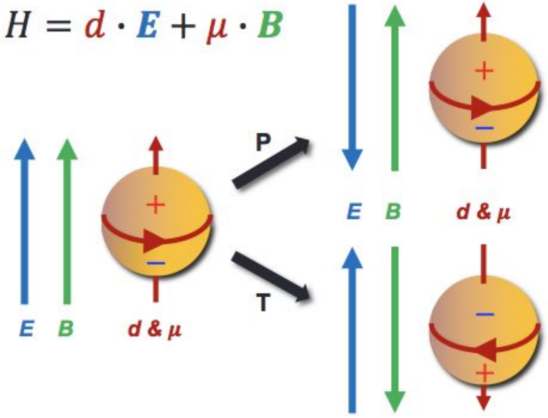
Phydes: an apparatus for the measurement of the electron EDM

Presentazione infrastrutture in acquisizione con il Progetto di Eccellenza "Frontiere Quantistiche"

The electron EDM

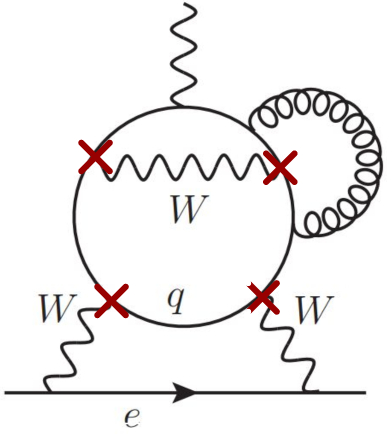
Electron Electric Dipole Moment (eEDM) ➔ asymmetric charge distribution along the particle spin



The eEDM is odd under both **P**arity and **T**ime-reversal ➔ **CP**-violating *(assuming CPT-invariance)*

In the **SM**, the eEDM is **predicted to be ~$10^{-38} \div 10^{-40}$ *ecm***, mainly arising from CP-violating CKM contributions

- first non-vanishing contributions at 4-loop level

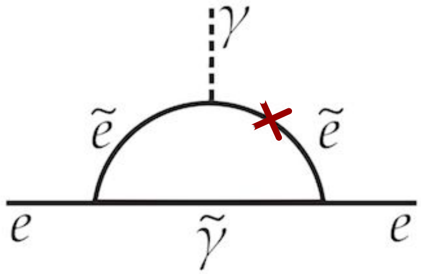


[Pospelov and Ritz - Phys. Rev. D 89, 056006]

eEDM as a probe for New Physics

CP violation is required to generate a cosmological matter-antimatter asymmetry

CPV in SM through the CKM matrix is many orders of magnitude below what is necessary!



In New Physics models, CP-violating terms may arise already at 1-loop level

Model-independent probe of possible New Physics sources of **CP** violation

naturally ~ α/π

CP phase from soft breaking naturally O(1)

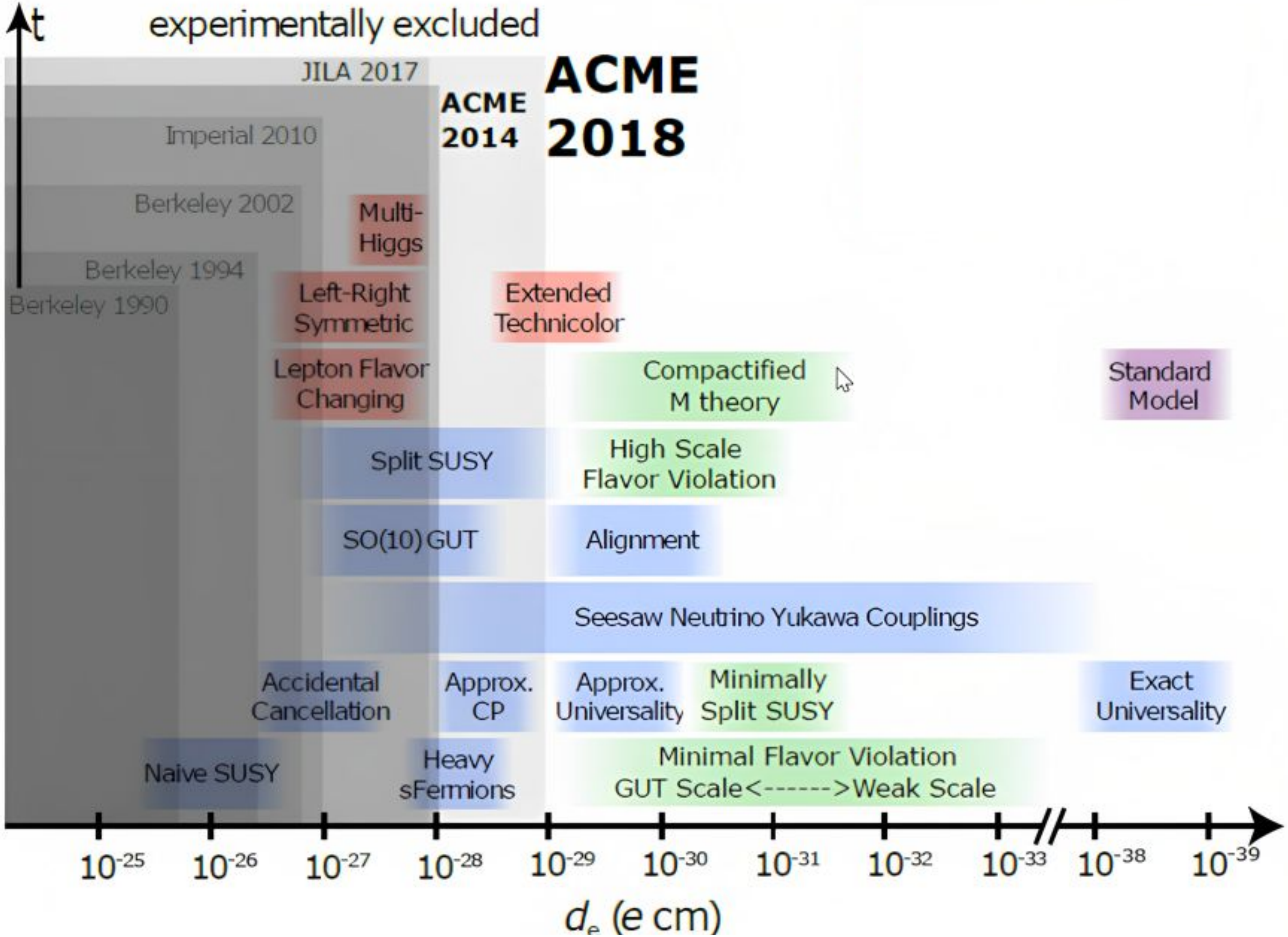
$$d_e \sim (\text{loop}) \times \frac{m_e}{\Lambda^2} \sin \varphi_{CP}$$

scale of SUSY breaking naturally ~200 GeV

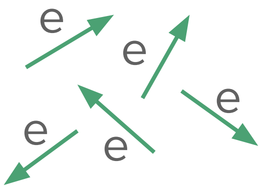
$\Rightarrow \sim 5 \times 10^{-25}$ cm naturally

Precision eEDM measurements can probe scales up to PeV to EeV, far beyond the reach of particle colliders

Most recent **experimental** results (from the ACME II collaboration) set eEDM **upper limit at ~10^{-29} *ecm***

