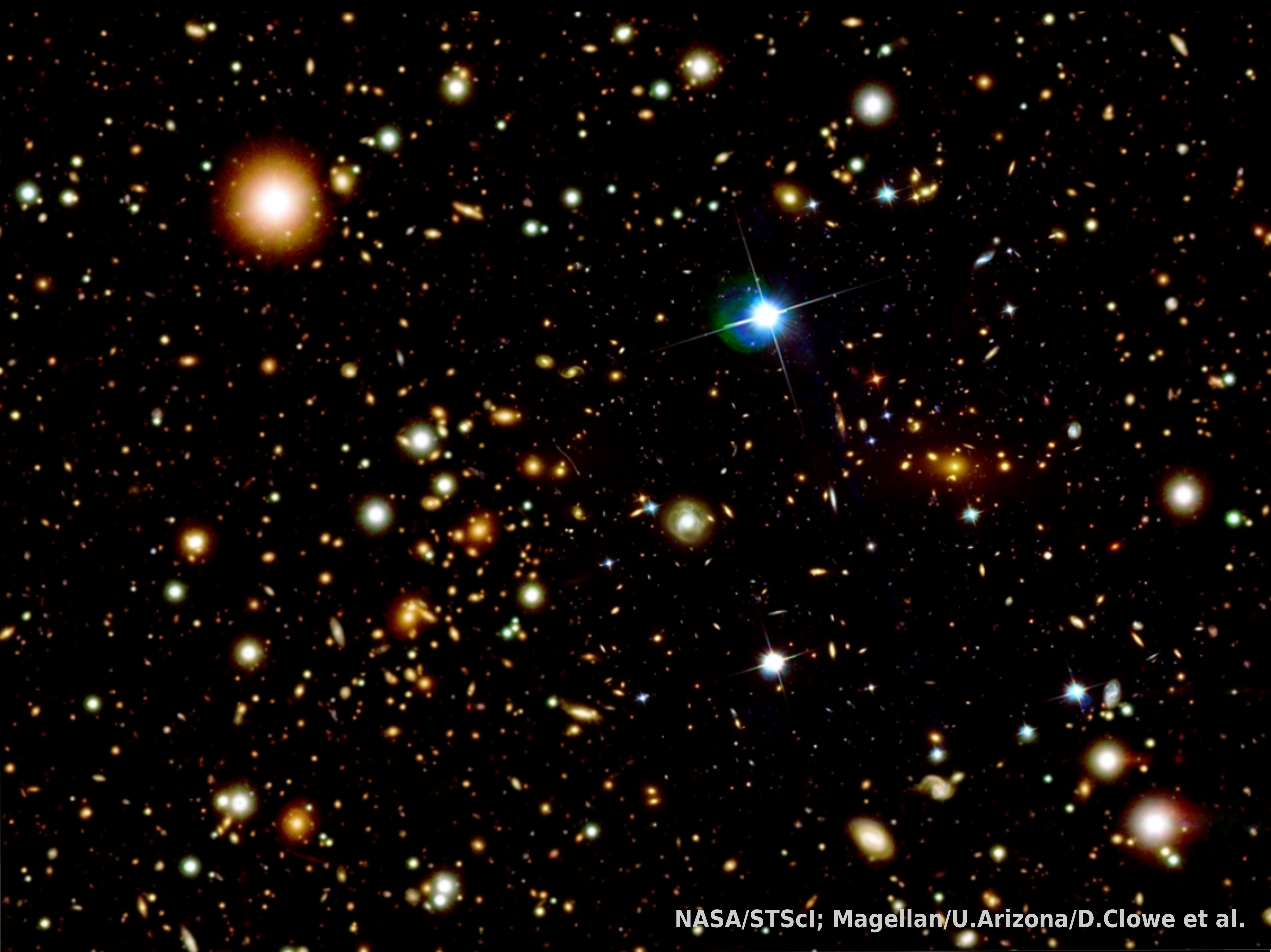
April, 2018 – **TU DRESDEN SEMINAR**

BELINA VON KROSIGK (BKROSIGK@PHYSICS.UBC.CA)

UNIVERSITY OF BRITISH COLUMBIA

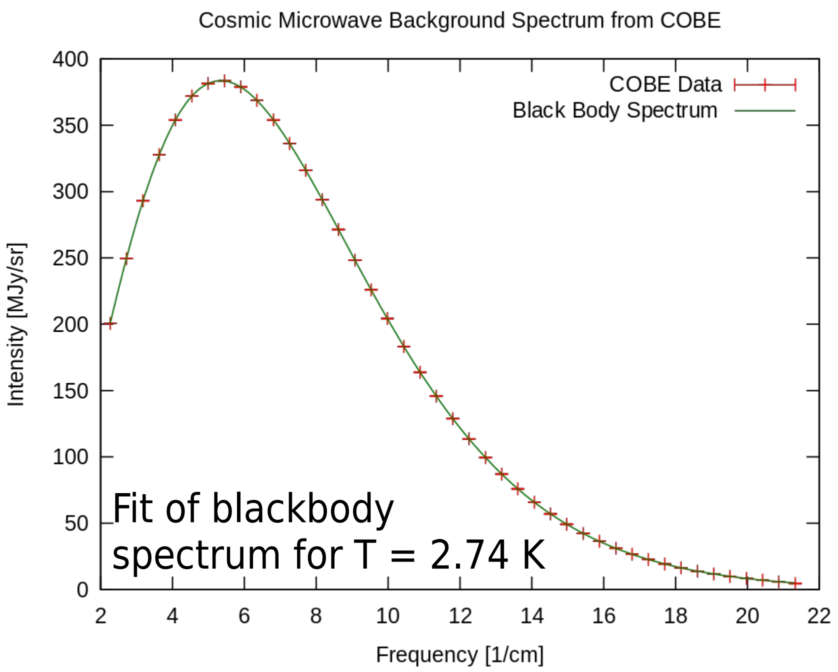
SEARCHING FOR DARK SECTOR PARTICLES WITH SuperCDMS AT SNOLAB

EVIDENCE FOR DARK MATTER

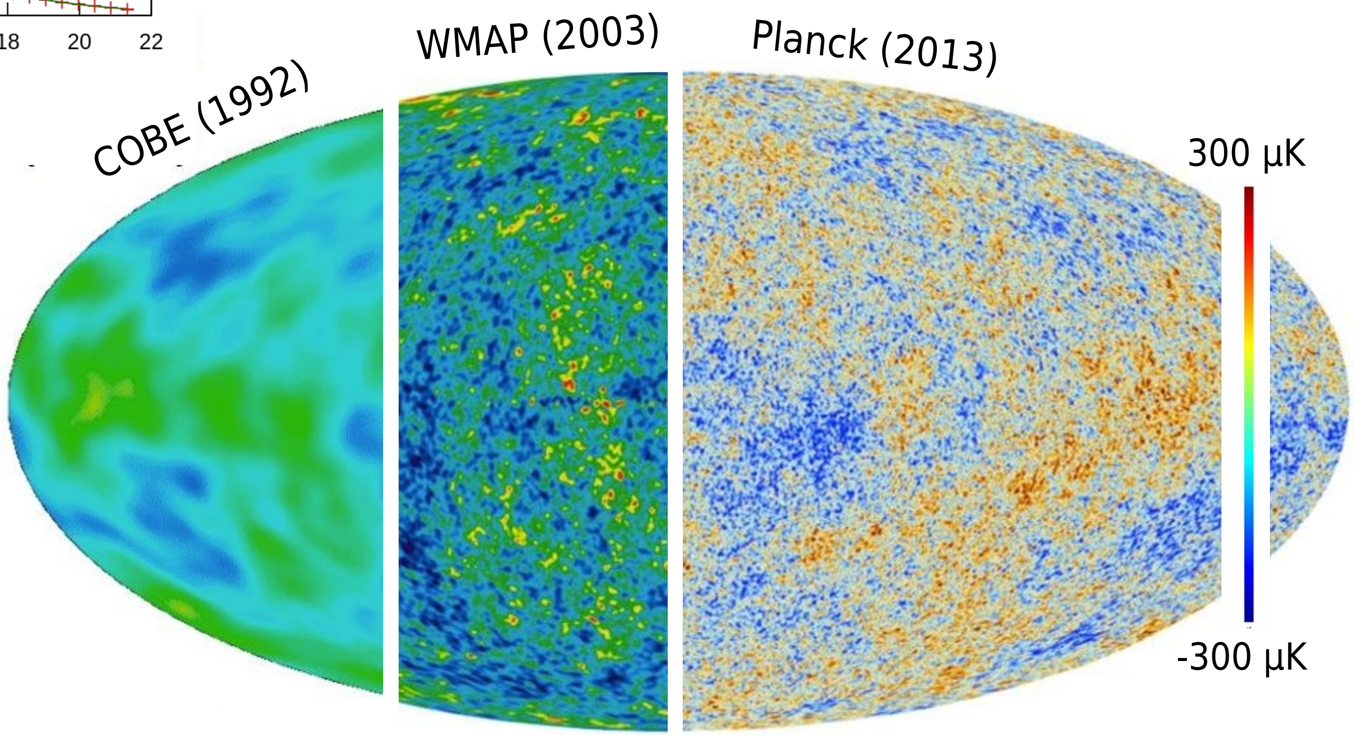

NASA/STScI; Magellan/U.Arizona/D.Clowe et al.


Most baryonic matter
(observed via X-rays)
Most mass
(observed via gravitational lensing)
X-ray: NASA/CXC/CfA/M. Markevitch et al.
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D. Clowe et al.
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

COSMIC MICROWAVE BACKGROUND

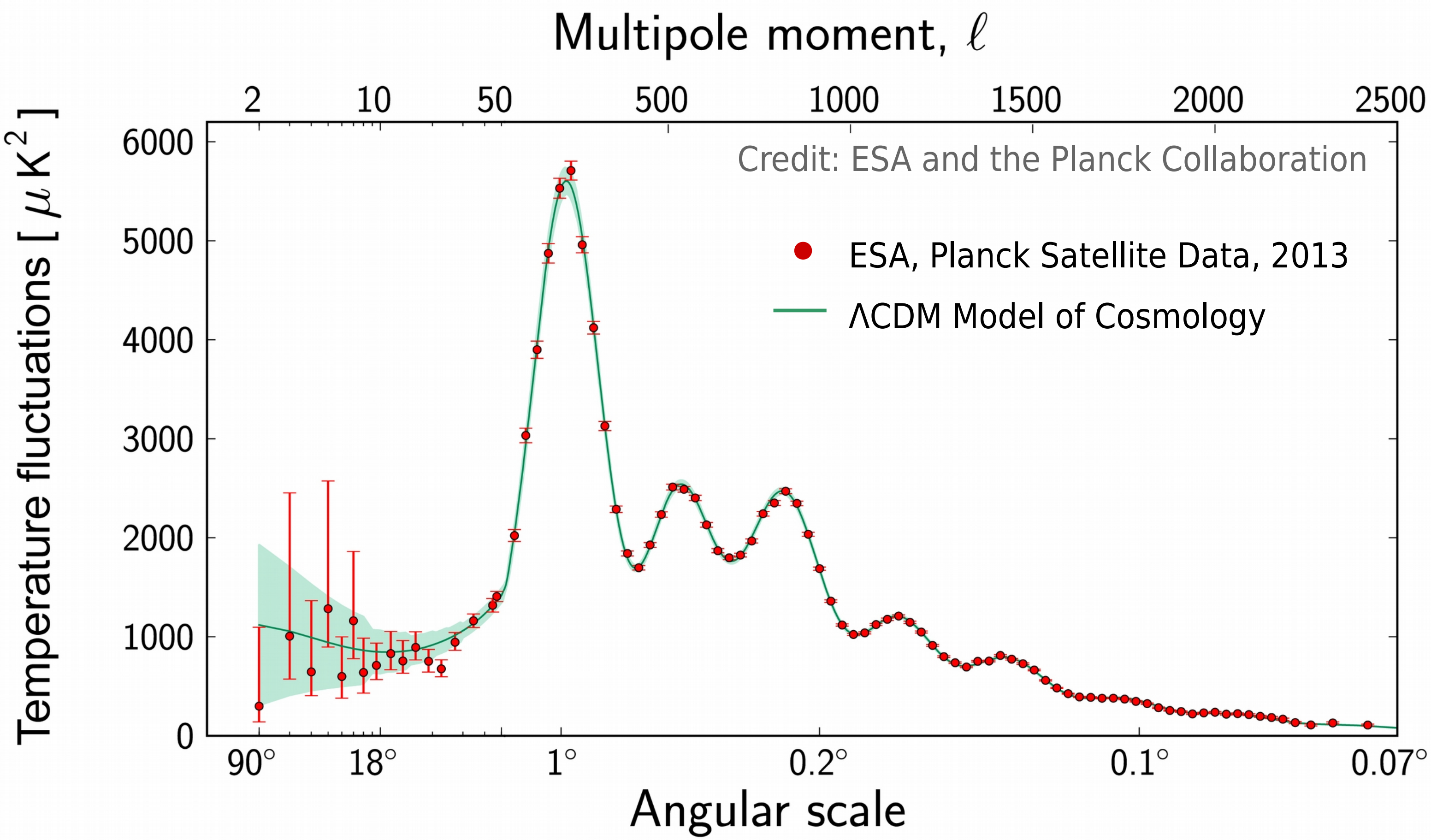


- Satellites measure tiny temperature fluctuations in the almost uniform Cosmic Microwave Background.



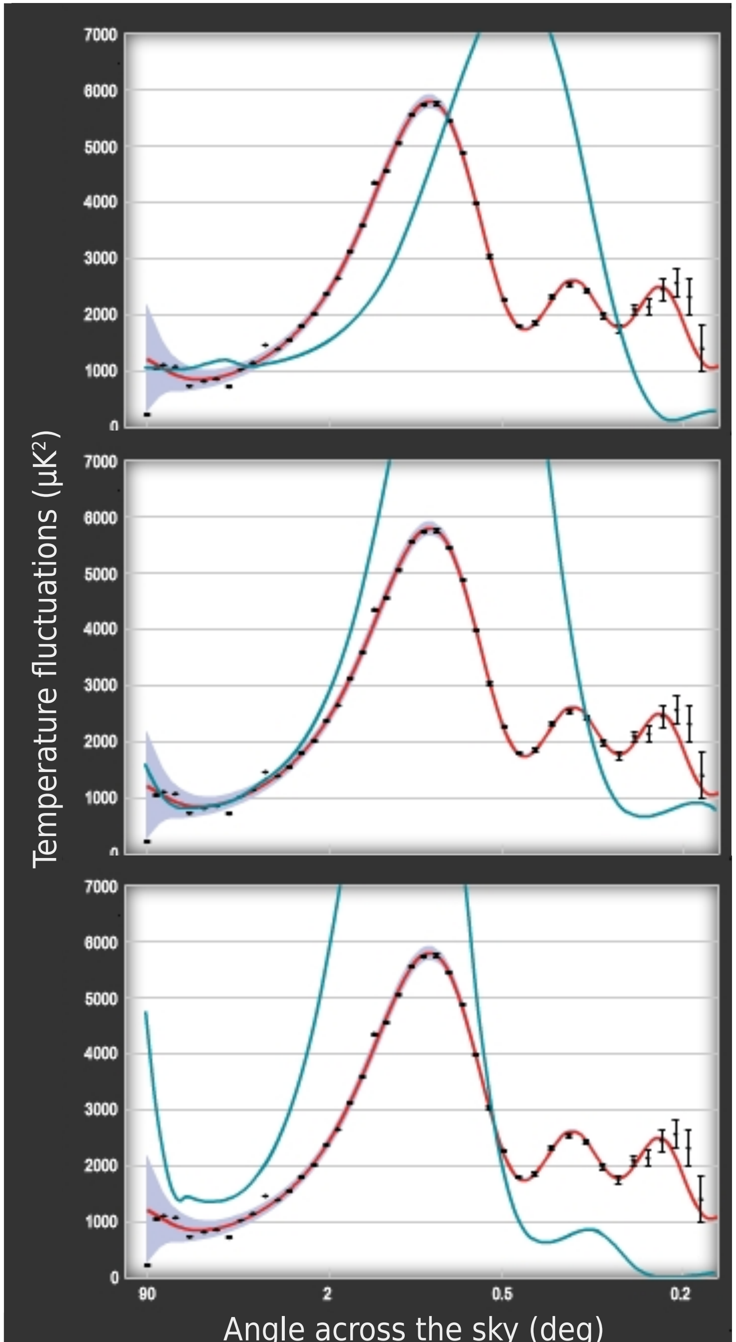
http://lambda.gsfc.nasa.gov/product/cobe/firas_monopole_get.cfm

COSMIC MICROWAVE BACKGROUND



- Power spectrum of temperature fluctuations.

COSMIC MICROWAVE BACKGROUND



Best fit ΛCDM model.
ΛCDM model with varying universe content.

How much ordinary matter can there be?

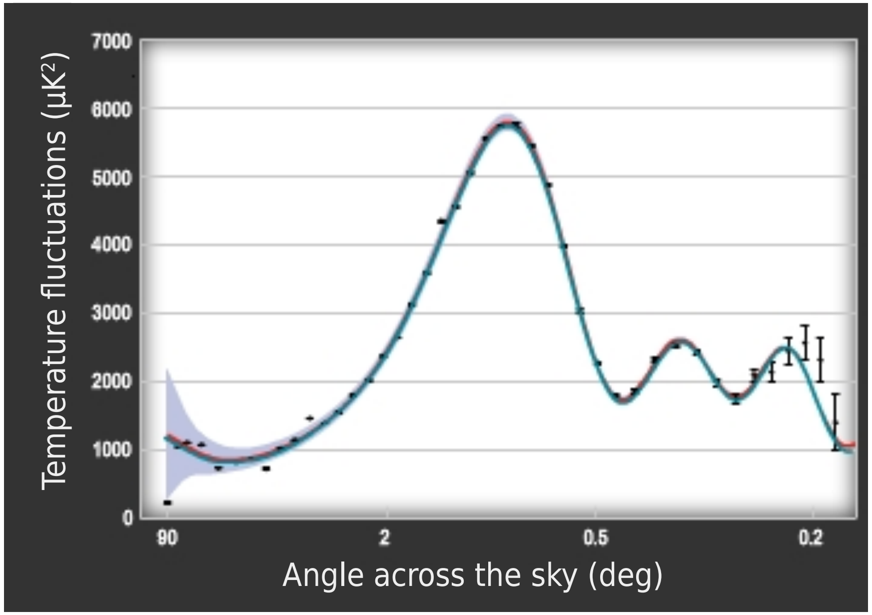
- Only ordinary matter?

