Title: Exploring the dark universe through molecules and nuclei

Date: Nov 02, 2018 01:00 PM

URL: http://pirsa.org/18110040

Abstract: <p>Repeated null-results at dark matter experiments targeted at WIMP masses, have resulted in the spotlight shifting to lighter dark matter and more exotic WIMP candidates. In this talk I shall present the rich level structure of molecules and nuclei as a tool to explore MeV scale dark matter and dark forces. I will also present a novel detector concept that supplies energy to dark matter, thus accessing inelastic dark matter parameter space.</p>

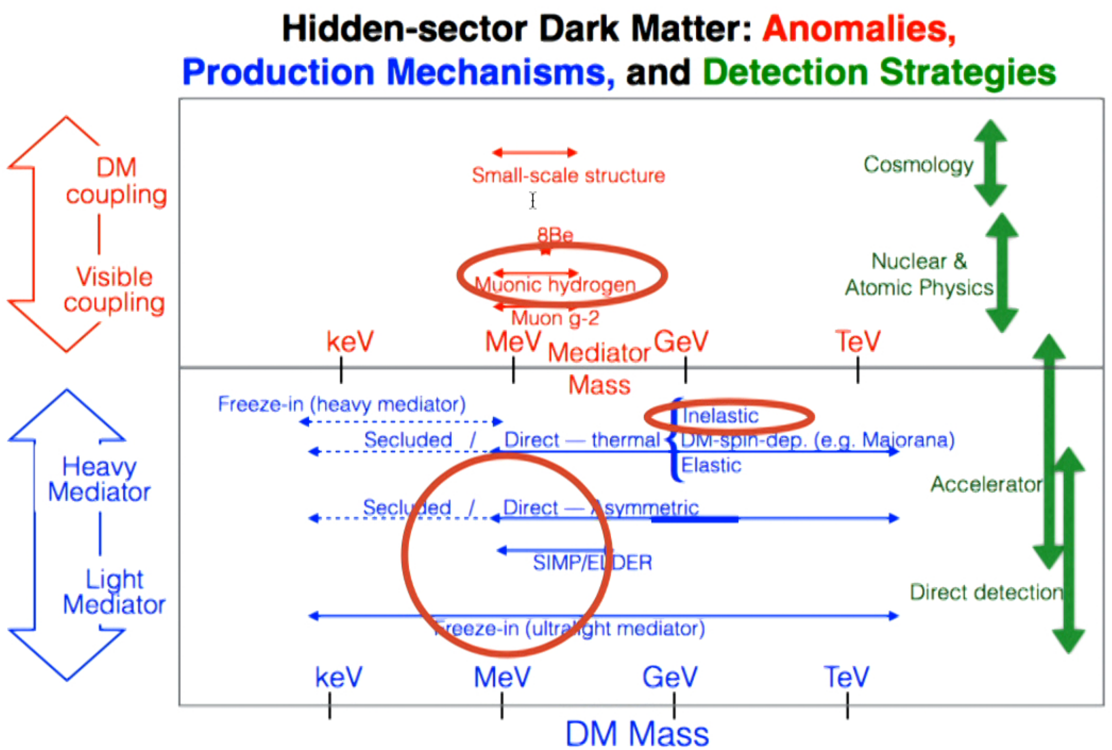
ADDITIONAL REFERENCES FOR TOPICS NOT COVERED

- Kaji, H.; Asanuma, Y.; Yahara, O.; Shibue, H.; Hisamura, M.; Saito, N.; Kawakami, Y.; Murao, M. (1984). "Intragastrointestinal Alcohol Fermentation Syndrome: Report of Two Cases and Review of the Literature". Journal of the Forensic Science Society. 24 (5): 461–71. doi:10.1016/S0015-7368(84)72325-5. PMID 6520589.
- Logan BK, Jones AW (July 2000). "Endogenous ethanol 'auto-brewery syndrome' as a drunk-driving defence challenge". Medicine, Science, and the law. 40 (3): 206–15. doi: 10.1177/002580240004000304. PMID
- . Adams, Cecil (May 2, 2008). "Did tin disease contribute to Napoleon's defeat in Russia?". The Straight Dope. Retrieved 17 August 2010.

OUTLINE

- Light Dark Matter Direct Detection through Molecular Excitations
- Detecting Baryonic Forces through a gamma decay experiment — GANDHI
- If time permits:Breaching the inelastic frontier with a new direct detection concept.

