The light dark matter search—

What's going on at an MeV?

Tom Melia, Kavli IPMU

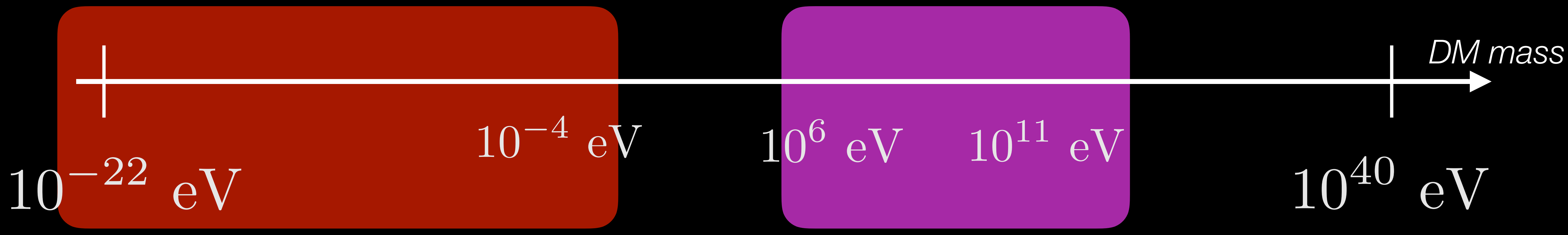
Cosmic Acceleration, Kavli IPMU 17th Feb 2020

The search for dark matter interactions in earth-based detection experiments must confront a possible mass range that spans more than sixty orders of magnitude

This necessarily makes search strategies diverse

Axion-like experiments: exploit coherence with resonance

WIMP-like experiments: energy deposits



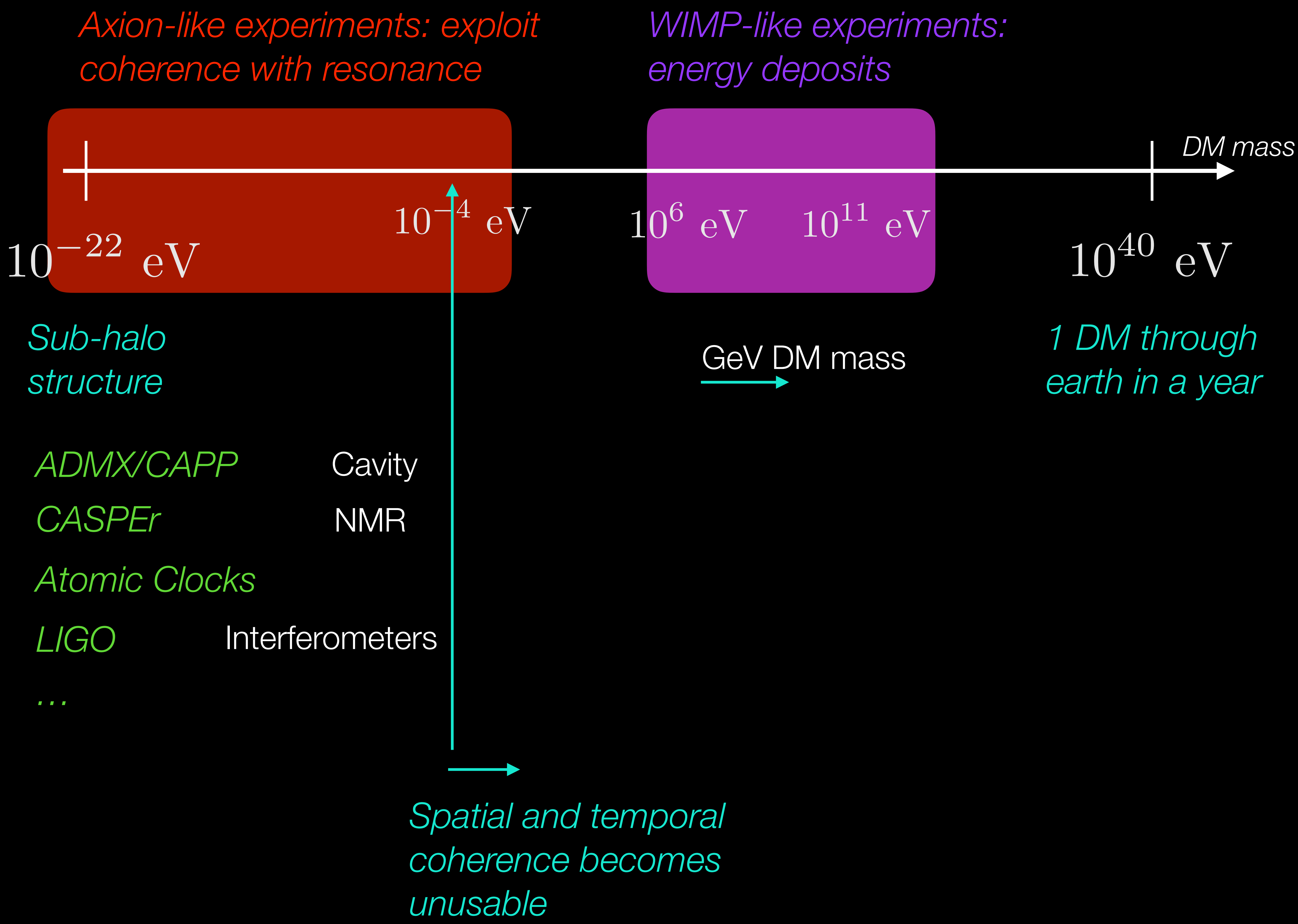
Sub-halo structure

GeV DM mass →

1 DM through earth in a year

ADMX/CAPP	Cavity
CASPEr	NMR
Atomic Clocks	
LIGO	Interferometers
…	

XENON	
LUX	Liquid Xe (recoil)
PANDAX	
CDMS	Ge / Si
PICO	C3F8
…	


Axion-like experiments: exploit coherence with resonance
WIMP-like experiments: energy deposits
DM mass
10^{-22} eV
10^{-4} eV
10^{6} eV
10^{11} eV
10^{40} eV
Sub-halo structure
GeV DM mass
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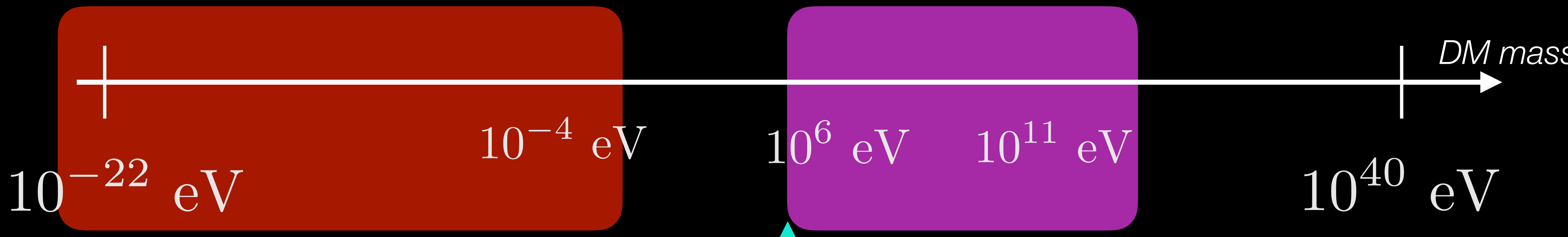
…
Spatial and temporal coherence becomes unusable

