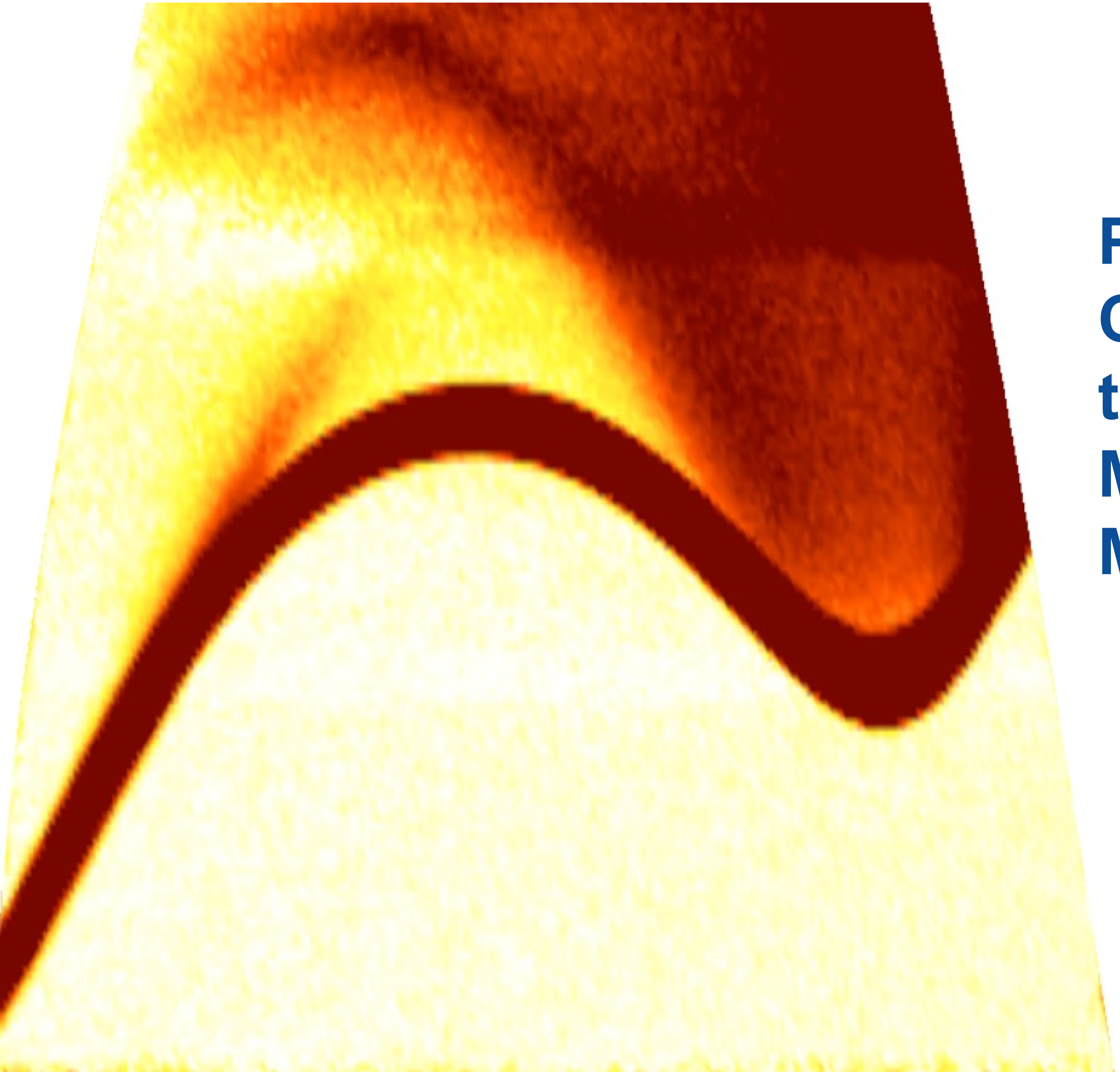
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

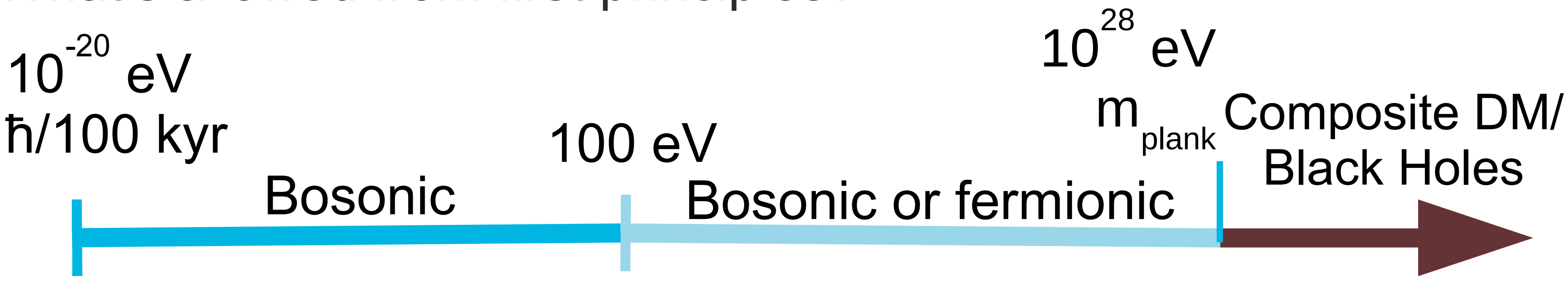


Prospects and Challenges for the Detection of MeV-scale Dark Matter

Alan E. Robinson
CAP Congress
29 May 2017

What could be the Dark Matter?

What's allowed from first principles?



10^{-20} eV
ħ/100 kyr

Bosonic

100 eV

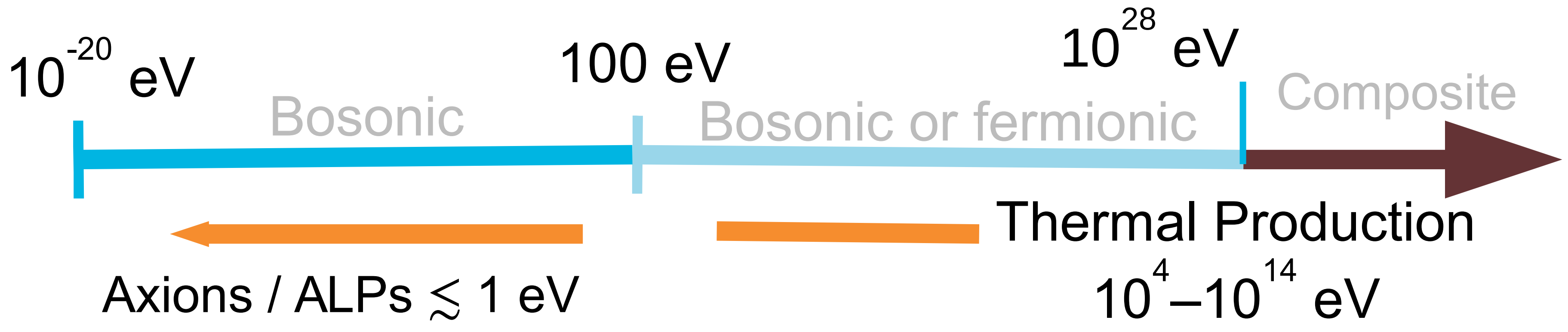
Bosonic or fermionic

10^{28} eV
m_{plank}

Composite DM/
Black Holes

What could be the Dark Matter?

