Dark Sectors 2016

Direct Detection of sub-GeV Dark Matter Primer

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prepared with input from:
Jeremy Mardon, Matt Pyle (WG conveners)
Tien-Tien Yu, Philip Schuster, and Natalia Toro

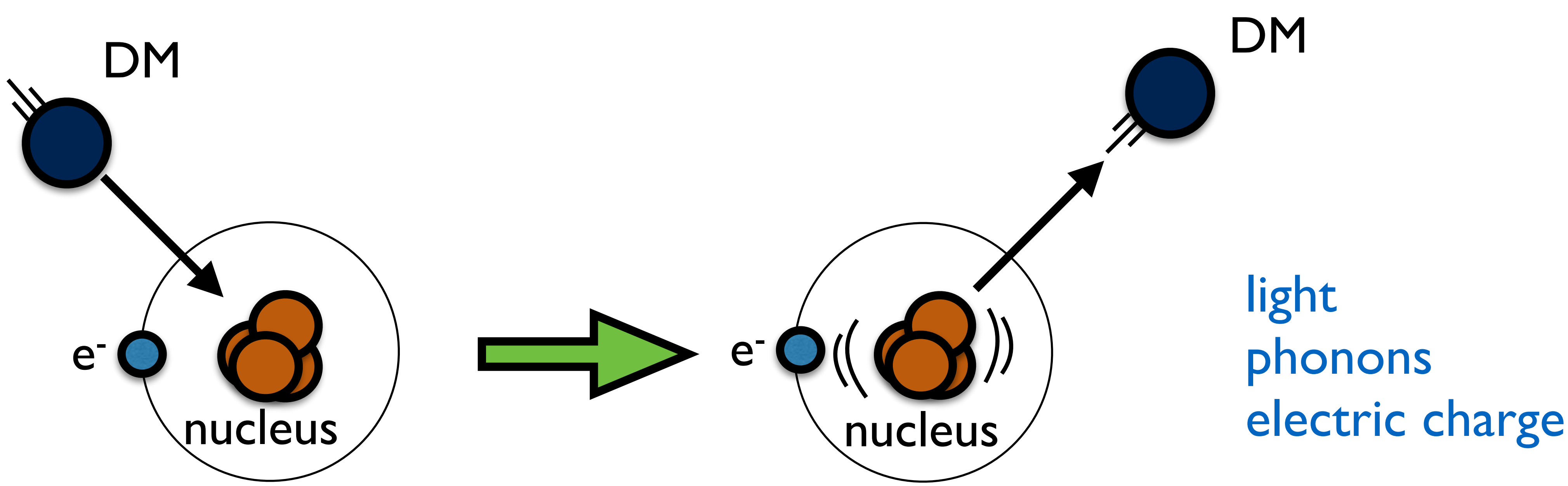
SLAC, April 28, 2016

Selected references

- RE, Mardon, Volansky, “Direct Detection of sub-GeV Dark Matter”, 1108.5383
- Graham, Kaplan, Rajendran, Walters, “Semiconductor Probes of Light Dark Matter”, 1203.2531
- RE, Manalaysay, Mardon, Sorensen, Volansky, “First Direct Detection Limits on sub-GeV Dark Matter from XENON10”, 1206.2644
- An, Pospelov, Pradler, “Dark Matter Detectors as Dark Photon Helioscopes”, 1304.3461
- Va’vra, “Molecular excitations: a new way to detect Dark matter”, 1402.0466
- An, Pospelov, Pradler, Ritz, “Direct Detection Constraints on Dark Photon Dark Matter”, 1412.8378
- Hochberg, Zhao, Zurek, “Superconducting Detectors for Super Light Dark Matter”, 1504.07237
- Lee, Lisanti, Mishra-Sharma, Safdi, “Modulation Effects in Dark Matter-Electron Scattering Experiments”, 1508.07361
- RE, Fernandez-Serra, Jeremy Mardon, Adrian Soto, Volansky, Tien-Tien Yu, “Direct Detection of sub-GeV Dark Matter with Semiconductor Targets”, 1509.01598
- Hochberg, Pyle, Zhao, Zurek, “Superconducting Detectors for Super Light Dark Matter”, 1504.07237
- Dzuba, Flambaum, Pospelov, Roberts, Stadnik, “Dark matter scattering on electrons: Accurate calculations of atomic excitations and implications for the DAMA signal”, 1604.04559
- Hochberg, Lin, Zurek, “Detecting Ultralight Bosonic Dark Matter via Absorption in Superconductors”, 1604.06800

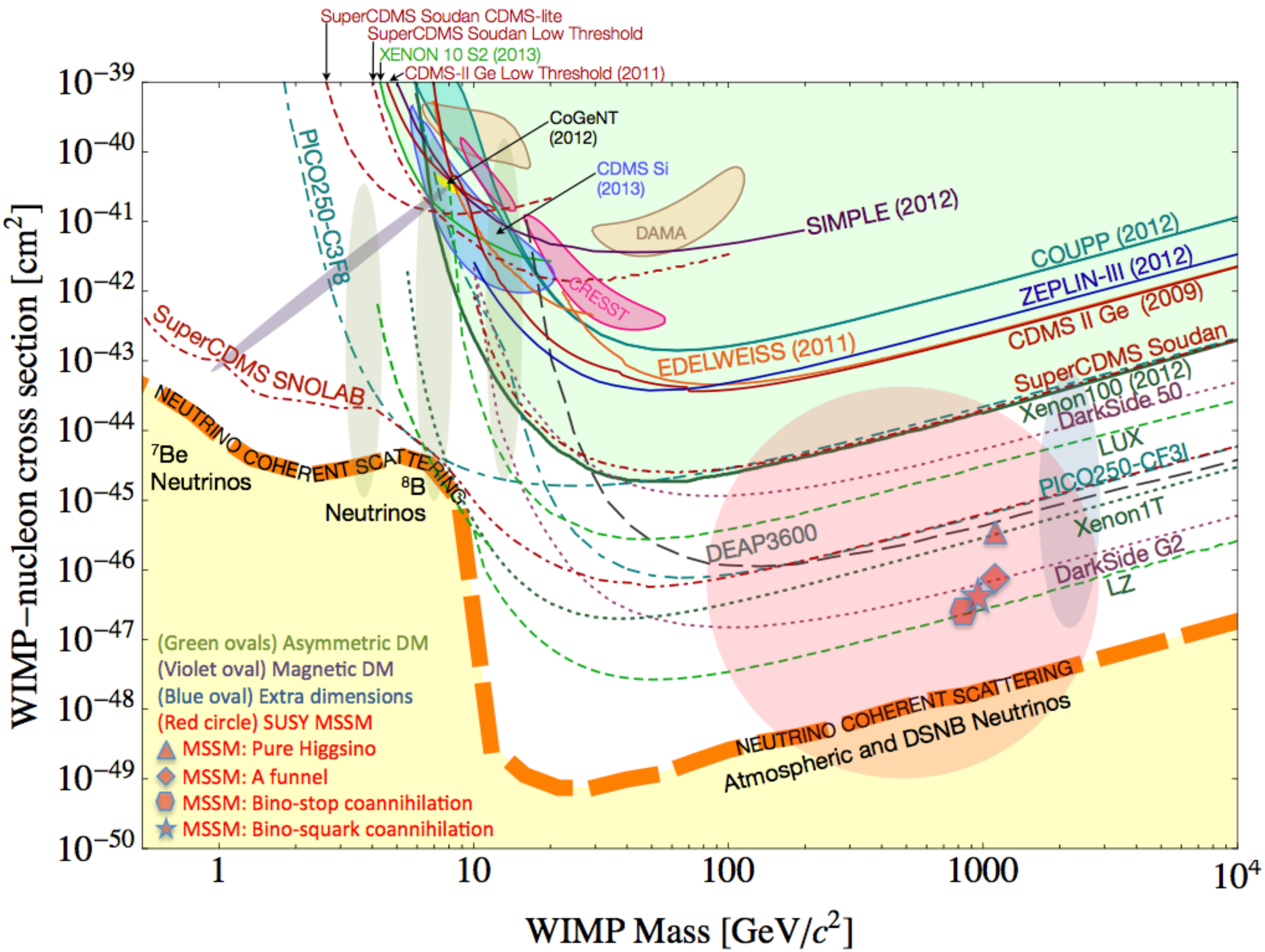
+ lots of work in progress (much discussed in WG)