- 1/2 ordinary matter?
- 1/2 dark matter?

- 1/3 ordinary matter?
- 1/3 dark matter?
- 1/3 dark energy?

https://map.gsfc.nasa.gov/resources/camb_tool/

COSMIC MICROWAVE BACKGROUND



- ~ 5% ordinary matter.
- ~ 27% dark matter.
- ~ 68% dark energy.

(since Planck 2013,
http://sci.esa.int/jump.cfm?oid=51557)

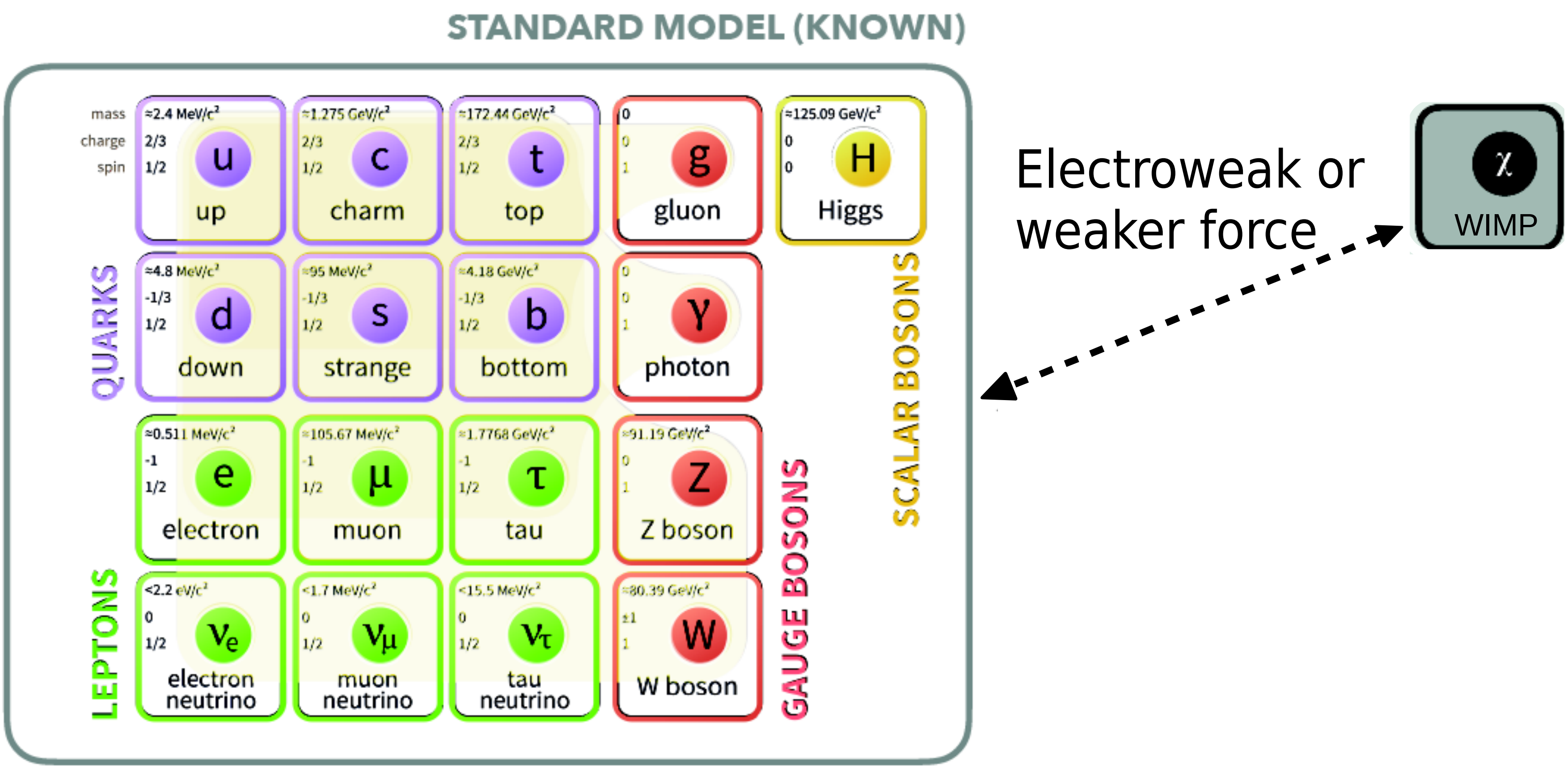
4/5

of matter is dark!

PARTICLE

DARK MATTER

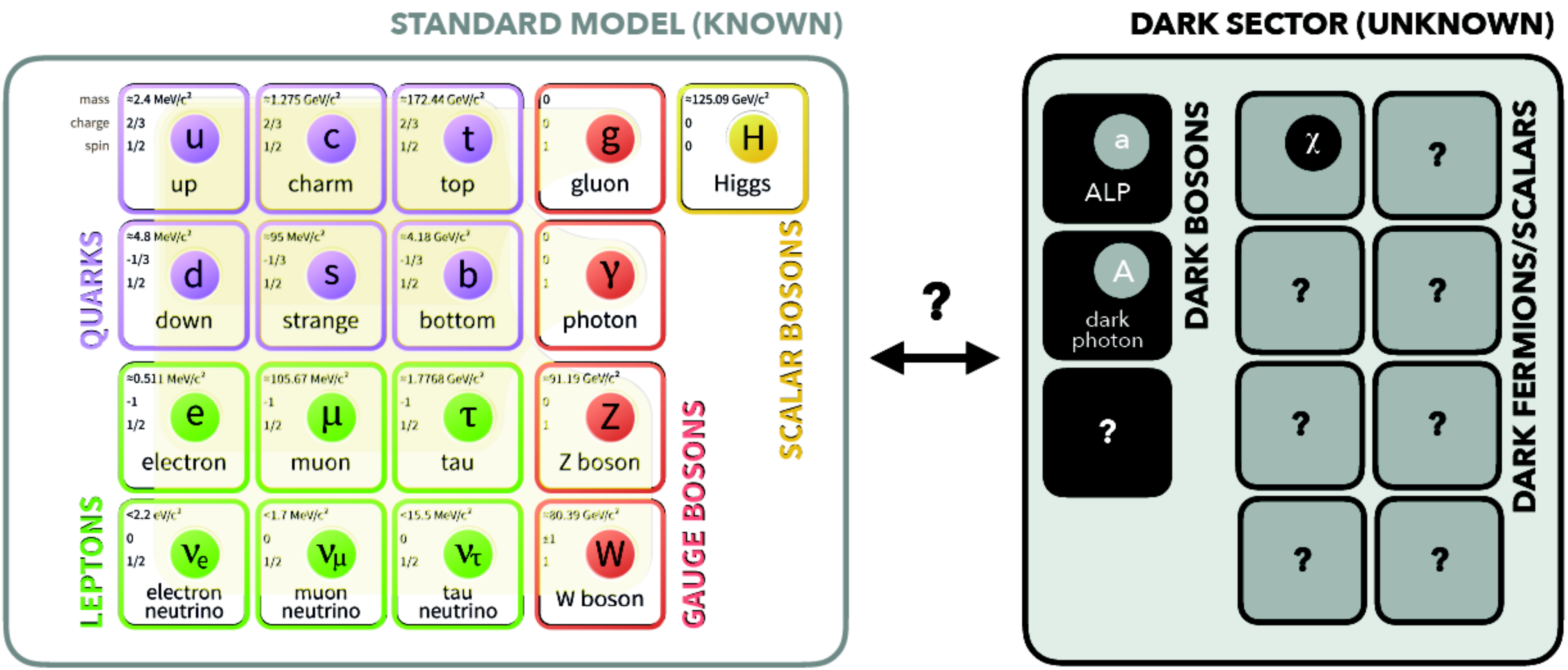
THE WIMP DARK MATTER CANDIDATE



“WIMP miracle”

- To obtain correct DM abundance today, requires $\langle\sigma v\rangle \sim 3\text{x}10^{-26}\text{cm}^3\text{s}^{-1}$.
  - Roughly what is expected for a ~100GeV particle that interacts via electroweak force.
- SUSY readily predicts such a particle.

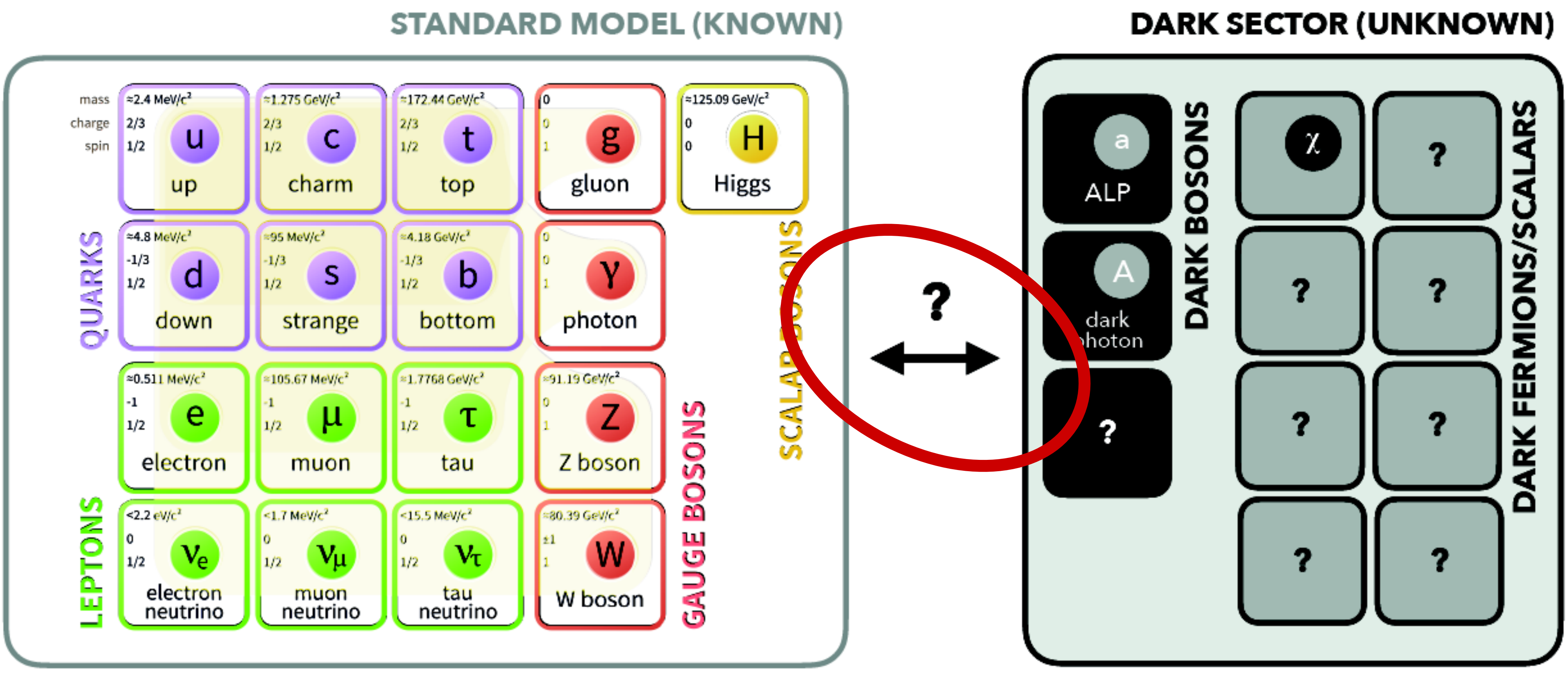
THE DARK SECTOR



- ALP: **a**xion-**l**ike **p**article.
- χ: dark matter particle (candidate e.g. WIMP).

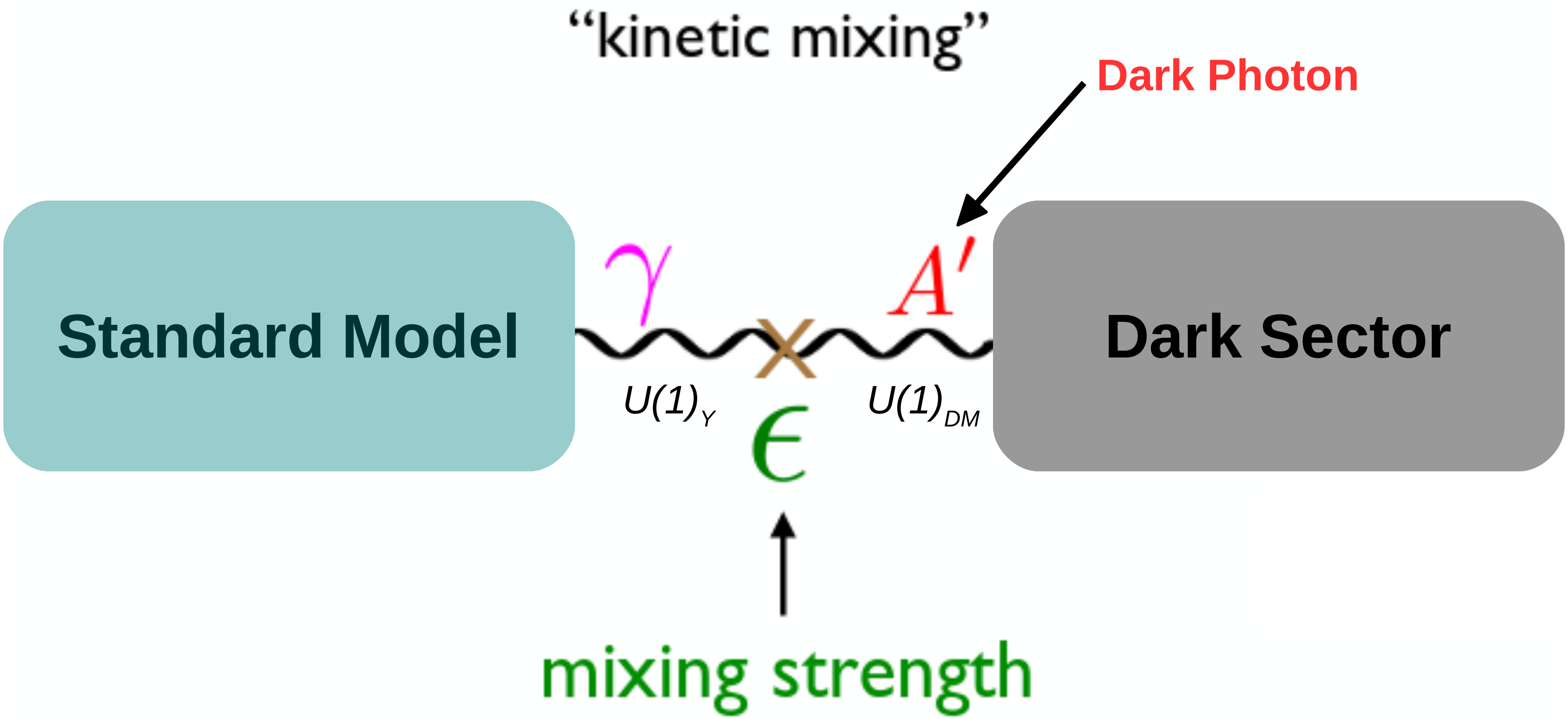
From T. Ferber

THE DARK SECTOR



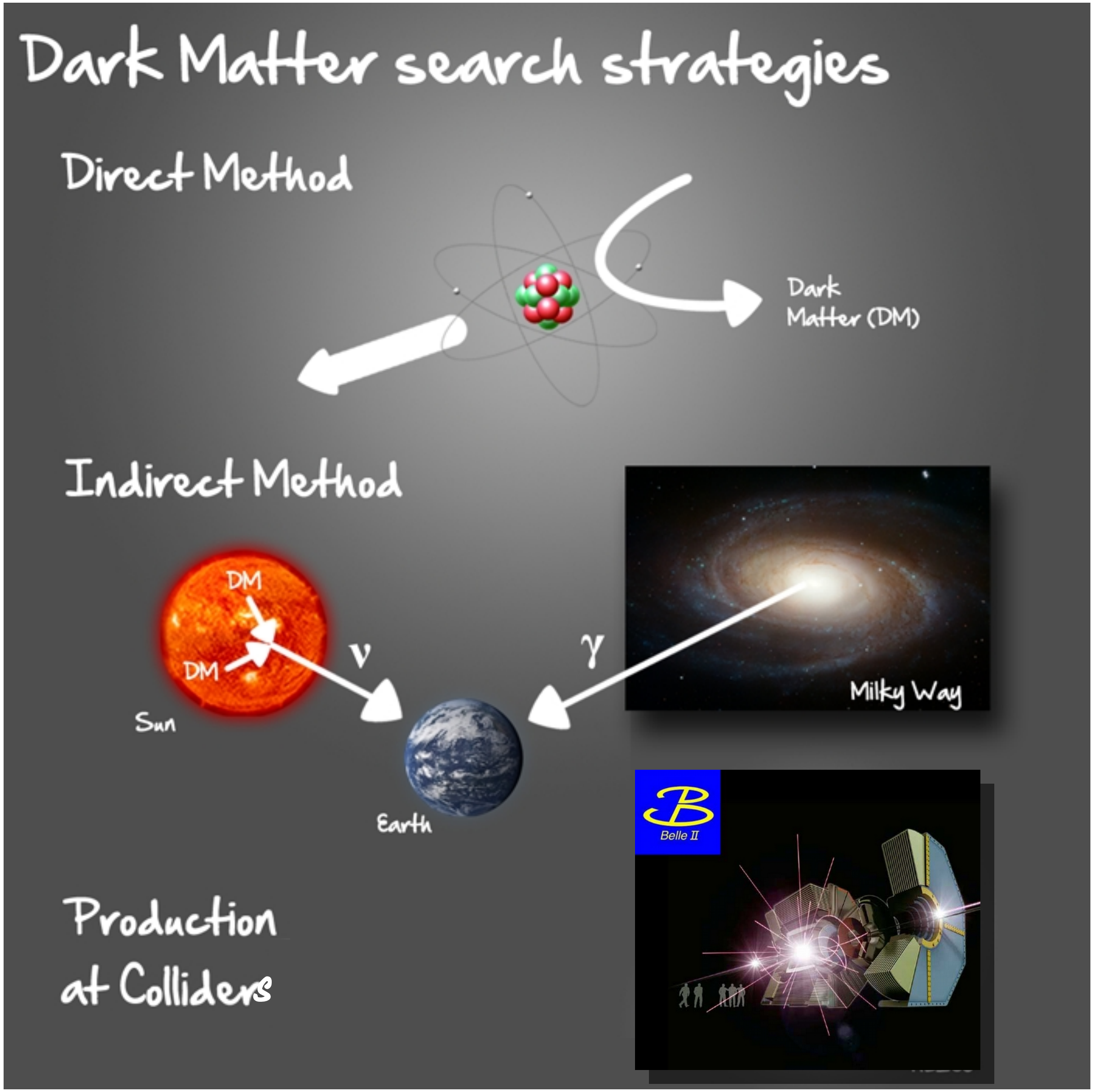
Portal?

