Development of continuous ionization detection of the PbF molecule:

Toward measurement of the electron's electric dipole moment (e-EDM.)

Neil Shafer-Ray

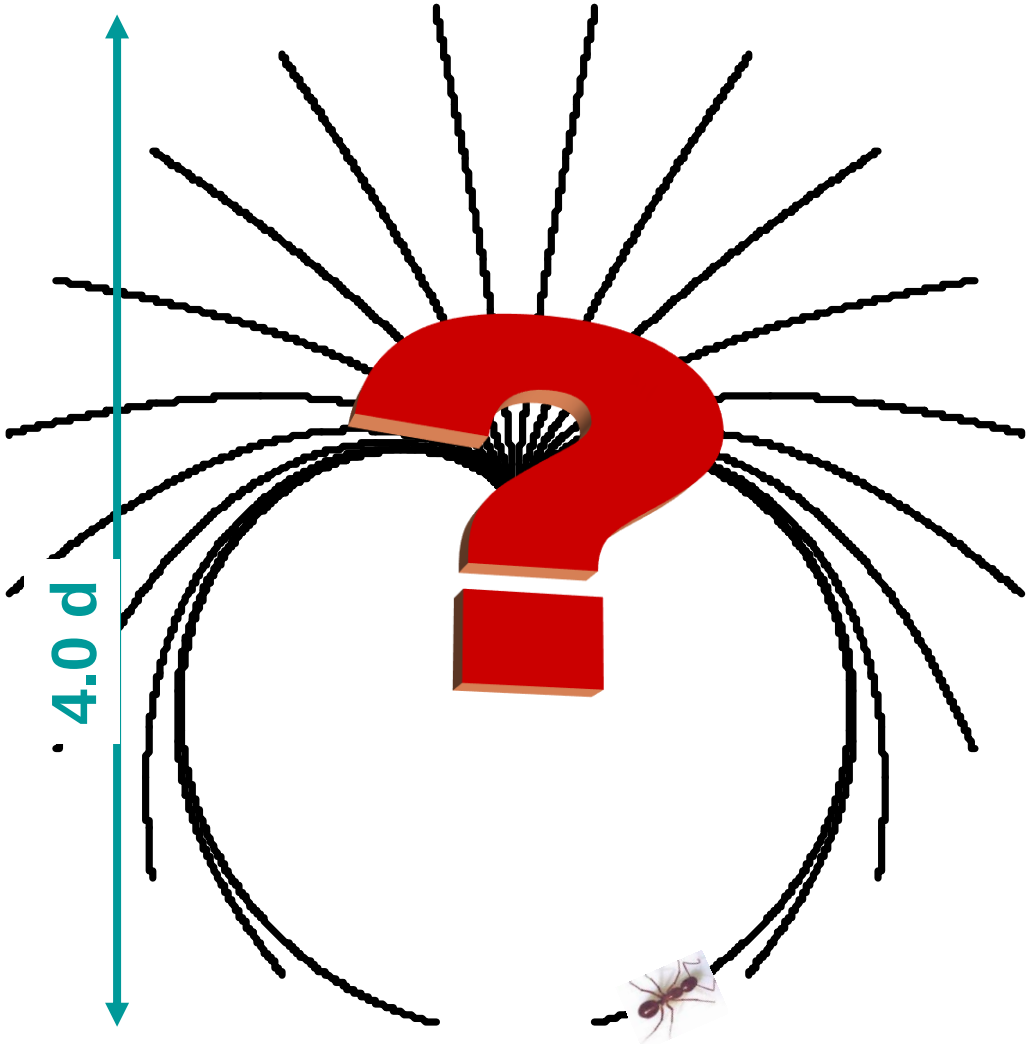
EPSCoR Program Review

BNL

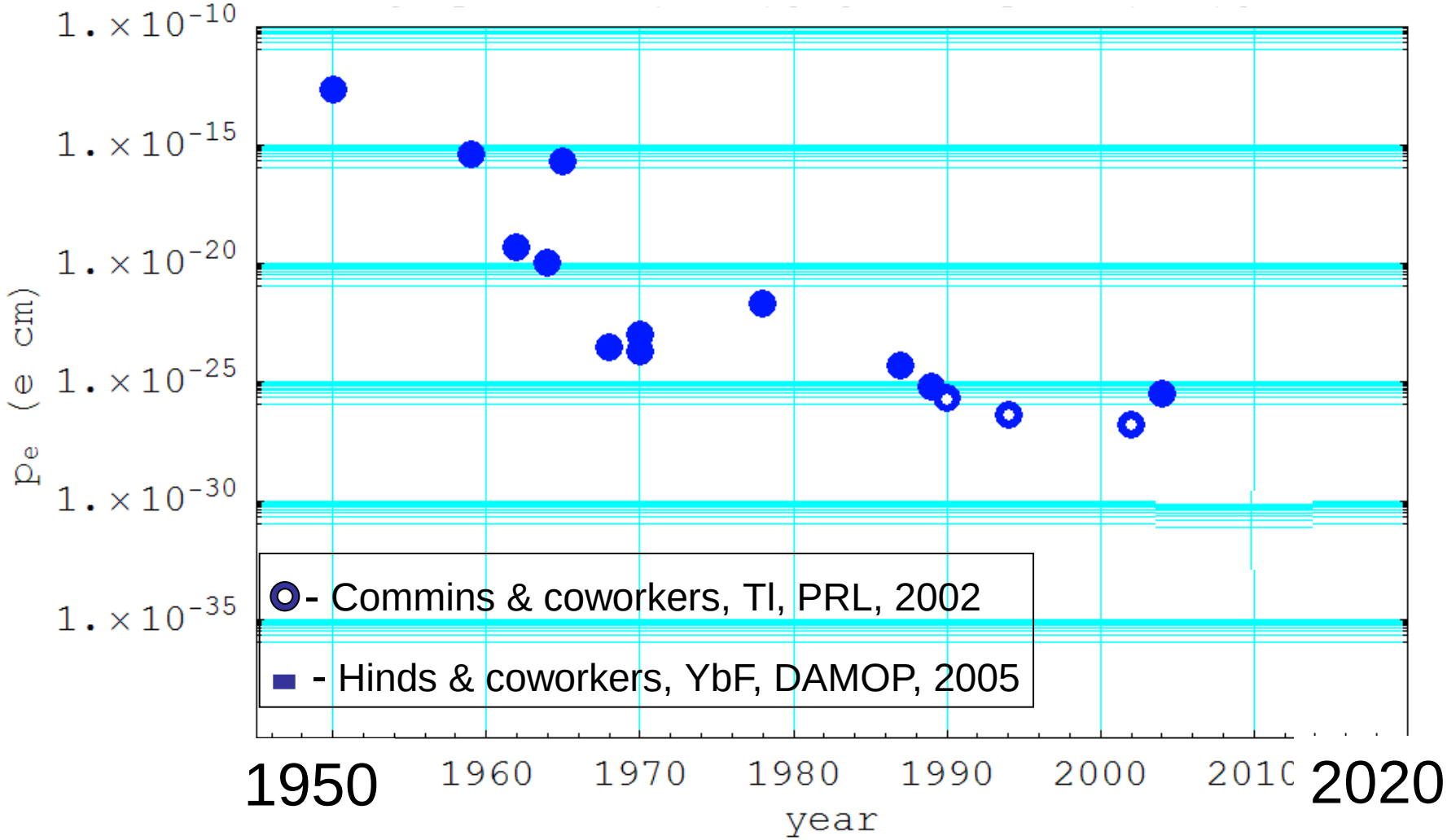
July 22, 2009

"Does an electron have an electric dipole moment?" Purcell and Ramsey, 1950.

Pursuit of an answer to this question led Ramsey to develop the separated oscillator technique (the heart of the modern atomic clock.)

