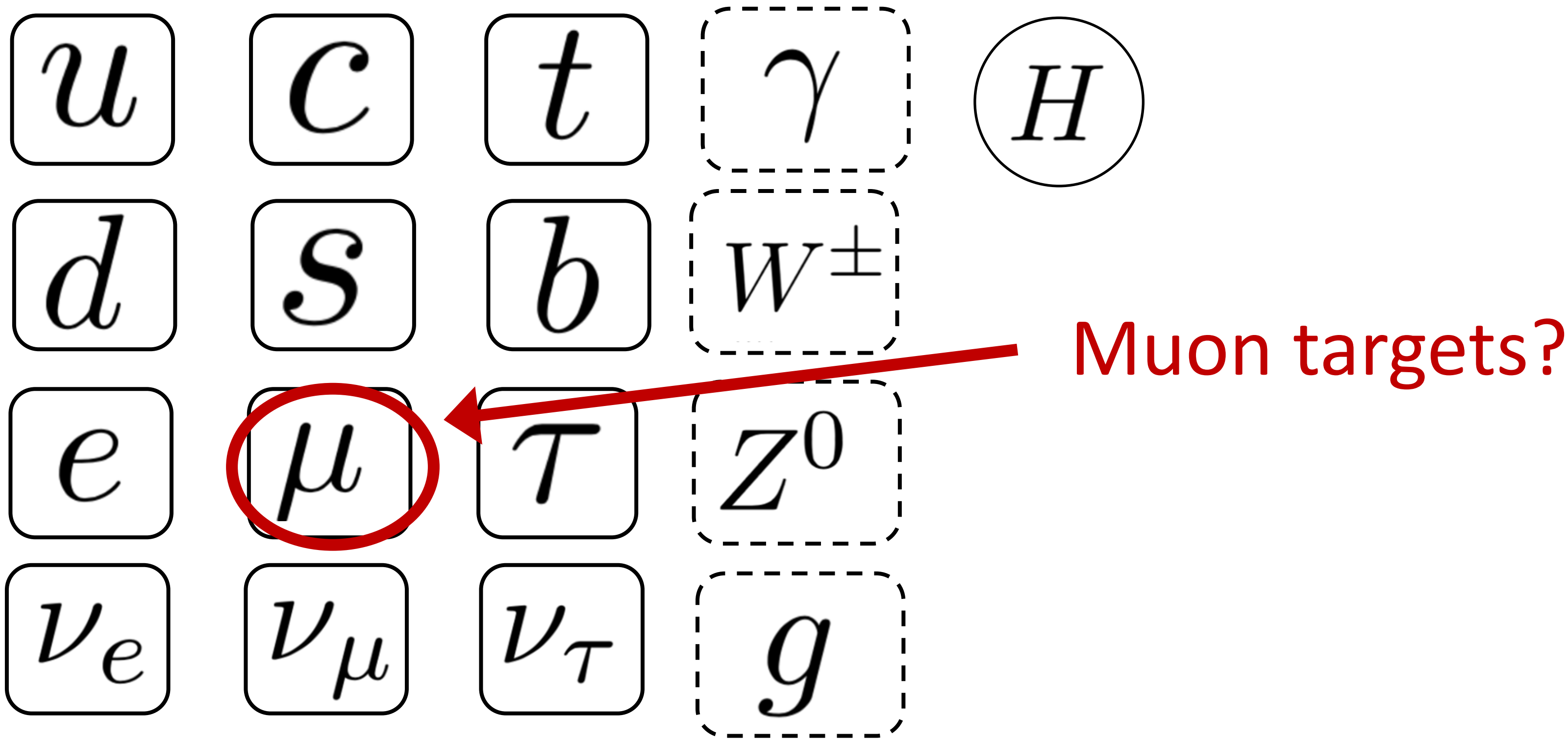
# Muon g-2 and EDM Experiments as Muonic Dark Matter Detectors

Ryan Janish

(Fermilab)

[RJ & Ramani, 2006.10069]

# Muonic Dark Matter




DM may be muophillic.

We ultimately seek a full theory of DM and its interactions.

# Muonic Dark Matter

Existing bounds on DM – muon interactions are from astrophysics, cosmology, or virtual effects.

## Astrophysics and Cosmology

| | |
|---|---|
| Long range forces on neutron stars | [Dror et al, 1909.12845], [Poddar et al, 1908.09732] |
| Supernovae cooling | [Bollig et al, 2005.07141] , [Croon et al, 2006.13942] |
| BBN ($N_{eff}$) | [Grifols and Masso, 9610205] |
| BH Superradiance | [Arvanitaki et al, 821575], … |

## Loop effects

| | |
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| Muon g - 2 | [Chen et al, 1701.07437] |
| Induced interactions | [Arvanitaki et al, 1405.2925], [Beznogov et al, 1806.07991], … |

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A direct terrestrial search is epistemically distinct and provides an opportunity for a surprising discovery.

Laboratory ceiling is higher (sensitivity will improve).

# Direct Muonic Dark Matter Detection

## Consider ultralight DM:

May have a coherent interaction over many muons

Large local DM number density can enhance detection

DM background field may apply a force on muons or a torque on muon spins.

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Muon spin precession is carefully measured in g-2 and electric dipole (EDM) experiments.

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[Bennett et al, 0602035]

Fermilab

[Grange et al, 1501.06858]

大強度陽子加速器施設 J-PARC

[Abe et al, 1909.03047]

PAUL SCHERRER INSTITUT PSI

[Adelmann et al, 0606034]

… ?

# DM in Muon g-2 and EDM Experiments

Conventional spin precession

Measurements of the muon magnetic dipole moment (g-2)

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# Spin Precession in a Storage Ring

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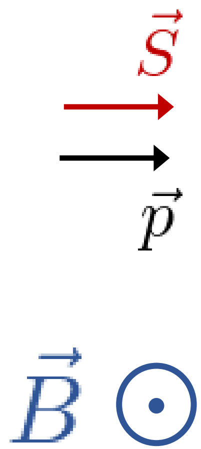

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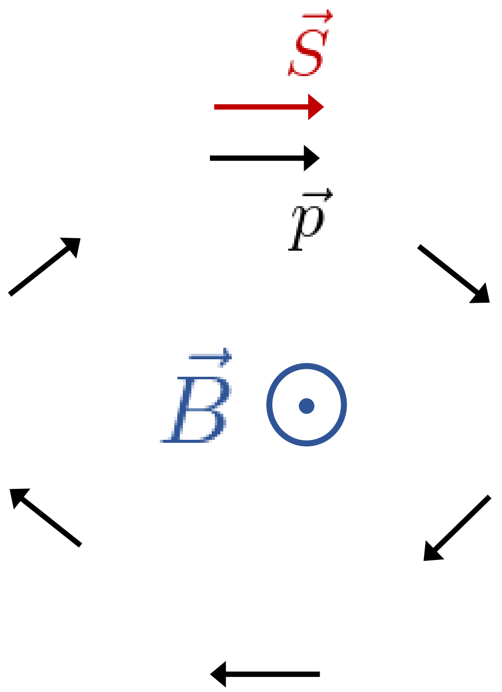

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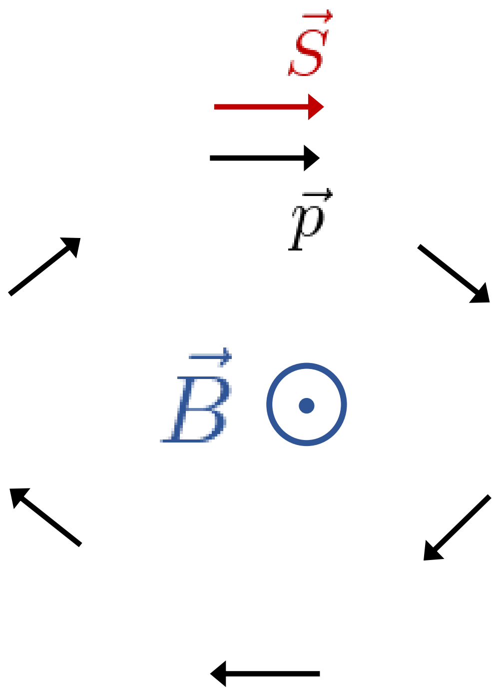
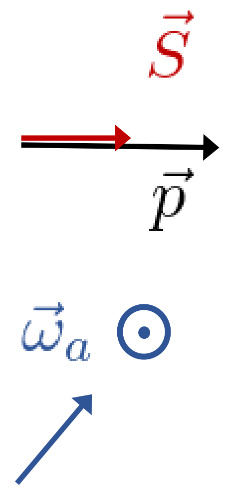



## Rotated Rest Frame




Rest Frame
Precession Frequency

$$\frac{2\pi}{\omega_a} \approx 5\ \mu s$$

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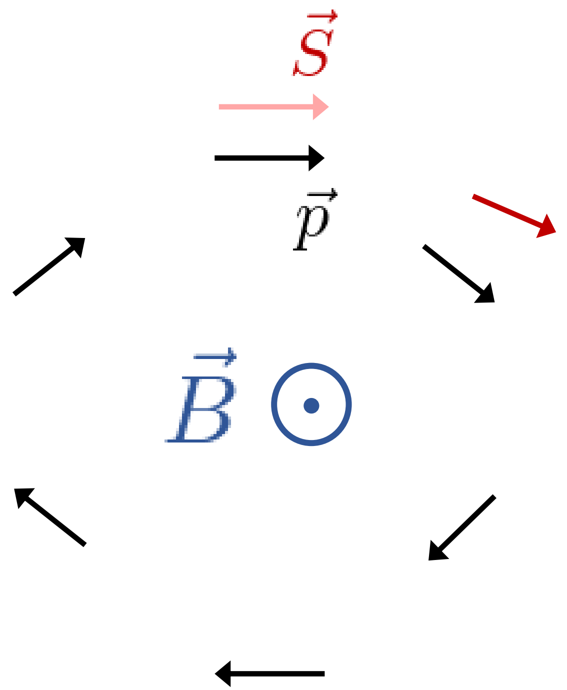


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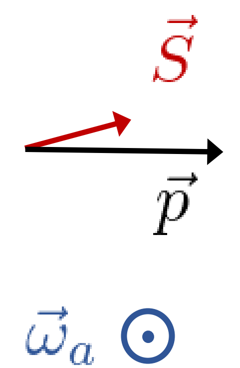


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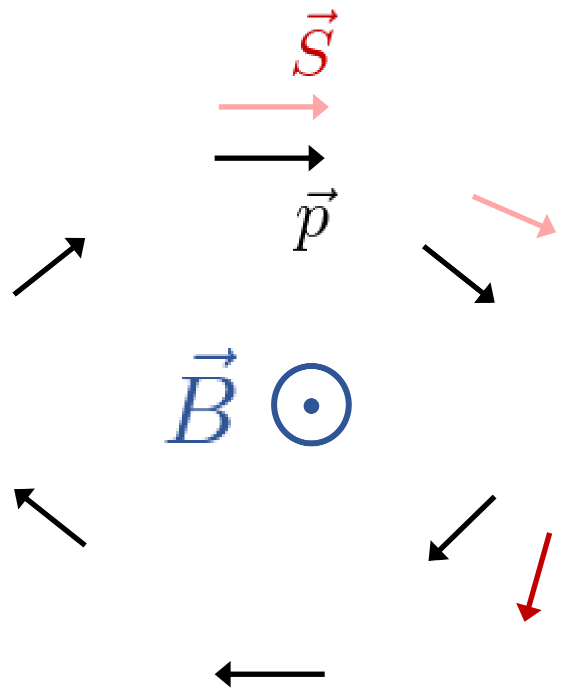


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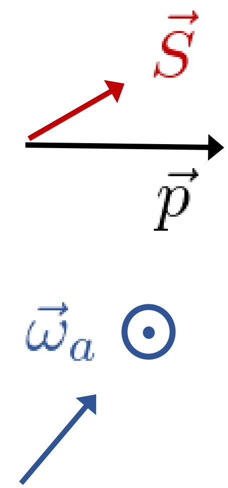


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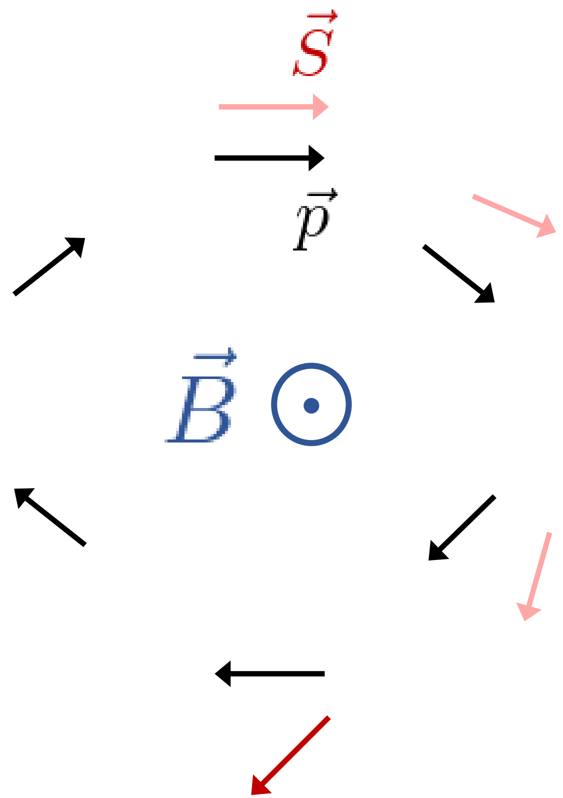


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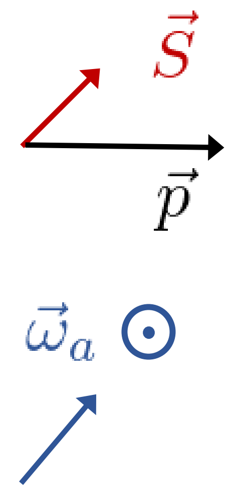


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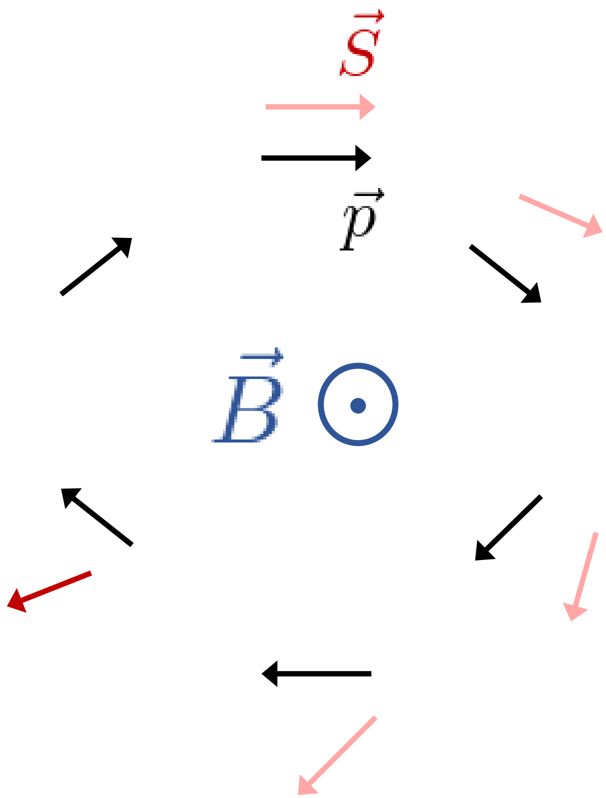


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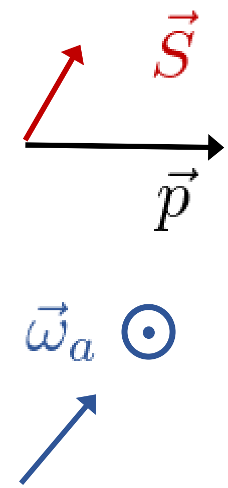


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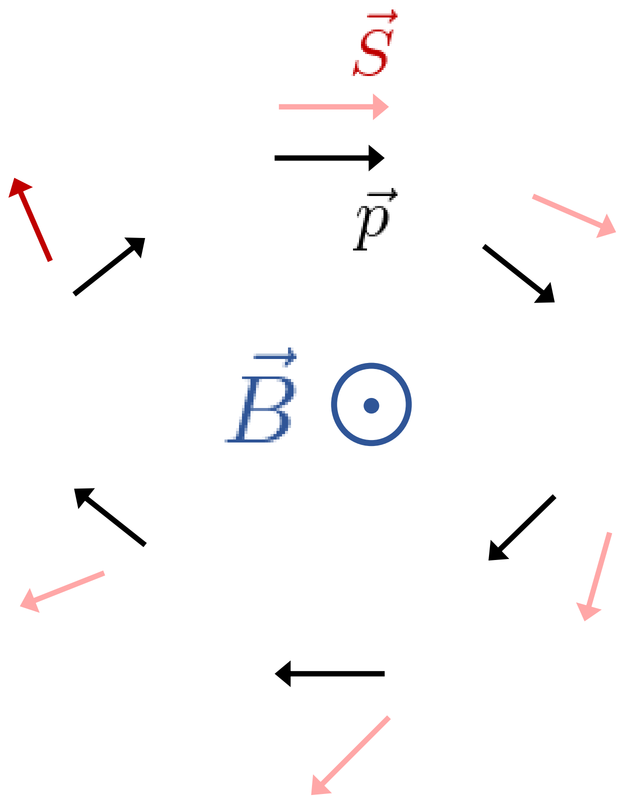


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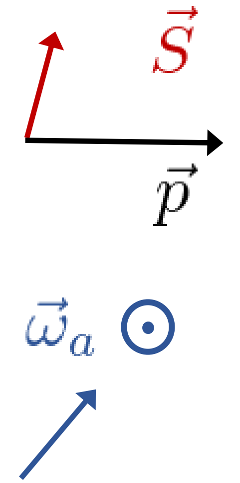


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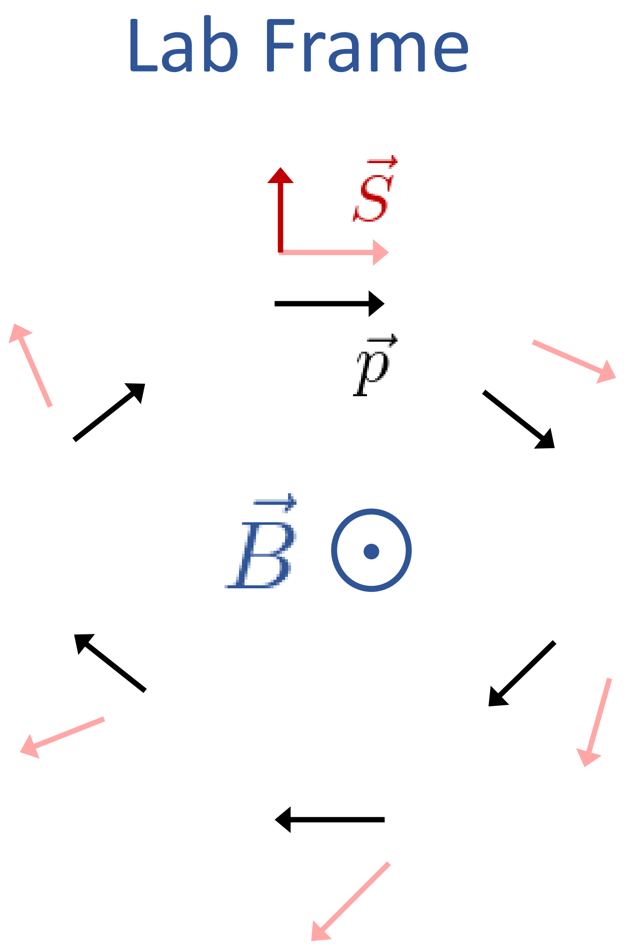