Axion-like experiments: exploit coherence with resonance

WIMP-like experiments: energy deposits



Sub-halo structure

1 DM through earth in a year

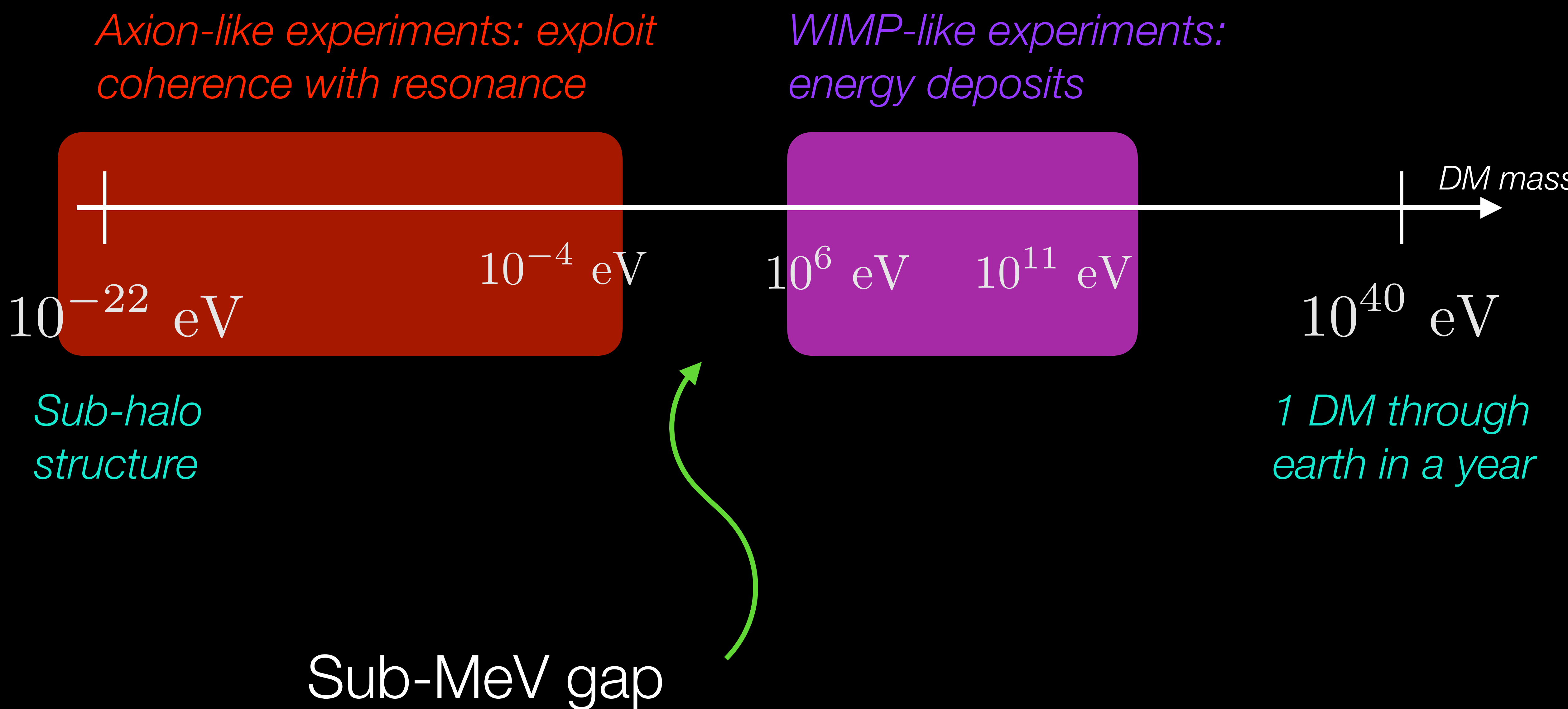
MeV DM mass

sub-GeV mass being probed

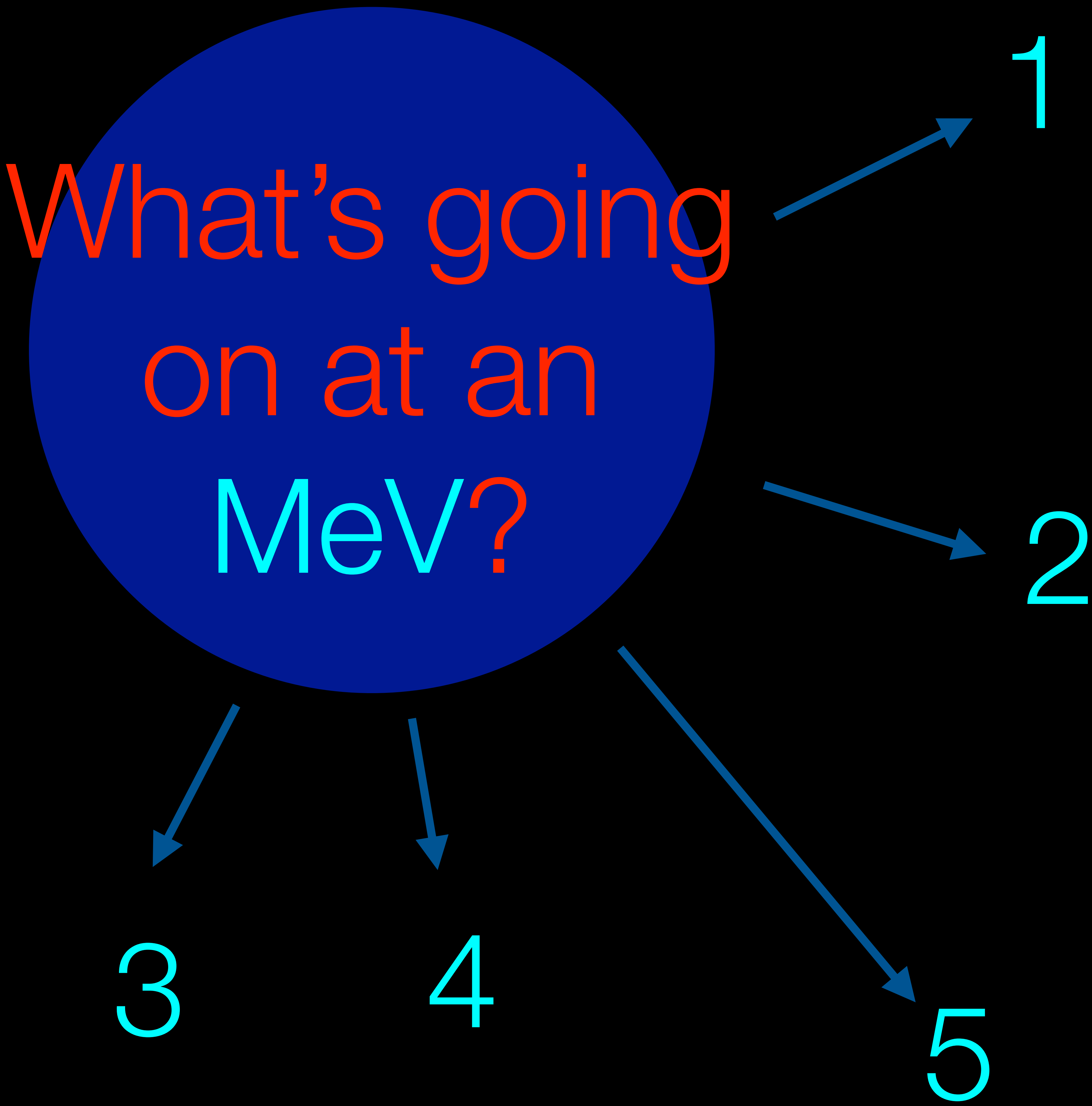
CRESST	Phonons/ ionization
superCDMS	
DarkSide (electron)	Ionization of Ar, Xe electrons
Xenon10 (electron)	
SENSEI	Electrons in semi-conductor

Few-10s eV energy deposit

$$\frac{1}{2} m_{DM} v^2 \sim 10^{-6} m_{DM}$$



What’s going on at an MeV?


What's going on at an MeV?
1
2
3
4
5

What's going on at an MeV?

Sensitivity gap in direct detection meV-eV energy deposit

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i.e. keV-MeV mass

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High Energy Astrophysics

1&3: Analysis and Detector Development

Our Activity (High Energy Astrophysics at IPMU)

eV	keV	MeV	GeV	TeV

Optical

Subaru

IPMU (Takada's group)

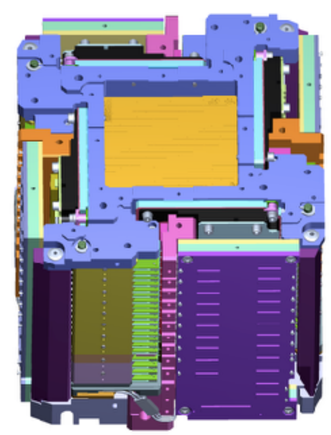
X-ray

Suzaku

Chandra
XMM-Newton
NuStar/Nicer

Archive Data and/or Proposed Obs.

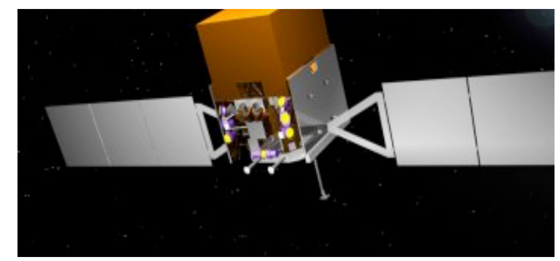
No Mission (Sensitivity Gap)



Detector Development future X-ray and MeV gamma-ray mission

Collaboration Member (we can access all the data)

GeV (Fermi)



TeV(H.E.S.S.)

