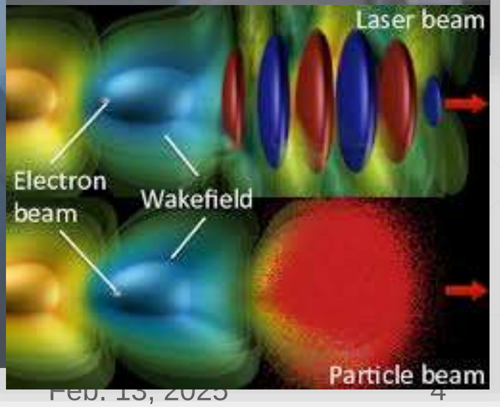
"Novel"

- Quantum Information (DQI)
- Gravitational Physics (DGRAV)
- Physics of Beams (DPB)

Physics of Beams and Accelerators







Key Characteristics of Beams

Type of particles:

- Electrons, protons, ions, positrons, photons, neutrons, muons, etc

Energy (per particle, per process):

- From ~MeV to ~PeV

Intensity (per beam, per bunch, per second…):

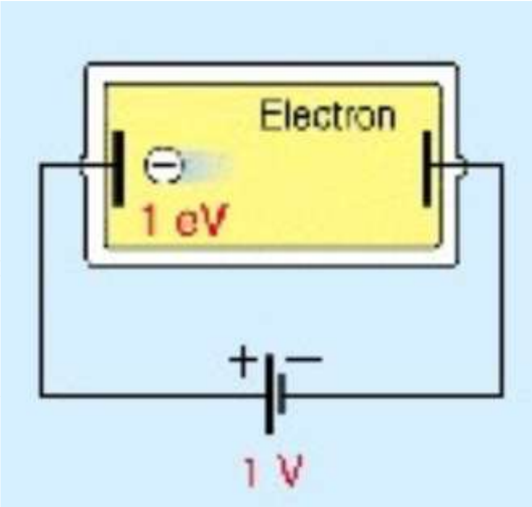
- From 1/s to ~10 MW

Directness (compactness in space, in time, in energy):

- From Å to mm, from fs to μsec, from ~ 0.0001% to 10%

ENERGY : UNITS

1 electron-Volt = 1.602 × 10^{-19} Joule



***femto* eV = 10^{-12} eV**

***micro* eV = 10^{-6} eV**

eV

***Mega* eV = 10^{6} eV**

***Tera* eV = 10^{12} eV**

ENERGY SCALES: COGNITION

1 thought (~ 5 sec)

~ 3.5 cal = 14 J

Over 10^{14} neural connections in a 1.5 kg brain, of ~ 6 10^{23} molecules →

~ 10^{-4} eV = 0.1 meV (per molecule)

ENERGY SCALES: BIOLOGY

Denaturation of (most) proteins starts at

~ 40°C $\quad$ *kT*=27 meV

Complete DNA degradation

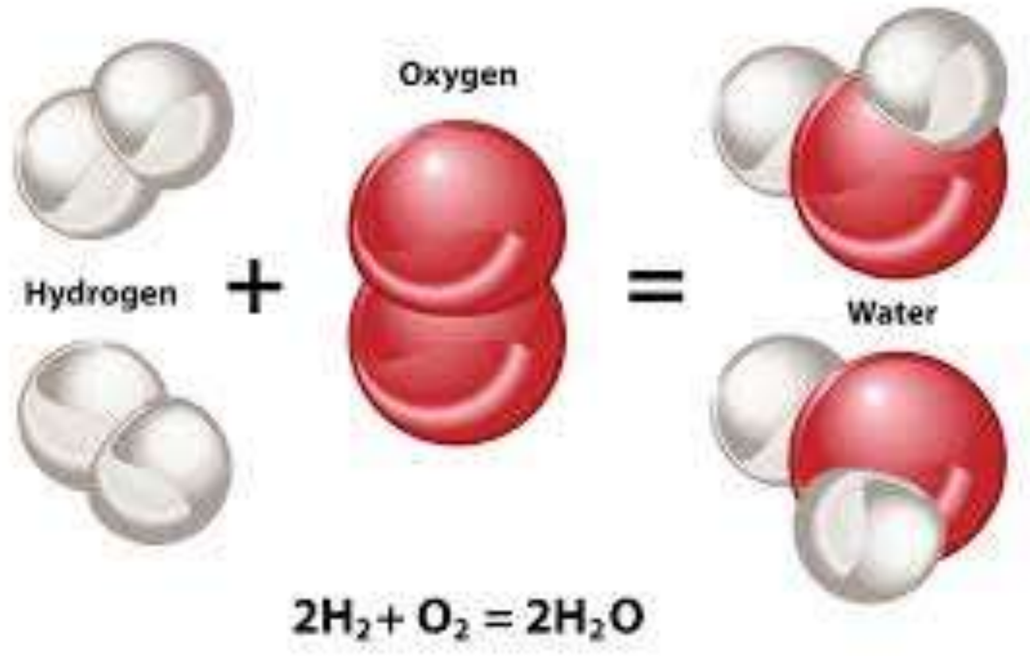
~ 190°C $\quad$ *kT*=40 meV

~ 0.03 eV
(per protein)

ENERGY SCALES: CHEMISTRY

Energy release in the oxidation (burning) of Hydrogen, the heat release is 286 kJ/mole

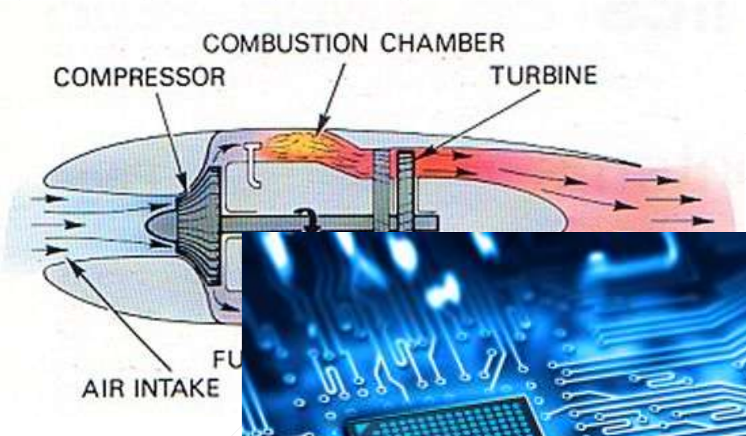
1 mole = 6 10 ^{23} molecules →

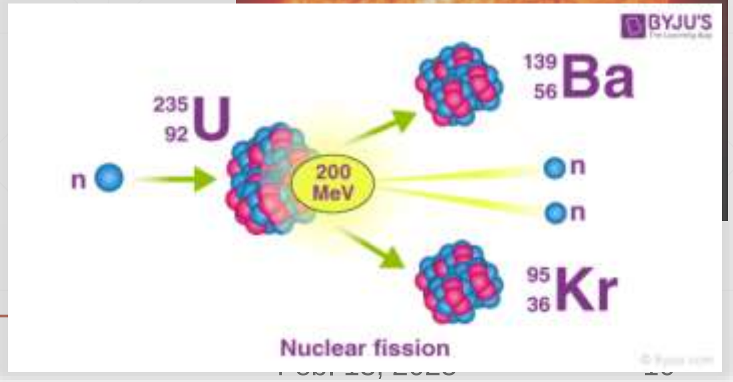


~ 3 eV
(per water molecule)

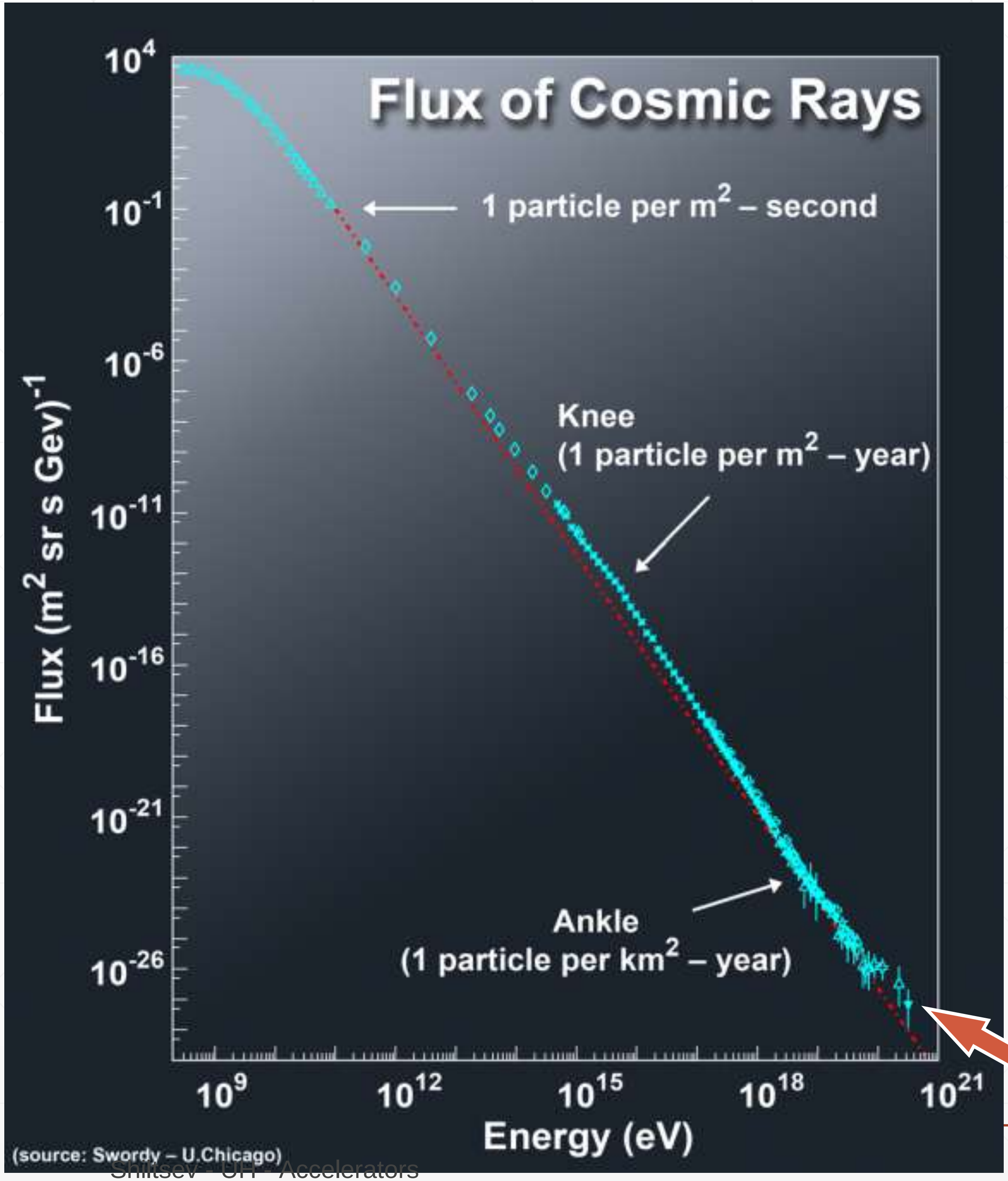
ENERGY SCALES: PHYSICS

Heat	**~0.1 eV**
Semiconductors	**~ 1-5 eV**
Lasers	**1 eV…10 keV**
Plasma	**1 eV … 1 keV**
Nuclear reactions	**0.01 – 10s GeV**

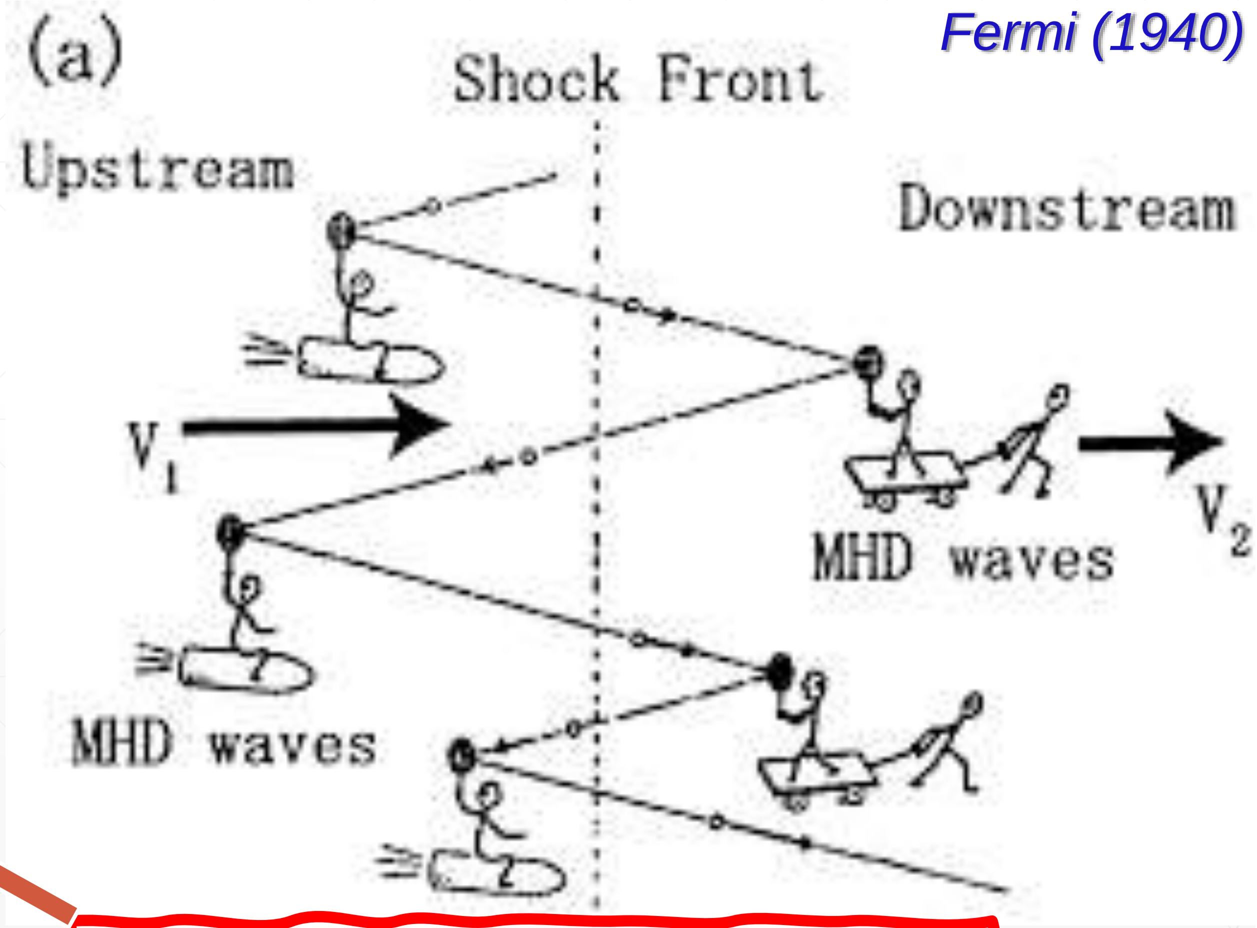




Cosmic Accelerators



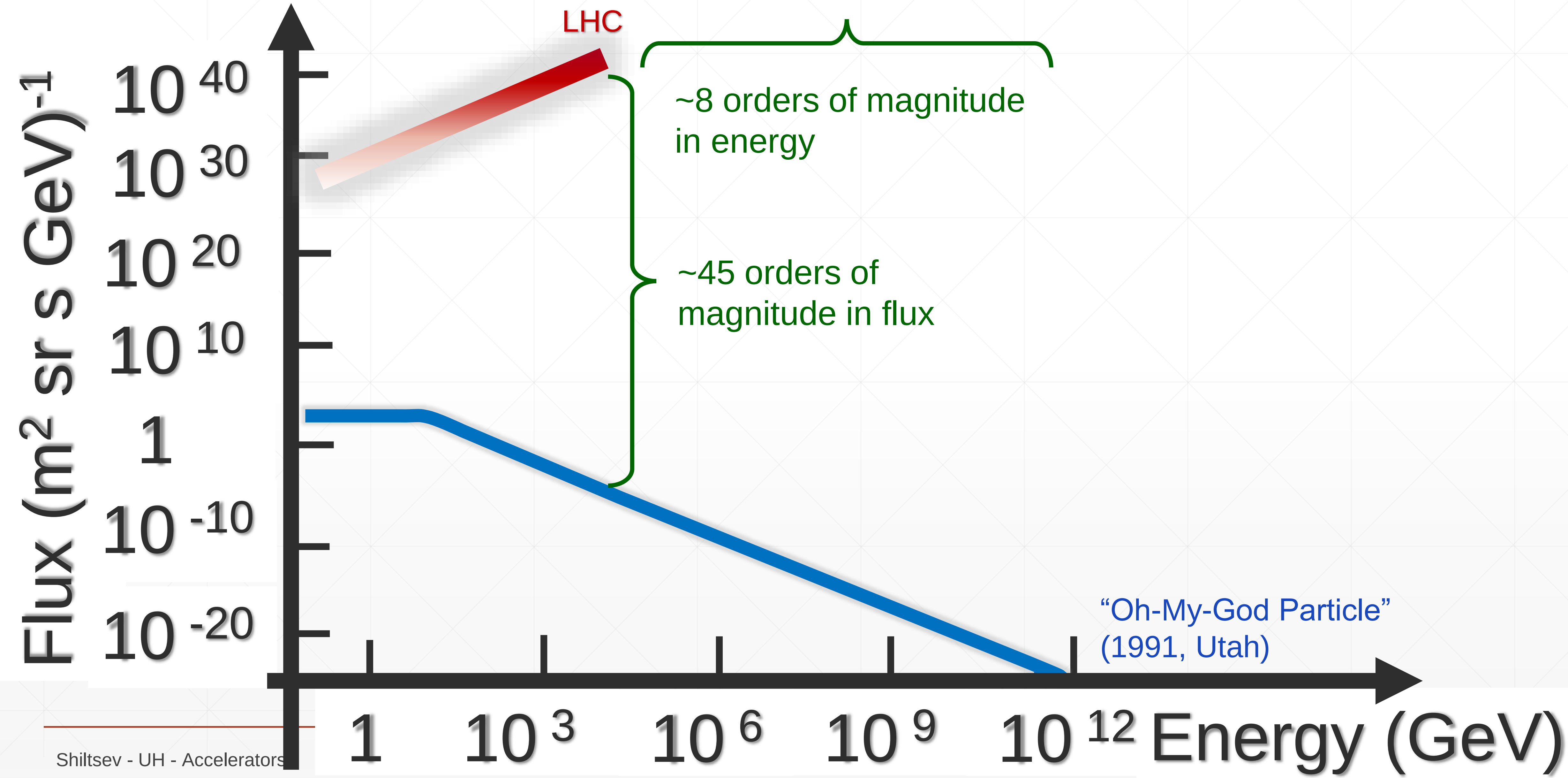
Fermi (1940)



