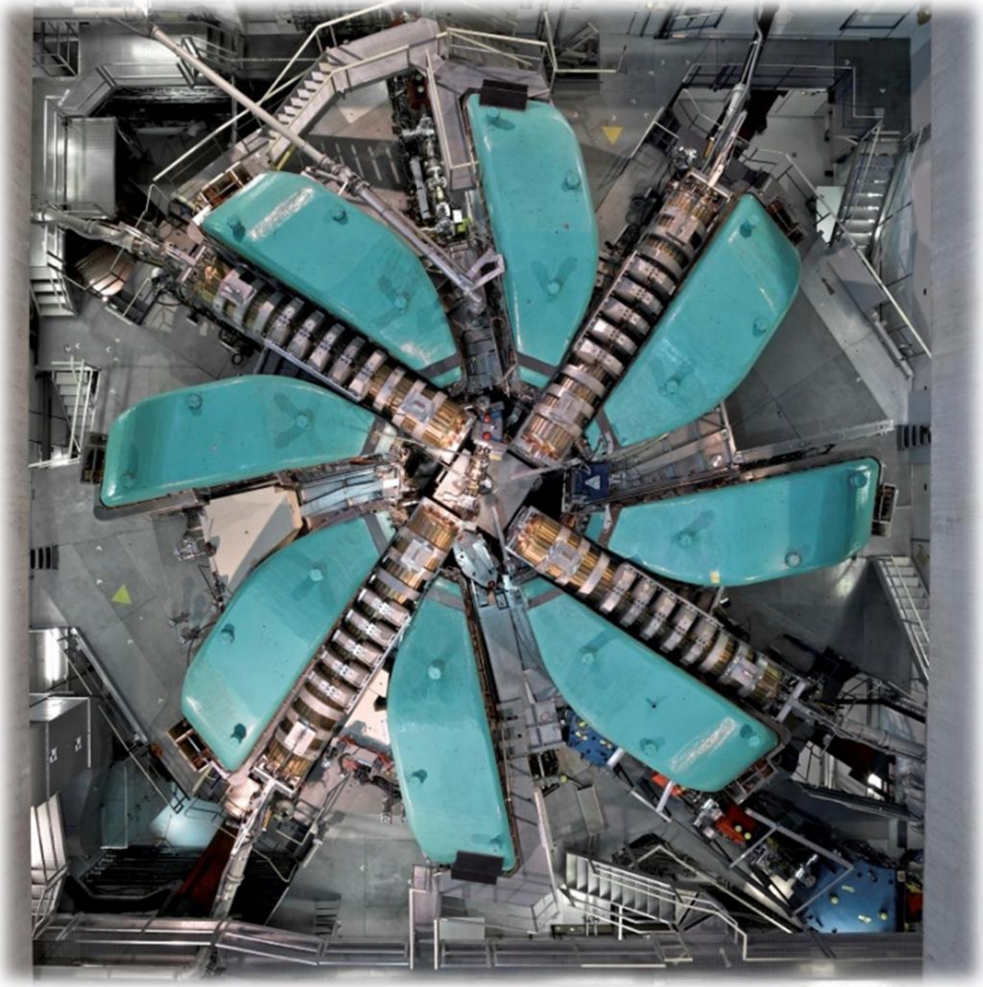
Precision particle physics at PSI

K.Kirch, ETH Zurich – PSI Villigen, Switzerland



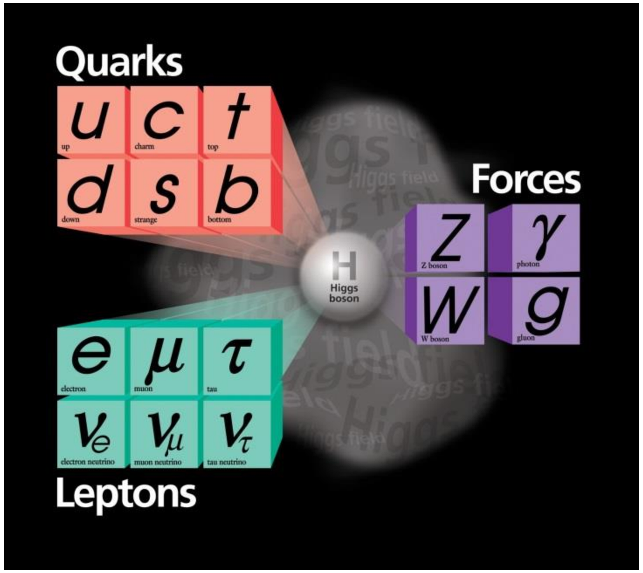
Using highest intensities of pions, muons and UCN for

- Precision measurements of Standard Model parameters
- Searches for physics beyond the Standard Model

The Standard Model of Particle Physics

- is extremely successful …
  (with some issues concerning neutrino masses,
  muon g-2, B-decays, …)

- … but does not explain
  - Gravity, Dark matter
  - Dark energy
  - 3 families
  - QCD theta term
  - Values of particle masses and couplings
  - Baryon Asymmetry of the Universe
  - Conservation of baryon and charged lepton number
  - …



PSI Laboratory for Particle Physics

LTP-Groups

- Theory
- High Energy Physics
- Muon Physics
- Ultacold Neutrons
- Electronics and Measurement Systems
- Detectors
- Applied Particle Physics and Irradiations

Academic links to universities: common professorships and teaching

Discovery Physics at high and low energies

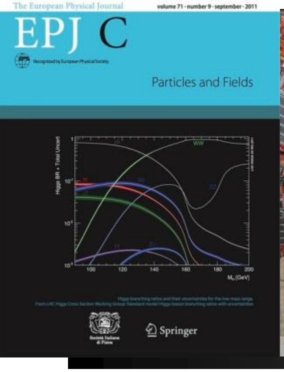
- **Precision measurements** (MuLan, CREMA, MuCap, MuSun, MUSE ..) **and searches for new physics** (MEG, nEDM, Mu3e, n2EDM, ...) **at PSI**
- **At LHC: Participation and key contributions to CMS** (Si-pixel R&D and data analysis, e.g. B-$\mu\mu$ at PSI)
- **Particle phenomenology**

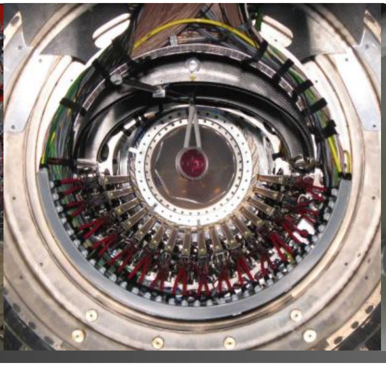
Collaborations with

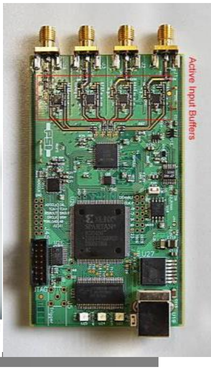
- all Swiss universities
- many universities and institutions world-wide

Outreach and Spin-off

- Detectors (pixel, gas and scintillation) for particle physics; n, μSR, x-rays
- Chip design, electronics and software for PSI and world-wide, e.g. DRS-4, elog, Midas, ...
- Irradiation using p, π, μ, e
- Zuoz schools (2016: 23rd!)
- PSI20xy workshop: PSI2016



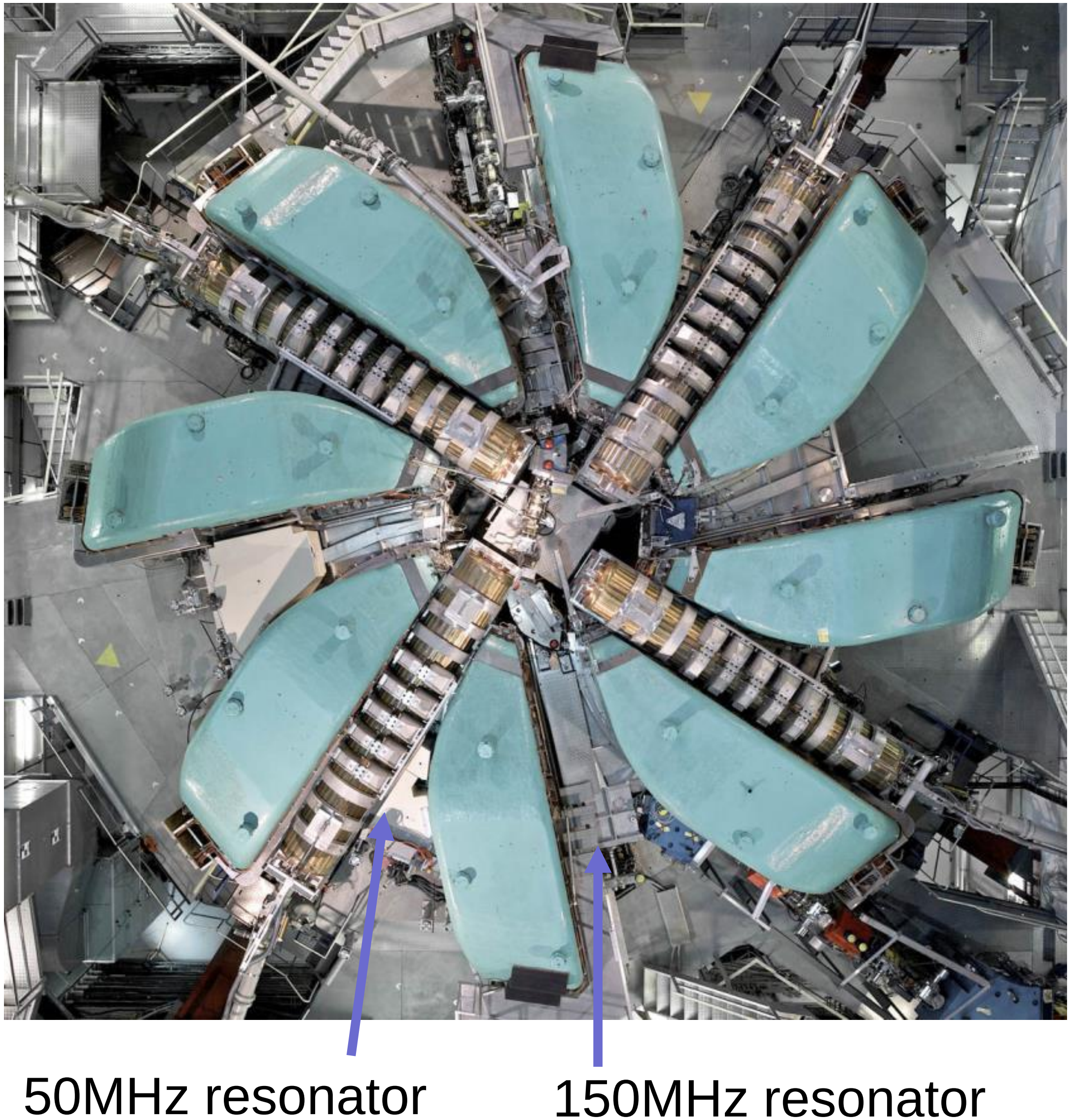



SINQ

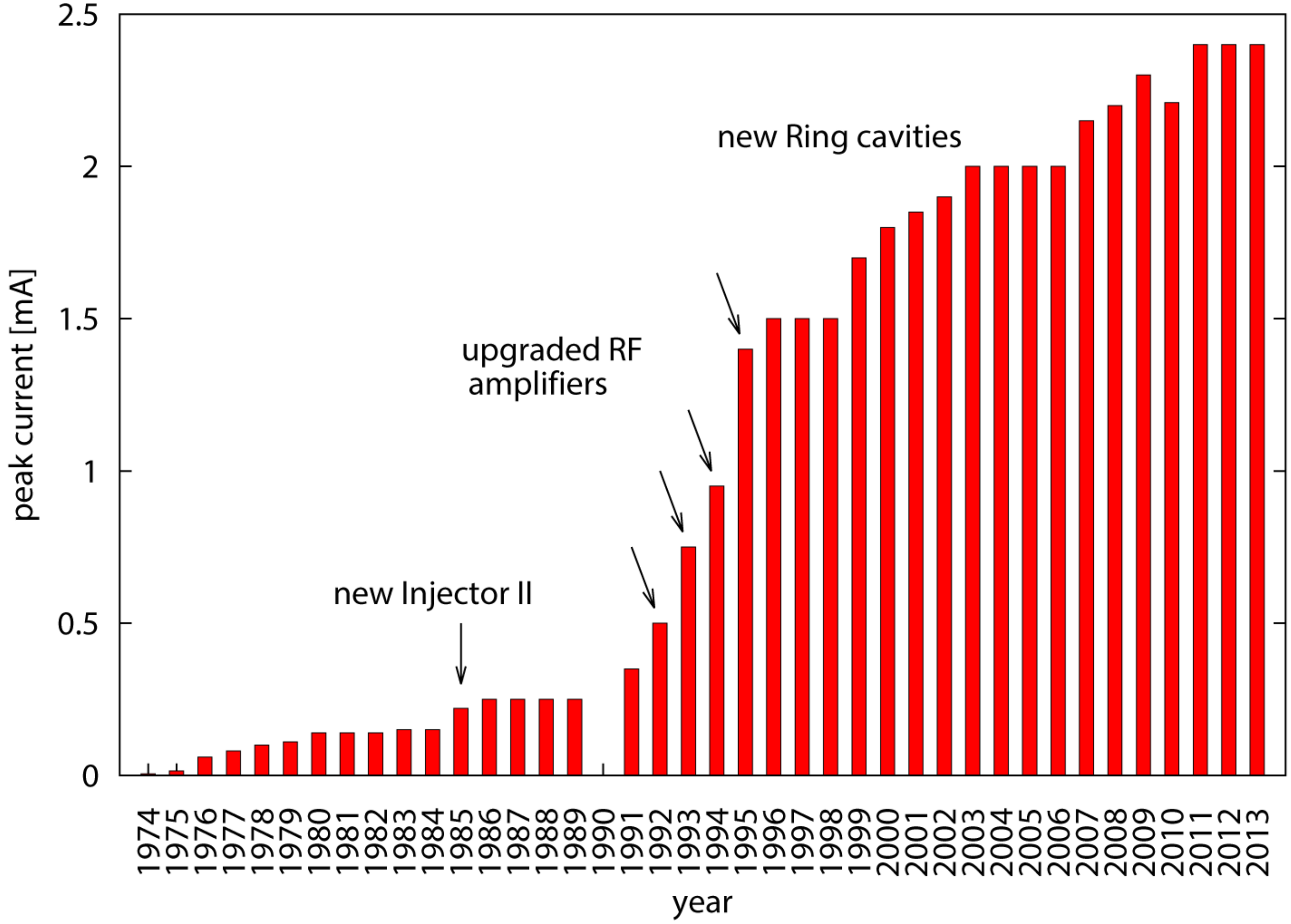
The Heart of HIPA: The Ring Cyclotron

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

[losses ∝ (turn number)^3, W.Joho]



History of maximum beampower



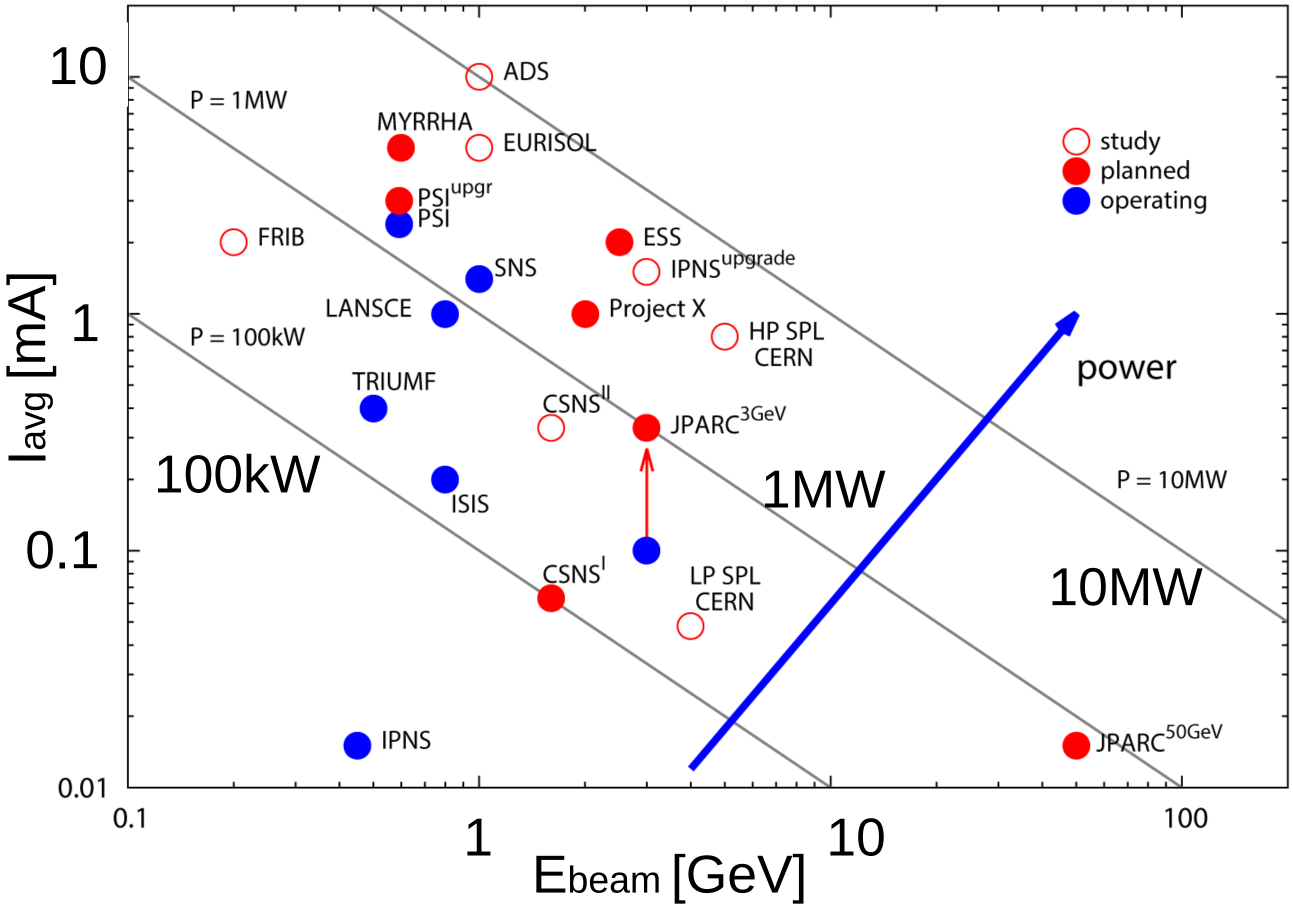
milestones:

- new injector cyclotron ('84)
- upgrading Ring RF power
- replacing Ring cavities
- new ECR source

Originally planned: ≈100μA
today: 2.400μA
[routine: 2.200μA]

Courtesy: M. Seidel

High Intensity Proton Accelerator – the international context



Courtesy: M. Seidel

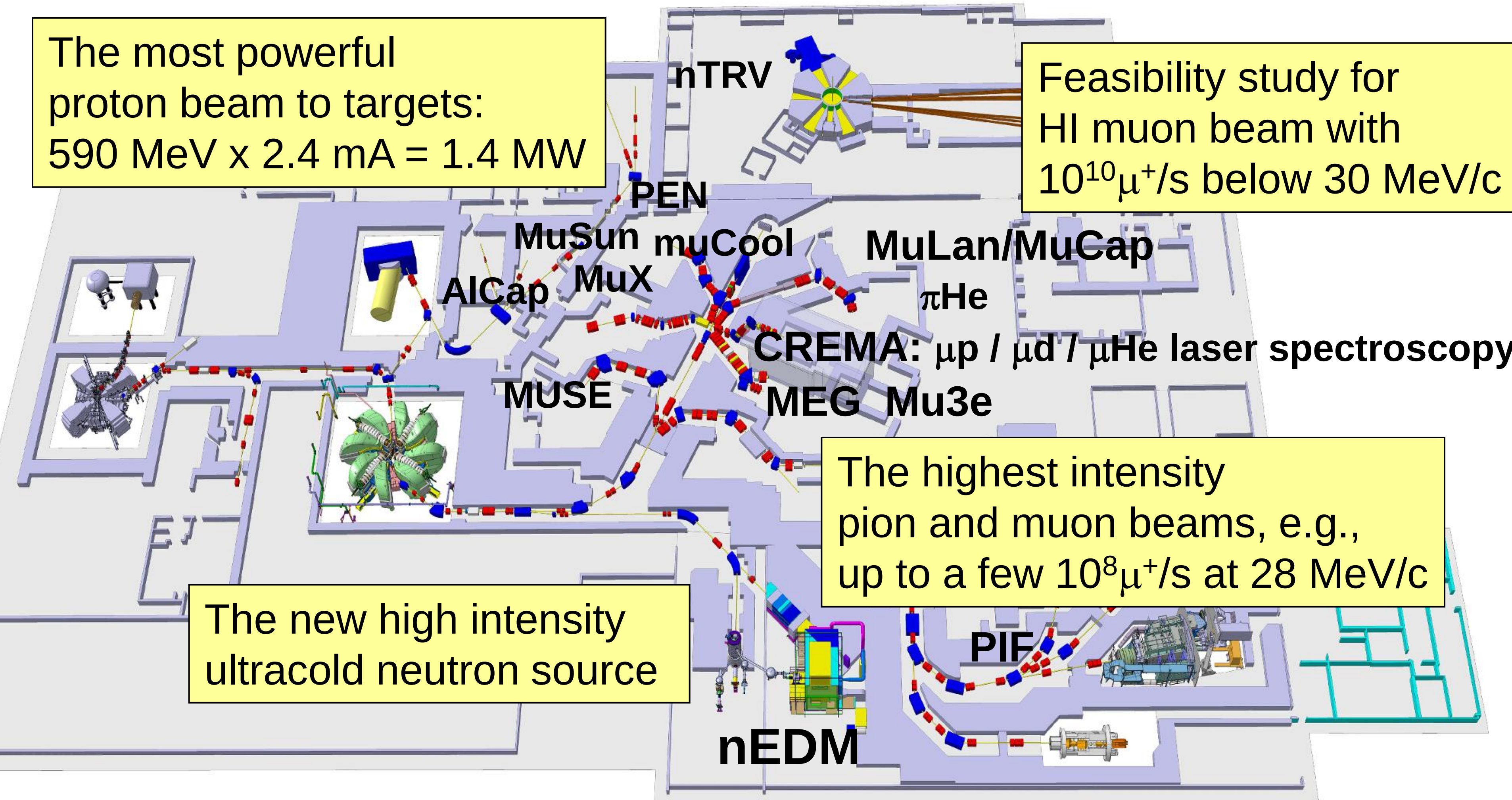
PSI HIPA serves three communities

The intensity frontier at PSI: π, μ, UCN

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

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

Feasibility study for
HI muon beam with
$10^{10} \mu^+$/s below 30 MeV/c

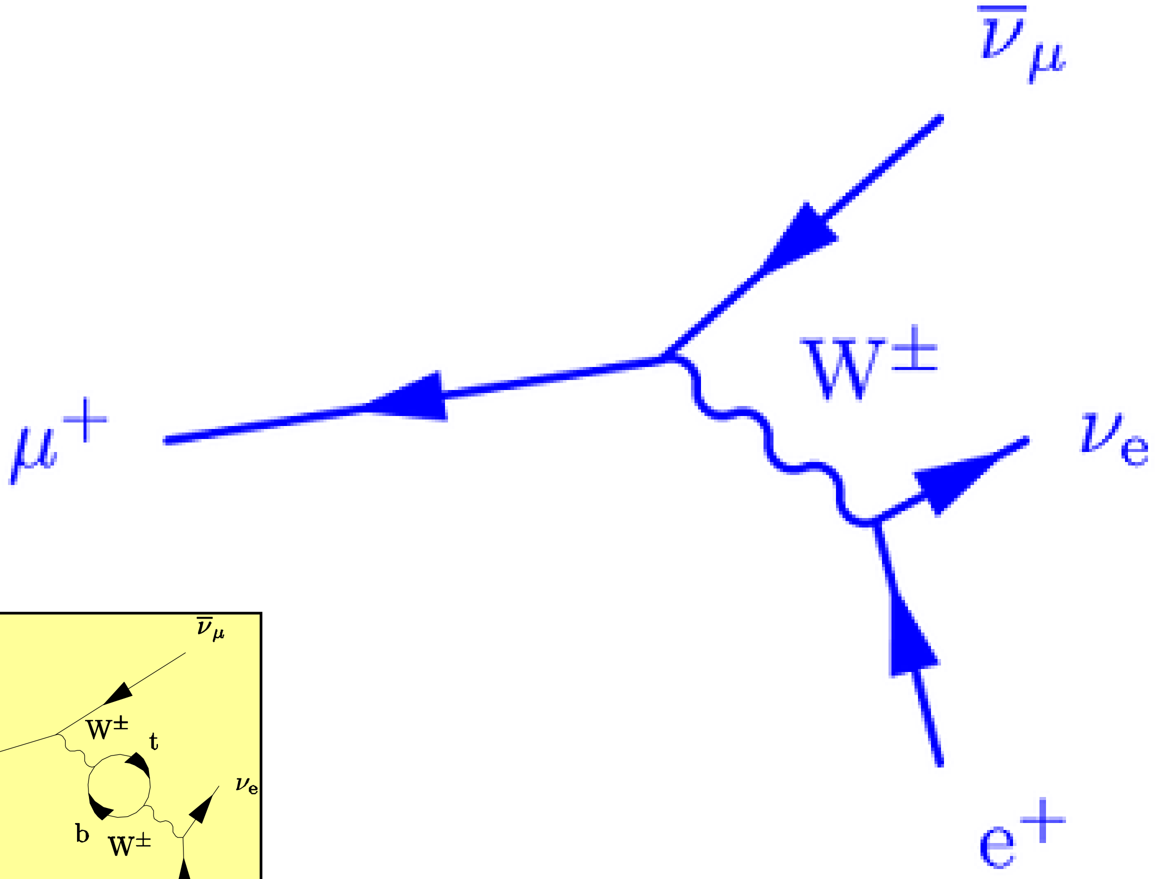


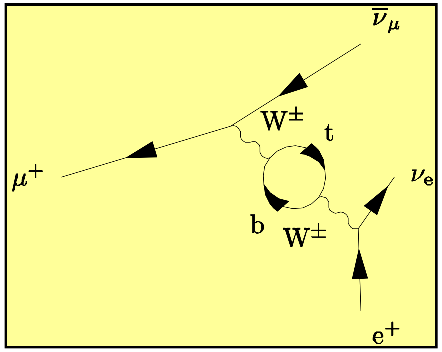
The highest intensity
pion and muon beams, e.g.,
up to a few $10^8 \mu^+$/s at 28 MeV/c

The new high intensity
ultracold neutron source

Swiss national laboratory with strong international collaborations

Precision physics I:
Ordinary muon decay





. . .