MINIMAL VECTOR PORTAL

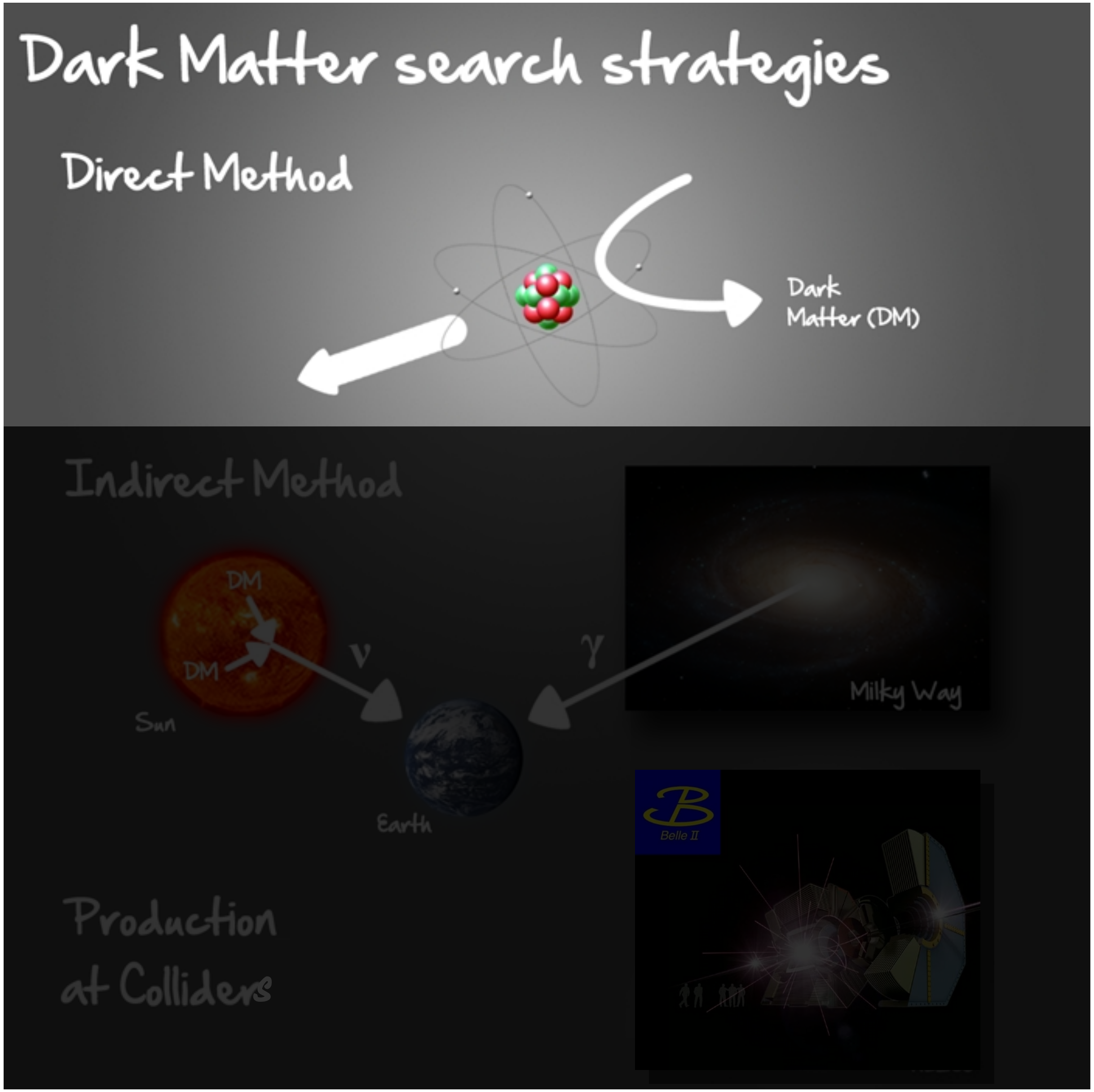


The *U(1)* vector mediators kinetically mix with kinetic mixing parameter *ε*.

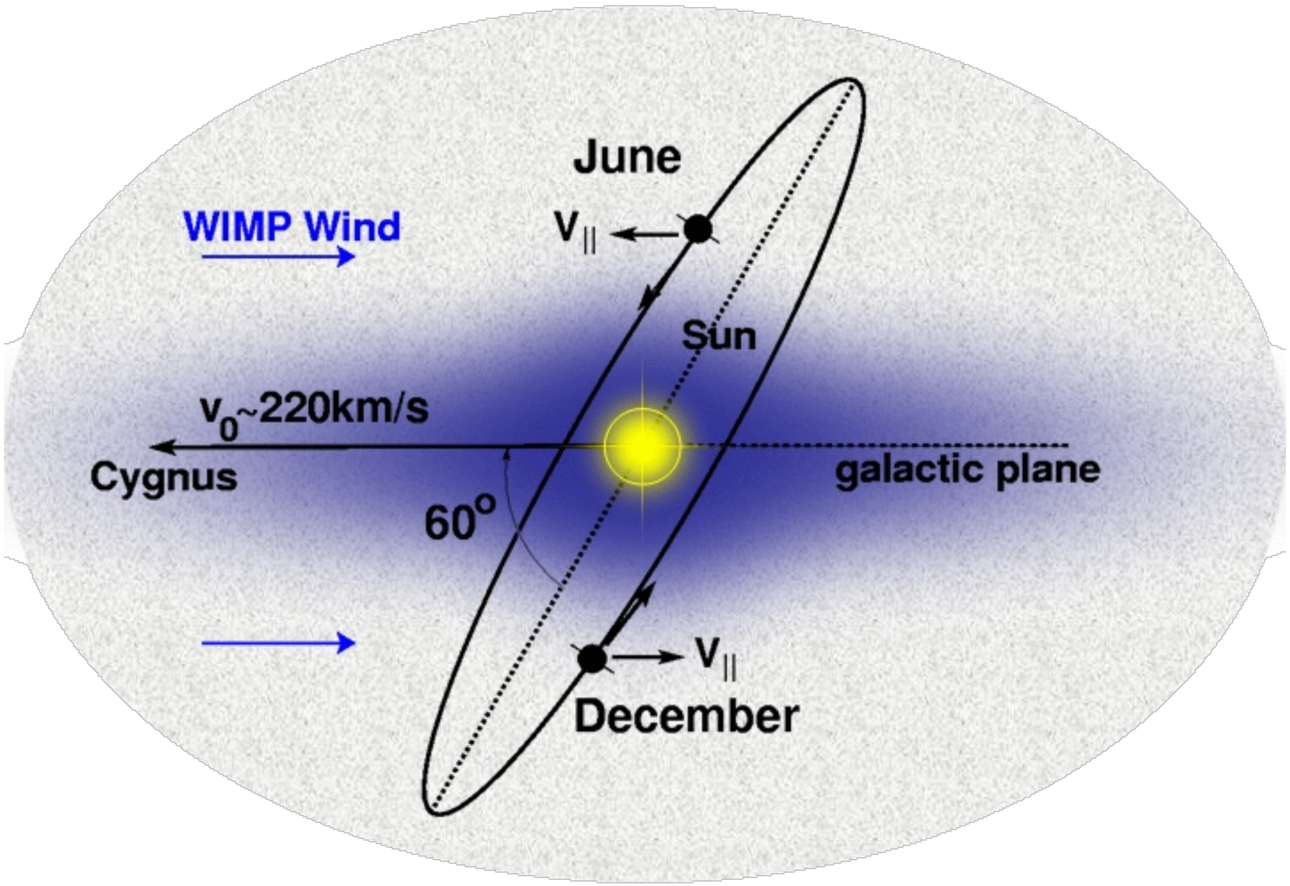
SEARCH STRATEGIES



SEARCH STRATEGIES



GALACTIC DARK MATTER



- DM halo large compared to ordinary matter.
- Solar System rotates about galactic center with speed of ~220 km/s.
- DM particles move isotropically with speeds of few hundred km/s.

SuperCDMS

(Cryogenic Dark Matter Search)

PAST AND FUTURE OF (Super)CDMS

CDMS @ SUF

1998 - 2002

SUF:
Stanford Underground Facility

SUF:
~10 m
~17 mwe

CDMS II @ Soudan

2003 - 2009

SuperCDMS @ Soudan

2009 - 2015

Soudan:
~700 m
~2000 mwe

SuperCDMS @ SNOLAB

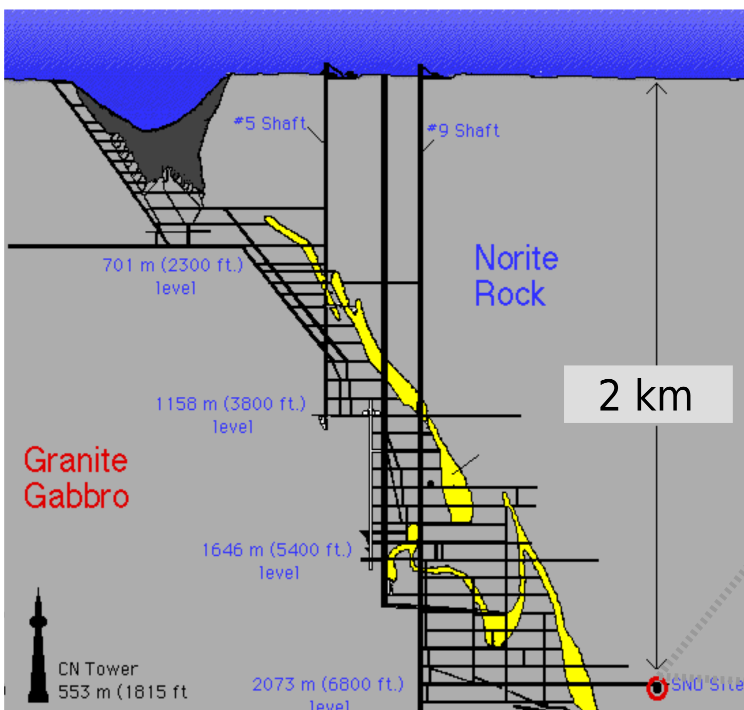
2020 - 2024

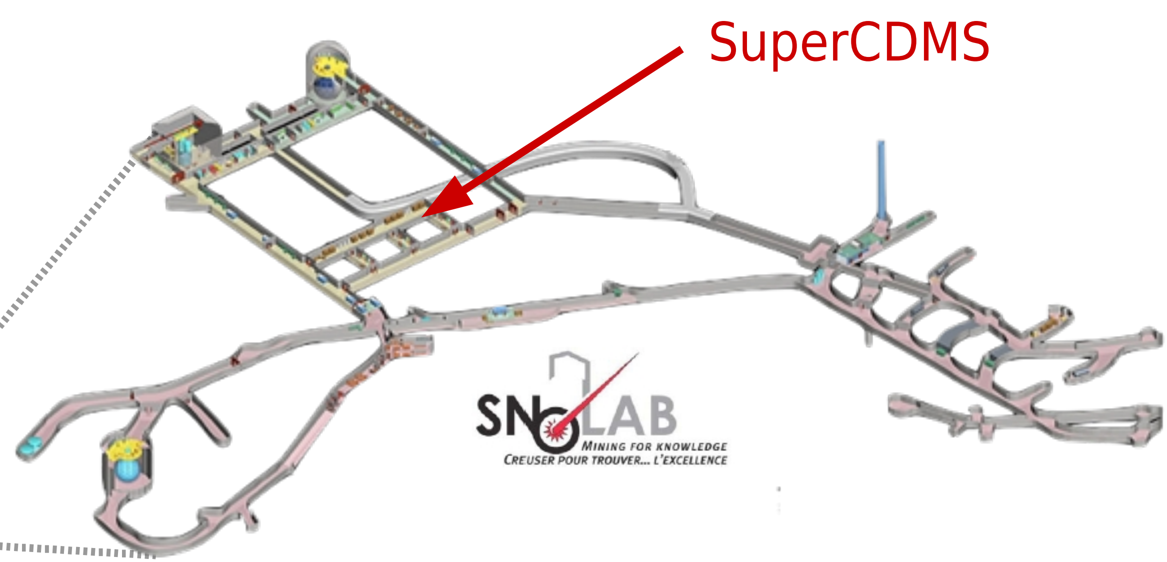
2024 - ...

SNOLAB:
~2000 m
~6000 mwe

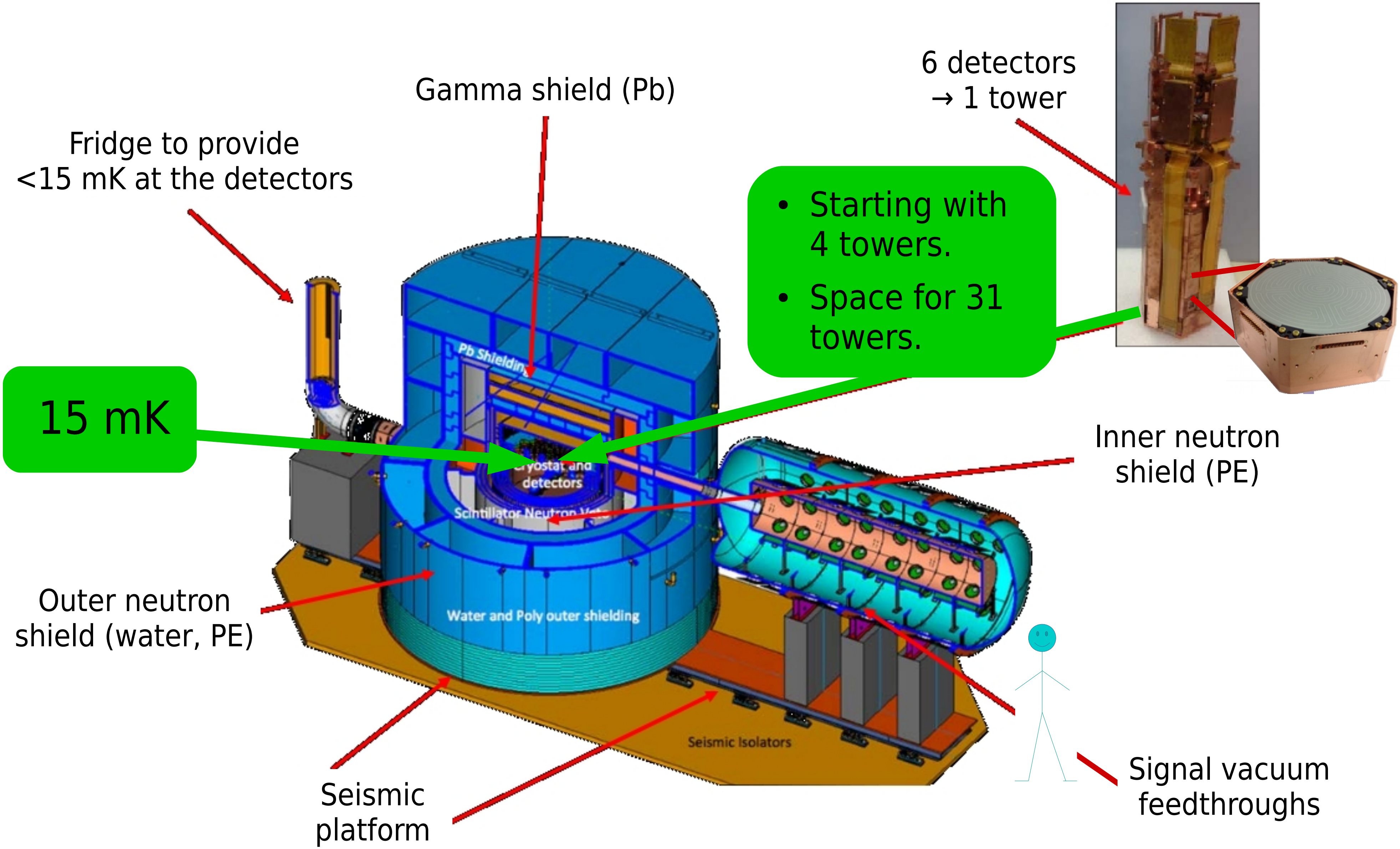
SuperCDMS AT SNOLAB

- Greater Sudbury, Ontario.
- ~2 km deep underground in an active mine.
  - ~6000 mwe overburden.
- Cleanroom class 2000.
- Home to ~10 experiments.

