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 Cockroft & Walton, Lawrence, van der Graaf:

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

>100 used in research now:

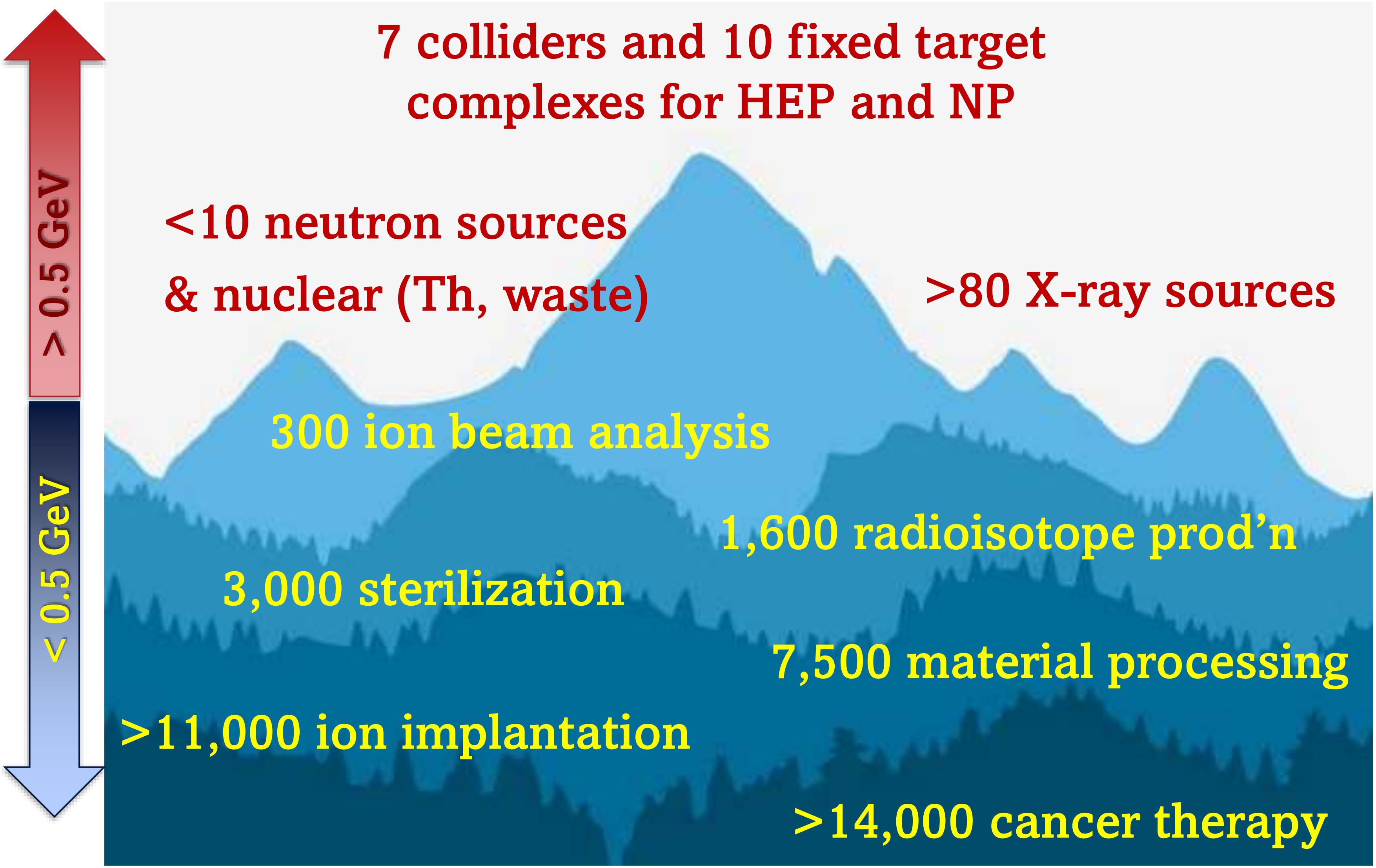
- with 4500 experts+15000 staff
- serving ~80,000 users (cond. matter, HEP, bio, NP, etc)

~ ¼ in the US

Pushing the envelope:

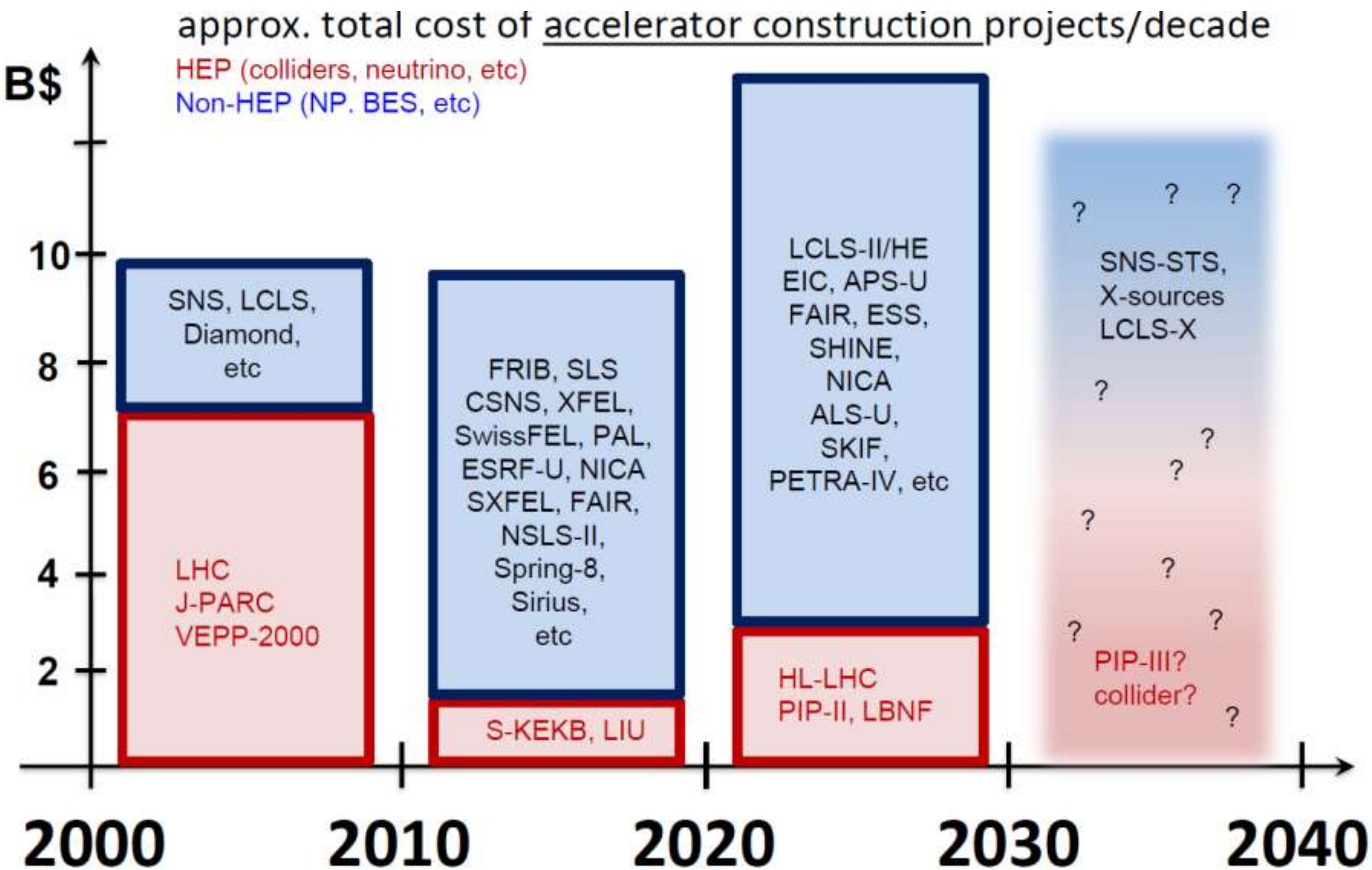
- Energy, performance(power, luminosity, brilliance, species), cost, complexity, size, R&D,…

Landscape of Accelerators

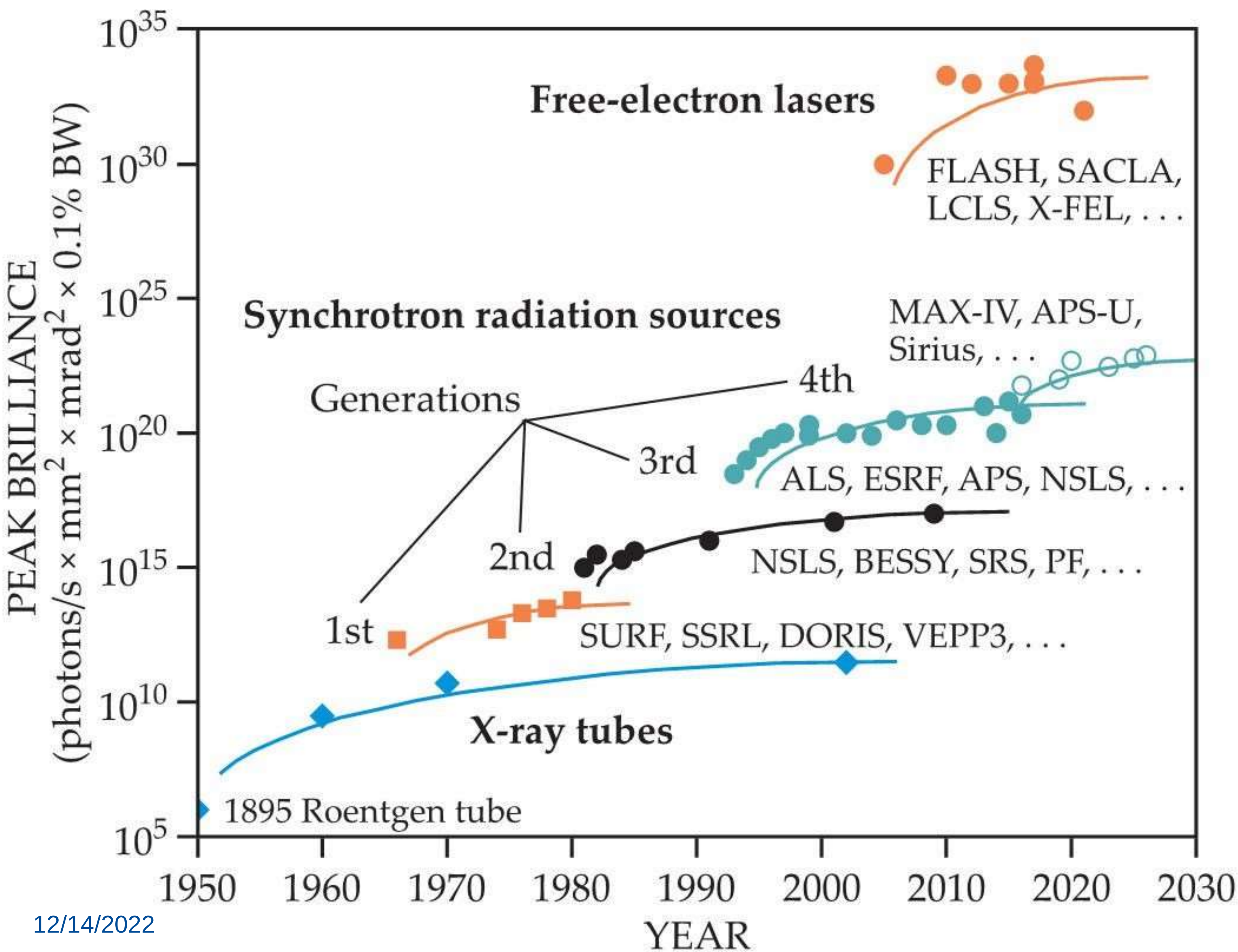


data from : A.Faus-Golfe, R.Edgecock, et al, EuCARD-2 Report: "Applications of Particle Accelerators in Europe." (2017); and V.Shiltsev, Physics Today (2020)

Accelerators Long Term Trends: HEP vs non-HEP



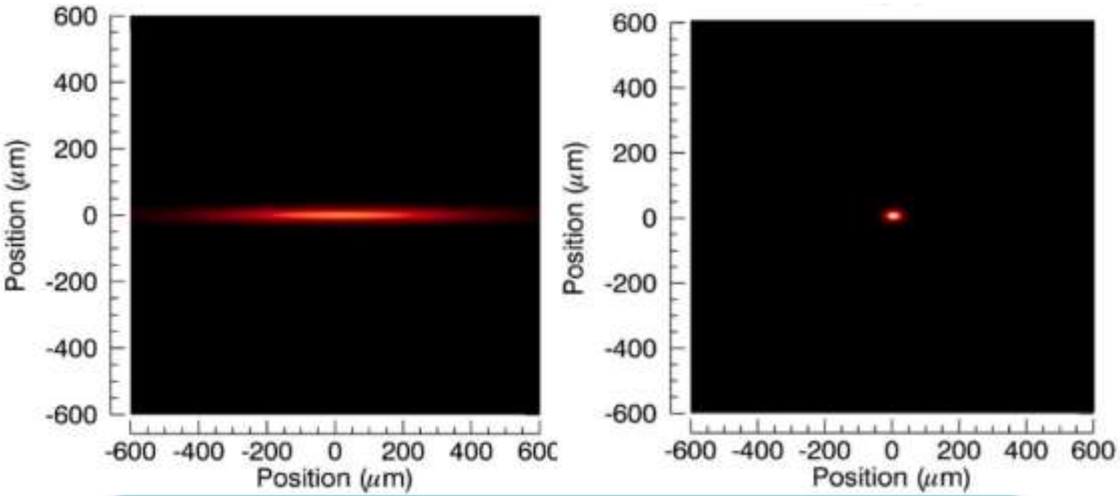
Revolution in Light Sources / X-ray Sources