How could DM be produced?



10^{-20} eV

100 eV

10^{28} eV

Bosonic

Bosonic or fermionic

Composite

Thermal Production

10^{4}–10^{14} eV

Axions / ALPs $\lesssim$ 1 eV

Produced by
spontaneous
symmetry breaking
in early universe

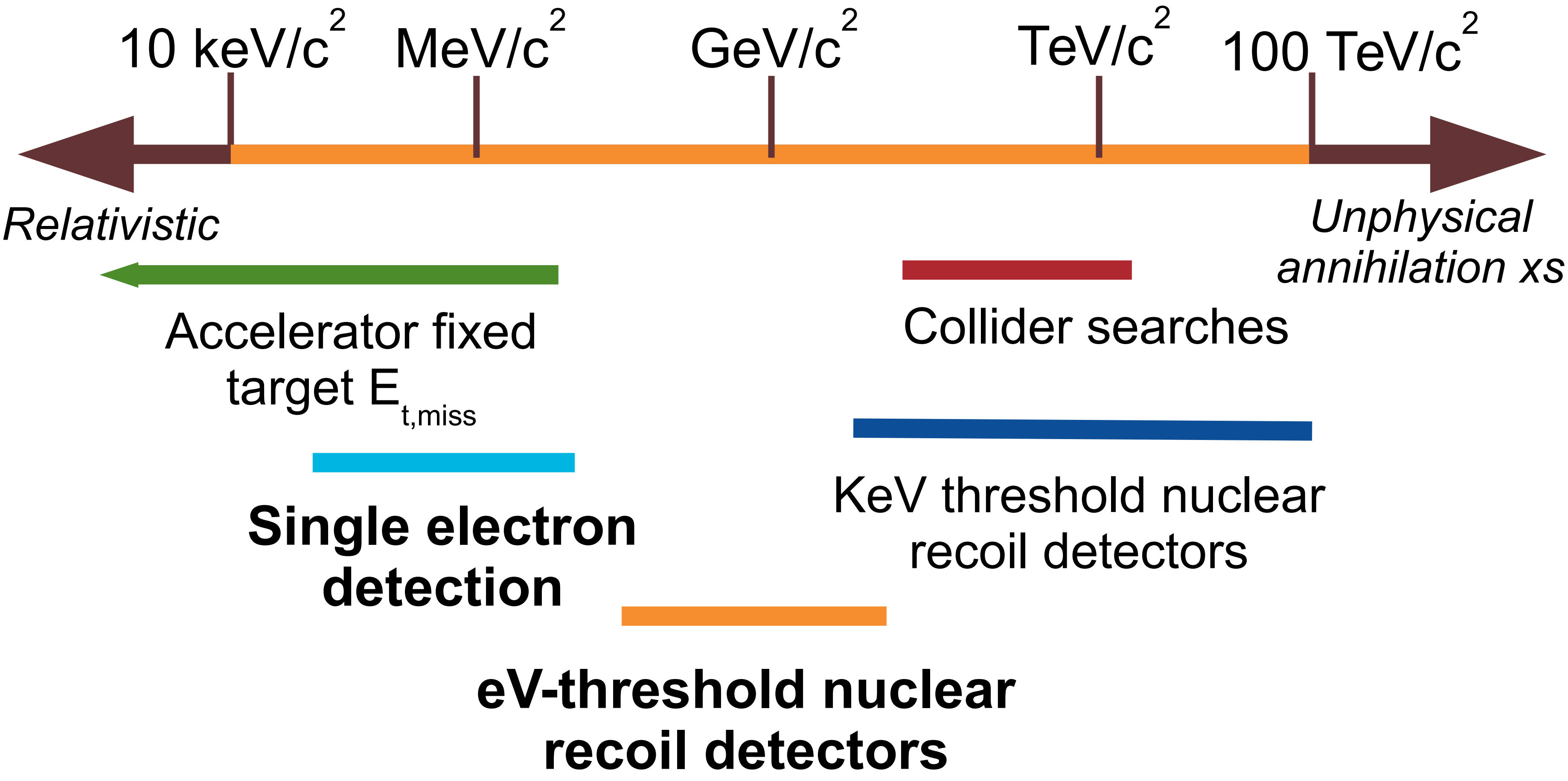
Produced by particle collisions.

Variations:

- WIMPs
- Dark Photon
- Assymmetric DM
- Freeze-in
- SIMP

Thermally Produced Dark Matter

How can we detect Dark Matter?



