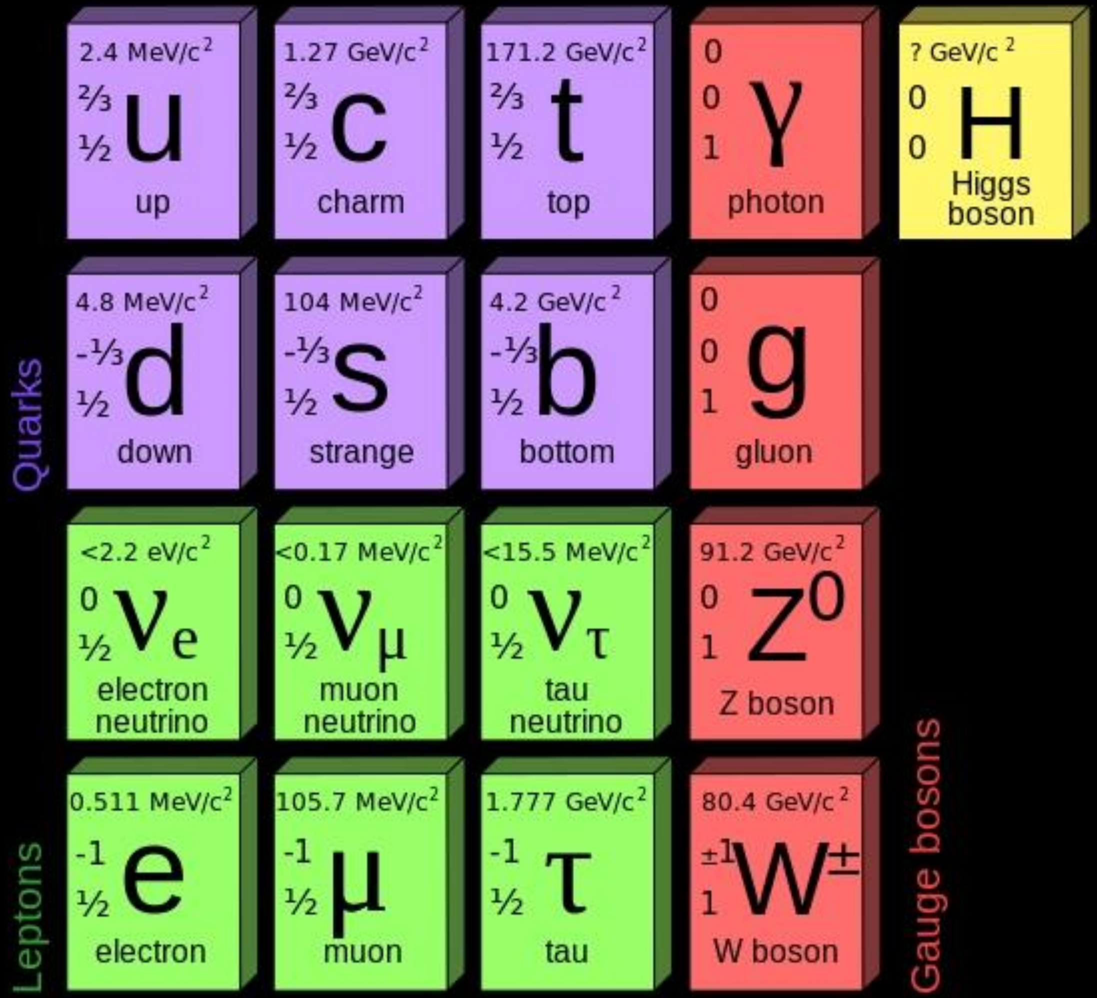
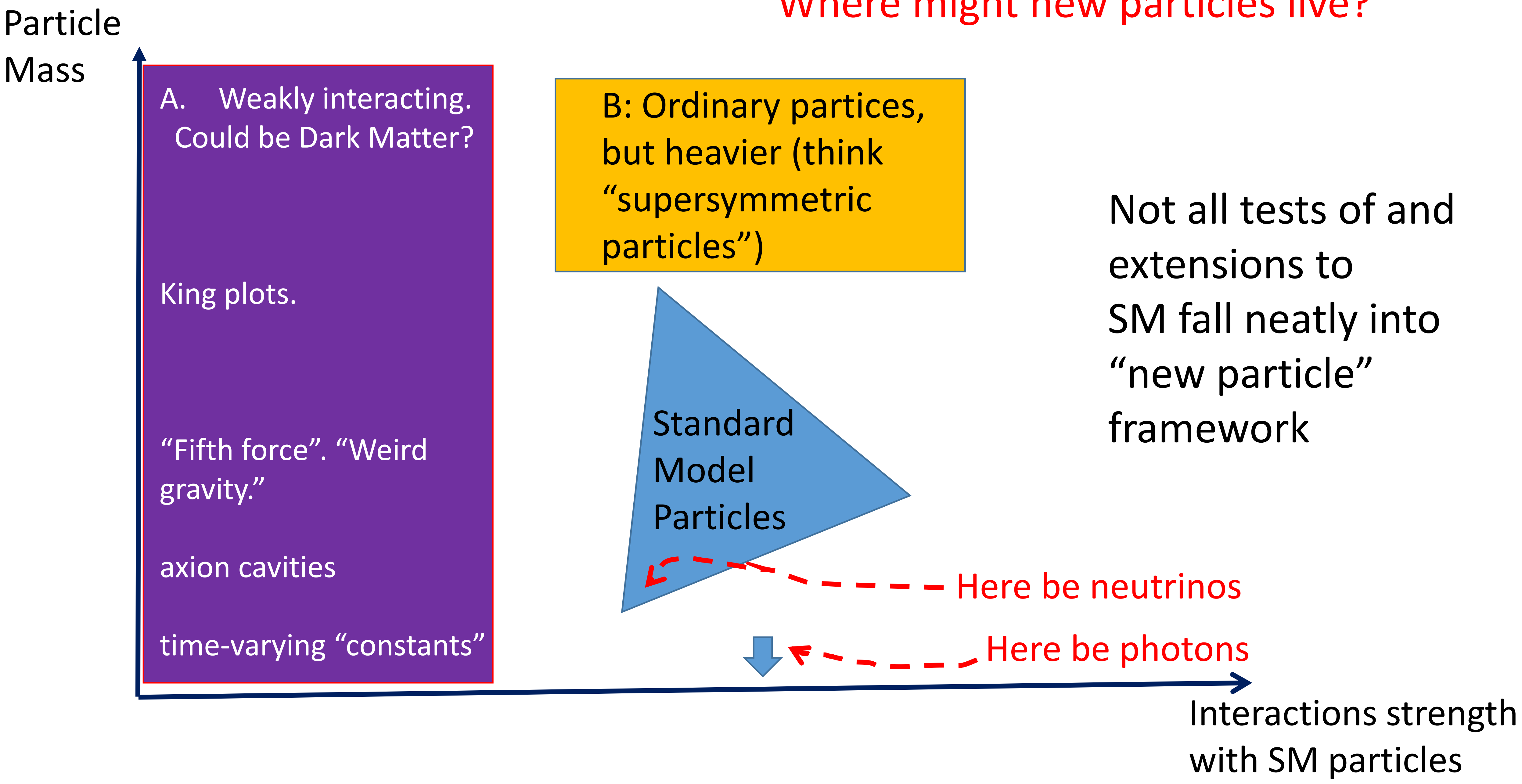


Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	? GeV/c^2 0 0 H Higgs boson
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson	Gauge bosons
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson	

Where might new particles live?



Particle Mass

A. Weakly interacting. Could be Dark Matter?

King plots.

“Fifth force”. “Weird gravity.”

axion cavities

time-varying “constants”

B: Ordinary partices, but heavier (think “supersymmetric particles”)

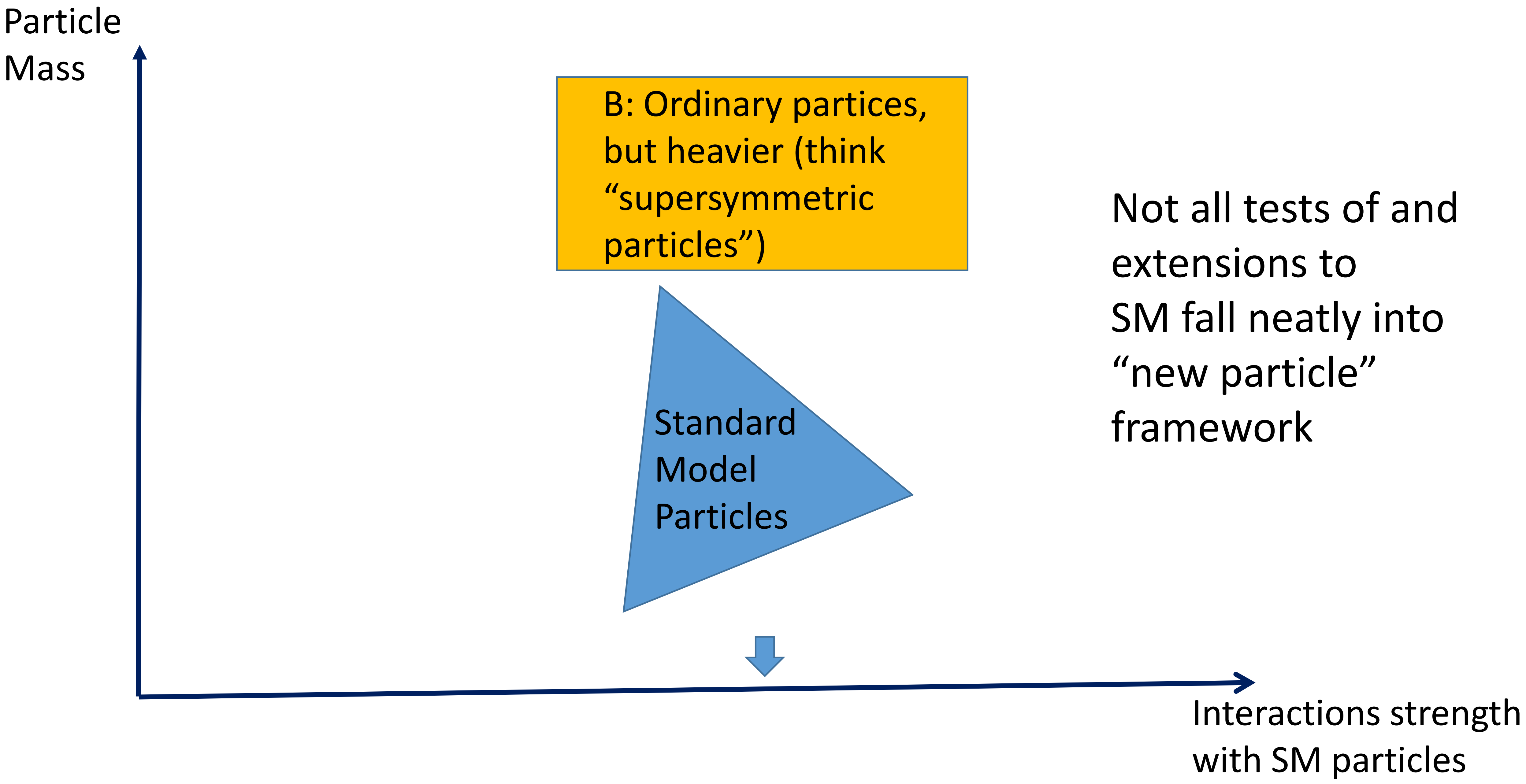
Standard Model Particles

Here be neutrinos

Here be photons

Interactions strength with SM particles

Not all tests of and extensions to SM fall neatly into “new particle” framework



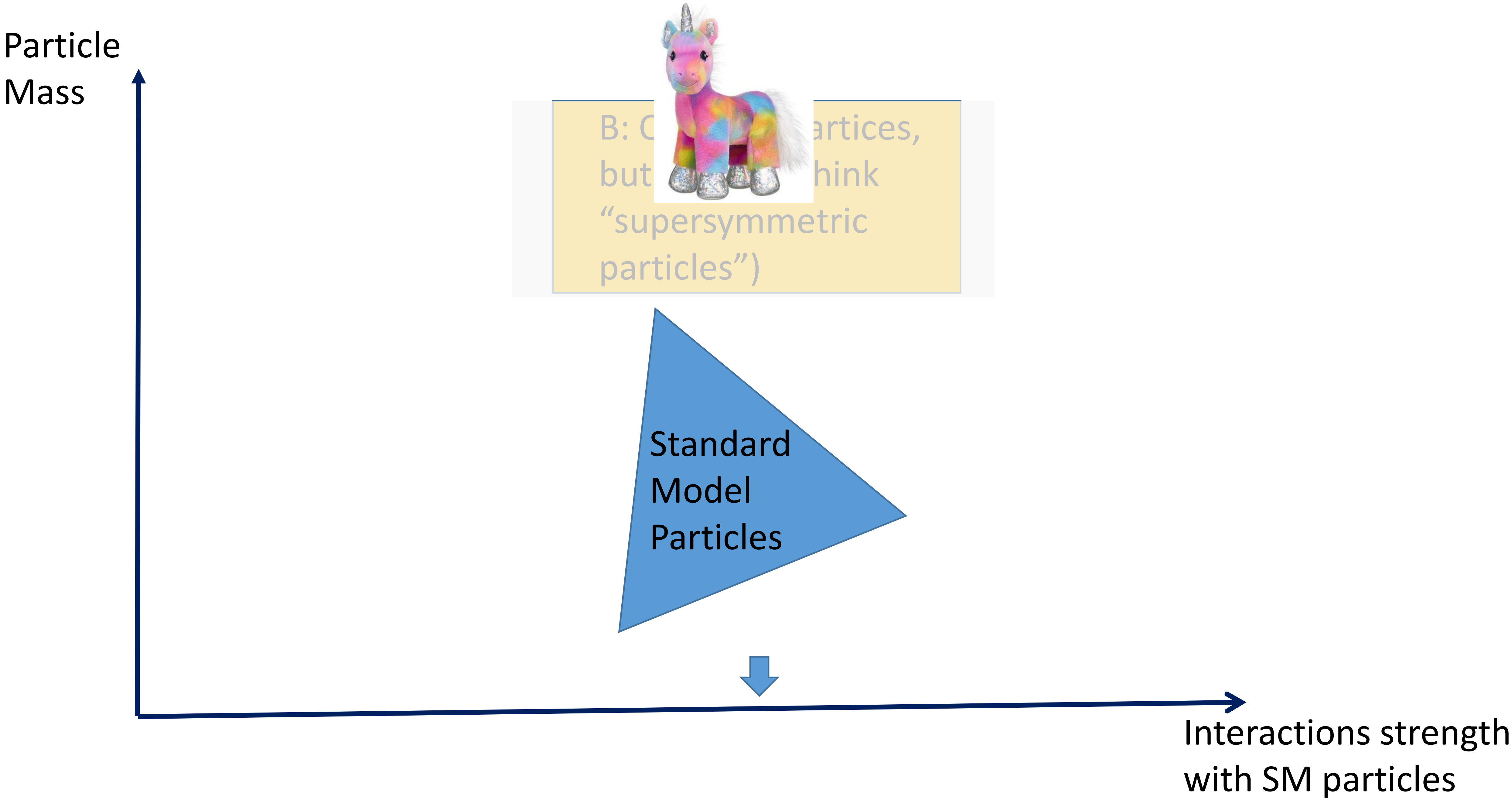
Particle
Mass

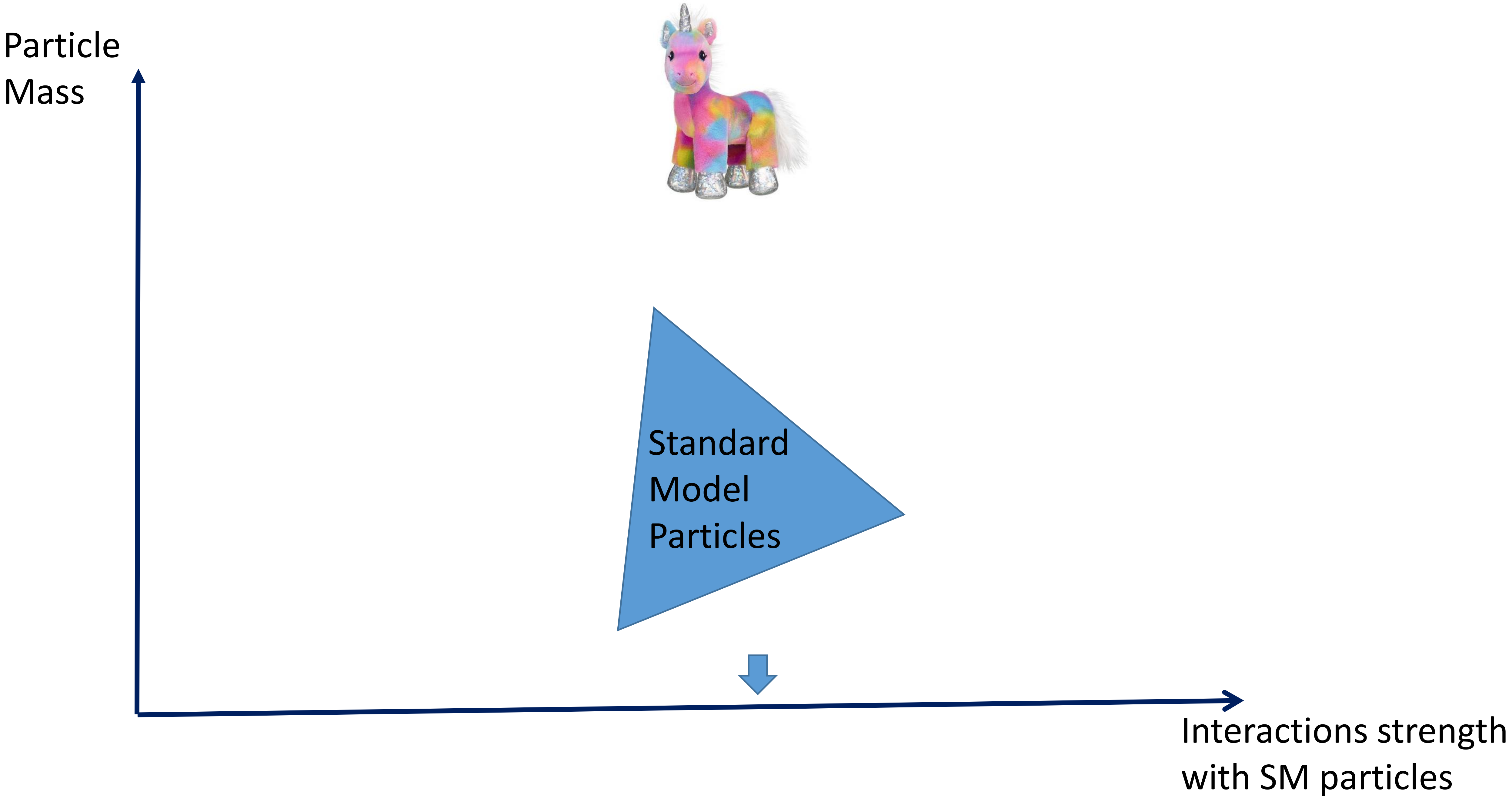
B: Ordinary partices, but heavier (think “supersymmetric particles”)

Standard Model Particles

Interactions strength
with SM particles

Not all tests of and extensions to SM fall neatly into “new particle” framework

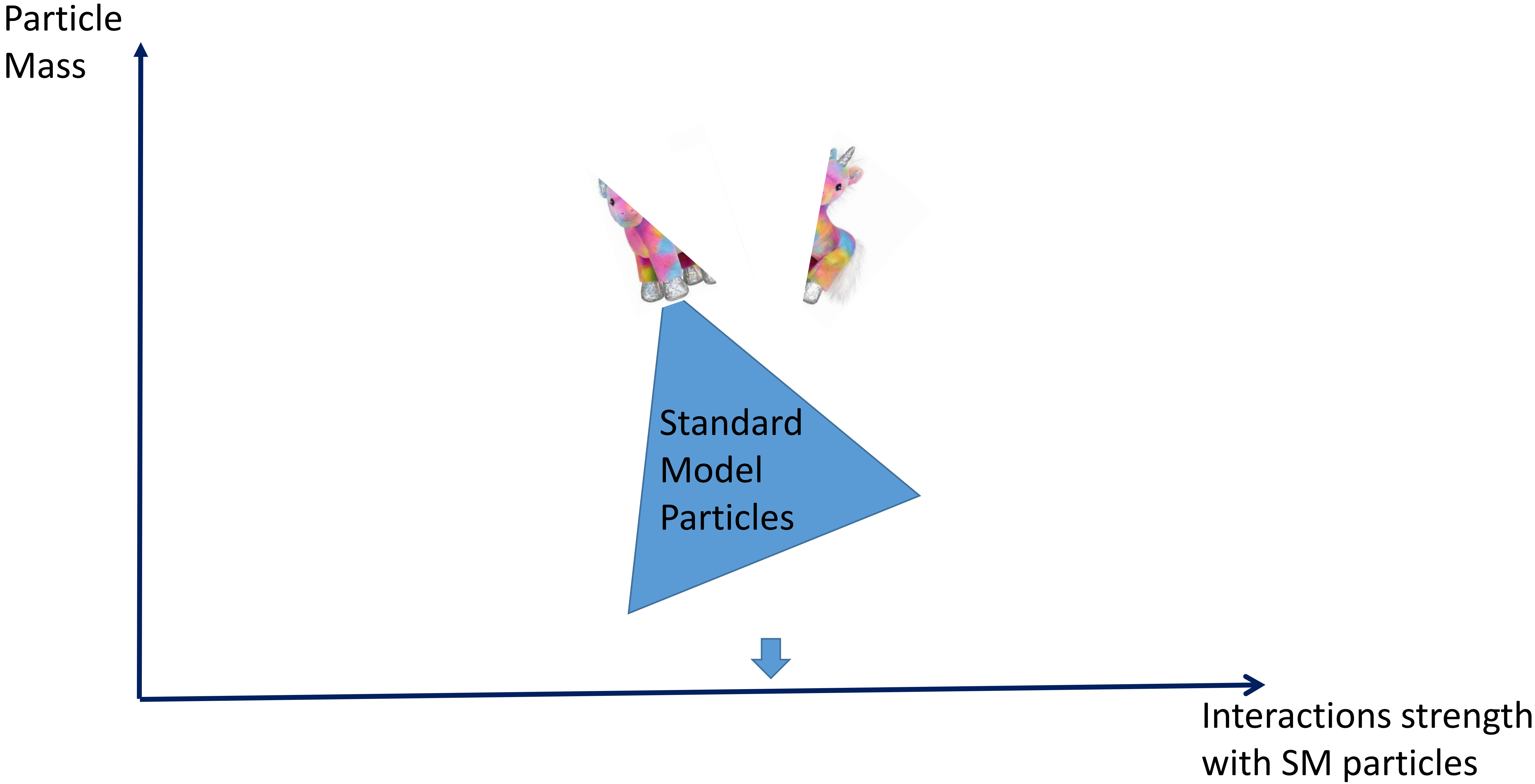
Particle
Mass
B: C artices,
but hink
“supersymmetric
particles”)
Standard
Model
Particles
Interactions strength
with SM particles