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

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

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

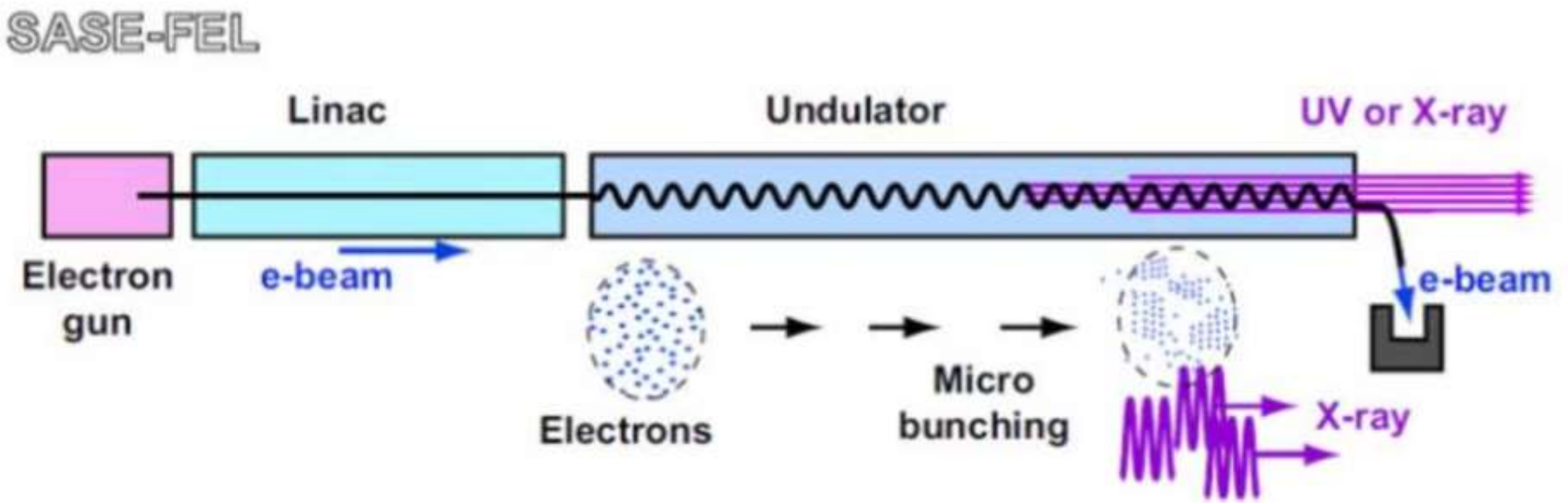


- 2024 – APS-Upgrade @ Argonne 6 GeV, 70 pm
- 2024 – SKIF @ Novosibirsk 3 GeV, 75 pm
- 2025 – SLS @ Swiss-PSI 2.7 GeV, 135 pm
- 2026 – ALS-Upgrade @ Berkeley, 2 GeV, 70 pm
- 2026 – HEPS @ Beijing 6 GeV, 60 pm
- 2027 – HALF @ Hefei 2.2. GeV, 85 pm
- 2029 – PETRA-IV @ Hamburg 6 GeV, 8 pm

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

aka

X-FELs



- 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@El., 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

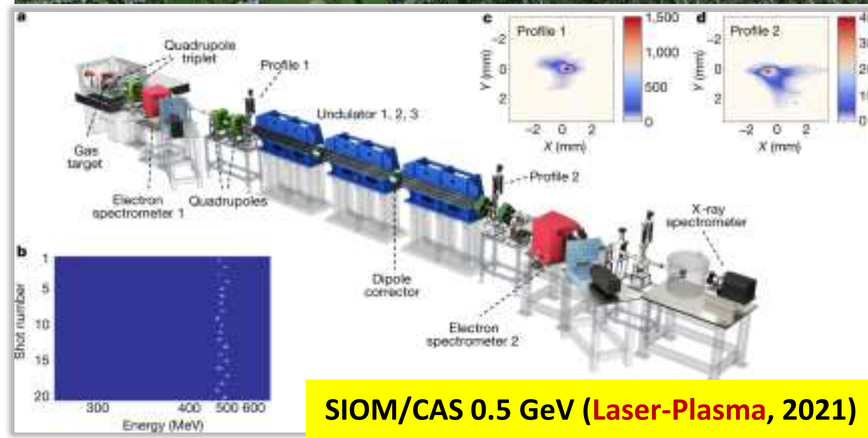
SIOM Shanghai, 0.5 GeV, plasma

2023 – LCLS-II, SLAC 4 GeV, SRF

2025 – SHINE, Shanghai 8 GeV, SRF

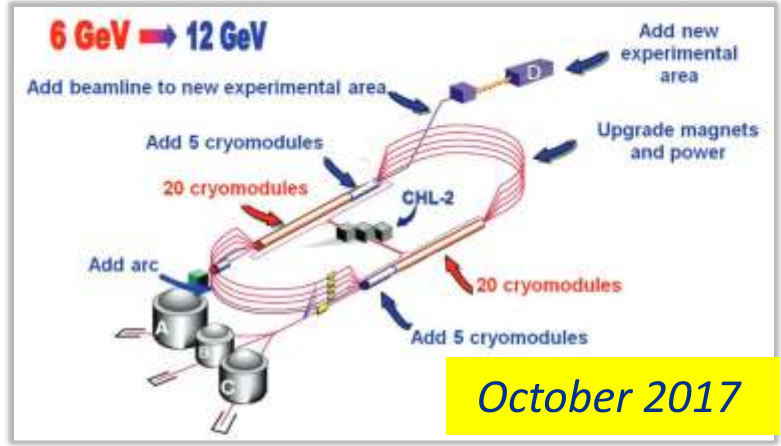
2031 – LCLS-II-HE, SLAC 8 GeV, SRF

2033 – SILA, Russia, 6 GeV, NC RF (?)



Electrons and Ions for Nuclear Physics

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

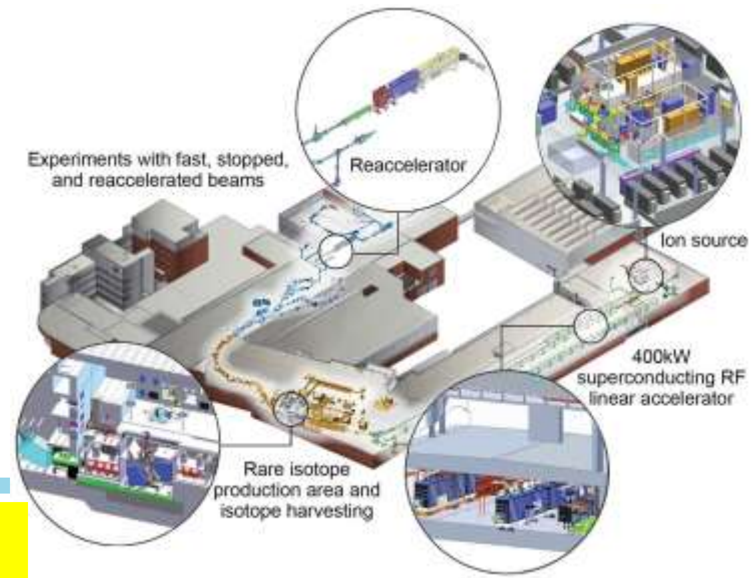


October 2017

2017-2019

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

Facility for Rare Isotope Beams (FRIB) at Michigan State University: 212 MeV/u ion SRF linac, 0.4MW power (5e13 ^{238}U/s)

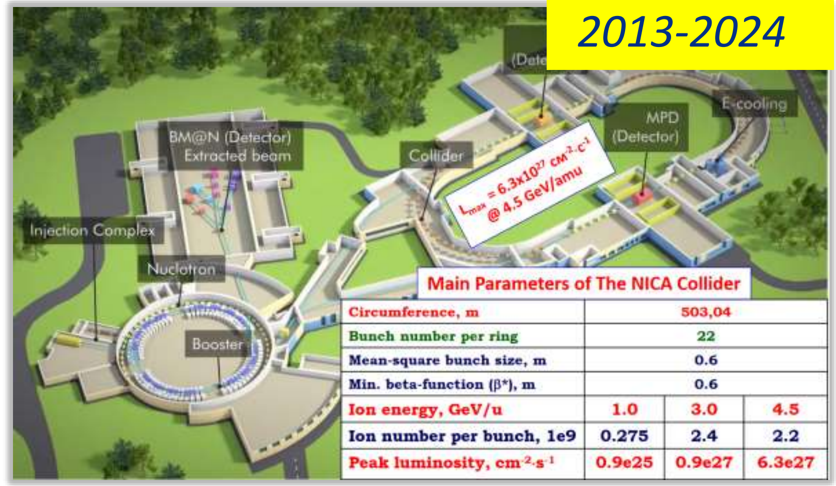


grand opening May 2, 2022

Ion Machines under Construction

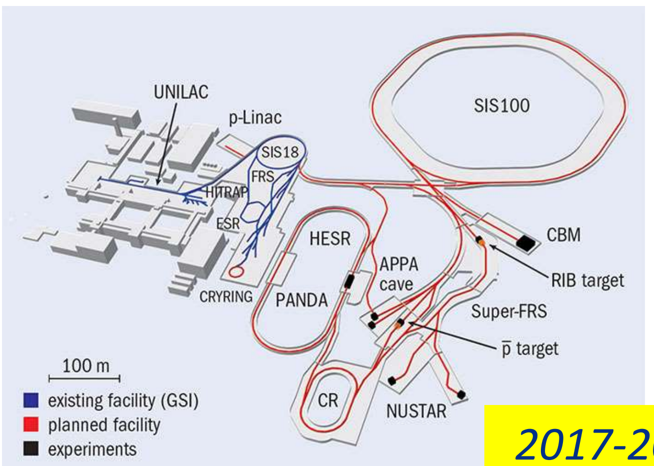
NICA Collider in JINR(Dubna): **4-11 GeV cme**, SC magnets; polarized *p, d* and ions (*Au*); $L \sim 10^{27}$ w. beam cooling

2013-2024



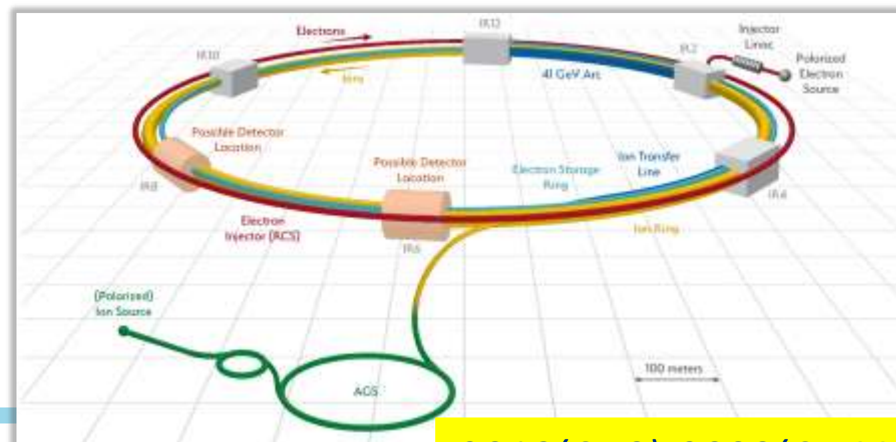
Main Parameters of The NICA Collider			
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β^*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, cm^{-2}·s^{-1}	0.9e25	0.9e27	6.3e27

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



2017-2029

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

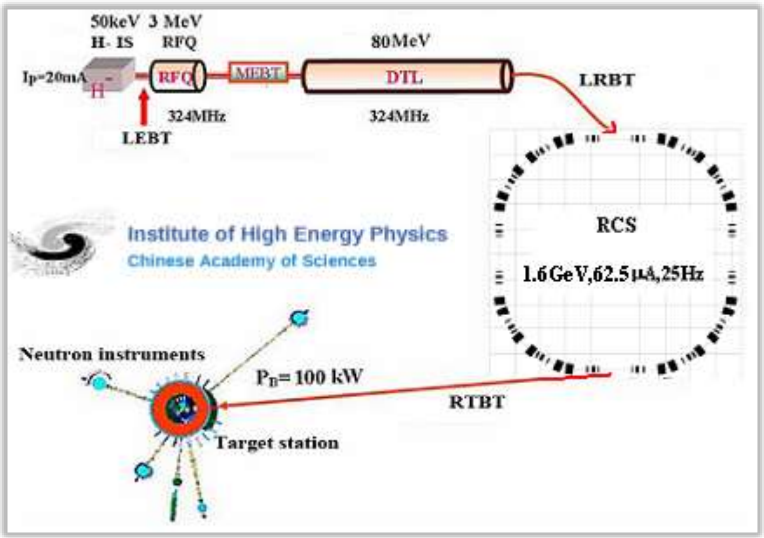


2019(CD0)-2033(CD4A)

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):

