



Landscape of Accelerators, *Snowmass'21* Planning for Future, and Ultimate Colliders

Vladimir SHILTSEV

Fermilab Colloquium, December 14, 2022

Content (Plan)

I. Highlights of modern accelerators

- Machines (e and p), technologies, beam physics

II. *Snowmass'21 Accelerator Frontier*

- HEP facilities: timeline, cost, R&D

III. Ultimate Colliders

90 Years of Accelerators

Since Cockcroft & Walton,
Lawrence, van der Graaf:

- 4 Nobel Prizes + led to ~1/3 of all Nobels in Physics and more

>100 used in research now:

- with 4500 experts+15000 staff
- serving ~80,000 users (cond. matter, HEP, bio, NP, etc)

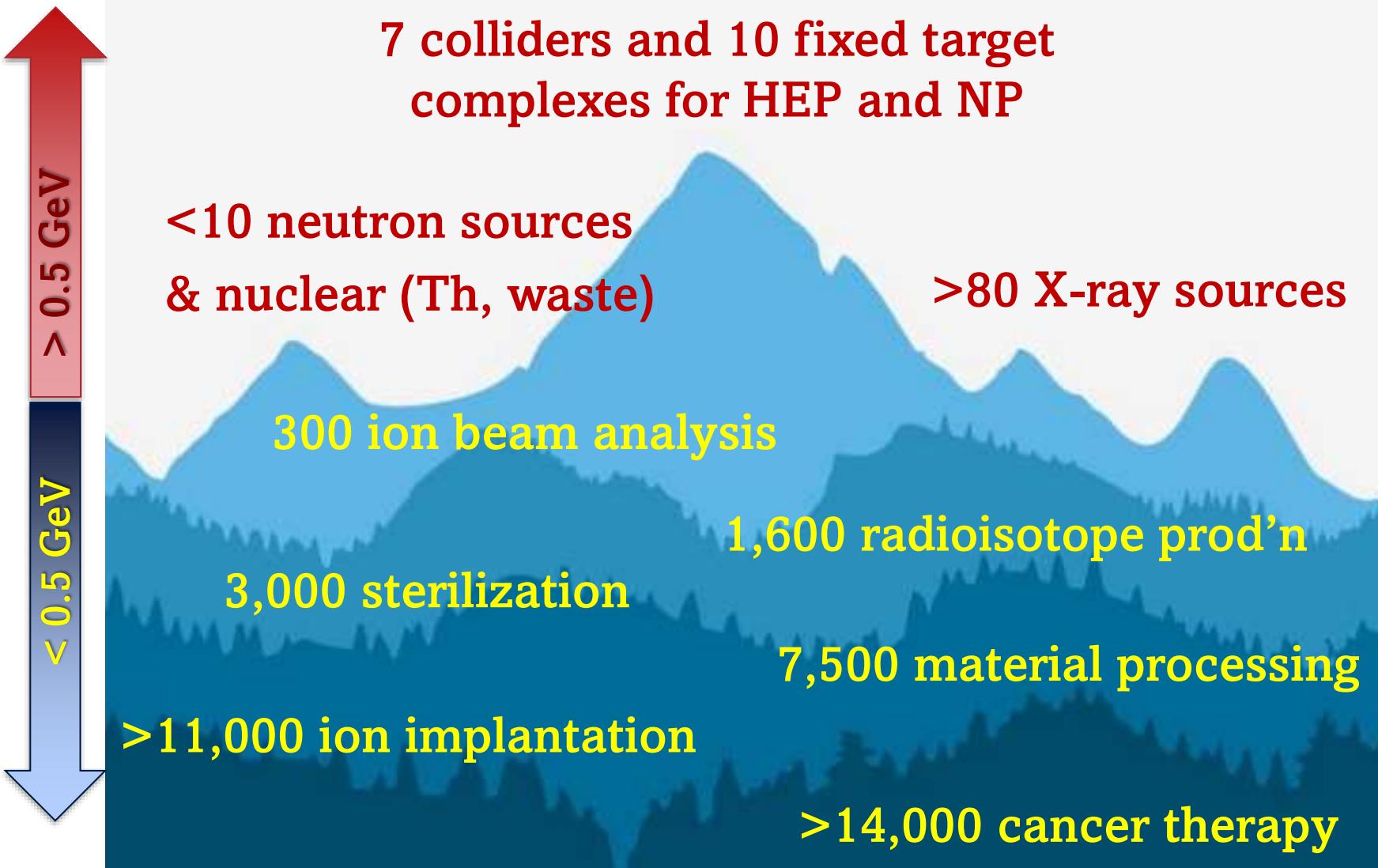
Pushing the envelope:

- Energy, performance(power, luminosity, brilliance, species), cost, complexity, size, R&D,...

~1/4 in the US

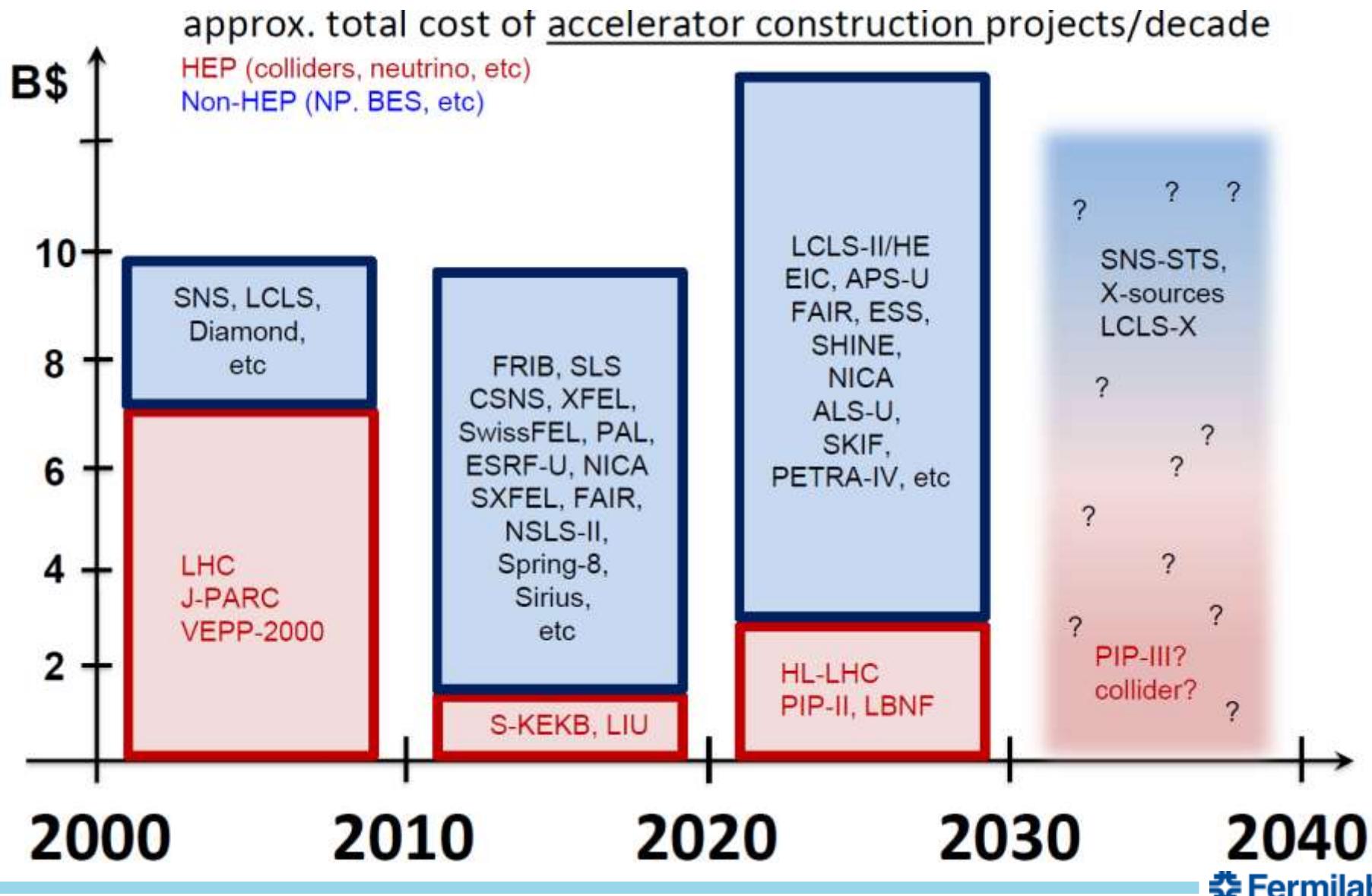


Landscape of Accelerators

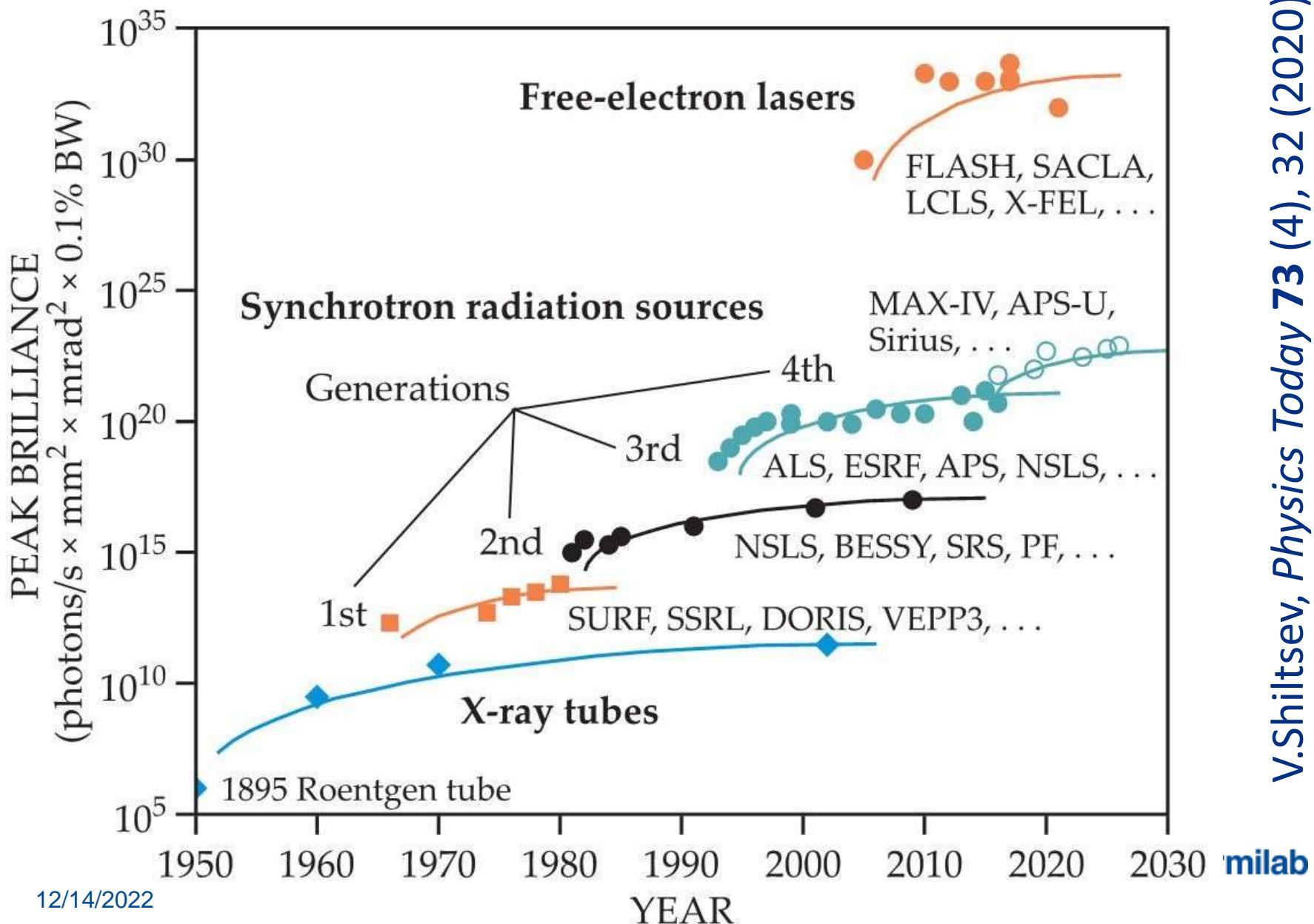


data from : A.Faus-Golfe, R.Edgecock, et al, EUCARD-2 Report: "Applications of Particle Accelerators in Europe." (2017); and V.Shiltsev, Physics Today (2020)

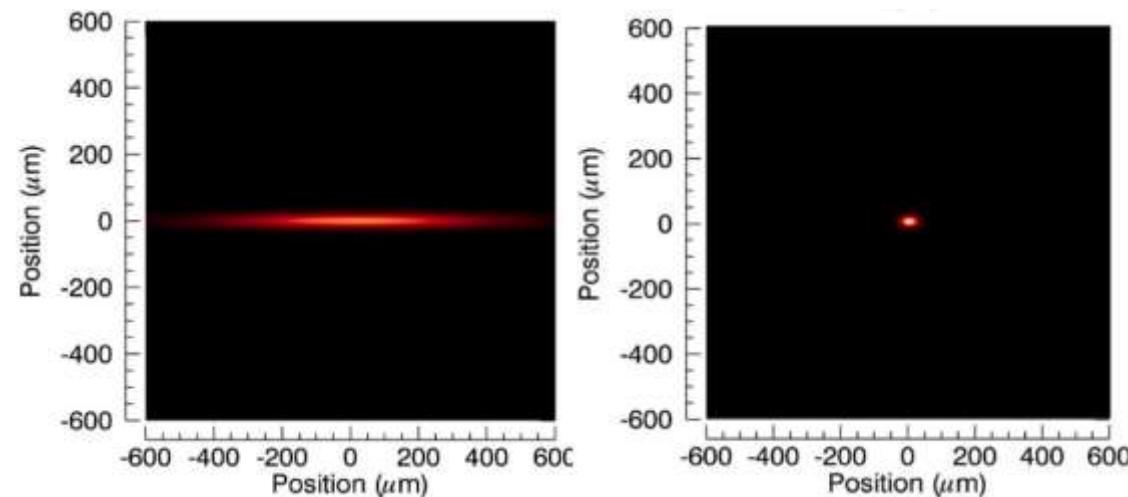
Accelerators Long Term Trends: HEP vs non-HEP