Traditional Direct Detection strategy:
look for nuclear recoils from DM-nucleus scattering



targeting "WIMPs": weakly-interacting massive particles w/ mass ~ 10-1000 GeV

Direct Detection Landscape

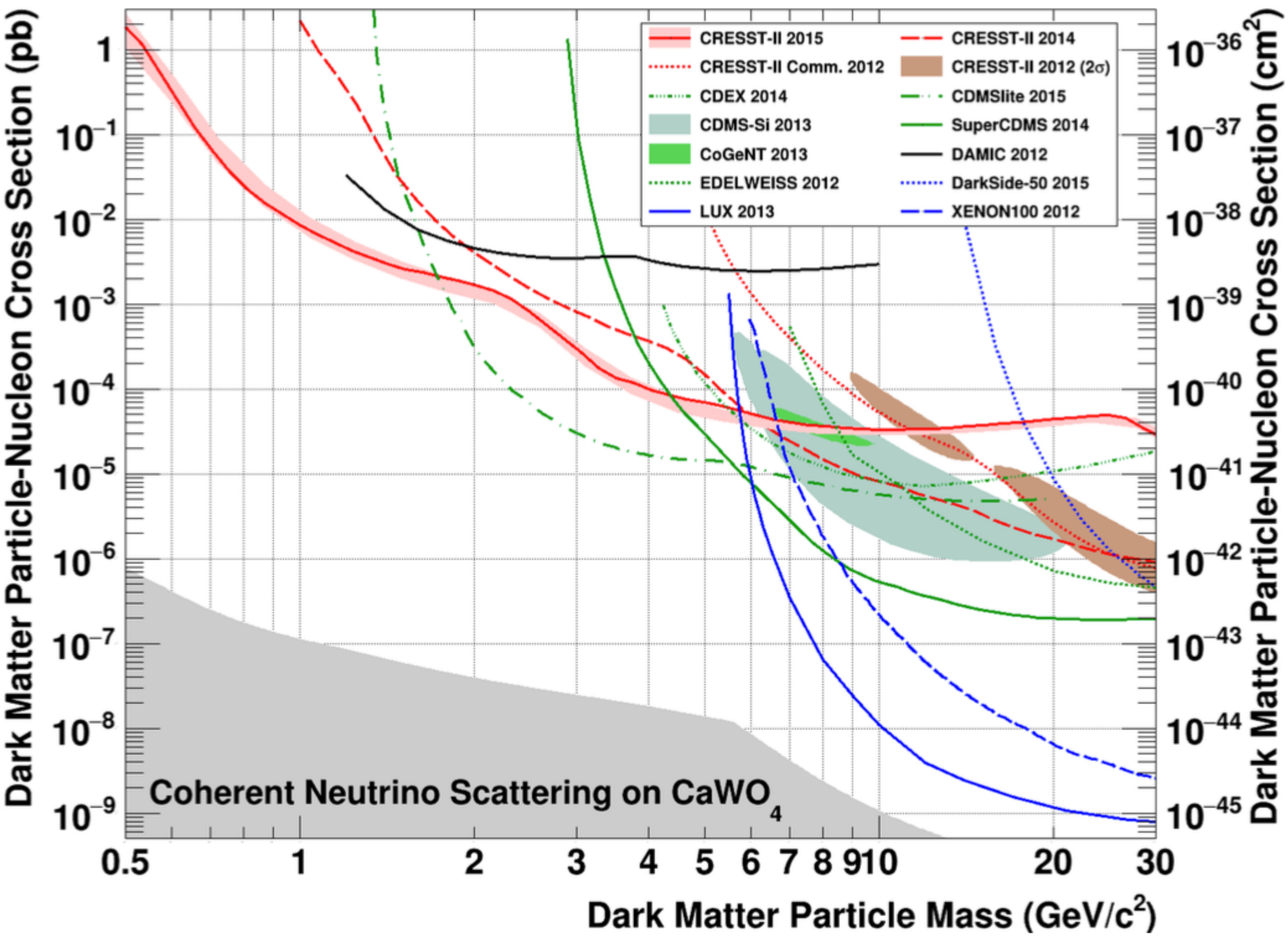


an active, important, and exciting program!

1310.8327

Direct Detection below 1 GeV?

current best limit from CRESST II



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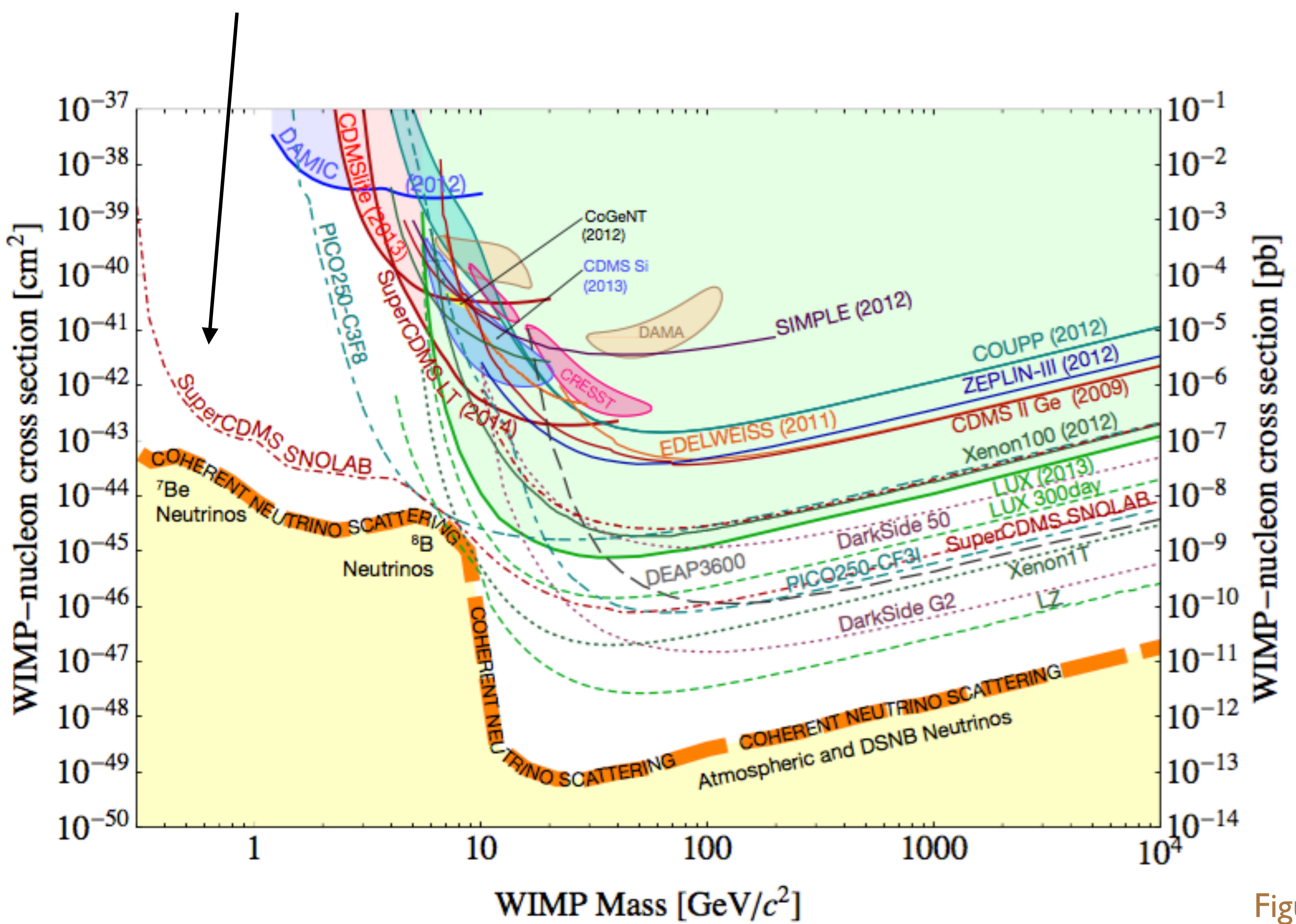
Direct Detection below 1 GeV?

