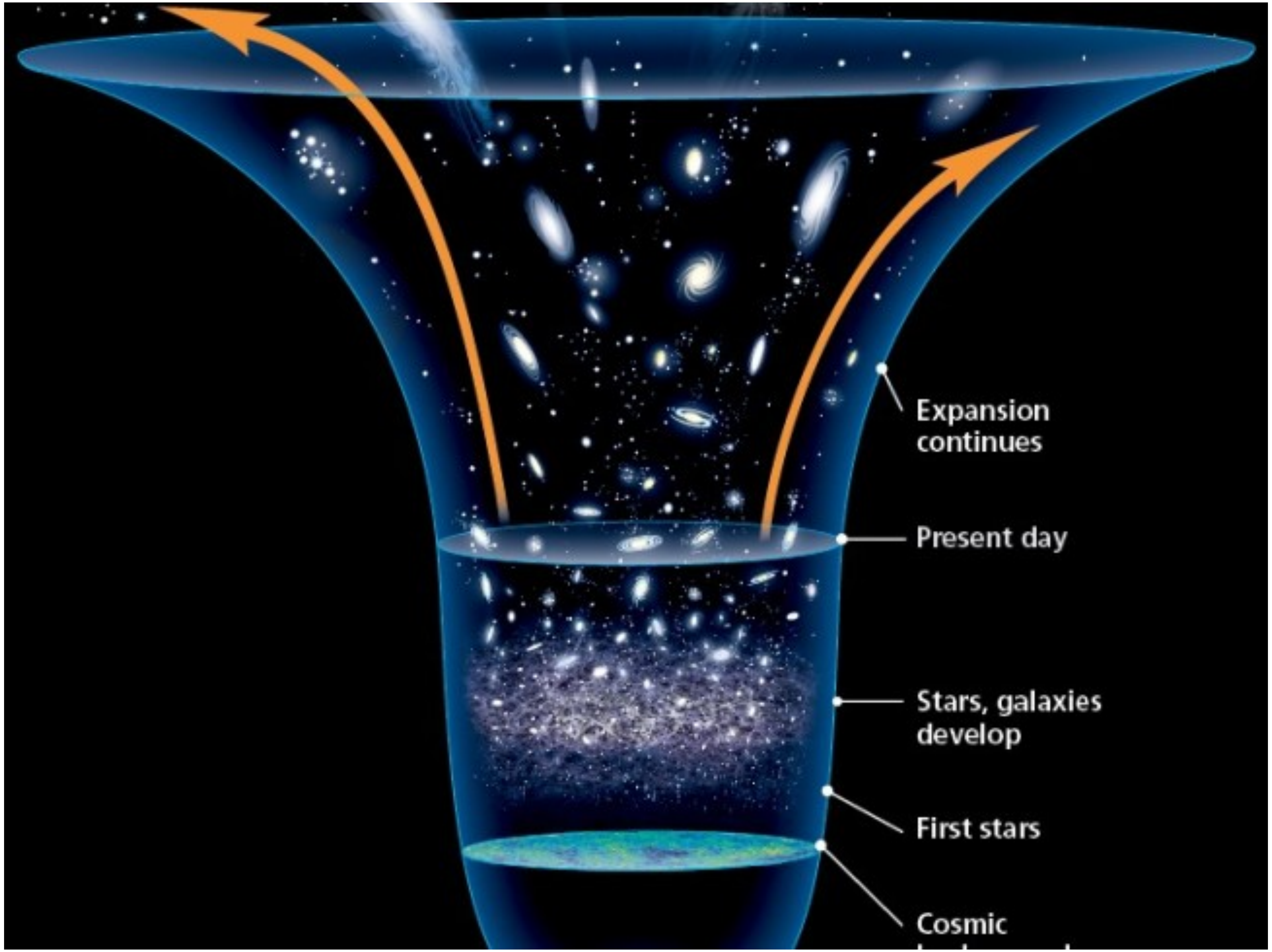
Direct Detection of Dark Energy

Surjeet Rajendran

Dark Energy



Accelerated Universe

What causes it?

Observational Constraint

$$w = \frac{p}{\rho} \lessapprox -0.95$$

Theoretical Assumption

$$w = \frac{p}{\rho} = -1$$

$$\Lambda$$

Cosmological Constant?

$$-1 \leq w \leq -0.95$$

Determine observationally. Test theory bias.

Constant Λ: No known natural mechanism to explain observed value

Only known explanations involve dynamical evolution - imply changing Λ

Gravitational measurement. Can we do better in the lab?