Diffusive shock acceleration

0.3 Zetta eV = 50 Joules !

ACCELERATORS vs COSMOS



Part II:

Landscape of Accelerators and Beams

Century of Accelerators

First ideas and working accelerators:

- 1924: Ising, 1928: Wideroe, Rutherford → Cockroft & Walton; 1929: Lawrence; van der Graaf

Century of success:

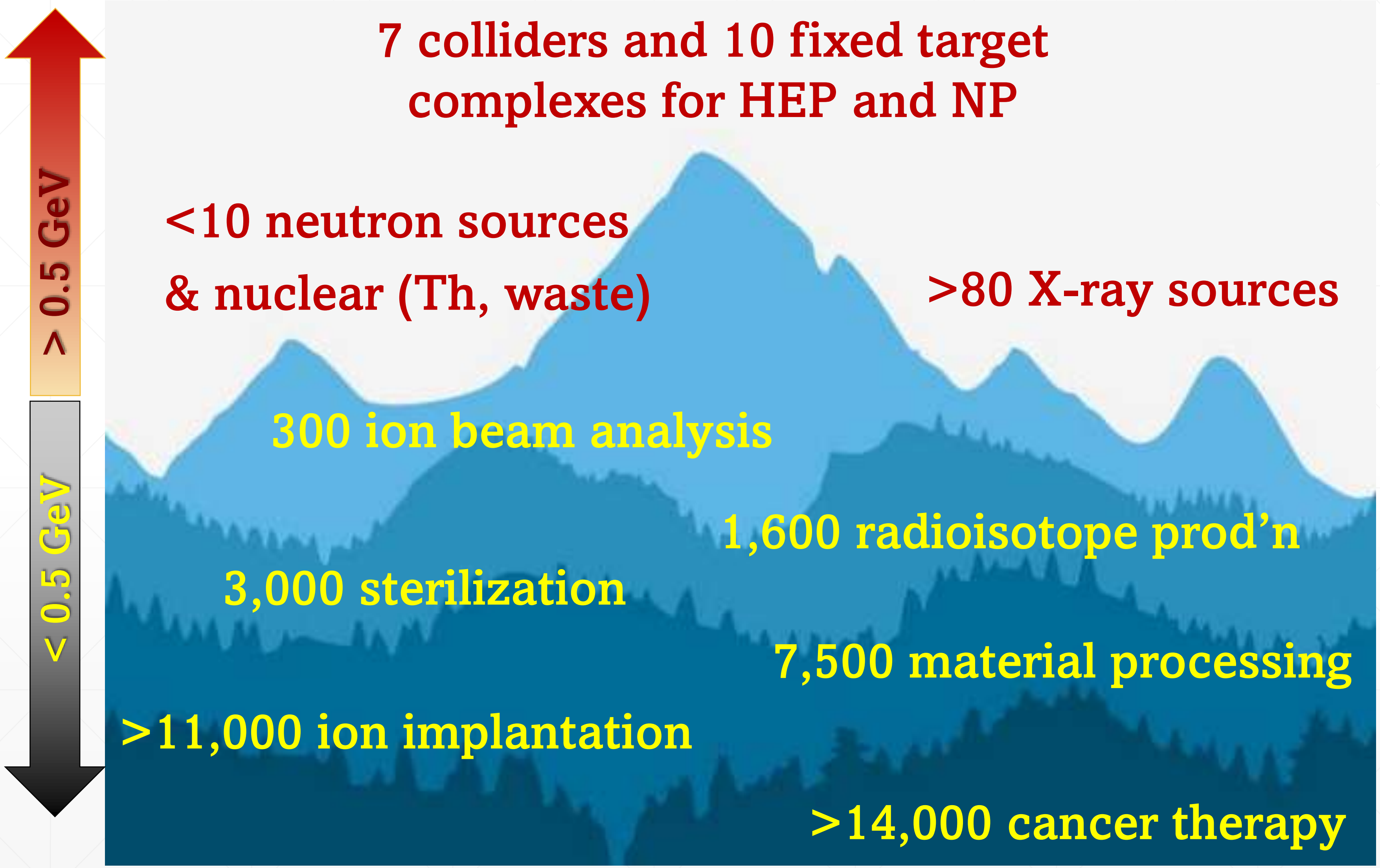
- From ~50 keV to ~10,000 GeV beam energy
- 4 Nobel Prizes (Lawrence, 1939; Cockroft and Walton, 1951; van der Meer, 1984)
- led to ~1/3 of all Nobels in Physics
- in Chemistry: 1997, 2003, 2006, 2009, 2012, 2017

>100 used in research now:

~ ¼ in the US

- serving ~80,000 users (condensed matter, biology nuclear physics, particle physics, etc.)

Landscape of Accelerators



data from : A.Faus-Golfe, R.Edgecock, et al, EuCARD-2 Report: "Applications of Particle Accelerators in Europe." (2017); and V.Shiltsev, Physics Today (2020)

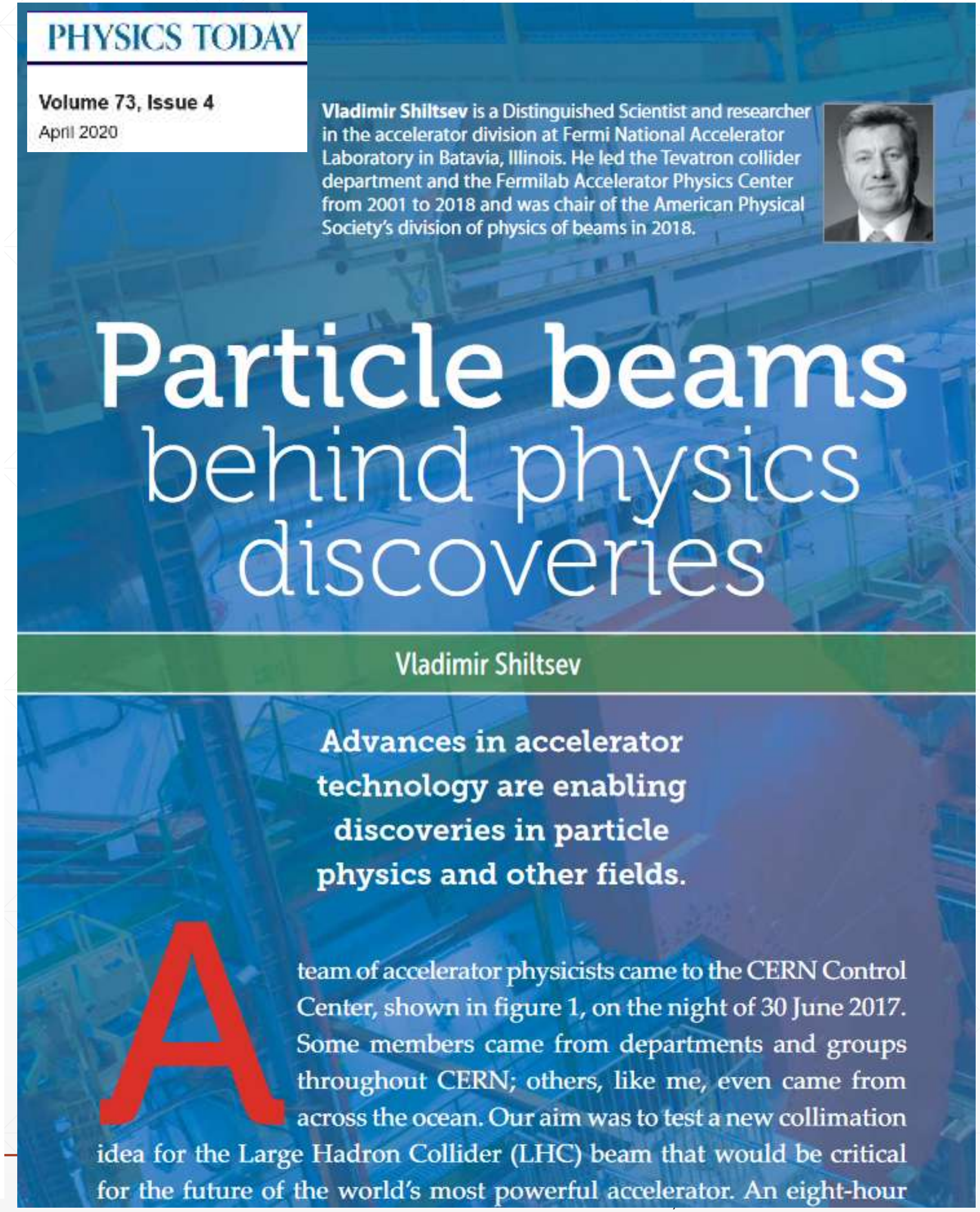
Accelerators In Numbers:

Just in the US:

- 16(out of total 28) national users facilities are based on accelerators
- they serve >20,000 users
- annual operation budget ~ 2B$

DOE Office of Science, NSF, DOD:

- next 10 yrs: ~8B$ worth of accelerator construction projects
- OHEP supports 1 B$ of accelerator R&D over the next decade
- dozen of dedicated Accelerator Sci. & Tech. facilities serve ~500 users


PHYSICS TODAY

Volume 73, Issue 4

April 2020

Vladimir Shiltsev is a Distinguished Scientist and researcher in the accelerator division at Fermi National Accelerator Laboratory in Batavia, Illinois. He led the Tevatron collider department and the Fermilab Accelerator Physics Center from 2001 to 2018 and was chair of the American Physical Society's division of physics of beams in 2018.

Particle beams behind physics discoveries

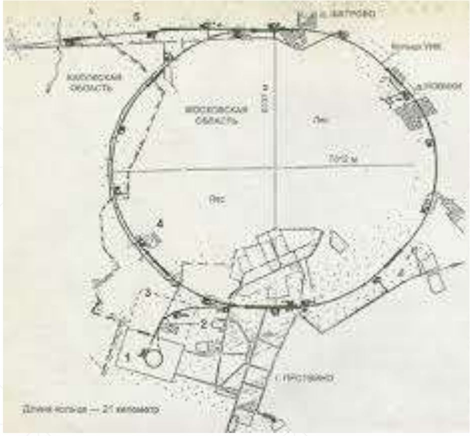
Vladimir Shiltsev

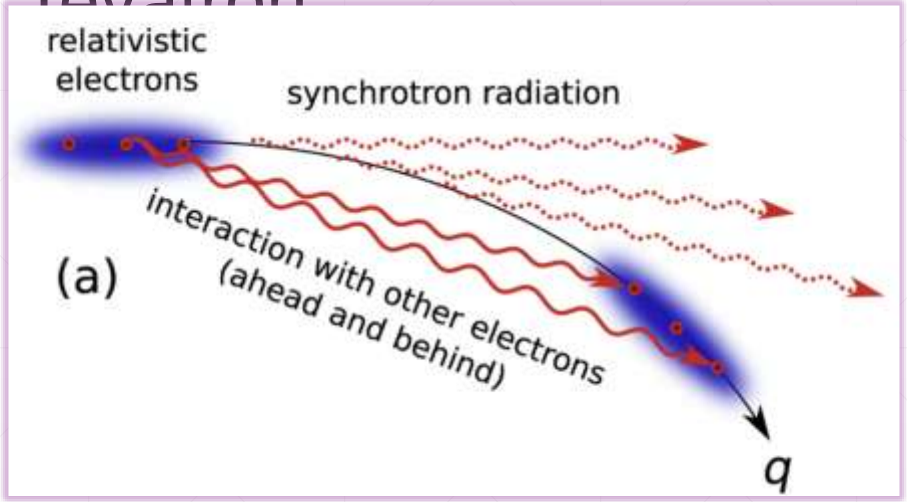
Advances in accelerator technology are enabling discoveries in particle physics and other fields.

A team of accelerator physicists came to the CERN Control Center, shown in figure 1, on the night of 30 June 2017. Some members came from departments and groups throughout CERN; others, like me, even came from across the ocean. Our aim was to test a new collimation idea for the Large Hadron Collider (LHC) beam that would be critical for the future of the world's most powerful accelerator. An eight-hour

What Beam Physicists Do (e.g., my own research)

External noises and ground motion effects in supercolliders and light sources → VLEPP, UNK, SSC, VEPP-3, APS, TESLA, Tevatron



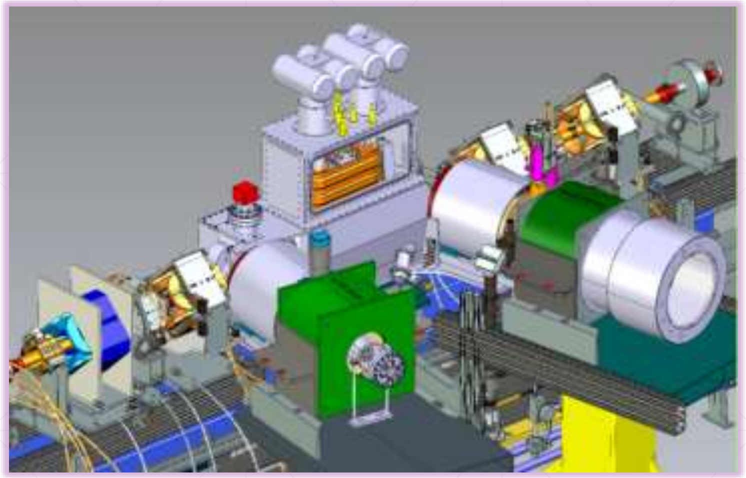


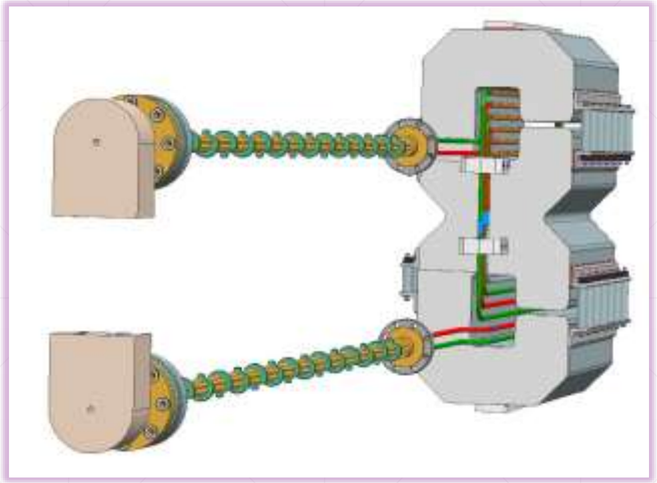
Coherent Synchrotron Radiation theory fundamental limit on max. brightness of ultra short electron bunches in colliders and XFELs

Tevatron *p-pbar* Collider Operations
1.98 TeV c.m.e., decade long Run II to discover Higgs, factor of ~40 increase of the luminosity in many (~30) steps…

(cont'd: after the Tevatron Run II)

Compensation of Space-Charge effects with electron lens in IOTA ring 70 MeV/c protons at Fermilab → for future rings for neutrino production and for a muon collider





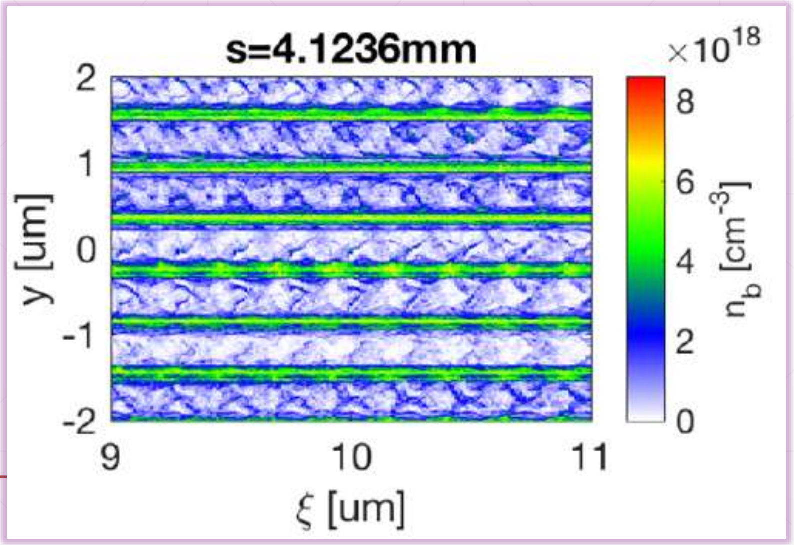
Superfast HTS dipole magnets with *dB/dt* ~ 1000 – 3000 T/s as needed for future muon colliders

