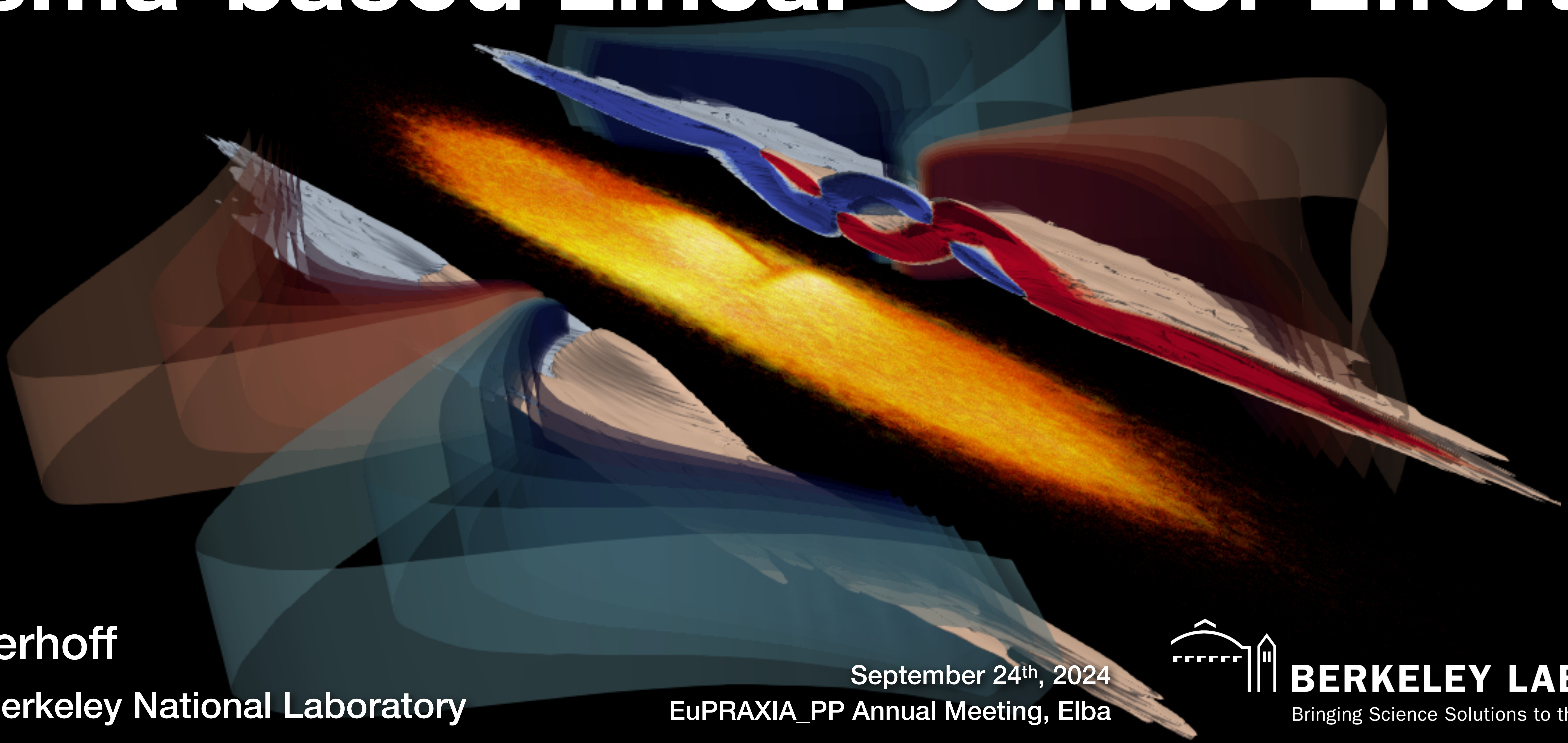
Overview of Plasma-based Linear Collider Efforts



Jens Osterhoff

Lawrence Berkeley National Laboratory

September 24th, 2024
EuPRAXIA_PP Annual Meeting, Elba

BERKELEY LAB
Bringing Science Solutions to the World

Work supported by the U.S. DOE, Office of Science, Office of High Energy Physics, under Contract No. DE-AC02-05CH11231

Figure credit: A. Formenti, R. Lehe (LBNL)

Particle colliders have been growing in size

Magnet technology and synchrotron radiation cause unfavorable scaling to higher energies

SppS (1981): 1.1 km radius
p^+/p^-, 900 GeV CM

HERA (1992): 1.0 km
$p^+/(e^-$ or $e^+)$, 320 GeV CM

Tevatron (1992): 0.95 km
p^+/p^-, 2 TeV CM

LEP (1989): 4.3 km
e^+/e^-, 209 GeV CM

LHC (2008): 4.3 km
p^+/p^+, 13.6 TeV CM

ISR (1971): 75 m
p^+/p^+, 62 GeV CM

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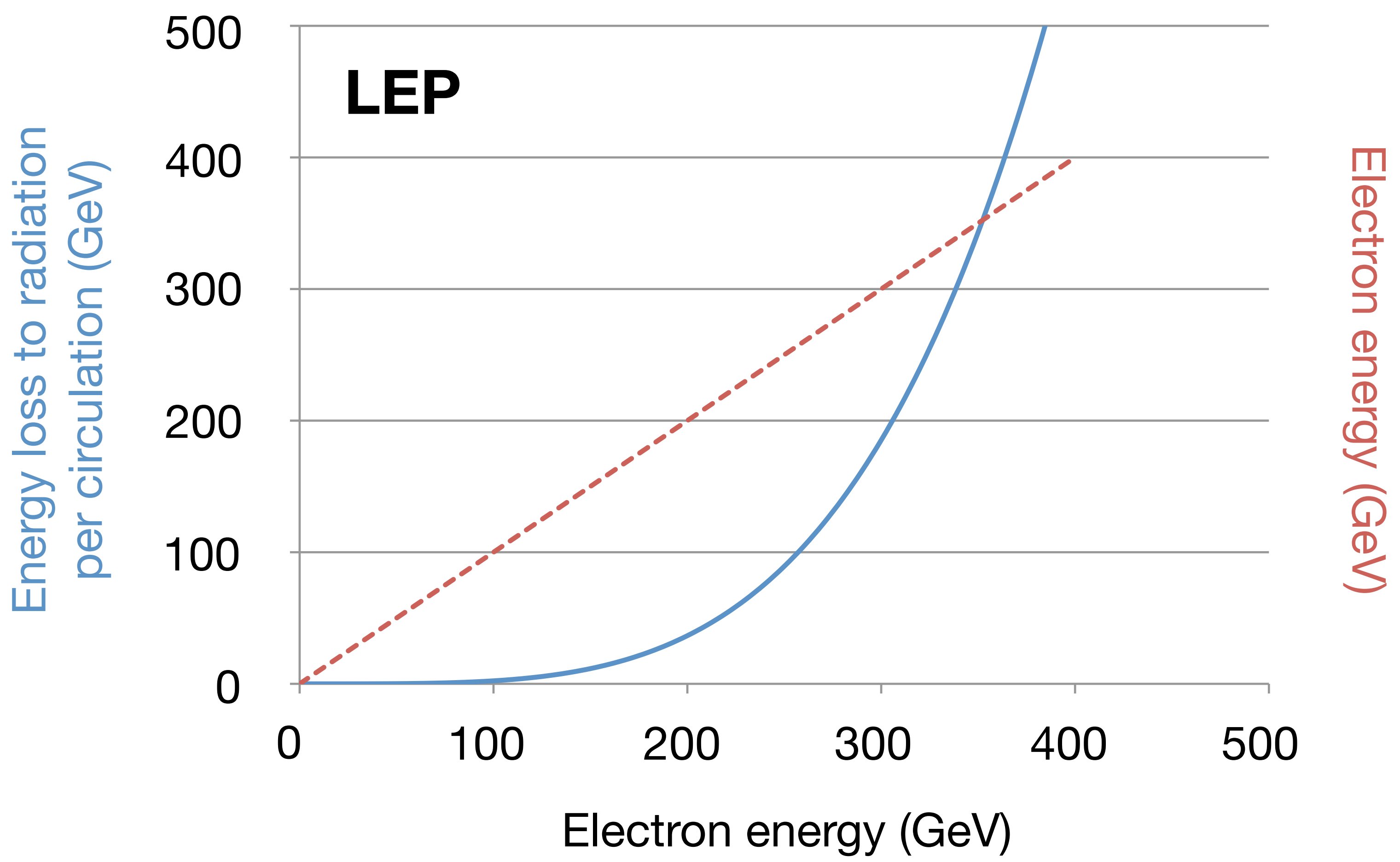
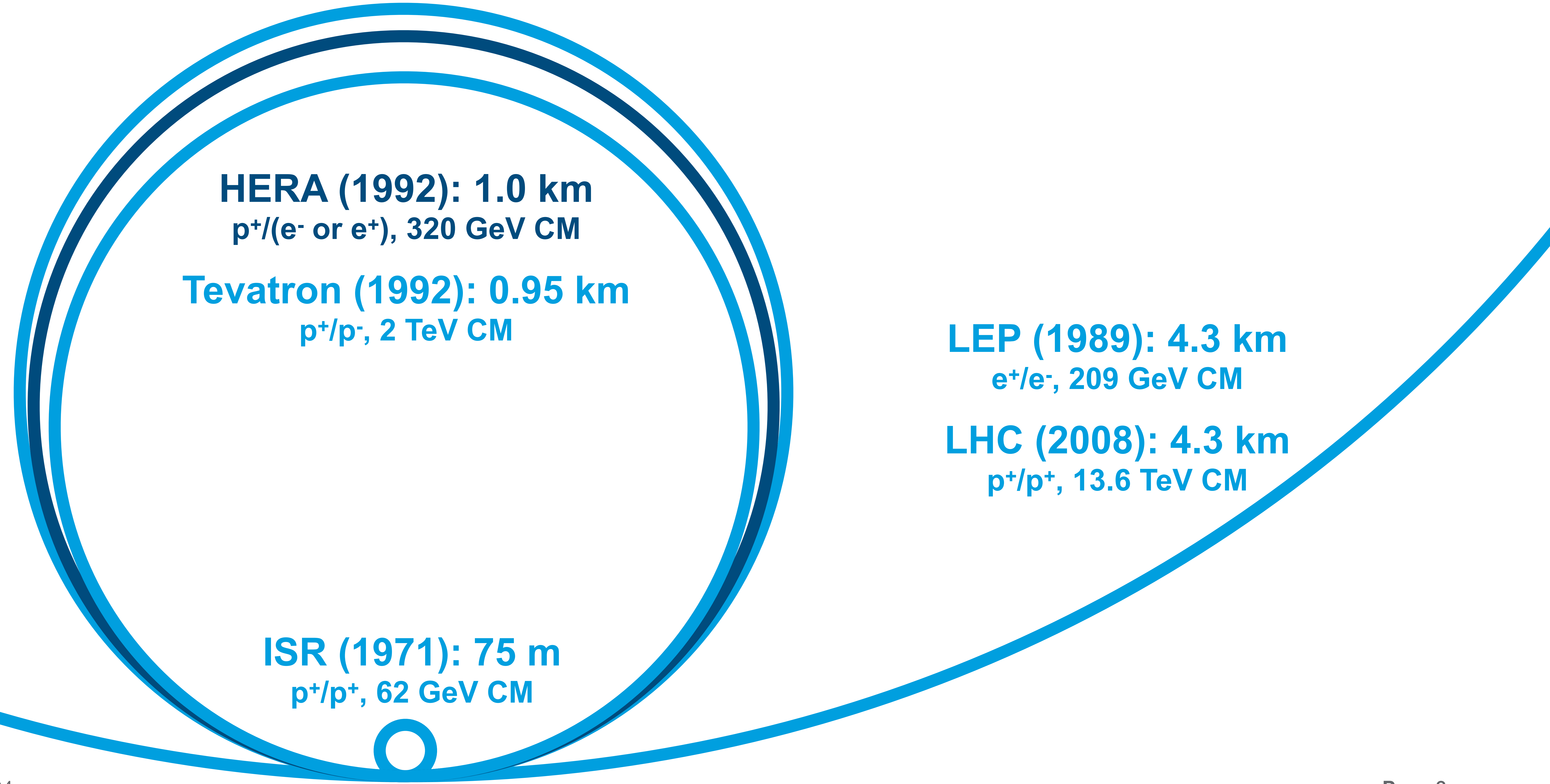


$$\Delta W_{syn} \propto \frac{1}{r^2}\frac{W_{kin}^4}{(m_e c^2)^4}$$



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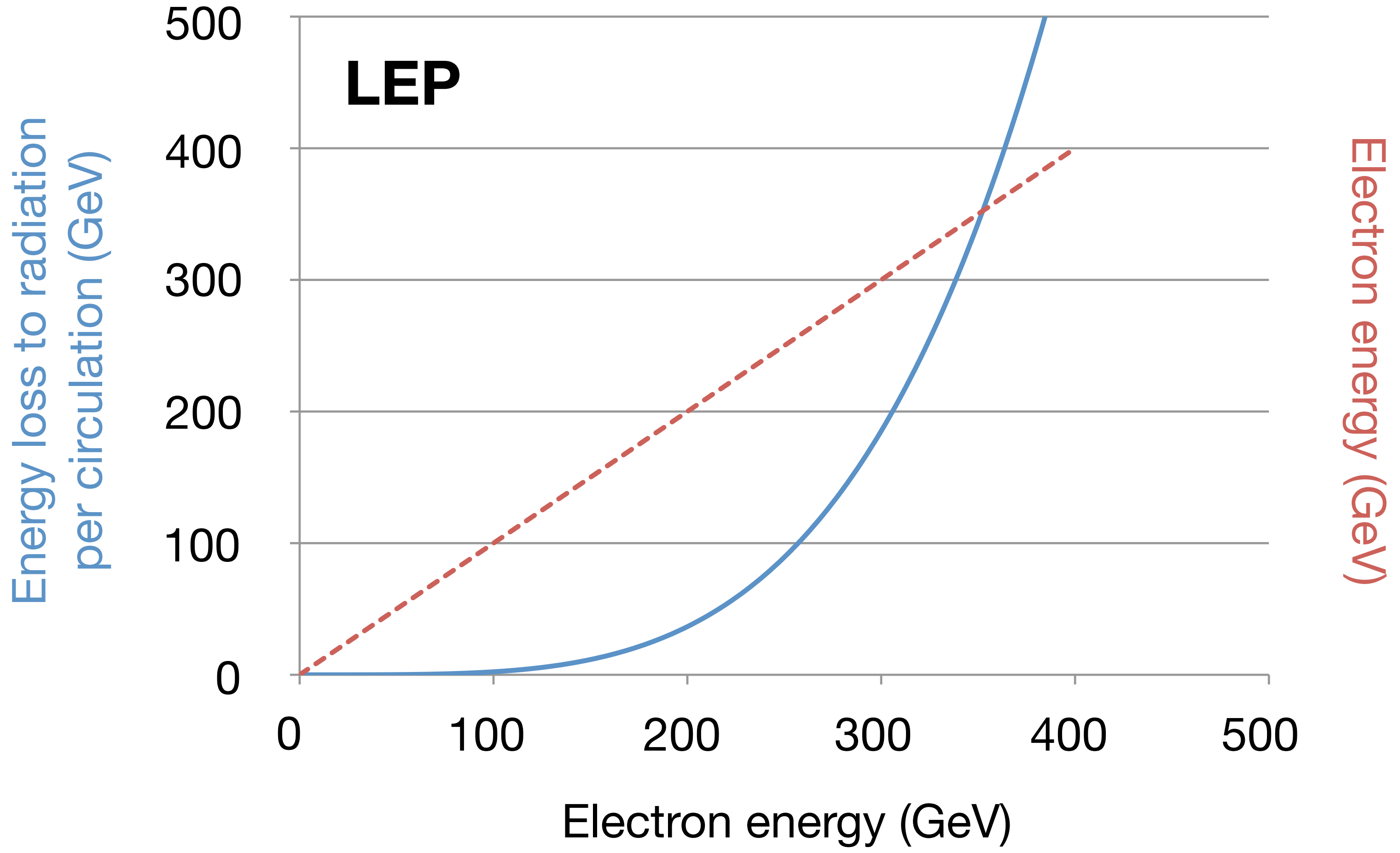

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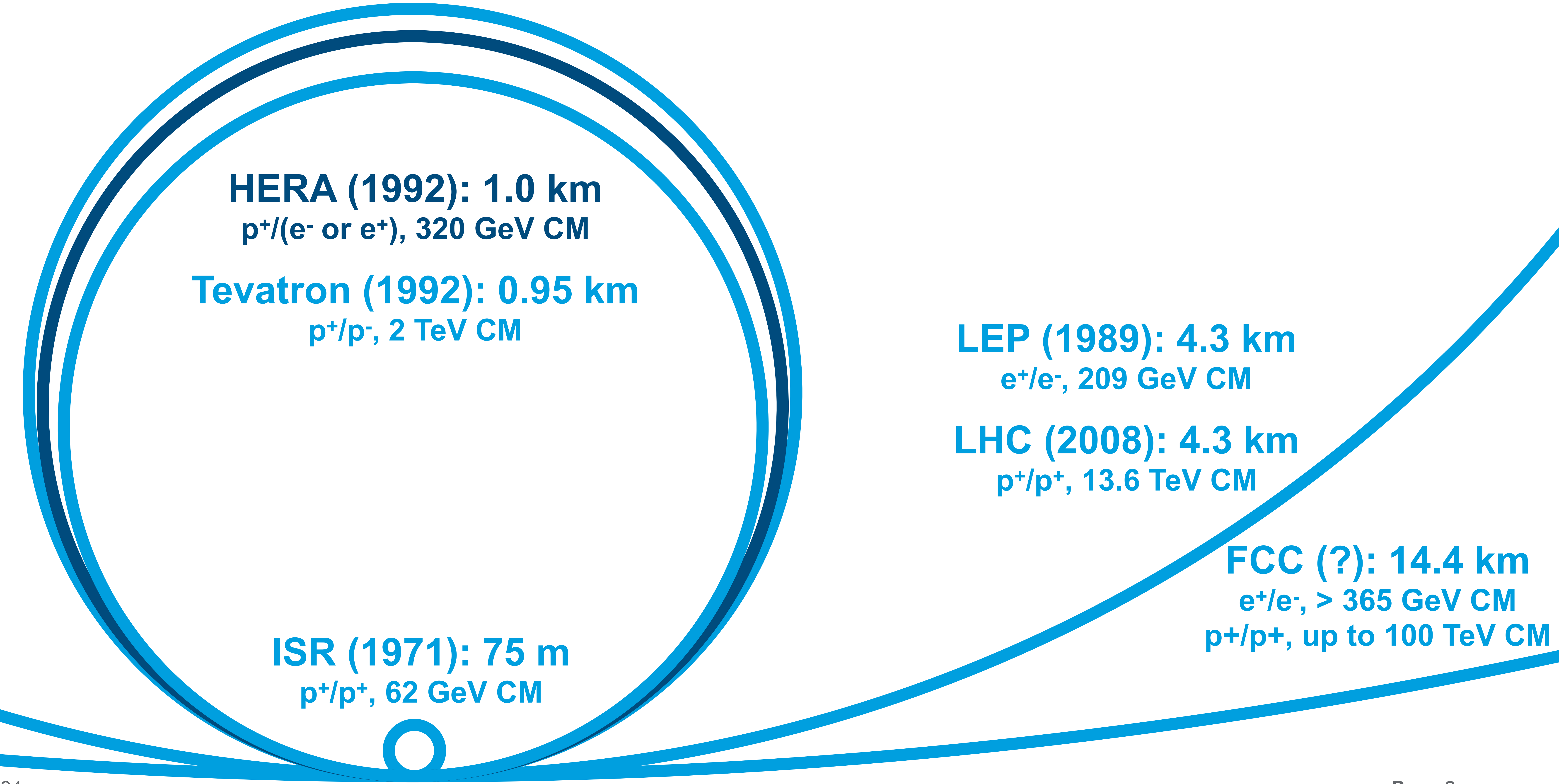

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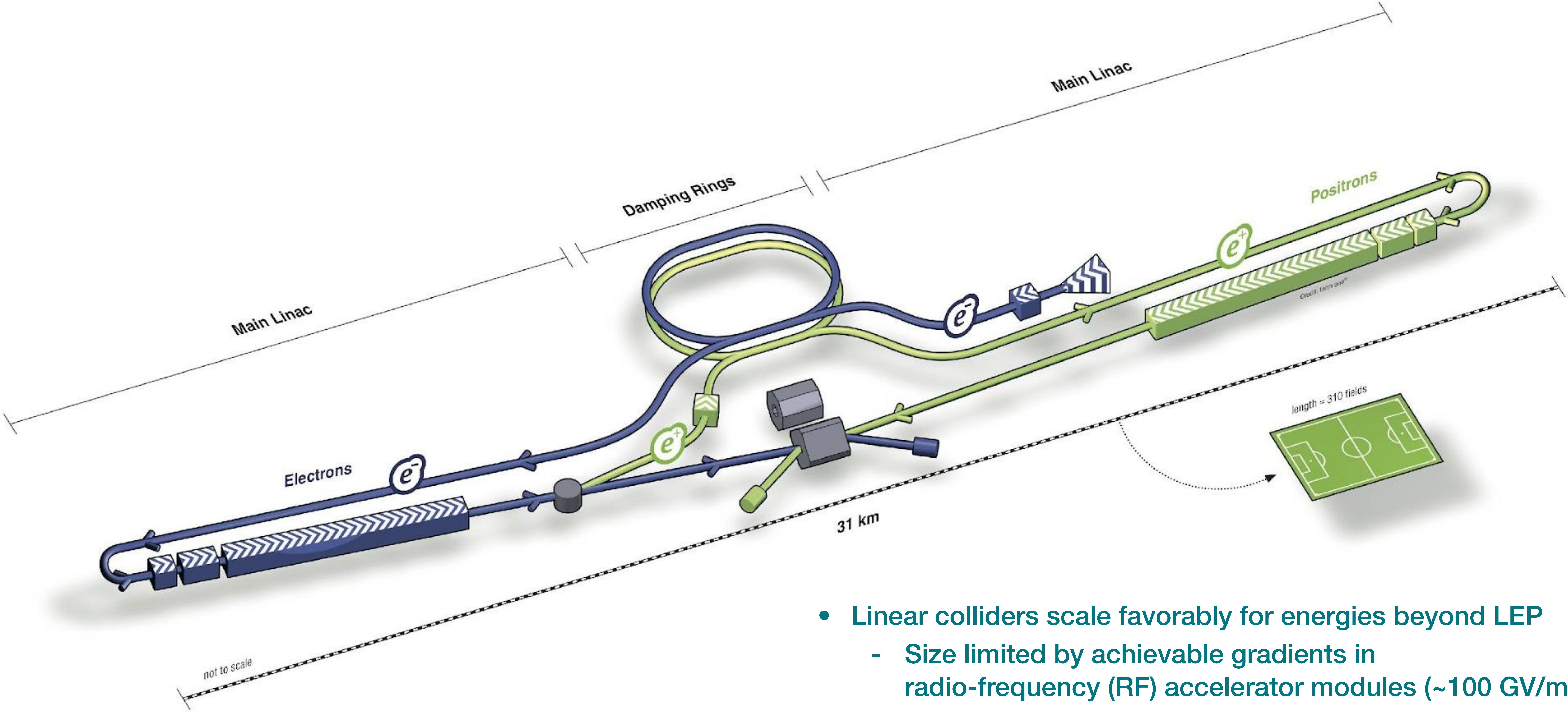
FCC (?): 14.4 km
e^+/e^-, > 365 GeV CM
p+/p+, up to 100 TeV CM

ISR (1971): 75 m
p^+/p^+, 62 GeV CM

The next step for electron/positron colliders could be linear

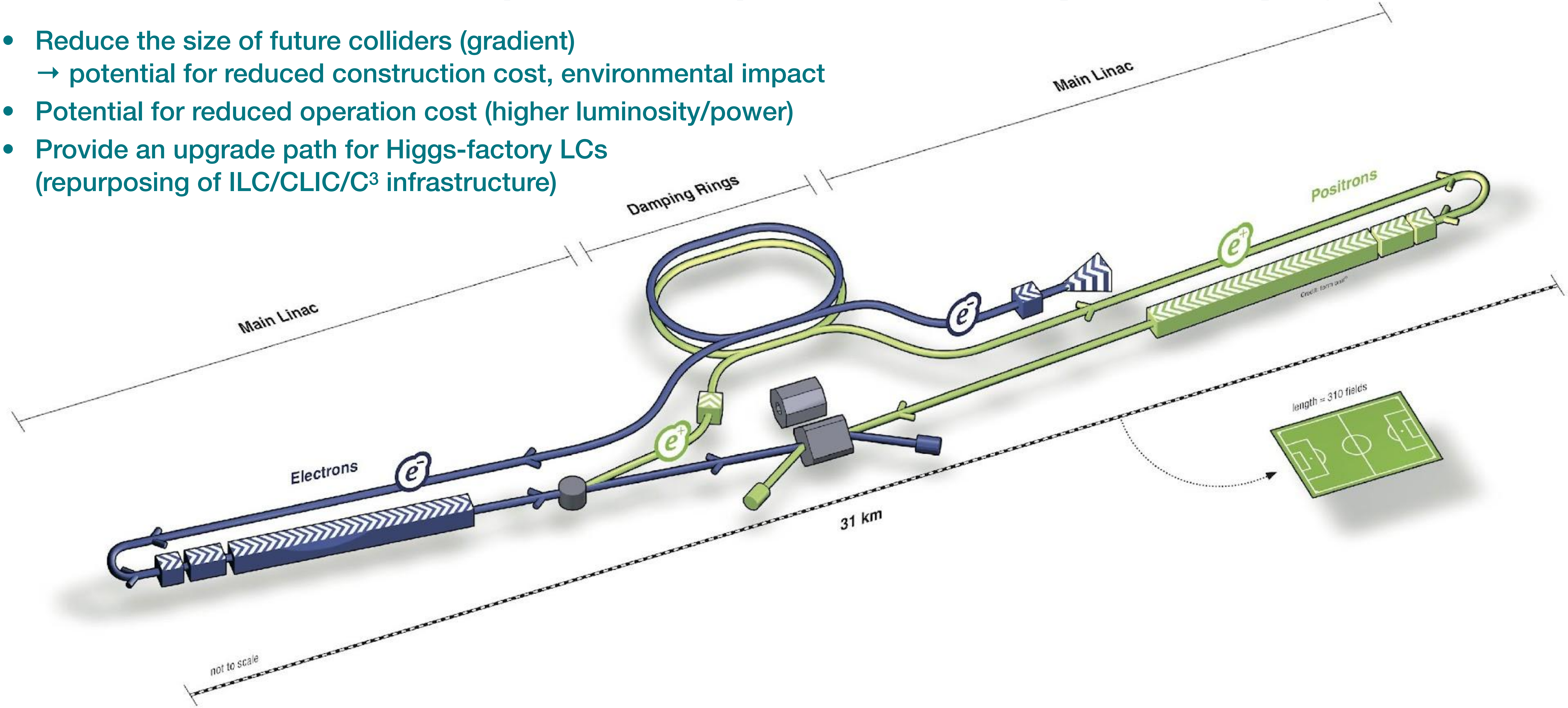


ILC / 500 GeV / 31 km

- Linear colliders scale favorably for energies beyond LEP
  - Size limited by achievable gradients in radio-frequency (RF) accelerator modules (~100 GV/m)
  - Main RF-options: ILC, CLIC, C^3
- Still a significant investment $\mathcal{O}$ (10^{10} Euro) and scale (10’s km)

Plasma accelerator (> 1 GV/m) mission for particle physics

- Reduce the size of future colliders (gradient)
  → potential for reduced construction cost, environmental impact
- Potential for reduced operation cost (higher luminosity/power)
- Provide an upgrade path for Higgs-factory LCs
  (repurposing of ILC/CLIC/C³ infrastructure)



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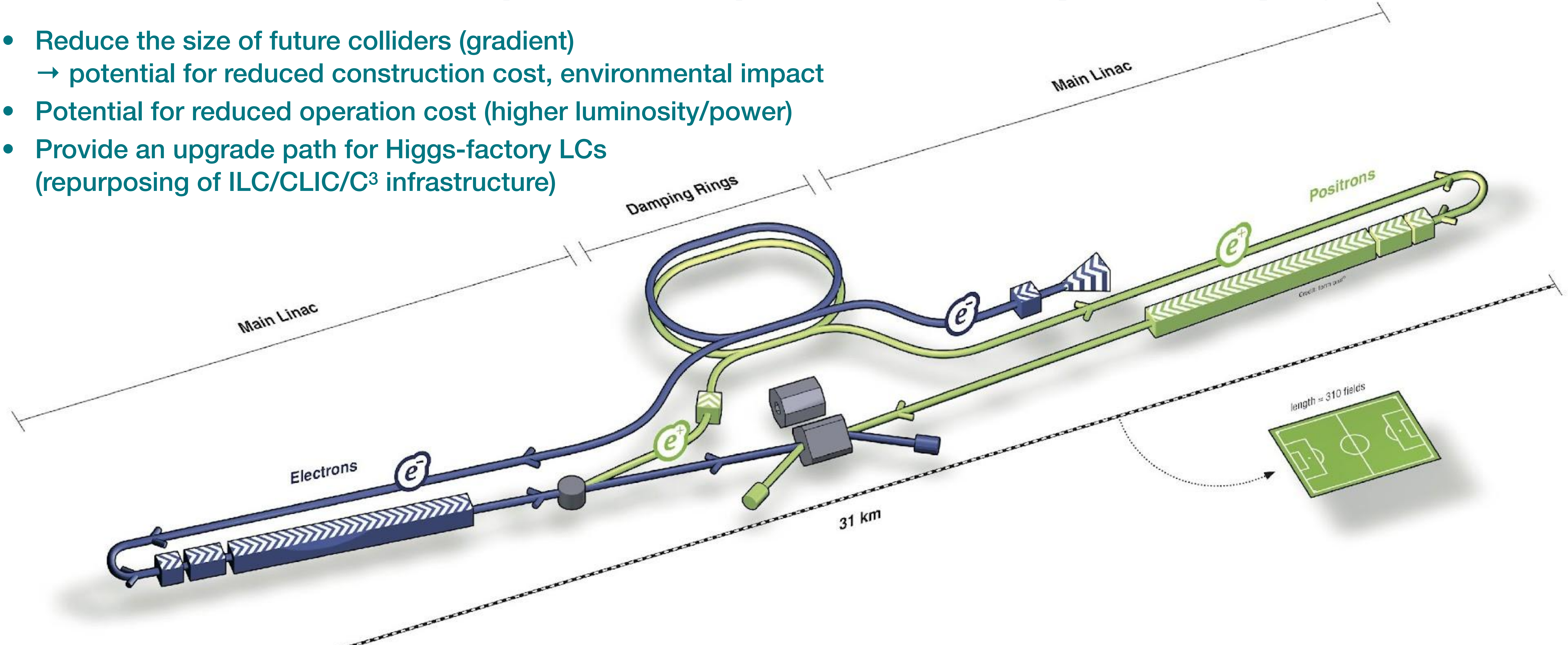

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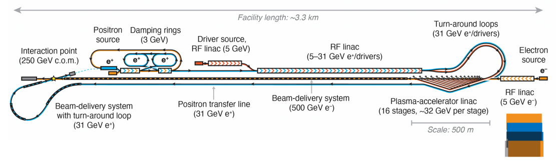

HALHF / 250 GeV / 3.3 km

Foster, D'Arcy, and Lindstrøm, **NJP** 25, 093037 (2023)

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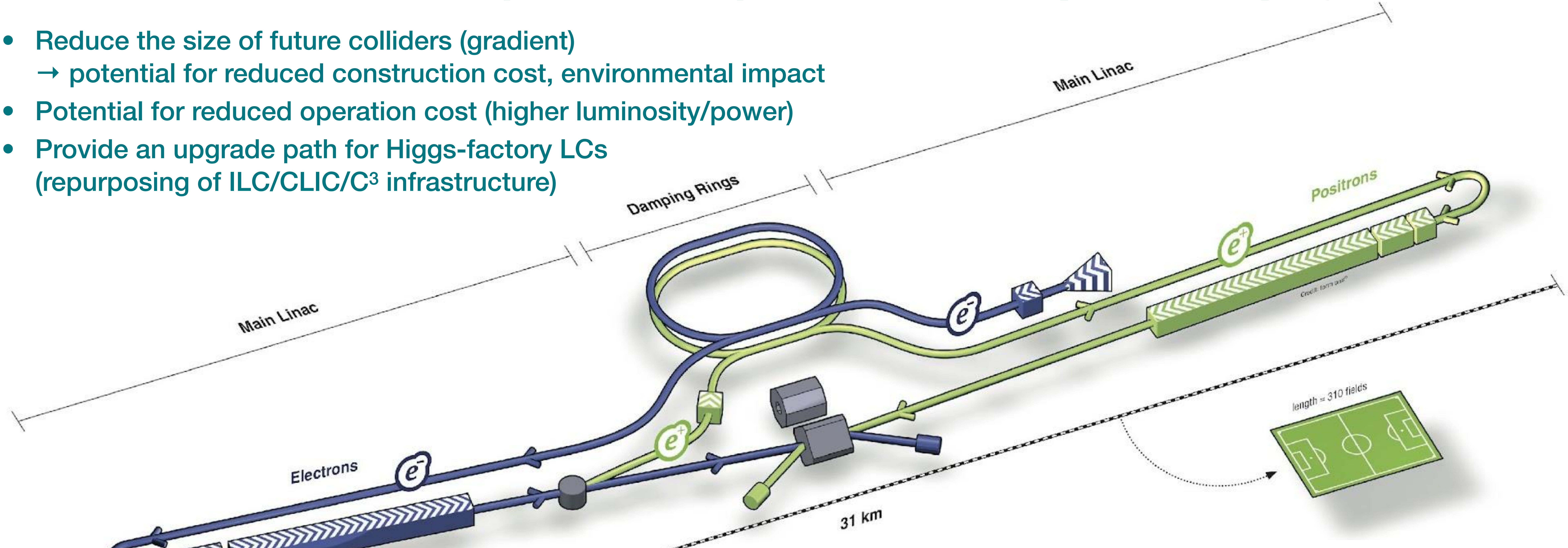

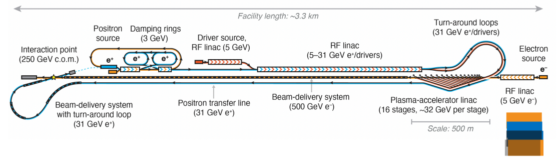

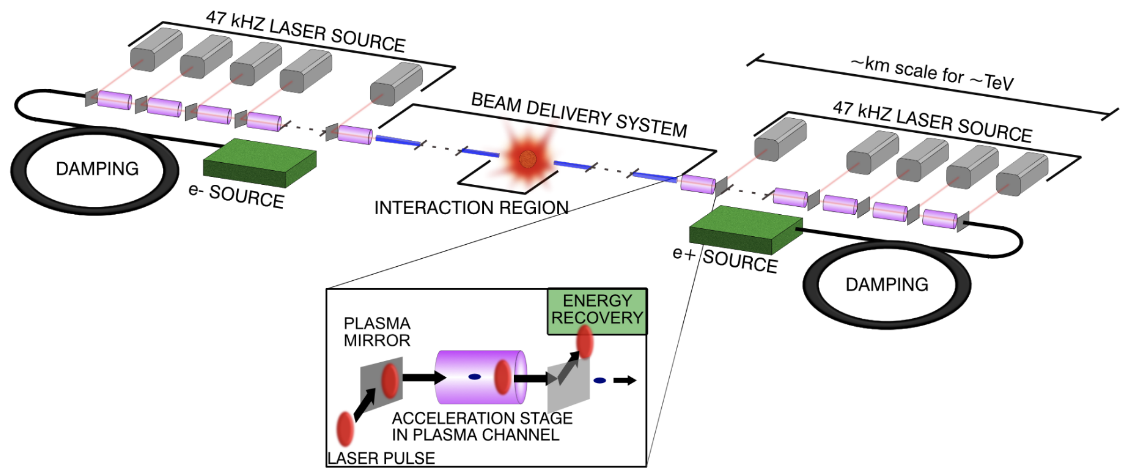

ILC / 500 GeV / 31 km

HALHF / 250 GeV / 3.3 km
Foster, D'Arcy, and Lindstrøm, **NJP** 25, 093037 (2023)

Energy Frontier Collider / 15 TeV / 6.6 km*
C.B. Schroeder *et al.*, **JINST** 18 T06001 (2023)

*for the linac, not including the BDS

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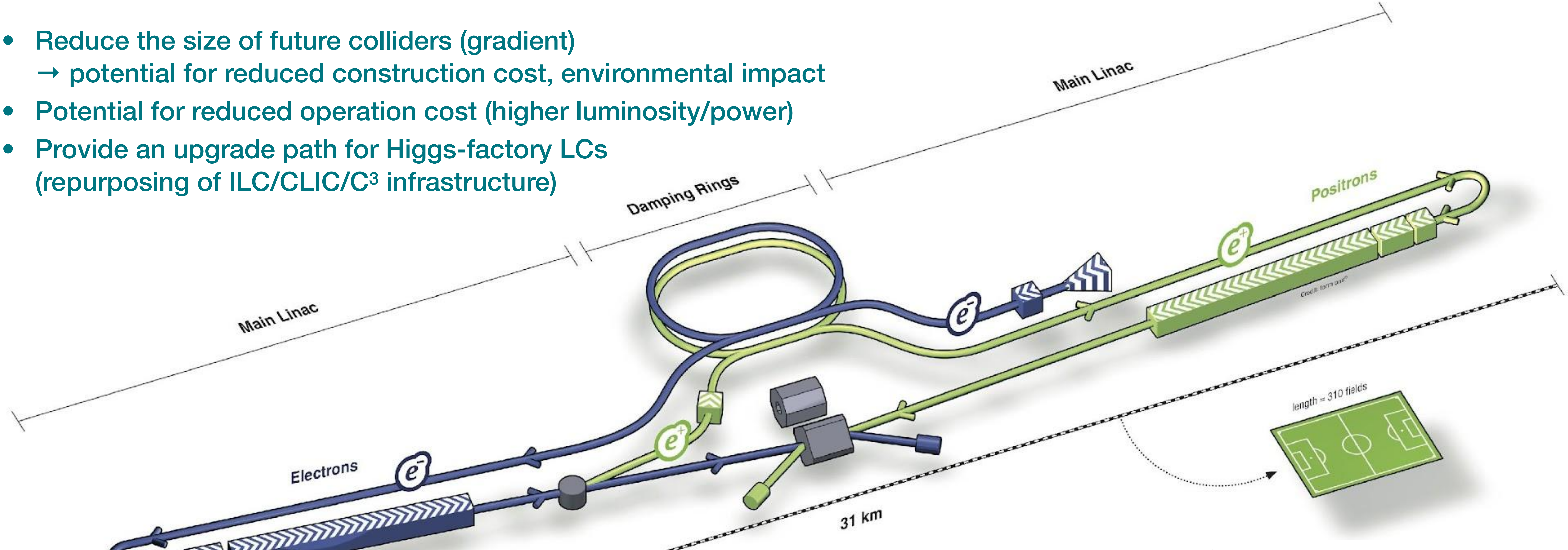

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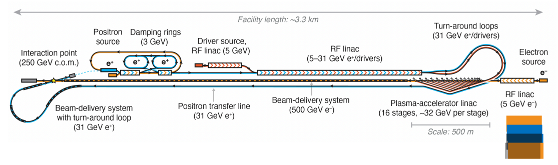

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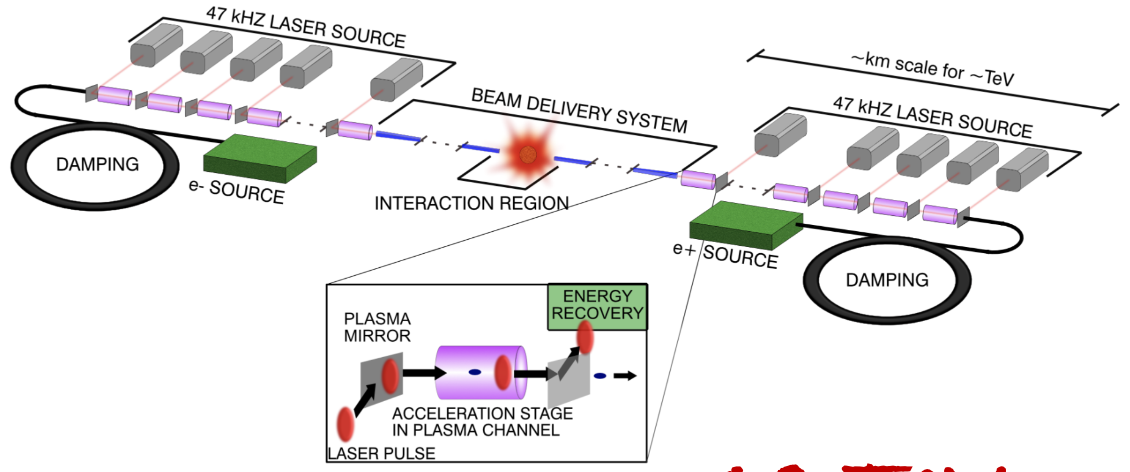


10 TeV

Energy Frontier Collider ~~/ 15 TeV~~ / 6.6 km*

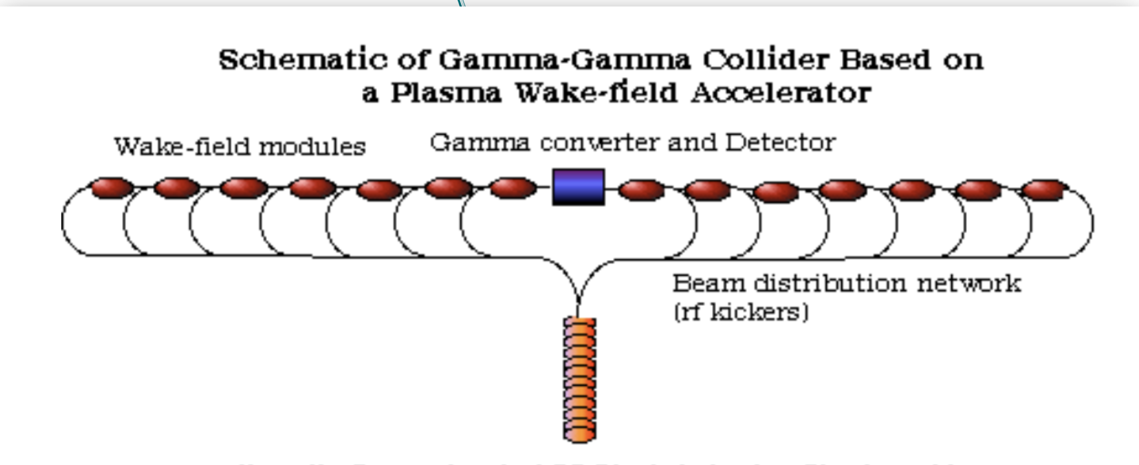
C.B. Schroeder *et al.*, **JINST** 18 T06001 (2023)