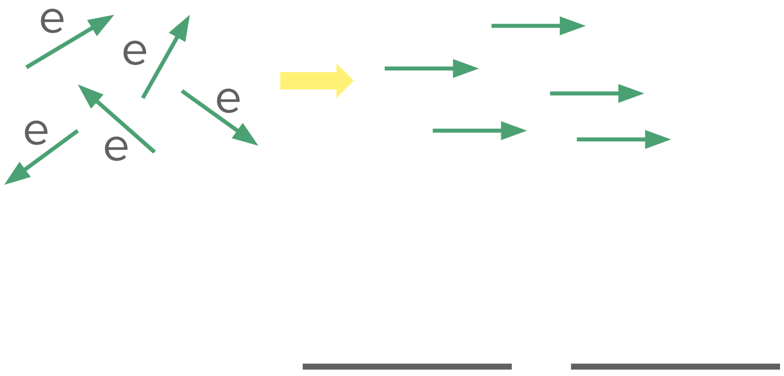

t
experimentally excluded
JILA 2017
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
ACME 2014
ACME 2018
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Compactified M theory
Standard Model
Split SUSY
High Scale Flavor Violation
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Minimally Split SUSY
Exact Universality
Naive SUSY
Heavy sFermions
Minimal Flavor Violation
GUT Scale<------>Weak Scale
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-38} 10^{-39}
d_e (e cm)

Measuring the eEDM



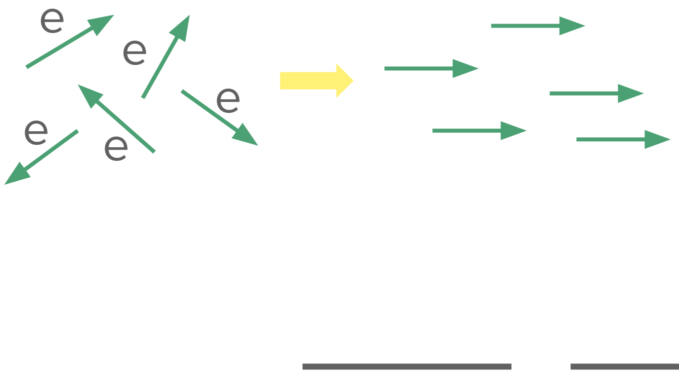
[from D. DeMille @ Sid Drell Symposium 2018]

Measuring the eEDM

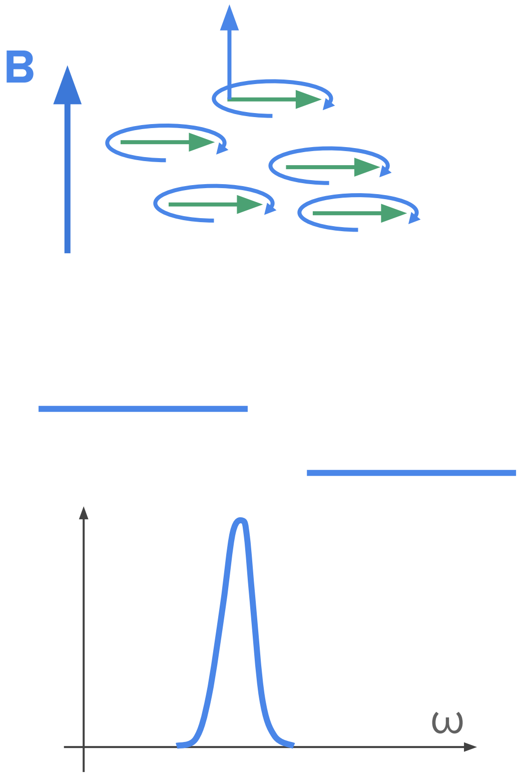


[from D. DeMille @ Sid Drell Symposium 2018]

Measuring the eEDM

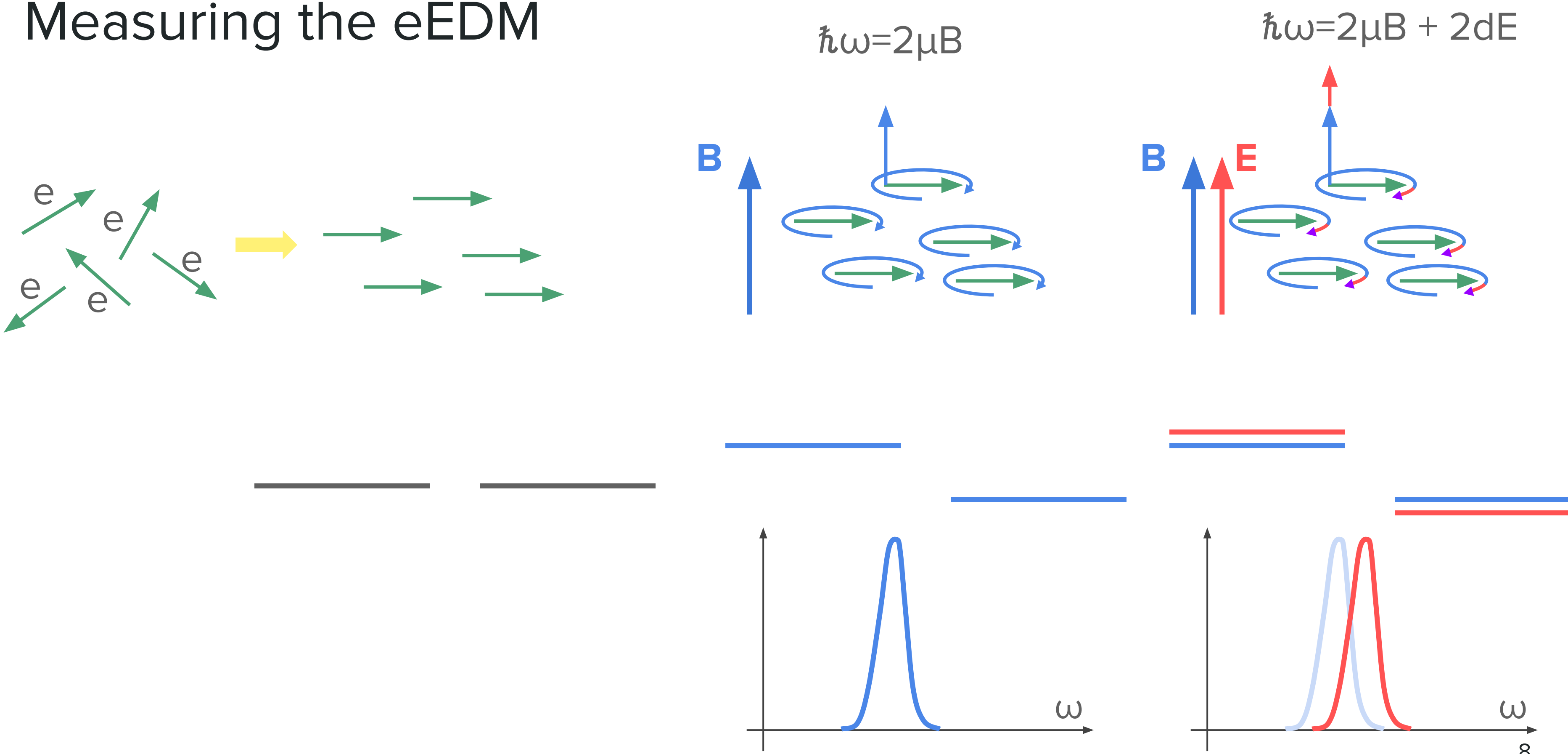


$\hbar\omega=2\mu B$



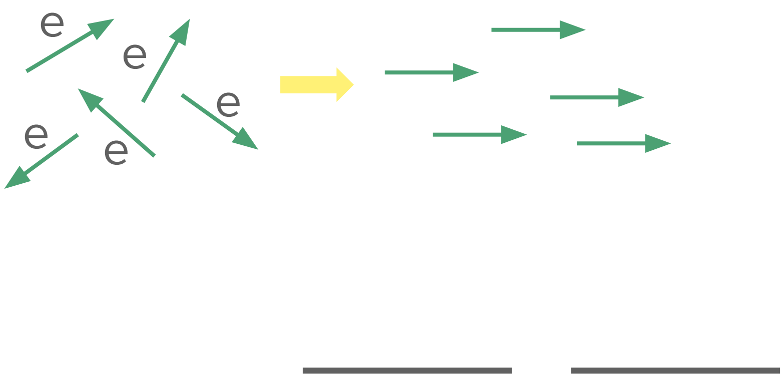
[from D. DeMille @ Sid Drell Symposium 2018]