$10\ \mathrm{keV}/c^2$ MeV/c^2 GeV/c^2 TeV/c^2 $100\ \mathrm{TeV}/c^2$

Relativistic

Unphysical annihilation xs

Accelerator fixed target $E_{t,miss}$

Collider searches

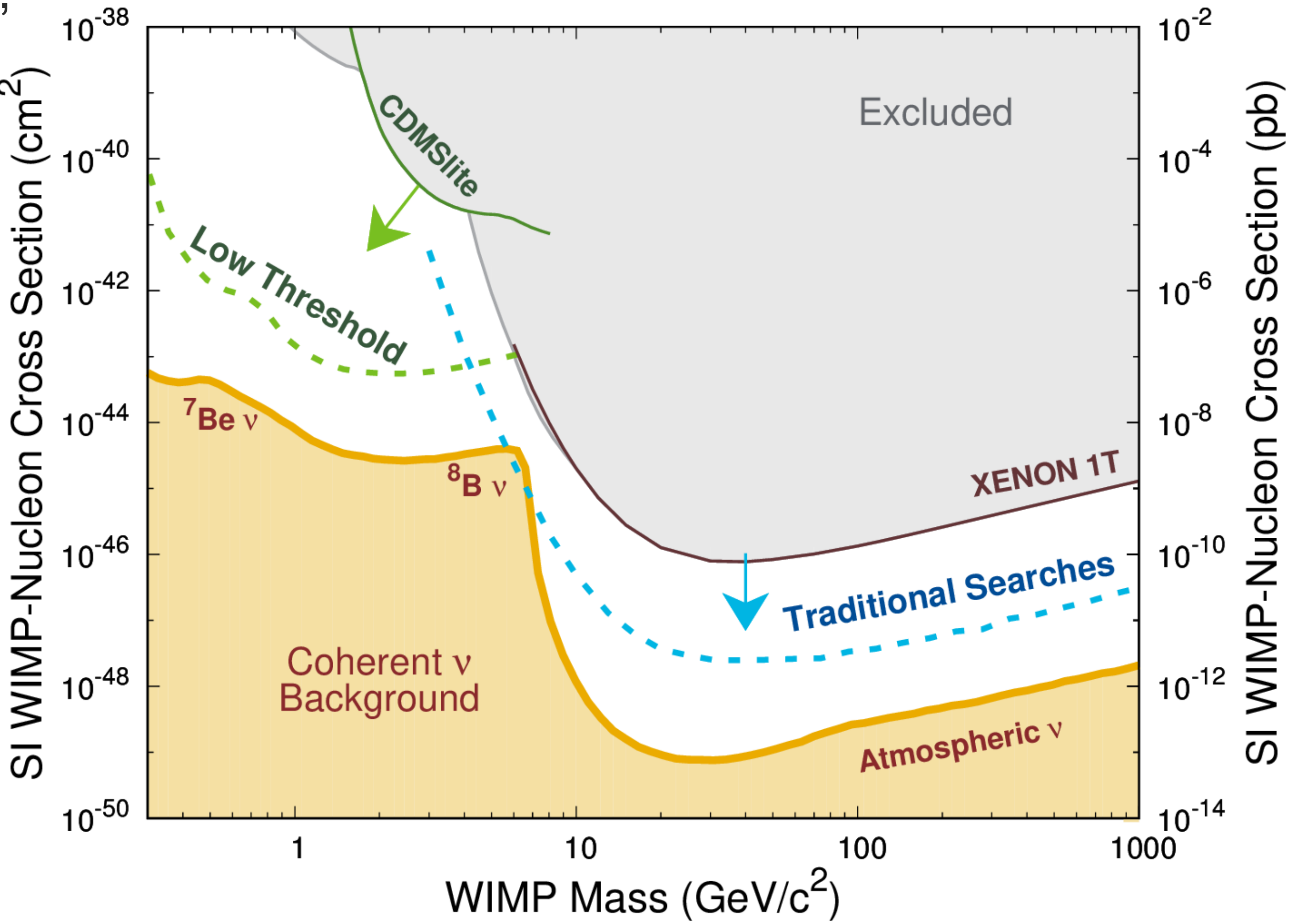
Single electron detection

KeV threshold nuclear recoil detectors

eV-threshold nuclear recoil detectors

Direct Detection Limits

- At high mass, direct detection models exist to and below the ‘neutrino floor’



Direct Detection Limits

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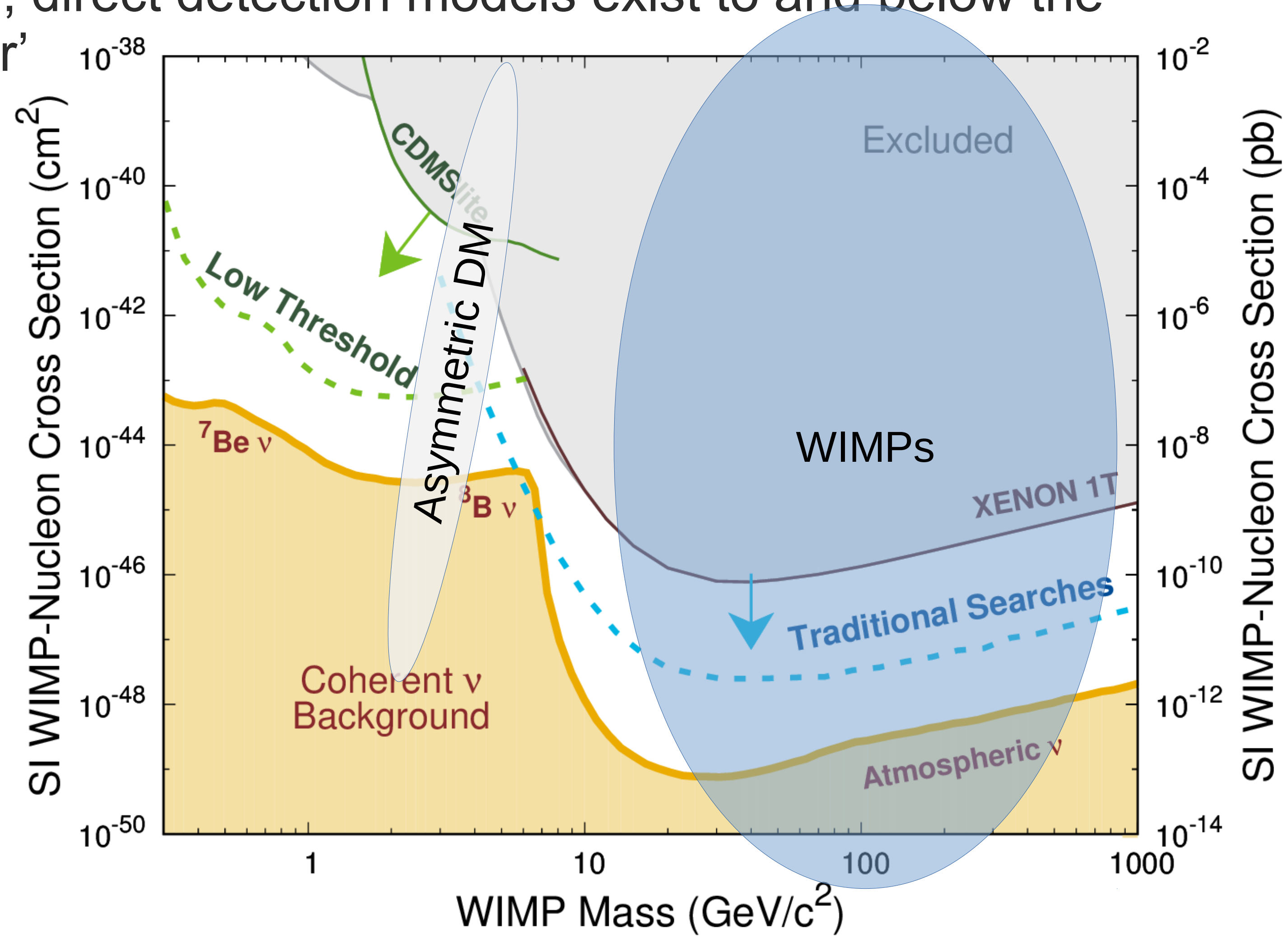
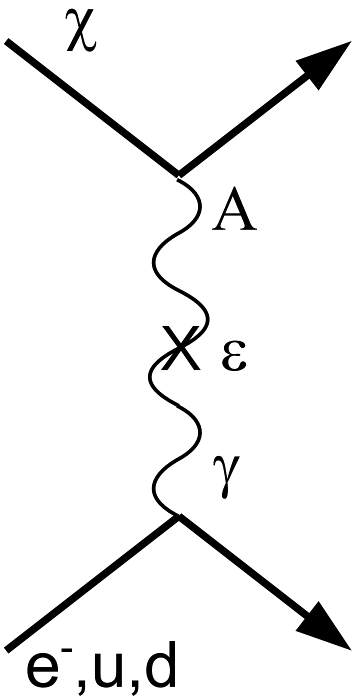
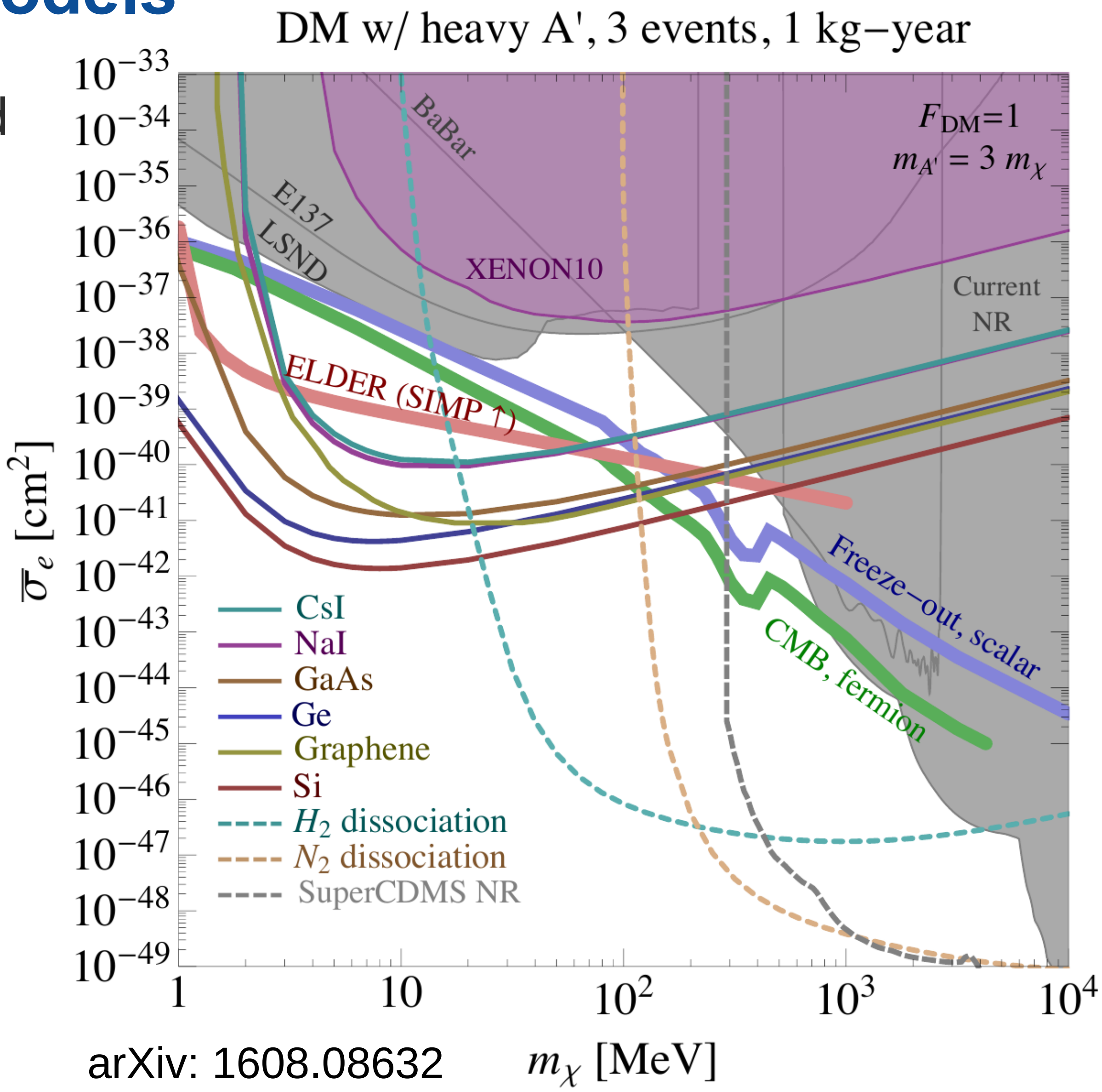