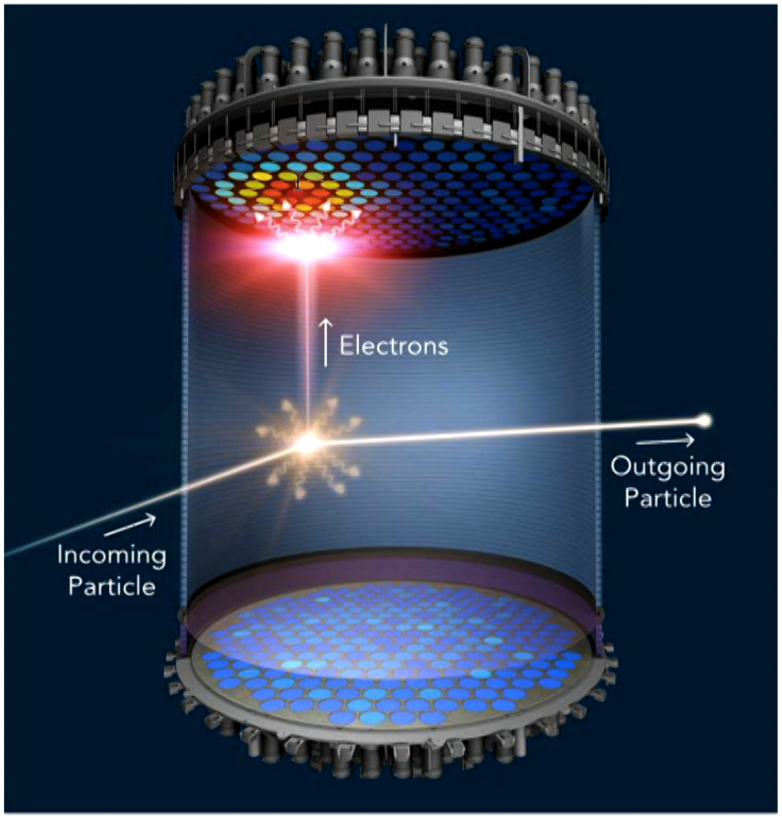
DARK MATTER LANDSCAPE



Cosmic Visions : 2017

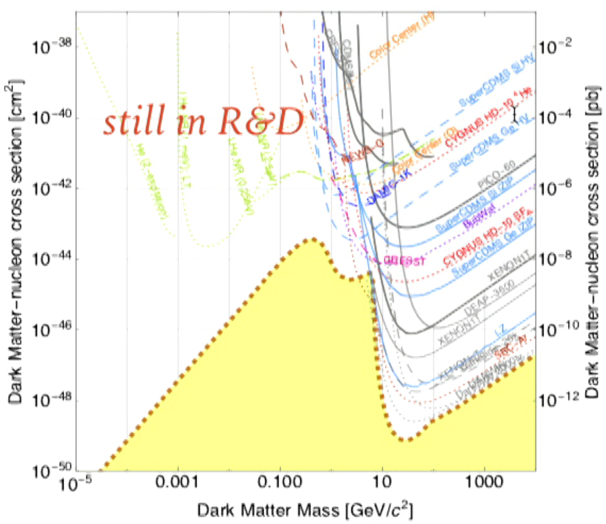
DIRECT DETECTION SCHEME

source:LUX-Zeplin

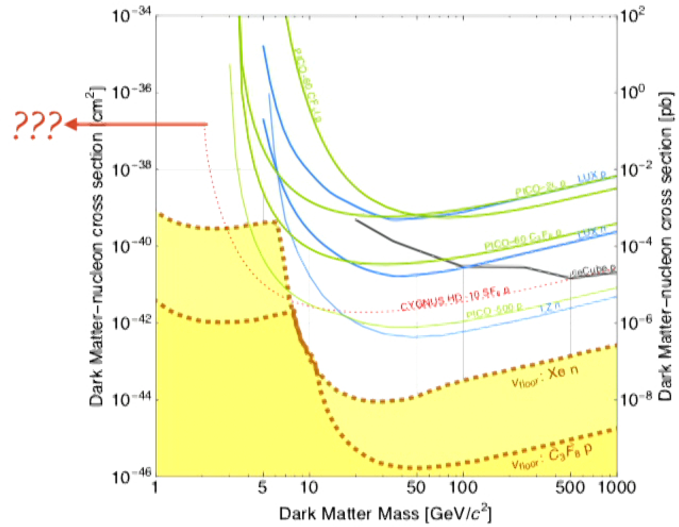


CURRENT STATUS OF DM DIRECT DETECTION

Nuclear Recoil



Spin-Independent



Spin-Dependent

source:Cosmic visions, 2017

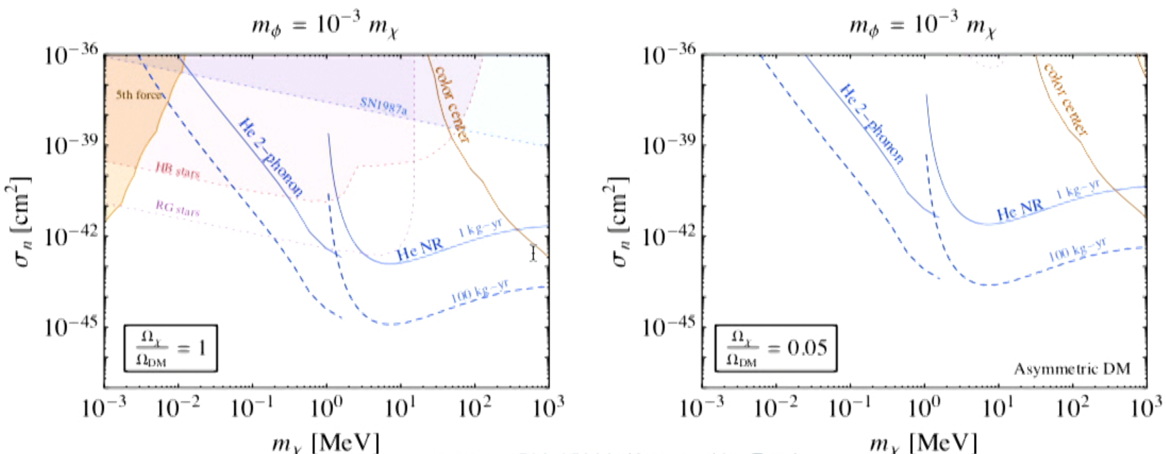
WHY?

- Kinematics
- Local density of DM assumed to be ~ 0.3 GeV/cm^3
- Larger number density of DM particles, however,
- Typical Recoil energy:

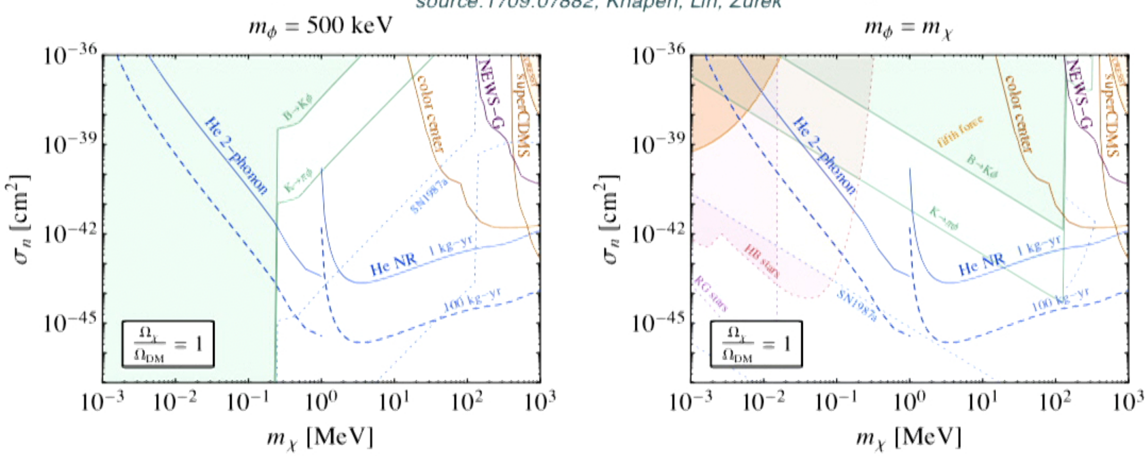
$$E_R < \frac{1}{2}\mu_{N\chi}v^2$$

- For MeV masses, this is eV, too small for conventional large tank detectors (few keV)

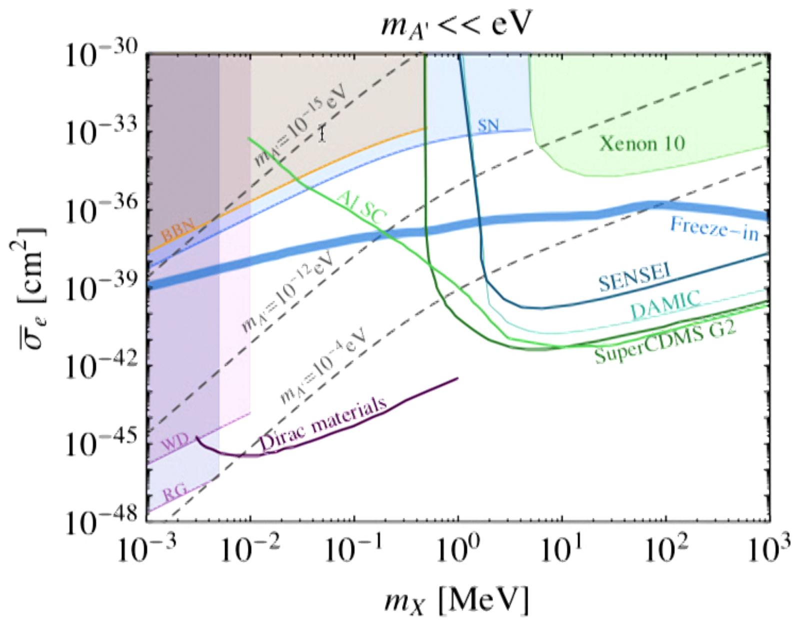
LIMITS ON MODELS FROM MEDIATORS



source:1709.07882, Knapen, Lin, Zurek



MILLI-CHARGED PARTICLES



GAPPED SYSTEMS

- Gapped systems, that can be excited by DM scattering.
- Find ways to Trigger on this.
- Examples: Semi-conductors, Super-fluid Helium, Polar crystals etc.

