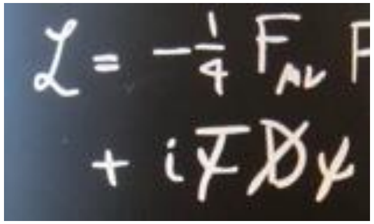
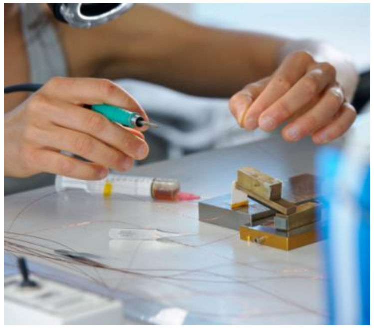
WG-5: Symmetries & Fundamental Interactions





Co-convenors:

Klaus Blaum, MPIK Heidelberg, Germany

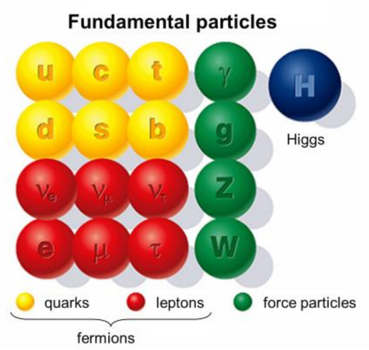
Klaus Kirch, ETH Zürich – PSI Villigen, Switzerland

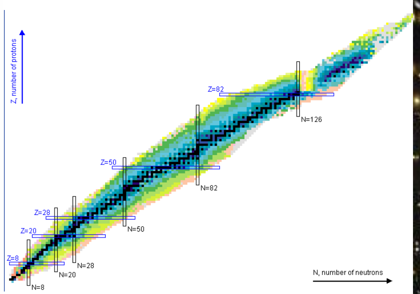
NuPECC Liaison:

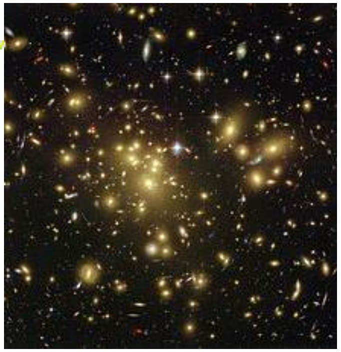
Joakim Nystrand, University of Bergen, Norway

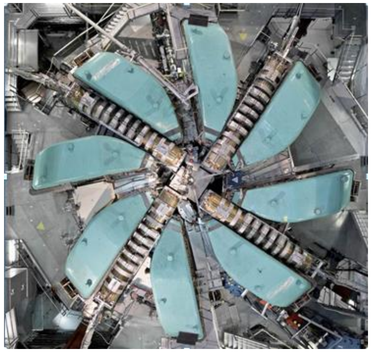
Hans Ströher, FZ Jülich, Germany

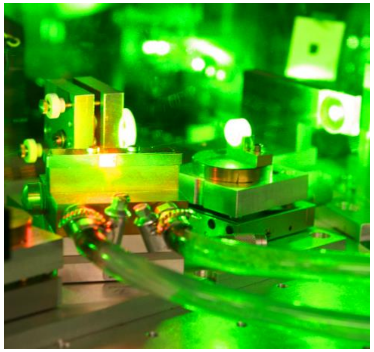
Eberhard Widmann, SMI Vienna, Austria









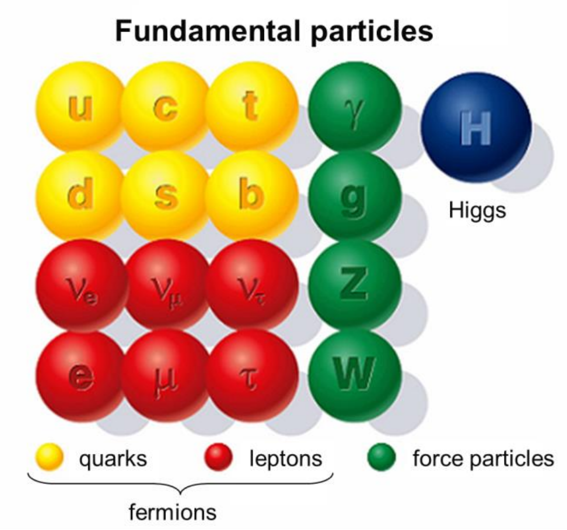


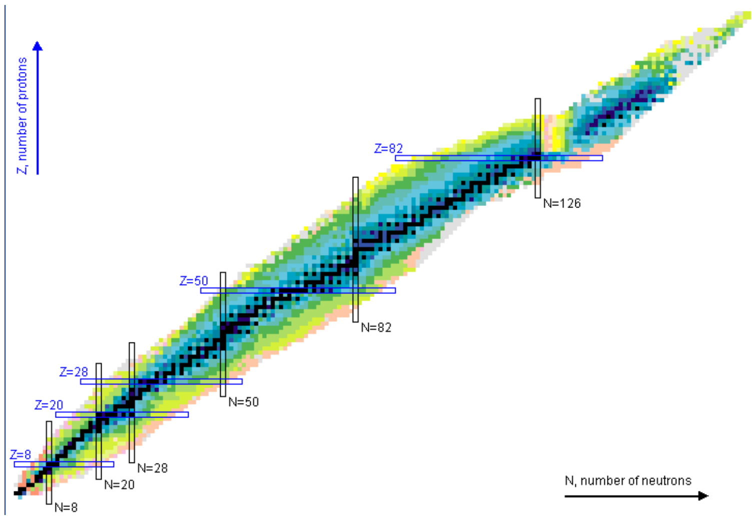
WG-5 members:

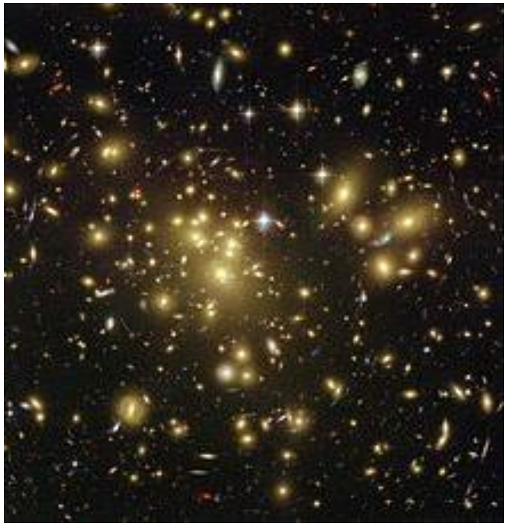
- H. Abele (Vienna) — neutron, weak int., gravity
- K. Blaum (Heidelberg) — symmetries, nuclei, traps
- K. Bodek (Krakow) — neutron, weak interaction
- D. Budker (Mainz) — atoms, axions, spectroscopy
- C. Curceanu (Frascati) — QM tests, exotic atoms
- M. Doser (Geneva) — symmetries, pbar, Hbar
- K. Kirch (Zürich, Villigen) — symmetries, EDM, exotic atoms
- E. Lienard (Caen) — weak interaction, nuclei, traps
- K. Pachucki (Warsaw) — QED theory, Standard Model
- R. Pohl (Mainz) — exotic atoms, spectroscopy
- T. Stöhlker (Jena, Darmstadt) — heavy ions, QED
- R. Timmermans (Groningen) — EFT, Standard Model
- C. Weinheimer (Münster) — Neutrinos, Dark Matter
- L. Willmann (Groningen) — atoms, symmetries, EDM

A 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, …

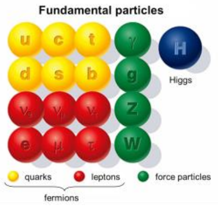




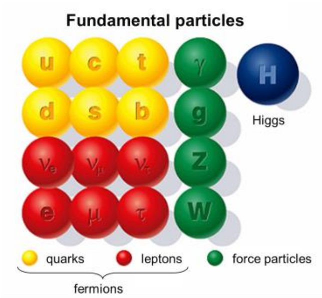


A part of what we should know better:

- 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



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



WG-5 report:

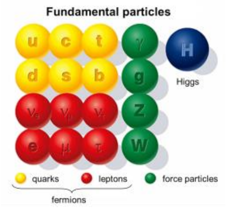
SM parameters   BSM Searches

Use nuclear physics, nuclear physics methods and synergies with other fields to investigate the most fundamental symmetries and interactions and tackle most of the before mentioned issues.

Provides some structure for the report only: Almost every high-precision measurement of SM parameters can be turned into a BSM search

Importance of theoretical physics

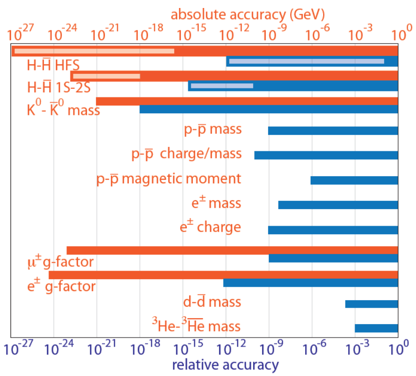
- Need reliable SM calculations at extremely high precision
  - high order QED (free and bound systems)
  - electro-weak contributions
  - hadronic contributions

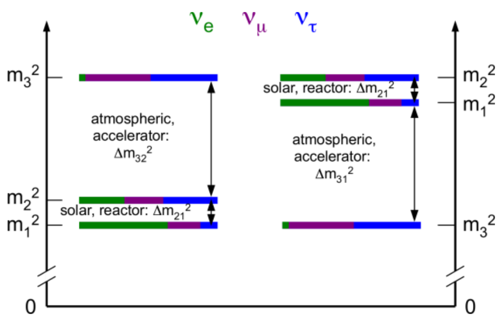


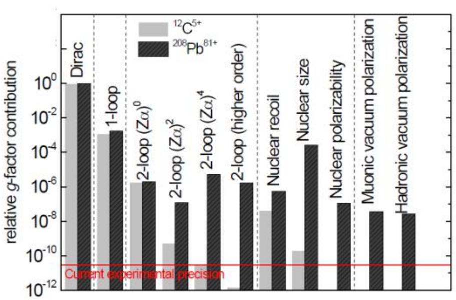
- Besides particular BSM models (and in absence of solid BSM signals so far), need model independent analysis of accessible observables
  - SMEFT framework (LI, CPT, …) $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots$
  - SME for Lorentz and CPT Violation
  - …

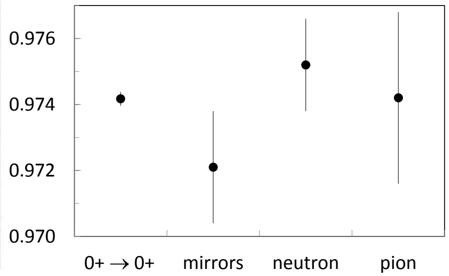
Sections and figures of the WG-5 report

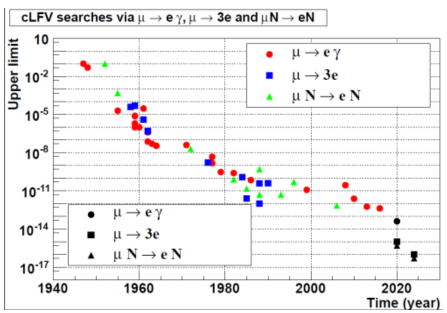
1. Introduction
2. SM parameters
3. Searches beyond the SM
4. Future directions
5. Recommendations





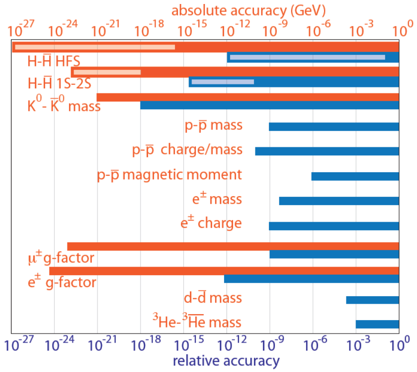


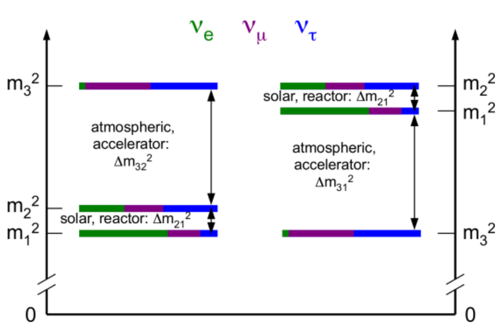


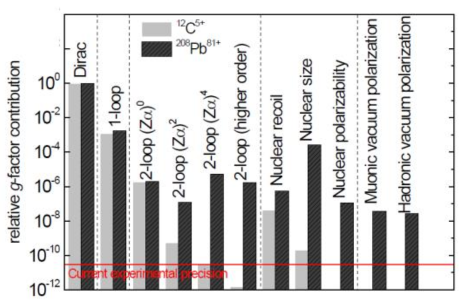


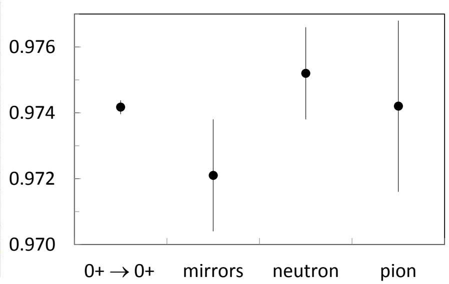
Sections and figures of the WG-5 report

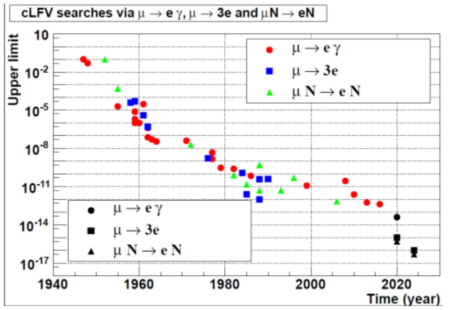
The talk cannot provide full coverage of the large and diverse field. It will rather be a walk through the report, give <u>some</u> examples and mention <u>some</u> highlights.











2. SM parameters

2.1 Leptons

2.1.1 Neutrinos

2.1.2 Charged leptons and fundamental constants

2.2 Baryons

2.2.1 Semileptonic decays

2.2.2 Quark mixing matrix

2.2.3 Nucleon and nuclear properties from atomic-physics measurements

Muonic hydrogen and the proton charge radius

Nucleon and nuclear polarizabilities

Combining muonic-atom spectroscopy with elastic electron scattering

Heavy muonic atoms

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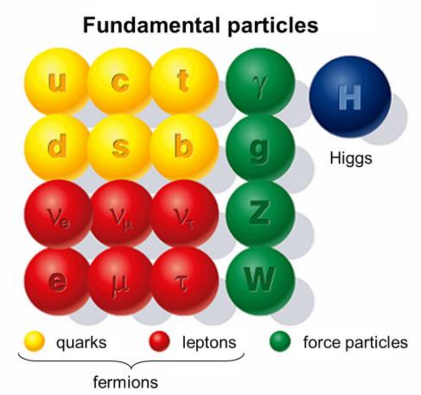
Precision nuclear spectroscopy of thorium-229



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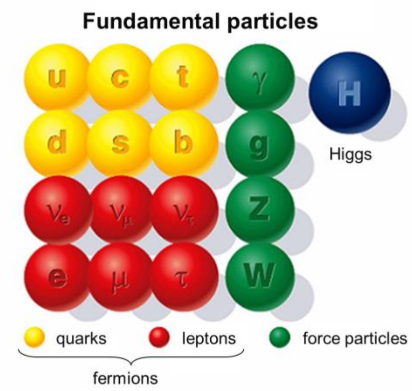
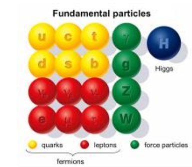
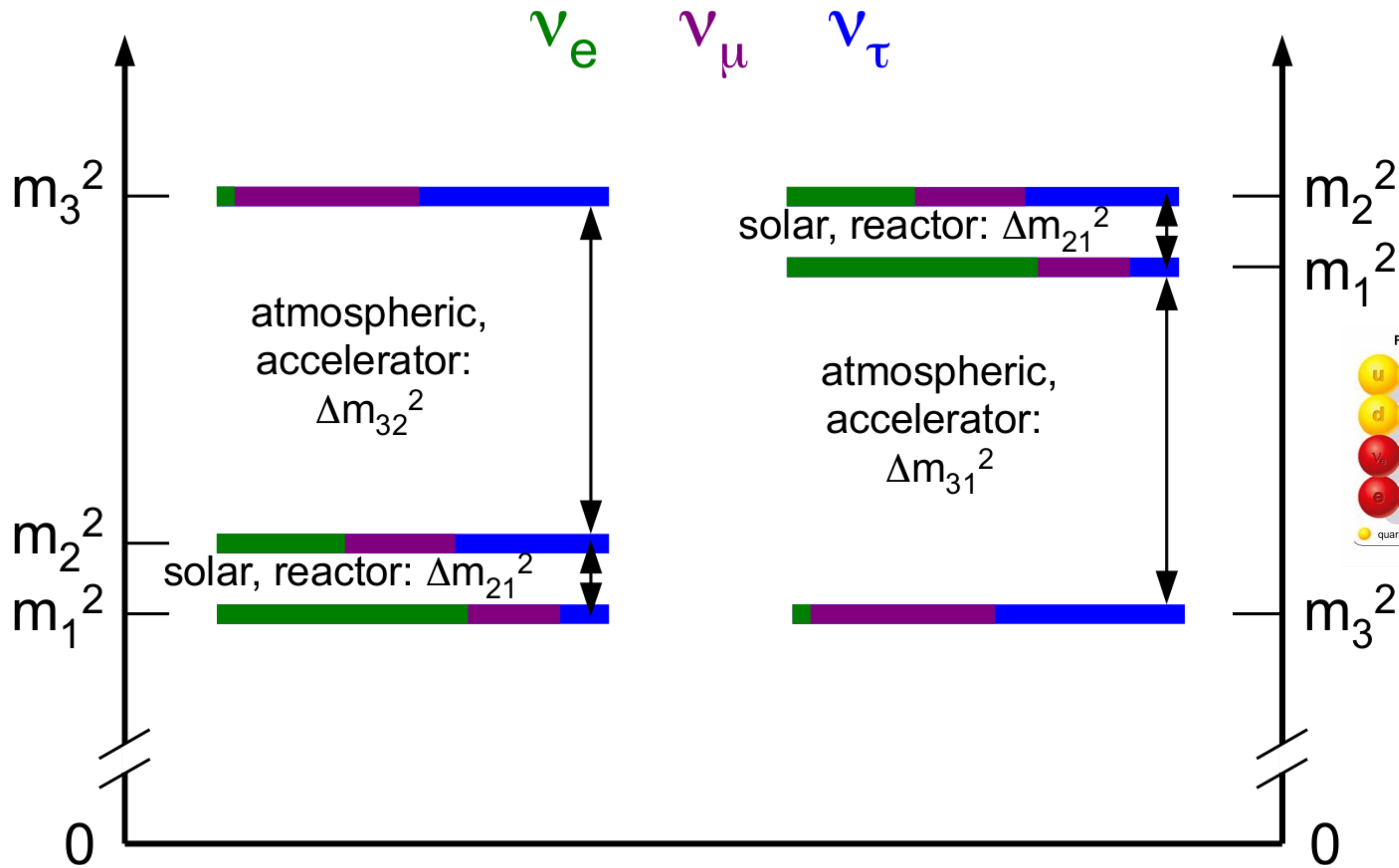


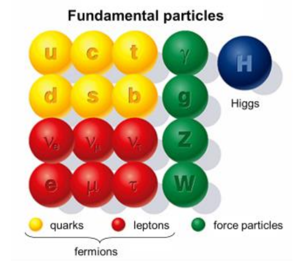
Some of the open issues in ν physics

- Absolute masses (and hierarchy)
  - Direct mass measurements (covered) vs. indirect cosmological determination (not covered)
- Nature of neutrinos
  - Dirac – Majorana; Lepton number violation?
- CP violation in neutrino mixing
  - Long baseline oscillation and high energy neutrino program (not covered) but:
  - need considerable work, in particular theoretical, on neutrino – nuclear cross sections especially in the range from few 100 MeV to several GeV (community input, should be included in LRP, → WG-3, WG-5 linking to WG-3)