Wakefield acceleration in nanostructures

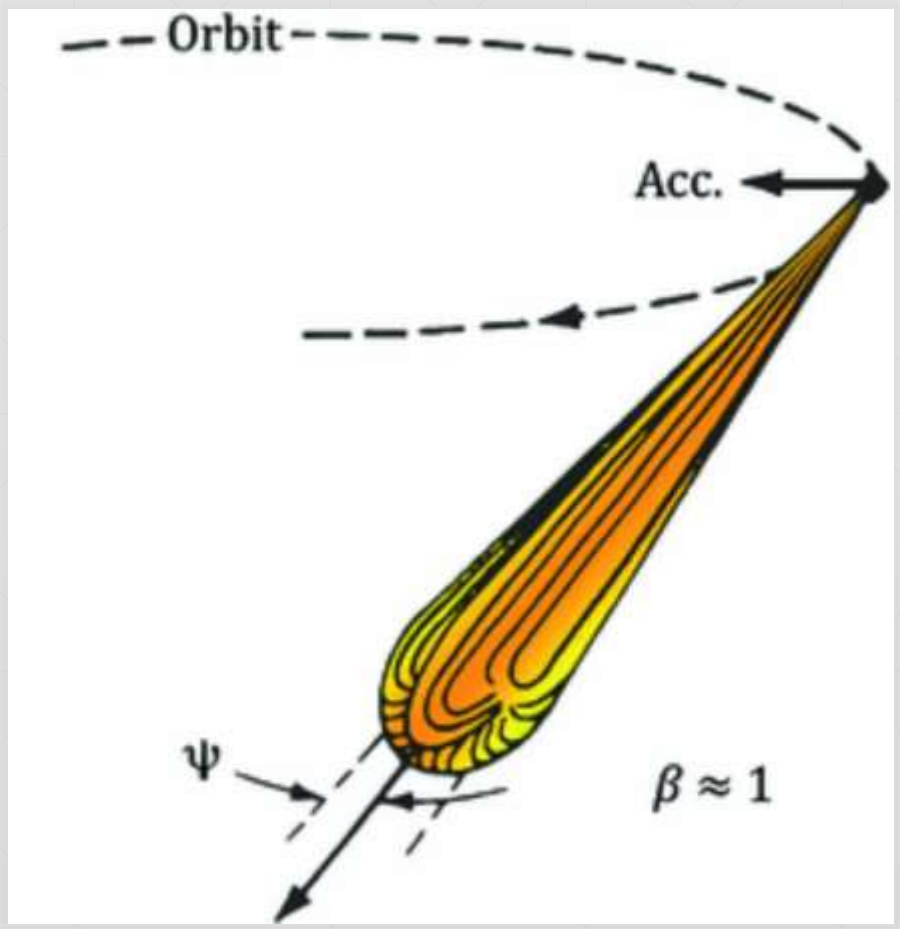
Excited by short 1x1x1μm^3 10 GeV *e*- bunch

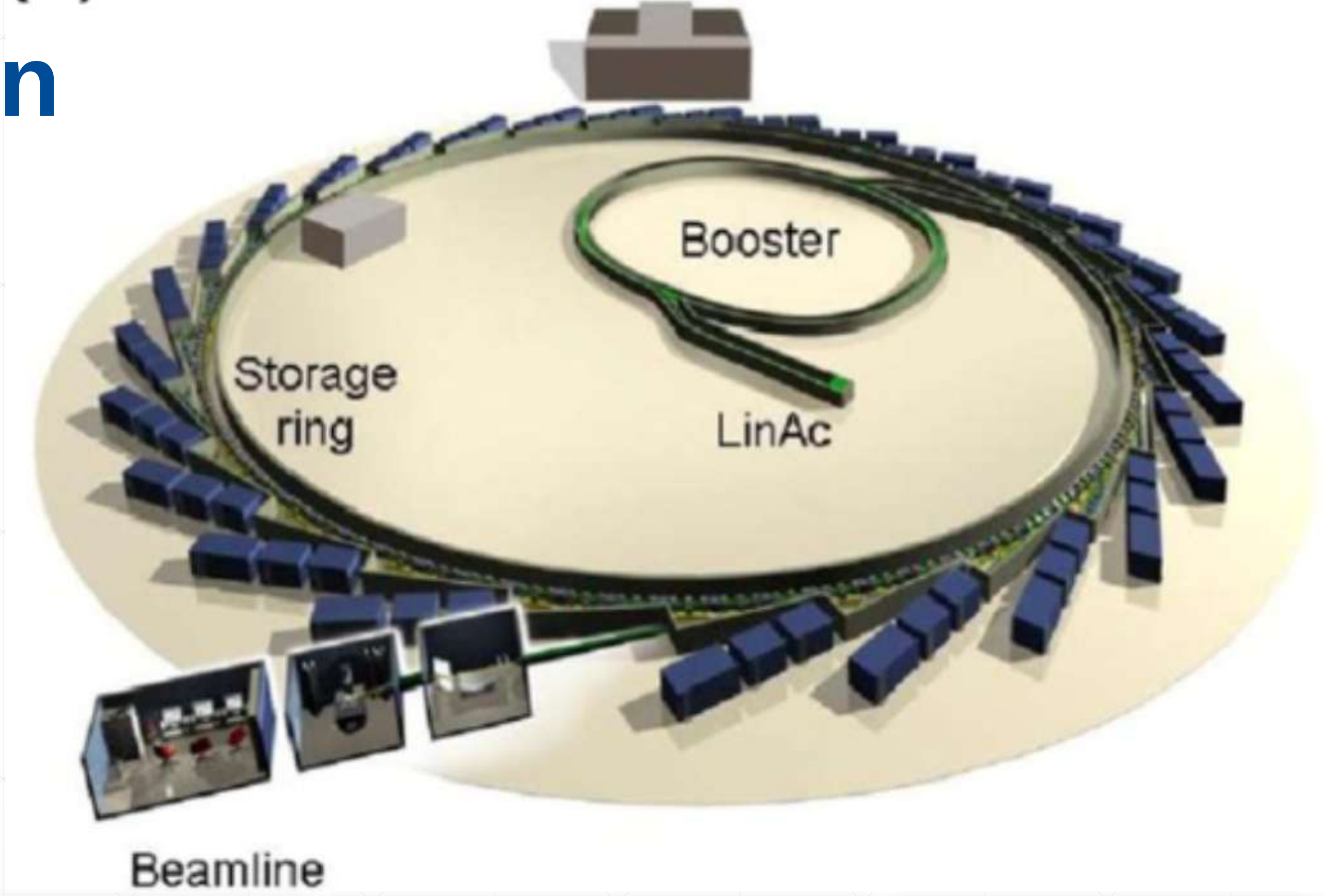
Demo experiment E336 at SLAC

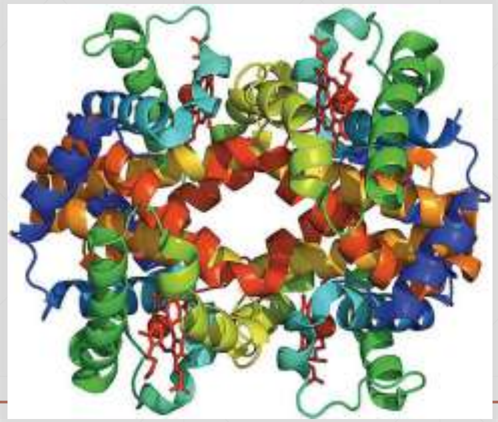
Wake-fields *O*(0.1-1 TV/m)

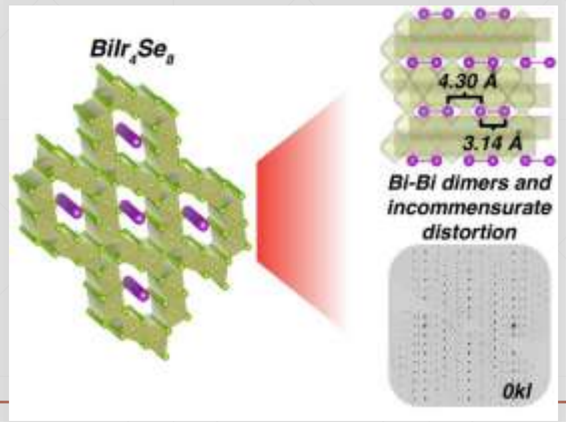


Synchrotron Radiation (of electrons)

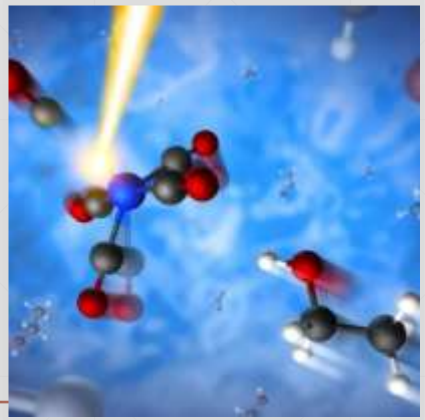




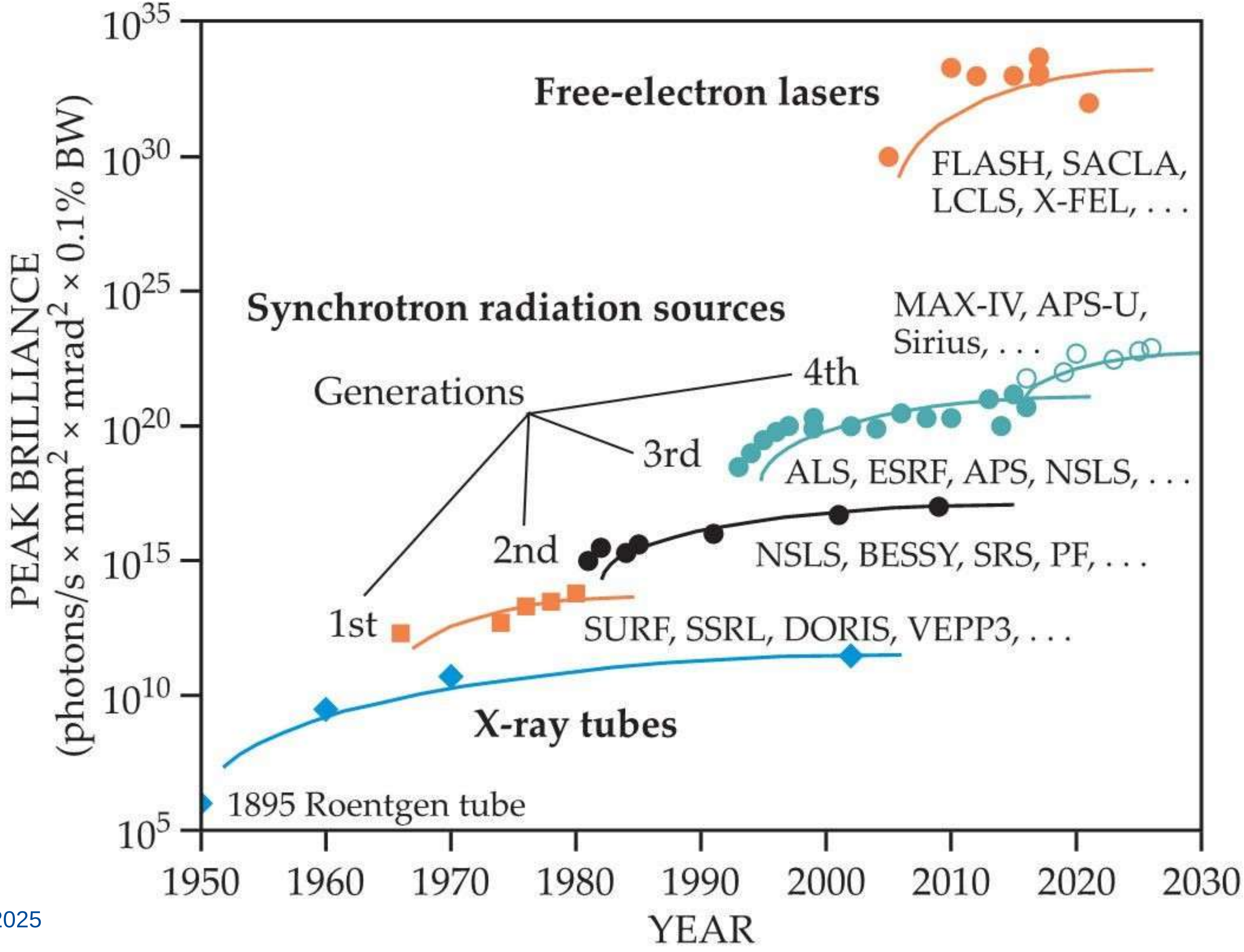

protein structure



solid state research

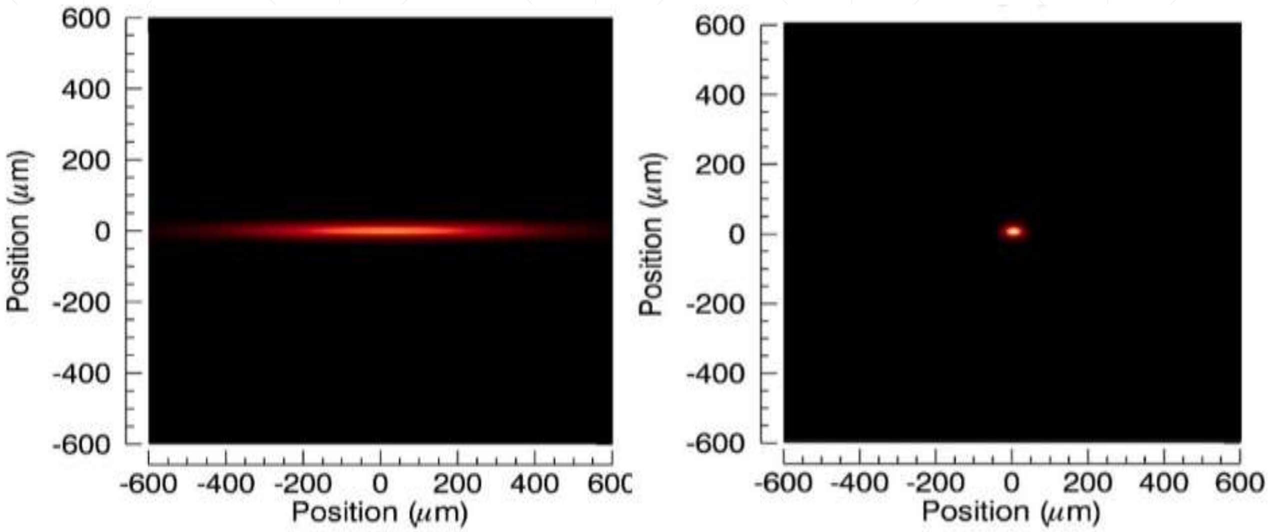

ultrafast chemistry

Revolution in Light Sources / X-ray Sources



V.Shiltsev, *Physics Today* **73** (4), 32 (2020)

4^{th} Generation Light Sources
aka *diffraction-limited storage rings*



“Multi-Band Achromat” (MBA) -
advanced beam optics lattice →
x100 brightness increase (1996)→

2024 – APS-Upgrade @ Argonne 6 GeV, 45 pm

2025 – SKIF @ Novosibirsk 3 GeV, 75 pm

2025 – SLS @ Swiss-PSI 2.7 GeV, 135 pm

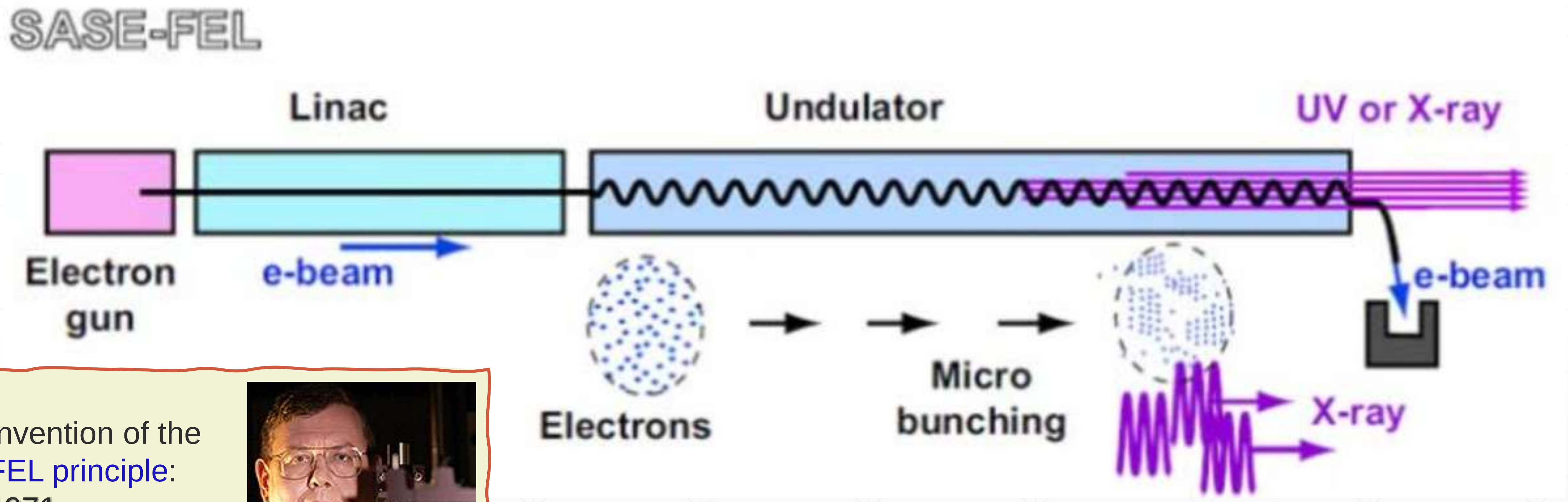
2026 – ALS-Upgrade @ Berkeley, 2 GeV, 70 pm