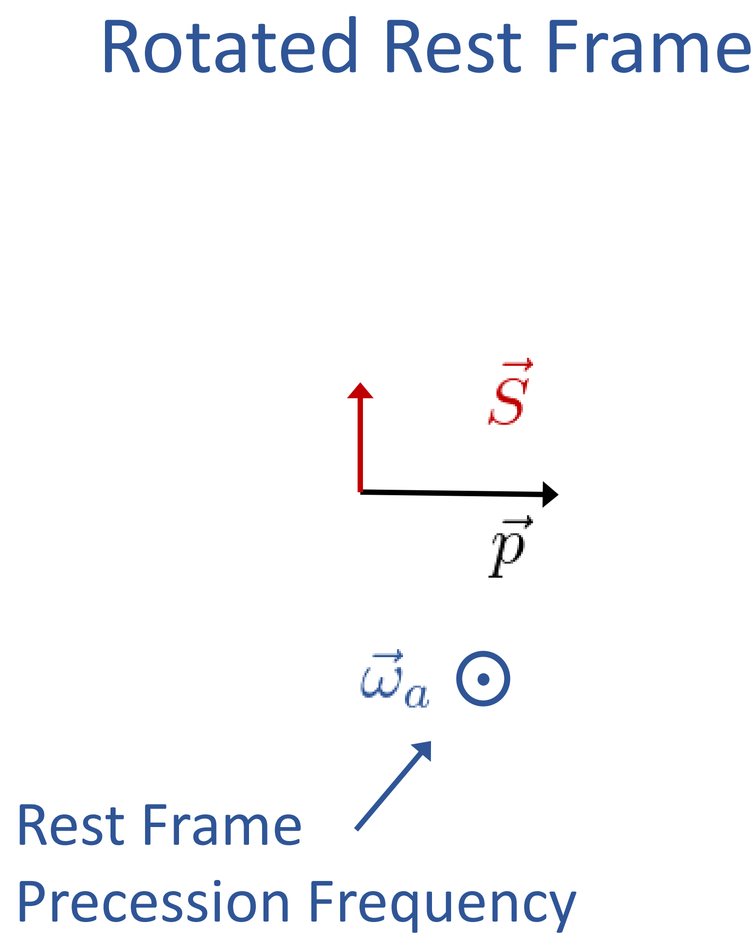


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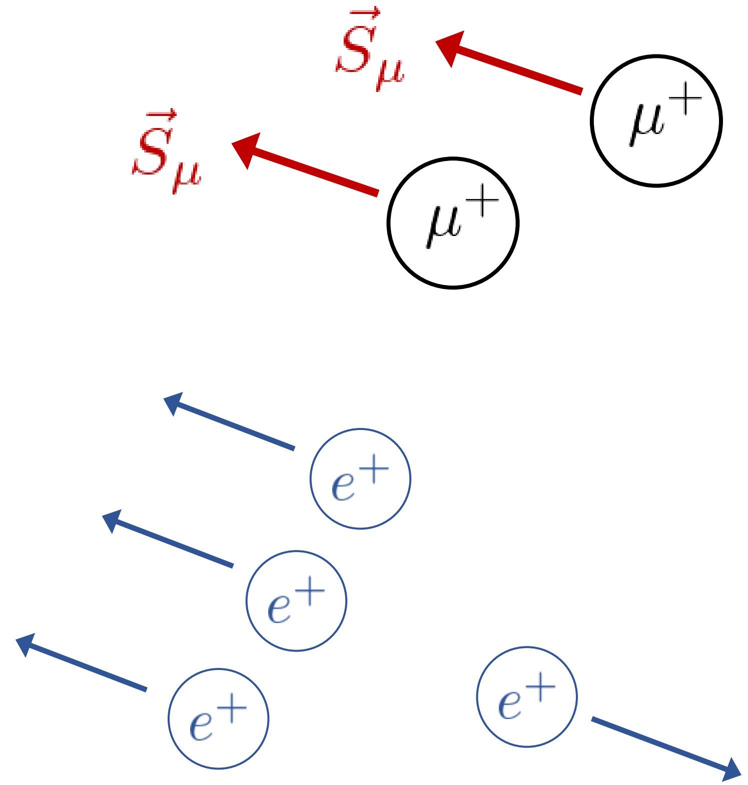
# Tracking Muon Spins

## Asymmetric Muon Decay

Positrons are preferentially emitted along the direction of the anti-muon spin.

Polarized muon bunch

Positron flux

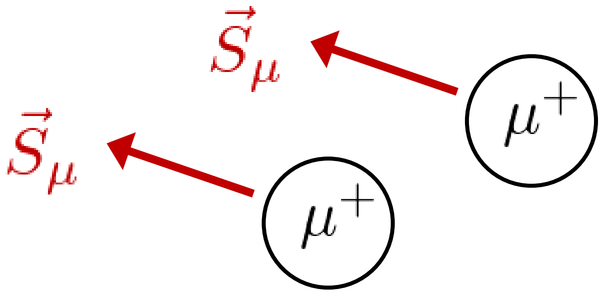


# Tracking Muon Spins

## Energy is a proxy for direction

The most energetic positrons are those emitted along the muon's momentum:

Polarized muon bunch

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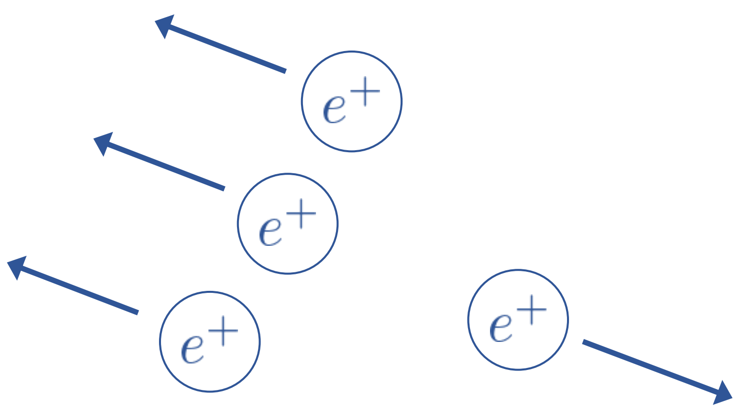

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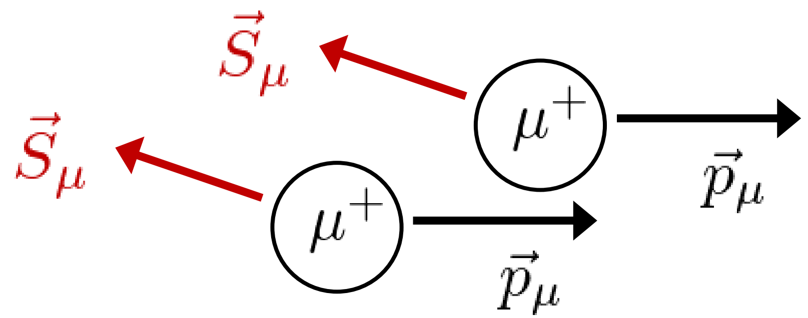
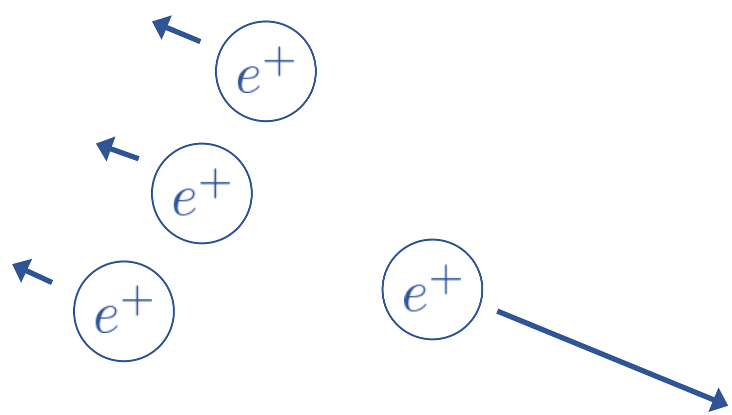



Positron flux

Few high energy positrons



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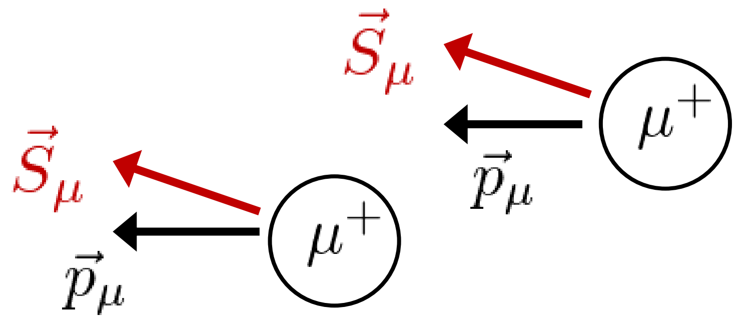


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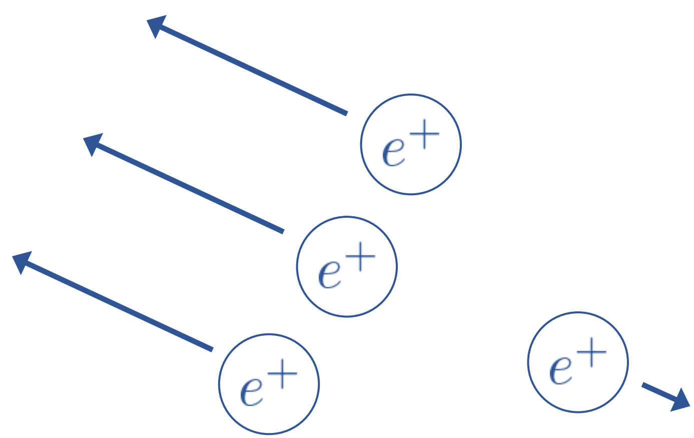


Many high energy positrons

# Momentum Count

The number of decay positions in the highest energy bin tracks the momentum-component of the muon spins:

$$N_T \propto \left(1 + \epsilon\, \vec{S} \cdot \vec{p}\right)$$

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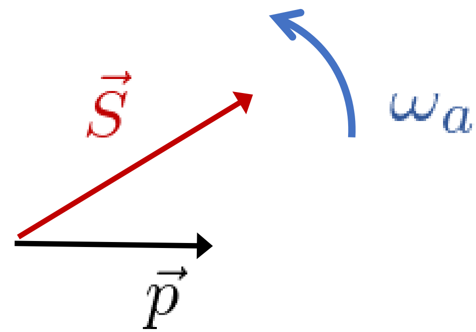
For SM precession:

(Rotated Rest Frame)

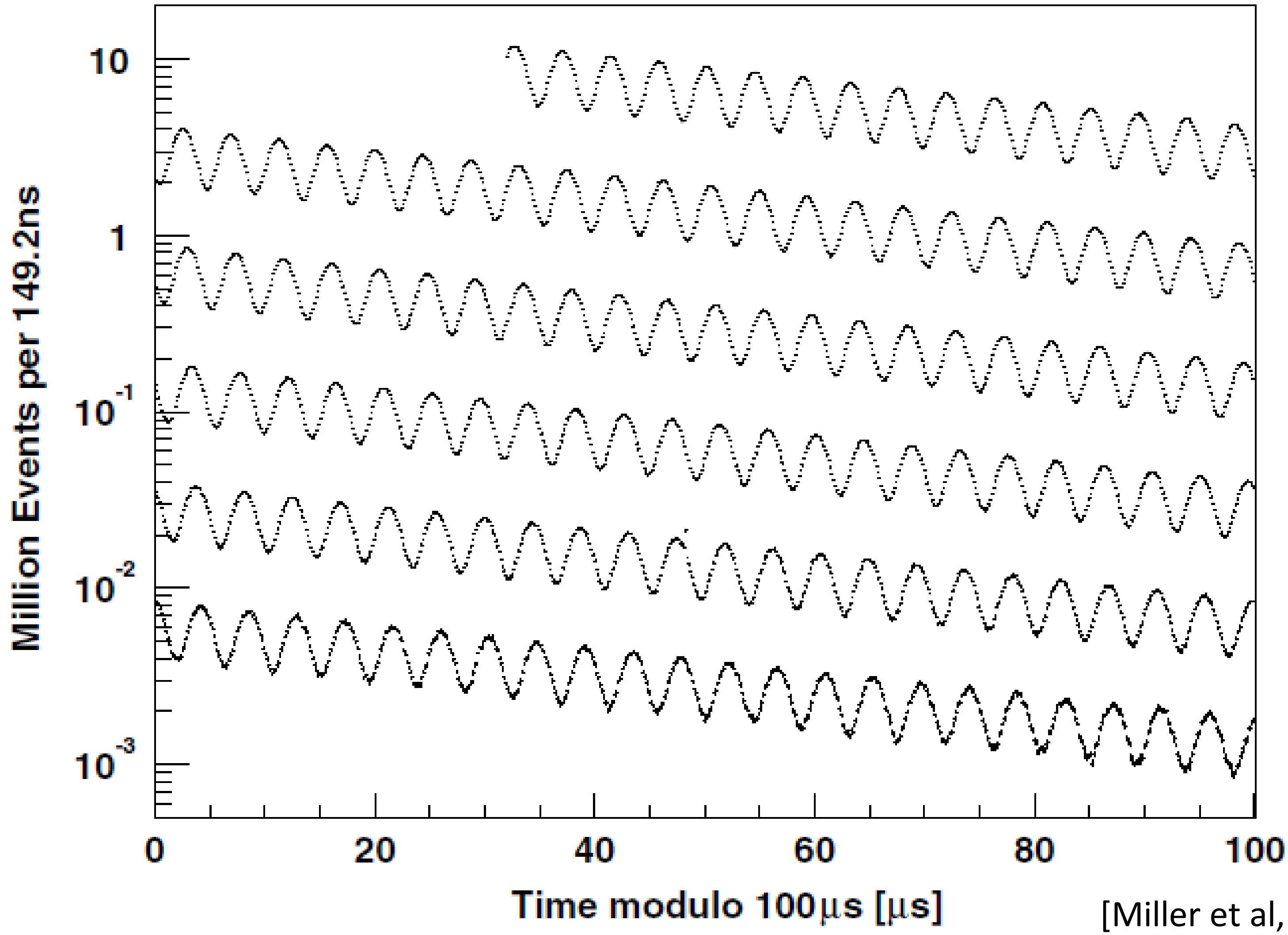



$$\vec{S} \cdot \vec{p} \propto \cos\left(\omega_a t\right)$$

$N_T$ oscillates at the rest-frame precession frequency.

# Momentum Count

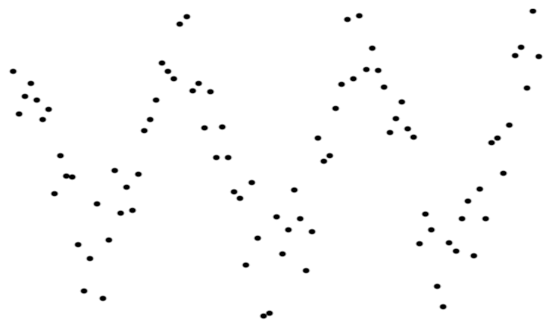
$N_T$ from BNL g-2 (3.6 billion detected positrons)




[Miller et al, 0703049]

# Stack and Fit

Bunch 1



Bunch 2

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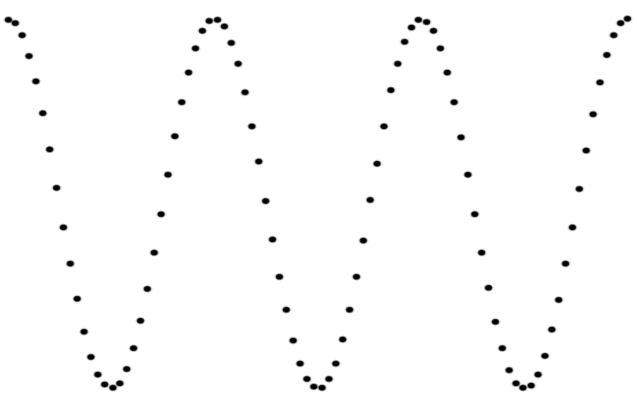
Align and sum $\approx 10^7$ bunches, collected over years.
(individual bunch data is retained)

Stacked



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Fit for frequency of stacked signal, this is $\omega_a$.

# g – 2 Precision

BNL results: $$\frac{\delta\omega_a}{\omega_a} \approx 0.5 \cdot 10^{-6}$$ [Bennet et al, 0602035]

$3.3\sigma$ deviation from SM prediction.

[Davier et al, 1908.00921]

Fermilab projections: $$\frac{\delta\omega_a}{\omega_a} \approx 10^{-7}$$ [Grange et al, 1501.06858]

J-PARC projections: $$\frac{\delta\omega_a}{\omega_a} \approx 10^{-7}$$ [Abe et al, 1909.03047]

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A moving electric dipole will precess in a magnetic field.  A muon EDM contributes to $\vec{\omega}_a$ as:

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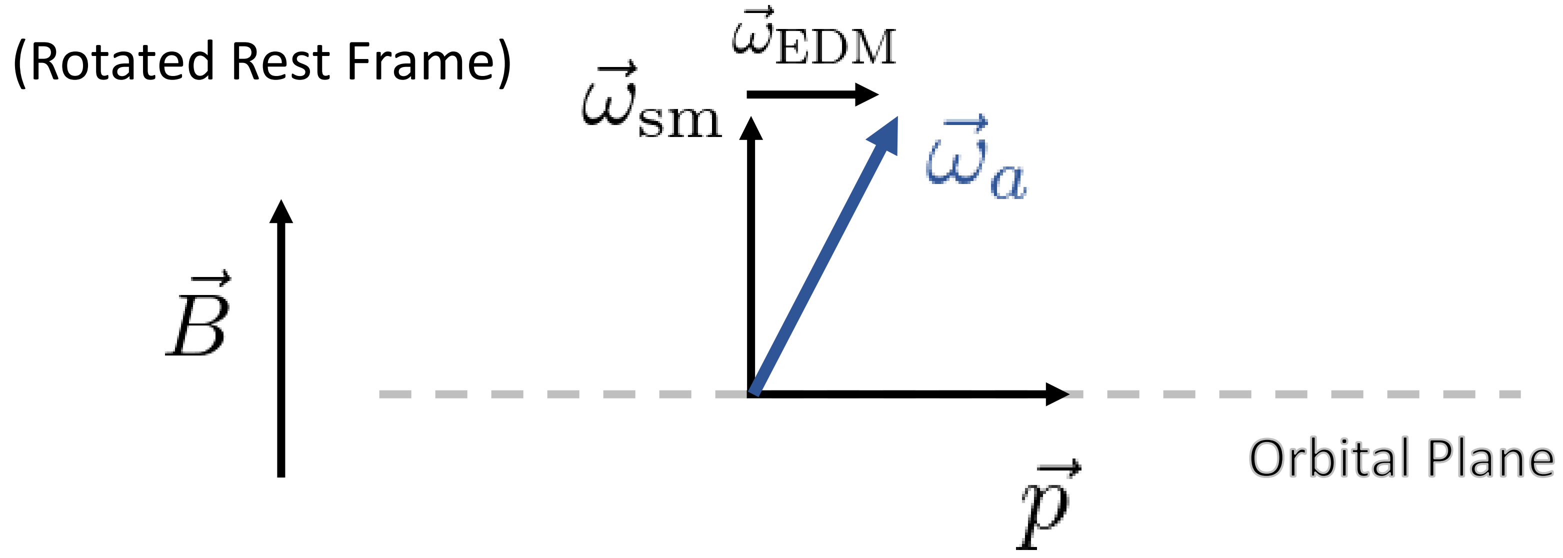

