Probing the Dark Sector with Atoms and Nuclei

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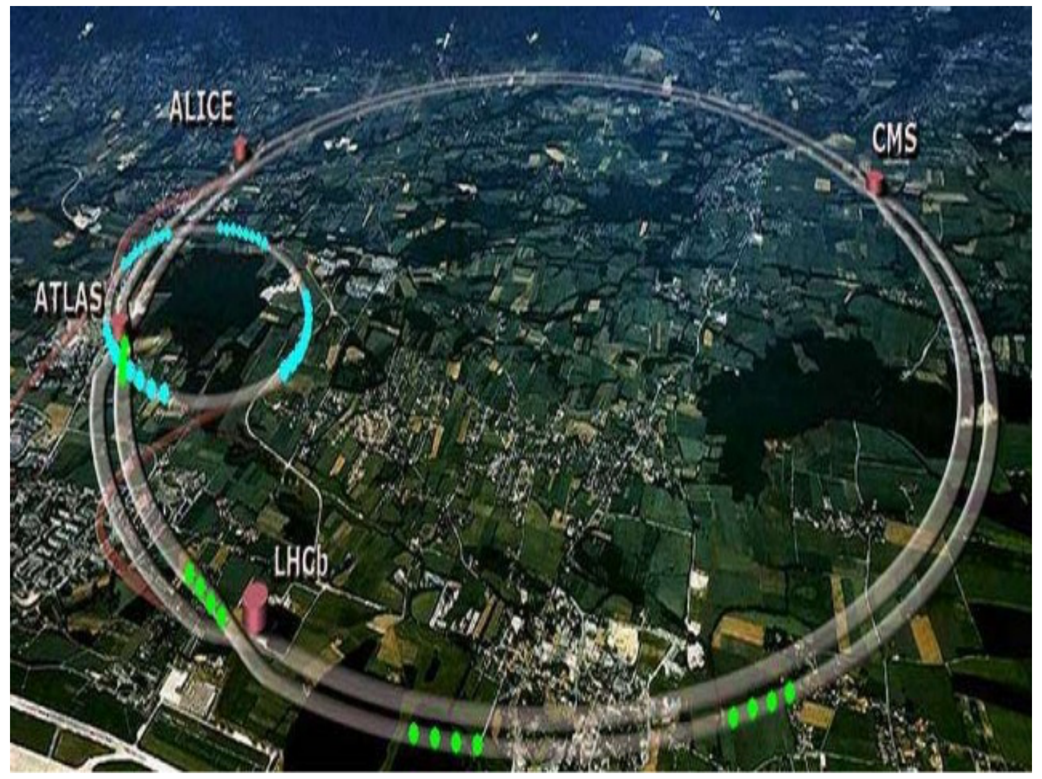
Grand Challenge of High Energy Physics

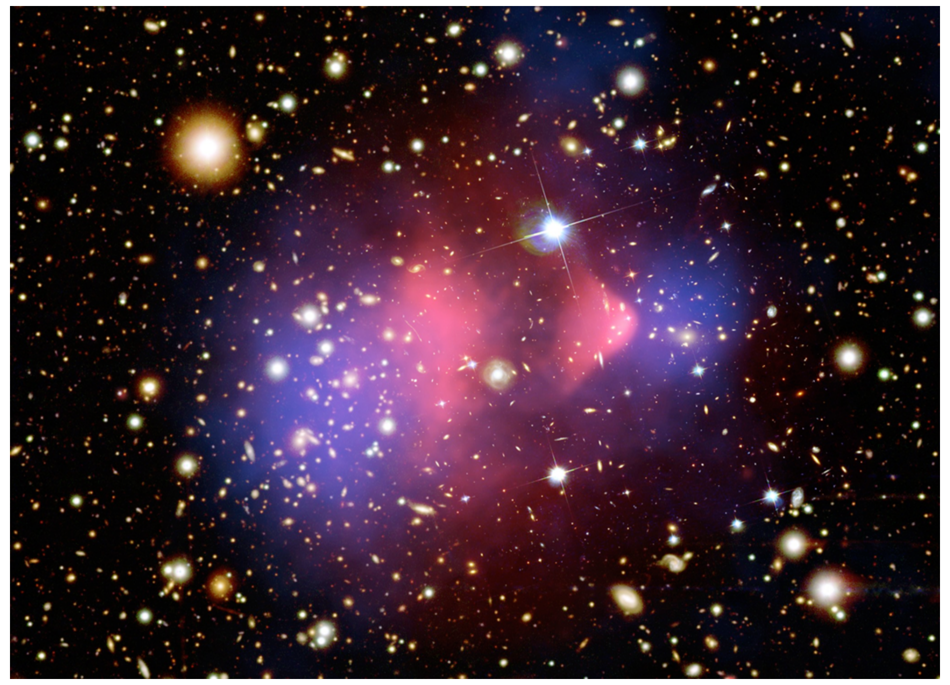
Standard Model experimentally established



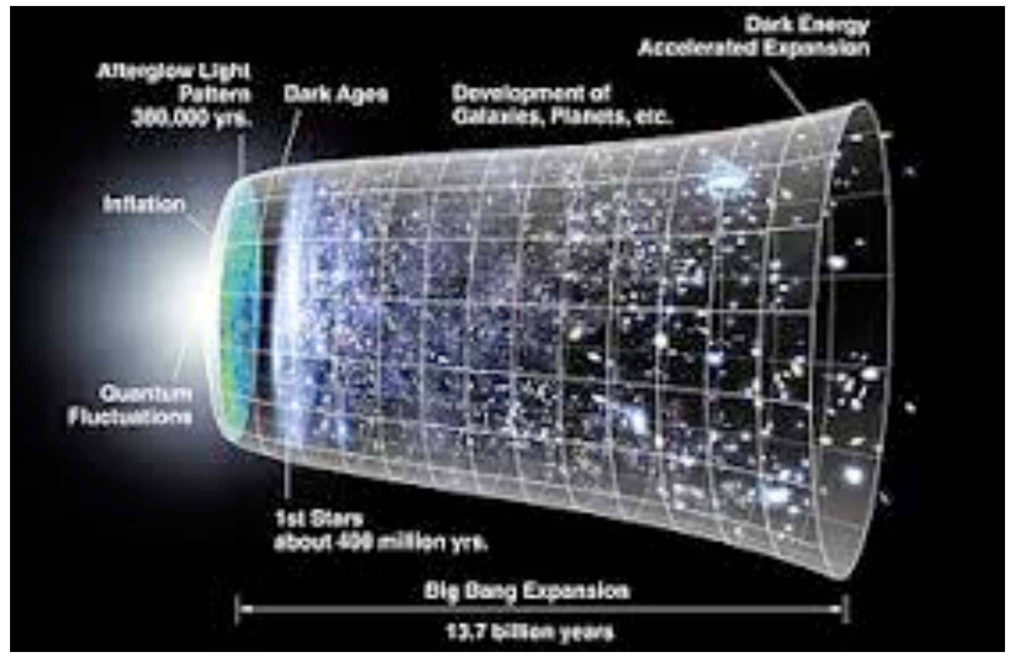



We know there is new physics out there

Matter?
Universe?



Dark Matter



Dark Energy

Hierarchy

Where is this new physics?

Where is this New Physics?

Mass? Strength?

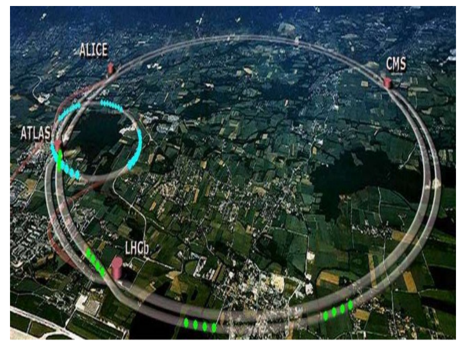
0 **Mass** 10^{19} GeV (Quantum Gravity)

1

Strength

Gravity

Colliders →



Dark Matter, Dark Energy, Inflation…

Neutrinos, Gravitational Waves

Strong Physics Case

How?

Precision => Quantum Sensing, High Statistics

Outline

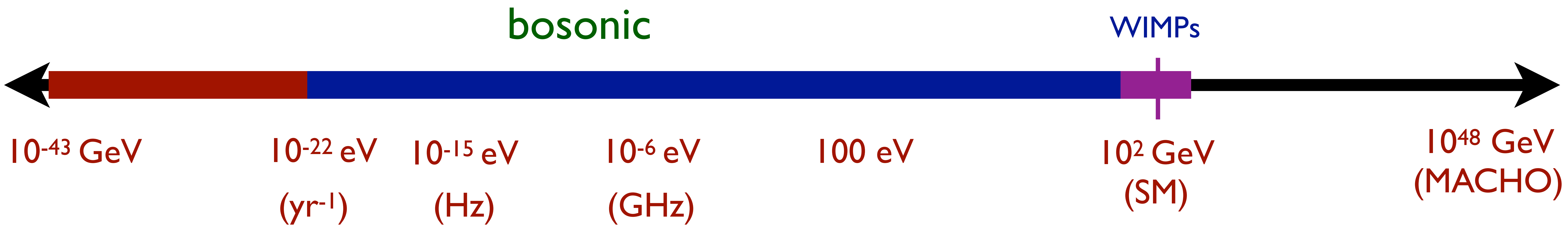
1. Dark Matter with Atom Interferometers and Clocks

2. Missing Energy in Nuclear Decays

3. Conclusions

Atoms and Dark Matter

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)
Soon to hit solar neutrino floor

Other Generic Candidates: Axions, Massive Vector Bosons, Dark Blobs

How do we make progress?