2026 – HEPS @ Beijing 6 GeV, 60 pm

2027 – HALF @ Hefei 2.2. GeV, 85 pm

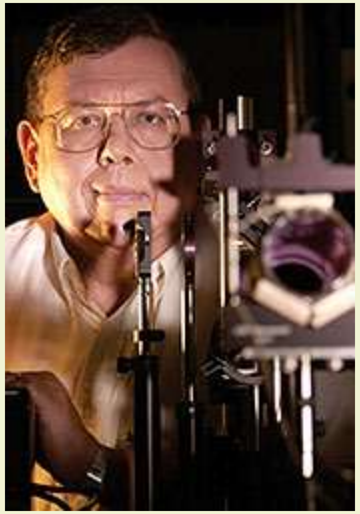
2029 – PETRA-IV @ Hamburg 6 GeV, 8 pm

Self-Amplified Spontaneous Emission (SASE)
Free Electron Lasers (FEL) aka X-FELs



Invention of the FEL principle: 1971

by John Madey (1943-2016)
Stanford/Duke/Hawaii



- High energy (0.1-10's of GeV) and High brightness electron beam
- Exponential growth of radiation power while in (10's of m) undulator
- Proposed in 1980, proof-of-principle demonstrations 1985-1998

X-FELs

2005 – FLASH, Hamburg 1 GeV, SRF

2009 – LCLS-I, SLAC 20 GeV, NC RF

2011 – SACLA, Japan x GeV, NC RF

2012 – FERMI@Elettra, Italy 2.2. GeV, NC RF

2017 – XFEL, Hamburg, 17.5 GeV, SRF

Pohang PAL-FEL, 10 GeV, NC RF

SwissFEL, PSI, 5.8 GeV, NC RF

DCLS FEL, China, 0.3 GeV, NC RF

2021 – Shanghai X-FEL, 1.6 GeV, NC RF

SIOM Shanghai, 0.5 GeV, plasma

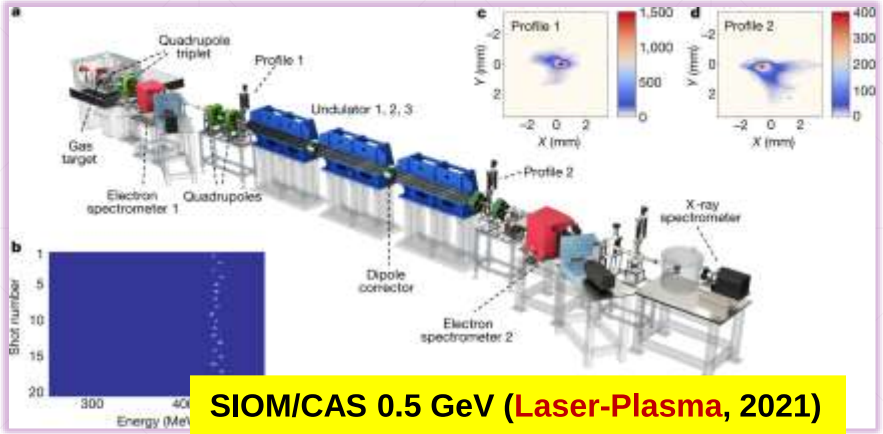
2024 – LCLS-II, SLAC 4 GeV, SRF

2025 – SHINE, Shanghai 8 GeV, SRF

2031 – LCLS-II-HE, SLAC 8 GeV, SRF

2033 – SILA, Russia, 6 GeV, NC RF (?)


European XFEL 17.5 GeV (SRF, 2017)



SIOM/CAS 0.5 GeV (Laser-Plasma, 2021)

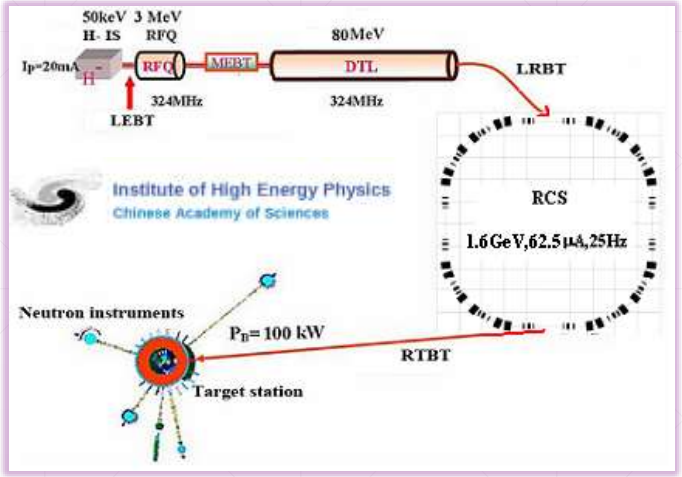
LCLS-II @ SLAC 4 GeV (SRF, 2023)

Shanghai SHINE 8 GeV (SRF, 2025)

Neutron Sources

Spallation Neutron Source (SNS) at ORNL:

- 1.4 MW 1 GeV SRF linac + ring since 2007
- Upgrade to 2MW on target in 2028
- Followed by 2nd target station and 2.8 MW



China Spallation Neutron Source (CSNS):

- 80 MeV linac and 1.4 GeV ring → target
- First neutrons Aug'2017, 0.1 MW Feb'2020
- Planned upgrades to 0.2 MW, then 0.5 MW

European Spallation Source (ESS), Lund:

- 5 MW 2 GeV pulsed SRF linac → target
- Construction started 2014, most cryomodules installed
- Beam energy 870 MeV…(now in a dump… soon on target)
- 1st users program in 2025

Full ops 2027

Accelerators for Nuclear Physics

Facility for Rare Isotope Beams

at Michigan State University (2022)

eg $^{238}U + ^{12}C \rightarrow$ rare ^{93}As ^{96}Se ^{88}Ga

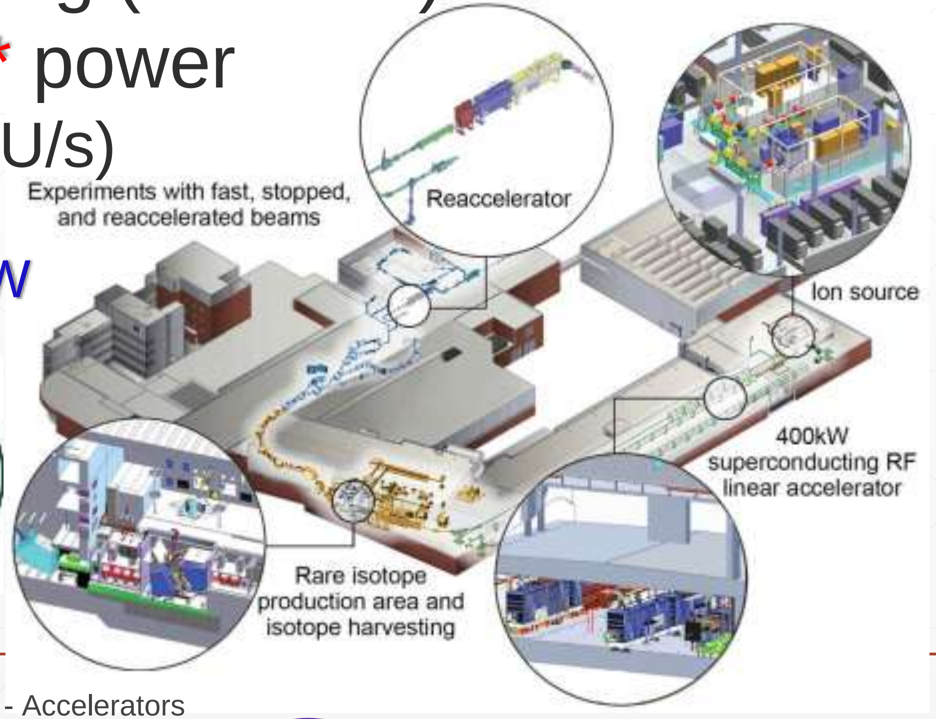
212 MeV/*u* ion SRF linac

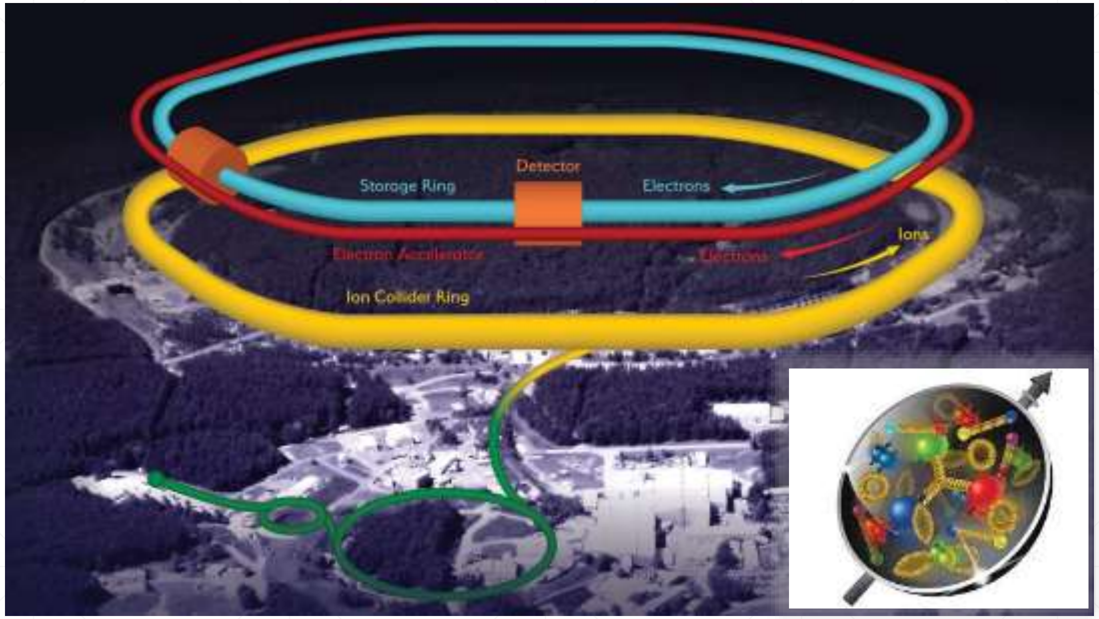
517m long (324 cav.)

0.4MW* power

(5e13 ^{238}U/s)

*now 10 kW





Electron-Ion Collider (EIC@BNL)

quarks/gluons of p,n's of nuclei

275 GeV p RHIC + 18 GeV e-

two rings, each 3834 m, 1(2) IPs

constr. started (CD-3a Apr. 2024)

end construction ca.2032; ~2.8B$

Part III:

Modern and Future Colliders

ENERGY: Brute Force Approaches

Particle Energy Increase

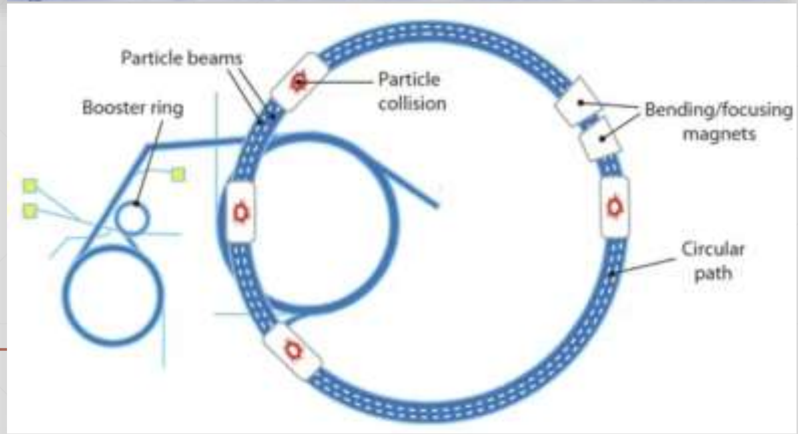
ΔE = Electric Field Gradient x Length

#1 Increase *length* = linac

(linear accelerator)

#2 Accelerate in a ring ($N_{turns}\,\Delta E$)
increase *circumference* as $E=0.3BR$

(synchrotrons)



ENERGY: Three Great Ideas

#1 Colliders

#2 [to be implemented – see below]

#3 [to be explored - see below]

Colliders

Center-of-mass energy (c.m.e. - available for transformative particle physics reactions)

$$E_{CM}=2E$$

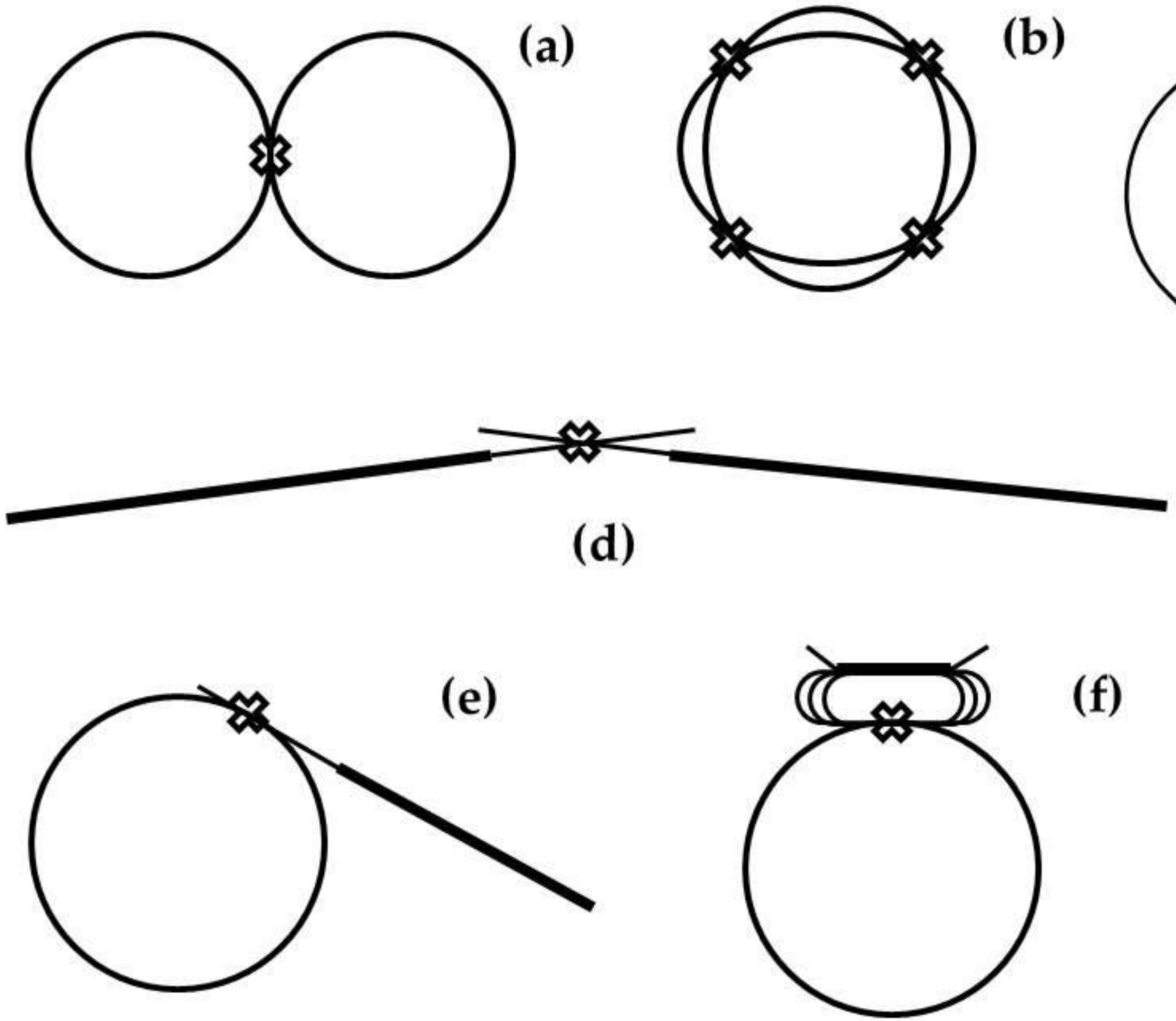
gain about x***120*** for LHC

31 colliders built

Compare with c.m.e. of a fixed target collisions:

$$E_{CM}=SQRT(2Emc^2)$$

Types of colliding beam facilities



First Colliders – 60! (1964-65)

