Northern Illinois University

ULTIMATE COLLIDERS

(A Look into the Future)

Vladimir SHILTSEV

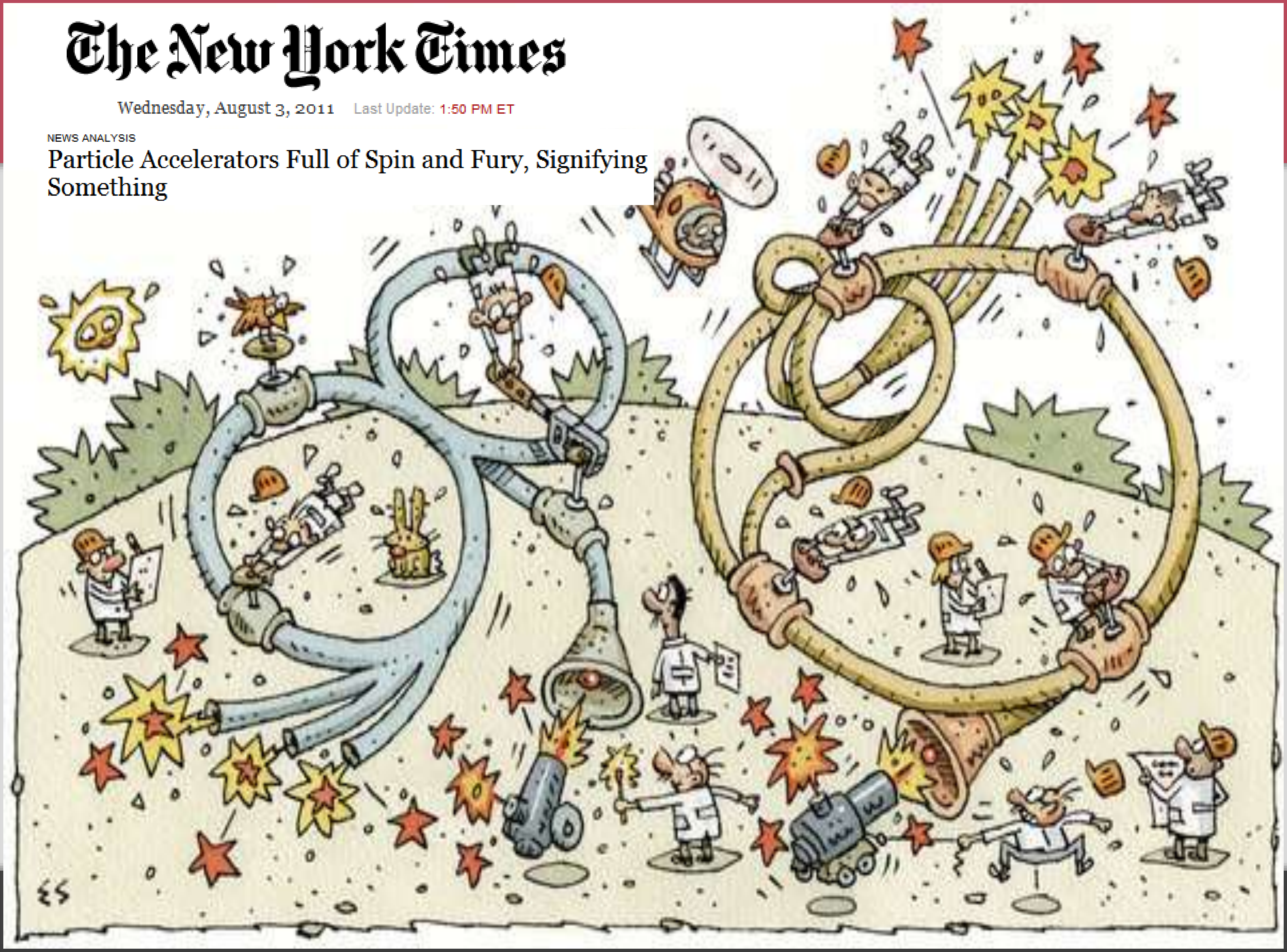
Galileo Galilei Institute · July 29, 2025 · Firenze, Italy

Exploring the Energy Frontier with Muon Beams

2011

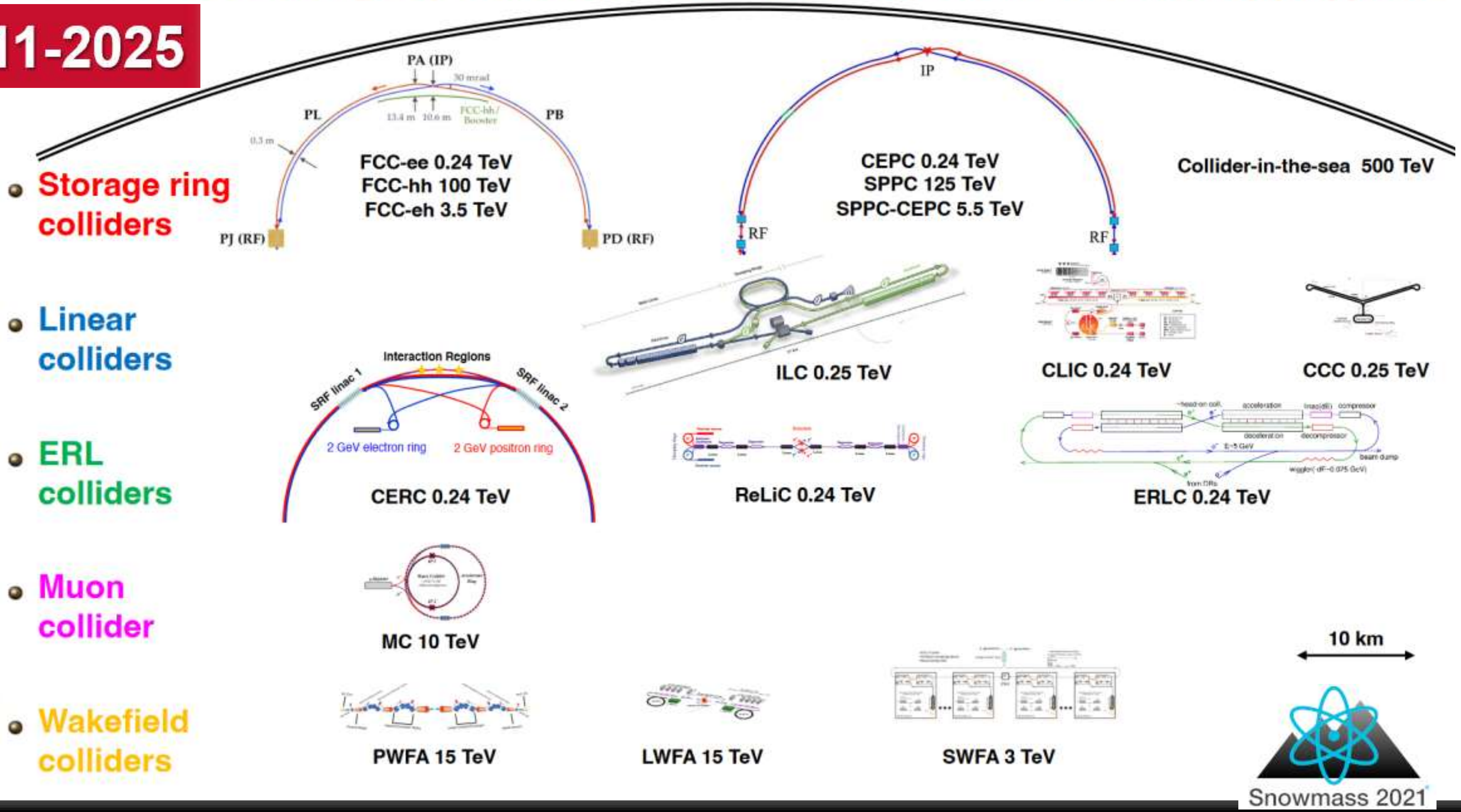
Le Roy mort,

Vive le Roy!



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

2011-2025



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

2025

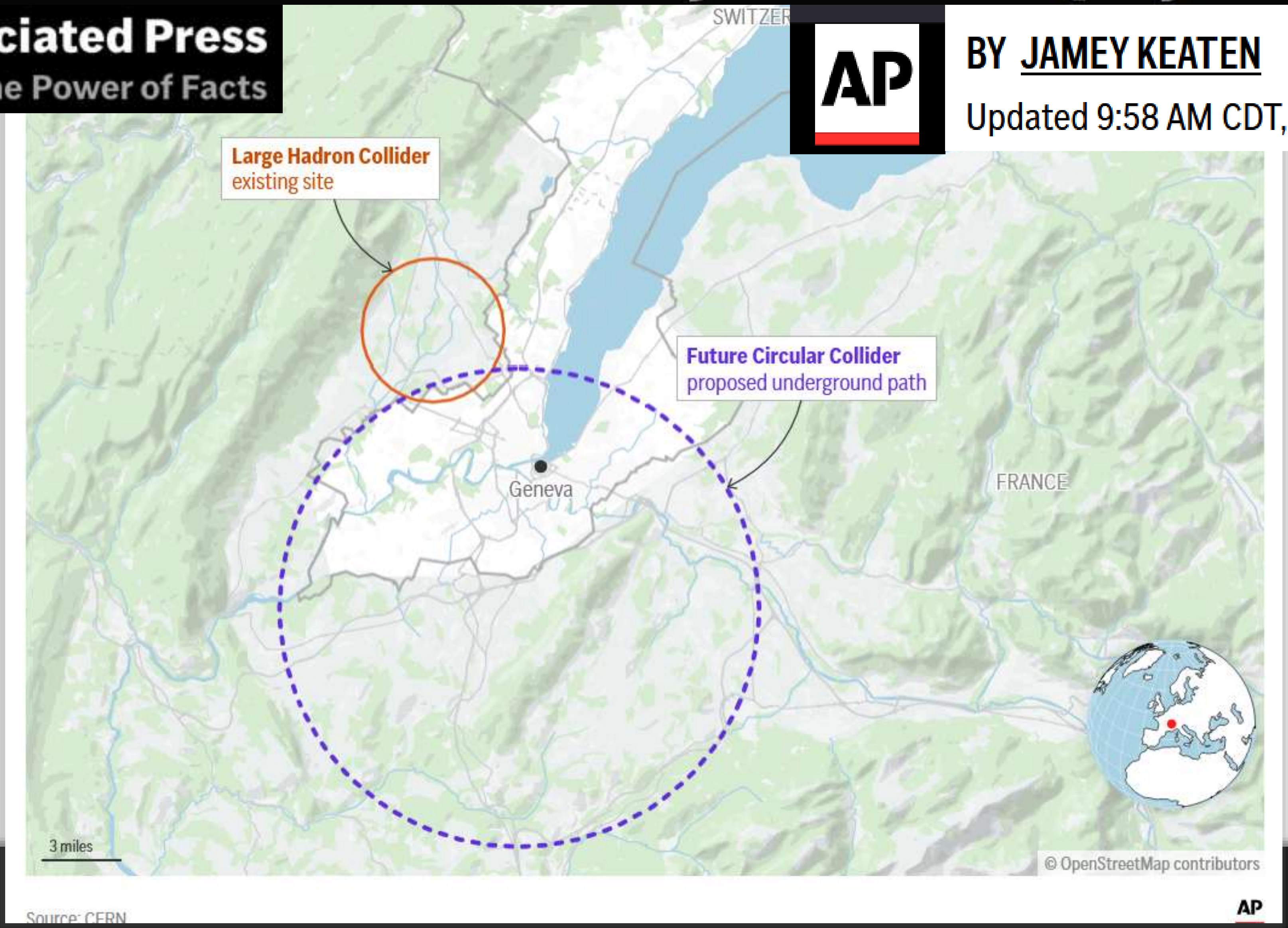
Scientists release plans for an even bigger atom smasher to address the mysteries of physics

The Associated Press
Advancing the Power of Facts

AP

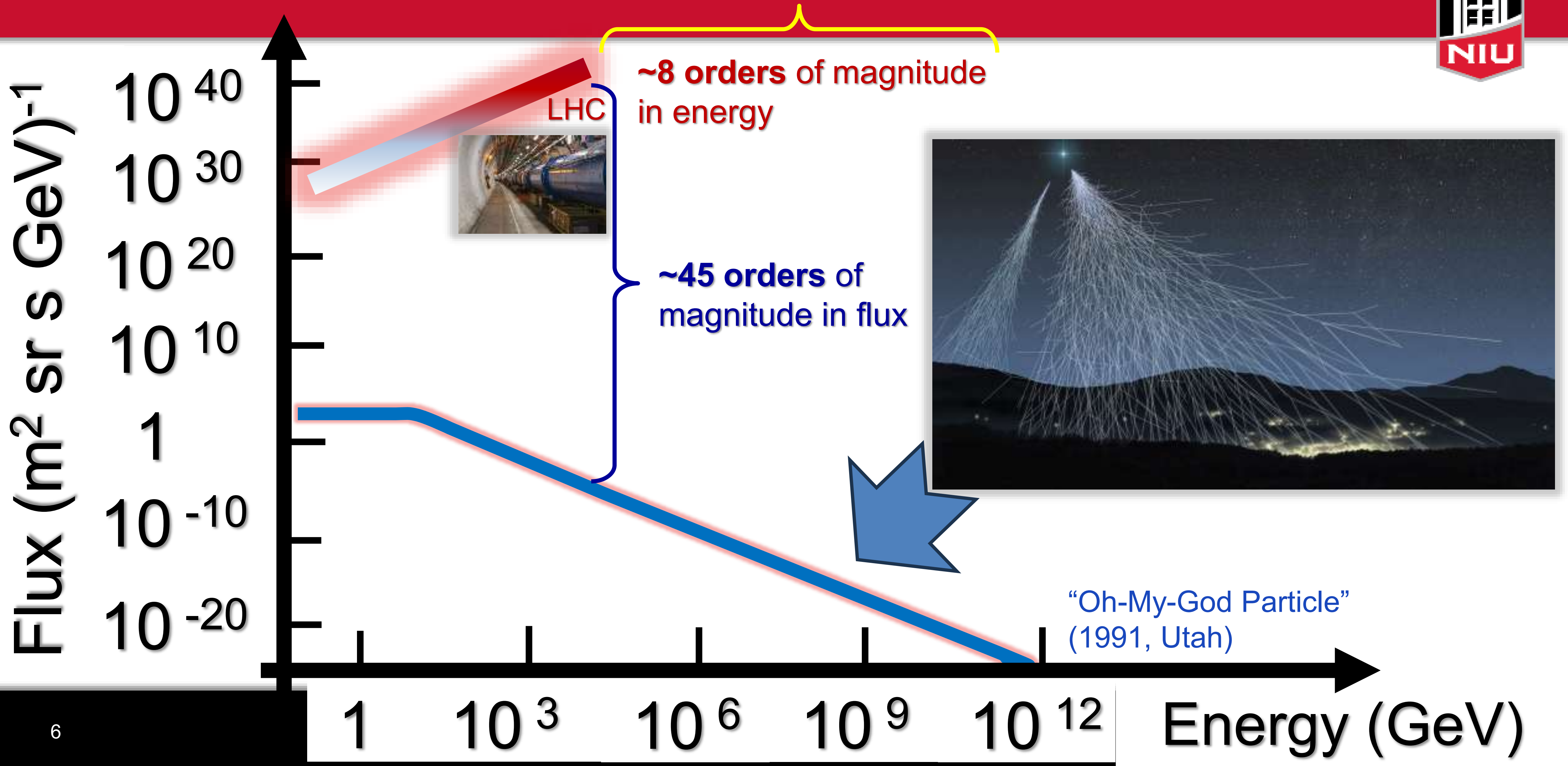
BY JAMEY KEATEN

Updated 9:58 AM CDT, April 1, 2025




QUO VADIS?

ENERGY: ACCELERATORS vs COSMOS



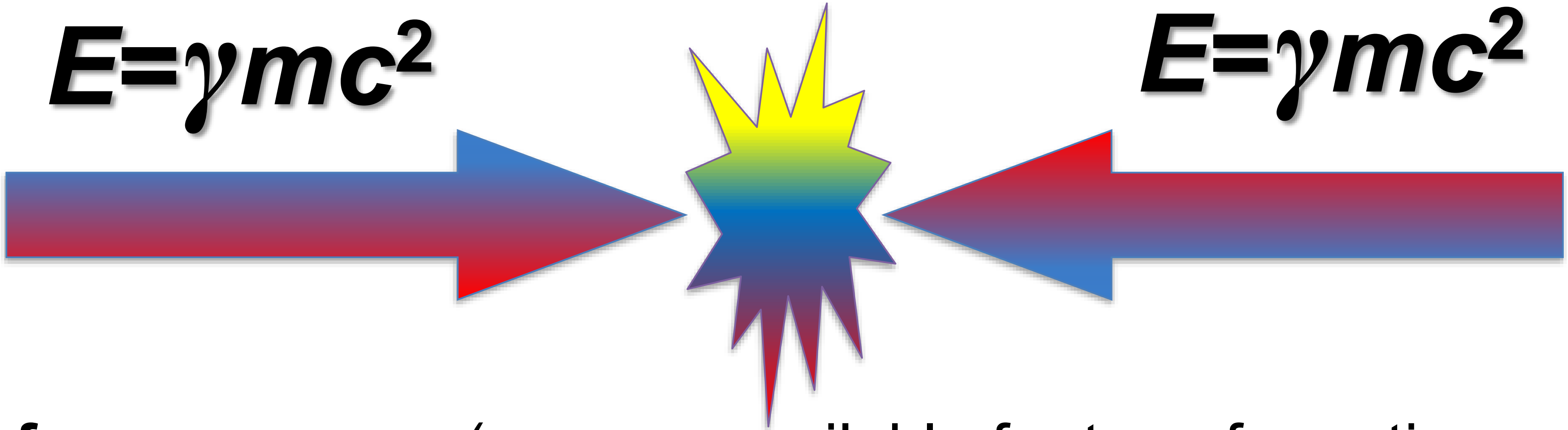
ENERGY: Three Great Ideas

#1 Colliders

#2 [Muon Colliders – to be explored]

#3 [Plasma Colliders – to be explored]

Trick #1: Colliders



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

$$E_{CM}=2E$$

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

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

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

31 colliders built

First Colliders – 60! (1964 - 65)

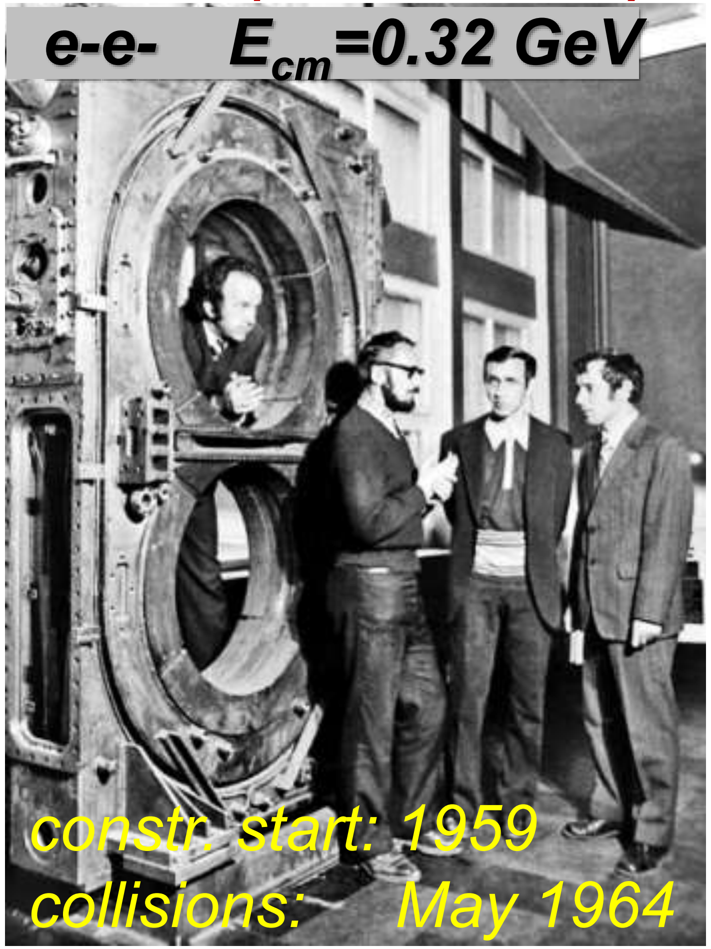
AdA (Frascati/Orsay)

e+e- E_{cm}=0.5 GeV

constr. start: 1960

collisions: mid-1964

VEP-1 (Novosibirsk)