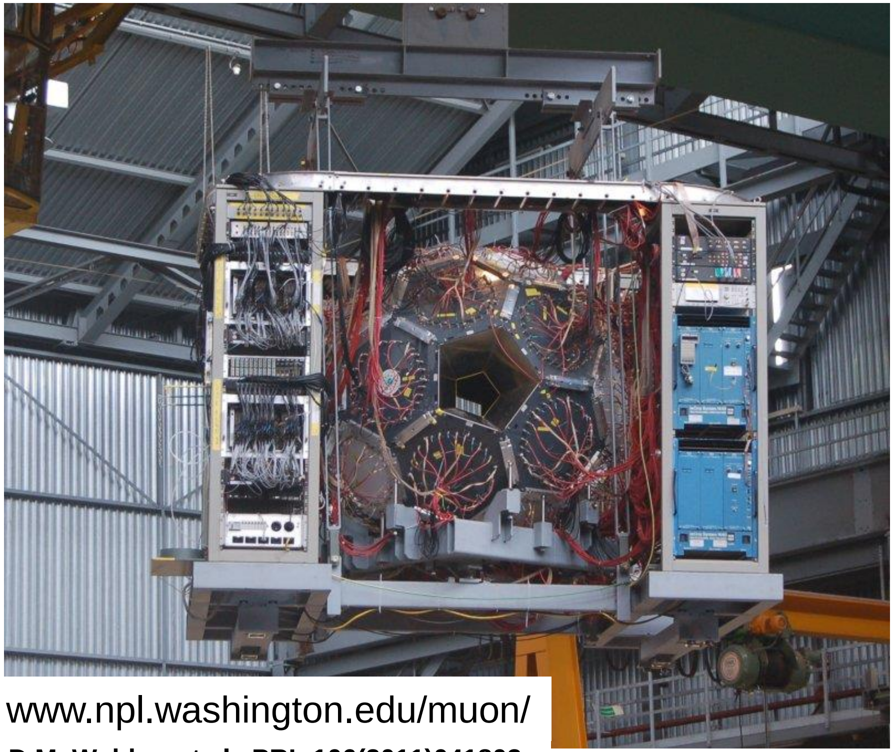
The Weak coupling constant G_F

Fundamental electro-weak parameters of the Standard Model

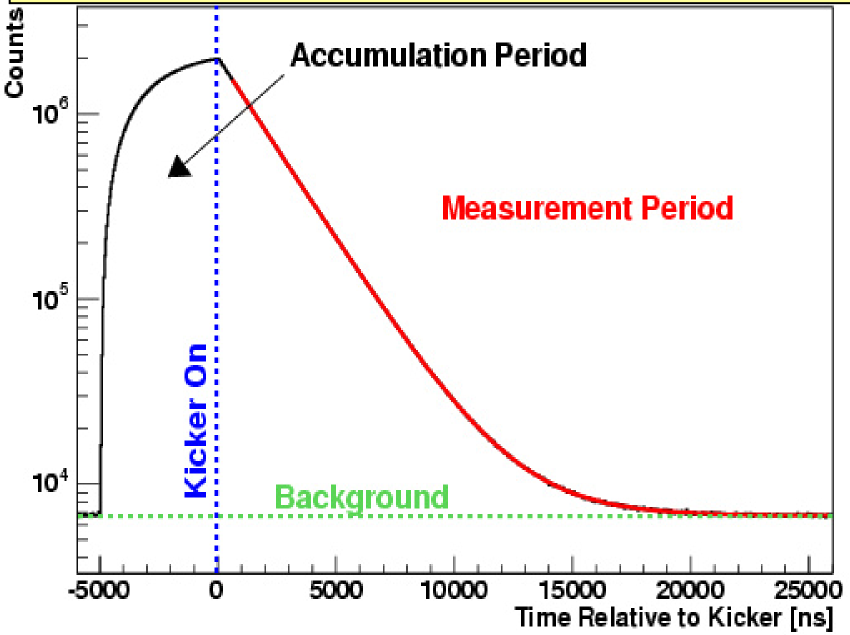
α	G_F	m_Z
0.00037ppm	4.1 → 0.5 ppm	23ppm

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

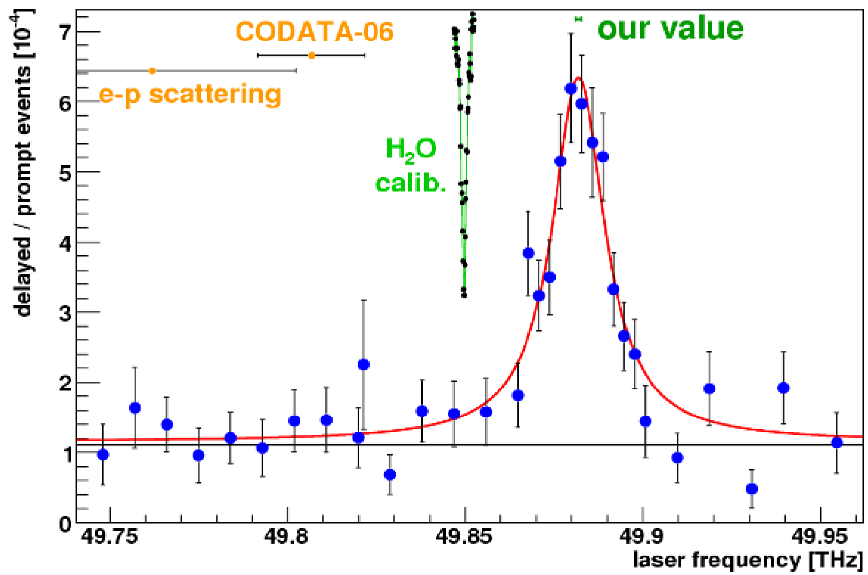
$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

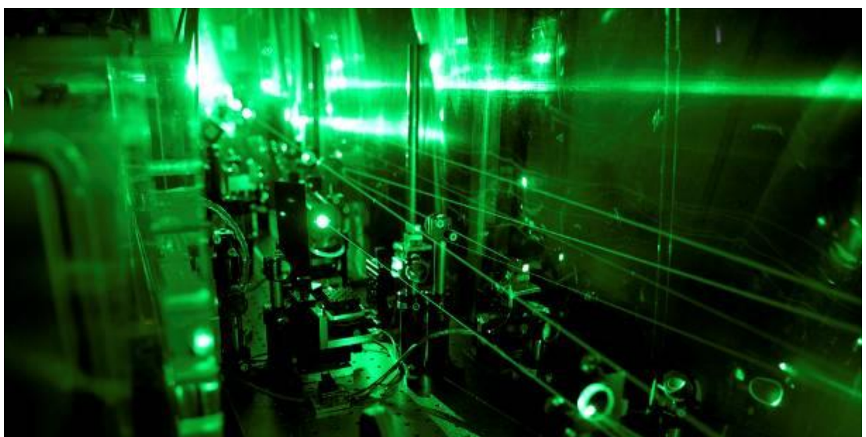
Precision physics II

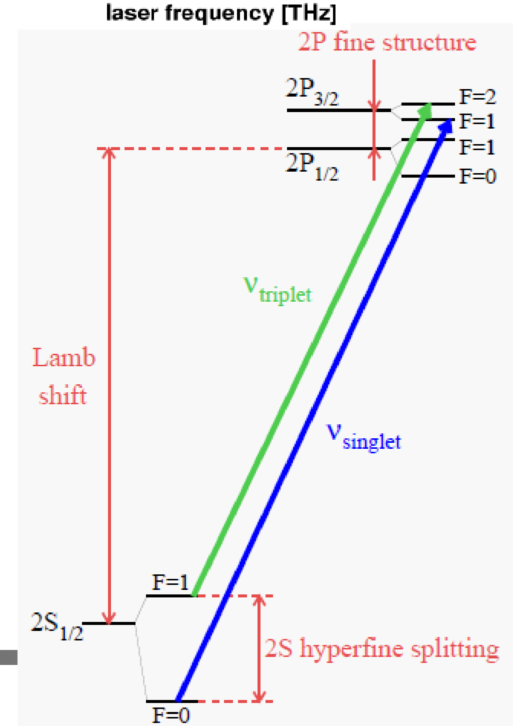
Bound state QED

The most precise value of the **proton charge radius** via a measurement of the Lambshift in muonic hydrogen

r_p=0.84087(39) fm

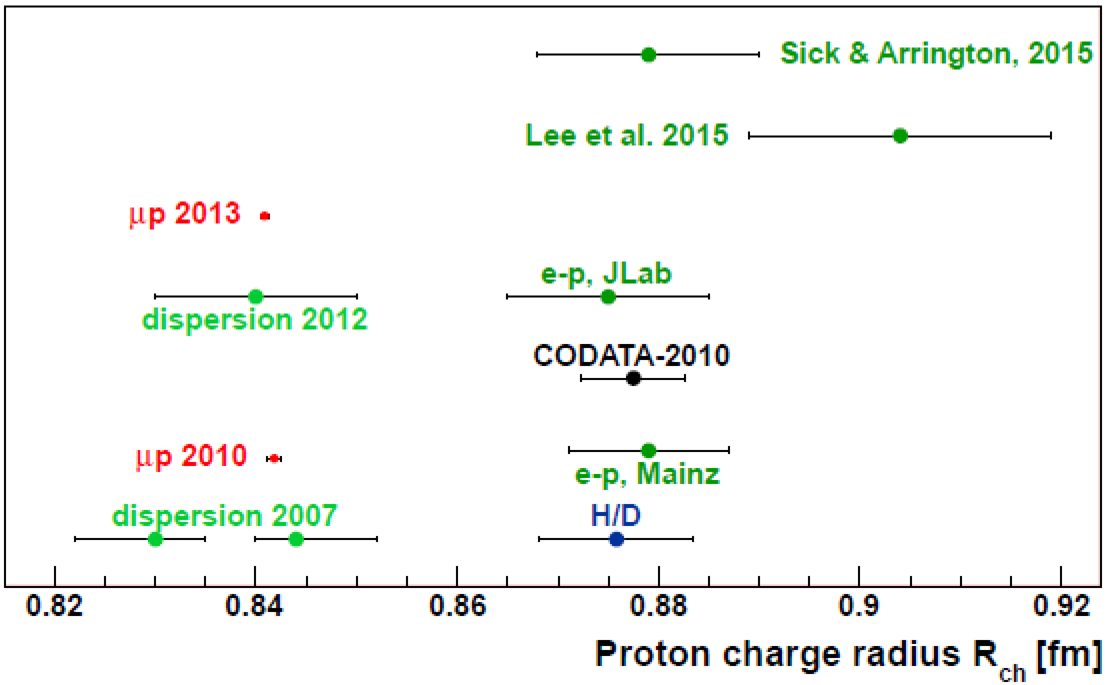




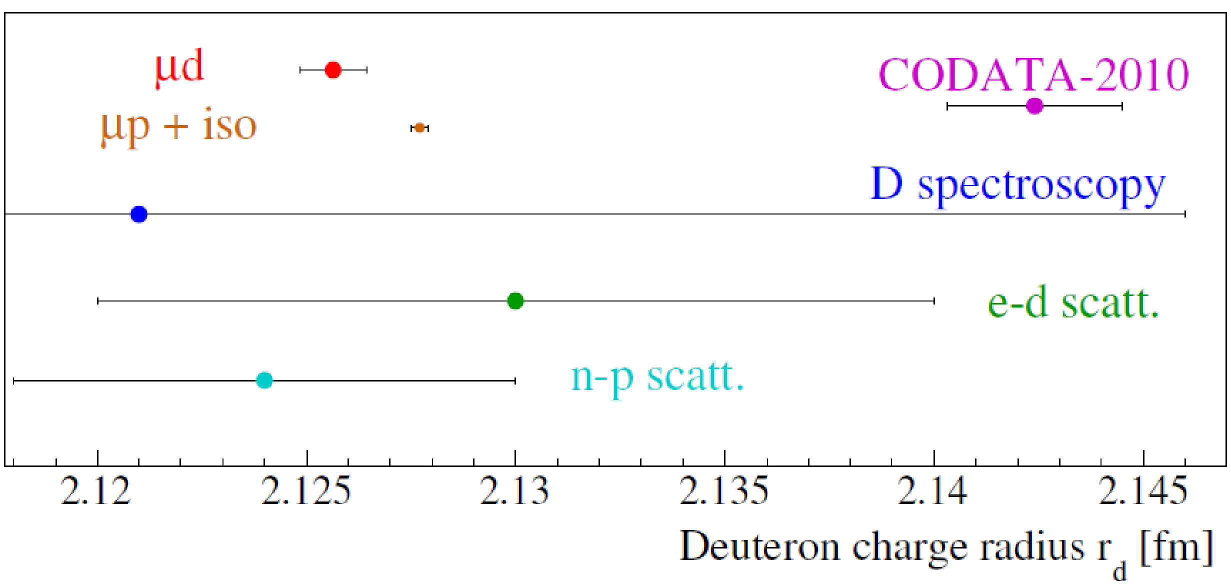


www.psi.ch/muonic-atoms

R. Pohl et al., Nature 466 (2010) 213
A. Antognini et al., Science 339 (2013) 417

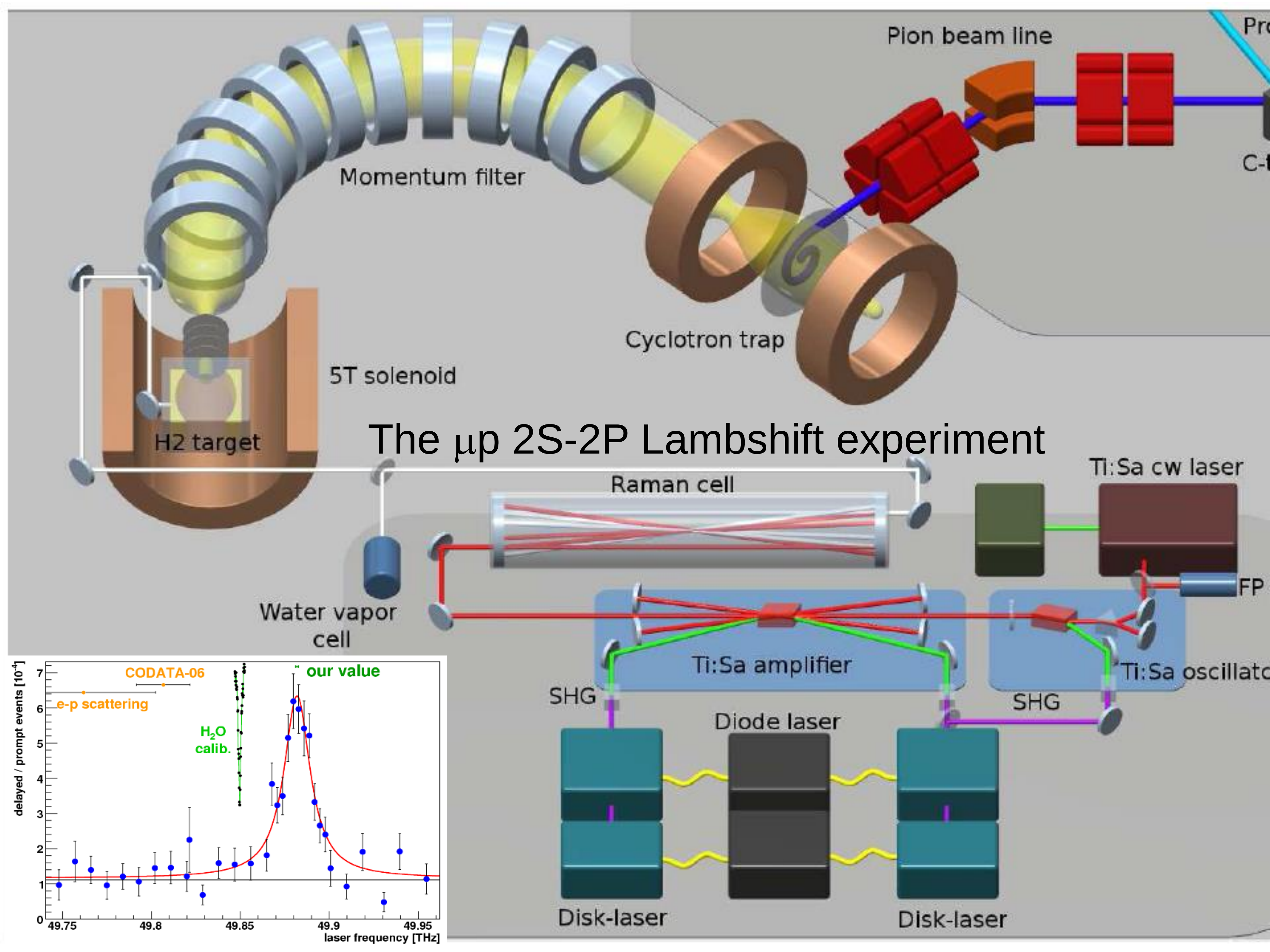


Charge radii of the proton and the deuteron extracted from precision measurement of the muonic atom 2S-2P Lambshift.
Also measured: muonic He-3, He-4.



Next spectroscopy:
- muonic p, He-3 HFS
- muonic radium
- Muonium 1S-2S

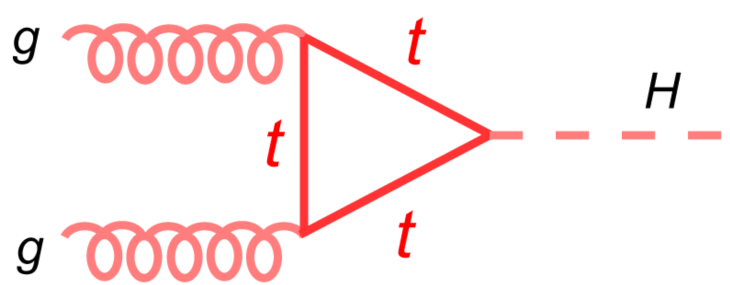
The μp 2S-2P Lambshift experiment

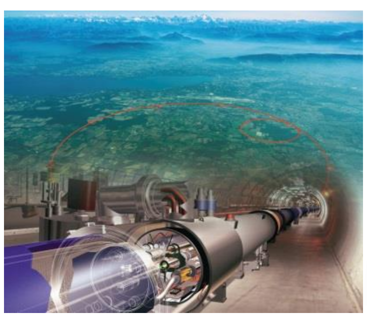


Search for new physics

High Energy

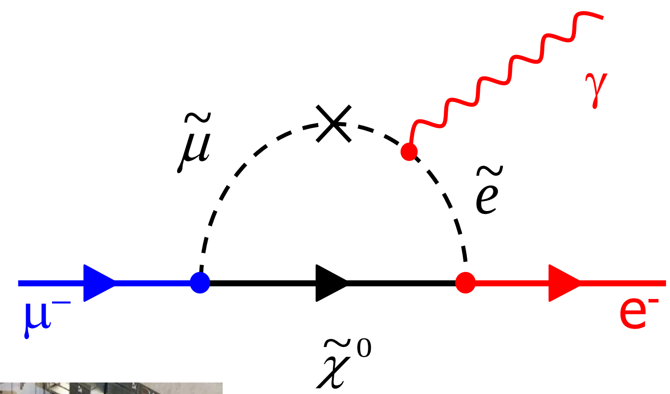
direct production of new particle

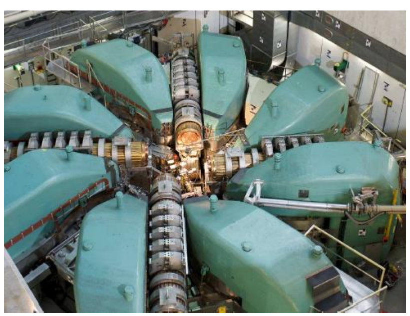


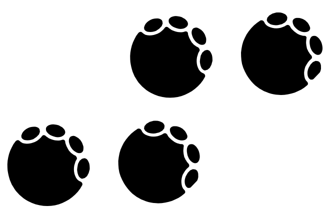


High Intensity

For example:
Search for μ→eγ

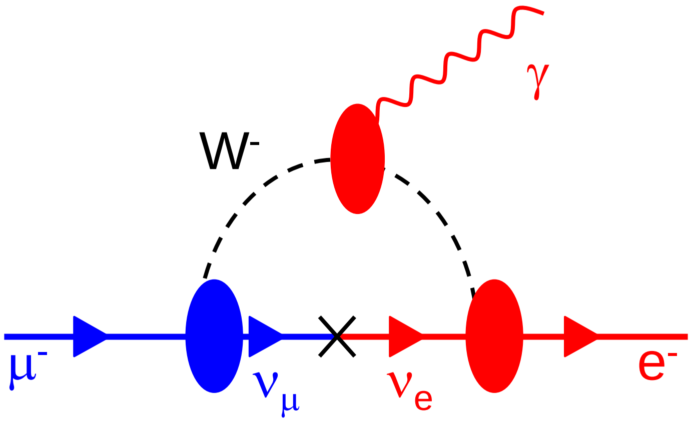






Charged Lepton Flavor Violation is small in the Standard Model

- Only known LFV so far: neutrino mixing
- cLFV suppressed by $(\delta m_\nu / m_W)^4$ and thus smaller than 10^{-50}
  → SM not observable
  → accidentally small !?
- Plenty of room for new physics



Expect from SM:

$BR(\mu\text{-}e\gamma) < 10^{-50}$

Experimentally so far:

$< 5.7 \times 10^{-13}$

PRL110(2013)201801

cLFV Searches: Current Situation

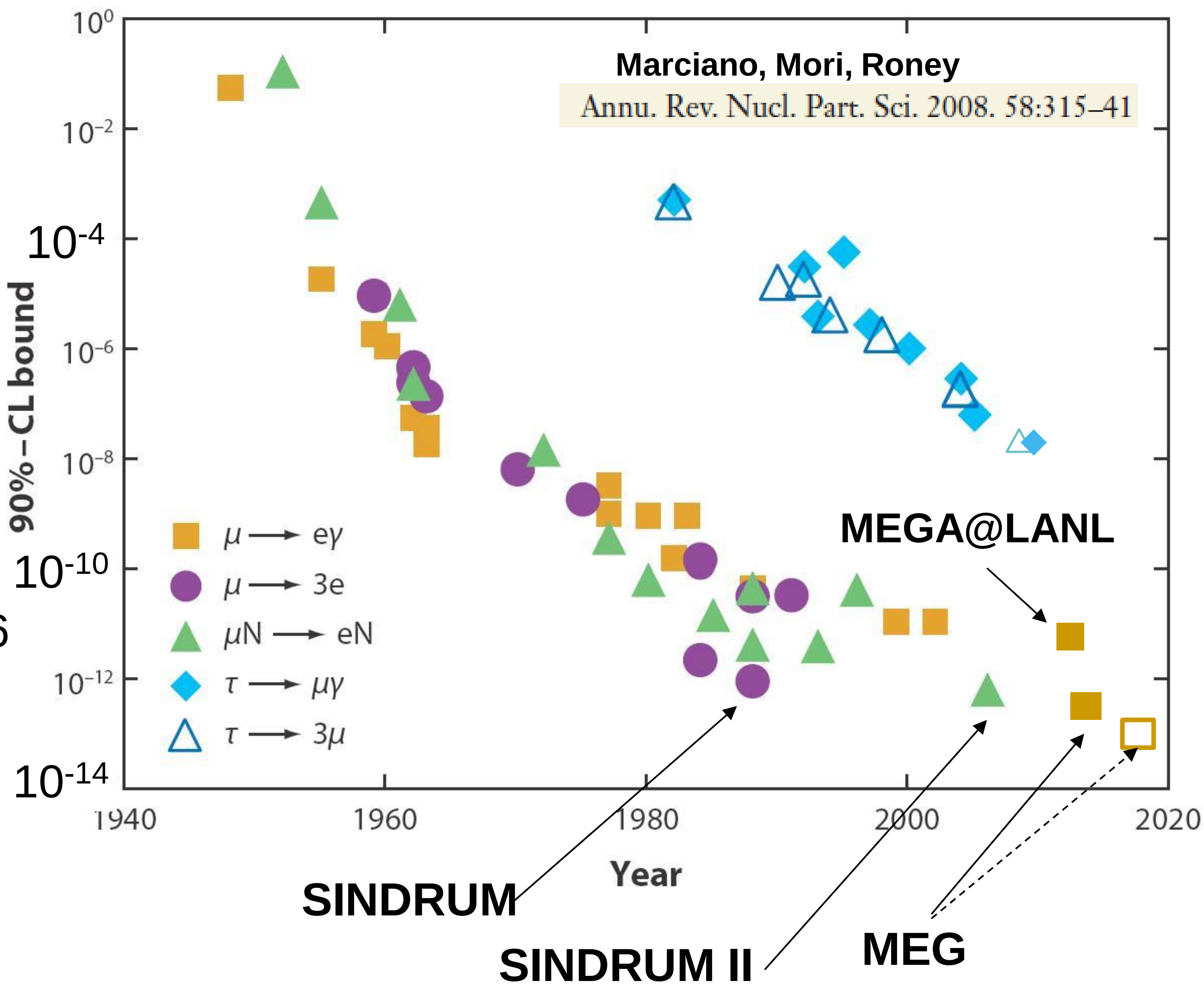
The present best limits on LFV are from muon experiments at PSI

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

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

$\mu^+ \rightarrow e^+ + \gamma$
BR < 5.7×10^{-13}
MEG 2013

[90 % C.L.]



