PAUL SCHERRER INSTITUT

Raziyeh Dadashi

Rasmus Ischebeck

DARK MATTER SEARCH
ARTIFICIAL INTELLIGENCE

DARK MATTER

A Brief Introduction

Raziyeh Dadashi

Topics

1. Dark Matter properties
2. Five main evidences for DM
   - Rotation of galaxies in the cluster
   - Rotation of stars in galaxies
   - Gravitational lensing
   - Cosmic Microwave Background
   - Structure formation
3. Cosmological origin of DM
4. Allowed mass range
5. Three main searches for DM
   - Scattering
   - Annihilation
   - Production

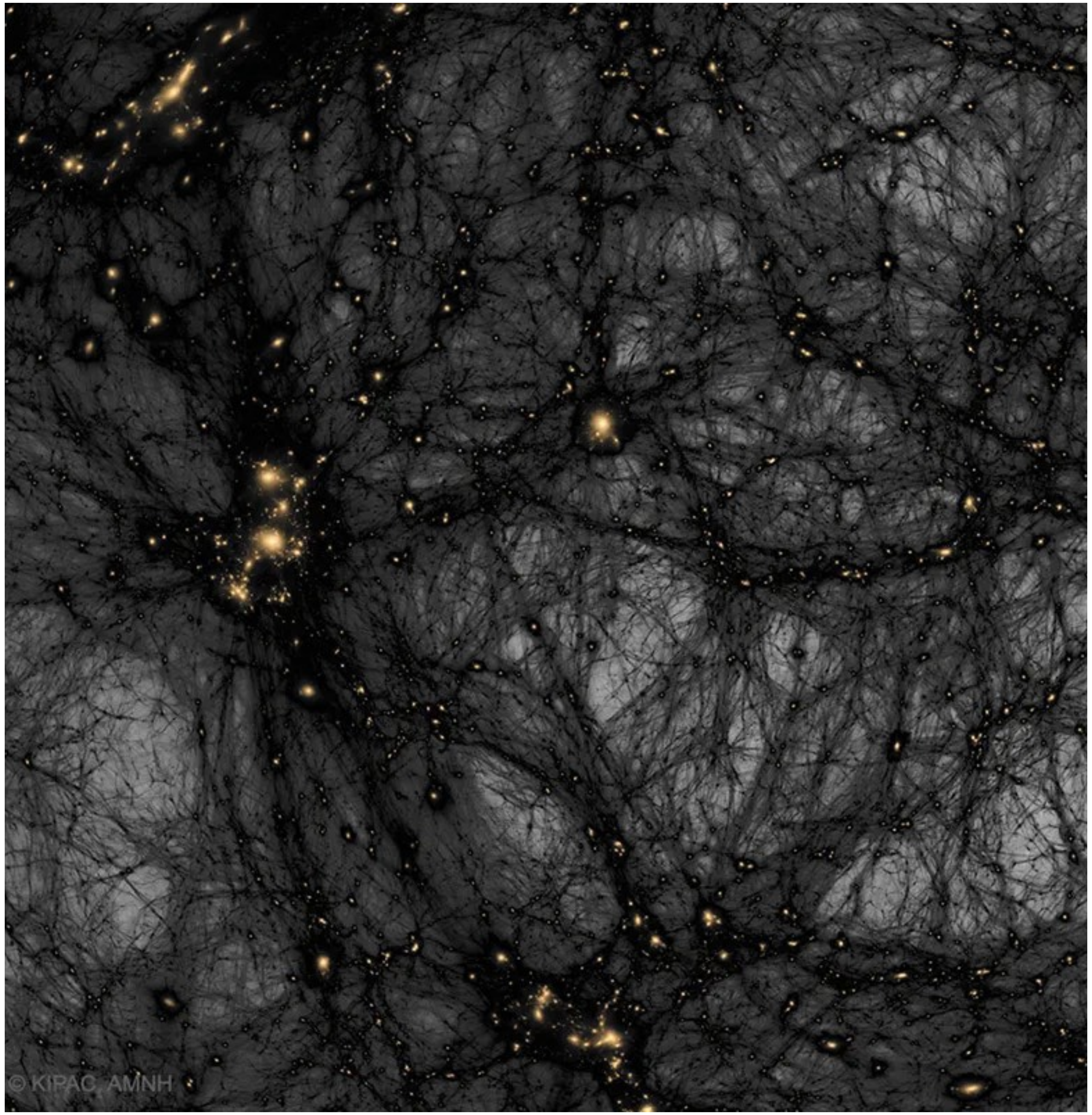


Image credit: Illustration Credit & Copyright Tom Abel & Ralf Kaehler (KIPAC, SLAC), AMNH

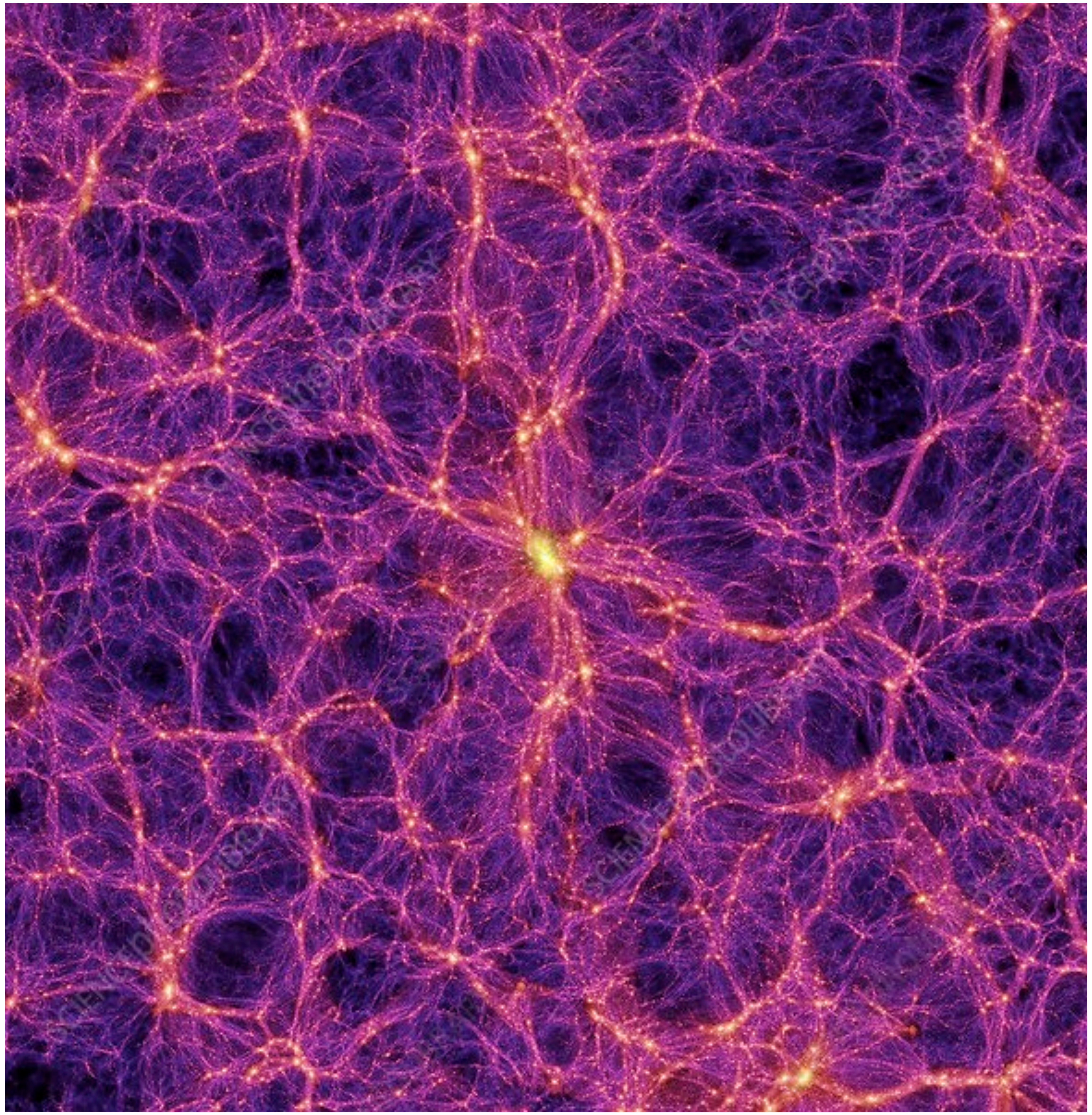
What is Dark Matter?

Dark Matter Properties

1. DM does not interact with electromagnetic forces.(No absorption or emission)

2. It is matter.

3. DM interacts weakly with SM particles and itself. (As weakly as weak nuclear forces or even weaker)



http://arxiv.org/abs/astro-ph/0504097

Evidences

1. Rotation of galaxies in the cluster

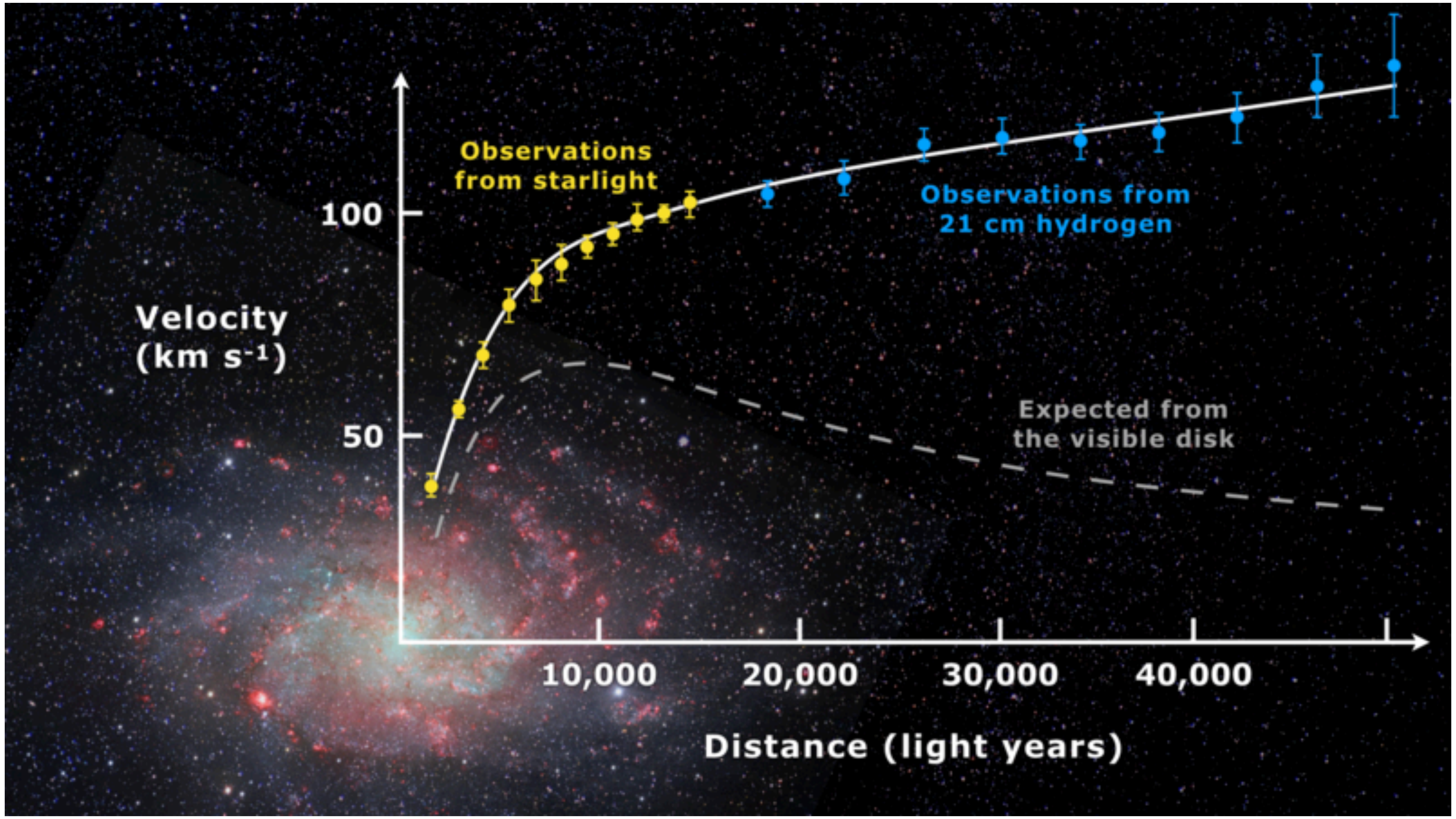
- 1933: First evidence was mentioned by Zwicky.
- Rotation of galaxies in Coma cluster was too fast.
- He concluded that 400 times more mass is needed compare to what we observe.

Authors & editors: Robert Nemiroff (MTU) & Jerry Bonnell (USRA)

Evidences

2. Rotation of stars in galaxies

- Simple rotational mechanics: velocity is inversely proportional to the distance. Then, far from the centre, stars rotation must be slower.
- 1970-1980: Rubin and Ford observed that the rotation of stars far from the centre of galaxies are too fast.
- They concluded: 1. There is much more mass than expected. 2. This mass is distributed at a larger area.

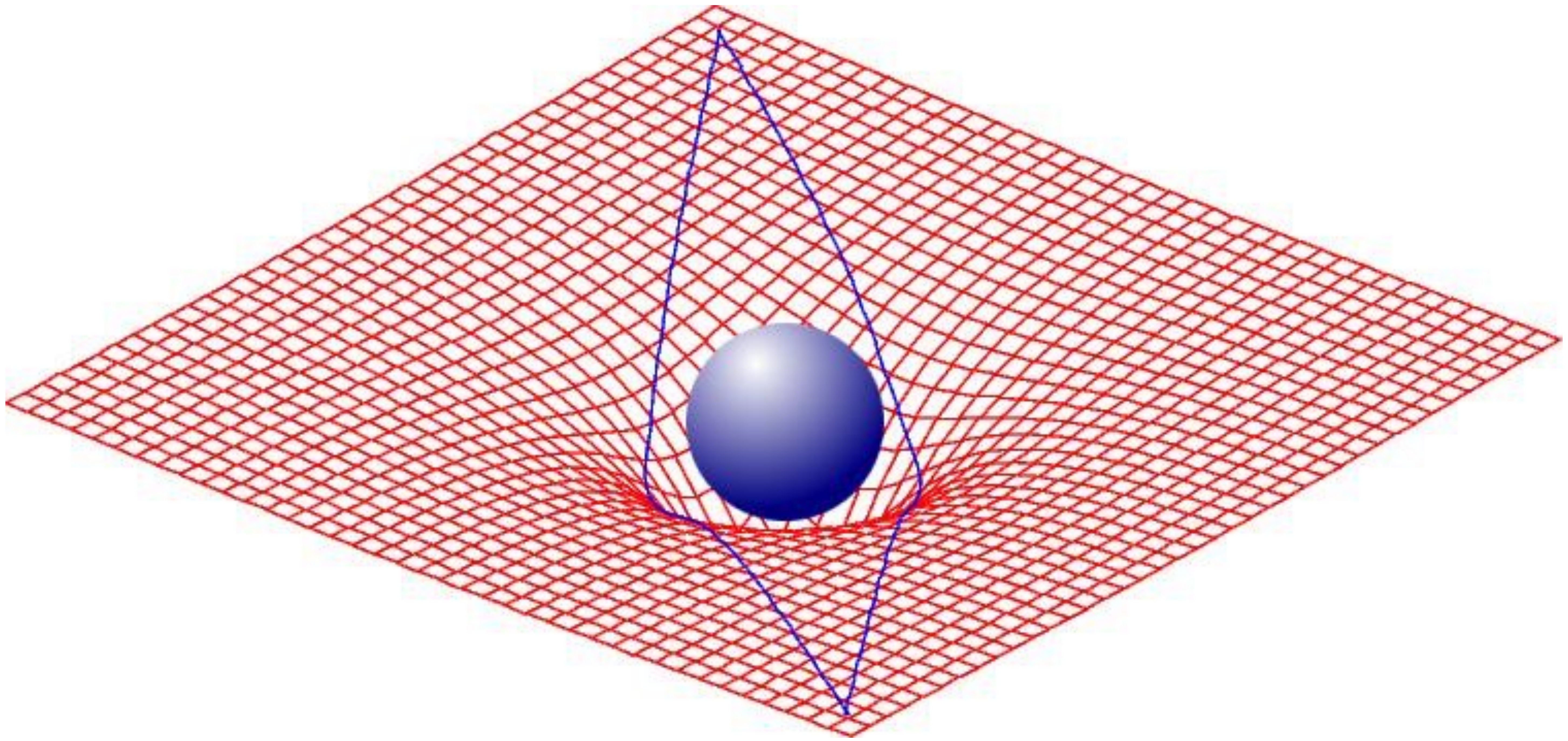


https://en.wikipedia.org/wiki/Galaxy_rotation_curve

Evidences

3. Gravitational lensing

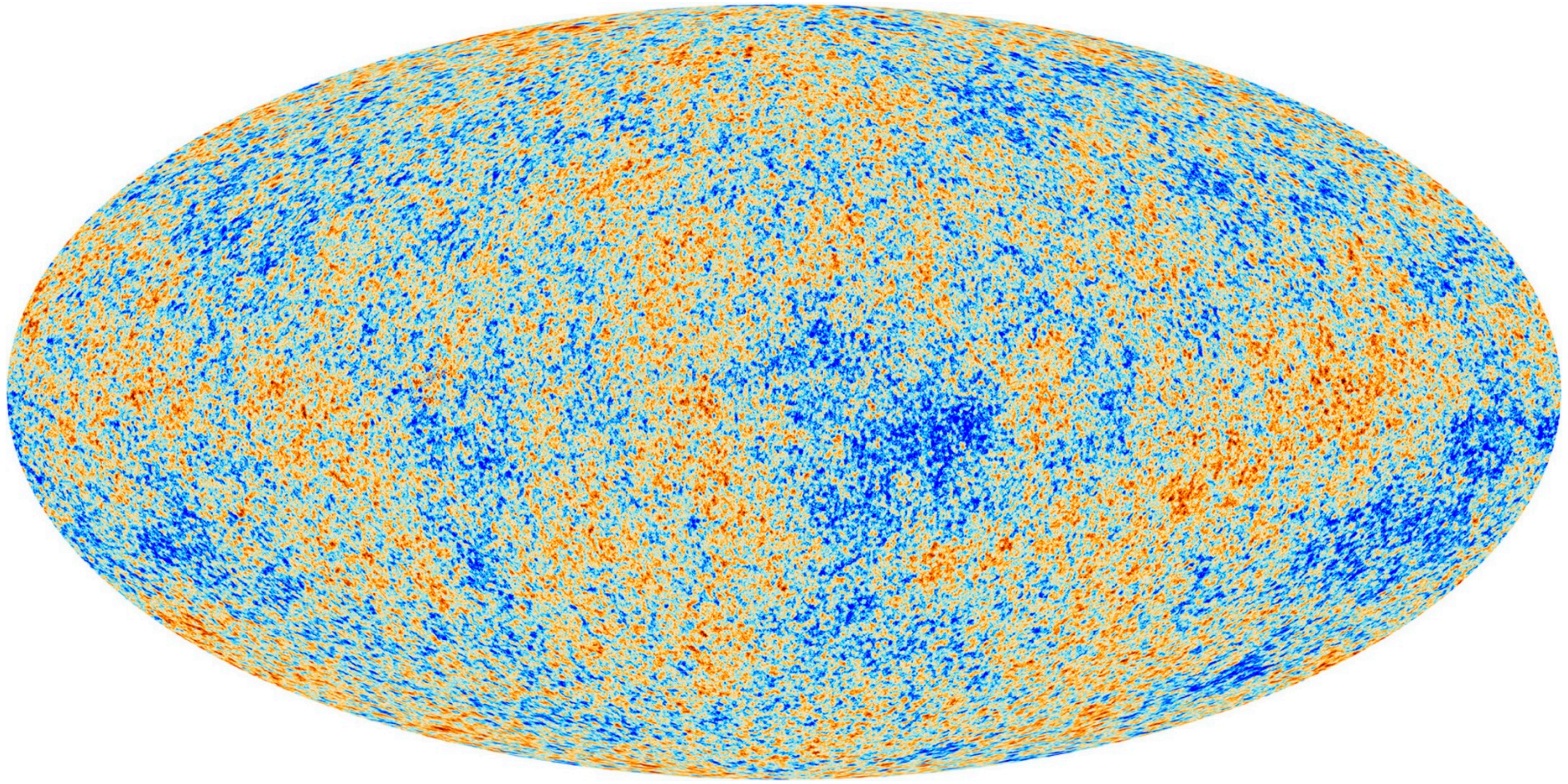
- General theory of relativity: gravity is caused by curvature of space-time.
- Mass curves the space and light is deviated (focused).
- According to the mass the focusing strength will be different.
- According to observations, normal mass is not enough to explain the observed lensing.



Evidences

4. Cosmic Microwave Background (CMB)

- 2013: detailed CMB image was taken by Planck satellite.
- CMB covers all the universe and can be detected in every direction.
- It belongs to the time when universe became neutral for the first time.
- CMB confirm the existence of DM.



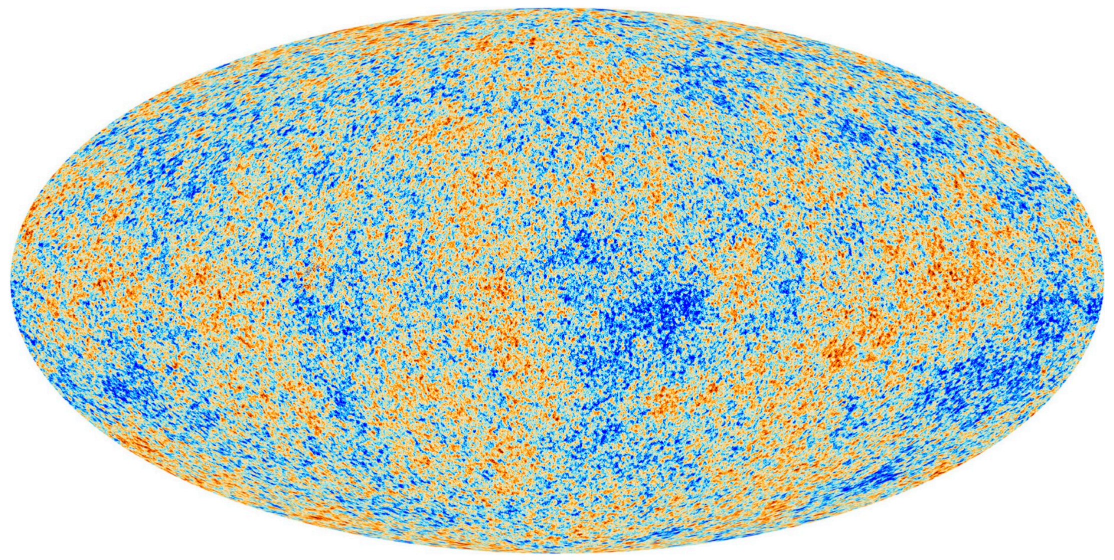
https://www.esa.int/ESA_Multimedia/Images/2018/07/Planck_s_view_of_the_cosmic_microwave_background

Evidences

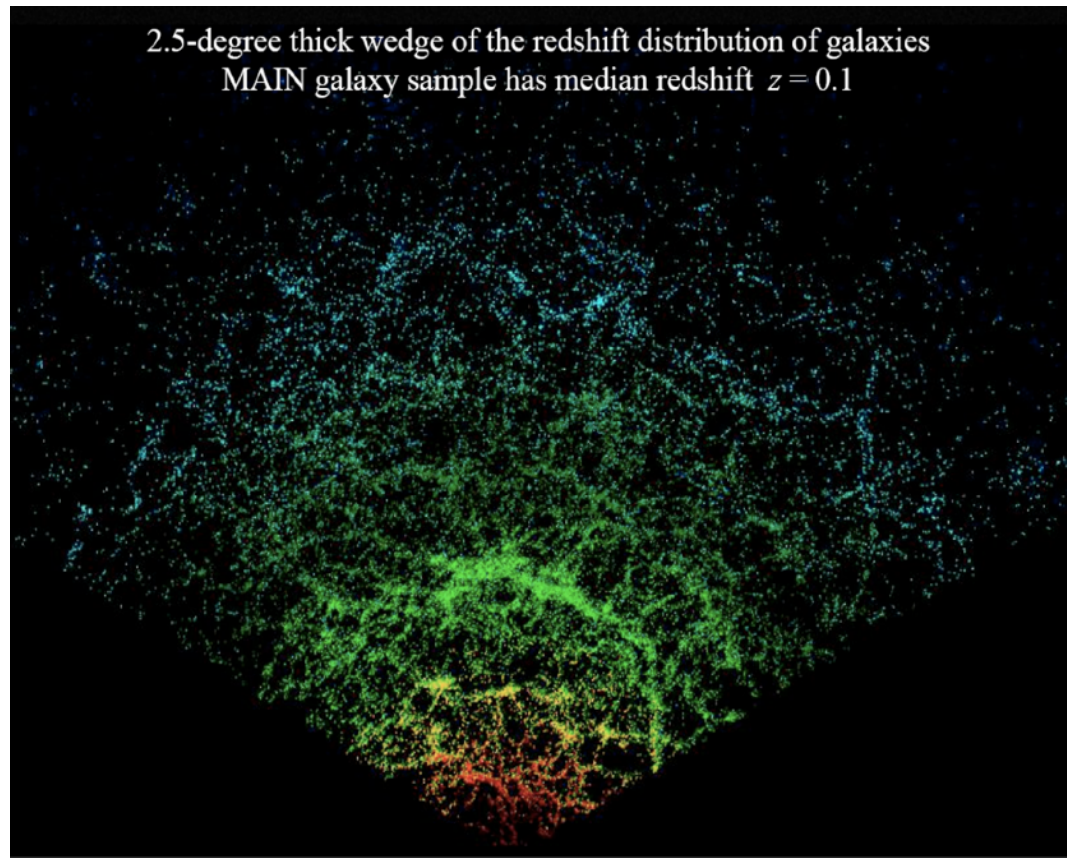
5. Structure formation

Density Contrast	Time
10^{-5}	380,000 years
$> 10^3$	13.8 billion years

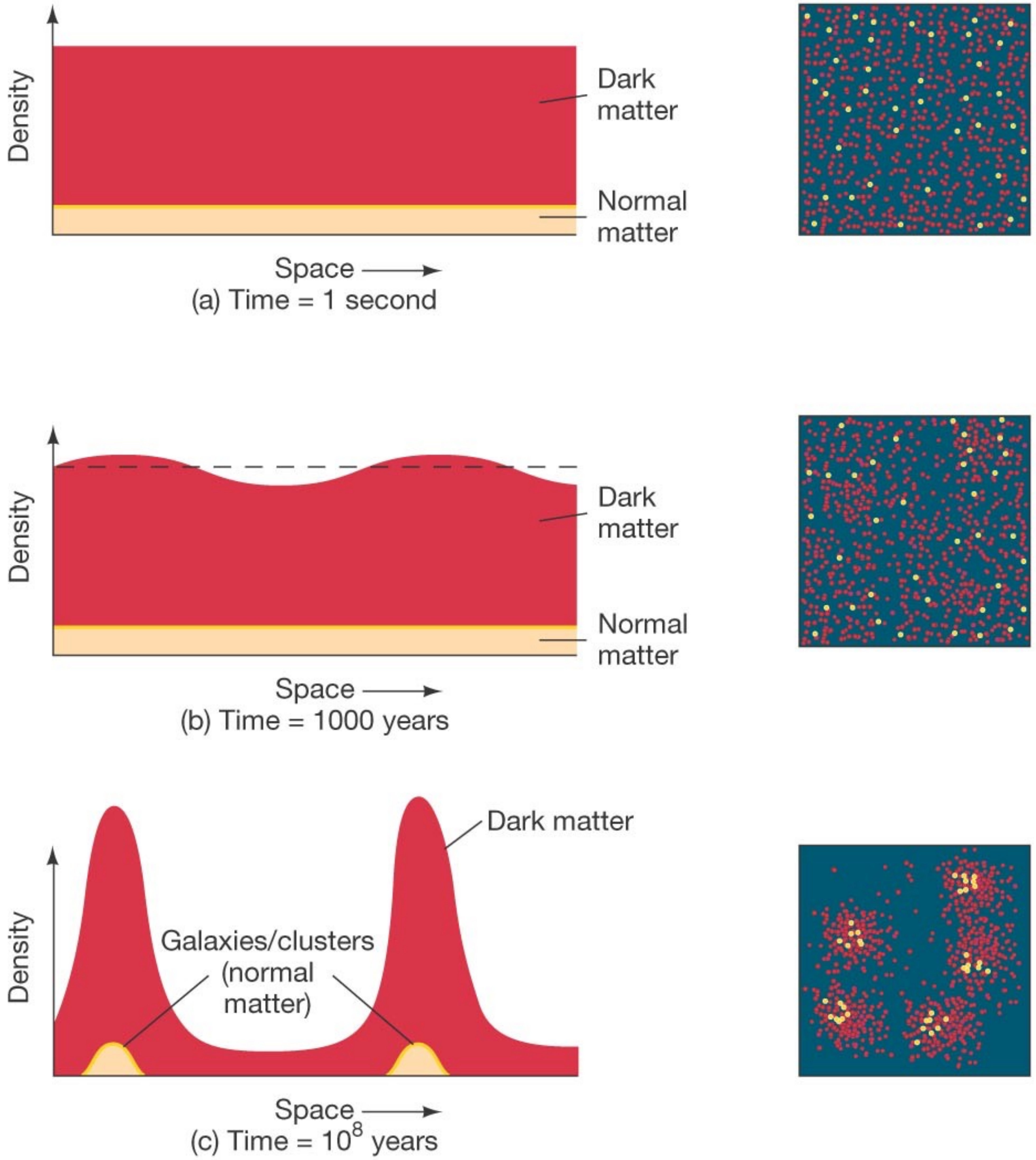
CMB



Cosmological Model



https://www.sdss.org/



Cosmological Origin of DM

DM is assumed as a thermal relic from the hot early universe

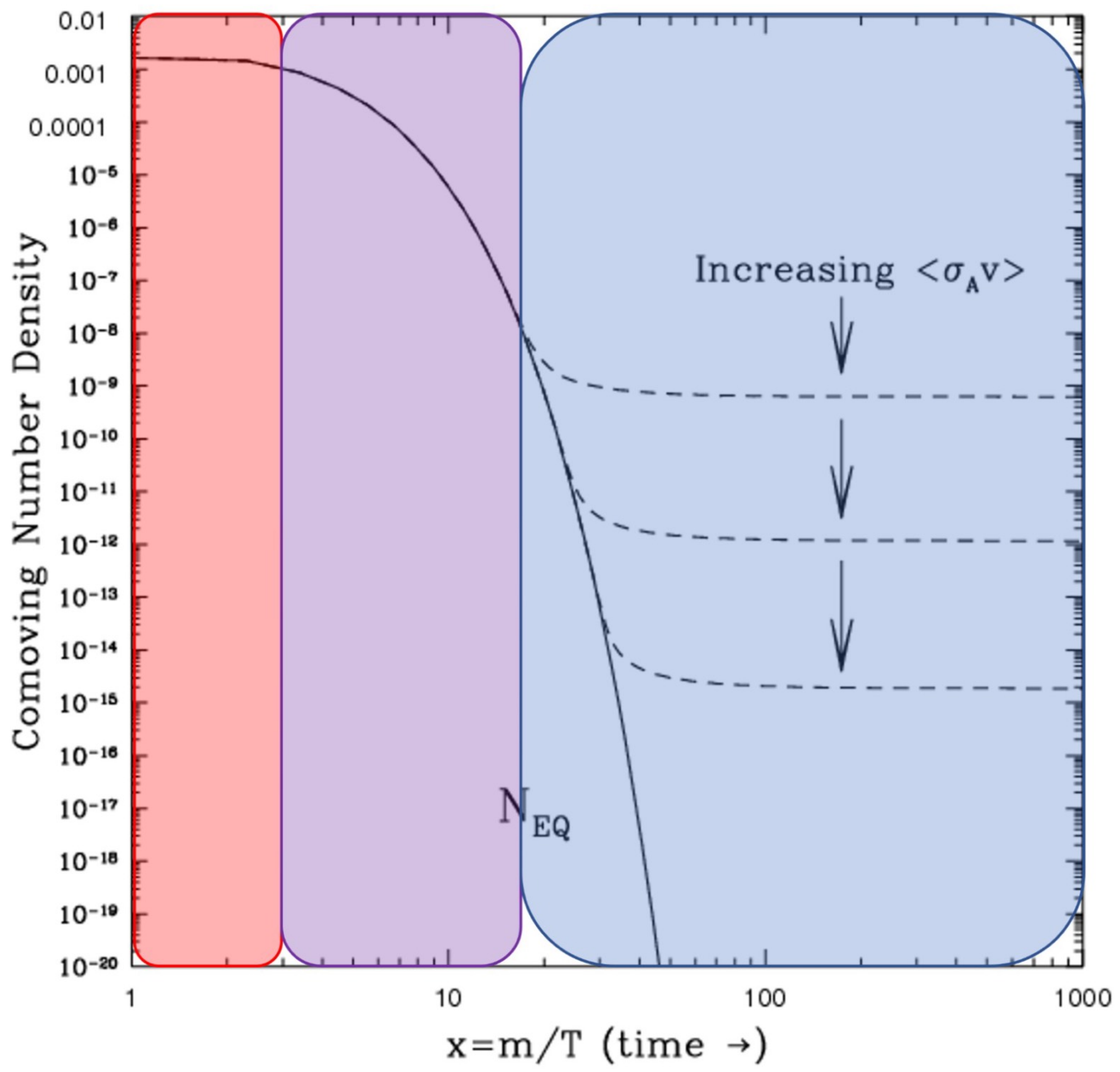
- Step 1: dark matter is in thermal equilibrium with the particle bath

$XX \longleftrightarrow ff$

- Step 2: no further production of DM, but there is still annihilation.

