Fundamental Symmetries and Spin Physics beyond SM

Wide Range of probes and techniques

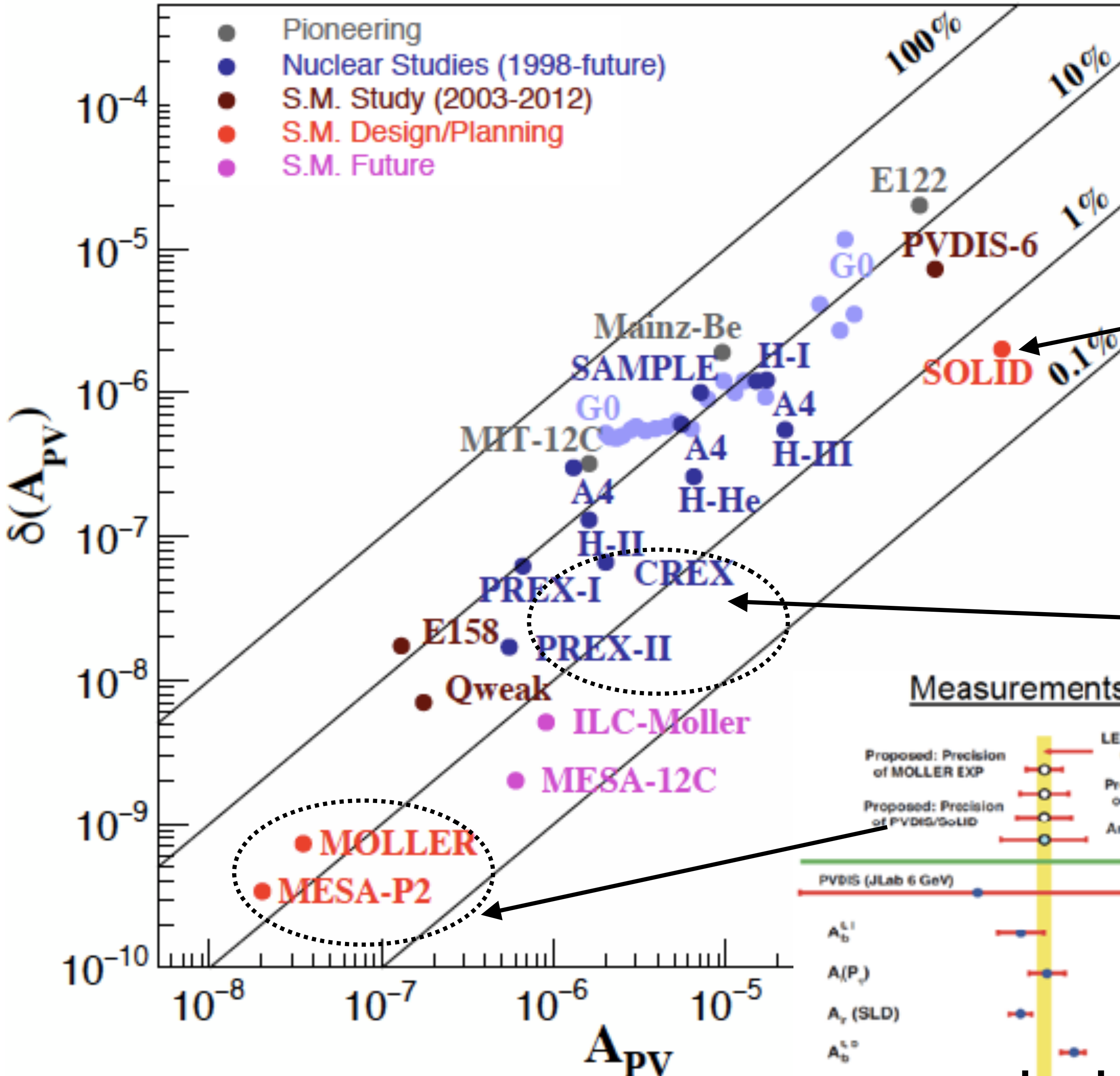
17 talks (6 theorists and 11 experimentalists)

- PV electron scattering (2 expt.),
- Exotic spin-dependent forces (1 expt., 1 theory)
- n electric dipole moments (3 expt., 1 theory)
- p, D EDM (2 expt., 1 theory)
- nuclear EDM (1 theory)
- charmed baryon EDM (1 theory/expt.)
- Atomic EDM (3 expt., 2 theory)
- Dark matter/axions (2 expt., 2 theory)

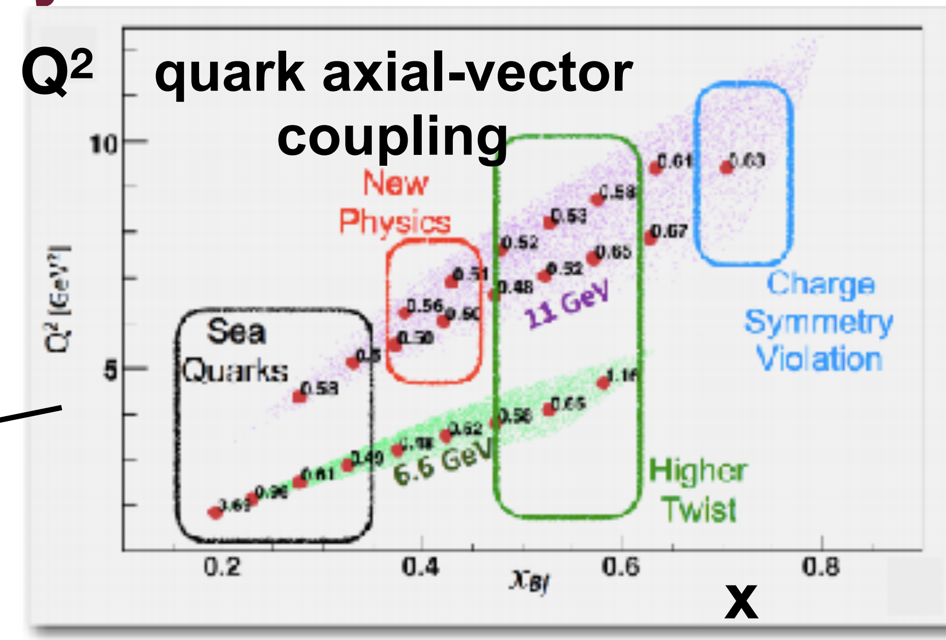
Dipangkar Dutta (MSU), Andreas Wirzba (FZ Jülich)

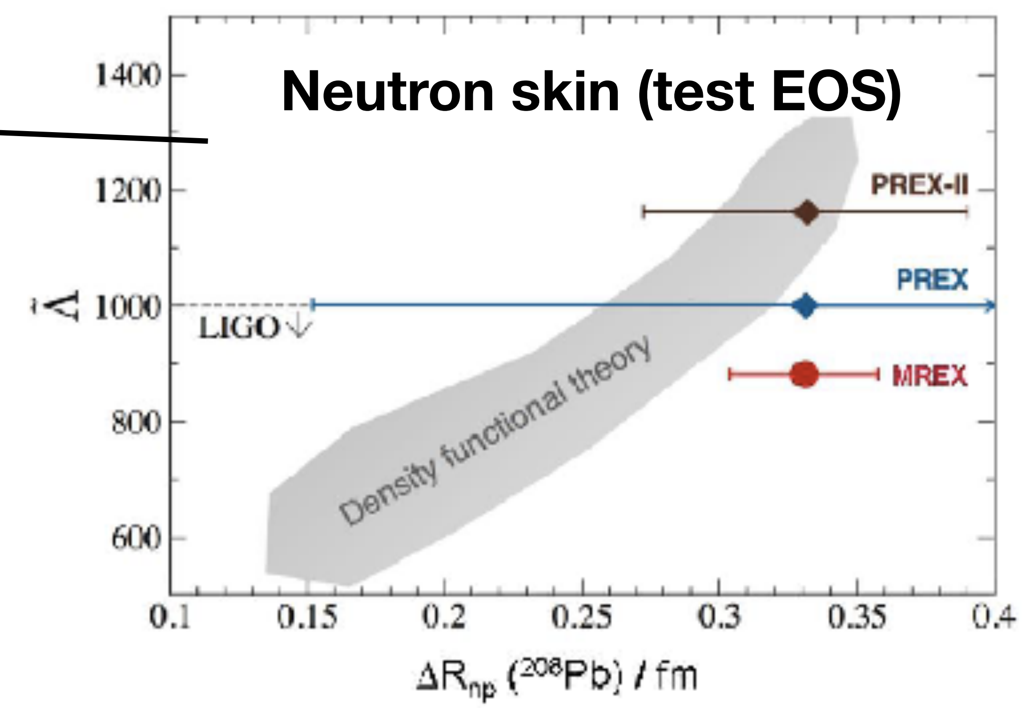
Parity violating electron scattering

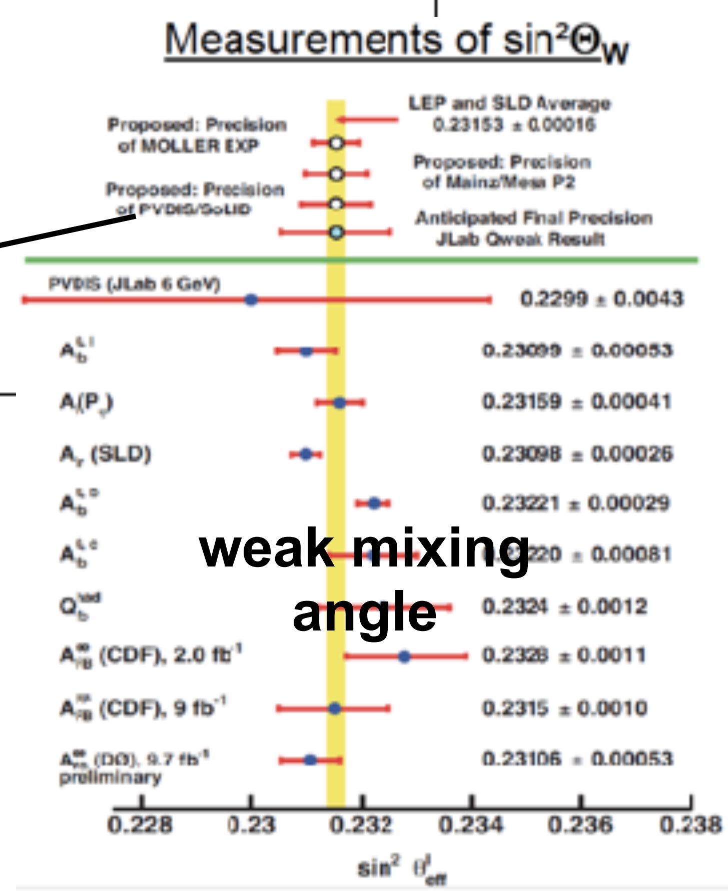
long history of improving precision and discovery



