# EXPLORING THE DARK UNIVERSE WITH MOLECULES AND NUCLEI

*Harikrishnan Ramani*
*BCTP, Berkeley*

*Common theme: repurposing bound states with rich energy levels for Dark Matter*

---

*Molecular excitations- arxiv:1904.XXXXX (Name for experiment under review)*
*with Jesus Perez-Rios, Rouven Essig, Oren Slone*

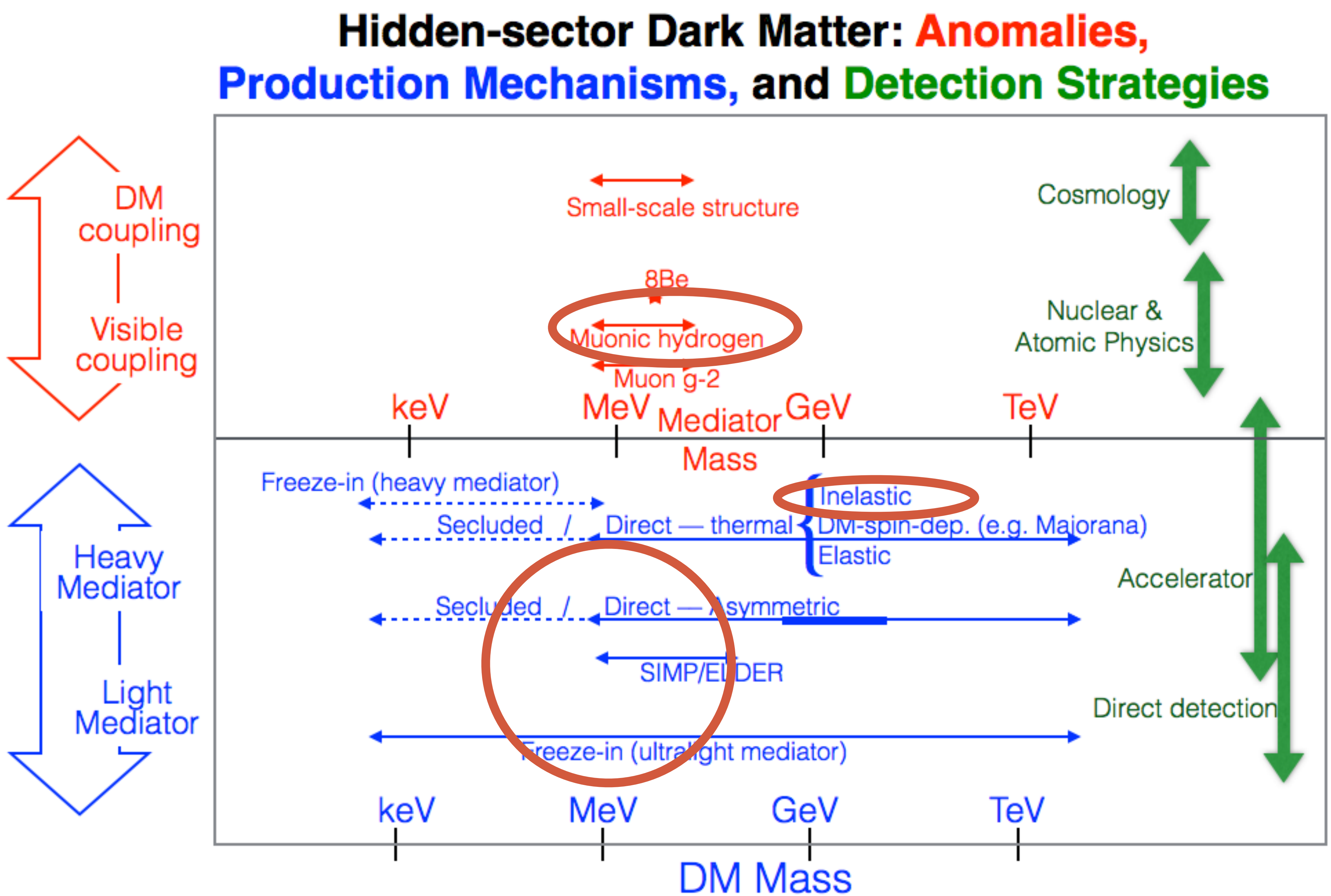
*GANDHI- arxiv:1810.06467*
*with Giovanni Benato, Alexey Drobizhev, Surjeet Rajendran*

*Metastable Isomers- Preliminary*
*with Maxim Pospelov, Surjeet Rajendran*
*with Lehnert et. al. (re-analysis of existing experimental data)*

# OUTLINE

- Light Dark Matter Direct Detection through Molecular Excitations
- Detecting Baryonic Forces through a gamma decay experiment — GANDHI
- A dark matter accelerator with metastable nuclei