$XX \longrightarrow ff$

- Step 3: DM density becomes constant (freeze out)



https://www.particlebites.com/?p=7004

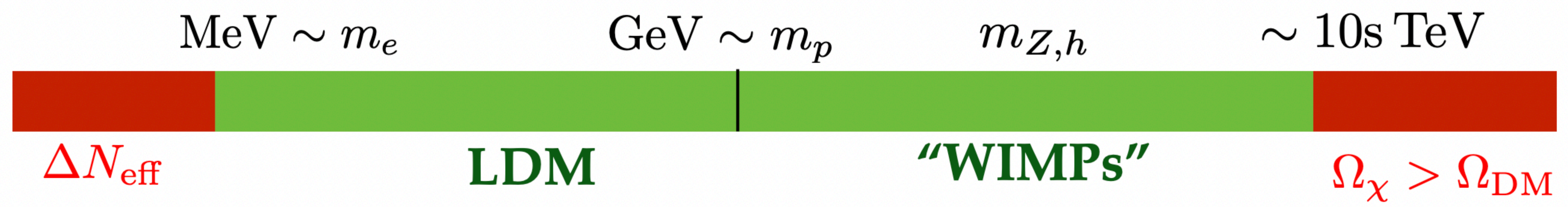
DM Mass Range

LDM & WIMPs

- Using quantum mechanics calculations and the observed density of the universe, it can be shown that a stable elementary particle which was once in thermal equilibrium cannot have a mass greater than 340 TeV.

$$\Omega_{DM} \propto < \delta\nu >^{-1} , < \delta\nu > \propto m_{DM}^{-2} \implies \Omega_{DM} \propto m_{DM}^{2}$$

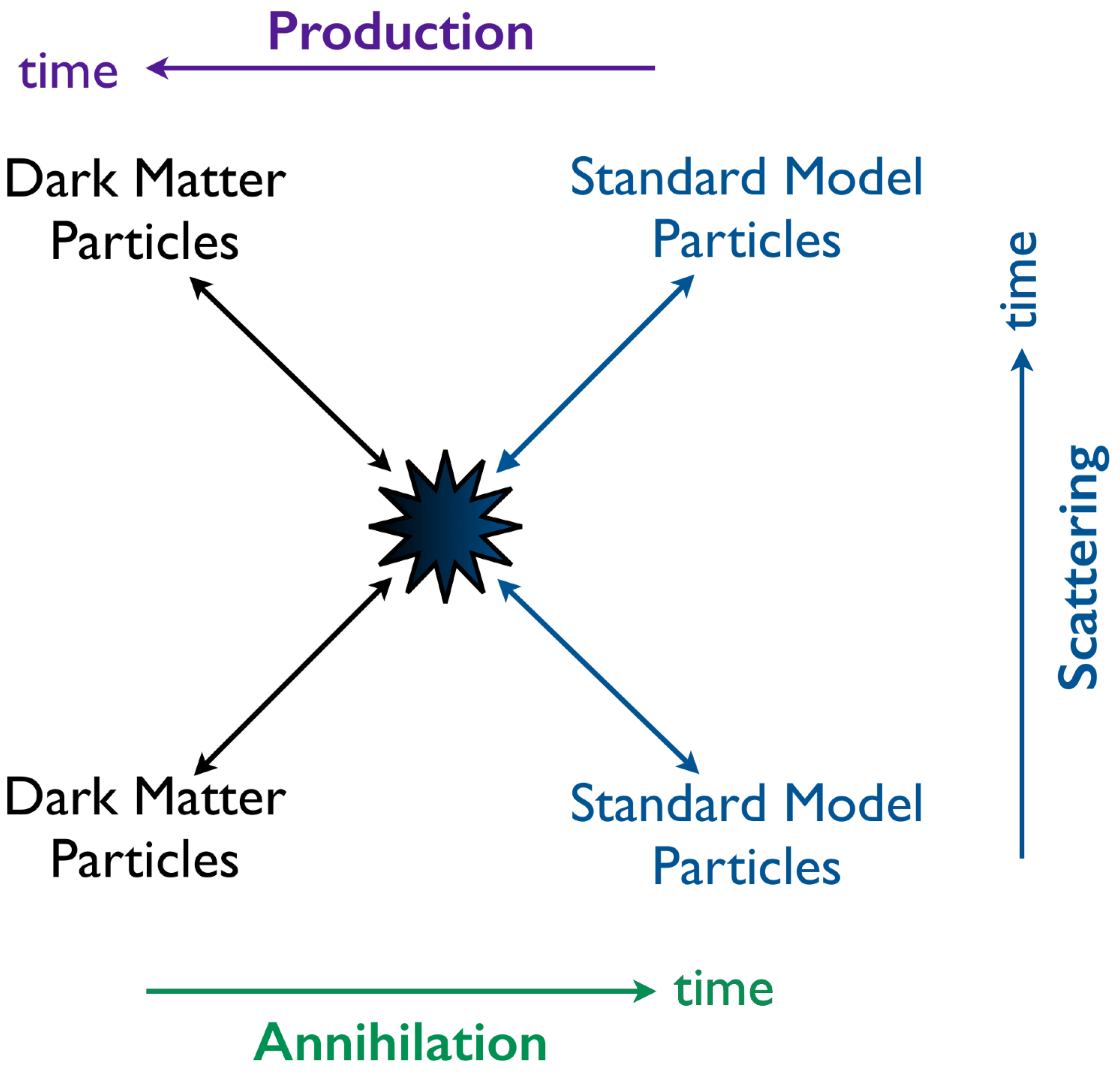
- Comparing the simulation results with observed matter power Spectrum of the universe, it is shown that masses below 10 keV are not allowed.



Search for the Dark Matter

Three main experimental approaches

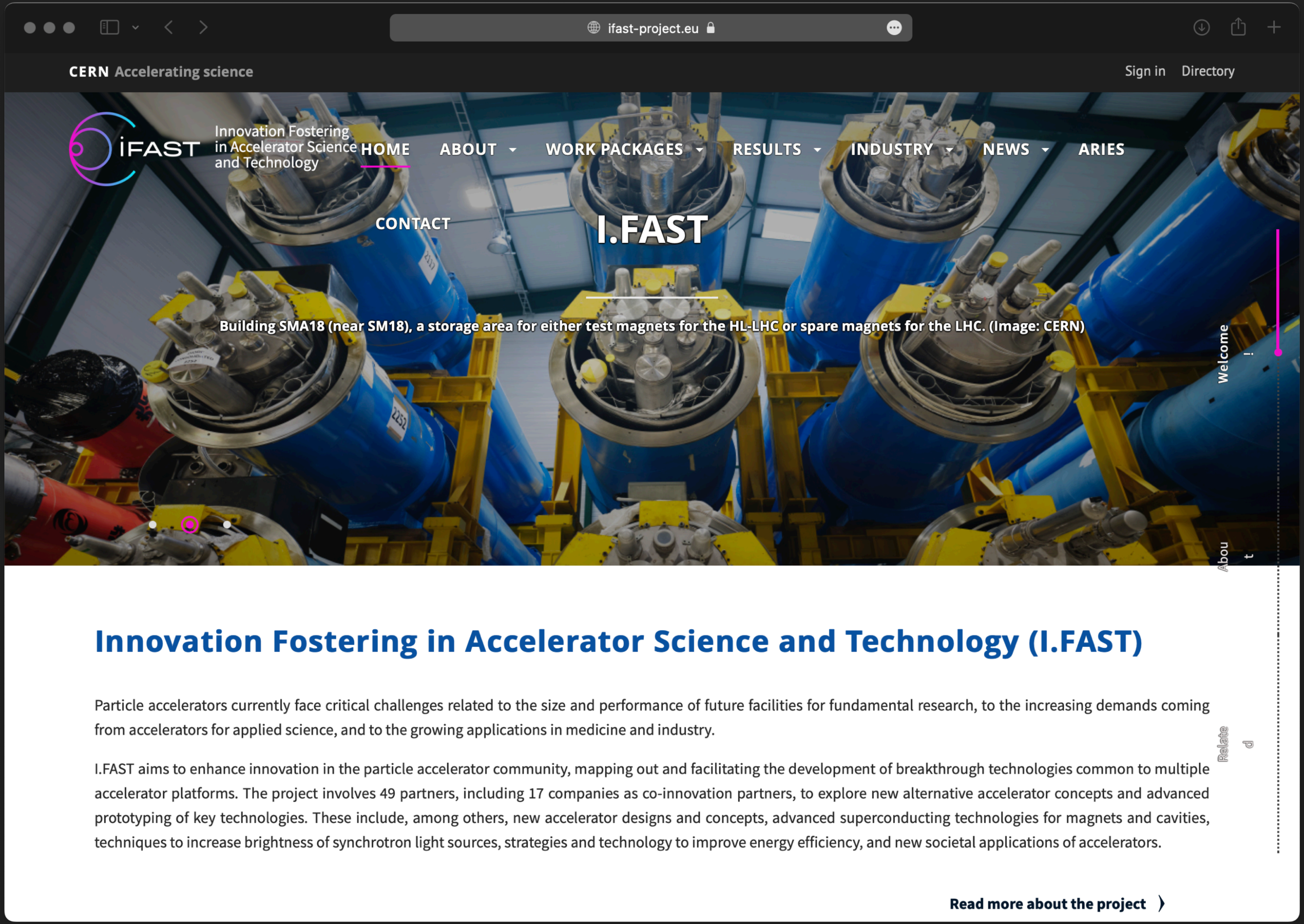
- **DM scattering** from normal matter
- Analysing astrophysical signals from **DM annihilation**
- **DM production** in particle accelerators



https://particleastro.brown.edu/dark-matter/

iFAST

- Collaborative project, funded by the EU
- Organized in work packages



iFAST WORK PACKAGES

- WP1: Management
- WP2: Communication
- WP3: Industry engagement
- WP4: Innovation, materials
- WP5: R&D strategies
  - 5.1 Muon colliders
  - 5.2 Pushing Accelerator Frontiers
    - 5.2.1 Dark Sector Searches
    - 5.2.2 Artificial Intelligence
  - 5.3 Improvement of Resonant slow Extraction spill quality
- WP6: Novel concepts
- WP7: Light sources
- WP8: Magnets
- WP9: Cavities
- WP10: Technologies
- WP11: Sustainability
- WP12: Applications
- WP13: Technology infrastructure
- WP14: Ethics requirements

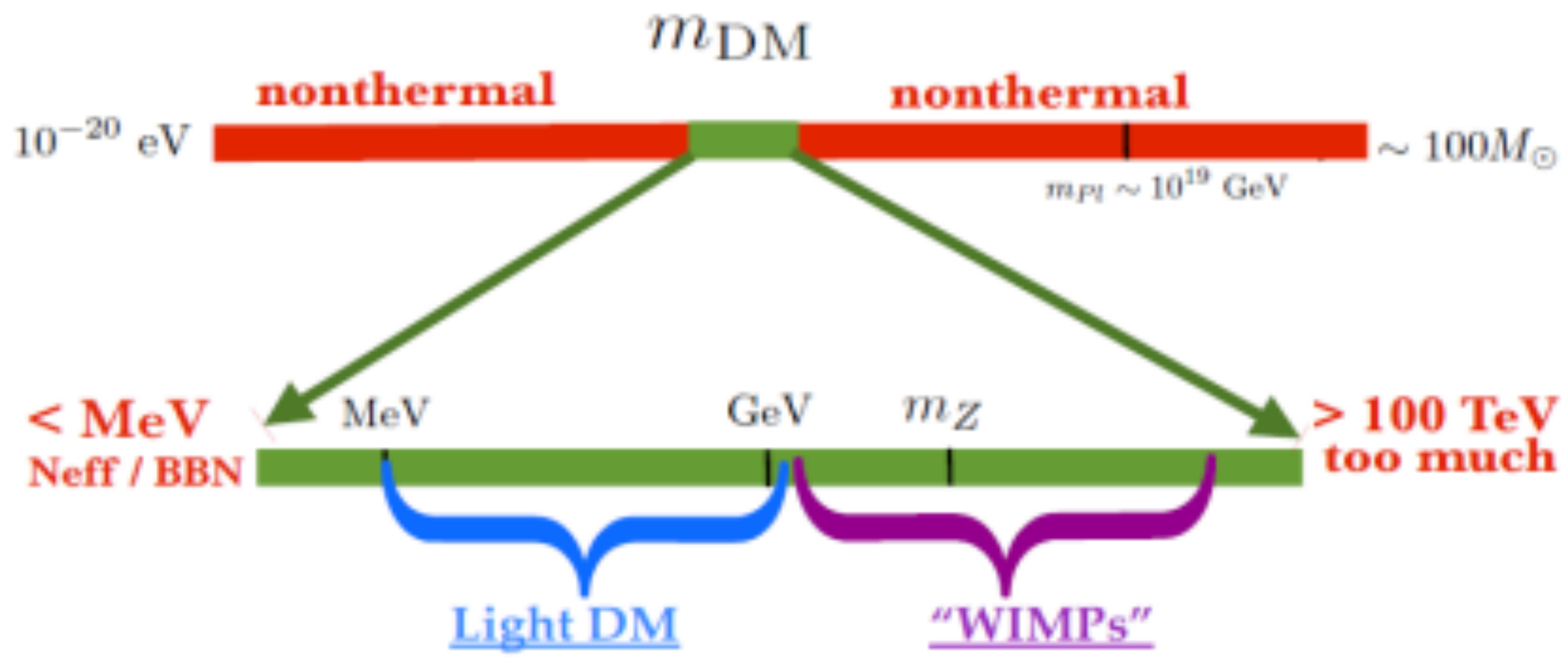
https://indico.cern.ch/event/1133593

DARK MATTER

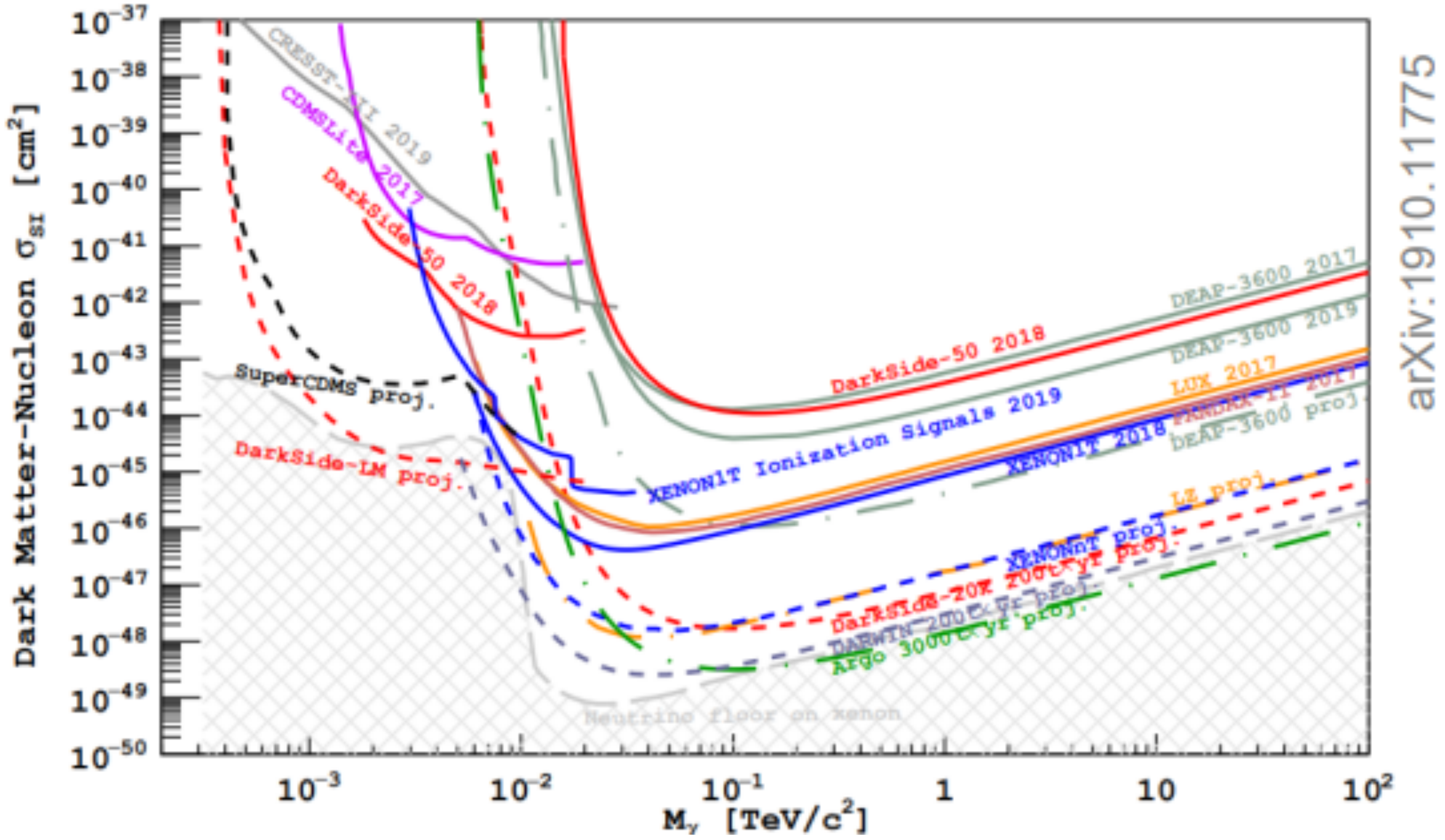
- Hidden Sector : Any Particles engaging in Feebly (or no) Interactions (FIPs) with the SM particles
  - Fair (but not necessary) starting point: *Dark Matter*

- 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!)



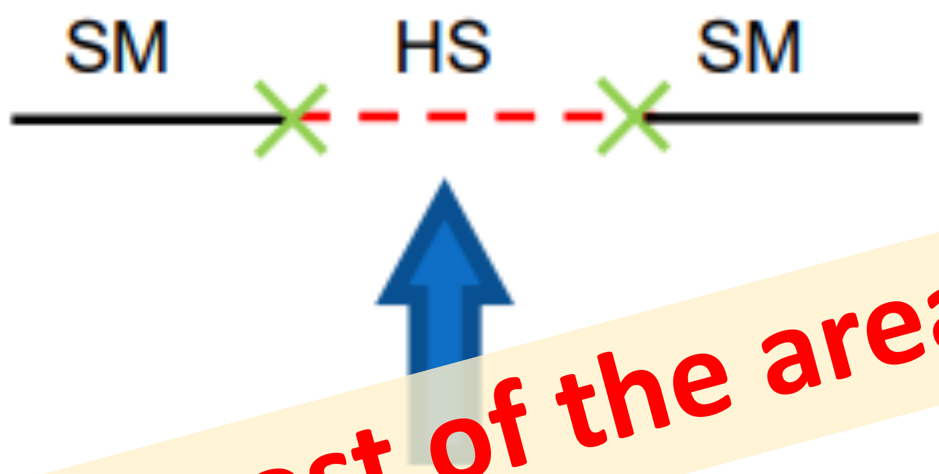
Direct searches for cosmic DM



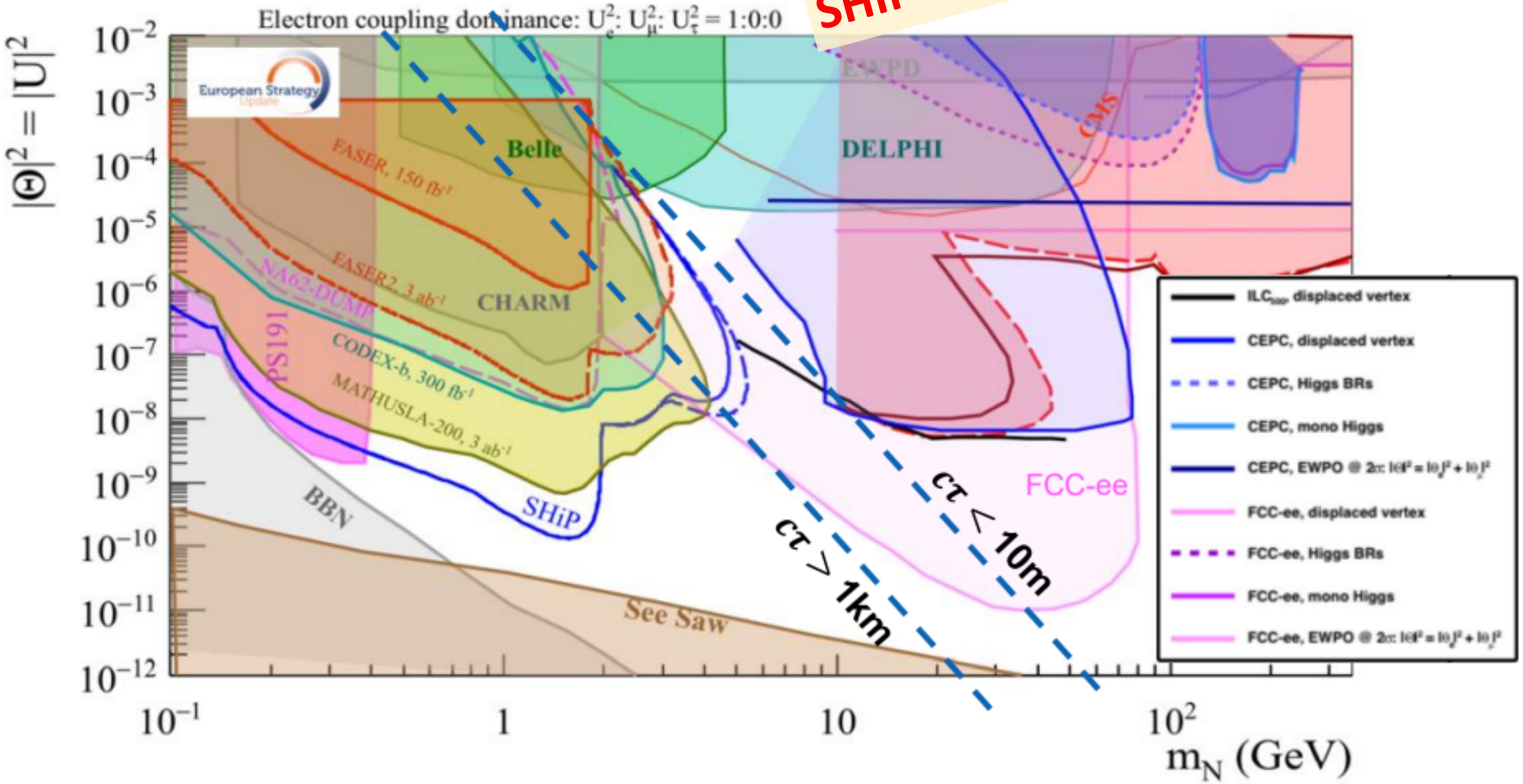
R. Jacobsson

- 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



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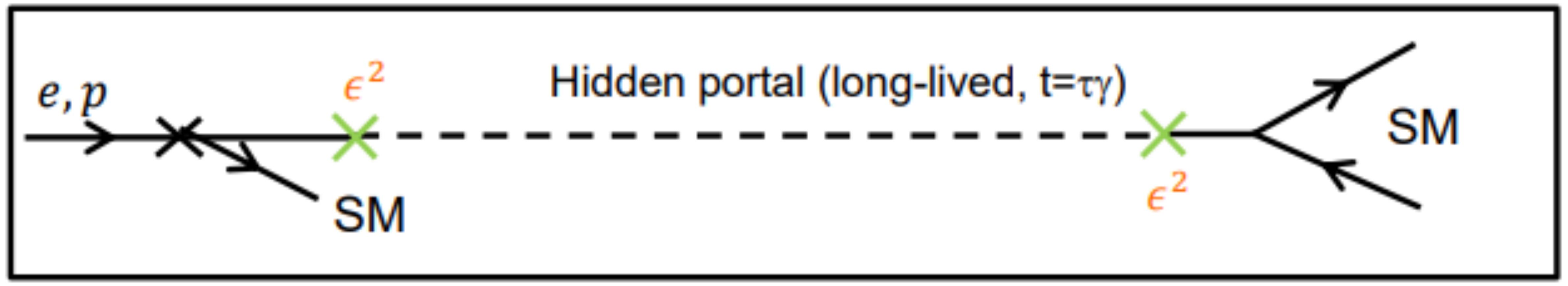
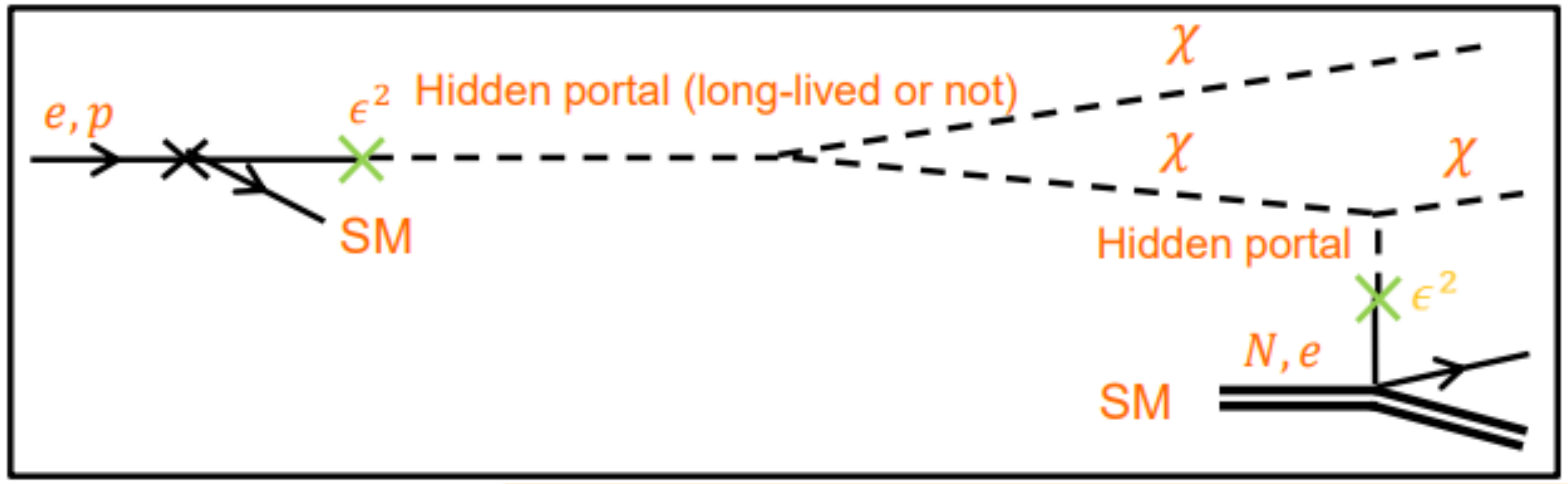
"Direct" (indirect visible)



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

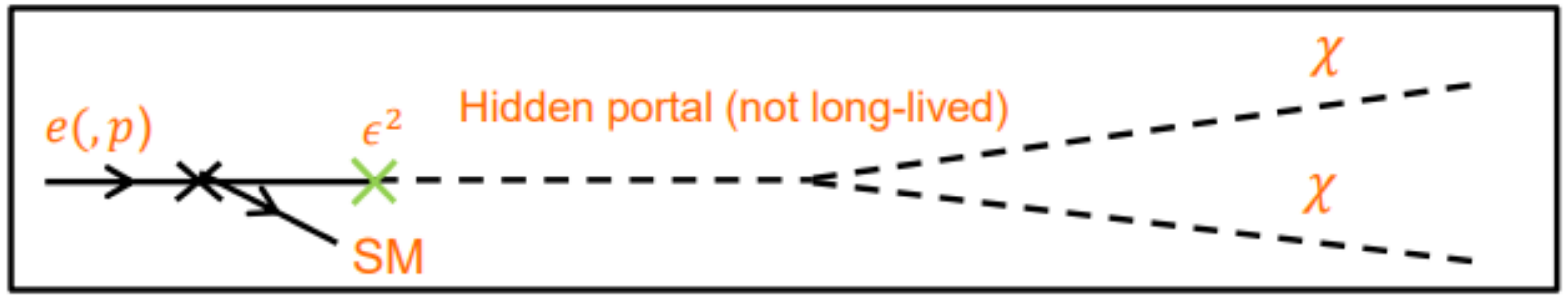
ϵ^4 dependence requires higher luminosity

➔ Background situation very different in the different techniques!

Indirect (invisible)

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

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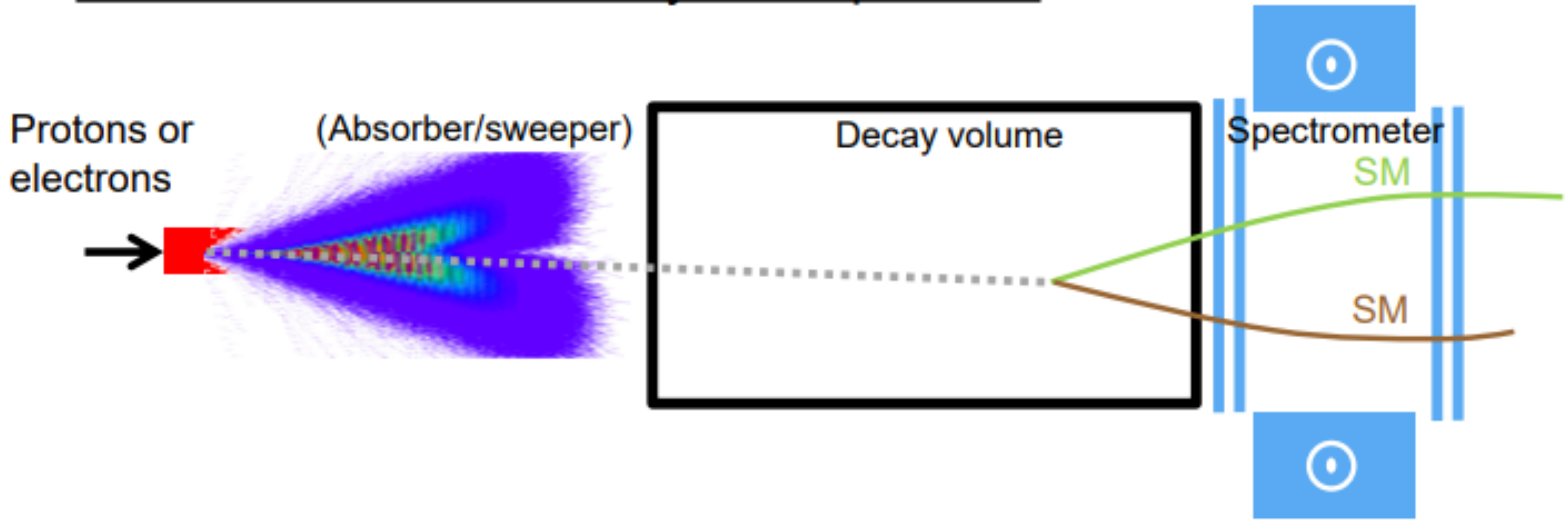
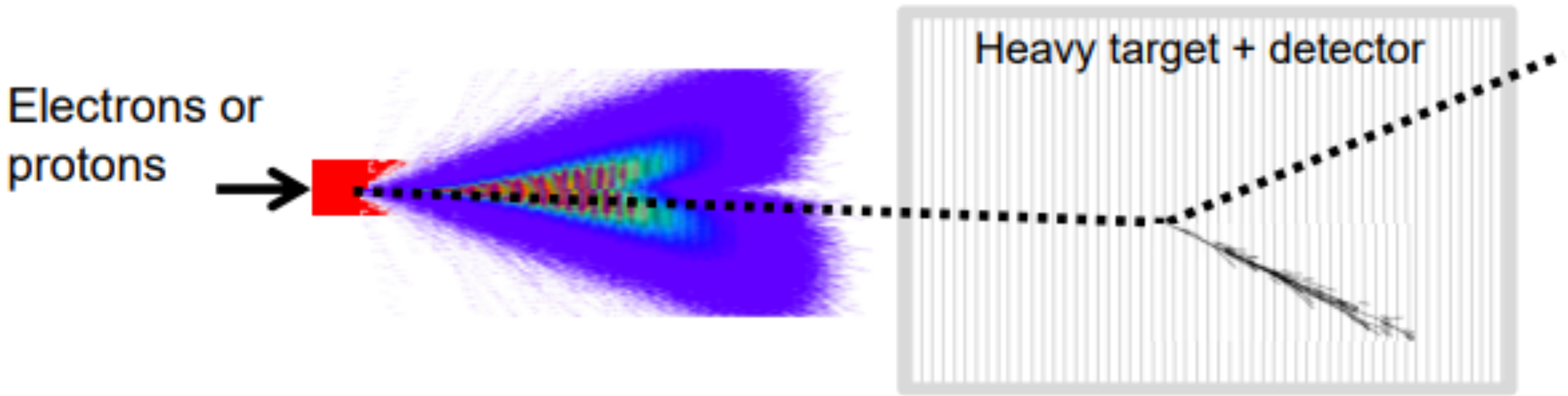
- Direct search: visible decay to SM particles



"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)

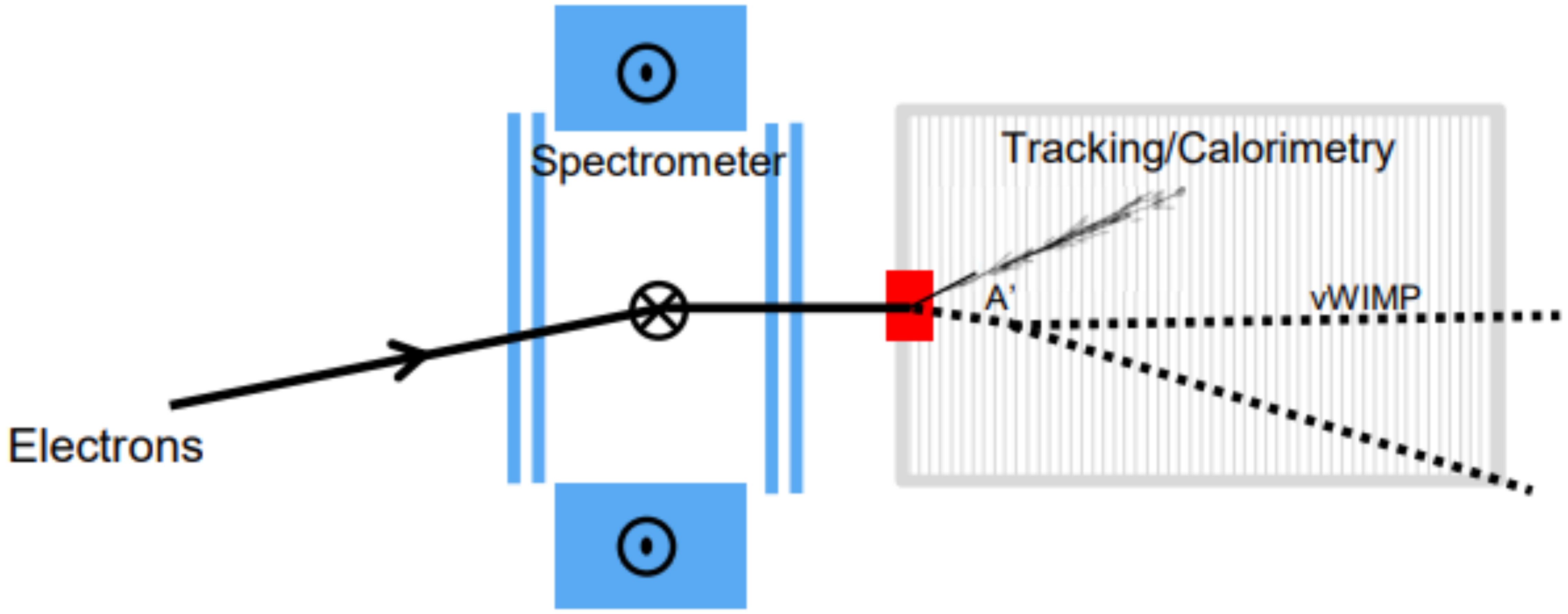
ATLAS, CMS, LHCb @LHC (no absorbers)
BELLE2@sKEKB (no absorber)
FASER@LHC
MATHUSLA@LHC (no spectrometer)

- 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^{12})
LDMX@SLAC/CERN (e@4-8/16, 10^{14} –

here advanced accelerators could play important role !

