Worldwide Search for the Neutron EDM

- Searches for particle EDMs are well motivated
  - See previous talk
- Present Sensitivity of neutron EDM
- Basics of neutron EDM experiments
- Overview of Future Neutron EDM Searches
  - Multiple experiments are underway
    - TUCAN/TRIUMF is next talk

B. Filippone
CIPANP/Intersections
5-29-2018

First Search for a Neutron EDM

- E.M. Purcell and N.F. Ramsey, *Phys. Rev*. **78**, 807 (1950)
  - **Searching for Parity Violation in Neutron Scattering**
  - **Pioneered Neutron Beam Magnetic Resonance**

Present Neutron Limit:
ILL-Grenoble neutron EDM Experiment

Baker et al, Phys Rev Lett 97, 131801 (2006)

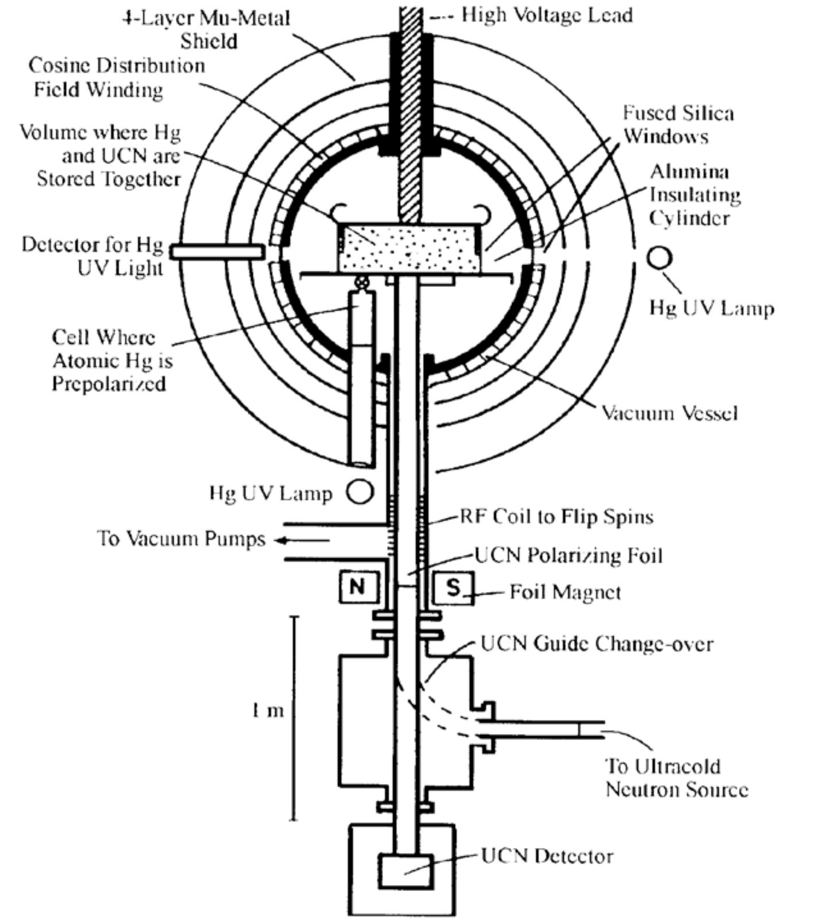
Pendlebury et al, Phys Rev D 92, 092003 (2015)

