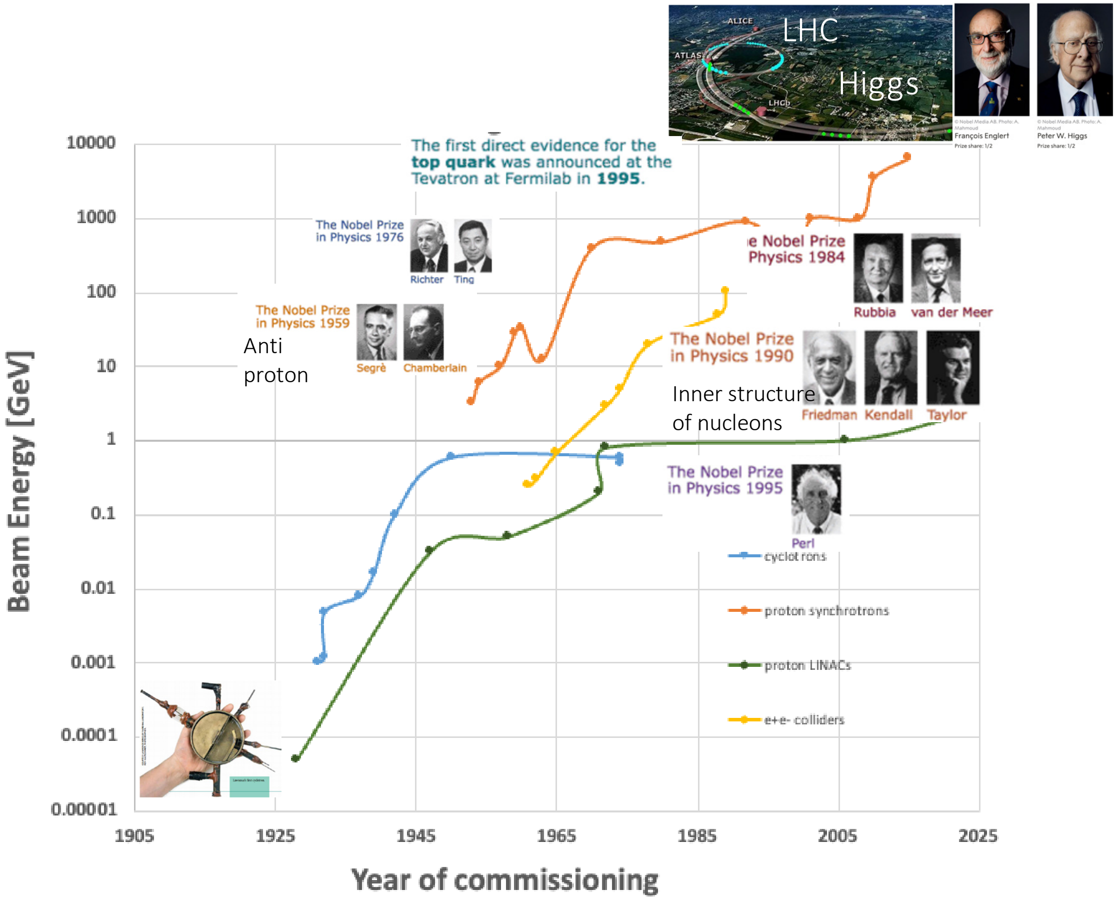
Ultimate Limits of Future Colliders

.

Mei Bai, SLAC
Vladimir Shiltsev, Fermilab
Frank Zimmermann, CERN

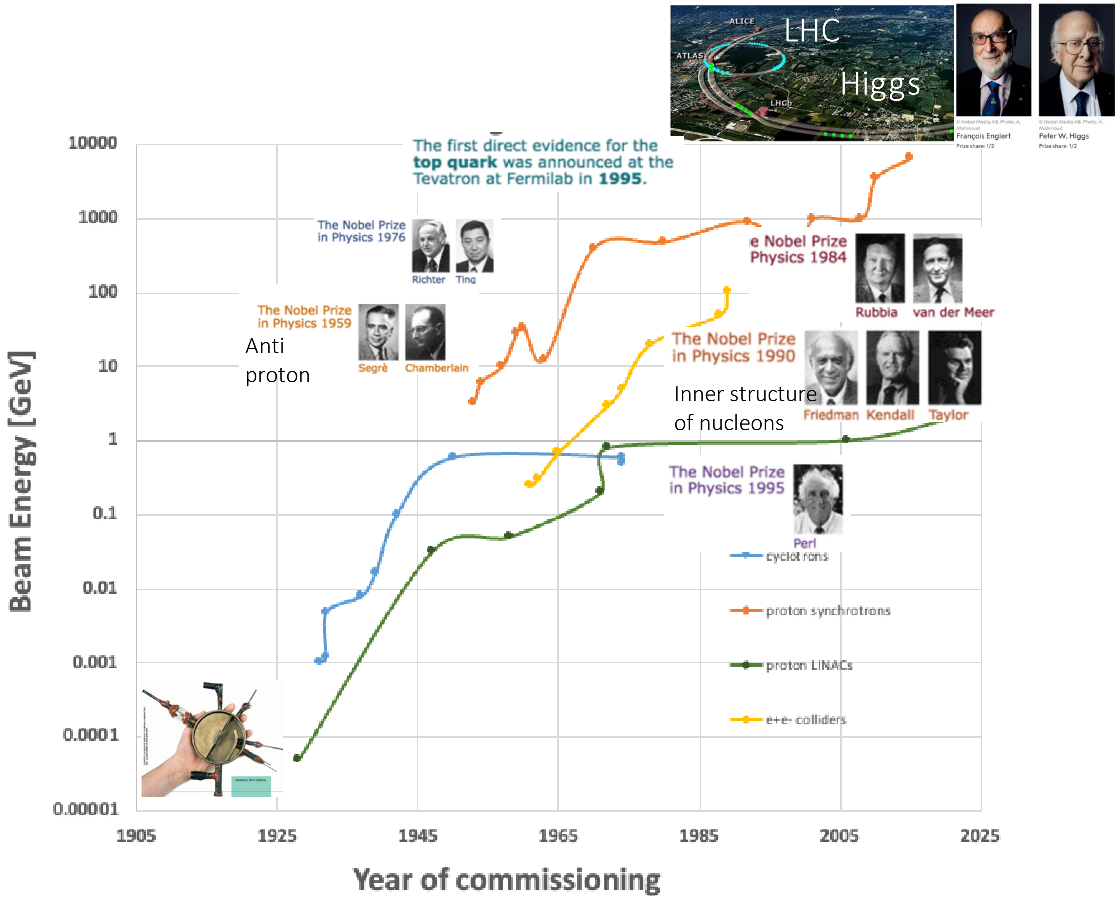
NAPAC, August 9, 2022

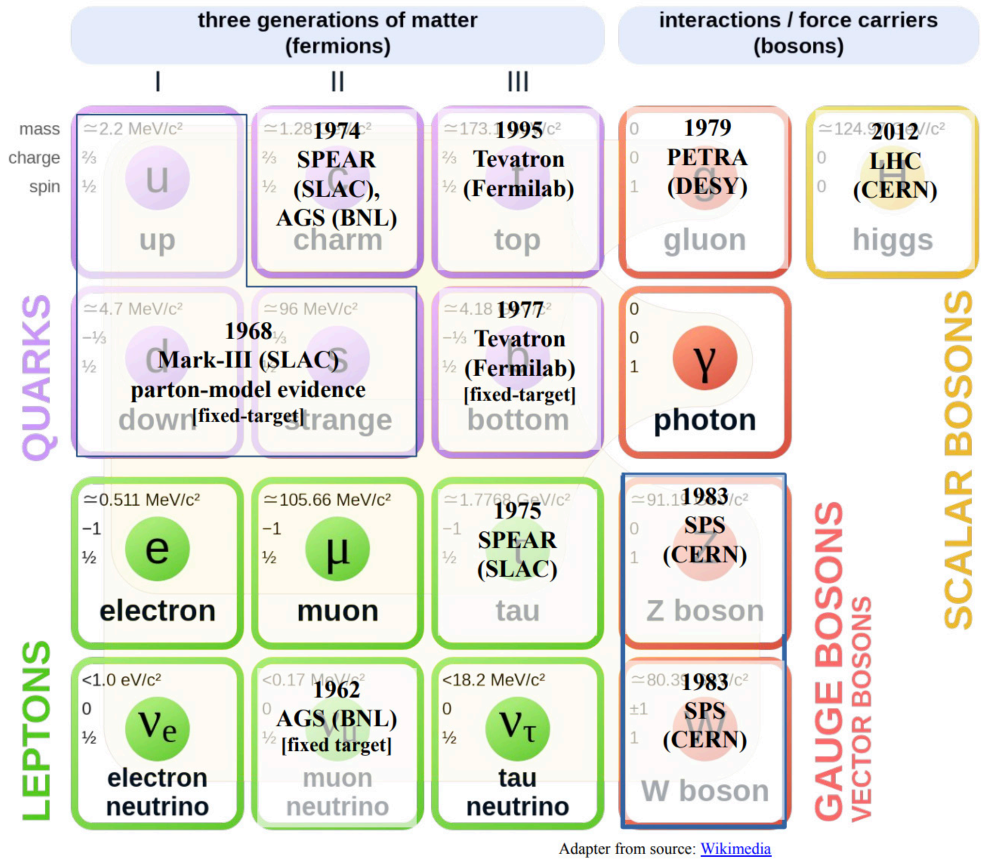
Engine of Discovery



Engine of Discovery

Particle Colliders have been instrumental in unraveling the building blocks of Standard Model



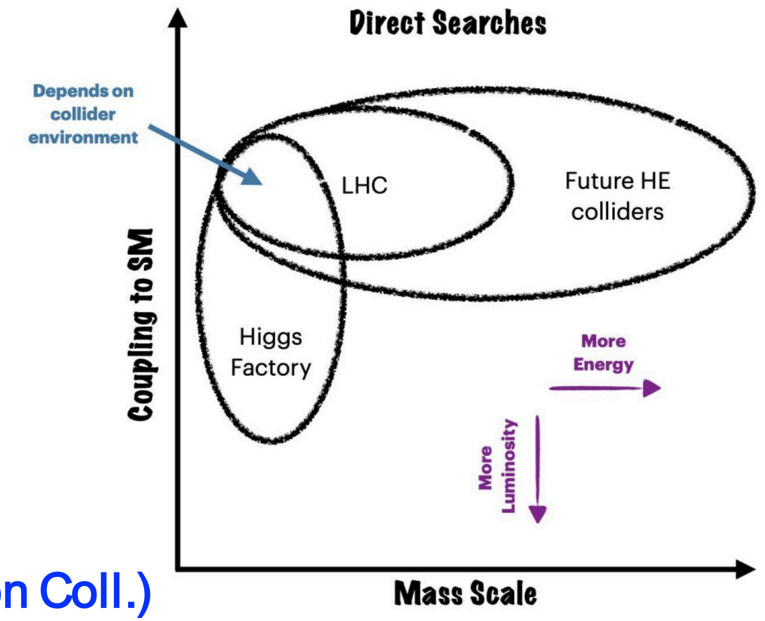


Simone Pagan Griso, The Physics case for Energy Frontier Discovery Machines, Snowmass Community Study Workshop, July 2022.