Upcoming Measurements

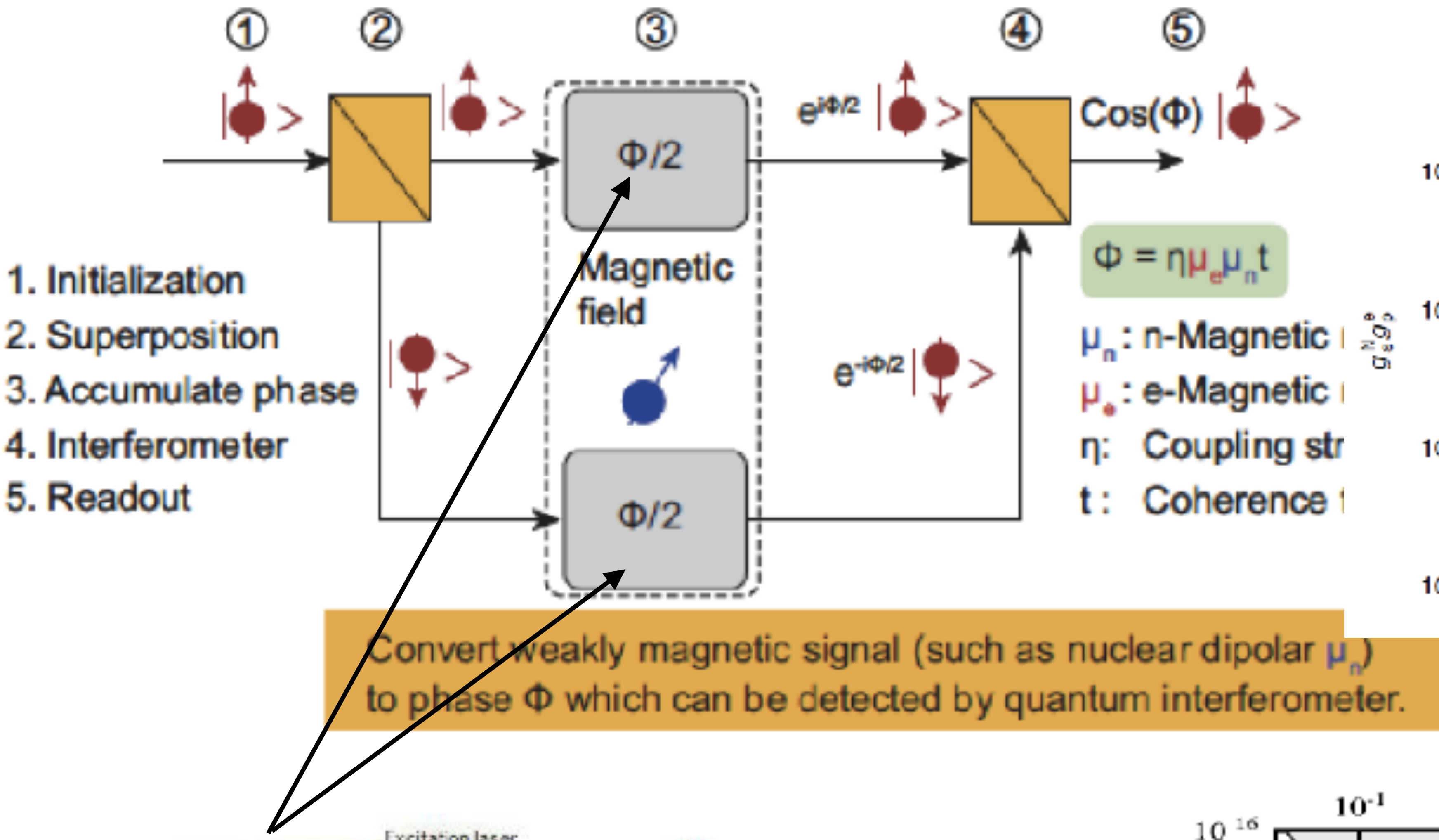




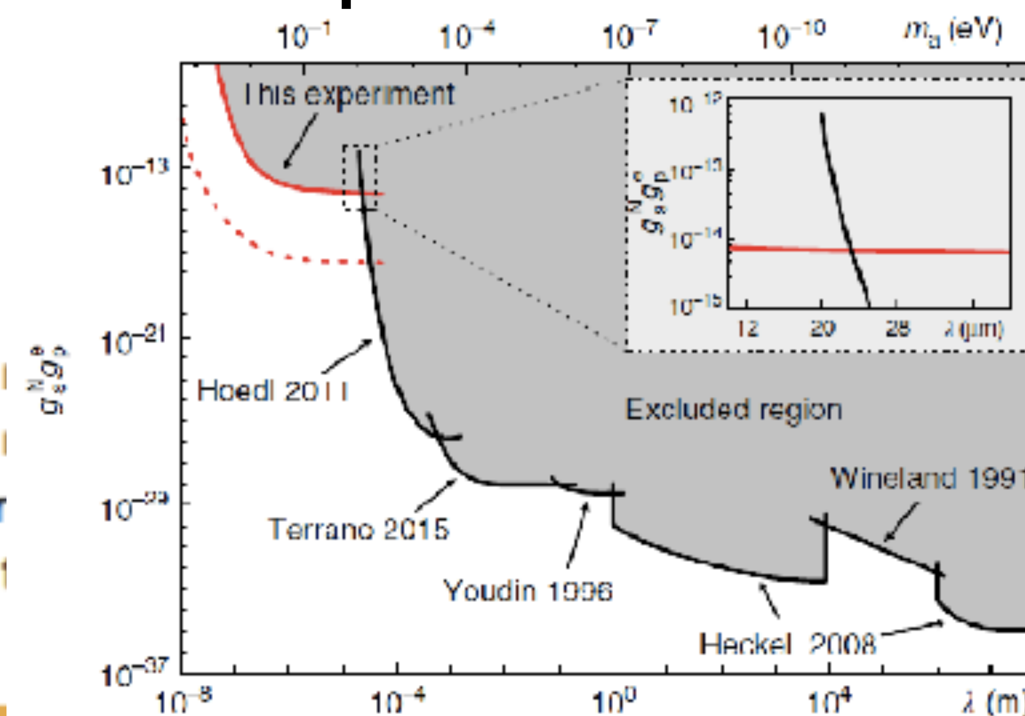


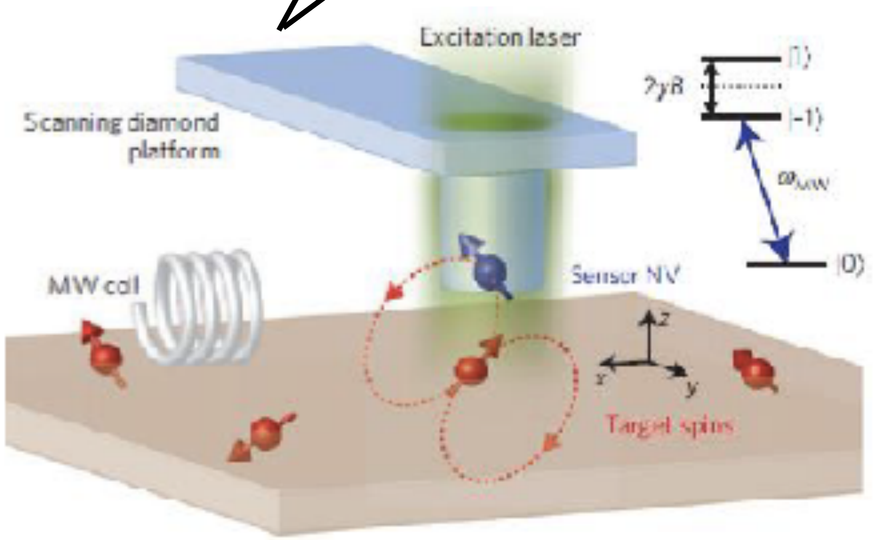
Ciprian Gal (UVa)
Sebastian Baunack (Mainz)

Exotic Spin Dependent Forces

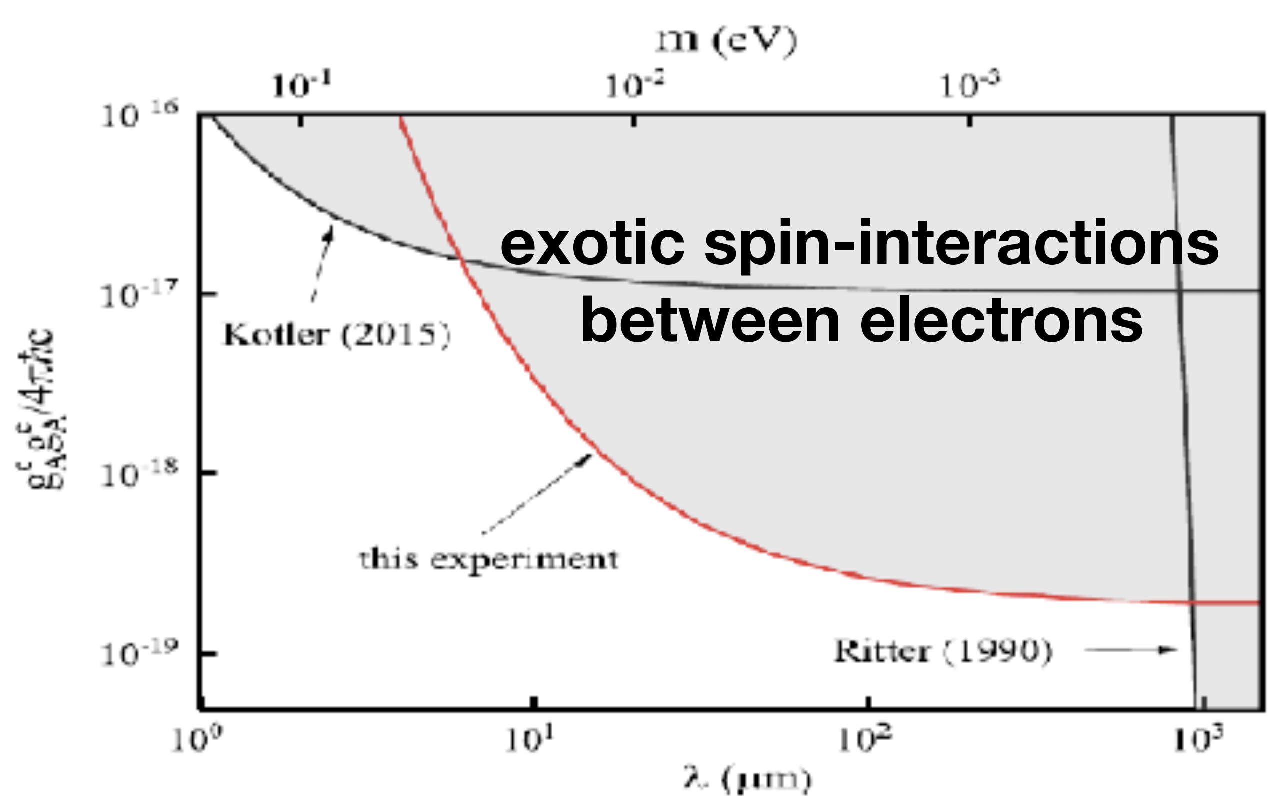


spin-mass interactions





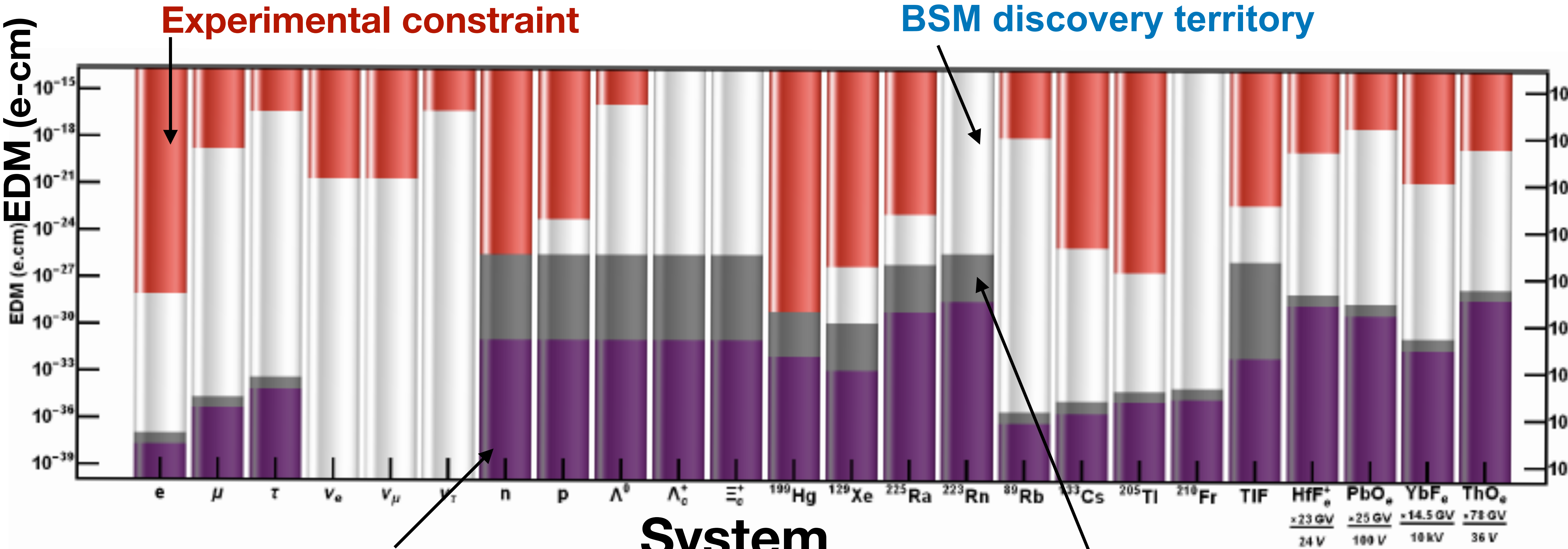
Nat. Phys. 9, 215 (2013)



