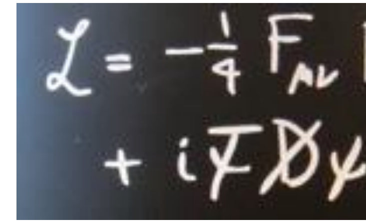
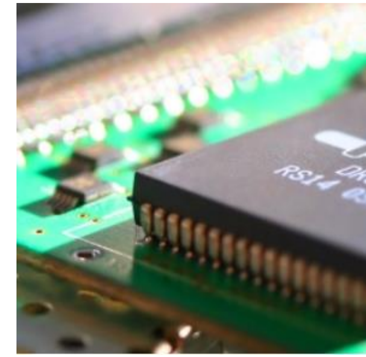
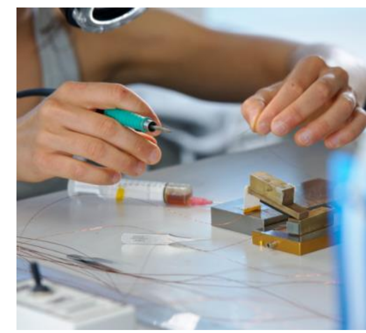
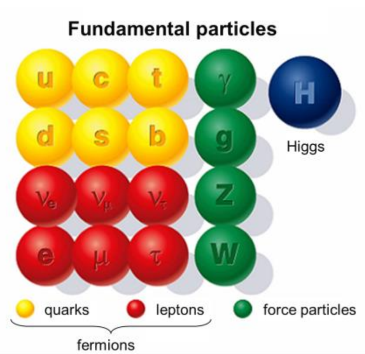
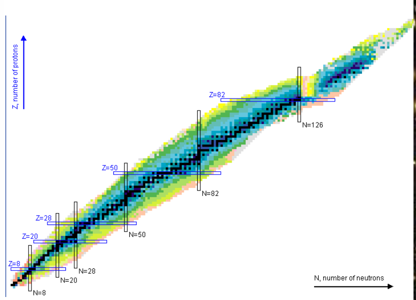
Symmetries and fundamental interactions

Precision experiments at low energies

K.Kirch, ETH Zurich – PSI Villigen, Switzerland

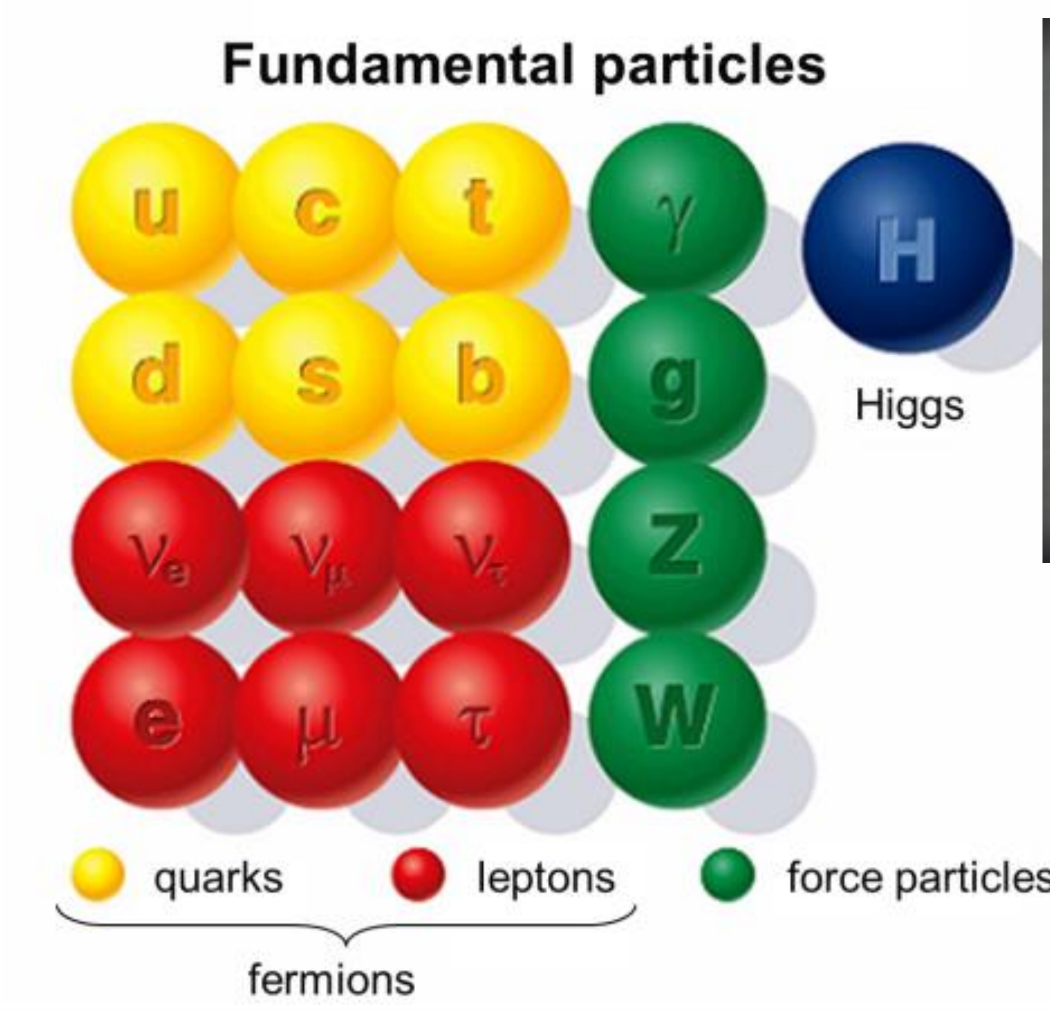


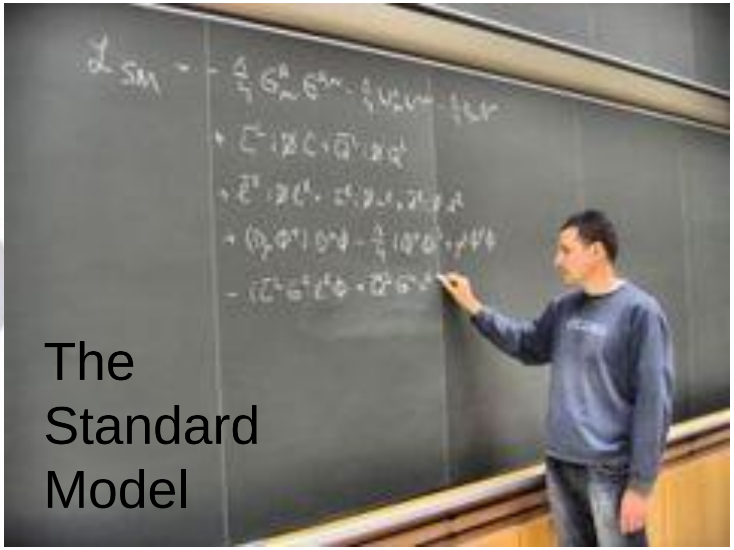

Symmetries and fundamental interactions

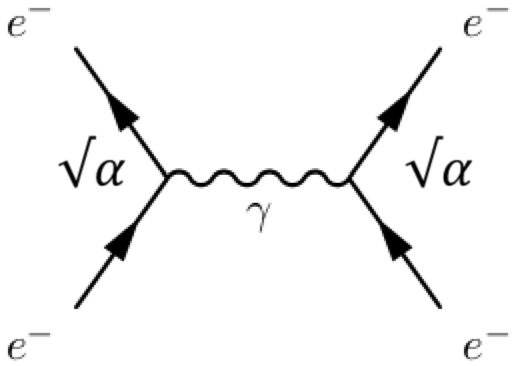
Precision experiments at low energies

- Reminder
  - Standard Model of Particle Physics
  - ‘Simple’ composite and fundamental systems
- One accelerator example
- Some issues of our present-day understanding
- 6 examples: Weak, QED, QCD, cLF, DM, $\bar{g}$

Standard Model building blocks

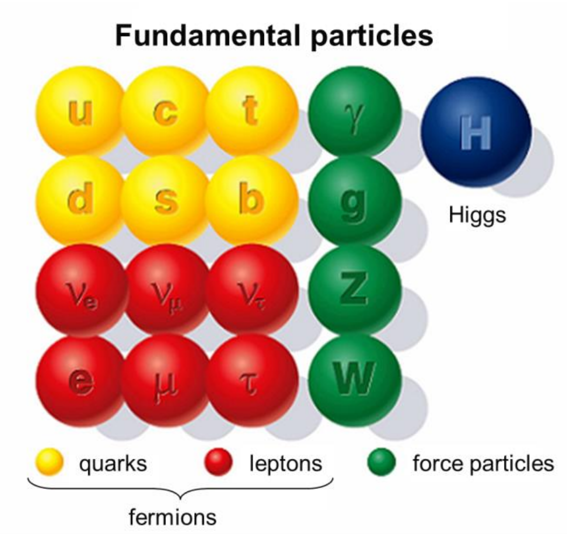


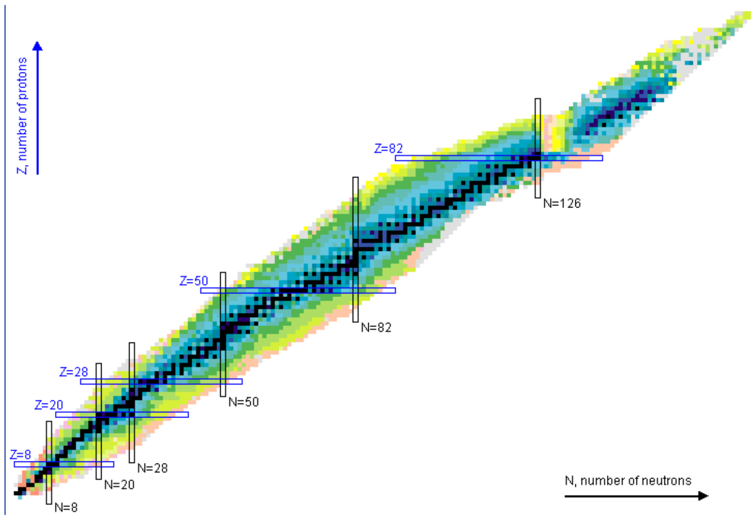


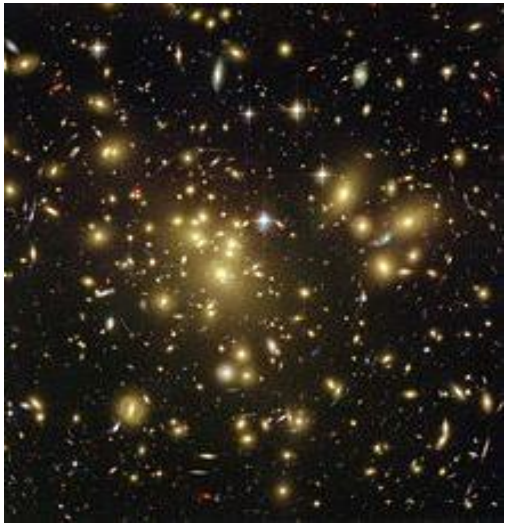


Part of what we know:

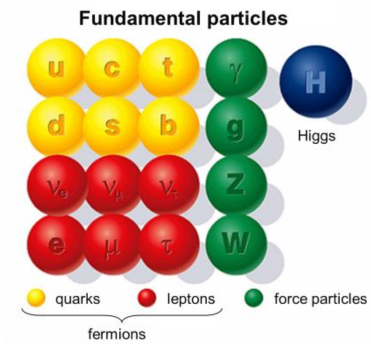
- A set of fundamental fermions
- A set of four fundamental interactions
- Exchange bosons for three interactions
- A Higgs boson
- QFT: Standard Model
- CFT: General Relativity
- Symmetries: Gauge Invariance, Lorentz, CPT, …





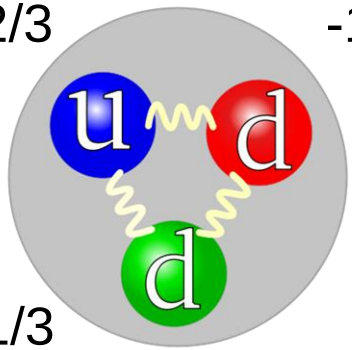


Composite system: The neutron



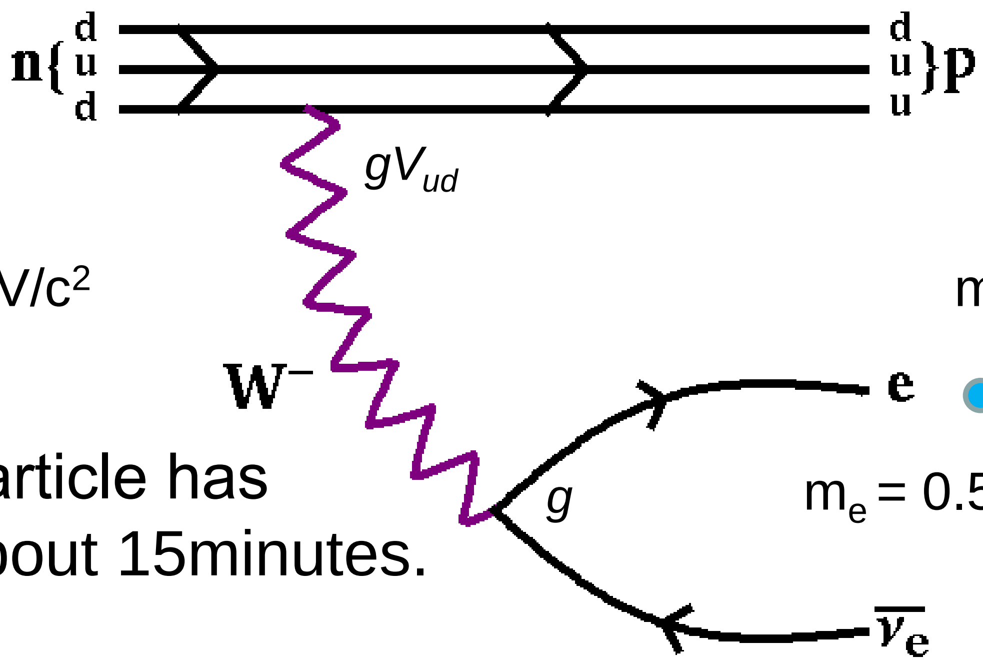
Spin 1/2

+2/3 -1/3

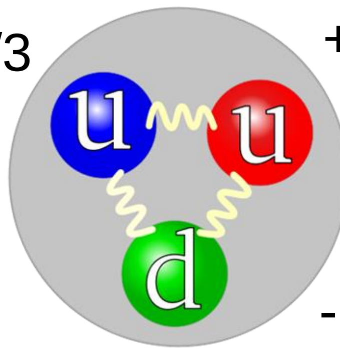


-1/3

$m_n = 939.57\ \mathrm{MeV/c^2}$



+2/3 +2/3



-1/3

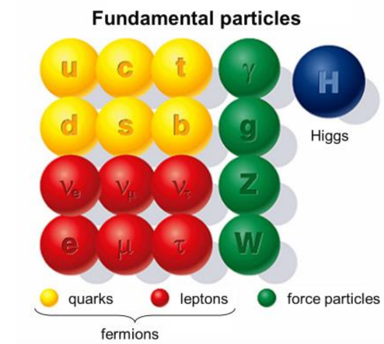
$m_p = 938.27\ \mathrm{MeV/c^2}$

$m_e = 0.511\ \mathrm{MeV/c^2}$

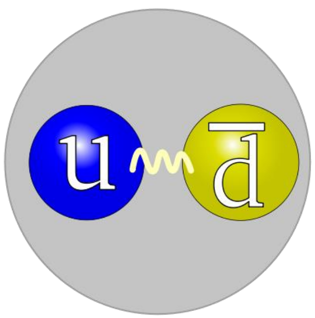
$m_\nu < 2\mathrm{x}10^{-6}\ \mathrm{MeV/c^2}$

… as a free particle has
a lifetime of about 15minutes.

