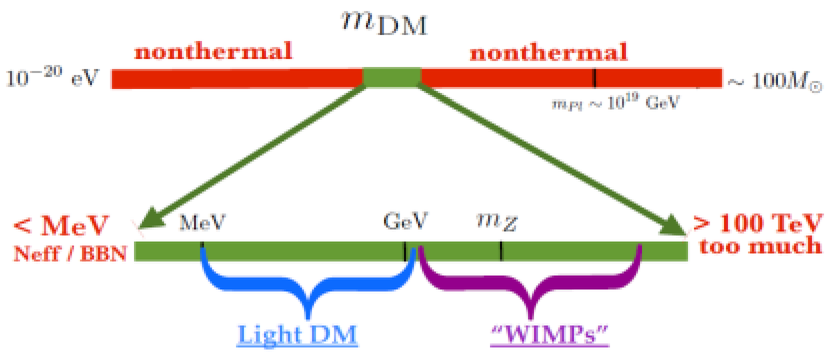
BSW22 – dark sector highlights

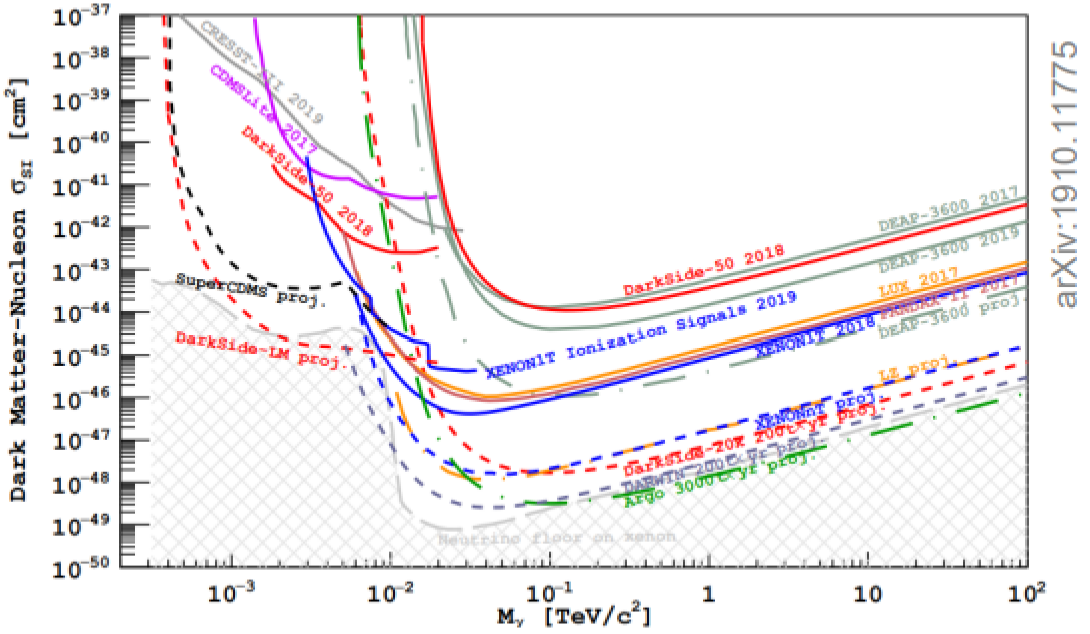
Angeles Faus-Golfe, Giuliano Franchetti and Frank Zimmermann

- Hidden Sector : Any Particles engaging in Feebly (or no) Interactions (FIPs) with the SM particles
  - Fair (but not necessary) starting point: *Dark Matter*

- Many reasons MeV – GeV region is particularly interesting….
  1. We know this mass scale exists !...
  2. Absence of hints for new particles at higher energies
  3. Possibility of thermal DM
  4. Cosmologically interesting and powerful constraints
  5. Largely unexplored territory
  6. And because we can!
     (…test many reasonable theoretical models!)

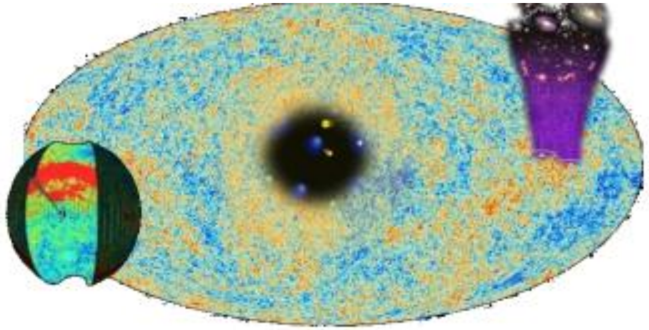


Direct searches for cosmic DM



R. Jacobsson

- At CMB $\delta\rho/\rho \sim 10^{-5}$
  - ➔ $\delta\rho/\rho$ grow with ~scale a during matter domination
  - ➔ $a_{today}/a_{dec} = 1 + z_{dec} \sim 10^3$
  - ➔ Not enough!



- DM can contribute in two ways:
  - Increasing mass density (increasing Jeans' scale for gravitational collapse $\propto \sqrt{T/m\rho}$)
  - Damping clustering of (too) small structures due to free-streaming $d_{FS} \propto v/\sqrt{\rho}$

- DM could produce a drop-off in the power spectrum of structures as a function of the scale
  - Wash out of structures with sizes in the range $10^6 - 10^8$ solar masses

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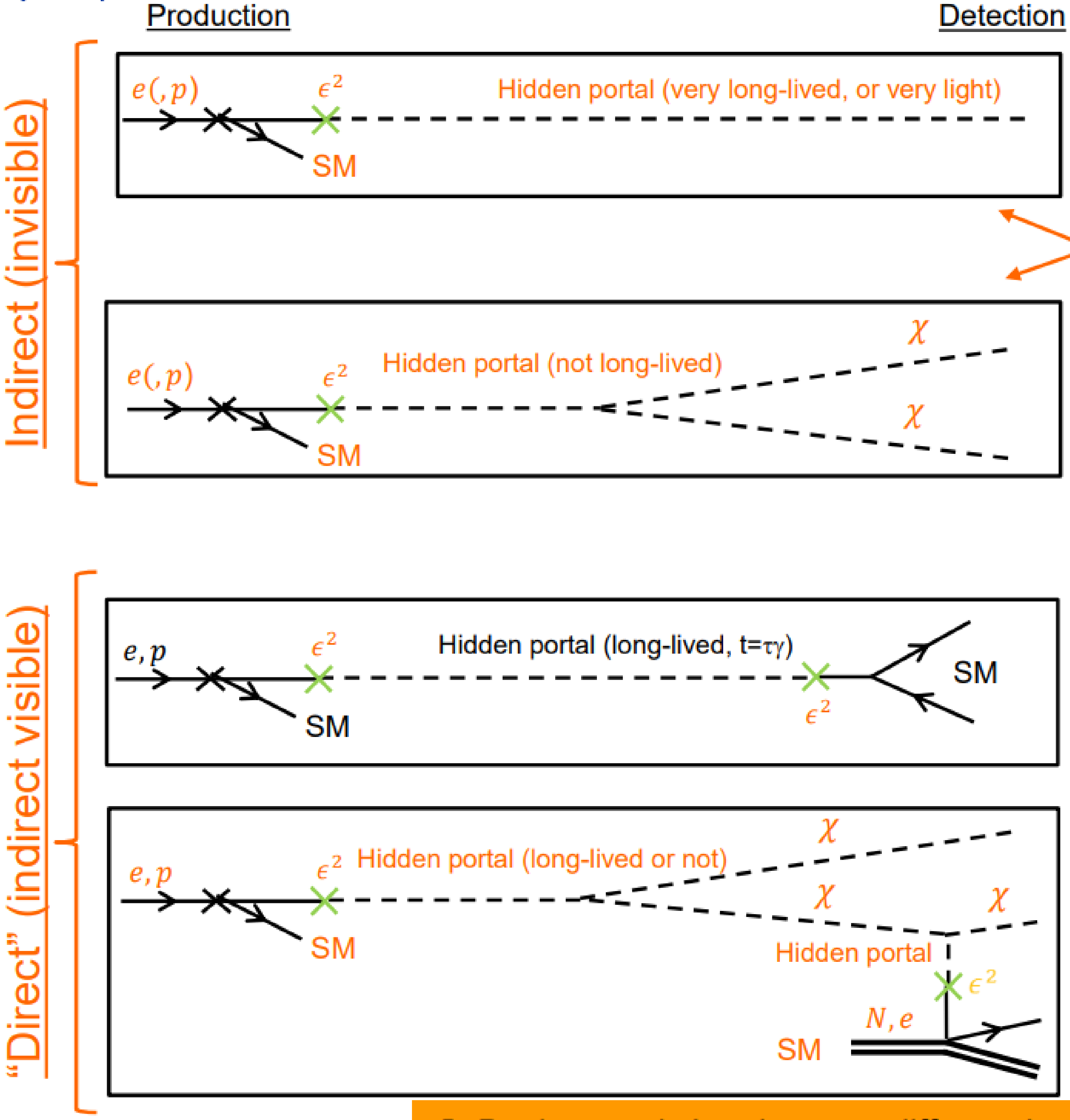


Note : $\epsilon \ll 1$

Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

ATLAS
CMS
LHCb
NA64
LDMX

Use of electrons limits search to Dark Photon mediator & ALPs

Decay signature ("displaced vertex")
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b
ATLAS
CMS
LHCb
NA62 (++)
NA64 (++)
FASER
SHiP

Dark matter scattering
Recoil against electron or nuclei
Probability $\propto \epsilon^4$
Model-dependent interpretation

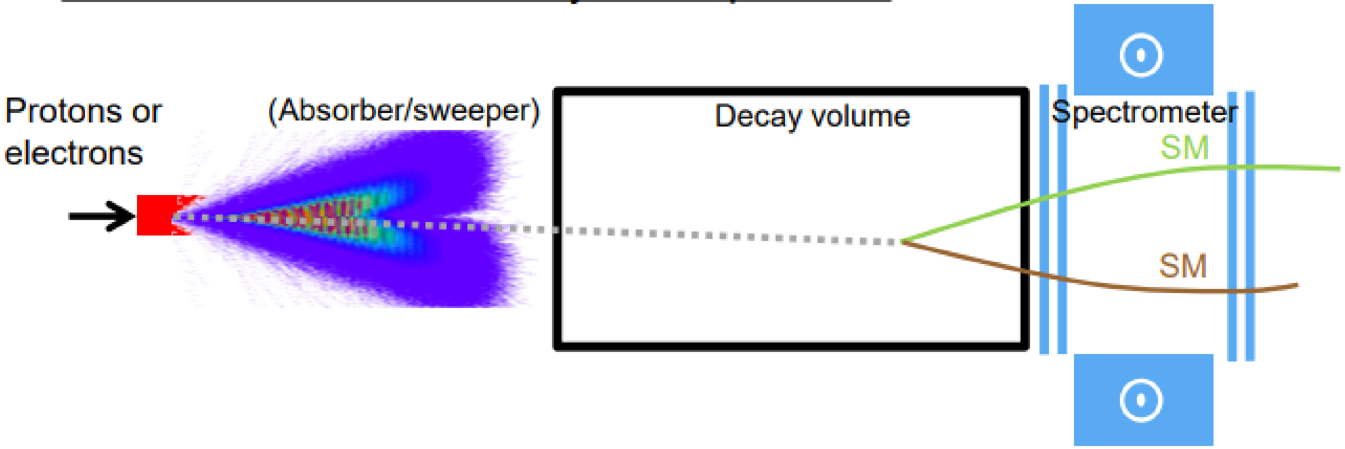
SHiP
SND@LHC

ϵ^4 dependence requires higher luminosity

➔ Background situation very different in the different techniques!

R. Jacobsson

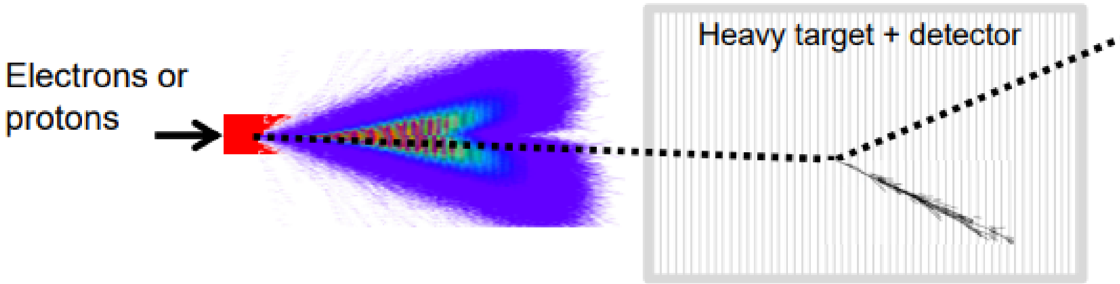
- Direct search: visible decay to SM particles



"Fixed target mode setups":
NA62++@CERN (p@400, 10^{18})
HPS, APEX, DarkLight@JLAB (e@1-10)
SHiP@CERN (p@400, 2×10^{20}),
SeaQuest@FNAL (p@120, 10^{18}–10^{20})
(LBNF@FNAL)

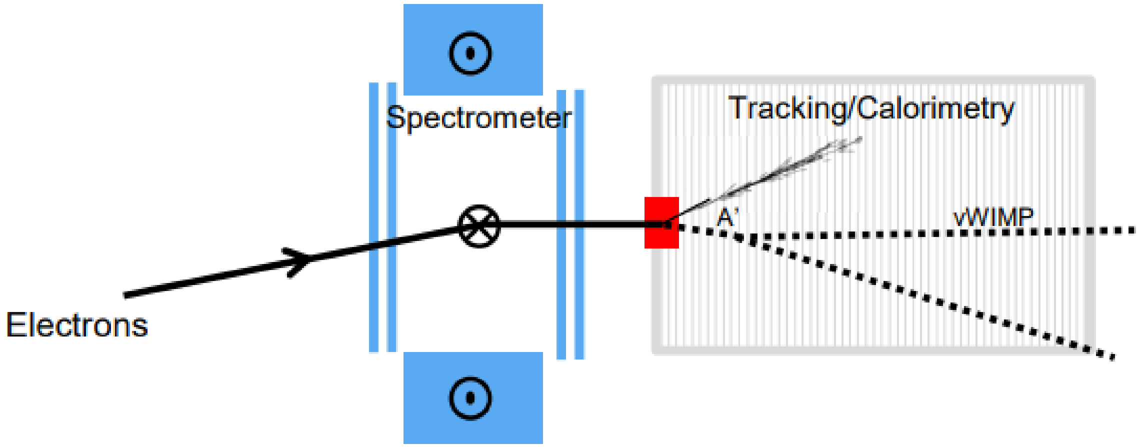
ATLAS, CMS, LHCb @LHC (no absorbers)
BELLE2@sKEKB (no absorber)
FASER@LHC
MATHUSLA@LHC (no spectrometer)

- Direct search: Scattering off atomic electrons and nuclei



"Fixed target mode setups":
BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
SHiP@CERN (p@400, 2×10^{20})
(interest for BDX-like experiments at LNF, Mainz (MESA), SLAC, Cornell…)

- Indirect search: Missing energy/momentum (slow extraction/electron association)



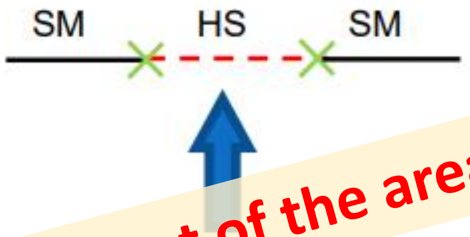
NA64/NA64++ @CERN (e@100, 10^{13})
LDMX@SLAC/CERN (e@4-16, 10^{14} - 10^{16})

here advanced accelerators could play important role !

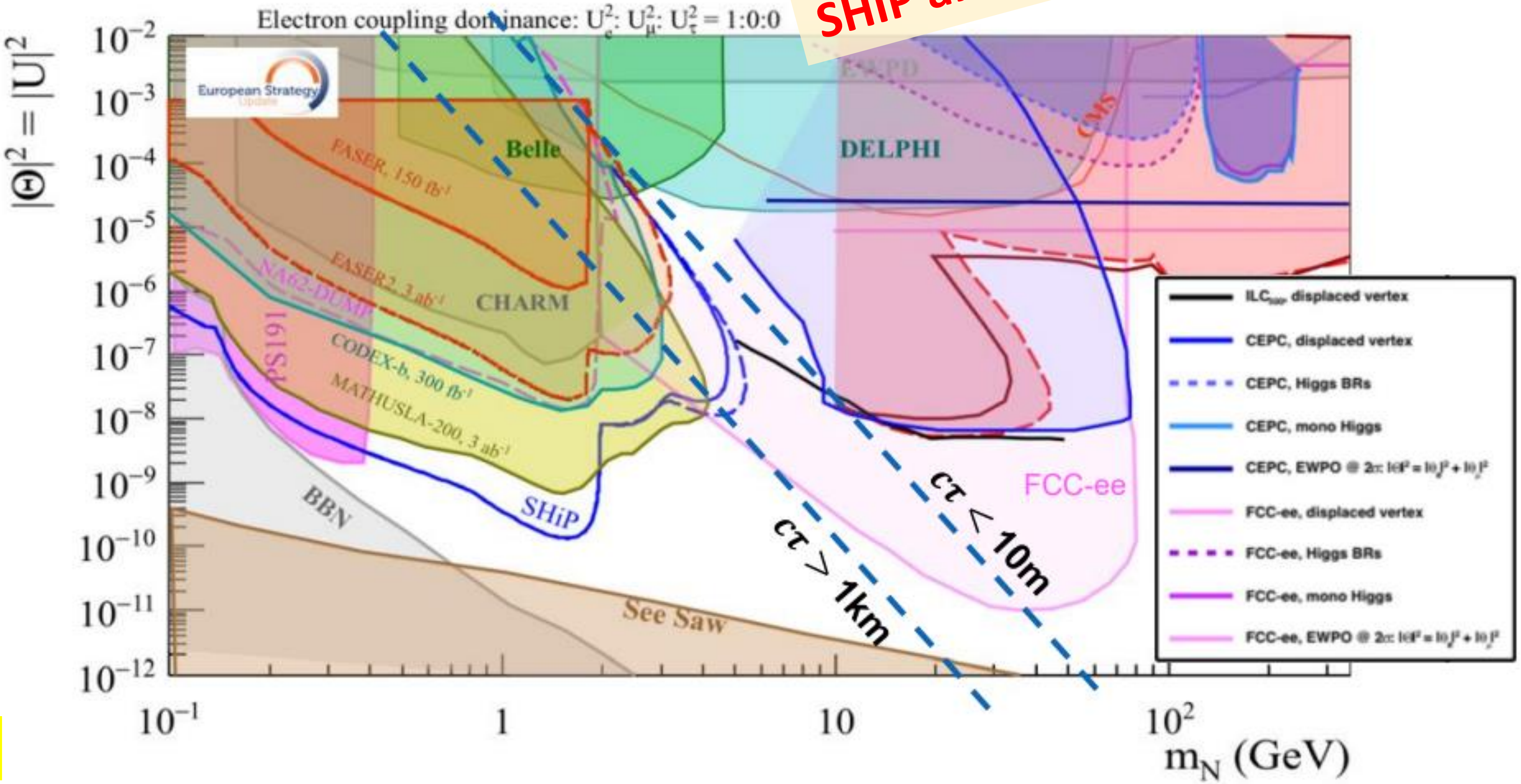
R. Jacobsson

- Acceptance and background are the biggest challenges!
  - Dilemma: background/pile-up versus absorbers/sweepers
  - New states are typically long-lived, e.g. HNL $\tau_N \sim \frac{96\pi^2 h}{|\mathcal{U}|^2 G_F^2 M_N^5}$