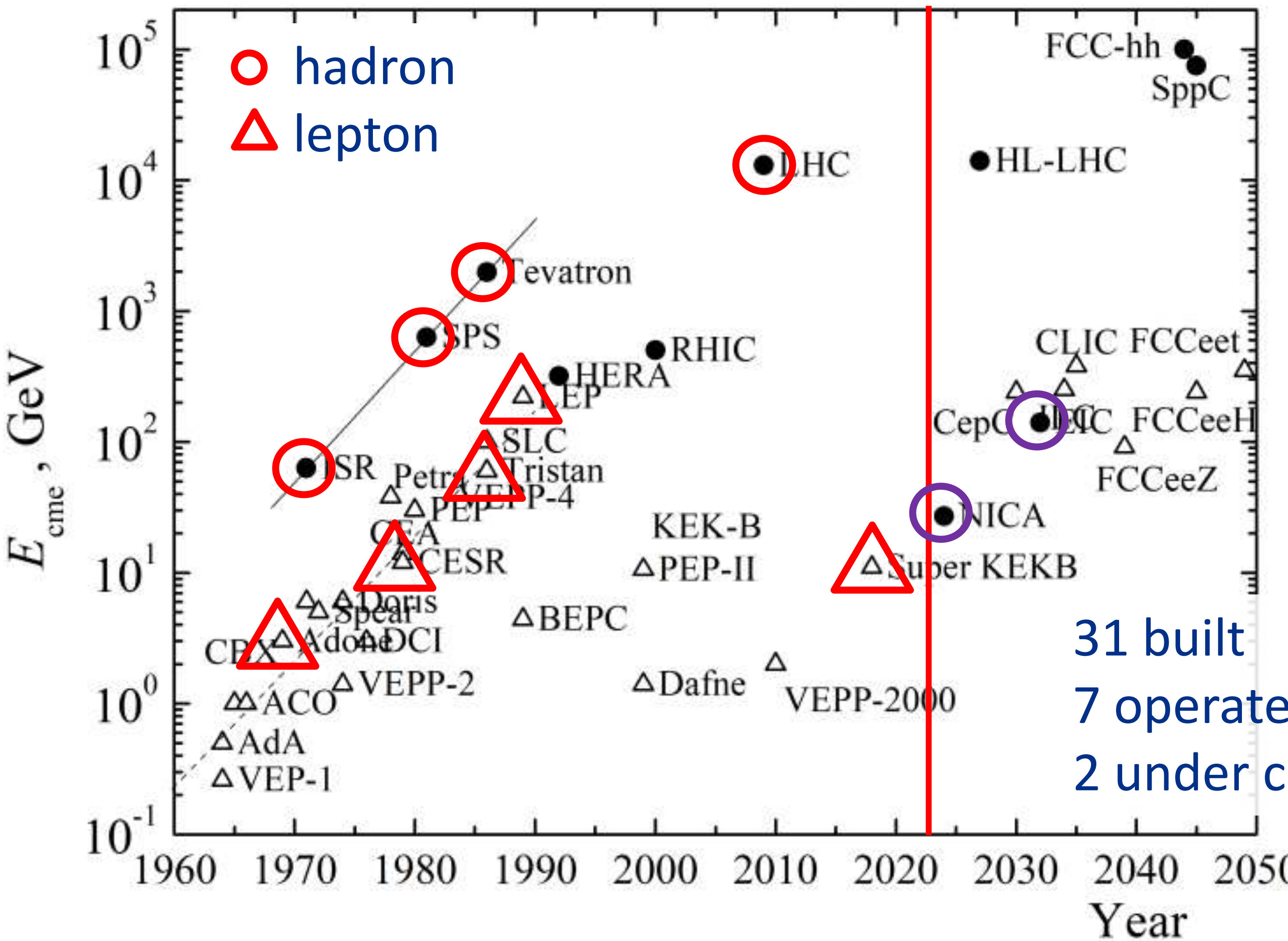
- 80 MeV linac and 1.4 GeV ring → target
- First neutrons Aug'2017, 0.1 MW Feb'2020
- Planned upgrades to 0.2 MW, then 0.5 MW

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)



31 built

7 operate now

2 under construction

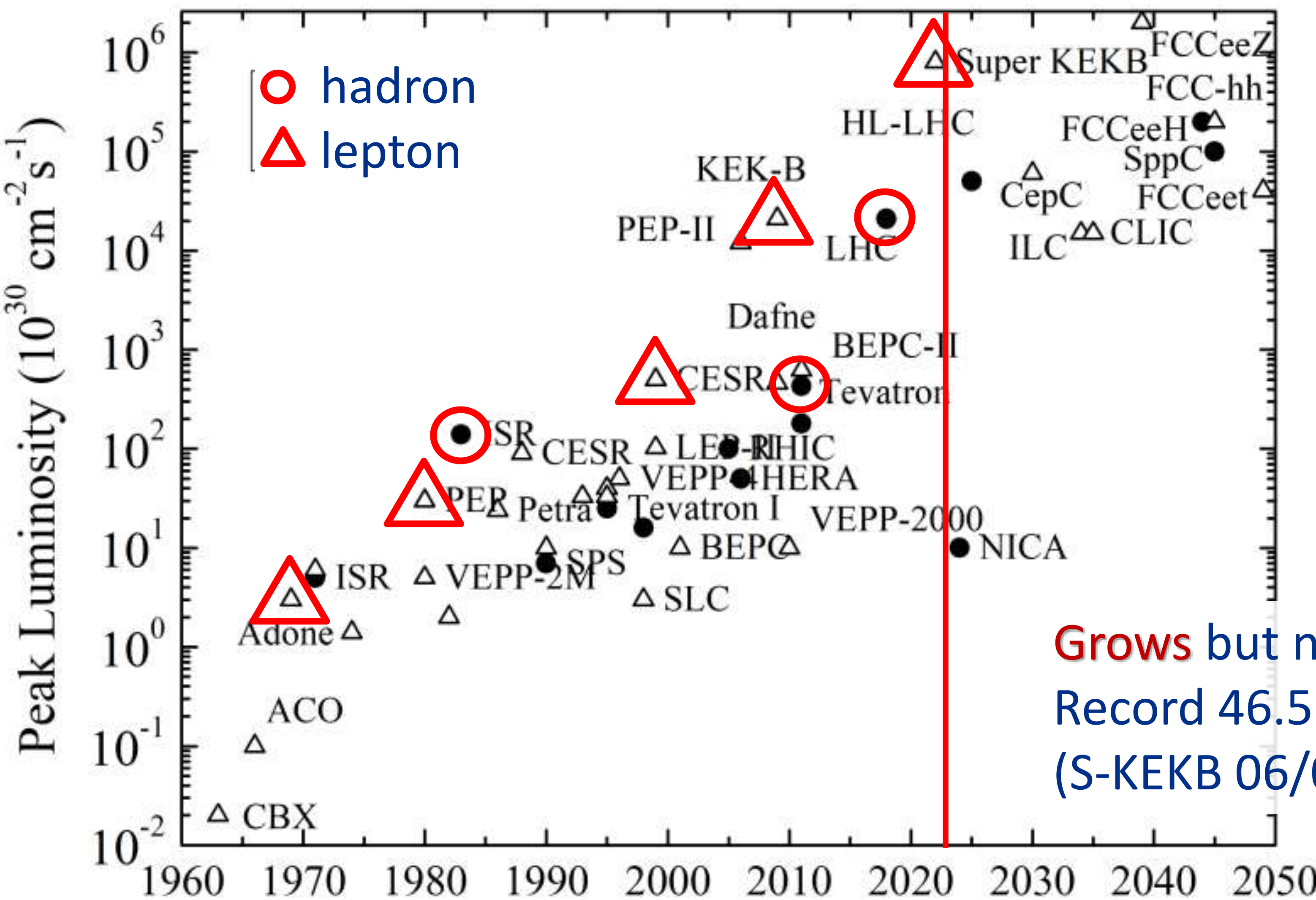
NICA

EIC

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

Collider Luminosities

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



Grows but not as E^2
Record 46.5 nb^{-1}s^{-1}
(S-KEKB 06/08/22)

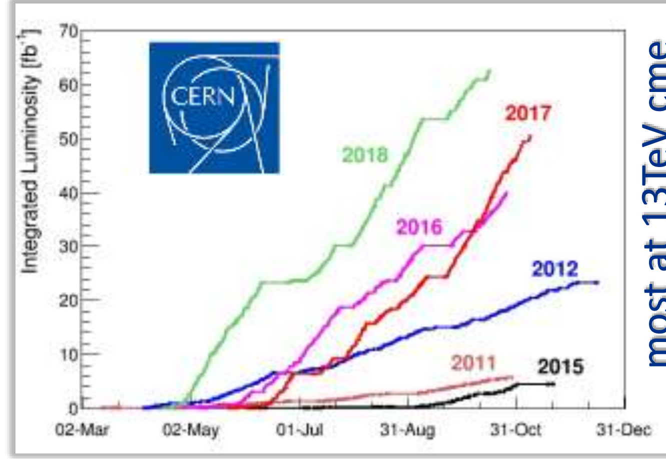
[V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006 (2021); V. Shiltsev, Phys. Usp. 55, 965 (2012)]

HEP Colliders

Seven in operation now

	Species	E_b (GeV)	C (m)	$\mathcal{L}_{peak}^{max}$	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	8×10^{35a}	2018–present

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

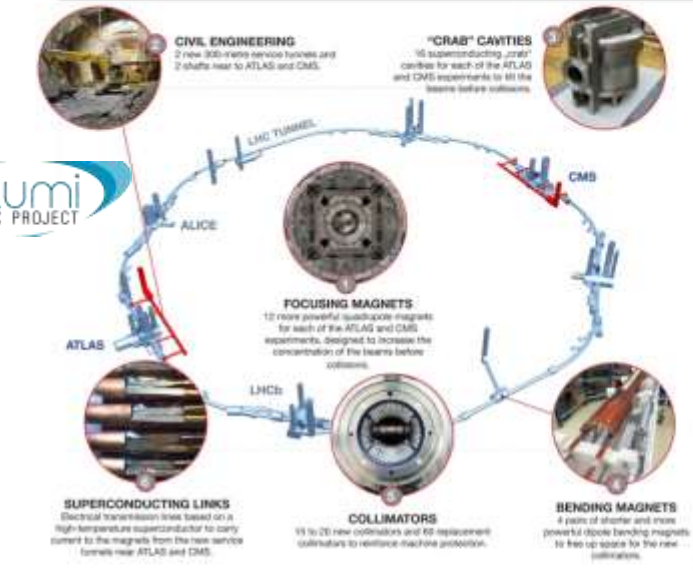


most at 13TeV cme

Highlights – LHC : *pp* 13→13.6 TeV cme

HiLumi HL-LHC PROJECT

- 190 fb-1/IP by now, x2 design luminosity
- High-Lumi upgrade by 2029: double beam current, smaller β^* (new Nb_3Sn 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*=4.7e34 cm^{-2}s^{-1}
- Design luminosity goal 60e34 cm^{-2}s^{-1}
- Now ~8% of the goal, slow progress, shutdown

Accelerator R&D - Few Examples

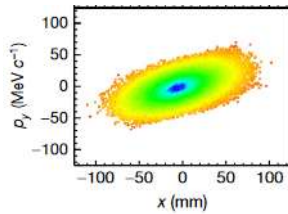
Record 14.5T Dipole (at FNAL, part of the US MDP)

