



MU Topic Fundamental Particles and Forces

Outlook

Isabell Melzer-Pellmann

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

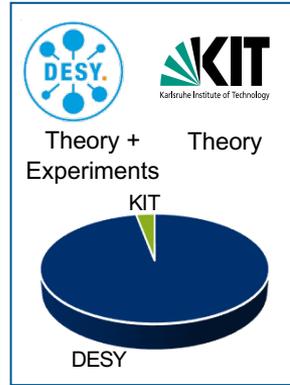
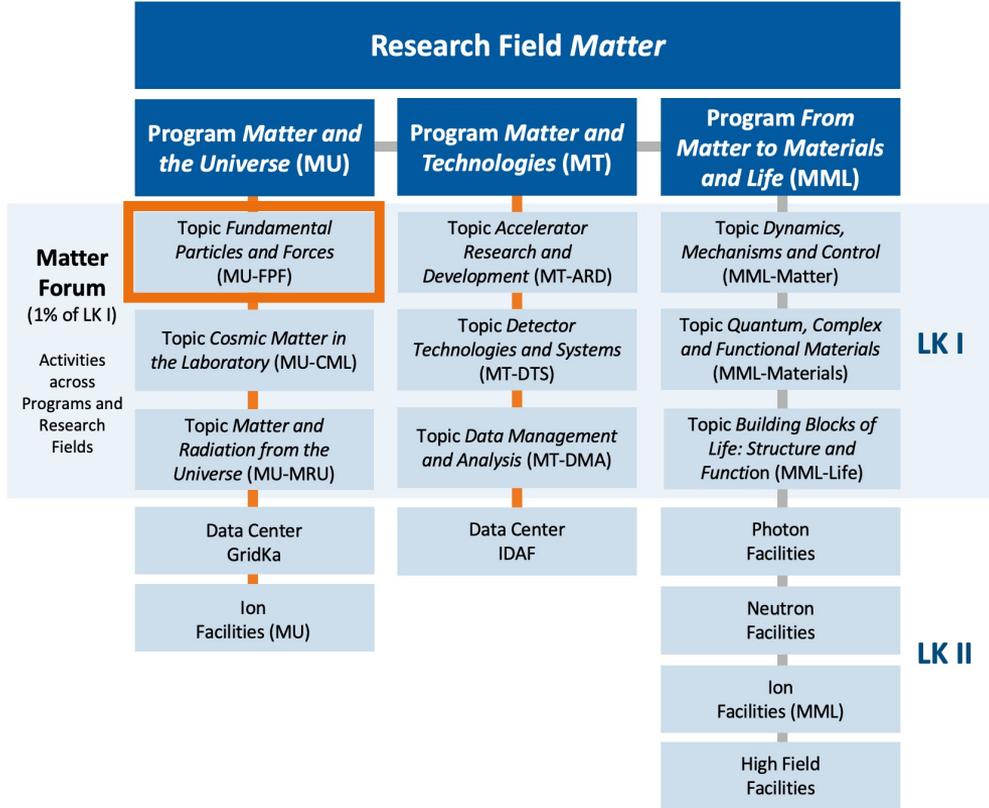
MU FPF
MATTER AND
THE UNIVERSE

KIT
Karlsruher Institut für Technologie



Reminder: FPF in MU

Particle physics at DESY and KIT (theory)



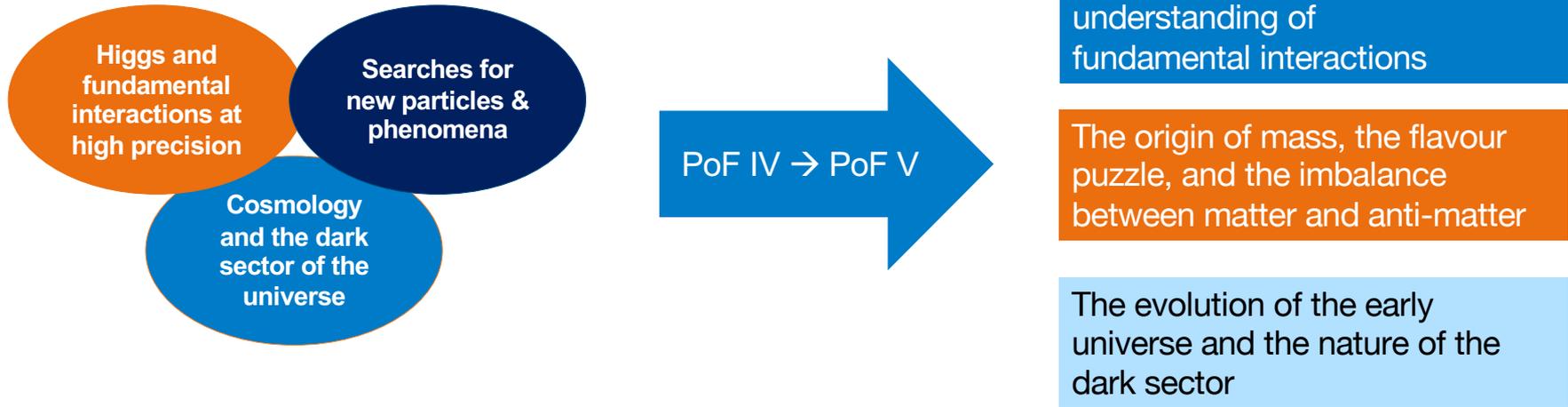
- 2 Helmholtz centers
- 3 locations
- 158 scientists
- 78 Ph.D. students
- 34 MEUR costs / a
- 42 nationalities

Topic spokespersons:
Isabell Melzer-Pellmann, Kai Schmidt-Hoberg



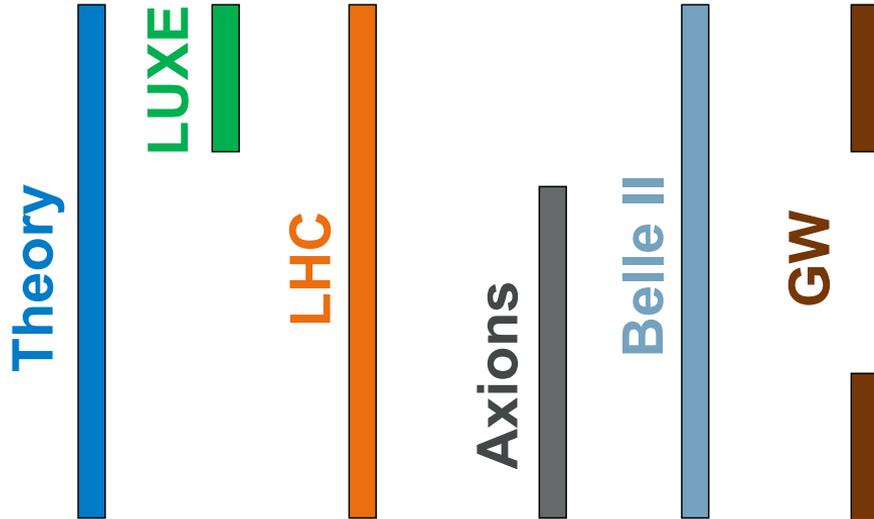
Changes from PoF IV to PoF V

Foreseen change / adaption of subtopic structure



Changes from PoF IV to PoF V

Foreseen change / adaption of subtopic structure



Pushing the limits of our understanding of fundamental interactions

The origin of mass, the flavour puzzle, and the imbalance between matter and anti-matter

The evolution of the early universe and the nature of the dark sector

Testbeam Facility (DESY)



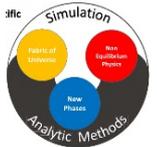
Detector Assembly Facility (DAF, DESY)