Discussion with people in IPMU (Matsumoto's "DarkMatter Club")

Multi Frequency Astronomy (IPMU)

High Energy Astrophysics

1&3: Analysis and Detector Development

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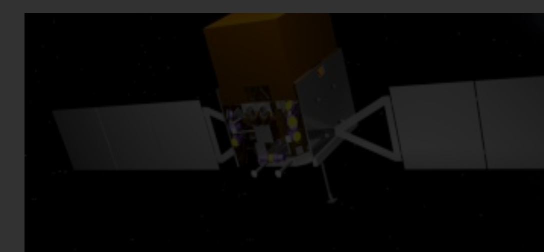

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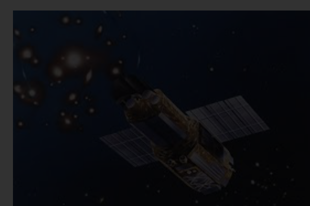

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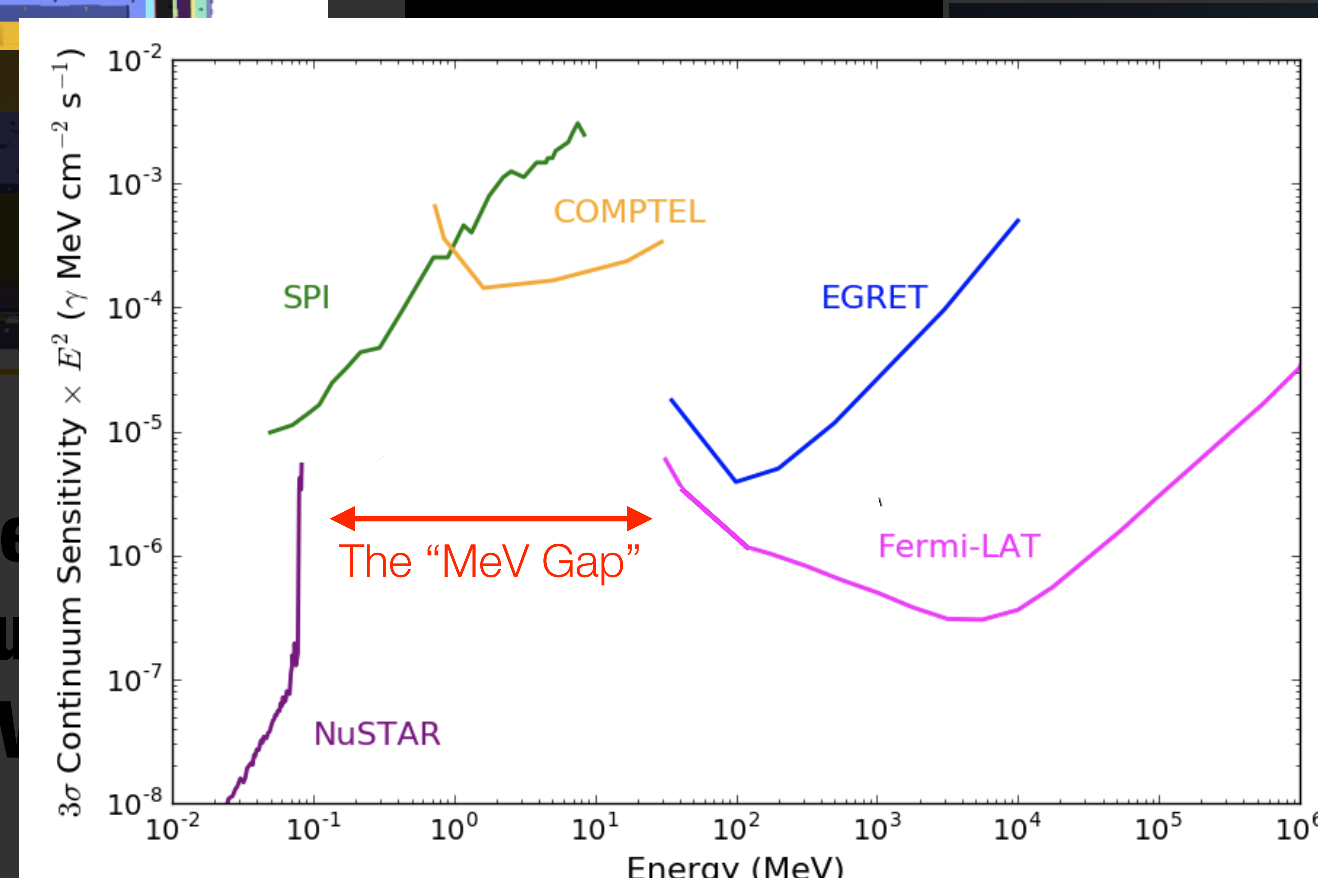
De
futu
Me

Collaboration Member
(we can access all the data)

GeV (Fermi)

TeV(H.E.S.S.)

Adapted from AMIGO collaboration 1907.07558



Multi Frequency Astronomy (IPMU)

What's going on at an MeV?

Sensitivity gap in direct detection meV-eV energy deposit

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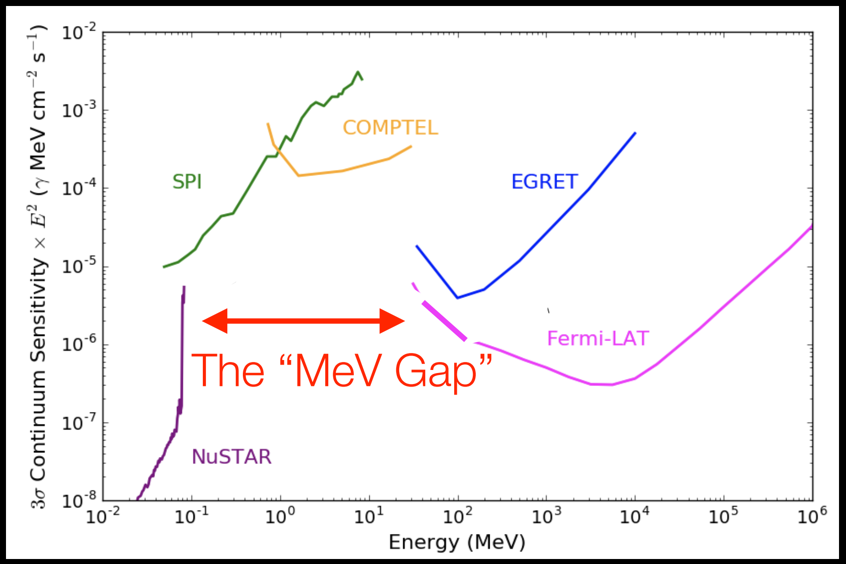
i.e. keV-MeV mass

Telescope sensitivity gap



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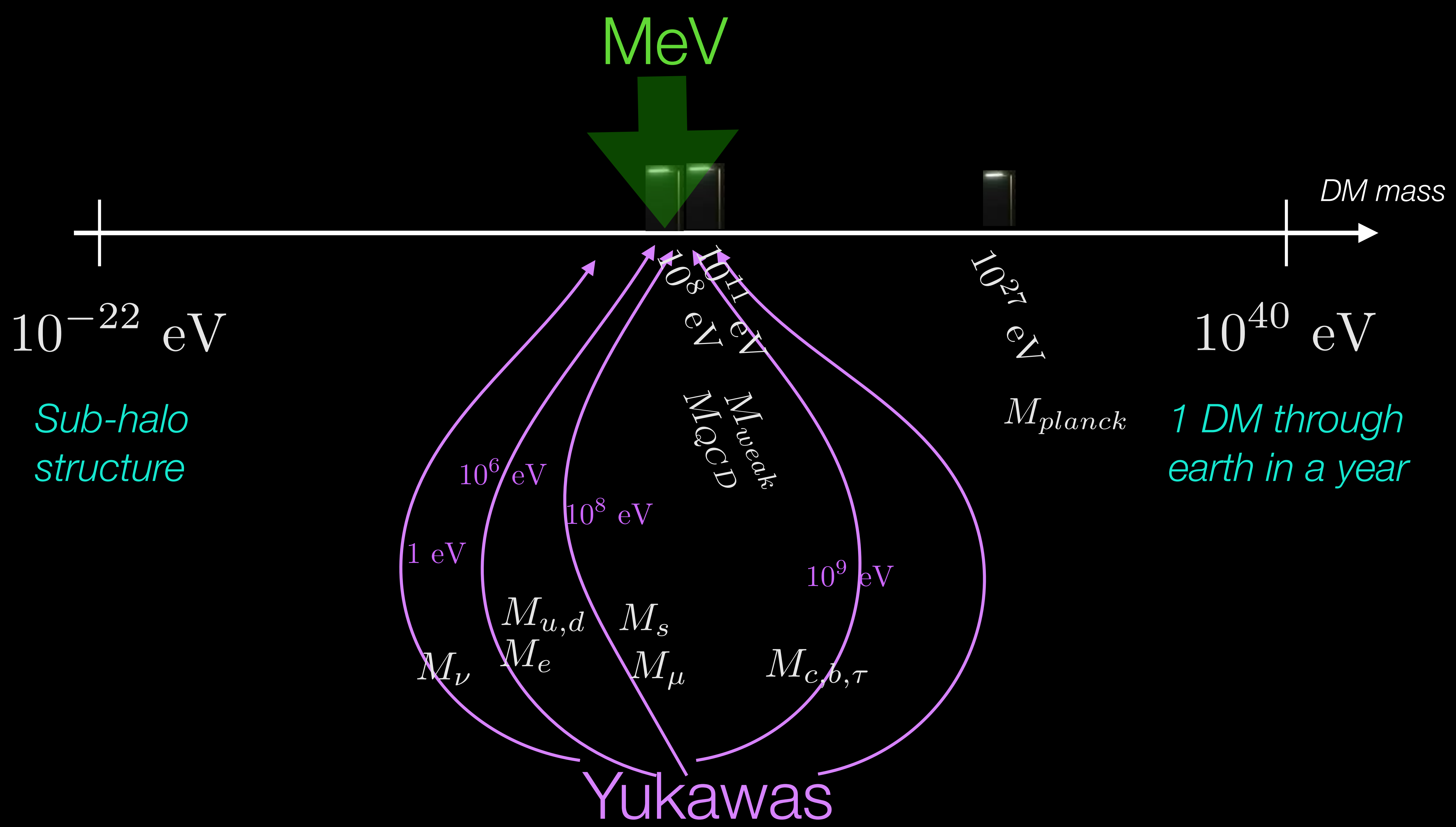
There exist models of keV-MeV DM that give 100% of DM abundance, not ruled out by astrophysics/cosmology, and are detectable in earth based experiments

e.g. Green, Rajendran 1701.08750; Knapen, Lin, Zurek 1709.07882

Relatively un-developed/explored theory space, e.g. using relatively (past decade) new mechanism of freeze in for relic abundance

