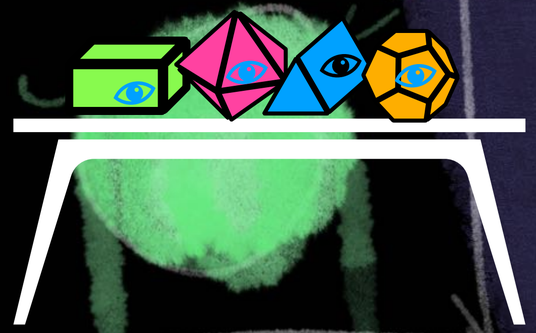
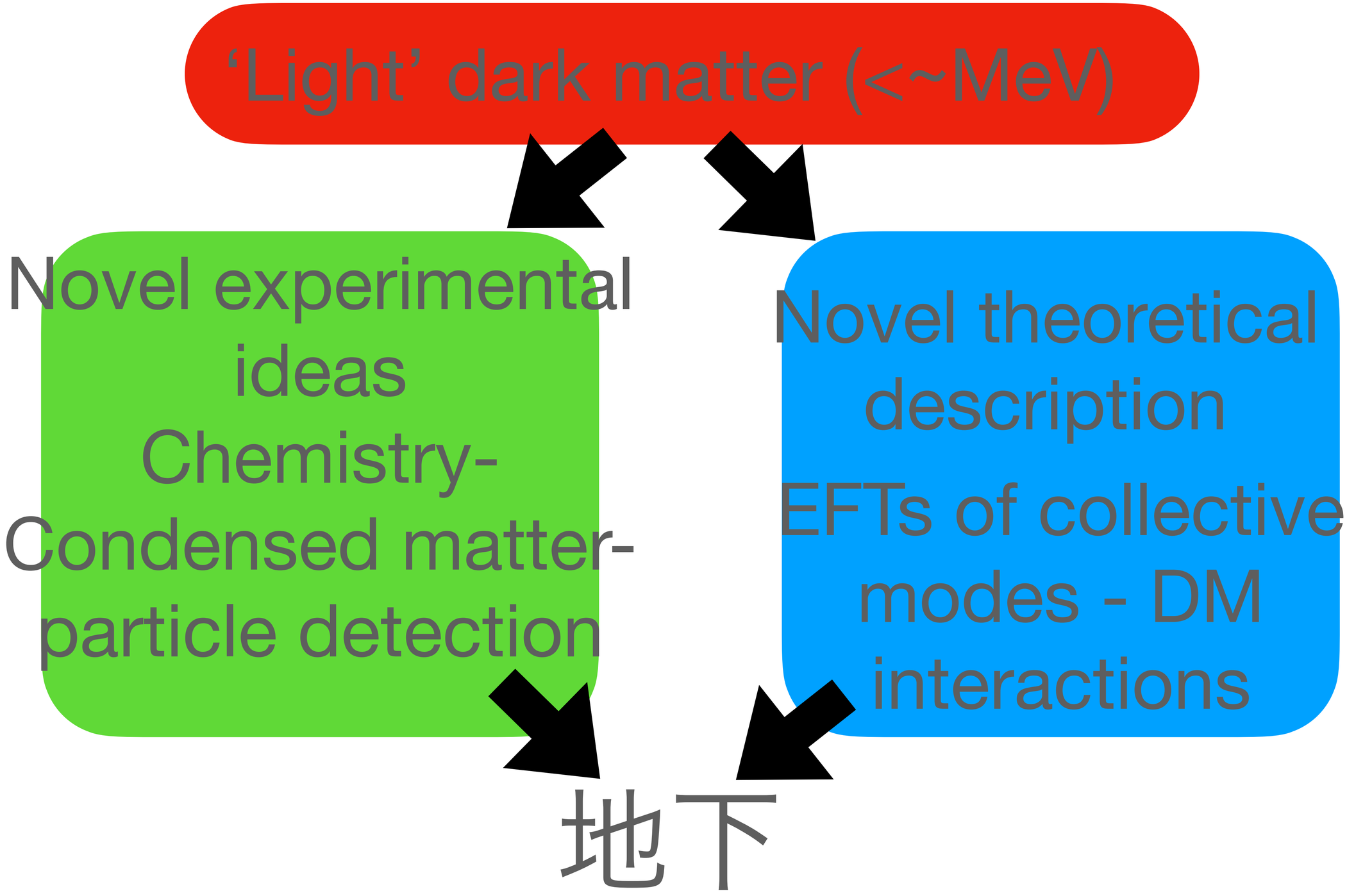
Detecting sub-MeV dark matter with chemistry and collective modes