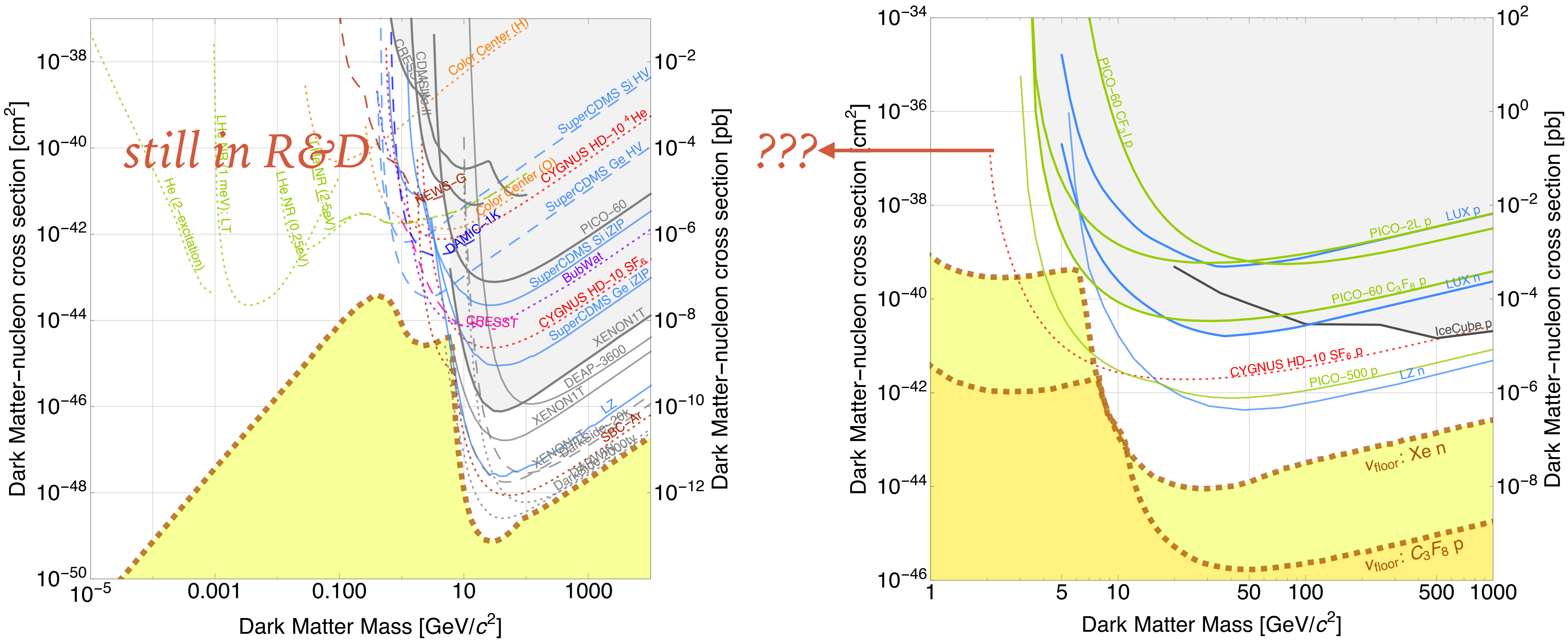
# DARK MATTER LANDSCAPE




*Cosmic Visions : 2017*

# CURRENT STATUS OF DM DIRECT DETECTION

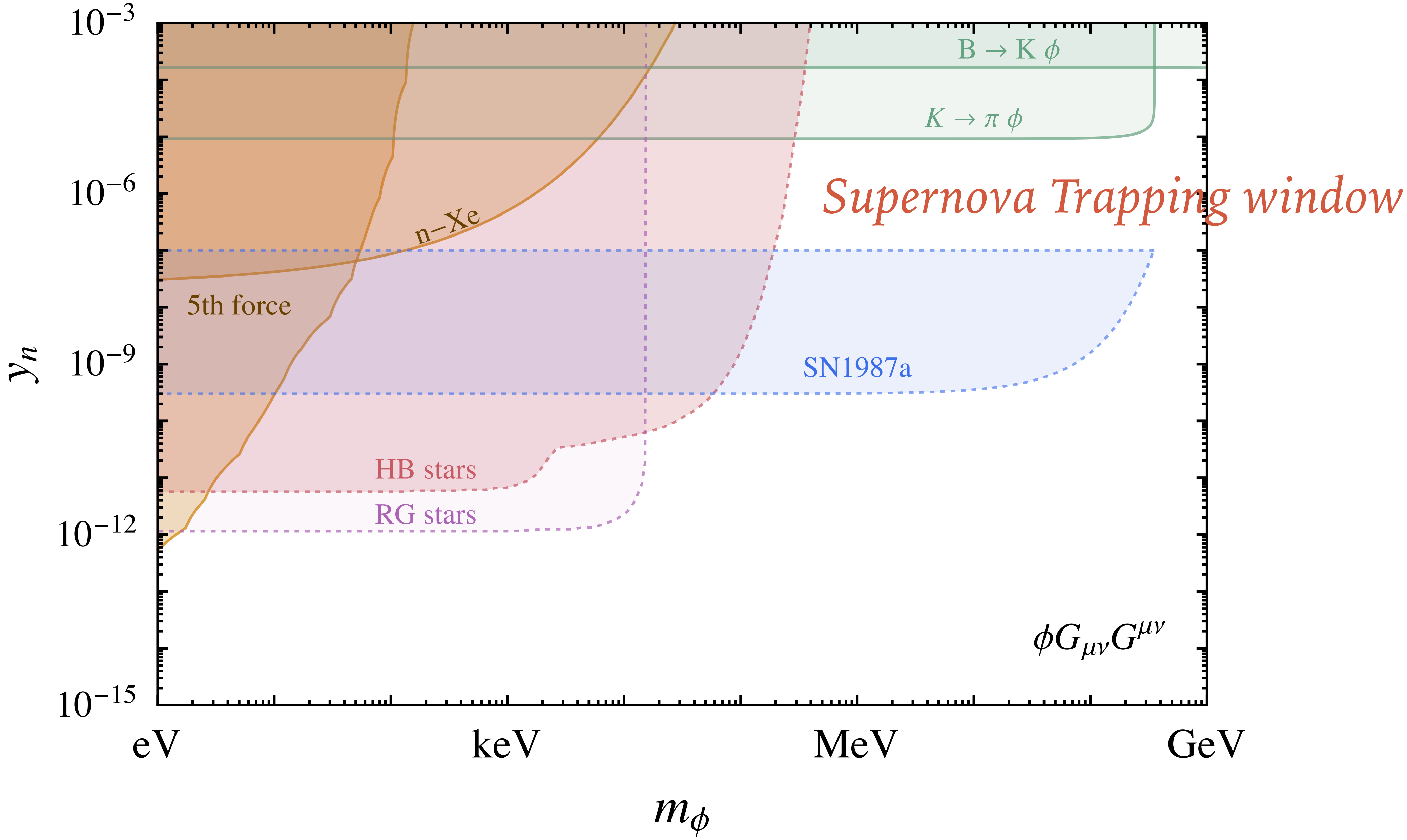
*Nuclear Recoil*




*Spin-Independent* *Spin-Dependent*

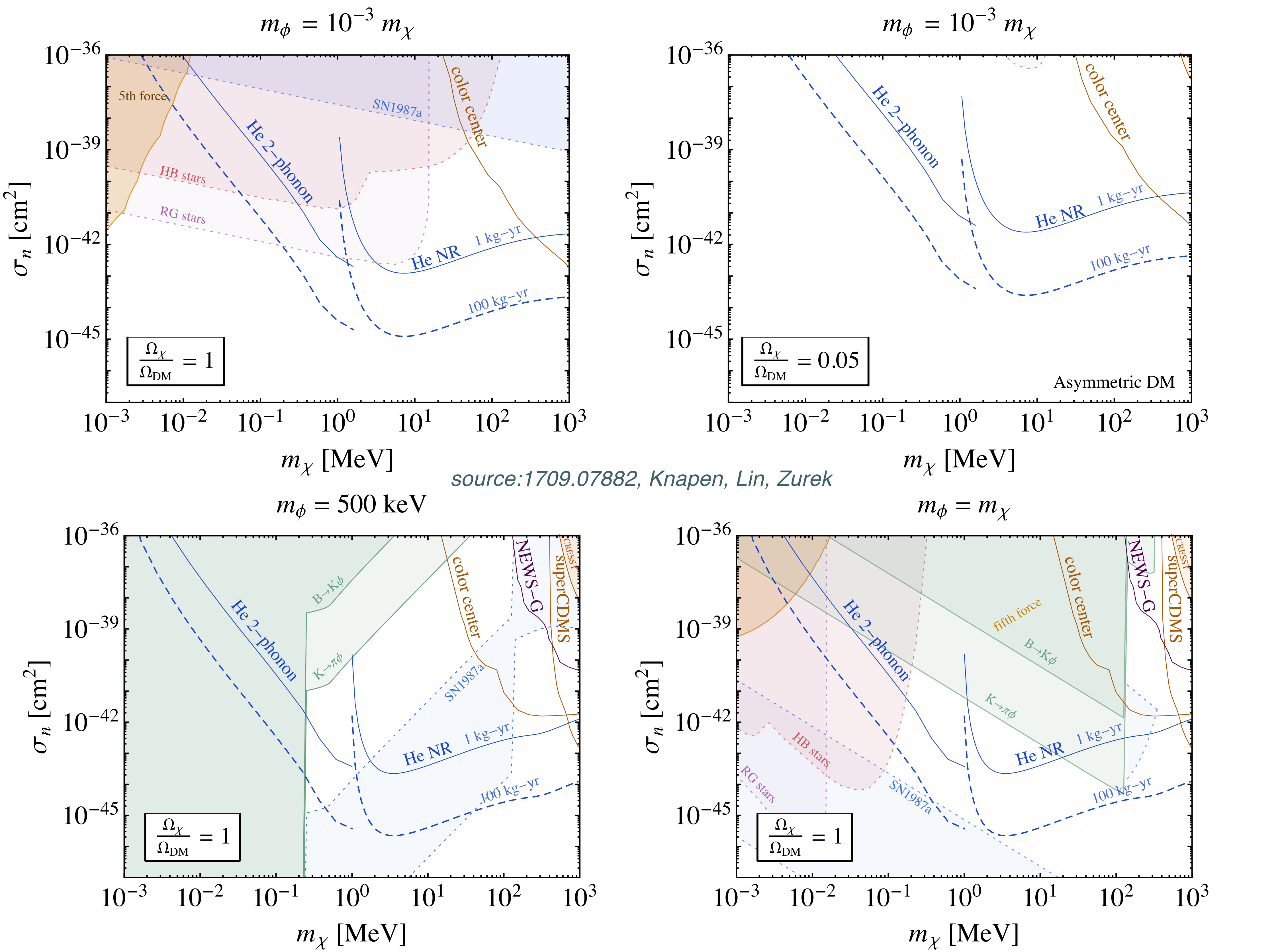
*source:Cosmic visions, 2017*

# CAN SET LIMITS USING LIMITS ON MEDIATOR




*Source:1709.07882, Knapen, Lin, Zurek*

# LIMITS ON MODELS FROM MEDIATORS




source:1709.07882, Knapen, Lin, Zurek

# INELASTIC SCATTER

- The total energy deposited in elastic scatter:

$$E_{\text{tot}} = \frac{q^2}{2m_{\text{N}}} \approx \frac{m_\chi}{m_{\text{N}}} \boxed{\frac{1}{2} m_\chi v_\chi^2}$$

- Extra $m_\chi/m_{\text{N}}$ suppression compared to the kinetic energy available. (from momentum +energy conservation)
- Inelastic scatter with target does not suffer from this.

# GAPPED SYSTEMS

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

*Inelastic scatter proposals*

*SENSEI(arXiv:1804.00088)*

*Polar Molecules (arXiv:1807.10291)*

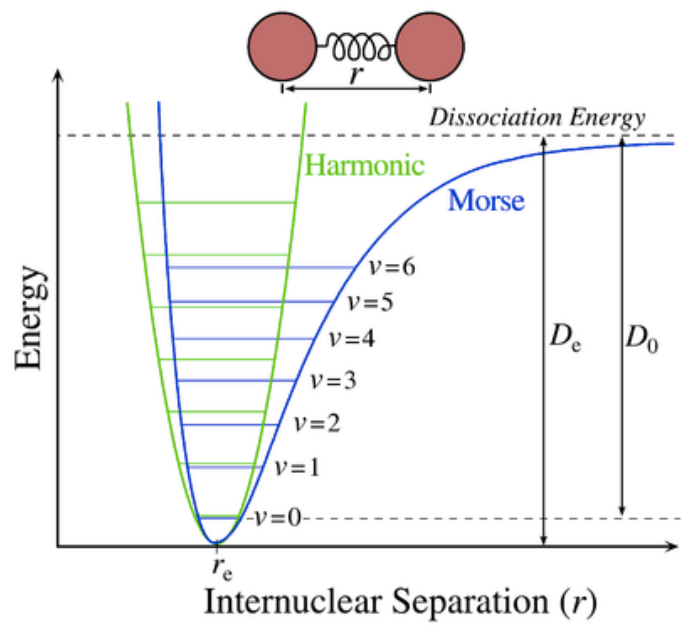
*Light Dark Matter Proposals References:*