Computing Centres GridKa and IDAF

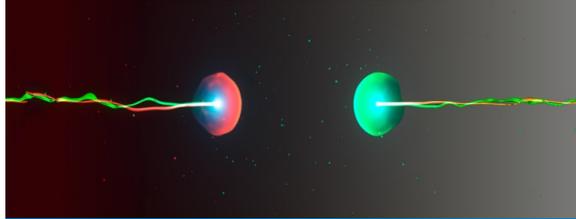


Wolfgang Pauli Centre



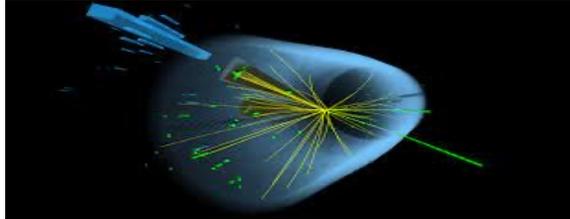
PoF V Subtopic Structure and Science Drivers

Our science drivers address the big questions of nature: Understanding the quantum universe



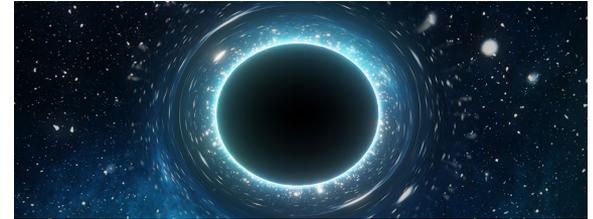
Pushing the limits of our understanding of fundamental interactions

- Strong-field QED
- Strong interactions, QCD
- Lattice QCD
- $g-2$



The origin of mass, the flavour puzzle, and the imbalance between matter and anti-matter

- Higgs boson
- Top and B physics
- Charge-parity violation
- Lepton flavour universality



The evolution of the early universe and the nature of the dark sector

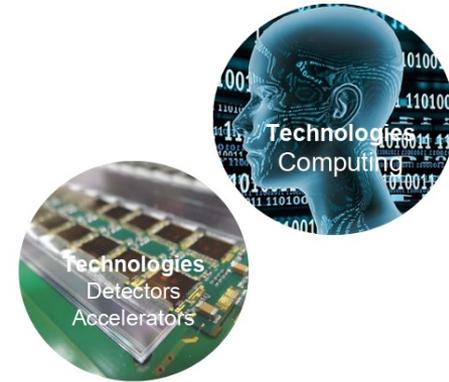
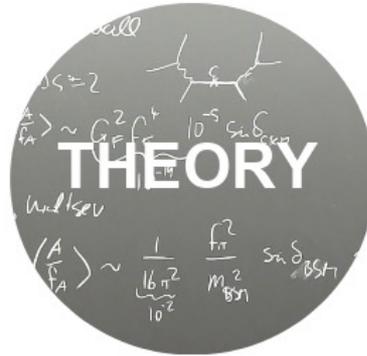
- Cosmology
- Axions, ALPs
- Gravitational waves
- Dark matter

Fundamental curiosity-driven science

- Development of cutting-edge technologies (detectors, computing, accelerators, lasers, ...)
- Very attractive for young high-potentials
- High potential for disruptive technology development important for society, e.g. WWW, imaging technologies, cloud computing, ...

Particle Physics at DESY: the Next 10-15 Years

Specific focus areas



Key contributions to global projects at CERN and KEK

- HL-LHC preparation and running in 2029 onwards
- Belle II: expect ~50/ab by 2034

Engage in planning and preparation for future projects (EPPSU decision by 2028)

Maintain broad and world-leading portfolio.

Establish WPC as world-leading interdisciplinary center for theoretical physics

Theory as “Idea factory”

ALPS II: first science run started running in May 2023.
BabyIAXO, LUXE: Solve challenges & find financial resources for PoF V
MADMAX: proof concept in prototyping phase & find financial resources
New ideas, e.g. HF GW local experiments (complementing ET)

~50% of topic resources go into technical work!

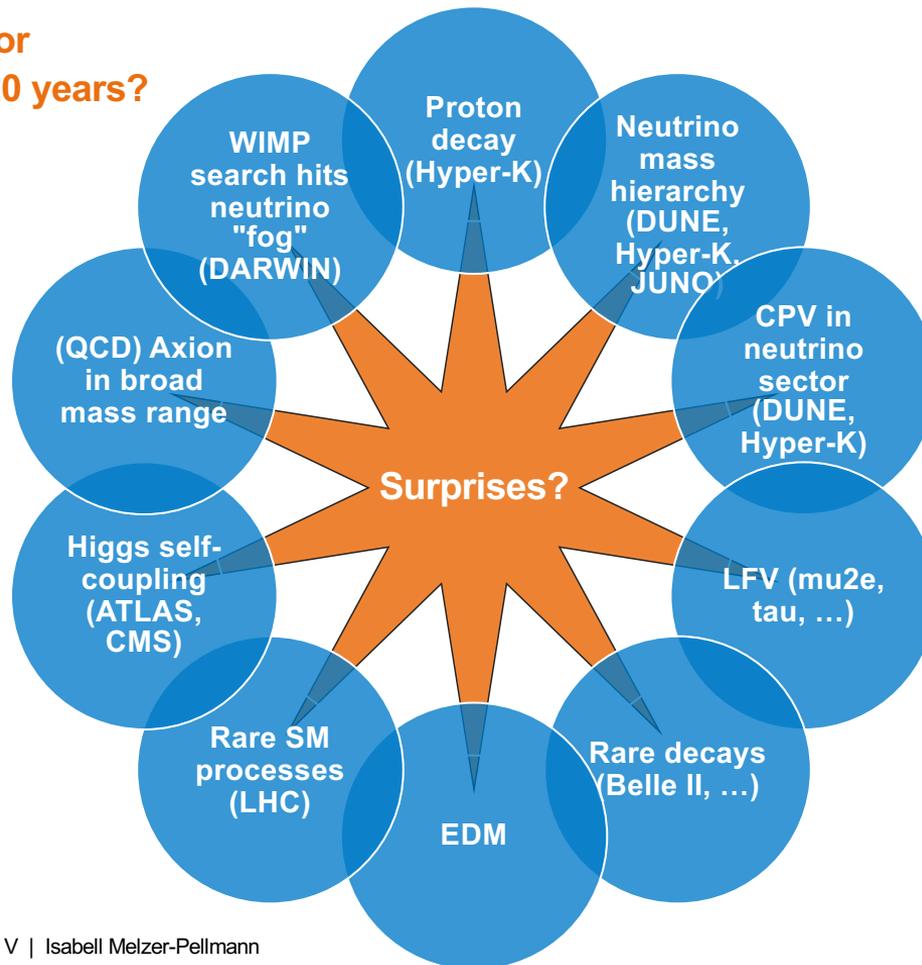
Strengthen innovation in detectors and computing

Increase 3rd party funding

Strengthen exchange across divisions

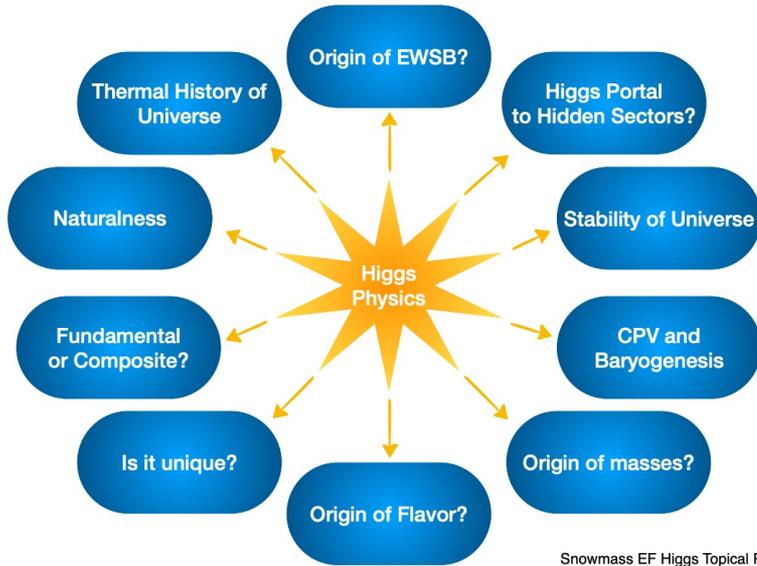
Particle Physics: Quo Vadis?