Revolution in Light Sources / X-ray Sources



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



2024 – APS-Upgrade @ Argonne 6 GeV, **70 pm**

2024 – 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**

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

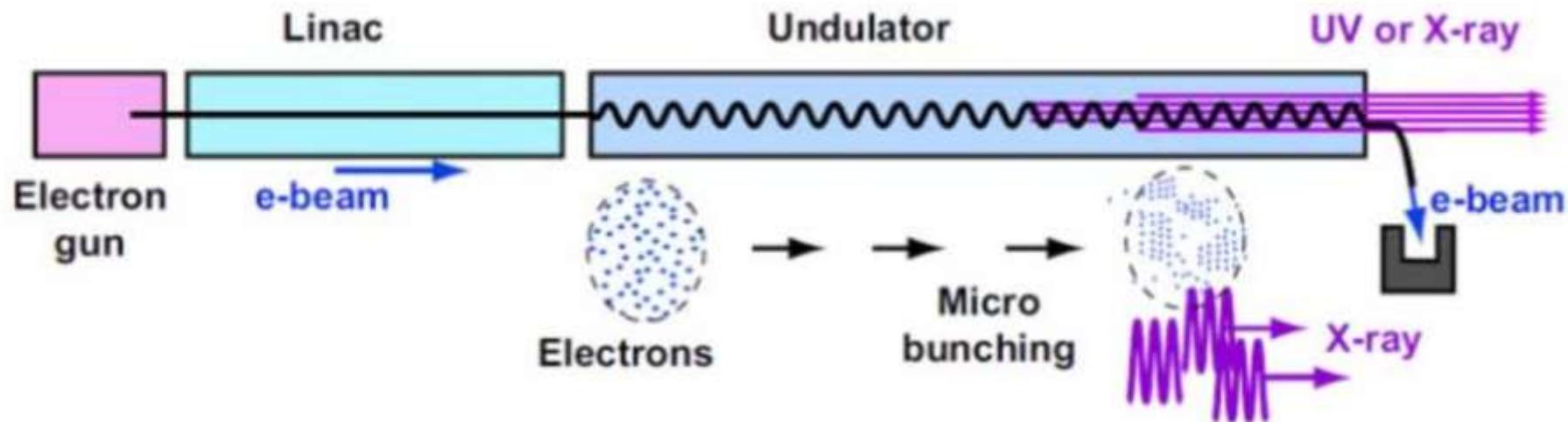


Self-Amplified Spontaneous Emission (SASE) Free Electron Lasers (FEL)

aka

X-FELs

SASE-FEL



- 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@Ei., 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**

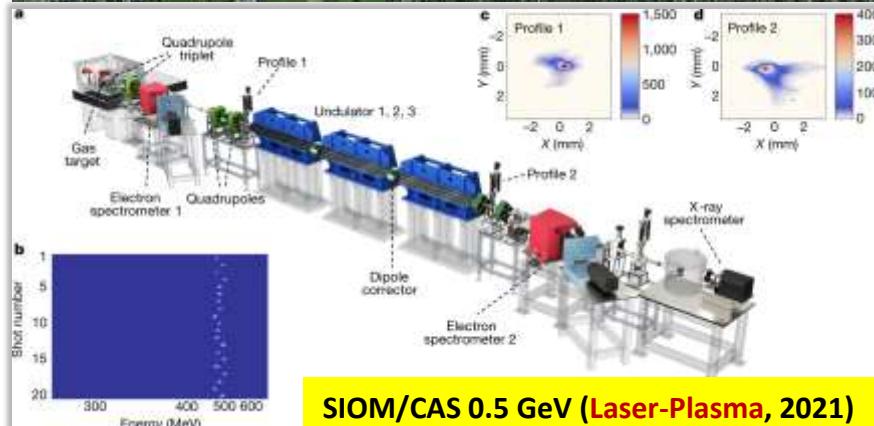
SIOM Shanghai, 0.5 GeV, **plasma**

2023 – LCLS-II, SLAC 4 GeV, **SRF**

2025 – SHINE, Shanghai 8 GeV, **SRF**

2031 – LCLS-II-HE, SLAC 8 GeV, **SRF**

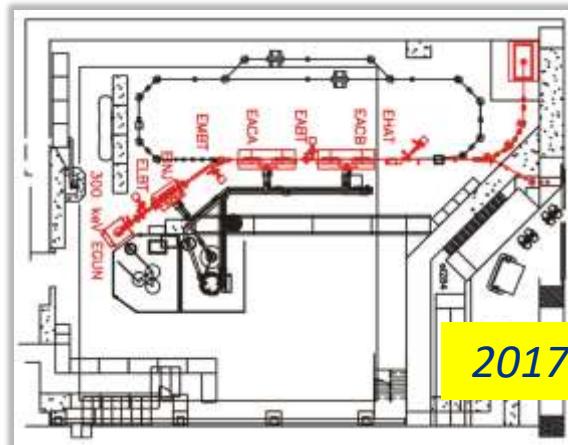
2033 – SILA, Russia, 6 GeV, **NC RF (?)**



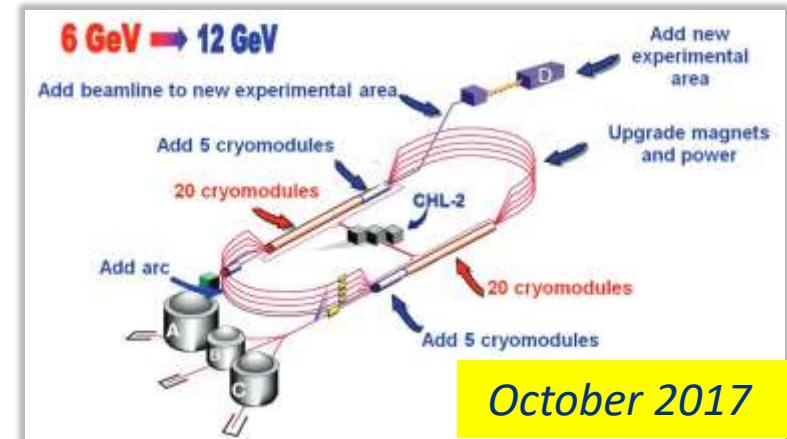
e-beam: 8 GeV
Photon energy: 0.4-25 keV
Pulse duration : 1-100fs
Repetition : 1MHz
Total length : 3.1km
ca 30m underground

Electrons and Ions for Nuclear Physics

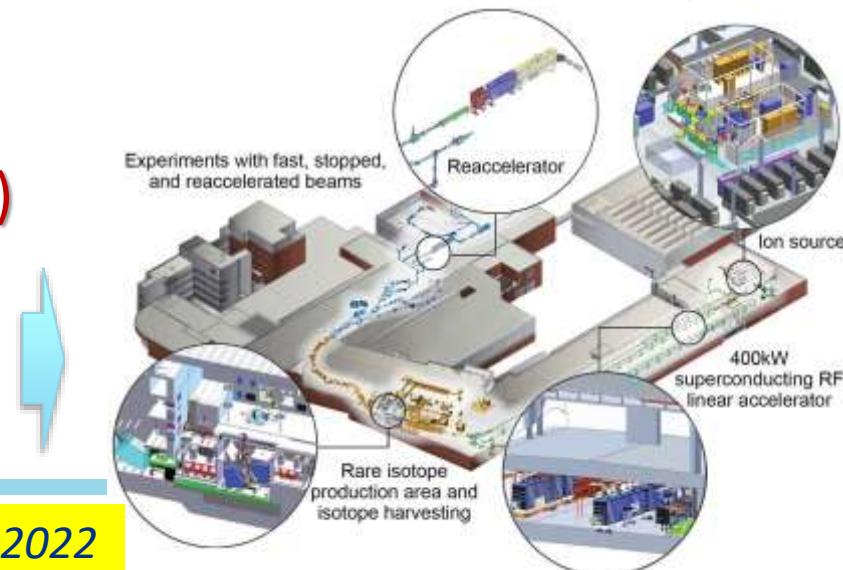
Continuous Electron Beam Accelerator Facility (CEBAF) at TJNAF : **12 GeV** electron beam energy upgrade (cw SRF linac)



Facility for Rare Isotope Beams (FRIB) at Michigan State University:
212 MeV/u ion SRF linac, **0.4MW** power (5×10^{13} $^{238}\text{U}/\text{s}$)



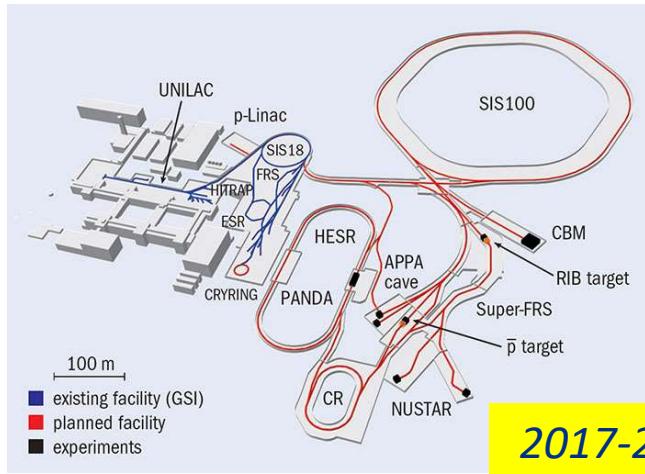
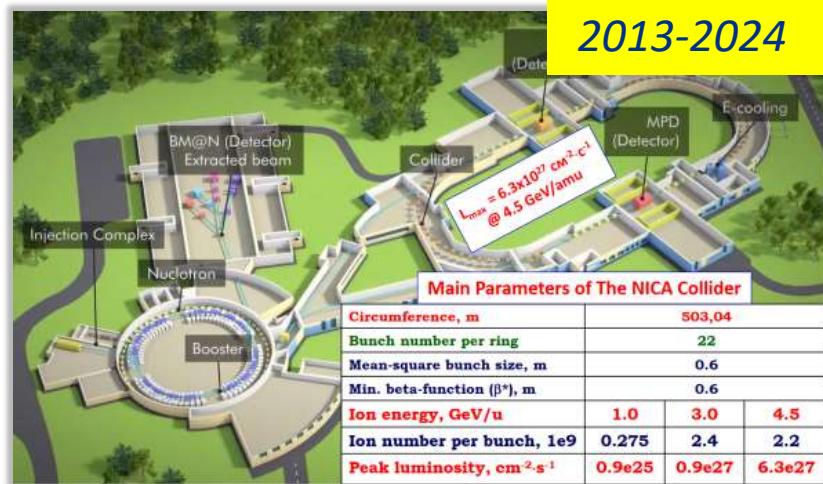
Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF : 30 MeV 10 mA cw SRF electron linac (**0.3 MW**)



Ion Machines under Construction

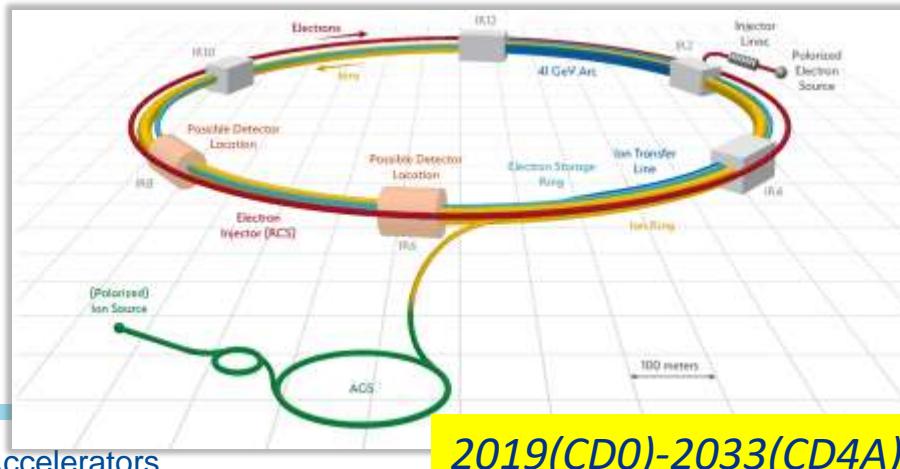
NICA Collider in JINR(Dubna): 4-11

GeV cme, SC magnets; polarized p , d and ions (Au); $L \sim 10^{27}$ w. beam cooling



Facility for Antiproton and Ion Research (FAIR) at GSI (Darmstadt): beamlines and rings SIS-100 1.1 km, 29 GeV p , 2.9 GeV/u ions, SC superferric 1.9 T magnets

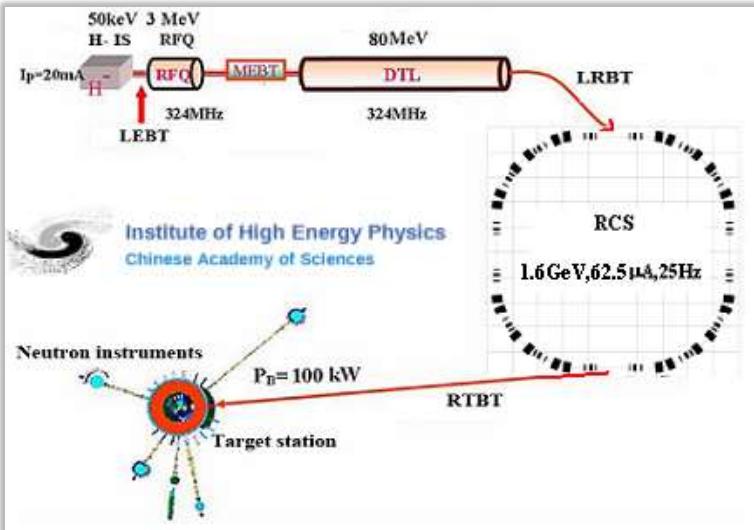
Electron-Ion Collider EIC at BNL:
275 GeV protons ring (RHIC) +
new 10-18 GeV e- ring, 70%
polarization, $L \sim 10^{34}$ w. cooling



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

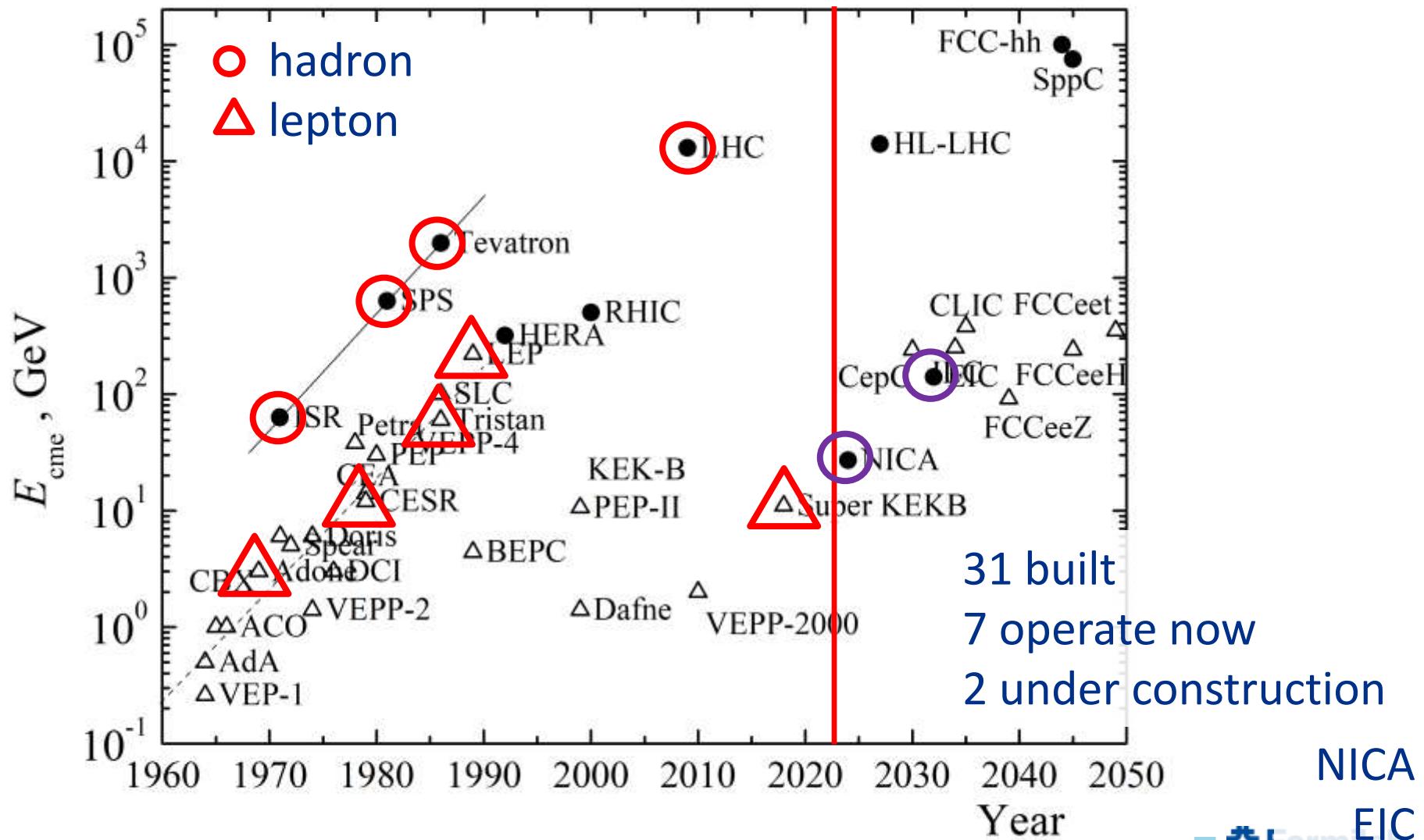


European Spallation Source (ESS), Lund:

- 5 MW 2 GeV pulsed SRF linac → target
- Construction started 2014, 80% complete
- RFQ beam to NC DTL1... DTL4 install'n
- 1st users program in 2024-25

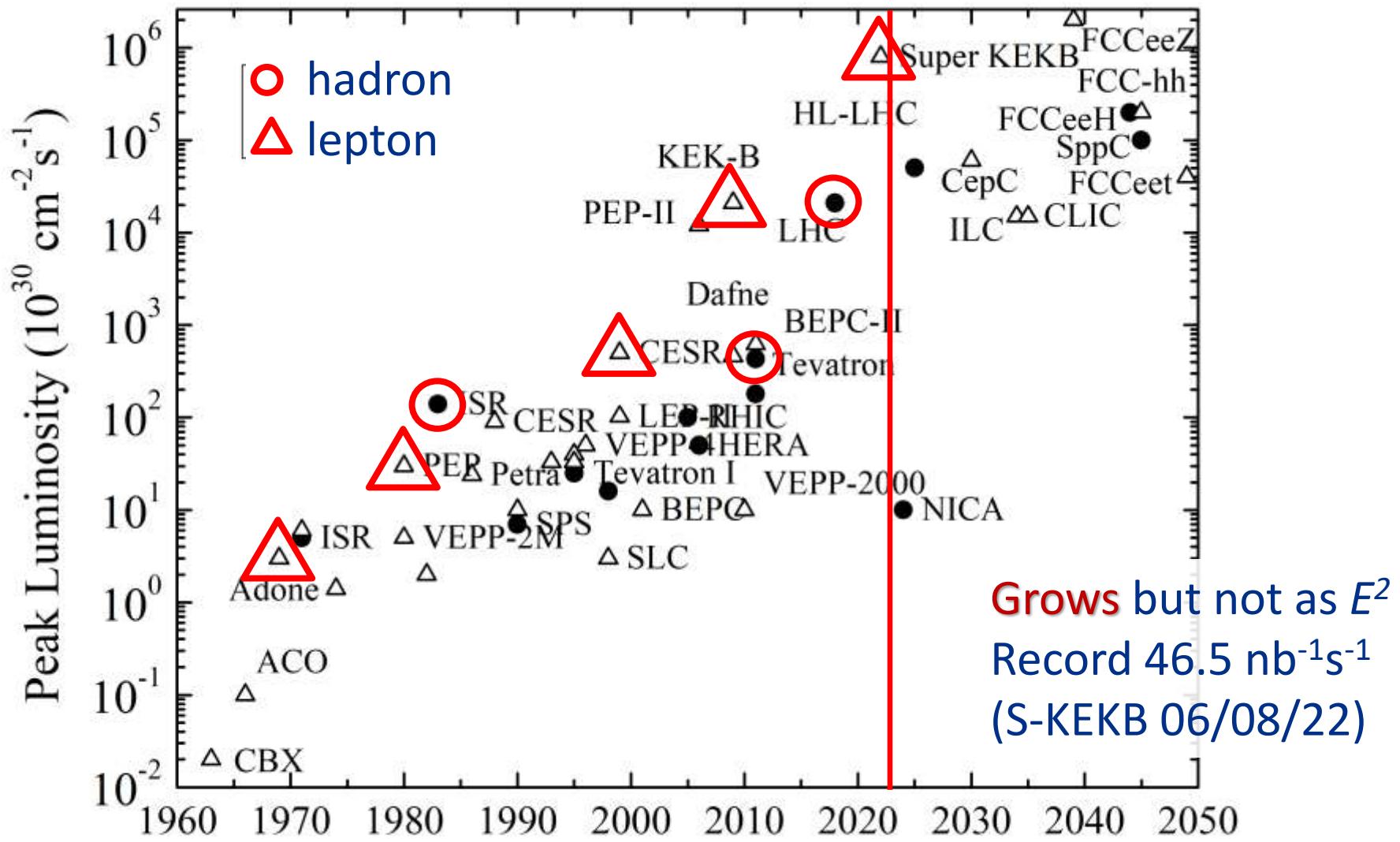
Colliders: Livingston Plot

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



Collider Luminosities

6-7 orders on magnitude in E_{CM} in 6 decades

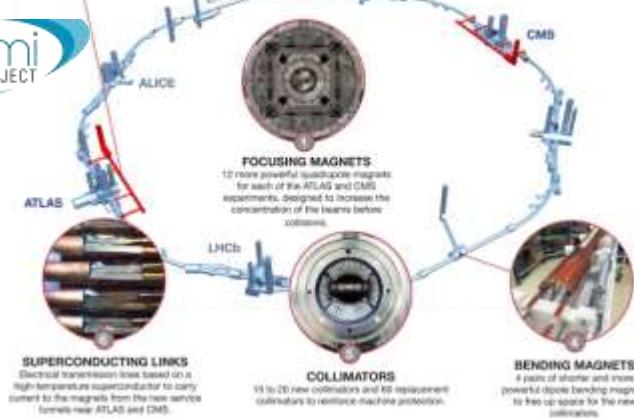
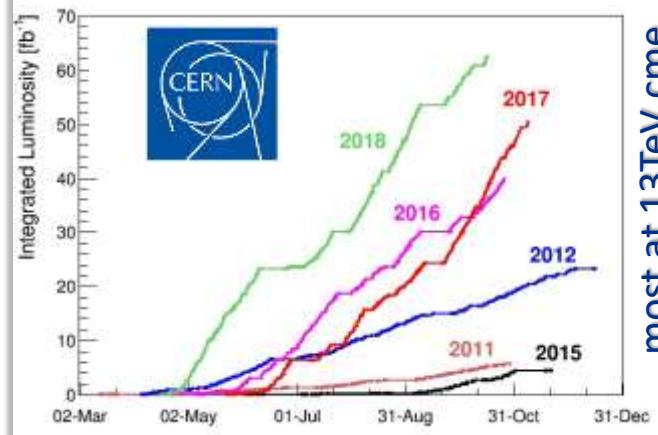


HEP Colliders

Seven in operation now

	Species	E_b (GeV)	C (m)	$\mathcal{L}_{\text{peak}}^{\max}$	Years
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979–present
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989–present
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997–present
RHIC	p, i	255	3834	2.5×10^{32}	2000–present
LHC	p, i	6500	26 659	2.1×10^{34}	2009–present
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010–present
S-KEKB	e^+e^-	7 + 4	3016	$8 \times 10^{35}^a$	2018–present

V. Shiltsev and F. Zimmermann: Modern and future colliders



Highlights – LHC : pp 13 → 13.6 TeV cme

- 190 fb $^{-1}$ /IP by now, x2 design luminosity
- High-Lumi upgrade by 2029: double beam current, smaller β^* (new Nb₃Sn IR magnets), “crabbing”, leveling @14 TeV → 250 fb $^{-1}$ /yr
- Followed by ~decade of ops to 3-4 ab $^{-1}$

Highlights – Super-KEKB: e+e- 7+4 GeV

- Startup in 2018, world record $L=4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Design luminosity goal $60 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Now ~8% of the goal, slow progress, shutdown

most at 13TeV cme

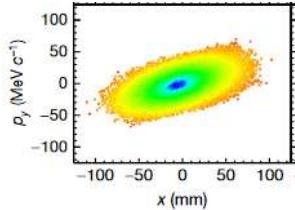
Accelerator R&D - Few Examples

Record 14.5T Dipole (at FNAL, part of the US MDP)

Nb3Sn conductor
Stress control



MAP/MICE: Ionization cooling of muons (140 MeV/c, RAL, UK)

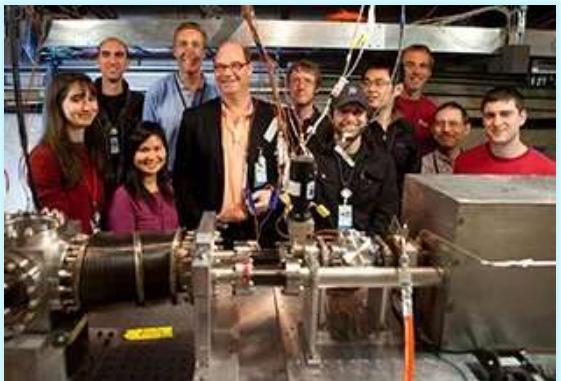


MICE
~10% in one pass



Plasma accelerators FACET-II (SLAC) and BELLA (LBNL)

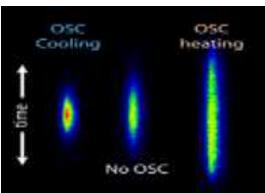
Unique e- beam
10 GeV, 1 nC, $\sim 1 \mu\text{m}^3$
 \rightarrow 9 GeV energy gain over 1.2 m plasma



Unique laser \rightarrow
8 GeV/0.2m
staging p.o.p
 $0.1+0.1$ GeV

IOTA Ring/Optical Stochastic cooling e- (100 MeV, FNAL)

soon – experiments with p 's



THz bandwidth

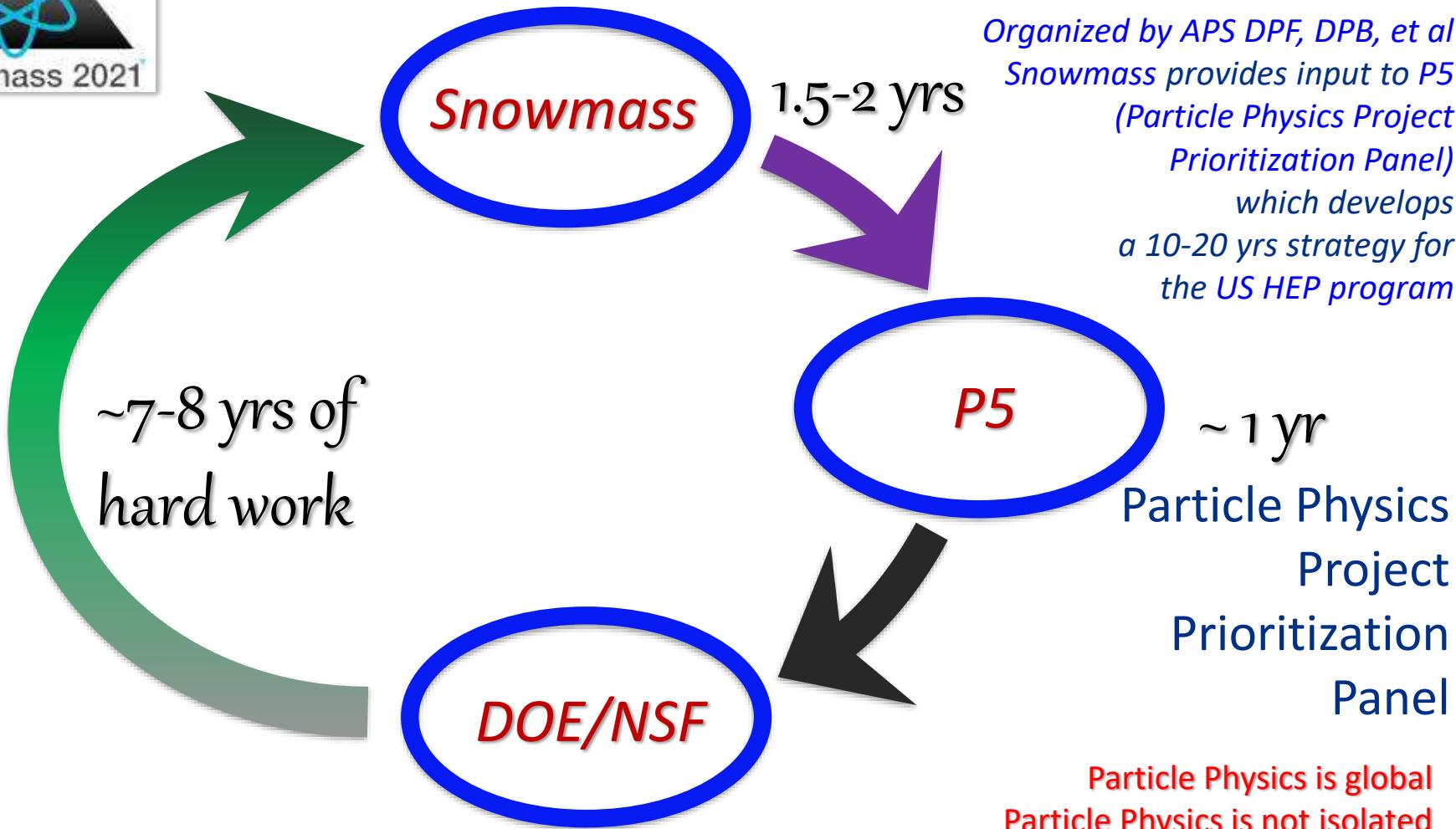


12/14/2022

Part II :

**Snowmass'21 –
*Planning For Future***

Snowmass'21 "a particle physics community study"



<https://www.snowmass21.org/>



Snowmass'21 Accelerator Frontier



Steve Gourlay
(LBNL)



Tor Raubenheimer
(SLAC)



Vladimir Shiltsev
(FNAL)

Focus:

- Understand the most important questions for the field of *Accelerator Science and Technology*
- Identify promising opportunities and tools to address them
- Consider a mix of large, mid, and small scale accelerator projects as well as R&D
- **Provide information to P5 to help develop a strategy for the US HEP**

Topical Groups (9): Beam Physics, Accelerators for Neutrinos and RPF, Higgs factories, Multi-TeV- & plasma colliders, Accel. Technologies
➤ **9 out of 30 group conveners from outside the US (Europe, Asia)**

Snowmass AF: Inputs and Discussions



- ❖ >500 People Took Part in the AF discussions:
 - ❖ ~25% early career scientists and engineers
 - ❖ Almost 100 attended the “final” meeting in Seattle in July’22
- ❖ 63 Topical Workshops & Meetings, 8 Cross-Frontier **Agoras**:
 - ❖ 5 on all types of colliders: ee, linear/circular, mumu, pp, advanced
 - ❖ 3 on experiments and accelerators for rare processes physics
- ❖ Special cross-Frontier Groups (e.g., AF-EF-TF-IF-NF):
 - ❖ eeCollider Forum, Muon Collider Forum, Implementation Task Force
 - ❖ 2.4MW design group FNAL, Nat'l Future Collider R&D Program proposal
- ❖ Summarized in Many Reports/Documents:
 - ❖ 257 Letters of Interest, **121 White Papers**
 - ❖ Reports of the Implementation Task Force, ee- and Muon Collider Fora
 - ❖ 9 AF Topical Group summary reports
 - ❖ **Accelerator Frontier Summary Report**



AF Report: Executive Summary

arxiv:2209.14136

“Intro”:

- Since last P5, this Snowmass’21 process

“Future Facilities”:

- *TBD by P5* – accelerator/people need to be part of P5; ITF analysis can greatly help
- *Multi-MW FNAL complex upgrade* will be priority for NF in 2030 (AccFrontier is ready)
- Many opportunities for Rare Processes (AF ready), incl. *PAR and utilize what we have*
- Several Higgs/EW factories are feasible: *FCCee, C3 and HELEN* to be explored
- $O(10 \text{ TeV/parton})$ needed for >2040 ’s, *muon colliders* to be explored/ pre-CDR by 2030
- Need an *Integrated Future Colliders R&D program* in OHEP to provide design reports by next Snowmass/P5’2030 and engage internationally (FCC, ILC, IMCC)

Accelerator Frontier

S. Gourlay, T. Ranjbenheimer, V. Shiltsev

G. Arribi, R. Asmussen, C. Barber, M. Bai, B. Belomestnykh, S. Berndsen, P. Blau, A. Bouc-Coll, J. Galapago, C. Geddes, G. Holzstaetter, M. Hogan, Z. Huang, M. Latron, D. Li, S. Lv, R. Milner, P. Moenneri, E. Nardi, M. Palmer, N. Parashuram, F. Pellegrini, E. Petyt, Q. Qin, J. Povet, T. Rose, G. Salda, D. Shatakin, V.-E. Sun, J. Tang, A. Volinber, B. Wisse, F. Zaneeranjan, A.V. Zlobin, H. Zwicky

For over half a century, high-energy accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity frontier research in high energy physics (HEP) continuously drive the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more power efficient. Despite these past efforts, the increasing size, cost and timescale required for modern and future accelerator-based HEP projects arguably distinguish them as the most challenging scientific research endeavors. In the meantime, the international accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals.

