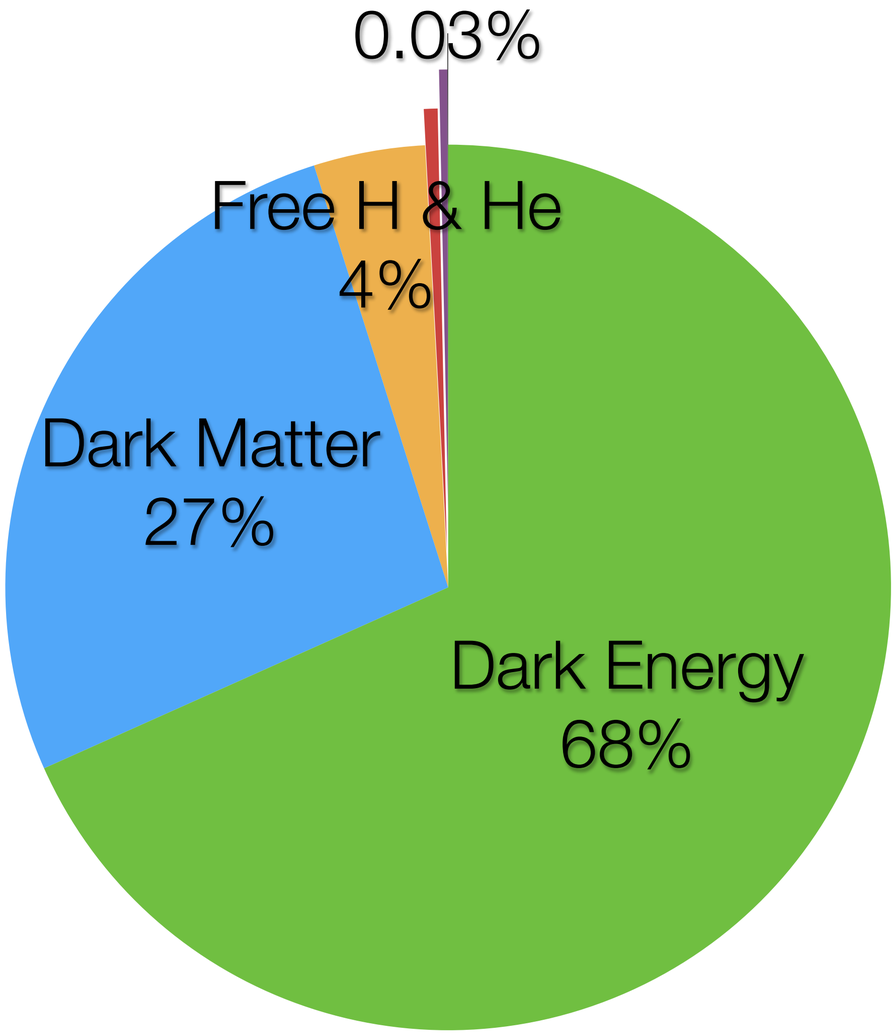
Low-Mass Dark Matter Searches

Rencontres de Blois

Snowmass2021 Cosmic Frontier:
The landscape of low-threshold dark matter direct detection in the next decade
arXiv:2203.08297

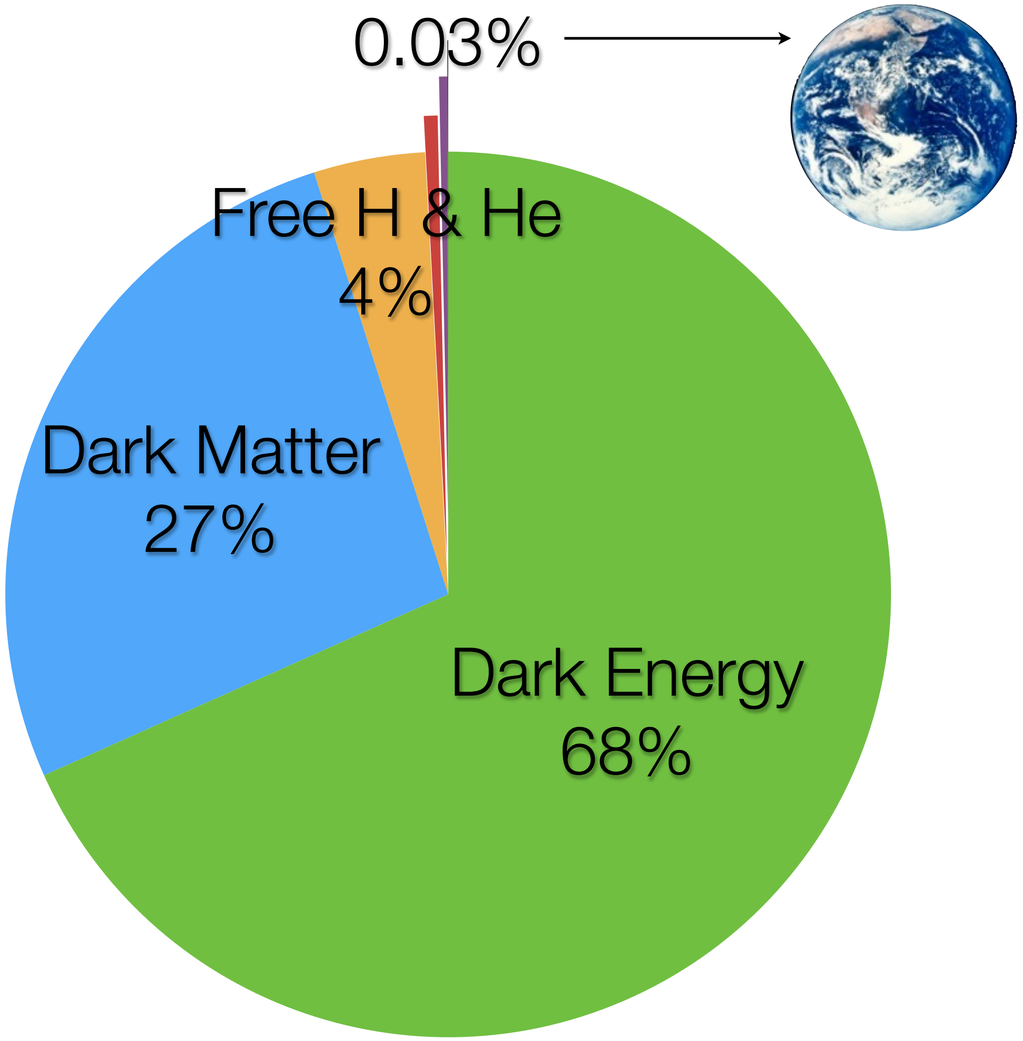
Enectalí Figueroa-Feliciano
Northwestern

The ΛCDM Model of Cosmology



- Dark Energy
- Dark Matter
- Free H & He
- Stars and Gas
- Neutrinos
- Heavy Elements (Us)

The ΛCDM Model of Cosmology



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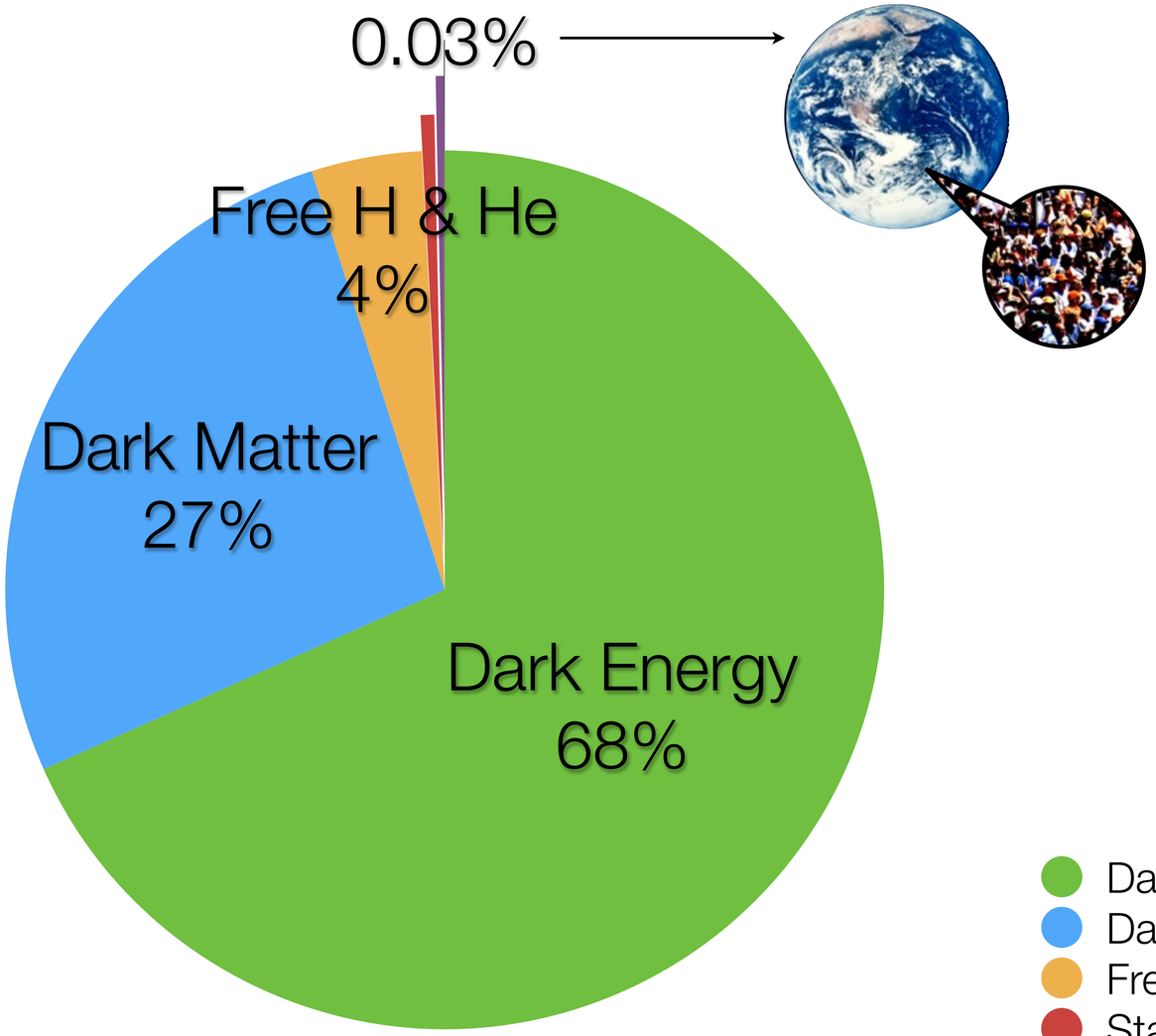

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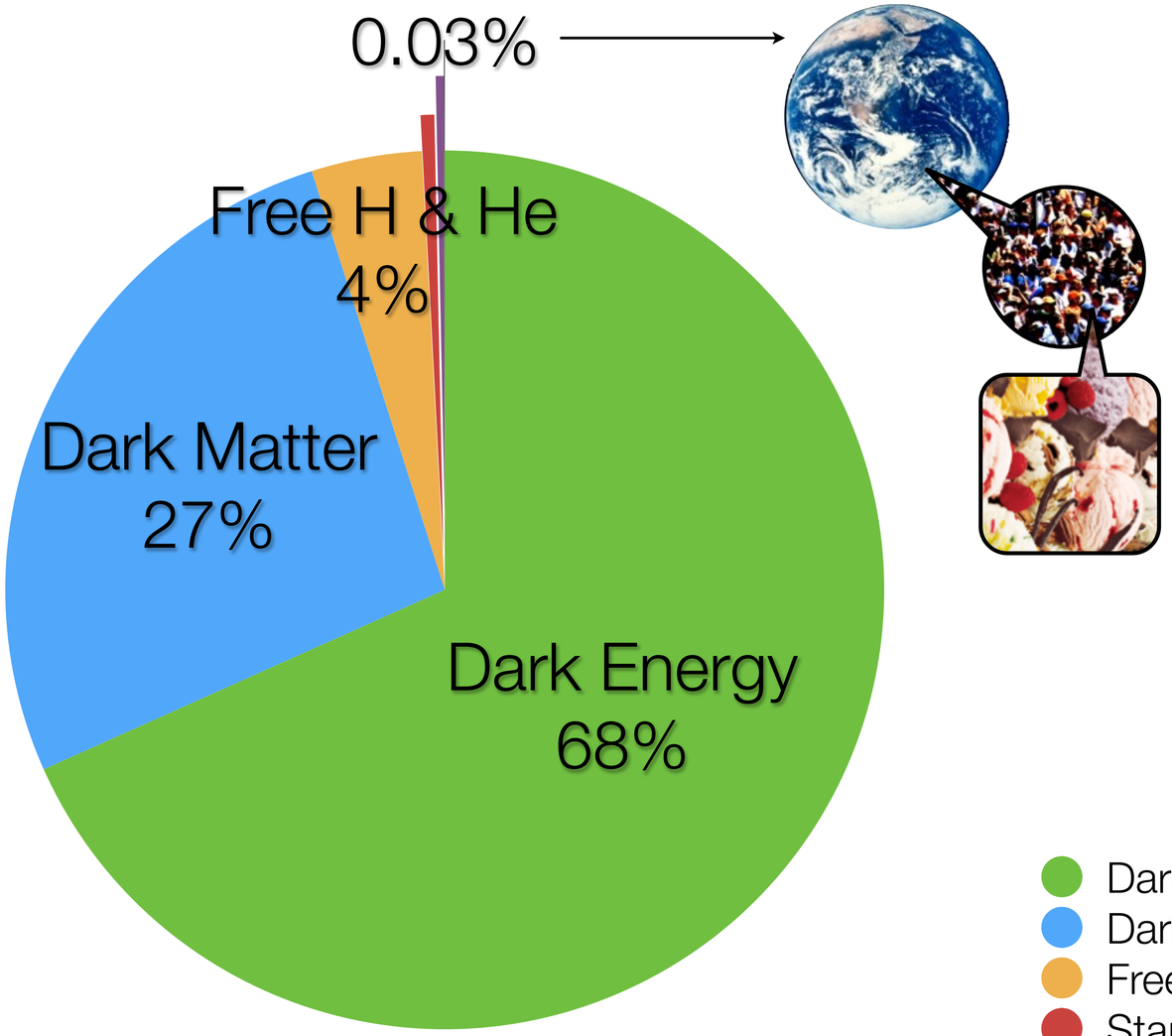

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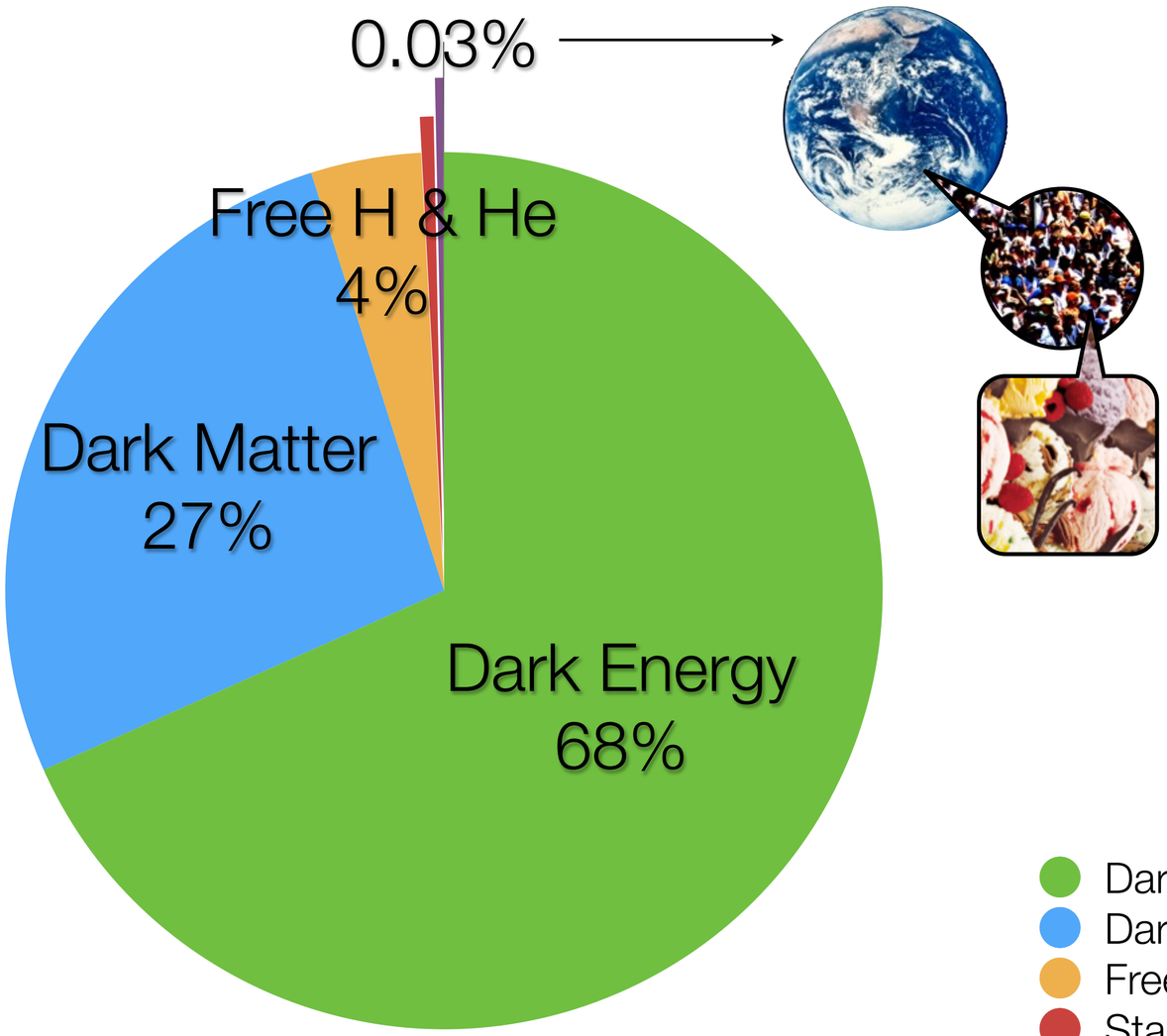

96% of the Universe is Dark Matter and Dark Energy!