Most sensitive LFV search

cLFV Searches: Current Situation

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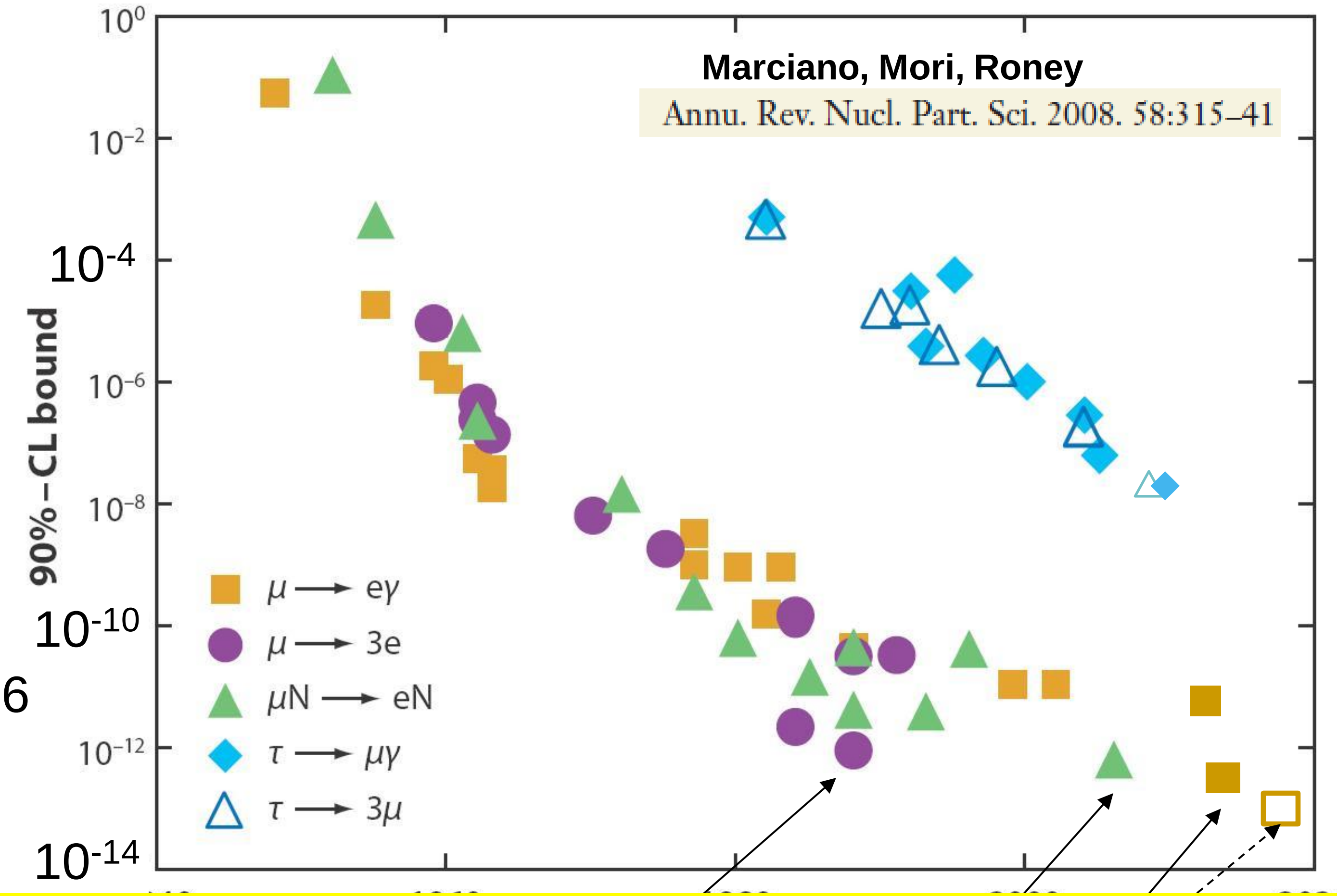
[90 % C.L.]



Next steps at PSI: MEG-II → 4 x 10^{-14}
Mu3e → 10^{-15} (πE5) → 10^{-16} (HiMB)

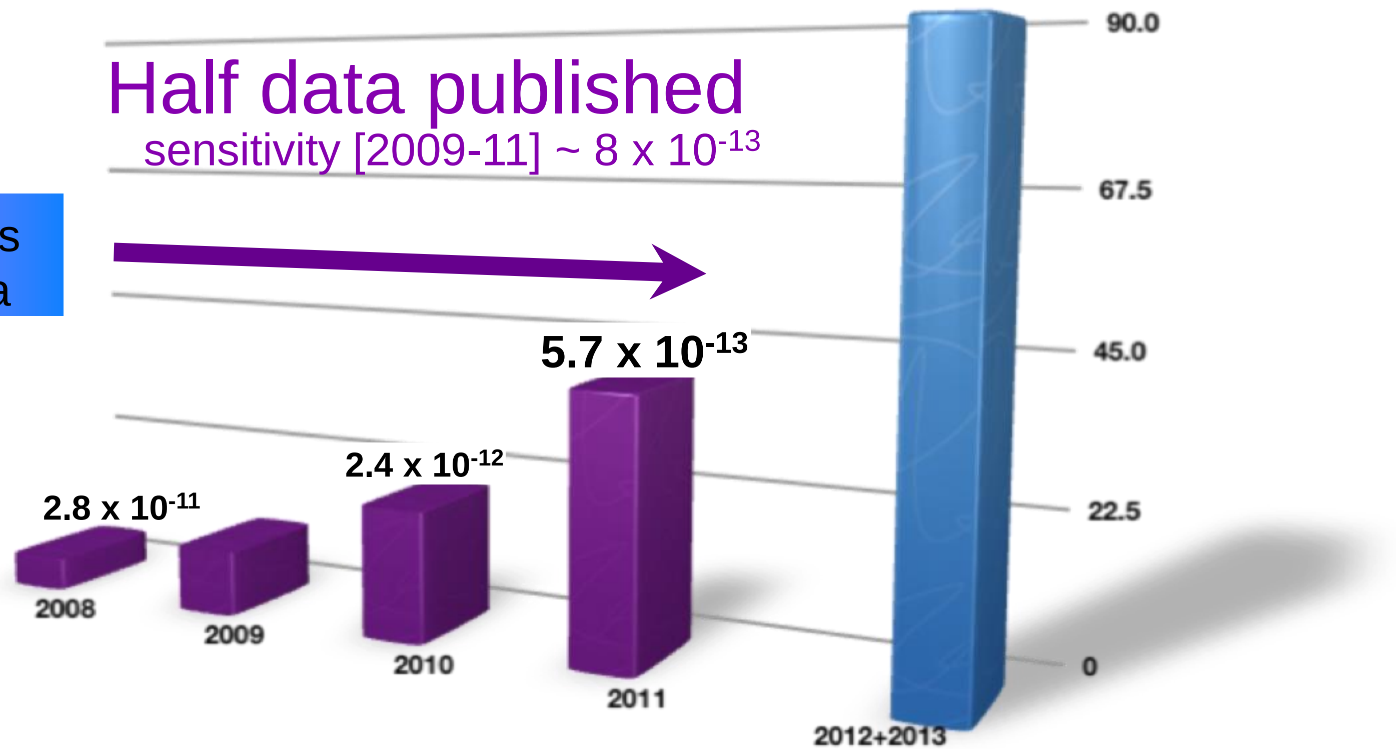
MEG analysis

Issues and Improvements in the $\mu \rightarrow e\,\gamma$ analysis

- Alignment of Muon Stopping Target
- Alignment of LXe Detector
- Analysis of Annihilation-of-Flight (AIF) Gamma Rays
- Recovery of Missing First Turns

Expect publication soon:
sensitivity [2009-13] ~ 5 x 10^{-13}

Improved analysis applied to all data



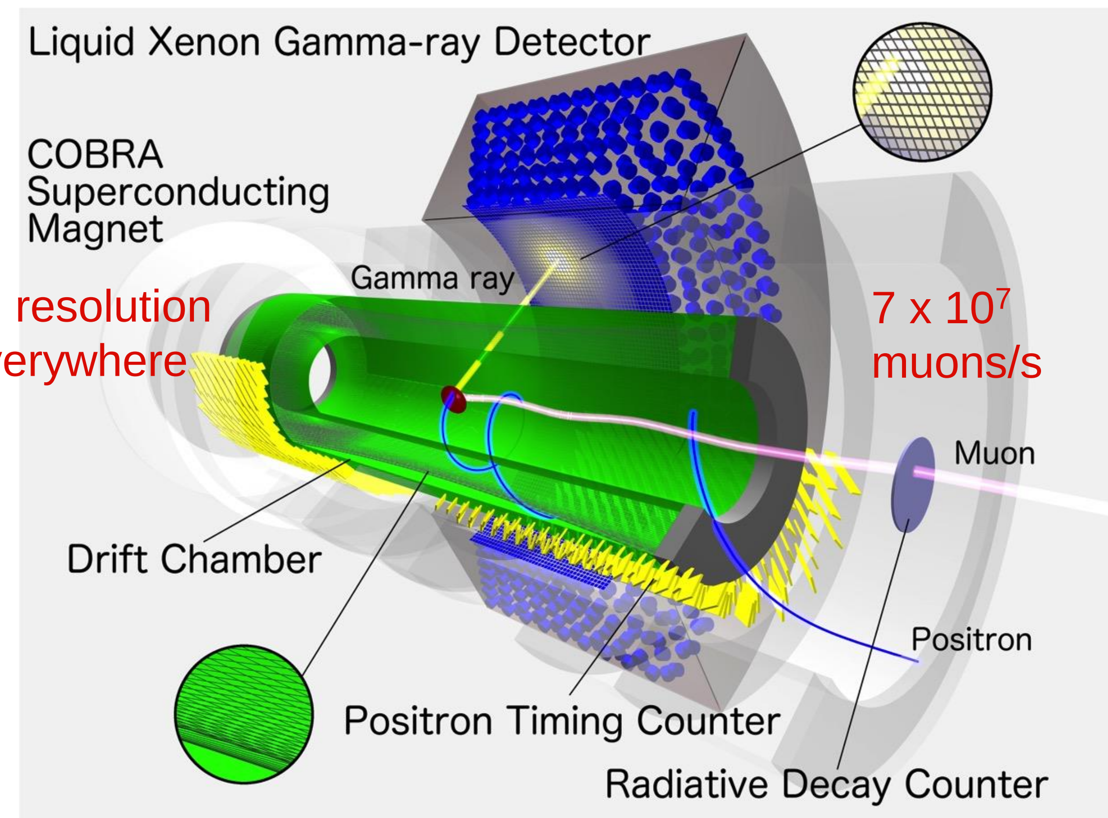
MEGII Status

Key elements:

- Higher beam intensity
- Higher detector efficiency and resolution
- Improved calibration methods
- New DAQ system

Sensitivity [2017-20] ~ 4 x 10^{-14}

x2 resolution everywhere



	MEG	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
ΔE/E (w< 2cm)	2.4%	1.1%
ΔE/E (w> 2cm)	1.7%	1.0%
t (ps)	67	<50
ε (%)	65	>70
p (keV)	306	130
θ (mrad)	9.4	5.3
φ (mrad)	8.7	4.8
t (ps)	70	35
ε (%)	40	88

MEGII Status

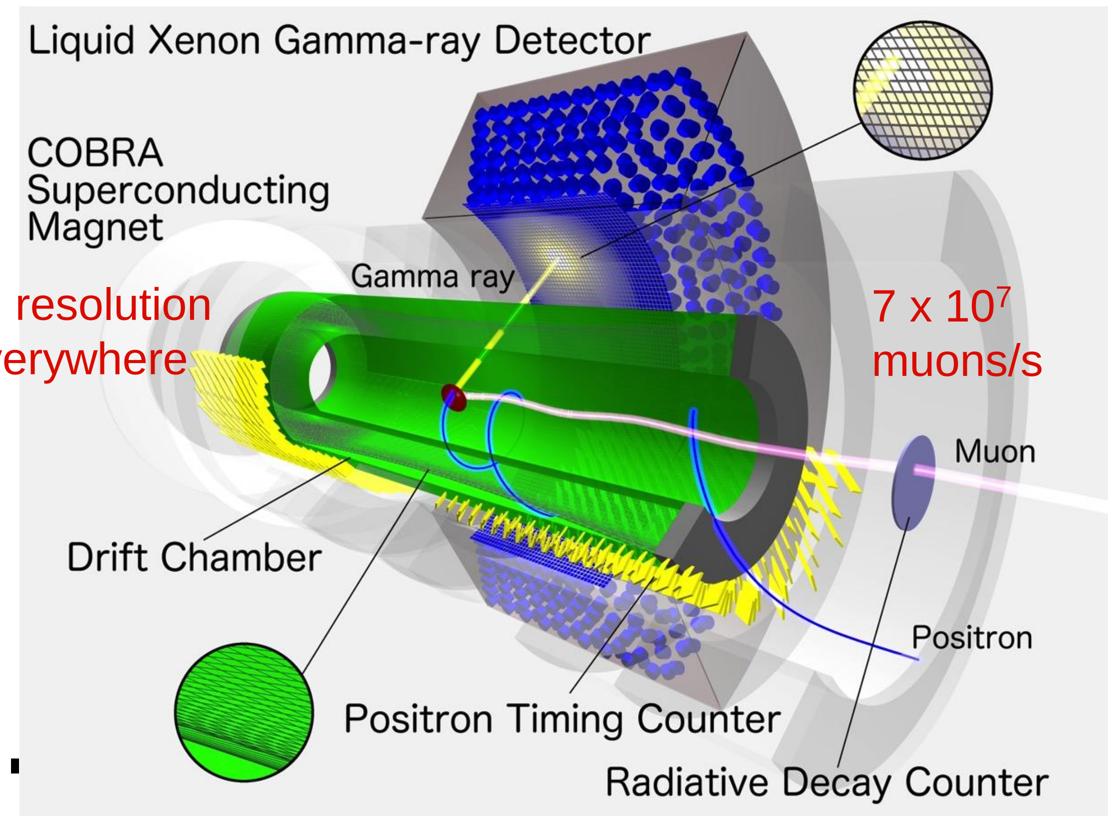
Key elements:

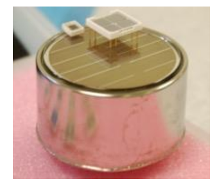
- Higher beam intensity
- Higher detector efficiency and resolution
- Improved calibration methods
- New DAQ system

2013 2014 2015 2016 2017-20

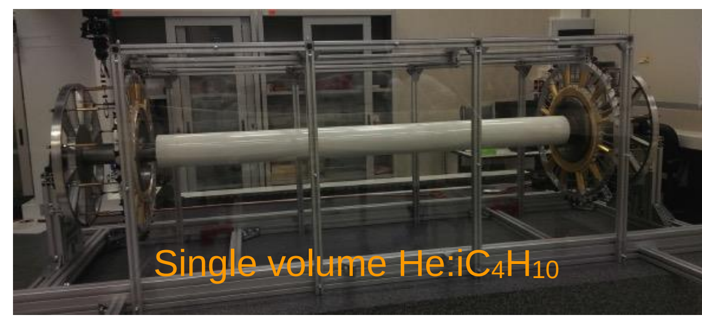
Design Construction PreEng Run Eng. Run Run

Sensitivity [2017-20] ~ 4 x 10^{-14}





Better uniformity w/ 12x12 VUV SiPM



Mu3e Status

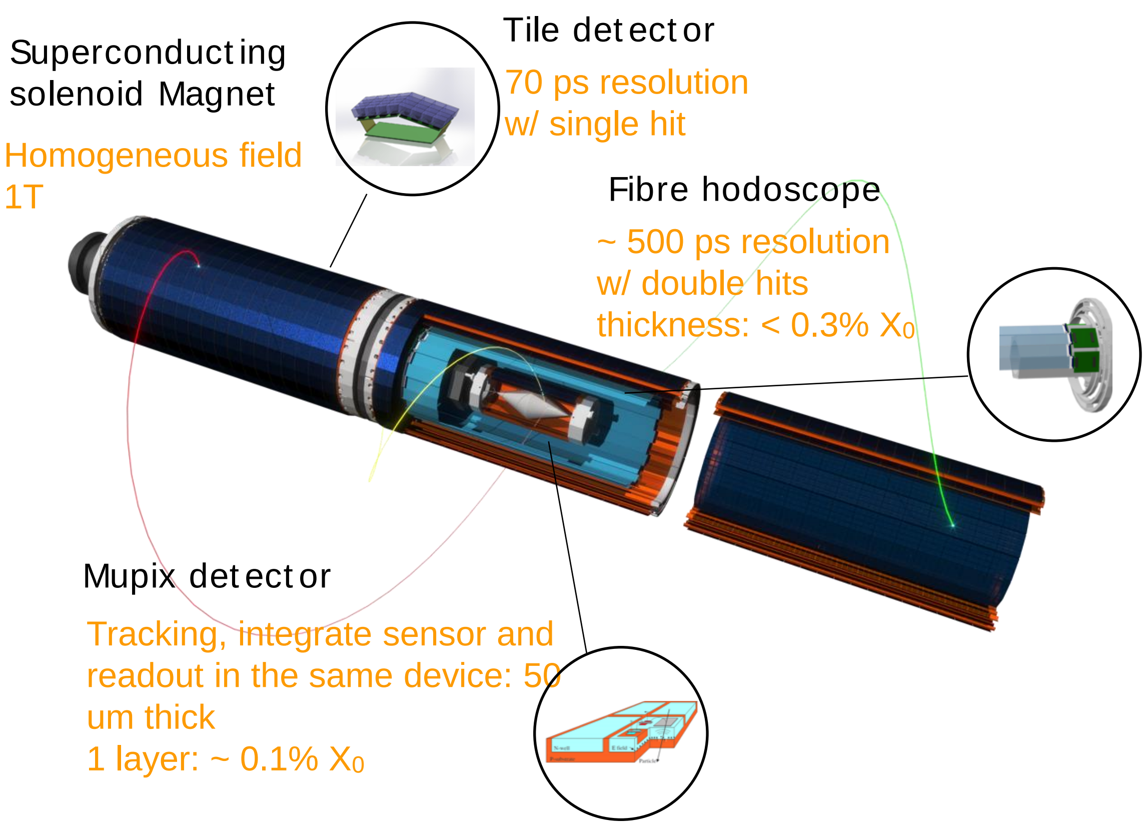
Key elements:

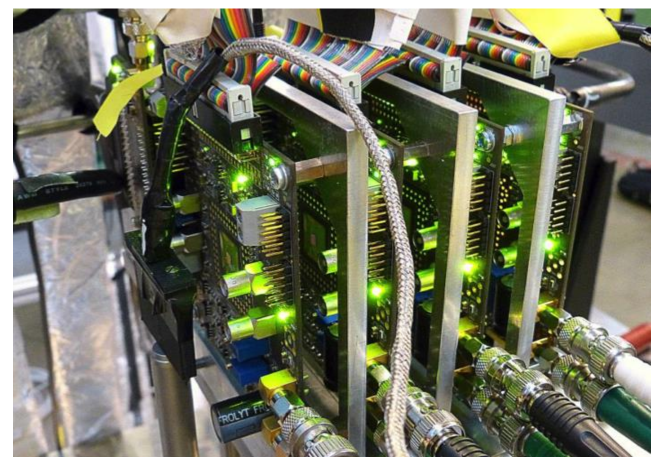
- Staged approach (here only phase I up to 10^8 muons/s)
- Impressive momentum resolutions
- Good timing also with minimal amount of material

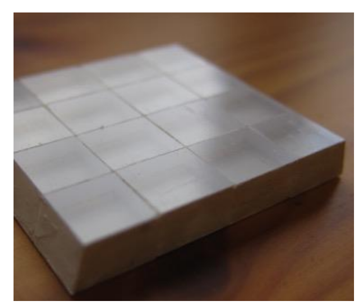
2013-5	2015-7		2017	2018-20
Design	Construction		Eng Run	Run

Sensitivity phase I [2018-20] ~ 10^{-15}

(Final Sensitivity phase II [202x] ~ 10^{-16})





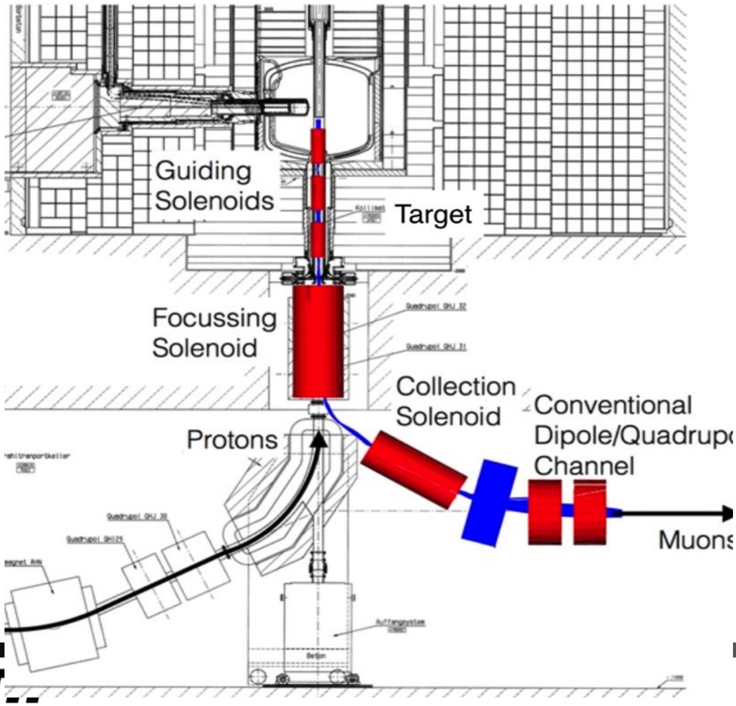


HiMB Status

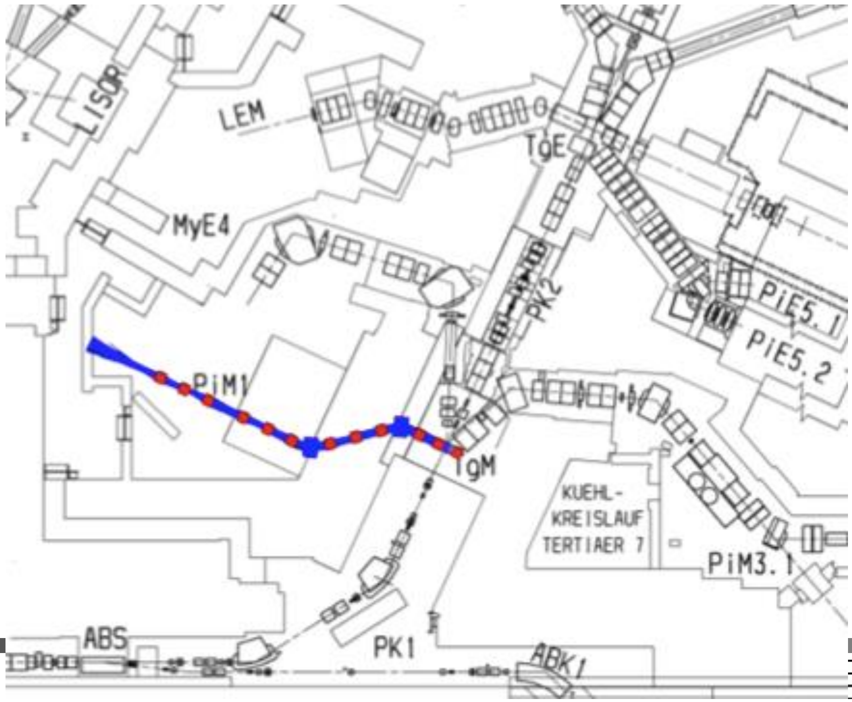
Feasibility studies ongoing

- HIMB@SINQ: 3×10^{10} muon/s at 1.7 mA(SINQ) prior to capture. Impractical as it would require removing beam-pipe constraints.
- HIMB@EH: a new solenoidal beamline coupled with a new 20 mm slanted graphite target. → **Very promising: $O(10^{10}$ muon/s) seems feasible**