Bosonic Dark Matter

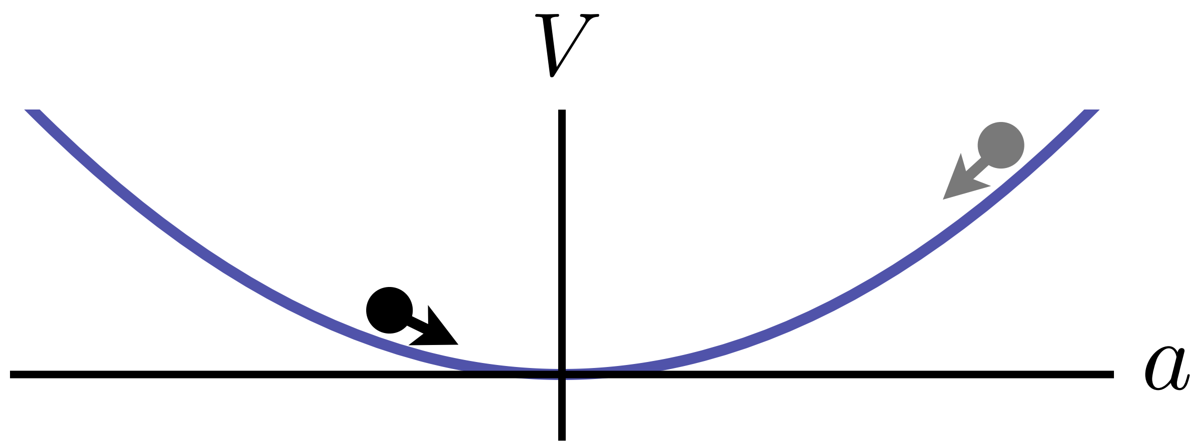
Photons

$$\vec{E} = E_0 \cos(\omega t - \omega x)$$

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

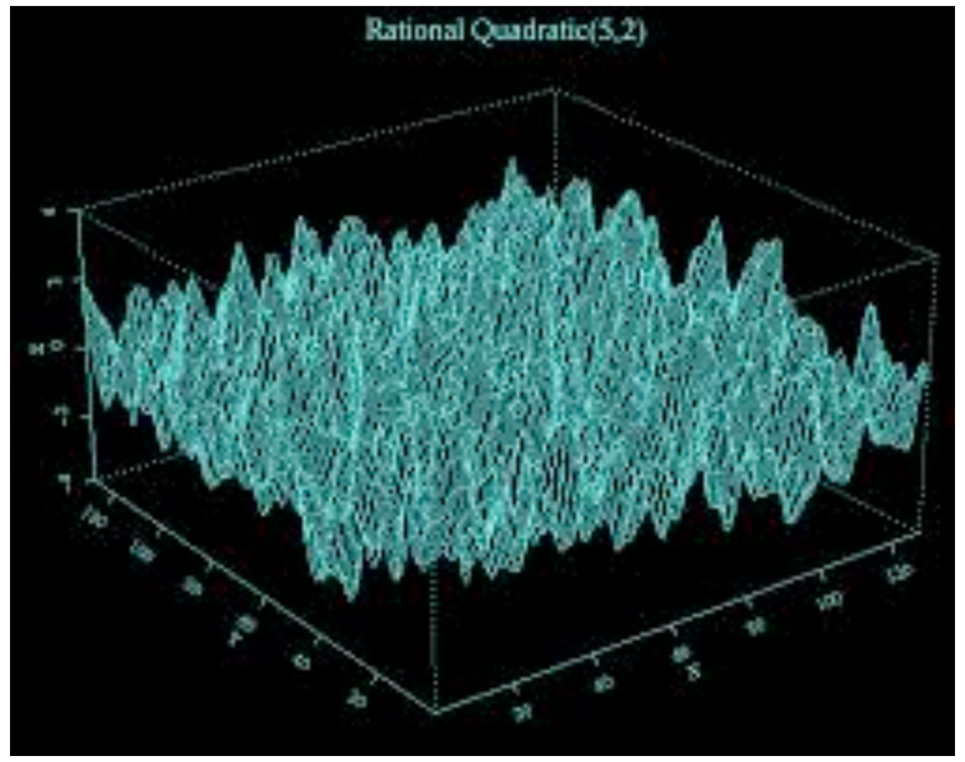


$$a(t) \sim a_0 \cos(m_a t)$$

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

Today: Random Field



Correlation length ~ $1/(m_a v)$

Coherence Time ~ $1/(m_a v^2)$ ~ 1 s (MHz/m_a)

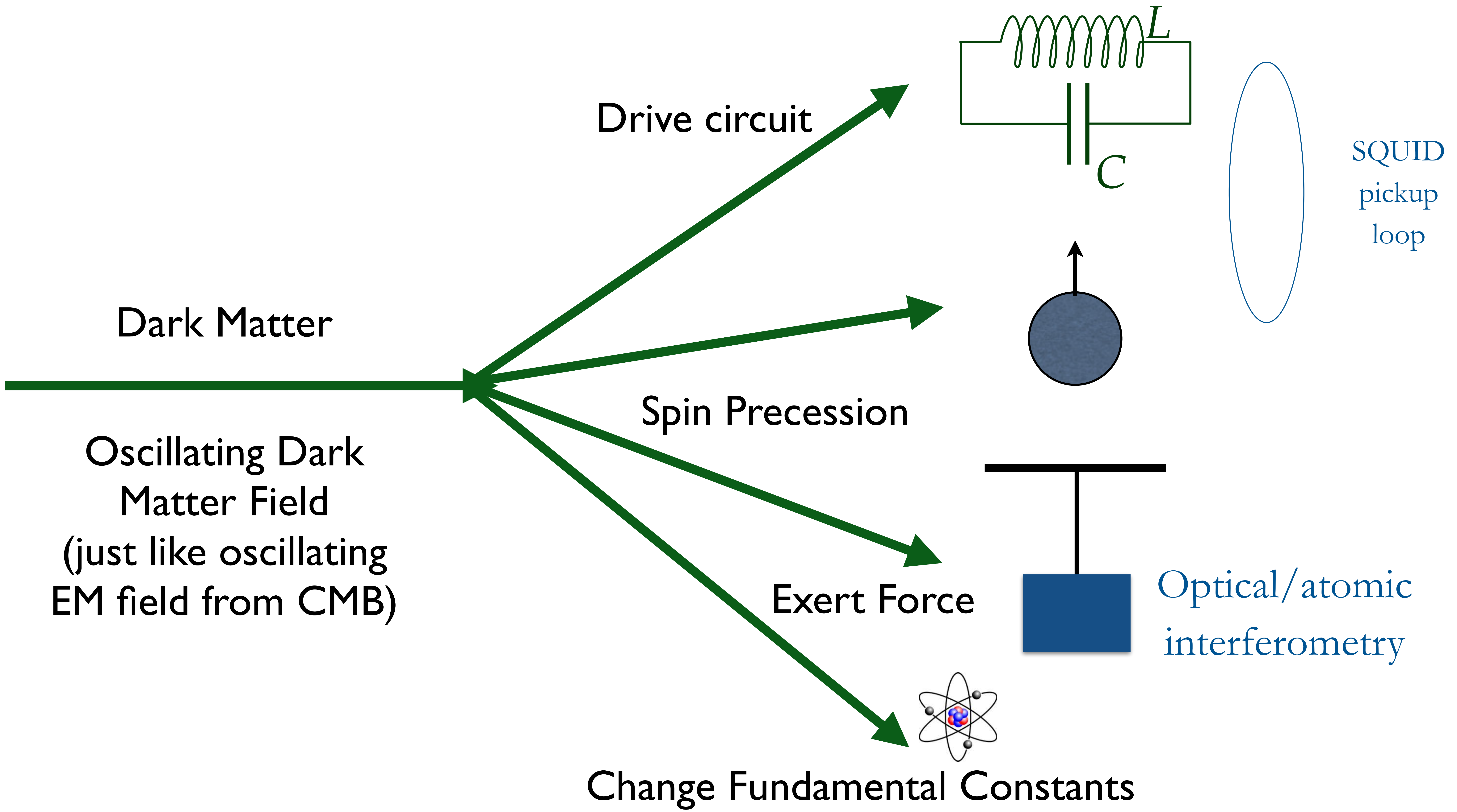
Detect effects of oscillating dark matter field

Resonance possible. Q ~ 10^6 (set by v ~ 10^{-3})

Observable Effects

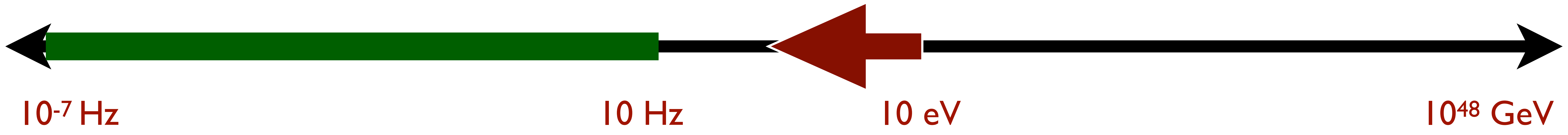
What can the dark matter do?

What can a classical field do?



a/c effect, narrow bandwidth around dark matter mass

Ultralight Dark Matter



Classical field, oscillating at frequency equal to dark matter mass

Prime Candidates: Dilatons, Relaxions, B-L Gauge Bosons

$$\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

Fine Structure

$$\frac{m_e}{M} \phi \bar{\Psi} \Psi$$

Electron Mass

$$A_\mu J^\mu_{B-L}$$

Isotope Dependent Force

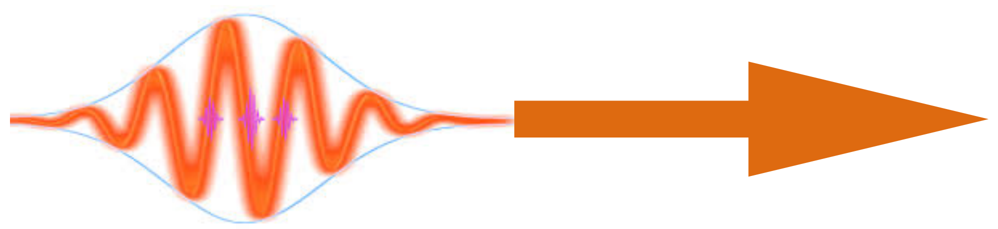
Oscillating, narrow-band (~ 10^{-6}) Signal

Concept

Protocol: Comparison of two quantum sensors

Two Kinds

Clocks Across Baseline



A

@ T, 2 T, 3T…

L

B

Record
Arrival Times

Null Result

Arrival at B: T+L, 2T +L, 3T+L…

Concept

Protocol: Comparison of two quantum sensors

Two Kinds

Clocks Across Baseline

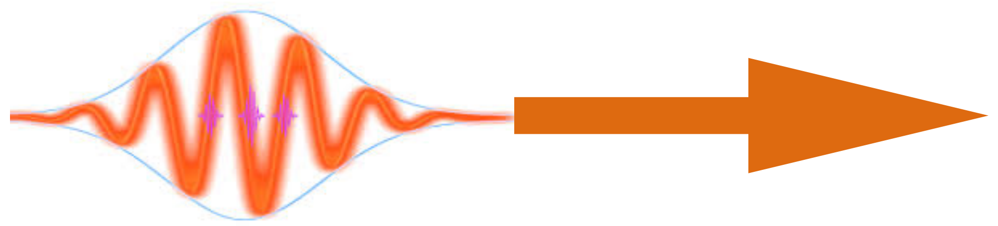
Falling Accelerometers

Null Result

Zero differential acceleration

New Physics?