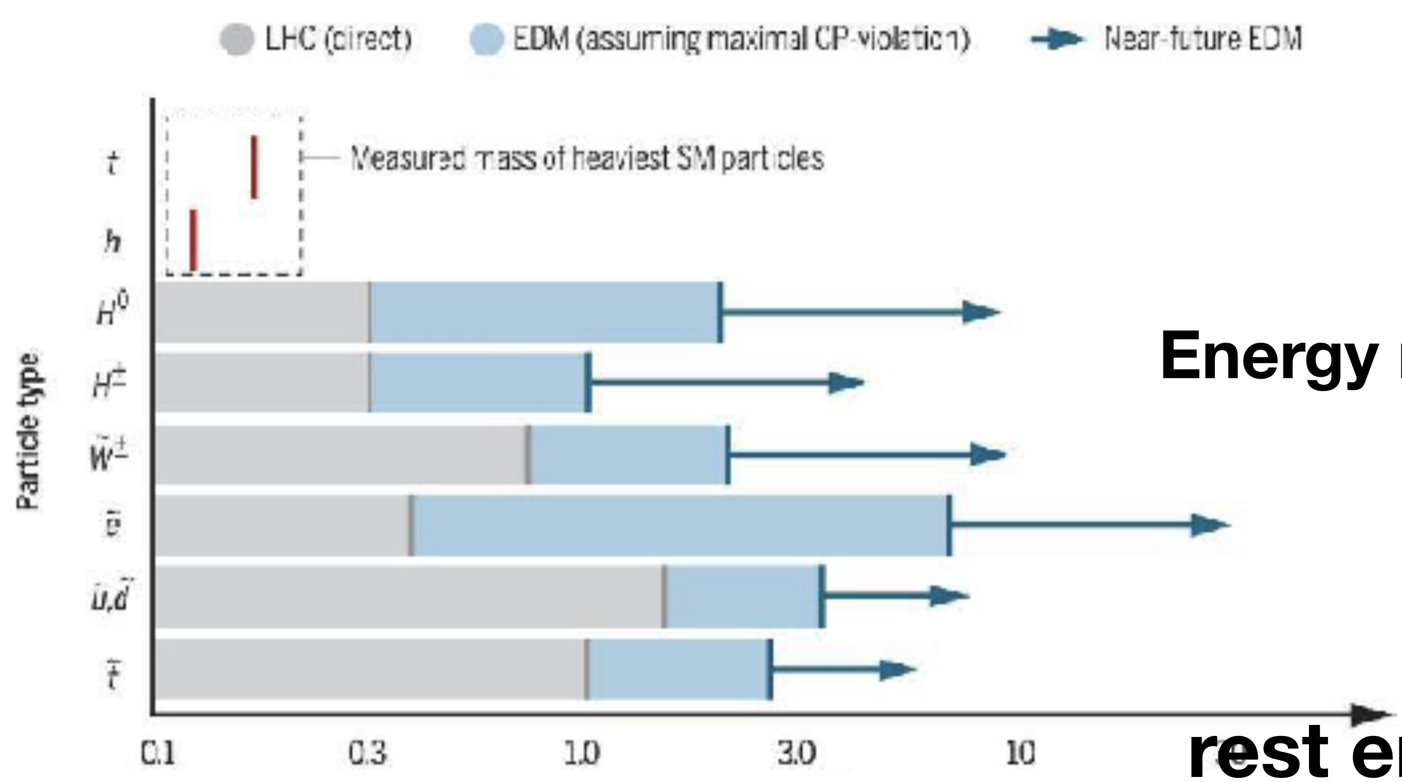
NV based diamond nanoscale magnetometer

Xing Rong (USTC, China)

EDM searches have tremendous discovery potential



Klaus Kirch (PSI)



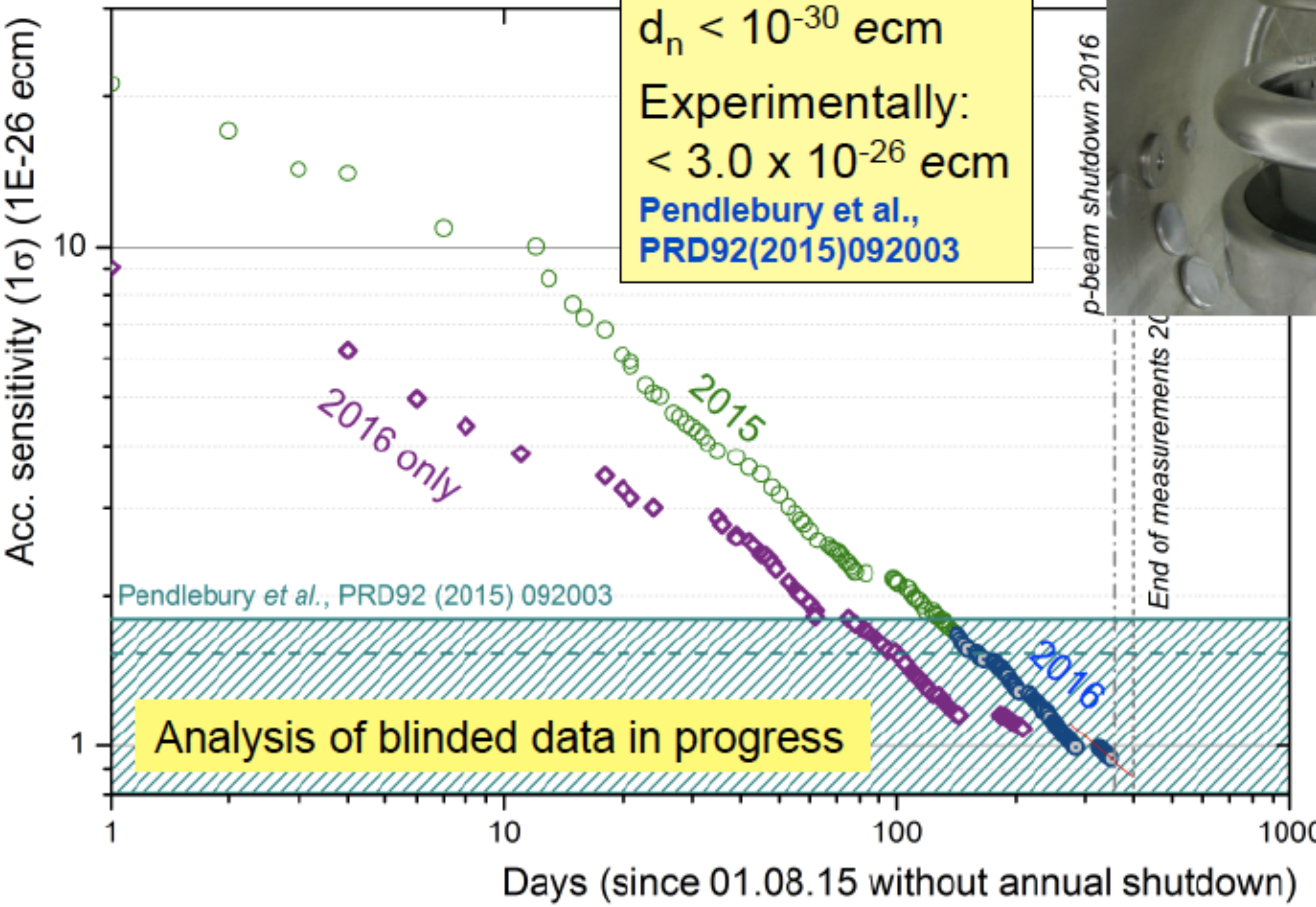
Energy reach of EDM searches

Matt Dietrich (ANL)

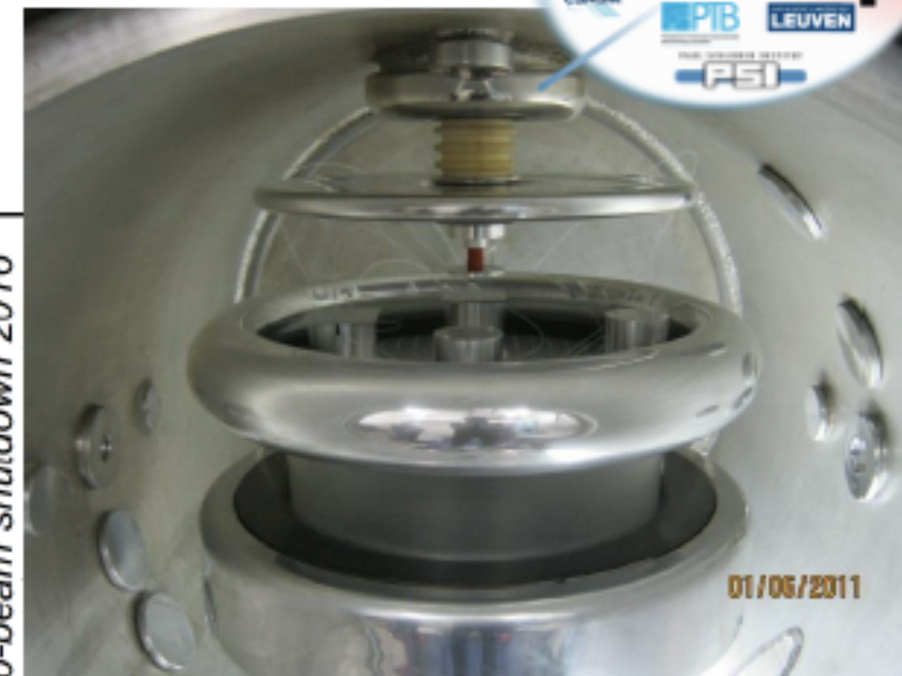
The neutron EDM itself …

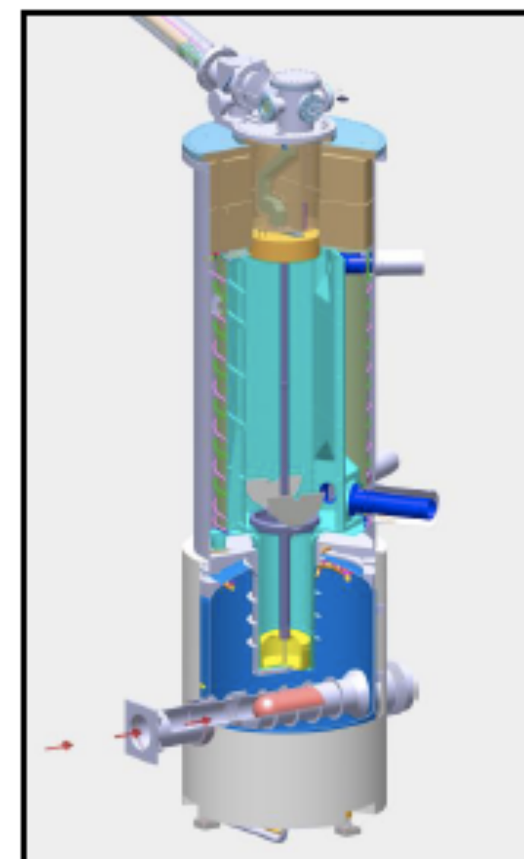
Expect from SM:
$d_n < 10^{-30}$ ecm

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



Analysis of blinded data in progress





Neutron EDM projects

	RAL SUSSEX ILL (Grenoble, FR)	PSI (Villigen, CH)		TUM ILL (Grenoble, Munich)		LANCSE EDM (Los Alamos, US)	SNS EDM (Oakridge, US)	PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)		TRIUMF (Vancouver, CA)	
temperature	**RT**	RT		RT	0.7 K	RT	0.7 K	**RT**		RT	
comag	**Hg**	**Hg**		none		Hg	^{3}He	**none**		Xe+Hg	
source	**reactor, turbine**	**spall., sD_2**		reactor, cold beam, ^{4}He		D2	spall, internal ^{4}He	reactor, turbine, ^{4}He		spall., ^{4}He	
nr of cells	**1**	**1**	2	2	> 100	1	2	2	>2	1	2
[UCN/cc]	**2**	**3**	5	10	1000	~ 50	125	**4**	10^4	700	
goal [e·cm]	**$3\cdot10^{-26}$**	$1\cdot10^{-26}$	$1\cdot10^{-27}$	$2\cdot10^{-27}$	$< 10^{-27}$	few 10^{-27}	$2\cdot10^{-28}$	$5\cdot10^{-26}$	$<1\cdot10^{-27}$		$1\cdot10^{-27}$
date	**2006**	**2017**	2019	2019	2021+	2019	2022	2015	2022	2017	2020
status	**done**	RAL exp. NEW LIMIT SOON $\sim1.10^{-26}$	new	Setup at ILL started: ‚PanEDM'		Sucessful source upgrade	Critical Component Demonstration			FIRST UCN OBSERVED from prototype source (2017)	