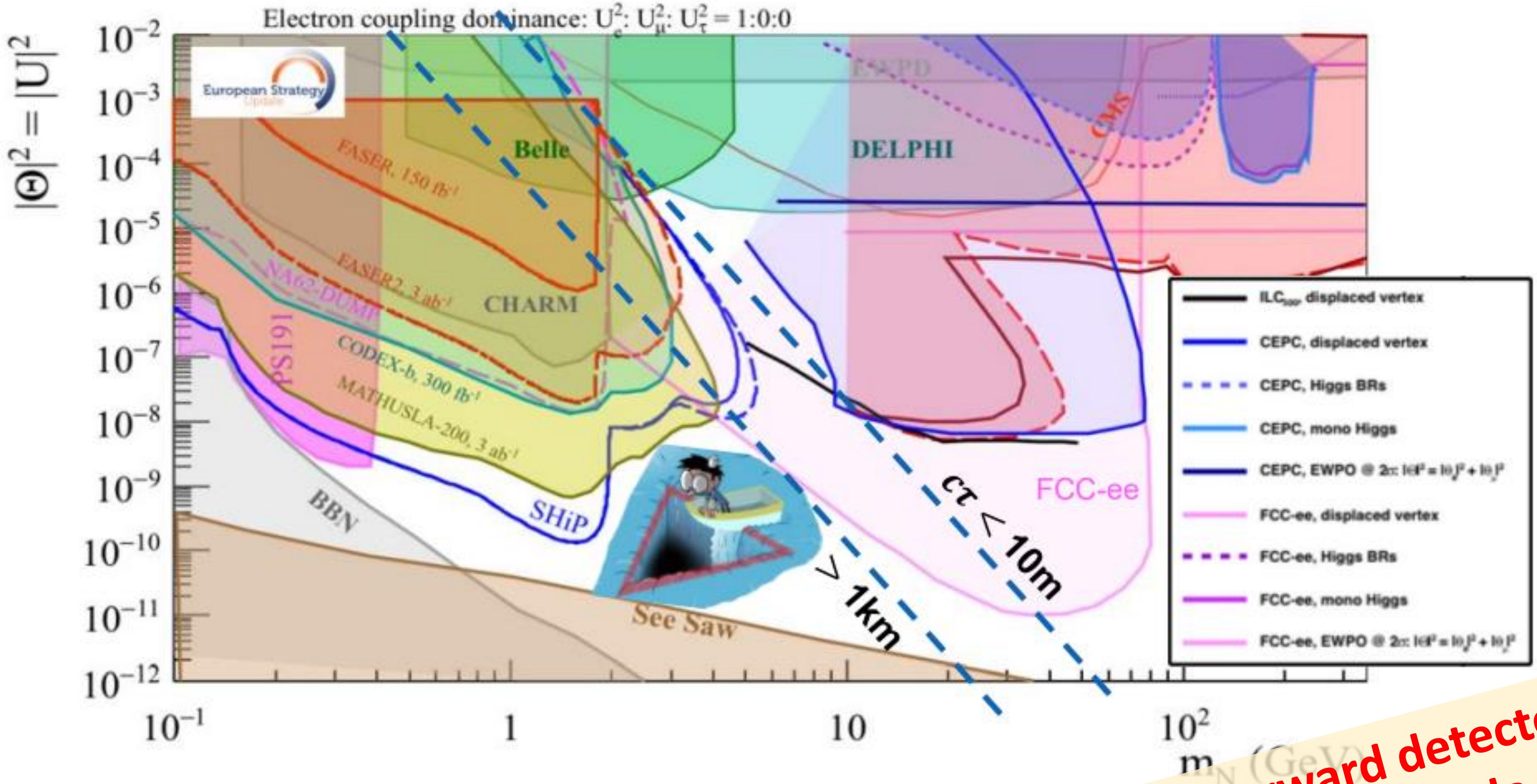
➔ Lifetime $\otimes$ $\epsilon \times 4\pi$ challenge



SHIP and FCC-ee cover most of the area



R. Jacobsson



distant forward detectors at collider cover Bermuda triangle

Bermuda triangle?

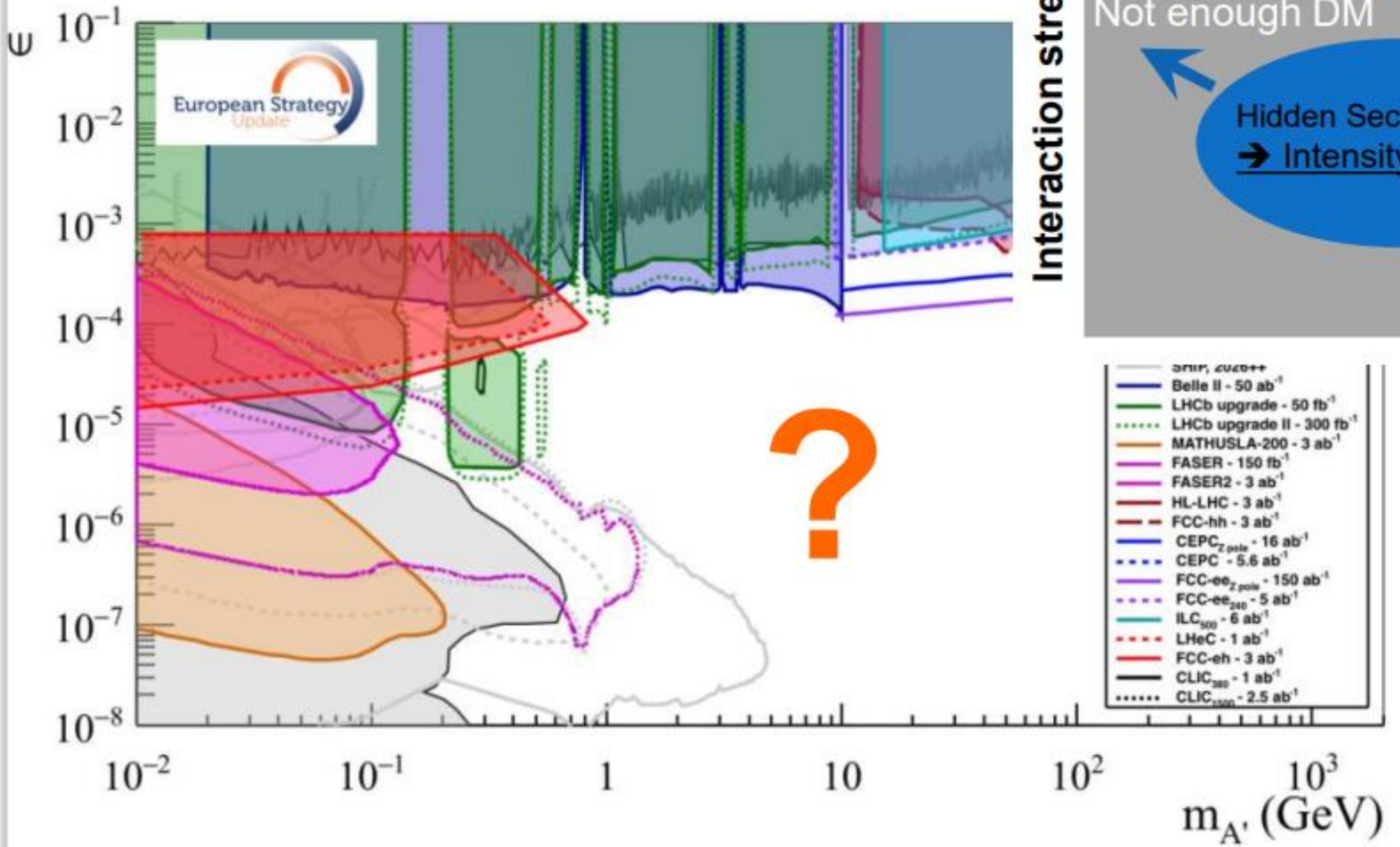
Production in B and W, Z decays with $c\tau\gamma$ ~ km's…

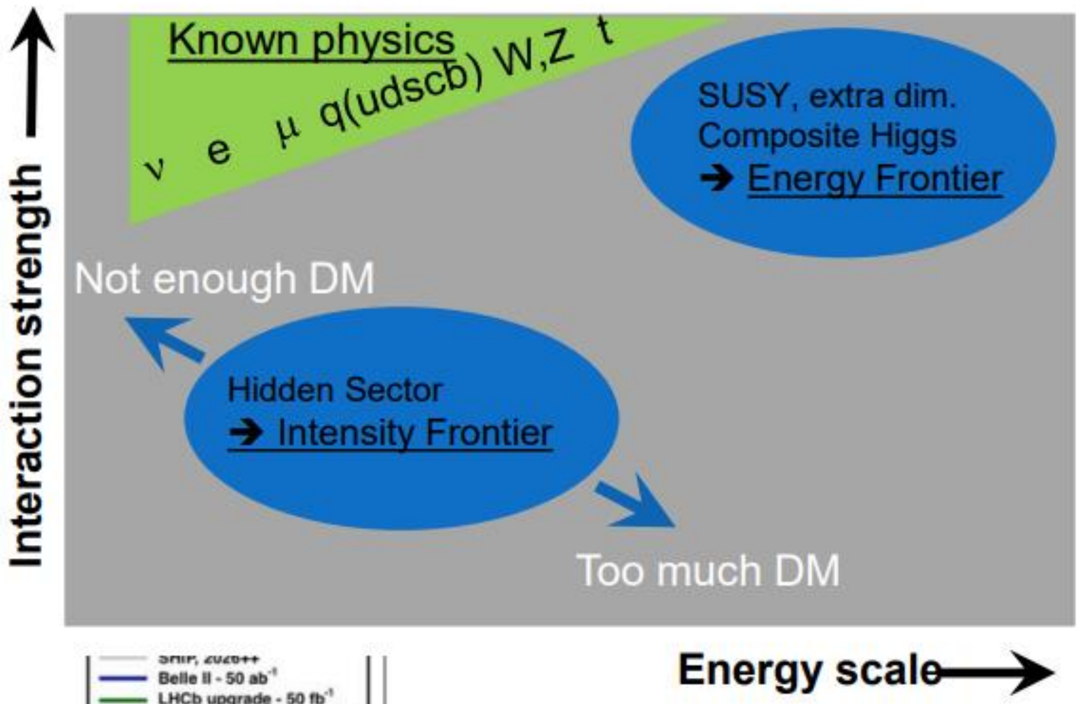
t-channel production from W exchange and forward large detectors a la $proton$-dump at distance from a collider IP?

R. Jacobsson

- Large number of options and huge parameter spaces
  - All parameter spaces have their "unreachable" regions, even physically attractive regions!

  ➔ Theoretical model building and cosmofrontier are essential guides!





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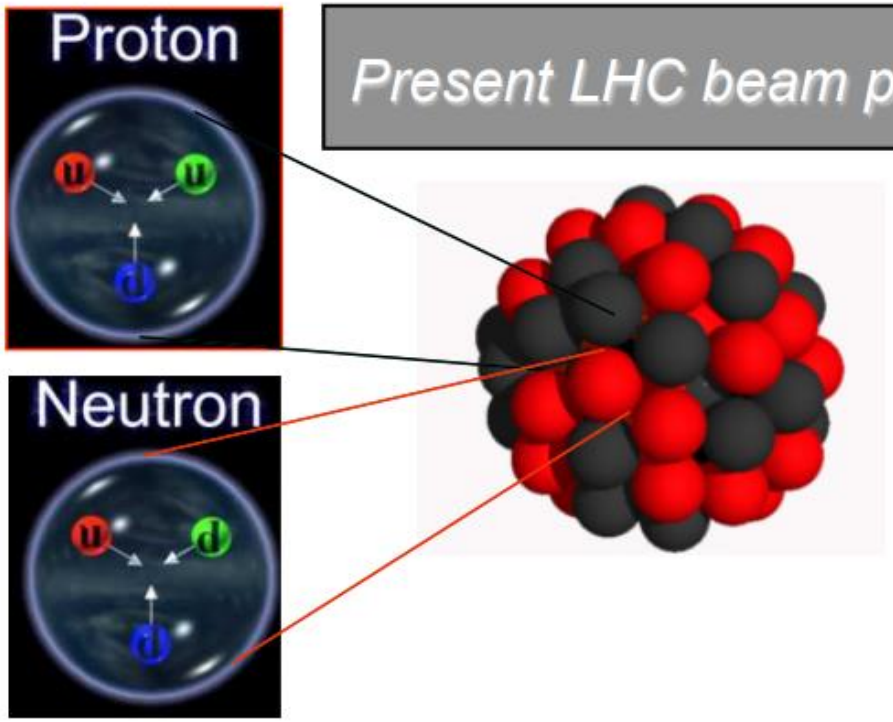
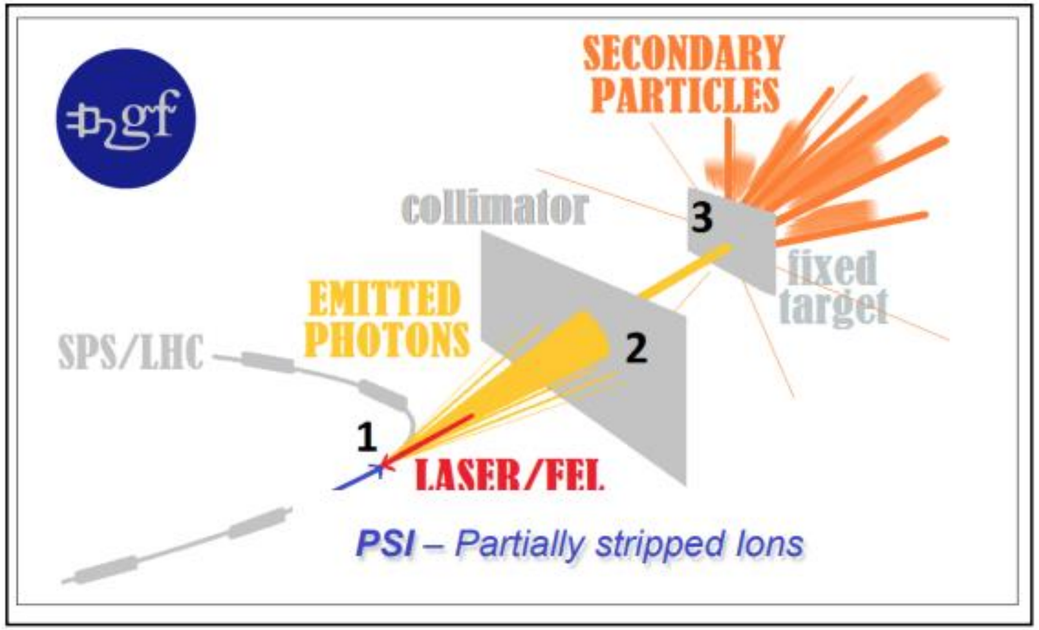
Present LHC beam particles:

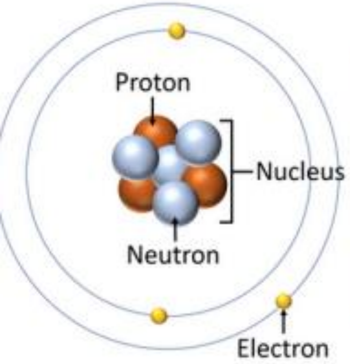


The Gamma Factory proposal for CERN

Mieczyslaw Witold Krasny (Paris U., VI-VII) (Nov 24, 2015)

e-Print: 1511.07794 [hep-ex]



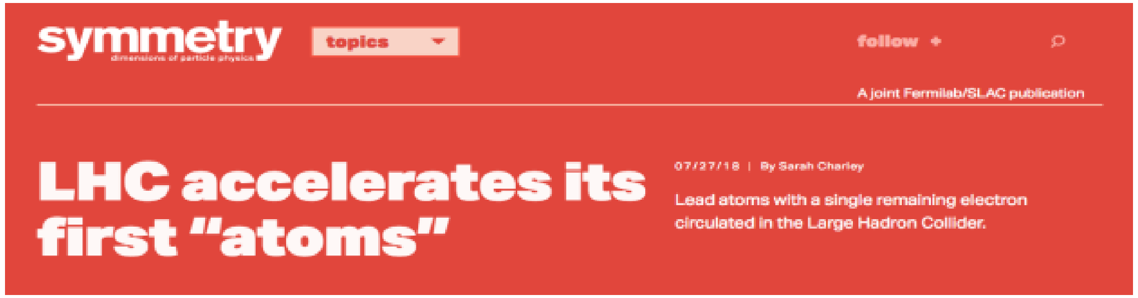


Future LHC beam particles:

Partially Stripped Ions (highly ionized atoms)

W. Krasny

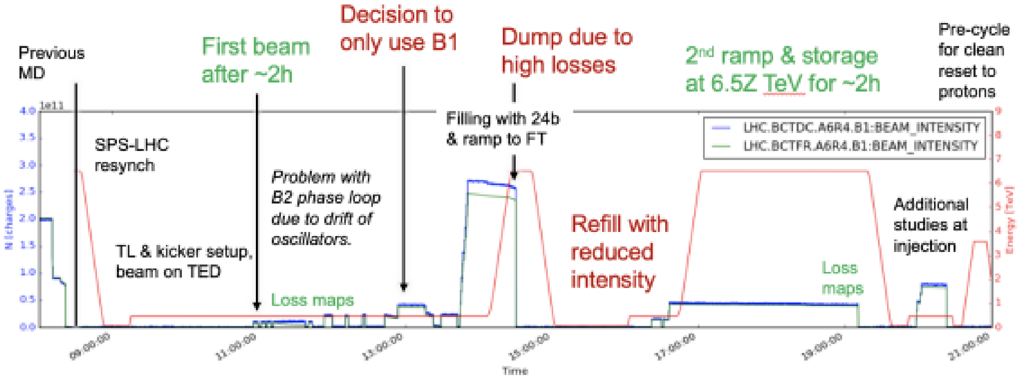
Atomic beams in the LHC (Hydrogen-like Lead)

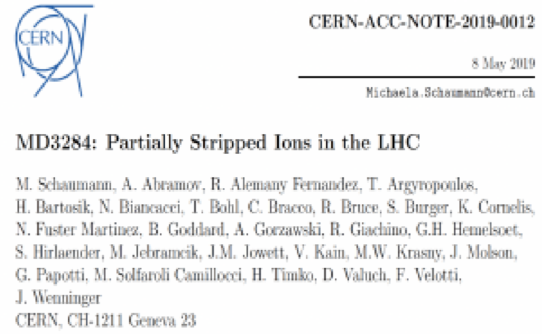

symmetry
dimensions of particle physics
topics
follow +
A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.