Trapped Ultra-Cold Neutrons (UCN) with N_{UCN} = 0.5 UCN/cc

|E| = 5 - 10 kV/cm

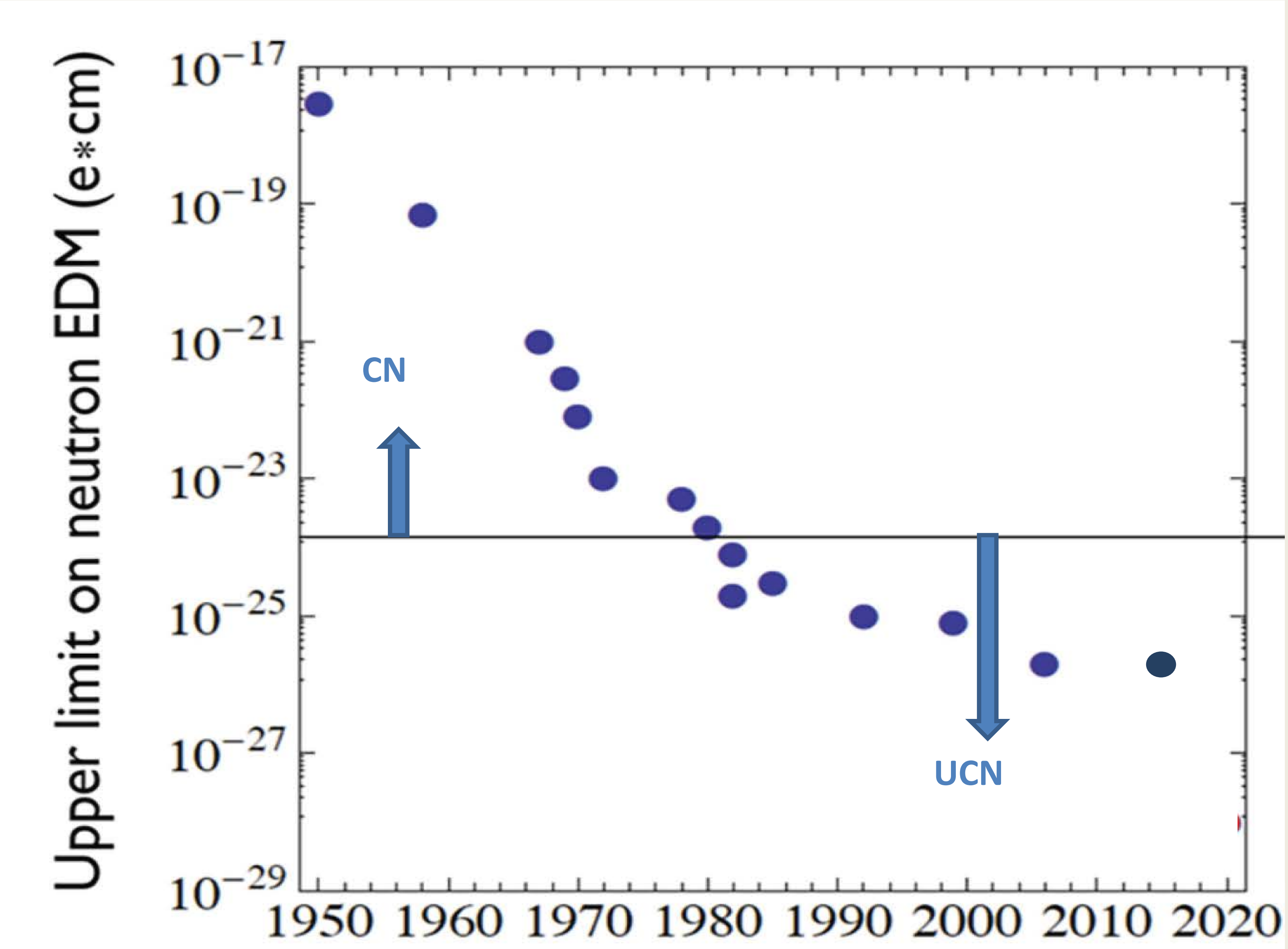
100 sec storage time

σ_d < 3 x 10^{-26} e cm
(90% C.L.)



Schematic of the ILL UCN EDM experiment incorporating a ^{199}Hg comagnetometer

Neutron EDM Limit vs. Time



What is precision for an EDM measurement?

$$\mathcal{E} = \hbar\omega = \vec{\mathbf{d}} \cdot \vec{\mathbf{E}}$$ → Uncertainty in d: $$\sigma_d \sim \frac{\Delta\mathcal{E}}{|\vec{E}|}$$

$$\Delta\mathcal{E}\Delta t \sim \hbar$$

Precise energy measurement requires long individual measurement time, giving

$$\sigma_d^1 \sim \frac{\Delta\mathcal{E}}{|\vec{E}|} \sim \frac{\hbar}{|\vec{E}|T_m}$$

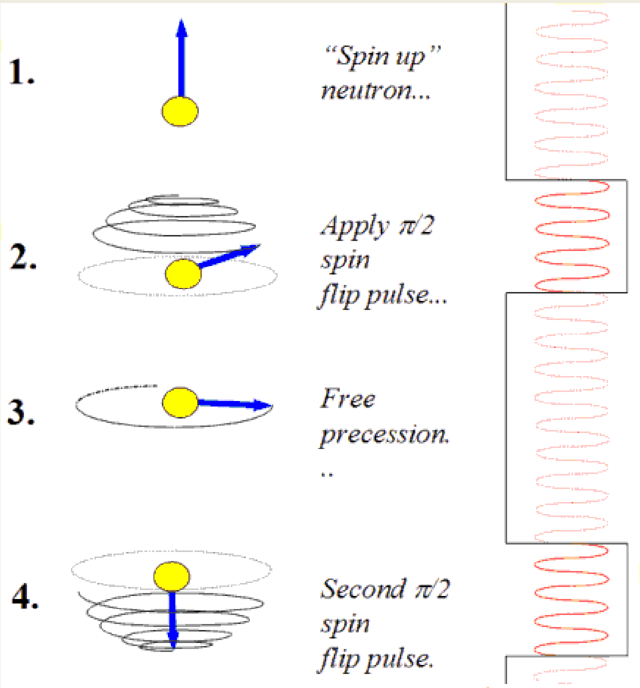
Coherence effect (→ T_m)

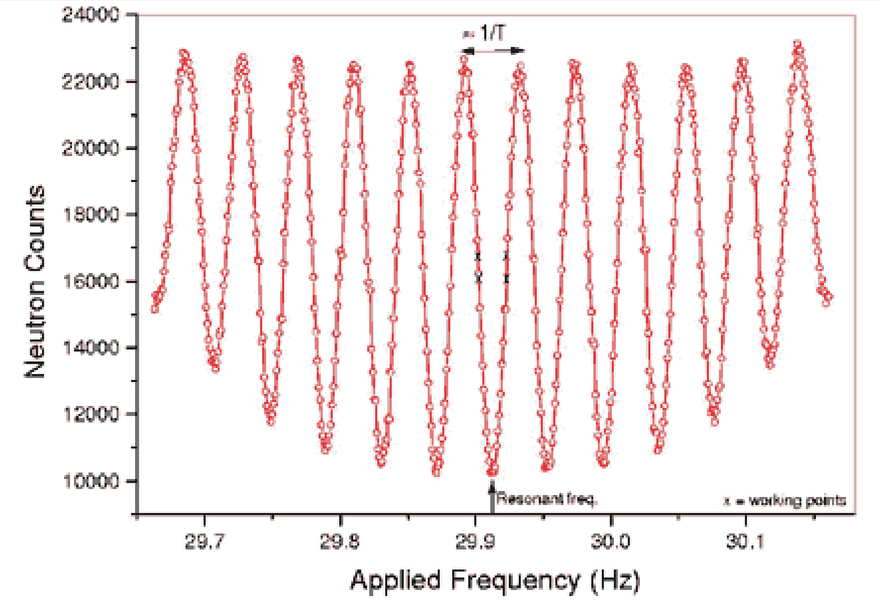
Can improve with counting statistics $\propto \dfrac{1}{\sqrt{\mathbf{N}}}$

How to measure frequency precisely:

- ILL used Ramsey separated-oscillatory field technique
  - Inject n ↑
  - Rotate by π/2 and precess for Δt
  - Spin rotates by ωΔt (>>1 radian)
  - Rotate back by π/2
  - Measure how many

    n↑ vs. n↓





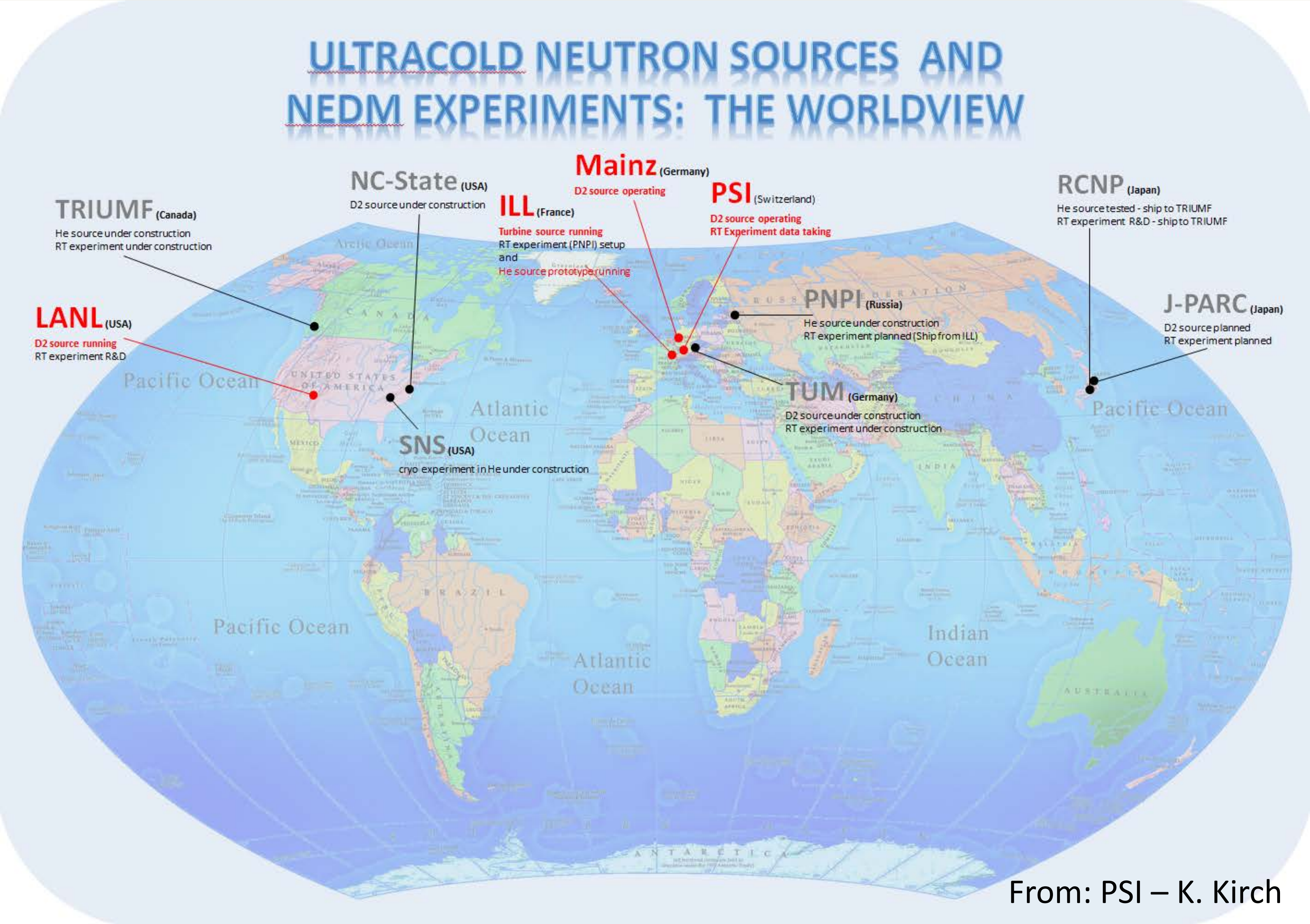
To improve sensitivity need new techniques

- Enhance number of stored neutrons
- Increase Electric field
- Minimize key systematic effects

Systematic Effects in nEDM

- Variation of B-field
  - Co-magnetometer cancels B-field variations
- Leakage currents from Electric Field
  - These may produce B-fields/heating that changes with E-field (must be less than 100pA)
- v x E effects are the largest sources of systematic error in previous ILL exp.
  - $\vec{B}_E = \vec{v} \times \vec{E} \rightarrow$ changes precession frequency
    - Adds false EDM ("geometric phase") when combined with B gradients

Neutron EDM Searches



From: PSI – K. Kirch

Neutron EDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
				Present neutron EDM limit < 300
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey, external Cs & Hg co-mag Xe or Hg co-magnetometer	Phase1 ~ 100 Phase 2 < 20
Munich FRMII/ILL	Solid D_2	Vac.	Room Temp. , Hg co-mag., also external 3He & Cs mag.	< 5
(TUCAN) RCNP/TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 100 < 20
SNS nEDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
LANL	Solid D_2	Vac.	R & D, Ramsey tech., Hg co-mag.	< 50

→ Exps. Under Construction

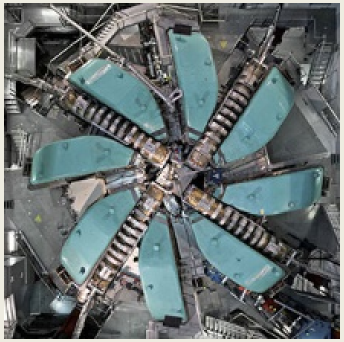
Neutron EDM Community: International Workshop every few years

Workshop on Neutron EDM Experimental Techniques
October 11-13, 2012
SNS, ORNL

Challenges of the world-wide experimental search for the electric dipole moment of the neutron
November 2-6, 2014
Ascona, Switzerland