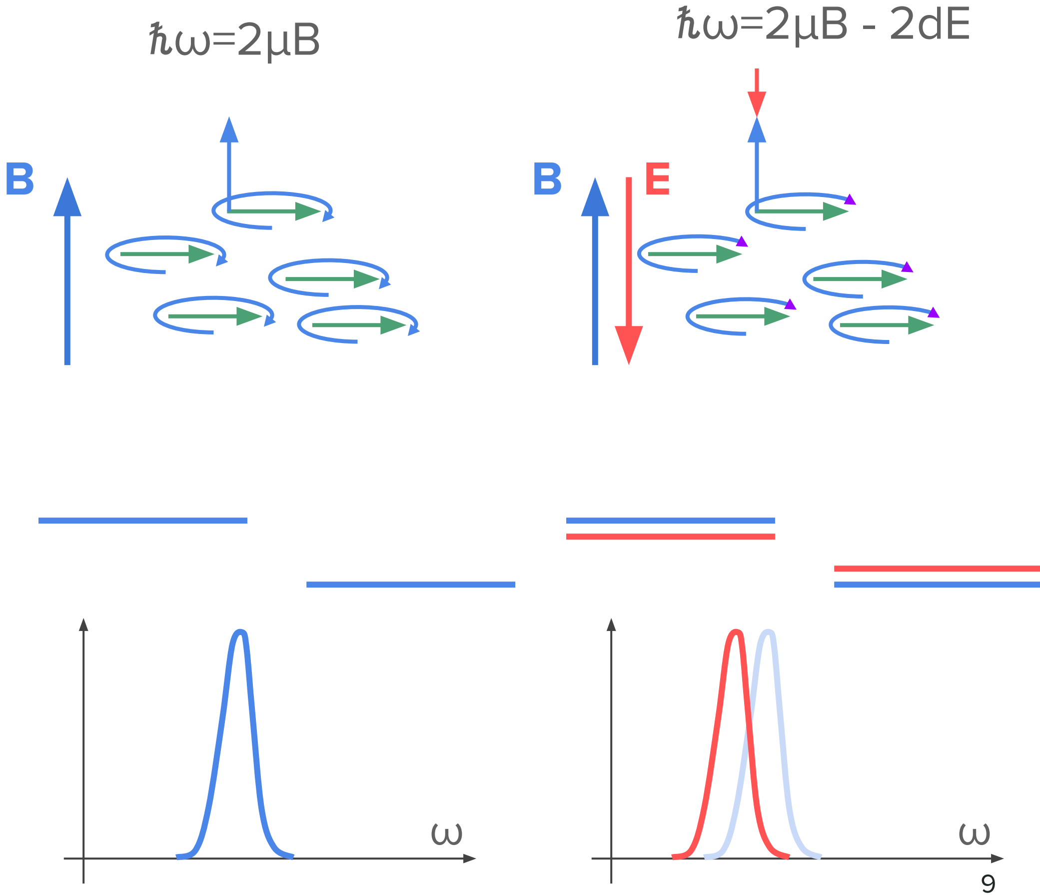
Measuring the eEDM



[from D. DeMille @ Sid Drell Symposium 2018]

Measuring the eEDM





[from D. DeMille @ Sid Drell Symposium 2018]

Measuring the eEDM

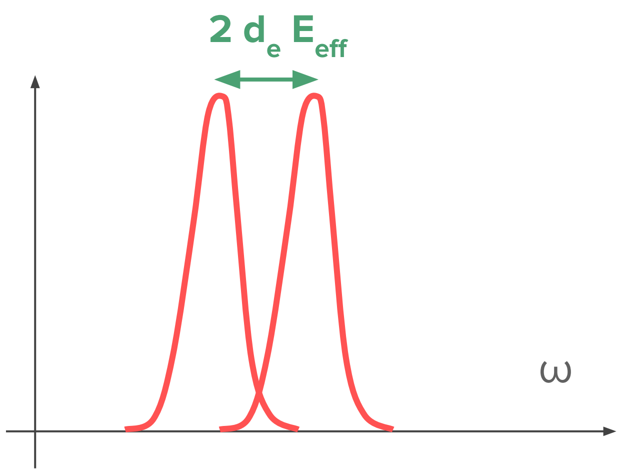
Figure of merit for the optimization of the measurement of the eEDM:

$$\delta d_e = \frac{1}{E_{eff}\ \tau\ \sqrt{N}}$$

E_{eff} → **Effective electric field**

τ → **Coherence time**

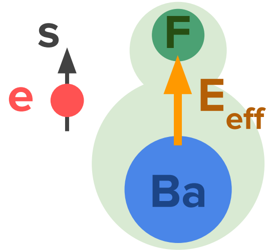
N → **Number of probed atoms/molecules**



PHYDES

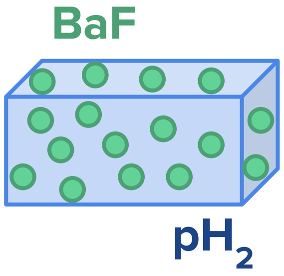
eEDM measurement apparatus using BaF diatomic polar molecules and ParaHydrogen

- Sigla INFN Gr. V for the R&D effort
  - **PI:** Giovanni Carugno
    + Borghesani, Gasparini, Zanetti, Pazzini, Gonella, Benettoni
- NQSTI - PNRR Tecnologie Quantistiche



Barium Monofluoride (BaF) will be used as the molecules are characterized by large effective electric fields $\mathbf{E}_{\mathbf{eff}}$ acting on the unpaired electron ($\propto Z^3_{Ba}$)

- large BaF polarization fraction with small (~100s *V/cm*) lab. **E** fields
- $\mathbf{E}_{\mathbf{eff}}$ on the unpaired e^- of the order of 100 *GV/cm*



BaF will be embedded in a inert **solid crystal of ParaHydrogen (pH_2)** to suppress residual guest-host interactions

- large number **N** of trapped BaF molecules ⇒ large n_e
- freedom of BaF polarization and rotation in the pH_2 lattice

[Sandars - Physics Letters, 14(3), 1965, 194-196]