Dark U(1) Sector Models

- Simplest unconstrained model at low masses
  - Heavy dark photon kinetically mixes with SM photon





arXiv: 1608.08632

How to see light dark matter

Build ultra low-threshold detectors $E_{recoil,max} = 2(\mu v)^2/m_N$

Challenge: Detector resolution degrades with detector size.

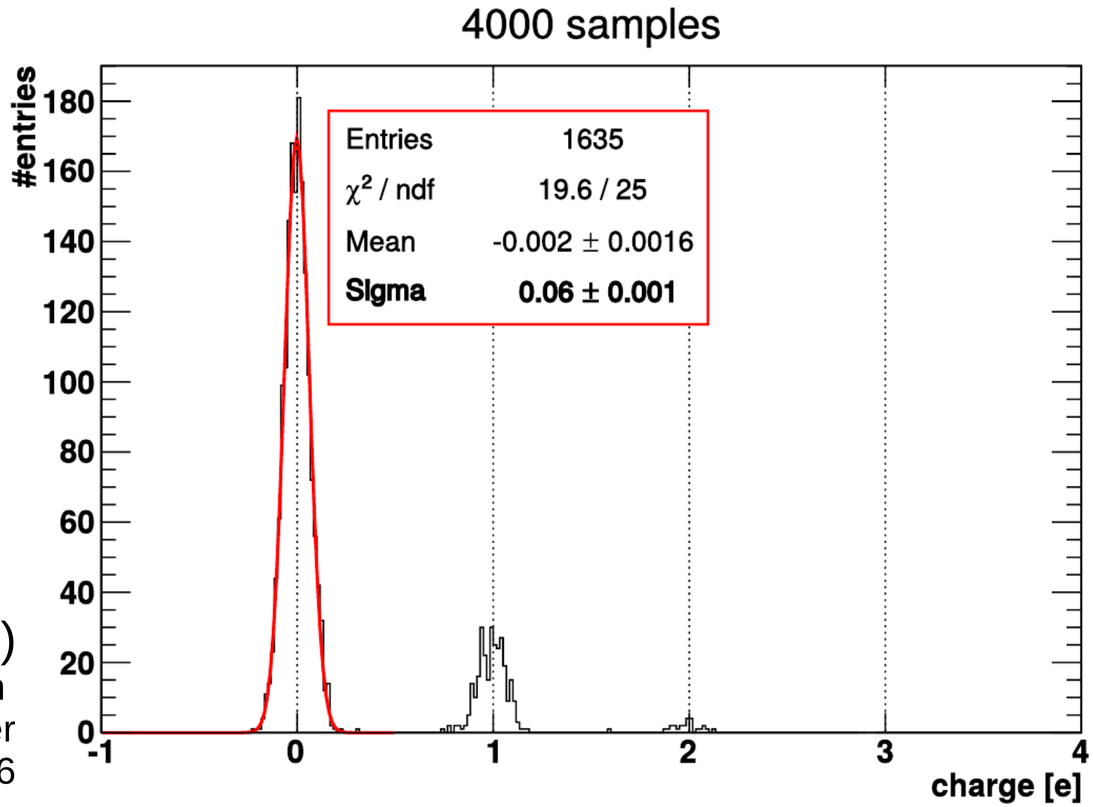
- Build experiments that concentrate signals onto small detectors.
  - New low-threshold technologies have been developed!