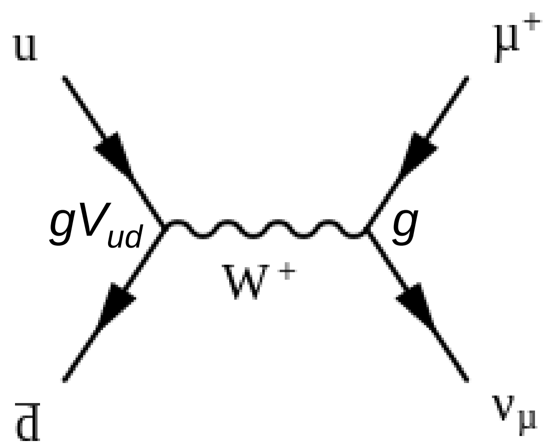
Composite system: The pion



Spin 0



π^+



Spin 1/2

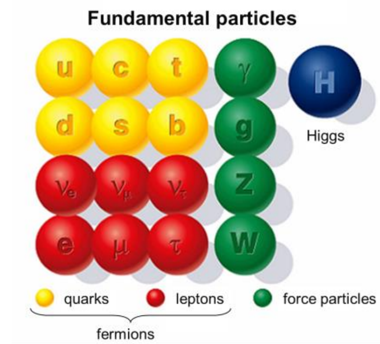
$m_\mu = 105.66$ MeV/c^2

$m_\nu < 2\text{x}10^{-6}$ MeV/c^2

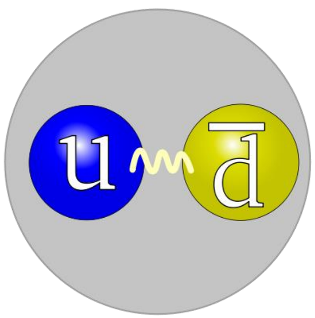
Spin 1/2

$m_\pi = 139.57$ MeV/c^2

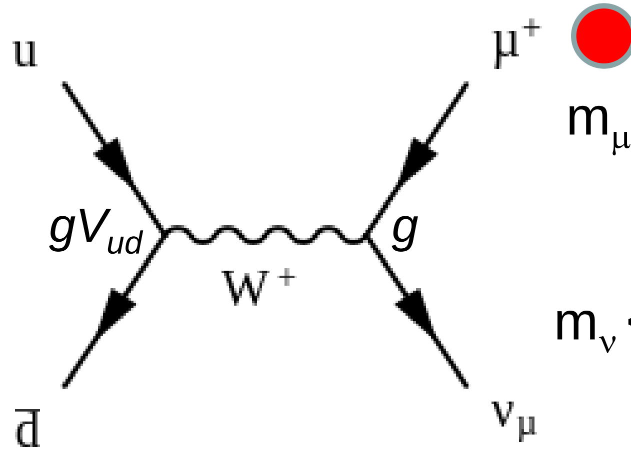
Composite system: The pion



Spin 0



π^+



$m_\pi = 139.57$ MeV/c^2

Spin 1/2

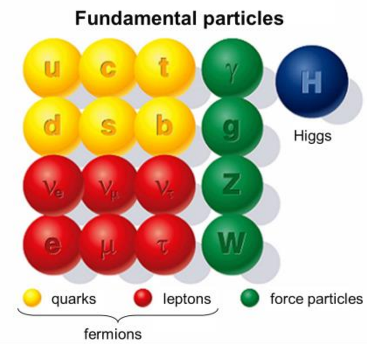
$m_\mu = 105.66$ MeV/c^2

$m_\nu < 2\text{x}10^{-6}$ MeV/c^2

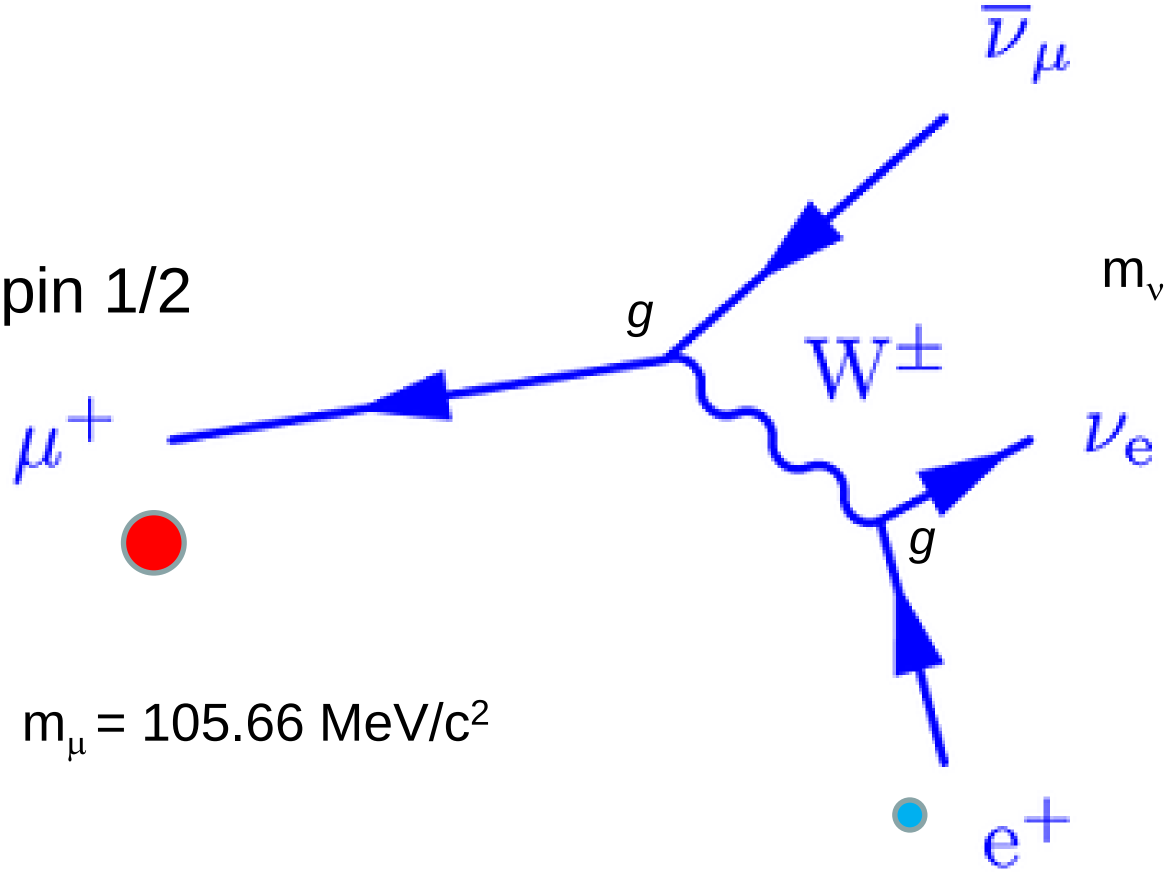
Spin 1/2

… and a source of muons

Fundamental particle: The muon



Spin 1/2

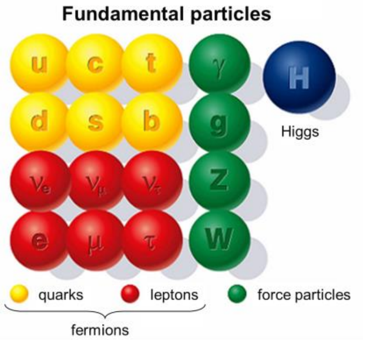


$m_\nu < 2x10^{-6}$ MeV/c^2

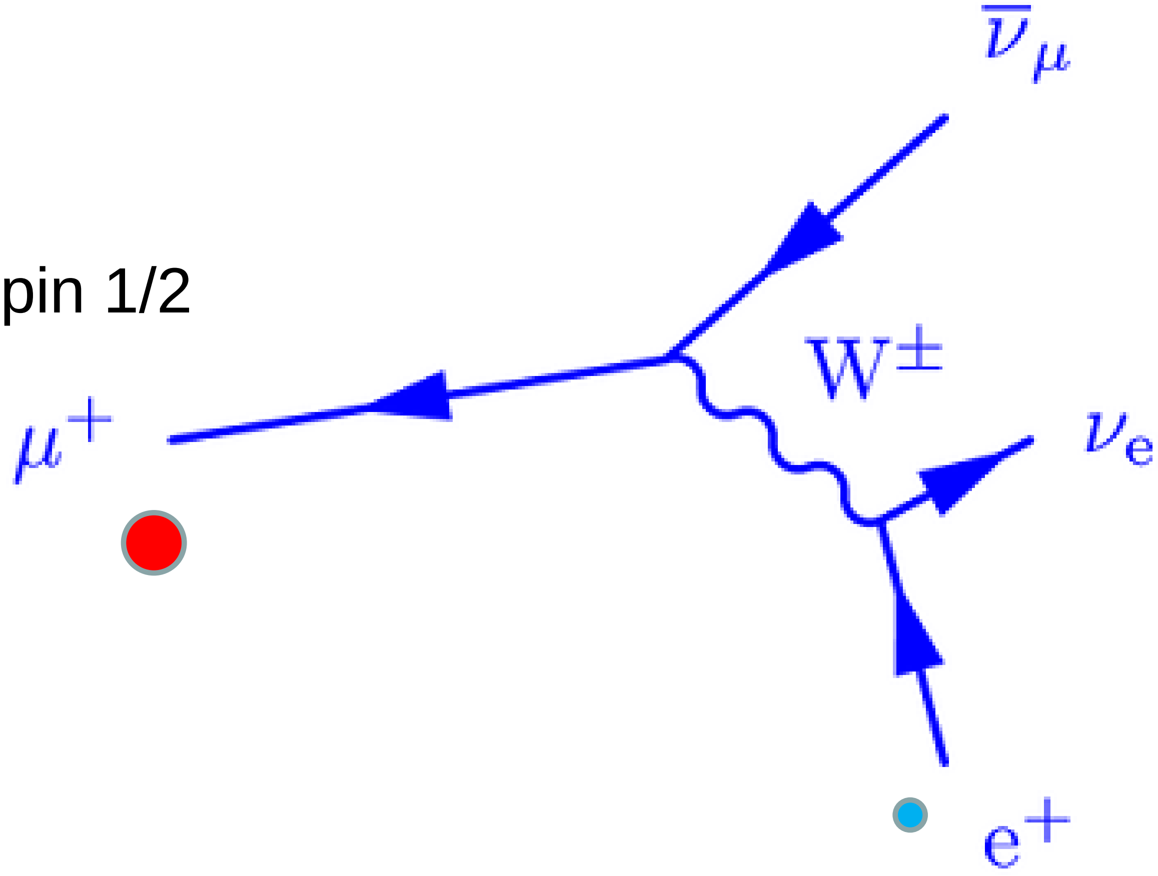