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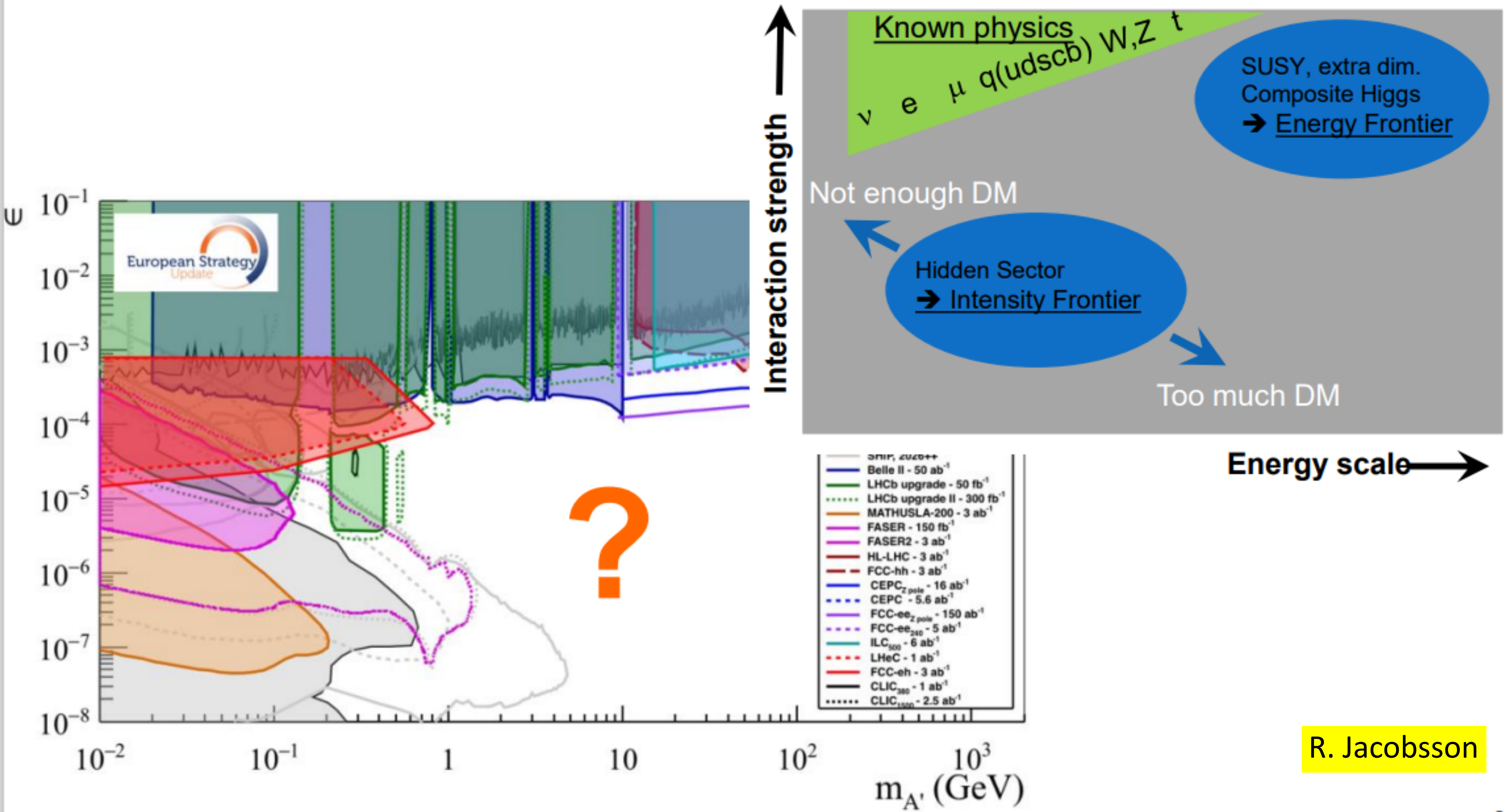
- Large number of options and huge parameter spaces
  - All parameter spaces have their "unreachable" regions, even physically attractive regions!

➔ Theoretical model building and cosmofrontier are essential guides!



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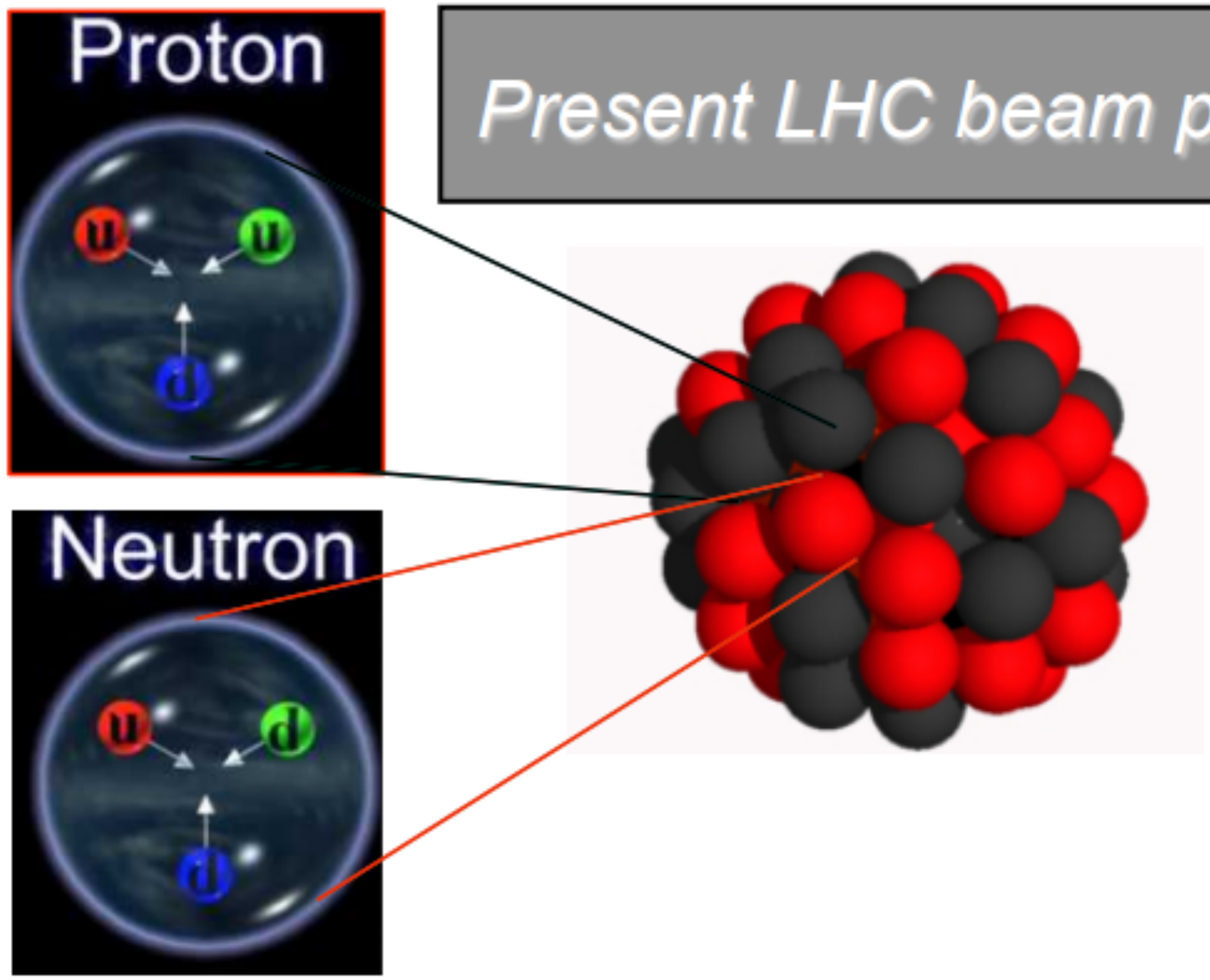
OPTIONS FOR LHC BEAMS

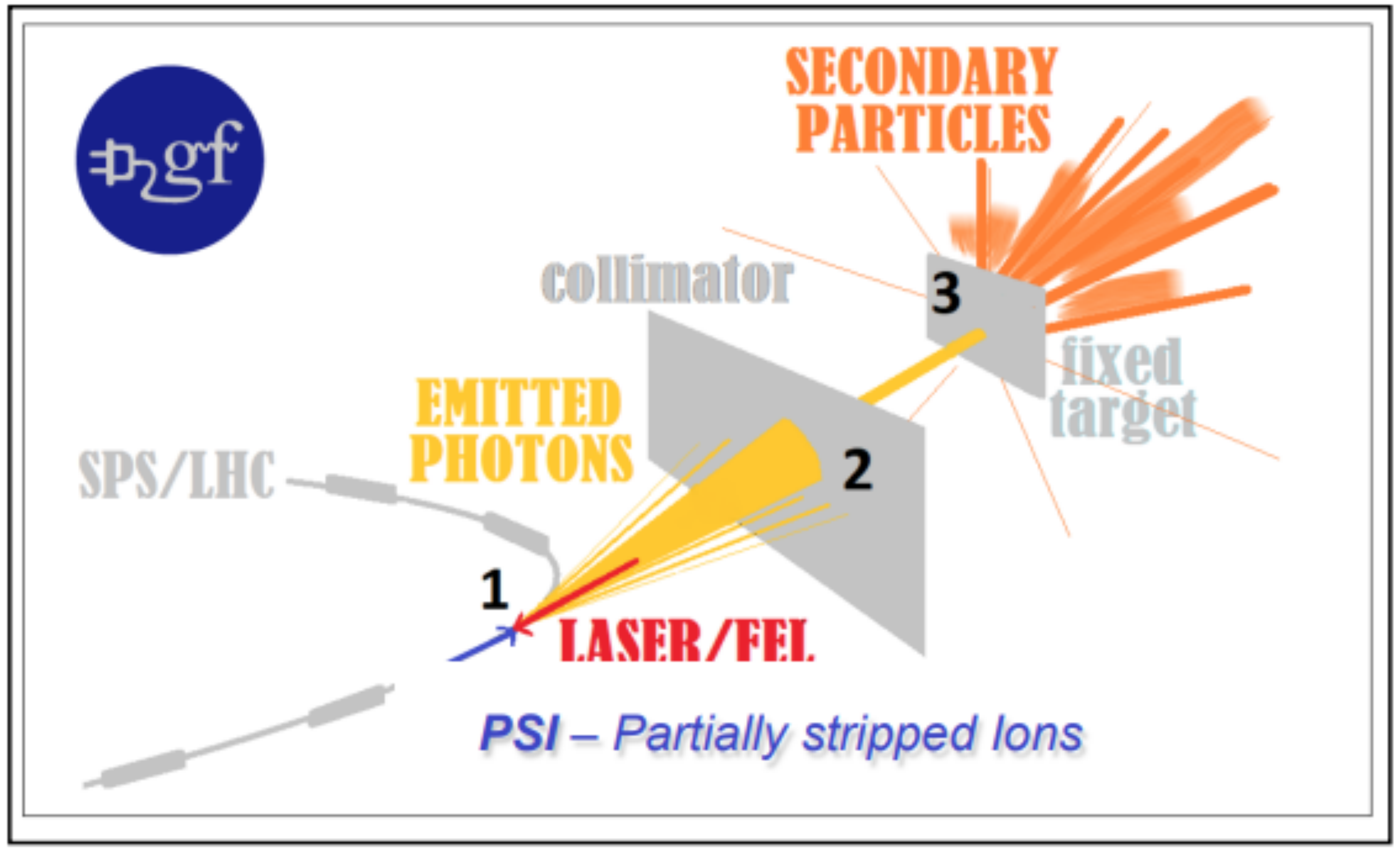


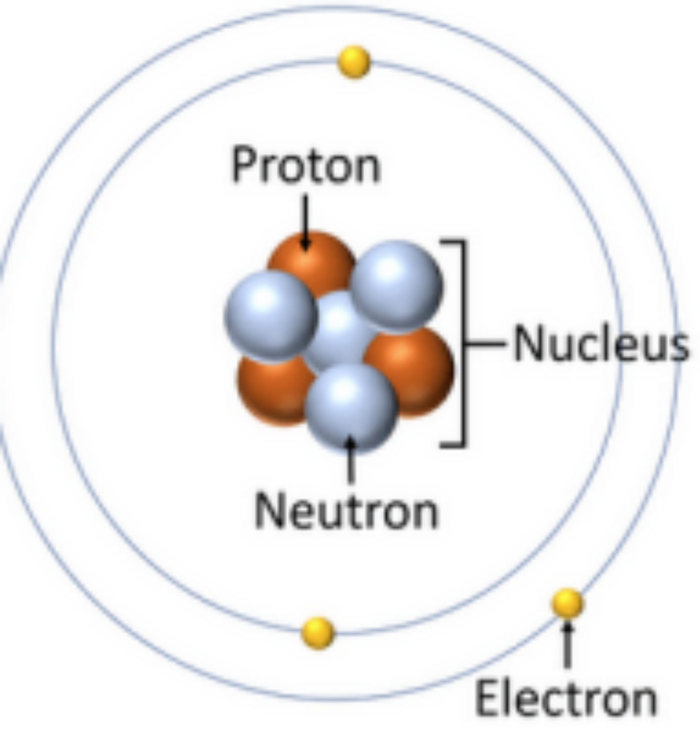
Present LHC beam particles:

The Gamma Factory proposal for CERN

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

e-Print: 1511.07794 [hep-ex]



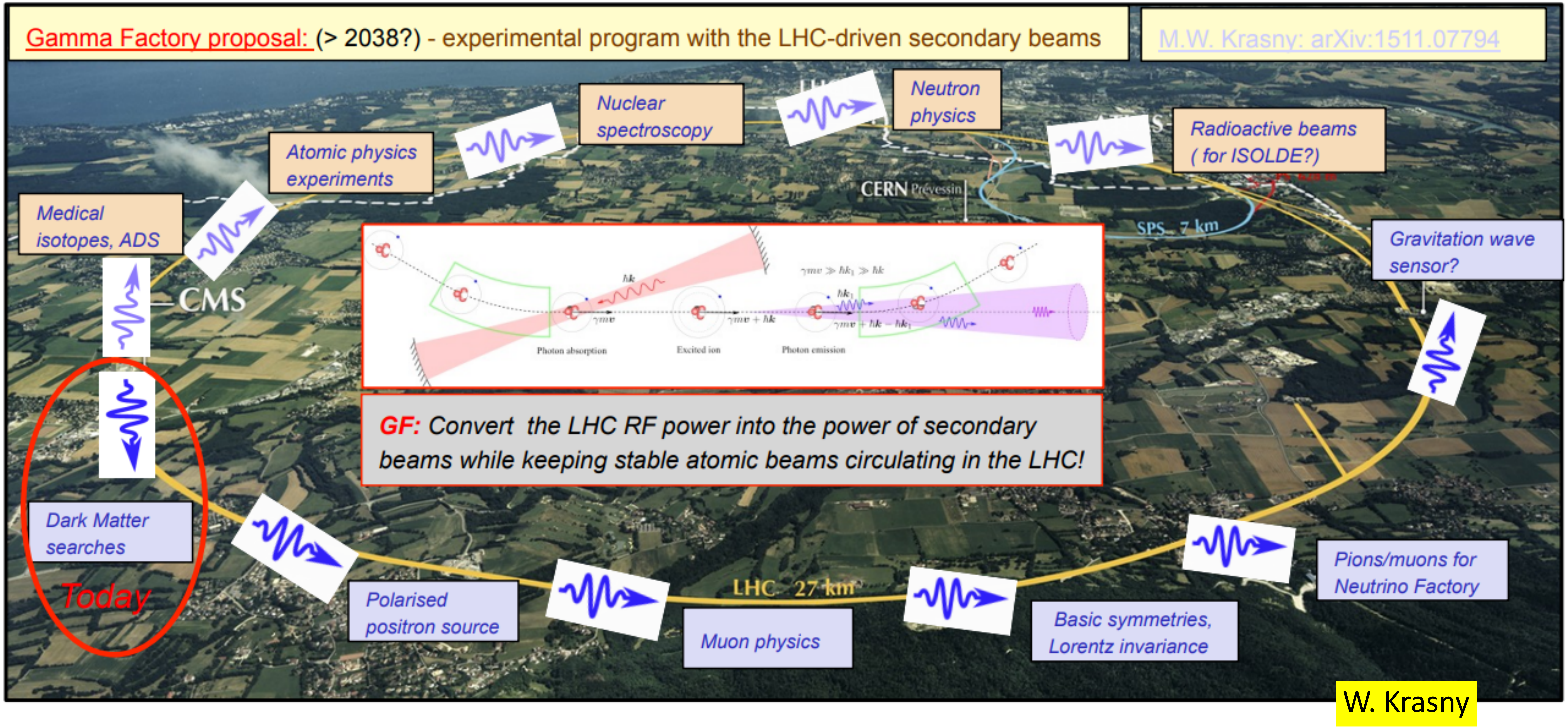


Future LHC beam particles:

Partially Stripped Ions (highly ionized atoms)

W. Krasny

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

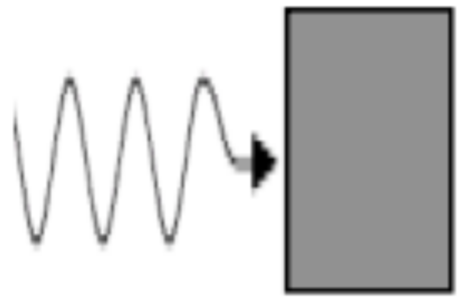


DM searches (and studies): Axion-Like-Particles (ALP) example

Collision schemes for ALP production:

Search phase	**"Production" phase**

γ_{GF} – B field
m_{ALP} < 1 keV



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

γ_{GF} – A collisions (LHC)
m_{ALP} ~ 10 MeV – 10 GeV

γ_{GF} – γ_{Laser} collisions
m_{ALP} ~ 1–100 keV

γ_{GF} – γ_{GF} collisions (LHC)
m_{ALP} ~ 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)

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

$$\gamma e \to eX$$

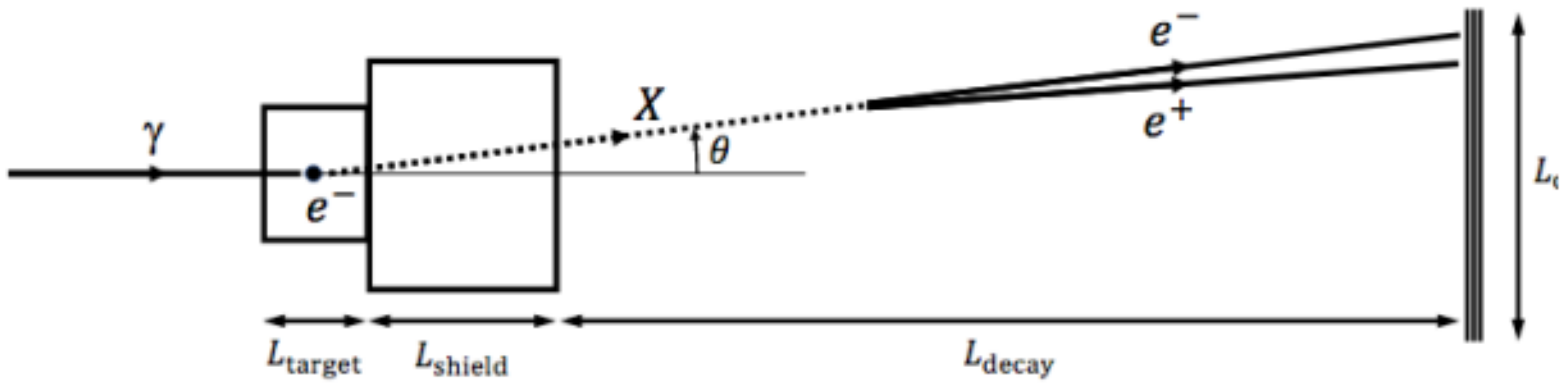


FIG. 1. **Experiment layout.** The experiment consists of a (graphite) target with thickn $L_{\rm target} = 1$ m, followed by a (lead) shield with thickness $L_{\rm shield} = 2$ m, an open air decay reg with length $L_{\rm decay}$, and a tracking detector, centered on the beam axis, which we take to 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,§]

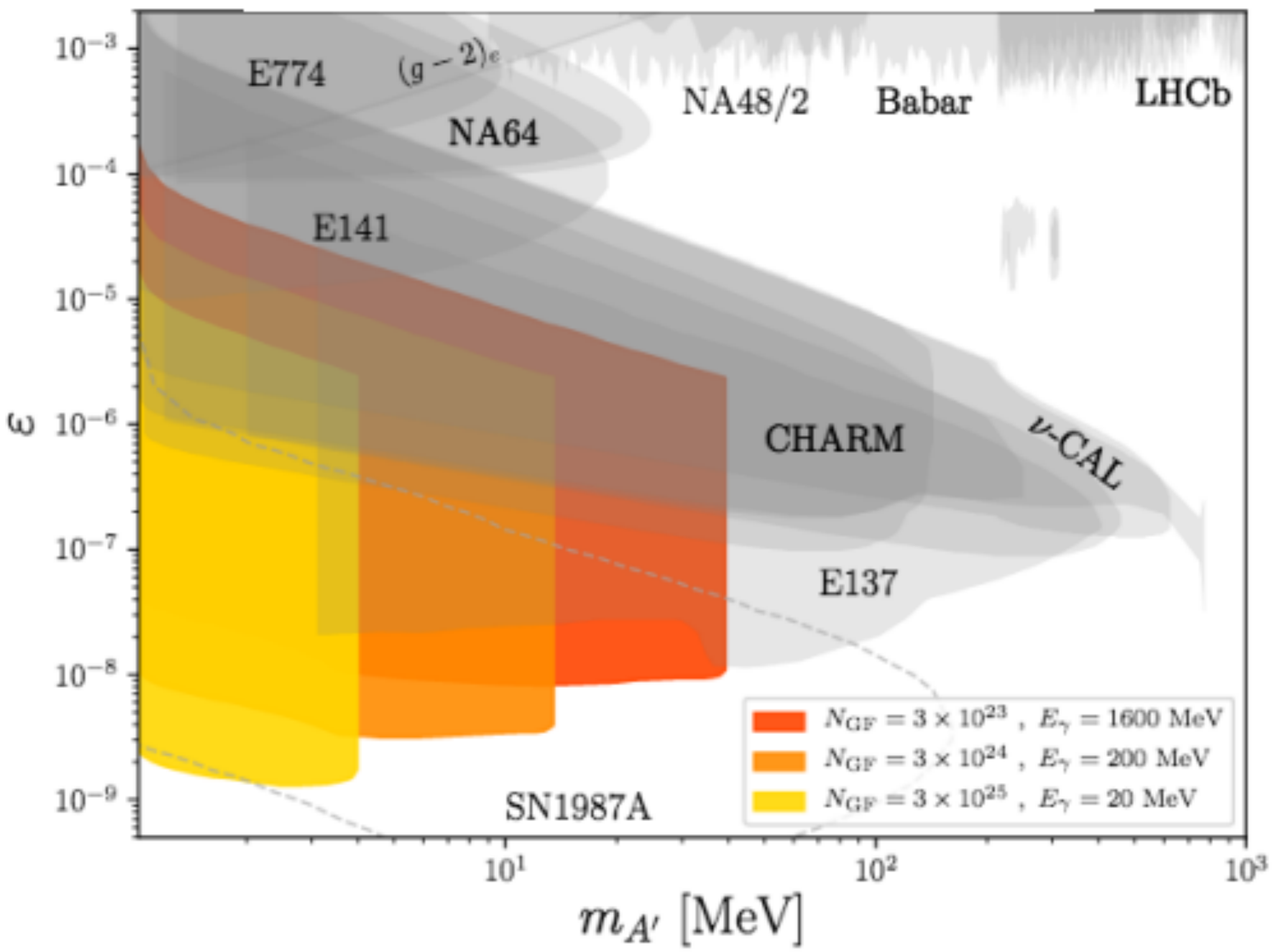
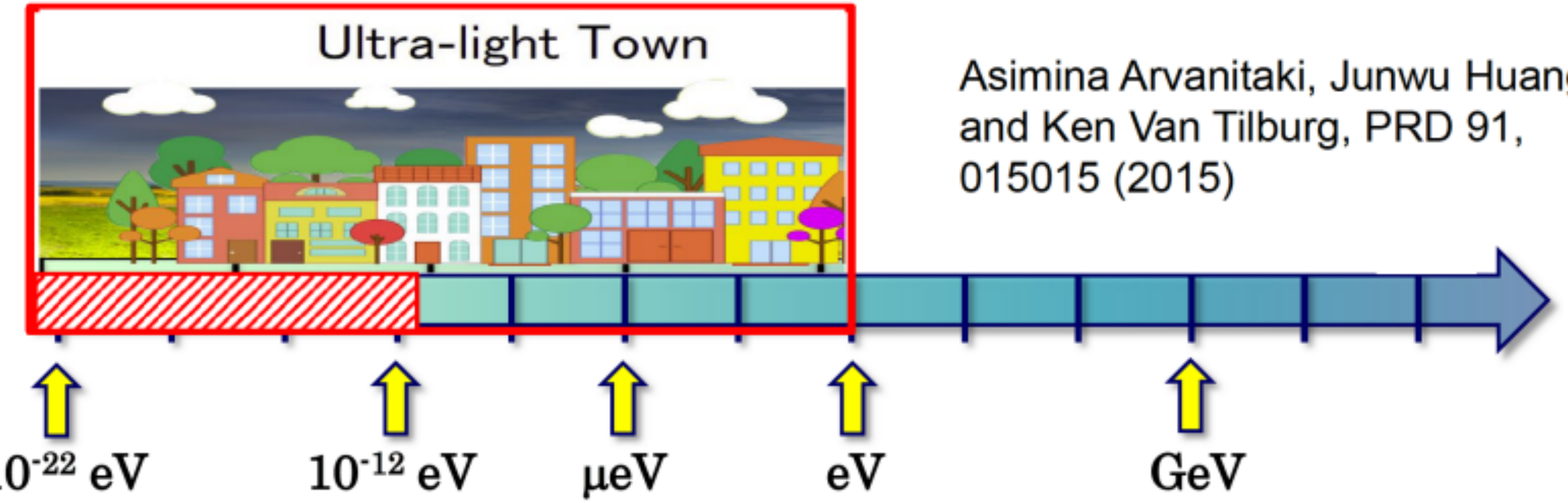


FIG. 3. **Dark photon sensitivity.** The sensitivity reach for the three sets of GF parameters $(E_\gamma, N_{\rm GF})$ indicated, each corresponding to a year of running, and detector parameters $L_{\rm decay} = 12$ m and $L_{\rm det} = 3$ m. The contours are for 3 e^+e^- signal events and assume no 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 $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \dots\right)$

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

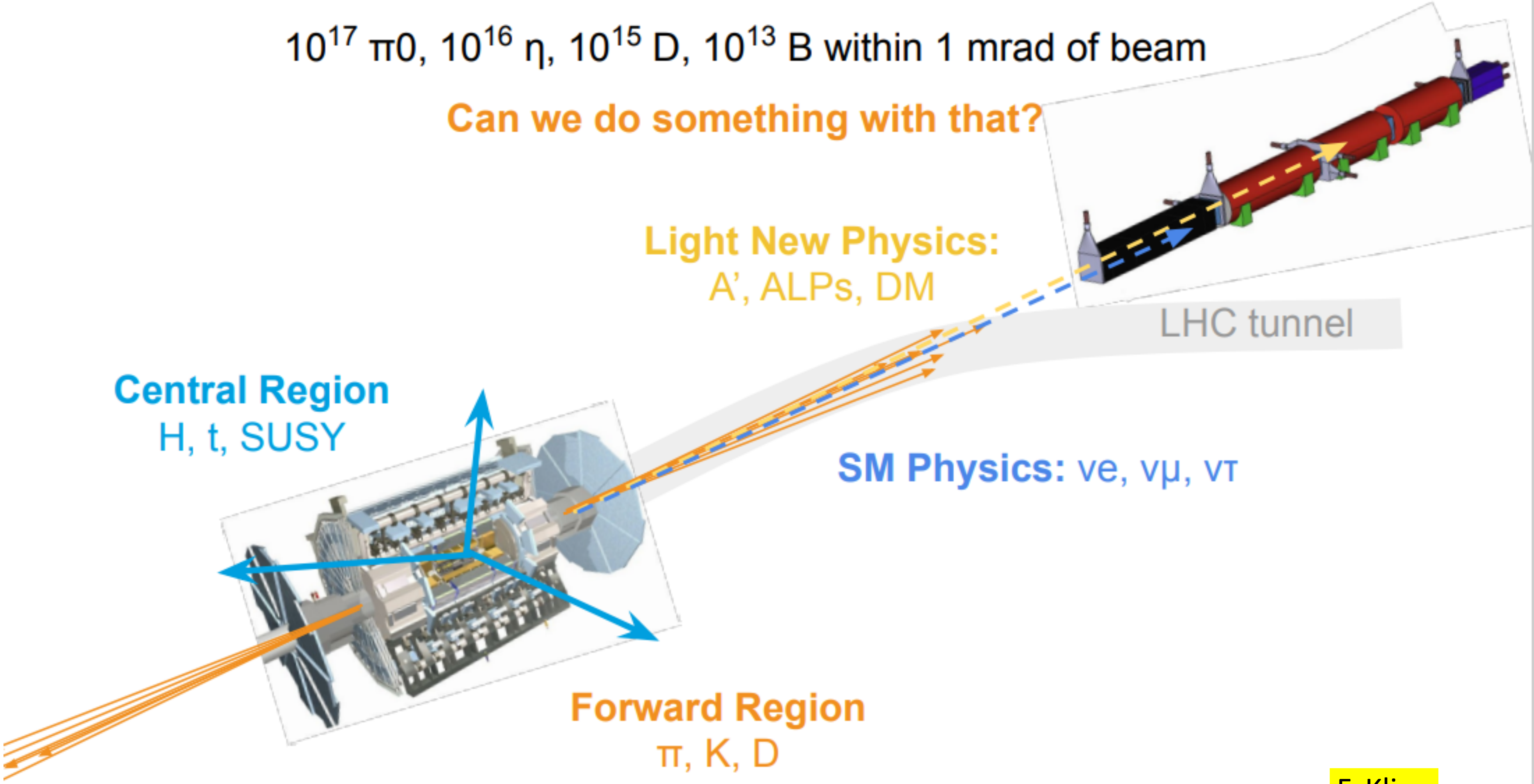
Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).

W. Krasny

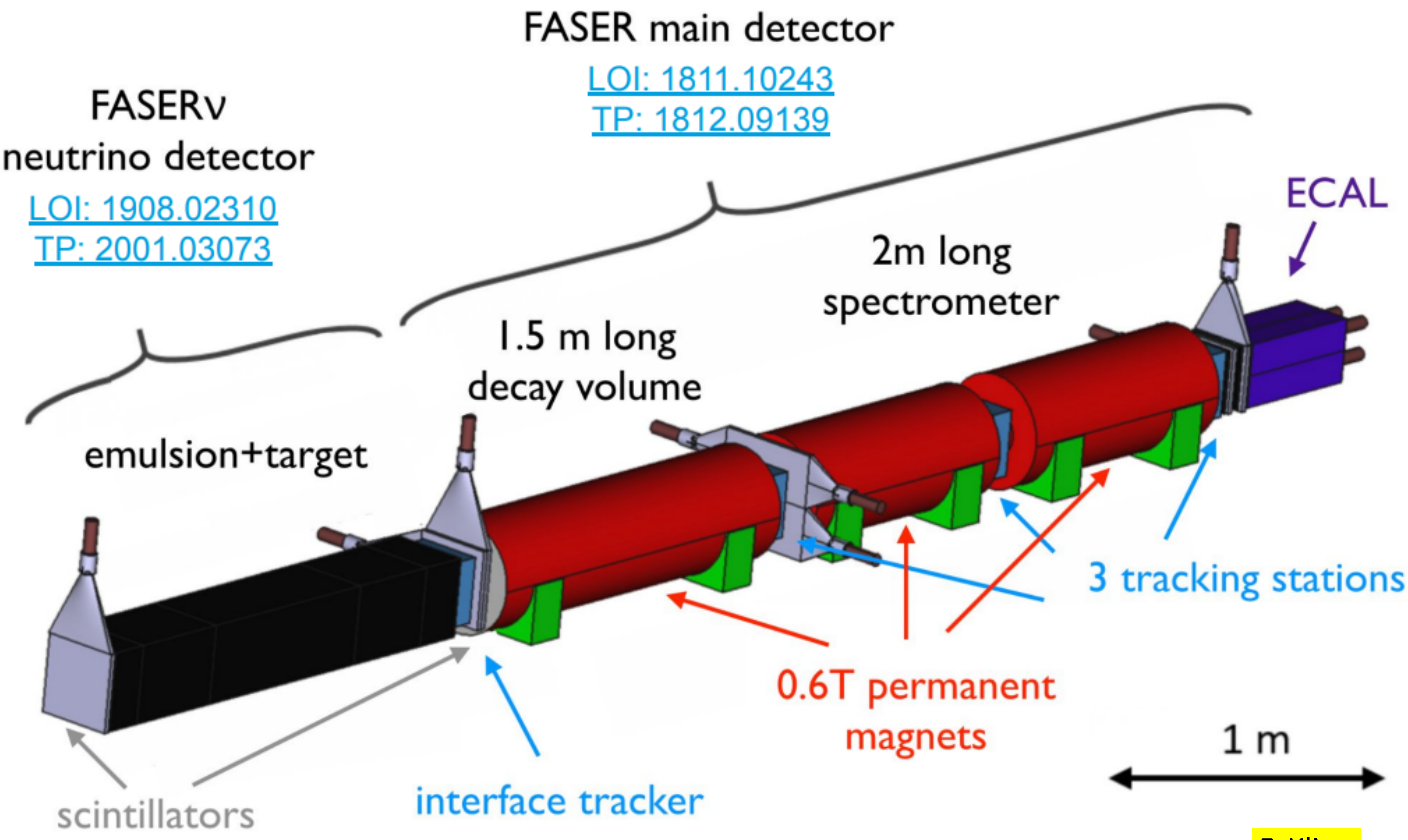
The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

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

Can we do something with that?