WG-5 report Fig. 1





Direct search for the neutrino mass:

investigation of endpoint of β-decay or EC

sensitive to average "electron neutrino mass": $m^2(\nu_e) := \Sigma\, |U_{ei}|^2\, m^2(\nu_{ei})$

complementary to $0\nu\beta\beta$ and cosmology

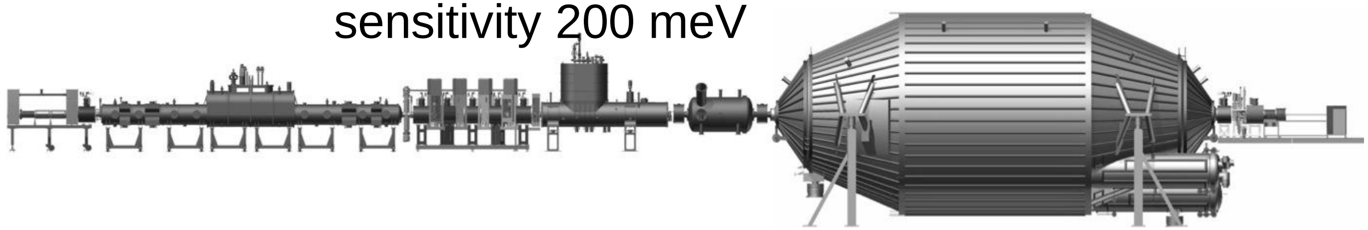
KATRIN:
tritium β-decay

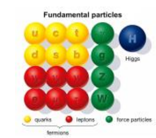
windowless gaseous T_2 source & MAC-E-Filter (ΔE=0.9eV)

technical commissioning ("1st light") in Oct. 2016

start of tritium data taking expected for end of 2017

sensitivity 200 meV





ECHo, HOLMES, NuMECS:

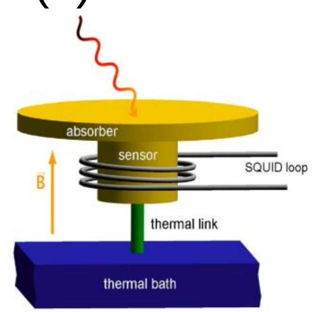
163Ho EC

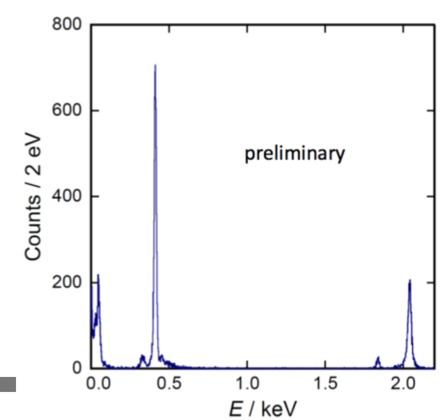
multiplexed array of cryogenic calorimeters (MM, TES)

measure electromagnetic deexcitation of EC daughter 163Dy*

near time sensitivity: O(1) eV

Other tritium β-decay R&D projects:
Project 8, PTOLEMY

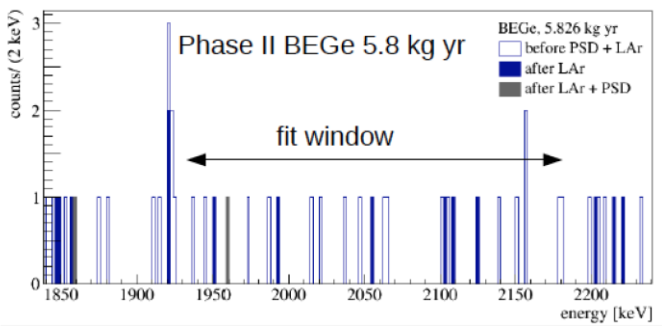




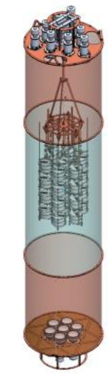
Courtesy: C. Weinheimer

Search for neutrinoless double β-decay: **sensitive to particle character**

requires BSM, L-violation, Majorana particles ($\nu = \overline{\nu}$)
sensitive to average "electron neutrino mass": $m_{ee}(\nu) := | \Sigma |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i) |$
complementary to single β-decay/EC and cosmology



GERDA@LNGS:
enriched ^{76}Ge ultra-low background detector array
GERDA II started data taking end of 2015:
bg of the BEGe detectors is as low as planned:
$0.7^{+1.2}_{-0.5}\ 10^{-3}$ cnt/(keV kg yr) (world record !)
limit on half-life > $5.3\ 10^{25}$ yr (90% C.L.)

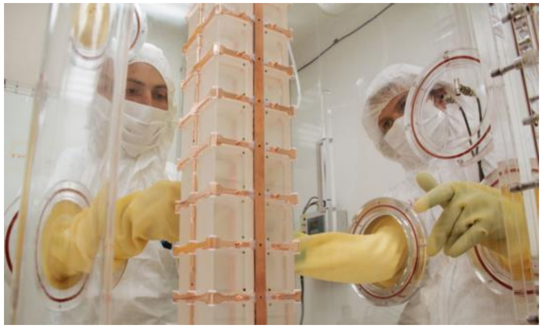


A new international collaboration to realize a 1t-^{76}Ge-experiment in steps formed out of GERDAII, Majorana and new groups in Oct. 2016

CUORE@LNGS: TeO_2 cryogenic bolometer array, natural abundance of ^{130}Te: 34%
fully commissioned, start of data taking in 2017

Many other double β-decay projects world-wide:

^{76}Ge	Majorana
^{82}Se	SuperNEMO
^{100}Mo	AMORE, LUNIEU
^{130}Te	SNO+
^{136}Xe	KamLAND-ZEN, EXO-200, nEXO, NEXT



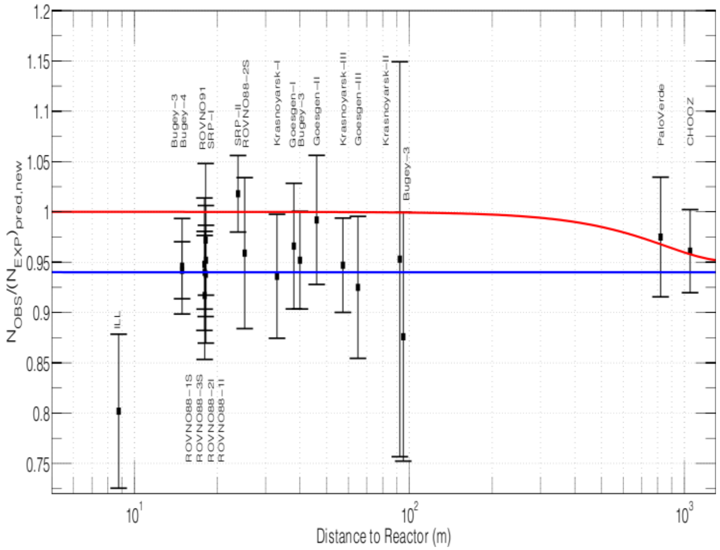
Courtesy: C. Weinheimer

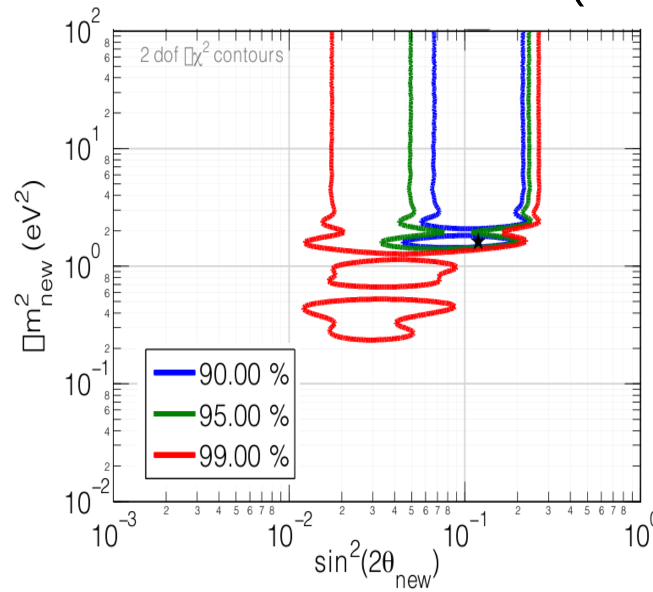
Search for sterile neutrinos:

4th (5th) generation of neutrinos, not coupling to Z,W

eV sterile neutrino motivated by "reactor neutrino anomaly"

sterile neutrinos could be even dark matter candidate if keV mass (warm DM)





Search for (light) sterile ν by very short baseline neutrino oscillation experiment:

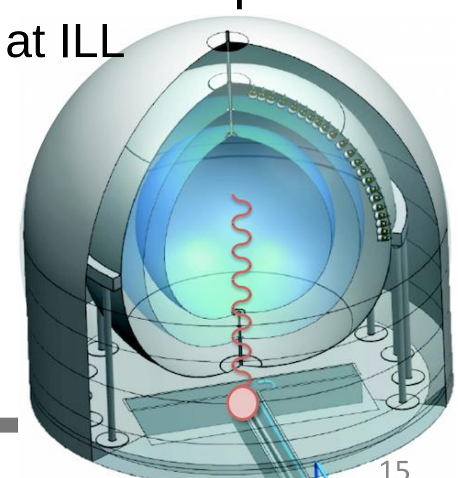
near reactor core: NUCIFER at Saclay, STEREO at ILL

near β- or EC-source: Borexino-SOX at LNGS

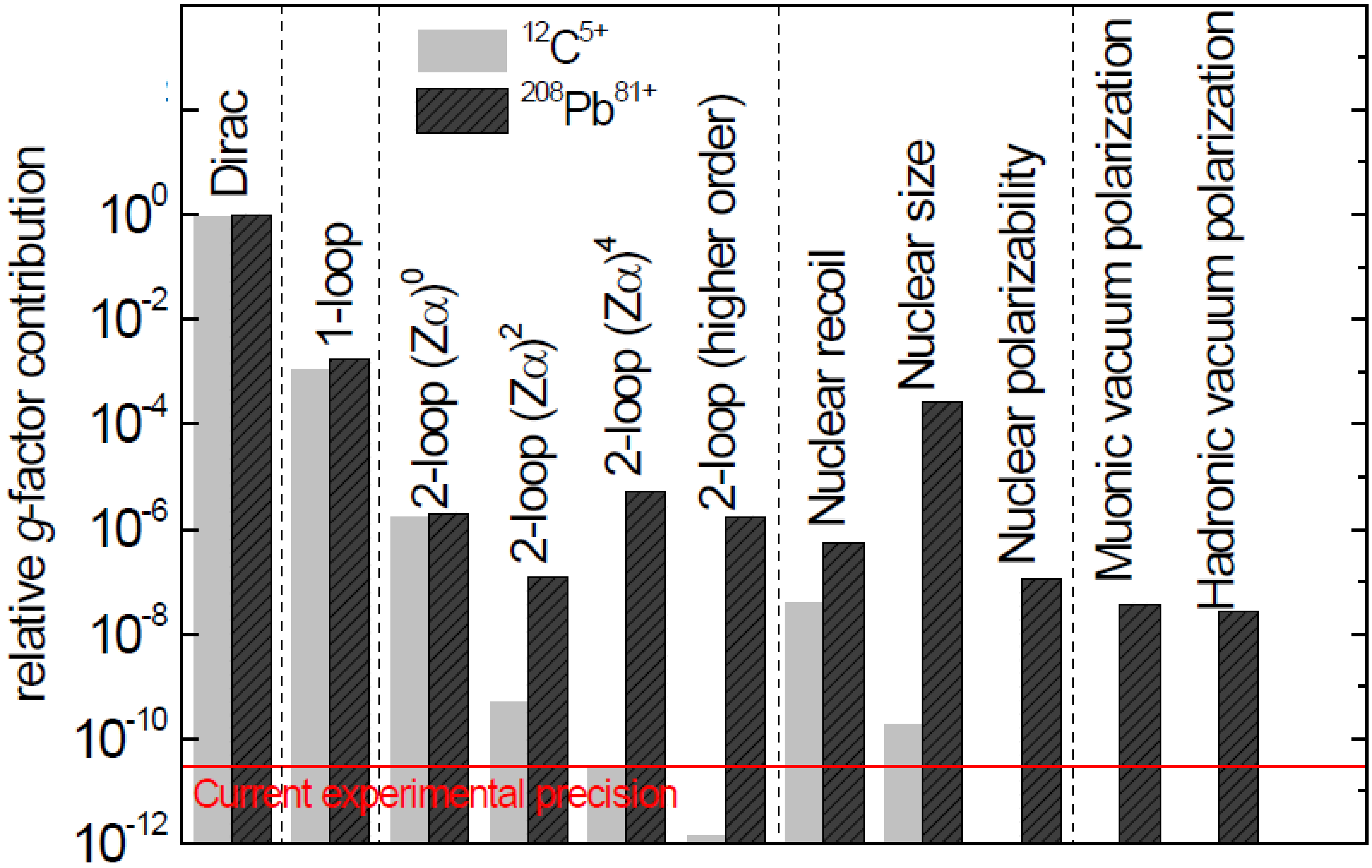
short baseline accelerator neutrinos: several detectors at FermiLab

atmospheric neutrinos IceCube at south pole

or by search for spectral distortion in β-spectrum: KATRIN at KIT



WG-5 report Fig. 2

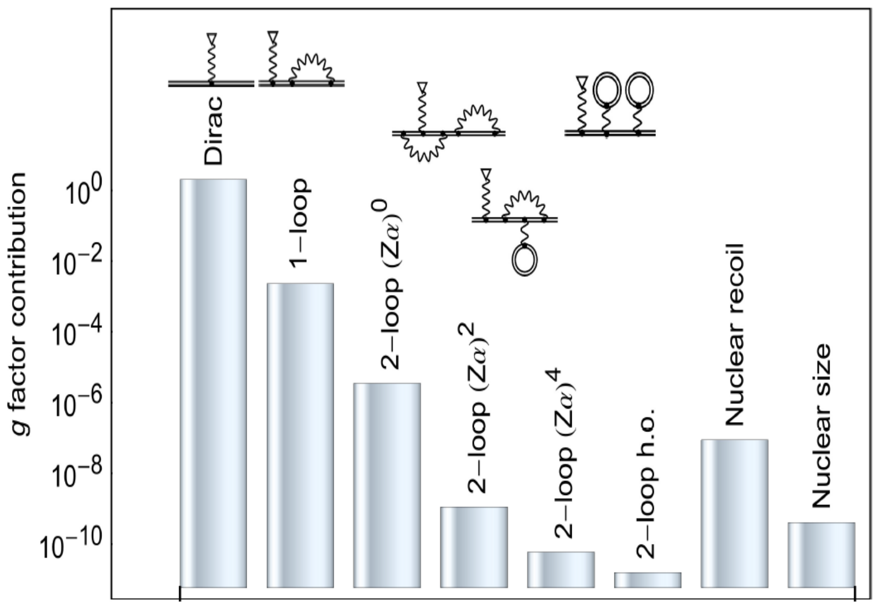


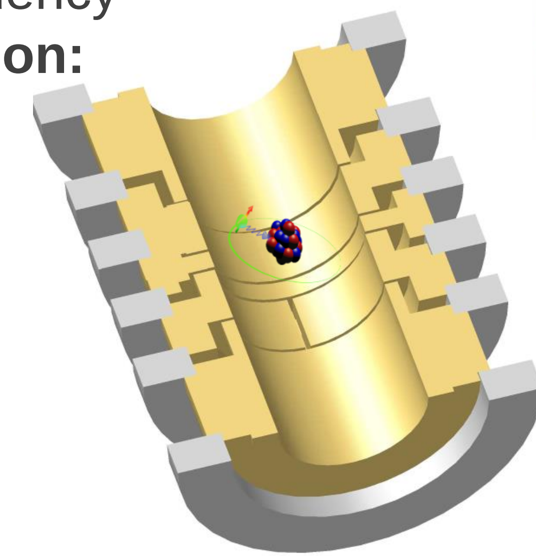
New determination of the electron mass

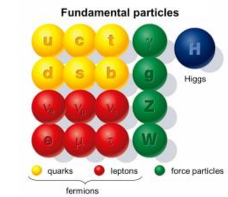
Electron mass from ultra-high precision frequency-ratio and QED theory of **hydrogenlike carbon:**

$$m_e = \frac{g_{theo}}{2} \frac{\omega_c}{\omega_L} \frac{e}{q_{ion}} m_{ion}$$

Harman, Keitel, Zatorski







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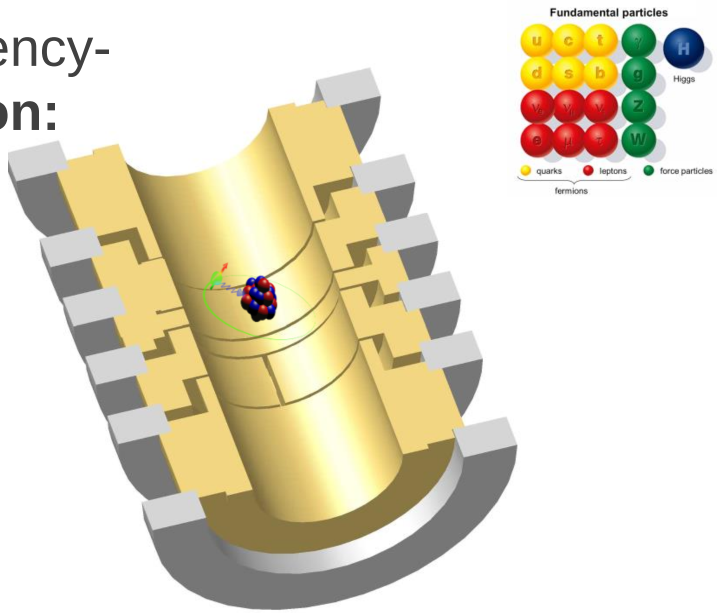

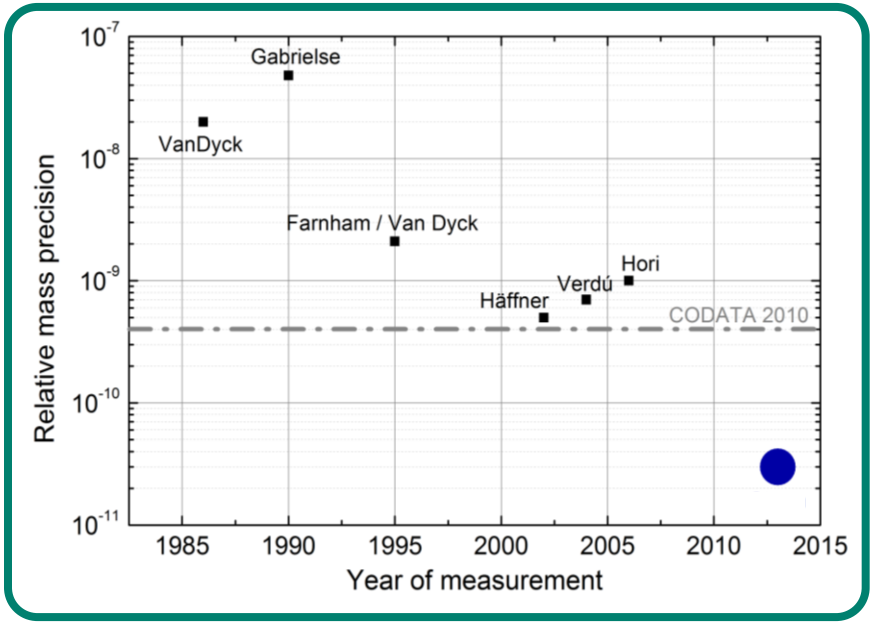

$m_e = 0.000548\,579\,909\,067(14)(9)(2)$u

A factor of 13 improved value

S. Sturm *et al.*, Nature 506(2014)467

Courtesy: K. Blaum

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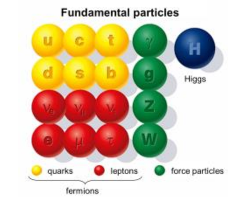