Major developments since the last Snowmass/HEPAP P5 strategic planning exercise in 2013-2014 include start of the PIP-II proton factory construction for the LHCb/DUNE neutrino program in the US; emergence of the FCCee/CEPC project for Higgs/EW physics research at CERN and in China, respectively; a significant reduction of activity related to linear collider projects (ILC in Japan and CLIC at CERN); and presumably, the end of the Muon Accelerator Program in the US and creation of the International Muon Collider Collaboration (IMCC) in Europe. The last decade saw several initial planning efforts, including the US DOE GARD Roadmap, Strategic Plan for Particle Physics and the Accelerator R&D Roadmap, EnPRAXIA, etc.

In addition, since the last Snowmass meeting that took place in 2013 was shortly after the confirmation of the Higgs, the goals for the Energy Frontier have changed as result of the LHC7 measurements. While a Higgs/EW factory at 250 to 300 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or low TeV $\nu^+ \nu^-$ collider has diminished. Instead, the community is focused on a 30+ TeV ($\nu^+ \nu^-$) discovery collider that would follow the Higgs/EW factory. This is an important change that will reform some of the accelerator R&D programs.

The technical maturity of proposed facilities ranges from class-ready to those that are still largely unexplored. Over 100 contributed papers have been submitted to the *Accelerator Frontier* of the US particle-physics-themed community planning exercise, Snowmass’21. These papers cover a broad spectrum of topics: beam physics and accelerator education, accelerators for neutrinos, colliders for Electron/Biggs studies and multi-TeV energies, accelerators for *Physics Beyond CDF/L3* and rare processes, advanced accelerator concepts, and accelerator technology for Radio Frequency cavities (RF), magnets, targets, and sources.

Future facility: The accelerator community in the US and globally has a broad array of accelerator technologies and expertise that will be needed to design and construct any of the near-term HEP accelerator projects. P5 will need to prioritize what option(s) should be developed. Planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process. Accelerator experts can contribute to the US and international projects under consideration by providing top-level metrics for expected cost-scales and technology/timeline evolution, following the ITF findings.

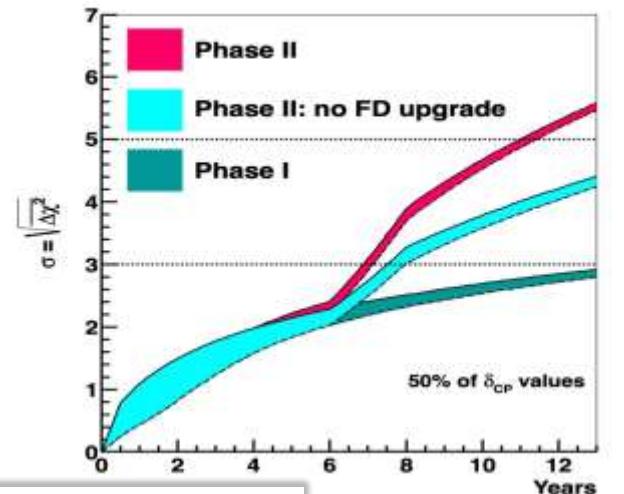
Among possible actively discussed future facility options are:

- A multi-MW beam power upgrade of the Fermilab proton accelerator complex that seems to be the highest priority for the neutrino program in the 2030s; corresponding accelerator technology and beam physics studies are needed to identify the most cost- and power-efficient solutions that could be timely implemented leading to breakthrough results of the DUNE neutrino program.
- Several beam facilities for axion and Dark Matter (DM) searches are shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAR (a 1 GeV, 100 kW PIP-II Accelerator Higgs); in general, we should efficiently utilize existing and upcoming facilities to explore dedicated or parallel opportunities for rare process measurements - examples are the SLAC SRF electron linear, MWs of proton beam power potentially available after construction of the PIP-II Higgs, spires of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC, etc.
- In the area of future colliders – several approaches are identified as both promising and potentially feasible, and call for further exploration and support: in the Higgs/EW sector – there is growing support for the FCCee at CERN and proposals of somewhat more advanced linear colliders in the US or elsewhere, such as C^3 and HELEN;
- At the energy frontier, the discovery machines such as $O(10 \text{ TeV} \nu^+ \nu^-)$ muon colliders have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these concepts could be explored technically and demonstrated in pre-CDR level reports by the end of this decade.

The U.S. HEP accelerator R&D portfolio presently contains no collider-specific items. This creates a gap in our knowledge-base and accelerator/technology capability gap. It also limits our national aspiration for a leadership role in particle physics in that the US cannot lead or even contribute to proposals for accelerator-based HEP facilities. To address the gap, the community has proposed that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) to carry-out technology R&D and accelerator design for future collider concepts. This program would aim to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, IMCC). It would support the development of design reports on collider options by the time of the next Snowmass and P5 (2029-2030), particularly for options that can feasibly be hosted in the US, and to create R&D plans for the decade past 2030. Without such a program there may be few accelerator-based proposals for a future P5 to evaluate.

Serving Neutrino Physics

- DUNE/LBNF needs kt-MW-years
 - 120 for Phase I (ca 2036)
 - 600-1000 for Phase II (ASAP)



$$\text{"MWyears"} = \frac{eN_{ppp}E_{beam}}{T_{cycle}} \times \text{Ops Time}$$

- Options:
 - Increase pulse intensity **N_ppp**
 - 0.8 GeV PIP-II & 8 GeV **RCS** or **Linac + accumulator ring**
 - Reduce cycle time **T_cycle**
 - 120 GeV MI ramp **1.33/1.2s → 0.6-0.7s**
 - Increase **operations time**
 - # of years vs race with Hyper-K
 - Annual **operational efficiency**



0.8 GeV PIP-II Linac
under construction (2028)
FNAL webcam Dec.8, 2022

Implementation Task Force

<https://arxiv.org/abs/2208.06030>



Steve Gourlay
(LBNL)



Tor Raubenheimer
(SLAC)

Katsunobu Oide
(KEK)

Jim Strait
(FNAL)



Vladimir Shiltsev
(FNAL)

Reinhard Brinkmann
(DESY)

John Seeman
(SLAC)

REPORT



Dmitry Denisov



Meenakshi Narain



Liantao Wang
(U.Chicago)



Sarah Cousineau
(ORNL)



Marlene Turner
(LBNL)



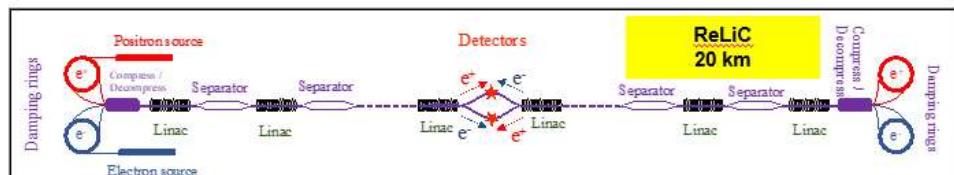
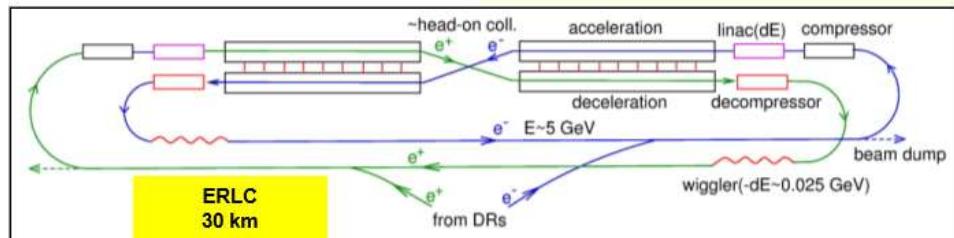
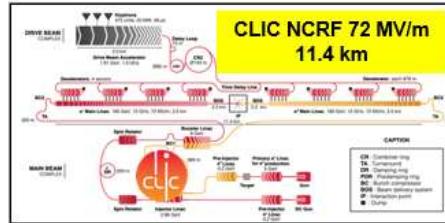
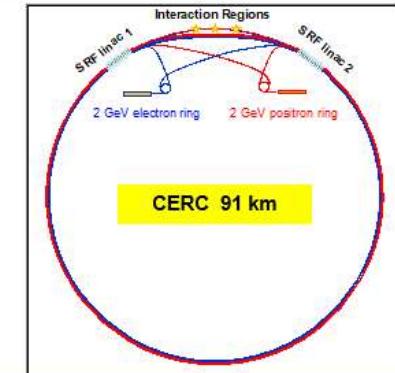
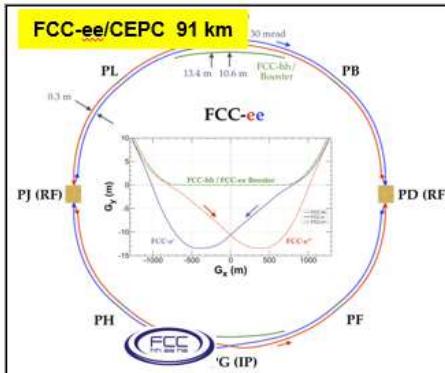
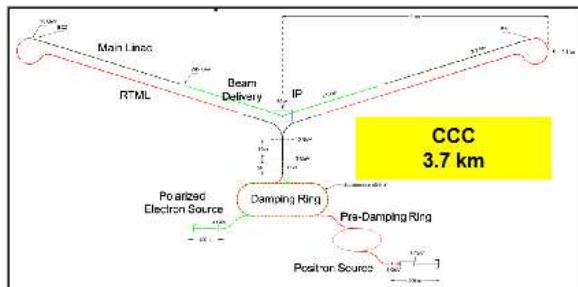
Spencer Gessner
(SLAC)

²Below I mostly follow T.Roser presentation in Seattle

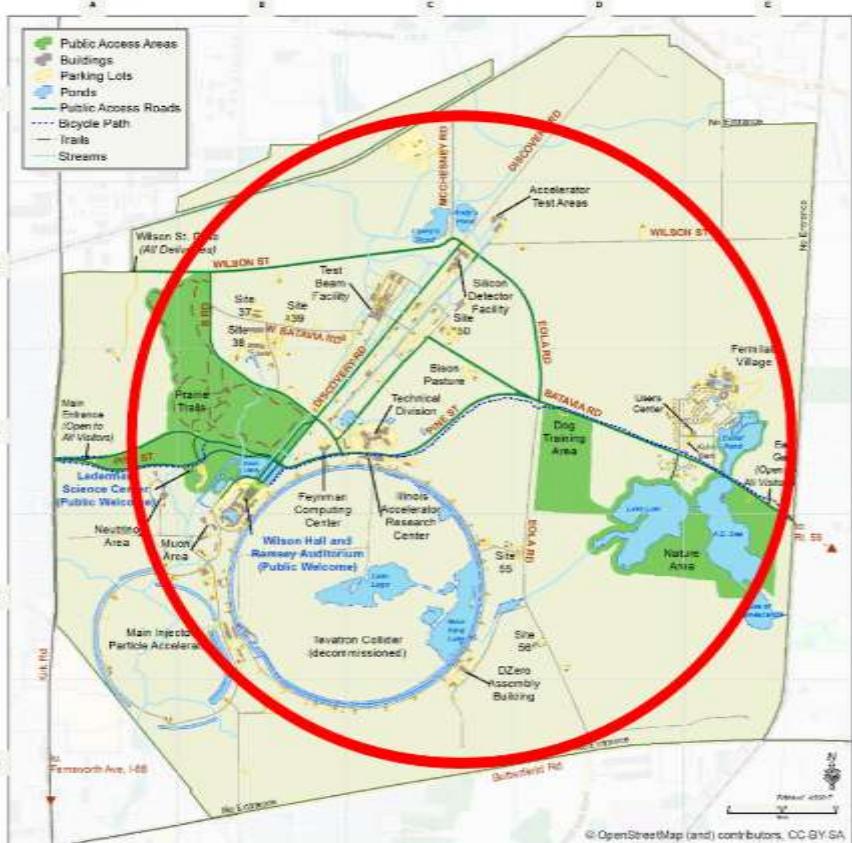
Proposals – Higgs/EW Physics

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



250 GeV cme Fermilab Site-Fillers



16-km collider e^+e^- ring

<https://arxiv.org/abs/2203.08088>

CCC

(cool copper collider)

HELEN

(TW SRF collider)



cool- or SC-RF e^+e^- linear colliders
7-km for 250 GeV, 12-km 0.5+ TeV

<https://arxiv.org/abs/2203.08211>
<https://arxiv.org/abs/2110.15800>

Fermilab

Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP@ Higgs (10^{34})	Years, pre-project R&D	Years to 1 st Physics	Cost Range (2021 B\$)	Electric Power (MW)	
Circular e^+e^-	FCCee (4 IPs)	0.24	7.7	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear e^+e^-	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C ³	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s -chan	XCC- $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
	$\mu\mu$ -Higgs	0.13	0.01	>10 ²⁶	19-24	4-7	200

ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10^{34})	Years, pre-project R&D	Years to 1 st Physics	Cost Range (2021 B\$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	$O(300)$
FCChh-100	100	30	>10	>25	30-50	~560

