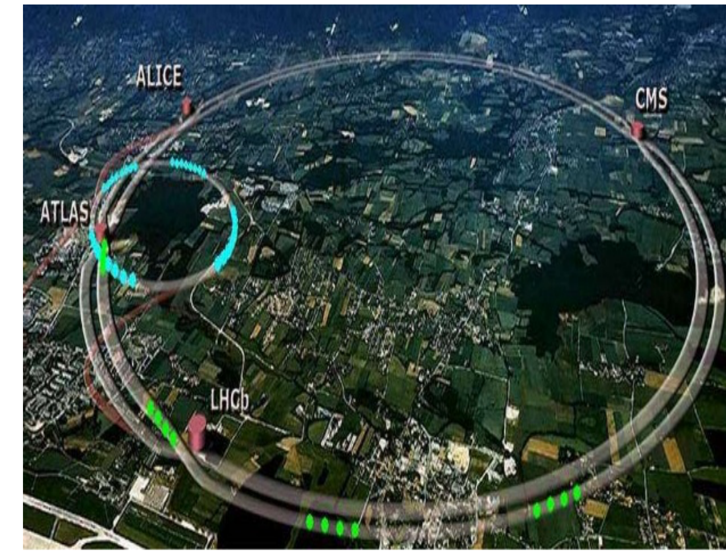
Precision Probes of New Physics with Nuclear and Atomic Physics

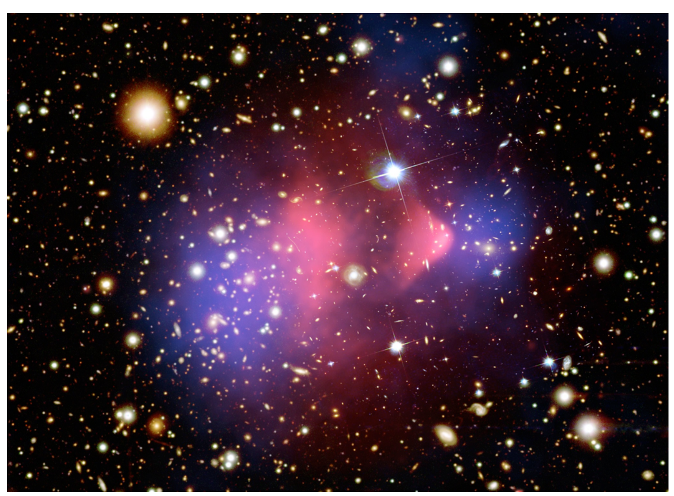
Surjeet Rajendran,
The Johns Hopkins University

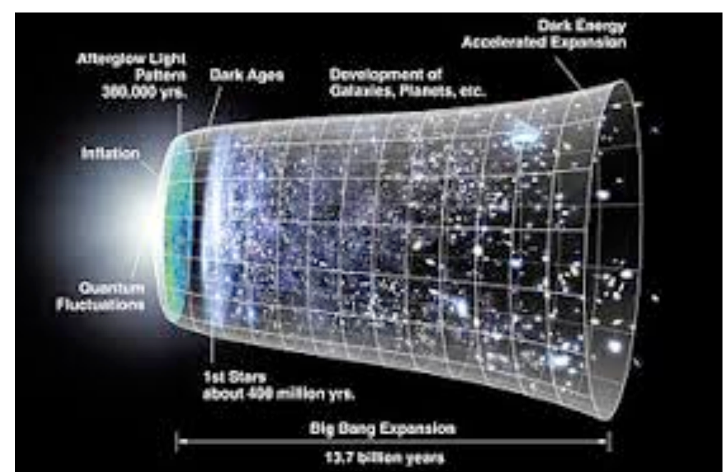
Grand Challenge of High Energy Physics

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?

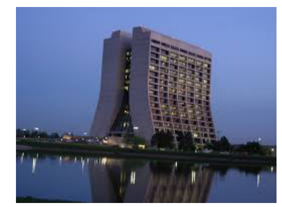
Mass? Strength?

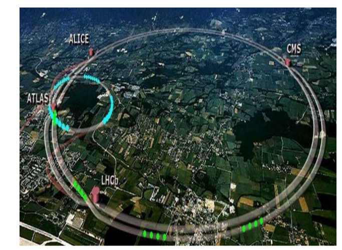
0 **Mass** 10^{19} GeV (Quantum Gravity)

1

Strength

Colliders →





Gravitational Waves,
Dark Matter,
Dark Energy

Strong Physics Case

Gravity

Where is this New Physics?

Mass? Strength?

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

1

Strength

Colliders →

Gravitational Waves,
Dark Matter,
Dark Energy

↓

How?

**Statistics, Amplification,
Quantum Sensing**

Gravity

Outline

1. The GANDHI Experiment

2. Magnetic Bubble Chambers

3. Directional Detection with NV Centers

4. Conclusions

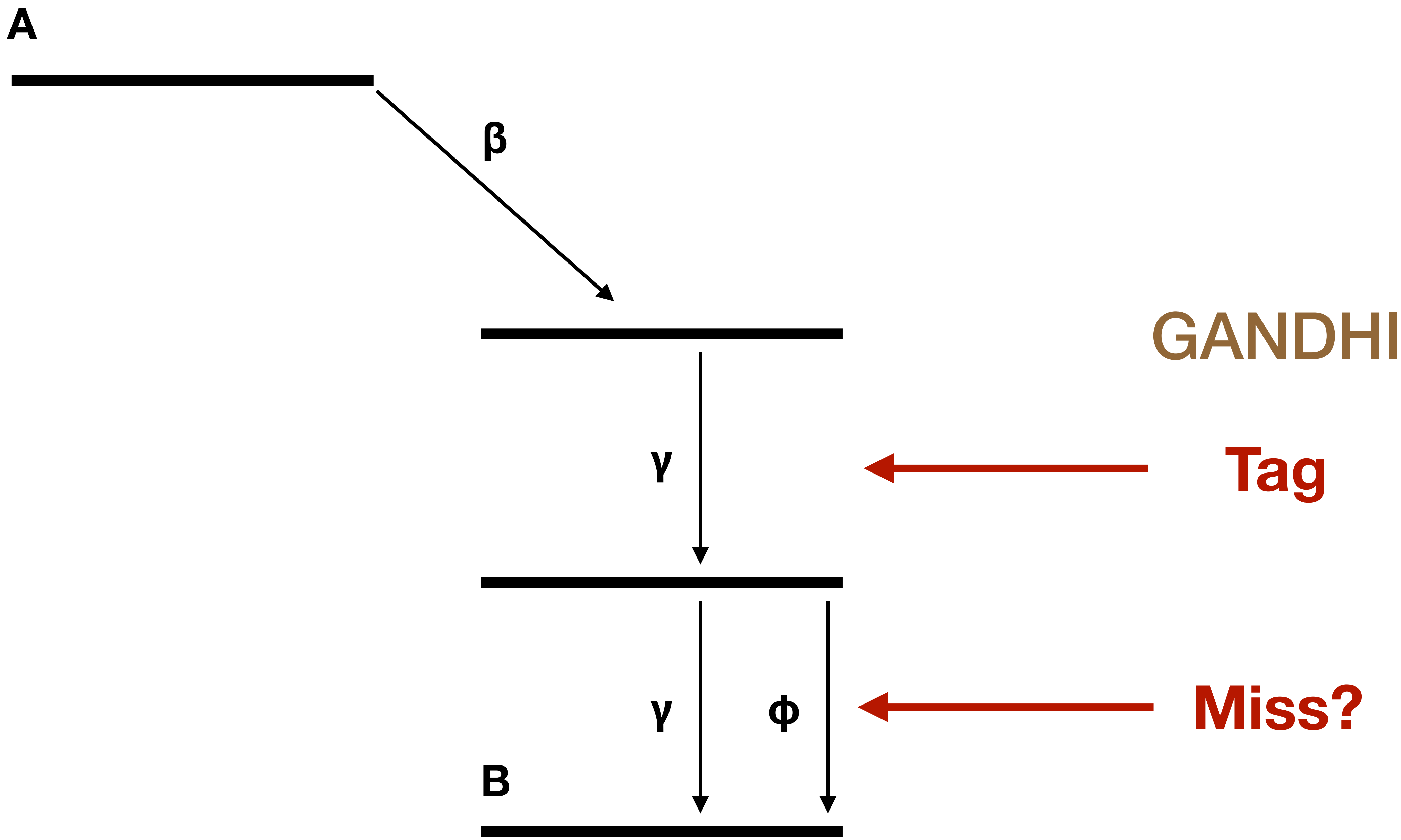
GAmma Nuclear Decays Hiding from Investigators Experiment (GANDHI)

Surjeet Rajendran
with

Giovanni Benato, Alexey Drobizhev and Hari Ramani

Proof of Concept:
Rupak Mahapatra (TAMU)

Missing Energy in Gamma Cascades



Aim: Single Event for Discovery

How well can we do?