Similar to laboratory detection of dark matter properties

Gravitational Measurements: dark matter is a cold, pressure-less gas.
$\sigma/m < cm^2/gm$

Does not mean $\sigma = 0$. Can probe $\sigma \sim 10^{-49}\ cm^2$ in the lab

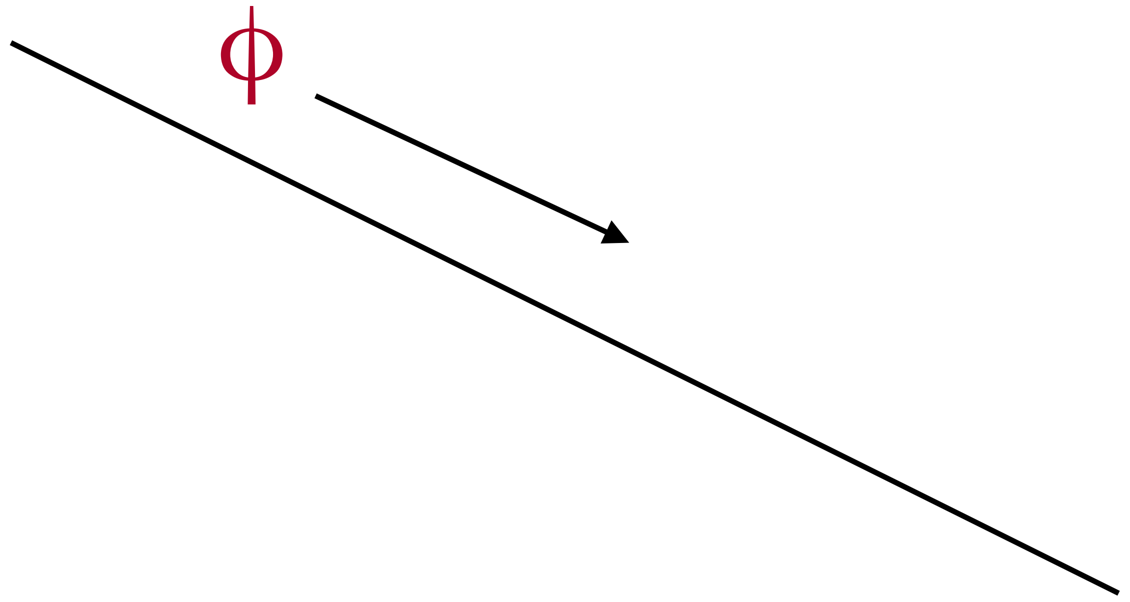
What are the signatures of dark energy?

What can the Dark Energy be?

w < -0.95 : Need fluid with free equation of state parameter.

Isotropic and homogeneous

Reasonable Possibility: Scalar Field (Quintessence)



$$w = \frac{\frac{\dot{\phi}^2}{2} - V}{\frac{\dot{\phi}^2}{2} + V}$$

Lagrangian for this scalar field?

$$m \lesssim H = 10^{-43} \ \mathrm{GeV}$$

Ultra-light field. Demand technical naturalness => axion-like, derivative interactions

$$\mathcal{L} \supset C\phi + \frac{\partial_\mu \phi}{f_a} \bar{\psi}\gamma^\mu \gamma_5 \psi + \frac{\phi}{f_a} F\tilde{F}$$

Kinetic Energy of Dark Energy < meV^2

Direct Detection

Experimental Observables

1. dc Signals (CMB, Spin Precession)