*Helium (arXiv:1611.06228)*

*Nuclear dissociation (arXiv:1608.02940 )*

# MOLECULES

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

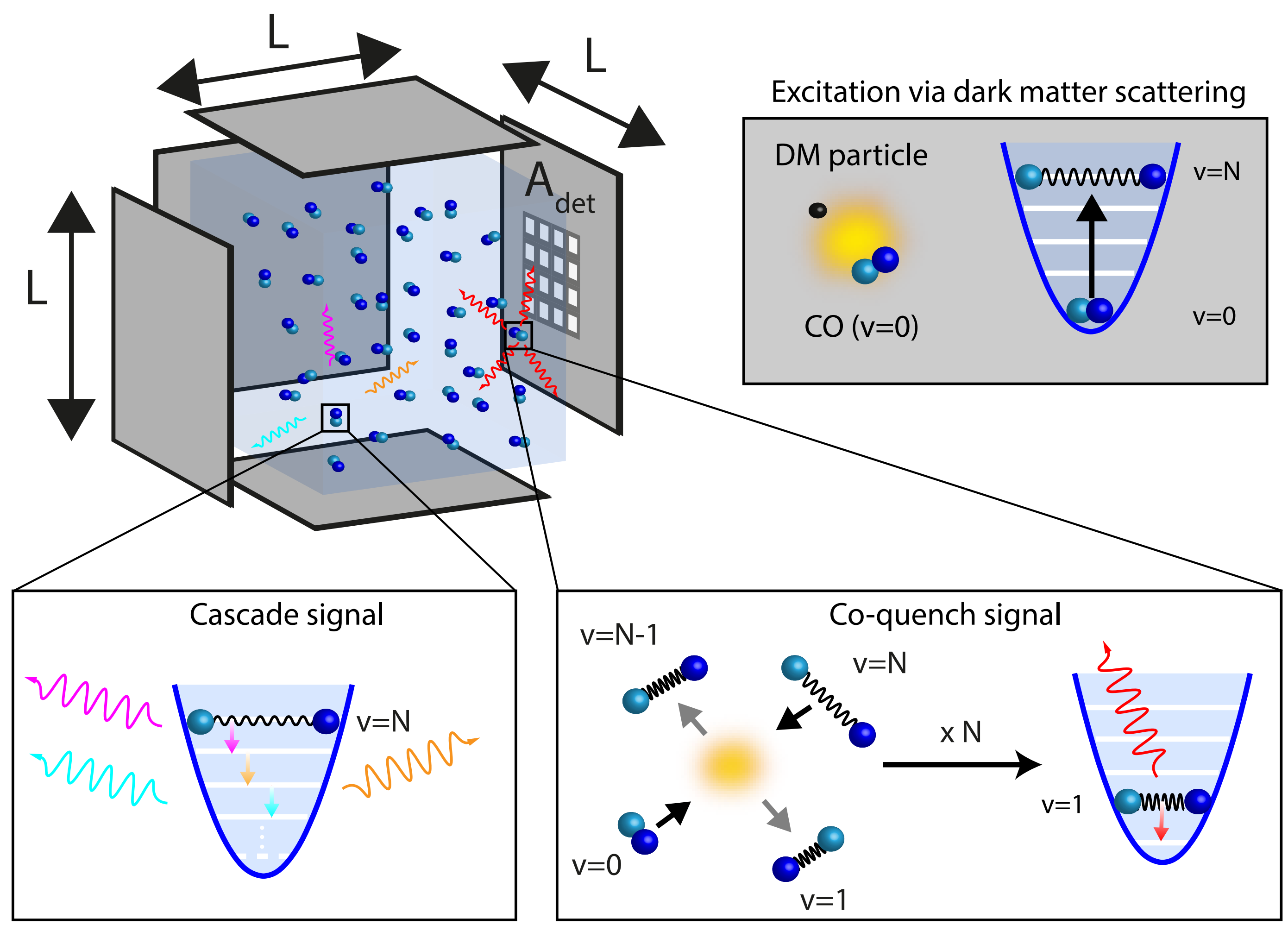



- A rich spectrum of vibrational levels (v) and rotational levels (j).
- v levels approximately equally spaced.
- Level splitting typically 500 meV.
- Corresponds to DM mass 500 keV and above.

*[1709.05354, Arvanitaki, Dimopoulos, Van Tilburg] for Absorption*

# DM SCATTERING OFF MOLECULES

- Method: Cool tank of molecular gas to ~ 55 K where only v=0 is populated
- BBR is naturally low.
- DM scatters molecules to some excited state (v’,j’).
- Excited State Decays by emitting v’ photon(s).
- Single photon detectors to detect signal.
- Require a multi-photon signal to beat other backgrounds.



# COMPETING PROCESS: QUENCHING

- Resonant collisional quenching:
- $AB(v) + AB(0) \longrightarrow AB(v\text{-}1) + AB(1)$
- 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.
- Resonant rates are pressure dependent

# TYPES OF SIGNAL PHOTONS

- Cascade photons:

$$\begin{aligned}&\mathrm{AB}(v') \rightarrow \mathrm{AB}(v'-1) + \gamma_{v'\rightarrow v'-1}\\ &\rightarrow \mathrm{AB}(v'-2) + \gamma_{v'\rightarrow v'-1} + \gamma_{v'-1\rightarrow v'-2} \rightarrow ...\\ &\rightarrow \mathrm{AB}(N_\mathrm{c}) + (v'-N_\mathrm{c})\cdot\gamma\end{aligned}$$

- At some pressure dependent $N_c$ this stops and leads to repeated collisional quenching.

$$\mathrm{AB}(v', J') + N\cdot\ \mathrm{AB}(0) \rightarrow \mathrm{AB}(v'-1, J_\mathrm{int}) + \mathrm{AB}(1, J_{\mathrm{fin},i})$$

$$+(N-1)\cdot AB(0) + E_{k,i} \rightarrow ... \rightarrow \sum_i^N \mathrm{AB}(1, J_{\mathrm{fin},i}) + E_k^\mathrm{tot}.$$

# TYPES OF SIGNAL PHOTONS

- Then each of these AB(v=1) molecules decay giving $N_c$ photons

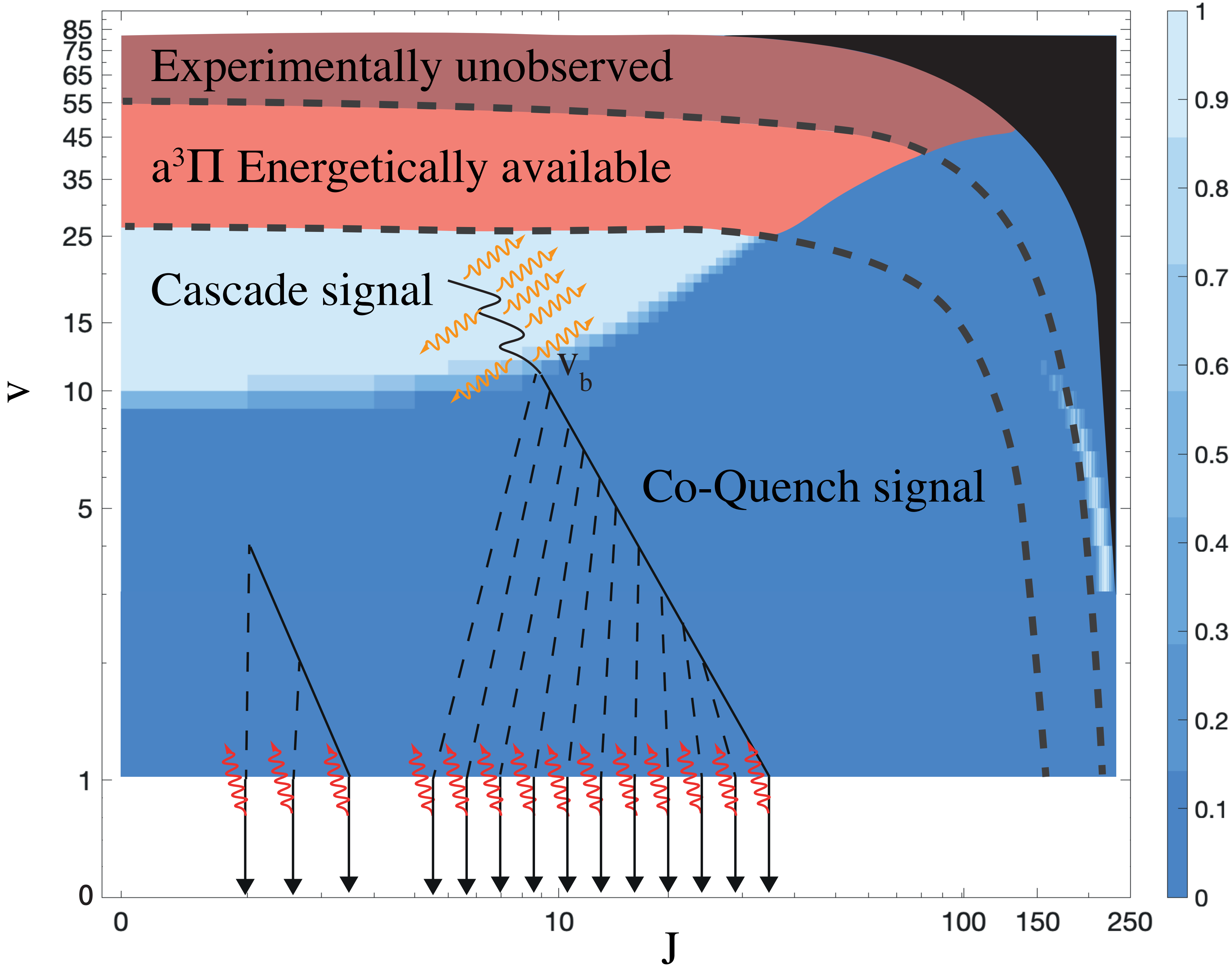
$$N_c \cdot \mathrm{AB}(1) \rightarrow N_c \cdot \mathrm{AB}(0) + N_c \cdot \gamma.$$

  - Starting with a DM excitation to v',

  we have v'-$N_c$ cascade and $N_c$ co-quench photons

- Co-Quench photons are resonant with ground state
- Employ Helium as buffer gas to induce pressure broadening
- Makes medium more transparent
- Still sensitive only to sub-volume of detector