Particle Mass

Standard Model Particles

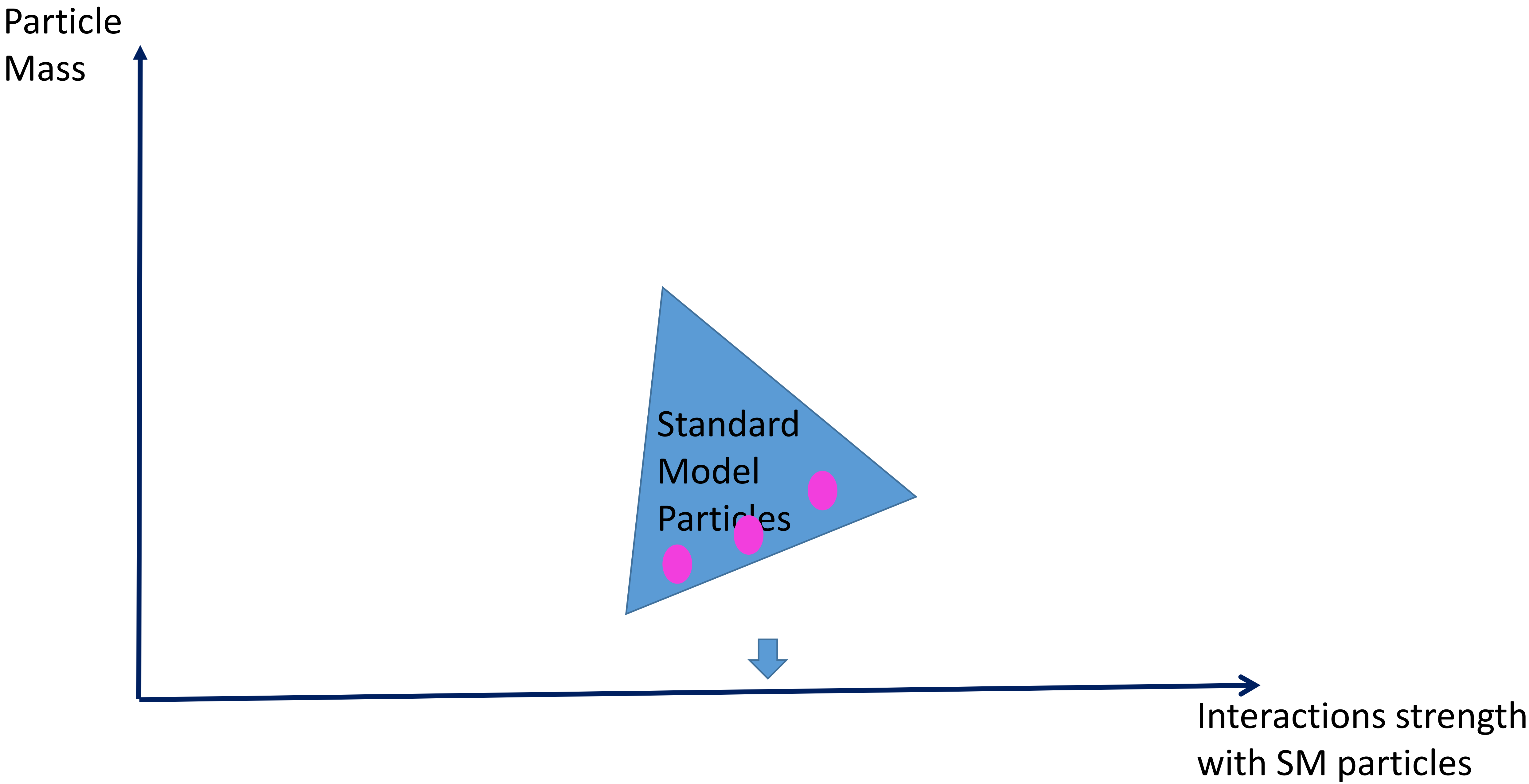
Interactions strength with SM particles

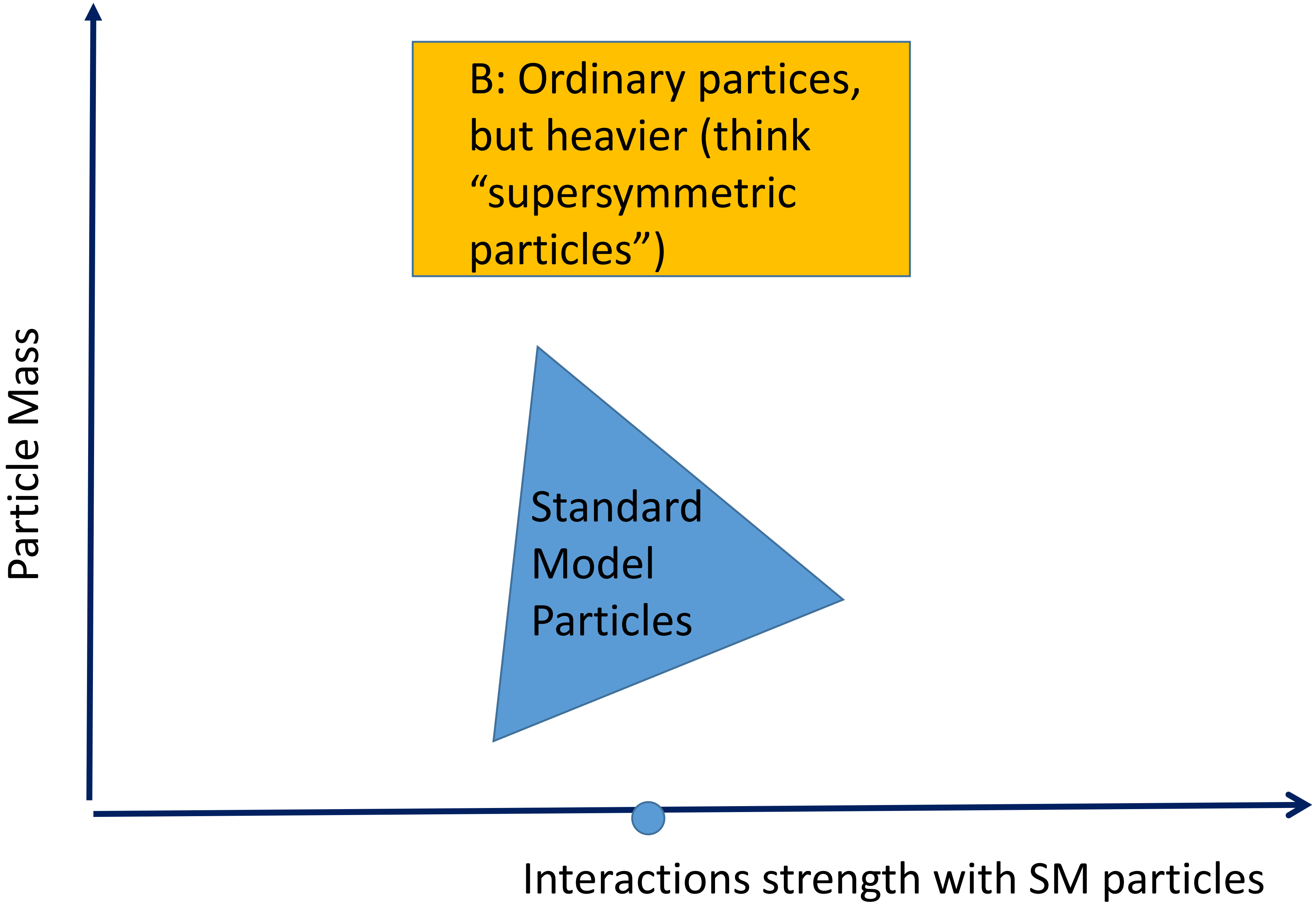


Particle
Mass

Standard
Model
Particles

Interactions strength
with SM particles

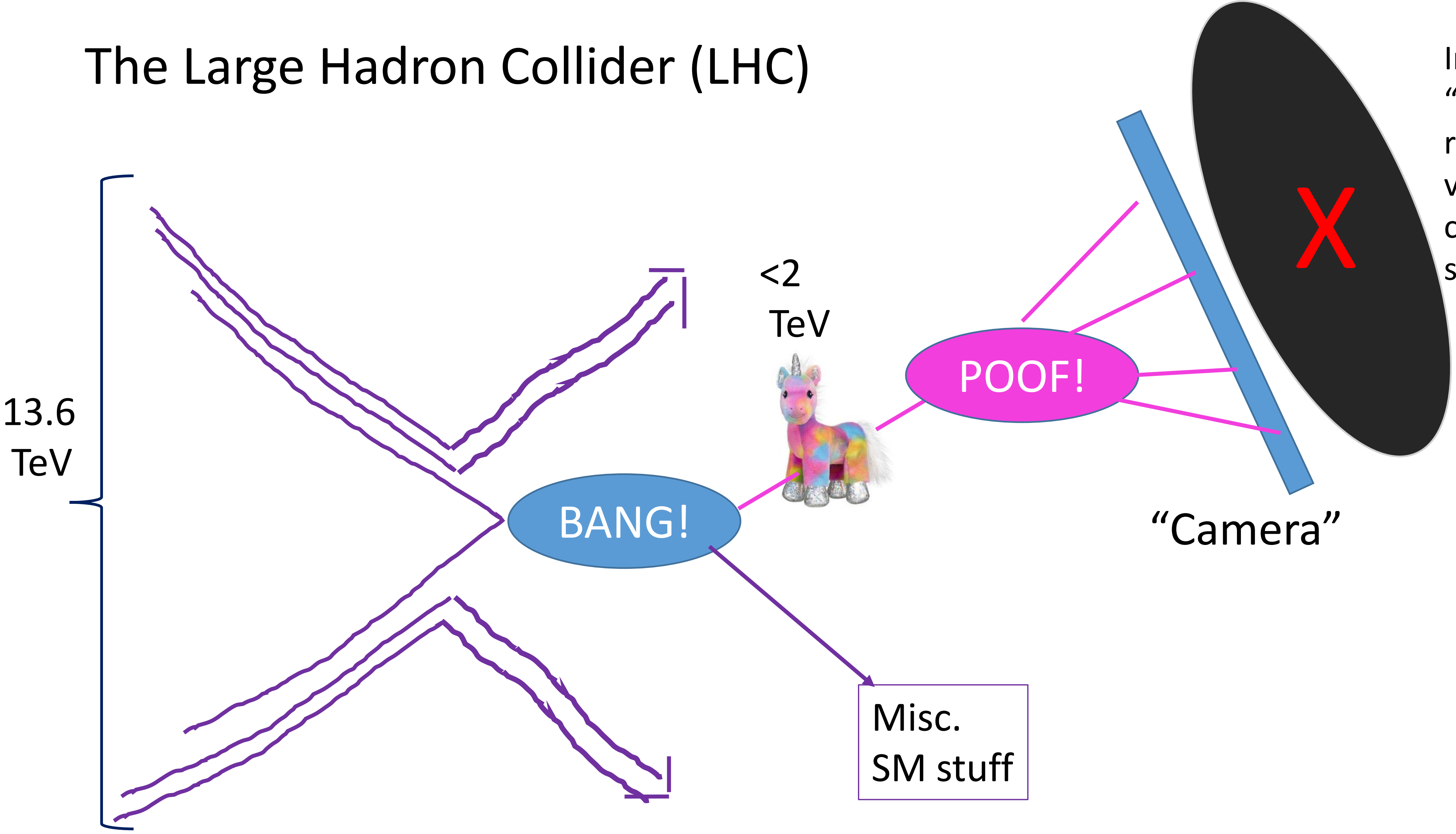

Particle
Mass
Standard
Model
Particles
Interactions strength
with SM particles



B: Ordinary partices, but heavier (think “supersymmetric particles”)

Standard Model Particles

The Large Hadron Collider (LHC)



13.6 TeV

BANG!

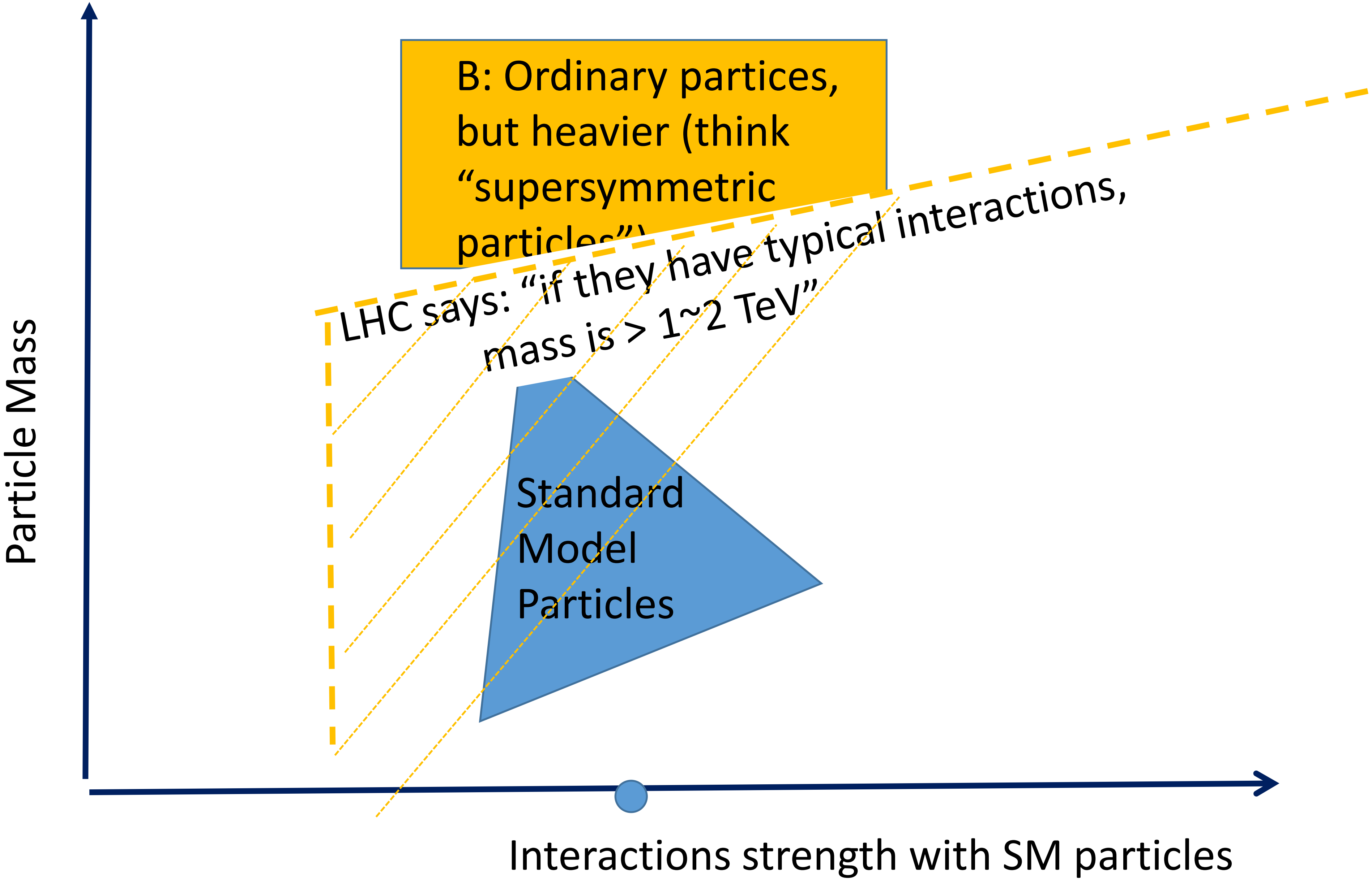
<2 TeV

POOF!

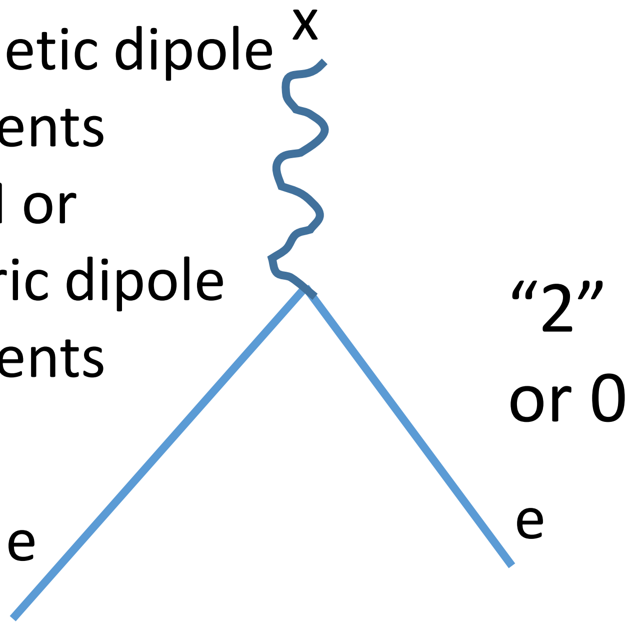
"Camera"

Misc. SM stuff

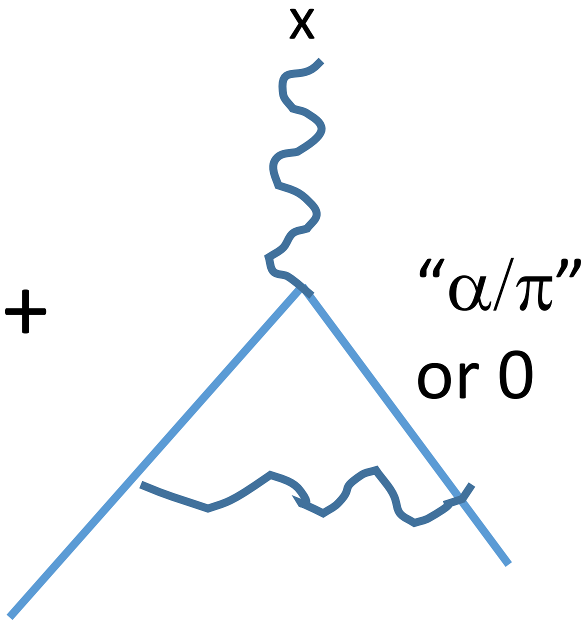
Image: "Unicorn.Guts" removed for violation of community standards



magnetic dipole moments MDM or electric dipole moments EDM!