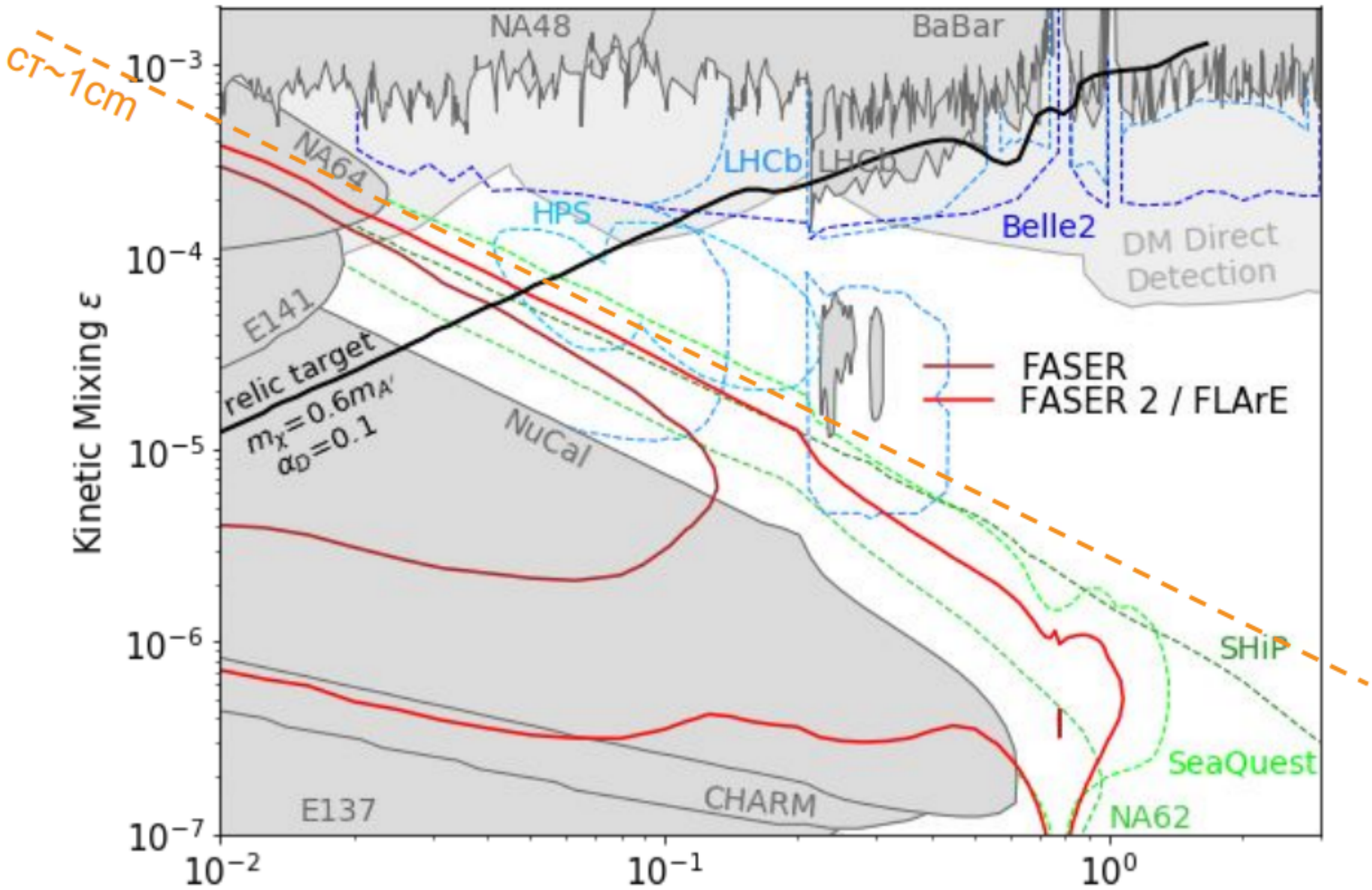


F. Kling



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

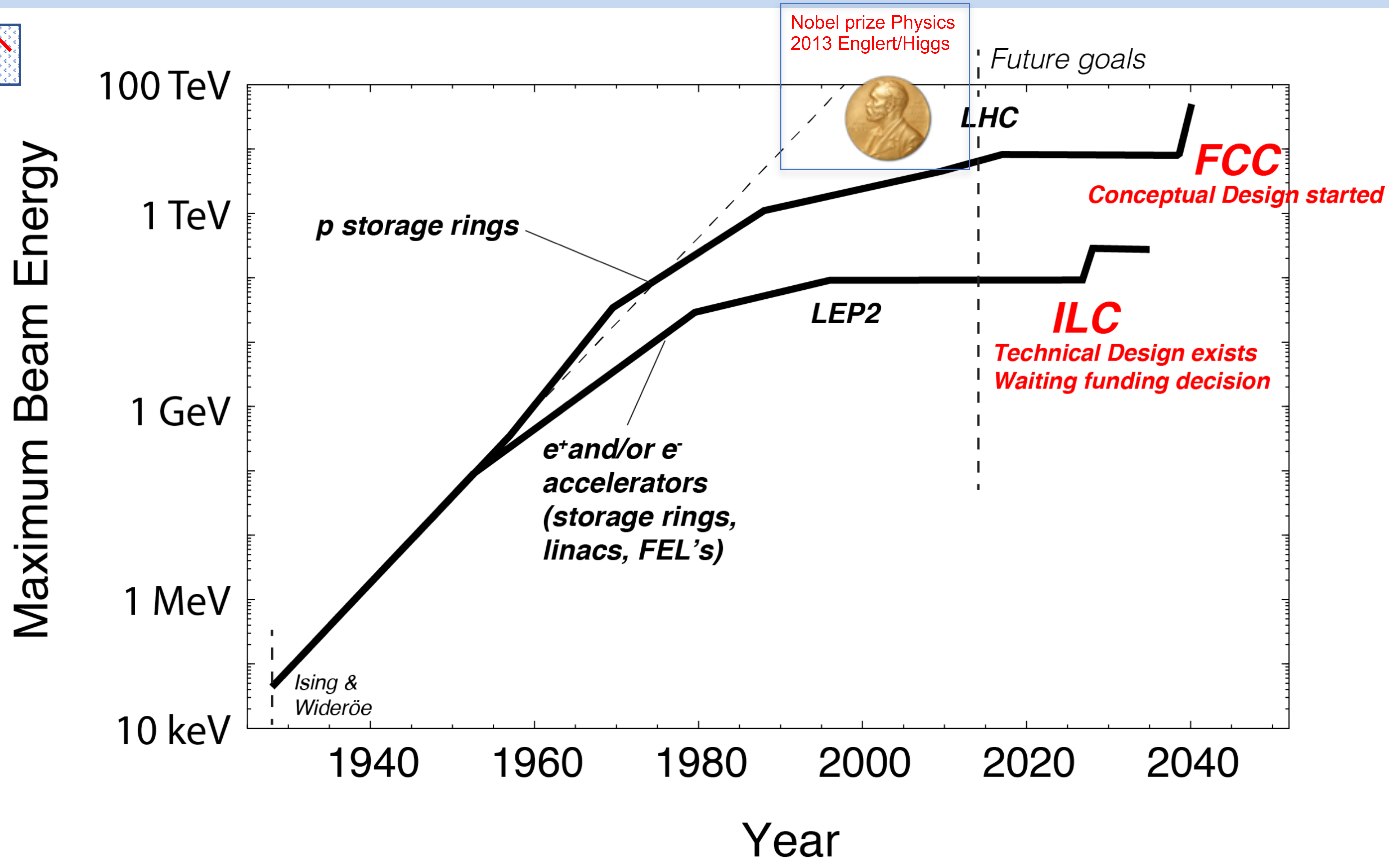


cτ~1cm
NA48
BaBar
NA64
LHCb
LHCb
HPS
Belle2
DM Direct Detection
E141
relic target
$m_\chi=0.6m_{A'}$
$\alpha_D=0.1$
NuCal
FASER
FASER 2 / FLArE
SHiP
SeaQuest
NA62
E137
CHARM
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]

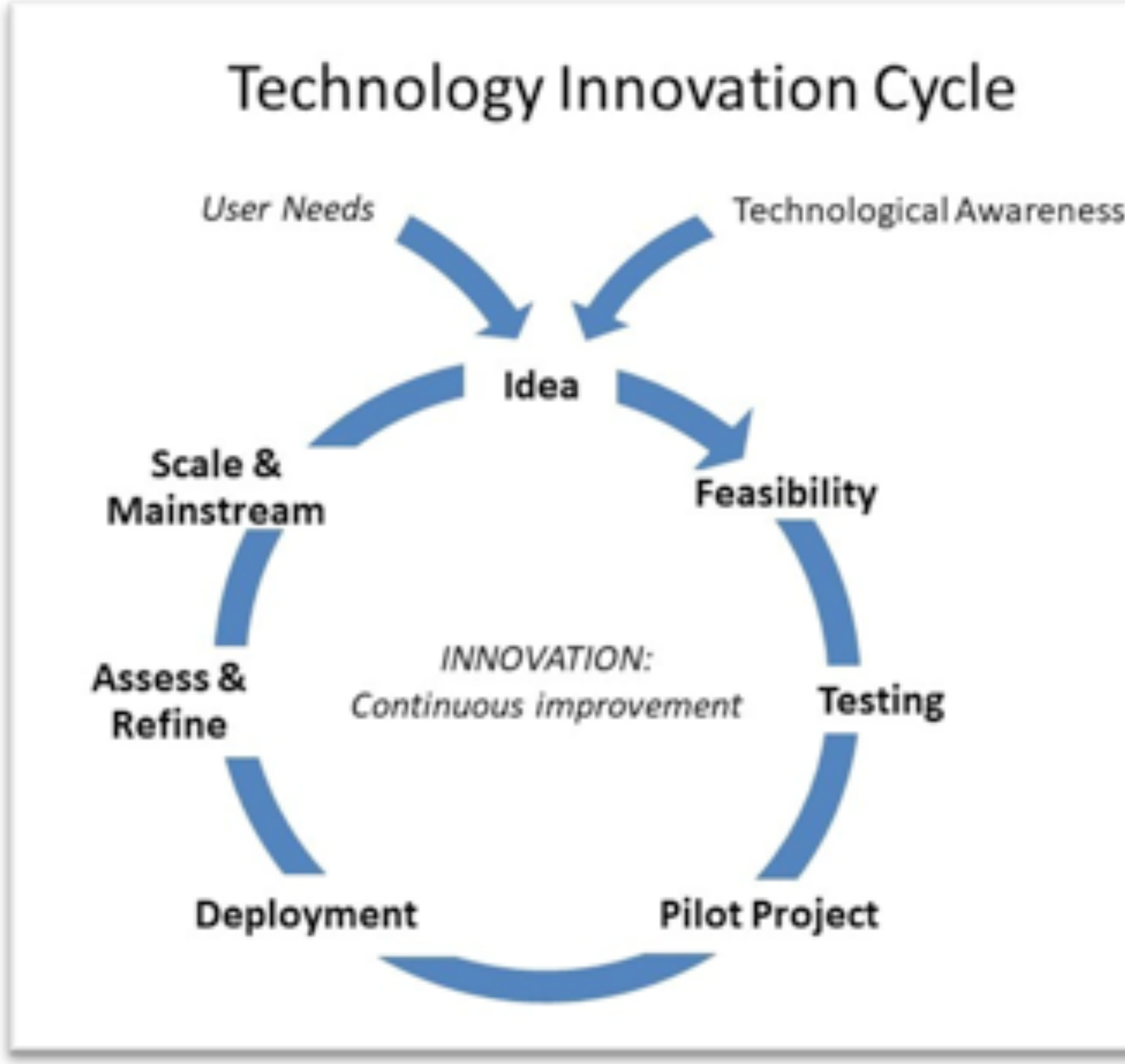
F. Kling

NOVEL ACCELERATORS

Livingston Curve: Success of RF Accelerators



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, …

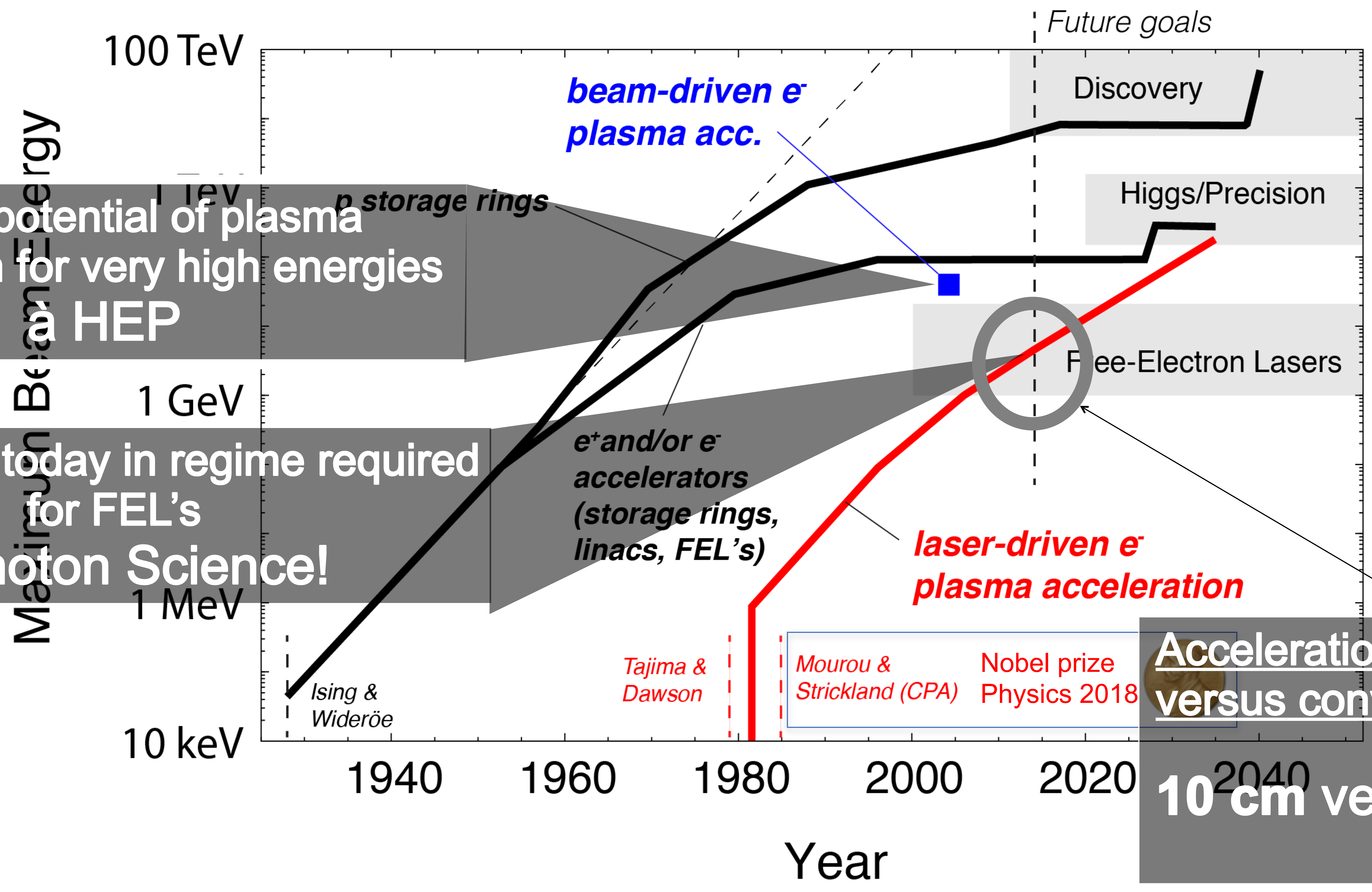


A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

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



Shows potential of plasma acceleration for very high energies à HEP

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

Acceleration length (new versus conventional):

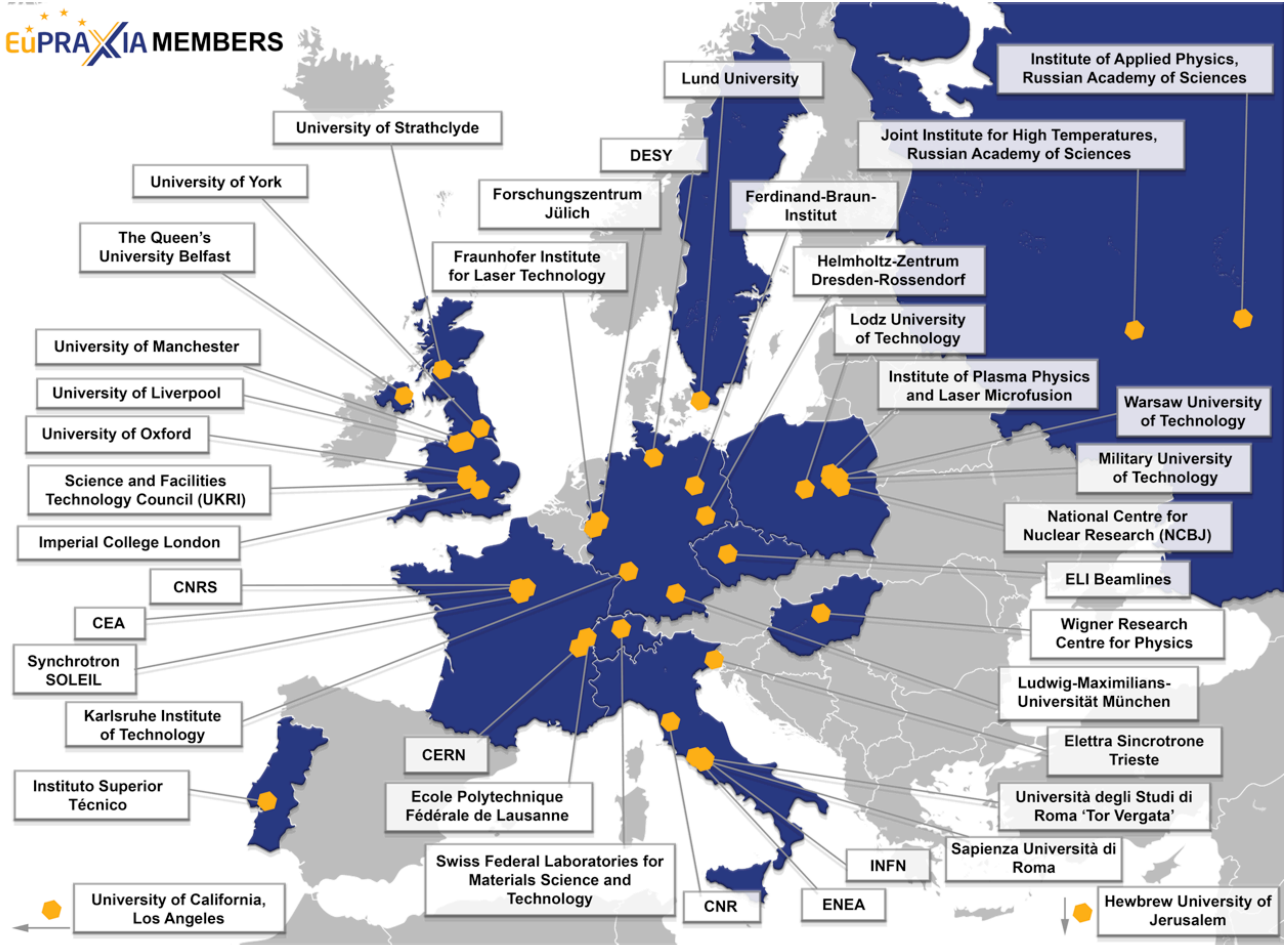
10 cm versus 100 m

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

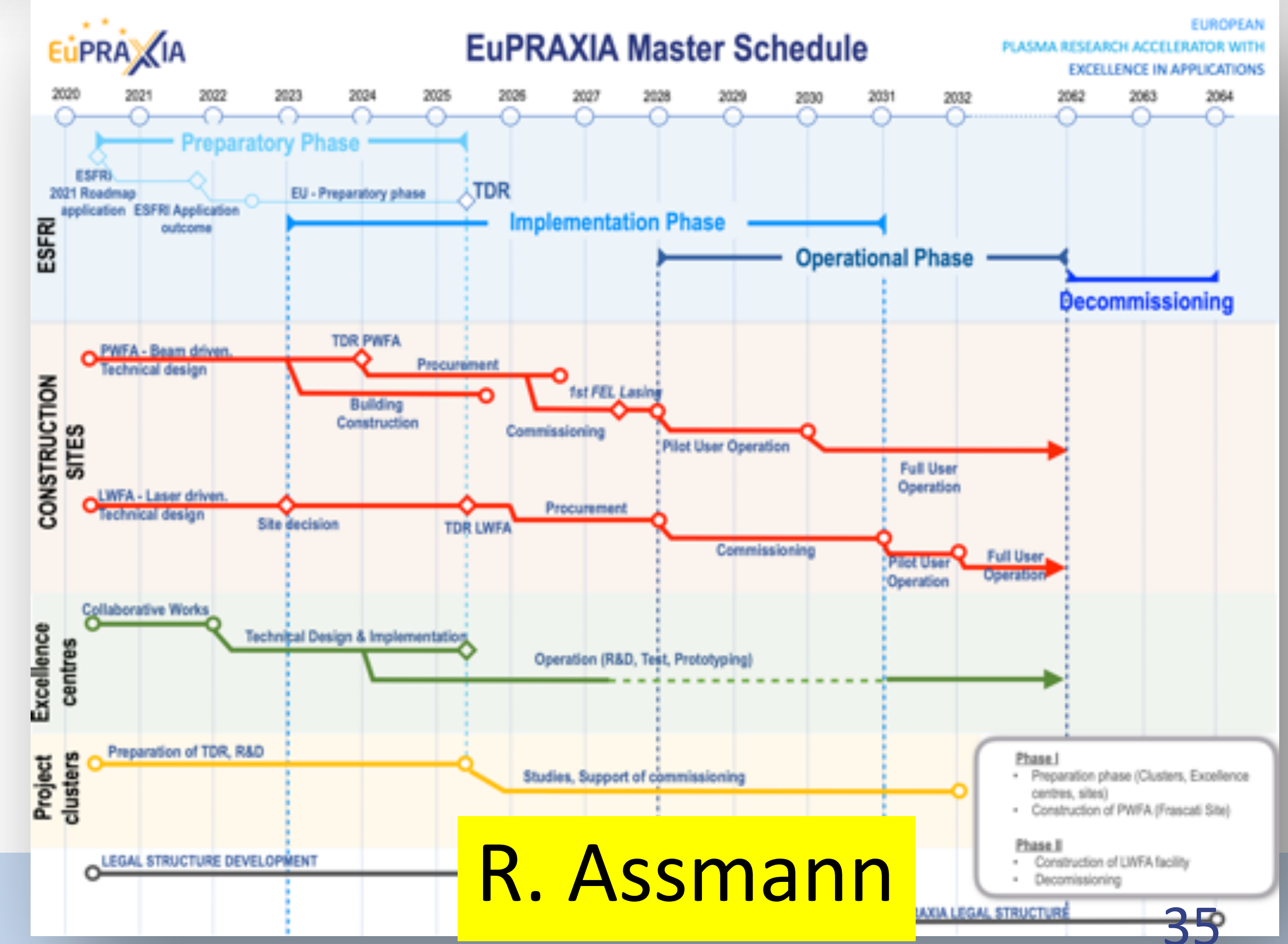
EuPRAXIA Schedule

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?

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

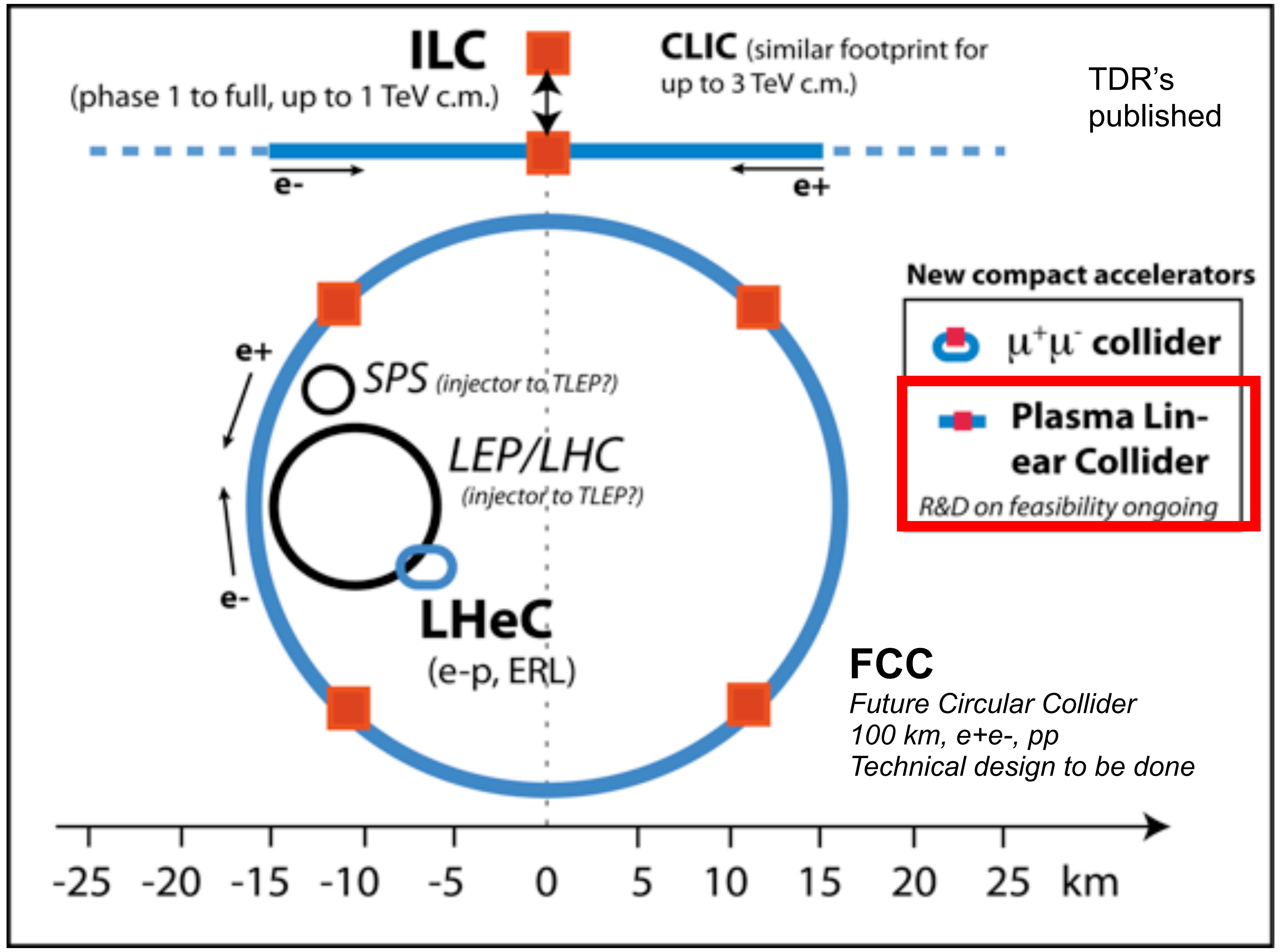


Table 1.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers [88]. Case 2 (LWFA) is a plasma-based scheme based on laser drivers [89]. Case 3 (DLA) is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

- **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

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 $E_x = -\frac{m\gamma_m\beta_m^2c^2}{eC/(2\pi)} = -5.27$ MeV/m and $B_y = 0$ with m and e the proton mass and charge and $C = 500$ m the circumf.
- Imperfect machine with average radial magnetic field $B_x \neq 0$
  - Vertical electric field $E_y = -\beta_m c B_x$ 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)

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

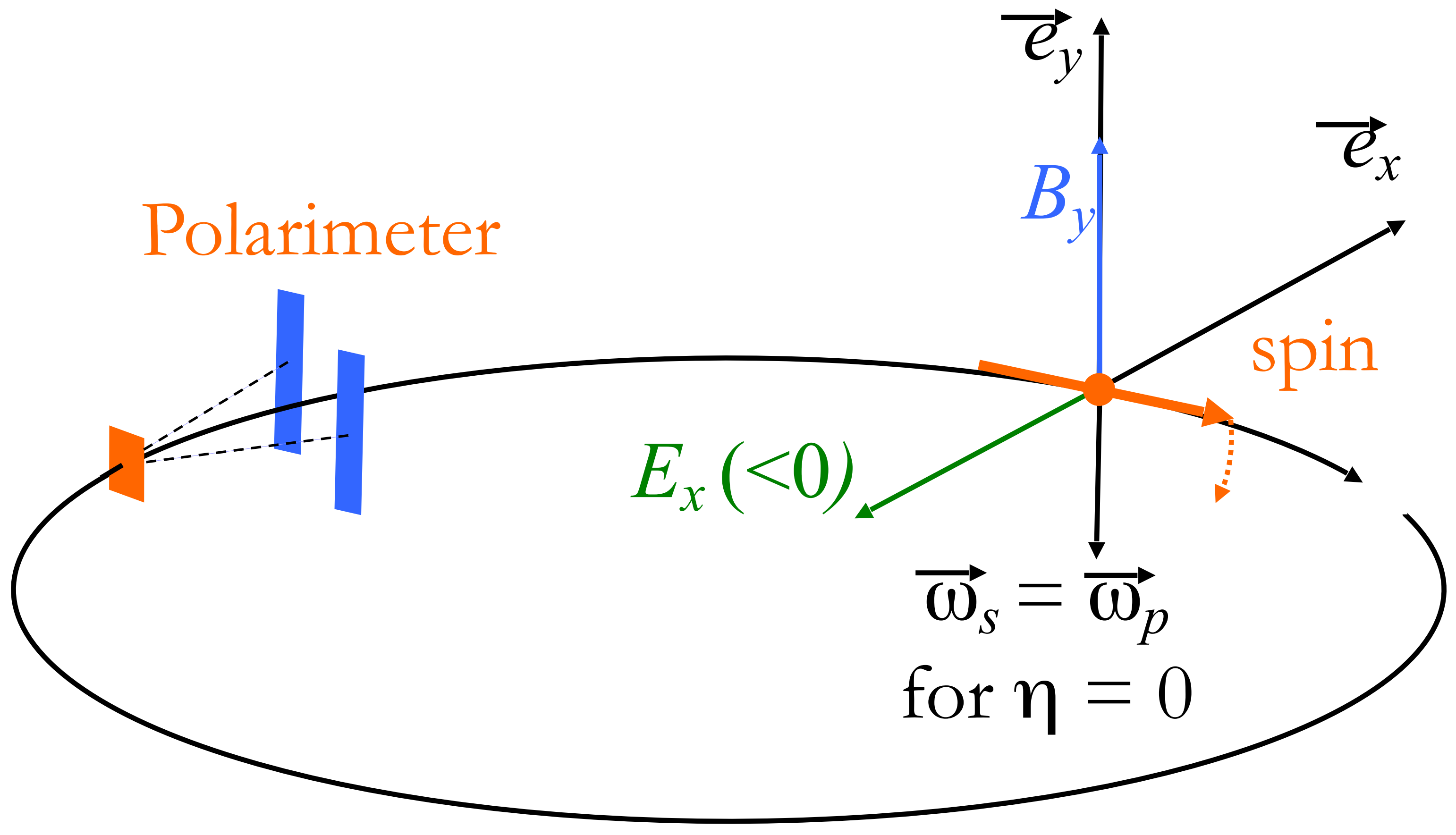
For "magic energy" keep only E_x

  - Gives

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

with $\vec{\omega}_p = -\frac{\beta_m c}{C/(2\pi)}$ describing the rotation of the direction

  - $\eta = 1.9\cdot10^{-15}$ corresponding to an EDM of $d = 10^{-29}$ e·cm or $B_x = -9.3$ aT give both $\omega_x = 1.6$ nrad/s



Sketch of a CP-EDM Ring

Gravity neglected

C. Carli

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

- **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.