Snowmass Energy Frontier Vision

- The immediate future is the HL-LHC

- The intermediate future is an e+ e - Higgs factory, either based on a linear (ILC, C3 , CLIC) or circular collider (FCC-ee, CepC).
  - It is important to realize at least one somewhere in the world.
  - A timely implementation and strong US support are important



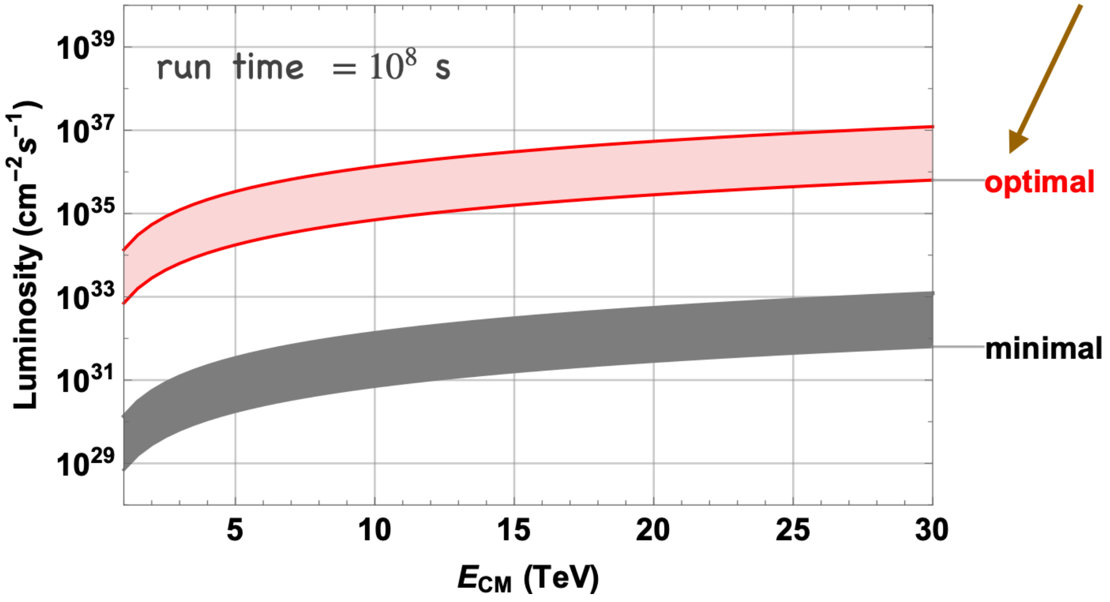
- In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Coll.)
  - A 10-TeV muon collider and 100-TeV pp collider (FCC-hh, SppC) directly probe the ~10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity and frameworks
  - The main limitation is technology readiness. A vigorous R&D program into accelerator and detector technologies will be crucial.

Future colliders for discovery

Lepton collider

Based on electroweak cross section.
Bands represent O(10) variation in signal rate

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



L. Wang, Physics limit of ultimate beams workshop series
https://indico.fnal.gov/event/46742/

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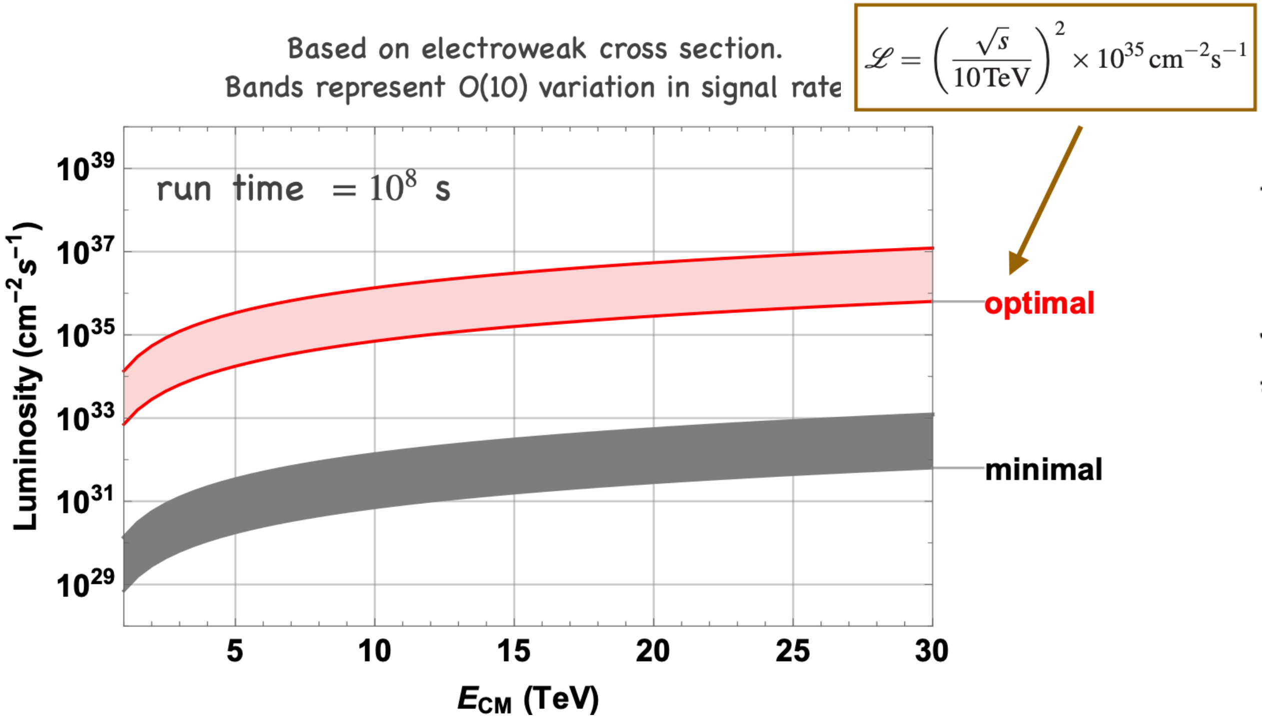

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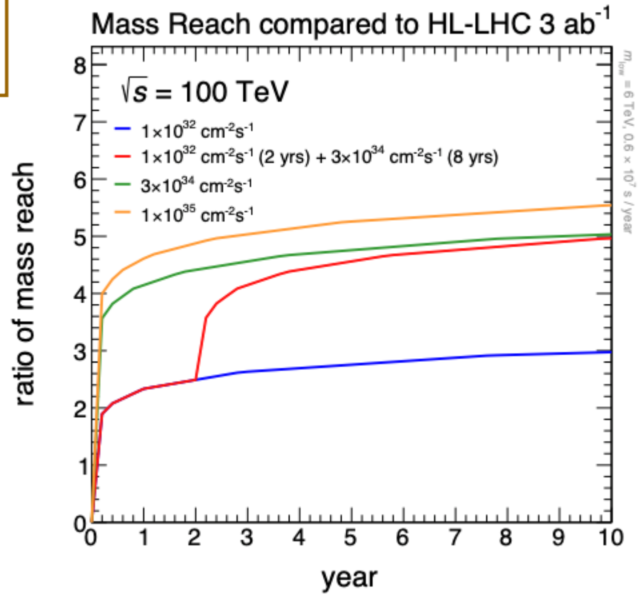
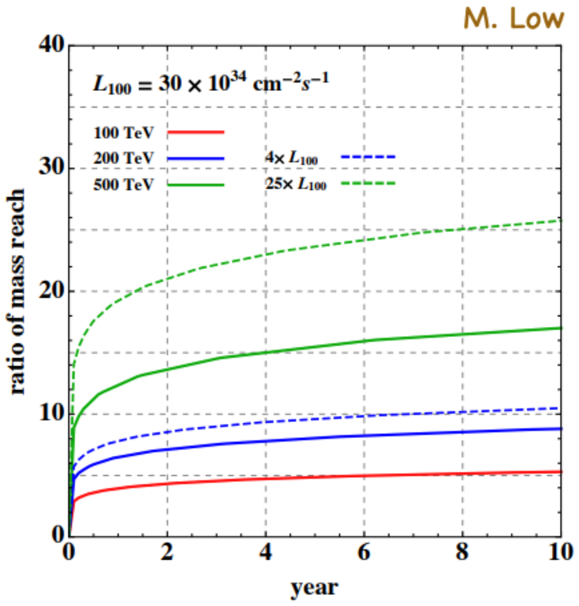
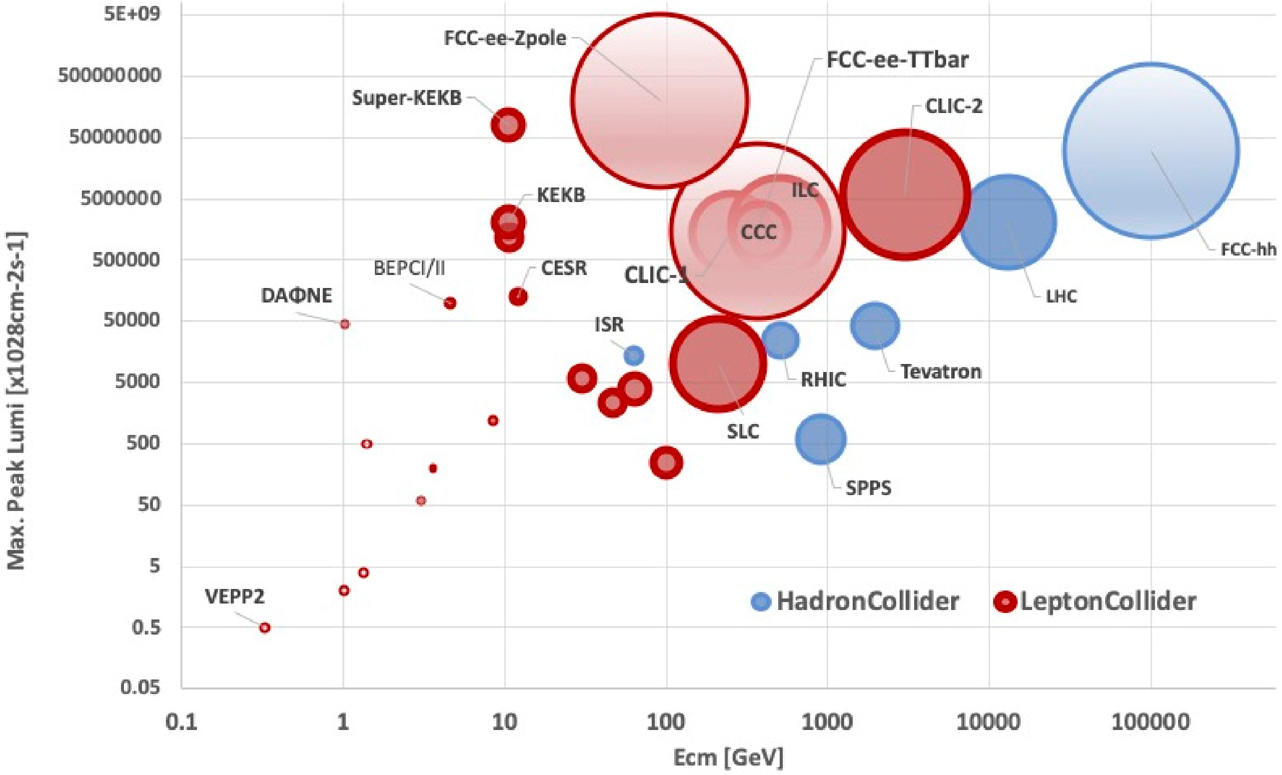
Hadron collider





- Ratio of reaching new physics particles scales more with energy than luminosity
- Also accommodates precision studies after the initial discovery

Collider Landscape



- Colliders have been the tool for probing the subatomic structures and discovery of new particles
- Currently, 5 electron-positron colliders, 2 hadron colliders are in operation
- Within the coming decade, at least two new colliders may come into operation, i.e. Nuclotron-based Ion Collider fAcility at JINR(Russia) and the Electron Ion Collider at BNL (USA)

First collider in 1961. Seven are currently in operation. Two, NICA and EIC, are under construction.