in future e.g. SuperCDMS: ~300 MeV



Figueroa-Feliciano

Difficult to probe much <100 MeV w/ Nuclear Recoils

inefficient energy transfer from DM to nucleus

$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v^2}{m_N} \simeq 1\ {\rm eV} \times \left(\frac{m_\chi}{100\ {\rm MeV}}\right)^2 \left(\frac{20\ {\rm GeV}}{m_N}\right)$$

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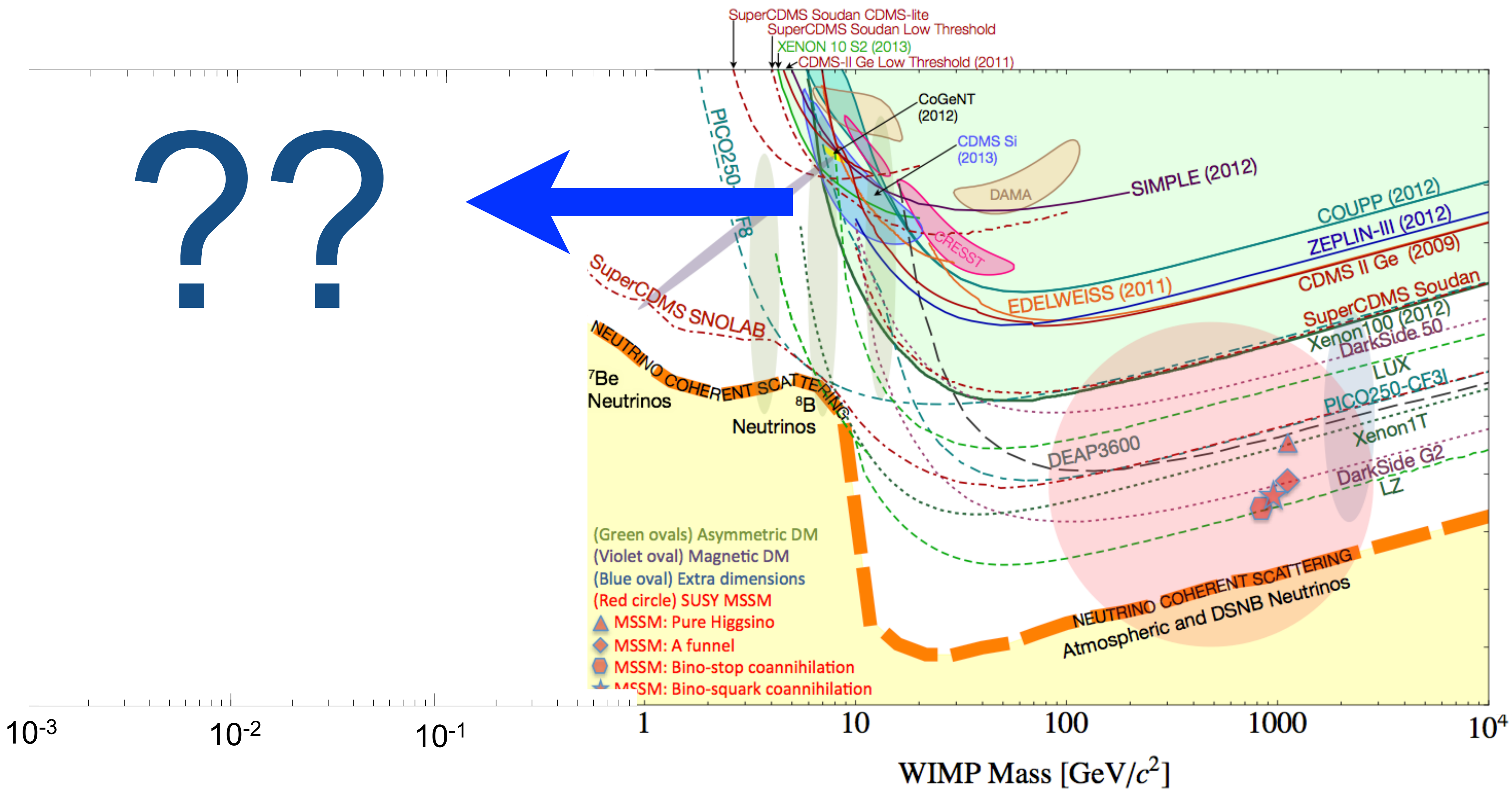
Exp	E_{th} (keV_{NR})	Ref
LUX	~3	1512.03506
DAMIC	~0.5	1510.00044
CDMSlite	~0.3	1509.02448
CRESST-II	~0.3	1509.01515

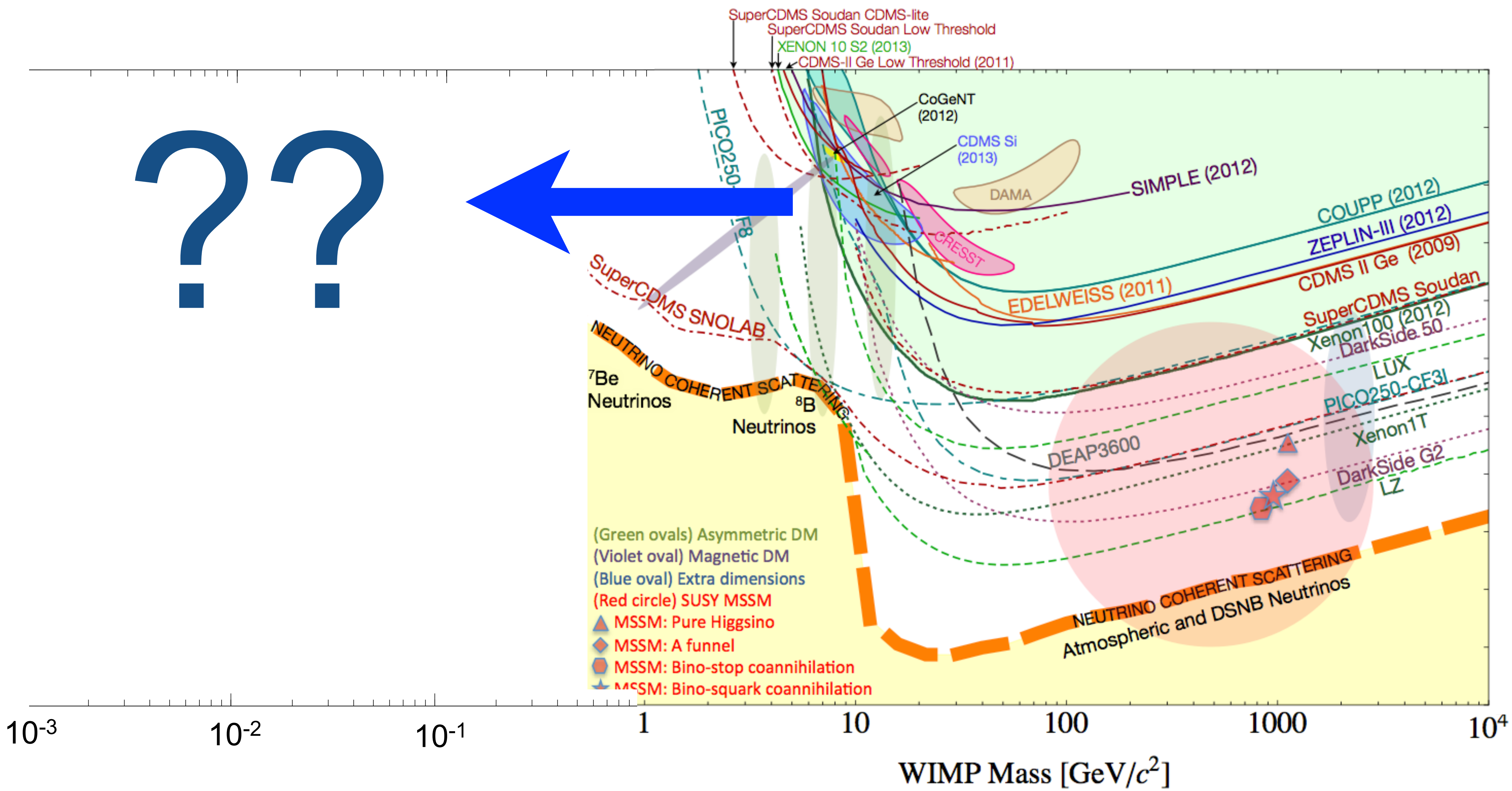
Can we go lower in DM mass?



and even lower??