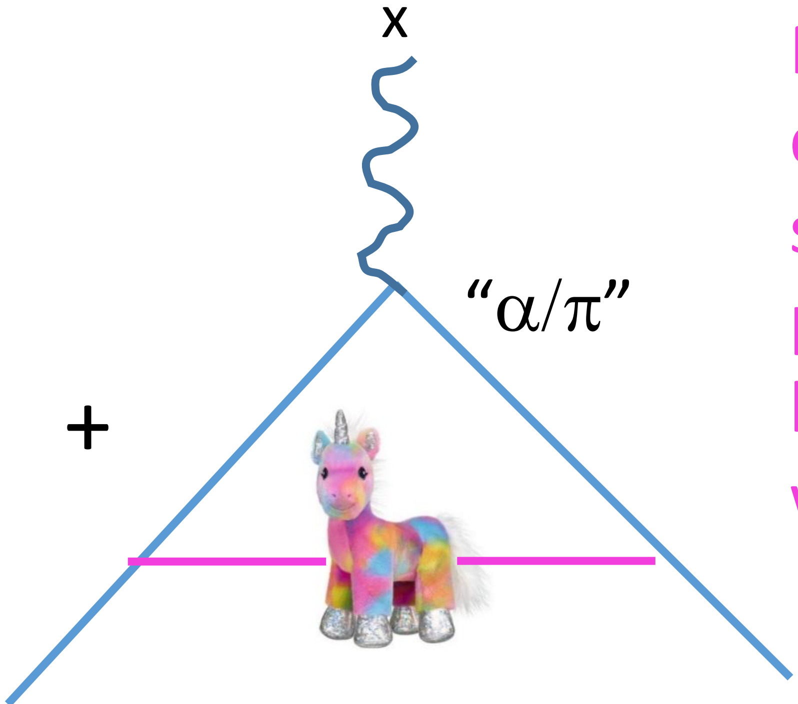
+



+ [SM contributions currently up to 5 loops and O(α^5)

or, for EDM, < 10^{-34})

+

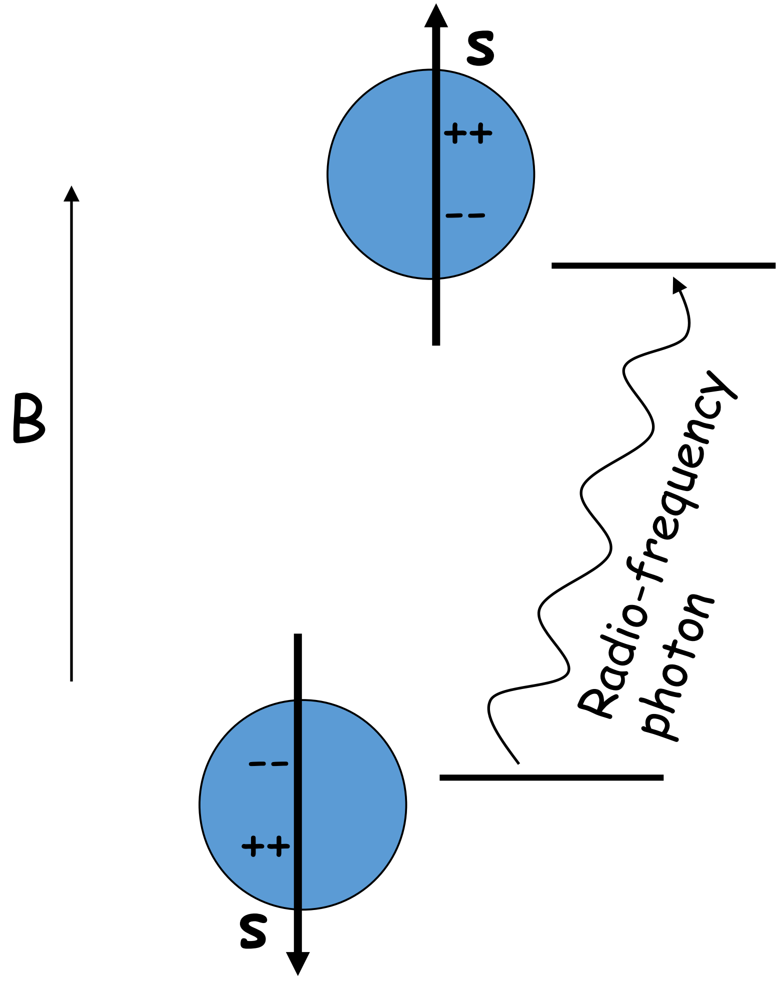


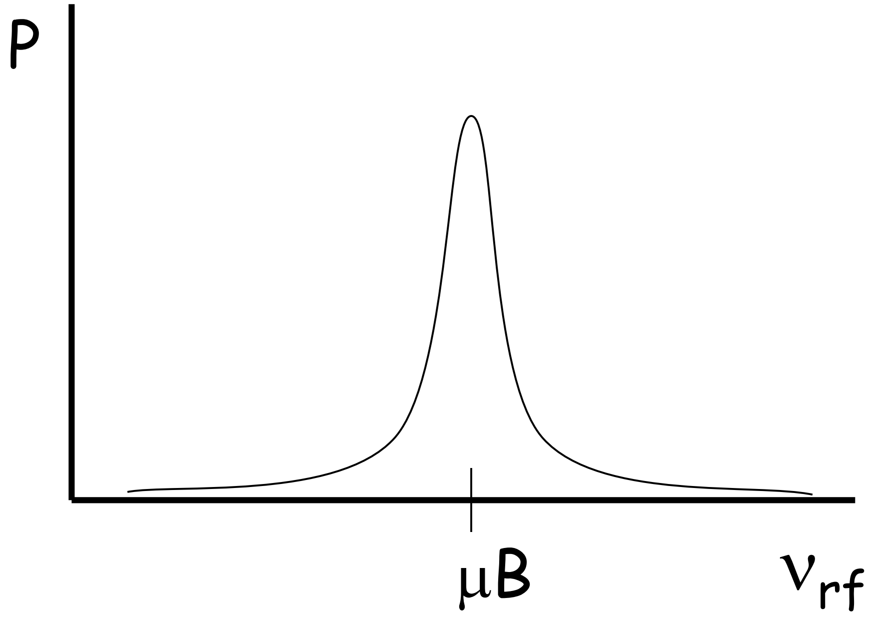
Plan: let’s measure dipole moment, subtract out SM prediction. Whatever’s left is a result of a loop with one “running unicorn”

This talk:
Mostly on new eEDM result

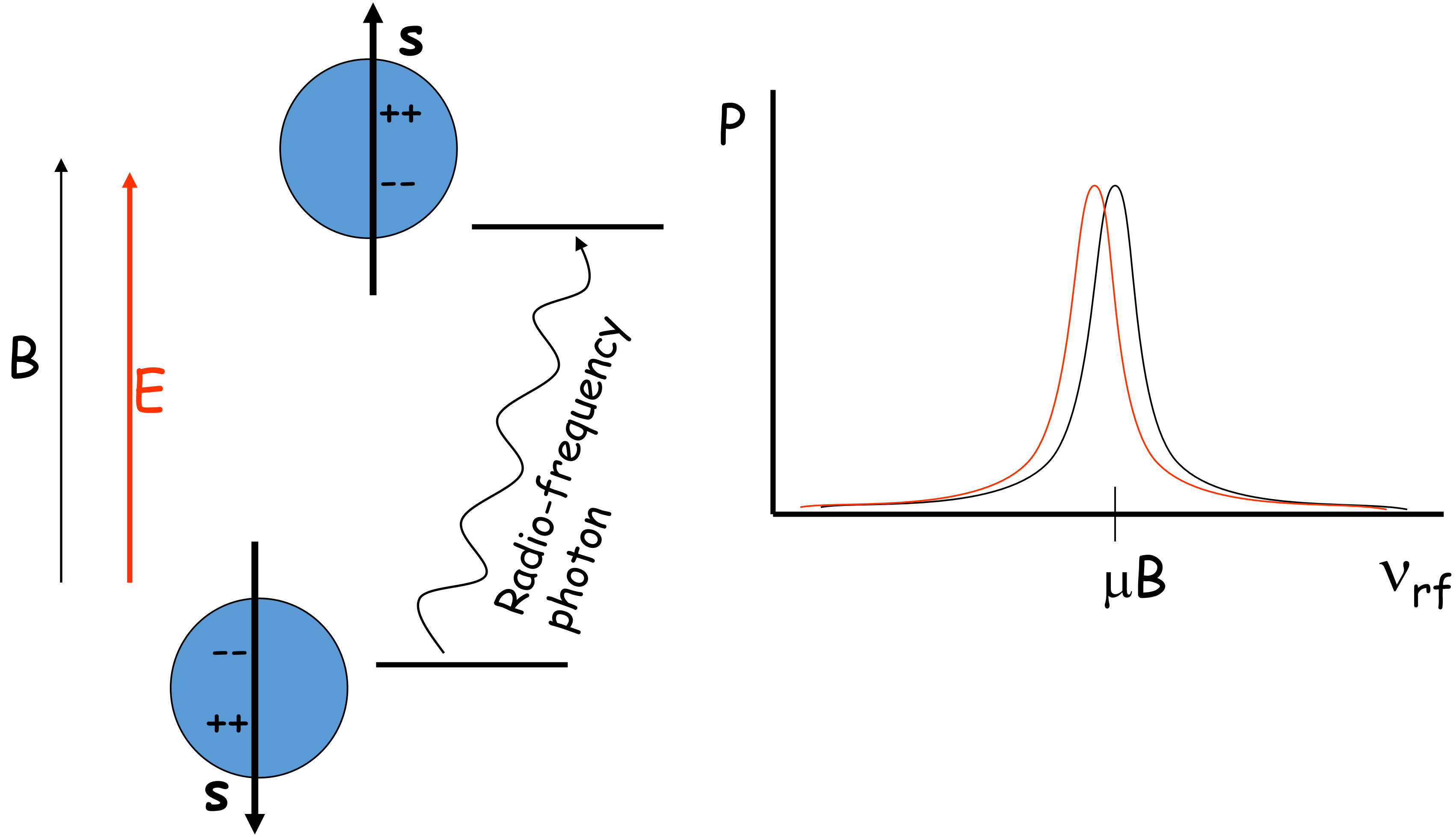
but I will touch also
on two recent record-setting
results on MDM (= “g minus two”)
(one eMDM, on μMDM)
Spoiler: we can think about all three in a unified framework.

How to measure eEDM? First, how do we measure eMDM?

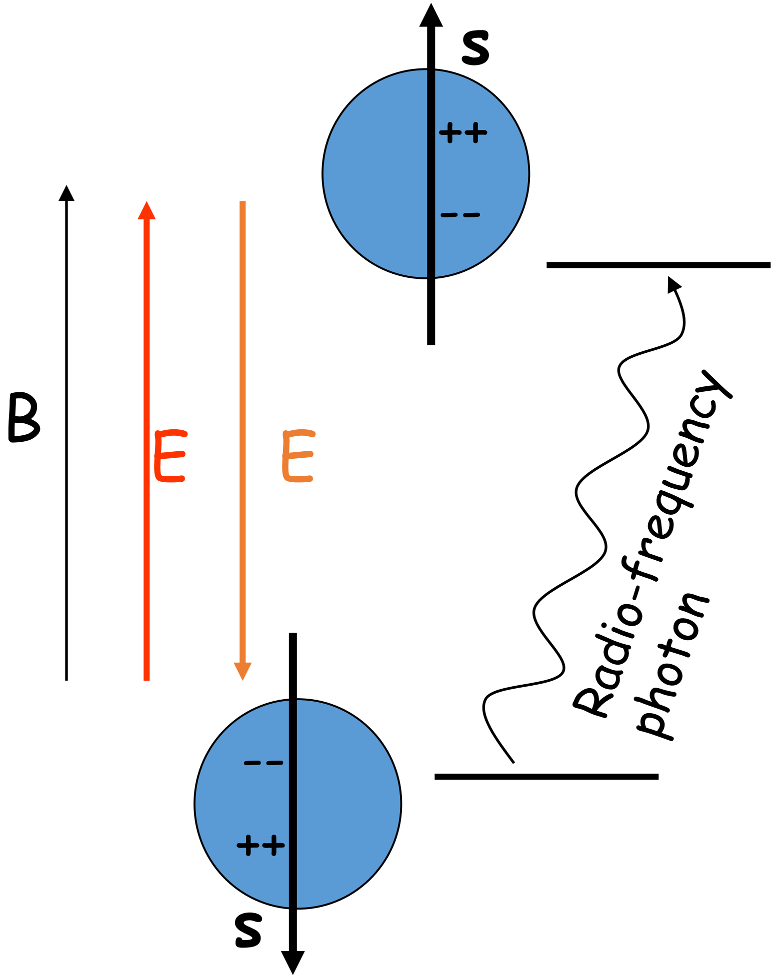


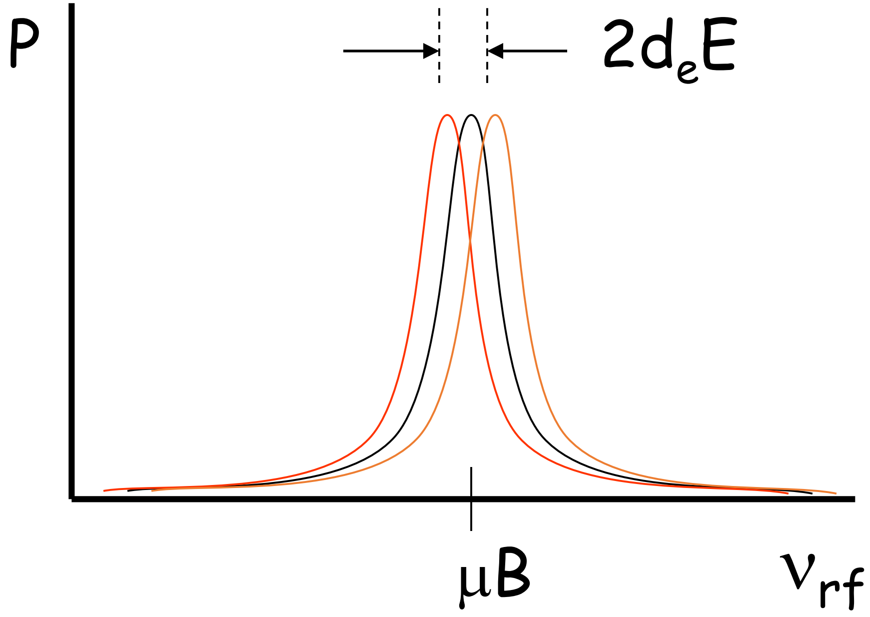


How to measure eEDM?



How to measure eEDM?





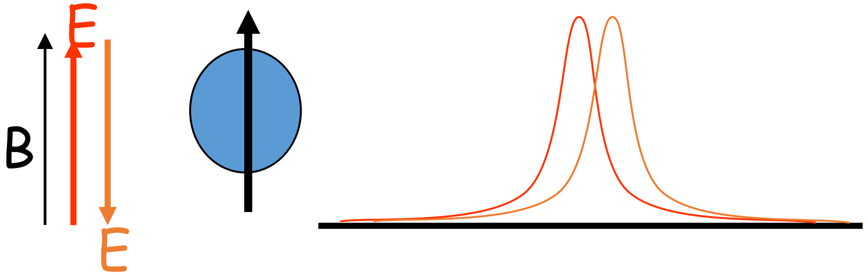

B
E
E

Figure-of-merit:
What makes a **good** EDM experiment?

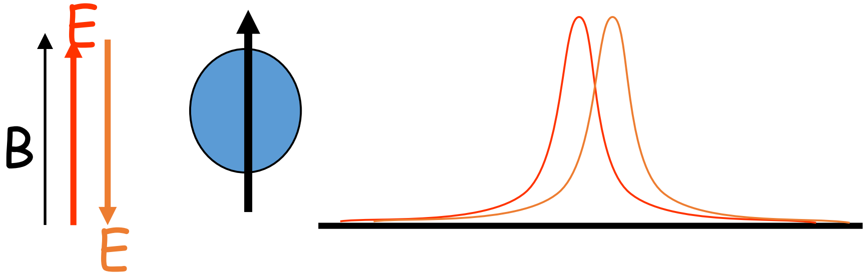
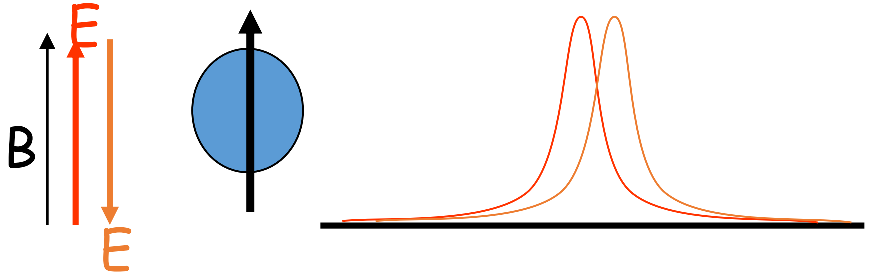
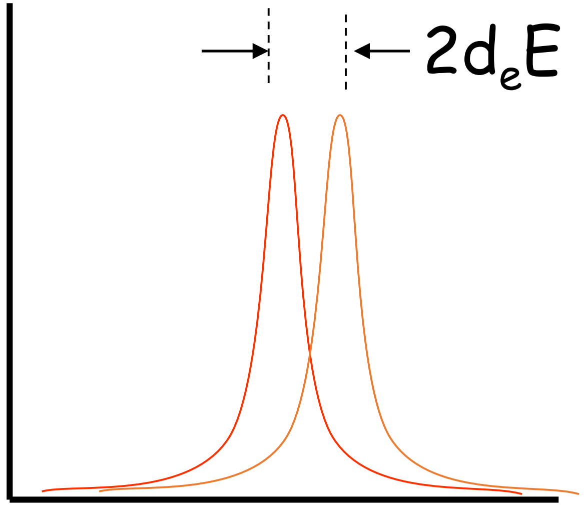


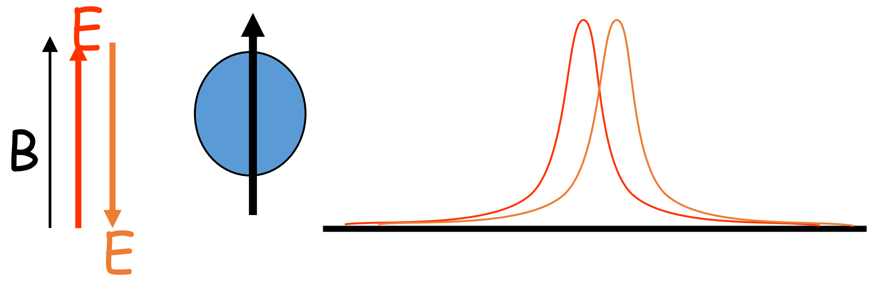
Figure-of-merit: What makes a good EDM experiment?

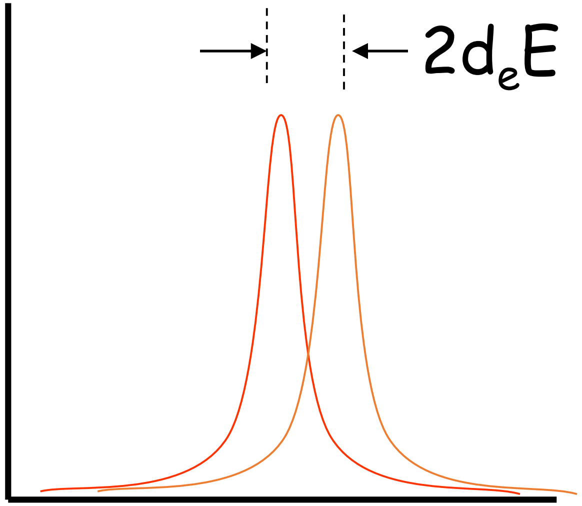




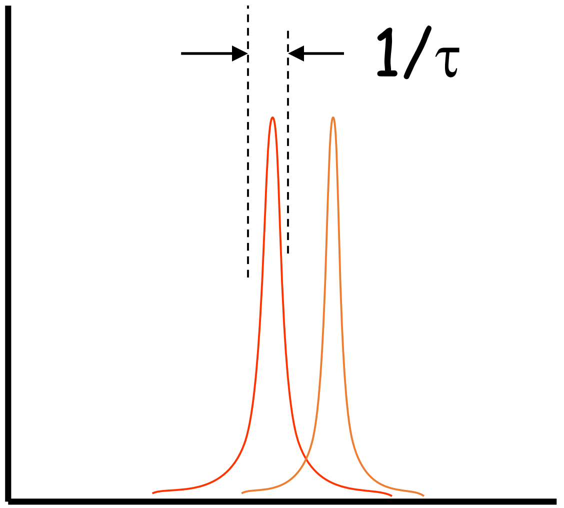
Big Electric Field!

Figure-of-merit: What makes a good EDM experiment?



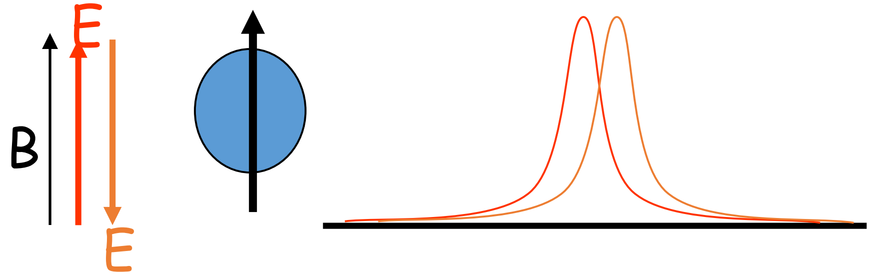


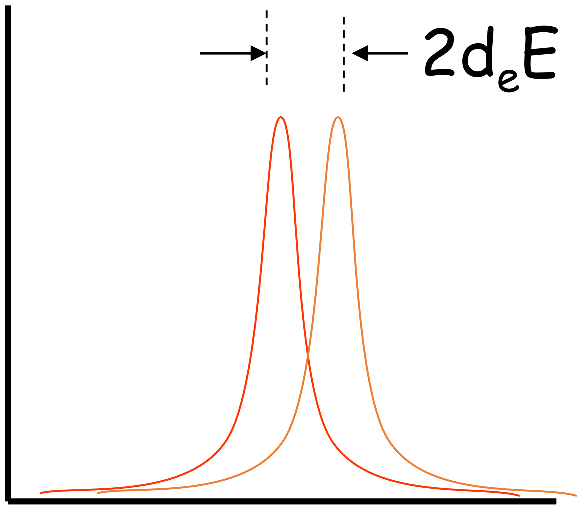
Big Electric Field!