HIMB@SINQ



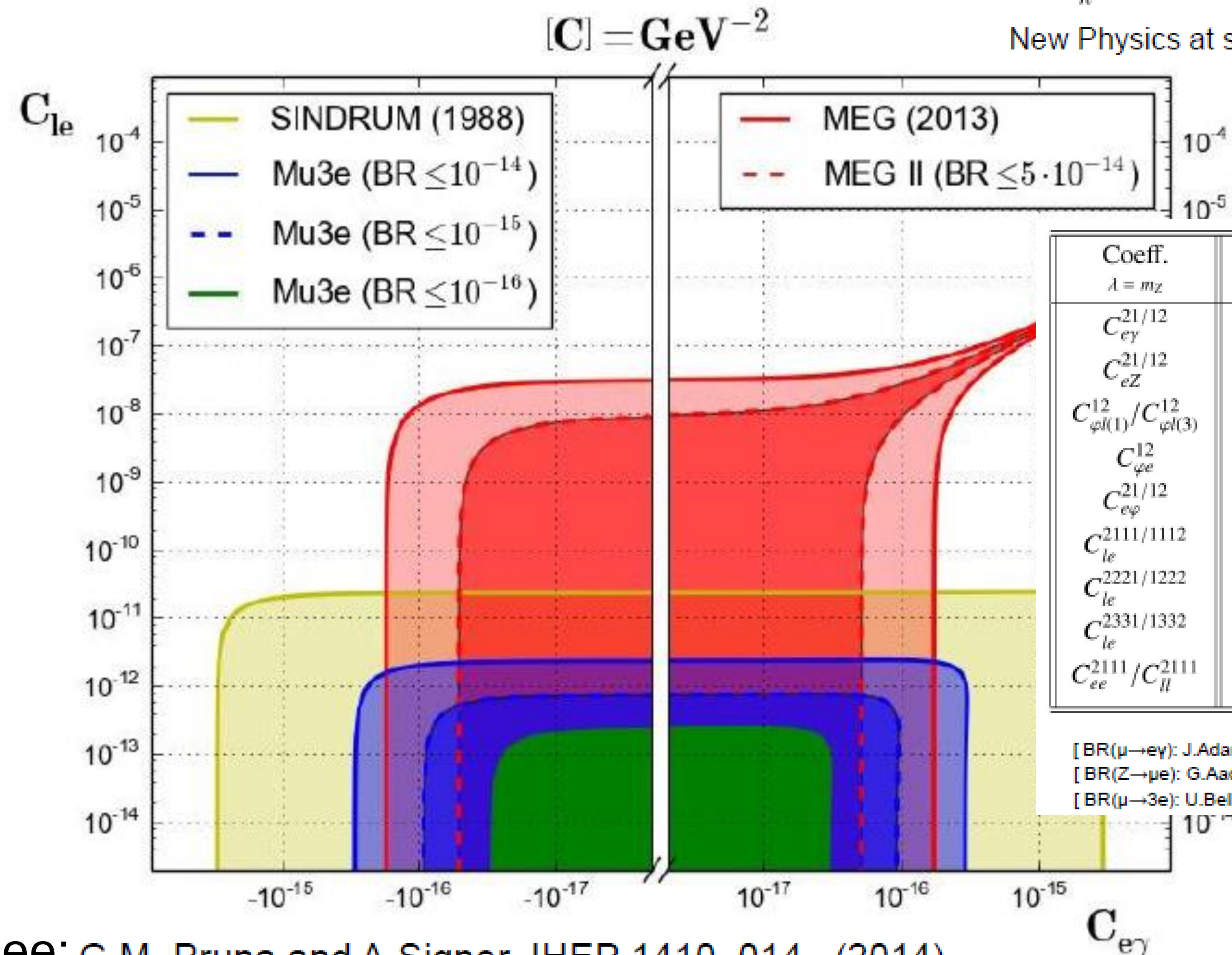
HIMB@EH



MEG and Mu3e complementarity

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

New Physics at scale $\Lambda \gg M_Z$



Coeff. $\lambda = m_Z$	$\mu^+ \to e^+\gamma$ BR≤ $5.7 \cdot 10^{-13}$	$Z \to e^\pm\mu^\mp$ BR≤ $7.5 \cdot 10^{-7}$	$\mu^+ \to e^+e^-e^+$ BR≤ $1.0 \cdot 10^{-12}$
$C_{e\gamma}^{21/12}$	$2.5 \cdot 10^{-16}$		$3.8 \cdot 10^{-15}$
$C_{eZ}^{21/12}$	$1.4 \cdot 10^{-13}$	$3.9 \cdot 10^{-8}$	$4.0 \cdot 10^{-8}$
$C_{\varphi l(1)}^{12}/C_{\varphi l(3)}^{12}$	$2.5 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$3.5 \cdot 10^{-11}$
$C_{\varphi e}^{12}$	$2.5 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$3.7 \cdot 10^{-11}$
$C_{e\varphi}^{21/12}$	$2.8 \cdot 10^{-8}$		$8.7 \cdot 10^{-6}$
$C_{le}^{2111/1112}$	$4.4 \cdot 10^{-8}$		$3.1 \cdot 10^{-11}$
$C_{le}^{2221/1222}$	$2.1 \cdot 10^{-10}$		
$C_{le}^{2331/1332}$	$1.2 \cdot 10^{-11}$		
$C_{ee}^{2111}/C_{ll}^{2111}$			$1.1 \cdot 10^{-11}$

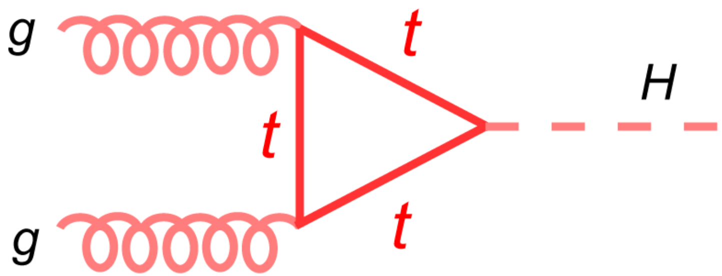
[BR(μ→eγ): J.Adam et al. (MEG), Phys. Rev. Lett. 110, 201801, (2013)]
[BR(Z→μe): G.Aad et al. (ATLAS), Phys. Rev. D90, 072010, (2014)]
[BR(μ→3e): U.Bellgardt et al. (SINDRUM), Nucl.Phys. B299, 1, (1988)]

See: G.M. Pruna and A.Signer JHEP 1410, 014 , (2014)

Search for new physics

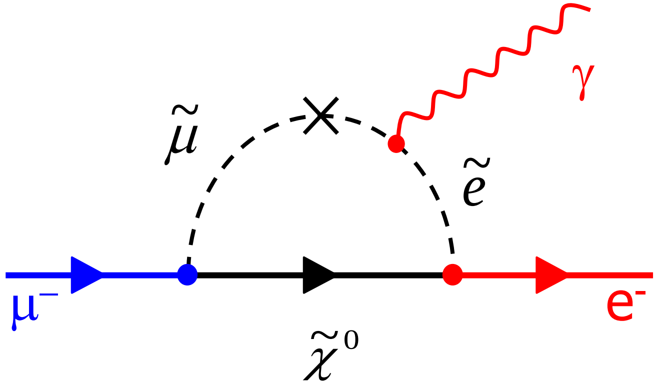
High Energy

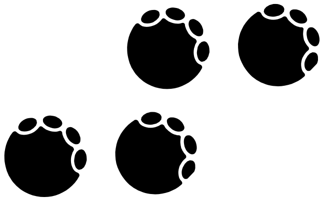
direct production of new particle



High Intensity

Search for $\mu \rightarrow e\gamma$

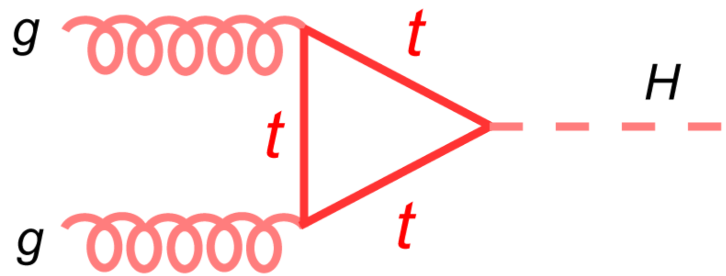




Search for new physics

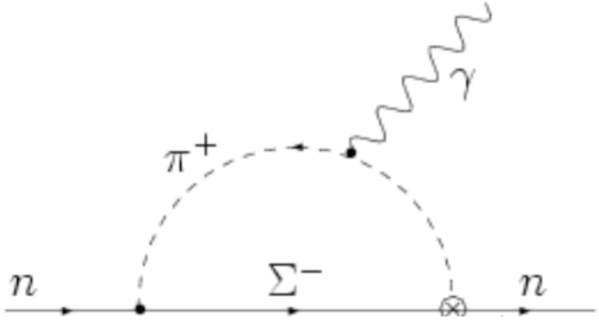
High Energy

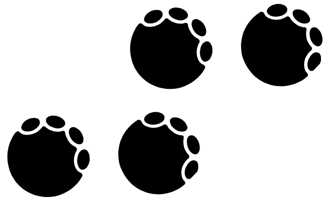
direct production of new particle



High Intensity

Search for nEDM

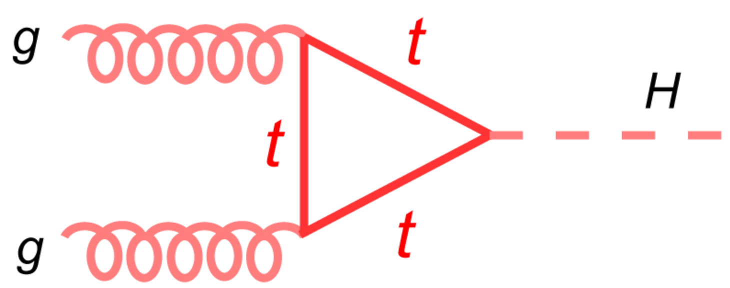




Search for new physics

High Energy

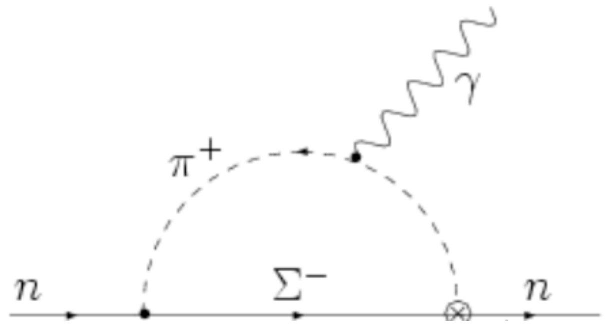
direct production of new particle



Mass reach: few TeV

High Intensity

Search for nEDM



Mass reach: 1 - 1000 TeV

Electric Dipole Moments are small in the Standard Model

- Leptons: 4th order electro-weak

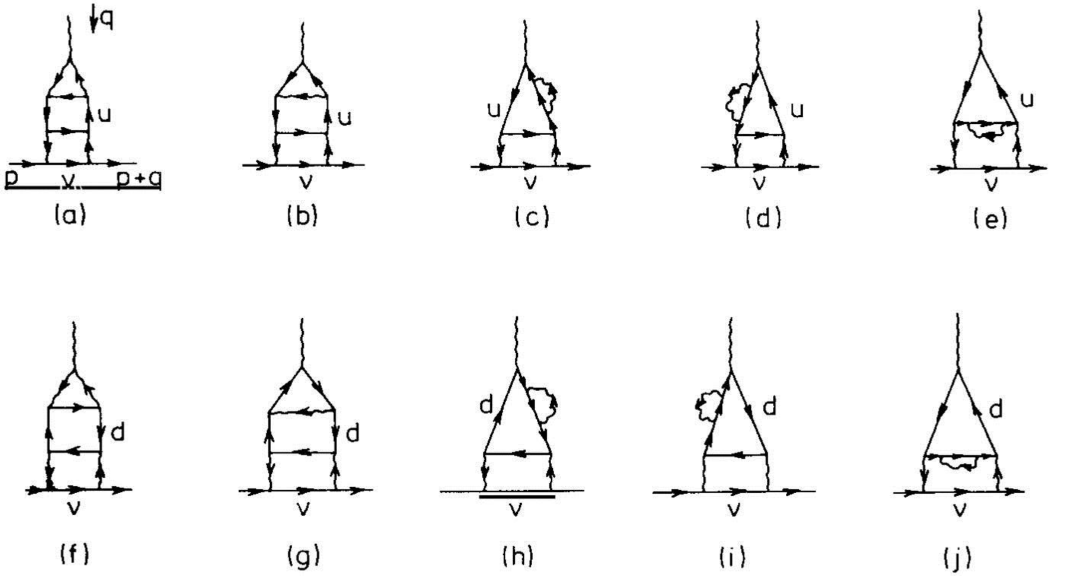
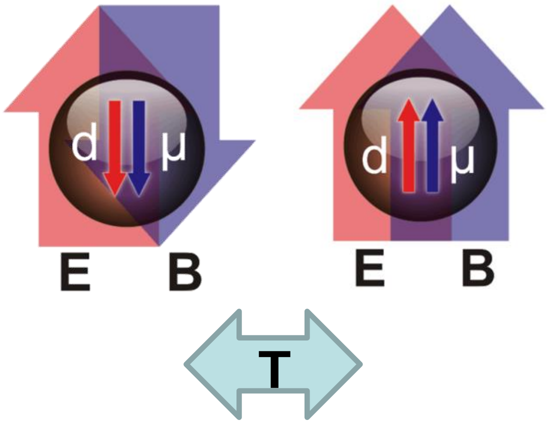


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

F. Hoogeveen:
The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322



Expect from SM, approximately:

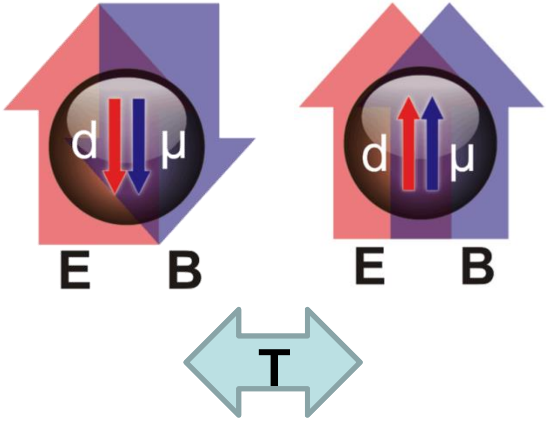
$d_e \leq 10^{-38}$ e•cm
$d_\mu \leq 10^{-36}$ e•cm
$d_\tau \leq 10^{-35}$ e•cm

Experimentally so far:

$d_e < 9 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

Electric Dipole Moments are small in the Standard Model

- Neutron, Proton, ..



$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky ‘86]

Expect from SM:

$d_n < 10^{-30}$ e•cm

Experimentally so far:

$< 2.9 \times 10^{-26}$ e•cm

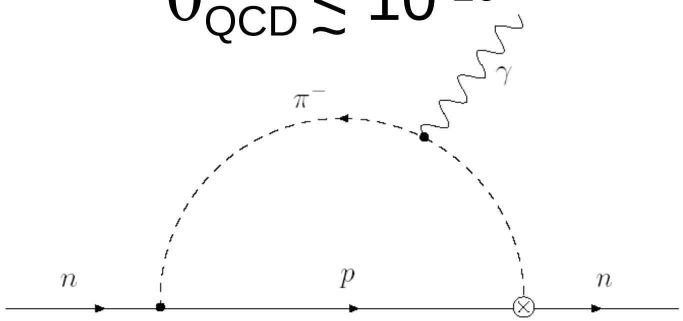
Caveat:

The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$$

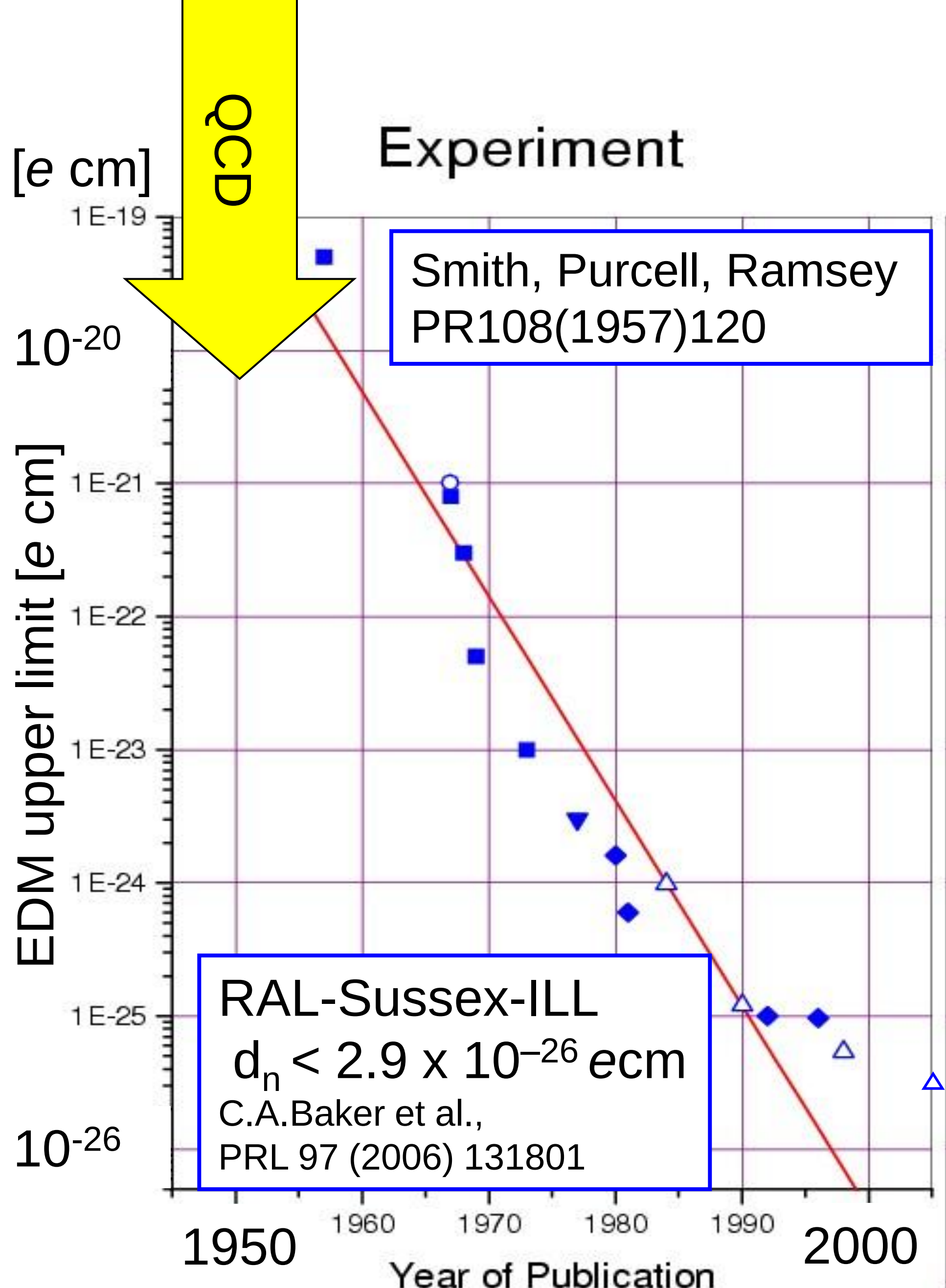
$$d_n \approx 10^{-16}\ e\ \text{cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

→ accidentally small !?



The SUSY CP problem

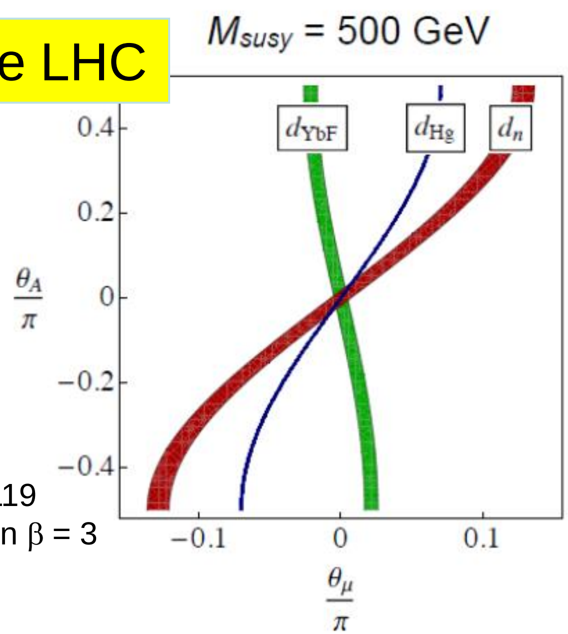
(for neutron and electron!)

$$d_n \approx 10^{-23}\, e\ \mathrm{cm} \left(\frac{300\ \mathrm{GeV}/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