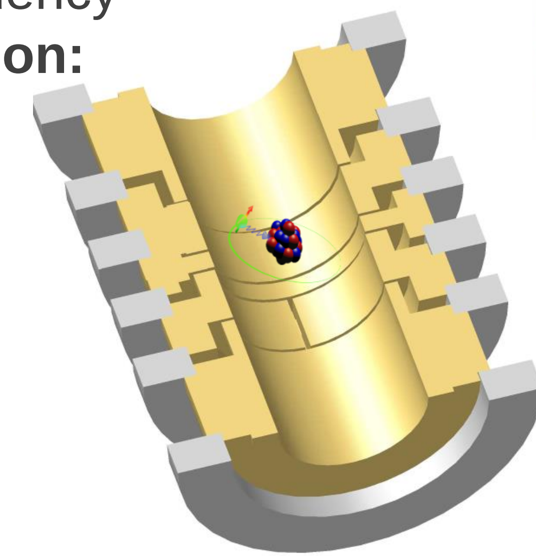

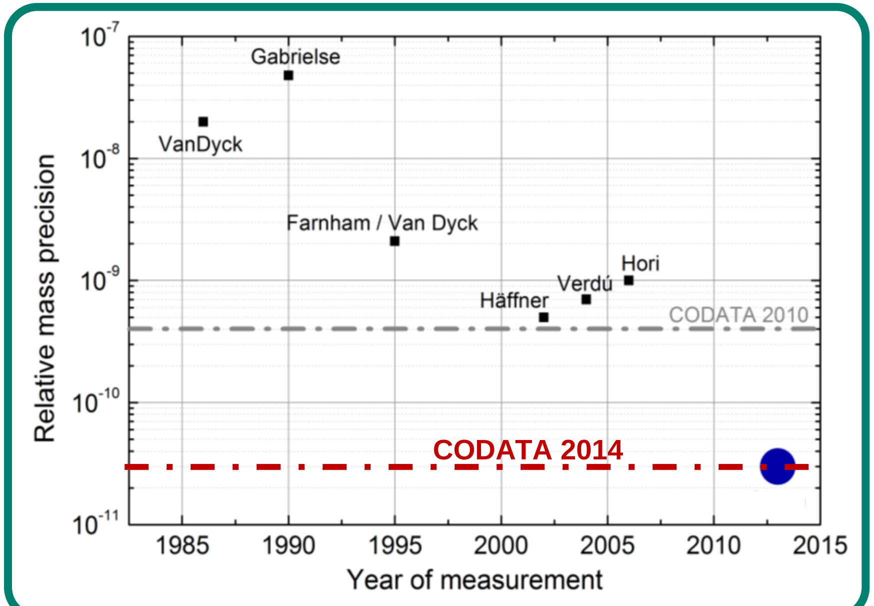

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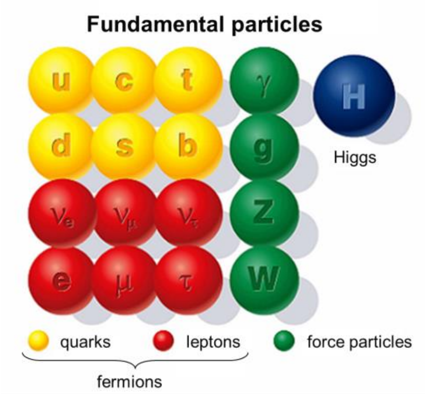
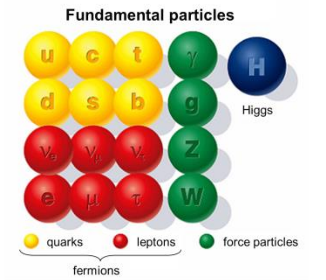
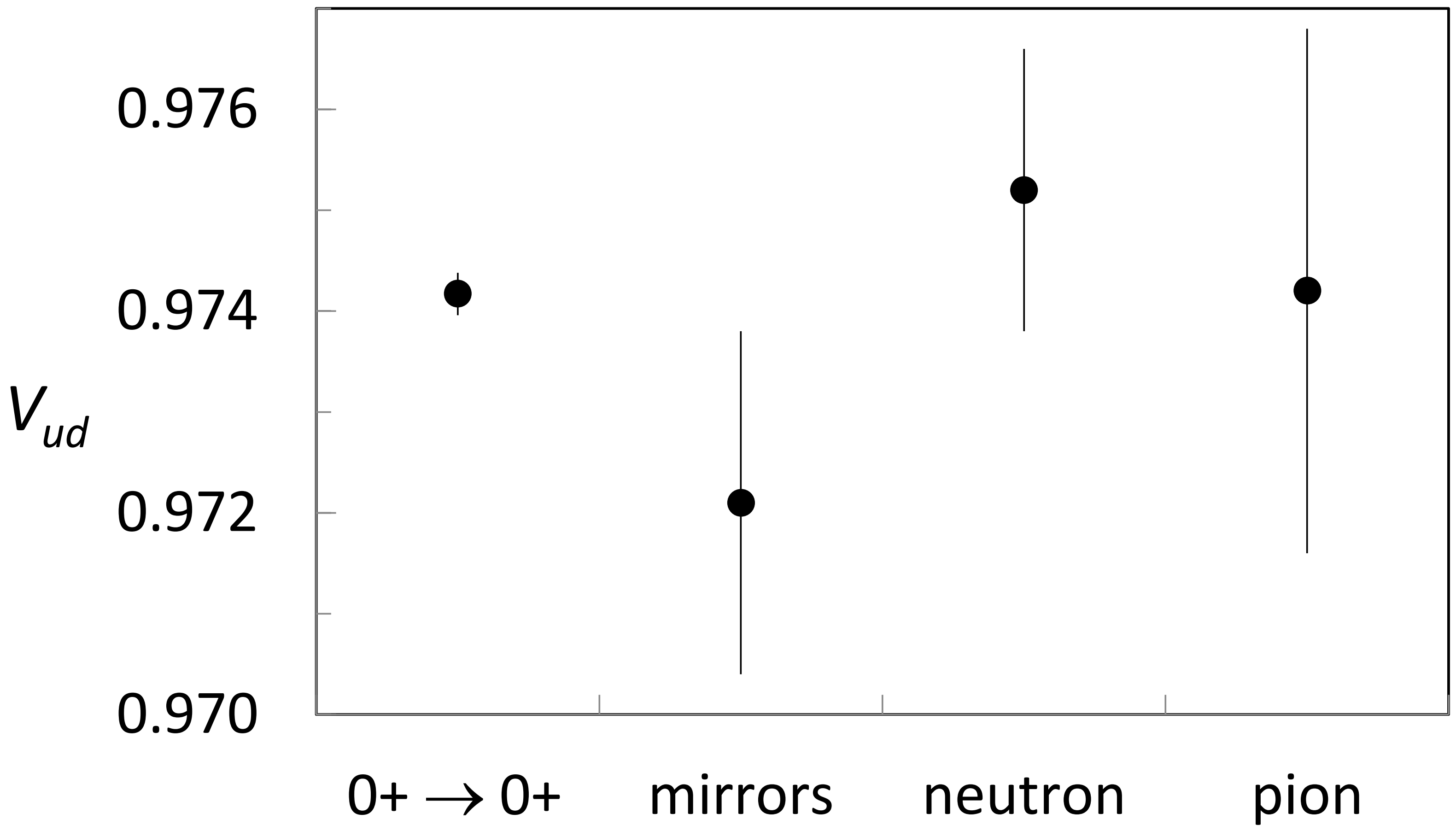


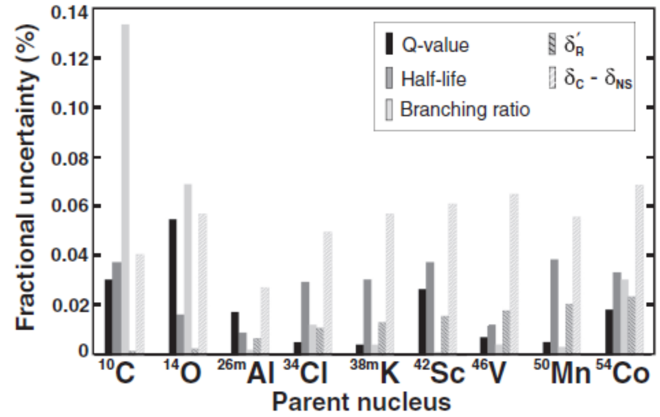
WG-5 report Fig. 3

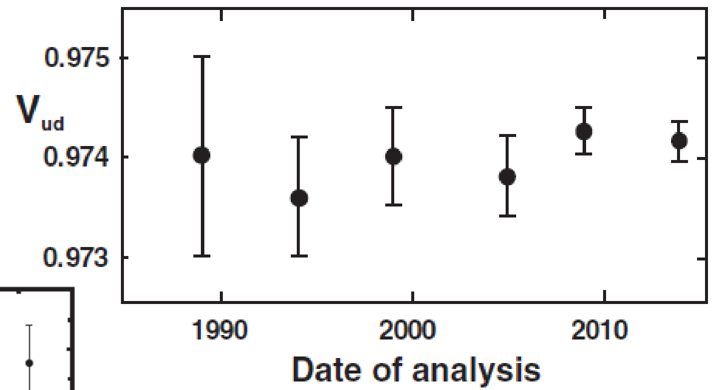


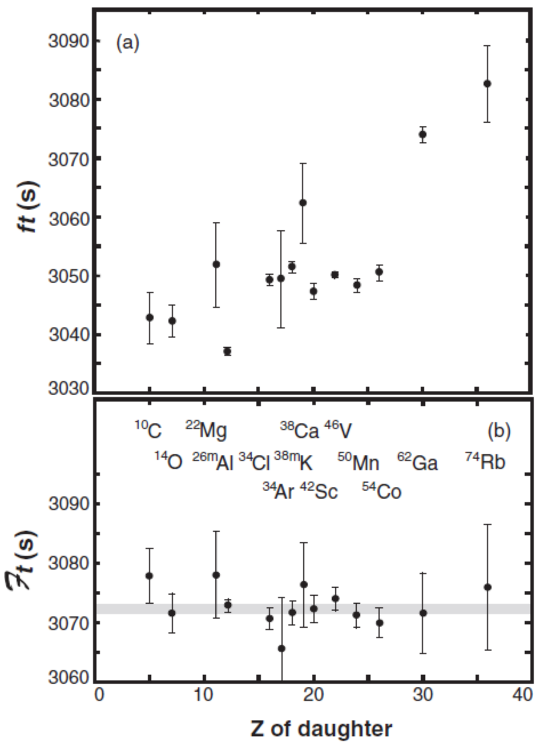


V_{ud} from superallowed $0^+ \rightarrow 0^+$

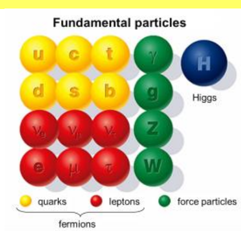
$$V_{ud} = 0.974\,17 \pm 0.000\,21 \quad (2 \times 10^{-4})$$

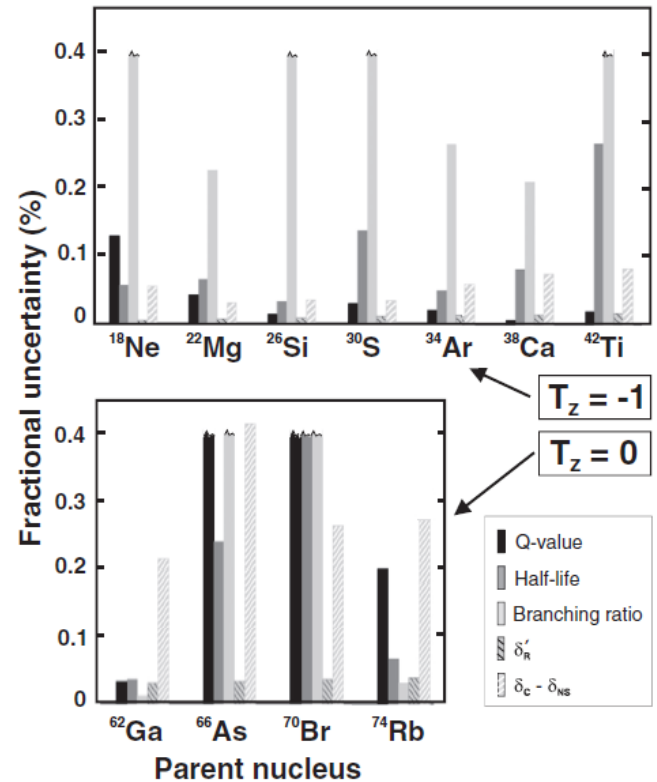






CKM unitarity test
at better than 10^{-3}
(needs also V_{us})



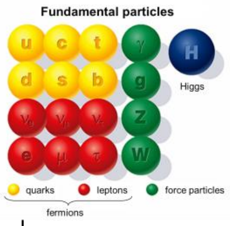


J.C. Hardy and I.S. Towner, 91PRC(2015)025501

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

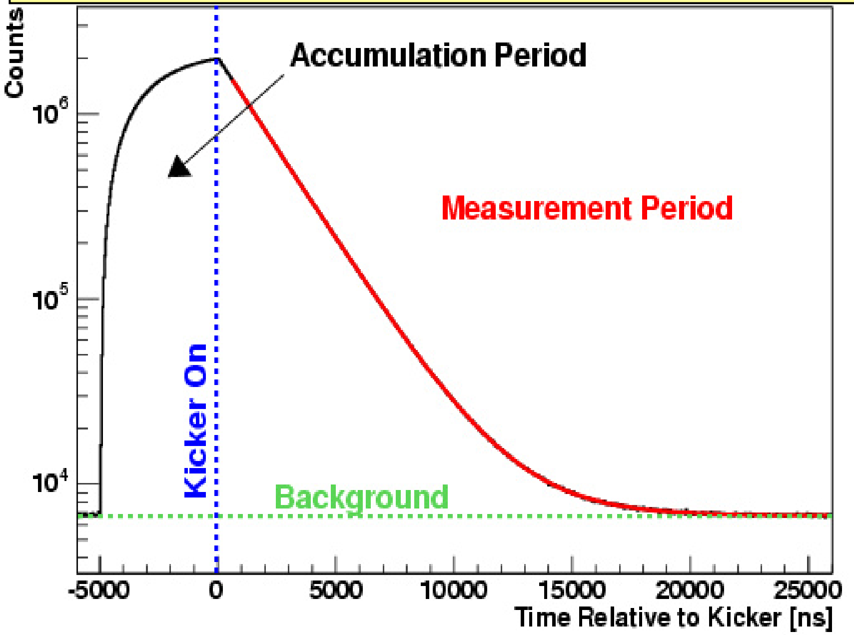


MuLan: The most precise measurement of any lifetime:

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

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

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)



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

Caution: β decay and G_F

$$V_{ud} = 0.974\,17 \pm 0.000\,21$$ (2 x 10^{-4})

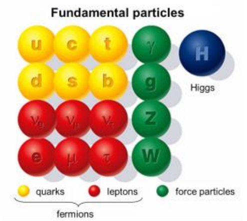
from superallowed $0^+ \rightarrow 0^+$ via

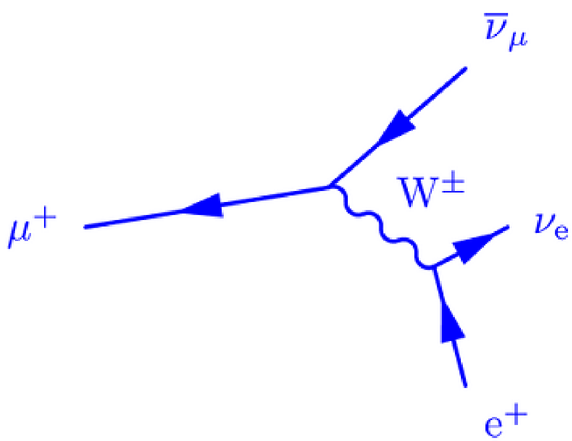
$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

Δ_R^V : Nucleus independent radiative corrections dominating uncertainty

using

$$G_F(\mathrm{MuLan}) = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$ (5 x 10^{-7})





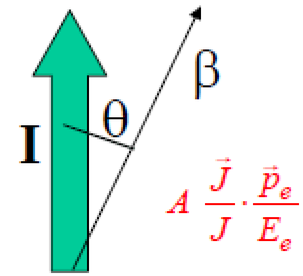
G_F determined assuming validity of the SM. In a model independent analysis G_μ it is not yet better constrained than 3-4 x 10^{-4}

High precision measurements in nuclear β decays (including n)

- Sensitive tool to test SM, complementary to high energy physics
- @ low energy, "traces" are hidden in correlations:

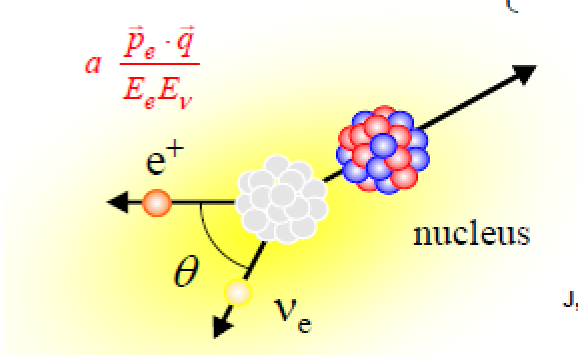
$$\omega\left(\langle \vec{J} \rangle \mid E_e, \Omega_e, \Omega_\nu\right) dE_e\, d\Omega_e\, d\Omega_\nu$$

$$\propto \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \quad \underbrace{p_e E_e (E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}}$$

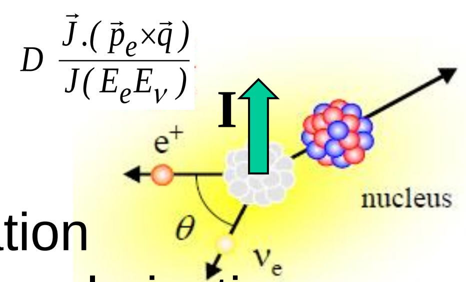


$$\text{x}\quad \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b\frac{\gamma m_e}{E_e} + A\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e} + D\frac{\vec{J}.(\vec{p}_e \times \vec{q})}{J(E_e E_\nu)} + \ldots \right\}$$

β-ν correlation	Fierz interference term (b ≡ 0 in standard model)	β-asymmetry	D-correlation



J,D, Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206



a, *b* : P,T invariant

A, *D* : P or T violation
→ require nuclear polarization

Courtesy: N. Severijns, E. Lienard

3 topics in nuclear (and neutron) β decay

Precision for significant contribution

- *Test of V-A theory, search for S,T currents in "pure" transitions*

a (C_S^2, C_V^2, C_T^2, C_A^2) — Pure GT: a_{GT} (C_T^2, C_A^2) = -1/3 (SM) — $< 10^{-3}$

Pure F: a_F (C_S^2, C_V^2) = +1 (SM)

b ($C_S \times C_V$, $C_T \times C_A$) — b = 0 (SM) — $\sim 10^{-3}$

Caution: Strong interaction contributions (e.g.: Weak magnetism)

- *In V-A framework, determination of V_{ud} (CKM matrix) in "mirror" transitions*

$$a_m = \frac{(1-\rho^2/3)}{(1+\rho^2)} \qquad A_m = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$

for a precise determination of the mixing ratio ρ = GT/F — $< 10^{-2}$

Caution: Strong and E-M "corrections" (Ex. : Radiative corrections)

- *Search for CP violation in "mirror" transitions* $({}^{A}_{Z1}X_{N1} \rightarrow {}^{A}_{Z=N1}Y_{N=Z1} + \beta + \nu)$

$$D = \frac{-2\rho \, Im(\delta_{JJ'} (\frac{J}{J+1})^{1/2} \frac{C_A^*}{C_A})}{(1+\rho^2)}$$