*for the linac, not including the BDS

Straw-person collider concepts have been under development for decades

A useful exercise to guide component R&D

Rosenzweig, Snowmass **1996**


Schematic of Gamma-Gamma Collider Based on a Plasma Wake-field Accelerator

Seryi, PAC **2009**

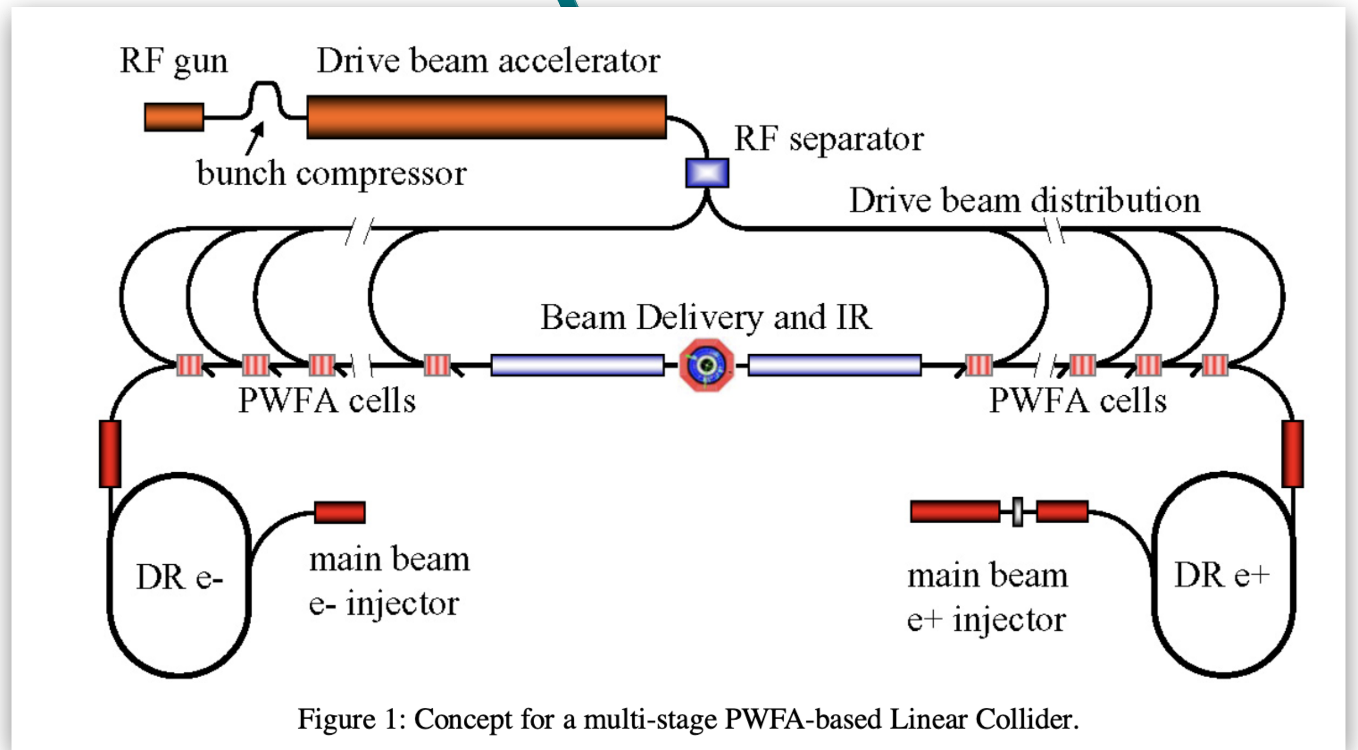


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

Adli, Snowmass **2013**

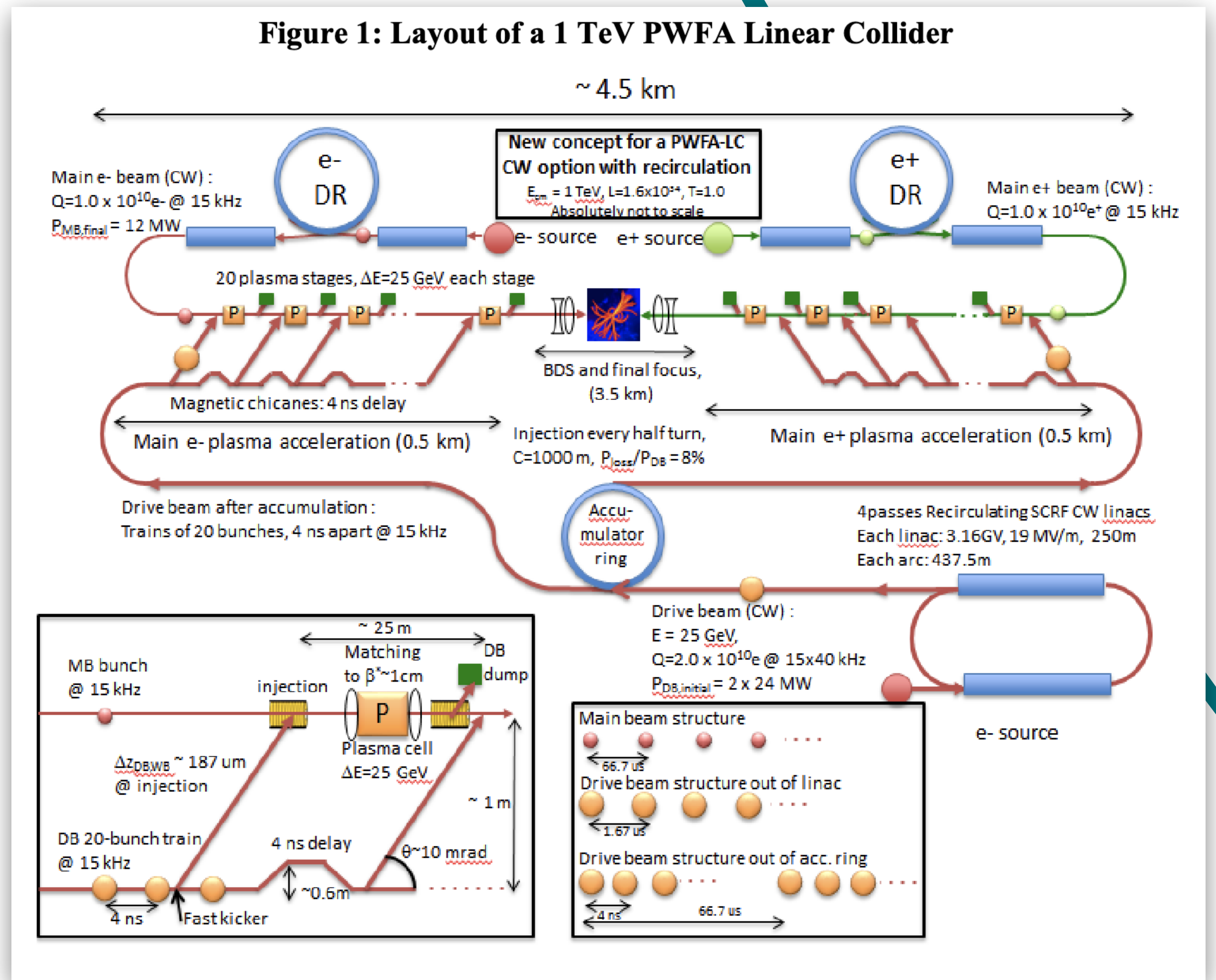
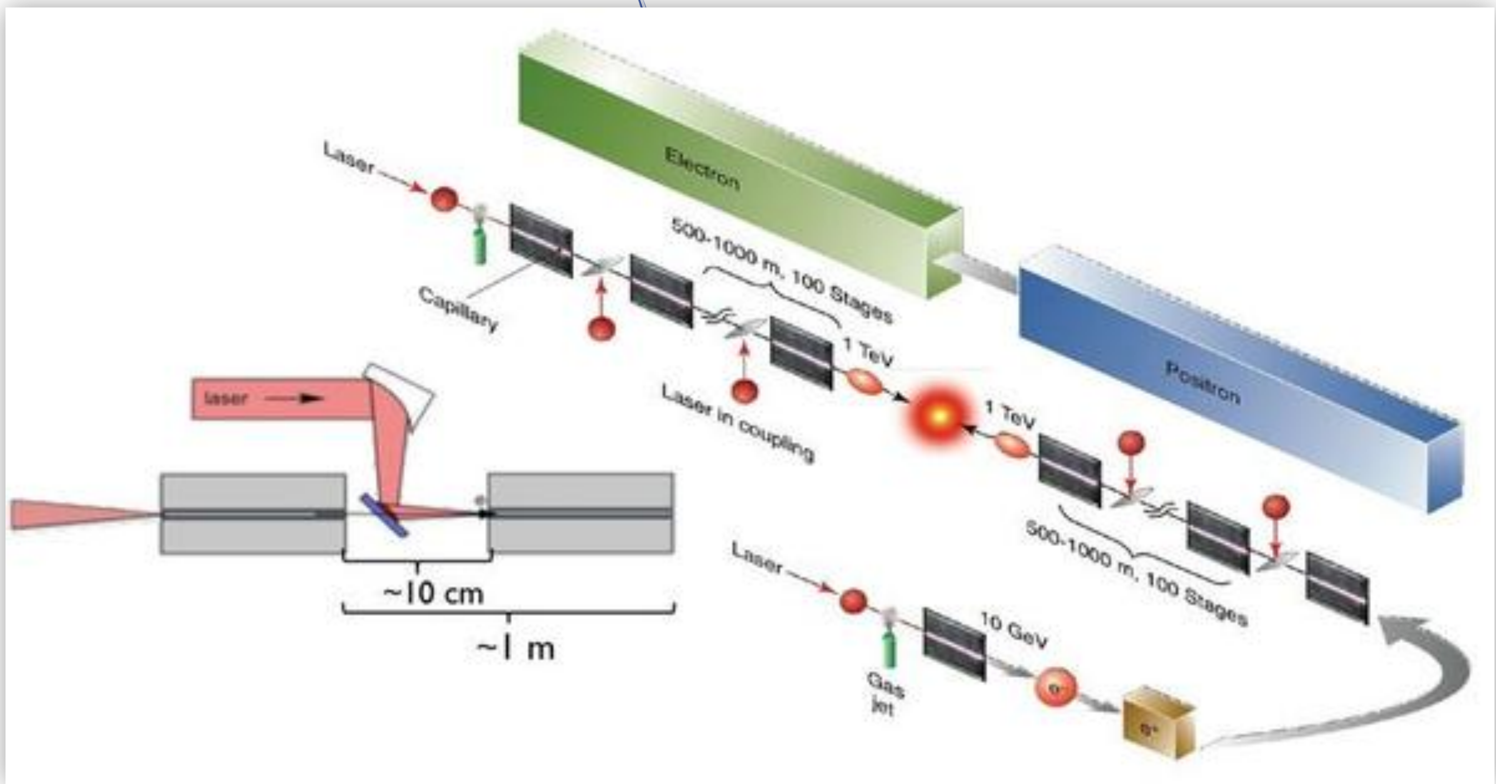


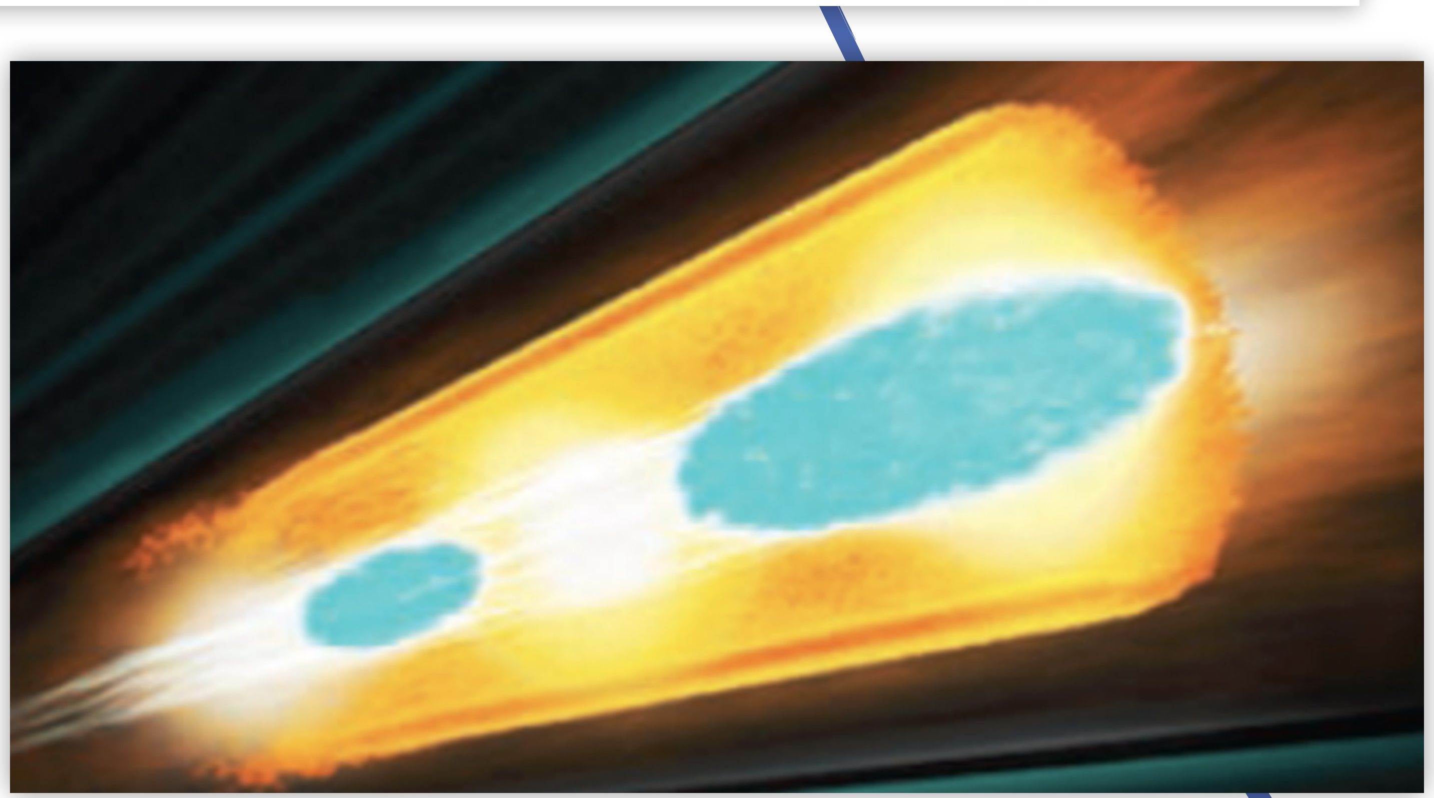
Figure 1: Layout of a 1 TeV PWFA Linear Collider

Beam-driven

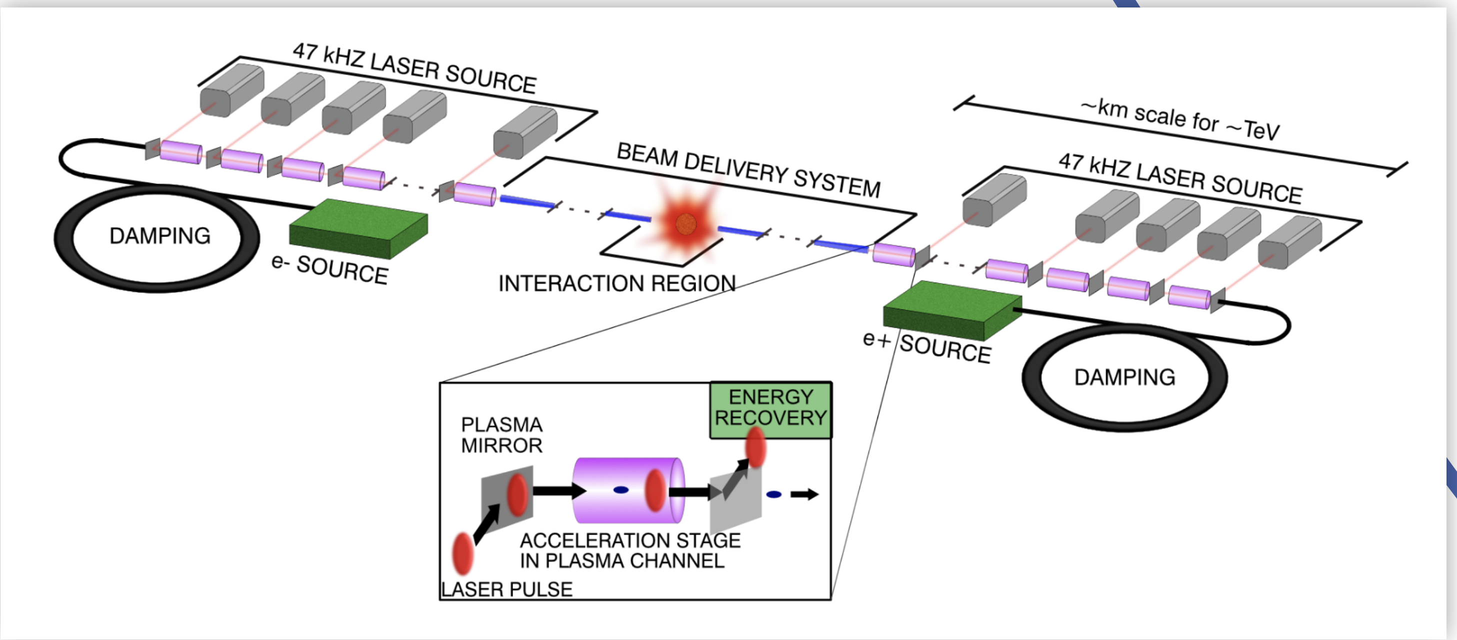
Leemans, Physics Today **2009**



Schroeder, NIM A **2016**



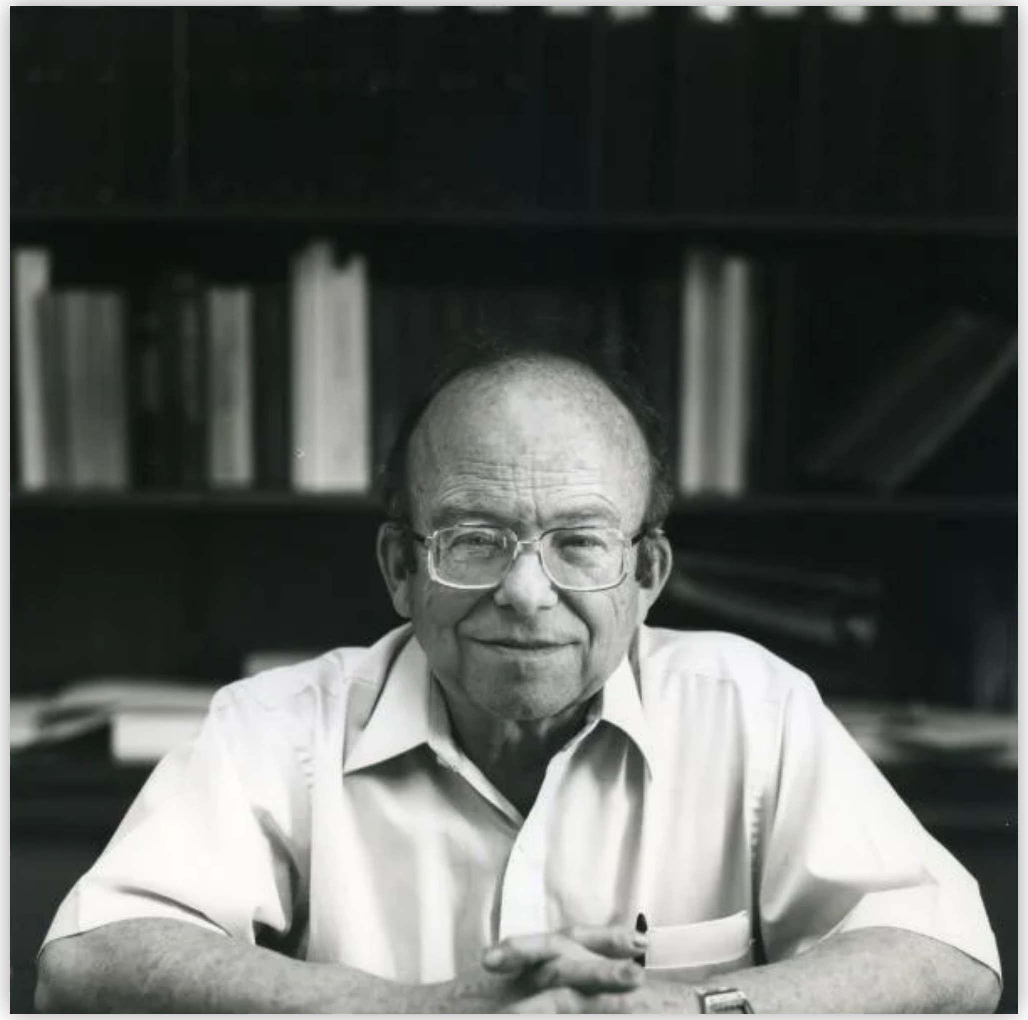
Schroeder, JINST **2023**

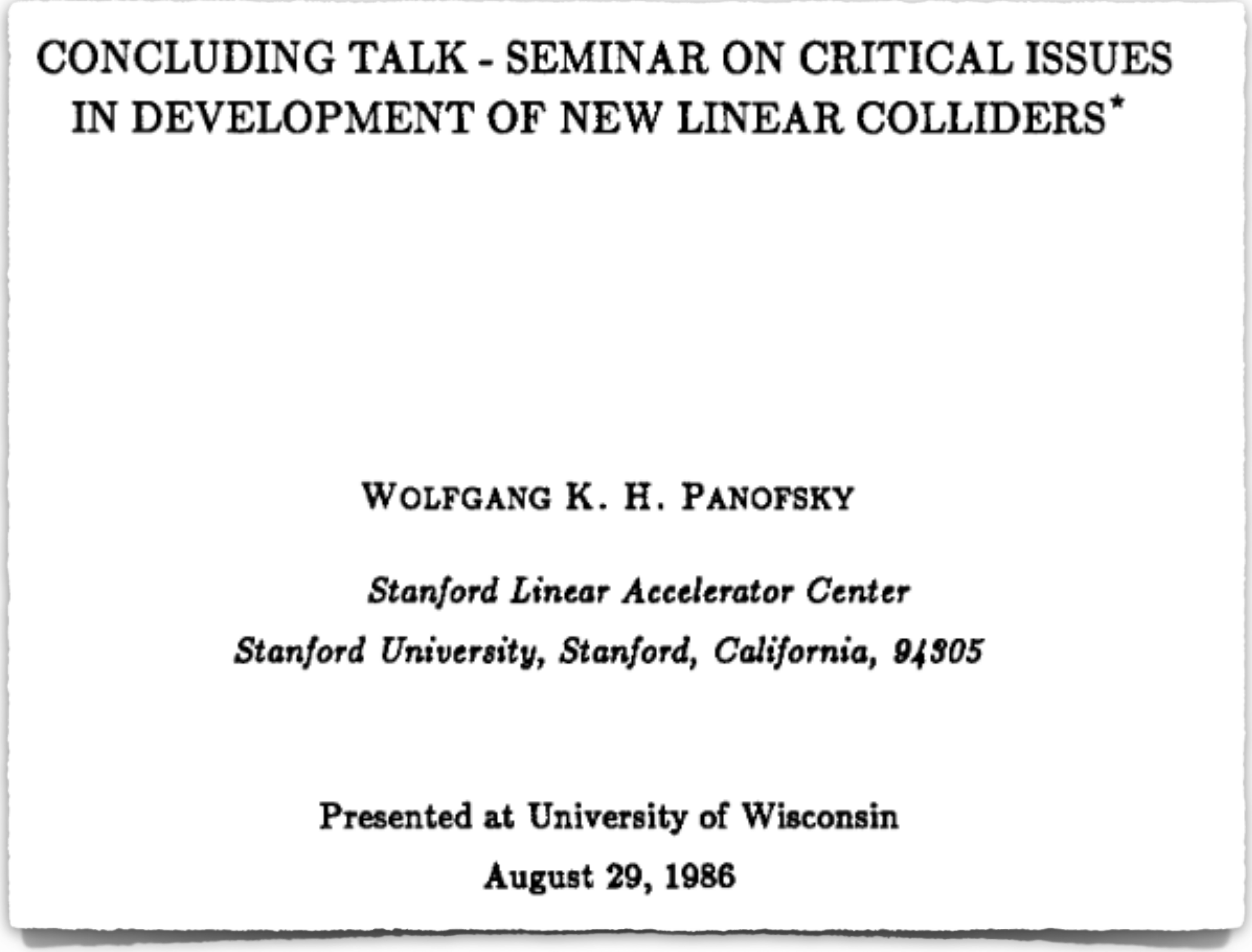


Laser-driven

What goes into collider design?

Let’s ask those that know, and learn!





CONCLUDING TALK - SEMINAR ON CRITICAL ISSUES IN DEVELOPMENT OF NEW LINEAR COLLIDERS*

WOLFGANG K. H. PANOFSKY

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Presented at University of Wisconsin
August 29, 1986

Symposium on Advanced Accelerator Concepts, Madison, WI, 1986

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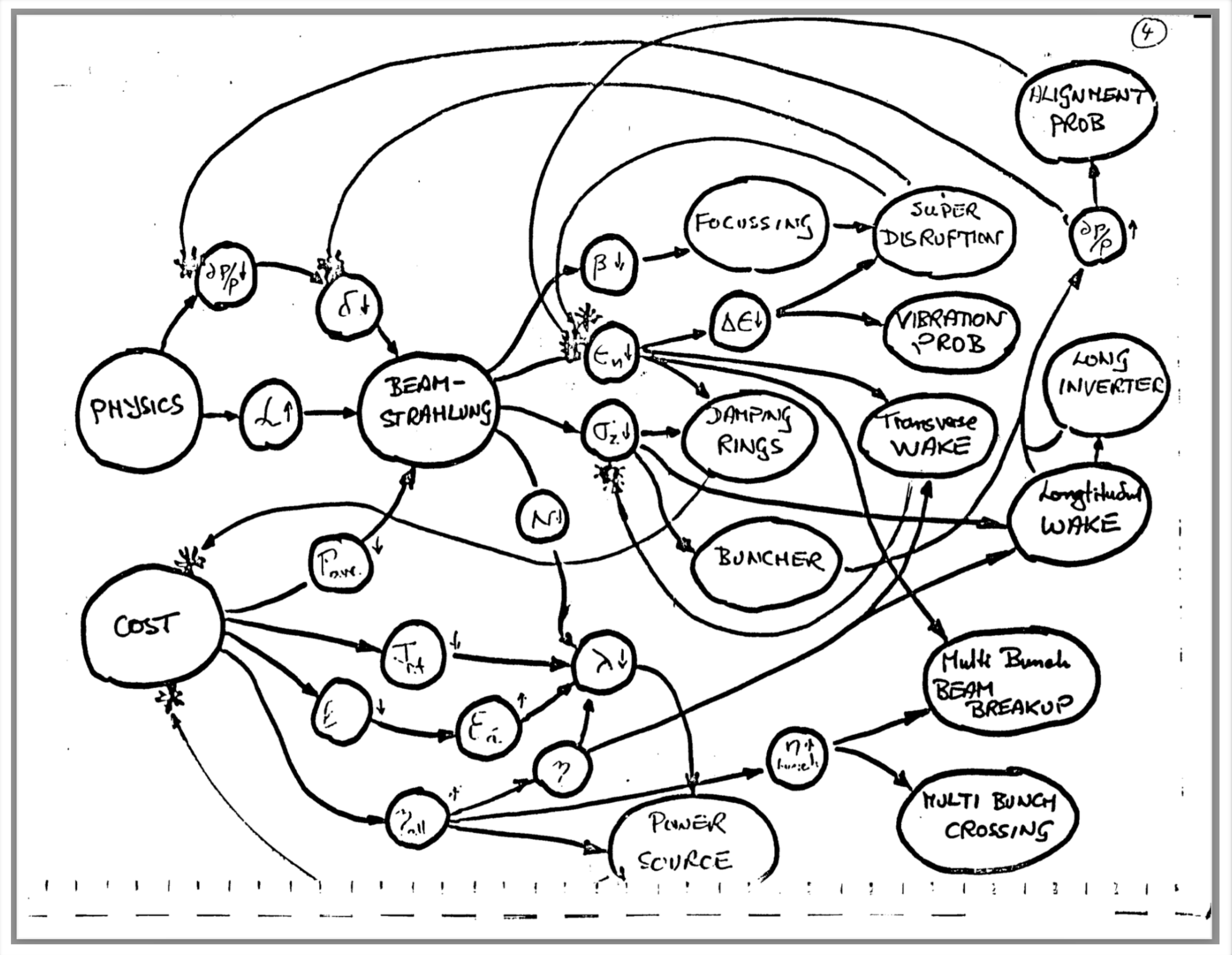
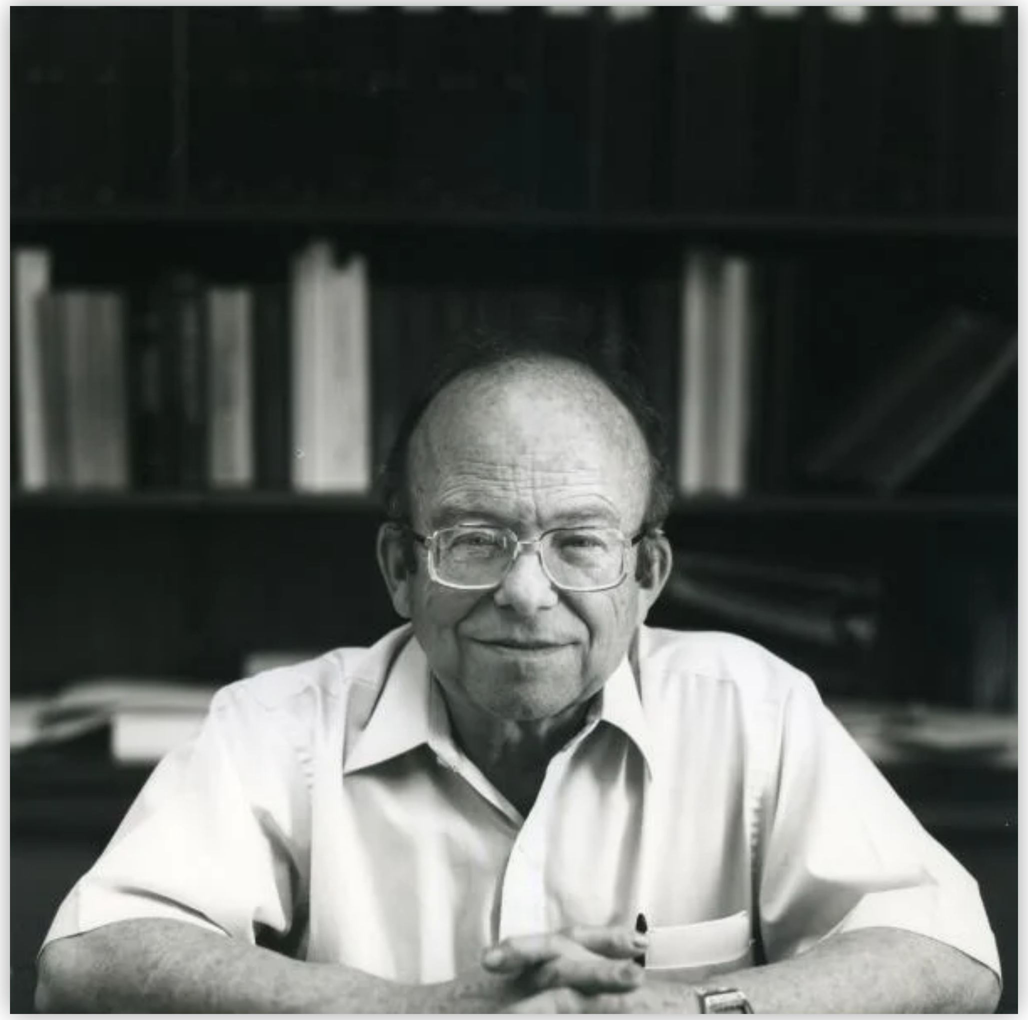
Let's ask those





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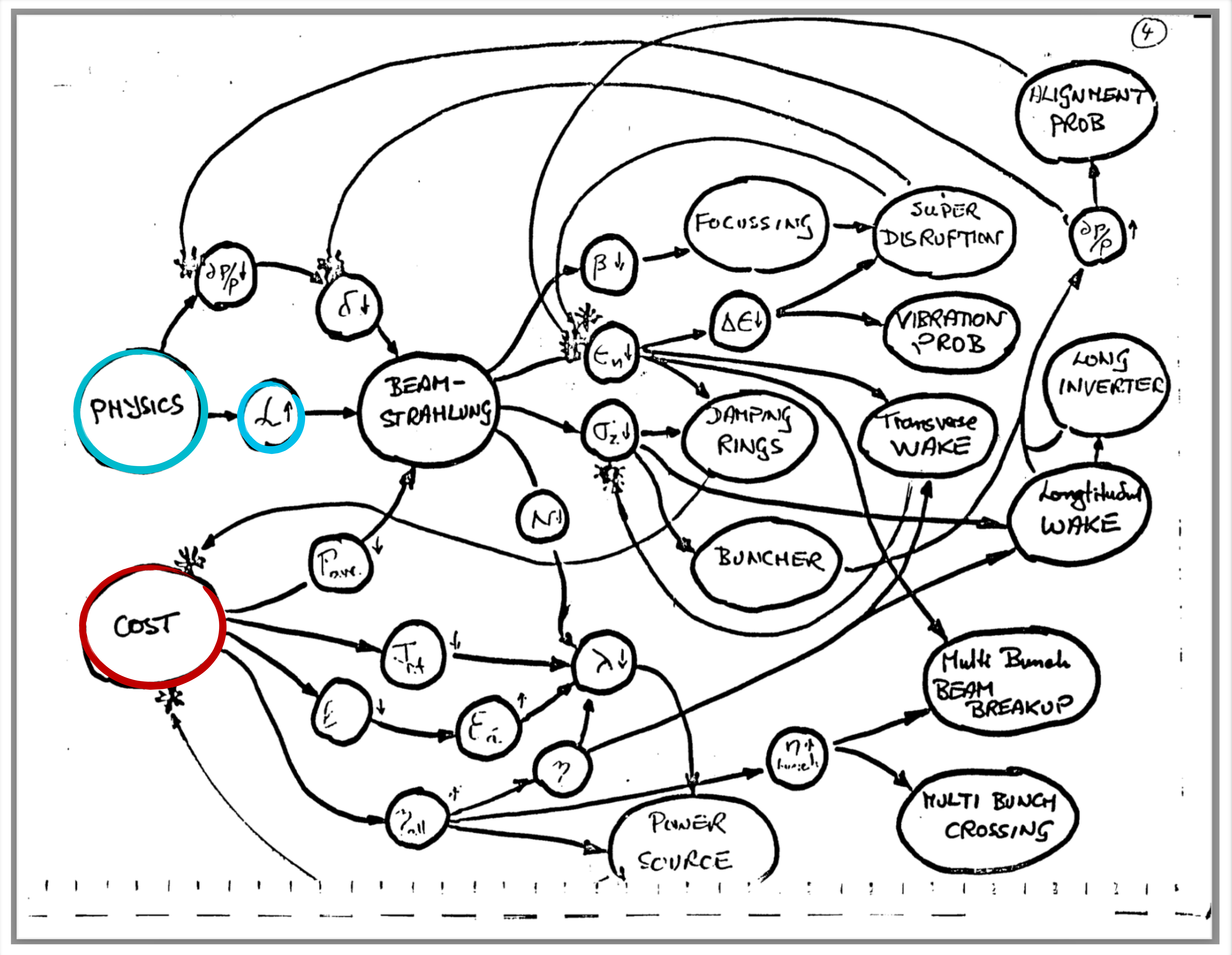

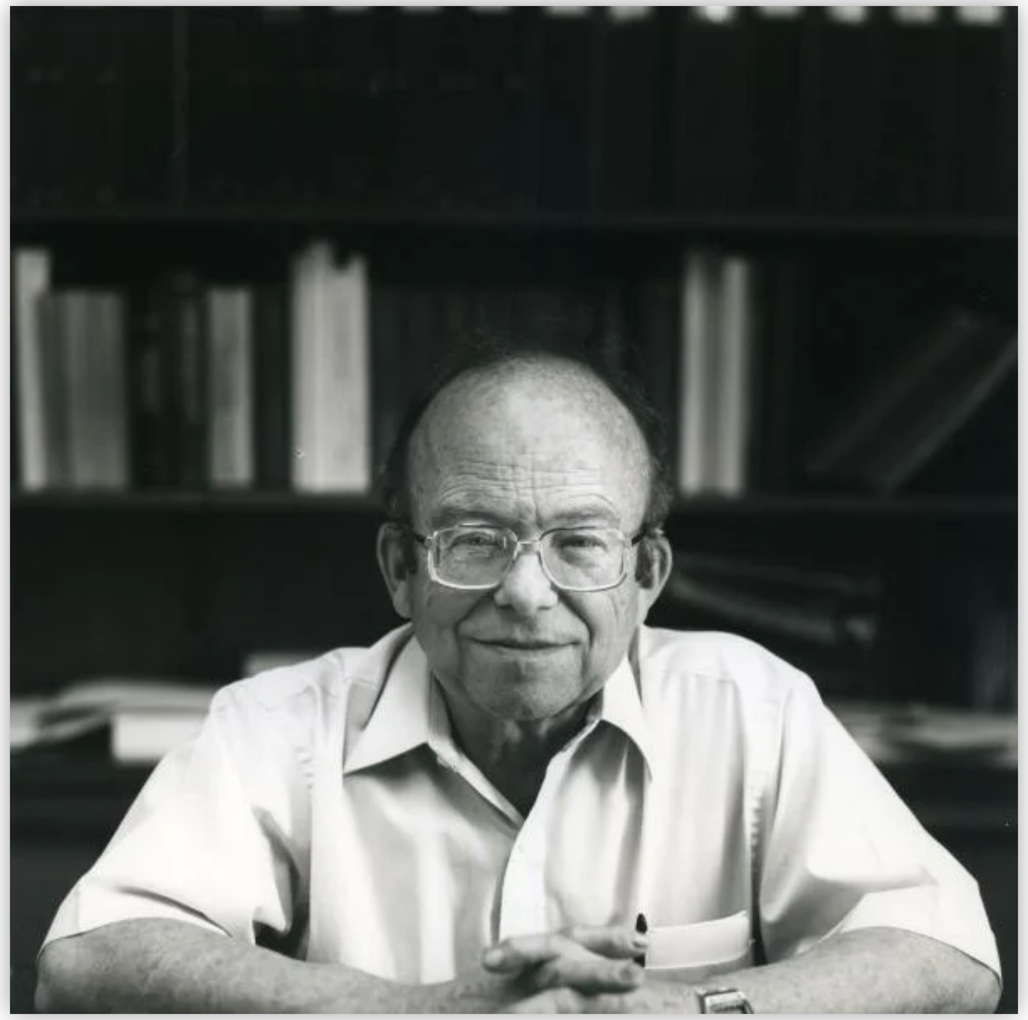

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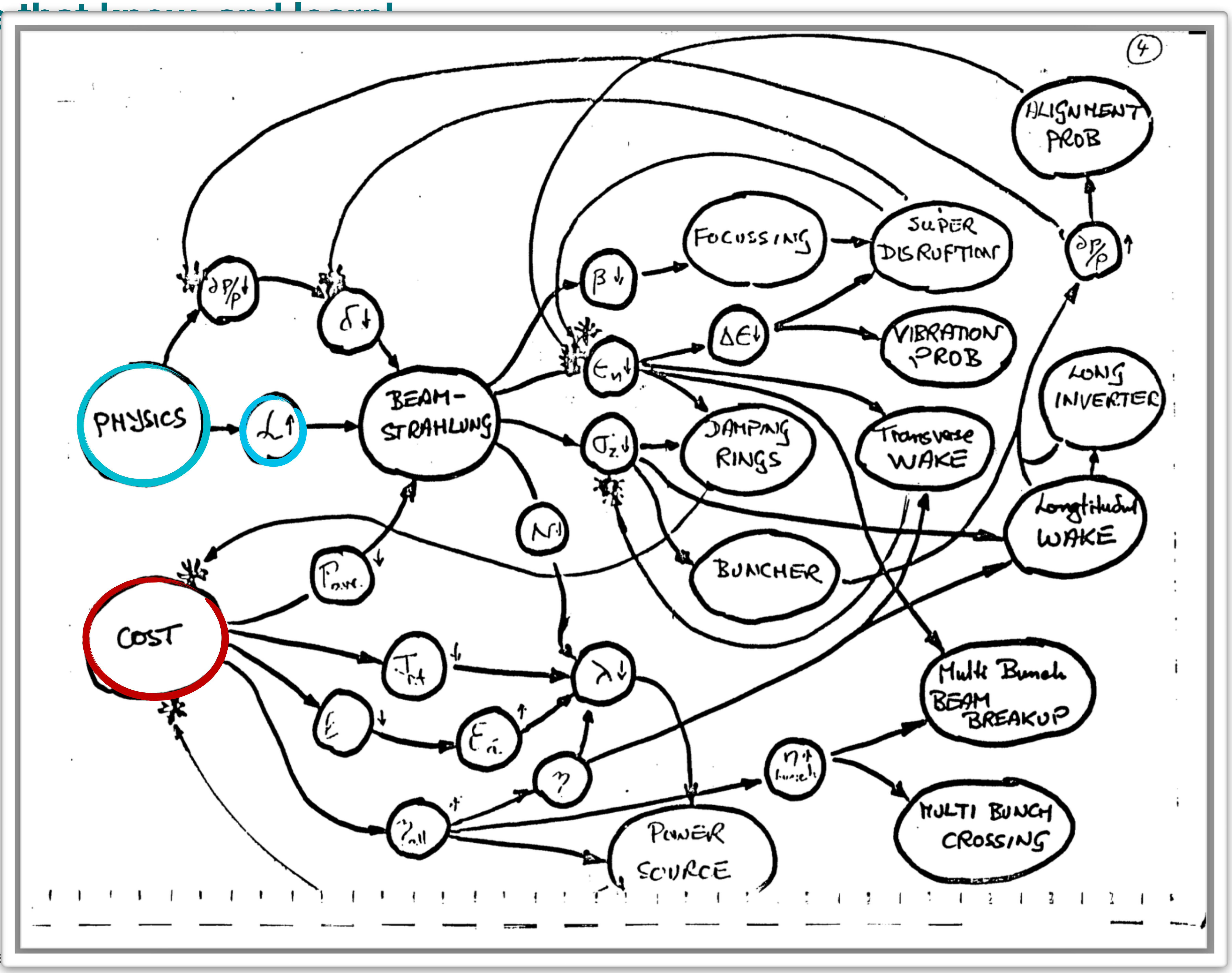
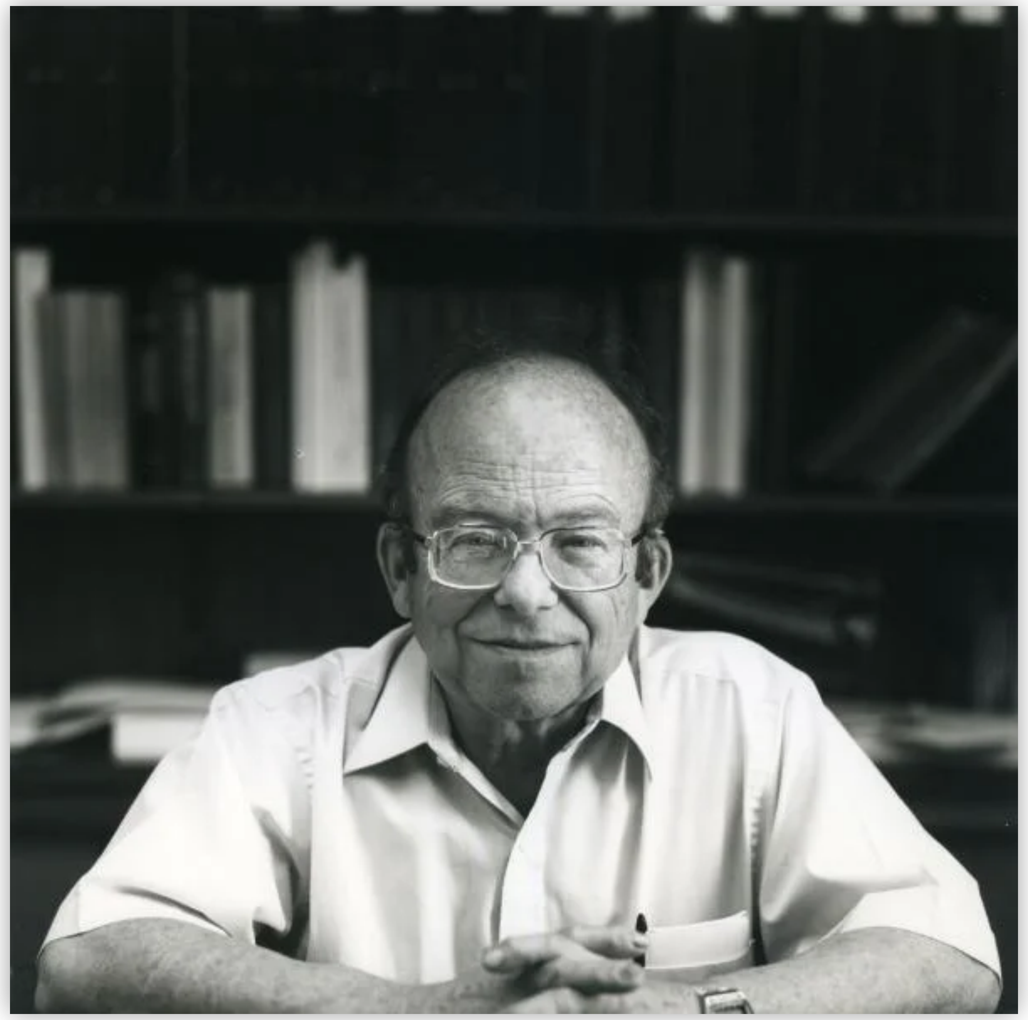


Environmental impact



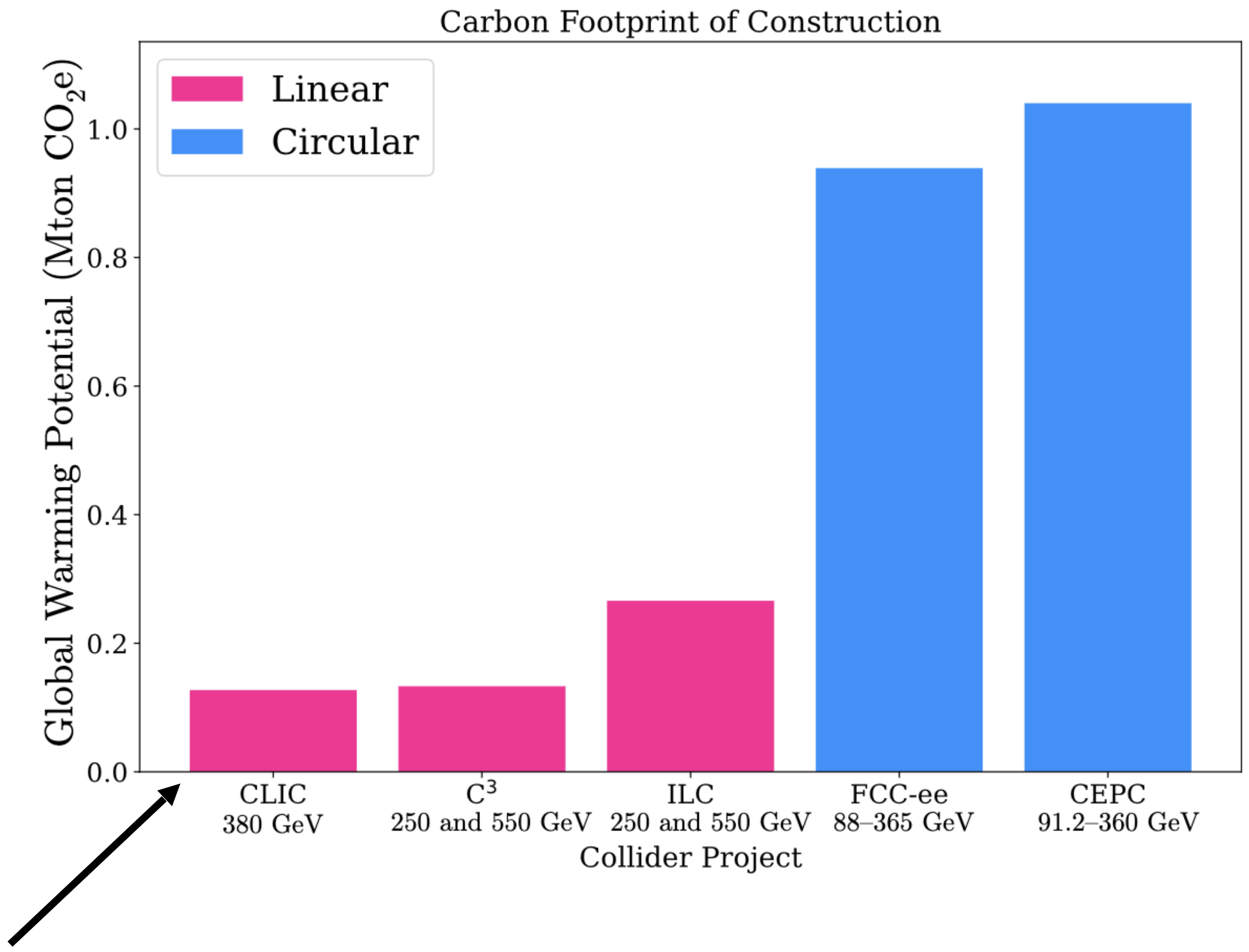
Environmental impact: a constraint of ever increasing importance

Environmental considerations are an explicit constraint on future colliders designs.