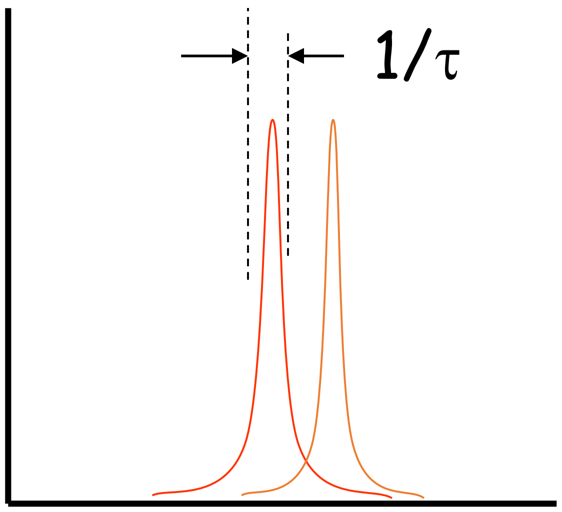
Long Coherence Time (narrow resonances)!

Figure-of-merit:
What makes a good EDM experiment?

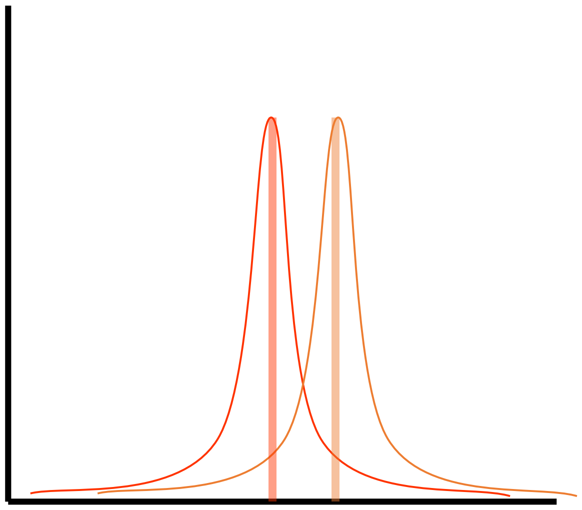




Big Electric Field!



Long Coherence Time (narrow resonances)!

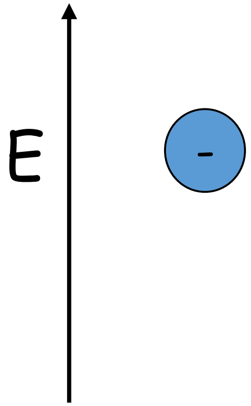


Large count rate (split resonance by $\sqrt{N_{eff}}$)

Combined Figure-of-merit: $E_{eff}\,\tau\,\sqrt{N_{eff}}$

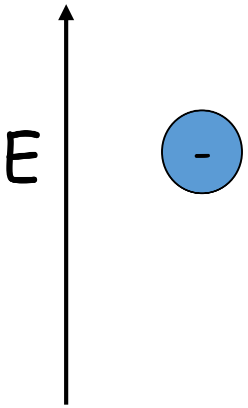
Problem:

Big E, long τ. Electron accelerates quickly, and is gone????

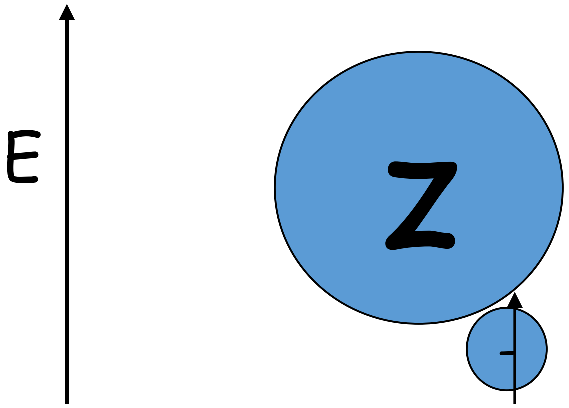


Problem:

Big E, long τ.   Electron accelerates quickly, and is gone????



Solution: Attach electron spin to
a big atomic nucleus!

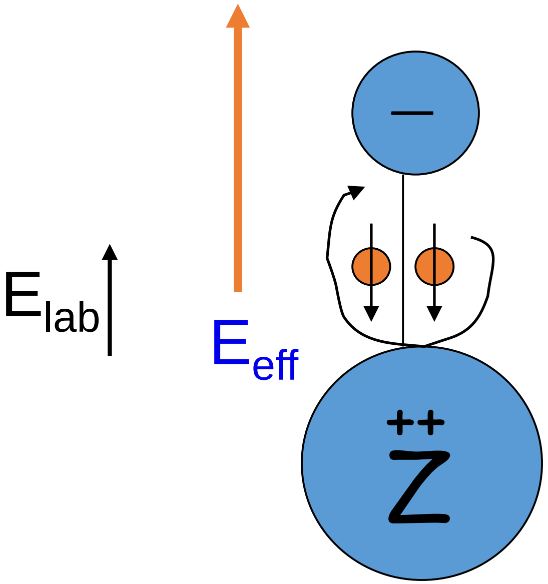


$$E_{eff} = a\, E_{lab}\, Z^3$$

(Pat Sandars)

Our approach. 1. Use molecule for big E_{eff}

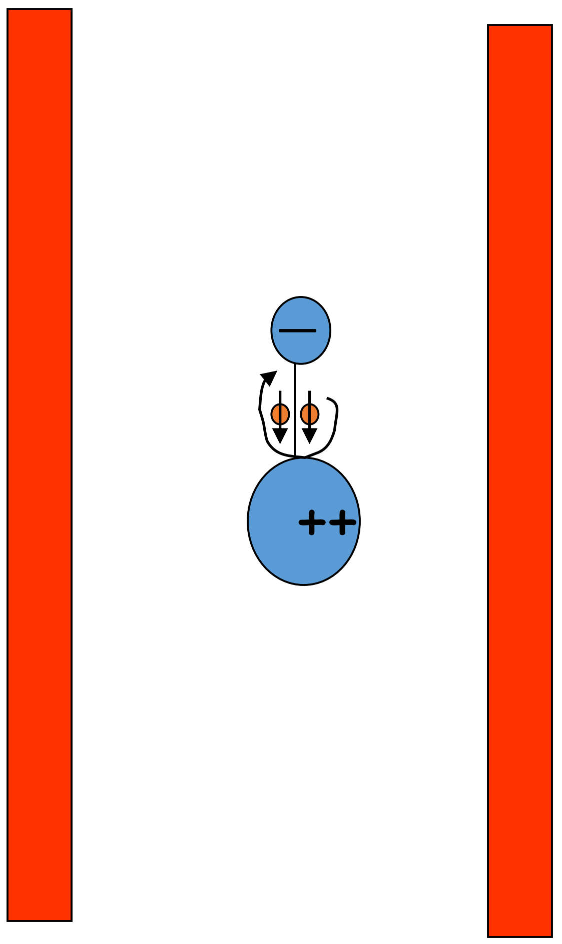
(we follow Hinds and Demille in this)



E_{lab} = 20 V/cm $E_{eff} > 2 \times 10^{10}$ V/cm

Our approach. 2. Use trapped ion for long τ

(coherence time of 3.0 seconds !!!)



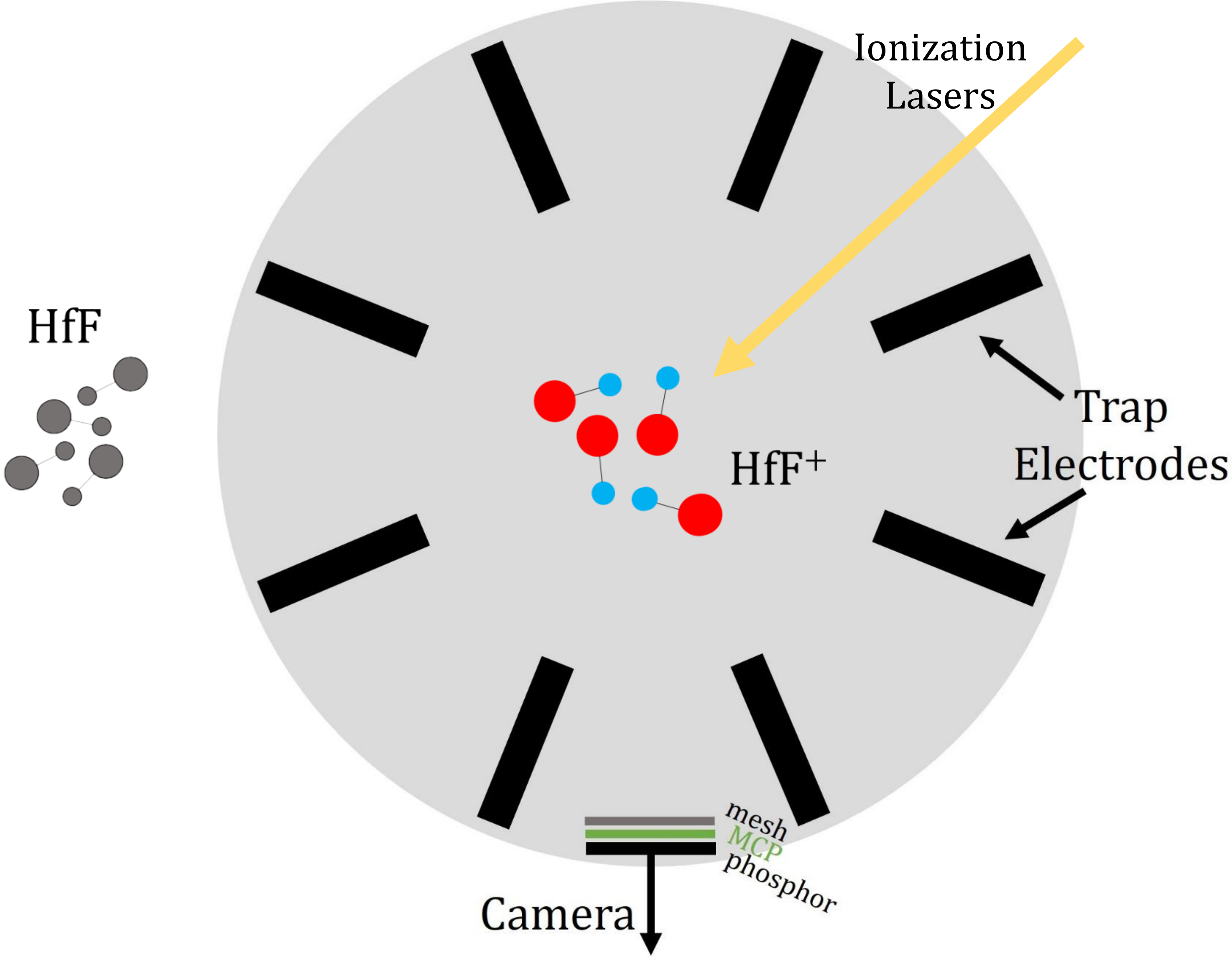
Our approach. 3. We want big count rate (= many ions in the trap!)

Solution: Use a really BIG ion trap!!

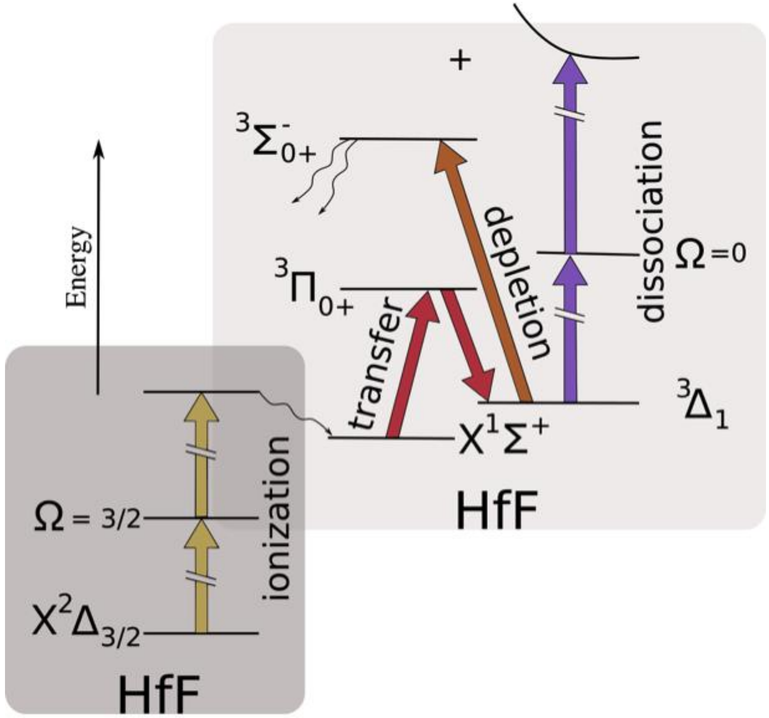
(Electrodes spaced by centimeters, not microns)

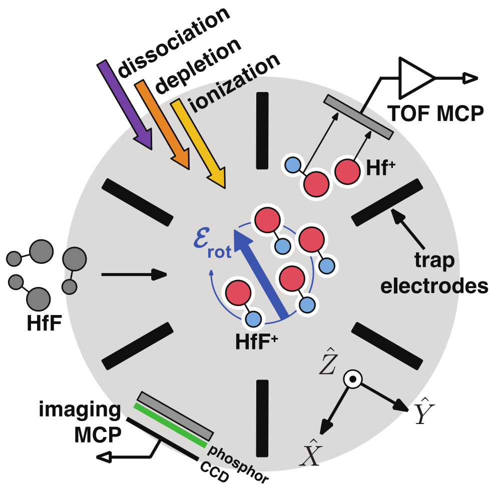
In one shot we trap 1000s of ions, and count 100s of ions on the side of a Ramsey fringe.