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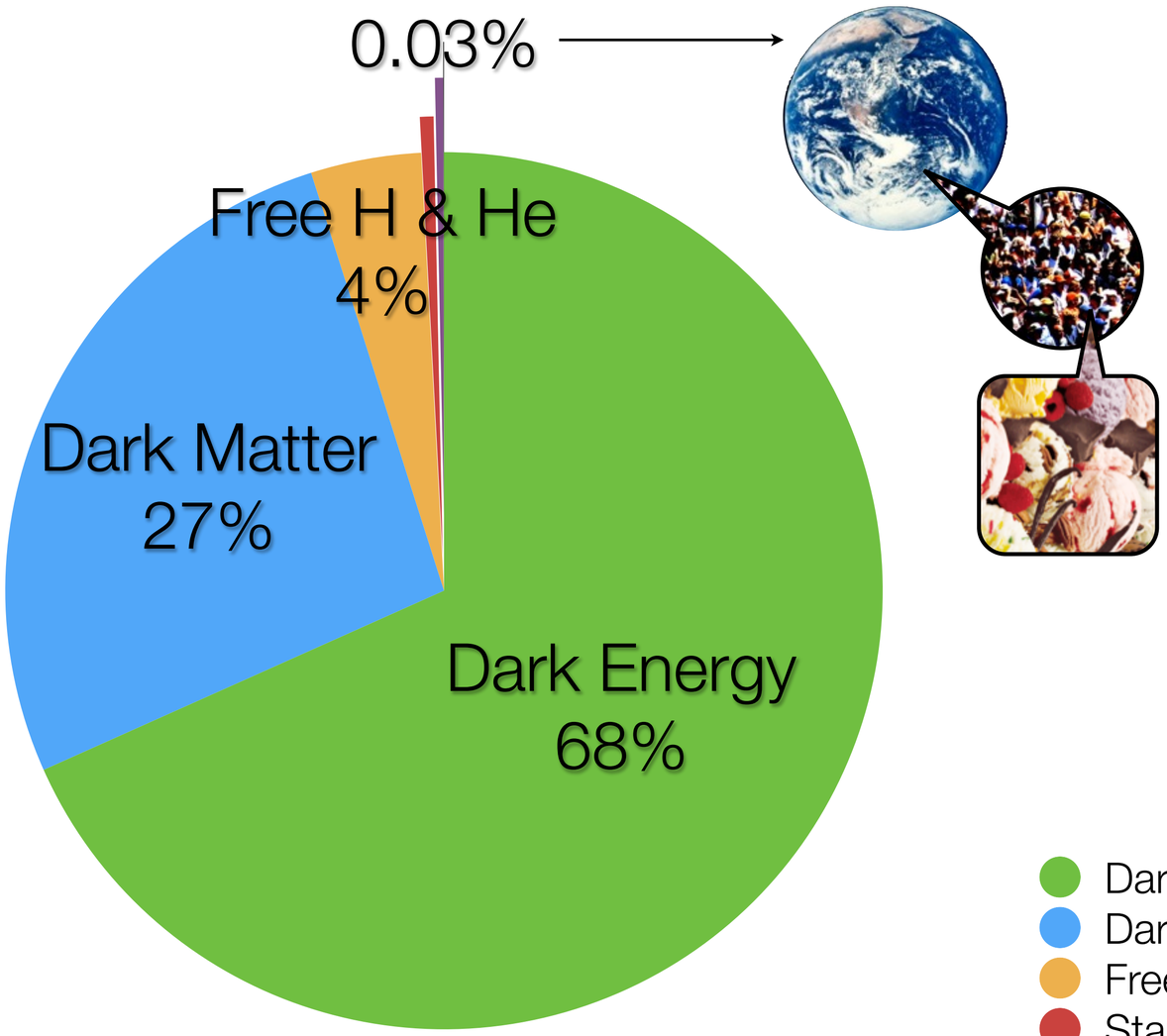
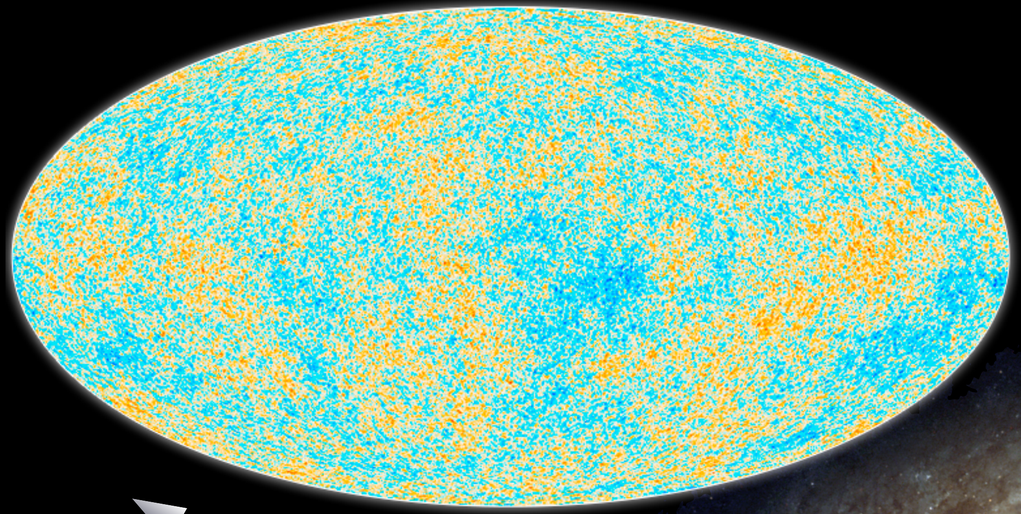


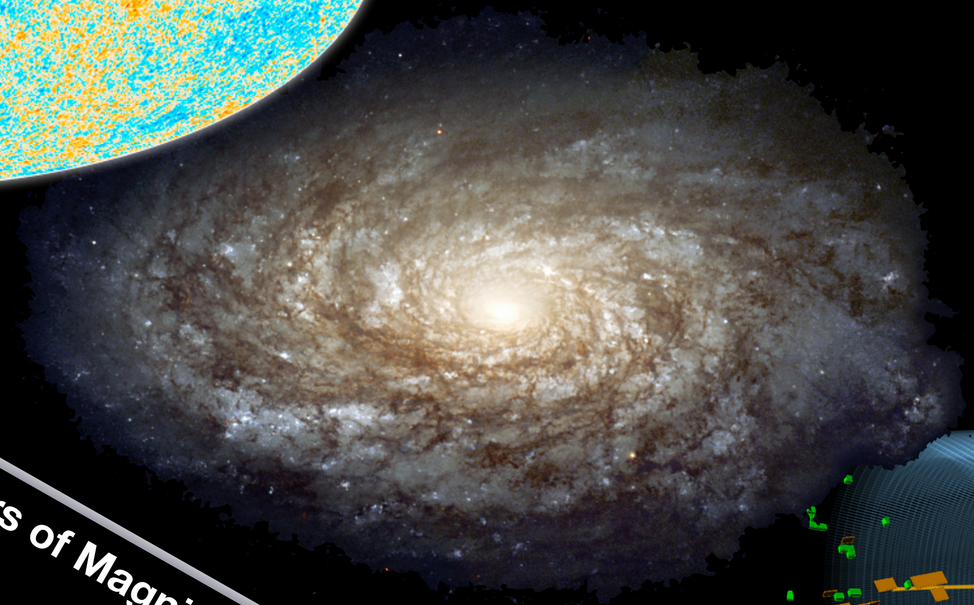
Dark Energy
Dark Matter
Free H & He
Stars and Gas
Neutrinos
Heavy Elements (Us)

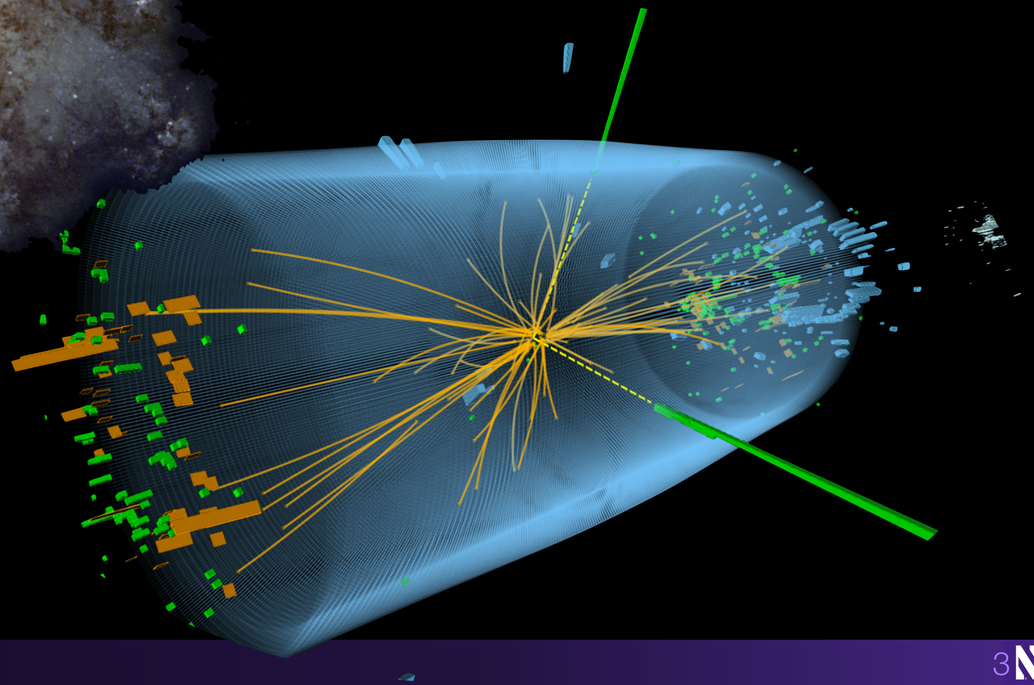
96% of the Universe is Dark Matter and Dark Energy!

We did not know the power of the dark side…

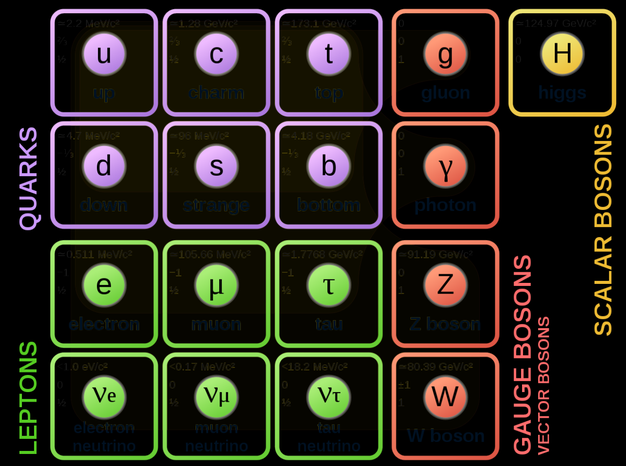
A Beautiful Problem in Physics

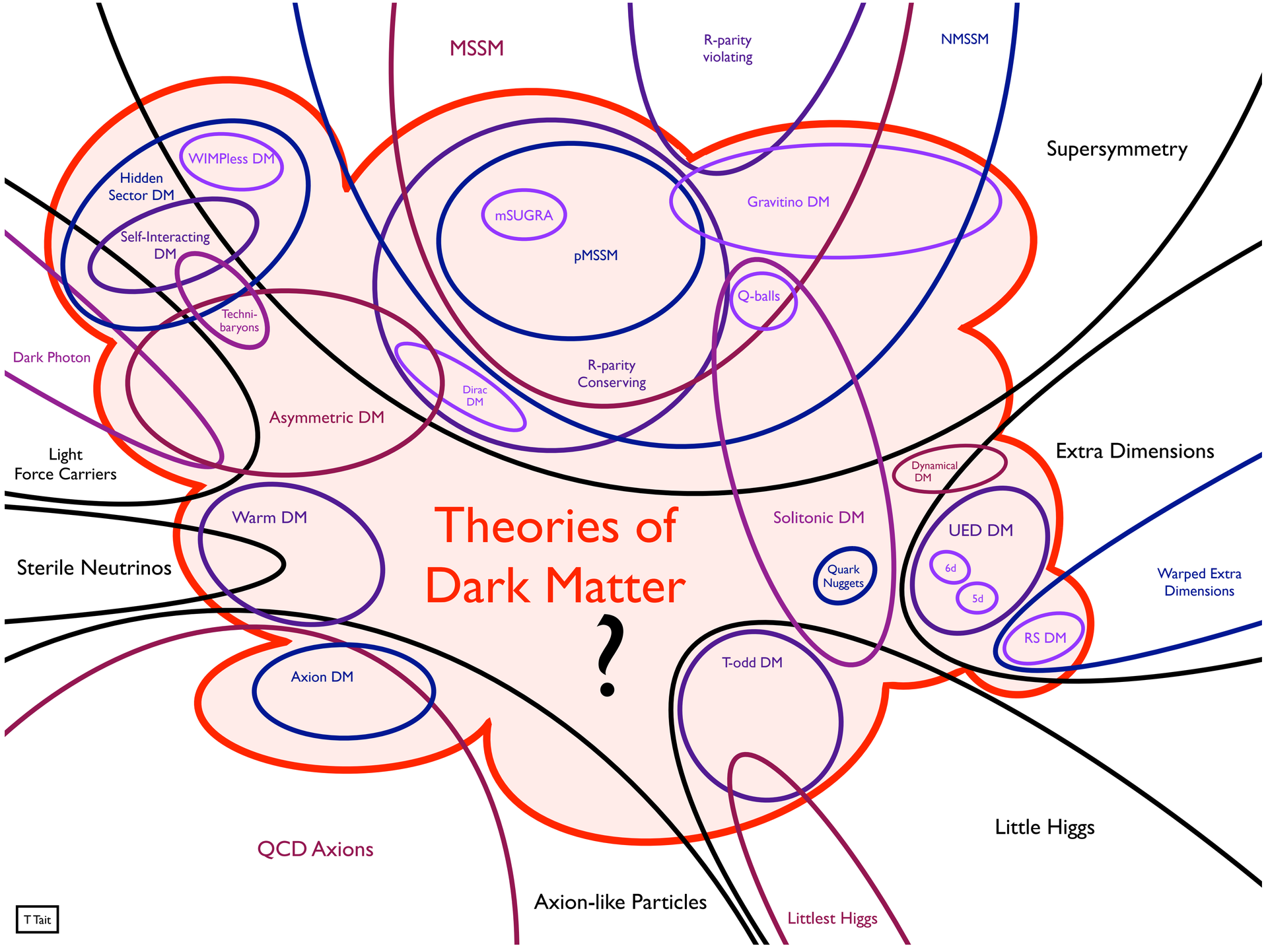






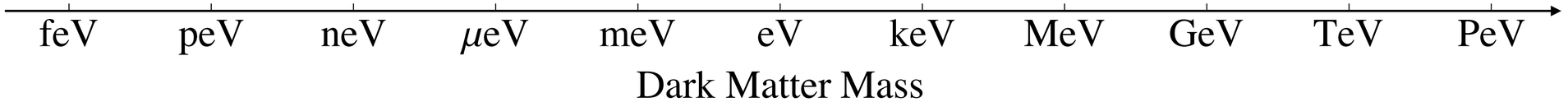
40 Orders of Magnitude!



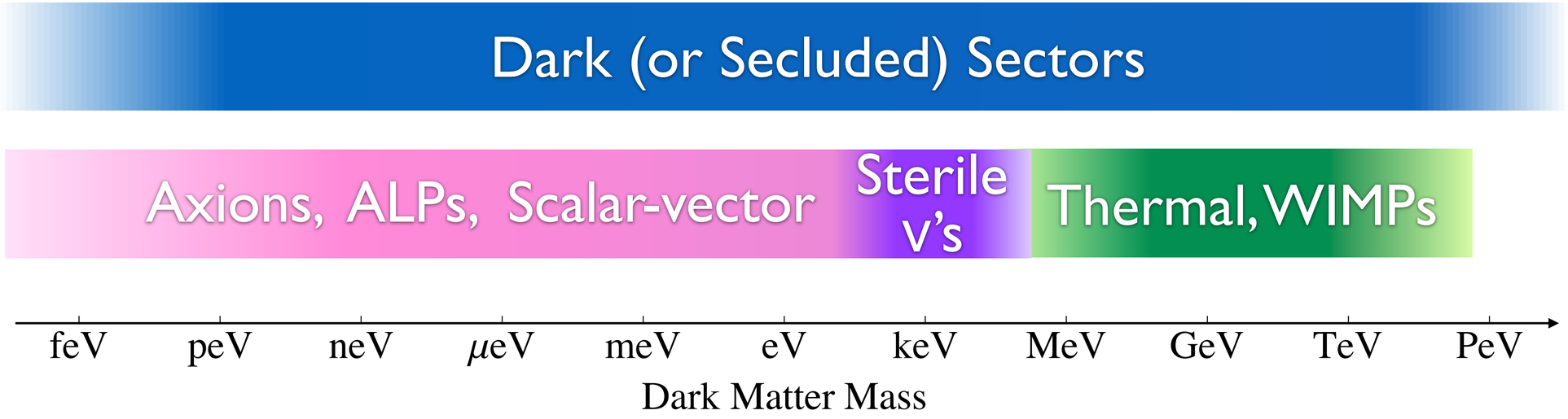

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Dark Matter Direct Detection Channels

Dark Matter Direct Detection Channels



Dark Matter Direct Detection Channels



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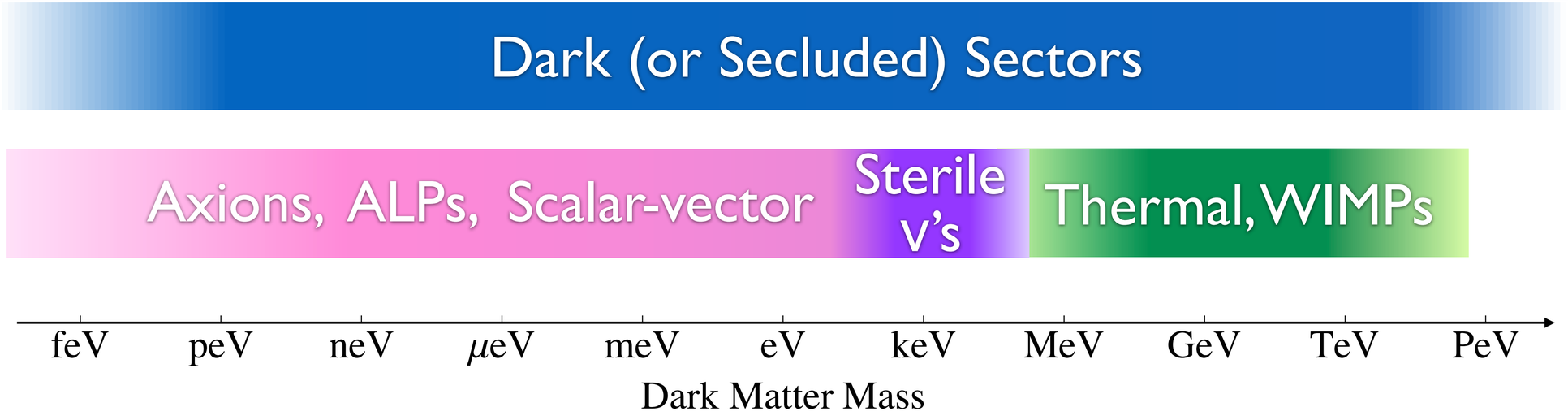

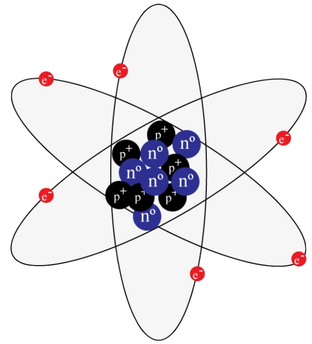

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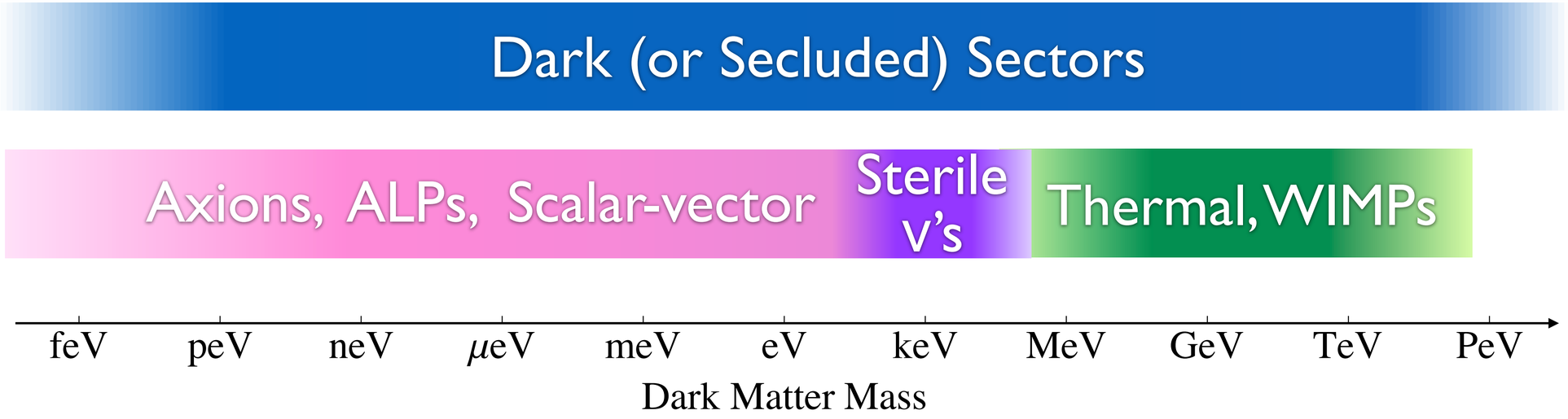
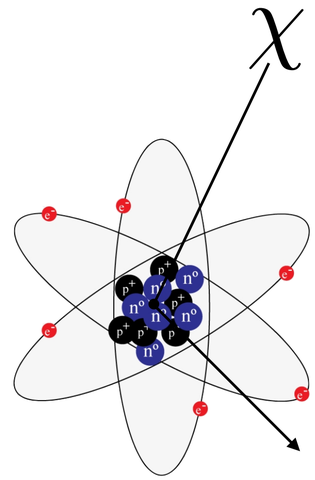