Plus, we are being forced to reconsider our ideas about naturalness & the weak scale, and what yardstick we should judge models by

(perhaps worth saying: ~MeV is a pretty well motivated place to search, given we know particles exist there)



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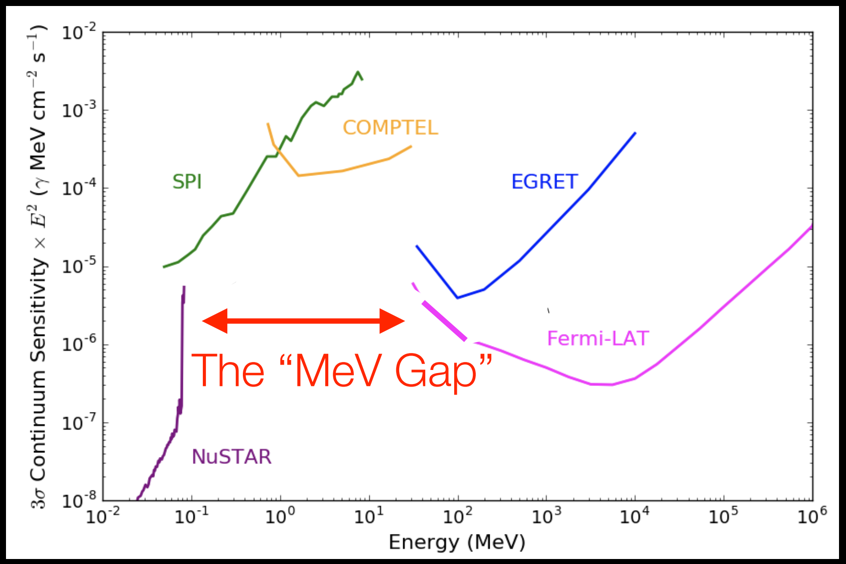

Theory motivation

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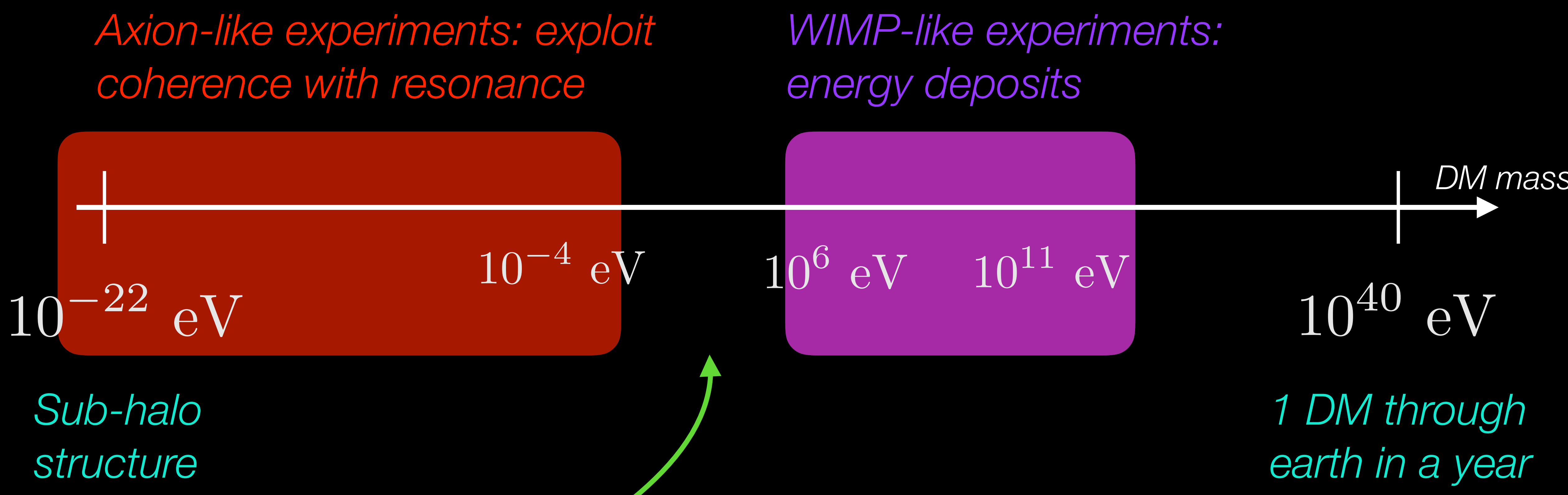


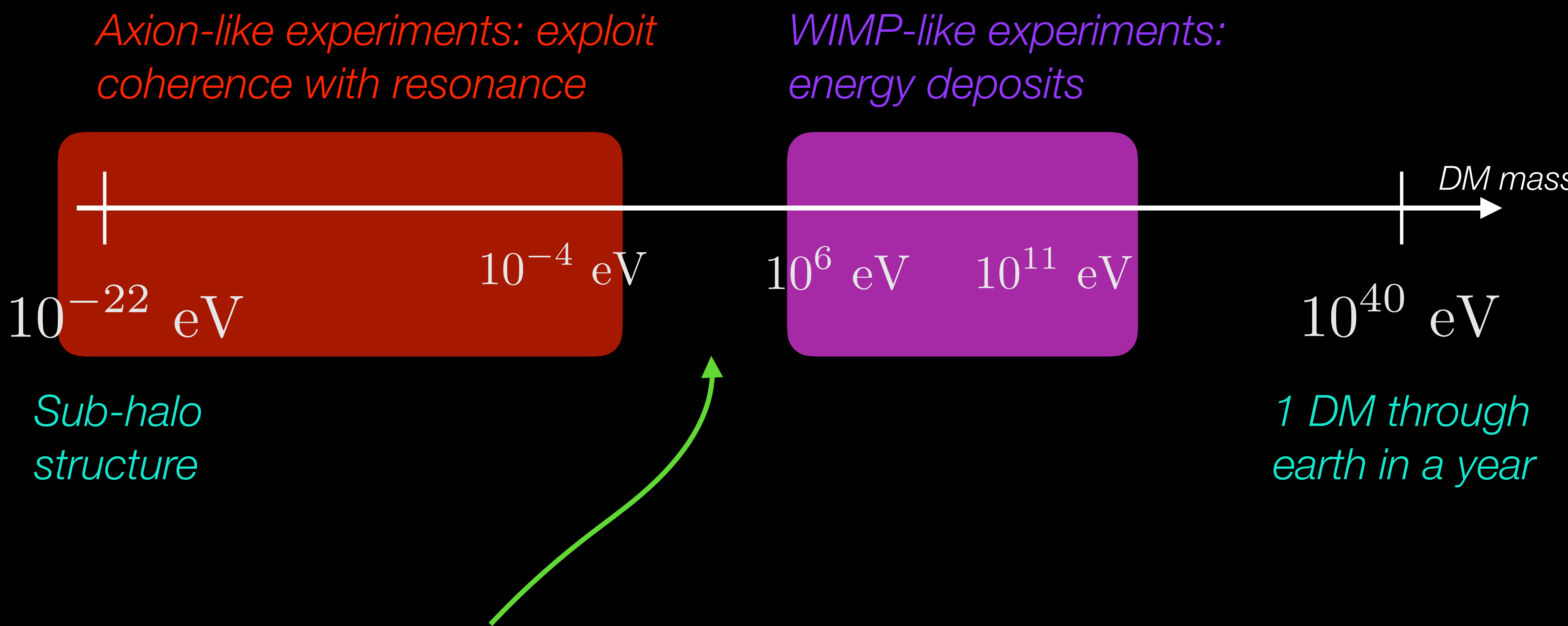
Sub-MeV window

Energy deposits < eV

This is the typical energy of quantum excitations of condensed matter systems, and is the energy scale of chemistry