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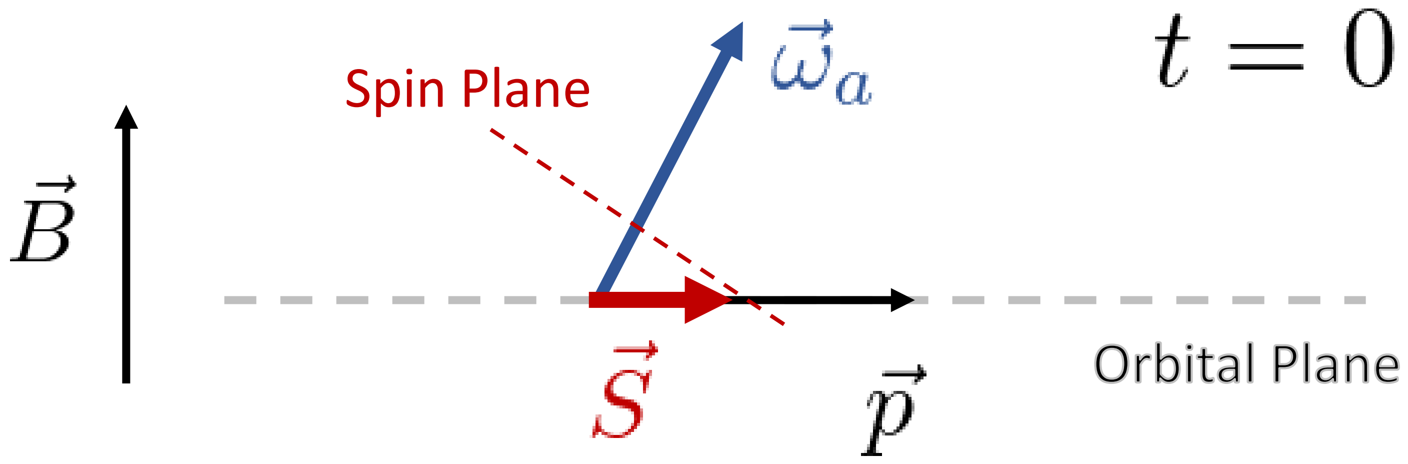

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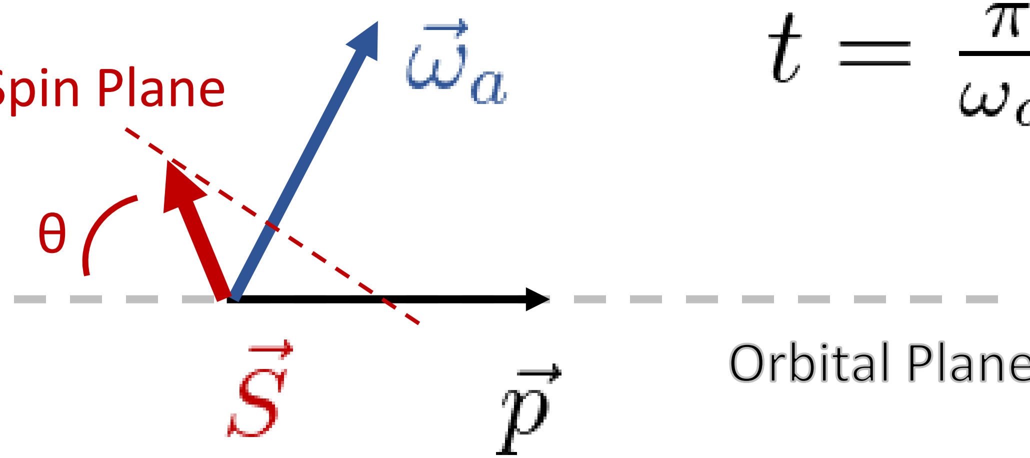
(Rotated Rest Frame)

$$t = \frac{\pi}{\omega_a}$$

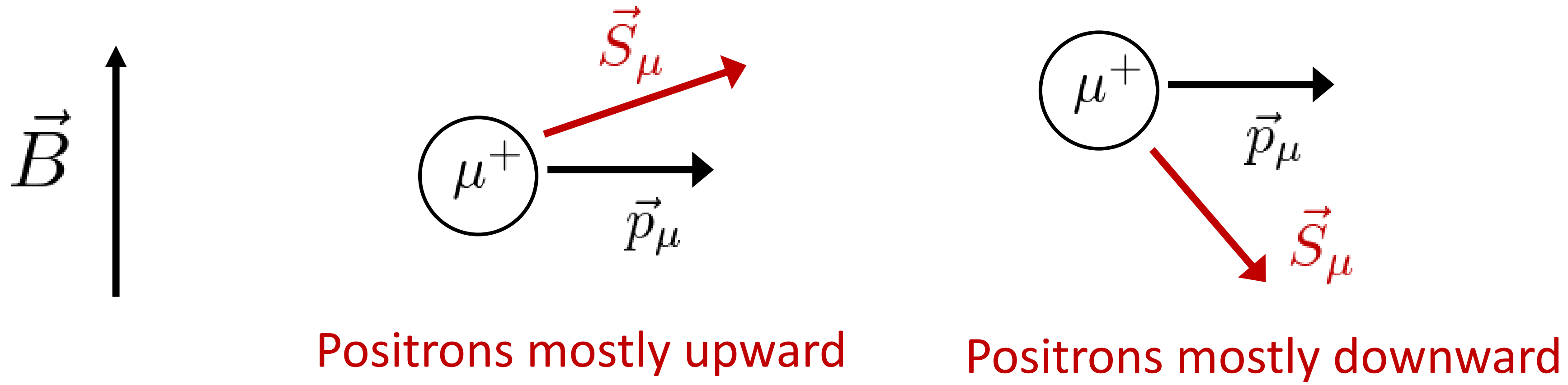
$$\theta \approx \frac{\omega_{\text{edm}}}{\omega_{\text{sm}}}$$



# Vertical Count

Detecting an EDM requires measuring upward vs downward moving positrons.

The momentum count is blind to this.




Measure the difference $\Delta N_B$ in the number of upward versus downward moving positrons:

$$\Delta N_B \propto \vec{S} \cdot \vec{B}$$

# Vertical Count

$$\vec{\omega}_{\mathrm{EDM}} = -2\, d_e \left(\vec{v} \times \vec{B}\right)$$

The momentum and vertical components of spin are:

$$\vec{S} \cdot \hat{p} = S_0 \cos\left(\omega_a t\right)$$

Phase shift between momentum and vertical counts.

$$\vec{S} \cdot \hat{B} = S_0 \frac{\omega_{\mathrm{edm}}}{\omega_{\mathrm{sm}}} \sin\left(\omega_a t\right)$$

$$\omega_a = \sqrt{\omega_{\mathrm{sm}}^2 + \omega_{\mathrm{edm}}^2}$$

Net increase in momentum count frequency – mimics anomaly.

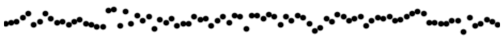
# Stack and Fit

Vertical Count, Bunch 1

Vertical Count, Bunch 2

Sum all bunches

Vertical Count, Stacked



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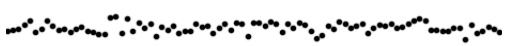

Momentum Count, Stacked

Fit stacked momentum count

$\omega_a, \ \phi_a$

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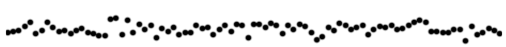
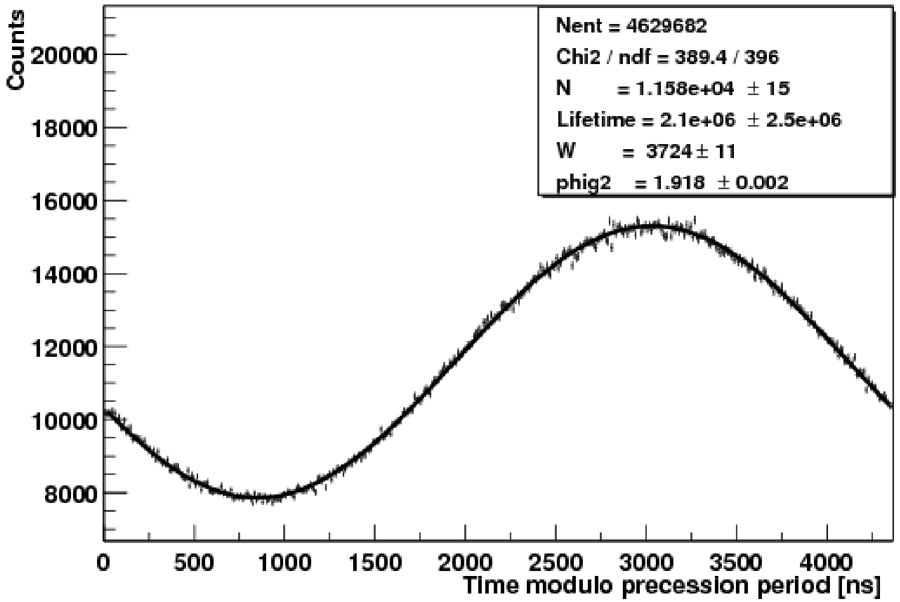


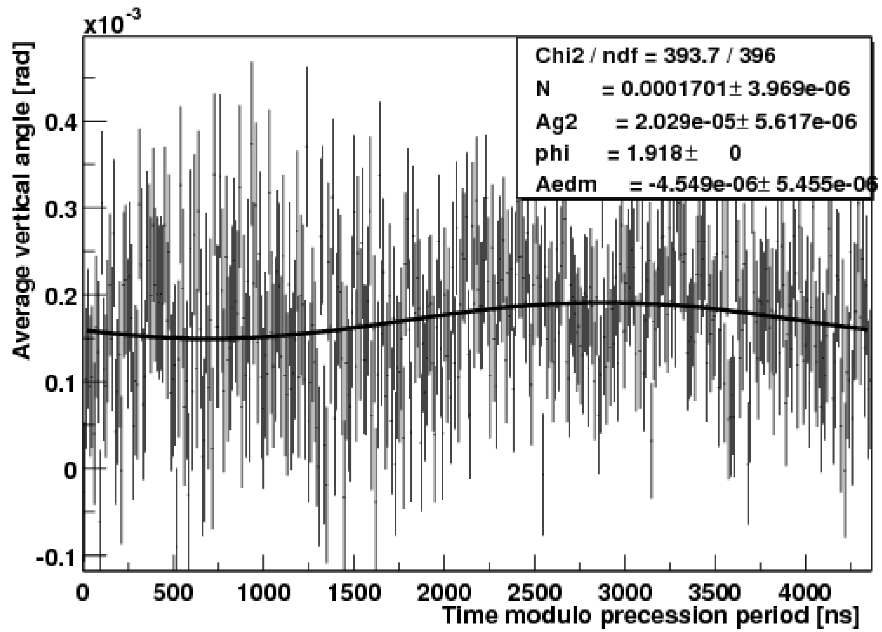
$\omega_a,\ \phi_a$

Fit stacked vertical count to: $A \sin\left(\omega_a t + \phi_a\right)$

# Stack and Fit

## BNL stacked momentum and vertical counts:




[Bennett et al, 0811.1207]

# Frozen Spin

A dedicated EDM search would do best by minimizing $\omega_{\rm sm}$ .

Choose laboratory EM fields to set $\omega_{\rm sm} = 0$ .

[Adelmann et al, 0606034]

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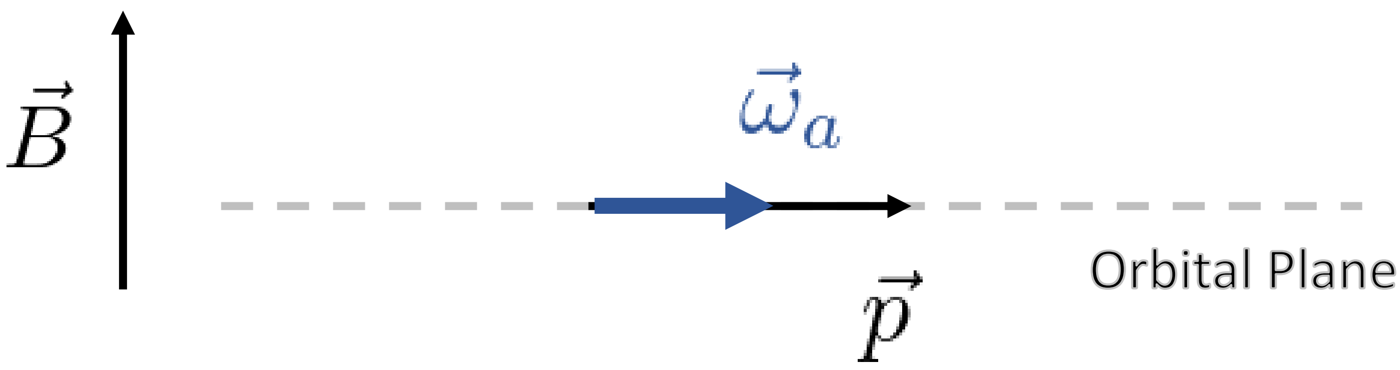

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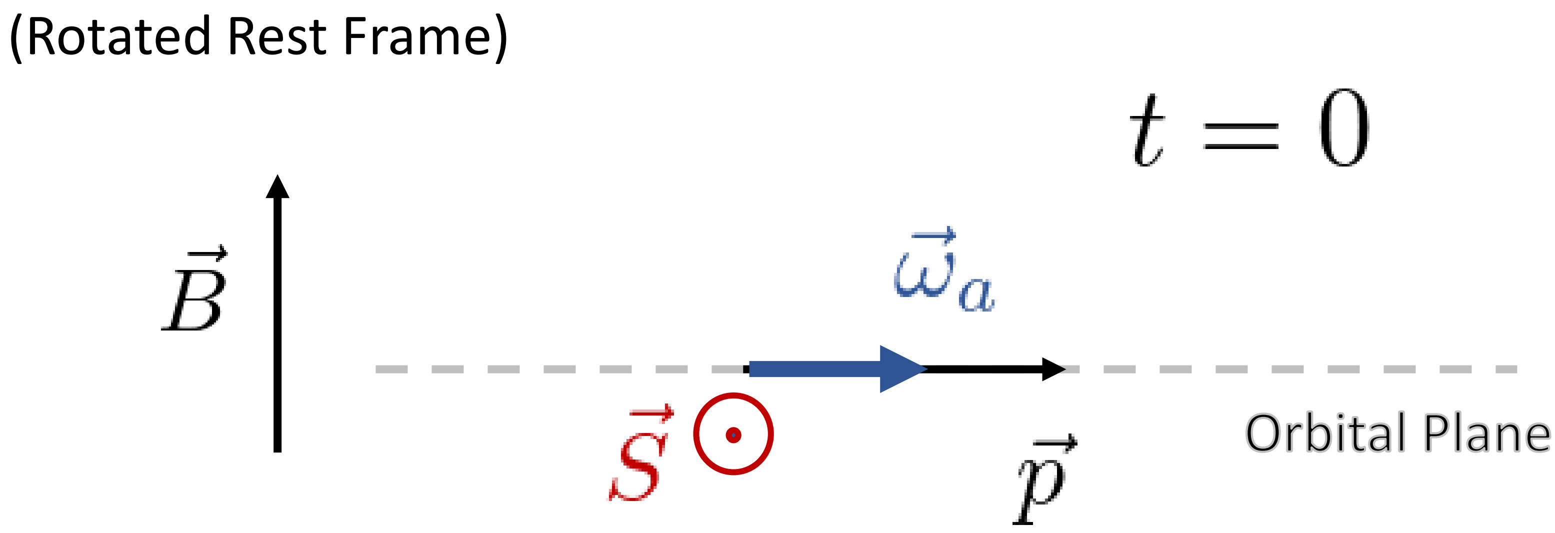

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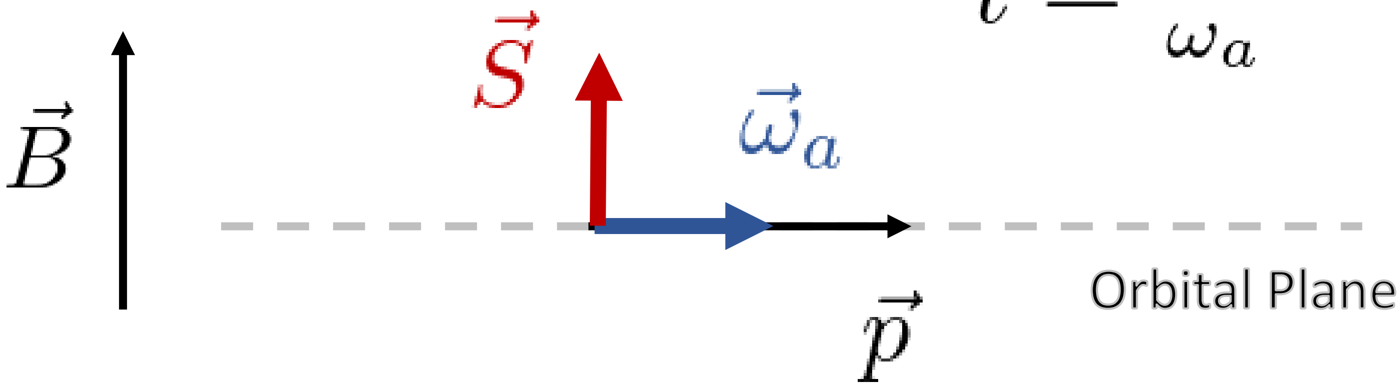


Vertical Count: $\vec{S} \cdot \hat{B} = S_0 \cos\left(\omega_{\rm edm} t\right) \approx S_0\, \omega_{\rm edm} t$

# EDM Precision

BNL: $\frac{\omega_\perp}{\omega_a} \gtrsim 5 \cdot 10^{-4}$

BNL null result limits the muon EDM to a value slightly too small $(4\sigma)$ to explain the total precession anomaly: $|d_e| < 1.9 \cdot 10^{-19}\, e\,\mathrm{cm}$

[Bennett et al, 0811.1207]

Fermilab and J-PARC projection: $\frac{\omega_\perp}{\omega_a} \gtrsim 5 \cdot 10^{-6}$

[Grange et al, 1501.06858]

[Abe et al, 1909.03047]

Frozen spin projection: $\frac{\omega_\perp}{\omega_\mathrm{a}} \gtrsim 10^{-9}$

[Adelmann et al, 0606034]

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# DM-perturbed Spin Precession

In a muon rest frame, the spin evolves according to:

$$\dot{\vec{S}} = \vec{\omega}_a(t) \times \vec{S}$$

SM precession:

$$\vec{\omega}_a(t) = -\frac{e}{m_\mu} a_\mu \vec{B} \equiv \vec{\omega}_{sm}, \quad a_\mu = \frac{1}{2}\left(g_\mu - 2\right)$$

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Effect of DM background:

$$\vec{\omega}_a(t) = \vec{\omega}_{\rm sm} + \vec{\omega}_{\rm dm}(t)$$

Momentum count measures $|\vec{\omega}_a(t)|$

Vertical count measures $\vec{\omega}_{\rm dm}(t) \perp \vec{\omega}_{\rm sm}$

# Ultralight Bosonic DM

DM is manifest locally as a AC classical background field

$$\phi(t) = \phi_0 \cos(m_{\rm dm} t)$$

Amplitude is set by the local DM energy density (and DM mass for scalars)

Oscillation frequency is the DM mass

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Amplitude is set by the local DM energy density (and DM mass for scalars)

Oscillation frequency is the DM mass

Expect $\vec{\omega}_{\mathrm{dm}}(t)$ to be time-dependent.

DC signals do arise from observables which depend on $\phi^2$.