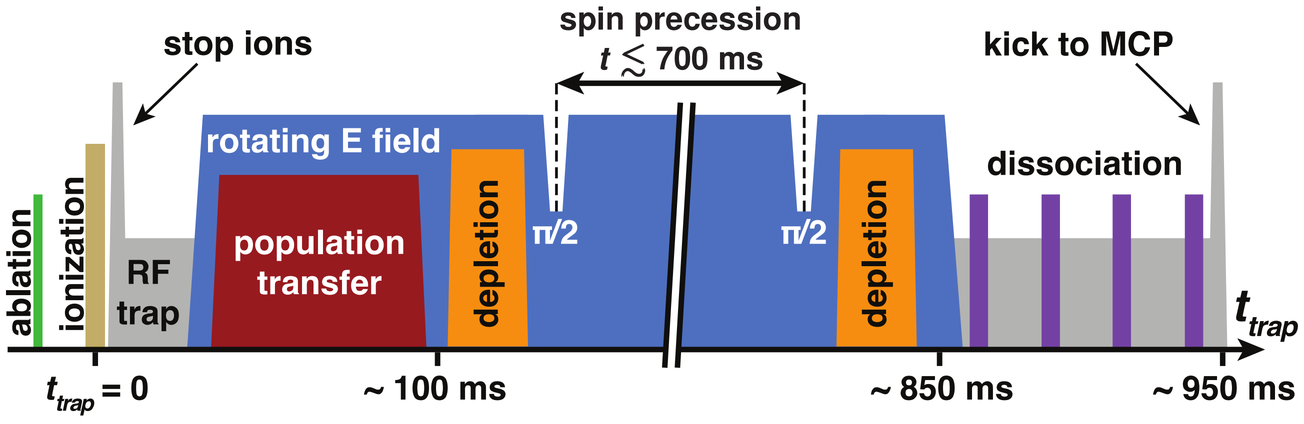
The Ion Trap


Ionization
Lasers
HfF
HfF^+
Trap
Electrodes
mesh
MCP
phosphor
Camera

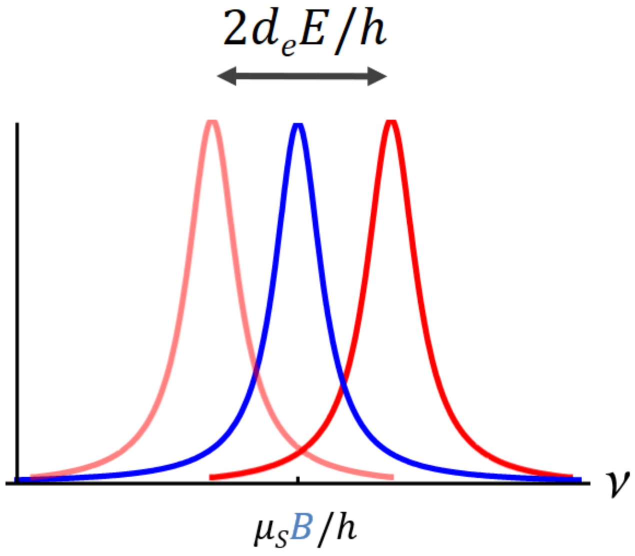
experimental procedure







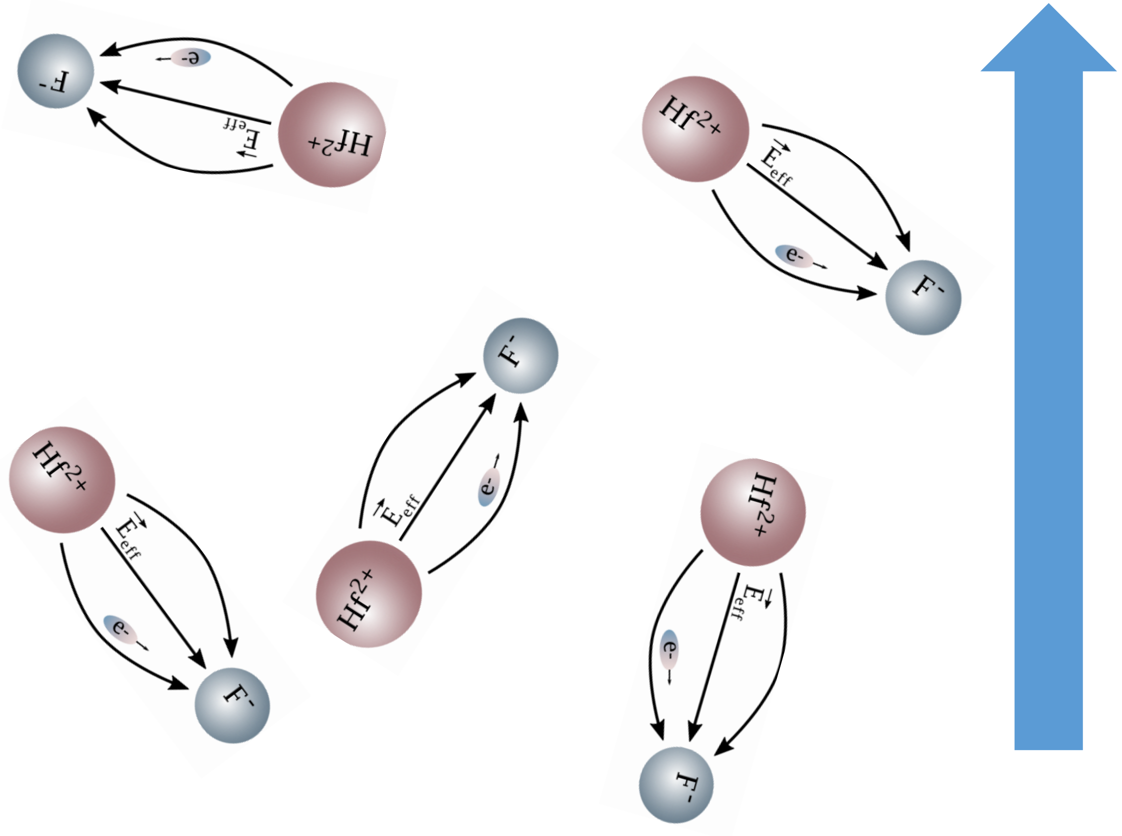
Molecular Alignment



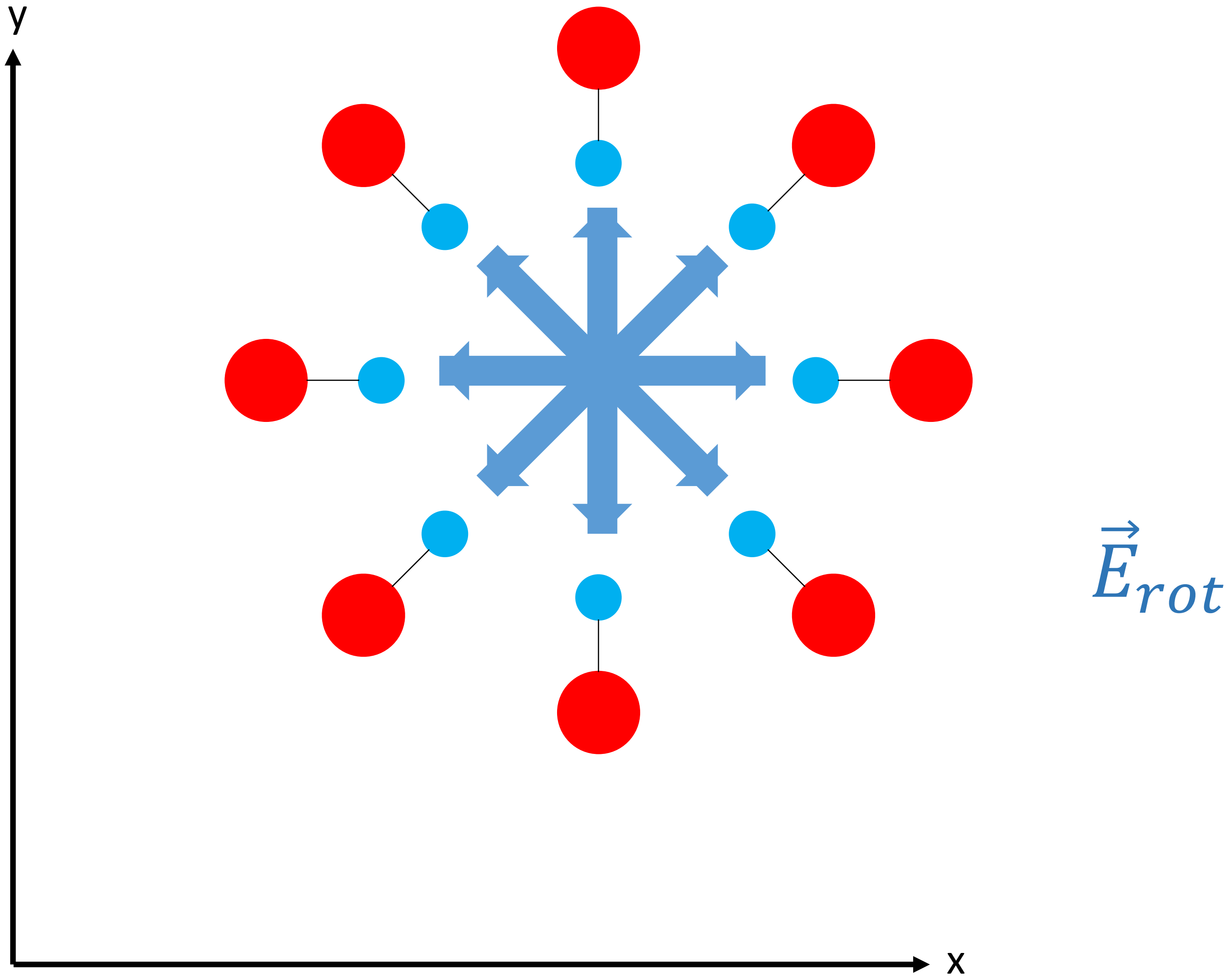
$$\vec{E} = \vec{E}_{eff}$$

$$\vec{B} = \vec{B}_{lab}$$

$$\vec{E} = \vec{E}_{lab}$$

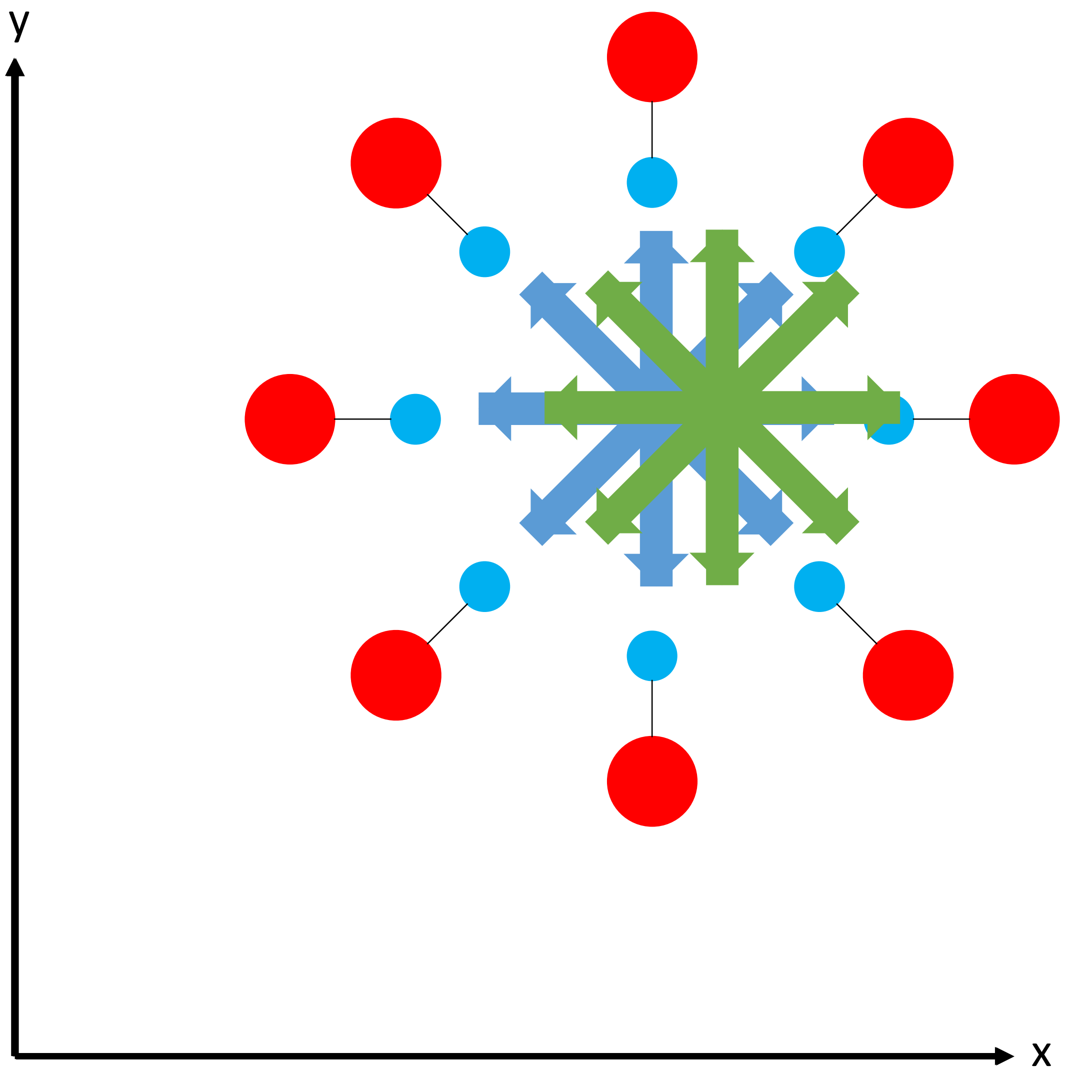


Rotating Fields



- Rotating E-Field:
  - $E_{rot} = 60\,\frac{\mathrm{V}}{\mathrm{cm}}$
  - $f_{rot} = 375\ \mathrm{kHz}$
  - Can switch between CW and CCW
  - Molecules rotate with $r_{rot} = 0.5\ \mathrm{mm}$

Rotating Fields



- Rotating E-Field:
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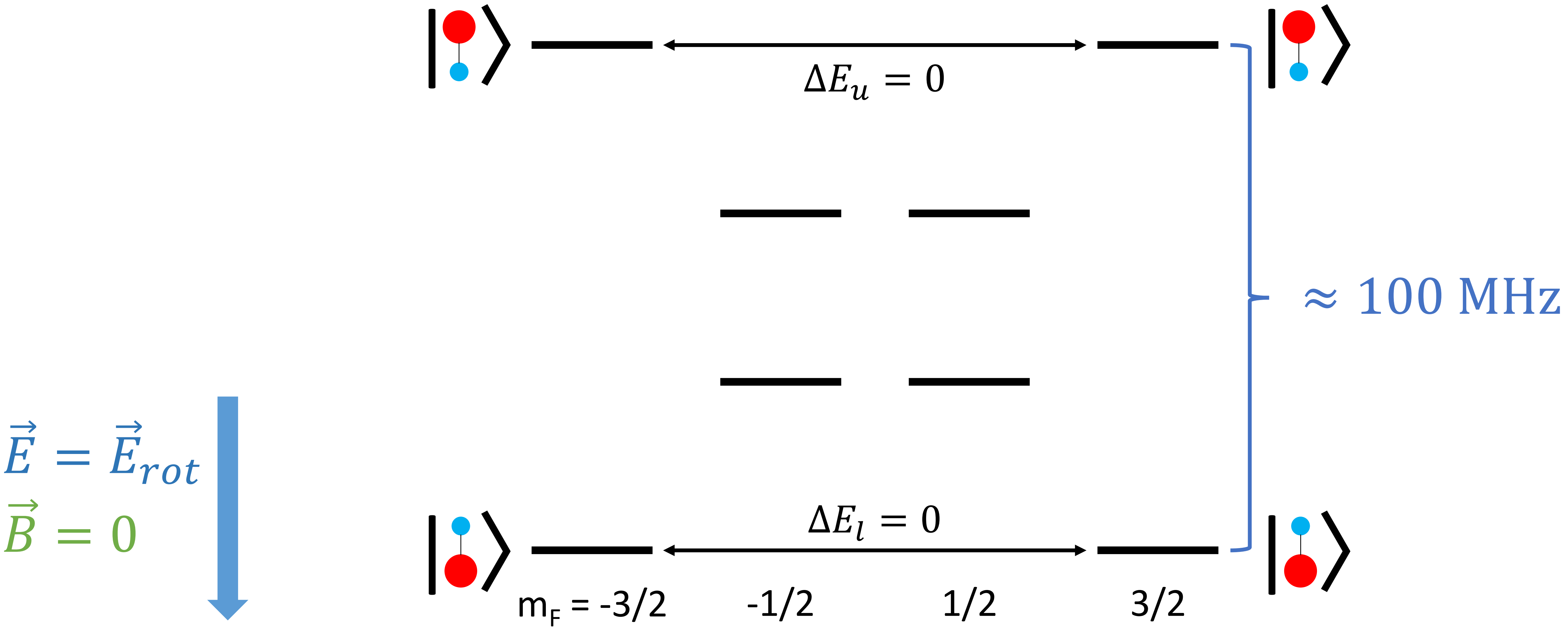
  - $f_{rot} = 375\ \mathrm{kHz}$
  - Can switch between CW and CCW
  - Molecules rotate with $r_{rot} = 0.5\ \mathrm{mm}$

$\vec{E}_{rot}$

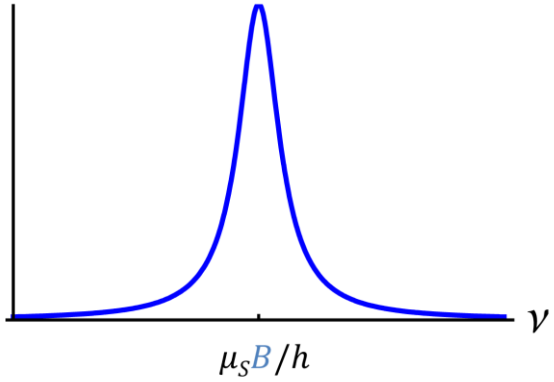
- “Rotating” B-Field
  - Static B-field gradient
  - $B_{ax} = 200\,\frac{\mathrm{mG}}{\mathrm{cm}}$
  - $B_{rot} = 10\ \mathrm{mG}$

$\vec{B}_{rot}$

Science State $^3\Delta_{|\Omega|=1}$ $v = 0$, J = 1, F = 3/2

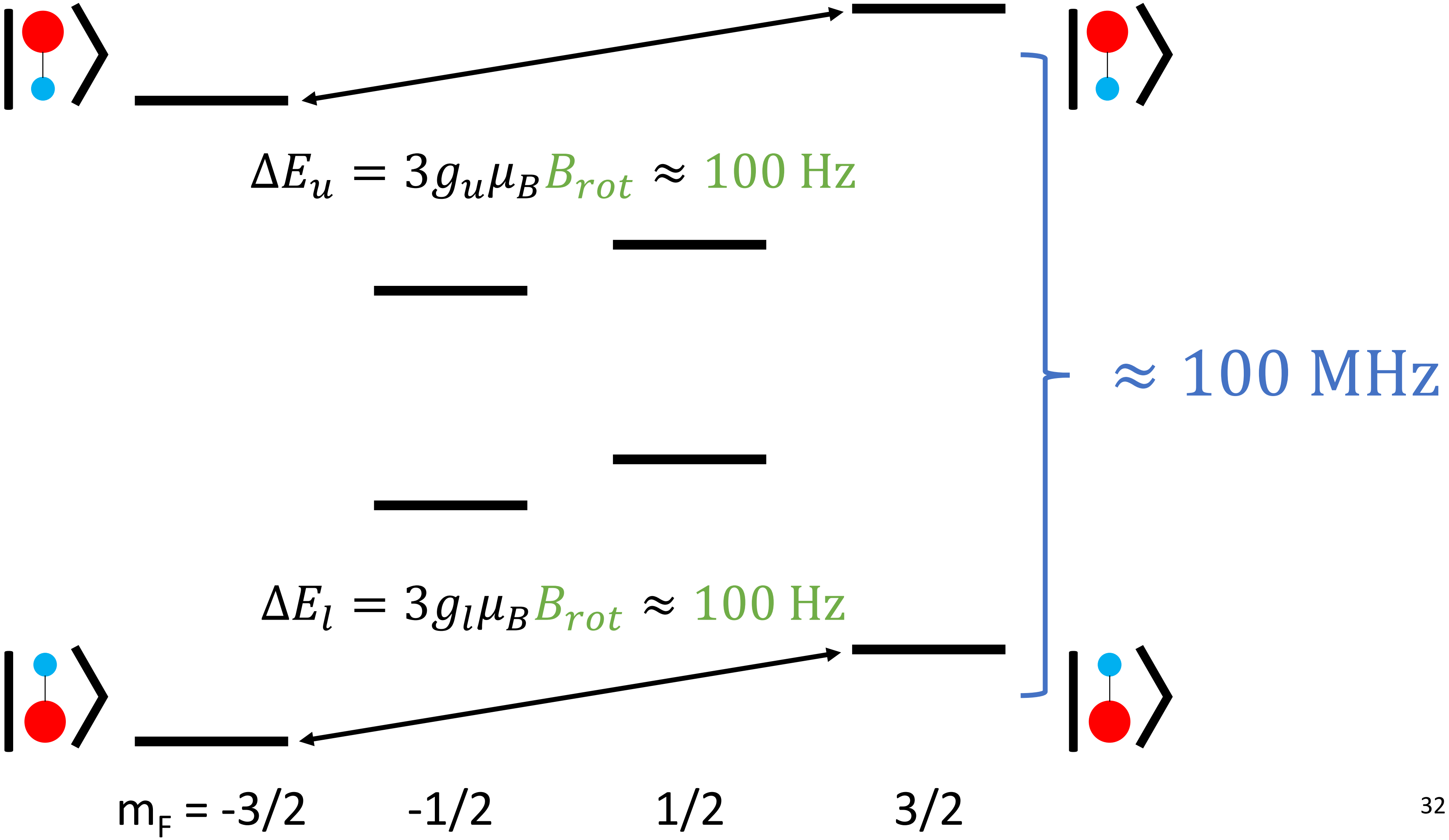


Science State $^3\Delta_{|\Omega|=1}$ v = 0, J = 1, F = 3/2



$\vec{E} = \vec{E}_{rot}$

$\vec{B} = \vec{B}_{rot}$



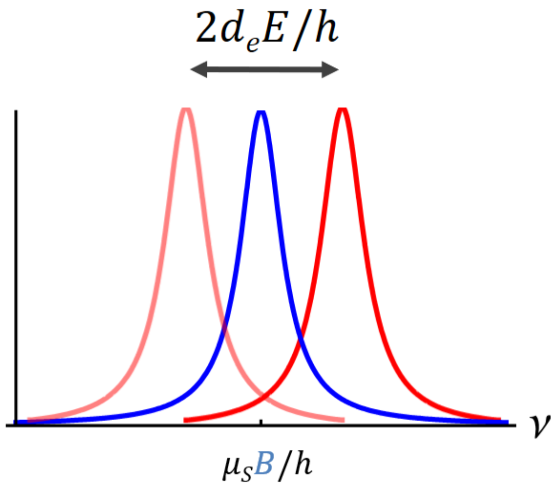
$\Delta E_u = 3 g_u \mu_B B_{rot} \approx 100\ \mathrm{Hz}$