CERN

CERN-ACC-NOTE-2019-0012

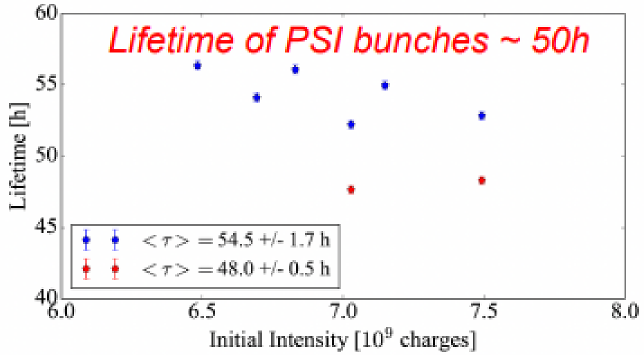
8 May 2019

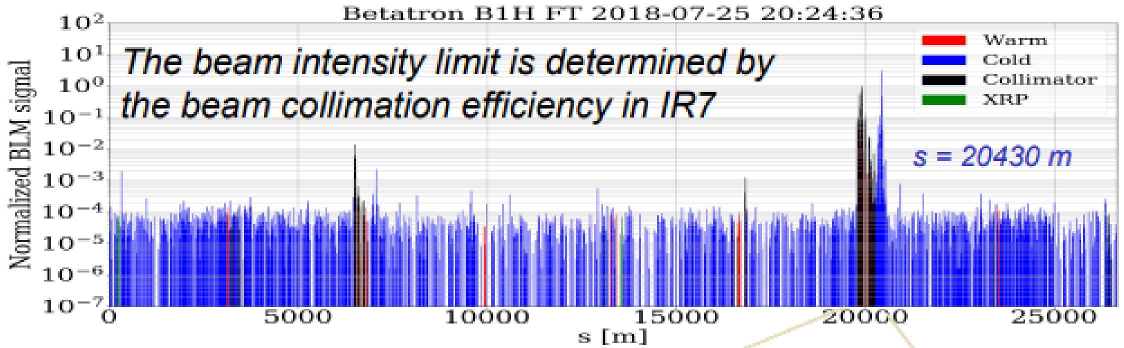
Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, M. Solfaroli Camillocci, H. Timko, D. Valuch, F. Velotti, J. Wenninger

CERN, CH-1211 Geneva 23

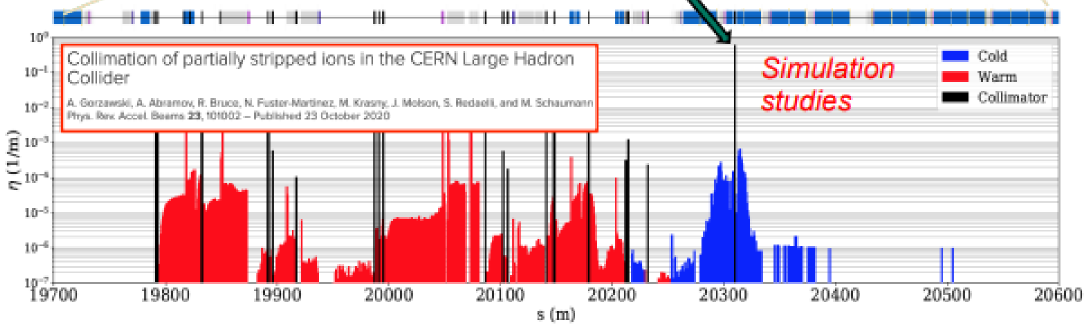




Mitigation strategies:

1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation*

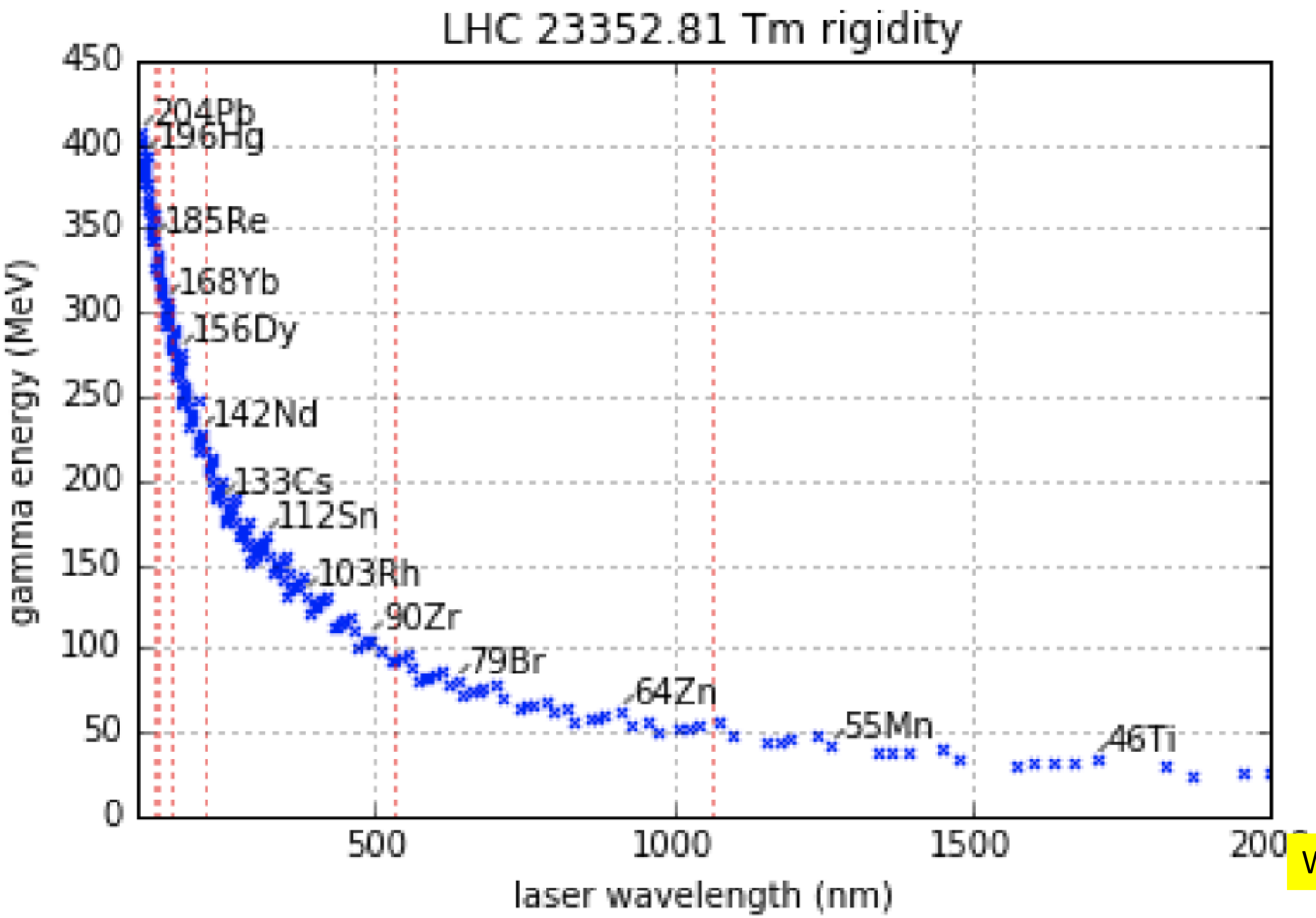
IR7 zoom



A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam is a natural next step…

W. Krasny

Radial n=1→ n=2 atomic excitation, maximal energy, zero crossing amgle



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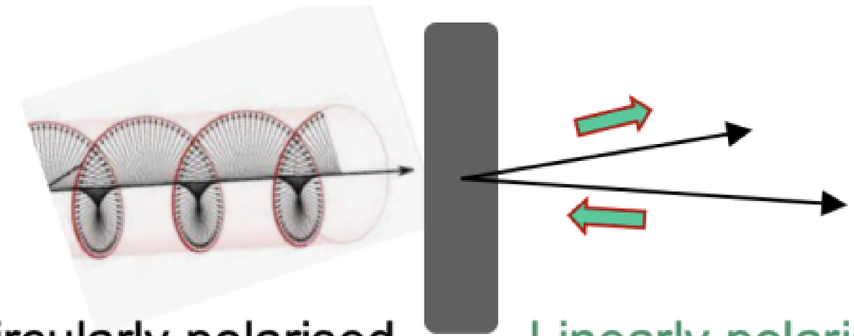
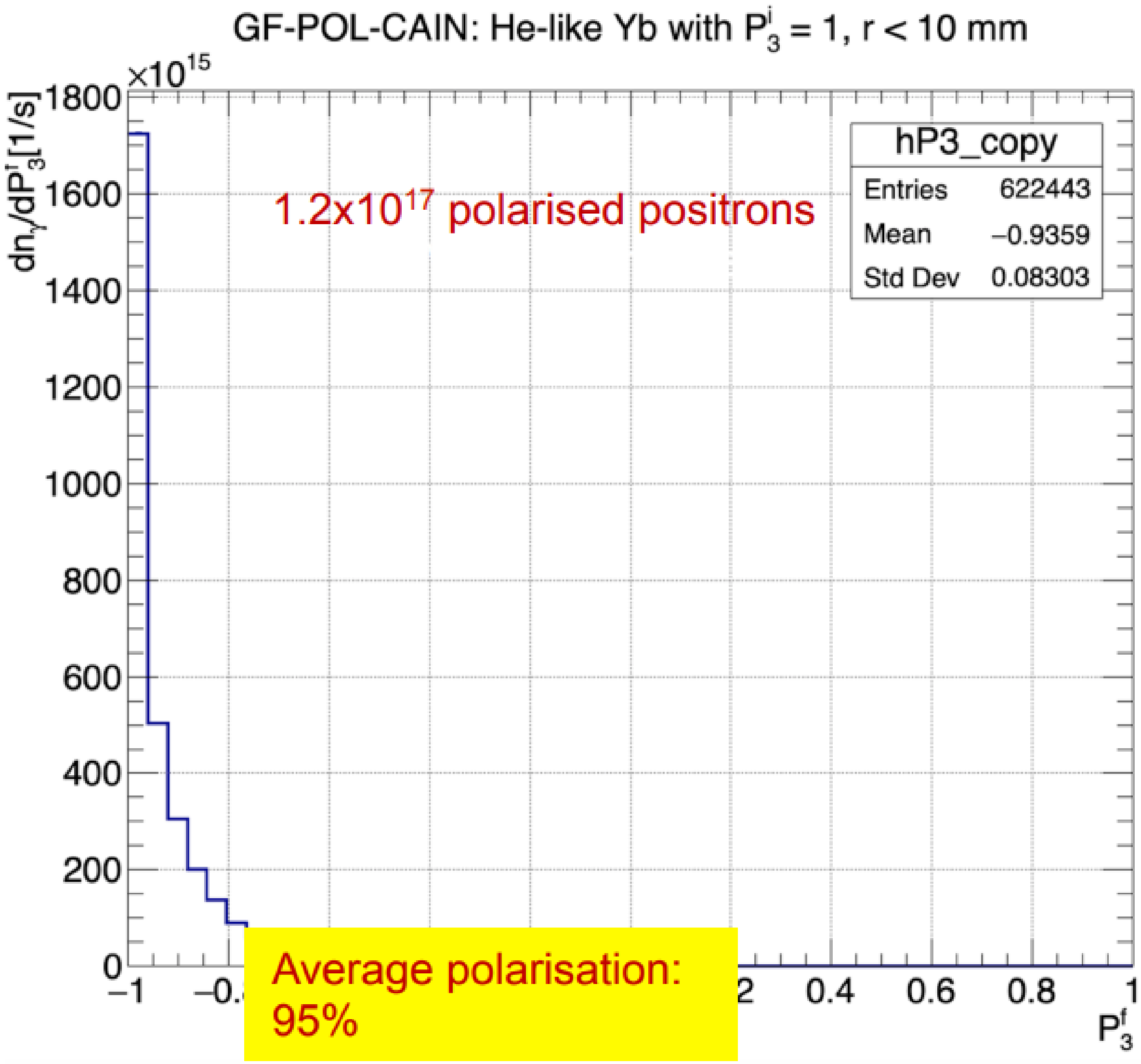
Polarized lepton source from polarized gamma beams



Circularly polarised gamma-rays

Linearly polarised leptons



W. Krasny

6.Tertiary beams' sources – Intensity/quality targets

- ***Polarised positrons*** – *potential gain of up to a factor of 10^4 in intensity w.r.t. the KEK positron source, satisfying both the LEMMA and the LHeC requirements*
- ***Pions*** – *potential, gain by a factor of 10^3, gain in the spectral density ($dN_\pi/dEdp_TdP$ [MeV^{-2} x MW^{-1}] with respect to proton-beam-driven sources at KEK and FNAL (P is the driver beam power)*
- ***Muons*** – *potential gain by a factor of 10^3 in intensity w.r.t. the PSI muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control, no necessity of the muon beam cooling (to be proven)?*
- ***Neutrinos*** – *fluxes comparable to NuMAX but: (1) Very Narrow Band Beam, driven by the small spectral density pion beam and (2) unique possibility of creating flavour- and CP-tuned beams driven by the beams of polarised muons*
- ***Neutrons*** – *potential gain of up to a factor of 10^4 in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power*
- ***Radioactive ions*** – *potential gain of up to a factor 10^4 in intensity w.r.t. e.g. ALTO*

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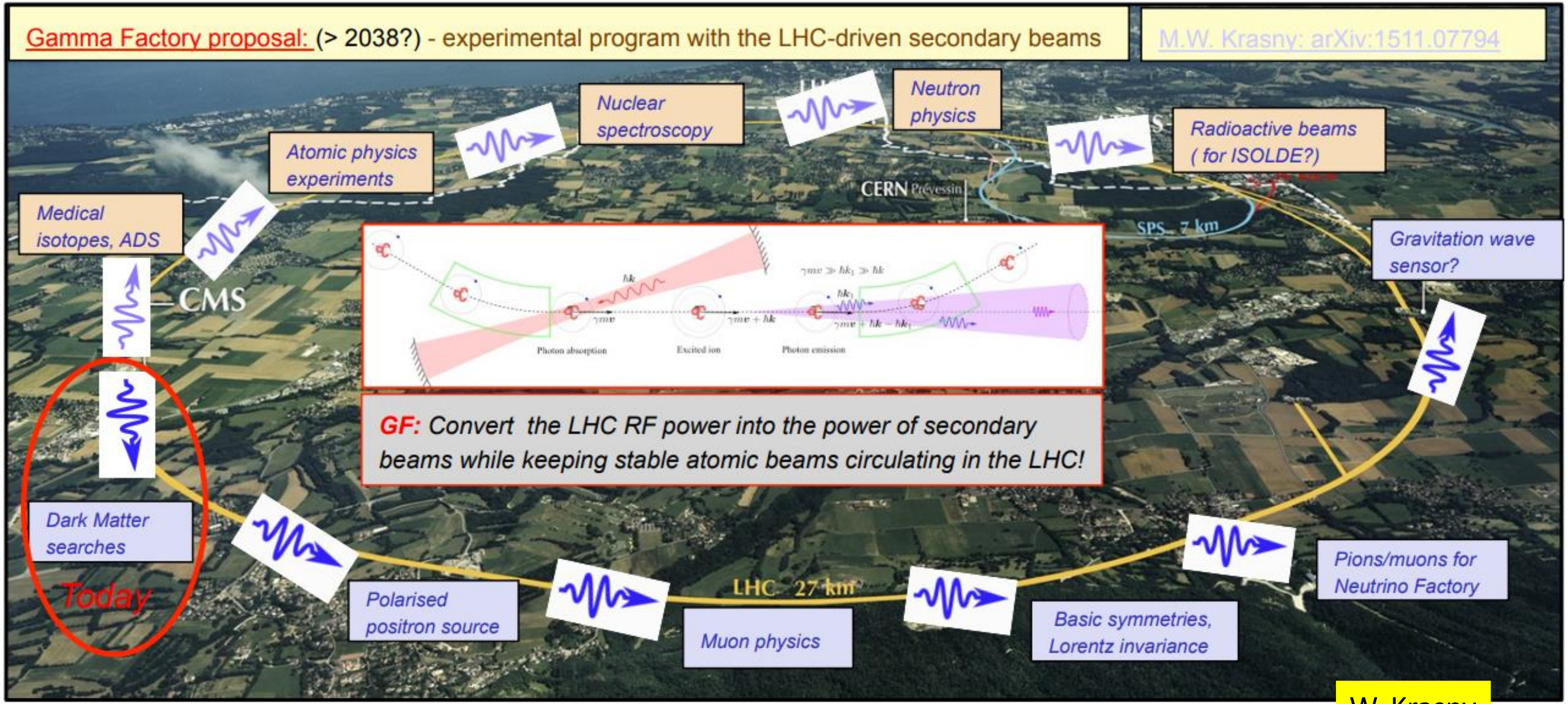
The LHC as a driver of secondary beams (operation mode)



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Energy footprint: Comparison of the DESY-XFEL and the CERN GF photon sources

DESY-XFEL

- Wall-pug power – 19 MW
- Driver beam power consumption – 600 kW
- Photon beam power 600 W
- **beam power efficiency ~ 0.1 %**
- **overall plug-power consumption efficiency ~ 0.003 %**

  (thanks to Andrea Latina for these numbers)

CERN-GF

- wall-pug power – 200 MW (total CERN)
- wall-pug power – 125 MW (LHC)
- beam lifetime 10 h
- **driver beam power consumption = photon beam power**

  (power to ramp the beam to requite energy negligible)
- **beam power efficiency ~ 99 %**
- **overall energy spending efficiency ~1%**

  (for 2 MW GF photon beams)

CERN **GF photon source** energy footprint is expected to be smaller, by a factor of 300, than the **DESY-XFEL** photon source…

…for the fixed power of the produced photon beam

W. Krasny

adp annalen der physik

Volume 534, Issue 3

Special Issue: Physics Opportunities with the Gamma Factory

March 2022

Issue Edited by: Dmitry Budker, Mikhail Gorchtein, Mieczyslaw Witold Krasny, Adriana Pálffy, Andrey Surzhykov

EDITORIAL

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From Einstein to CERN's Gamma Factory – the Story of *Annalen der Physik* Continues

W. Krasny

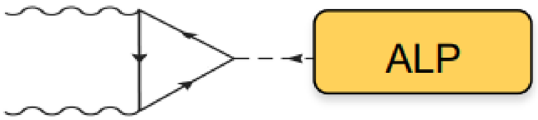
The dark matter detection in GF

- "Produce and detect" DM particles (photon beams)
- Detect the cosmic origin DM particles (fully and partially stripped ion beams)

W. Krasny

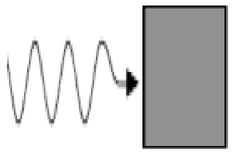
DM searches (and studies): Axion-Like-Particles (ALP) example

Collision schemes for ALP production:



Search phase

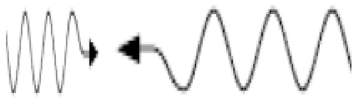
γ_{GF} – B field
$m_{ALP} < 1$ keV



γ_{GF} – A collisions (beam dump)
$m_{ALP} \sim 1$ keV – 10 MeV

γ_{GF} – A collisions (LHC)
$m_{ALP} \sim 10$ MeV – 10 GeV

"Production" phase



$\gamma_{GF} - \gamma_{Laser}$ collisions
$m_{ALP} \sim 1$–100 keV

$\gamma_{GF} - \gamma_{GF}$ collisions (LHC)
$m_{ALP} \sim 100$ keV – 800 MeV

Concurrent, rich QED programme (e.g. vacuum birefringence studies)

Three principal advantages of the Gamma Factory photon beams:

- ***Large fluxes**: ~10^{25} photons on target over year (SHIP – 10^{20} protons on target).*
- ***Multiple ALP production schemes** covering a vast region of ALP masses **(sub eV – GeV)***
- ***Once** ALP candidate **seen** → a unique possibility to **tune** the GF beam **energy** to the **resonance**.*

W. Krasny

Gamma Factory dark photon discovery potential
(beam-dump search mode)

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

$$\gamma e \to eX$$

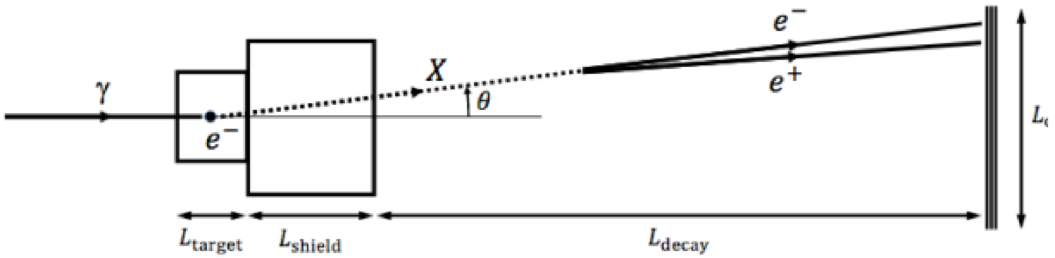


FIG. 1. **Experiment layout.** The experiment consists of a (graphite) target with thickn
$L_{\rm target} = 1$ m, followed by a (lead) shield with thickness $L_{\rm shield} = 2$ m, an open air decay reg
with length $L_{\rm decay}$, and a tracking detector, centered on the beam axis, which we take to b
circular disk with diameter $L_{\rm det}$. The GF photon beam enters from the left and produces an
particle through dark Compton scattering $\gamma e \to eX$. The X particle is produced with an angl
relative to the GF beamline and decays to an e^+e^- pair, which is detected in the tracking detect

Gamma Factory Searches for
Extremely Weakly-Interacting Particles

Sreemanti Chakraborti,[1,*] Jonathan L. Feng,[2,†] James K. Koga,[3,‡] and Mauro Valli[2,§]