# Ultralight Bosonic DM

DM is manifest locally as a AC classical background field

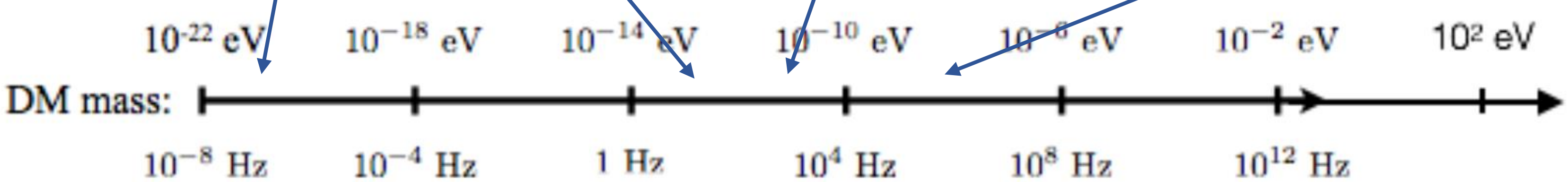
$$\phi(t) = \phi_0 \cos(m_{\mathrm{dm}} t)$$

$10^{-21}$ eV = 1 year

$10^{-13}$ eV = fill rate

$10^{-11}$ eV = bunch duration

$10^{-9}$ eV = $\omega_a$



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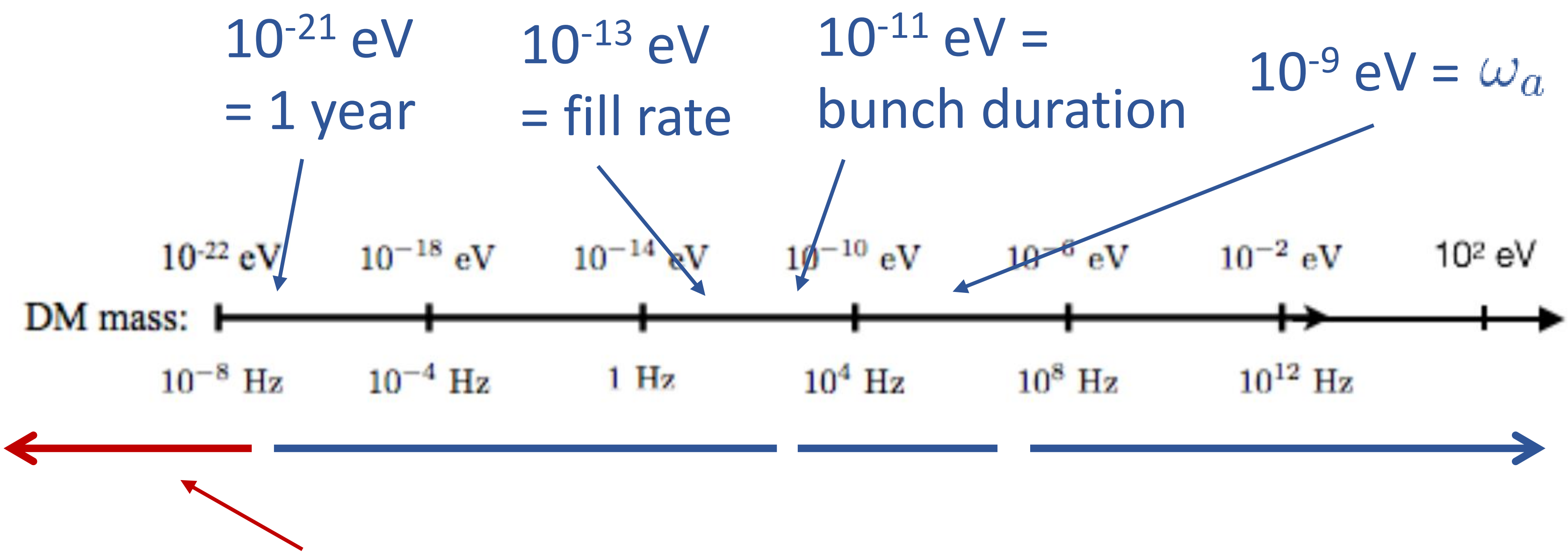


DM field is effectively static.

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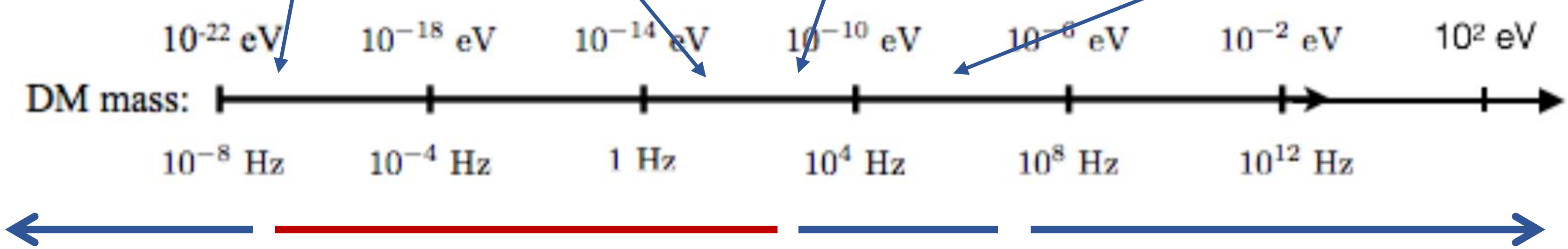


DM field is static over each bunch, but oscillates many times over the lifetime of the experiment.

# Ultralight Bosonic DM

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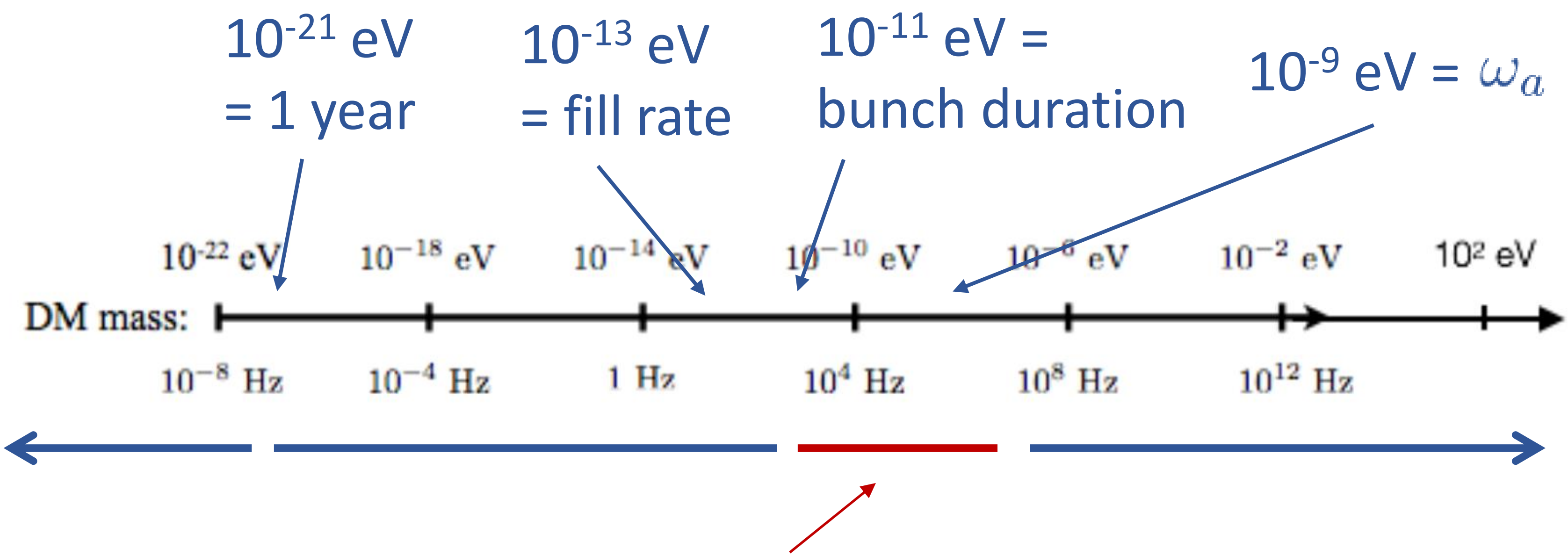


DM field oscillates within each bunch.

# Ultralight Bosonic DM

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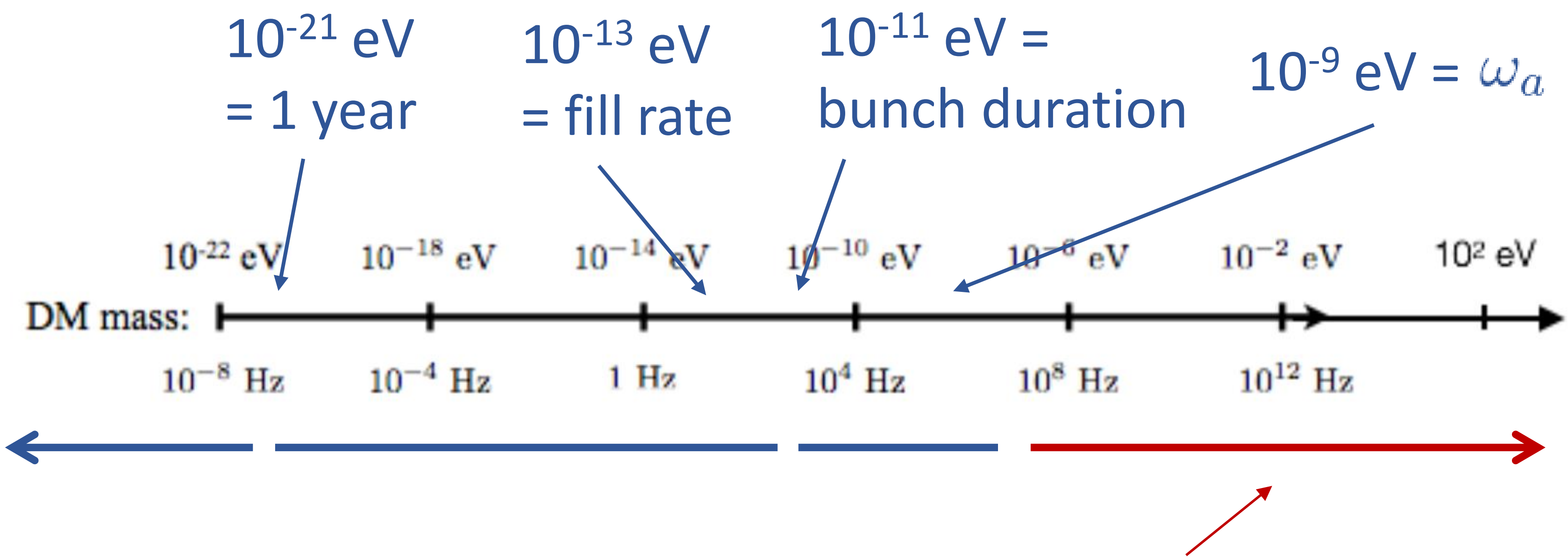


DM field oscillates faster than the SM precession.
Signal is suppressed here and mimics known systematics.

# Ultralight Bosonic DM

DM is manifest locally as a AC classical background field

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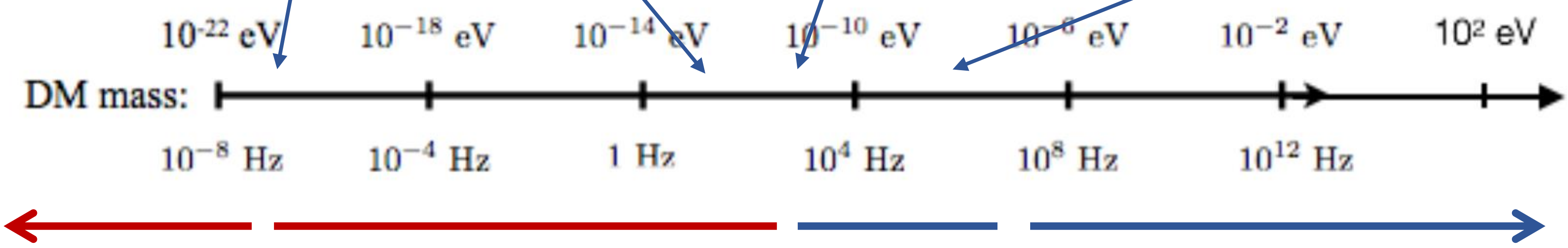


Focus of this work.

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$$\mathcal{L} \supset y\,\phi\bar{\mu}\mu$$

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DM background field is:

$$\phi(t) = \sqrt{\frac{2\rho_{\rm dm}}{m_\phi}}\cos\left(m_\phi t\right)$$

DM field generates a time-varying muon mass and MDM:

$$m(t) = m_\mu + y\phi(t)$$

$$\vec{\mu} = \frac{e\,g_\mu}{2\,m(t)}\,\vec{S}$$

# A Scalar DM Precession Signal

Rest frame precession frequency:

$$\vec{\omega}_a(t) = -\frac{e}{m(t)} a_\mu \vec{B}$$

$$\approx \vec{\omega}_{\rm sm}\left[1 - \frac{y}{m_\mu}\sqrt{\frac{2\rho_{\rm dm}}{m_\phi}}\cos\left(m_\phi t\right)\right]$$

Solve the precession equation:

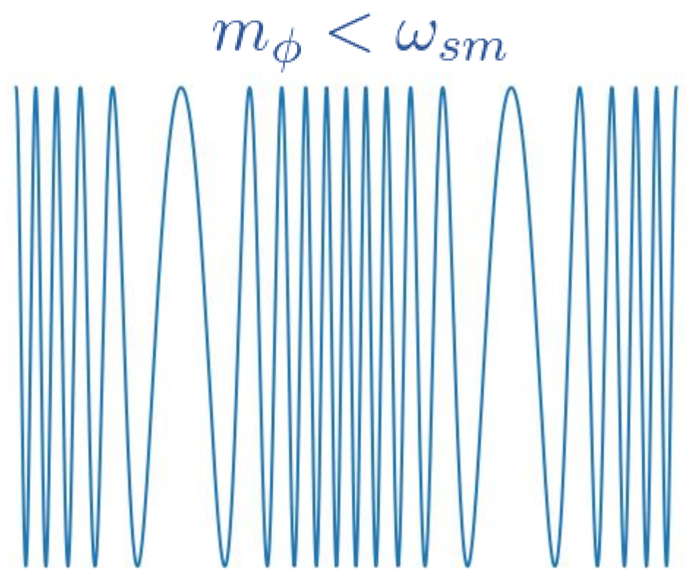
Spin precesses about $\hat{B}$ with an instantaneous angular frequency $|\vec{\omega}_a(t)|$.

# Frequency Modulation

Vertical count vanishes as in SM.

Momentum count exhibits has frequency modulation:

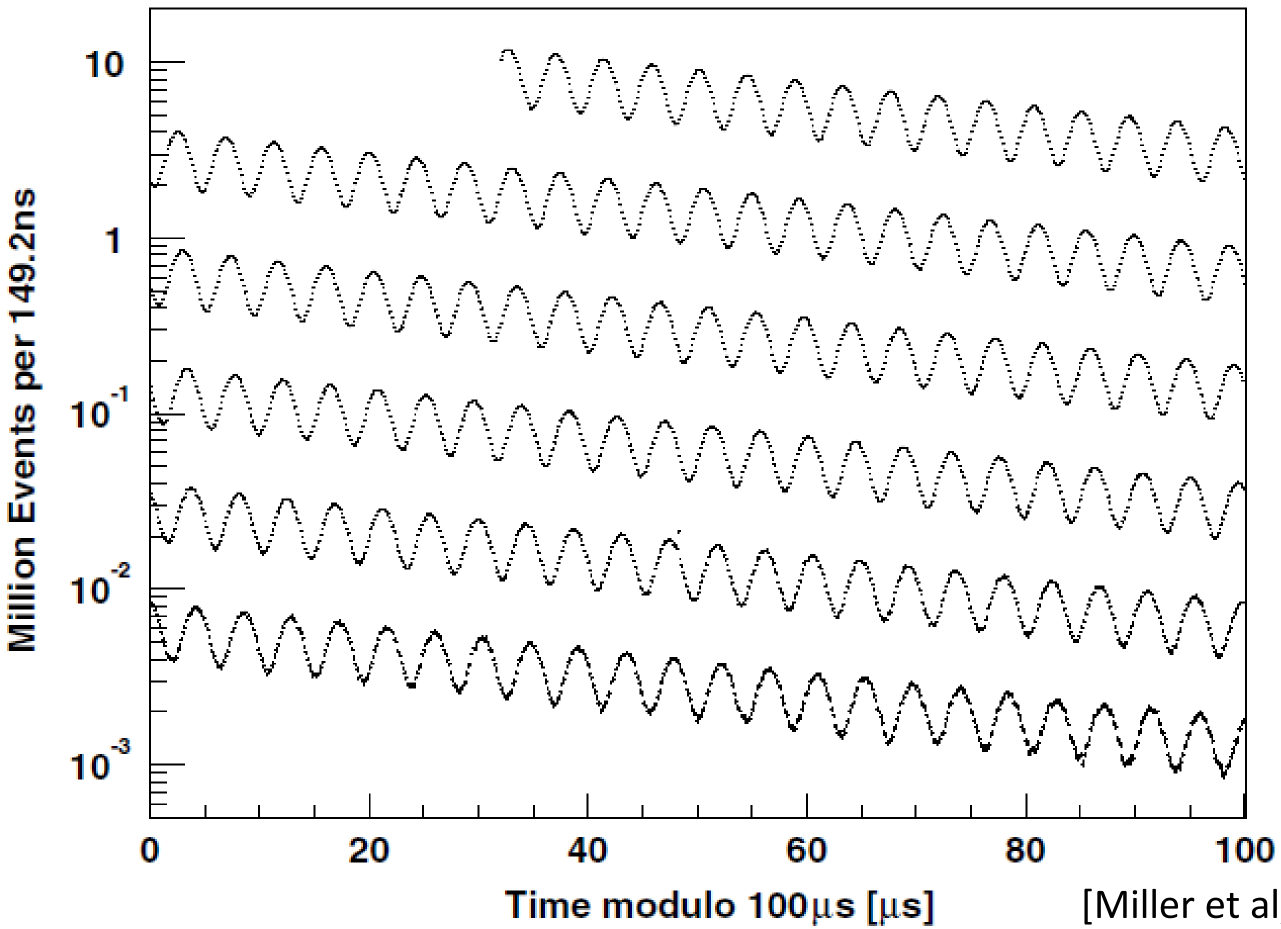
$$\vec{S} \cdot \vec{p} = S_0 \cos\left[\omega_{\mathrm{sm}} t + \frac{\omega_{\mathrm{dm}}}{m_\phi} \sin\left(m_\phi t\right)\right]$$




Gradual drift in the local precession frequency

# Stacking of the FM DM Signal

Could FM precession be hiding in the g-2 data?




[Miller et al, 0703049]

# Stacking of the FM DM Signal

Could FM precession be hiding in the g-2 data?

Yes - stacking averages away the modulation.

The stacked data is a sum of cosines at different frequencies:

$$S_p \sim \left(\text{oscillation at } \langle\omega(t)\rangle\right) \cdot \left(\text{envelope with scale } \sigma_{\omega(t)}\right)$$

Small deviation from the SM value

$$\langle\omega(t)\rangle \sim \omega_{\rm sm} + \omega_{\rm dm}\frac{1}{\sqrt{N_{\rm bunches}}}$$

Envelop is nearly flat over each bunch

$$\sim \left(1 - \omega_{\rm dm}^2 t^2\right)$$

# Time-Resolved Frequency Tracking

## Can we detect FM precession?

Yes – use archived data to measure the precession frequency as a function of time.