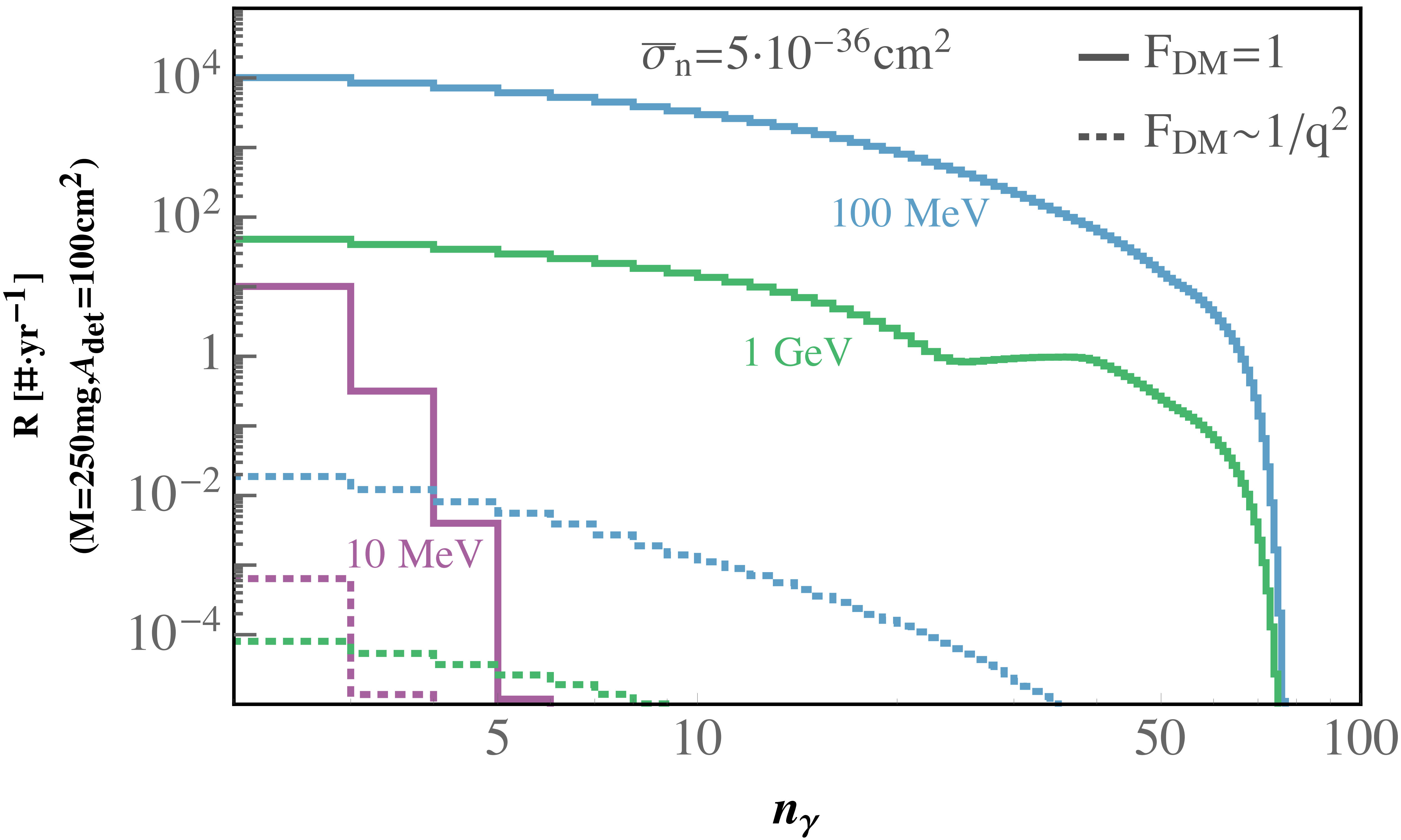
# DECAY SCHEME



# BACKGROUNDS

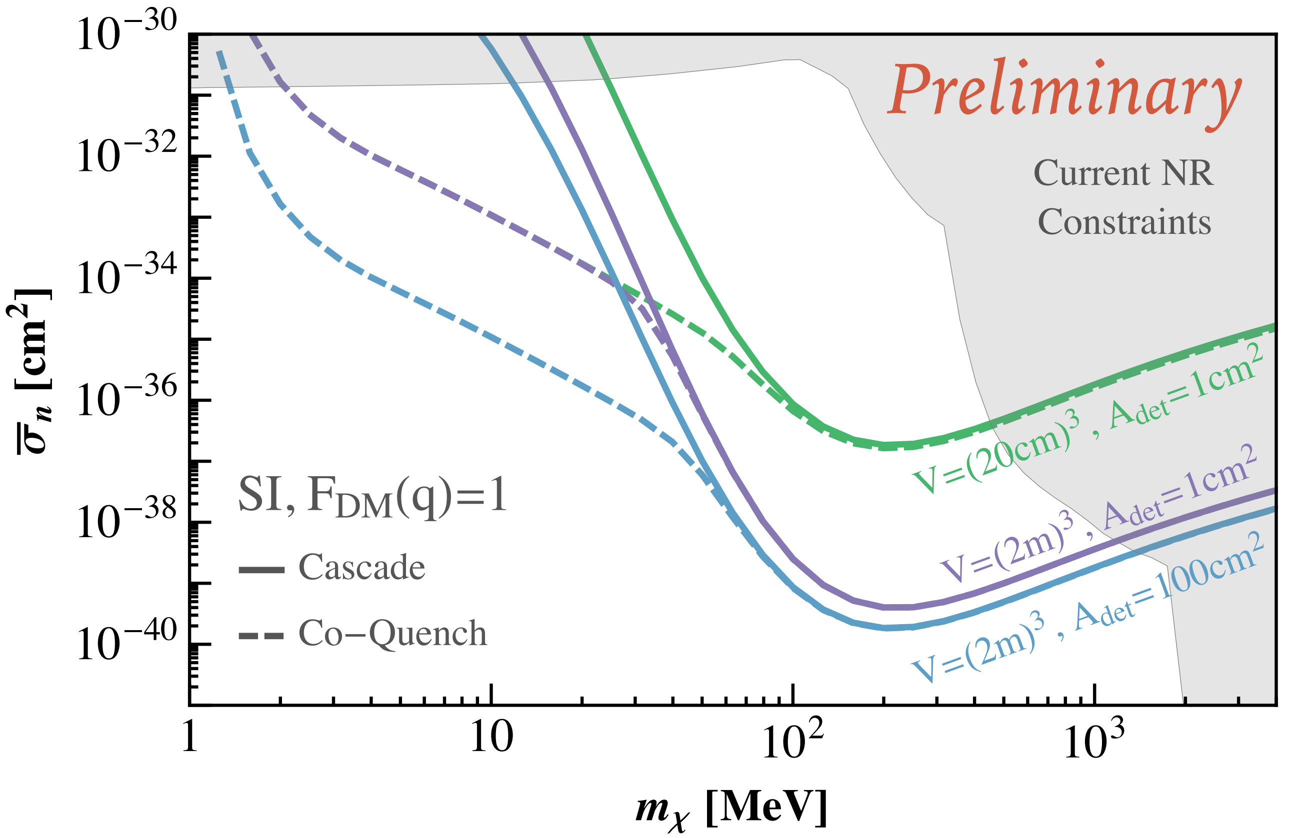
- Thermal population of higher excited states — too low
- BBR — too low at 55K.
- Dark counts of the detector (MKIDs, Nanowires etc)— still R&D required to determine
- Radio / Cosmogenics