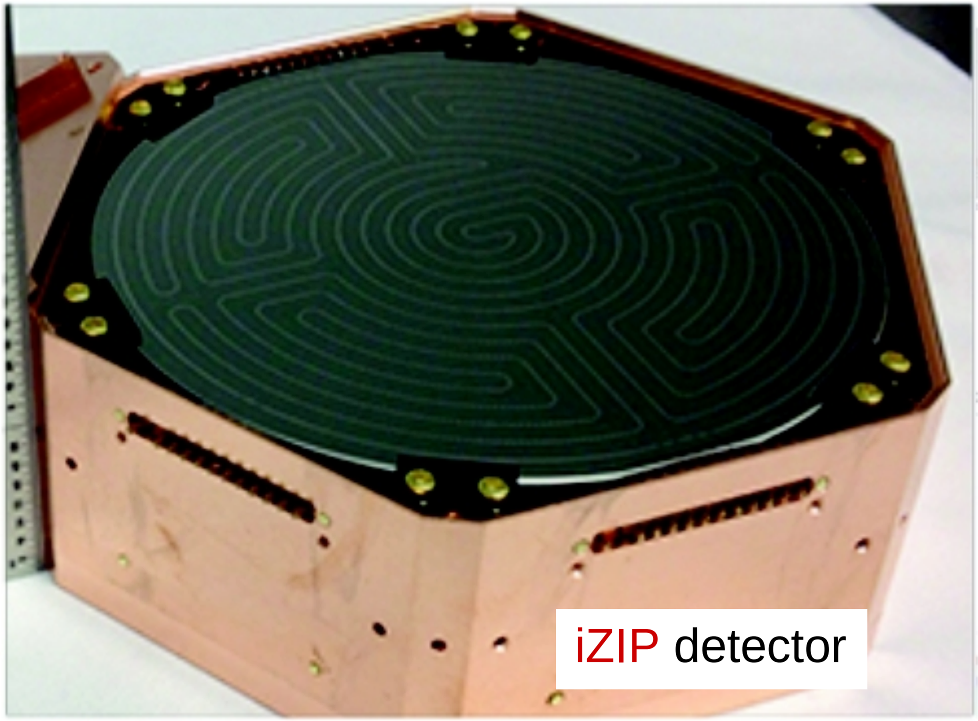


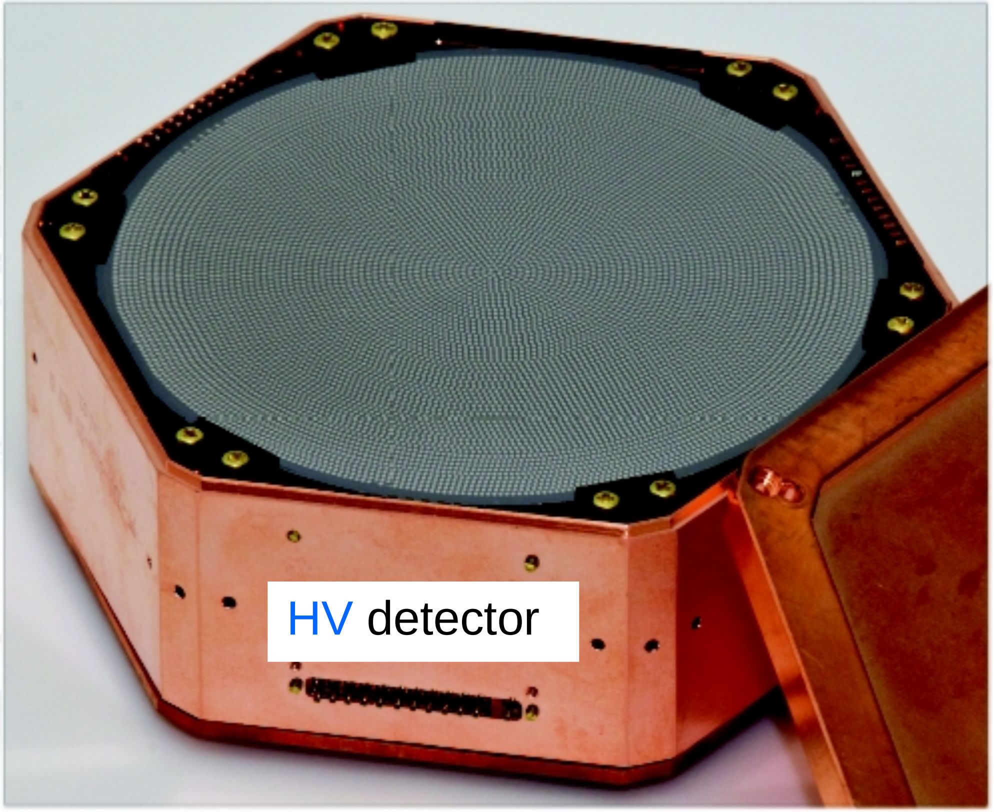


THE SuperCDMS EXPERIMENT



THE SuperCDMS DETECTORS



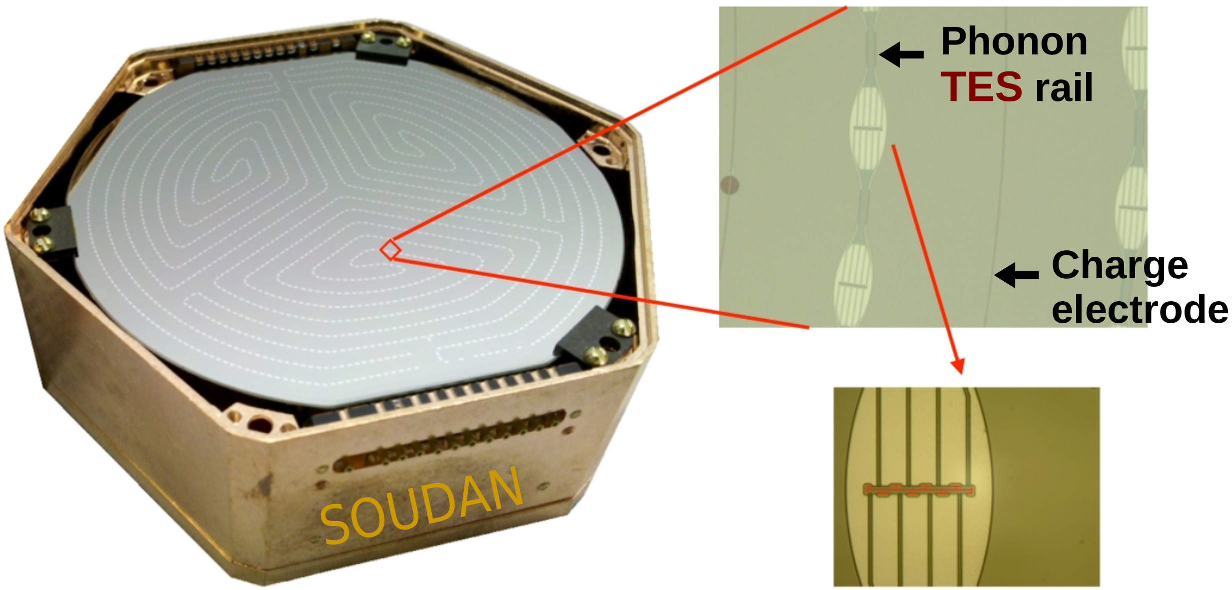


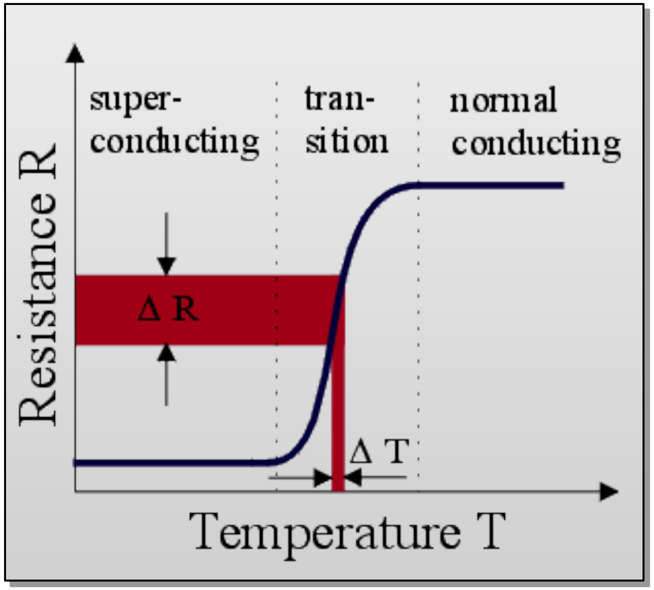
- Size of about an Ice Hockey puck.

- Two crystal types:
  - **Germanium**: 1.4 kg per detector.
    ~ 25 kg total.
  - **Silicon**: 0.6 kg per detector.
    ~ 3.6 kg total.

- Two detector types:
  - 12 iZIP detectors.
  - 12 HV detectors.

PHONON SIGNAL



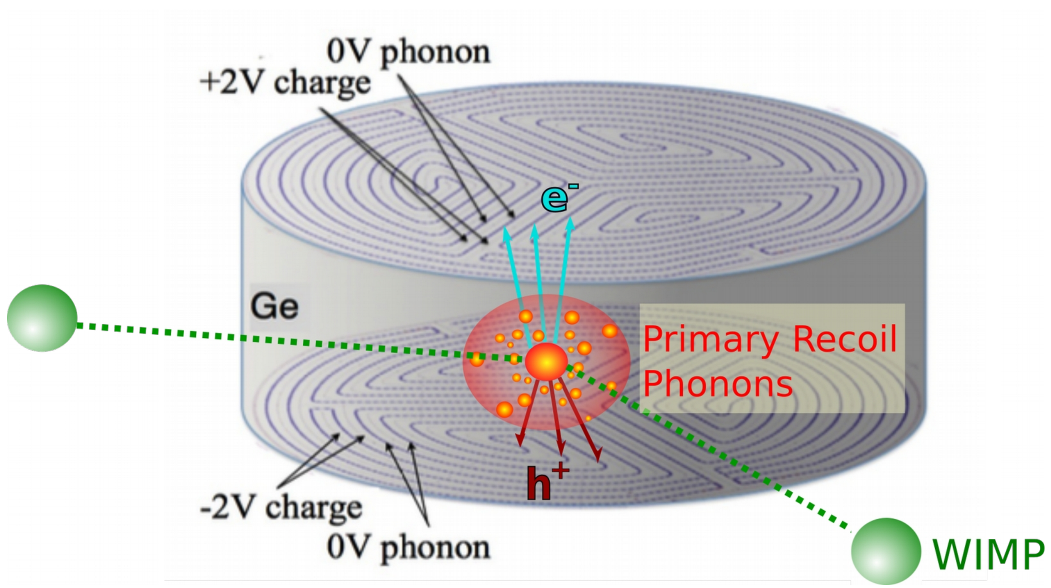


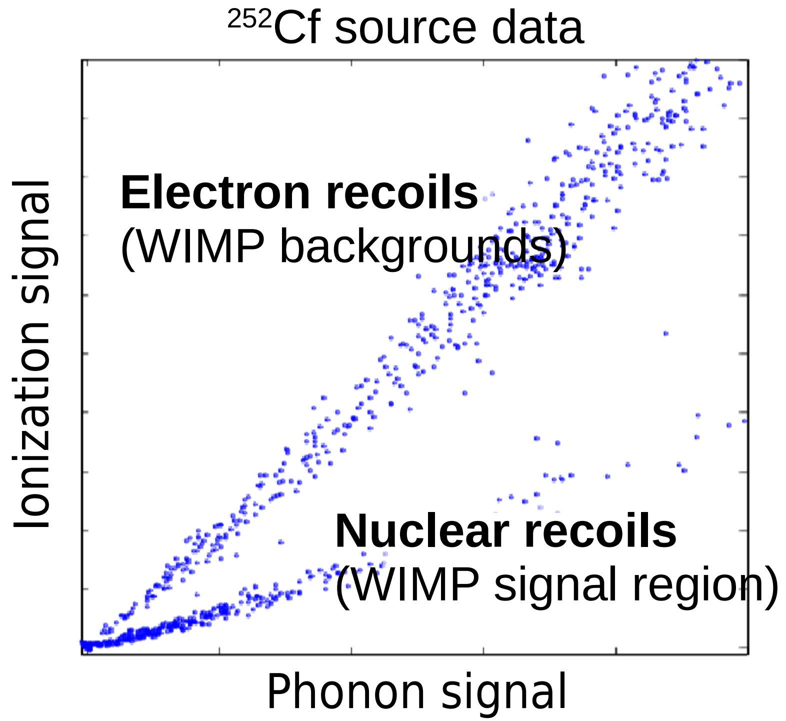
$$\Delta T = \frac{\Delta E}{C(\,T\,)}$$

- Energy deposition Δ*E* heats crystal.
- Heat capacity *C*(*T*) of crystal ~ T^3.
  - Sensitive to small Δ*E* at cryogenic temperatures.
- Thermal vibrations in crystal: phonons.
- Transition Edge Sensor (TES):
  - Superconducting metal film (W) with T_c ~ 50 mK.
  - Small Δ*T* yield large changes in resistance Δ*R*.

iZIP DETECTORS

interleaved **Z**-Sensitive **I**onization and **P**honon detectors.



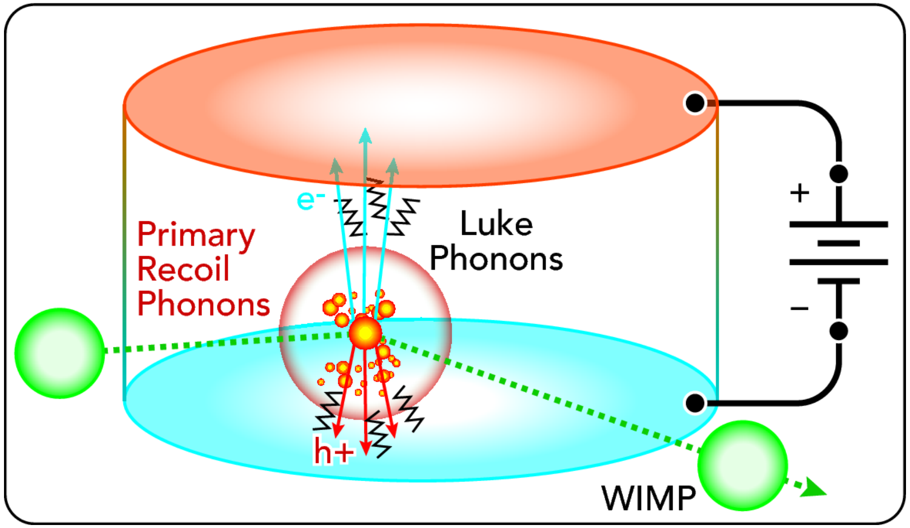


- **Phonon signal**: Heat / energy deposition.
- **Ionization signal**: e^-/h^+ pair production.
  - Reduced for nuclear recoil.
- **Combination**: Efficient discrimination between nuclear and electron recoil events.

HV DETECTORS

CDMSlite: **l**ow **i**onization **t**hreshold **e**xperiment.

$V_{bias} \sim 100$ V

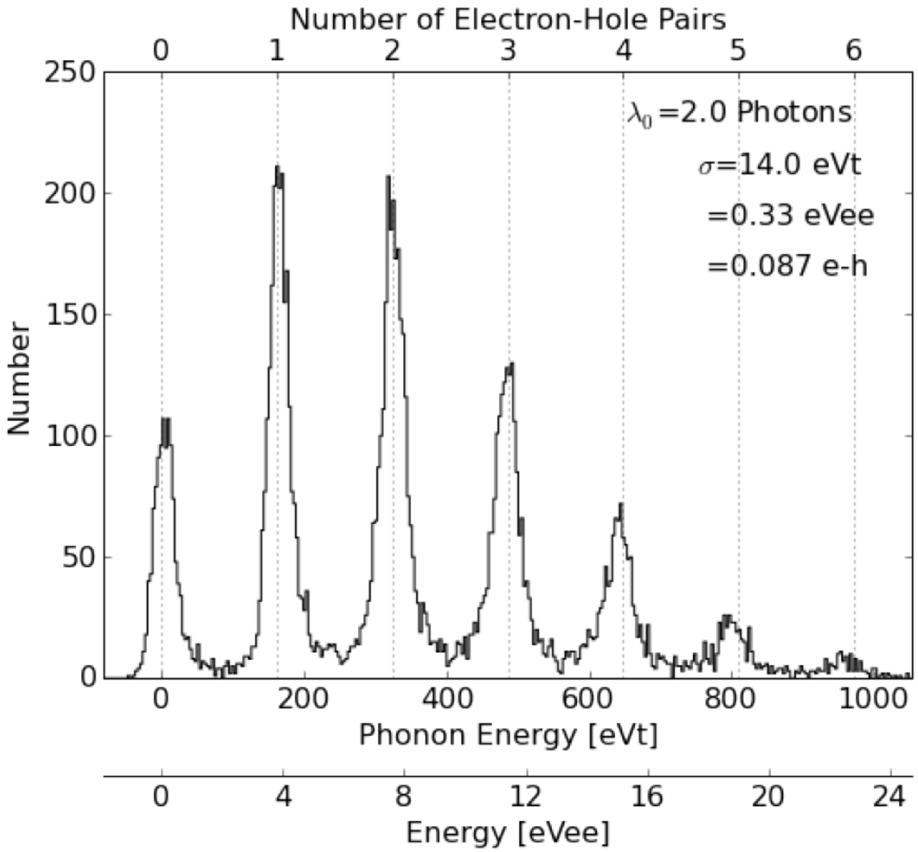


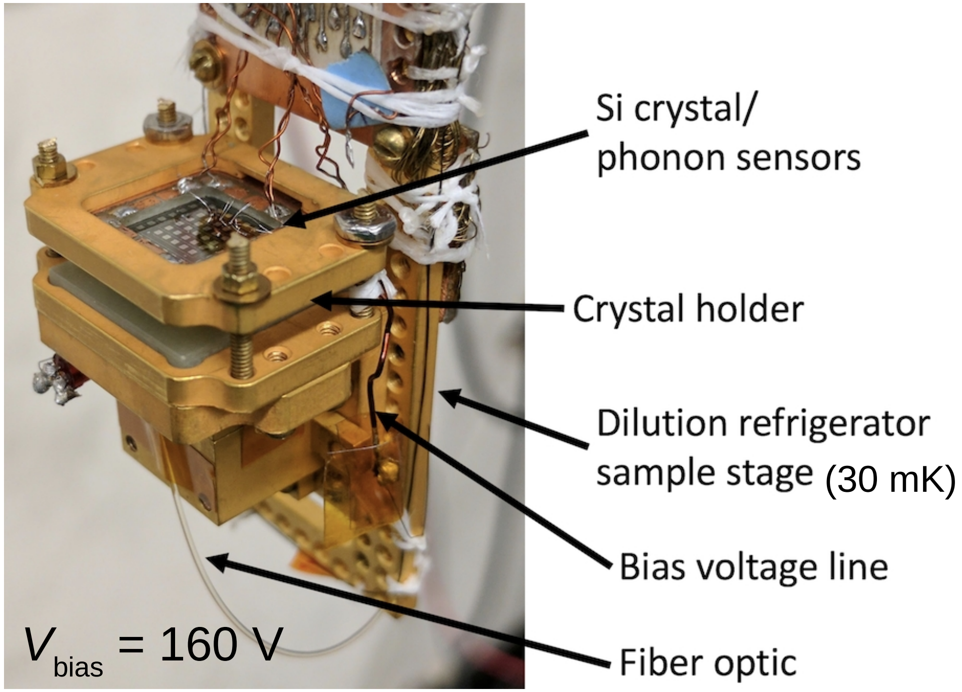
- e^-/h^+ produce extra phonons as they drift to electrodes.
  - Neganov-Trofimov-Luke phonons.
  - Large V_{bias} => large **phonon amplification of ionization signal**.

- **Effective threshold of one/few e^-/h^+ pairs.**
- Trade-off: no discrimination between electon recoil and nuclear recoil.

SILICON HVeV QUANTIZATION DEVICE

R.K. Romani et al., Appl.Phys.Lett. 112 (2018) 043501





- Single e/h-pair sensitivity recently demonstrated in 0.93 g Si chip by members of the SuperCDMS Collaboration.
- Threshold at band gap allows to reach sub-MeV WIMP masses!