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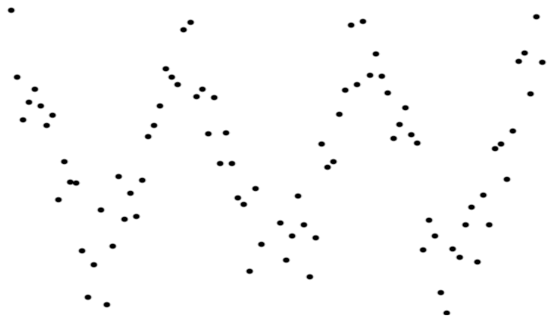
Bunch 1



Bunch 2

Individually fit each bunch

Time series $\omega_a(t)$

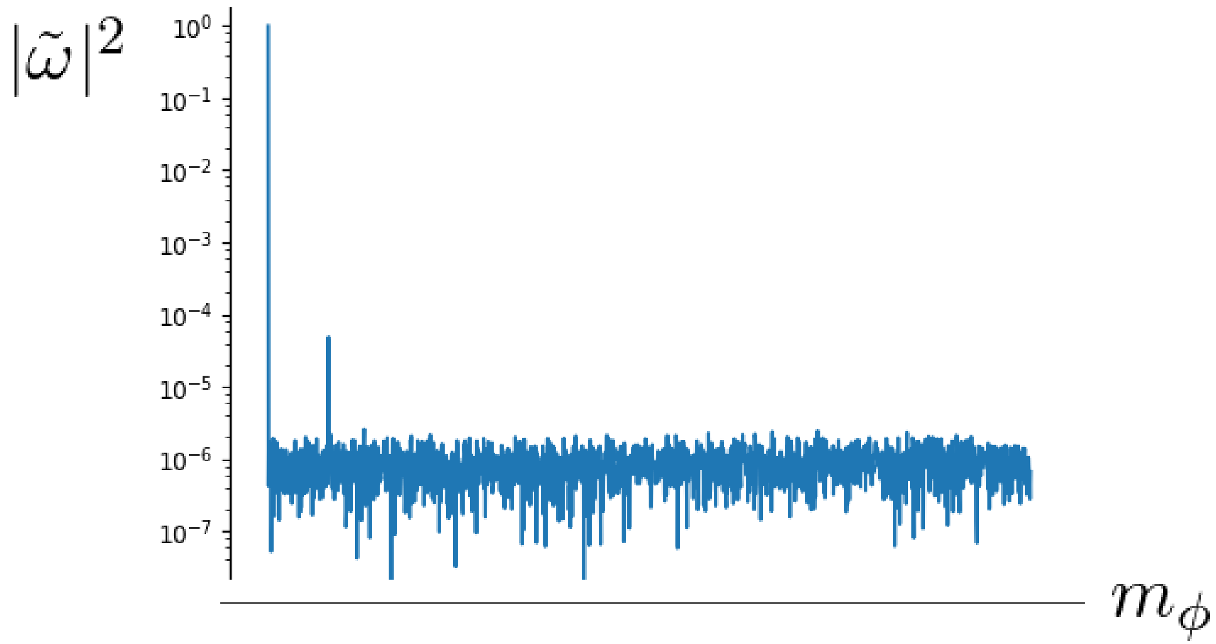
$10^6$ data points

Noise:

$$\sigma_\omega \approx 10^{-3}\omega_{sm}$$

# Time-Resolved Frequency Tracking

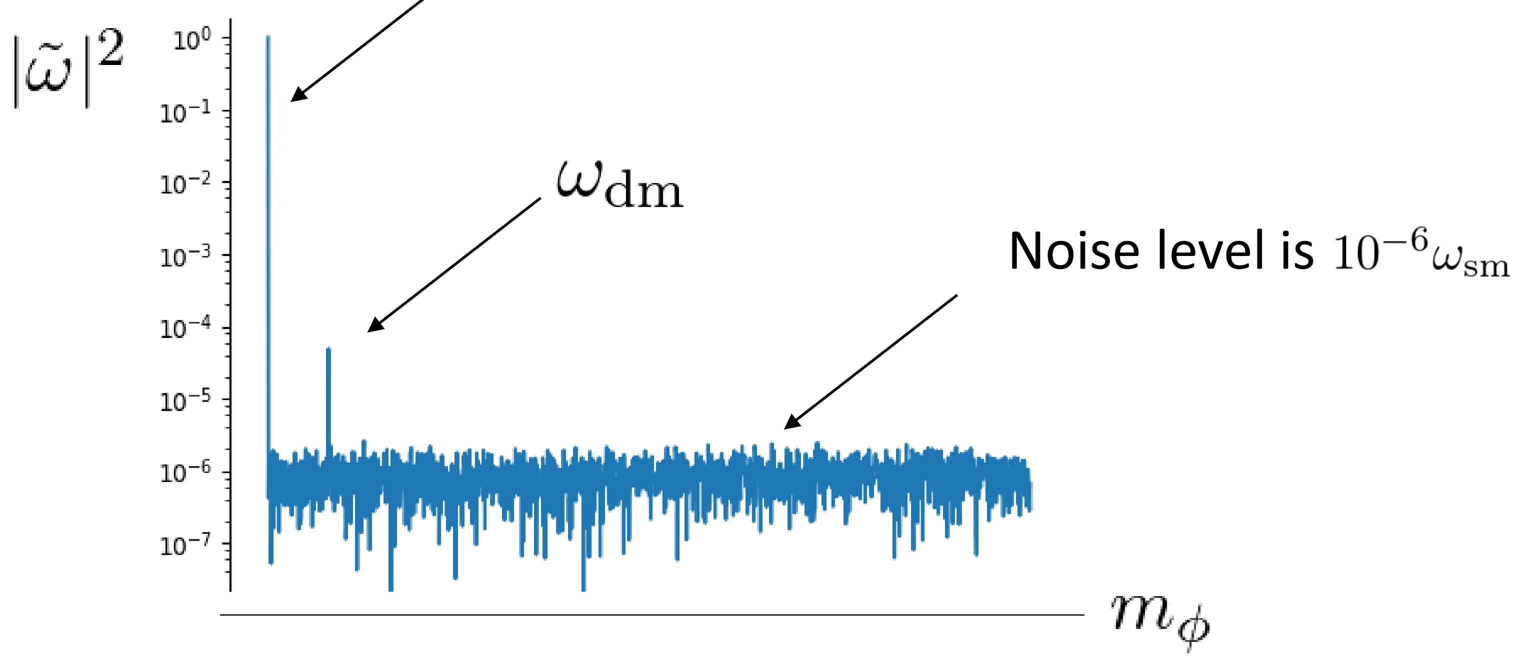
Fourier transform of $\omega_a(t)$:



# Time-Resolved Frequency Tracking

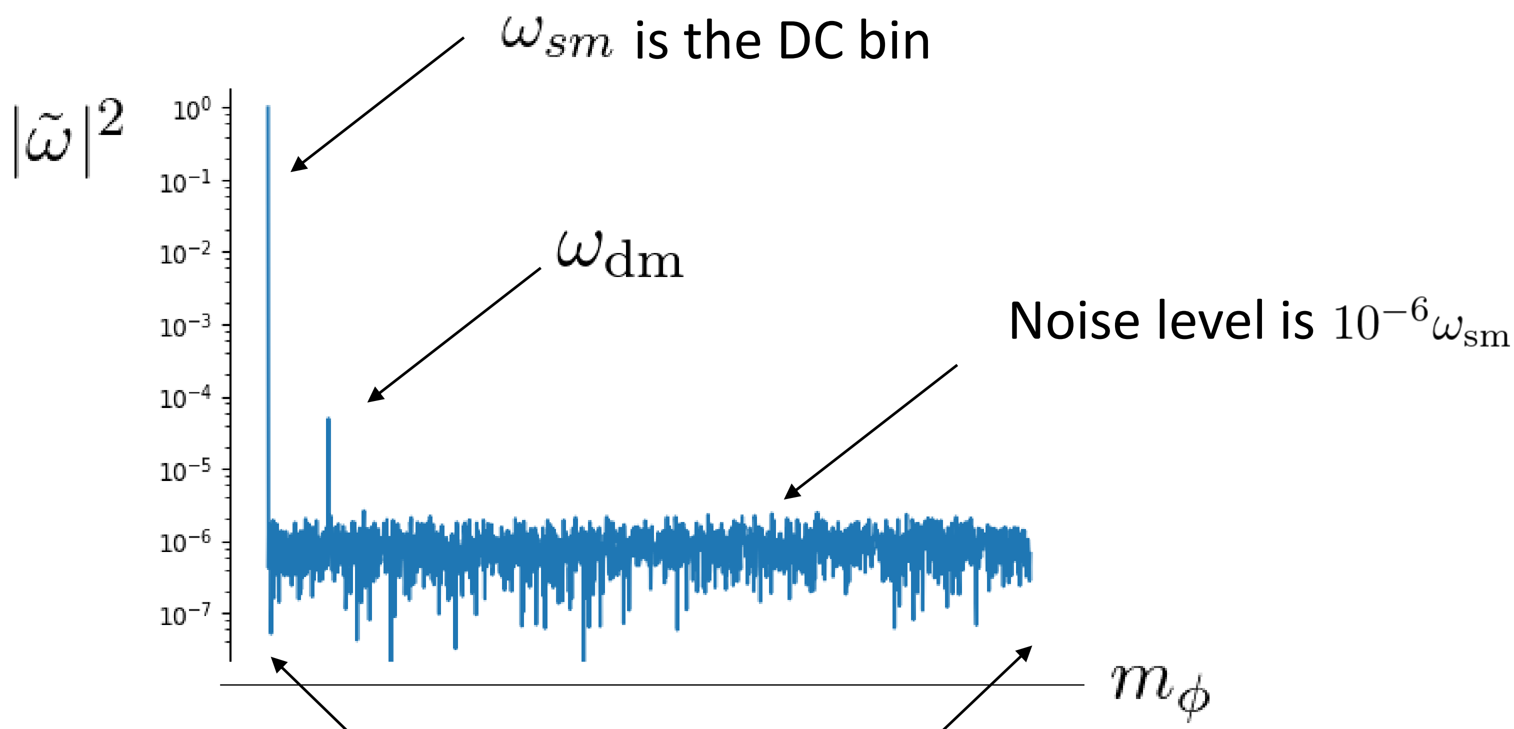
Fourier transform of $\omega_a(t)$:

$\omega_{sm}$ is the DC bin



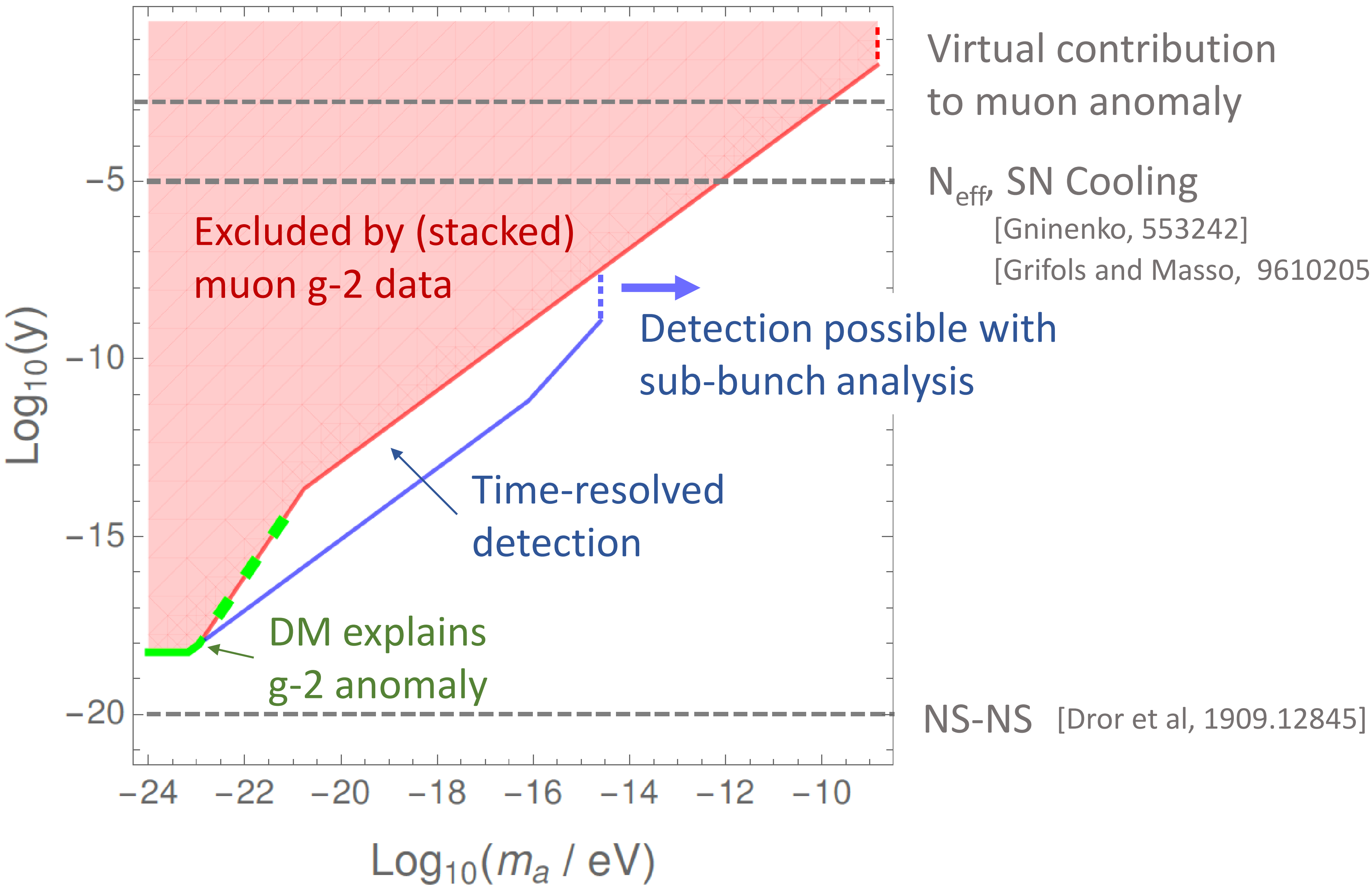
# Time-Resolved Frequency Tracking

## Fourier transform of $\omega_a(t)$:




$$10^{-23}\,\mathrm{eV} \sim \frac{1}{T_{\mathrm{run}}} < m_\phi < \frac{N_{\mathrm{bunches}}}{T_{\mathrm{run}}} \sim 10^{-15}\,\mathrm{eV}$$

# Detection Reach for DM-Muon Yukawa



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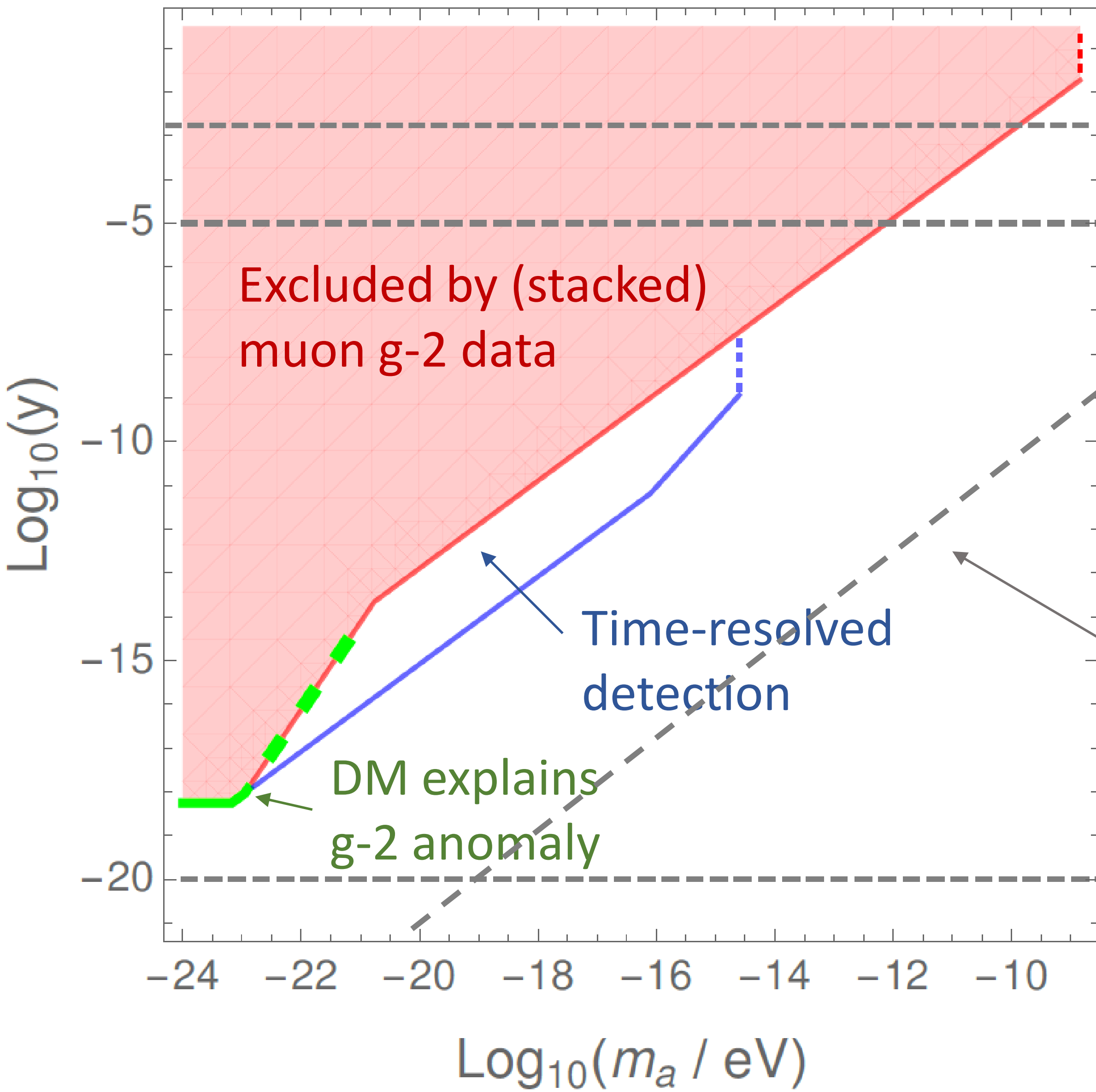


Virtual contribution to muon anomaly

$N_{eff}$, SN Cooling
[Gninenko, 553242]
[Grifols and Masso, 9610205]

Atomic clock $\phi F F$
[Arvanitaki et al, 1405.2925]

NS-NS [Dror et al, 1909.12845]

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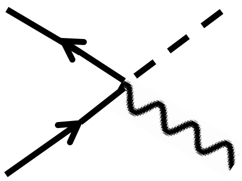
# A DM EDM Signal

Pseudoscalar DM of mass $m_a$ with an EDM interaction:

$$\mathcal{L} \supset -\frac{i}{2} g \, a \, \bar{\mu} \, \sigma_{\alpha\beta} \, \gamma_5 \, \mu \, F^{\alpha\beta}$$



DM field generates an time-varying EDM for the muon. The precession frequency is:

$$\vec{\omega}_a = \omega_{sm} \hat{B} + \omega_{dm} \cos\left(m_a t\right) \left(\hat{p} \times \hat{B}\right)$$

$$\omega_{dm} = 2g \frac{\sqrt{2\rho_{dm}}}{m_a} v_\mu B$$

# A DM EDM Signal

$$\mathcal{L} \supset -\frac{i}{2} g\, a\, \bar{\mu}\, \sigma_{\alpha\beta}\, \gamma_5\, \mu\, F^{\alpha\beta},$$

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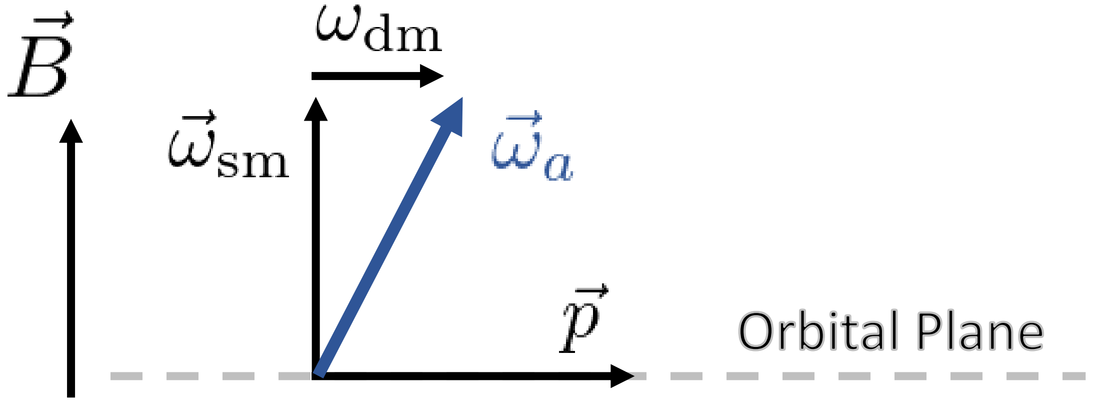