$m_\mu = 105.66$ MeV/c^2

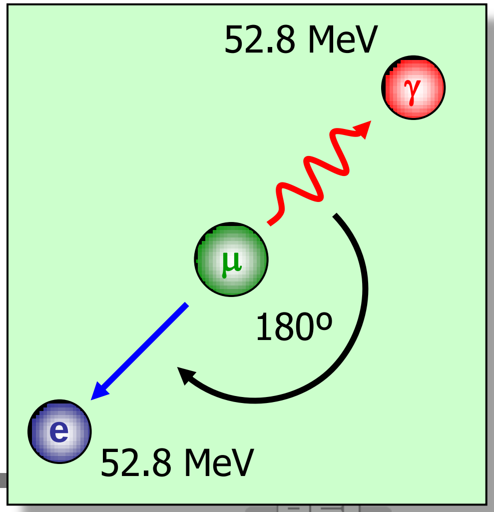
$m_e = 0.511$ MeV/c^2

Fundamental particle: The muon

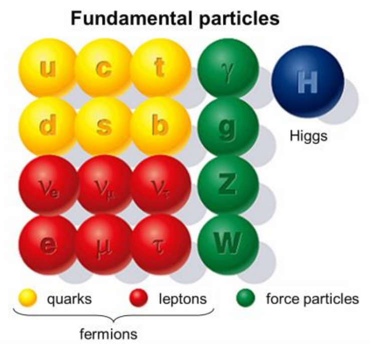


Spin 1/2

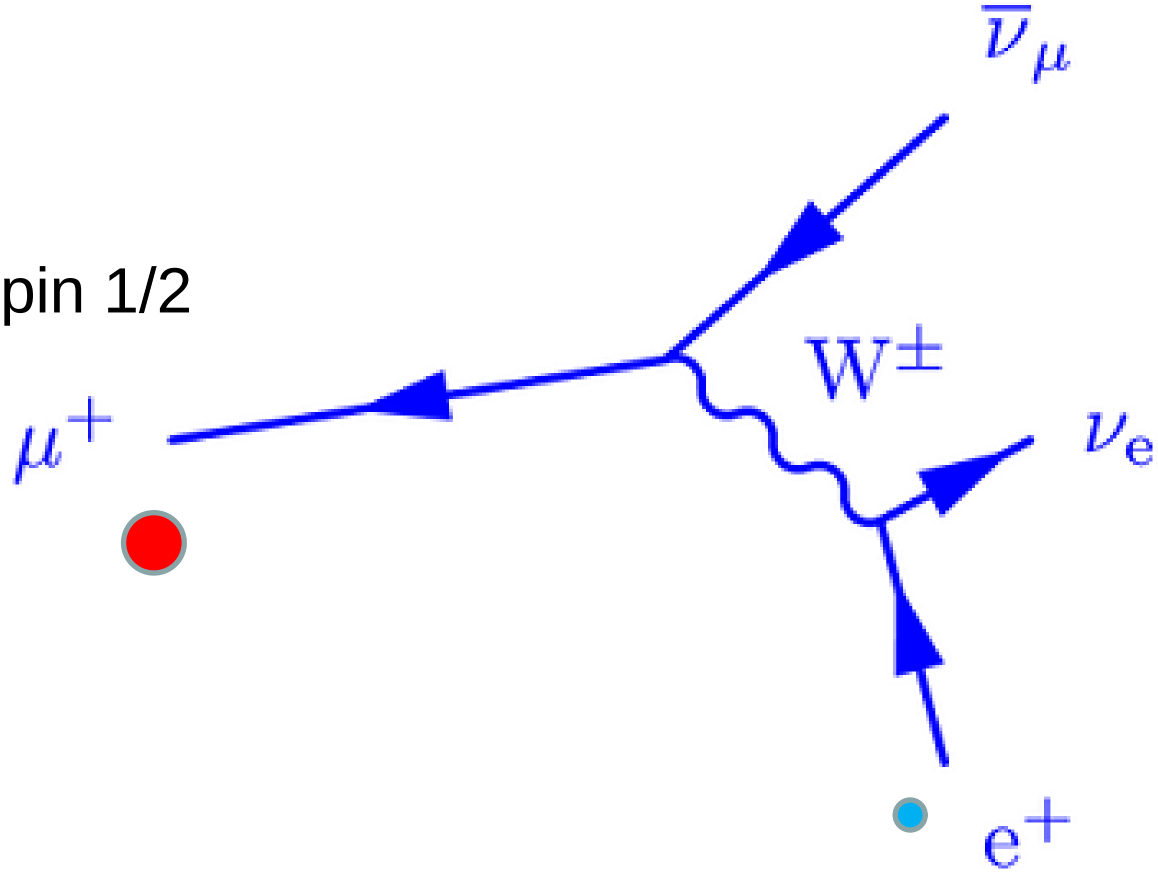


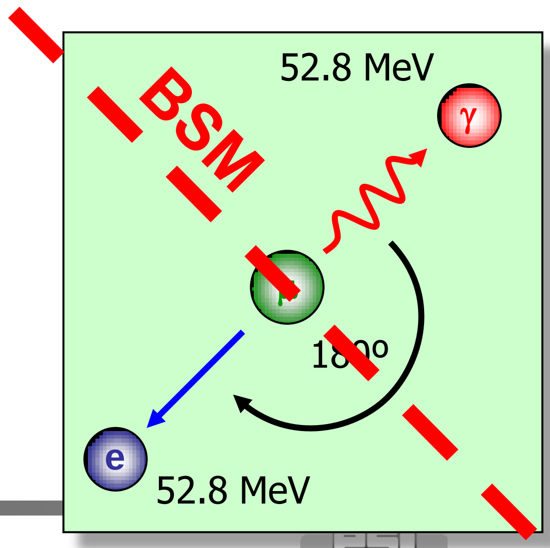


Fundamental particle: The muon

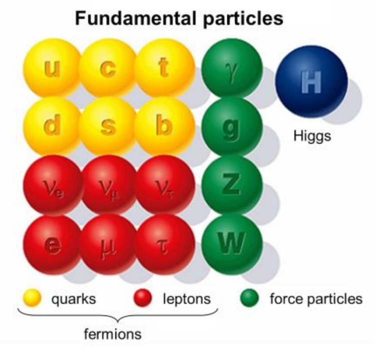


Spin 1/2

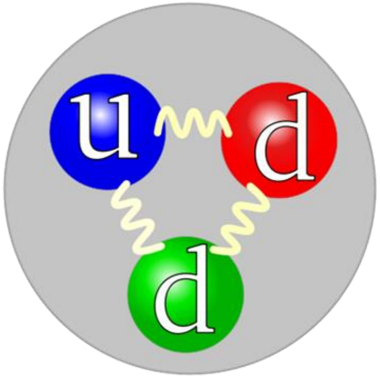


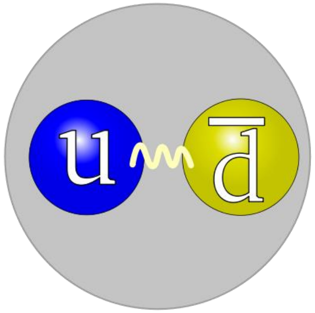


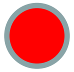
The lightest unstable particles of their kind



Neutron	Pion	Muon







Baryon	Meson	Lepton

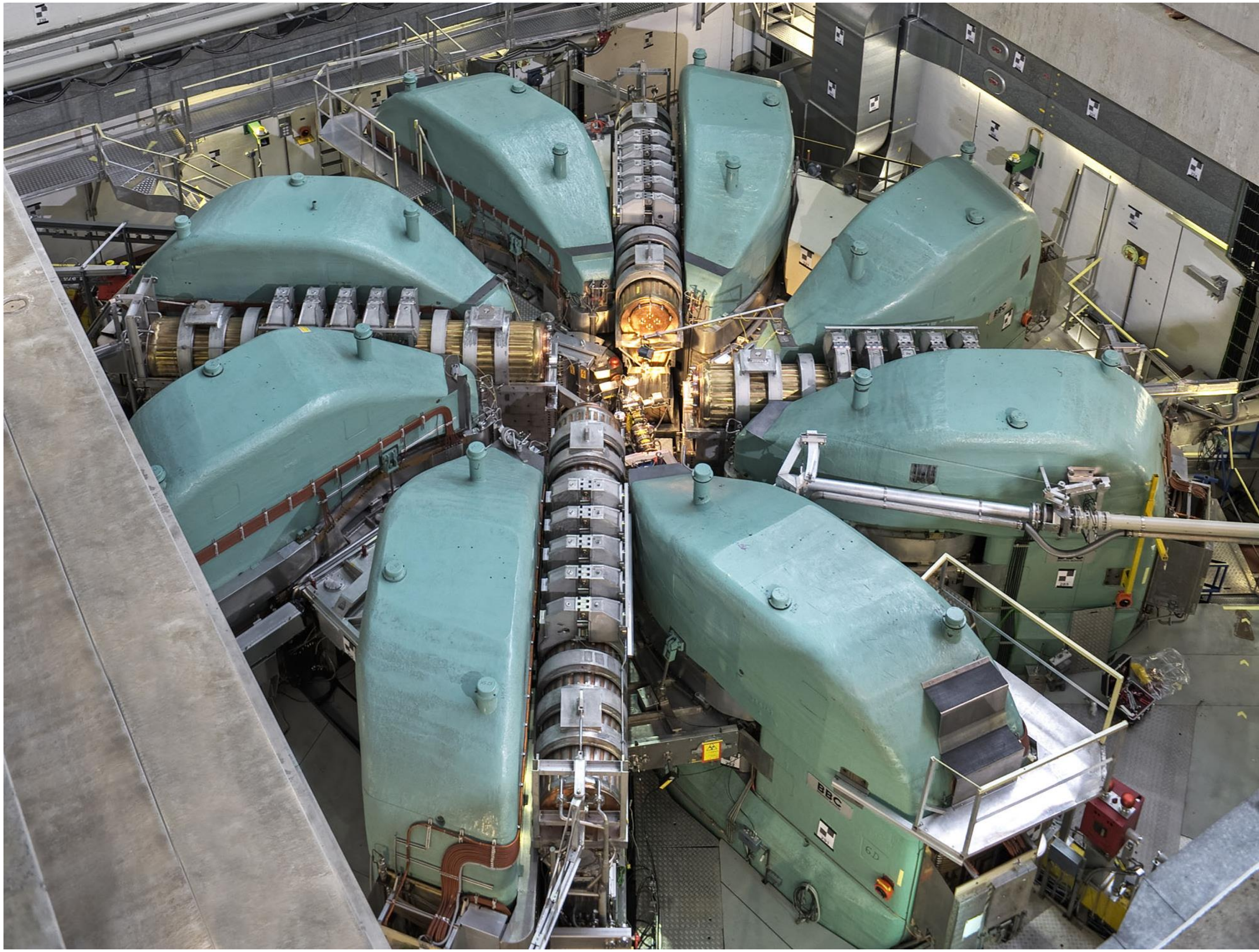
PSI ring cyclotron

produces
the world-wide highest intensities of the lightest unstable particles of their kind:

Mesons:
Pions,
π^+, π^-, π^0

Leptons:
Muons, μ^+, μ^-

Baryons:
UCN, n

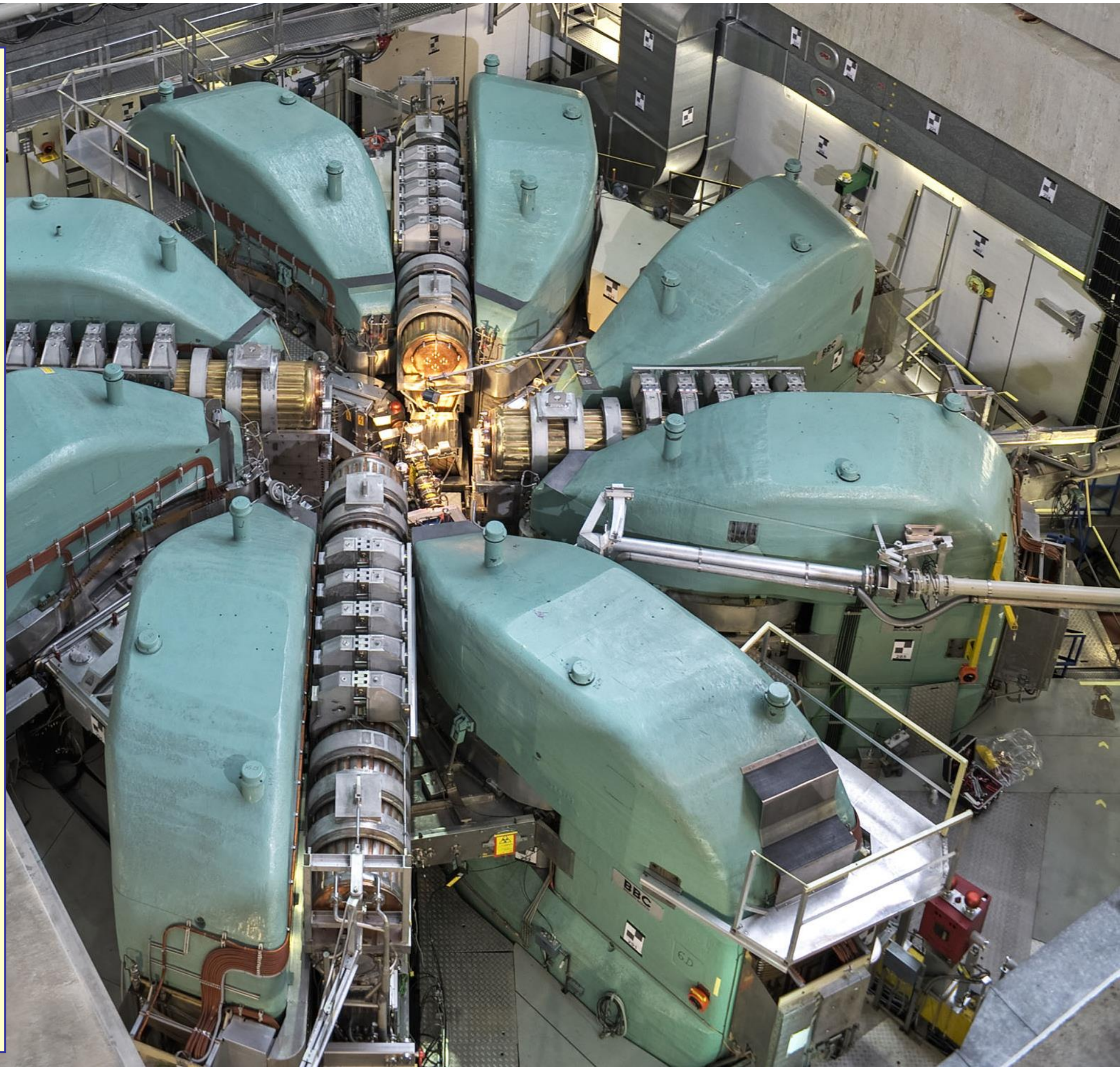


PSI ring cyclotron

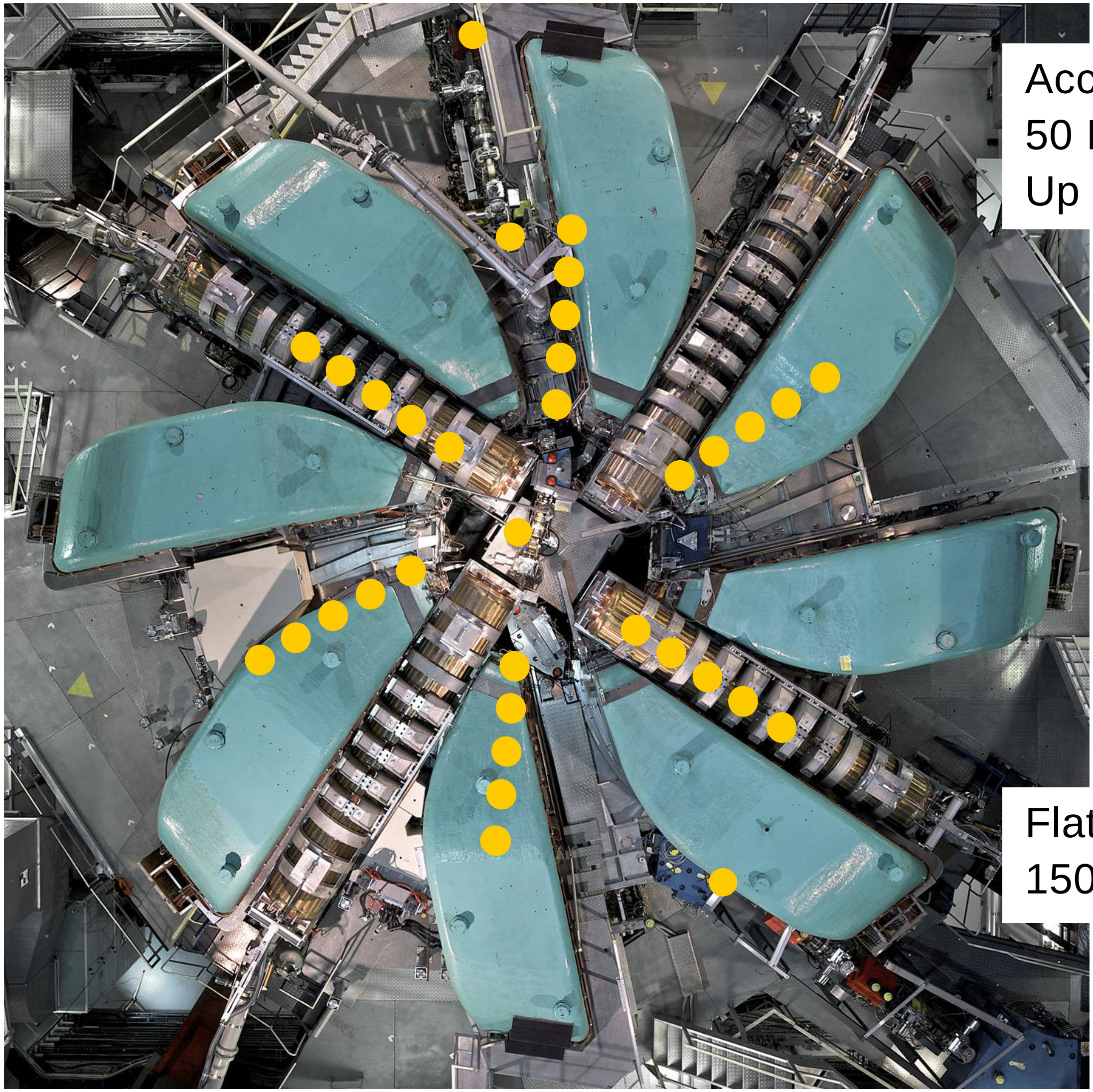
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

[losses ∝ (turn number)^3, W.Joho]

- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW



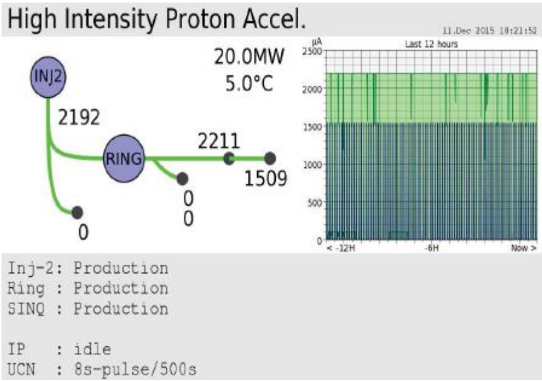
PSI ring cyclotron



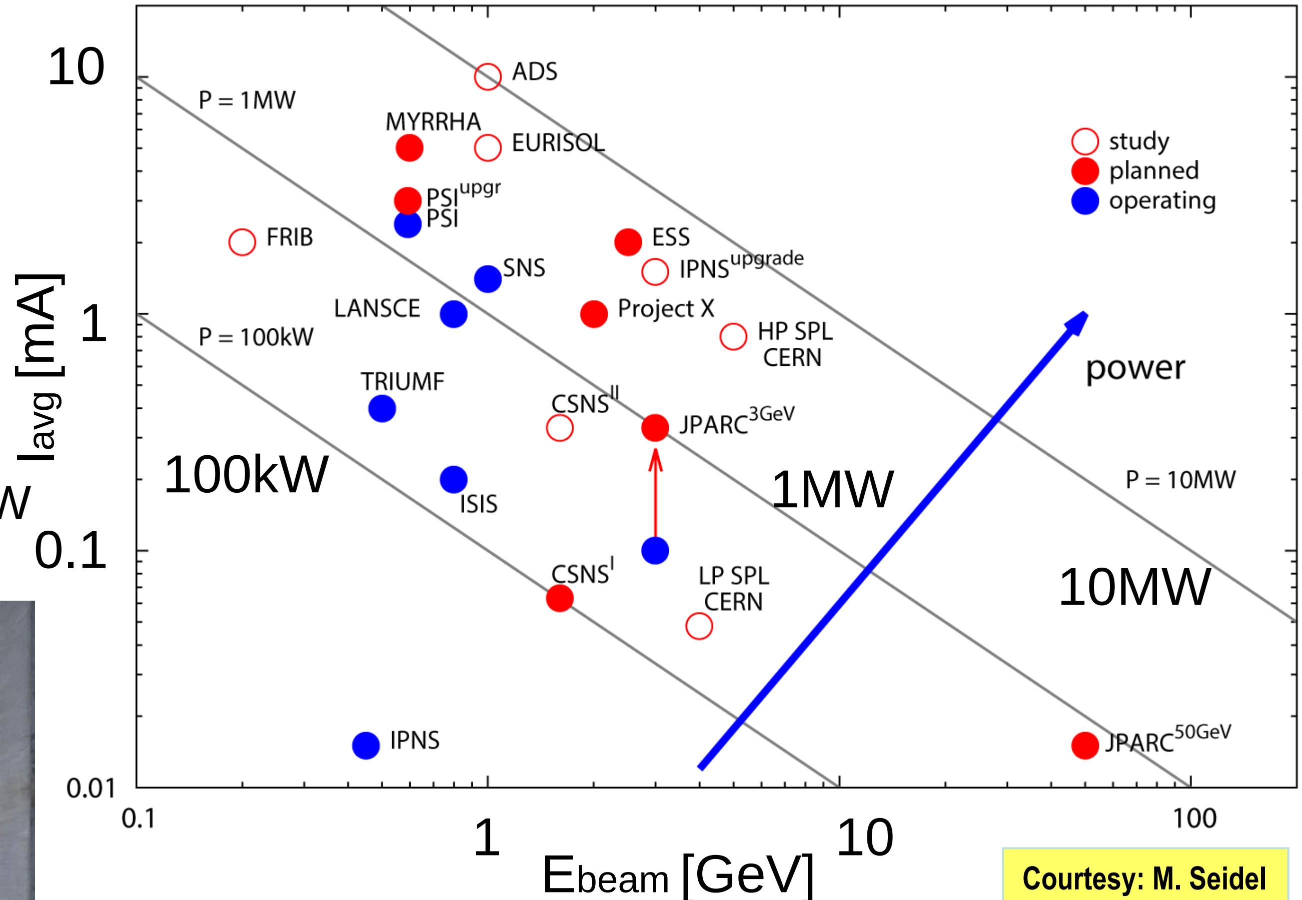
Accelerating cavity
50 MHz
Up to 1.2 MV/p

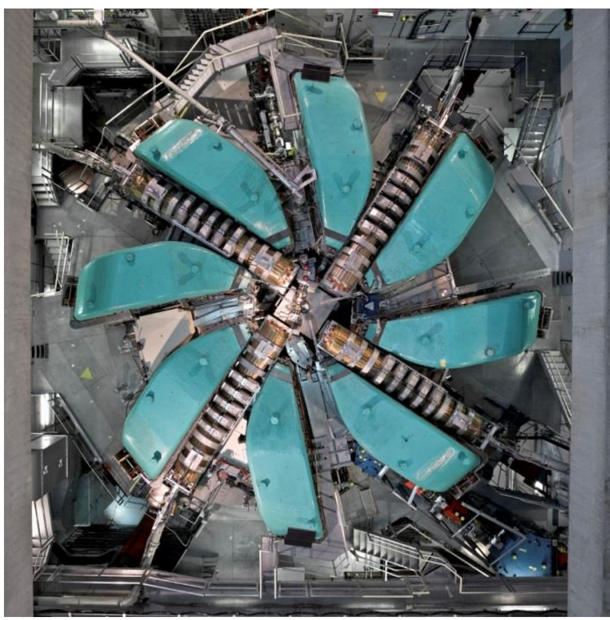
Flat top cavity
150 MHz

PSI ring cyclotron



The most powerful
proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW



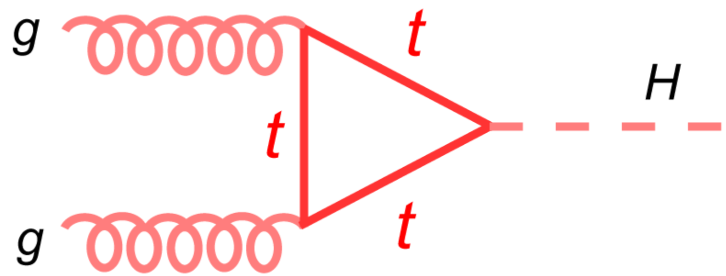


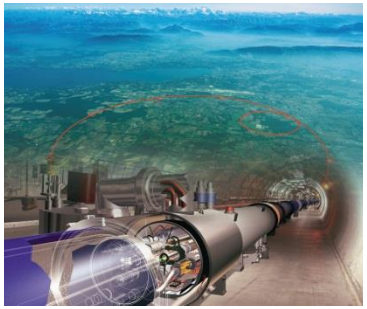
HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions
at low momenta and of ultracold neutrons.

Search for new physics

High Energy

direct production of new particle

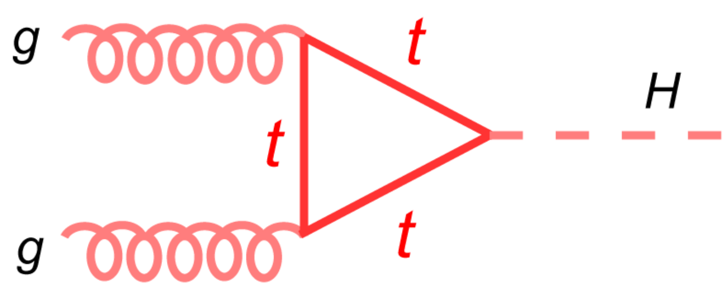


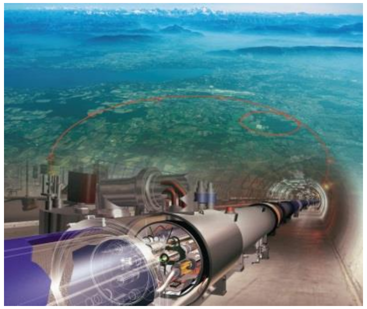


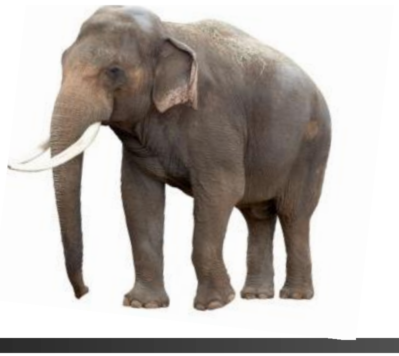
Search for new physics

High Energy

direct production of new particle

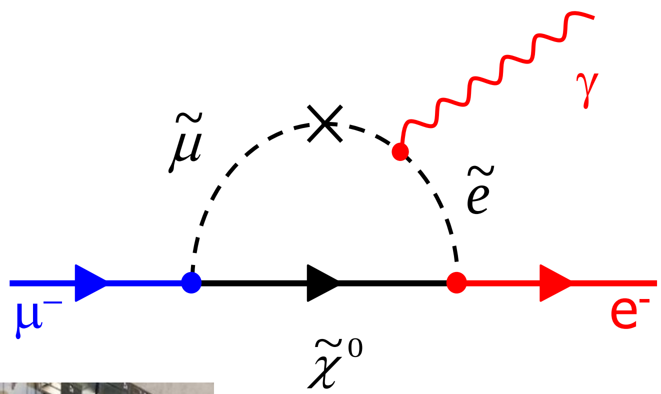


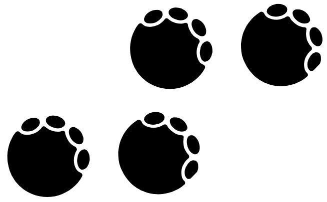




High Intensity & high precision

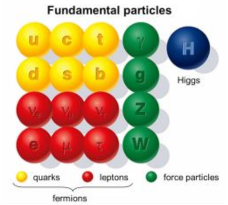
Search for $\mu \rightarrow e\gamma$



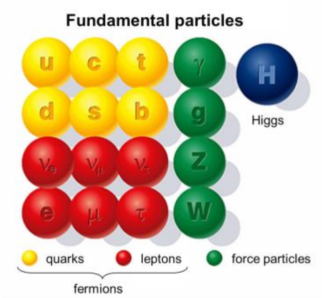


Part of what we should know better:

- Standard Model SM:
  - 19 param.: masses, couplings, mixings, CP phases, θ_{QCD}, Higgs vev
  - measurements of all parameters: as accurate and precise as possible
  - EW scale – hierarchy problem
  - $\theta_{QCD} < 10^{-9}$ – strong CP problem



- Beyond SM
  - Neutrino masses, mixing angles, CP-violation (7+ parameters)
  - Nature of neutrinos, Lepton#V
  - Lorentz, spin-statistics, CPT symmetries?
  - Baryon#V, Lepton#V, charged Lepton Flavor Violation?
  - Baryon asymmetry of the universe, CPV?
  - Dark Matter? Dark Energy?
  - Exotic interactions? Axions? ALPs? Others?
  - Gravity and SM together? Gravitational interaction of antiparticles



Strategy for progress

SM parameters

BSM Searches

Use synergies of particle, nuclear and atomic physics methods (and even other fields)