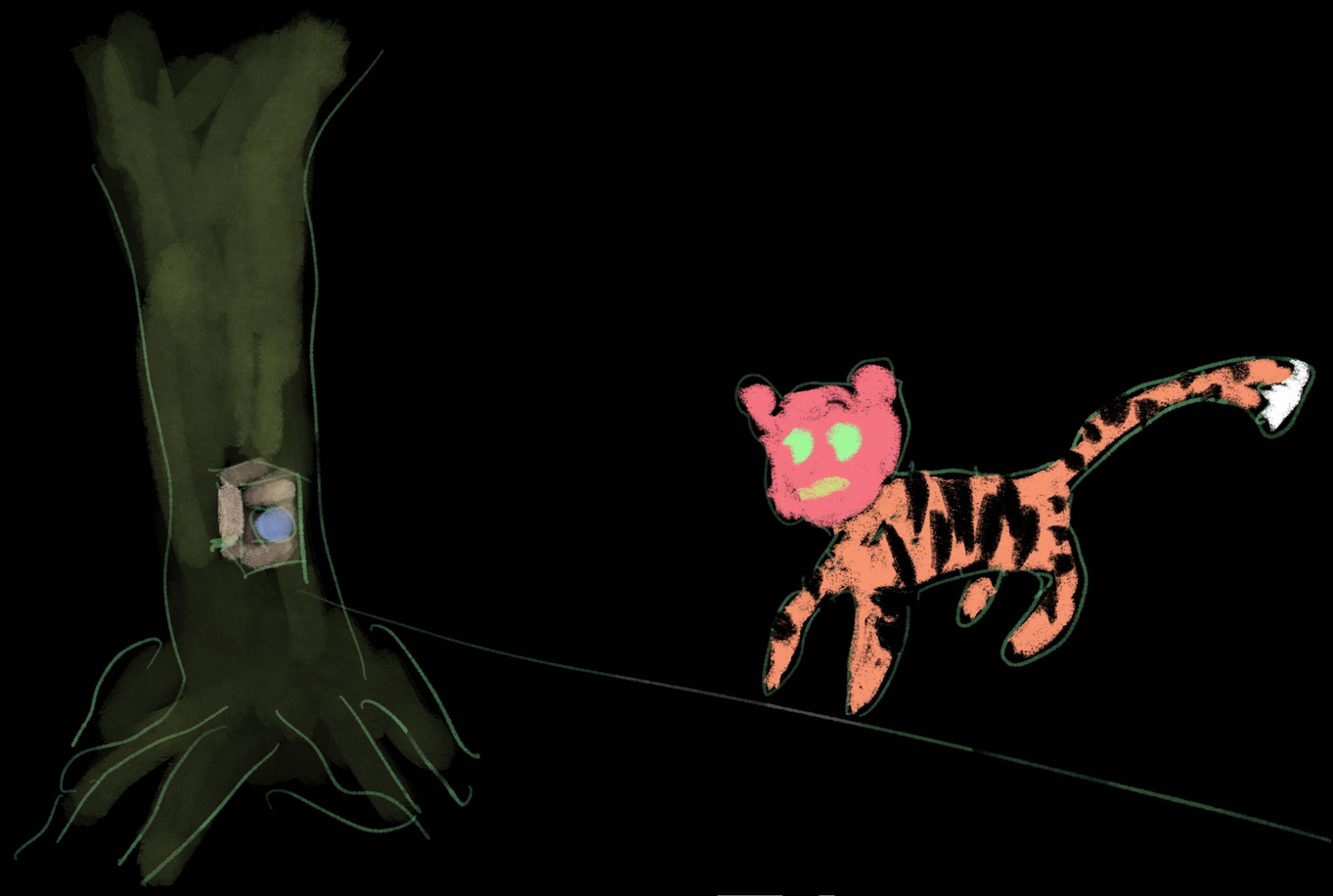


Tom Melia, Kavli IPMU
新学術「地下宇宙」領域研究会


‘Light’ dark matter (<~MeV)
Novel experimental ideas
Chemistry-Condensed matter-particle detection
Novel theoretical description
EFTs of collective modes - DM interactions
地下

We have long been searching for DM in underground detectors…

On the principle of:



Trigger

On the principle of:

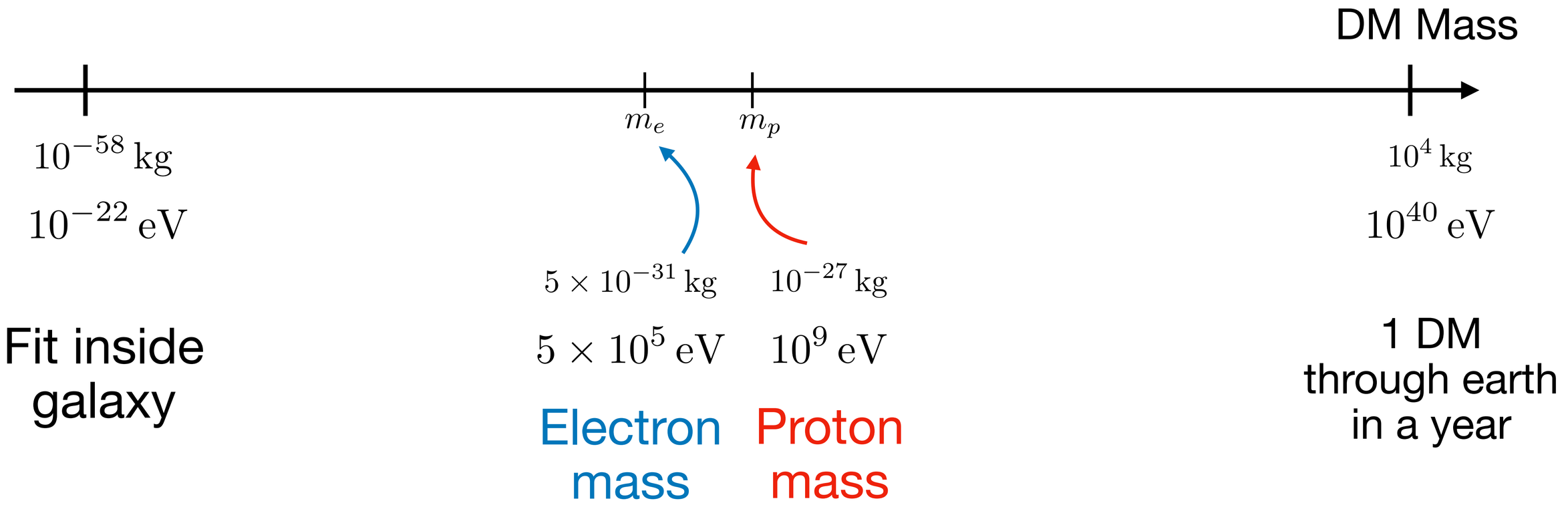
Trigger

However, observations do not tell us the mass scale of dark matter

We do not know what is the right type of trigger to use

The size of this trigger problem is a more than sixty orders of magnitude one

The size of this trigger problem is a more than sixty orders of magnitude one



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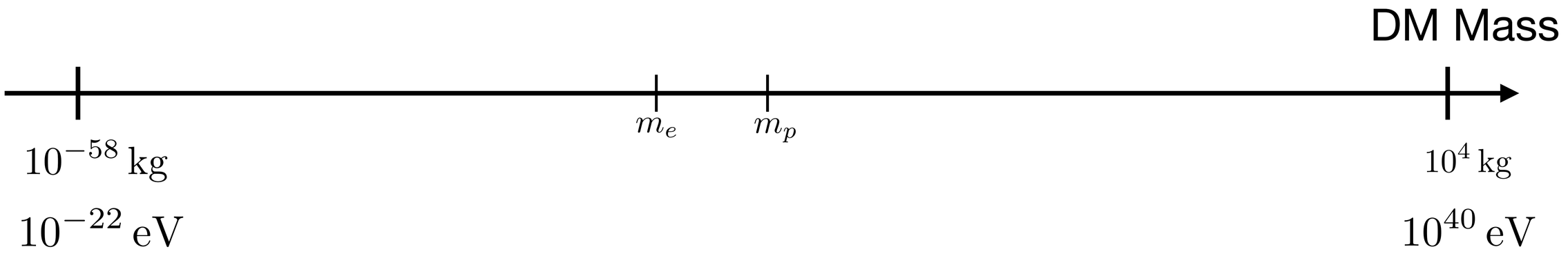