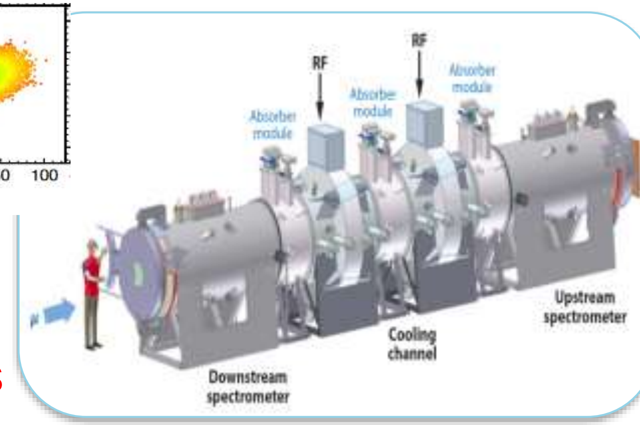
Nb3Sn conductor

Stress control

U.S. MAGNET DEVELOPMENT PROGRAM

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





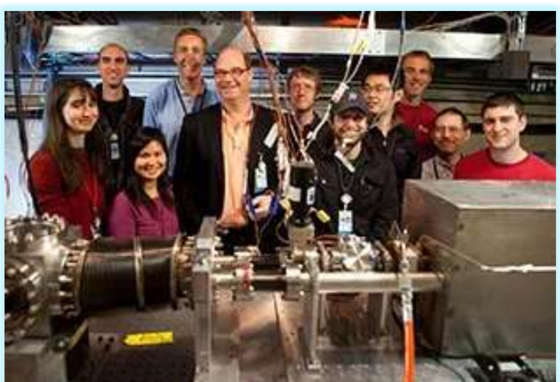
MICE ~10% in one pass

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

Unique *e*- beam
10 GeV, 1 nC, ~1 μm³
→ 9 GeV energy gain over 1.2 m plasma

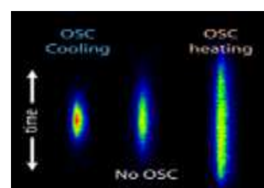
Unique laser → 8 GeV/0.2m

staging p.o.p 0.1+0.1 GeV



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

soon – experiments with *p*’s



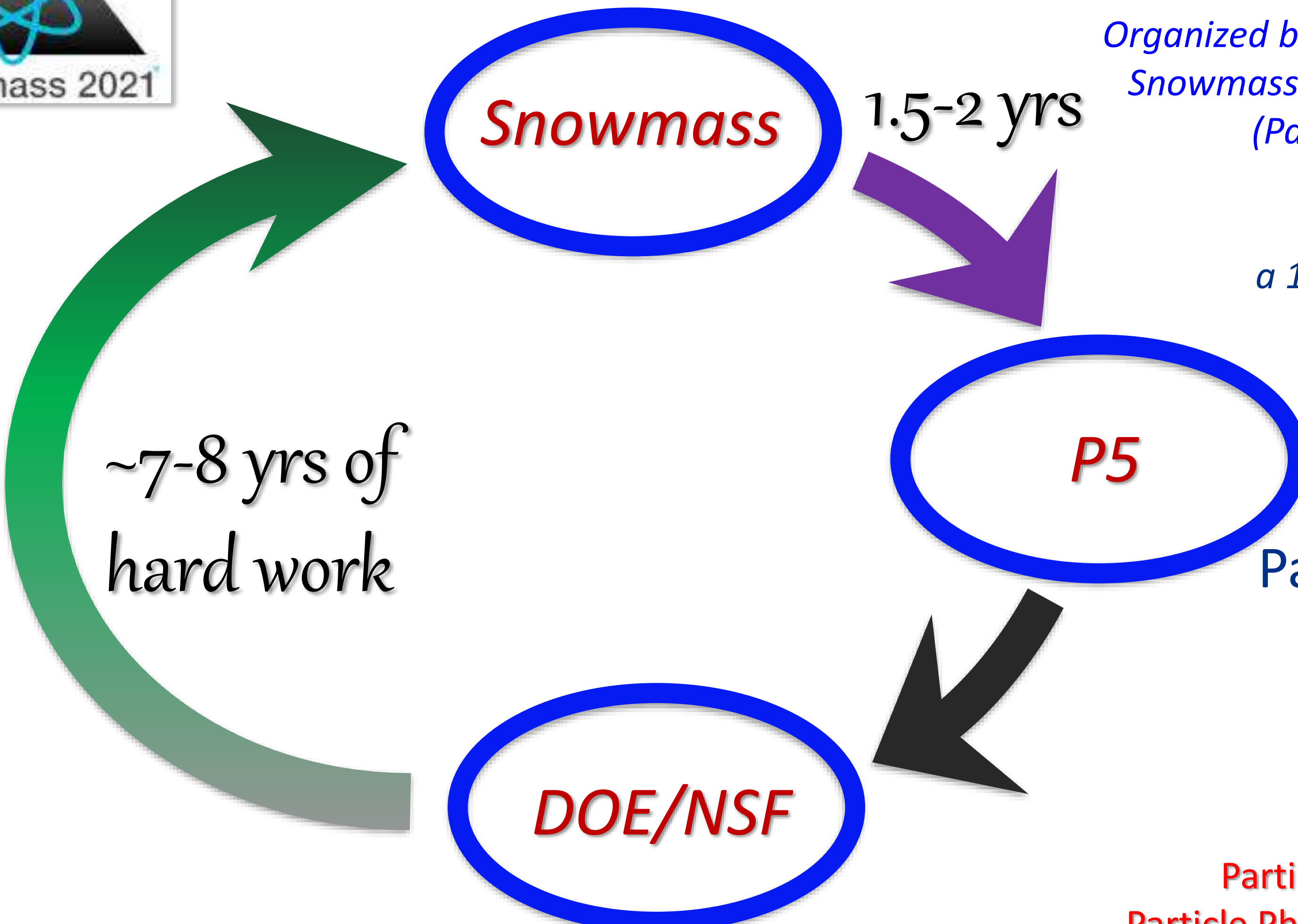
THz bandwidth

Part II :

Snowmass’21 –
Planning For Future

Snowmass'21 *"a particle physics community study"*

Snowmass 2021



Organized by APS DPF, DPB, et al
Snowmass provides input to P5
(Particle Physics Project
Prioritization Panel)
which develops
a 10-20 yrs strategy for
the US HEP program

~ 1 yr

Particle Physics
Project
Prioritization
Panel

Particle Physics is global
Particle Physics is not isolated

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

Snowmass 2021

- >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

Snowmass 2021

arxiv:2209.14136

“Intro”:

- Since last P5, this Snowmass’21 process

“Future Facilities”:

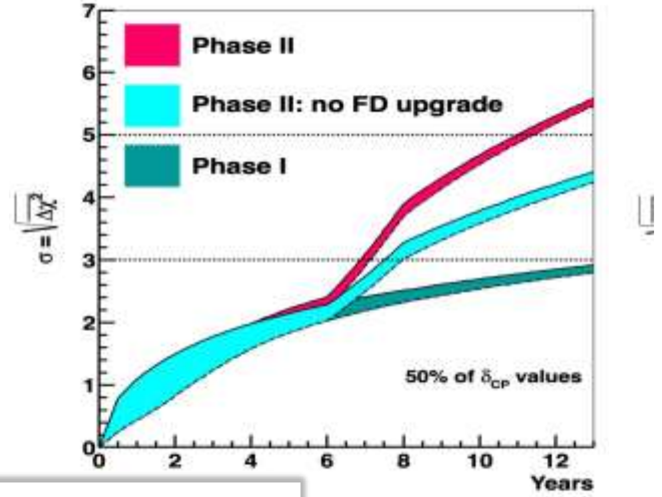
- *TBD by P5* – accelerator/people need to be part of P5; ITF analysis can greatly help
- *Multi-MW FNAL complex upgrade* will be priority for NF in 2030 (AccFrontier is ready)
- Many opportunities for Rare Processes (AF ready), incl. *PAR and utilize what we have*
- Several Higgs/EW factories are feasible: *FCCee, C3 and HELEN* to be explored
- *O*(10 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. Raubenheimer, V. Shiltsev

Serving Neutrino Physics

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



$$"MW\,years" = \frac{eN_{ppp}E_{beam}}{T_{cycle}} \times Ops\,Time$$

- 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

- The Accelerator Frontier **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider p…
  - Higgs/EW factories (focu…
  - Lepton colliders…
  - Lepton a…
  - F…
- ITF a… …bgroups):
  - Ph… …mpact), beam parameters
  - Size, …mplexity, power, environment
  - Technical risk, readiness, and R&D required
  - Cost and schedule

Combined experience in construction and commissioning of >20 accelerator projects

…run

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)

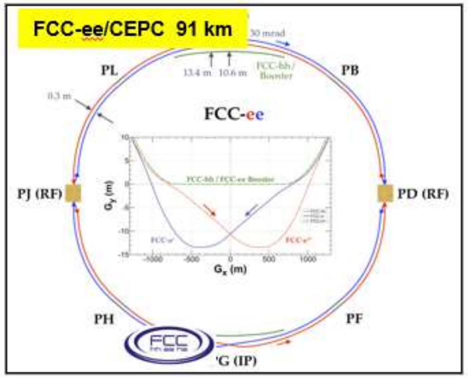
Below I mostly follow T.Roser presentation in Seattle

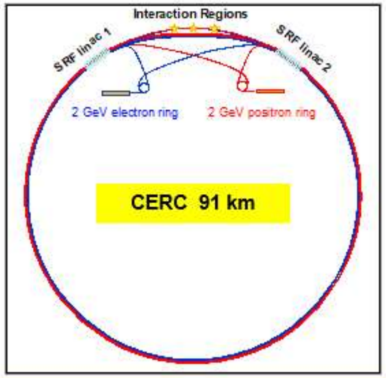
Proposals – Higgs/EW Physics

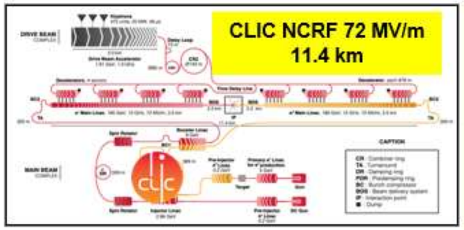
6

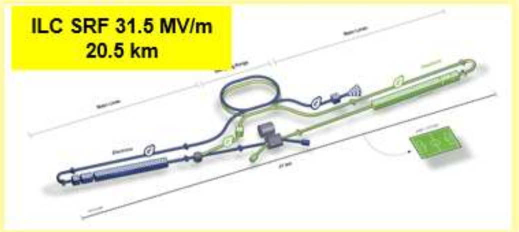
Higgs factory concepts (10)

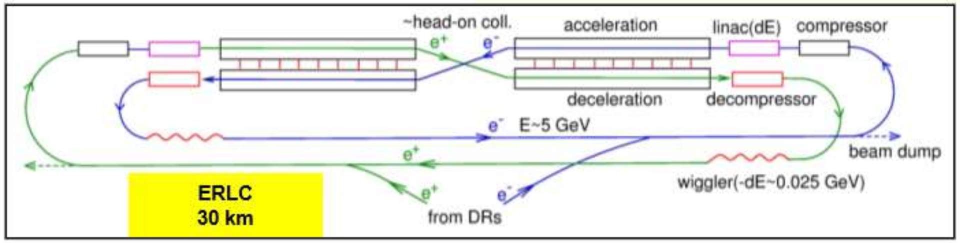
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ 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

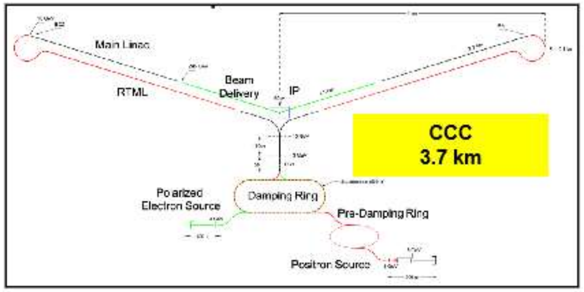


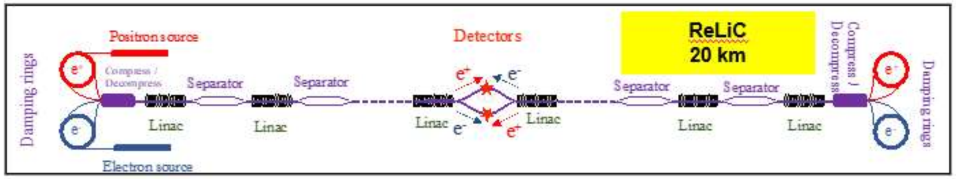






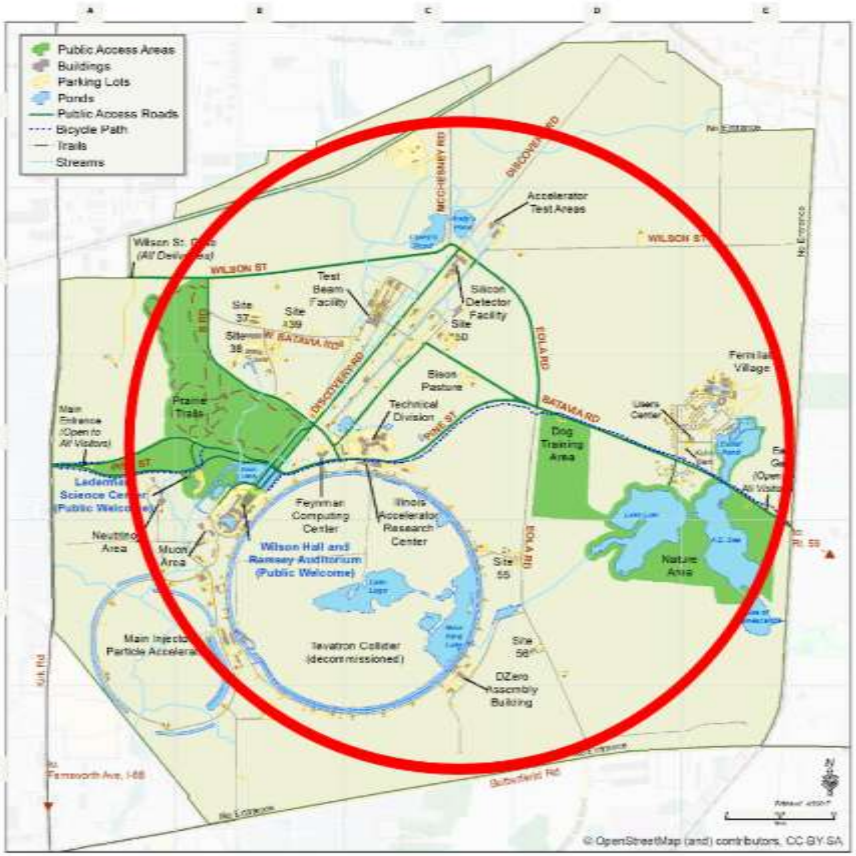






Fermilab

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 1st 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-γγ	0.125	0.1	5-10	19-24	4-7	90
	μμ-Higgs	0.13	0.01	>10	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 1st 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

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

Why muon colliders?

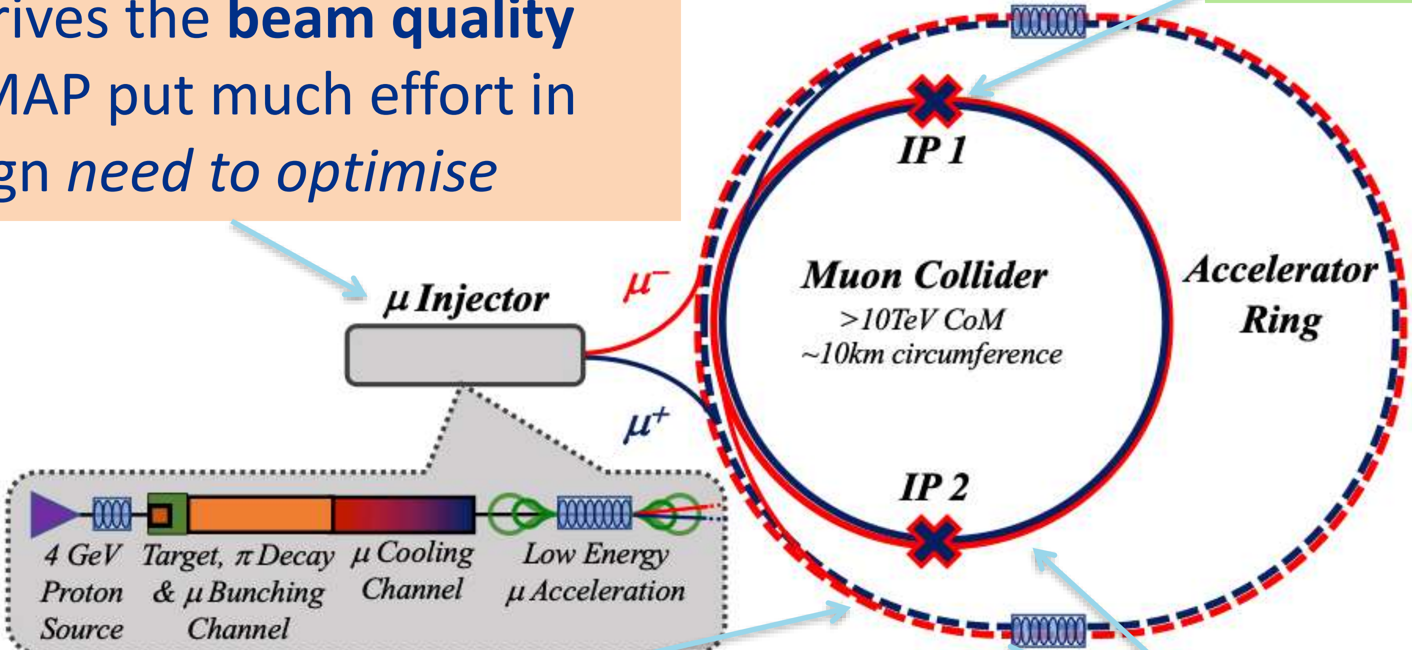
- (Snowmass Energy Frontier) HEP aspires 10+ TeV cme/parton
- Muon Collider is a viable option for the HEP future:
  - Combines discovery reach and precision physics
  - x7 energy reach vs *pp* – eg 14 TeV *μμ* = 100 TeV pp
  - *μ*'s do not radiate when bent → acceleration in rings:
    - *Smaller(est) 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