Many of the questions can be addressed by experiments at high intensity, high precision and low energies

Almost every high-precision measurement of SM parameters can be turned into a BSM search

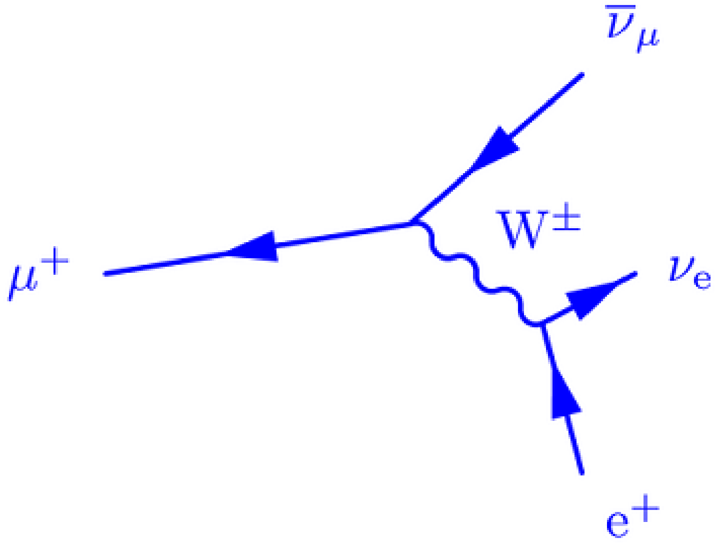
Symmetries and fundamental interactions

in 6 examples

of precision experiments at low energies

Example 1

- The measured value of the muon lifetime determines the Fermi coupling constant G_F



$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

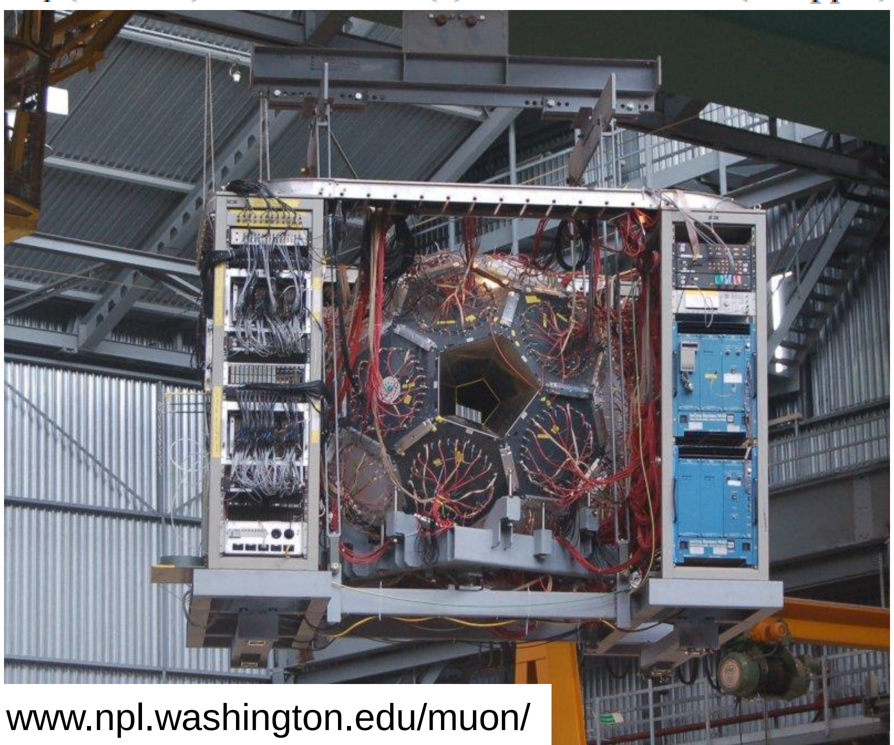
The Weak coupling constant G_F

Fundamental electro-weak parameters of the Standard Model

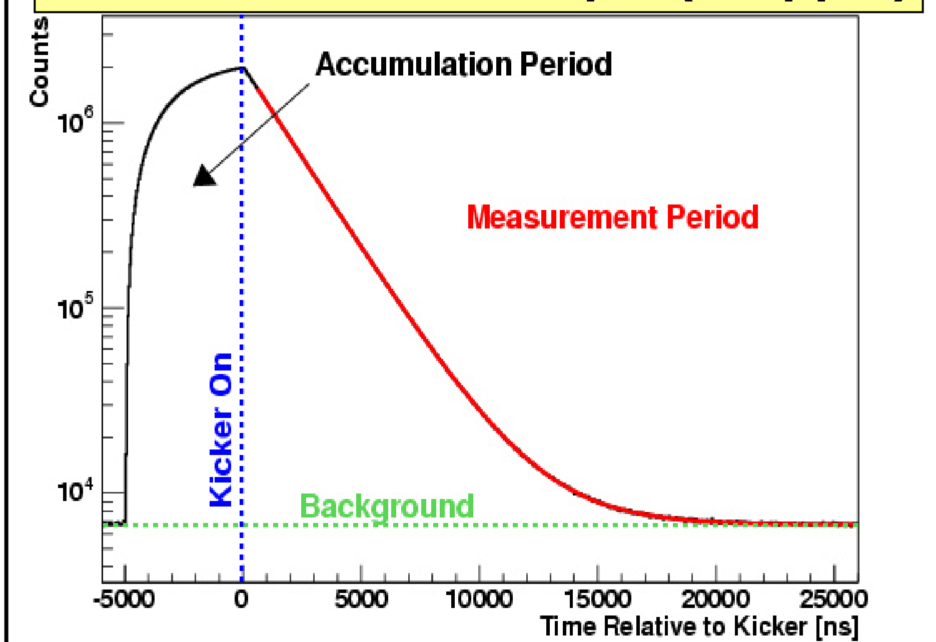
α	G_F	m_Z
0.00023ppm	4.1 → 0.5 ppm	23ppm

MuLan: The most precise measurement of any lifetime:

$G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}\ (0.5\ \text{ppm})$



τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)



www.npl.washington.edu/muon/

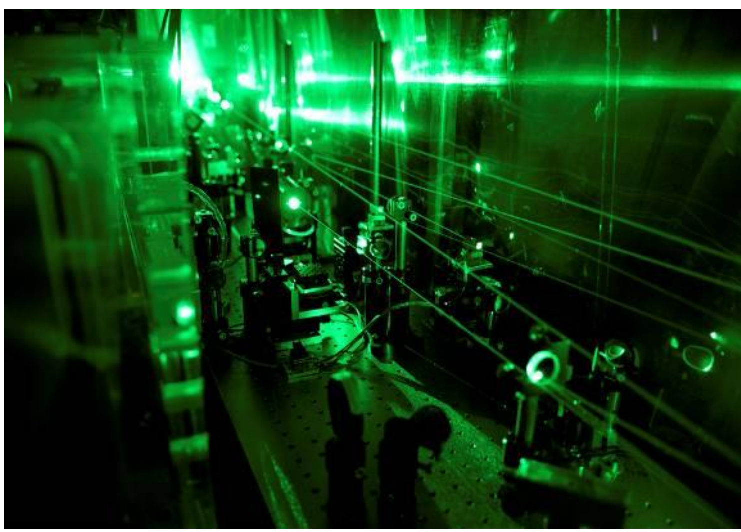
D.M. Webber et al., PRL 106(2011)041803

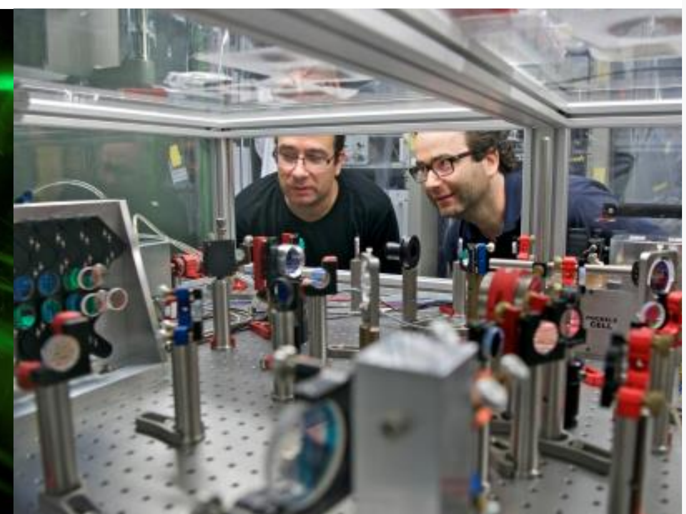
V. Tishchenko et al., PRD 87(2013)052003

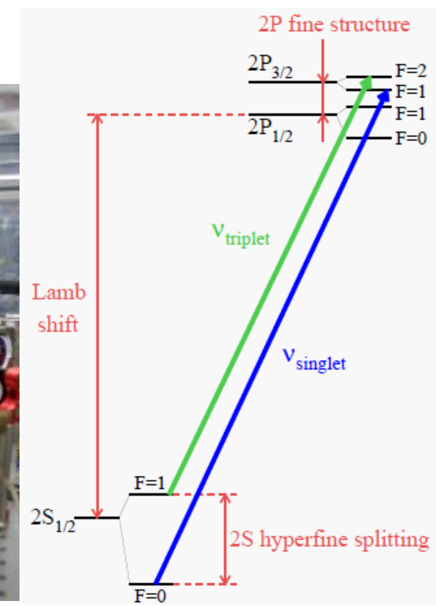
$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

Example 2

- The 1S-2S transition in hydrogen is known to 4×10^{-15}. This allows comparison with QED at a level of 10^{-12} limited by the uncertainty in the proton charge radius
- The Lambshift 2S-2P in muonic hydrogen is highly sensitive to the proton charge radius leading to an order of magnitude improvement