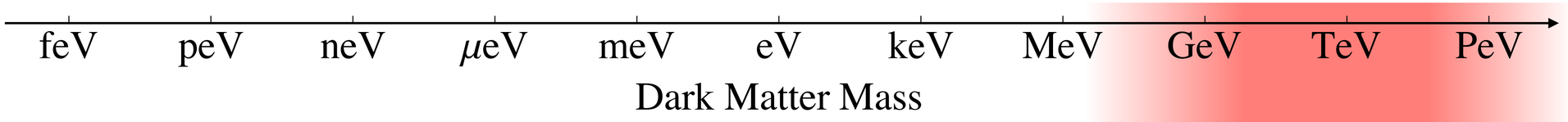
Dark Matter Direct Detection Channels

Dark (or Secluded) Sectors

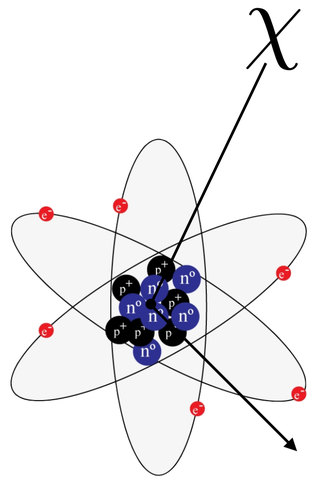
Axions, ALPs, Scalar-vector

Sterile ν's

Thermal, WIMPs



Nuclear Recoils



Dark Matter Direct Detection Channels

Dark (or Secluded) Sectors

Axions, ALPs, Scalar-vector | Sterile ν's | Thermal, WIMPs

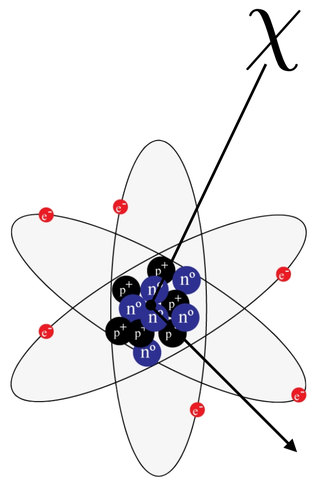
feV peV neV μeV meV eV keV MeV GeV TeV PeV

Dark Matter Mass

10^{-46} 10^{-40} 10^{-34} 10^{-28} 10^{-22} 10^{-16} 10^{-10} 10^{-4} 10^{2} 10^{5} 10^{5}

Max Recoil Energy in Silicon [eV]

Nuclear Recoils



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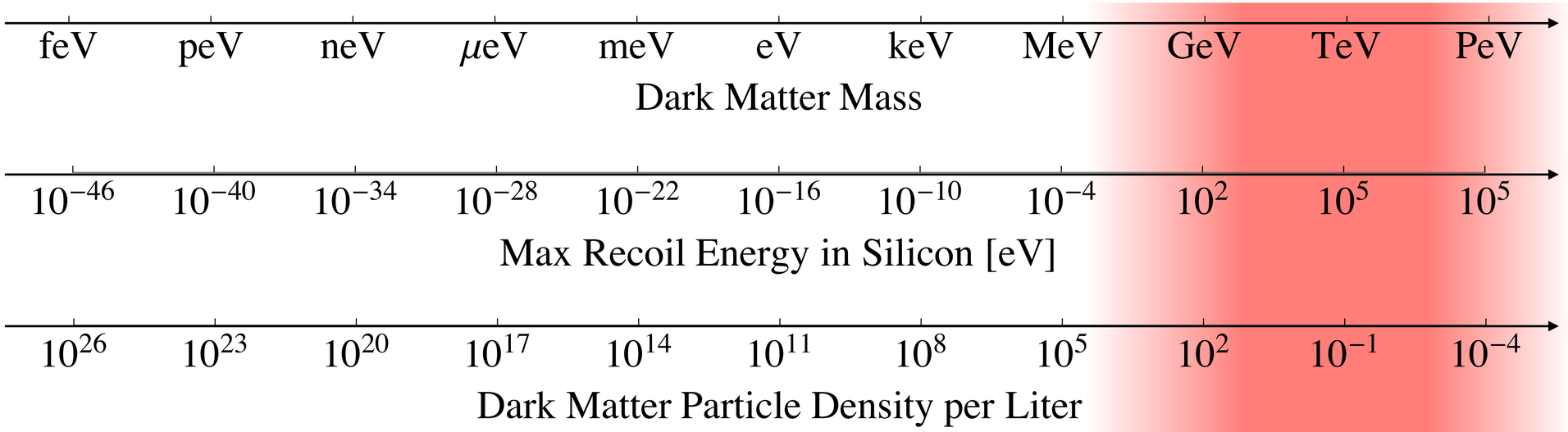

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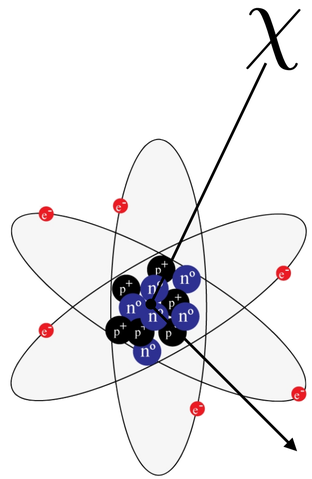


Dark Matter Direct Detection Channels

Dark (or Secluded) Sectors

Axions, ALPs, Scalar-vector | Sterile ν's | Thermal, WIMPs

feV	peV	neV	μeV	meV	eV	keV	MeV	GeV	TeV	PeV

Dark Matter Mass

10^{-41}	10^{-35}	10^{-29}	10^{-23}	10^{-17}	10^{-11}	10^{-5}	10^{0}	10^{1}	10^{1}	10^{1}

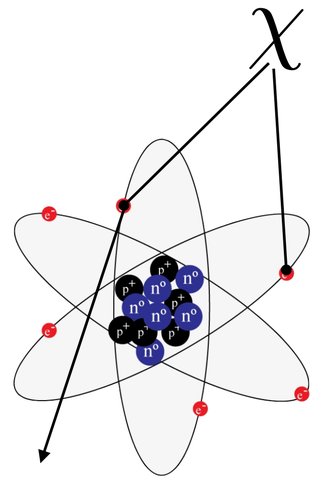
Max Electron Recoil Energy [eV]

10^{26}	10^{23}	10^{20}	10^{17}	10^{14}	10^{11}	10^{8}	10^{5}	10^{2}	10^{-1}	10^{-4}

Dark Matter Particle Density per Liter

Electron Recoils

Nuclear Recoils



Dark Matter Direct Detection Channels

Dark (or Secluded) Sectors

Axions, ALPs, Scalar-vector | Sterile ν's | Thermal, WIMPs

feV peV neV μeV meV eV keV MeV GeV TeV PeV

Dark Matter Mass

10^{-41} 10^{-35} 10^{-29} 10^{-23} 10^{-17} 10^{-11} 10^{-5} 10^{0} 10^{1} 10^{1} 10^{1}

Max Electron Recoil Energy [eV]

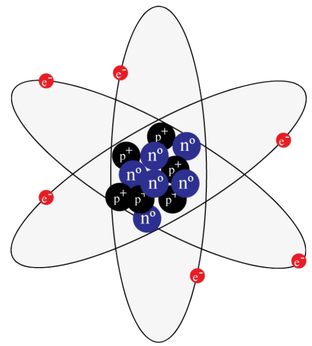
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

Mean Distance Between Particles [m]

10^{12} 10^{9} 10^{6} 10^{3} 10^{0} 10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18}

Dark Matter Particle Wavelength [m]

Electron Recoils | **Nuclear Recoils**



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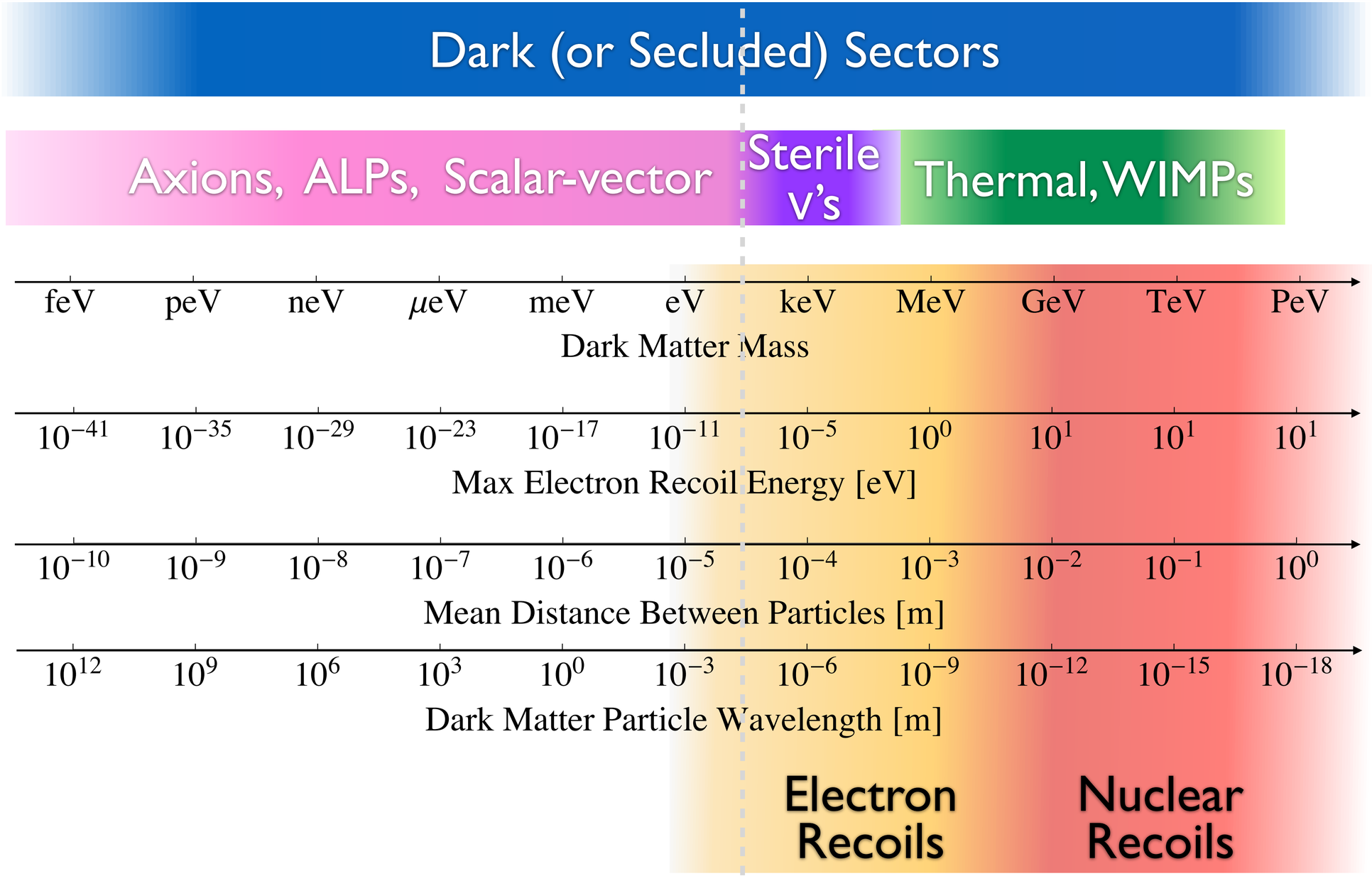

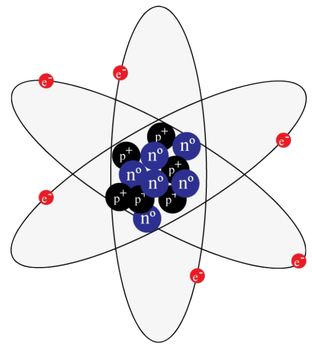

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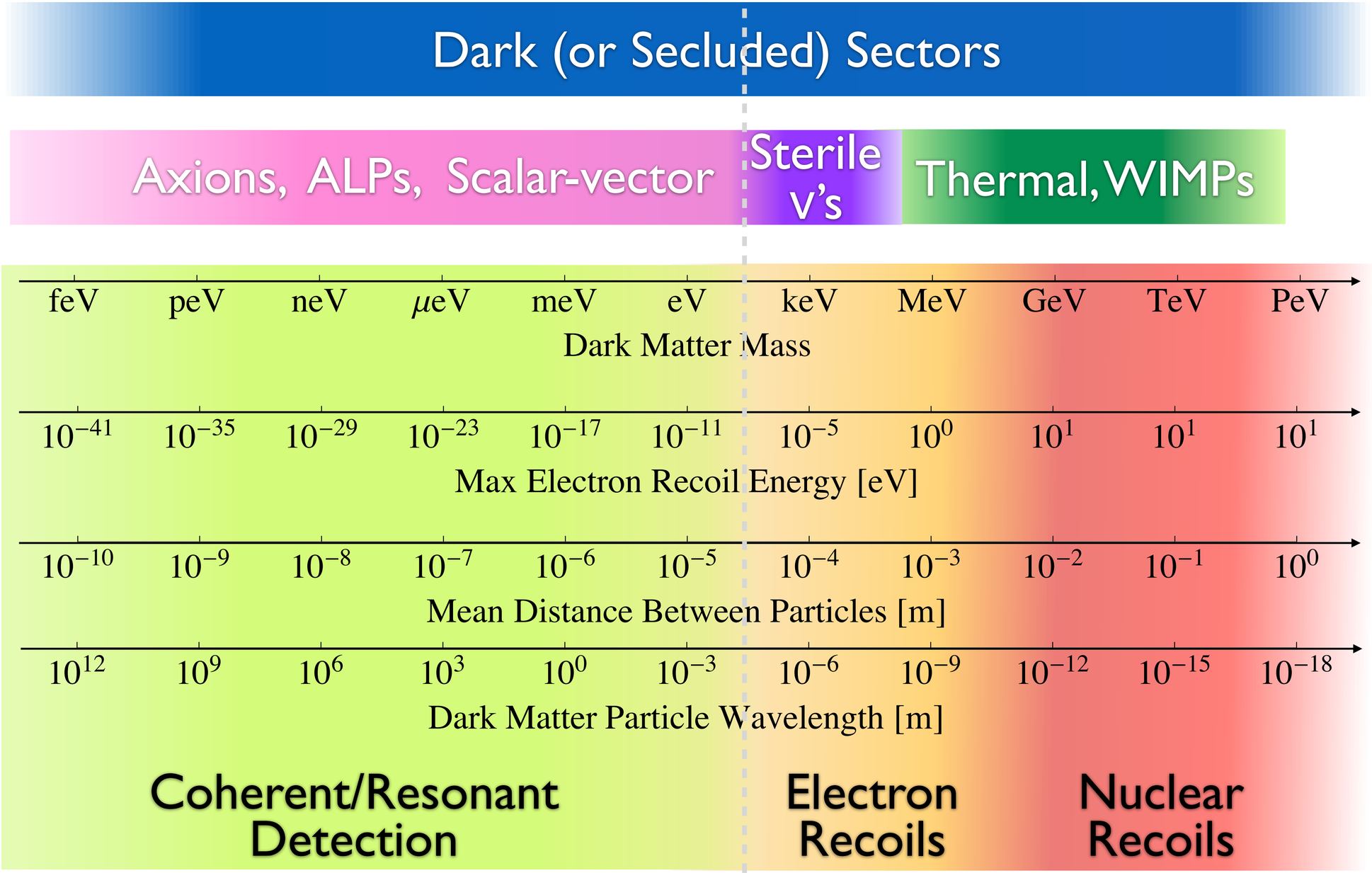

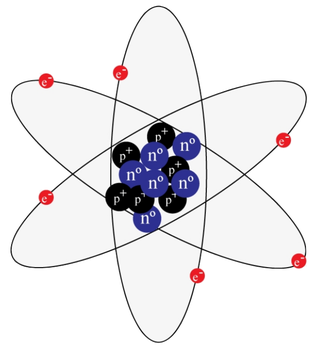

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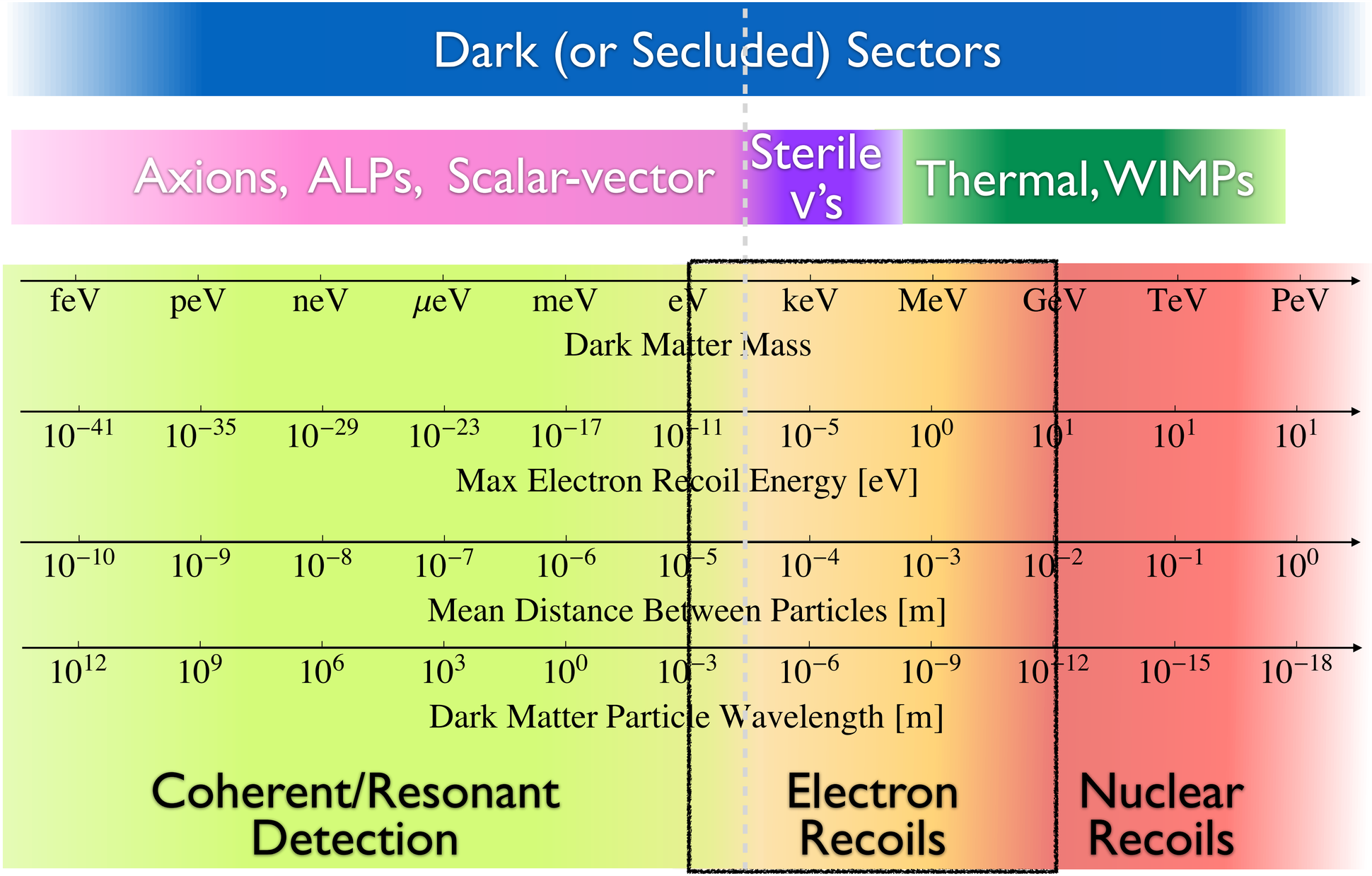