AdA (Frascati/Orsay)

e+e- E_{cm}=0.5 GeV

constr. start: 1960

collisions: mid-1964

VEP-1 (Novosibirsk)

e-e- E_{cm}=0.32 GeV

constr. start: 1959

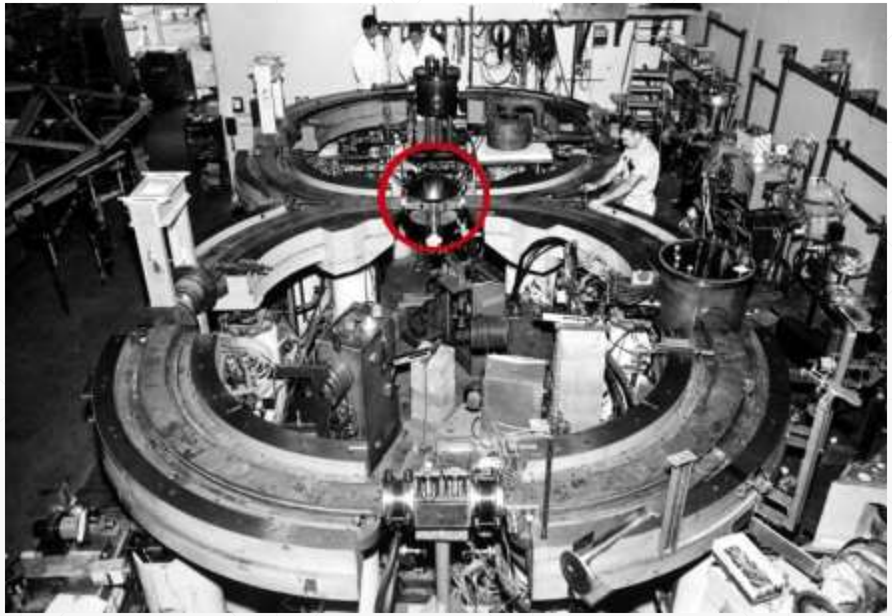
collisions: May 1964

CBX (Stanford/Princeton)

e-e- E_{cm}=1.0 GeV

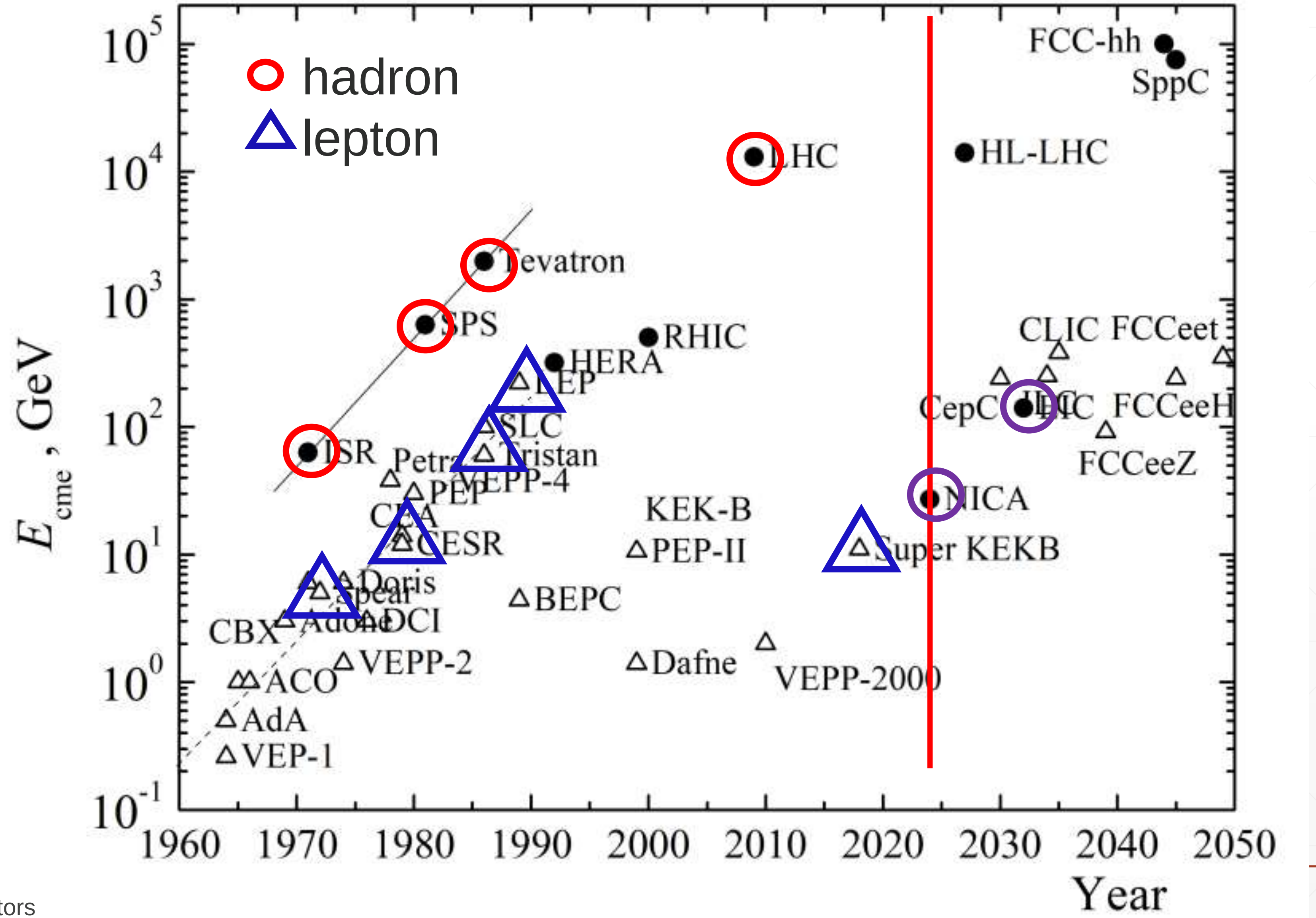
constr. start: 1959

collisions: March 1965



Energy of Colliders (aka *Livingston Plot*)

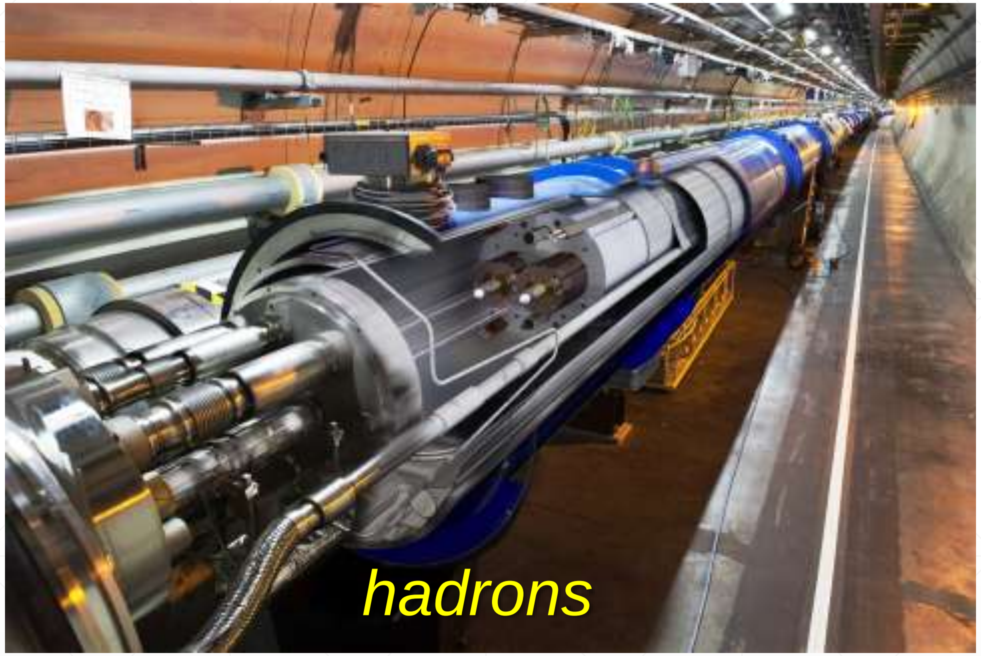
5 orders of magnitude in E_{CM} in 6 decades (0.2 GeV → 14 TeV)



V. Shiltsev, F. Zimmermann, Rev. Mod. Phys. 93, 015006 (2021)
V. Shiltsev, Phys. Usp. 55, 965 (2012)

Colliders of Nowadays (7 Ops, 2 Constr.)

VEPP-4M, BEPC, DAFNE, RHIC, LHC, VEPP-2000, Super-KEKB, NICA (2025), EIC (2032)



Super-KEKB (KEK, Japan):

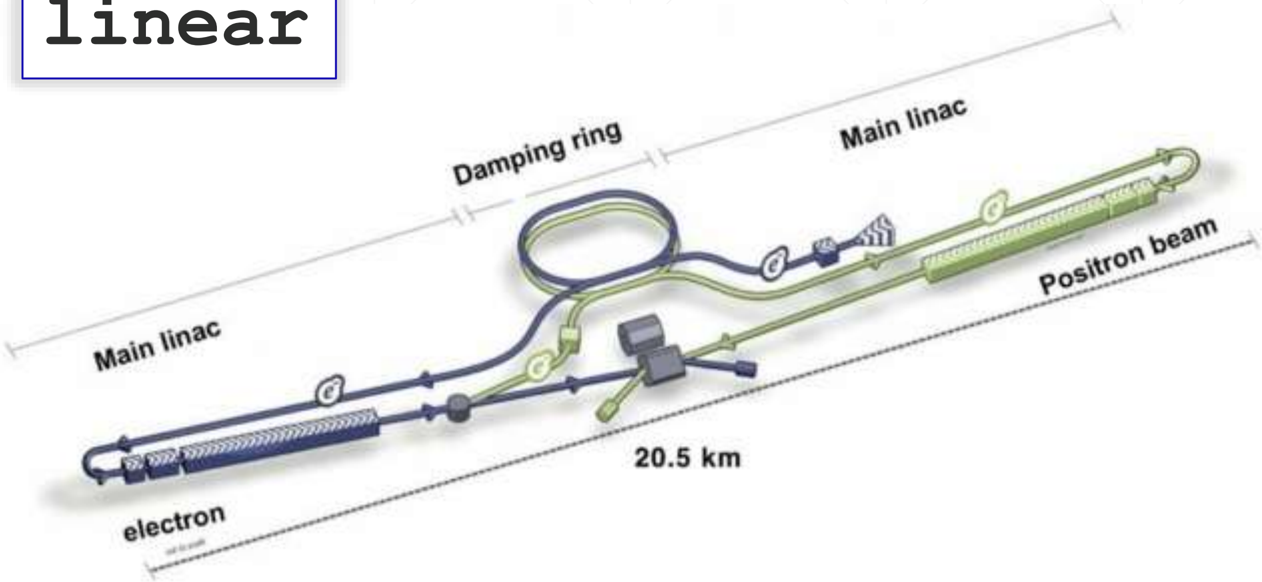
7 GeV e- + 4 GeV e+
3.0 km tunnel, 1 detector
Normal-conducting magnets, SC RF
Record Lumi 5.1e34 $cm^{-2}s^{-1}$

LHC (CERN):

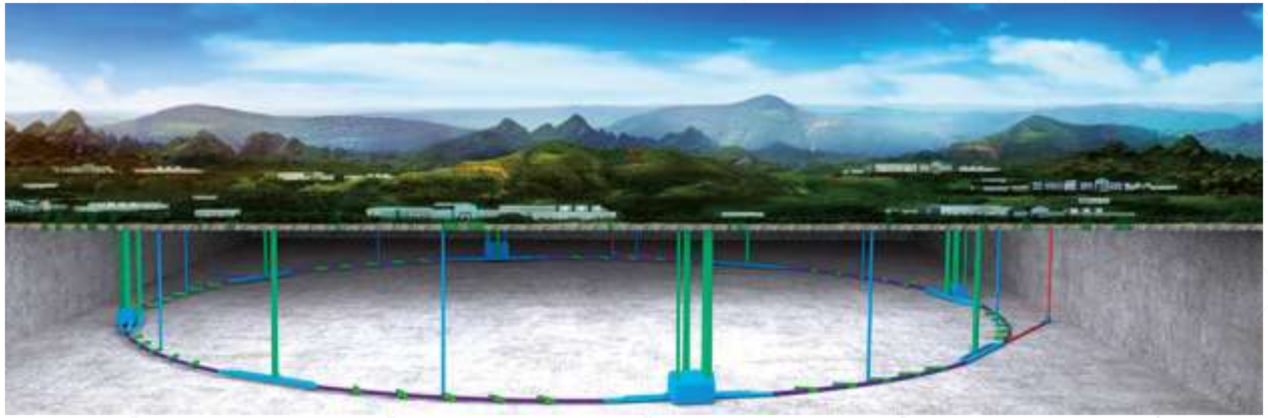
6.8 TeV protons + 6.8 TeV protons
26.7 km tunnel, 4 detectors
Superconducting magnets, SC RF
Record Lumi 2.62e34 $cm^{-2}s^{-1}$

Future Colliders in Asia - Aspirations

linear



circular



ILC (Japan) e+e-

~21 km, E_{cm} =250(500) GeV

31.5 MV/m 1.3 GHz SRF

TDR (2013): cost ~7B$* +10kFTEs

CEPC/SPPC (China) e+e-/pp

100 km, E_{cm} =91…360 GeV

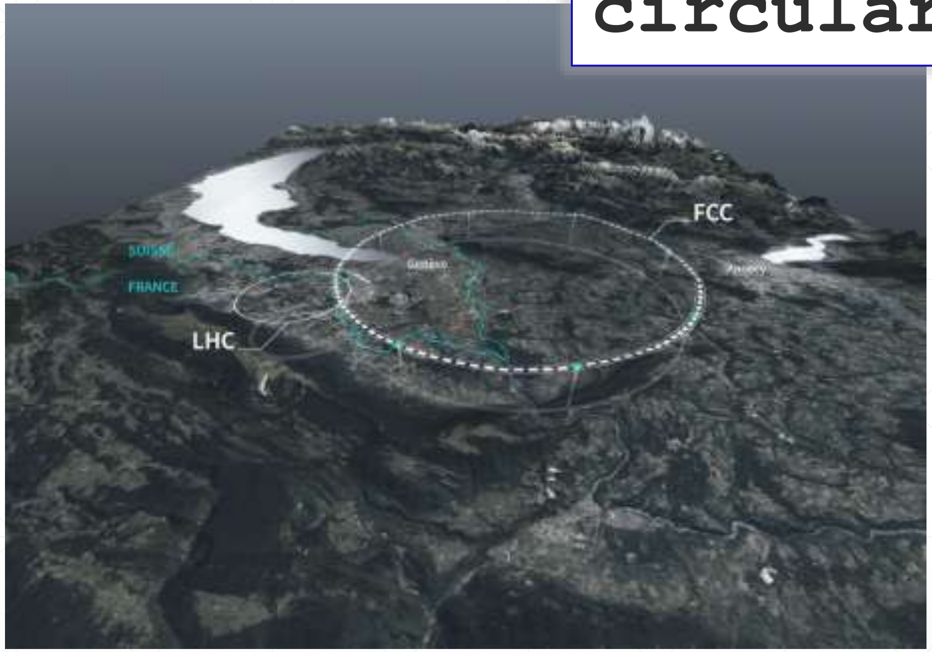
NC magnets and 60MW SRF

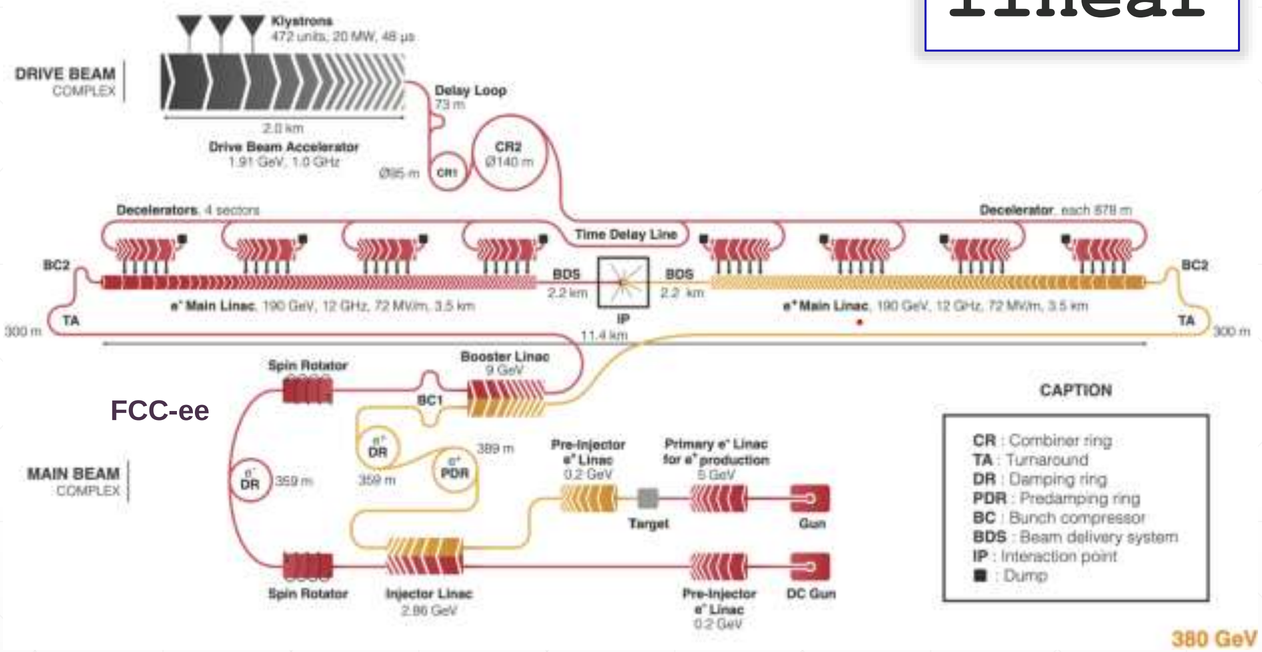
TDR (Dec'2023): 36BCNY(5.2B$)*

*not incl. contingency and escalation

*no labor, escalation, contingency, R&D, and spares

Future Colliders in Europe - Aspirations





FCCee [→hh] (CERN) e+e-

91 km, E_{cm} =91…365 GeV

NC magnets and 100MW SRF

CDR (2018): cost ~12BCHF *

CLIC (CERN) e+e-

11 km, E_{cm} =380 GeV [3 TeV]