Baryonically coupled ϕ, mass <~ MeV

Outline

1. Nuclei

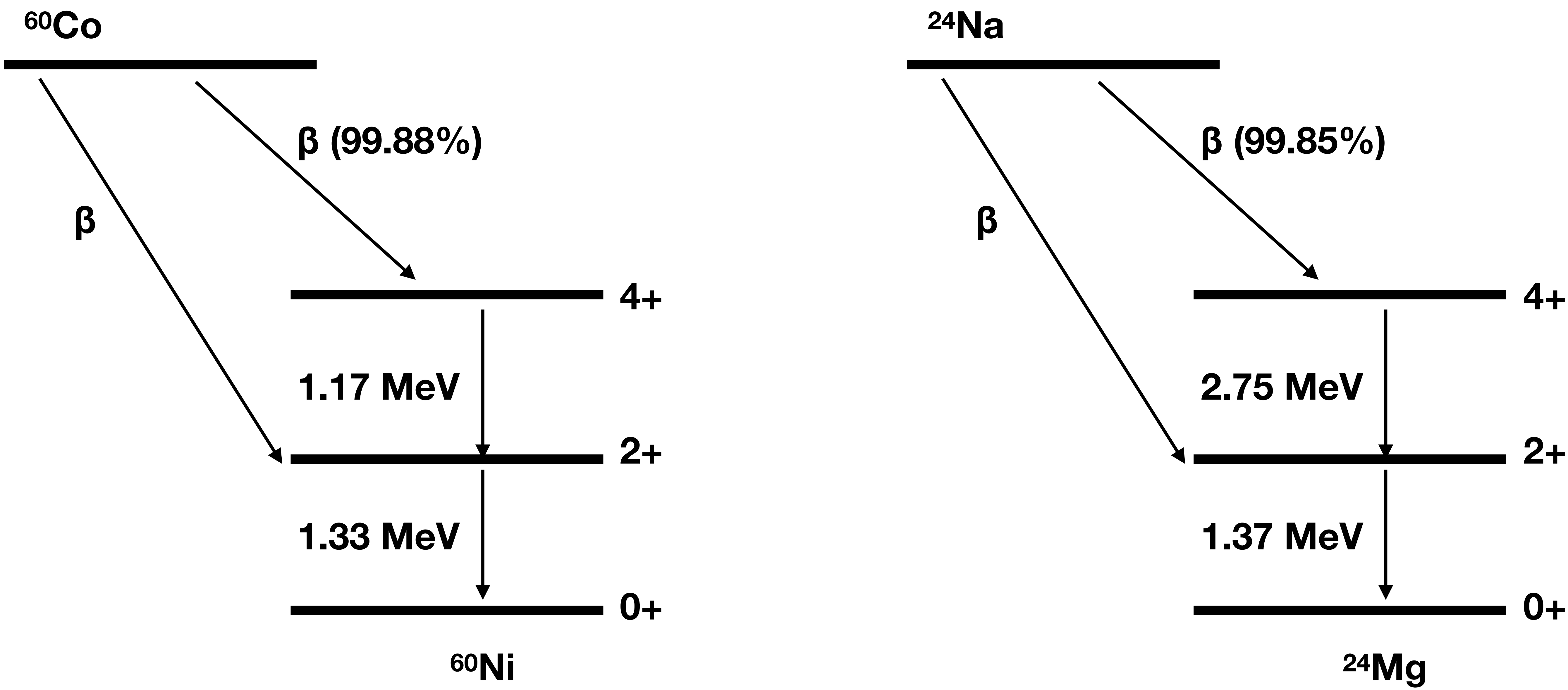
2. Setup

3. Theory/Reach

Nuclei

Nuclei

Lifetime, Cascade Efficiency, Availability



$t_{1/2}$ ~ 5 years | $t_{1/2}$ ~ 15 hr

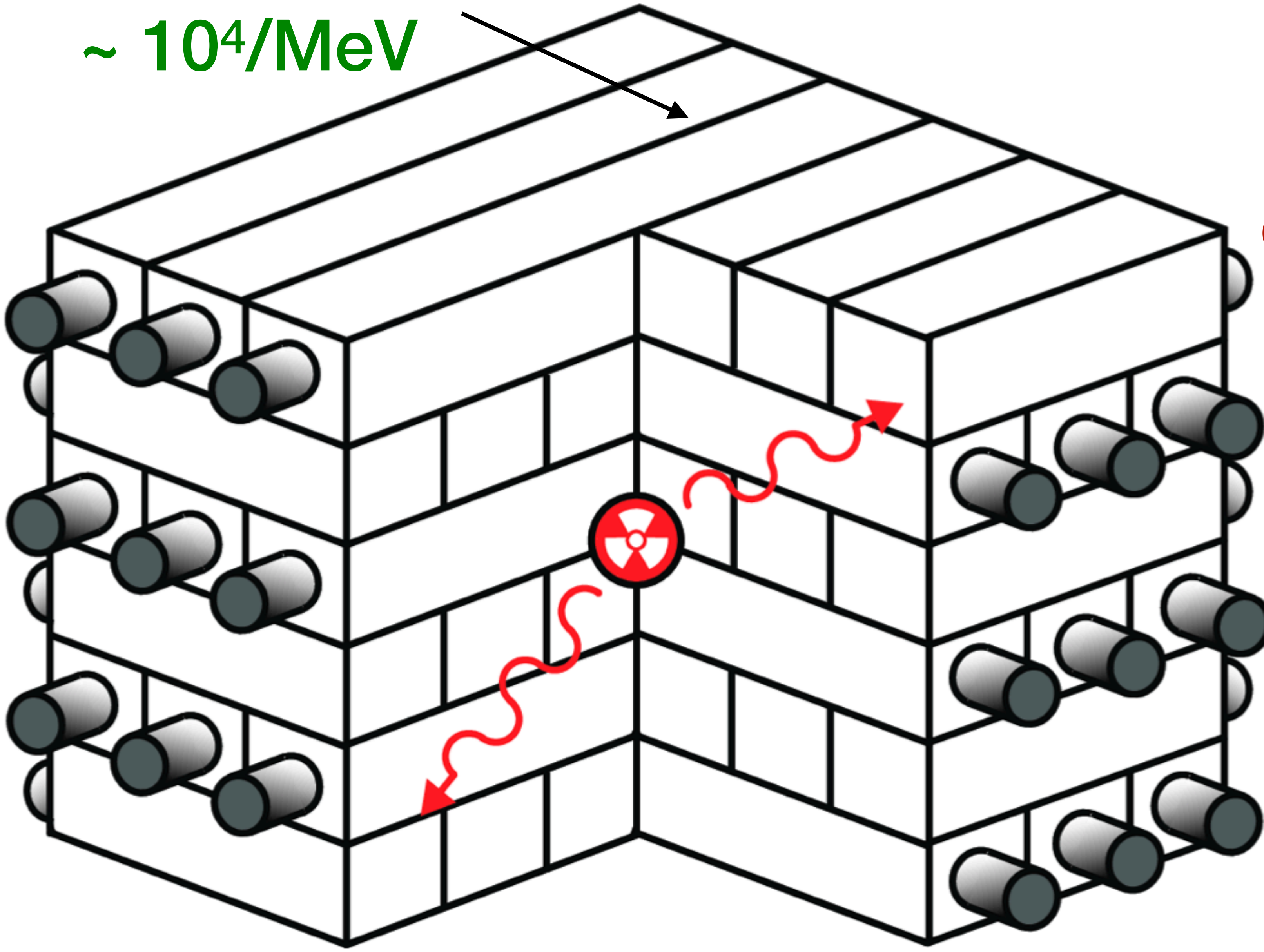
Similar energy Gammas | Medical Isotope

Parity of States -> scalars and vectors

Setup

Setup

Scintillator
~ 10^4/MeV



Initial Goal: 10^{-11}
Eventual Goal: 10^{-14}

Observe Individual Event
No pile up

High Event Rate
Fast Scintillator

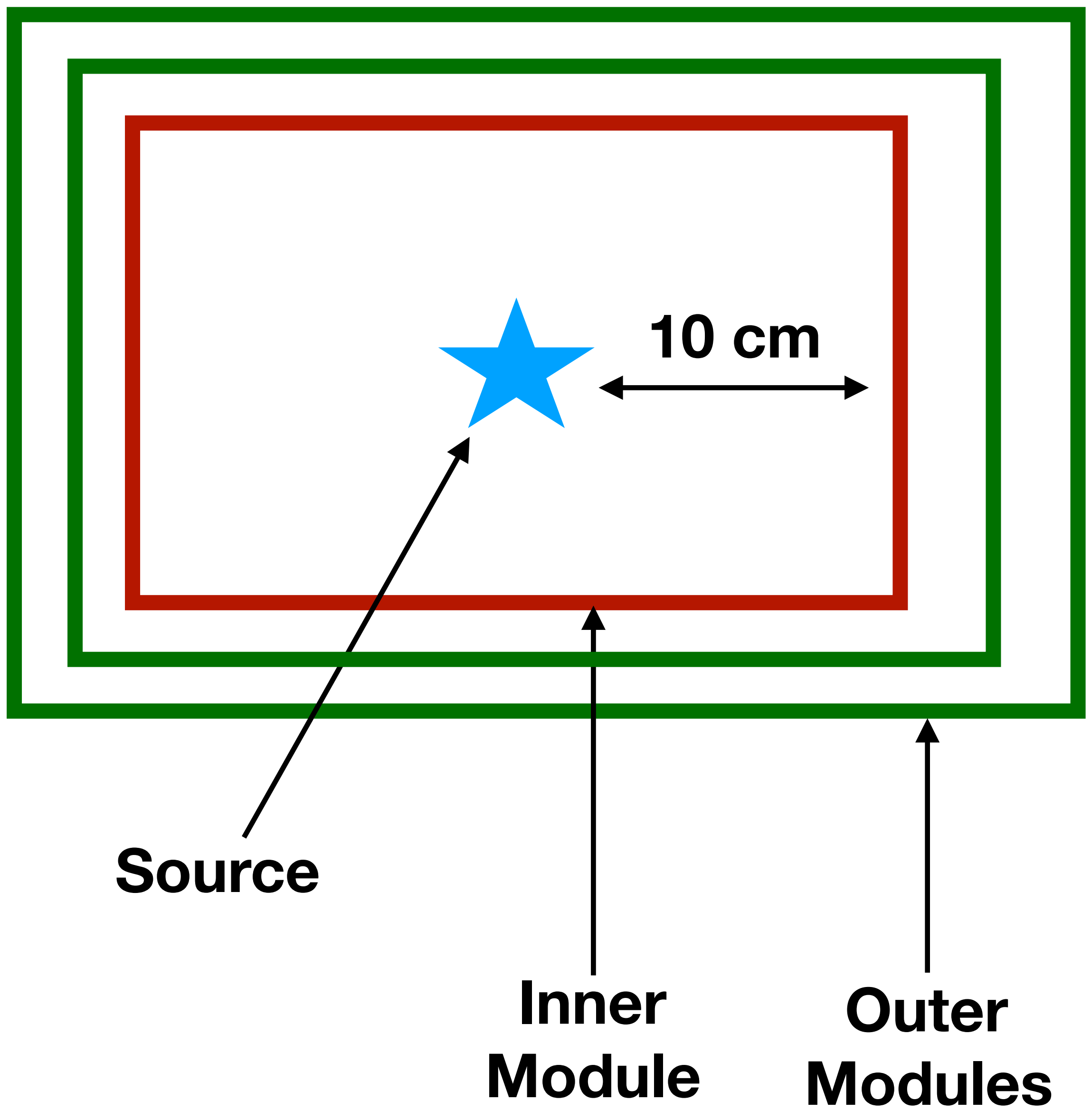
Plastics or Crystals
~ ns response

~ 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

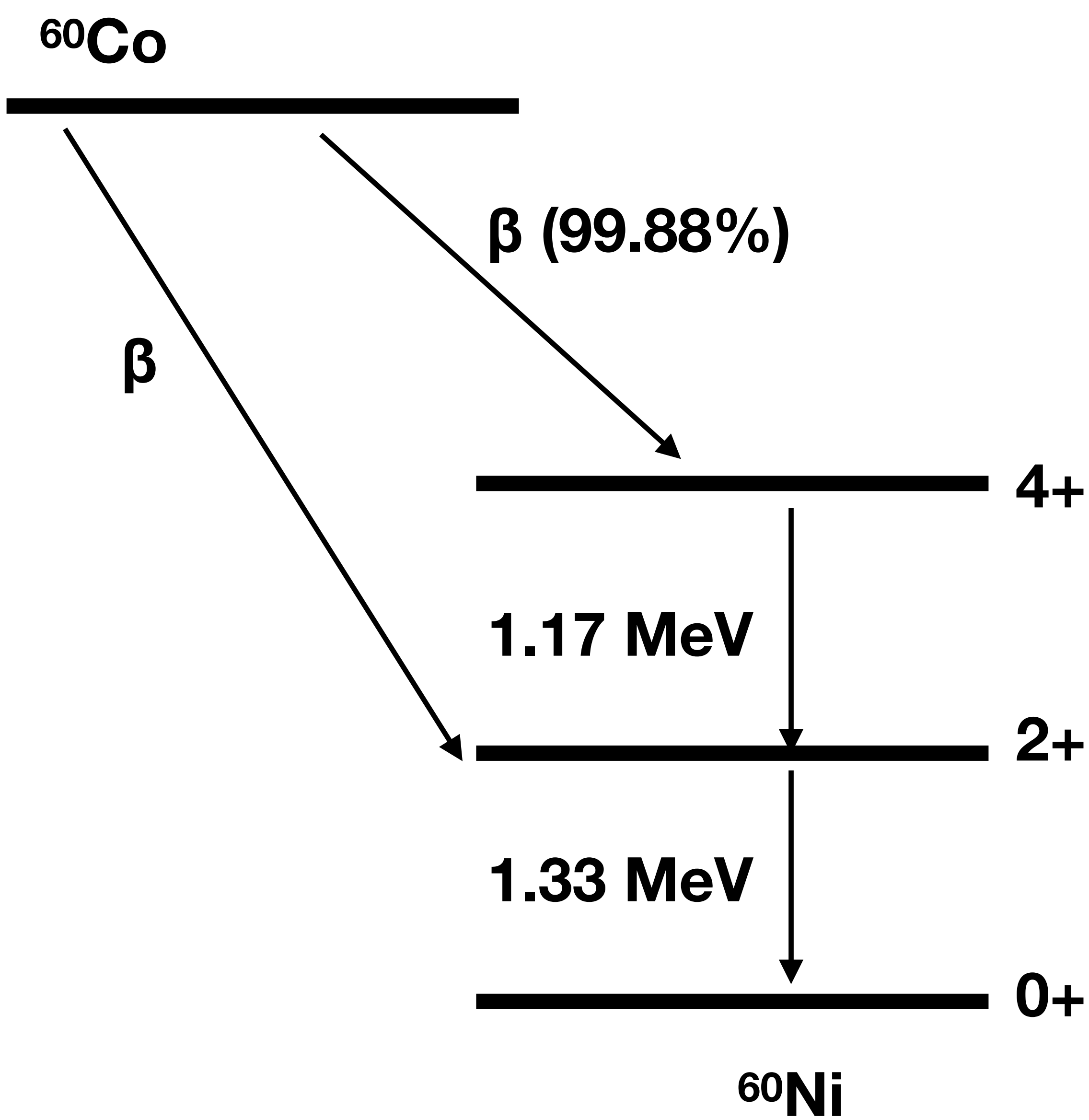
2. Within ~ ns, observe 1st γ in inner module

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

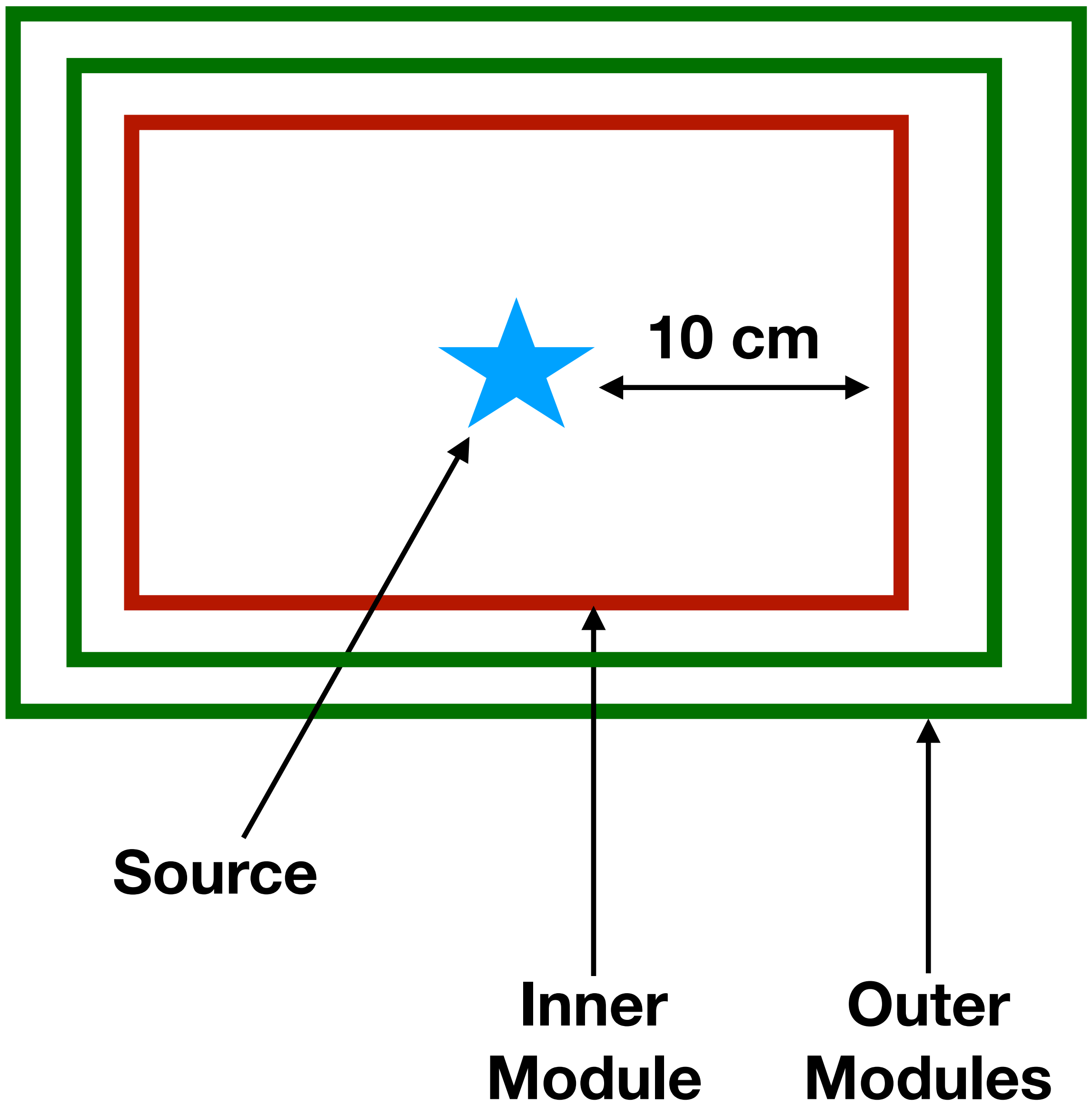
Populate 2+ @ 10^{-3}.