D = 0 (SM)

D can be ≠ 0 — $< 10^{-4}$

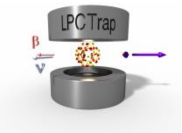
ONLY IF $\rho \neq 0$ & $\rho \neq \infty$

Caution: FSI contribution → need for advanced theoretical calculations

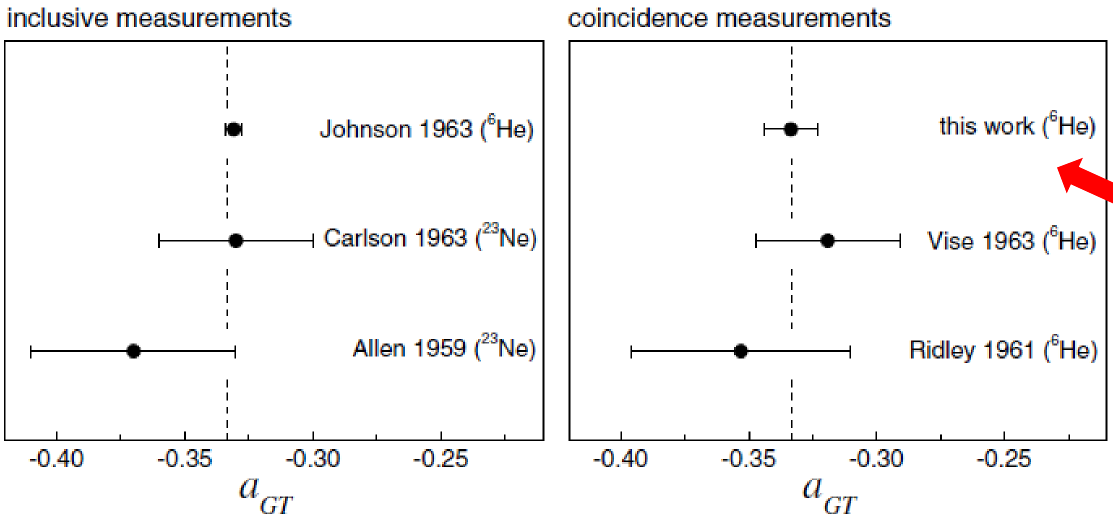
Courtesy: E. Lienard

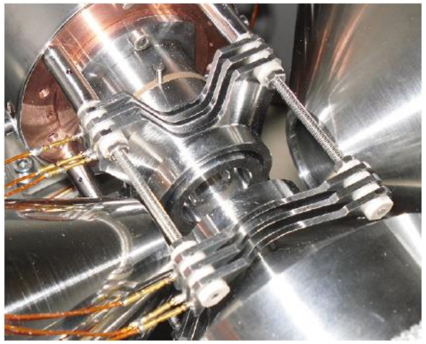
$$a\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu}$$

with LPCTrap @ GANIL



J. Phys. G: Nucl. Part. Phys. 38 (2011) 055101 — X Fléchard *et al*





Paul Trap

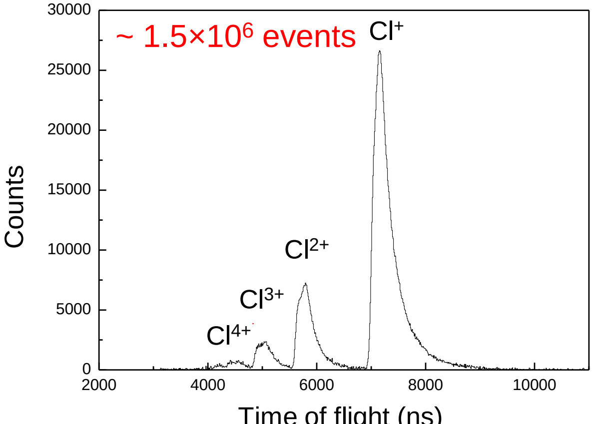
First measurement in ^{6}He

10^5 good coincidences

β – recoils → $\Delta a/a$ ~ 3%

New data available with large potential of high precision (^{6}He, ^{19}Ne, Ar)

Example: ^{35}Ar — Mirror decay → a (ρ) → V_{ud} → Alternative: $A\frac{\vec{J}\cdot\vec{p}_e}{J E_e}$



$\Delta a/a$ (expected):

0.4% - 0.7%

$\Delta V_{ud}/V_{ud}$ (mirrors):

9×10^{-4} - 1.5×10^{-3}

- More sensitive to ρ (^{35}Ar)
  Severijns & Naviliat PST152(2013)
- First measurements @ Vito/Isolde from 2018
- $\Delta A/A$ (expected) < 1%
  → $\Delta V_{ud}/V_{ud}$ < 9×10^{-4}

Courtesy: E. Lienard

Lienard et al HI236 (2015)

One of the **neutron decay** frontiers:
PERC – Proton Electron Radiation Channel

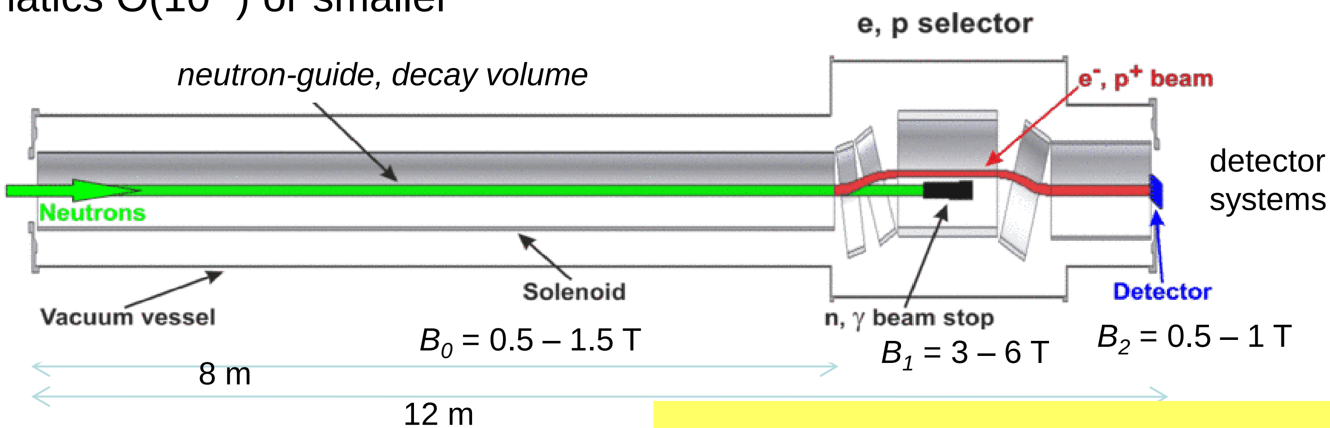
Features

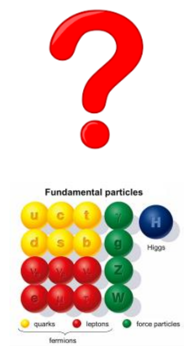
- (pulsed) cold neutron beam in a guide
- magnetic filter
- extraction of electrons and protons
- systematics $O(10^{-4})$ or smaller

Observables

- electron-, neutrino- & proton asymmetry
- electron & proton spectrum
- Fierz interference, weak magnetism

FRM II





Timeline

- magnet under construction,
- delivery 12/2017
- first beam: end of 2018

Impact on V_{ud}

Aim: order of magnitude improvement
on beta asymmetry, **$\Delta A/A = 5\times10^{-4}$**

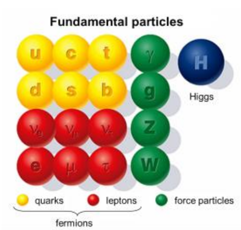
Assuming 0.1s neutron lifetime:

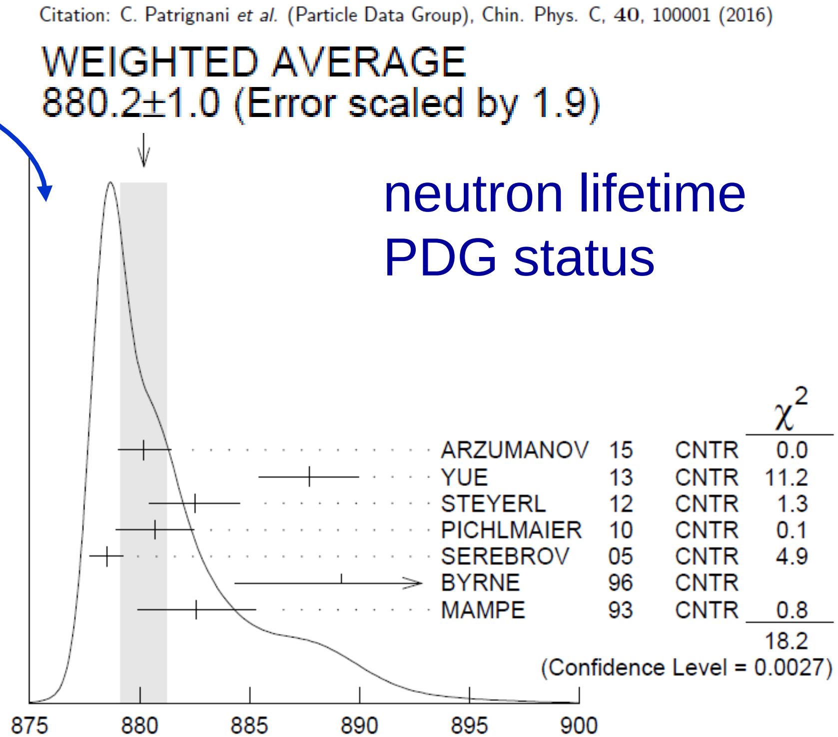
$$|V_{ud}| = 0.97xxx\ (19)_{RC}(6)_{\tau}(10)_{A}$$

Courtesy: B. Märkisch

Progress in fundamental neutron physics

- Maintenance and upgrades of existing neutron sources at ILL, FRM II, PSI with major FNP activities
  - n-decay, lifetime, nEDM, UCN sources, gravitational states
- New technologies
  - many, e.g. improved detectors
- New European facility: ESS Lund
  - Neutron decay channel
  - nnbar, nEDM
  - Parity violation studies
  - BRAND



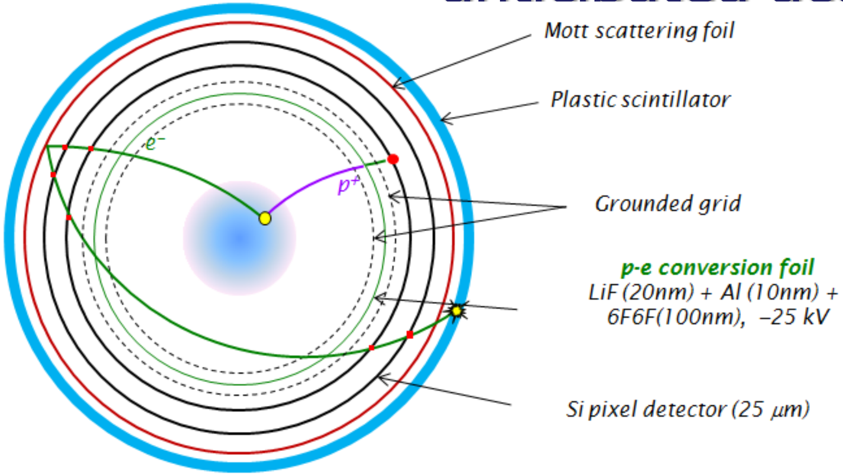


neutron lifetime PDG status

UCN and CN efforts world-wide underway to improve on τ_n

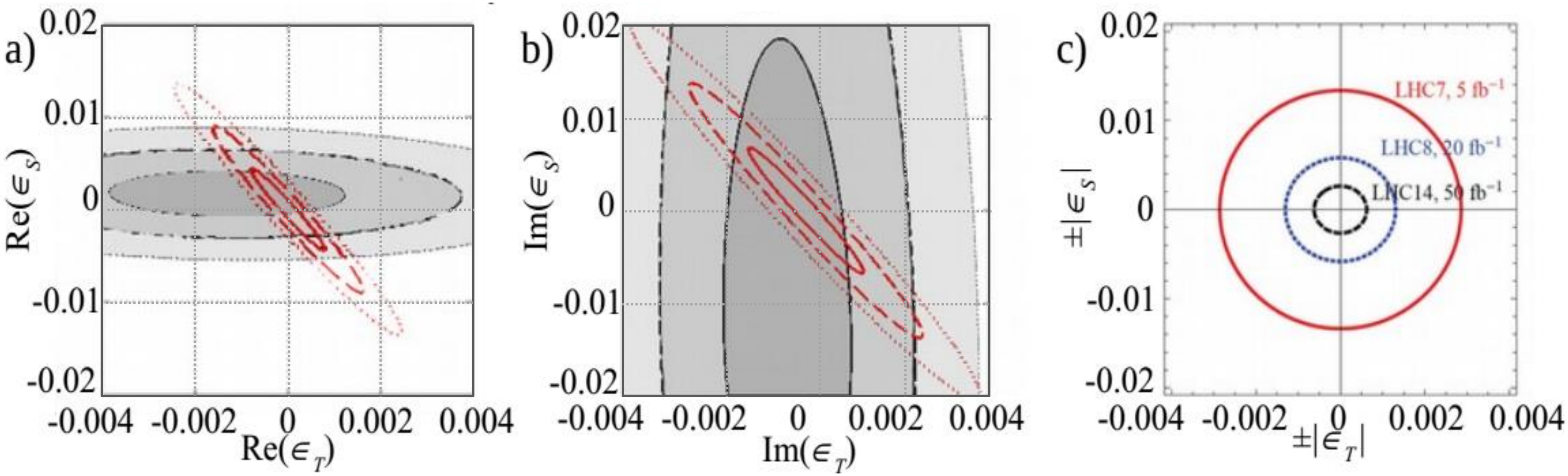
One possible future **neutron decay** frontier (ESS):

BRAND: ***H*, *L*, *N*, *R*, *S*, *U*, *V*** measurement with anticipated accuracy of **5×10^{-4}**



- "High Energy approach":
  - Electron tracking with HV-MAPS
  - Proton momentum from TOF and hit position
  - Decay origin reconstruction

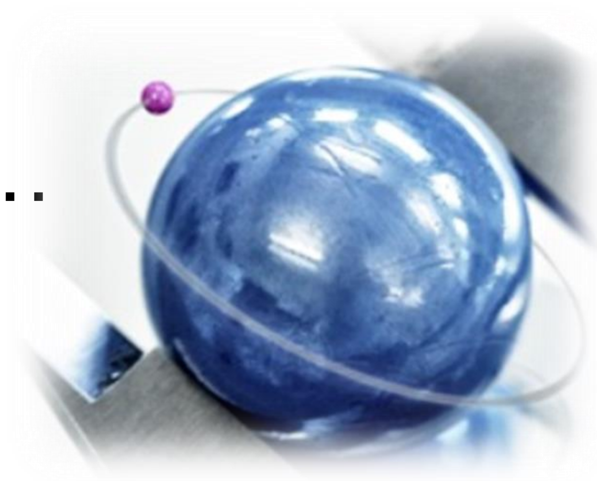
M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)

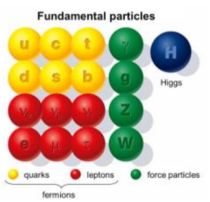


Courtesy: K. Bodek

Light exotic atoms …

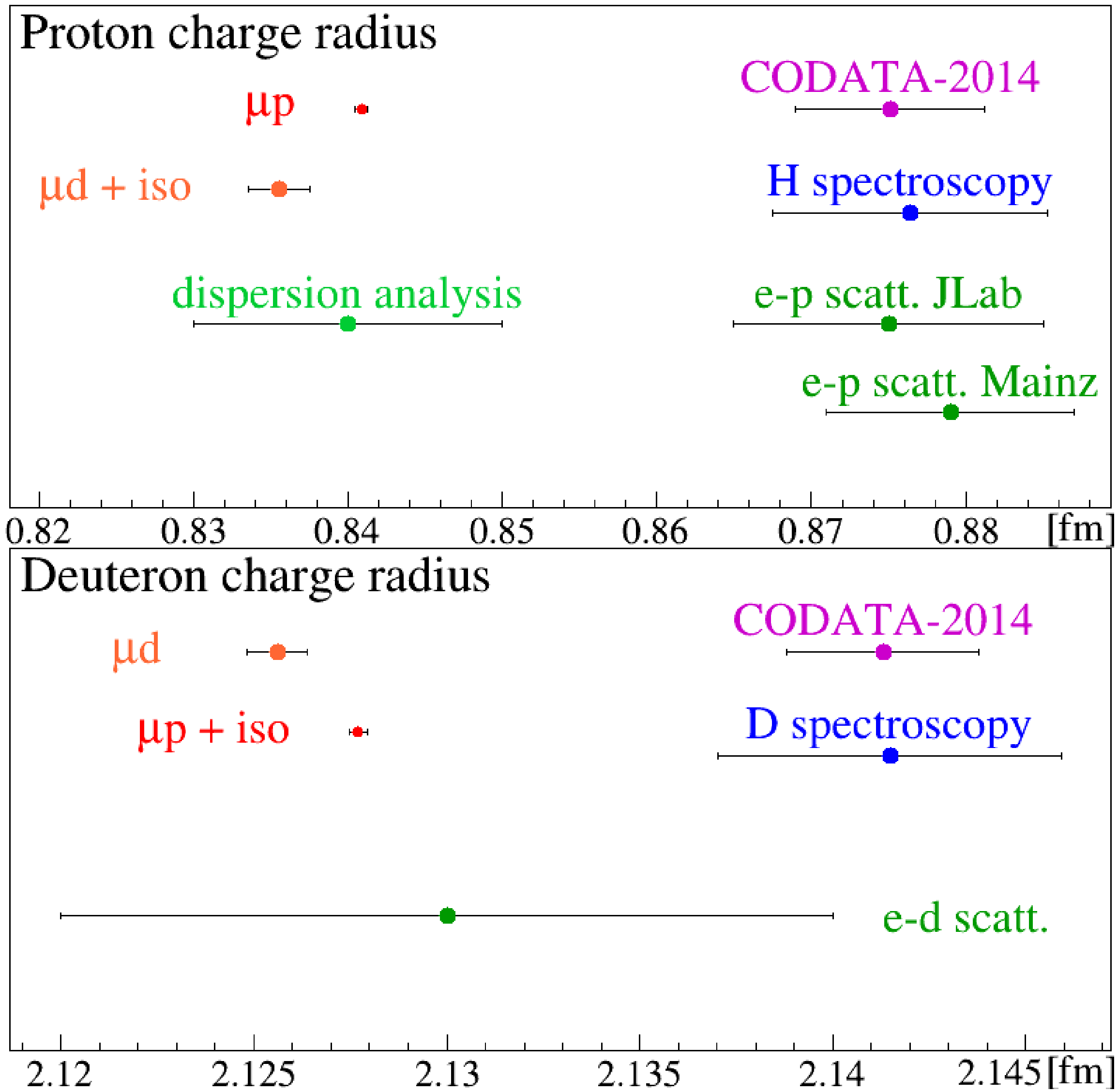
- Positronium, Muonium
- Muonic p, d, He-3, He-4, …
- Kaonic, pionic p, d, He, …
- Antiprotonic helium
- Antihydrogen

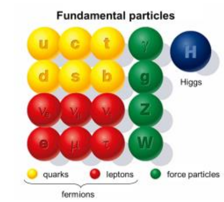




… used to measure fundamental constants, test QED, weak&strong interactions, search for BSM and develop new technology