Light Dark Matter Proposals References:

SENSEI(arXiv:1804.00088)

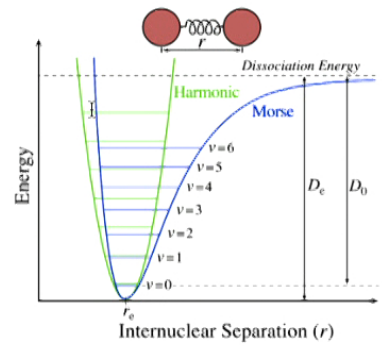
Polar Molecules (arXiv:1807.10291)

Helium (arXiv:1611.06228)

Nuclear dissociation (arXiv:1608.02940)

MOLECULES

- Described by a Morse Potential.
- Approximately a Harmonic Oscillator potential.



- A rich spectrum of vibrational levels (v) and rotational levels (j).
- v levels approximately equally spaced.
- Level splitting typically 500 meV.
- Corresponds to DM mass 500 keV and above.

Extremely useful reference: arXiv:1709.05354, Arvanitaki, Dimopoulos, Van Tilburg. for Absorption

DM SCATTERING OFF MOLECULES

- Method: Cool tank of molecular gas to temperatures where only v=0 is populated ~ 40 K.
- DM scatters molecules to excited state
- Excited State Decays by emitting photon.
- Single photon detectors to detect signal
- Require a multi-photon signal to beat other backgrounds.

MOLECULAR CANDIDATES

- Homo-nuclear molecules: large decay times and low quenching rates.
- Hetero-nuclear molecules with smaller decay times preferred.
- If Dipole moment too large, quenching cross-sections become too large.
- Carbon Monoxide (CO) works is an ideal middle-ground, more candidates might be out there.

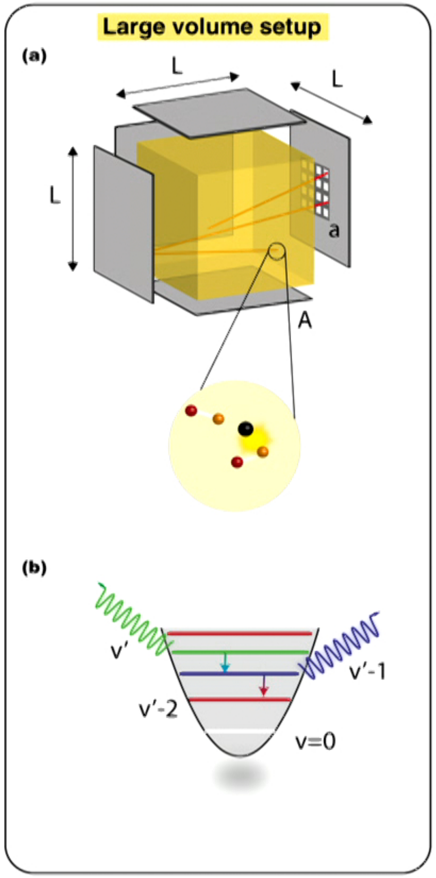
OVERVIEW OF RATES

- Decay rate set by the Einstein coefficient
- resonant collisional quenching:
- $CO(v) + CO(0) \longrightarrow CO(v\text{-}1) + CO(1)$
- Rate abnormally large because of the approximately harmonic evenly spaced energy levels.
- Resonant quenching rates lower for higher excited state where harmonic potential is a bad approximation.
- $CO(v) + He \rightarrow$ inclusive and $CO(v) + CO(0) \rightarrow$ inclusive might also be important.

INCREASING PHOTON MFP

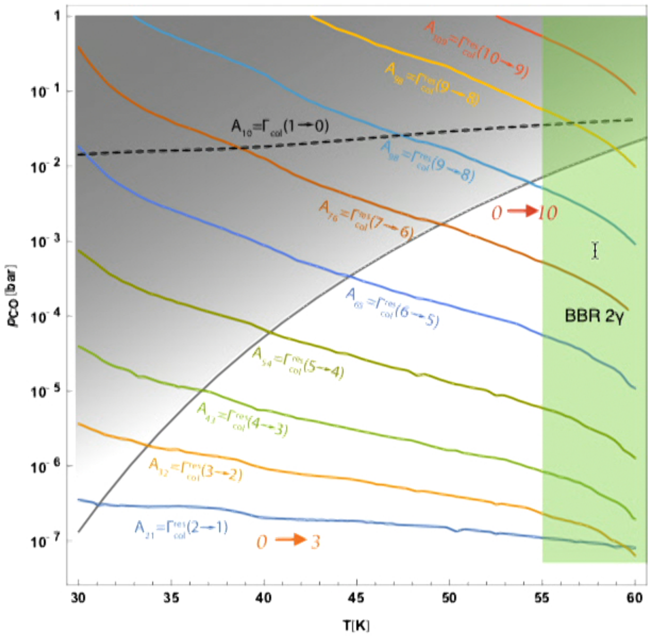
- A large volume setup: Excite to a large v, look for off resonant
- v⟶v-1 and subsequently v-1⟶v-2>0
- Both photons are off resonant with v=0 state, essentially infinite MFP
- Large number of reflections before hitting detector.
- Subdominant: v⟶v-4 and subsequently v-4⟶v-8 > 0

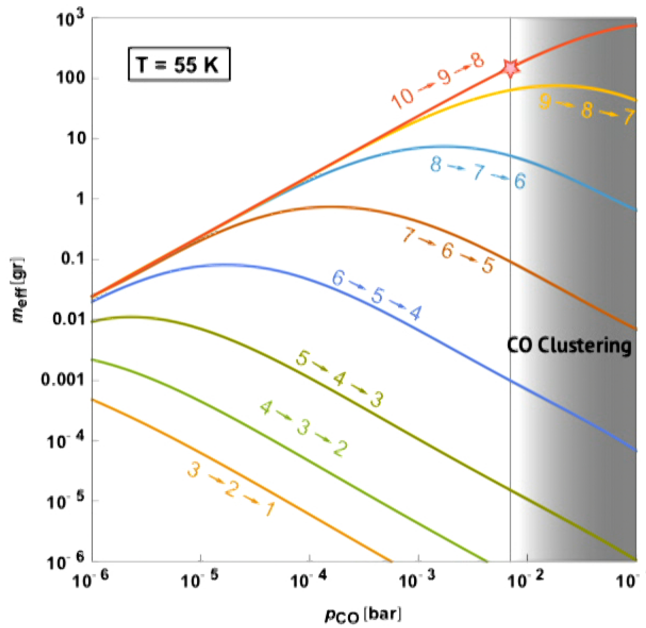
A LARGE VOLUME SETUP



- Results in a very large tank, size limited by refrigeration limitations and reflection efficiency of the mirrors.
- To prevent resonant quenching go to very low pressures.
- Higher pressures allowed for larger excited states (even spacing no longer true)

RATE COMPARISON



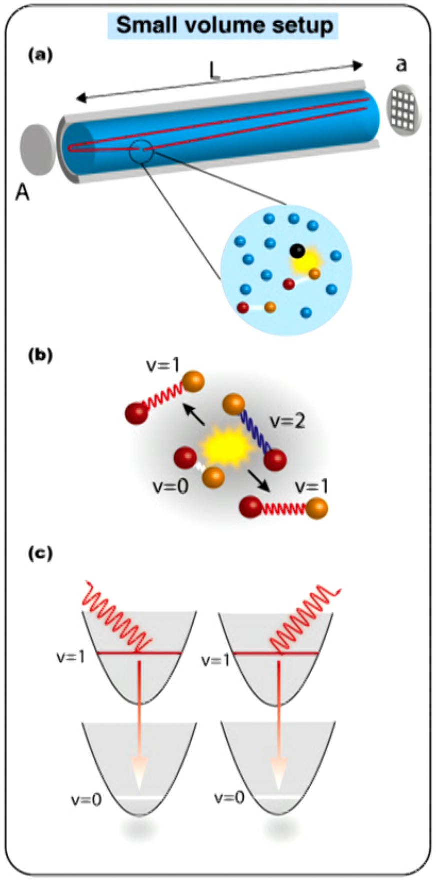


- Rate Hierarchies and Clustering again Important
- At the expense of higher energy splitting, go to higher target masses.