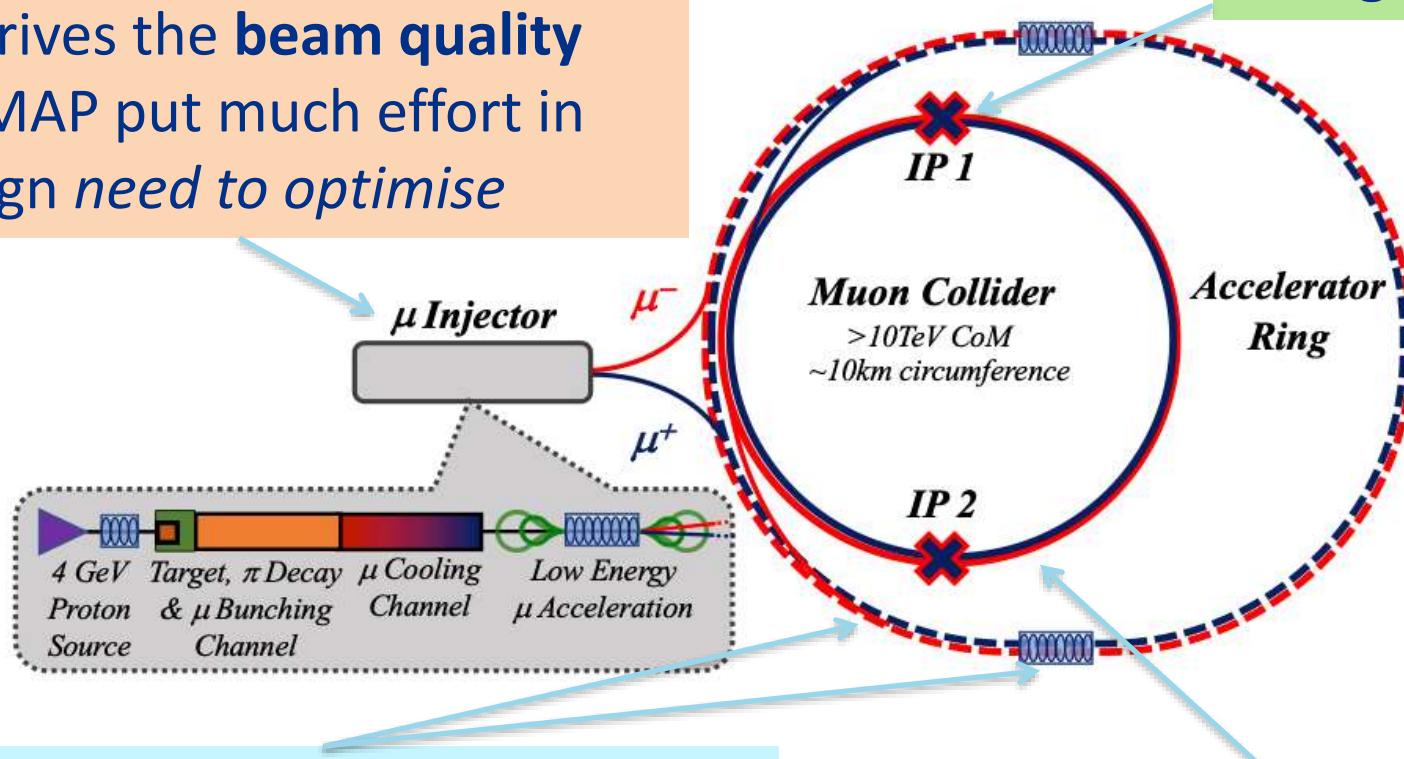
Why muon colliders?

- (Snowmass Energy Frontier) HEP aspires 10+ TeV cme/parton
- Muon Collider is a viable option for the HEP future:
 - Combines discovery reach and precision physics
 - $\times 7$ energy reach vs pp – eg 14 TeV $\mu\mu = 100$ TeV pp
 - μ 's do not radiate when bent → acceleration in rings:
 - *Smaller(est) footprint* – 10-15 km vs 50-100 km
 - *(Best) power efficiency* – *Lumi/Power* grows with energy
 - *Low(est) cost* – due to compactness and power efficiency
- (ITF) 3-10 TeV Muon Collider can be designed in ~10-15 yrs and built in 20-25 yrs from now:
 - *Past studies in the US and UK (+now in CERN)* – *big advance*
 - *No insurmountable obstacles identified*
 - *But challenging technologies and design require R&D*

10+ TeV Muon Collider: Key Challenges

1) Physics case with 10 ab⁻¹

5) Drives the **beam quality**
US MAP put much effort in
design *need to optimise*

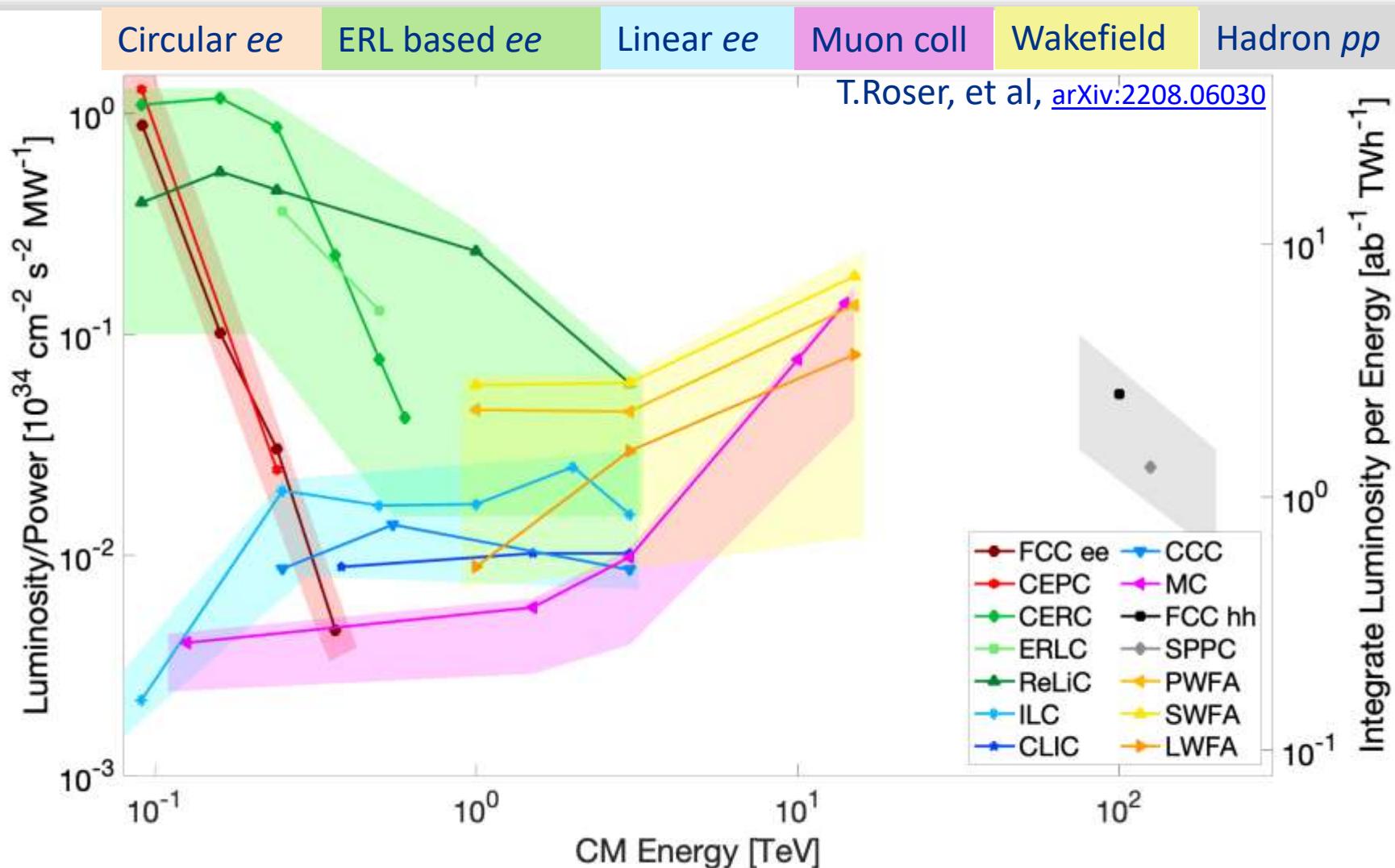


4) Cost and power consumption limit energy reach e.g. 25-35 km accelerator for 10-14 TeV collider, also may impact **beam quality**

2) Dense neutrino flux mitigated by mover system and siting of the 10-14 km collider ring

3) Beam-induced background

Luminosity per Power

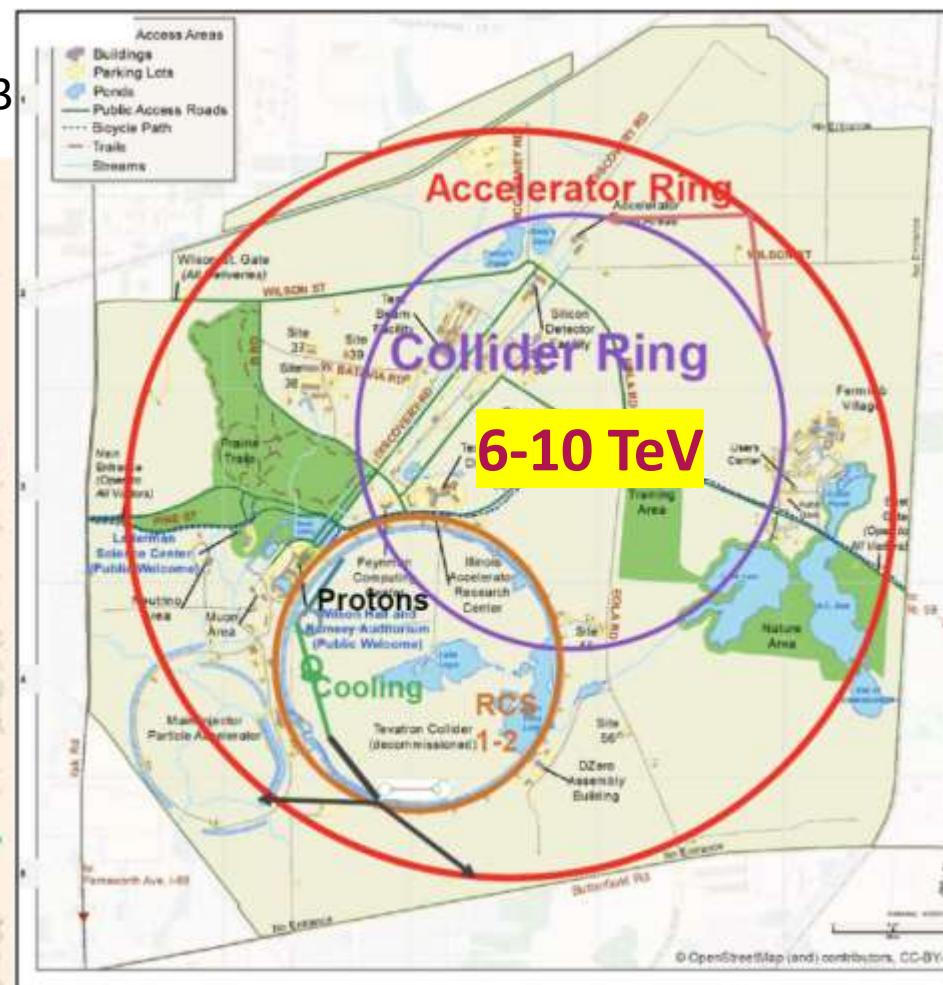
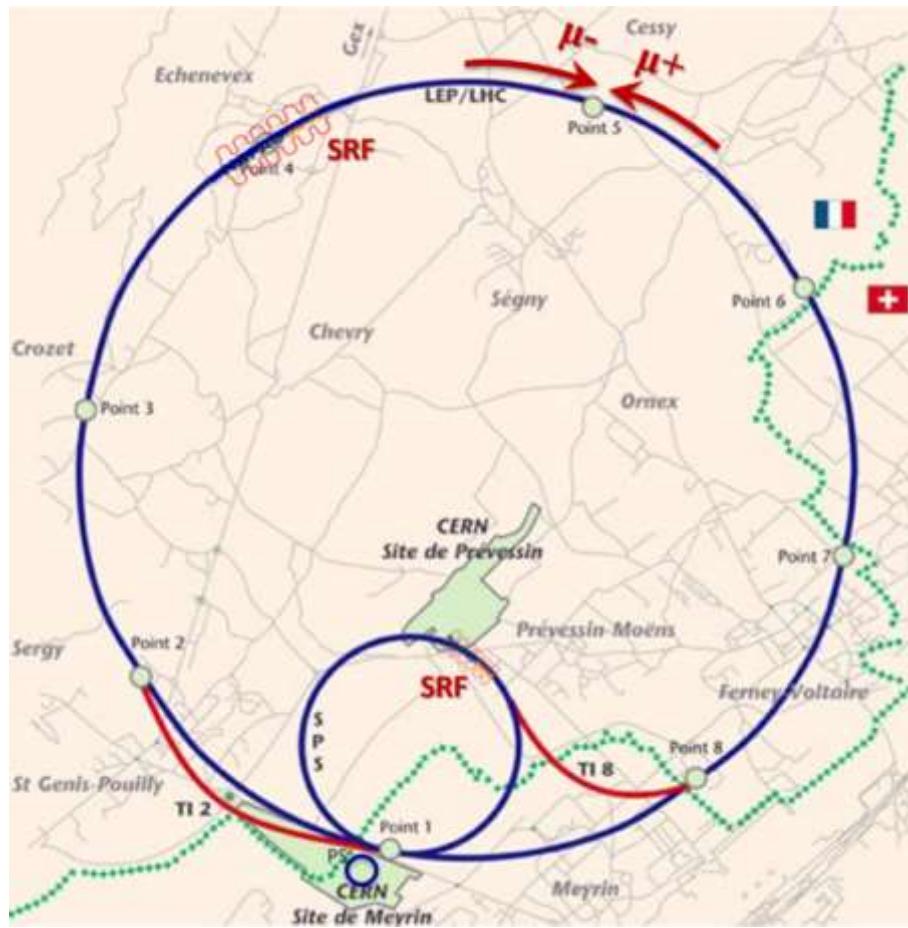


Luminosity is per IP, Integrated luminosity assumes 1e7 seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

Big Advantage : Re-Use of Infrastructure

Pulsed 14 TeV MC in LHC Tunnel

D. Neuffer and V. Shiltsev 2018 JINST **13** T10003



Future Colliders Options for US

P. Bhat, et al, arXiv: 2203.08088

Also: staging is possible – eg 3 or 6 TeV



Snowmass 2021

Accelerator Frontier Recommendation (to P5)