2-beam NC RF 70-100 MV/m

CDR (2018): cost 5.9 BCHF *

*no labor, escalation, or contingency

*no 11,5kFTEs of labor, no escalation, no contingency

Future Colliders in the US: ["Trick #2"] Muons

At very high energies:

- (anti)electrons *e+/e-* (light particles *m*=0.511 MeV) radiate too much when bent → impossible accelerating in rings;
- linear *e+/e-* radiofrequency accelerators are free of that problem but are long and expensive (~ x 5/TeV)

e+e- circular

e+e- linear

Options left:

- (heavy) protons and ions *p+/ions* (*m*=1 GeV) can be accelerating in rings up to ~100 TeV, but they are composite particles (plus, cost a lot if *C*~100 km)

p+p+ circular

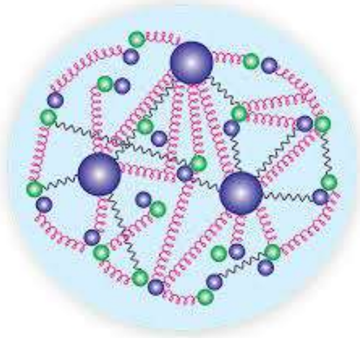
"The trick": collide *muons* - they are heavy (*m*=0.1 GeV) and point-like

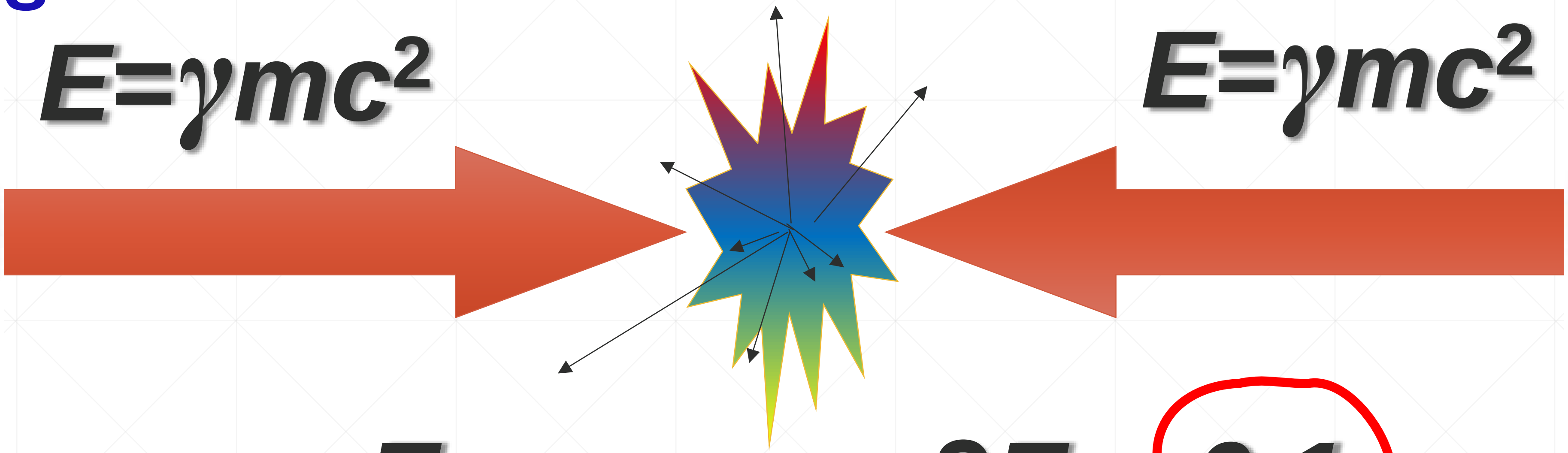
so, a) can be accelerated in rings, and b) muons are NOT composite

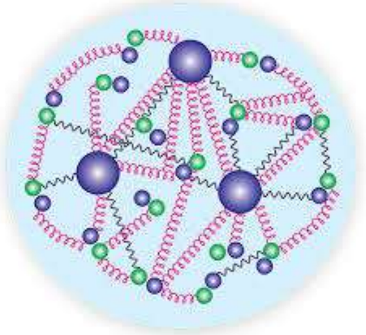
Leptons vs Hadrons

Protons

$E=\gamma mc^2$ $\qquad$ $E=\gamma mc^2$







$$E_{\text{CM partons}} \approx 2E \times 0.1$$

Leptons

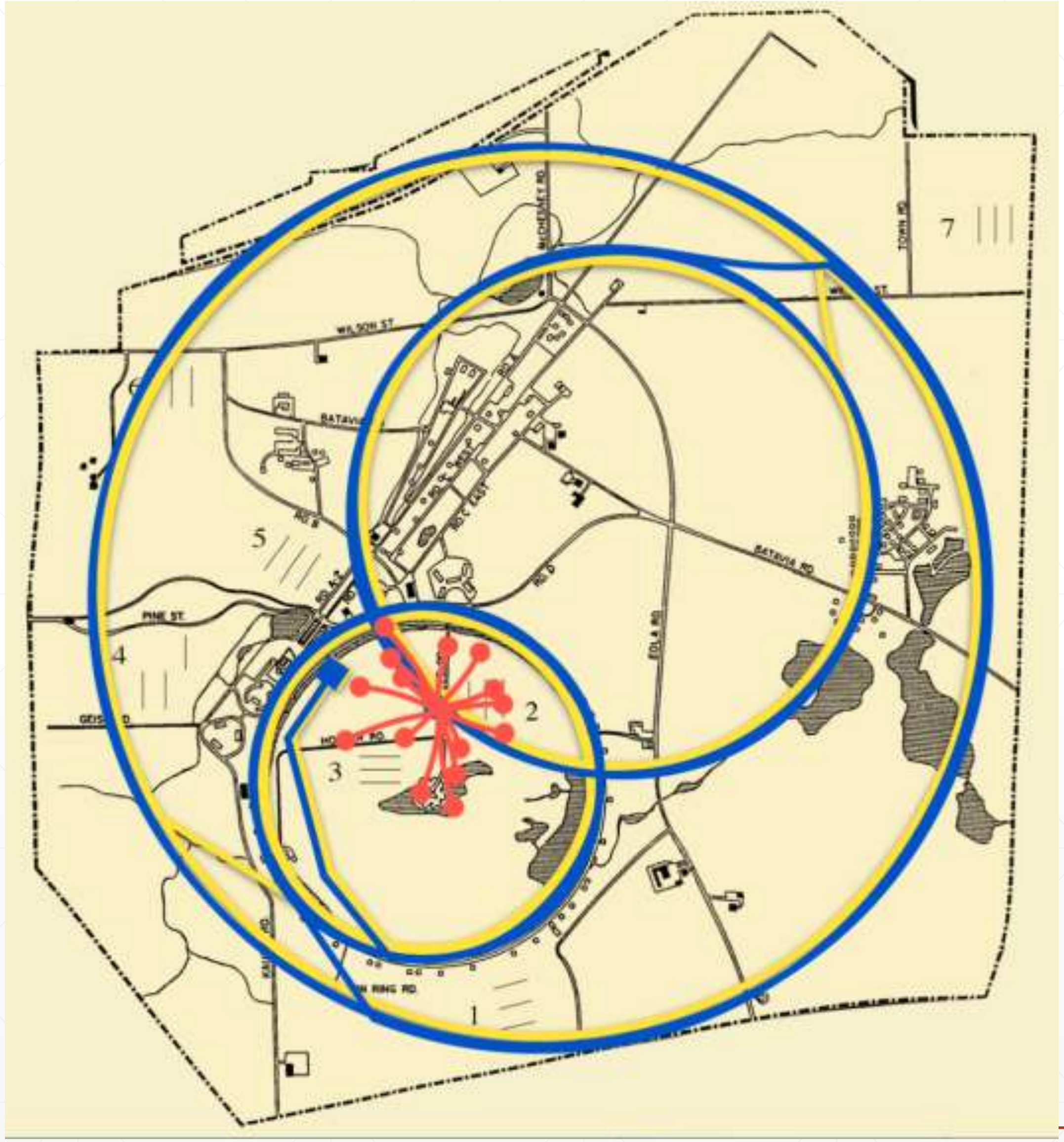
$e+$ $\qquad$ $e-$

$\mu+$ $\qquad$ $\mu-$

$\tau+$ $\qquad$ $\tau-$

$$E_{\text{CM leptons}} = 2E$$

Muon Colliders in the US



Fermilab site: about 3 x 4 miles, 6,800 acres

circular | compact | low(er) cost

low(est) power consumption

Muons decay quickly 2.2μs×γ

→ Fast production, cooling (size reduction) & acceleration

Muon Collider eg at FNAL μ+μ-

Circumference ~10 km, E_{cm} =3…10 TeV

NC+SC magnets and SRF

*Cost ~12-18 B$ * (ITF, 2021)*

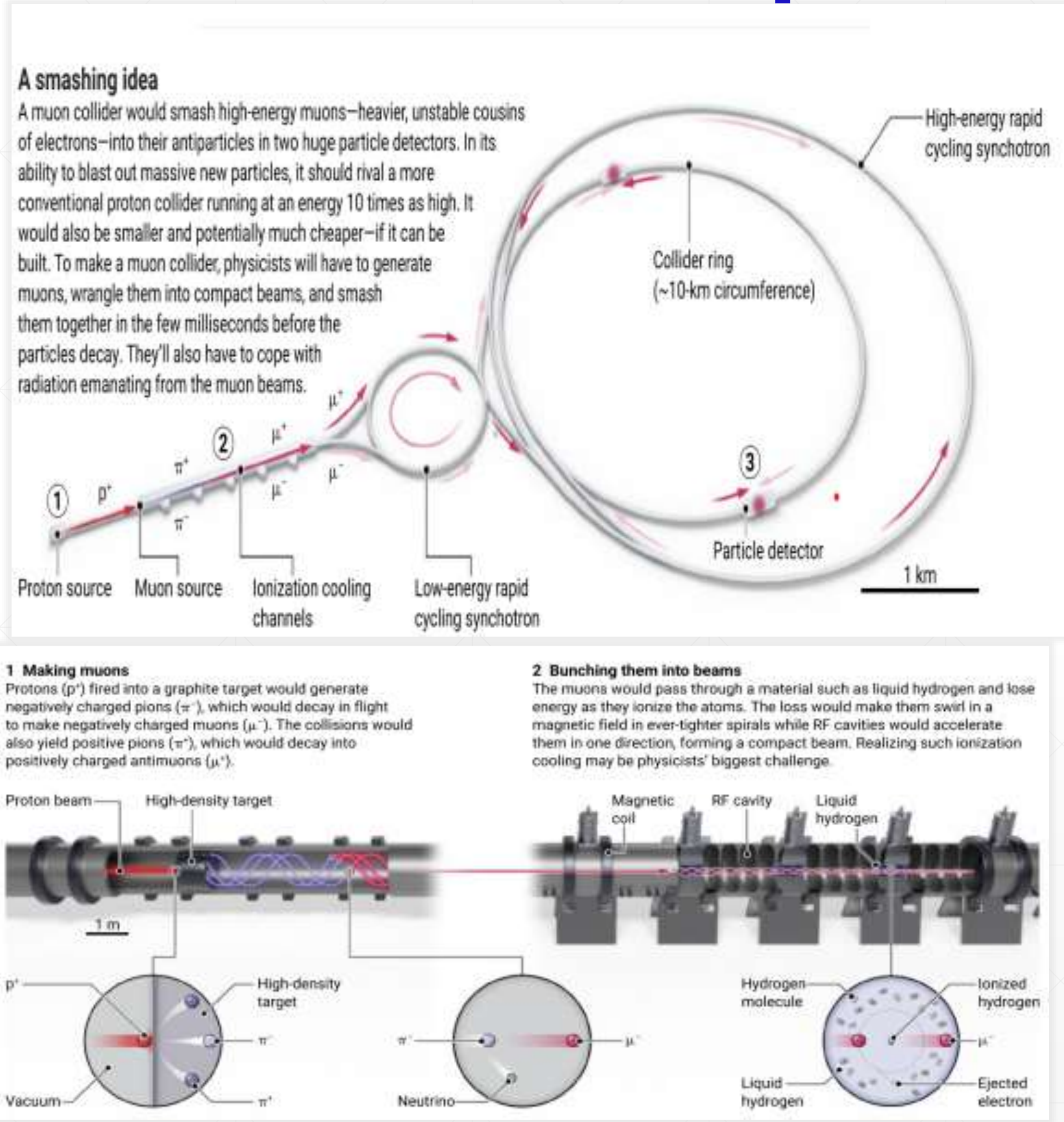
20 yrs of R&D

*no labor, escalation, or contingency

Muon Collider: Challenges and R&D Topics

R&D re: Energy Reach/Cost

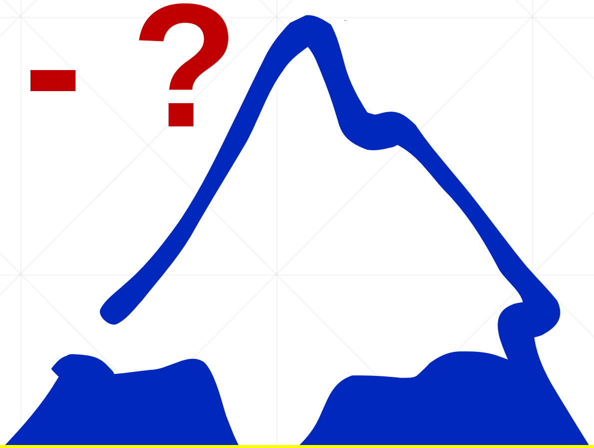
- Fast magnets for the accelerator rings (~few ms, ~20 km)
- Economical high-gradient pulsed SRF (~few ms, ~20-40 GeV)
- Collider ring 12-16 T superconducting magnets (DC, ~10 km)
- Civil construction (~40 km)
- Power infrastructure (~360 MW)



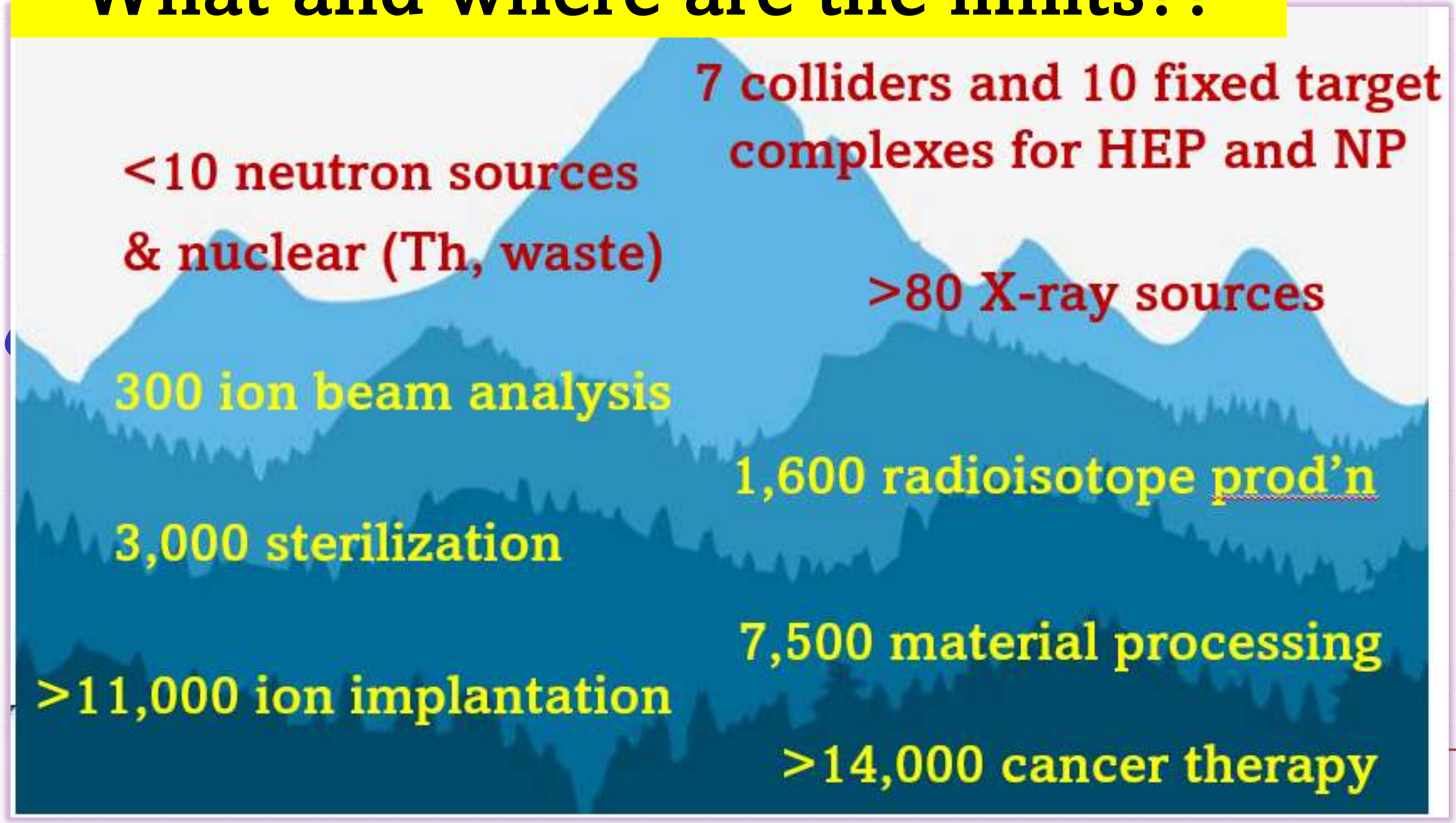
R&D re: Luminosity Goals

- Proton driver: 1-4 MW at 5-20 GeV; accumulate bunches with up to 10^14 particle, compress to few ns; deliver at 5-10 Hz rate
- Targets and cooling: DPAs, ~15 T SC solenoid with ~2 m aperture; high-gradient NC RF in 2-14 T SC solenoids of the ionization cooling channel
- Challenging MDI due to muon decays; neutrino flux dilution

Future - ?