WG-5 report Fig. 4





Courtesy: A. Antognini, R. Pohl

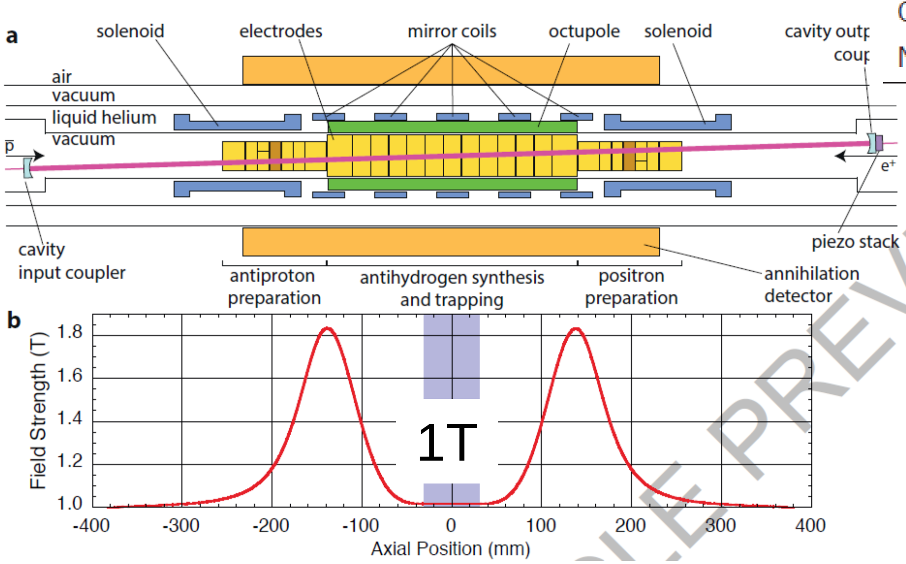
1S-2S spectroscopy of trapped Hbar

This H-Hbar comparison: CPT test at 10^{-10}

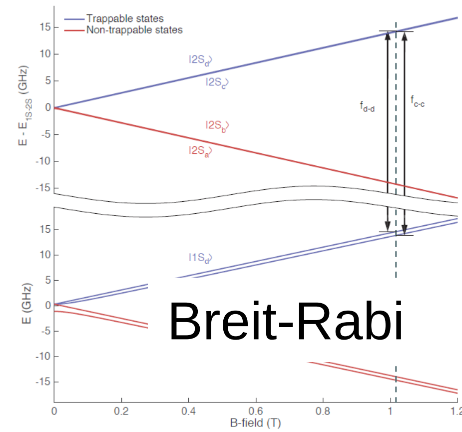
6 collaborations at CERN-AD aim at 1S-2S, HFS, gbar, magnetic moments, masses, charge, … at highest precision. [H(1S-2S)~few10^{-15}]

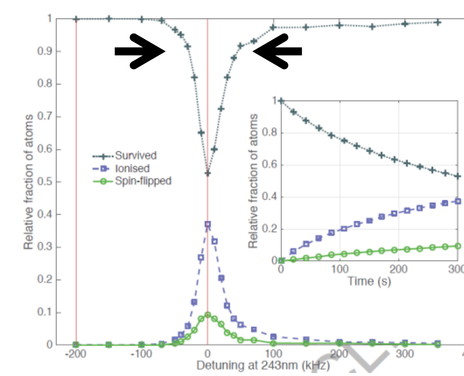
Table 1 | Detected events during the 1.5 s ramp down of the trap magnets

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12



~100kHz O(10^{-10})





1T

Simulation

M. Ahmadi et al., Nature (2016) doi:10.1038/nature21040

3. Searches beyond the SM

3.1 Fundamental-symmetry tests

Searches for *CP* and *T* violation

***P* violation in atoms, ions and molecules**

Searches for CPT and Lorentz violation

Spin-statistics tests

Search for cLFV

3.2 Dark Matter, Dark Energy and exotic forces

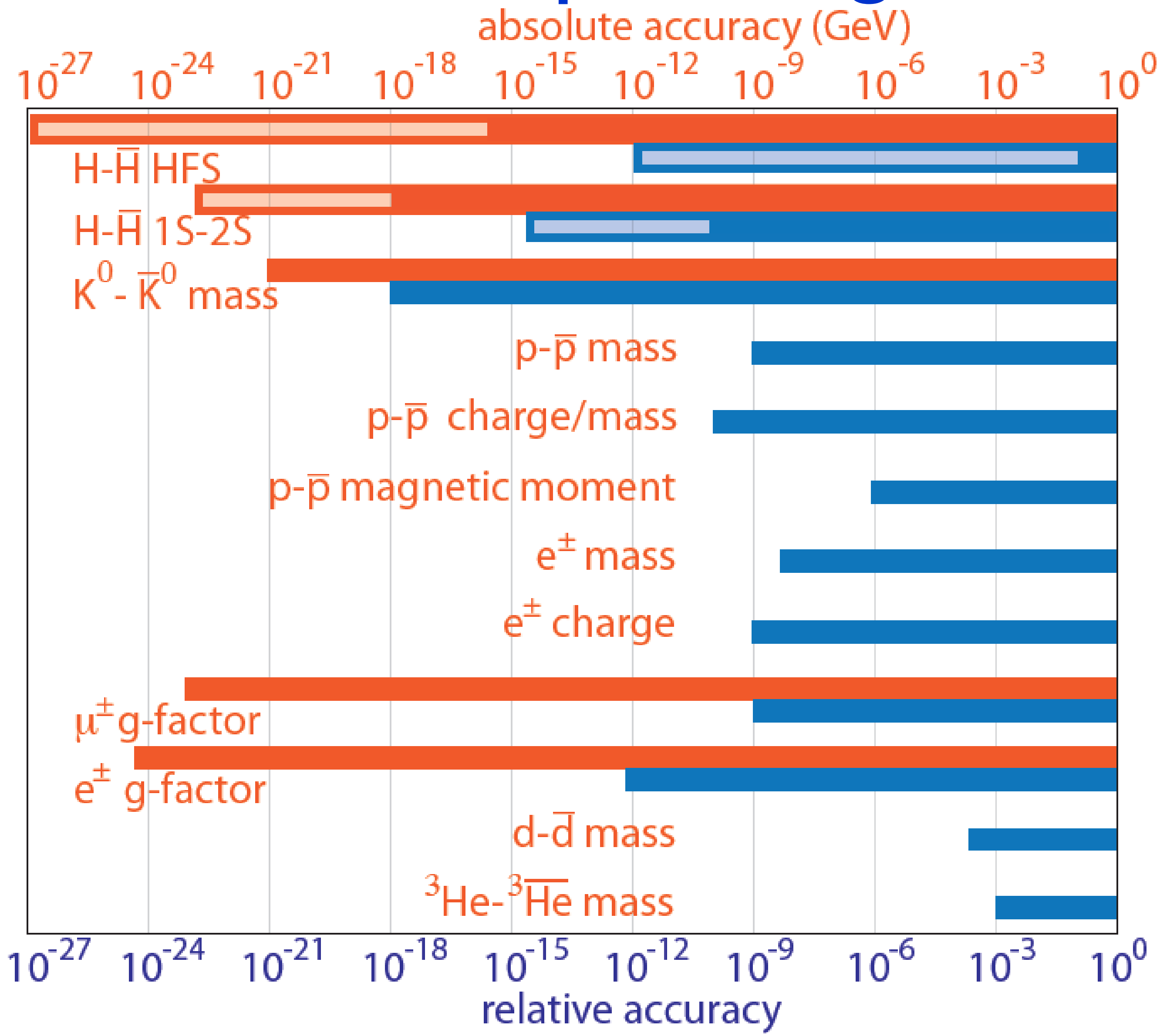
3.2.1 Direct Search for Dark Matter Particles

3.2.2 Test of Dark Energy models with precision experiments

3.2.3 Exotic forces

3.3 Temporal and spatial variation of fundamental constants

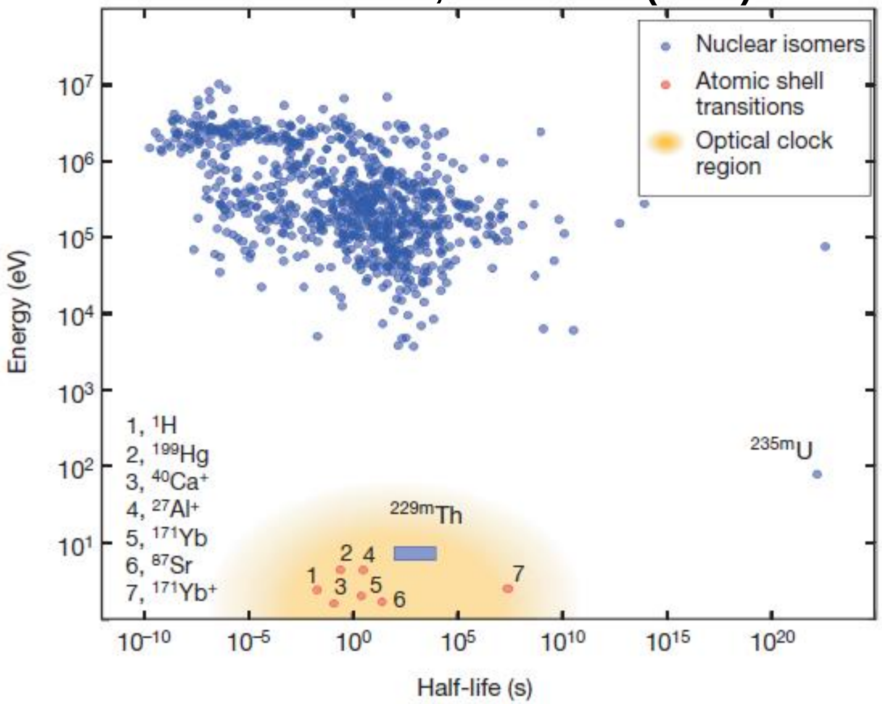
WG-5 report Fig. 5



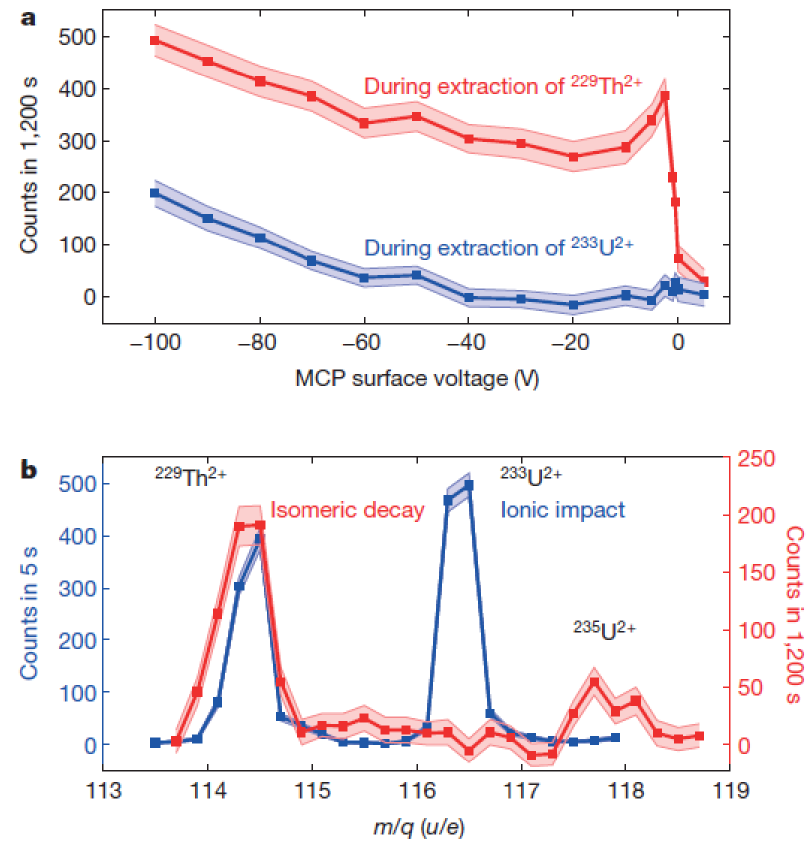
Courtesy: M. Doser

Detection of the ^{229m}Th clock transition

L. von der Wense et al., Nature 533(2016)47



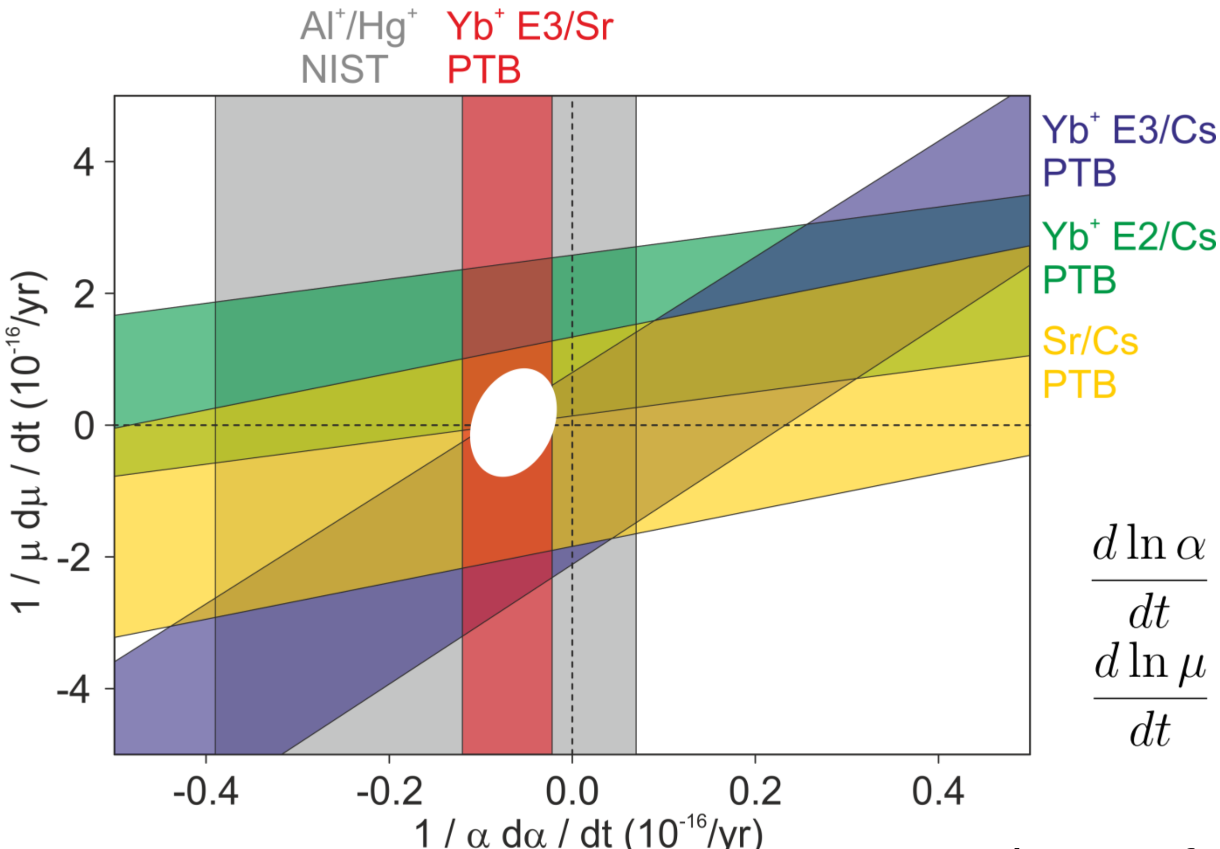
May open up the era of nuclear laser spectroscopy offering also very exciting ….



…. opportunities for symmetry tests, constancy of fundamental constants, etc.

[complementary in some sense to highly charged ions]

Improved limits on temporal variations of fundamental constants: α and $\mu=m_p/m_e$



$$\frac{d\ln\alpha}{dt} = (-6.5 \pm 4.7)\cdot 10^{-18}\ \mathrm{yr}^{-1}$$

$$\frac{d\ln\mu}{dt} = (4 \pm 82)\cdot 10^{-18}\ \mathrm{yr}^{-1}$$

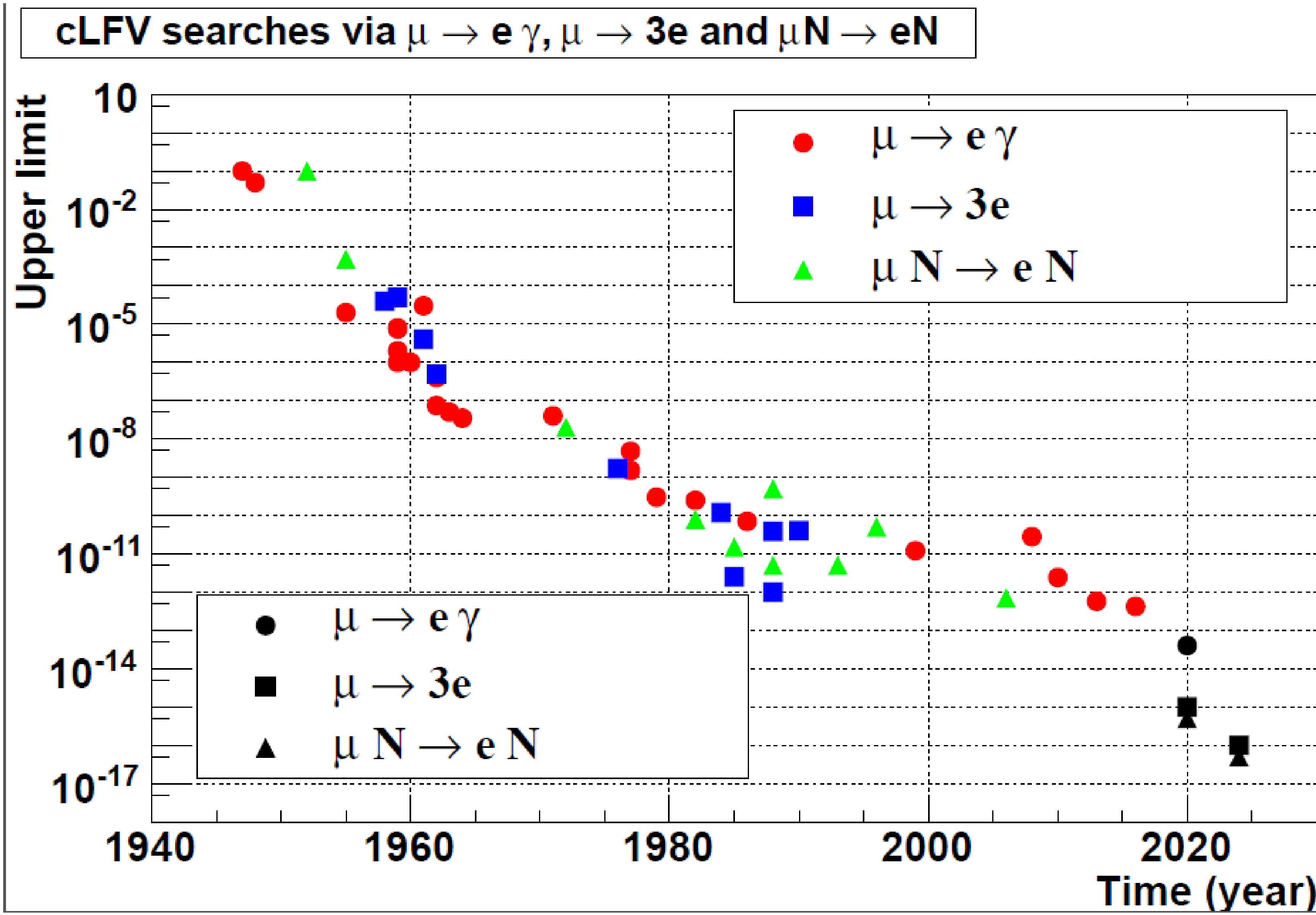
Al^+/Hg^+:
T. Rosenband et al.
Science 319(2008)1808

Earlier analysis:
N. Huntemann et al., PRL113(2014)210802

Comparisons of optical clocks (Yb^+ single ion, E2 and E3 transitions, Sr lattice clock) and primary Cs fountain clocks at PTB.