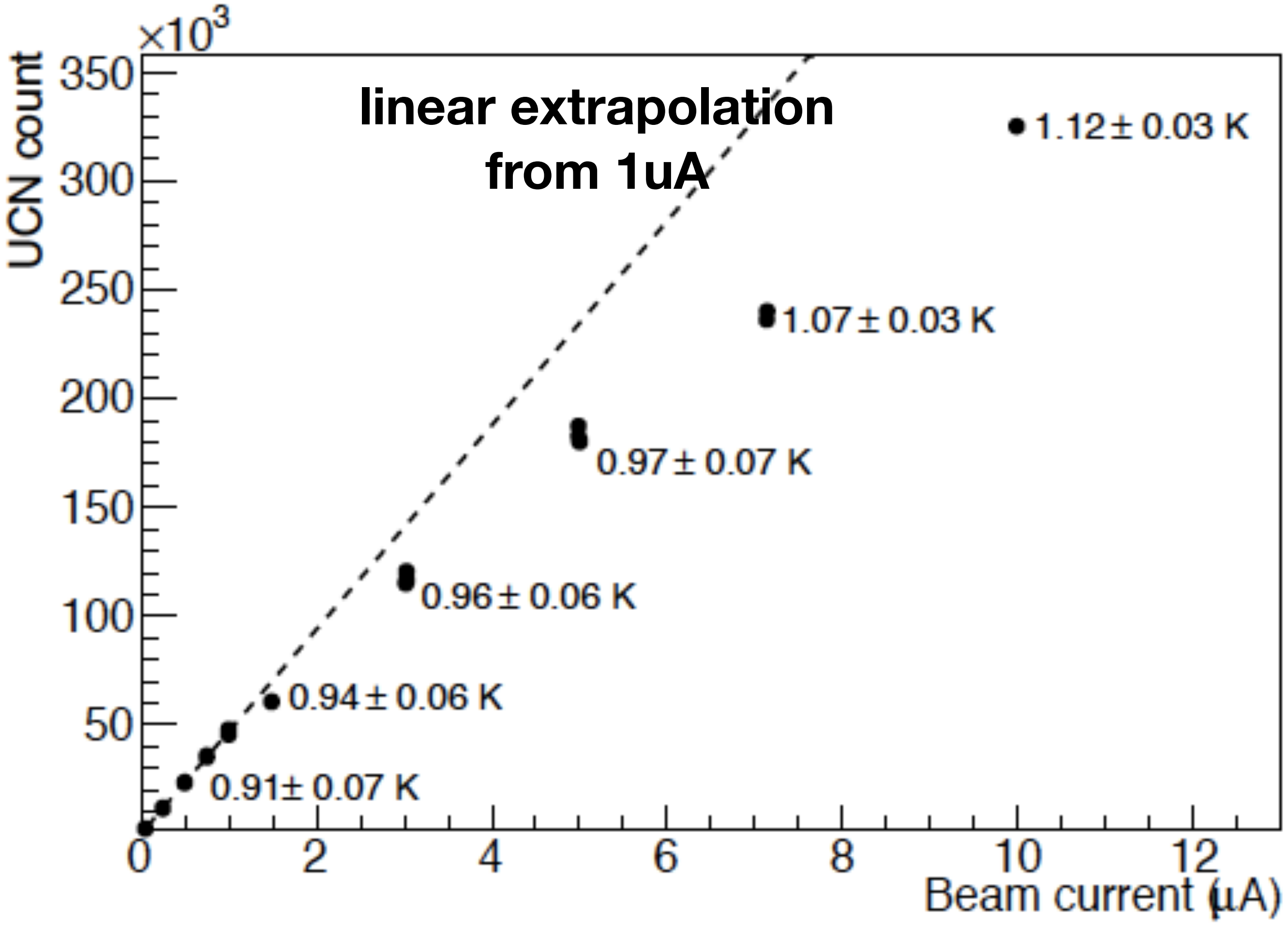
+ Crystal EDM (Nagoya)
+ Beam EDM (Bern)

Phase -II is projected to achieve 1.5×10^{-29} e-cm

Peter Fierlinger (TUM)

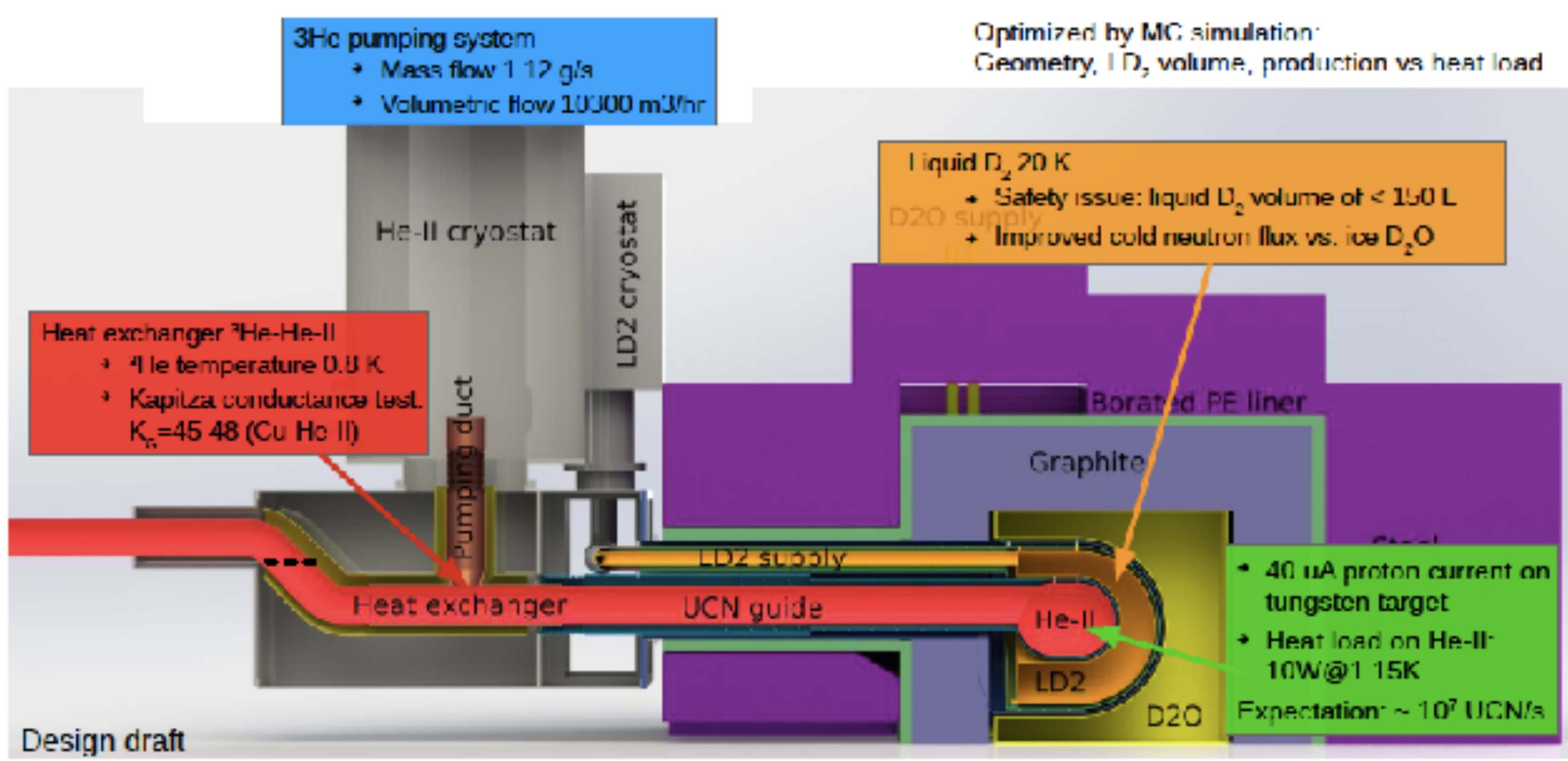
New Kid on the Block (TRIUMF UCN source)

TUCAN Collaboration



Preliminary # of UCNs from prototype source for 60s of beam on target

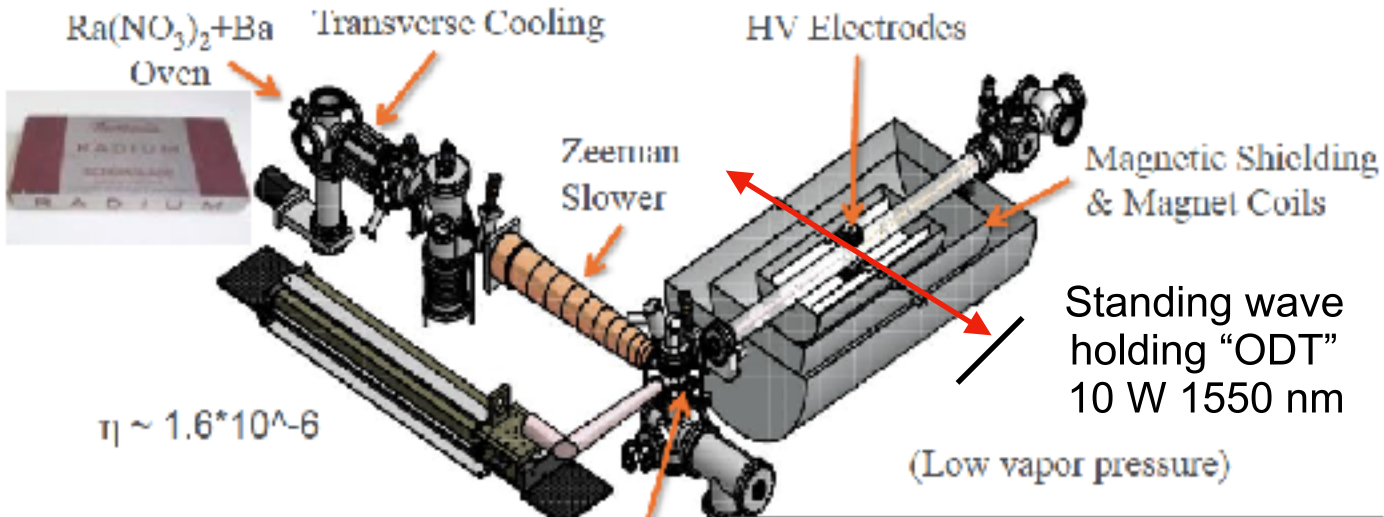
New source design
10^7 UCN/s expected

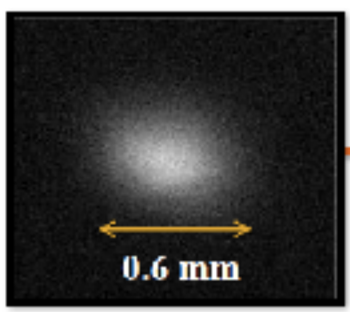


Beatrice Franke (TRIUMF)

Radium EDM

Matt Dietrich (ANL)



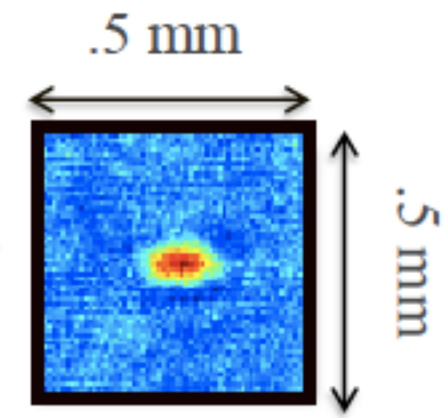


^{226}Ra MOT
200,000 atoms
40 μK

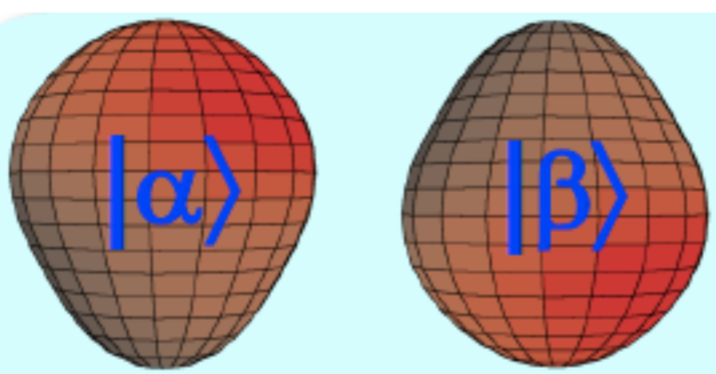
For EDM:	For Testing:
Ra-225	Ra-226
I = 1/2, J = 0	I = 0, J = 0
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