→

Matching of energy scales suggests such systems should be good targets



Sub-MeV window

Energy deposits < eV at proposal/R&D stage

Superfluid He

Schutz and Zurek, Phys.Rev.Lett. 117 (2016) no.12, 121302

Superconductors

Hochberg, Zhao, and Zurek, Phys.Rev.Lett. 116 (2016) no.1, 011301

Magnetic bubble chambers

Bunting, Gratta, TM, and Rajendran, Phys.Rev. D95 (2017) no.9, 095001

Sapphire/ polar crystals

Knapen, Lin, Pyle, and Zurek, Phys.Lett. B785 (2018) 386-390

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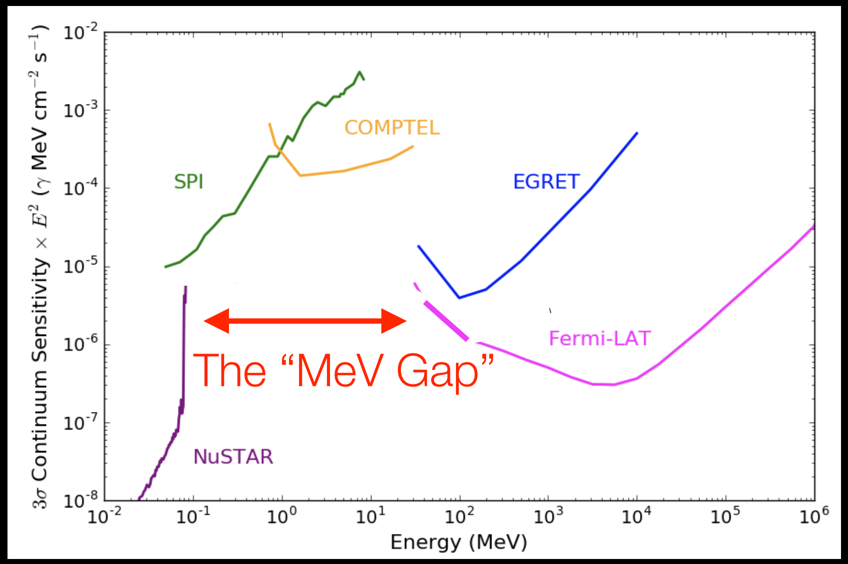


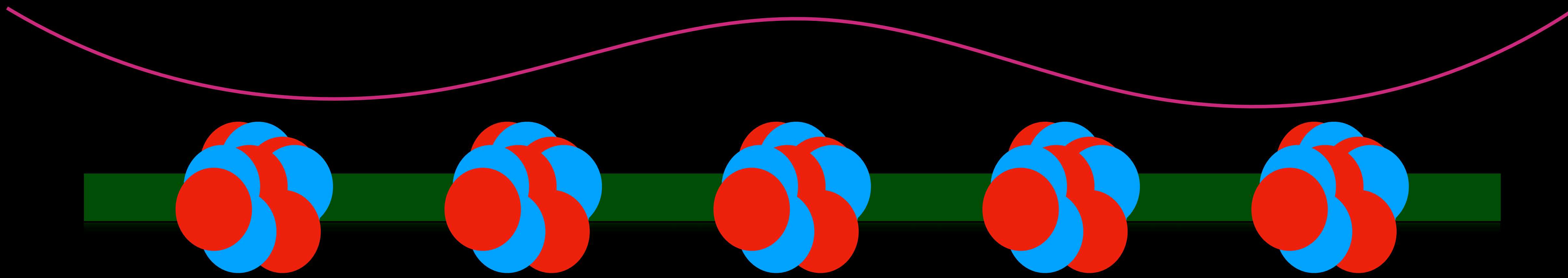
Theory motivation

Condensed matter, quantum devices, chemistry

New technologies under R&D, with broad applications

5

DM de Broglie wavelength > interatomic spacing



We are used to characterising DM via its interaction with particles. Here, DM doesn’t resolve individual nuclei/atoms…

At these energies in materials, phonons (crystal/molecule vibrations) are the relevant particle description

Symmetries perhaps less familiar, so can expect novel features in DM interactions

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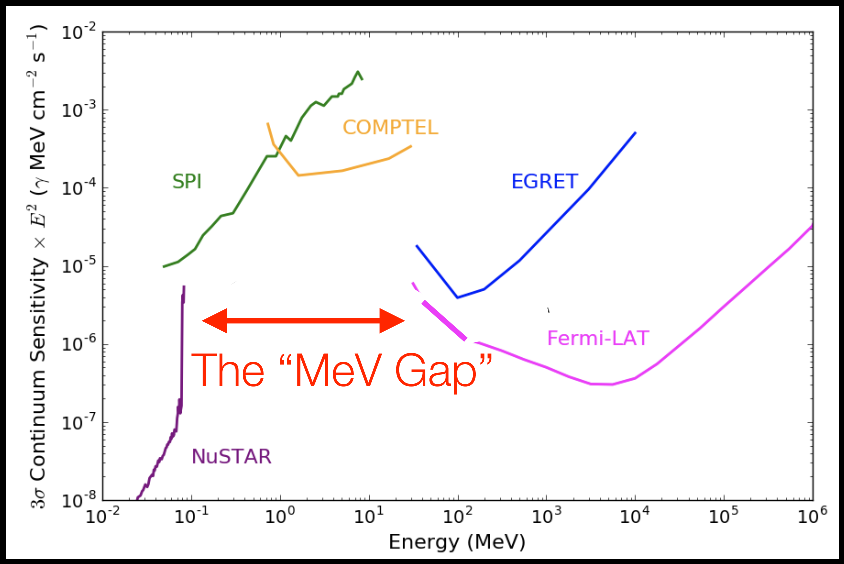

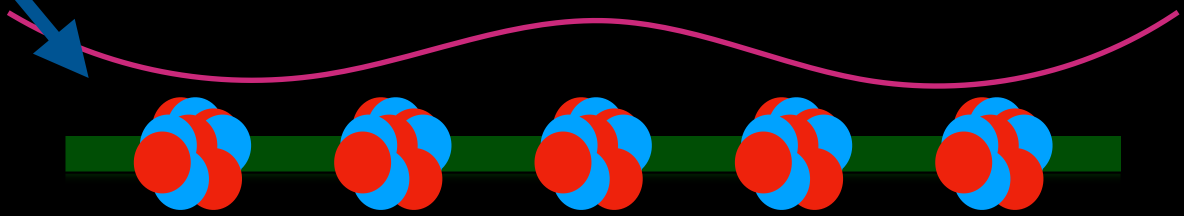

New theoretical input needed to determine rate and nature of DM interaction

Theory motivation

Condensed matter, quantum devices, chemistry

New technologies under R&D, with broad applications

What's going on at an MeV?

Remainder of this talk I'll focus on this

Sensitivity gap in direct detection meV-eV energy deposit

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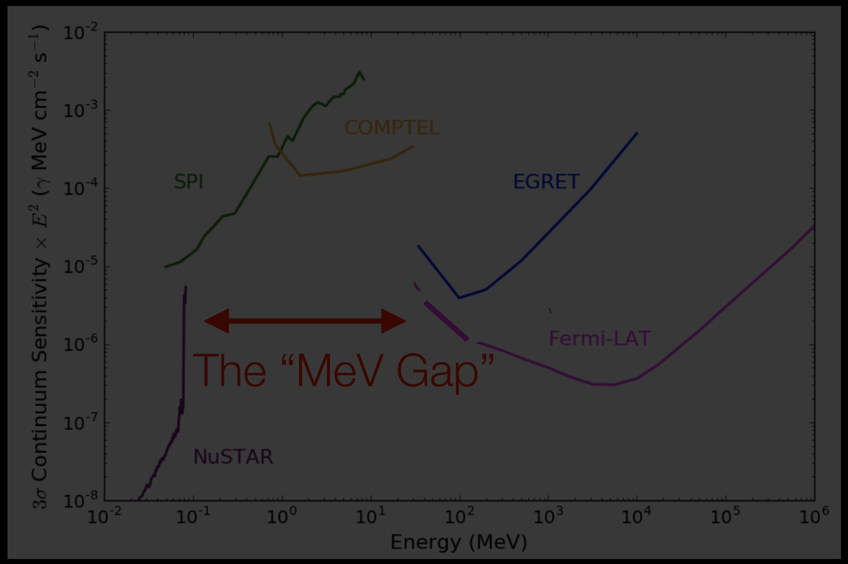

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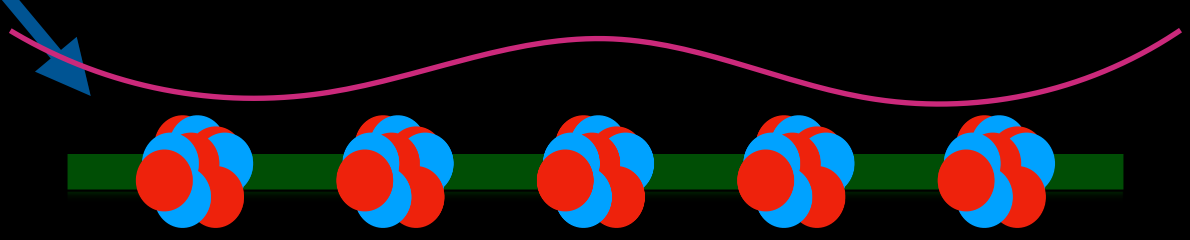