Protocol: Clocks across a baseline



A ⟵⟶ B

L

@ T, 2 T, 3T…

Null Result

Arrival at B: T+L, 2T +L, 3T+L…

New Physics

Arrival at B: T+L+ε, 2T +L-ε, 3T+L+ε…

What can cause this change?

Record
Arrival Times

New Physics?

Protocol: Clocks across a baseline

A ⟷ B

L

@ T, 2 T, 3T…

Record Arrival Times

Gravitational Waves: L -> L + h L sin(ωt)

Dark Matter: Time variations in fundamental constants α, m_e

New Physics?

Protocol: Falling Accelerometers

Null Result
Zero differential acceleration

New Physics
Differential acceleration

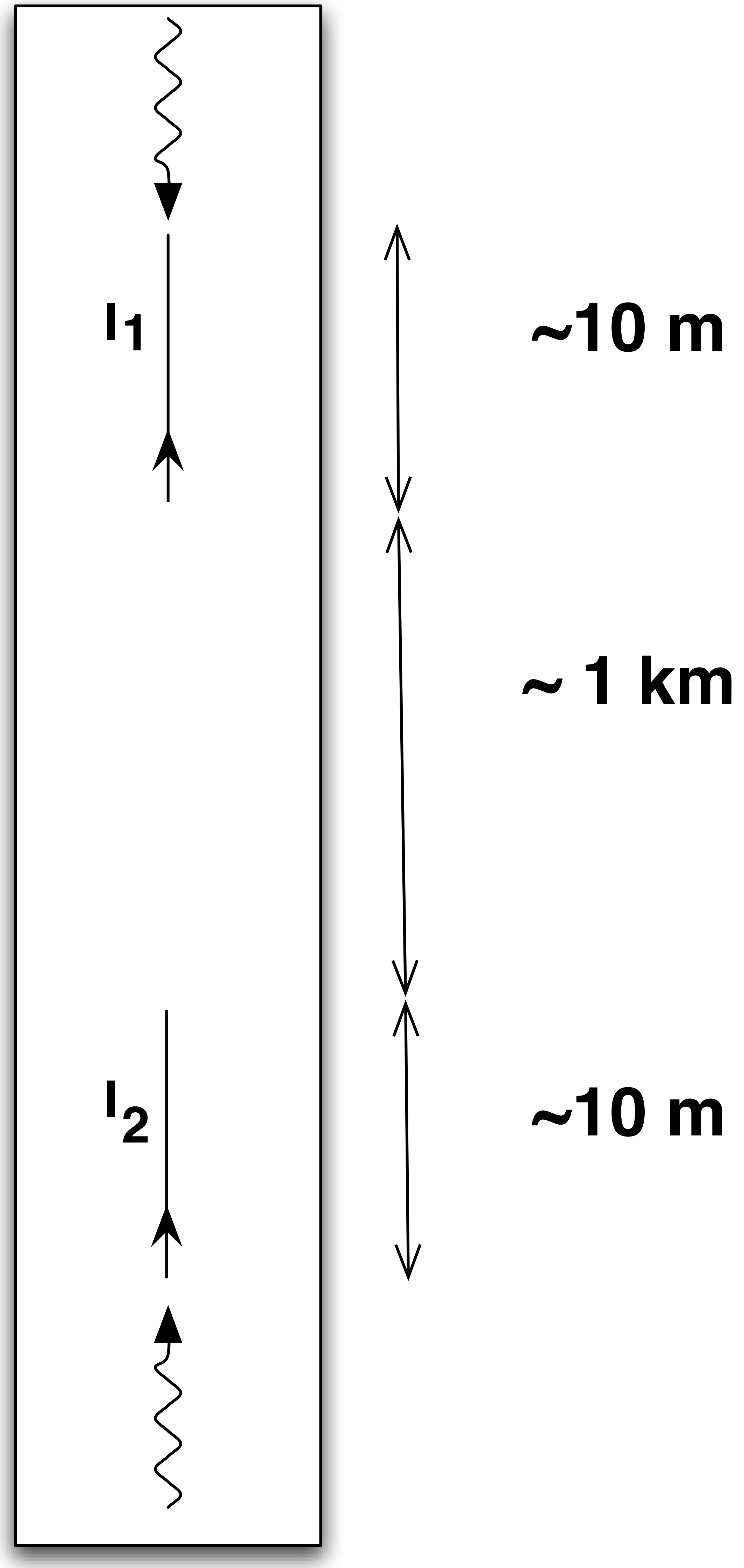
What can cause this change?

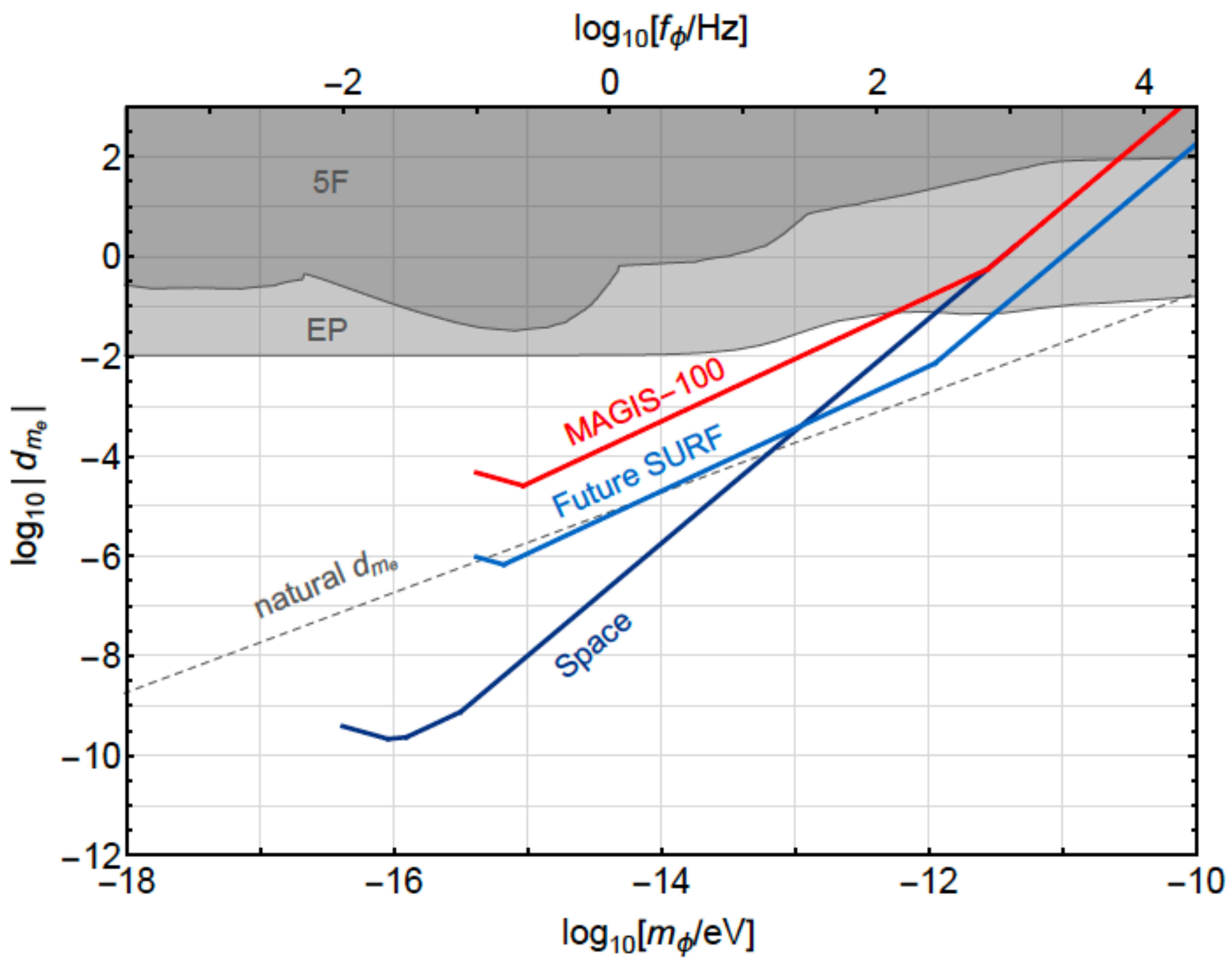
New Physics?

Protocol: Falling Accelerometers

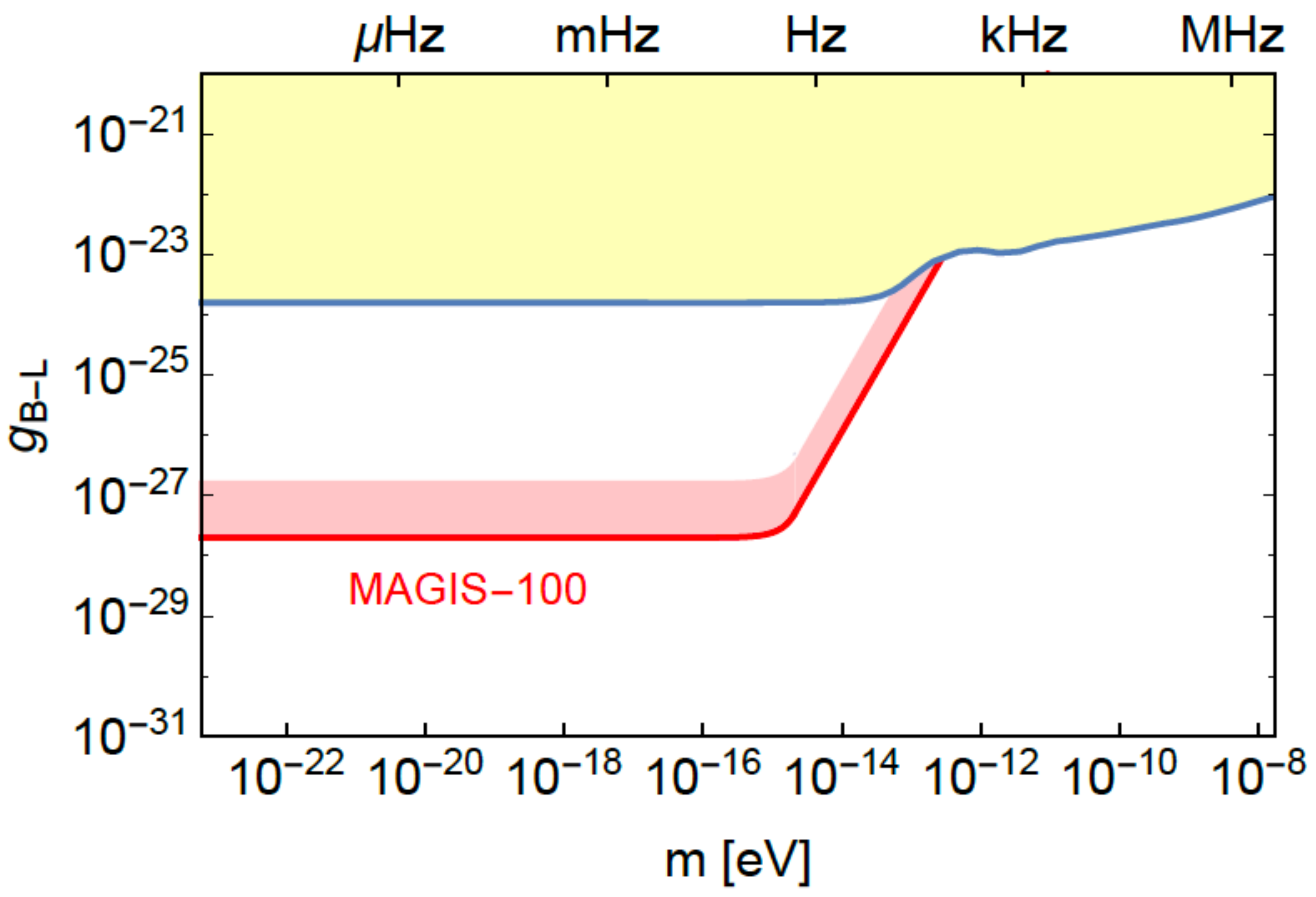
Force from Dark Matter, Earth, Transients (composite dark matter, strings, domain walls etc.)