# PHOTON SPECTRUM

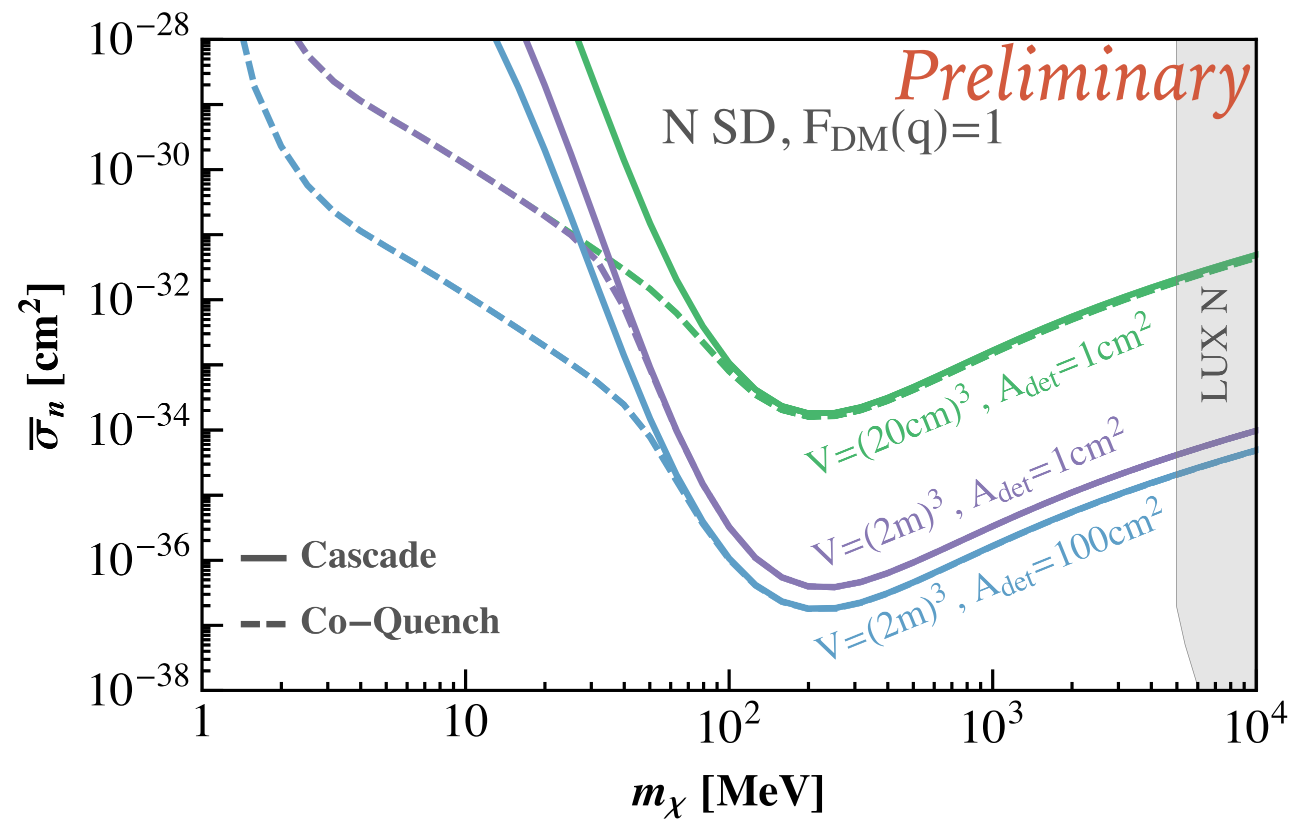


# REACH

*Spin Independent*



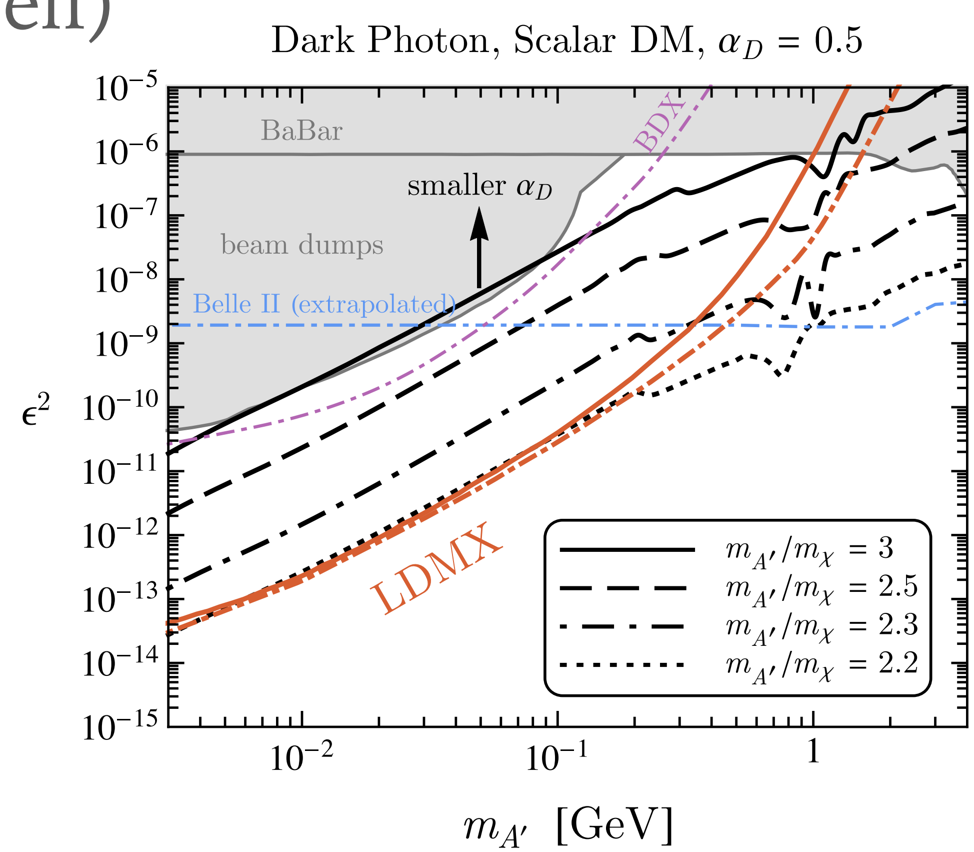

*Spin Dependent*



# HOW ABOUT CONSTRAINING THE MEDIATOR ITSELF INSTEAD?

# LIGHT DARK MATTER MEDIATORS

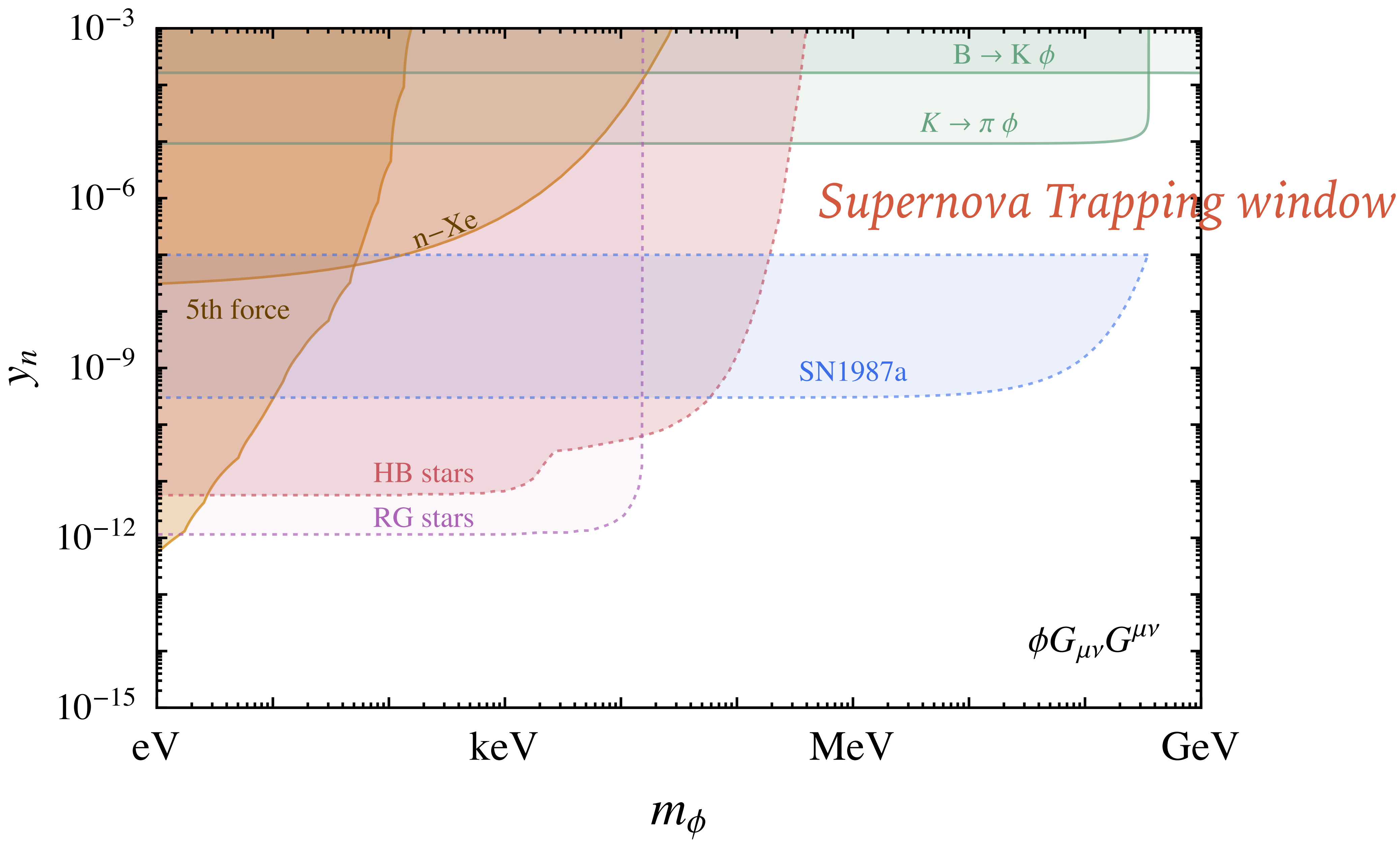
- For LDM DD, mediator cannot be too heavy to keep cross-sections accessible.
- Opportunity to constrain the mediator itself.
- NA64, BDX, LDMX etc are proposed to look for forces coupled to electrons (or DM itself)




*Source:LDMX*

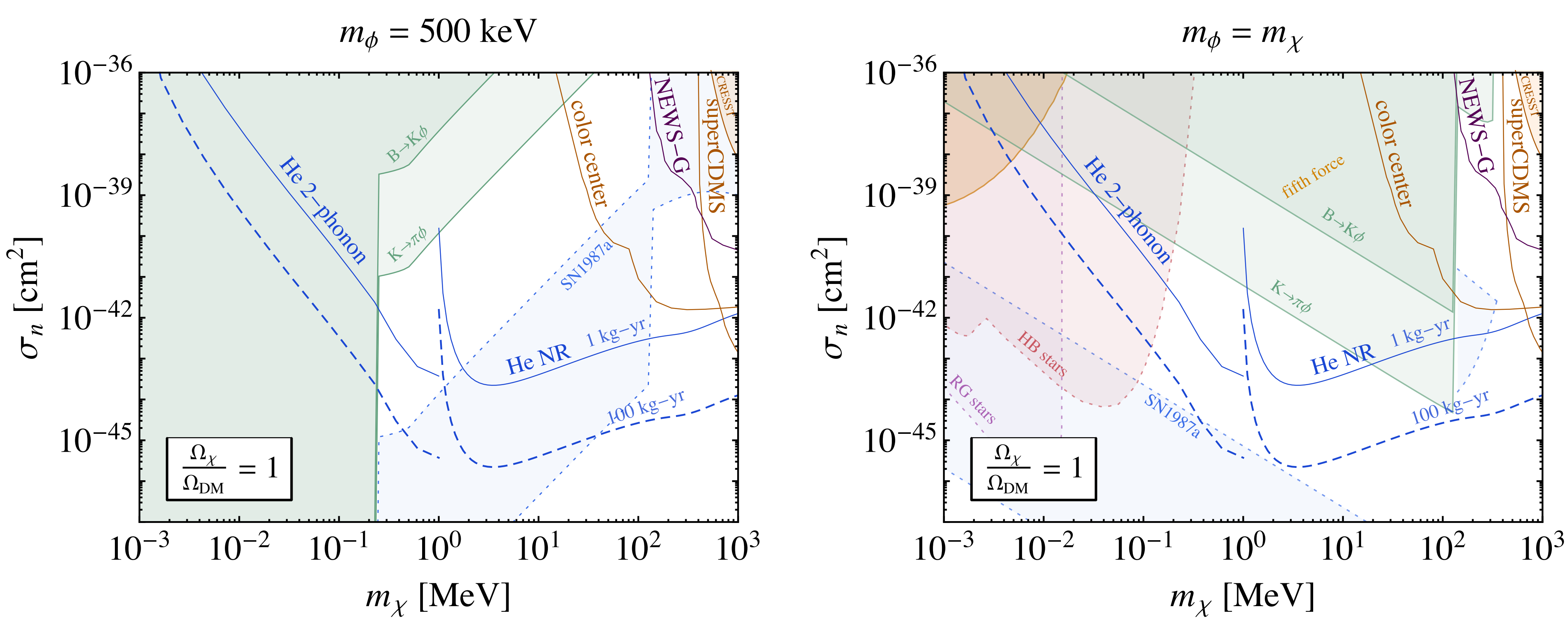
- Nucleophilic forces are harder to constrain.