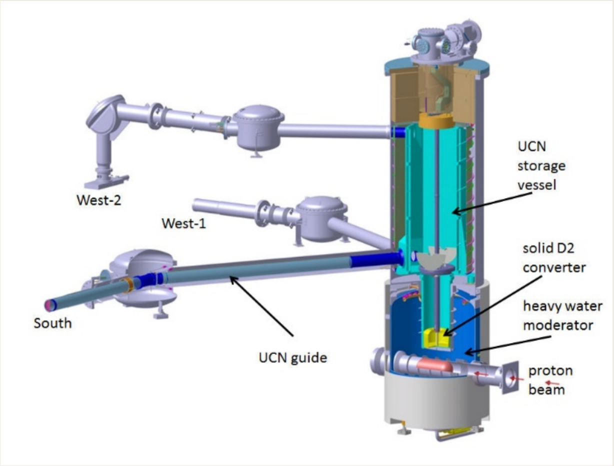
nEDM 2017
October 15-20, 2017
Harrison Hot Springs, BC, Canada

Neutron EDM at PSI



- Data taking with ILL apparatus completed
  - Analysis nearly done: $\sigma_d = 1.1 \times 10^{-26}$ (statistical)

    Corresponds to 1.8×10^{-26} @ 90% CL



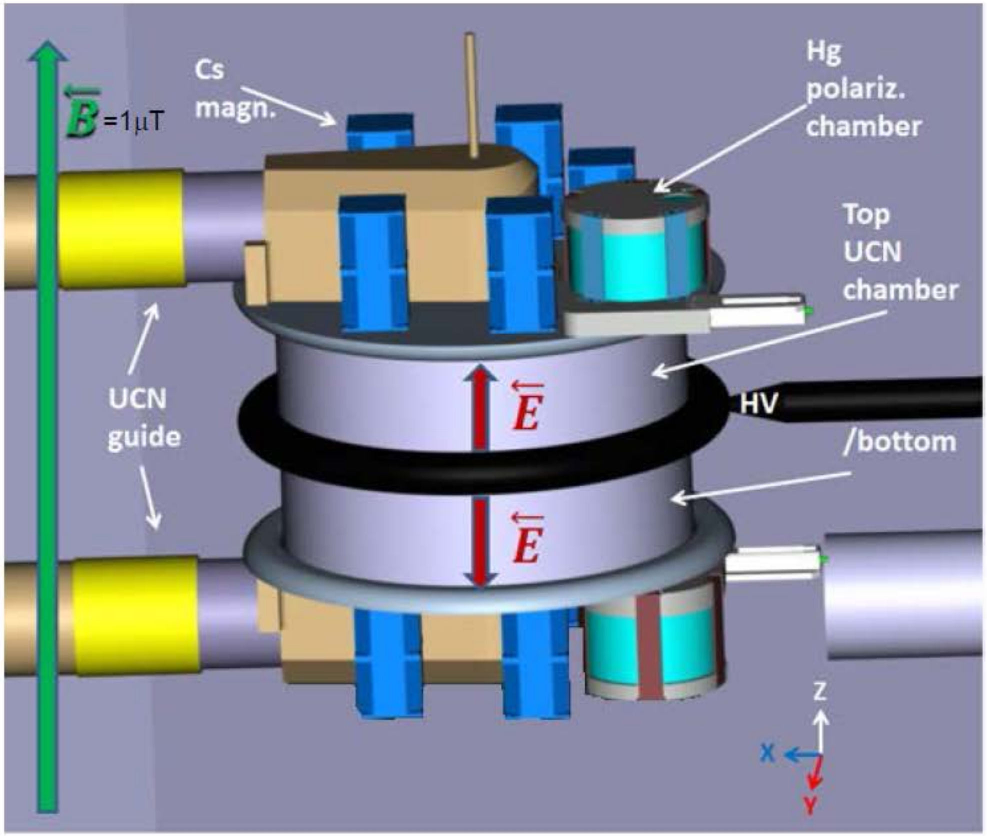
- Construction underway for next phase: n2EDM

- n2EDM data taking begins 5/21

2 larger cells at lower elevation for enhanced UCN

PAUL SCHERRER INSTITUT PSI

Main features of the new apparatus - core setup



Inspired by the pioneering Gatchina double-chamber setup **I.Altarev et al. JETP Lett.44(1986)460** and several years of our **own upgrade and operating experience** with the present nEDM setup

- 2 neutron precession chambers

- Hg co-magnetometer in both chambers with laser read out

- Baseline scenario: UCN chamber with materials and coatings as present chamber, but larger diameter of storage volume - upgrades in development

- Surrounded by calibrated Cs arrays on ground potential (>50 sensors)

- large NiMo (^{58}NiMo) coated UCN guides

Simulation results:

present nEDM chamber as benchmark,
selected n2EDM chambers and positions,
calculated using the average UCN source performance in 2016

(e.g. 139 nEDM data taking days in 2016)

	Current	n2EDM	n2EDM	n2EDM	n2EDM	n2EDM	n2EDM
phase ID (cm) coating	2016 average 47 dPS	comm. 47 dPS	comm. 47 iC	meas. 80 dPS	meas. 80 iC	meas. 100 dPS	meas. 100 iC
α E (kV/cm) T (s) N	0.75 11 180 15′000	0.8 15 180 50′000	0.8 15 180 100′300	0.8 15 180 121′000	0.8 15 180 292′000	0.8 15 180 160′000	0.8 15 180 400′000
$\sigma(d_n)$ (e·cm) per day	11×10^{-26}	4.1×10^{-26}	2.8×10^{-26}	2.6×10^{-26}	1.7×10^{-26}	2.3×10^{-26}	1.4×10^{-26}
$\sigma(d_n)$ (e·cm) 500 data days	5.0×10^{-27}	1.8×10^{-27}	1.3×10^{-27}	1.2×10^{-27}	7.5×10^{-28}	1.0×10^{-27}	6.4×10^{-28}