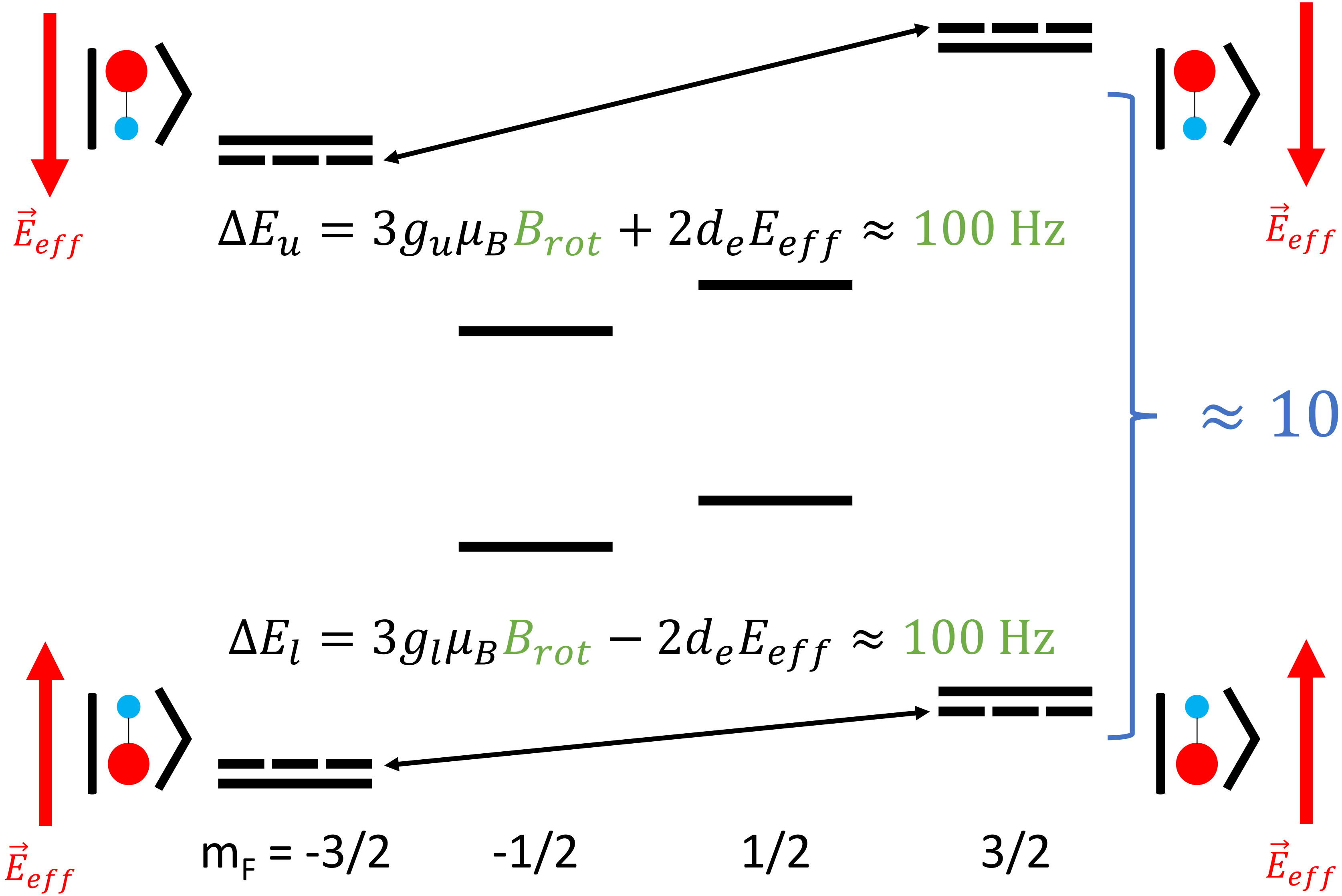
$\approx 100\ \mathrm{MHz}$

$\Delta E_l = 3 g_l \mu_B B_{rot} \approx 100\ \mathrm{Hz}$

m_F = -3/2 -1/2 1/2 3/2

Science State $^3\Delta_{|\Omega|=1}$ $v = 0$, $J = 1$, $F = 3/2$

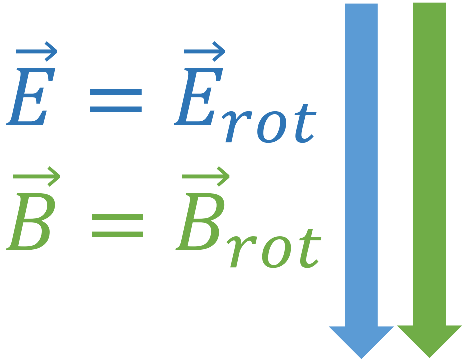




$$\Delta E_u = 3g_u\mu_B B_{rot} + 2d_eE_{eff} \approx 100\text{ Hz}$$

$$\Delta E_l = 3g_l\mu_B B_{rot} - 2d_eE_{eff} \approx 100\text{ Hz}$$

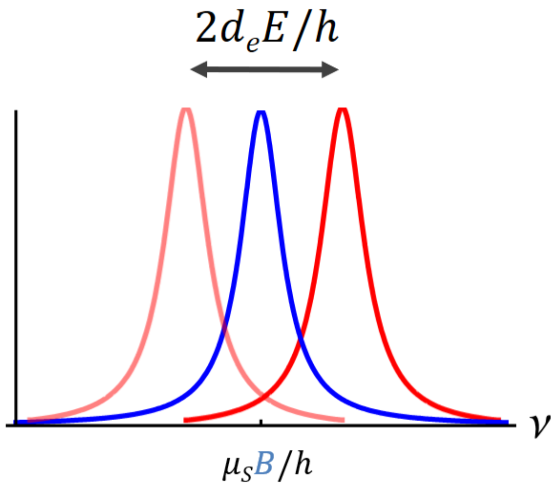
$m_F = -3/2$ -1/2 1/2 3/2



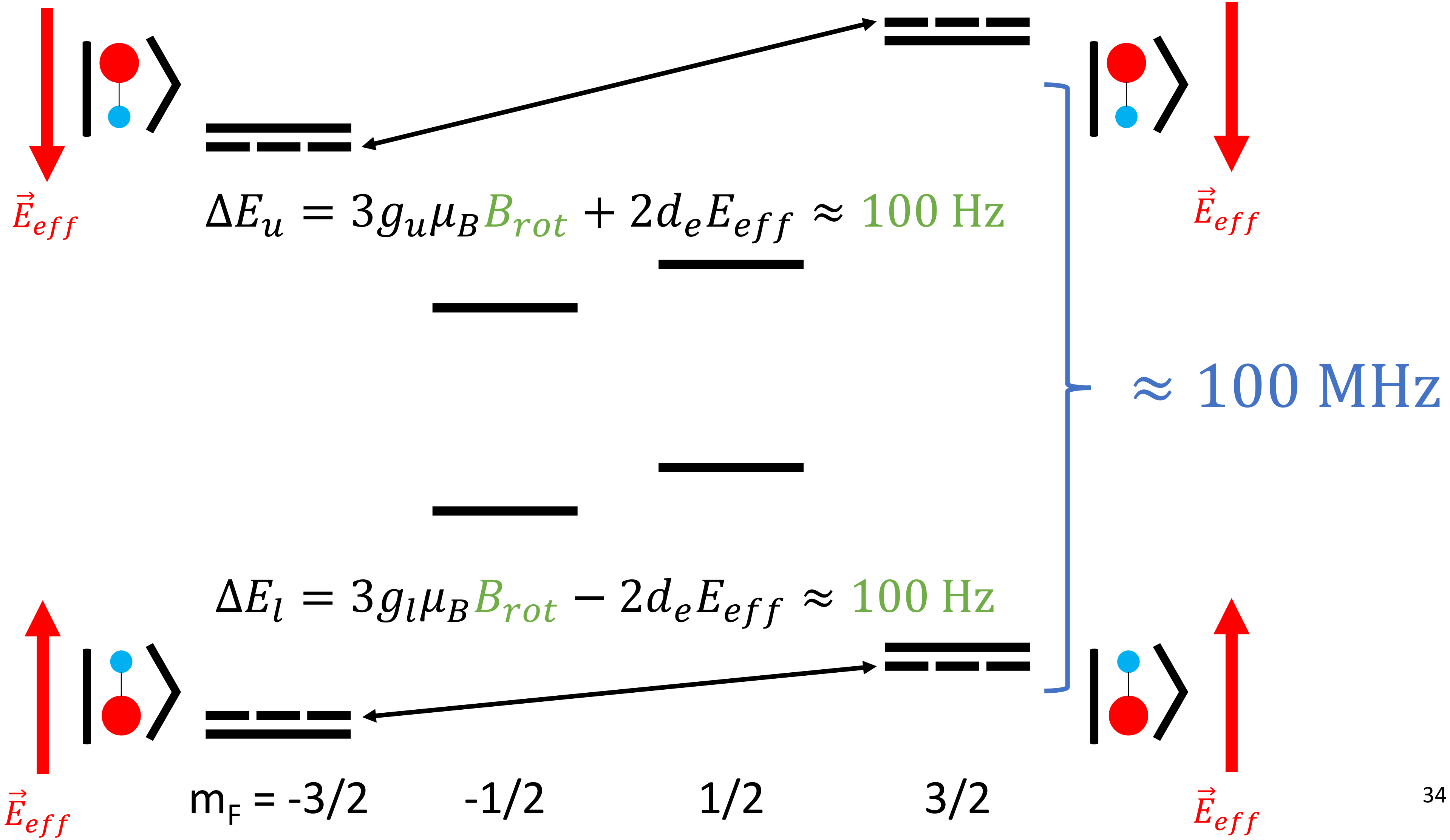
$$\vec{E} = \vec{E}_{rot}$$

$$\vec{B} = \vec{B}_{rot}$$

Using Omega=1 states to cancel many effects, the Demille idea. We have cheerfully stolen it from ACME.



$$\vec{E} = \vec{E}_{rot}$$
$$\vec{B} = \vec{B}_{rot}$$



$$\Delta E_u = 3 g_u \mu_B B_{rot} + 2 d_e E_{eff} \approx 100\ \text{Hz}$$

$$\Delta E_l = 3 g_l \mu_B B_{rot} - 2 d_e E_{eff} \approx 100\ \text{Hz}$$

Our approach. 3. We want big count rate (= many ions in the trap!)

In one shot we trap 1000s of ions, and count 100s of ions on the side of a Ramsey fringe.

counting 400 ions at shot noise, we should measure the evolved Ramsey phase to $1/(400)^{1/2}$ 0.05 radians in one shot.

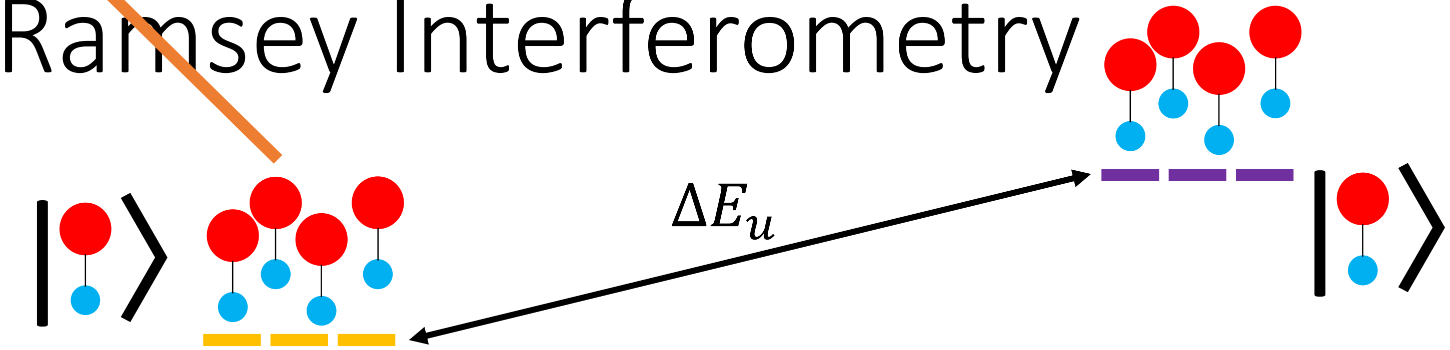
BUT! pulsed lasers ablation, two-photon photo-ionization, two-photon photo-dissociation. Spin-flips counted affected by 5 pulsed lasers plus 5 seconds worth of E-field and B-field drift.

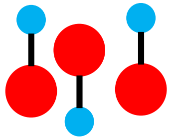
We were lucky if we could see

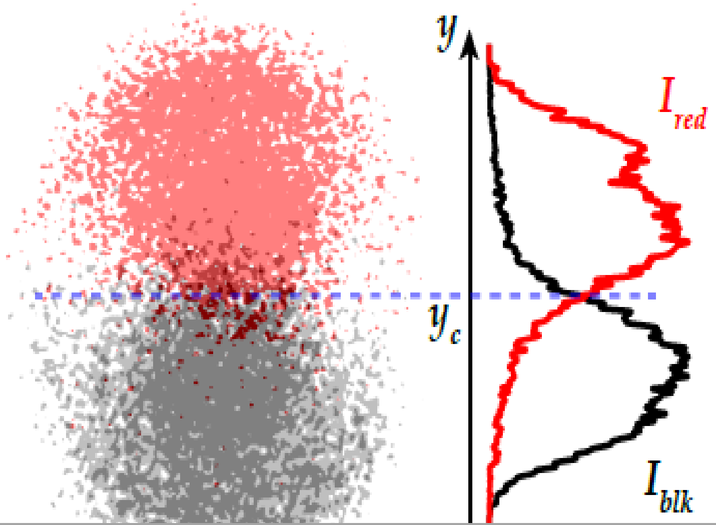
$\delta < 0.15$ radians in a shot!

Angle-resolved photo-dissociation: help from Tanya Zelevinsky!

Ramsey Interferometry

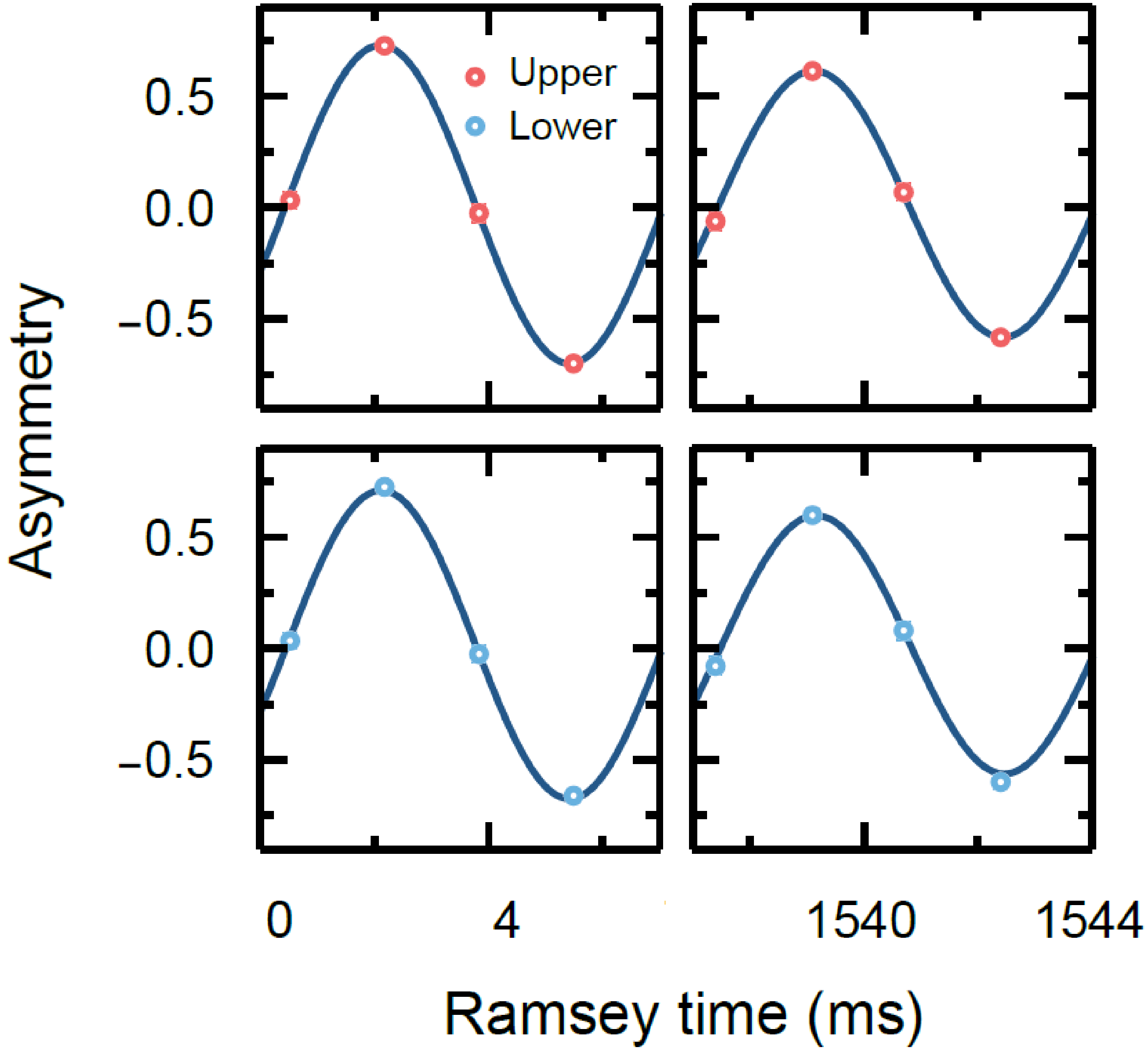


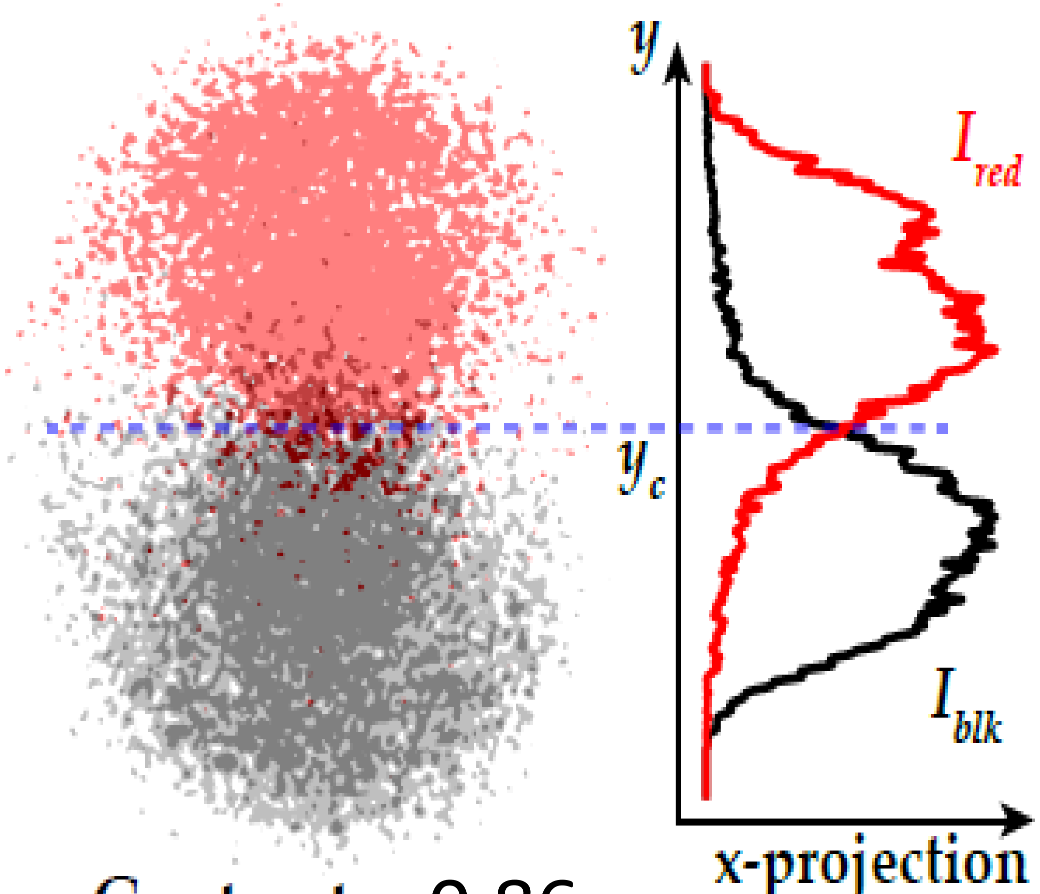




We reject most common-node noise, get close to QPN limit.