# STATUS OF NUCLEOPHILIC FORCES - SCALAR MODEL




*Source:1709.07882, Knapen, Lin, Zurek*

# LOOPHOLES TO BUILD DM MODELS…

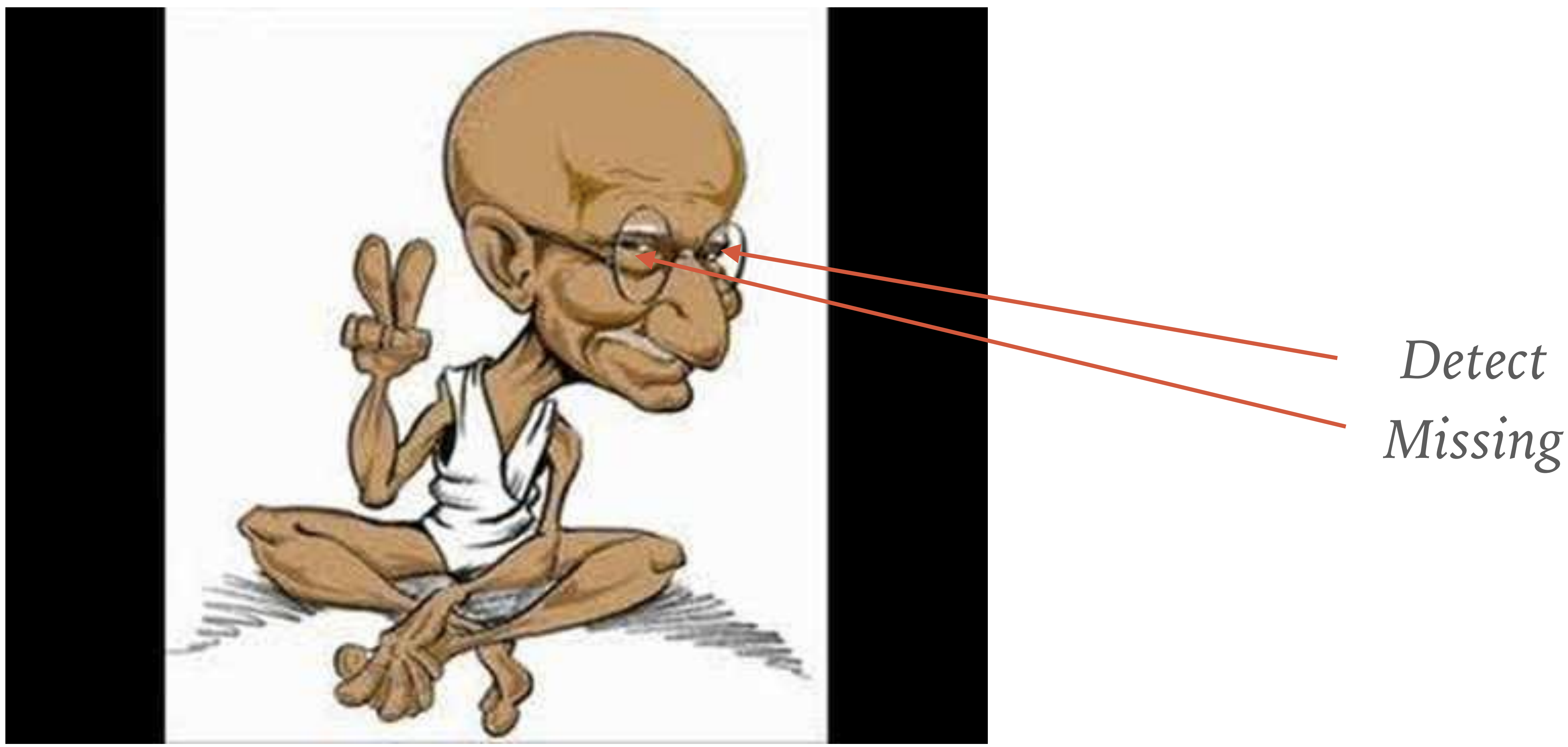


# MET

- missing energy experiments stay agnostic to decay modes
- furthermore, pay small factor only once
- how do we do this for a baryonic force?
- MET search for baryons is a messy enterprise.
- Missing Gamma decays
- Usual large number: EOT
- Here: Avogadro number of decaying nuclei