Challenge: Maintaining low-backgrounds at low thresholds

Challenge: Calibrating detector energy scales at low thresholds

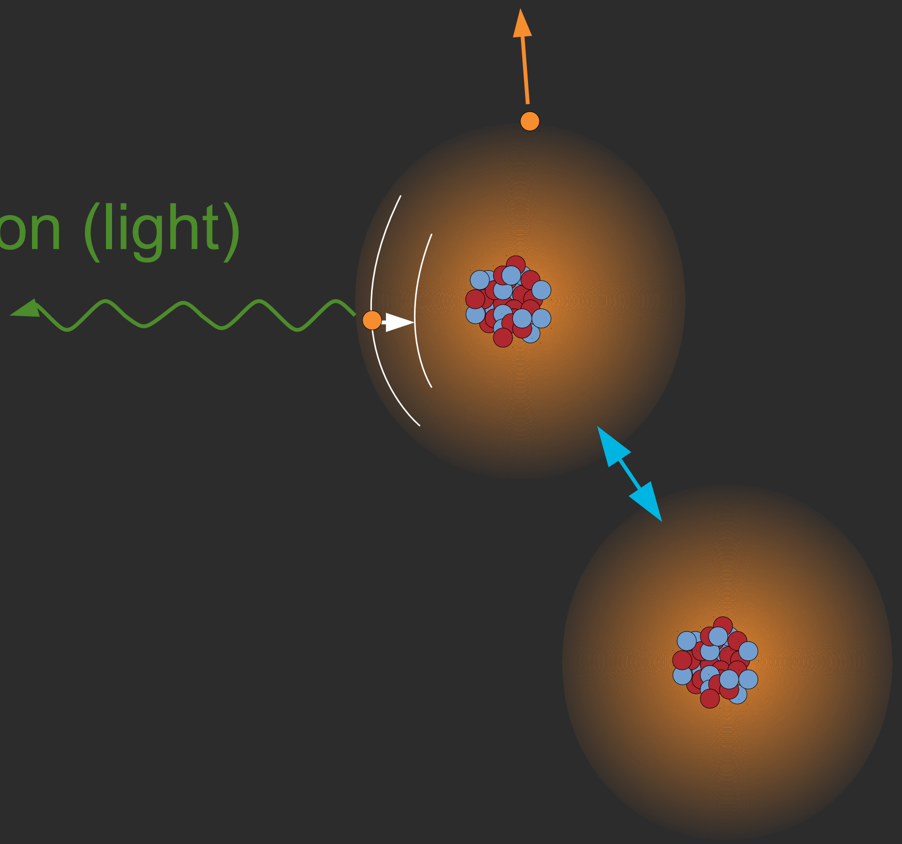
Ultra-low threshold experiments

- Skipper CCDs
  - Recently demonstrated by J. Tiffenberg @ FNAL
  - Single e^- sensitivity by repeatedly sampling the trapped charge and baseline of a CCD readout diode.



J. Tiffenberg (FNAL)
LBNL workshop on
direct detection of dark matter
December 2016

Detecting Recoils

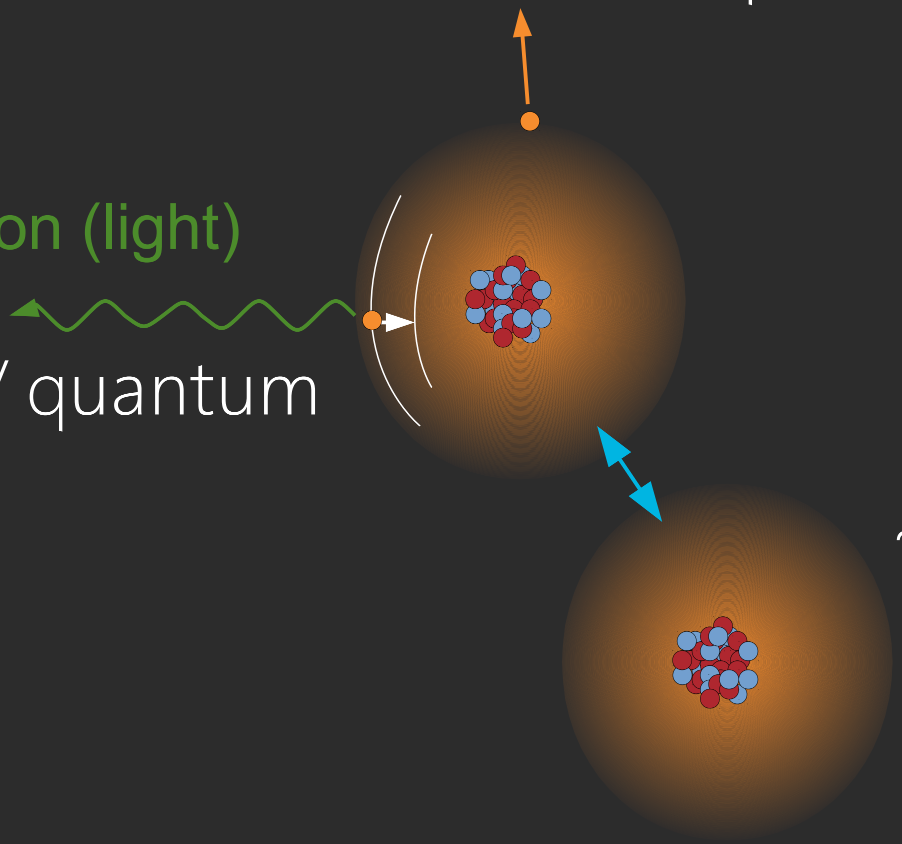


Ionization (free electrons)

Scintillation (light)

Phonons
(heat or sound)

Detecting Recoils



Ionization (free electrons)

~3 eV / quantum

Scintillation (light)

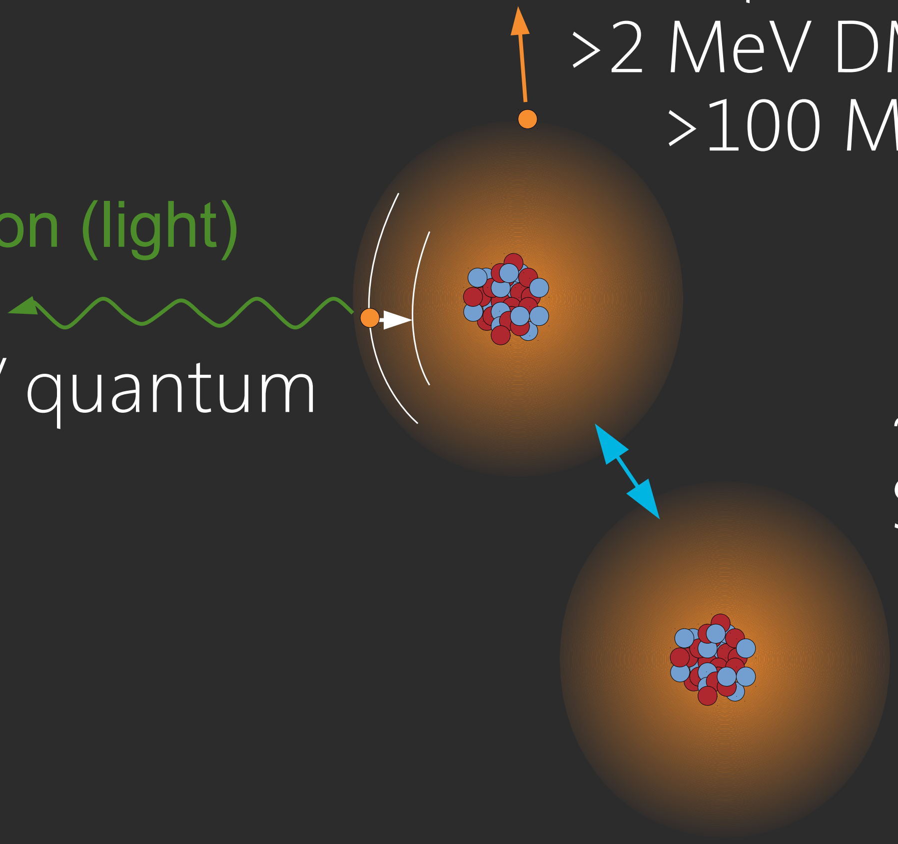
~10 eV / quantum

~meV / quantum

Phonons

(heat or sound)

Detecting Recoils – Ultimate sensitivities



Ionization (free electrons)

~3 eV / quantum

>2 MeV DM on e^-

>100 MeV/c2 DM on Si atom

Scintillation (light)