2. ac (THz) signals

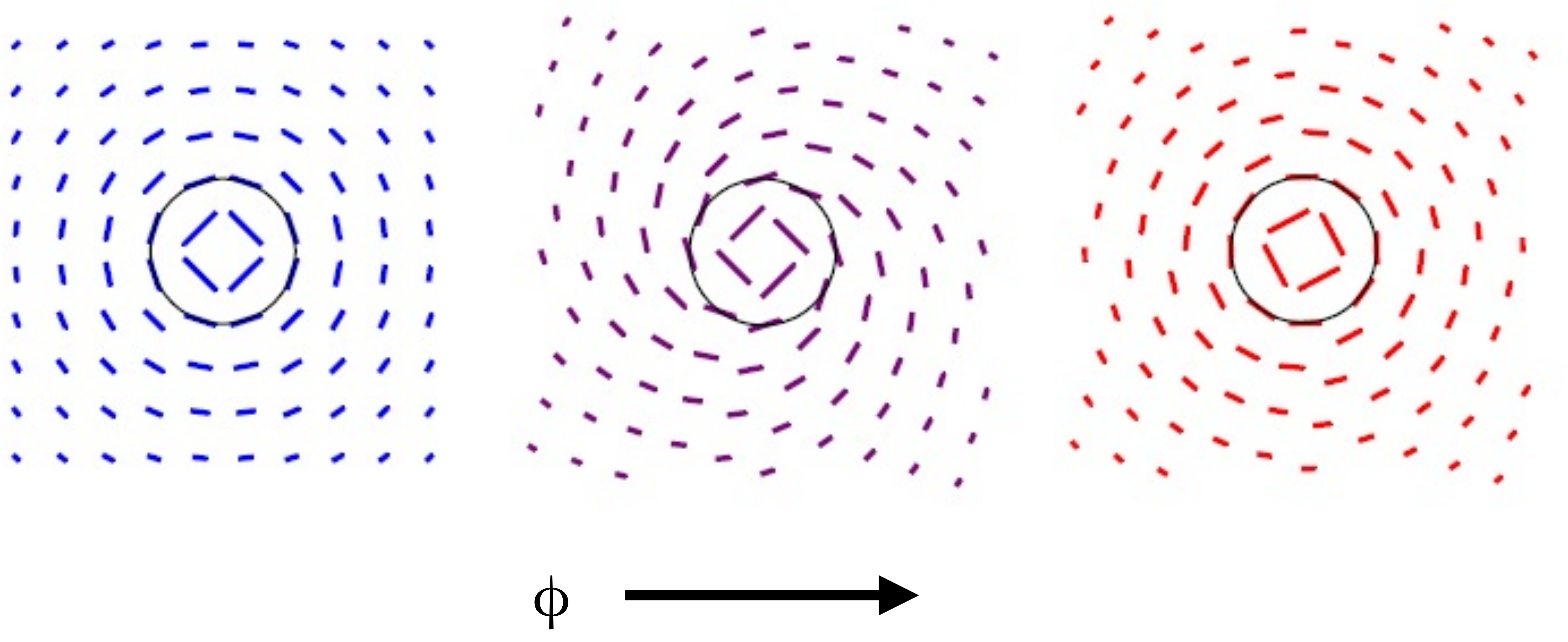
3. Conclusions

dc Signals

dc Signal: Cosmic Microwave Background

$$\frac{\phi}{f_\gamma} F\tilde{F}$$

$$\dot{\phi} \implies \text{Rotation of polarization of light}$$



The polarization of the CMB rotates as ϕ rolls (Homogeneous scalar)

E-mode => B-mode

$$\frac{\dot{\phi}}{f_\gamma}\frac{1}{H} = \frac{\dot{\phi}}{\mathrm{meV}^2}\frac{M_{pl}}{f_\gamma} \lesssim 1$$

Current CMB Measurements already very constraining!

dc Signal: Spin Precession

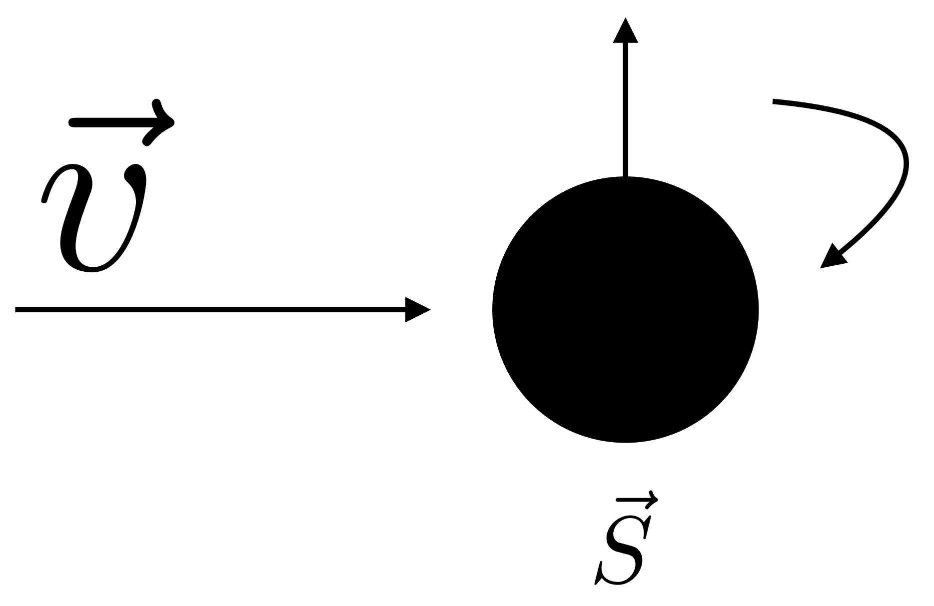
$$\frac{\partial_\mu \phi}{f_\psi} \bar{\psi}\gamma^\mu \gamma_5 \psi$$

$$\implies \frac{\dot{\phi}}{f_\psi} \vec{v}.\vec{S}$$

Relative Motion between the dark energy and spin

Think of it as a new dark magnetic field

Like magnetic field, spin precesses about the direction of motion



Measure Spin Precession - similar to axion dark matter searches (CASPER)