Courtesy: E. Peik

WG-5 report Fig. 6

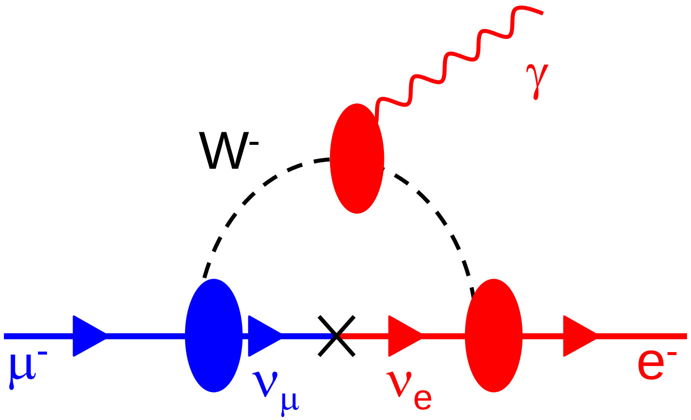


Courtesy: A. Papa

Charged Lepton Flavor Violation:

tiny in the Standard Model

- cLFV suppressed by $(\delta m_\nu/m_W)^4$
  - → SM not observable
  - → accidentally small !?
- Plenty of room for new physics
- New experimental efforts underway
  - MEG II, Mu3e
  - Mu2e, COMET, DeeMe



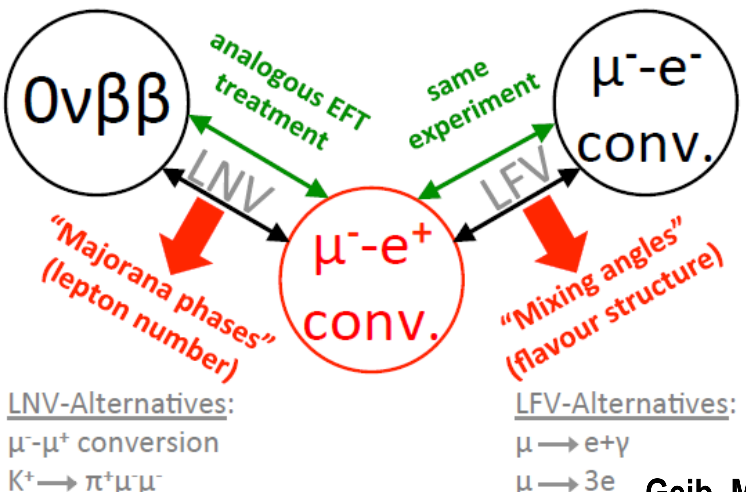
Expect from SM:

BR(μ-eγ) < 10^{-50}

Experimentally so far:

< 4.2 x 10^{-13}

A.M. Baldini et al., EPJC76(2016)434

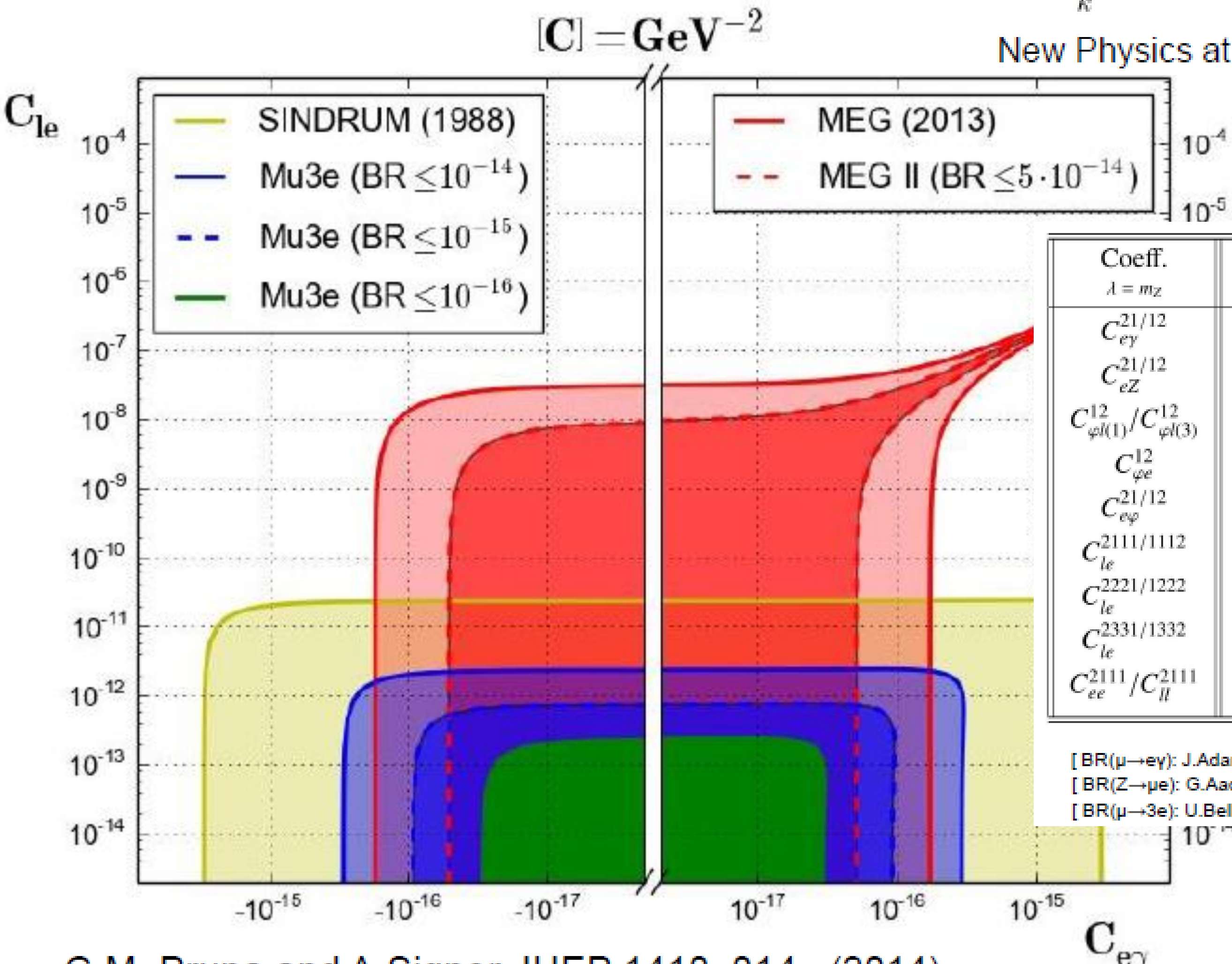


Geib, Merle, Zuber, arXiv:1609.09088

MEG and Mu3e complementarity

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

New Physics at scale $\Lambda \gg M_Z$



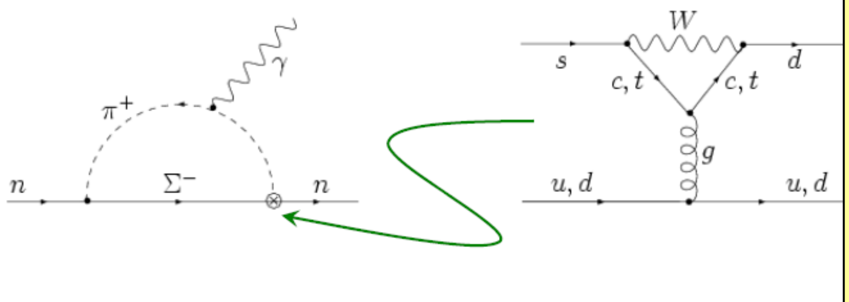
Coeff. $\lambda = m_Z$	$\mu^+ \to e^+\gamma$ $BR \leq 5.7 \cdot 10^{-13}$	$Z \to e^\pm\mu^\mp$ $BR \leq 7.5 \cdot 10^{-7}$	$\mu^+ \to e^+e^-e^+$ $BR \leq 1.0 \cdot 10^{-12}$
$C_{e\gamma}^{21/12}$	$2.5 \cdot 10^{-16}$		$3.8 \cdot 10^{-15}$
$C_{eZ}^{21/12}$	$1.4 \cdot 10^{-13}$	$3.9 \cdot 10^{-8}$	$4.0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

[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)]

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

Electric Dipole Moments tiny in SM ?

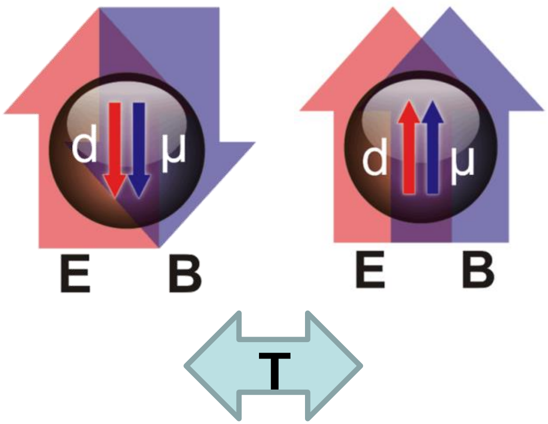
- Neutron, Proton, ..



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

[Khriplovich & Zhitnitsky '86]

Expect from SM:
$d_n < 10^{-30}$ e•cm
Experimentally:
$< 3.0 \times 10^{-26}$ e•cm
Pendlebury et al., PRD92(2015)092003



Most sensitive probe of BSM CP violation

- Leptons: 4^{th} order EW

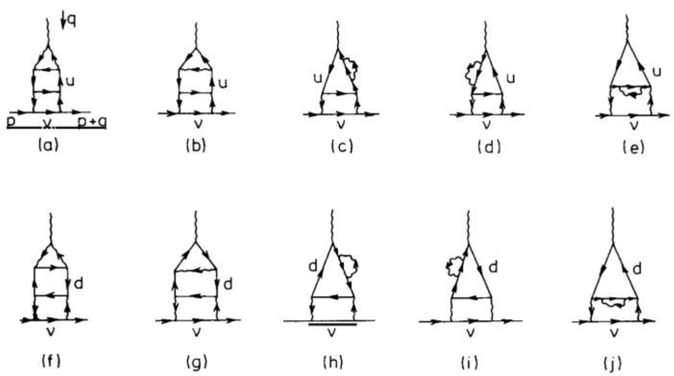


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[Hoogeveen '90]

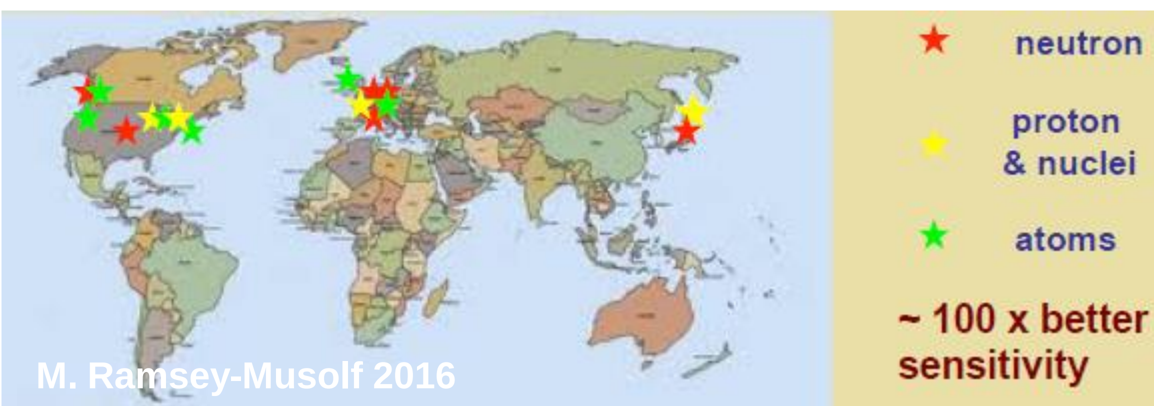
Expect from SM:
$d_e \leq 10^{-38}$ e•cm
$d_\mu \leq 10^{-36}$ e•cm
$d_\tau \leq 10^{-35}$ e•cm
Experimentally:
$d_e < 9 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

ThO molecule
Baron et al., Science 343(2014)269

muon g-2 storage ring
Bennett et al., PRD80(2009)052008

Progress with EDM searches

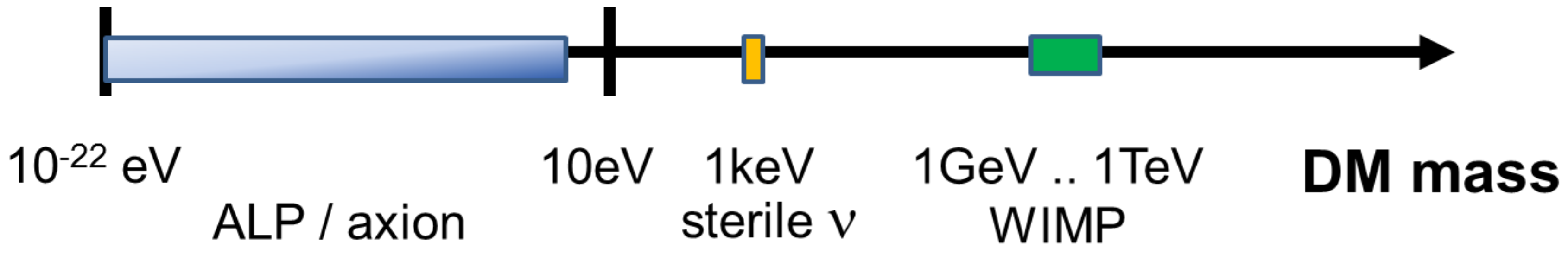
- Electron EDM: Next improvements from polar molecules (e.g. YbF, ThO) expected; some searches with paramagnetic atoms (Cs, Fr)
- Nuclear EDM: Hg-199 $d_{Hg} \leq 7.4\times10^{-30}$ e•cm **(Graner et. al, PRL116(2016)161601),** other efforts use different diamagnetic atoms (Xe-129, Ra-225)
- Neutron EDM: Various international collaborations
- Muon EDM: new g-2 experiments
- Other charged particle EDM: Proton, Deuteron, …
  R&D by storage ring collaboration, JEDI with precursor at COSY

Need multiple systems, to discover finite EDM and to eventually disentangle BSM physics

Some unique opportunities in Europe

WG-5 report Fig. 7

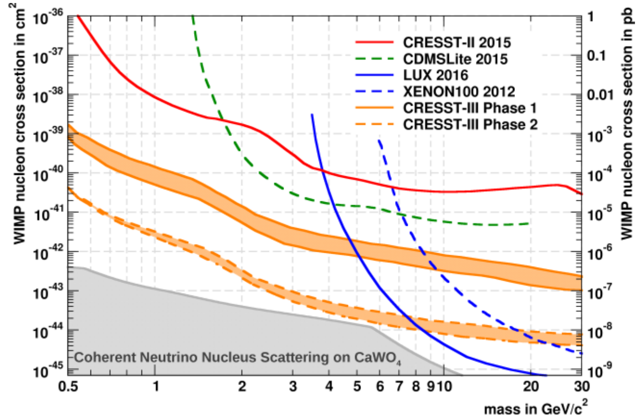


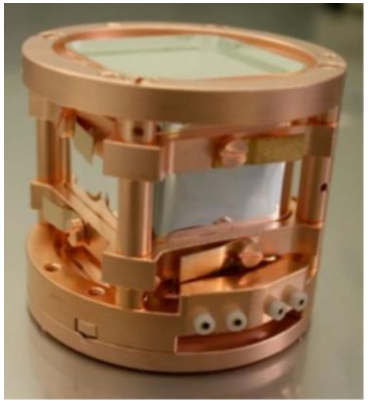
Dark Matter – possible mass scale

Direct search for WIMP dark matter

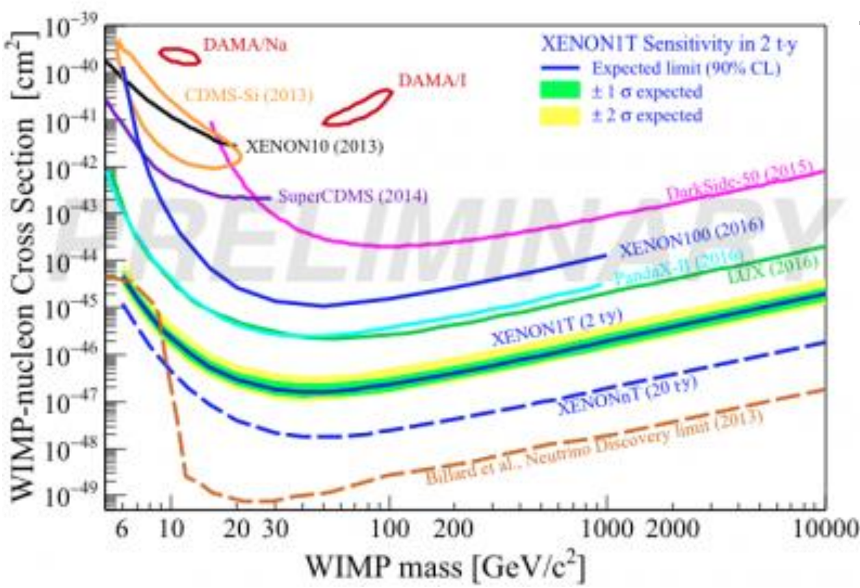
by looking for recoil off nuclei

Light WIMP search (< 10 GeV)
by cryogenic bolometers:
CRESST III, EDELWEISS, SuperCDMS

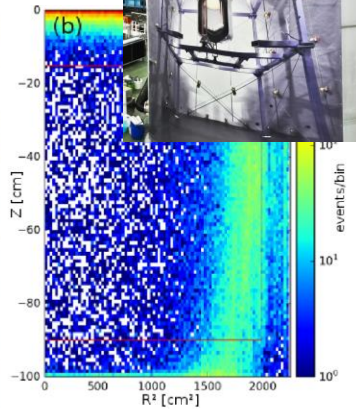




Medium/Heavy WIMP search (> 10 GeV) by liquid noble Xe, Ar TPCs or single phase:
LUX, PandaX, XENON1T/nT, DEAP-3600, XMASS, DarkSide-20k, DARWIN



The largest DM detector XENON1T is running at LNGS

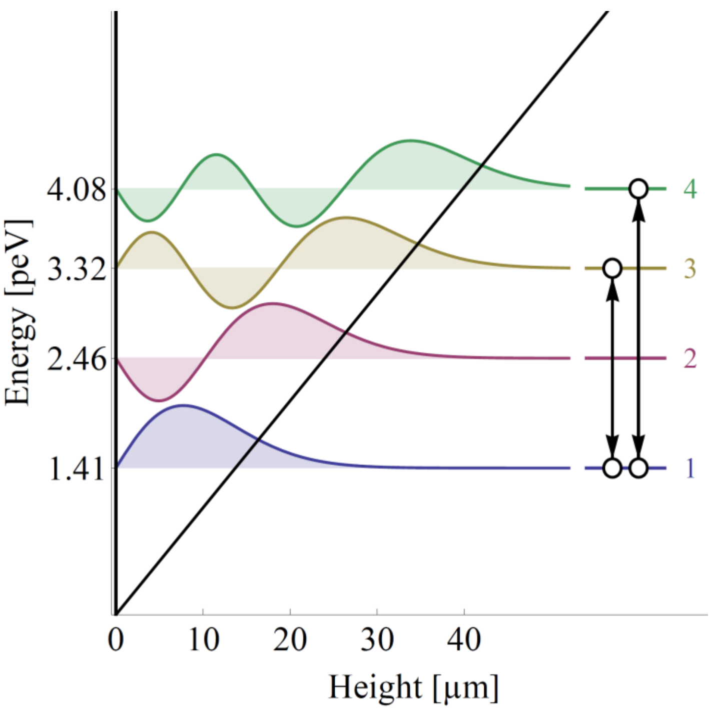


Courtesy: C. Weinheimer

Gravity Resonance Spectroscopy

- Observation of Resonant Transitions between Gravitational Energy Eigenstates of Ultra-Cold Neutrons