Clearly, search strategies must be diverse

$$\lambda = \frac{h}{mv}$$

overlapping wave-like | particle-like

DM Mass

$10^{-58}\,\mathrm{kg}$

$10^{-22}\,\mathrm{eV}$

m_e

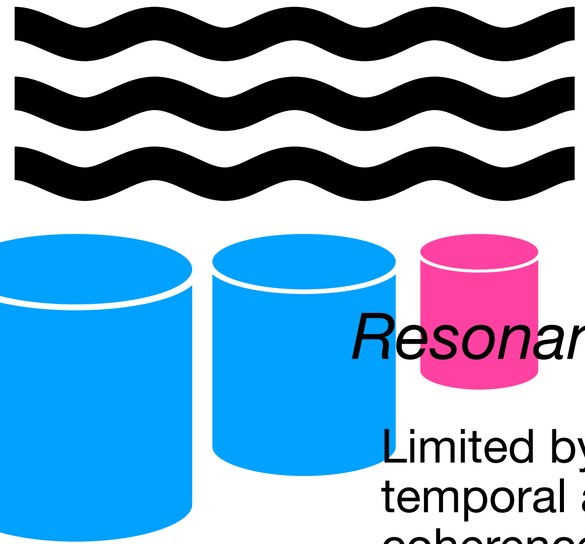
$10^{-4}\,\mathrm{eV}$

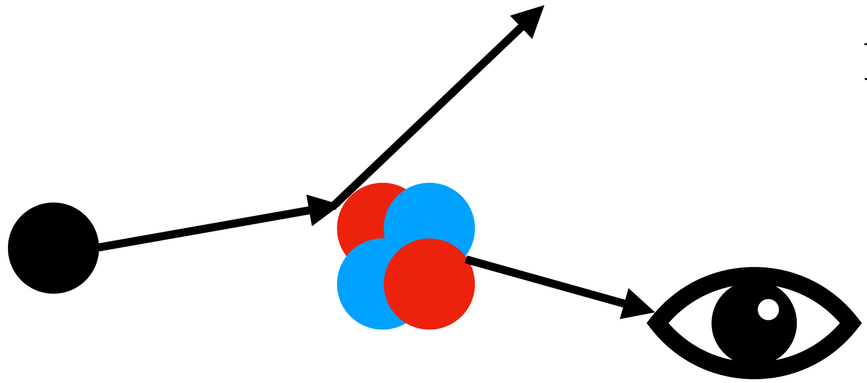
m_p

$10^{6}\,\mathrm{eV}$

$10^{4}\,\mathrm{kg}$

$10^{40}\,\mathrm{eV}$

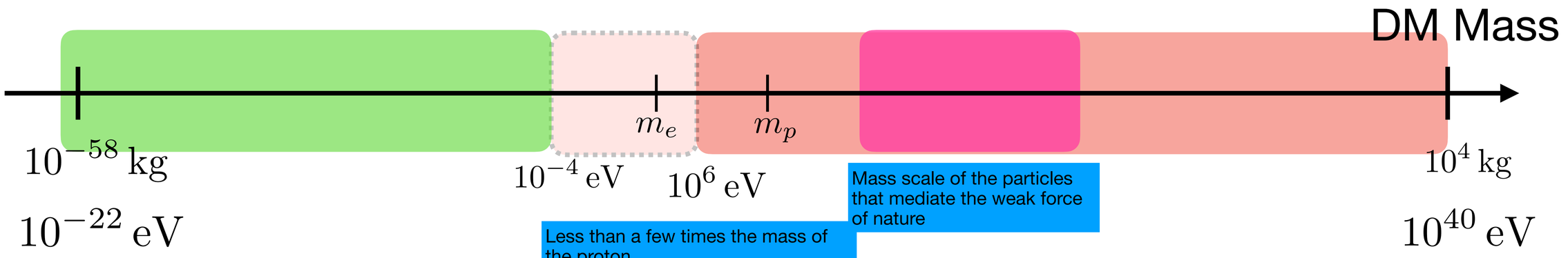




Resonance

Limited by loss of DM temporal and spatial coherence

Limited by ability to detect recoil (energy threshold)



Axions

WIMPs

“Light WIMPs”