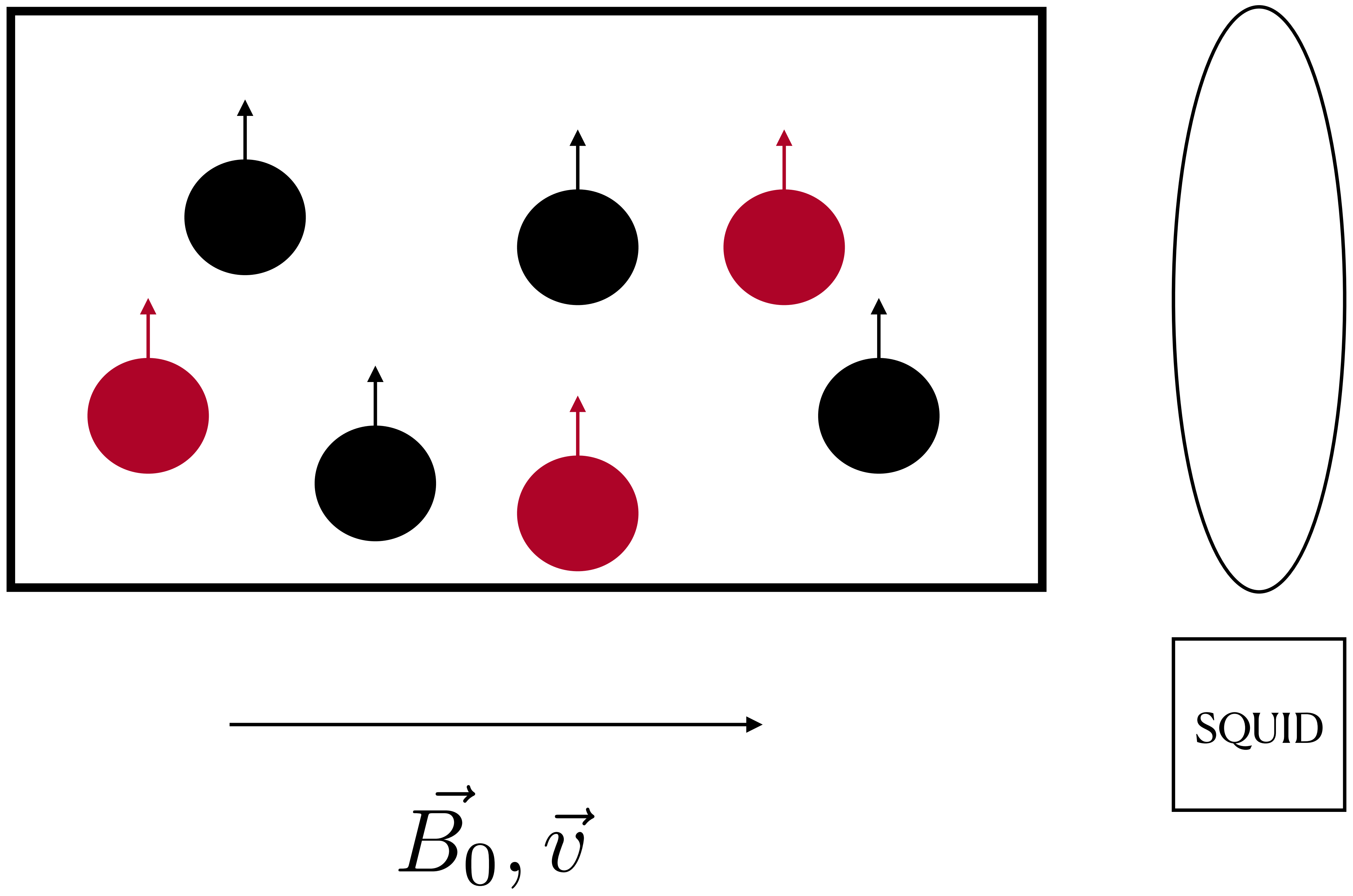
Challenges: Signal is dc - need to combat low frequency noise, Dark energy is less abundant in galaxy than dark matter

Advantage: Signal is coherent forever

dc Signal: Spin Precession

Many experiments look for Lorentz Violation

Dark Energy application first discussed by Pospelov and Romalis



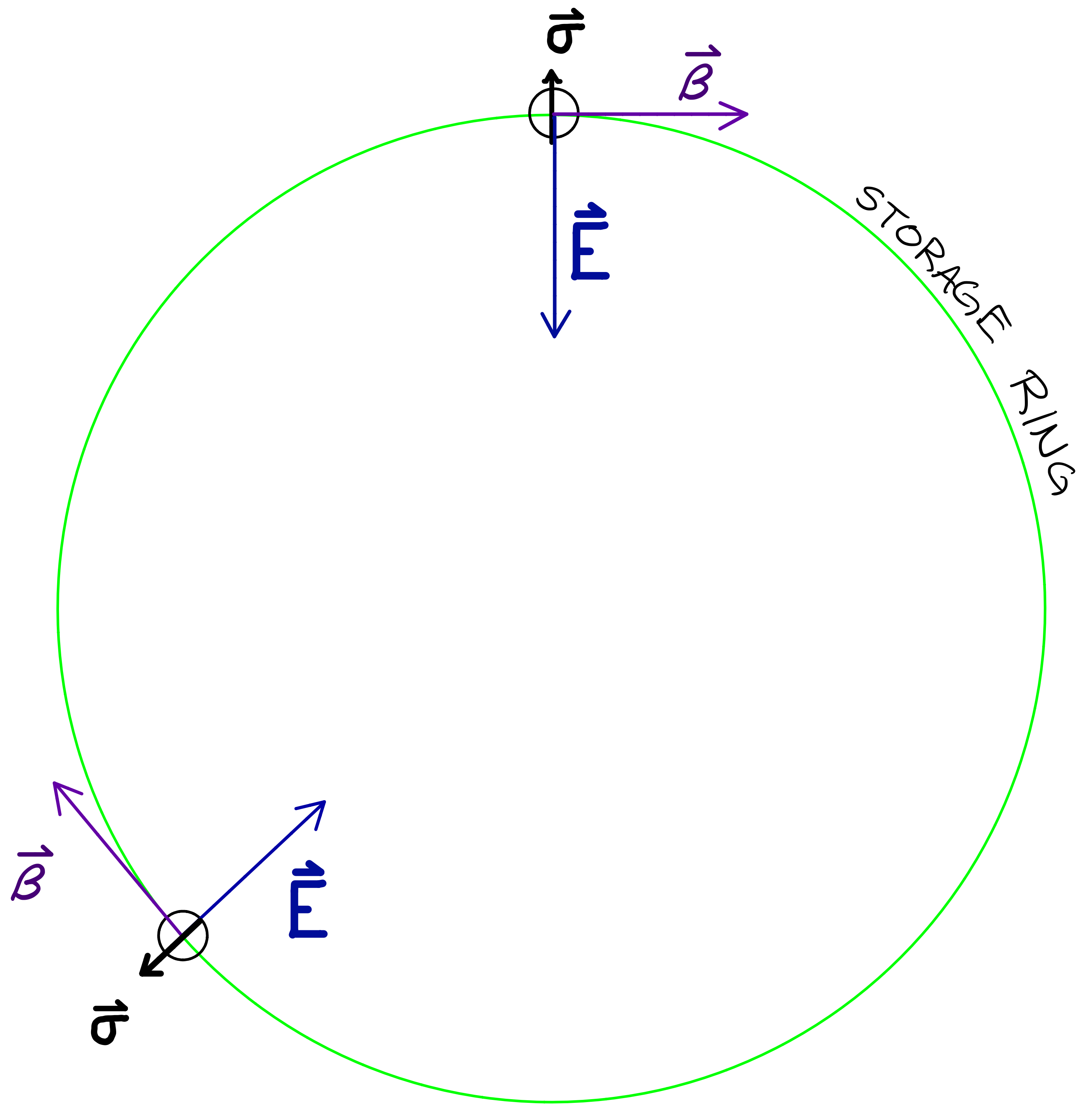
Dual Species Magnetometry
(Xe/He, Xe/K, Xe/Rb)