Where do we expect major progress in the next 10-20 years?



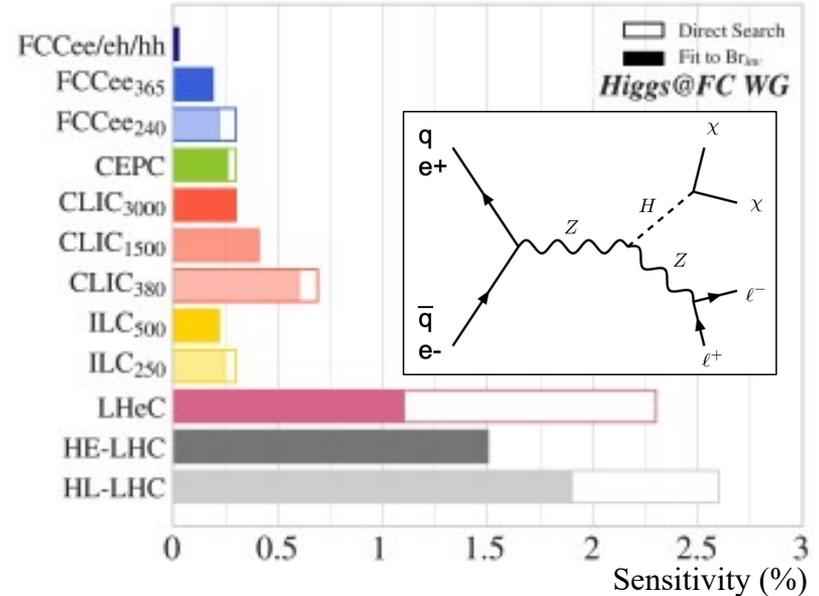
Higgs Precision Measurements

“Higgs is the most important actor ... the reason for building the next colliders is to study the Higgs boson to death, full stop” (Nima Arkani-Hamed)



Snowmass EF Higgs Topical Report
S. Dawson, P.M., I. Ojalvo, C. Vernieri et al
2209.07510

The Higgs boson is the most bizarre particle ever!



E.g. invisible Higgs: major improvements compared to current sensitivity of ~10%

- HL-LHC : <2.6%
- e+e- colliders: ~0.3%
- FCC-hh: ~0.025% (below SM value)

LUXE: Exploring Strong-Field QED

In collaboration with the European XFEL

LUXE

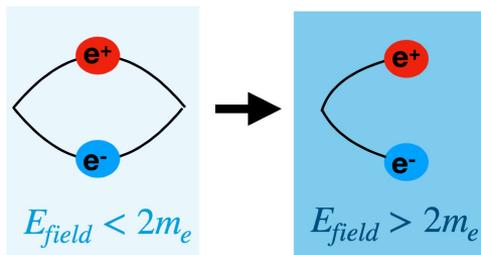
arXiv:2308.00515

Technical Design Report for the LUXE Experiment

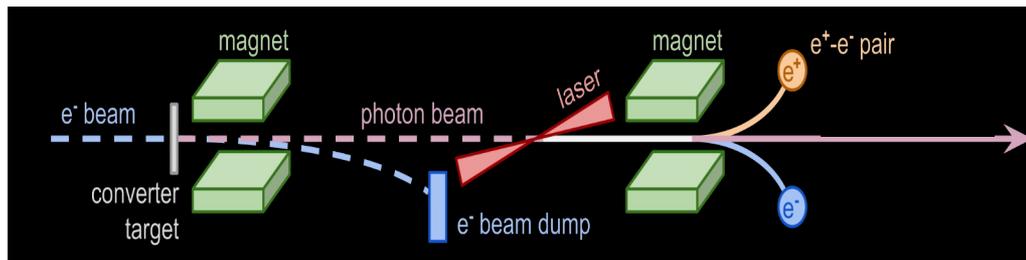
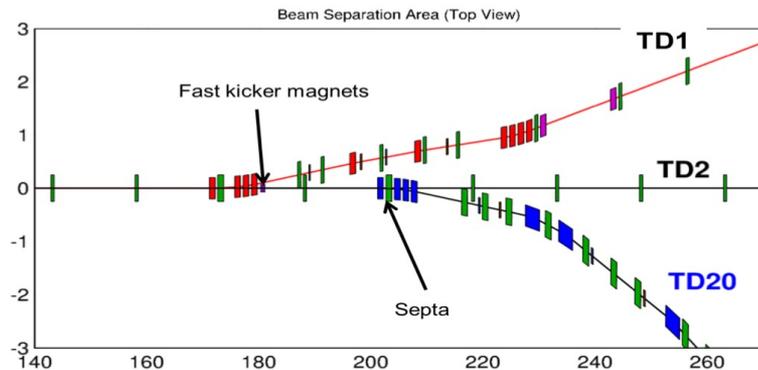
2 Aug 2023

Critical field phenomenon QED at “Schwinger limit” still unobserved – now use XFEL electron beam in collision with strong laser to create critical field:

$$E_{\text{crit}} = \frac{mc^2}{e\chi_C} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm}$$



Expectation: Observation of Breit-Wheeler pair creation + modified Compton scattering + room for BSM (axions etc.)



Recent achievements and plans:

- TDR out!
- Plan for tunnel / accelerator modifications (extraction beam line)
- Hoping for installation in XFEL shutdown in 2025

Axion Experiments

Current constraints and future expectations

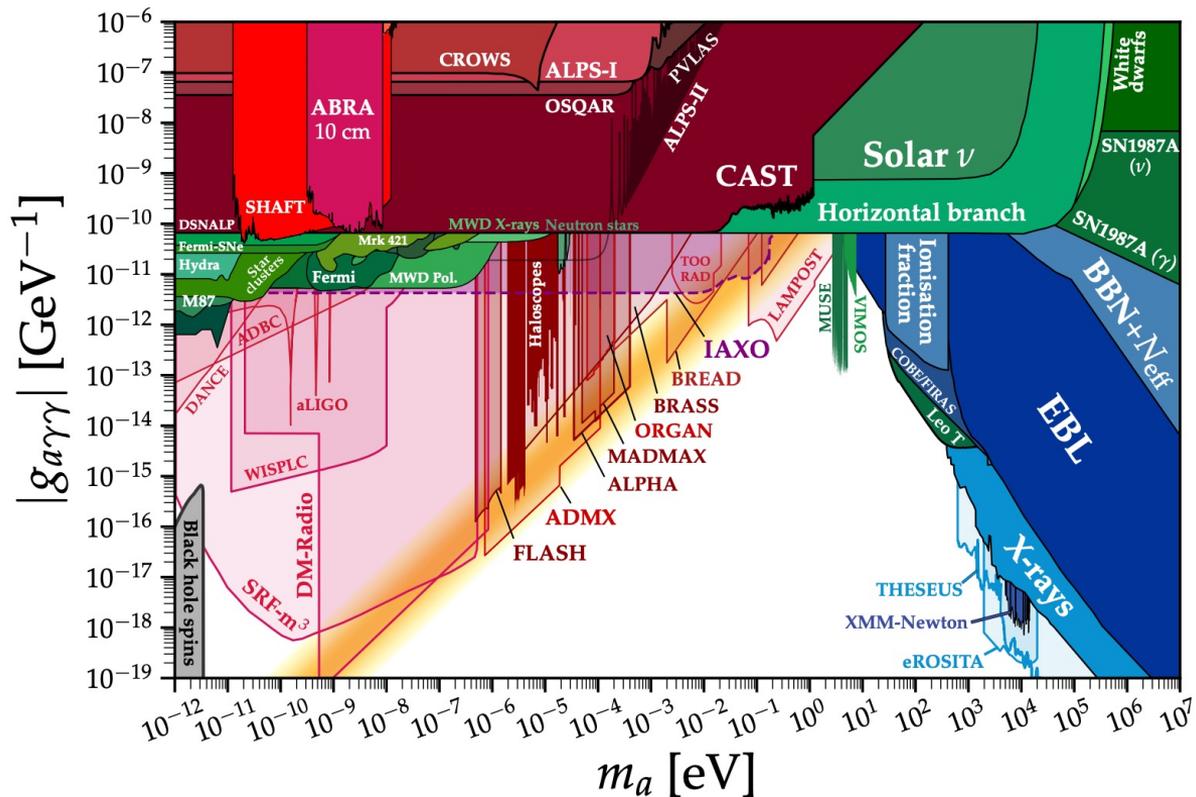
Interests in axions is growing –
DM candidates, “only” solution to
strong CP problem ...