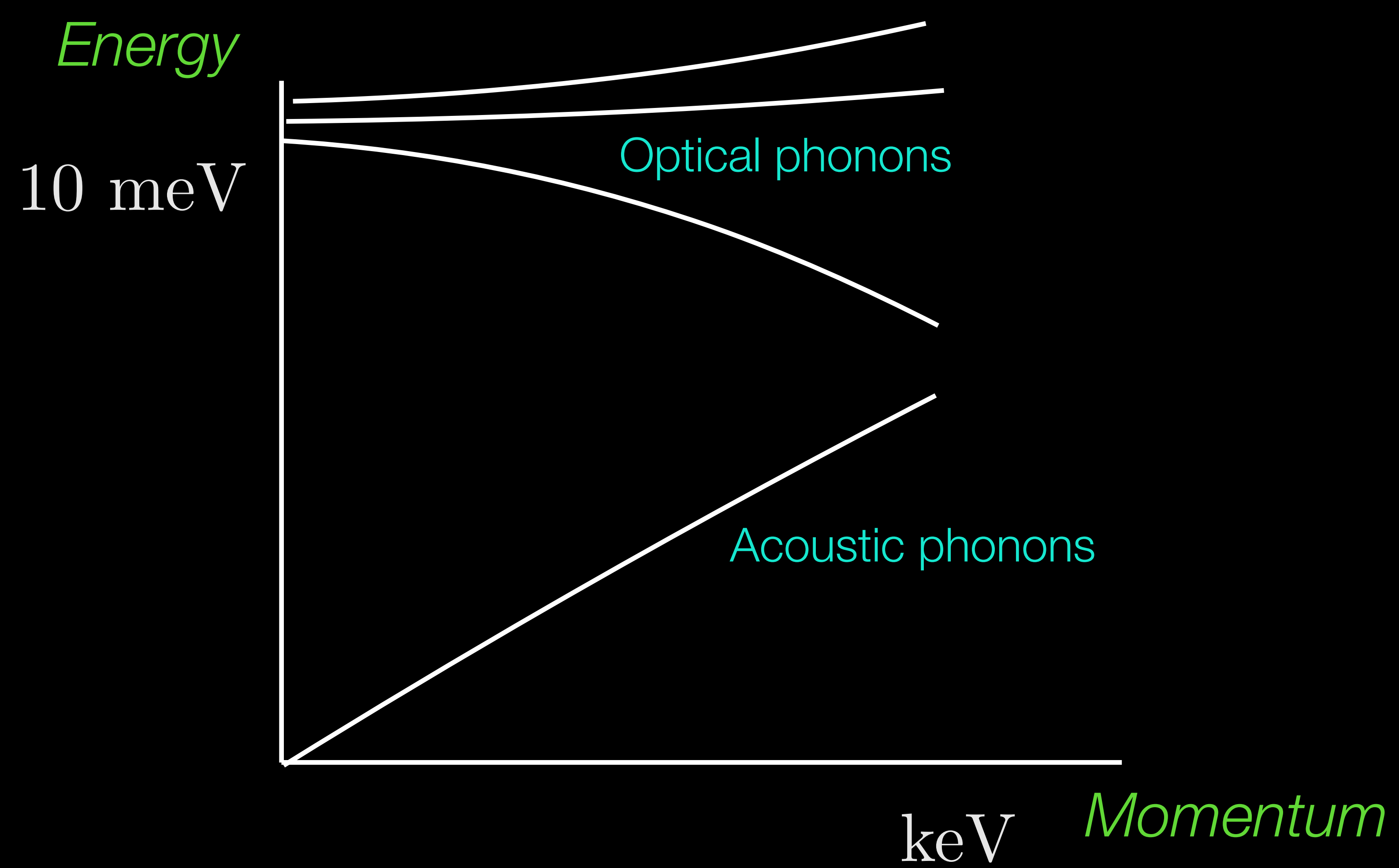
New theoretical input needed to determine rate and nature of DM interaction

The Dark Matter - Phonon Coupling

Phonons are quanta of vibrations, and are prototypical excitations in condensed matter systems

In crystals and molecules, it turns out that the dark matter-phonon coupling has a curious feature, with implications for direct detection experiments

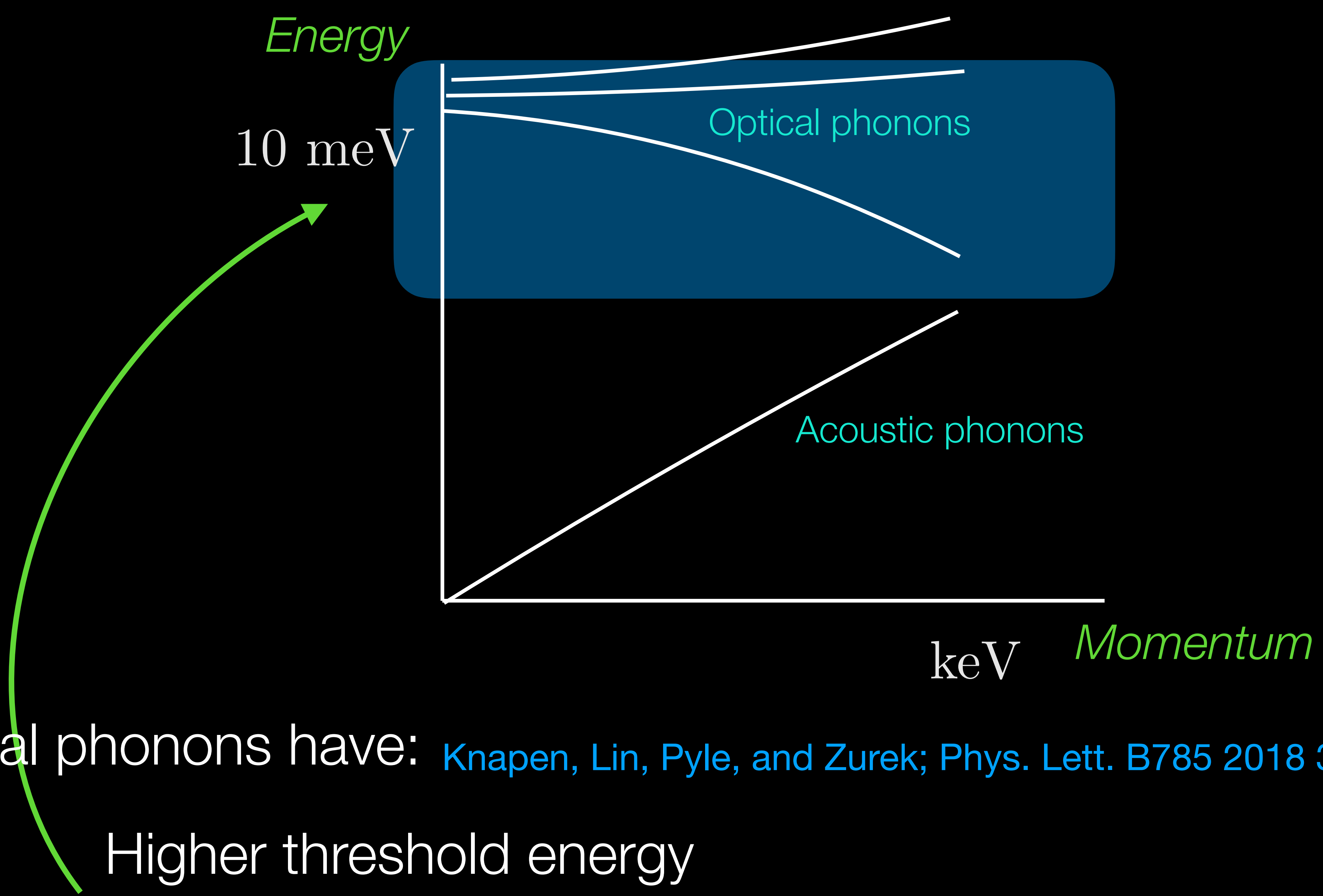
Phonon band-structure of crystals



DM energy scales

M_{DM}	$q_{DM} = M_{DM} v$	$E_{DM} = \frac{1}{2} M_{DM} v^2$
MeV	keV	eV
keV	eV	meV

Phonon band-structure of crystals



Optical phonons have: Knapen, Lin, Pyle, and Zurek; Phys. Lett. B785 2018 386-390