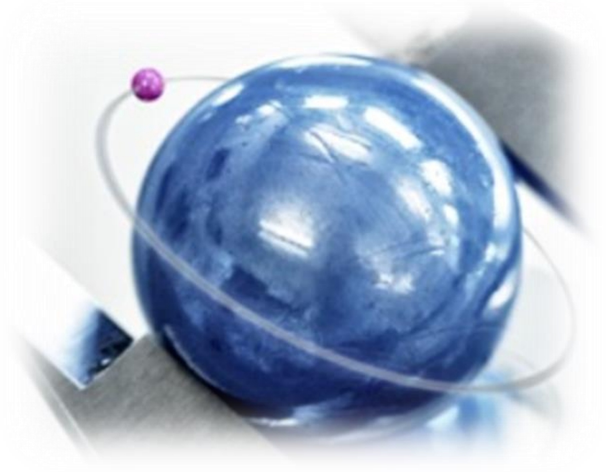




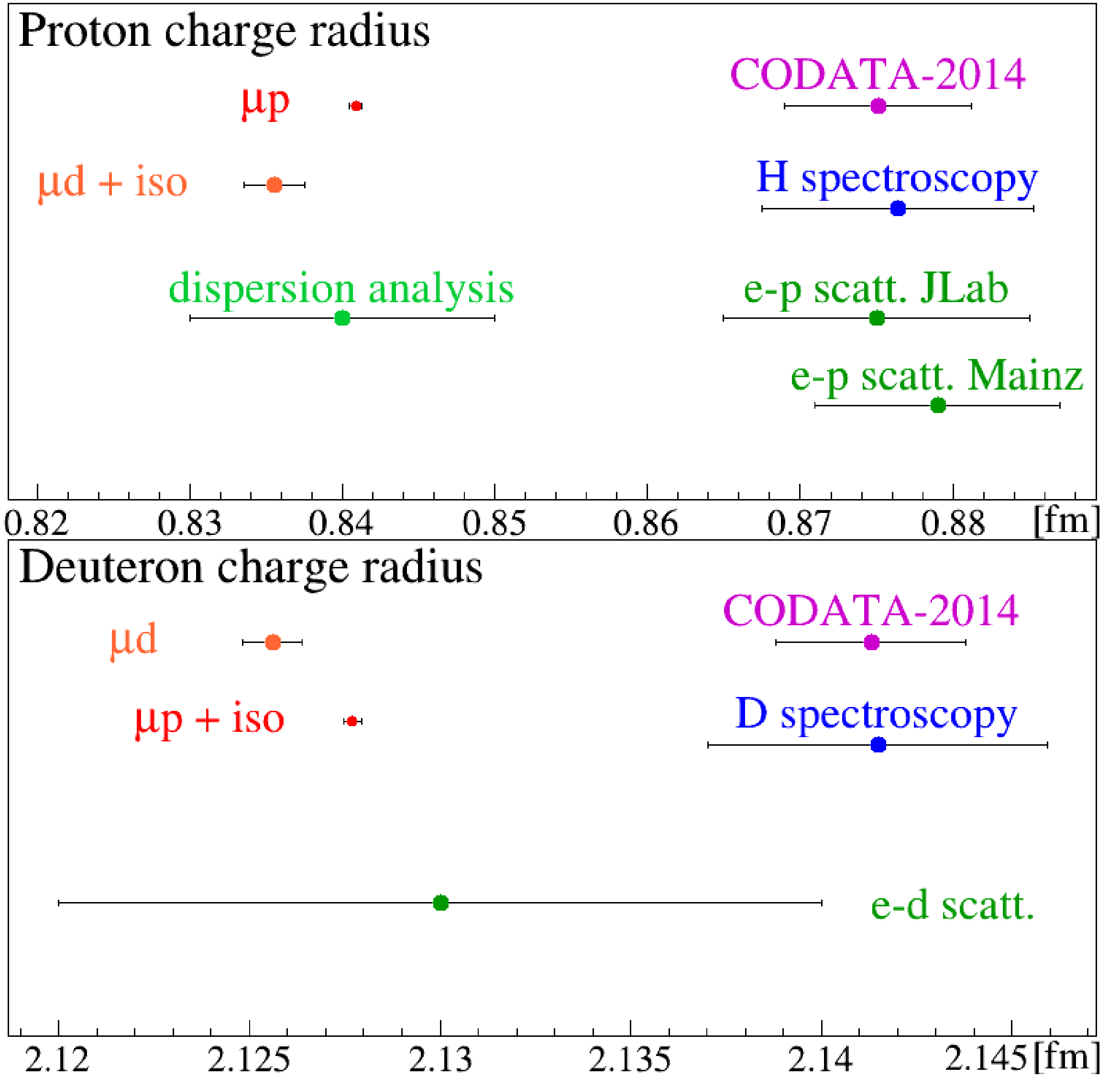


Proton and deuteron charge radii

r_p=0.84087(39) fm

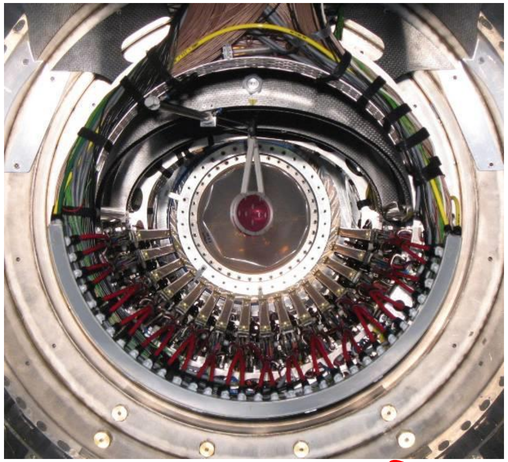


r_d=2.12562(78) fm

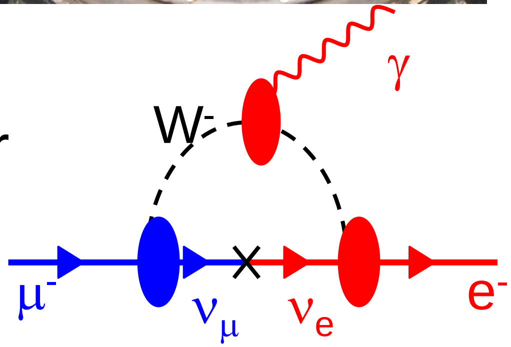


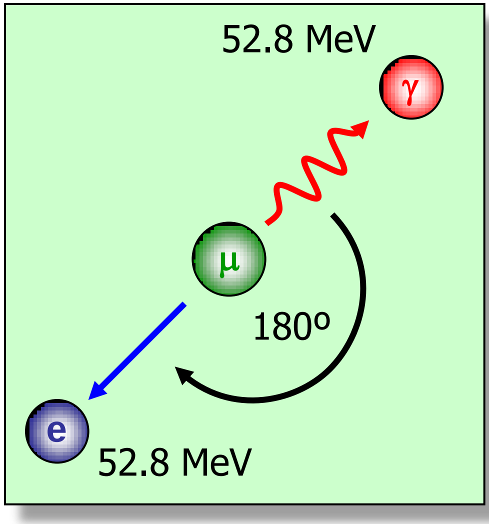
A. Antognini et al., Science 339 (2013) 417
R. Pohl et al., Science 353 (2016) 669

Example 3



- The decay of a positive muon into a positron and a photon violates charged lepton flavor
- Neutral leptons violate lepton family number
- Charged lepton flavor may also be violated, actually many BSM models predict substantial cLFV
- Muons are extremely sensitive probes for cLFV in decays like $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and $\mu^- \rightarrow e^-$ conversion





cLFV Searches: Current Situation

The present best limits on cLFV

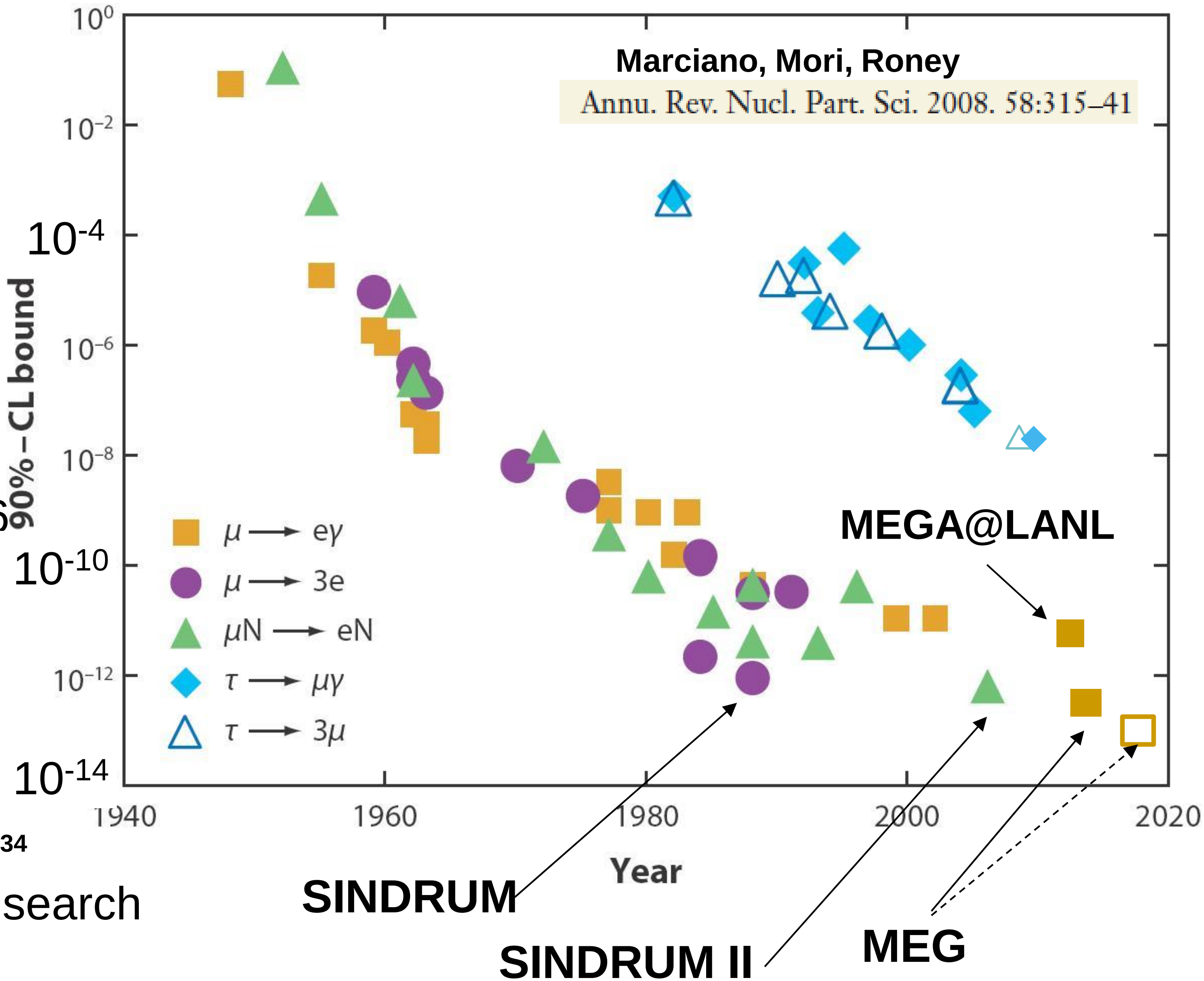
$\mu^+ \to e^+ee$
BR < 1 x 10^{-12}
SINDRUM 1988

$\mu^- + Au \to e^- + Au$
BR < 7 x 10^{-13}
SINDRUM II 2006

$\mu^+ \to e^+ + \gamma$
BR < 4.2 x 10^{-13}
MEG 2013

[90 % C.L.]

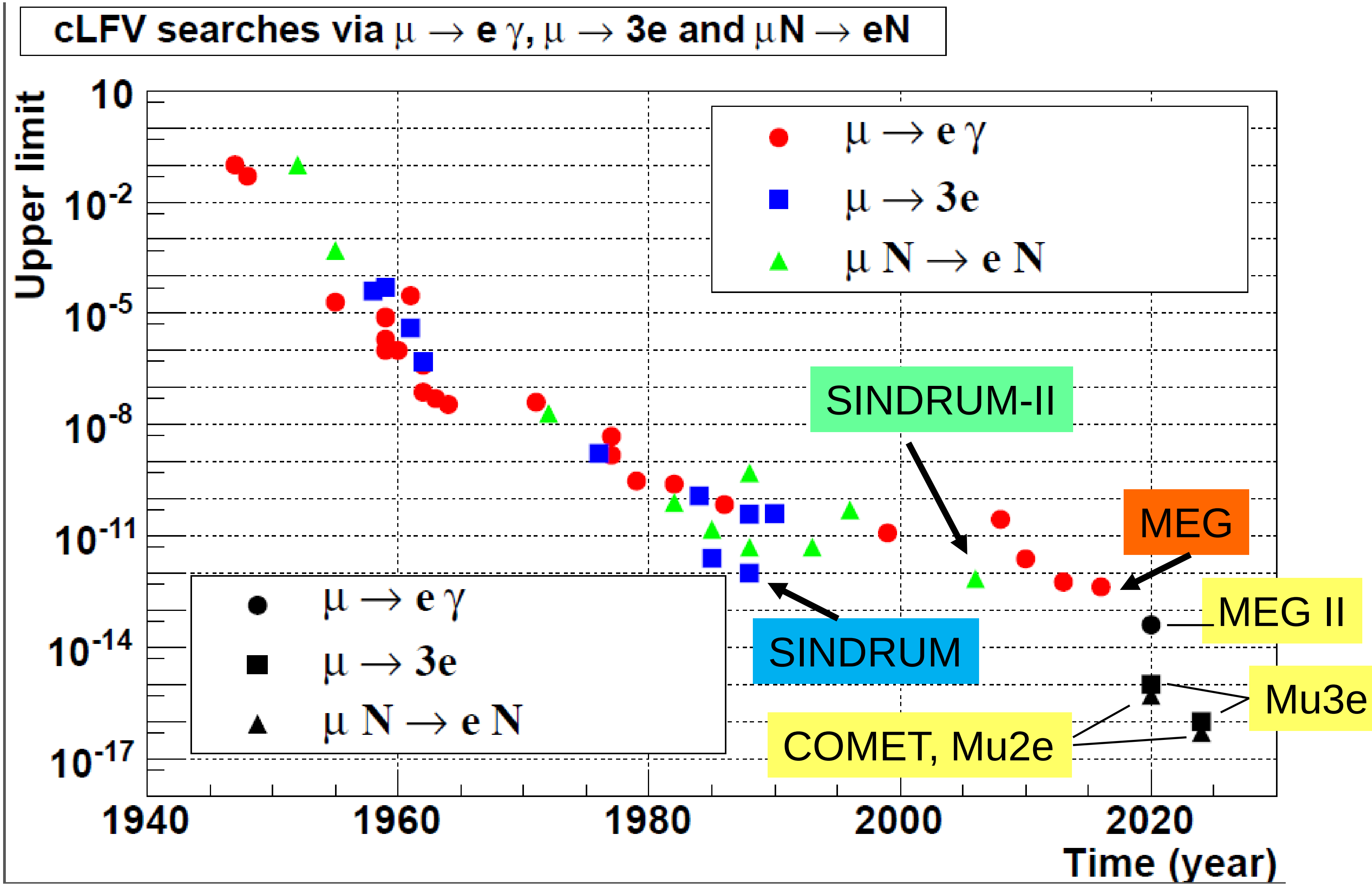
A.M. Baldini et al. EPJ C 76 (2016), 434



Most sensitive cLFV search

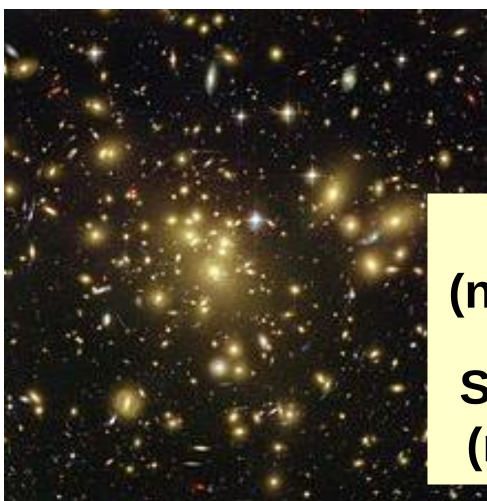
MEG II, Mu3e @PSI and Mu2e, COMET

@FNAL @J-PARC



Example 4

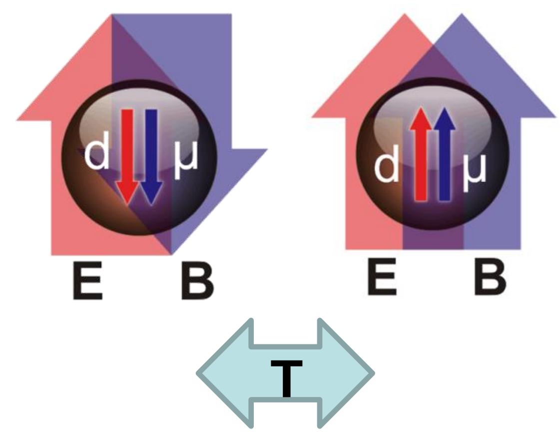
- Explanations of the Baryon Asymmetry of the Universe require additional CP violation
- Permanent EDM of fundamental spin systems such as the neutron are the most sensitive probes for BSM CPV
- The neutron EDM also measures $\theta_{QCD} \approx 10^{16} \times d_n / ecm$