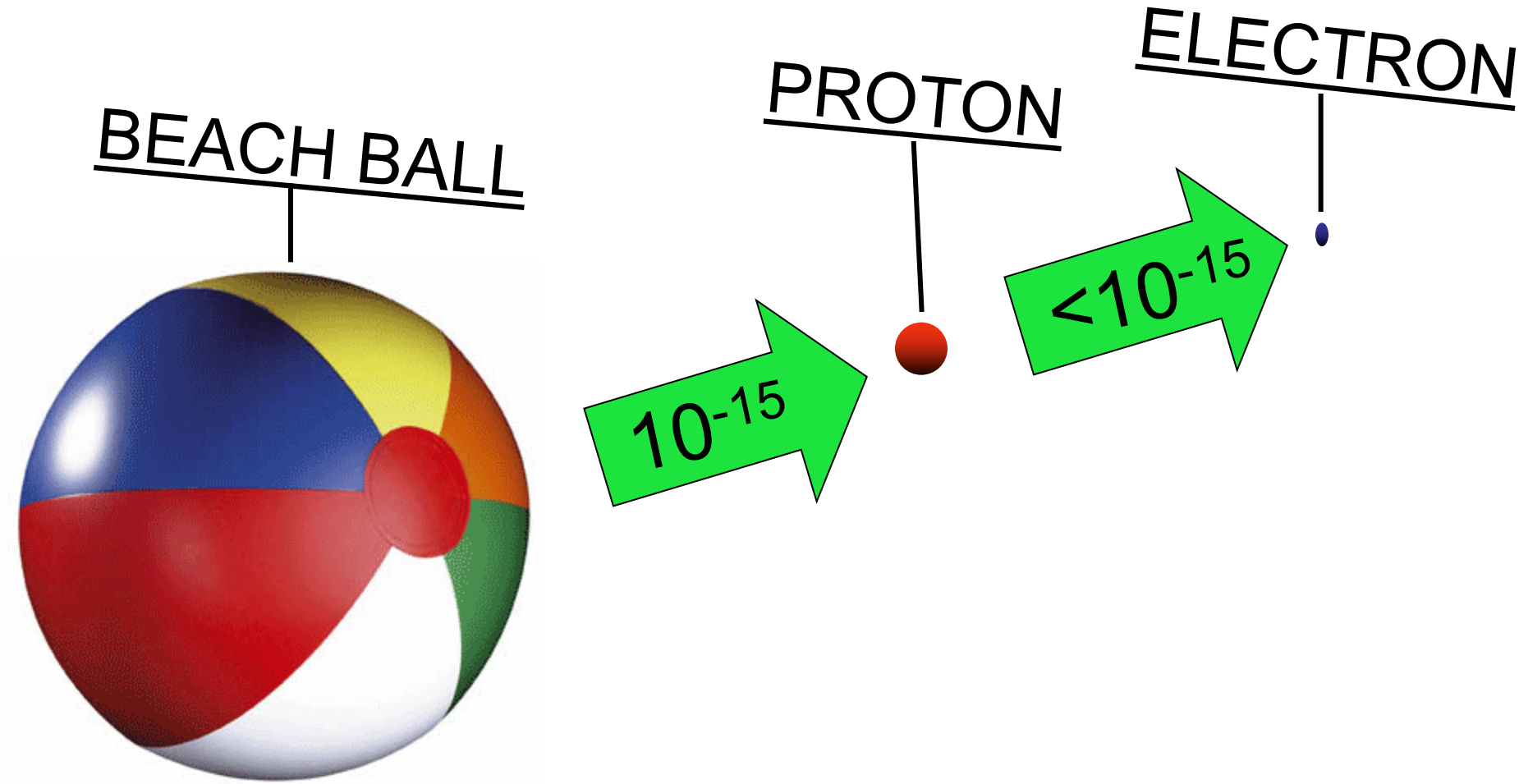


EXPERIMENTAL LIMITS ON THE e-EDM



$d_{exp} < \sim 1.6\ 10^{-27}$ cm

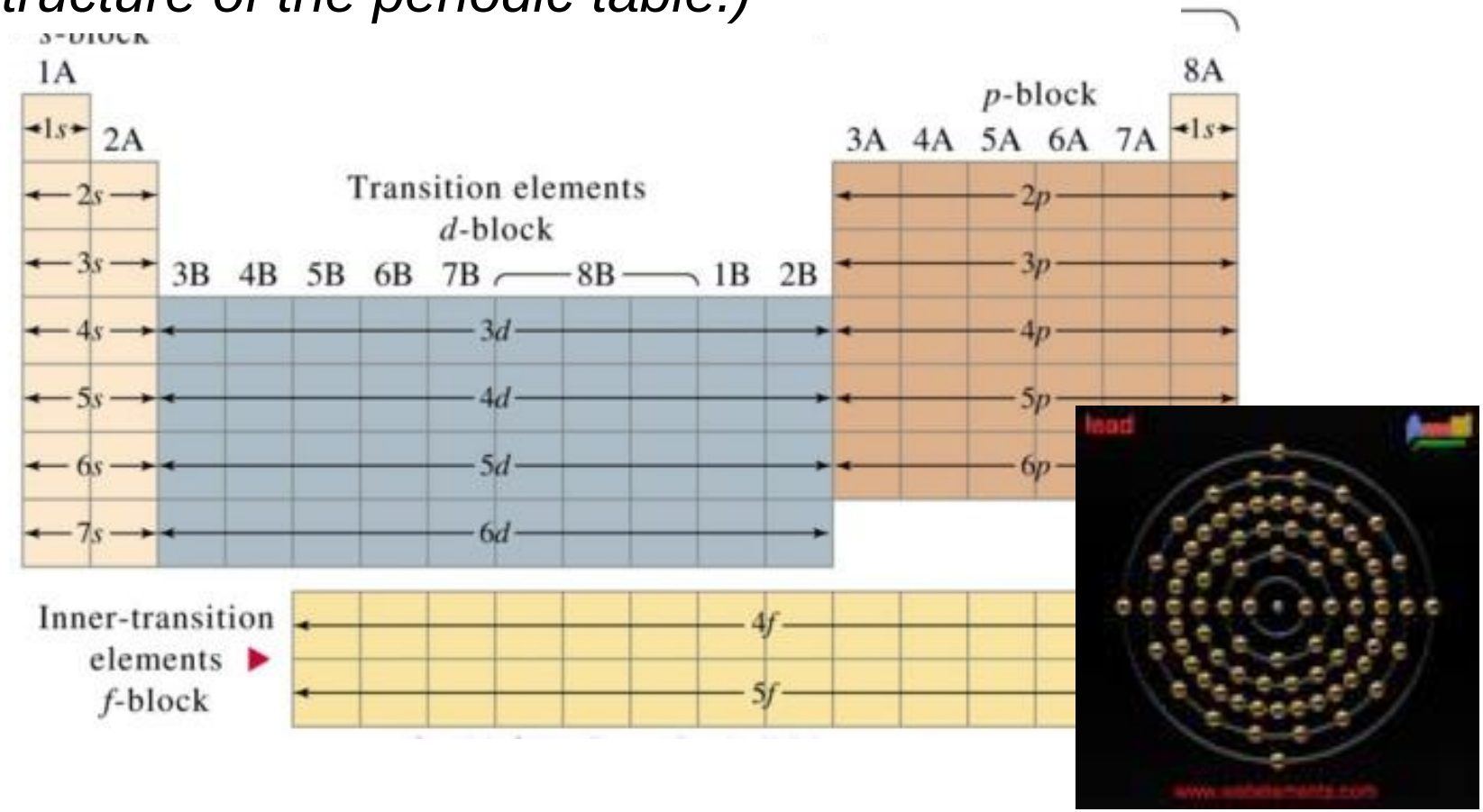
Current Limit on the Size Scale d of the Electron



The e-EDM is not only small, it's (T) odd. ..

An e-EDM would be proportional to the spin of the electron: $\vec{p} = \mu_B g_{edm} \vec{S}$.

(A new vector degree of freedom would change the shell structure of the periodic table.)



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<u>A dipole proportional to spin is time-reversal violating.</u>

video (played forward) from www.engr.colostate.edu/~dga/pool/high_speed_videos

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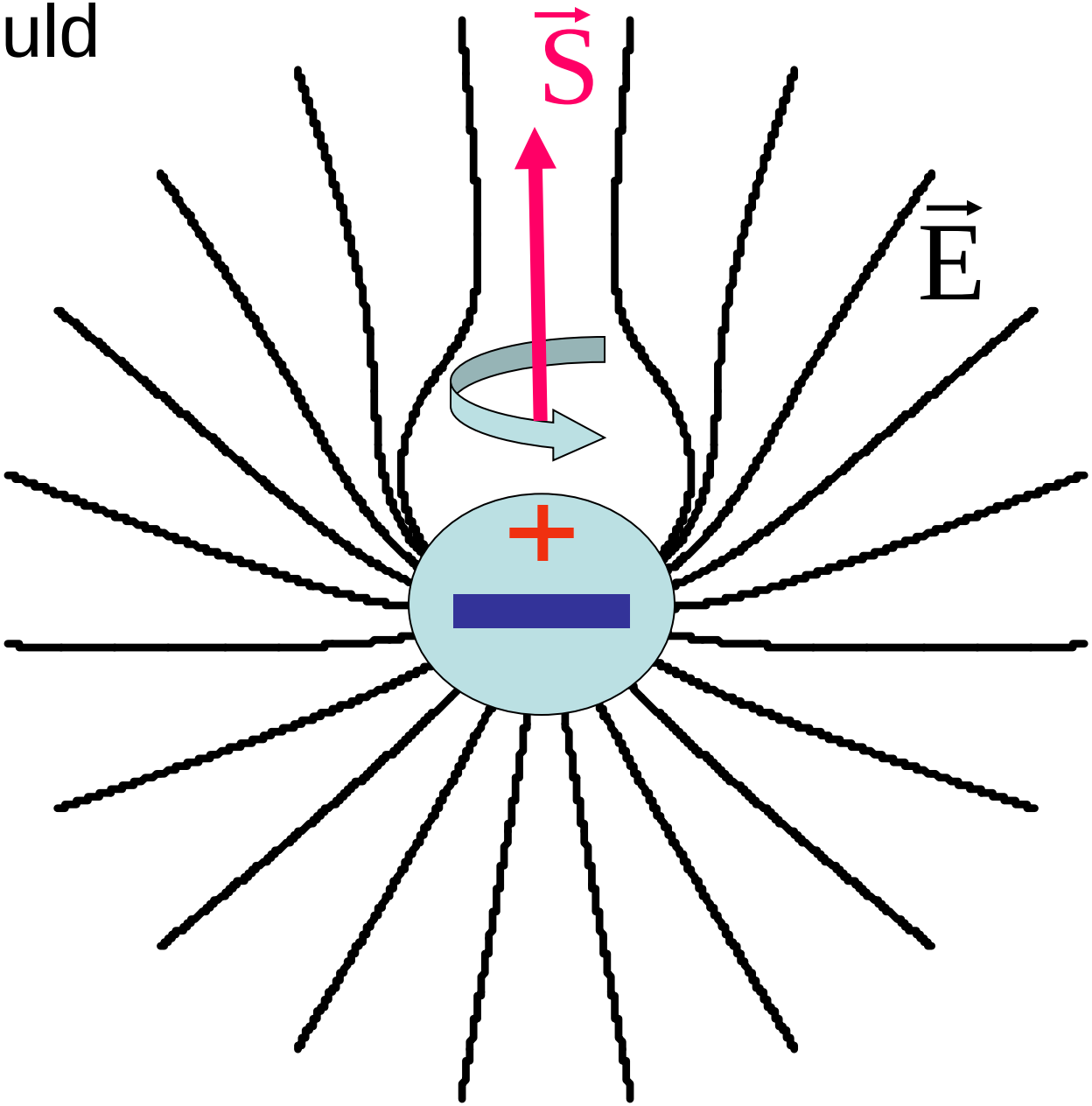
<u>A dipole proportional to spin is time-reversal violating.</u>

A process is time-reversal violating when one can tell if a video of the process is being played forward or backwards.

video (played forward) from www.engr.colostate.edu/~dga/pool/high_speed_videos

An e-EDM would beT- violating because extra positive charge always in direction of the spin (for $g_{edm}>0$.)



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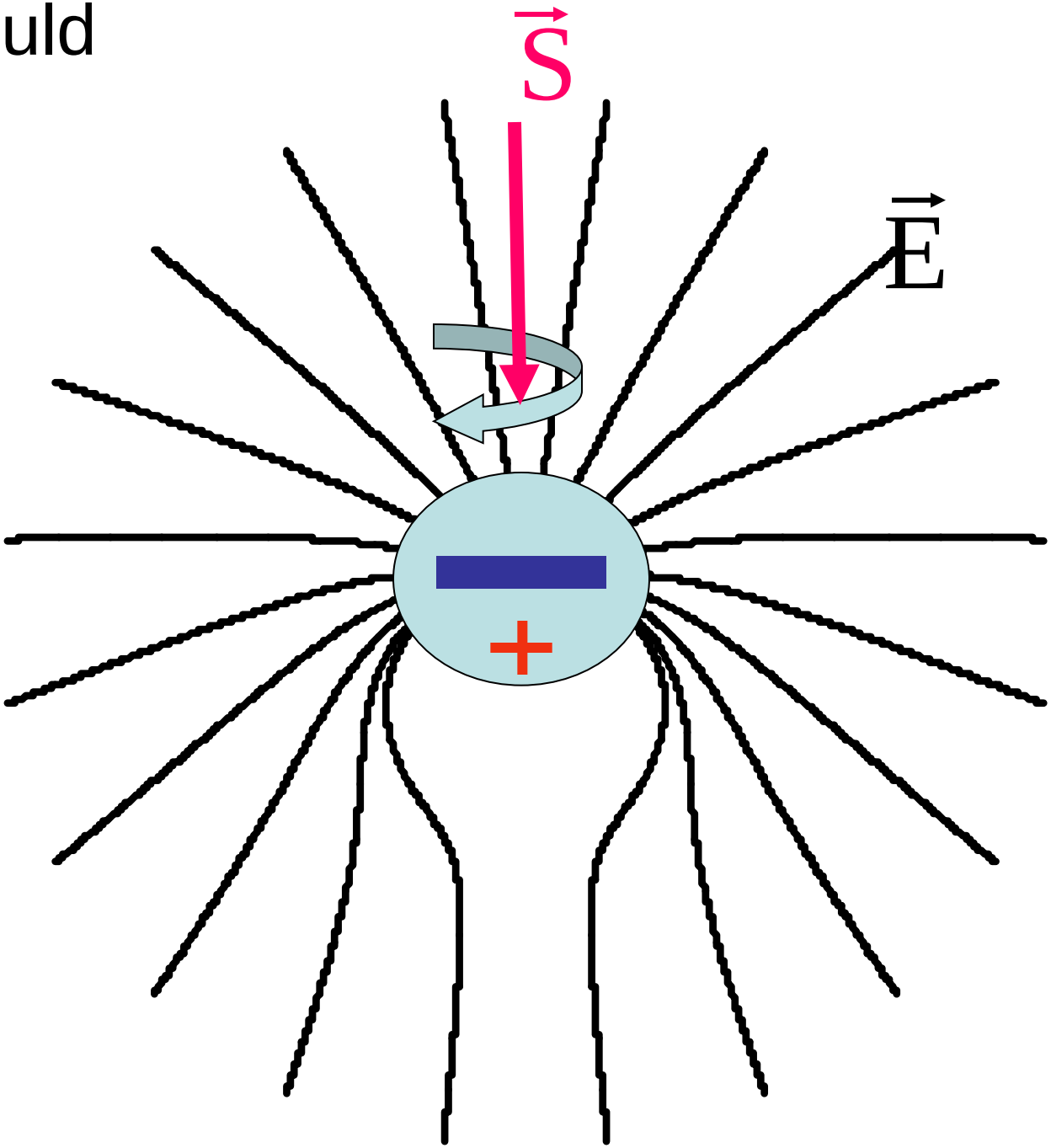
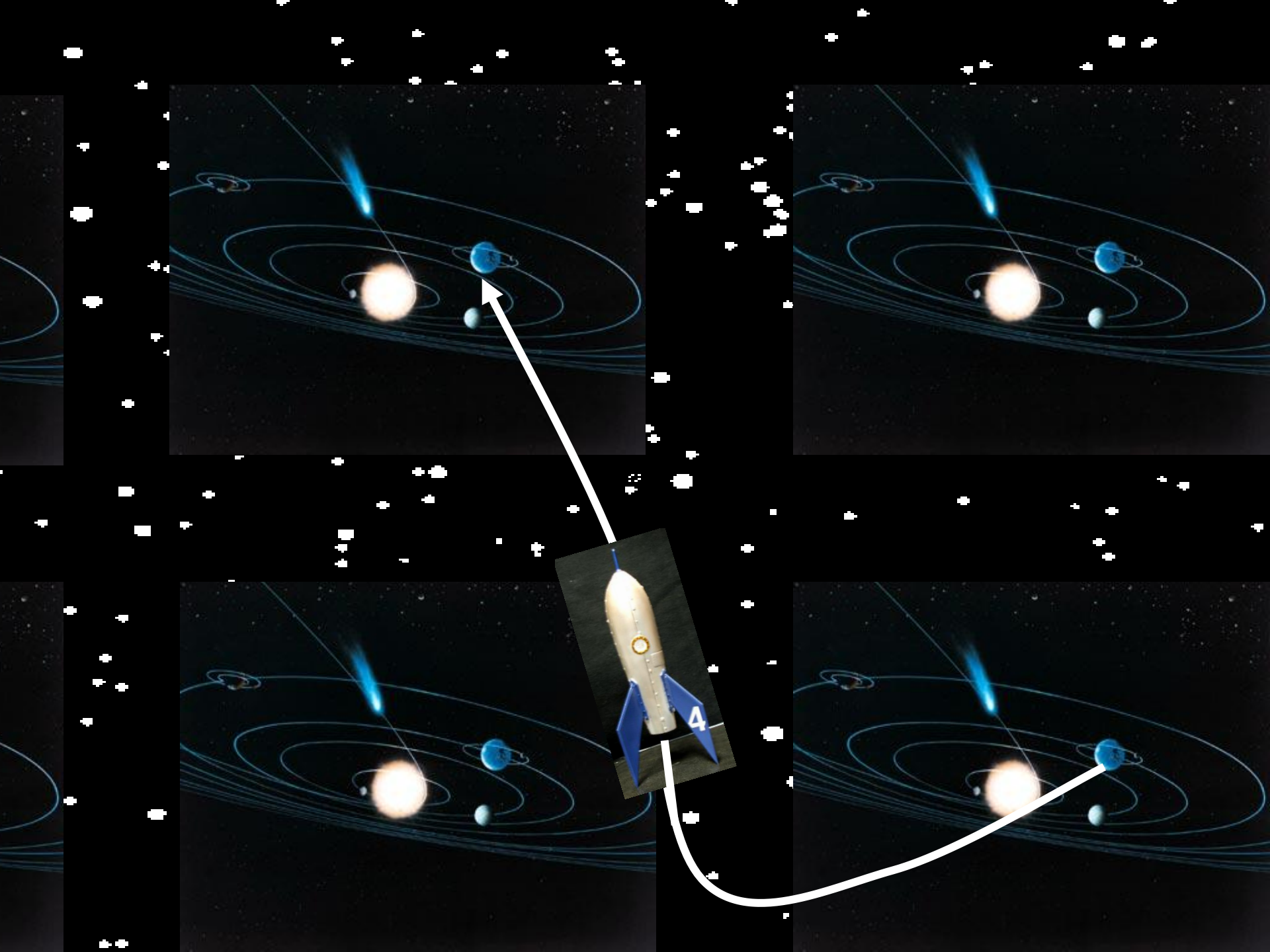
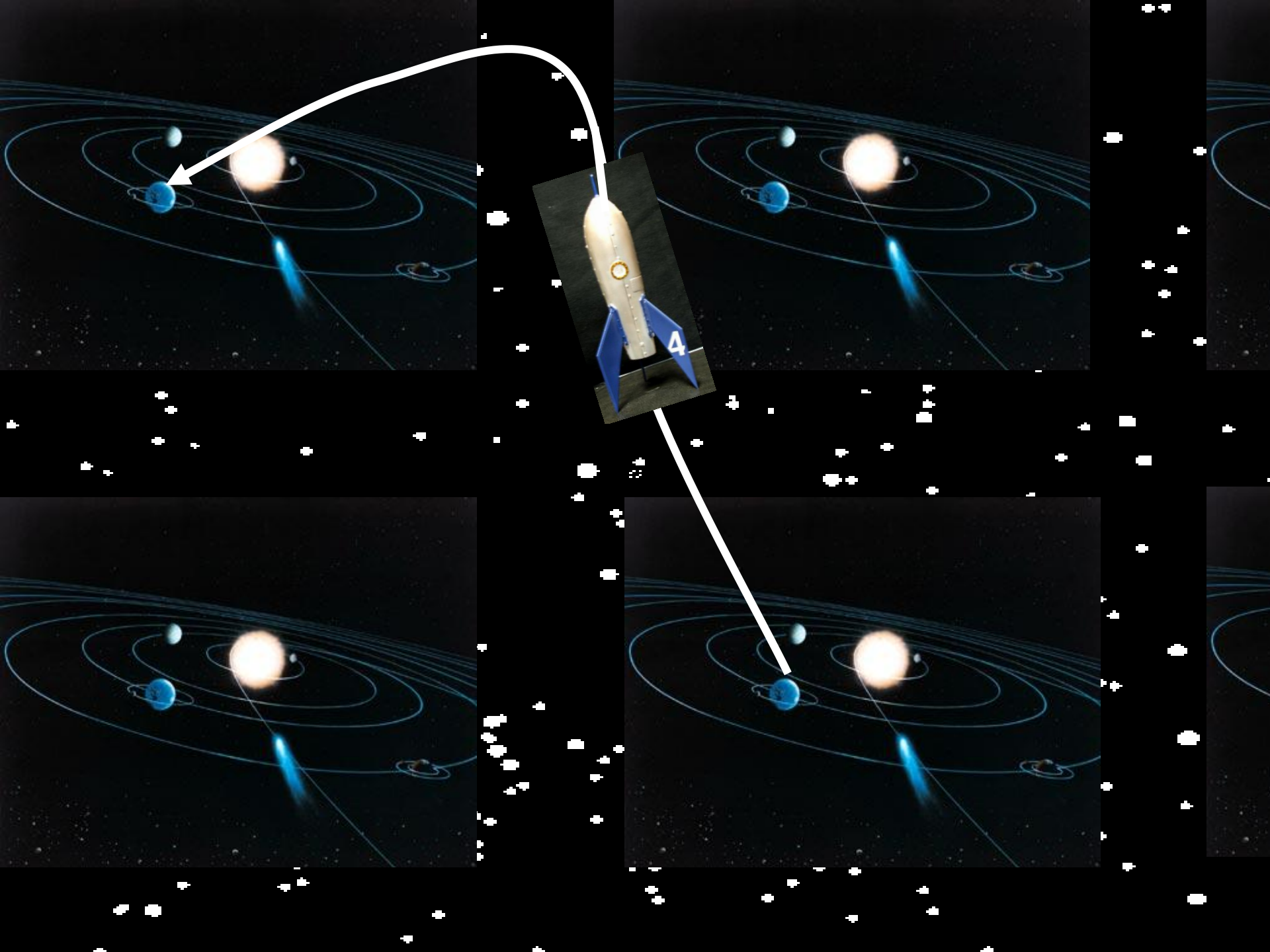