Limiting factors of current collider: Luminosity

In general, luminosity is given by

$$L = \frac{f_{rep} n_b N_b^2}{4\pi \sigma_x^* \sigma_y^*} F_{geom} = \frac{1}{2\pi} \frac{P_{wall}\eta}{E_{cm}} \frac{N_b}{\sigma_x^* \sigma_y^*} F_{geom}$$

where, f_{rep} is the repetition/revolution rate, n_b is the number of bunches, N_b is the number of particles per bunch, σ_x^* and σ_y^* are the rms beam size at IP, P_{wall} is the wall plug power and beam power $P_{beam} = P_{wall}\eta = f_{rep} n_b N_b \, \gamma m C^2$. F_{geom} is the scaling factor due to hourglass effect, etc.

for lepton colliders, scales the beam brightness accordingly

- Beam instability, beam-beam effect, beamstrahlung effect, Oide effect, etc
  - Crab-crossing, crab-waist, resonance correction, nano beam, flat beam, etc

In the case of $\sigma_z \simeq \beta_y^*$, $\boldsymbol{L \propto \frac{P_{wall}\eta}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\epsilon_y}} F_{geom}}$, where δ_{BS} is the energy loss due to beamstrahlung.

- For muon, neutrino radiation dose w.r.t safety regulations

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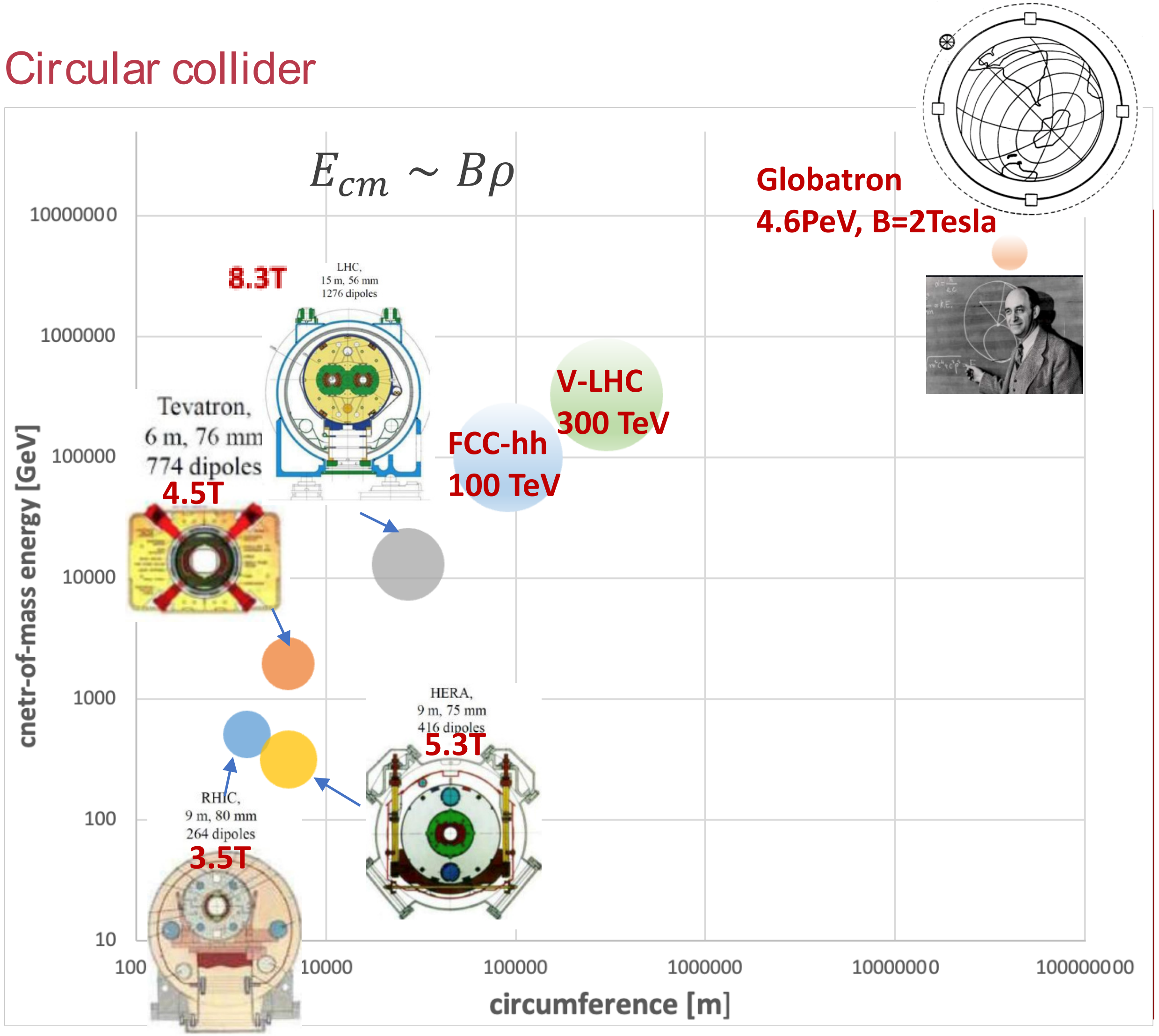
Limiting factors of current collider: Energy

Circular collider



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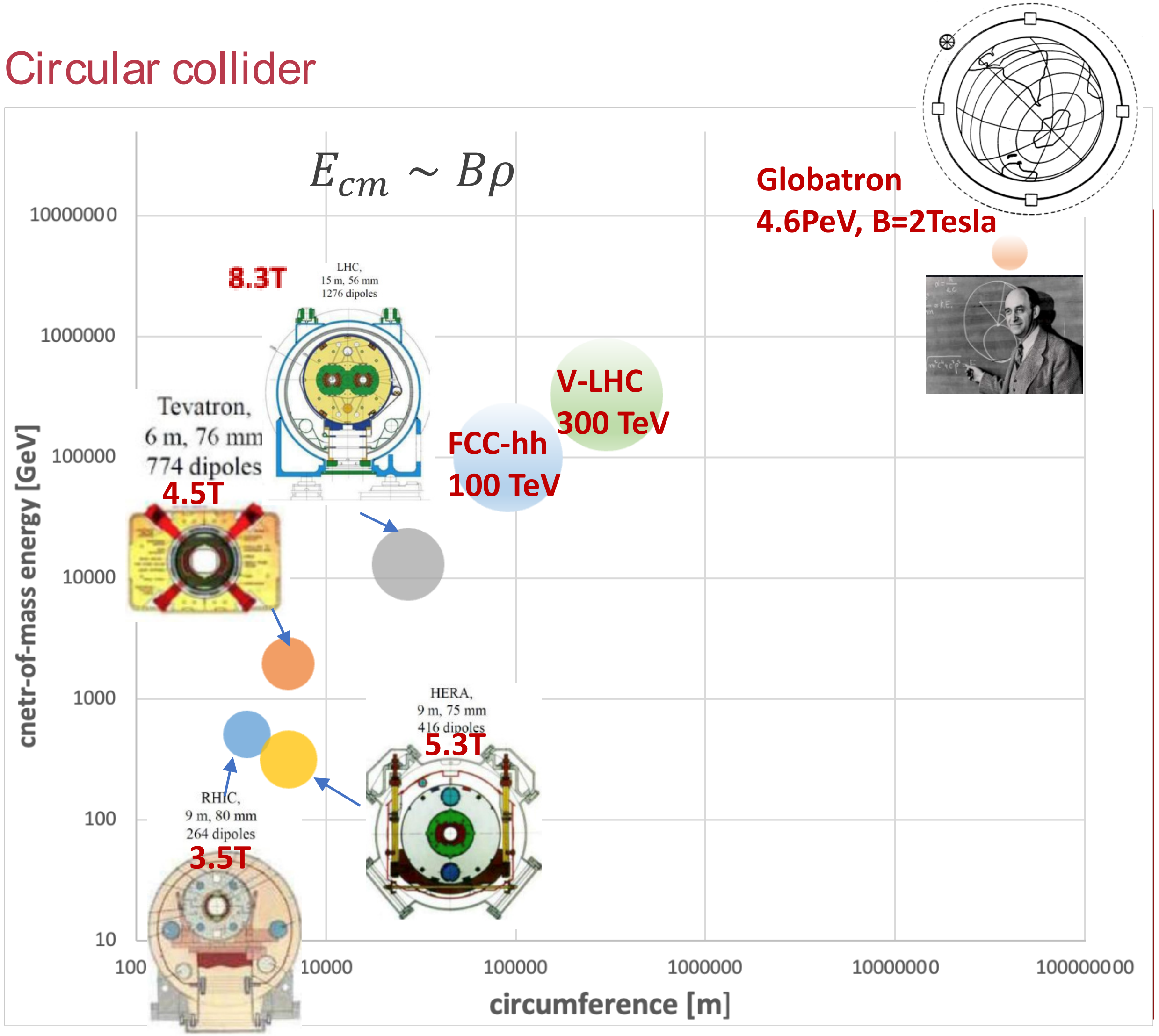

Other limiting factors

Energy loss due to synchrotron radiation

$$U_{SR} = C_\gamma \frac{E^4}{\rho} = 88.46 \frac{\mathrm{r_0}}{\mathrm{r_e}} \left(\frac{\mathrm{m_e}}{\mathrm{m_0}}\right)^3 \frac{E^4[GeV]}{\rho[m]}$$

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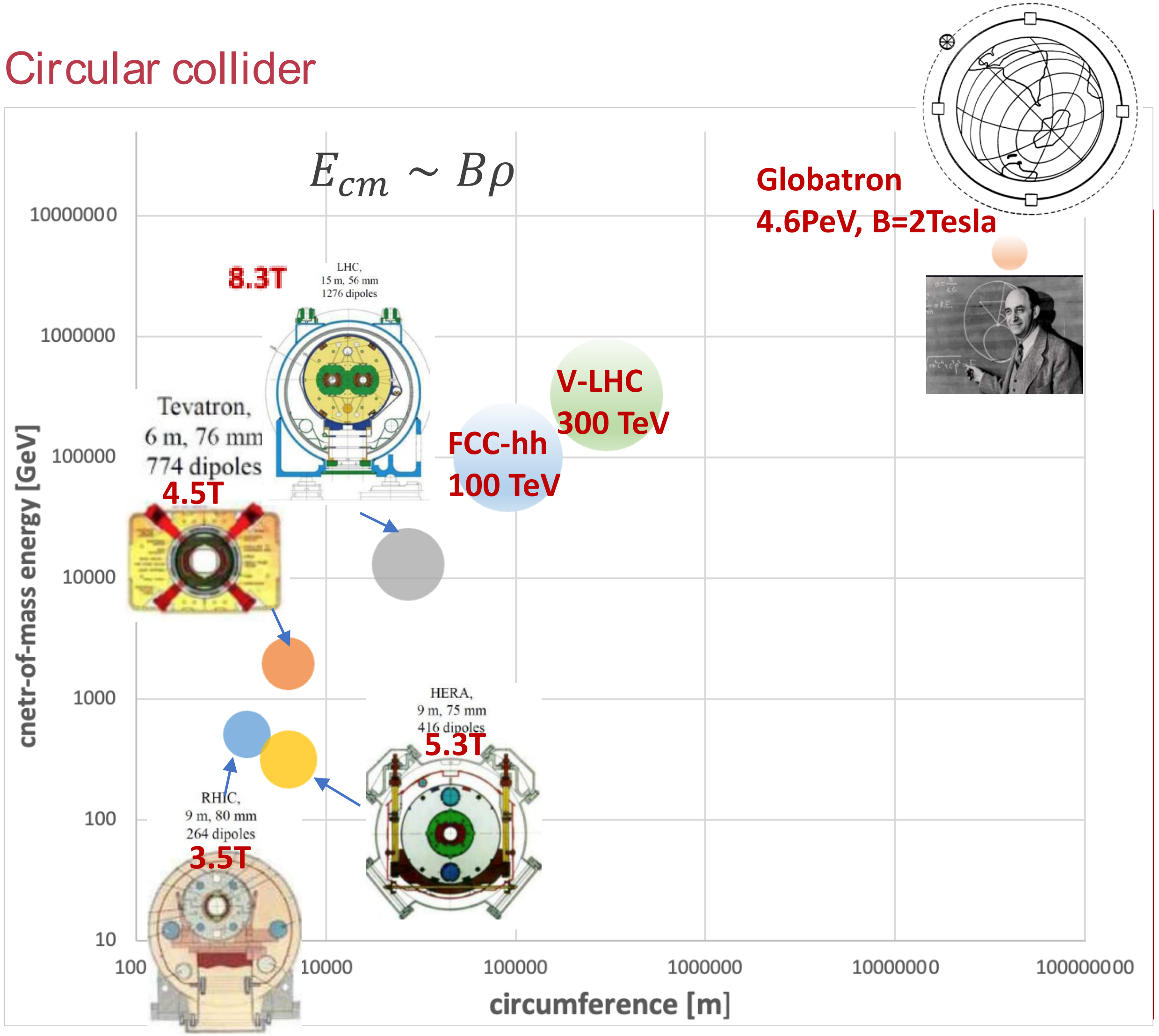