3) Beam-induced background

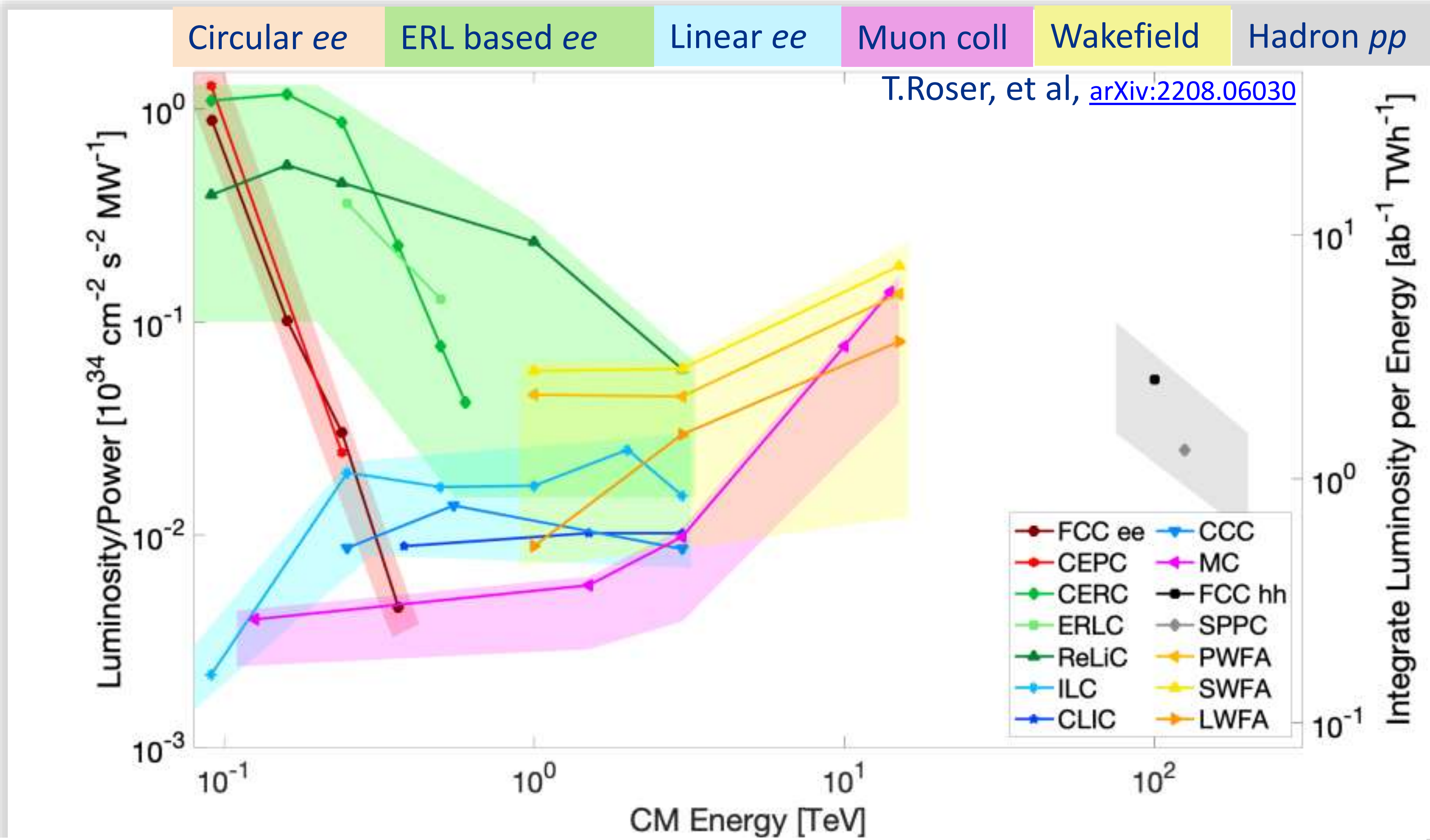
5) Drives the **beam quality**
US MAP put much effort in design *need to optimise*



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

Luminosity per Power

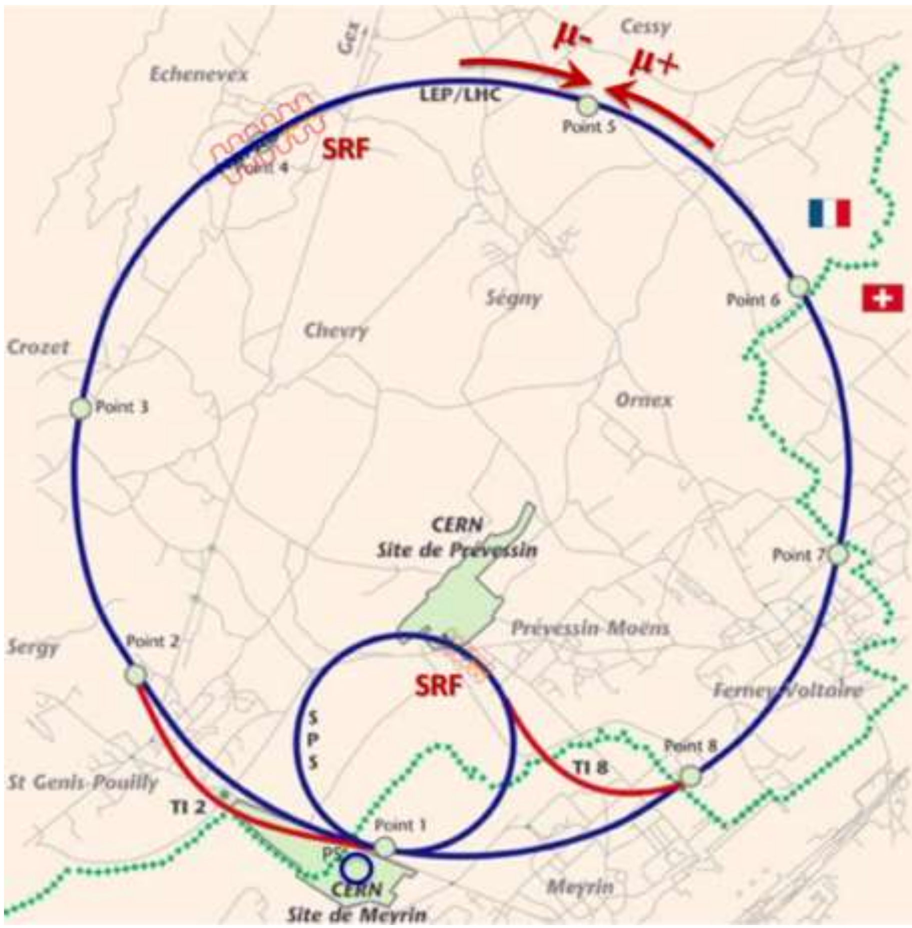


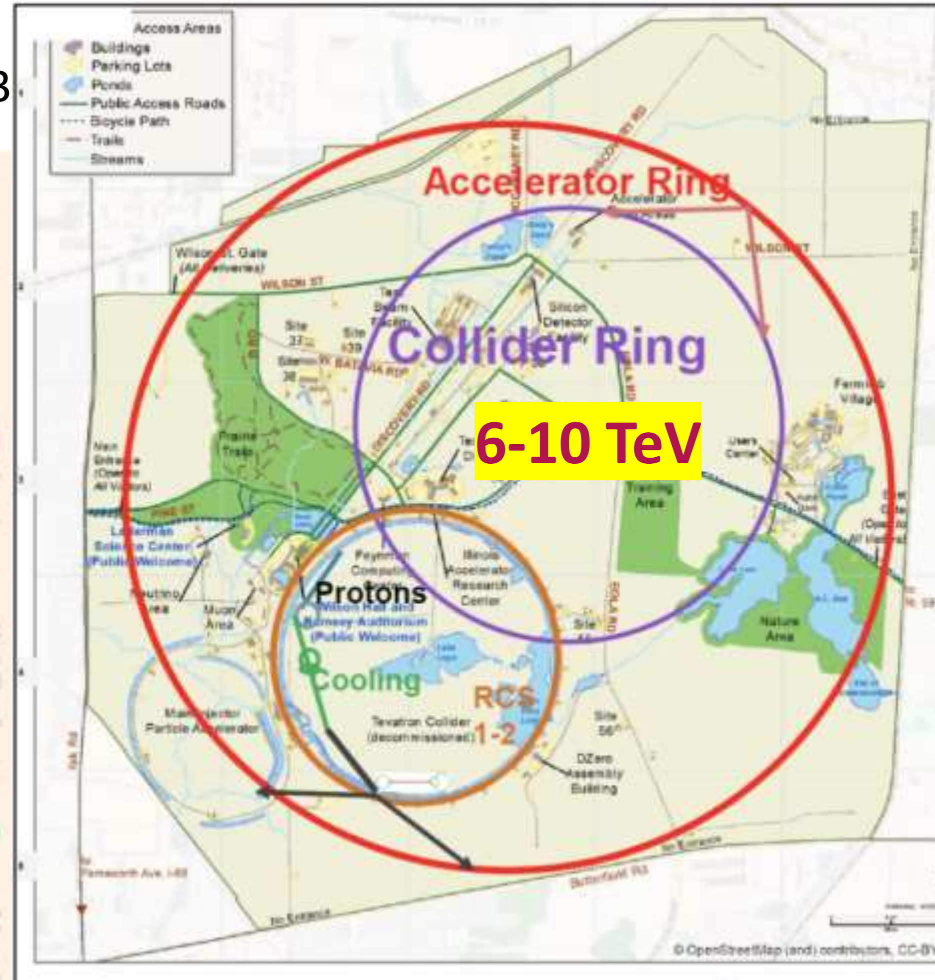
Luminosity is per IP, Integrated luminosity assumes 1e7 seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

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

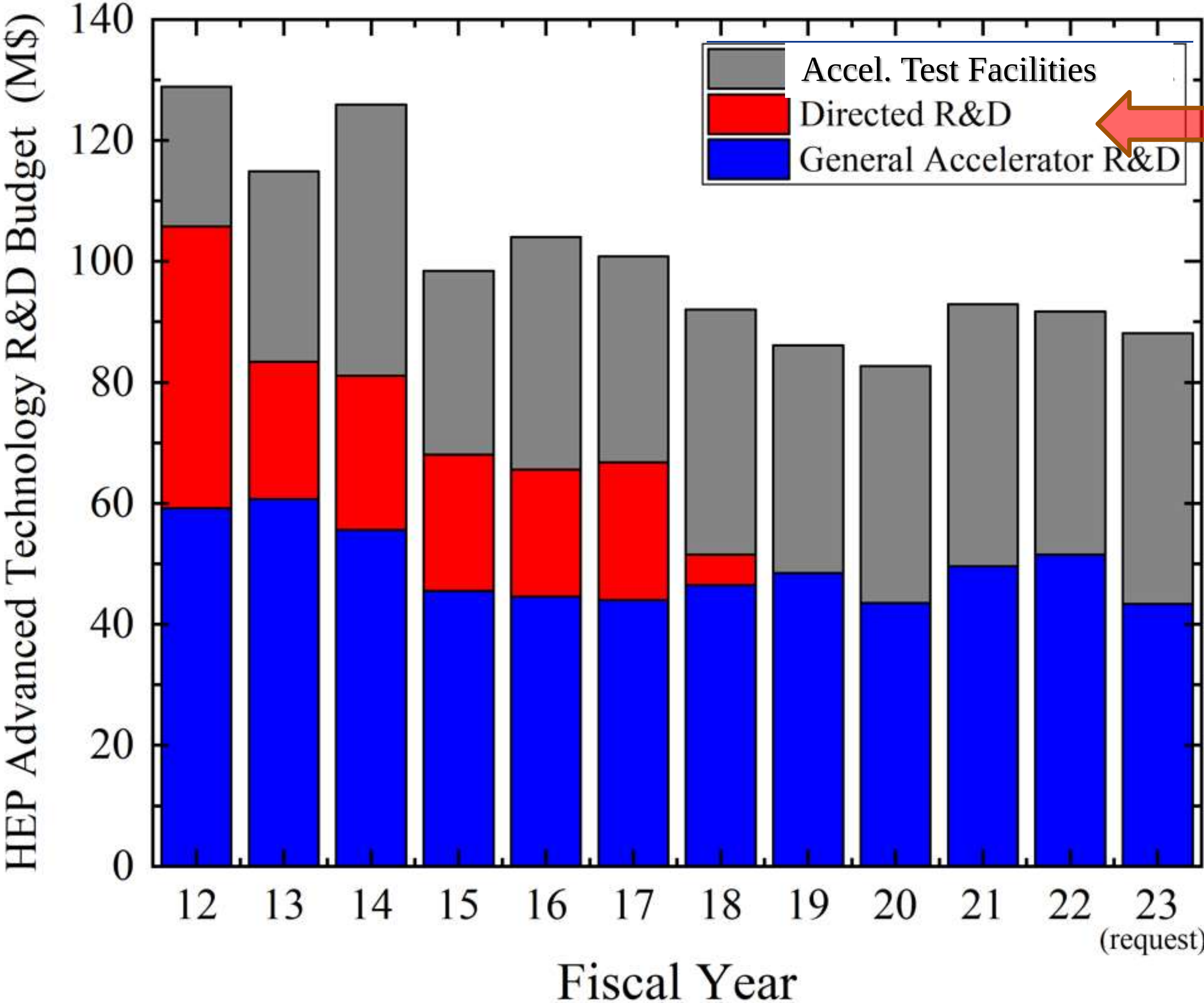
Accelerator Frontier Recommendation (to P5)