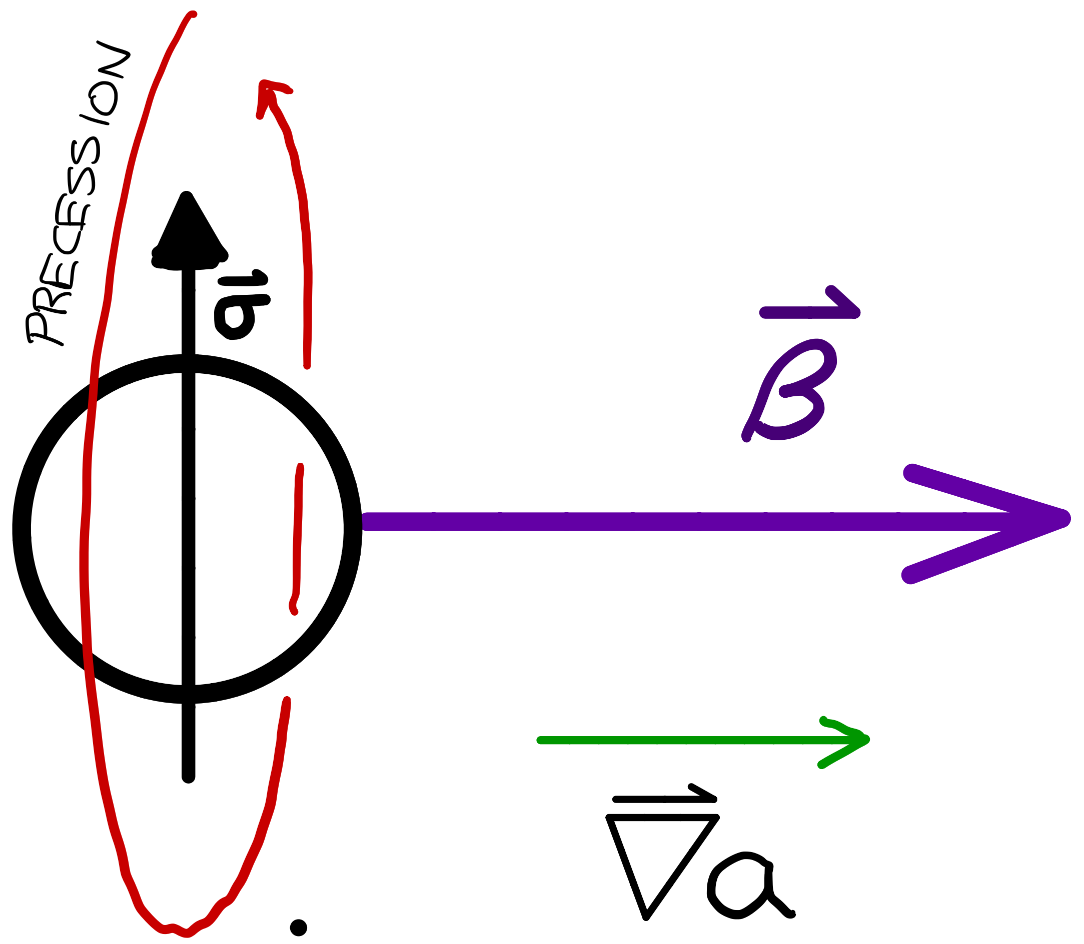
Measure Differential Precession Rate

In general, ratio of magnetic moments different from ratio of dark energy couplings