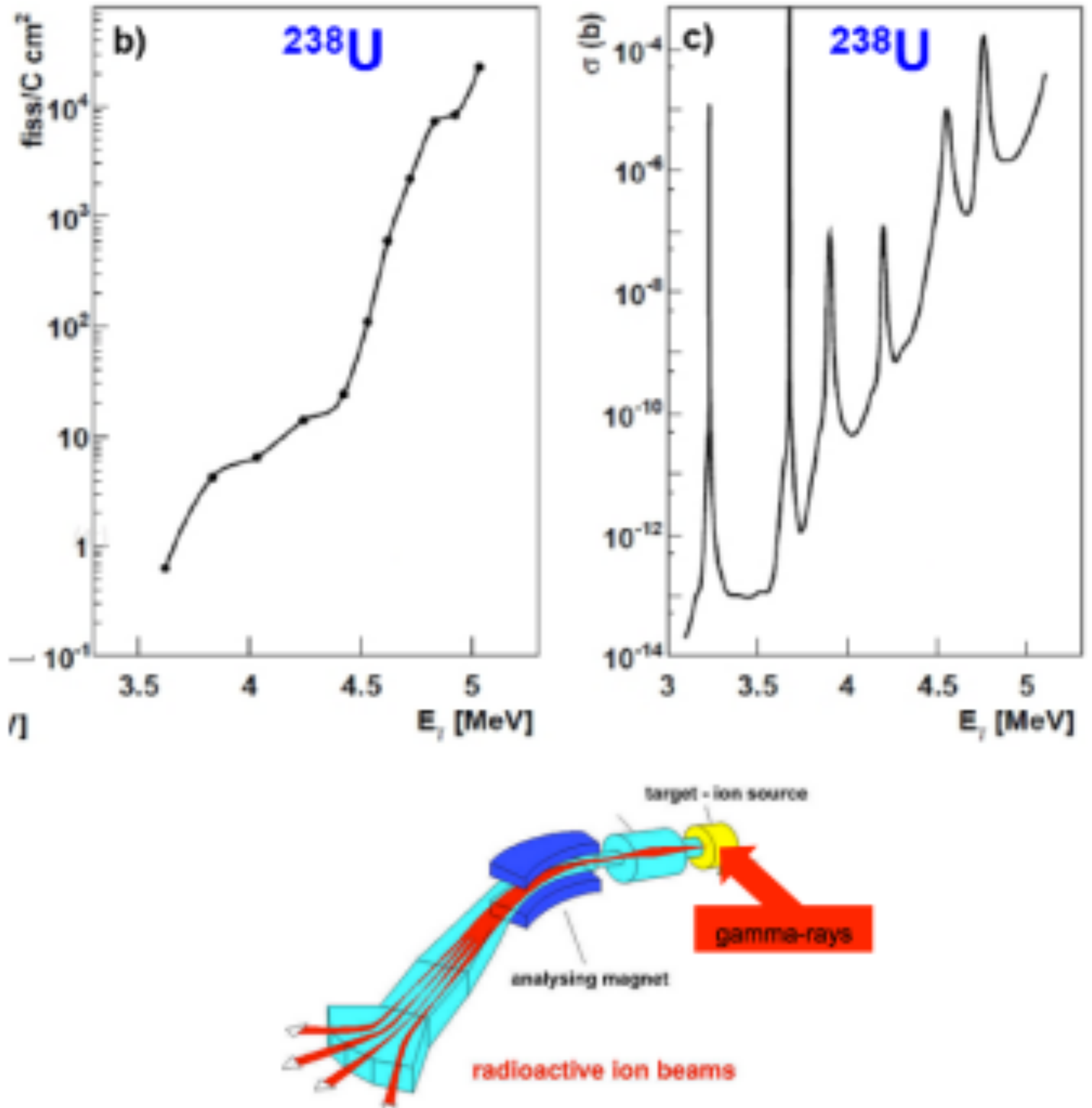
(M.W.Krasny et al., H1-06/97-523 note)

W. Krasny

<u>Example 3:</u>

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

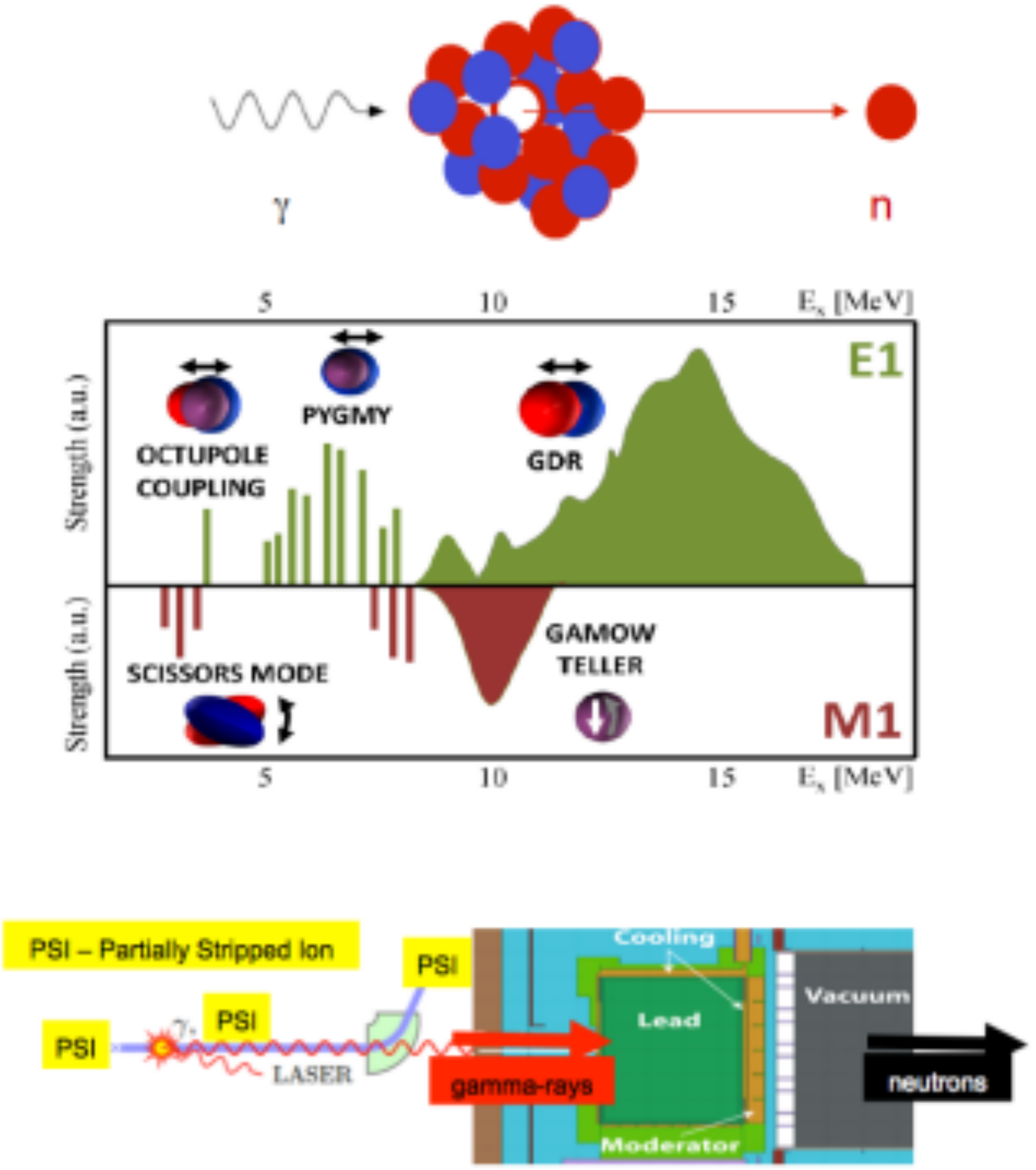
Nuclear fission



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

W. Krasny

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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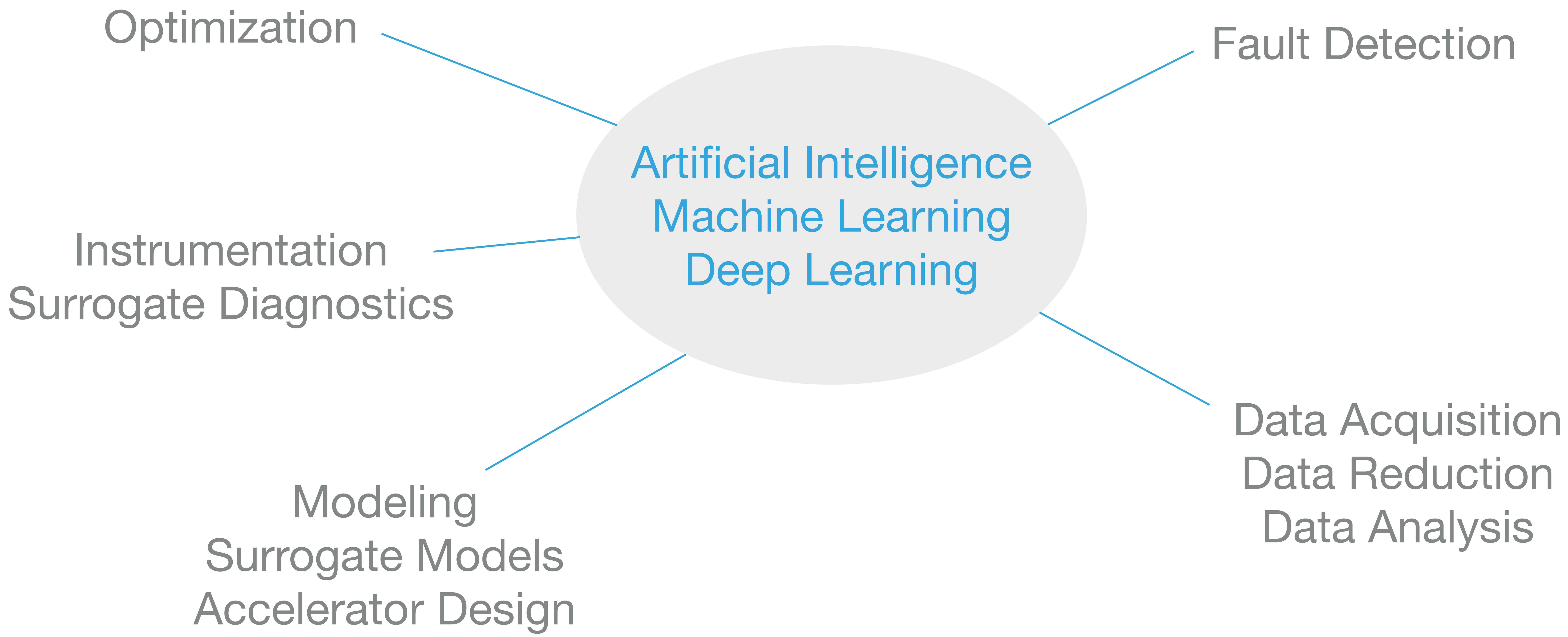
W. Krasny

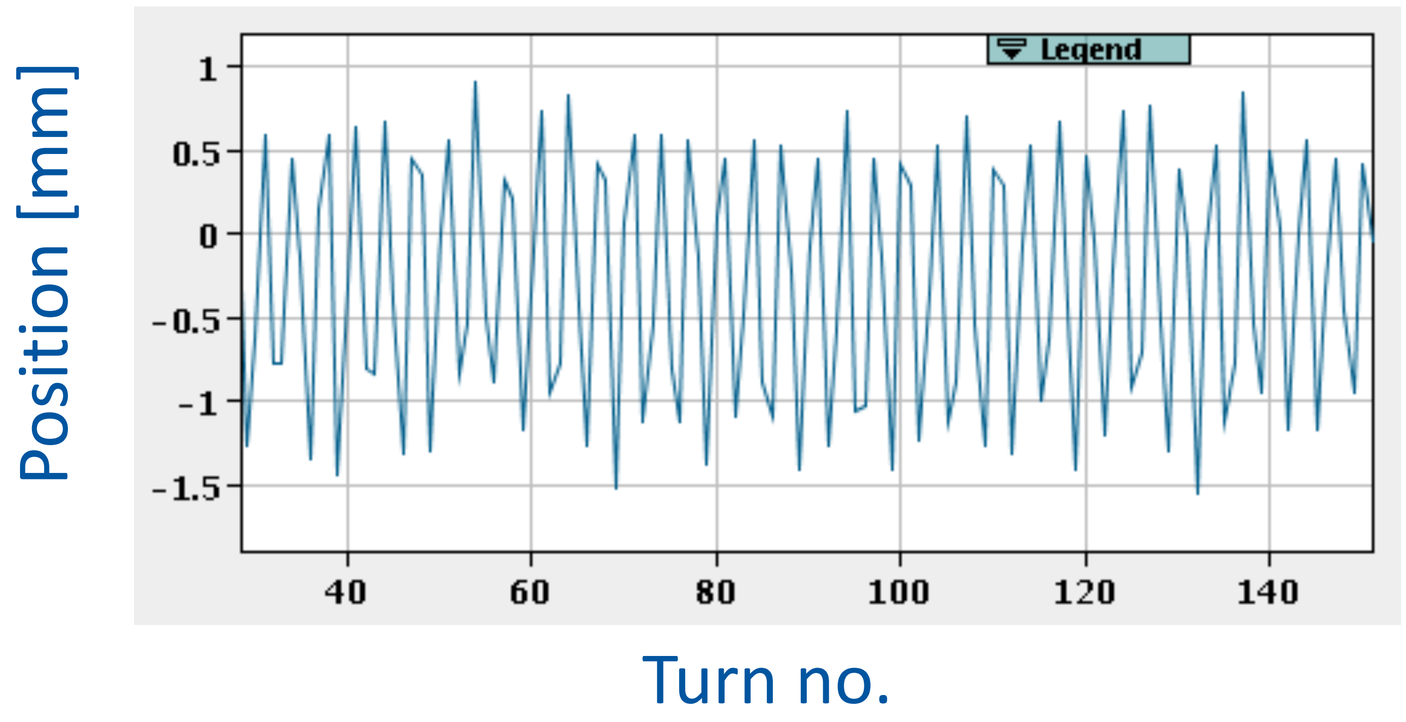
MACHINE LEARNING

USE OF MACHINE LEARNING FOR ACCELERATORS



How faulty BPMs affect the optics measurements?

Turn-by-turn beam position

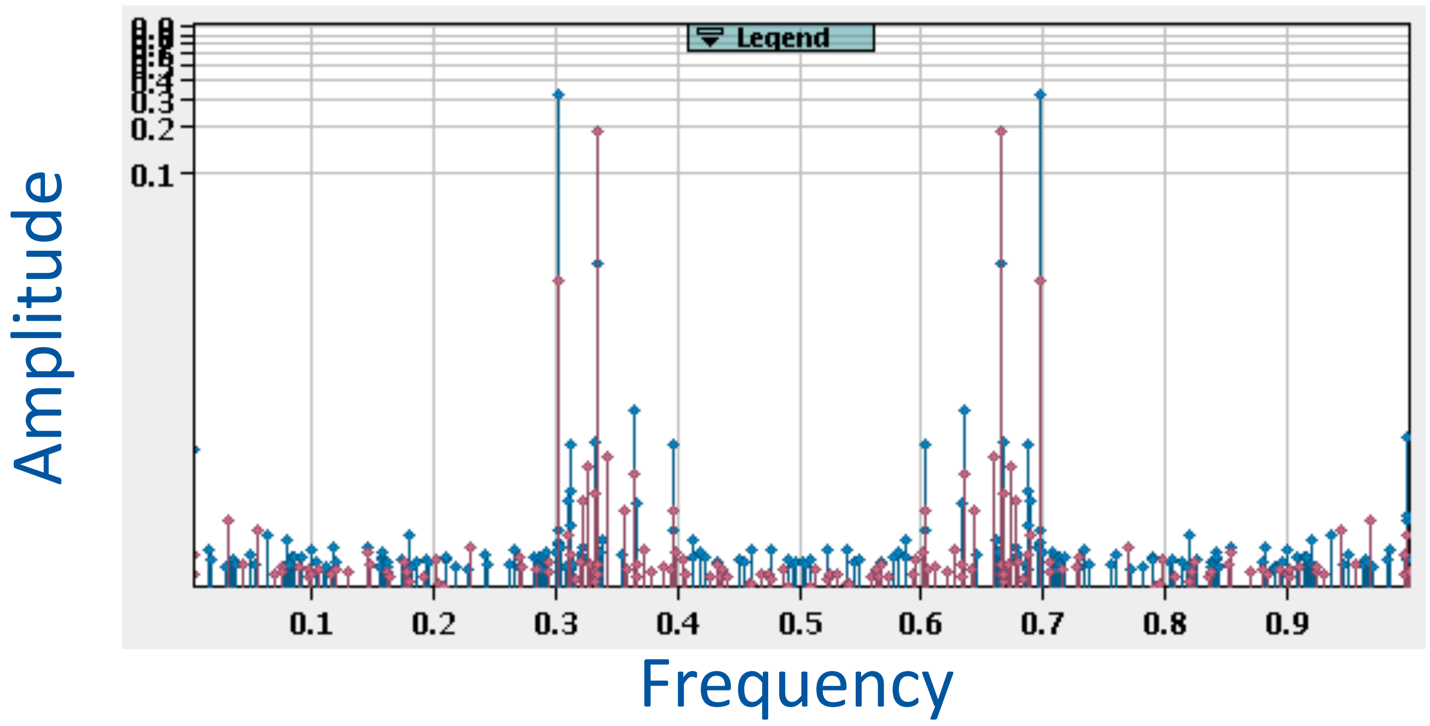


- Excite the beam to perform transverse oscillations.

→ **Beam Position Monitors (BPMs) to measure the beam centroid turn-by-turn**

Denoising (SVD)
Signal cuts

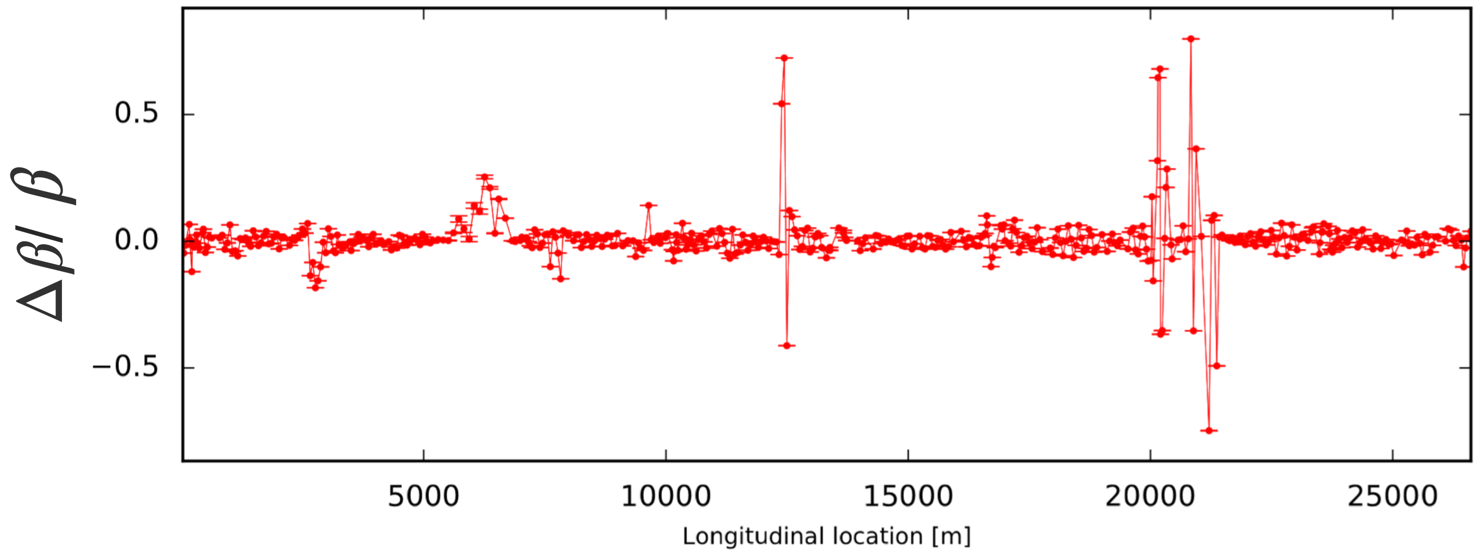
Spectrum



- Harmonic analysis using Fast Fourier Transform (FFT)

Semi-automatic and manual cleaning of outliers

Optics



- Compute beta-beating and other optics functions

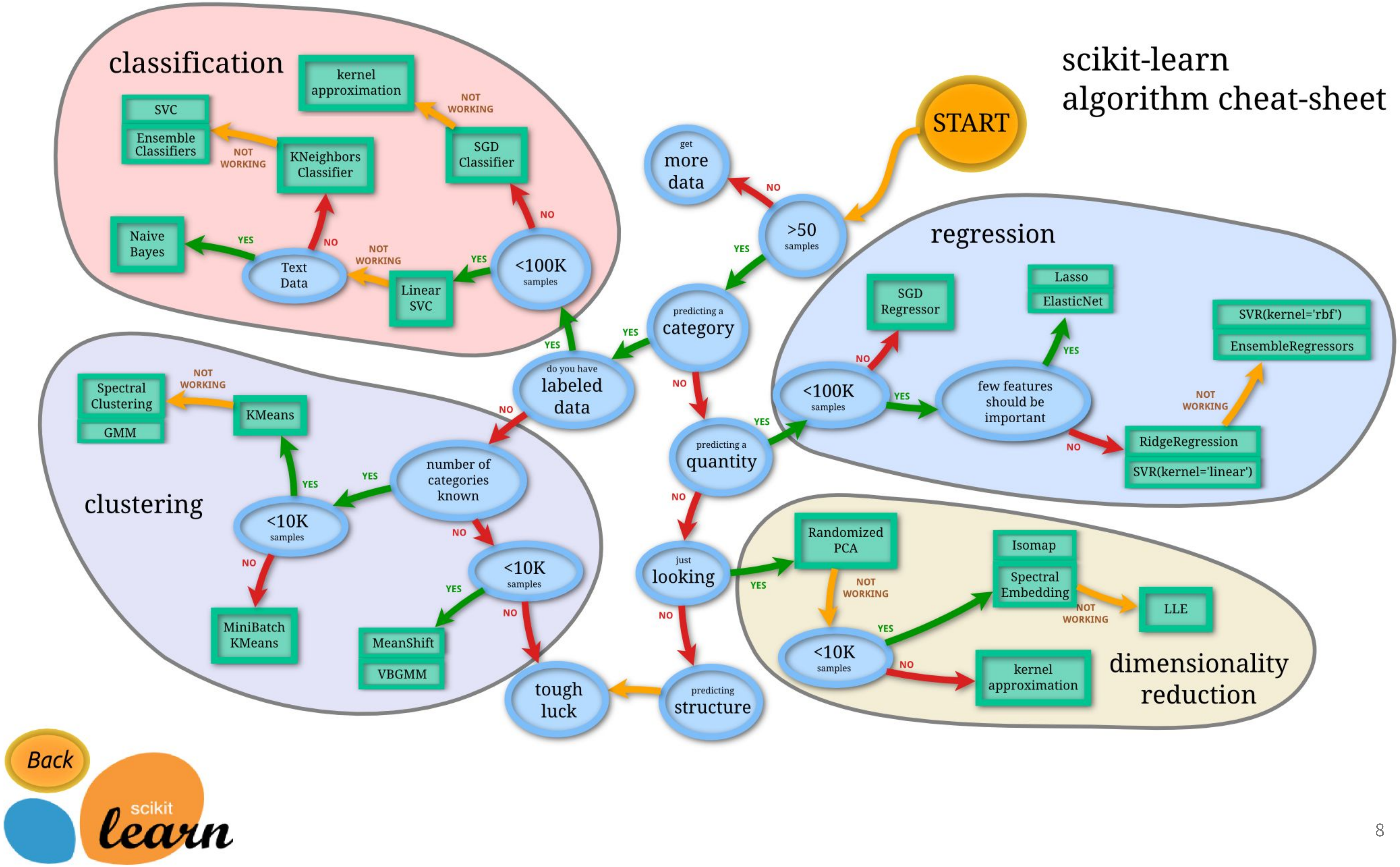
Unphysical values still can be observed

What are the limitations of traditional techniques?

"AN OBSERVATION WHICH DEVIATES SO MUCH FROM OTHER OBSERVATIONS AS TO AROUSE SUSPICIONS THAT IT WAS GENERATED BY A DIFFERENT MECHANISM."

Stephen Hawking

A jungle of methods



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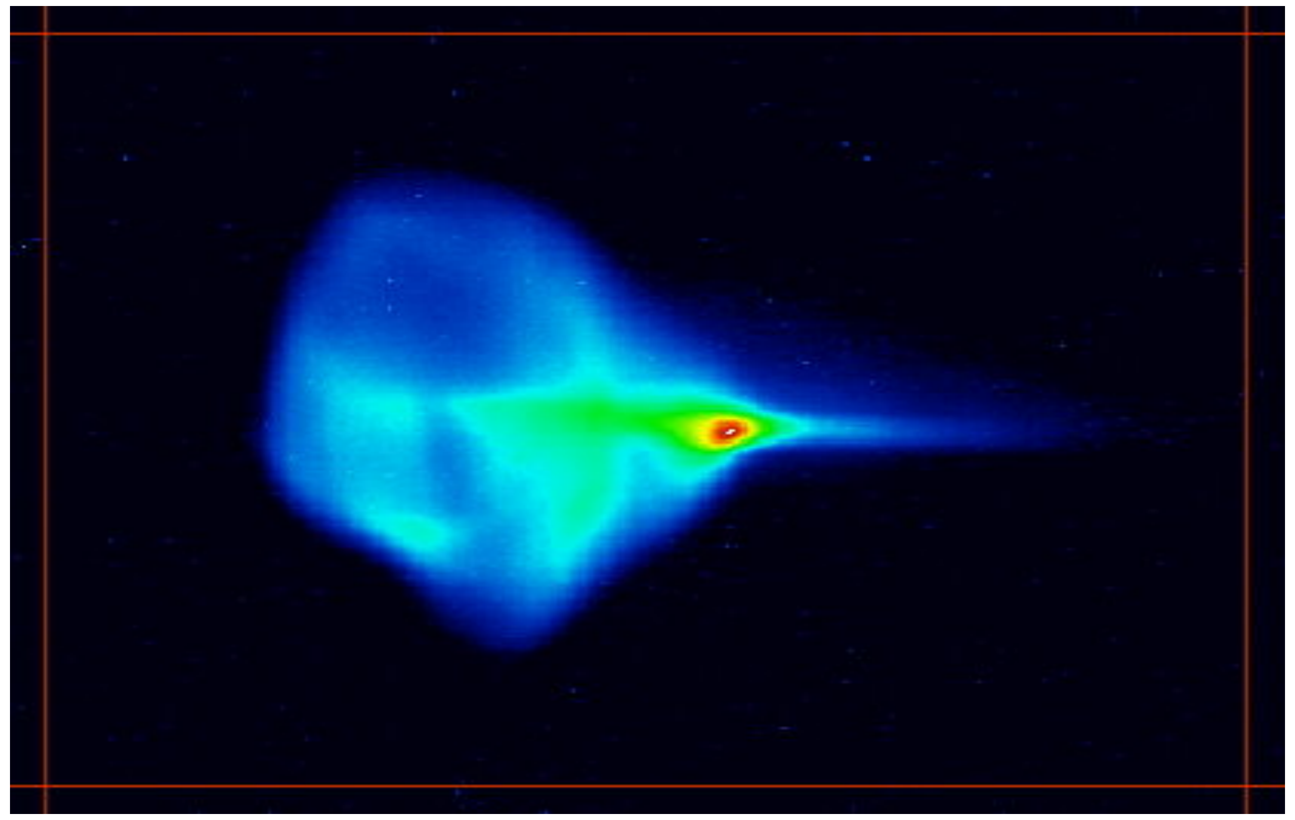
Accelerator Control and Diagnostics Challenges

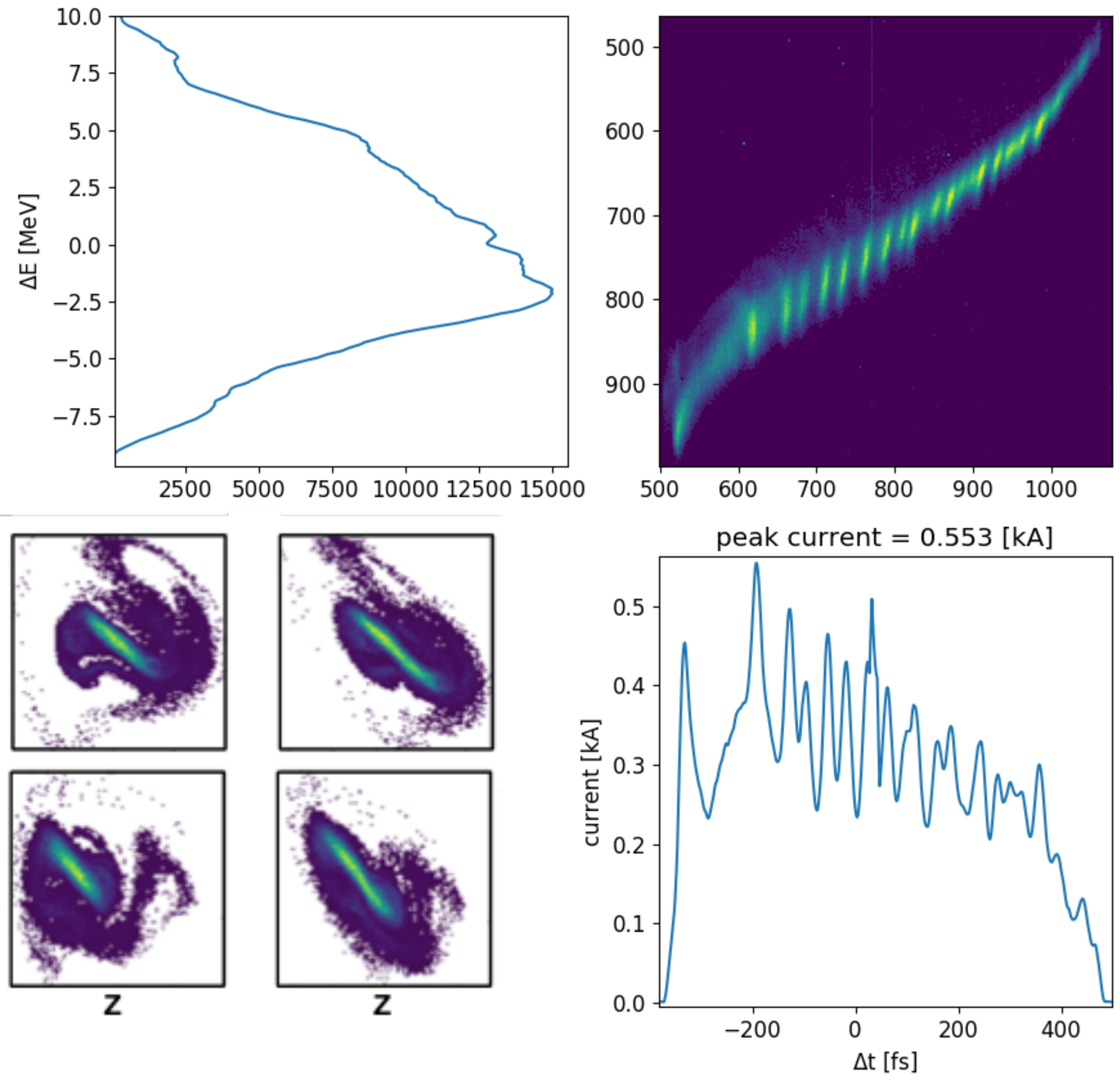
Time-varying accelerator components and beams

- **Wakefields, Space charge**
- **Coherent synchrotron radiation**

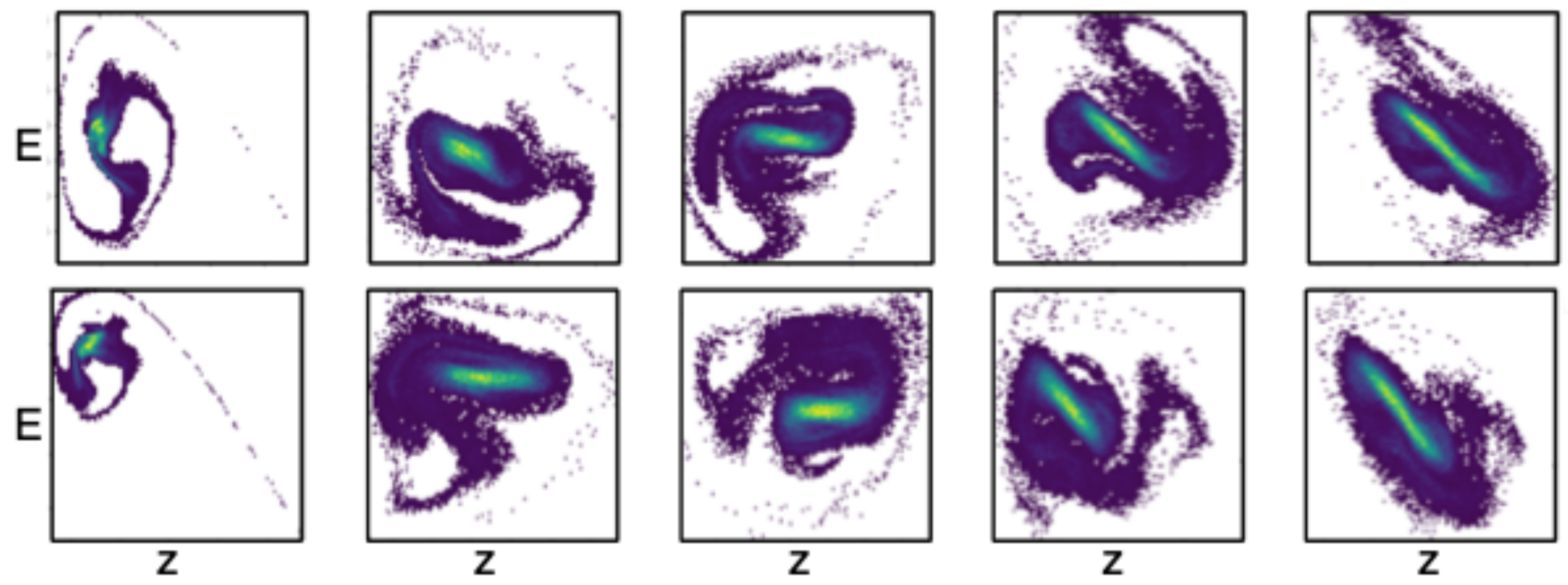


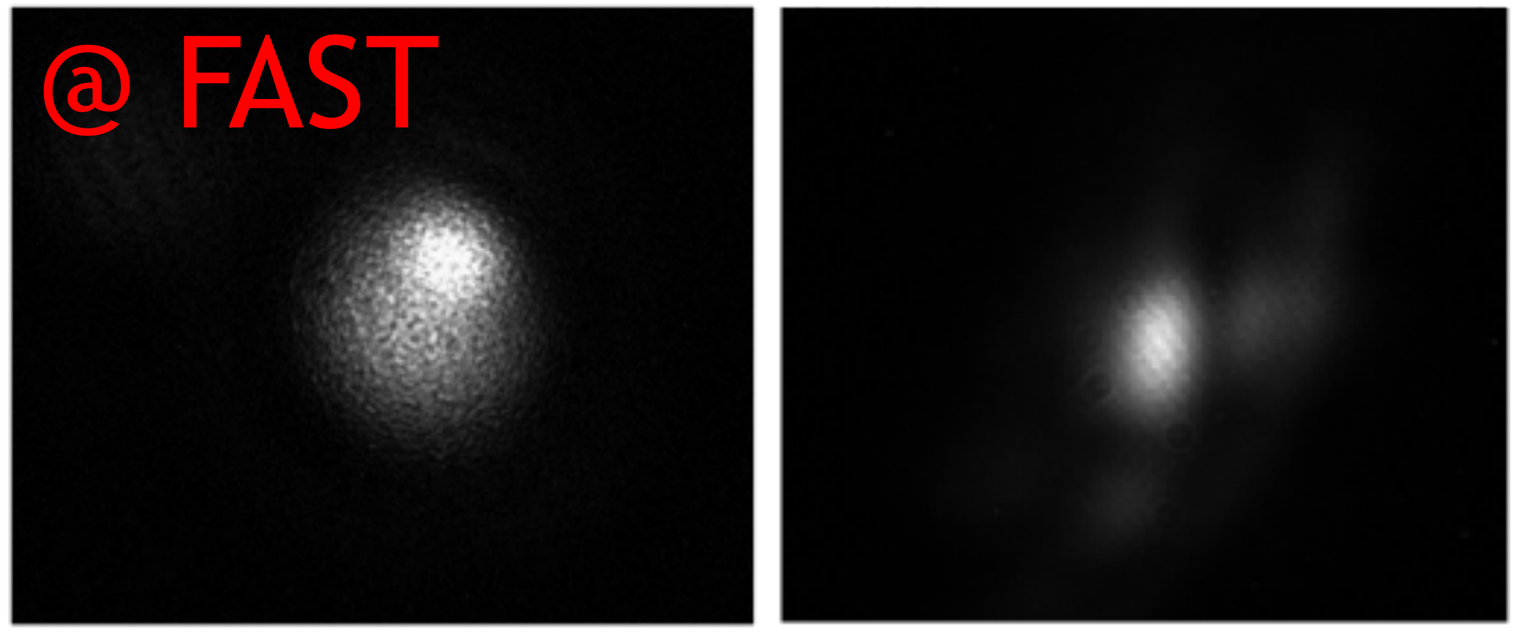
Typical 2D (x,y) beam profile, not a simple Gaussian.