Higher threshold energy

Can have large density of states

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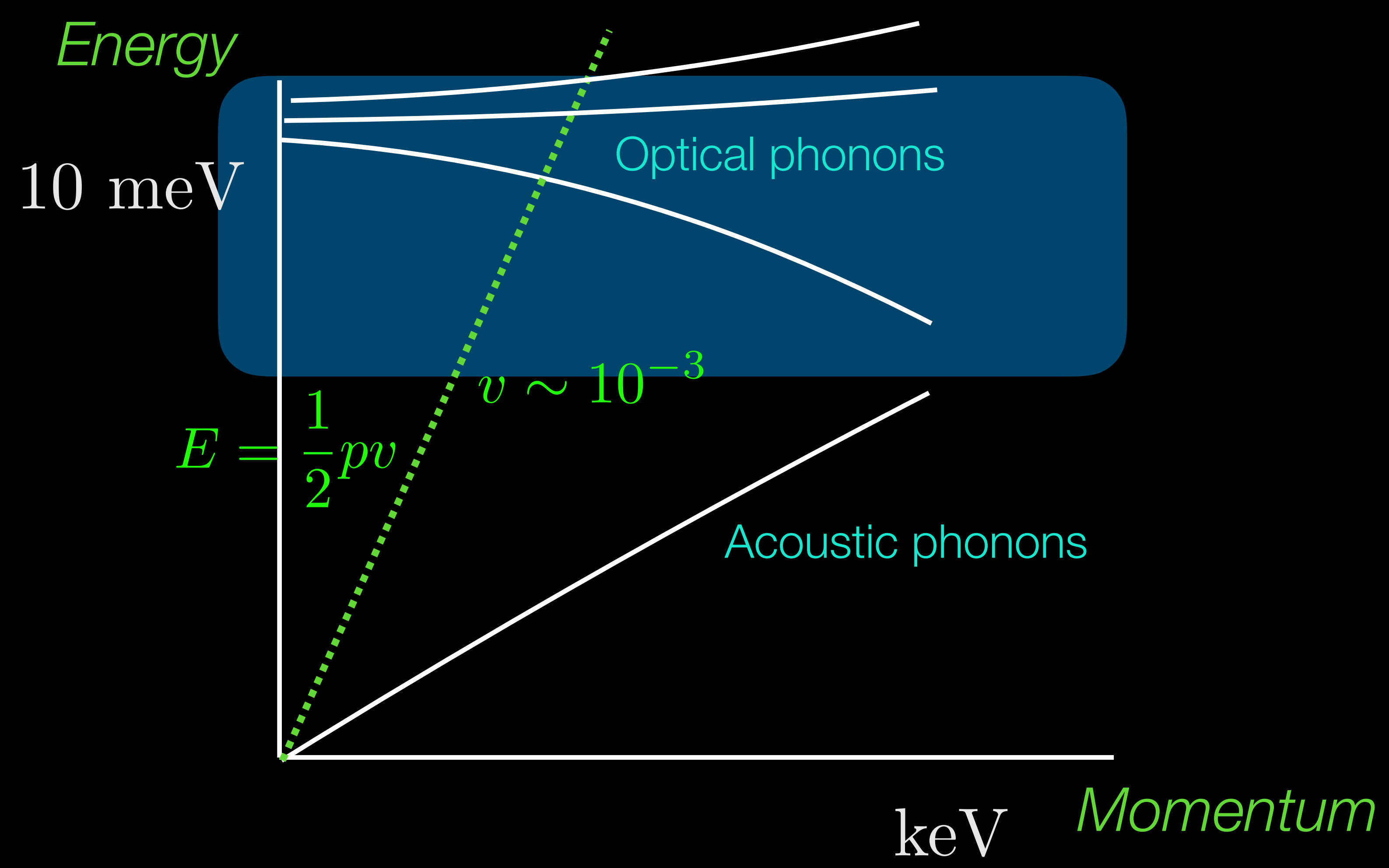

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Higher threshold energy

Can have large density of states

Kinematics to match DM kinematics

The coupling-to-mass effect in DM-phonon scattering

Cox, TM, and Rajendran; arxiv 1905.05575

When the coupling of the DM to each atom is proportional the atom's mass, the leading order scattering off optical phonons vanishes at small momentum transfer

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> When the coupling of the DM to each atom is proportional the atom's mass, the leading order scattering off optical phonons vanishes at small momentum transfer

Coupling proportional to mass is generic:

Low momentum transfer -> coherence over atom

Couplings away from the unitarity limit -> effective coupling scales with number of constituents

The coupling-to-mass effect in DM-phonon scattering

Cox, TM, and Rajendran; arxiv 1905.05575

When the coupling of the DM to each atom is proportional the atom's mass, the leading order scattering off optical phonons vanishes at small momentum transfer

It holds for a general DM scattering potential of the form

$$V = \sum_{l=1}^{N} g_l \, V(\mathbf{r} - \mathbf{r}_l)$$

Here N is the number of atoms in the molecule

Or (by Bloch's Theorem) the number of atoms in the unit cell of a crystal

Simple proof

Scattering matrix element is, in the Born approximation

$$\langle \Phi_f | V(\mathbf{q}) \sum_l g_l e^{i\mathbf{q}\cdot\mathbf{r}_l} | \Phi_i \rangle \quad f \neq i$$

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Expand this at low q   q< 1/(size molecule or unit cell) ~ keV

$$= iV(\mathbf{q})\,\mathbf{q} \cdot \langle \Phi_f | \sum_l g_l \mathbf{r}_l | \Phi_i \rangle$$

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Now setting $g_i = g\, m_i$

$$= iV(\mathbf{q}) g\, \mathbf{q} \cdot \langle \Phi_f | \sum_l m_l \mathbf{r}_l | \Phi_i \rangle$$

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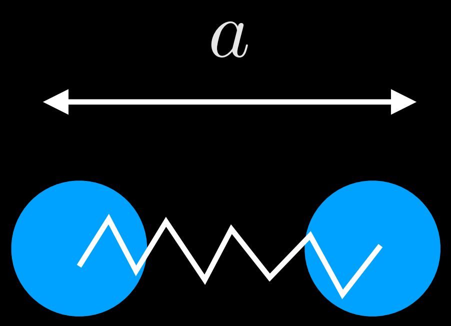
and identifying

$$\sum_{l=1}^{N} m_l \mathbf{r}_l = \mathbf{X}_{CM}$$

This can never induce internal changes

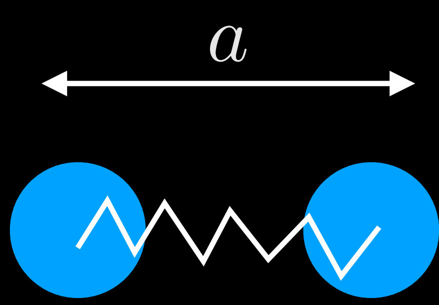
Simple example

Di-molecule



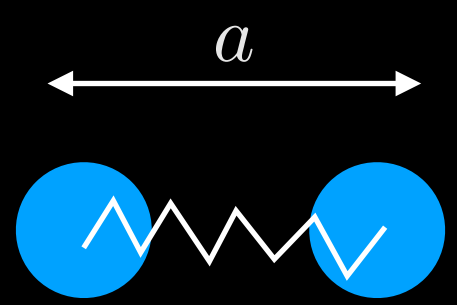
(Unit cell of a crystal with more than one atom works in essentially the same way)

Di-molecule



$$H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + \frac{1}{2}\mu w^2 (x')^2$$

Di-molecule



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Matrix element for phonon creation

$$\mathcal{M} \sim \langle 1| \left(g_1\, e^{iq\cdot r_1} + g_2\, e^{iq\cdot r_2}\right) |0\rangle$$

Rate proportional to

$$|\mathcal{M}|^2 \propto \frac{q^2}{Mw} \left(g_1^2 m_2^2 + g_2^2 m_1^2 - 2 g_1 g_2 m_1 m_2 \cos qa\right)$$

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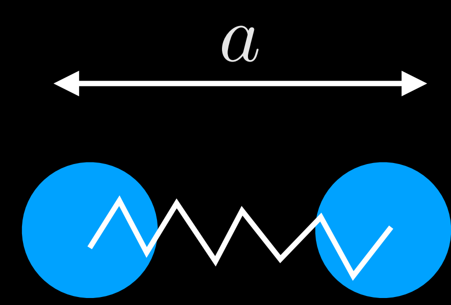

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This factor per phonon

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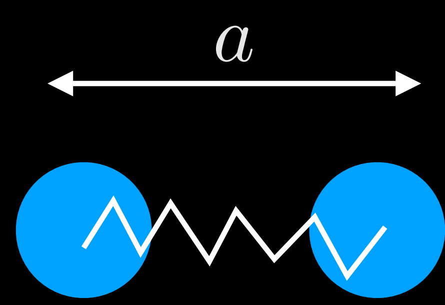

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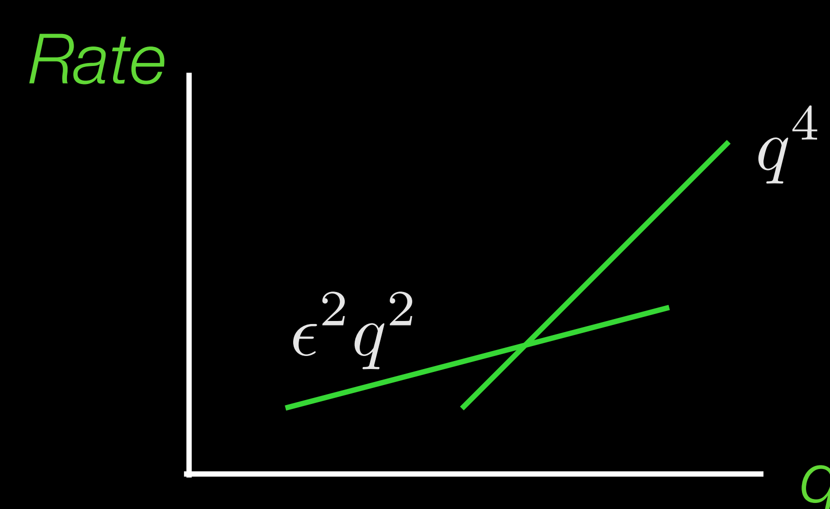
$$|\mathcal{M}|^2 \propto q^2 g^2 \mu \left(\epsilon^2 + (qa)^2 + \ldots \right)$$