Anomalous relative precession indicative of dark energy

dc Signal: Spin Precession





$$\frac{\dot{\phi}}{f_\psi}\vec{v}.\vec{S}$$

Storage Ring EDM Experiment: Look for anomalous precession induced by EDM of nucleon

Systematics well understood
Development underway (Brookhaven, Fermilab, IBS Korea)

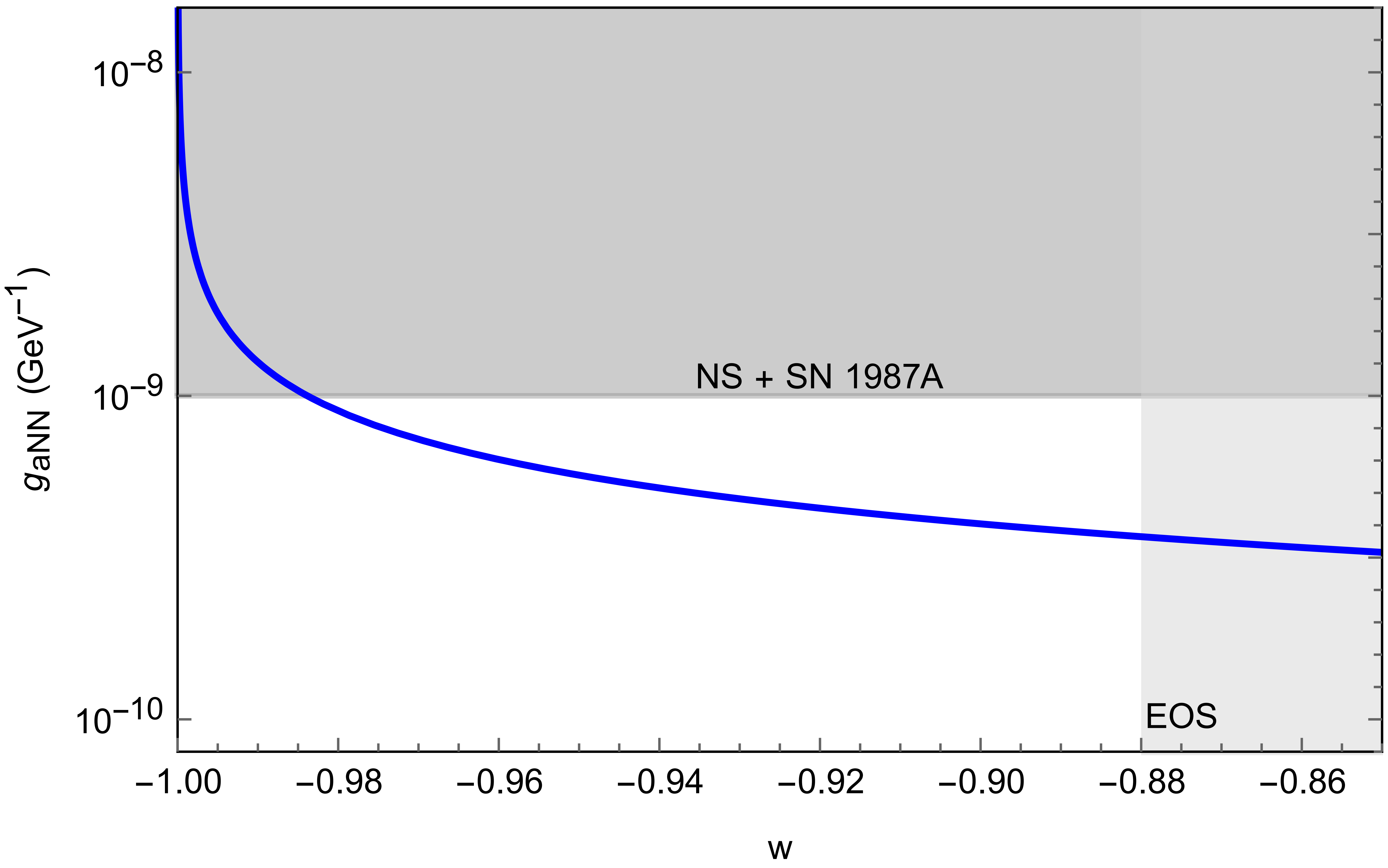
Same setup can be used - but orient spin radially, so that it precesses out of the plane

Relativistic Beam Velocity increases signal

Use counter-propagating beams to combat systematics

arXiv:2005.11867

Projected Sensitivity



1000 s storage time (protons), 10^{-6} phase resolution

Lorentz Violation experiments also have comparable sensitivity

ac Signals

(In progress)
With Kim Berghaus, Peter Graham,
David E. Kaplan and Guy Moore

ac Signals

For Dark Matter, in addition to “direct” detection, we also have “indirect” detection i.e. conversion of dark matter to relativistic radiation

Can Dark Energy produced relativistic radiation i.e. can it decay?

Dark Matter: Mass spans a huge range, relativistic radiation spread over very large range of energies

Dark Energy: mass is below Hubble, kinetic energy <~ meV^2

Relativistic Radiation below meV (~ 10 THz) - can be in the form of dark sector particles, photons and neutrinos

Energy density in dark energy radiation >> CMB energy density - happens today, unconstrained by early universe

Discovery requires new class of sensors

ac Signals

Want technically natural interactions. How do we convert the kinetic energy into radiation?