The WIMP paradigm

A “sprinkle and leave” in the early universe

1) gives the correct dark matter abundance

2) give a signal in an earth based detector

3) also has signals at colliders like the LHC

And its connection with supersymmetry

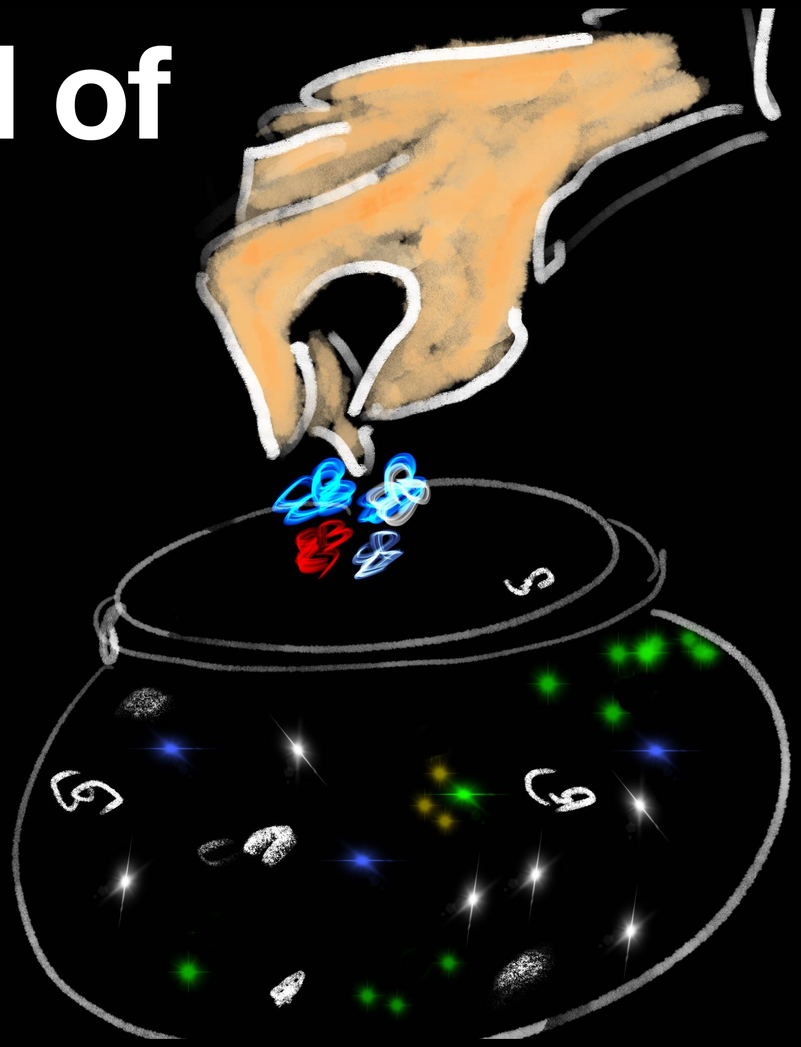
Light WIMPs

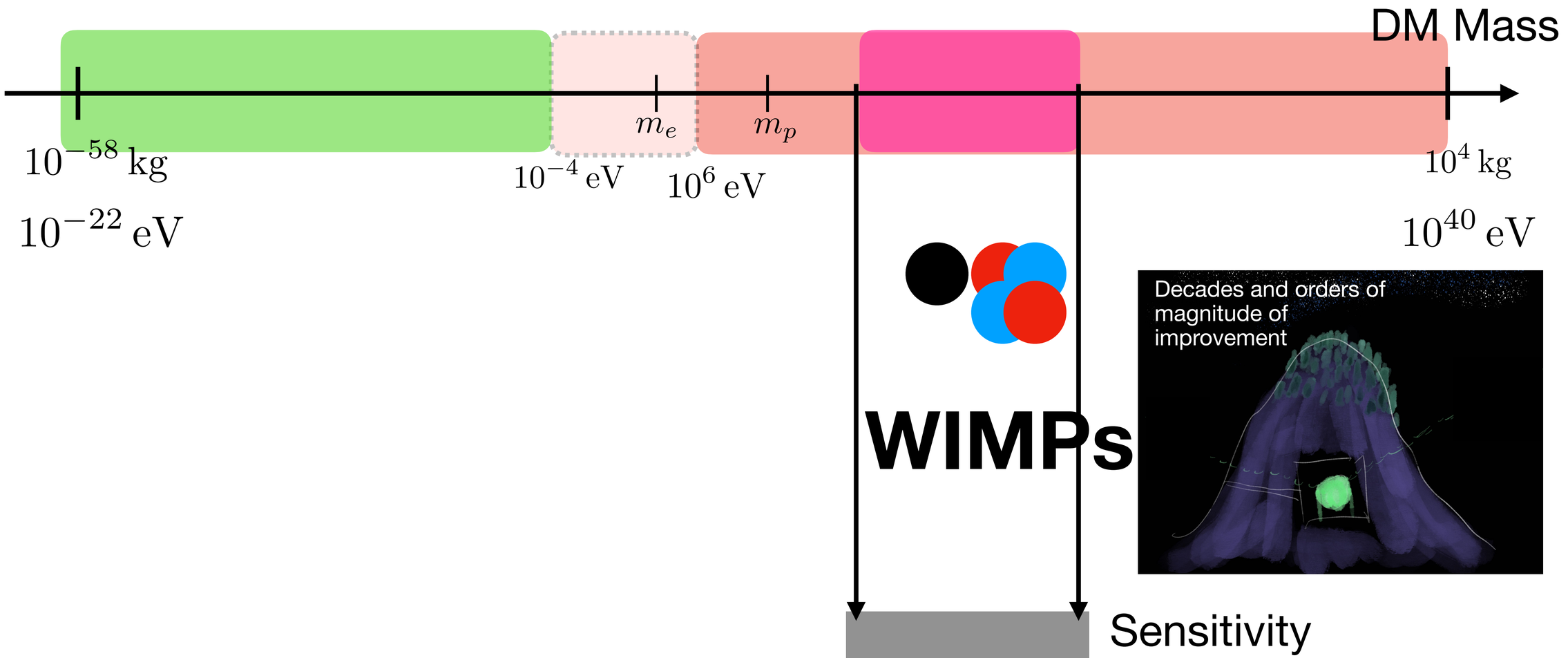
Different kind of sprinkle

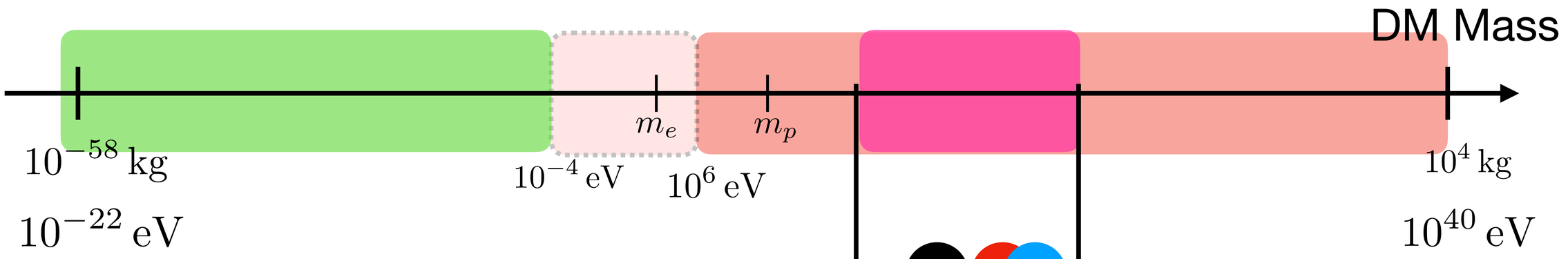
1) simple models that give the correct dark matter abundance

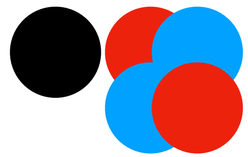
2) have a signal in an earth based detector