MAGIS Projected Reach





Atomic Energy Levels



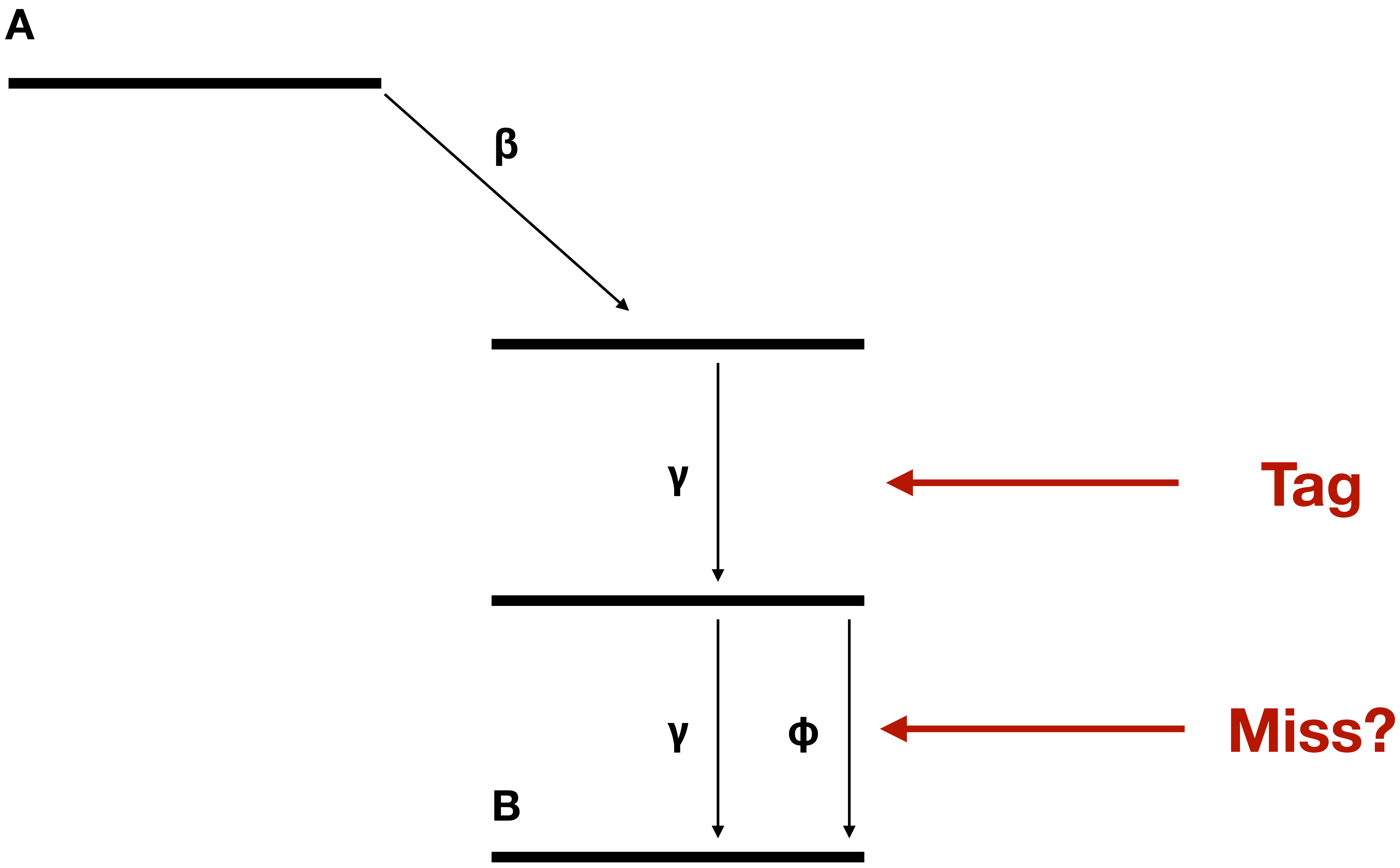
Accelerometer

100 m prototype being constructed at Fermilab

~$10M from Moore, ~$2.5M+ from DoE

Missing Energy in Nuclear Decays

Missing Energy in Gamma Cascades



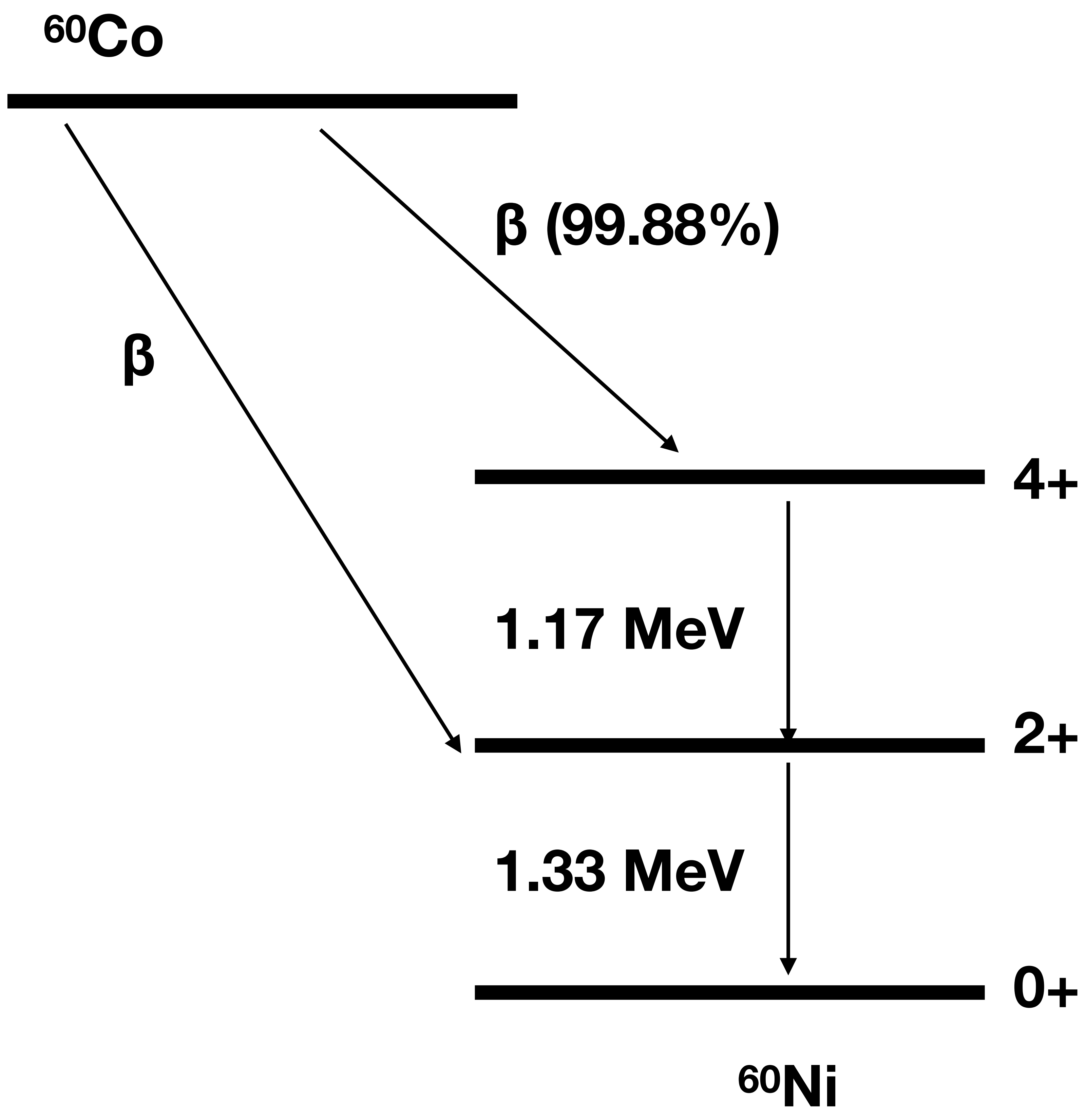
Aim: Single Event for Discovery

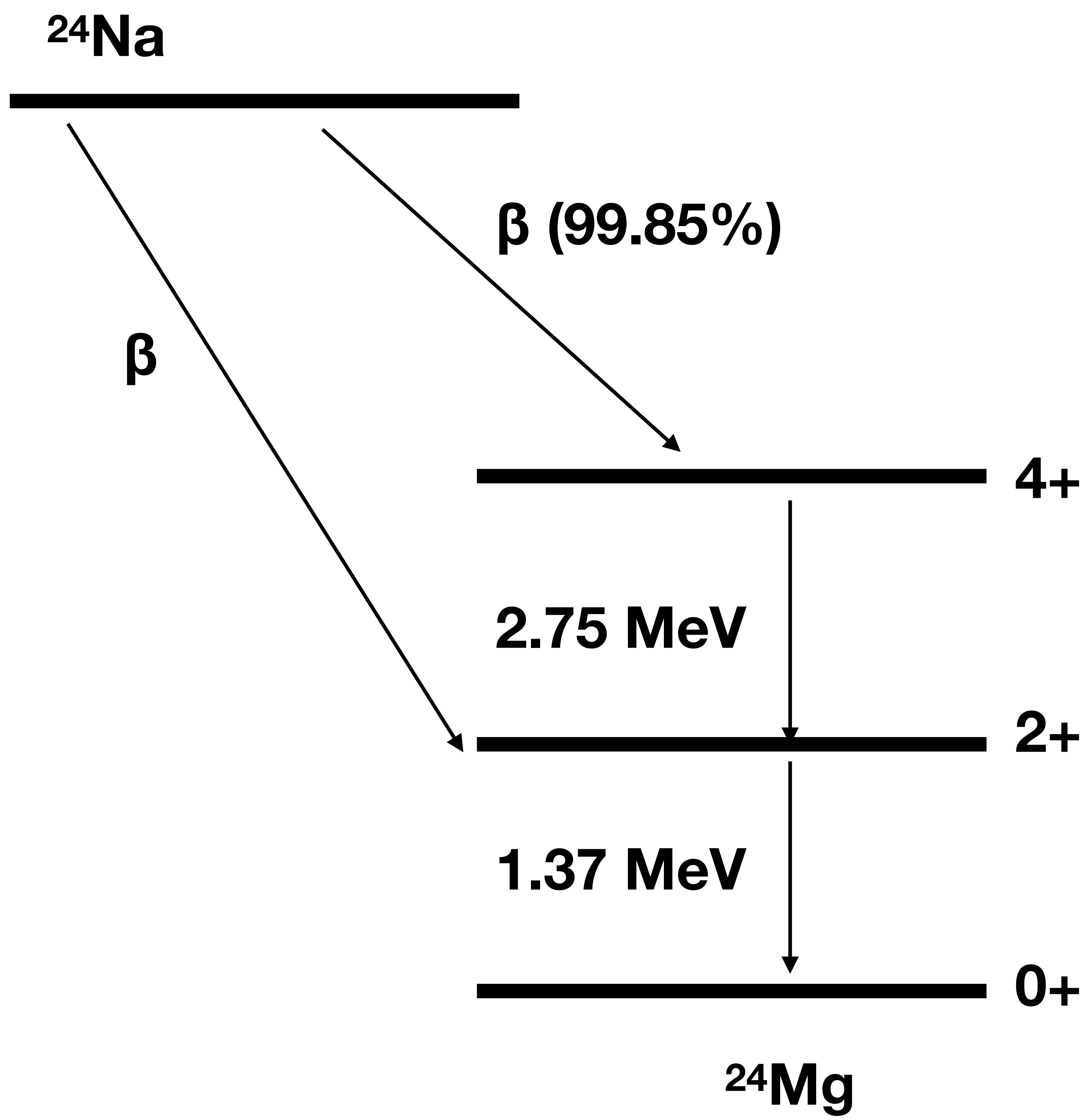
How well can we do?