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)

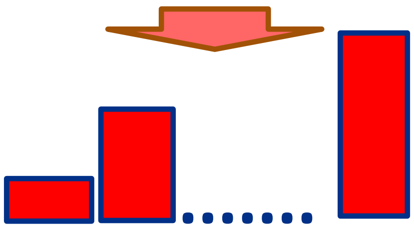
Such a program needed to make an informative decision on future HEP facility ~2031

Future Colliders R&D Program - Initiative



Completed:
US ILC
US LARP (LHC)
US MAP (Muon)

Proposed for FY24-30:
Future Colliders



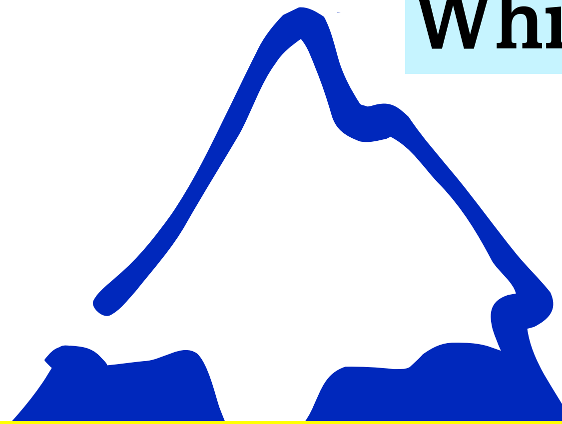
Integrated program:
FCCee, ILC,
C^3, HELEN,
Muon Collider, etc
In US and abroad
Design and R&D

https://arxiv.org/abs/2207.06213

Part III :

Limits of Colliders

Future - ?



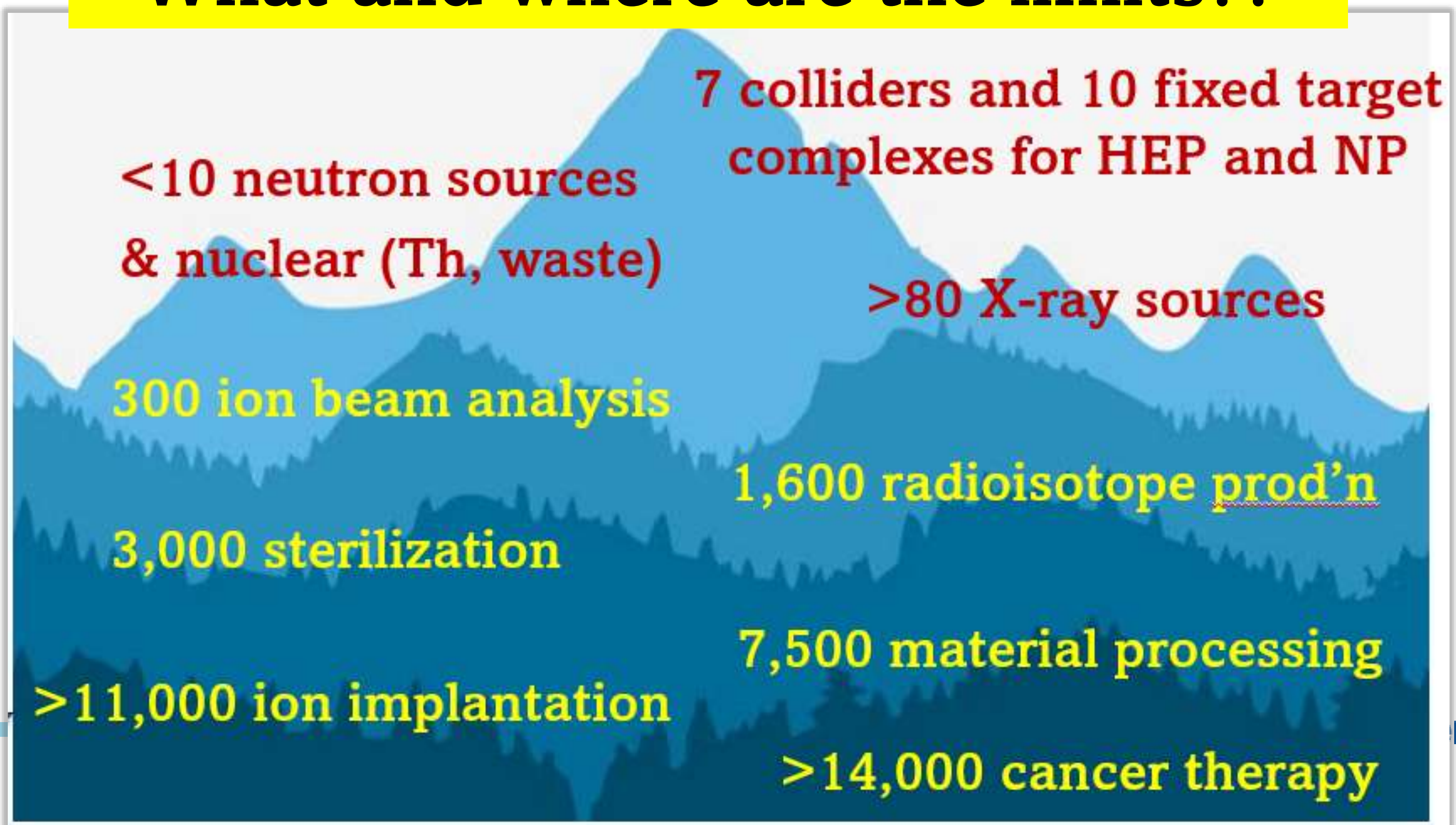
Which technologies?

Existing?

Emerging?

Exotic?

What and where are the limits??

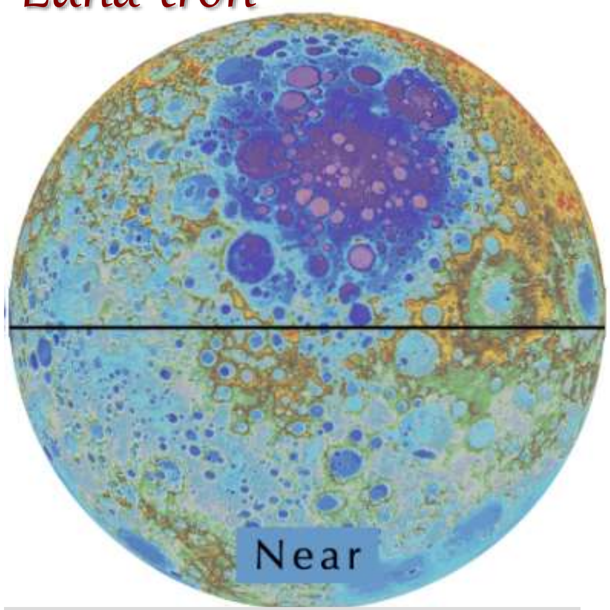


Circular *pp* Colliders

- Known technology (magnets)
- Major limitations:
  - Size (magnetic field *B*), power, cost
  - Synchrotron radiation → *Lumi ~R/E*^{3}
  - Beam-beam, burn-off, pileup, instabilities

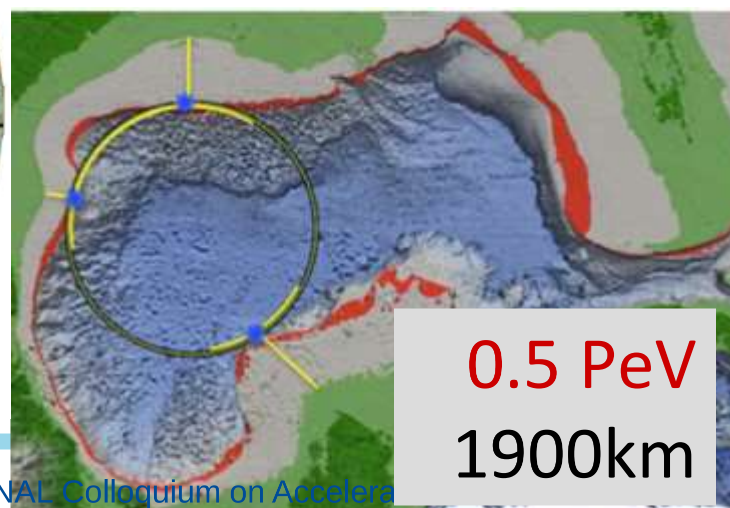
0.1 PeV

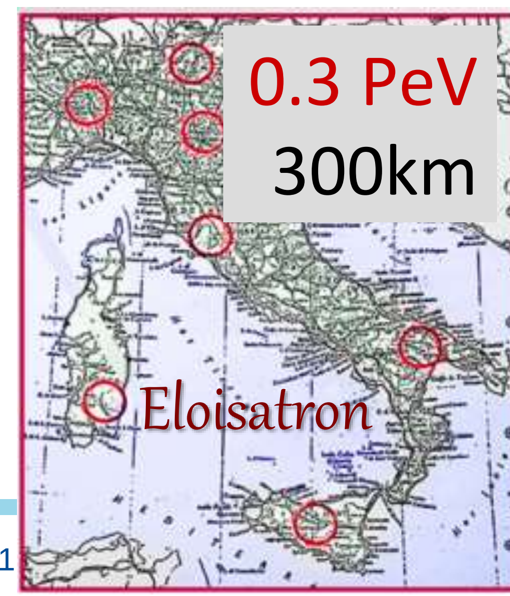
Luna-tron



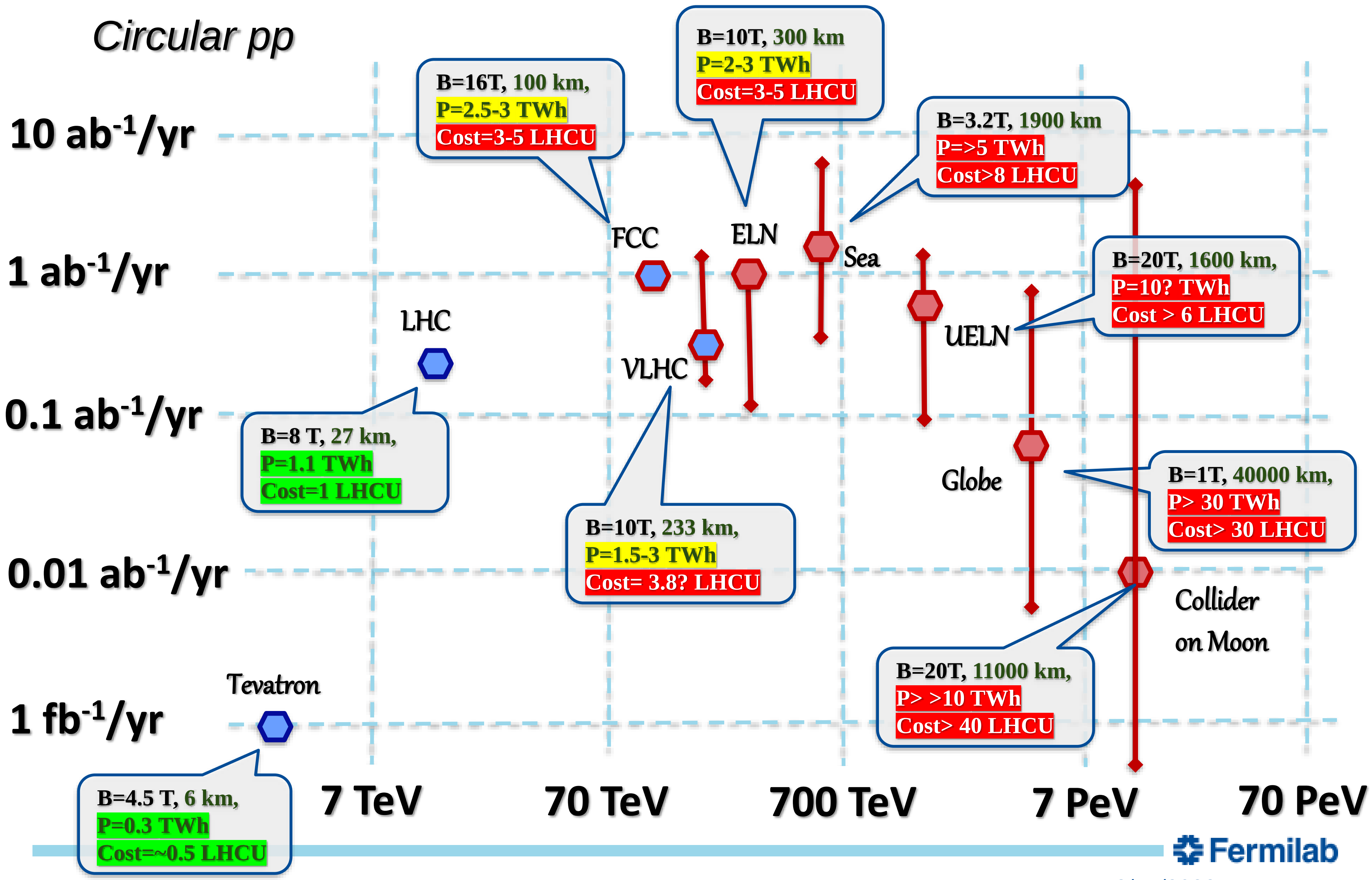
14 PeV,11000km

Collider-in-the-Sea





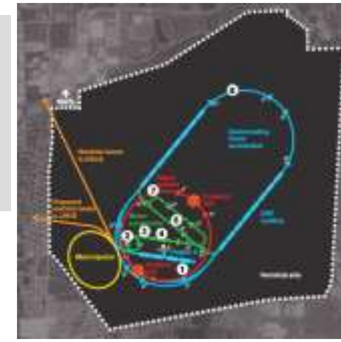
pp Colliders: *Lumi, Power, Cost* vs *Energy*