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Energy limit

- For electron/positron: $E_{cm} \leq 500\ GeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- For muon: $E_{cm} \leq 600\ TeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- For proton: $E_{cm} \leq 10\ PeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$

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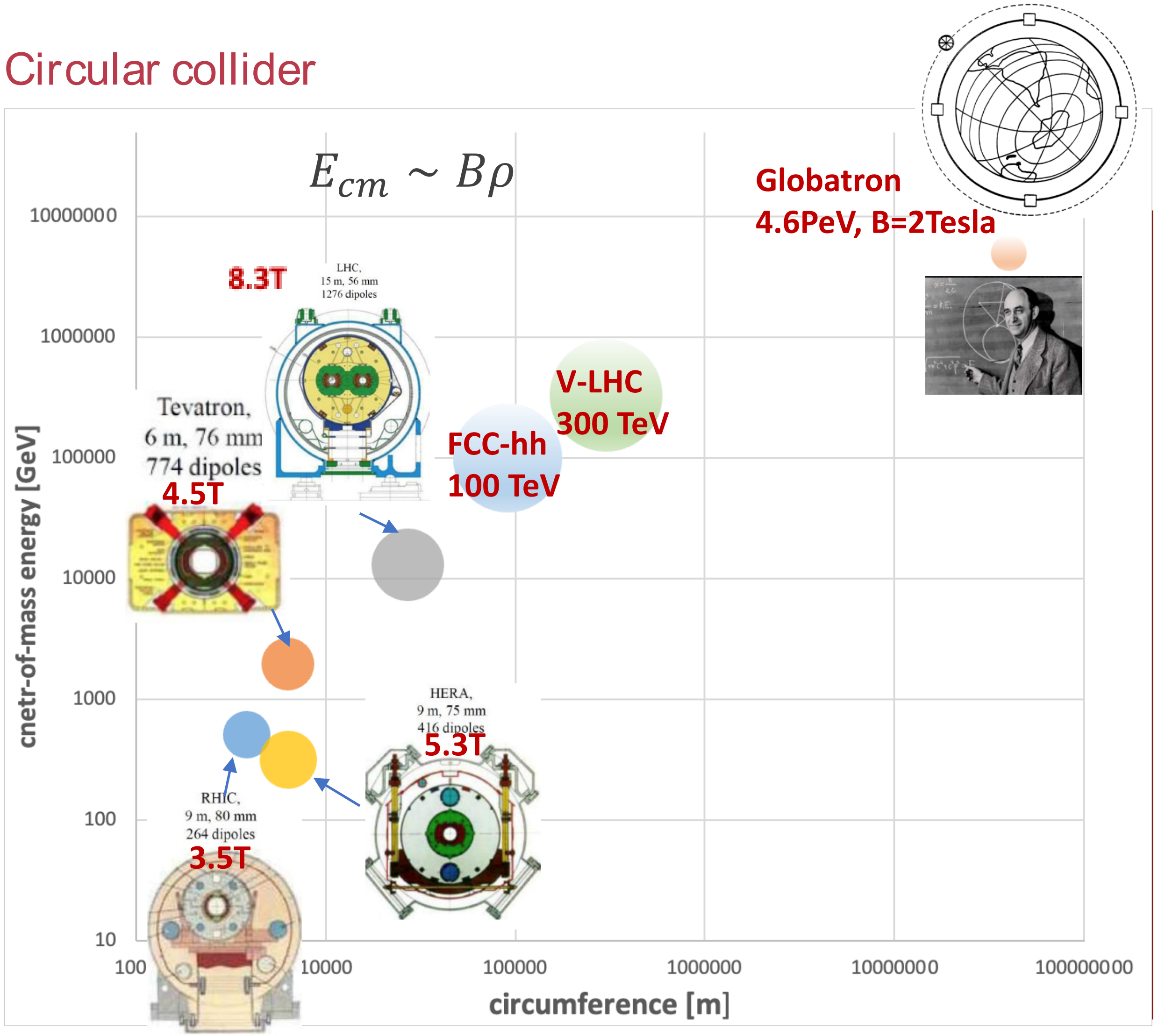

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Production and survival: unstable particles such as muon

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

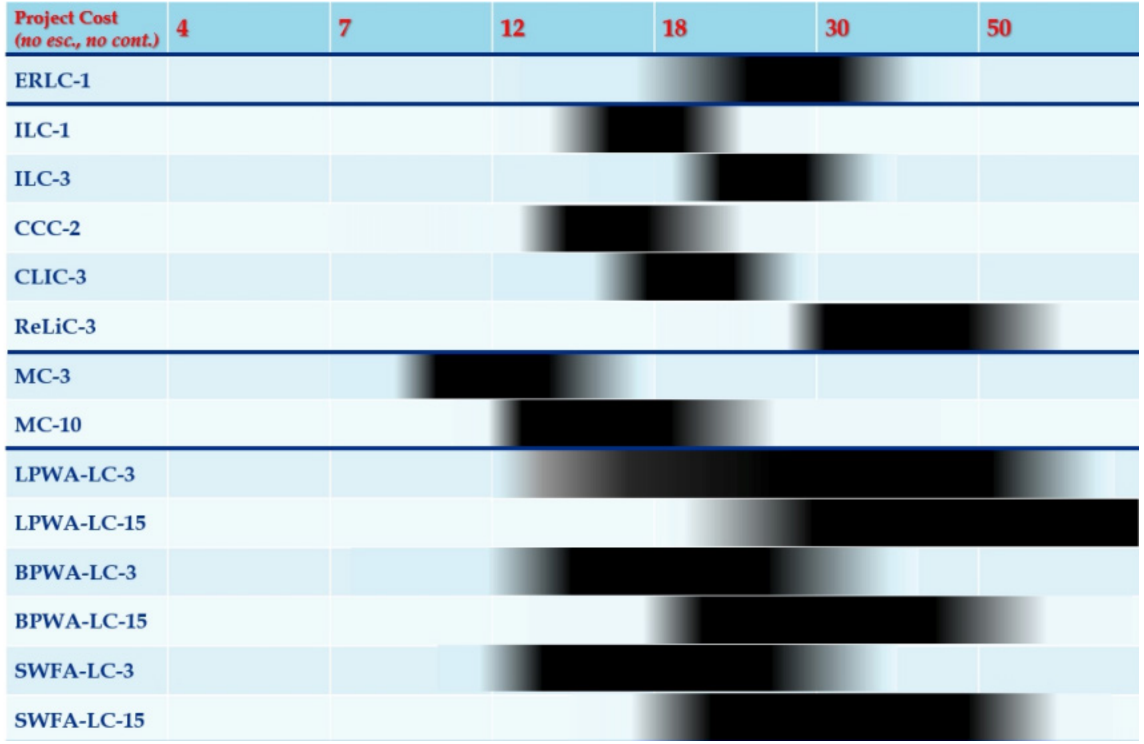
is the lifetime, $\tau_0 \sim 2.2\mu s$ for muons.

Societal sustainability: cost

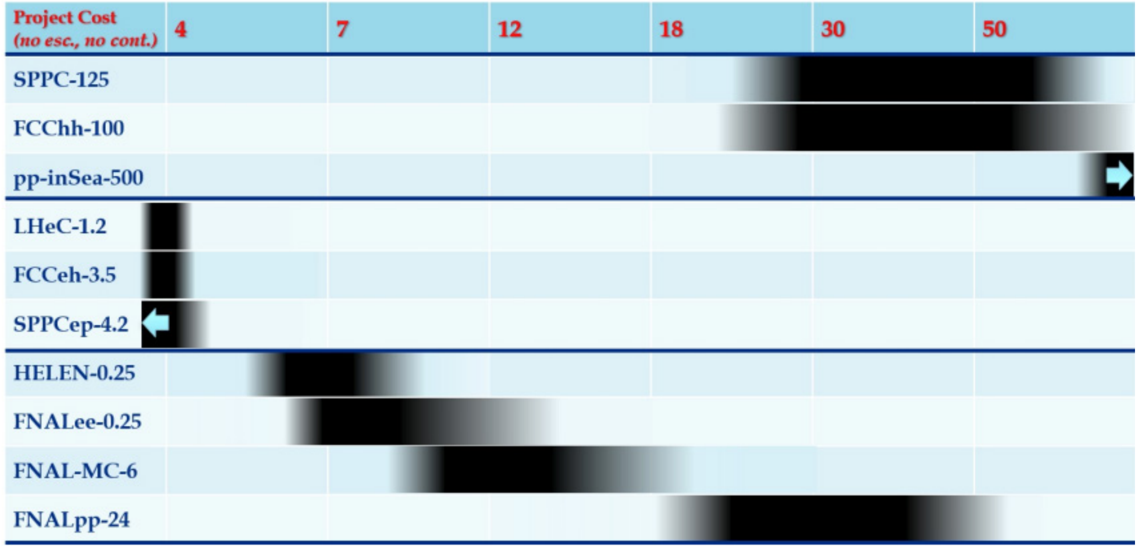
Snowmass Implementation Task Force report:

https://indico.fnal.gov/event/22303/contributions/245261/attachments/157255/205819/2022%2007%2018%20ITF%20Snowmass%20talk.pdf