Can we go lower in DM mass?

Yes!



and even lower??

Can we go lower in DM mass?

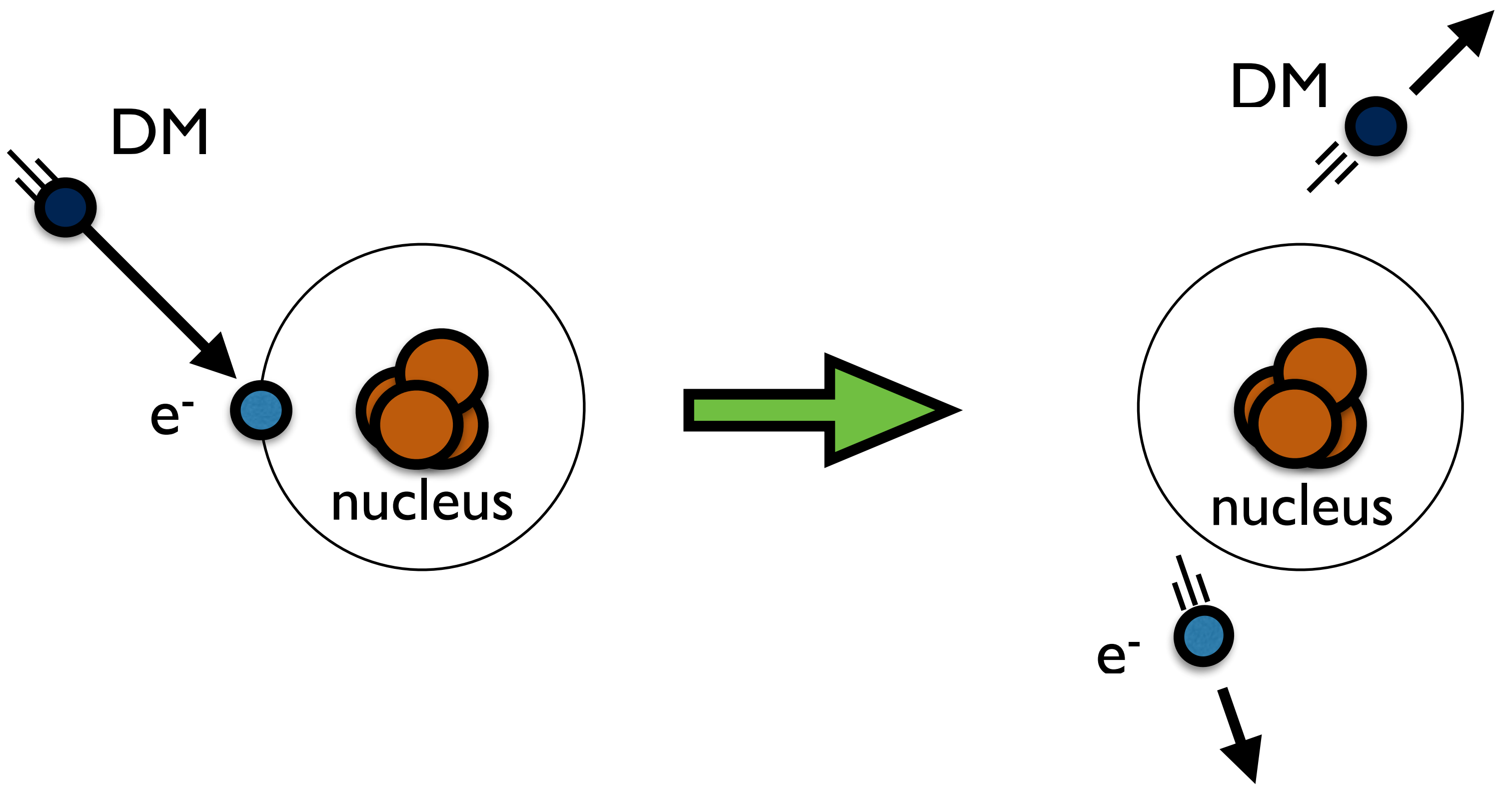
Yes!

How?

Main discussion item of
Direct Detection working group

Common strategy: use DM-electron recoils

DM-electron scattering



Signal depends on detector setup

e.g. one/a few e^- or γ, phonons from drifting e^-…

Recoiling e^- can access entire DM kinetic energy!

(in principle)

$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2$$

total available energy

nuclear recoil

Typical momentum & energy transfer

Typical momentum transfer is set by e^- not DM

$$q_{\rm typ} \sim \alpha m_e \sim 4 \text{ keV}$$

(for outer shell electron)

(see backup slide for more details)

Typical momentum & energy transfer

Typical momentum transfer is set by e$^-$ not DM

$$q_{\rm typ} \sim \alpha m_e \sim 4\ {\rm keV}$$

(for outer shell electron)

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$

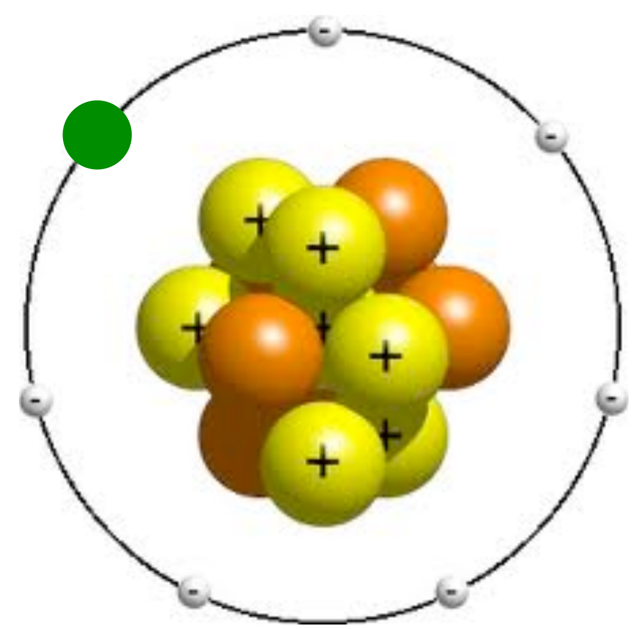
$\Delta E \gtrsim 4\ {\rm eV}$ requires q on tail of e$^-$ wavefunction

(see backup slide for more details)

Target materials?

Target materials?