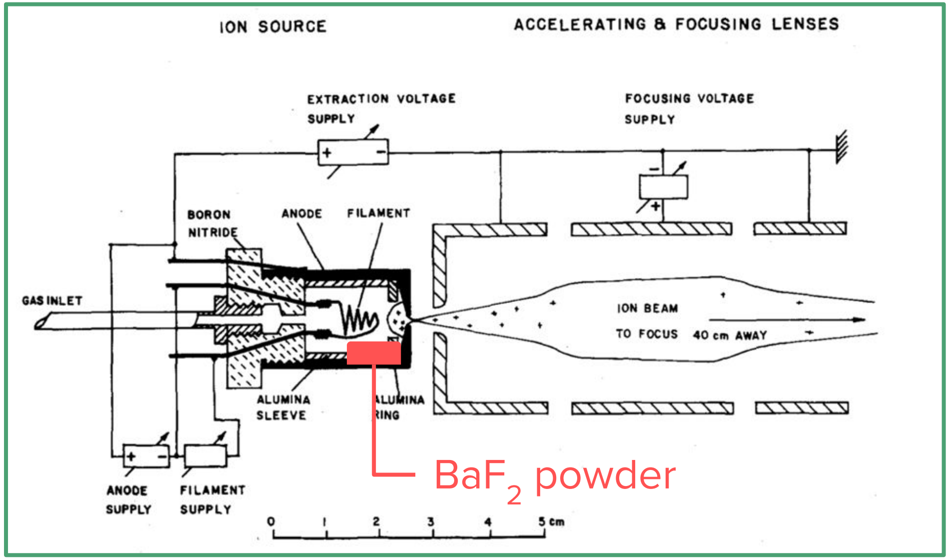
PHYDES - BaF line production

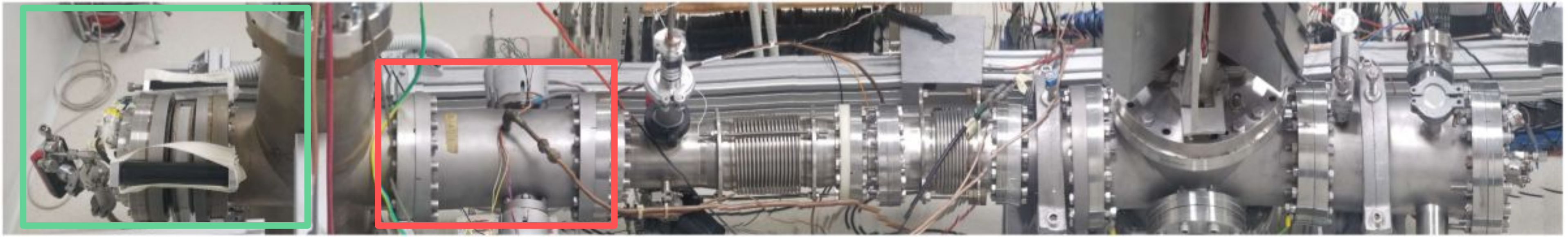
BaF beam preparation with isotopic separation:

- BaF injection + ionization
- Wien filter (**B**x**E**) for mass selection

Preliminary tests with Xe^+ beam (mass similar to BaF):

- Beam current 100 nA
- Final Xe^+ energy = 5 eV
- Estimate of ~ 100 ppm for BaF^+ on pH_2 target





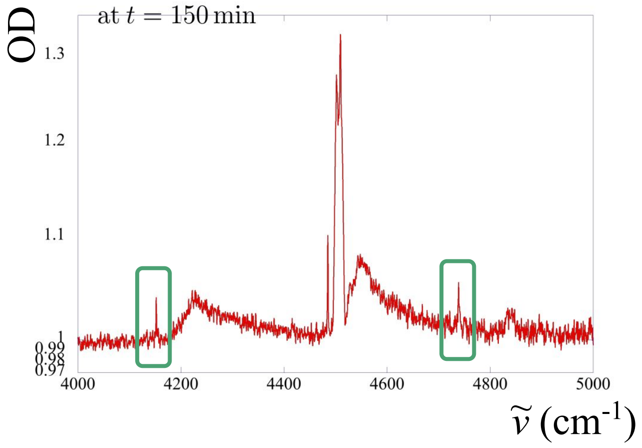
PHYDES - pH2 production and BaF neutralization

Para-H_2 (nuclear spin J=0) is produced via spin-spin interaction of H_2 with iron-oxide powder

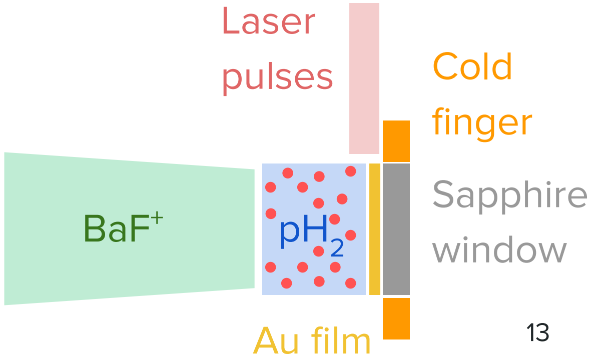
A continuous flow of pH_2 is sprayed onto a sapphire window kept at ~ 2.7 K

FTIR spectroscopy allows to monitor the growth rate of the crystal and the para-vs-ortho H_2 fraction.
From preliminary estimates:

- growth rate ~ 120 μm/hour
- fraction of ortho-H_2 ~ 3%

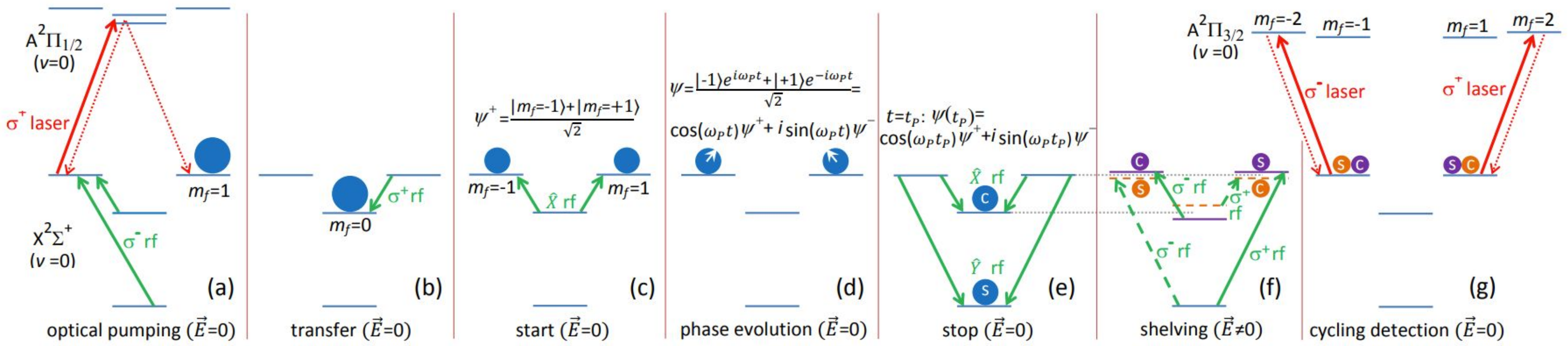


BaF^+ neutralization before the embedding in pH_2 will be realized by **photo-extraction of e^- from a *Au* film on the sapphire surface**



PHYDES - eEDM measurement

The system will have to go through a fine state preparation for the actual signal extraction



[Vutha, Horbatsch, Hessels - Phys. Rev. A 98, 032513]

2 different measurement approaches can be set up, based on **squid** / **optical fluorescence** methods

The **cooling temperature (ideally < 1 K)** of the final pH_2+BaF system will possibly be one of the most important factors for boosting the eEDM result, as it will **improve the coherence time τ** and **decrease the phonon-induced noise**

The *proton* EDM

Possibilities to extend this effort towards the **proton EDM**

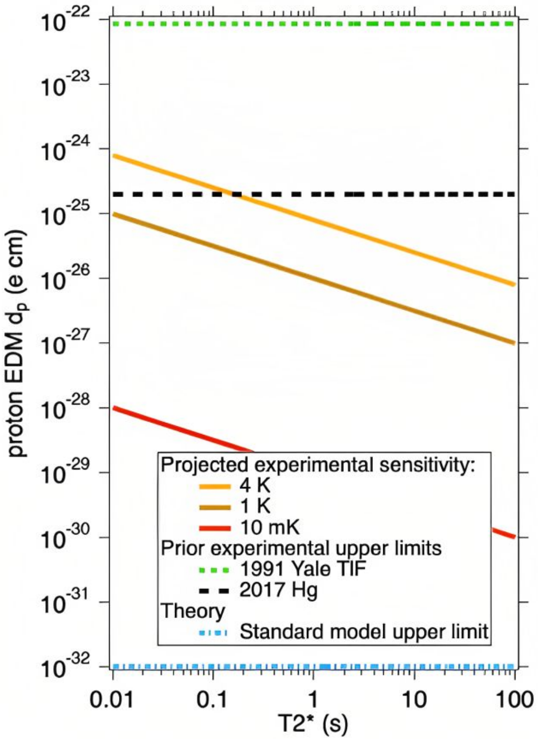
Probing the nucleus (proton/nucleon) EDM by **implanting isotopic impurities @ 100 ppm level in the pH_2 solid matrix**

pH_2 is a non-active NMR target ⇒ NMR of **HD**-doped pH_2 to probe pEDM

- Provide pH_2 cryo-cooling < 100 mK (***crucial!***)
- Appropriate spin state preparation
- Apply 9 T **B** field
- Sense pick-up signal