RECAP DETECTORS

iZIP

- 1. default detector.
- Phonon and charge signal readout.
- **Efficient Electron Recoil / Nuclear Recoil discrimination.**

HV

- 2. default detector.
- Phonon amplification of charge signal.
- Phonon signal readout only.
- **Low threshold.**

HVeV

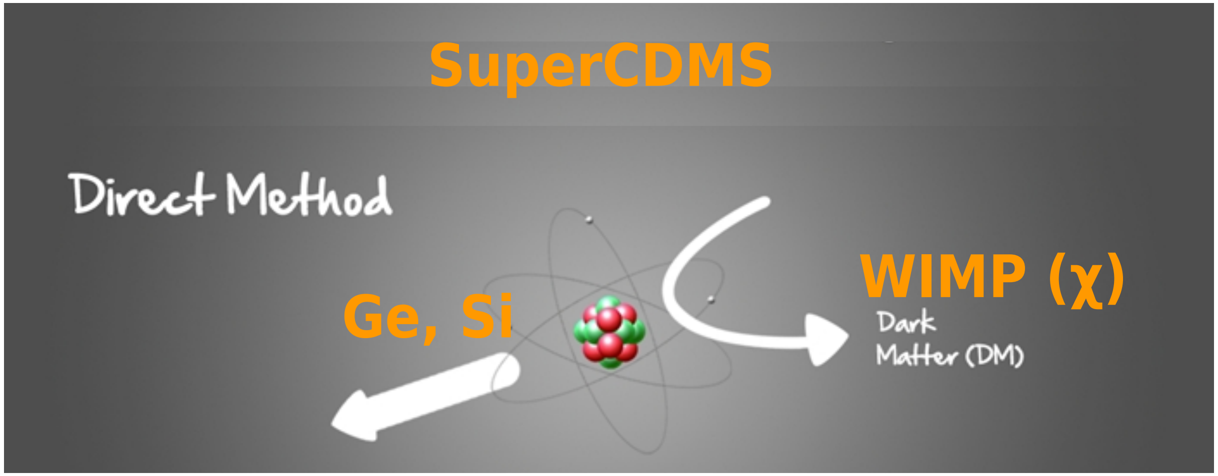
- Demonstrator chip.
- Phonon amplification of charge signal.
- Phonon signal readout only.
- **Ultra-low threshold (band gap).**
- **Single e/h-pair sensitivity.**

WIMP SEARCH

AT SuperCDMS

Signature: **Nuclear Recoil**.

WIMP - NUCLEON SCATTERING

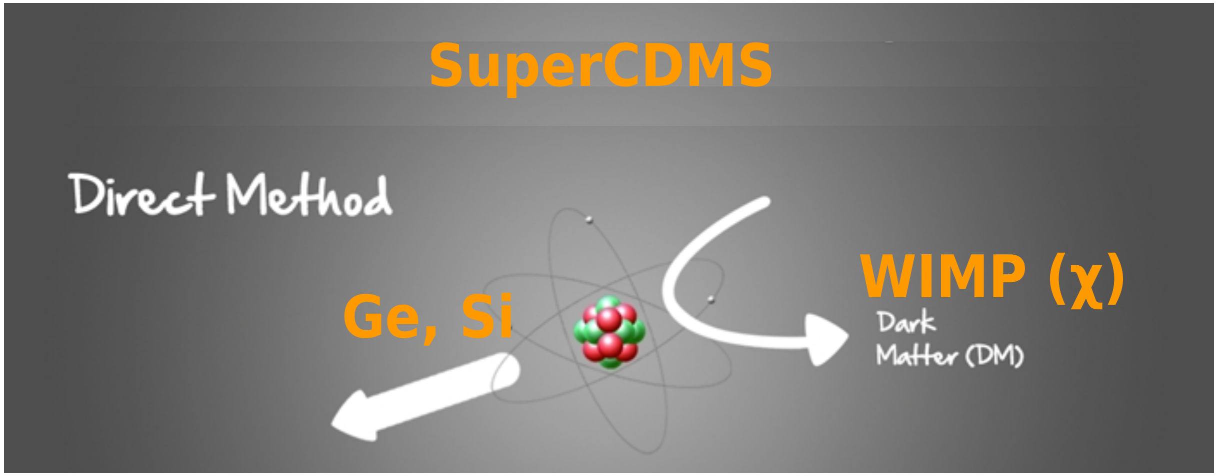


Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

Recoil energy of nucleus.

WIMP - NUCLEON SCATTERING



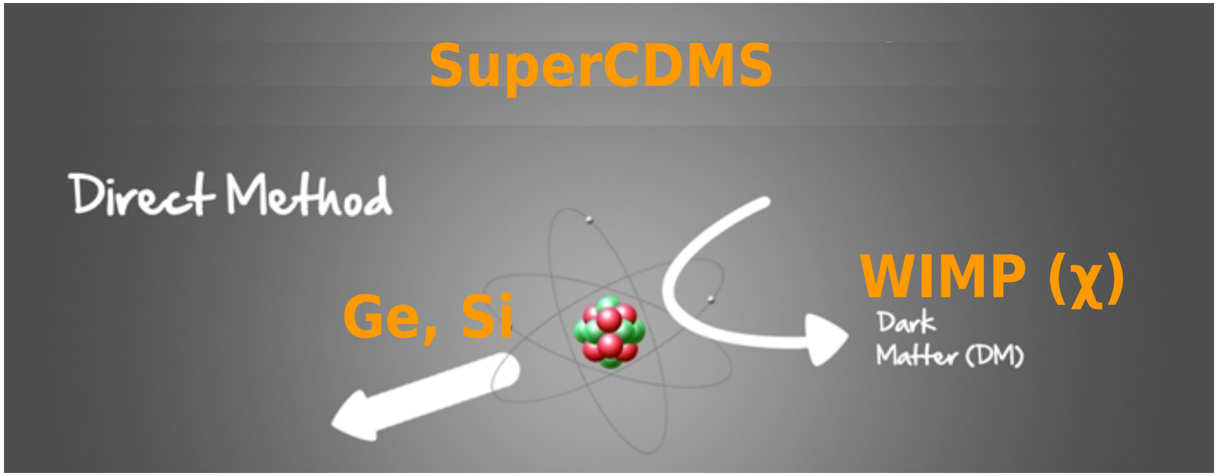
astrophysics properties

Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

ρ_0: Local dark matter density.
T: Integral over local dark matter velocity distribution.
v_o: Large-radius asymptotic Galactic circular velocity.

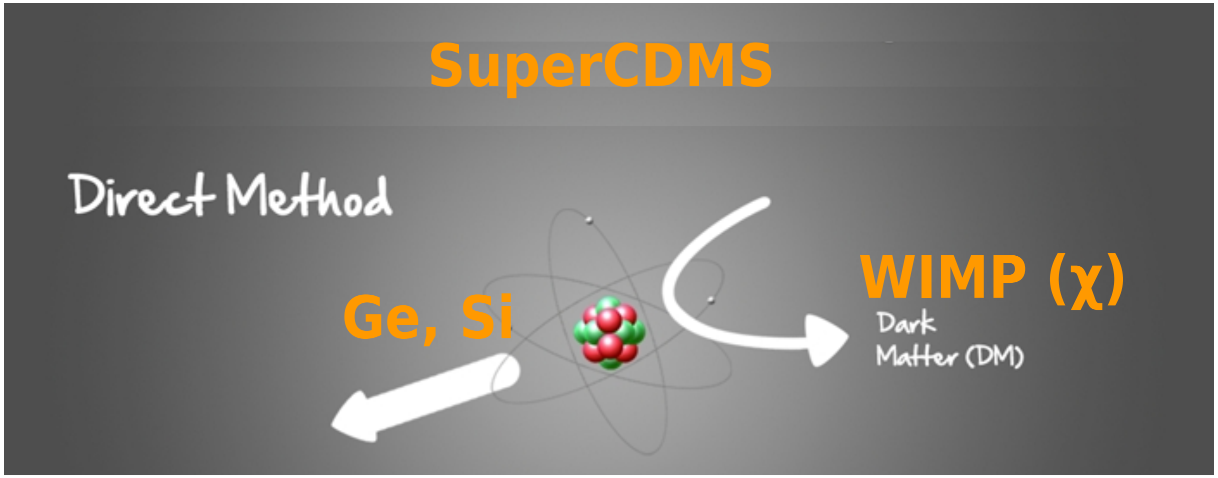
WIMP - NUCLEON SCATTERING



		nuclear structure	astrophysics properties
Interaction Rate [events/keV/kg/day]	$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi}$	$\frac{F^2(E_R)}{m_r^2}$	$\frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$

F: Form factor (quantum mechanics of interaction with nucleus).
m_r: Reduced mass (WIMP, nucleon).

WIMP - NUCLEON SCATTERING



	particle theory	nuclear structure	astrophysics properties

Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

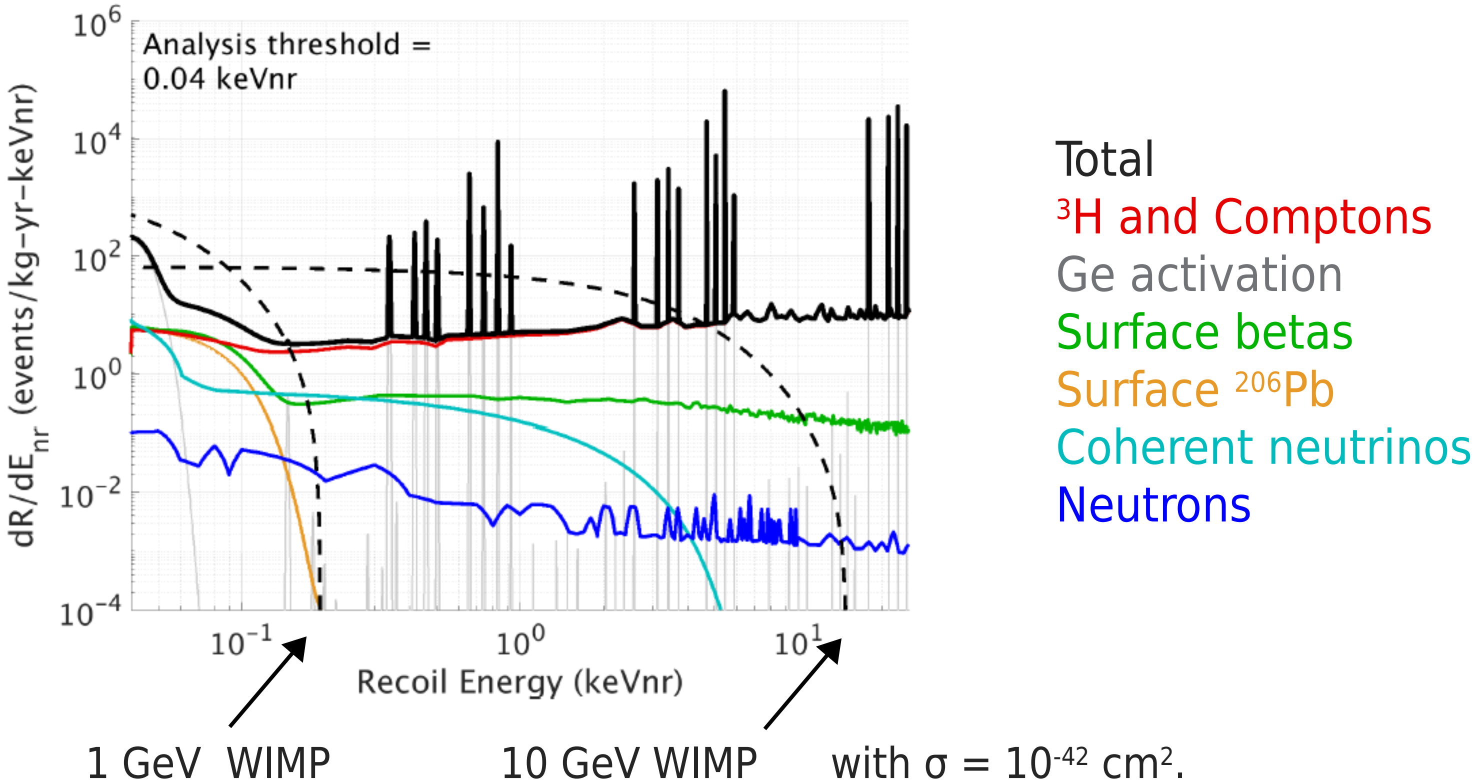
σ_o: WIMP-nucleon scattering cross-section.

m_χ: WIMP mass.

WIMP Nuclear Recoil SPECTRUM

- **Spin-independent (SI) elastic WIMP-nucleon scattering.**
  - **Primary Dark Matter search.**
- Spin-dependent (SD) elastic WIMP-nucleon scattering.
- Dominant backgrounds have Electron Recoil signature.

Prediction in
Ge HV detectors
after fiducial cuts:

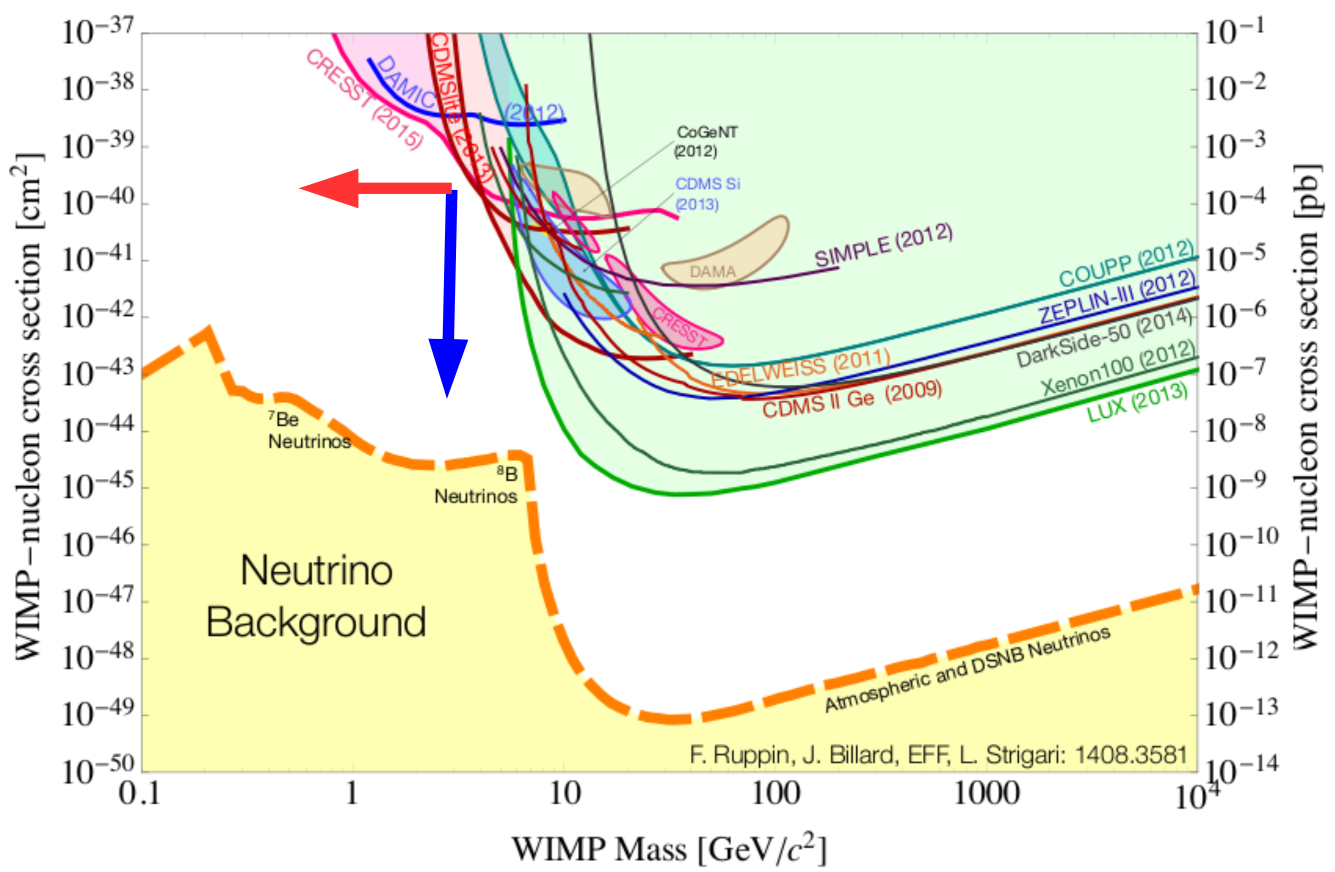


with $\sigma = 10^{-42}$ cm^2.