Type	Examples	E_{th} (eV)	$m_{DM,\,th}$ (MeV)	Status
Noble liquids	xenon argon helium	~10 eV (atom)	~5 MeV	Done w/ XENON10 data; improvements possible



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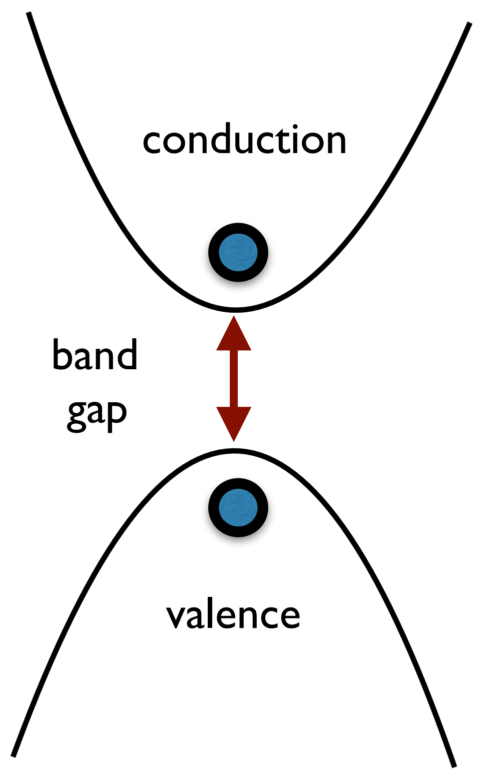

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Semiconductor bandgap is below "typical" electron recoil energy — no wavefunction suppression

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In WG, we'll hear about semiconductors (T.-T. Yu), superconductors (Y. Zhao), scintillators (T.-T. Yu), graphene (Y. Kahn), superfluids (K. Zurek)…

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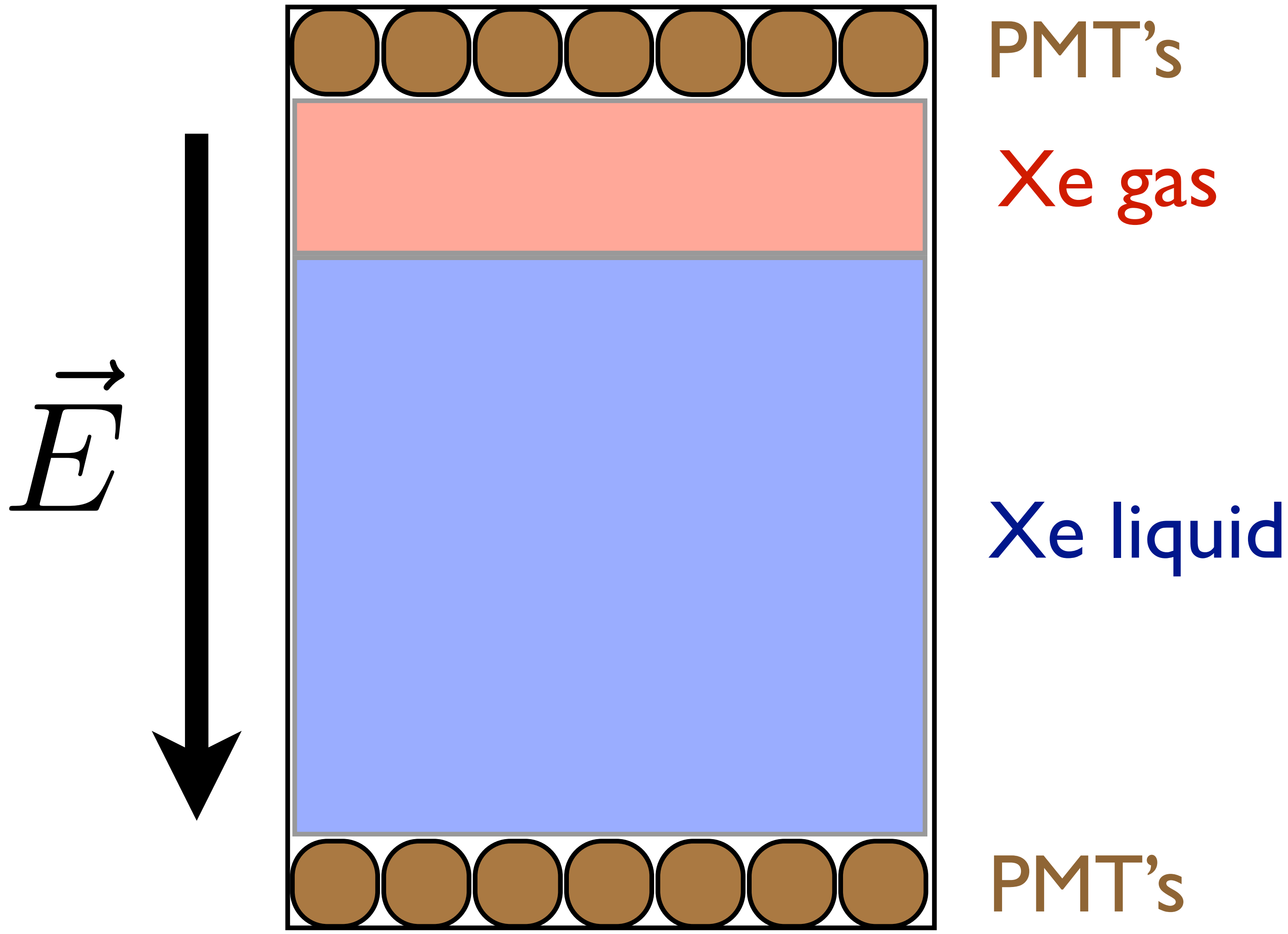
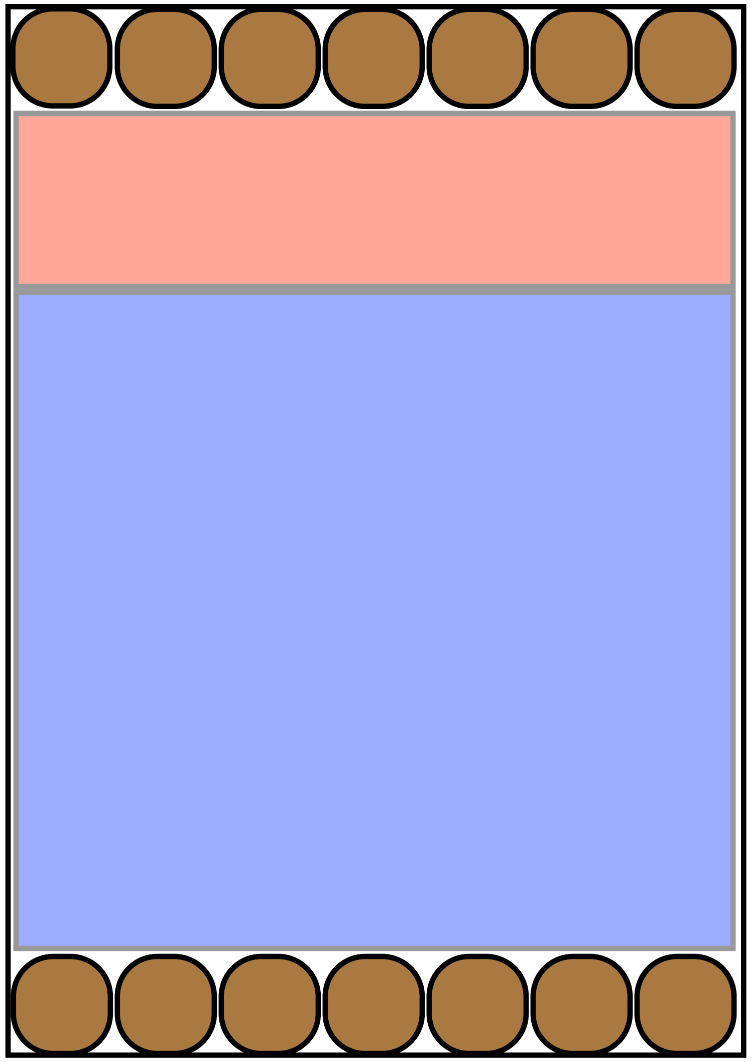
XENON10 detector schematic



ran in 2006/2007, sensitive to single electrons!