What and where are the limits??



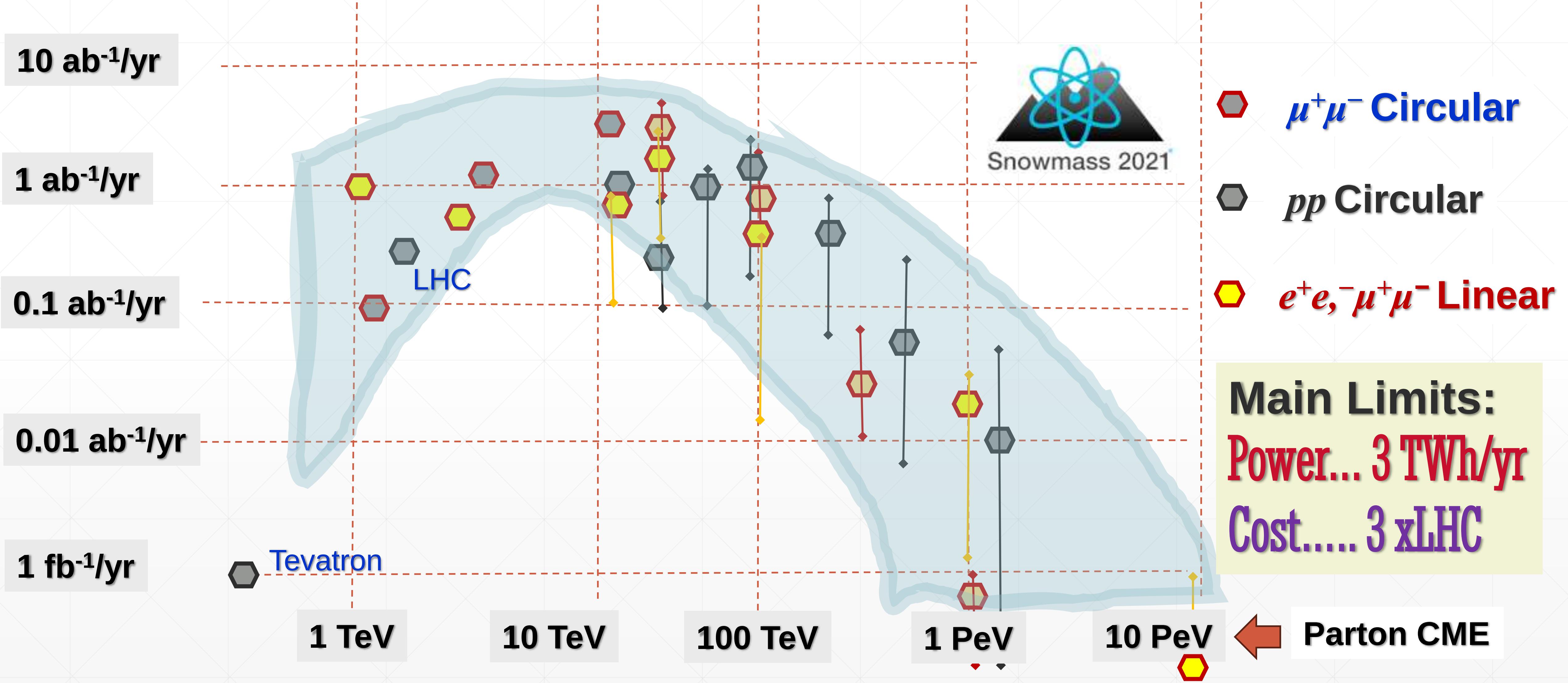
Main factors:

Center-of-Mass Energy
Luminosity
Size
Cost
Power consumption
Technical feasibility
Timescale of constr'n

Which technologies?

Existing?
Emerging?
Exotic?

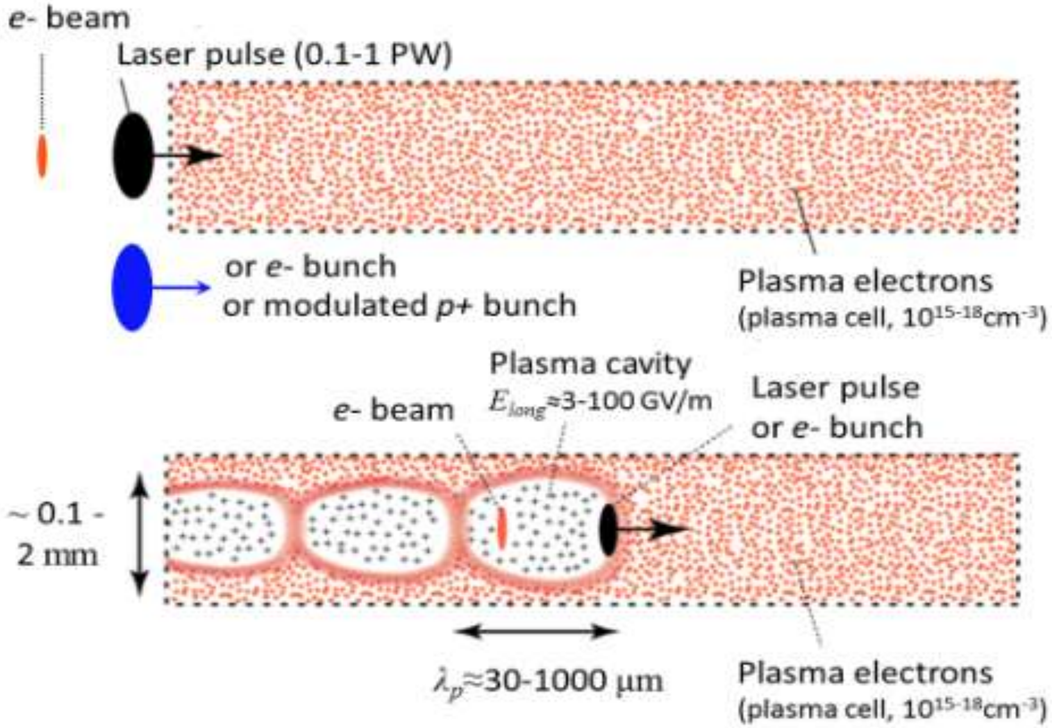
Ultimate Colliders *Luminosity* vs *Energy*



Main Limits:
Power… 3 TWh/yr
Cost….. 3 xLHC

V.Shiltsev, "Ultimate Colliders" (Oxford Encyclopedia, 2023); **DOI:** 10.1093/acrefore/9780190871994.013.118

“Trick #3”: Ultra-High Gradients in Plasma



From 0.1 GV/m (in traditional RF accelerators) to 10-100 GV/m in plasma

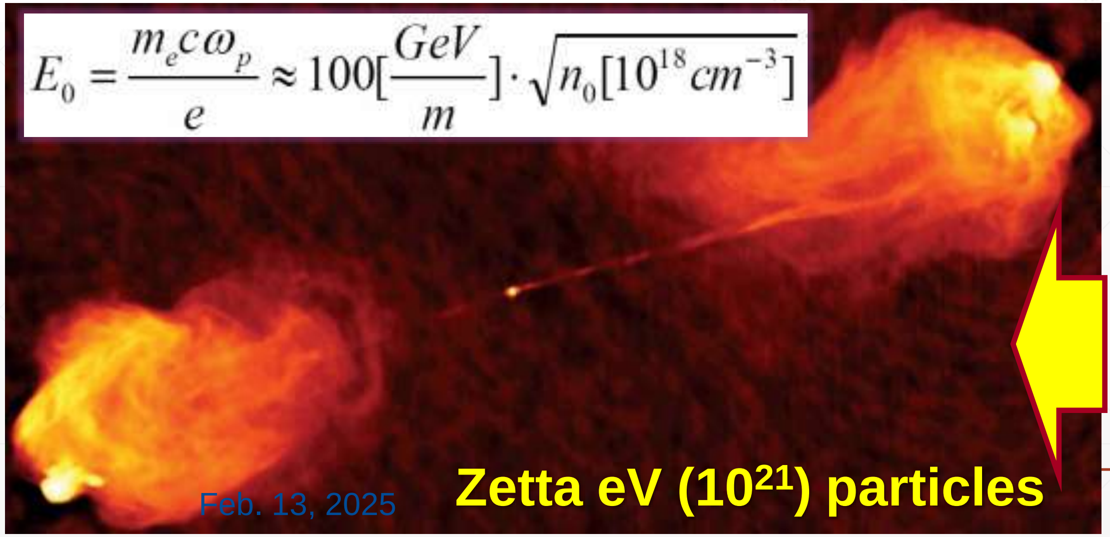
Three ways to excite plasma (drivers)

- laser *dE* ~ 10 GeV ($6\cdot10^{17}$ cm^{-3} 0.1 m)
- *e-* bunch *dE* ~ 9 GeV (~10^{17} cm^{-3} 1.3 m)
- *p+* bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10 m)

Impressive proof-of-principle demos!

In principle, plasma PeV *μ+μ-* colliders could be feasible…staging, cost and power of such TBD

UHECRs from EM shock waves in the ultra-dense *jets* of accreting magnetized black holes



Take Away Message

#1 Accelerators and beams – a dynamic and actively growing field of physics

#2 High impact across physics, bio, chem, med, and industry - driving demand for beam sci/eng's

#3 Vast opportunities, esp. in university research - backed by DOE, NSF, others

#4 Intriguing challenges ahead – pushing from TeV's scales to PeV's and even ZeV's

Lets do beams: a) great physics, b) useful, c) fun !

Thank you for your attention!

BACK UP SLIDES

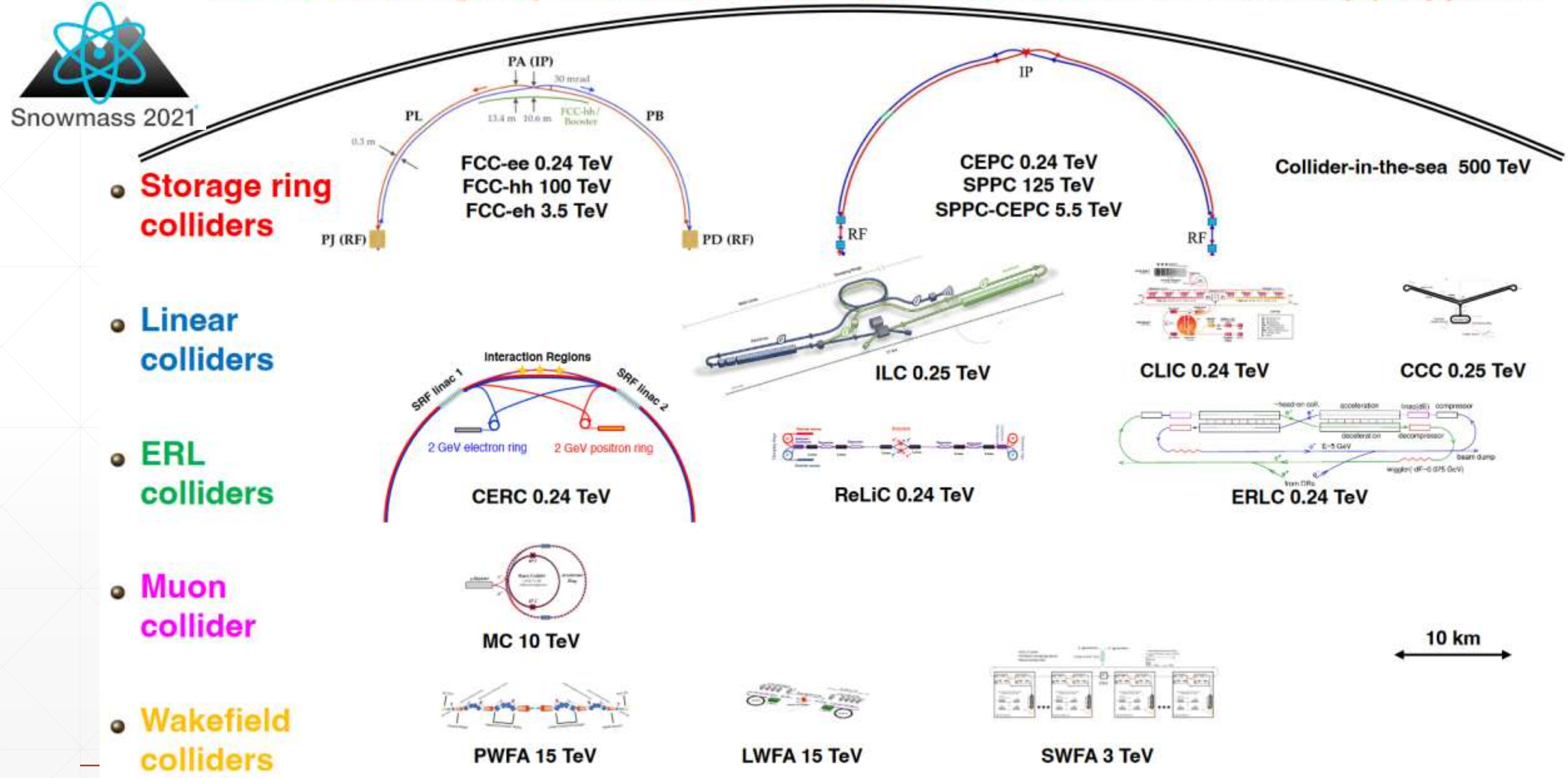
High Energy Particle Physics: Planning

- 2014 *P5* report was focused on *HL-LHC* and *ILC* (and *LBNF/DUNE*)
- The ILC situation had a bumpy development (ups & downs) since then
- 2020 European Strategy supported *FS ~100 TeV FCChh* and *FCCee*
- The US *Snowmass*'21 (2020-2023):
  - Many (~all) collider proposals discussed
  - Comparative evaluation by the *Implementation Task Force* (*ITF*)
  - Input to *P5* (series of meetings) → 2023 *P5 Recommendations 2c and 4a*
- [Next steps?]

Snowmass 2021

Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, ...

- **Storage ring colliders**
- **Linear colliders**
- **ERL colliders**
- **Muon collider**
- **Wakefield colliders**



Thomas Roser *et al* 2023 *JINST* **18** P05018

Implementation Task Force

- *Key questions:* "…What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facility?" …[colliders only!]
- *ITF charge:* "..develop metrics and processes to facilitate the evaluation of proposals and allow a fair comparison between them, including the expected costs, using the same accounting rules, schedule, and R&D status."


Reinhard Brinkmann (DESY)


Sarah Cousineau (ORNL)


Dmitri Denisov (BNL)


Spencer Gessner (SLAC)


Steve Gourlay (LBNL)


Philippe Lebrun (CERN)


Meenakshi Narain (Brown U.)


Katsunobu Oide (KEK)

- **US, Europe, Asia**
- Incl. liaisons with

  Energy Frontier,
  Theory Frontier,
  Snowmass Young.