Multi-TeV lepton collider proposals



Multi-TeV hadron and lepton-hadron collider proposals



Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

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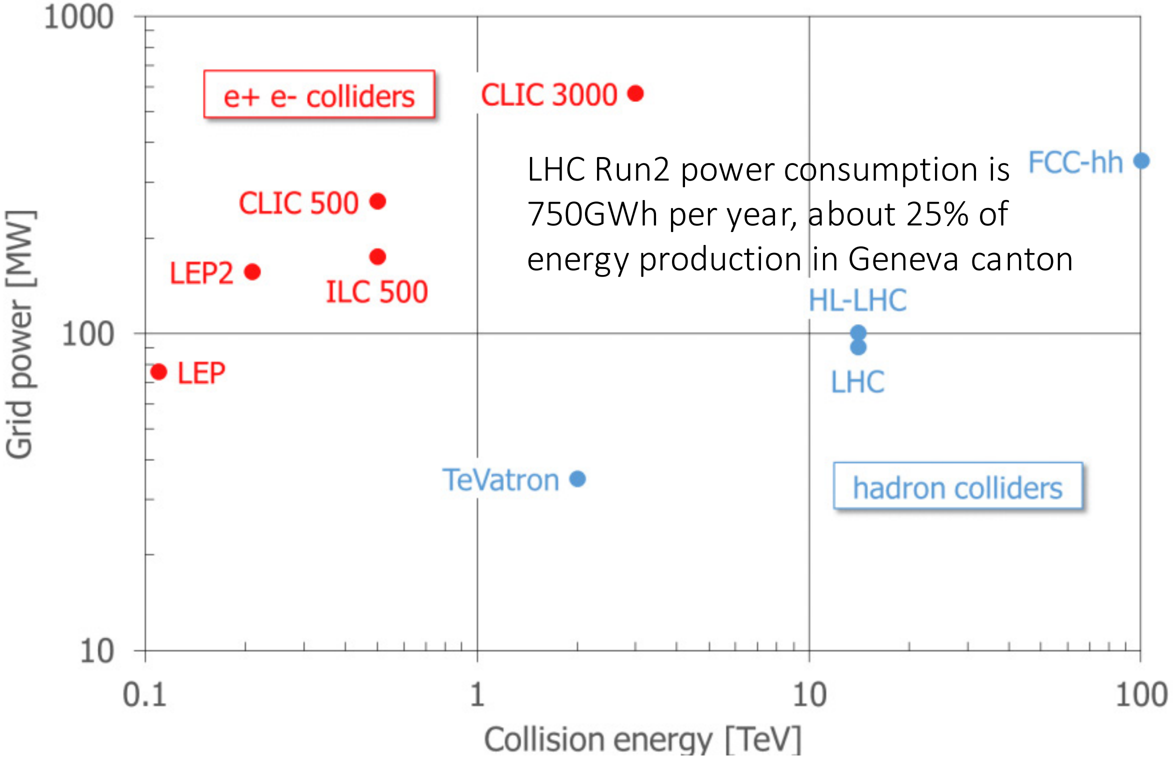
Societal sustainability: power consumption

Snowmass Implementation Task Force report

Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	280	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	14 km	I	I
CLIC (0.38 TeV)	170	13.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	100 km	II	I
ReLiC (0.24 TeV)	370	20 km	II	I
ERLC (0.24 TeV)	250	60 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	3 km	I	II
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	42 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
ReLiC (3 TeV)	~780	360 km	III	I
MC (3 TeV)	~230	10-20 km	II	III
LWFA (3 TeV)	~340	1.3 km	II	I
PWFA (3 TeV)	~230	14 km	II	II
SWFA (3 TeV)	~170	18 km	II	II
MC (14 TeV)	~300	27 km	III	III
LWFA $\gamma\gamma$ (15 TeV)	~210	6.6 km	III	I
PWFA $\gamma\gamma$ (15 TeV)	~120	14 km	III	II
SWFA $\gamma\gamma$ (15 TeV)	~90	90 km	III	II
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	110 km	II	III

Power consumption



LHC Run2 power consumption is 750GWh per year, about 25% of energy production in Geneva canton

P. Lebrun, 4th Workshop Energy for Sustainable Science at Research Infrastructures, 23-24 November 2017, Magurele, Romania

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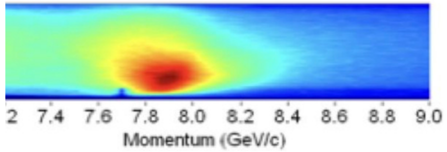
Advanced Acceleration Concept based collider

Plasma based accelerator

- Acceleration gradient:
  - Laser Wake Field Acceleration (LWFA)
    - 8GeV energy gain in 20cm plasma with $3x10^{17}$ cm^{-3} was achieved at BELLA, LBL

A. J. Gonsalves et al. PRL (2019)



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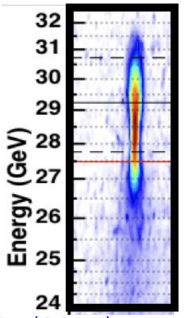
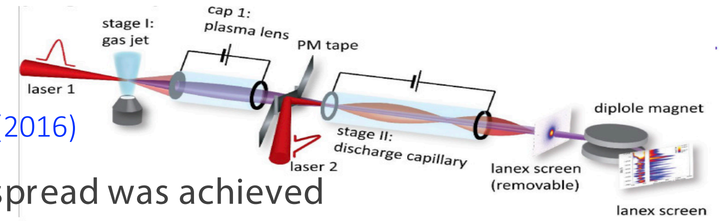


M. Litos et al. PPCF (2015)

- Staging:
  - Proof-of-principle staging of LWFAs (~100 MeV energy gain) using high gradient plasma-lenses



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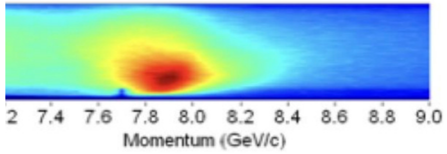

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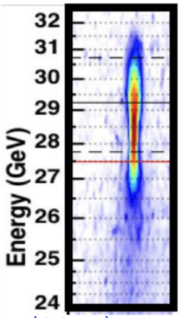

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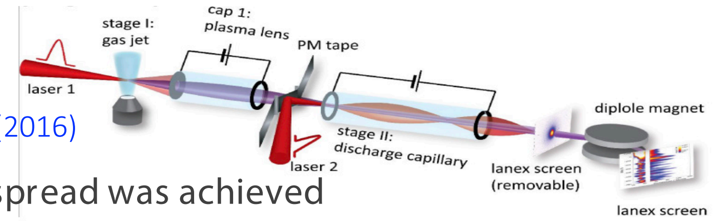

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  - Bunch intensity, momentum spread, emittance

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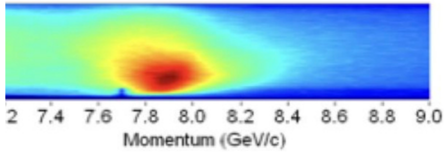

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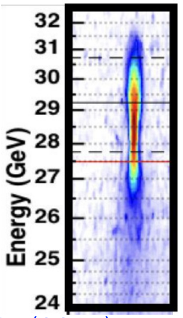

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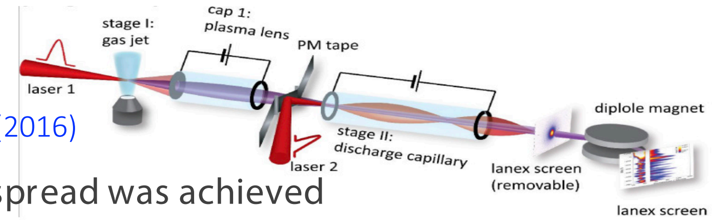

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  - Promising new technology: fiber laser

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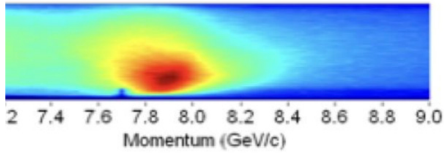

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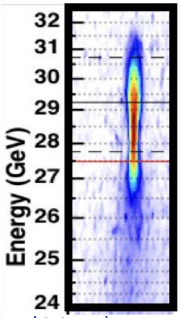

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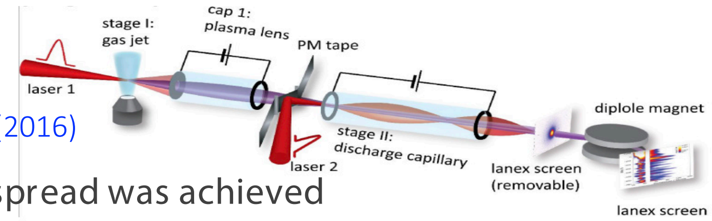

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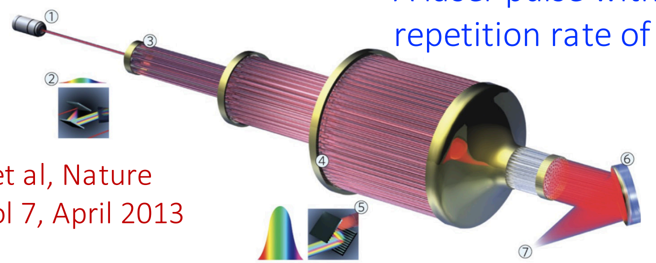
A laser pulse with >10J at a repetition rate of ~10kHz



G. Mourou, et al, Nature Photonics, vol 7, April 2013

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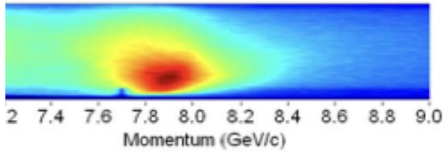

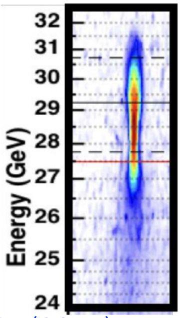

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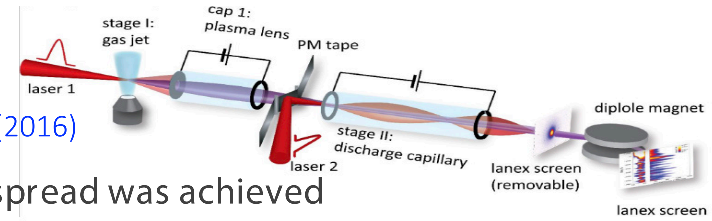

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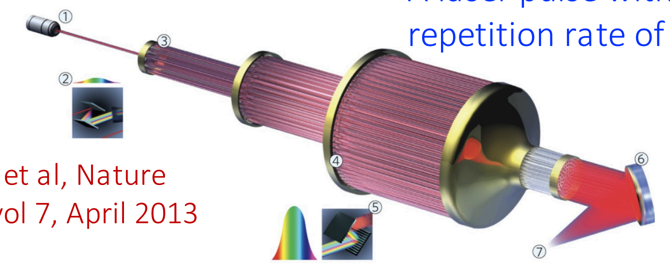
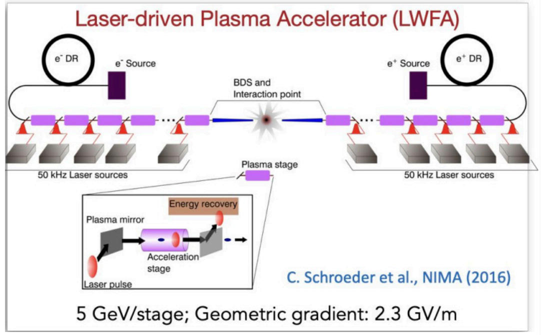
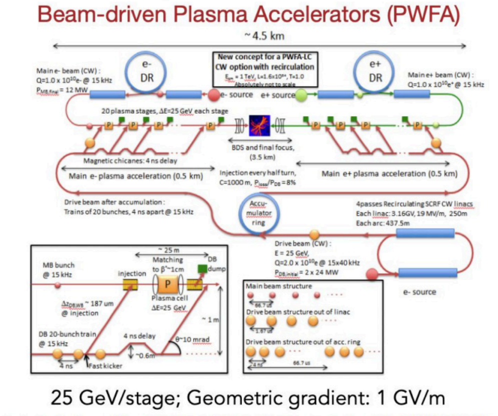


G. Mourou, et al, Nature Photonics, vol 7, April 2013

- Multiple staging





E. Adli et al., arXiv:1308.1145 (2013); Chen et al., arXiv2009:13672

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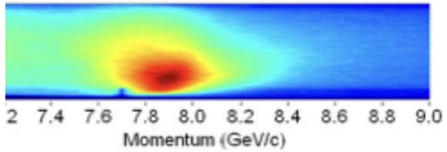

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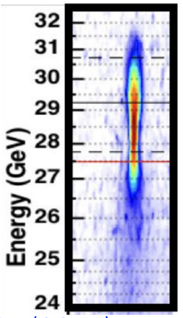