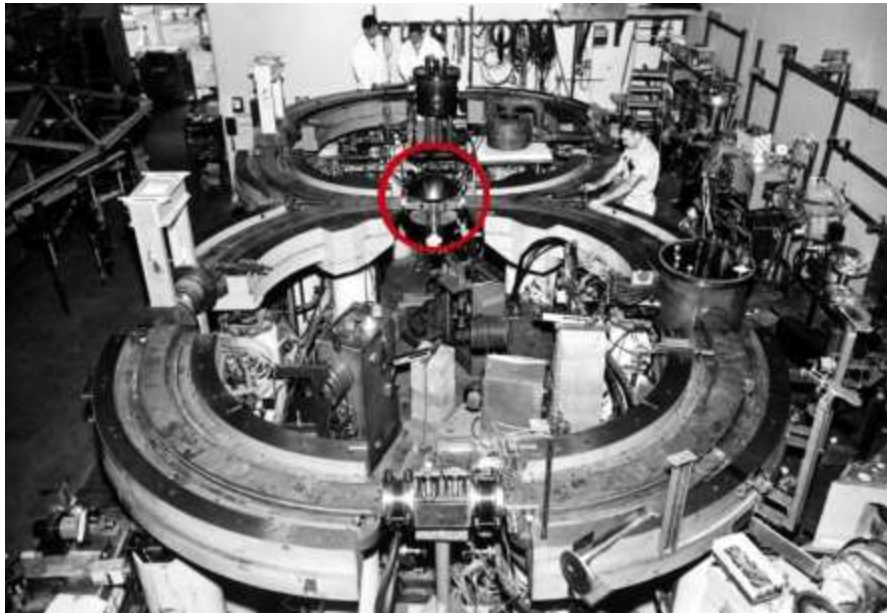


CBX (Stanford/Princeton)

e-e- E_{cm}=1.0 GeV

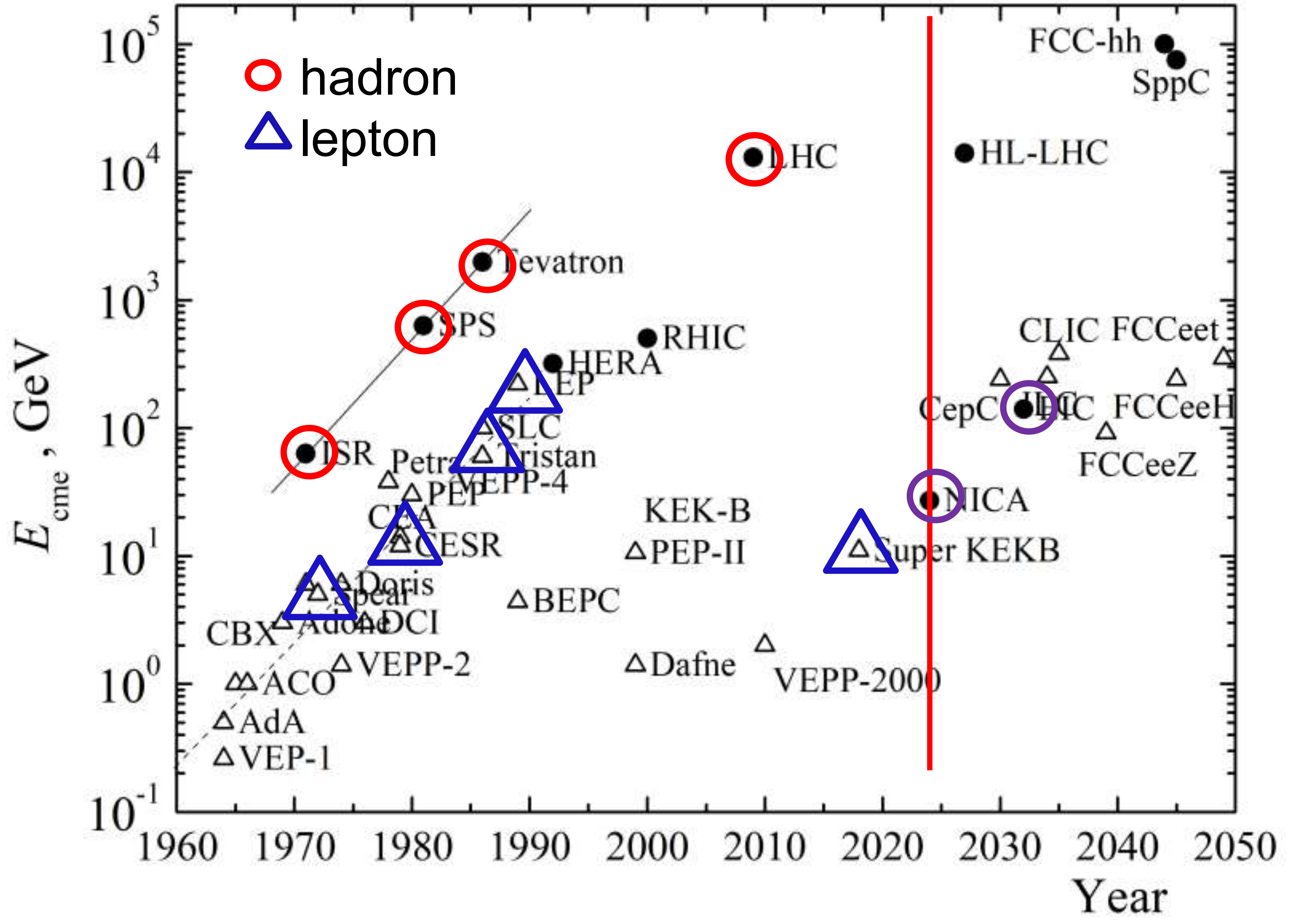
constr. start: 1959

collisions: March 1965



Energy of Colliders (aka *Livingston Plot*)

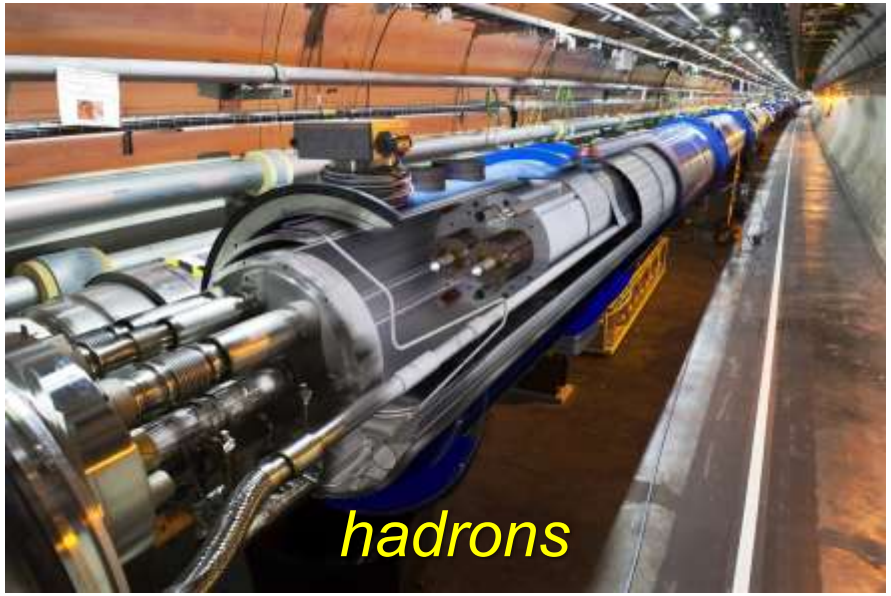
5 orders of magnitude in E_{CM} in 6 decades (0.2 GeV → 14 TeV)



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

Colliders Now (7 Ops, 2 Constr.)

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



Super-KEKB (KEK, Japan):

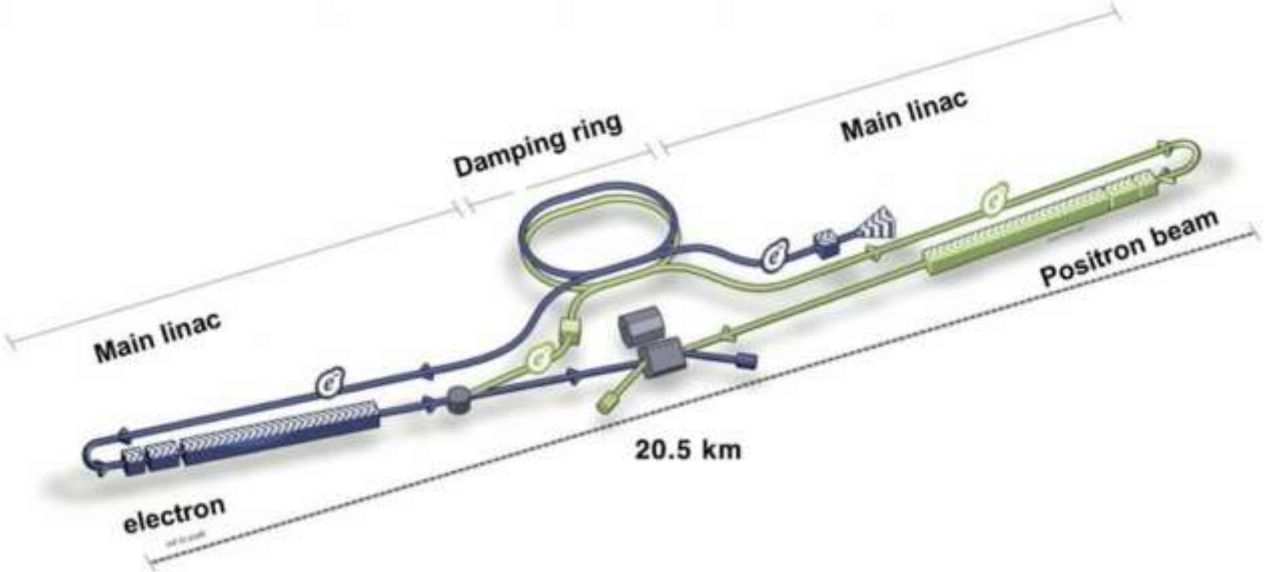
7 GeV *e-* + 4 GeV *e+*
3.0 km tunnel, 1 detector
Normal-conducting magnets, SC RF
Record Lumi 5.1e34 $cm^{-2}s^{-1}$ (→60)

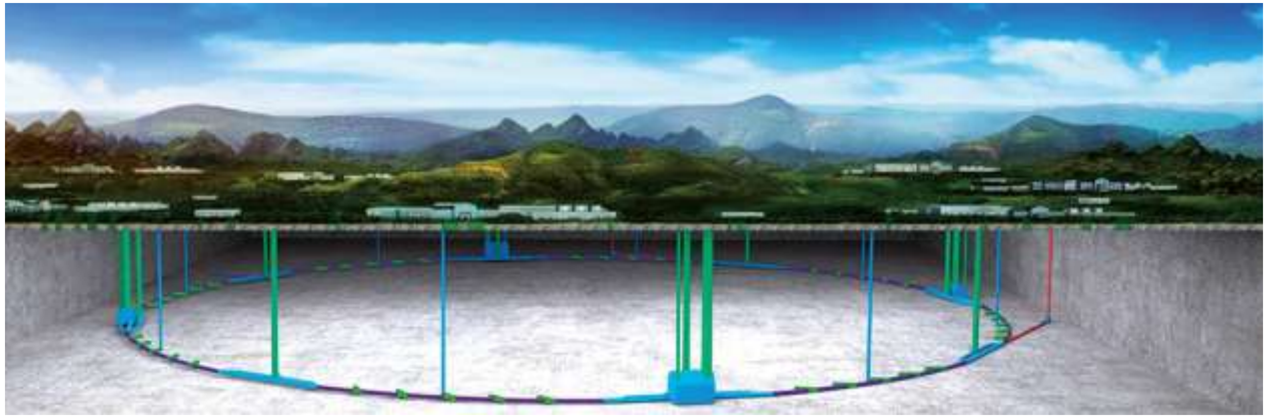
LHC (CERN):

6.8 TeV protons + 6.8 TeV protons
26.7 km tunnel, 4 detectors
Superconducting magnets, SC RF
Record Lumi 2.6e34 $cm^{-2}s^{-1}$ (HL-LHC→5)

**cost of construction: 3.6 BCHF (CERN), ~10B$ (US*)*

Future Colliders in Asia - Aspirations





ILC (Japan) e+e-

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

31.5 MV/m 1.3 GHz SRF

TDR (2013): cost ~8.1B$* +10kFTEs

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

100 km, E_{cm} =91…360 GeV

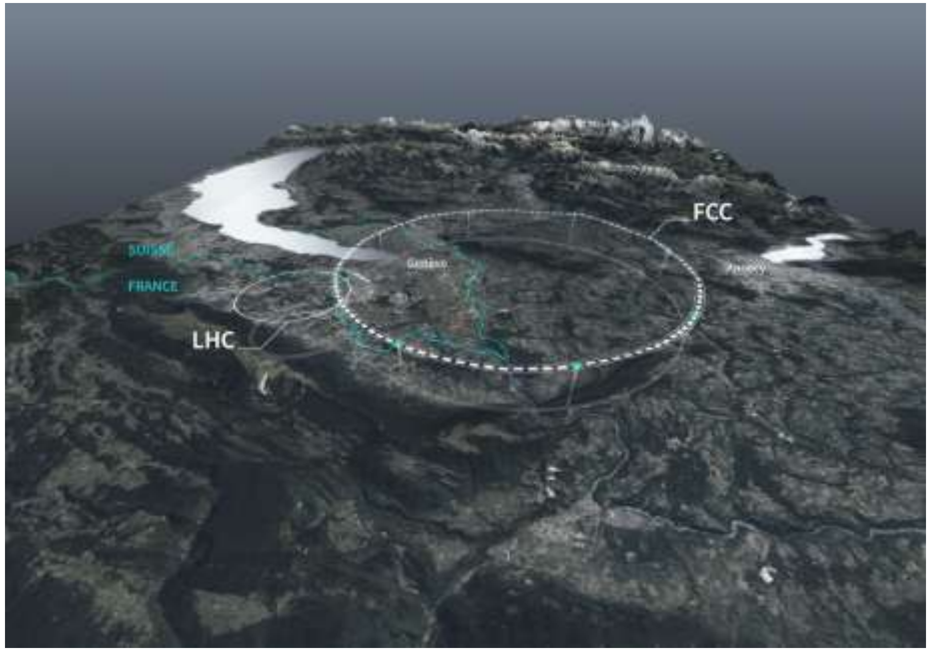
NC magnets and 60MW SRF

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

*2024: not incl. labor, contingency and escalation

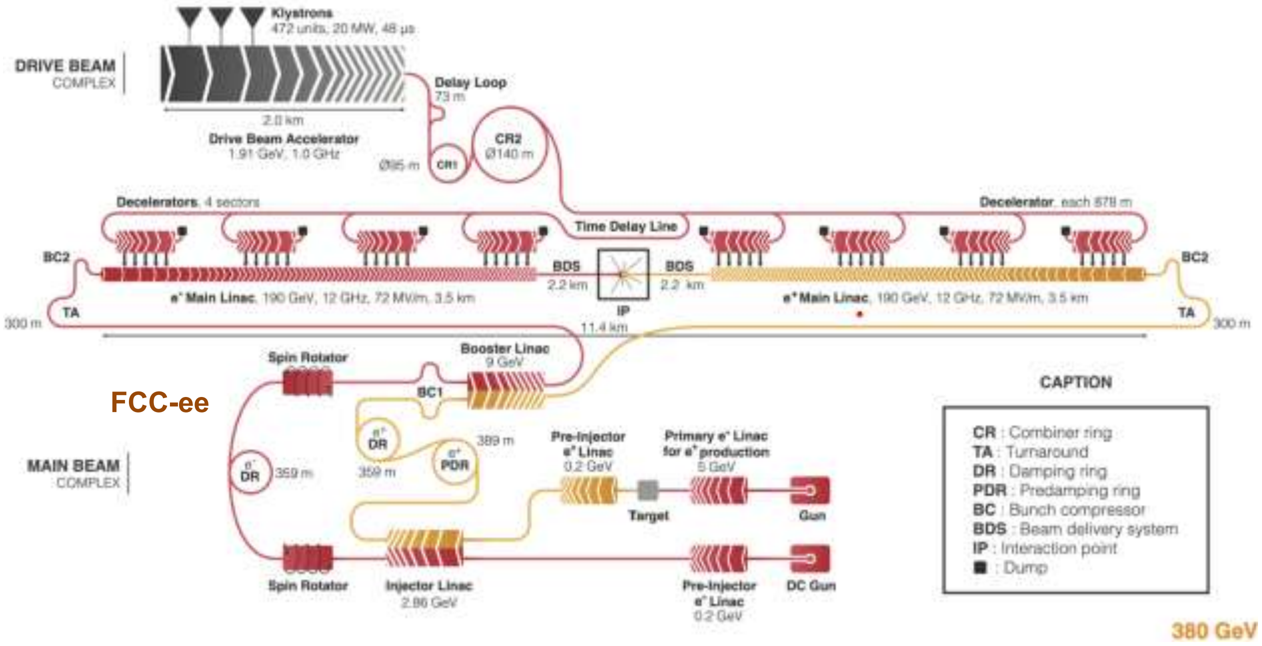
*no labor, escalation, R&D, spares / w. contingency

Future Colliders in Europe - Aspirations



FCCee [→hh] (CERN) e+e-

91 km, E_{cm} =91…365 GeV
NC magnets and 100MW SRF
*FSR (2025): cost ~14BCHF **



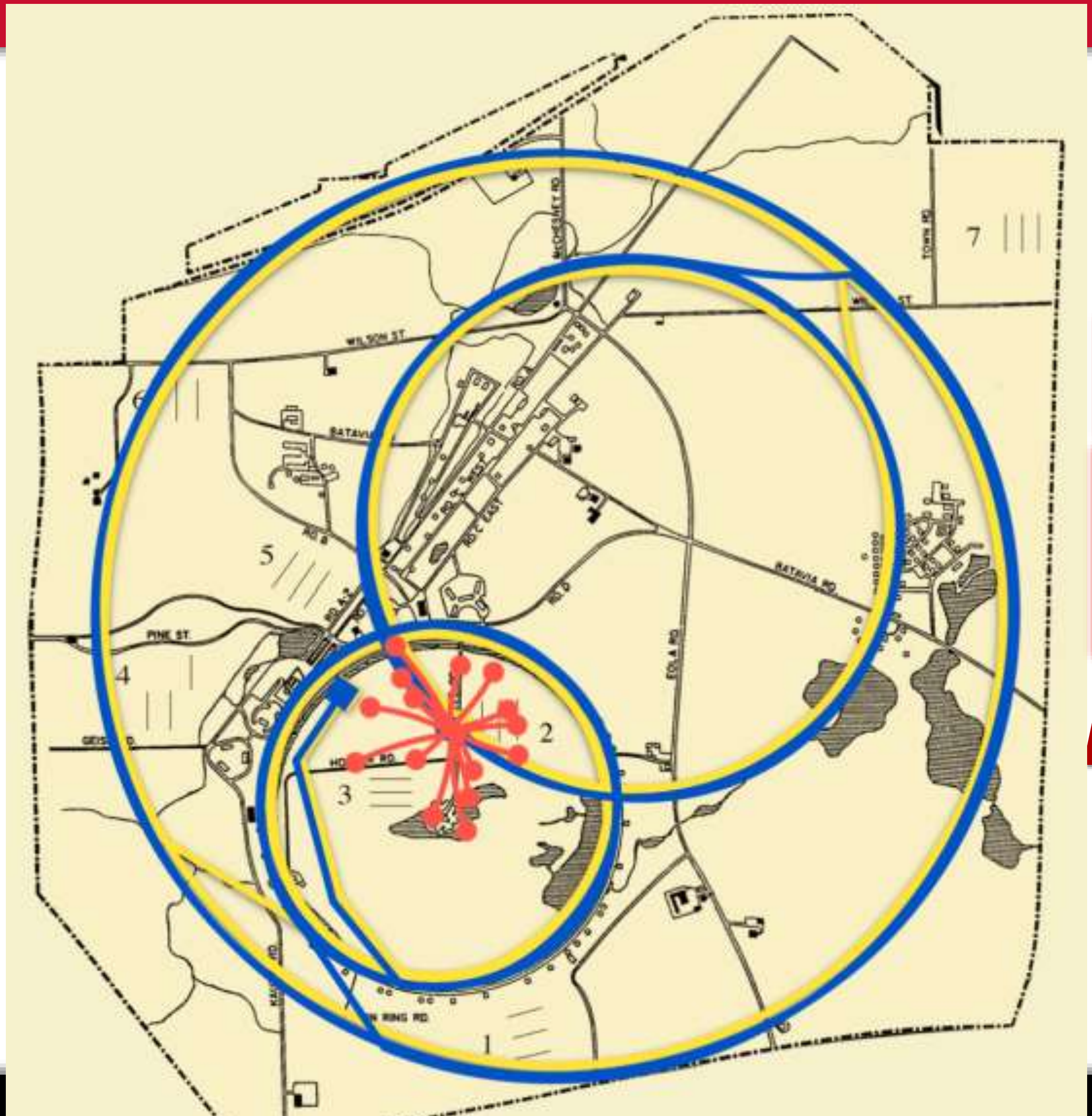
CLIC (CERN) e+e-

11 km, E_{cm} =380 GeV [3 TeV]
2-beam NC RF 70-100 MV/m
*CDR (2018): cost 7.3 BCHF **