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

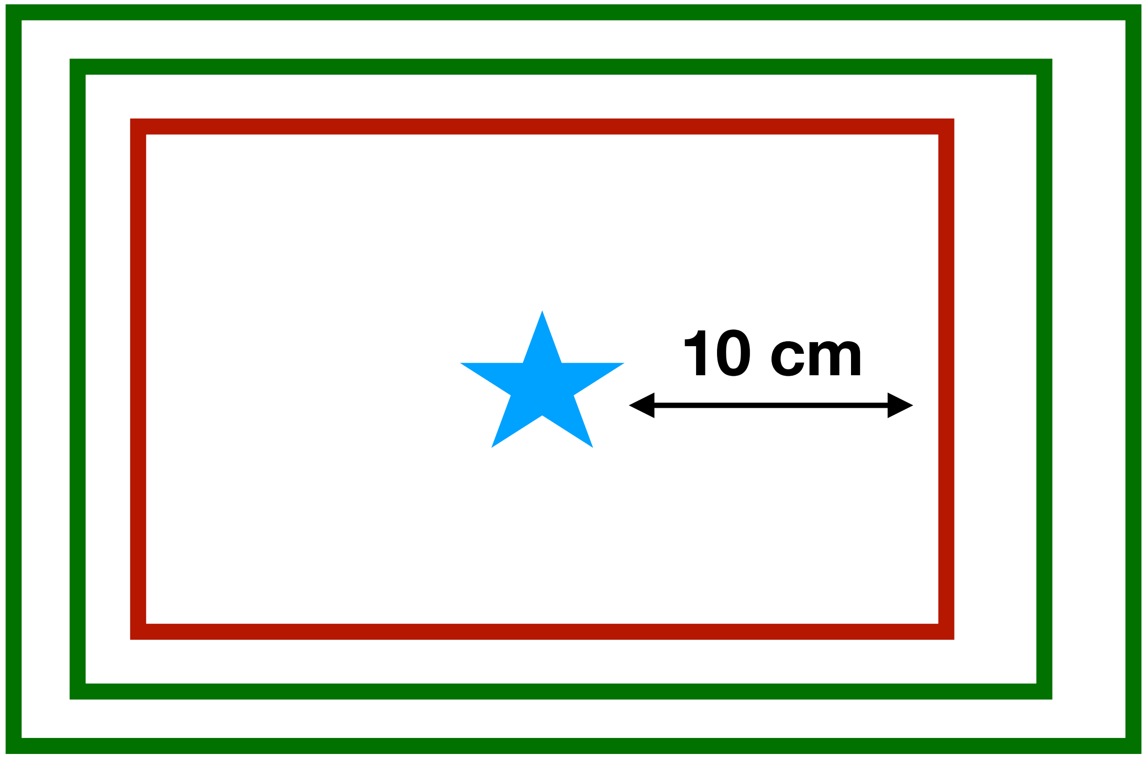
PMT: Q ~ 0.25

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

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

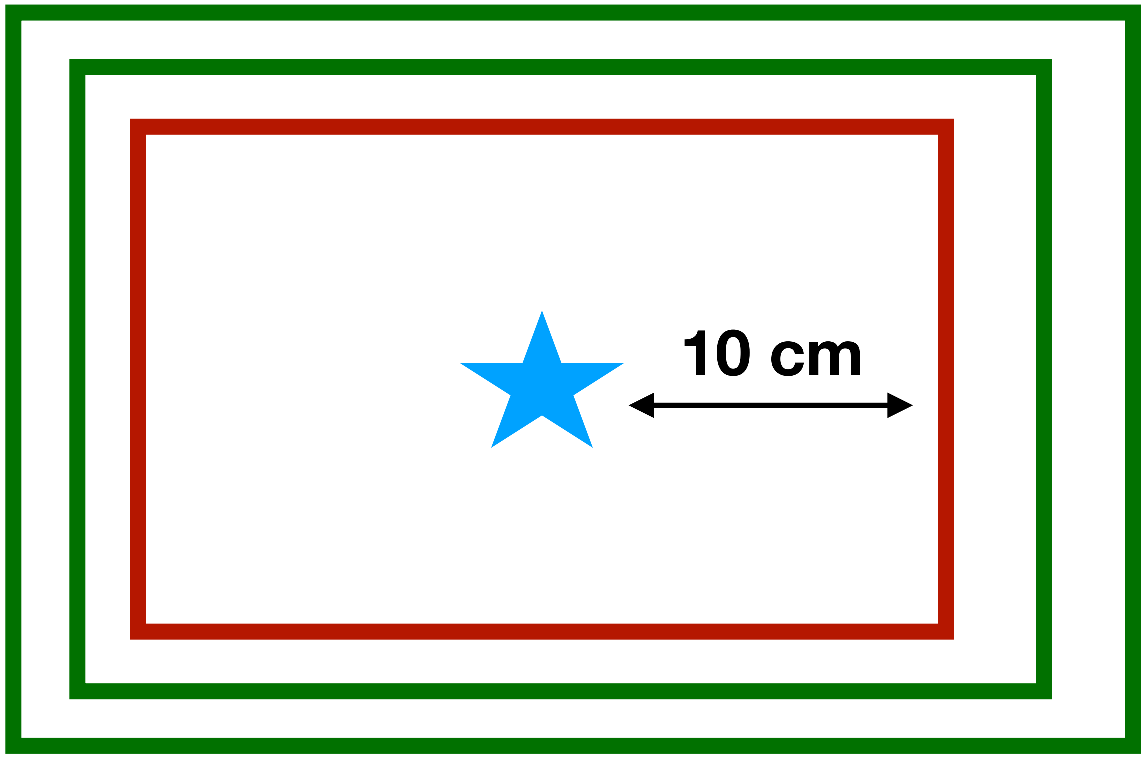
Long lived β at right energy?

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

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

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

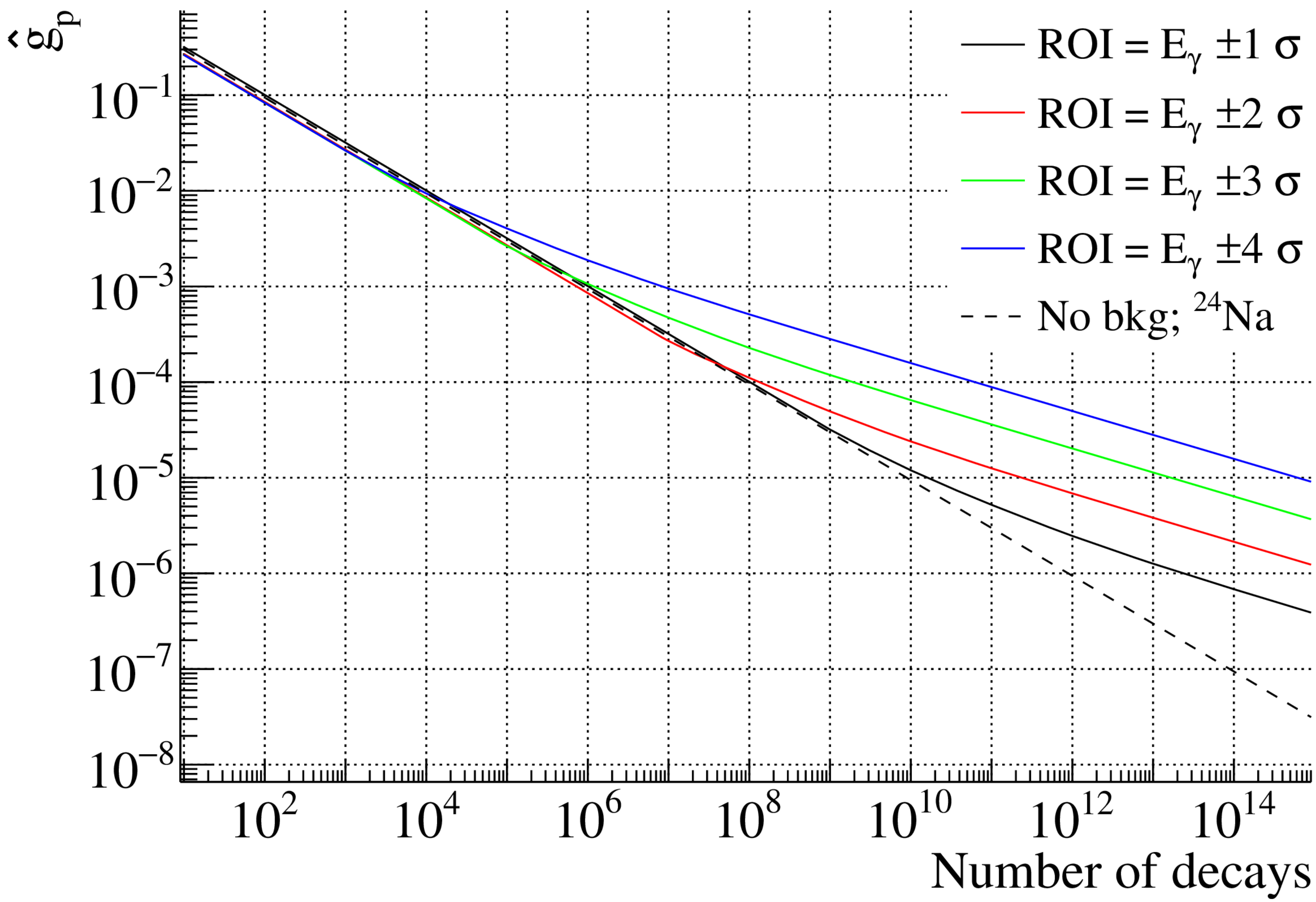
$$\frac{\Gamma_\phi}{\Gamma_\gamma} \sim \frac{g_p^2}{e^2}$$

Poor constraints on baryonic forces > 100 keV

Relevant for light dark matter experiments

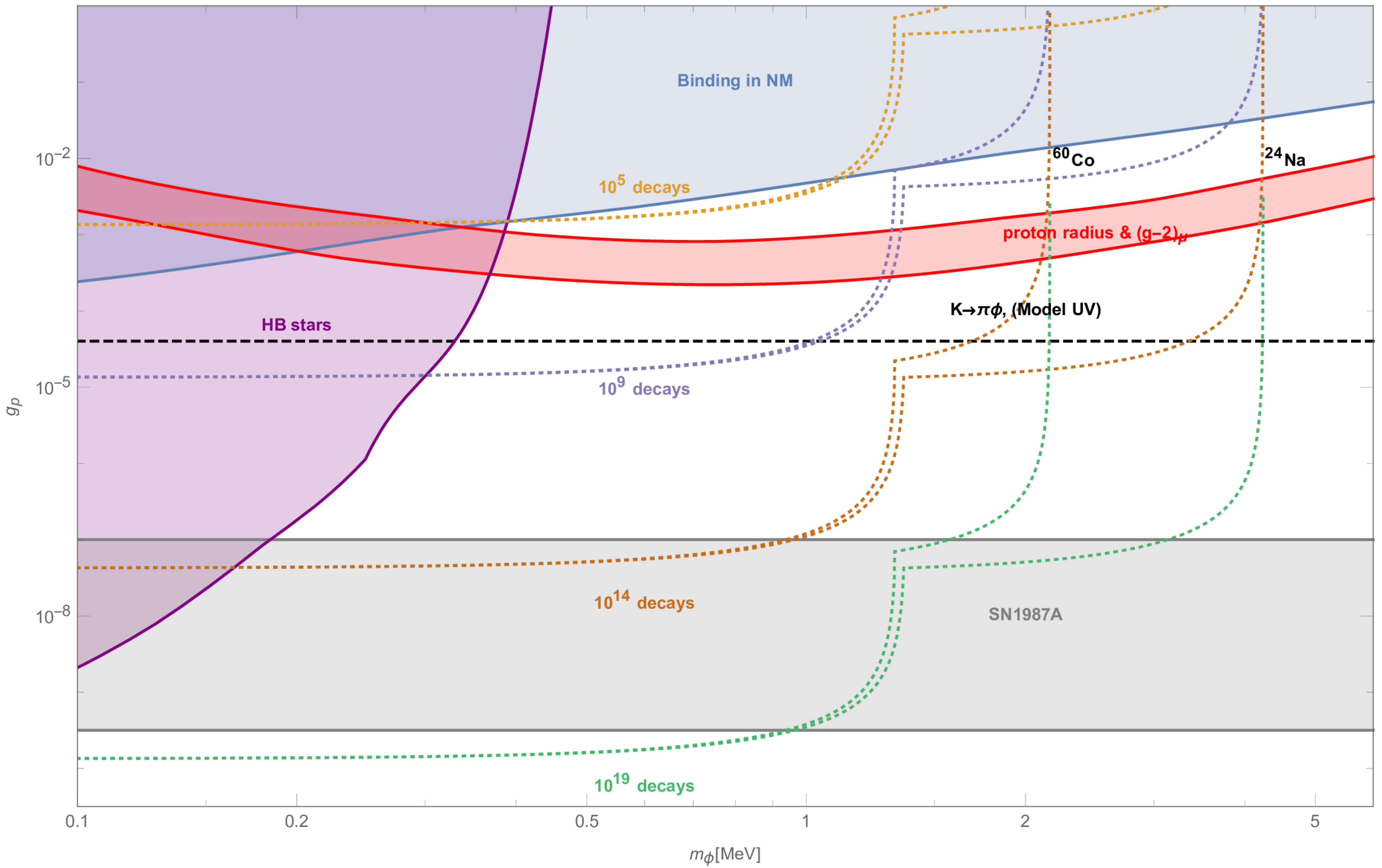
Potentially cause Type 2 Supernova

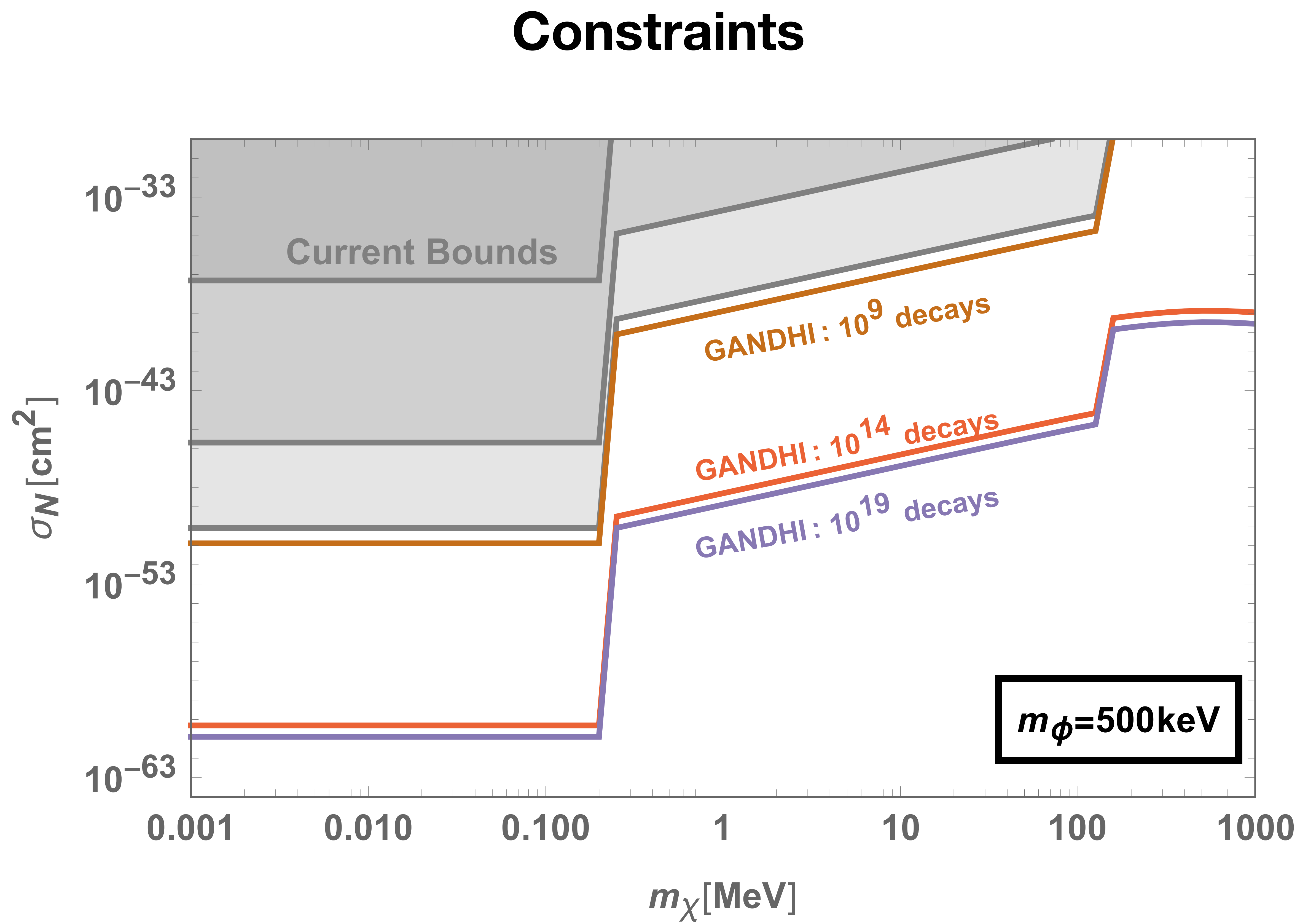
Reach



$\hat{g}_p$
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





Constraints
Current Bounds
GANDHI : 10^9 decays
GANDHI : 10^14 decays
GANDHI : 10^19 decays
m_ϕ=500keV
σ_N [cm^2]
10^−33
10^−43
10^−53
10^−63
0.001
0.010
0.100
1
10
100
1000
m_χ [MeV]

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?