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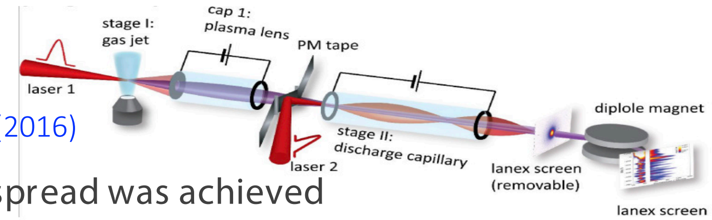

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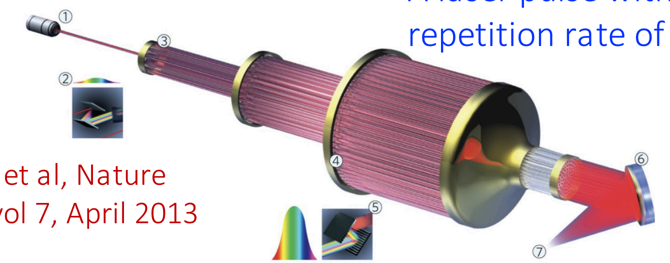

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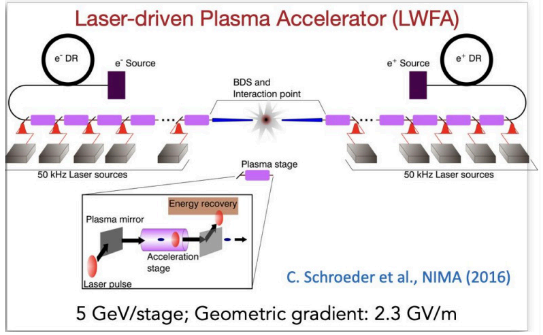
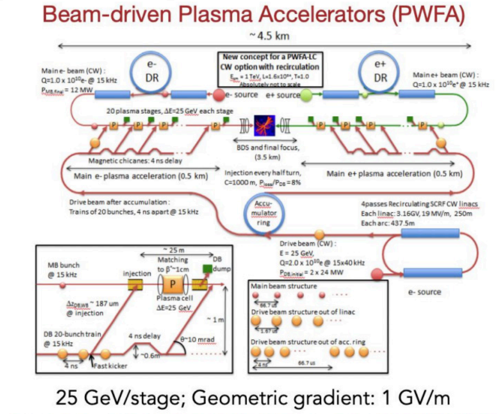
- Multiple staging





E. Adli et al., arXiv:1308.1145 (2013); Chen et al., arXiv2009:13672

- Positron beam for e+e- collider

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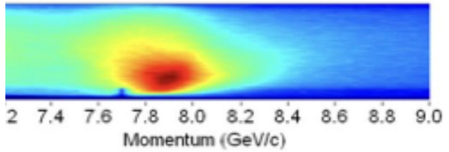
Advanced Acceleration Concept based collider

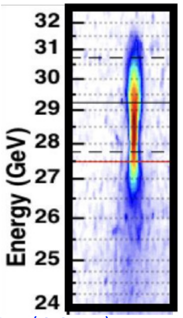
Plasma based accelerator

- Acceleration gradient:
  - Laser Wake Field Acceleration (LWFA)
    - 8GeV energy gain in 20cm plasma with $3x10^{17}$ cm^{-3} was achieved at BELLA, LBL

A. J. Gonsalves et al. PRL (2019)

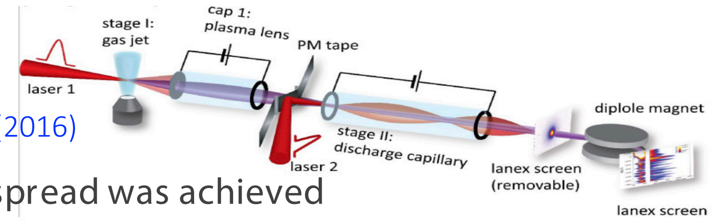


  - Beam driven plasma wakefield(PWFA)
    - 9GeV energy gain in 1.3m was achieved at FACET SLAC



M. Litos et al. PPCF (2015)

- Staging:
  - Proof-of-principle staging of LWFAs (~100 MeV energy gain) using high gradient plasma-lenses



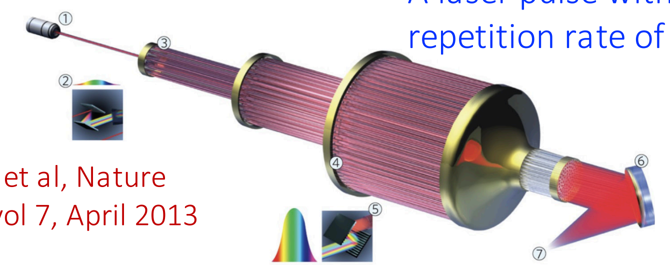
S. Steinke et al. Nature (2016)

- Beam quality: $\sim 10^{-3}$ energy spread was achieved
- Plasma recovery at high repetition rate was recent observed at FLASH Forward, R. D'Arcy et al., Nature (2022)

Challenges towards collider

- Beam quality
  - Bunch intensity, momentum spread, emittance
- High average power laser at high repetition rate
  - Promising new technology: fiber laser

A laser pulse with >10J at a repetition rate of ~10kHz



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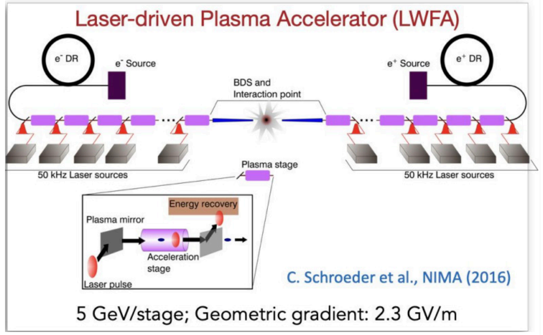

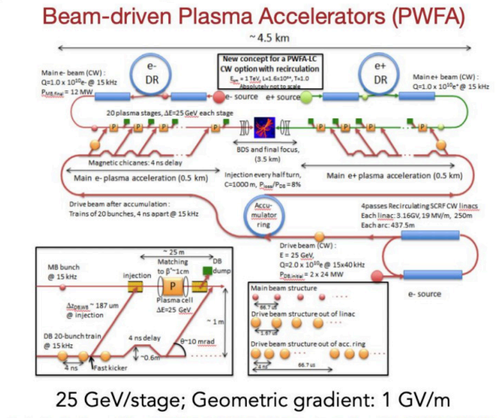

E. Adli et al., arXiv:1308.1145 (2013); Chen et al., arXiv2009:13672

- Positron beam for e+e- collider
- Beamstrahlung

Ultimate Collider: at the quantum limit

Emittance of a bunch of N_b fermion particles at quantum limit is

$$\gamma\epsilon_{x,y,z}^{QM} = \sqrt[3]{N_b}\frac{\bar{\lambda}_p}{4};$$

Where N_b is the number of particles, $\bar{\lambda}_p$ is the particle's de Broglie wavelength. For electron/positron, $\bar{\lambda}_p \sim 0.4$ pm. With such emittance, the corresponding luminosity for 1 TeV center-of-mass collision is on the order of $10^{51} cm^{-2} s^{-1}$, orders of beyond what is desired for the next energy frontier colliders.

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Grand challenge:

In addition to generating such beam and preserving through acceleration and transport, the required technique for beam diagnostics and steering is not yet within the reach of current accelerator and beam technology.

SLAC

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Ultimate energy is the Planck energy:

$$E_{pl} = \sqrt{\hbar C^5/G} \simeq 1.2 \times 10^{19}\text{GeV}$$

where G is the gravitational constant.

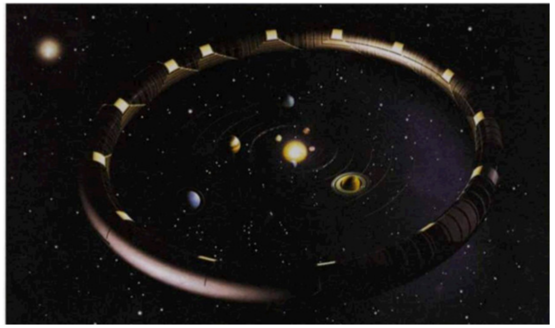
The acceleration gradient at the Sauter-Schwinger limit is

$$E_{max} = \frac{m_e^2 c^3}{q_e \hbar} \simeq 1.3 \times 10^9 \text{ GV/m},$$

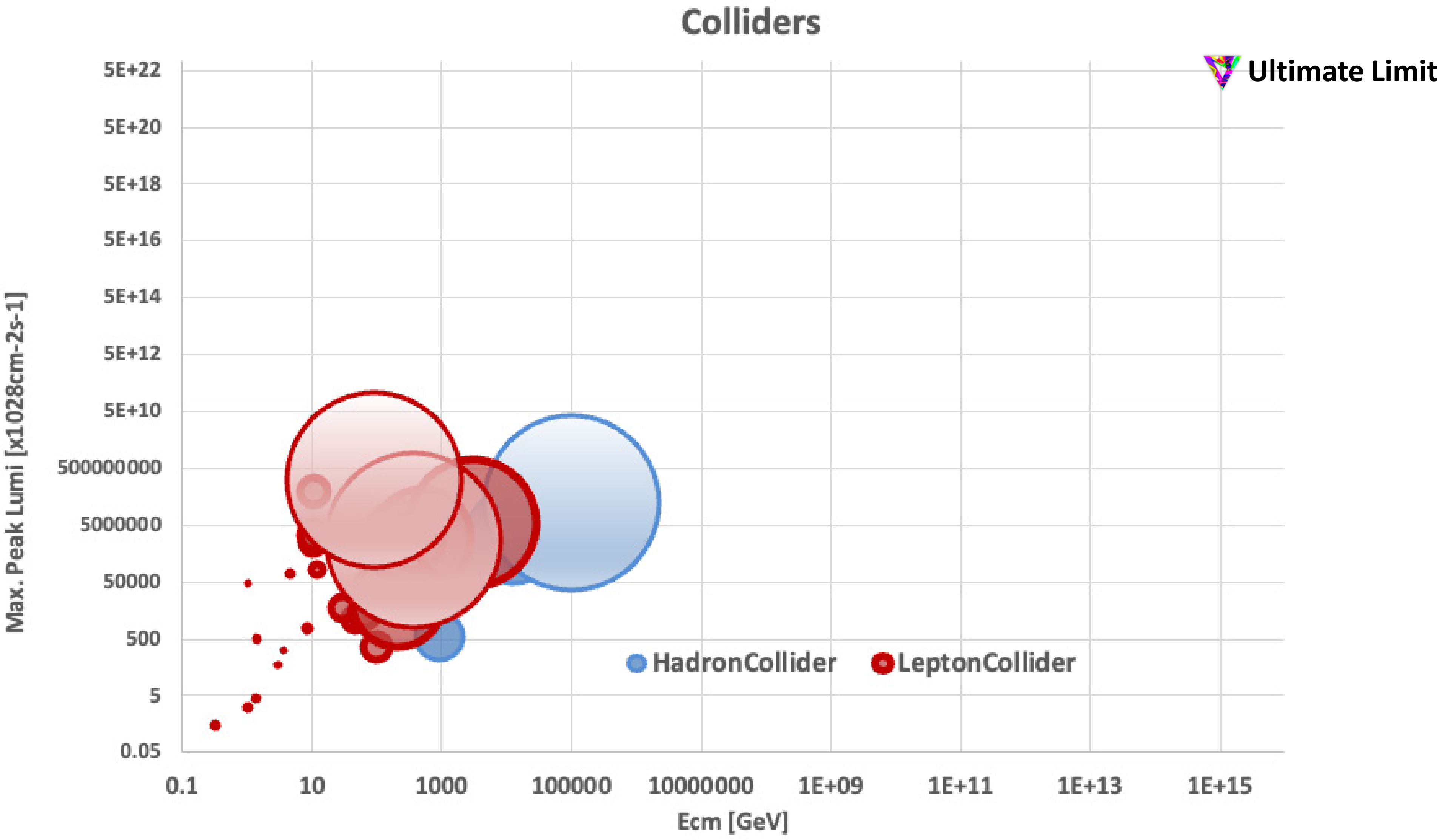
which means one needs about 10^{10} m long linac or globatron with $> 10^{12}$T magnets, which is beyond the Sauter-Schwinger limit!