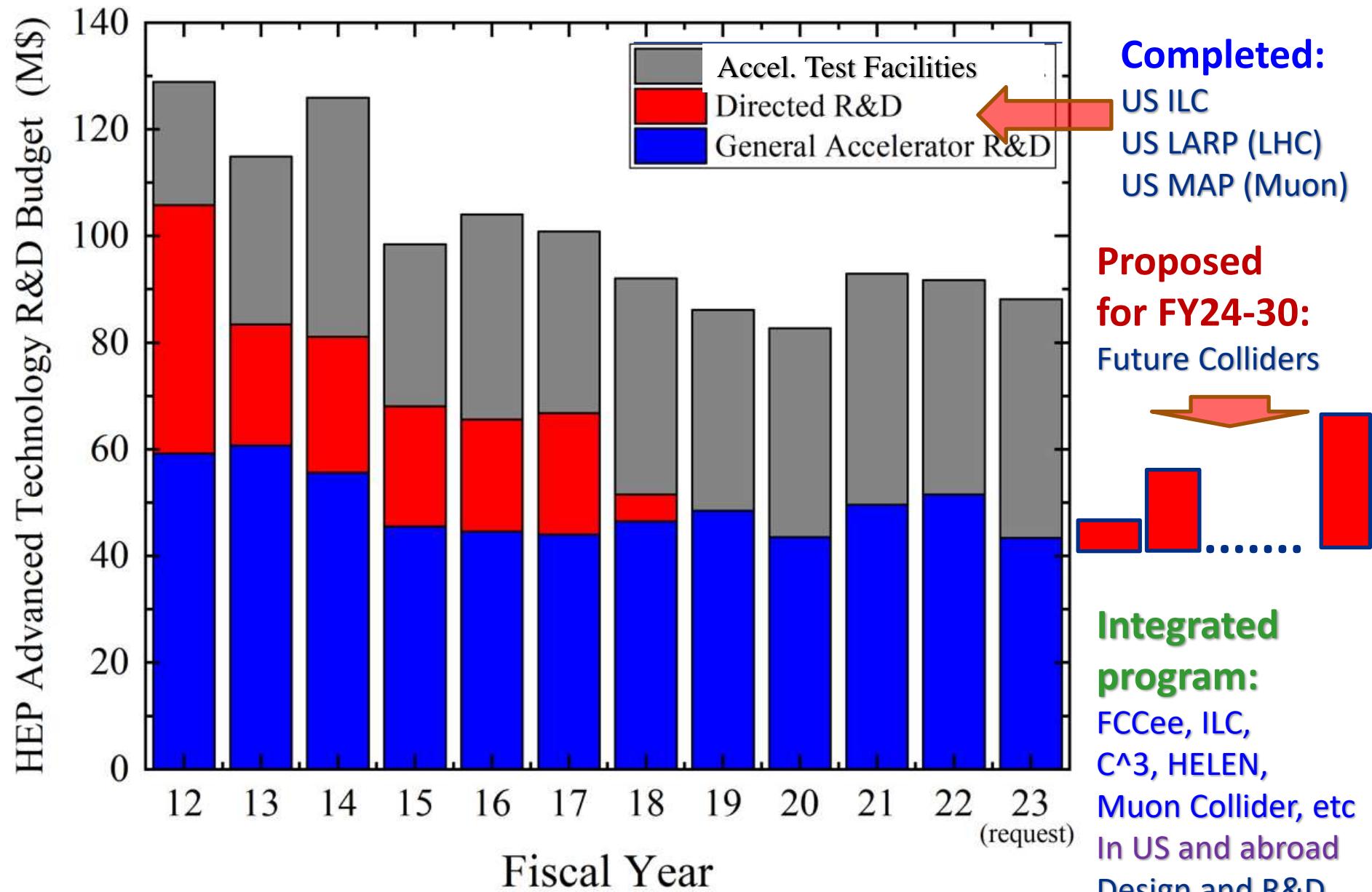
On Colliders: We need an **integrated future collider R&D program** to engage in the design and to coordinate the development of the next generation collider projects:

- to address in an integrated fashion the technical challenges of promising future collider concepts, that are not covered by the existing *General Accelerator R&D* (GARD) program.
- to enable synergistic U.S. engagement in ongoing global efforts (e.g., FCC, ILC, IMCC)
- to develop collider concepts and proposals for options feasible to be hosted in the U.S. (e.g., CCC, HELEN, Muon Collider, etc)

#Frontier

Such a program needed to make an informative decision on future HEP facility ~2031

Future Colliders R&D Program - Initiative



Part III :

Limits of Colliders

Future - ?

Which technologies?

Existing?

Emerging?

Exotic?

What and where are the limits??

<10 neutron sources
& nuclear (Th, waste)

300 ion beam analysis

3,000 sterilization

>11,000 ion implantation

7 colliders and 10 fixed target complexes for HEP and NP

>80 X-ray sources

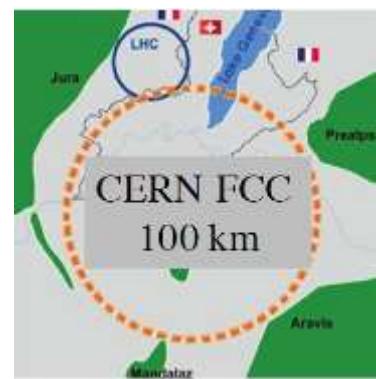
1,600 radioisotope prod'n

7,500 material processing

>14,000 cancer therapy

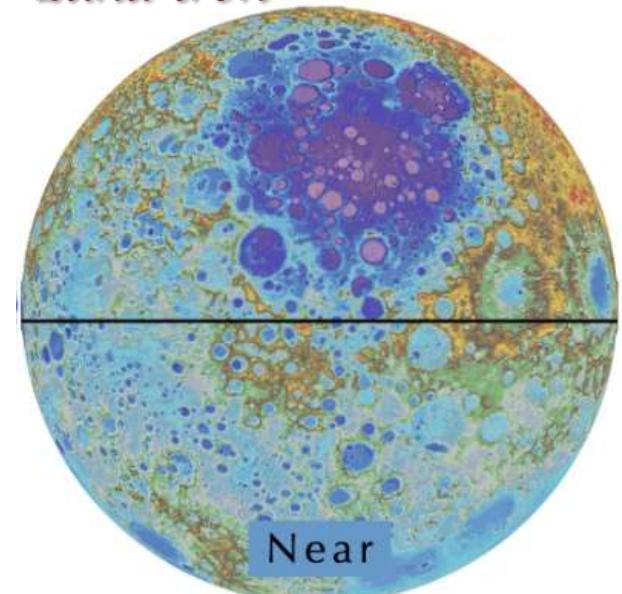
Circular pp Colliders

0.1 PeV



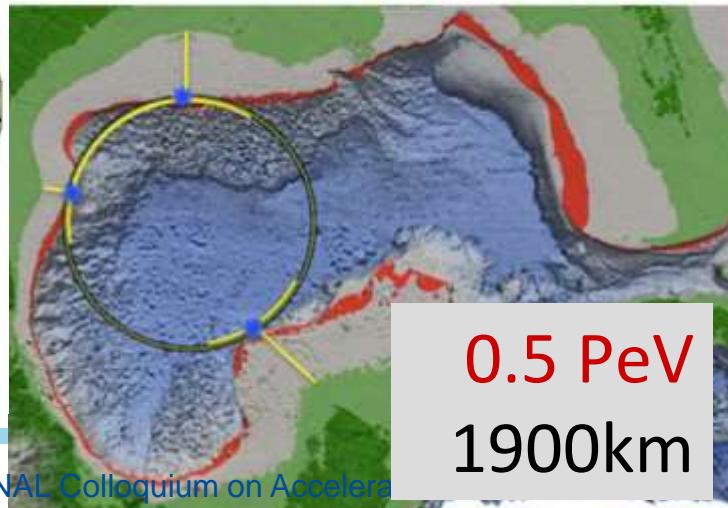
- Known technology (magnets)
- Major limitations:
 - Size (magnetic field B), power, cost
 - Synchrotron radiation $\rightarrow Lumi \sim R/E^3$
 - Beam-beam, burn-off, pileup, instabilities

Luna-tron



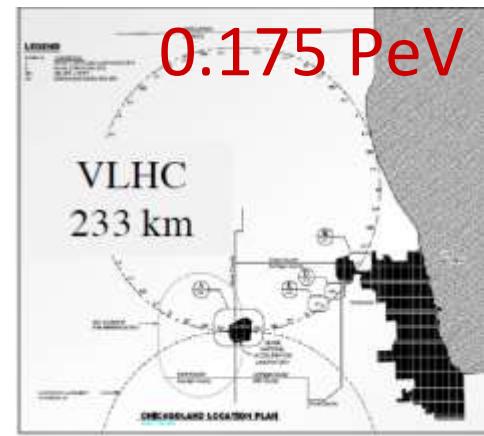
14 PeV, 11000km

Collider-in-the-Sea

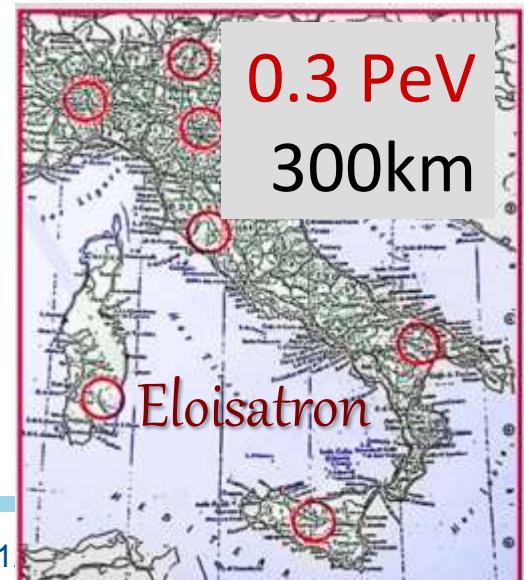


0.5 PeV
1900km

0.175 PeV

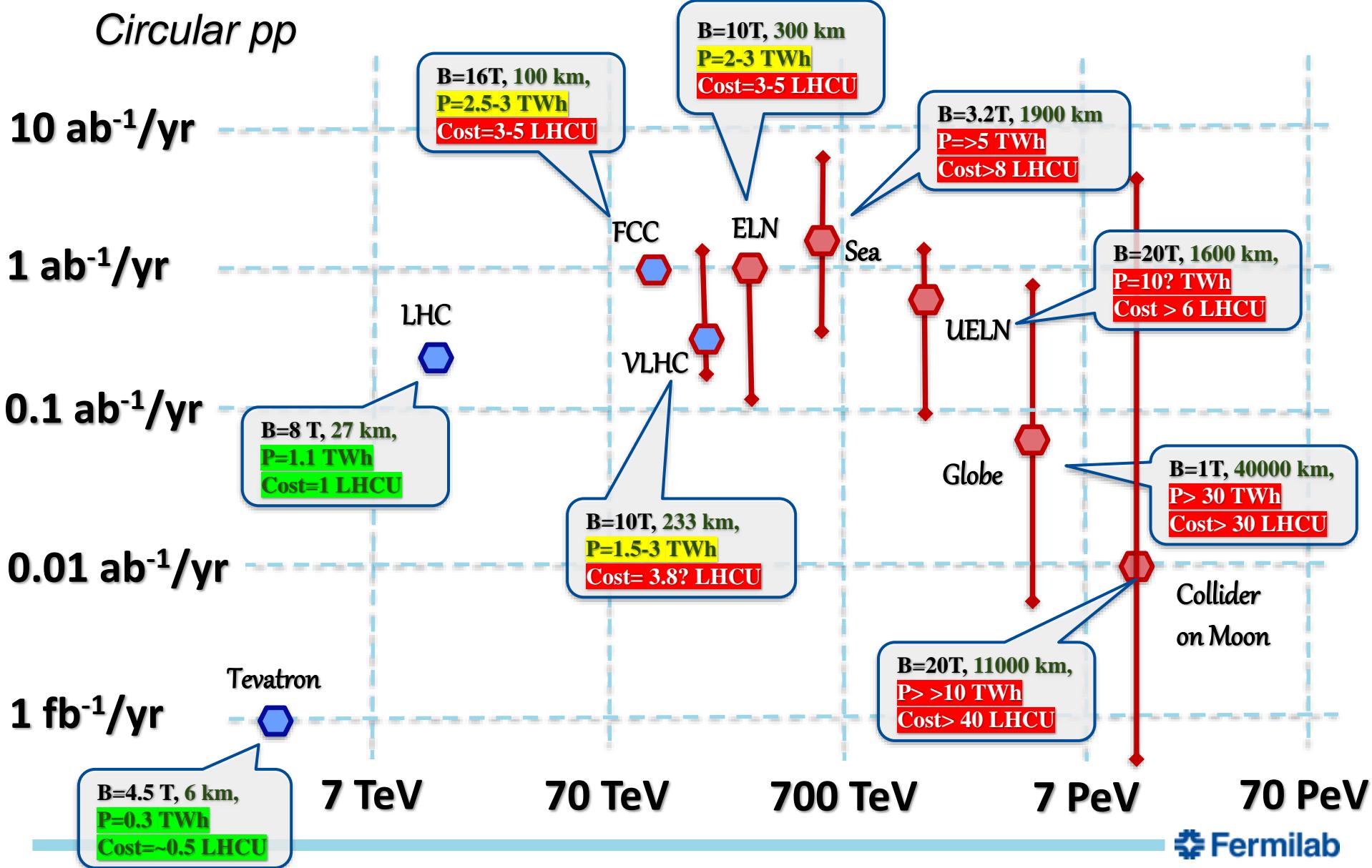


0.3 PeV
300km



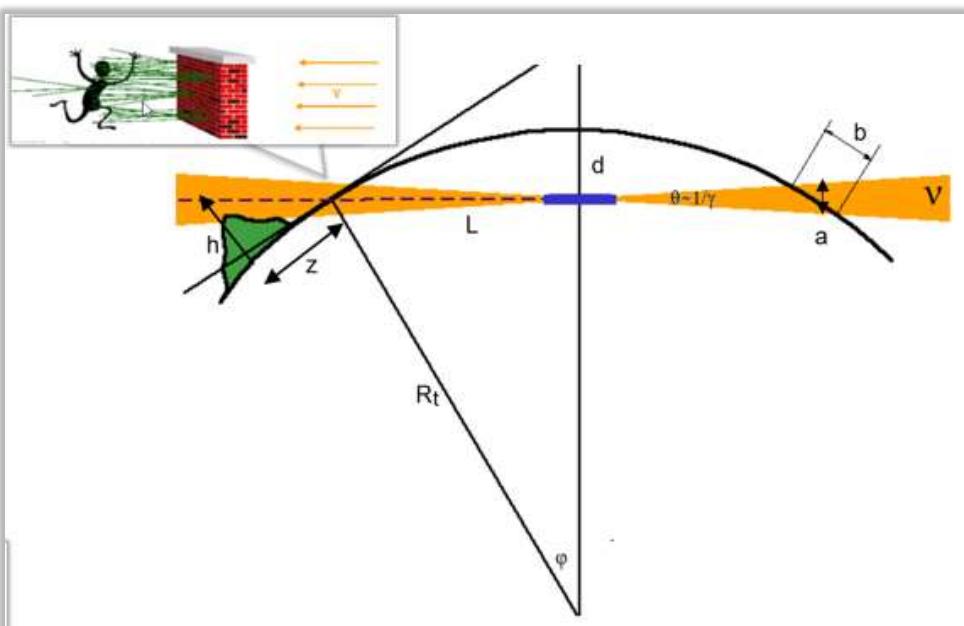
pp Colliders: Lumi, Power, Cost vs Energy

Circular pp



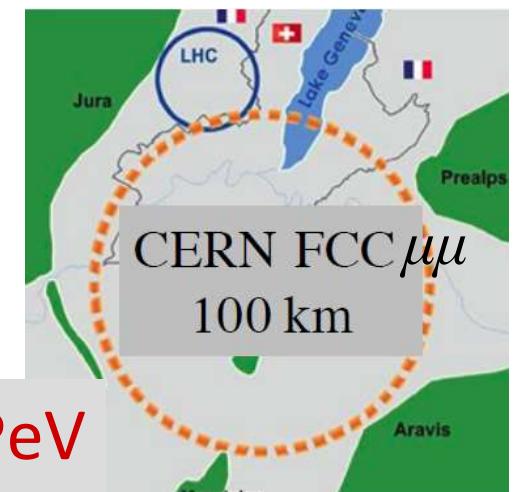
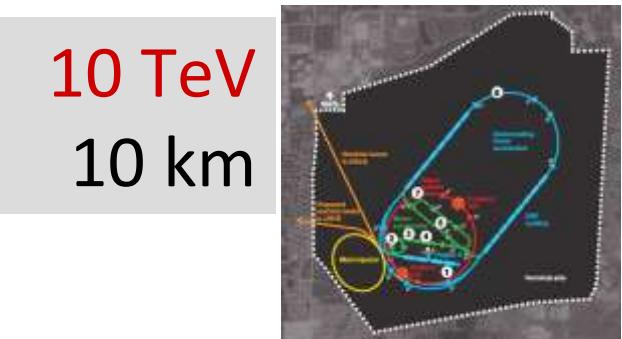
Circular $\mu^+\mu^-$ Colliders