3) also have signals at colliders like the LHC, B-factories

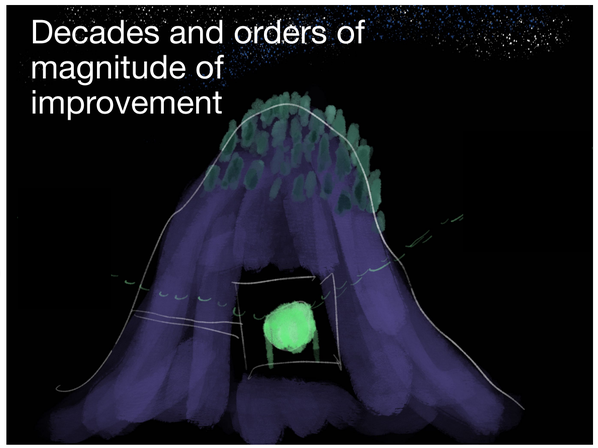



DM Mass
m_e
m_p
10^{-58} kg
10^{-22} eV
10^{-4} eV
10^{6} eV
10^{4} kg
10^{40} eV
WIMPs
Decades and orders of magnitude of improvement
Sensitivity



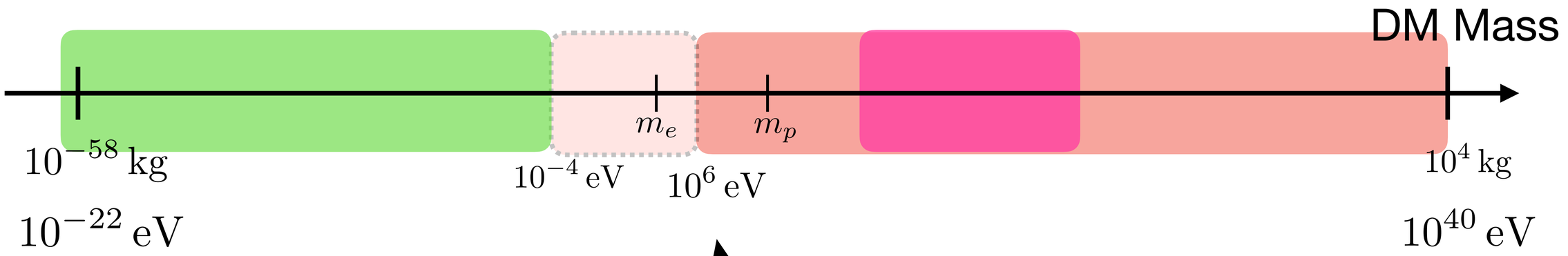


WIMPs

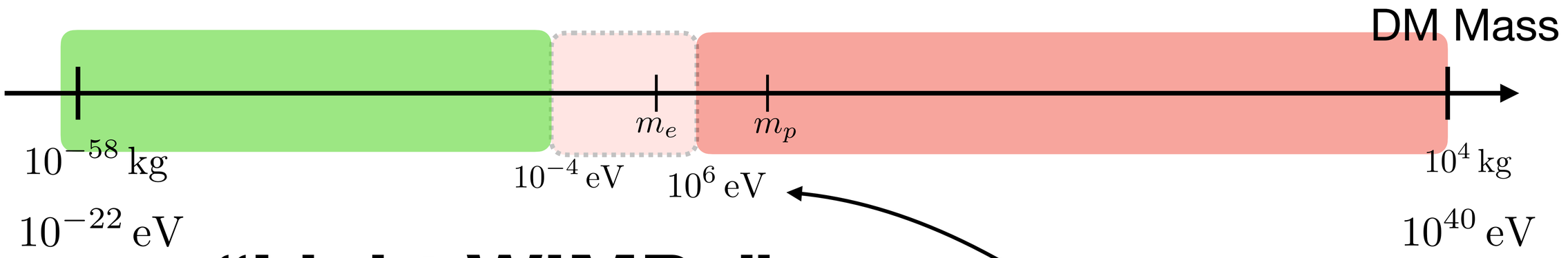


Lower threshold to probe light WIMP sensitivity gap

Sensitivity

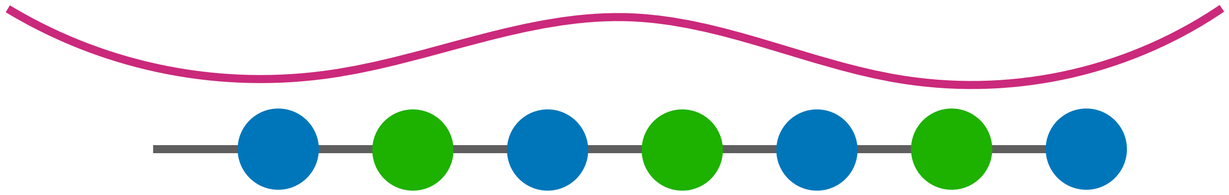


Another reason for this differentiation…



“Light WIMPs”