Theory expectation for axion as
dark matter (in simple models)
 $10^{-6} < m_{axion} < 10^{-2}$ eV

Very small fraction of relevant
parameter space probed as yet,
but ...

... will cover entire mass range
down to 10^{-9} eV in the next
decade or so!

Very dynamic area and DESY is
in the middle of it!



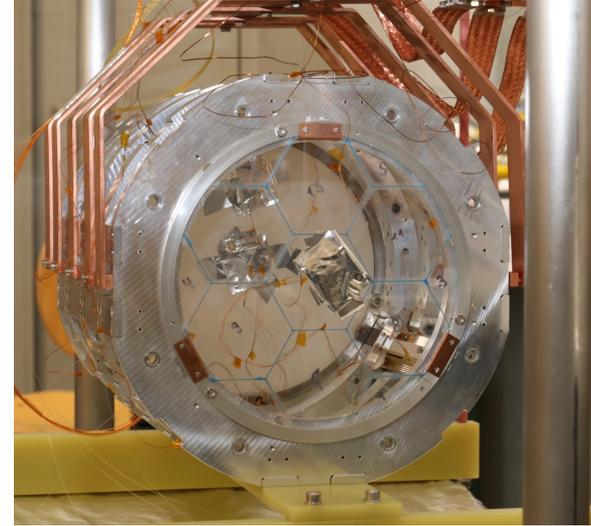
Future Axion Experiments

Preparing for BabyIAXO and MADMAX, turning DESY into THE axion centre worldwide



BabyIAXO – precursor of IAXO, the International Axion Observatory.

- Helioscope is planned to be installed in the HERA south (ex-ZEUS) hall in the coming years.
- Most pressing problem: procurement of SC magnet cable – currently no non-Russian vendor



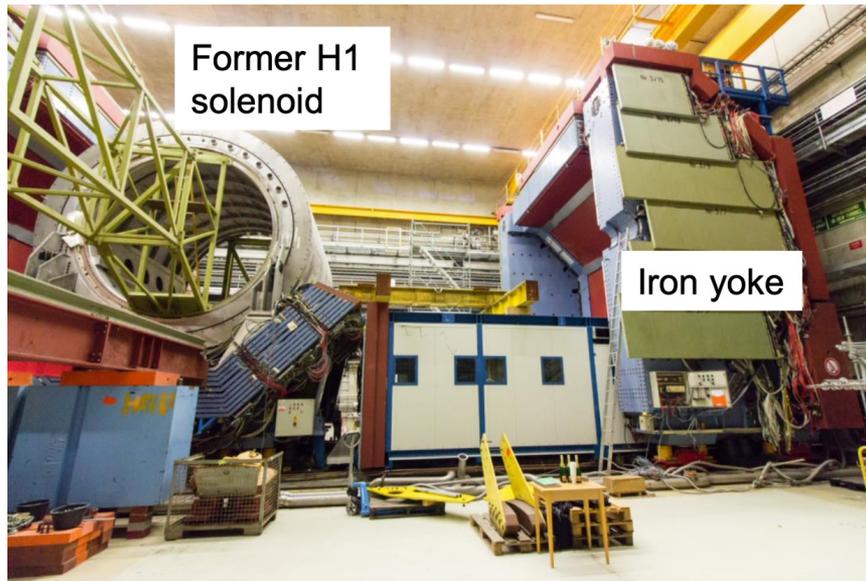
MADMAX – the axion and DM haloscope

- Planned to be installed in the HERA hall north (ex-H1) in the coming years
- Magnet development ongoing. Calculation on magnets prototype finished and quench propagation in s.c. cable is well understood.
- Feasibility studies for use of old H1 iron yoke

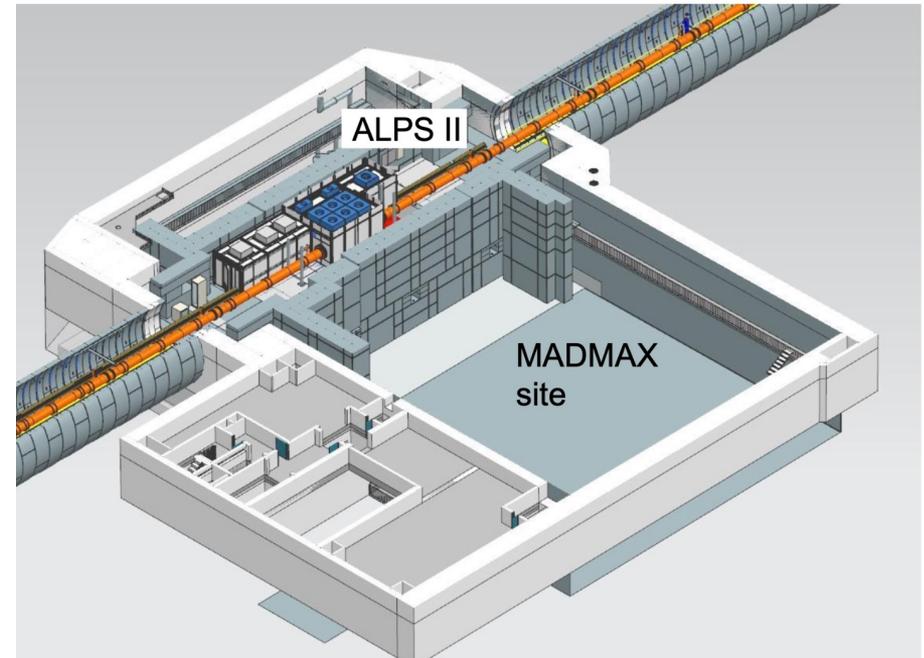
Cryoplatfom at DESY

Distribution system of liquid helium (at ~ 4.5 K)

- Located 30 m underground at HERA Hall North
- Supply for up to three experiments (e.g. MADMAX)
- In construction, operation from 2026