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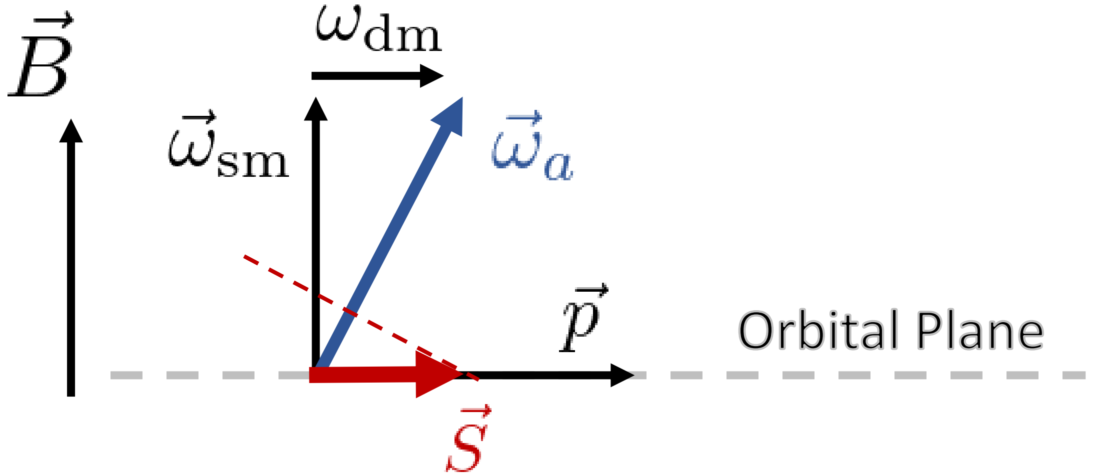

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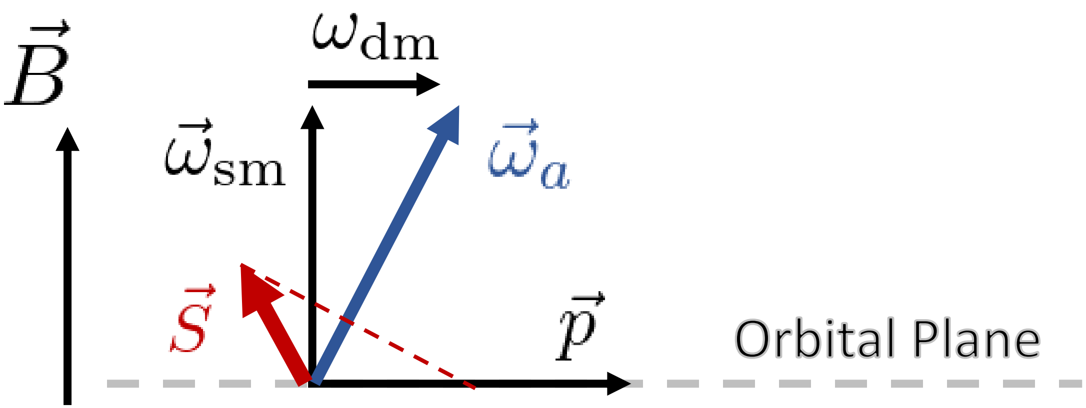

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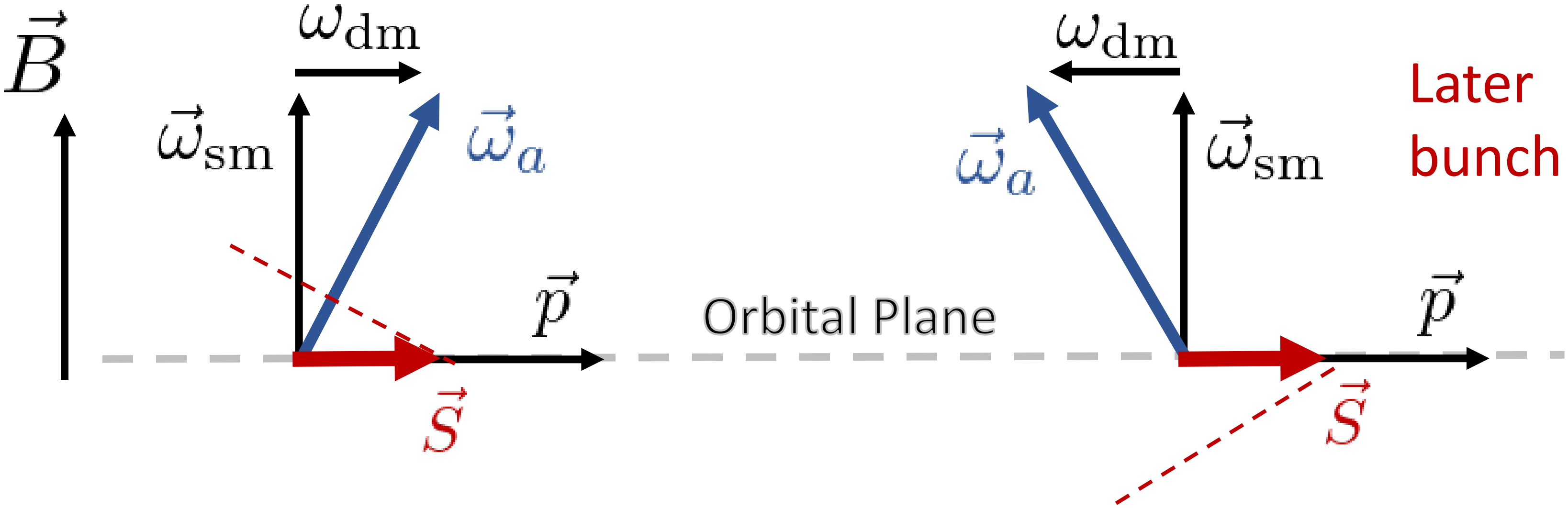

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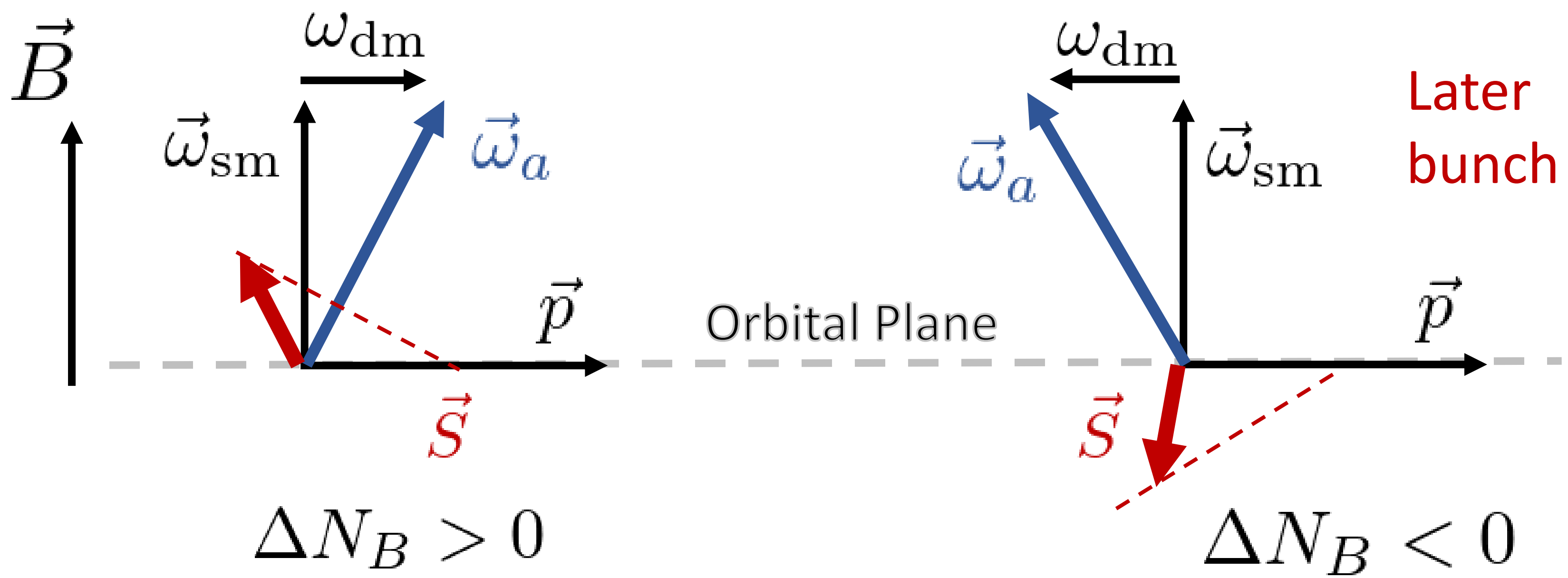


Vertical count has amplitude modulation

$$\vec{S} \cdot \hat{B} = S_0 \frac{\omega_{\rm dm}}{\omega_{\rm sm}} \cos\left(m_{\rm dm} t\right) \sin\left(\omega_a t\right)$$

# A DM EDM Signal

$$\mathcal{L} \supset -\frac{i}{2} g\, a\, \bar{\mu}\, \sigma_{\alpha\beta}\, \gamma_5\, \mu\, F^{\alpha\beta}, \qquad \omega_{dm} = 2g \frac{\sqrt{2\rho_{dm}}}{m_a} v_\mu B$$

Momentum count has frequency modulation and a shift.

Spin precesses with an instantaneous angular frequency $|\vec{\omega}_a(t)|$:

$$|\vec{\omega}_a(t)| = \sqrt{\omega_{\rm sm}^2 + \omega_{\rm dm}^2(t)} \approx \omega_{\rm sm} + \frac{1}{2} \frac{|\omega_{\rm dm}|^2}{\omega_{\rm sm}} \cos^2\left(m_{\rm dm} t\right)$$

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$$= \left(\omega_{\rm sm} + \frac{1}{4}\frac{|\omega_{\rm dm}|^2}{\omega_{\rm sm}}\right) + \frac{1}{4}\frac{|\omega_{\rm dm}|^2}{\omega_{\rm sm}} \cos(2 m_{\rm dm} t)$$

Positive frequency shift – explains g-2 anomaly

Frequency modulation

# Time-Resolved Amplitude Tracking

Can we reveal AM in the vertical counts, analogous to the FM precession in the momentum counts?

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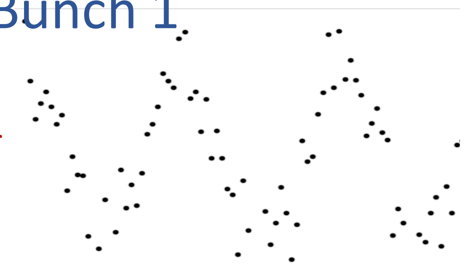
Momentum Count, Bunch 1



Fit each momentum count

$\omega_a(t),\ \phi_a(t)$

Vertical Count, Bunch 1

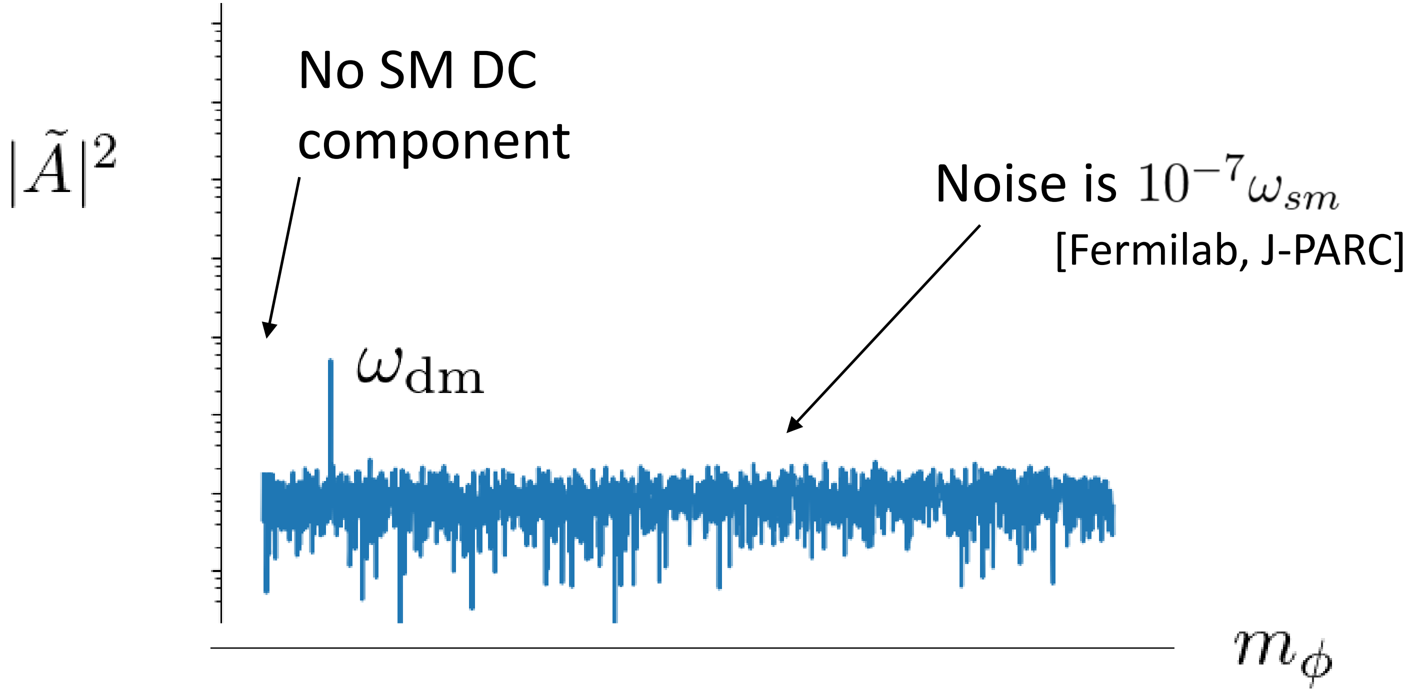
Fit corresponding vertical count to: $A \sin\left(\omega_a t + \phi_a\right)$

Time series

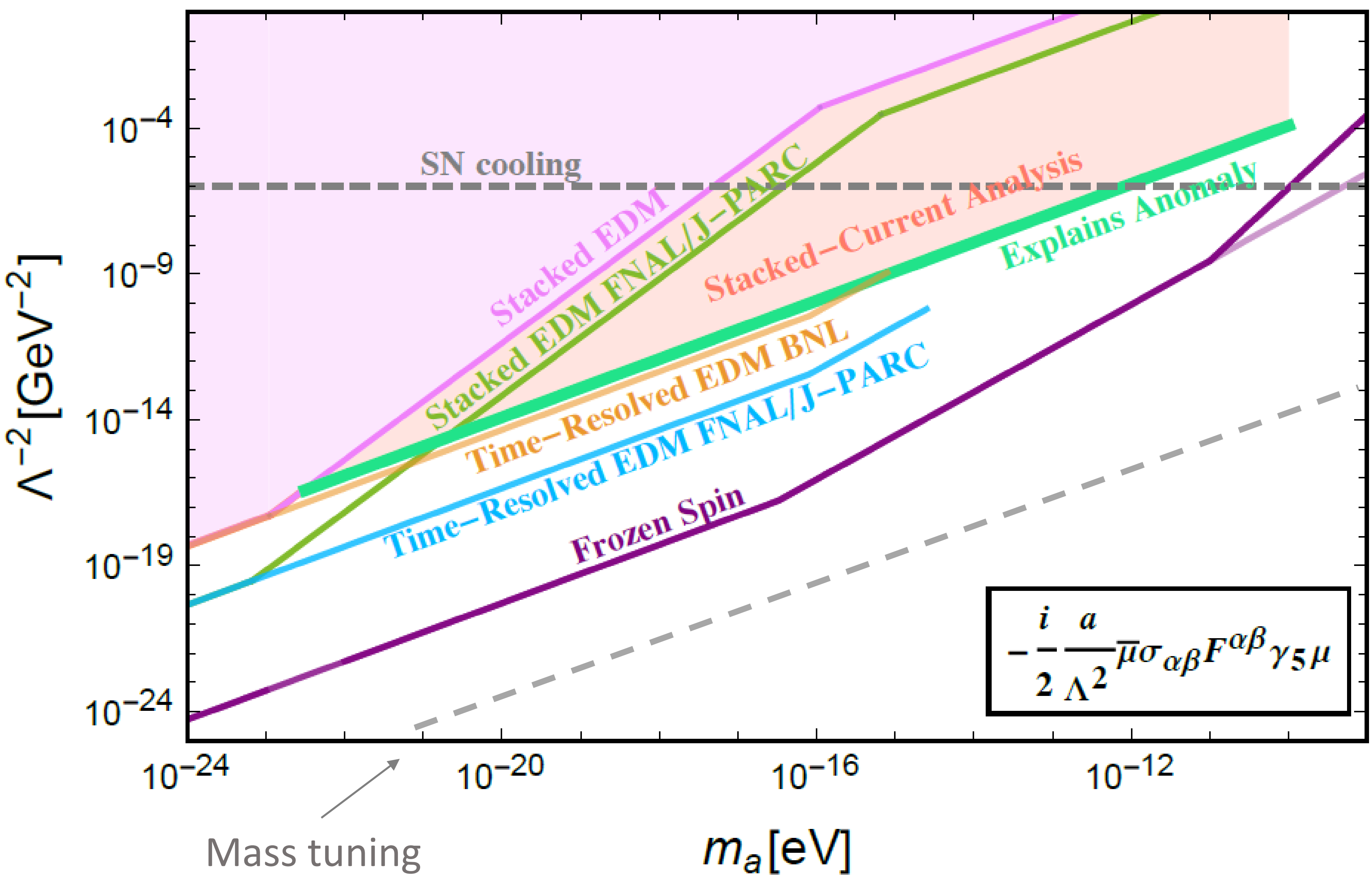
$A(t) \propto \omega_\perp(t)$

# Time-Resolved Amplitude Tracking

Fourier transform of vertical amplitude:



# Detection Reach for Muon EDM Coupling



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# ALP-Muon Wind

$$\mathcal{L} \supset g\, \partial_\nu a\, \bar{\mu}\, \gamma^\nu \gamma_5\, \mu$$

In the rest frame of the muon: $H \supset g\, \vec{\nabla} a \cdot \vec{S}$

Muon spin precesses about the relative velocity of DM, which is essentially the muon velocity.

$$\vec{\omega_a} = \omega_{sm} \hat{B} + \omega_{dm} \cos\left(m_a t\right) \hat{v}$$

$$\omega_{dm} = g \sqrt{2 \rho_{dm}}$$

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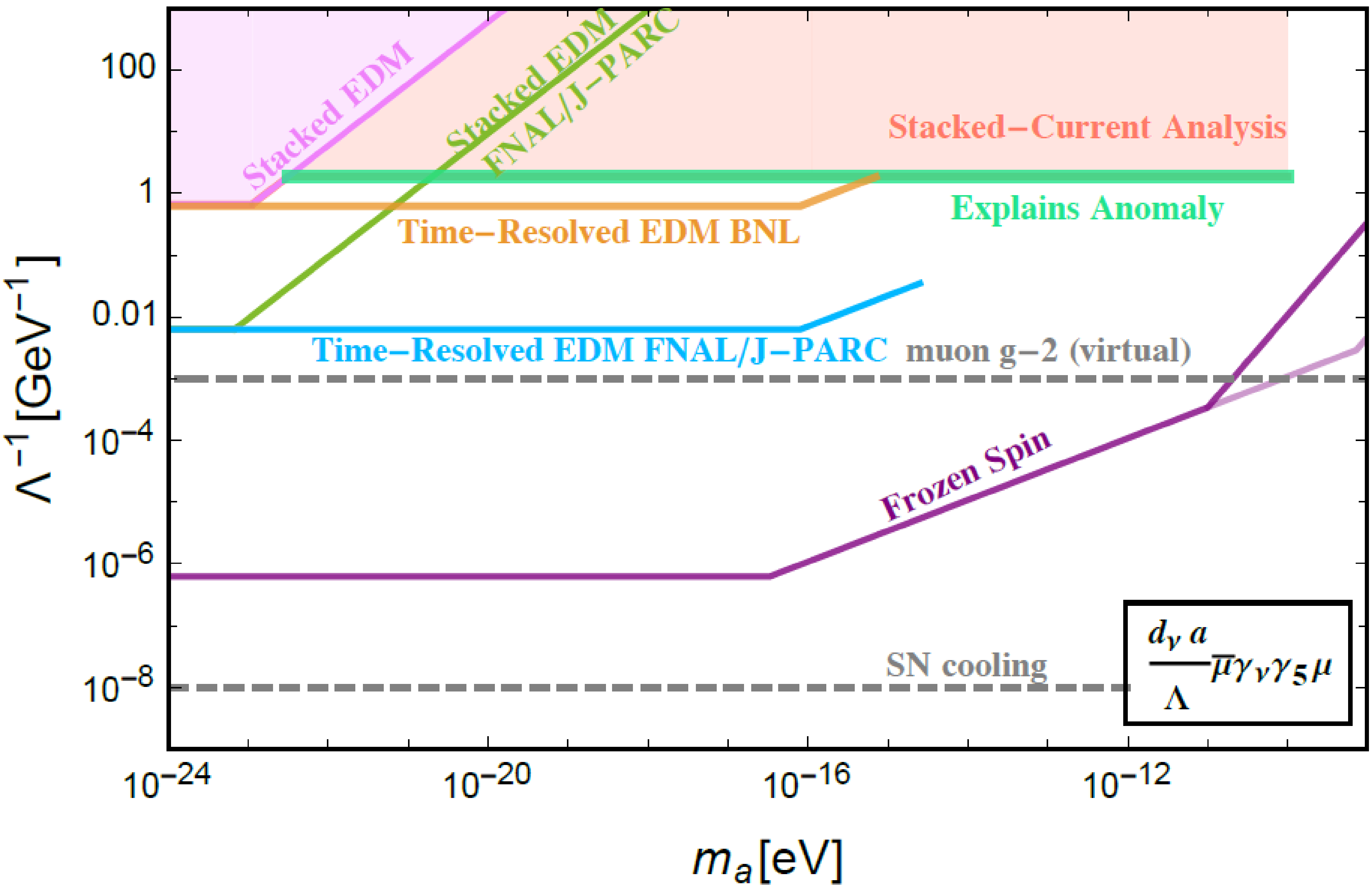
$$\omega_{dm} = g\, \sqrt{2 \rho_{dm}}$$

This is an oscillating perpendicular perturbation – the precession dynamics and detection limits are qualitatively the same as the EDM coupling.