The fluctuations in energy prices and climate change have brought energy consumption considerations to the foreground of the upcoming European Strategy for Particle Physics (ESPP).

The carbon impact of colliders comes from:

- Construction
- Operation



PRX ENERGY 2, 047001 (2023)

Compact colliders use less concrete!

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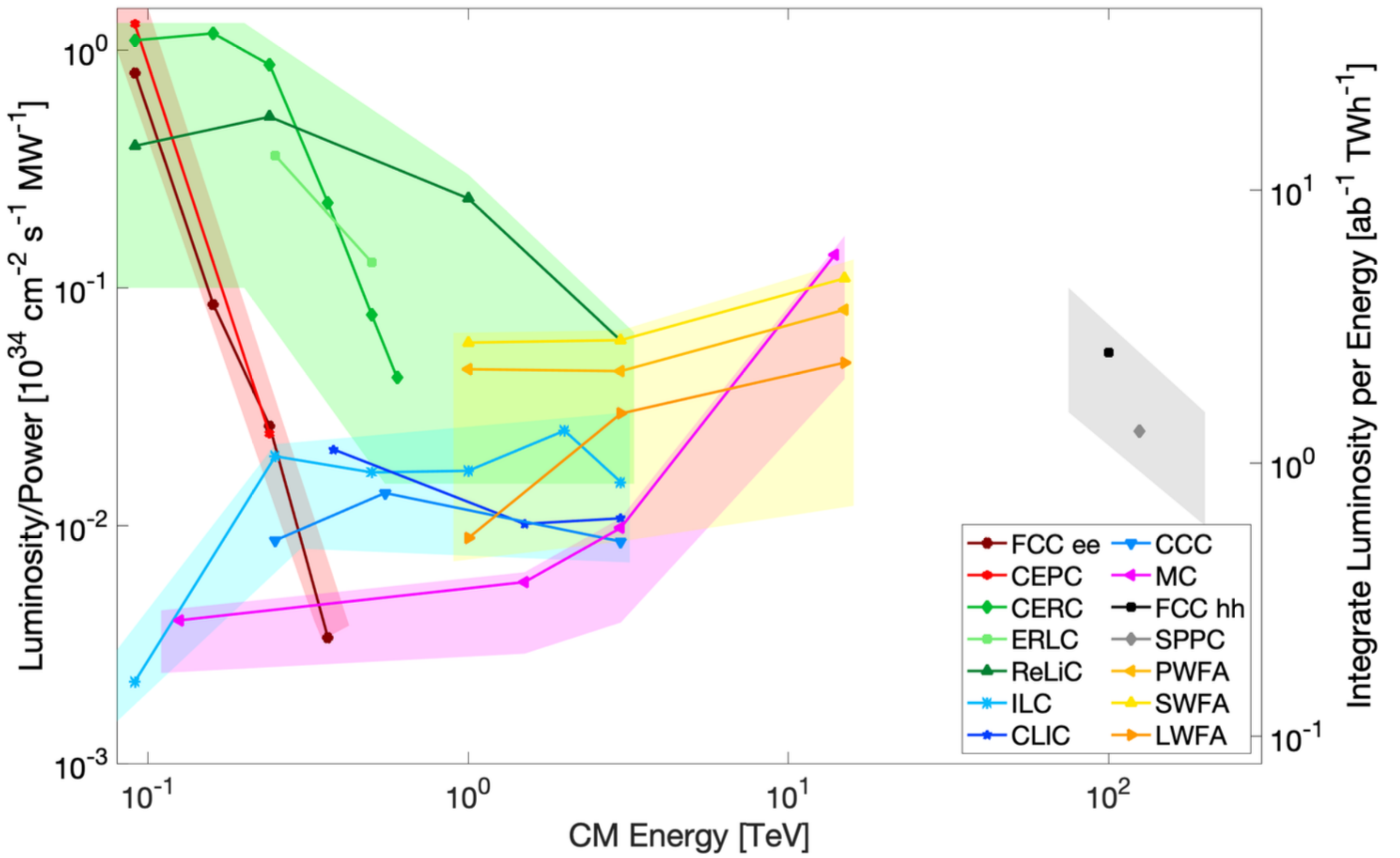
ITF Report, JINST (2023)



The key metric is "luminosity-per-beam-power"

~ physics per $$$

Basic considerations on luminosity-per-power optimization

For a given luminosity and energy target, we can place strong constraints on collider designs

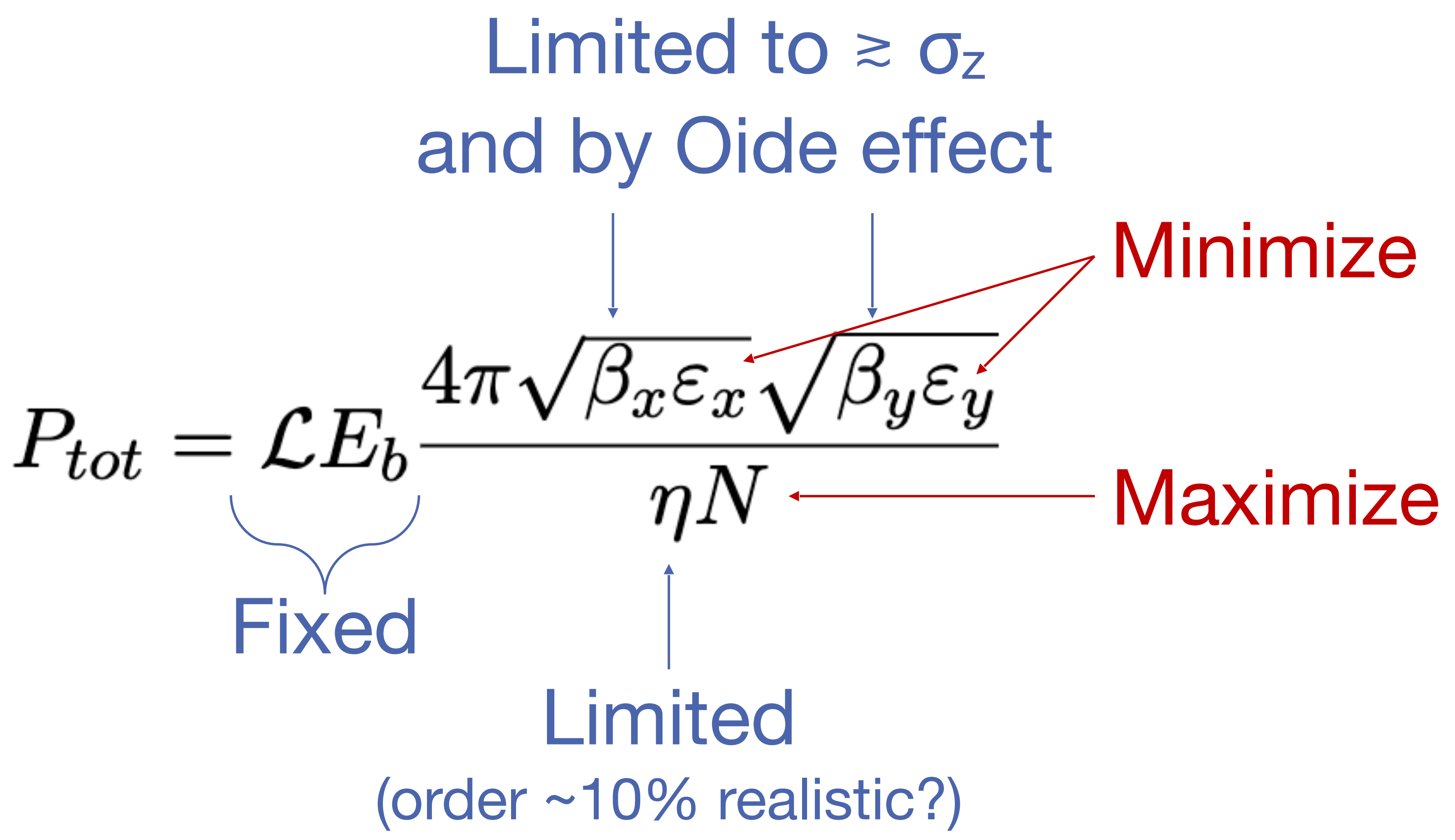
Geometric Luminosity

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

Figure of Merit:
Luminosity per power

$$\frac{\mathcal{L}}{P_{tot}} = \frac{\eta N}{4\pi\sigma_x\sigma_y E_b}$$

<u>10 TeV collider:</u> E_b = 5 TeV and $\mathcal{L}$ = 10^{35} cm^{-2} s^{-1}



Limited to ≳ σ_z
and by Oide effect

Minimize

$$P_{tot} = \underbrace{\mathcal{L}E_b}_{\text{Fixed}} \frac{4\pi\sqrt{\beta_x\varepsilon_x}\sqrt{\beta_y\varepsilon_y}}{\eta N}$$

Maximize

Limited
(order ~10% realistic?)

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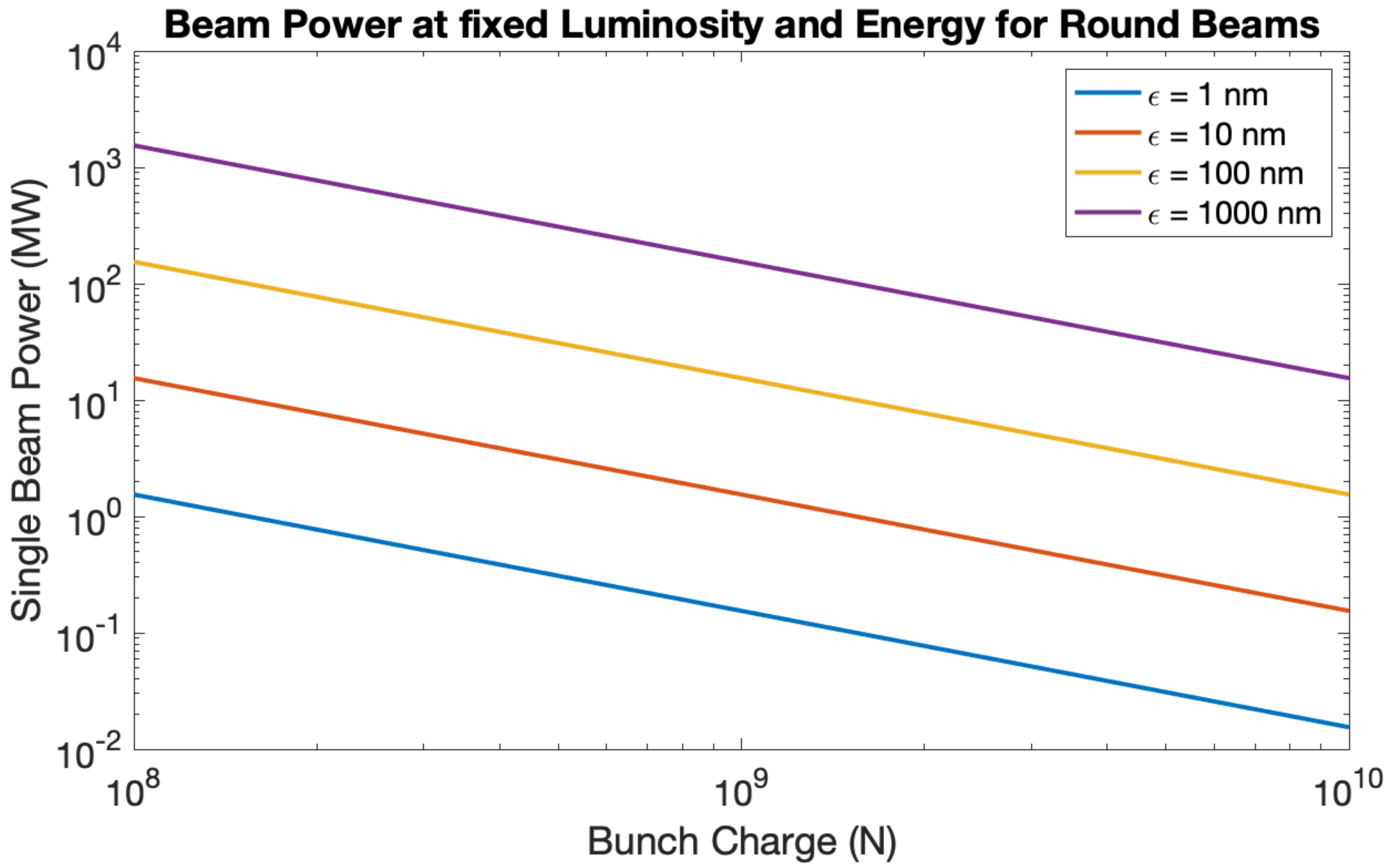

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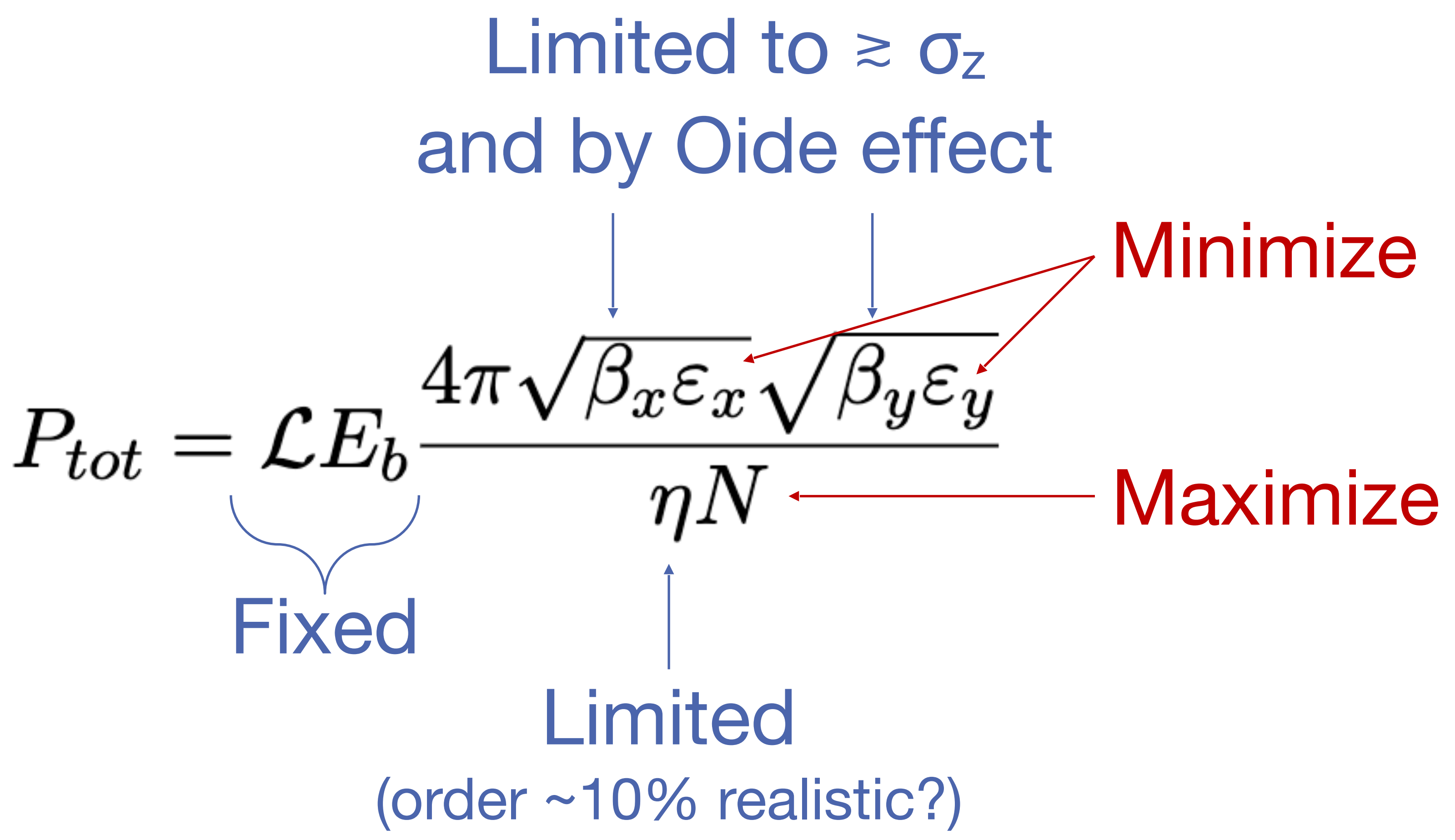

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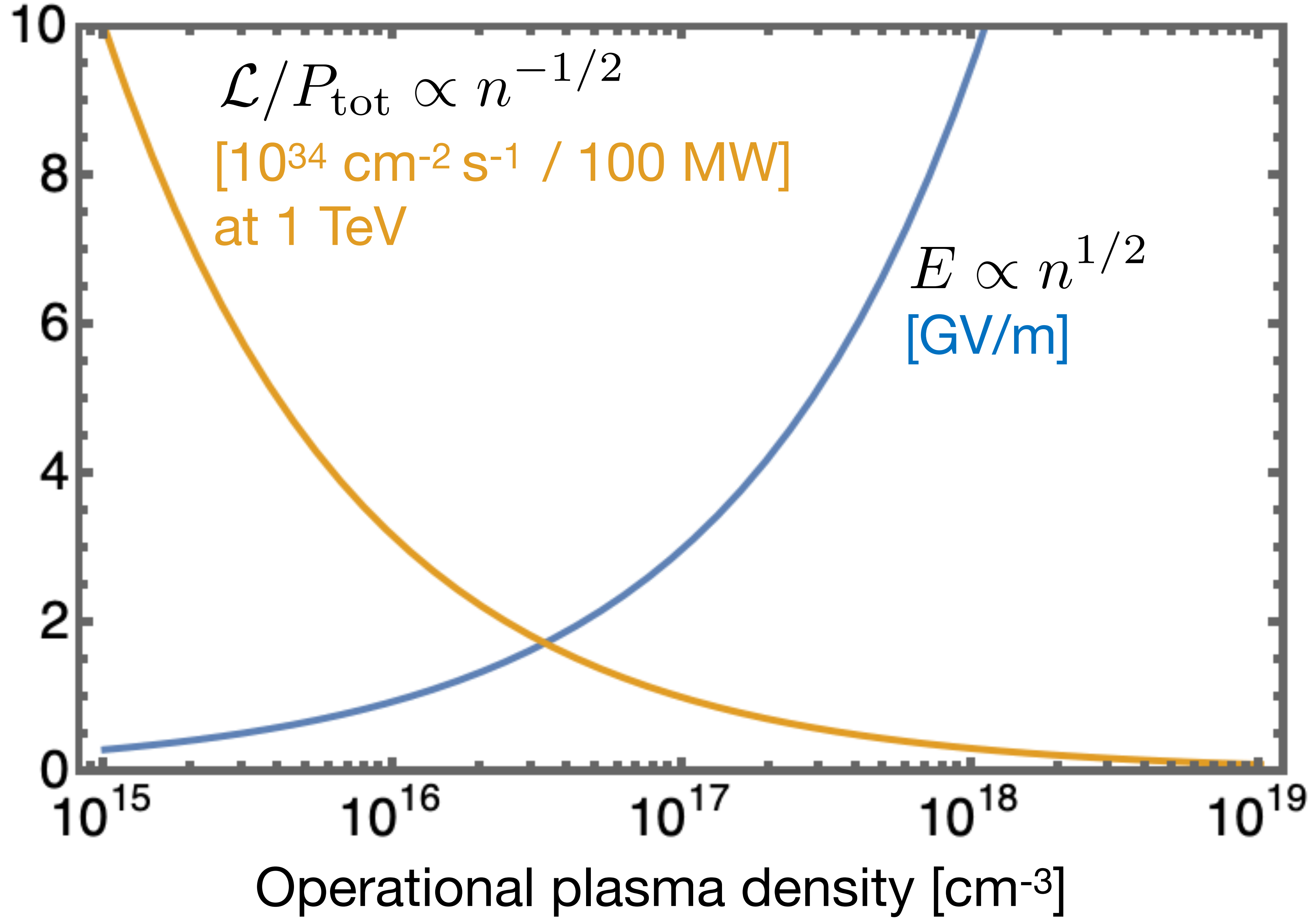

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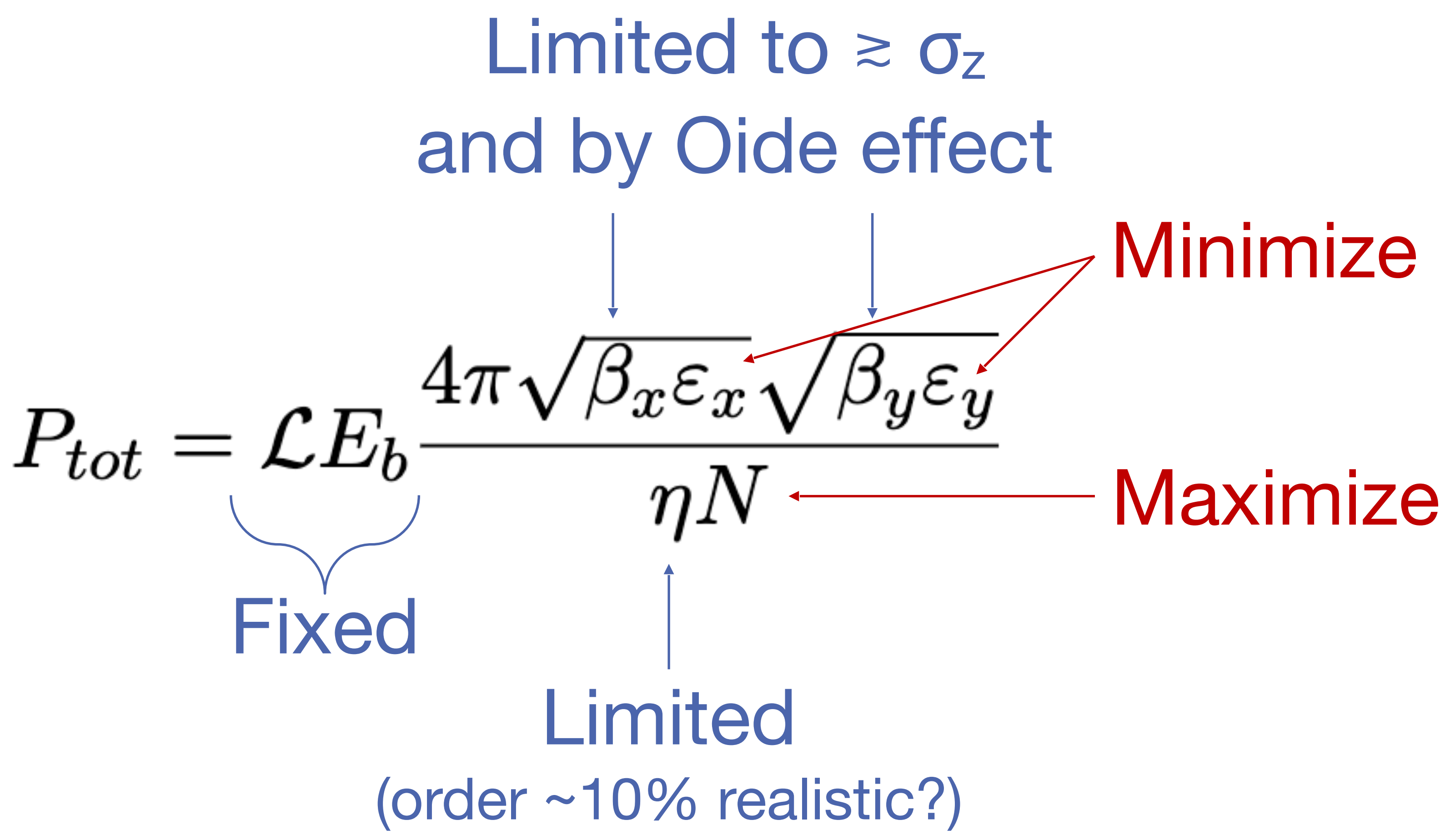

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Trade-off between L/P$_{\text{tot}}$ and acceleration gradient has to be made

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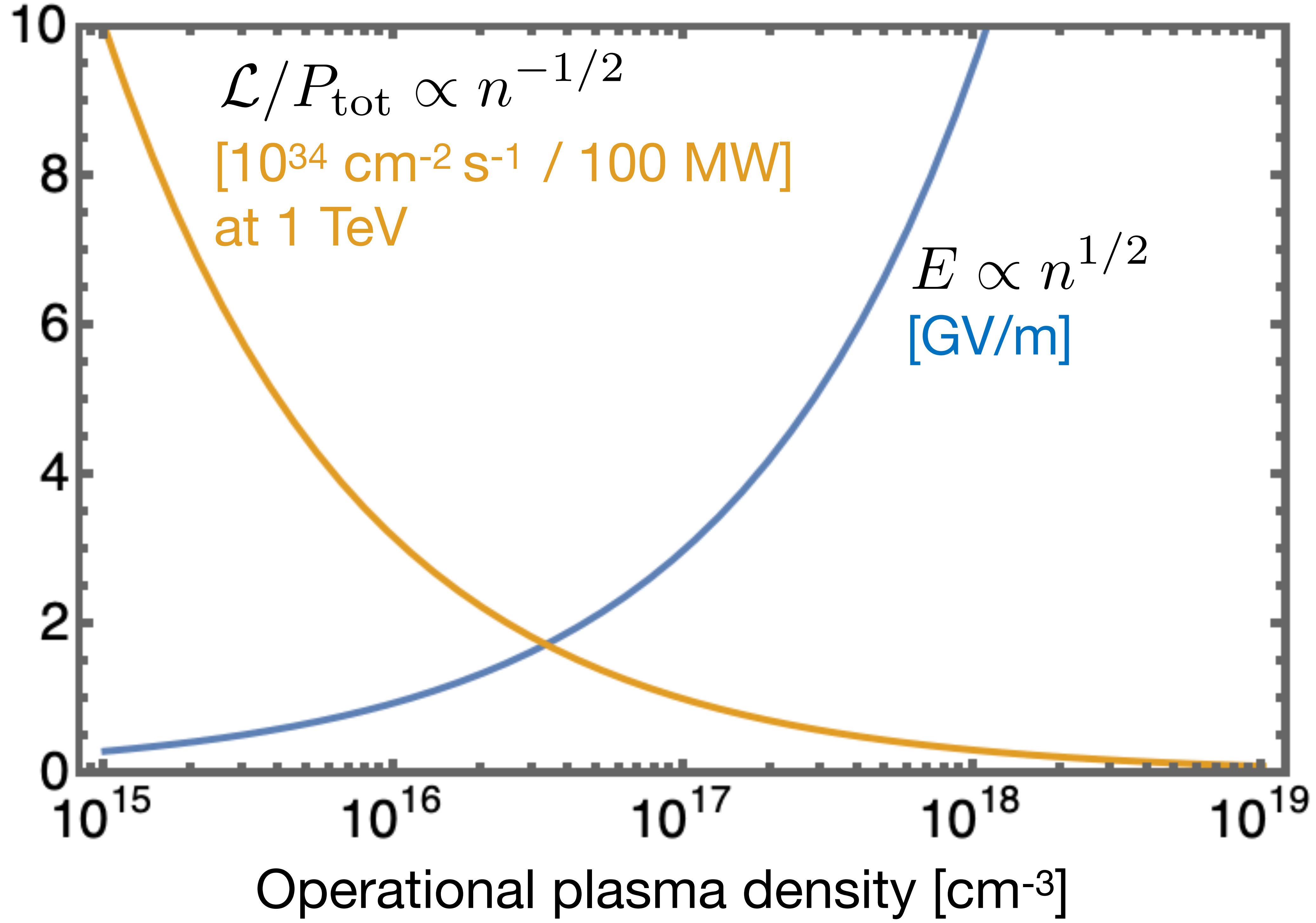

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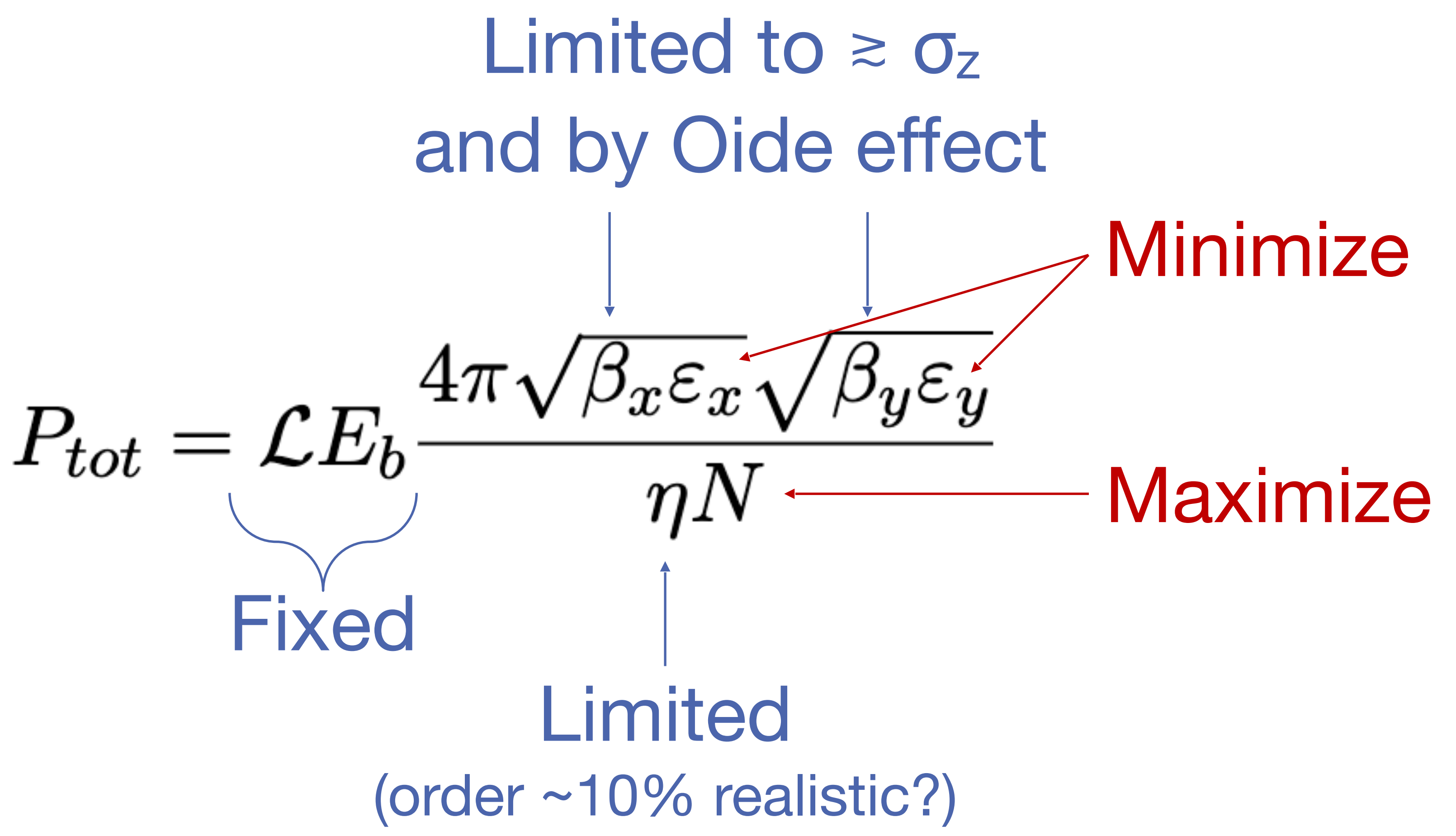

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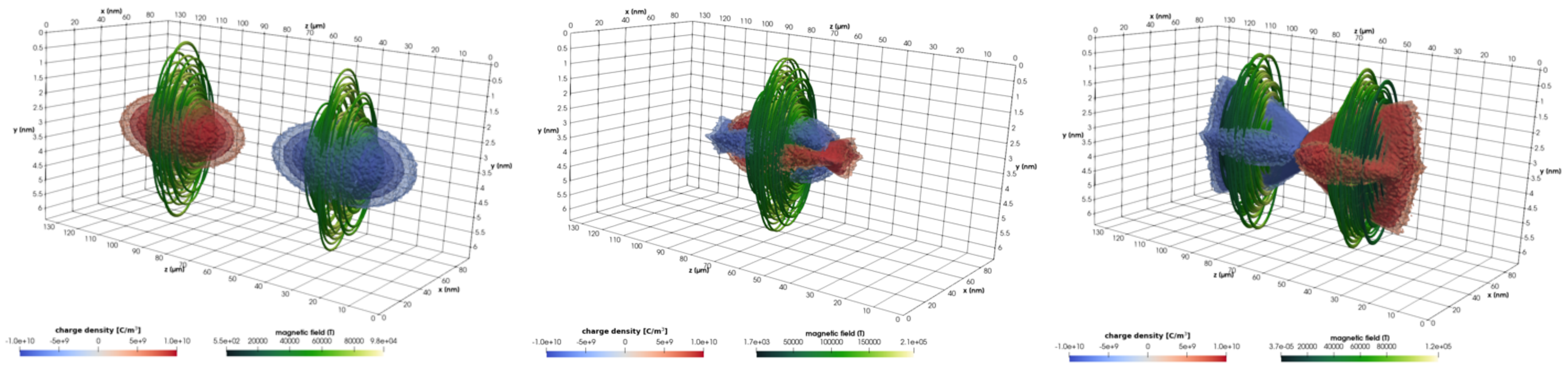
But wait! What about Beamstrahlung...?

Plasma accelerators mitigate Beamstrahlung

Short particle bunches save power

Beamstrahlung (radiation during collisions) reduces the energy of the colliding particles, broadens luminosity spectrum.



also: beam disruption (shape), secondary e^+/e^- pair creation

Number of emitted photons per particle:

$$n_\gamma \propto N^{2/3}\sigma_z^{1/3} \propto n^{-1/2}$$

P. Chen and K. Yokoya (1995)
C.B. Schroeder *et al.*,
PRASTB 13, 101301 (2010)

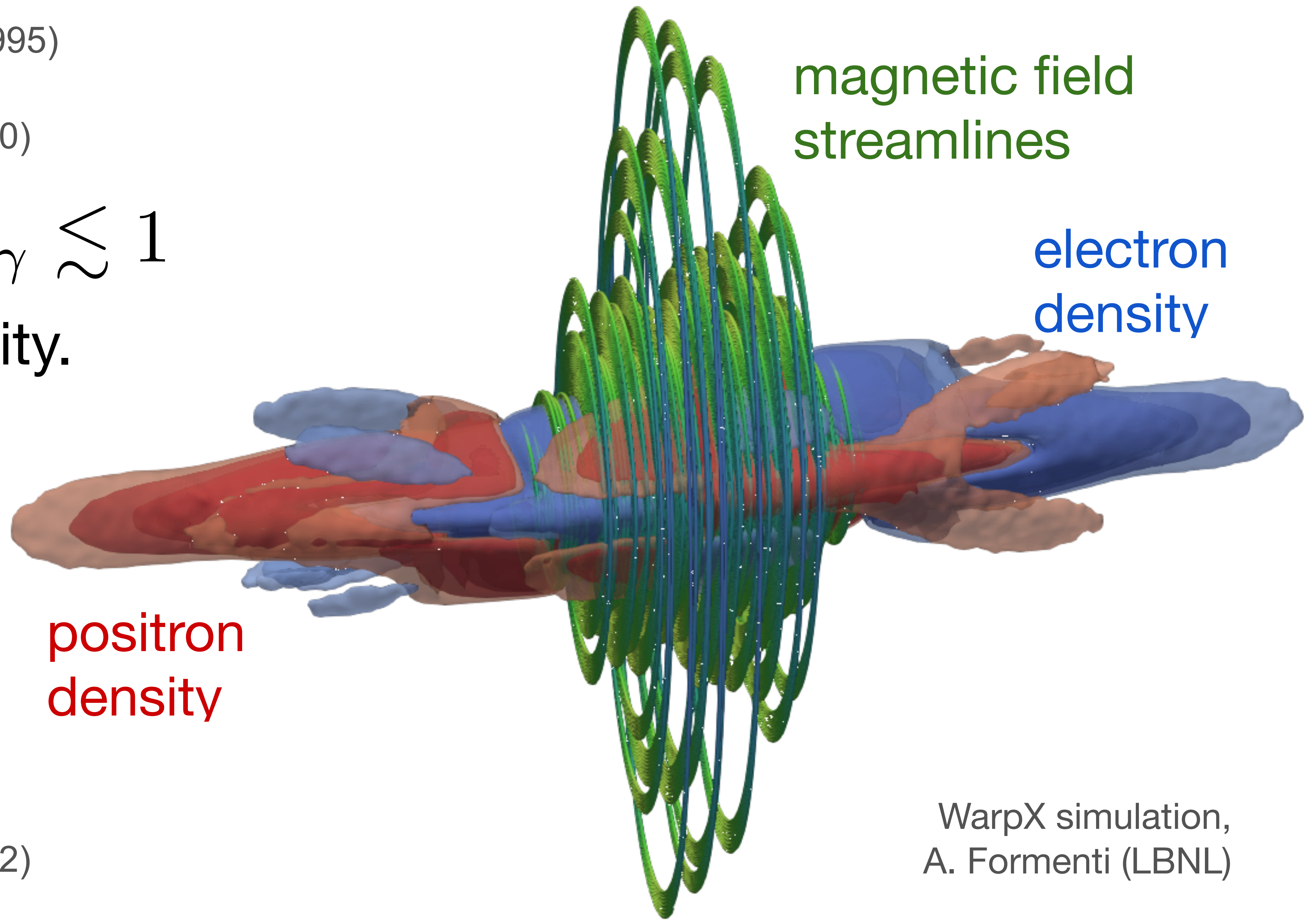
Traditionally, linear colliders desire low beamstrahlung: $n_\gamma \lesssim 1$

- Upper limit for charge per bunch, lower limit for plasma density.
- Flat beams are favored.

Short beams in wakefield accelerators mitigate beamstrahlung and save power.