Upper limits on pEDM can be extracted exploiting large T2* relaxation coherence time ⇒ higher than 1 sec

Experimental sensitivity strongly dependent on the cryo capabilities and the **homogeneity of the B field**



Requests

Leiden Cryogenics **Dilution Refrigerator** *[Model CF-CS110-200-1PT-1T-100mK]*

Cryogenic refrigeration system:

- Base temperature slightly below **100 mK**
  ➜ eEDM

- **Can be later upgraded** to reach ~15 mK or <10 mK temperatures
  ➜ pEDM

- Cooling system as a long-lasting asset for all experimental activities within the **LaTeQ** lab / **DFA**

Currently received a quotation for **250 k€** from Leiden Cryogenics
- **50 k€** can be taken from PNRR

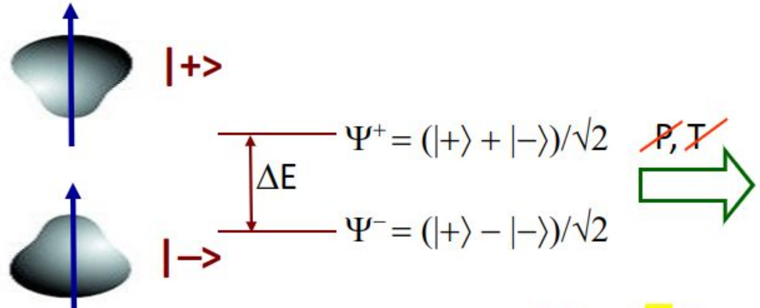
⇒ **~200 k€ request**

Atomic EDM w/ Shiff moment: Octupole Enhancement

No atomic EDM due to EDM of the nucleus - Schiff's Theorem

Electrons screen applied electric field

➔ Need for octupole deformation to enhance the Shiff moment



$\Psi^{+} = (|+\rangle + |-\rangle)/\sqrt{2}$

$\Psi^{-} = (|+\rangle - |-\rangle)/\sqrt{2}$

$\Psi^{+} = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$

$\Psi^{-} = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$

$$\alpha = \frac{\langle \Psi^{-} | V^{PT} | \Psi^{+} \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$

$S_{lab} \sim e Z A^{2/3} \beta_2 \beta_3^2/\Delta E$

$\beta_2, \beta_3 \sim 0.1$

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	—	50.2	55.2	160.5	40.1	0.22		
10^5 S (efm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (ecm)	**2000**	2700	**2100**	2800			-5.6	0.8

[Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel]

Production at Legnaro National Laboratory - Requests

$^{232}ThO_2$ target

- p(40 MeV)+^{232}Th ➔ ^{229}Pa - 150 mb
- p(70MeV) +^{232}Th ➔ ^{225}Ac - 10 mb

Estimated intensity at LNL:

- ^{229}Pa by ^{232}Th(p,4n): 10^9 s^{-1} (if extraction efficiency 0.05)

Developments ⇒ Molecular fluoride beams of heavy elements: Ac, Pa

Some molecular beams are already developed:

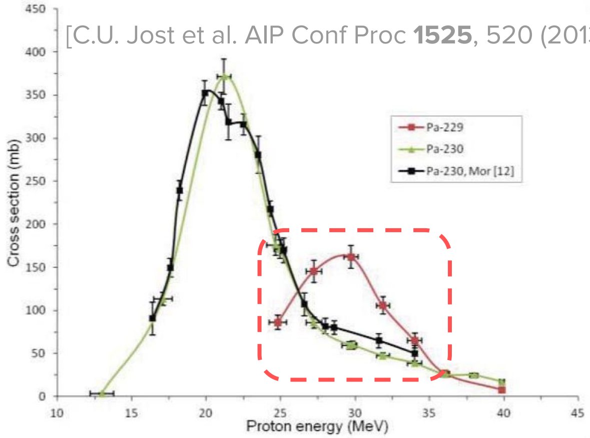
- SF6 gas + Sr (calibrated solutions used for the SIS/PIS efficiency tests) > **SrF**
- SF6 gas + Ba (calibrated solutions used for the SIS/PIS efficiency tests) > **BaF**
- Molecular beams for new elements to be developed ➔ **PhD thesis**

Requests:

- ~10 k€ ➔ vacuum chamber dedicated to the molecular beam source
- ~10 k€ ➔ for the sources and elements dedicated to injection
- ~5 k€ ➔ for consumables necessary for the functioning of the sources

⇒ **~25 k€ request**

[C.U. Jost et al. AIP Conf Proc **1525**, 520 (2013)]