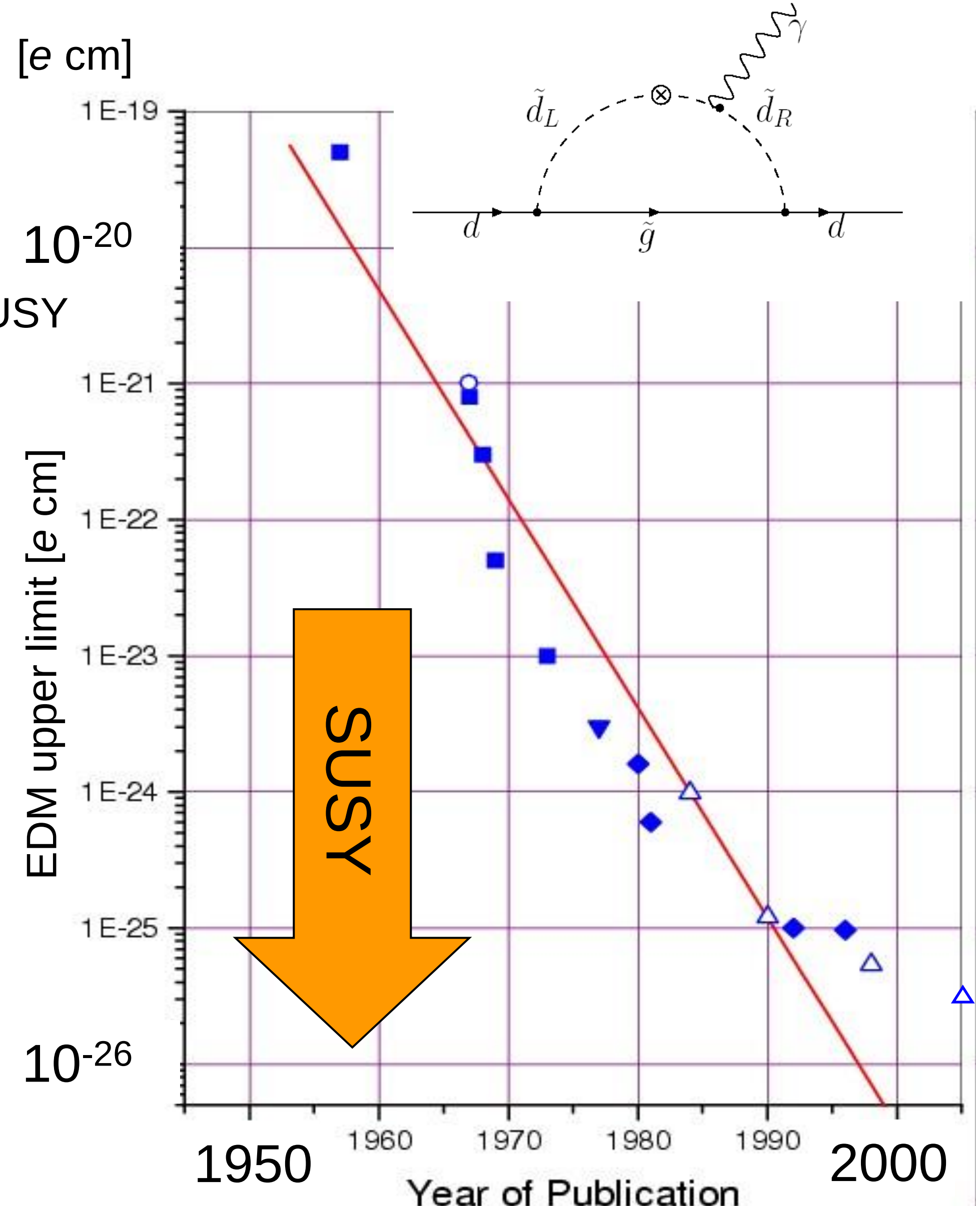
Why is ϕ_{SUSY} so small ?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)

pre LHC



See: Pospelov, Ritz, Ann. Phys. 318(2005)119 for M_{SUSY} = 500GeV, tan β = 3

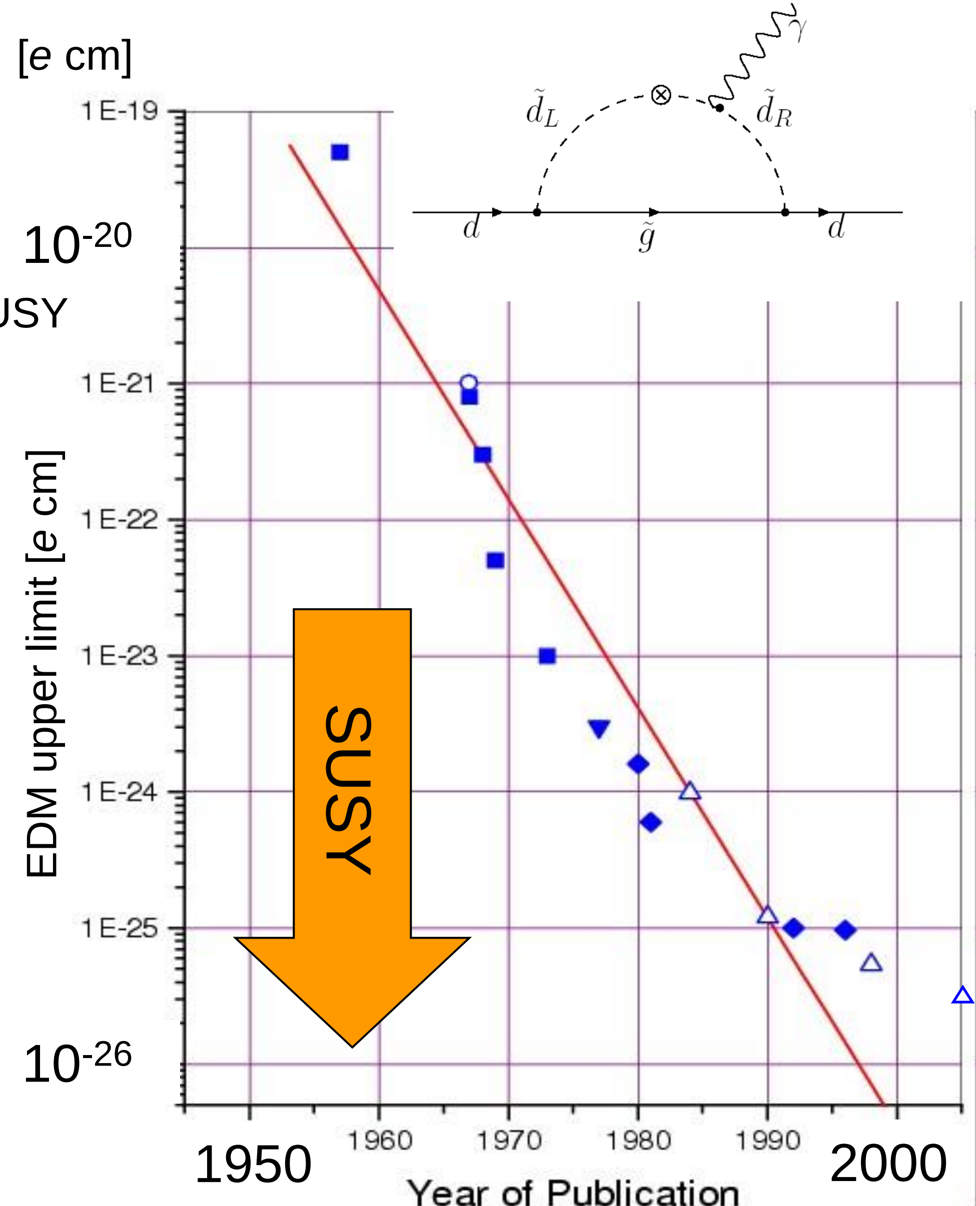


ETH

The SUSY CP problem

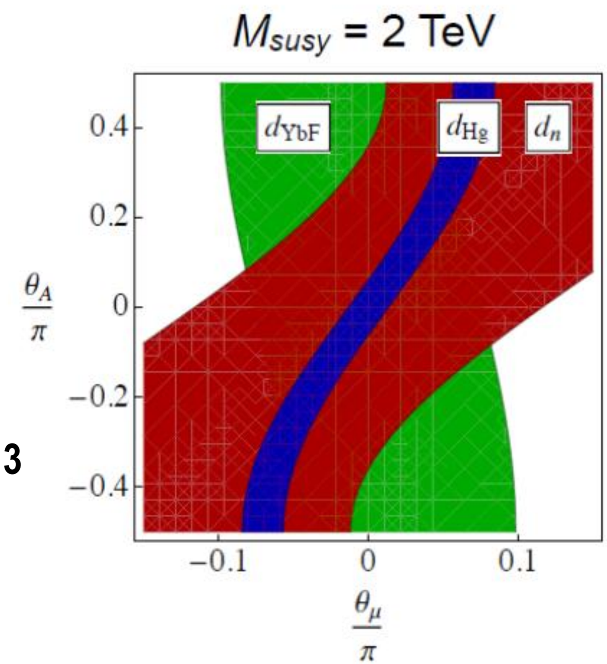
(for neutron and electron!)

$$d_n \approx 10^{-23}\ e\ \text{cm} \left(\frac{300\ \text{GeV}/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$



Why is ϕ_{SUSY} so small ?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)



A. Ritz, update 2013

The SUSY CP problem

(for neutron and electron!)

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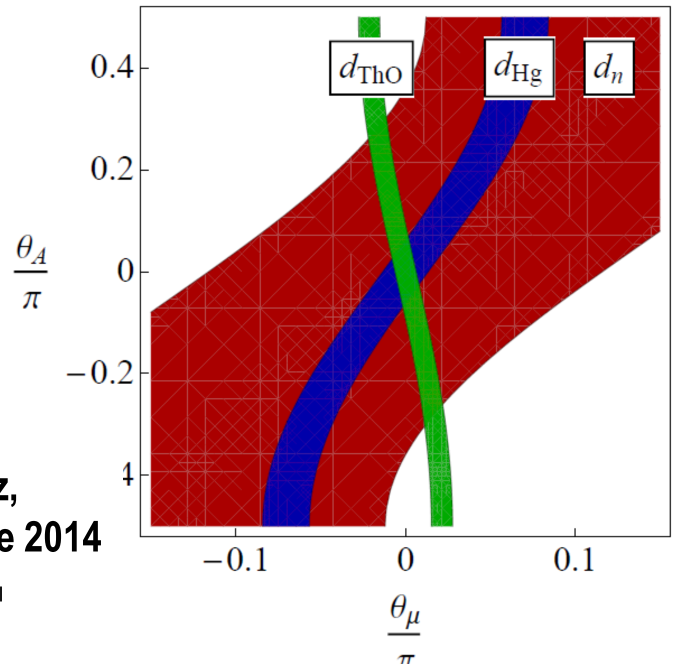
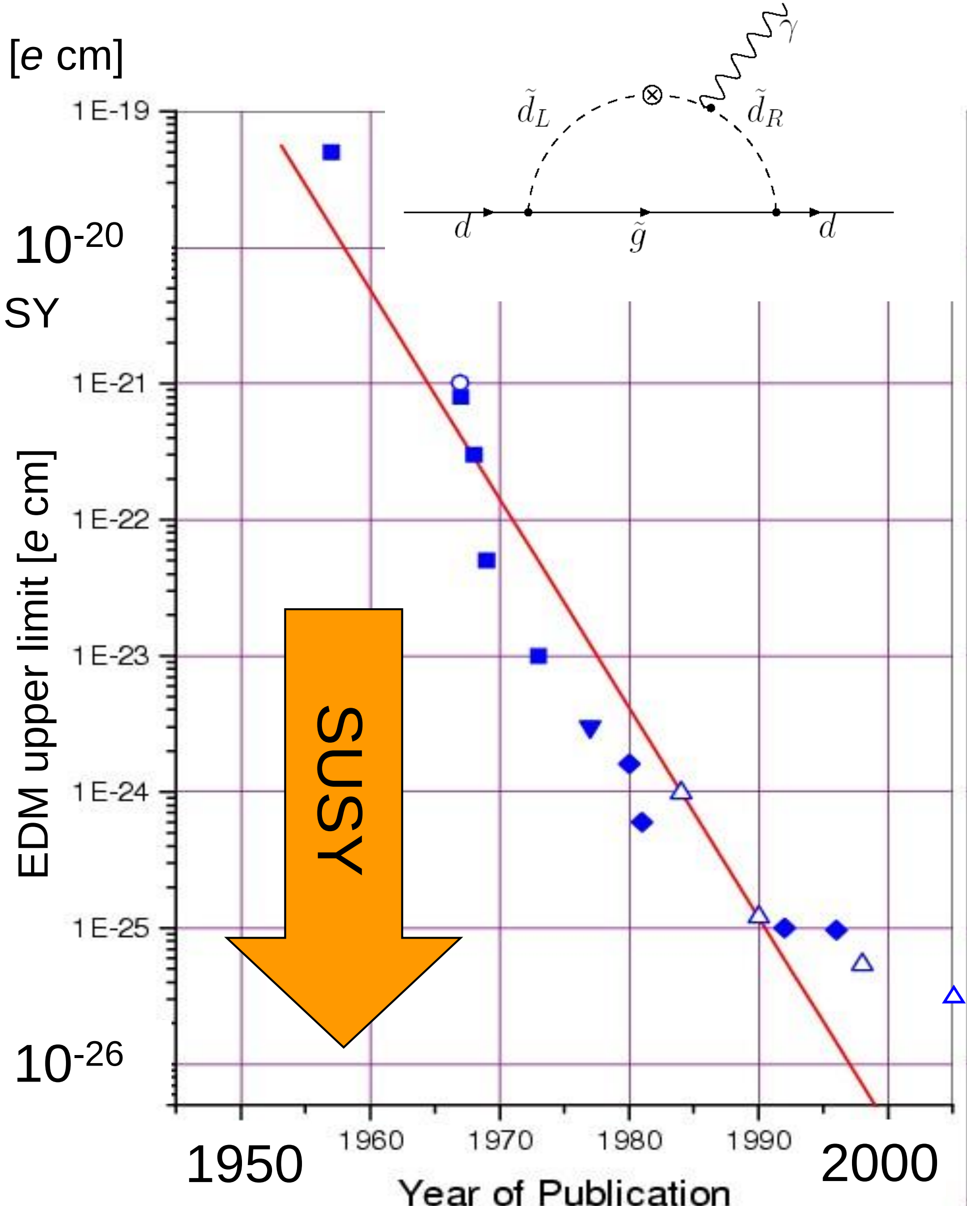


A. Ritz, update 2014



The SUSY CP problem

(for neutron and electron!)

$$d_n \approx 10^{-23}\, e\, \mathrm{cm} \left(\frac{300\ \mathrm{GeV/c^2}}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

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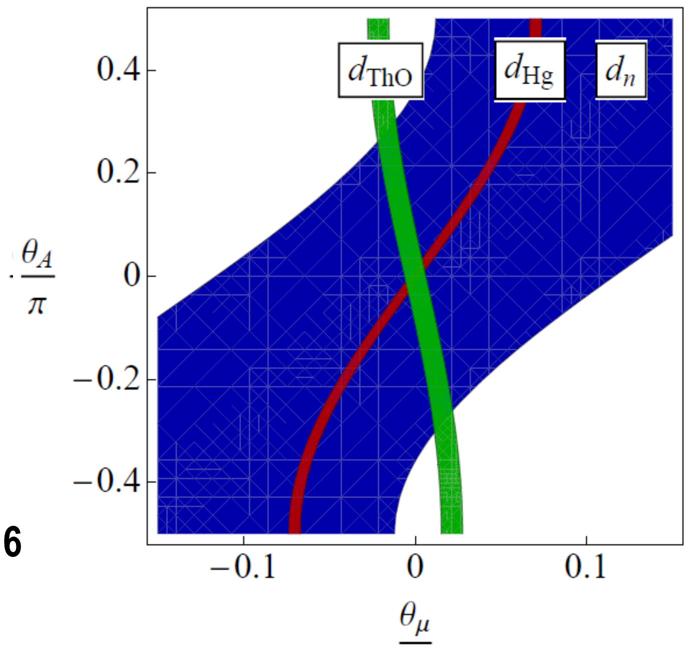
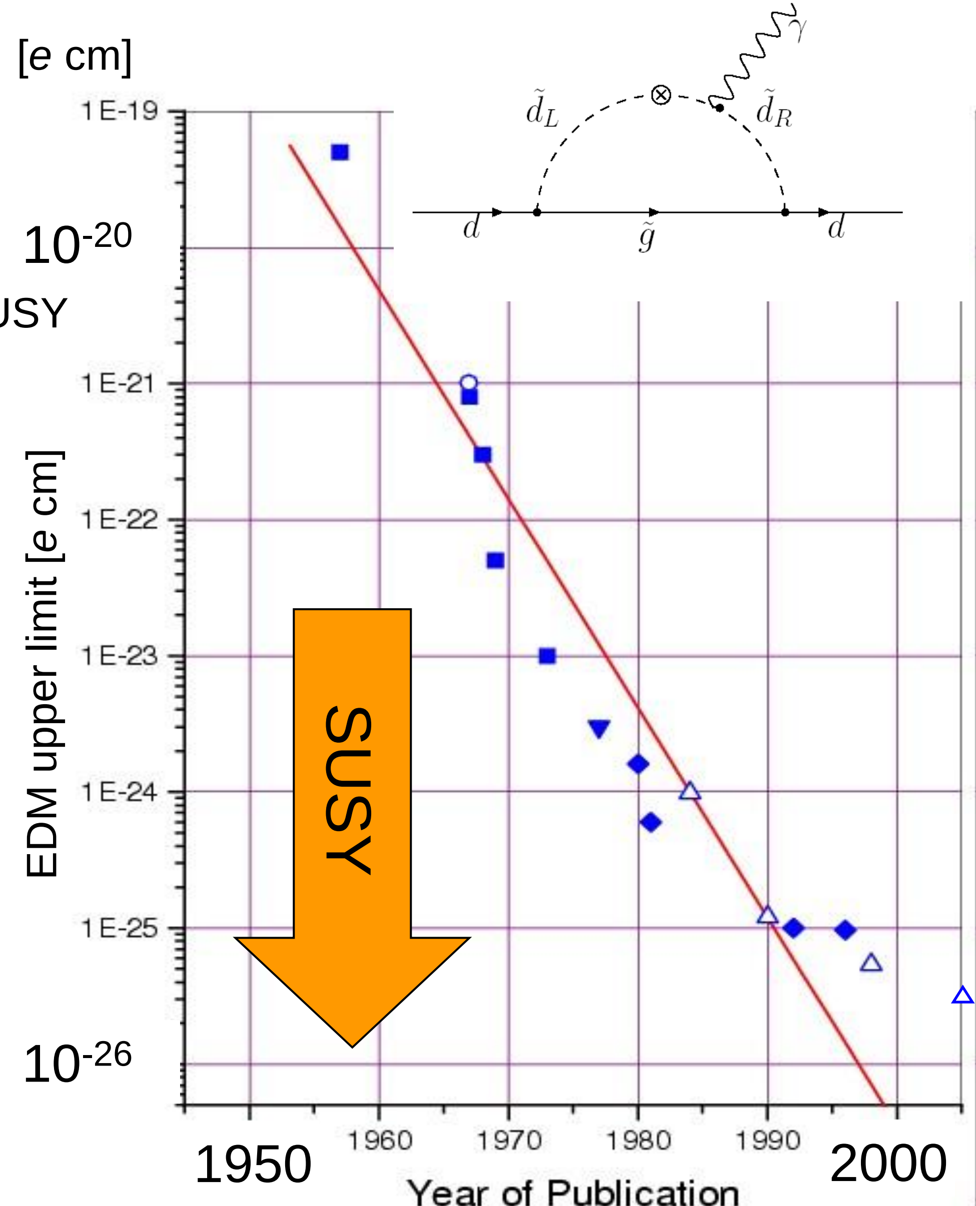
(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)



A. Ritz, update 2016



ETH

The BAU CP Problem

Nature has probably violated CP when generating the Baryon asymmetry !?

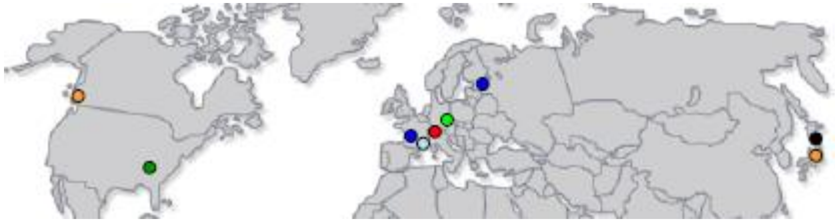
Observed*:
$(n_B - n_{\bar{B}}) / n_\gamma = 6 \times 10^{-10}$

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]

* WMAP + COBE, 2003
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$

UCN sources



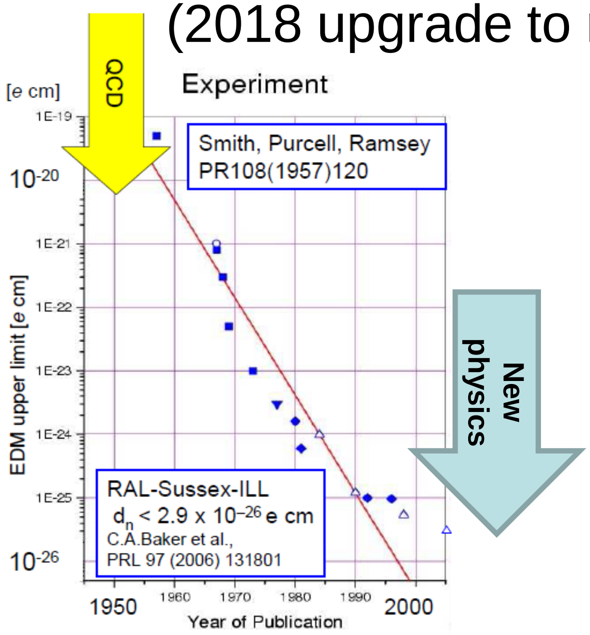
[some belong to specific experiments]

- Operating:
  - ILL PF-2 (turbine)
  - LANL (sD2)
  - **PSI (sD2)**
  - TRIGA Mainz (sD2)
  - RCNP (SF-He)
  - ILL SUN2 (SF-He)
  - ILL: Sun1 GRANIT
  - [NIST: lifetime]
- R&D and construction
  - ILL SuperSUN
  - TRIUMF/RCNP
  - PNPI WWR-M
  - NCSU PULSTAR
  - FRM-2
  - SNS-EDM
- Possible projects
  - J-PARC
  - PIK
  - ESS

Neutron EDM projects

(Essentially all of them aiming at 1-2 orders of magnitude improvement)

- Operating:
  - PNPI, ILL@ILL
    (result 2013/14, upgrading)
  - **nEDM@PSI**
    (2018 upgrade to n2EDM)



- R&D and construction
  - @RCNP/TRIUMF
  - @FRM-2
  - @SNS
  - @PNPI
  - @LANL
- Possible future projects
  - @J-PARC
  - @PIK
  - @ESS

All nEDM competitive today use ultracold neutrons – UCN

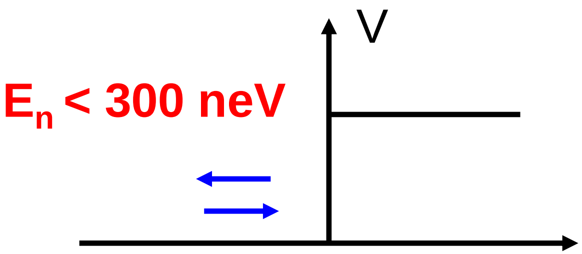
UCN: similar to ideal gas with temperatures of milli-Kelvin

(very dilute and not in thermal equilibrium with walls)

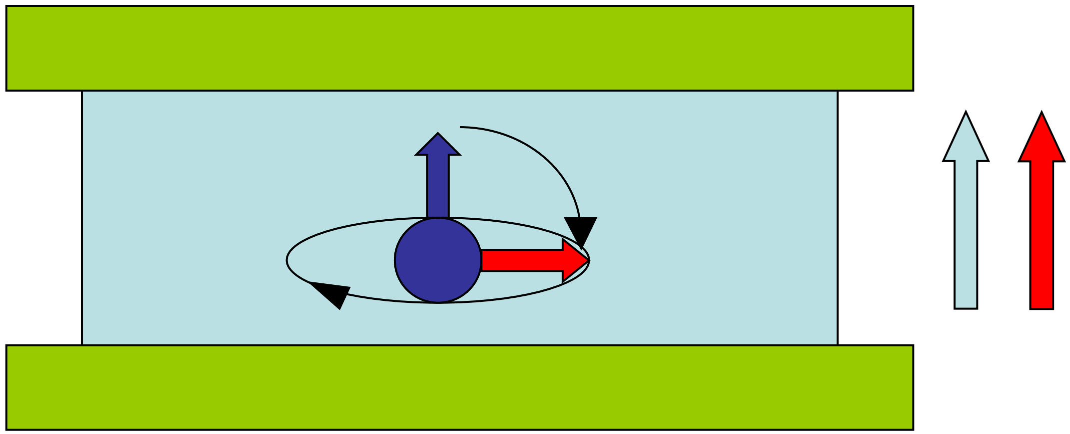
move with velocities of few m/s

have kinetic energies of order 100 neV

strong	magnetic	gravitation
Fermi potential V_F	**$V_m = -\mu B$**	**$V_g = m_n g h$**
↓	↓	↓
300 neV	**60 neV T^{-1}**	**100 neV m^{-1}**
	↓	↓
	5 T field -> 300 neV	**3 m up -> 300 neV**

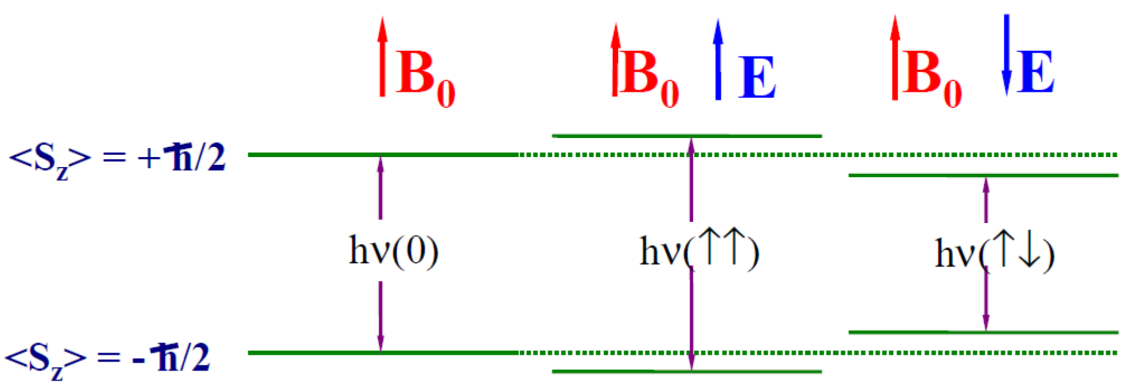


How to measure the neutron (or other) electric dipole moment ?