~10 eV / quantum

~meV / quantum

Sensitivity to below

0.5 MeV/c^2

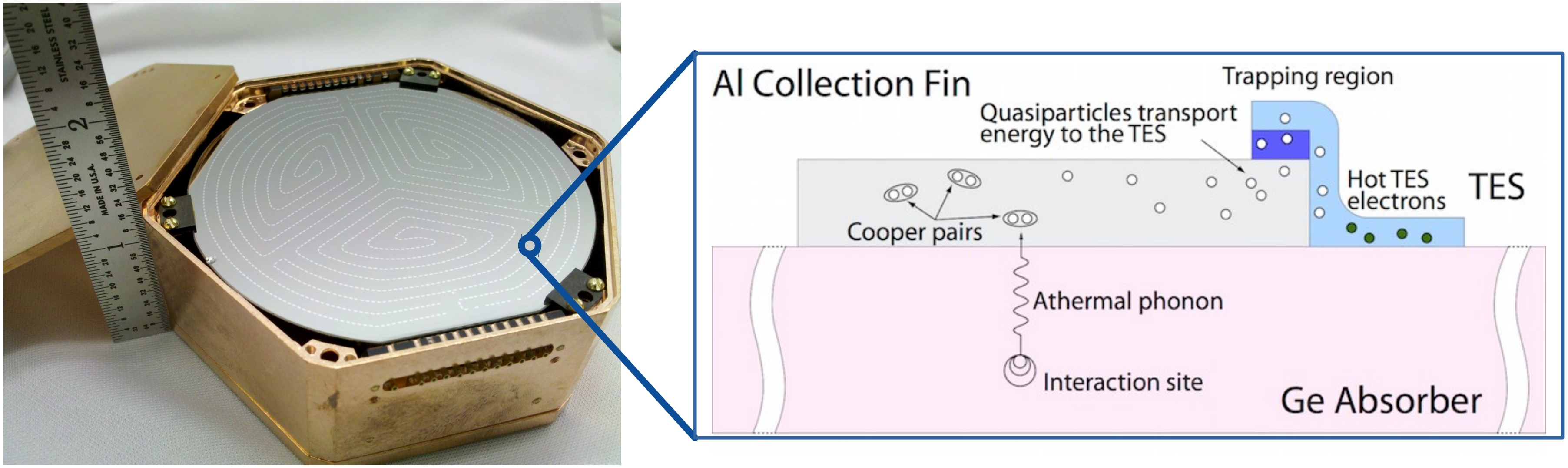
Phonons

(heat or sound)

Phonon Detection

e.g. SuperCDMS SNOLAB

- Concentrates phonons and detects them using tungsten at its superconducting transition (Transition Edge Sensor)
- Design resolution of 5-10 eV
- Operations in 2020



Background processes

Sources of spontaneous energy deposition

- Thermal fluxuations
  - Operate at cryogenic temperatures

Background processes

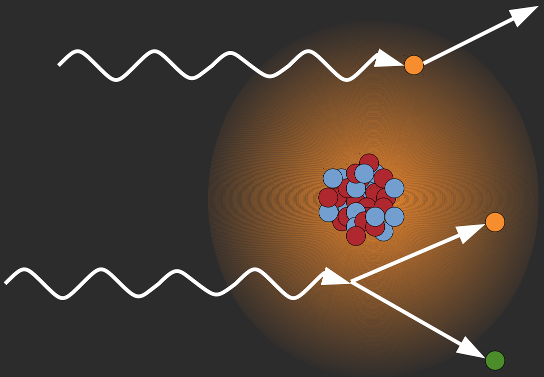
Sources of spontaneous energy deposition

- Thermal fluxuations
  - Operate at cryogenic temperatures
- Radiation, penetrating photons

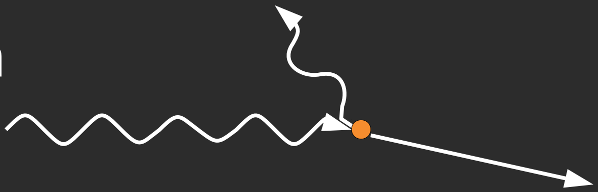
Background Radiation Processes from Photons

Penetrating MeV γ radiation

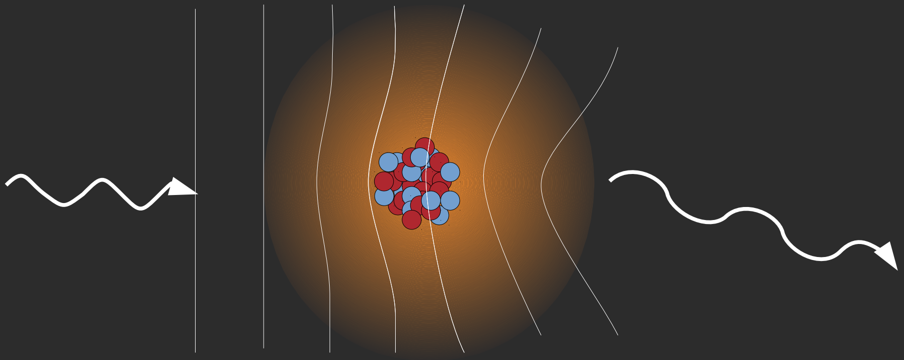
- Deposits of full photon energy
  - Photoelectric effect
  - Pair-production



- Compton scattering
  - Mitigated by ER/NR discrimination
  - Cut off below electron binding energies (~eV – keV).