INCREASING THE PHOTON MFP

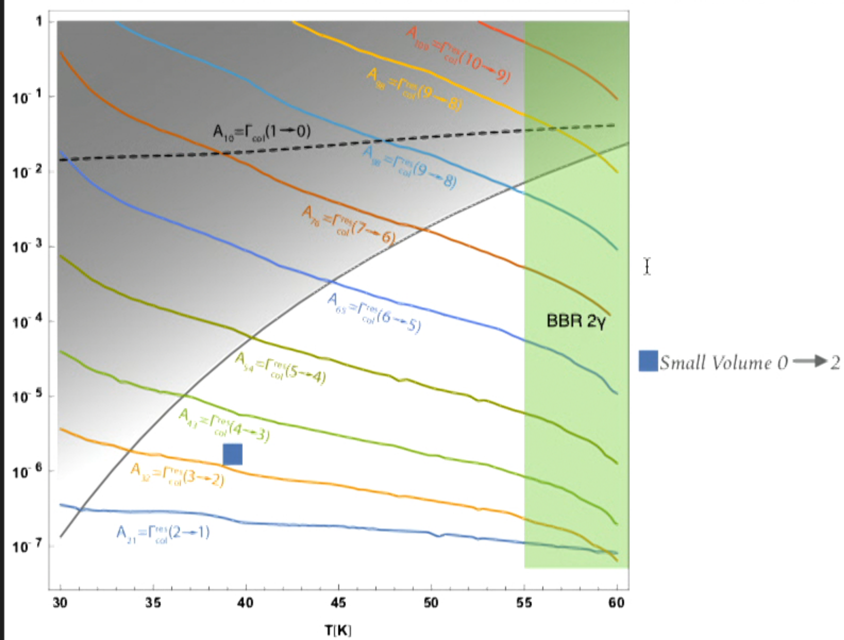
- Method2 : Pressure Broadening through Helium Buffer gas
- Collisions with He are not efficient at quenching CO
- Collisions disrupt the decay process causing a larger width.
- Pressure Broadening → a more transparent CO drastically increasing MFP
- Multiple CO isotopes (6) and j states (4) are also mutually transparent.
- More mutually transparent gases could also be added.

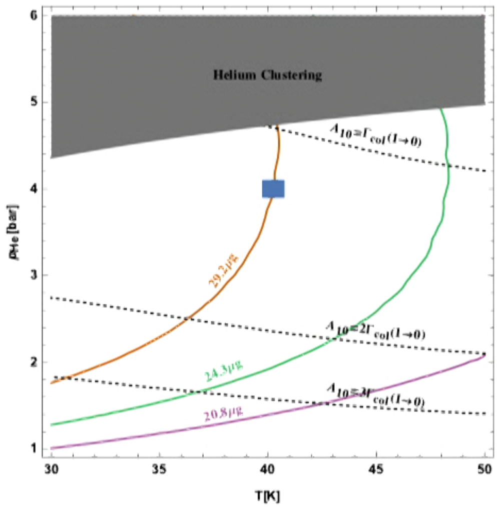
A SMALL TANK SETUP



- A relatively smaller tank, dimensions set by the MFP and the area of the detector.
- Cover the walls with mirrors.
- v=2 followed by resonant quenching
- i.e. (2+0⟶1+1). High rate because of approximate equal spacing.
- each v=1 decays through approximately time coincident photons.
- Both photons reach the lids with high probability.

RATE COMPARISON





- ➤ Operating temperature & pressure set by:
- ➤ Rate hierarchies
- ➤ Keeping CO and He in the gas phase

TARGET MASS

Setup	Experimental Parameters				m_{eff}
	Partial CO Pressure	Total Pressure	Detector Area	Excited State (v')	
Small Vol. (current)	10 μbar	4 bar	1cm^2	2,3 and 4	30 μgr
Small Vol. (5 year projection)	10 μbar	4 bar	100cm^2	2,3 and 4	3 mgr
Large Vol. Low P (current)	0.6 μbar	0.6 μbar	1cm^2	3	3.5 mgr
Large Vol. High P (current)	5 mbar	5 mbar	1cm^2	10	150 gr

Microwave Kinetic Inductance Detectors (MKIDs)

Transition Edge Sensor (TES)?

Subdominant Branching fractions using PMTs

CROSS-SECTION CALCULATION

$$\langle \sigma v \rangle = \bar{\sigma}_n \sum_i \int \frac{q dq}{2\mu_{\chi n}^2} f_{PN,i}^2 |F_{\rm DM}(q)|^2 \langle |F_{{\rm mol},v'J'}(q)|^2 \rangle_i \eta(v_{\rm min}(q))$$

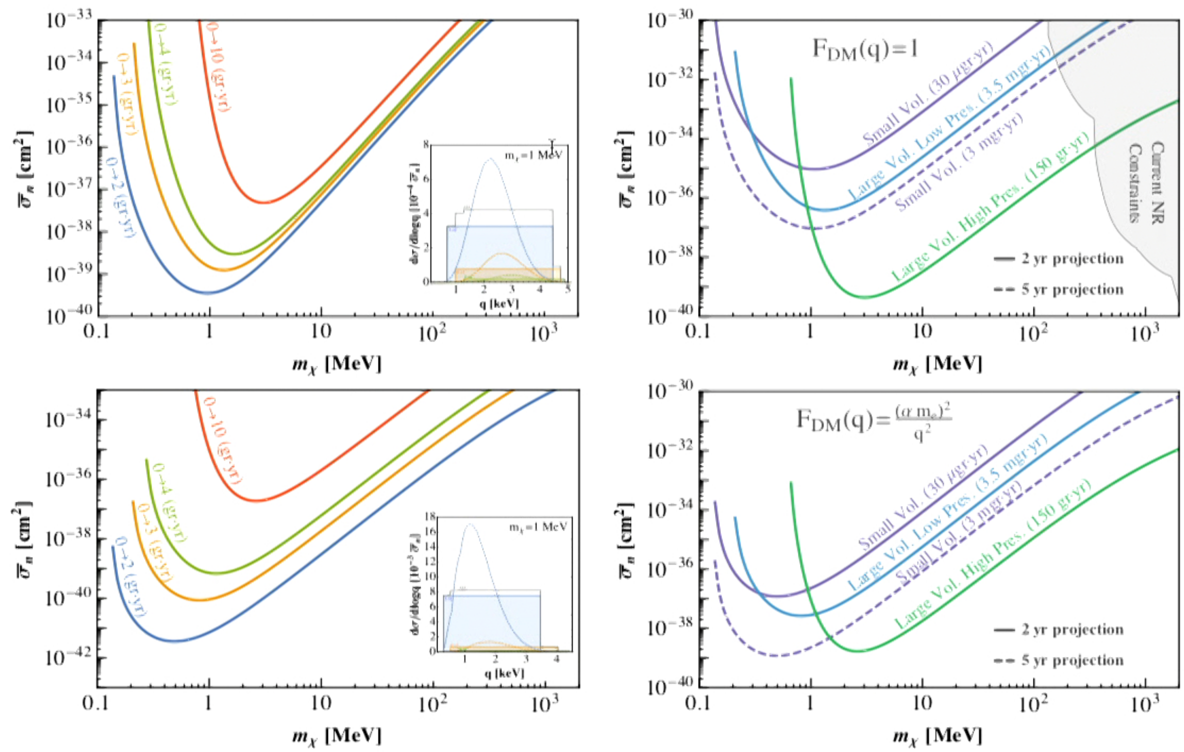
$\mu_{\chi n}$	*Reduced Mass*
$\eta(v_{\rm min}(q))$	*Captures DM velocity distribution*
$\bar{\sigma}_n$	*Reference Cross-section*
$F_{\rm DM}(q)$	*Dark Matter Form Factor*