**no 15kFTE of labor, escalation, or contingency*

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

Future Muon Collider 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; 17±4 BCHF IMCC'25)*

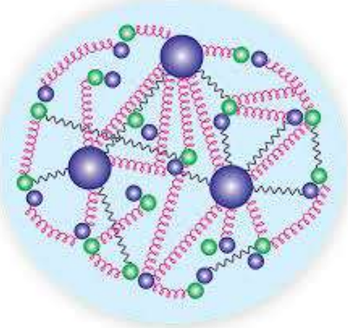
20 yrs of R&D

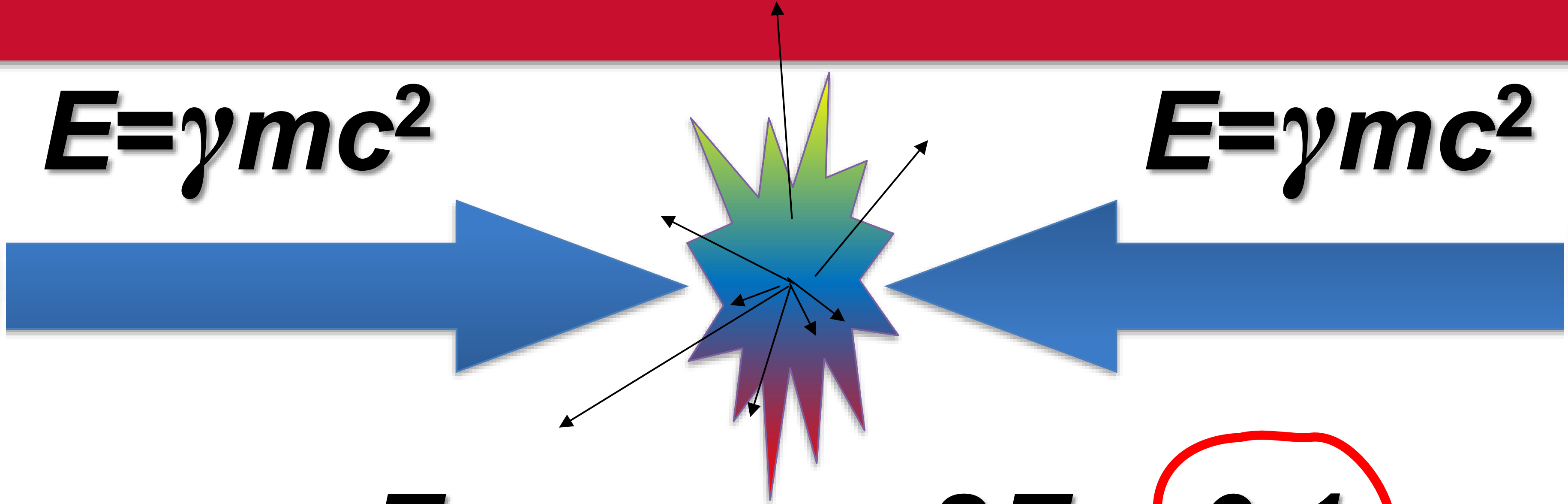
**no labor, escalation, or contingency*

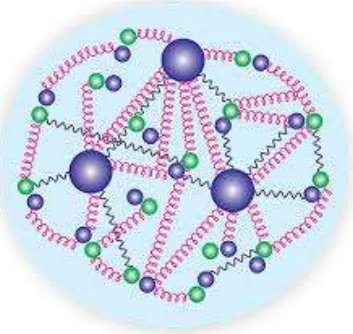
Our Trick #2: Leptons vs Hadrons

Protons

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







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

Leptons

$e+$	$e-$
$\mu+$	$\mu-$
$\tau+$	$\tau-$

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

Muon Collider Challenges and R&D Topi...

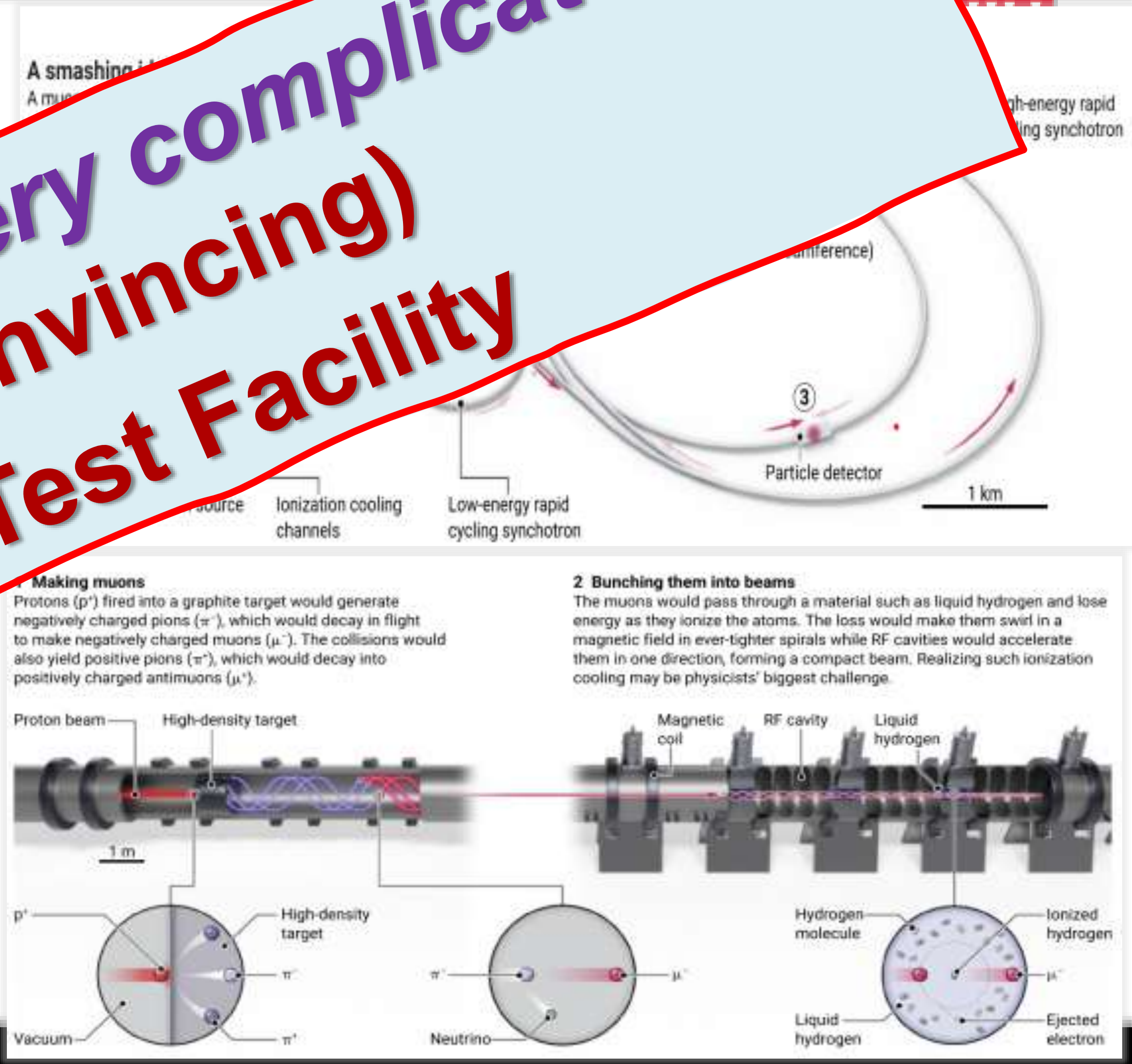
R&D re: Energy Reach/Cost

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

R&D re: ...

- ... ...nches ... deliver at 5-10 ...
- Ta... ...SC solenoid with ~2 m ape... ...RF in 2-14 T SC solenoids of the ioni... ...nel
- Challe... ...due to muon decays; neutrino flux dilution

“ …no showstopper, but very complicated…”
Requires a (Convincing) Demonstrator Test Facility



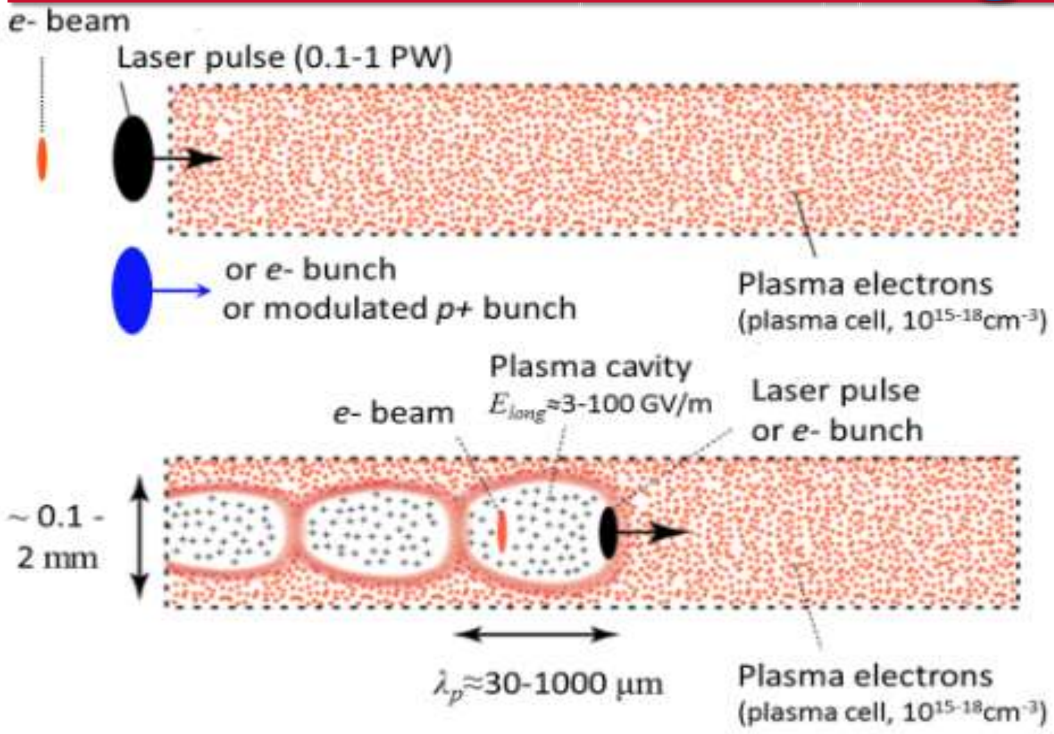
10+ TeV pCM Colliders - Summary

	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

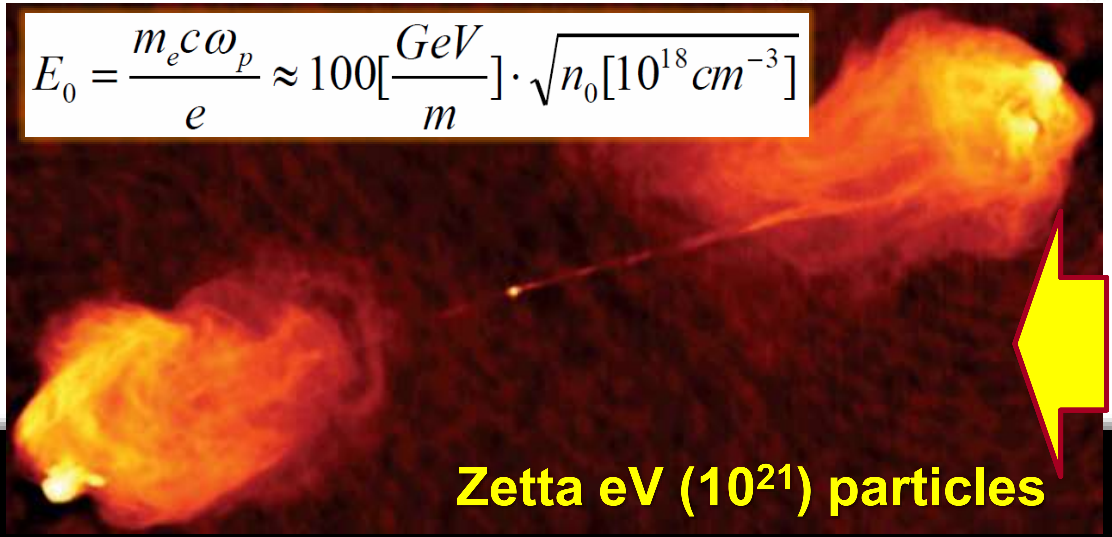
From the *Snowmass'21* Implementation Task Force report - T.Roser *et al* 2023 *JINST* **18** P05018

Snowmass 2021

"Trick #3": Ultra-High Gradients in Plasma



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



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

Three ways to excite plasma (drivers)

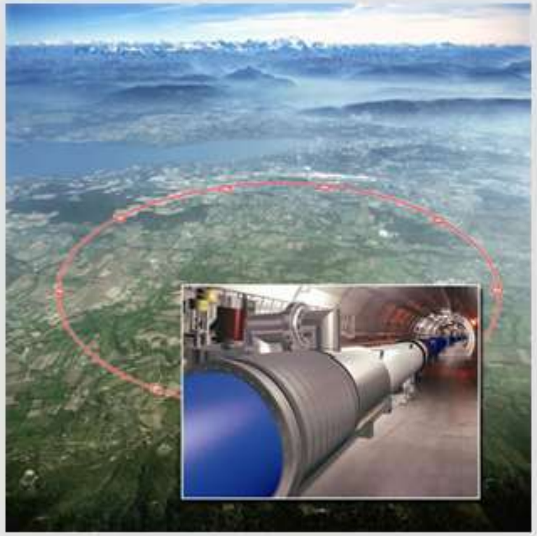
- laser *dE* ~ 10 GeV (~$3\cdot10^{17}$ cm^{-3} 0.1-0.3 m)
- *e-* bunch *dE* ~ 9 GeV (~10^{17} cm^{-3} 1.3 m)
- *p+* bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10 m)

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

On Ultimate Colliders



1920s **1970s** **2020s** **2070s ?**

V.Shiltsev, *“Ultimate Colliders”* (Oxford Encyclopedia, 2023); https://arxiv.org/abs/2309.15960

Factors and Limits

- Main factors to consider feasibility of future colliders used to be
  - Feasibility of ***E***nergy
  - Feasibility of ***L***uminosity
  - Feasibility of ***C***ost
- The *European Strategy* (2019, 2025) and *Snowmass'21* (2020-2023) discussions revealed additional limits:
  - ***Time*** to construct and commission
  - ***Societal limits***: # of experts, size of facility, radiation, etc
  - ***Environmental impacts***: power consumption, carbon footprints, scarcity of resources (*He*, *Nb*, *W*, etc), excavated materials, etc

Here we will only briefly touch some important points

Limits on Energy

- for e-/e+: $E_{cm} \leq 500\ GeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- for muons: $E_{cm} \leq 600\ TeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- for protons: $E_{cm} \leq 10\ PeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$

- Synchrotron radiation defines linear vs circular if $U_{SR} < E$

$$U_{SR} = C_\gamma \frac{E^4}{\rho} = 88.46 \frac{\mathrm{r}_0}{\mathrm{r}_\mathrm{e}} \left(\frac{\mathrm{m}_\mathrm{e}}{\mathrm{m}_0}\right)^3 \frac{E^4[GeV]}{\rho[m]}$$

- Production and survival: unstable particles such as muons

$$\frac{dN}{dt} = -\frac{N}{\gamma\tau_0};\ \gamma = \gamma_i + z\frac{d\gamma}{dz}$$

where τ_0 is the lifetime, $\tau_0 \sim 2.2\mu s$ for muons…need fast acceleration

for muons $G \gg 3\ \mathrm{MeV\ m^{-1}}$

for τ-leptons $G \gg 0.3\ \mathrm{TeV\ m^{-1}}$

- Staging efficiency (losses) per stage for M stages $\geq \eta = 1 - 1/M$

- Reach vs technology within limited space /area:

Circumference 100 km , B<16 T , *E*<50 TeV
Circumference 40,000 km, B=1 T, *E*<1.3 PeV
Length 50 km , G<0.1 GV/m, *E*<5 TeV
Length 10 km, G<1 TV/m, *E*<10 PeV

Limits on *Luminosity*

- General Equation

$$L = f_0 n_b N^2 / 4\pi\sigma^2$$

  - *sheer beam power*

$$P_b = f_0 n_b N \gamma m c^2$$

$$L = P_b^2 / (4\pi\gamma n_b \varepsilon \beta^* m^2 c^4) \propto P_b^2 / E$$

  - *e/p SR rad. power*

$$L \propto (\xi/\beta^*)(P_{SR}/2\pi R)(R^2/\gamma^3))$$

  - *μ→ν radiation dose*

$$D \propto (dN/dt)E^3/\Phi$$

flux dilution factor

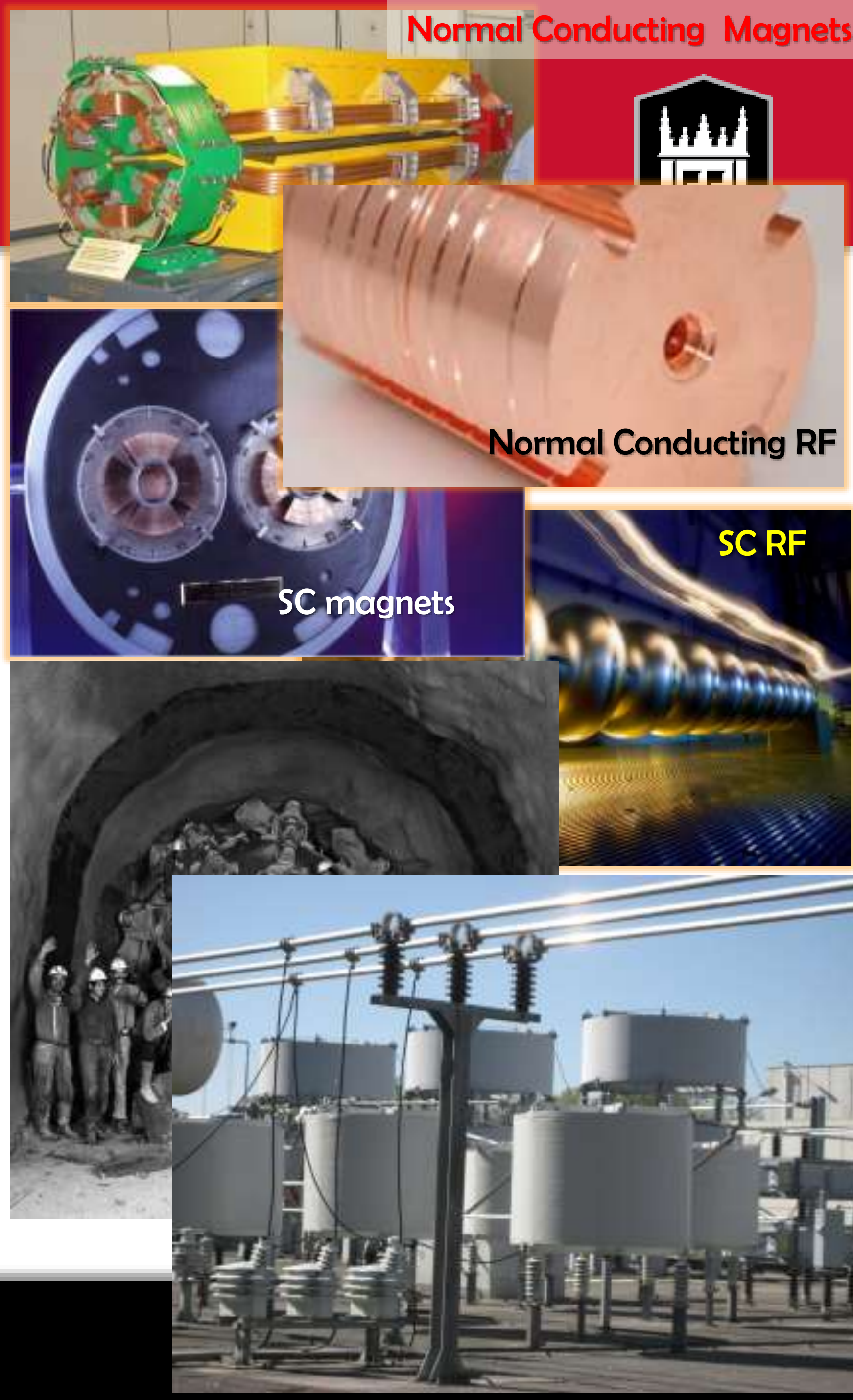
$$L \propto B \frac{D\Phi}{E^2} \frac{N}{4\pi\epsilon_n\beta^*}$$