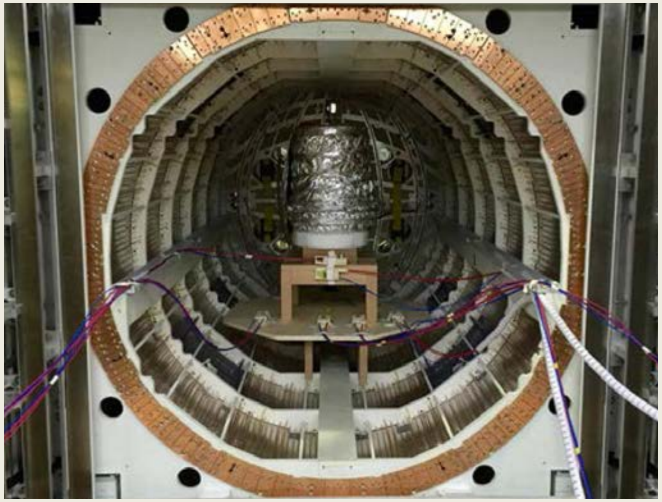
Baseline

different chamber sizes , improved coatings (presently investigating different options)
E = 180 kV (no HV magnetometer)
α ~ 0.85 (depolarization by bouncins and B gradient)

Goal is 1.3 x 10-27 e-cm sensitivity = 2.1 x 10 -27 e-cm @ 90% CL in 500 days ~ 4 yrs

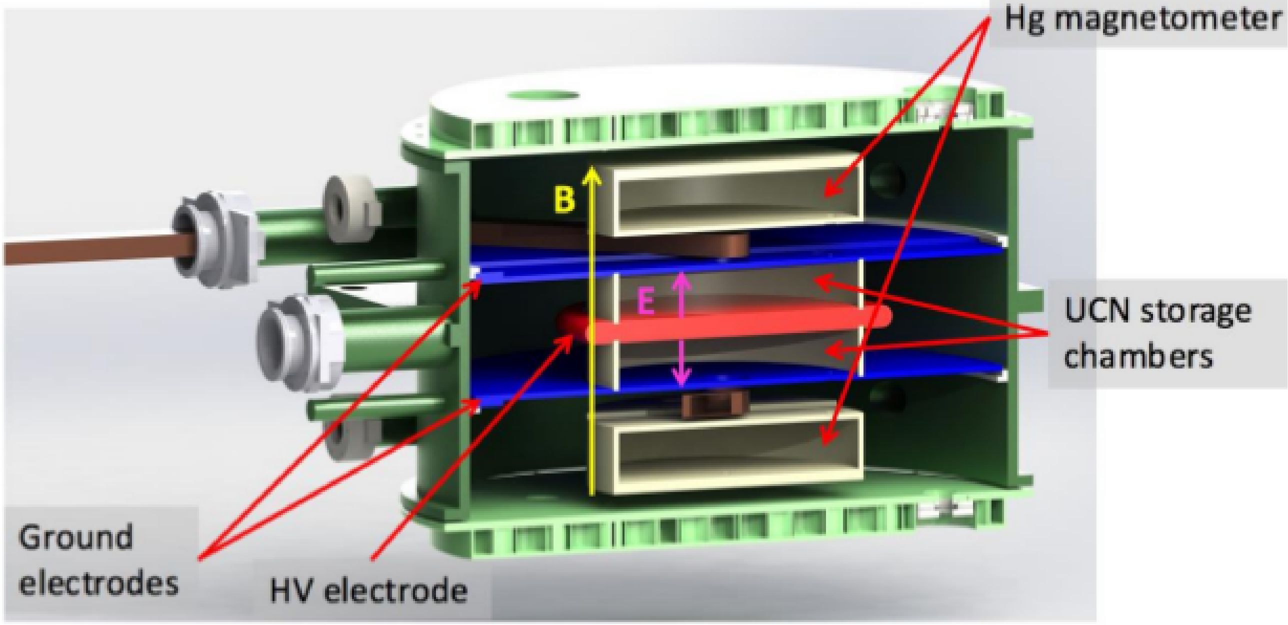
Neutron EDM at Munich/ILL

- Apparatus for EDM largely completed
- Running at FRMII Reactor requires regulatory approval – earliest ~ 2023 (P. Fierlinger)
- Approved at ILL to move most hardware for initial production running with SuperSun LHe source



Our EDM apparatus

- Berkeley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM (FRM, Cluster), UIUC, Yale
- Ramsey experiment with UCN trapped at room temperature, ultimately cryogenic
- Double chamber with co-magnetometer as option (if really needed)
- Long-term stable ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers available
- Portable: first measurements with UCN at ILL in 1.5 years from now

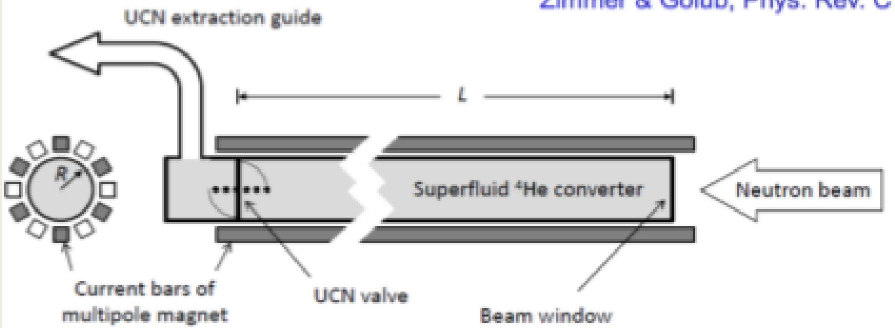


I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

The upgrade for EDM: Super-SUN (under construction at ILL)