Dimensions: height = 16 m, area = 1222 m²



The DESY Test Beam Facility

Status and future – also in PETRA IV times

Status today

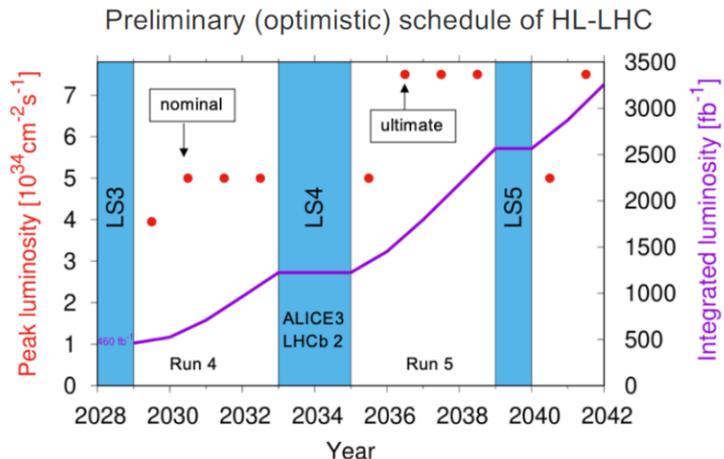
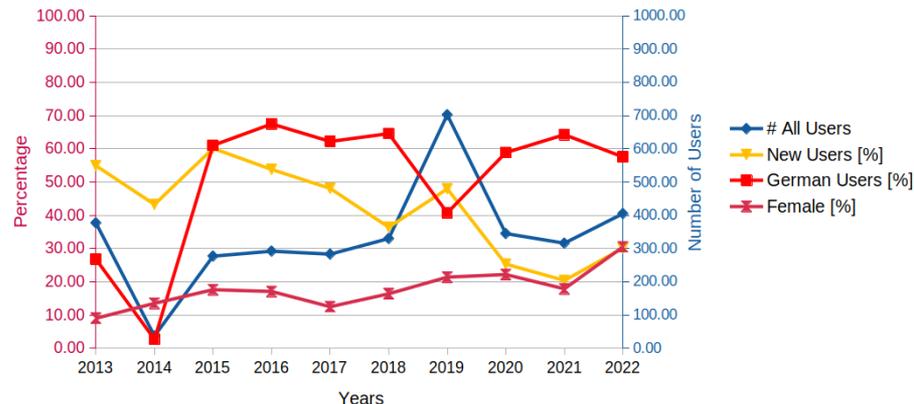
- Operation of 3 beamlines with ~6 GeV at DESY II
- Besides CERN only multi-GeV test beam facility in Europe
- Every year > 400 users

Demand for test beam in 2027 and beyond

- Clear demand for test beam extending over a decade or more
- Driven by HL-LHC, nuclear physics programme and smaller-scale particle and nuclear physics projects

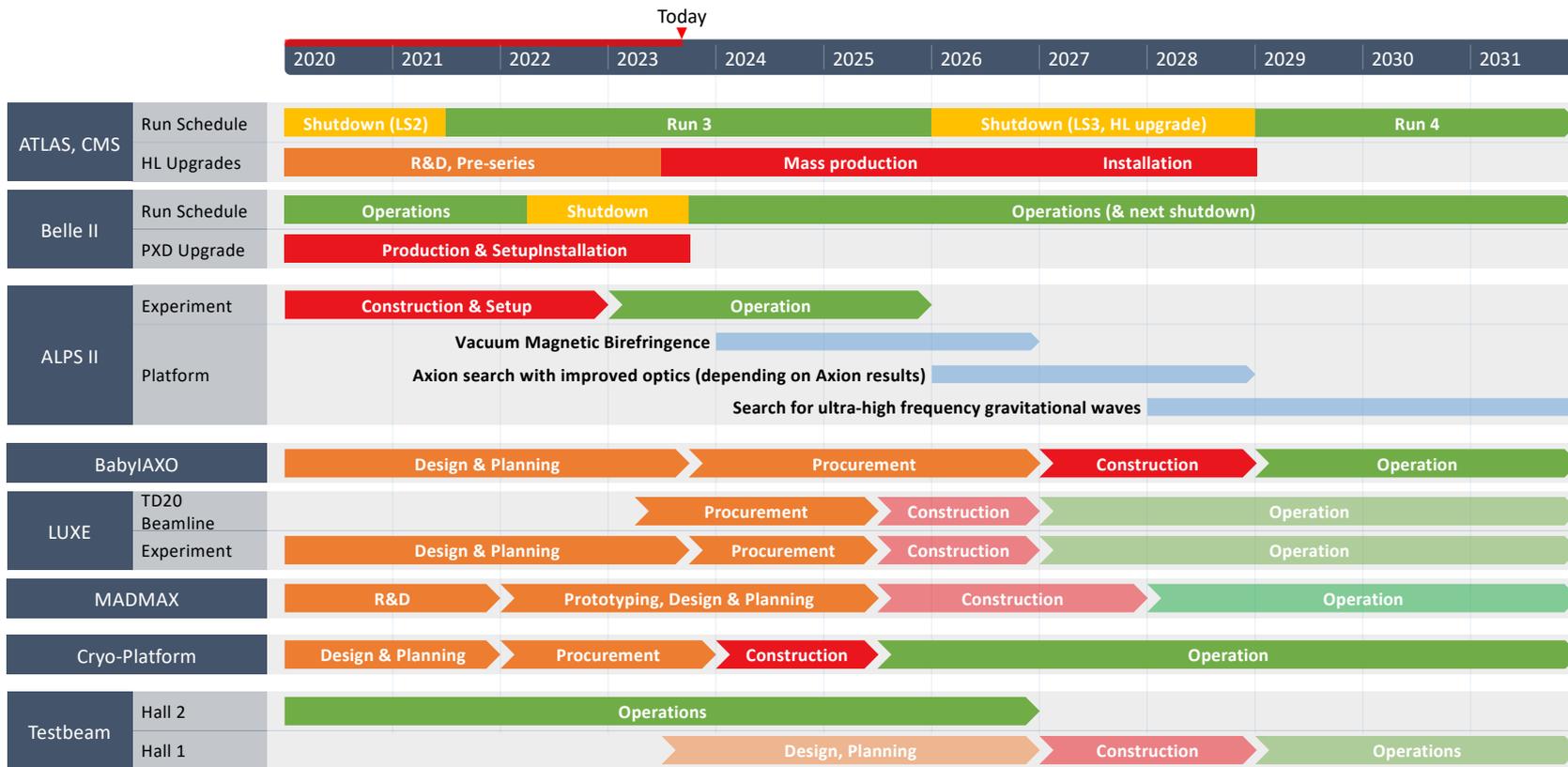
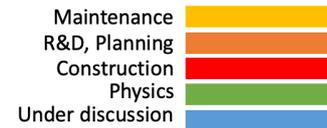
A future test beam facility at DESY IV

- The PETRA IV projects foresees a new injector DESY IV; but current layout does not allow for test beam facility
- To make it usable for a test beam facility, DESY IV requires modest modifications
- If implemented, again leading world-class facility for the next decade or two