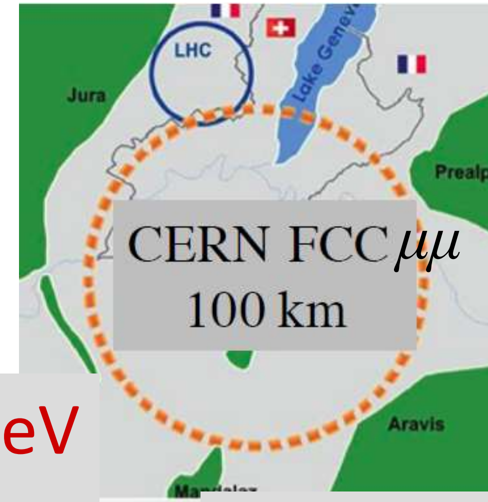


Circular $\mu+\mu-$ Colliders

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

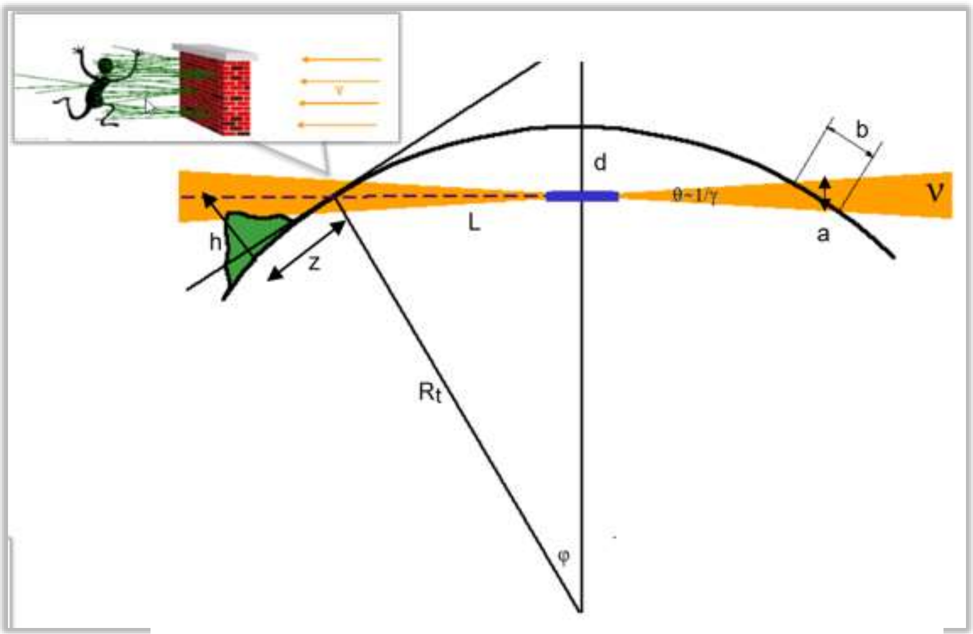
10 TeV
10 km



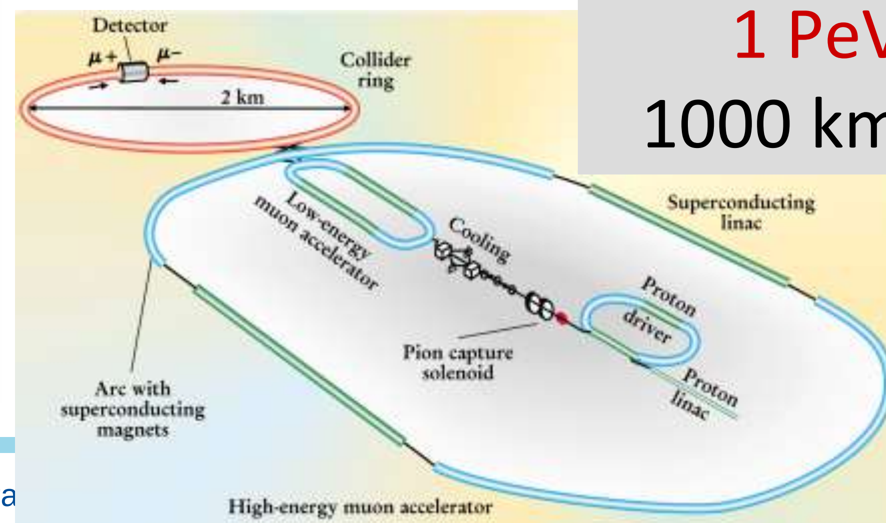


CERN FCC $\mu\mu$
100 km

0.1 PeV

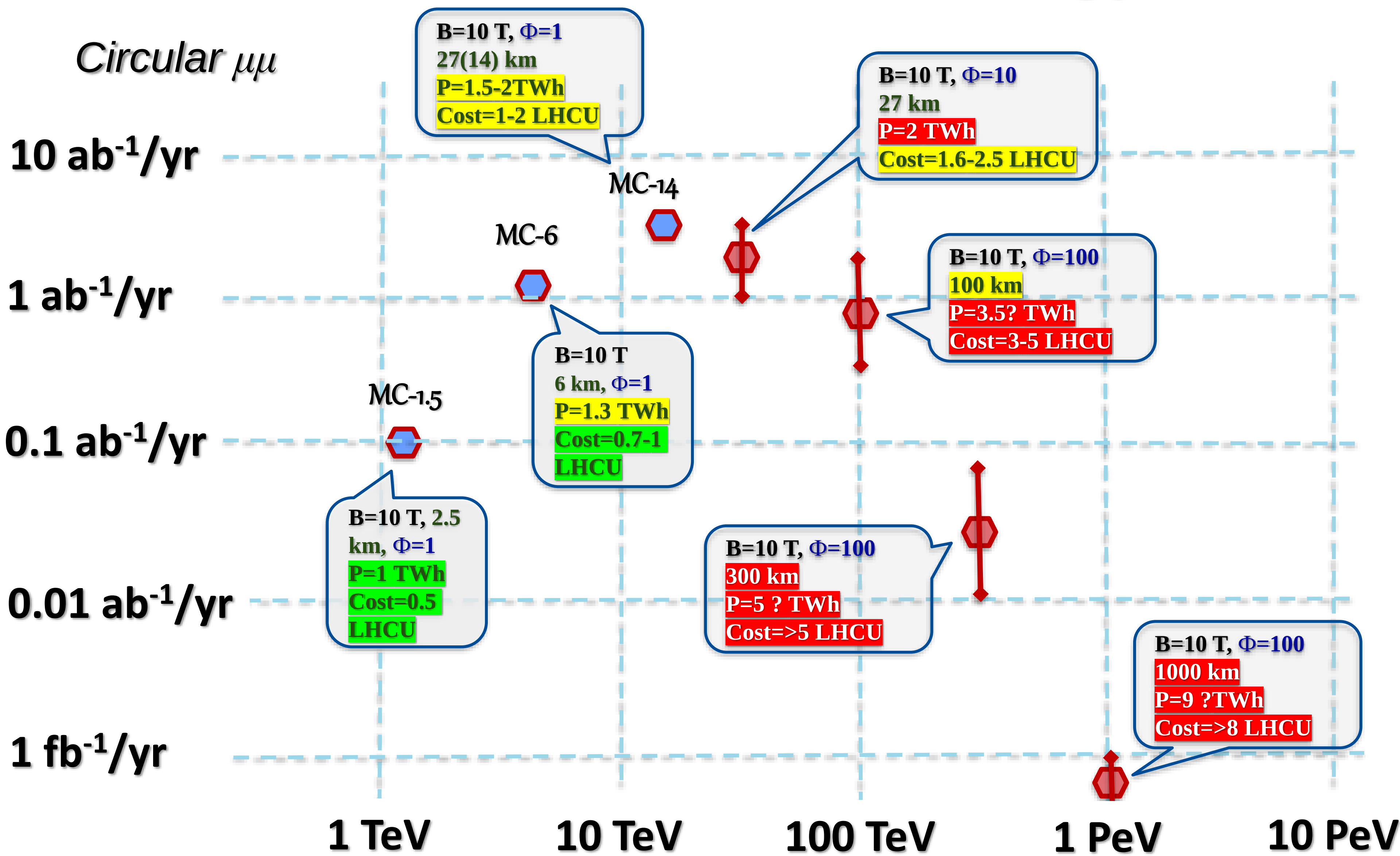


1 PeV
1000 km



Cone gets narrower with energy
Cross section grows with energy

MC: *Lumi* and *Cost* vs *Energy*

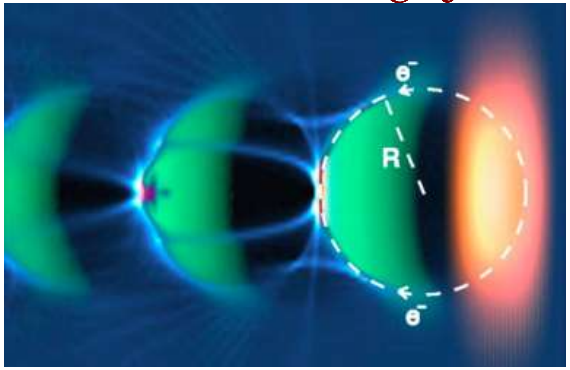


Linear *e+e-* Colliders

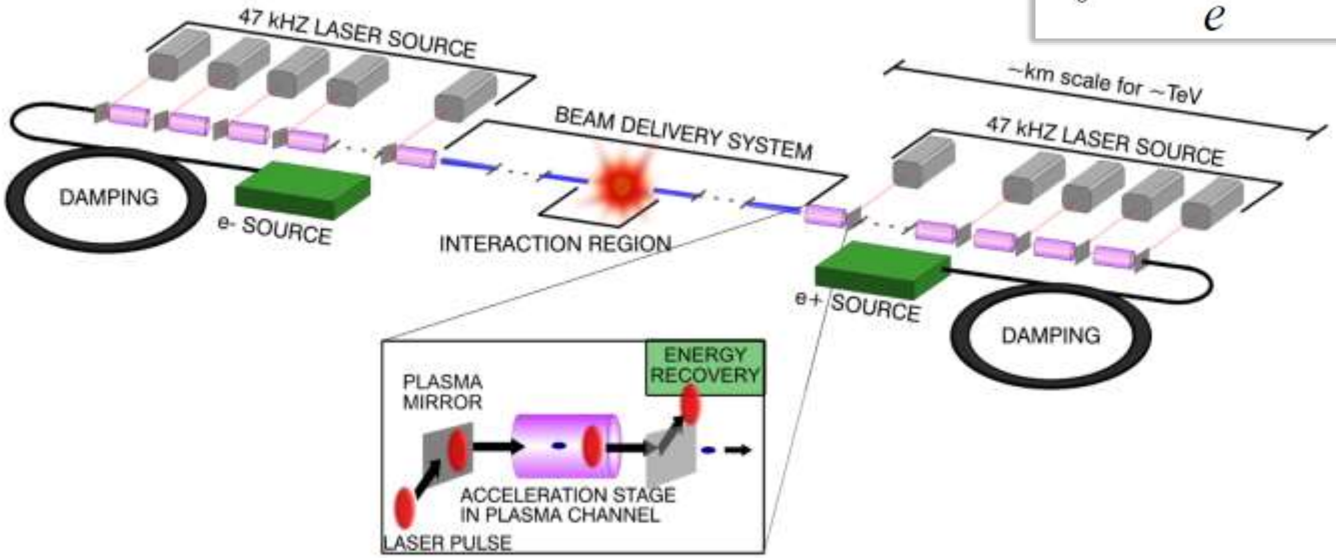
- Either RF acceleration (50-200 MeV/m) or wake-field acceleration in plasma (2-5 GeV/m)
- Major limitations:
  - 100% energy spread at IP (beamstrahlung)
  - One-time collisions ineffective → *Lumi ~P/(Eσ)*
  - Very long/complex *Final Focus* to get nm IP size
  - Extreme sensitivity to nm jitters of 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