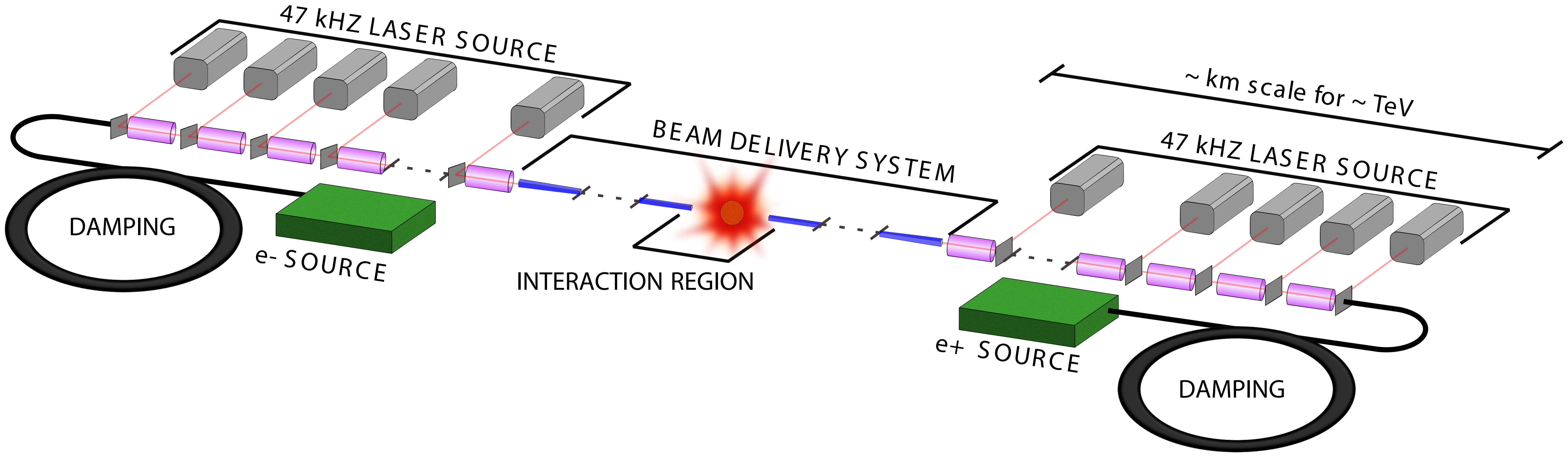
$$\frac{\mathcal{L}}{\mathcal{E}_{\mathrm{cm}}^2} \propto \frac{n_\gamma^{3/2} P_{\mathrm{beam}}}{\sigma_z^{1/2}\gamma^{5/2}}$$

C.B. Schroeder *et al.*,
PRASTB 15, 051301 (2012)



WarpX simulation,
A. Formenti (LBNL)

Plasma collider components and challenges



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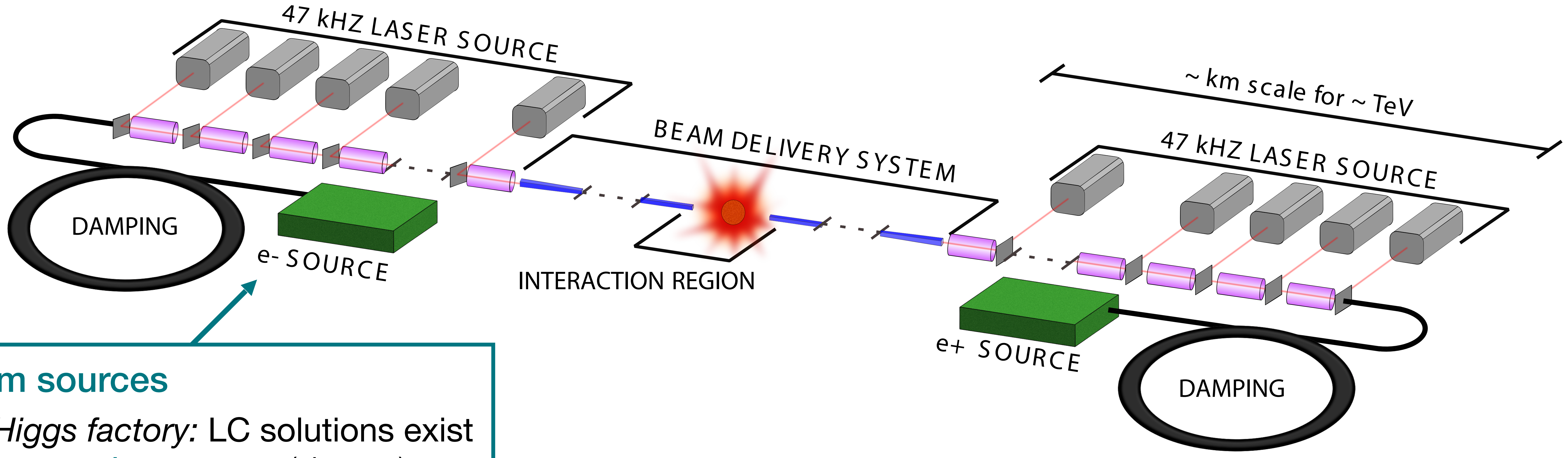

Beam sources

- *Higgs factory:* LC solutions exist
  opportunity - compact (cheaper) sources from plasmas
- *10 TeV collider:* undefined, potentially a key issue

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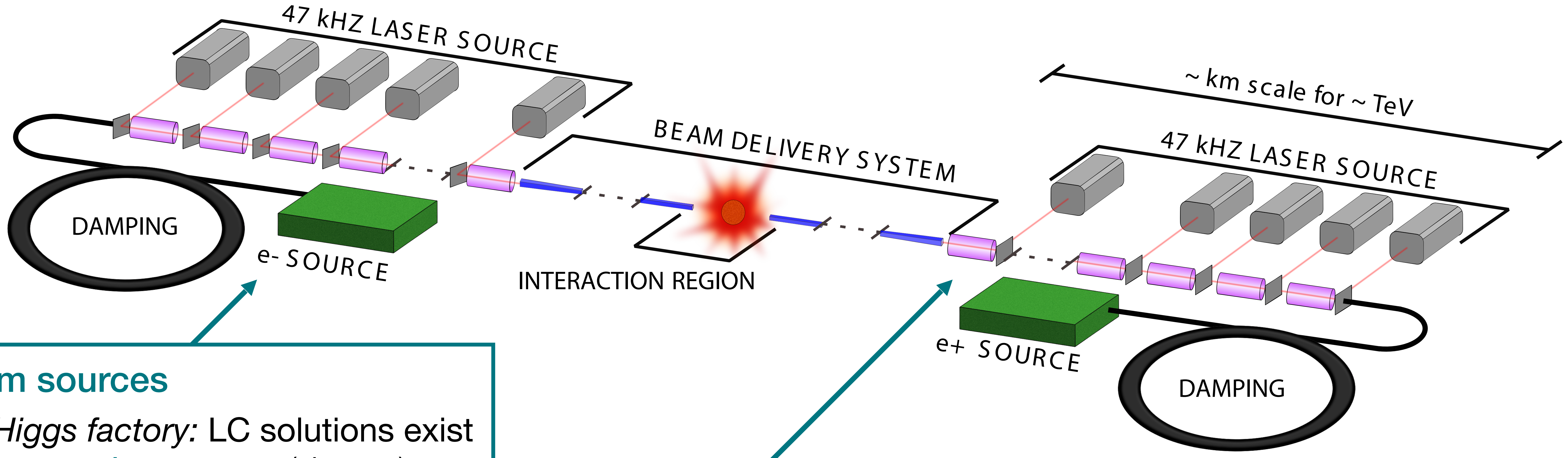
Plasma collider components and challenges



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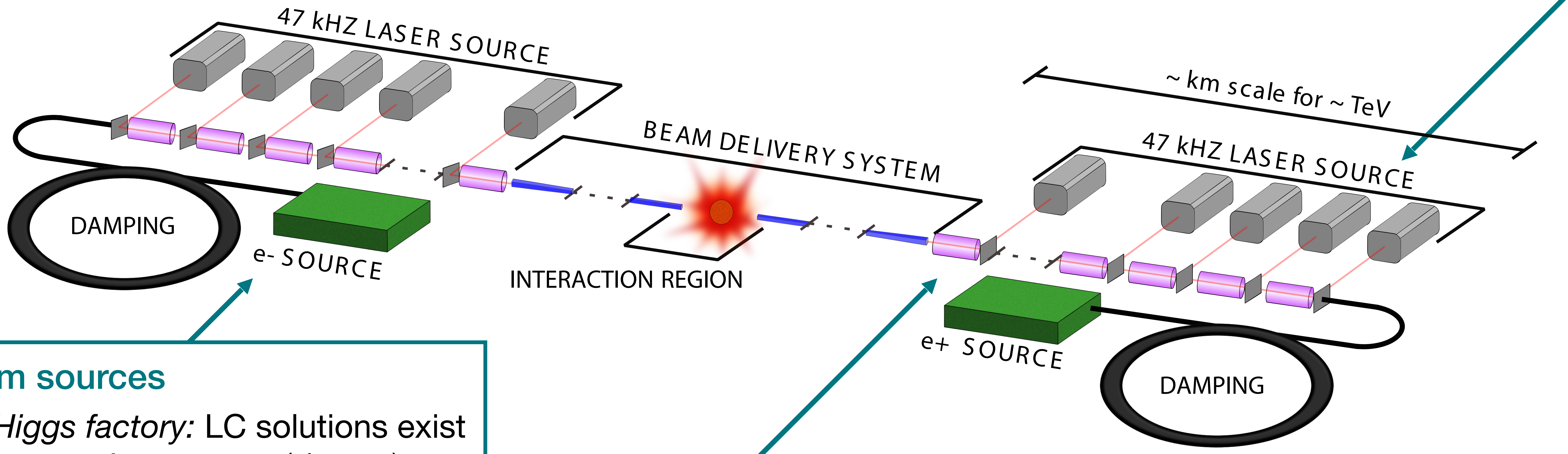
Plasma stages + coupling

- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters
  + critical - rep. rates & bunch structure (CW vs. burst), power handling
- *Staging:* requires detailed concepts, additional test facilities
  + critical - driver in-/out-coupling, geometric gradient

Plasma collider components and challenges



Driver technology

- *Beams:* technology exists in principle
  cost, gradient, efficiency, distribution optimization
- *Lasers:* do not exist, R&D paths identified
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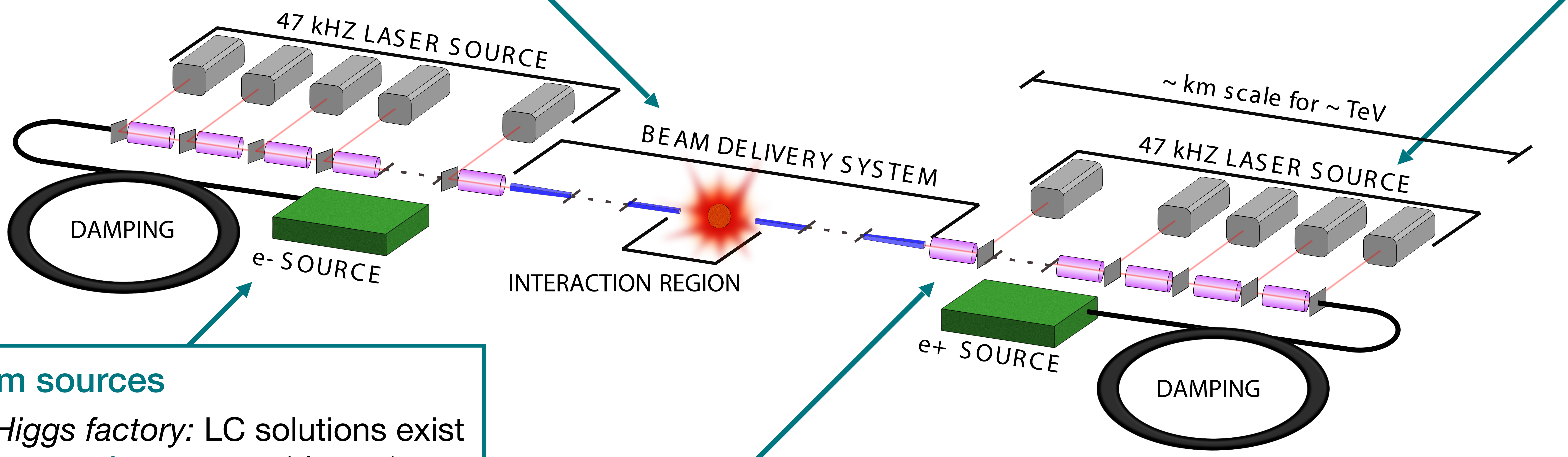

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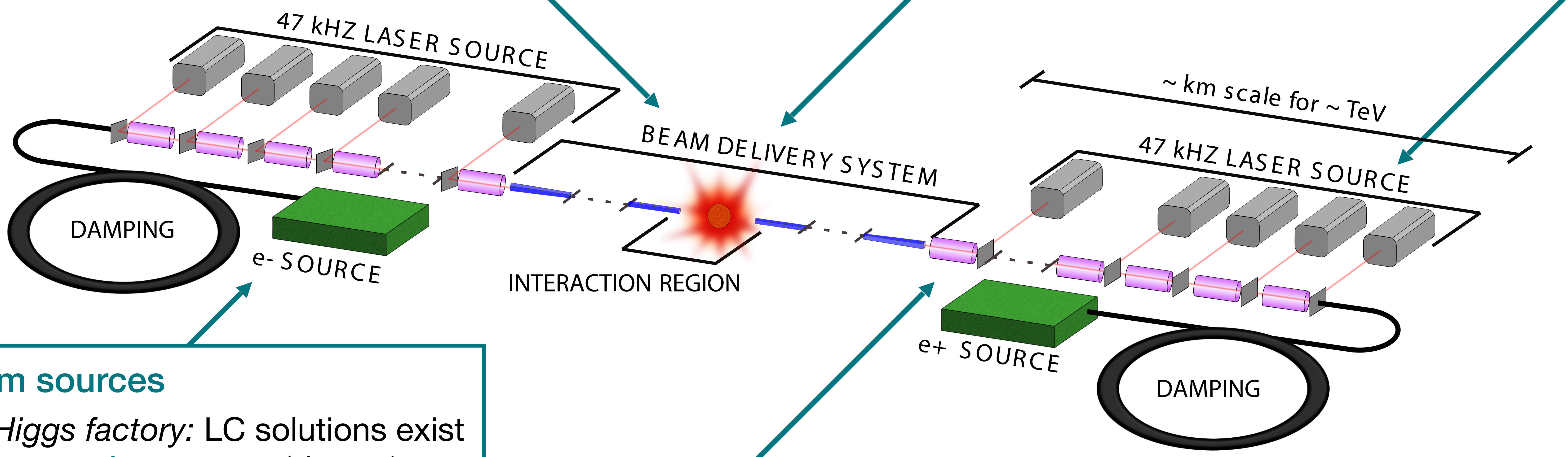

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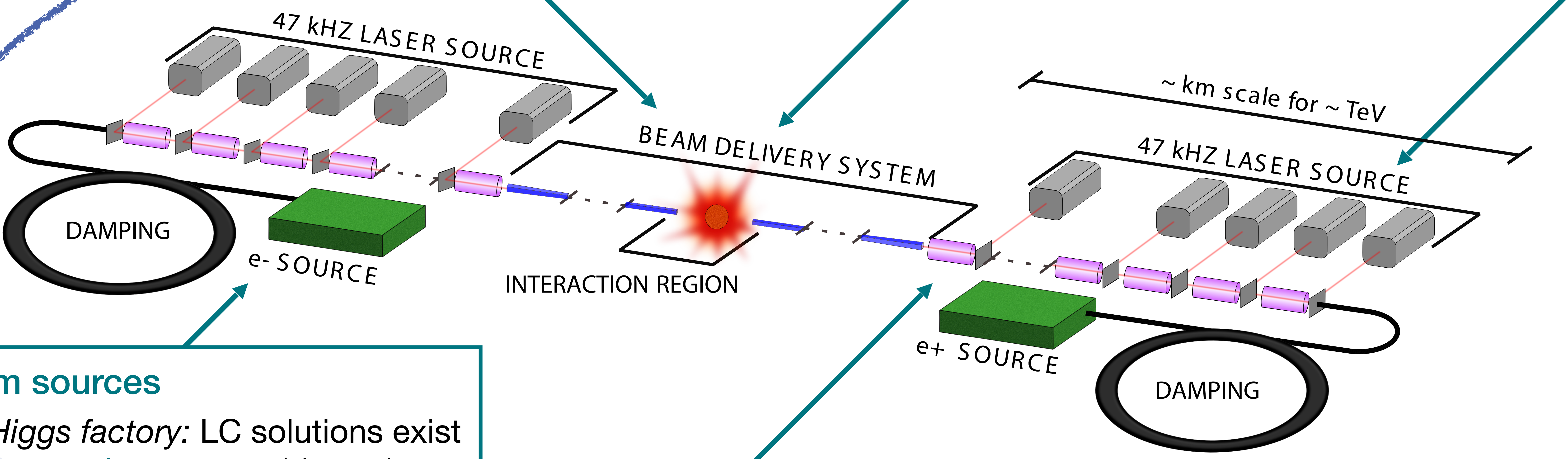

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- Turn components into self-consistent machine
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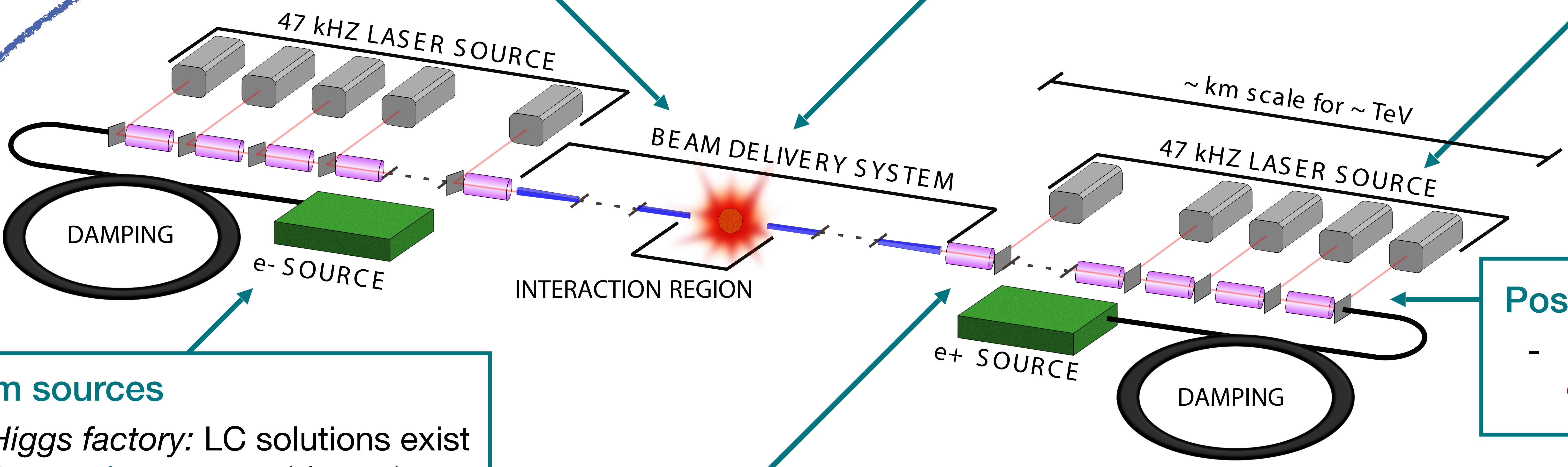

Positron acceleration

- No concept exists (yet) that fulfills needs
  critical - beam quality, efficiency, resilience

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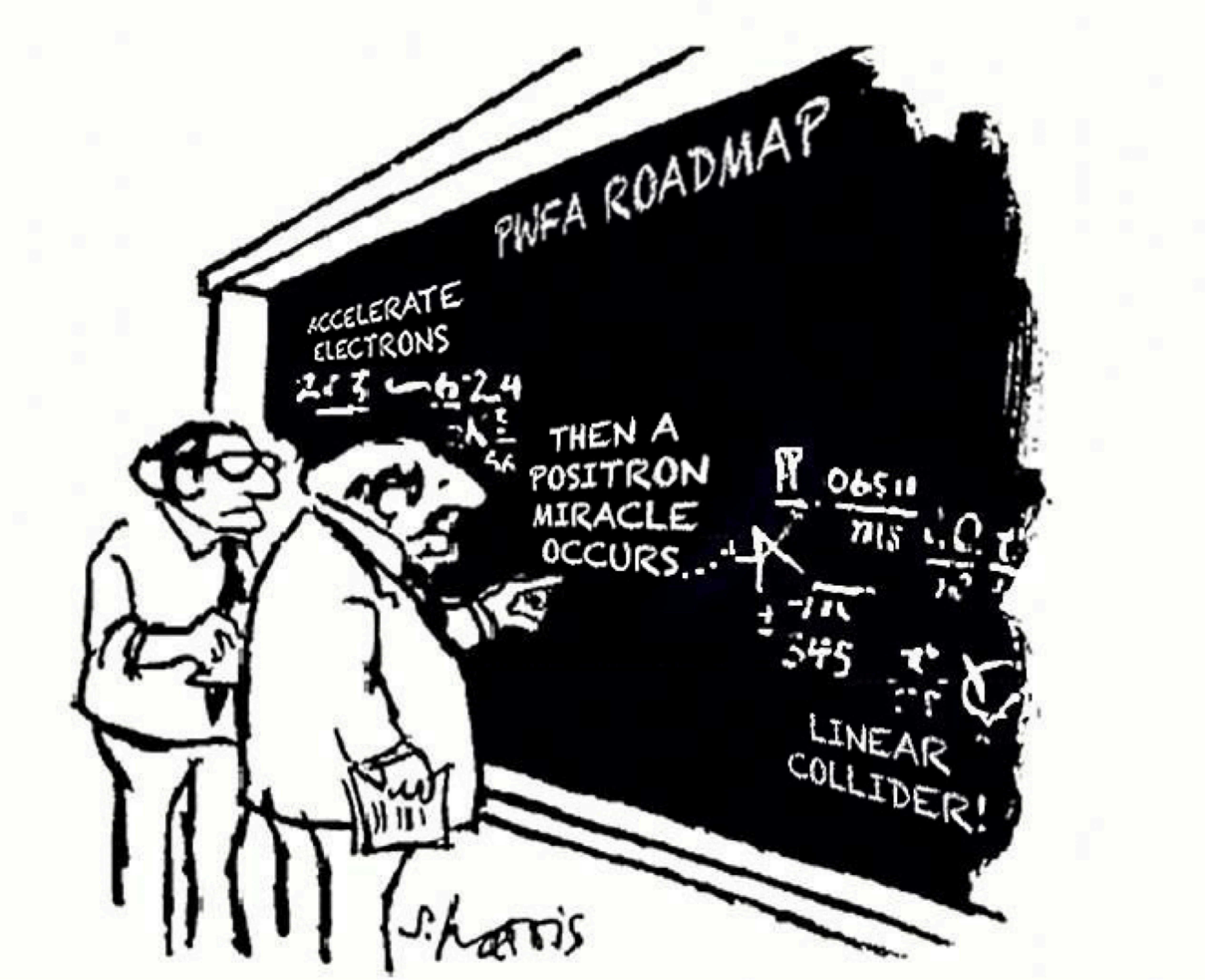
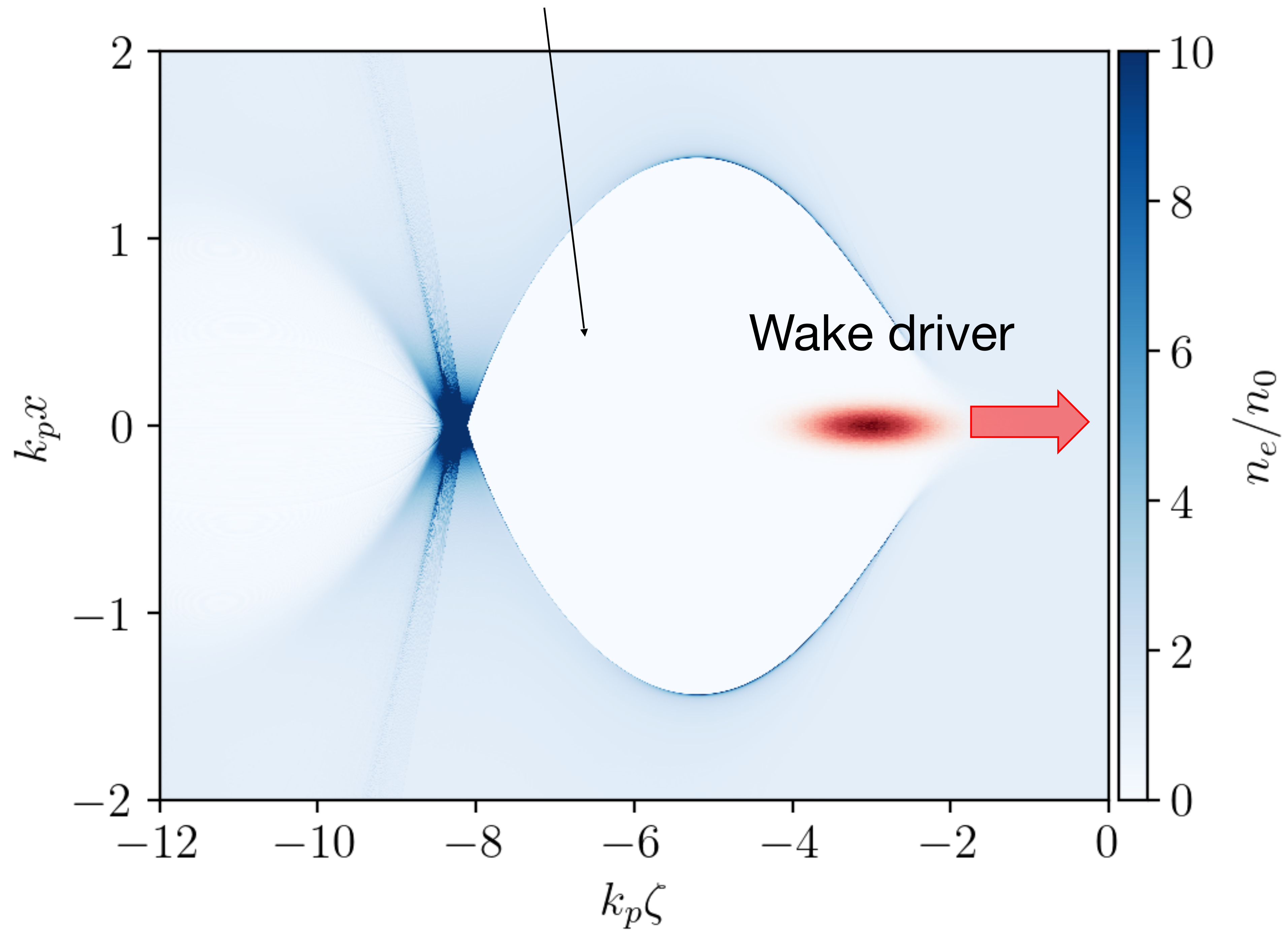


Adopted from S. Harris
and C. Lindstrøm

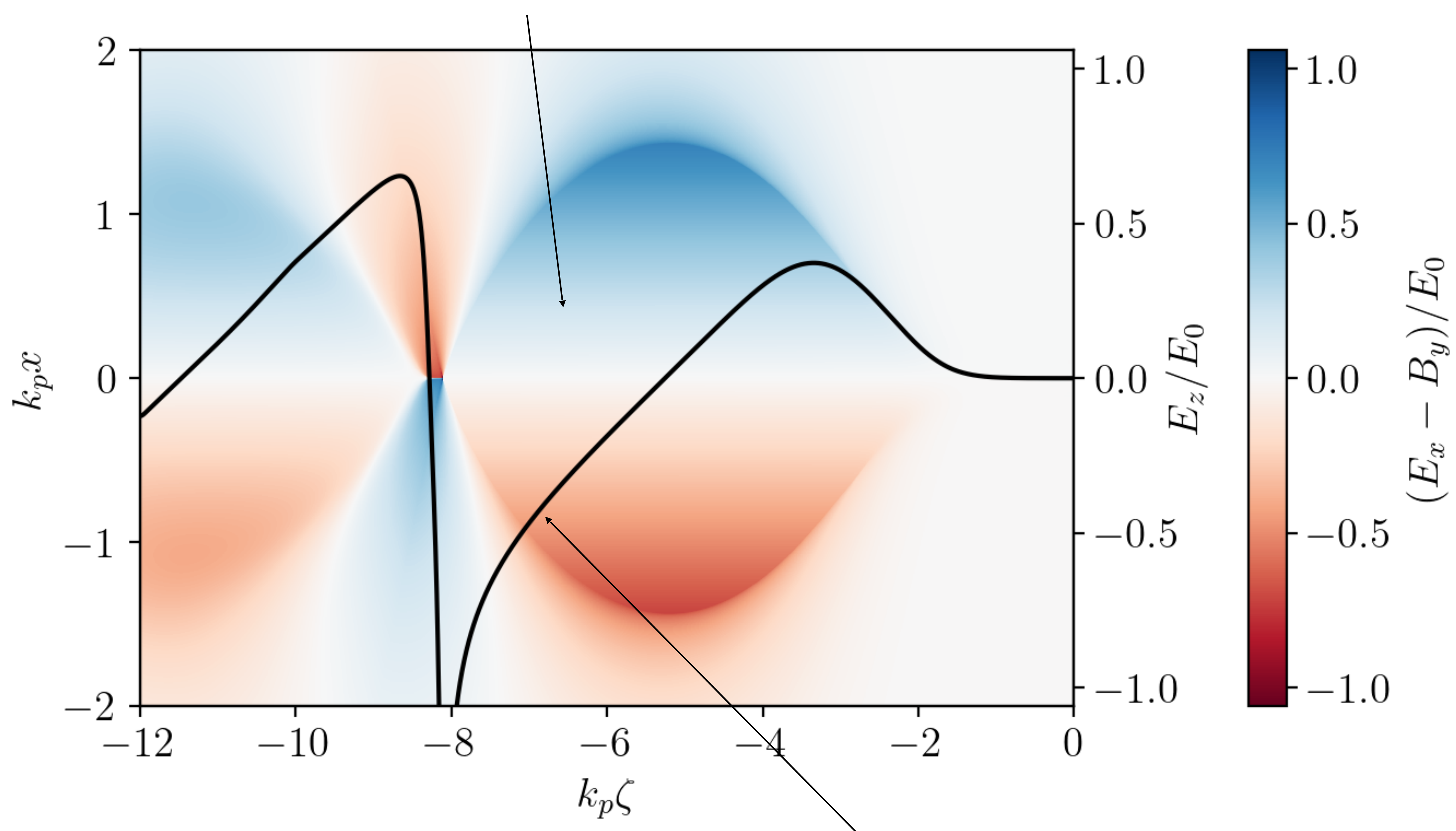
Plasma accelerators enable high-quality, high-gradient *electron* acceleration

The positron challenge is created by plasma charge asymmetry

Ion background



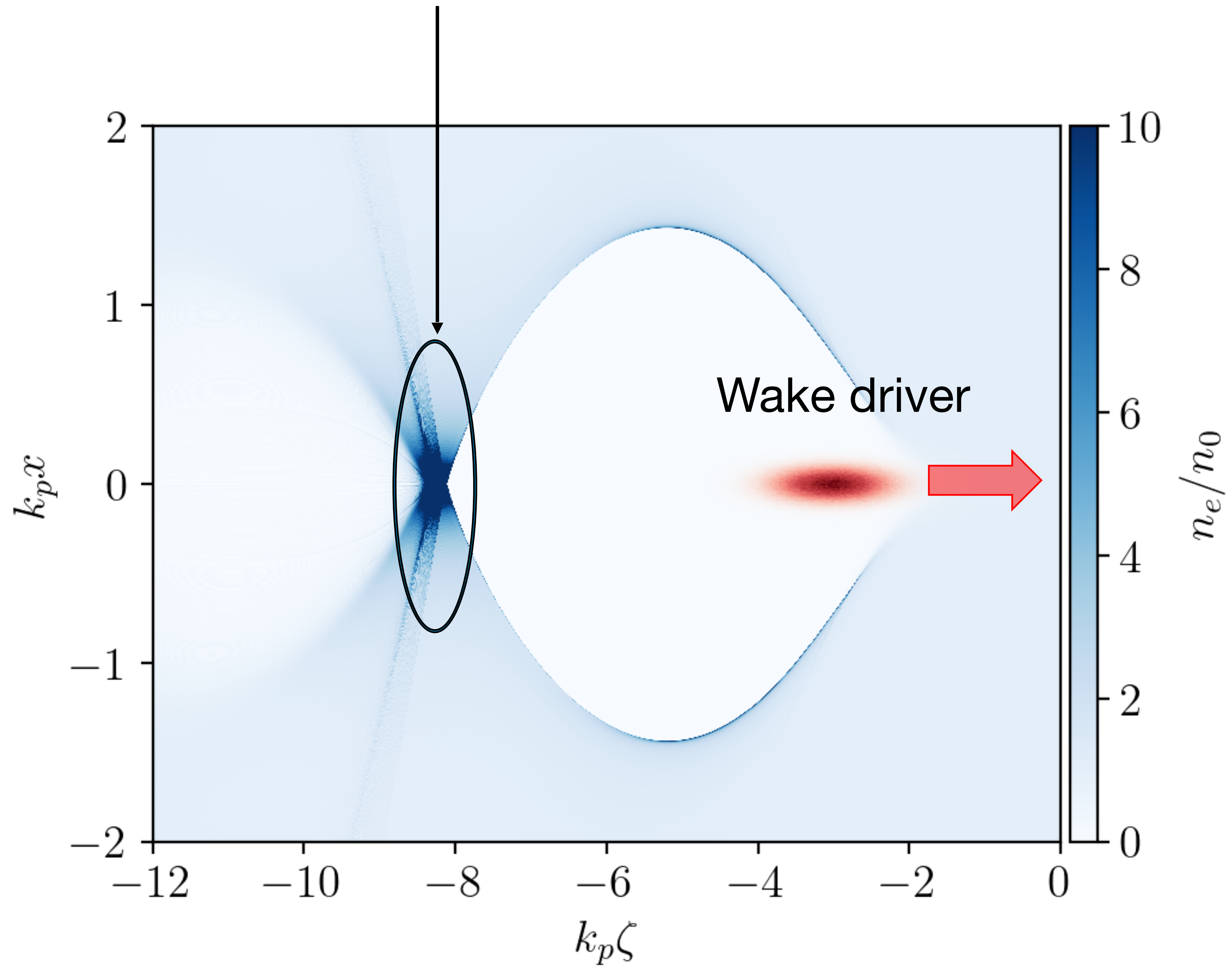
Linear focusing fields



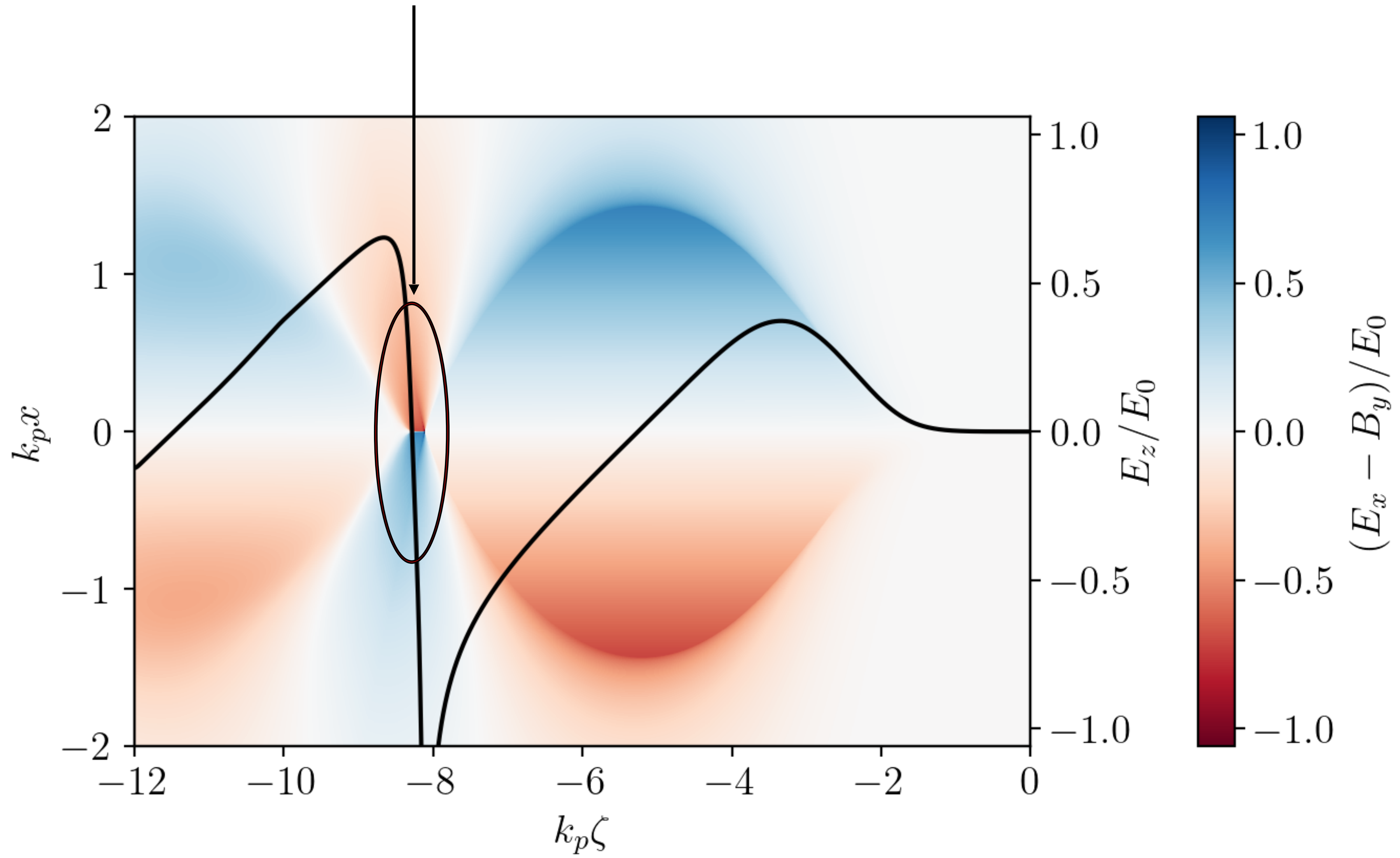
Strong accelerating fields

Only the electron spike at the back of the wake supports e⁺ acceleration

The positron challenge is created by charge asymmetry (high mobility of plasma electrons vs. ions)


High-density electron cusp

Wake driver


Focusing field for positrons

The pragmatic approach:

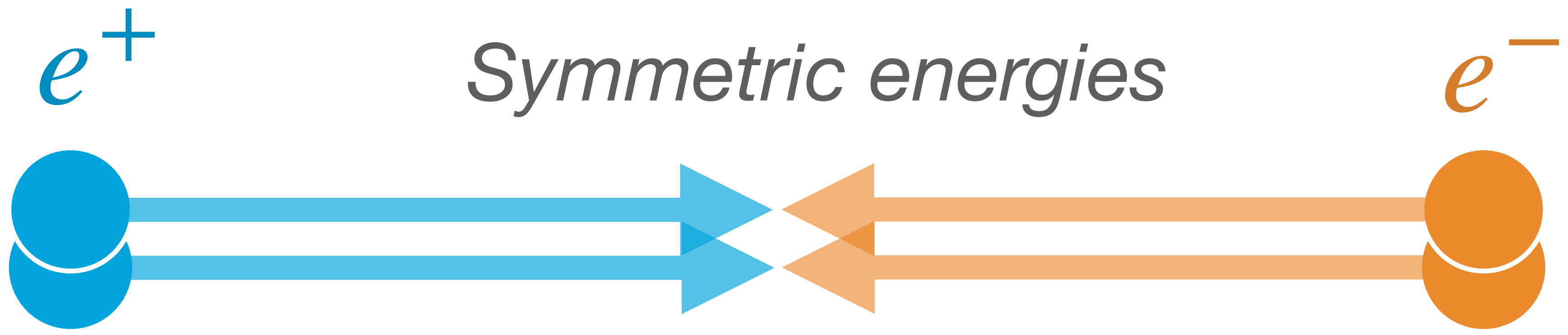
use **plasma** to **accelerate electrons**

but **RF** to **accelerate positrons**

HALHF

Can we use **asymmetric e+/e- energies** to reduce cost?

- Minimum centre-of-mass energy required for Higgs factory: $\sqrt{s} \approx 250\,\mathrm{GeV}$



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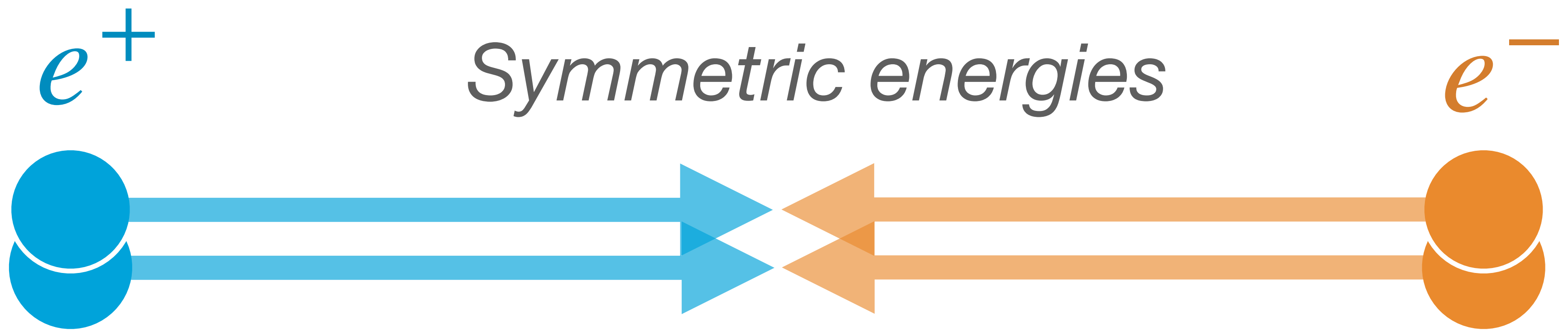

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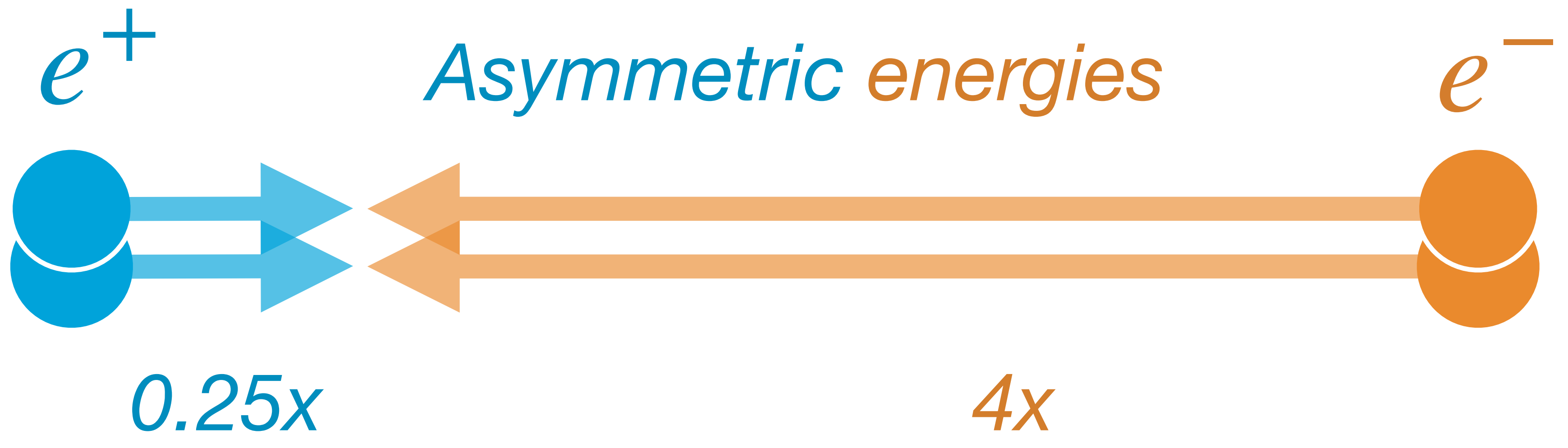
- A reasonable (but not necessarily optimized) choice is:
  - Electrons (from PWFA): **E_e = 500 GeV** (4x higher)
  - Positrons (from RF accelerator): **E_p = 31 GeV** (4x lower)
  - Boost: **γ = 2.13**
    (HERA had a boost of γ ≈ 3)



Consequences of **asymmetric e+/e− collisions**

ILC params

E (GeV)	σ_z (µm)	N (10^{10})	ϵ_{nx} (µm)	ϵ_{ny} (nm)	β_x (mm)	β_y (mm)	$\mathcal{L}$ (µb^{-1})	$\mathcal{L}_{0.01}$ (µb^{-1})	P/P_0
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- β functions are scaled to maintain the beam size at the IP
- Asymmetric energies lead to a slight reduction in luminosity (from GUINEA-PIG)

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Use shorter bunches to compensate
for smaller IP beta functions

- > **Asymmetric energies give similar luminosity**
- > However, **more power is required** (to boost the collision products)

Mitigating the power-efficiency problem: **asymmetric charge**

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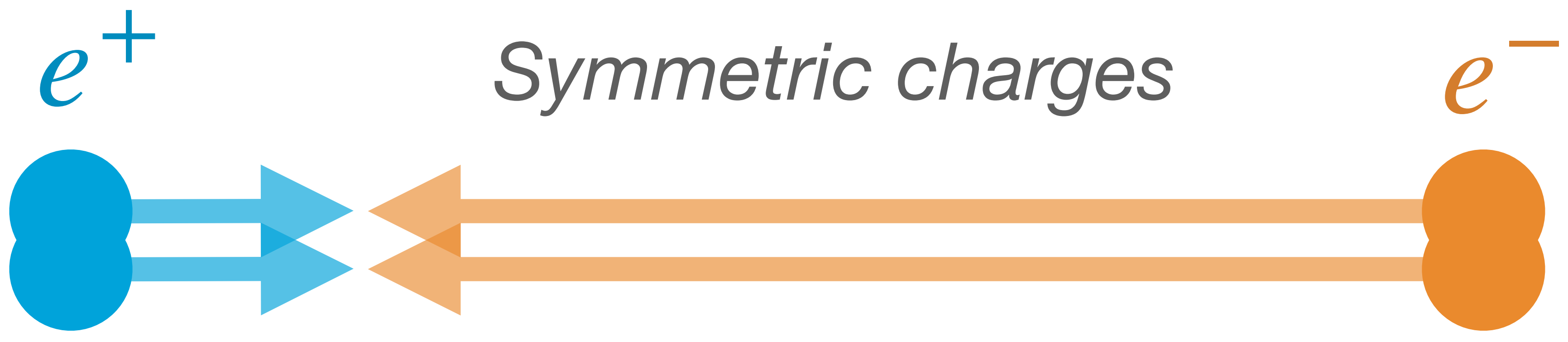