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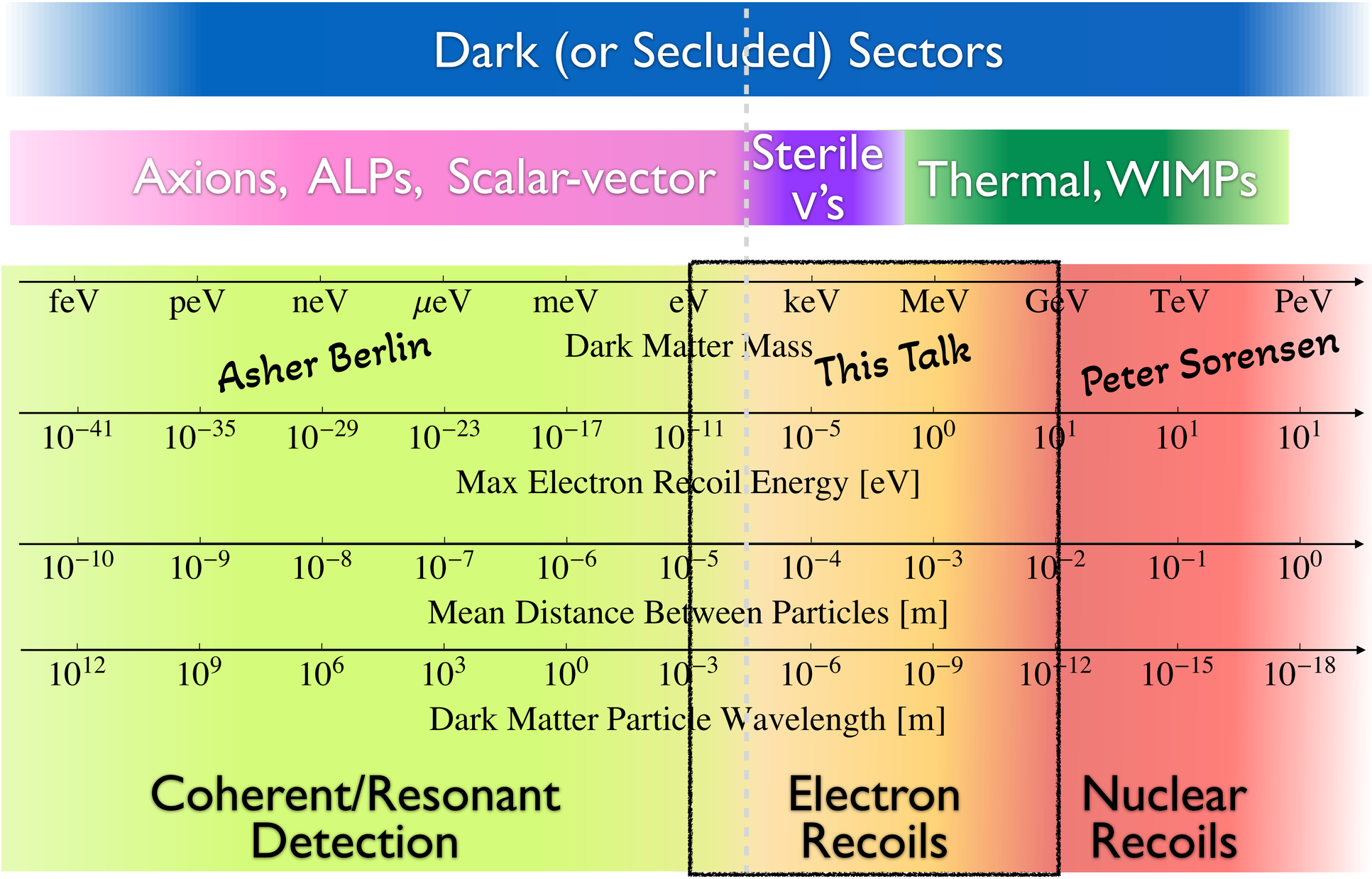
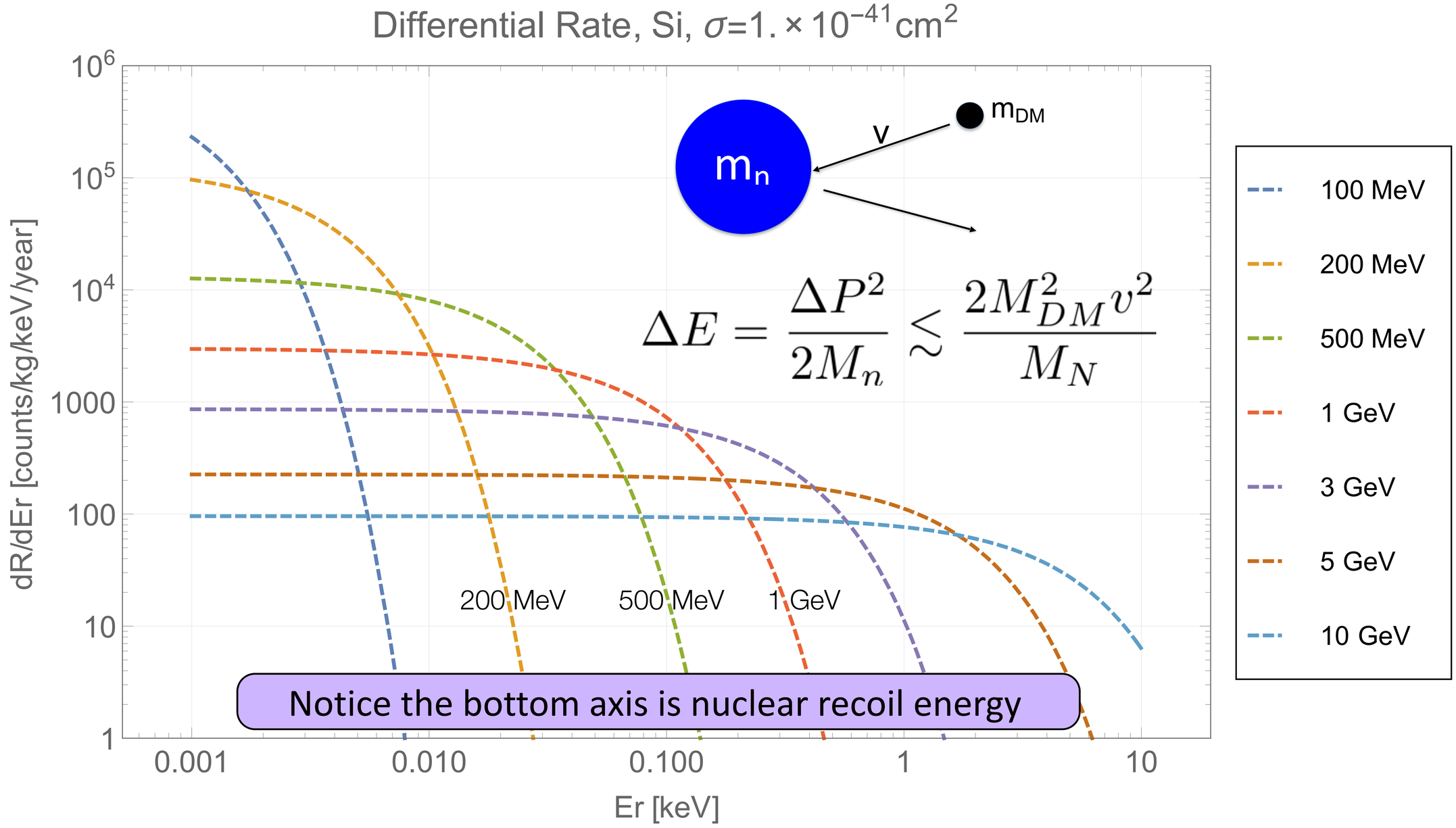
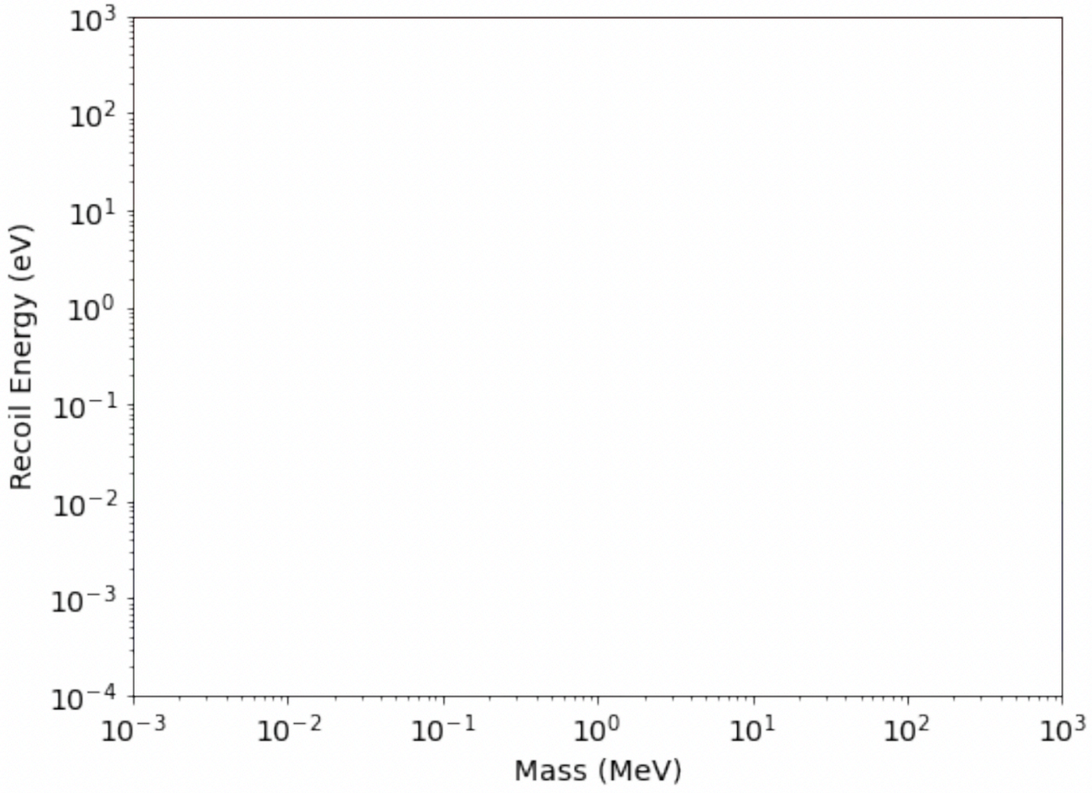


The low-mass DM Direct Detection Challenge



The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



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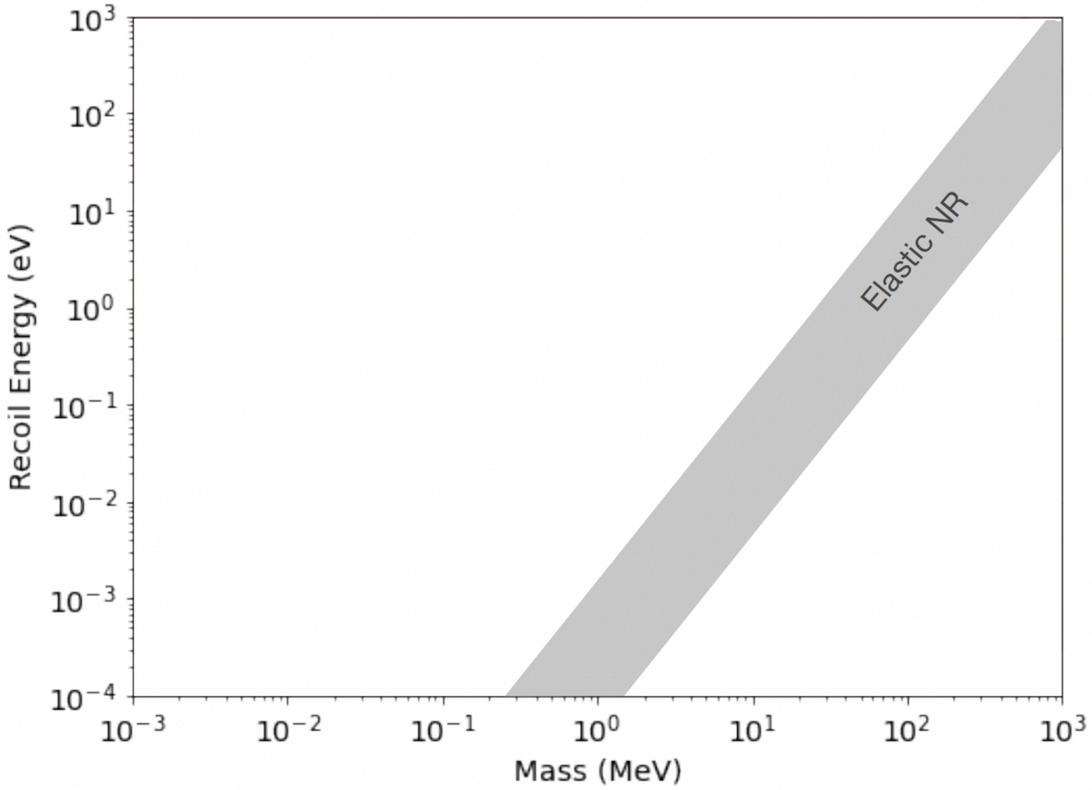
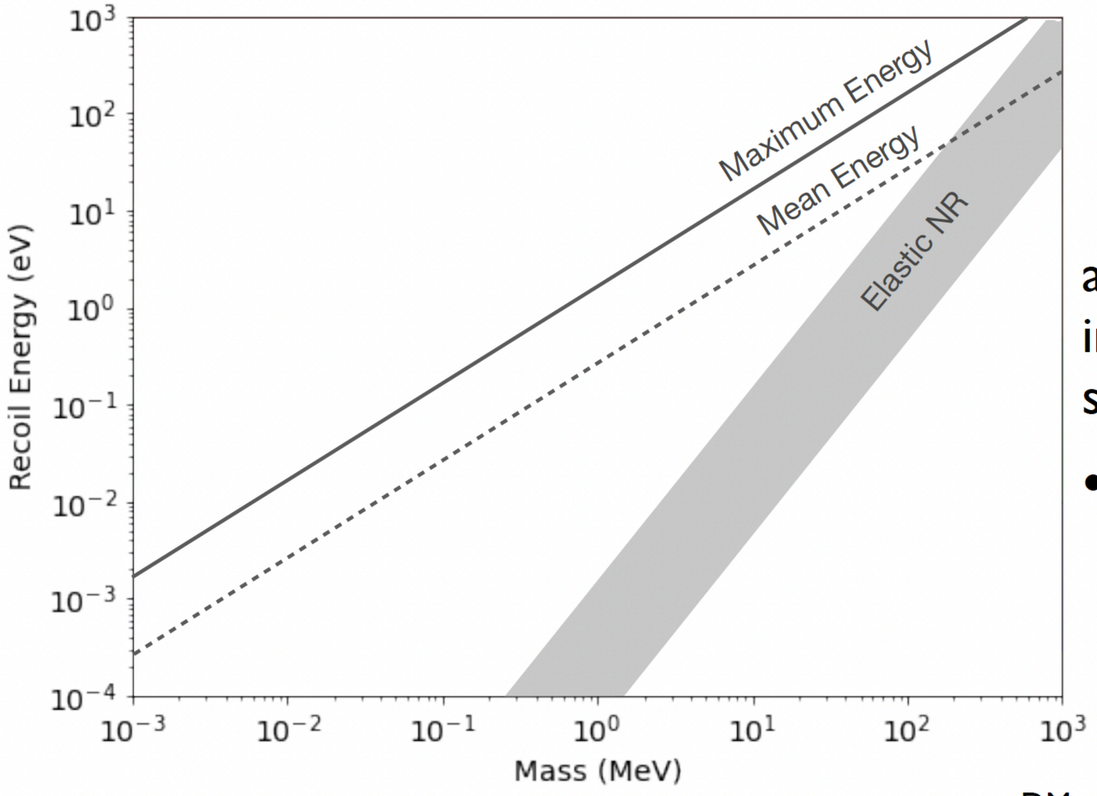


elastic DM-nucleus scattering:

$$E_{\rm NR} = \frac{q^2}{2m_N} \sim 1\ {\rm eV} \left(\frac{m_{\rm DM}}{100\ {\rm MeV}}\right)^2 \left(\frac{28\ {\rm GeV}}{m_N}\right)$$

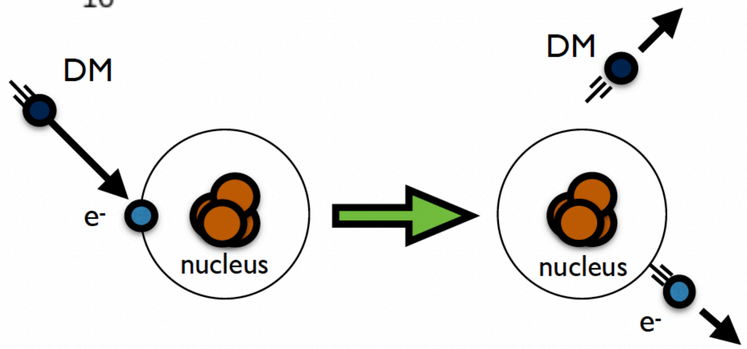
The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering



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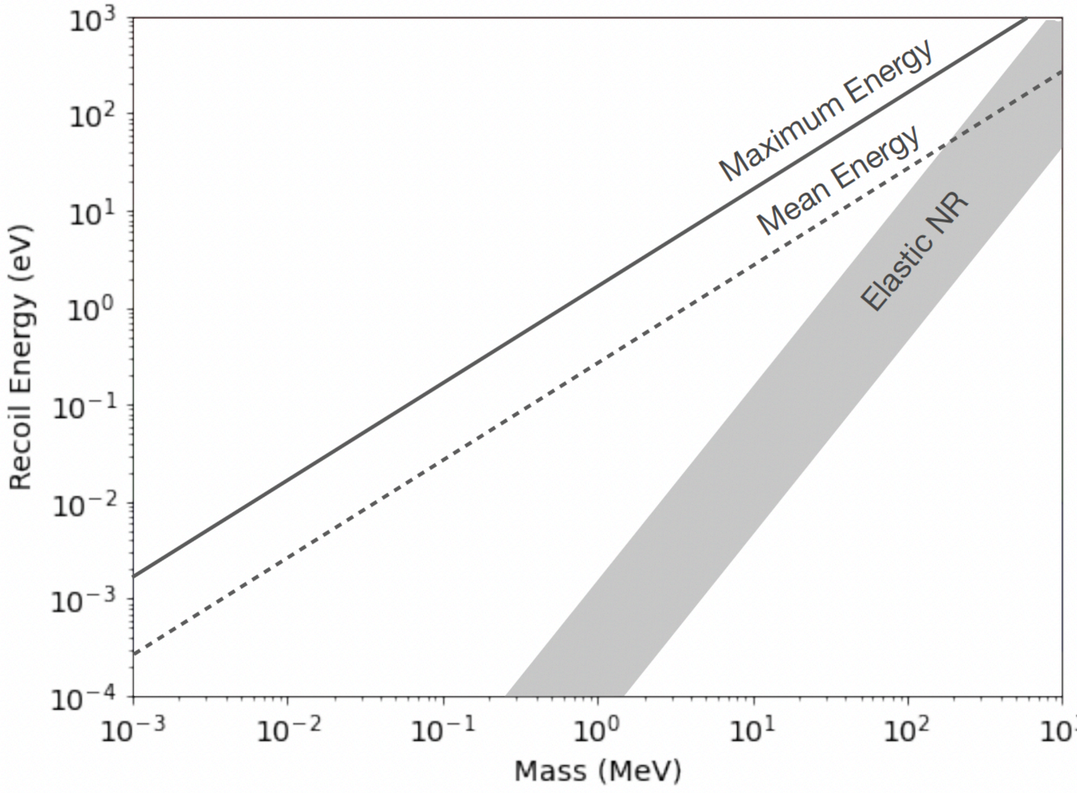
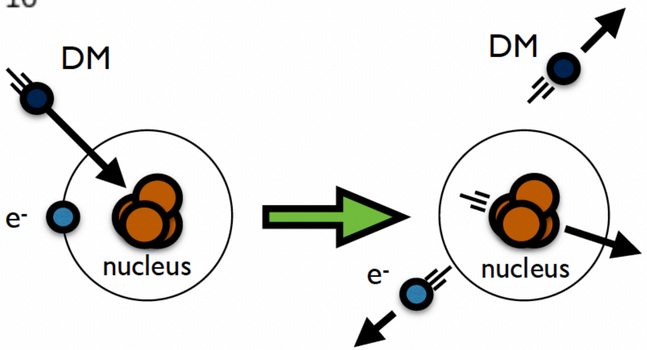