Couple ϕ to a new non-abelian gauge group

$$\mathcal{L} = \frac{1}{2g^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} + \frac{\phi}{f}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + C\phi$$

The rolling of ϕ can convert its kinetic energy into dark gluon radiation. Self interactions of the gluons thermalizes the glue sector

$$\partial^\mu\partial_\mu\phi = -C + \frac{\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}}{f}$$

$$\mathrm{Tr}G\tilde{G} = \frac{\Gamma_{sp}}{T}\frac{\dot{\phi}}{f}$$

Sphalerons extract kinetic energy from the field, providing friction for the field

$$T \sim \left(\frac{C^2 f^2}{H N_c^7 \alpha^5}\right)^{1/7}$$

Completely unconstrained hidden sector, can pick parameters to get T ~ meV (f << TeV), with C limited by kinetic energy of ϕ

Dark Radiation

Converted kinetic energy to dark glue. How can we detect this?

$$\frac{\bar{\psi}\psi G^2}{\Lambda^3}$$

Direct coupling to the Standard Model is dimension 7
Hard to probe

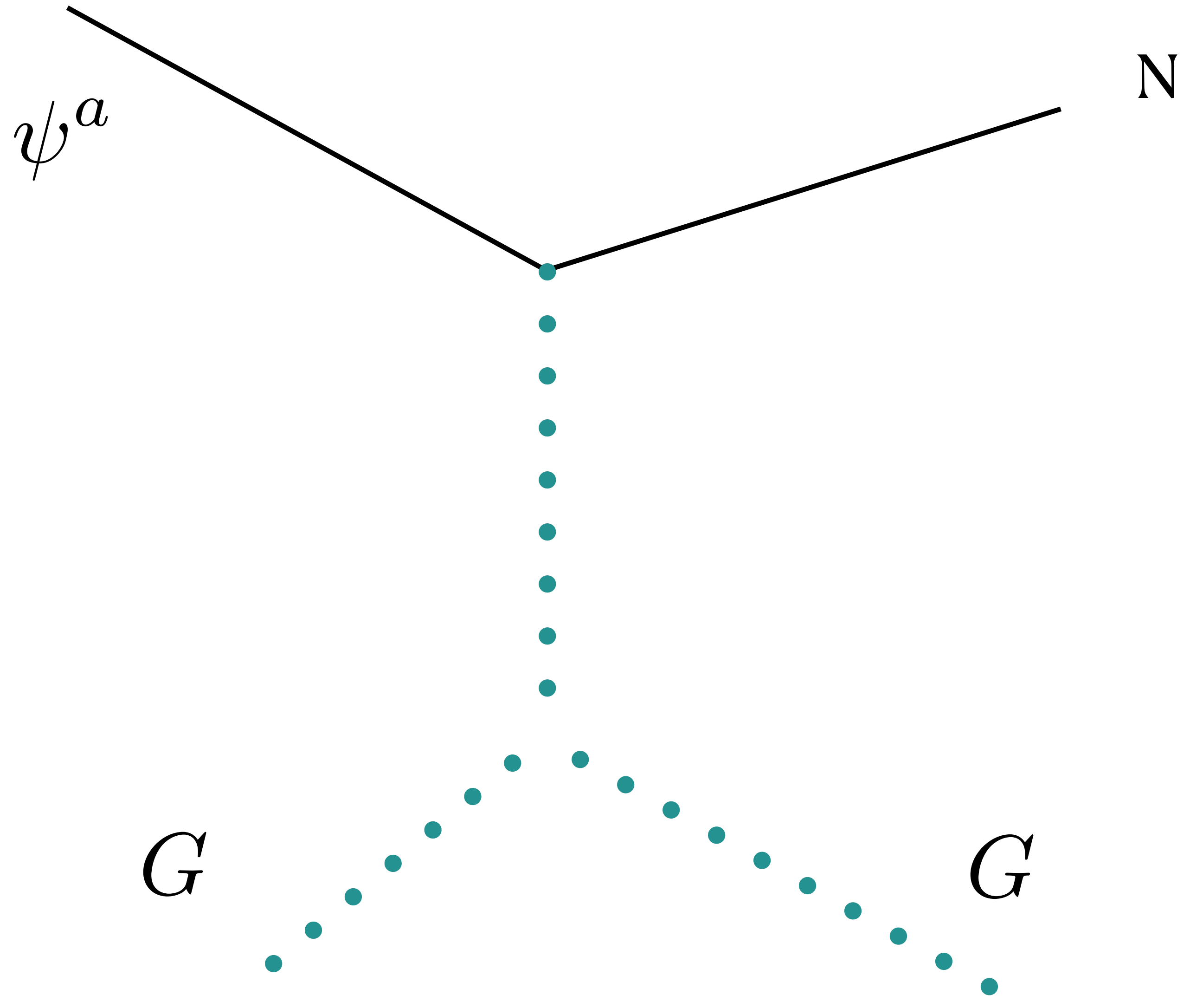
But, turn on dark sector interactions with hidden photons, milli-charged particles, right handed neutrinos
(Well studied portals since these are the lowest dimension ways to couple to the standard model)

$$\mathcal{L} \supset \bar{\psi}\left(\gamma^{\mu} D_{\mu} + m\right)\psi$$

e.g. Milli-charged under E&M, fundamental representation of non-abelian sector. Could also be coupled to a hidden photon sector