  - *LC power, BS, jitter*

$$L \propto (P/E)(N_\gamma/\sigma_y)$$

Cost is set by the Scale (*energy, length, power*) and Technology

- *Accelerator technology* (magnets NC and SC, RF and SCRF, etc) **~50±10 %**
- *Civil construction technology* **~35±15 %**
- *Power production, delivery and distribution technology* **~15±10 %**



Rough Cost Estimates of Large Accelerators

Higher energy *E* → usually bigger size *L*, more power *P* → higher costs:

- Where is the societal limit on the cost of colliders?
- Cost ranges estimates – detailed vs parametric models

The αβγ cost model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

$\alpha \approx$ 2B$/sqrt(L/10 km) for tunnel/civil

$\beta \approx$ 10B$/sqrt(E/TeV) for SC/NC RF

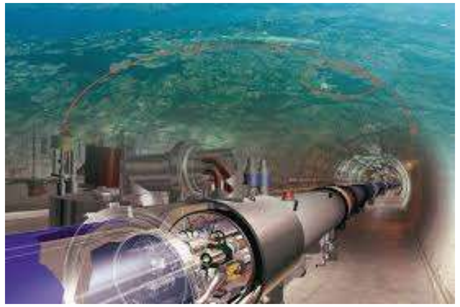
$\beta \approx$ 2B$ /sqrt(E/TeV) for SC magnets

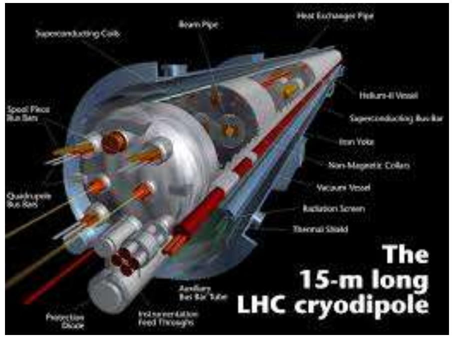
$\beta \approx$ 1B$ /sqrt(E/TeV) for NC magnets

$\gamma \approx$ 2B$/sqrt(P/100 MW) for site power

V.Shiltsev, "A phenomenological cost model for high energy particle accelerators", *JINST* 9 T07002 (2014)

An Example – Large Hadron Collider:





- ***αβγ – Model:***
  - 40 km of tunnels
  - 14 TeV c.o.m SC magnets
  - ~150 MW of site power

$$2\sqrt{40/10} = 4$$

$$2\sqrt{14} = 7.5$$

$$2\sqrt{150/100} = 2.5$$

TOTAL PROJECT COST (est.) : **14B$ ± 4.5B$**

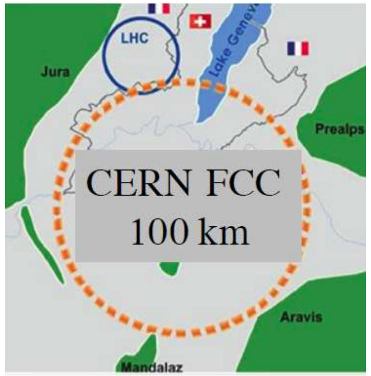
- **ITF T.Roser talk @ PLUB-II Workshop (USD 2021):**
  - existing injector complex **4.6 B$**
  - new accelerator systems **4.06 B$**
  - new infrastructure and civil **2.75 B$**
  - explicit labor **~1.4 B$**

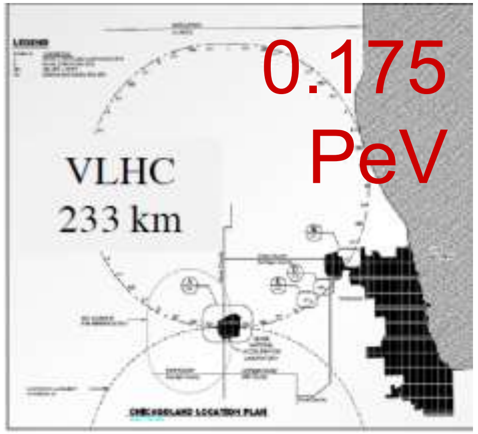
Total: **12.8B$**

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

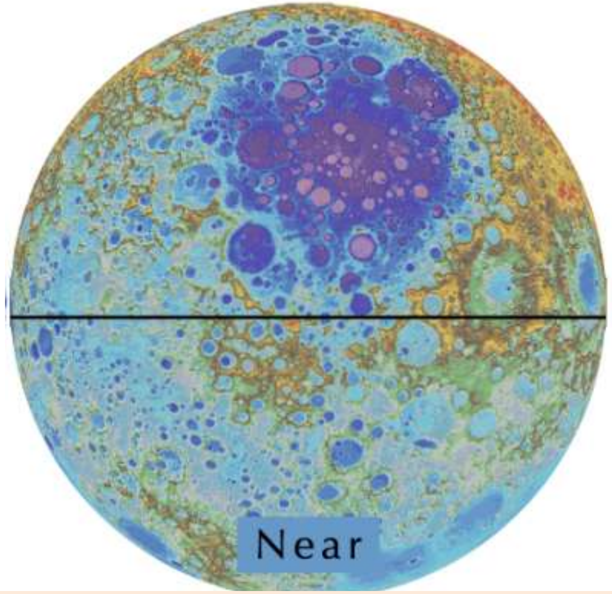
0.1 PeV





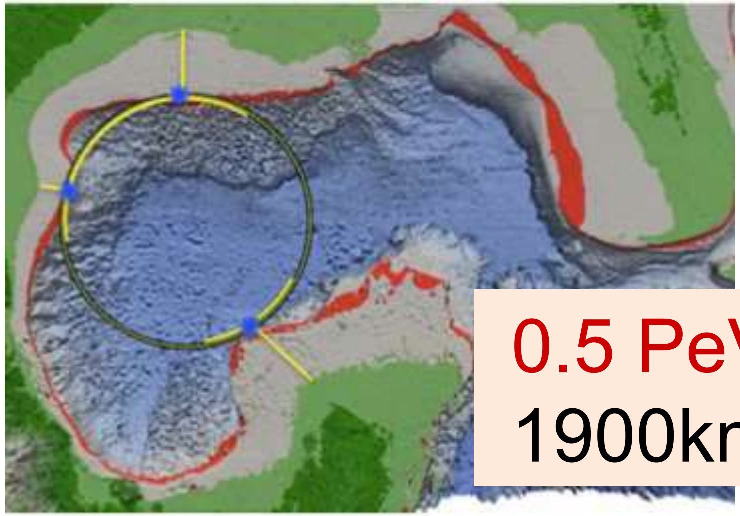
0.175 PeV

Luna-tron

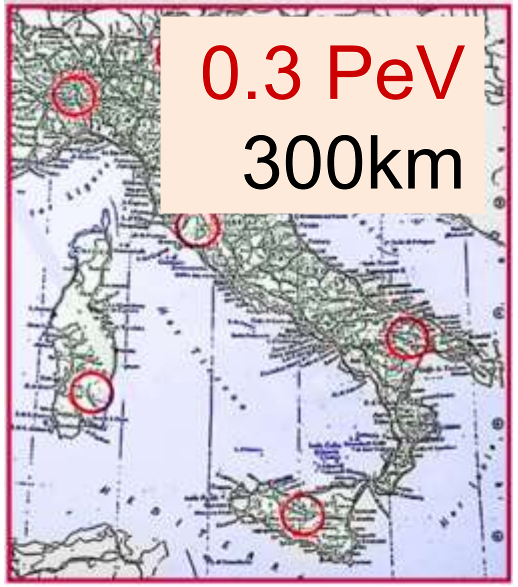


14 PeV,11000km

Collider-in-the-Sea



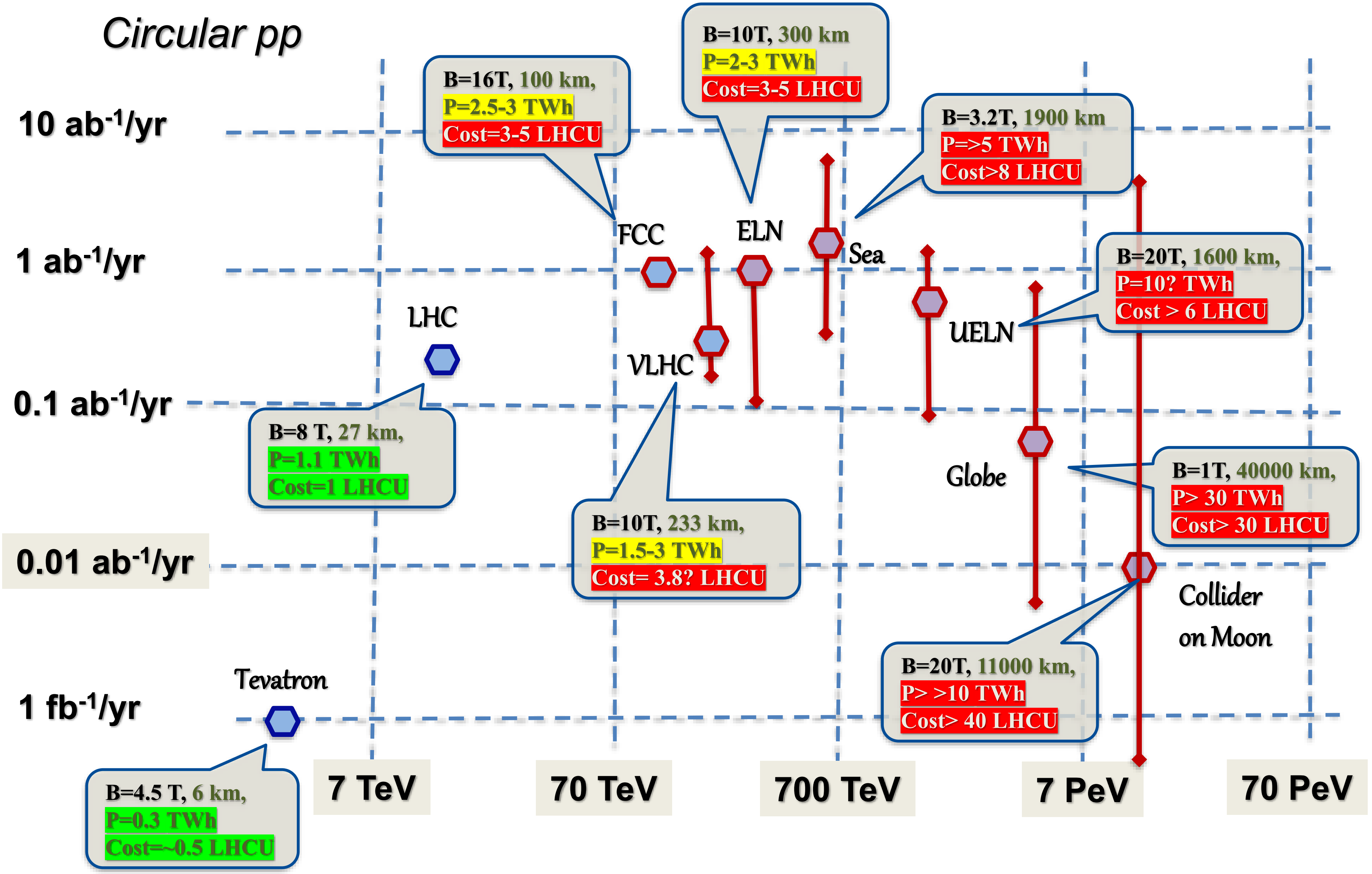
0.5 PeV
1900km



0.3 PeV
300km

Eloisatron

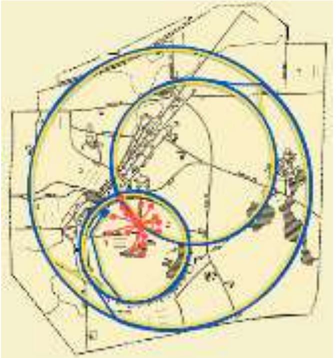
pp Colliders: *Lumi, Power, Cost* vs *Energy*

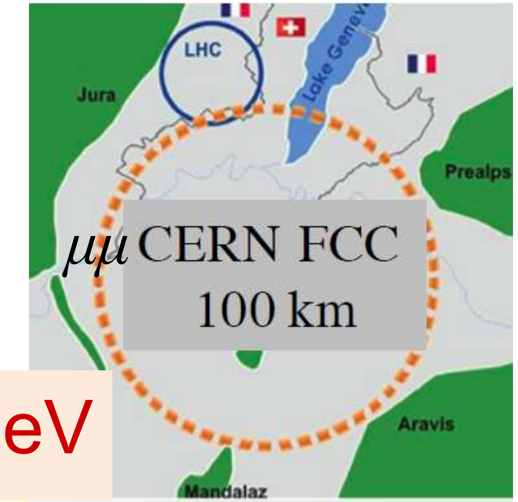


Circular $\mu+\mu-$ Colliders

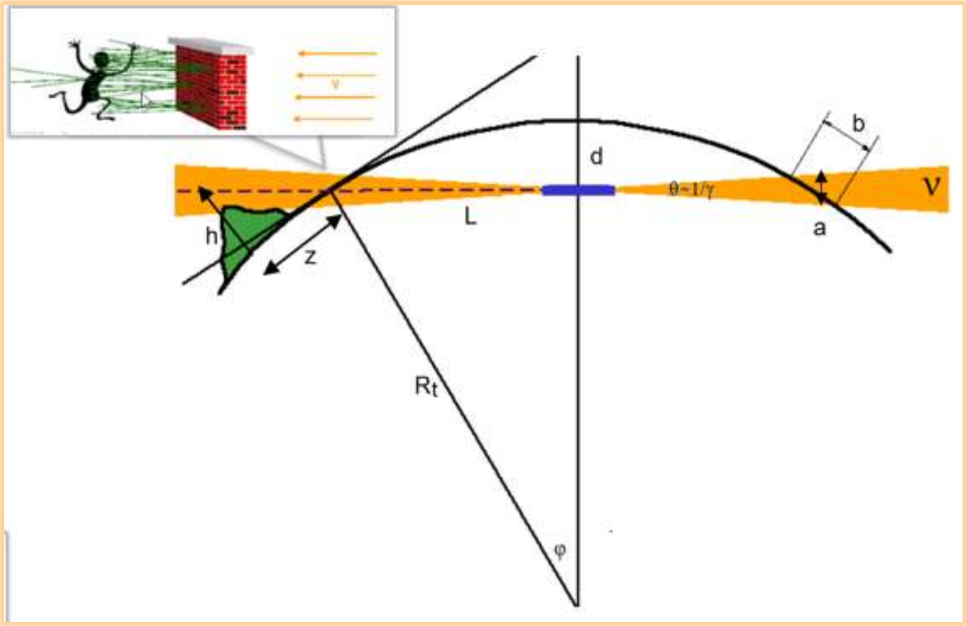
- Known technology (magnets, RF)
- Major limitations:
  - Size (magnetic field *B*), power, cost
  - Ionization cooling of muons
  - SR energy loss @ 50-100 TeV
  - Neutrino flux → *Lumi* ~Φ/E^2