EuXFEL: μBunch Instabilities



LANSCE

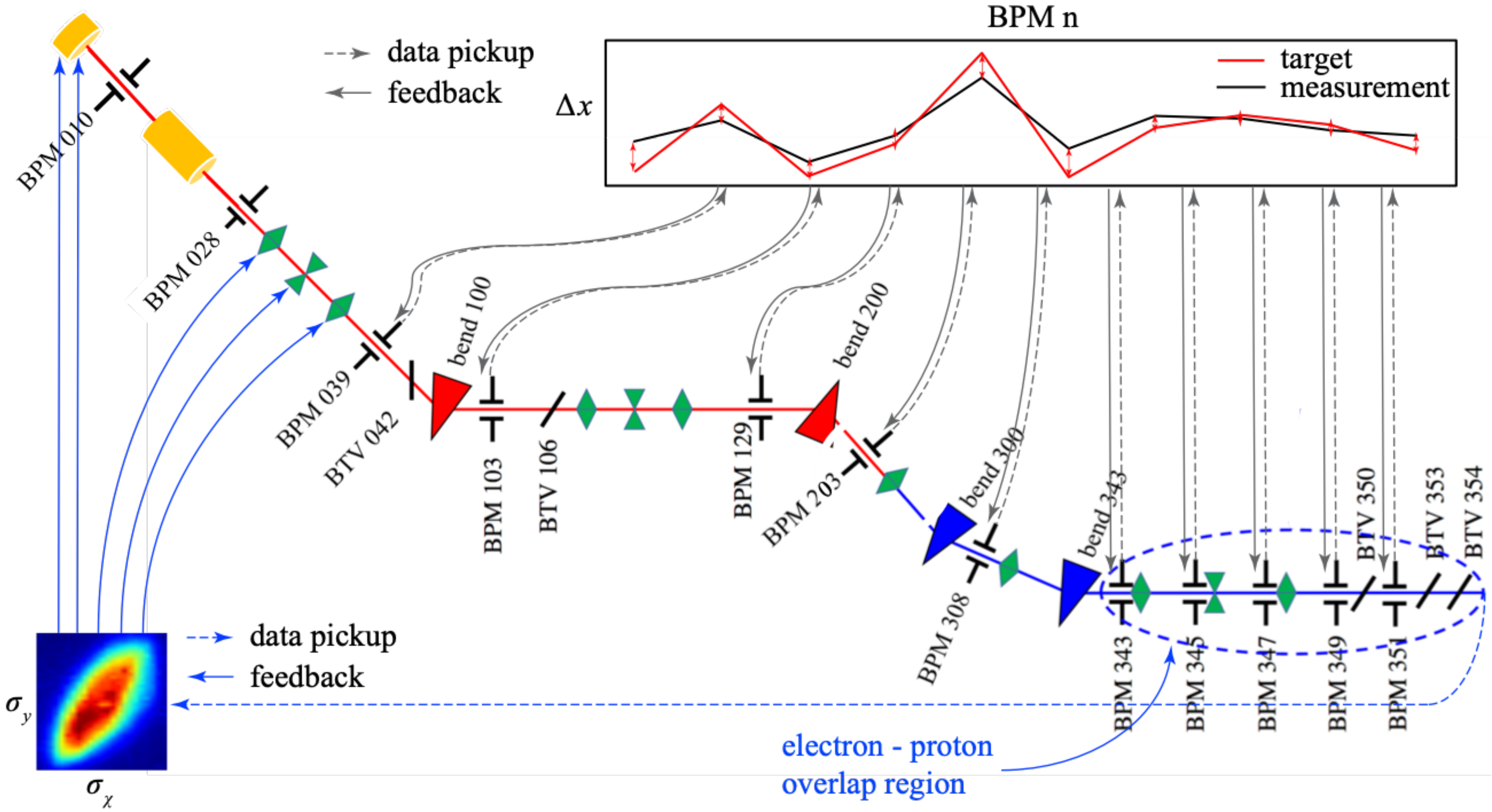


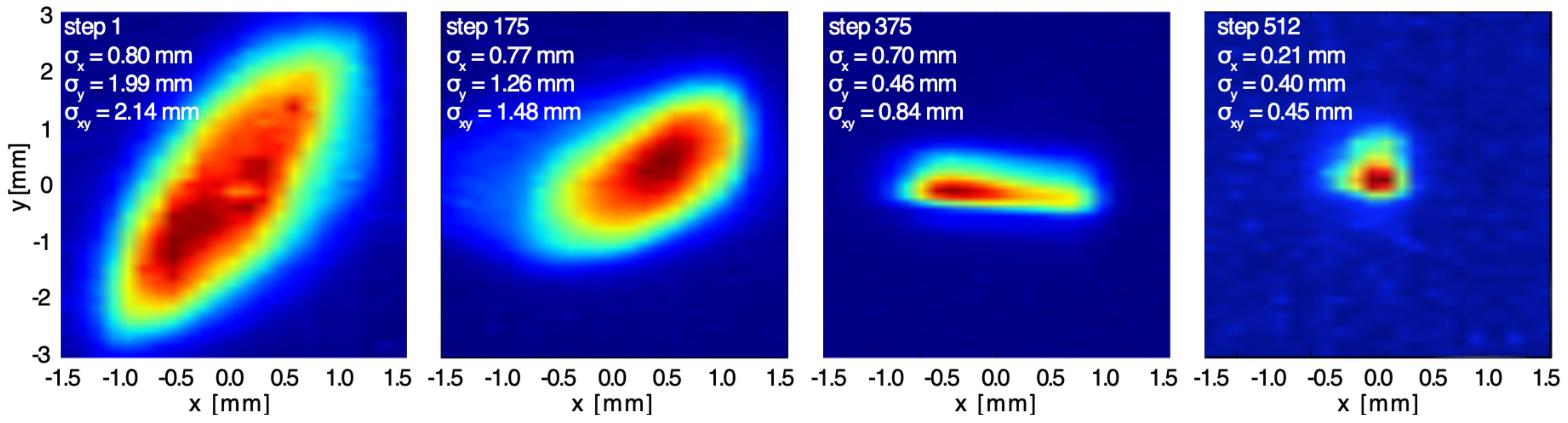


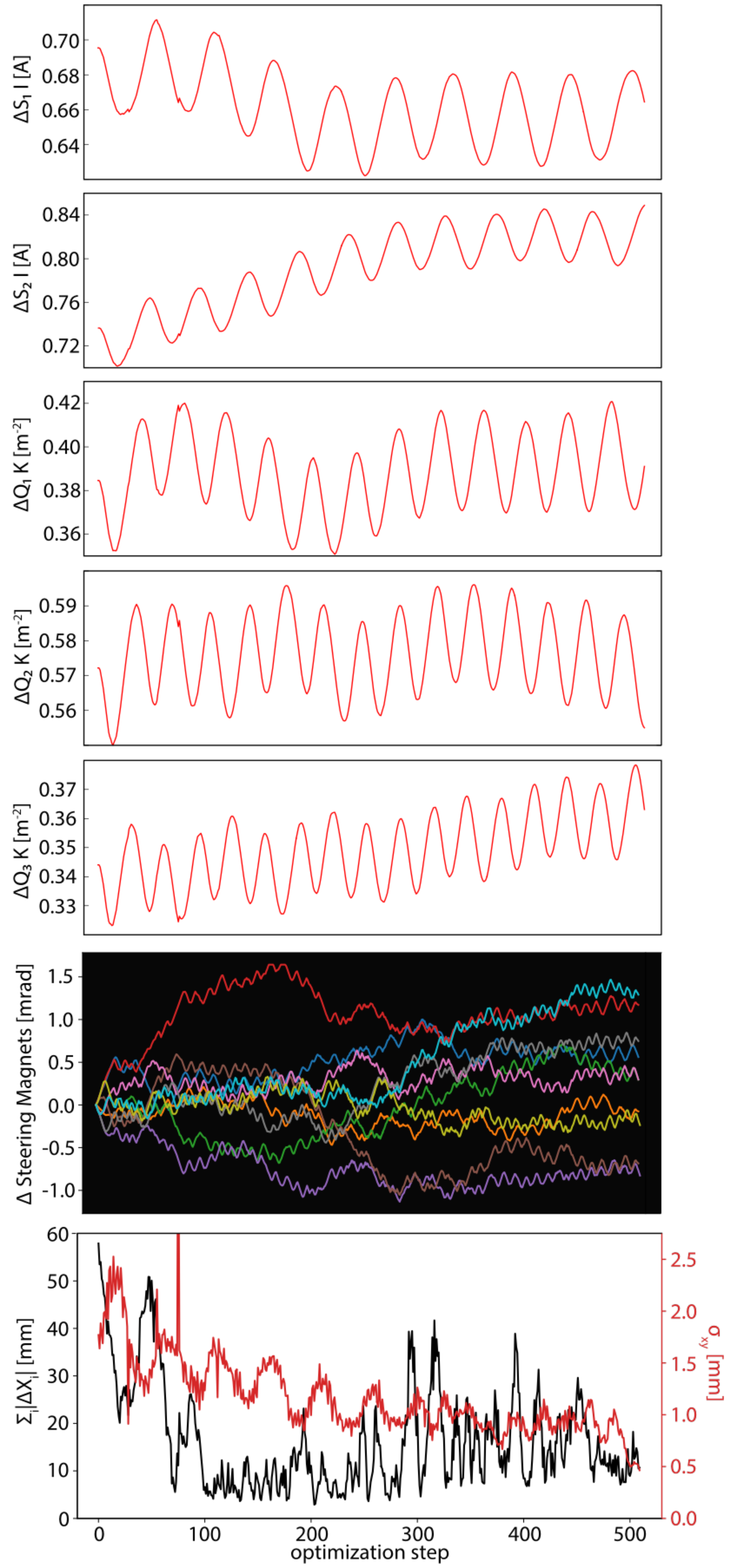
Example images of laser spot (10 Aug. 2016, 11 Nov. 2017)

Real-time multi-objective optimization at AWAKE

Simultaneous emittance growth minimization and orbit control

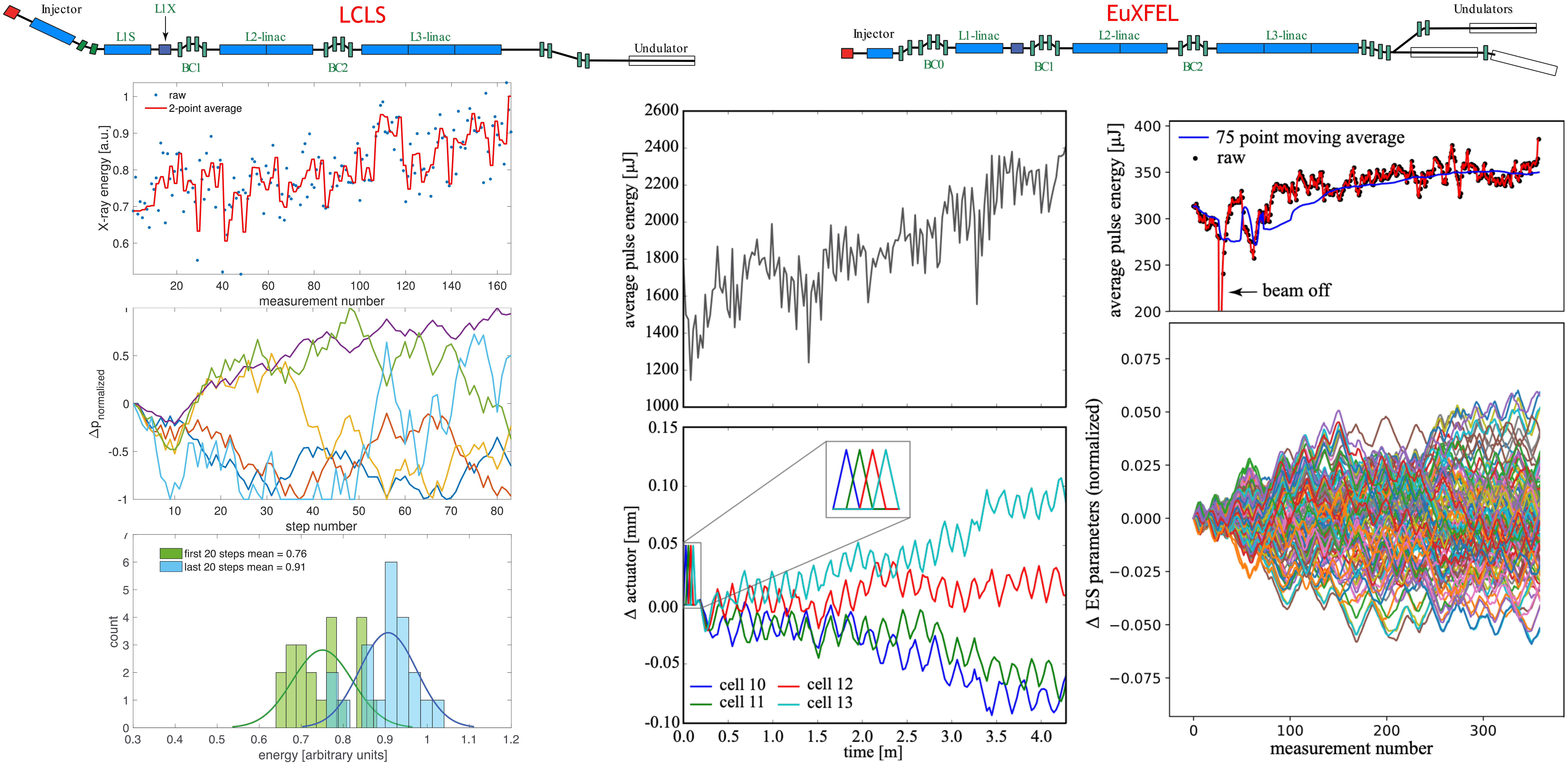






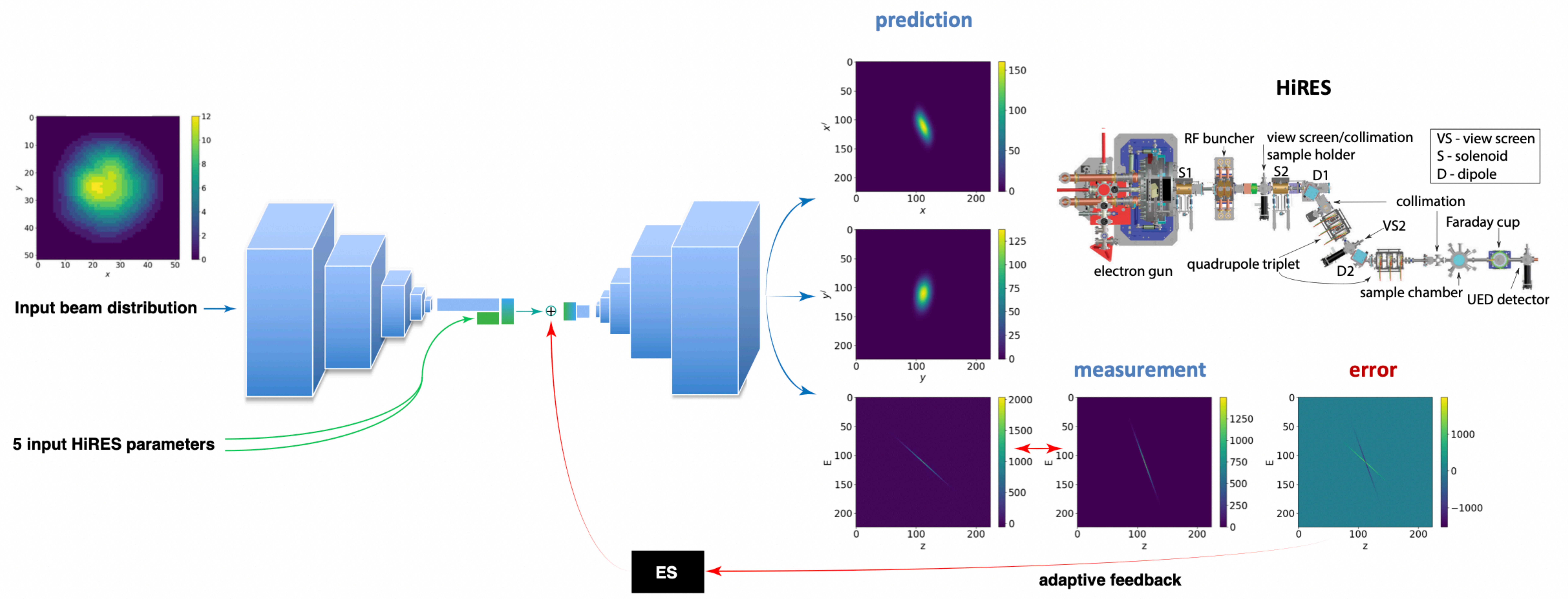
A. Scheinker, et al. “Online Mulit-Objective Particle Accelerator Optimization of the AWAKE Electron Beam Line for Simultaneous Emittance and Orbit Control.” *AIP Advances* 10.5 (2020): 055320 https://doi.org/10.1063/5.0003423

Model-independent Adaptive Feedback for pulse energy maximization at **LCLS & EuXFEL**



A. Scheinker, et al. "Model-independent tuning for maximizing free electron laser pulse energy." Physical Review Accelerators and Beams, 22.8, 082802, 2019. https://doi.org/10.1103/PhysRevAccelBeams.22.082802

HiRES – Compact Ultra-fast Electron Diffraction (UED)



Two Workshops

AI/ML for Particle Accelerator, X-Ray Beamlines and Electron Microscopy

Nov 1, 2021, 10:00 AM → Nov 3, 2021, 4:00 PM US/Central

Virtual

https://indico.fnal.gov/event/50731/

Description **AI for Particle Accelerators, X-ray Beamlines, and Electron Microscopy Workshop @ ANL**

Advances in instrumentation have dramatically increased the complexities associated with experimental facilities. This includes enhanced facility capabilities as well as a substantial increase in the data generated. Consequently, the control and diagnostics of these experimental facilities are becoming increasingly complex, and the large output data streams necessitate smarter and more automated management and analyses of the data. Artificial Intelligence (AI) methods hold the promise of substantially improved management, control, and data analyses with the potential to dramatically increase experimental efficiencies as well as expanding and accelerating scientific discoveries.

Argonne is the home to world-leading facilities such as the Advanced Photon Source (APS), the Argonne Tandem Linear Accelerator (ATLAS), the Argonne Wakefield Accelerator (AWA), and the Electron Microscopy Center at the Center for Nanoscale Materials (CNM). In order to highlight AI opportunities in these facilities, Argonne is hosting a workshop on AI for with participants drawn from 3 communities: particle accelerators, X-ray beamlines and electron microscopy. The goals of the workshop are:

AI for Accelerators - A Snapshot at Fermilab

https://indico.fnal.gov/event/52417/

Friday Jan 14, 2022, 1:00 PM → 2:40 PM US/Central

Anthony Tiradani (Fermilab), Erik Gottschalk (Fermilab), Lila Anderson (Fermilab), Tia Miceli (Fermilab)

Description Showcase of current work on AI/ML for accelerators. (no registration needed)

What's the buzz about Artificial Intelligence for our accelerator systems?

Efforts have been ramping-up in the past couple of years to use Artificial Intelligence and Machine Learning (AI/ML) to enhance the performance of our accelerators and beamlines. We anticipate even more action in the coming year. Come hear from machine experts and engineers as they present advances in our latest AI/ML projects and what the future holds.

Audience take-aways:

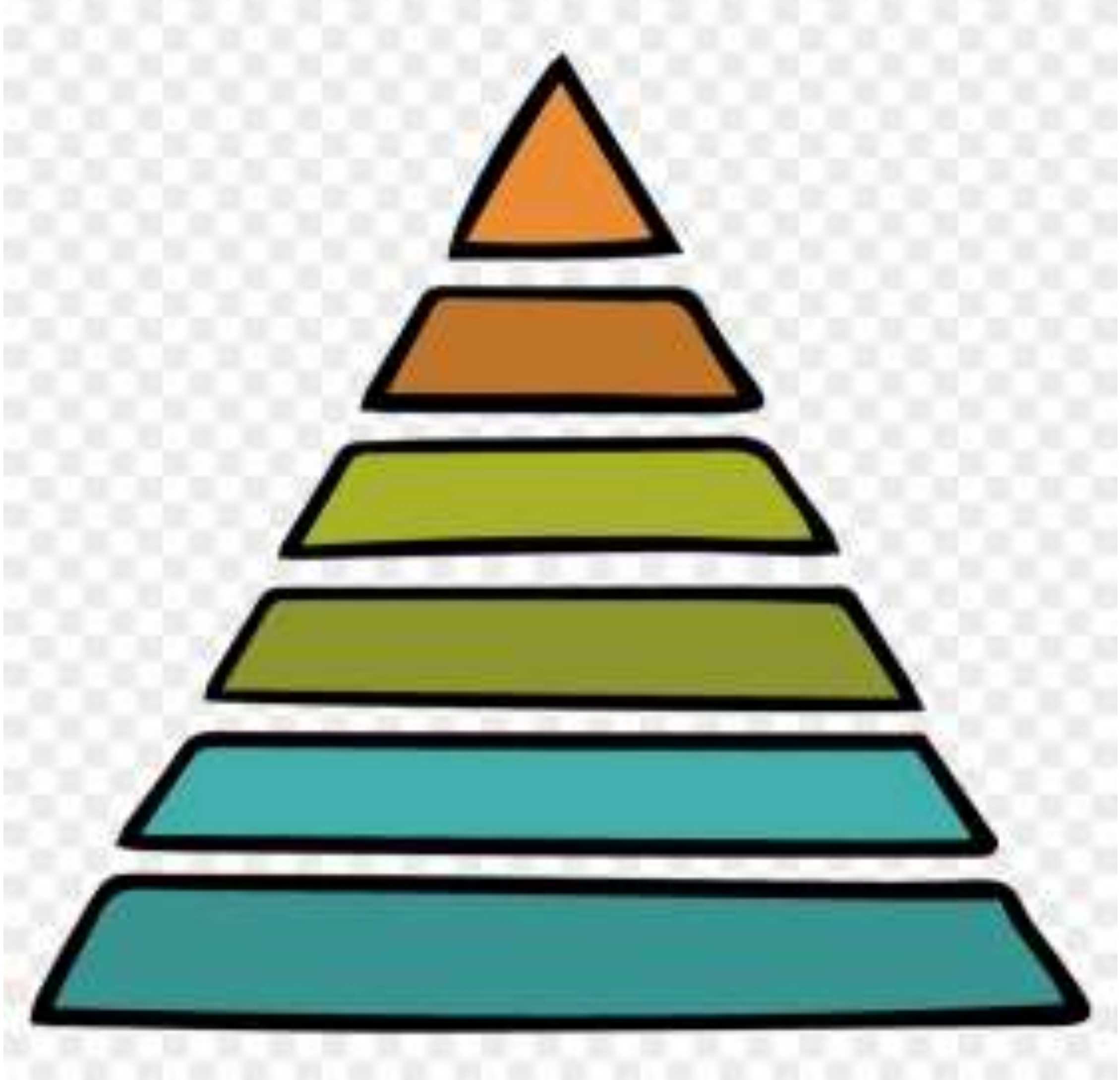
1. What are the current AI/ML accelerator controls projects
2. What are the plans for modernizing the accelerator control system to support AI/ML
3. How do Accelerator Division's AI/ML endeavors support Fermilab

Examples of AI/ML Activities/Projects

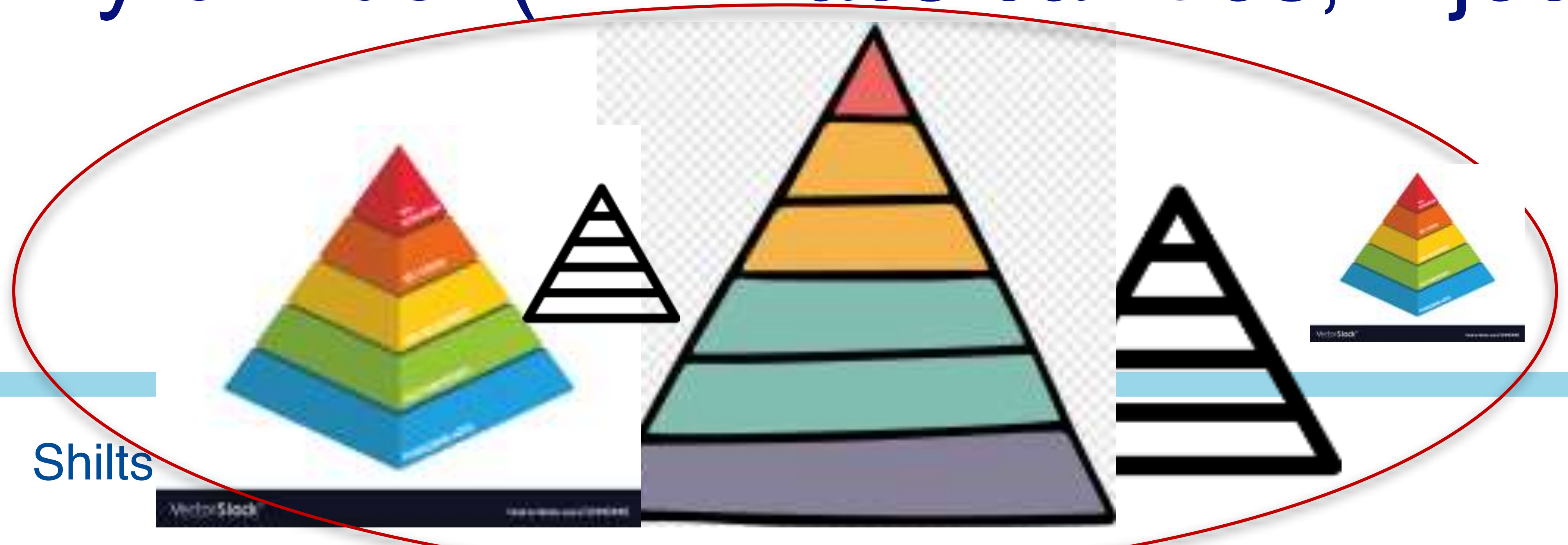
1. Machine learning for Linac RF Optimization Longitudinal optimization
2. Booster Gradient Magnet Power Supply Control
3. "Big Data" Booster Control
4. Orbit Alignment at PIP2IT Using Bayesian Optimization
5. AI/ ML for NuMI Target System Monitoring
6. Real-time quench detection
7. FAST/IOTA RF gun stabilization and optimization
8. MI loss minimization vs MI or RR situation
9. Stabilization of 8 GeV slow extraction from Muon-C ring
10. 6D Cooling optics design with ML elements

Main Message

- Complexity is about
  - Dissimilarity
    - Magnets, RF, plasma, cooling, drivers, FF, etc
  - And Hierarchy:
    - Eg LHC 1 ring
      O(10) sectors
      O(100) cells
      O(1000) main magnets
      $O(10^4)$ aux magnets,
      $O(10^5)$ control channels

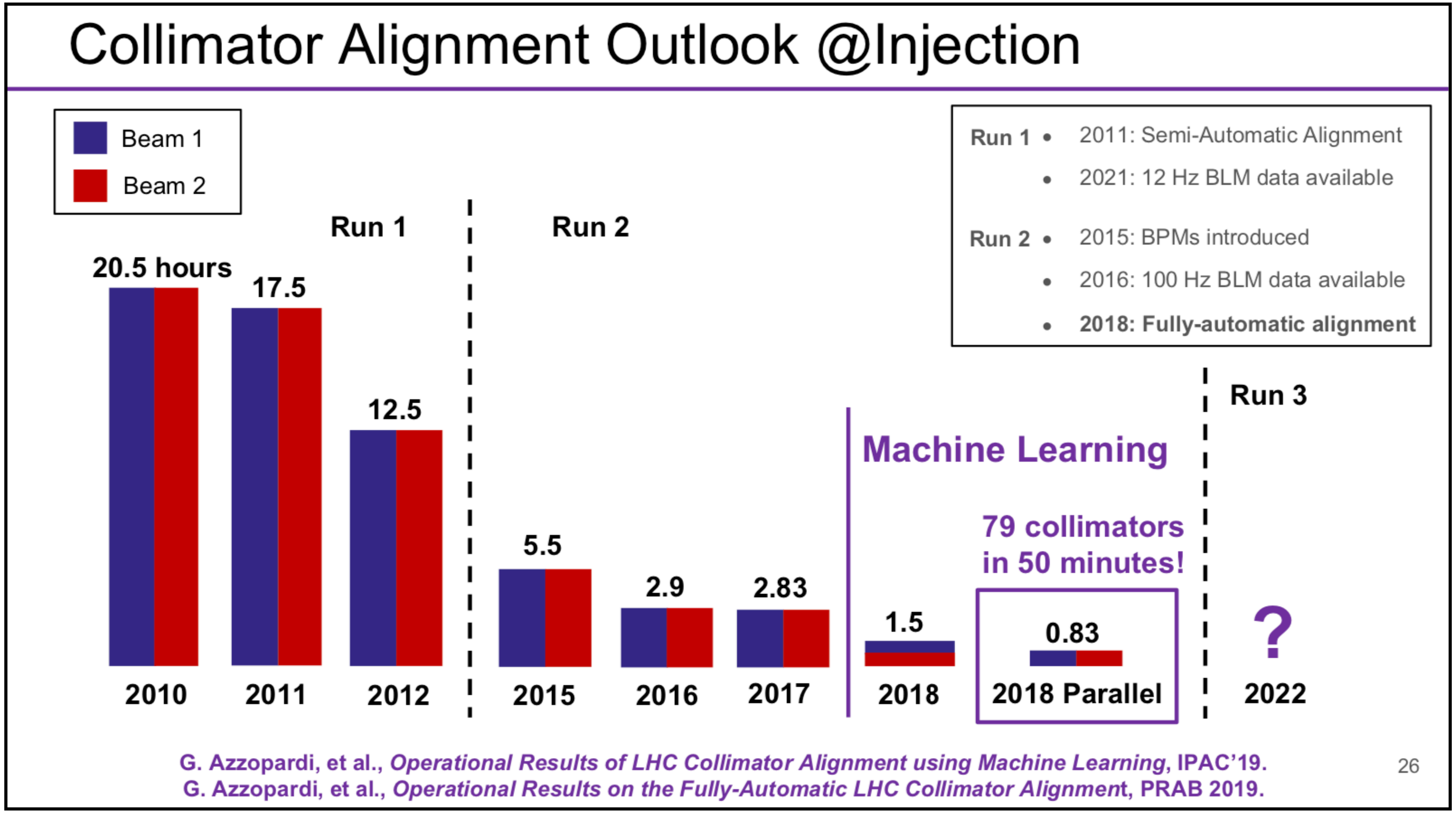


- Other "Pyramids" (RF linacs/cavities, injectors, etc)



Back to CERN: Speed up commissioning

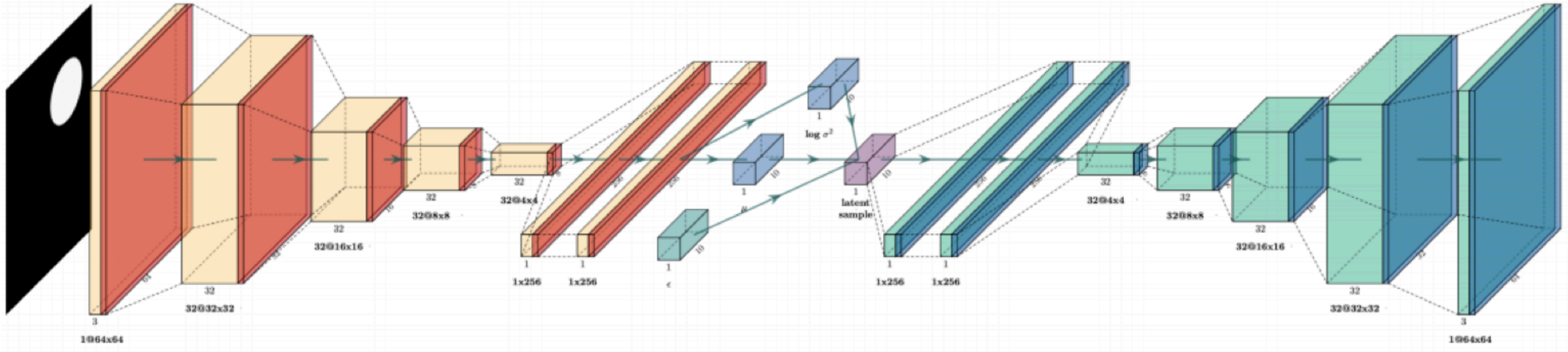
Almost 100 collimators in the LHC…

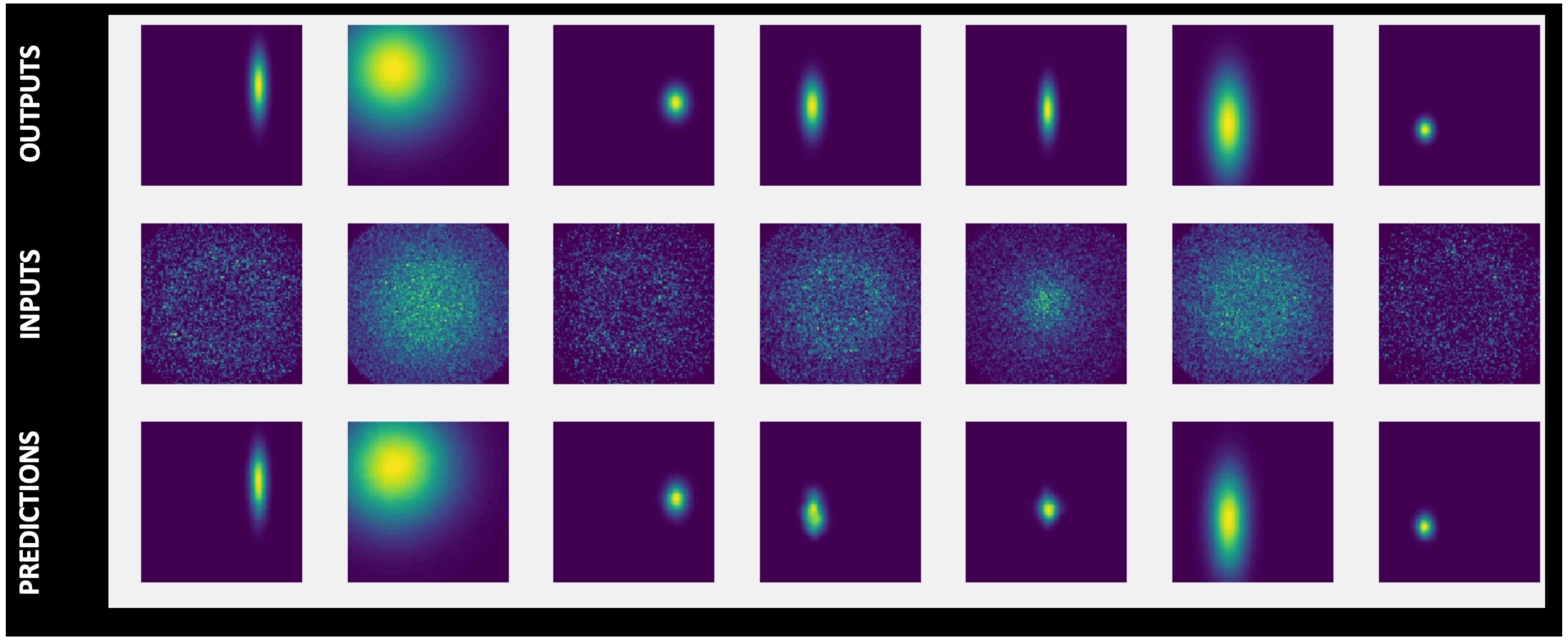


G. Azzopardi et al.

Efficient operation: more diagnostics...