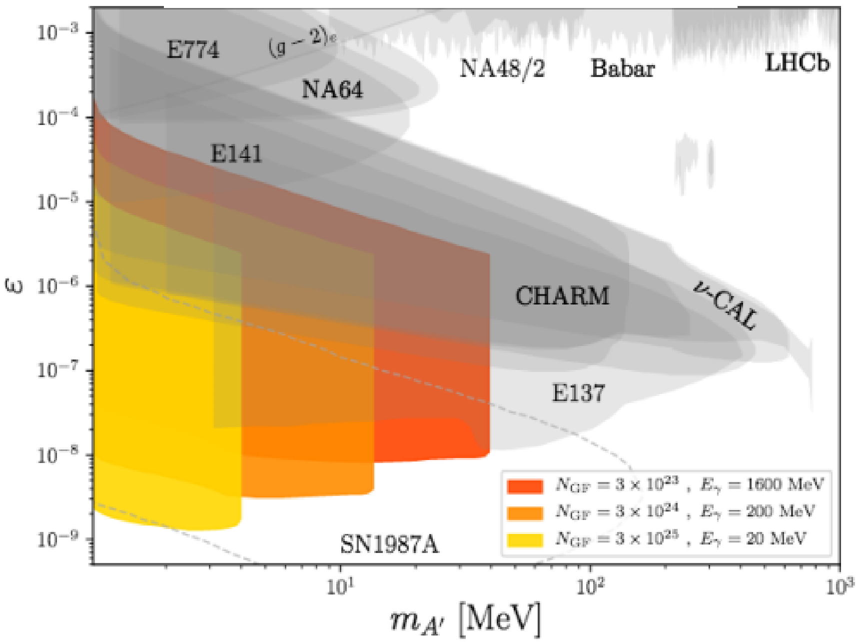
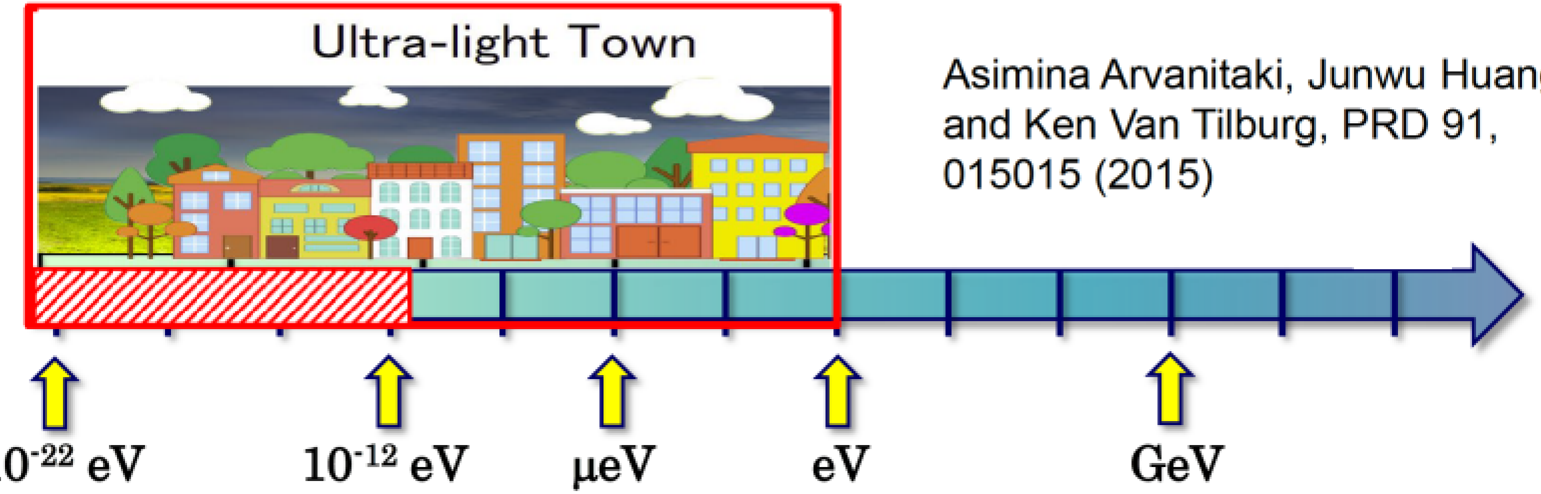


FIG. 3. **Dark photon sensitivity.** The sensitivity reach for the three sets of GF parameters ($E_\gamma, N_{\rm GF}$) indicated, each corresponding to a year of running, and detector parameters $L_{\rm decay}$ = 12 m and $L_{\rm det}$ = 3 m. The contours are for 3 e^+e^- signal events and assume no background. The gray shaded regions are existing bounds from the terrestrial experiments indicated [32–42] (for further details, see also [43, 44]), from $(g-2)_e$ [45], and the dashed gray line encloses the region probed by supernova cooling, as determined in Ref. [46].

W. Krasny

How to detect ultralight dark matter with clocks?



Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, PRD 91, 015015 (2015)

Dark matter field $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$

couples to electromagnetic interaction and “normal matter”

It will make fundamental coupling constants and mass ratios oscillate

Atomic energy levels will oscillate so clock frequencies will oscillate

Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).

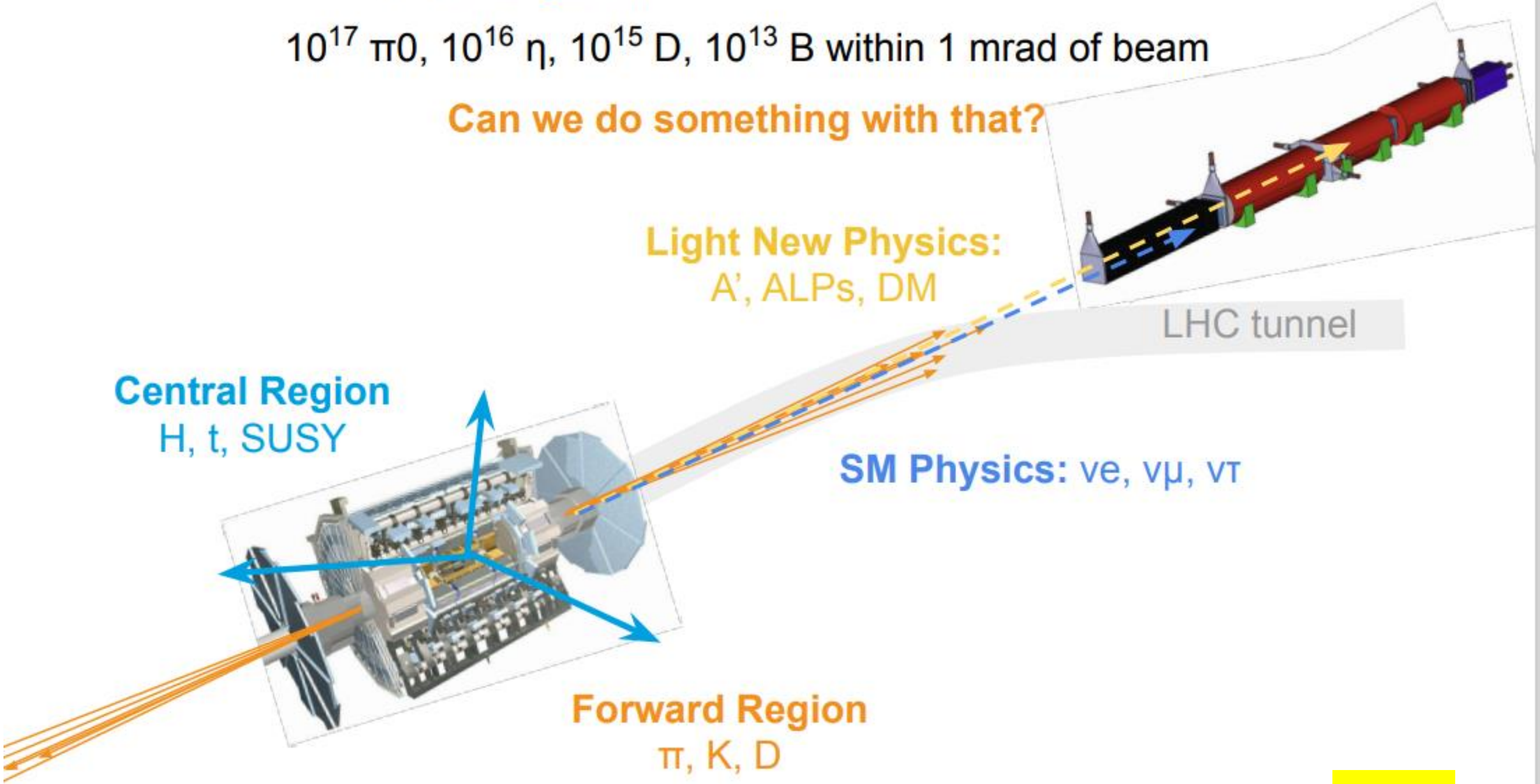
W. Krasny

- *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*
- *Examples of such tools were presented in this talk*
- *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires "relatively" minor infrastructure investments*
- *Gamma Factory has a significant potential to produce, detect and investigate the properties of the keV/MeV mass-range DM particles (if they exist)*
- *Its potential to detect DM waves of cosmic origin remains to be demonstrated*

W. Krasny

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam



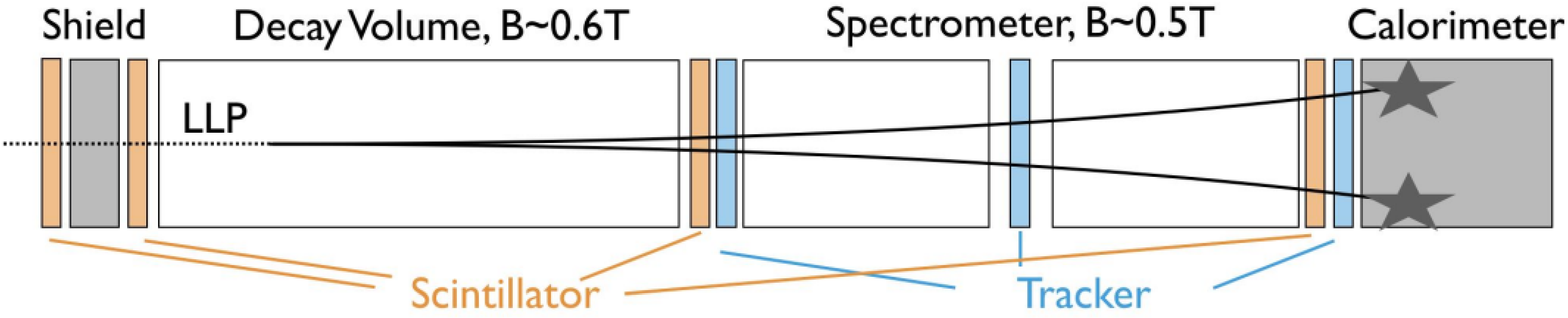
F. Kling

FASER: search for light long-lived particles

pp → LLP + X,   LLP travels ~ 480m,   LLP → charged tracks + X

Signal is striking:

* highly energetic charged particles (E ~ TeV)
* common vertex in an empty decay volume
* point back to the IP through 90 m of rock



Background considerations:

* large flux of muons from the LHC cause muon-associated radiative events
* use scintillators veto to reduce BG to negligible levels

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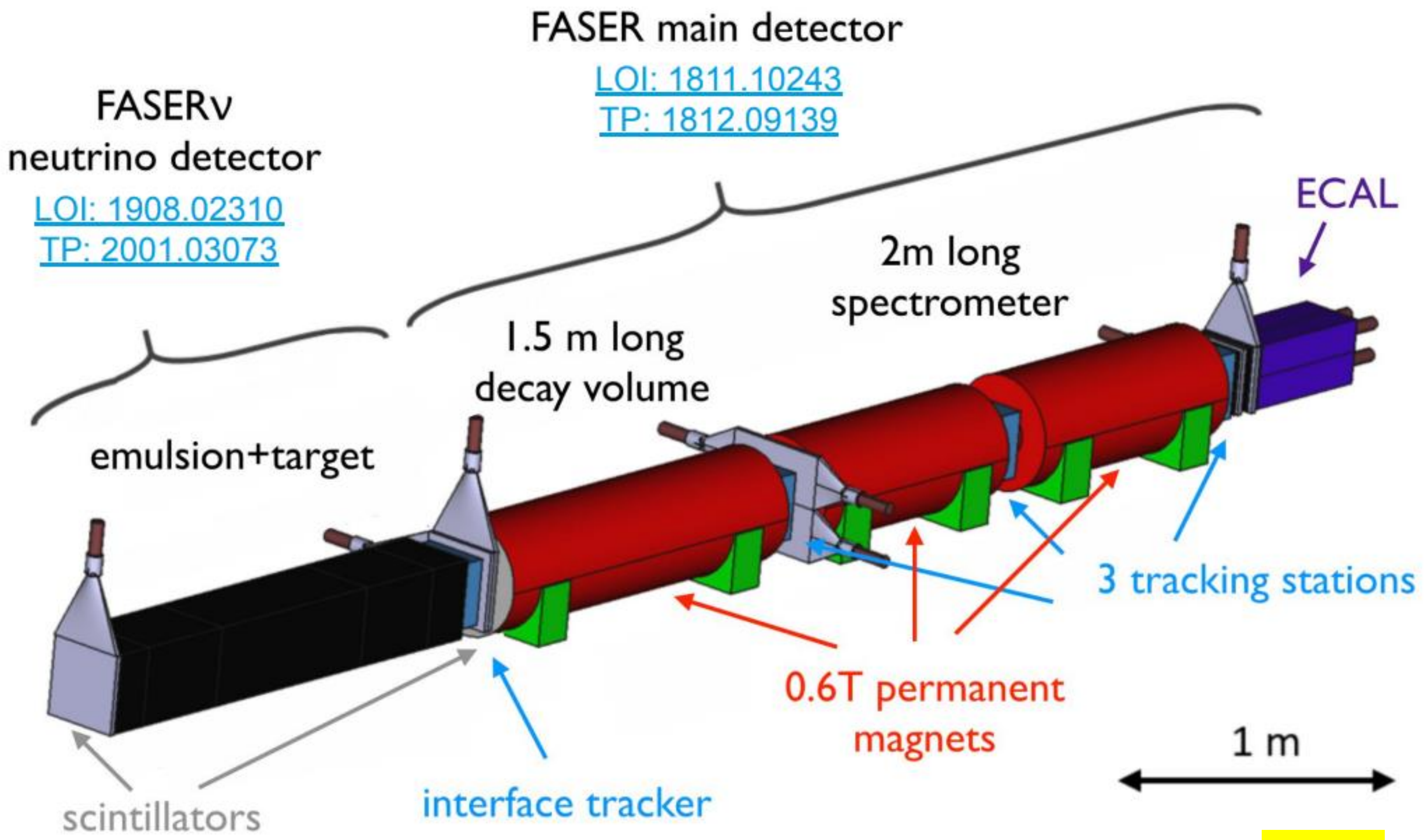

FASER main detector
LOI: 1811.10243
TP: 1812.09139
FASERν
neutrino detector
LOI: 1908.02310
TP: 2001.03073
ECAL
2m long
spectrometer
1.5 m long
decay volume
emulsion+target
3 tracking stations
0.6T permanent
magnets
1 m
scintillators
interface tracker

F. Kling

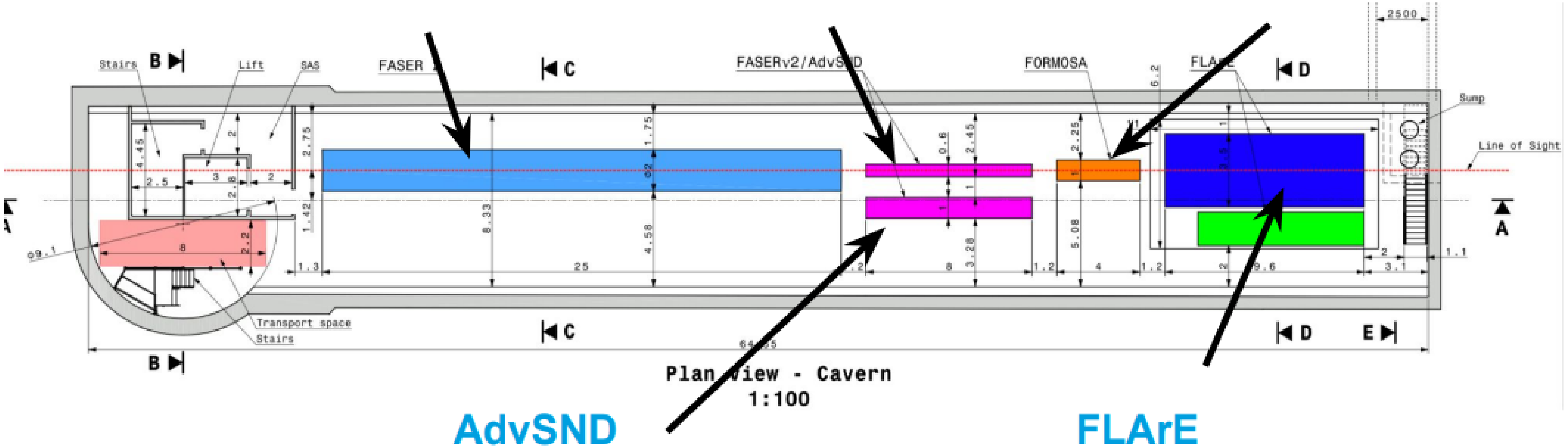
Forward Physics Facility.

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

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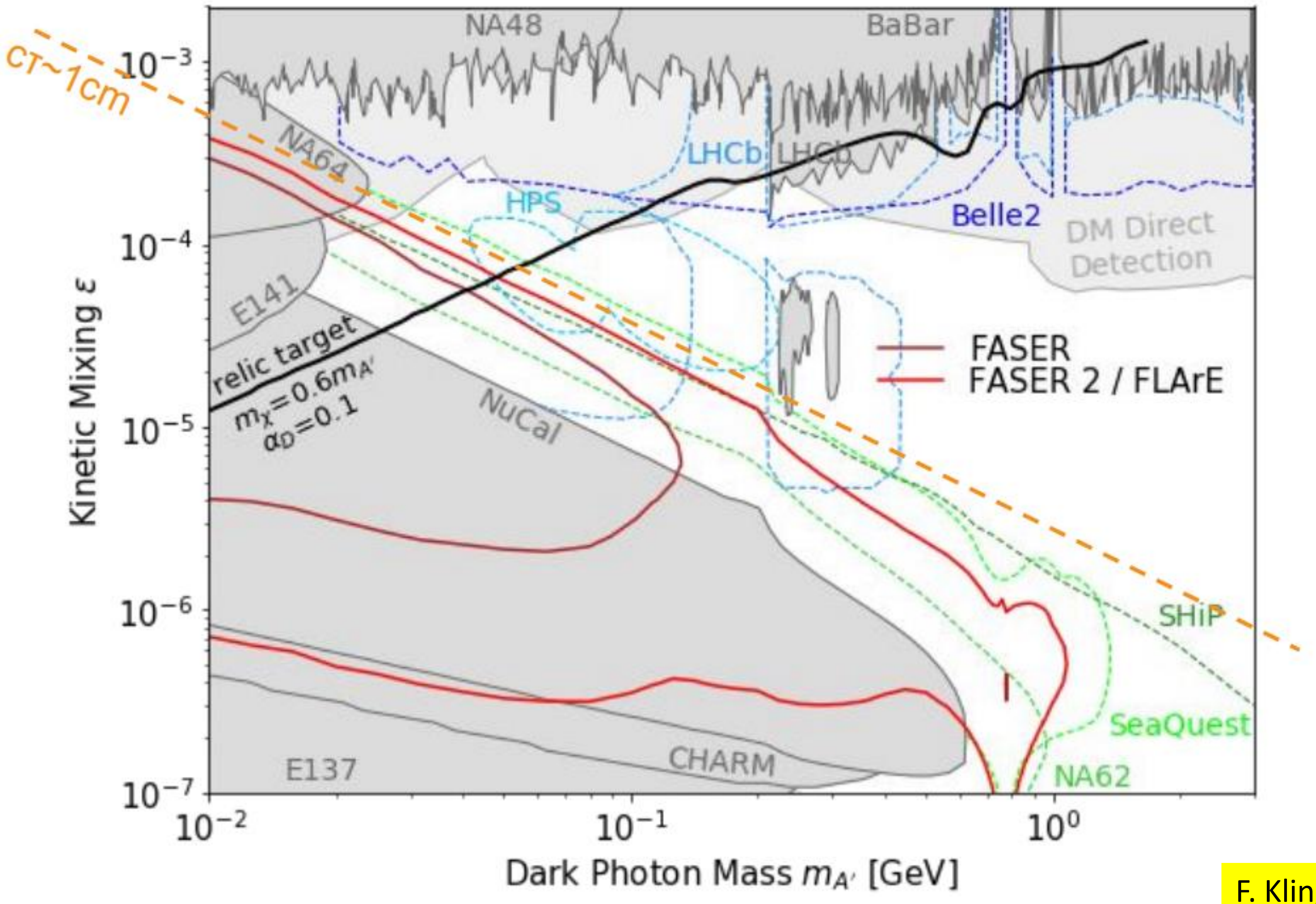
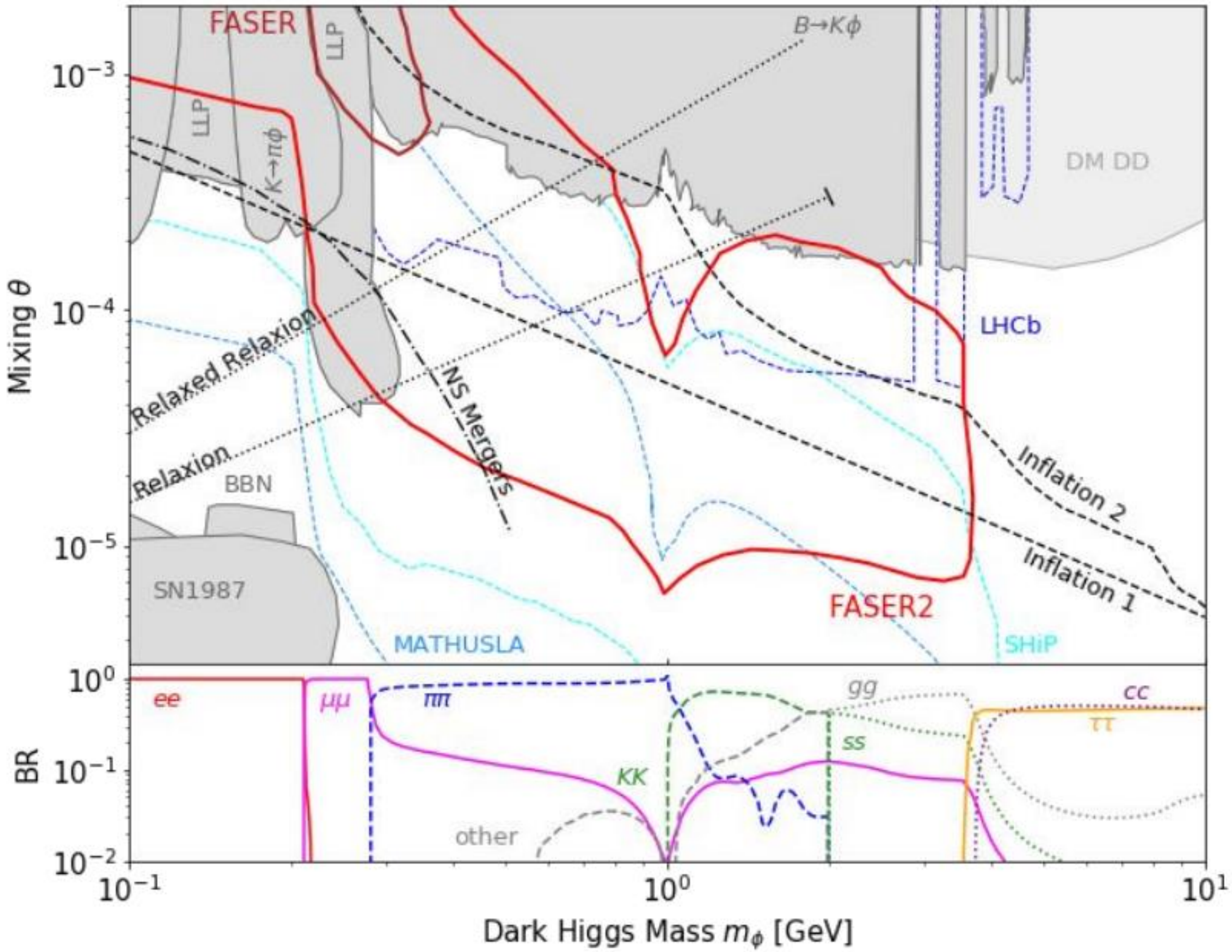