4

$\vec{S}$
www.worldofstock.com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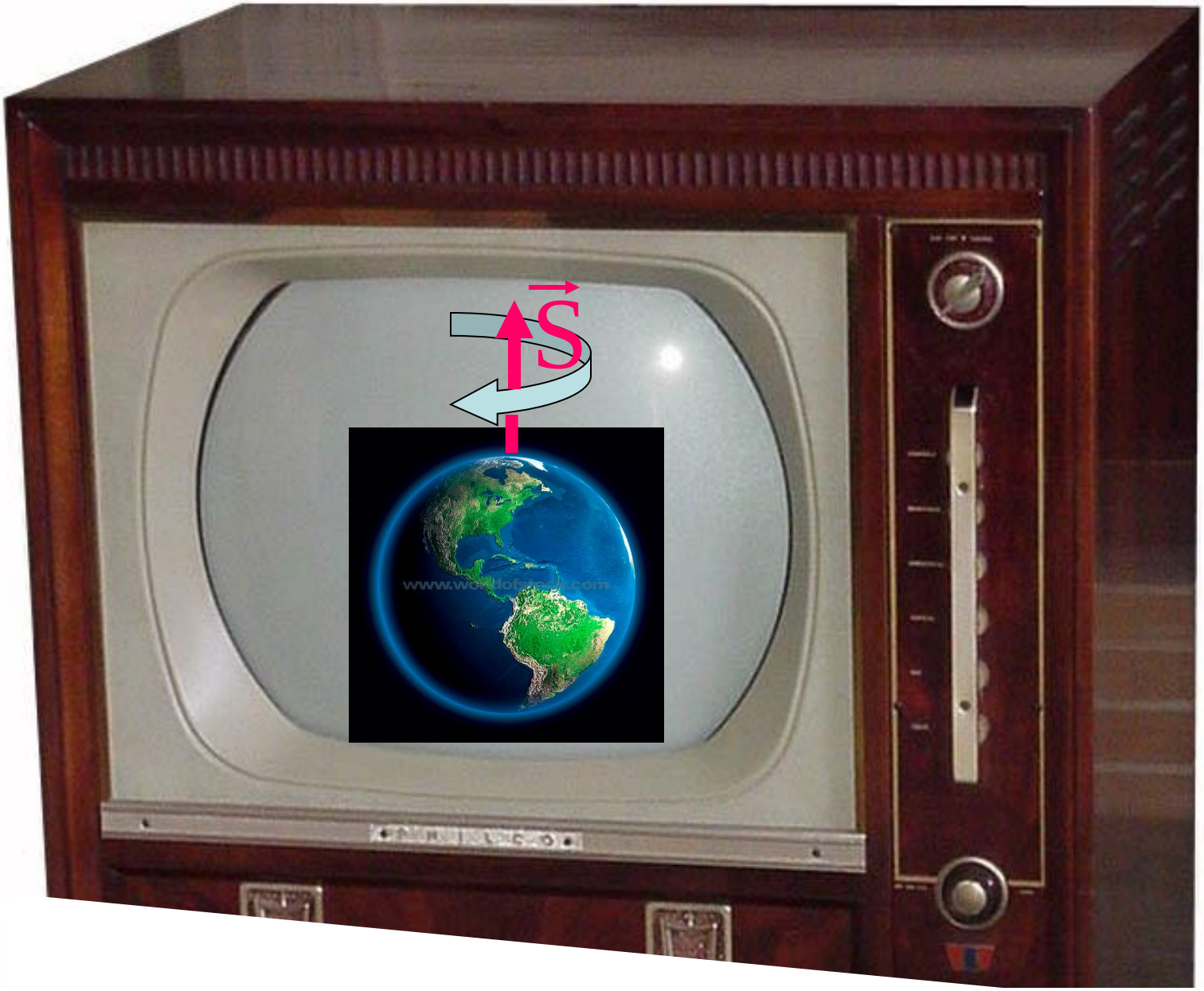
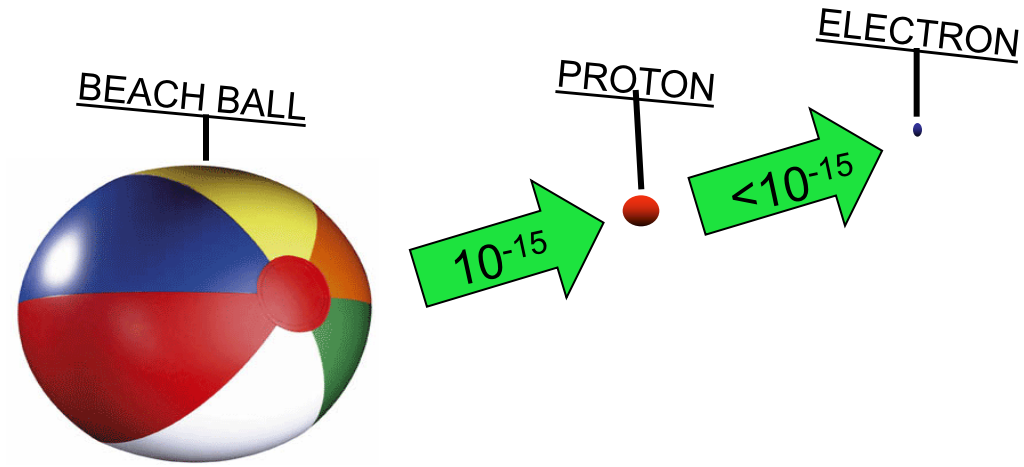

$\vec{S}$

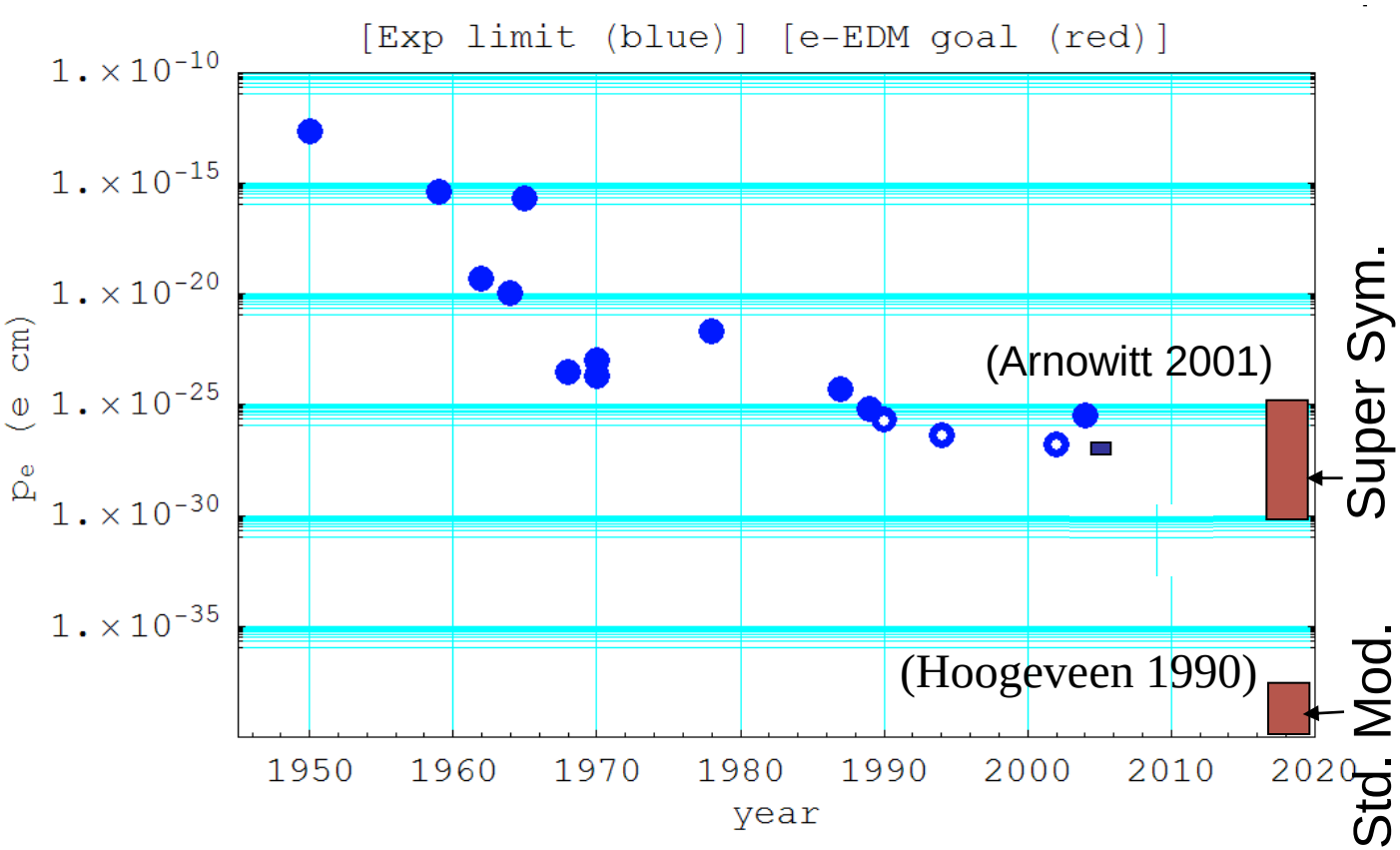
e-EDM Summary



Its small.