Baryonically coupled ϕ, mass <~ MeV

Nuclei

Lifetime, Cascade Efficiency, Availability





$t_{1/2}$ ~ 5 years

Similar energy Gammas

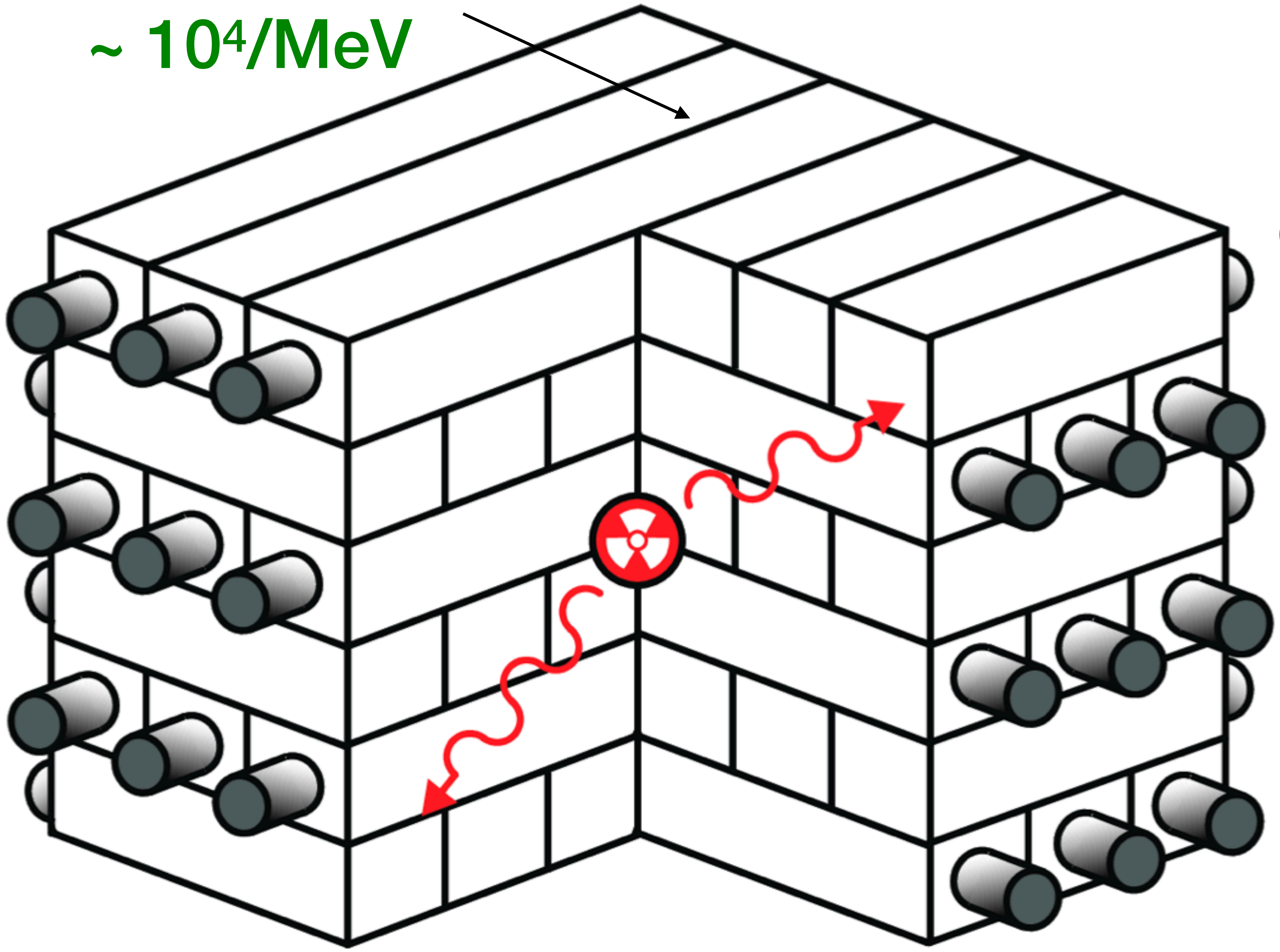
$t_{1/2}$ ~ 15 hr

Medical Isotope

Parity of States -> scalars and vectors

Setup

Setup



Initial Goal: 10^{-11}

Eventual Goal: 10^{-14}

Observe Individual Event

No pile up

High Event Rate

Fast Scintillator

Plastics or Crystals

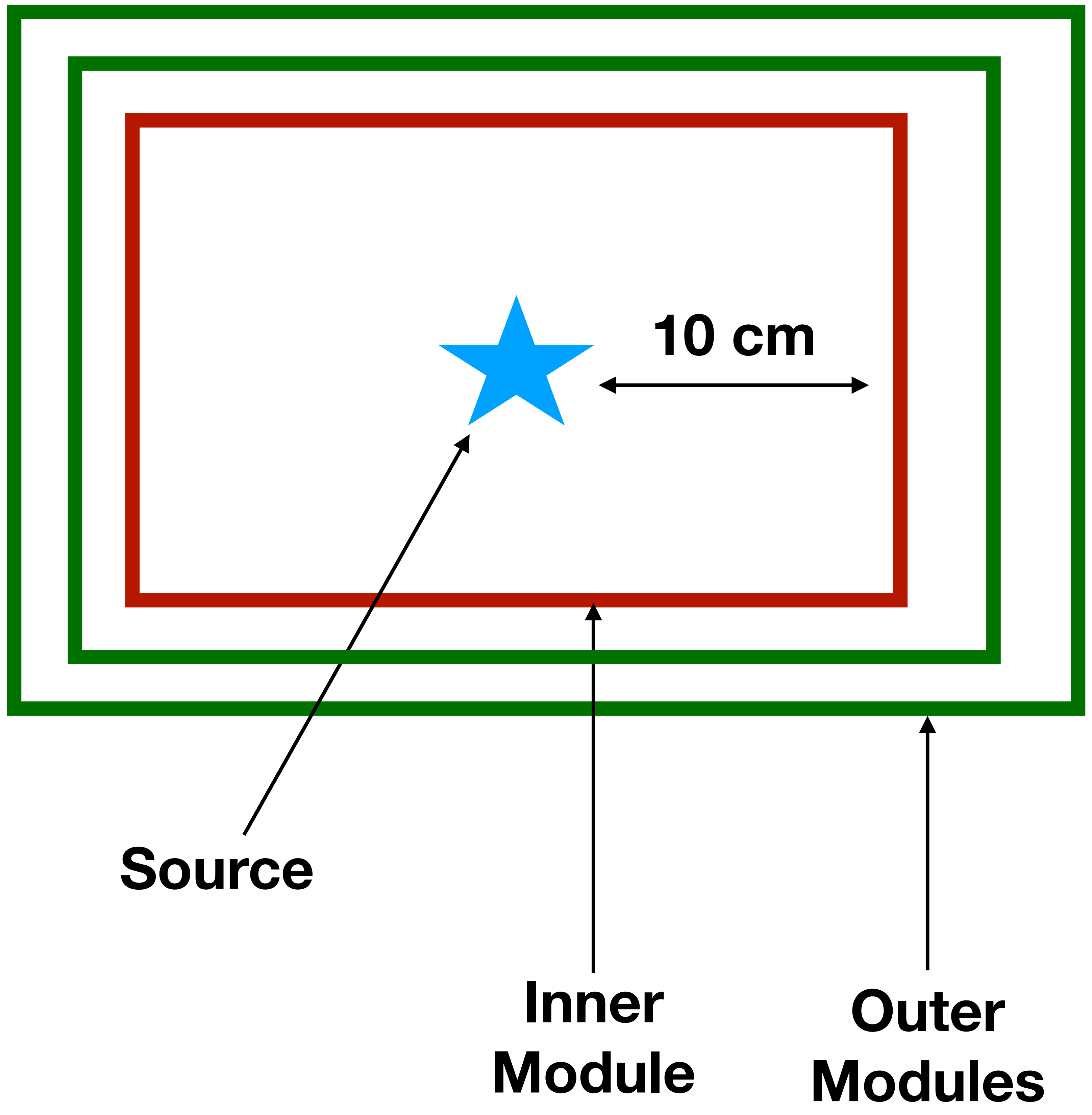
~ ns response

~ 30 radiation lengths

Plastics: ~ 10 m, cheap, make large modules

Crystals: ~ 2 m, harder to grow. CMS E-cal

Protocol



Signal

1. Observe β activity consistent with initial decay