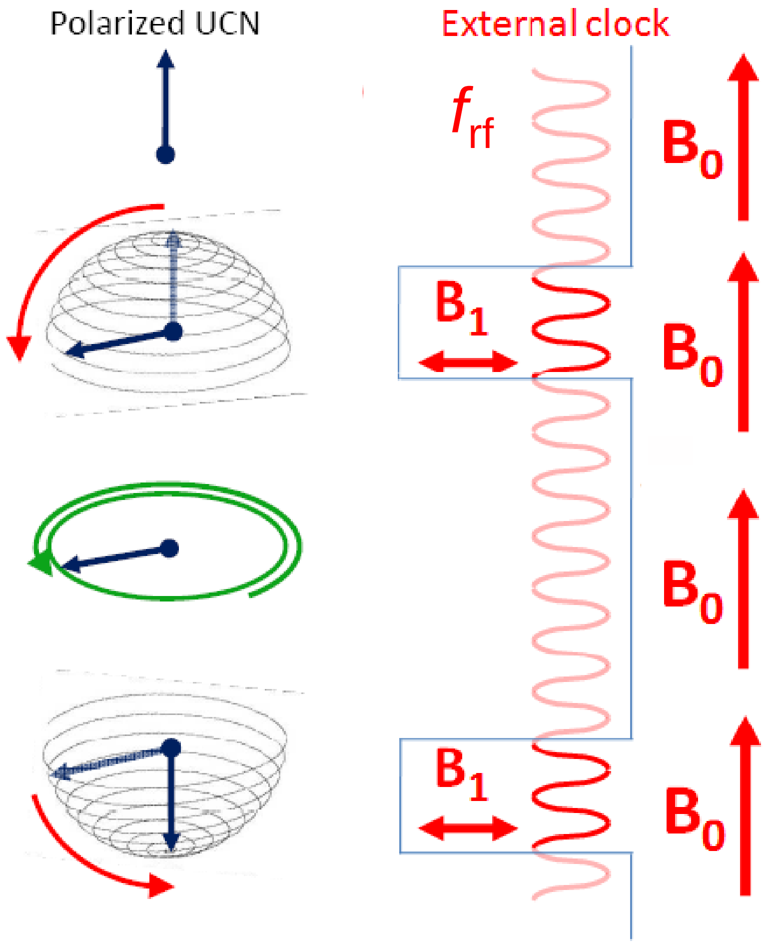
$$h\nu_{\uparrow\uparrow} = 2\ (\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\ (\mu B - d_n E)$$

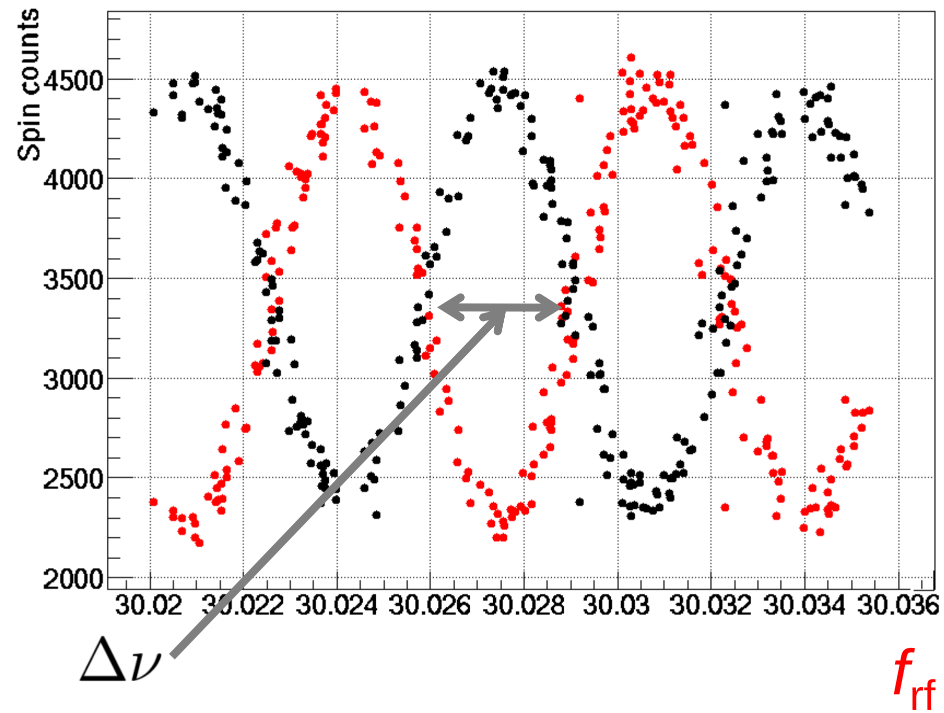
$$h\Delta\nu = 4\ d_n\ E$$



$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

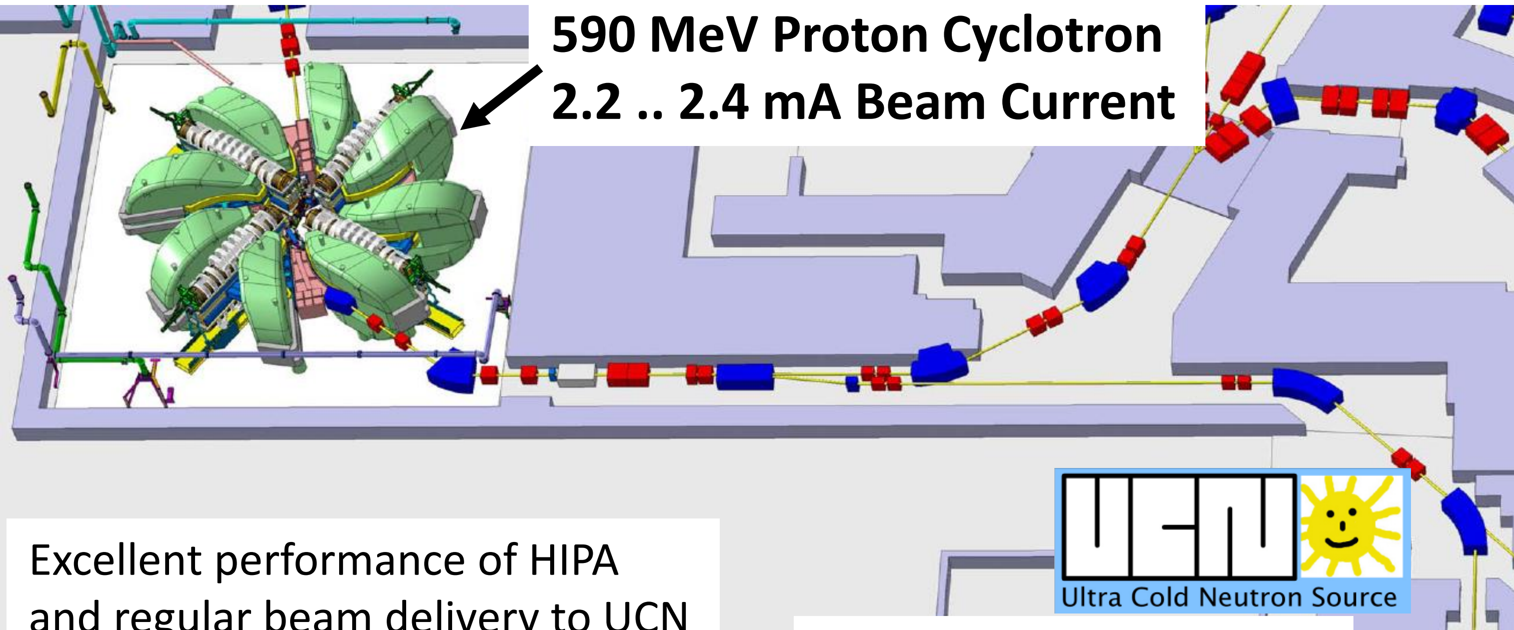
Ramsey's method with UCN

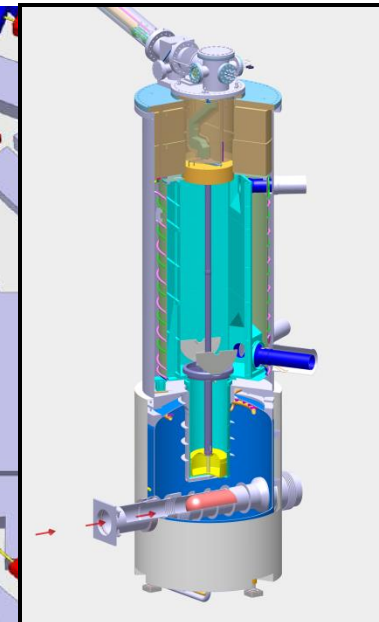




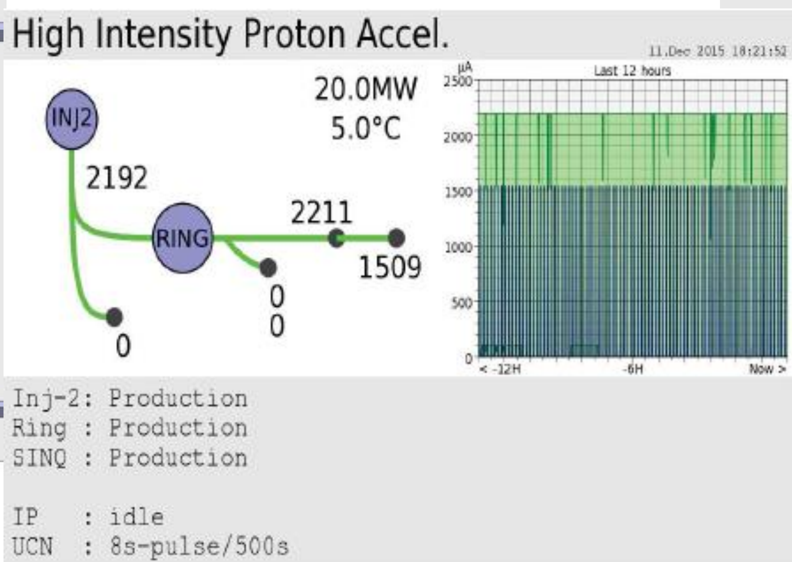
$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

Ultracold Neutron Source & Facility





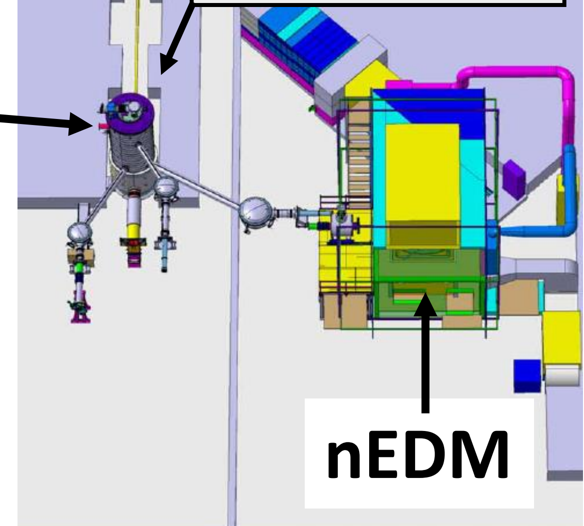
Excellent performance of HIPA and regular beam delivery to UCN



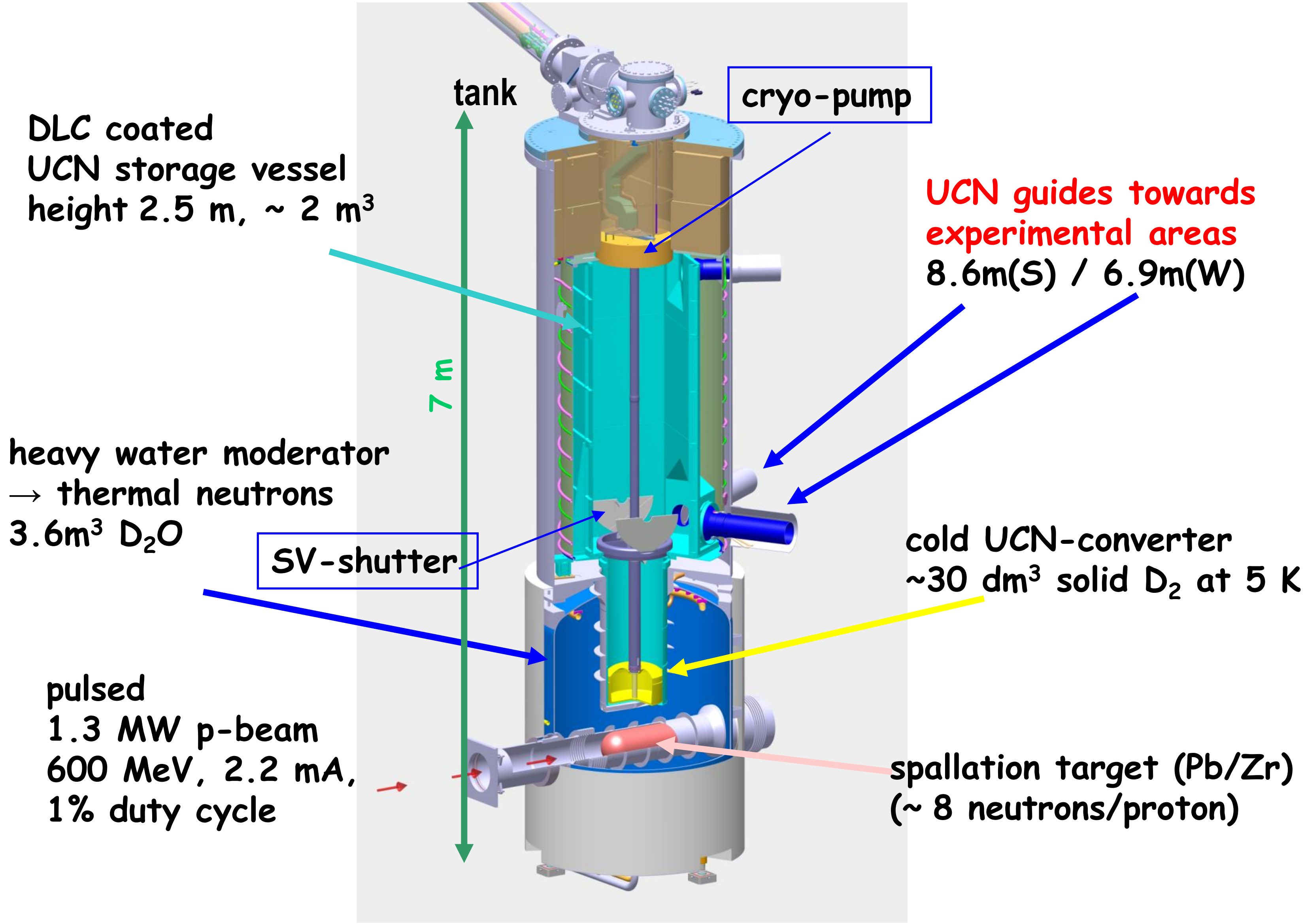
UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
- UCN to nEDM since 2012

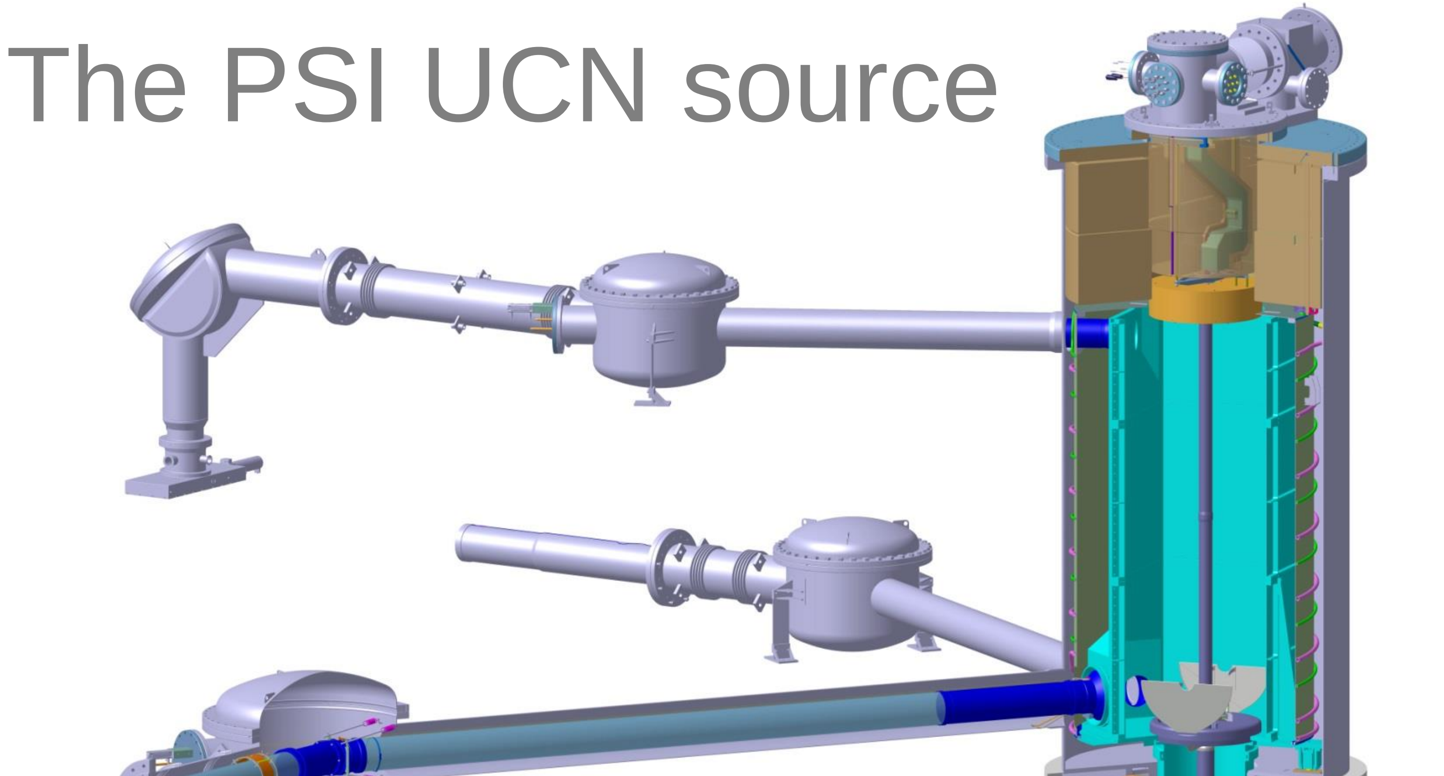
  -> intensity 90x over 2010
- Increased duty factor 2015: 20 → 40 μA average
- 2016: towards 60μA

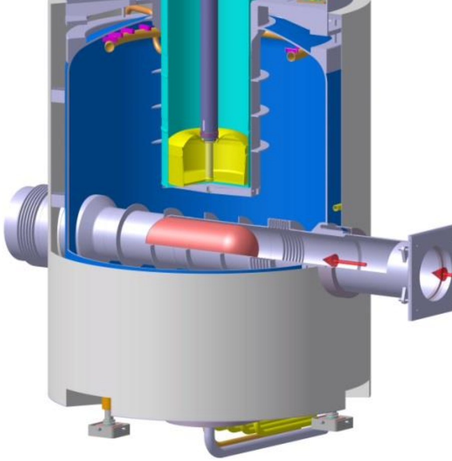


The PSI UCN source

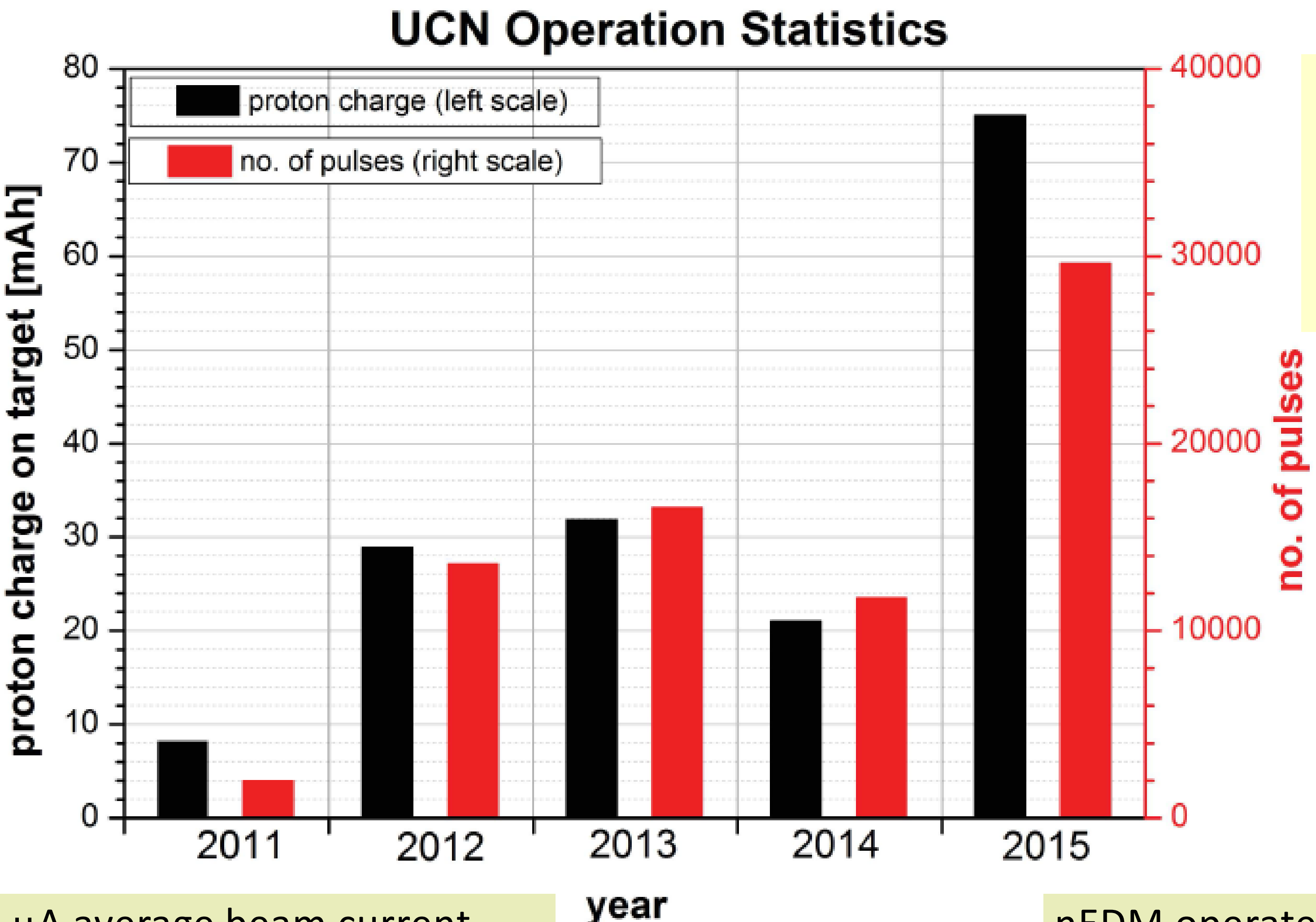


The PSI UCN source





Getting routine with operation



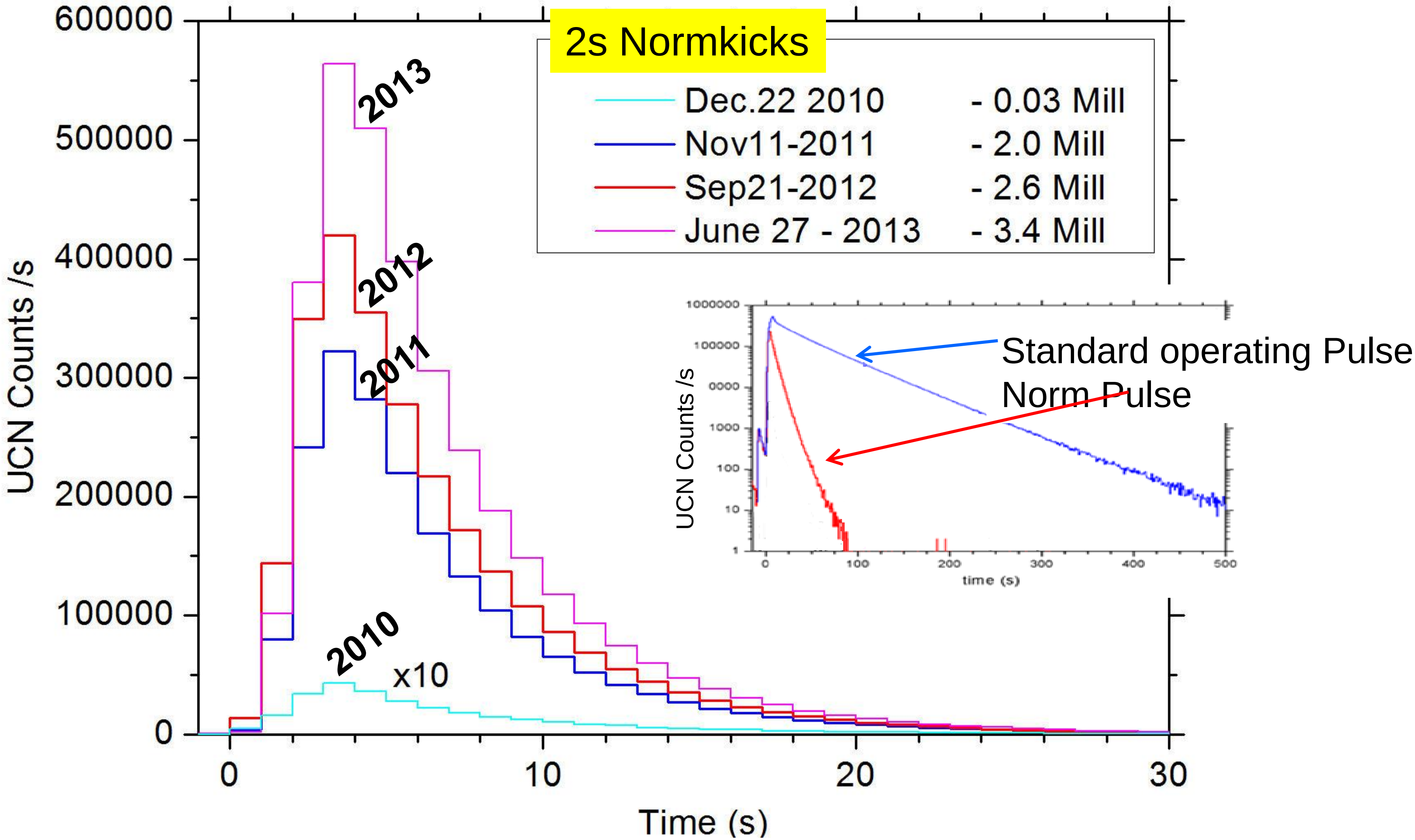
1 typical pulse
~ few seconds,
5E16 p on target,
4E17 spallation n,
1E9 UCN