Variational Auto-encoders for radiation hard **Optical Fibre Imaging** → next generation beam profile monitors?



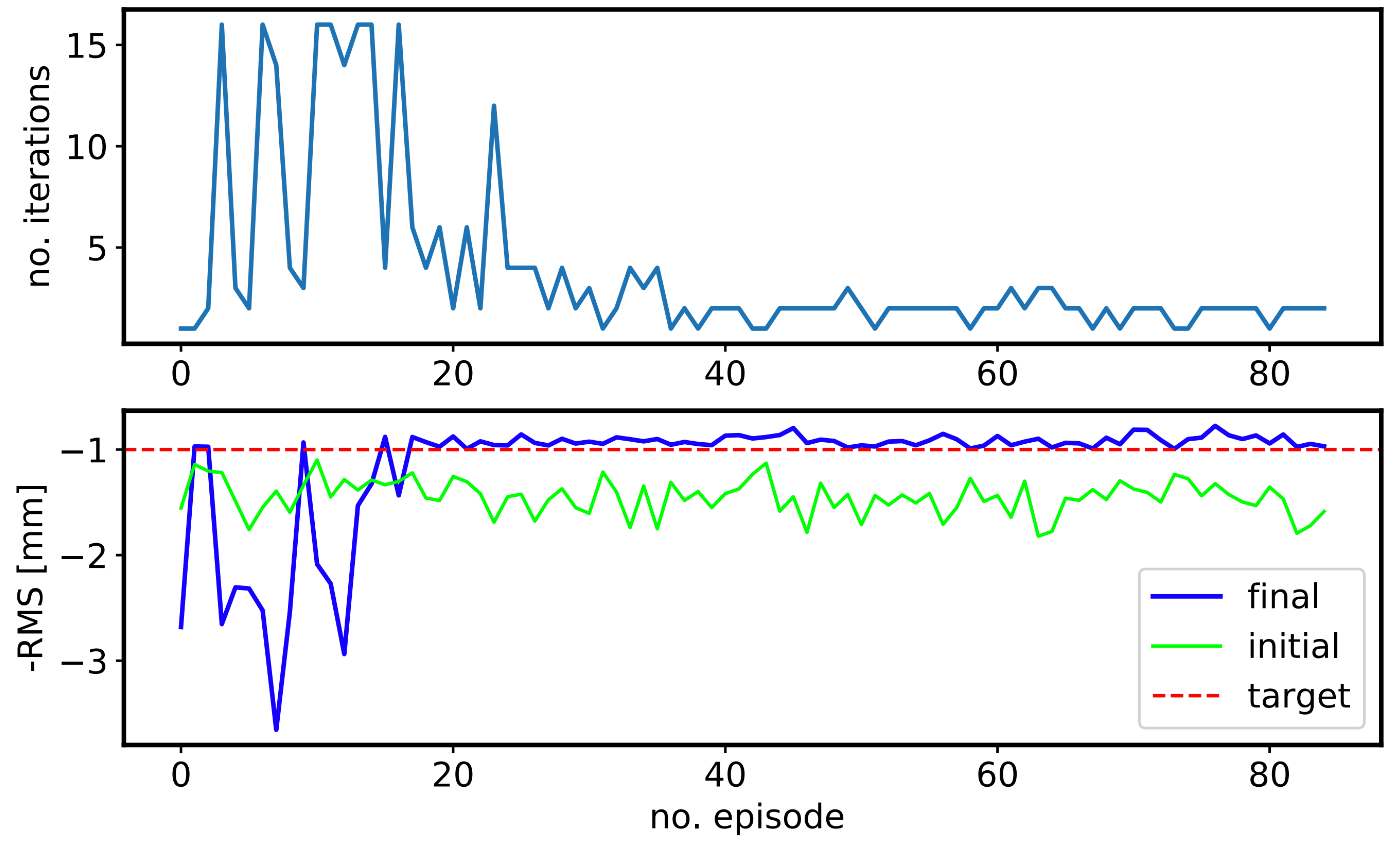


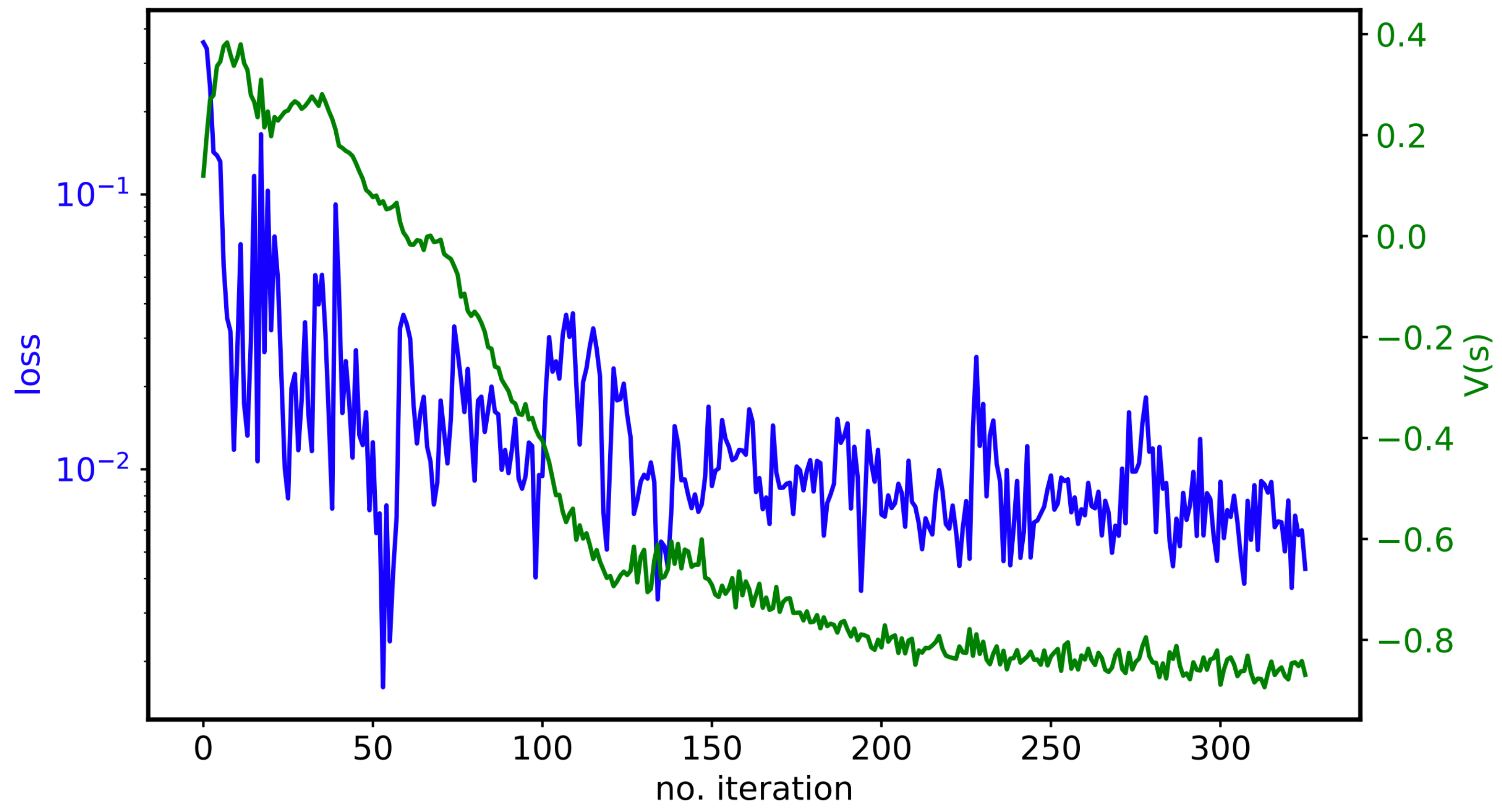
G. Trad

Reinforcement Learning as part of the Toolkit

Real world Application: Linac4 H^- commissioning run (16 DOF)

- Similarly to AWAKE beam line, using **NAF with *Prioritised Experience Replay***
- **Hyper-parameters:** quite some tuning necessary to avoid running into machine safety constraints during exploration
- After training for **~25 episodes** (~125 iterations), agent starts correcting well
- Corrects to **better than 1 mm RMS** within 3 iterations
- Value function converges to -0.85, corresponding to **0.85 mm RMS**



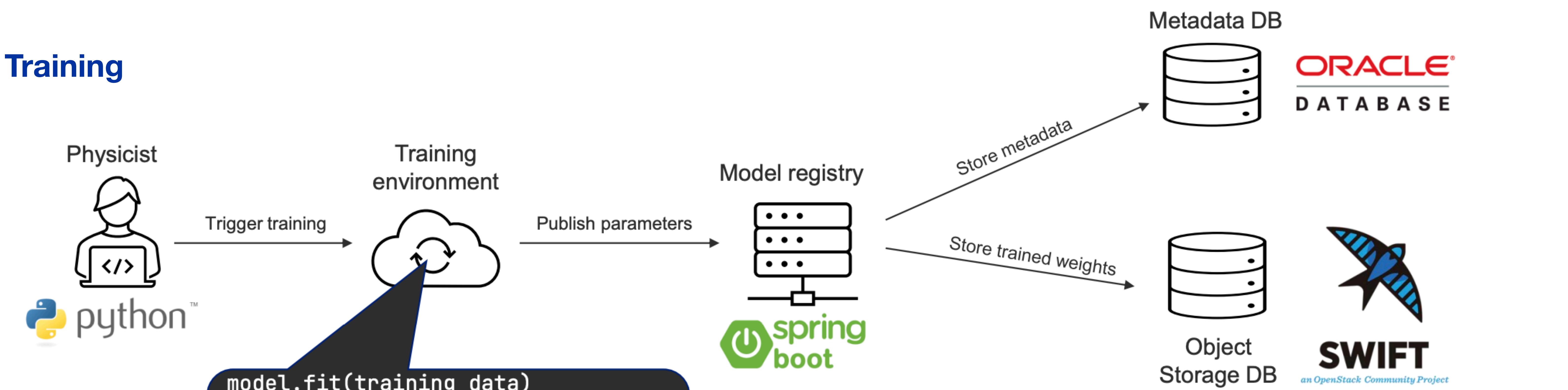


→ **still various transfer lines not well modelled at CERN.**

2022: train RL agent for TL LINAC3-LEIR

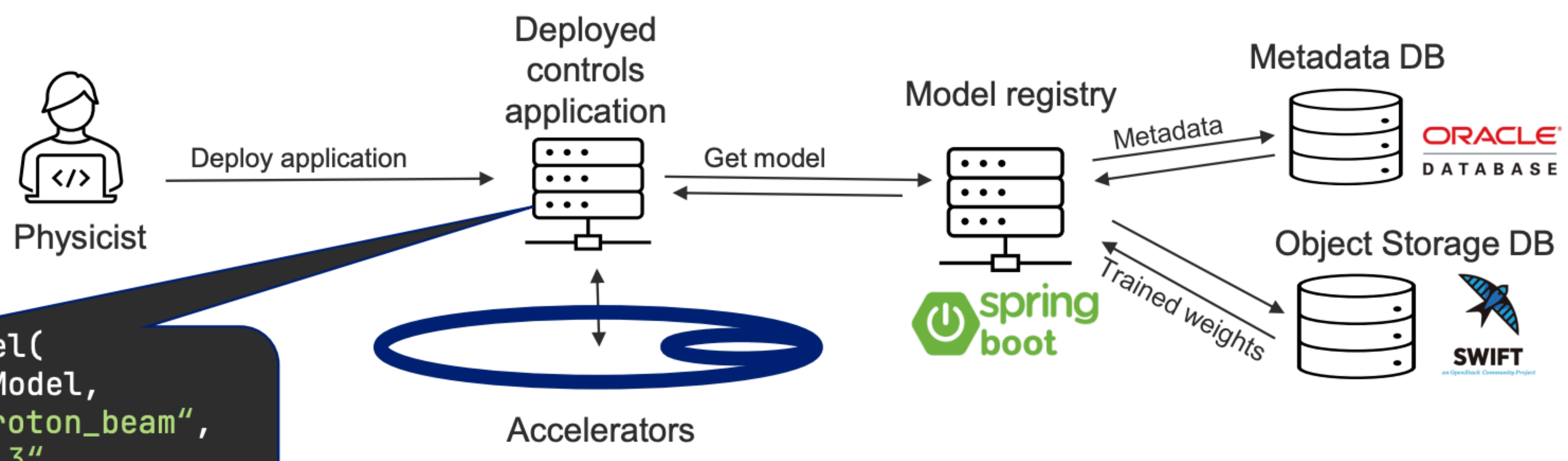
Infrastructure: Machine Learning Platform

Training




```
model.fit(training_data)
client.publish_parameters_version(
    model,
    name = "proton_beam_config",
    version = "2.0.3"
)
```

Inference
(Deployment)




```
model = client.create_model(
    model_type = BeamLineModel,
    model_parameters = "proton_beam",
    params_version = "2.0.3"
)
result = model.predict(input)
```

J.-B. De Martel et al., *Machine Learning Platform - Deploying and Managing Models in the CERN Control System*, Dec 2021

Detection of faulty Beam Position Monitors

Problem: Faulty BPMs **are a-priori unknown**:

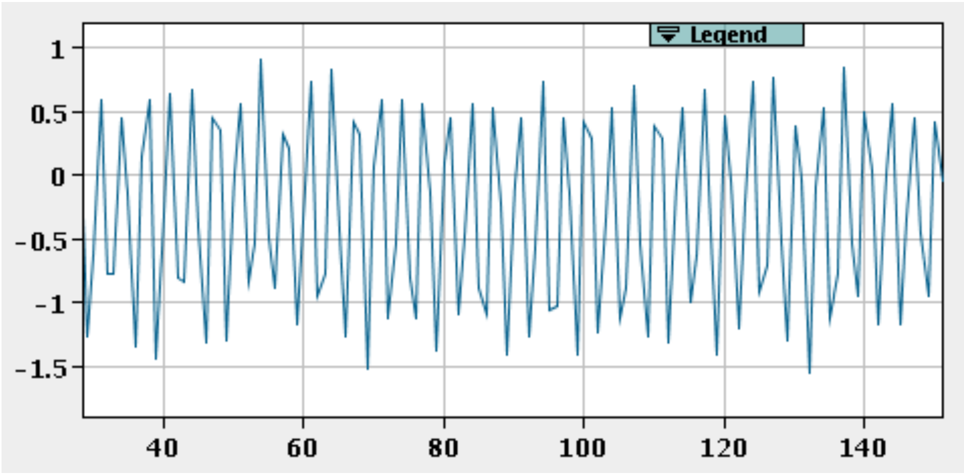
—> cause erroneous computation of optics functions

—> manual cleaning is required

—> repeating optics analysis after manual cleaning

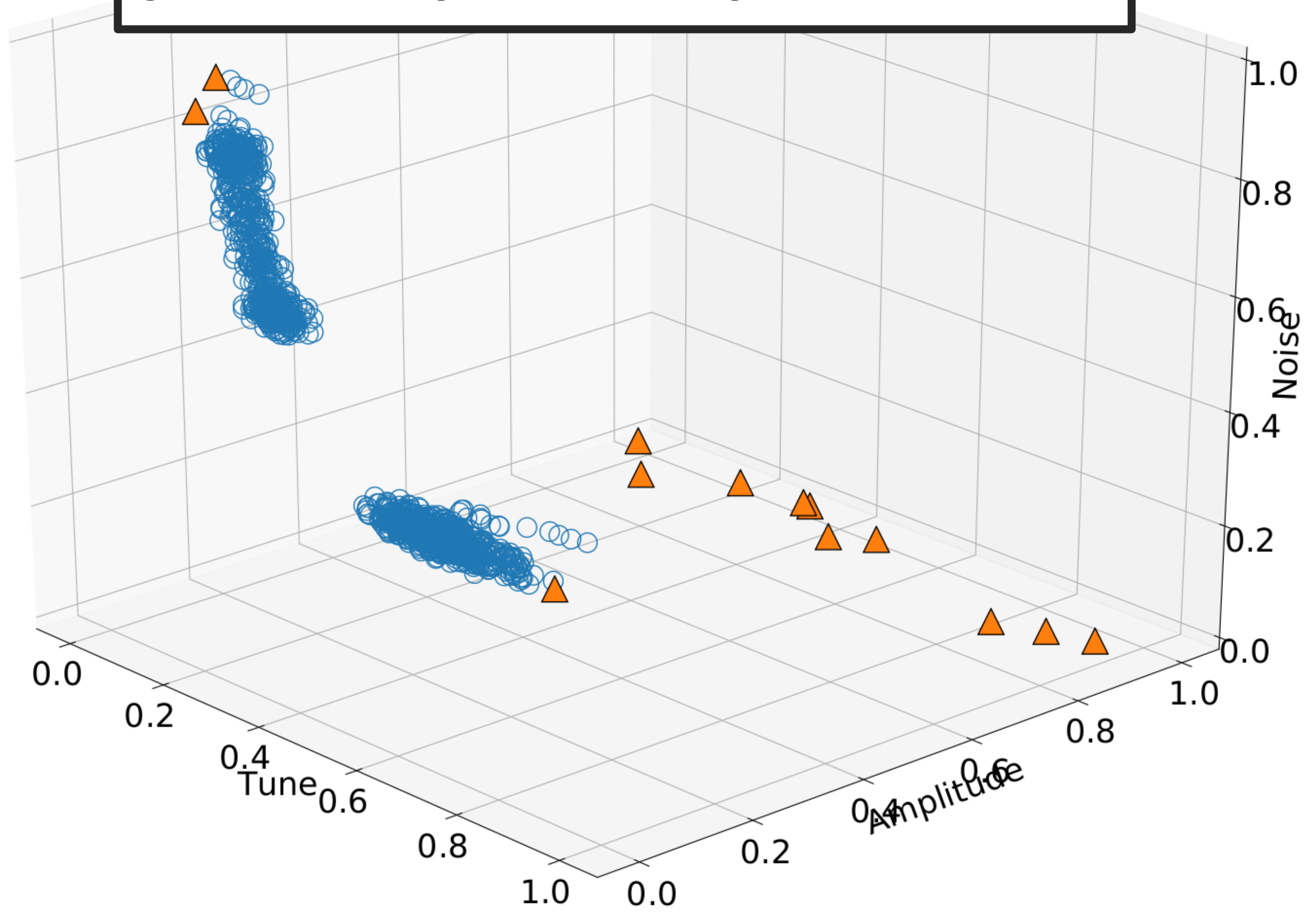
Anomaly detection using Unsupervised Learning

Harmonic analysis of all BPMs

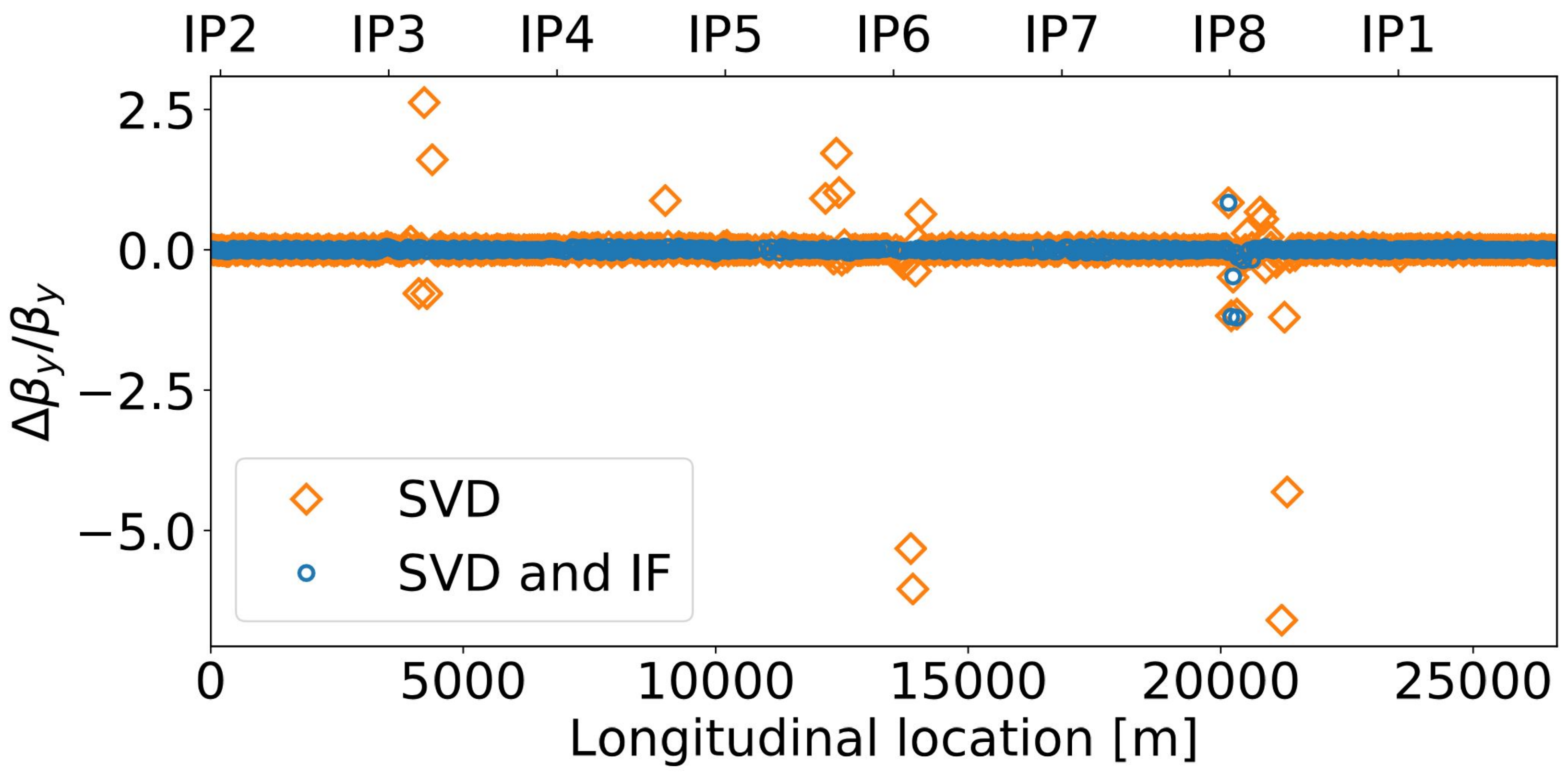


Detection of faulty signal

prior to optics computation



Avoid the appearance of erroneous optics computation



- Outlier detection based on combination of several signal properties
- Immediate results

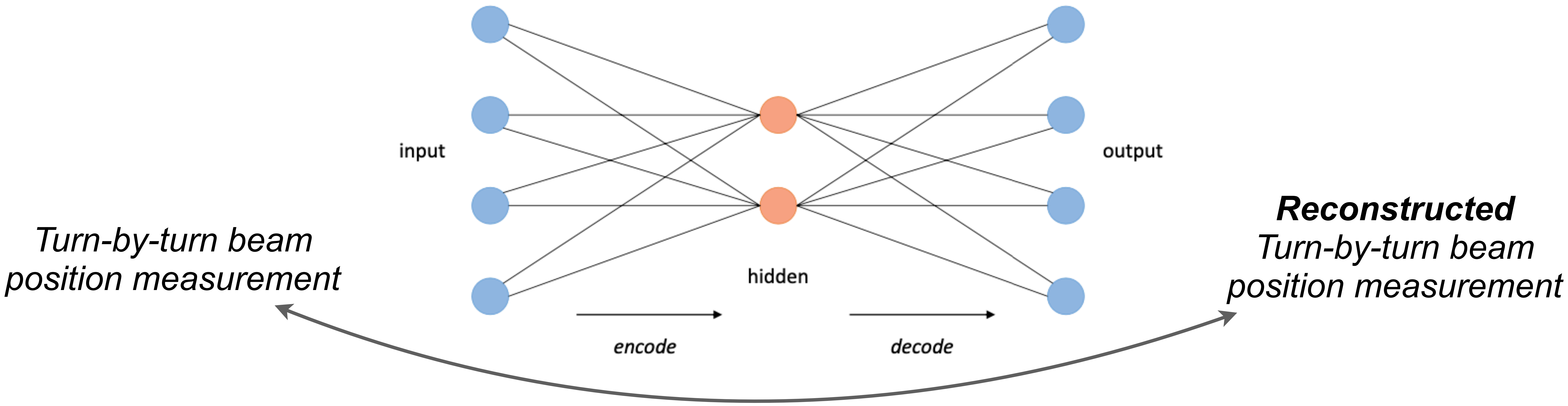
Alternative approach: Autoencoder NN

- Autoencoder can be trained to reproduce the input data in the output layer

Anomaly detection:

1. Training on “clean” data
2. Verify that cleaned signal can be reconstructed with desired low prediction error
3. Reconstruct anomalous signal: prediction error will be higher

—> Need to define a threshold for prediction error to define anomalies



Difference is low for good signal
high for faulty signal

In collaboration with University di Napoli Federico II, A. Apicella, A. Gilardi

Optics control in HL-LHC studies

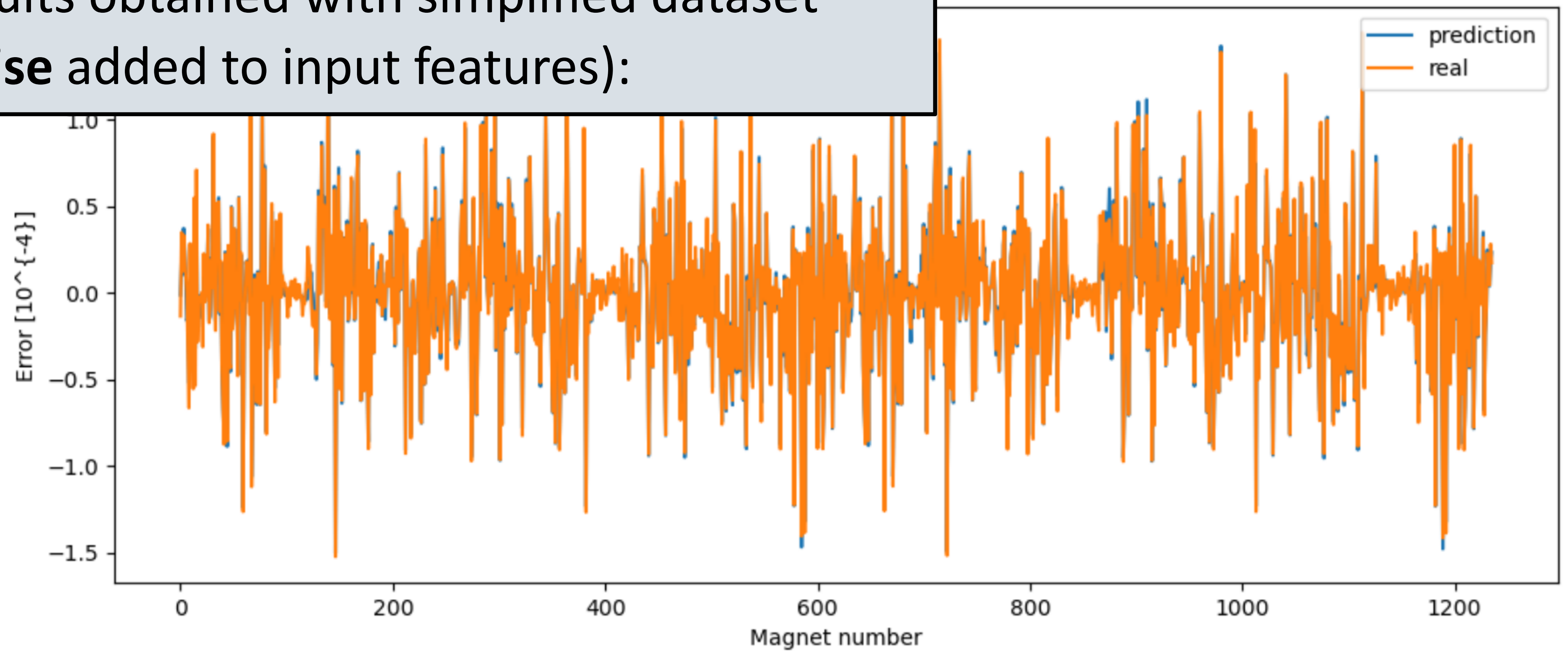
High Luminosity Large Hadron Collider: Upgrade of the LHC to push the performance in terms of beam size and luminosity.

•The local linear optics correction at the IR will be essential to ensure the HL performance.