$$\langle |F_{{\rm mol},v'J'}(q)|^2 \rangle \equiv \left\langle \left| \int d^3 r e^{i \frac{\mu_{12}}{m_1} \mathbf{q}\cdot\mathbf{r}} \Psi_{v'J'}^*(\mathbf{r}) \Psi_{vJ}(\mathbf{r}) \right|^2 \right\rangle$$

Molecular Form Factor

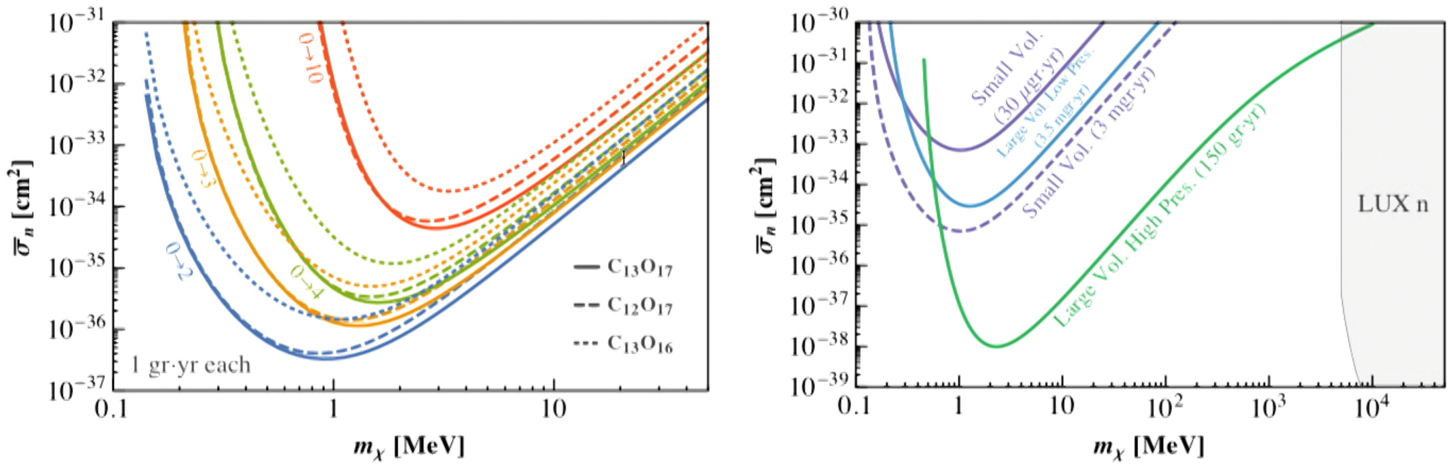
REACH

Spin Independent



REACH

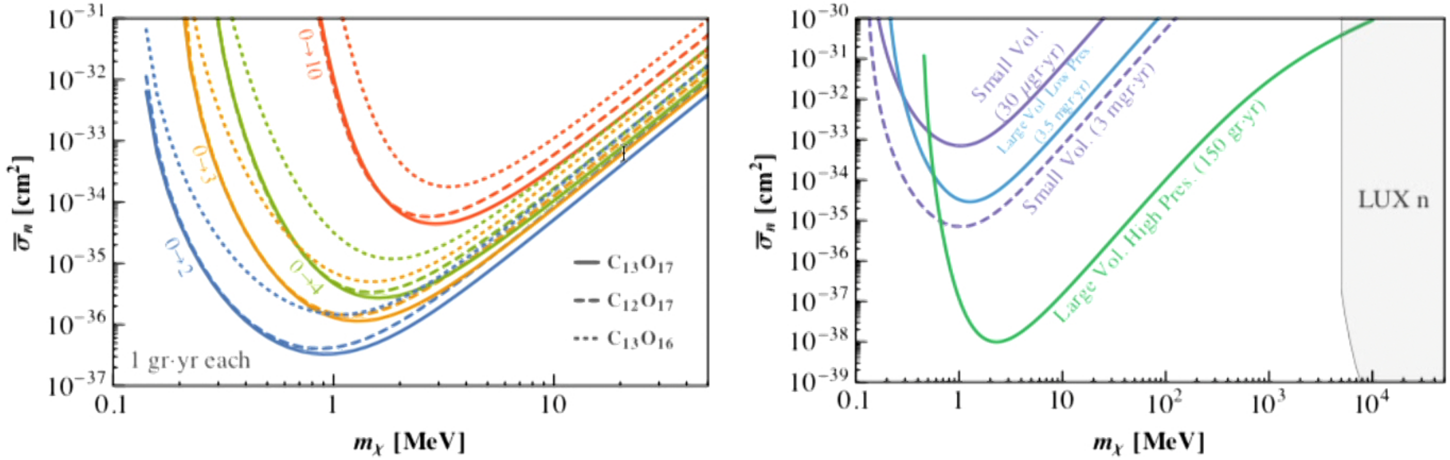
Spin Dependent



- ➤ Introduction of Odd-proton/Odd-neutron isotopes
- ➤ Increases transparency
- ➤ Sensitivity to Spin-Dependent interactions

REACH

Spin Dependent



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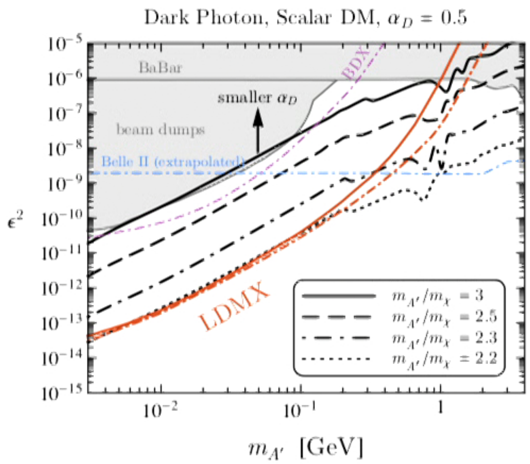
PART 2

HOW ABOUT CONSTRAINING THE MEDIATOR ITSELF INSTEAD?