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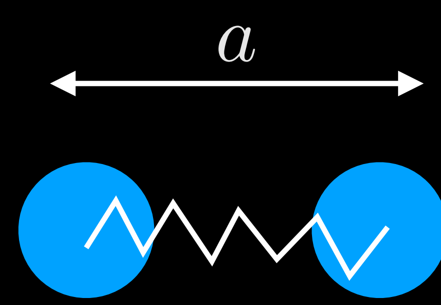

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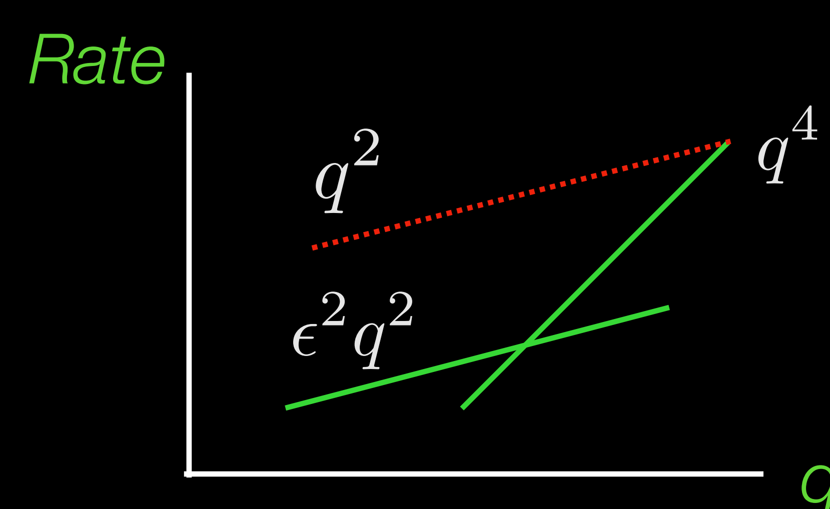
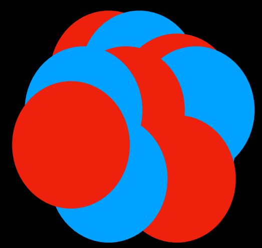


Material consequences

Characterisation of materials



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Atomic number and atomic mass only differ due to binding energy effects

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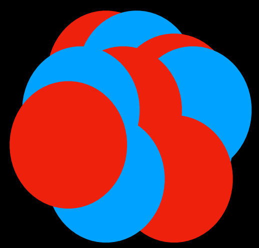

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Suppression of LO term by ϵ^2

$g_p = g_n$

Always in the coupling to mass limit

Deviations of $\epsilon \sim \mathcal{O}(10^{-3})$ *due to binding energy*

Must calculate higher order terms to reliably estimate rate

$g_p \neq g_n$

*Deviations determined by difference in the **ratio** Z/A*

Expect $\epsilon \sim \mathcal{O}(0.01 - 0.1)$

Select materials with <u>mix</u> of light (Z/A=1/2) and heavy (Z/A~0.4) elements, or contain hydrogens (Z/A=1)

Simplest of systems already provides curiosities with implications for DM detector material

What's going on at an MeV?

Sensitivity gap in direct detection meV-eV energy deposit

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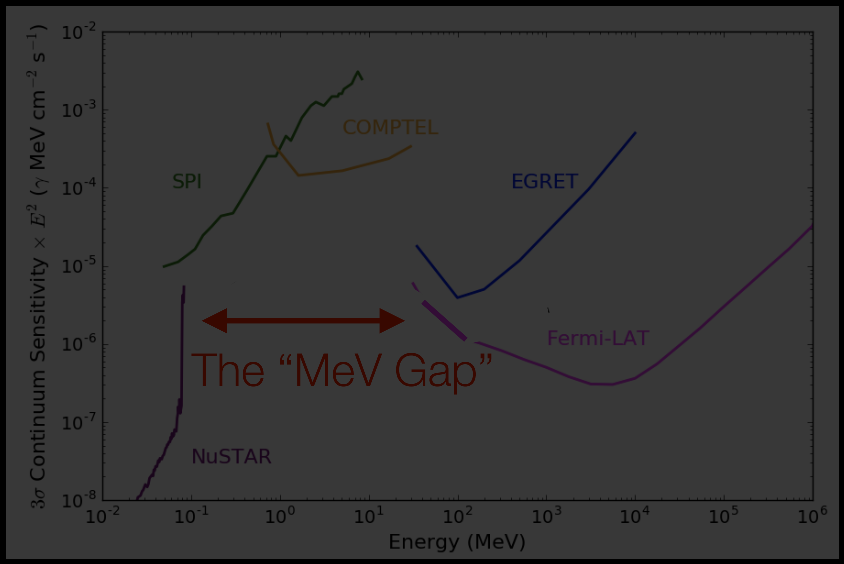
i.e. keV-MeV mass

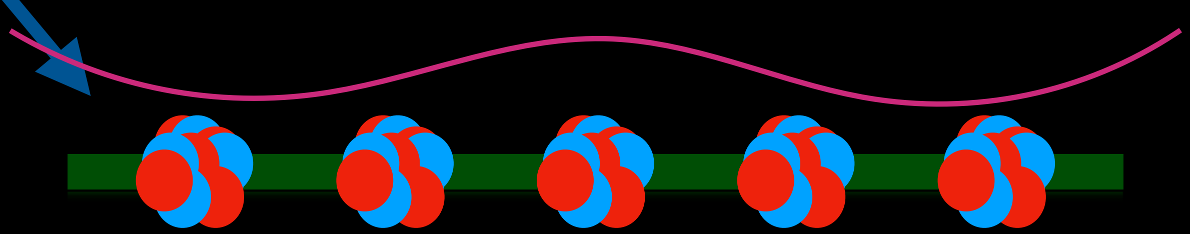
Telescope sensitivity gap



Theory motivation

Condensed matter, quantum devices, chemistry

New technologies under R&D, with broad applications



New theoretical input needed to determine rate and nature of DM interaction

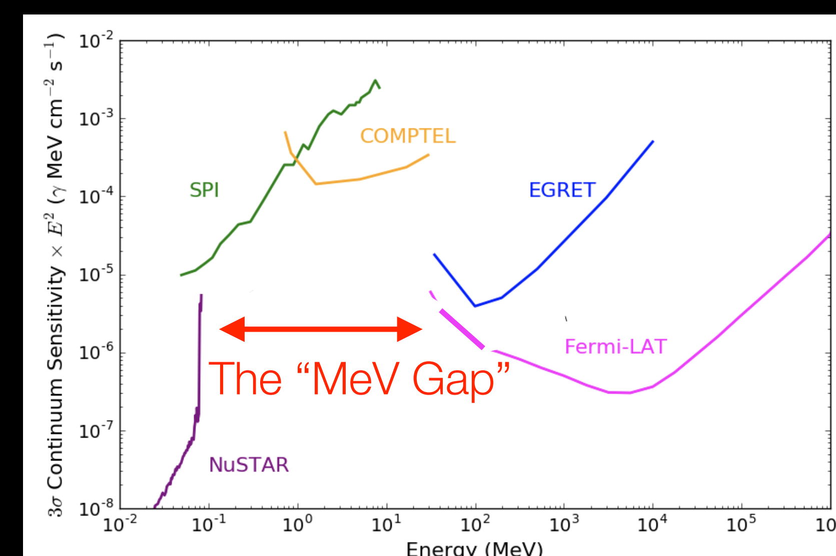
Lots going on at an MeV!

Sensitivity gap in direct detection meV-eV energy deposit

$$\frac{1}{2} m_{DM} v^2 \sim 10^{-6} m_{DM}$$

i.e. keV-MeV mass

Telescope sensitivity gap



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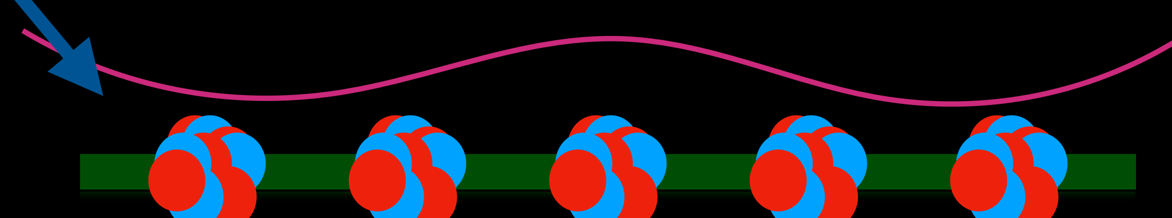

New theoretical input needed to determine rate and nature of DM interaction