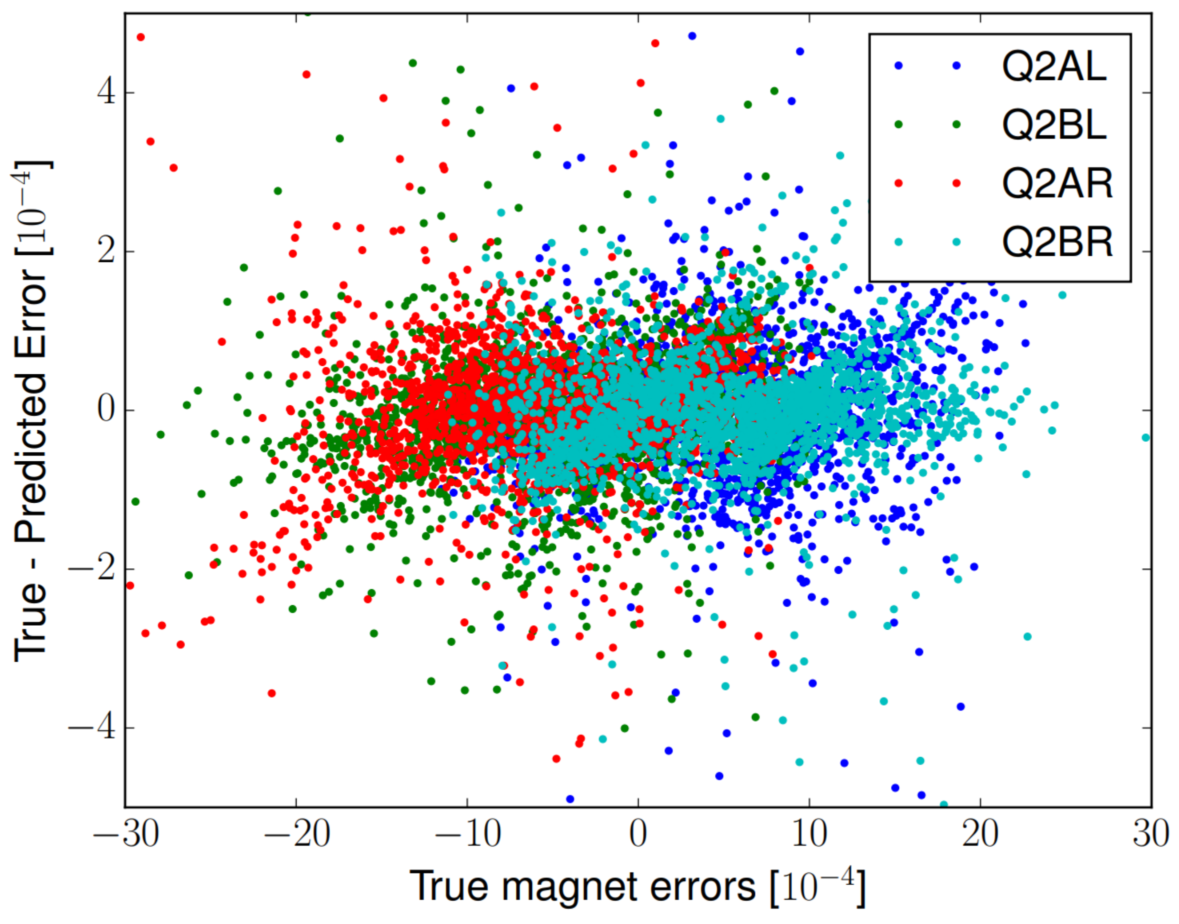
•Current LHC strategies might impose limitations → new correction strategies are needed.

Work by Hector Garcia Morales, BE-ABP

Preliminary results obtained with simplified dataset (**no noise** added to input features):

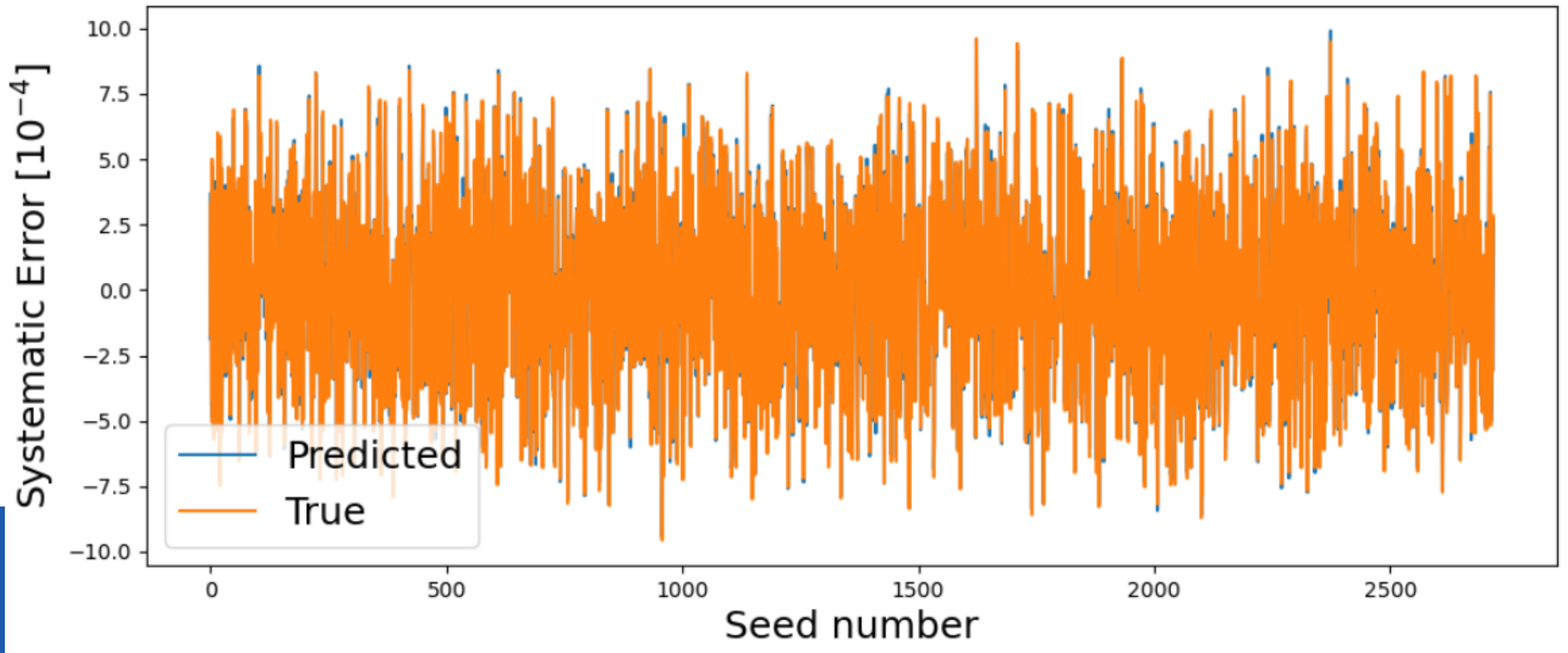


Full set of quadrupoles all around the ring



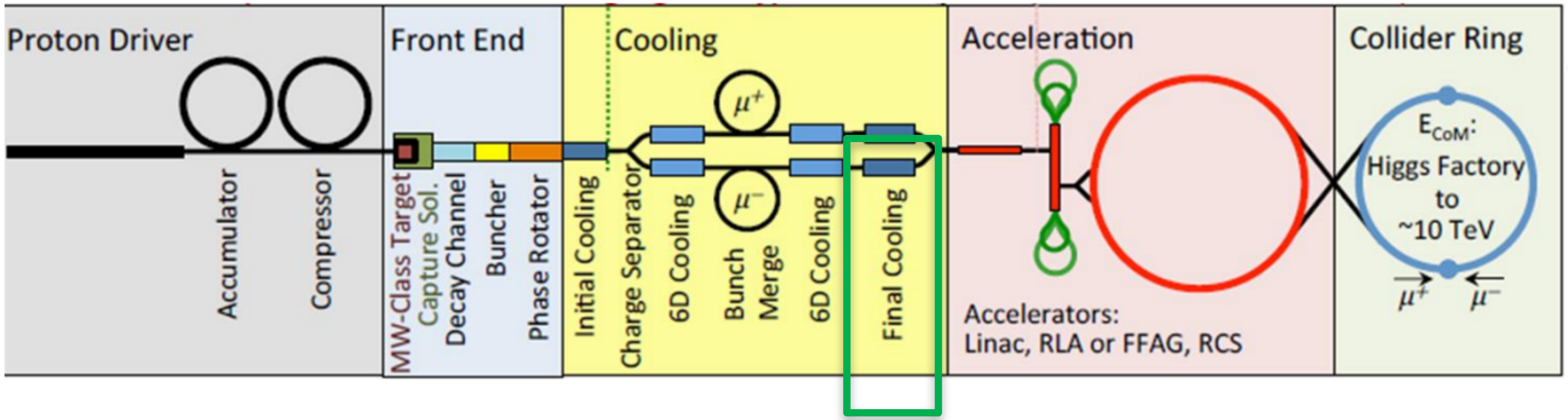
Inner Triplet magnets in Interaction Regions

- Systematic part of the gradient error (unknown) may have a significant impact on the β-beating.



Challenges of Final Cooling for the Muon Collider

- Proton driven scheme: muons are produced by p+-target interaction
- Muon beam is produced with a **large transversal momentum** —> cooling is required
- Short lifetime of muons —> **ionization cooling**



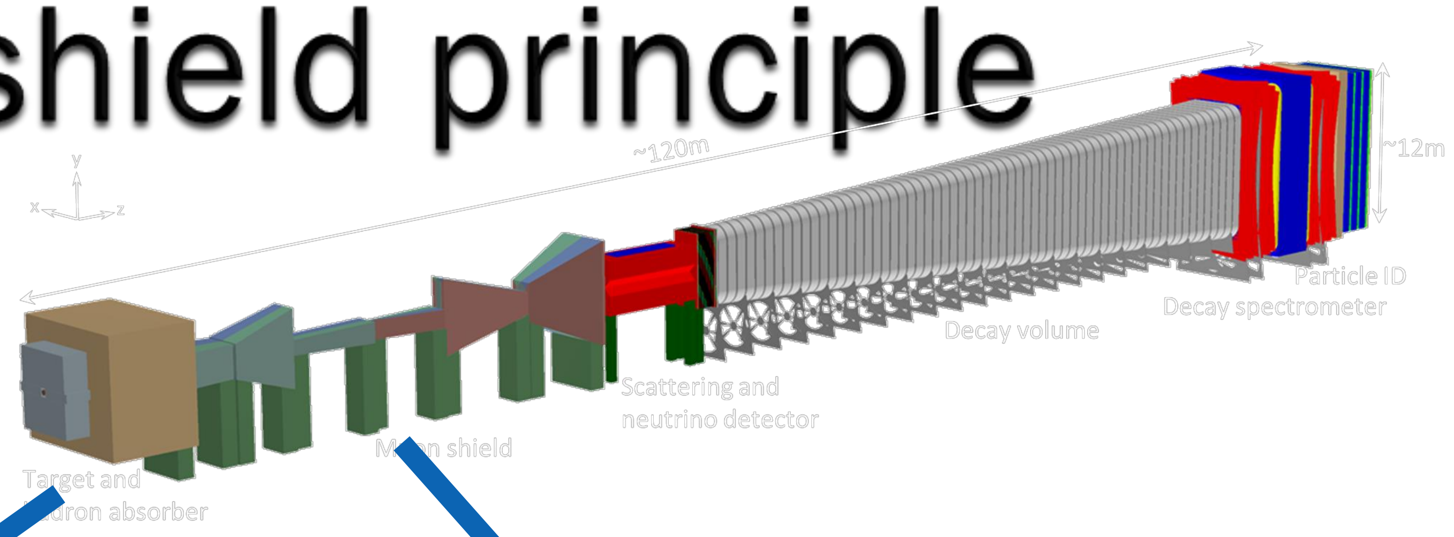
$$L \propto \frac{\gamma^3}{CI} \frac{N_0^2}{\epsilon_{\perp,N}}$$

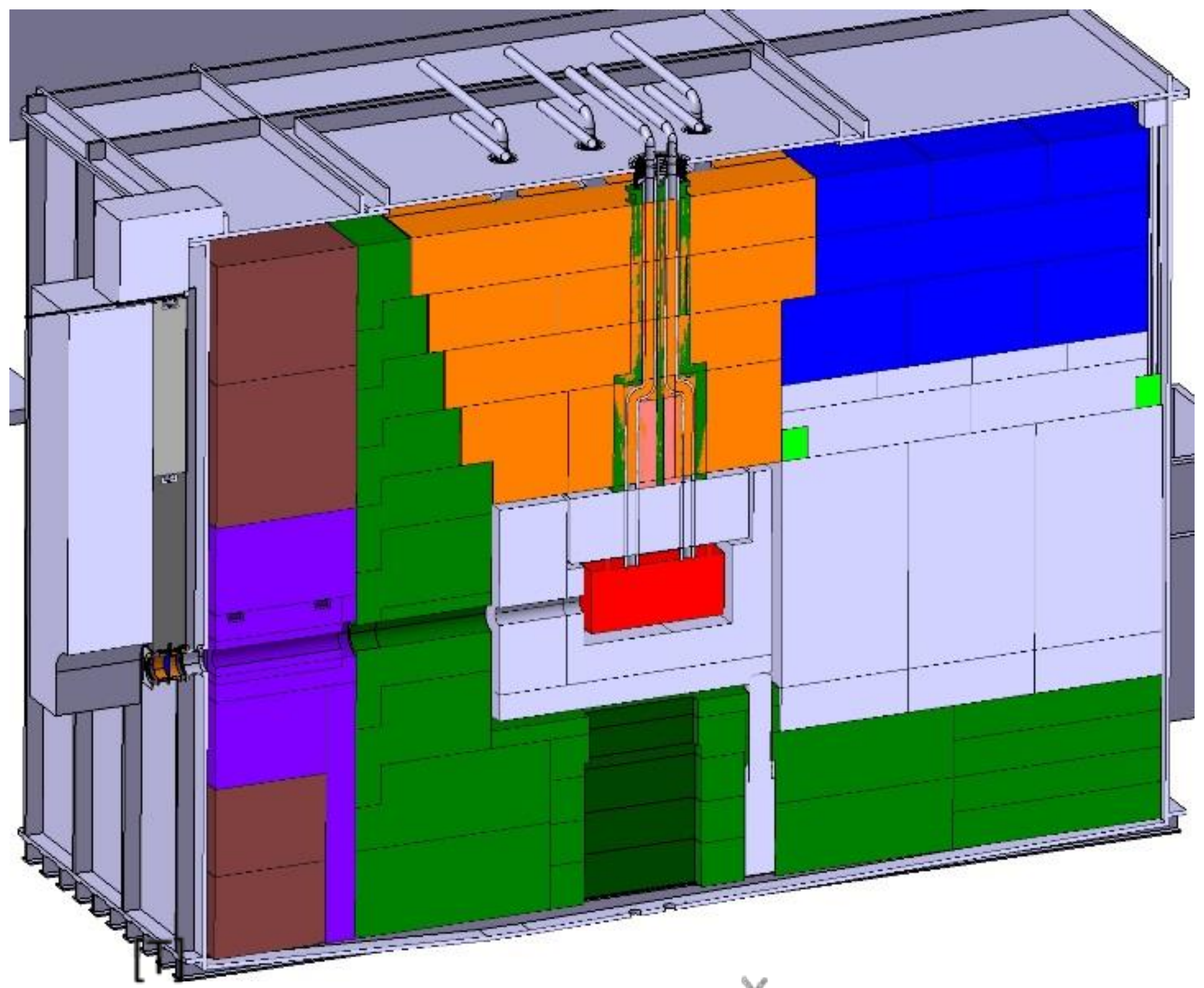
https://muoncollider.web.cern.ch/design/general-parameters

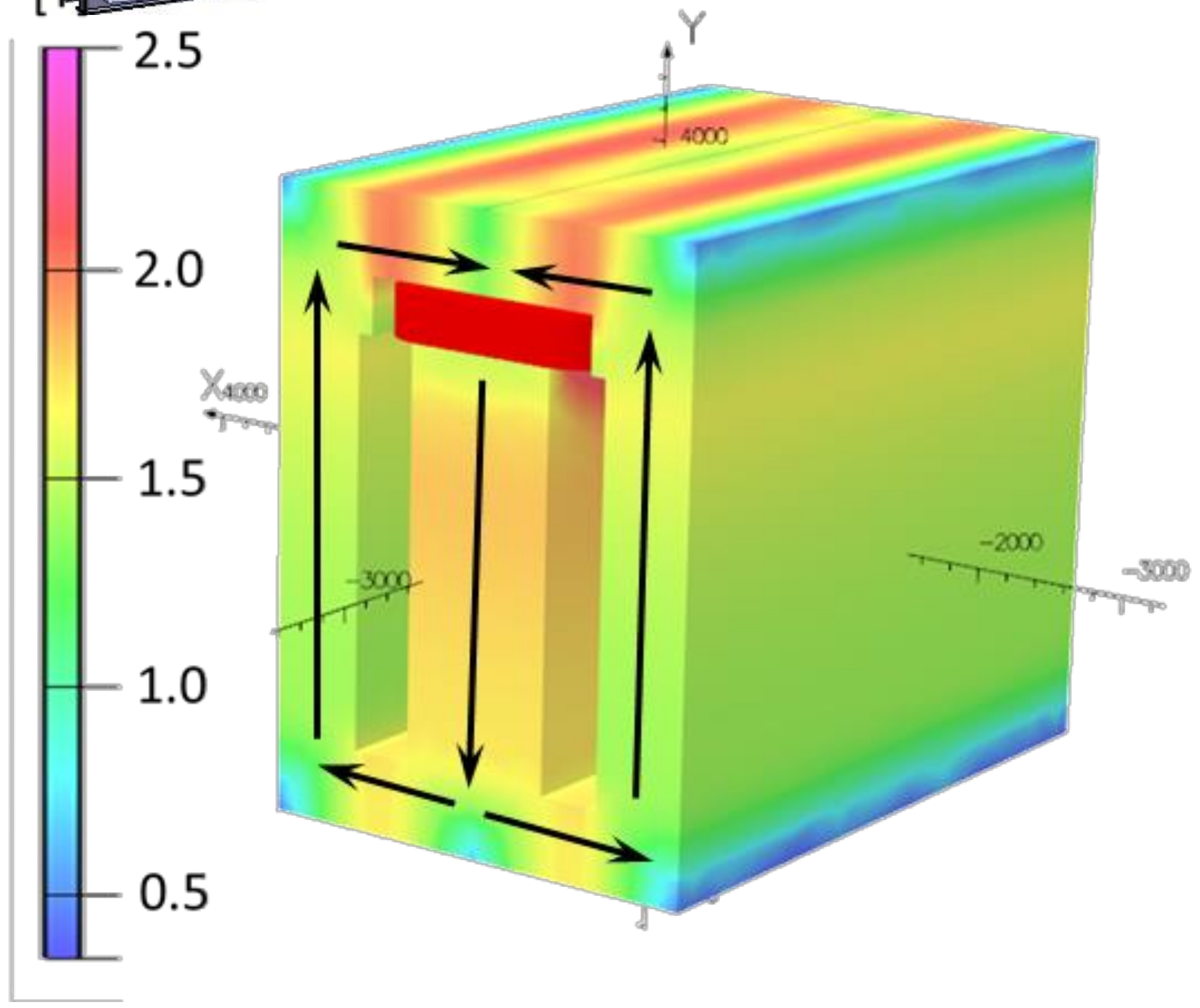
- Beams with transversal emittance ϵ_{trans} of 0.3 mm are provided after the 6D cooling
- Final cooling: ϵ_{trans} = 0.05 mm has been achieved by H. K. Sayed (10.1103/PhysRevSTAB.18.091001)
- ϵ_{trans} = 0.025 mm is expected to be required before acceleration.

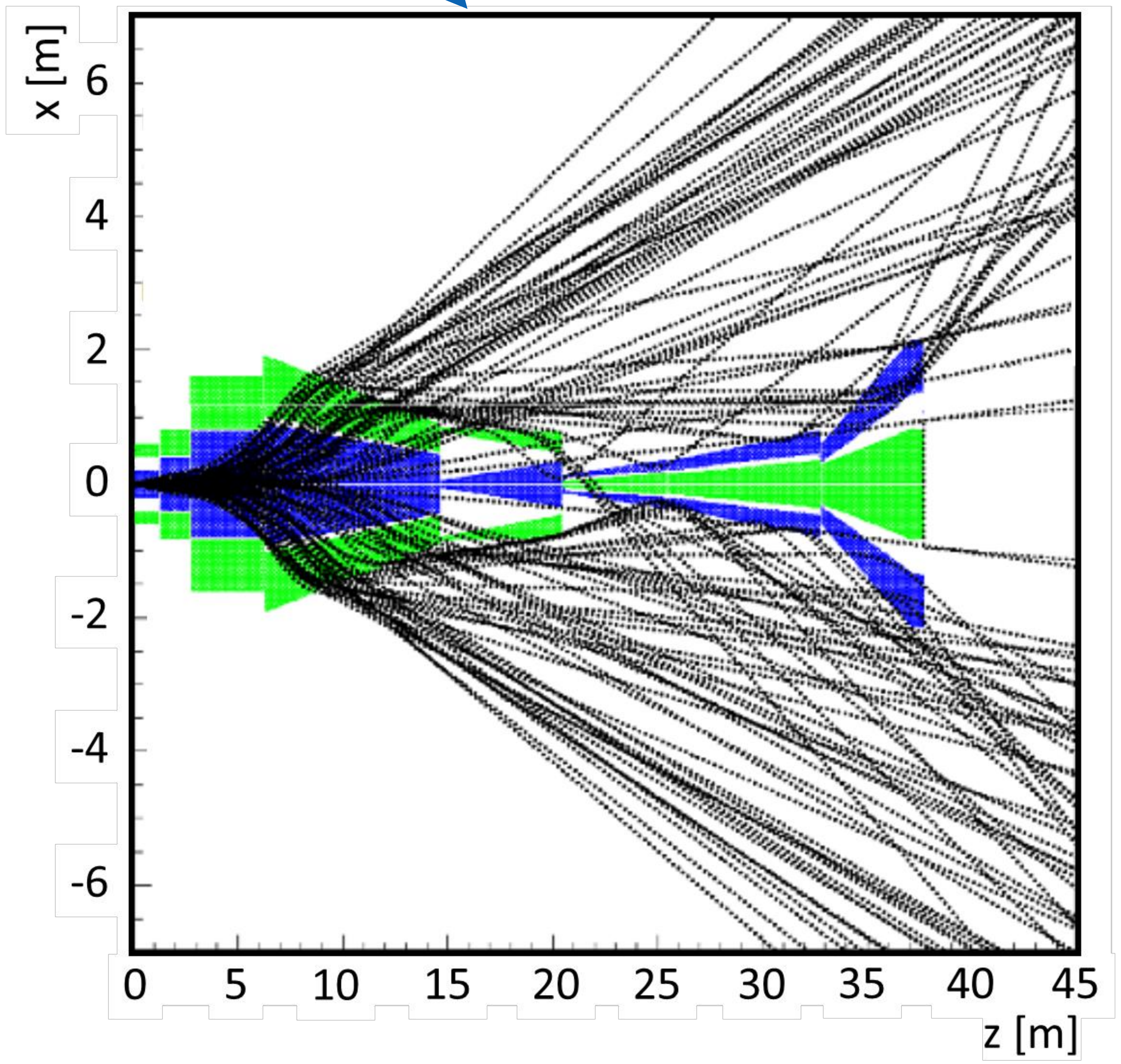
[1] U.S. Muon Accelerator Program, FERMILAB-CONF-13-307-APC

Magnetic shield principle

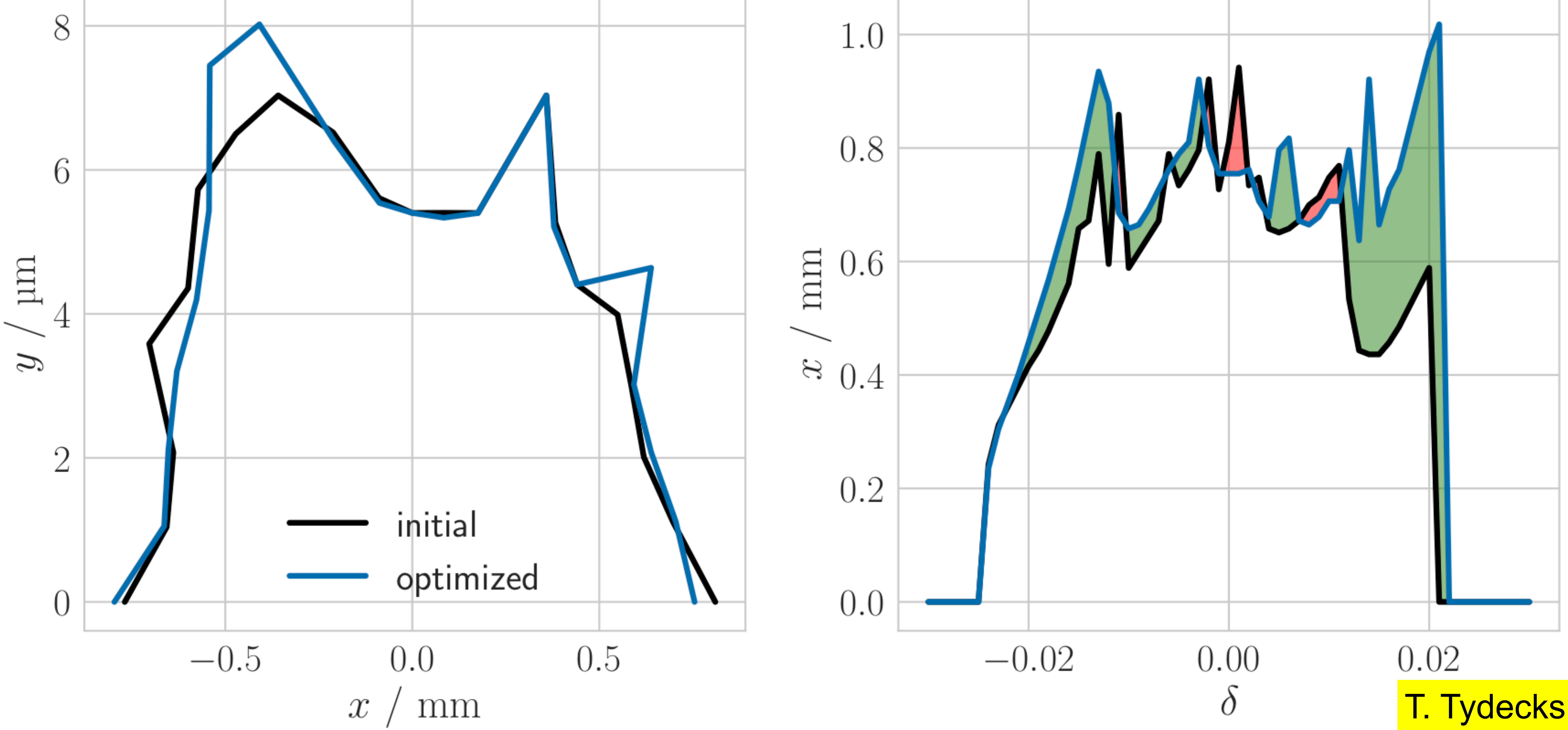








optimized DA & MA

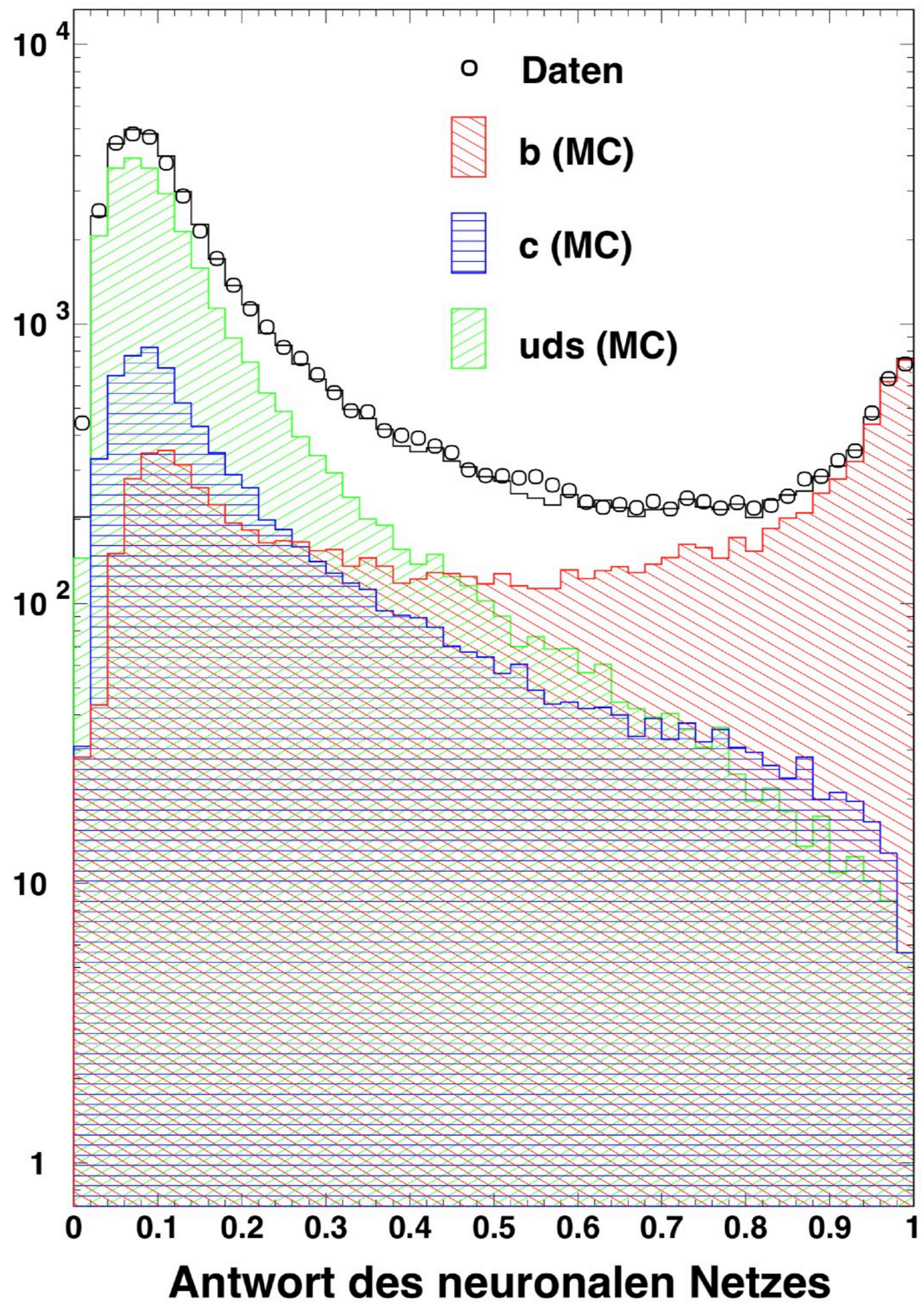


T. Tydecks, FCC-ee CDR

Dynamic aperture (left) and momentum aperture (right) for reference lattice (black) and optimised lattice (blue). The area of dynamic aperture is improved by 3.1% while area of momentum aperture is increased by 18%.

MACHINE LEARNING FOR HEP DATA ANALYSIS

- Improving interpretation of detector data (2002)



- Discovery of the Higgs particle (2012)

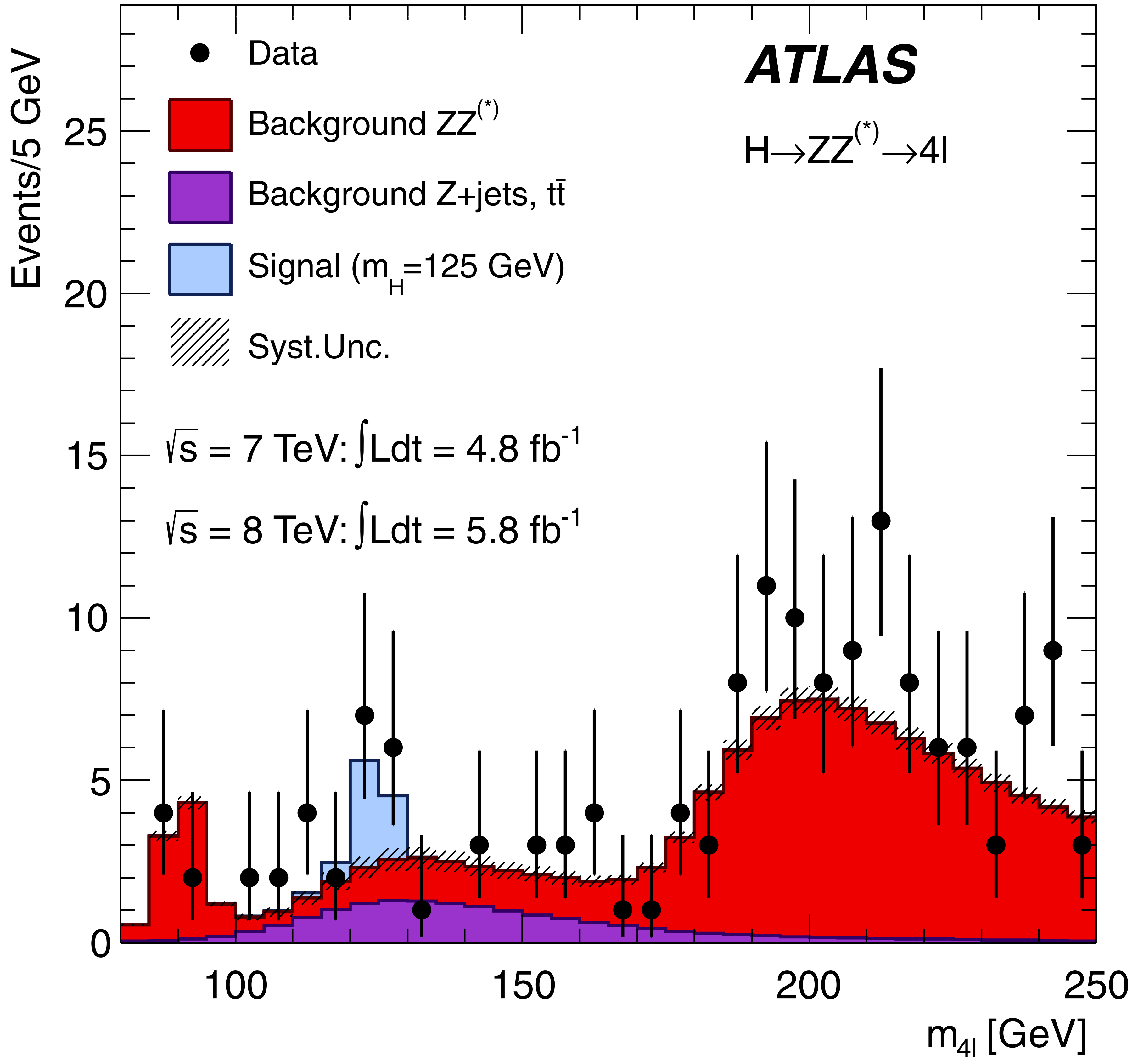


Fig. 2. The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The signal expectation for a SM Higgs with $m_H = 125$ GeV is also shown.

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?

TENTATIVE CONCLUSIONS

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 ?