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal



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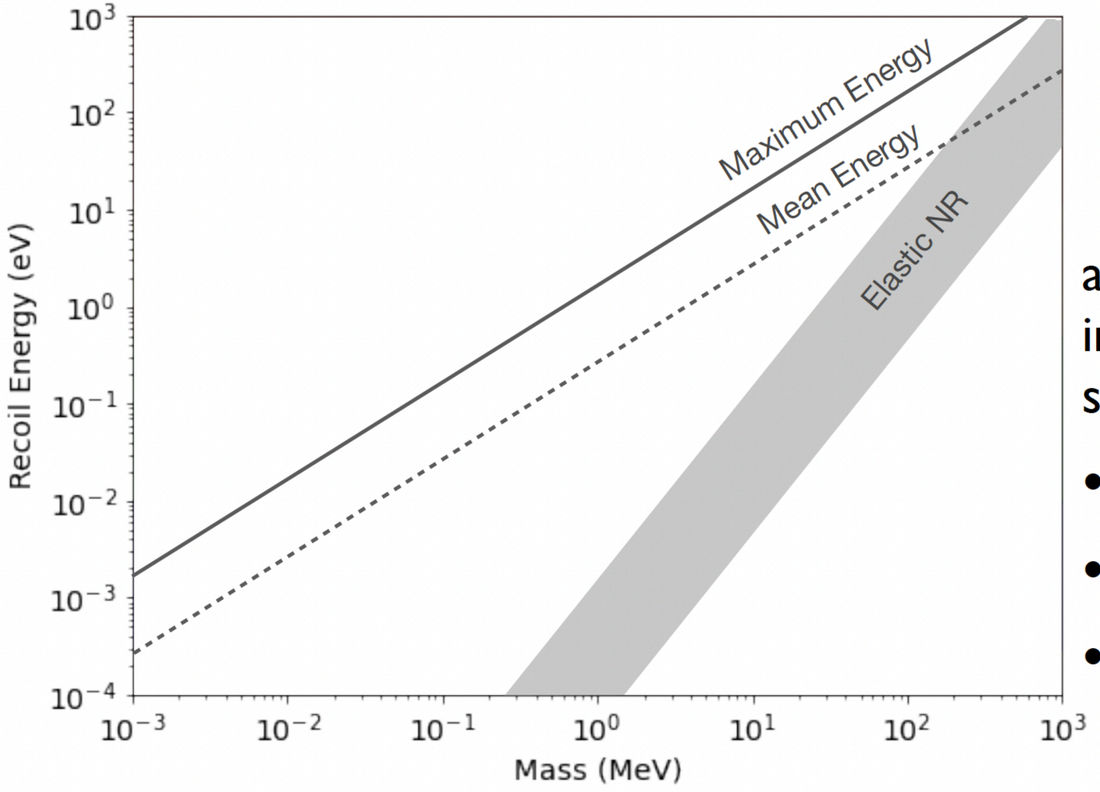
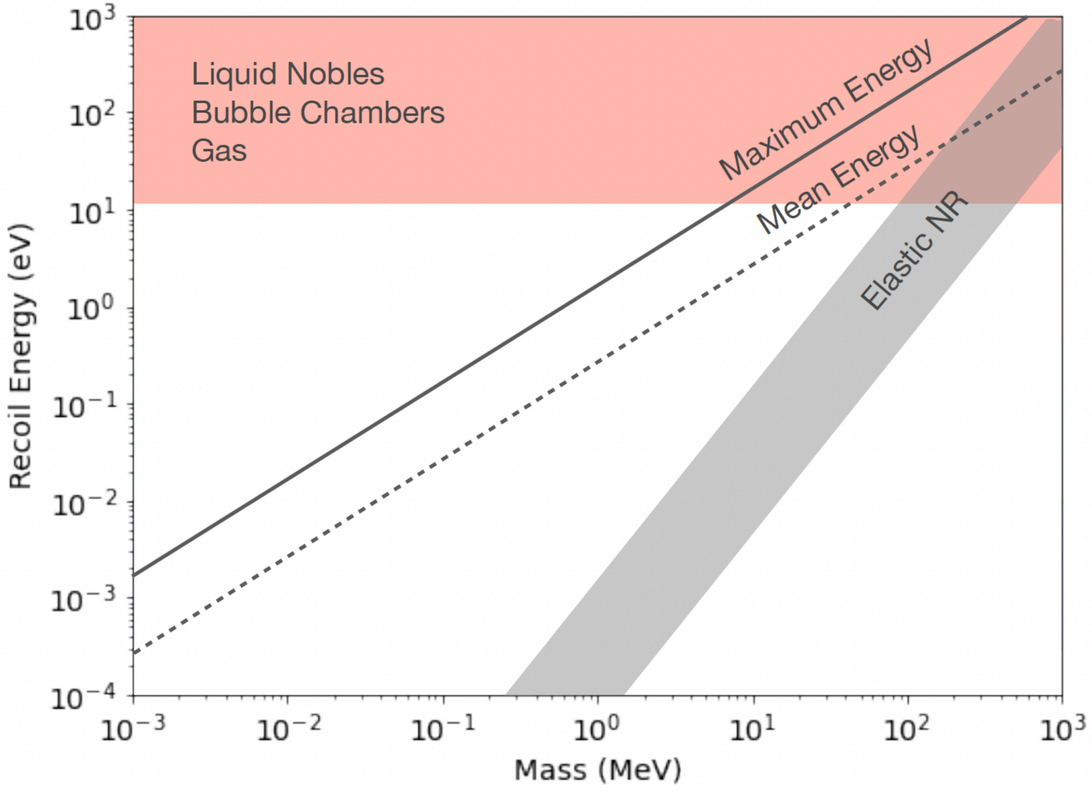


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal
- DM scattering w/ collective modes (e.g. phonons, magnons)

The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



$\Delta E \sim 10$ eV

e.g. Xe, Ar, He

The low-mass DM Direct Detection Challenge

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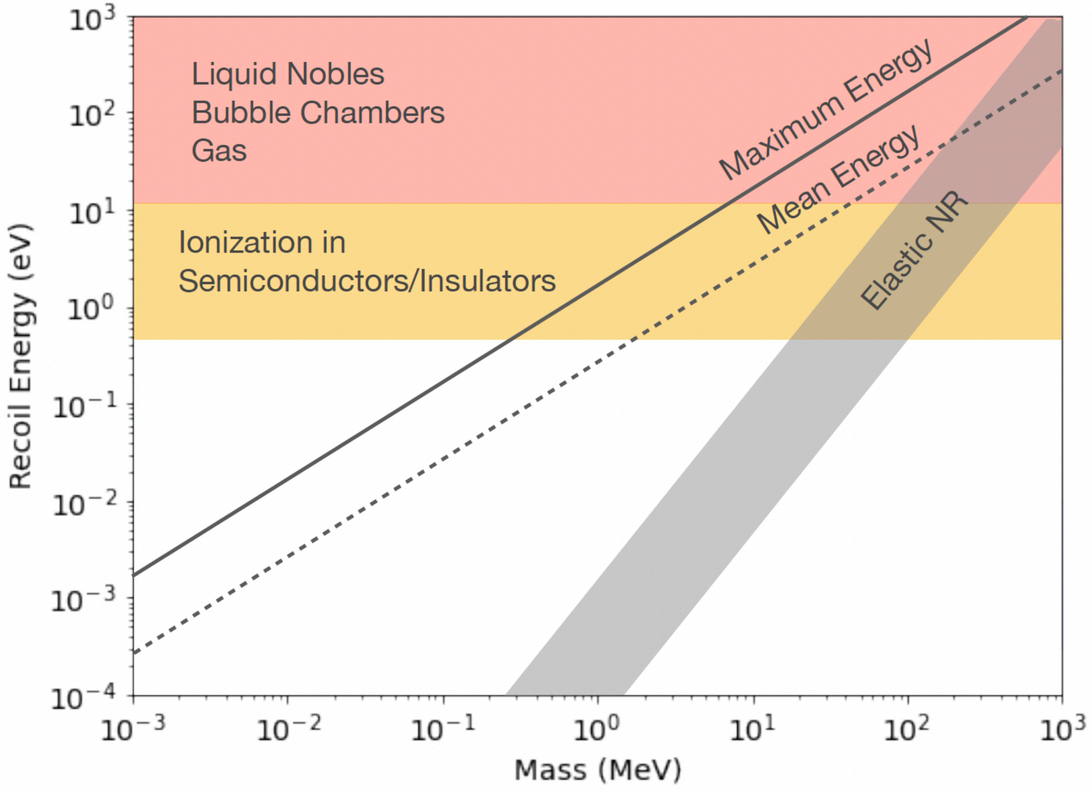
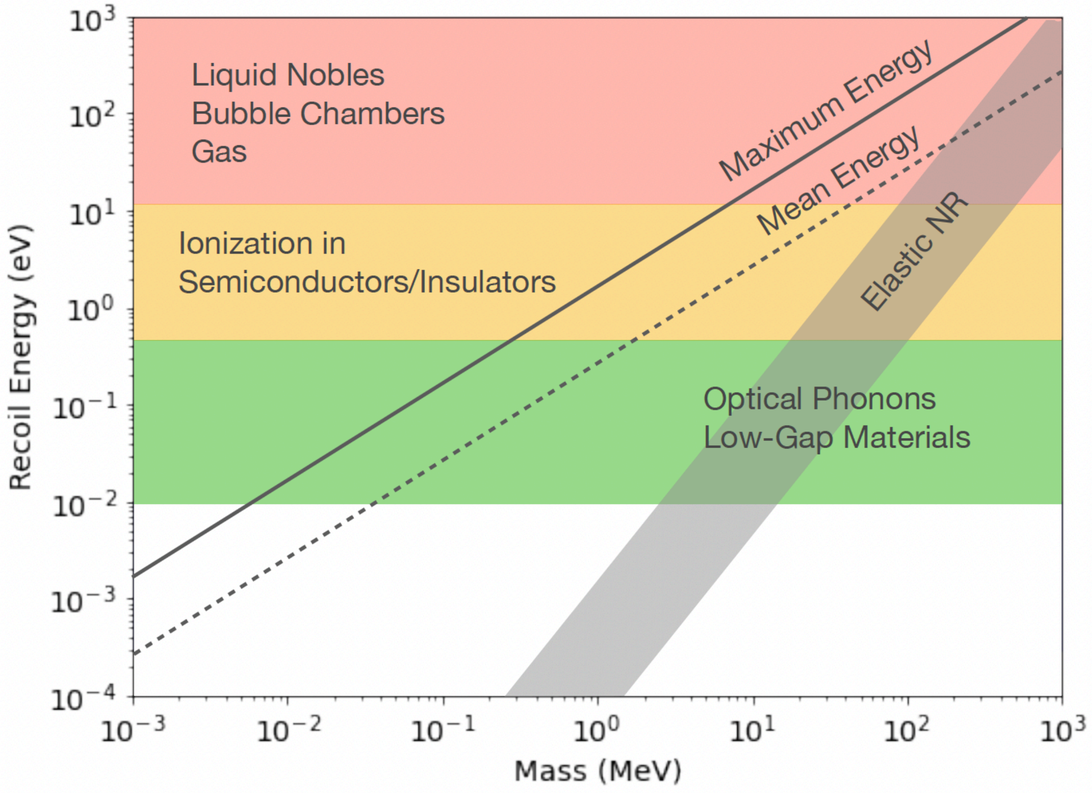


$\Delta E \sim 1$ eV

e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



$\Delta E \sim 10 - 100$ meV

e.g. GaAs, sapphire, Dirac materials, doped s/c, …

The low-mass DM Direct Detection Challenge

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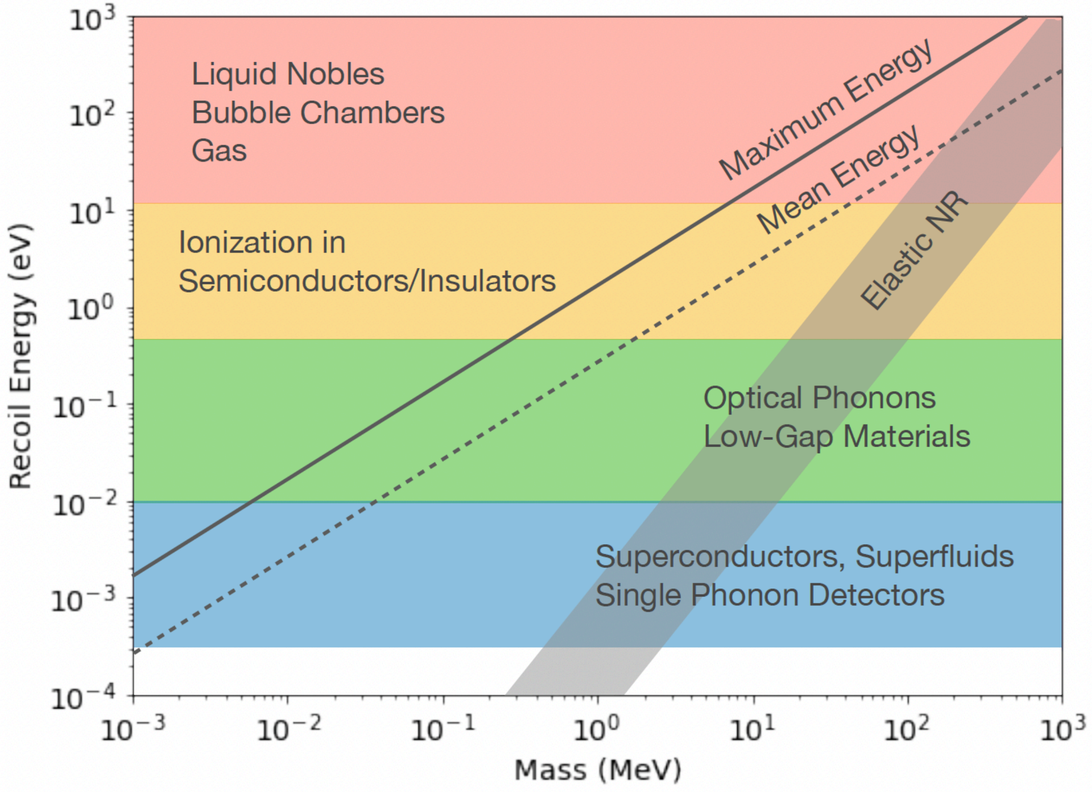

$\Delta E \sim 1$ meV

e.g. superfluids,
superconductors

The low-mass DM Direct Detection Challenge

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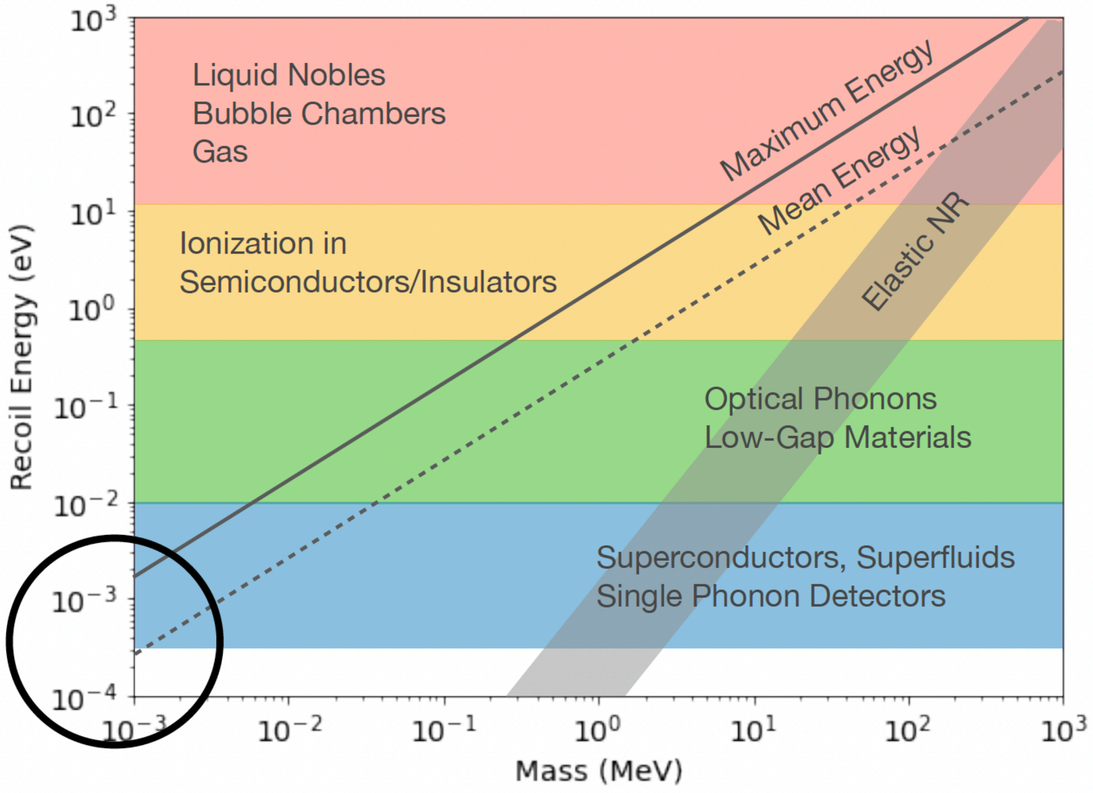
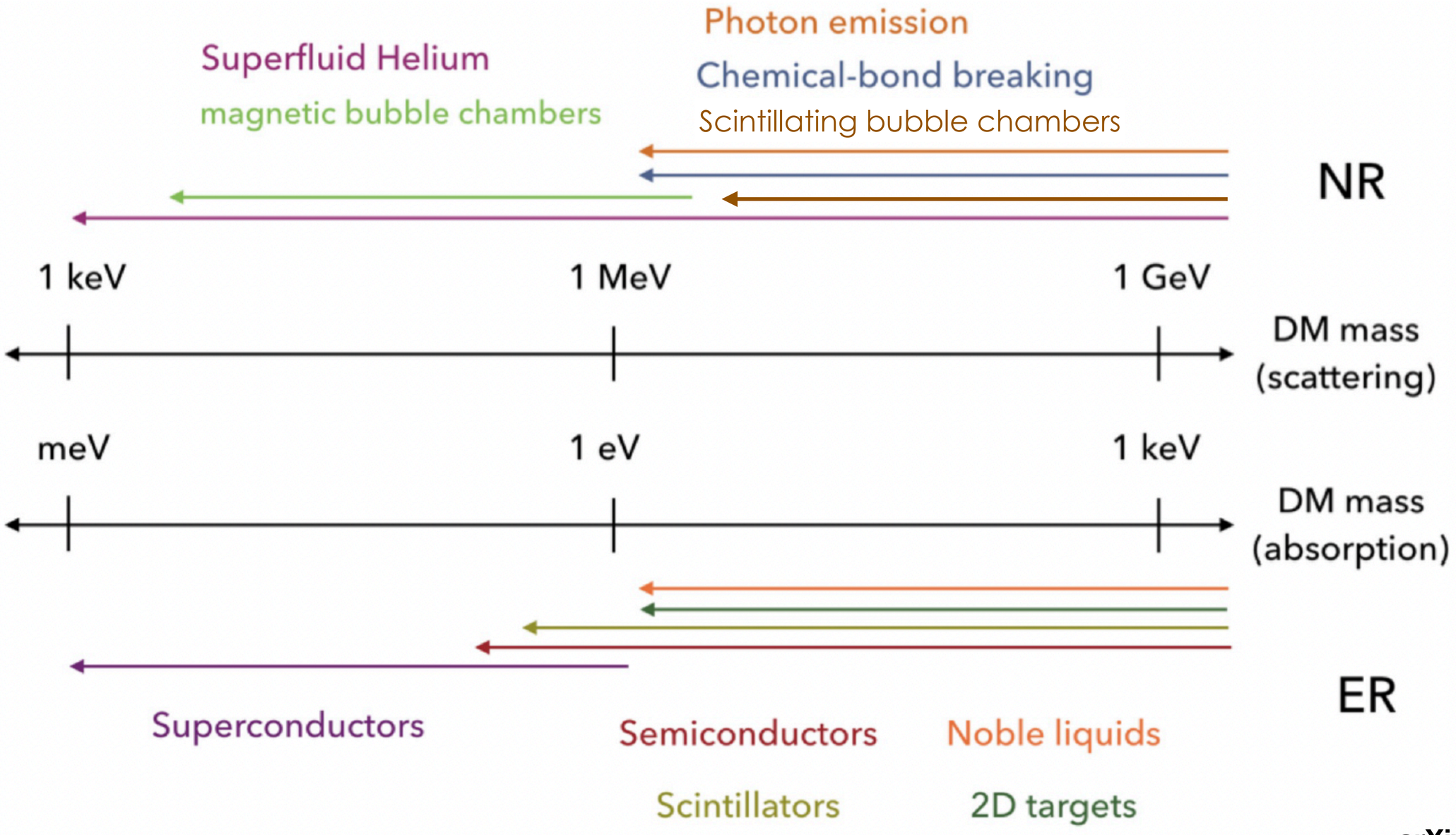


ultimate reach: keV masses w/ single phonon excitations
or electron recoils from low-gap materials