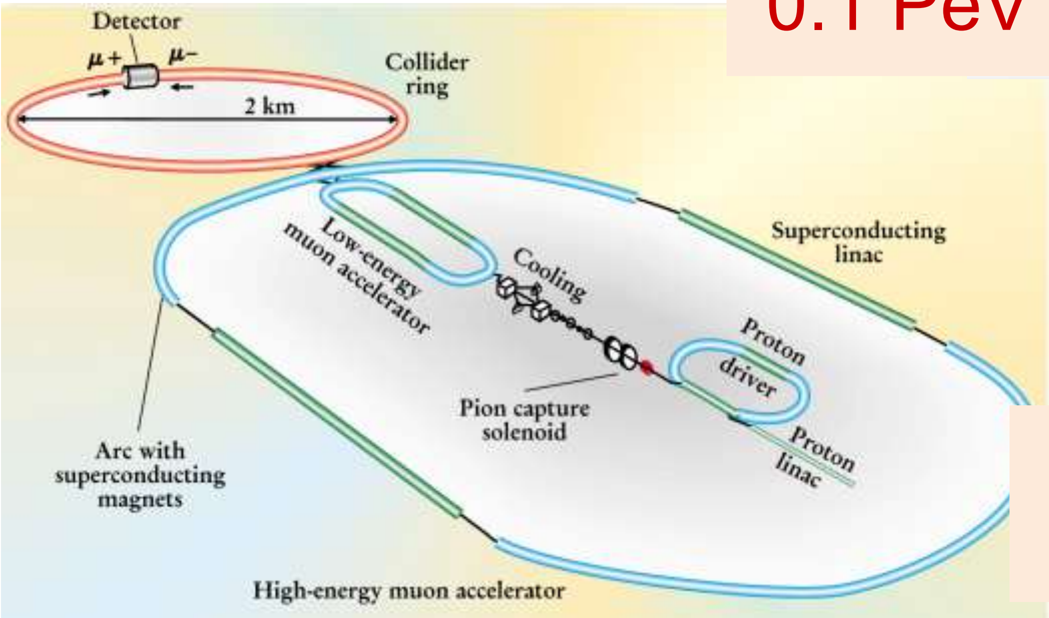
10 TeV
~10 km





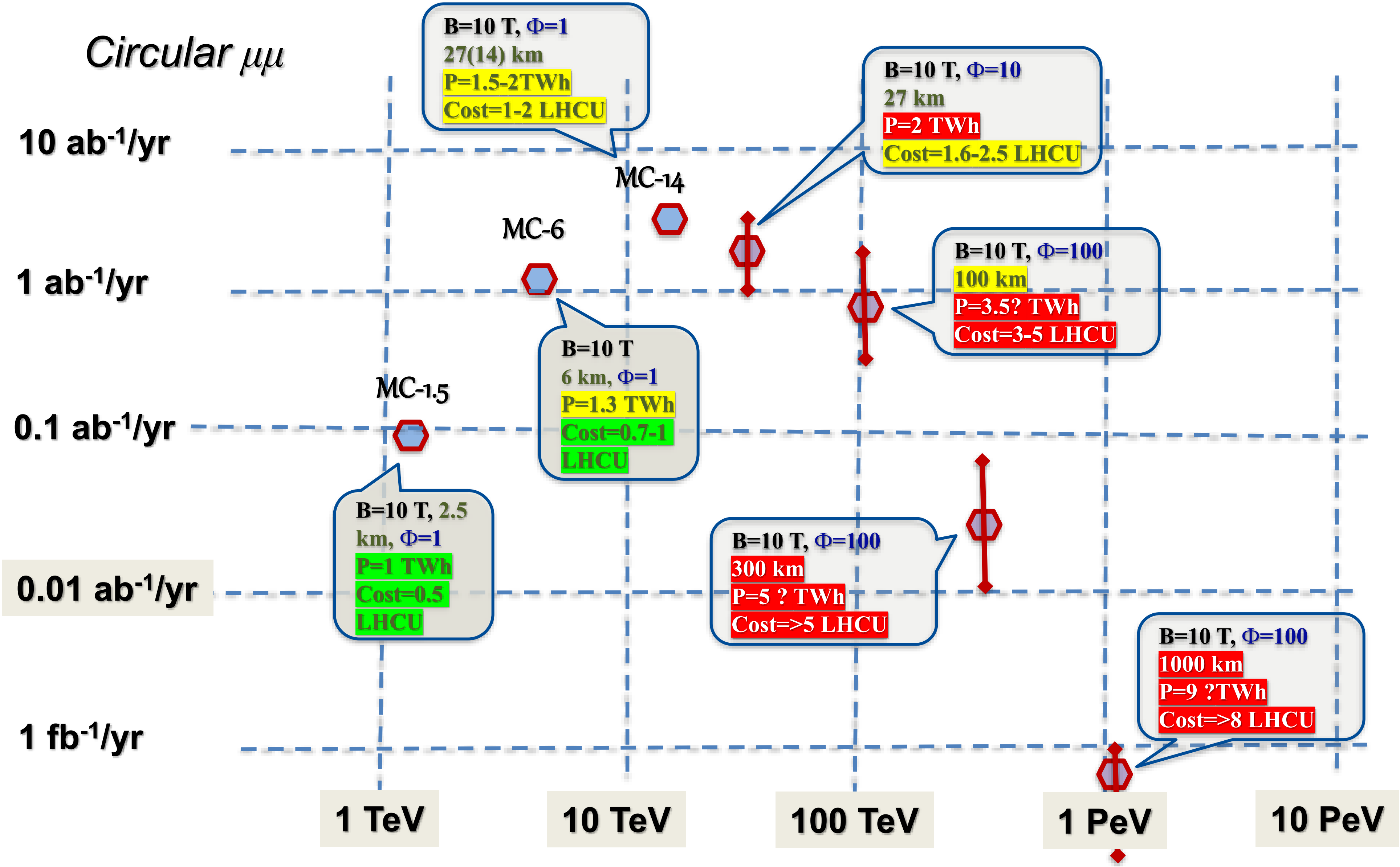
0.1 PeV





1 PeV
1000 km

MuColl: *Lumi* and *Cost* vs *Energy*

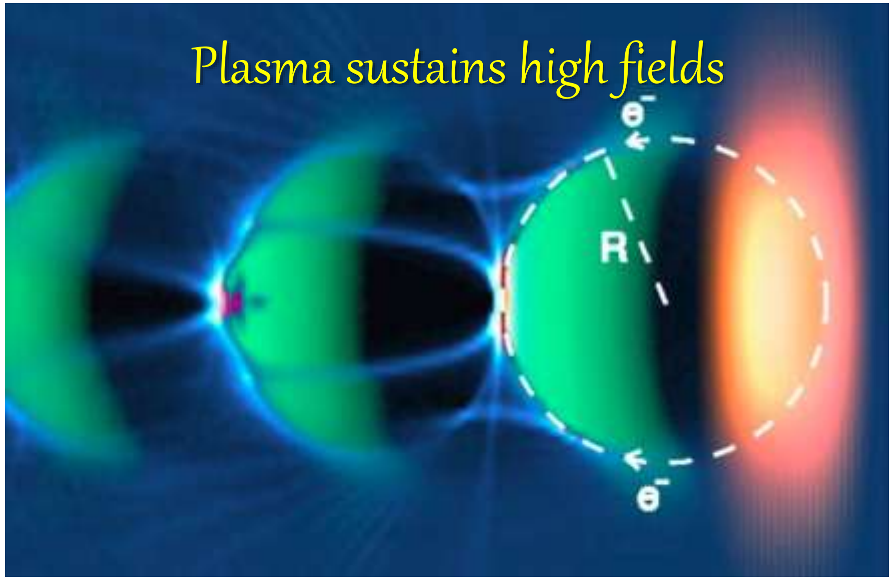


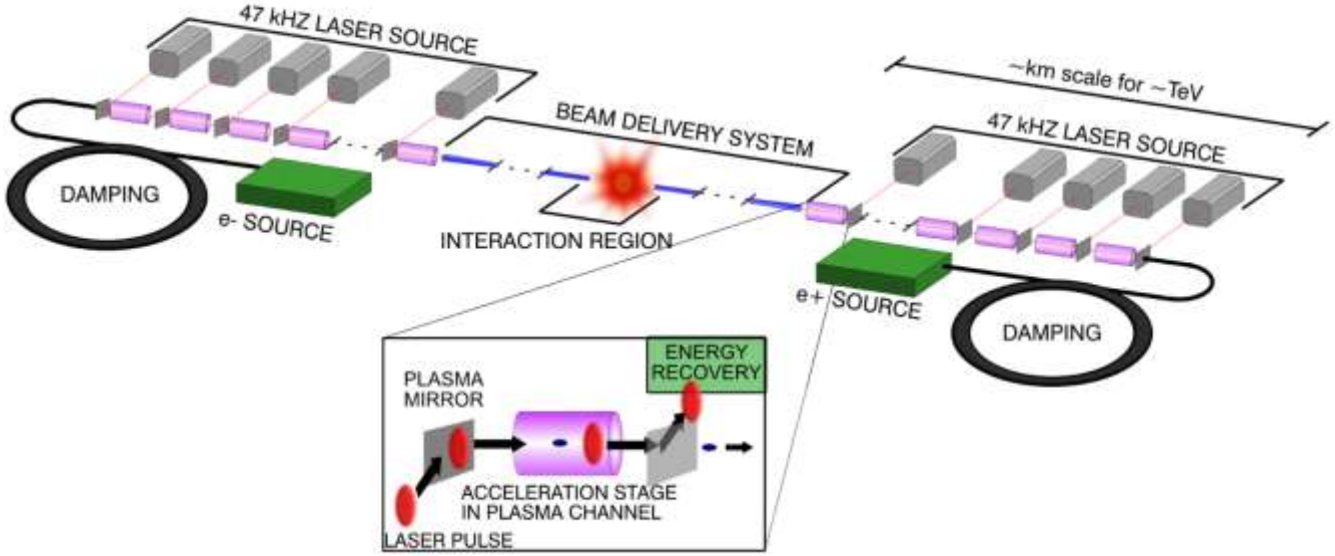
Linear *e+e-* Colliders

- Either RF acceleration (50-200 MeV/m) or wake-field acceleration in plasma (2-5 GeV/m)

15 TeV *e+e-*
100+ km
10-15 km

- 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

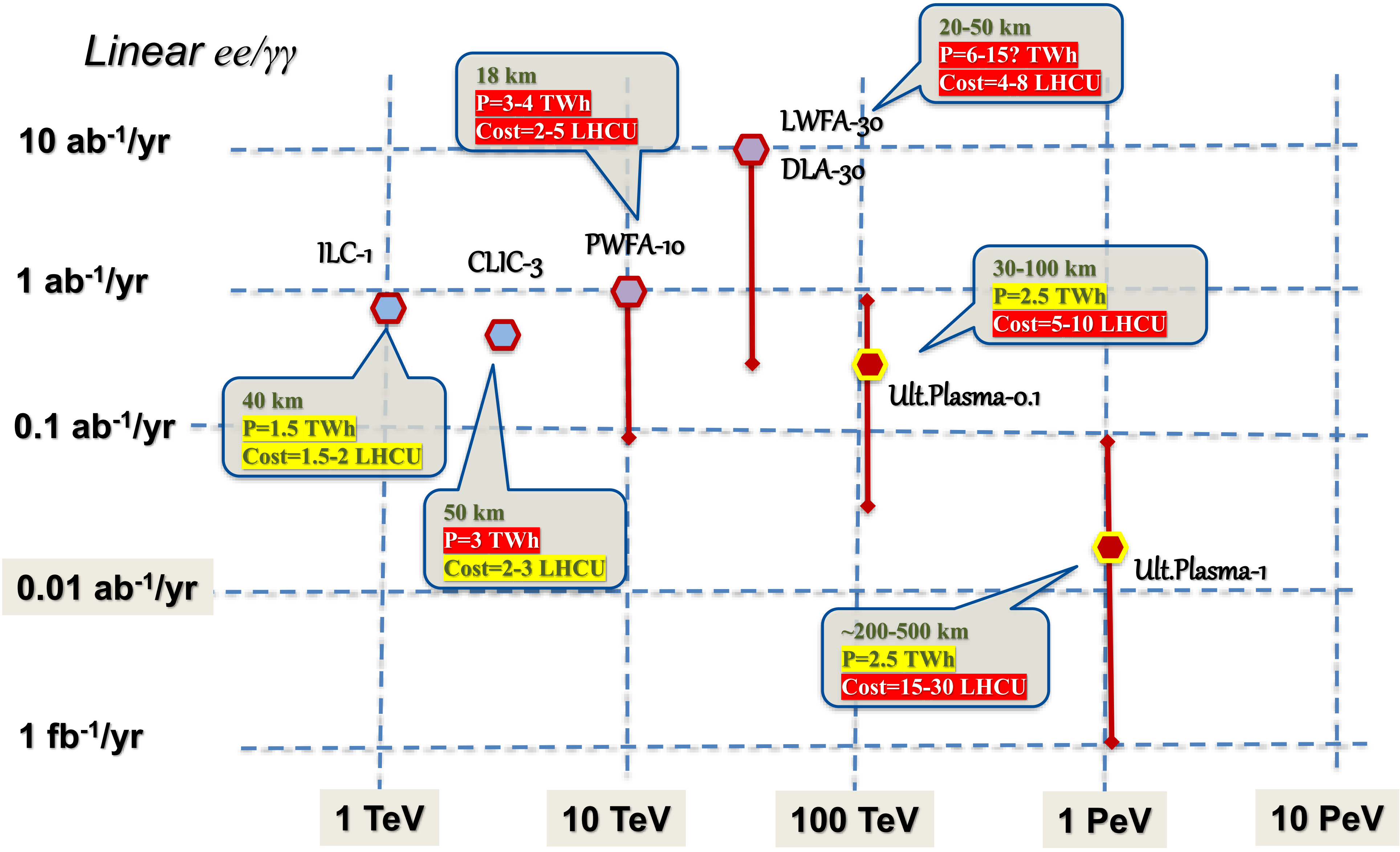




$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Takes about 1 GW of electric power even for 15 TeV

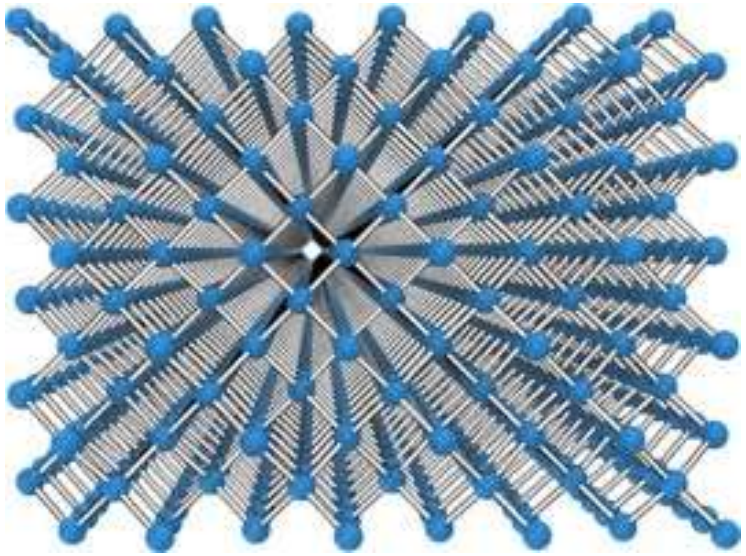
Linear RF and Plasma: *Lumi* and *Cost* vs *Energy*



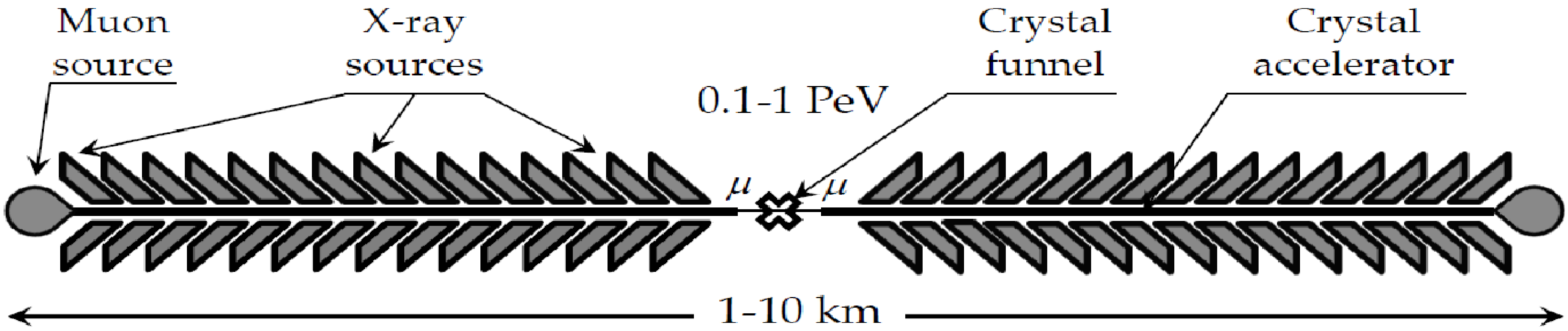
Exotic Colliders

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

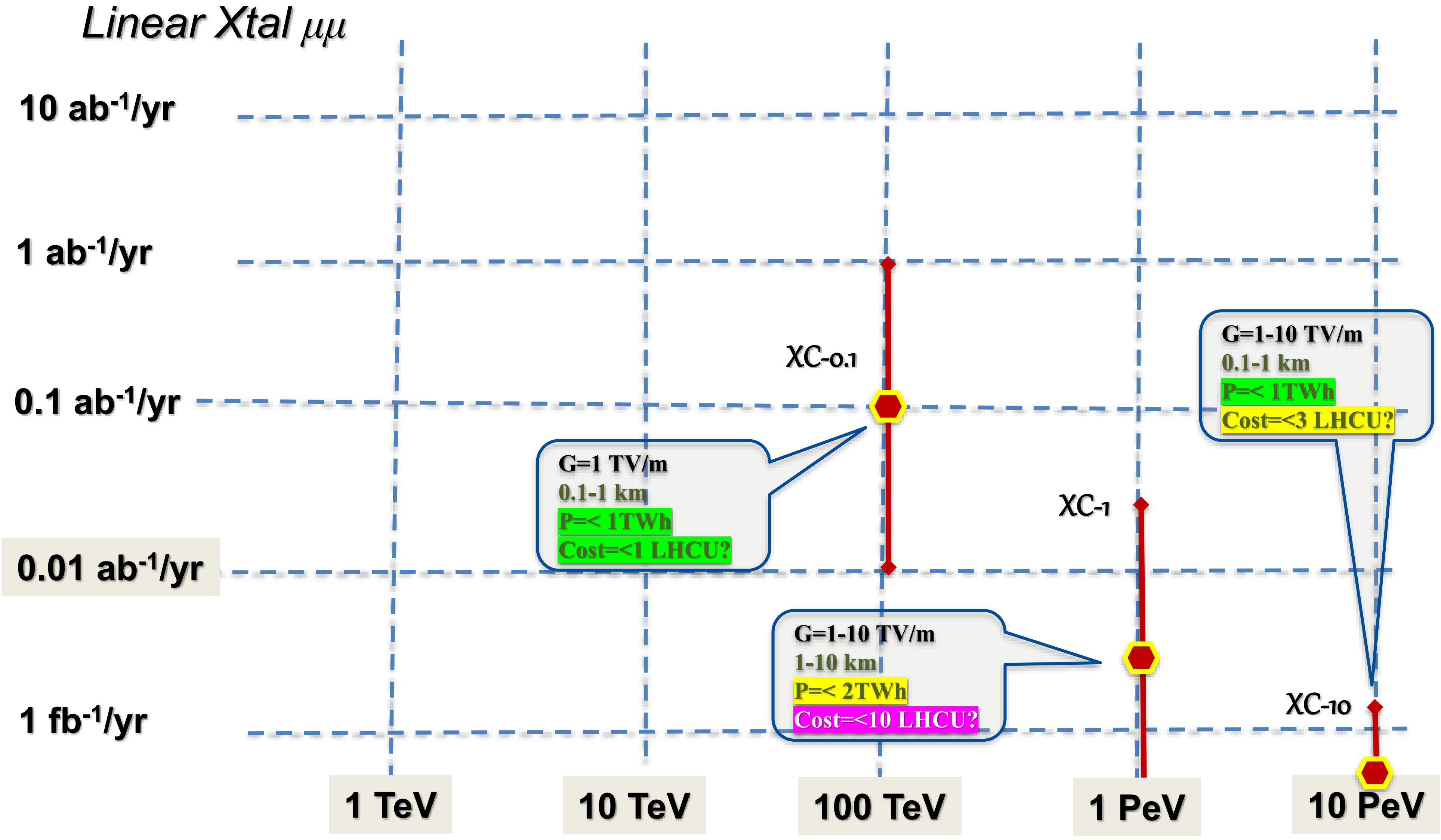
- Plasma-wakefield acceleration **and** channeling in structured media, eg CNTs or crystals (***only muons!!!***)
- Major advantages:
  - solid density → 1-10 TV/m gradients
  - continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled *betatron radiation*)
  - small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



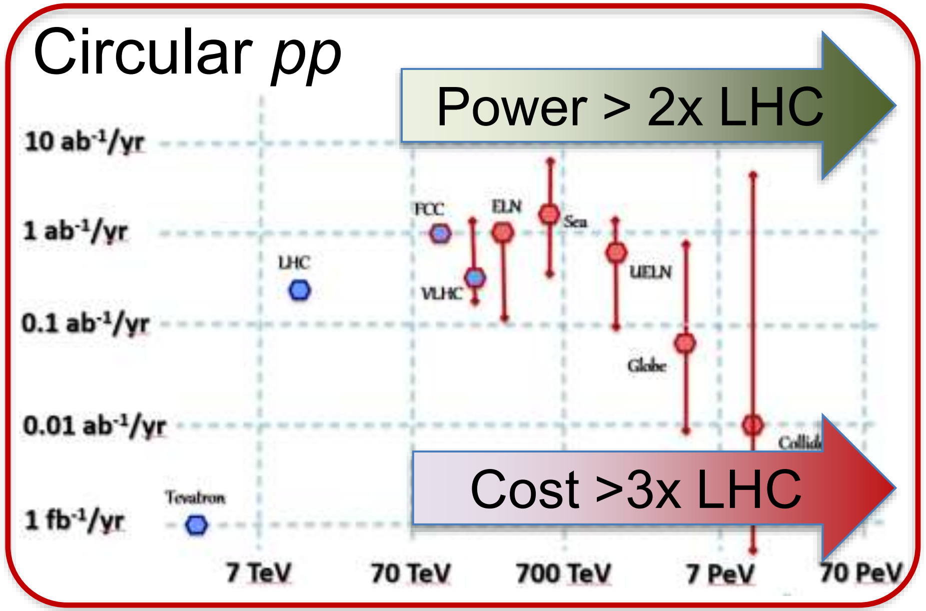
1980's-1990's T.Tajima/R.Cavenago
1990's-2000's P.Chen/R.Noble
2010's-2020's V.Shiltsev, S.Corde