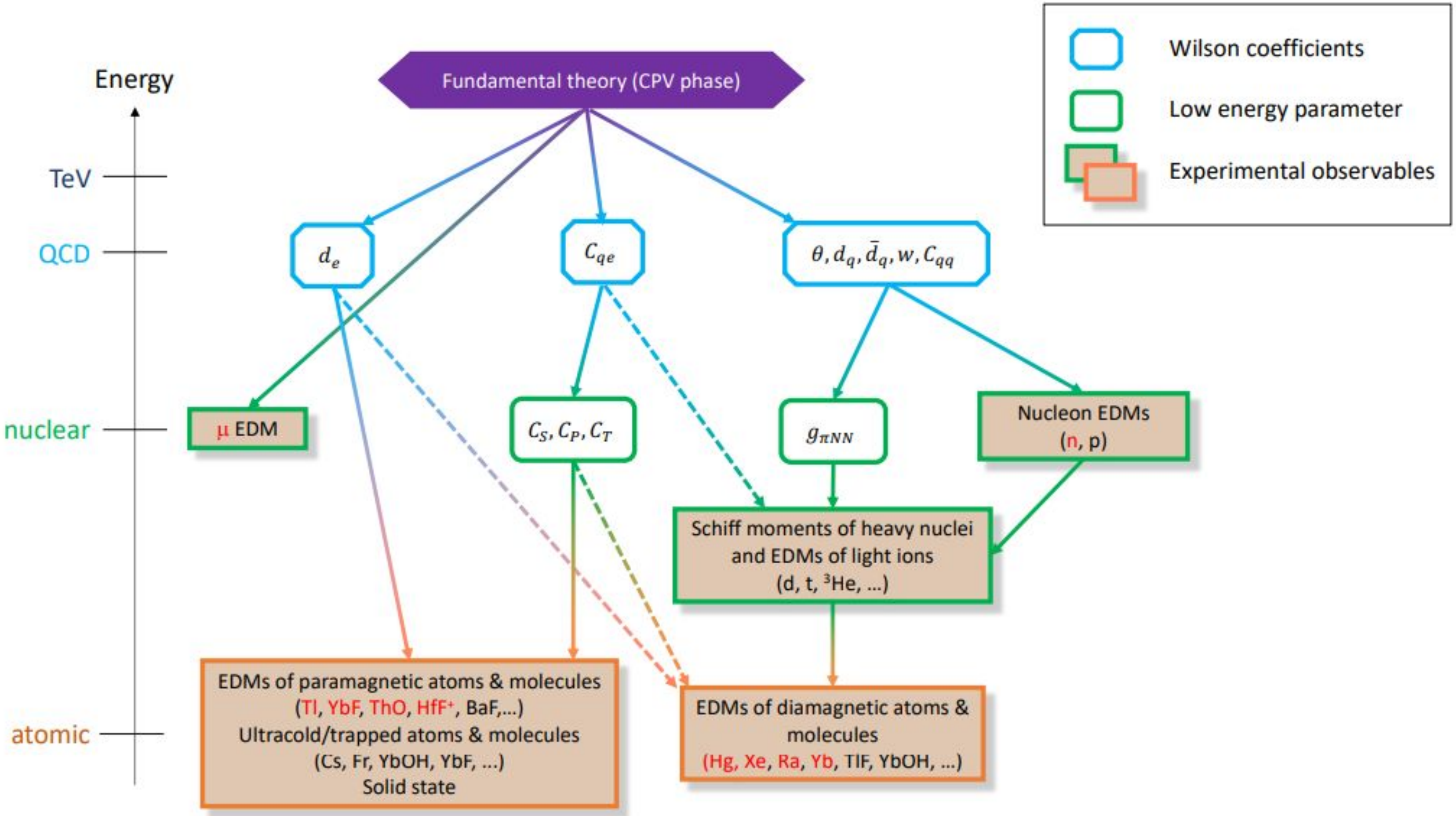


^{226}Ra target

- p(15 MeV)+^{226}Ra ➔ ^{225}Ac - 700 mb
  (batch mode: τ = 10 days)
- p(70MeV)+^{226}Ra ➔ ^{223}Fr - 3 mb

Leiden quotation

Item	QTY	Description	Euro
1	**1**	**Cryogen-Free dilution refrigerator Model LC CF-CS110-100mK**	220.000
2		**Optimized mixture (furnished by customer)**	~17 Liter
3	1	Ultra-sensitive LCR bridge inclusive Break Out Box and cables. **(necessary)**	9.500
4	1	Calibrated RuO2 resistance thermometer	1.100
	Wiring		
5	2	CuNi wires in 2 sets of 24 twisted wires (some wires used for thermometry)	Standard
		Packing, shipping and insurance	
6	1	**Packing, shipping and insurance (tentative quote. Final invoice will depend on the packing and shipping company invoice)** *Incoterms: DAP (Delivered at Place)*	15.000
7	1	Installation and final performance demonstration at the end users location	7.000
	Total		252.600



[Blum, Winter, et al - arXiv:2209.08041]

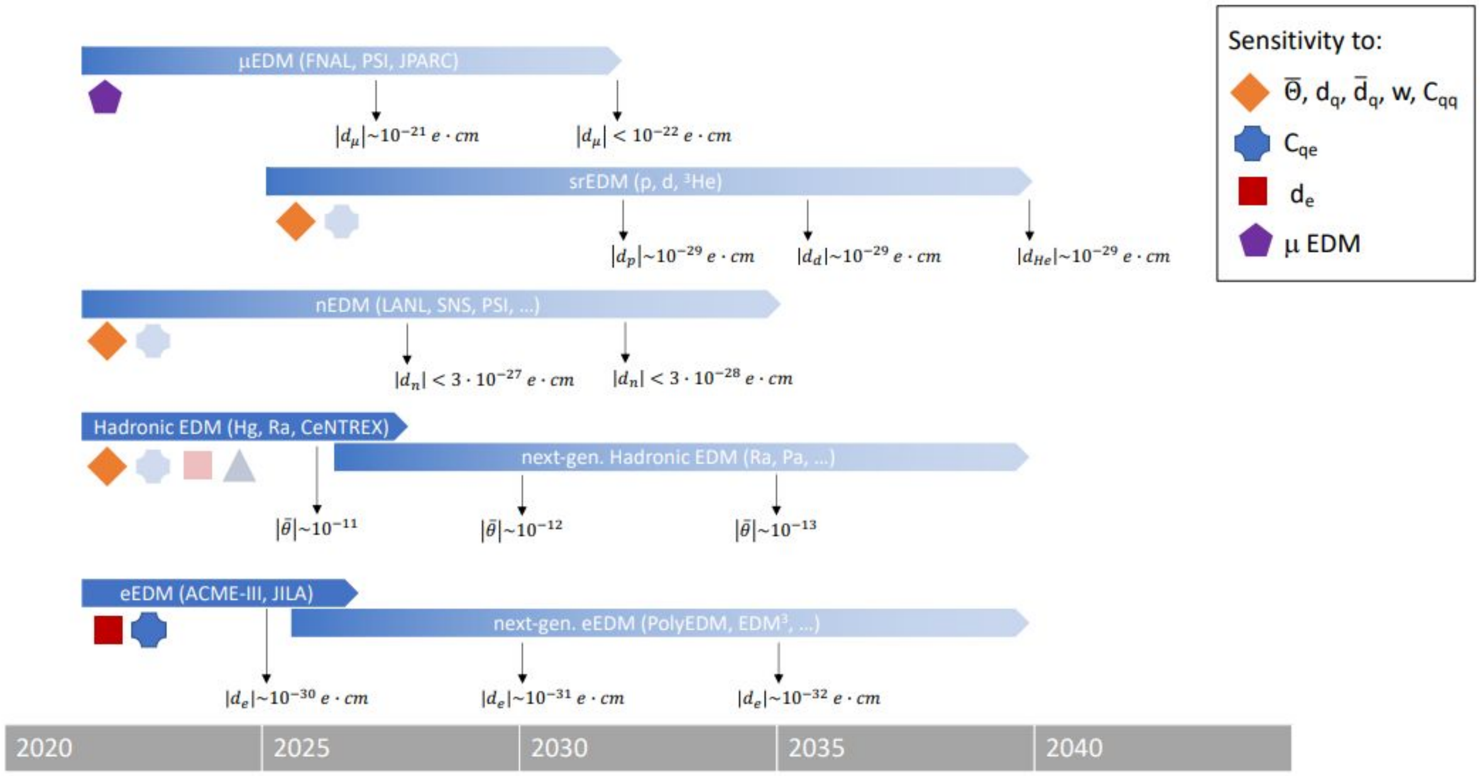
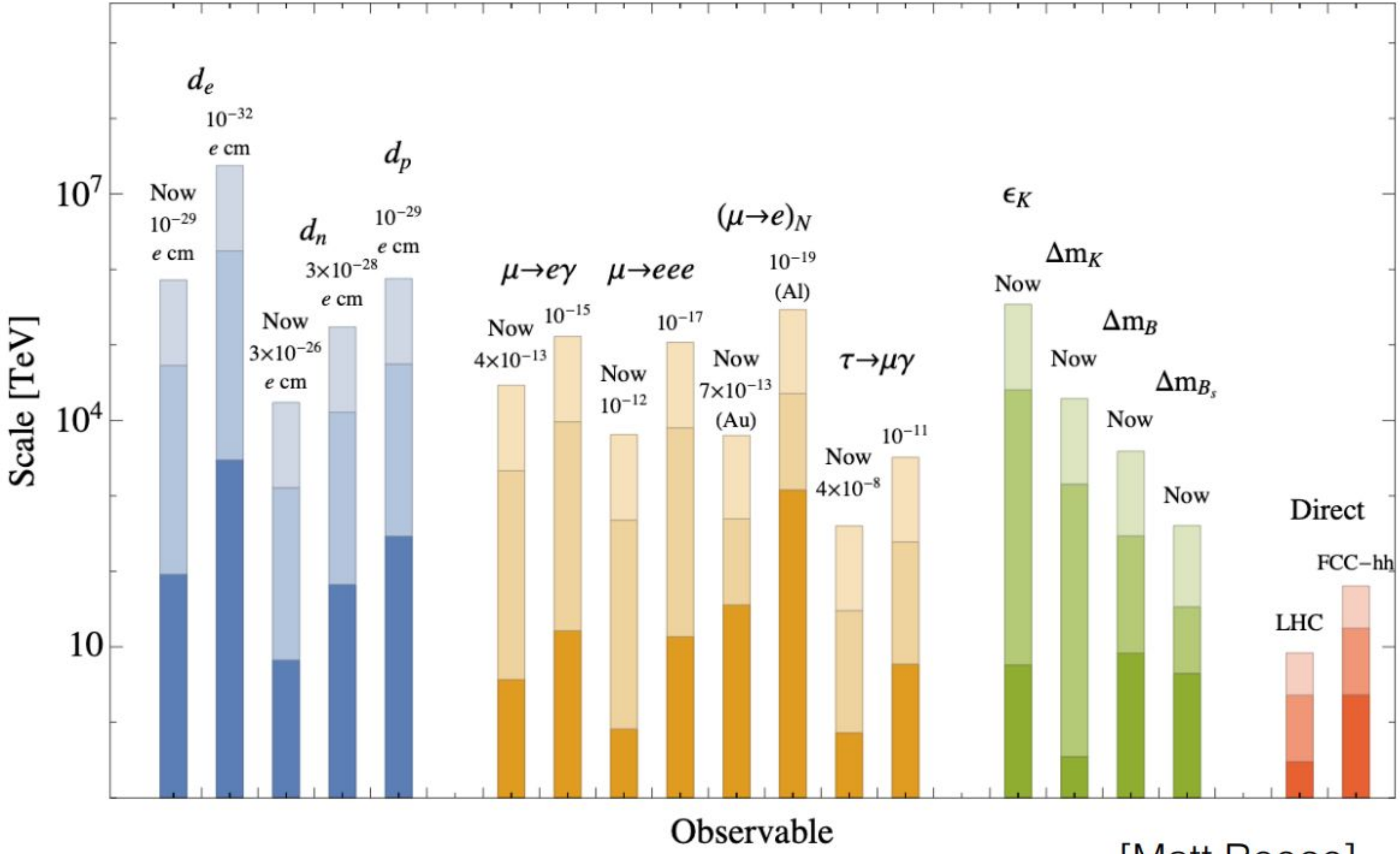