cτ~1cm
NA48
BaBar
NA64
LHCb
LHCb
HPS
Belle2
DM Direct Detection
E141
relic target
$m_\chi=0.6m_{A'}$
$\alpha_D=0.1$
NuCal
FASER
FASER 2 / FLArE
SHiP
SeaQuest
NA62
E137
CHARM
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]

F. Kling

Long-Lived Particles: Dark Higgs.

Higgs-like scalar: likes to couple to heavy particles → produced in B decay



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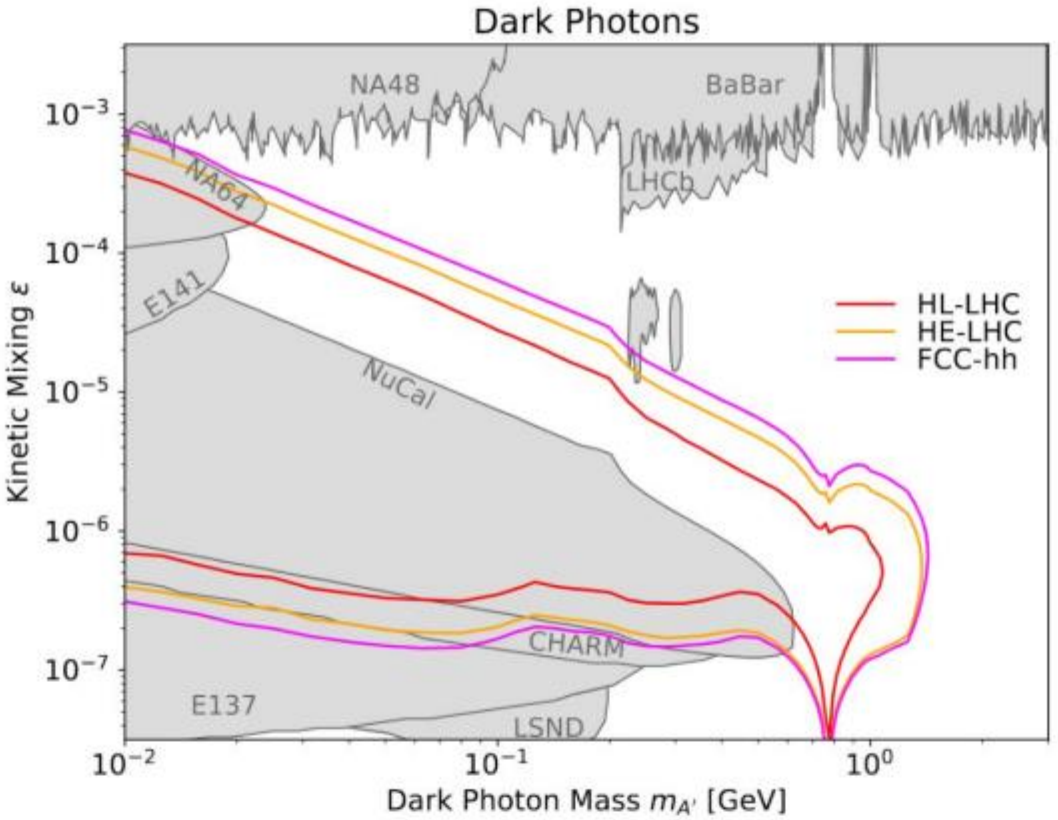
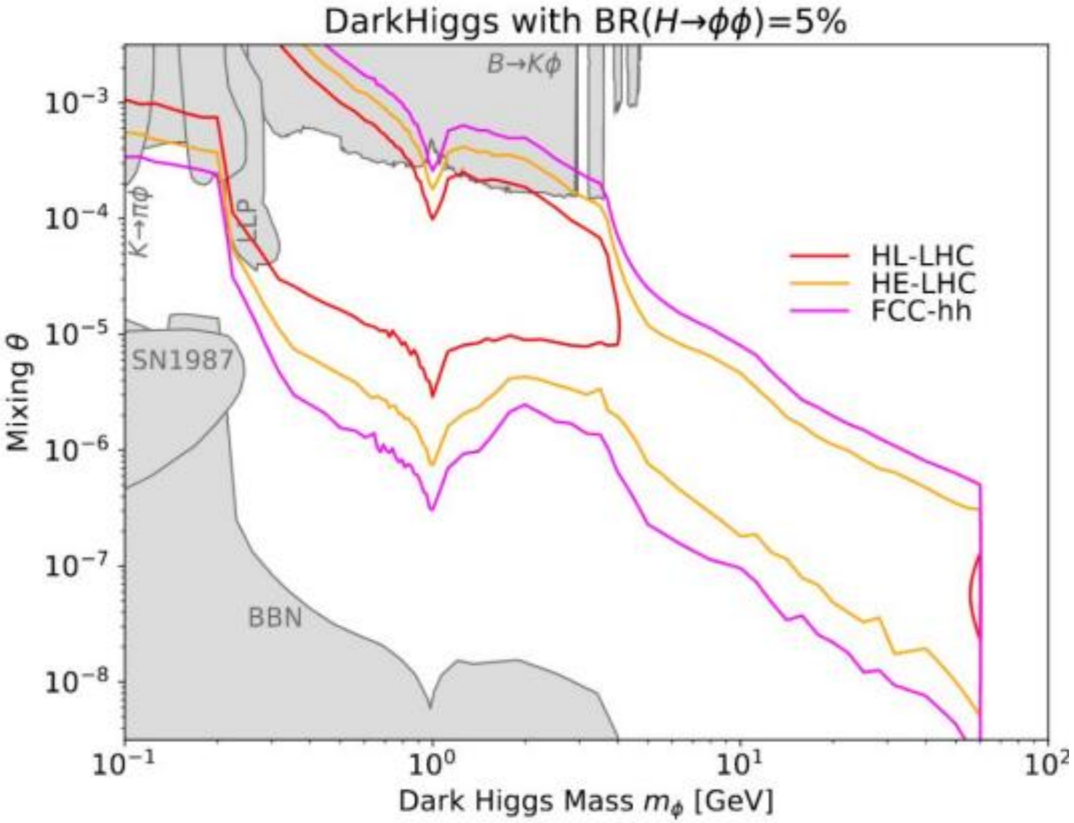
How about future colliders?

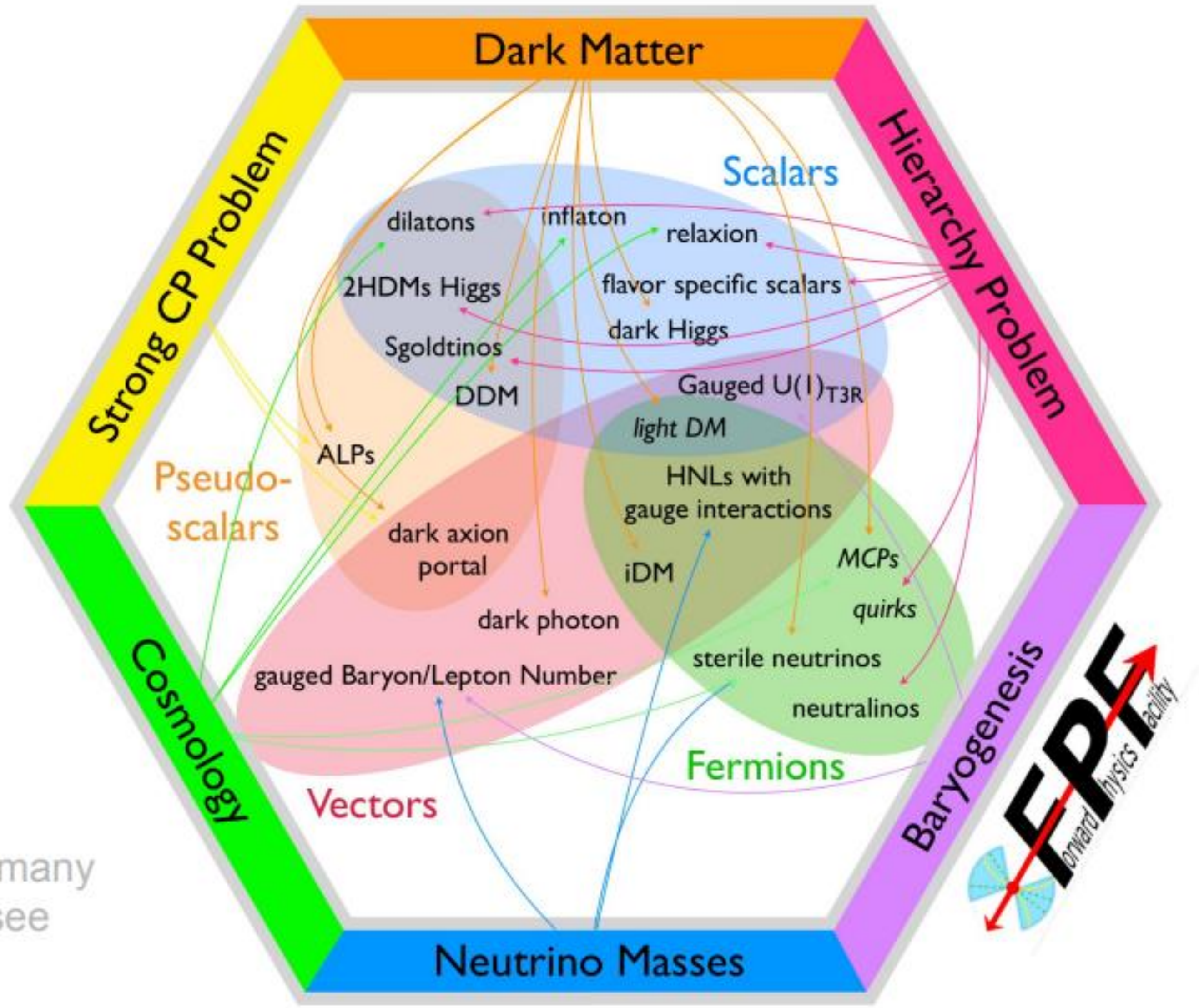
Really depends on the model and production mode.





F. Kling

BSM Physics Searches at the FPF.



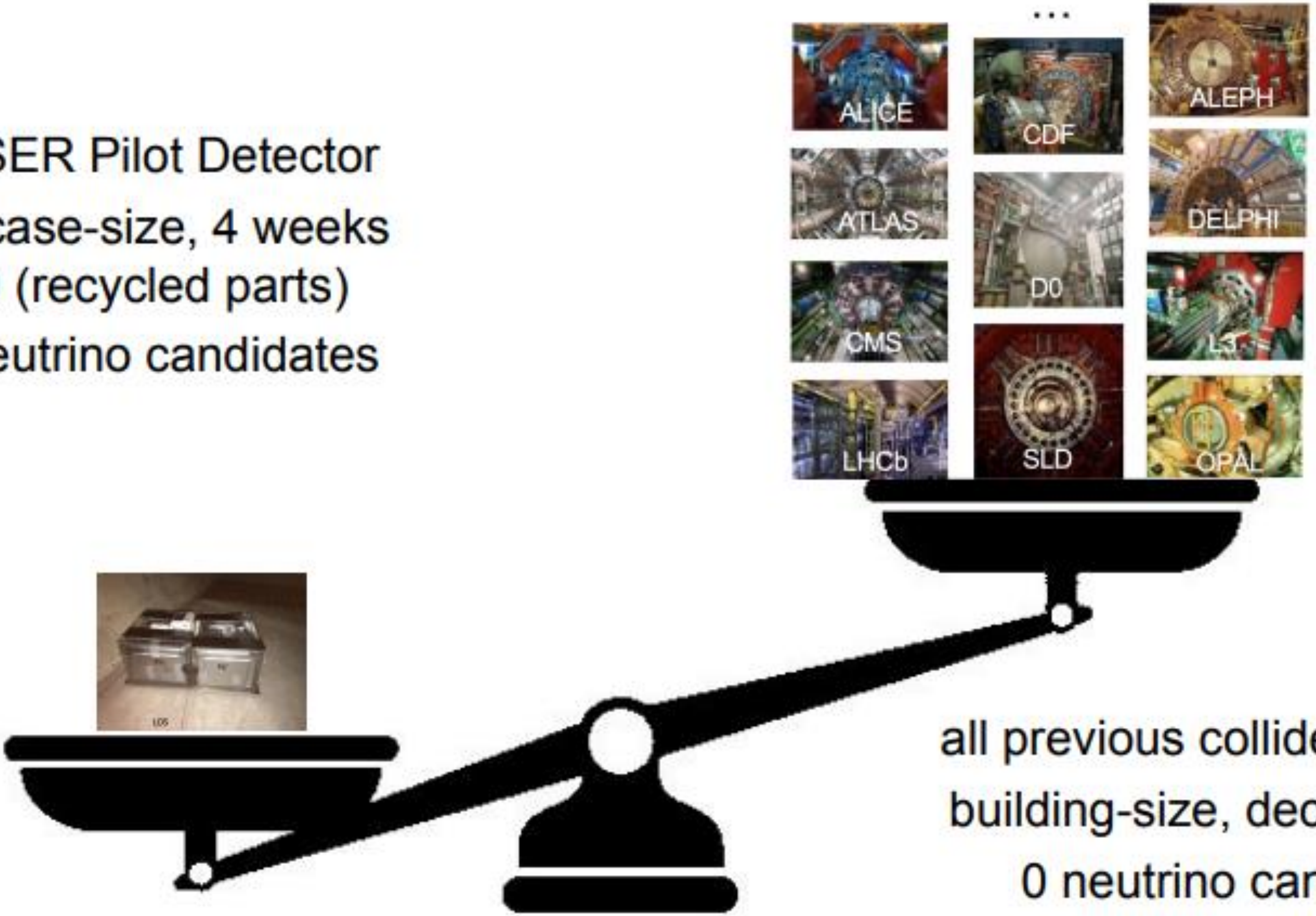
For details on many more models see 2203.05090.

F. Kling

FASER Pilot Detector

suitcase-size, 4 weeks
$0 (recycled parts)

6 neutrino candidates



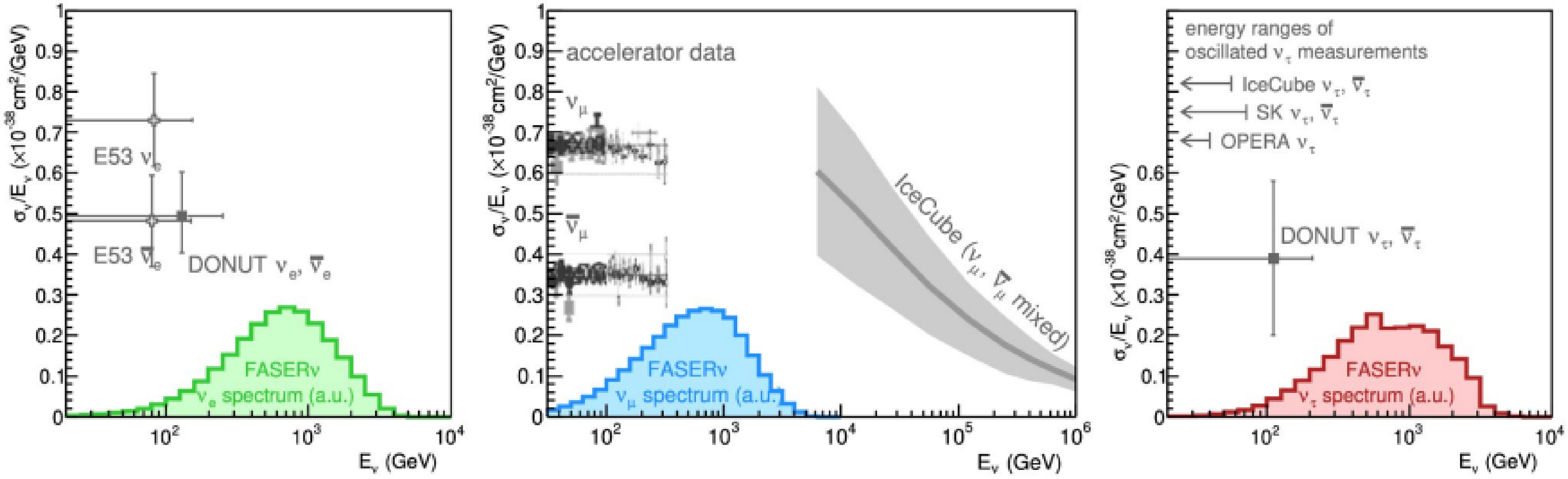
all previous collider detectors

building-size, decades ~$1B

0 neutrino candidates

F. Kling

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.