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

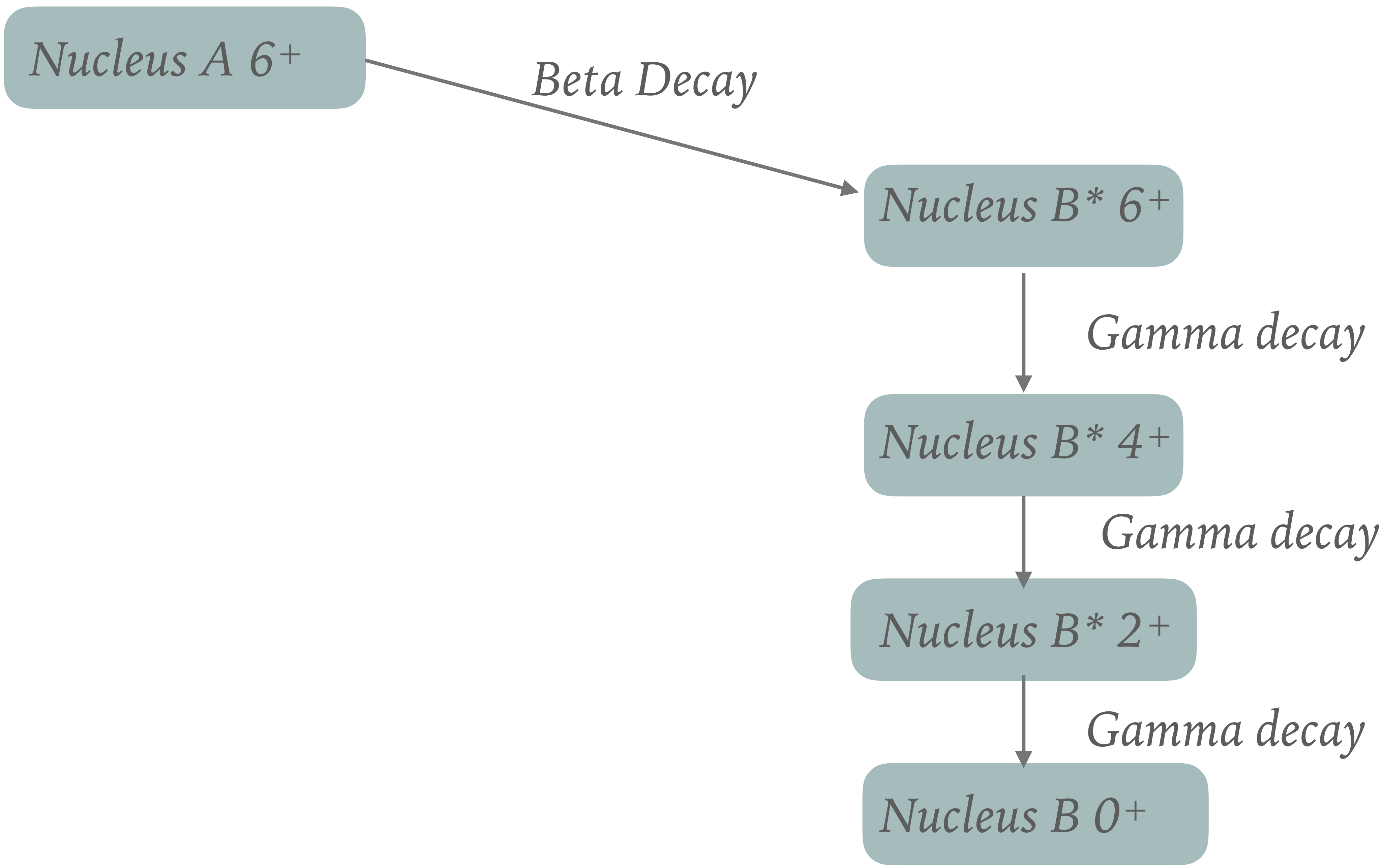
## NUCLEAR PHYSICS FOR PEACE




*Quotes wrongly attributed to Mahatma Gandhi:*

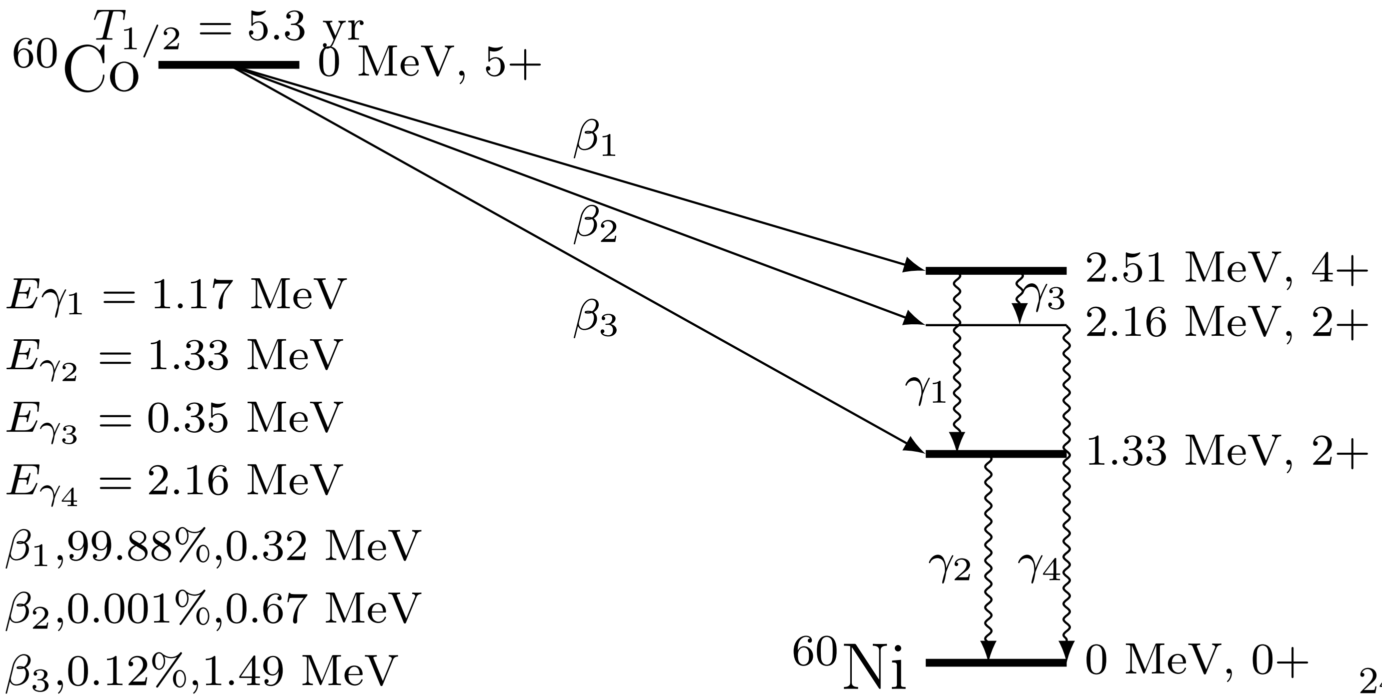
*“A gamma for a gamma makes… ”*

# CASCADE GAMMA DECAYS SCHEMATIC

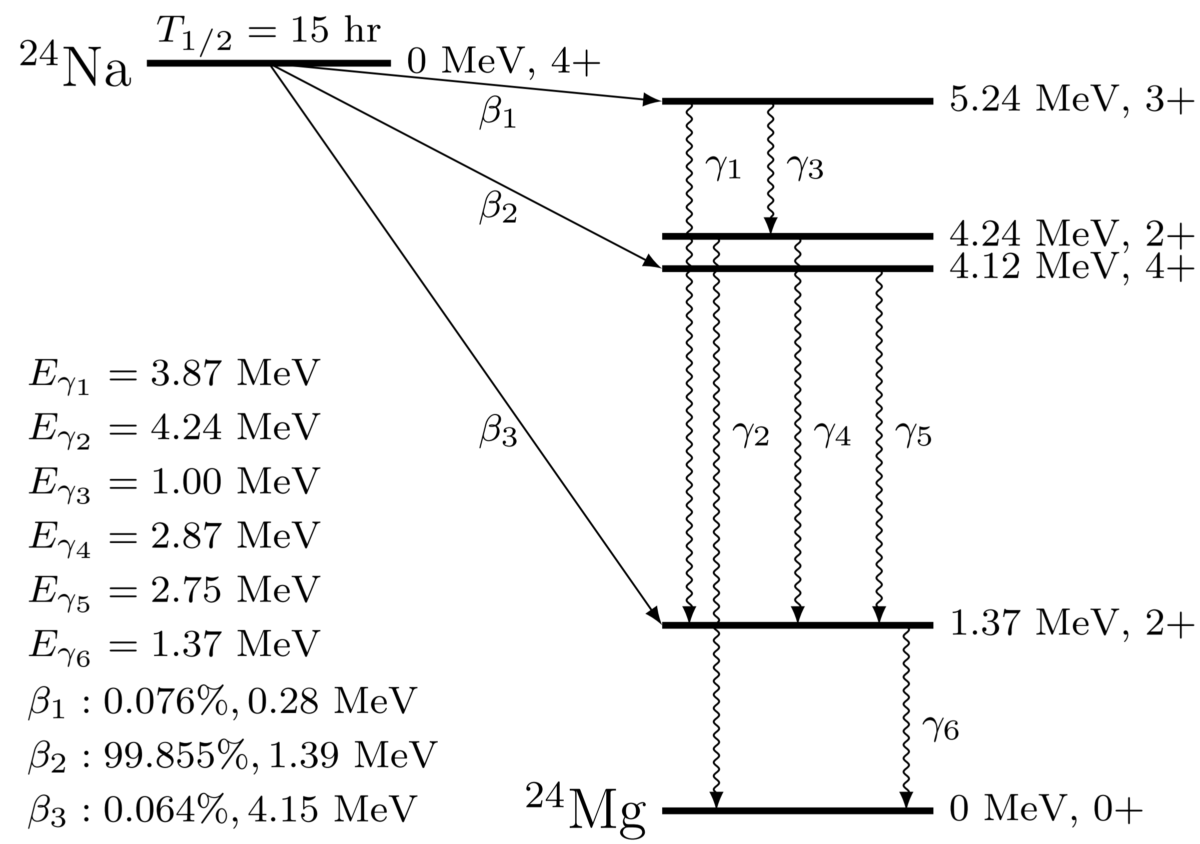



*Cascades happen because it is easier to shed two units of spin at a time rather than shedding all 6 at once.*

# EXAMPLES



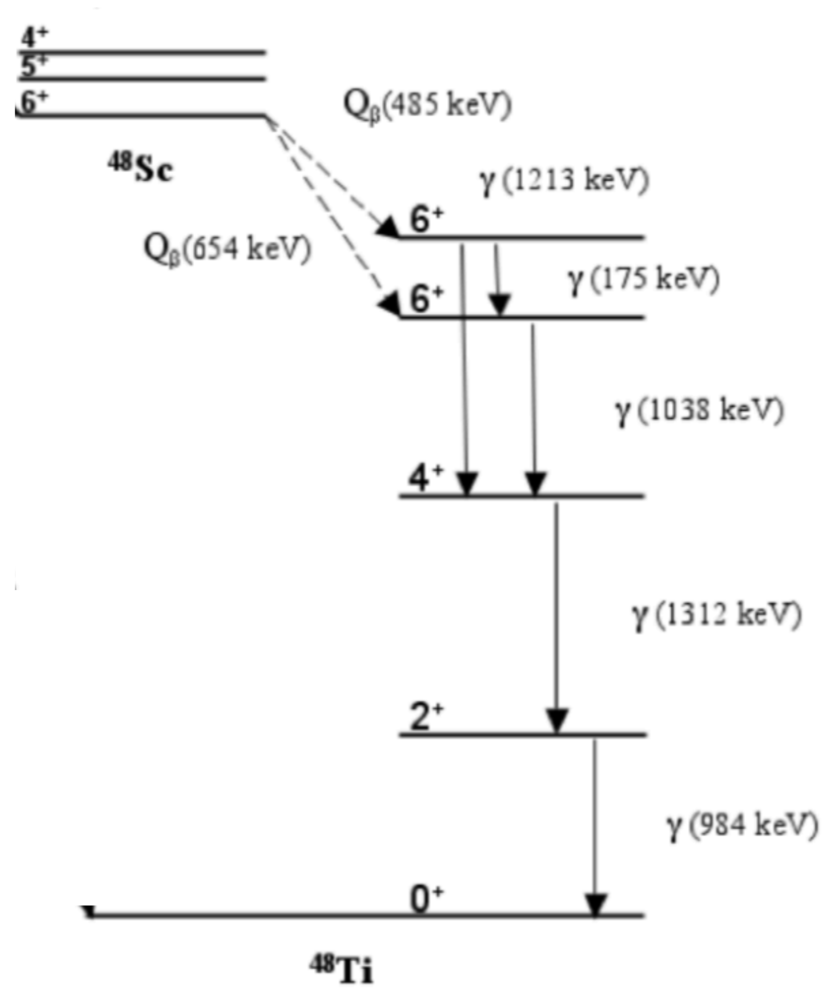

$E\gamma_1 = 1.17$ MeV
$E_{\gamma_2} = 1.33$ MeV
$E_{\gamma_3} = 0.35$ MeV
$E_{\gamma_4} = 2.16$ MeV
$\beta_1$,99.88%,0.32 MeV
$\beta_2$,0.001%,0.67 MeV
$\beta_3$,0.12%,1.49 MeV




$E_{\gamma_1} = 3.87$ MeV
$E_{\gamma_2} = 4.24$ MeV
$E_{\gamma_3} = 1.00$ MeV
$E_{\gamma_4} = 2.87$ MeV
$E_{\gamma_5} = 2.75$ MeV
$E_{\gamma_6} = 1.37$ MeV
$\beta_1 : 0.076\%, 0.28$ MeV
$\beta_2 : 99.855\%, 1.39$ MeV
$\beta_3 : 0.064\%, 4.15$ MeV

# OTHER ISOTOPE CANDIDATES

$^{46}Sc$, $^{124}Sb$, $^{48}V$, $^{154}Eu$, $^{207}Bi$ and finally $^{48}Sc$



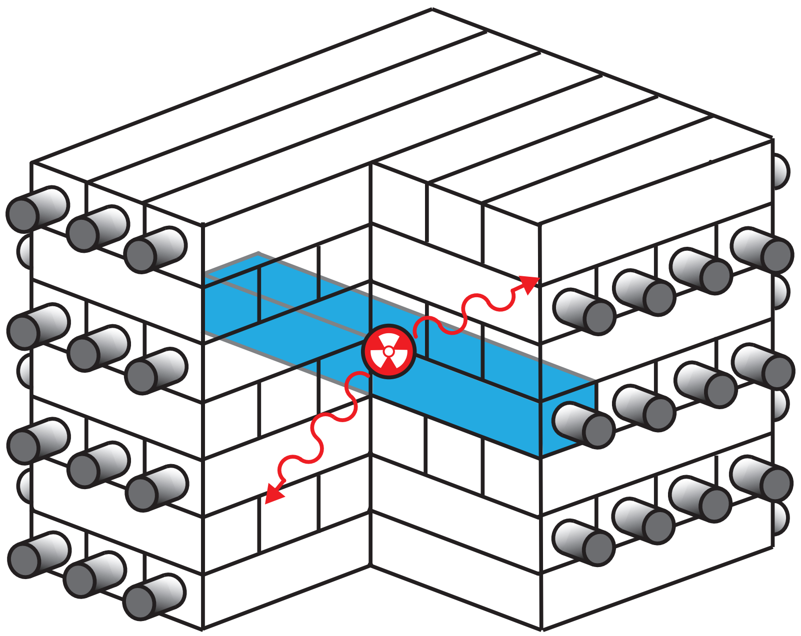
# SIGNAL

- Cobalt foil inside a hermetically sealed detector
- Trigger on first gamma
- Signal event is :
- beta
- first gamma
- (missing subsequent gamma)
- All other gammas
- No other energy deposit in the timeframe

# PHOTON DETECTION

- Photon detection with minimum dead-time
- Energy resolution, very important.
- Minimal dead regions/cracks, hermeticity sealed.
- 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.