J. R. Guest et al., PRL 98 093001 (2007) 21 Argonne

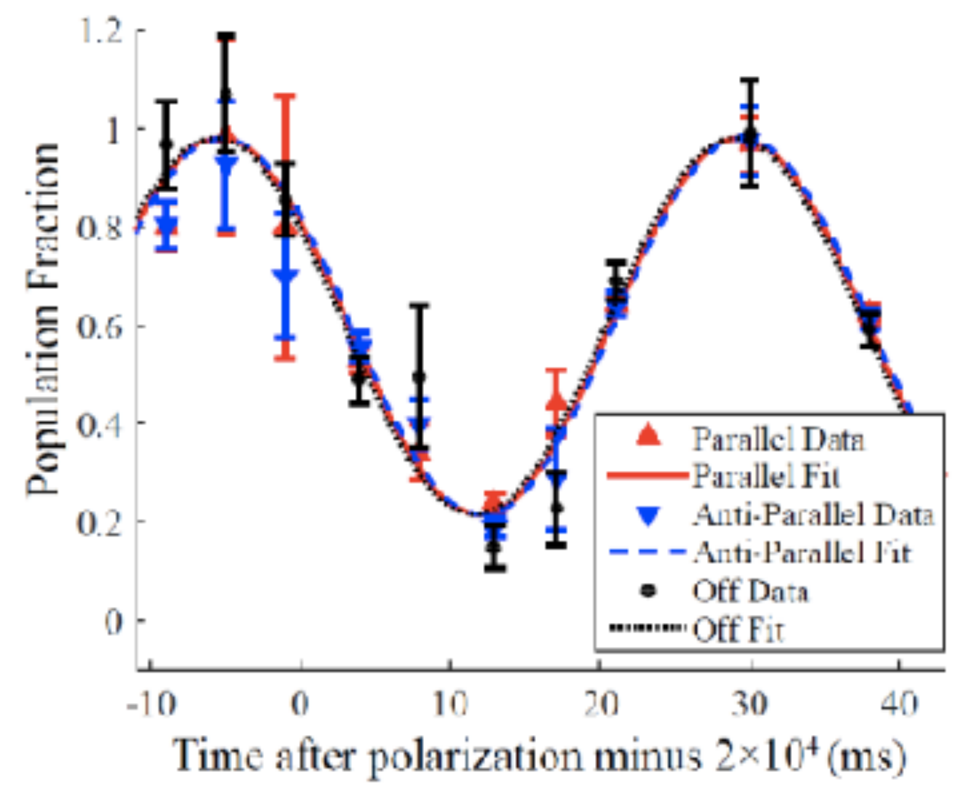
700 atoms
Ra-225



Absorption Imaging



A large quadrupole and octupole deformation results In an enhanced Schiff moment
– *Auerbach, Flambaum & Spevak (1996)*



$\chi^2/25 = 1.4$

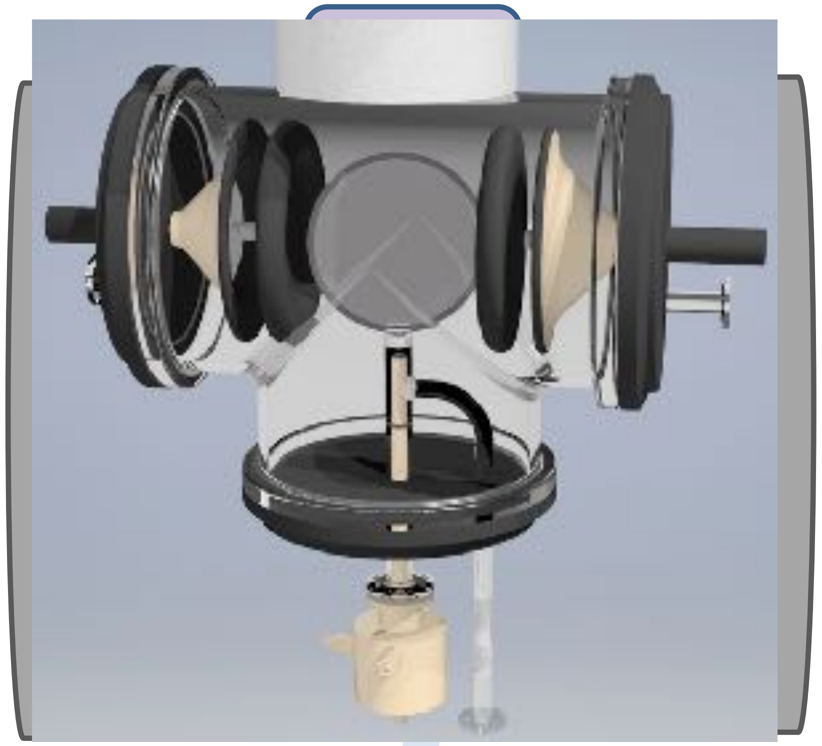
$$d_{Ra\text{-}225} = (4 \pm 6_{stat} \pm 0.2_{syst}) \times 10^{-24}\ e\text{-cm}$$

$$d_{Ra\text{-}225} < 1.4 \times 10^{-23}\ e\text{-cm}\ 95\%\ C.L.$$

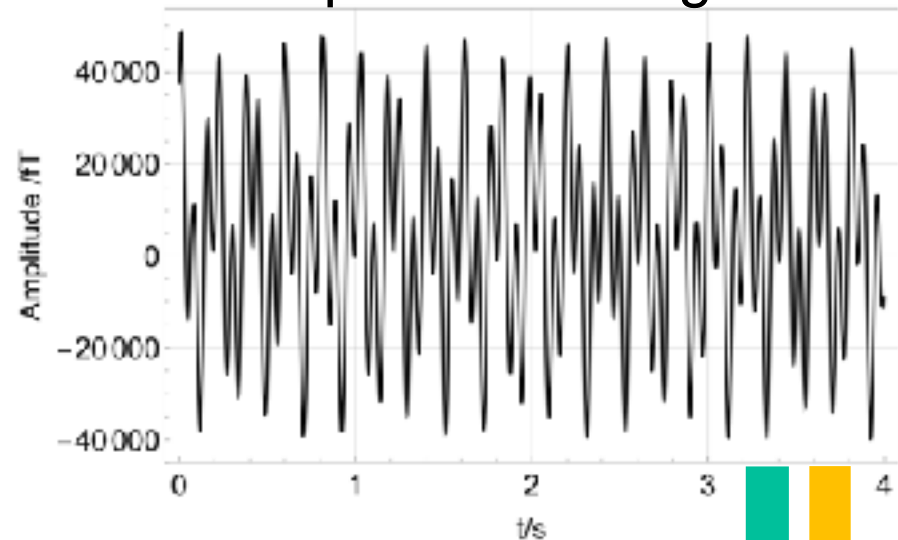
M. Bishof *et al.* PRC 94, 025501 (2016)

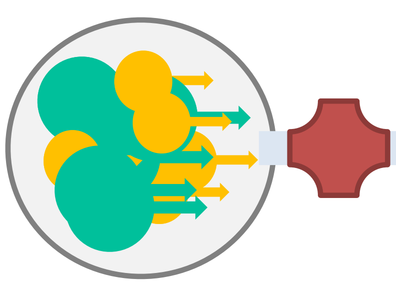
BSM searches with hyper-polarized gasses:
($^3He/^{129}Xe$ spin clocks)

W. Heil (Mainz)
Stefan Zimmer (Heidelberg)



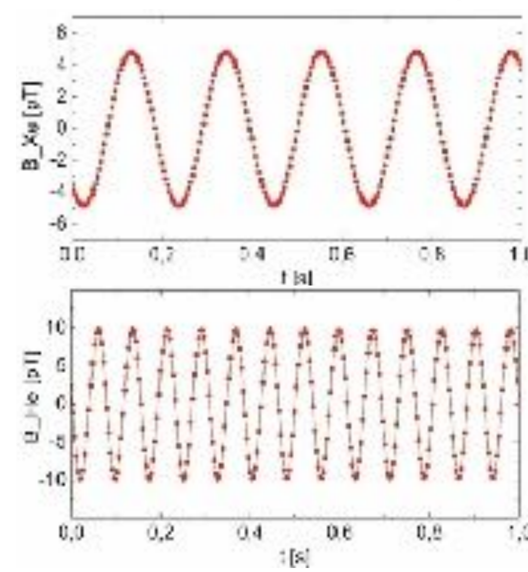
precession signal





$\vec{E}$:

$\vec{B}$: 400nT



^{129}Xe:

^3He:

<u>^{129}Xe electric dipole moment</u>

<u>(MIXe$\vec{d}$-collaboration):</u>

$$|d_{Xe}| < 1.2\times10^{-27}\ ecm\ (95\%\ CL)$$

- <u>Search for neutron spin coupling to a Lorentz and CPT-violating background field</u>

$$V(r)/\hbar = \langle \tilde{b} \rangle \hat{\varepsilon}\cdot\vec{\sigma}/\hbar \qquad \tilde{b}_\perp^n < 8.4\times10^{-34}\ GeV\ \ (68\%\ C.L.)$$

tightest constrains
in the matter sector

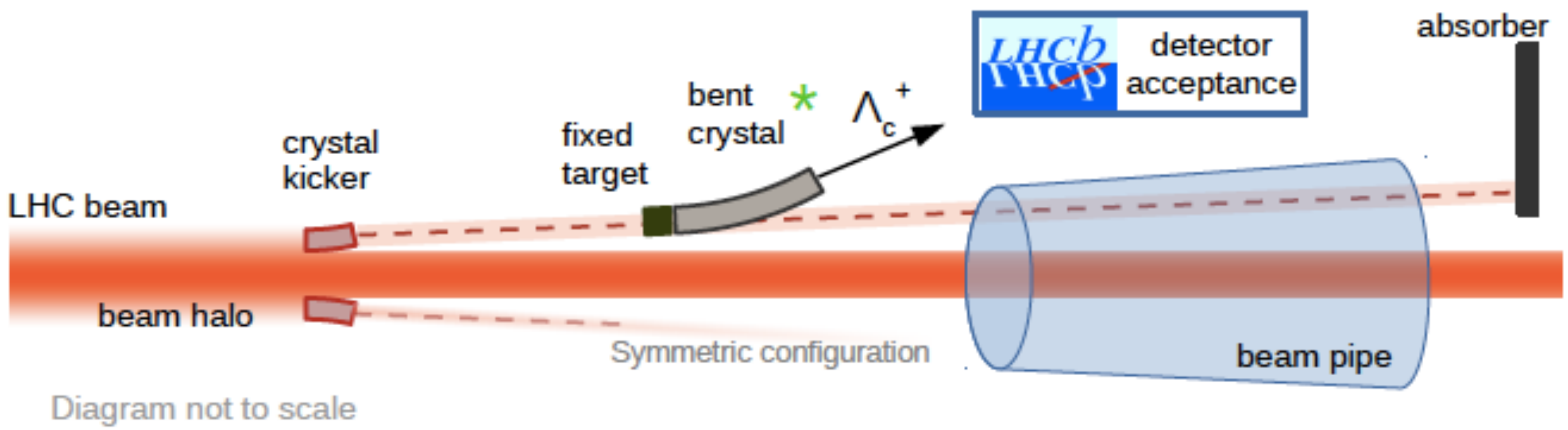
- <u>Short range spin-dependent interaction (axion search):</u>

$$V(r) = \frac{g_S g_P}{8\pi}\frac{(\hbar)^2}{m_n}(\sigma_n\cdot\hat{r})\left[\frac{1}{r\lambda}+\frac{1}{r^2}\right]e^{-r/\lambda}$$

new upper limits for $g_s^N g_p^n$
in the range 10^{-3} m < λ < 10^1 m

ARIADNE: probing QCD axion parameter space

EDM of Charmed Baryons using bent crystals @ LHCb



- How to *put* polarized Λ_c^+ inside the crystal
  - Fixed-target + bent crystal in LHCb beam pipe
  - Incident beam: 7 TeV protons extracted from LHC beam halo using bent crystals ≈ 100m upstream of the target
  - Feasibility proven by UA9 collaboration Physics Letters B 758 (2016) 129
  - Initial **transversal polarization** $\mathbf{s_0} \approx$ **50%**
- How to measure the spin precession
  - Angular distribution of the decay $\Lambda_c^+ \to pK^-\pi^+$

$$dN/d\Omega \propto 1 + \alpha \mathbf{s} \cdot \mathbf{k}$$

Phys. Lett. B 757 (2016) 426
CERN-SPSC-2016-030
Eur. Phys. J. C 77 (2017) 181
JHEP 1708 (2017)
Eur. Phys. J. C 77 (2017) 828