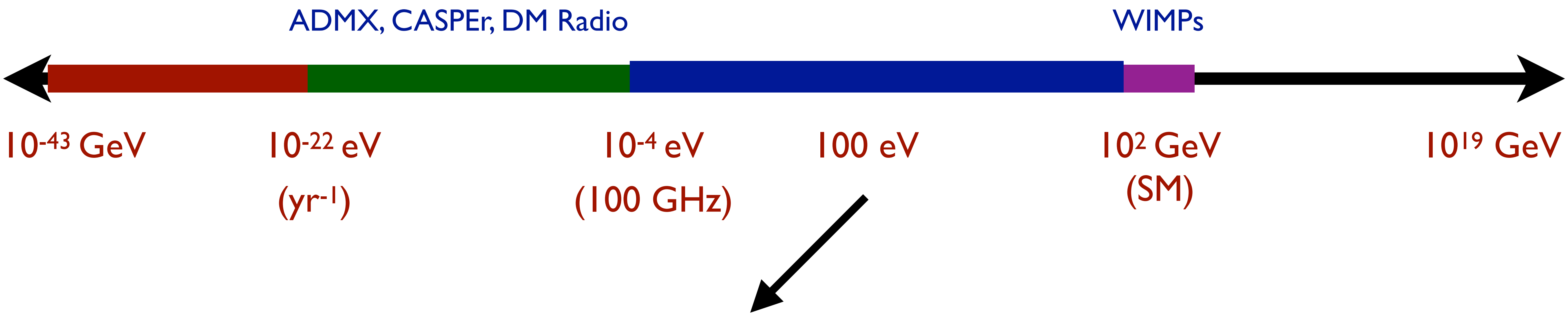
Axions: M1 transitions - ^{65}Cu -> ^{65}Ni?

Magnetic Bubble Chambers

with

Phil Bunting, Giorgio Gratta, Michael Nippe, Jeffrey Long, Rupak Mahapatra and Tom Melia

The Dark Matter Landscape



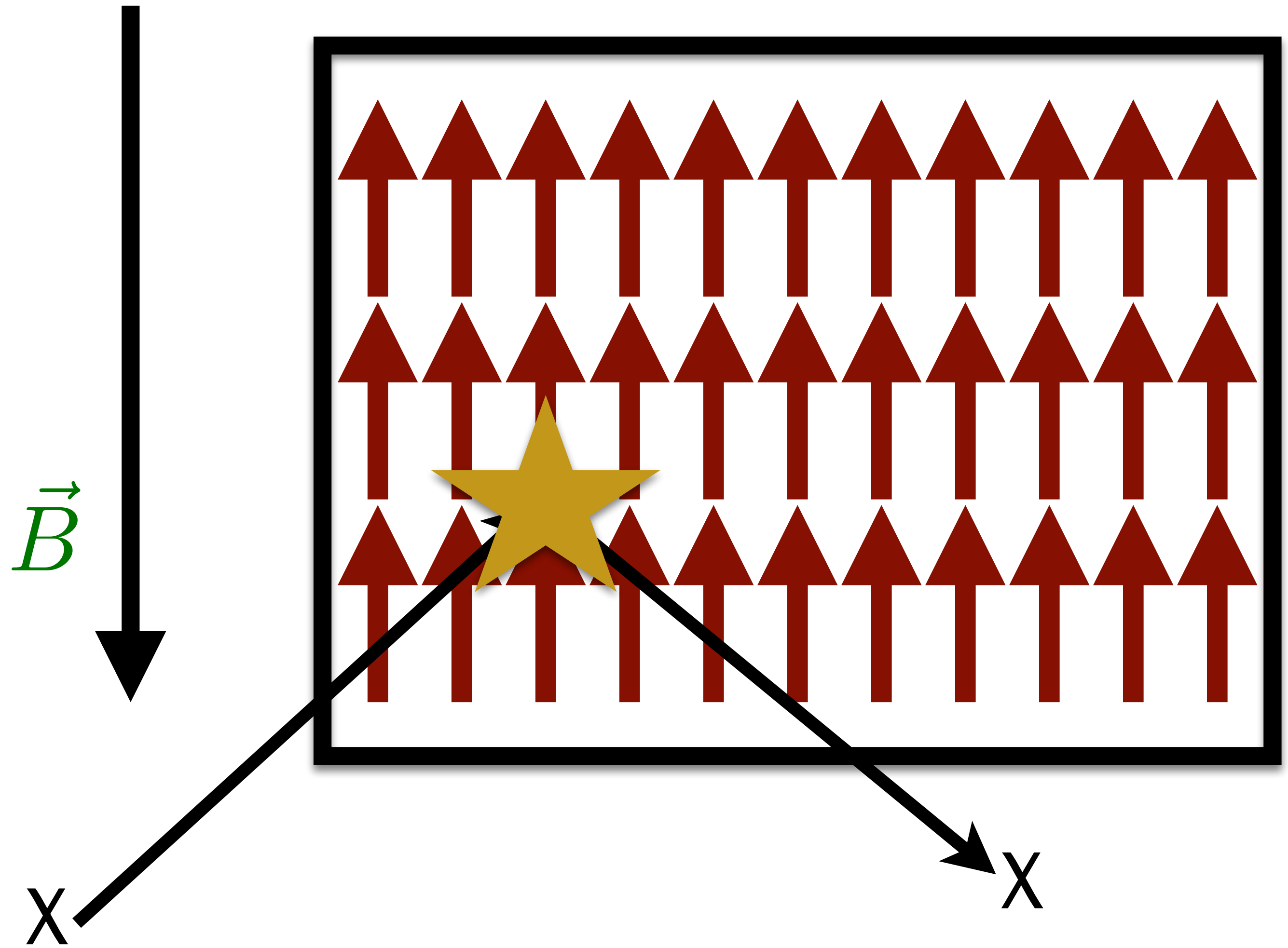
What about this range?

Coherence time of signal too short for phase measurement to work. Energy deposition too small to be been using conventional WIMP calorimeters

Need amplification of deposited energy (meV - keV)

Challenge: Need large target mass. Rare dark matter event. Requires amplifier stability > years

Concept

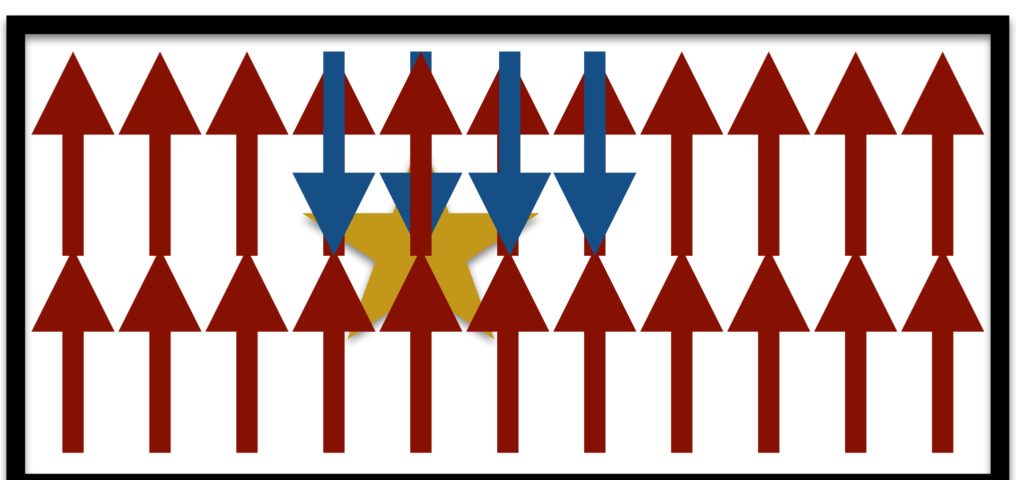


Consider magnet with all spins aligned

Spins now in metastable excited state with energy ~ g μ B

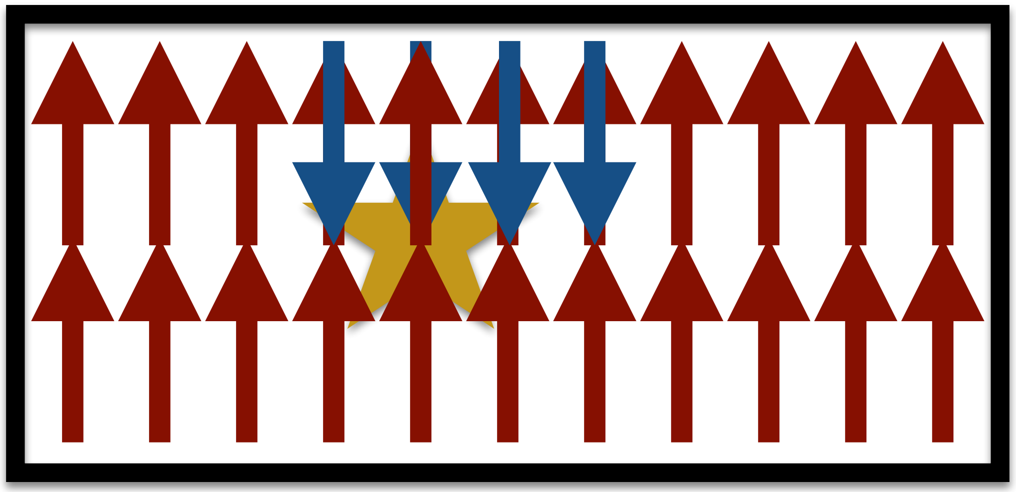
Dark Matter collides, deposits heat. Causes meta-stable spin to flip

Spin flip releases stored Zeeman energy (exothermic). Released energy causes other spins to flip, leading to magnetic deflagration (burning) of material.



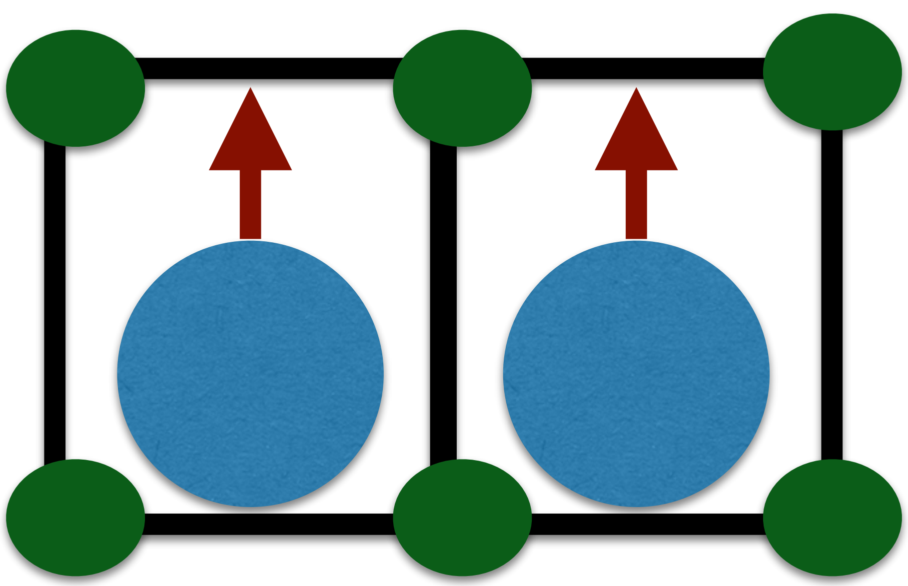
Amplifies deposited energy. Like a bubble chamber. Is this possible? Stability?

Single Molecular Magnets



Will not happen in a ferromagnet - spins are strongly coupled.

Need weak spin-spin coupling. But need large density - necessary for heat conduction. Can't use gas.



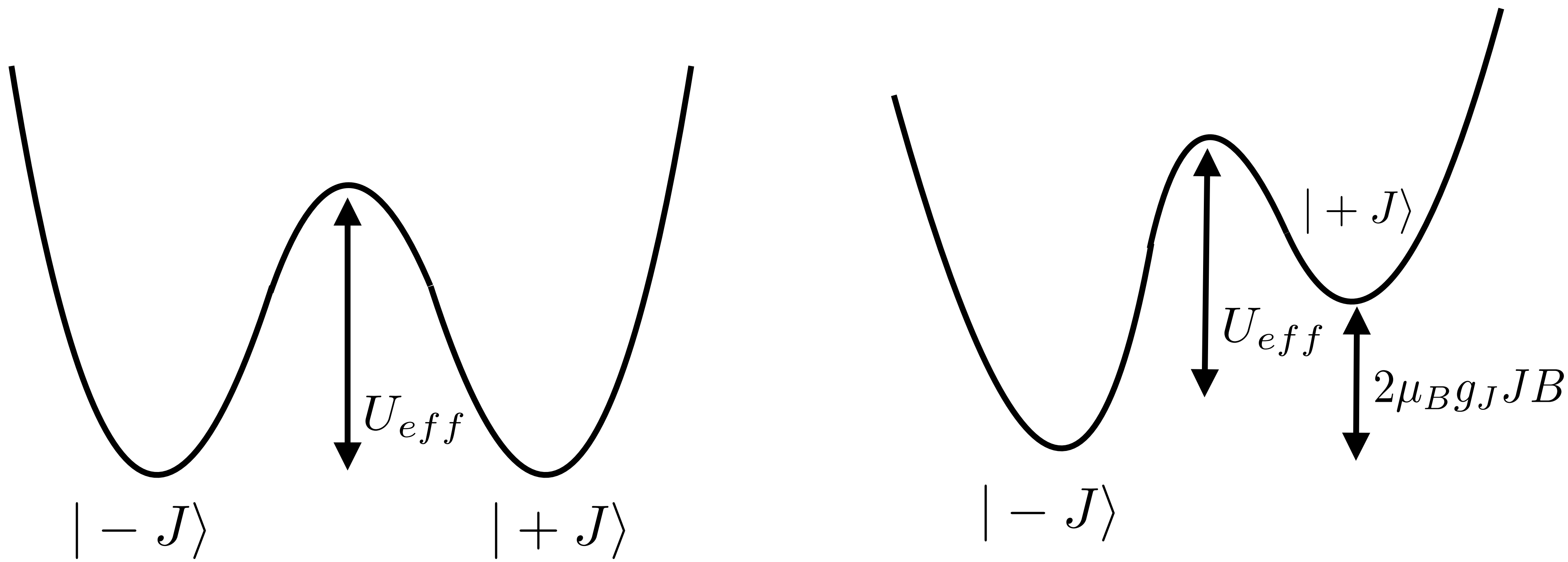
Organo-Metallic complexes. Central metal complex surrounded by organic material.