- Known technology (magnets, RF)
- Major limitations:
 - Size (magnetic field B), power, cost
 - Ionization cooling of muons
 - Neutrino flux $\rightarrow Lumi \sim \Phi/E^2$



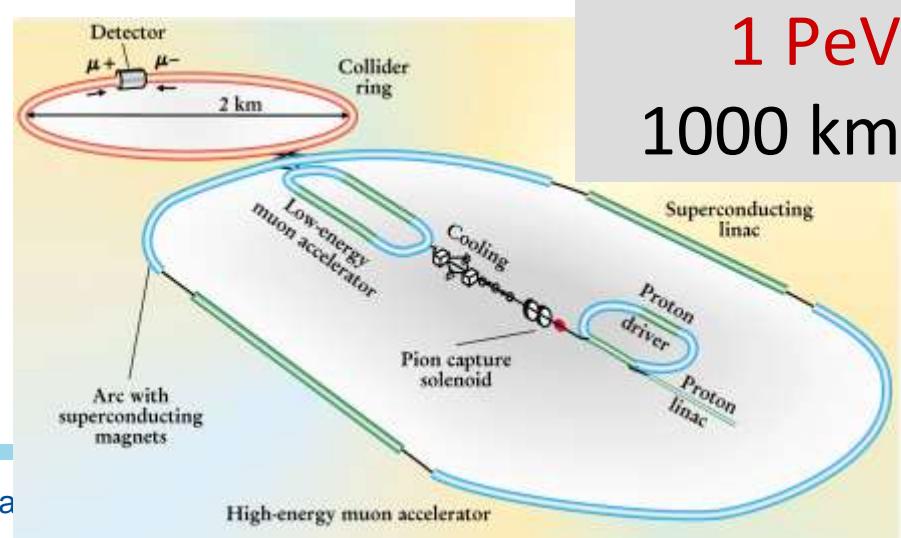
Cone gets narrower with energy
Cross section grows with energy

10 TeV
10 km



0.1 PeV

1 PeV
1000 km



MC: *Lumi and Cost vs Energy*

Circular $\mu\mu$

$10 \text{ ab}^{-1}/\text{yr}$

$1 \text{ ab}^{-1}/\text{yr}$

$0.1 \text{ ab}^{-1}/\text{yr}$

$0.01 \text{ ab}^{-1}/\text{yr}$

$1 \text{ fb}^{-1}/\text{yr}$

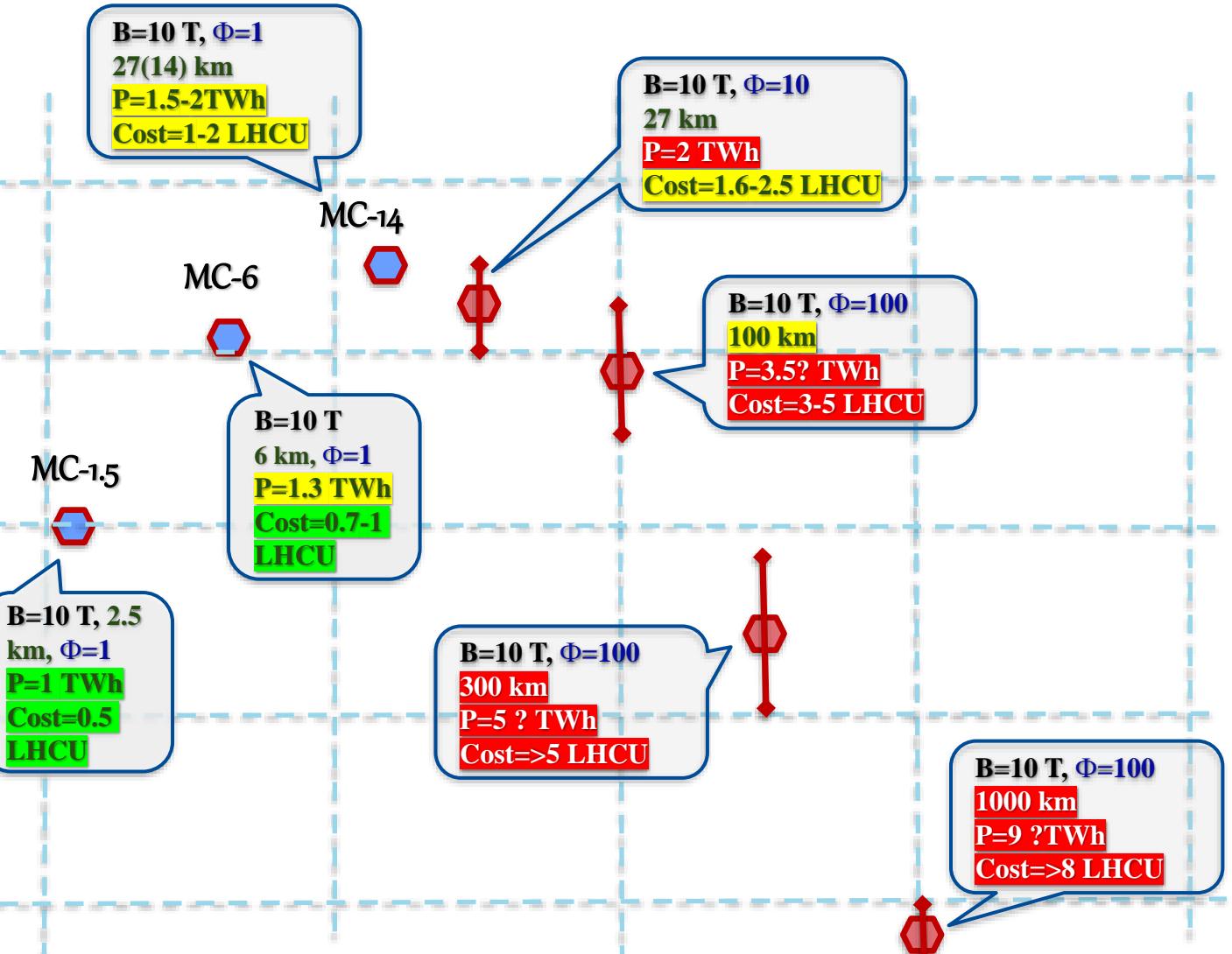
1 TeV

10 TeV

100 TeV

1 PeV

10 PeV



Linear $e+e-$ Colliders

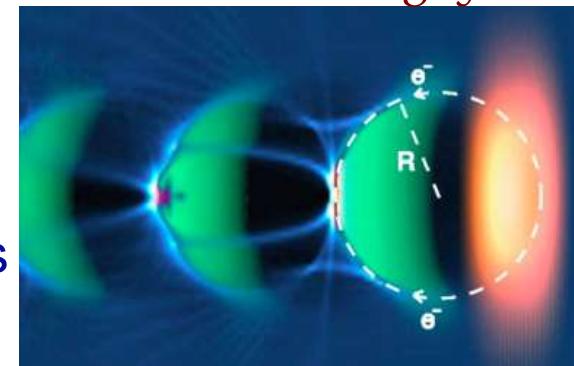
- Either RF acceleration (50-200 MeV/m) or →
wake-field acceleration in plasma (2-5 GeV/m) →
- Major limitations:
 - 100% energy spread at IP (beamstrahlung)
 - One-time collisions ineffective → $Lumi \sim P/(E\sigma)$
 - Very long/complex *Final Focus* to get nm IP size
 - Extreme sensitivity to nm jitters of linac elements
 - In plasma – ultra-strong focusing hurts staging, impossible(?) to accelerate positrons

15 TeV $e+e-$

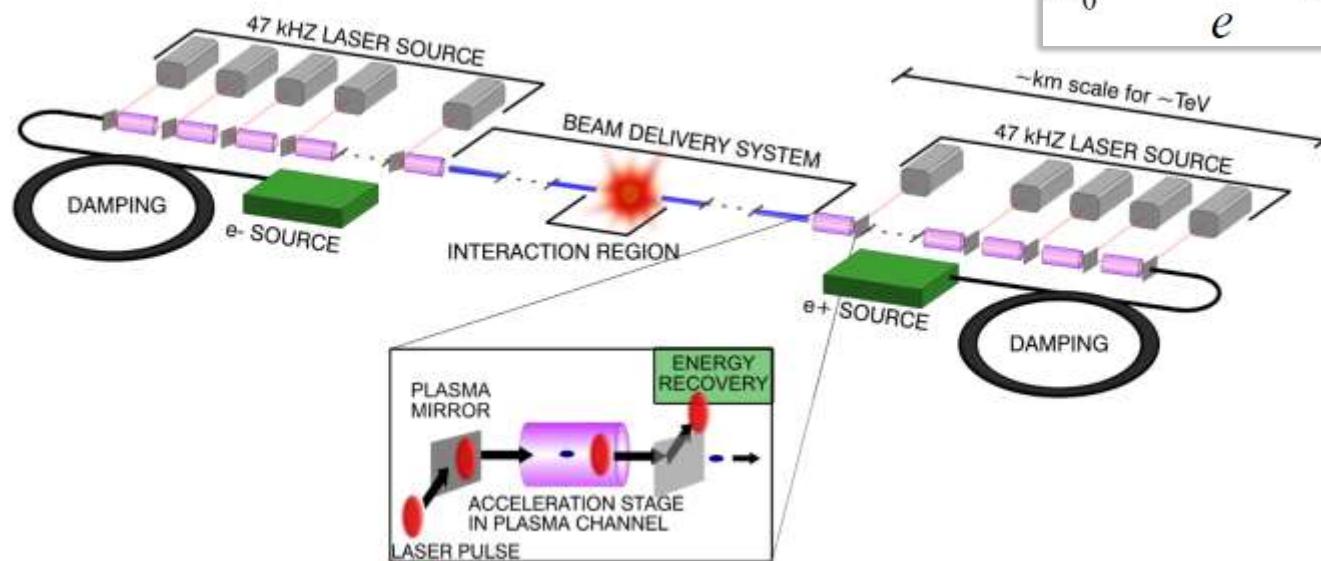
100+ km

10-15 km

Plasma sustains high fields



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[\frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{cm}^{-3}]}$$