DM de Broglie wavelength > interatomic spacing

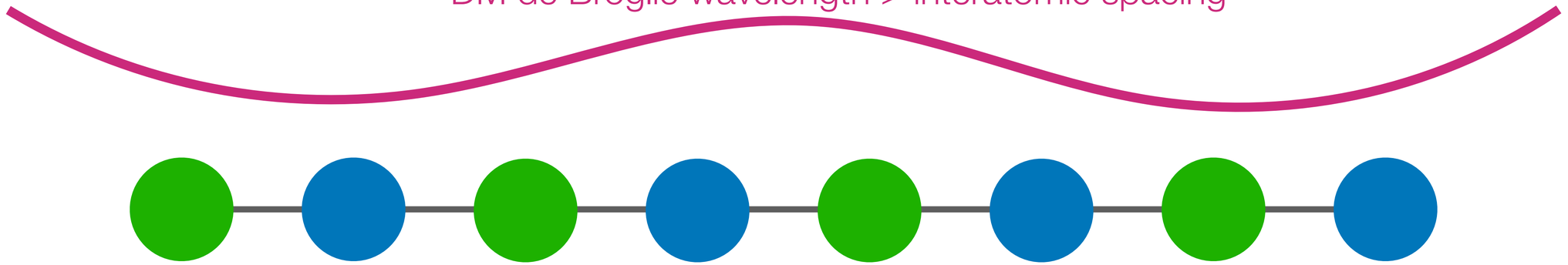


$$\lambda = \frac{h}{mv}$$

See collective modes

Light WIMPs see collective modes

DM de Broglie wavelength > interatomic spacing

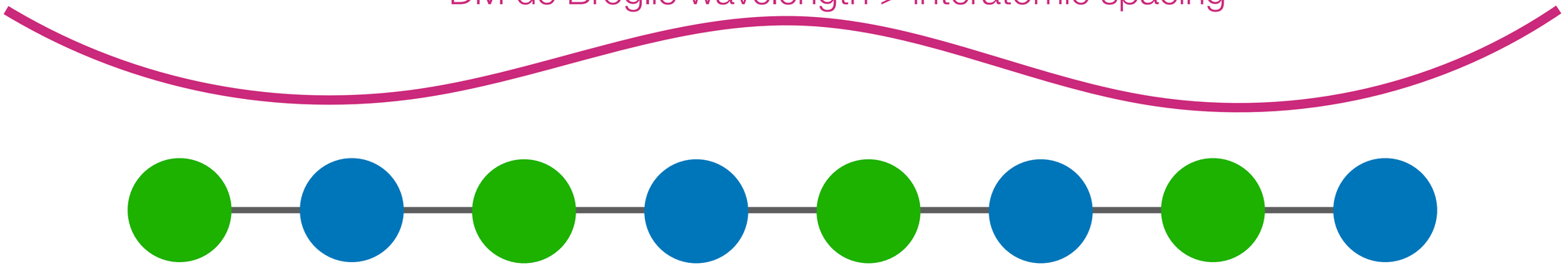


Important theory input!

Radically changes phenomenology of Light WIMP detection from that of their heavier cousins

Light WIMPs see collective modes

DM de Broglie wavelength > interatomic spacing



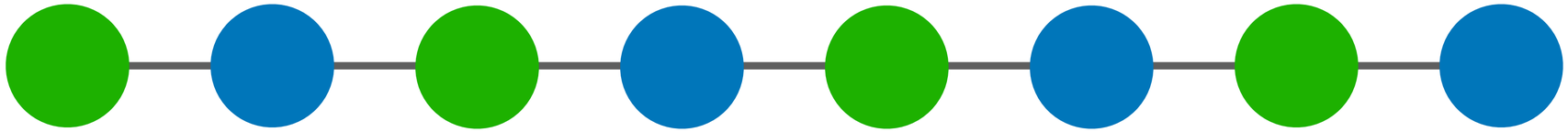
We are used to characterising DM via its interaction with particles

Its just that here, the quanta of collective modes are the relevant particle description

Symmetries are different, perhaps less familiar, so can expect novel features in Light WIMP scattering

Light WIMPs see collective modes

DM de Broglie wavelength > interatomic spacing



Novel theoretical description

EFTs of collective modes - DM interactions

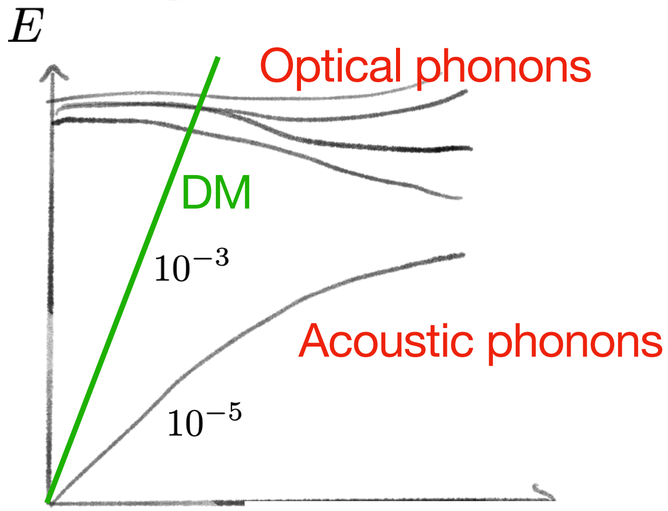
Single ‘optical’ phonon

Cox, **TM**, and Rajendran; PRD 100 no 5, 055011 (2019)

Two acoustic phonons

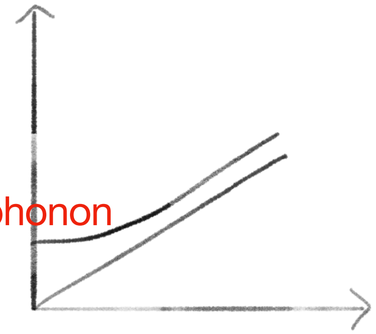
Campbell-Deem, Cox, Knapen, Lin, **TM**, PRD 101 055011 (2020)

In crystals



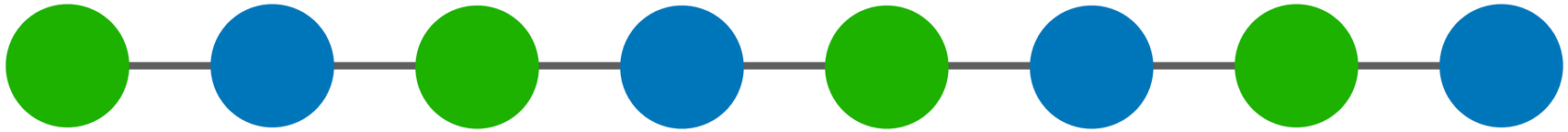
Esposito, Geoffray, **TM**, Phys Rev D 102 (2020)

Novel EFT



Light WIMPs see collective modes

DM de Broglie wavelength > interatomic spacing



Surprising cancellations

Precise calculations required to get reliable DM rate

Single ‘optical’ phonon

Cox, **TM**, and Rajendran; PRD 100 no 5, 055011 (2019)