It's T violating.

e-EDM Summary



It's worth searching for.

How Does One Search for an e-EDM?

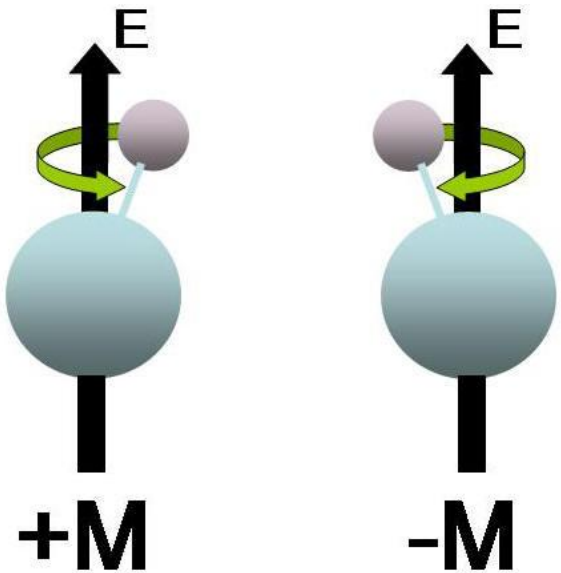
T Symmetry leads to a M degeneracy of any molecule or atom that is not broken by an electric field along the quantization axis.

The existence of an electron electric dipole moment would break this symmetry.

To search for an e-EDM we will look for

$\Delta U = U_{+M} - U_{-M}$

in a strong E field.



Major Difficulty: A background magnetic field mimics an EDM.

The current limit of 1.6 x 10^{-27} e cm has been set by observing ground-state Tl atoms.

Heavy paramagnetic molecules are approximately10,000 times more sensitive to an *e*-EDM than atoms. (Splitting of mHz instead of μHz.)

Can we reach 10^{-31} *e* cm??

Active drill sites:

PbF: University of Oklahoma (Shafer-Ray)

ThO: Yale, Harvard, (DeMille, Doyle, Gabrielse)

HfF^+: NIST, NRC, University of Colorado (Eric Cornell, John Bohn)

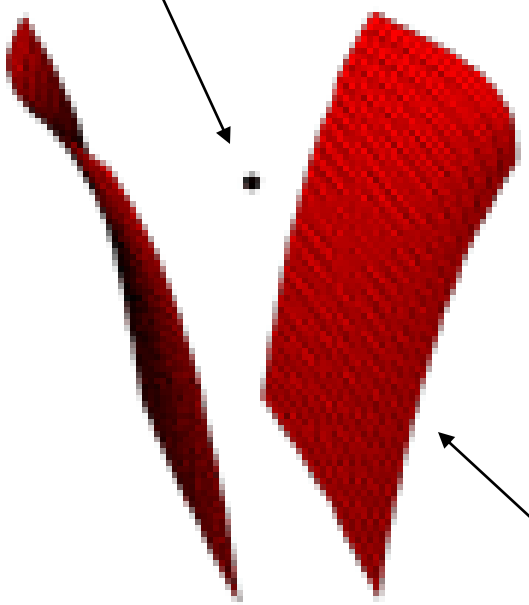
YbF: Oxford (Ed Hinds)

PbO: Yale (David DeMille)

WC: Michigan (Aaron Learnhardt)

To measure the small energy difference between M states, we first proposed
to produce very cold PbF molecules and confine them to a *Stark Graviational Trap.*

PbF

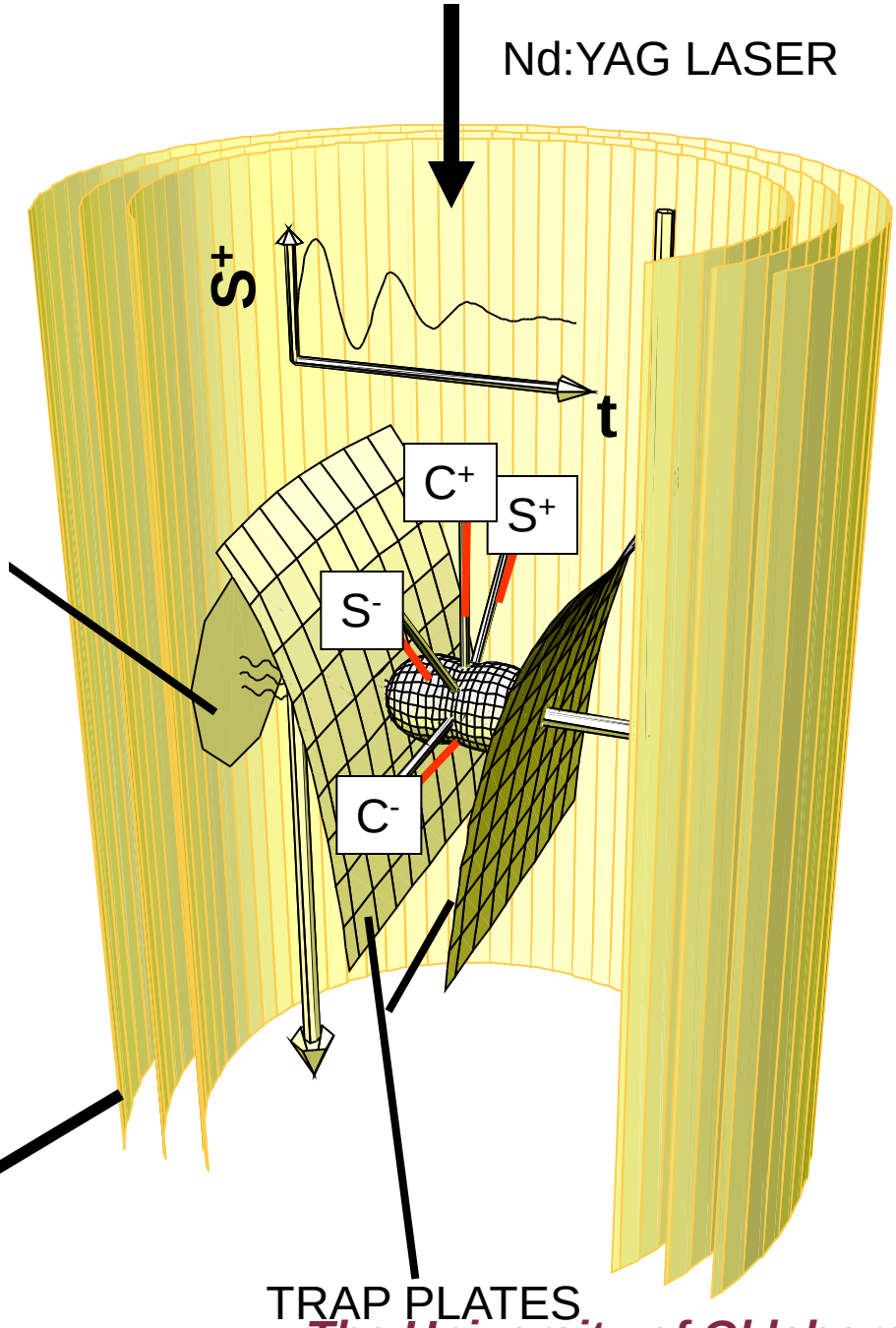


HIGH VOLTAGE PLATES

Rupasinghe and Shafer-Ray, *The Effect of the Geometric Phase on the Possible Measurement of the Electron's Electric Dipole Moment using Molecules Confined by a Stark-Graviational Trap,* PRA 2008

The PbF molecules could then be polarized (put in a superposition of M states.)

This polarization would then rotate at a rate $\Delta U/h$

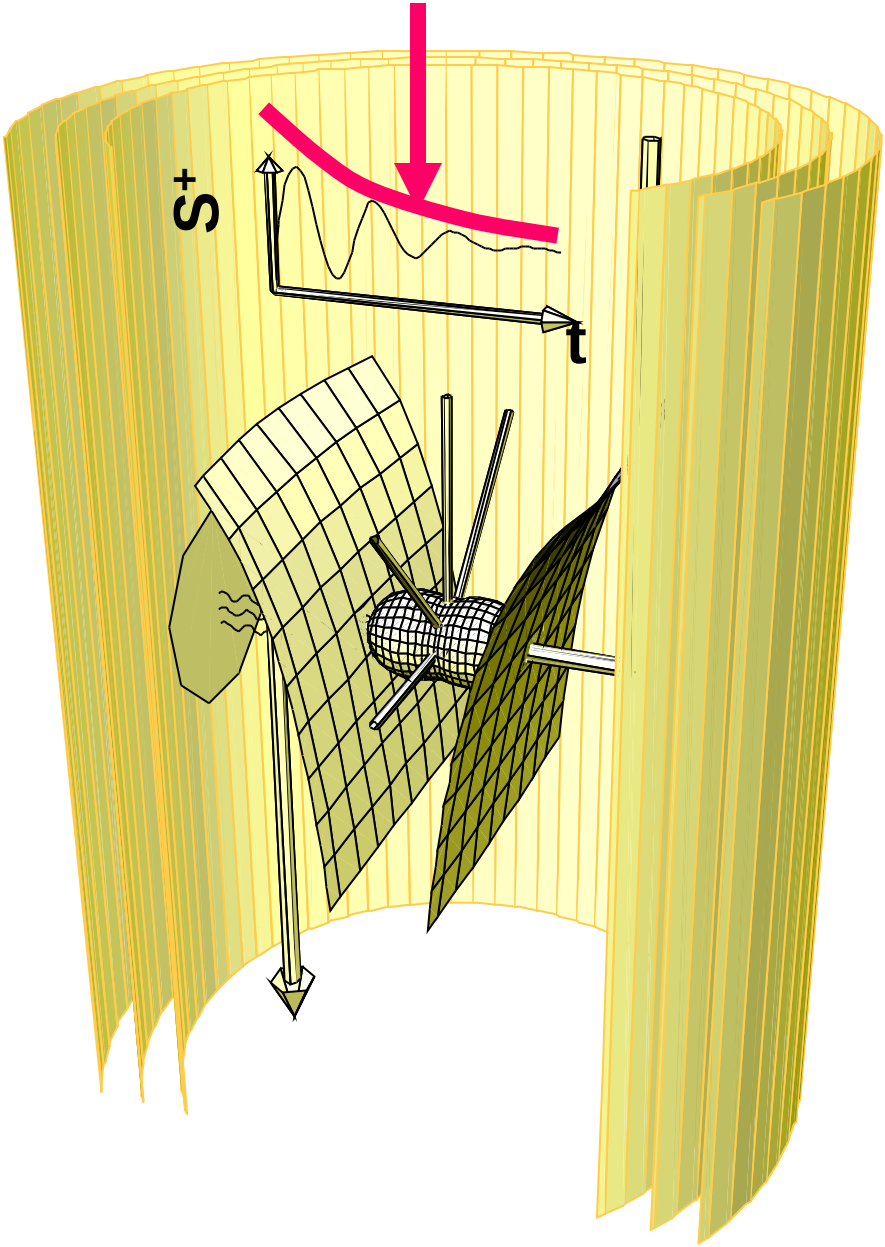


FIRST EPSCoR - SPONSORED PROJECT:

What is the expected coherence time of the measurement?

Answer: Bad news! The geometric phase effect couples the angular momentum of the center-of-mass motion of the molecule to the internal angular momentum of the molecule.

Signal amplitude decays at a rate τ.