LIGHT DARK MATTER MEDIATORS

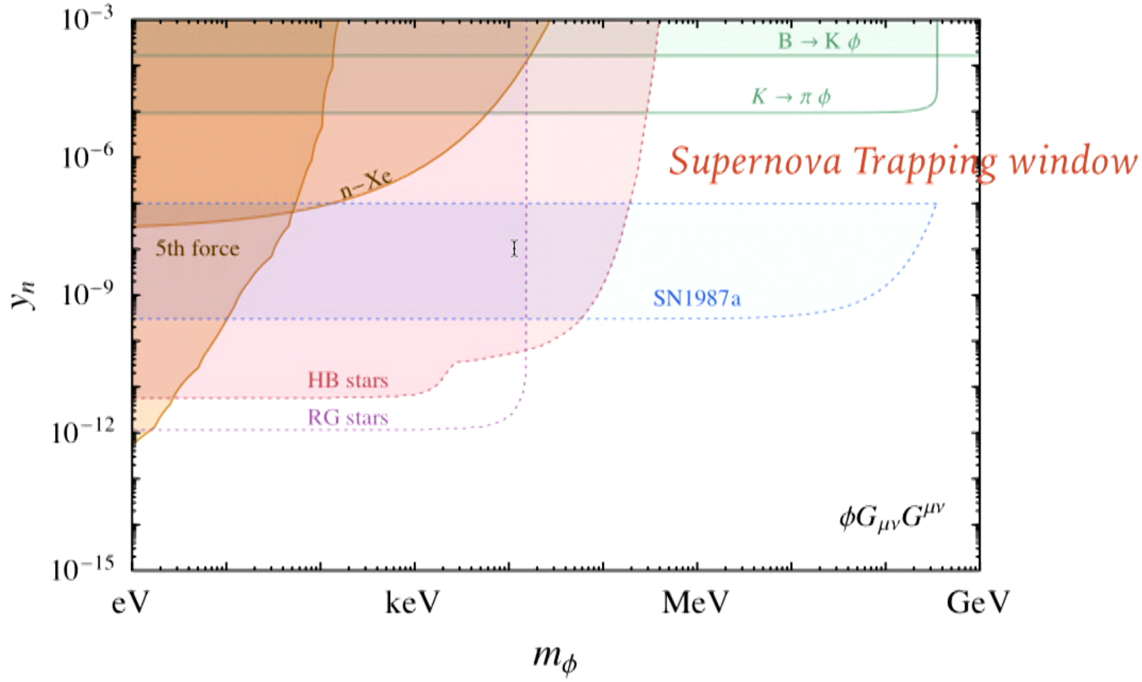
- For LDM Direct Detection, mediator cannot be too heavy; rate drops precipitously.
- Opportunity to constrain the mediator itself.
- NA64, BDX, LDMX etc are proposed to look for forces coupled to electrons



Source:LDMX

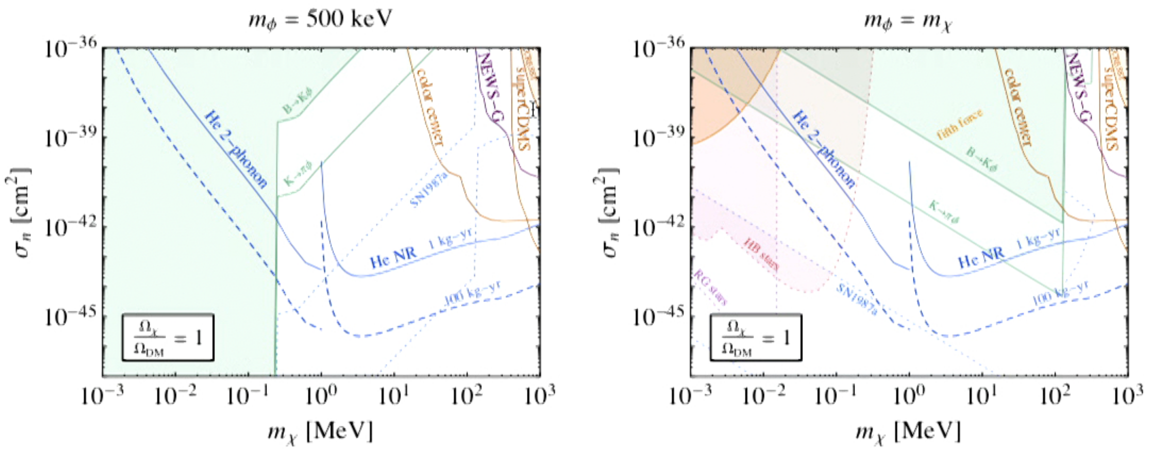
- Nucleophilic forces are harder to constrain.

STATUS OF NUCLEOPHILIC FORCES - SCALAR MODEL



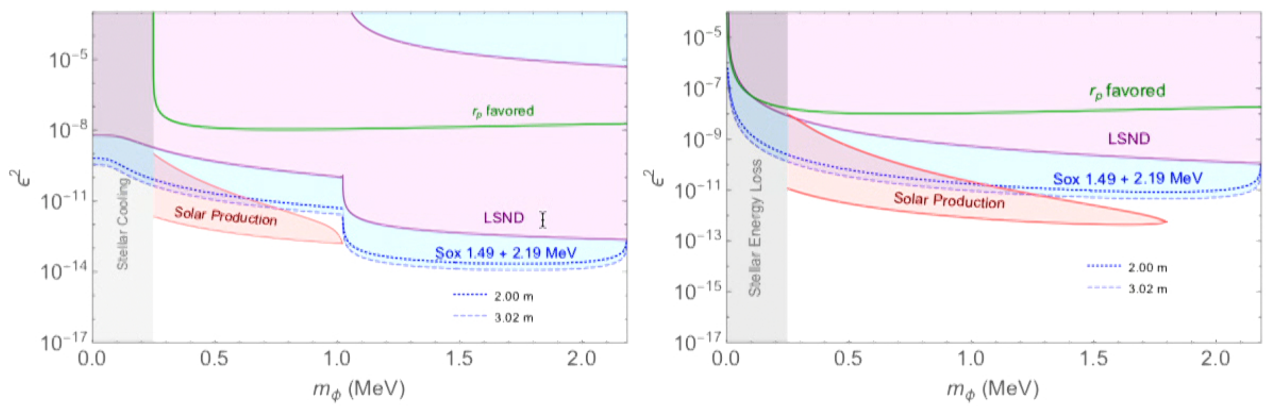
Source:1709.07882, Knapen, Lin, Zurek

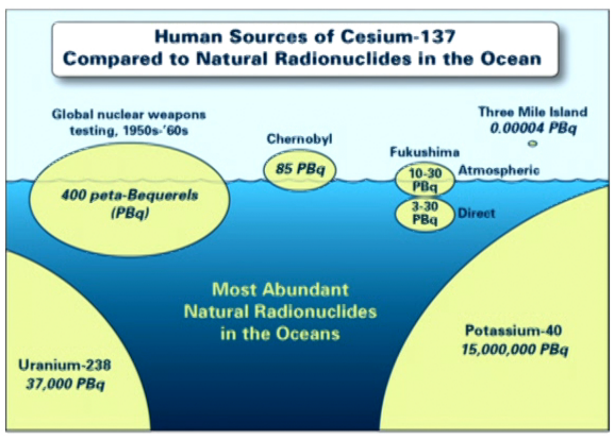
LOOPHOLES TO BUILD DM MODELS...