Sub-GeV DM scattering off electrons

DM



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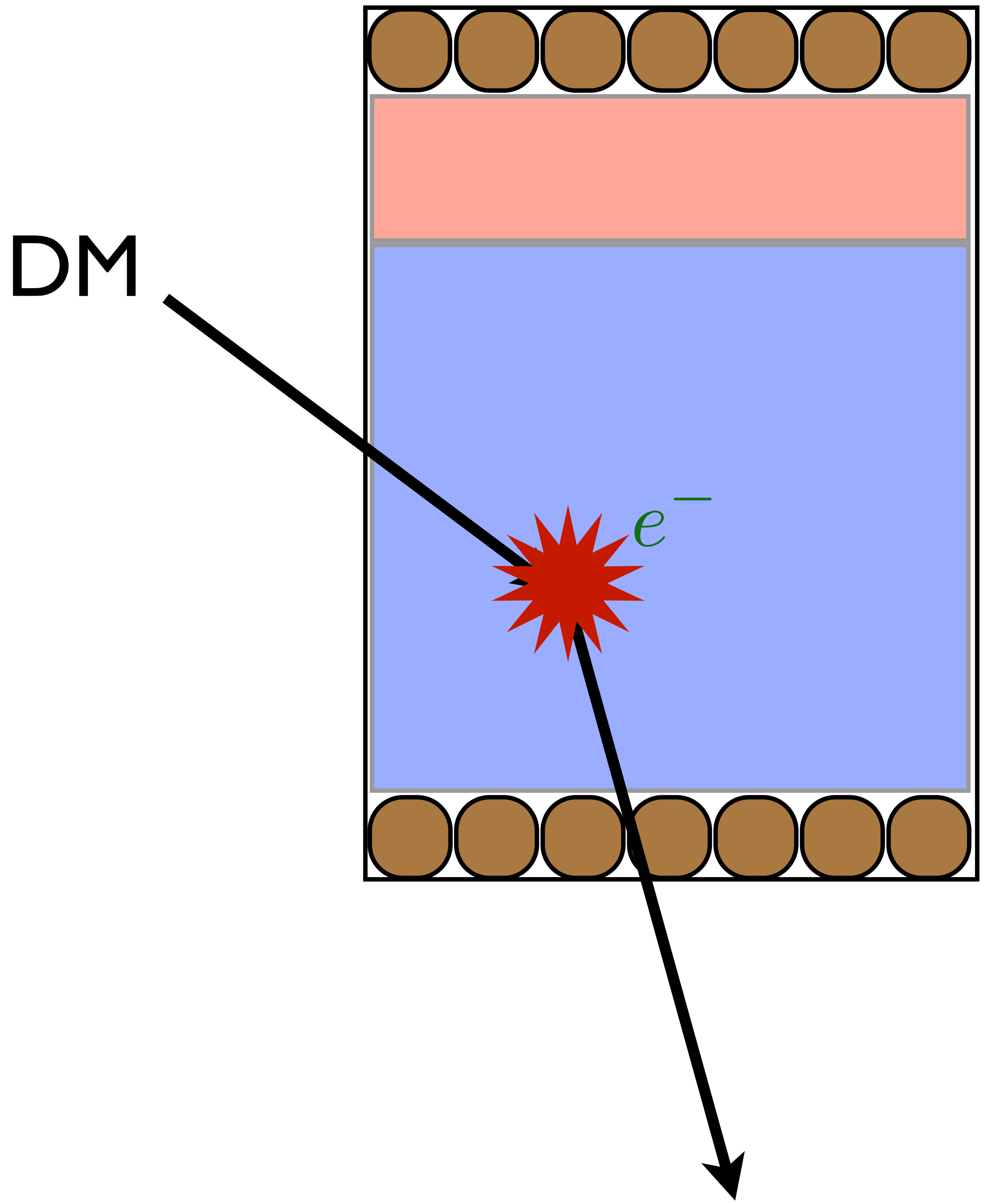

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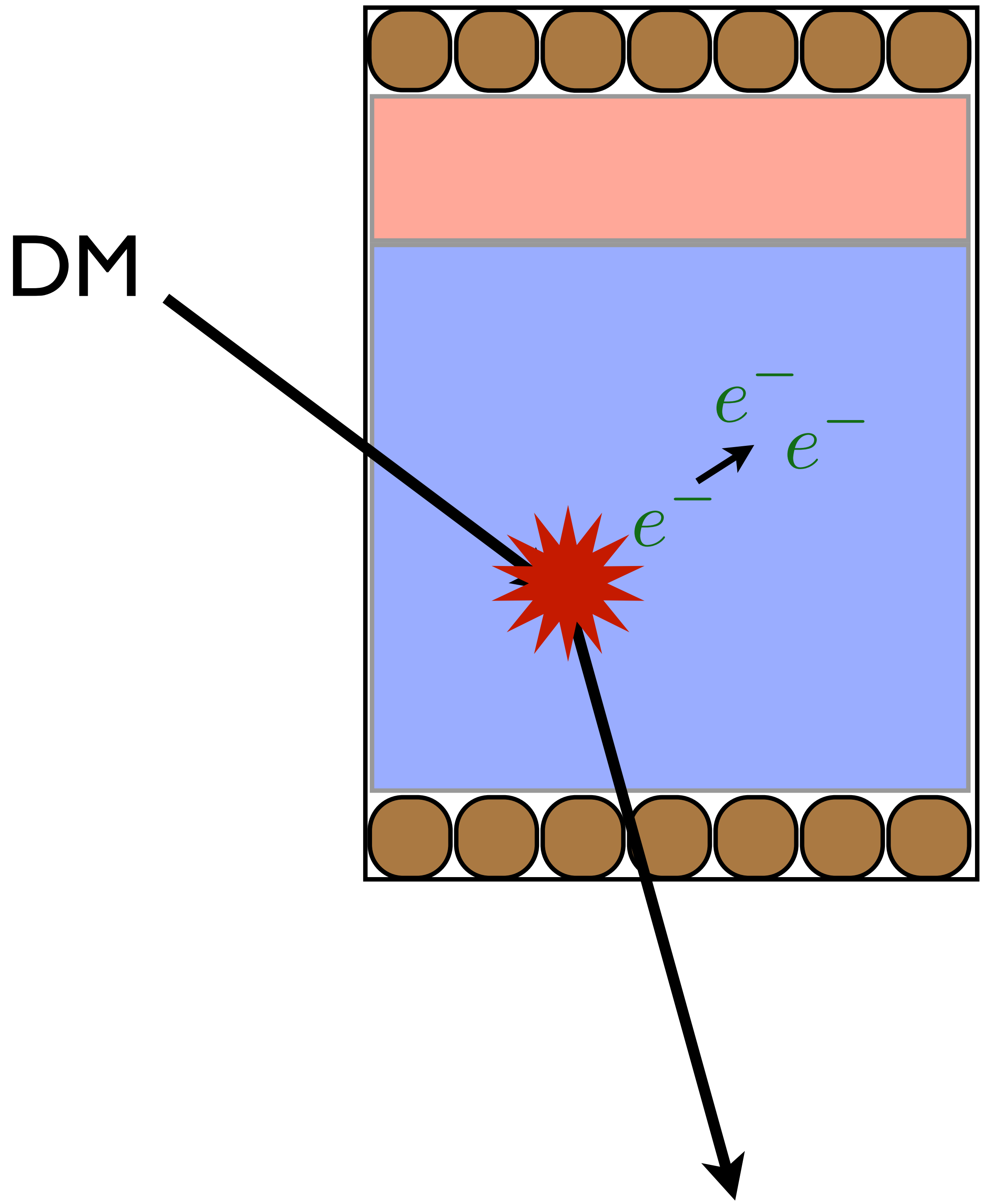
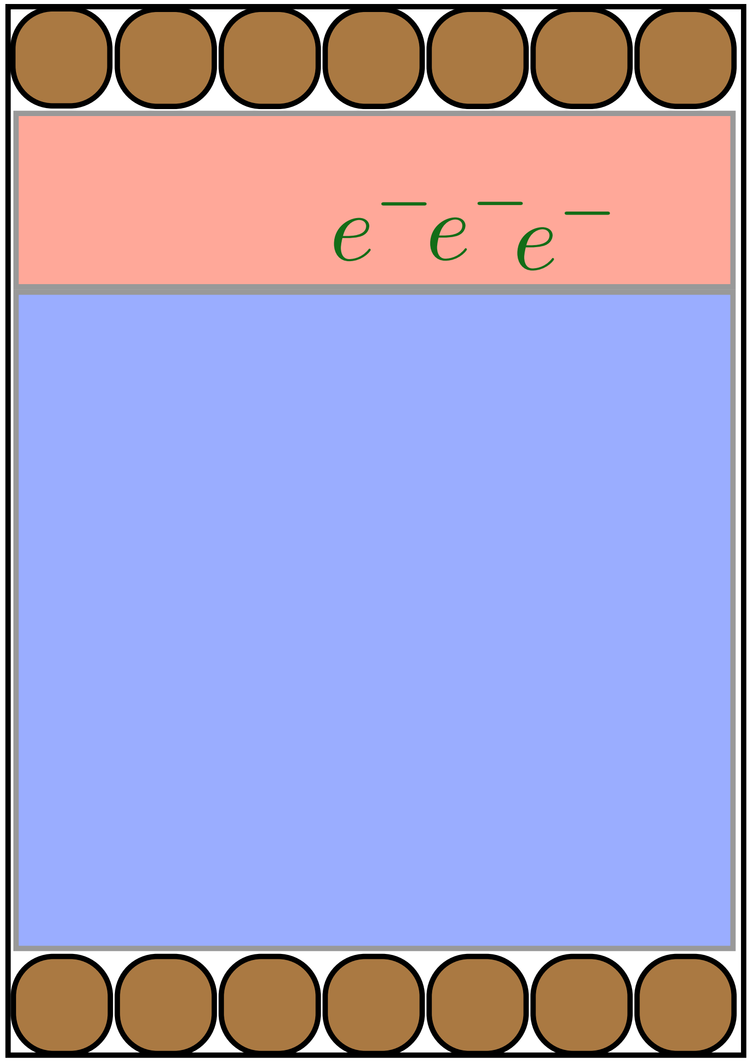