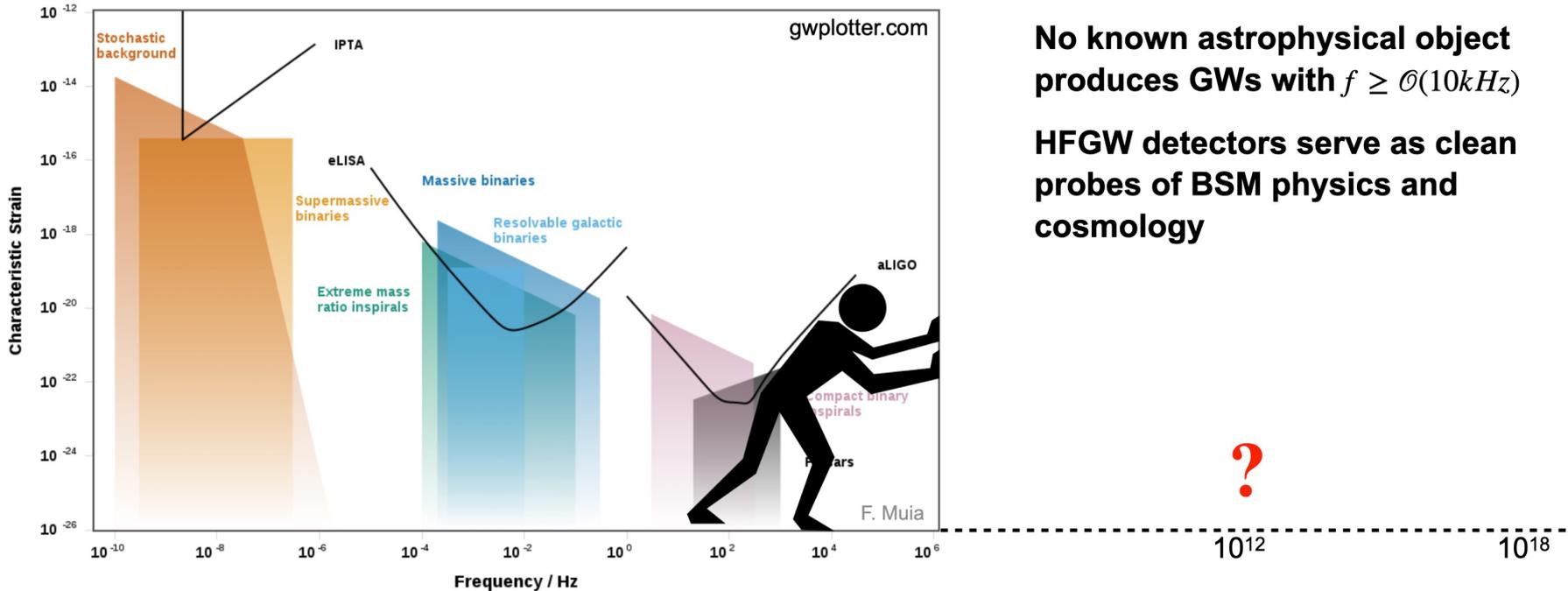
Timeline for LHC, Belle II and experiments at DESY

Including not fully funded projects



High-frequency Gravitational Waves

Focus on high-frequency experiments with particular relevance for cosmology!



No known astrophysical object produces GWs with $f \geq \mathcal{O}(10\text{kHz})$

HFGW detectors serve as clean probes of BSM physics and cosmology



High-frequency Gravitational Waves

Search with cavities

- GW interaction with cavity walls
 - Spherical cavities for high Q factor
 - Distance between two cells is used to tune ω_G
 - MAGO collaboration published first results in 2005
 - Collaboration moved to Virgo due to funding decisions
- DESY/UHH + FNAL now continue R&D program.
- Since July the MAGO cavity is at DESY for measurements and matching simulations
- Use from Cryoplatfrom for cooling
- Still a lot of R&D to be done:
 - Low-noise cooling and electronics, suspension system, ...
 - Collaboration with DESY accelerator division / UHH experts
- **Estimated sensitivity:**
 - $\sim 6 \times 10^{-21} \text{ Hz}^{1/2}$ from 1.8 to 2.2 kHz (near mech. resonance)
 - $\sim 8 \times 10^{-23} \text{ Hz}^{1/2}$ projected for the final (larger) cavity design



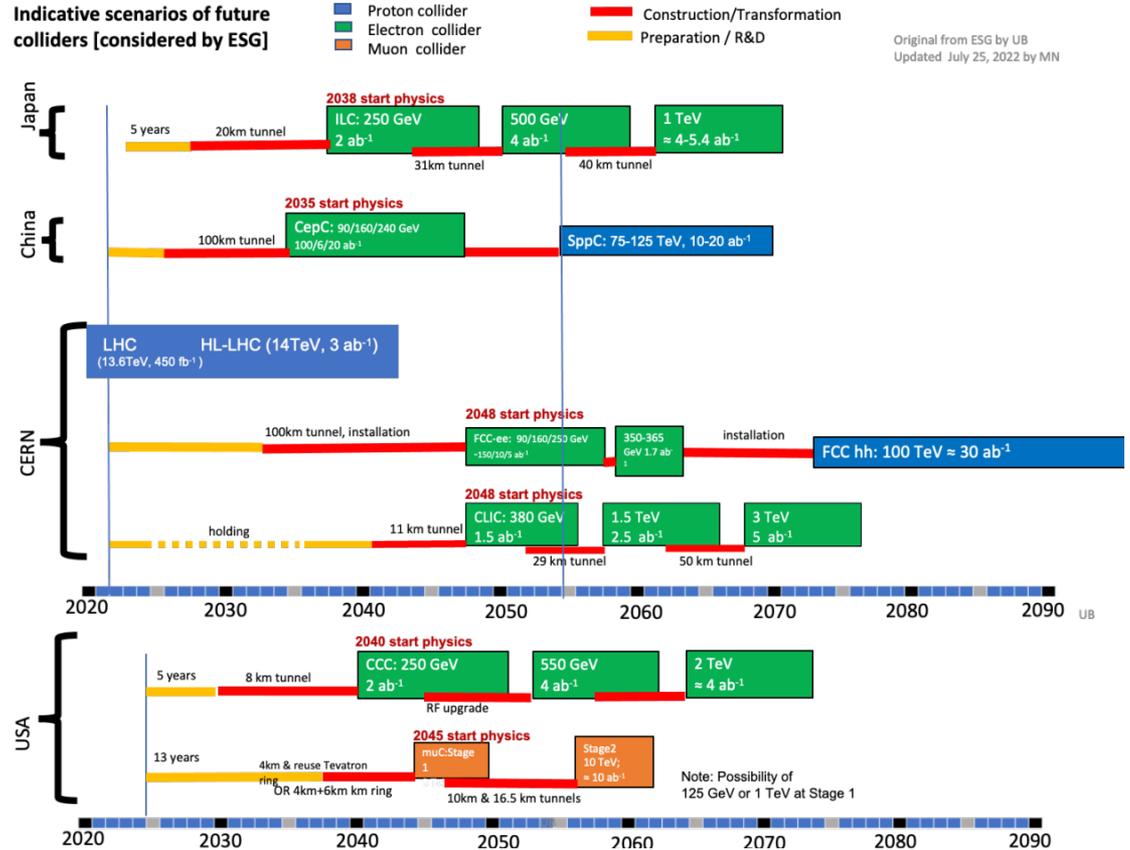
MAGO cavity at DESY

PIER Seed Grant obtained for the development of the cavity control

Timelines for possible new collider projects

As updated for Snowmass

- Technologically-driven
→ start of data-taking in ~late 30ies (except for CERN projects due to coupling to HL-LHC programme → late 40ies)
- ILC and CEPC require political decisions very soon to maintain timelines shown here
- If Higgs factory will be built elsewhere, CERN could to for FCChh directly (~60ies)

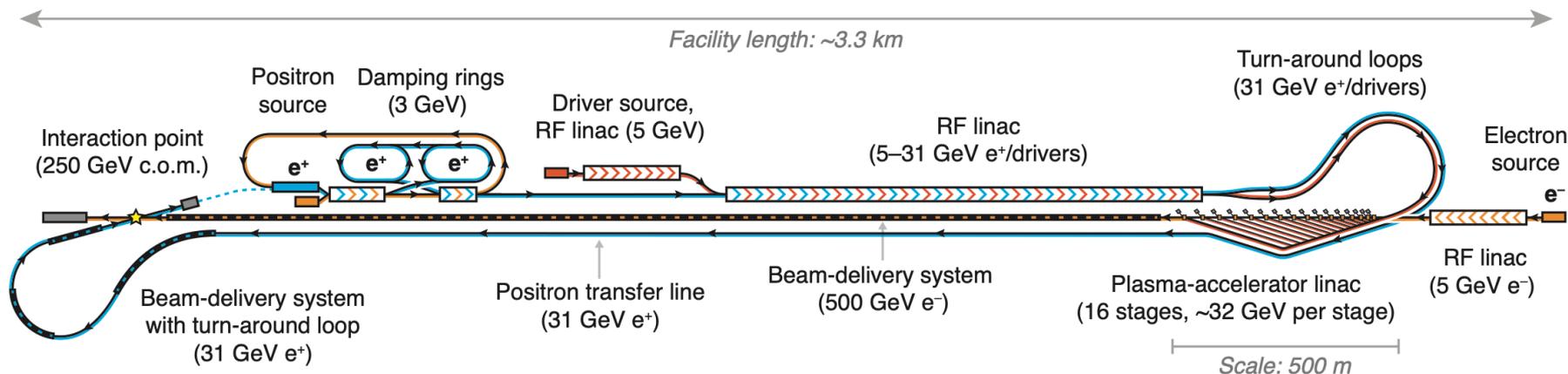


The HALFH Concept

The next step in lepton colliders? A Hybrid Asymmetric Linear Higgs Factory

Hybrid concept to reach central European strategy goal of a Higgs factory as highest priority:

- 500 GeV electron beam accelerated by a beam-driven plasma wakefield accelerator
 - 31 GeV positron beam accelerated by a conventional accelerator
- Center-of-mass energy of 250 GeV!