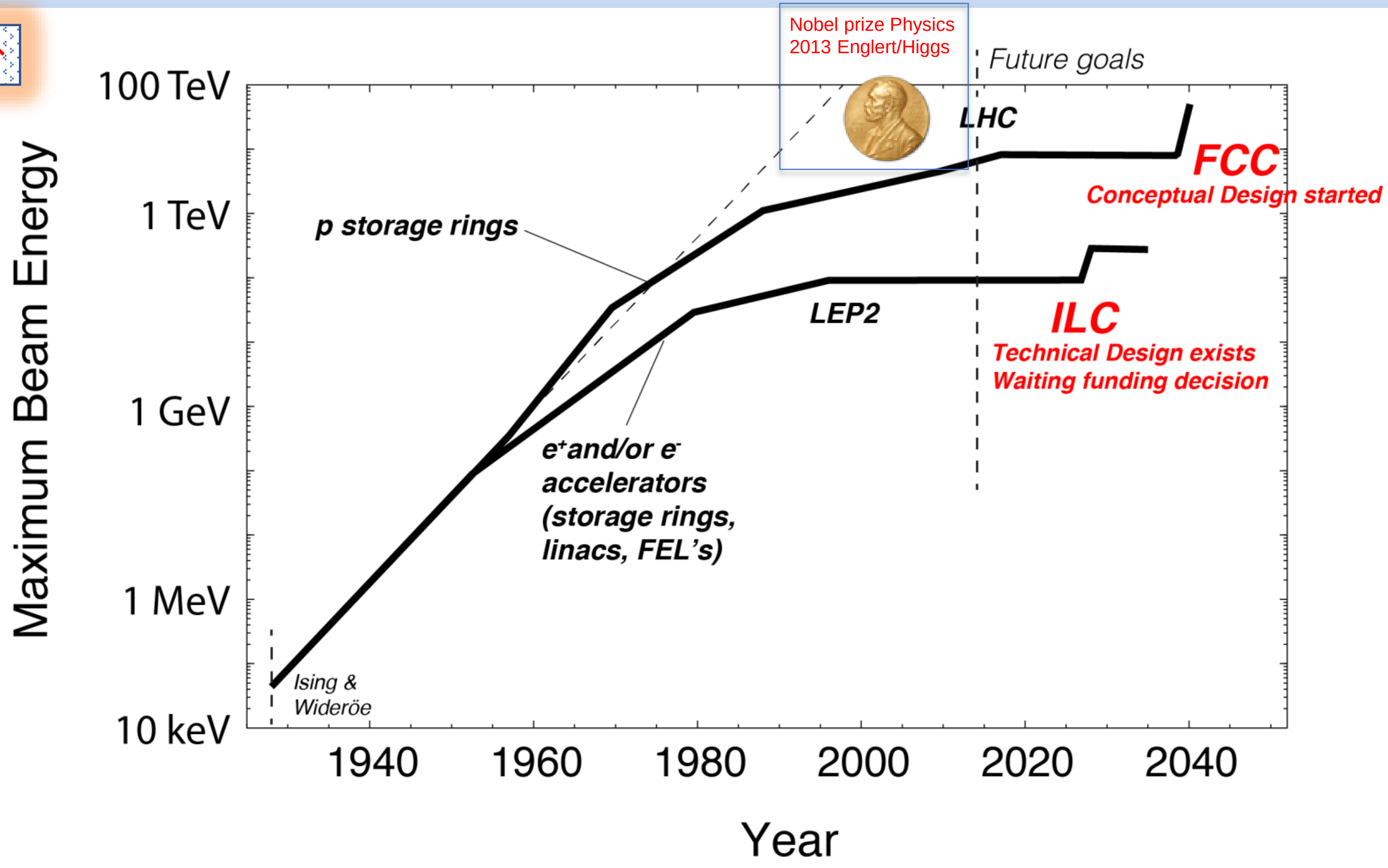
FASERv and SND@LHC will detect O(10k) neutrinos.

Proposed FPF experiment have potential to detect O(1M) neutrinos.

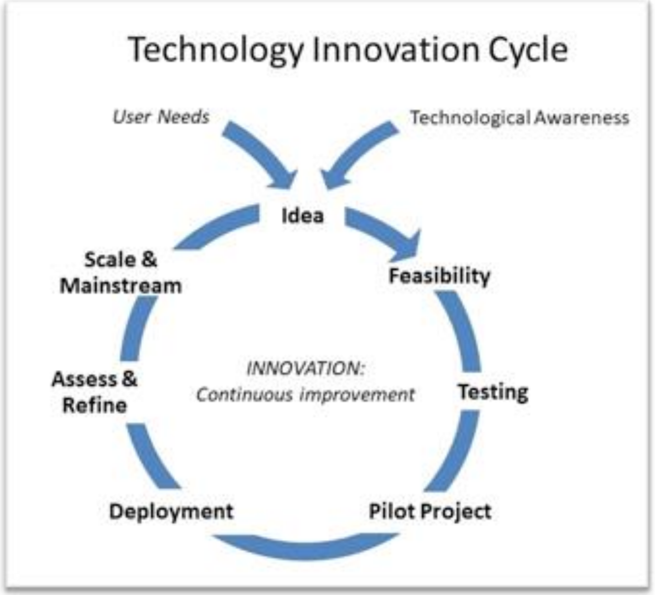
F. Kling

Livingston Curve: Success of RF Accelerators

Horizon 2020



Examples of **new ideas and solutions**: RF, AG focusing, beta squeeze, stochastic cooling, polarized beams, super-conducting magnets/RF, advanced materials for vacuum/collimators, plasma / laser accelerators, …



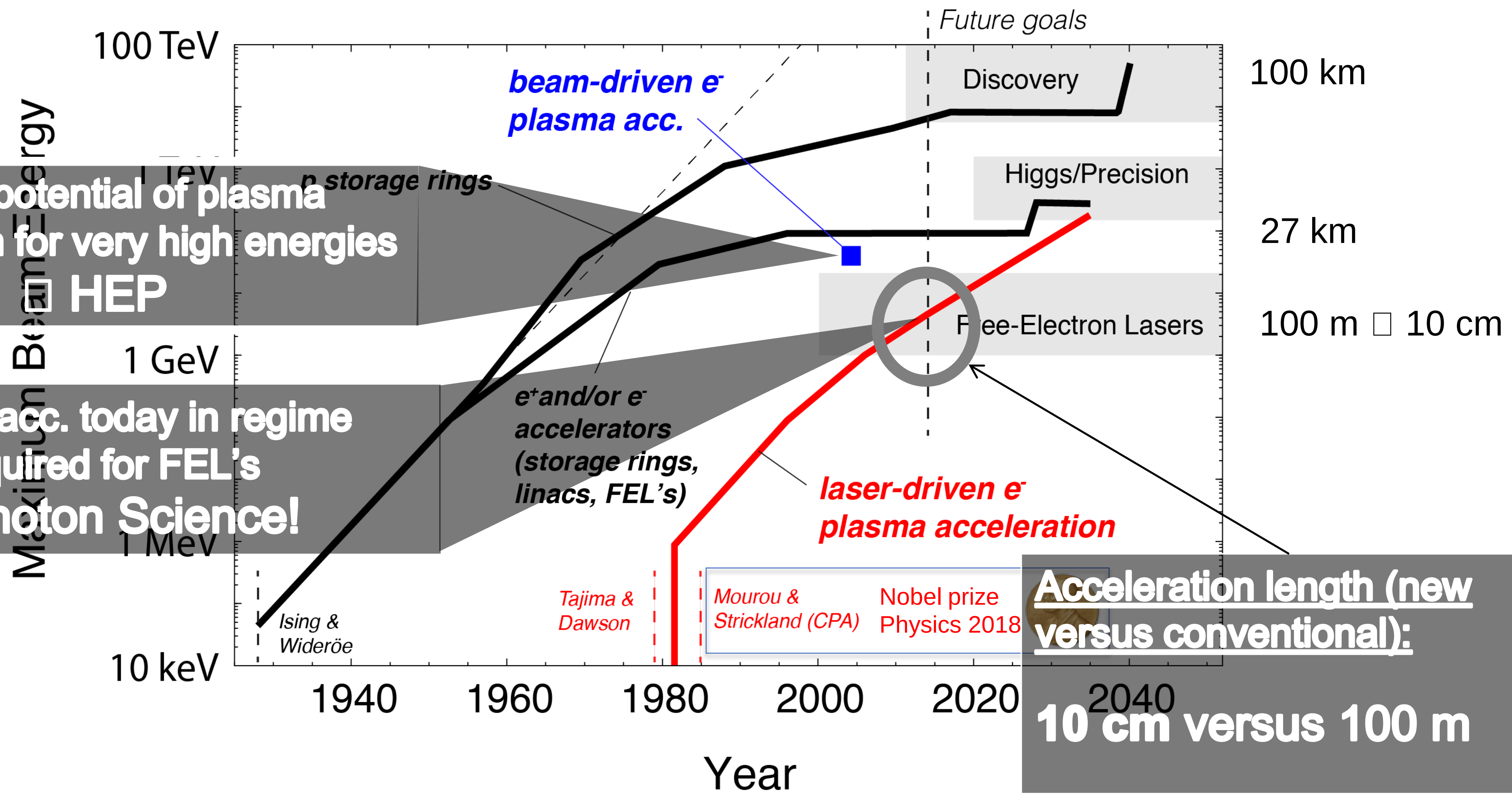
A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

Master-pieces of technology: LHC, LHC HiLumi, SuperKEKb, DAFNE, LEP, LEP-2, Tevatron, HERA, RHIC, SLC, Eu-XFEL, SwissFEL, SACLA, ESRF-EBS, …

R. Assmann

The Plasma Accelerator Opportunity

Horizon 2020



Shows potential of plasma acceleration for very high energies □ HEP

Plasma acc. today in regime required for FEL's □ Photon Science!

Acceleration length (new versus conventional):

10 cm versus 100 m

R. Assmann

Timely to Build Something Useful

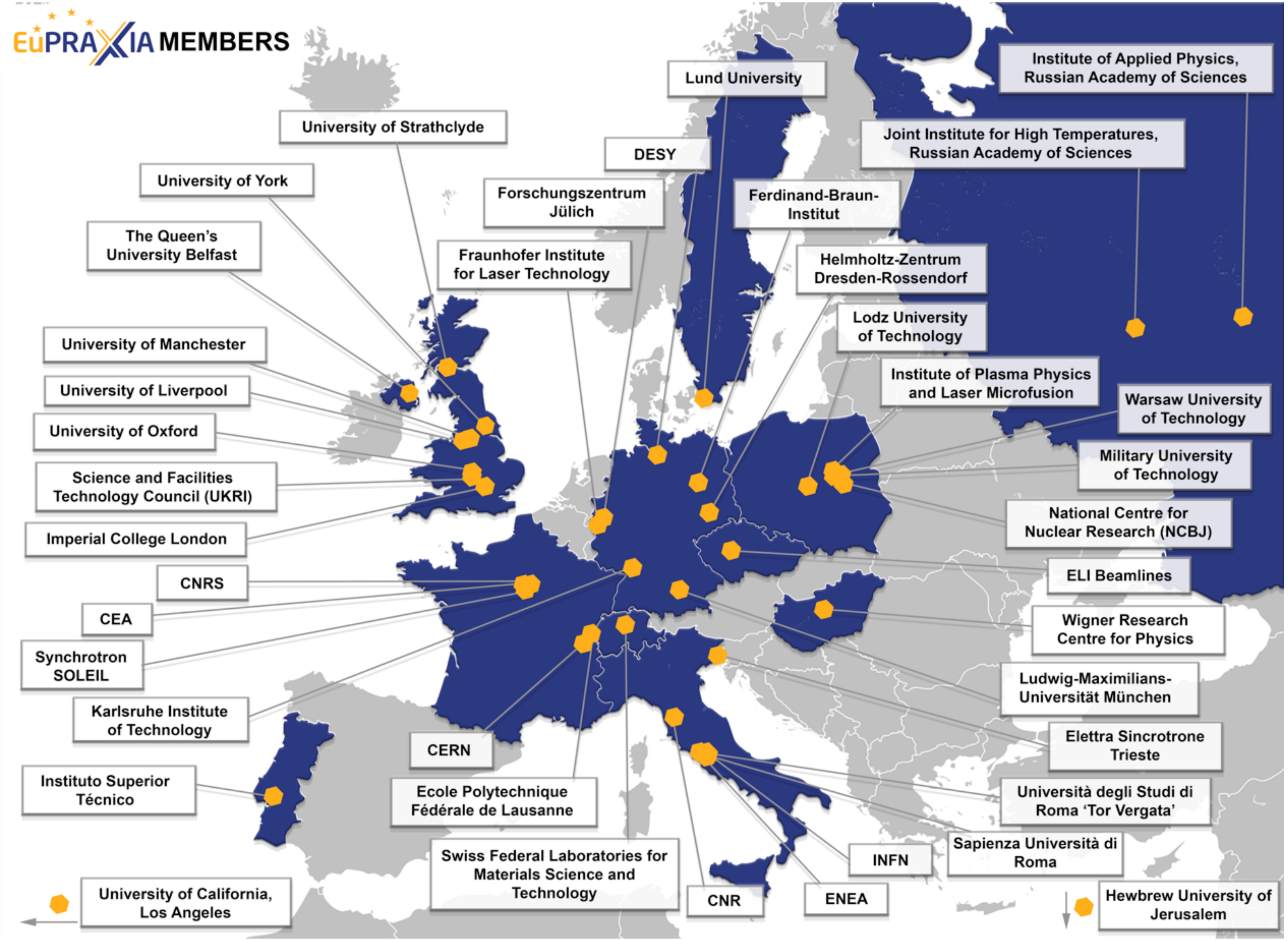
- Particle accelerators are a fascinating research topic but define their **purpose through producing usable beams** for important research or applications.
- **RF based particle accelerators serve about 70,000 users** in science, enabling discoveries, advances in human knowledge.
- Plasma particle accelerators have made **great progress** but have not served in a user facility so far.
- “Emerging since 40 years”: timely to **demonstrate first user applications before end of 2020`s** (within 50 years of idea).
- Basic R&D can continue in parallel but we should focus on usable beam.

R. Assmann

Consortium

(from 16 to 40 members in new Dec 2020 consortium)

Horizon 2020



40 Member institutions in:

- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, Forschungszentrum Jülich, HZDR, KIT, LMU München)
- **United Kingdom** (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- **Poland** (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
- **Portugal** (IST)
- **Hungary** (Wigner Research Centre for Physics)
- **Sweden** (Lund University)
- **Israel** (Hebrew University of Jerusalem)
- **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- **United States** (UCLA)
- **CERN**
- **ELI Beamlines**

plus Spain & Greece

R. Assmann

ESFRI Projects Roadmap 2021

https://roadmap2021.esfri.eu

PAG 18

ESFRI PROJECTS

PHYSICAL SCIENCES & ENGINEERING

NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
EST	European Solar Telescope	single-sited		2016	2029*	200.0	12.0
ET	Einstein Telescope	single-sited		2021	2035*	1,912.0	37.0
EuPRAXIA	European Plasma Research Accelerator with Excellence in Applications	distributed		2021	2028*	569.0	30.0
KM3NeT 2.0	KM3 Neutrino Telescope 2.0	distributed		2016	2020	196.0	3.0

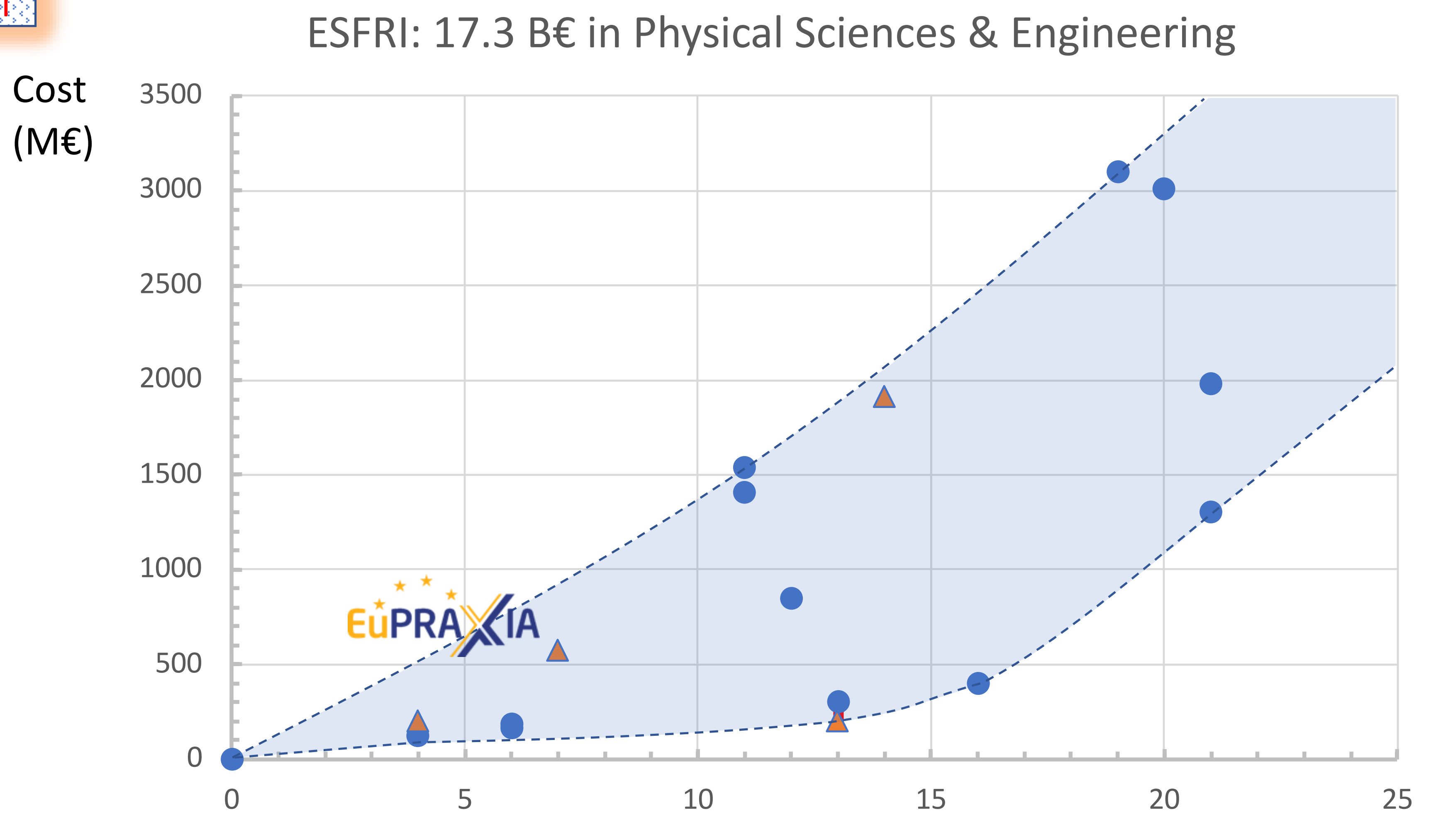
- Two new entries in 2021: **Einstein Telescope (ET)** and **EuPRAXIA**
- EuPRAXIA is the only accelerator facility selected in the last 5 years
- EuPRAXIA is the first plasma accelerator facility ever included

PHYSICAL SCIENCES & ENGINEERING

R. Assmann

ESFRI Roadmap 2021
(Physical Sciences & Engineering – Projects Red Triangles)

Horizon 2020



Average project duration: *12.4 years*
Average project cost: *1.08 B€*

Area	Figures
Accelerator Facilities	• 10.1 B€ invest • 730 M€ OP / year
Telescopes	• 6.0 B€ invest • 197 M€ OP / year
Laser Facilities (ELI)	• 0.85 B€ invest • 80 M€ OP / year
Reactor neutrons (ILL)	• 0.19 B€ invest • 100 M€ OP / year
Magnet lab (EMFL)	• 0.17 B€ invest • 20 M€ OP / year