Figure 3-1. *Timelines for the major current and planned EDM searches with their sensitivity to the important parameters of the effective field theory (see Fig. 3-2 for details). Solid (shaded) symbols indicate each experiment's primary (secondary) sensitivities. Measurement goals indicated by the black arrows are based on current plans of the various groups.*

[Blum, Winter, et al - arXiv:2209.08041]

Bounds on Λ (scale of NP) for dimension six (4-fermion) operators O_i : $\sum_i \frac{C_i}{\Lambda^2} O_i$



[Matt Reece]

Model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j\gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

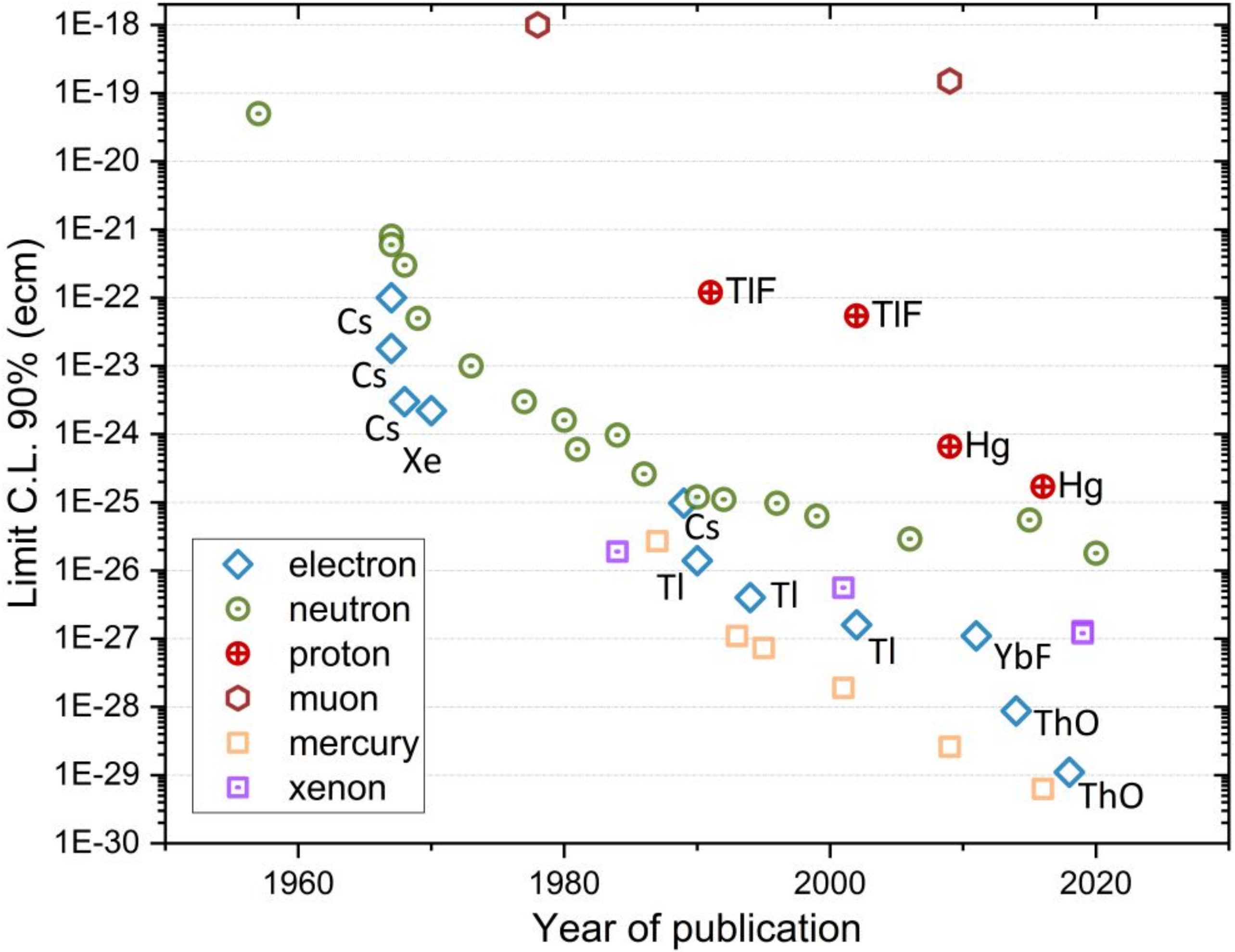
- **EDMs vs.** $(g-2)_\mu$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}}\right) \; e\,\mathrm{cm}\,,$$

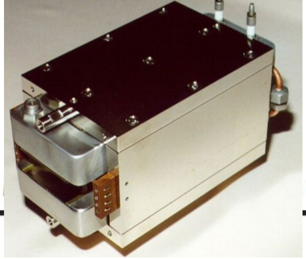
$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22} \, \phi_\mu^{CPV} \; e\,\mathrm{cm}\,.$$