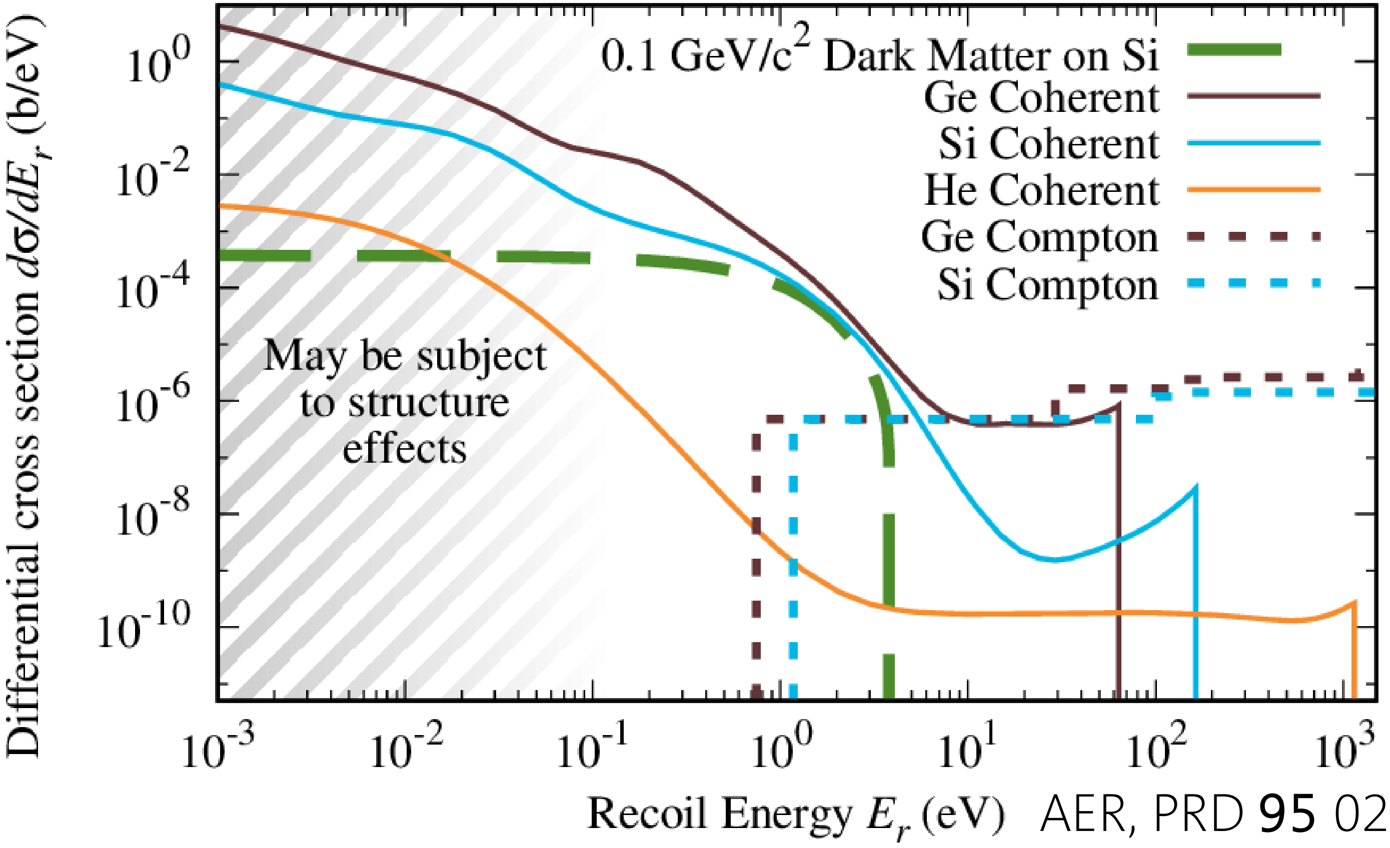
- Coherent scattering
  - Changes photon direction
  - Nuclear recoil



Coherent Photon Scattering Background

- Well studied process responsible for x-ray diffraction.

Expected low-energy photon background spectrum



AER, PRD **95** 021301(R) (2017)

Background processes

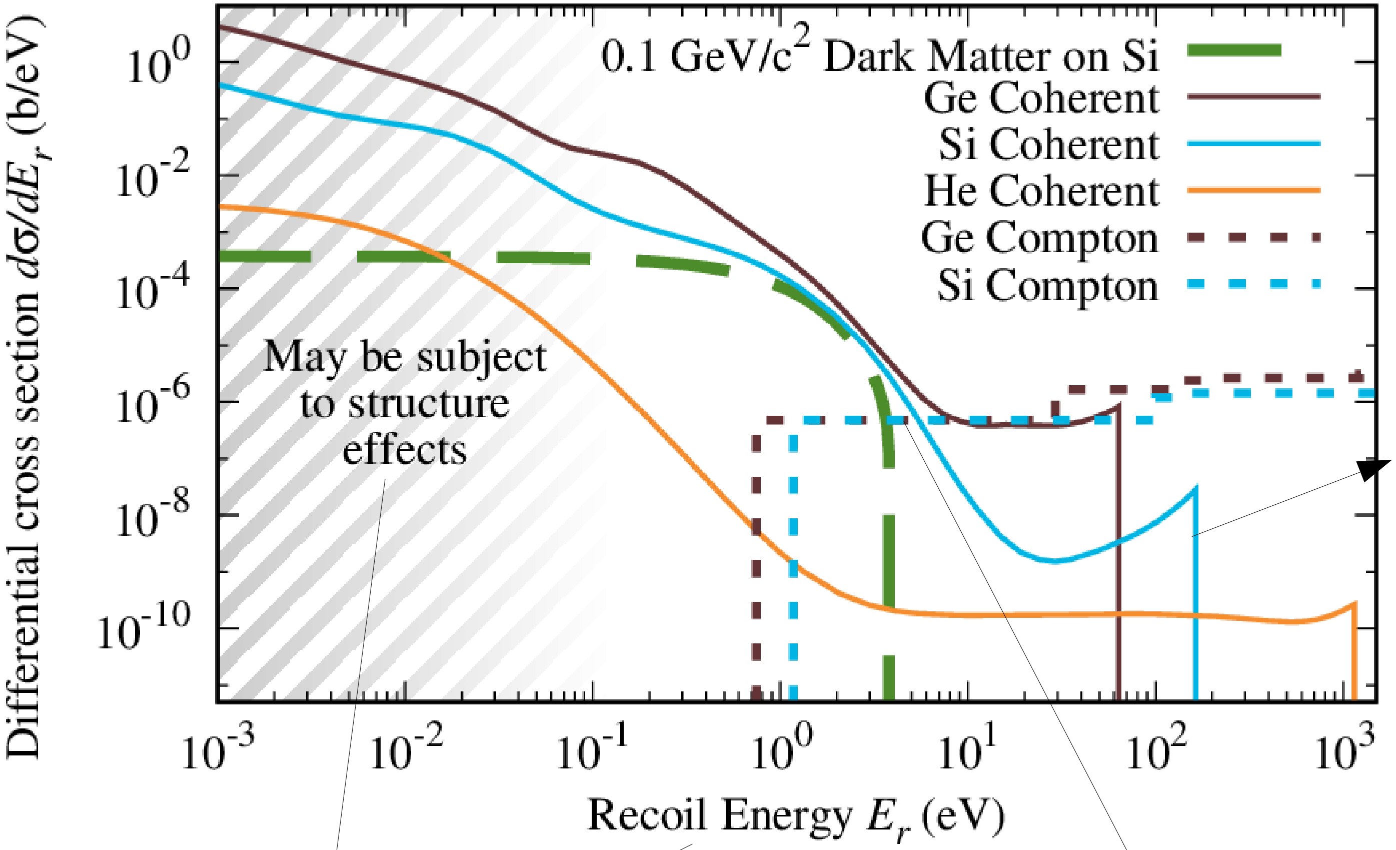
Sources of spontaneous energy deposition

- Thermal fluxuations
  - Operate at cryogenic temperatures
- Radiation, penetrating photons
  - Coherent photon scattering
- Microacoustic noise
- Non-thermal dark current
- Electrons accelerated over small voltages

Energy scale calibration

- Traditional method: irradiation by γ-ray or neutrons
  - Most scatters are too energetic for eV-scale.
- New methods
  - IR photons: see Muad Ghaith, at 15:30
  - Low-energy (~10 V) accelerators
  - Nuclear Thomson scattering
  - Thermal neutron capture recoils

Energy scale calibrations



Cutoff may be used for calibration

X-axis is recoil momentum transfer. In many bodied systems, $E_r \neq q^2/2m$

Compton electrons are quantized

Further Reading

- Dark Sectors workshop report
  - arXiv:1608.08632
- LBNL sub-eV workshop
  - indico.physics.lbl.gov/indico/event/298/
- DOE Cosmic Visions workshop
  - indico.fnal.gov/conferenceDisplay.py?confId=13702