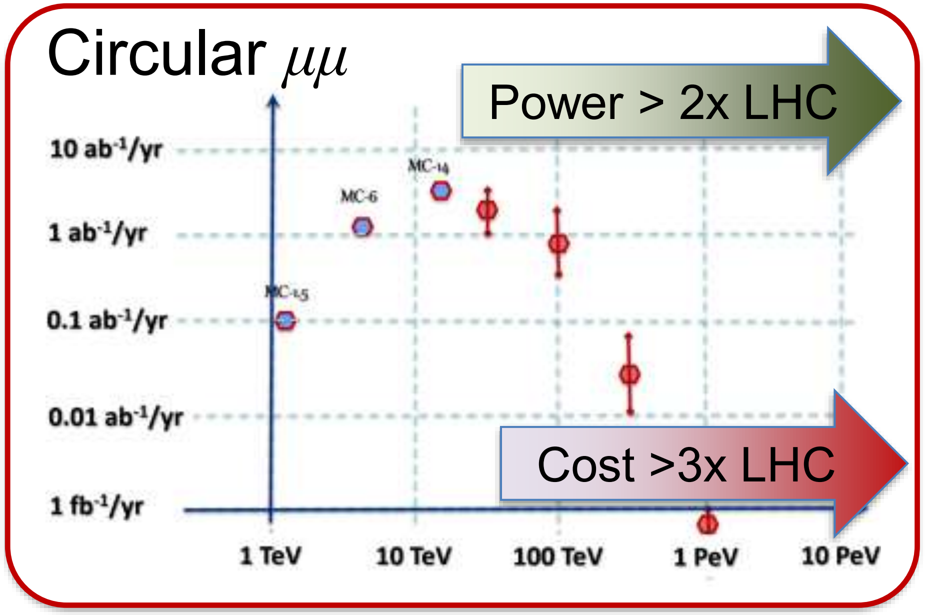


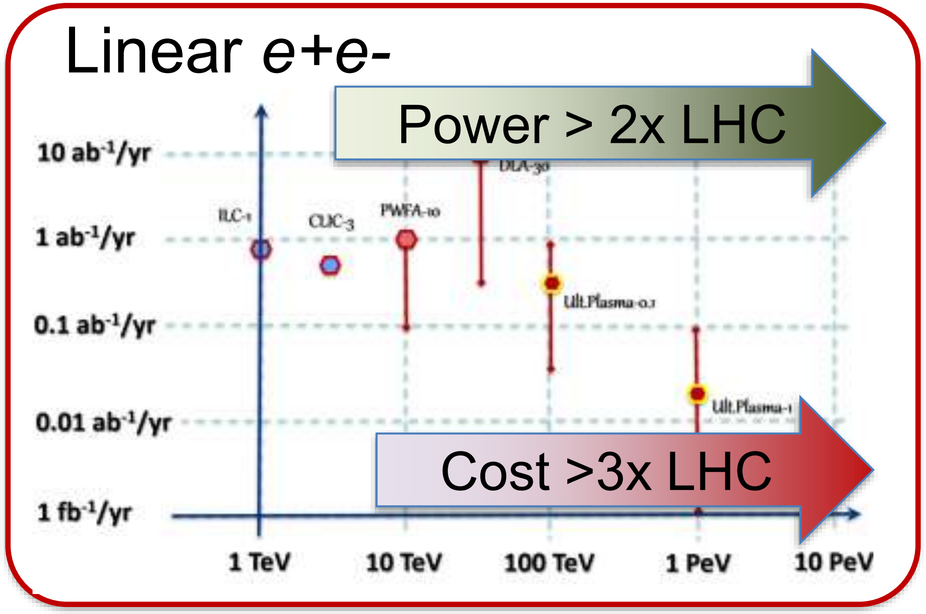
Xtal Colliders: *Lumi* and *Cost* vs *Energy*

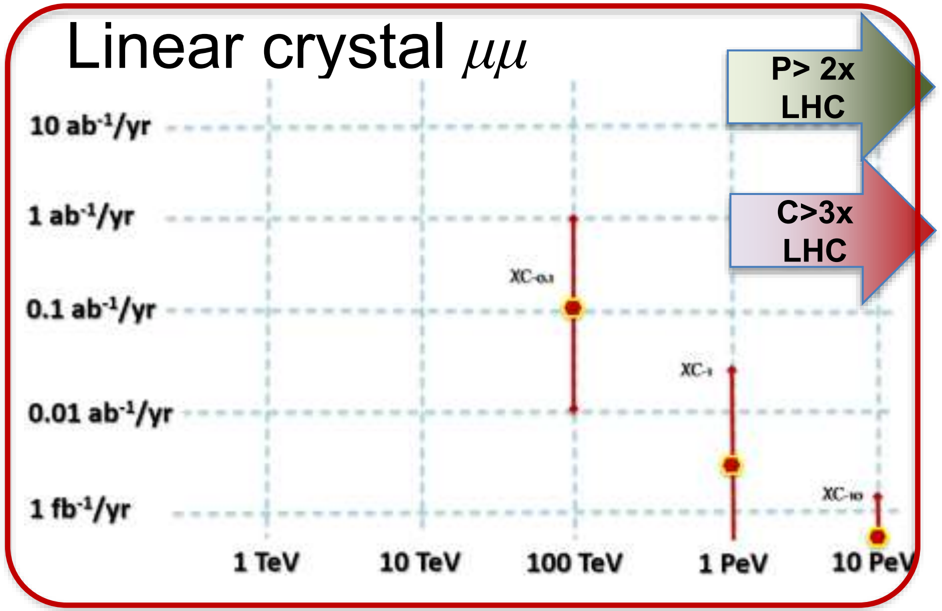


Limits (Electric Power and Cost)

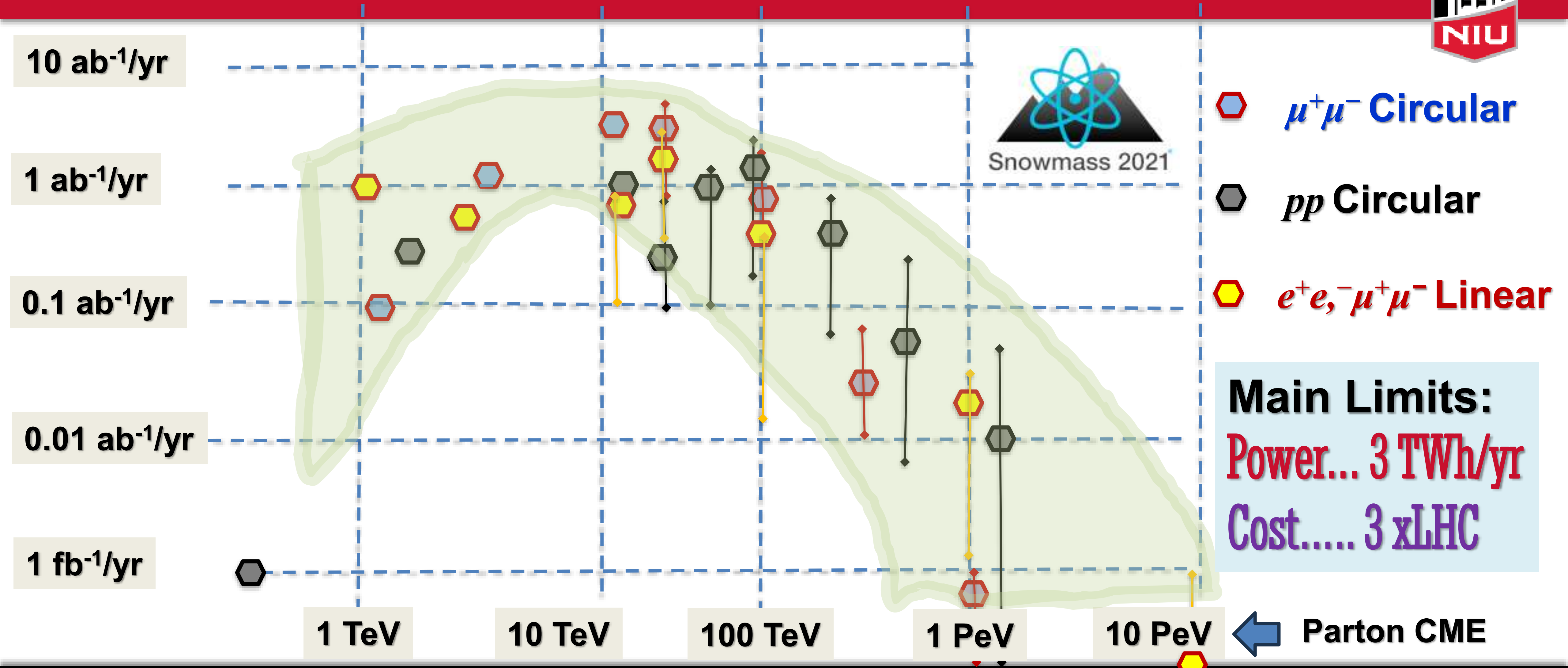








Ultimate Colliders *Luminosity* vs *Energy*



Main Limits:

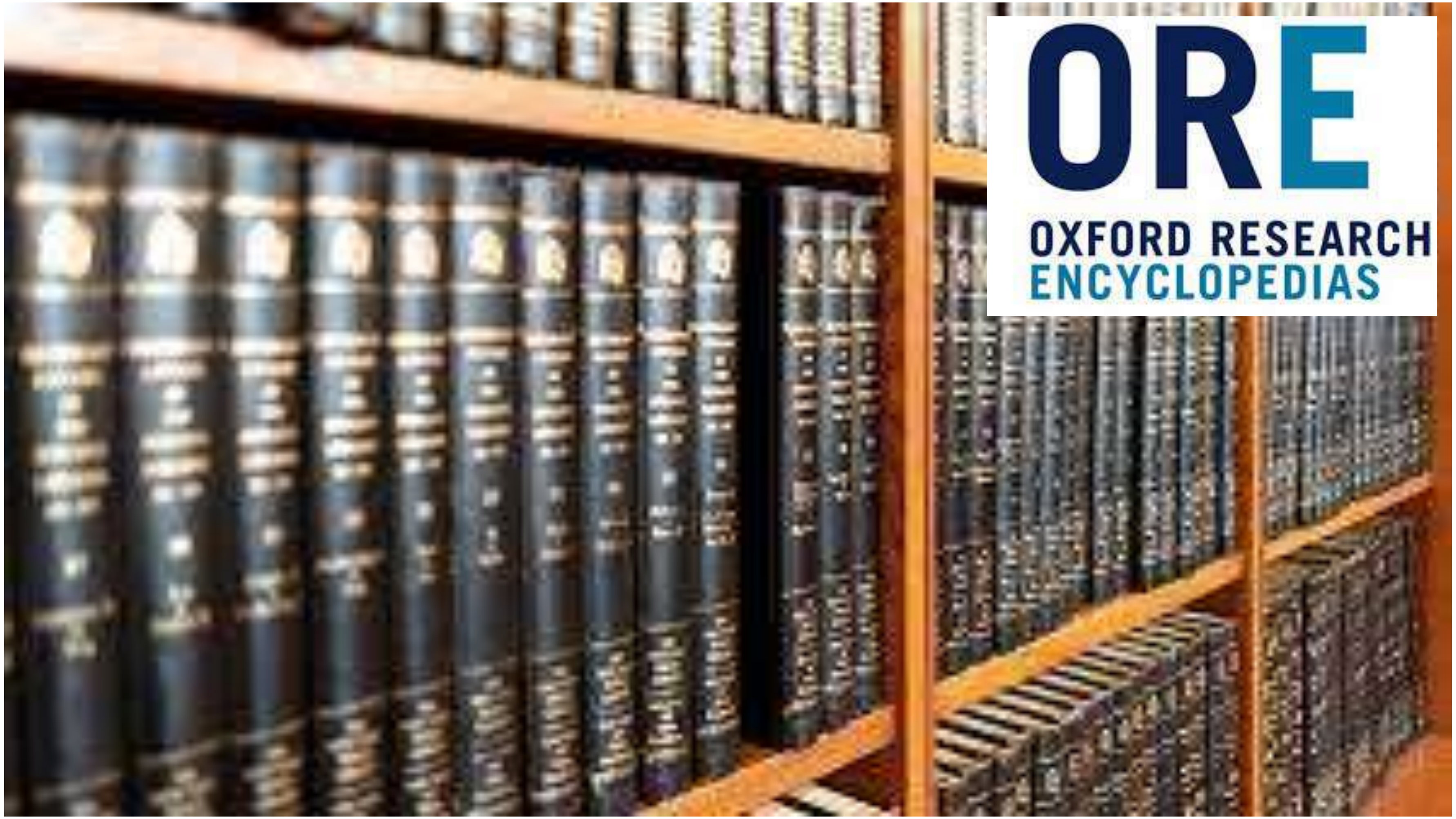
Power... 3 TWh/yr

Cost..... 3 xLHC

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

“...Muons seem to be the particles of choice for future ultimate HEP colliders.”

V.Shiltsev, “Ultimate Colliders” (2023)



DOI: 10.1093/acrefore/9780190871994.013.118

also in arXiv: https://arxiv.org/abs/2309.15960

Summary

- Colliders were a great success – now celebrate 60 years!
- 31 built, 7 operate now, 2 under construction (NICA, EIC for *Nuclear Physics*)
- There are HEP collider plans in Europe, Asia and in the US (recent *European Strategy, Snowmass*'21 and *P5*)
- HEP priorities for the next 2 decades:
  – Construction of Higgs Factory(ies)
  – R&D on 10+ TeV pCM colliders (*pp*, *μμ*,…)
- Ultimate colliders can be very high energy but low luminosity

More On Ultimate Colliders (1)

- **For ultimate high energy colliders:**
  - Major thrust is *Energy*
  - Major concern/limit *is Cost*
  - Main focus is *Luminosity* and *Power*
- **Cost:**
  - Critically dependent on core acceleration technology
  - Existing injectors and infrastructure greatly help
- **High *Energy* means low *Luminosity* :**
  - Don't expect more than 0.1-1 ab^{-1}/yr at 30TeV - 1 PeV
  - Assume *P*ower limited to 1-3 TWh/yr (1-3 x LHC)

More on Ultimate Colliders (2):

- **For considered collider types:**
  - **Circular *pp* – limit is close or below 100 TeV (~14 TeV pcm)**
  - **Circular ee – limit is ~0.4-0.5 TeV**
  - **Circular $\mu\mu$ – limit is between 30 and 50 TeV**
  - **Linear RF ee/$\gamma\gamma$ } – limit is between 3 and 10 TeV**

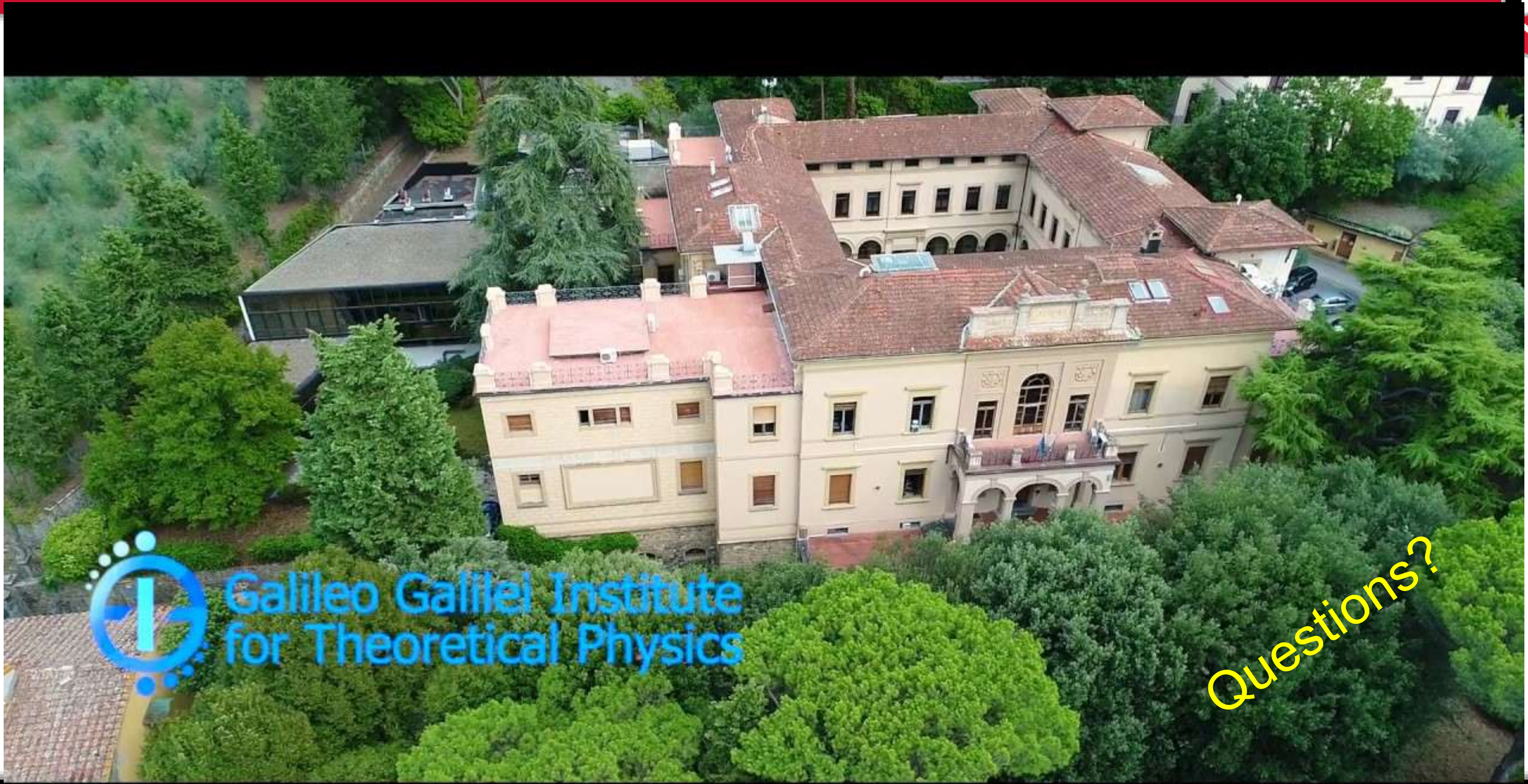
    Plasma ee/$\gamma\gamma$
  - **Exotic crystal $\mu\mu$ – promise of 0.1-1 PeV, low *L*uminosity**
- **Muons are the particles of the future**

Helpful/cited references (next slide)

(Some) References:

1. *αβγ* model – V.Shiltsev, *JINST* 9 T07002 (2014).
2. RMP Colliders – V.Shiltsev, F.Zimmermann, *Rev.Mod.Phys.* (2021); see also arxiv
3. NatPhys MC – K.Long, et al, *Nature Physics* (2021), see also arxiv
4. Eloisatron – W.Barletta, in *AIP Conference Proceedings*, vol. 351, no. 1, pp. 56-67(1996).
5. Xtal collider – V.Shiltsev, *Physics Uspekhi*, v.55 (10), p.1033 (2012)
6. F.Zimmermann – *NIMA* 909 (2018): 33-37; see also ARIES Workshops summary
7. T.Raubenheimer - Phys. Rev. ST Accel. Beams 3, 121002 (2000)
8. D.Schulte Plasma Colliders – *Rev.Accel.Sci.Tech.* 9 (2016): 209-233.
9. Granada ALEGRO – Input to *EPPSU*, #007a (Granada, 2019)
10. *Modern Muon Physics: Selected Issues*, I.Strakovsky, et al (Nova, 2020)
11. 2019 Crystal Workshop - eds. T.Tajima et al *Beam Acceleration in Crystals and Nanostructures* (World Scientific, 2020)
12. *CPT*-theorem – V.Shiltsev *Mod. Phys. Lett. A*, vol. 26, No. 11 (2011) pp. 761-772
13. Cheap magnets – V.Kashikhin, Fermilab beams-doc-8948 (2021)

Grazie per l'attenzione!