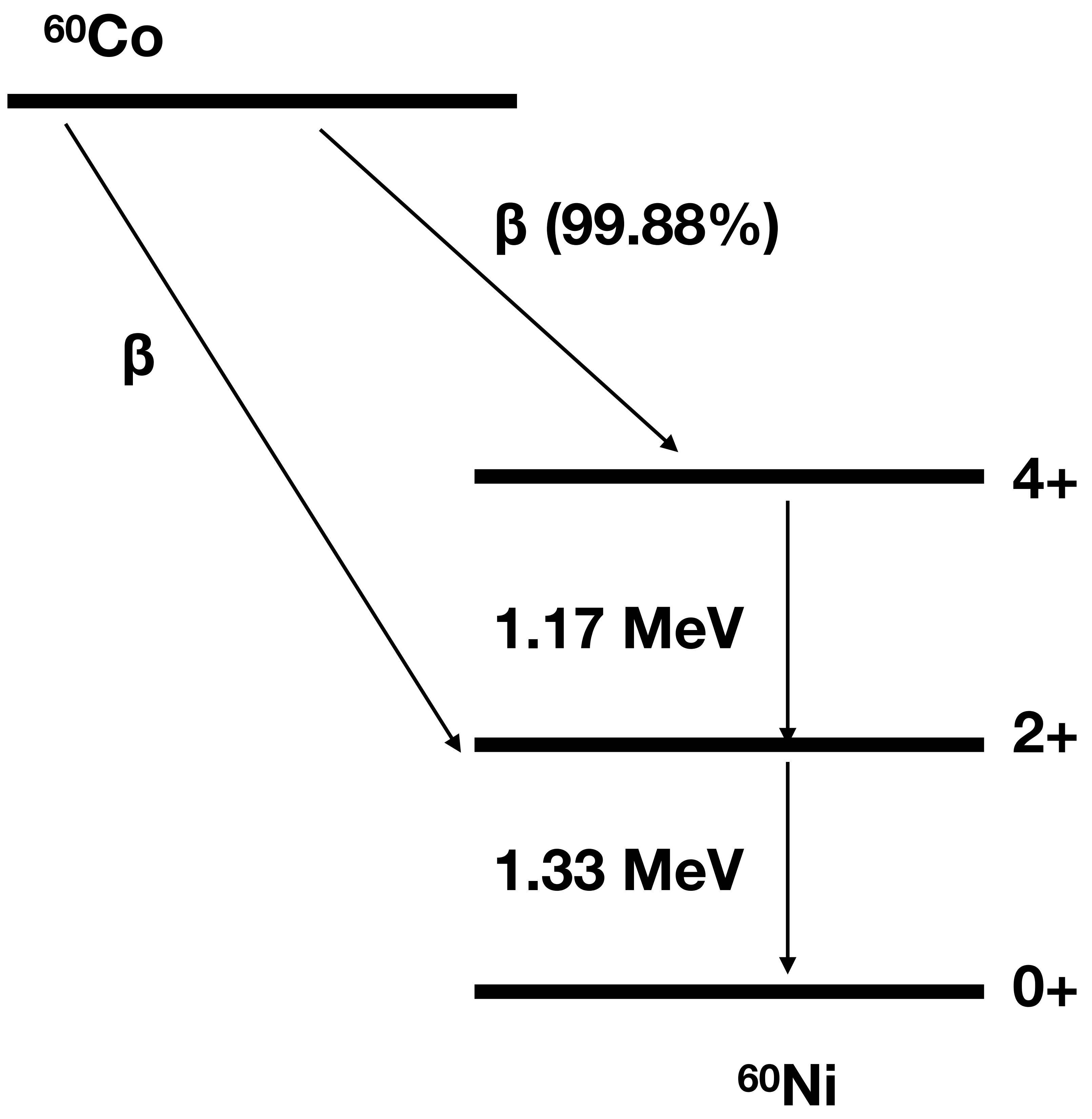
2. Within ~ ns, observe 1st γ in inner module

3. In that ~ ns, no other energy in detector

Backgrounds?

Intrinsic Background for ^{60}Co

Can 2nd γ fake 1st?



Energy Resolution

Produce both. Confuse 1.33 MeV γ for 1.17 MeV γ

Requiring single γ only eliminates background

Soft β to 2+ and Soft Compton γ

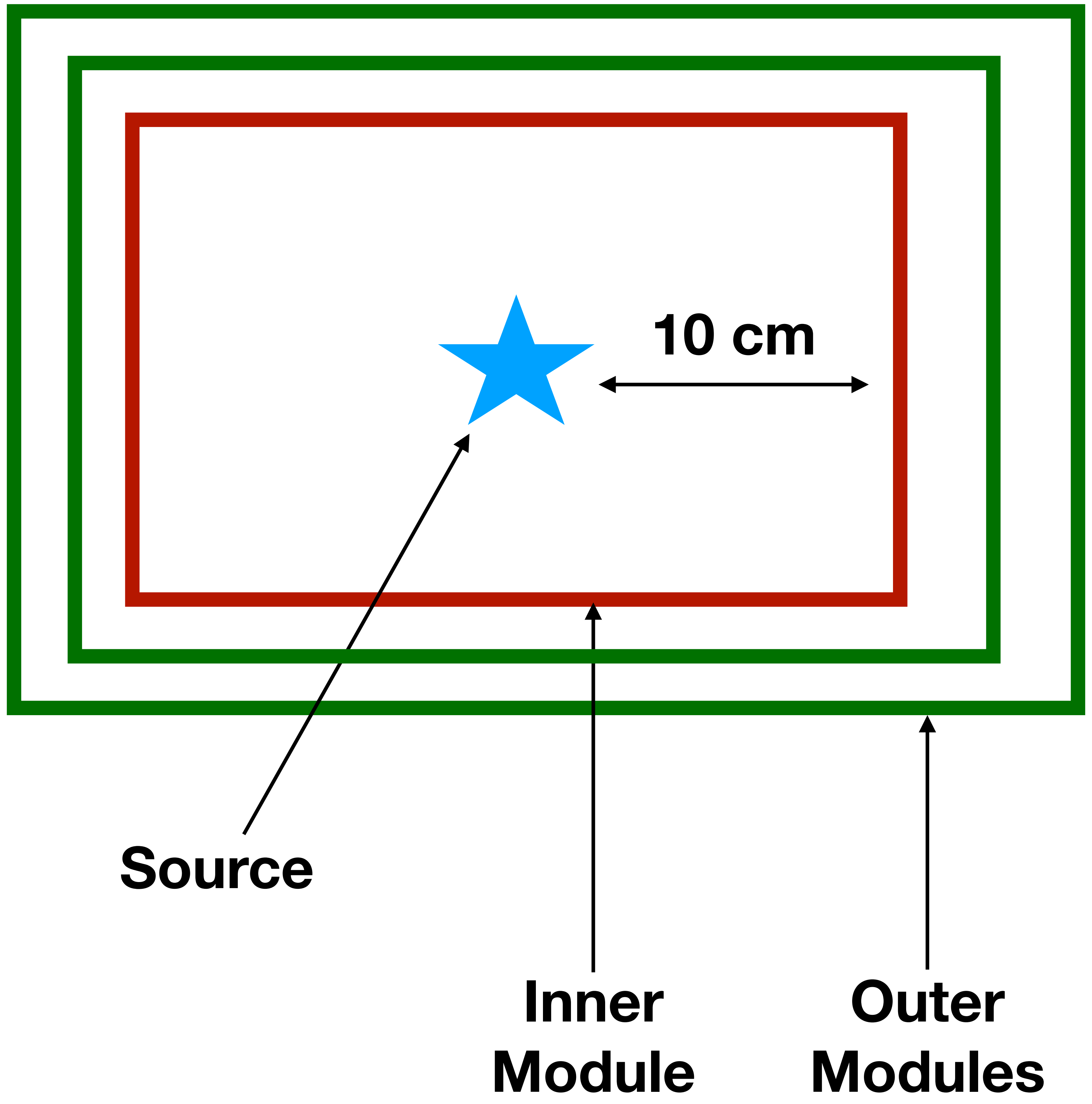
Populate 2+ @ 10^{-3}.

Soft β + Soft 1.33 MeV = β to 4+ and 1.17 γ?

Soft β + Energy Resolution of 1.33 MeV?

Geometry

Soft β to 2+ and Soft Compton γ



Geometry separates β & γ.

Confusion only if both hit same scintillator (~ cm)

Simulated reach ~ 10^{-11}

Possible Elimination?