an energetic outgoing
e^- can ionize other e^-'s

Sub-GeV DM scattering off electrons



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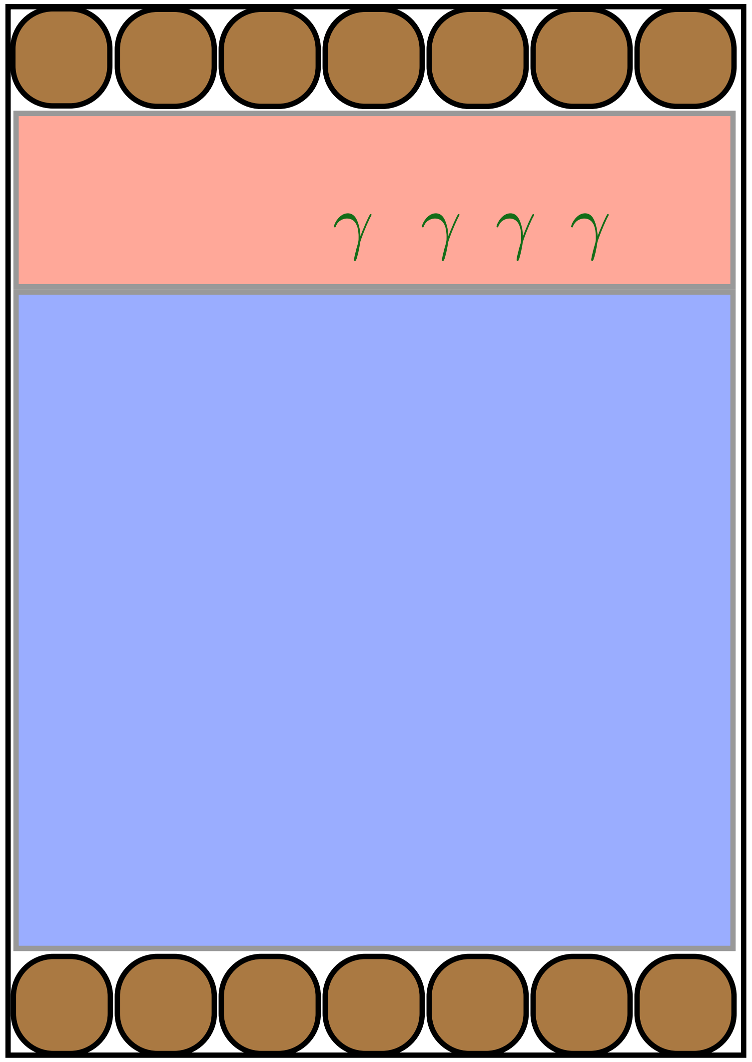

an energetic outgoing e^- can ionize other e^-'s

one e^- produces ~27 detected photons
("S2-signal")

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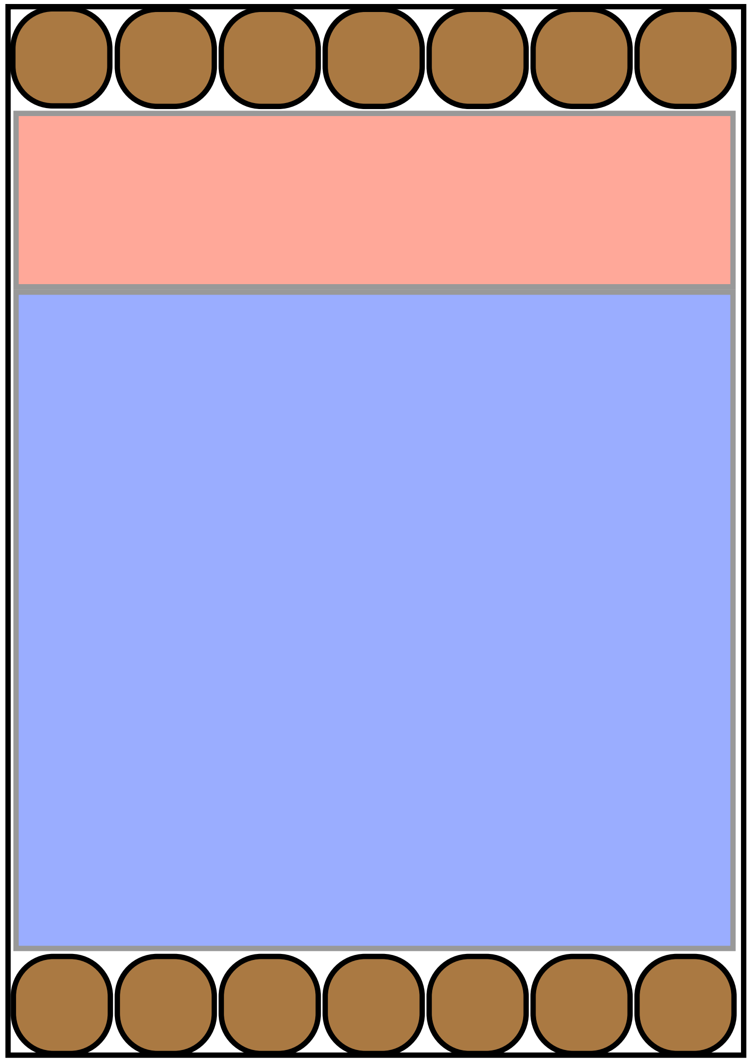