Two acoustic phonons

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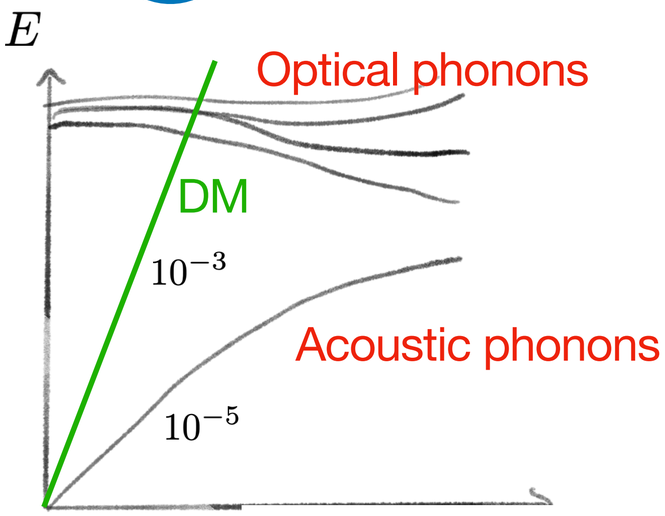
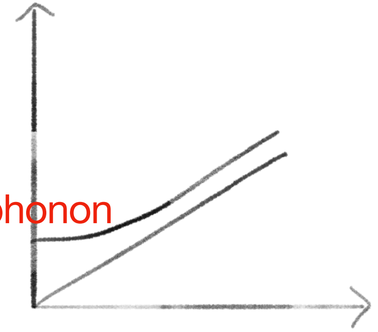


Esposito, Geoffray, **TM**, Phys Rev D 102 (2020)

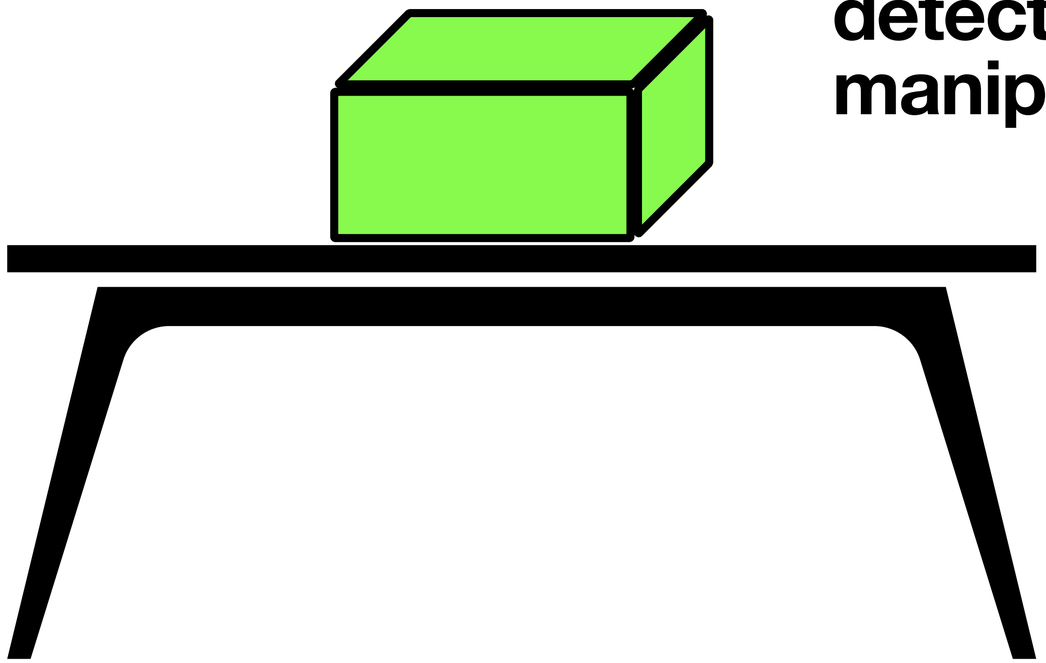
Novel EFT



Condensed matter, quantum devices, chemistry

Tabletop experiments

Piggyback on R&D for detecting and manipulating single quanta



Condensed matter, quantum devices, chemistry

Chemical crystals as
Magnetic bubble chambers

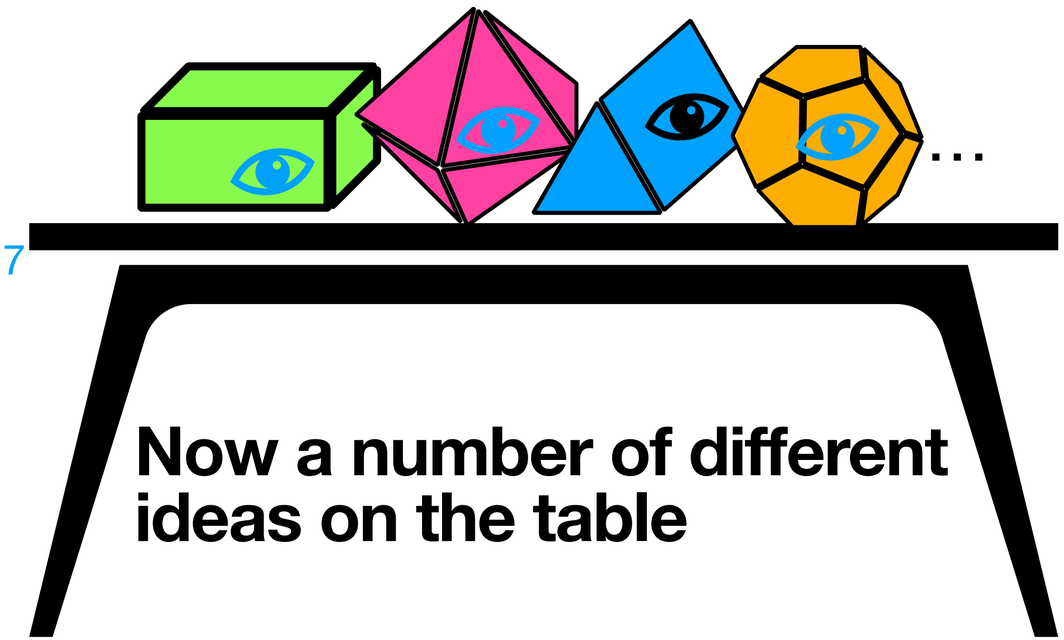
Bunting, Gratta, **TM**, and Rajendran,
Phys.Rev. D95 (2017) no.9, 095001

Superconductors

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

Multiphonons in
superfluid helium

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



Phonons in crystals e.g.
sapphire,
semiconductors

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

…

Condensed matter, quantum devices, chemistry

Proof of principle of mechanism (at higher energy)