A 5 PBq source and Borexino right next to it

1706.00424. Pospelov, Tsai.





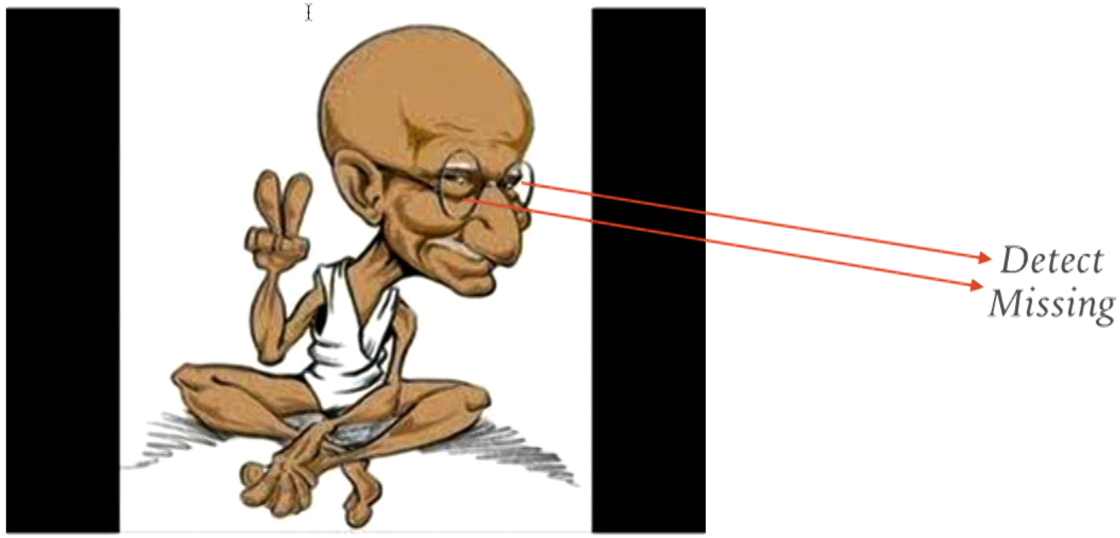
Maybe a nuclear waste facility?

MET

- missing energy experiments stay agnostic to decay modes
- furthermore, pay small factor only once
- how do we do this for a baryonic force though? doing MET search for baryons is a messy enterprise.
- 10 MBq?

THE GAMMAS FROM NUCLEAR DECAYS HIDING FROM INVESTIGATORS (GANDHI) EXPERIMENT

NUCLEAR PHYSICS FOR PEACE



Quotes wrongly attributed to Mahatma Gandhi:

"A gamma for a gamma makes… "

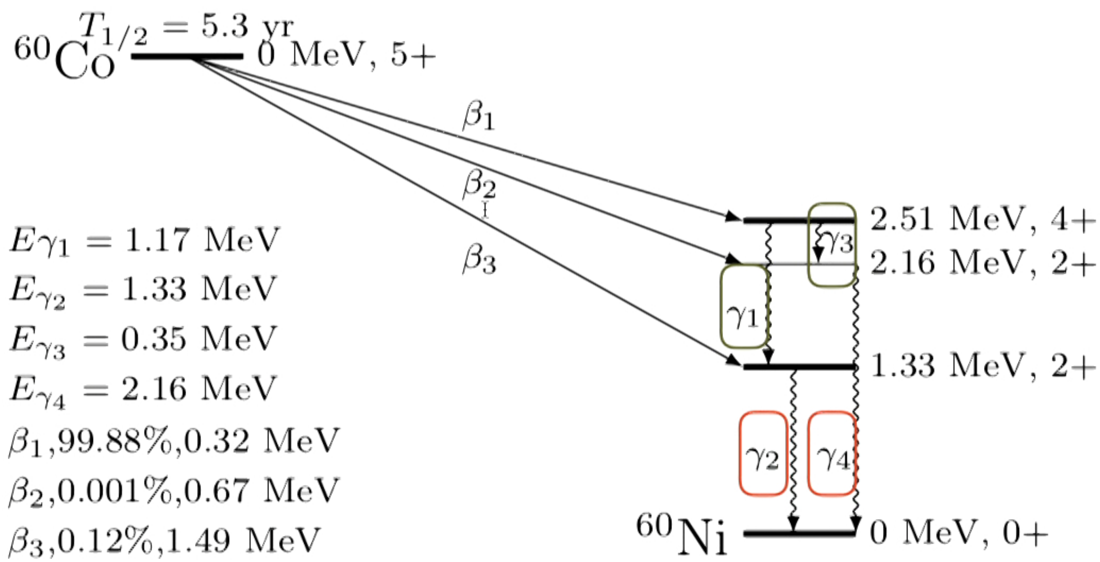
WHAT IS THE LARGE NUMBER?

- Need for large statistics. typically EOT in a beam-type exp.
- Avogadro number of decaying nuclei is a naturally large number
- Can we do nuclear gamma decays and look for MET?

ISOTOPE SELECTION

- Isotopes which are long-lived, high energy gamma emitters.
- Decay sequence that is trigger-able
- Industrial production is a plus.
- Candidates: ^{60}Co, ^{24}Na, ^{65}Ni.

CASCADE GAMMA DECAYS IN COBALT DECAYS



Cascades happen because it is easier to shed two units of spin at a time rather than shedding 4 all at once.

SIGNAL

- Cobalt foil inside a hermetically sealed detector
- Trigger on first gamma
- Signal event is a beta+first gamma+missing subsequent second gamma

PHOTON DETECTION

- Photon detection with minimum dead-time
- Energy resolution, very important.
- Minimal dead regions/cracks, hermeticity.
- Intrinsic Radioactivity needs to be kept low
- Large detector volumes might be required to make sure second gamma was not missed, difficult to grow crystals.
- Plastic Scintillators are ideal choice - BC-404
- A Hybrid plastic Scintillator core + liquid scintillator body might work also.

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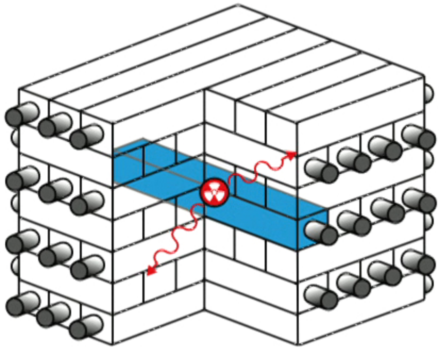
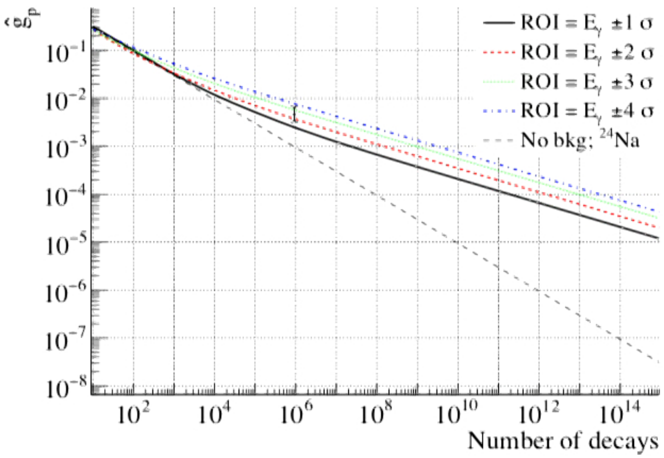
DETECTOR SCHEME



- Hermetic Detector divided into 3 modules
- Central modules to completely stop betas ~ cm
- Inner module to detect majority of the gammas ~ 10cm. Require detection of first gamma here
- Outer module depending on the efficiency required.