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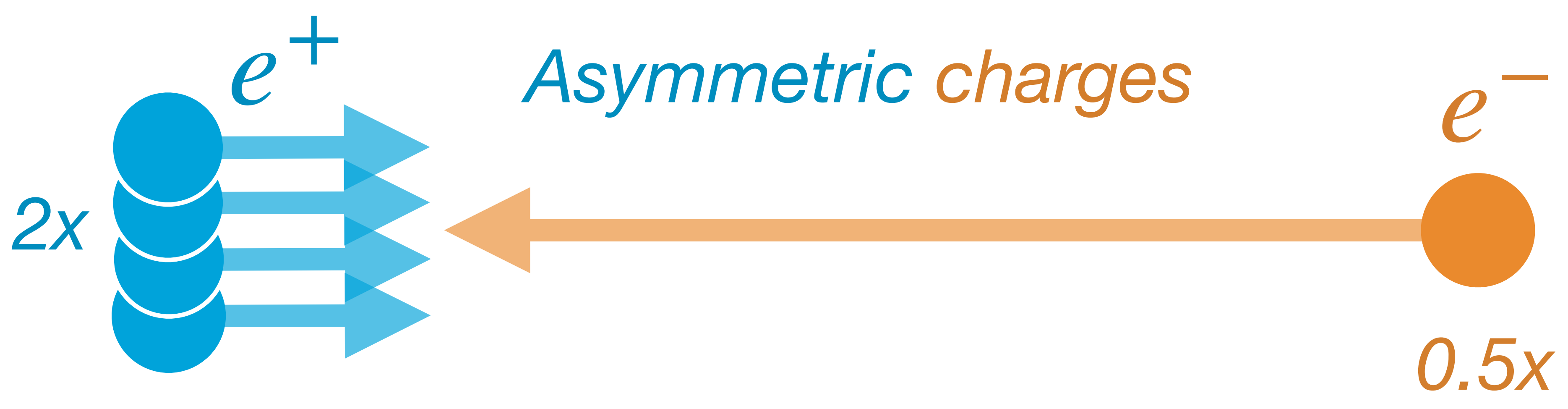

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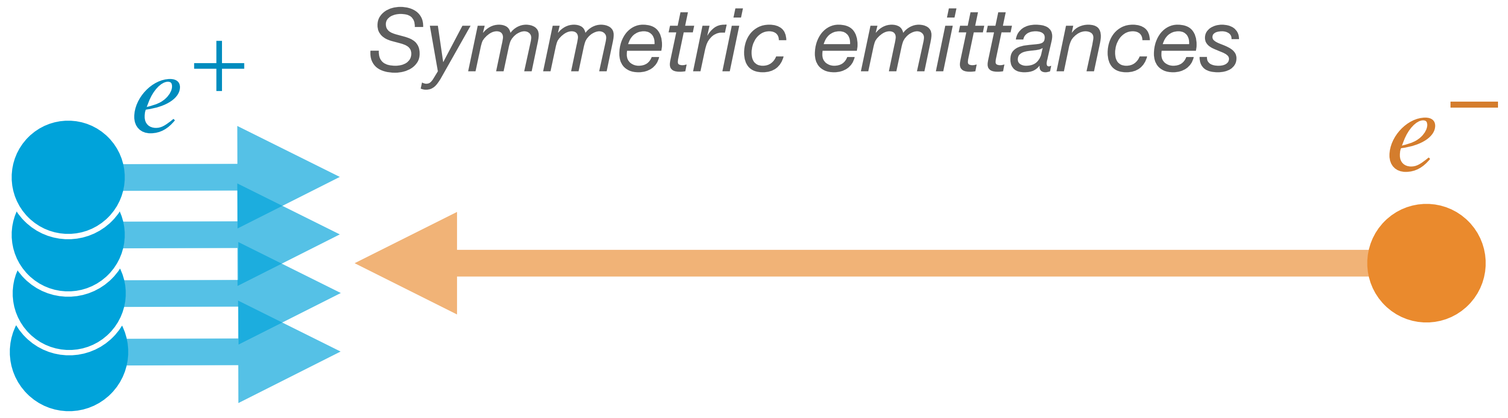

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31.3 / 500	75 / 75	4 / 1	10 / 80	35 / 280	3.3 / 6.5	0.10 / 0.20	0.94	0.54	1.25
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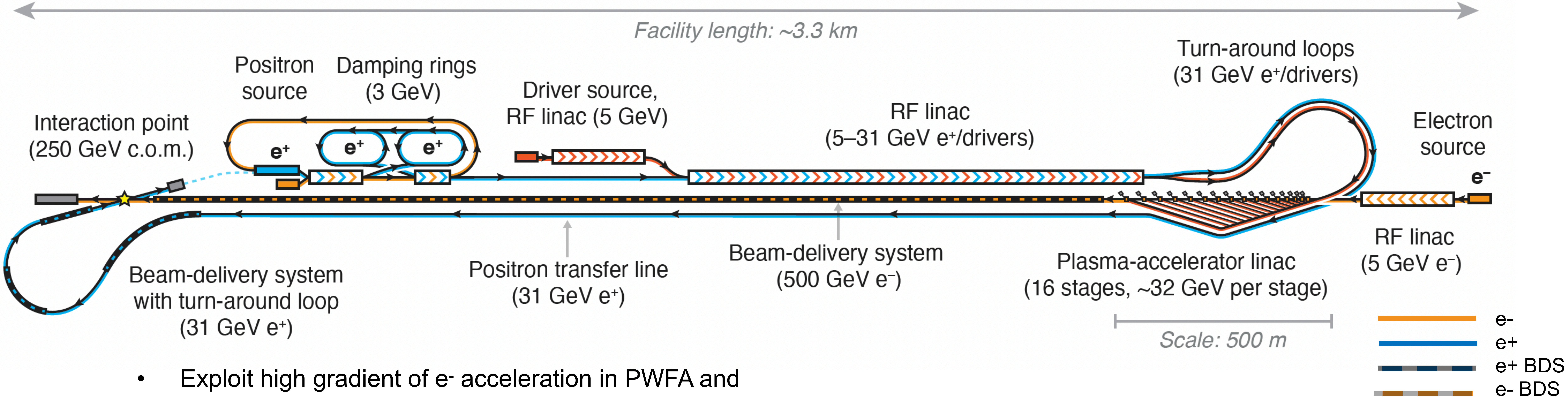
Utilizing plasma technology for a compact and cost-effective Higgs factory

The Hybrid Asymmetric Linear Higgs Factory (HALHF) Concept

Foster, D'Arcy, and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy, and Foster, arXiv:2312.04975



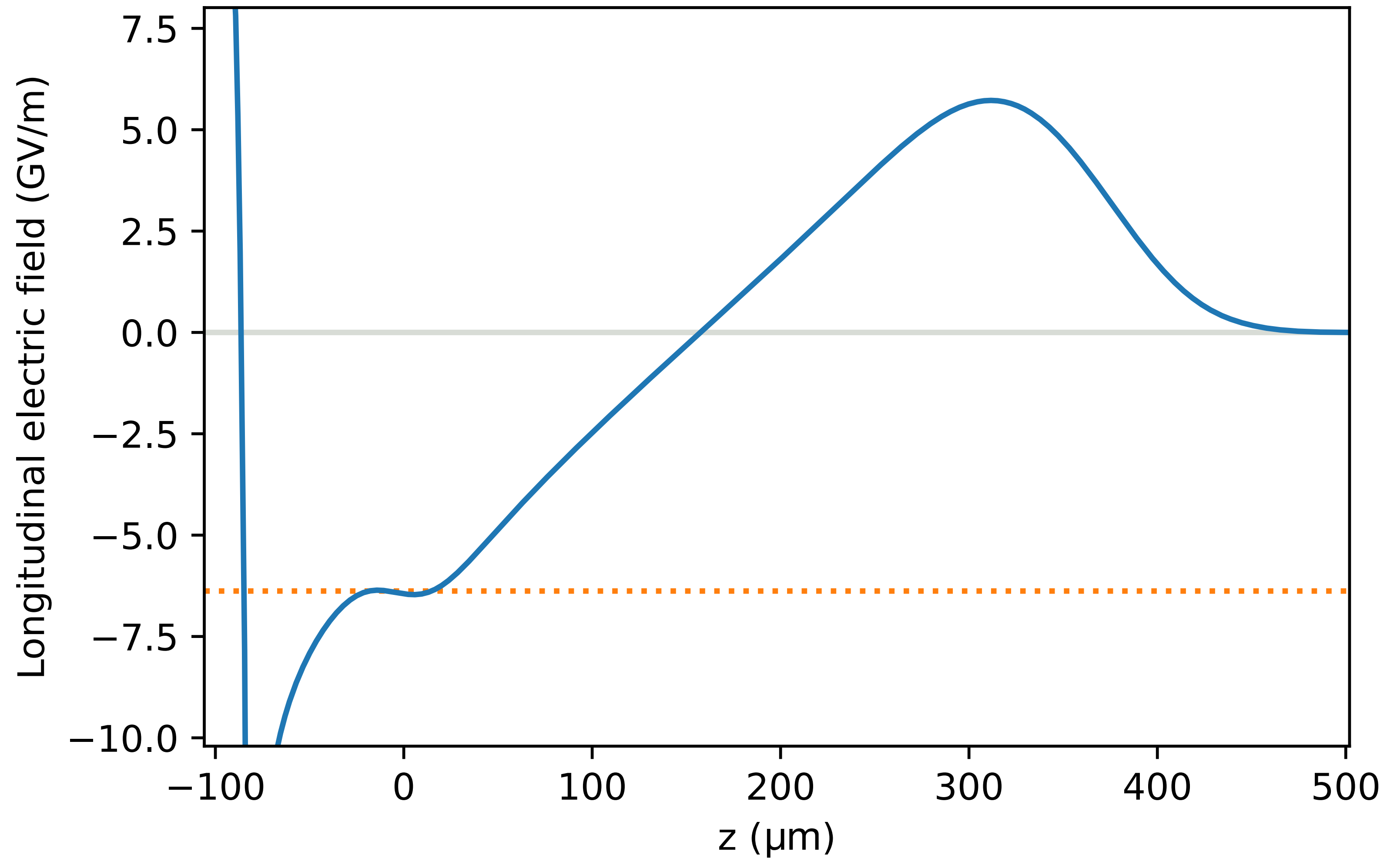
- Exploit high gradient of e^- acceleration in PWFA and avoid difficulty of e^+ acceleration by using conventional RF linac, reducing cost by low $E(e^+)$ (31 GeV) and high $E(e^-)$ (500 GeV), boost $\gamma \sim 2.7 \rightarrow E_{CM} \sim 250$ GeV.

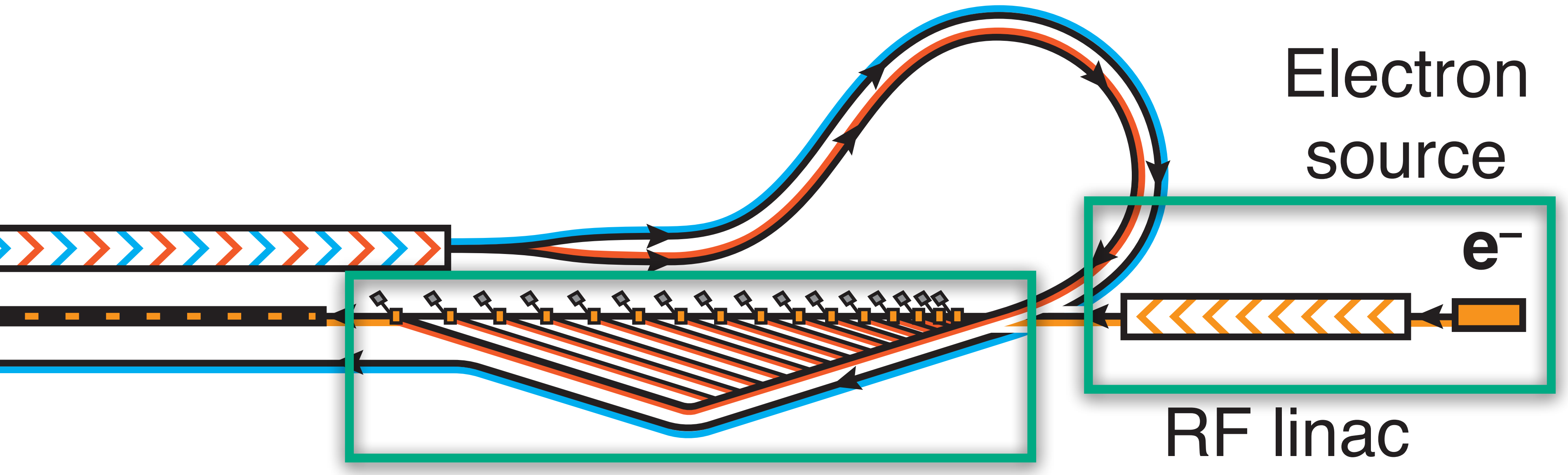
- Reduce running costs by increasing current $\mathbf{I}(e^+)$ and reducing $\mathbf{I}(e^-)$; this & asymmetric emittance (increased for e^-) ease PWFA requirements.

- Requires innovations in **positron source** (2x charge of ILC), high-efficiency (heavily beam-loaded) **RF linac**, **BDS** (small beta functions 3.3 x 0.1 mm^2), **driver distribution**, **plasma modules** and **staging** (see earlier slides), boosted-frame Higgs-factory **detectors**

At the core: **a multistage plasma-based linac**

- ***Length***: 16 PWFA stages (5-m long): ~400 m total length
- ***Gradient***: 6.4 GV/m (in plasma)—1.2 GV/m (average)
- ***Efficiency***: 38% = 72% (wake input) x 53% (wake extraction)
- No damping ring required due to high-emittance electrons





Turn-around loops
(31 GeV e⁺/drivers)

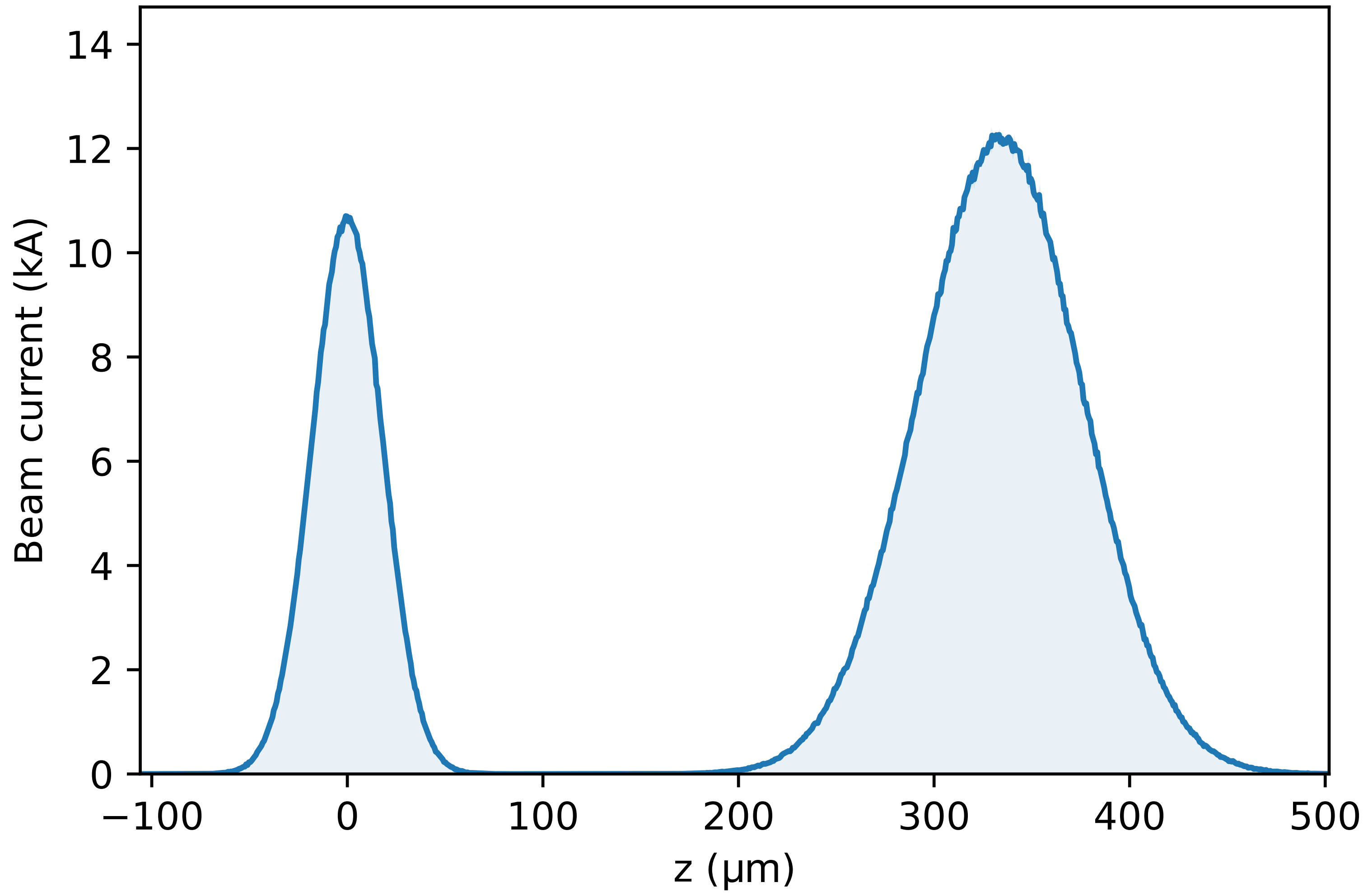
Electron
source

Plasma-accelerator linac
(16 stages, ~32 GeV per stage)

RF linac
(5 GeV e⁻)

PWFA linac parameters

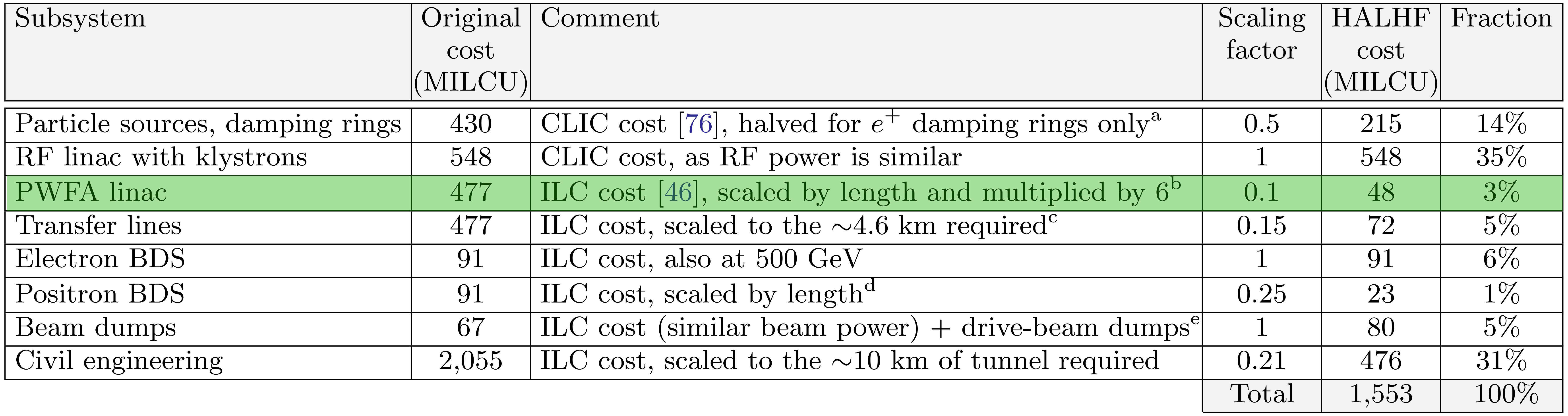
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.7
Driver bunch length (rms)	μm	27.6
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	74
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	39
Wall-plug-to-beam efficiency	%	19.5
Cooling req. per stage length	kW/m	100



Simulated with Wake-T
Plasma density: 7 x 10^{15} cm^{-3}
Driver/witness charge: 4.3/1.6 nC

Rough cost estimates for HALHF

- Scaled from existing collider projects (ILC/CLIC) where possible ➞ not exact
  - European accounting (2022 $): **~$1.9B** (**~1/4 of ILC TDR cost** @ 250 GeV)
  - US accounting (“TPC”): **$2.3–3.9B** ($4.6B from ITF model for RF accelerators)
- Dominated by conventional collider costs (97%) — **PWFA linac only ~3% of the cost**

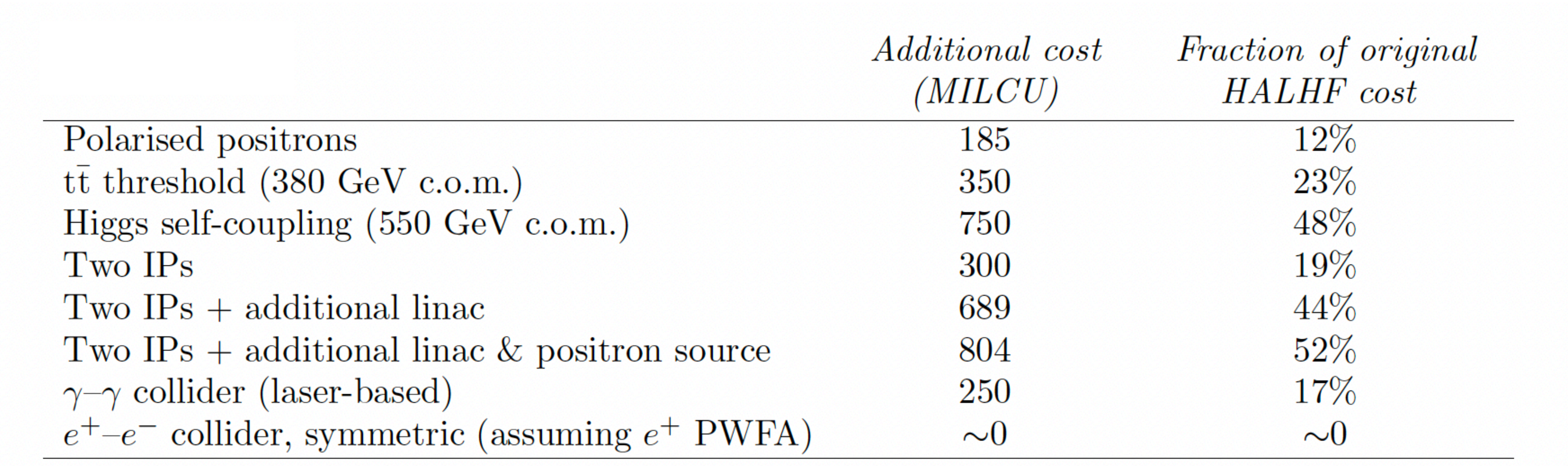


Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [76], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [46], scaled by length and multiplied by 6[b]	0.1	48	3%
Transfer lines	477	ILC cost, scaled to the ~4.6 km required[c]	0.15	72	5%
Electron BDS	91	ILC cost, also at 500 GeV	1	91	6%
Positron BDS	91	ILC cost, scaled by length[d]	0.25	23	1%
Beam dumps	67	ILC cost (similar beam power) + drive-beam dumps[e]	1	80	5%
Civil engineering	2,055	ILC cost, scaled to the ~10 km of tunnel required	0.21	476	31%
			Total	1,553	100%

- Estimated **power usage is ~100 MW** (similar to ILC and CLIC):
  - 21 MW beam power + 27 MW losses + 2×10 MW damping rings + 50% for cooling/etc.

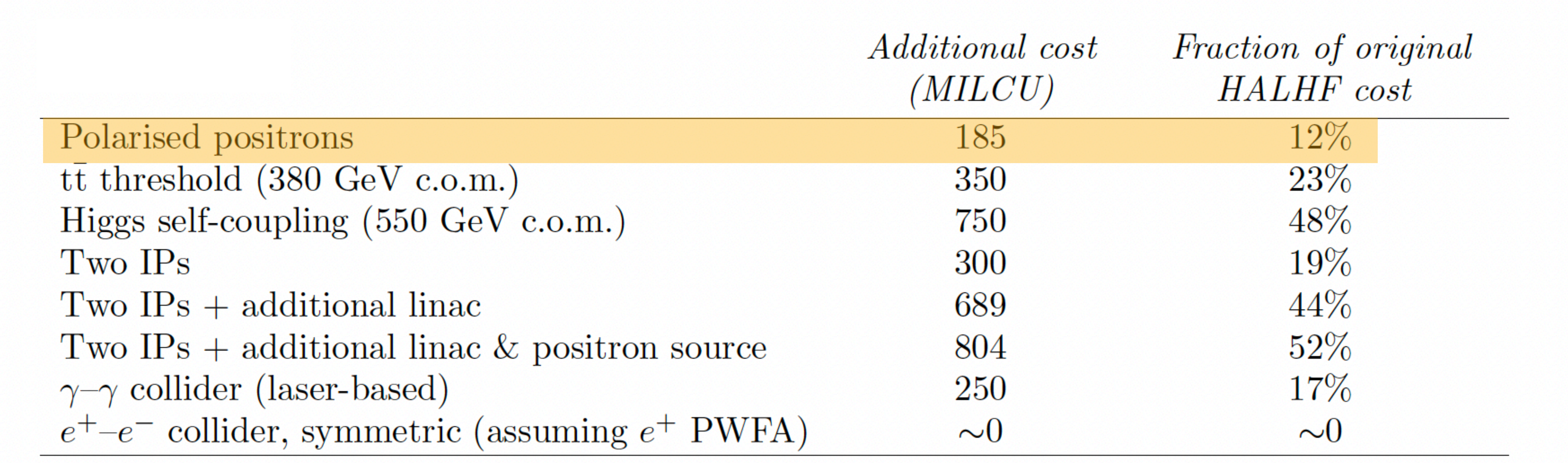
The reference currency (the “ILCU”) is the United States dollar (USD) as of January, 2012

Upgrade options are being investigated



	Additional cost (MILCU)	*Fraction of original HALHF cost*
Polarised positrons	185	12%
$t\bar{t}$ threshold (380 GeV c.o.m.)	350	23%
Higgs self-coupling (550 GeV c.o.m.)	750	48%
Two IPs	300	19%
Two IPs + additional linac	689	44%
Two IPs + additional linac & positron source	804	52%
γ–γ collider (laser-based)	250	17%
e^+–e^- collider, symmetric (assuming e^+ PWFA)	$\sim$0	$\sim$0

Upgrade options are being investigated



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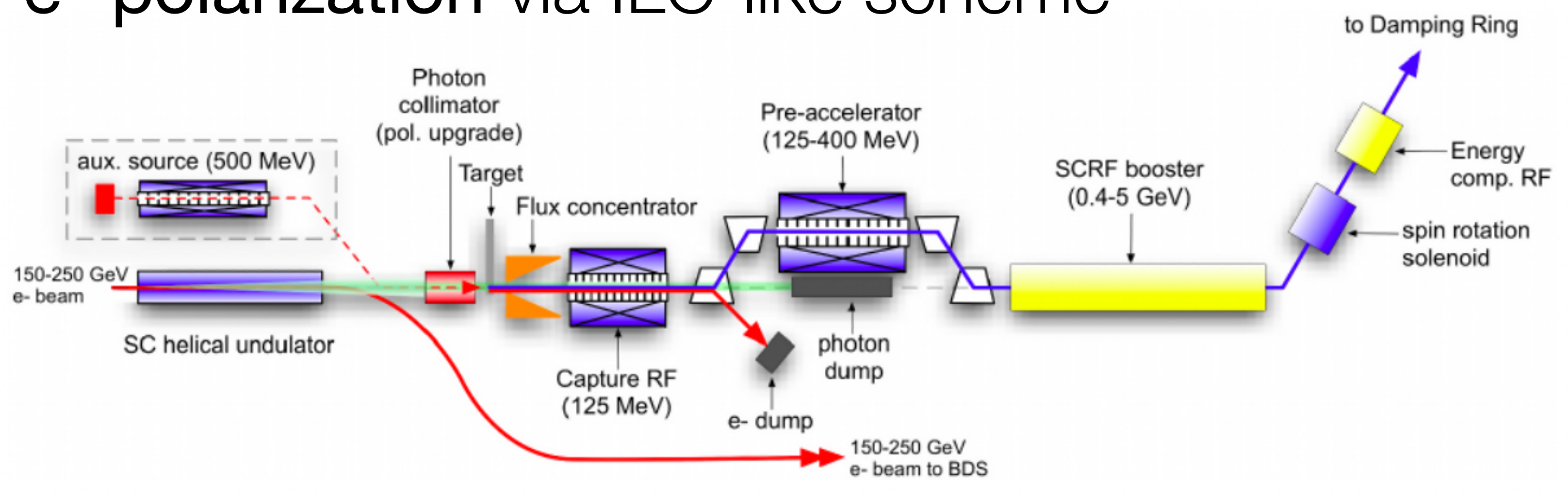
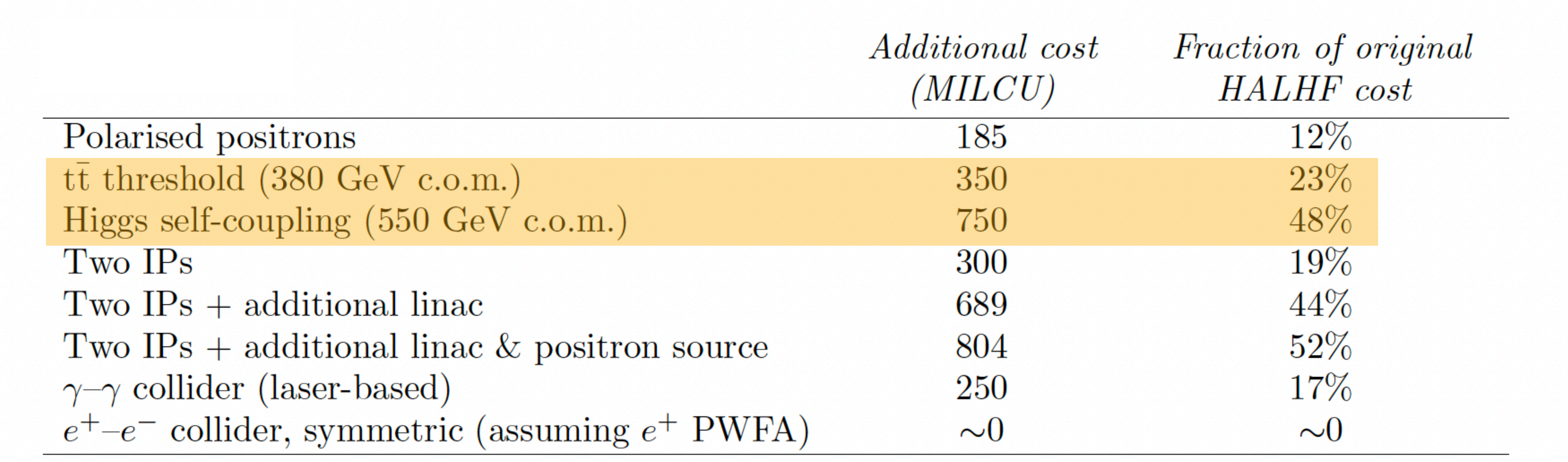
- e^+ **polarization** via ILC-like scheme



Upgrade options are being investigated



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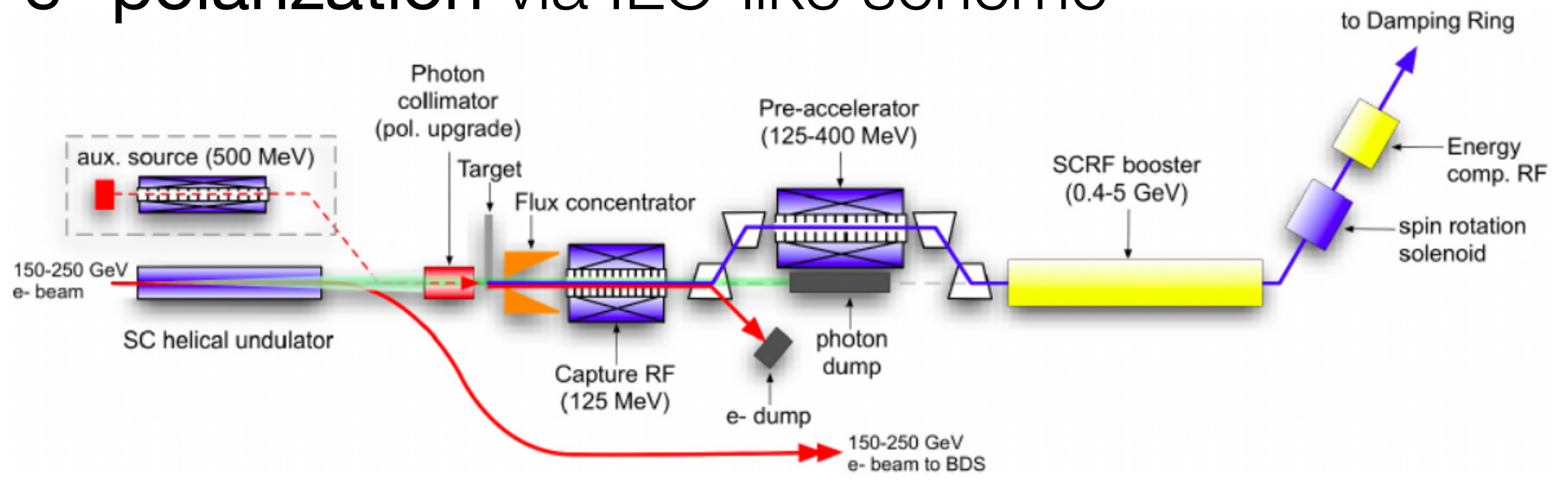
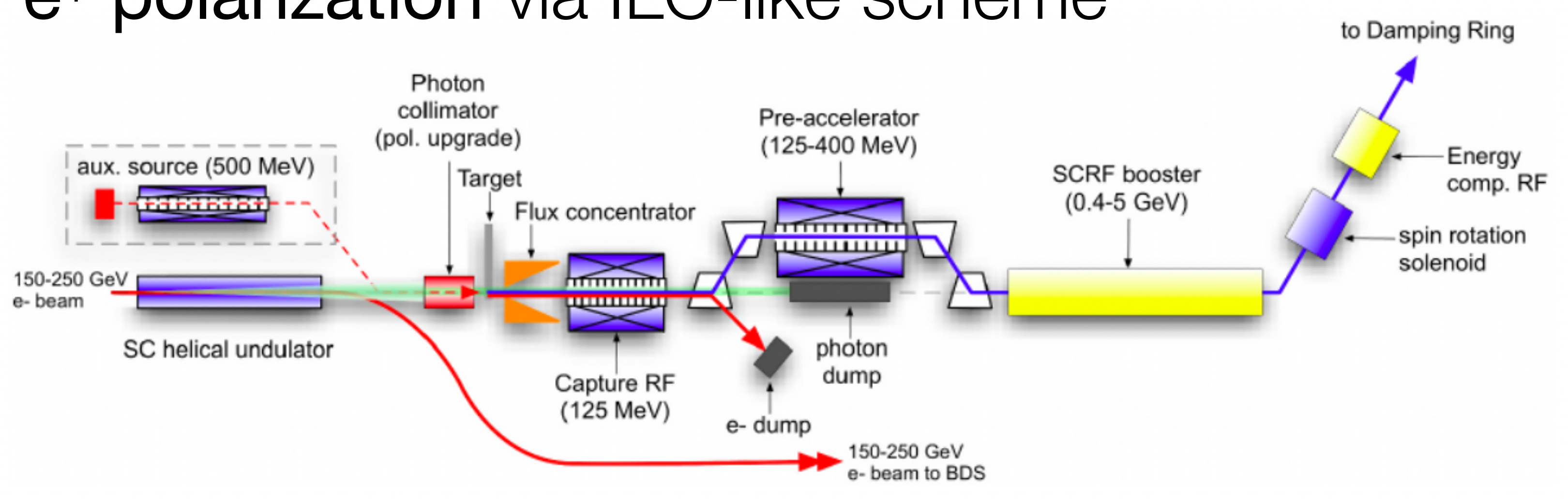
- **e^+ polarization** via ILC-like scheme

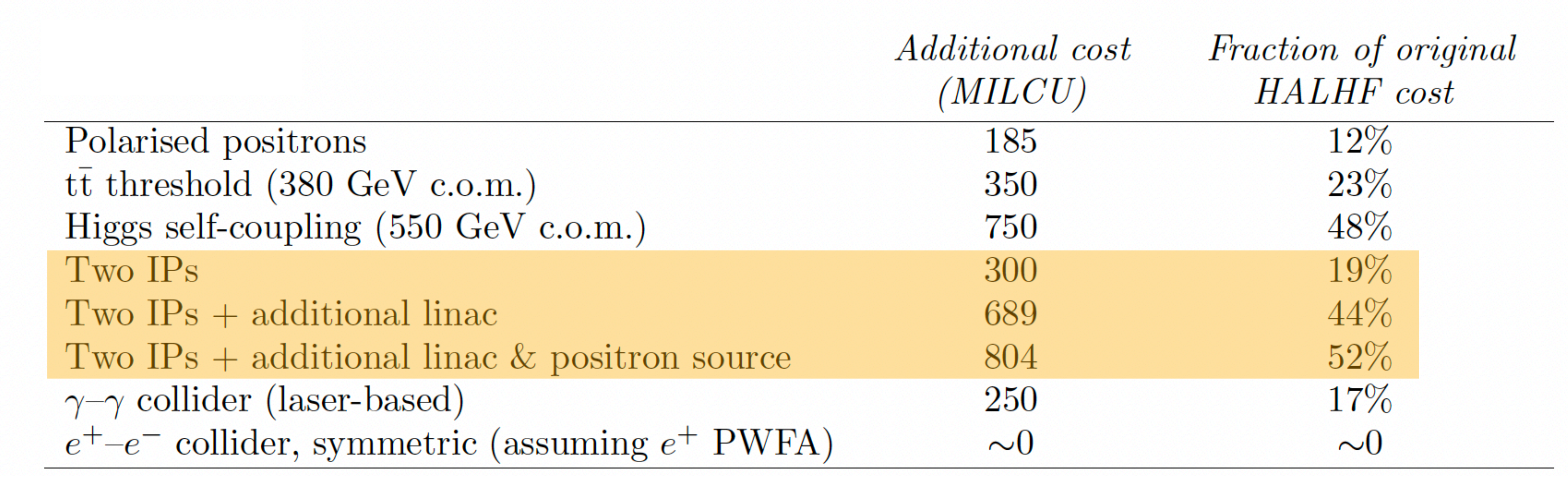


- **380 GeV c.o.m.:** length +10%, power +25%
- **550 GeV c.o.m.:** PWFA linac length +64%, RF linac length doubled, power +90%

Upgrade options are being investigated

- **e⁺ polarization** via ILC-like scheme





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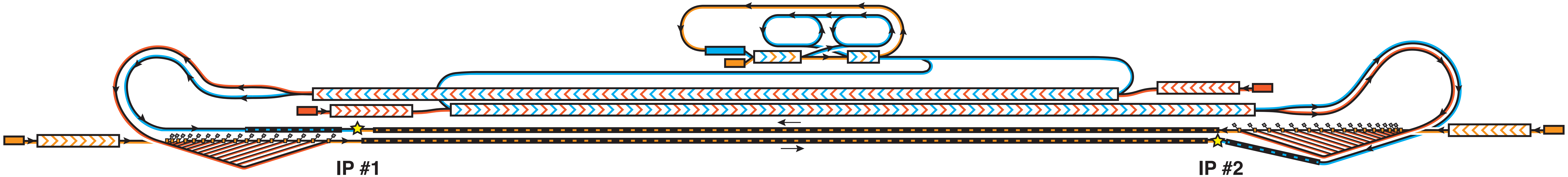
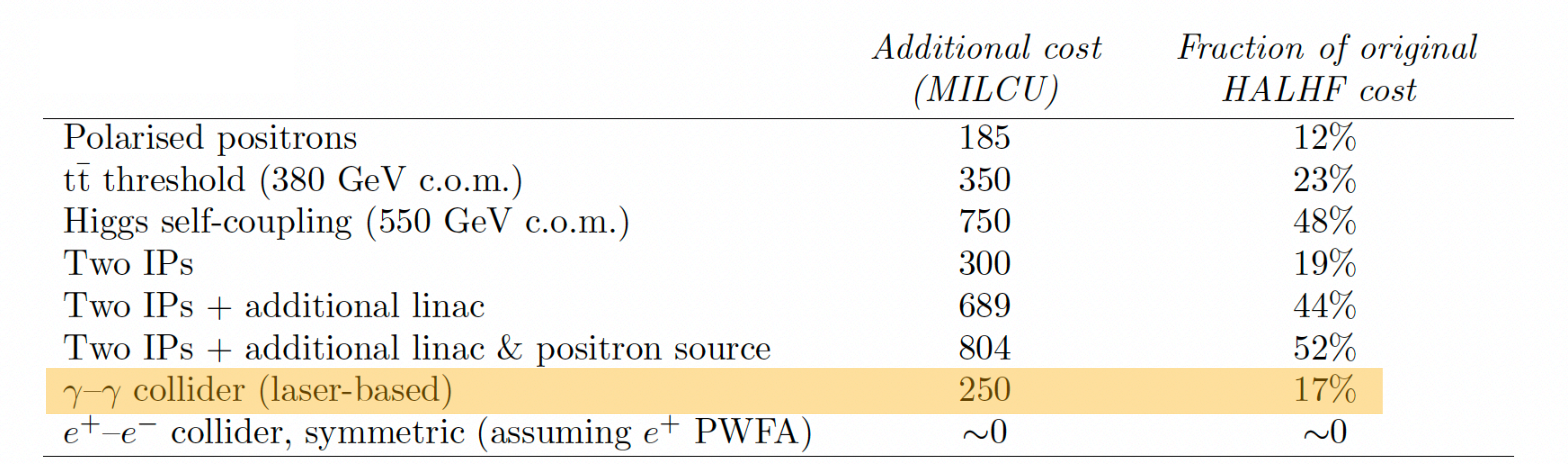
- **380 GeV c.o.m.:** length +10%, power +25%
- **550 GeV c.o.m.:** PWFA linac length +64%, RF linac length doubled, power +90%
- Two Interaction Points (IPs)
  - Single IP seen as weakness of LCs
  - Politically important (systematics, 2x physicists)



IP #1
(250 GeV c.o.m. e⁺–e⁻)

IP #2
(250 GeV c.o.m. e⁺–e⁻)

Making HALHF whole again: returning to symmetry for TeVs



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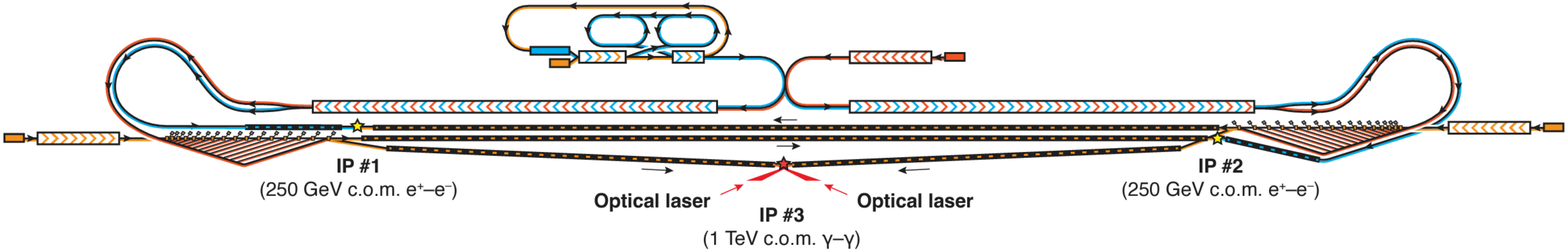
e^+–e^- collider, symmetric (assuming e^+ PWFA)	$\sim$0	$\sim$0