40 μA average beam current can result in max. 1 mAh / day

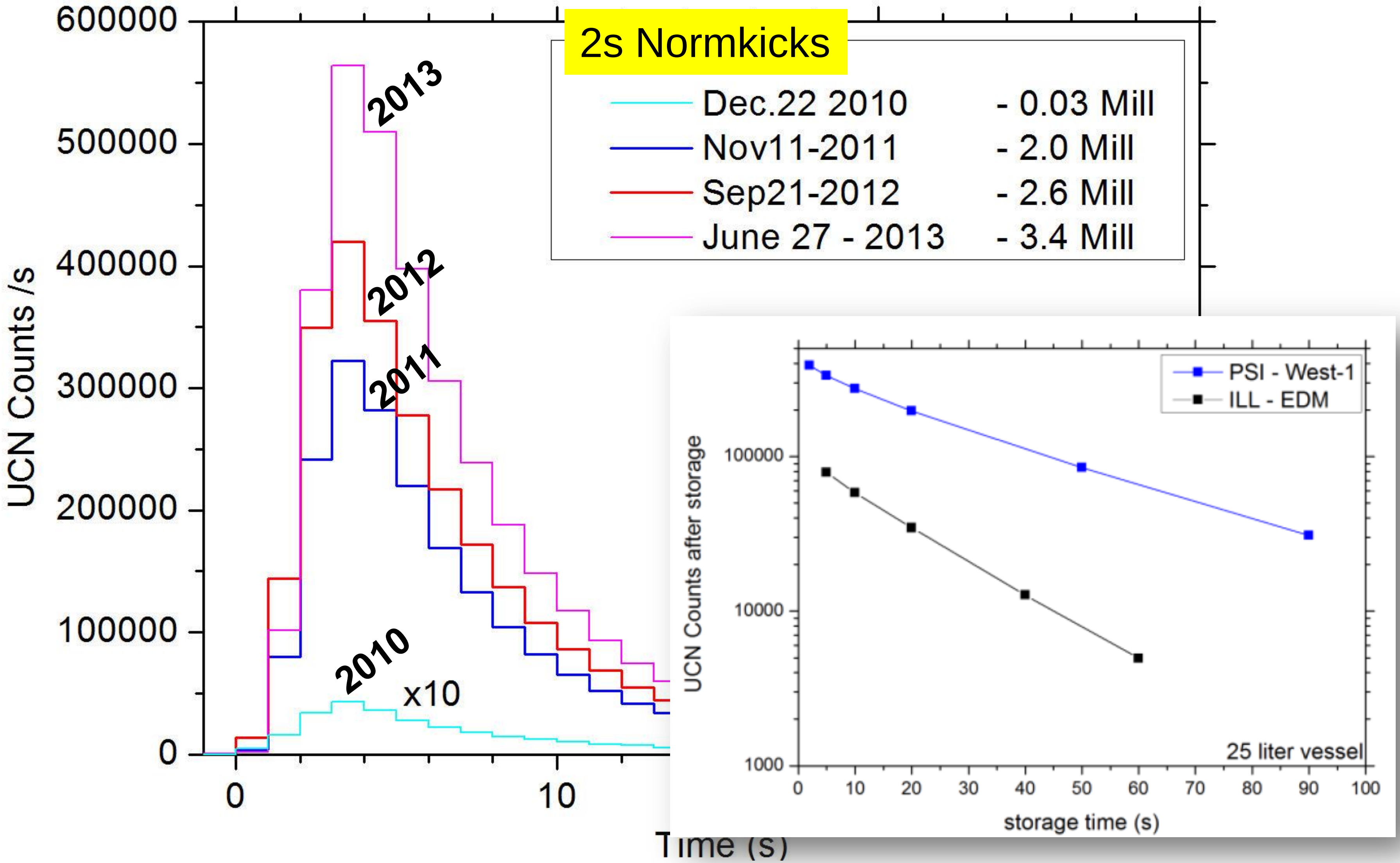
nEDM operates with approx. 250 pulses per day

Continuous improvement under way:

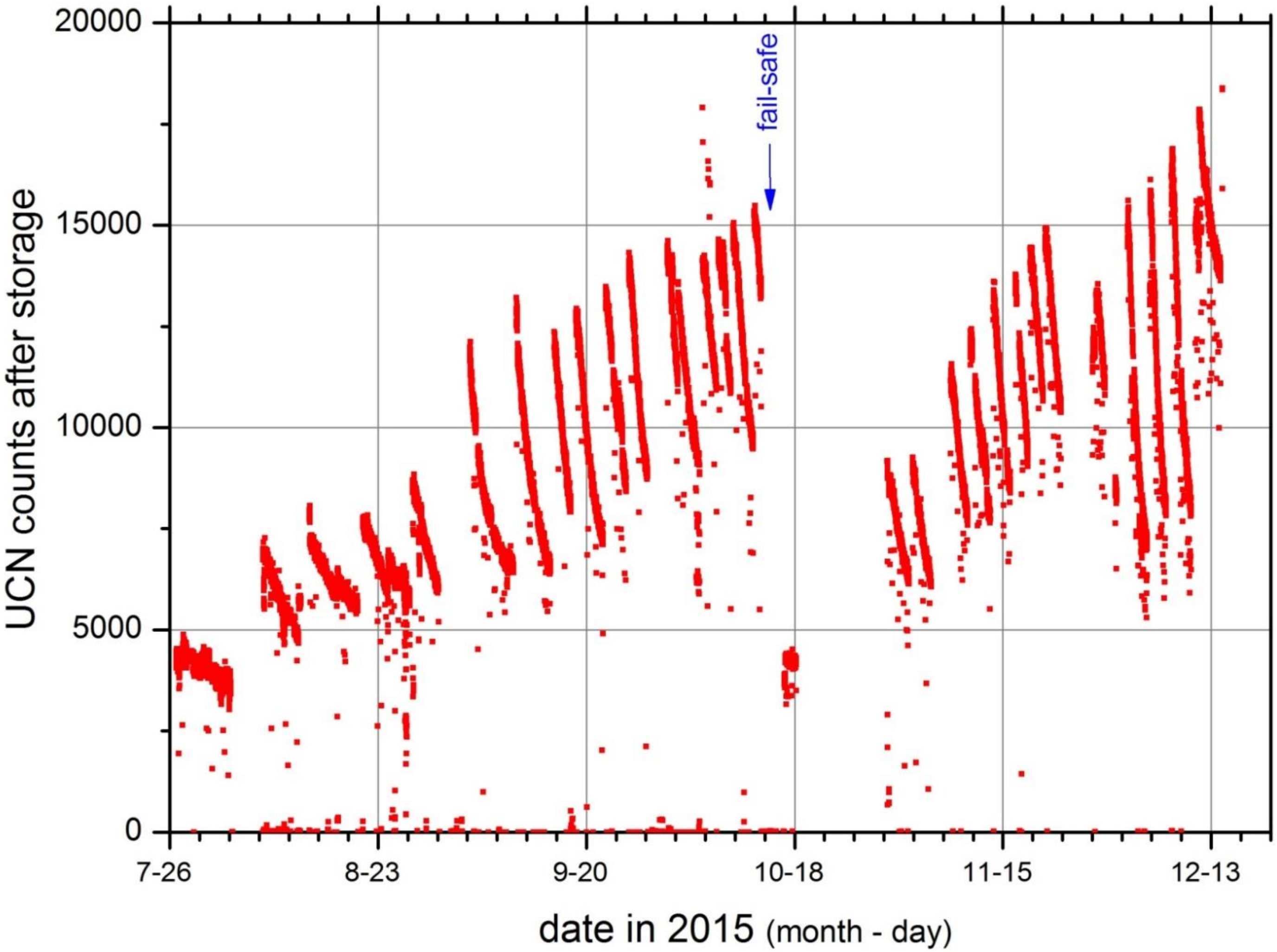
UCN per proton pulse



Continuous improvement under way



UCN source – nEDM counts



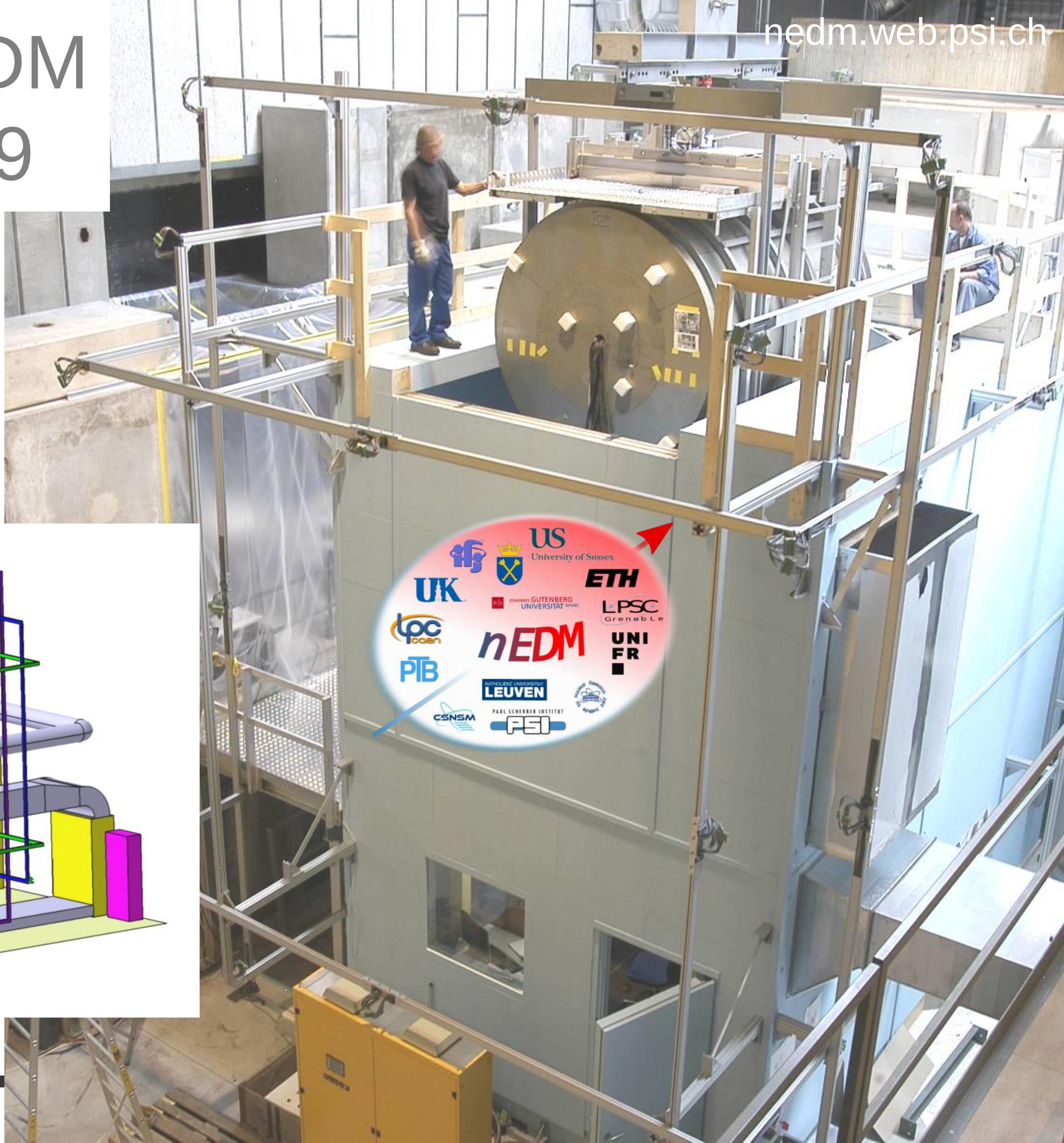
UCN counts after 180s of storage in the nEDM precession chamber

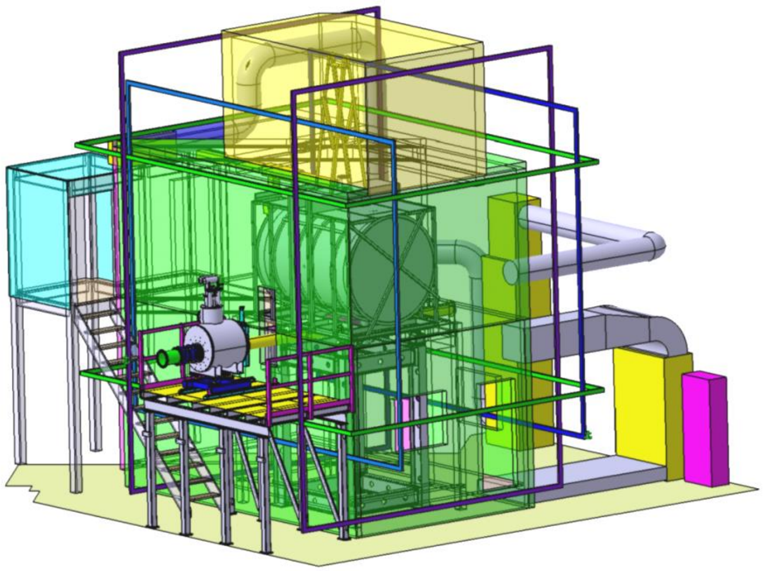
Main features:

- operation / failsafe
- fast UCN output decrease
- Recovery after conditioning
- Overall positive trend

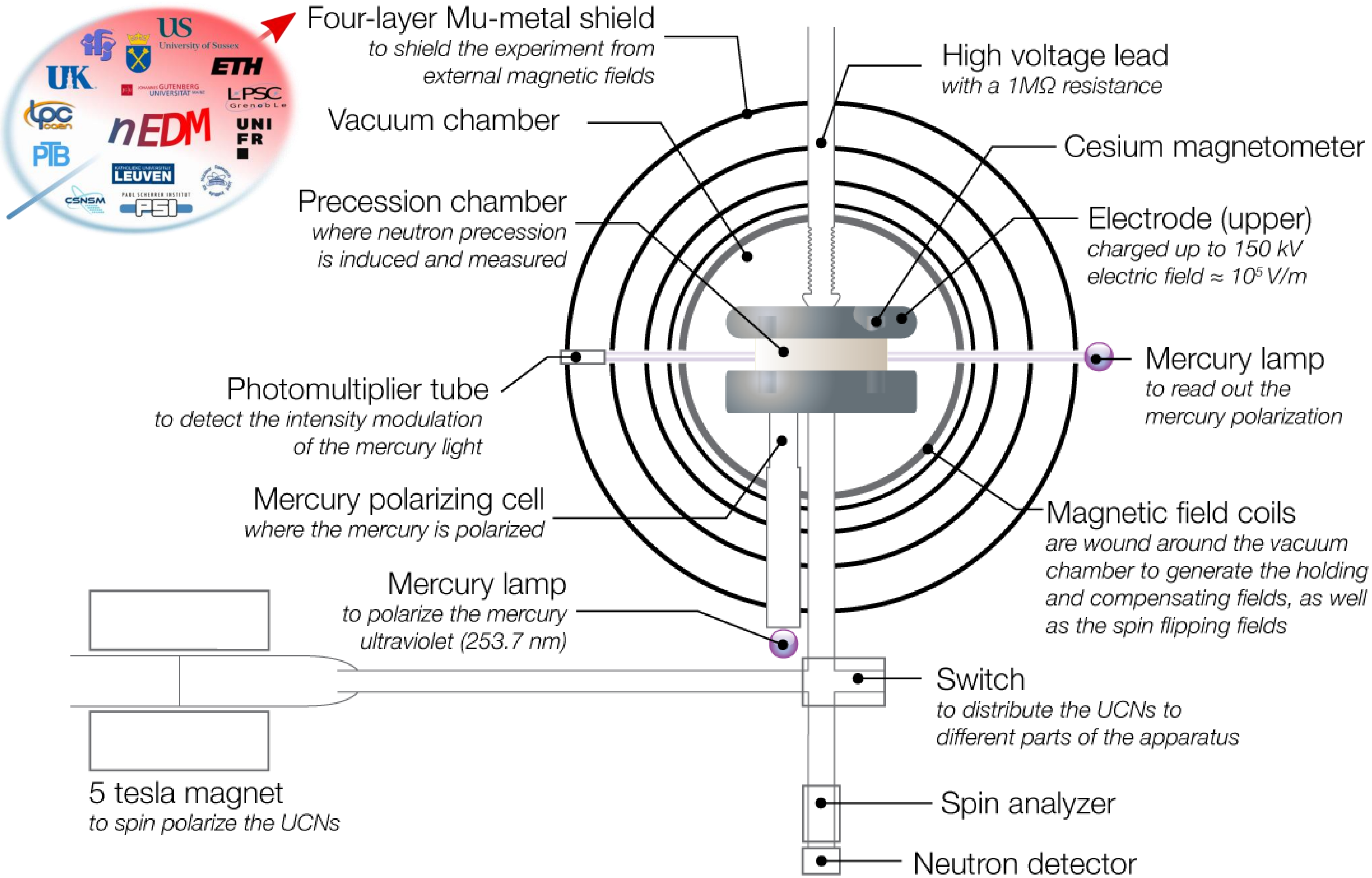
Installing nEDM at PSI in 2009

Coming from ILL
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801

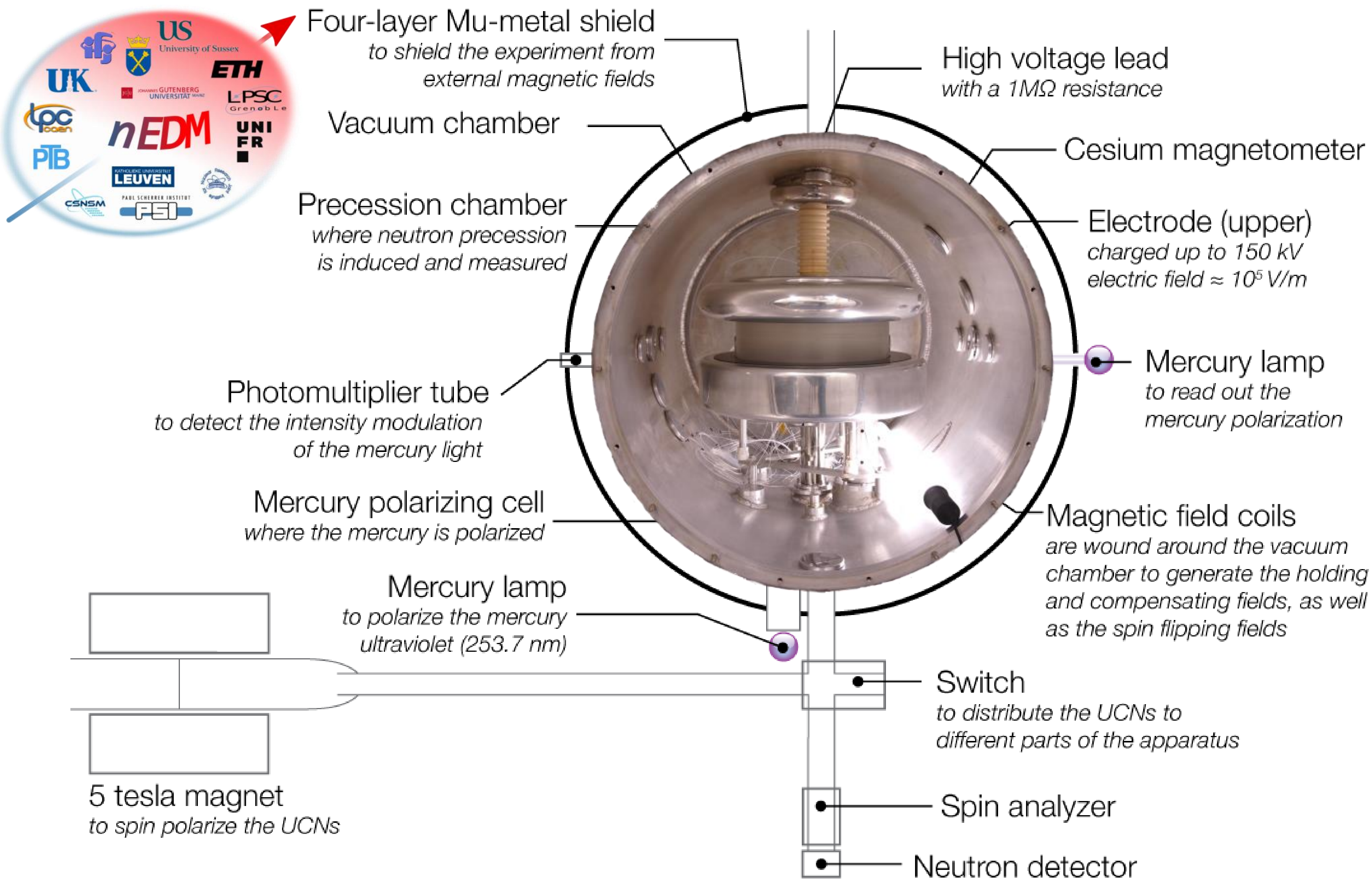




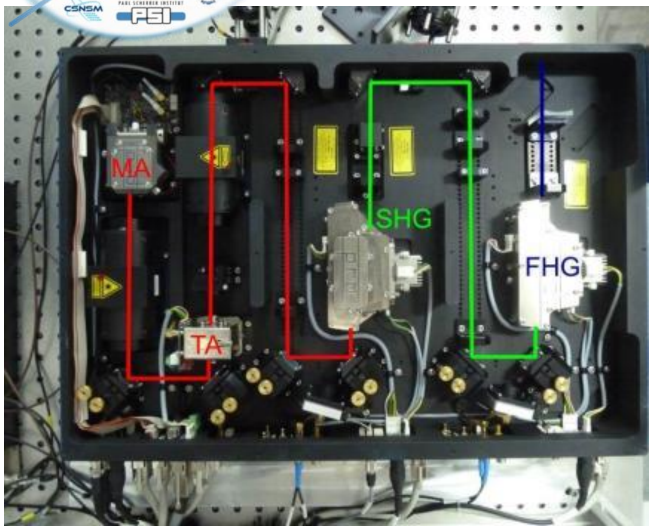
The nEDM spectrometer

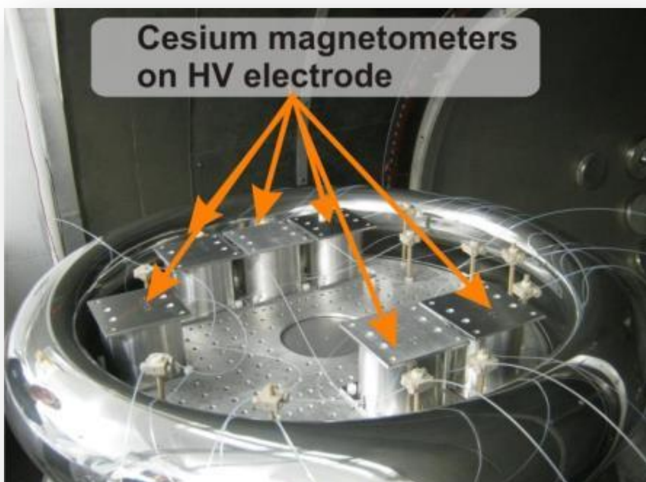


The nEDM spectrometer



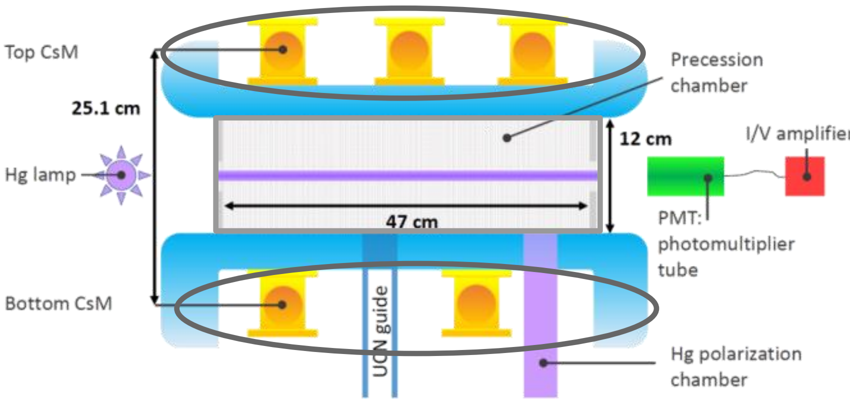
Features of nEDM@PSI





- Hg-199 co-magnetometer
  - improved S/N by factor >4
  - laser read-out proven, being implemented
- CsM array
  - 16 scalar sensors in operation (6 HV)
  - vector CsM proven
- B-field
  - homogeneity (T2~1000s)
  - reproducibility (~50pT), after degaussing (~200pT)
- Simultaneous spin analysis
- Known systematics well under control down to ~2 x 10^{-27} *e*cm