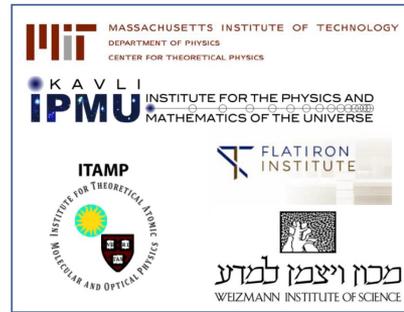


**Currently exploring the concept for physics potential and R&D needs – possibly a cost-efficient alternative!
Input for next update of European strategy for particle physics?**

The Wolfgang Pauli Center

Uniting the different theory groups of Universität Hamburg and DESY

- Mission to a **leading center for theoretical physics** that pursues and promotes interdisciplinary research to address the fundamental challenges in our **understanding of matter, materials and the universe**
- Fostering collaboration between **particle physics, astrophysics and cosmology, mathematical physics, condensed matter, quantum optics and chemical physics**
- Strategic partnerships with theory institutes both within Germany and internationally
- 350 theorists (faculty, postdocs, PhD students) from 12 different institutions

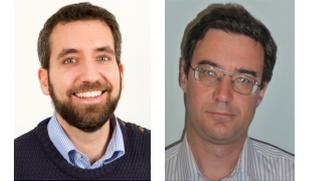


New building for WPC identified, likely to be moving in next year

FPF at KIT

Outlook on PoF V

- **FPF at KIT:** 8 FTE from HGF, 7 Principal Investigators funded by university mission
 - **Theory:** Blanke, Heinrich, Kahlhöfer, Melnikov, Mühlleitner, Nierste, Steinhauser plus 6 postdocs
 - **Computing** (algorithms for HL LHC data analysis): Giffels, Quast
- **Scope and strategy for PoF V:**
 - Calculations for ATLAS, CMS, Belle II and future experiments: precision Higgs physics, Dark Matter at colliders, BSM B physics
 - KIT research complementary to DESY theory research
 - Link to astroparticle theory in MRU: Dark Matter model building
 - Strengthen Collaborative Research Center TRR 257, *Particle Physics Phenomenology after the Higgs Discovery*
 - For HL LHC era: improve codes and workflows, GPU technology



Summary

Changes in the Topic FPF for the PoF V period

Finalisation of LHC upgrades by end of POF IV

- HL-LHC start delayed to 2029
- Maintain robust engagement at ATLAS and CMS during POF V but shift resources in part to on-site experiments

Belle II

- Schedule delayed: continue engagement to collect 50/ab until 2034

Rich on-site experiment programme at DESY foreseen for PoF V

- ALPS II running, LUXE, BabyIAXO and MADMAX in POF V planned
 - BabyIAXO delayed due to inability to use Russian cable supplier
 - MADMAX and LUXE funding to be secured
- R&D on high-frequency GW experiments using local infrastructure

Next major CERN project (Higgs factory):

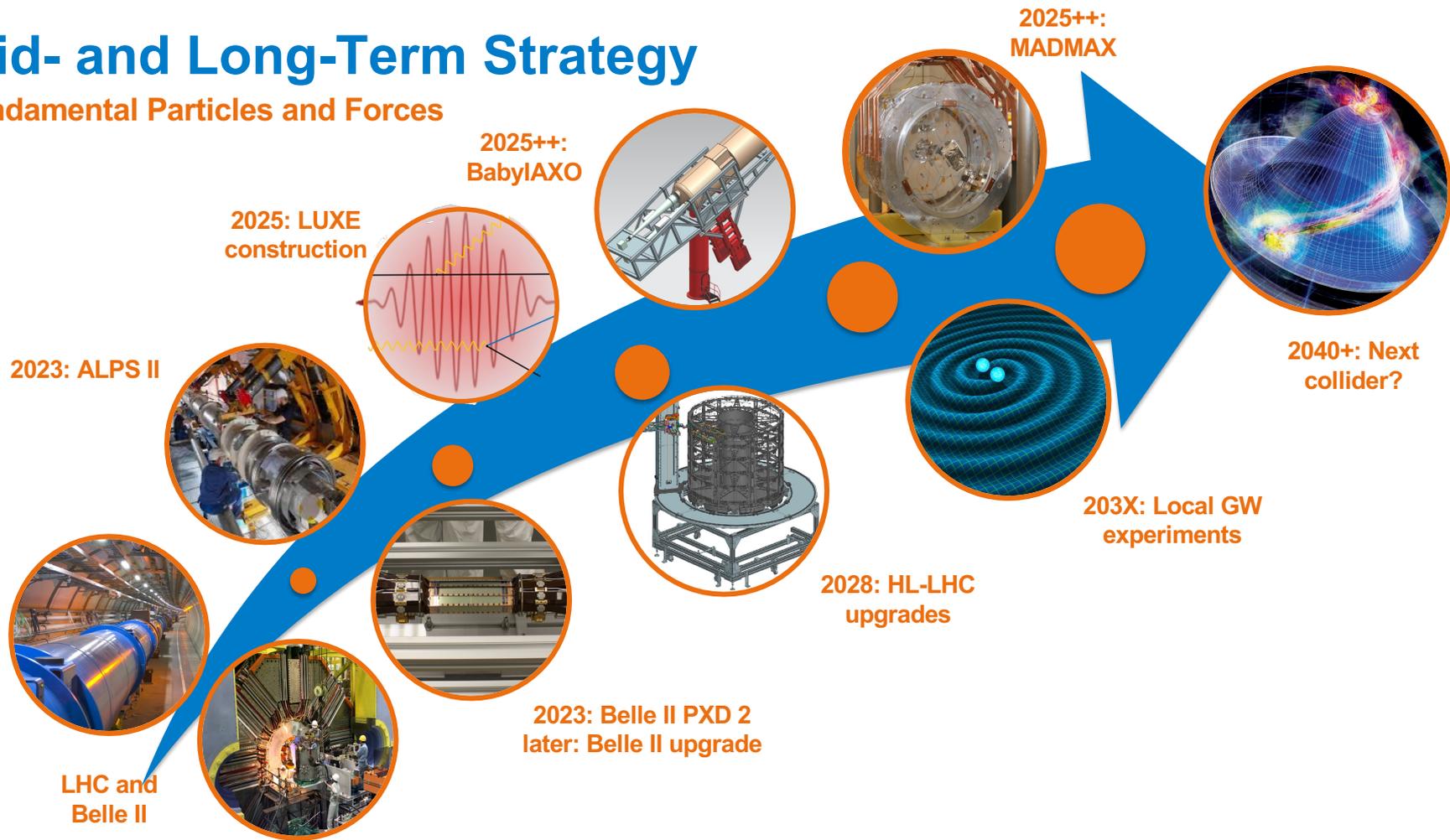
- Expect decision ~2028 => contribute to R&D and decision