- Third IP for γ-γ collisions
  - Laser and XFEL options are discussed



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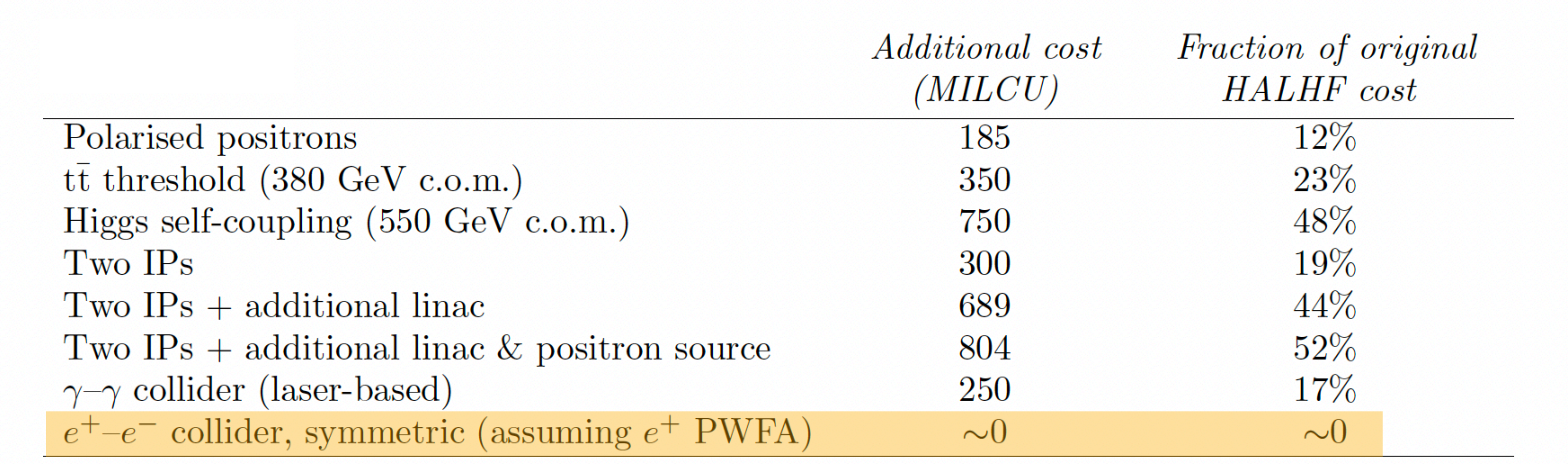

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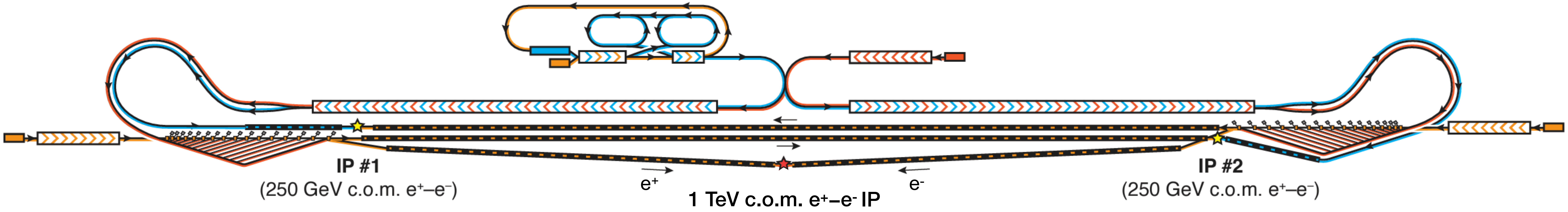
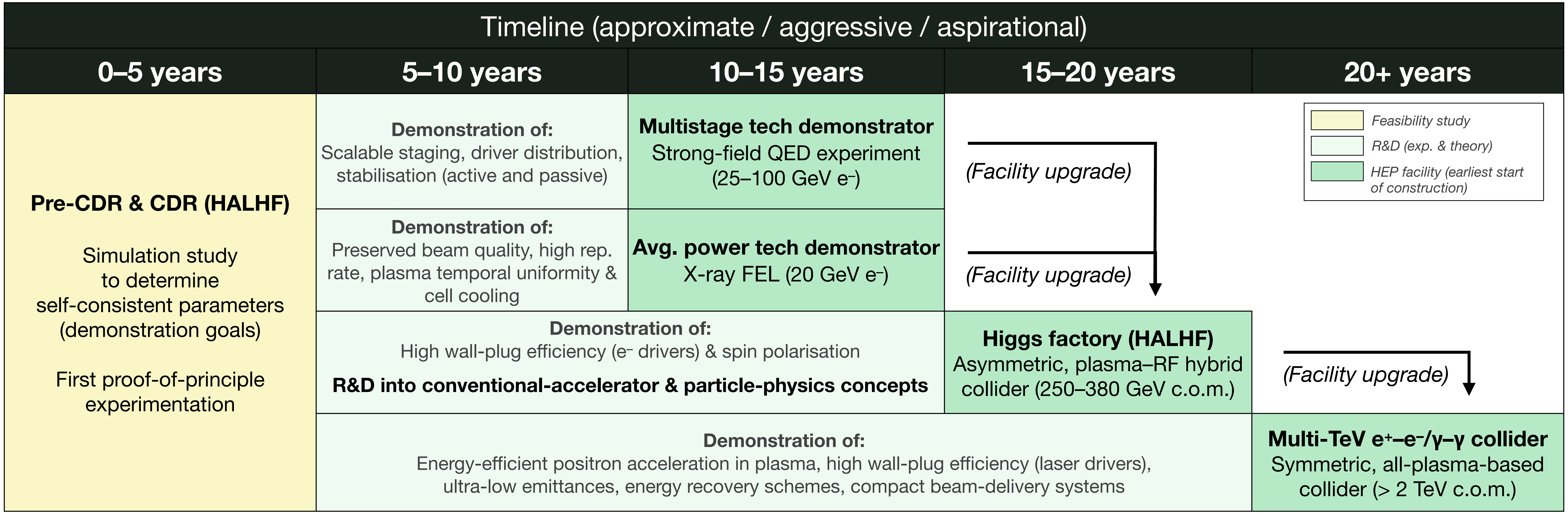
γ–γ collider (laser-based)	250	17%
e^+–e^- collider, symmetric (assuming e^+ PWFA)	~0	~0

- HALHF does not scale to the energy frontier
  - a multi-TeV collider
    will have to be symmetric again



Rough timeline for HALHF (and beyond)

- *Short term (0–5 yrs):* Pre-CDR & CDR
- *Near term (5–15 yrs):* Tech. Demonstrators — **strong-field QED, X-ray FEL, and beyond**
- *Long term (15–20 yrs):* Delivery of HALHF — **intense R&D required**
- *Upgrades (20+ yrs):* Upgrade path for HALHF (many options available)



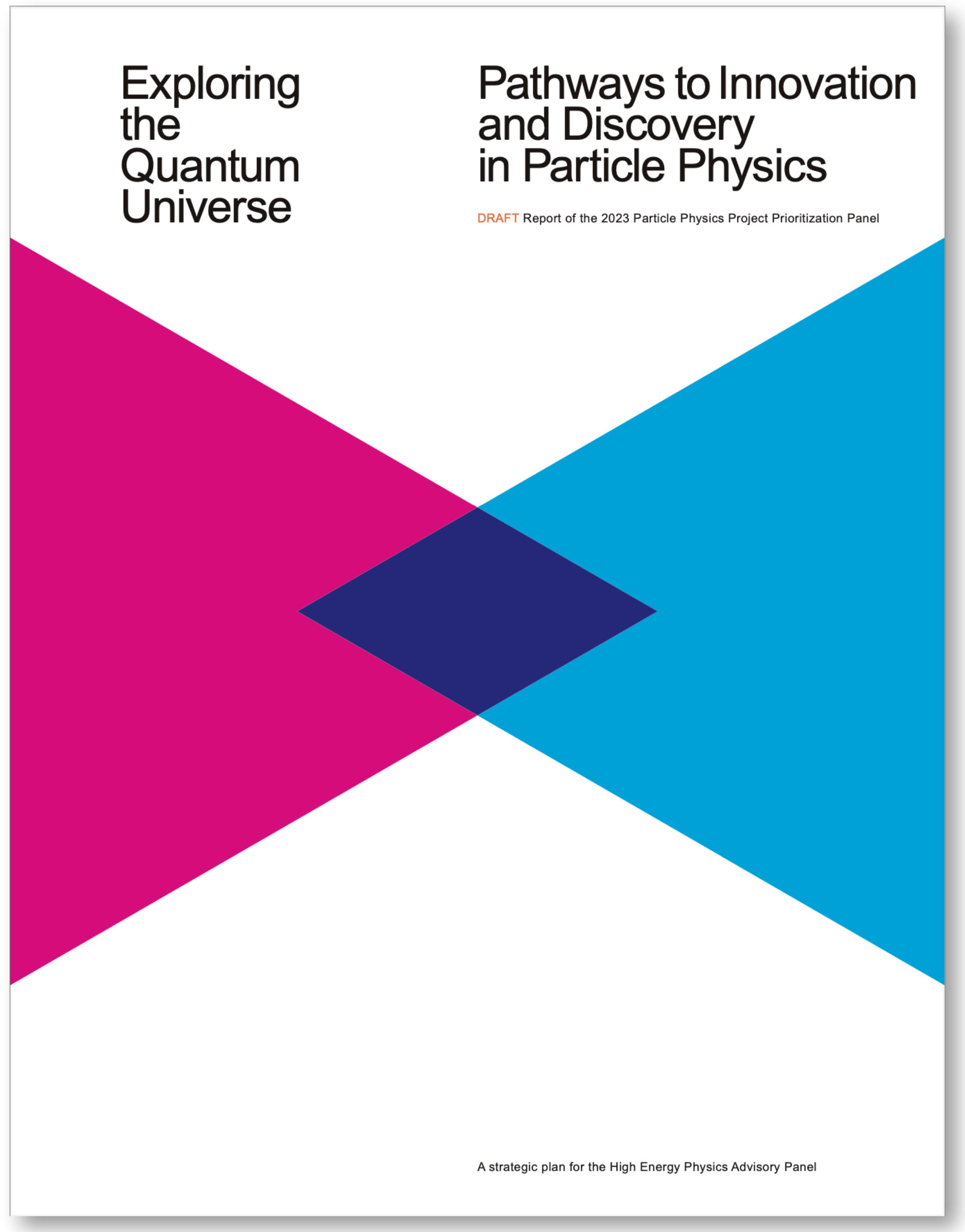
Timeline (approximate / aggressive / aspirational)

0–5 years	**5–10 years**	**10–15 years**	**15–20 years**	**20+ years**
Pre-CDR & CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	
	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)	*(Facility upgrade)*	
	Demonstration of: High wall-plug efficiency (e^- drivers) & spin polarisation **R&D into conventional-accelerator & particle-physics concepts**		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

🟨 *Feasibility study*
⬜ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

10 TeV pCM wakefield collider

P5 prioritizes accelerator R&D toward a future 10 TeV pCM collider



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

DRAFT Report of the 2023 Particle Physics Project Prioritization Panel

A strategic plan for the High Energy Physics Advisory Panel

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

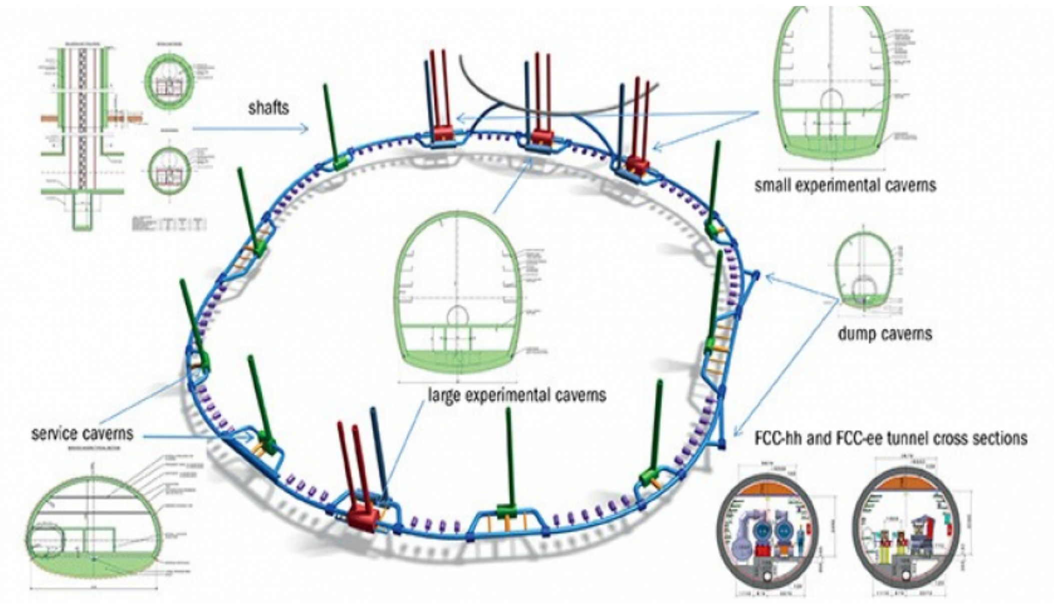
Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5 and Recommendation 6).

> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

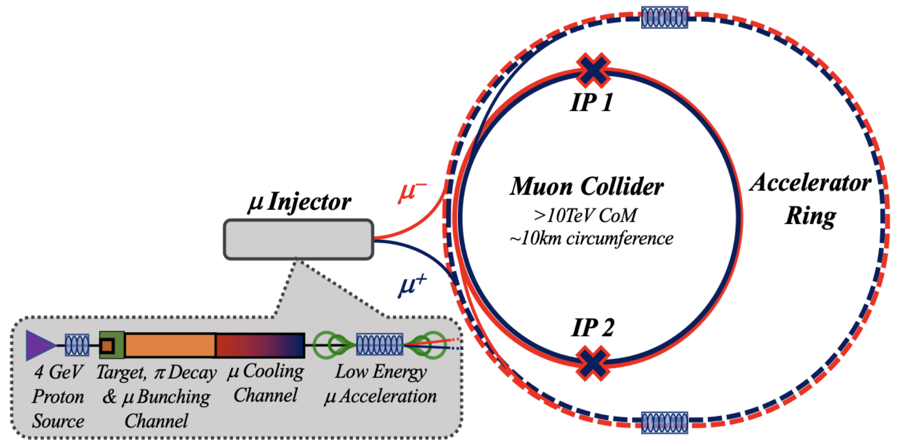
Proton collider

Key needs: high field magnets, detectors



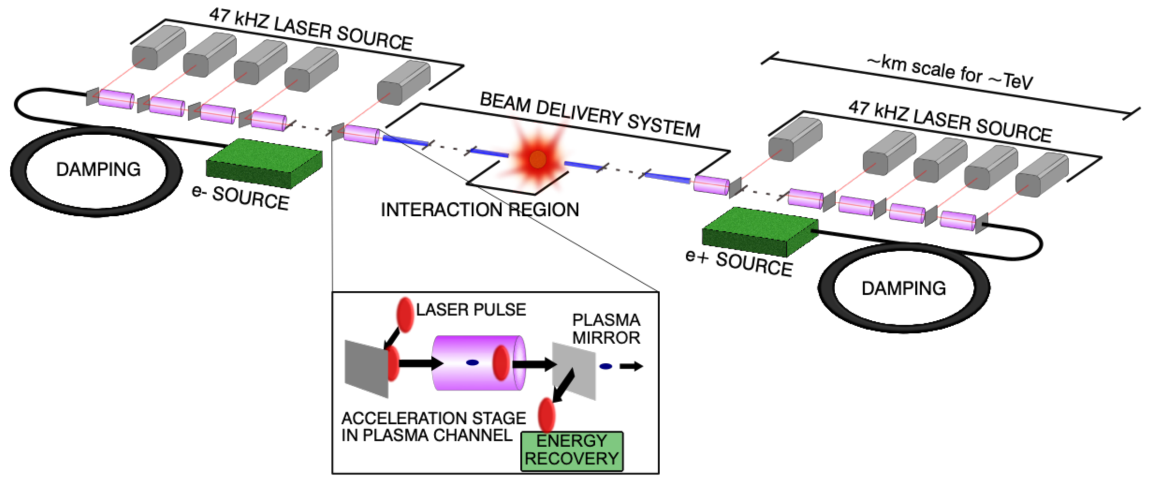
Muon collider

Key needs: targets, cooling



Linear wakefield lepton collider

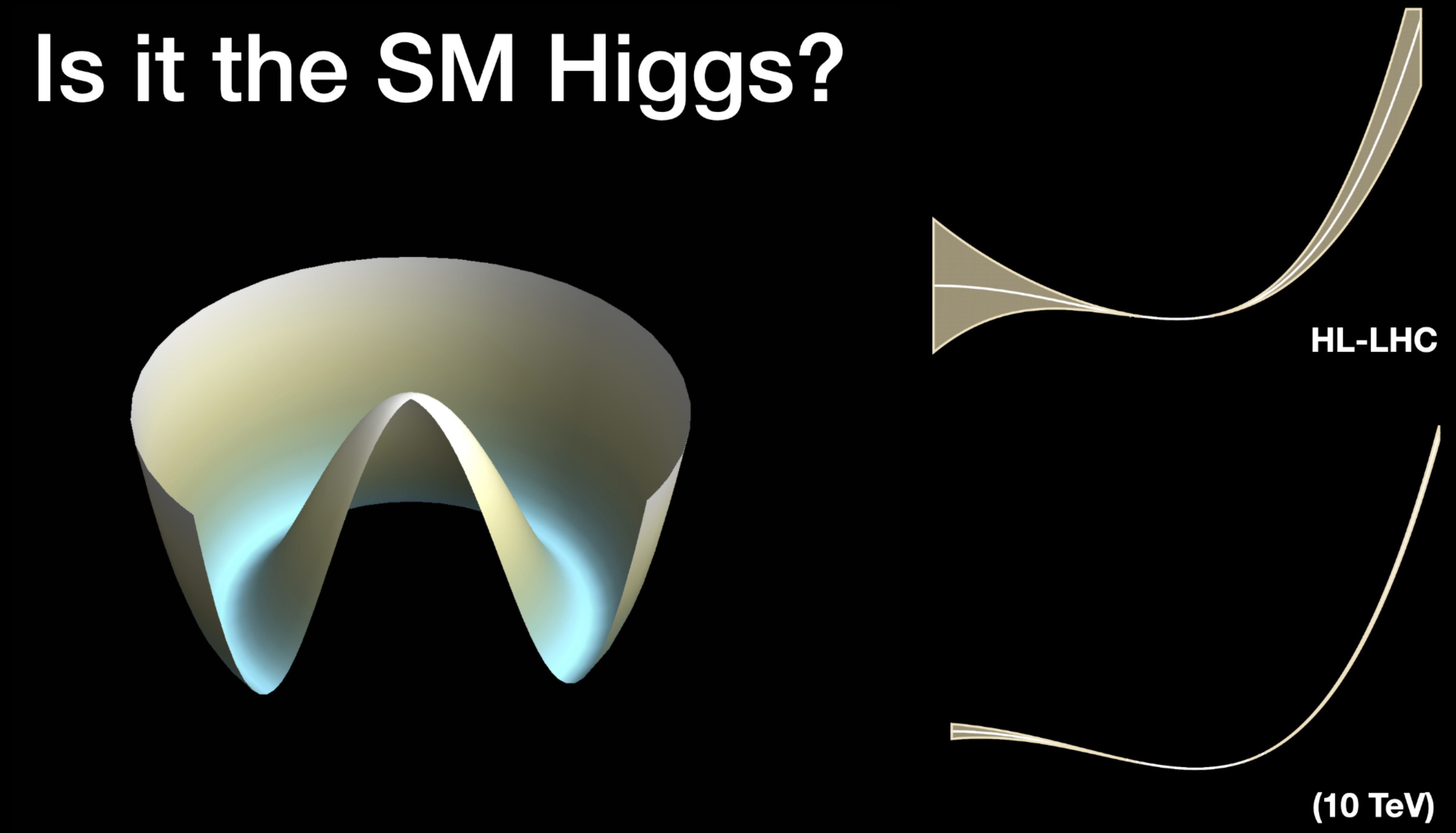
Key needs: discussed before

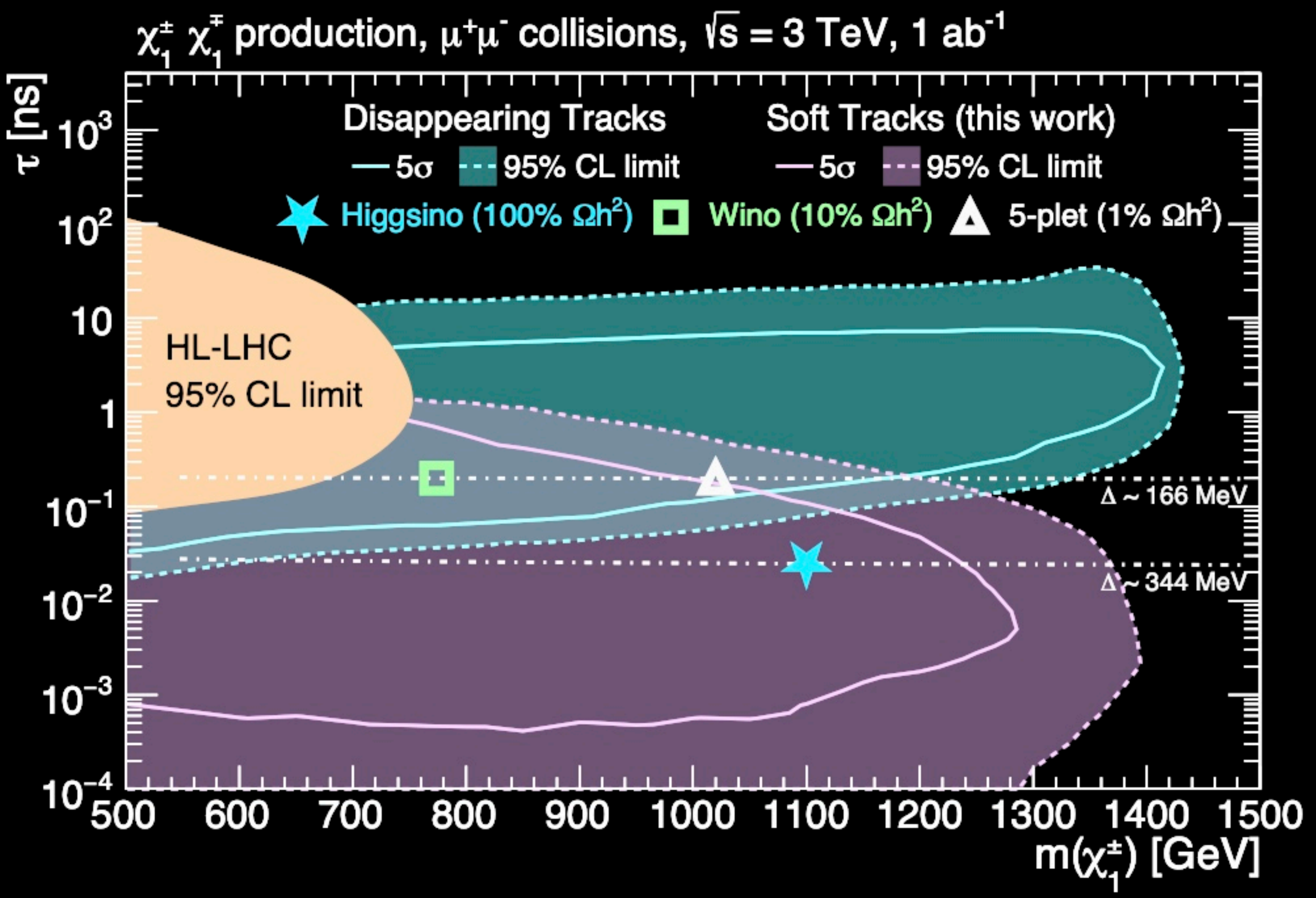


Why a 10 TeV pCM collider?

A high priority for P5 and a discovery machine to explore nature far beyond the capabilities of HL-LHC.

Is it the SM Higgs?





[Capdevilla, Meloni, Zurita 2405.08858]

Needed to measure ***Higgs potential***.
Compatible with the minimal assumption of the SM?
Electroweak symmetry breaking can be explored.

Beyond the SM physics: reasonable natural mass target for dark matter candidates, if weakly interacting, can be set. Such machines would explore this.

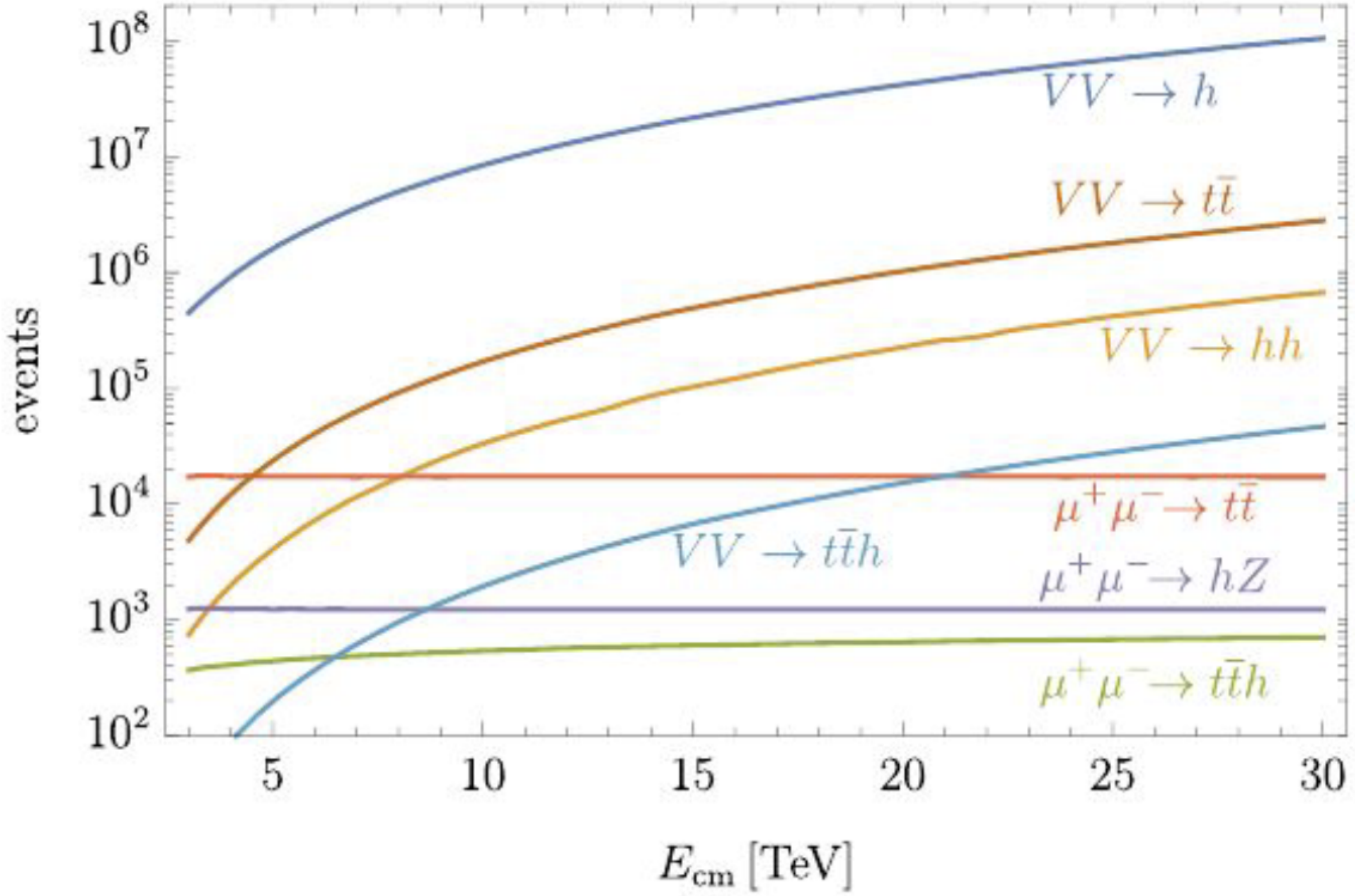
A new paradigm for particle collisions at the 10 TeV scale

Vector Boson Fusion (VBF) to dominate s-channel annihilation

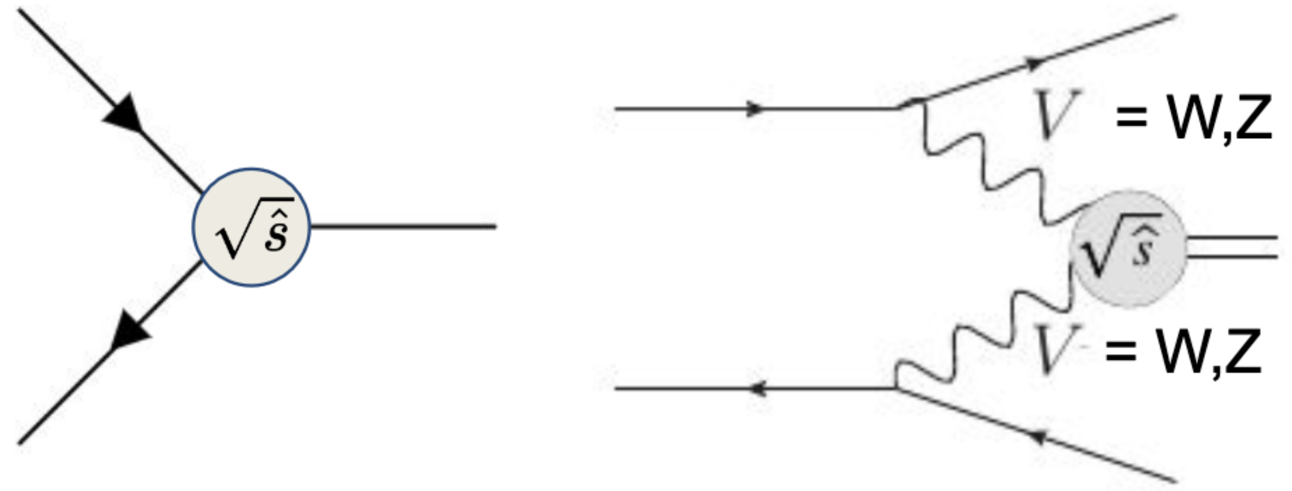
Luminosity dominated by cross-sections from the **VBF process at 10 TeV**, rather than s-channel annihilation traditionally associated with electron-positron linear colliders.

Advantageous for luminosity requirements at 10 TeV.

VBF provides the largest production channels for high-energy e^+e^-, e^-e^-, $\gamma\gamma$, and $\mu^+\mu^-$ colliders.



A 10 TeV linear collider may not have to be an electron-positron collider.



$\sigma \sim 1/\hat{s}$ $\sigma \sim \log \hat{s}$

Simone Pagan Griso (LBNL)
and
Muon Collide Forum Report
arXiv:2209.01318

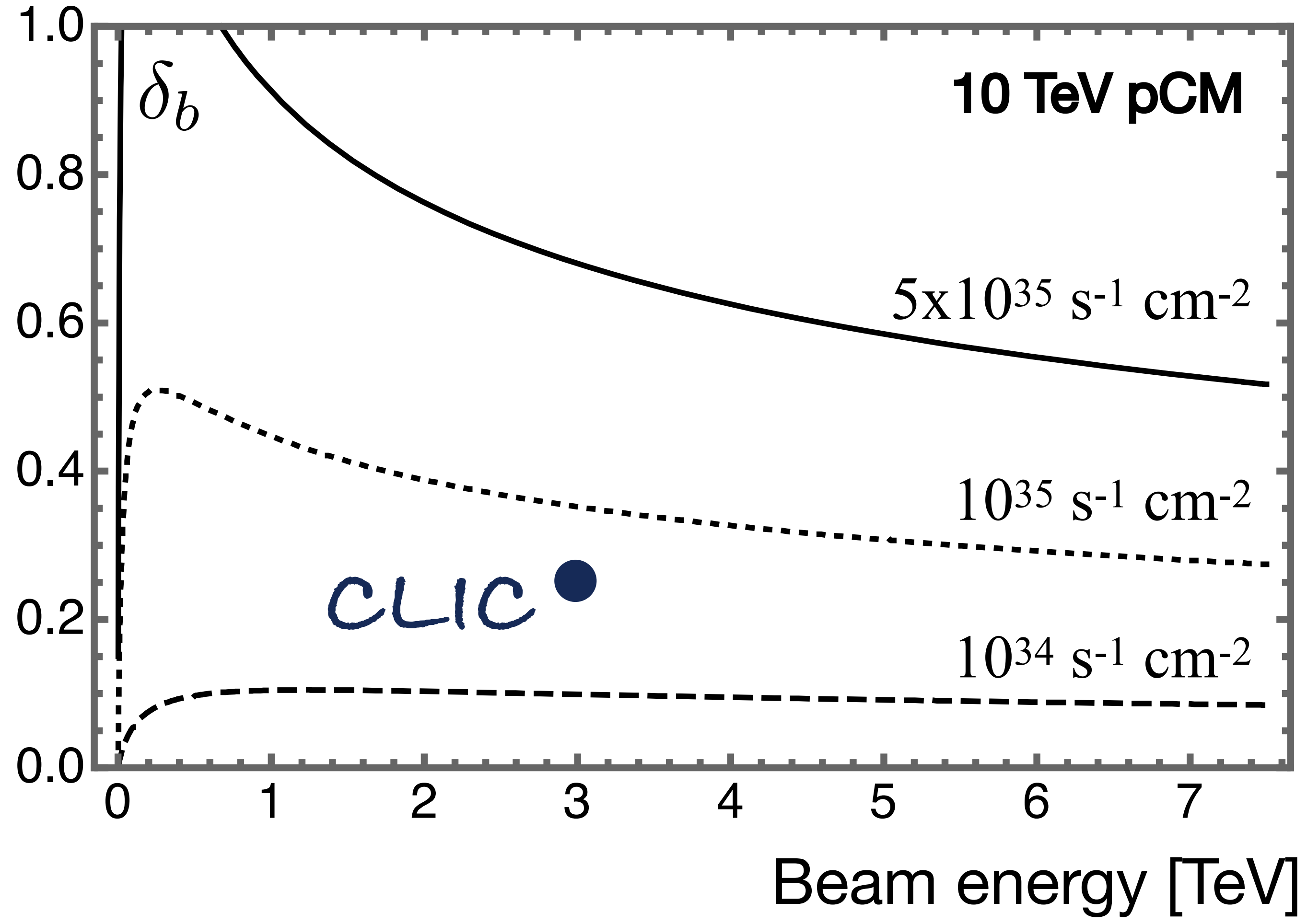
Beamstrahlung at 10 TeV must be revisited incl. quantum effects

10 TeV linear colliders will operate in the high (quantum) beamstrahlung regime

- Large beamstrahlung effects hard to avoid, can we deal with it?
  IP needs to be studied together with particle and detector physicists

Average fractional particle energy loss:

$$\delta_b \propto \frac{N^{2/3}\sigma_z^{1/3}}{(\sigma_x+\sigma_y)^{2/3}\,\gamma^{1/3}}$$



Reduce IP beam size (emittance) to achieve luminosity

$\sigma_y/\sigma_x = 16$

$\sigma_y/\sigma_x = 20$

$\sigma_y/\sigma_x = 50$

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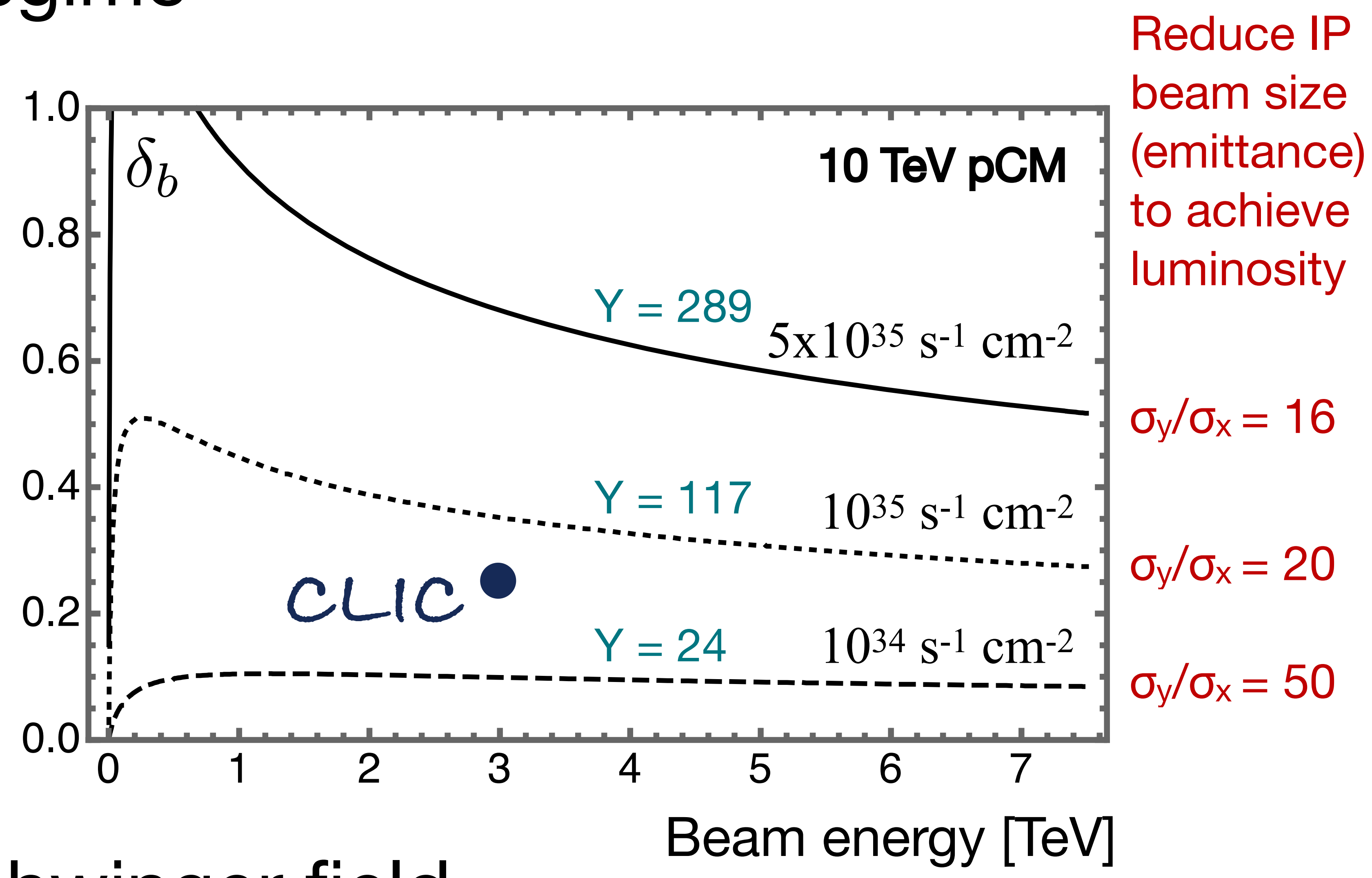
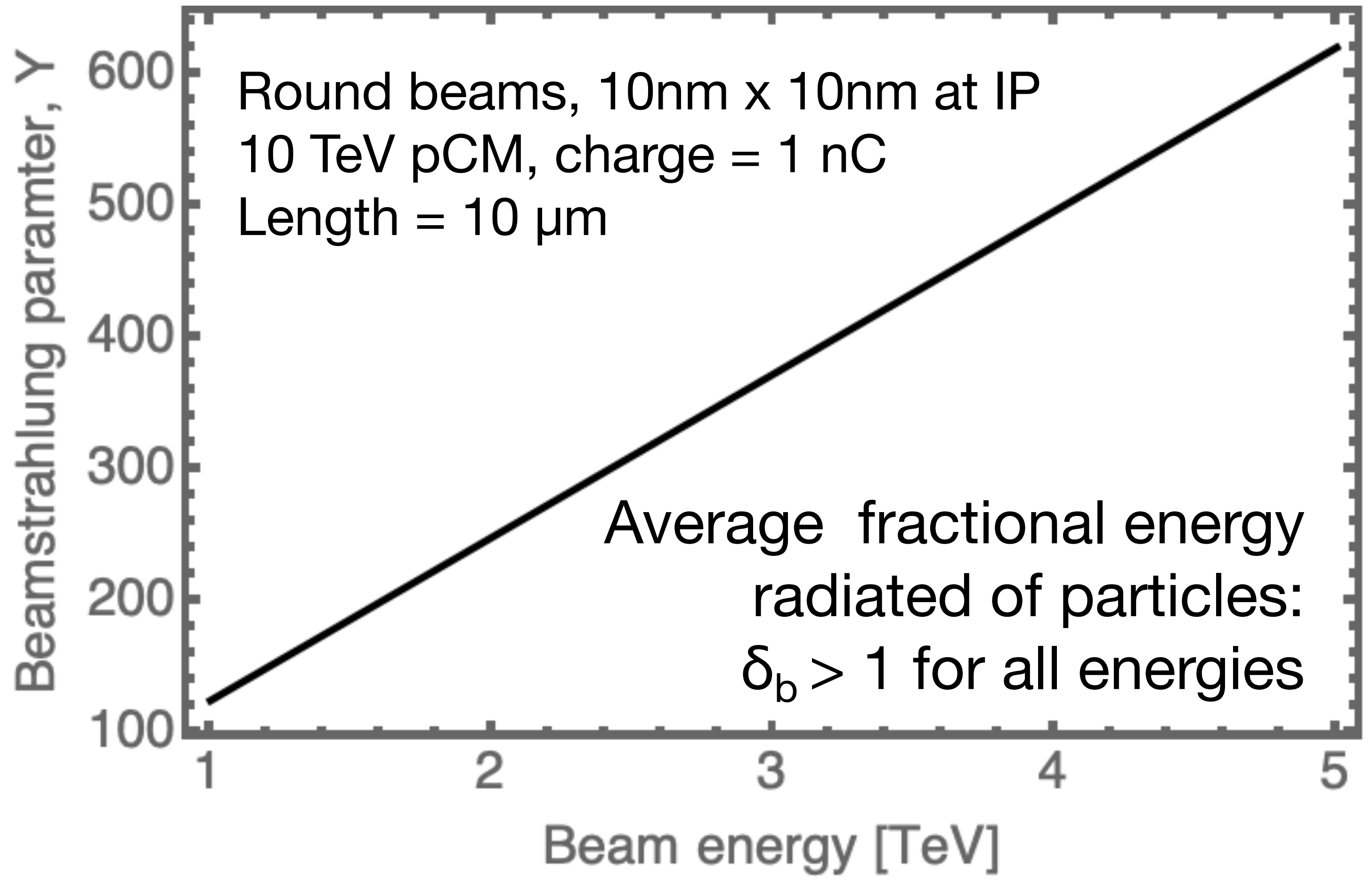


- Quantum: mean beam field in beam rest frame large compared to Schwinger field
  Unclear whether approximations/models in GUINEA-PIG, CAIN are valid for this regime

Beamstrahlung parameter (mean field strength of beam normalized to Schwinger field):

$$\Upsilon = \gamma\langle E+B\rangle/E_c \approx \frac{5r_e^2\gamma}{6\alpha(\sigma_x^*+\sigma_y^*)}\frac{N}{\sigma_z}$$

Also note: quantum beamstrahlung theory breaks down for Y > $\alpha^{-3/2}$ ~ 1000



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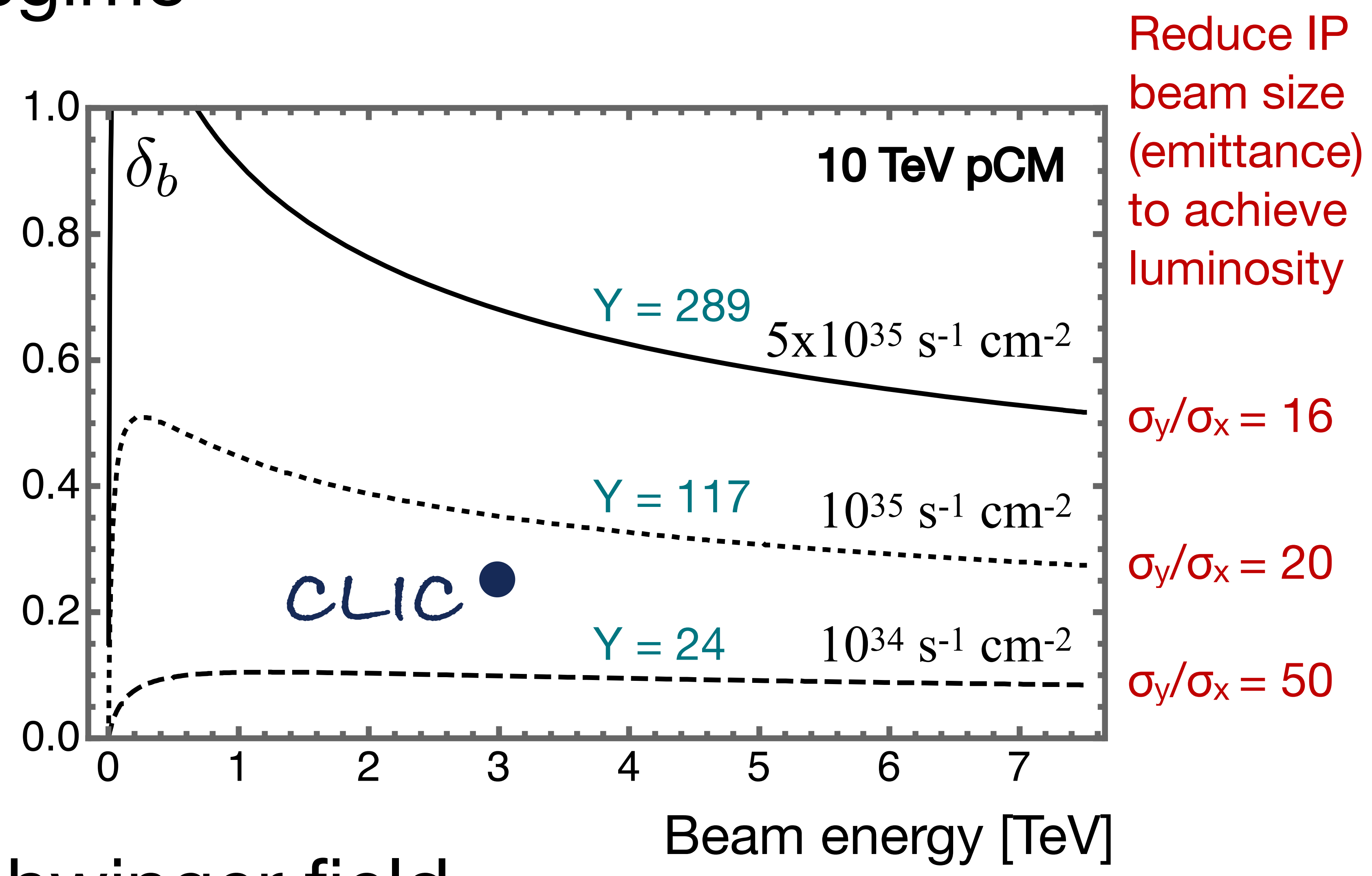

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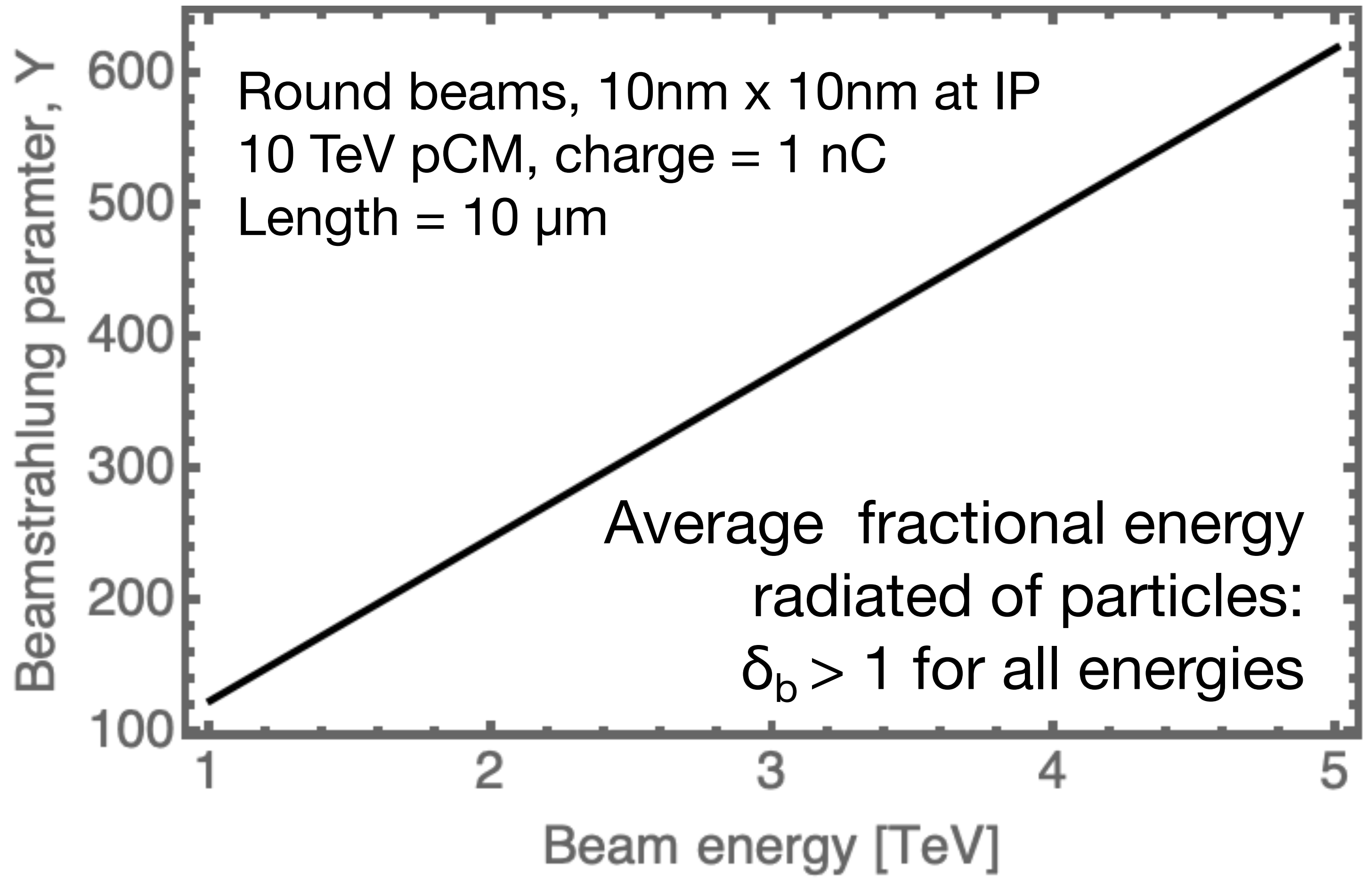

A new regime. We will consider:

- *e*$^+$*e*$^-$, *e*$^-$*e*$^-$, $\gamma\gamma$ collisions
- Round beam collisions in addition to flat beam collisions

A New Study

P5 (2023),
p. 85

> 6.4.1 Particle Physics Accelerator Roadmap
>
> Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress along this emerging technology path.