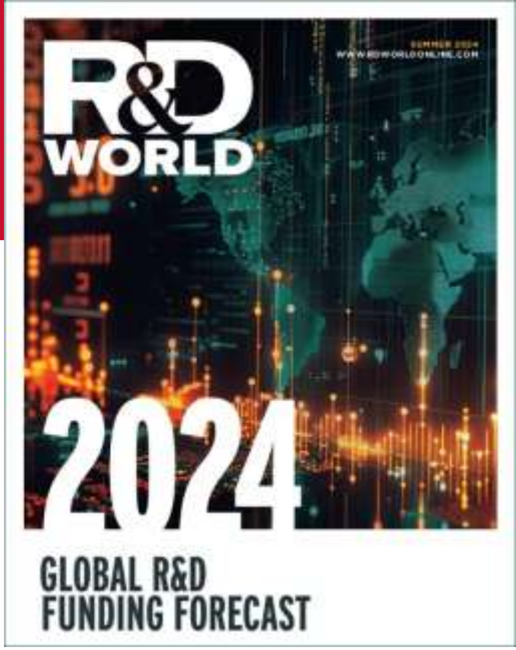


Scale of Numbers

- World's Total GDP ~106,000 B$
- World's Total R&D ~2,800 B$
  - that is ~2.7% of the above
- World's Basic Sciences ~400 B$
  - that is ~14% of the above
- World's Particle Physics ~4.5 B$
  - that is ~1.2% of the above

Very generous for ~16,000 researchers

(about 0.2% of ~8 million in the R&D sector)



"Really Big" Accelerator

- Even in the most successful scenatrio
  - fully international project
  - construction over 10 years
  - 30% all resources (1.5B$/yr)

⇒ ~20 B$

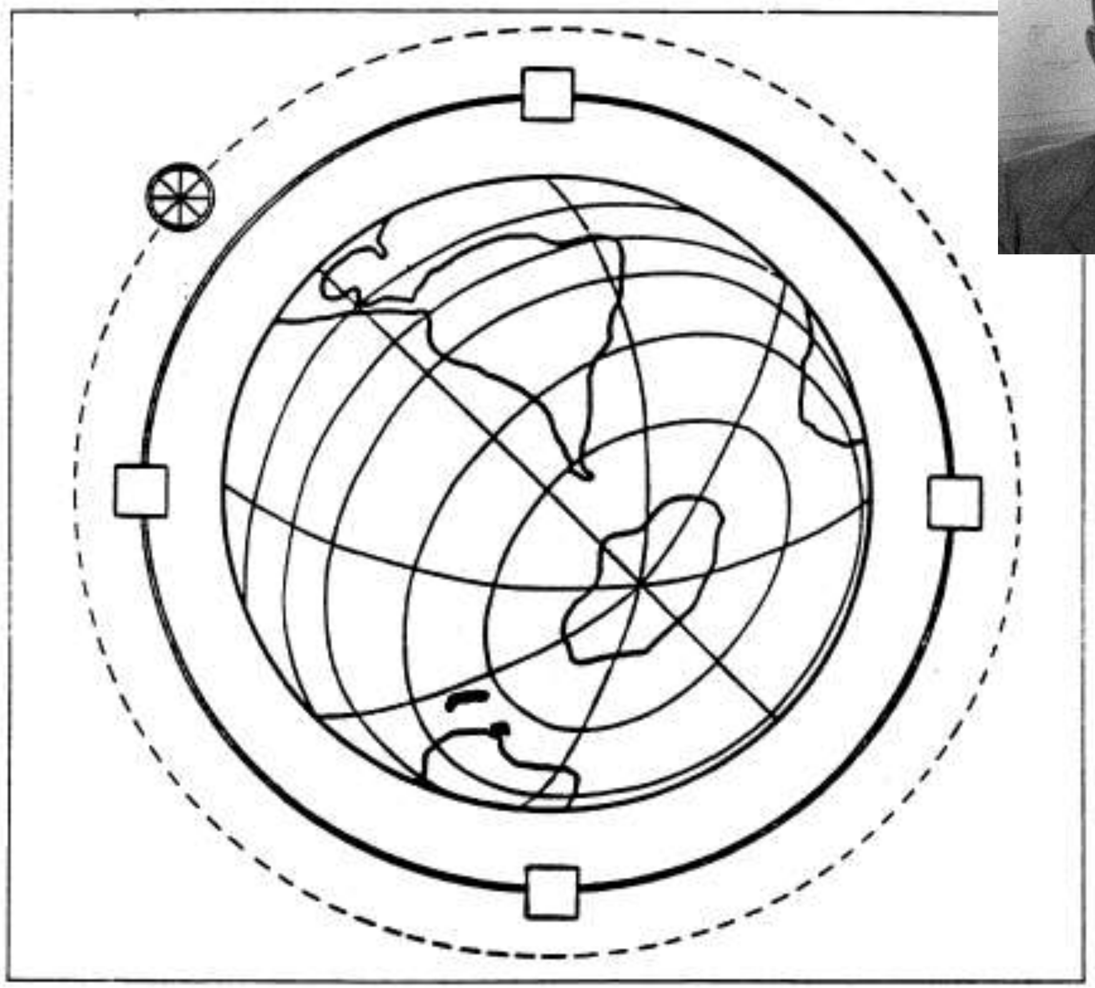
- Key cost drivers are
  - Length of the tunnel
  - Cost of the accelerating elements
  - Total accelerator site electric power

Defining the "Phase-Space"

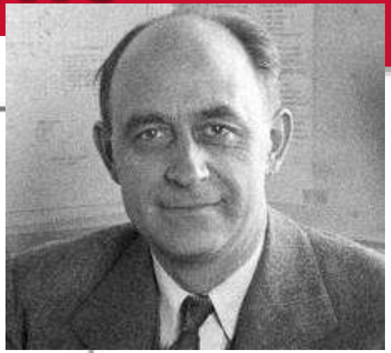
- We want "Interesting Physics"
  - *Physics* $\propto$ log(*Energy*)
  - 100-1000+ TeV (10-100 × LHC)
  - decent luminosity
- … but we should "live within means":
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

An Example of "Over the Limit"

- "globaltron"
  - 40,000 km
  - >> 1000 B$



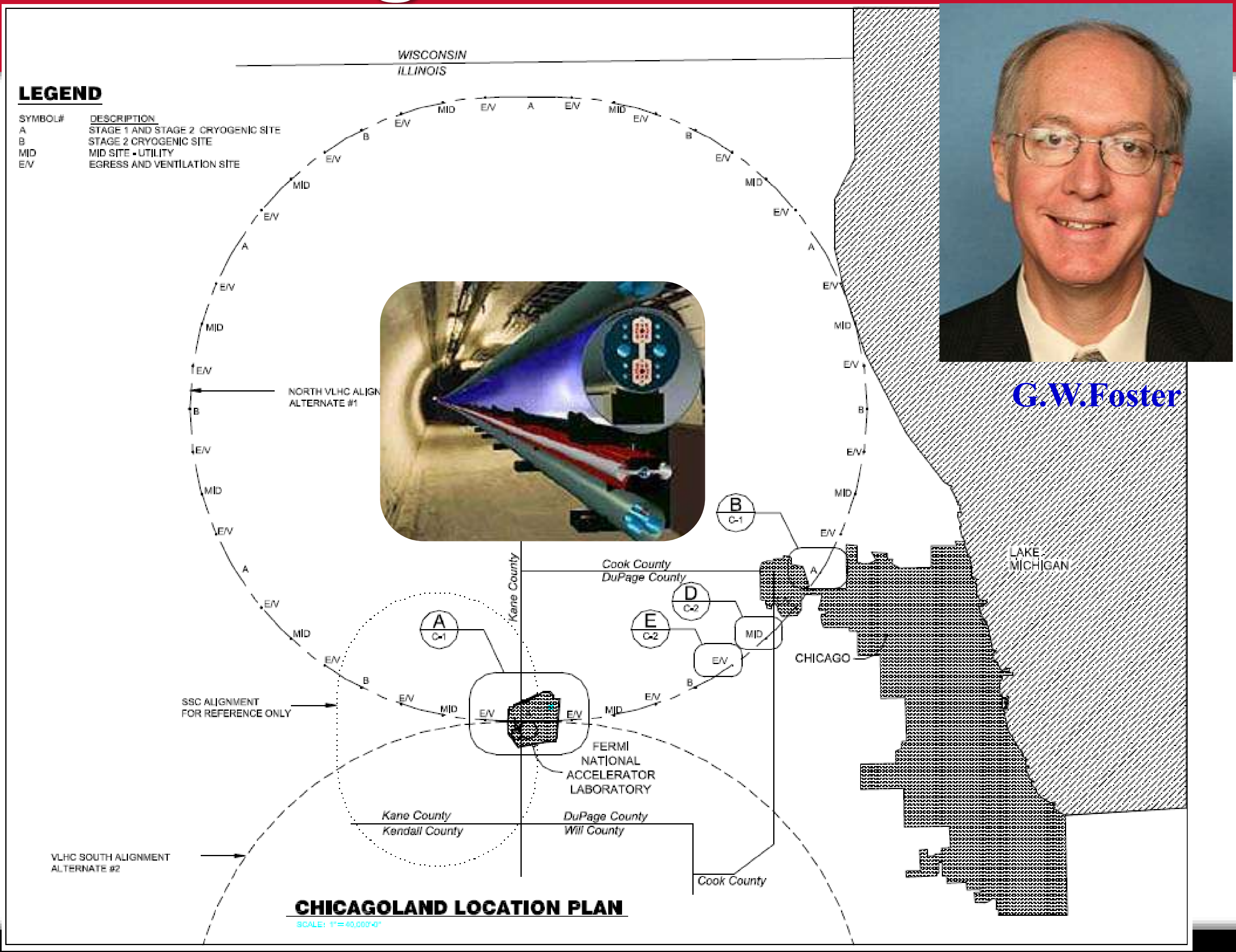
From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.



E.Fermi

Another "Too Big of a Machine"

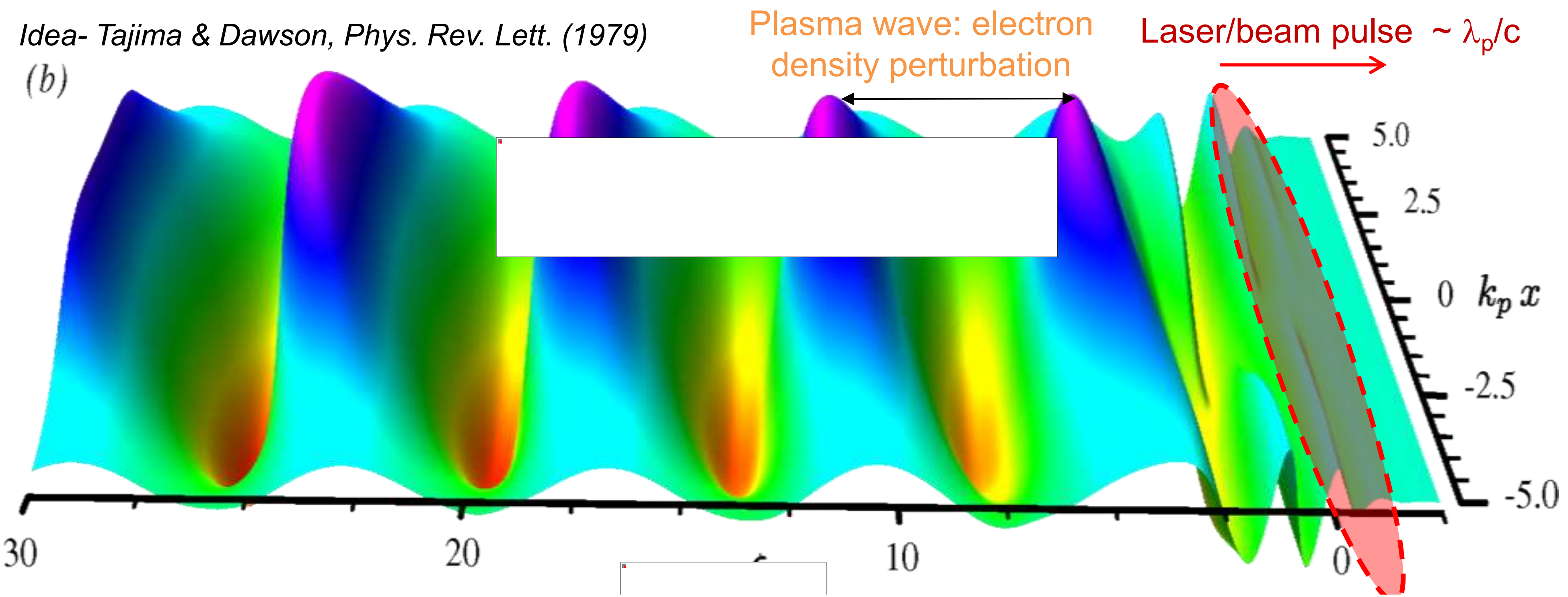
- VLHC or "*pipetron*"
  - ➤ 233 km , >10 B$



G.W.Foster

Excitation of Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)

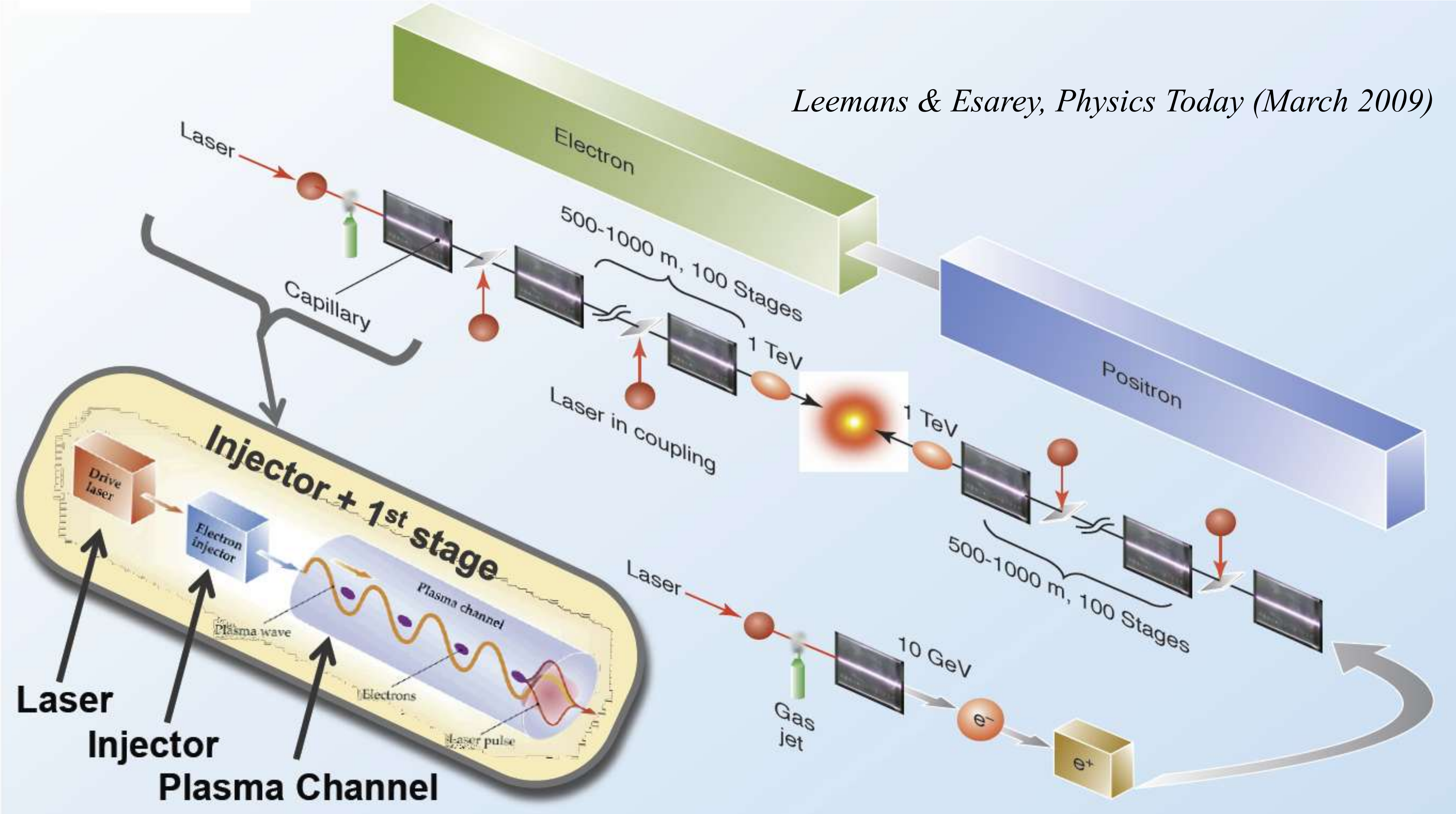


$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

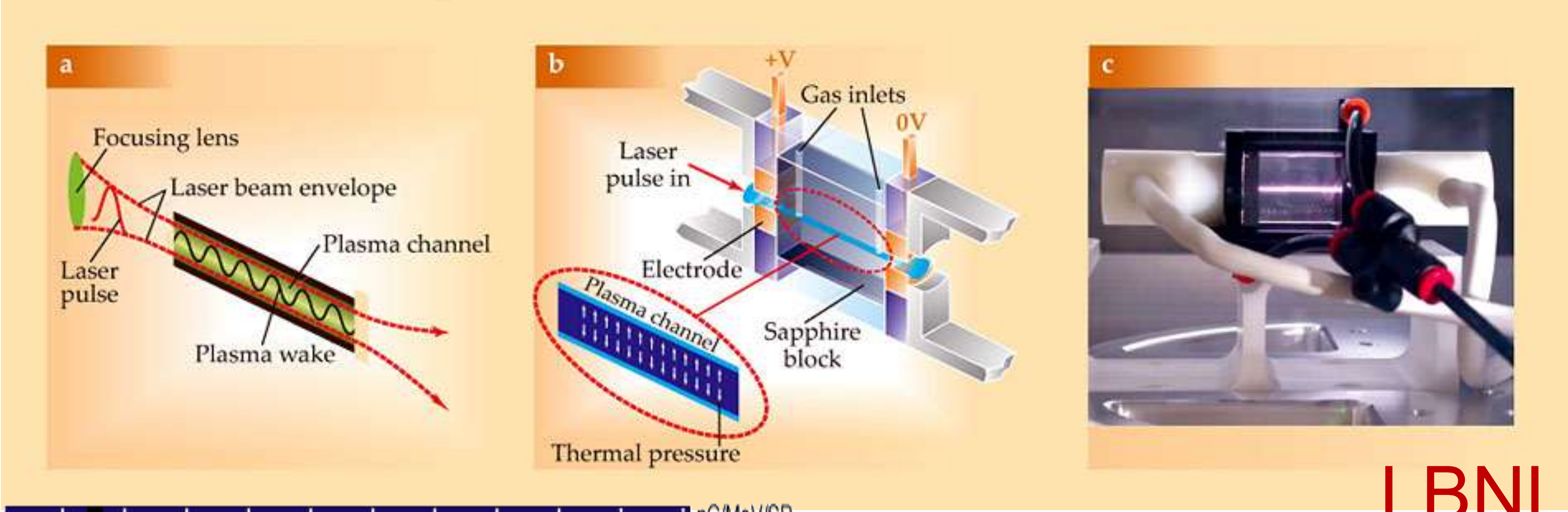
Option A:
Short intense e-/e+/p bunch
10^{18}cm^{-3}, 100 GV/m, λ_p~30μm

Option B:
Short intense laser pulse
~10^{17}cm^{-3}, 30 GV/m, λ_p~100μm

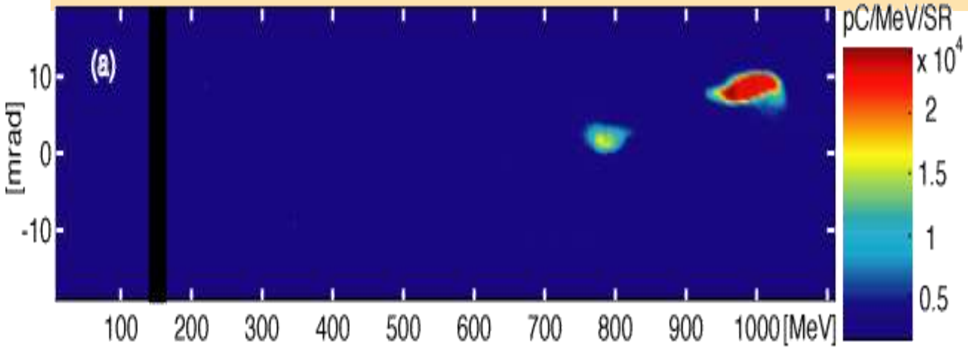
Laser Plasma e+e- Linear Collider



Laser-plasma: First Results



LBNL



- Achieved ~30 GV/m (Berkeley)
  - 1 GeV over 3 cm with 40 TW laser
  - 2 J laser → 0.03 J beam (η=1.5%)

Serious issues are seen:

- speed of light in plasma <*c*
- need many stages of acceleration
- Very high cost of laser power
- hard to accelerate e+
- e- and e+ radiate too much if *E>1-3* TeV (even in linear channel)