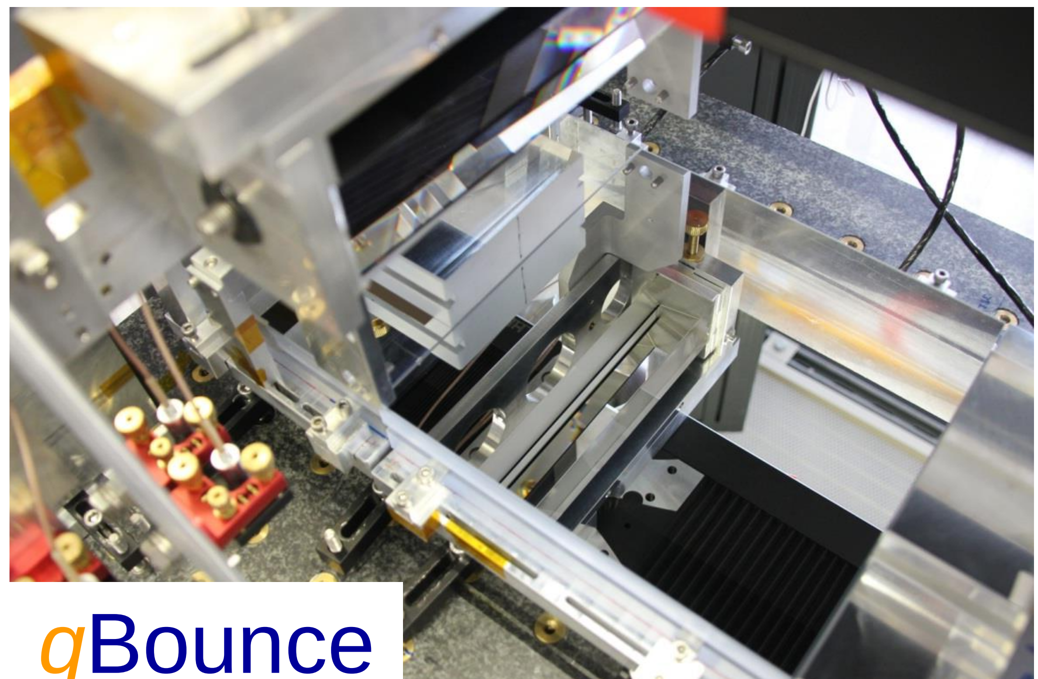
H.Abele et al., PRD 81(2010)065019,
T. Jenke et al, Nat. Phys. 7(2011)468



- Limit on DM axion couplings in the astrophysical axion window and on Dark Energy Chameleon Fields

T. Jenke et al, PRL112(2014)151105

[for axion limits, see also S. Afach et al., PLB745(2015)58
for Chameleons also P. Hamilton et al., Science349(2015)849]

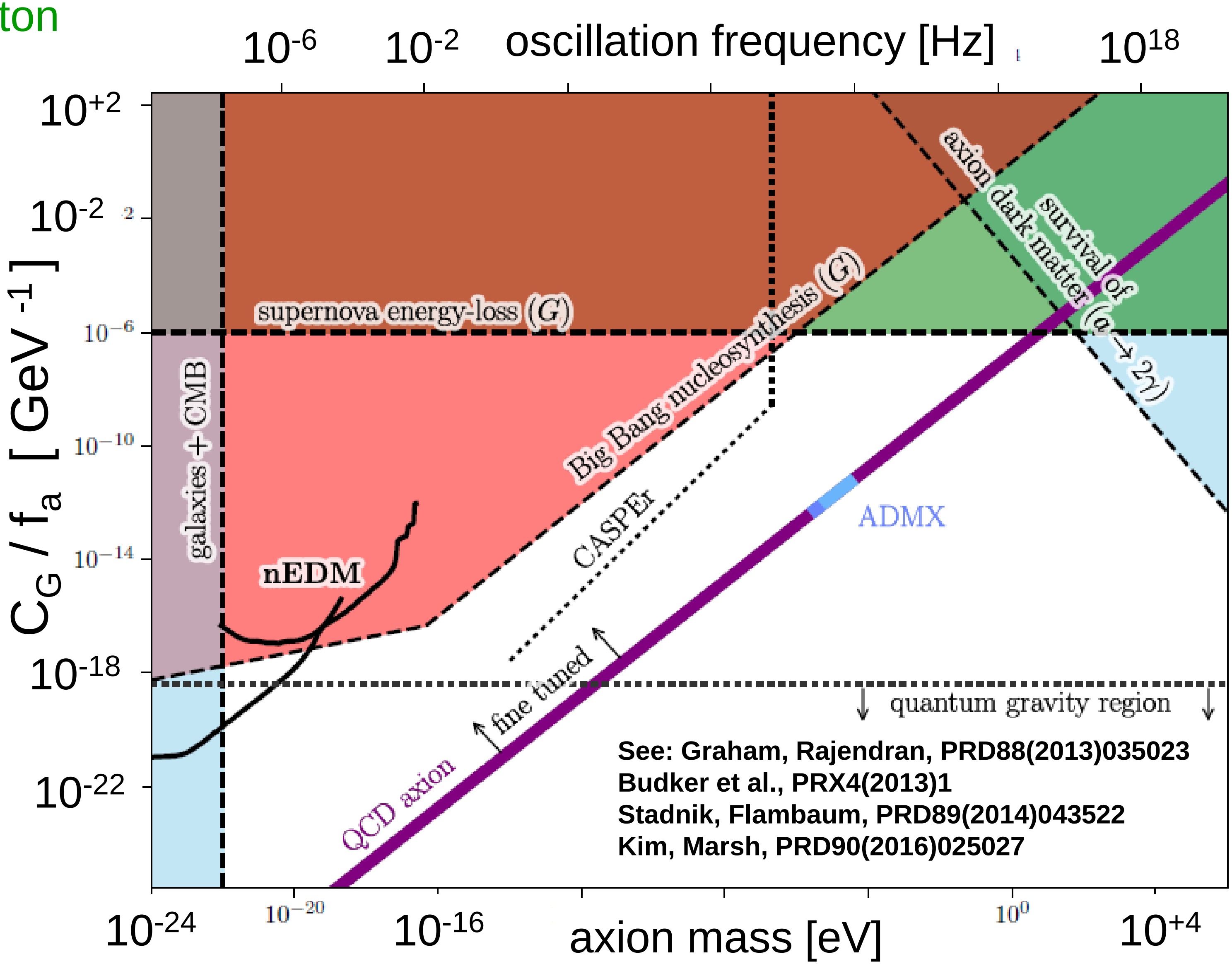


*q*Bounce

Rabi – Setup at ILL to measure resonant transitions

Complementary to searches for axion-photon couplings:

Search for axion – gluon coupling



See: Graham, Rajendran, PRD88(2013)035023
Budker et al., PRX4(2013)1
Stadnik, Flambaum, PRD89(2014)043522
Kim, Marsh, PRD90(2016)025027

Courtesy: M. Rawlik

4. Future directions

Electroweak Interaction

Neutrinos

Fundamental Symmetries

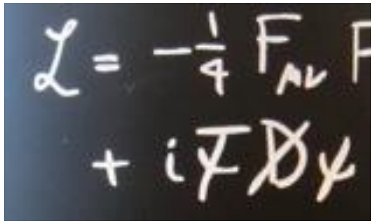
5. Recommendations

Priority 1.: Support of small-sized laboratories and university groups

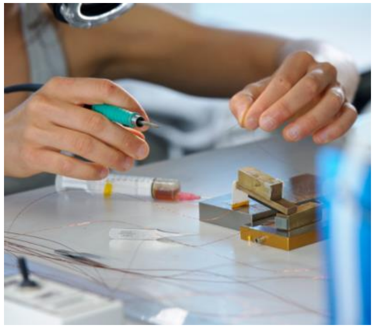
Priority 2.: Theory support

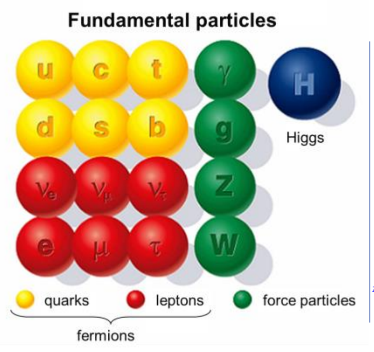
Priority 3.: Facilities

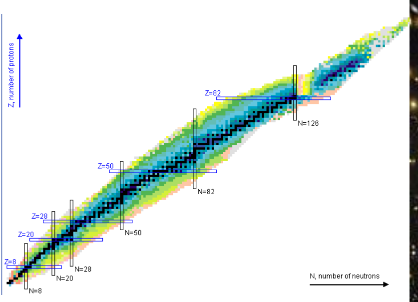
Symmetries & Fundamental Interactions

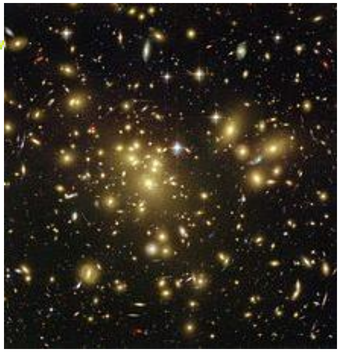


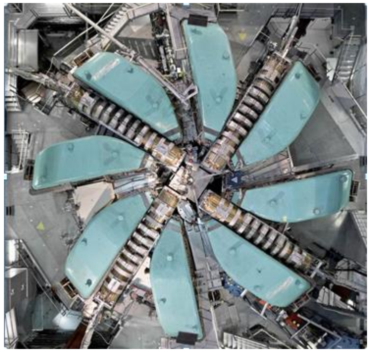
- Large and diverse community
  - many interfaces to neighboring fields
  - important technological developments
  - both, small scale and large projects
  - Ideal training ground for students
- Major progress since last LRP … and ahead
  - Many considerably improved SM parameters
  - Greatly improved limits on BSM physics
- Need for strong theory collaboration and support
- Need for, both, small and large scale facilities

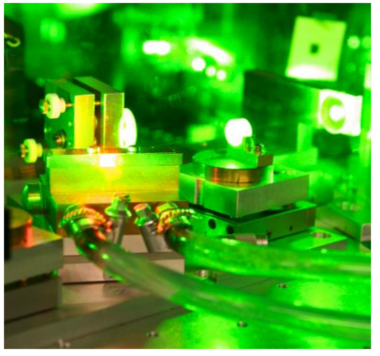








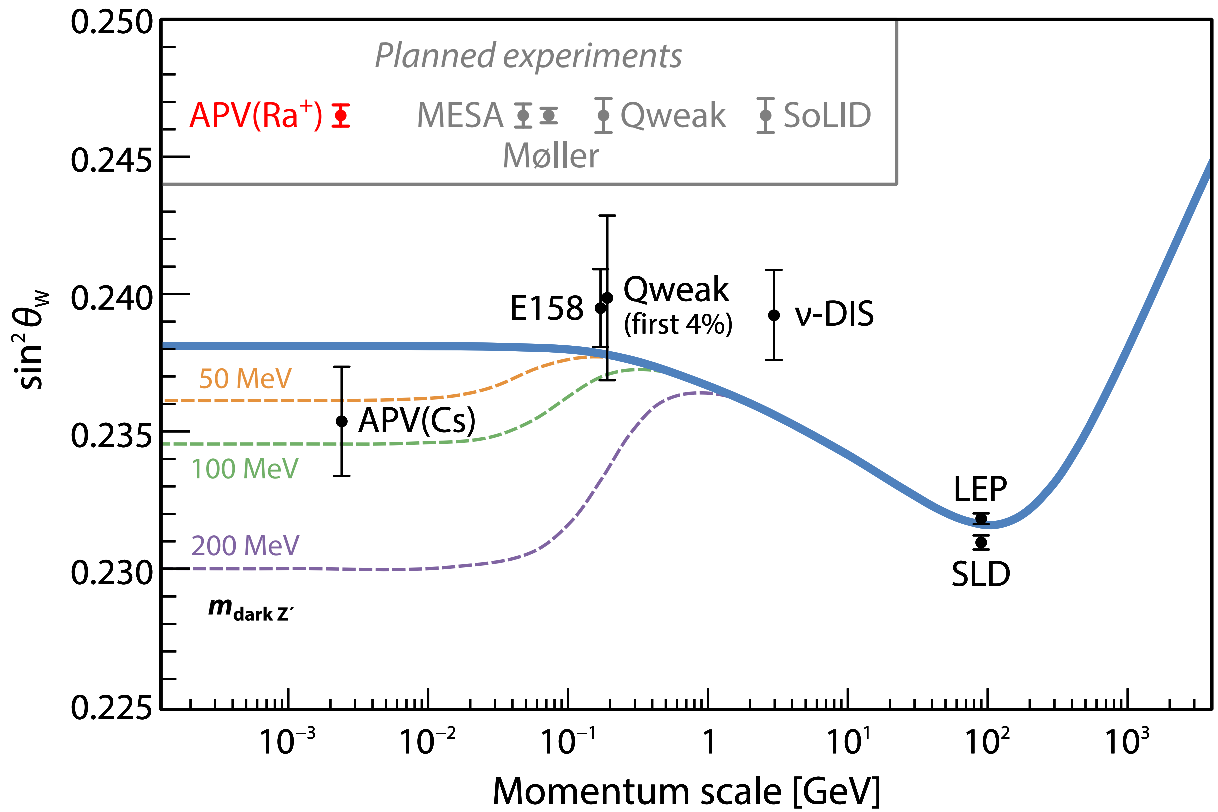




Some backup slides

Weak Interactions in SM

Connecting different Energy Scales



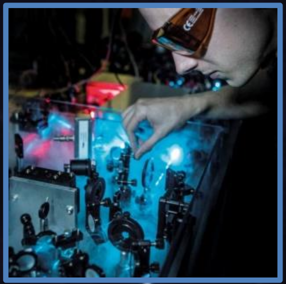
Kumar, Marciano, Annu. Rev. of Nucl. Part. Sci. **63,** 237 (2013)
Davoudiasl, Lee, Marciano, Phys. Rev. D **89**, 095006 (2014); Phys. Rev. D **92**, 055005 (2015)

Courtesy: L. Willmann

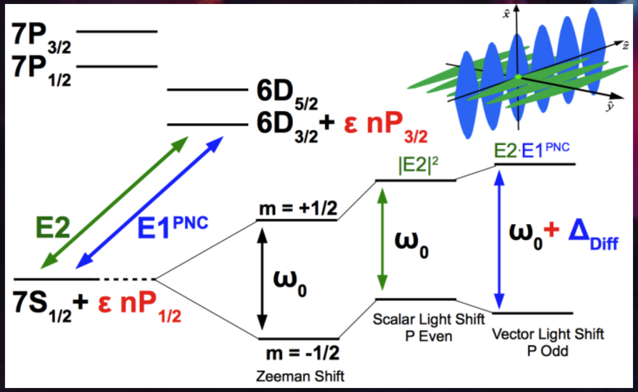
university of groningen

APV in Single Trapped Ba^+/Ra^+

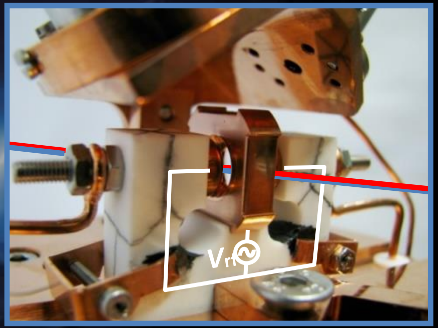
Choice of best suited systems



Unique sensitivity to Atomic Parity Violation

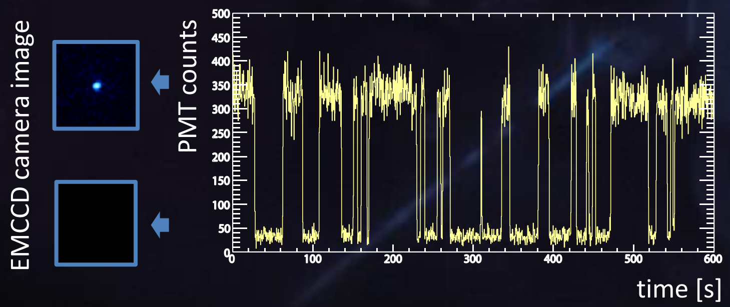


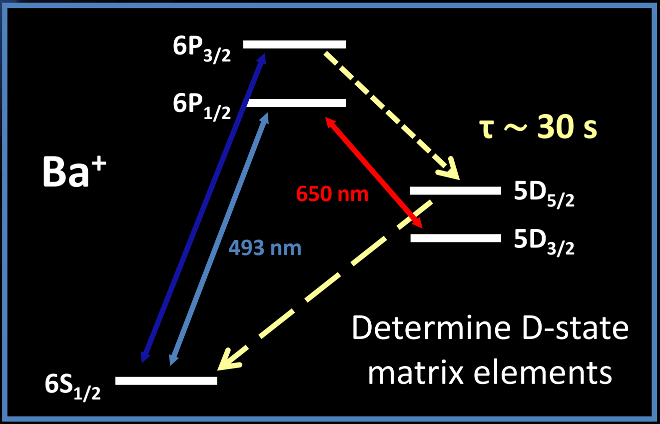
State-of-the-art ion trapping
Synergy with atomic clock



Simple calculable atomic structure

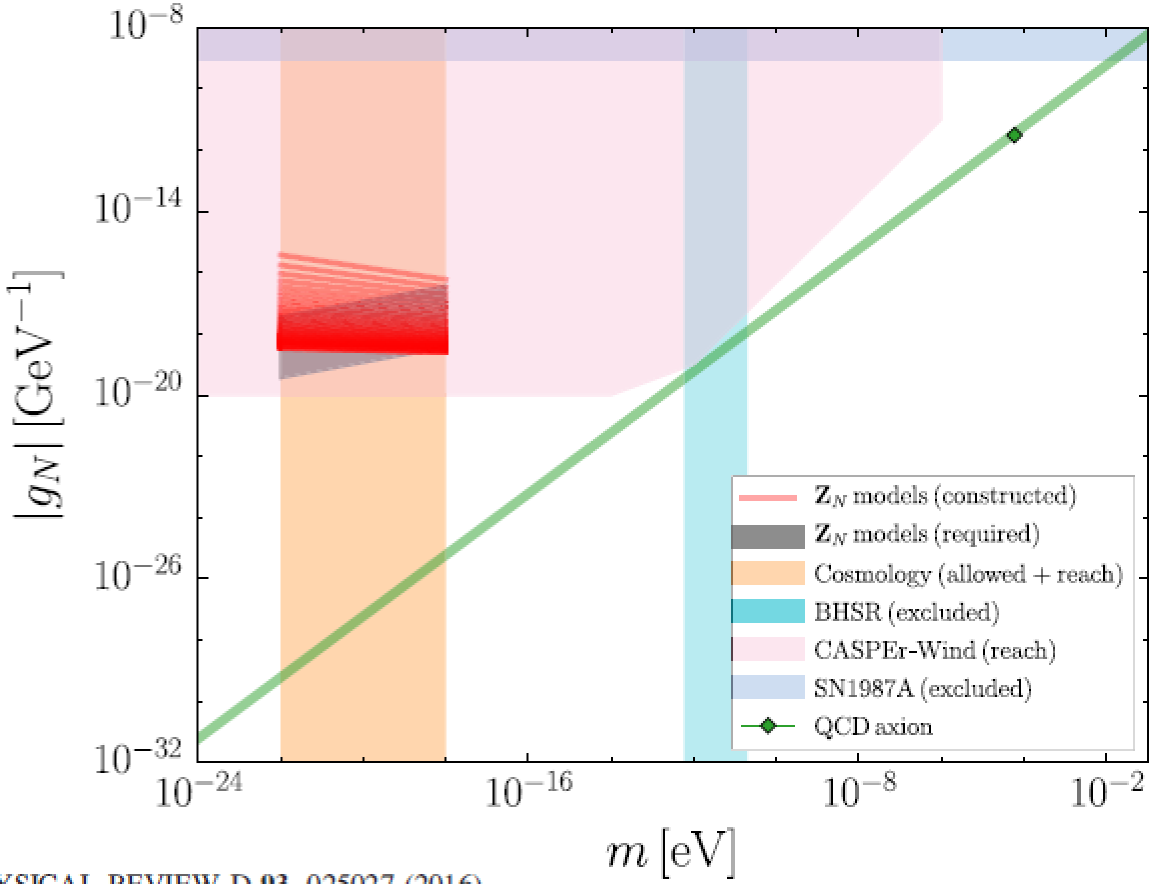
Precision Spectroscopy Methods well developed