Responding to the P5 call, we propose a study for a 10 TeV pCM wakefield collider with:

- **self-consistent beam parameters** throughout the machine.
- an **end-to-end design (not CDR-level)** with reduced models where appropriate.
- **environmental impact considered** throughout.
- **close partnership with**
  - **HEP theorists and experimentalists**
    to define a physics program with commensurate machine and detector parameters.
  - **specialists from the broad accelerator community**
    to build on existing know how in collider design and subsystems (e.g. sources and BDS);
    to examine and incorporate upgrade paths of existing linear collider designs with wakefield technology.

The study will

- guide continued development of advanced accelerators
- identify demonstrator facilities beyond established needs

The study will yield a unified design concept that points a path forward

The 10 TeV pCM Design Study is a unified activity with a unified product:
A paper study on the end-to-end design concept of a (L/P/S)WFA collider.

The unified concept is a 10 TeV machine that collides e^+e^-, e^-e^-, or $\gamma\gamma$ at target luminosity.

- Our methodology is consistent with a design based on different technology options, or a collider that is comprised of multiple advanced accelerator technologies.
- Significant parts of the machine will be based on non-AAC accelerator technologies.
- The study will take into account staging / upgrade paths.

Multiple paths are a strength and acknowledges the current TRL-level.

- We do not yet know which accelerator technologies are the most feasible.

We invite you to join the effort!

- This is the start of a Design Study of a **10 TeV parton-center-of-momention (pCM) collider** based on **wakefield accelerator (WFA) technology**.
- This initiative was triggered by the 2023 US P5 Report, but it is a **global undertaking**.
- This effort is launched by the advanced accelerator concepts (AAC) community with a goal **to strongly engage the particle physics** and **broad accelerator communities** worldwide.
- The details of this study are under development.
We hope you join and help to define and conduct the study!

Initiated by E. Esarey, C. Geddes, S. Gessner, G. Ha, M. Hogan, C. Jing, X. Lu, R. Margraf-O'Neal, B. O'Shea, J. Osterhoff, P. Piot, J. Power, C. B. Schroeder, J. van Tilborg, J.-L. Vay

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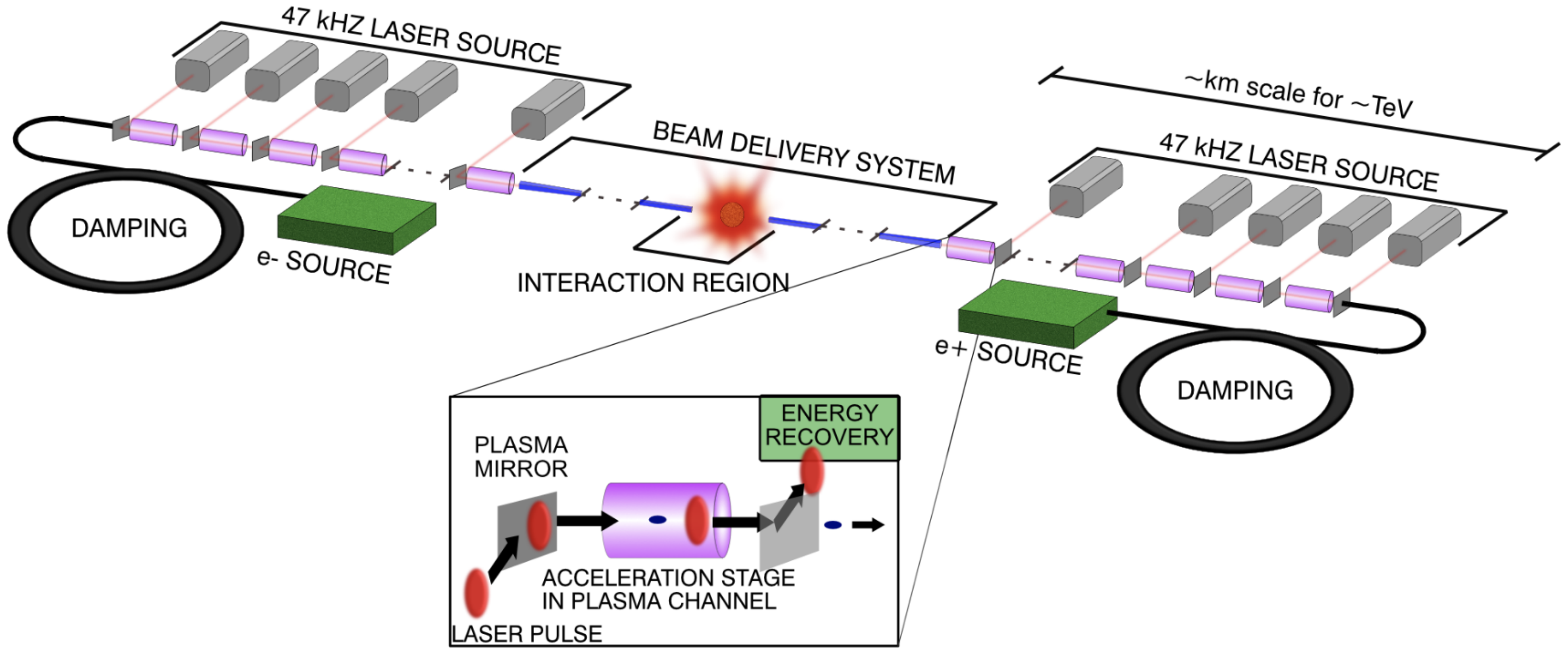
Tentative working groups are assessing and are connecting collider components

- System integration and optimization
- Beam sources (incl. damping rings)
- Drivers
    - Laser
    - Beams - SWFA
    - Beams - PWFA
- Linacs
    - LWFA
    - SWFA
    - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- Simulations/computing/AI



Green = Broader accelerator community

Orange/blue/purple = AAC specific

Red = HEP and broader community

Working group structure and convenorship not finalized yet, but will be soon. Your participation is appreciated!

Example: Beam Sources working group

Technology metrics:

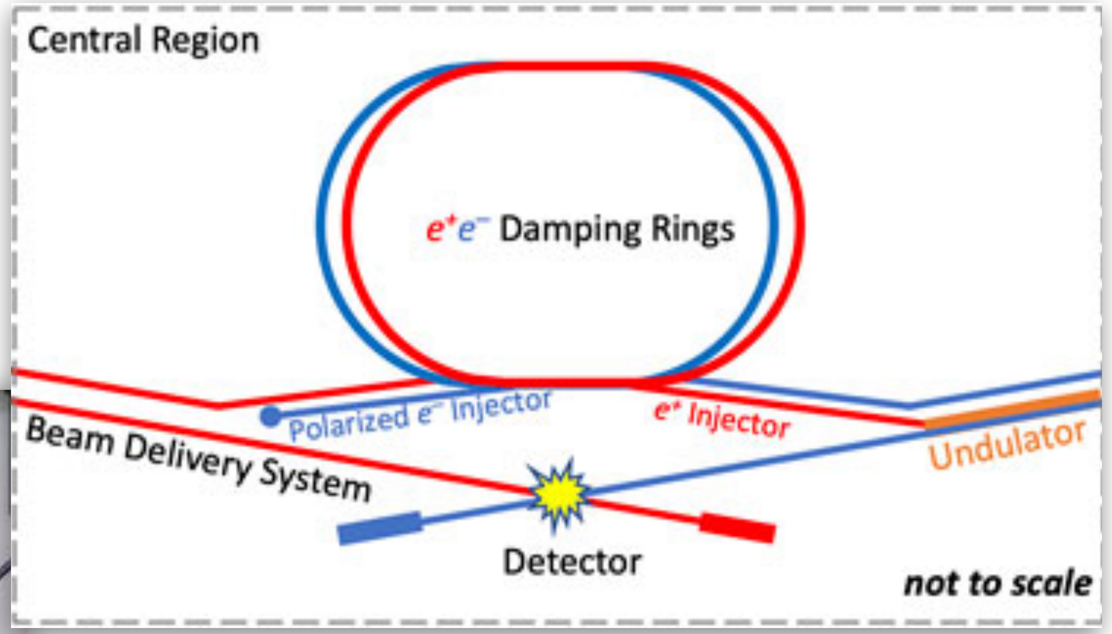
- Bunch charge
- Emittance
- Brightness
- Stability
- Experimental demonstrations

The development of metrics by each working group will inform the global design metrics for the collider.

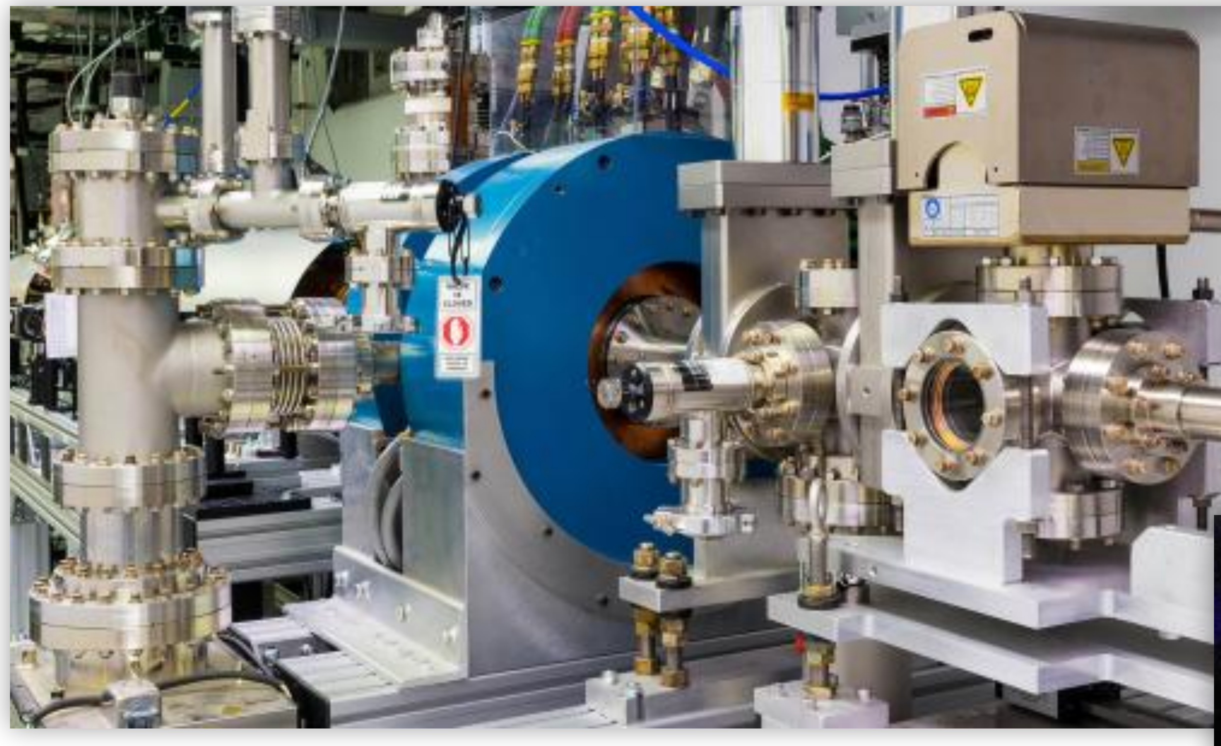
Working groups will then reconsider their technologies based on global metrics.

Possible technologies:

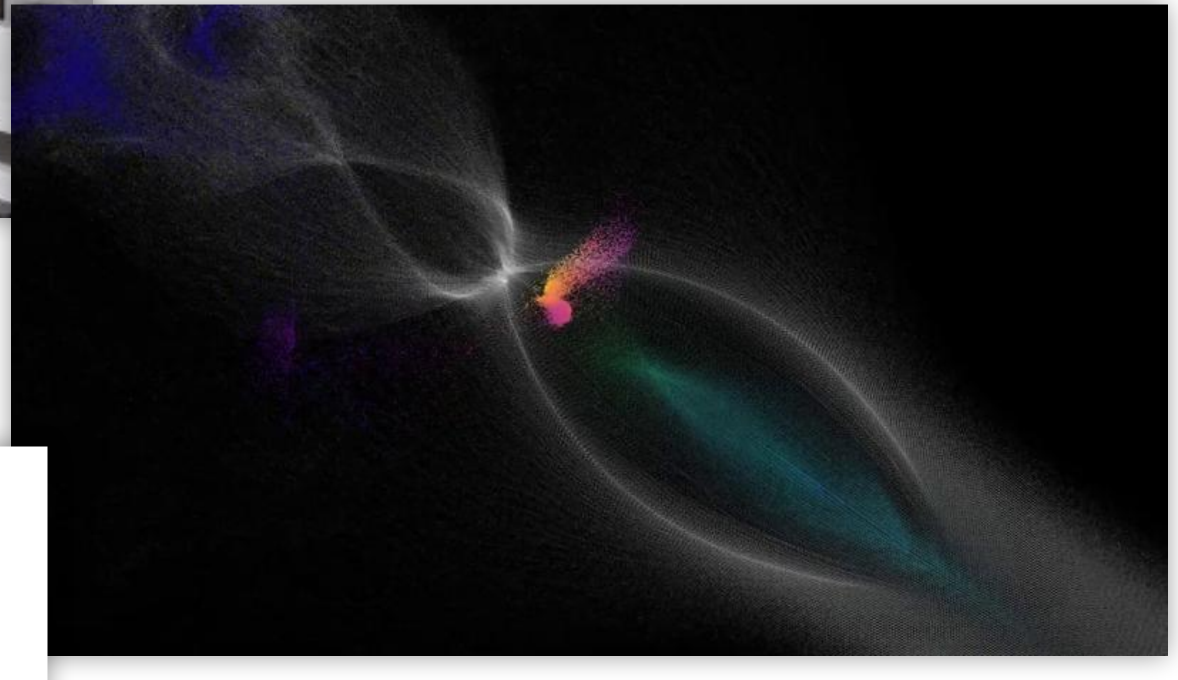
Damping rings



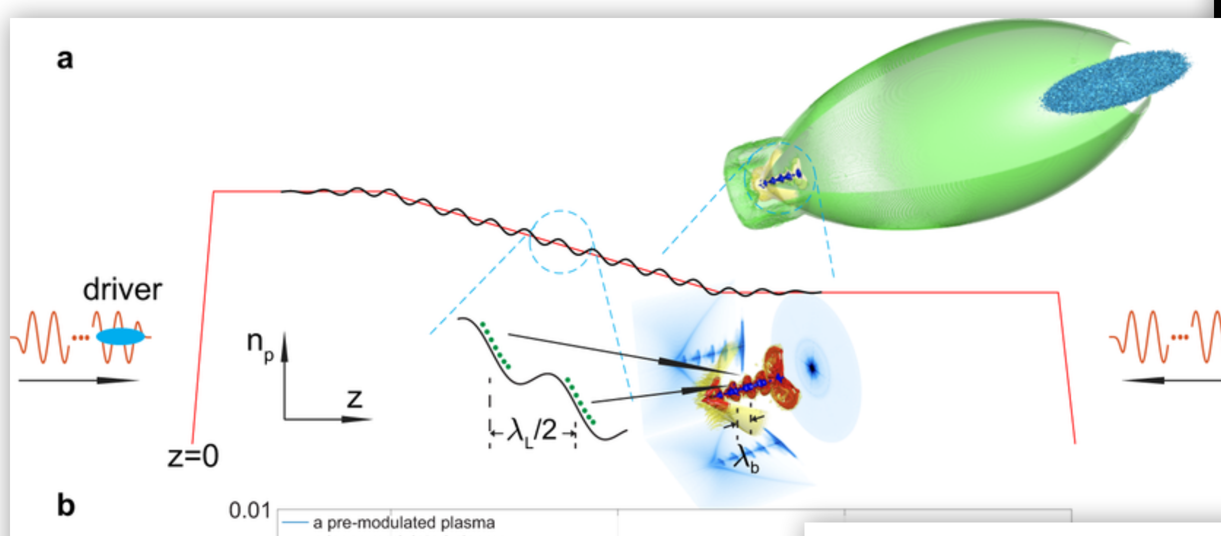
RF photocathodes



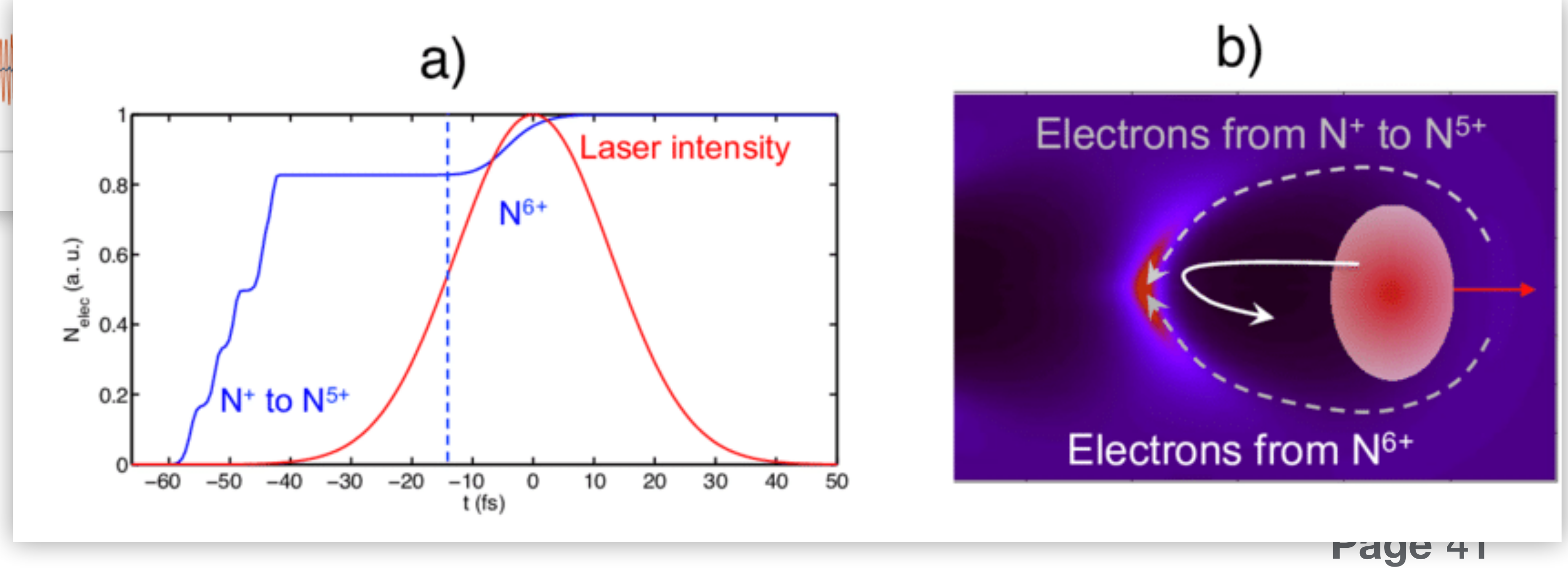
Trojan Horse



Downramp injection



Ionization injection



Tentative Study Timeline

Ongoing

Study organization.

Solicit input from HEP physicists on e^+e^-, e^-e^-, $\gamma\gamma$ collisions.

Year 1

Unified study of SWFA/PWFA/LWFA for electron arm of linac

Intensify engagement on non-AAC systems and begin work on BDS, sources, etc

Provide community input for the next ESPP, March 2025

Year 2

Review tech options and converge on accelerator concepts.

Review options and converge on HEP collider type (e^+e^-, e^-e^-, $\gamma\gamma$)

Intensify engagement with HEP on detectors

Year 3

Collaboration on designs and self-consistent parameters.

Identification of required R&D and demo facilities

Year 4

End-to-end design study report due sometime in 2028.

Engagement beyond AAC

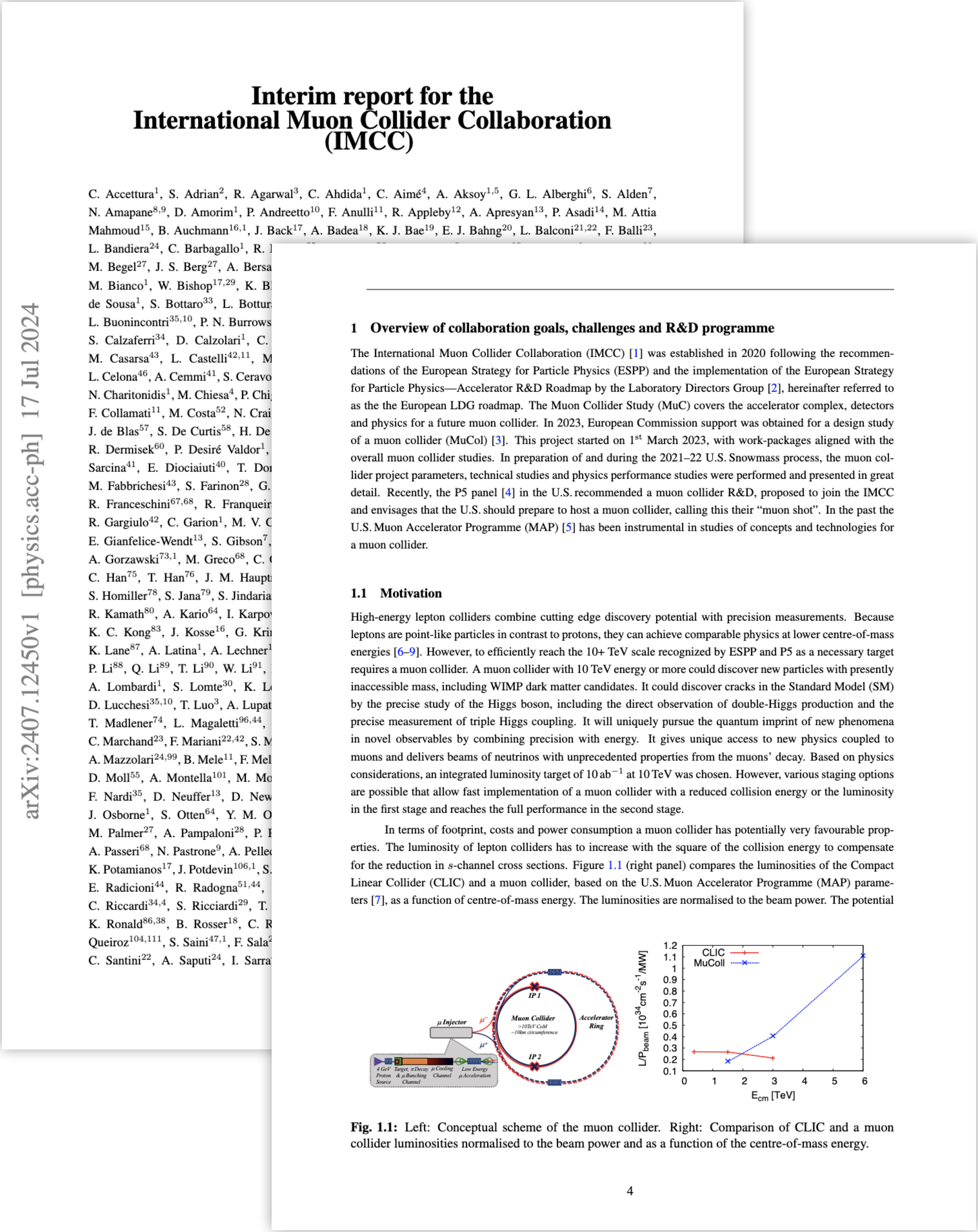
Tentative Deliverables

Year 1:
- WG metrics and technology options.
- Global metrics determined by community.
- Input to ESPP.

Year 2:
- Interim "metric-aware" design report.

Year 3:
- R&D and facilities roadmap.
- Design report updates.

Year 4:
- End-to-end design study on 10 TeV collider.



arXiv:2407.12450v1 [physics.acc-ph] 17 Jul 2024

Interim report for the
International Muon Collider Collaboration
(IMCC)

C. Accettura[1], S. Adrian[2], R. Agarwal[3], C. Ahdida[1], C. Aimé[4], A. Aksoy[1,5], G. L. Alberghi[6], S. Alden[7],
N. Amapane[8,9], D. Amorim[1], P. Andreetto[10], F. Anulli[11], R. Appleby[12], A. Apresyan[13], P. Asadi[14], M. Attia
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M. Casarsa[43], L. Castelli[42,11],
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N. Charitonidis[1], M. Chiesa[4], P.
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R. Dermisek[60], P. Desiré Valdor[1],
Sarcina[41], E. Diociaiuti[40], T.
M. Fabbrichesi[43], S. Farinon[28], G.
R. Franceschini[67,68], R.
R. Gargiulo[42], C. Garion[1], M. V.
E. Gianfelice-Wendt[13], S. Gibson[7],
A. Gorzawski[73,1], M. Greco[68], C.
C. Han[75], T. Han[76], J. M.
S. Homiller[78], S. Jana[79], S.
R. Kamath[80], A. Kario[64], I.
K. C. Kong[83], J. Kosse[16], G.
K. Lane[87], A. Latina[1], A.
P. Li[88], Q. Li[89], T. Li[90], W. Li[91],
A. Lombardi[1], S. Lomte[30], K.
D. Lucchesi[35,10], T. Luo[3], A.
T. Madlener[74], L. Magaletti[96,44],
C. Marchand[23], F. Mariani[22,42], S.
A. Mazzolari[24,99], B. Mele[11], F.
D. Moll[55], A. Montella[101], M.
F. Nardi[35], D. Neuffer[13], D.
J. Osborne[1], S. Otten[64], Y. M.
M. Palmer[27], A. Pampaloni[28], P.
A. Passeri[68], N. Pastrone[9], A.
K. Potamianos[17], J. Potdevin[106,1], S.
E. Radicioni[44], R. Radogna[51,44],
C. Riccardi[34,4], S. Ricciardi[29], T.
K. Ronald[86,38], B. Rosser[18], C.
Queiroz[104,111], S. Saini[47,1], F.
C. Santini[22], A. Saputi[24], I.

1 Overview of collaboration goals, challenges and R&D programme

The International Muon Collider Collaboration (IMCC) [1] was established in 2020 following the recommendations of the European Strategy for Particle Physics (ESPP) and the implementation of the European Strategy for Particle Physics—Accelerator R&D Roadmap by the Laboratory Directors Group [2], hereinafter referred to as the the European LDG roadmap. The Muon Collider Study (MuC) covers the accelerator complex, detectors and physics for a future muon collider. In 2023, European Commission support was obtained for a design study of a muon collider (MuCol) [3]. This project started on 1st March 2023, with work-packages aligned with the overall muon collider studies. In preparation of and during the 2021–22 U.S. Snowmass process, the muon collider project parameters, technical studies and physics performance studies were performed and presented in great detail. Recently, the P5 panel [4] in the U.S. recommended a muon collider R&D, proposed to join the IMCC and envisages that the U.S. should prepare to host a muon collider, calling this their "muon shot". In the past the U.S. Muon Accelerator Programme (MAP) [5] has been instrumental in studies of concepts and technologies for a muon collider.

1.1 Motivation

High-energy lepton colliders combine cutting edge discovery potential with precision measurements. Because leptons are point-like particles in contrast to protons, they can achieve comparable physics at lower centre-of-mass energies [6–9]. However, to efficiently reach the 10+ TeV scale recognized by ESPP and P5 as a necessary target requires a muon collider. A muon collider with 10 TeV energy or more could discover new particles with presently inaccessible mass, including WIMP dark matter candidates. It could discover cracks in the Standard Model (SM) by the precise study of the Higgs boson, including the direct observation of double-Higgs production and the precise measurement of triple Higgs coupling. It will uniquely pursue the quantum imprint of new phenomena in novel observables by combining precision with energy. It gives unique access to new physics coupled to muons and delivers beams of neutrinos with unprecedented properties from the muons' decay. Based on physics considerations, an integrated luminosity target of $10\,\text{ab}^{-1}$ at 10 TeV was chosen. However, various staging options are possible that allow fast implementation of a muon collider with a reduced collision energy or the luminosity in the first stage and reaches the full performance in the second stage.

In terms of footprint, costs and power consumption a muon collider has potentially very favourable properties. The luminosity of lepton colliders has to increase with the square of the collision energy to compensate for the reduction in s-channel cross sections. Figure 1.1 (right panel) compares the luminosities of the Compact Linear Collider (CLIC) and a muon collider, based on the U.S. Muon Accelerator Programme (MAP) parameters [7], as a function of centre-of-mass energy. The luminosities are normalised to the beam power. The potential

Fig. 1.1: Left: Conceptual scheme of the muon collider. Right: Comparison of CLIC and a muon collider luminosities normalised to the beam power and as a function of the centre-of-mass energy.

4

https://arxiv.org/pdf/2407.12450

ALEGRO goal is a compact energy frontier collider

Community required a forum to globally coordinate their R&D for particle physics

ALEGRO
Advanced LinEar collider study GROup

Coordinated by B. Cros & P. Muggli

- ALEGRO was created as an outcome of the ANAR2017 workshop at CERN
- Mandate by ICFA: “to coordinate the preparation of a proposal for an advanced linear collider in the multi-TeV energy range.”
  - also looking at upgrade paths for a future linear collider and repurposing of facilities
  - intermediate energy facilities (Higgs/nonlinear QED/fixed target/…)
- ALEGRO brings the community together
  - runs a workshop series:
    Oxford (2018), CERN (2019), DESY (2020 → 2023), Lisbon (2024)
  - next at SLAC **(March 4-6, 2025)**
  - provides strategic input for decision makers (e.g. to the ESPP, …)

Location: DESY Hamburg, Germany
Organisation: Brigitte Cros, Richard D’Arcy, Patric Muggli, Jens Osterhoff
Administration: Daniela Koch

Conclusion

Plasma accelerator technology is of high interest for the future of particle physics

- Reduce the size of future colliders (reduced construction cost, environmental impact)
- Potential for reduced operation cost (higher luminosity/power)
- Upgrade path for Higgs-factory LCs (repurposing of ILC/CLIC/C^3 infrastructure - LCVision)

The community is making progress to deliver self-consistent concepts

- Higgs Factory → HALHF collaboration is pioneering system integration and optimization
- Energy Frontier → 10 TeV pCM wakefield collider end-to-end design effort launched in US

What is needed for these studies to be successful?

- Strong AAC community engagement.
- Close partnership with particle physics theorists & experimentalists *(physics case, detectors)*.
- Close partnership with experts from the broad accelerator community *(sources, BDS, system integration and optimization, upgrade paths)*.

Join us!
Click here to sign up, or scan:

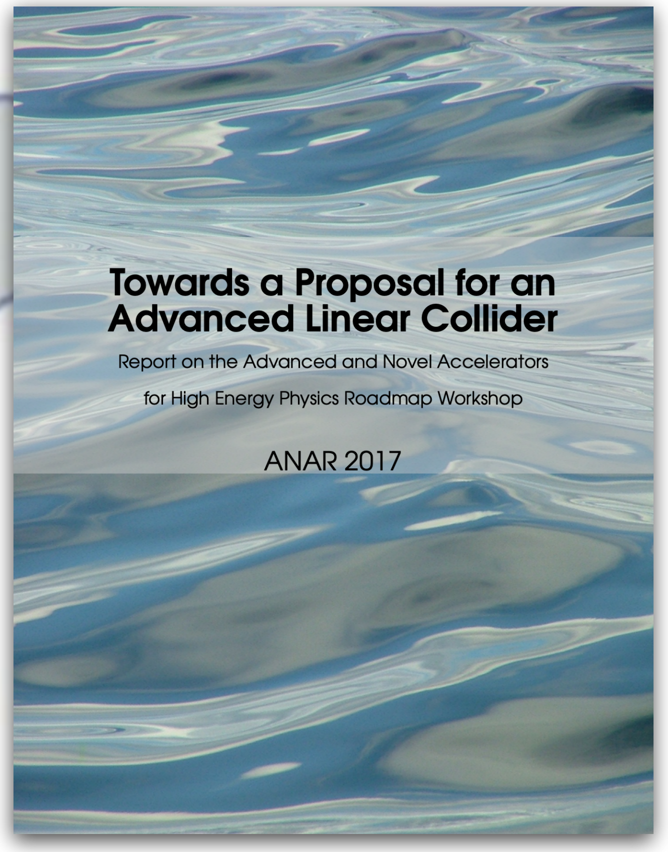
Backup material

Advanced accelerator research is a global enterprise

ALEGRO

Advanced LinEar collider study GROup

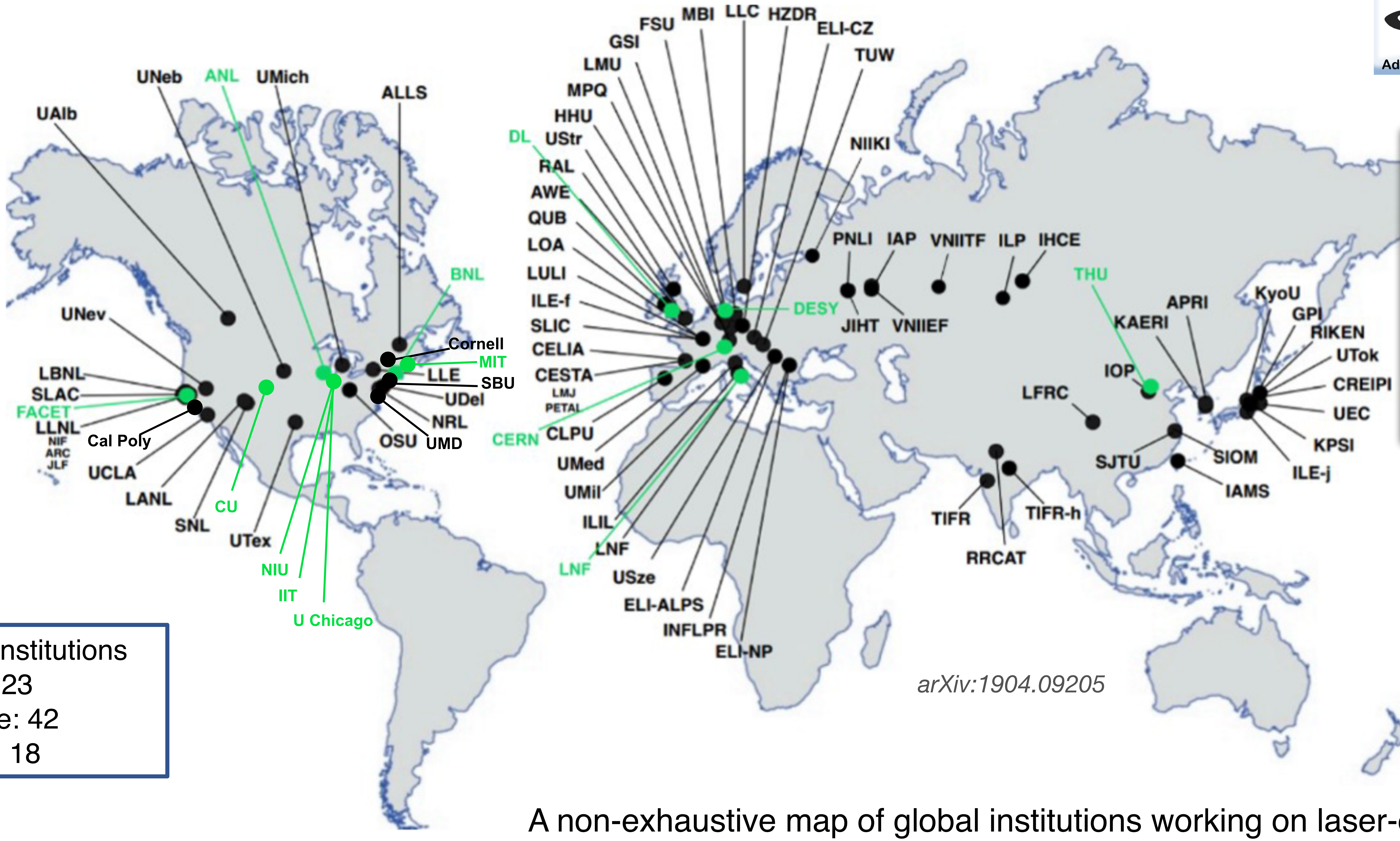
founded in 2017



Towards a Proposal for an Advanced Linear Collider

Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop

ANAR 2017



arXiv:1904.09205

Number of Institutions
US: 23
Europe: 42
Asia: 18

A non-exhaustive map of global institutions working on laser-driven plasma acceleration (**black**) and beam-driven plasma/structure acceleration (**green**).