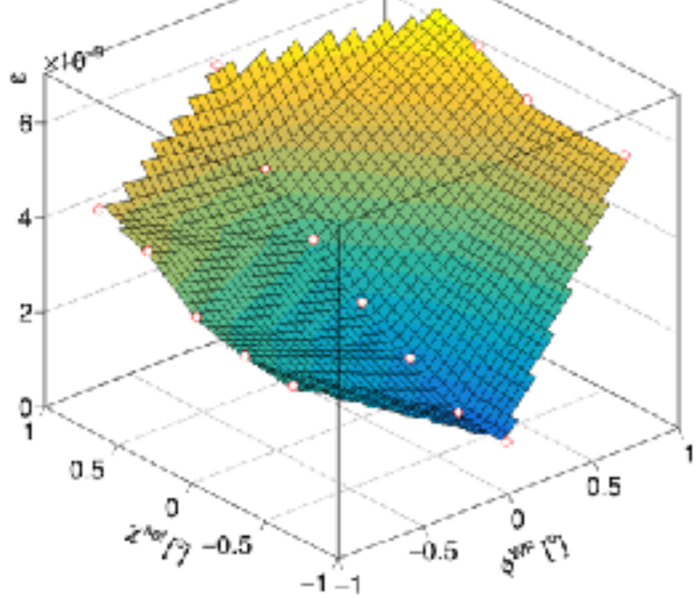
- With **few weeks** of data taking ($\approx 10^{15}$ protons on target) the EDM sensitivity would reach $\sigma_\delta \approx 10^{-17}$ **ecm**

- The Λ_c^+ **magnetic moment** can be measured, for the first time, with $\sigma_{g-2} \approx 4 \times 10^{-3}$

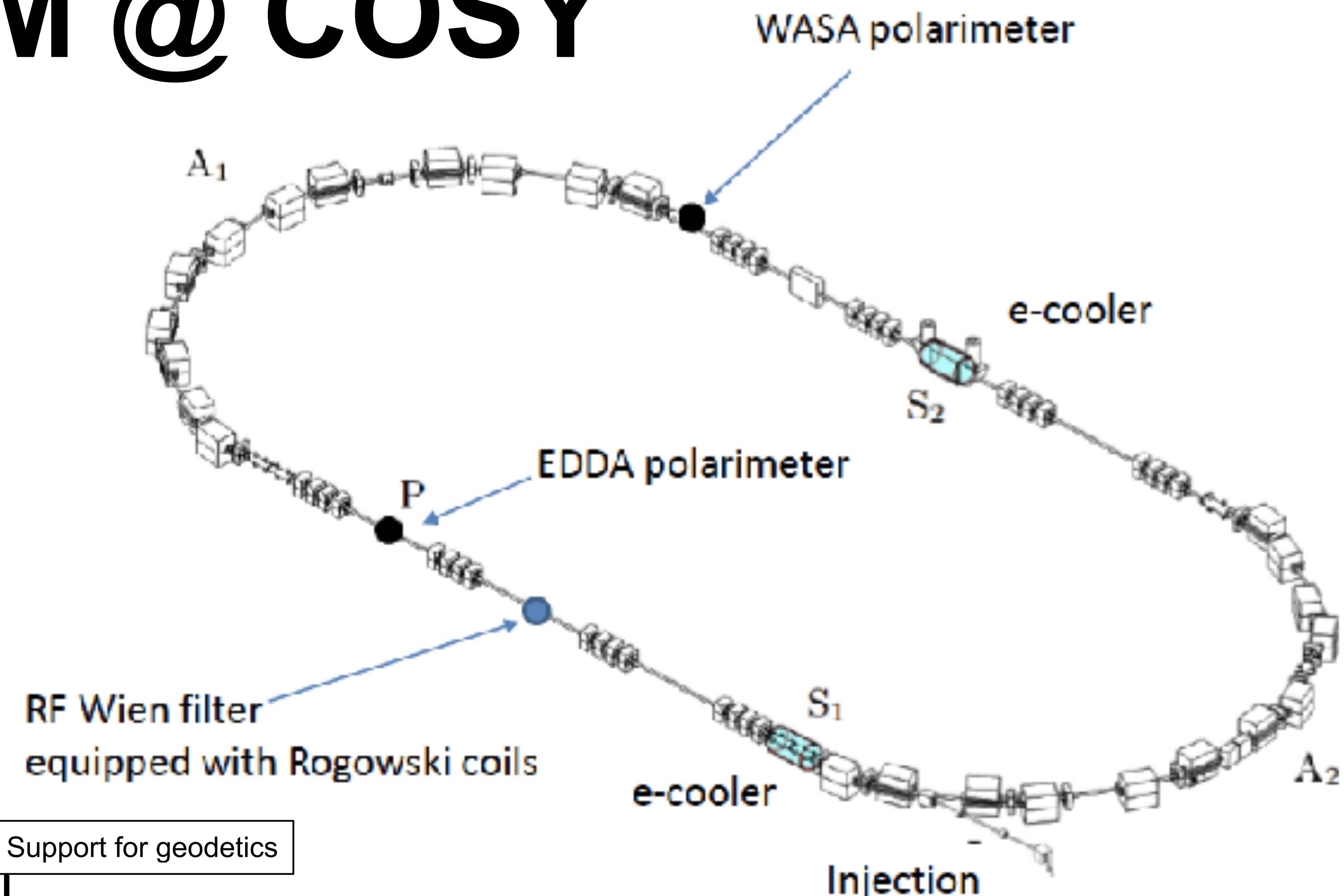
Joan Ruiz Vidal (Valencia)

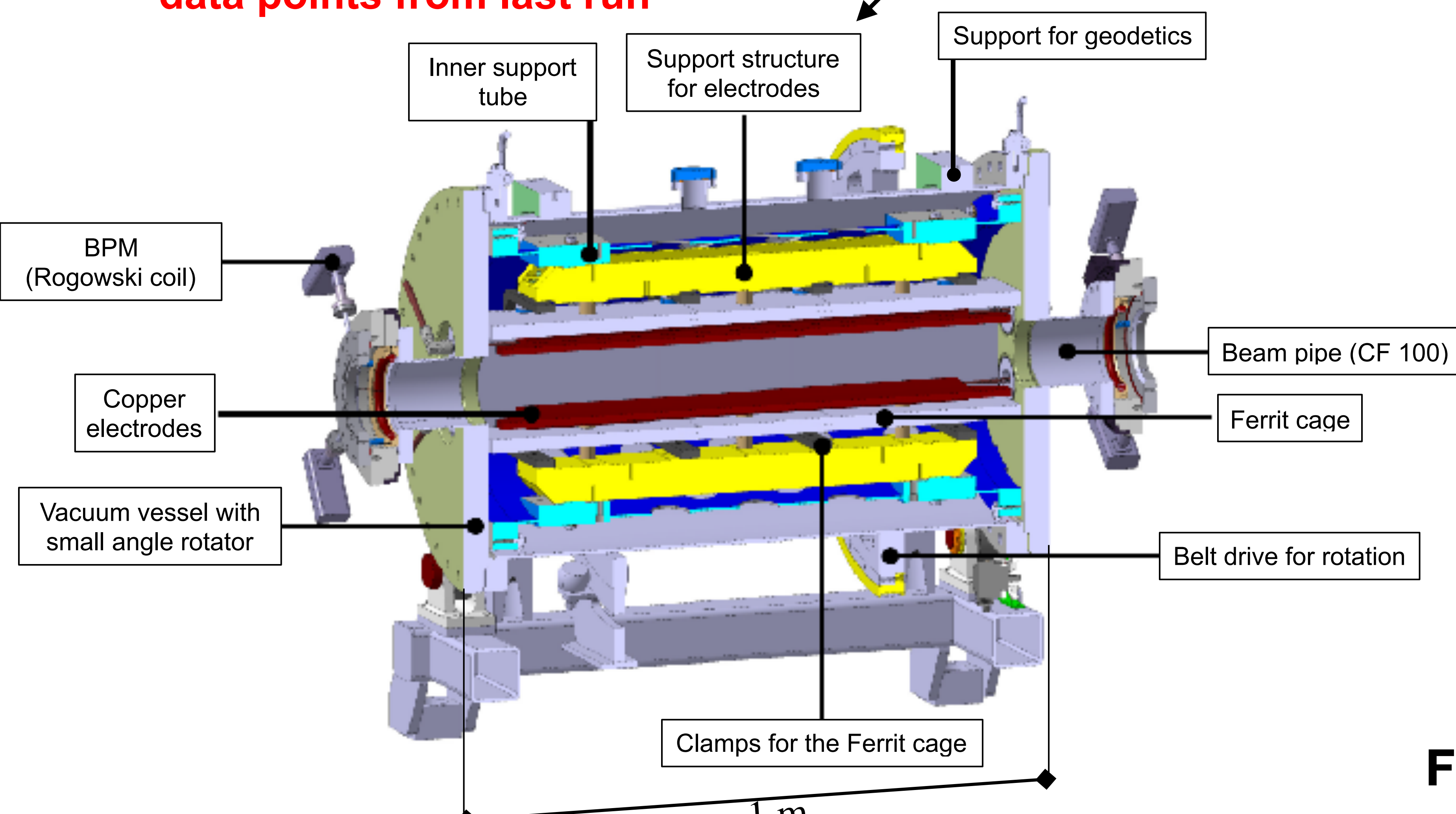
^{2}H EDM @ COSY

Resonant Build-up with RF Wien Filter



data points from last run





Next steps:
Improve beam position monitors & Siberian snake.

First EDM measurement with deuterons (Nov./Dec. 2018)

Frank Rathmann (FZ Jülich)

What can theory (lattice) say about the nEDM?

Contribution of quark EDM to neutron EDM

Rajan Gupta (LANL)

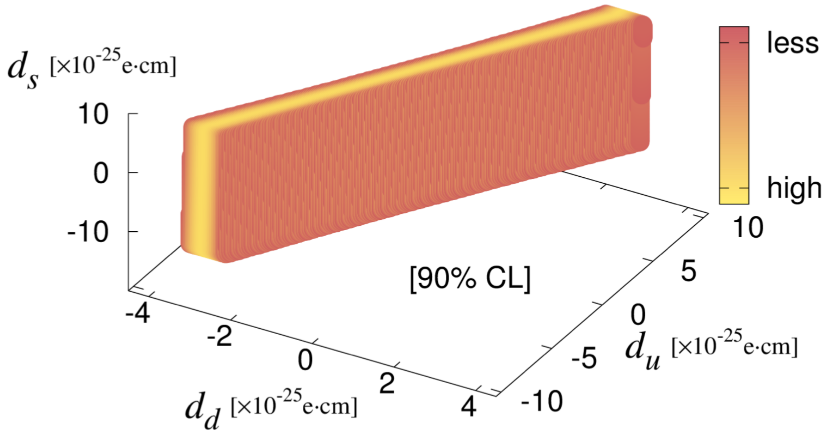
$$g_T^d = 0.784(28); \quad g_T^u = -0.204(11); \quad g_T^s = -0.0027(16)$$

2015 results: $g_T^d = 0.774(66); \quad g_T^u = -0.233(28); \quad g_T^s = -0.008(9)$

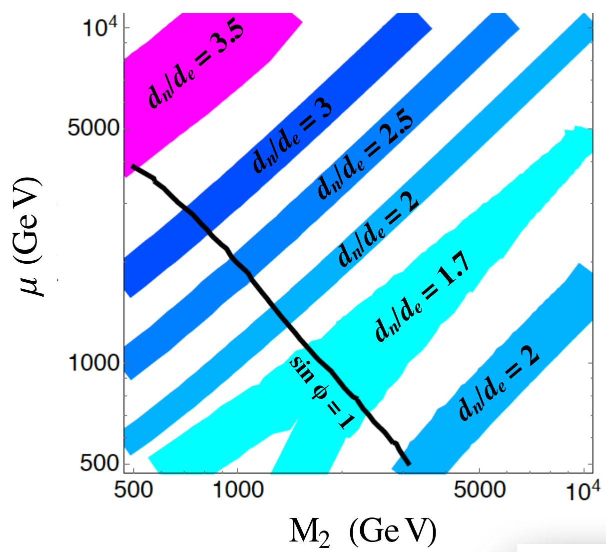
$$d^{\text{qEDM}}_{\text{n, lattice}} \approx \frac{3}{5}\, d^{\text{qEDM}}_{\text{n, quark model}}$$