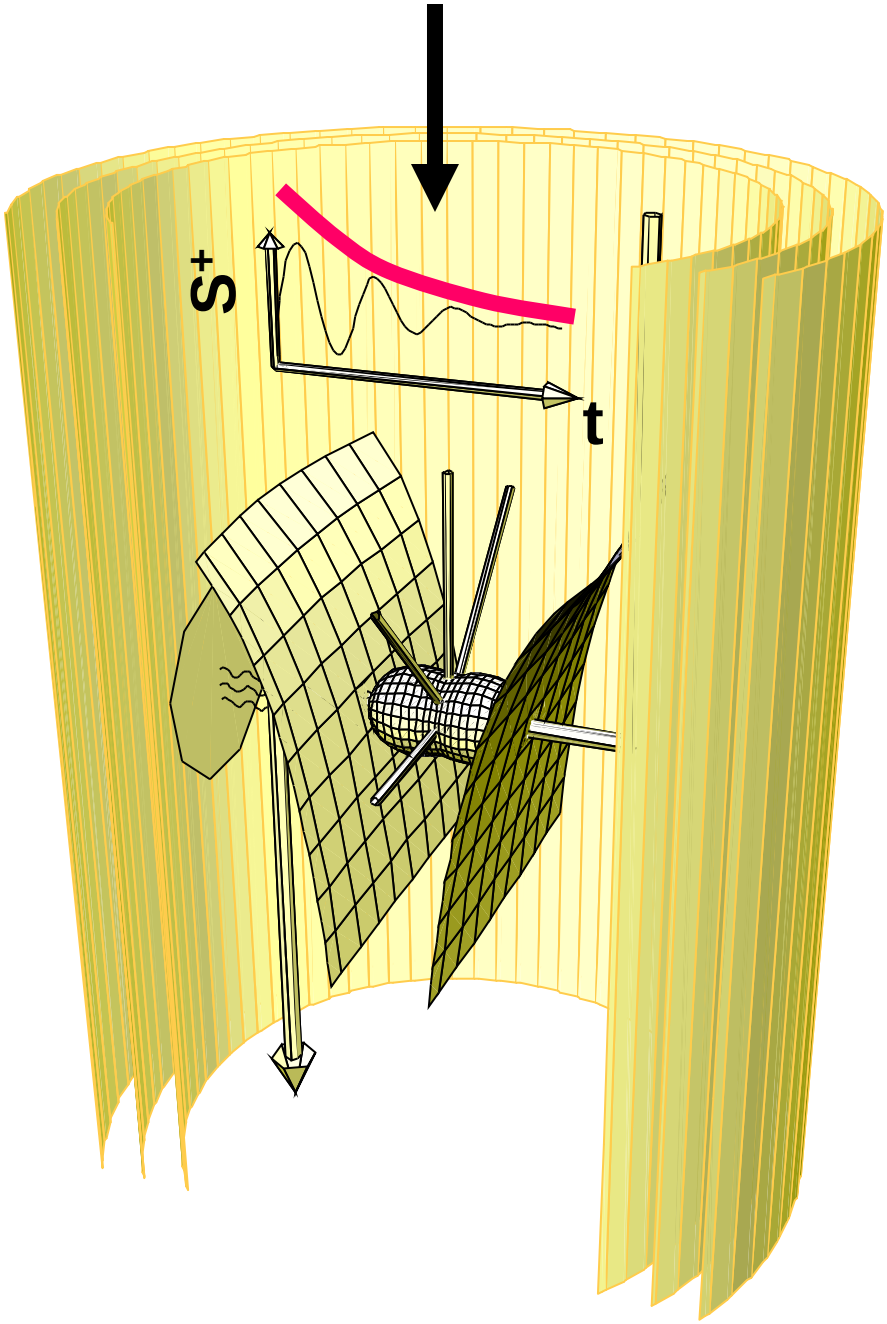
FIRST EPSCoR - SPONSORED PROJECT:

What is the expected coherence time of the measurement?

$$\tau^{-1} = \frac{5}{2}\omega\left(\frac{T}{\tilde{T}}\right)^2$$

$$\tau \approx (1\text{sec})\left(\frac{T}{0.027K}\right)^{-2}$$

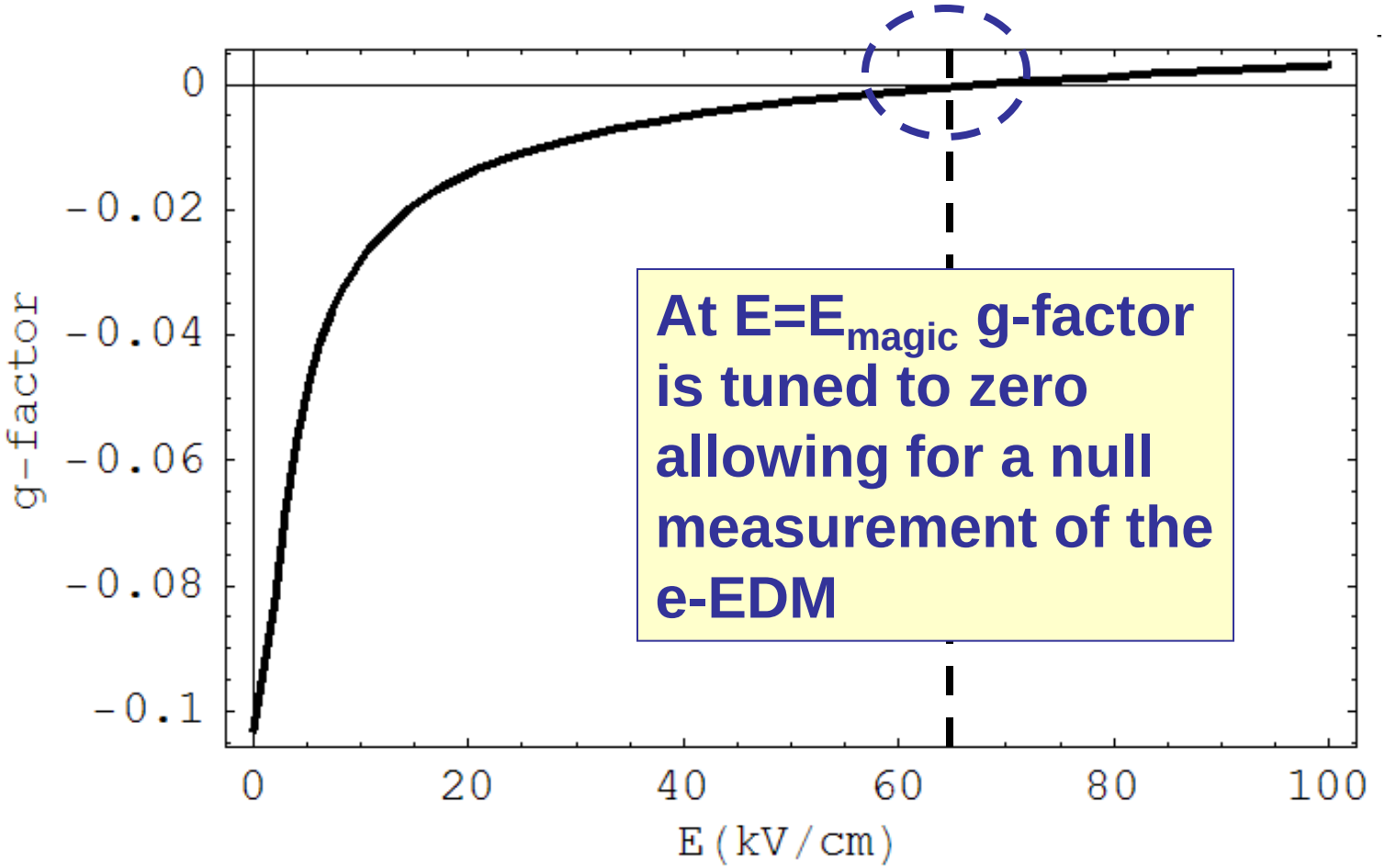
Problem: We do not know how to make a cold enough sample of PbF to make the experiment compete with a molecular beam experiment.



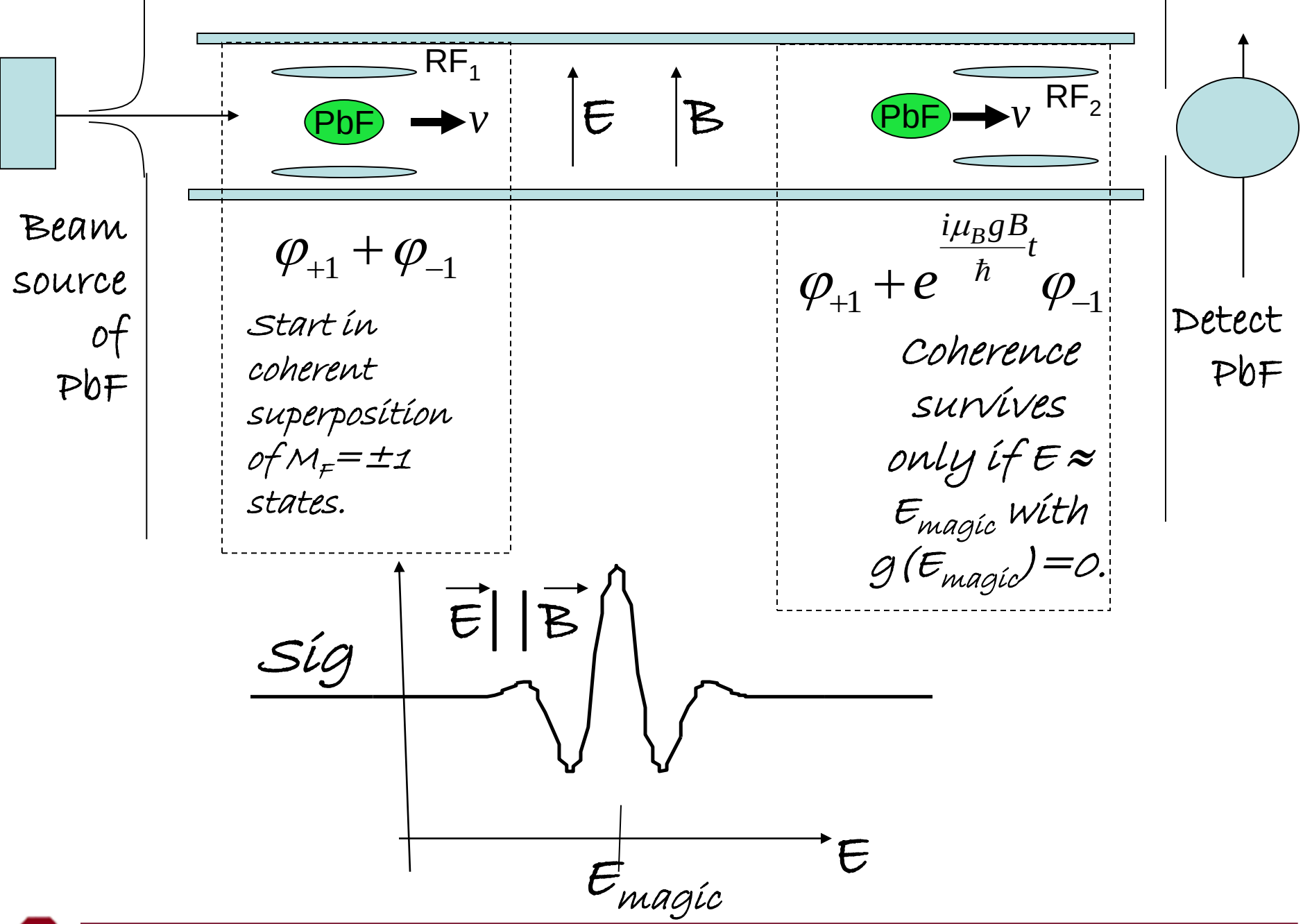
Research shifted to producing a source and detection scheme to improve an ultra-sensitive beam resonance experiment already underway.