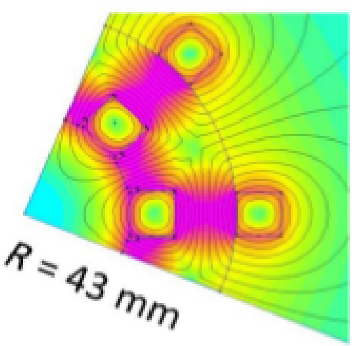
For calculations of UCN storage see:

Zimmer & Golub, Phys. Rev. C **92** (2015) 015501

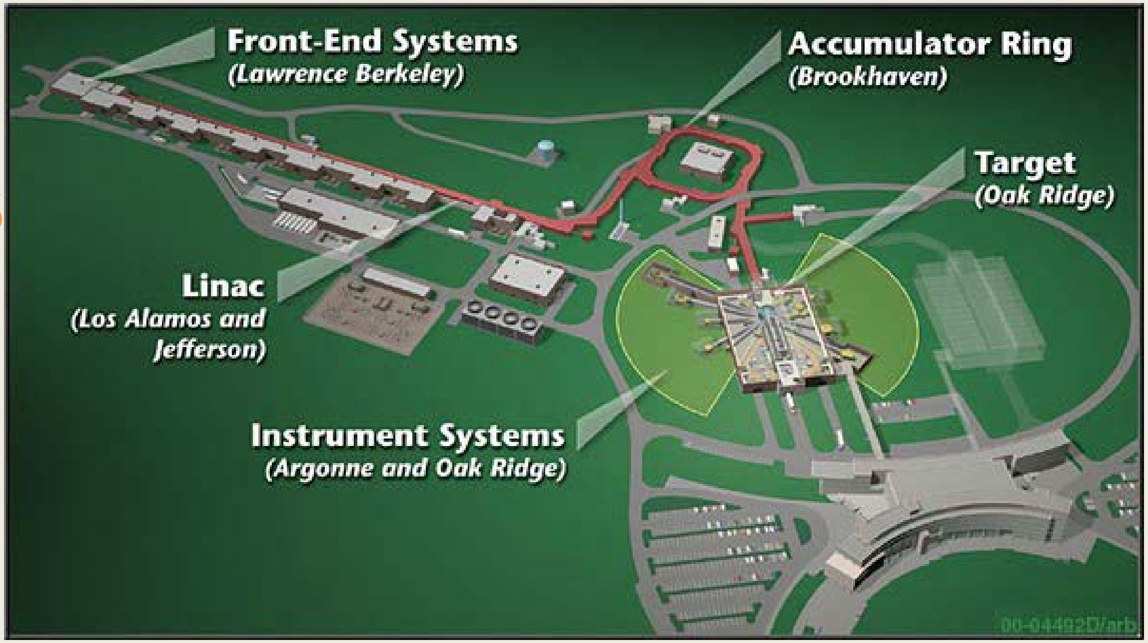


	SuperSun stage I		SuperSun stage II	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3		1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		2217760	
EDM sensitivity				
E	2,00E+04	V/cm	2,00E+04	V/cm
alpha	0,85		0,85	
T	250	s	250	s
N after time T (1/e)	398000		794000	
Number of EDM cells	2		2	
Sensitivity (1 Sigma, 1 cell)	3,9E-25	ecm	8,7E-26	ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25	ecm	6,1E-26	ecm
Preparation time	150	s	150	s
Measurements per day	216		216	
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26	ecm	4,2E-27	ecm
Sensitivity 100 days	**1,9E-27**	**ecm**	**4,2E-28**	**ecm**
Limit 90% 100 days	**3,00E-27**	**ecm**	**7,00E-28**	**ecm**

- Single-user facility
- Converter volume: 12 liters
- UCN production rate: 10^5 /s (E < 230 neV)
- UCN saturation number: 4×10^6 (2018) 2×10^7 (2019)



nEDM Experiment at Oak Ridge Spallation Neutron Source - SNS



Concept:
R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

- High trapped neutron densities
  – *Cold neutrons from spallation source cooled to UCN via phonon scattering in superfluid He*

- LHe as HV insulator
  – *high electric fields*

- Use of a $^3\vec{He}$ co-magnetometer and superconducting shield
  – *Control and measure magnetic field systematics*

- Variation of LHe temperature to study v x E systematics
  – measure ^{3}He false EDM for different mfp (0.5mm – 8 cm)

- Precession frequency measurement via two techniques:
  – *free precession*
  – *dressed spin techniques*