# 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.

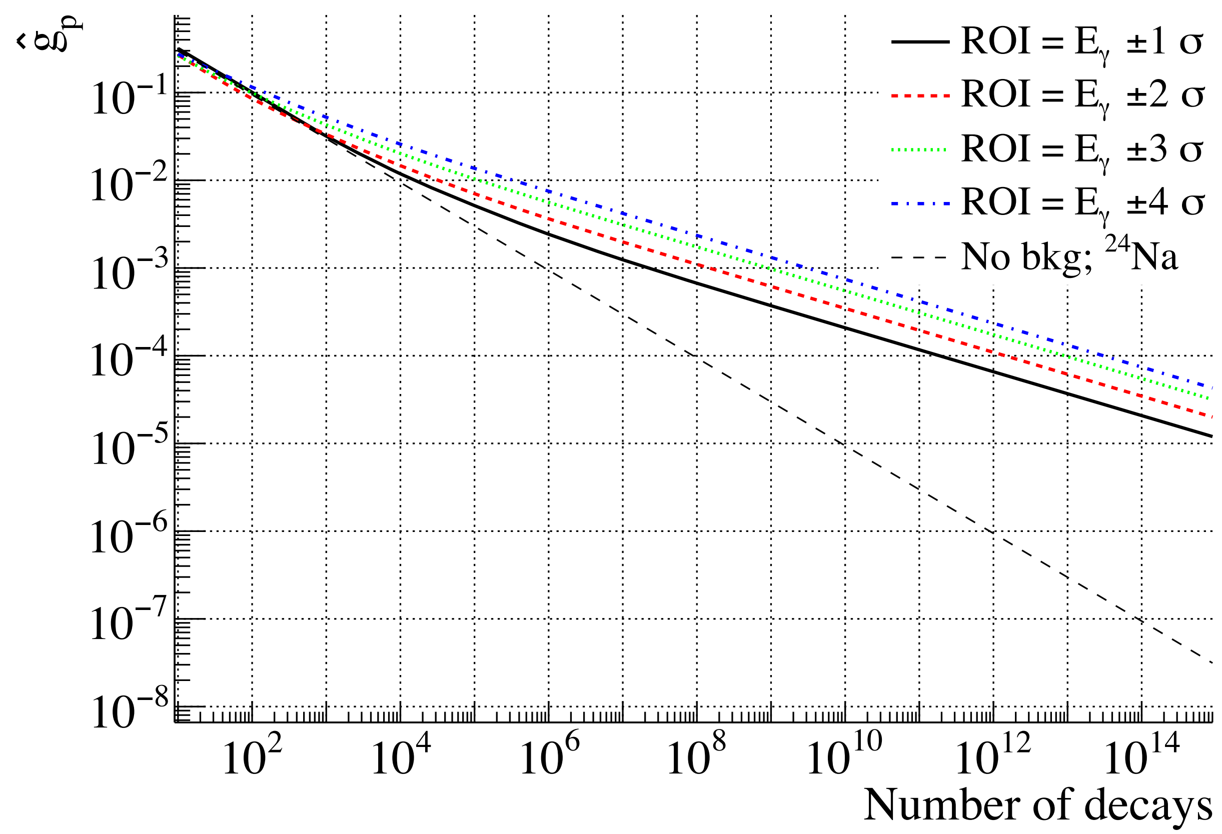
# INVISIBLE BRANCHING FRACTION

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

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

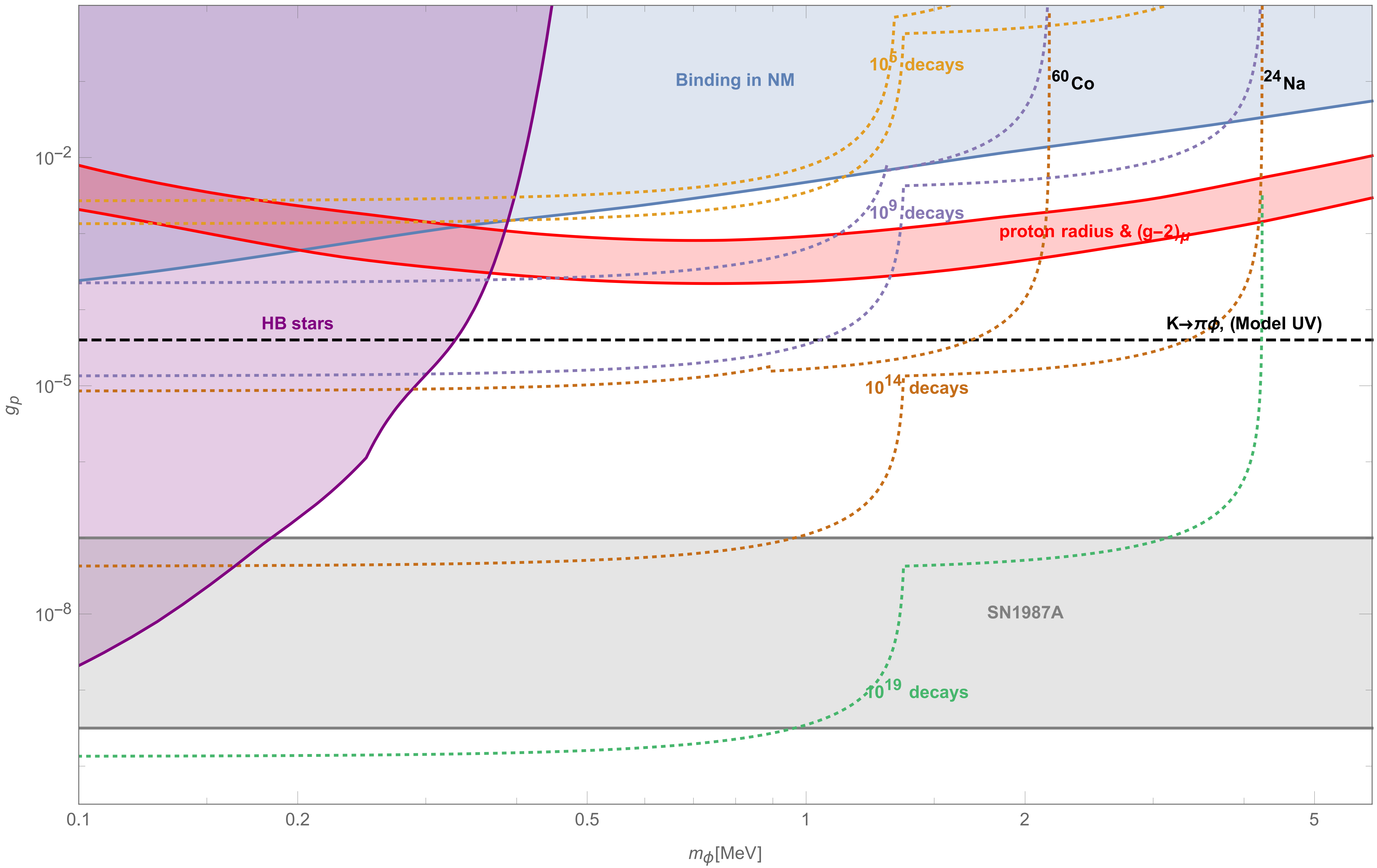
# 1.33 MEV GAMMA MIMICKING 1.17 MEV GAMMA

*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….

# REACH

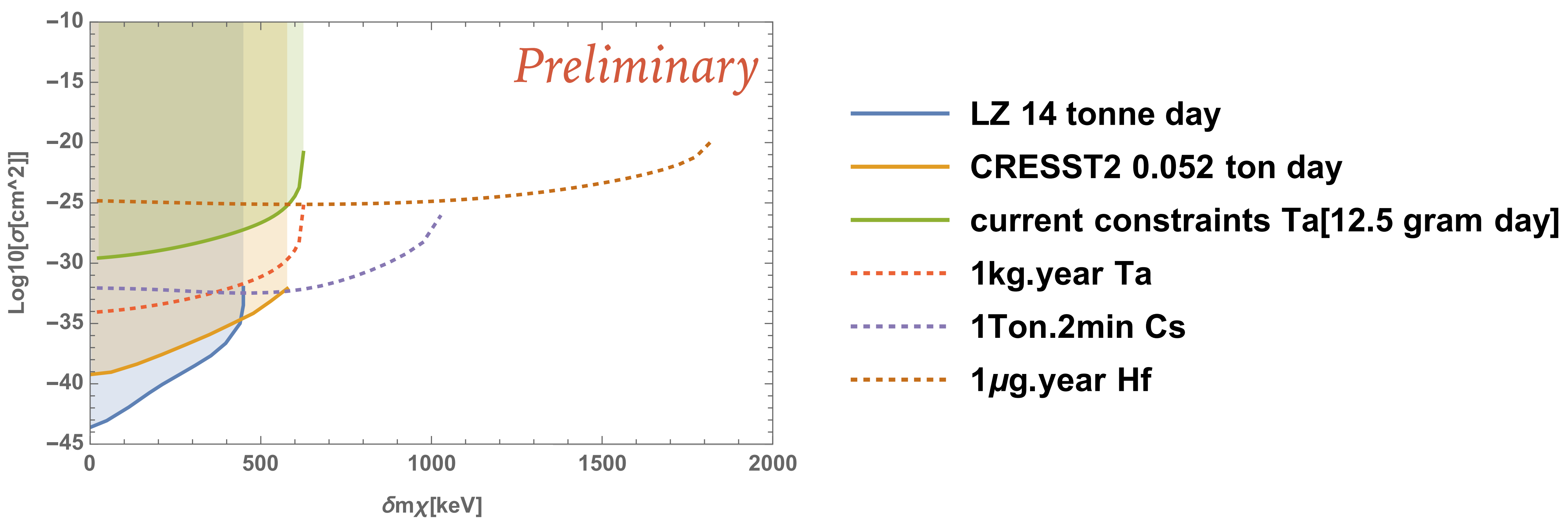



Source for existing limits: Knapen et al. and Y.-S. Liu, D. McKeen, and G. A. Miller ,1605.04612

# A DARK MATTER ACCELERATOR

# DARK MATTER ACCELERATOR

- Slow Moving/ Inelastic Dark matter very hard to constrain terrestrially
- Metastable nuclei — long lifetime in excited state because of angular momentum suppression during decay
- This suppression does not exist for scattering
- DM can down-scatter metastable nuclei and steal energy



# CONCLUSIONS

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