Weak coupling between adjacent metal complexes - but still large density

Each molecule acts as an independent magnet

Recently discovered systems. Few 100 known examples. Can make large samples. Magnetic deflagration experimentally observed and well studied in Manganese Acetate complexes

Magnetic Deflagration



System well described by 2 level Hamiltonian.
Two states separated by energy barrier.

Turn on magnetic field, metastable state decays to ground state through tunneling

$$\tau \propto \tau_0 \exp\left(U_{\text{eff}}/T\right)$$

Ultra-long lived state at low temperature - localized heating rapidly decreases life-time, decay results in more energy release

Condition for Deflagration

Initially heat region of size λ to T

Thermal Diffusion, lowers T

$$\tau_{\mathrm{D}} \propto \lambda^2$$

Spin flips, releases energy, increases T

$$\tau \propto \tau_0 \, \exp\left(U_{\mathrm{eff}}/T\right)$$

Deflagration occurs as long as we heat a sufficiently large region

U_{eff} and τ_0 sets the detector threshold. Short τ_0 and small U_{eff} means tiny energy deposit will sufficiently heat up material to trigger deflagration. Low threshold

Known examples with $\tau_0 \sim 10^{-13}$ s, $U_{eff} \sim 70$ K, enabling 0.01 eV thresholds

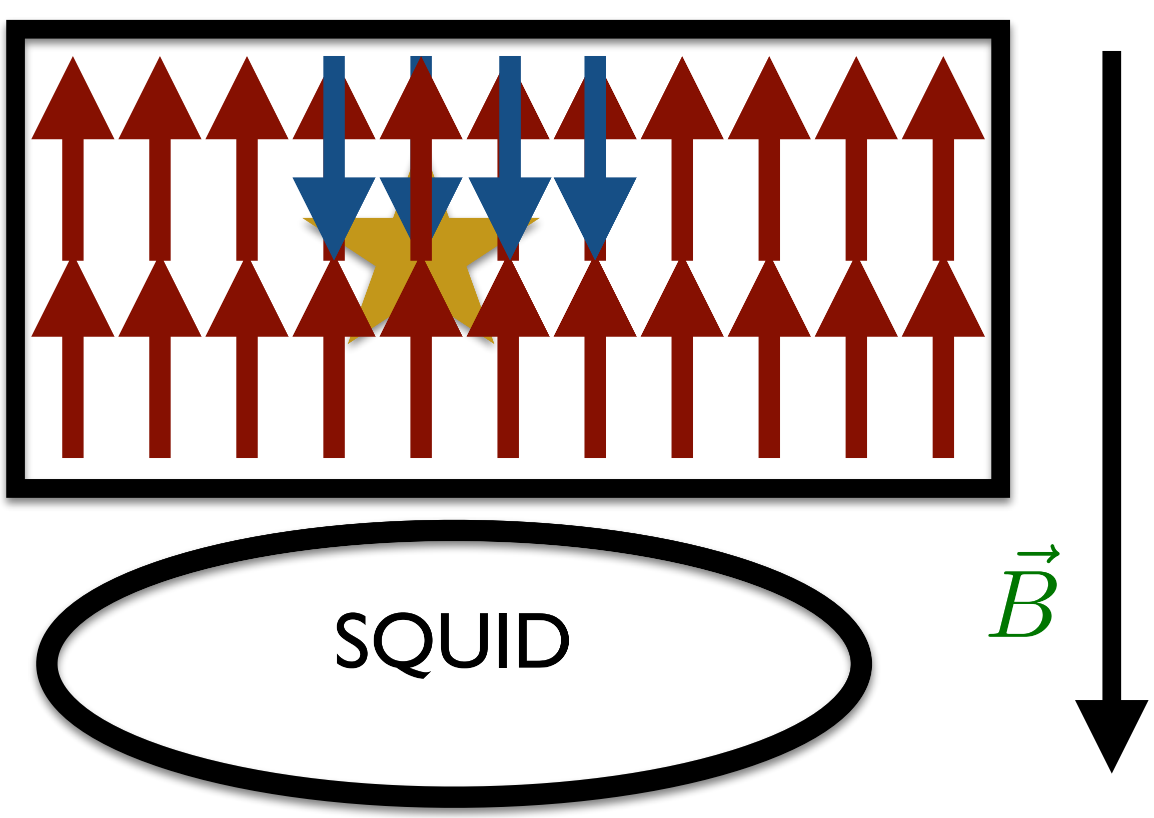
Detector Stability

High energy (> MeV) background from radio-active decays.

Detect MeV events using conventional means. Actual background at low energy very low - forward scattering of compton events

Problem: MeV events will constantly set off detector. Reset time vs operation time? Big problem for bubble chambers like COUPP

Expected background ~ 1/(m² s). Initial detector size ~ (10 cm)³ (kg mass), 1 background event ~ 100 s



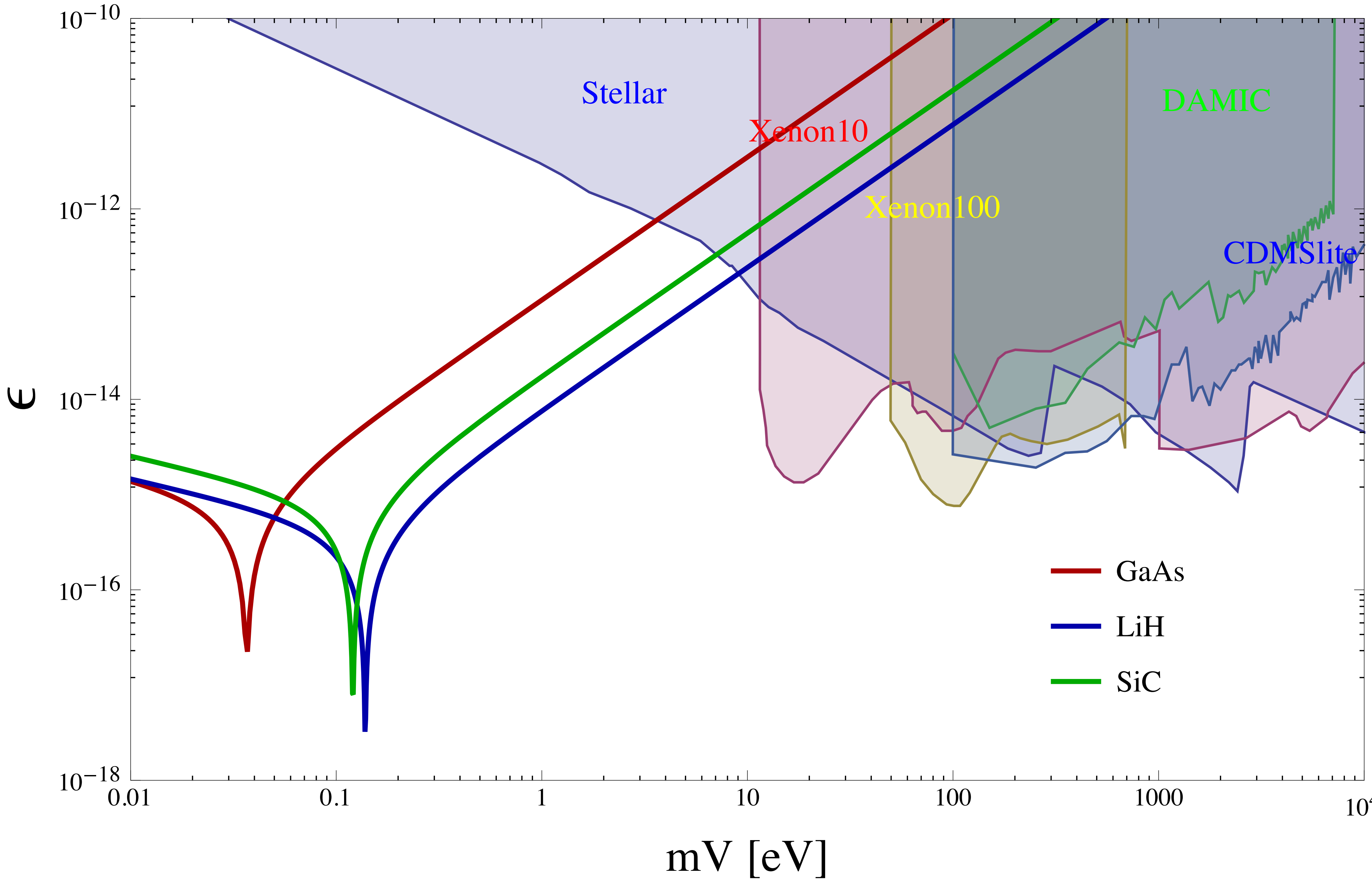
With precision magnetometers, don't need entire crystal to flip

Within ~ 10 μs, flame ~ 10 - 100 μm. Visible with SQUID.

Shut off B, turn off fuel. Deflagration stops. Lose ~ (10 - 100 μm)³ of volume every 100 s.

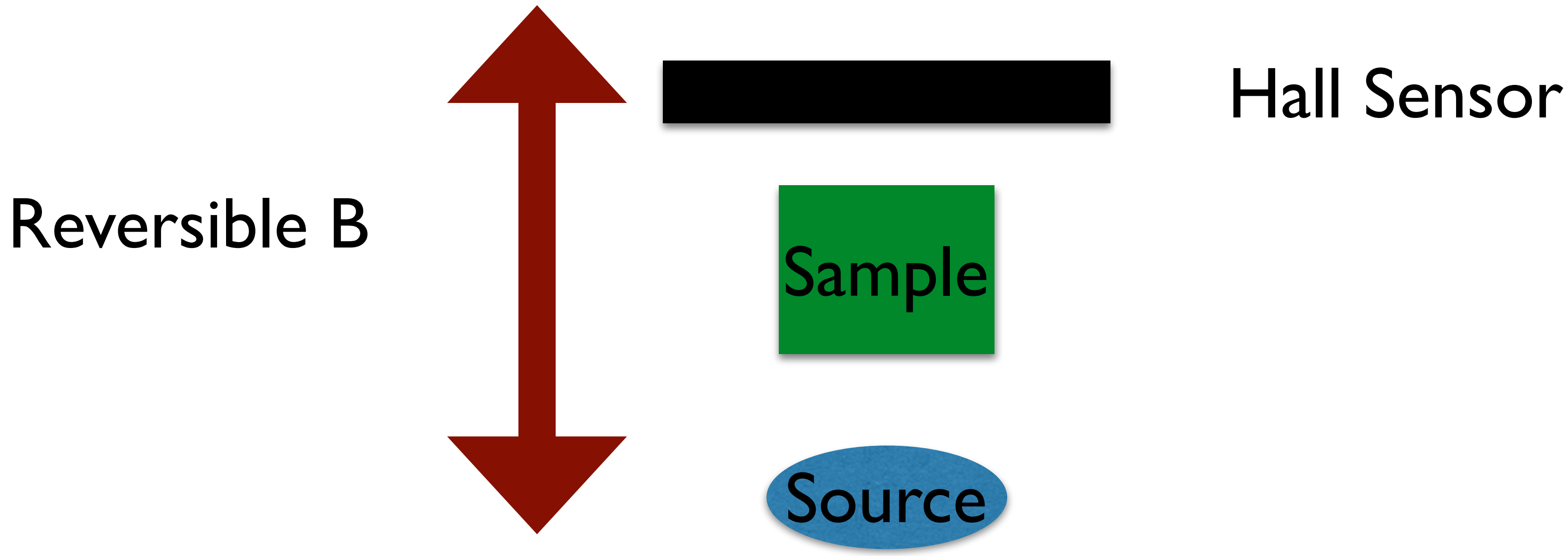
Potential Reach

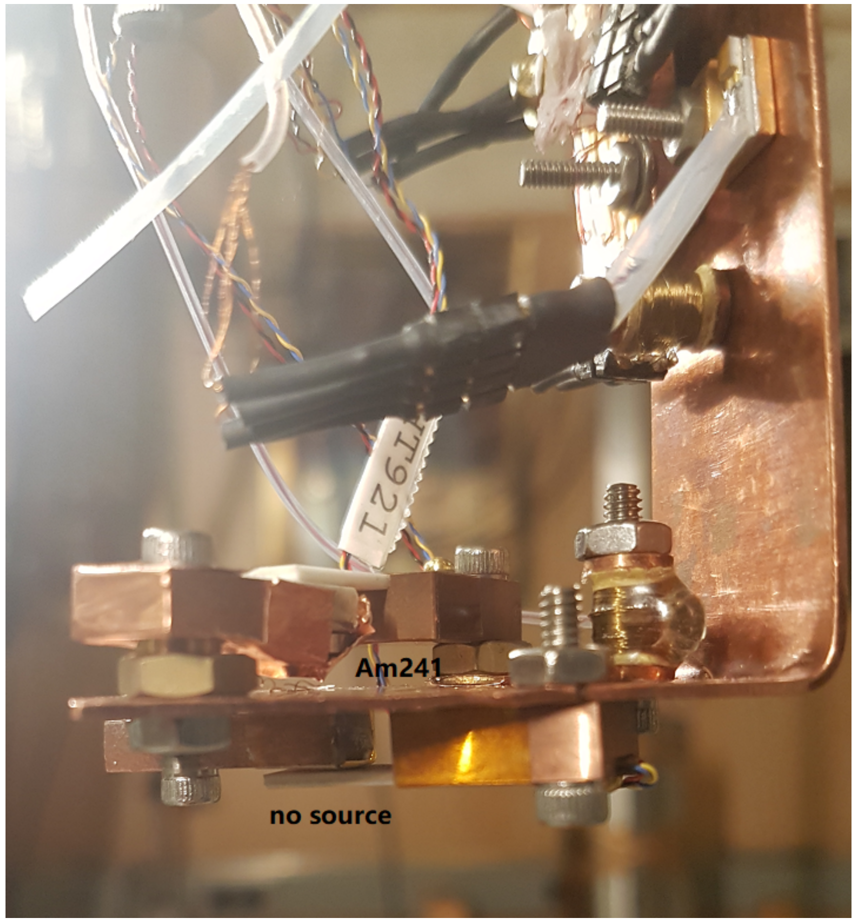
$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon\, A'_\mu\right)$$