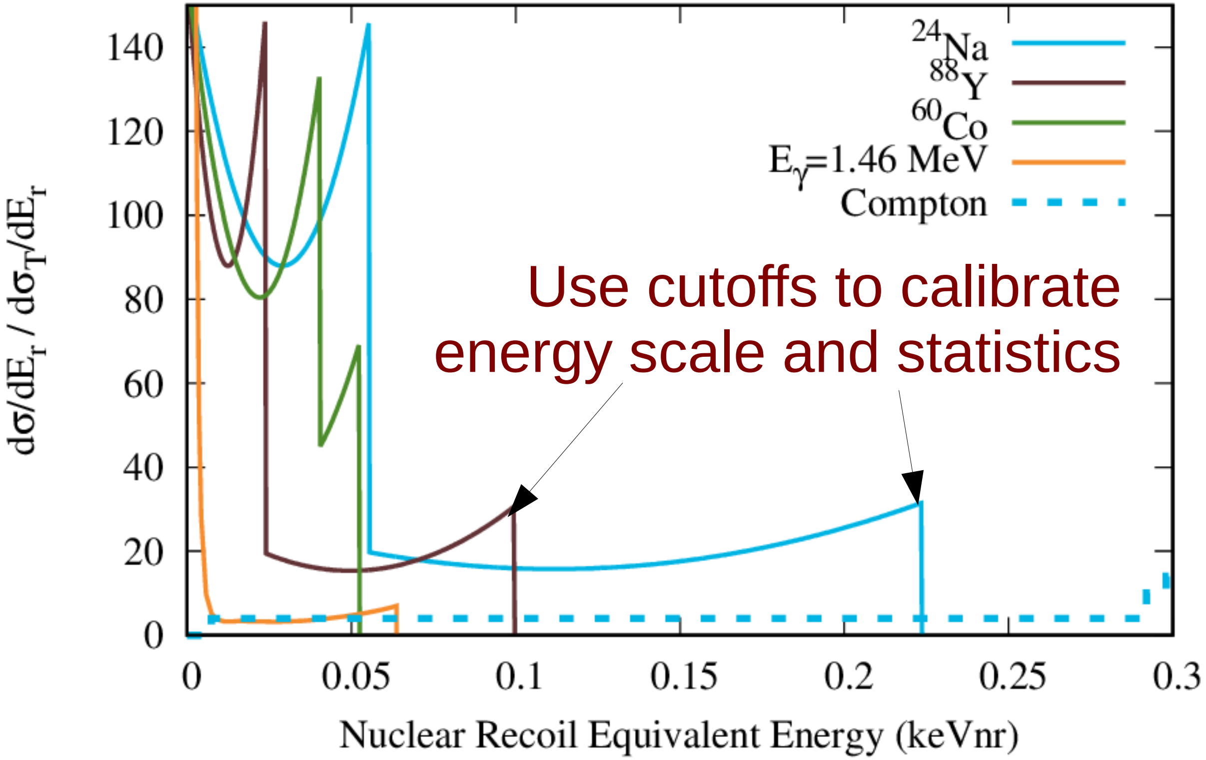
- Many other promising low-threshold technologies. E.g.:
  - Scintillating bolometers
  - Liquid helium

Coherent photon scattering calibrations

- Coherent Photon scattering
  - Tunable edge energy with a variety of high energy photon sources:
  - 24Na, 88Y, 12C(4.4 MeV)

Expected photon calibration spectrum

with 10% nuclear recoil ionization yield



Use cutoffs to calibrate energy scale and statistics

Cover Photo

Beauvois et al.
PRB **94** 024504

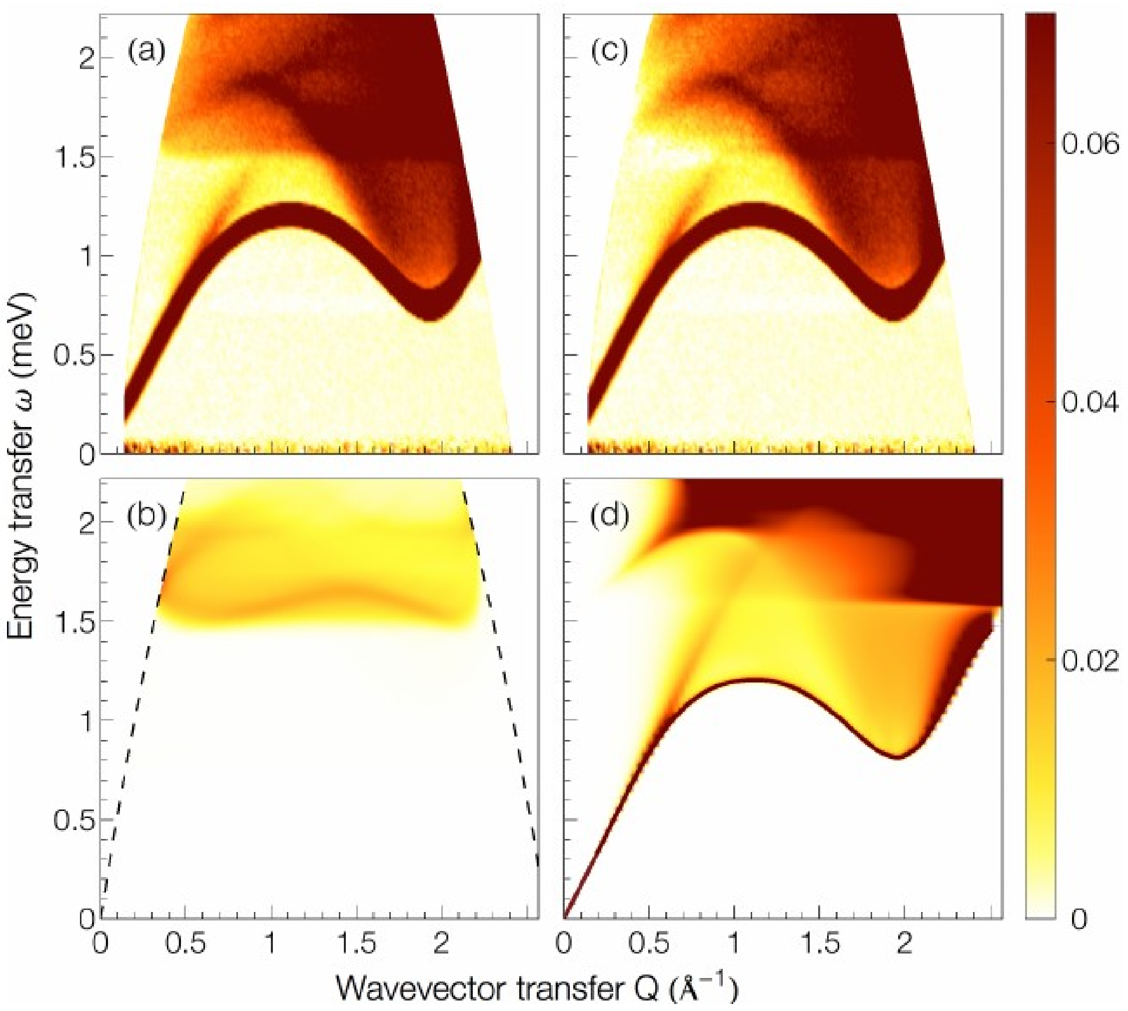


FIG. 1. (color online) (a) $S(Q,\omega)$ of superfluid ^{4}He measured as a function of wave vector and energy transfer, at saturated vapor pressure and temperature $T \leq 100\,\mathrm{mK}$. Con-