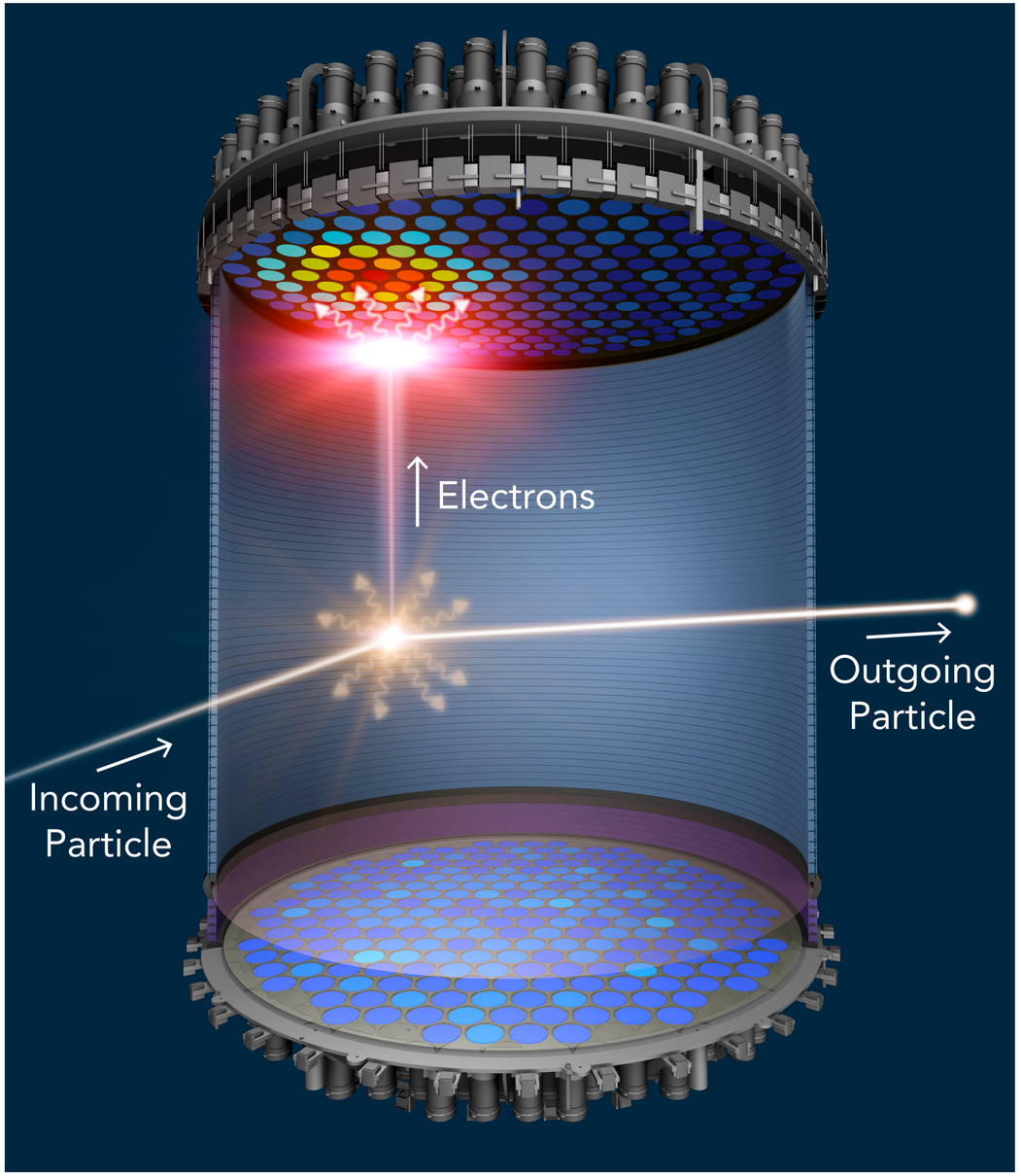
Many new technologies under development!



arXiv:1707.0459

Noble Liquid Time Projection Chambers

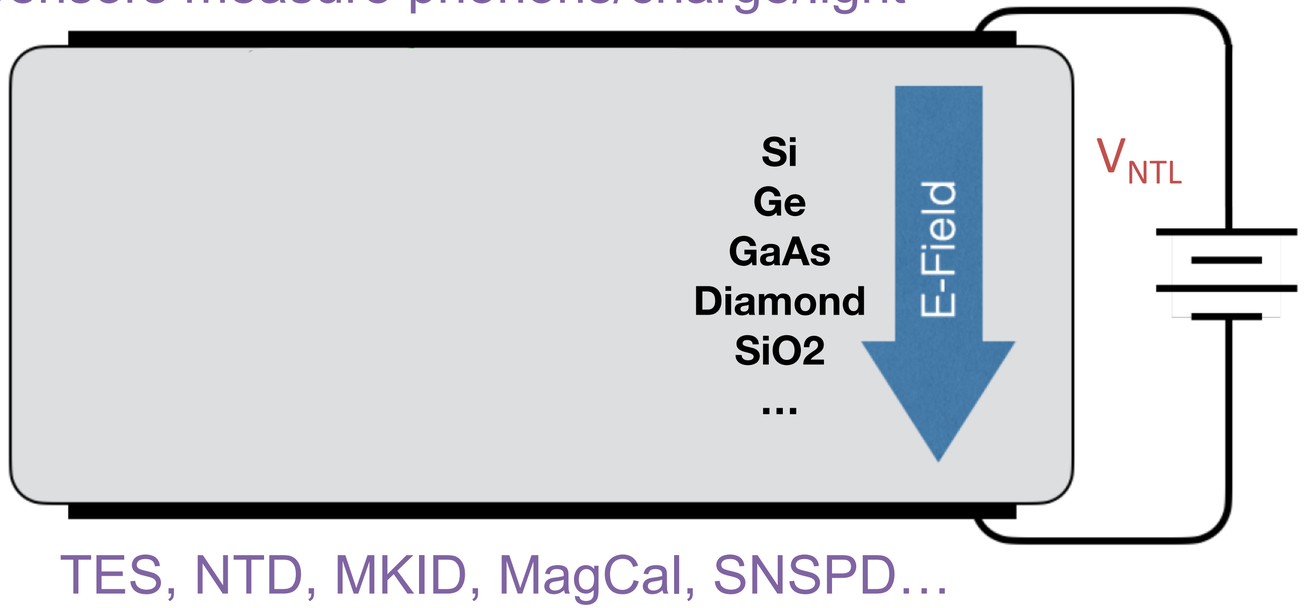
- S1: initial light from scintillation of liquid
- S2: Signal from drifted electrons creating a second avalanche of scintillation when crossing from the liquid to gas phase.
- Can also get some particle ID from pulse shape
- XENON10/100/1T/nT, LZ, DarkSide, PandaX, …



Cryogenic Crystal Detectors

SuperCDMS, EDELWIESS, CRESST, etc.

Sensors measure phonons/charge/light

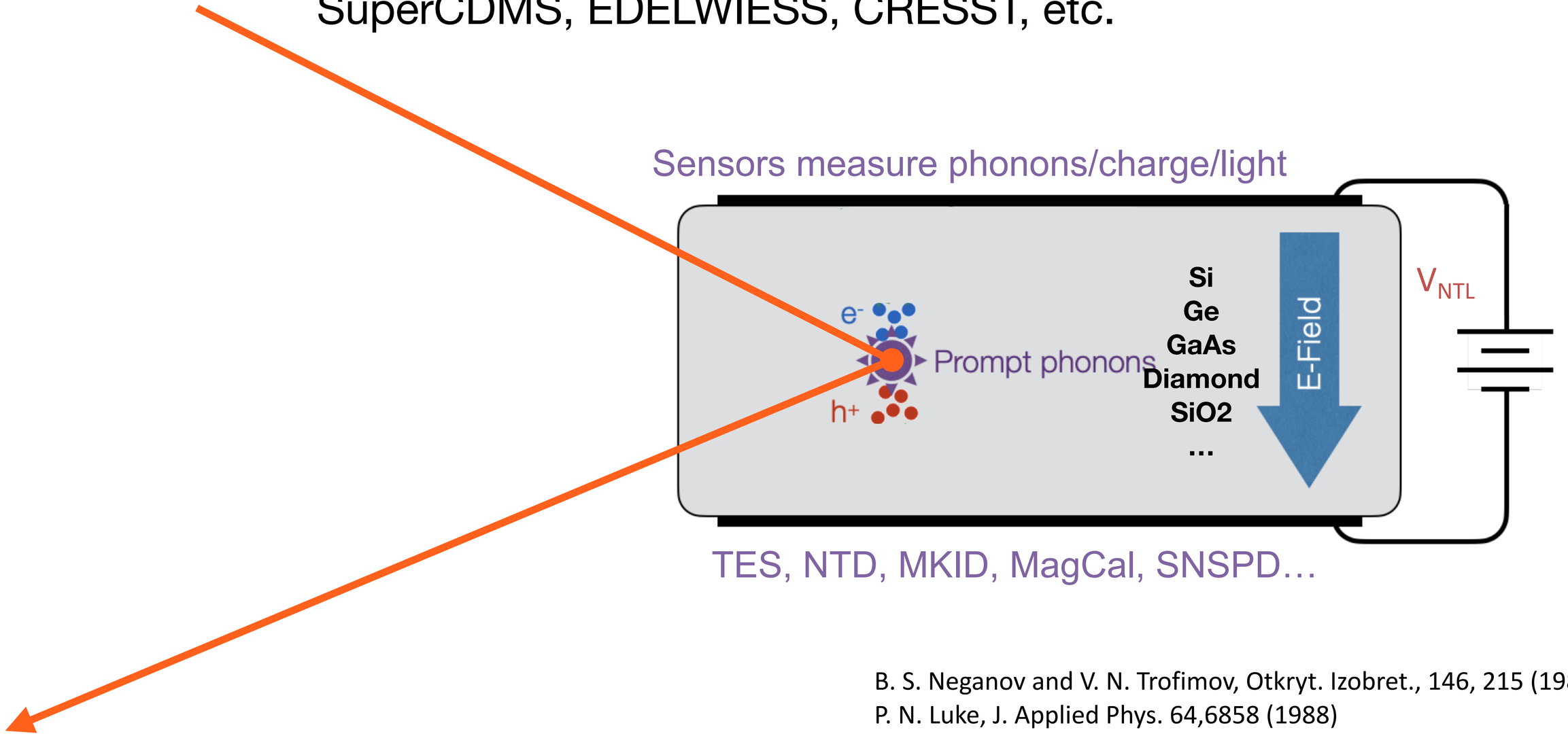


TES, NTD, MKID, MagCal, SNSPD…

B. S. Neganov and V. N. Trofimov, Otkryt. Izobret., 146, 215 (1985)
P. N. Luke, J. Applied Phys. 64,6858 (1988)

Cryogenic Crystal Detectors

SuperCDMS, EDELWIESS, CRESST, etc.



B. S. Neganov and V. N. Trofimov, Otkryt. Izobret., 146, 215 (1985)
P. N. Luke, J. Applied Phys. 64,6858 (1988)

Cryogenic Crystal Detectors

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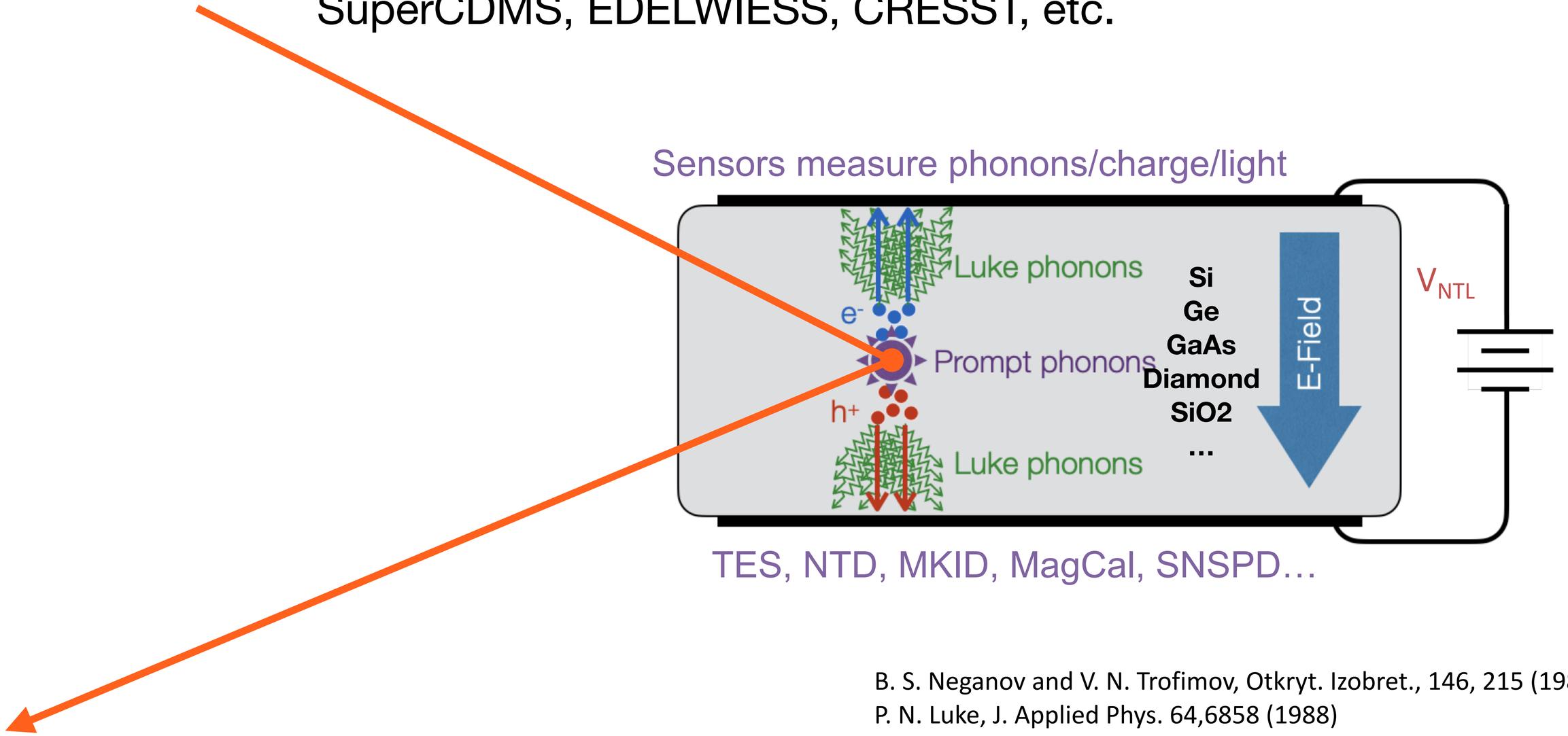

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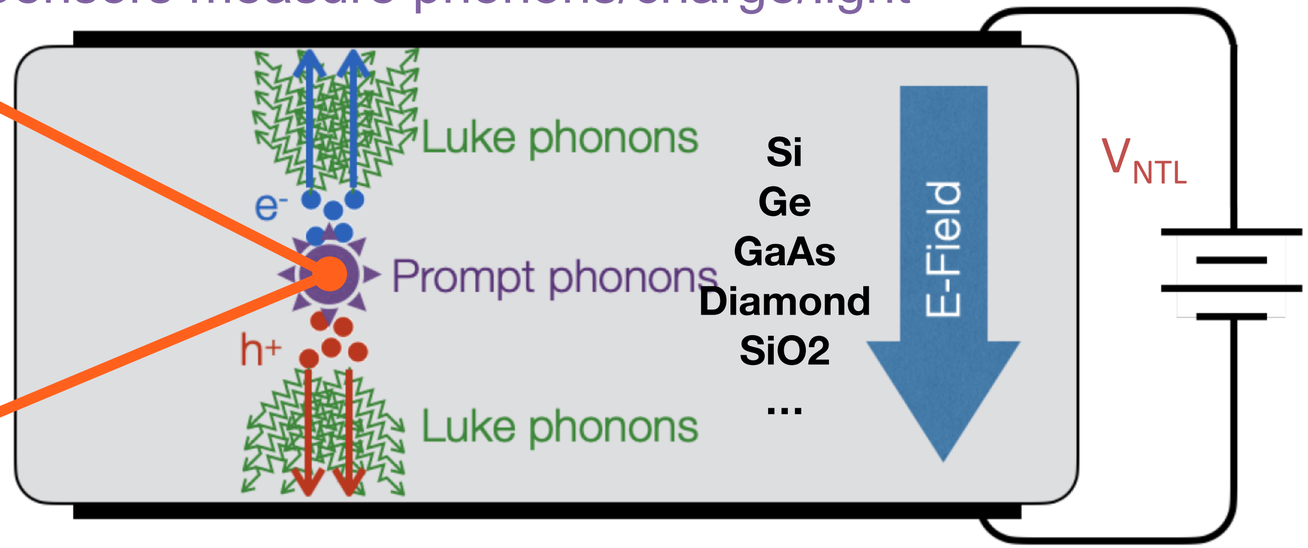
Cryogenic Crystal Detectors

SuperCDMS, EDELWIESS, CRESST, etc.