Chemical crystals as Magnetic bubble chambers

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

Quantum Detection using Magnetic Avalanches in Single-Molecule Magnets

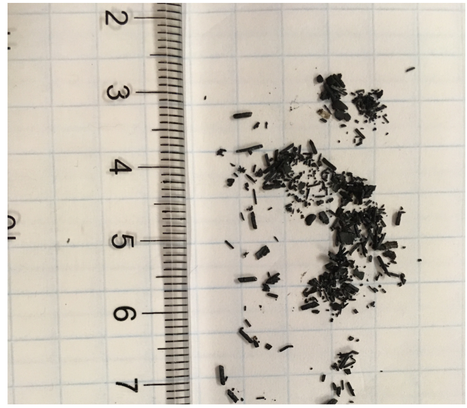
Hao Chen,[1] Rupak Mahapatra,[1] Glenn Agnolet,[1] Michael Nippe,[2] Minjie Lu,[1] Philip C. Bunting,[3] Tom Melia,[4] Surjeet Rajendran,[5] Giorgio Gratta,[6] and Jeffrey Long[7]

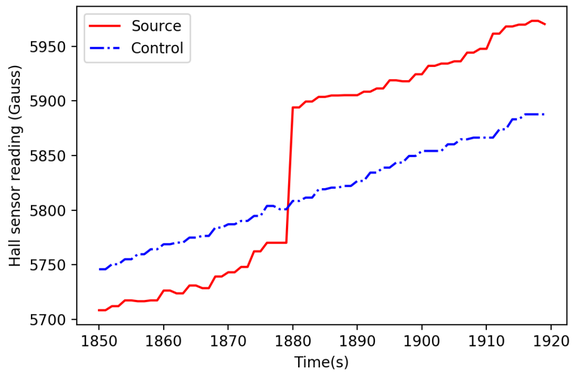
[1] *Department of Physics and Astronomy, Texas A&M University, College Station, TX, 77843*
[2] *Department of Chemistry, Texas A&M University, College Station, TX, 77843*
[3] *Department of Chemistry and Biochemistry, University of California San Diego, La Jolla, California 92093*
[4] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[5] *Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218*
[6] *Physics Department, Stanford University, Stanford, CA, 94305*
[7] *Chemistry Department, University of California, Berkeley, CA, 94720*

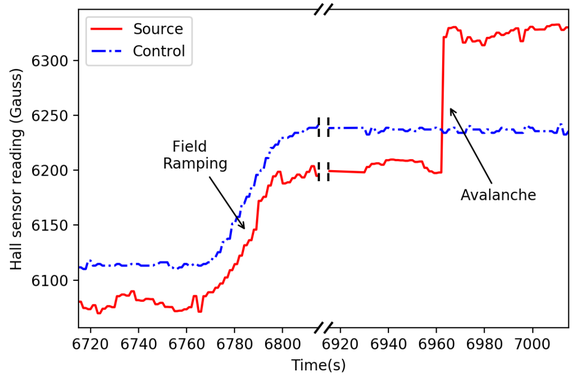
(Dated: February 19, 2020)

We report the first experimental demonstration of magnetic avalanches induced by scattering quanta in single-molecule magnet (SMM) crystals made of Mn12-acetate, establishing the use SMMs as particle detectors for the first time. While the current setup has an energy threshold the MeV regime, our results motivate the exploration of a wide variety of SMMs whose properti could achieve 10 meV thresholds. If developed, such detectors could serve as single quantum senso of infrared photons with high efficiency and low dark count rate, and enable the direct detection sub-GeV dark matter.

physicists / chemists





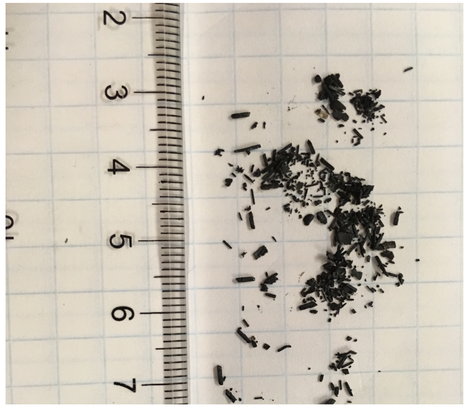


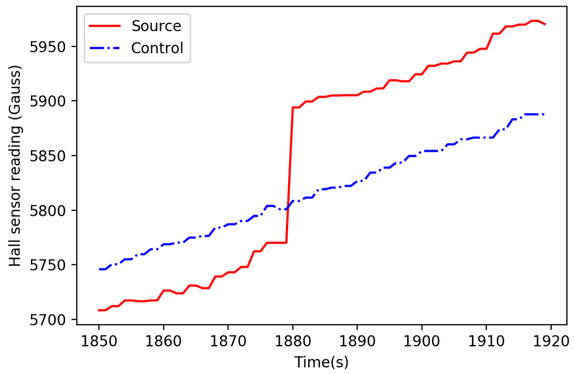
Condensed matter, quantum devices, chemistry

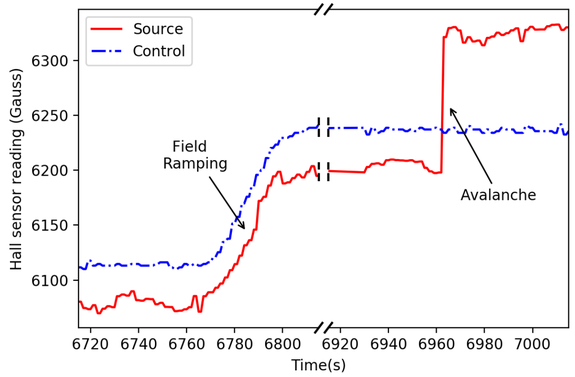
Ongoing collaboration incl. Fukushima group chemistry (Tokyo Tech), Hashimoto Group solid state (U Tokyo GSFS) in Japan, S. Matsumoto (IPMU) and Mahapatra and Rajendran groups in the US

Chemical crystals as
Magnetic bubble chambers

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







physicists chemists

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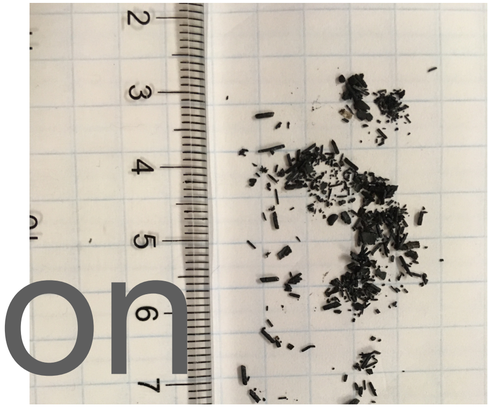

We hope to get 地下 soon