Hawking's solartron!

"The Universe in a Nutshell", by Stephen William Hawking, Bantam, 2001



Looking forward



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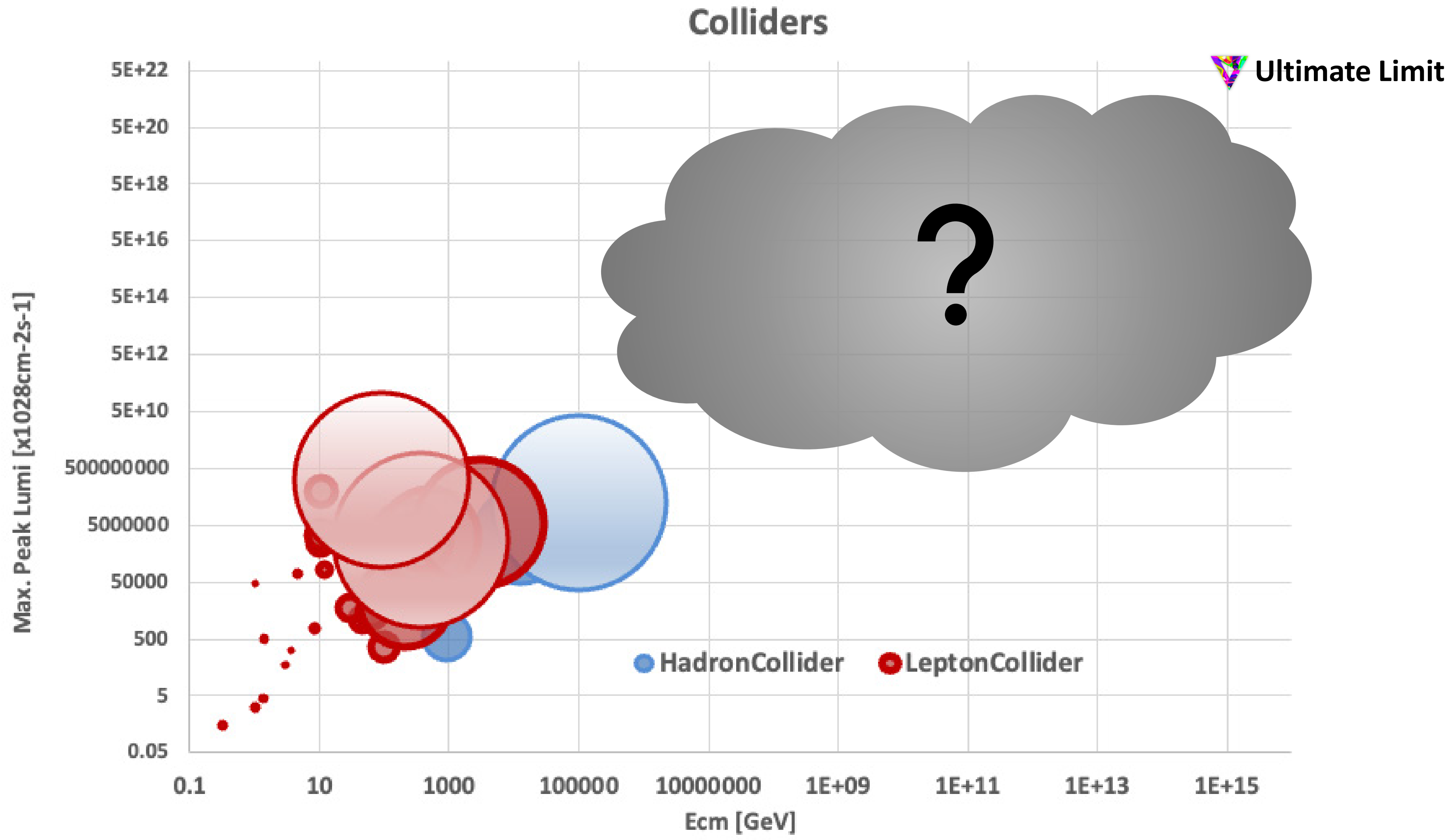

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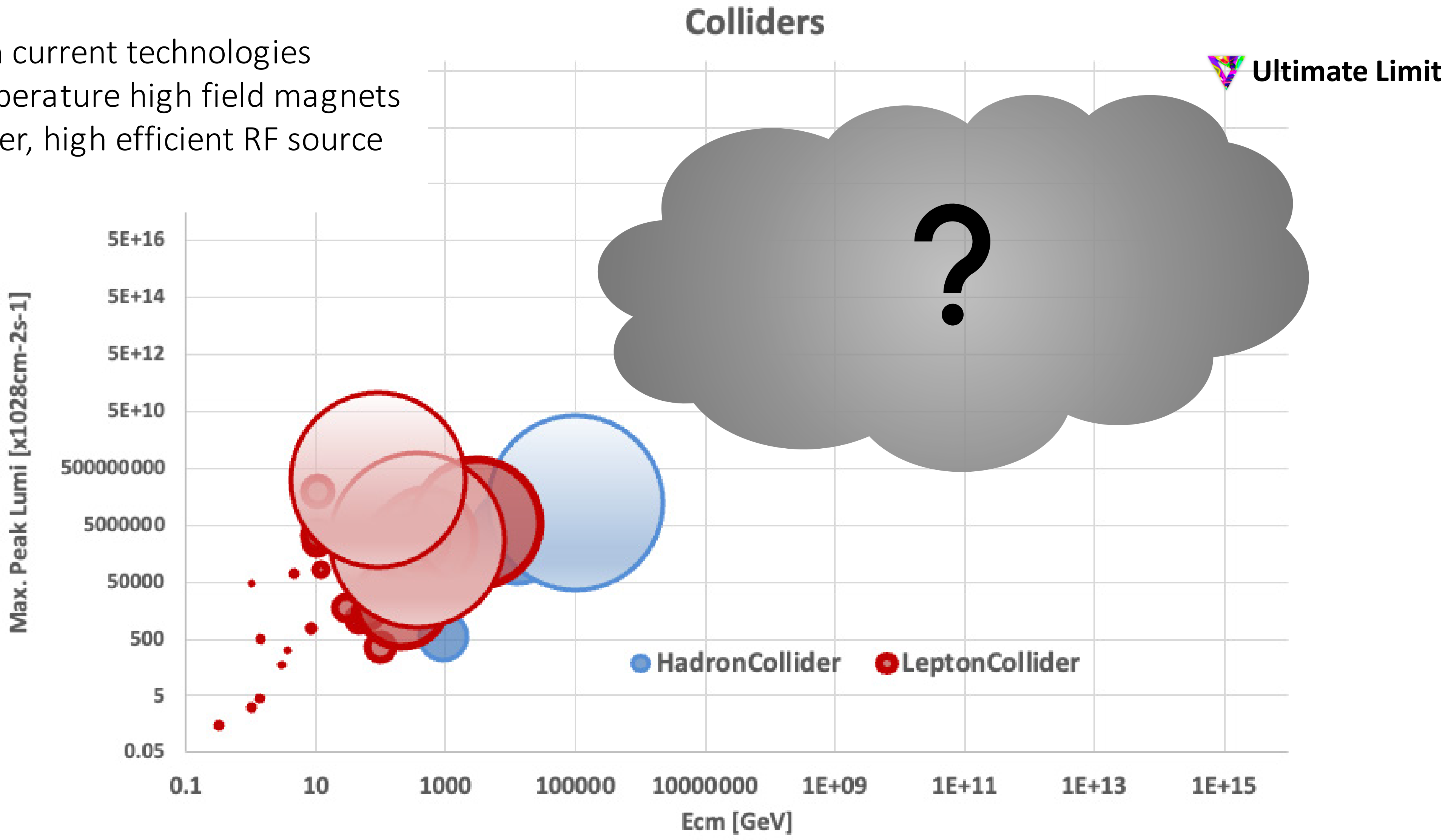
Looking forward

Great leap in current technologies

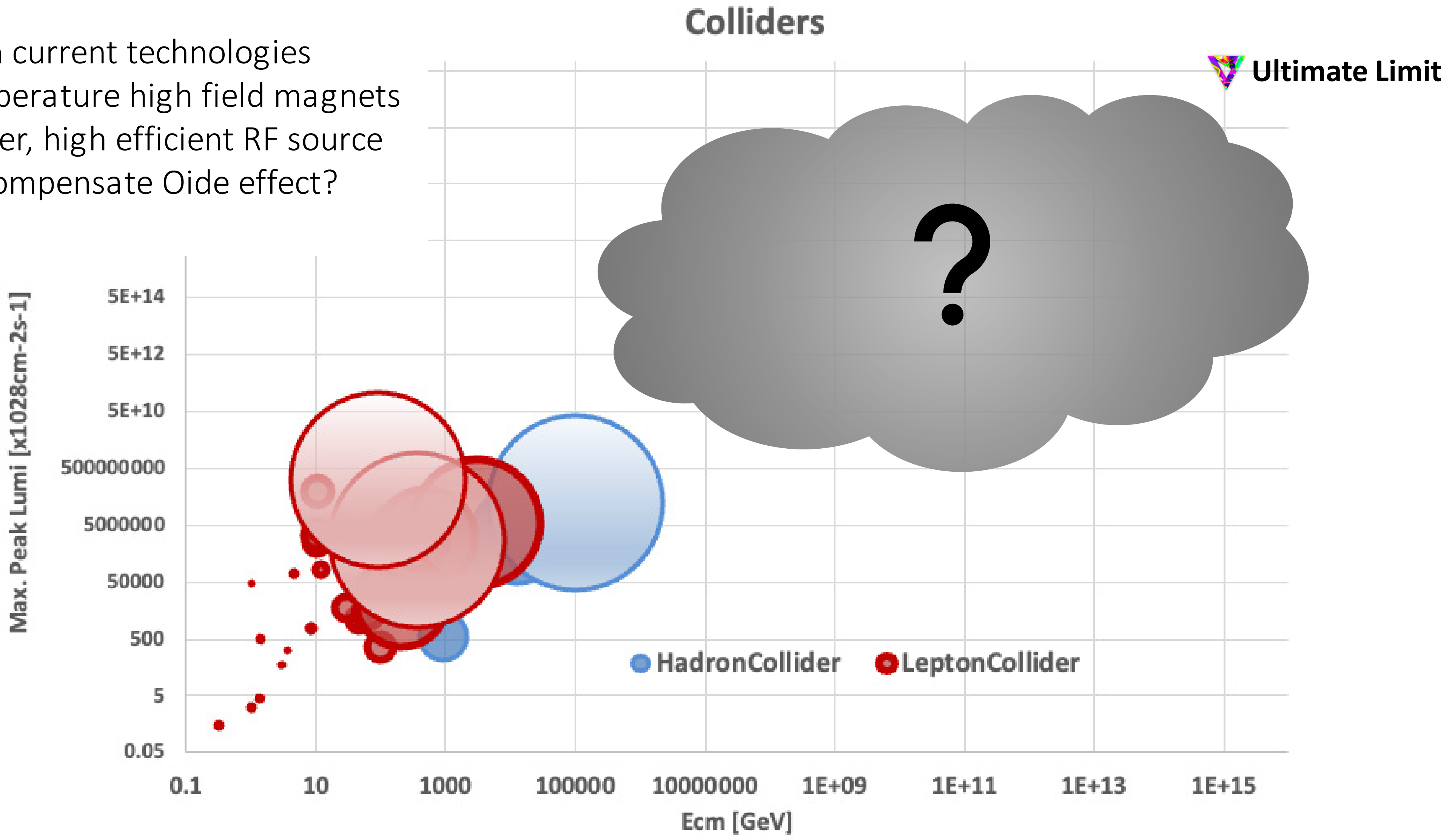
- High temperature high field magnets
- High power, high efficient RF source



Looking forward

Great leap in current technologies

- High temperature high field magnets
- High power, high efficient RF source
- Can we compensate Oide effect?