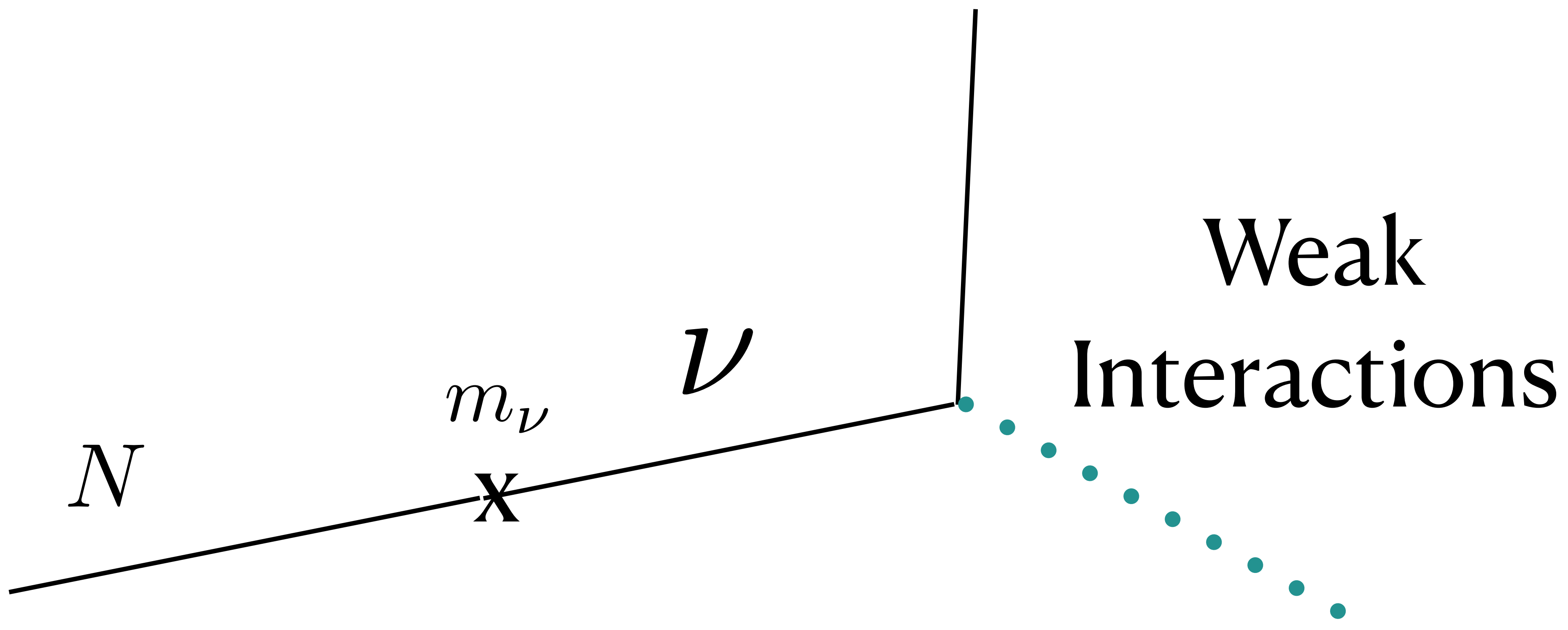
Right Handed Neutrinos

$$\mathcal{L} \supset \frac{1}{f_N} G^a_{\mu\nu} \psi^a \sigma^{\mu\nu} N$$



Efficient (i.e. during the current age of the universe) conversion of energy from dark glue into right handed neutrino

Thermalized population of right handed neutrinos at meV energies



At low energy (meV), conversion of N to neutrino is not suppressed! So N behaves like a thermalized population of neutrinos - at meV temperatures!

10x the temperature of CνB

Detection

Challenge: Detect meV scale milli-charged particles

No existing experiments - but plenty of upcoming ideas (e.g. using EM cavities to search for milli-charged particles)

Challenge: Detect meV scale hidden photons.

Leverage work done for single IR photon detection, use work done for dark matter detection in this mass range

For neutrinos, this signal is significantly bigger than what PTOLEMY (tritium end point to detect CνB) looks for - but PLOLEMY is a very hard experiment

Interesting challenge for detection community!

Conclusions

Given the state of the cosmological constant problem, it is worth testing if the dark energy is changing - i.e. does it have a kinetic energy?

If so, this kinetic energy can have non-gravitational interactions with the standard model i.e. makes lab detection possible and not just cosmological measurement

dc Signals: Spin rotation, whether of light or nucleon/electron

Current experiments can probe dark energy: CMB B-mode measurements, Lorentz violation experiments, Storage Ring EDM Experiments

ac Signals: Arise from the decay of dark energy - at most at meV scale. Could be significantly higher than CMB energy density today

Discovery requires new class of sensors