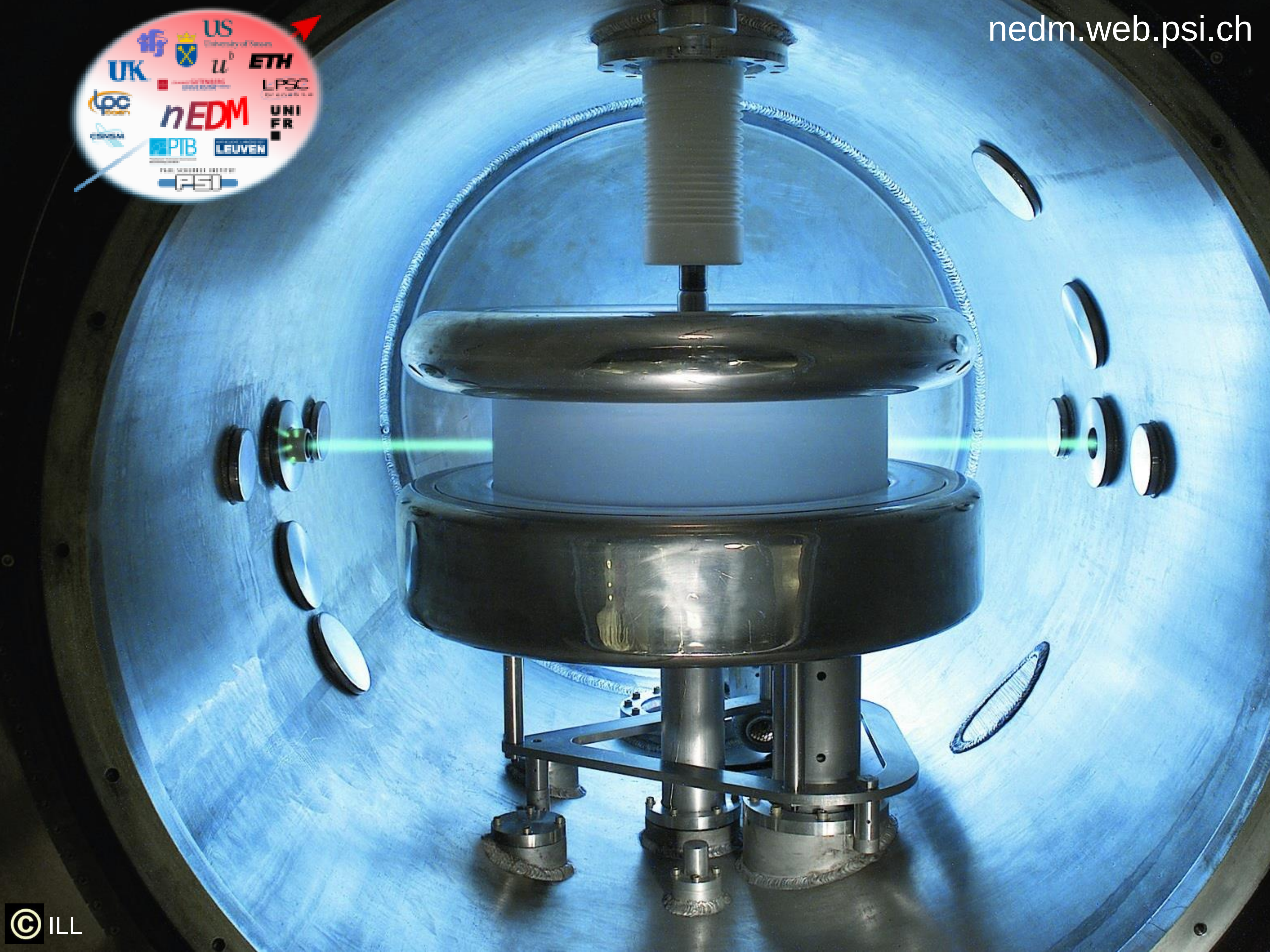


Observed:
$(n_B - n_{\bar{B}})/n_\gamma = 6 \times 10^{-10}$

SM expectation:
$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett.5(1967)24

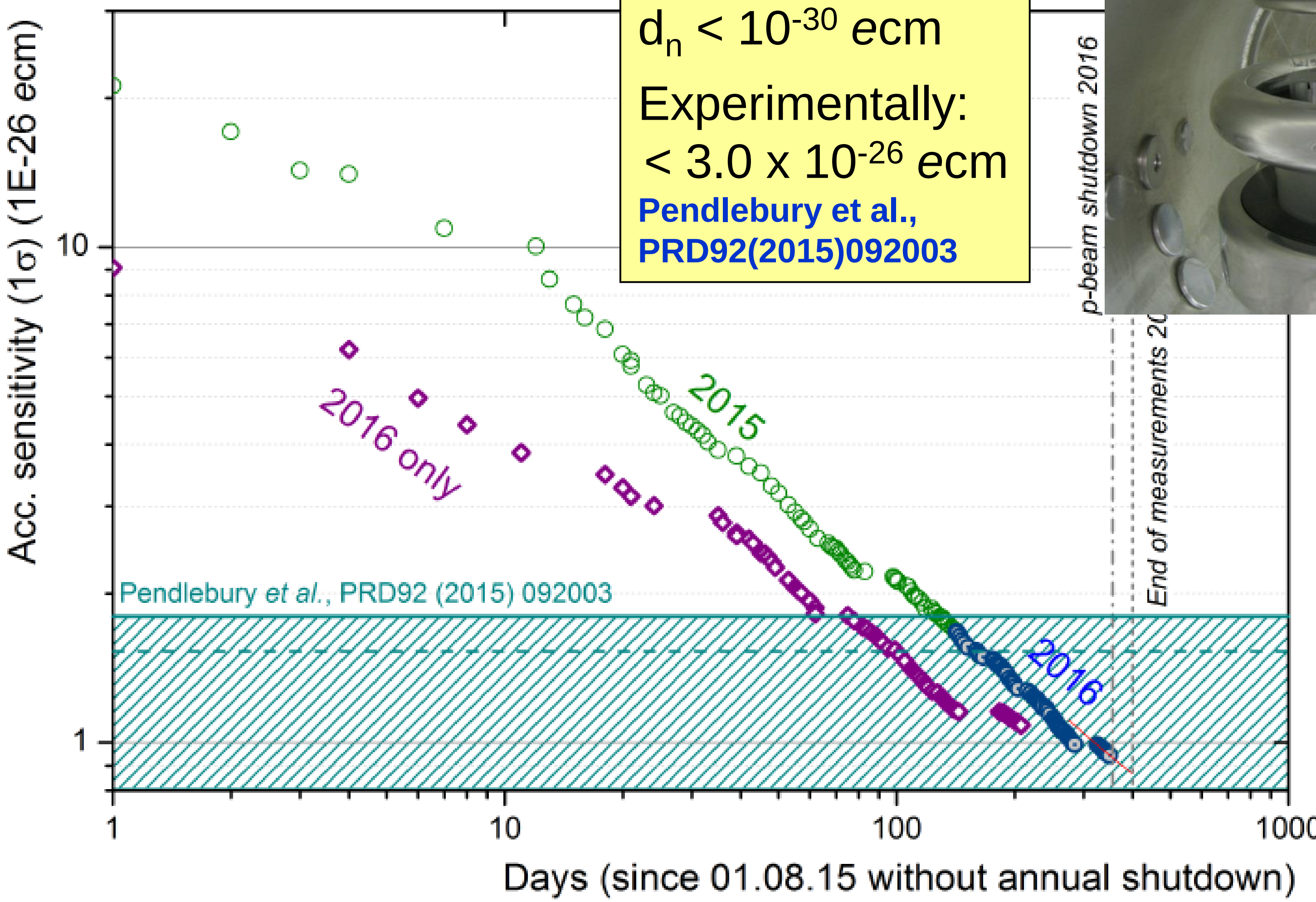


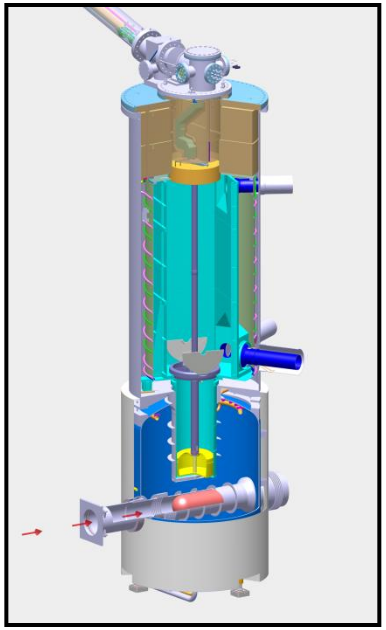

nedm.web.psi.ch
nEDM
ETH
PTB
LEUVEN
PSI
© ILL

Searching for the neutron EDM

Expect from SM:
$d_n < 10^{-30}$ *e*cm

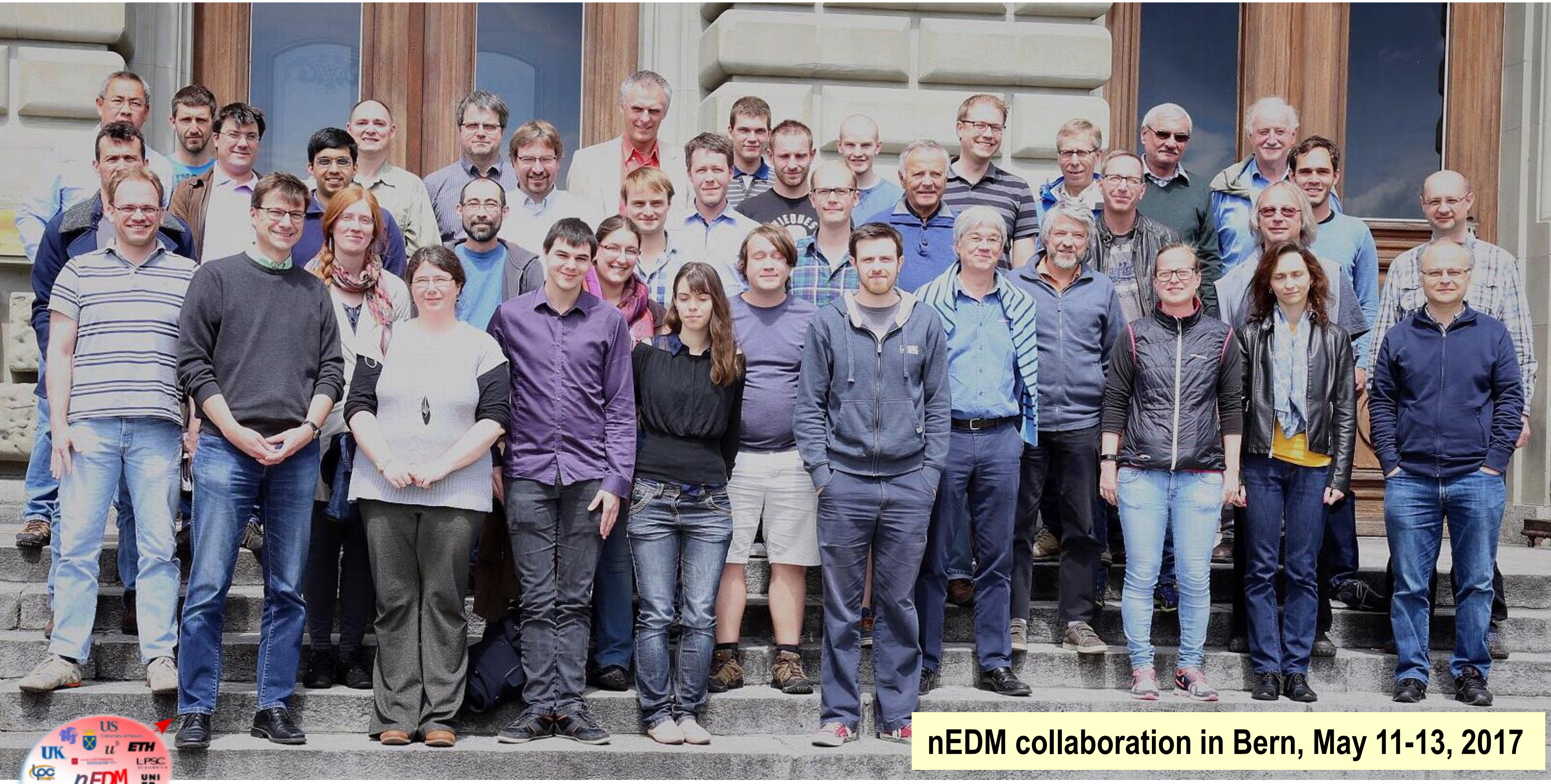
Experimentally:
$< 3.0 \times 10^{-26}$ *e*cm
Pendlebury et al., PRD92(2015)092003



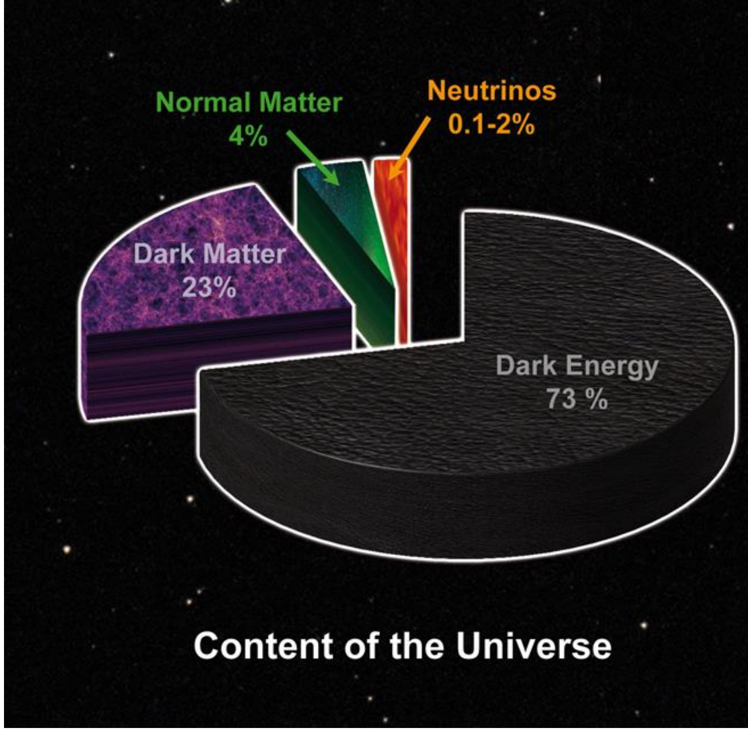


n2EDM

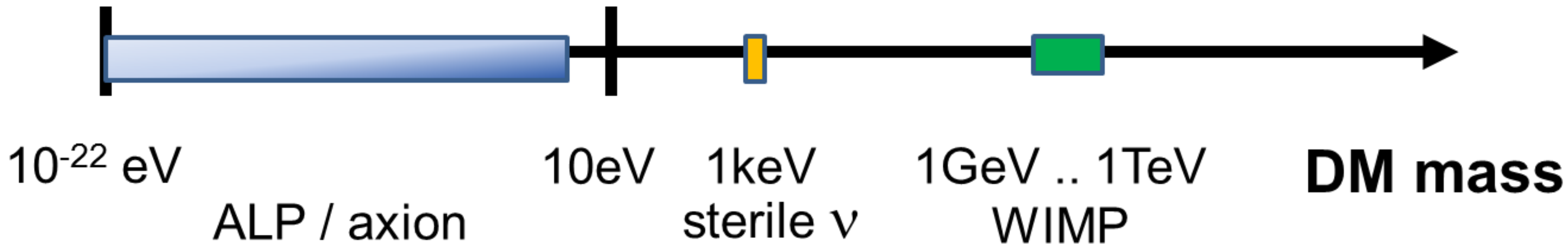
The nEDM collaboration starts assembling the successor experiment in fall 2017 and plans to be back online 2020 for an order of magnitude improvement in sensitivity.