Separate source from inner module.
Require well separated β & γ

Absent in ^{24}Na where $E_1 >> E_2$

Energy Resolution

Soft β to 2+ and mis-measured energy

Measure energy from light yield (LY)

Light yield set by quantum efficiency of photodetector (Q)

Plastic Scintillators: LY ~ 10000/MeV

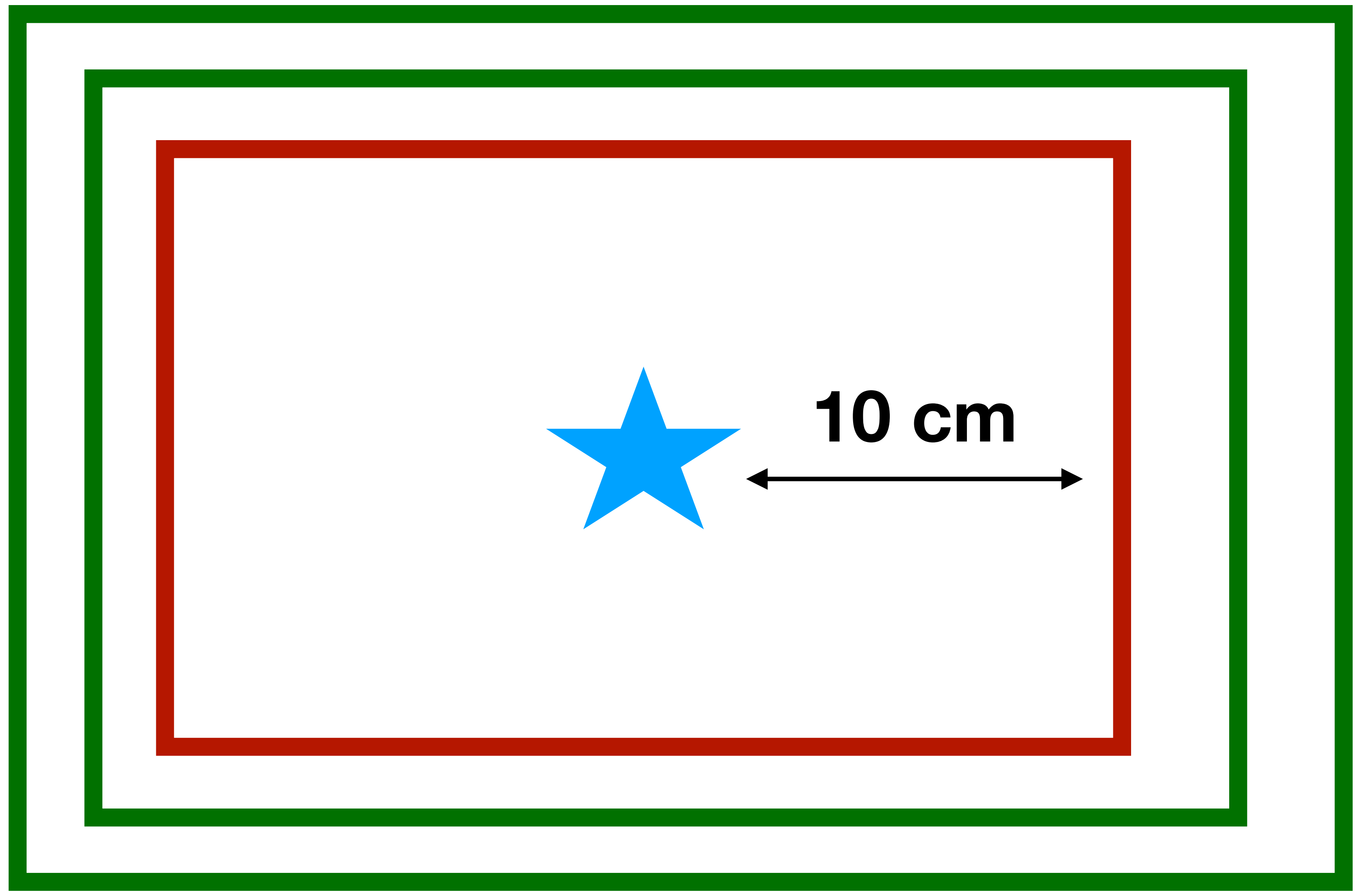
PMT: Q ~ 0.25

$$\mathrm{LY} \times E \times Q \pm \sqrt{E \times LY \times Q} \implies E_m$$

Simulated reach ~ 10^{-11}

Absent in ^{24}Na where $E_1 >> E_2$

Other Backgrounds



Detector Dead Volumes?

Well calibrated inner modules

Radiation Damage < 10^4 Grays

Further limit through separation

Radioactive Contaminants

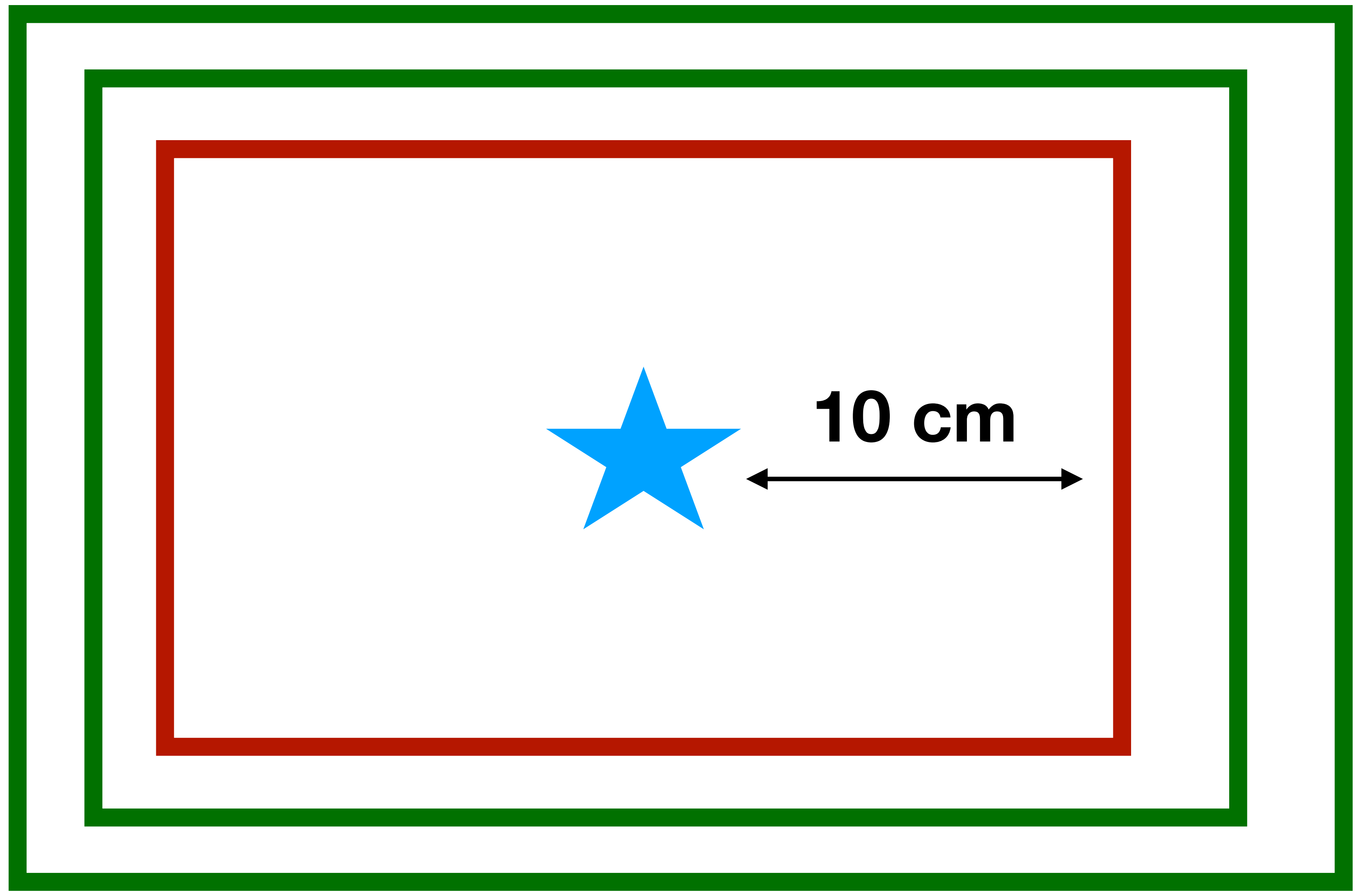
Long lived β at right energy?

None for ^{24}Na.

^{40}K for ^{60}Co - mBq/gm in some plastics.

Demand well separated β and γ in central module, ns timing

Triggers



Trigger

@ 10^{-11}, not as hard as LHC

@ 10^{-14}, comparable to LDMX

Cosmic Rays

Veto event with energy outside inner module

Require well separated β and γ in inner modules within ~ ns

Many radiation lengths separate inner module from environment

Protyping underway in Texas A&M by Rupak Mahapatra's group

Theory/Reach

Model

$$\mathcal{L} \supset g_p \phi \bar{\Psi}_p \Psi_p + \mu^2 \phi^2$$

Need Branching fraction in E2 transitions.

Similar to γ transitions

$$H^{\phi}_{\text{int}} = g_p R^i_p R^j_p \nabla_i \nabla_j \phi \qquad H^{\gamma}_{\text{int}} = e R^i_p R^j_p \nabla_i \epsilon_j$$

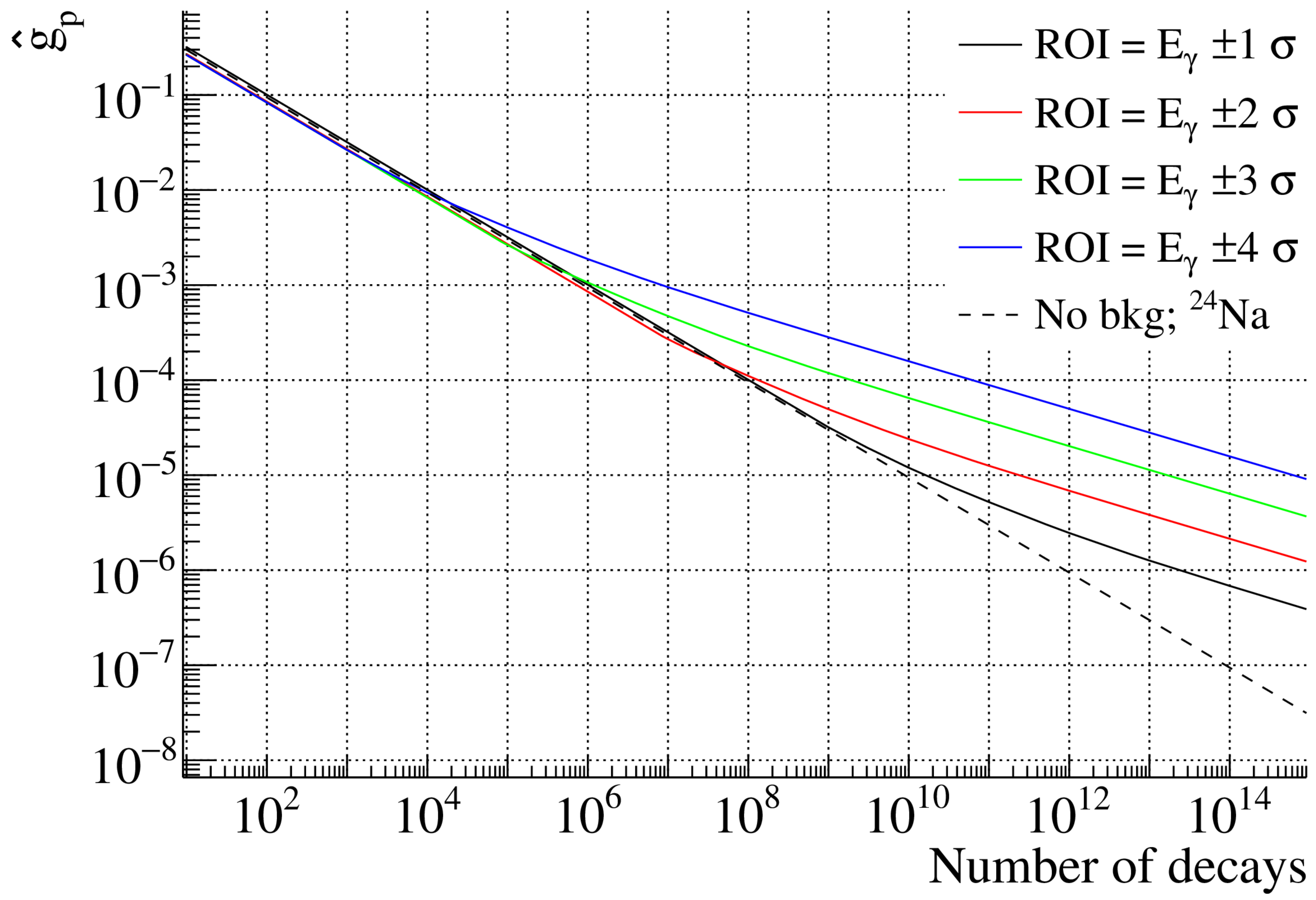
$$\frac{\Gamma_\phi}{\Gamma_\gamma} \sim \frac{g_p^2}{e^2}$$