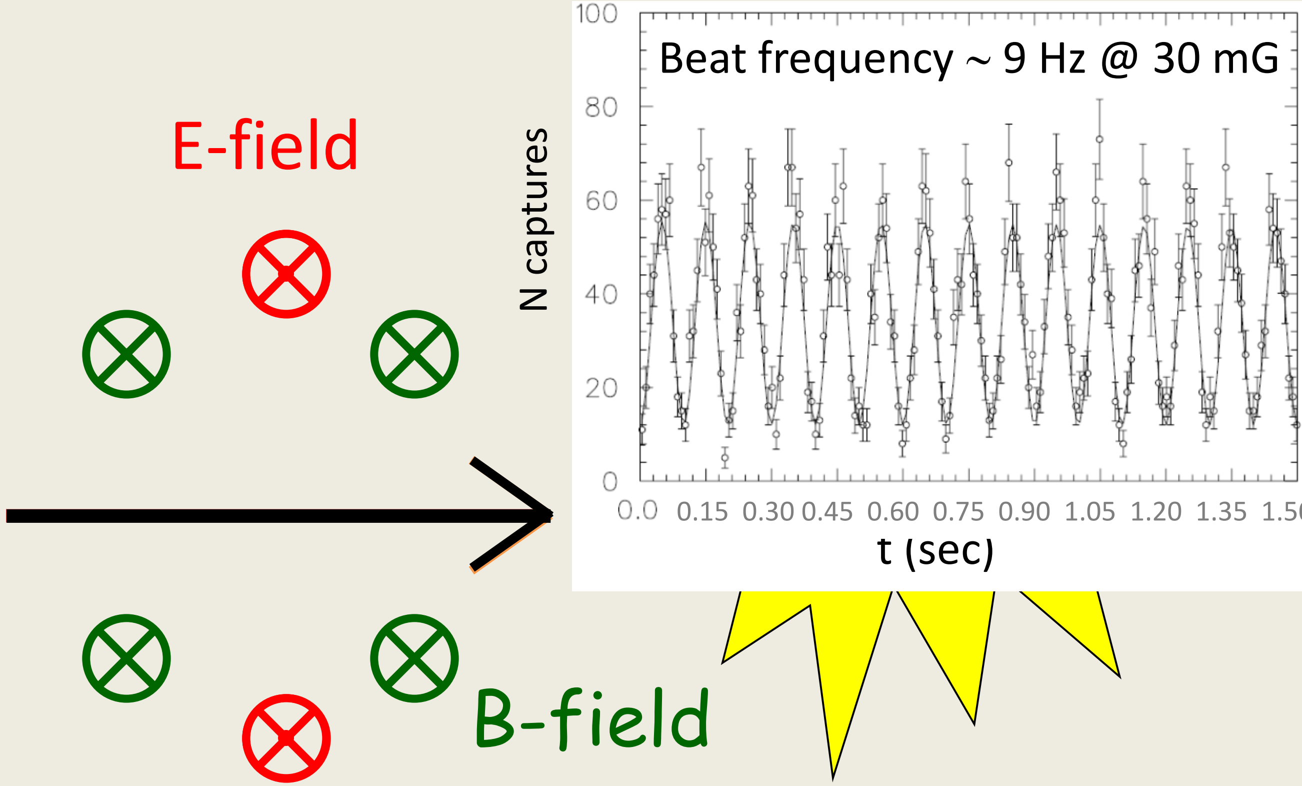
- Sensitivity reach: **$d_n < 3 \times 10^{-28}$ e-cm (in 3 calendar yrs)**

Free Precession Measurement

1. **Polarized neutrons & polarized ^{3}He in cell**
2. **Measure n+^{3}He capture vs. time (note: $\sigma_{\downarrow\uparrow} >> \sigma_{\uparrow\uparrow}$)**