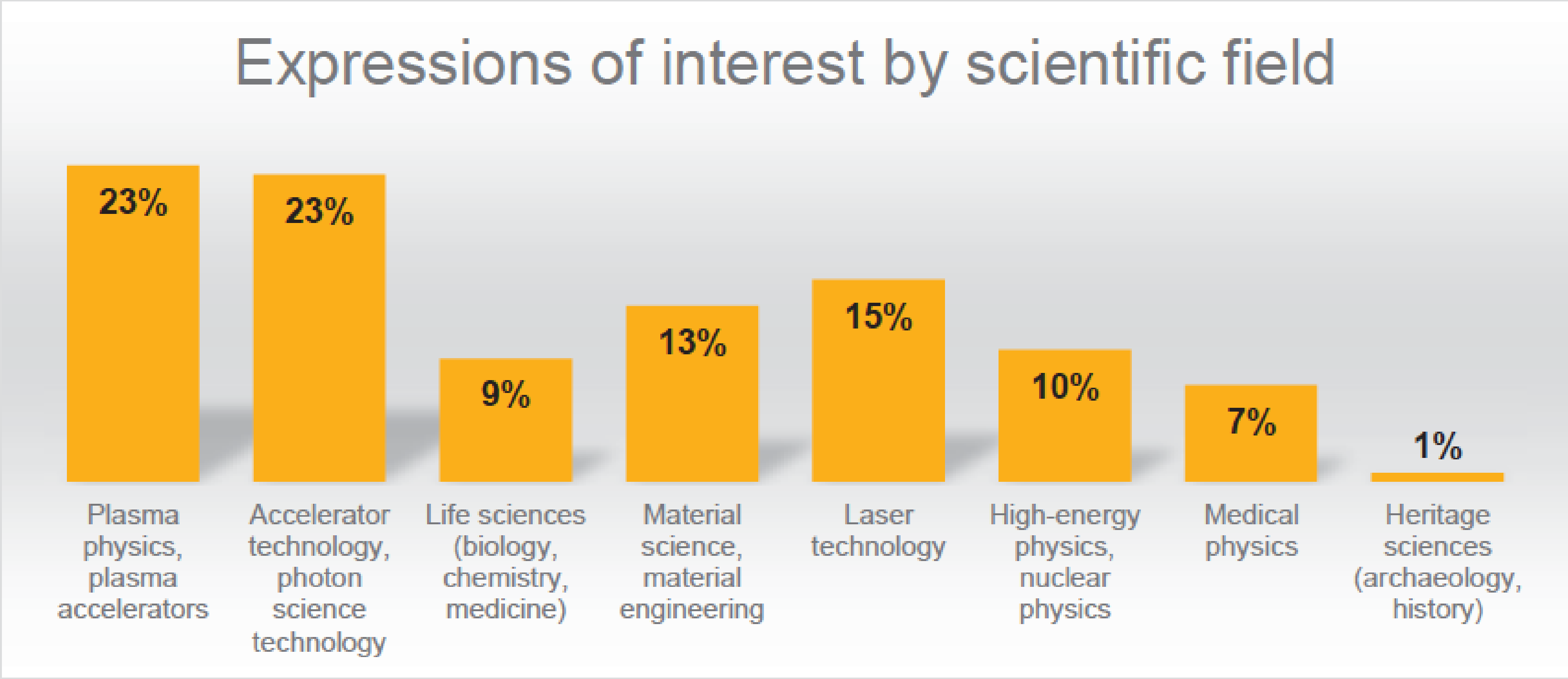
R. Assmann

EuPRAXIA Deliverables and User Interests

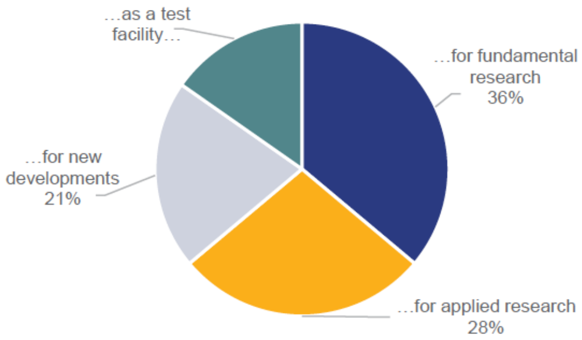
Horizon 2020

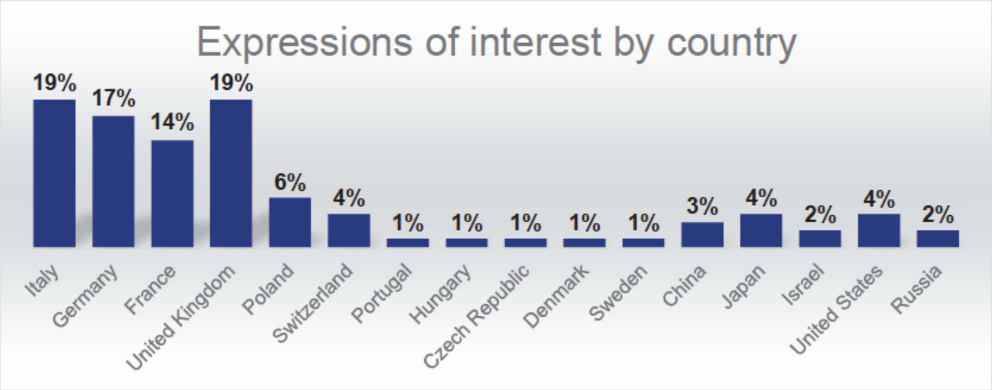
EuPRAXIA is designed to deliver at 10-100 Hz ultra-short pulses of

- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10^{10})
- FEL light (0.2-36 nm, 10^9-10^{13})



Expressions of interest from **95 research groups** representing several thousand scientists in total.

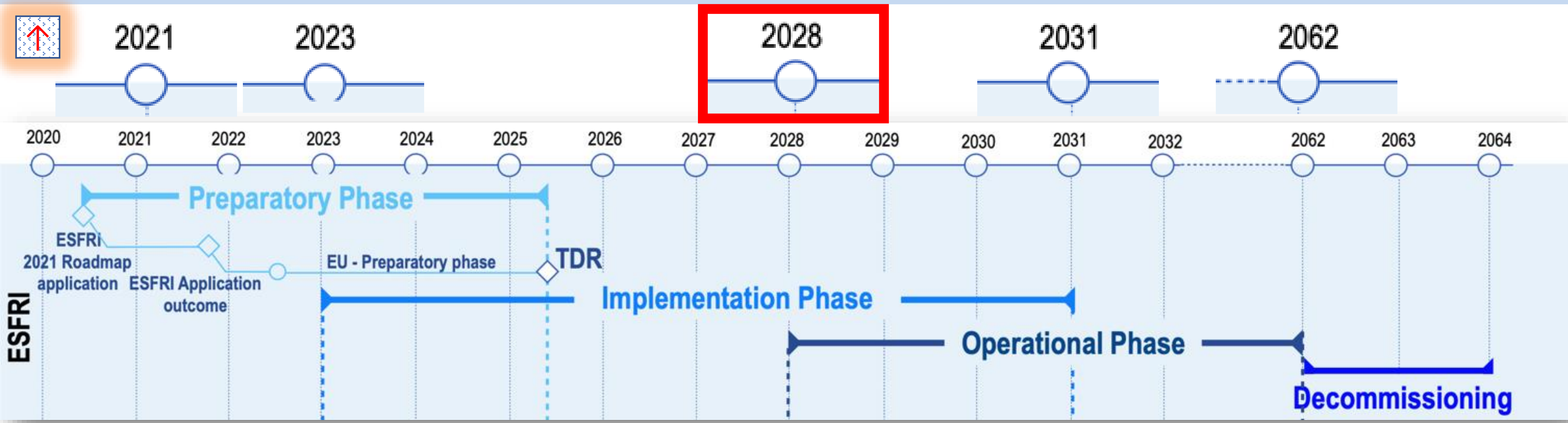




R. Assmann

EuPRAXIA Schedule

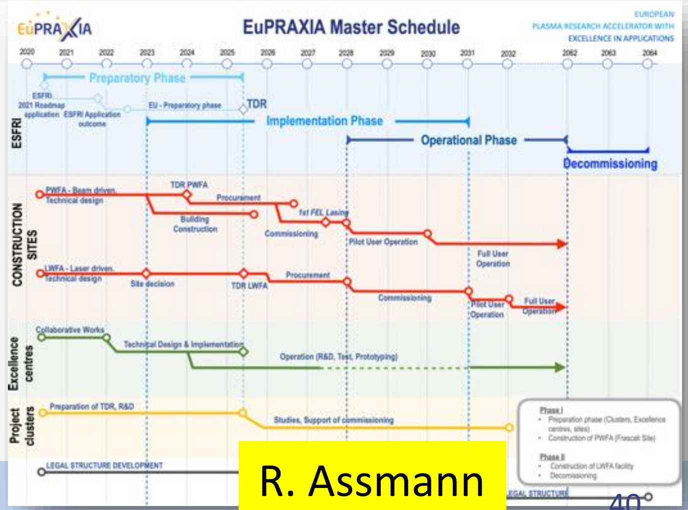
Horizon 2020



SUCCESS – ON TRACK

European World-Class RI on compact accelerators for the end of the 2020's to the beginning of the 2060's

More detail in Master Schedule



R. Assmann

Can we shrink the Linear Collider?

Horizon 2020

Provide e- and e+ beams in the TeV energy regime and produce > 10^{34} cm^{-2} s^{-1} luminosity

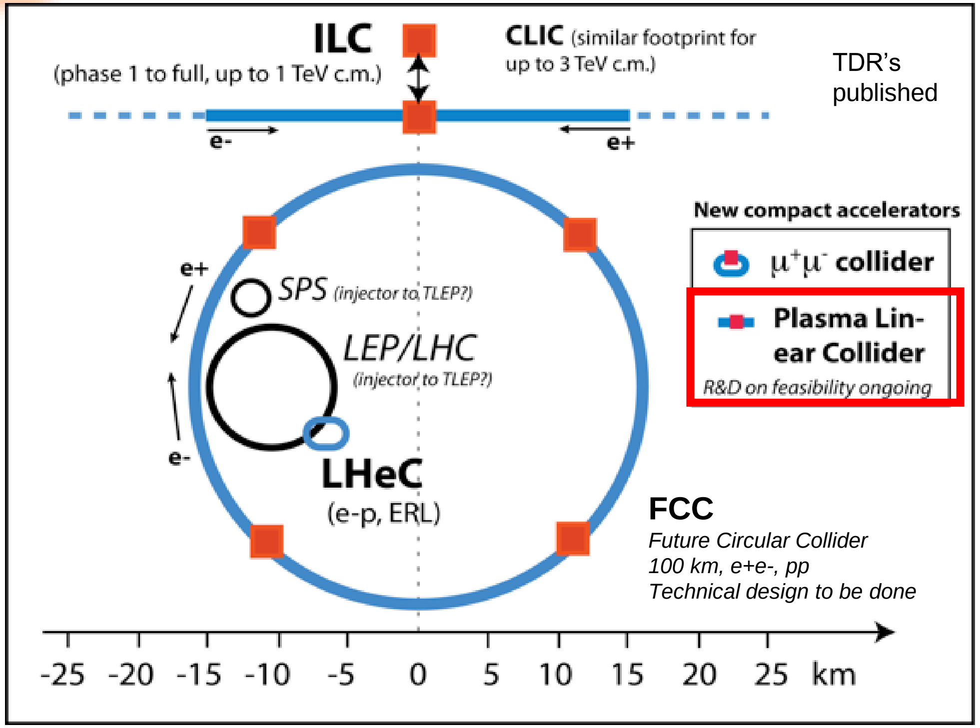


Table 1.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers [88]. Case 2 (LWFA) is a plasma-based scheme based on laser drivers [89]. Case 3 (DLA) is a dielectric-based scheme [34].

Parameter	Unit	PWFA	LWFA	DLA
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	10^{34}cm^{-2}s^{-1}	1.1	1.0	1.9

from expert panel report

- **No fundamental show-stopper but a lot of R&D still required.**
- There can be very interesting and useful interim steps (non-linear QED, fixed target, dark matter, …)
- **Devil is in the details!** Answer requires detailed simulation, calculations, R&D, designs and tests!
- How and when can we arrive at readiness for for high energy particle physics, e.g. a TeV collider?

R. Assmann

Can we shrink the Linear Collider?

Provide e- and e+ beams in the TeV energy regime and produce > 10^{34} cm^{-2} s^{-1} luminosity

Parameter	Unit	PWFA	LWFA	DLA
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
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Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		>10	
Luminosity regime (simple scaled calculation)	$10^{34}cm^{-2}s^{-1}$	1.1	1.0	1.9

from expert panel report

R. Assmann

Possible Beam Parameters Spreadsheet I

Horizon 2020

	Reference	Yellow report CERN - 2018 - 010 - M (2018)	SLAC-PUB-15426 arXiv:1308.1145 (2013)	Phys. Rev. ST Accel. Beams 13, 101301 – (2010)	Rev. Mod. Phys. 86, 4 (2014)	Eur. Phys. J. Special Topics 229, 3675-4284 (2020)	
		CLIC X band RF design *self-consistent, simulated design, TDR*	**Plasma SRF beam-driven (PWFA)** *collider concepts, not simulated, next: pre-CDR*	**Plasma laser-driven (LWFA)** *collider concepts, not simulated, next: pre-CDR*	**Dielectric collider** *collider concepts, not simulated, next: pre-CDR*	**EuPRAXIA 5 GeV plasma beam driven** (ultim.), simulated CDR design	**EuPRAXIA 5 GeV plasma laser driven** (ultim.) simulated CDR design
IP electron rate [C/s]		1,47E-05	2,40E-05	9,60E-06	1,53E-05	2,00E-09	3,00E-09
high quality beam	Bunch charge [nC]	**0,83**	**1,60**	**0,64**	**4,80E-06**	**0,04**	**0,03**
see emittance below	Number of bunches	352	1	1	**159**	1	1
	Repetition rate [Hz]	50	**15000**	**15000**	**2,00E+07**	50	**100**
Beam power [kW] as function of beam energy E ($=E_{cm}/2$)							
E [eV]	5,00E+09	73	120	48	76	0,01	0,02
E [eV]	1,90E+11	2786	4560	1824	2900	n/a	n/a
E [eV]	1,00E+12	14661	24000	9600	15264	n/a	n/a
E [eV]	2,00E+12	29322	48000	19200	30528	n/a	n/a
Efficiency energy conversion			*(incl cryo)*				
	Wall plug to driver	58,00%	20,00%	**30,00%**	**40,00%**	58,00%	0,01%
	Driver to beam	22,00%	**40,00%**	**20,00%**	**30,00%**	5,00%	10,00%
	Wall plug to beam	12,76%	8,00%	6,00%	12,00%	2,90%	0,00%

Column 1: *CLIC reference design*
Columns 2-4: *Advanced collider sketches*
Column 5-6: *EuPRAXIA conceptual design*

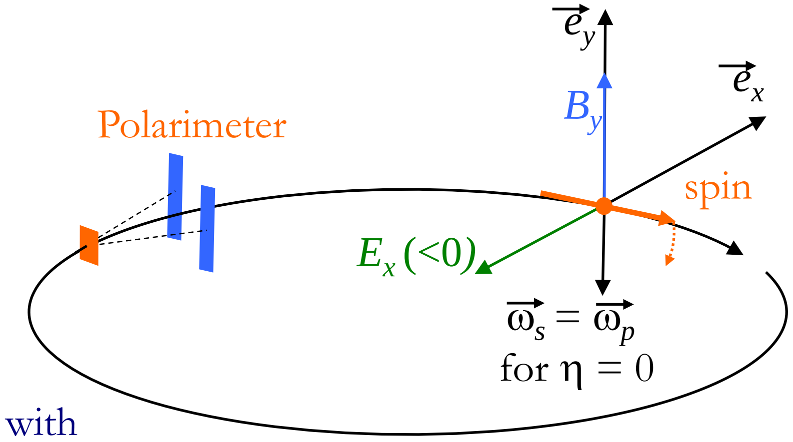
In next 8 years:

- Up to **3e9 C/s** high quality beam at up to 5 GeV?
- Designed with European laser industry, RF labs
- Tradeoff with quality: can imagine factor 10 more rate with lower quality, not much more

R. Assmann

Recap of standard fully electric charged particle Electric Dipole Moment (cpEDM) ring

- "Frozen spin" concept (for MDM, neglecting EDM)
  - Initial longitudinal polarization is maintained
- "Magic energy" – ideal case
  - "Frozen spin" with radial electric field only choosing rel. factors $\gamma = \gamma_m = \sqrt{1+1/G}$ and $\beta = \beta_m = 1/\sqrt{1+G}$ with $G = (g-2)/2 = 1.728...$ describing the proton EDM (average) fields $\bar{E}_x = -\frac{m\gamma_m \beta_m^2 c^2}{eC/(2\pi)} = -5.27\ \mathrm{MeV/m}$ and $B_y = 0$ with m and e the proton mass and charge and $C = 500\ \mathrm{m}$ the circumf.



Sketch of a CP-EDM Ring

- Imperfect machine with average radial magnetic field $\bar{B}_x \neq 0$ Gravity neglected
  - Vertical electric field $\bar{E}_y = -\beta_m c \bar{B}_x$ from quadrupoles compensates resulting vertical deflection
- Rotation of spin vector $\vec{S}$ in machine with additional radial magnetic field
  - Described by Thomas-BMT equation (NO subtraction of angular frequency for rotation of direction)

$$\frac{d\vec{S}}{dt} = \vec{\omega}_s \times \vec{S} \qquad \vec{\omega}_s = -\frac{e}{m}\left[\left(G+\frac{1}{\gamma}\right)\vec{B}_\perp + (G+1)\frac{\vec{B}_\parallel}{\gamma} - \left(G+\frac{1}{\gamma+1}\right)\vec{\beta}\times\frac{\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}_\perp}{c} + \frac{1}{\gamma}\frac{\vec{E}_\parallel}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

For "magic energy" keep only E_x

  - Gives

$$\bar{\vec{\omega}}_s = \left(-\frac{e}{m}\left(\frac{G+1}{\gamma_m^2}\right)\bar{B}_x + \frac{\eta\gamma_m\beta_m^2 c}{C/\pi}\right)\vec{e}_x + \vec{\omega}_p \quad \text{with} \quad \bar{\vec{\omega}}_p = -\frac{\beta_m c}{C/(2\pi)}$$

describing the rotation of the direction

  - $\eta = 1.9\times10^{-15}$ corresponding to an EDM of $d = 10^{-29}\ e\times\mathrm{cm}$ or $\bar{B}_x = -9.3\ \mathrm{aT}$ give both $\bar{\omega}_x = 1.6\ \mathrm{nrad/s}$

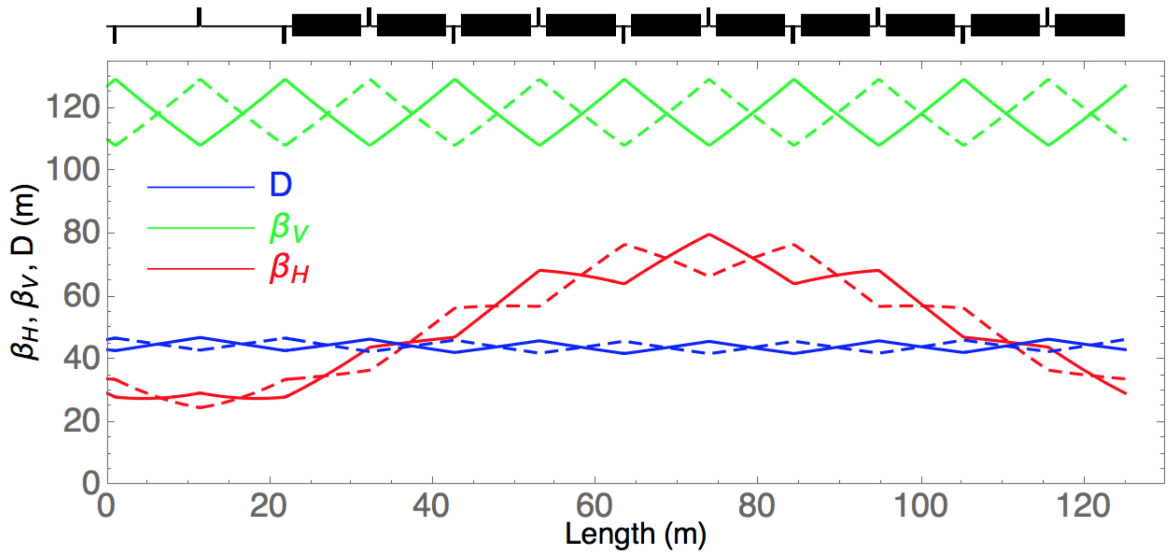
C. Carli

Hybrid Ring Concept - Proposal

Hybrid ring proposed by S. Haciomeroglu and Y.K. Semertzidis (see PRAB 22, 034001 (2019) and arXiv:1806.09319)

- Ring operated at "magic energy" with electro-static bends without gradient (field index $m = 0$)
  - Geometry taken from strong focusing "magic energy" electric ring
  - Quadrupoles magnetic with strength $d B_y / dx = \pm 0.1$ T/m and $k = \pm 0.0428\ \mathrm{m}^{-2}$ (length $l_Q = 0.4$ m)
    - Operation with two counter-rotating beams
    - Thus, quadrupole polarity opposite for CW and CCW beam
  - Working point $Q_H = 1.754$, $Q_V = 0.673$ almost identical for two beams
  - Significant variations of horizontal betatron functions with periodicity four and larger dispersion
    - Impact on IBS to be evaluated
  - Tuning of machine for both beams more delicate
    - Closed orbit
    - Working point
    - Chromaticity and 2nd order dispersion for spin coherence

- Note some analogies with, e.g., "doubly magic" proposal (superposition of electric and magnetic fields)