Absorption obtained from photoabsorption. Exposure of 1 kg-year

Trial using Mn-Ac



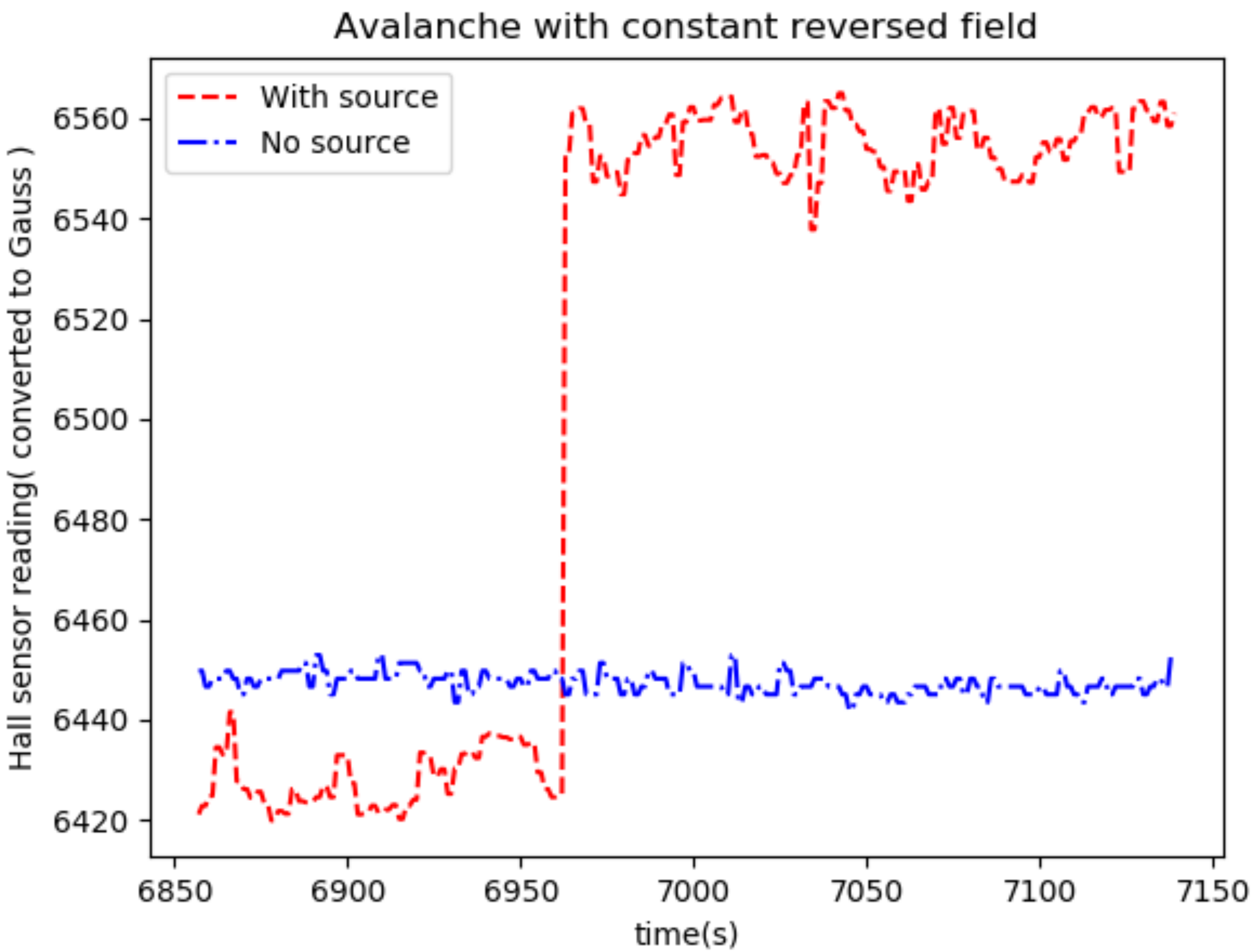


Two sets of Mn12-Ac and Hall sensors

One with μCi Am 241 α source
One without source

Metastability? Deflagration?

Results



Avalanche only observed with source

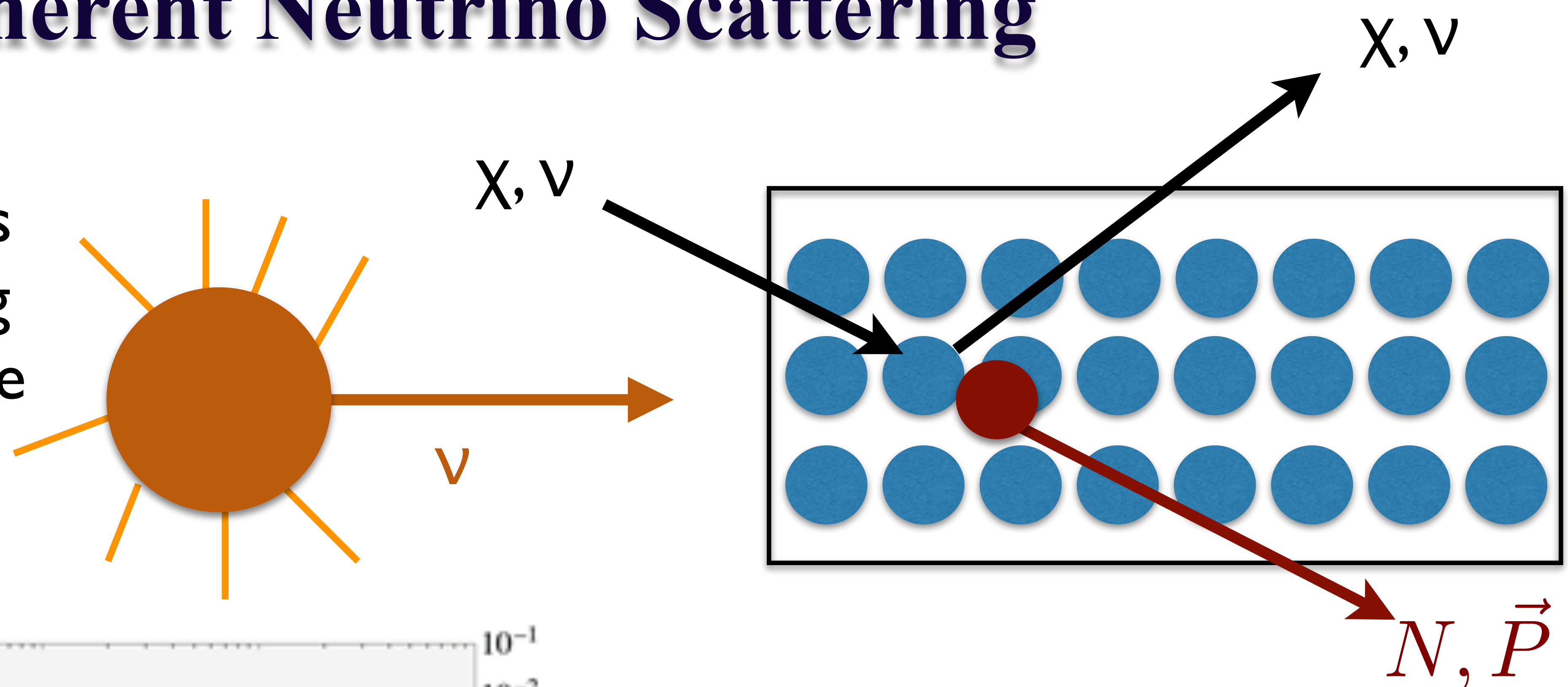
Mn12-Ac has high threshold (~ few MeV) - using new materials now

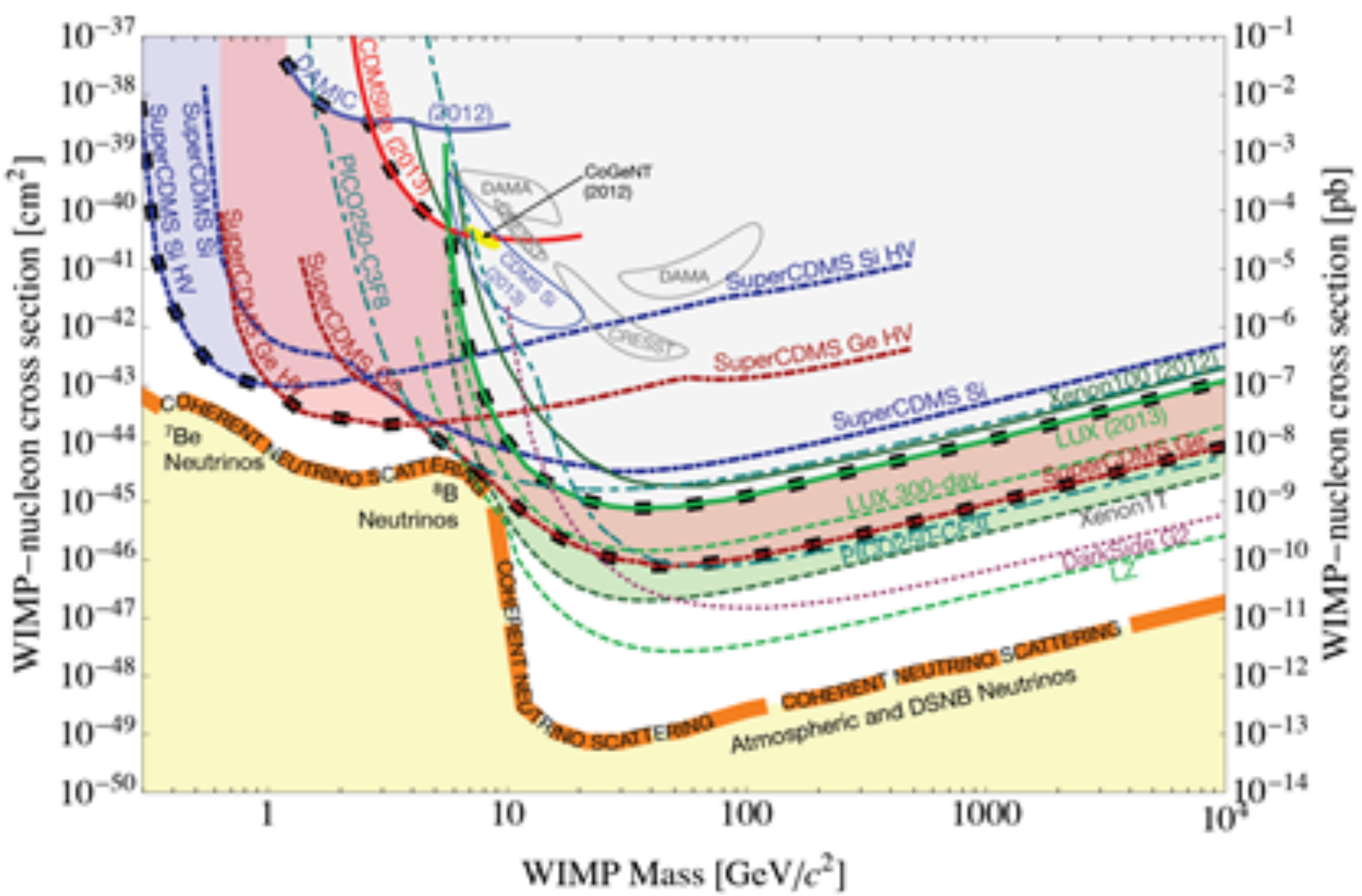
Directional Detection of Dark Matter with Crystal Defects

with
Misha Lukin, Alex Sushkov, Ron Walsworth and Nicholas Zobrist

Coherent Neutrino Scattering

Neutrinos and WIMPs have similar scattering topologies - rare, single particle collision with detector





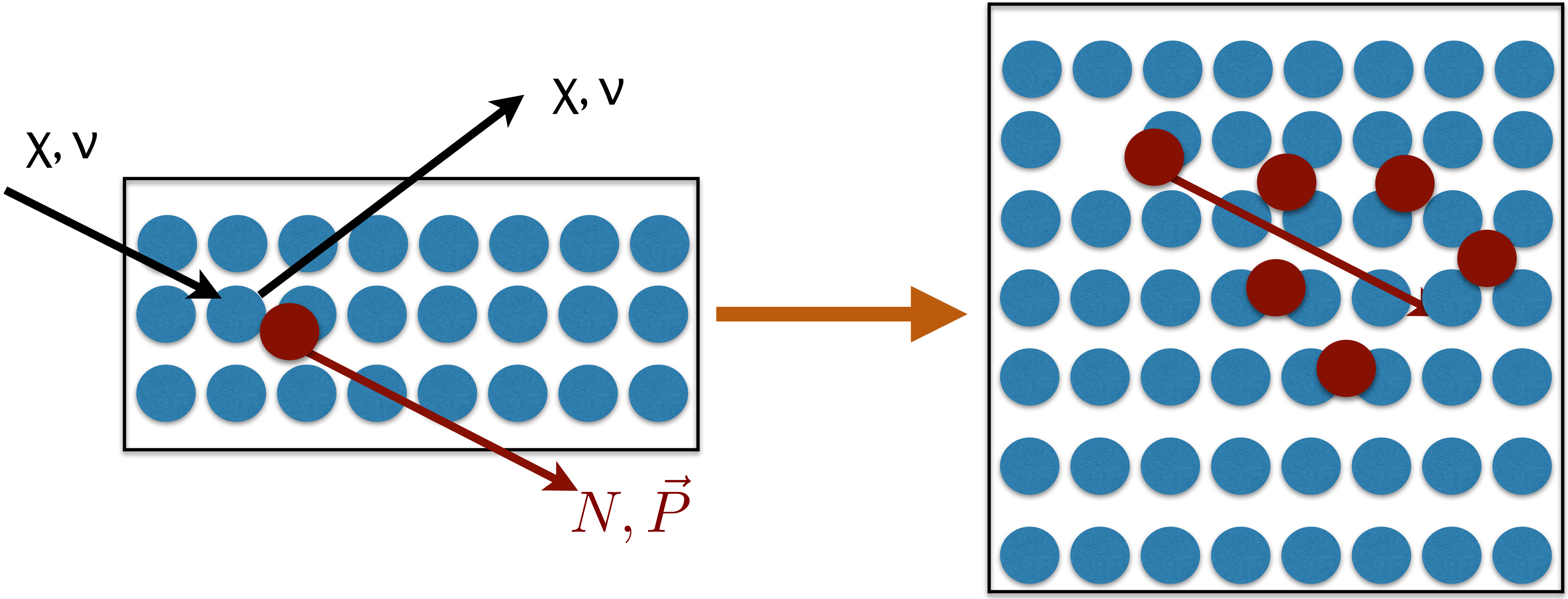
Sun produces neutrinos. Irreducible background.

Go beyond next generation?

Isotropic Dark Matter. Know location of Sun. Veto nuclear recoils coming from Sun's direction

Challenge: Big Target Mass. Need directional detection at solid state density.