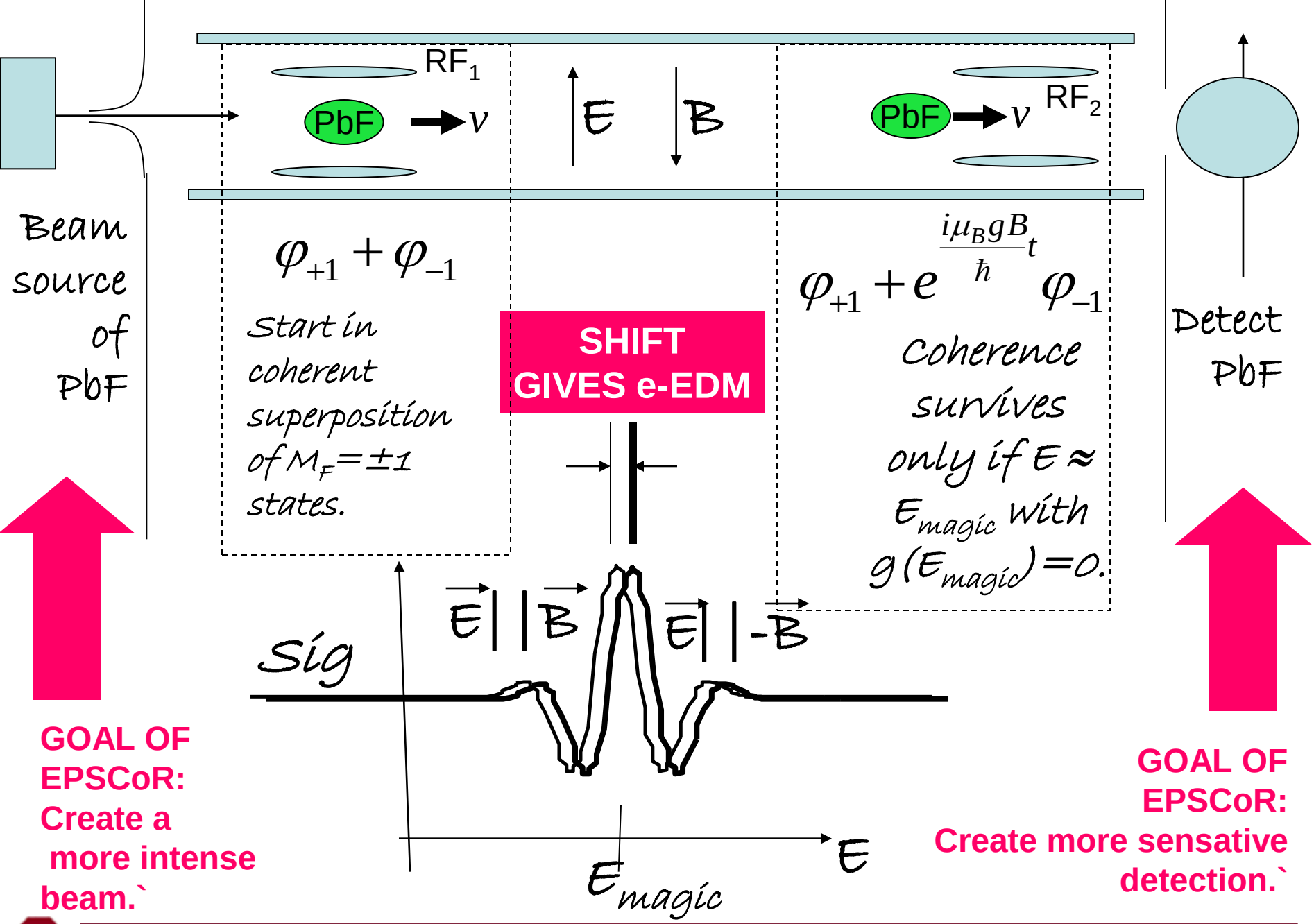
g factor of the $^{208}Pb^{19}F$, F=1, $|M_F|$=1 ground state:

Shafer-Ray, PRA,73, 34102,2006



At $E=E_{magic}$ g-factor is tuned to zero allowing for a null measurement of the e-EDM

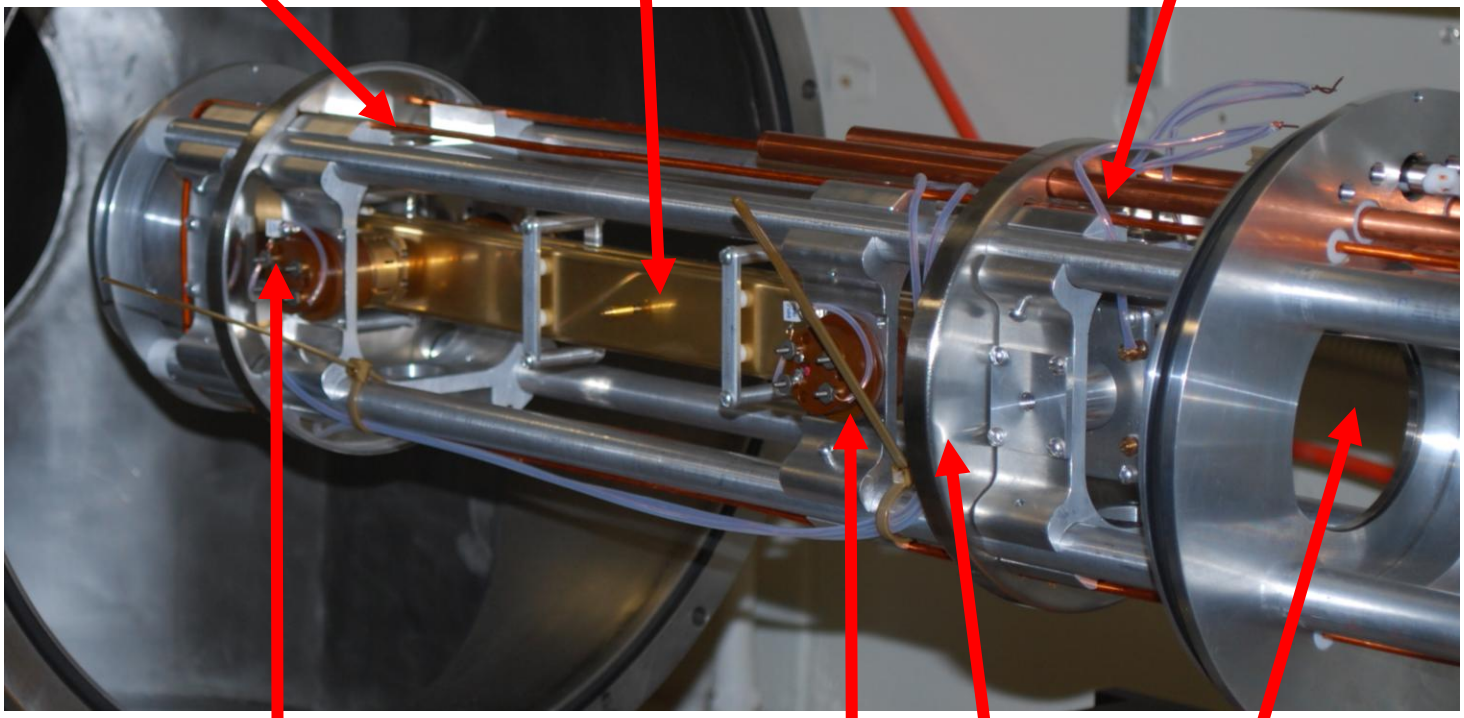

RF1
PbF
v
E
B
PbF
v
RF2
Beam source of PbF
$\varphi_{+1} + \varphi_{-1}$
Start in coherent superposition of $M_F = \pm 1$ states.
$\varphi_{+1} + e^{\frac{i\mu_B g B}{\hbar} t} \varphi_{-1}$
Coherence survives only if $E \approx E_{magic}$ with $g(E_{magic}) = 0$.
Detect PbF
Sig
$\vec{E} \| \vec{B}$
E_{magic}
E

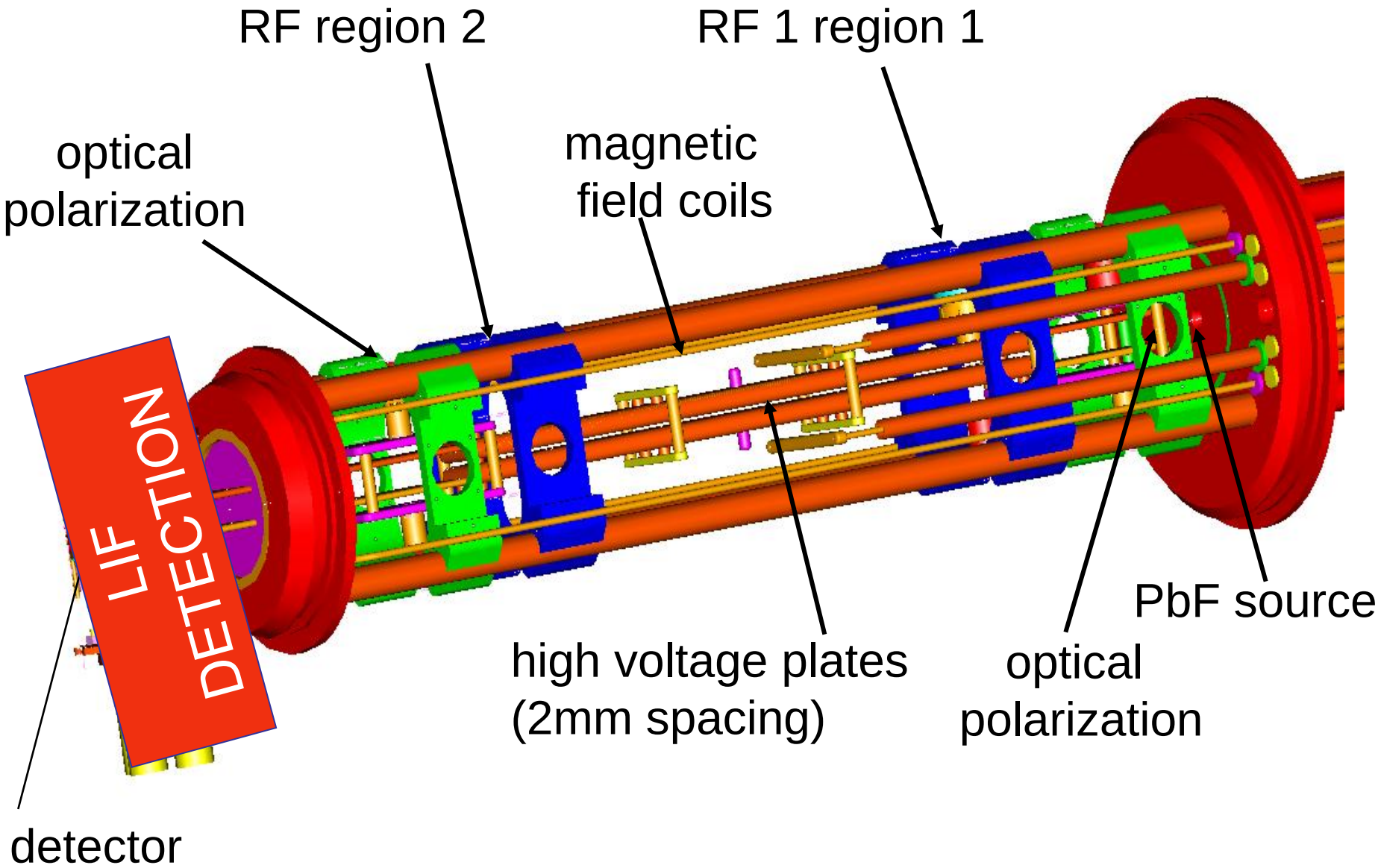


GOAL OF EPSCoR: Create a more intense beam.`

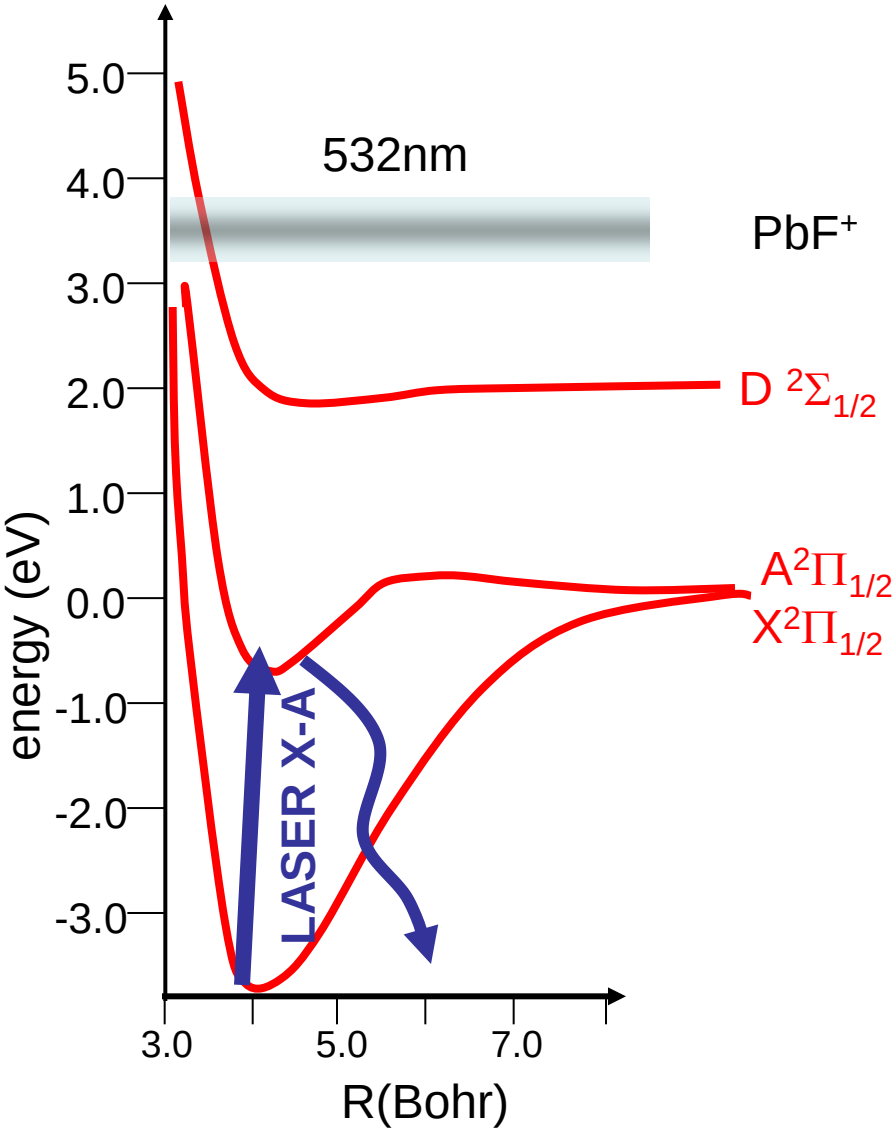
GOAL OF EPSCoR: Create more sensative detection.`