1.33 MEV GAMMA MIMICKING 1.17 MEV GAMMA

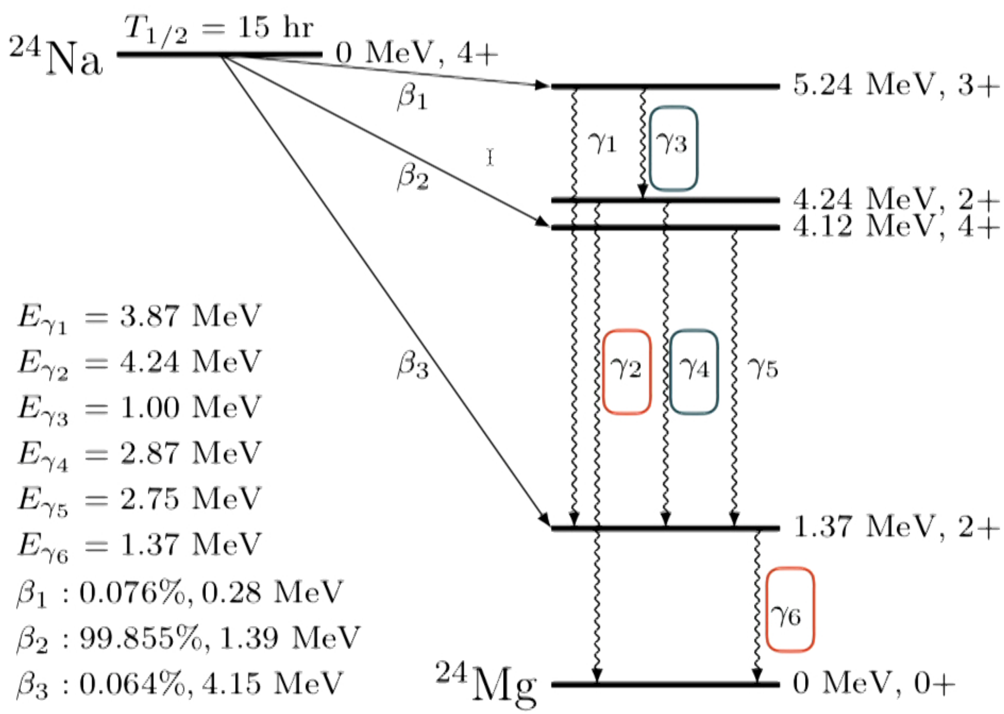
Mixing angle



- As statistics increase, need tighter cuts in order to keep the tails of the singular second gamma from causing fakes. Happens mainly because $E_2 > E_1$
- 24Na does not suffer from this….

^{24}NA

Will need experiment to happen close to source.



TOY MODEL

$$\mathcal{L} = g_p \phi \bar{p} p$$

For an E_2 transition,

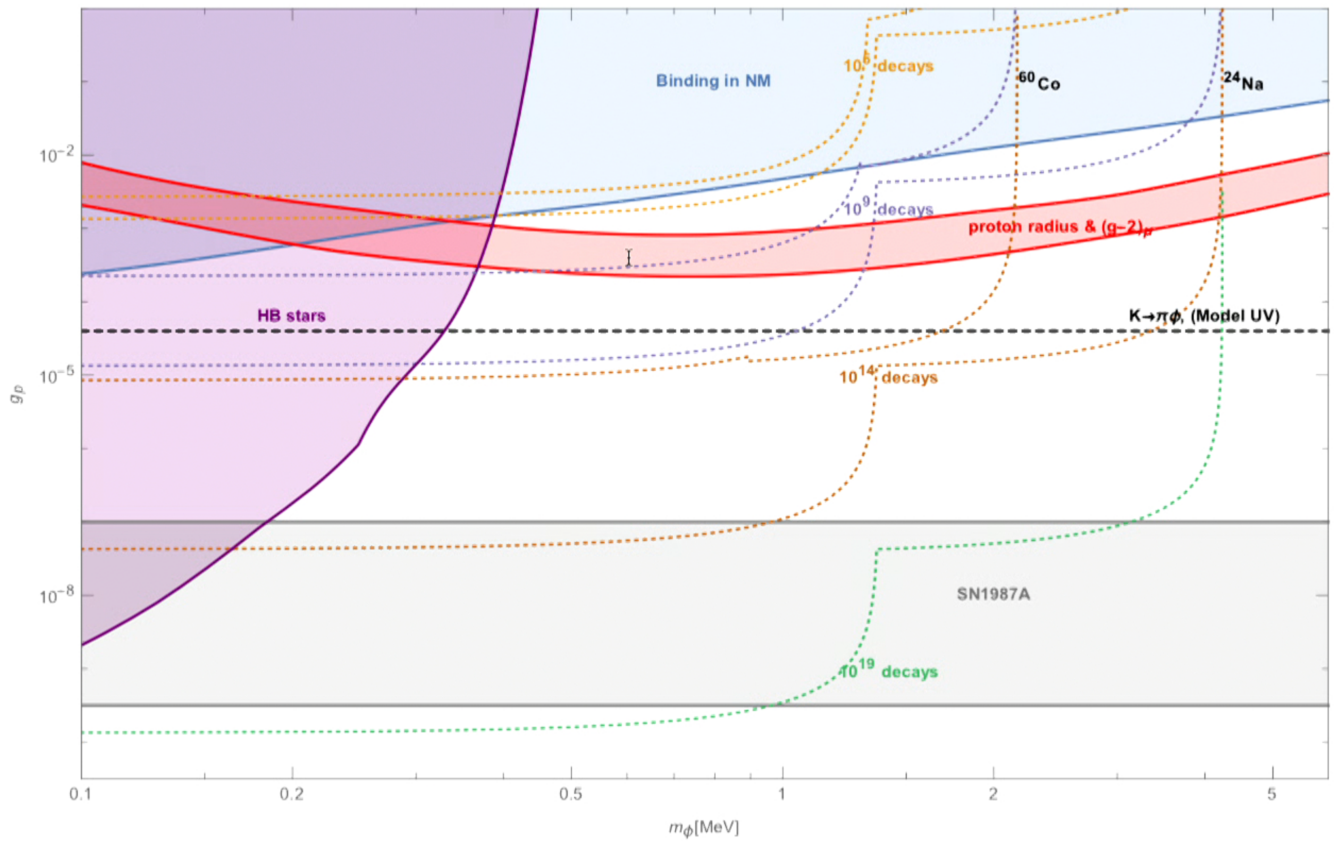
$$H_{\text{int}}^{\phi} = g_p R_p^i R_p^j \nabla_i \nabla_j \phi(k)$$

$$H_{\text{int}}^{\gamma} = e R_p^i R_p^j \nabla_i \epsilon_j$$

Invisible branching fraction:

$$\frac{\Gamma(\phi)}{\Gamma_{\gamma,E_2}} \sim \frac{1}{2} \left(\frac{g_p}{e}\right)^2 \left(1 - \frac{m_\phi^2}{\omega^2}\right)^{\frac{5}{2}}$$

REACH



Source for existing limits: Knapen et al. and Y.-S. Liu, D. McKeen, and G. A. Miller ,1605.04612

OUTLOOK

- If we can find E_0 transitions with triggering, we could do even better: SM is a 2 photon decay
- M_1 transitions are useful for axion searches.

CONCLUSIONS

- A rich spectrum of molecules and nuclei could be used for unique dark matter experiments
- Molecular vibrations for Light Dark Matter scattering experiments
- Nuclear gamma decays for Baryonic Forces
- Nuclear Isomers for Inelastic Dark Matter Direct Detection