Example 5

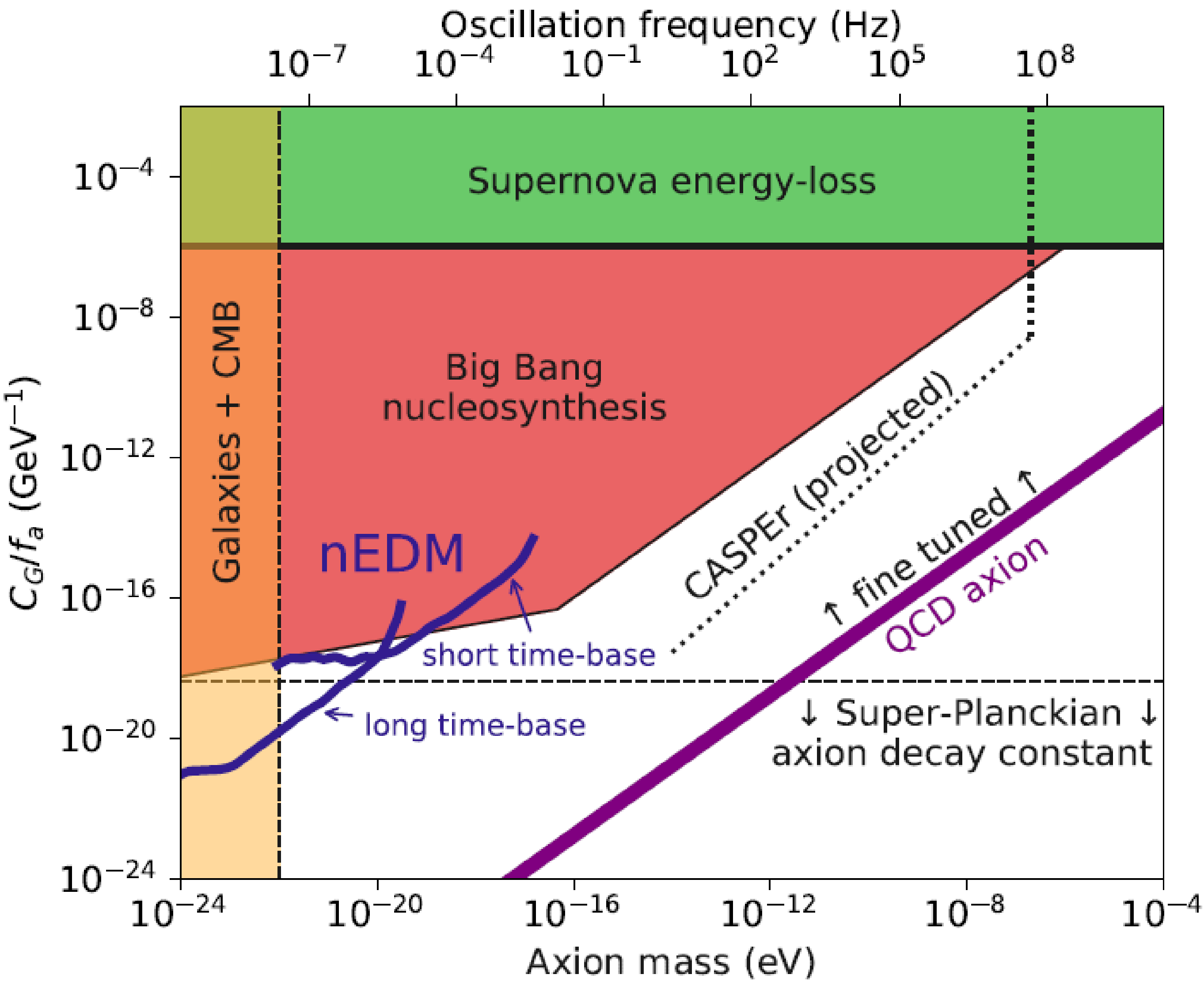


- The smallness of θ_{QCD} can be explained invoking axions
- Axions and ALPs are viable candidates for Dark Matter
- The neutron EDM is sensitive to axions and ALPs, some of which could produce oscillating EDM values



nEDM limiting axions

axion-gluon couplings and DM interpretation



2017 Preliminary:
PhD theses
M. Rawlik (ETHZ),
N. Ayres (USussex).
nEDM in collaboration with
M. Fairbairn,
V.V. Flambaum,
D.J.E. Marsh,
Y.V. Stadnik

See:

Graham, Rajendran, PRD88(2013)035023

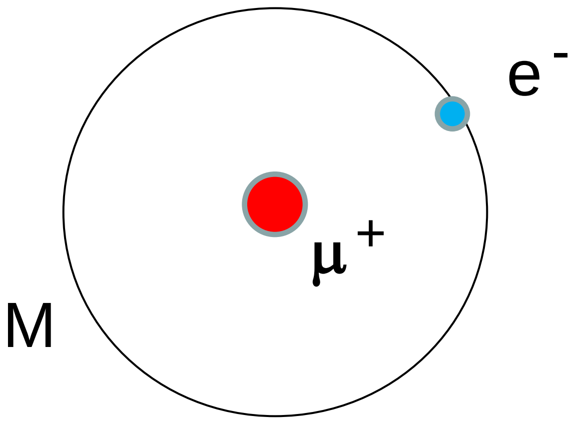
Budker et al., PRX4(2013)1

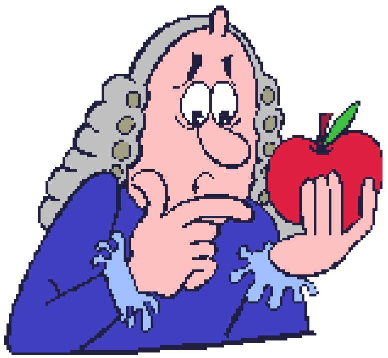
Stadnik, Flambaum, PRD89(2014)043522

Kim, Marsh, PRD90(2016)025027

(Last) Example 6

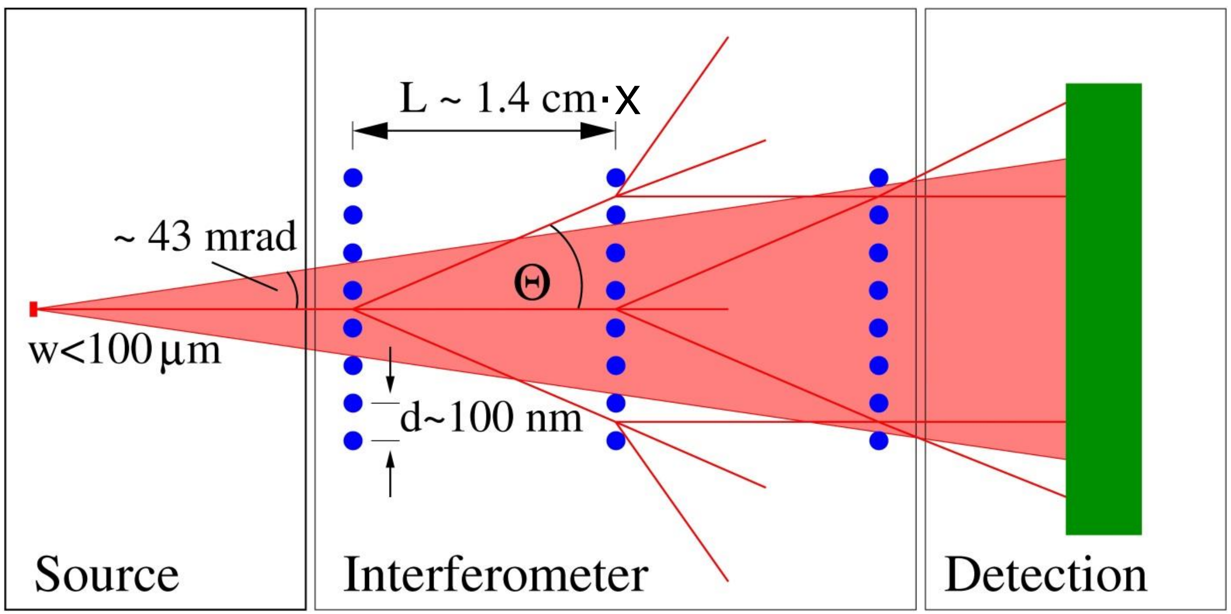
- We do not yet know how an ultimate quantum theory of gravity will look like
- General Relativity is extremely well tested - but only involving matter (and light, and binding energy)
- No direct measurement of antimatter falling in the Earth gravitational field has been done at an interesting level of precision yet
- Even the concept of 'antigravity' is still around and calls for a direct measurement



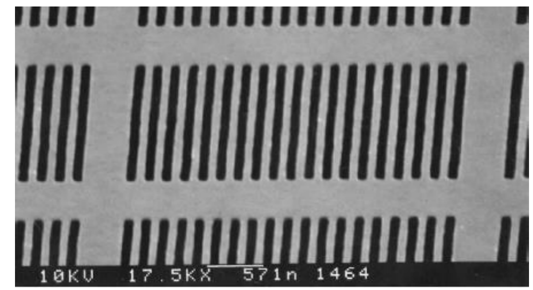


Muonium Antimatter Gravity Experiment

- Use new M beam (based on muCool slow muon beam and M production of SF-He)
- Measure gravitational phase shift in atom interferometer
- Determine sign of $\overline{g}$ in one day
- Measure $\overline{g}$ to few percent within a year



D.M. Kaplan et al., arXiv:1601.07222, K. Kirch, arXiv:physics/0702143



C. David et al.
Microelectr. Eng. 30 (1996) 57

$$S \approx 0.3\ g/\sqrt{\#\ \text{days}}$$

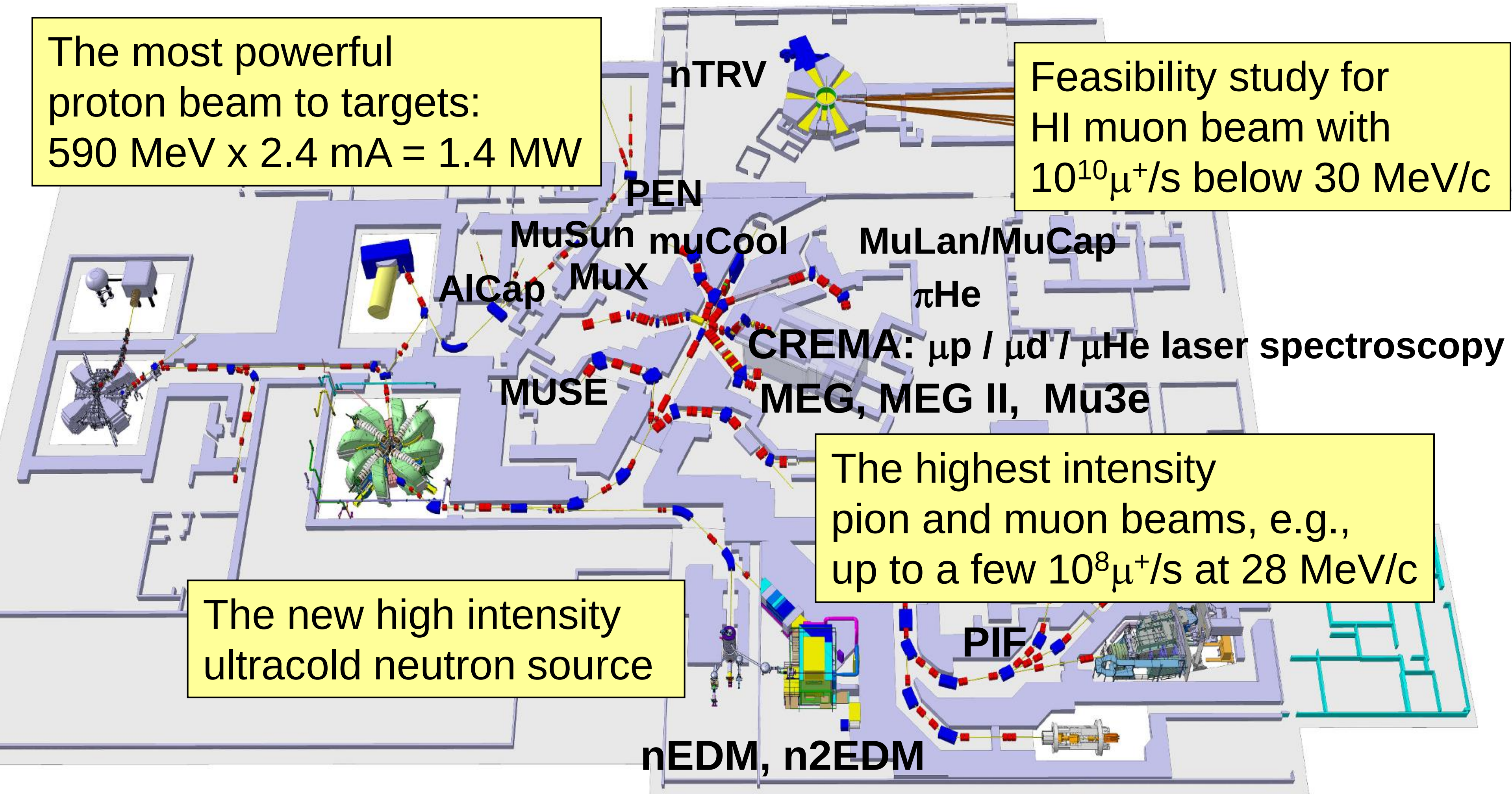
Mach-Zehnder type atom interferometer

D.W. Keith et al.
An interferometer for atoms,
Phys. Rev. Lett. 66 (1991) 2693


SINQ

The intensity frontier at PSI: π, μ, UCN

Precision experiments with **the lightest unstable particles** of their kind



Swiss national laboratory with strong international collaborations


Any questions?
Klaus Kirch, ETHZ - PSI
arts-wallpapers.com
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