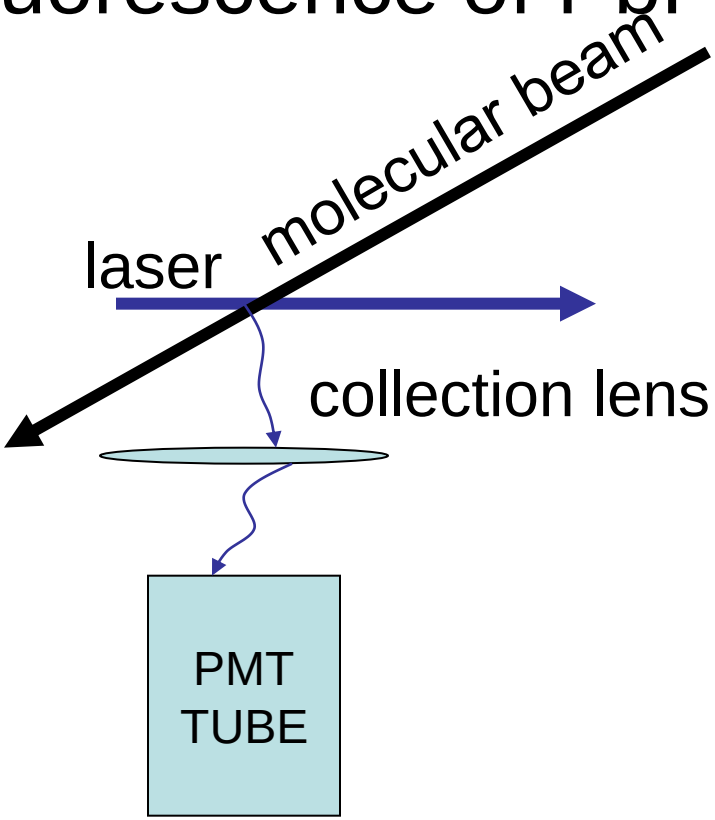
PbF MOLECULAR BEAM e-EDM EXPERIMENT



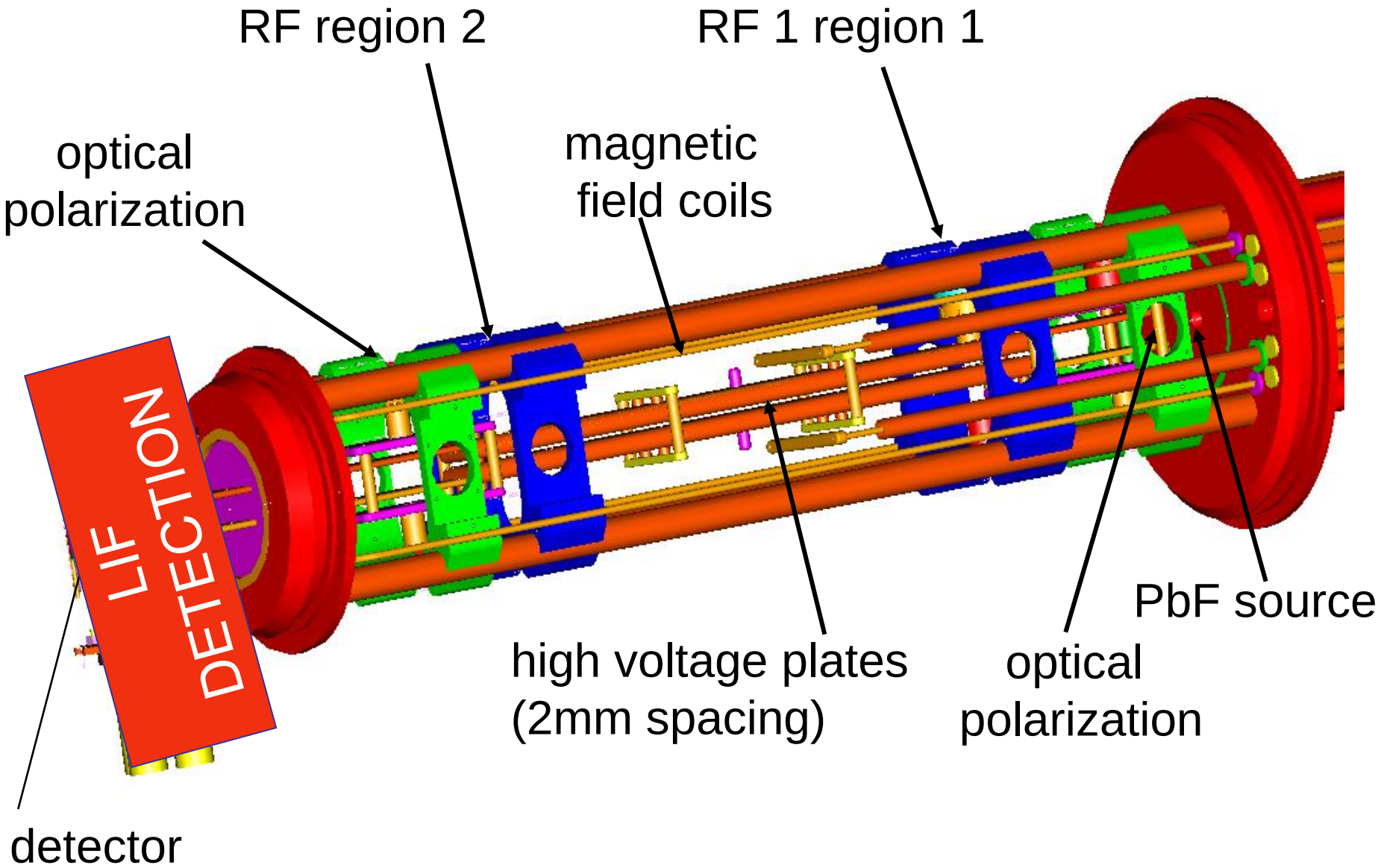

RF region 2
RF 1 region 1
optical polarization
magnetic field coils
LIF DETECTION
PbF source
high voltage plates (2mm spacing)
optical polarization
detector

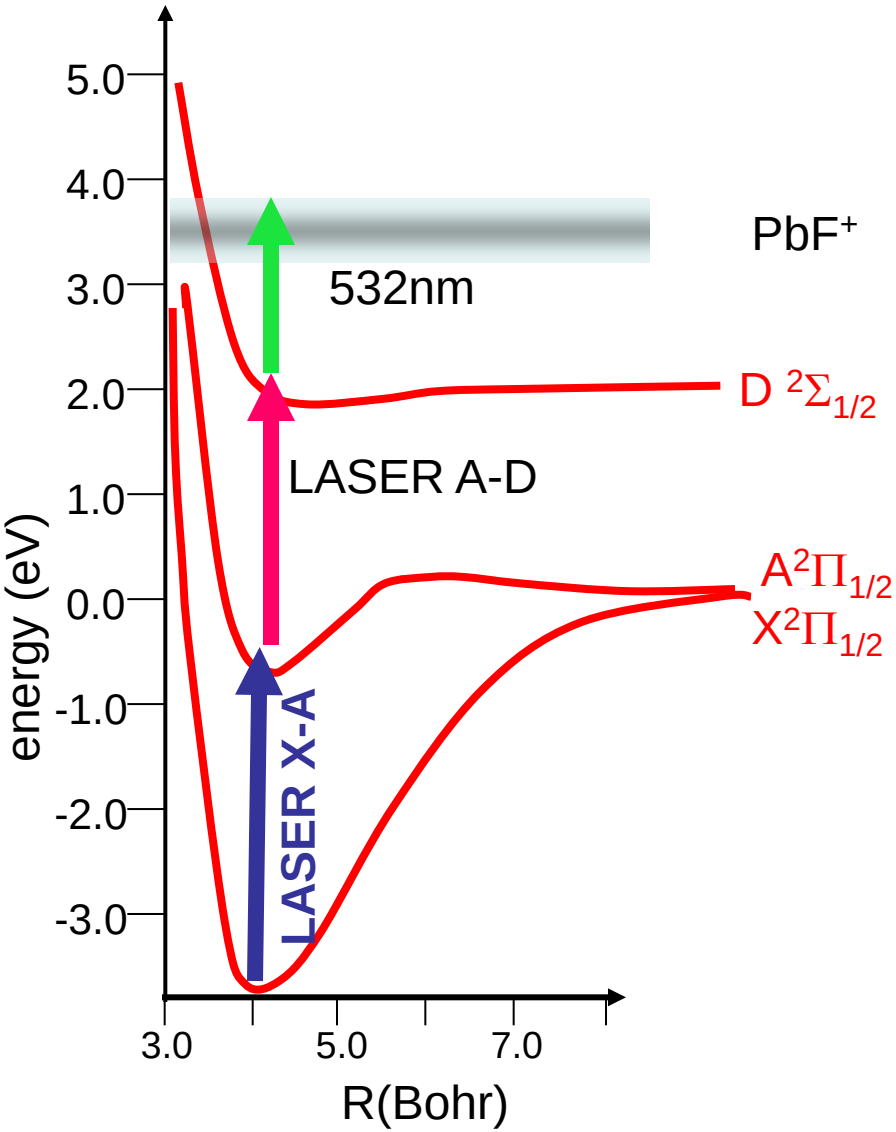
(PRE-EPSCoR) Laser-Induced Fluorescence of PbF





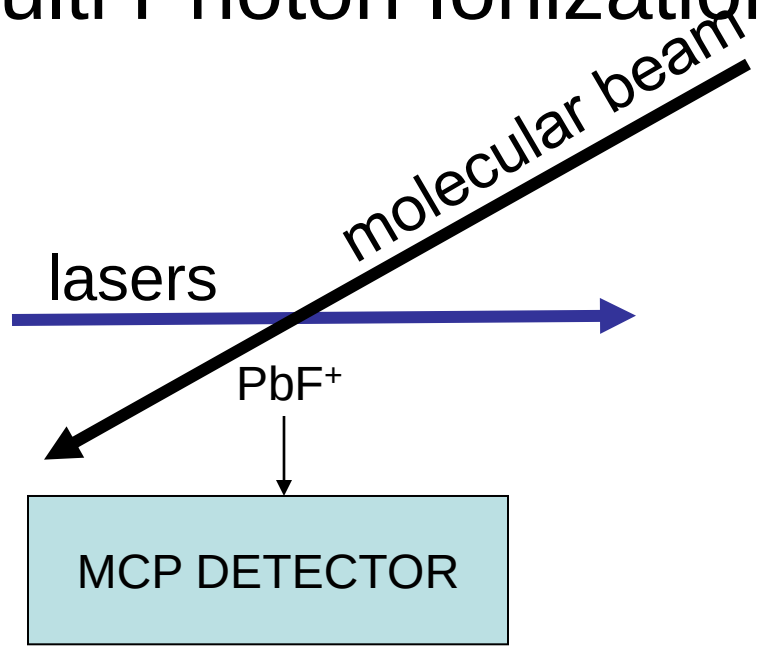
Limited to 1/1,000 collection efficiency, no mass discrimination.