Ramsey Fringes





Contrast = 0.86

Experimental Chops

$\vec{B} \parallel \vec{E}$

Upper Doublet

$\vec{B} \parallel \vec{E}$

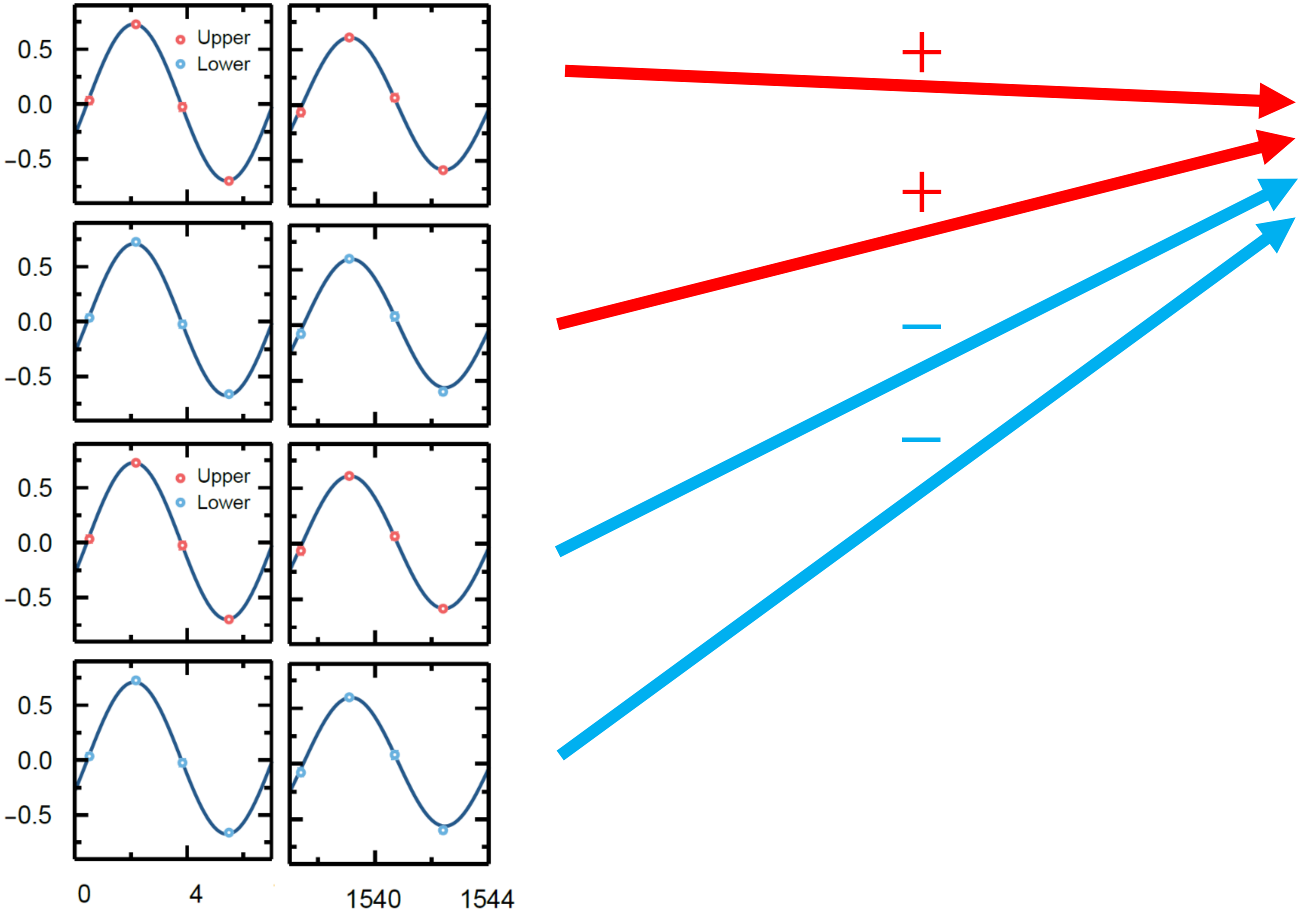
Lower Doublet

$\vec{B} \parallel -\vec{E}$

Upper Doublet

$\vec{B} \parallel -\vec{E}$

Lower Doublet



$$f^0 = 3g\mu_B B_{rot} \approx 100\ \mathrm{Hz}$$

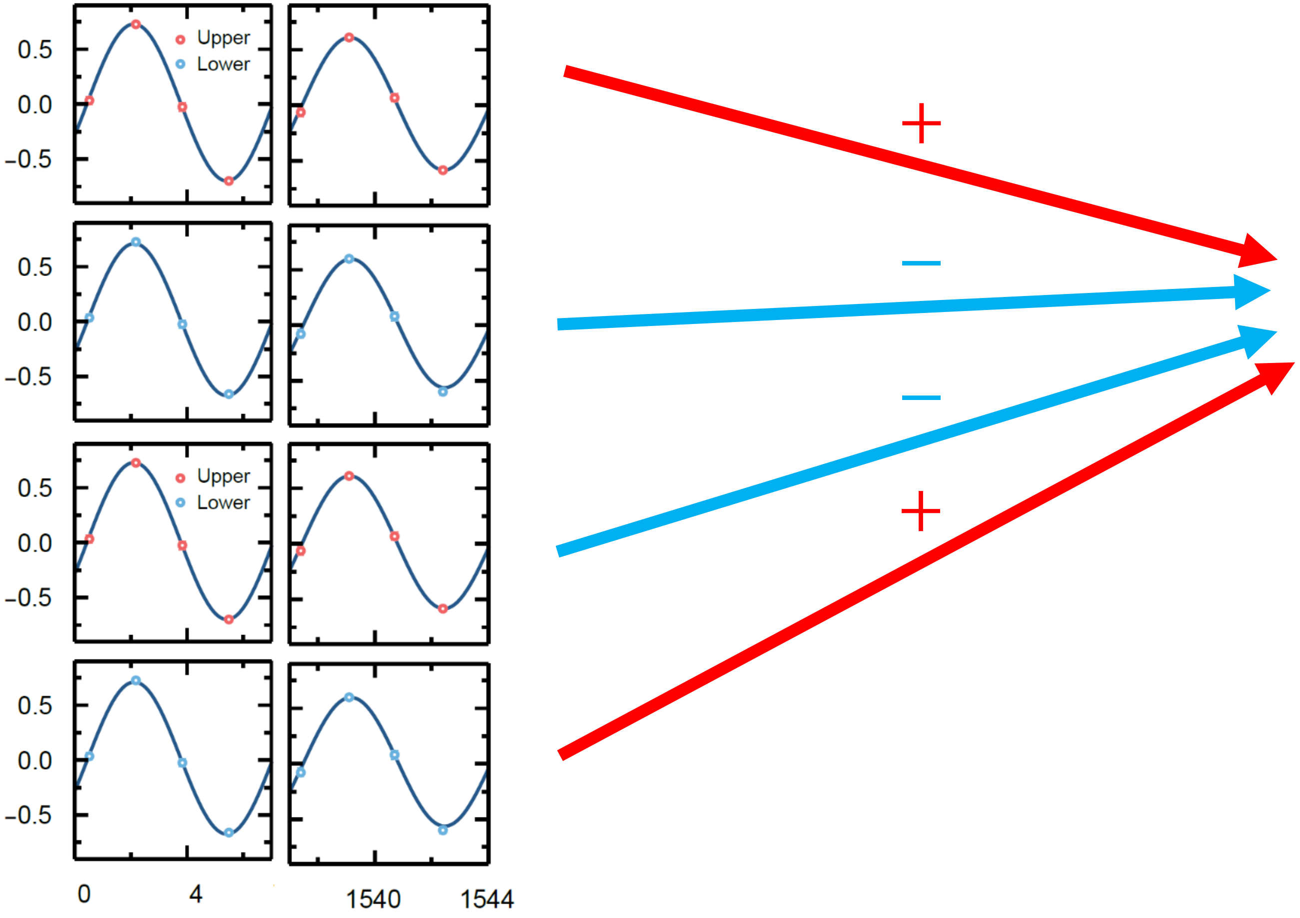
Experimental Chops

$\vec{B} \parallel \vec{E}$ Upper Doublet

$\vec{B} \parallel \vec{E}$ Lower Doublet

$\vec{B} \parallel -\vec{E}$ Upper Doublet

$\vec{B} \parallel -\vec{E}$ Lower Doublet



$$f^0 = 3g\mu_B B_{rot} \approx 100\text{ Hz}$$

$$f^D = 3\delta g\mu_B B_{rot}$$

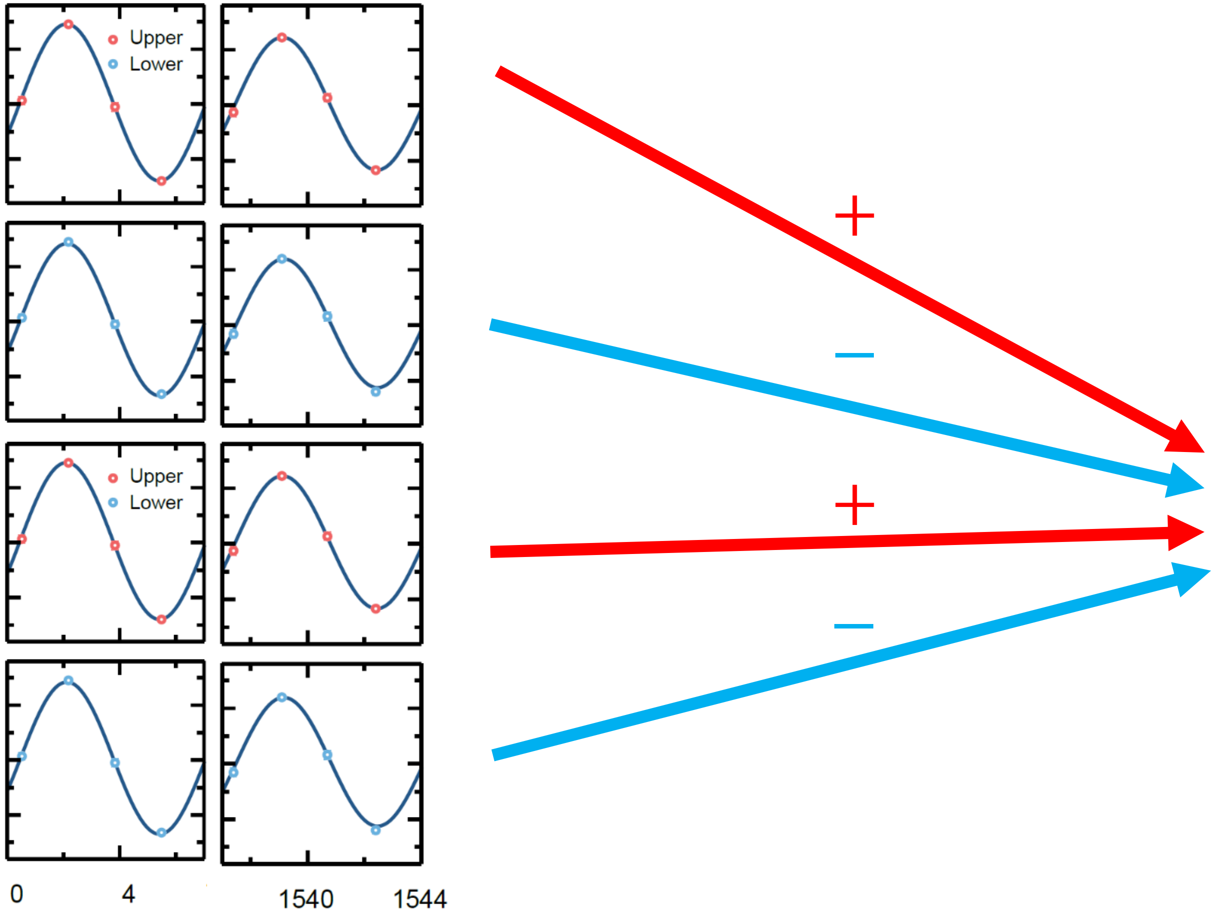
Experimental Chops

$\vec{B} \parallel \vec{E}$
Upper Doublet

$\vec{B} \parallel \vec{E}$
Lower Doublet

$\vec{B} \parallel -\vec{E}$
Upper Doublet

$\vec{B} \parallel -\vec{E}$
Lower Doublet



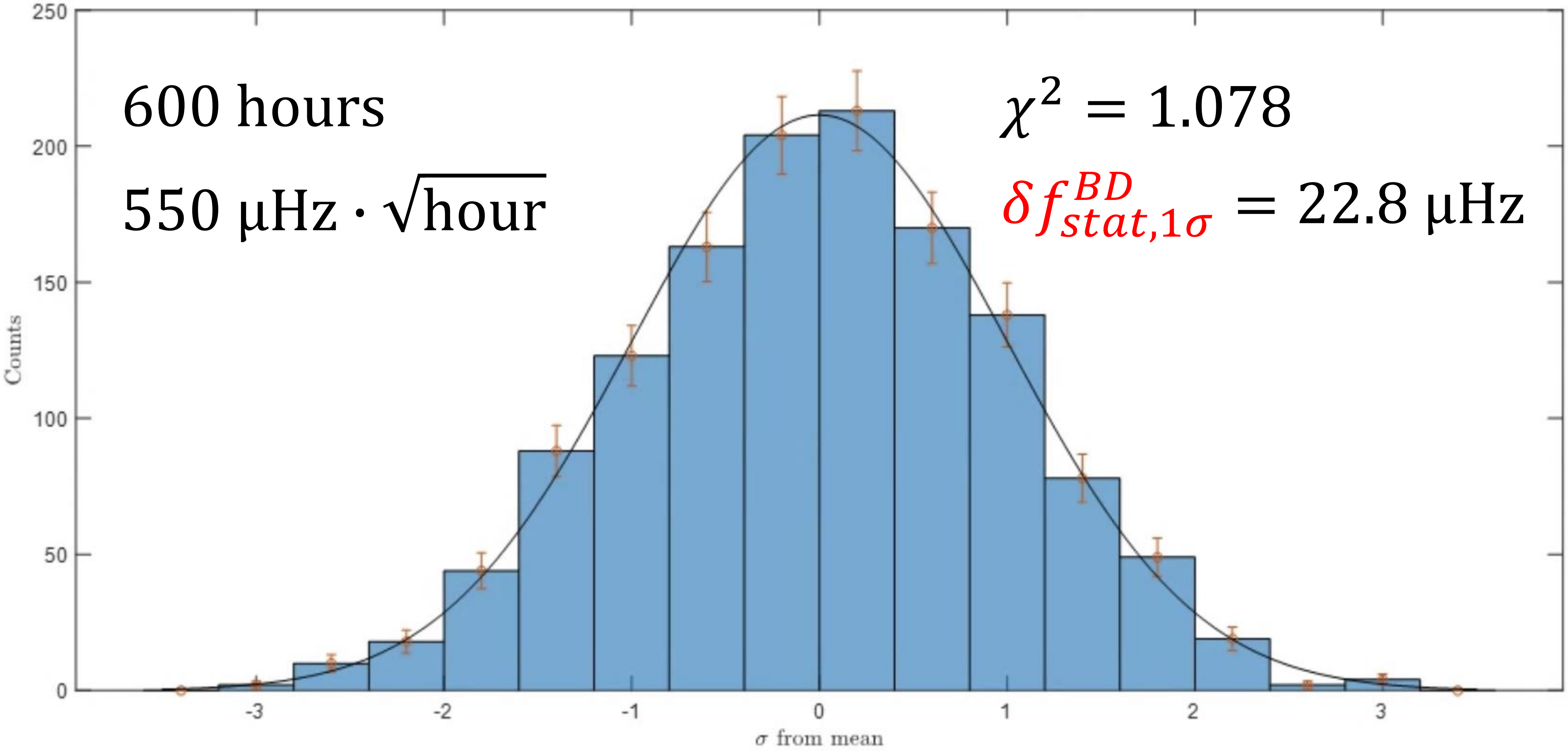
$$f^0 = 3g\mu_B B_{rot} \approx 100\text{ Hz}$$

$$f^D = 3\delta g\mu_B B_{rot}$$

$$f^{BD} = 2d_e E_{eff}$$

Statistical Result

Data taken blind!

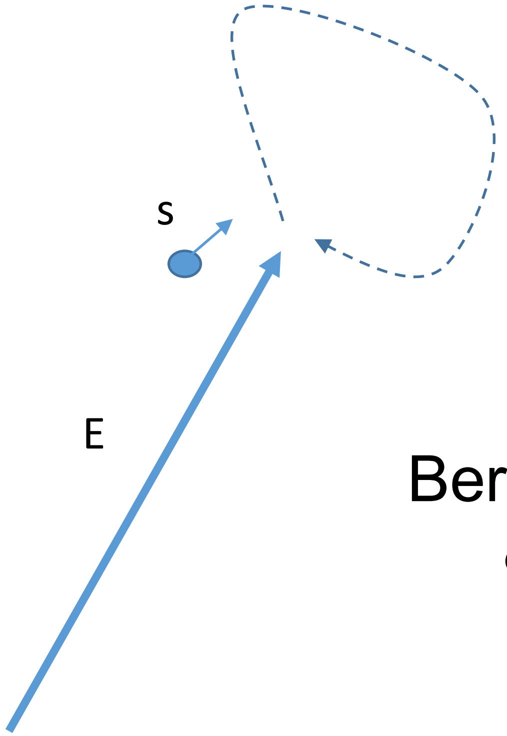


600 hours

$550\ \mu\text{Hz} \cdot \sqrt{\text{hour}}$

$\chi^2 = 1.078$

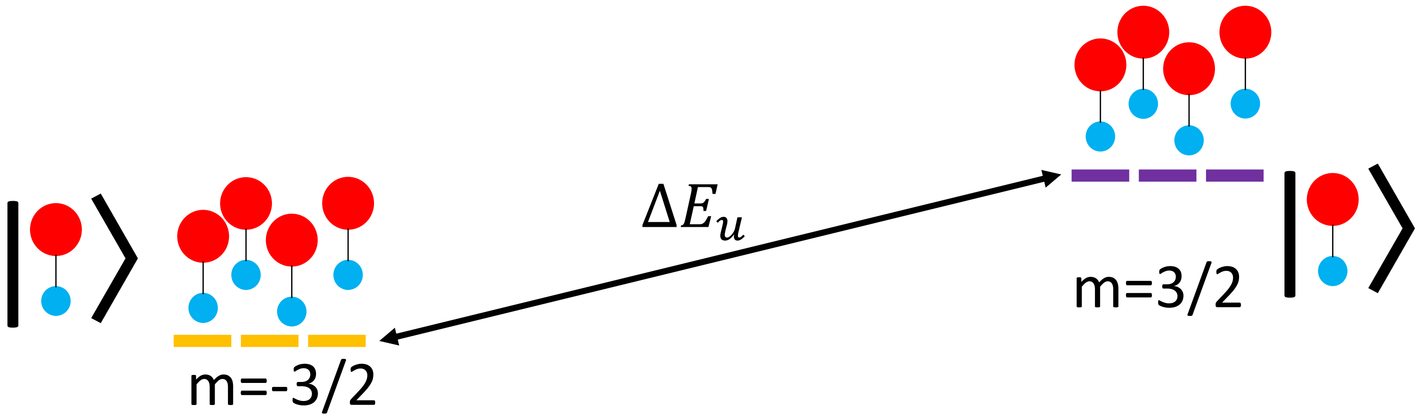
$\delta f^{BD}_{stat,1\sigma} = 22.8\ \mu\text{Hz}$



$\mathcal{A}$ = solid angle swept out
by changing bias field.

Berry's phase after one cycle:

$$\delta\phi = m\,\mathcal{A}$$

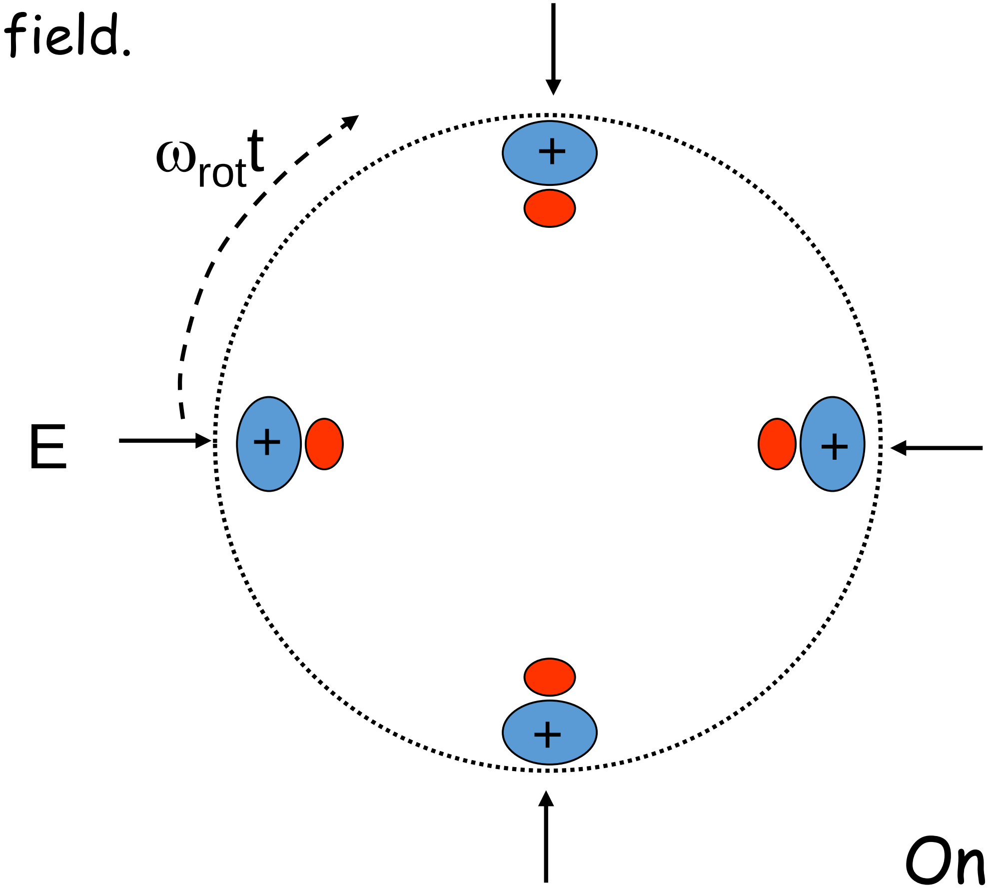


!!!!!Use rotating E-field bias!!!!!

-E-field defines quantization axis

-Excellent rejection of lab-frame residual

B-field.

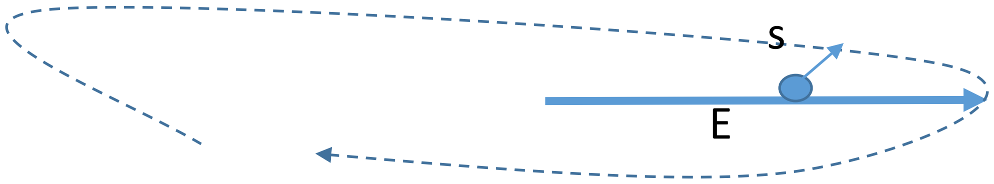


Leanhardt et al, J. Mol. Spec. (2011)   [25 typeset pages]

One does Zeeman-level spectroscopy then in the rotating frame.

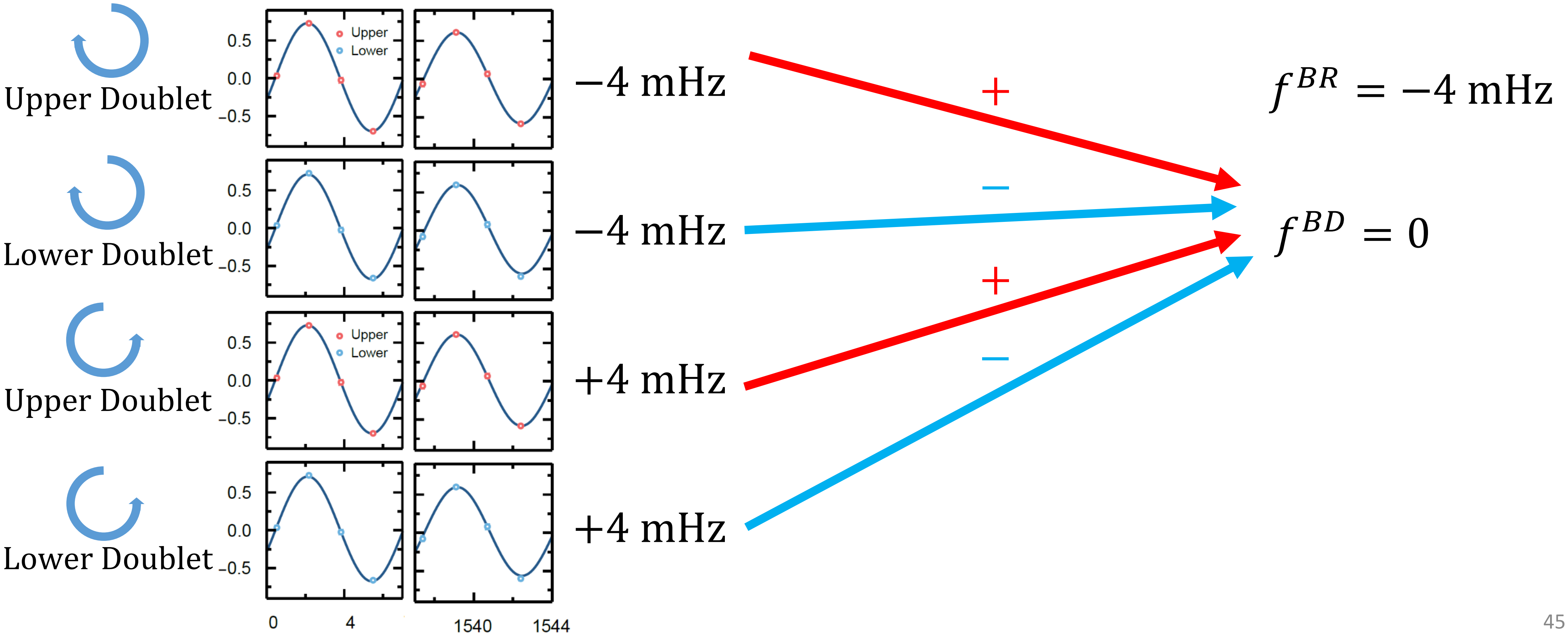
$\mathcal{A}$ = solid angle swept out
by changing bias field.

Berry's phase after one cycle:
$\delta\phi = m\mathcal{A}$



Basic scale of Berry's phase related freq shift in our experient 1.1 MHz. Rough place to do 20 μHz spectroscopy?