WIMP - NUCLEON SCATTERING REACH

Lower threshold

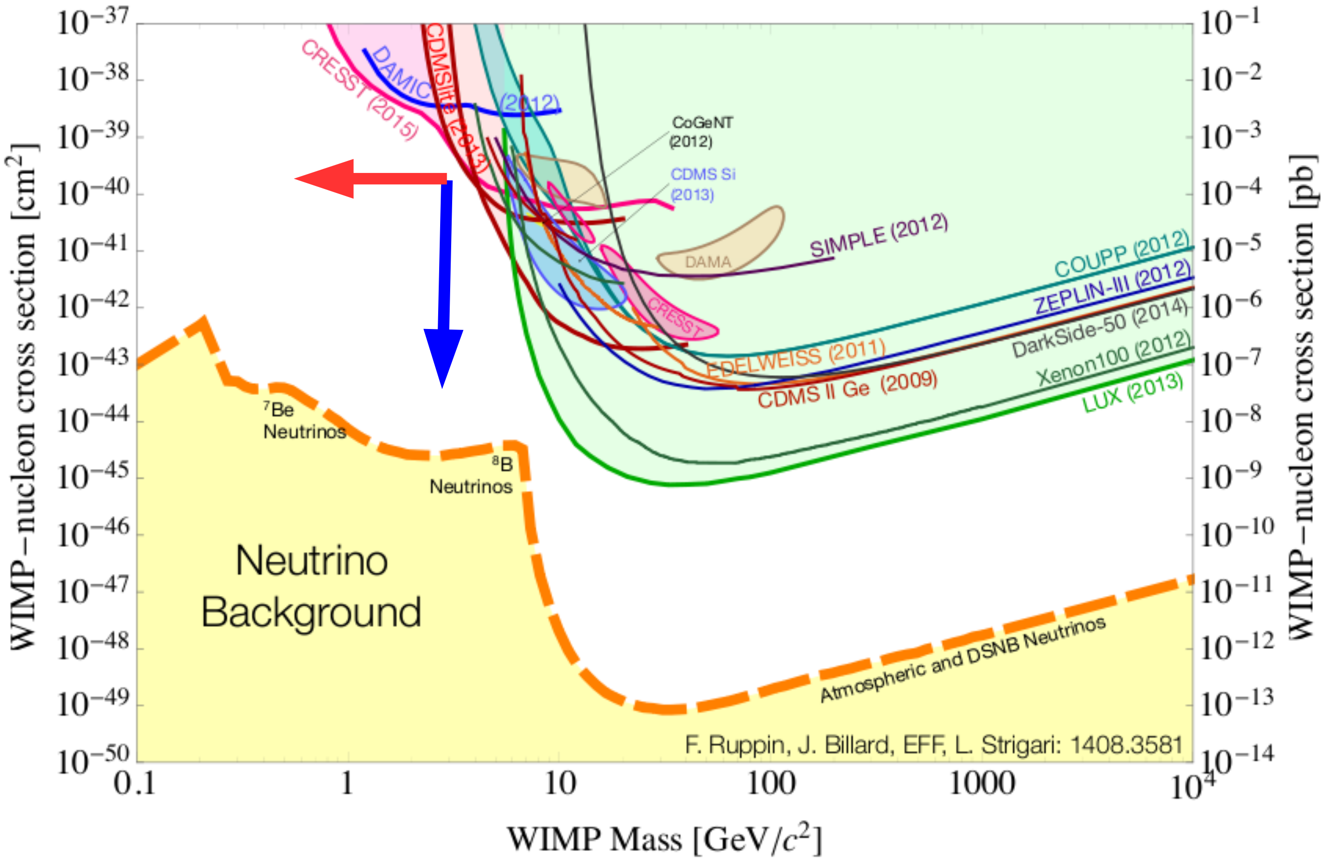
Lower background + more exposure



WIMP - NUCLEON SCATTERING

Lower threshold

Lower background + more exposure



→ **Build dedicated low threshold detectors** (HV detectors).

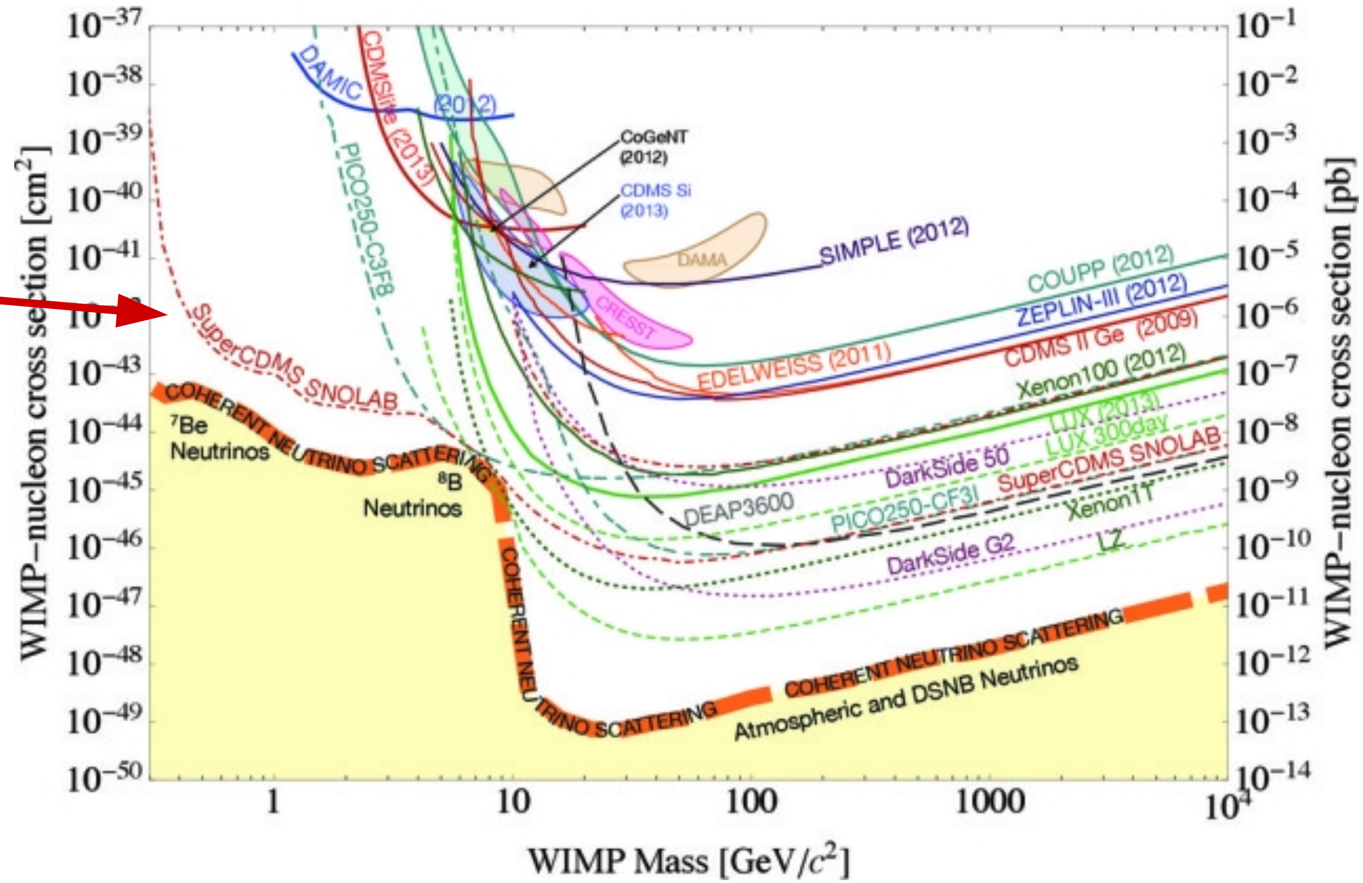
→ **Go deeper:** 6000 mwe (SNOLAB) instead of 2000 mwe (Soudan).

→ **Build bigger:** 100 kg·yr Ge + 14.4 kg·yr Si instead of 6.8 kg·yr Ge.

MAIN SCIENCE GOAL OF SuperCDMS

SuperCDMS projected sensitivity

(2020-2024)

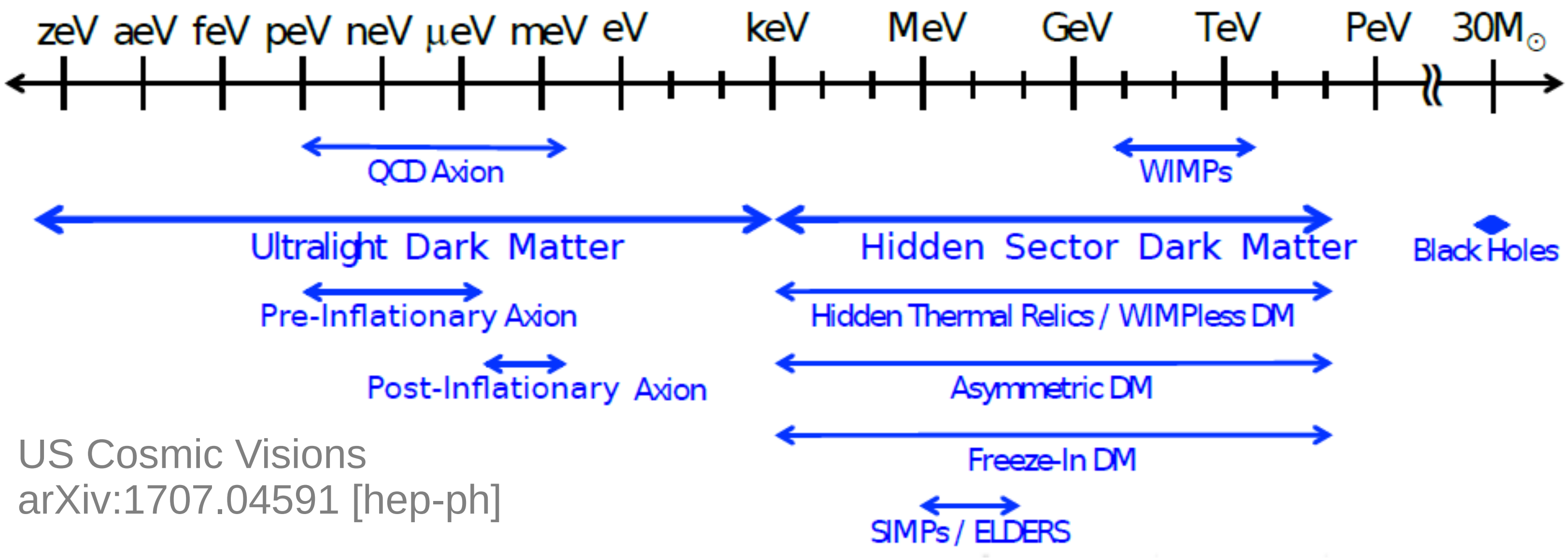


- Observe WIMPs of mass $m_\chi \sim$ GeV/c².
- Or (if nature is less generous):
  - Improve sensitivity x10 for $m_\chi \leq 10$ GeV/c² over existing limits.
  - Probe WIMP masses well below $m_\chi = 1$ GeV/c².

BEYOND STANDARD WIMP SEARCH AT SuperCDMS

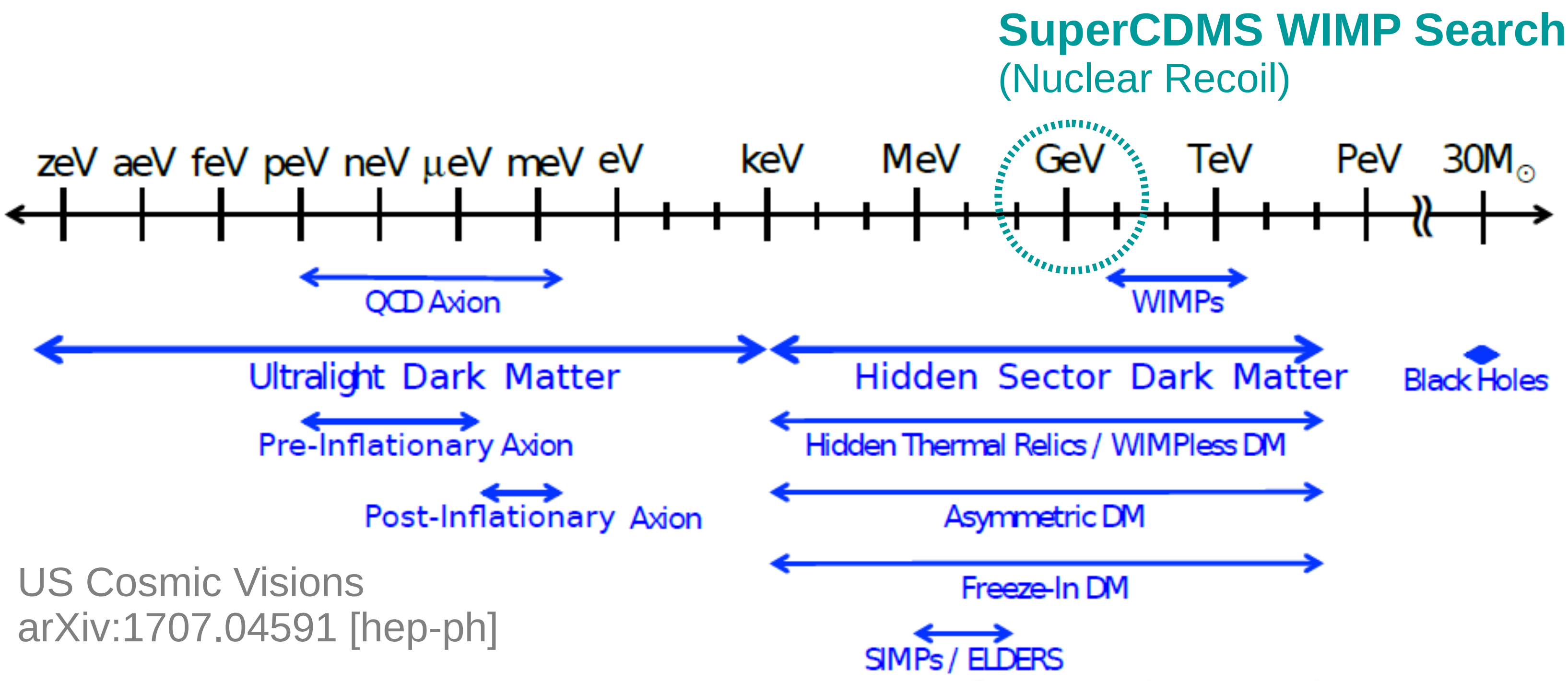
Signature: **Electron Recoil**.

DM DETECTION CHANNELS - Electron Recoil



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

DM DETECTION CHANNELS - **Electron Recoil**

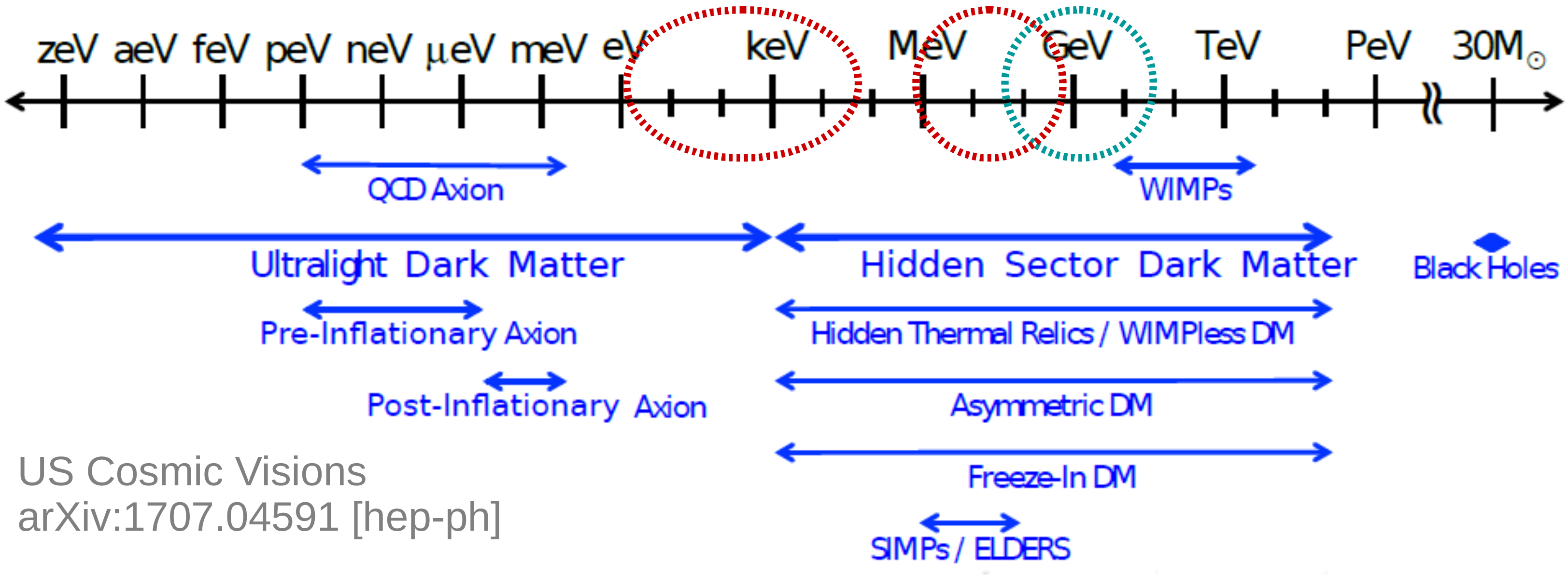


US Cosmic Visions
arXiv:1707.04591 [hep-ph]

DM DETECTION CHANNELS - **Electron Recoil**

SuperCDMS DM Search
(Electron Recoil)

SuperCDMS WIMP Search
(Nuclear Recoil)