The two counts are now in-phase, which may introduce additional systematic errors.

[Bennett et al, 0811.1207]

# Detection Reach for ALP-Muon Wind



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# Muonic Vector DM

Ultralight vector DM manifests as a local dark electric and magnetic field:

$$E_{\rm dm} = \sqrt{2\rho_{\rm dm}}\cos\left(m_{\rm dm}t\right)$$

$$B_{\rm dm} = v_{\rm dm}E_{\rm dm}$$

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Four distinct contributions to precession – the dominant one is the component of $\vec{E}_{\rm dm}$ transverse to the orbital plane:

$$\vec{\omega}_{\rm dm} = \frac{g_{\rm dm}}{m_\mu\gamma^2}\,\vec{v}\times\vec{E}_{\rm dm}$$

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Not observable at BNL or Fermilab, as vertical trapping EM fields will screen $\vec{E}_{\rm dm}$!

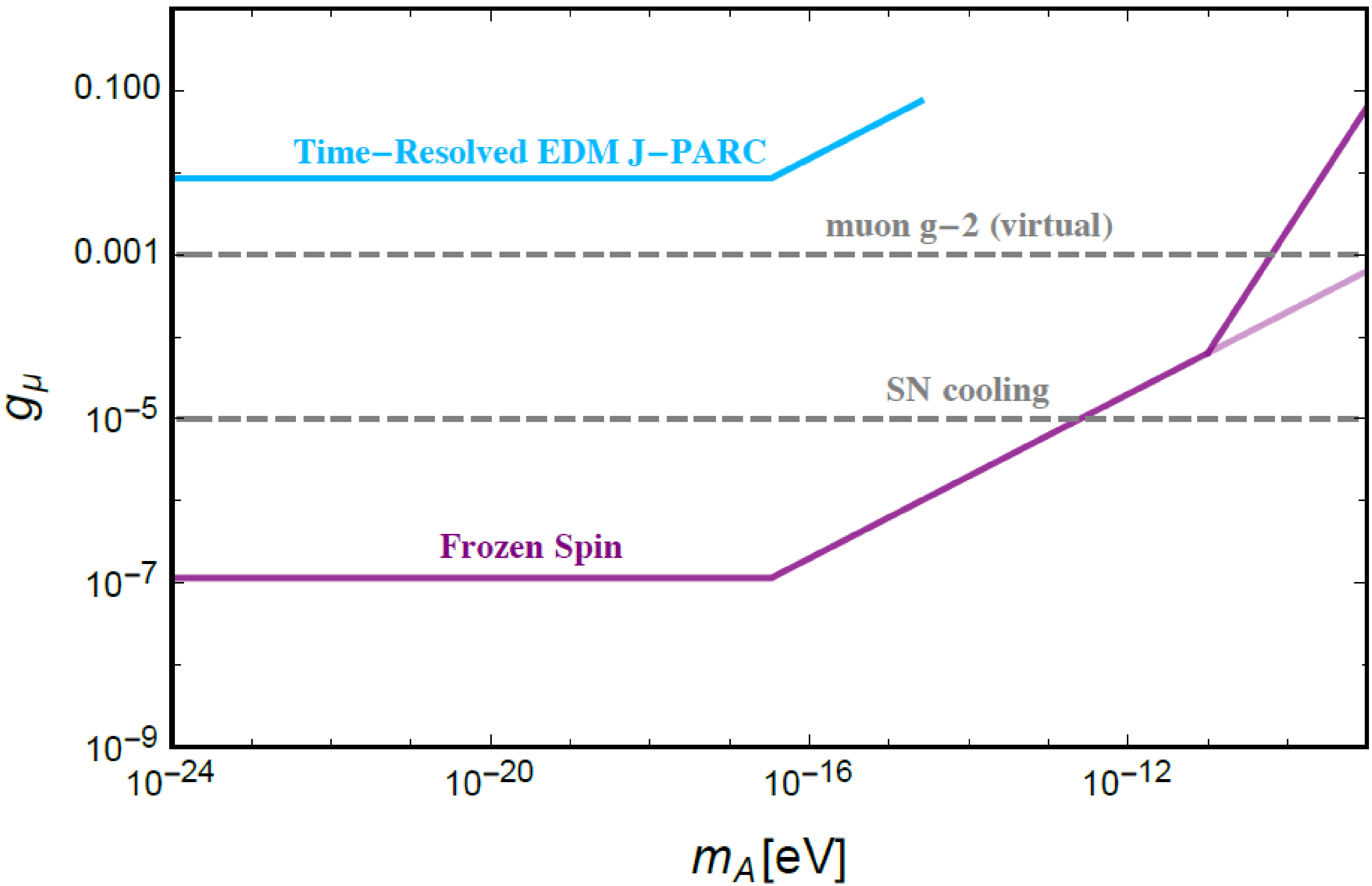
[Bennett et al, 0602035]

[Grange et al, 1501.06858]

Observed at J-PARC or future frozen spin searches.

[Abe et al, 1909.03047] [Adelmann et al, 0606034]

# Muonic Vector DM



# Muon g-2 and EDM Experiments as DM Detectors

A new search for ultralight DM using muon spin targets.

# Muon g-2 and EDM Experiments as DM Detectors

A new search for ultralight DM using muon spin targets.

Direct, terrestrial limits on muophillic DM.

Detection reach for (albeit tuned) DM-muon interactions, pending reanalysis of previous and upcoming g-2 data.

DM may explain the muon g-2 anomaly via coherent interaction with DM background field (not via loops).

Approach improves with ongoing development of g-2 and EDM measurement techniques (e.g., frozen spin experiments).

# Muon g-2 and EDM Experiments as DM Detectors

Extra Slides

# Constraints from Stacking the FM DM Signal

The envelope is detectable as a failure to fit the momentum count as a pure oscillation.

A decaying envelope is already present due to muon losses, modeled and empirically fit to be an $\approx 10\%$ decay

Allowed: $(\omega_{dm} T_{\text{bunch}})^2 < 10\%$ [Bennet et al, 0602035]

If the envelop is ignorable, it follows that the stacked frequency is the discrete mean of the individual bunch frequencies

$$\omega_{\text{stack}} = \omega_{sm} + \omega_{dm} \left( \frac{1}{N_{\text{bunches}}} \Sigma_{t_i} \cos\left(m_\phi t_i\right) \right)$$

$$\Rightarrow \quad \left|\omega_{\text{stack}} - \omega_{sm}\right| \sim \frac{\omega_{dm}}{m T_{\text{run}}} \qquad \left[\text{if } m \lesssim \frac{N_{\text{bunches}}}{T_{\text{run}}}\right]$$

Deviation must be less than (or equal!) the observed frequency.

# Yukawa Coupling: Static Limit

For sufficiently small $m_\phi$, the DM background provides a static contribution to $m_\mu$ which will be included in the computation of $\omega_{sm}$ – no anomaly is observed.

We then constrain the linear drift of $m_\mu$ between (g-2) experiments and the previous determination of $m_\mu$.

In practice, use the magnetic moment ratio $\mu_\mu/\mu_p$ determined from the hyperfine splitting of muonium instead of $m_\mu$ [Liu et al, 1999]

$$|\omega_{stack} - \omega_{sm}| \sim \Delta T_{m_\mu} \partial_t \omega_{dm} \qquad \left[\text{if } m_\phi \lesssim \frac{1}{T_{\text{total}}}\right]$$

Time between (g-2) and muonium experiments

Total span of (g-2) experiment

# Yukawa: Loop Effects

$$\mathcal{L} \supset y\,\phi\bar{\mu}\mu$$

A few of the more egregious examples:

Generates couplings to electrons, nucleons and photons which are highly constrained by atomic clocks and EP tests.

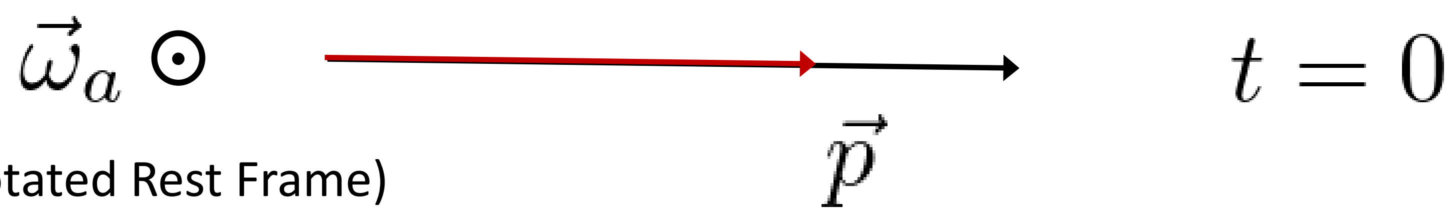
[Arvanitaki et al, 1405.2925]

Induced $\phi^2\bar{n}n$ produces a matter-dependent potential for the DM, may screen it from terrestrial experiments.

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction




(Rotated Rest Frame)

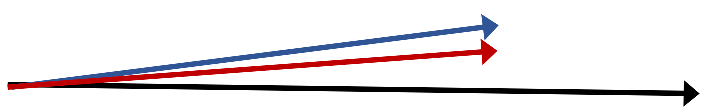
# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction

$\vec{\omega}_a \odot$

(Rotated Rest Frame)



$\vec{p}$

$$0 < t < \frac{\pi}{m_\phi}$$

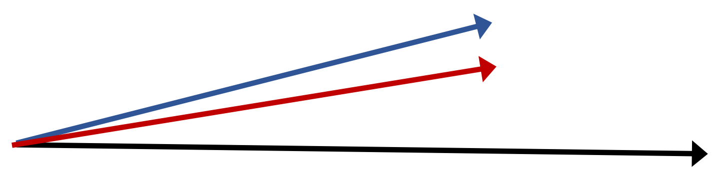
# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction

$\vec{\omega}_a \odot$

(Rotated Rest Frame)



$\vec{p}$

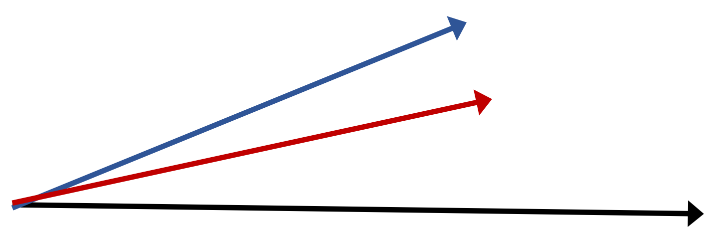
$$0 < t < \frac{\pi}{m_\phi}$$

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction

$\vec{\omega}_a \odot$



$\vec{p}$

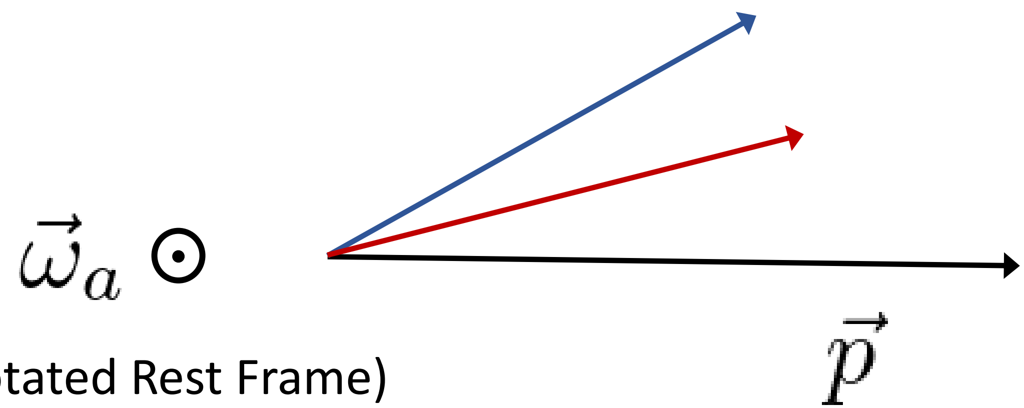
$0 < t < \frac{\pi}{m_\phi}$

(Rotated Rest Frame)

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction



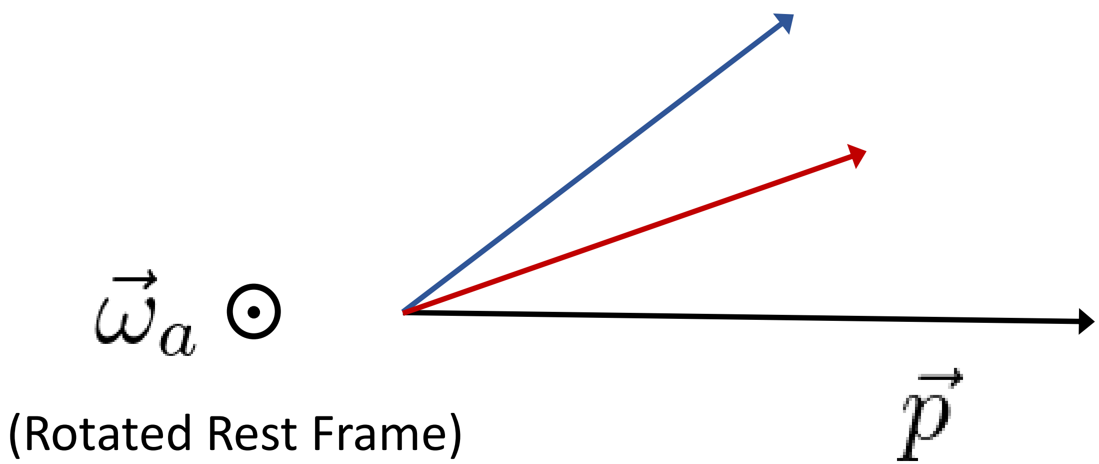

(Rotated Rest Frame)

$$0 < t < \frac{\pi}{m_\phi}$$

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction

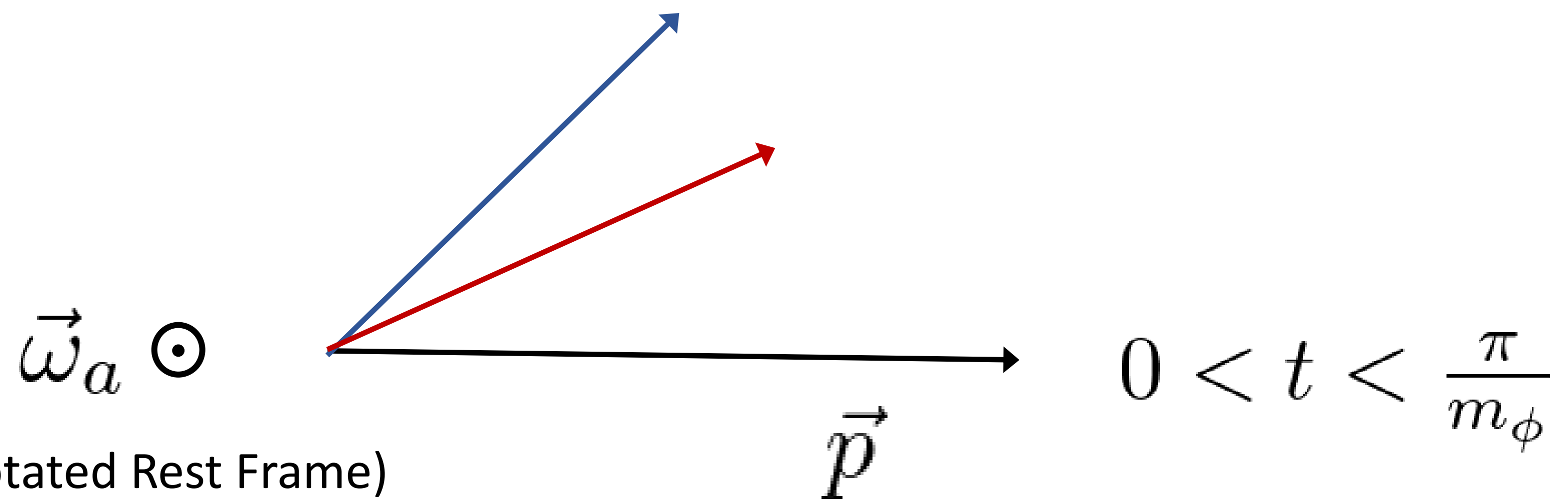



$0 < t < \frac{\pi}{m_\phi}$

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction



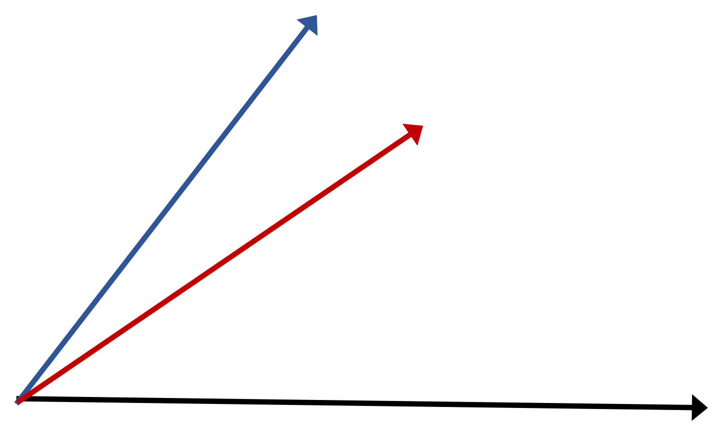

(Rotated Rest Frame)

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction

$\vec{\omega}_a \odot$



(Rotated Rest Frame)