Frequency ratio R



^{199}Hg

UCN

$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lights}} \right.$$

Magnetic moments

$$\frac{\gamma_n}{2\pi} = 29.164705(55)\ \mathrm{MHz/T}$$

[1.89 ppm]

γ_{Hg}

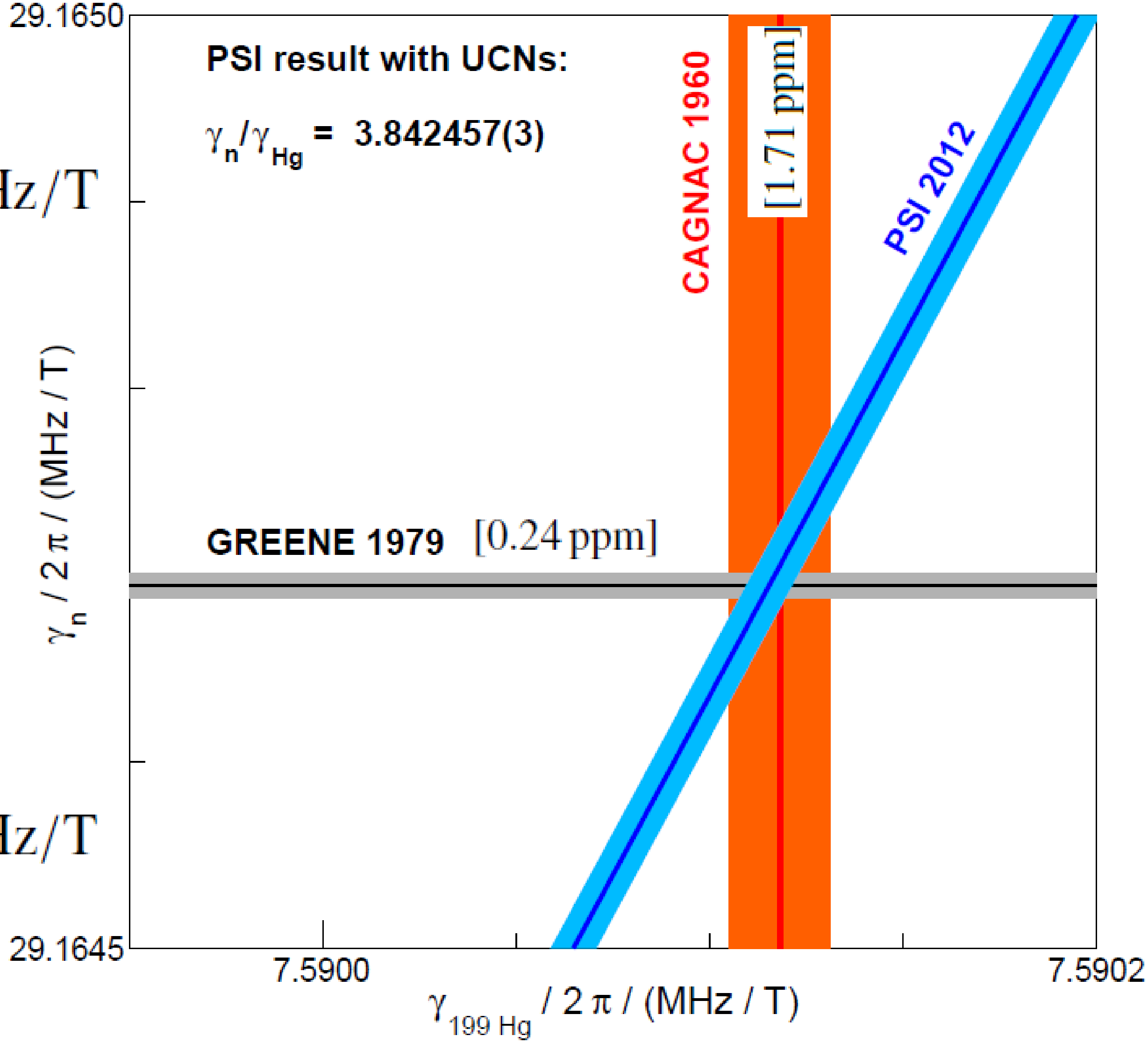
$$\gamma_n/\gamma_{Hg} = 3.8424574(30)$$

[0.78 ppm]

γ_n

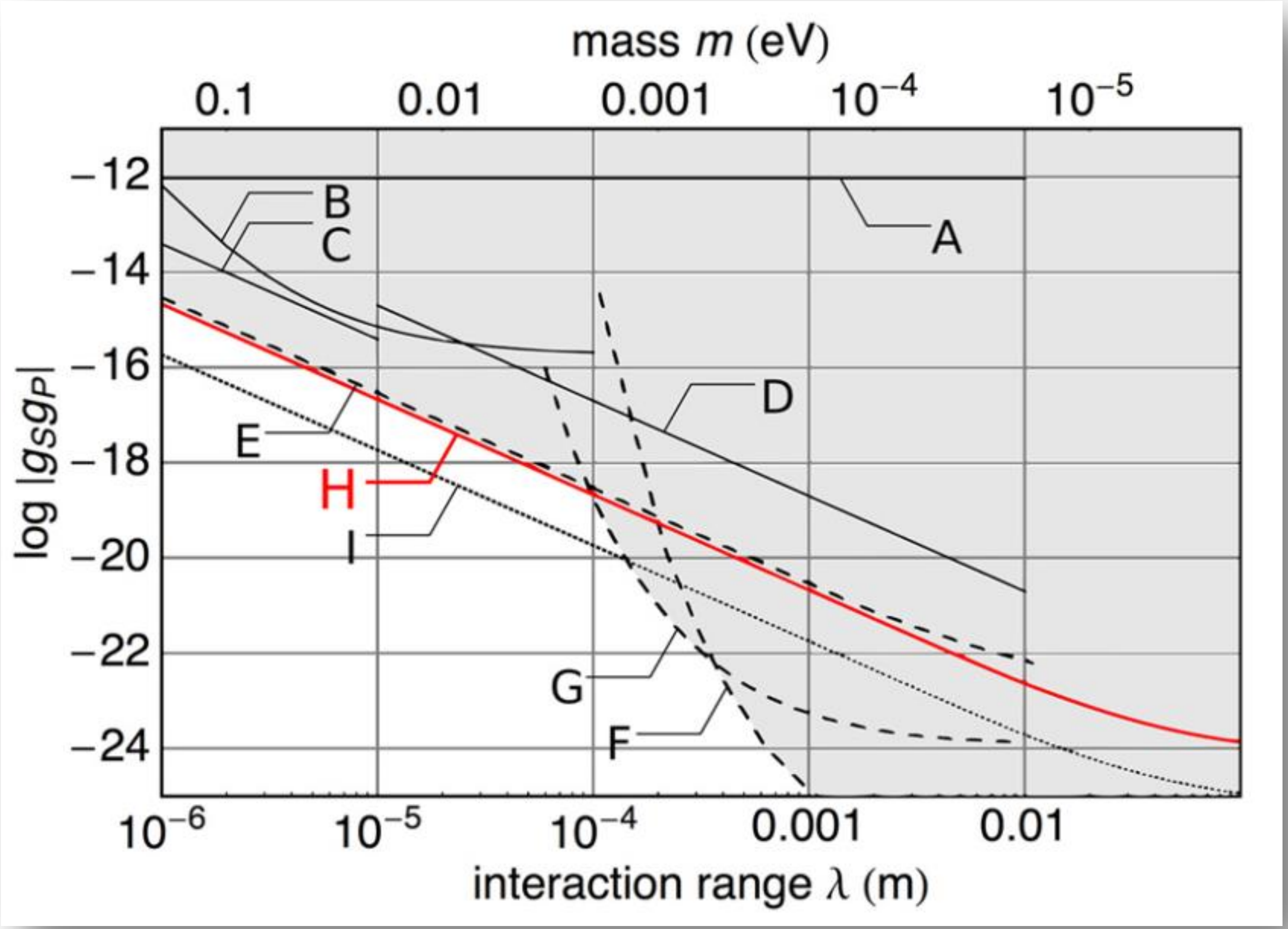
$$\frac{\gamma_{Hg}}{2\pi} = 7.5901152(62)\ \mathrm{MHz/T}$$

[0.82 ppm]



S. Afach et al., PLB 739 (2014) 128

Spin-dependent exotic interactions

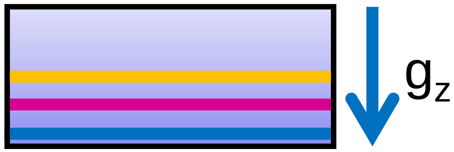


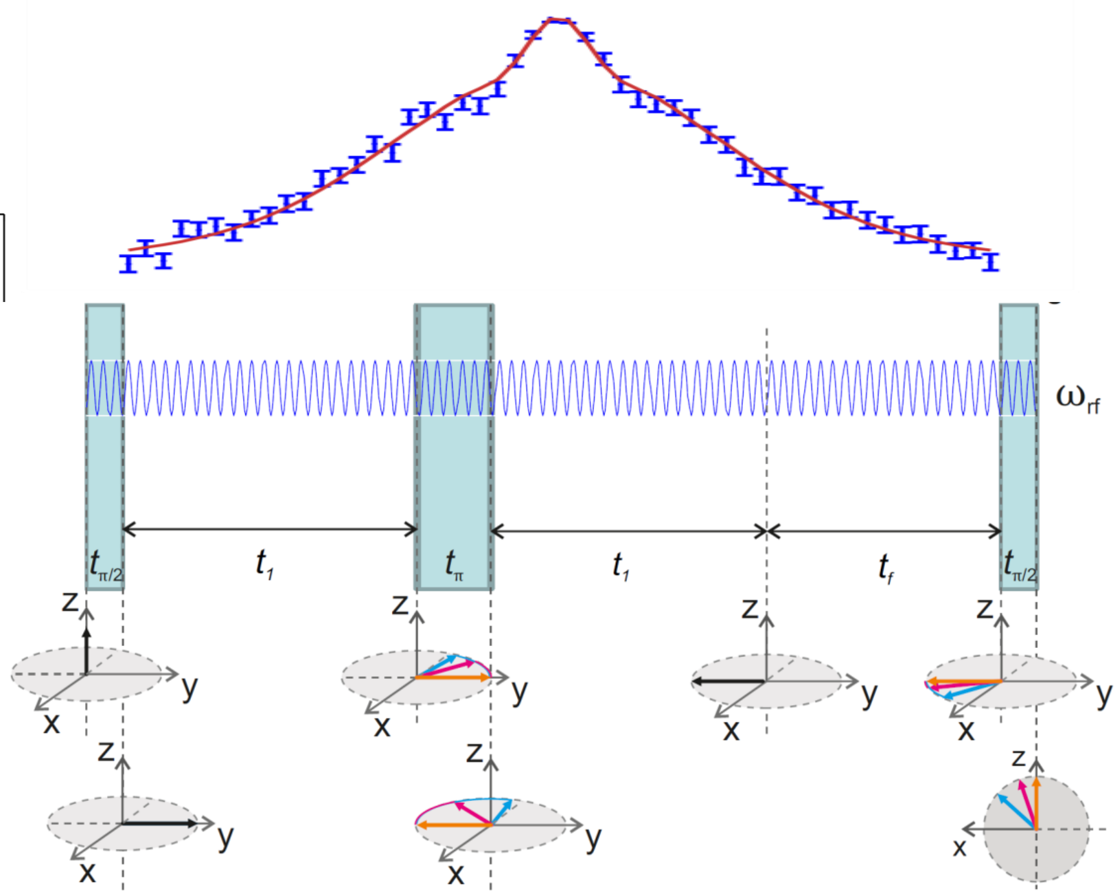
PhD thesis
B. Franke, 2014

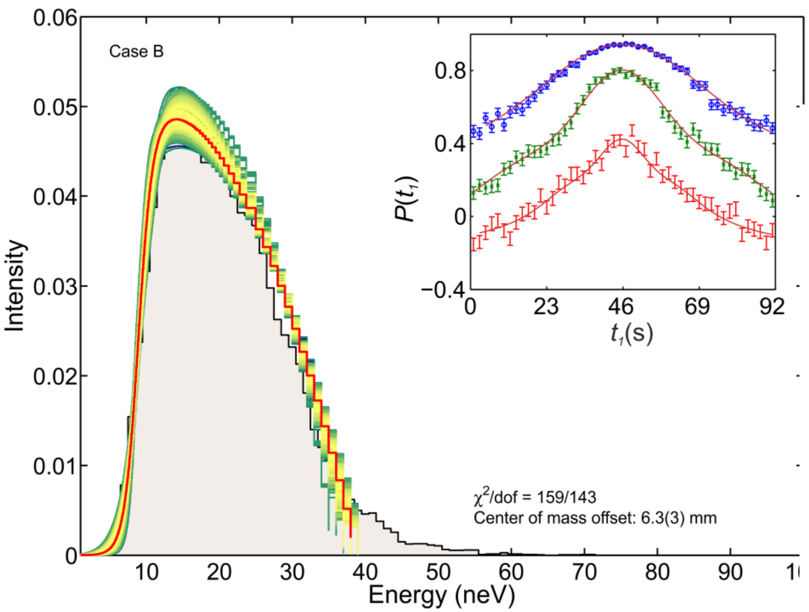
S. Afach et al., PLB 745 (2015) 58

Spin-echo spectroscopy

A spin-echo recovers energy dependent dephasing for $T = 2t_1$ in a magnetic field with vertical gradient.





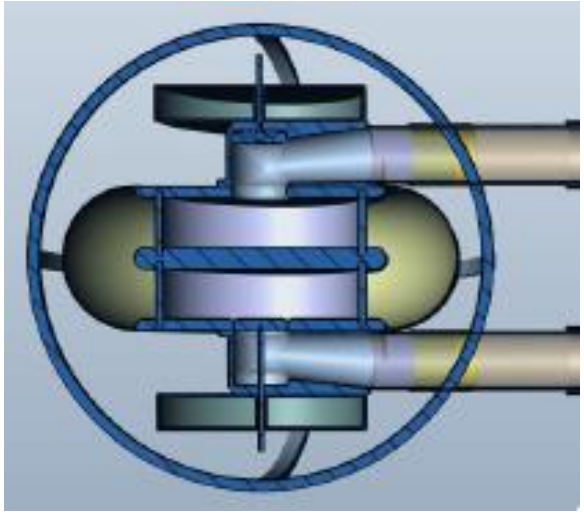


S. Afach et al., PRL114(2015)162502

Towards new limits
Neutron EDM search

$$\sigma(d_N) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

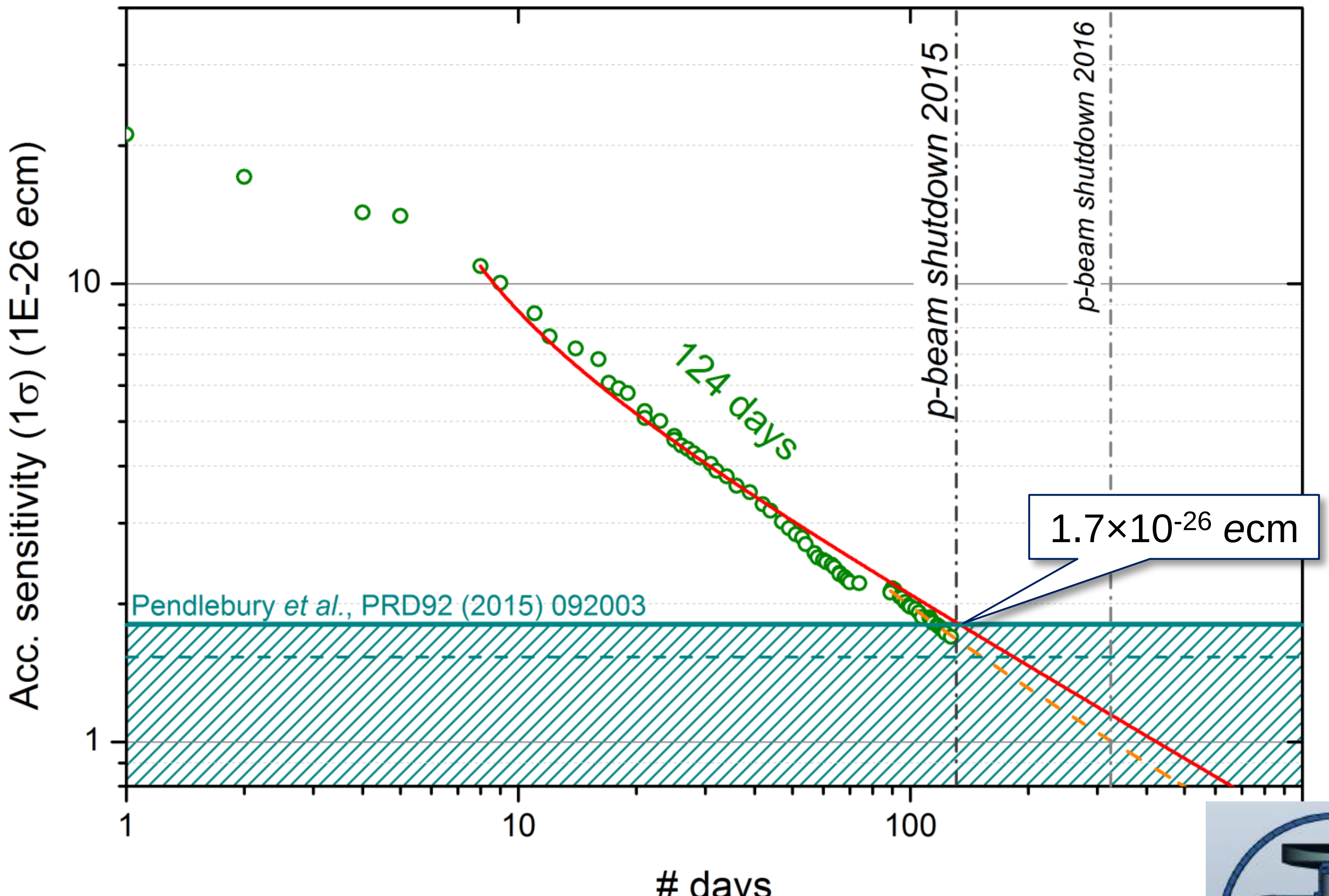
	RAL/Sx/ILL*		PSI 2013		2015	
	best	avg	best	avg	best	avg
E-field	10	8.3	12	10.3	11	**11**
Neutrons	18 000	14 300	10 500	6 500	**14 800**	10350
T_{free}	130	130	200	180	**180**	180
T_{duty}	240	240	340	340	300	300
α	0.6	0.453	0.62	0.57	**0.8**	0.75
σ/d (10^{-25}ecm)	2.3	3.0	1.5	2.8	**1.1**	**1.9**



Once nEDM runs out of steam statistically, it will be replaced by n2EDM (~2018)

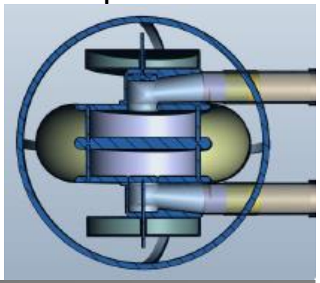
Towards new limits

Neutron EDM search



psw 14/12/15

The slope determines the path forward



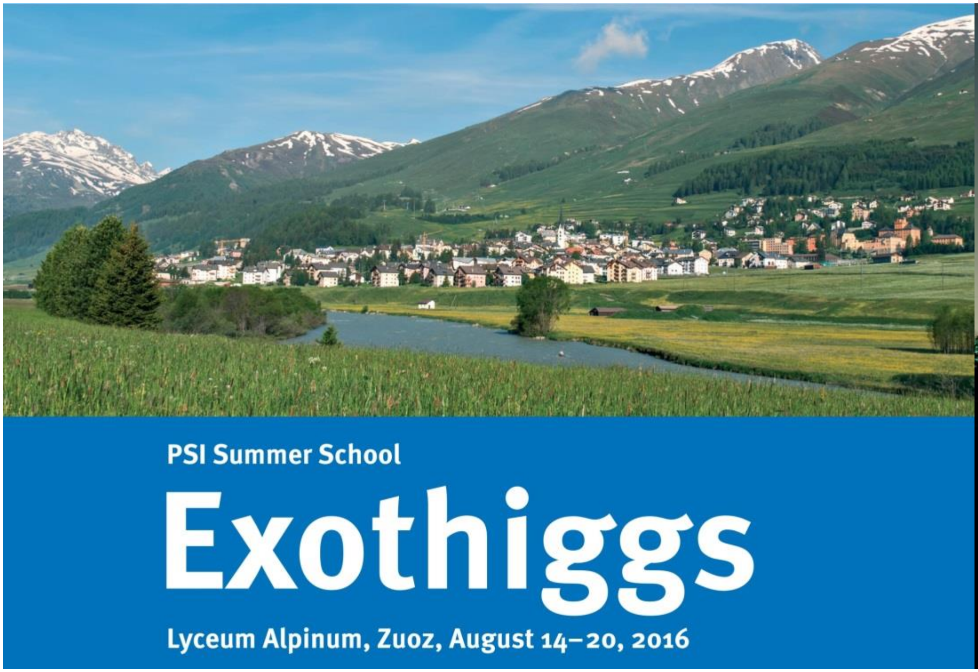
Exciting times ahead

- Expect new MEG result shortly
- UCN source performance continuously improving
- New nEDM result 2016/17
- Lambshift 2S-2P in μHe being analyzed
- HiMB feasibility study under way
- MEG II and Mu3e progress very promising
- Phase space compression experiment muCool demonstrated milestones …

see you perhaps at PSI2016?

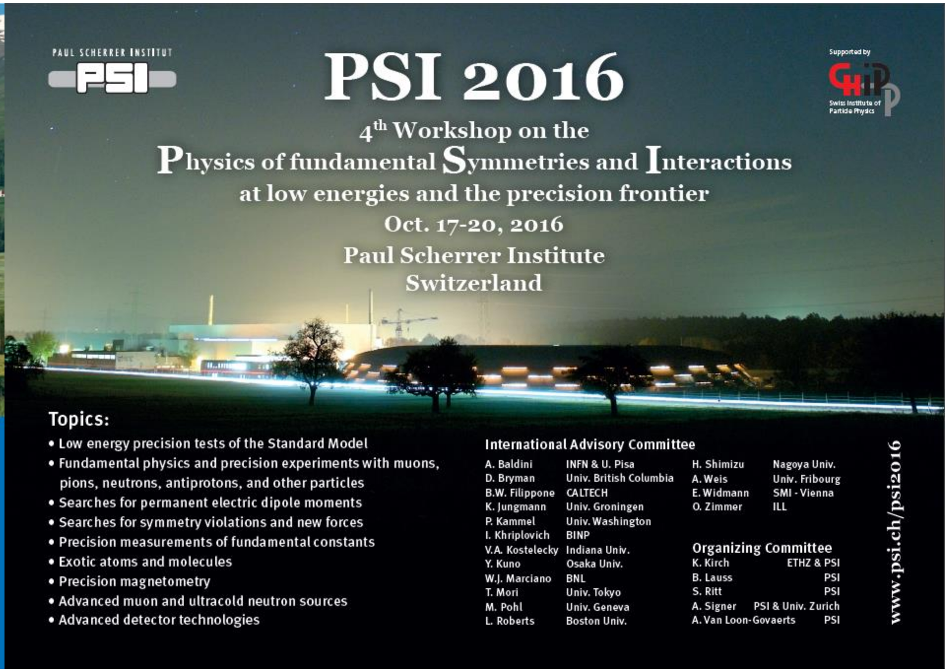
LTP organizes the PSI20xy conferences and the Particle Physics Zuoz school

www.psi.ch/particle-zuoz-school



August 14 – 20, 2016

www.psi.ch/psi2016



October 17 – 20, 2016

Picture: K. Schuhmann