Berry’s Phase: Gravity



Upper Doublet $-4\ \mathrm{mHz}$

Lower Doublet $-4\ \mathrm{mHz}$

Upper Doublet $+4\ \mathrm{mHz}$

Lower Doublet $+4\ \mathrm{mHz}$

$f^{BR} = -4\ \mathrm{mHz}$

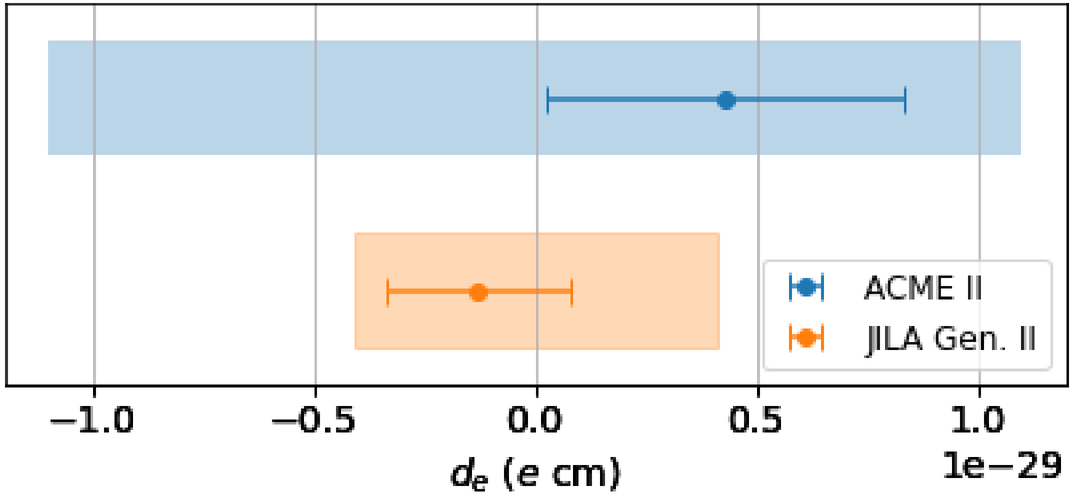
$f^{BD} = 0$

```
'mean fB correction = 0.18102 uHz'


ans =

    'fBD BLINDED = 16101.0957 +/- 22.7935 (stat) +/- 7 (syst) uHz'


ans =

    'fBD UNBLINDED = -10.9319 +/- 22.7935 (stat) +/- 7 (syst) uHz'


ans =
```

Generation II

Official announcement paper:
arXiv:2212.11841, submitted to Science

Systematics analyses paper:
arXiv:2212.11837, submitted to PRA



Experiment	Interrogation time	1σ statistical	1σ systematic	1σ total	90% confidence
JILA Gen. I (2017)	314 hours	77×10^{-30} e cm	1.7×10^{-30} e cm	79×10^{-30} e cm	130×10^{-30} e cm
ACME Gen. II (2018)	350 hours	3.1×10^{-30} e cm	2.6×10^{-30} e cm	4.0×10^{-30} e cm	11×10^{-30} e cm
JILA Gen. II (Nov, 2022)	550 hours	2.0×10^{-30} e cm	0.6×10^{-30} e cm	2.1×10^{-30} e cm	4.1×10^{-30} e cm

In last two years there have been three new record-setting measurements of lepton dipole moments:

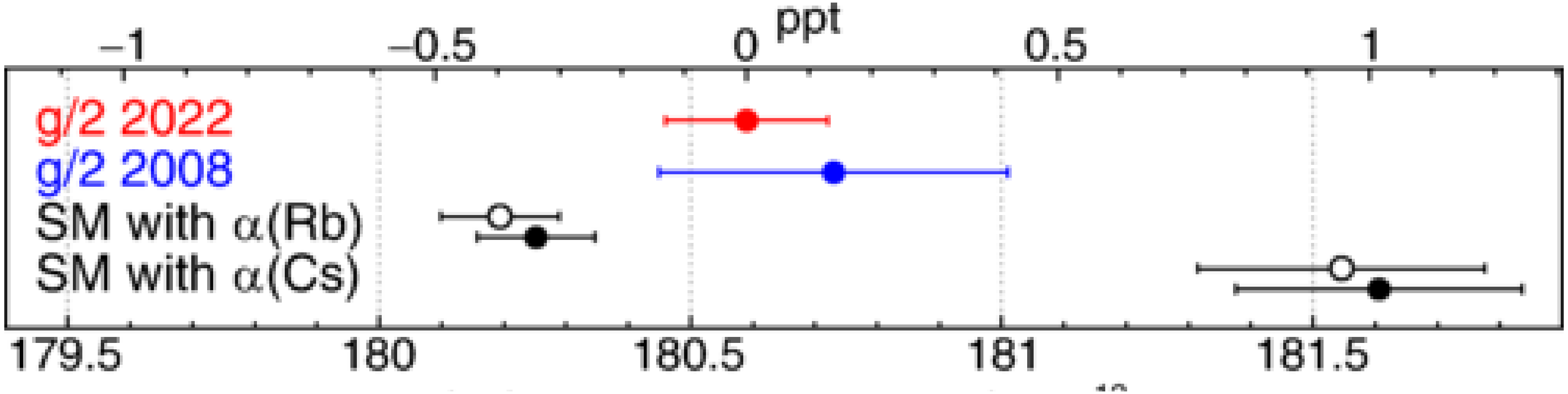
muon magnetic dipole (fermi lab)

electron magnetic dipole (northwestern/harvard)

electron electric dipole (JILA)

How do they compare?

Best electron magnetic moment measurement, 2022



μ_e= 2 + alpha/pi

Problems with "standard model background."

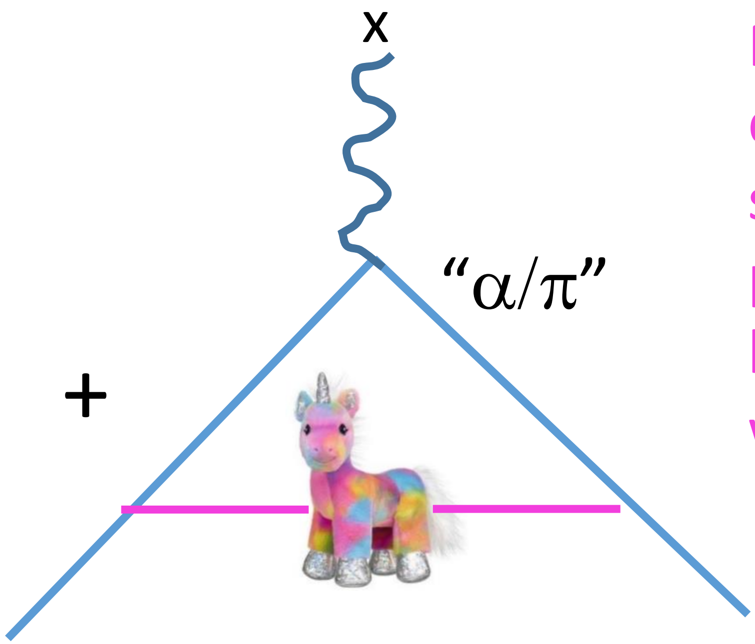
muon MDM also has ongoing question with SM background.

s

For now, assume SM background issues are resolved.

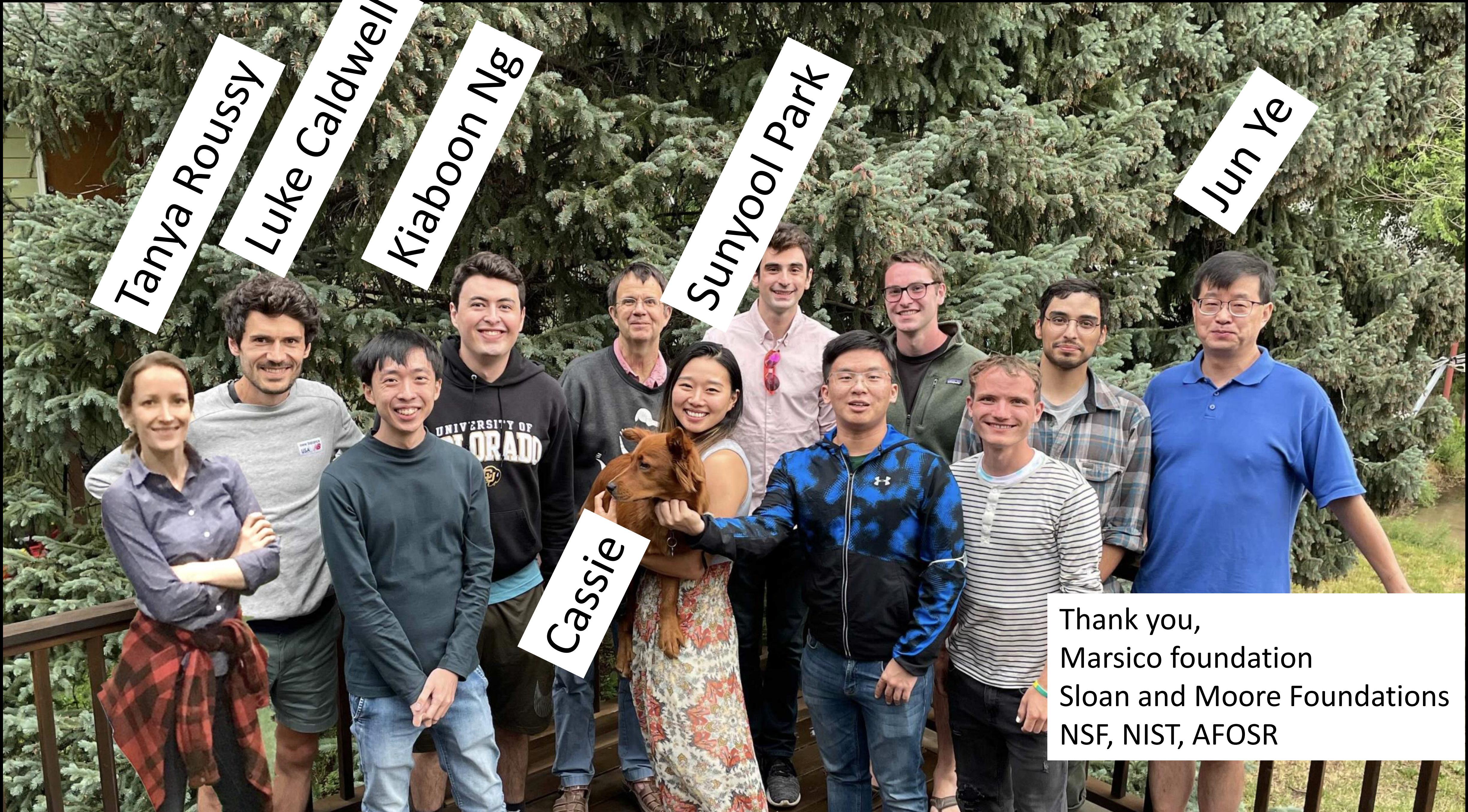
	relative precision	absolute units 10^{-30} e-cm	relative mass detectable	Recall John Doyle’s talk, and include “2-loop”	grain of salt “1-loop”
$\delta\ \mu_e$	0.1 ppt	2×10^6	1	4 GeV	40 GeV
$\delta\ \mu_\mu$	1 ppb	5×10^7	3	12 GeV	120 GeV
$\delta\ d_e$	1	2	1000	4000	40,000 GeV

+



Plan: let’s measure dipole moment, subtract out SM prediction. Whatever’s left is a result of a loop with one “running unicorn”

LHC:
~2000 GeV
(Must always be << nominal collision energy)



Tanya Roussy

Luke Caldwell

Kiaboon Ng

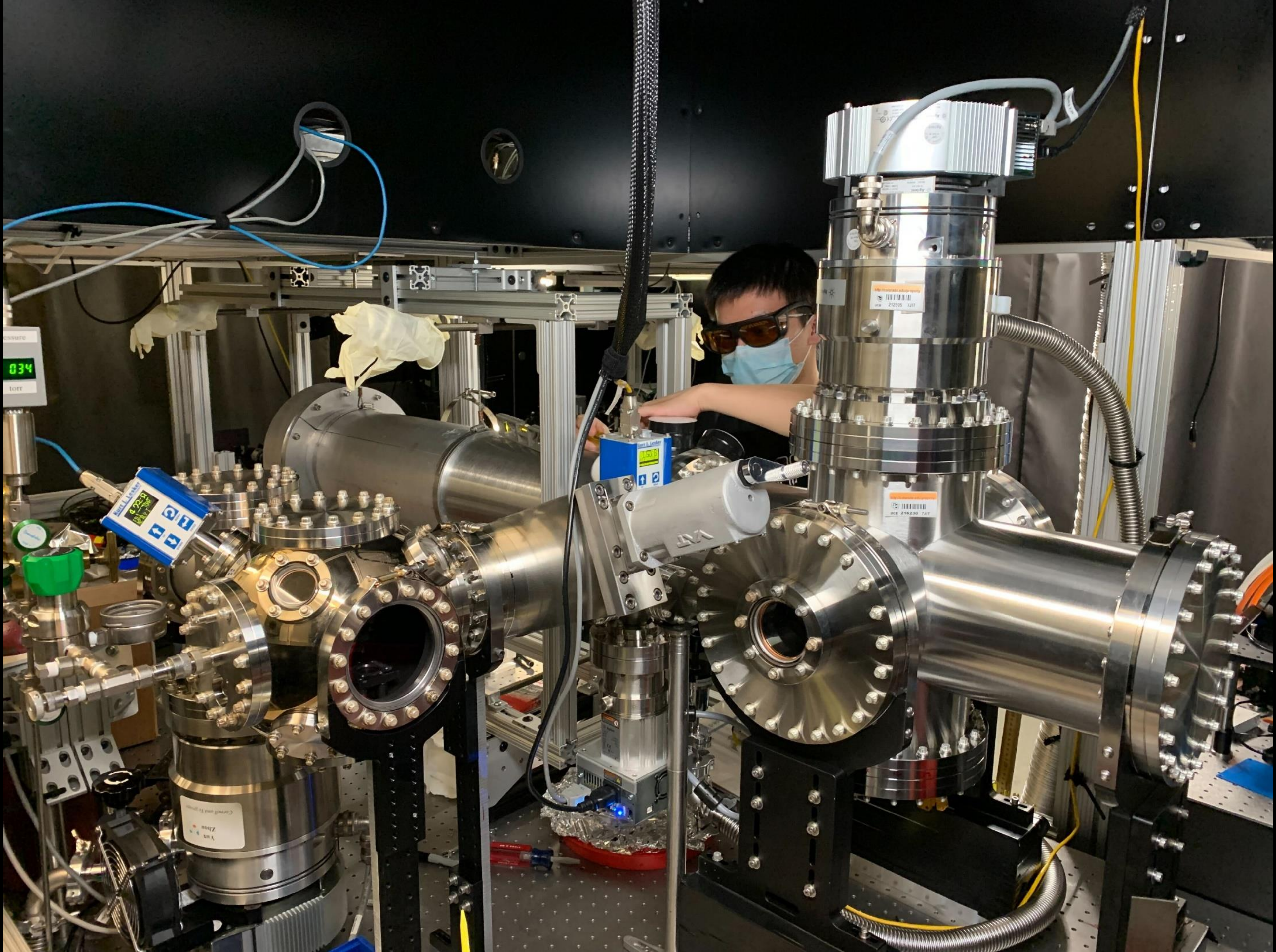
Sunyool Park

Jun Ye

Cassie

Thank you,
Marsico foundation
Sloan and Moore Foundations
NSF, NIST, AFOSR

Recall Didi Leibfried's talk on shuttling ions!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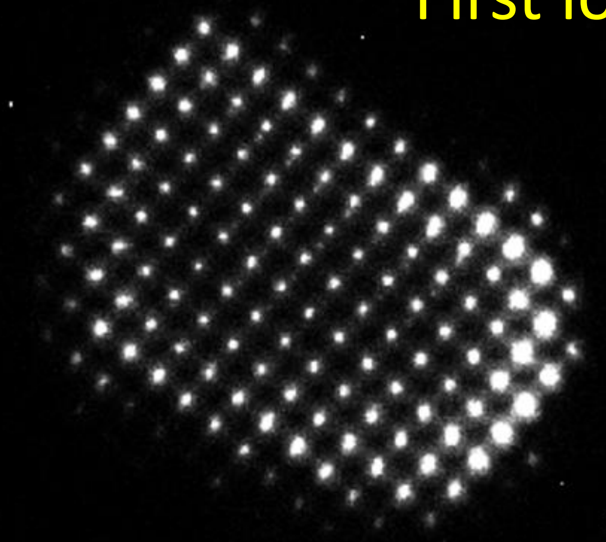
Kurt J. Lesker
VAT



JILA Generation Three:

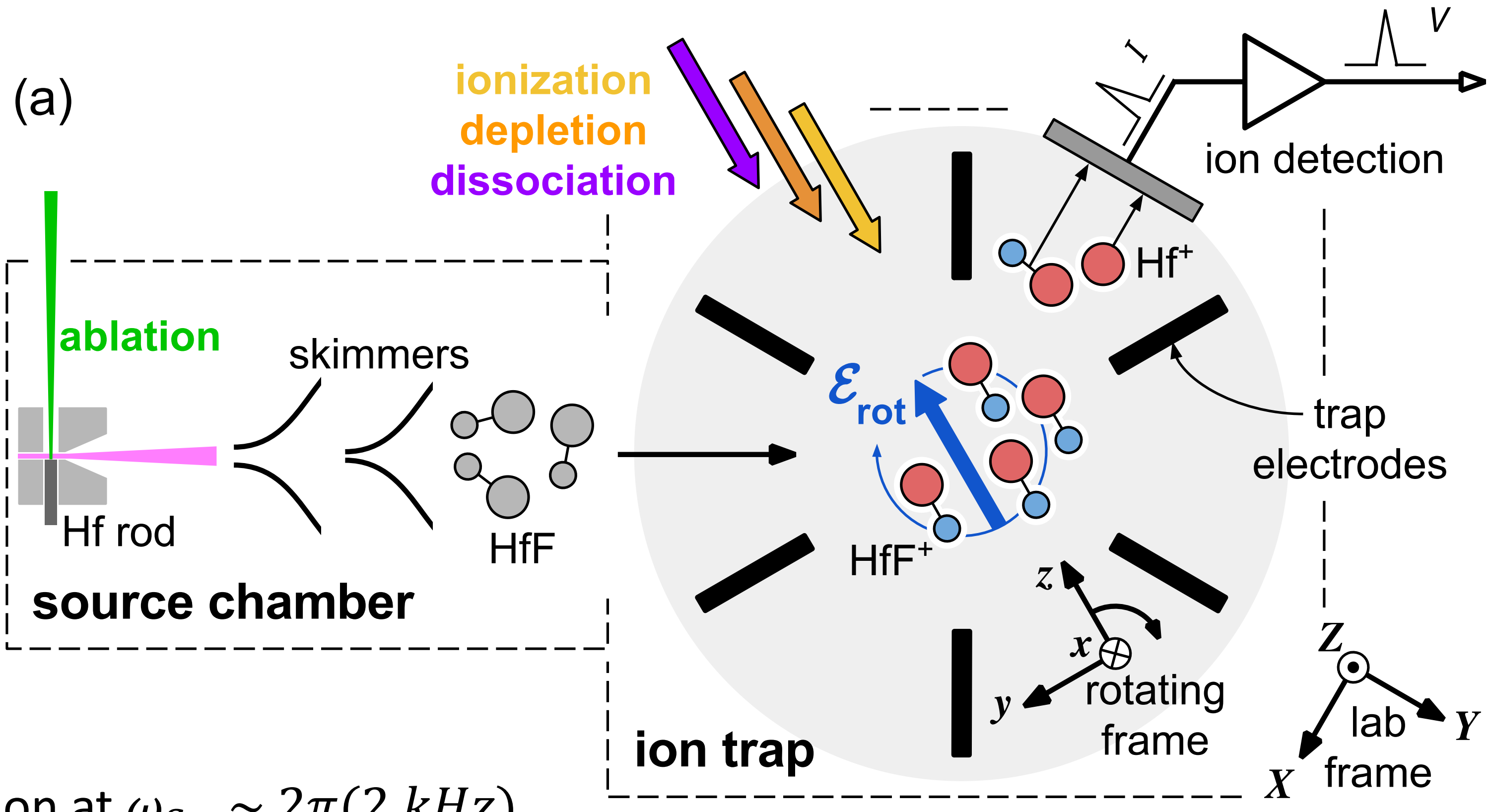
First ions, June 2022!

		units of $2x10^{-30}$ e-cm	scaled by lepton mass	Relative mass sensitivity	Recall John Doyle's talk, and include grain of salt
$\delta\,\mu_e$	= 2.5 x 10^{-24} e-cm	10^6	10^6	1	4 GeV, 40 GeV
$\delta\,\mu_m$	= 5 x 10^{-23} e-cm	$2.5x10^7$	10^5	3	12 GeV, 120 GeV
$\delta\,d_e$	= 2 x 10^{-30} e-cm	1	1	1000	4000, 40,000 GeV

eEDM and MDM are both precision spectroscopy experiments. Why the factor of one million?

	MDM	JILA EDM
Effective fields.	B= 10 Tesla = $3x10^7$ V/cm	E = $3x10^{10}$ V/cm (factor of 1000)
Count rate	electrons $2x10^{-3}$/sec	HfF^+ 10^2/sec (“ $(10^4)^{1/2} = 100$)
Coherence time	muons 50 microseconds	3 seconds (factor of 10^5)

Apparatus



Secular trap motion at $\omega_{Sec} \sim 2\pi(2\ kHz)$
"RF" micromotion at $\omega_{rf} = 2\pi(50\ kHz)$
Rotational micromotion at $\omega_{rot} = 2\pi(375\ kHz)$

Rotating magnetic field: <u>not sensitive to DC fields</u>