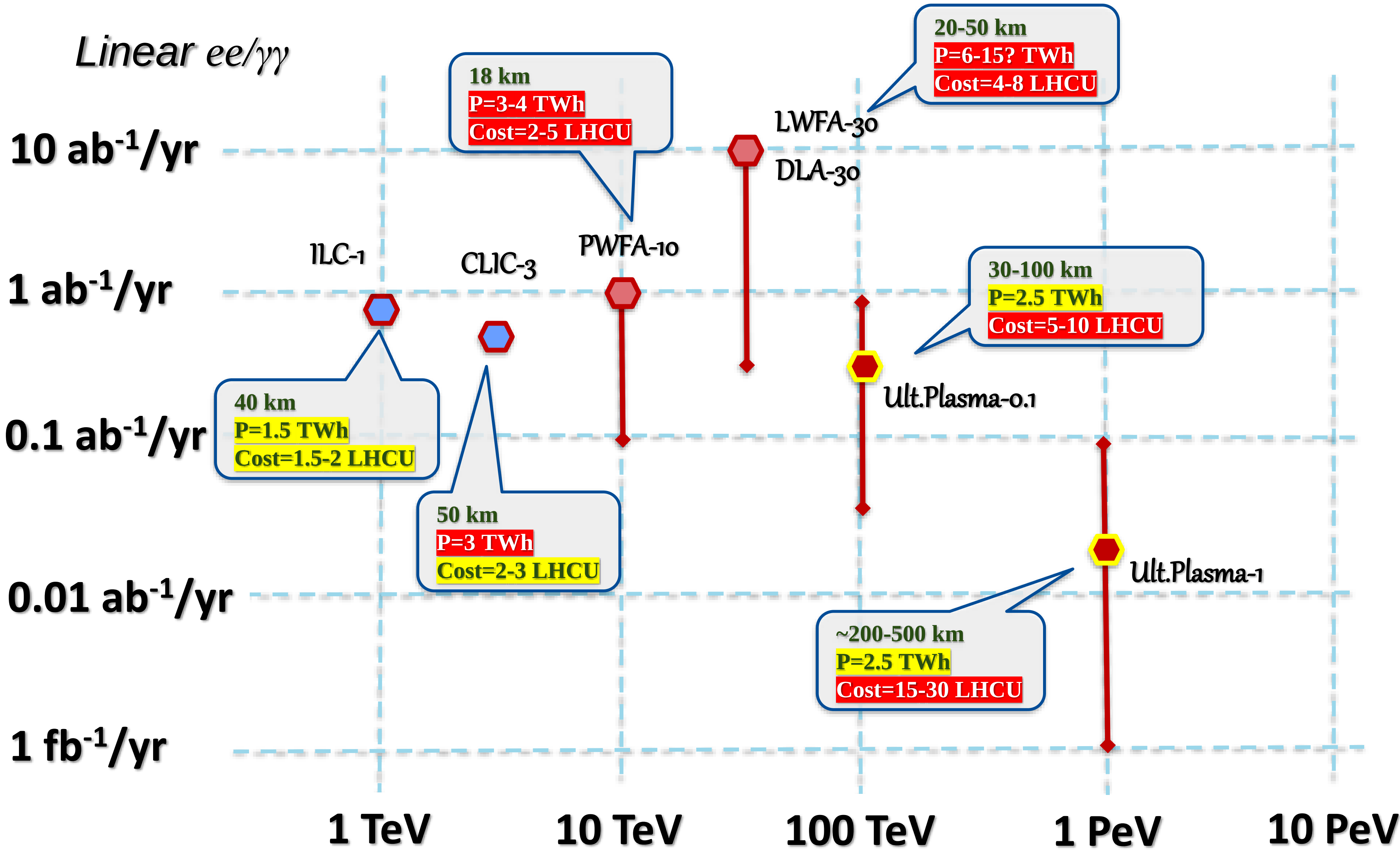


$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$



Takes about 1 GW electic power even for 15 TeV

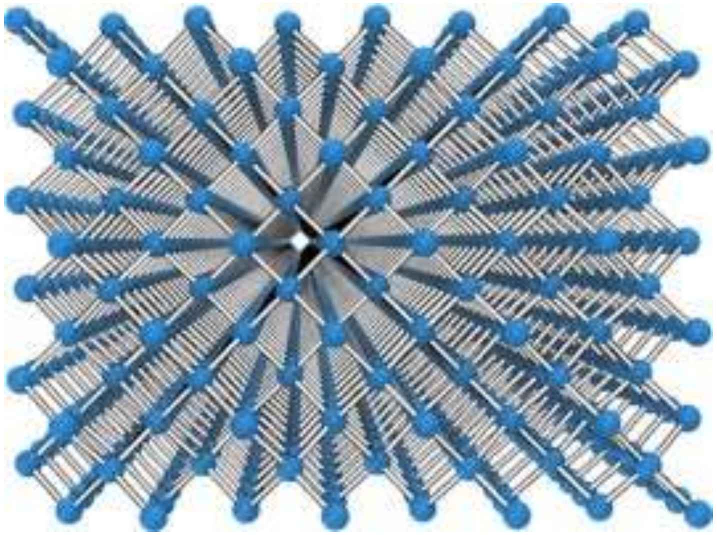
Linear RF and Plasma: *Lumi* and *Cost* vs *Energy*



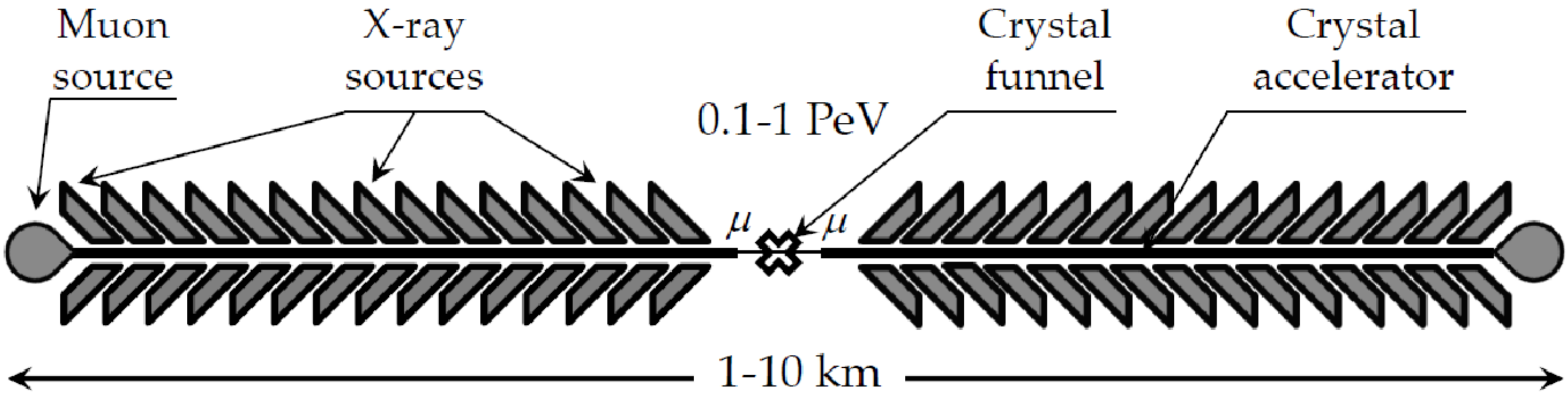
Exotic Colliders

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

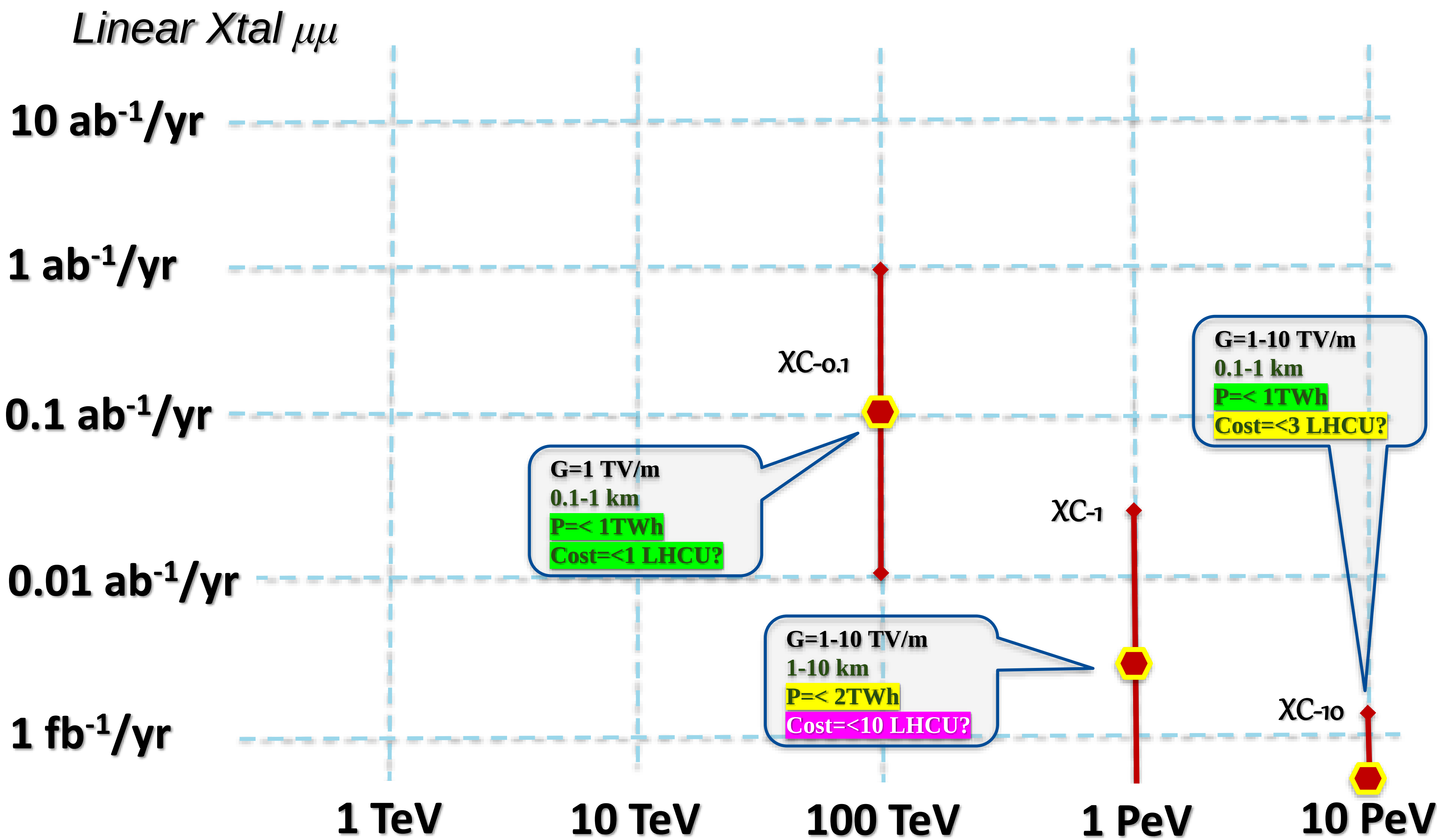
- Plasma-wakefield acceleration **and** channeling in structured media, eg CNTs or crystals (***only muons!!!***)



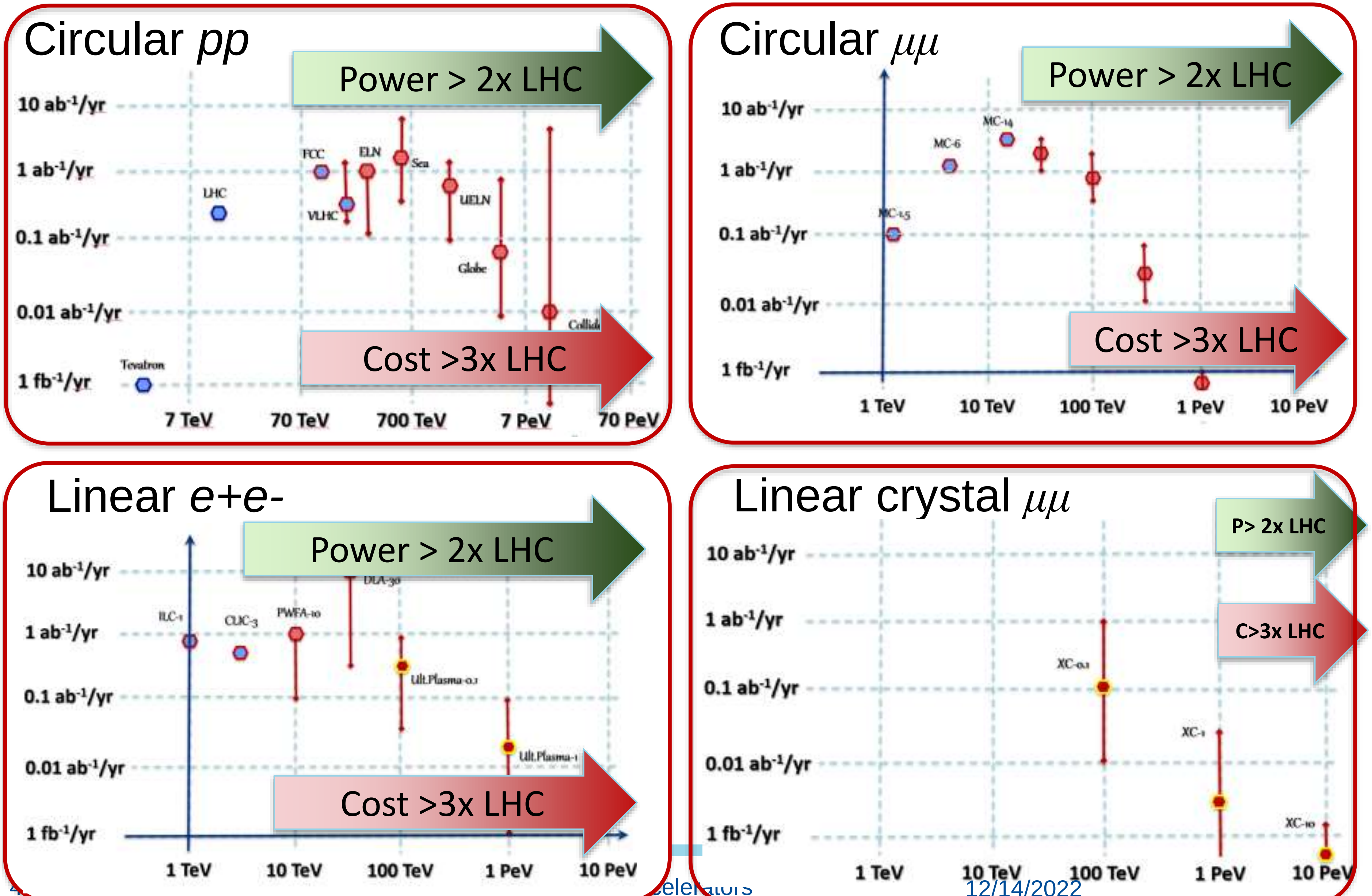
- Major advantages:
  - solid density → 1-10 TV/m gradients
  - continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled *betatron radiation*)
  - small size promises low cost
- *Lumi ~1/E²* …totally unproven yet concept:
  - proof-of-principle experiment *E336* @ SLAC



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



Limits (Electric Power and Cost)



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*(5GeV) – 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,μμ,ee*)

Summary (2):

- ***Snowmass'21* Accelerator Frontier on colliders:**
  - **Higgs factories sorted out by *Cost, Luminosity* and *Power***
    - *FCCee, ILC, C^3 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 *P*ower < 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 *L*uminosity**
- **Muons are particles of the future !**

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

Thanks for your attention!