Tor Raubenheimer (SLAC)


Thomas Roser (BNL, Chair)


John Seeman (SLAC)


Vladimir Shiltsev (FNAL)


Jim Strait (FNAL)


Marlene Turner (LBNL)

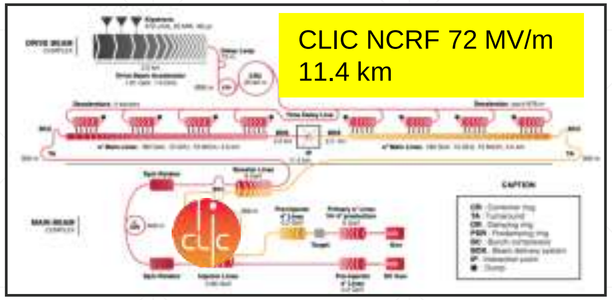

LianTao Wang (U. Chicago)

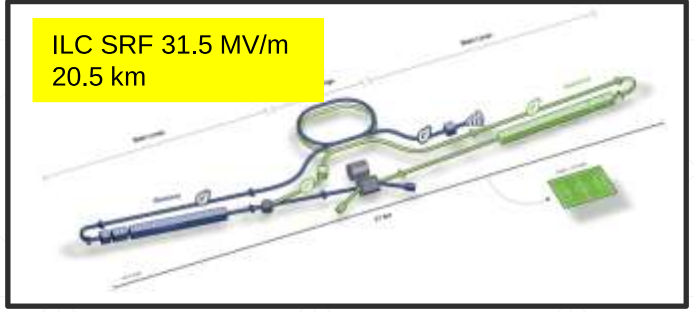
ITF: Process and Criteria

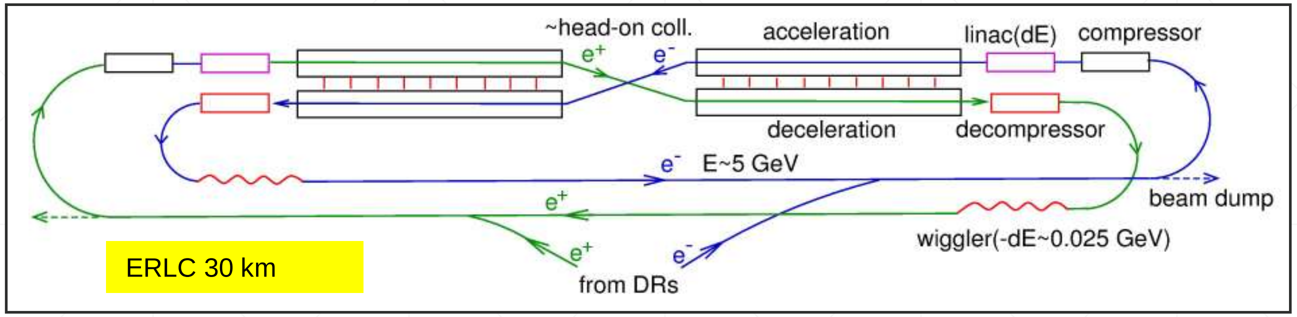
- Collected spreadsheets from proponents of 24 major collider proposals; >60 parameter each.
- Analyzed, evaluated, and compared the proposals with regard to:
  - Physics reach and impact (CM energy and luminosity reach)
  - Technical risk, technical readiness, and validation
  - Size, complexity, power consumption, and environmental impact
  - Cost and schedule
- Summary reported at the *Snowmass'21* and to *P5*
- Full report published as T.Roser *et al* 2023 *JINST* **18** P05018

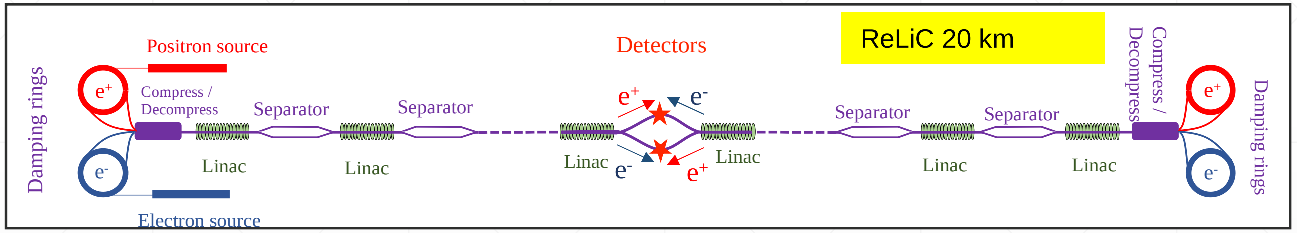
Higgs Factory Concepts (10)

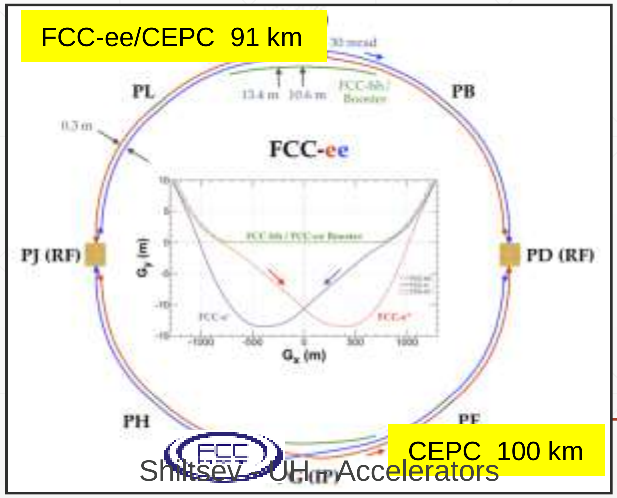
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 1$ TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee $(\gamma\gamma)$, $\sqrt{s} = 0.125 - 0.14$ TeV
MC (Higgs factory)	$\mu+\mu-$, $\sqrt{s} = 0.13$ TeV

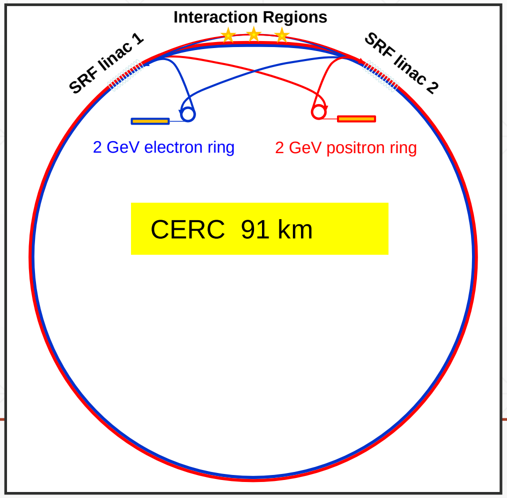


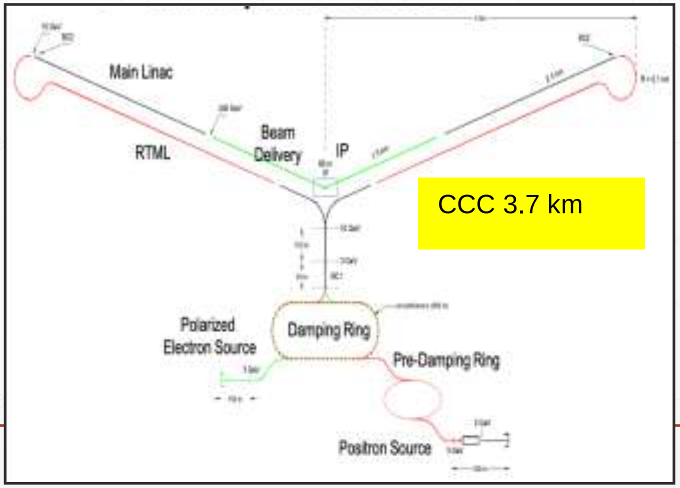


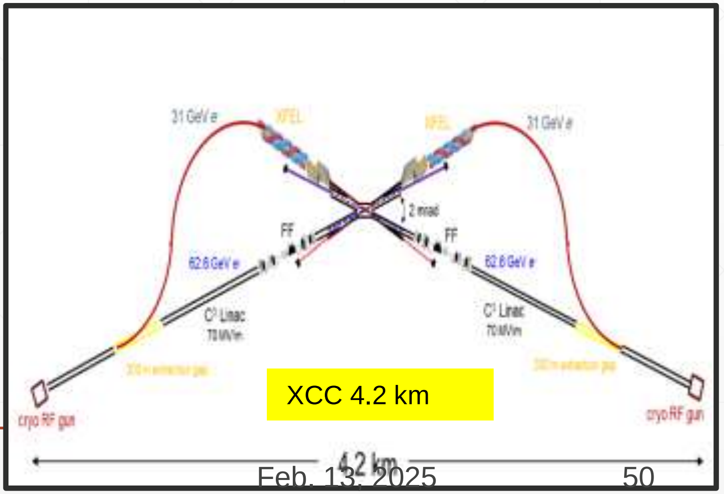












ITF Higgs Factories Summary Table

	CME* (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st physics	Cost range (2021 B$)	Electric Power (MW)
FCCee e^+e^-	0.24	7.7	0-2	13-18	12-18	290
CEPC e^+e^-	0.24	8.3	0-2	13-18	12-18	340
ILC e^+e^-	0.25	2.7	0-2	<12	7-12	140
CLIC e^+e^-	0.38	2.3	0-2	13-18	7-12	110
CCC e^+e^-	0.25	1.3	3-5	13-18	7-12	150
CERC e^+e^-	0.24	78	5-10	19-24	12-30	90
ReLiC e^+e^-	0.24	165	5-10	>25	7-18	315
ERLC e^+e^-	0.24	90	5-10	>25	12-18	250
XCC $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
MC $\mu^+\mu^-$	0.13	0.01	>10	19-24	4-7	200

*luminosity and electric power values are given for one energy

2024 US-CERN SOI

- April 26, 2024: a joint "*Statement of Intent between the United States of America and the European Organization for Nuclear Research (CERN) concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science*" was signed at The White House. The US-CERN SOI was signed by Deirdre Mulligan, *The White House Principal Deputy Chief Technology Officer,* and Fabiola Gianotti, *the CERN Director-General*. Among other topics, the SOI expresses an intention by the United States to collaborate on a future **FCC Higgs Factory** should the CERN Member States determine the project feasible.

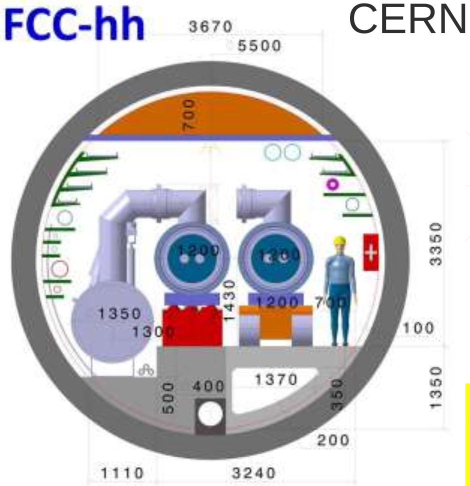
ITF on High Energy Collider Concepts(14)

Name	CM energy range
FCC-hh	pp, $\sqrt{s} = 100$ TeV
SPPC	pp, $\sqrt{s} = 75 - 125$ TeV
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV
LHeC	ep, $\sqrt{s} = 1.2$ TeV
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV
CEPC-SPPC-ep	ep, $\sqrt{s} = 5.5$ TeV

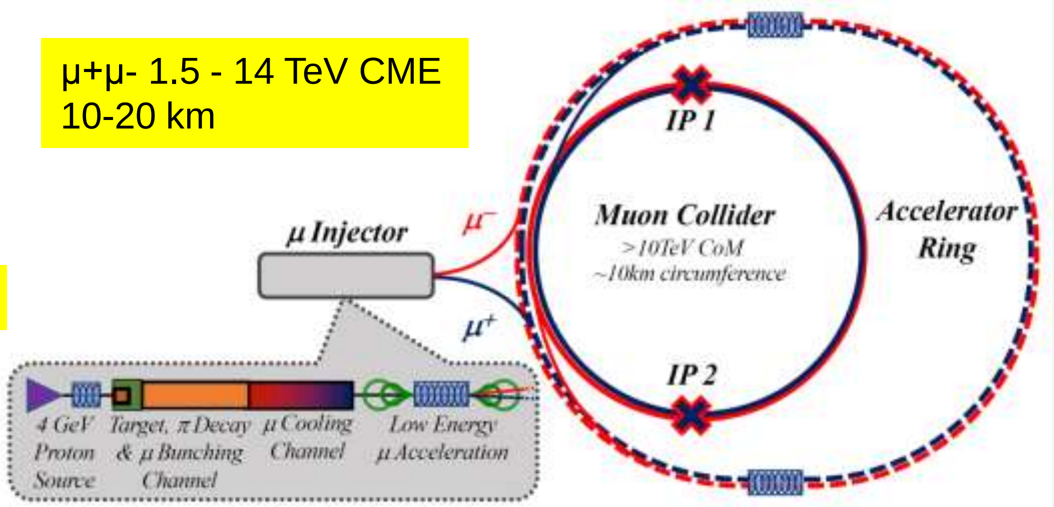
Name	CM energy range
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV
High Energy CCC	e+e-, $\sqrt{s} = 1 - 3$ TeV
High Energy ReLiC	e+e-, $\sqrt{s} = 1 - 3$ TeV
Muon Collider	μ+μ-, $\sqrt{s} = 1.5 - 14$ TeV
Laser-driven WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV
Particle-driven WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV
Structure WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV

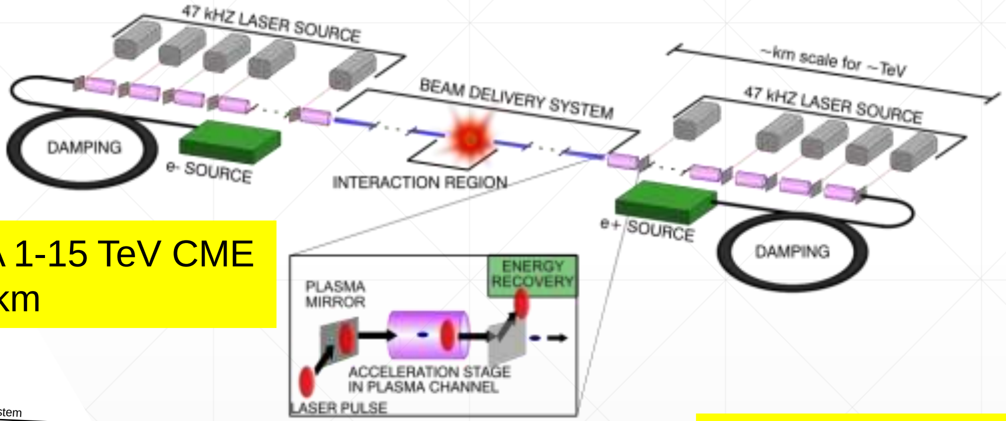
FCC-hh 100 TeV, 16 T magnets, 91 km

CERN

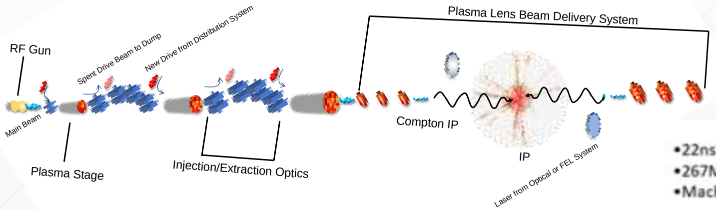


μ+μ- 1.5 - 14 TeV CME
10-20 km



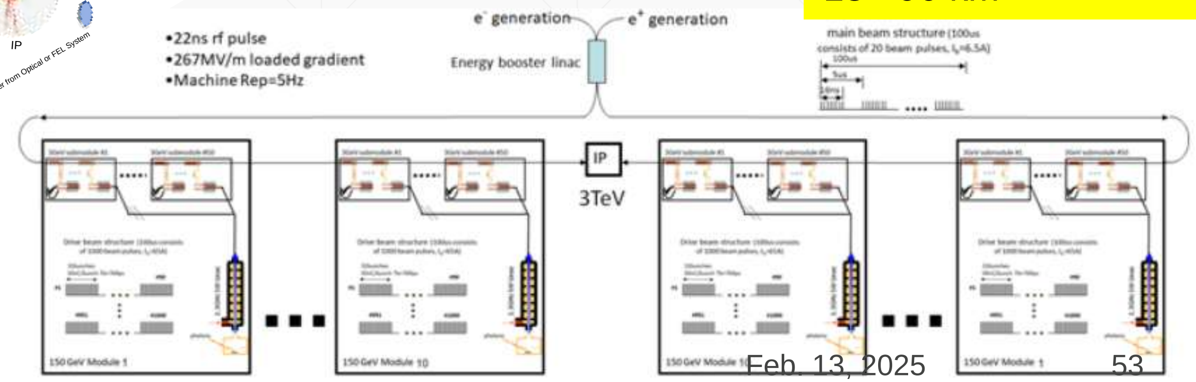


LWFA 1-15 TeV CME
1 - 7 km



PWFA 1-15 TeV CME
~ 14 km

SWFA 1-15 TeV CME
18 - 90 km



ITF 10+ TeV pCM Colliders Summary

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st physics	Cost range (2021 B$)	Electric Power (MW)
MuColl-FNAL $\mu^+\mu^-$	6-10	20	>10	19-24	12-18	*O*(300)
Plasma WFA e^+e^-	15	20	>10	>25	18-50	*O*(600)
FCChh-100 SPPC pp	100 125	30 13	>10	>25	30-50 30-80	~560 ~400

2023 P5 Recommendations

- **Recommendation 4a:** Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on **proton**, **muon**, or **possible wakefield technologies**, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** […]

- …Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.
- …Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress with this emerging technology path.