Collision Aftermath



Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Collision Aftermath

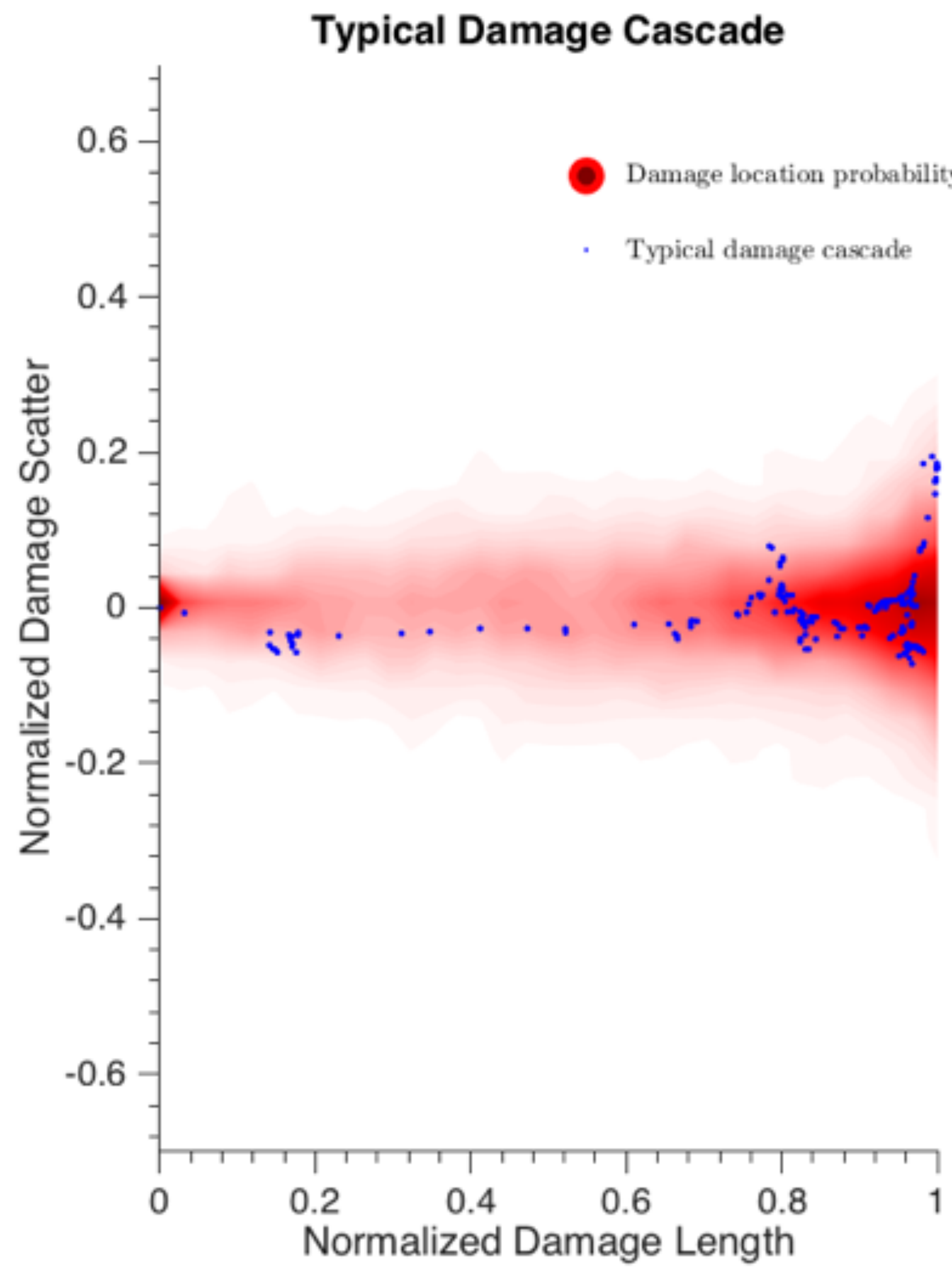
Tell-tale damage cluster well correlated with direction of initial ion, localized within ~ 50 nm

Results of TRIM simulation, 30 keV initial ion

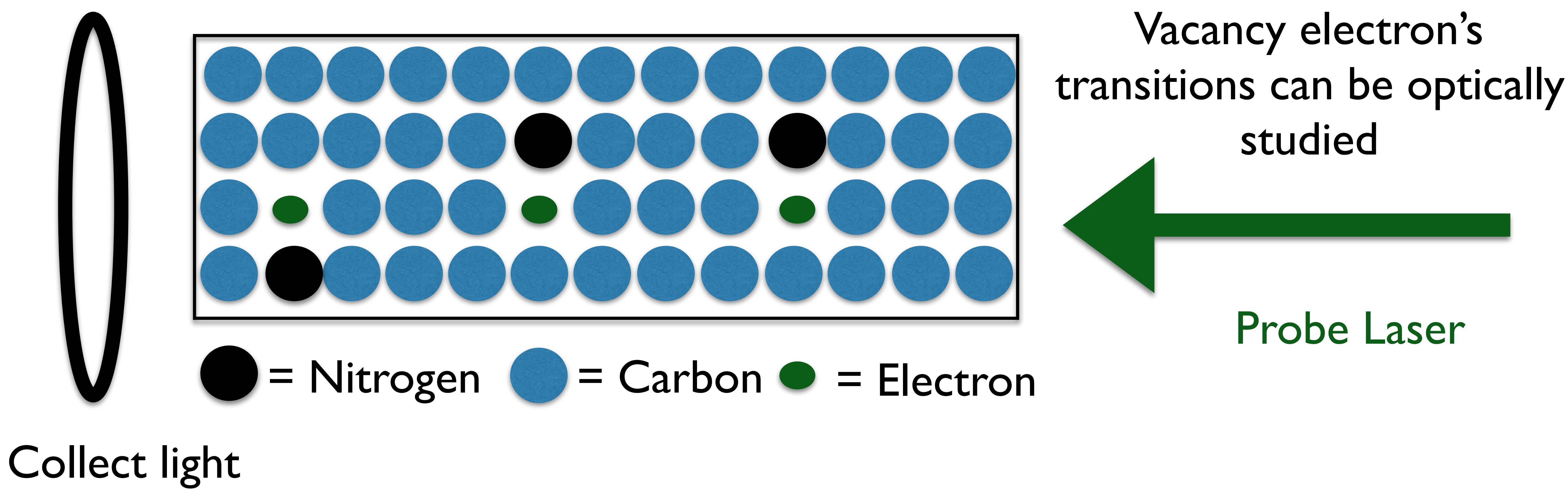
O(200 - 300) vacancies and interstitials, lattice potential ~ 30 eV

Damage cascade well correlated with direction of input ion

Need nano-scale measurement of damage cascade



Nitrogen Vacancy Center in Diamond



Electronic levels sensitive to crystal environment ~ 50 nm scale

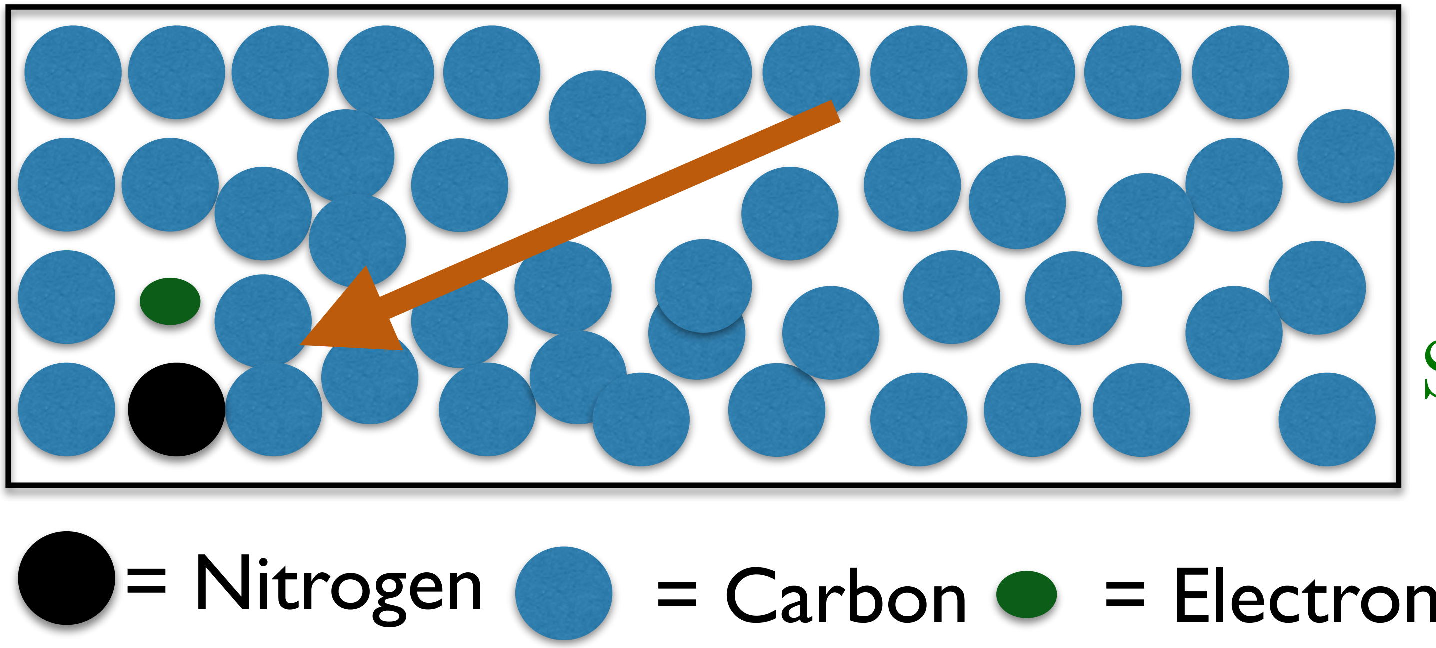
~ 1 per $(30\ \text{nm})^3$ of NV centers in bulk diamond demonstrated

Nano-scale measurements experimentally demonstrated. Active development of sensors by many groups around the world.

Can this be used for directional detection? What is the effect of the damage cascade on a NV center?

Note: similar phenomenology applies to F-centers of Metal Halides

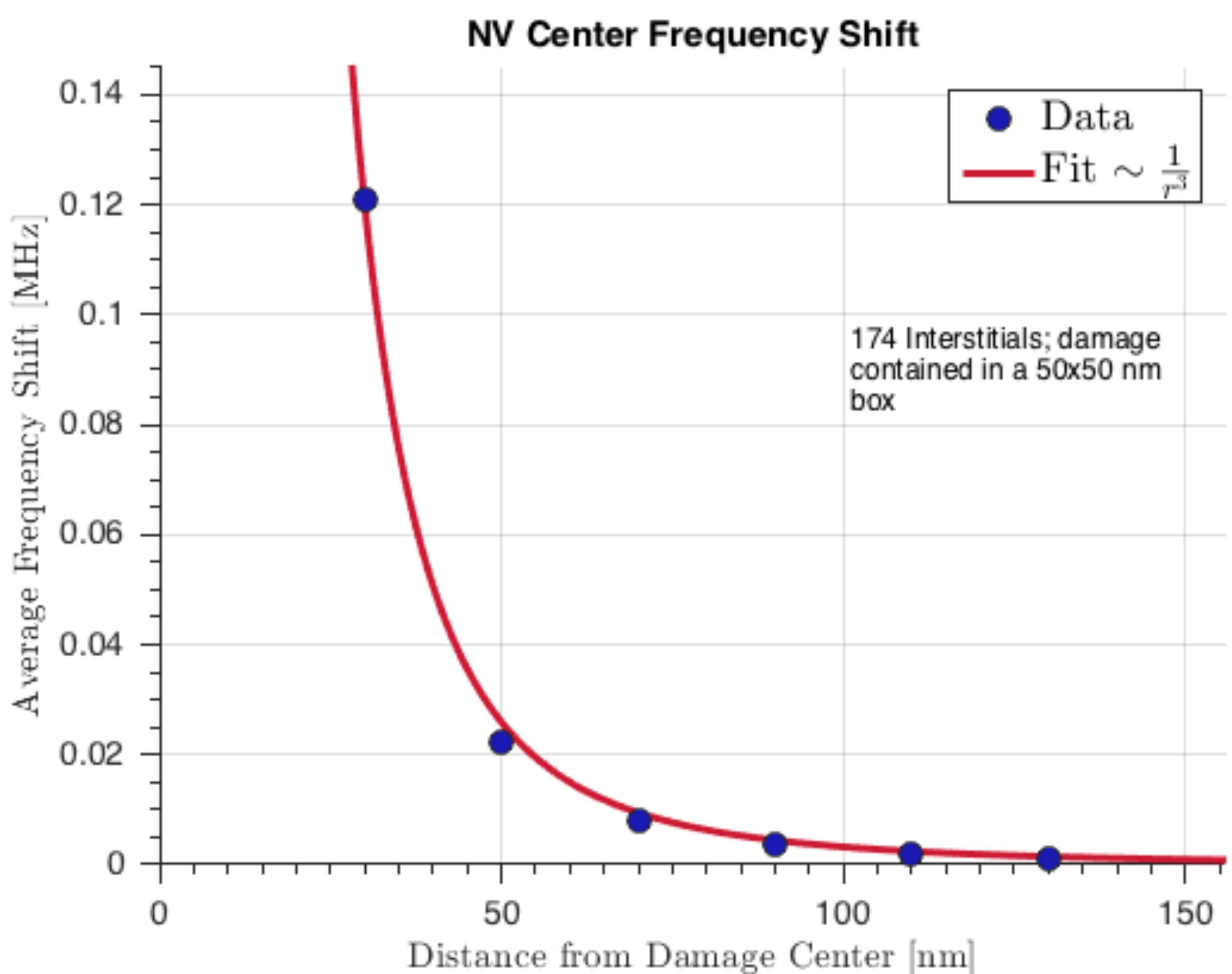
Damage Cascade and NV Centers



Damage leads to strain in crystal. Strain shifts transition line

Strain: $\nabla u \propto \frac{1}{r^3} \times \mathcal{O}(100-300)$

(Hooke's Law)