Poor constraints on baryonic forces > 100 keV

Relevant for light dark matter experiments

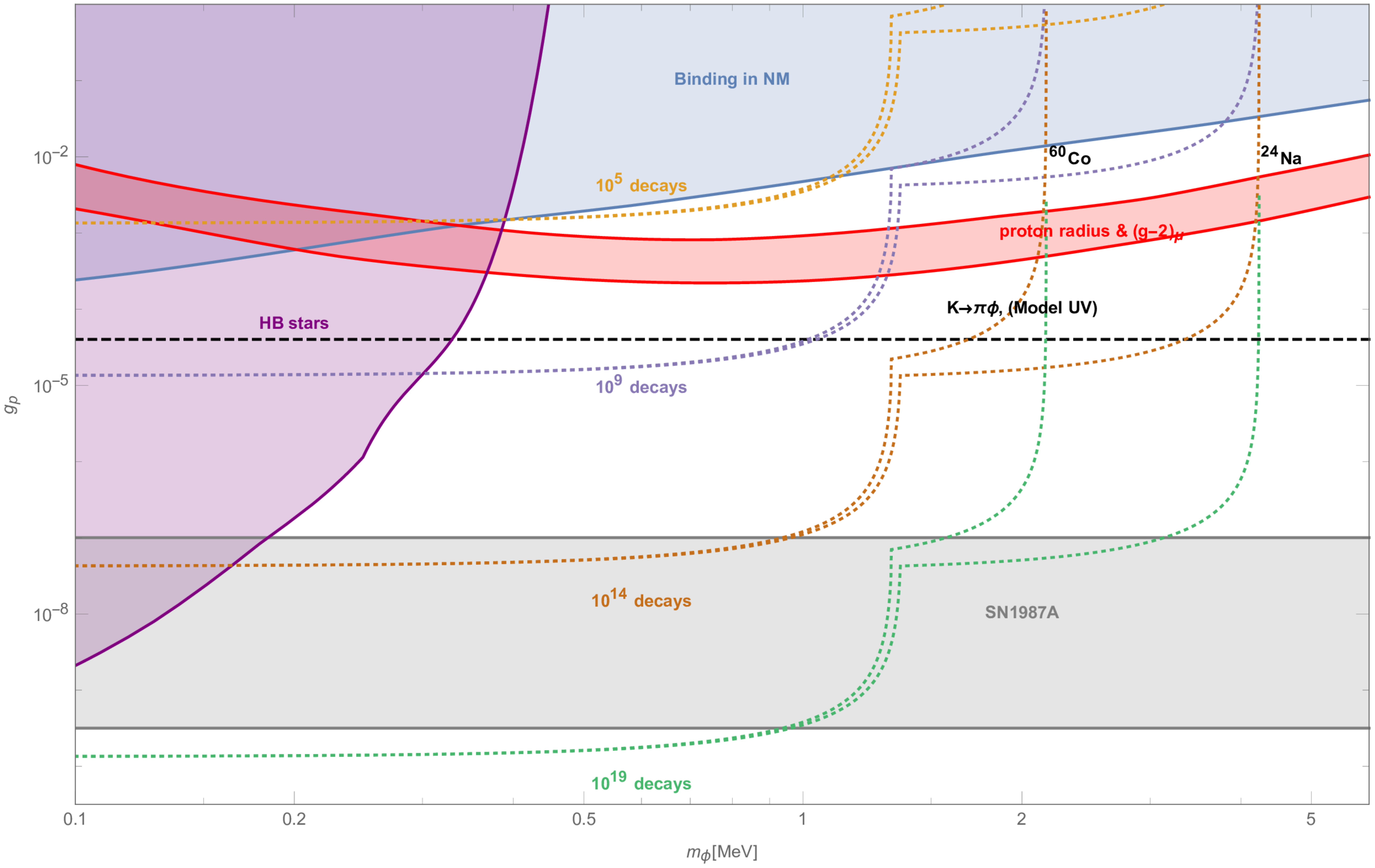
Potentially cause Type 2 Supernova

Reach



$\hat{g}_p$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
Number of decays
ROI = E_γ ±1 σ
ROI = E_γ ±2 σ
ROI = E_γ ±3 σ
ROI = E_γ ±4 σ
No bkg; ^{24}Na

Constraints



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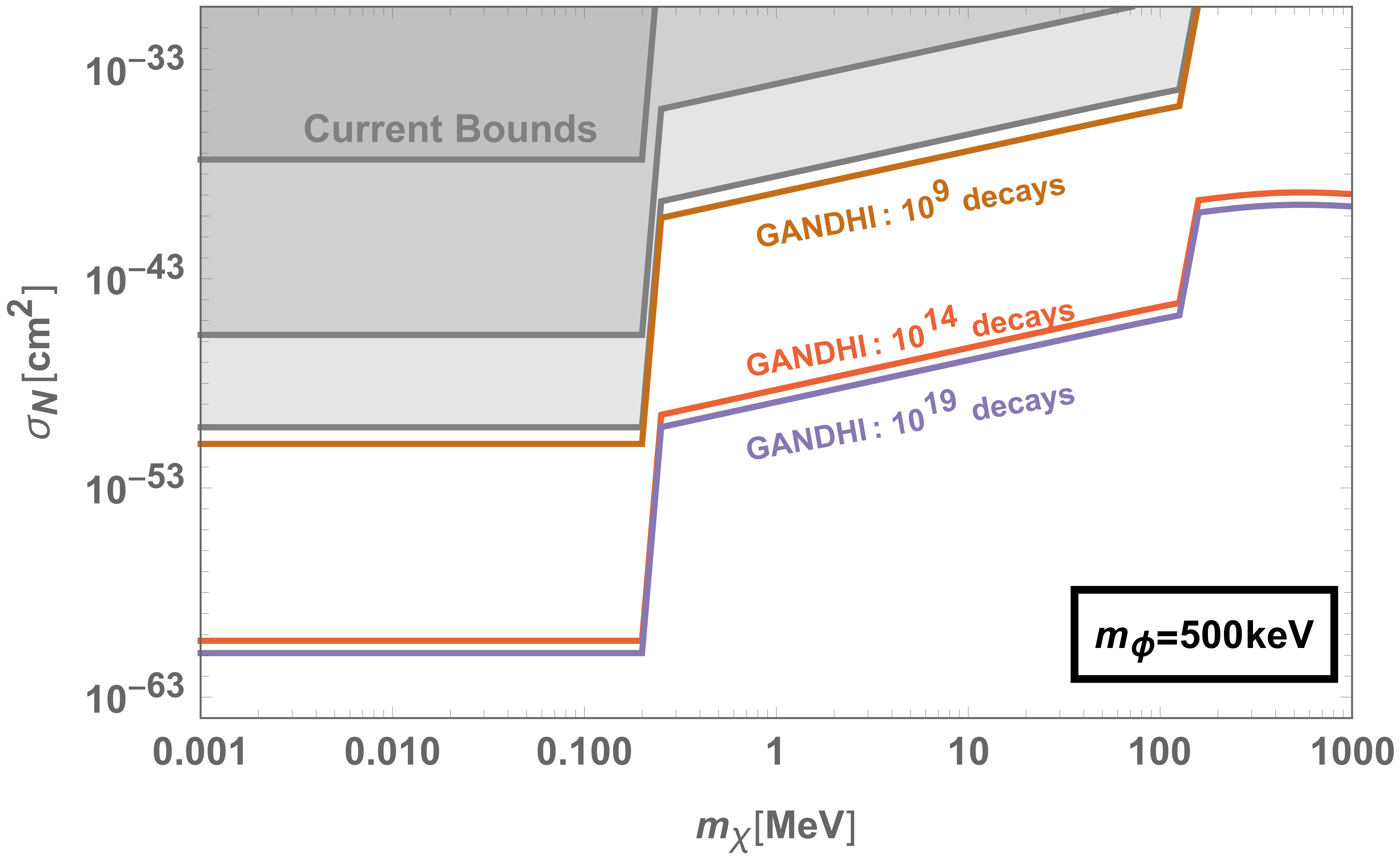

Probe Past Supernova?
(> 10^{12}/s)

Not limited by availability of source. Complex Handling!

Avoid pile up?

Resolve individual events - hard to get good energy resolution beyond ns response times

Geometric Separation of Events

Hard Limit: Trigger Electronics!

Better Nuclear Levels?

Gamma Cascades in forbidden channels? Enhanced branching fraction for scalars?

Axions: M1 transitions - ^{65}Cu -> ^{65}Ni?

Conclusions

Where is this New Physics?

Mass? Strength?

0 **Mass** 10^{19} GeV (Quantum Gravity)

1

Strength

Colliders →

Dark Matter, Dark Energy, Inflation…

Neutrinos, Gravitational Waves

Strong Physics Case

How?

Precision => Quantum Sensing, High Statistics

Gravity