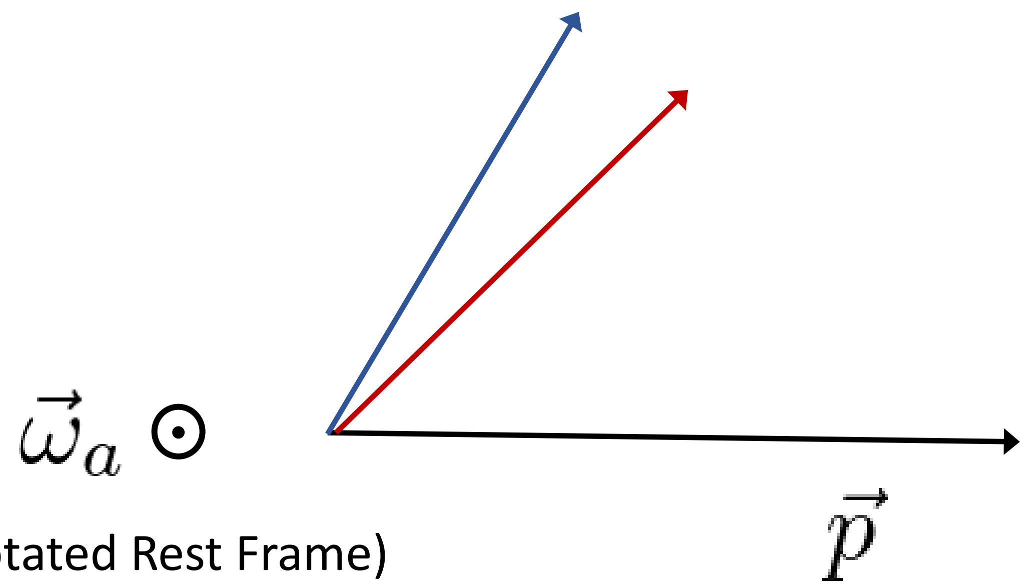
$\vec{p}$

$$\frac{\pi}{m_\phi} < t < \frac{2\pi}{m_\phi}$$

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction



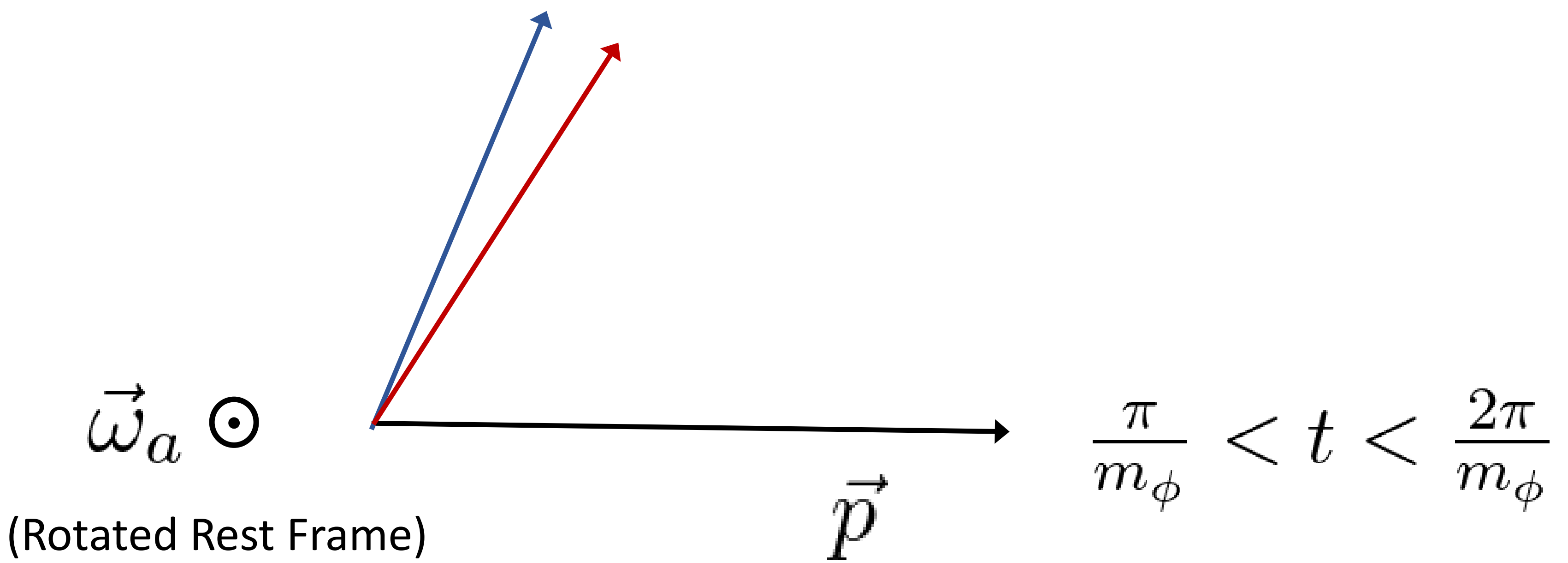

(Rotated Rest Frame)

$$\frac{\pi}{m_\phi} < t < \frac{2\pi}{m_\phi}$$

# A Scalar DM Precession Signal

DM Yukawa coupling

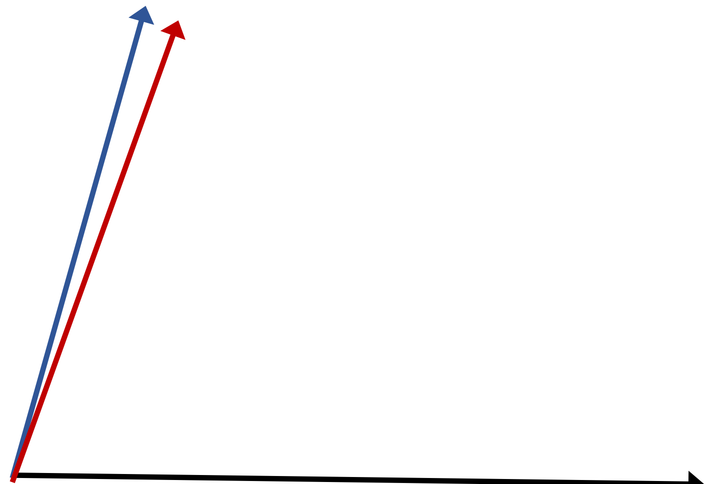
No DM interaction



# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction



$\vec{\omega}_a \odot$

(Rotated Rest Frame)

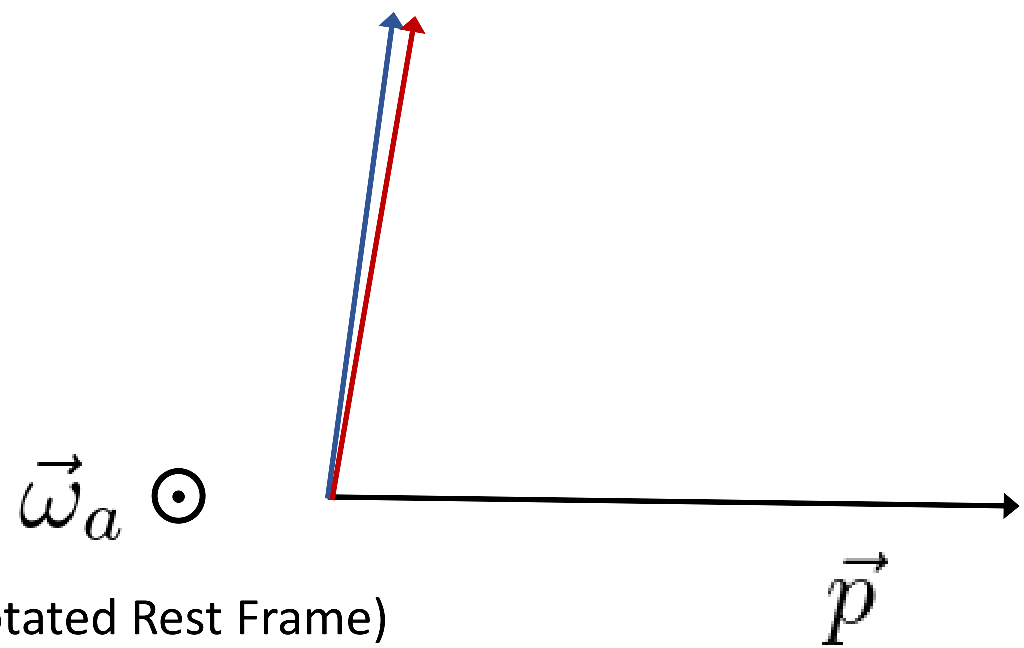
$\vec{p}$

$$\frac{\pi}{m_\phi} < t < \frac{2\pi}{m_\phi}$$

# A Scalar DM Precession Signal

DM Yukawa coupling

No DM interaction



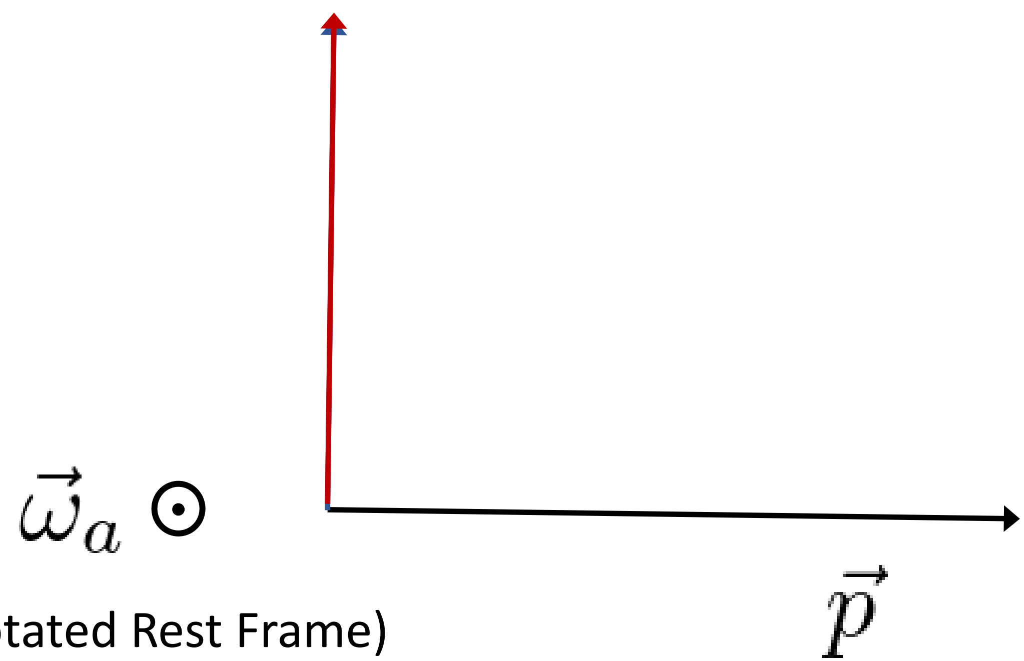

$$\frac{\pi}{m_\phi} < t < \frac{2\pi}{m_\phi}$$

(Rotated Rest Frame)

# A Scalar DM Precession Signal

DM Yukawa coupling

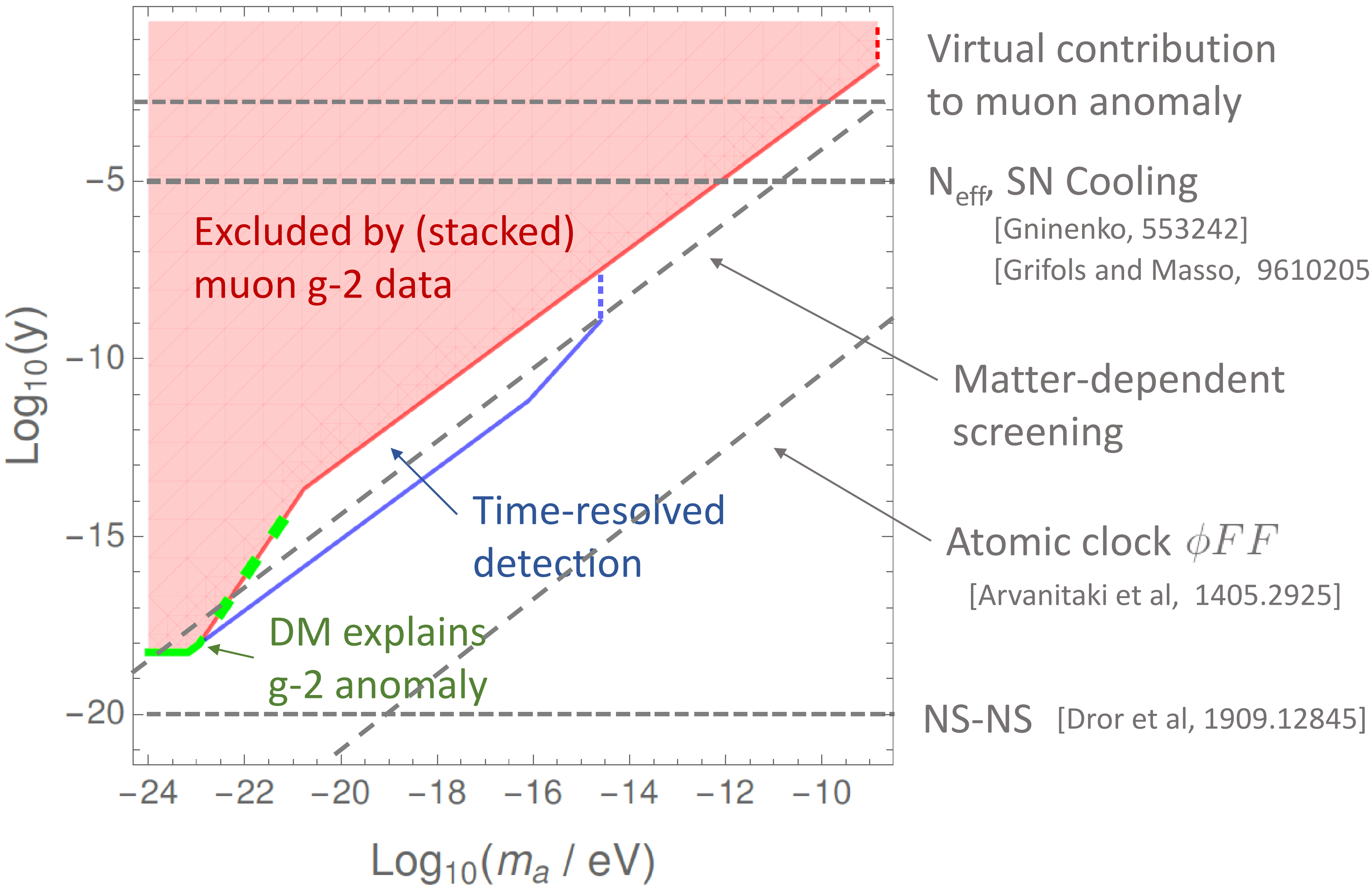
No DM interaction




(Rotated Rest Frame)

$$t = \frac{2\pi}{m_\phi}$$

# Detection Reach for DM-Muon Yukawa



# A DM EDM Signal

Precession trajectory (quasi-static limit):

$$S_p = S_0 \underline{\cos} \left[ \left( \omega_{sm} + \frac{\omega_{dm}^2}{4\omega_{sm}} \right) t + \frac{\omega_{dm}^2}{8\omega_{sm}} \sin(2m_a t) \right]$$

$$S_B = S_0 \frac{\omega_{dm}}{\omega_{sm}} \cos(m_a t) \underline{\sin} \left[ \left( \omega_{sm} + \frac{\omega_{dm}^2}{4\omega_{sm}} \right) t + \frac{\omega_{dm}^2}{8\omega_{sm}} \sin(2m_a t) \right]$$

AC Amplitude Modulation

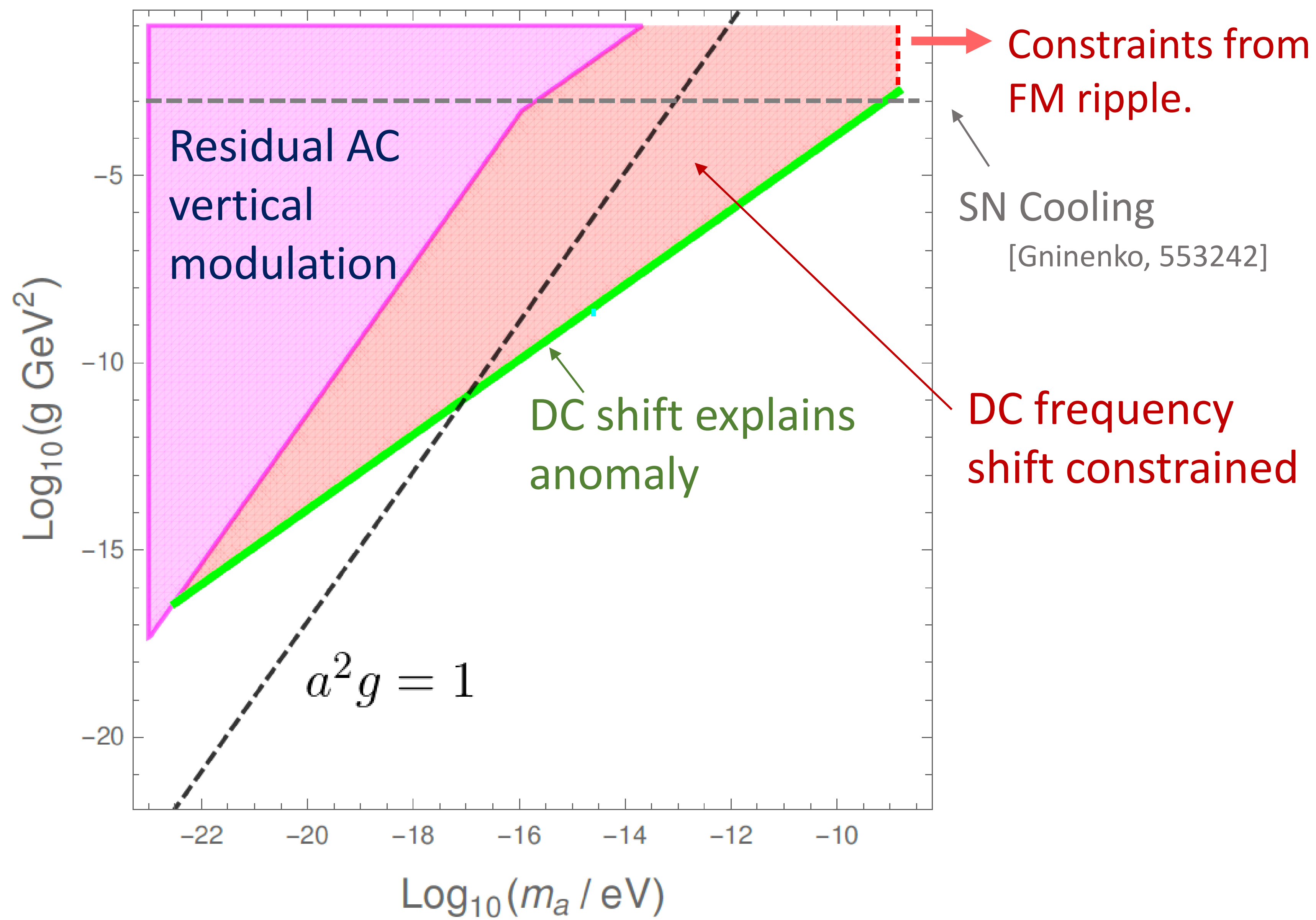
Fixed phase shift between counts

Immediate constraints (or explanation):

Static FM is a $\rho_{dm}$–dependent apparent contribution to $a_\mu$.

AM of vertical count will average away in the stacked EDM measurement – we may place constraint from the residual of that averaging.

# Limits on ALP DM-Muon EDM Coupling



# Muonic Vector DM

Vector DM generates a dark electric and magnetic field,

$$E_{\rm dm} = \sqrt{2\rho_{\rm dm}}\cos\left(m_{\rm dm}t + \alpha\right)$$
$$B_{\rm dm} = v_{\rm dm}\sqrt{2\rho_{\rm dm}}\sin\left(m_{\rm dm}t + \alpha\right)$$

$B_{dm}$ is too small to be observed in existing experiments

$$\frac{\omega_{\rm dm}}{\omega_{\rm sm}} = \frac{g_{\rm dm}}{e}\frac{B_{\rm dm}}{B_0} \approx 10^{-6} g_{\rm dm}\,\left(\frac{3\,{\rm T}}{B_0}\right)$$

$E_{dm}$ may be observed in experiments that do not use the “magic momentum” to cancel electric field precession (e.g., J-PARC, frozen spin)

* disfavored by NS-NS inspiral and solar neutrino oscillations ($L_\mu - L_\tau$)