Takes about 1
GW electric
power even
for 15 TeV

Linear RF and Plasma: *Lumi* and *Cost* vs *Energy*

Linear $ee/\gamma\gamma$

$10 \text{ ab}^{-1}/\text{yr}$

$1 \text{ ab}^{-1}/\text{yr}$

$0.1 \text{ ab}^{-1}/\text{yr}$

$0.01 \text{ ab}^{-1}/\text{yr}$

$1 \text{ fb}^{-1}/\text{yr}$

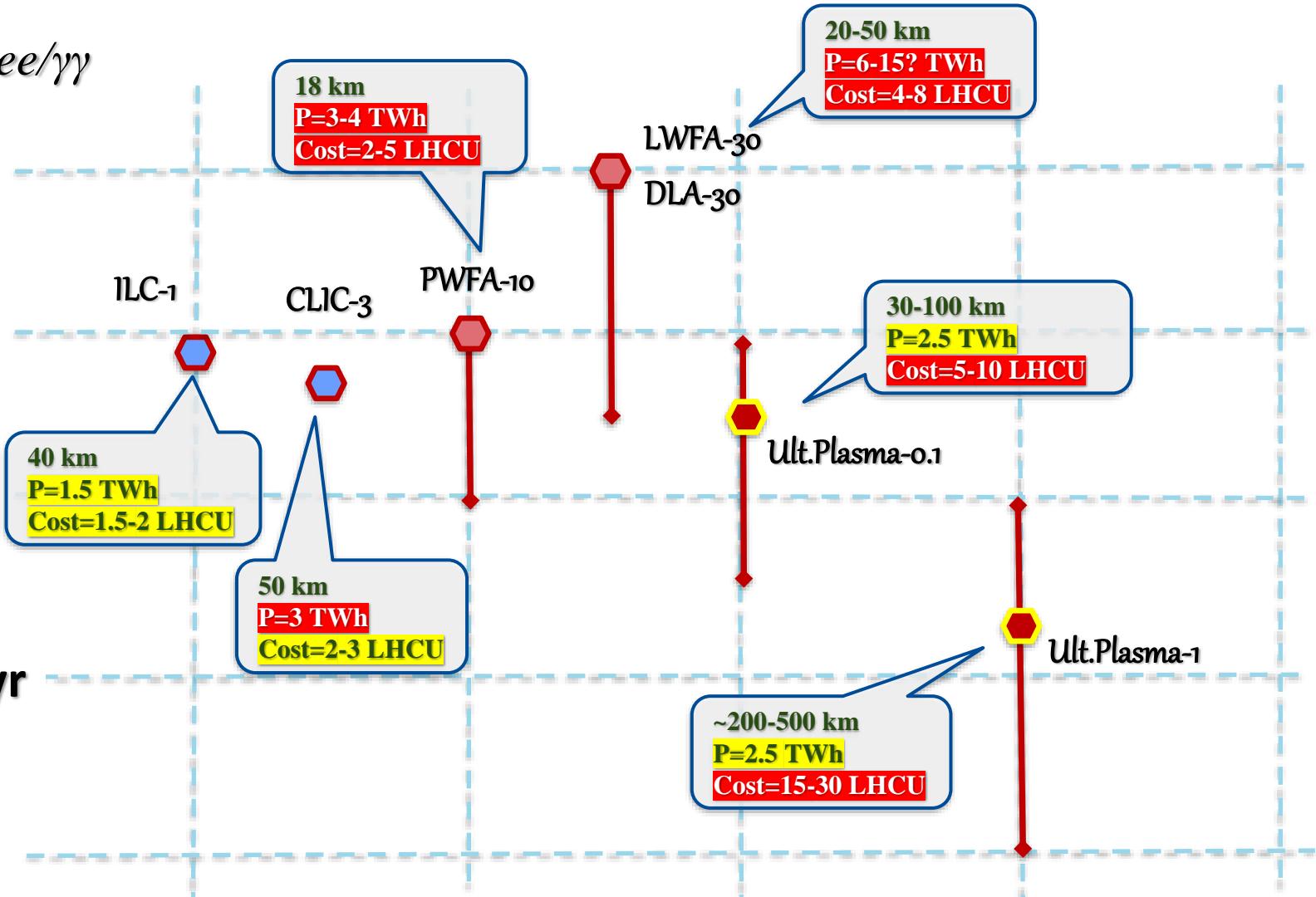
1 TeV

10 TeV

100 TeV

1 PeV

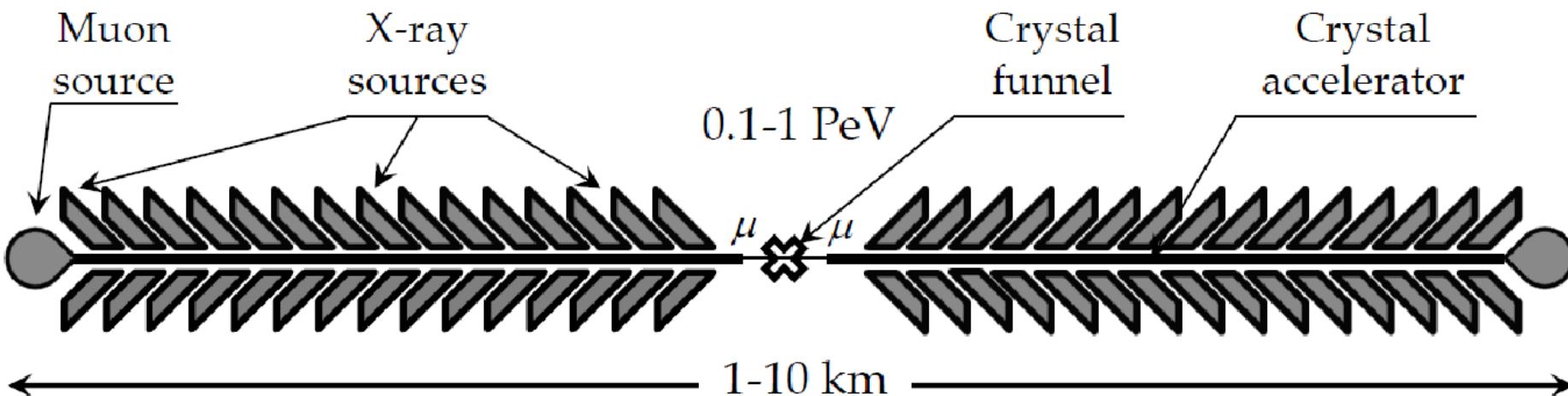
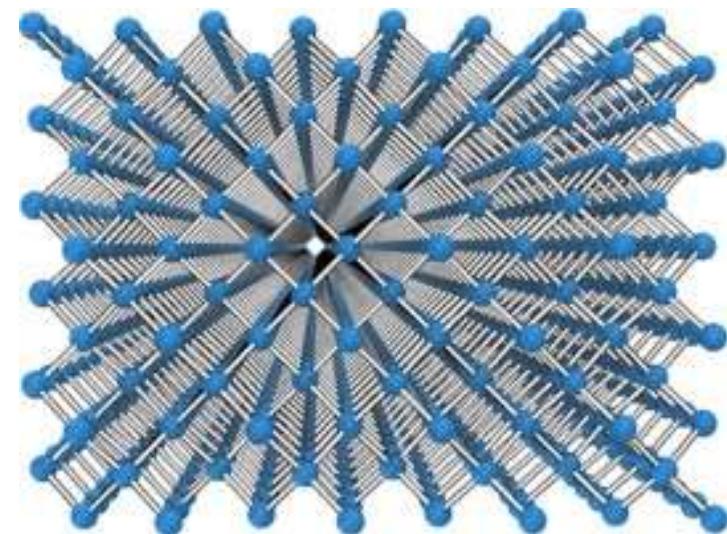
10 PeV



Exotic Colliders

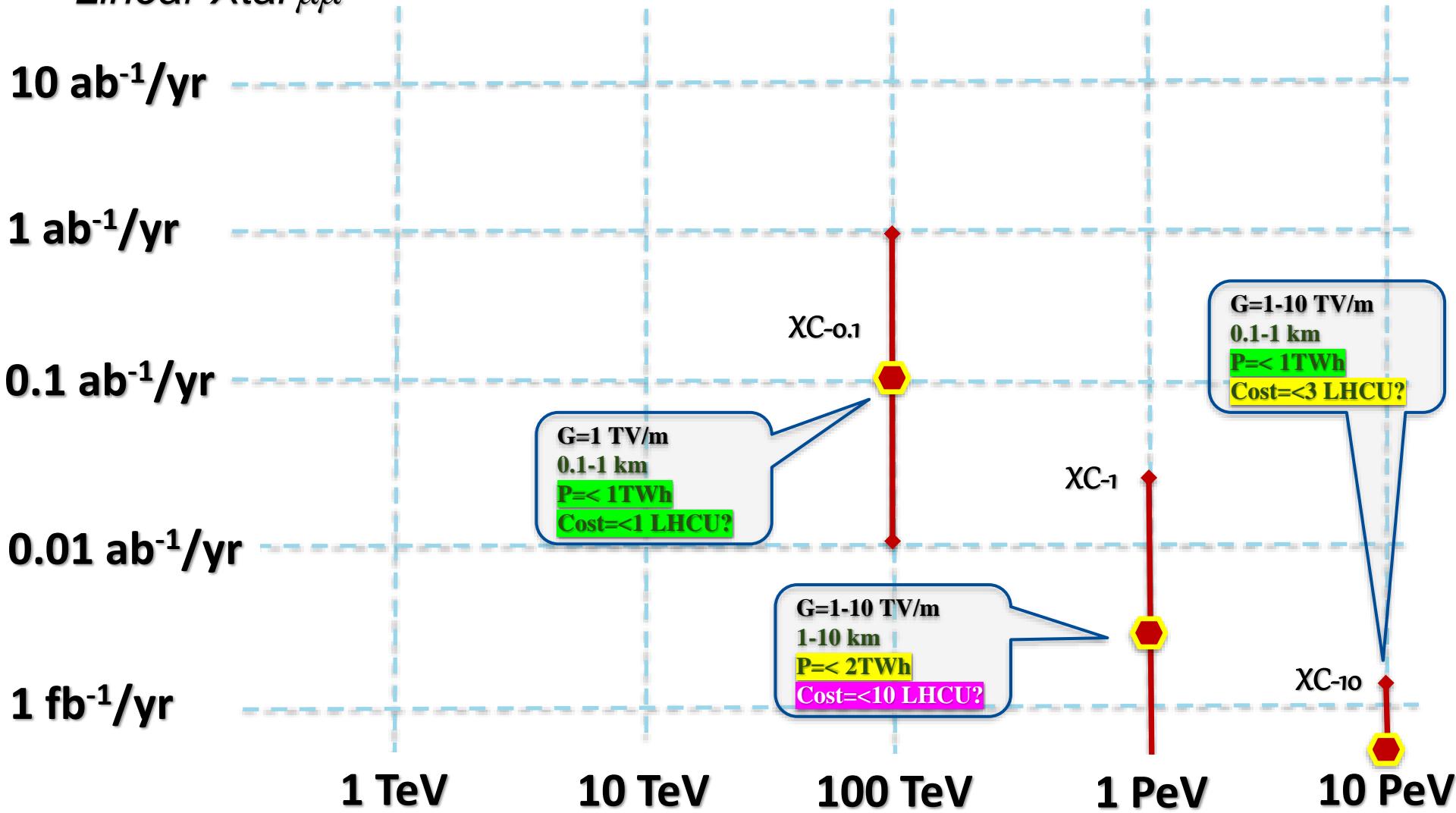
- Plasma-wakefield acceleration **and** channeling in structured media, eg CNTs or crystals (**only muons!!!**)
- Major advantages:
 - solid density → 1-10 TV/m gradients
 - continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled *betatron radiation*)
 - small size promises low cost
- $Lumi \sim 1/E^2$...totally unproven yet concept:
 - proof-of-principle experiment *E336* @ SLAC

$$E [\text{GV}/\text{m}] \approx 100\sqrt{n_0 [10^{18} \text{ cm}^{-3}]}$$



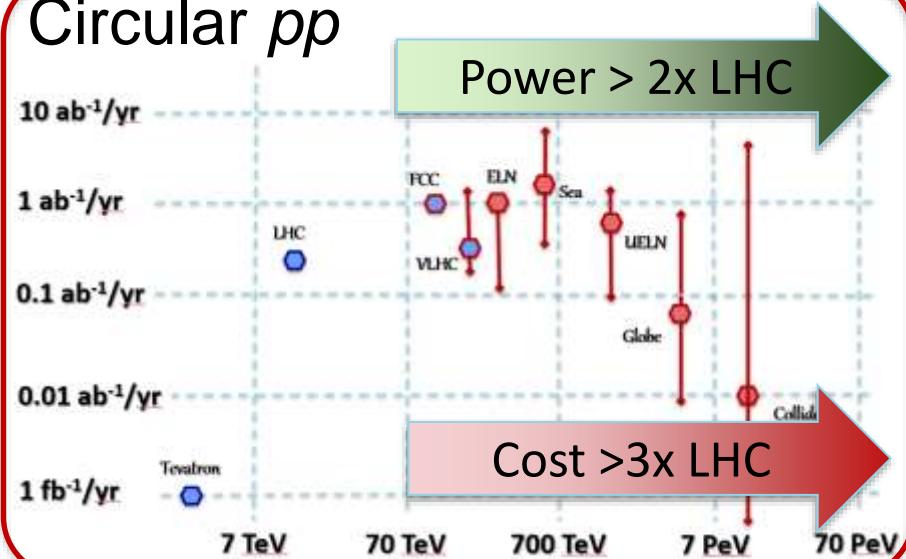
Xtal Colliders: *Lumi* and *Cost* vs *Energy*

Linear Xtal $\mu\mu$

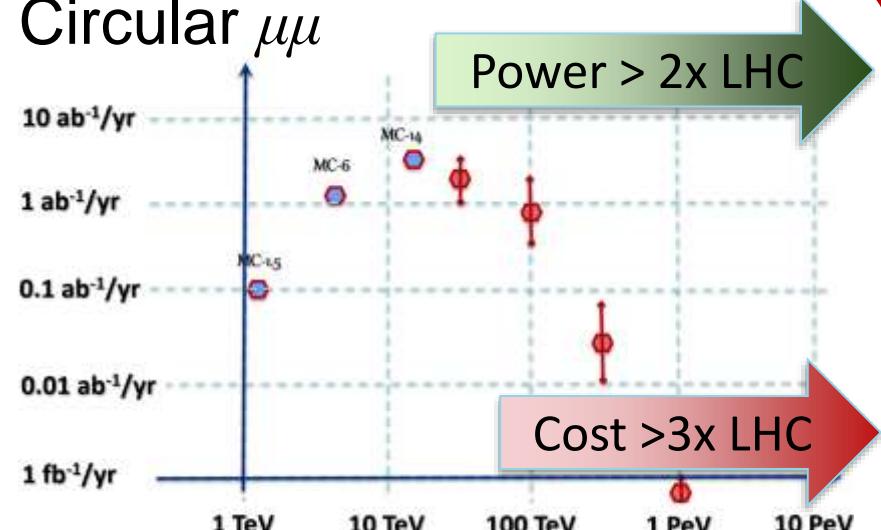


Limits (Electric Power and Cost)

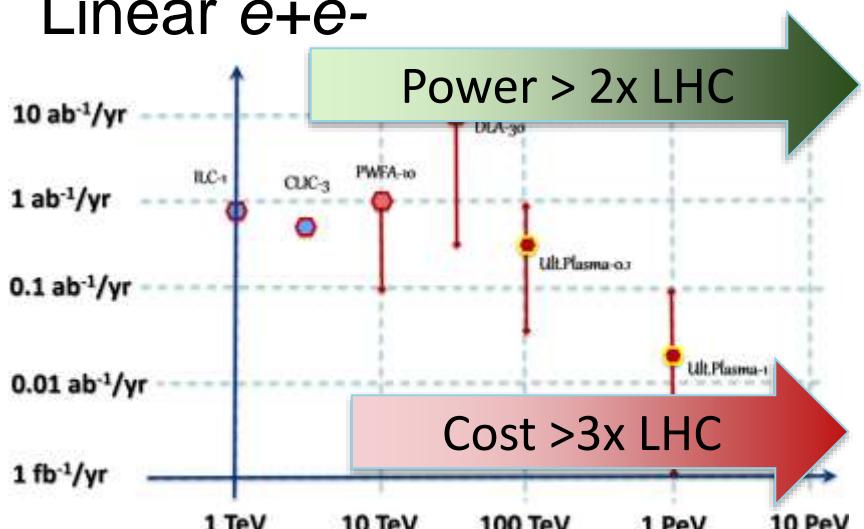
Circular pp



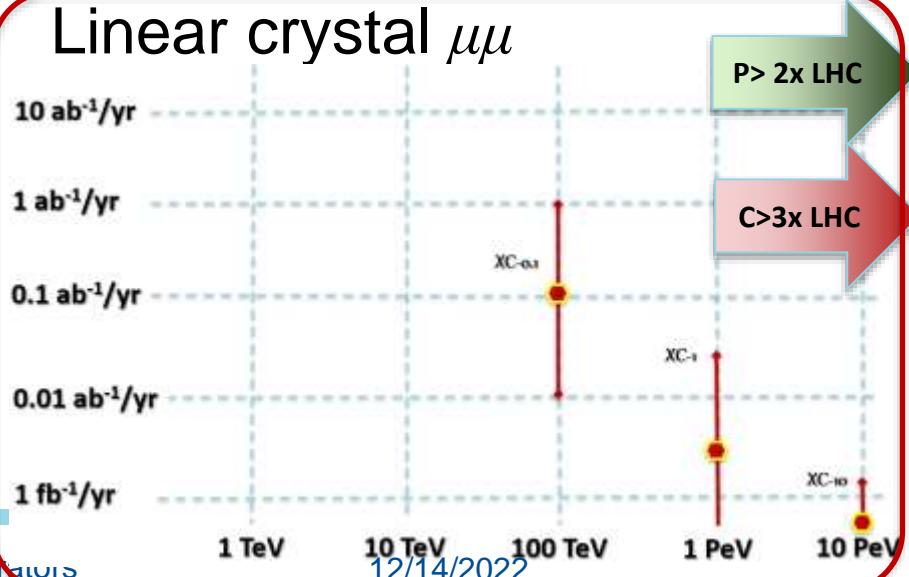
Circular $\mu\mu$



Linear $e+e-$



Linear crystal $\mu\mu$



To Summarize:

- **Accelerator and beam physics impressive progress:**
 - Just over the past 5 years – new accelerators for NP, BES, neutrinos and rare processes, colliders:
 - e.g., FRIB, XFELs, China SNS, power records at FNAL and JPARC, luminosity records at LHC and SuperKEKB
 - Physics of beams breakthroughs:
 - Several new beam cooling schemes, plasma acceleration to $O(5\text{GeV})$ – with beams good enough for FELs
 - Core technology advances:
 - Records in RF gradients, B -field, dB/dt rate, MWs beam targets
- **Bright future ahead:**
 - Next: XFELs, NICA, High Lumi LHC, PIP-II, ESS, EIC, etc
 - Future: Higgs factories (linear or circular), Multi-TeV colliders ($pp, \mu\mu, ee$)

Summary (2):

- **Snowmass'21 Accelerator Frontier on colliders:**
 - Higgs factories sorted out by *Cost, Luminosity and Power*
 - *FCCee, ILC, C³ and HELEN* – *current favorites*
 - **10+ TeV cme/parton frontier collider options are very few:**
 - Limits due to *Cost, Luminosity and Power*
 - *Muon colliders 3-6-10-14 TeV* - *favorites according to the ITF*
 - To decide on HEP options – need to restart **Collider R&D in US**
- **What's beyond 15 TeV/parton – not clear:**
 - All acceleration technologies have limits
 - **What's certain:** *high energy means low luminosity*
 - Less than 1-0.1 ab⁻¹/yr at 30TeV -1 PeV if *Power < 1-2TWh/yr*

Summary (3):

- **For considered collider types - limitations:**
 - Circular ee – limit is ~0.4-0.5 TeV
 - Linear RF ee/ $\gamma\gamma$ } – limit is between 3 and 10 TeV
 - Plasma ee/ $\gamma\gamma$ }
 - Circular pp – limit is 50-70 TeV (7-10 TeV cme per parton)
 - Circular $\mu\mu$ – limit is between 30 and 100 TeV
 - Exotic crystal $\mu\mu$ – promise of 0.1-1 PeV, low Luminosity
- **Muons are particles of the future !**

Let's do accelerators – they are a) useful and b) fun !

Thanks for your attention!