VUV Scintillation in He converted to visable via TPB

3. **Flip E-field direction**



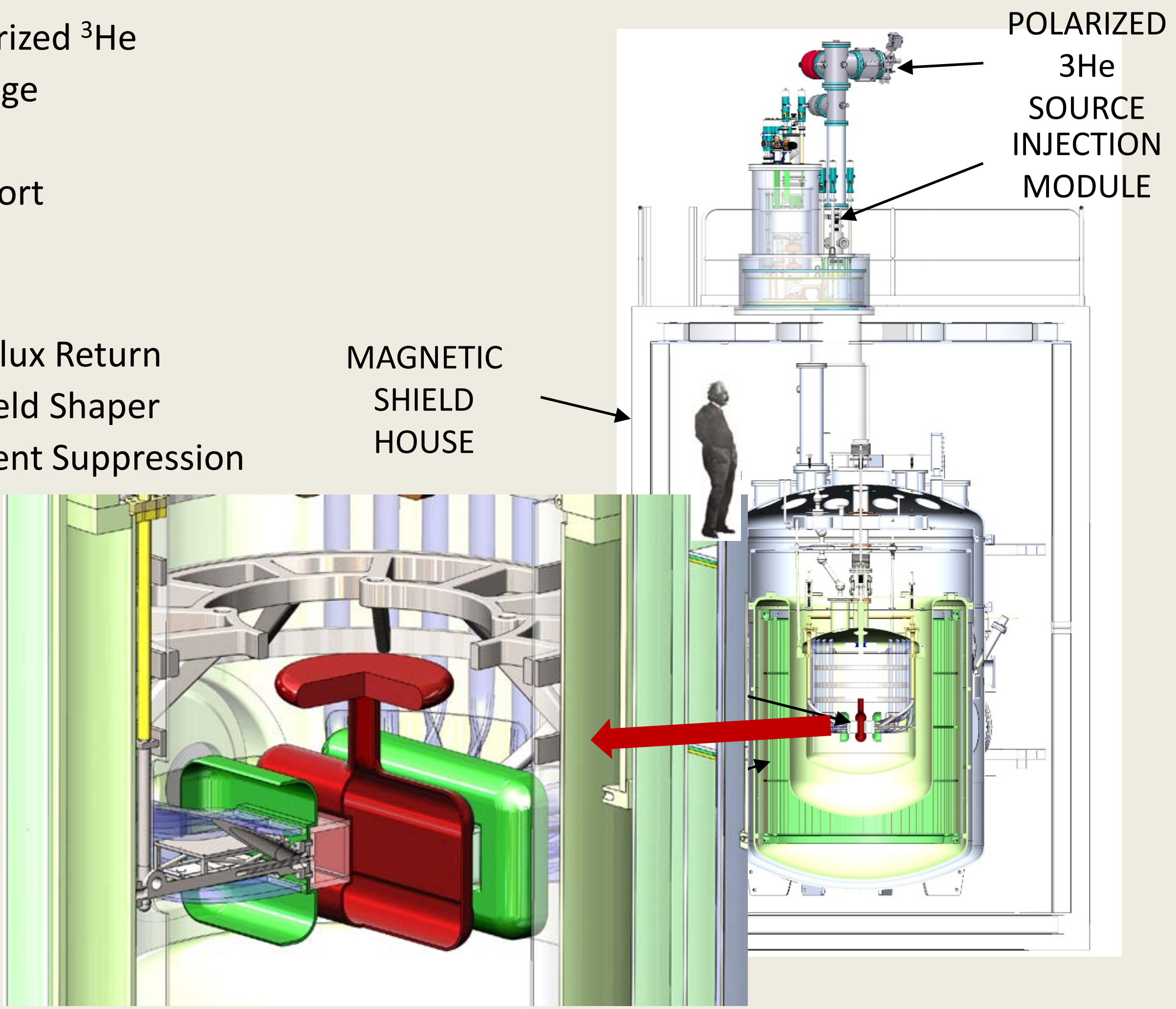
^{3}He functions as co-magnetometer

^{3}He EDM shielded by atomic electrons

^{3}He precession frequency measured via SQUID pickup

Main Experimental Components

- Polarized ^{3}He System
  - Atomic Beam Source of 99% polarized ^{3}He
  - 0.30K Non-Magnetic Dilution Fridge
  - ^{4}He Purification System
  - Heat Flush System for 3He transport
- Cryogenic Magnet System
  - Spin Precession B_0 Magnet with Flux Return
  - Superconducting Shield and B_0 Field Shaper
  - Dressed Spin Coils and Eddy Current Suppression
  - Gradient Field Monitor
- Central Detector System
  - 1500 L Superfluid He @ 0.45K
  - Two Measurement Cells
  - HV System
  - Scintillation light readout
  - SQUID readout for ^{3}He precession



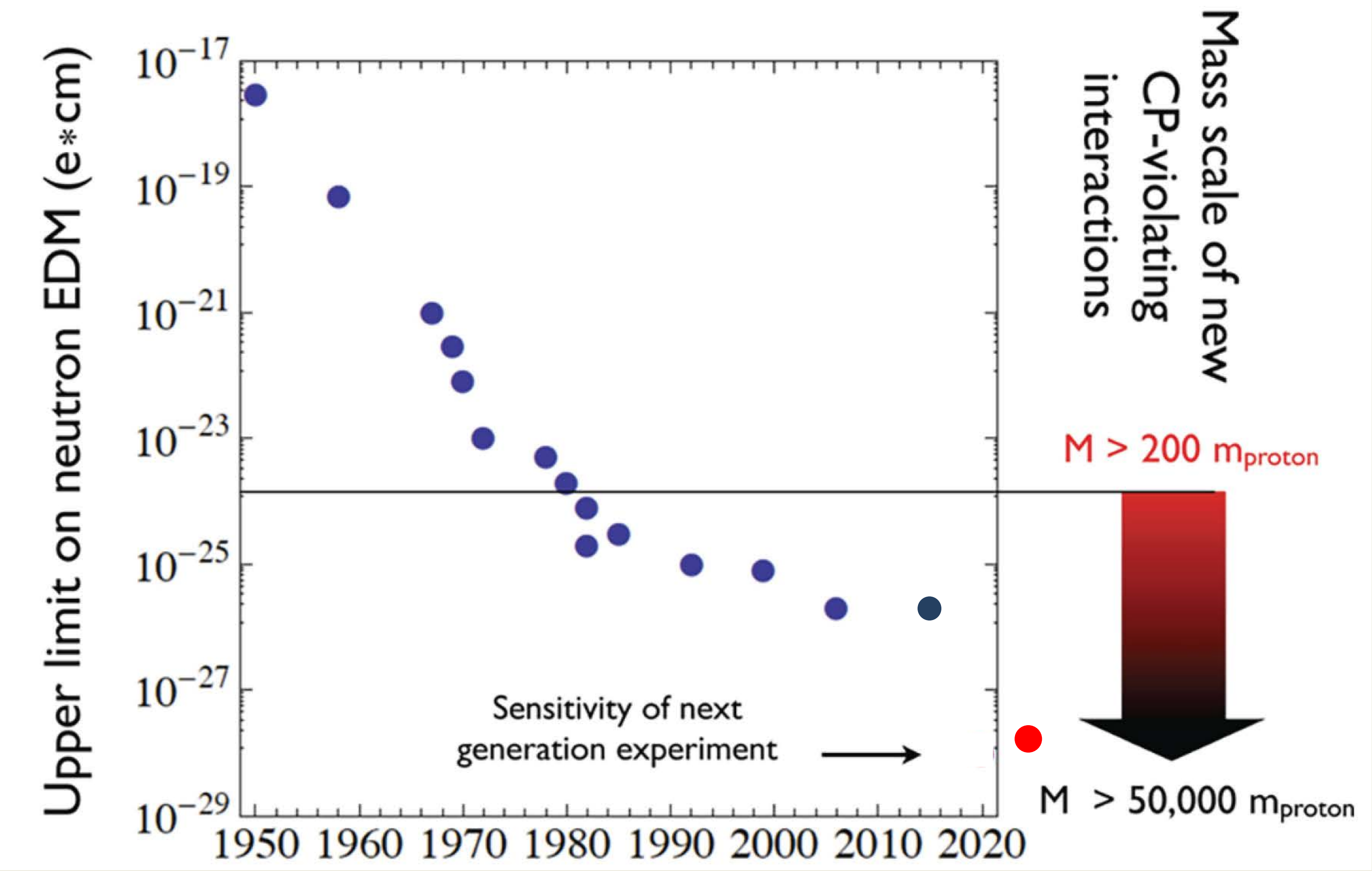
NOTE: Neutron beam goes into page

- Systematics and Operational Studies (SOS) Apparatus
  - Polarized ^{3}He and UCN (from PULSTAR Reactor) in full-size measurement cell

Status of nEDM@SNS

- R&D recently completed on HV, ^{3}He and cryo-magnet (Critical Component Demonstration)
- Beginning full hardware construction
- Hardware completion & commissioning: 2021-2023
- Initial data-taking: 2023

Sensitivity of Future nEDM Searches



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