RF region 2
RF 1 region 1
optical polarization
magnetic field coils
LIF DETECTION
PbF source
high voltage plates (2mm spacing)
optical polarization
detector



EPSCoR funding allowed us to develop

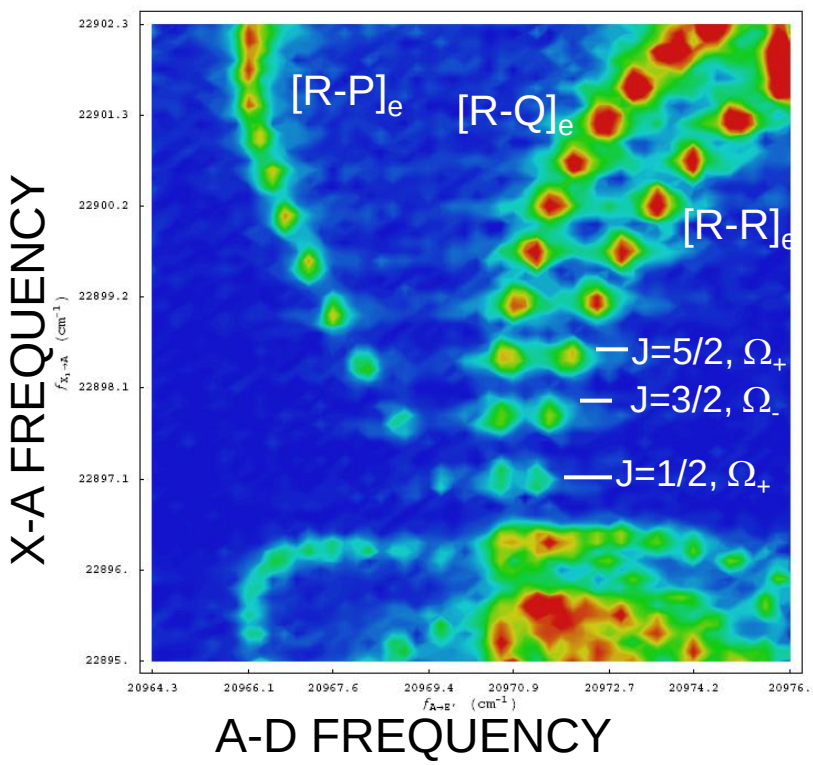
Resonance Enhanced Multi Photon Ionization

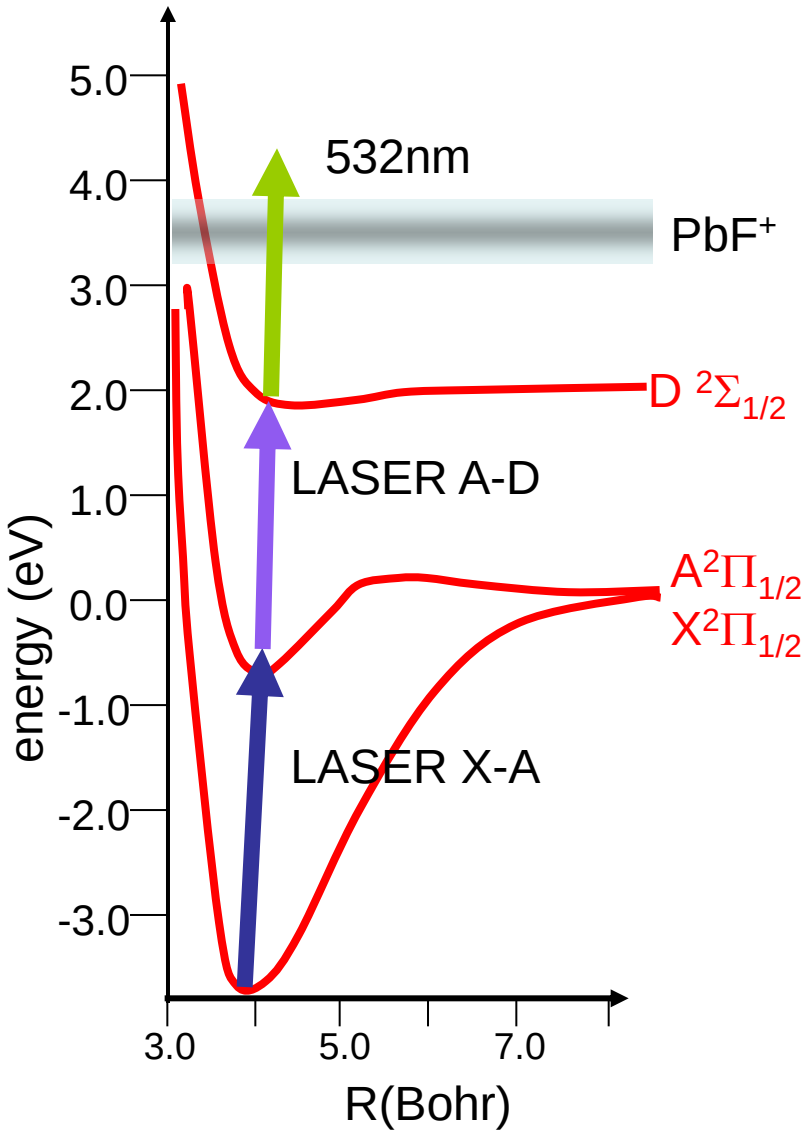


ADVANTAGE: Mass discrimination allows for very low background.

We have observed X→A→I→PbF^+ with I = B, D, E0, E1, F0, and F1 and obtained new spectroscopic constants and lifetimes of these states.

Sivakumar, McRaven, Shafer-Ray,Phys Rev A, 2008





Problems with conventional REMPI:

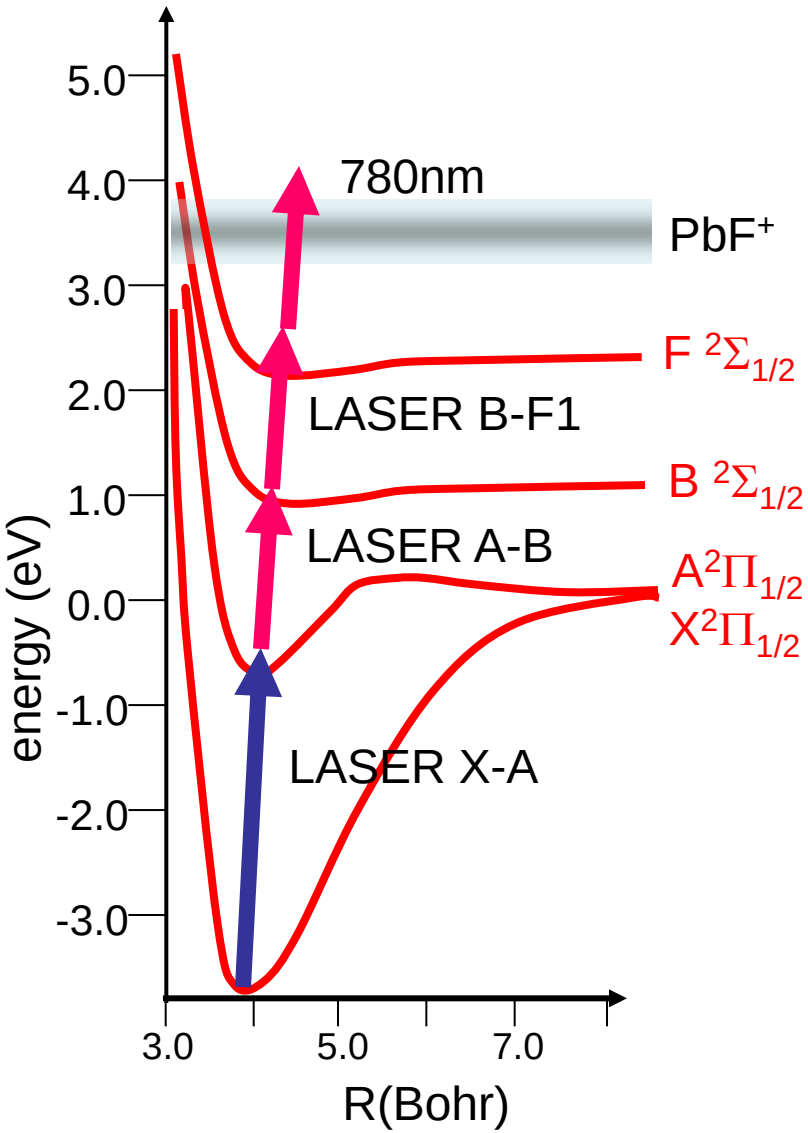
Our pre-EPSCoR REMPI laser system:
8 ns Nd:YAG -pumped dye lasers firing at a 10Hz rep rate.

Effective duty cycle: 1: 10^{-4}

Ultimate bandwidth (1 GHz) an order of magnitude too big to resolve hyperfine structure.

Large 1/f noise from 10Hz rep rate.

Continuous REMPI developed with EPSCoR funds:



Continuous REMPI developed with EPSCoR funds:

780nm
76MHz
6ps

436nm
cw
10MHz

multichannel scalar

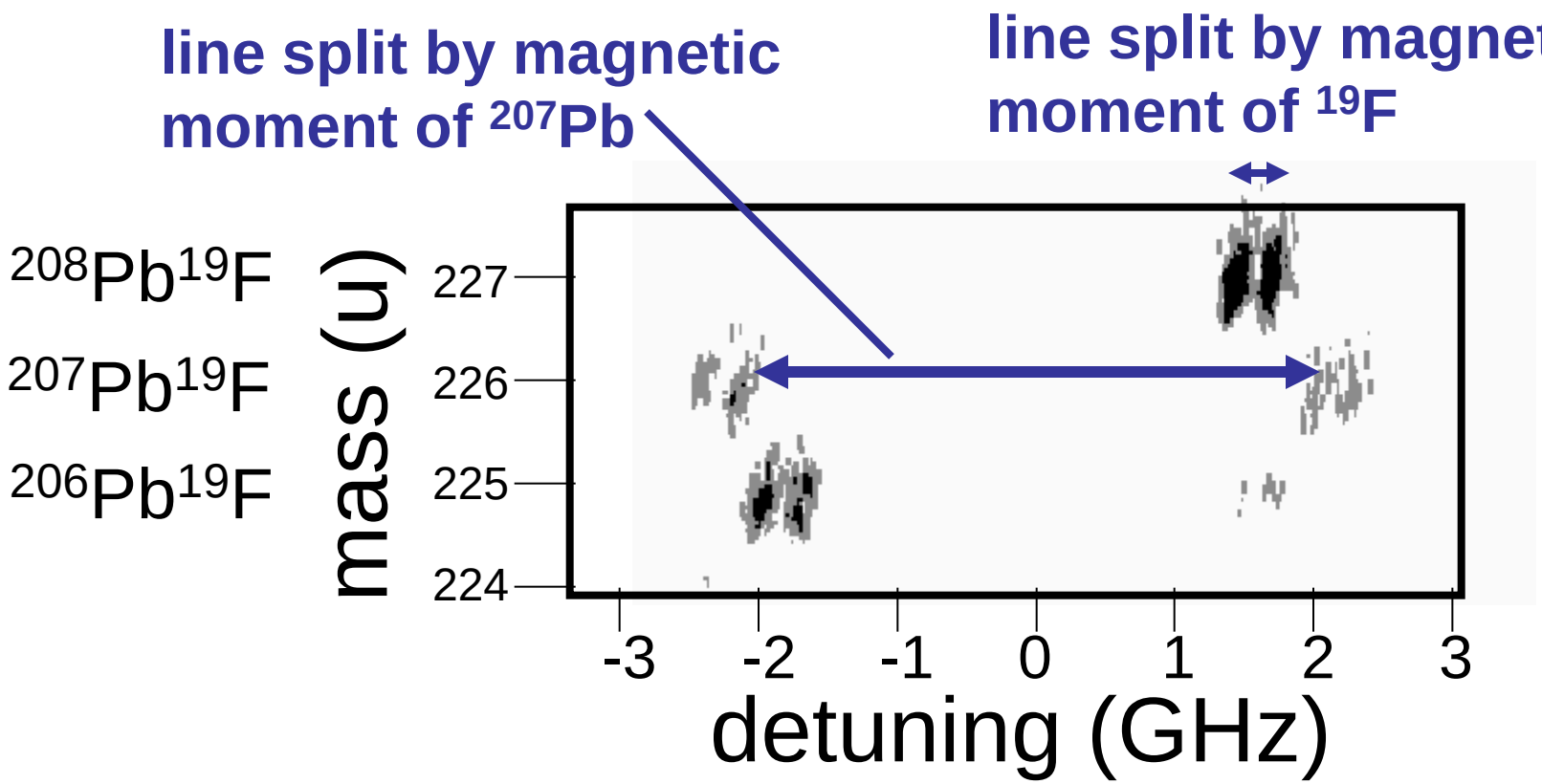
MCP

PbF^+

e^-

MCP

Continuous REMPI of the $X_1(v=0,J=55/2,\Omega_-)\rightarrow A(v=1,J=57/2,\Omega-)$ transition



SUMMARY

1) We are searching for the e-EDM - something small, T-violating, and worth looking for.

2) With EPSCoR funds,we have

Derived an appropriate Hamiltonian for incorporating the geometric phase effect for polarization experiments involving trapped atoms, neutrons, or molecules.

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$$H_{GEO} = \frac{2m_i \hbar i}{M} \sum_{n=x,y,z} \left[\left(\left(\nabla_n \frac{\vec{e}}{e} \right) \times \frac{\vec{e}}{e} \right) \cdot \hat{z} \right] \nabla_n$$

SUMMARY

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2) With EPSCoR funds,we have

Advanced a new type of spectroscopy (cw-REMPI) that has the potential to be far more sensitive than conventional REMPI. Implications for residual gas analyzers, atomic clock technology, pollutant monitoring, . . .

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SUMMARY

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2) With EPSCoR funds,we have

Created a 1700 K molecular beam source.

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SUMMARY

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2) With EPSCoR funds,we have

Measured the spectroscopic properties of 8 states of PbF. By doing so we have found

-i- New efficient ionization schemes.

-ii- Mistakes in the presumed electronic structure of PbF.

-iii- Coincidental resonances that will allow for low-field polarization of PbF (kV/cm instead of 60kV/cm.)

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SUMMARY

1) We are searching for the e-EDM - something small, T-violating, and worth looking for.

2) With EPSCoR funds,we have

Provided research opportunities for 3 PhD students.

Milinda Rupasinghe

Sivakumar Poopalasingam

Chris McRaven

ACKNOWLEDGEMENTS

Department of Energy
National Science Foundation

BNL Collaborators: Greg Hall and Trevor Sears

Students: Chris, Siva, and Milinda