Courtesy: L. Willmann

Ultra-low energy example



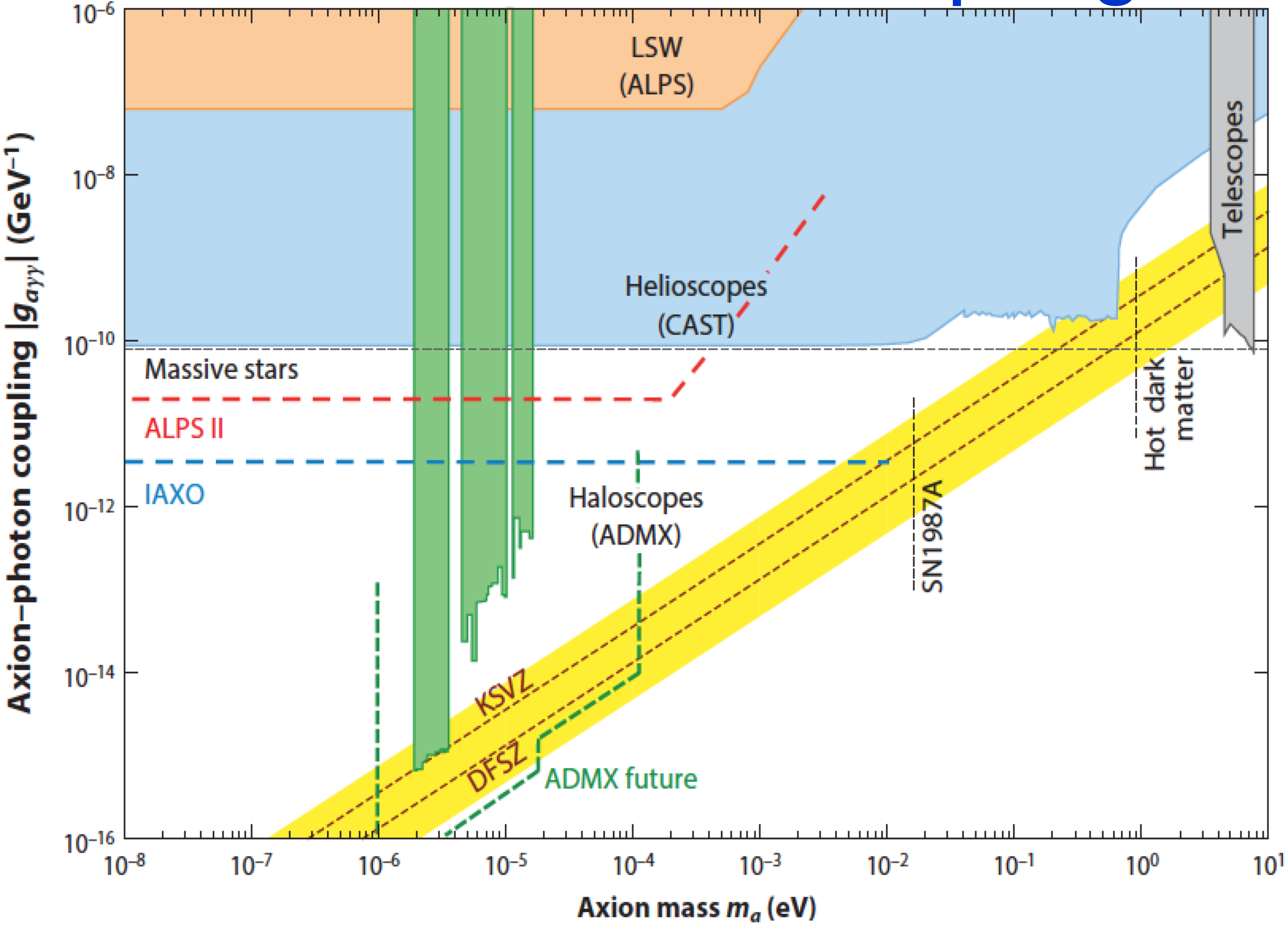
Axions &
Ultralight bosons

PHYSICAL REVIEW D **93**, 025027 (2016)

An ultralight pseudoscalar boson

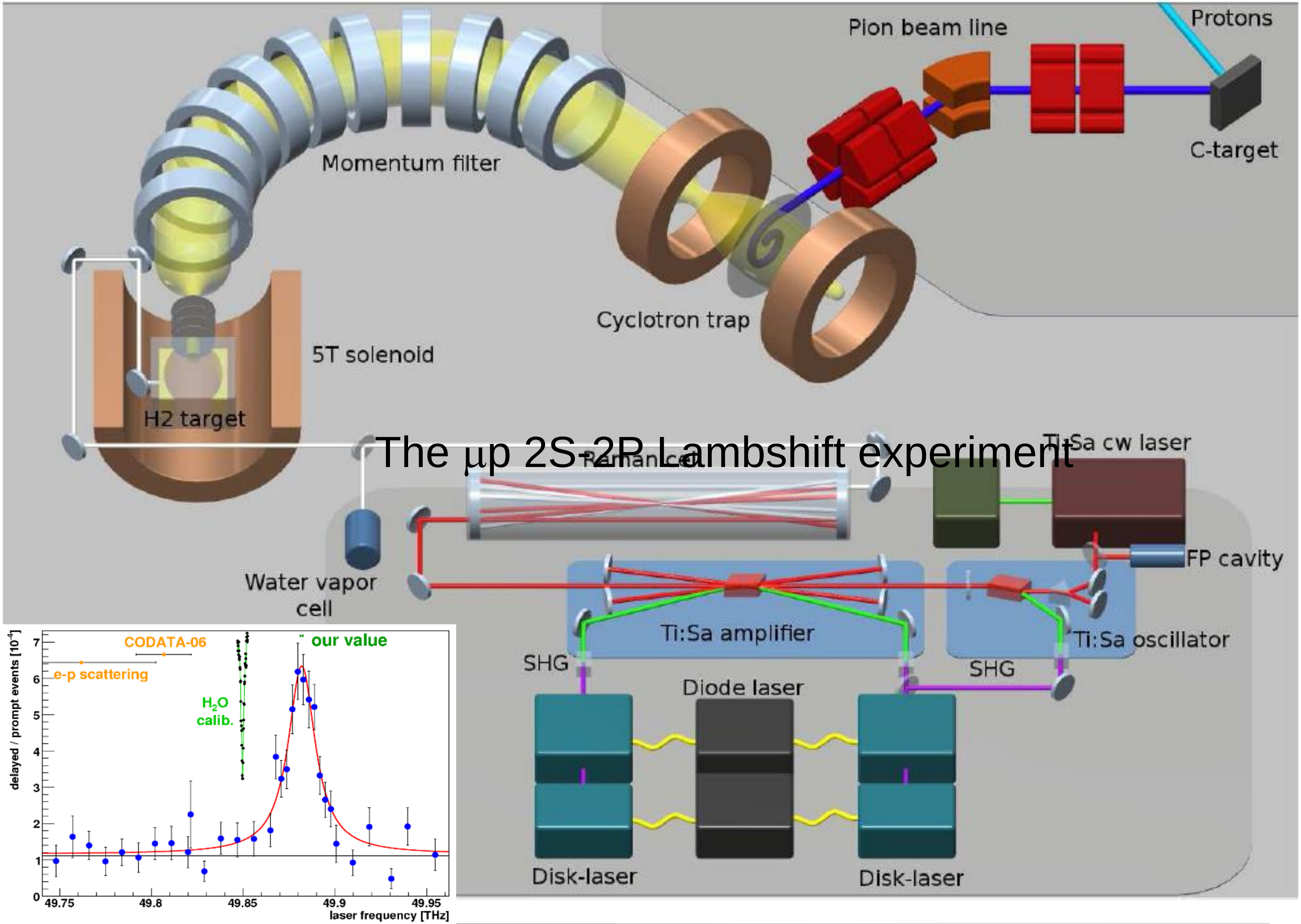
Jihn E. Kim[1,2] and David J. E. Marsh[3,4]

Axion – Photon coupling



Courtesy: K. van Bibber, D. Budker

The μp 2S-2P Lambshift experiment



Courtesy: A. Antognini, R. Pohl

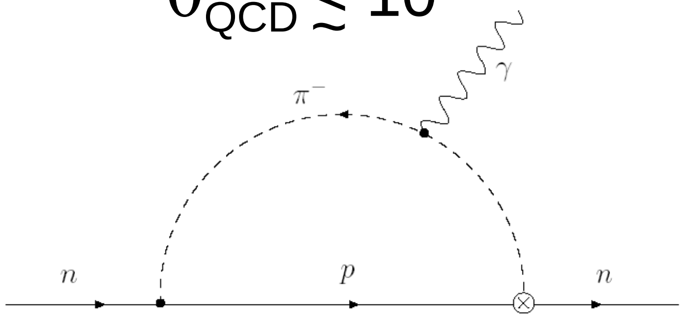
Caveat:

The strong CP problem

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

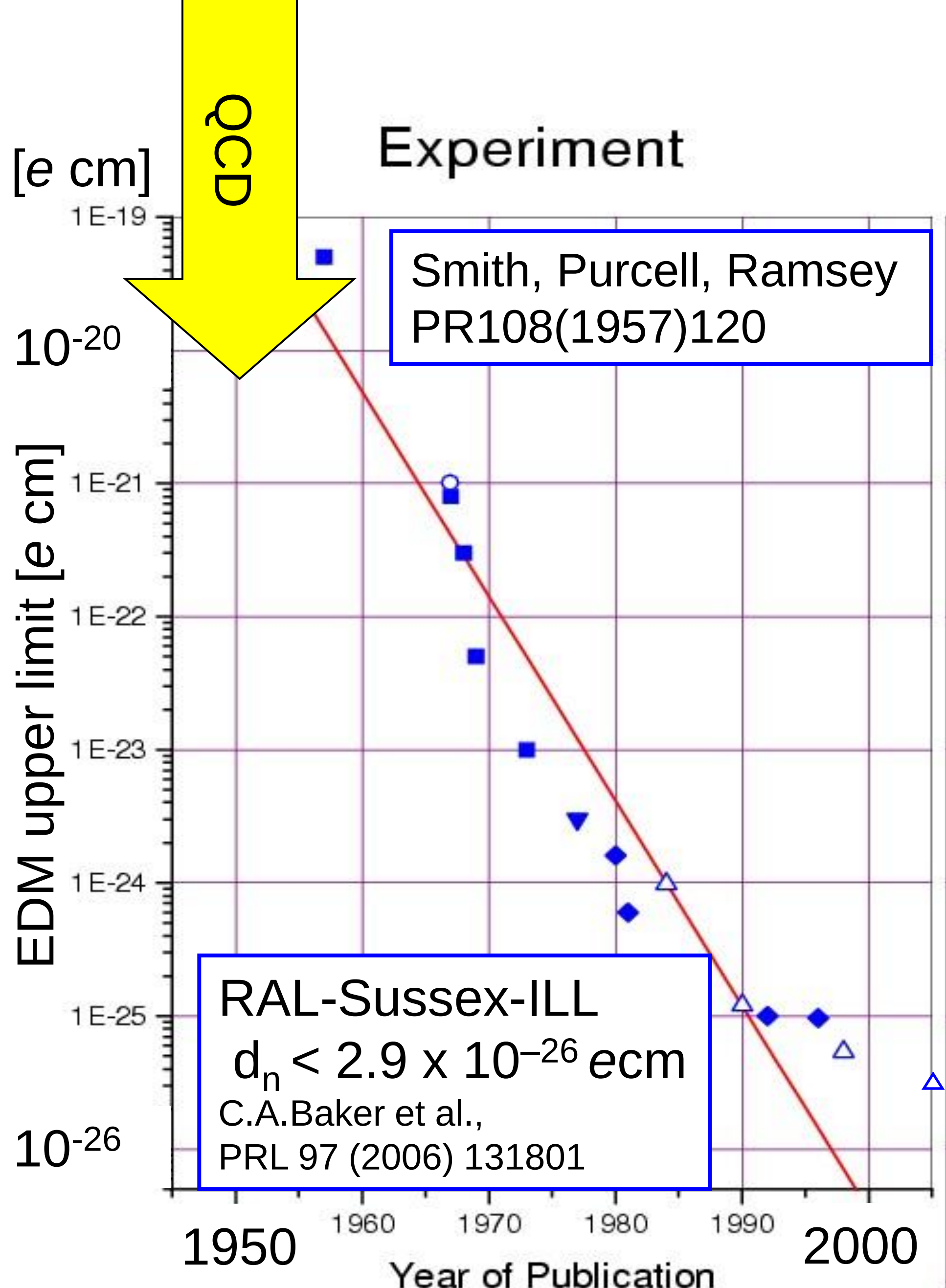
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

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



Why is θ_{QCD} so small ?

→ accidentally small !?



Electric dipole moment of Hg-199

$d_{Hg} \leq 7.4\text{x}10^{-30}$ e•cm

(Graner et. al, PRL116(2016)161601)

TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e \cdot \mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{Hg}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e \cdot \mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{Hg}/(0.135\ e \cdot \mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22, 23]
$(\widetilde{d}_u - \widetilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\mathrm{cm}^{-1})$	5.7×10^{-27} cm	[25]
C_S	$\mathbf{d}_{Hg}/(5.9 \times 10^{-22}\ e \cdot \mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{Hg}/(6.0 \times 10^{-23}\ e \cdot \mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{Hg}/(4.89 \times 10^{-20}\ e \cdot \mathrm{cm})$	1.5×10^{-10}	see text

cLFV Searches: Current Situation

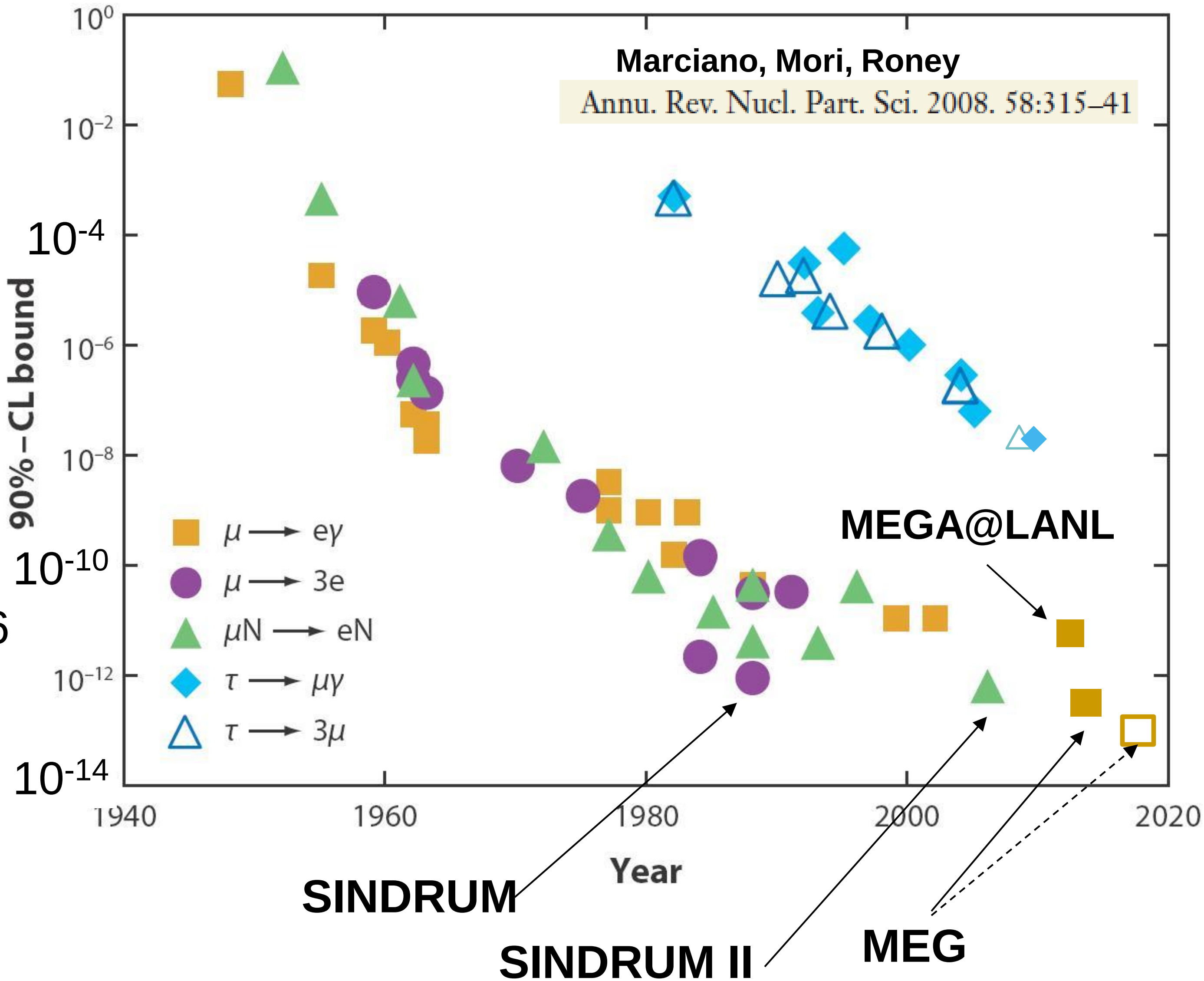
The present best limits on LFV are from muon experiments

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

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

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

[90 % C.L.]



Most sensitive LFV search

Kaonic atoms

- **Kaonic atoms measurements** give **unique informations for the understanding of strong interactions** at low-energy in strangeness sector; this is fundamental to understand chiral symmetry breaking and Equation of State of neutron stars (connected to gravitational waves from binaries where neutron stars are involved)
- **Kaonic atoms measurements** allow to extract the negatively charged kaon mass – important to test **CPT** by comparison with positively charged kaon mass; also an important parameter in many other sectors
- **Kaonic atoms are studied at**: DAFNE Collider at LNF-INFN and at the J-PARC facility: DAFNE Collider unique facility (best low-energy kaon beam!)
- Trigger **technological development**: detector (Silicon Drift Detectors, TES, SiPM etc) systems which are also applied in: medicine, industry, safety etc

Courtesy: C. Curceanu

Spin-statistics tests

- Spin-Statistics and Permutation-symmetry tests are proving theories going beyond the standard ones. The resulting division of particles into fermions and bosons is one of the true cornerstones of modern physics. SST is proved in the framework of relativistic field theory using the assumptions of causality and Lorentz invariance in 3 + 1 spacetime dimensions, along with a number of subtler implicit assumptions. SST test means modifications of the assumptions!
- Today's experiments are able to test the SST at highest precision levels (ex. VIP experiment at LNGS) – 10**-30 probability of Pauli Exclusion Principle violation test.
- Rigorous tests of quantum mechanics investigate foundations of our theoretical understanding of Nature. Experiments testing quantum mechanics and its possible limits use various systems, such as elementary particles, photons, neutrons, nuclei, atoms, and molecules.

Courtesy: C. Curceanu

PRL **104**, 253604 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Spectroscopic Test of Bose-Einstein Statistics for Photons

D. English,[1,*] V. V. Yashchuk,[2] and D. Budker[1,3]

[1]*Department of Physics, University of California, Berkeley, California 94720-7300, USA*
[2]*Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Nuclear Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 4 February 2010; revised manuscript received 12 May 2010; published 25 June 2010)

Using Bose-Einstein-statistics-forbidden two-photon excitation in atomic barium, we have limited the rate of statistics-violating transitions, as a fraction ν of an equivalent statistics-allowed transition rate, to $\nu < 4.0 \times 10^{-11}$ at the 90% confidence level. This is an improvement of more than 3 orders of magnitude over the best previous result. Additionally, hyperfine-interaction enabling of the forbidden transition has been observed, to our knowledge, for the first time.

VOLUME 83, NUMBER 20 PHYSICAL REVIEW LETTERS 15 NOVEMBER 1999

Search for Exchange-Antisymmetric Two-Photon States

D. DeMille,[1] D. Budker,[2] N. Derr,[3,*] and E. Deveney[3,†]

probability v that photons are in exchange-antisymmetric states: $v < 1.2 \times 10^{-7}$.

Courtesy: D. Budker