Relation between charges g_T^q, couplings d_q^γ, and the neutron EDM d_n

$$d_n = d_u^\gamma g_T^u + d_d^\gamma g_T^d + d_s^\gamma g_T^s + \cdots$$



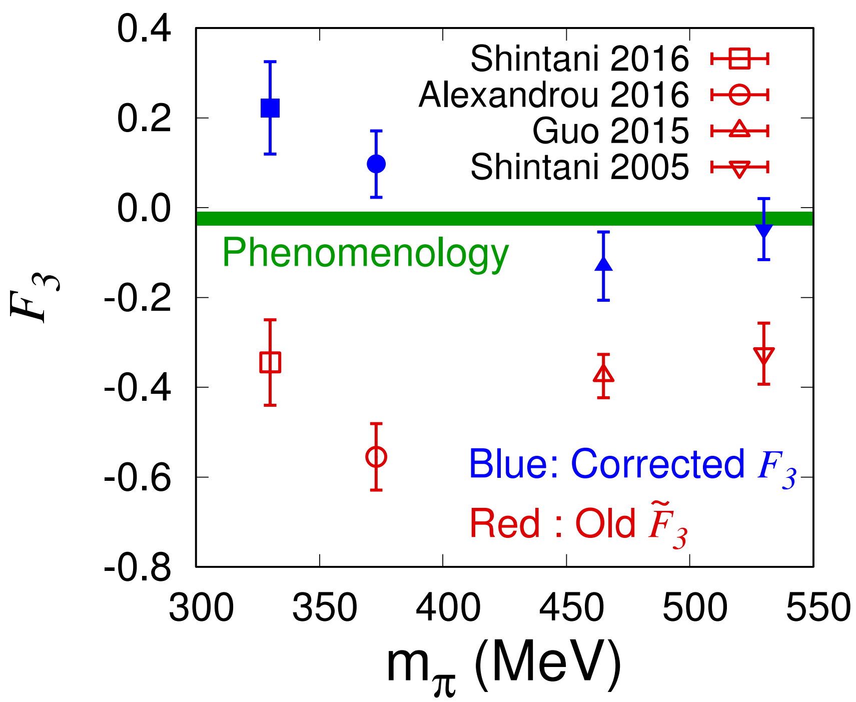
Constraint on d_n in Split SUSY



This is the only result so far on nEDM from lattice QCD

QCD θ term:

$$F_2 = \cos(2\alpha)\tilde{F}_2 - \sin(2\alpha)\tilde{F}_3$$
$$F_3 = \sin(2\alpha)\tilde{F}_2 + \cos(2\alpha)\tilde{F}_3$$

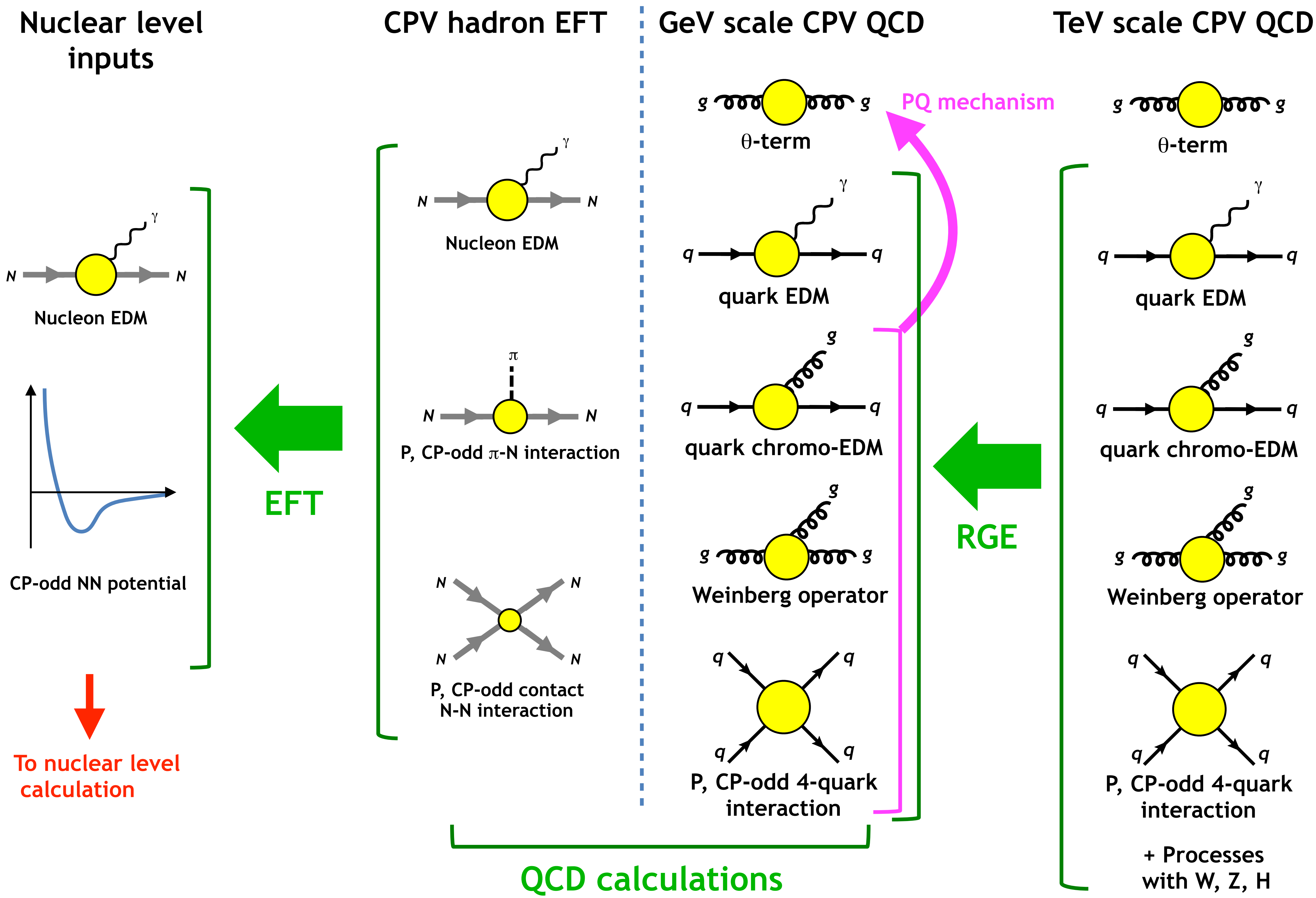


- **QCD θ-term**
  Actively being calculated and progress at $M_\pi > 330$ MeV; need better variance reduction to get precision at $M_\pi = 135$ MeV
- **Quark EDM**
  Calculated: $g_T^d = 0.784(28)$; $g_T^u = -0.204(11)$; $g_T^s = -0.0027(16)$
- **Quark Chromo EDM**
  Exploratory studies show signal in connected contribution; next step: disconnected diagrams & renormalization/mixing
- **Weinberg Three-gluon Operator**
  Exploratory studies just started
- **Four-quark Operators**
  Not yet explored

Should have better estimate of accuracy achievable in 1-2 years

Nodoka Yamanaka (IPN Orsay)

Hadronic CP violation: from QCD to hadron level



EDM of light nuclei and counting rule

EDM of light nuclei can be measured using storage rings
⇒ No Schiff's screening
⇒ Very high sensitivity to new physics expected

- Isovector coupling obeys a counting rule

$$d_A^{(pol)} \sim d({}^{2/3}H) + n \times 0.005\, G_\pi^{(1)}\, e\ \mathrm{fm}$$

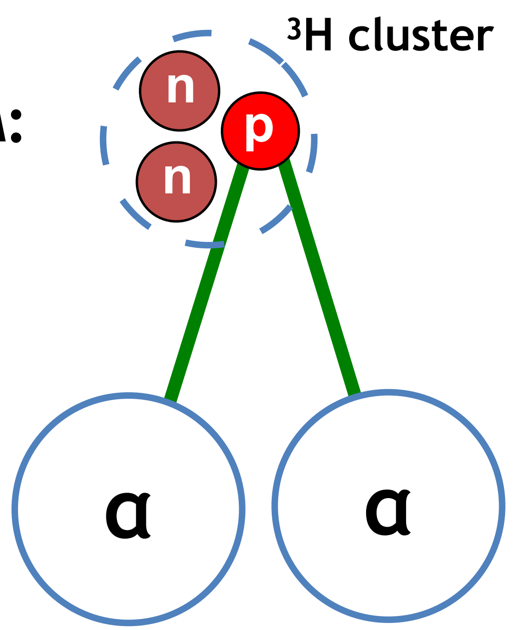
EDM of cluster with open shell

α-N polarization (times # α-N combinations)

⇒ Explained by the cluster structure

NY, T. Yamada, Y. Funaki, in preparation

Example of ^{11}B EDM:



$d_{^{11}B} = 0.02\, G^{(1)}_\pi\, e$ fm

- Isoscalar and isotensor appears from single valence nucleon and ^{3}H cluster (vanish for α-N polarization)

Spin in curved space-time and gravity induced false EDM effects

Kolya Nikolaev (Landau ITP)

The Earth as a laboratory: storage rings rests on the terrestial surface.

No real need in full machinery of General Relativity: weak field approximation is OK: it suffices to know the free fall acceleration $\vec{g}$, the Earth rotation is a fairly trivial effect.

Two principal effects:

- The spin-orbit interaction in the Earth gravitational field (the de Sitter precession, aka the geodetic effect (1916))
- Focusing EM fields are imperative to impose the closed paricle orbit in a storage ring compensating for the particle weight: first derivation by Silenko & Teryaev (2005) for magnetic case
- The both effects have similar structure and both produce false EDM signal in frozen spin pure electric ring
- No explicit separation of the two in otherwise fundamental Orlov et al. (2012)

False EDM from gravity induced imperfection

Kolya Nikolaev (Landau ITP)

- Absolute evil in an all electric EDM ring - false EDM signal

- Obukhov et al. (2016))

$$\vec{\Omega}_{gE} = \frac{1 - G(2\gamma^2 - 1)}{\gamma c^2}[\vec{v} \times \vec{g}]$$

- Upon the frozen spin constraint $v^2 = \frac{1}{1+G}$

$$\vec{\Omega}_{gE} = \frac{g\sqrt{G}}{c}\vec{e}_r$$

- First derived by Orlov et al. (2012) by brute force solution of GR equations without explicit separation of the spin-orbit and focusing effects.

- Similar derivation by Laszlo et al. arXiv: 1803.01395 [gr-qc], Wedn., A11, 17:55

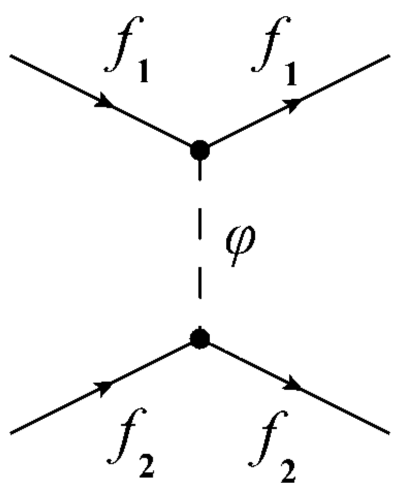
- Orlov et al (2012): gravity under full control , false effects can be cancelled out with counterrotating beams

→ **Standard Candle to study systematics**

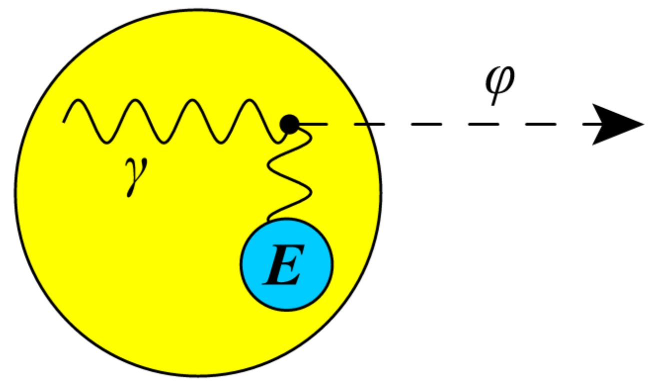
Yevgeny Stadnik (JGU Mainz)