Turn off – nuclear recoil
Turn on – charge detector

Sensors measure phonons/charge/light



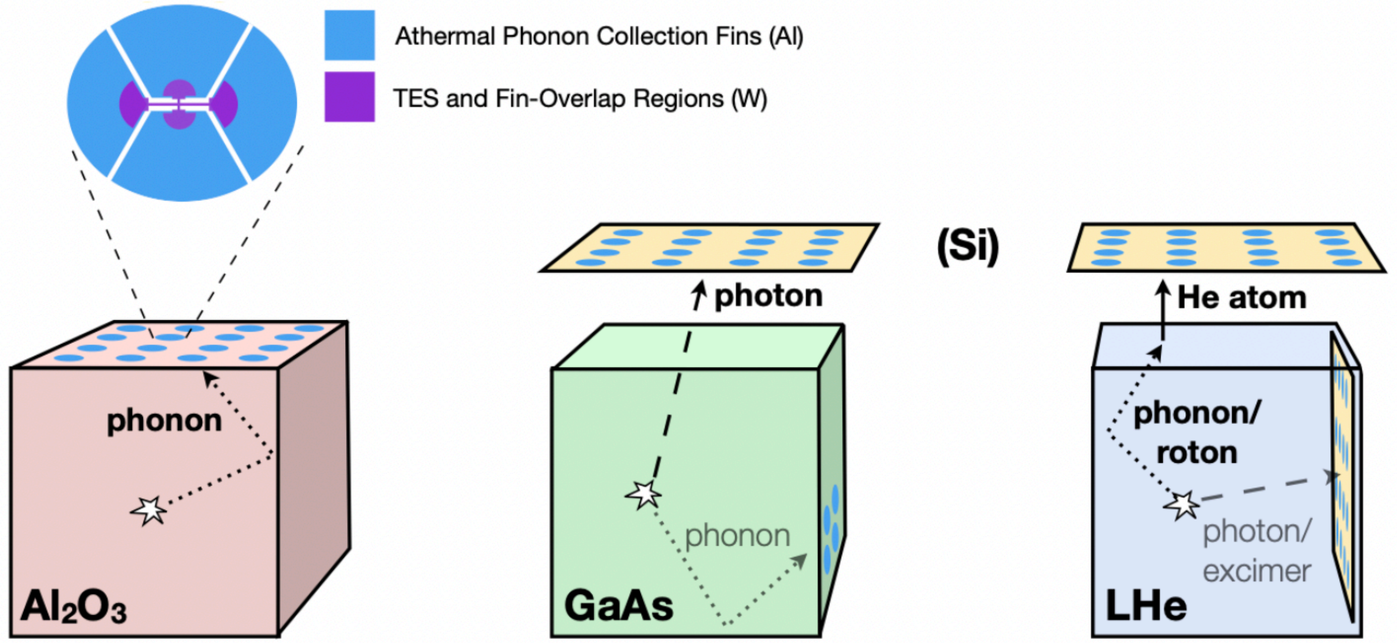
TES, NTD, MKID, MagCal, SNSPD…

B. S. Neganov and V. N. Trofimov, Otkryt. Izobret., 146, 215 (1985)
P. N. Luke, J. Applied Phys. 64,6858 (1988)

TESSERACT

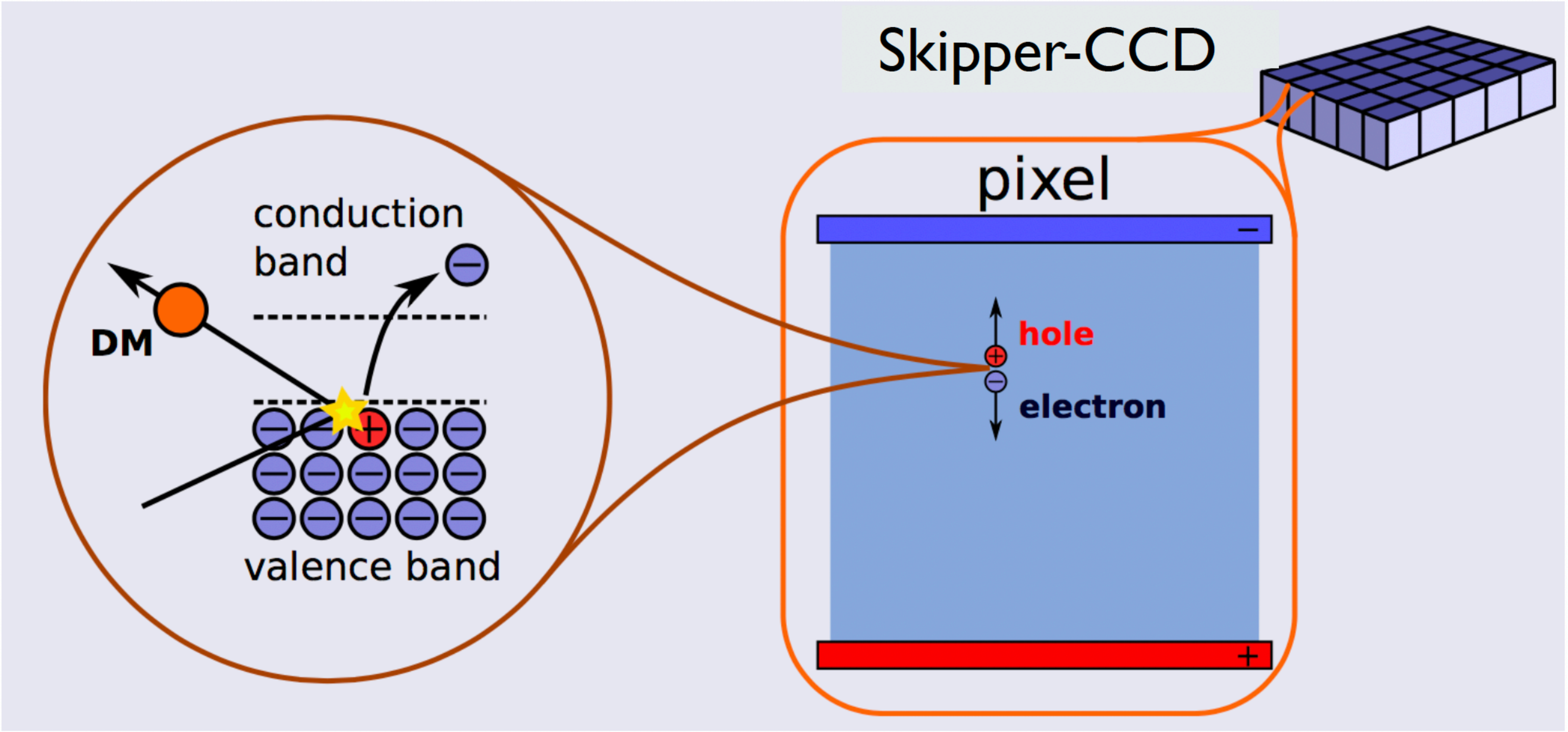
Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

Goal: use multiple target materials + advances in TES sensor technology



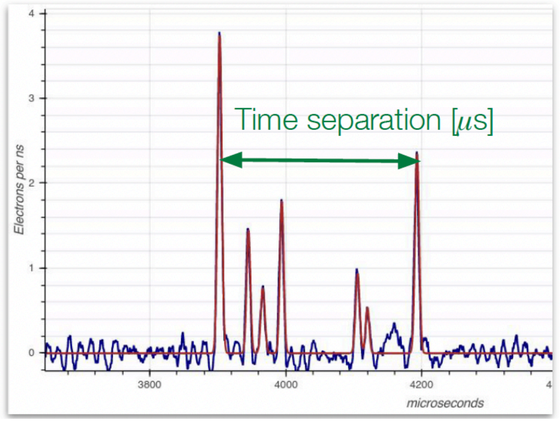
Liquid helium experiment (HeRALD)
GaAs and Sapphire-based experiments (SPICE)

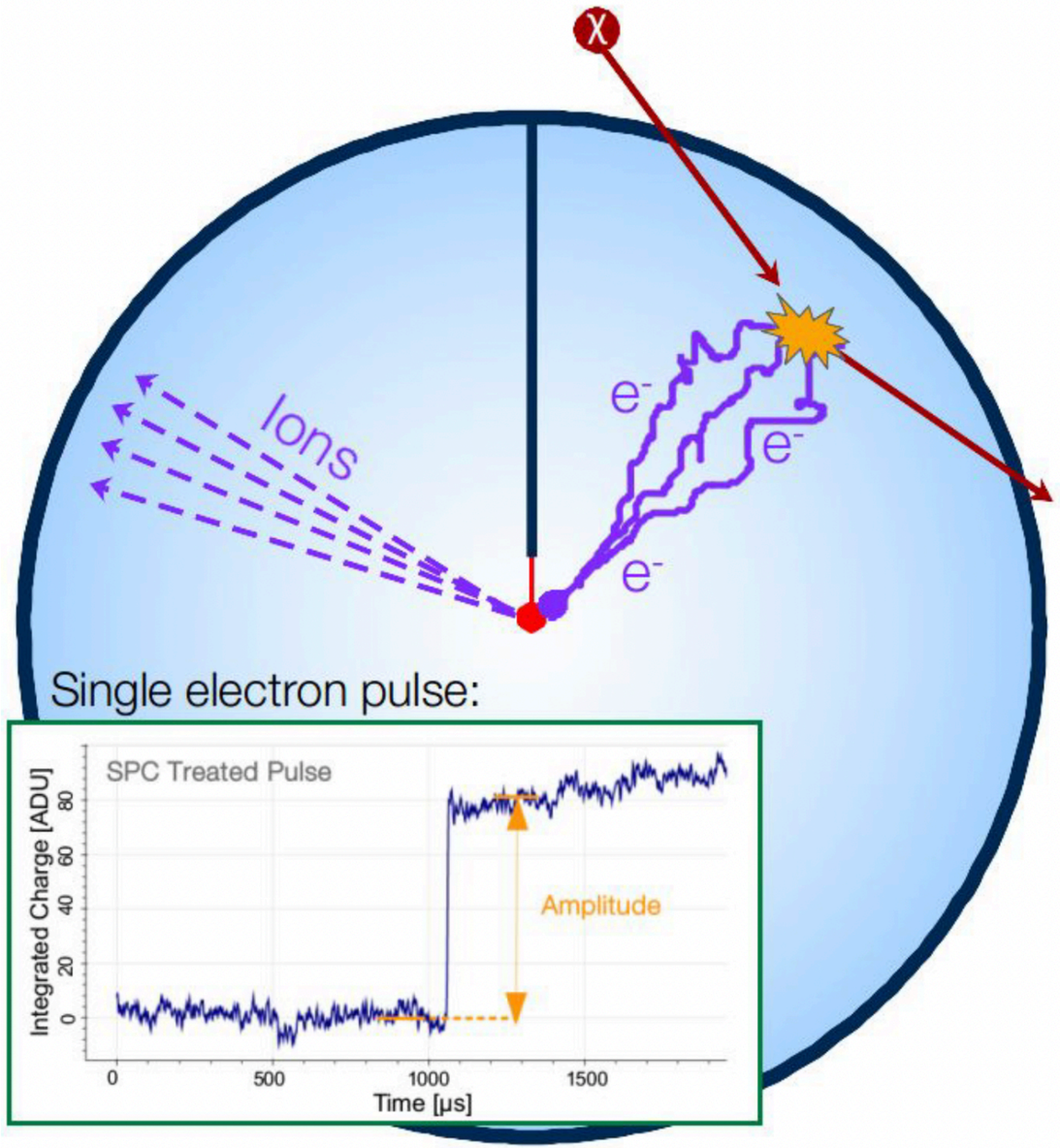
SENSEI, DAMIC-M, OSCURA



NEWS-G

Single e⁻ ionization threshold!





(1) Primary Ionization

$$\langle \#PE \rangle = \frac{E}{W(E)}$$

$$W_{\rm nr} = W_\gamma / Q(E)$$ Neon: W_γ ~ 36 eV/pair, Q ~ 0.2

(2) Drift of charges

Radially-dependent diffusion allows for fiducialization

(3) Avalanche of secondary e⁻/ion pairs

Amplification of signal through Townsend avalanche (tunable with V)

(4) Signal formation

Current induced by the secondary ions drifting away from anode

(5) Signal readout

Current integrated and digitized

Scintillating Bubble Chambers

Liquid Noble Bubble Chambers

Objective:

Quasi-background-free detection of sub-keV Nuclear Recoils

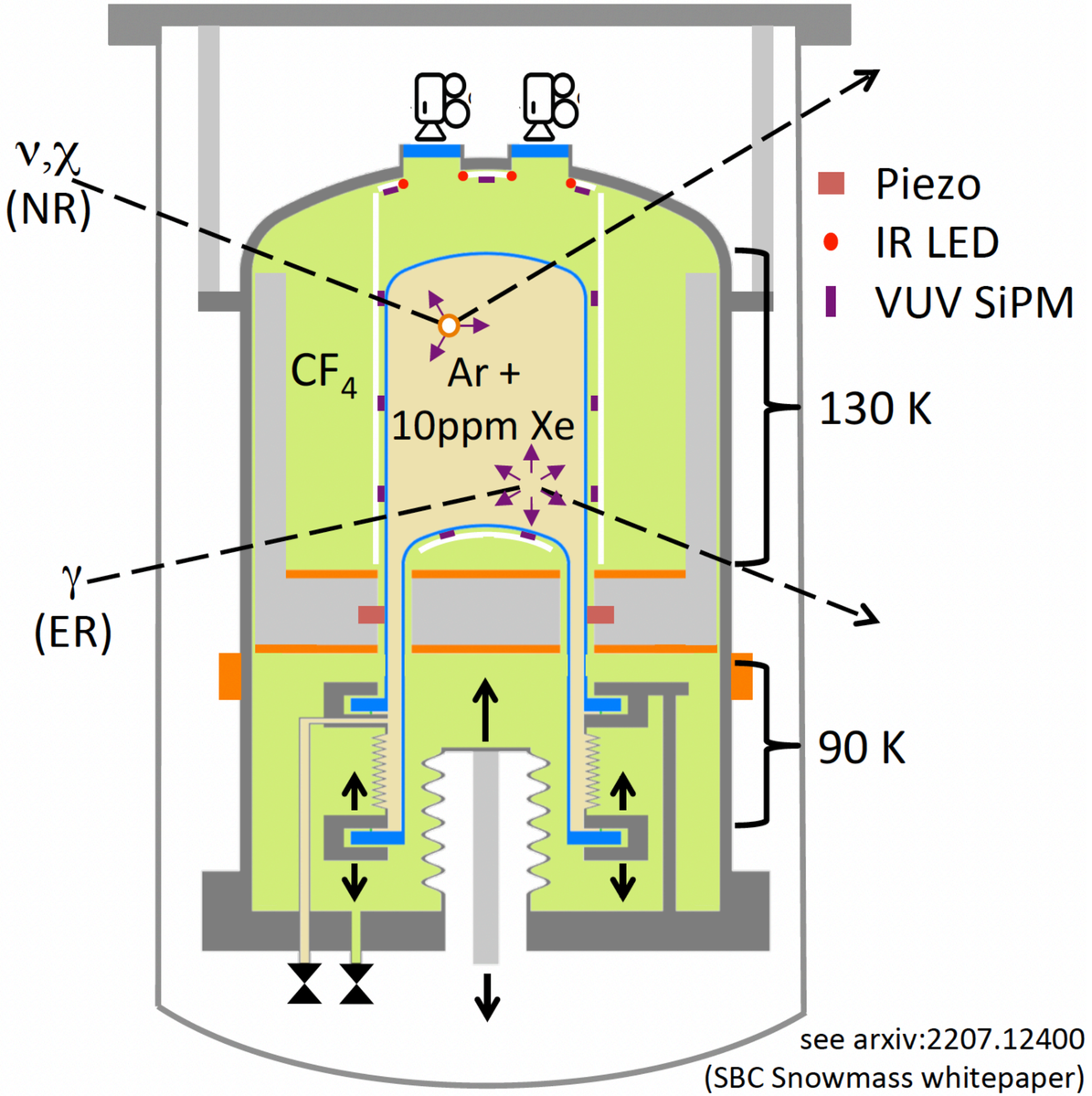
Signal:

Single bubble with little or no coincident scintillation

Backgrounds:

ER's (beta, gamma):
No bubbles

NR's (fast neutron):
Multiple bubbles
Strong coincident scintillation



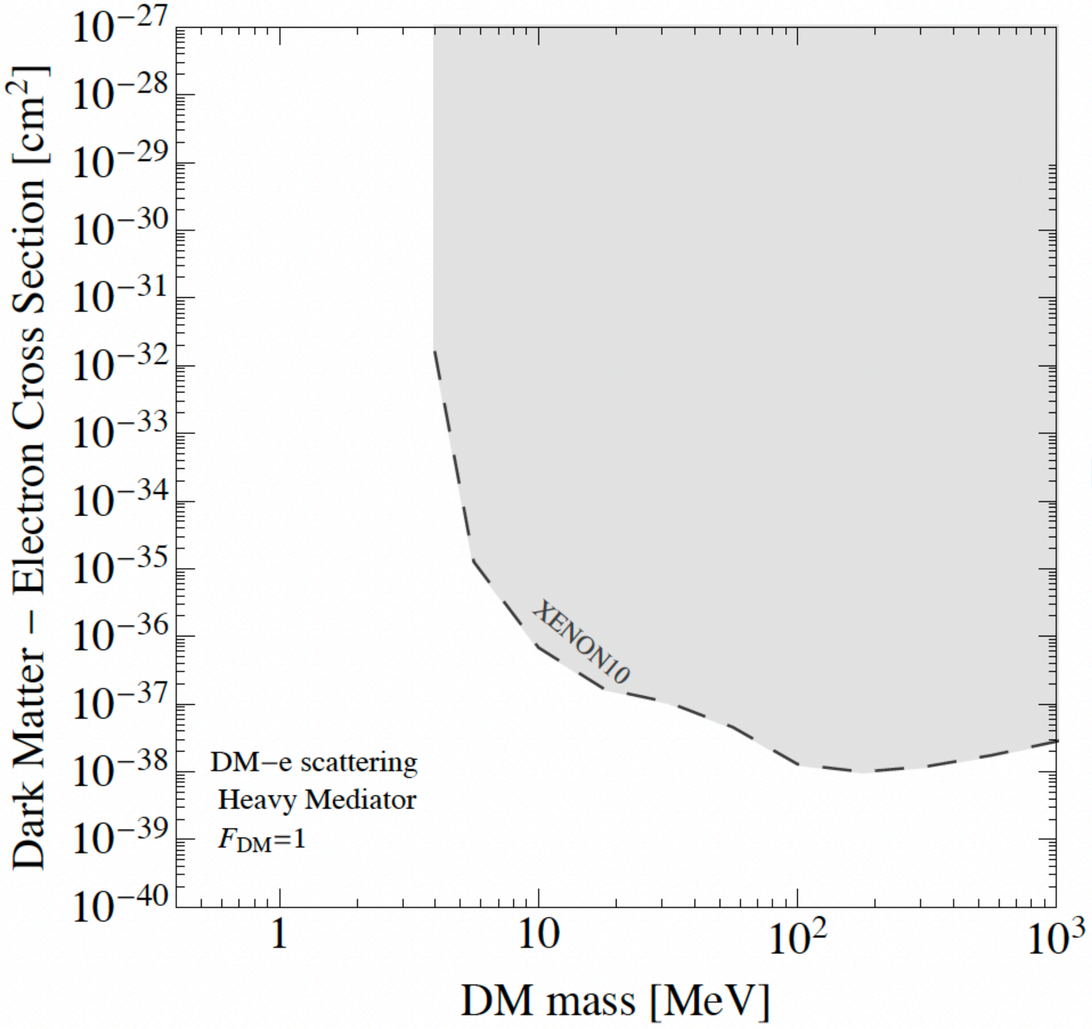
see arxiv:2207.12400
(SBC Snowmass whitepaper)

Many other technologies

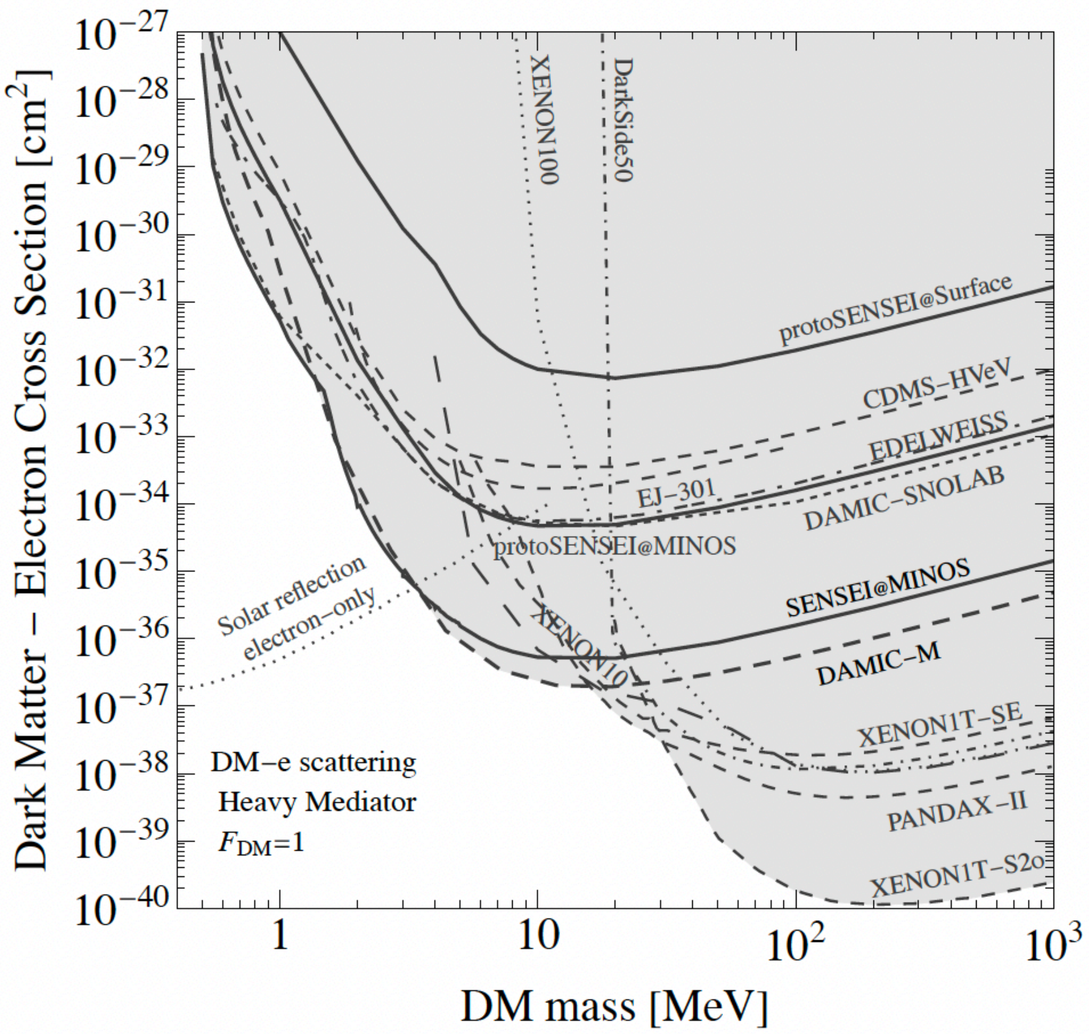
- SNSPDs
- Qubits
- MKIDs
- Quantum Charge Parity Detectors
- Narrow-gap Semiconductors (SPLENDOR)
- Supercooled water (Snowball chamber)
- Hydrogen-doped Liquid Xenon