Looking forward

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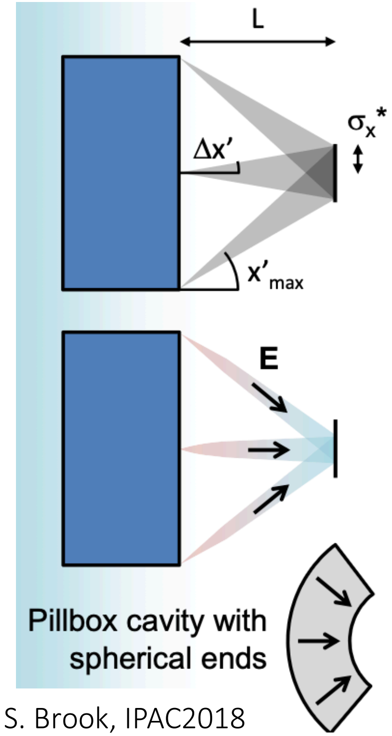
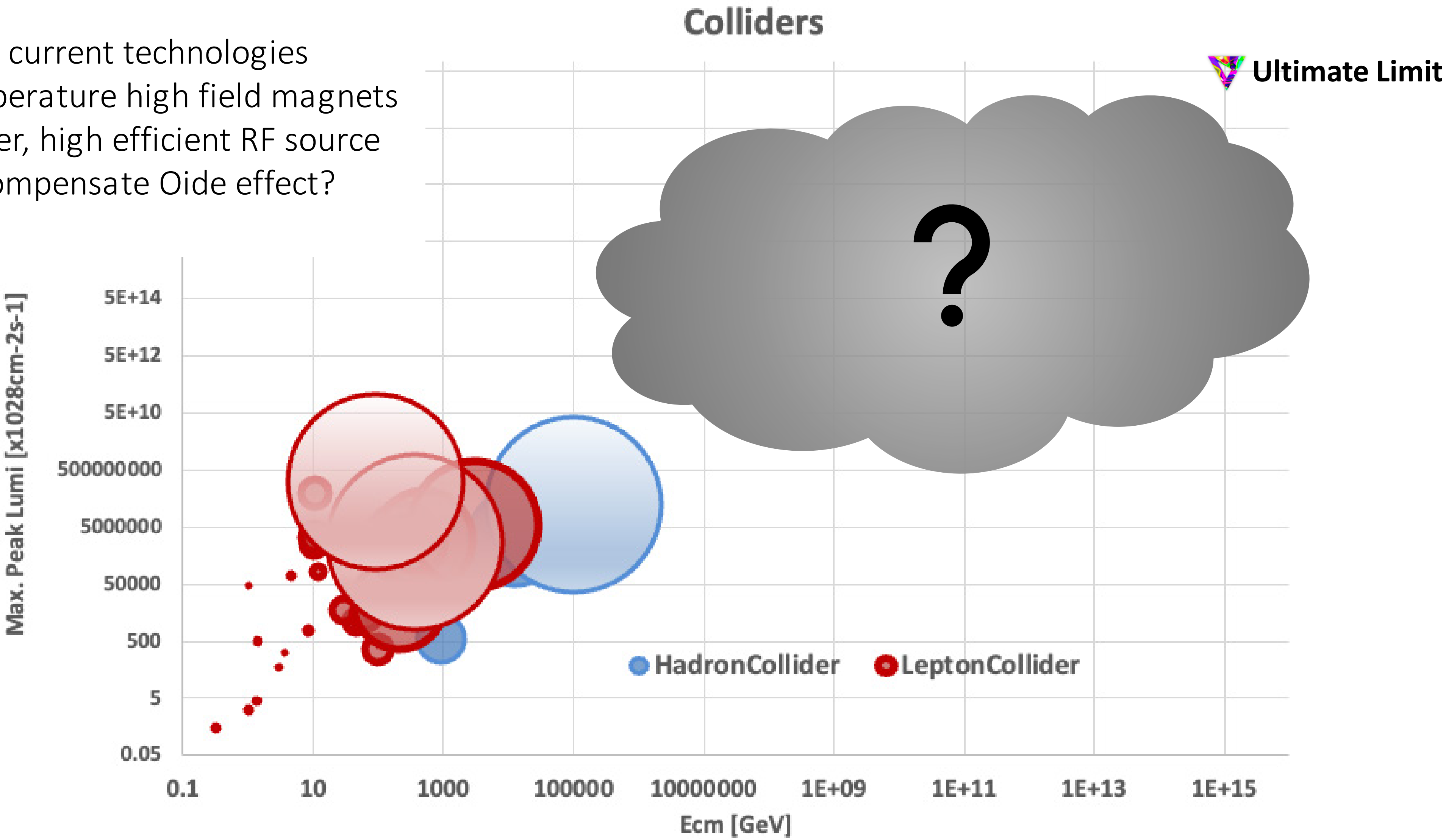


S. Brook, IPAC2018



Looking forward

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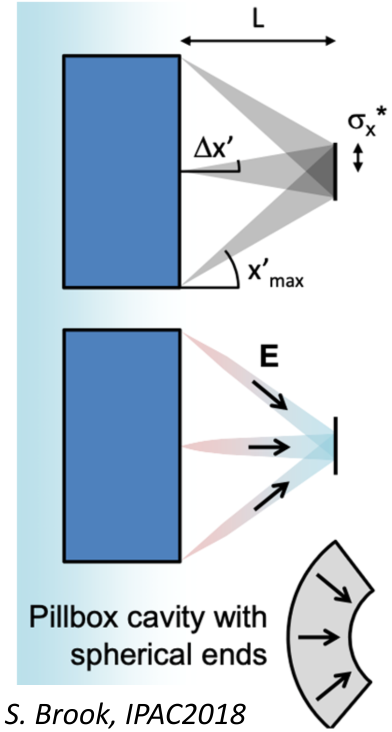
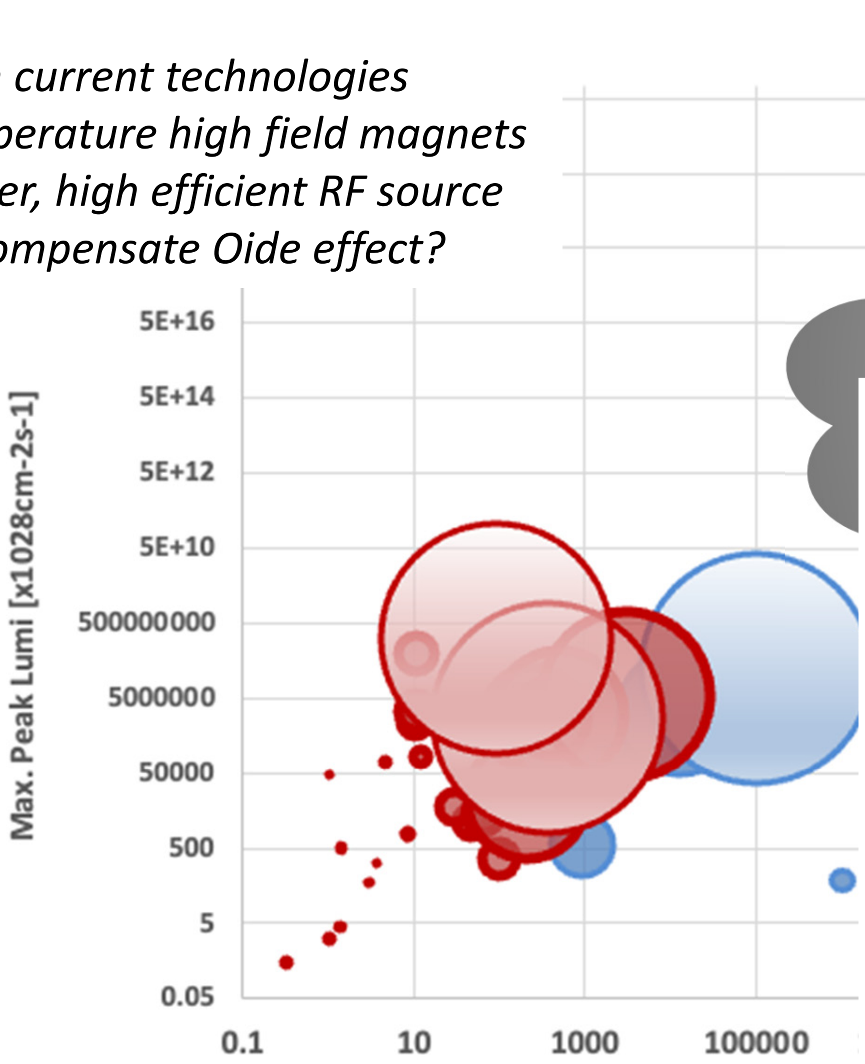
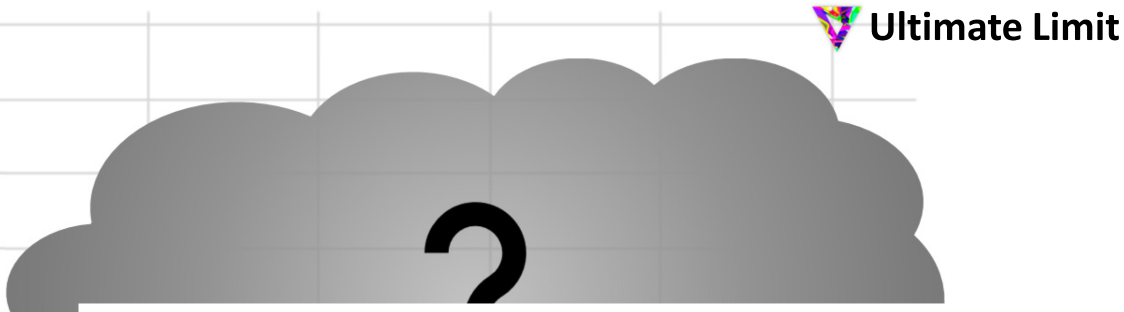


S. Brook, IPAC2018





Disruptive approaches

- *Crystal channeling/nano tube for accelerating and/or focusing positively charged particles, such as muons*
  - *~0.1– 10s TeV/m acceleration gradient*
  - *Quantum luminosity*

$$L^{QM} = f_{rep}\frac{n_{ch}N_c^2\sqrt{KE}}{2\pi\hbar c}$$

Chen, Physics Limit of Ultimate Beams Workshop series, Feb. 2021,
Chen, Noble, "Crystal channel collider: Ultra-high energy and luminosity in the next century", (1998)
Shiltsev, Phys. Uspekhy 55 (2012), 965

- *Crystalline-beam collider*

  J. Wei, A. Sessler, 6th EPAC, 1998, p862

- *Blackhole factory to approach Planck energy*
- *Mössbauer acceleration*

  S. Brook, IPAC2018

NEWS | 08 August 2022

Particle physicists want to build the world's first muon collider

The accelerator would smash together this heavier version of the electron and, researchers hope, discover new particles.

Elizabeth Gibney

There are several possible accelerators that could follow the Large Hadron Collider. Credit: Denis Balibouse/Reuters/Alamy