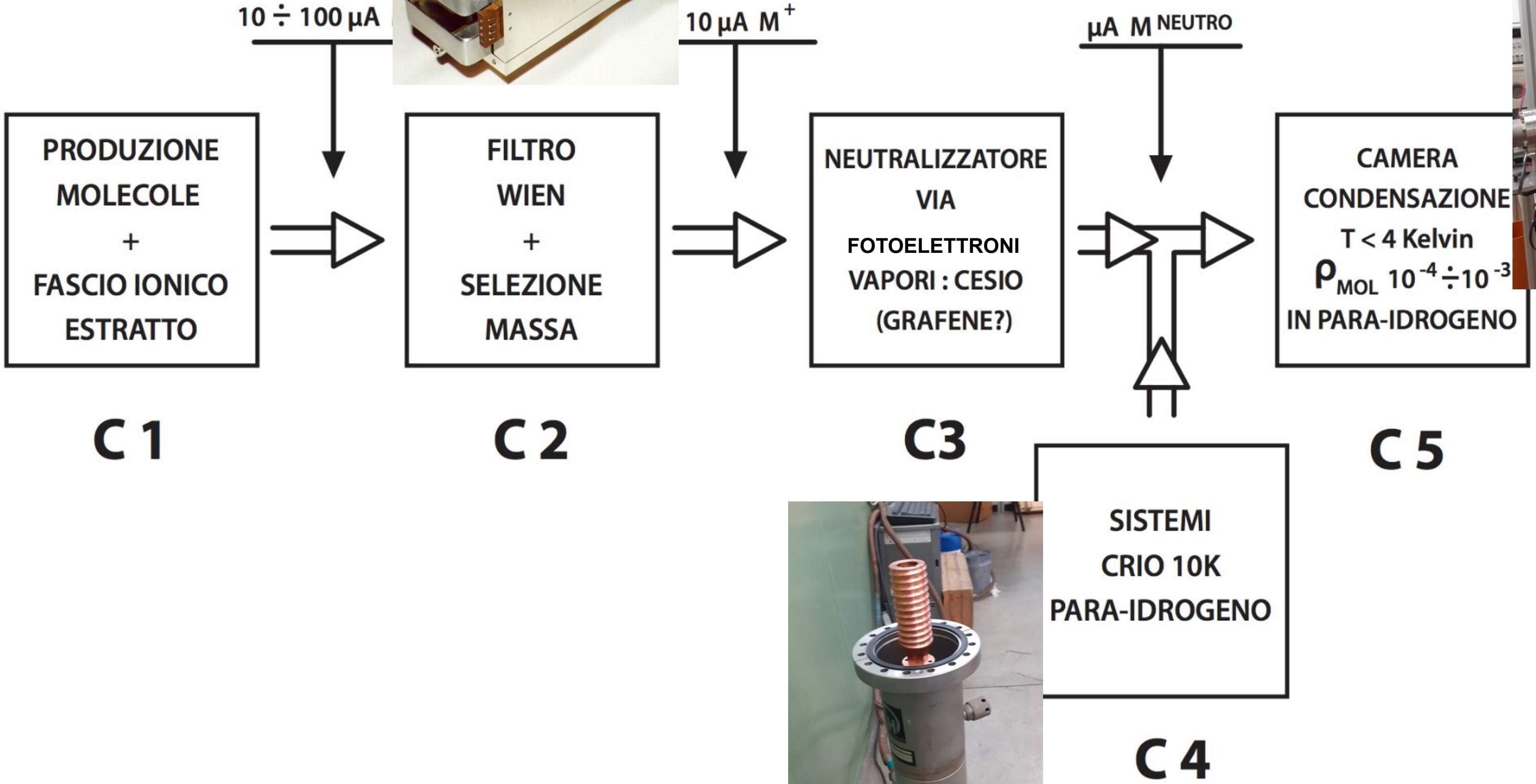
- **Main messages:**
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ **are still allowed!**

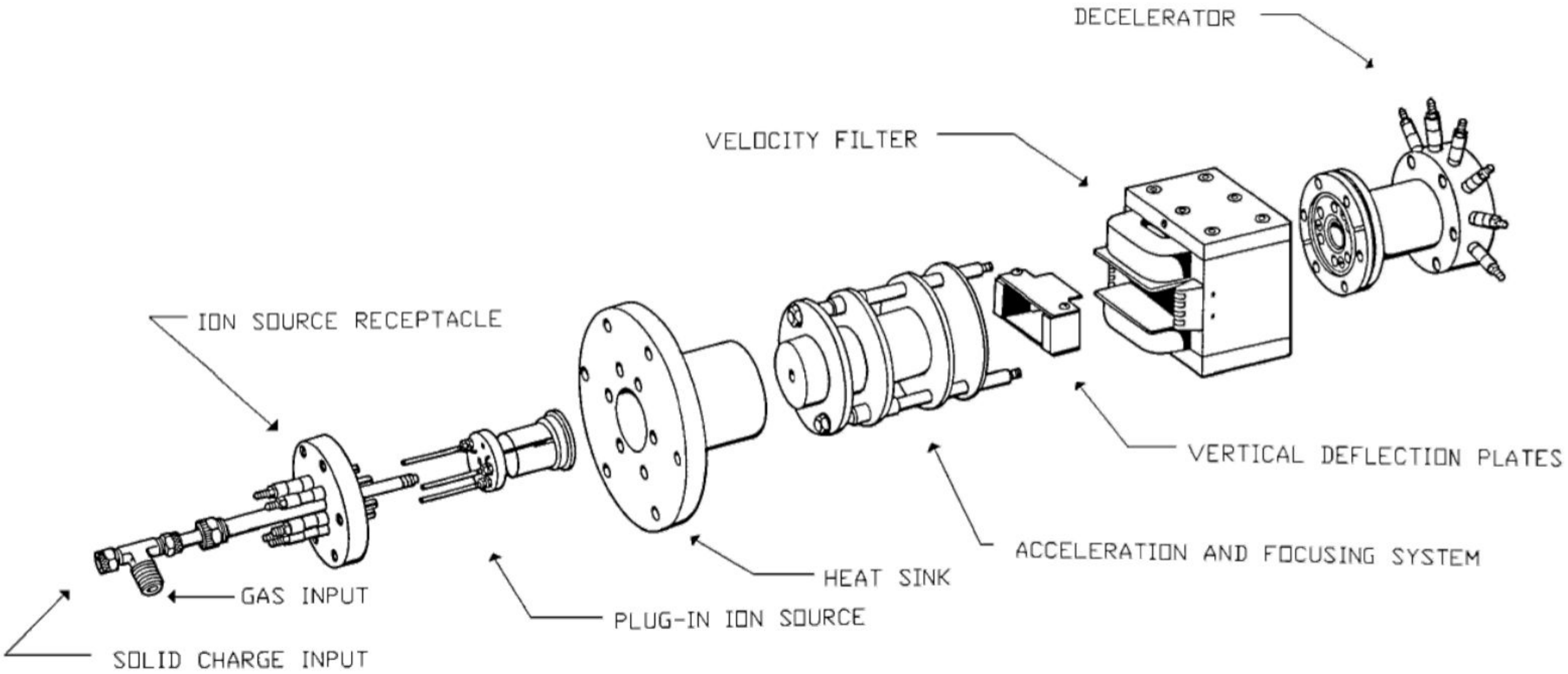
[Giudice, P.P., & Passera, '12]



[Chislett, Crivellin, Hoferichter, Schmidt-Wellenburg - Prospects for a Muon g − 2/EDM Measurement Using Re-accelerated




10 ÷ 100 µA
10 µA M +
µA M NEUTRO
PRODUZIONE MOLECOLE + FASCIO IONICO ESTRATTO
FILTRO WIEN + SELEZIONE MASSA
NEUTRALIZZATORE VIA FOTOELETTRONI VAPORI : CESIO (GRAFENE?)
CAMERA CONDENSAZIONE T < 4 Kelvin ρ MOL 10 -4 ÷ 10 -3 IN PARA-IDROGENO
SISTEMI CRIO 10K PARA-IDROGENO
C 1
C 2
C3
C 4
C 5


DECELERATOR
VELOCITY FILTER
ION SOURCE RECEPTACLE
VERTICAL DEFLECTION PLATES
ACCELERATION AND FOCUSING SYSTEM
HEAT SINK
GAS INPUT
PLUG-IN ION SOURCE
SOLID CHARGE INPUT