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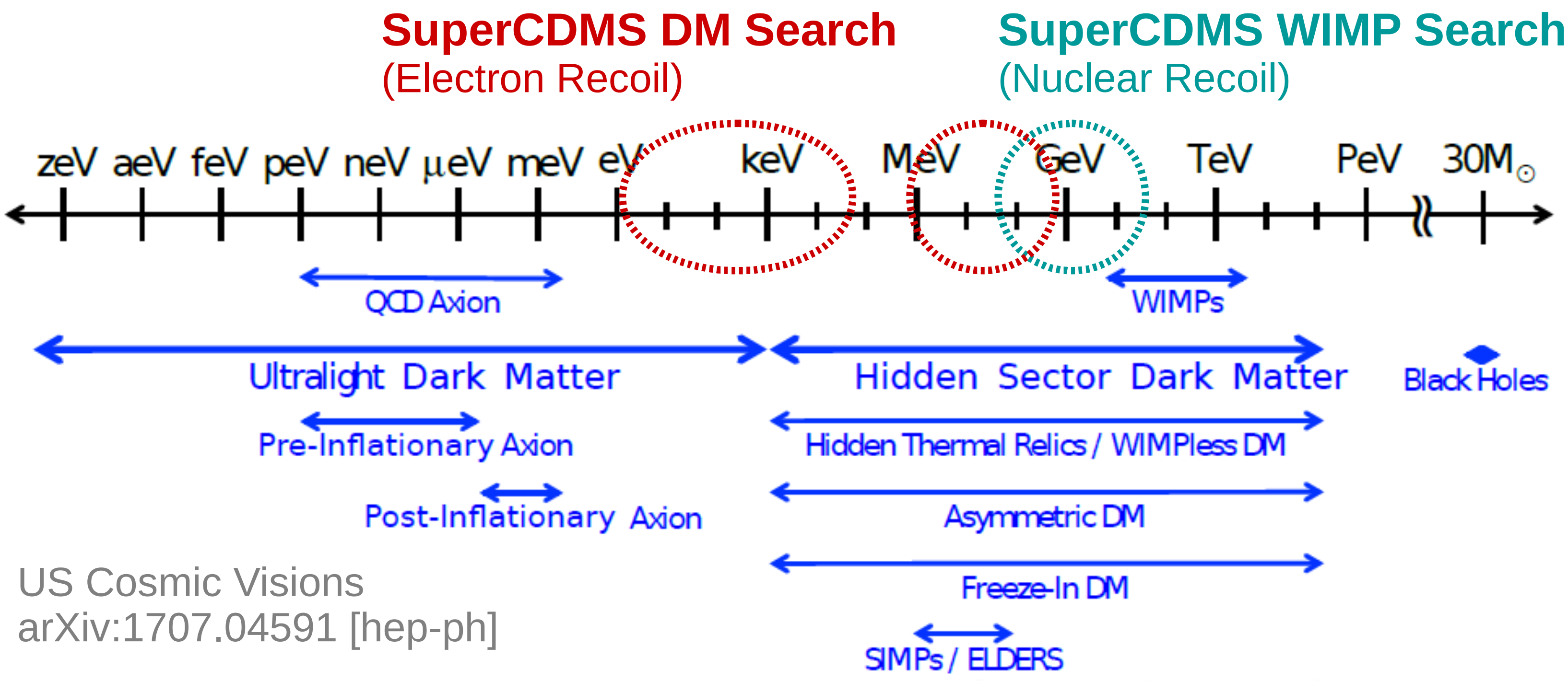
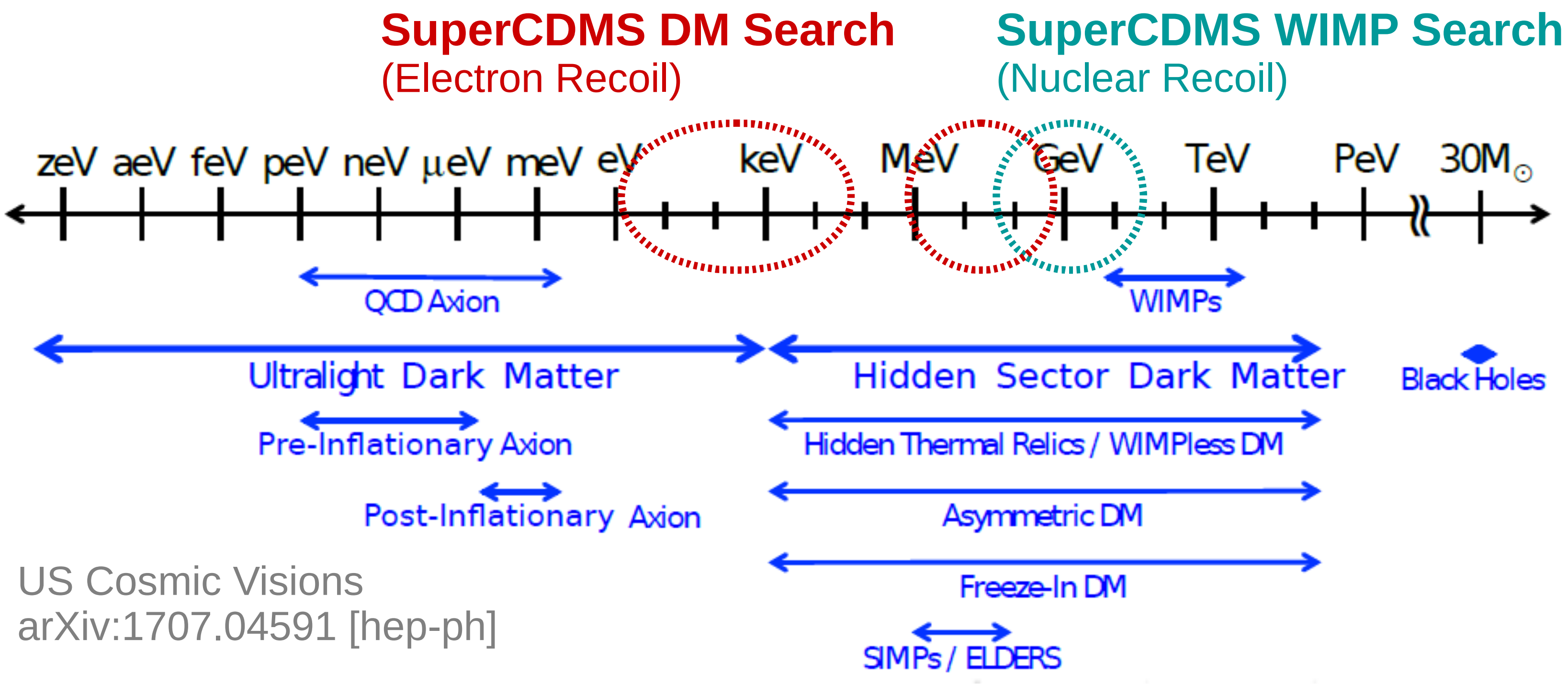
DM DETECTION CHANNELS - Electron Recoil



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

- Absorption of relic dark photons.
- Absorption of relic Axion-Like Particles (ALPs).
- Coherent Primakoff conversion of solar ALPs.
- “Bremsstrahlung” after inelastic DM-nucleon scattering.
- DM-electron scattering.

DM DETECTION CHANNELS - Electron Recoil



- Absorption of relic dark photons.
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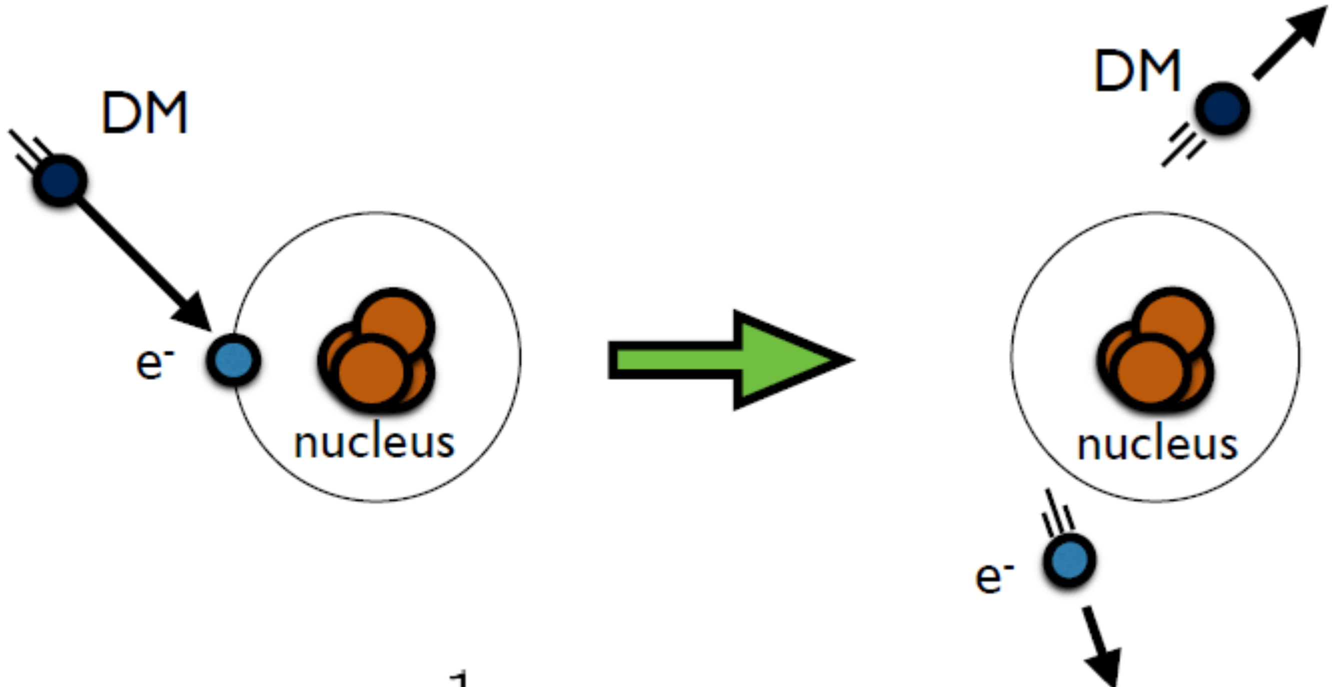
DARK MATTER - ELECTRON SCATTERING

From R. Essig



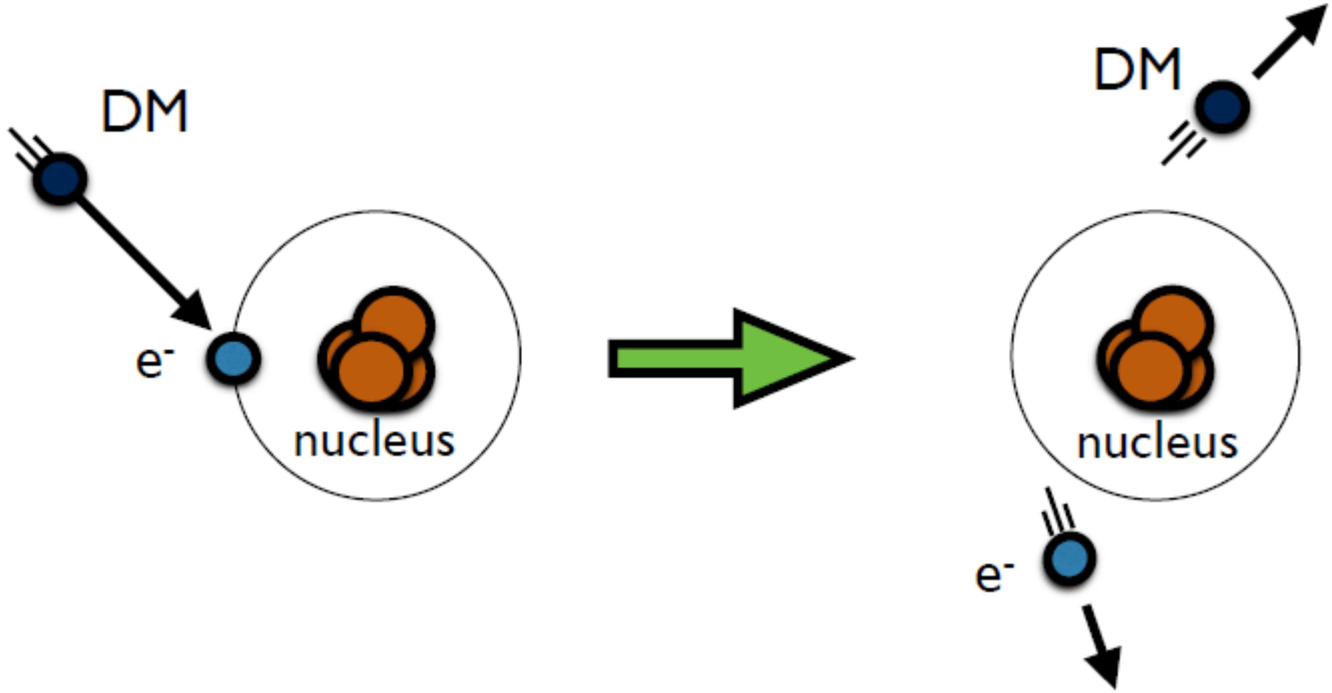
$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > E_{\rm bind.}$$ of O(10 – 100 eV)

$$v_{\rm DM} \lesssim 800 \text{ km/s} \implies m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{E_{\rm bind.}}{1 \text{ eV}}\right)$$

$\implies$ **m_{DM} << GeV accesible.**

DARK MATTER - ELECTRON SCATTERING

From R. Essig



- Typical momentum transfer (outer shell): $q_{typ} \sim \alpha m_e \sim 4$ keV.
- Bound e^- does not have definite momentum.
- Momentum transfer higher than 4keV possible, if q on the tail of the e^- wavefunction.

PRODUCTION RATE

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\,\mathrm{d}q\,|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

atomic form factor:

$$|f(k,q)|^2 = \left|\int d^3x\,\psi_f^*(\vec{x})\psi_i(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

Open source tools available: **Quantum-Espresso**, **QEdark**.

arxiv.org:1509.01598v2

PRODUCTION RATE

DM model parameters **solid state physics**

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\,\mathrm{d}q\,|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

$\overline{\sigma}_e$: DM-electron scattering cross-section.

$\mu_{\chi e}$: Reduced DM electron mass.

PRODUCTION RATE

DM model parameters **solid state physics**

$$\frac{d\langle\sigma v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\, dq\, |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

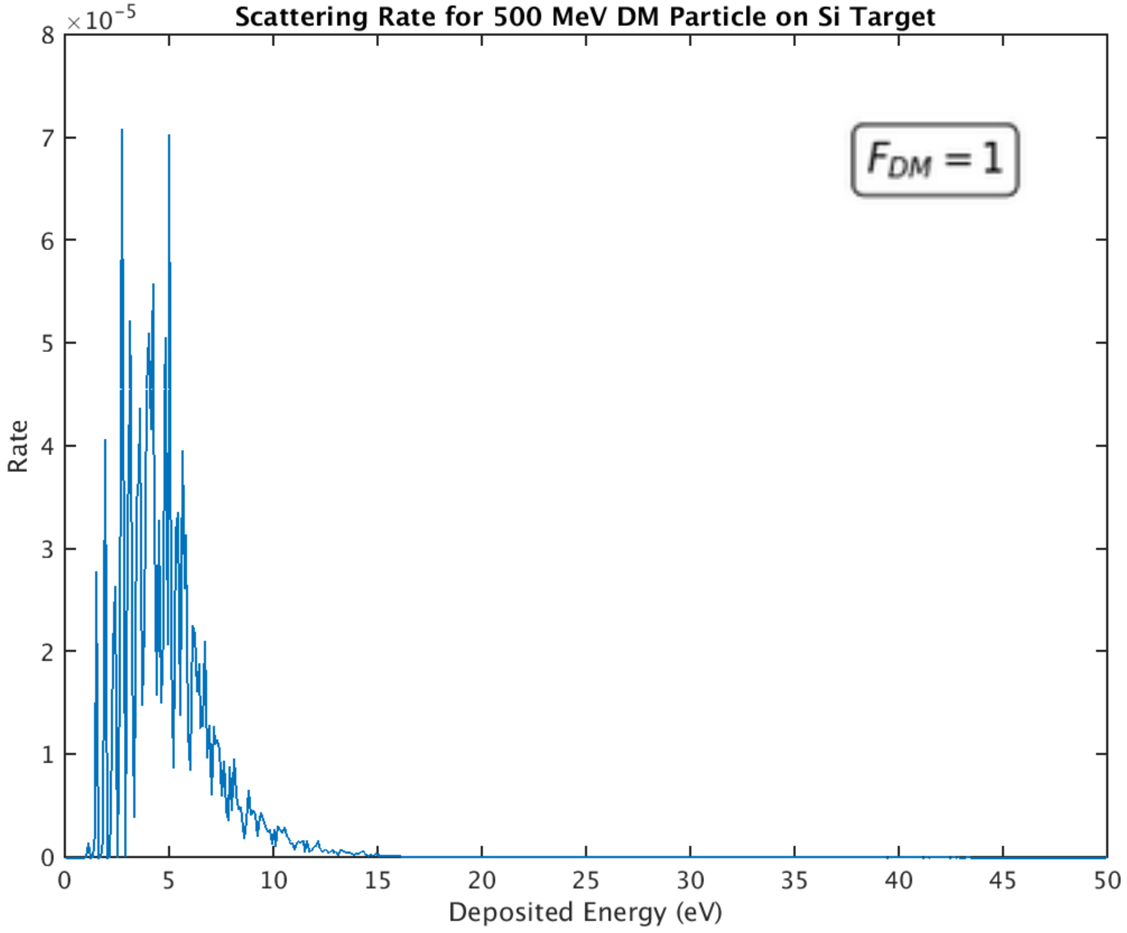
Dark Matter form factor

$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2}$$

- "Heavy" A' (>> αm_e).
  - $m_{A'} \sim m_{DM}$
  - $F_{DM}\,(q) \approx 1$.
- Generates relic DM density via freeze-out.

- "Ultra-Light" A' (<< αm_e).
  - $m_{A'}$ << keV.
  - $F_{DM}\,(q) \sim 1/q^2$.
- Generates relic DM density via freeze-in.

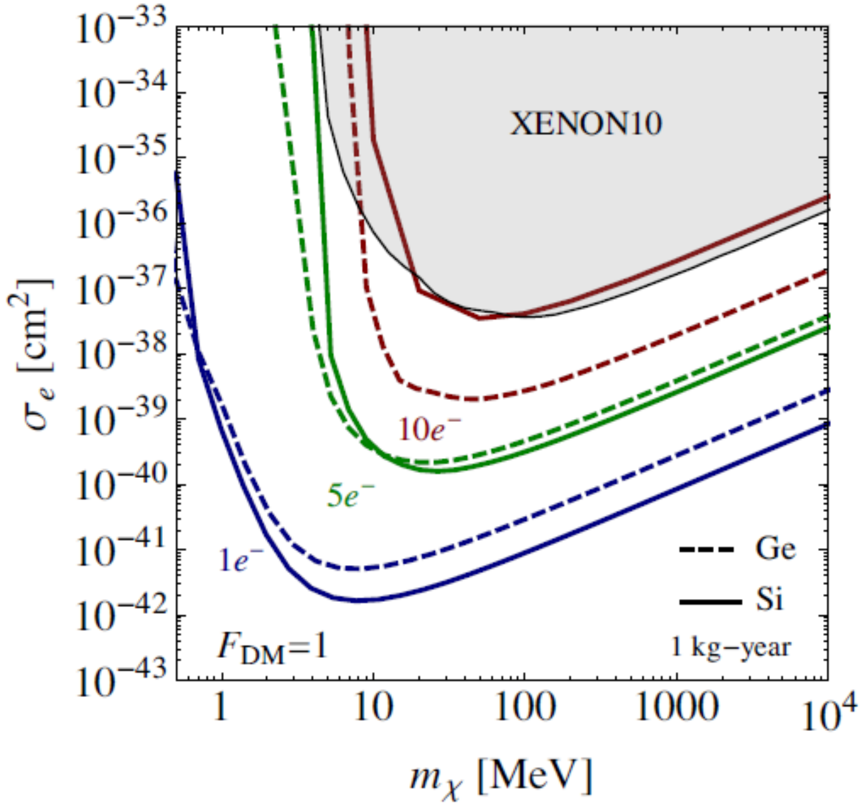
Sub-GeV WIMP Electron Recoil SPECTRUM



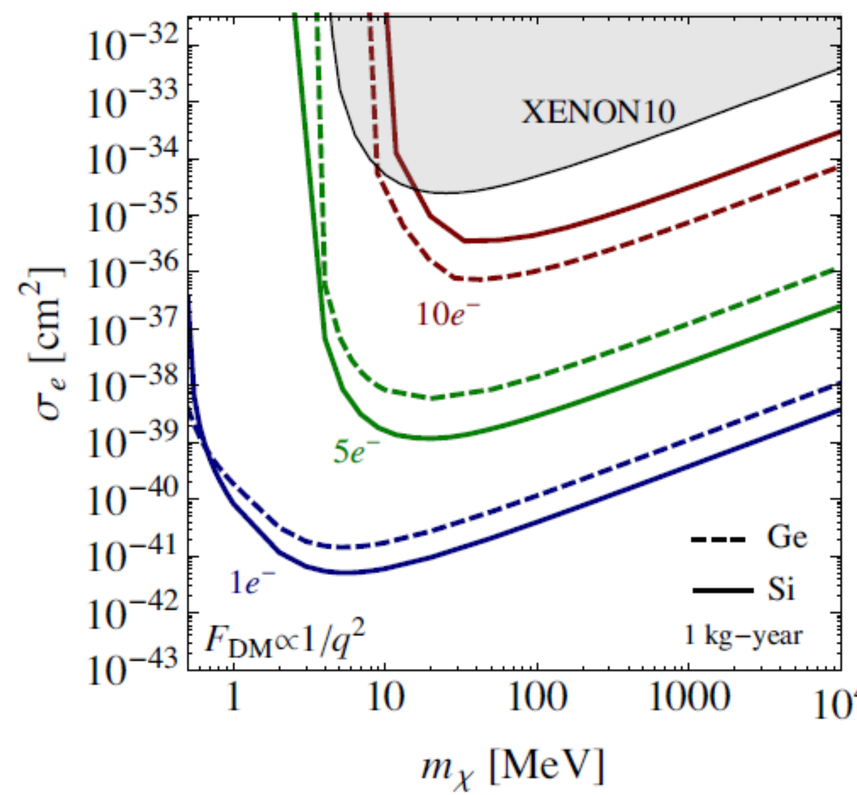
Threshold matters!