Huge Progress of the last 11 years…

2012



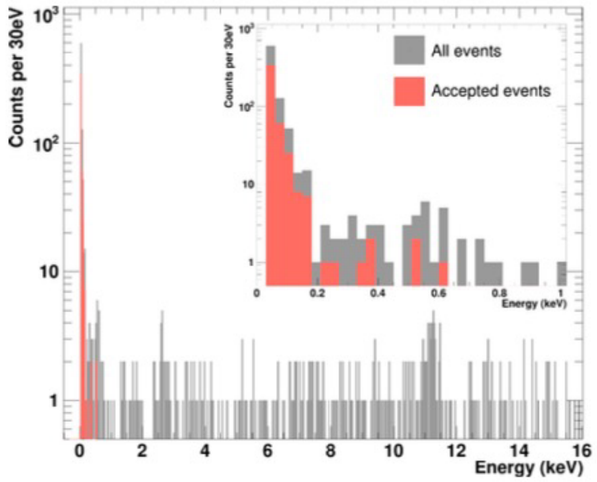
2023



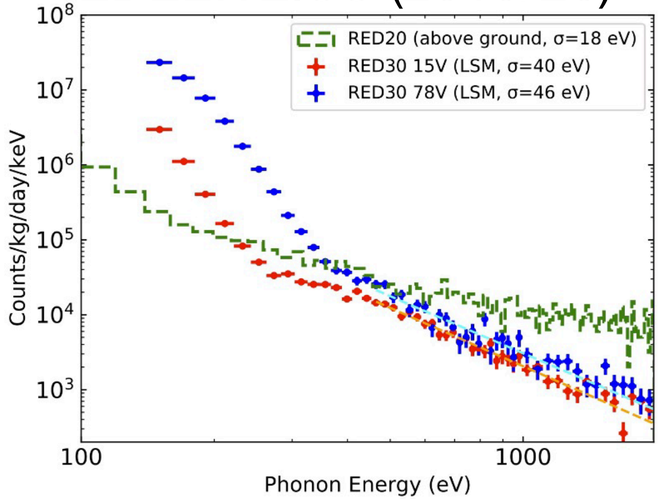
Challenges: Low-energy excess and other backgrounds

https://scipost.org/SciPostPhysProc.9.001

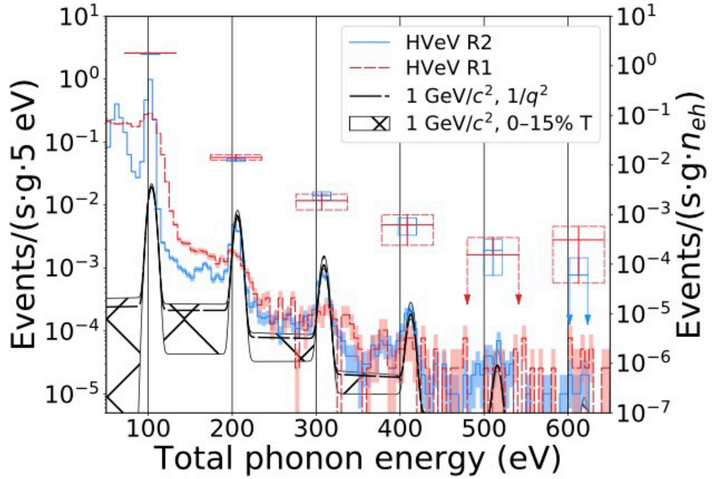
CRESST-III (2019)



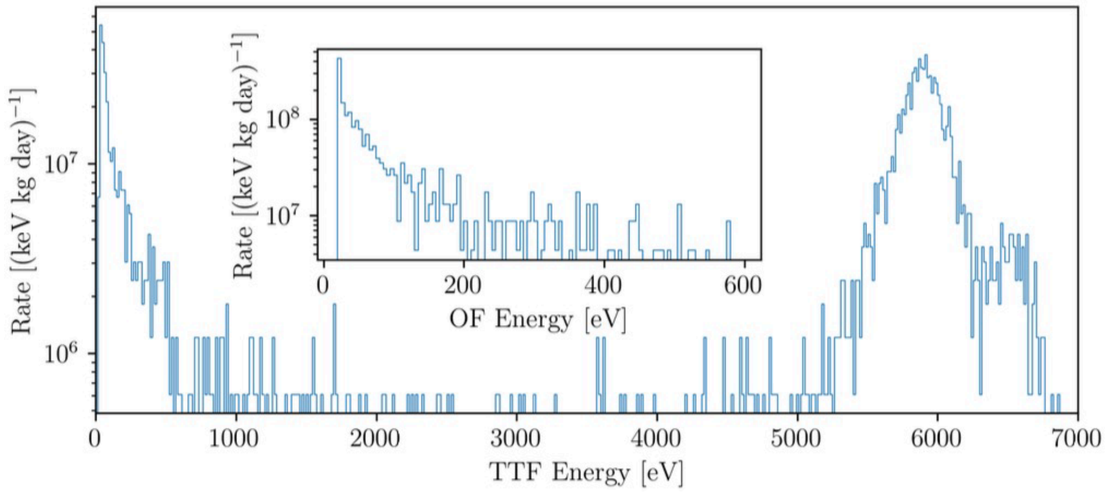
EDELWEISS (2019/20)



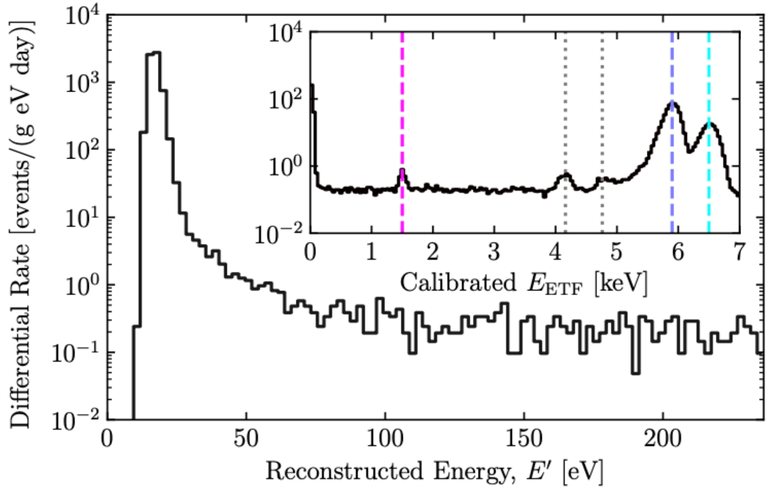
SuperCDMS HVeV (2021)



NUCLEUS (2017)



SuperCDMS CPD (2021)



Challenges: Calibrating low-energy processes

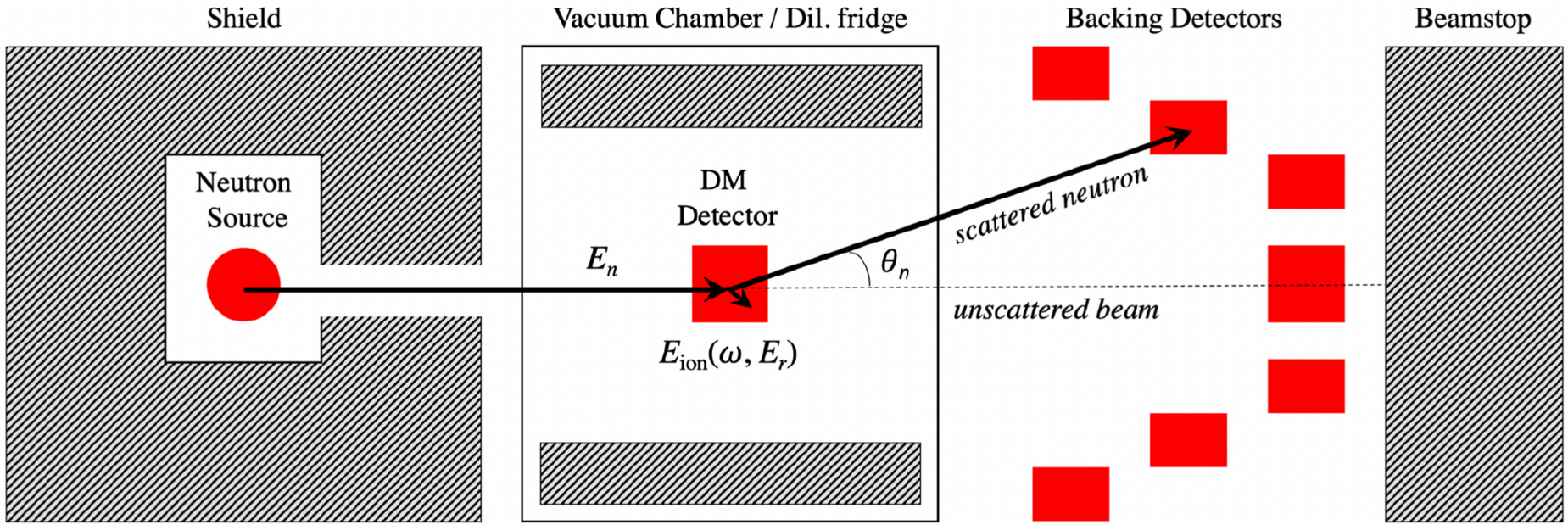
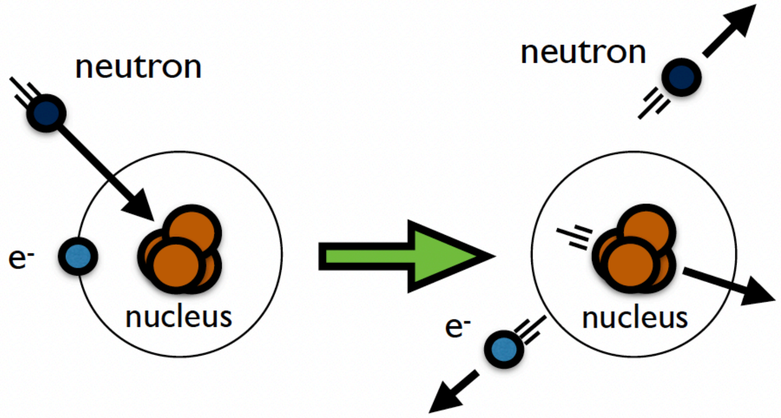
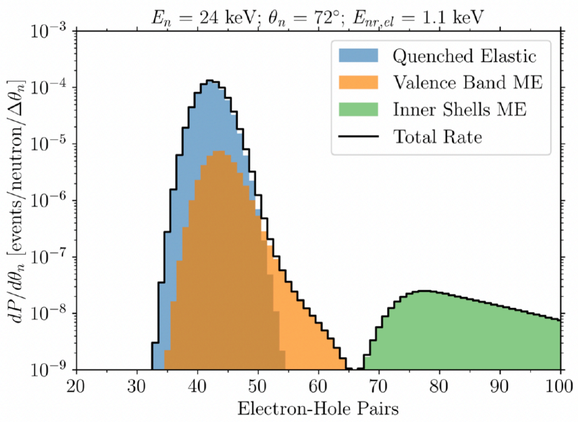


Fig from: Adams, Baxter, Day RE, Kahn, 2210.04917

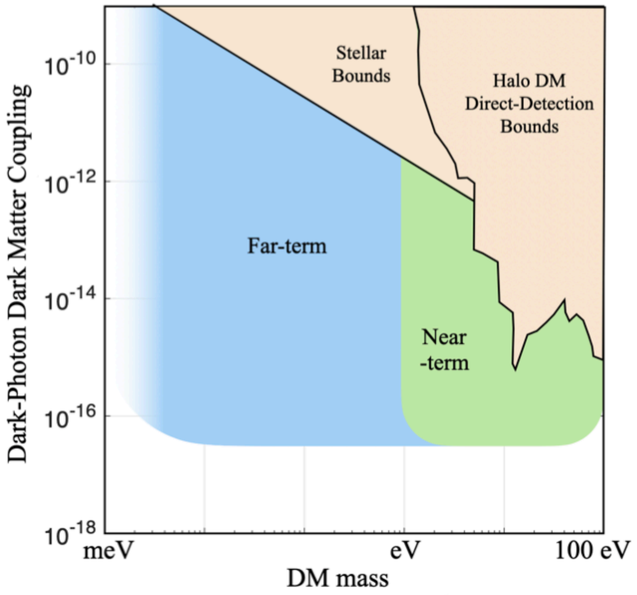
Migdal, Cherenkov, radiative recombination, transition radiation, molecular excitations, collective phonon modes, mignons, etc…

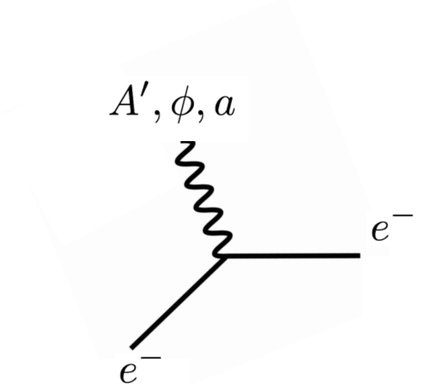




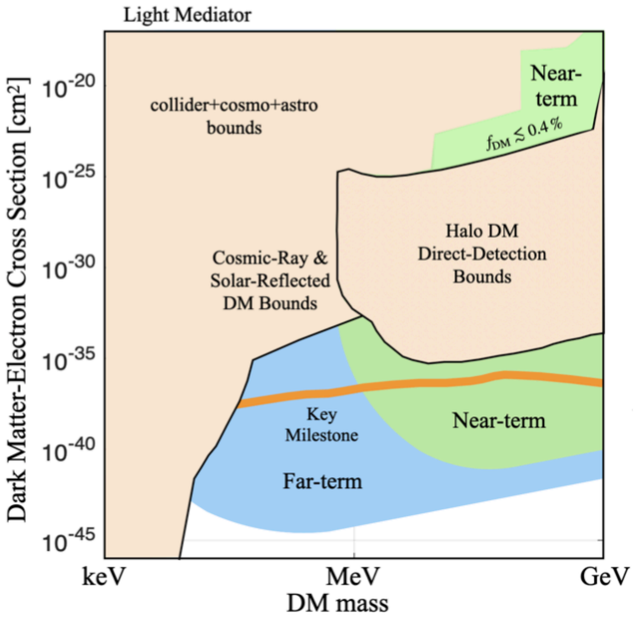
Lots more parameter space left to explore!

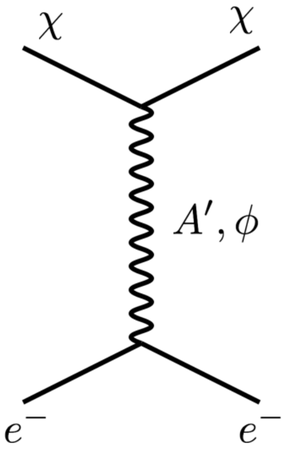
Absorption

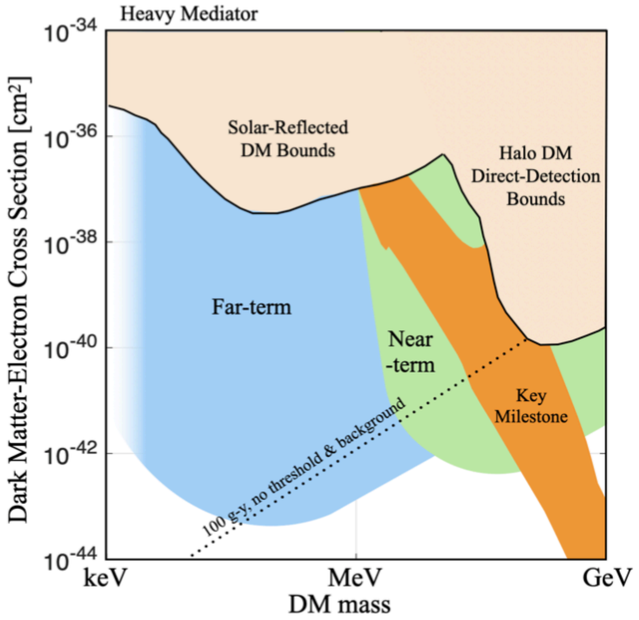


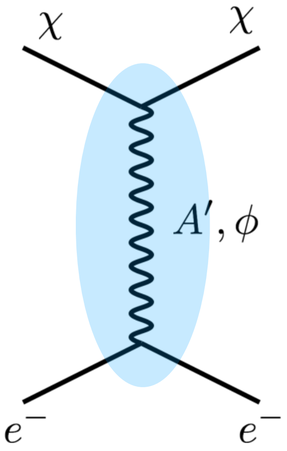


Electron Recoils

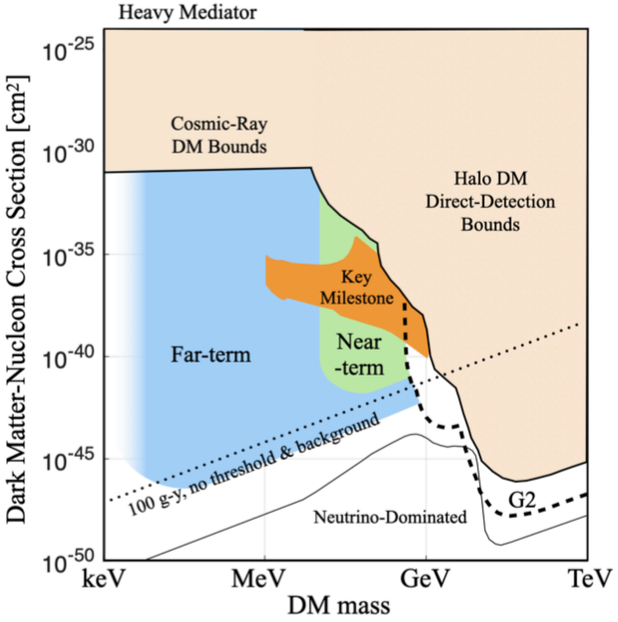


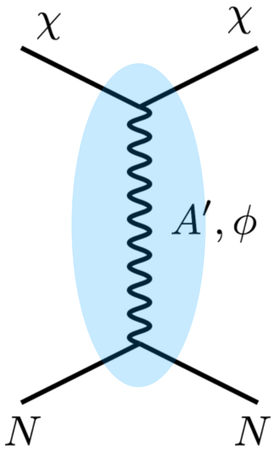






Nuclear Recoils





arXiv:2211.09978,1707.0459

Conclusions

- Dark Matter remains one of the great questions in physics
- New theoretical and experimental advances have opened up new parameter space to search for dark matter
- The next ten years will see rapid improvement in the sensitivity of experiments over orders of magnitude of parameter space
- Many interesting benchmark models for low-mass dark matter will be reached in this time frame
- A positive signal would herald a new chapter in our search for physics beyond the standard model!