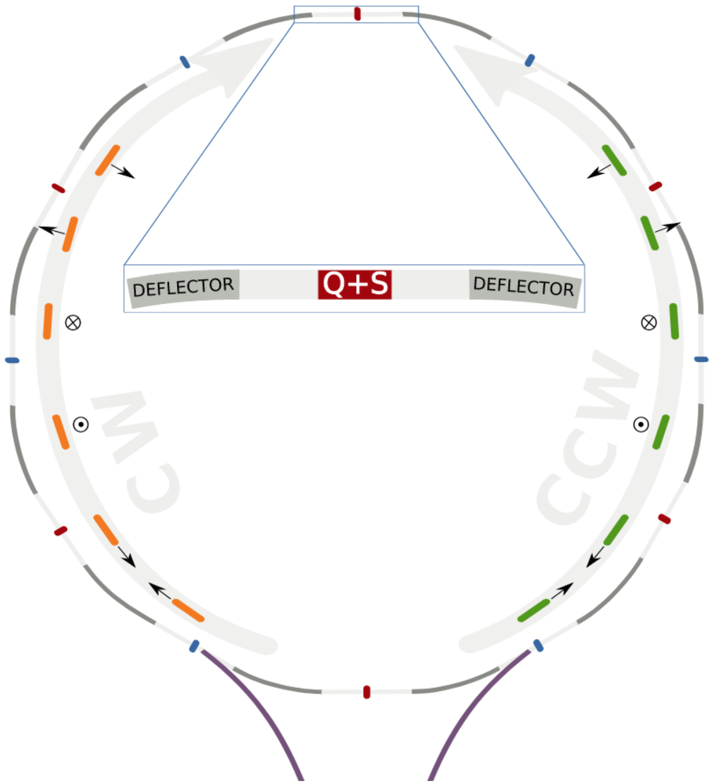
Twiss parameters for one out of four periods for the CW (solid lines) and the CCW (dashed lines) beam

C. Carli

Hybrid Ring Concept –
Recent proposal for high periodicity lattice

- "Symmetric-Hybrid" ring
  - Each quadrupole is symmetry point
  - "Vertical velocity effect" due to vertical quadrupole misalignments disappear
    - Vertical velocity effect is transfer of radial spin component into vertical direction
    - Proportional to average slope inside bending elements
    - (Kind of) rotation around longitudinal axis
    - Misaligned quadrupole at symmetry point gives vanishing average slope and effect
  - Beam based methods for mitigation of systematic effects
    - Intentional quad movement to
  - Many other possible effects not (yet) studied (see list below with some possible effects)

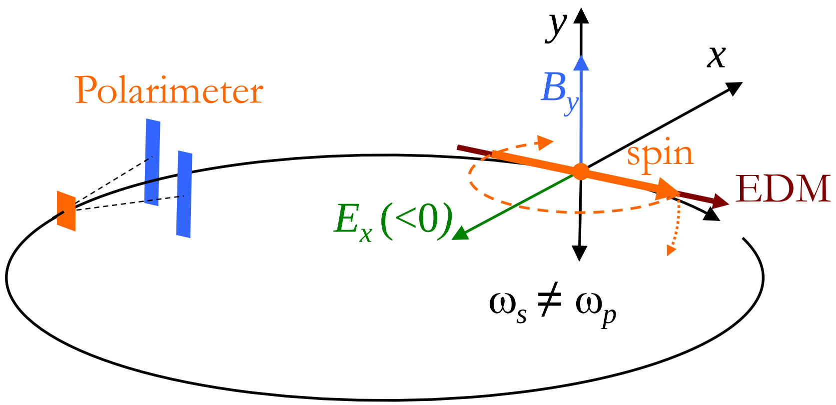
Z. Omarov et al., Comprehensive symmetric-hybrid ring design for a proton EDM experiment at below 10^{-29} e.cm, Phys. Rev. D 105, 032001 (2022)



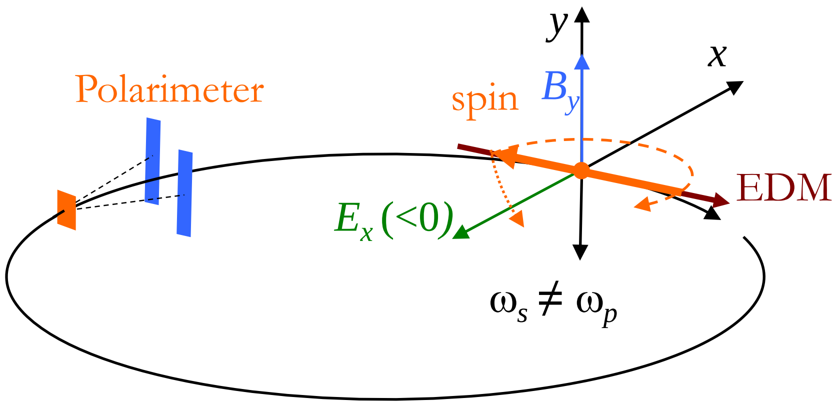
Schematic of the Symmetric-Hybrid ring

C. Carli

Search for oscillating EDMs –
Signature of coupling from axions



Initial situation
Spin and EDM parallel



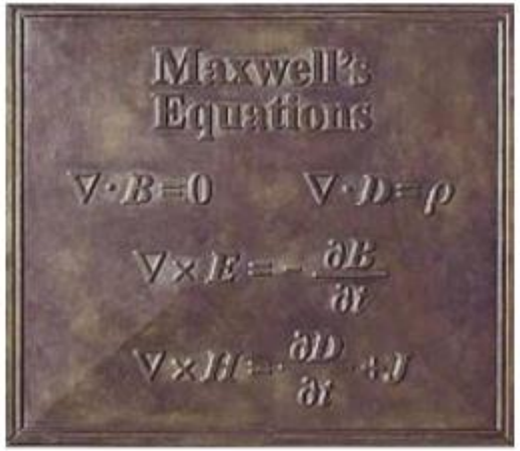
Half an oscillation period later
Spin and EDM antiparallel

- Spin rotation w.r.t. particle direction with frequency equal to EDM oscillation
  - Oscillating EDM means that ratio between EDM and spin oscillates $\eta = \eta_0 + \hat{\eta}\sin\left(\omega_{axion} t + \varphi_0\right)$
    - Frequency range and stability?
    - Resonance condition $\left|\omega_s - \omega_p\right| = \omega_{axion}$!
    - Long-term build up of vertical spin component
  - Many systematic effects strongly mitigated!
  - Severely limited by statistics (need for runs with different possible spin oscillation frequencies)?
    - Say frequencies fixed over one 1000 s store
    - Build-up of vertical polarization over full duration for below 1 mHz frequency range!

C. Carli

Leitmotif:

The tools driven revolution is the next logical step



"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson

W. Krasny

The general physics questions (those that can be formulated outside the present modelling paradigms)

1. *Are there undiscovered principles of nature (new physical laws)?*
2. *Why the Universe obeys Quantum laws?*
3. *Is it a deep principle … or a temporary fix?*
3. *What is the deep reason for the successes of gauge theories?*
4. *How the fact that we exists biases our laws of nature (physics beyond the fine-tuned anthropic excuse)?*
5. *In particular, why should a human-unbiased physics mechanism predict the cosmological constant and dark matter abundance in the bizarre anthropic range?*
6. *Is there a place for organized structures in the early evolution of the Universe, can we discover their fossils 10^9 years later ?*
7. *What is the mechanism producing confined energy grains (elementary particles)(or, in the present day language, their coupling strengths to the Higgs field)?*

W. Krasny

The urgent societal questions (their importance are amplified by the Russian aggression of Ukraine)

1. *Can we invent, design, and operate particle-beam-driven clean energy sources?*

2. *Can we produce rather than buy the plug-power necessary for the next generation of high-energy, high-current new accelerators locally, in situ, in our HEP research centers?*

W. Krasny

Facts 2022

3. New, unorthodox research ideas and methods are becoming more and more difficult to pursue within the "community-voice-driven" large collaborations and research centres ("scientific populism?")

W. Krasny

- **Prevailing paradigm: dedicated searches**

The form of the Lagrangian of an extension of the standard model (e.g. SUSY), implemented in the form of event generator determines the search method (very often a machine learning process to optimizing/reducing the search phase-space).

- **Less popular: Generic searches**

(1) Emphasis on scrutinizing the Standard Model processes in the full phase-space accessible.
(2) Search for new phenomena unbounded by the perturbative-field-theory paradigms.
(3) Emphasis on specially designed experimental tools and methods to establish the physics origin of new phenomena in the model-independent way.

(M.W.Krasny et al., H1-06/97-523 note)

W. Krasny

*1. Electron beam and 4π detector for the Electron-Ion Collider (EIC) – studies of the **QCD** in its full complexity at BNL*

W. Krasny

The merits of the cold isoscalar beams

1. ***The impact of the modelling uncertainties of partonic emittances*** *(longitudinal and transverse) on the achievable measurement precision can be drastically reduced* ***and controlled the LHC data alone*** *(no precision brick-walls coming from the LHC-external data, PDFs, and PS models). Significantly* ***higher systematic precision*** *in measuring the* ***EW parameters*** *by using* ***isoscalar ion beams*** *rather than proton beams (as in the earlier fixed target experiments).*

2. ***A Z^4 leap in photon fluxes*** *– access to* ***exclusive Higgs boson production in photon–photon collisions*** *– unreachable for the pp running mode.*

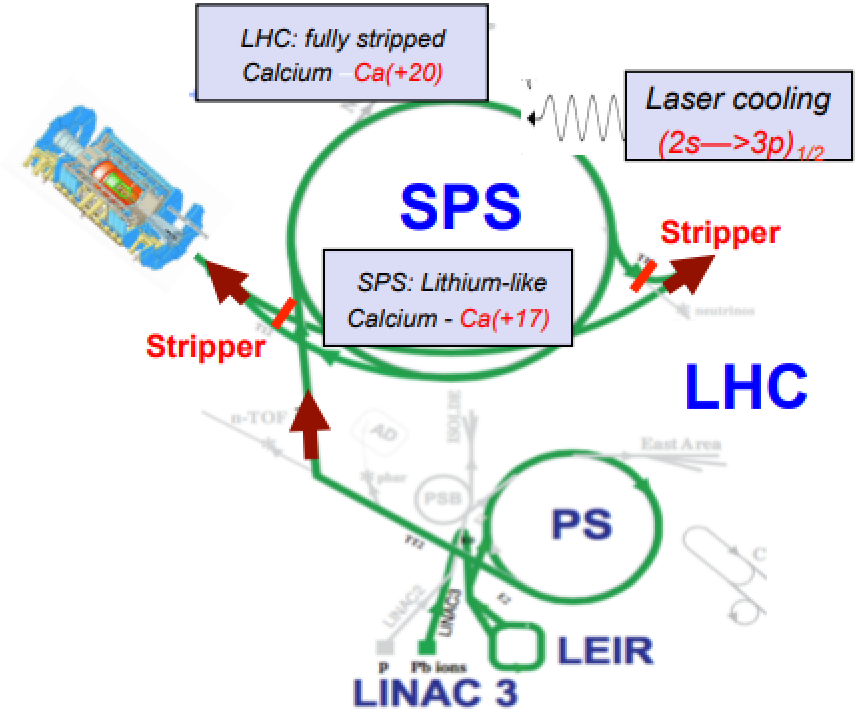
3. ***Lower pileup background*** *at the equivalent (high) nucleon-nucleon luminosity.*

4. ***New research opportunities*** *for the EW symmetry breaking sector.*

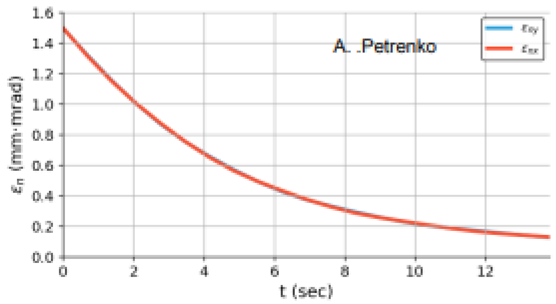
W. Krasny

Gamma Factory path to HL(AA)-LHC:

A concrete implementation scheme with Ca beams



Ion Source + Linac: *charge state after stripping:* Ca(+17)



Reduction of the transverse x,y, emittances by a factor of 5 can be achieved in 9 seconds – *sufficiently short to avoid the CA(+17) beam losses in the SPS.*

Optical stochastic cooling time for the Ca beam, if necessary, at the top energy – 1.5 hours (V. Lebedev)

Parameter	Value
$s^{1/2}$ [TeV]	7
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5 x 10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6
N_b	3 x 10^9
$\varepsilon_{(x,y)n}$ [μm] (1)	**0.3**
IBS [h]	1–2
β^* [m]	0.15
L_{NN} [$cm^{-2}s^{-1}$]	**4.2 x 10^{34}**
Nb of bunches	1404
Collisions/beam crossing	**5.5**

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7. Beams for the accelerator driven energy sources with nuclear waste transmutation capacities

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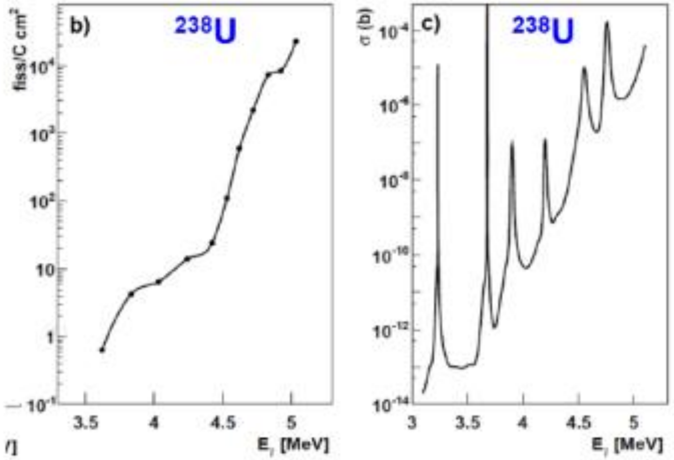
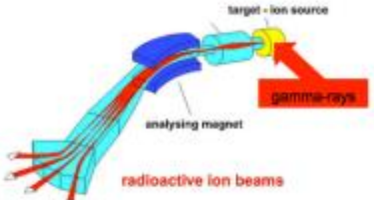
Example 3:

New type of accelerator driven energy sources driven by the Gamma Factory photon beams (including transmutation of nuclear waste!)

Nuclear fission

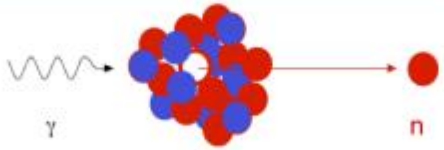


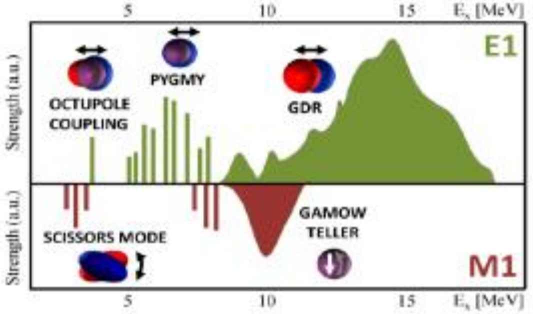


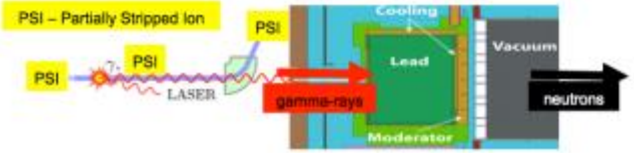
Achievable photo-fission rate :

Number of photo-fissions ~10^{14} 1/s

Resonant neutron production







Achievable production rate of primary neutrons:

neutrons ~10^{15} 1/s

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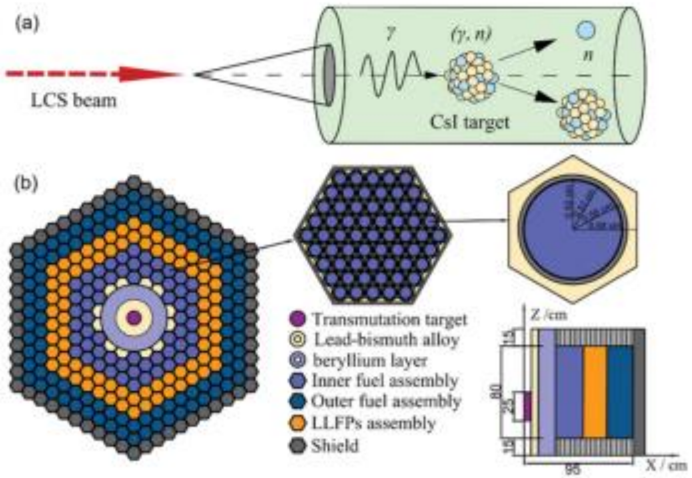
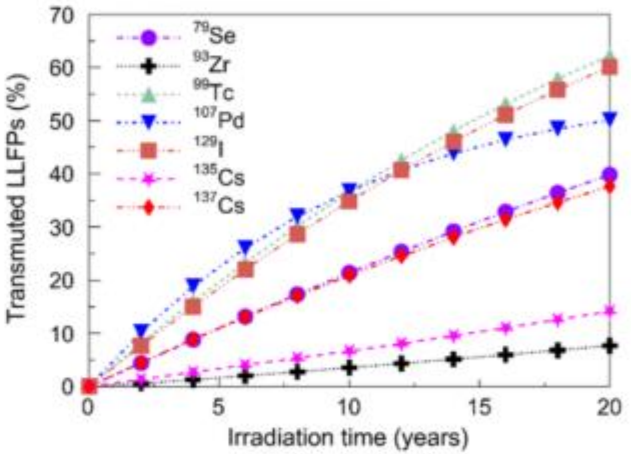
Example

New type of accelerator driven energy sources driven by the Gamma Factory photon beams (including transmutation of nuclear waste!)





Physical quantity	Value
Effective multiplication factor (k_{eff})	0.979
Reactivity (ρ)	−0.019
Effective multiplication factor for prompt neutrons (k_p)	0.977
Eigenvalue (α)	−0.003
Effective delayed neutron fraction (β_{eff})	0.007
Neutron generation time (Λ) (μs)	0.523
Neutron worth of PNS (φ)	1.319
Sub-critical effective multiplication factor (k_s)	0.984

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Energy footprint of the Gamma Factory beams : Comparison of the DESY-XFEL and the CERN GF photon sources

DESY-XFEL

- Wall-pug power – 19 MW
- Driver beam power consumption – 600 kW
- Photon beam power 600 W
- **beam power efficiency ~ 0.1 %**
- **overall plug-power consumption efficiency ~ 0.003 %**

  (thanks to Andrea Latina for these numbers)

CERN-GF

- wall-pug power – 200 MW (total CERN)
- wall-pug power – 125 MW (LHC)
- beam lifetime 10 h
- **driver beam power consumption = photon beam power**

  (power to ramp the beam to requite energy negligible)
- **beam power efficiency ~ 99 %**
- **overall energy spending efficiency ~1%**

  (for 2 MW GF photon beams)

CERN **GF photon source** energy footprint is expected to be smaller, by a factor of 300, than the **DESY-XFEL** photon source…

…for the fixed power of the produced photon beam

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tentative conclusions

Dark Sector Accelerators

- need to pursue tool-driven revolution in science
- EIC is on the way – will help unravel QCD mysteries
- SHIP, FPF, GF, and FCC-ee are promising for dark sector
  - decision on SHIP and FPF needed within a year
- distant forward detectors at all future high-energy colliders ?!
- we recommend studies of dark sector reach for DIMUS and for GF-μ source + plasma-based μ source & accelerator
- dielectric acceleration interesting approach for dark sector searches, DLA acc. design & experimental demonstration required
- EDM ring : in-depth studies including prototype ring recommended
- GF-driven subcritical reactor & waste transmutation -> autonomous (self-powered) accelerators
- next HEP collider ? – how complex can or should it be?

Machine Learning

- Machine Learning already widely contributes to exploitation of operating accelerator facilities – dozens of successful developments at CERN, DESY, FNAL, LANL, PSI and SLAC
- we expect that ML will become a standard
- ML should be used for design optimization of future machines
- ML should be standard topic in accelerator education
- ML could be instrumental for dark sector beam performance
- further work is needed on time-varying systems
- additional benefit or special applications for quantum computing?
- seek collaborations with ML experts from other sectors
- we recommend testbed for self-controlling complex accelerator
- how far can we go ?


thank you all for participating and coming to Valencia !!