Axions & ALPs, scalar-pseudoscalar interactions, pseudo-magnetic fields

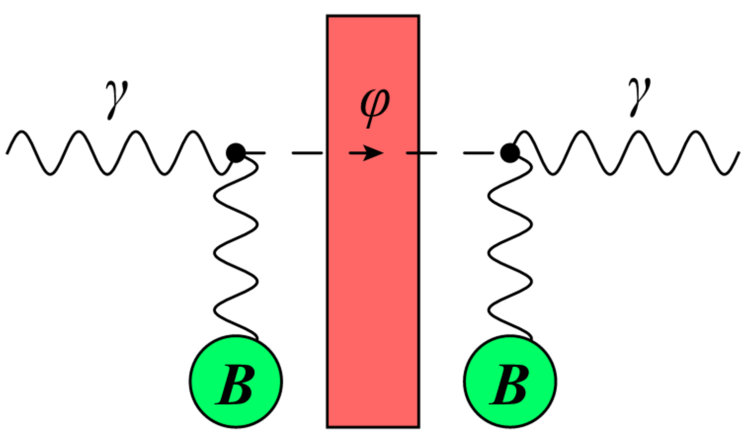
Manifestations of Dark Bosons



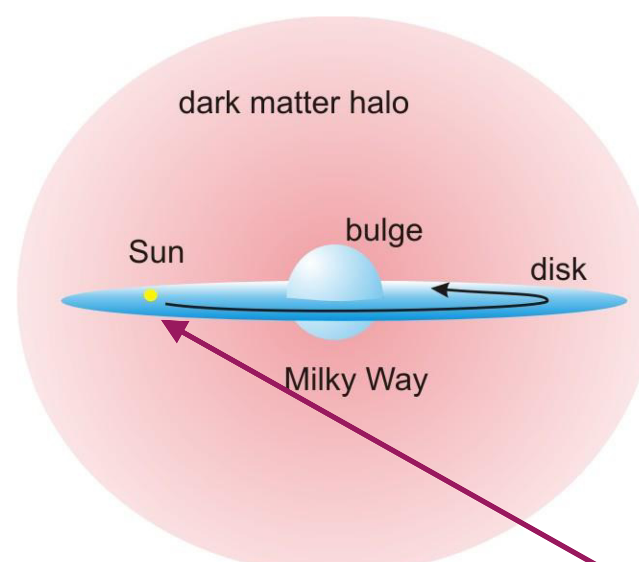
New forces



Stellar emission



Interconversion with ordinary particles



Dark matter

$\rho_{DM} \approx 0.4$ GeV/cm^3

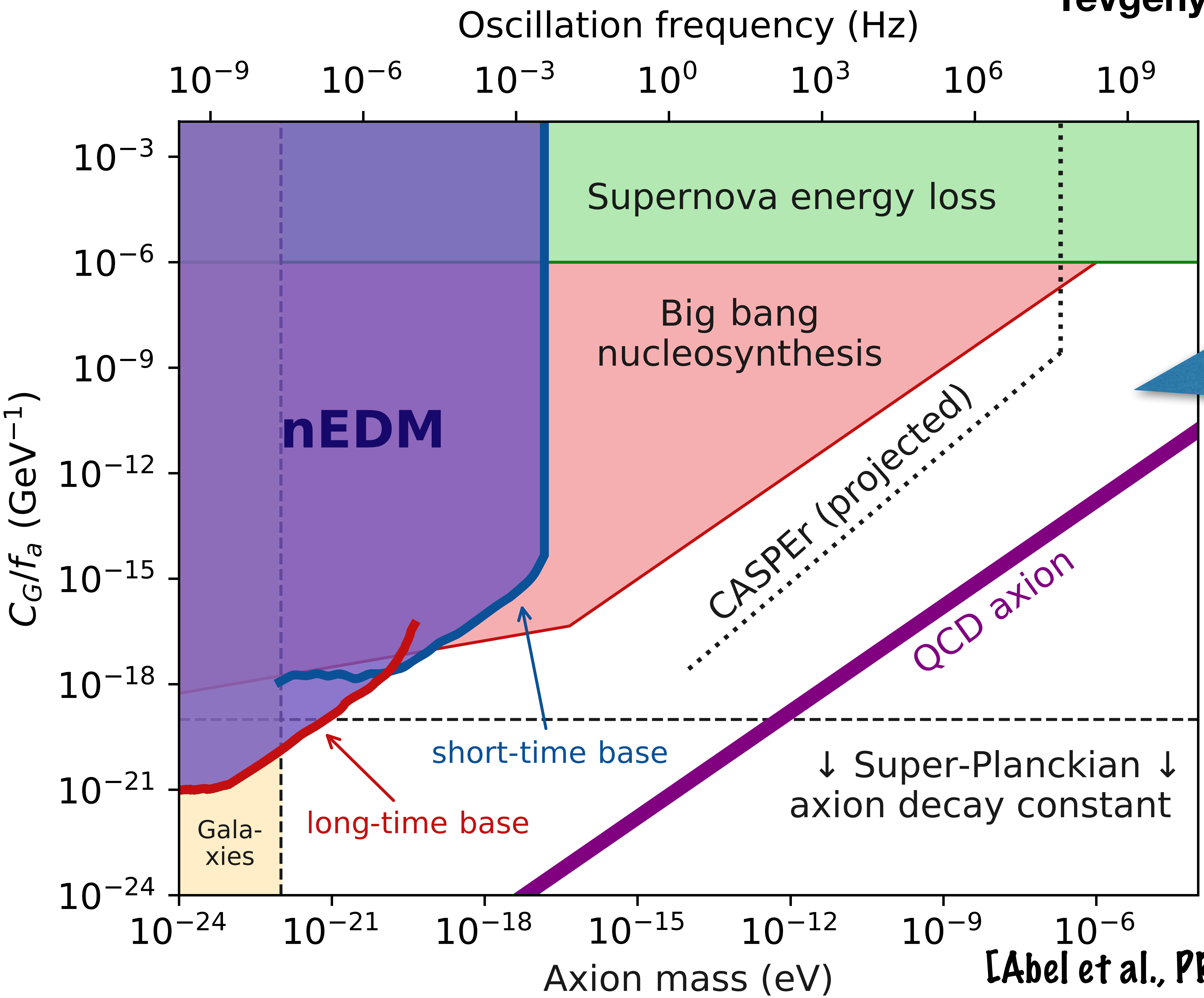
$v_{DM} \sim 300$ km/s

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: **[nEDM collaboration, Abel et al., PRX 7, 041034 (2017)]**

3 orders of magnitude improvement!

Yevgeny Stadnik (JGU Mainz)



[Abel et al., PRX, 2017]

Storage Ring see Frank Rathmann's plenary talk

,

Susan Gardner (U Kentucky)

Our dark-dominated universe and its baryon asymmetry speaks to possible **hidden (or visible?!)** particles, interactions, symmetries and more that we may yet discover

Such new physics could arise at either

i) **high energies** with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary

– or –

ii) **low energies** with **very weak** couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!

New High or Low Energy Physics?

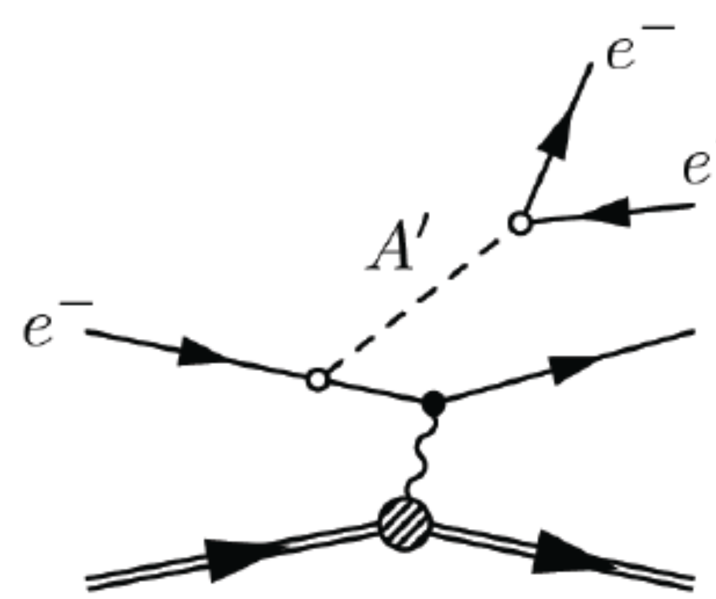
With new low energy degrees of freedom (dof) new dimension 4 operators appear....

Including SM dof act as "portals" to a hidden sector

$$\mathcal{L}_{\dim\leq 4} = \frac{\kappa}{2} V^{\mu\nu} F'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N$$

[Batell, Pospelov, and Ritz, 2009; Bjorken, Essig, Schuster, Toro, 2009]

- Vector Portal
- Higgs Portal
- Neutrino Portal



Hunting Hidden Forces....

Much focus on the dark photon A′ & the **vector portal**…

note impact on μ g-2 (only simple A′ excluded) [Pospelov, 2009]

Susan Gardner (U Kentucky)

Mechanisms of 0ν ββ decay

Why the energy scale of B-L violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \lambda v_{\rm weak}^2/\Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\rm weak}$, then naturally $m_\nu \ll m_f$! N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that m_ν is small just because $d \gg 4$ and Λ need not be so large.

[EFTs: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

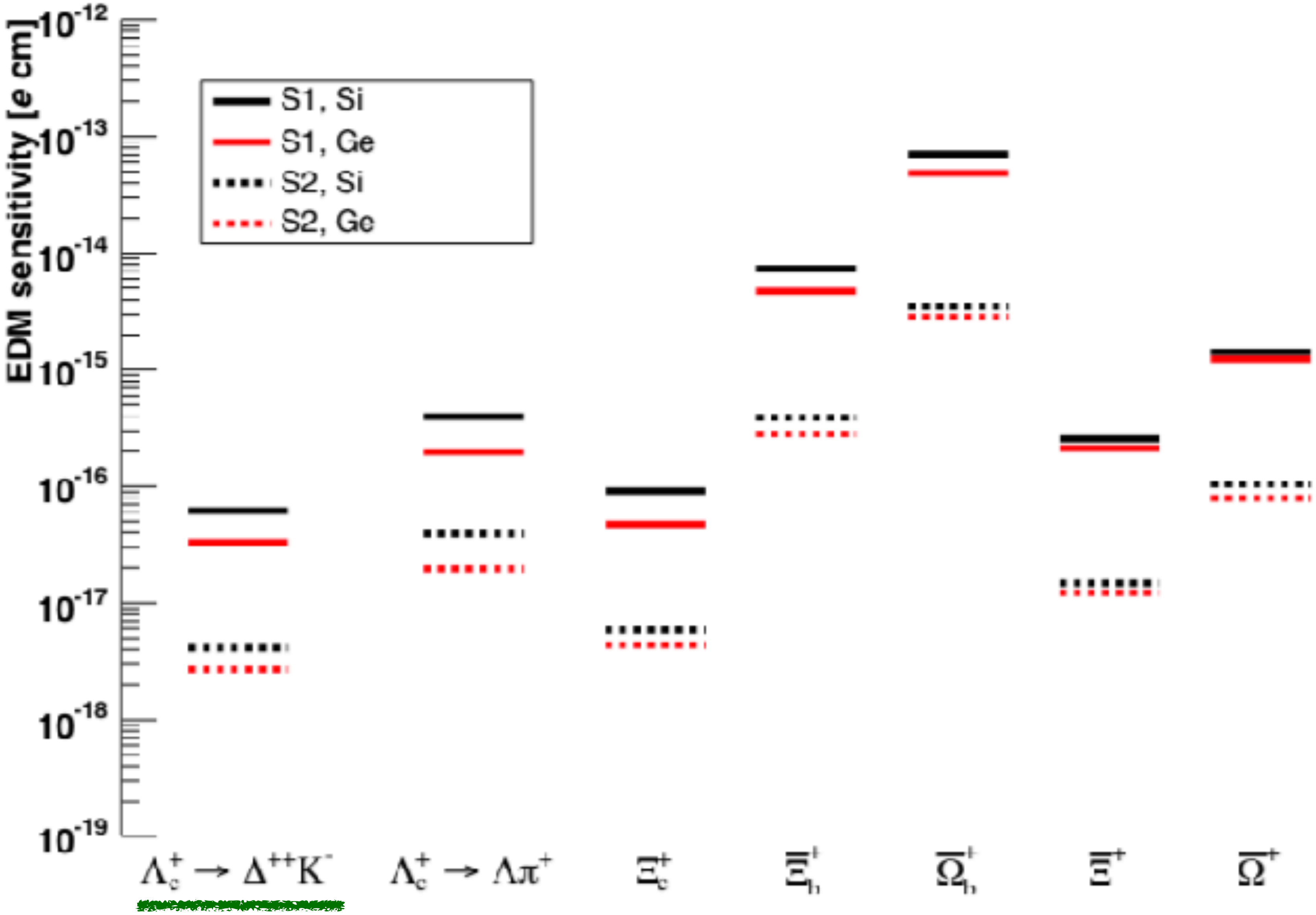
Can we establish the scale of $\mathcal{B} - \mathcal{L}$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension ("short range") operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider B-L violation in the quark sector: via n-$\bar{\rm n}$ transitions

Heavy-Baryon EDMs

Joan Ruiz Vidal (IFIC Valencia)



S1: Configuration at the LHCb
S2: Dedicated experiment at the LHC

Material of the crystal:
→ **Silicon**
→ **Germanium**

Feasibility of a dedicated experiment (S2) explored in EPJ C77 (2017) 828

Final Words

Session 6/F:
Fundamental Symmetries and Spin-Dependent BSM

Lots of current activity,
many new upcoming results expected → **huge discovery potential**

(see Spin2020)

exciting times ahead

Thank you

to the organizers
(especially Paolo & Andrea),

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(+ apologies for butchering
their talks) **of session 6/F,**

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Dipangkar Dutta (MSU), Andreas Wirzba (FZ Jülich)