Luminosity of Super-high E Colliders

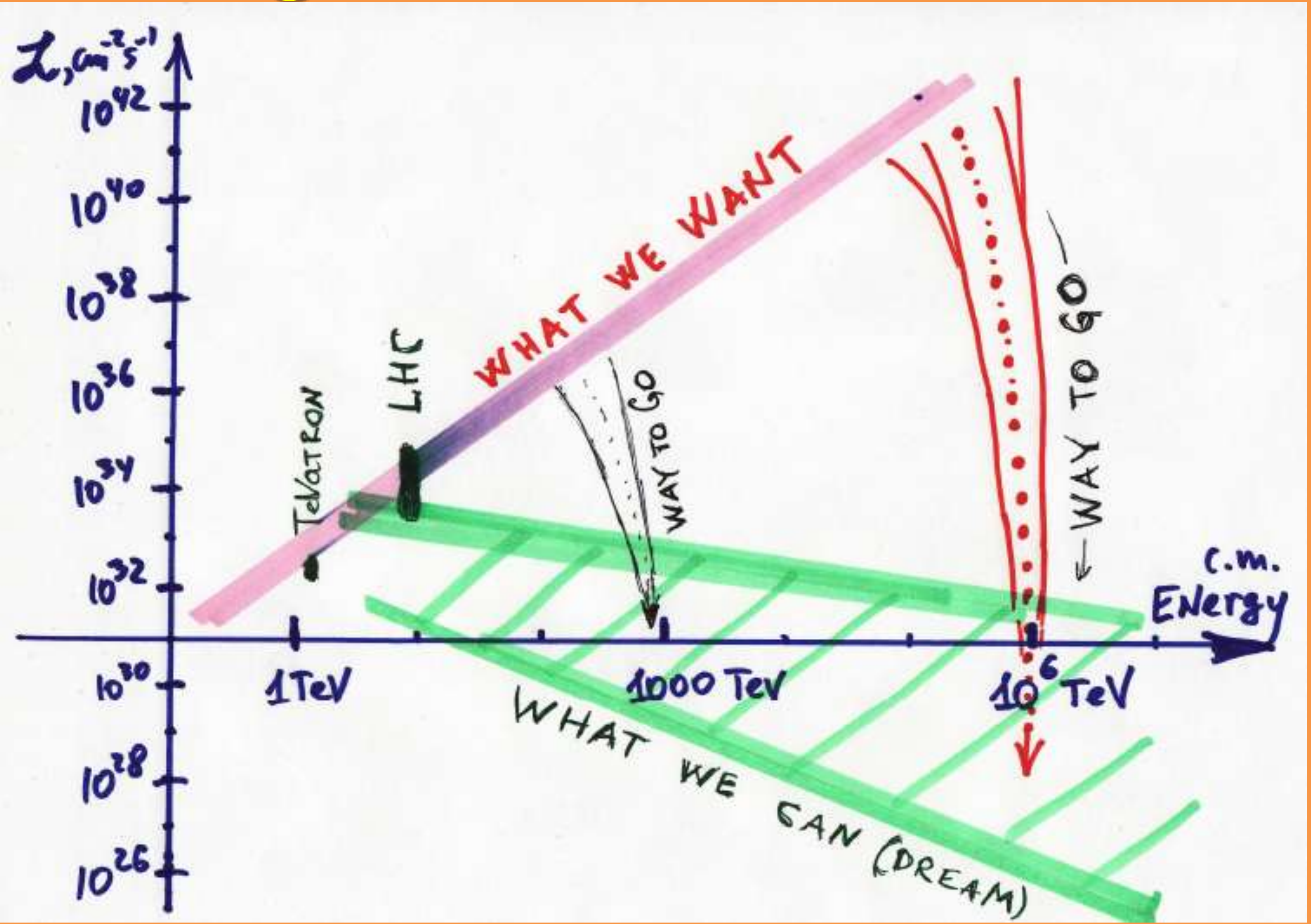
- High energy particle reactions are rare
  - cross sections of QED reactions drop with energy as ~ *1/ E^2*
  - correspondingly, we tried to increase the luminosity

$$L = f \frac{N_1 N_2}{A}$$

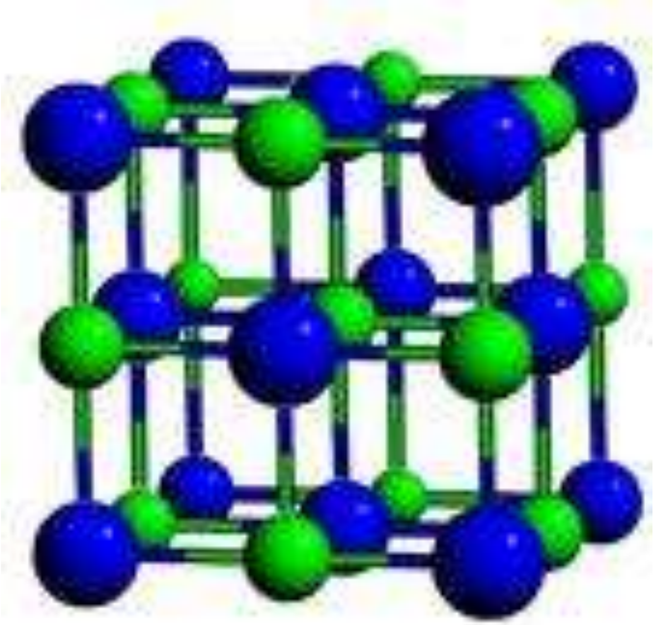
- But there is power
  - ***P=f eN E - must be less than 10 MW***

    alternative – to reduce beam size at the IP – beam cross section **A**

Paradigm Shift Needed



Yet Another Option : Crystals

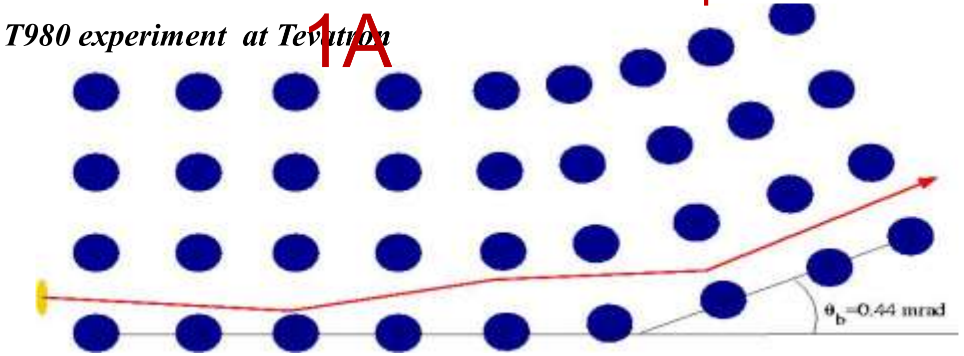


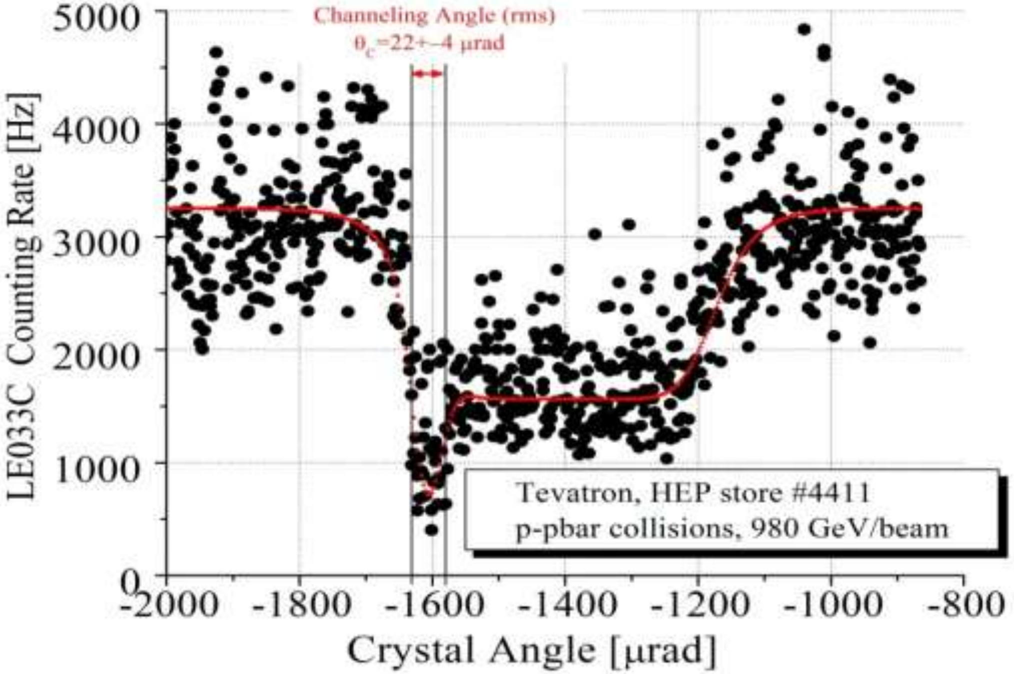
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

10^{22} cm^{-3} → 10 TV/m, λ_p~ 1A

P.Chen
R.Noble
R.Ruth

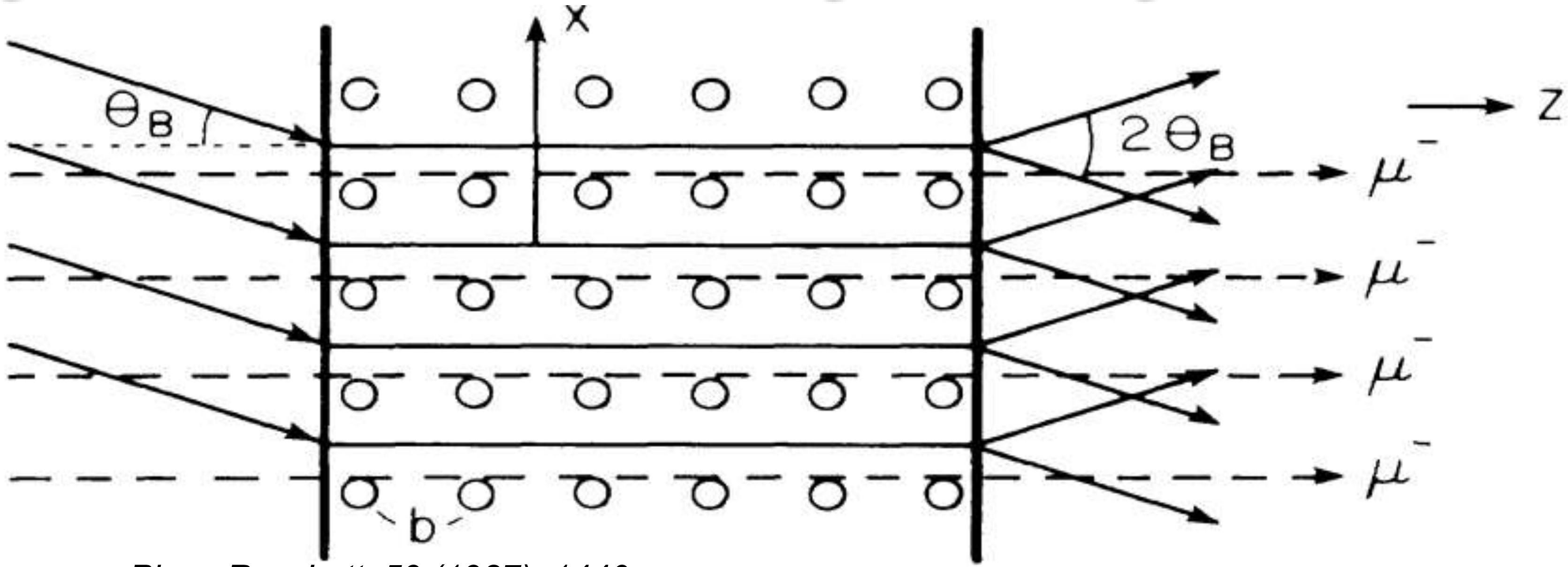
T980 experiment at Tevatron





- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)

Crystal Excitation by X-Rays



Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm

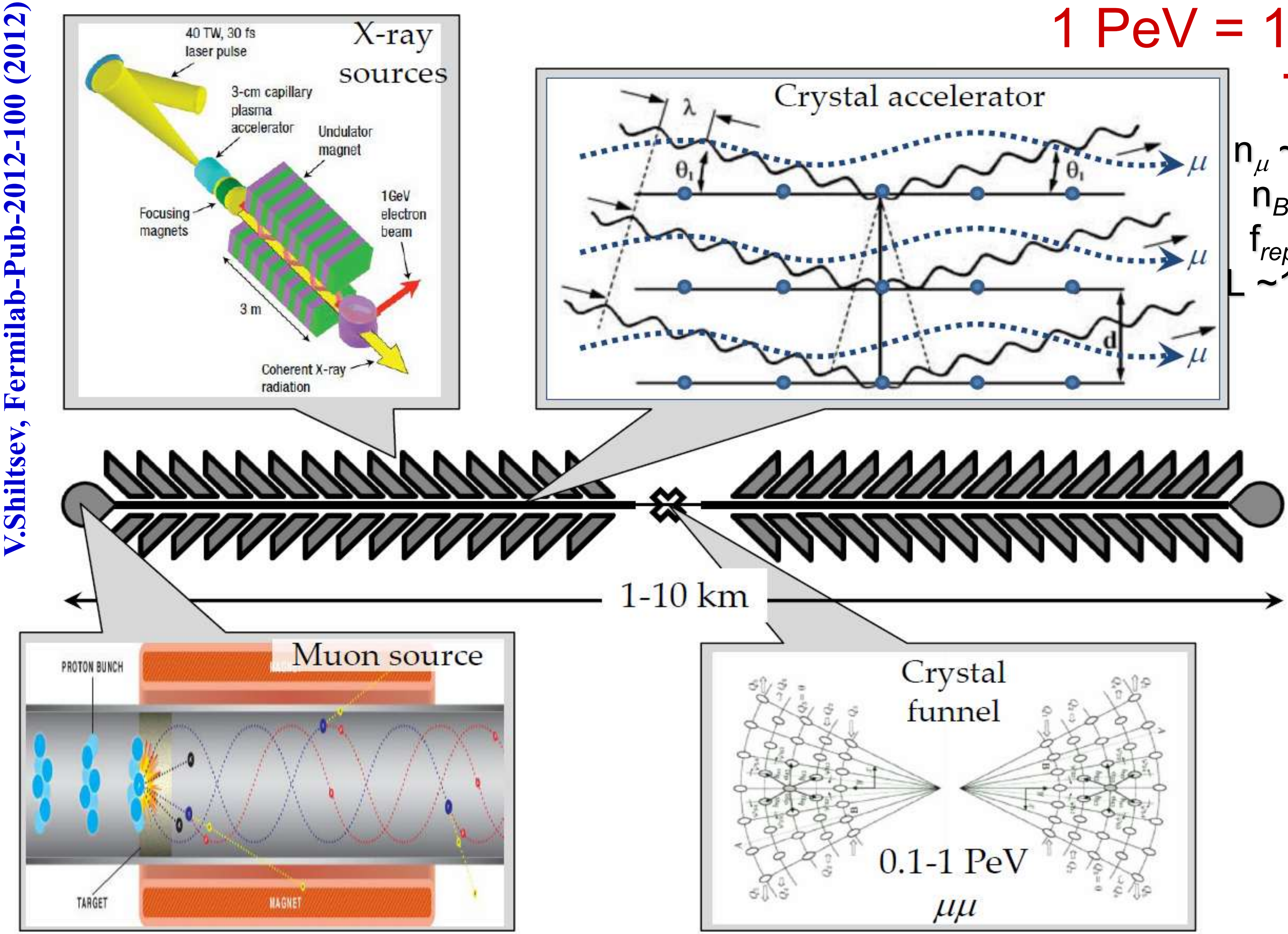
- Muons preferred
  - No bremstrahlung, no nucl.
- μ+ rad length 10^9 cm
  - total energy~10^9 GeV

Linear μ+μ- Crystal X-ray Collider

V.Shiltsev, Fermilab-Pub-2012-100 (2012)

1 PeV = 1000 TeV

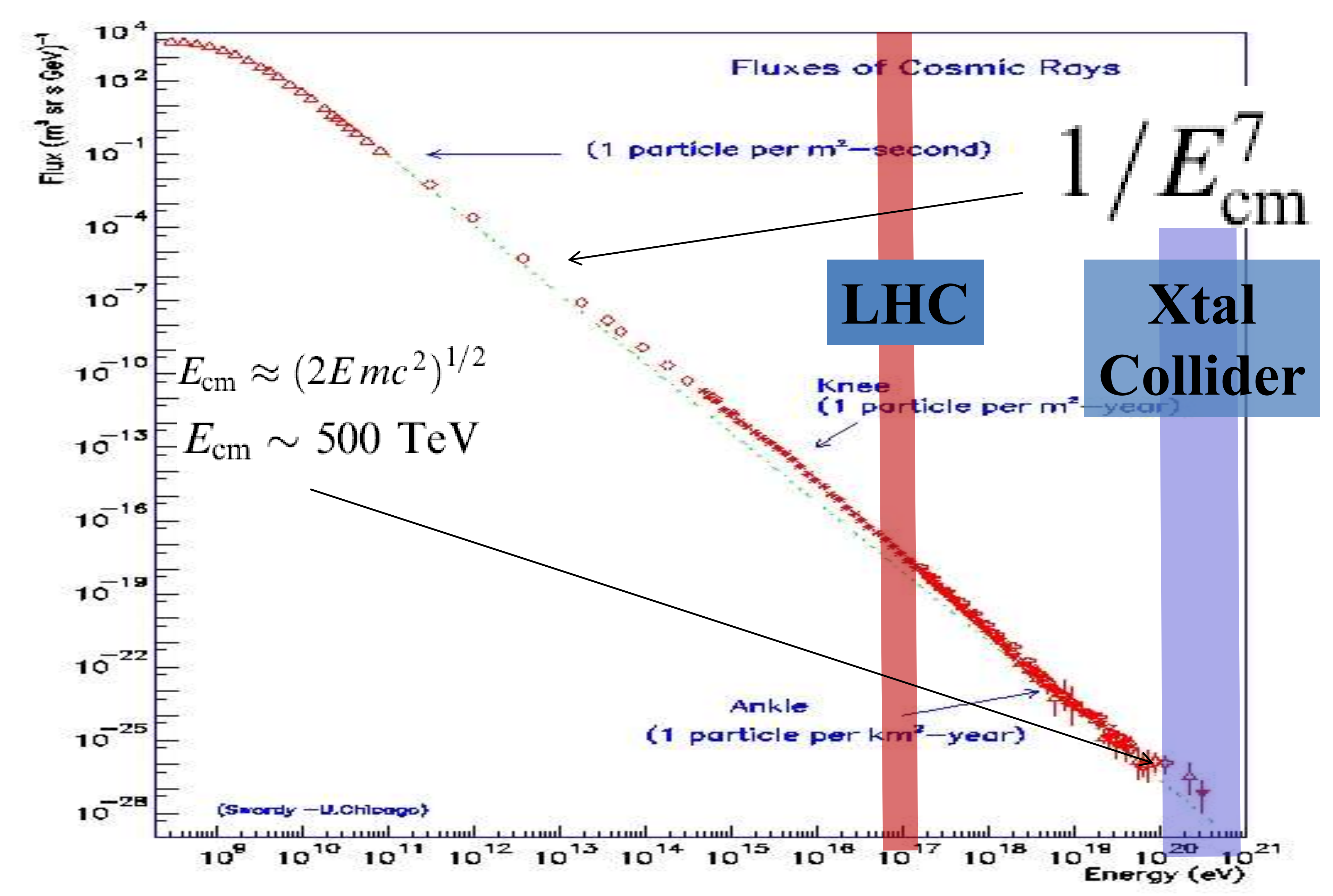
n_{μ} ~1000
n_B ~100
f_{rep} ~10^6
L ~$10^{30\text{-}32}$



Comparison of Future Options

	Dielectric based	Plasma based	Crystal channeling
Accelerating media	micro-structures	ionized plasma	solid crystals
Energy source: option 1 option 2	optical laser e^- bunch	e^- bunch optical laser	x-ray laser
Preferred particles	any stable	e^-, μ^-	μ^+, p^+
Max accelerating gradient	1-3 GV/m	30-100 GV/m	0.1-10 TV/m
c.m. energy reach in 10 km	3-10 TeV	3-50 TeV	10^3-10^5 TeV
# stages/10 km: option 1 option 2	10^5-10^6 10^4-10^5	~100 10^3-10^4	~1

Compare with Cosmic Rays



$1/E_{\rm cm}^7$

$E_{\rm cm} \approx (2Emc^2)^{1/2}$

$E_{\rm cm} \sim 500$ 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

ITF: HF Cost Estimates

ITF used: a) various **models to estimate the cost** (e.g. 5- and 31-parameters) ; b) **known costs of existing installations** and reasonably expected cost of novel equipment; c) for **future technologies, the cost estimate is quite conservative**, and one should expect cost reductions from pre-project R&D.

Horizontal scale is approx. logarithmic for the project total cost in 2021 B$ without contingency and escalation.

Black horizontal bars with smeared ends indicate the cost est. range for each machine.