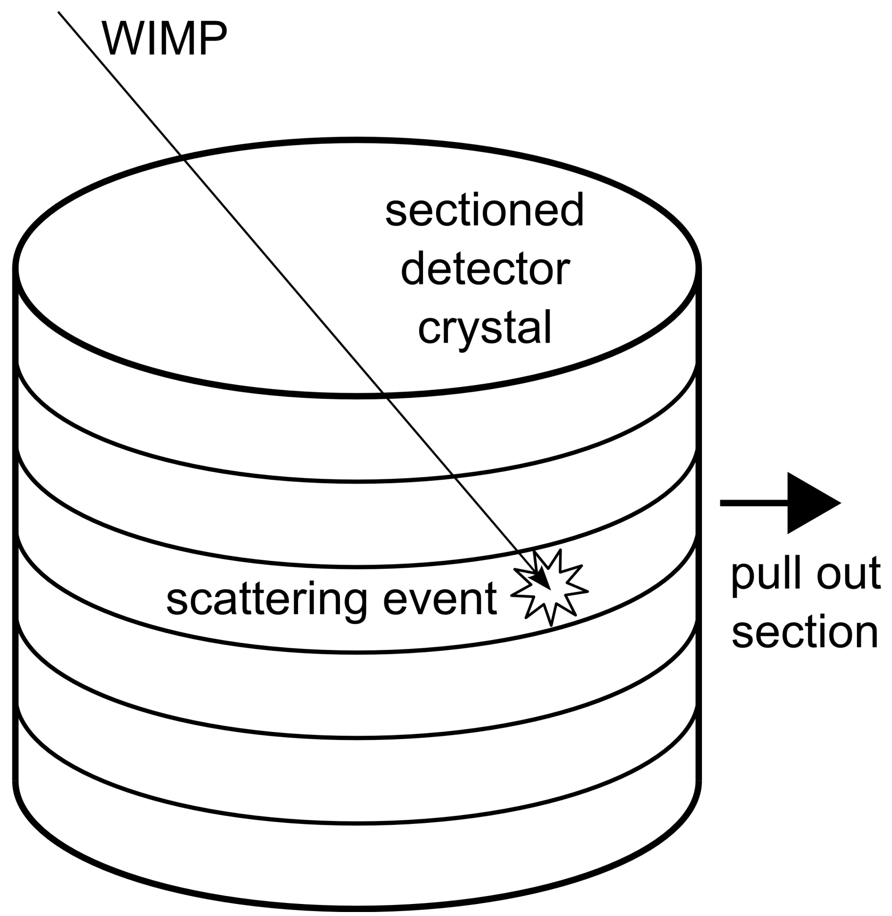


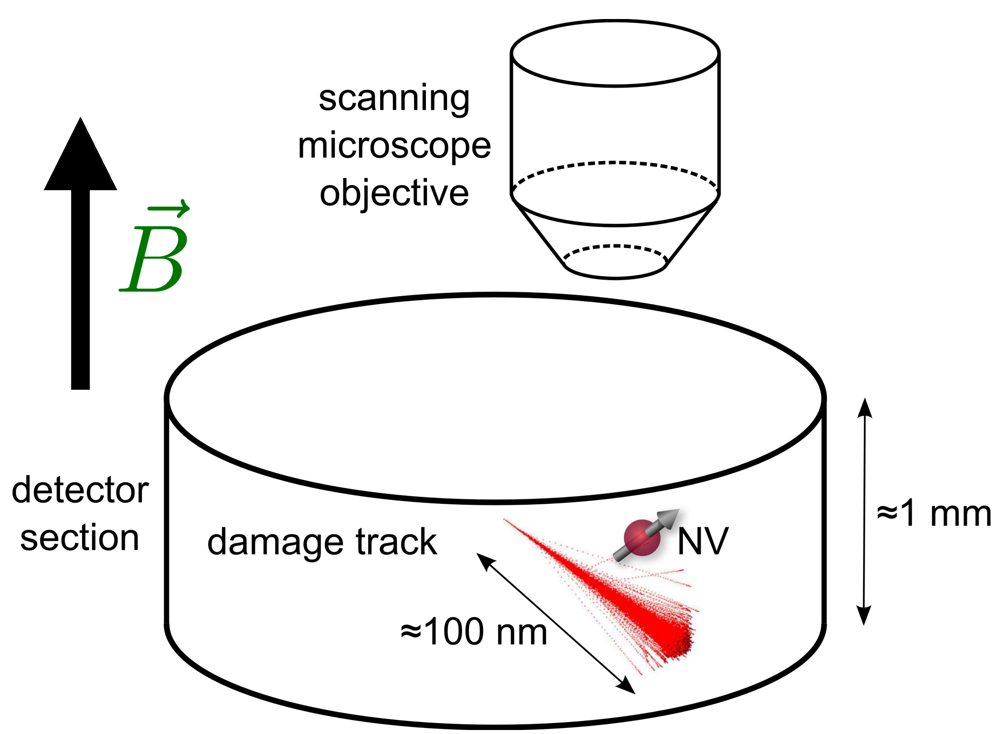
TRIM simulation of damage cascade - calculate strain using Hooke's law

NV center shift ~ 100 kHz @ 30 nm
Natural line width ~ kHz

Single NV center has sensitivity to cascade!

Detector Concept





Large detector, segments of thickness ~ mm

NV center density ~ 1 per (30 nm)^3

Conventional WIMP scattering ideas (scintillation, ionization etc.) to localize interesting events

Expect few events/year that could be WIMP or neutrinos

Pull out segments of interest. Conventional schemes localize events to within mm

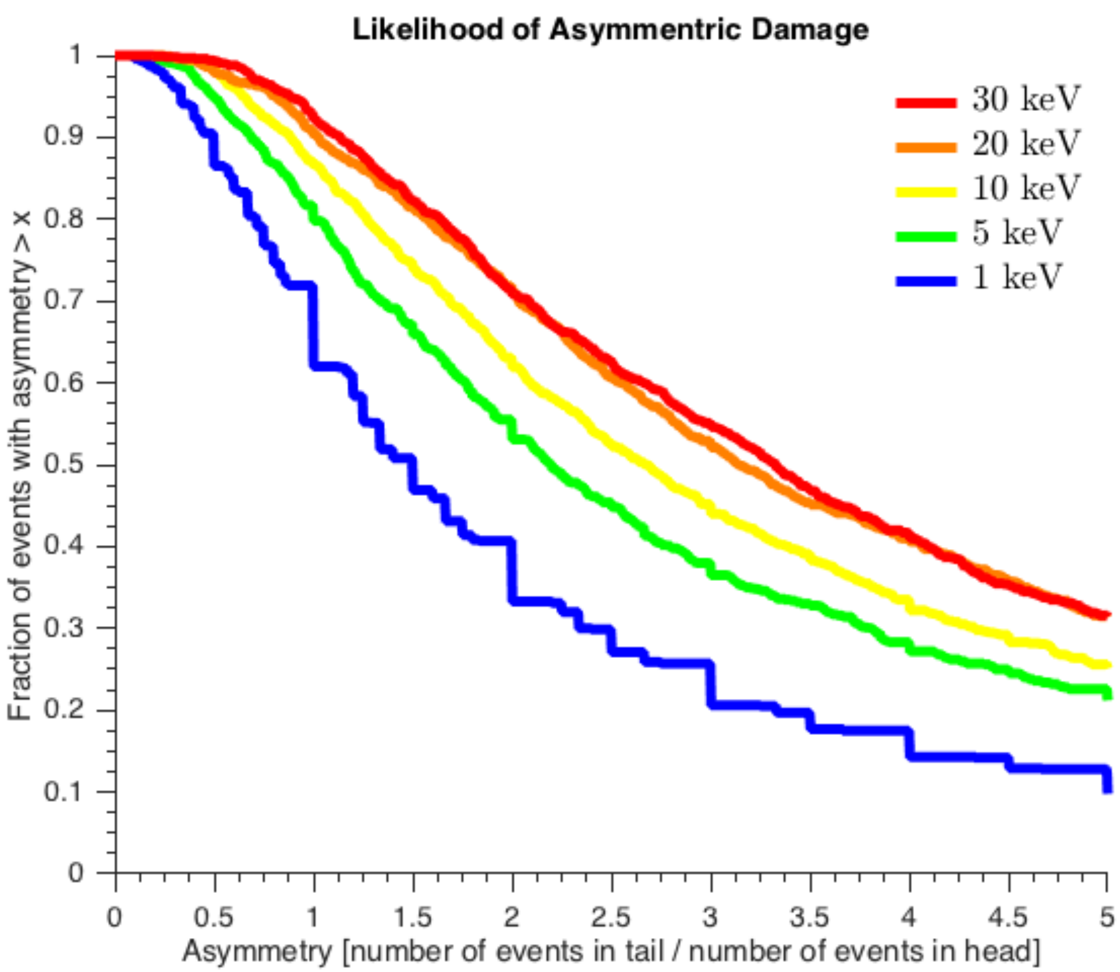
Micron-scale localization by simply shining light - damaged area will have measurable frequency shifts

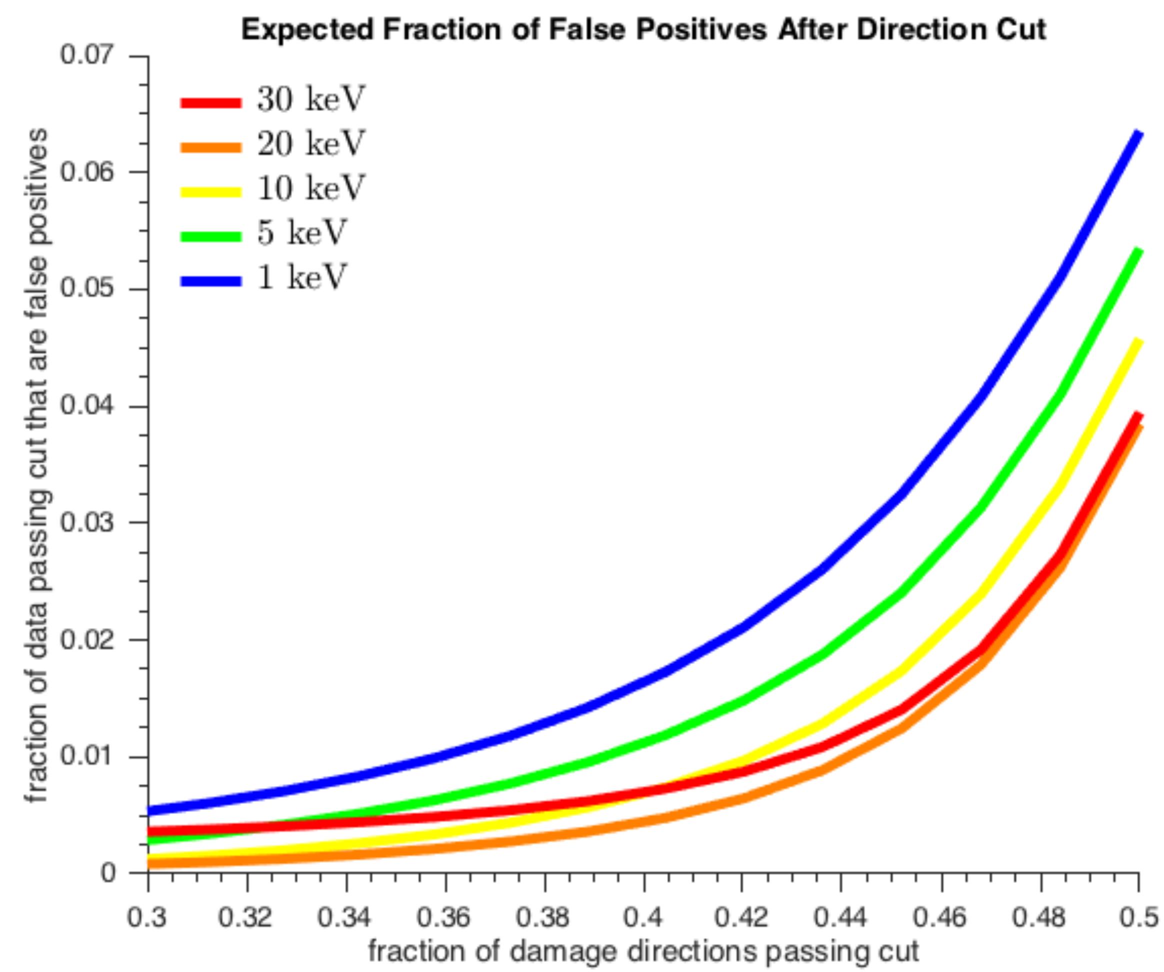
For nano-scale resolution, apply external magnetic field gradient - hence need segmentation

Results

Take crystal. Grid of NV centers with density 1 per (30 nm)^3

Run ~ 1000 TRIM simulations, get cascade for each. Can grid distinguish direction (including head vs tail)?





More damage in tail vs head used for discrimination. Above 10 keV, efficiency > 80%, false positive < 4%

5 σ detection with few events!

Conclusions

Where is this New Physics?

Mass? Strength?

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

1

Strength

Colliders →

Gravitational Waves,
Dark Matter,
Dark Energy

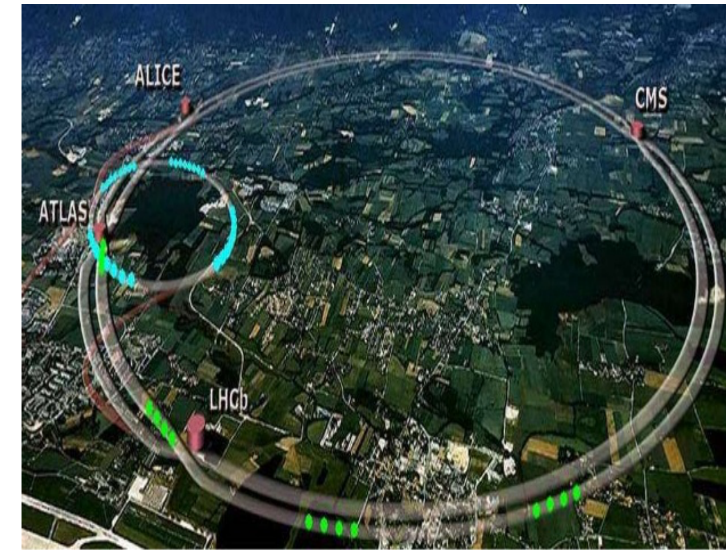
↓

Strong Physics Case

Gravity

Technology Outlook



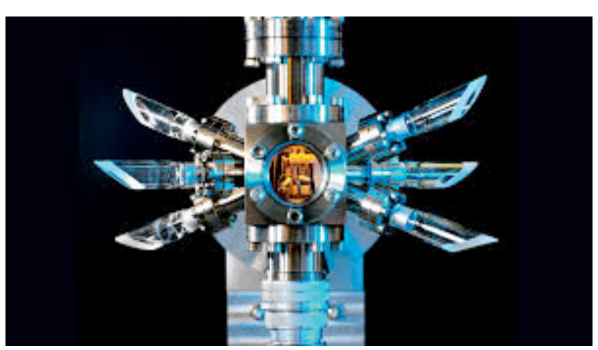



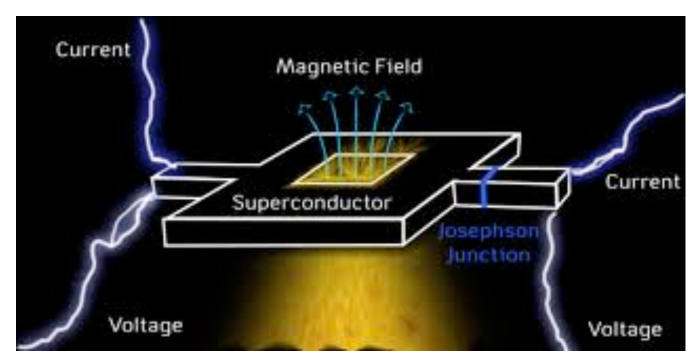
Dramatic Evolution in Colliders in the 20th century

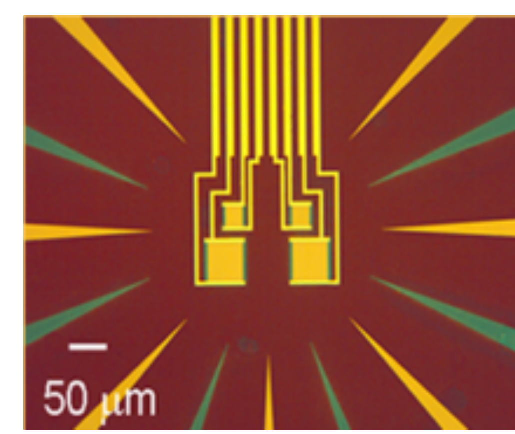
Why?

Humanity mastered electromagnetism in the 1900s

Now, at the anvil of quantum control







Time to find weakly coupled physics!