Advanced accelerator research in the US

Large Beam Test Facilities
Universities
National Labs

BELLA
BERKELEY LAB

FAST/IOTA
Fermilab

AWA
Argonne NATIONAL LABORATORY

Stony Brook, Cornell, MIT, Maryland, Rochester

M ZEUS

UCLA

Stanford, CU Boulder, Cal Poly, UC Irvine

Brookhaven National Laboratory
ATF

SLAC NATIONAL ACCELERATOR LABORATORY
FACET-II

ELL
UNIVERSITY OF Nebraska Lincoln

UT^3
TEXAS The University of Texas at Austin

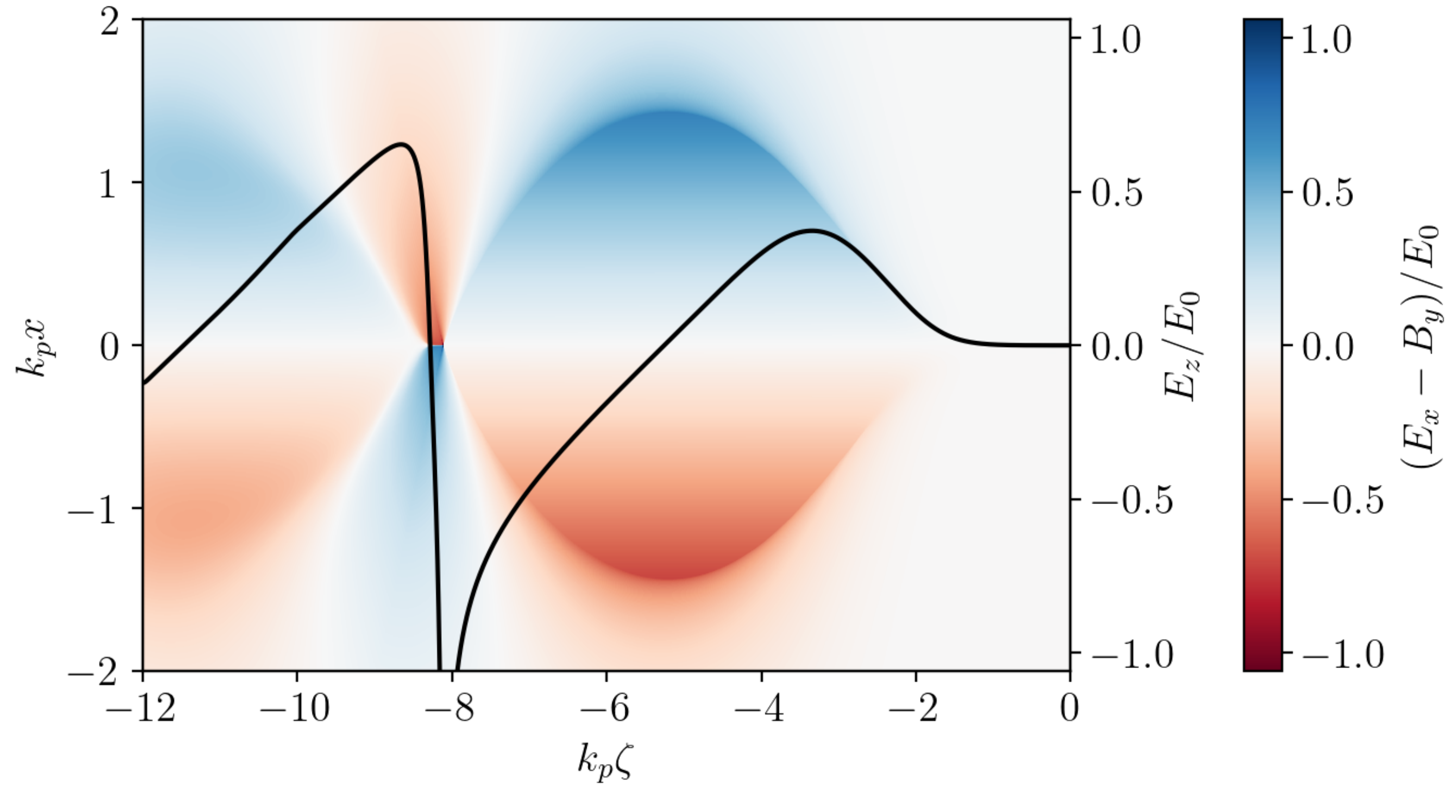
NIU, IIT, MSU, U Chicago, UT Austin, Nebraska, Michigan

Universities with WFA programs

New promising positron acceleration concepts are emerging

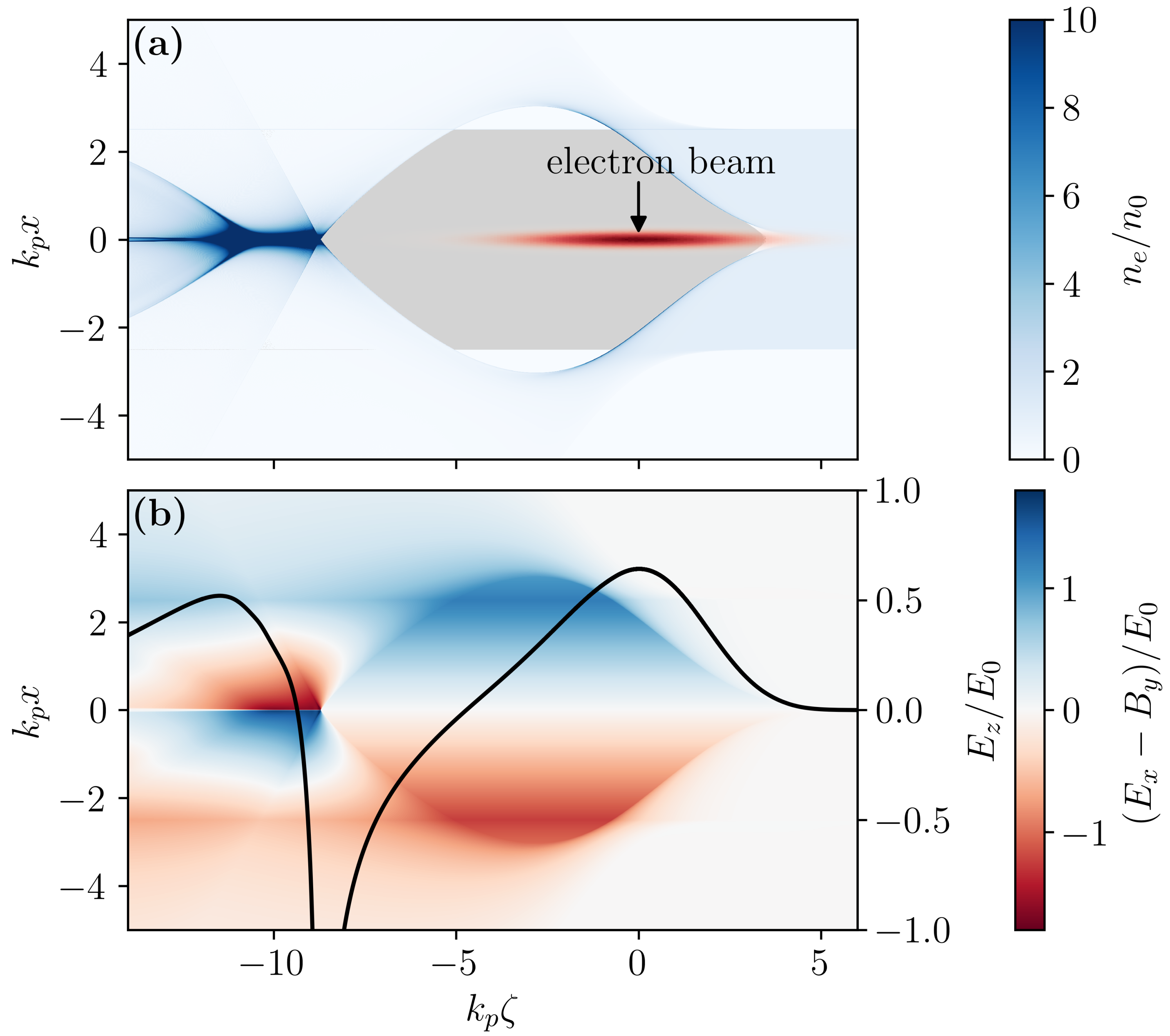
New plasma-based schemes could provide pathway to high beam quality, stability, high efficiency

→ Need a test facility!



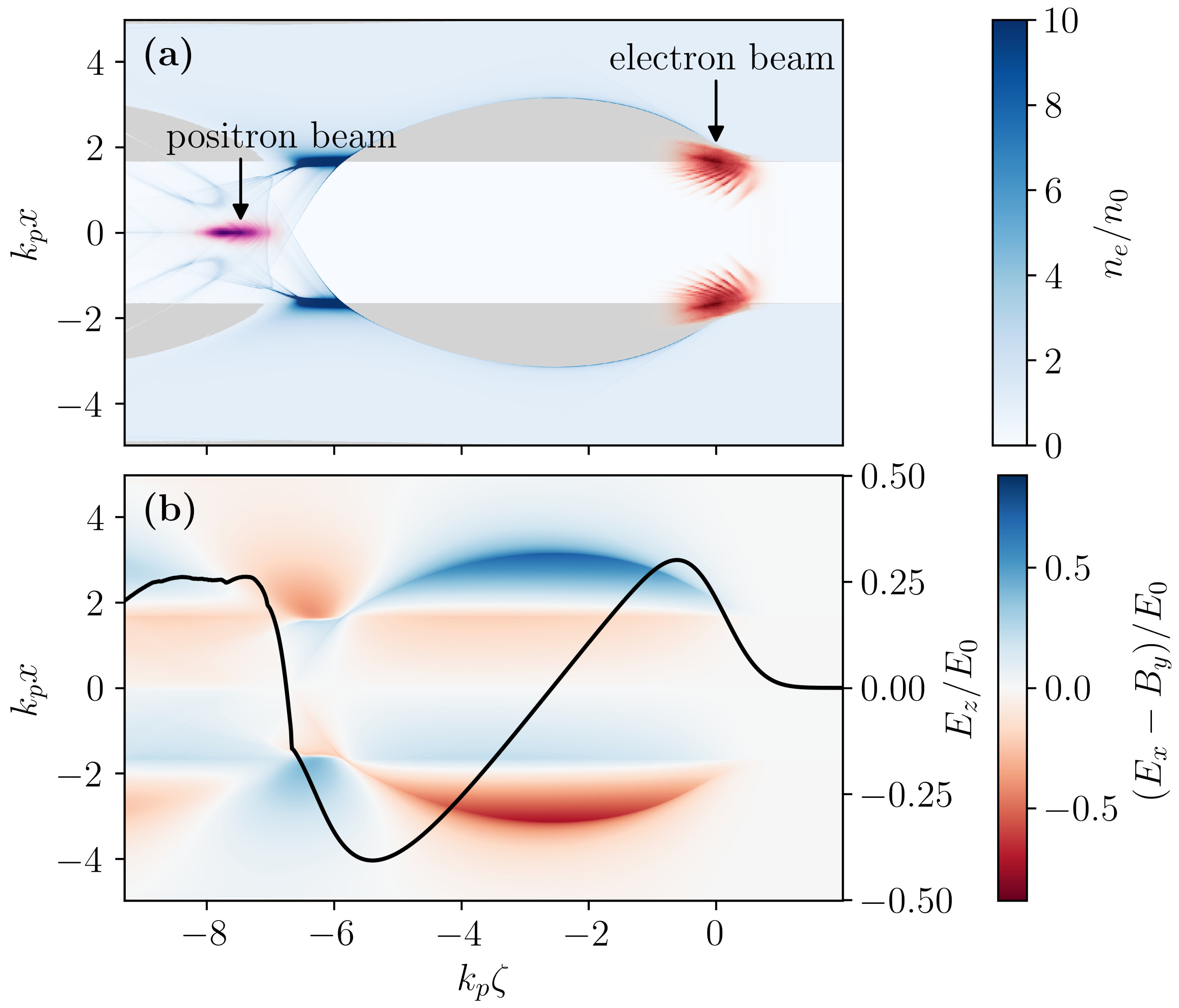
More concepts:
Lotov, PoP 14, 023101 (2007)
Zhou et al. arXiv:2211.07962v1 (2022)
Wang et al. arXiv. 2110.10290 (2021)
Liu et al., PRAppl 19, 044048 (2023)

Finite plasma channels and electron filaments



Finite plasma channels:
Diederichs et al., PRAB 22, 081301 (2019)
Diederichs et al., PRAB 23, 121301 (2020)
Diederichs et al. PoP 29, 043101 (2022)
Diederichs et al. PRAB 25, 091304 (2022)

Asymmetric drive beams in a hollow core plasma channel



Hollow core plasma channels:
Zhou et al., PRL 127, 174801 (2021)
Zhou et al., PRAB 25, 091303 (2022)
Silva et al., PRL 127, 104801 (2021)

Discovery and mitigation of emittance mixing for flat beams

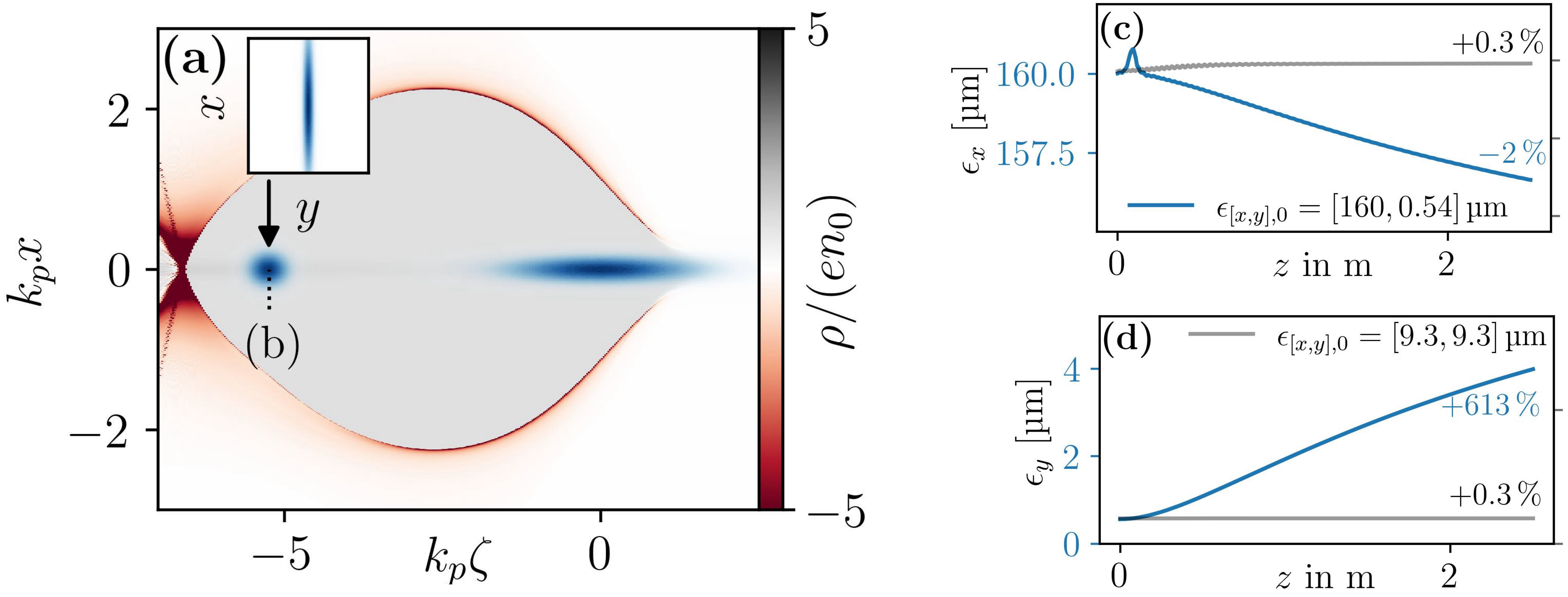
Transverse wakefields with ion motion

$$\frac{E_x - B_y}{E_0} = \frac{k_p x}{2}\left[1 + \alpha_x H\left(\frac{r^2}{2L_x^2}\right)\right]$$

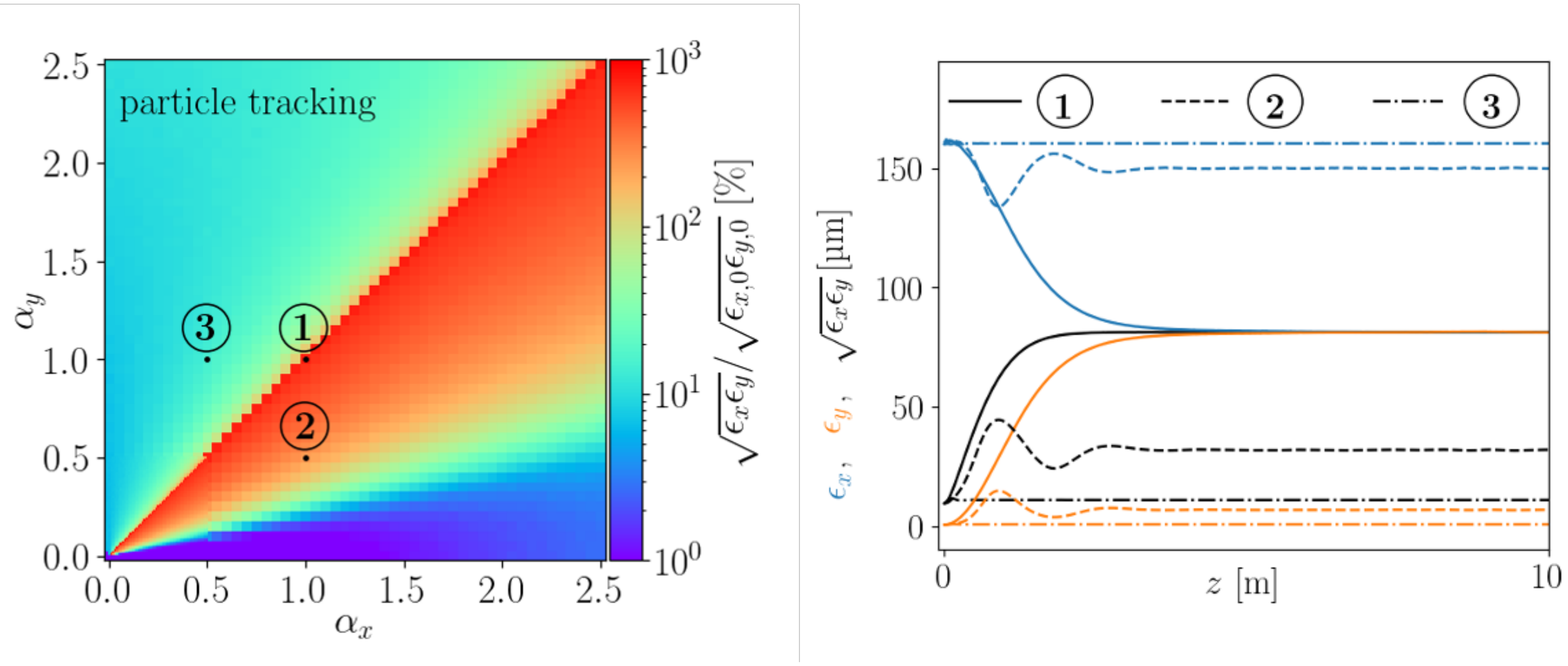
$$\frac{E_y + B_x}{E_0} = \frac{k_p y}{2}\left[1 + \alpha_y H\left(\frac{r^2}{2L_y^2}\right)\right]$$

Coupled nonlinearity: $r = \sqrt{x^2 + y^2}$ facilitates x-y coupling and emittance growth

C. Benedetti *et al.*, **PRAB** 20, 111301 (2017)



- **NL trans. wakefields couple motion in trans. planes** → can lead to emittance exchange
- Most severe for resonant betatron motion
- Breaking resonance mitigates beam-quality degradation
- **Flat drive beams** (Nonlinear force is non-axisym.), **laser drivers** (ion motion is negligible) mitigate effect



S. Diederichs *et al.*, under review at **PRL** (2024)

Conceptual physics considerations determine parameter ranges

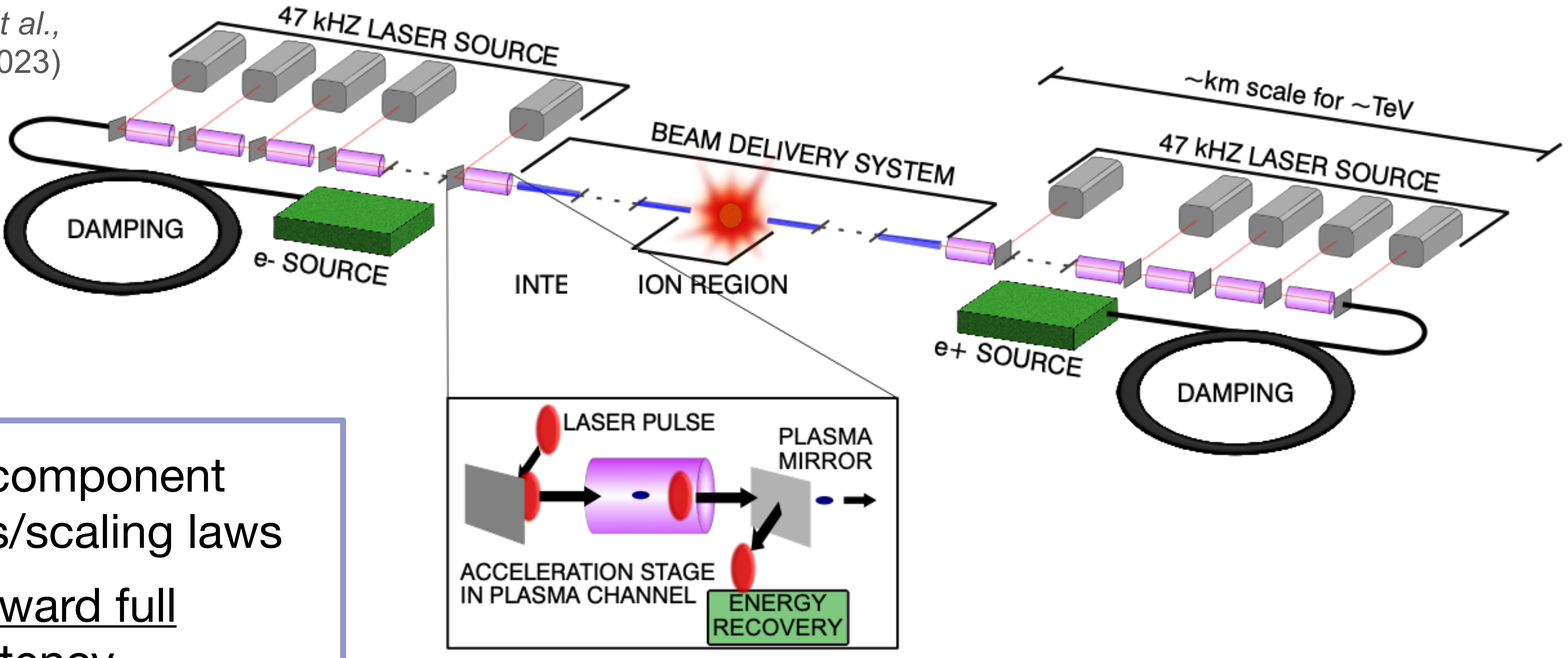
Basic design choices driven by system optimization

- Minimizing linac length (gradient > GV/m)
- Maximizing energy efficiency (luminosity/power)

} Restricts plasma density range, energy gain per stage → staging

- Plasma density sets bunch charge (also limited by Beamstrahlung), luminosity requires repetition rate

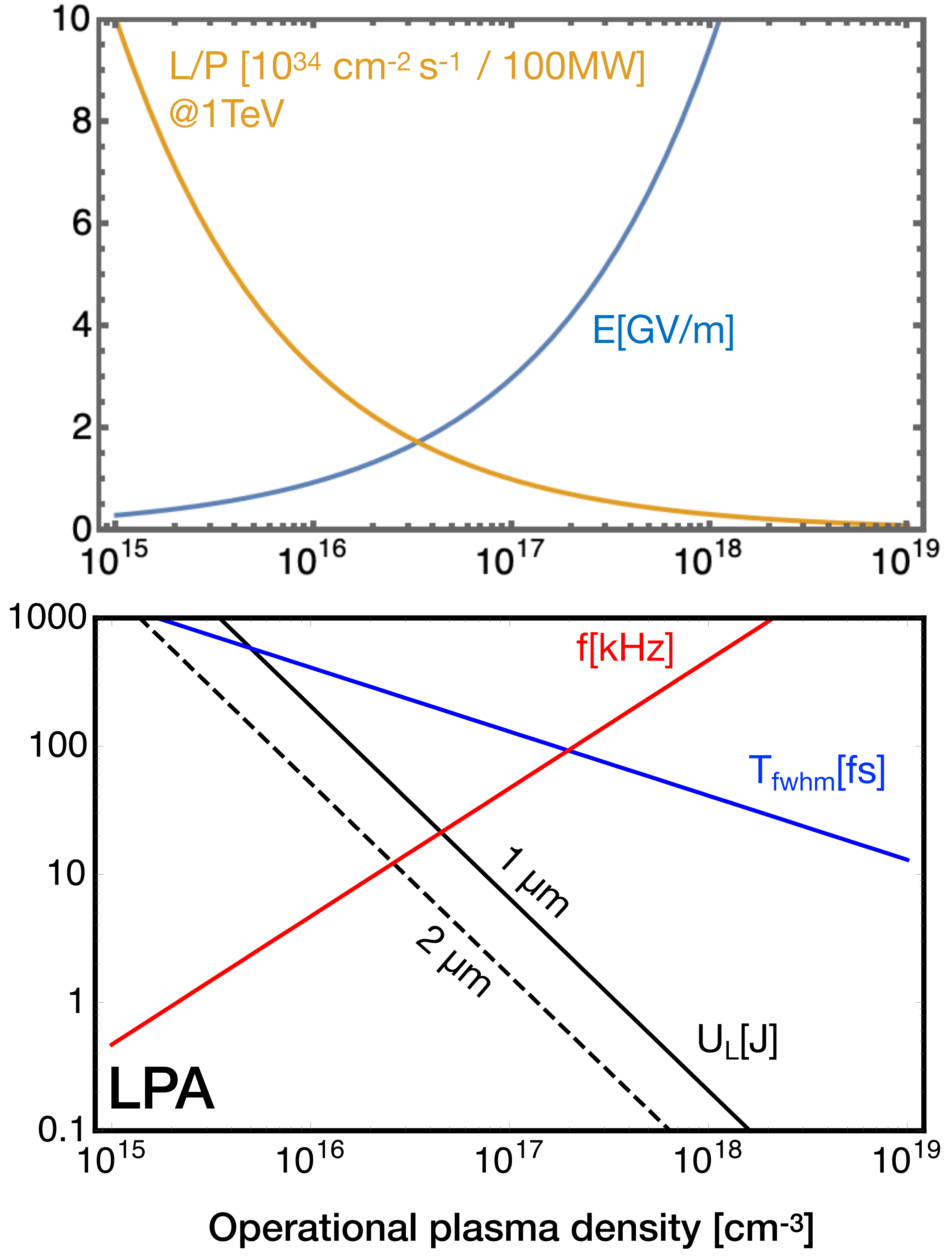
C.B. Schroeder *et al.*,
JINST 18 T06001 (2023)



- Based on component simulations/scaling laws
- Working toward full self-consistency

Conceptual collider parameter sets derived during Snowmass

T. Barklow *et al.*, JINST 18 P09022 (2023);
C.B. Schroeder *et al.*, JINST 18 T06001 (2023)



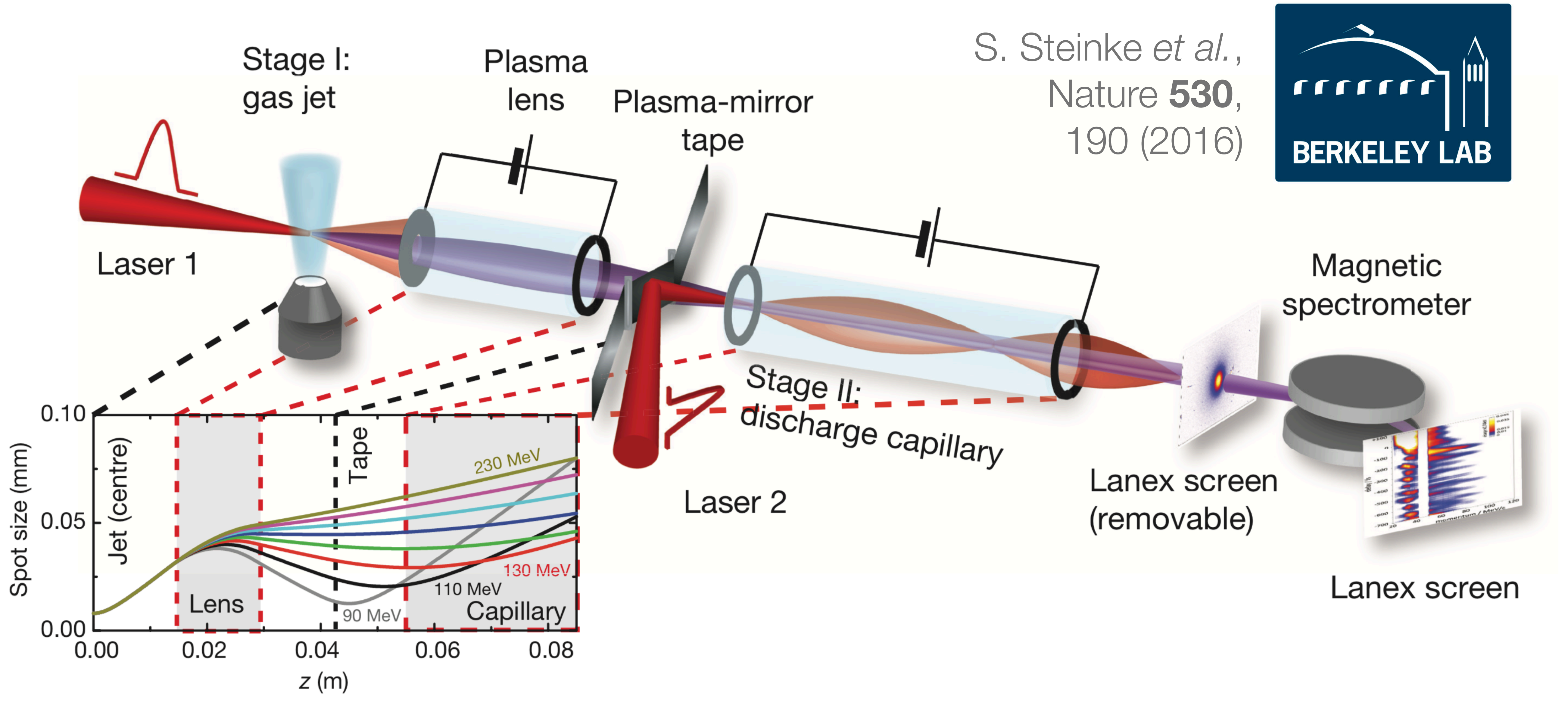
Staging of plasma modules comes with many challenges

Further R&D essential → next generation experiments start in 2025

Challenges

- In- and out-coupling of drivers
- Synchronization of drivers at fs-scale
- Isochronicity (R_{56}) cancellation/control (for correct beam loading)
- Emittance preservation between stages:
  - Matching of beta function for all energies
  - Transverse alignment and stability
  - Dispersion cancellation
  - Coulomb scattering
- Driver distribution scheme
- CSR management
- Compactness (for a TeV/km average accelerating gradient)
- Tolerances & jitter

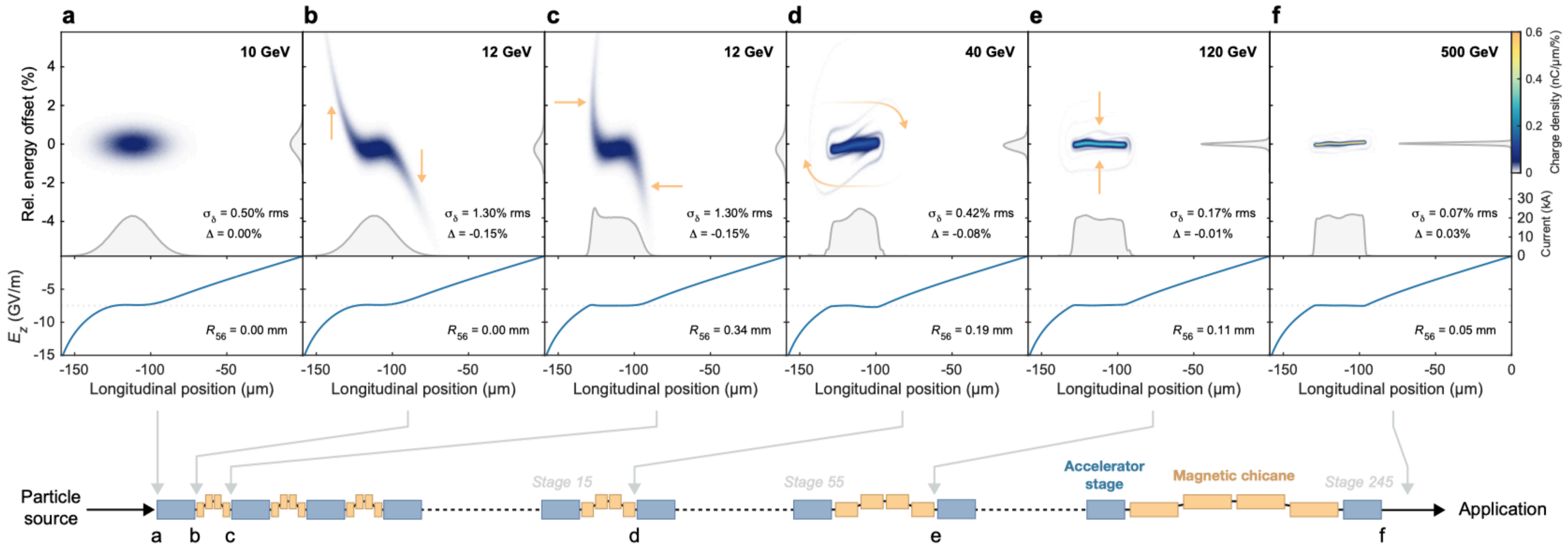
Staging proof-of-principle



S. Steinke *et al.*, Nature **530**, 190 (2016)

Temporal self-correction in staging

C.A. Lindstrøm, arXiv:2104.14460 (2021)



Capability gap in laser driver technology exists, coherent combination of fibers most promising, kBELLA to scale up

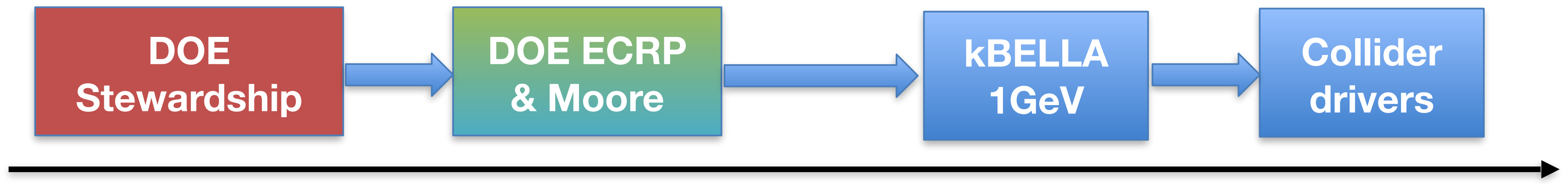
Novel laser technology needed to fulfill collider demands

in repetition rate (Hz → ~50 kHz), efficiency (0.1% → 10s %)

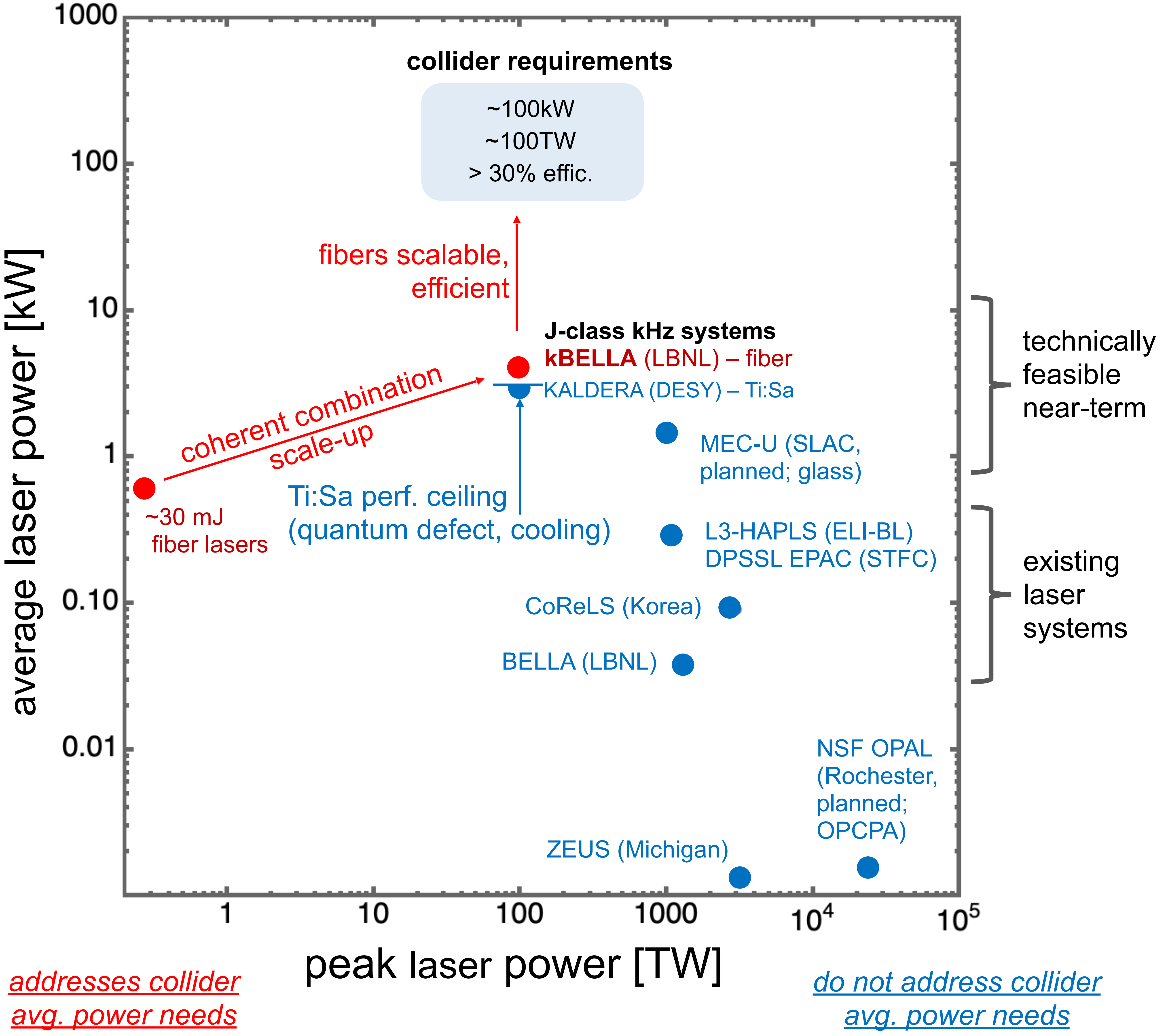
Promising emerging laser architectures

- Cryo-cooled **Yb:YAG** (λ = 1 µm), R&D at CSU
- **Tm:YLF** (λ = 1.9 µm), R&D at LLNL
- **Coherent combination of fiber lasers** (λ = 1 µm), R&D at LBNL, Michigan, Jena, École Polytechnique
  - potential for highest efficiency
  - 1 µm to minimize # of accelerator stages
  - monolithic design for robustness, serviceability

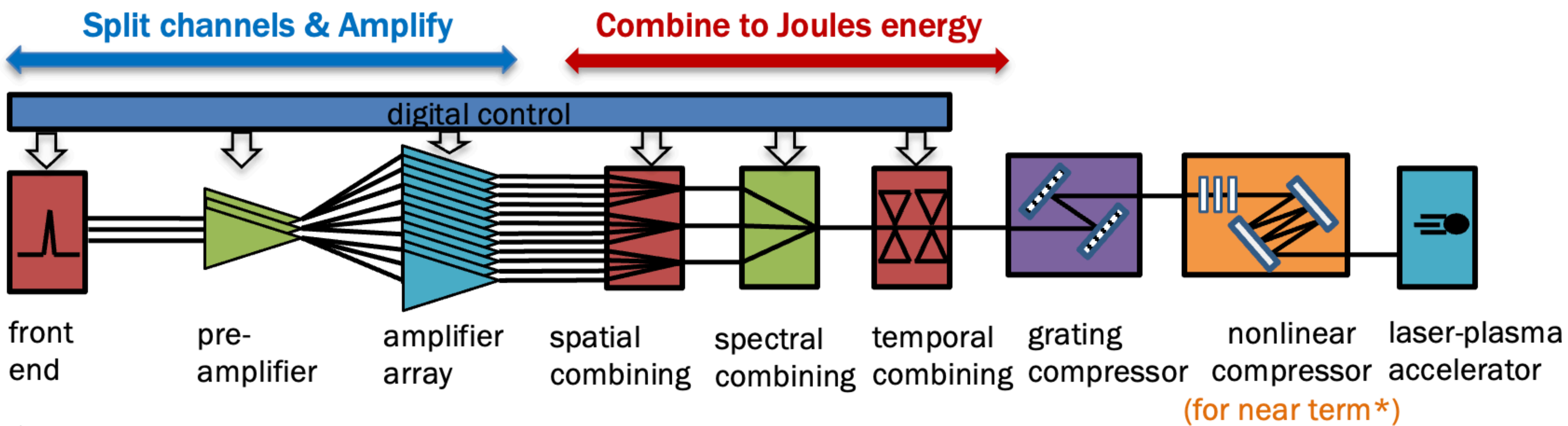
kBELLA addresses the driver rate, efficiency gap



Type	Research (funded)	Research (funded)	Facility	Facility
Energy	0.1 J	0.2 J	3 J	6 J
Duration	100 fs	30-50 fs	30 fs	30/100 fs
Power	1 kW	1 kW	3-30 kW	300 kW



Efficient, high power, ultrafast fiber lasers offer path to kHz and future colliders



Split channels & Amplify

Combine to Joules energy

digital control

front end

pre-amplifier

amplifier array

spatial combining

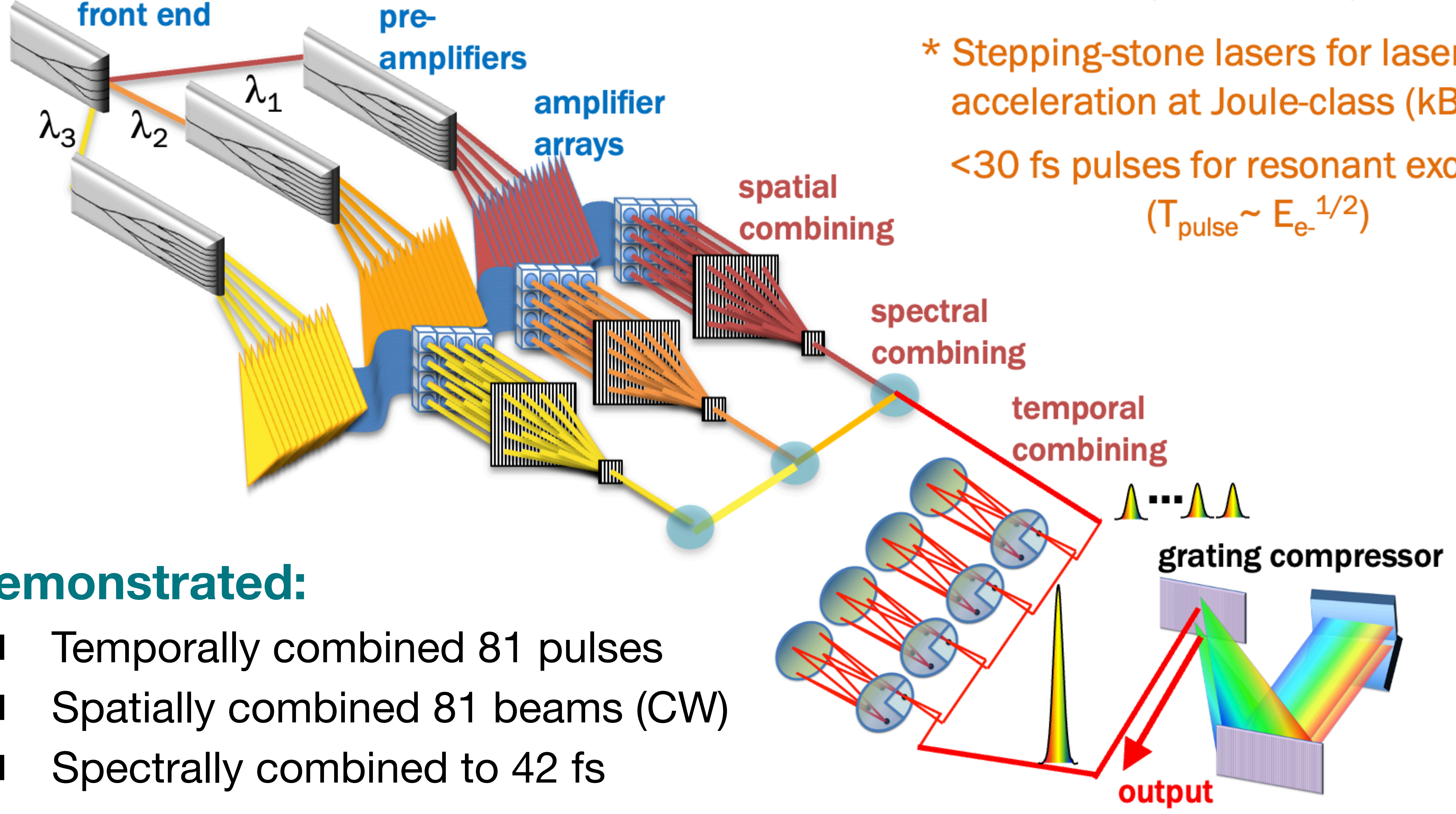
spectral combining

temporal combining

grating compressor

nonlinear compressor
(for near term*)

laser-plasma accelerator



front end

pre-amplifiers

amplifier arrays

spatial combining

spectral combining

temporal combining

grating compressor

output

* Stepping-stone lasers for laser-plasma acceleration at Joule-class (kBELLA):

<30 fs pulses for resonant excitation
($T_{pulse} \sim E_{e-}^{1/2}$)

Demonstrated:

- ❑ Temporally combined 81 pulses
- ❑ Spatially combined 81 beams (CW)
- ❑ Spectrally combined to 42 fs
- ❑ Spatial-temporally combined to 27mJ, kHz

Under construction: 10% kBELLA prototype

27 spatial beams, 81 temporal pulses, 3 spectral bands (200mJ, 1kW, 30 fs)

Collider need: Joules at 30-100fs

- Efficiency circa 30%
- Rates of 10-100 kHz

Technology: Coherent addition of fiber lasers

- Most efficient laser technology: meets need

Challenge: Fibers < mJ each, typically > 100fs

Solution: Combine pulses in space,
in color, and in time

- Combine 100 pulses from 1 fiber into a single energetic pulse
- Combine 100's fibers → Joules, 100's kW
- Combine 3 spectral bands for 30 fs