Theory

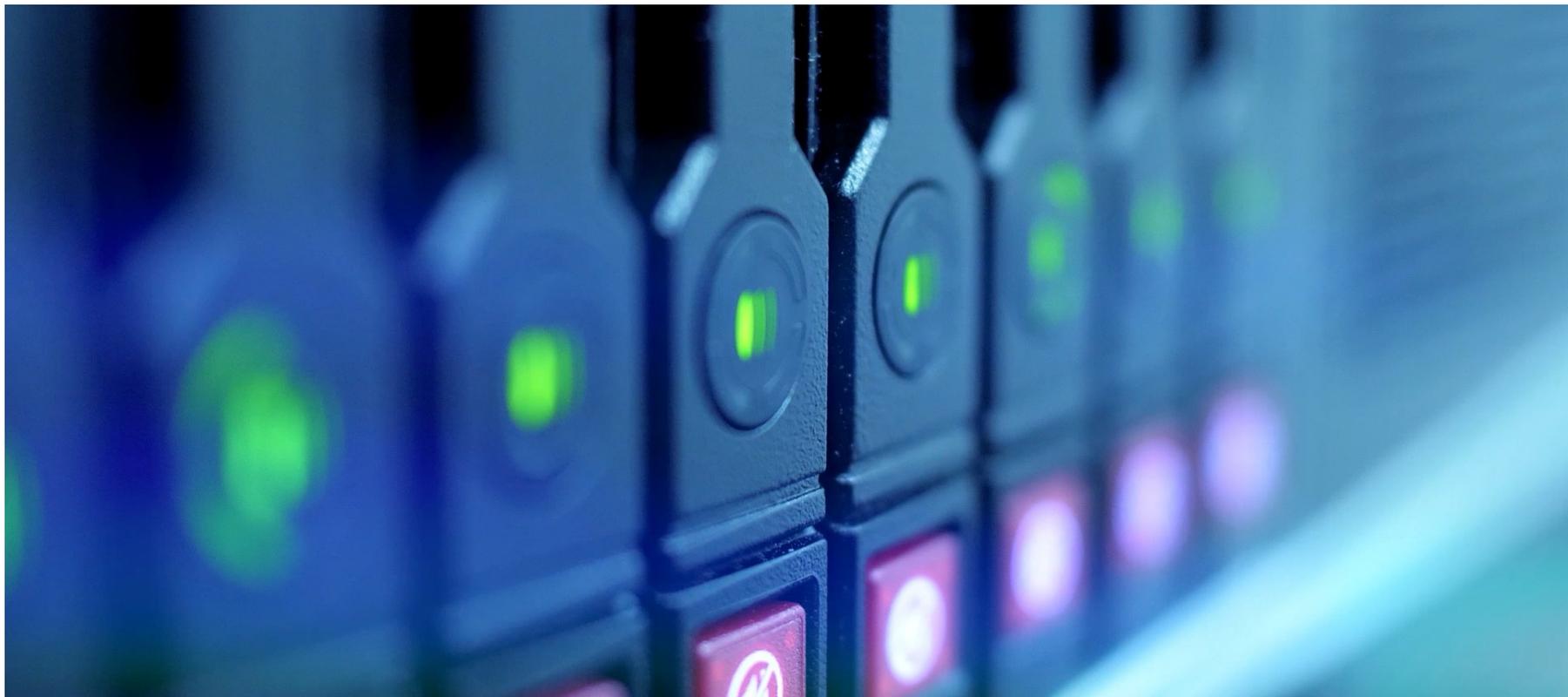
- Maintain activities at current level of resources
- Leverage Wolfgang Pauli Centre to strengthen leading role of Hamburg theory

Mid- and Long-Term Strategy

Fundamental Particles and Forces

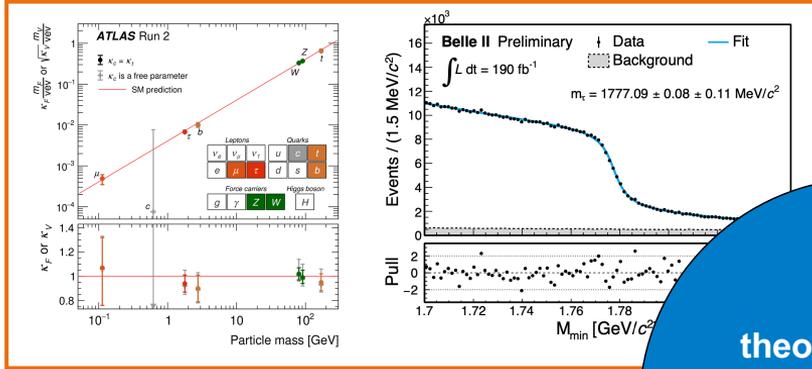


BACKUP

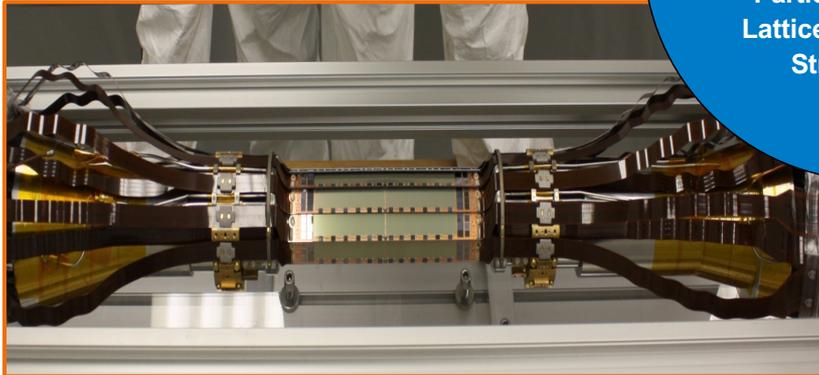


Portfolio of Activities

Particle physics at DESY and KIT (theory)



Leading contributions to global collider projects at CERN, KEK. Physics exploitation.

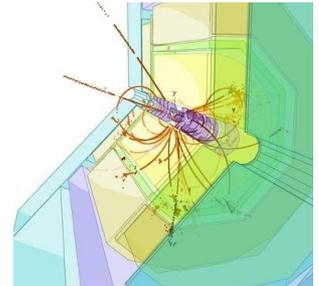
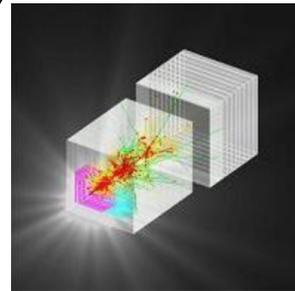


Attractive on-site programme (axions, QED, GW, ...)

Broad theory portfolio

Collider Physics
Particle Cosmology
Lattice Gauge Theory
String Theory

Technology R&D, preparations for future projects



Future Colliders: e+e- Colliders and Higgs Factories

EPPSU number one priority

CERN is very focussed on the FCC (90.7 km circular e+e- collider)

- End of '23: Midterm review of FCC feasibility study; End of '25: Final feasibility study
- Linear collider R&D for ILC and CLIC supported at lower level

China: focussed on CEPC (100 km circular e+e- collider): 5-year plan in 2025

Japan and the ILC

- Critical R&D still supported (ITN for 4 years); funding scenario unclear

New idea from SLAC: Cool Copper Collider (C3): R&D needed

- US P5 strategy process still ongoing!

New idea at DESY: “HALHF” hybrid collider including plasma-based acceleration

Energy Recovery Linacs: considered for ep collider, demonstrator facilities starting

→ Need a decision with next EPSSU update by 2028