POTENTIAL SENSITIVITY

Predicitions by Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu:



$$F_{\mathrm{DM}} = 1$$

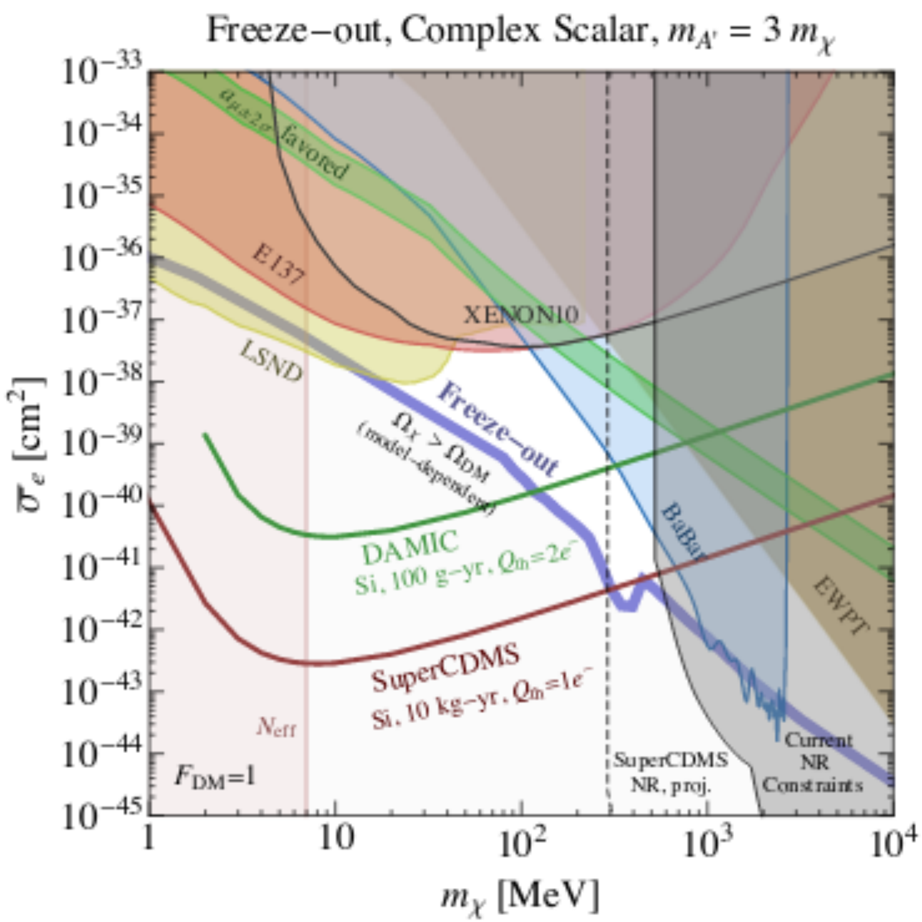


$$F_{\mathrm{DM}} \propto 1/q^2$$

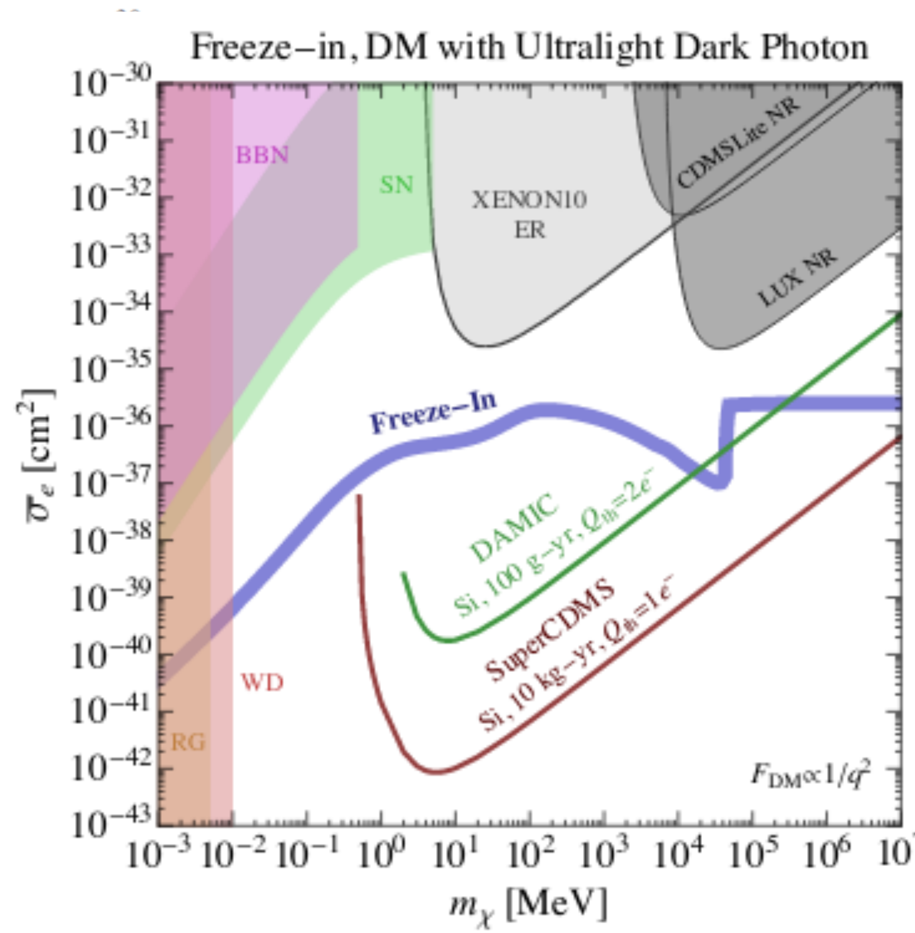
POTENTIAL SENSITIVITY

Predicitions by Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu:

Probe freeze-in/-out target.

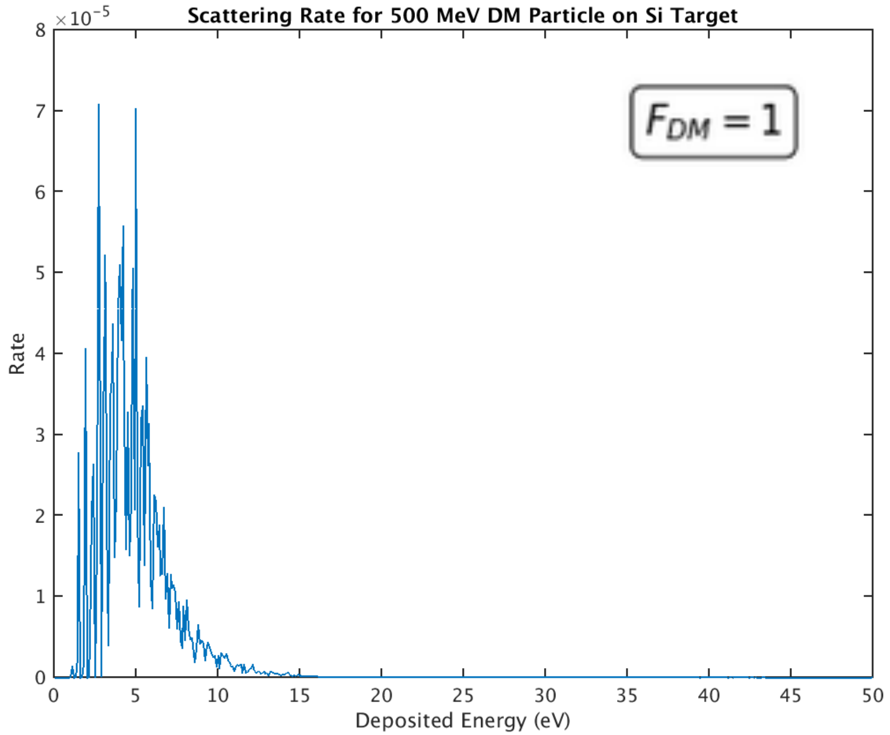


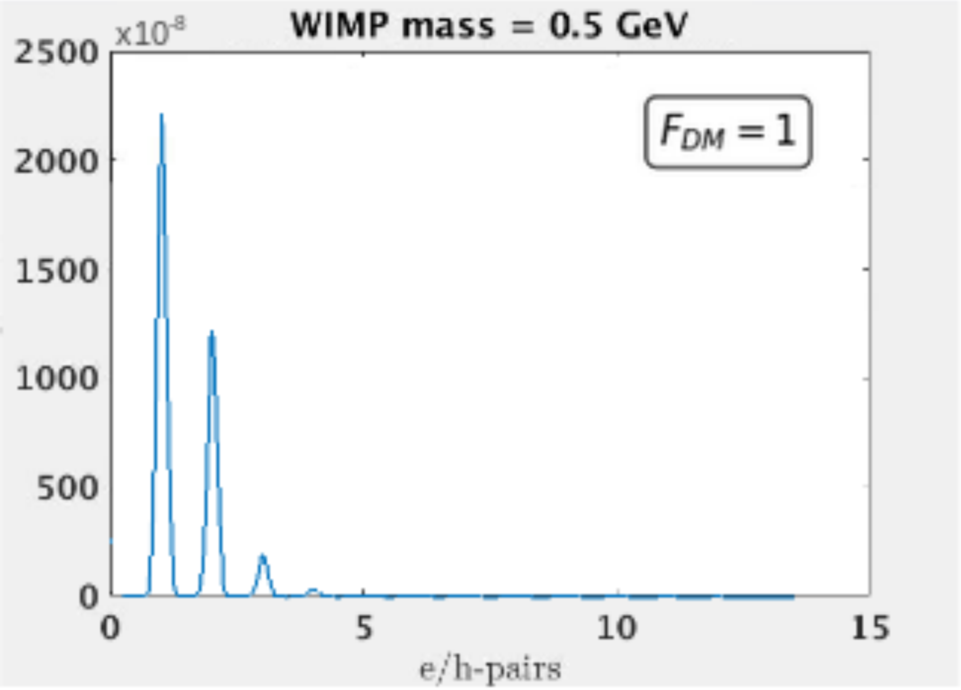
$$F_{\rm DM} = 1$$



$$F_{\rm DM} \propto 1/q^2$$

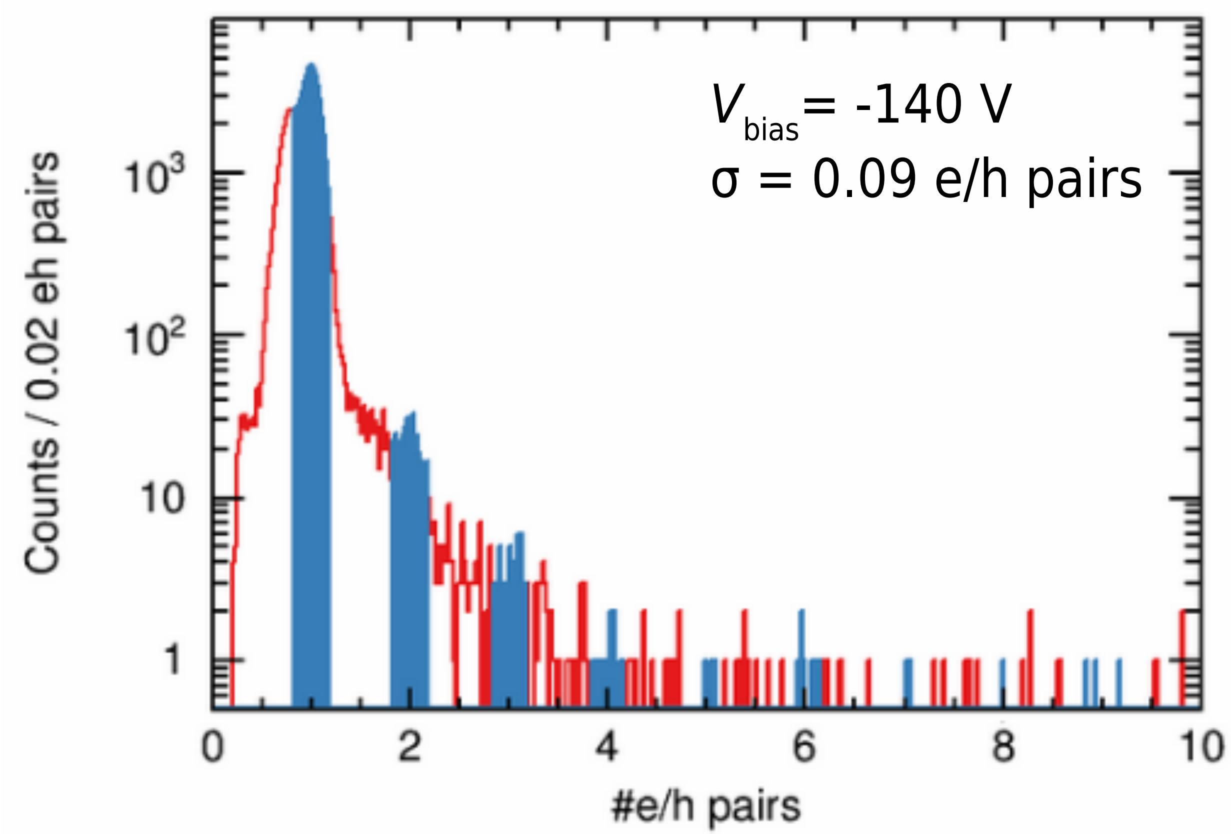
Sub-GeV WIMP **Electron Recoil** SPECTRUM





Quantized DM Spectrum.

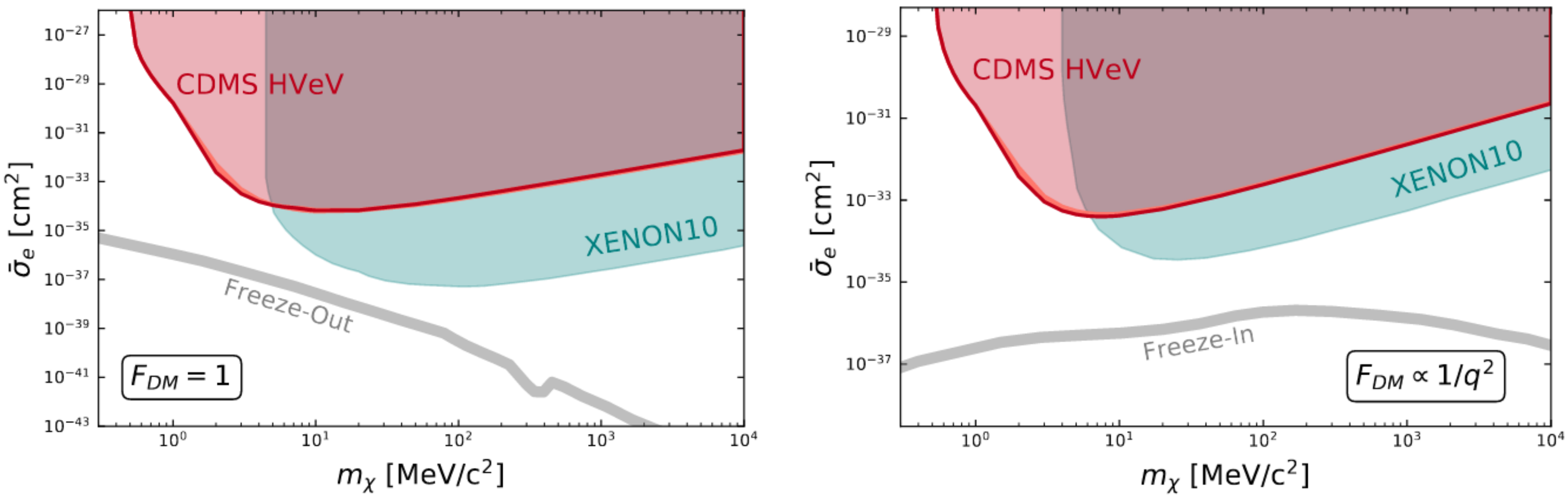
CDMS HVeV light-WIMP SEARCH



- No background subtraction.
- DM signal is quantized:
  => Only considering e/h pair peak regions within ∓2σ.
- ~0.5 g-day exposure.

CDMS HVeV LIMITS (90% CL)

SuperCDMS Collaboration, arXiv:1804.10697
submitted to PRL



- Covering new parameters space (direct searches) ~0.5 g-day exposure!

CONCLUSION

- **Dark matter** is currently one of the greatest mysteries in particle and astroparticle physics.

- Plausible canidates within the dark sector hypothesis include **WIMPs**, **ALPs** and **dark photons**.

- SuperCDMS has world-leading sensitivity to the spin-independent **WIMP - nucleon scattering** cross section σ_N at low masses.

- SuperCDMS is sensitive to ALPs and ultra-light dark photons with the potential to reach new parameter space.

- Lowering the threshold, SuperCDMS will be increasingly sensitive to **dark matter – electron scattering.**

    - **New parameter space has been reached with a demonstrator Si chip and ~0.5 g-day exposure!**