an energetic outgoing e^- can ionize other e^-'s

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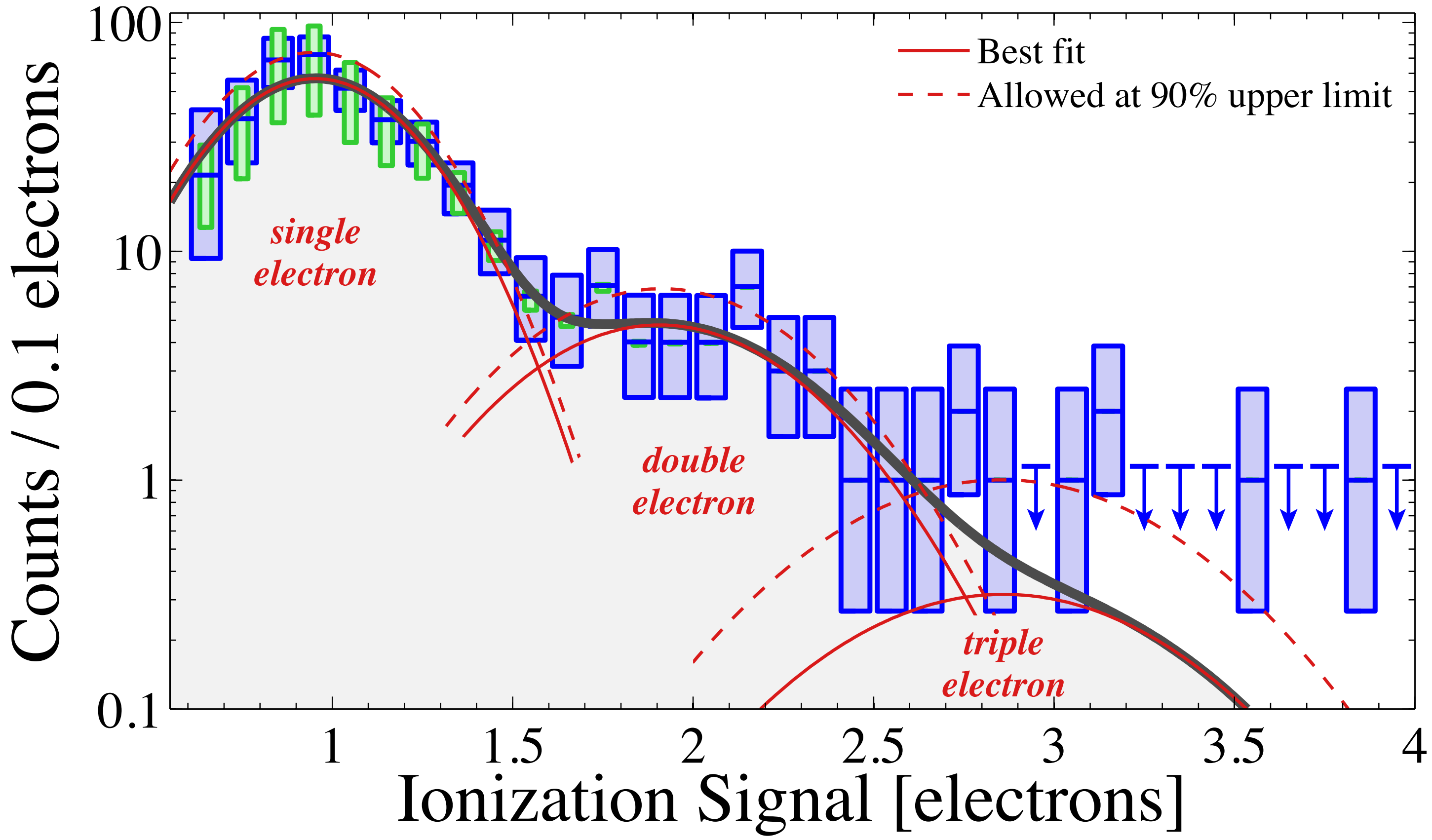
("S2-signal")

The XENON10 data

from published "S2-only" analysis, 1104.3088 (15 kg-days)



90% c.l. upper bounds (counts/kg/day):

1 e^-: 34.5

2 e^-: 4.5

3 e^-: 0.83

conservative limit: require DM signal < data

DD limits down to a few MeV

RE, Manalaysay, Mardon, Sorensen, Volansky

Comments on XENON10 result

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- Can you detect a DM event down to m_{DM} ~ few MeV?
  - Yes

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- Where does the large single-e^- background come from?
  - Not a general "physics" background, but seems specific to dual-phase detectors (also present in LUX, XENON100), e.g.
    - e^- gets trapped at liquid-gas interface & released later
    - e^- gets trapped by impurities and released later
    - e^- emission by cathode

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    - e^- gets trapped by impurities and released later
    - e^- emission by cathode

$\Longrightarrow$ DM also produces events with several electrons!
Even 3- or 4-electron events (much less background)
can probe DM down to ~10-20 MeV

Beyond XENON10

need a different detector to probe smaller DM masses & have reduced backgrounds

e.g. semiconductor targets

WG will feature many recent and new ideas (w/ various targets)

Current best limit from a semiconductor (DAMIC, Si)

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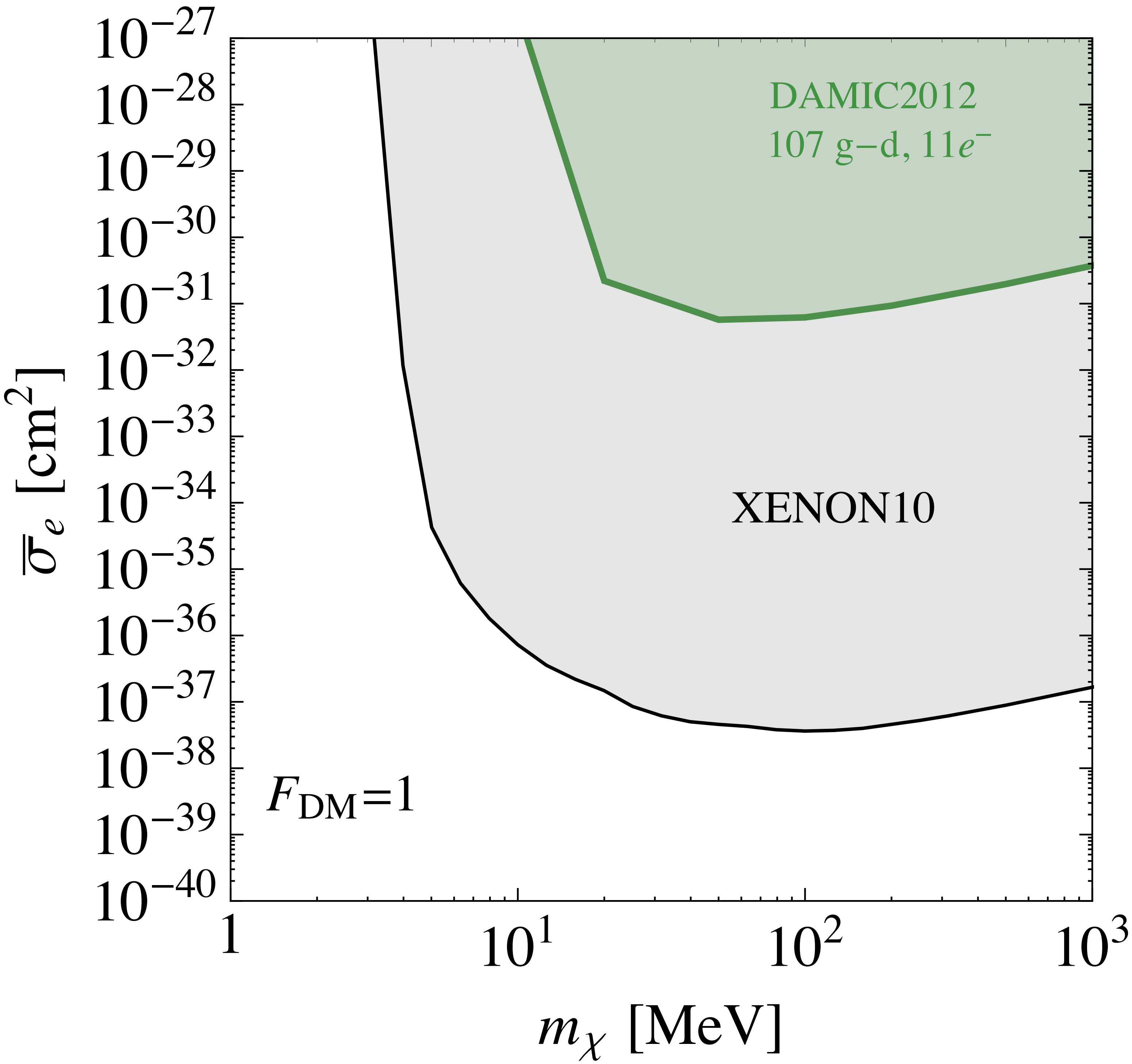
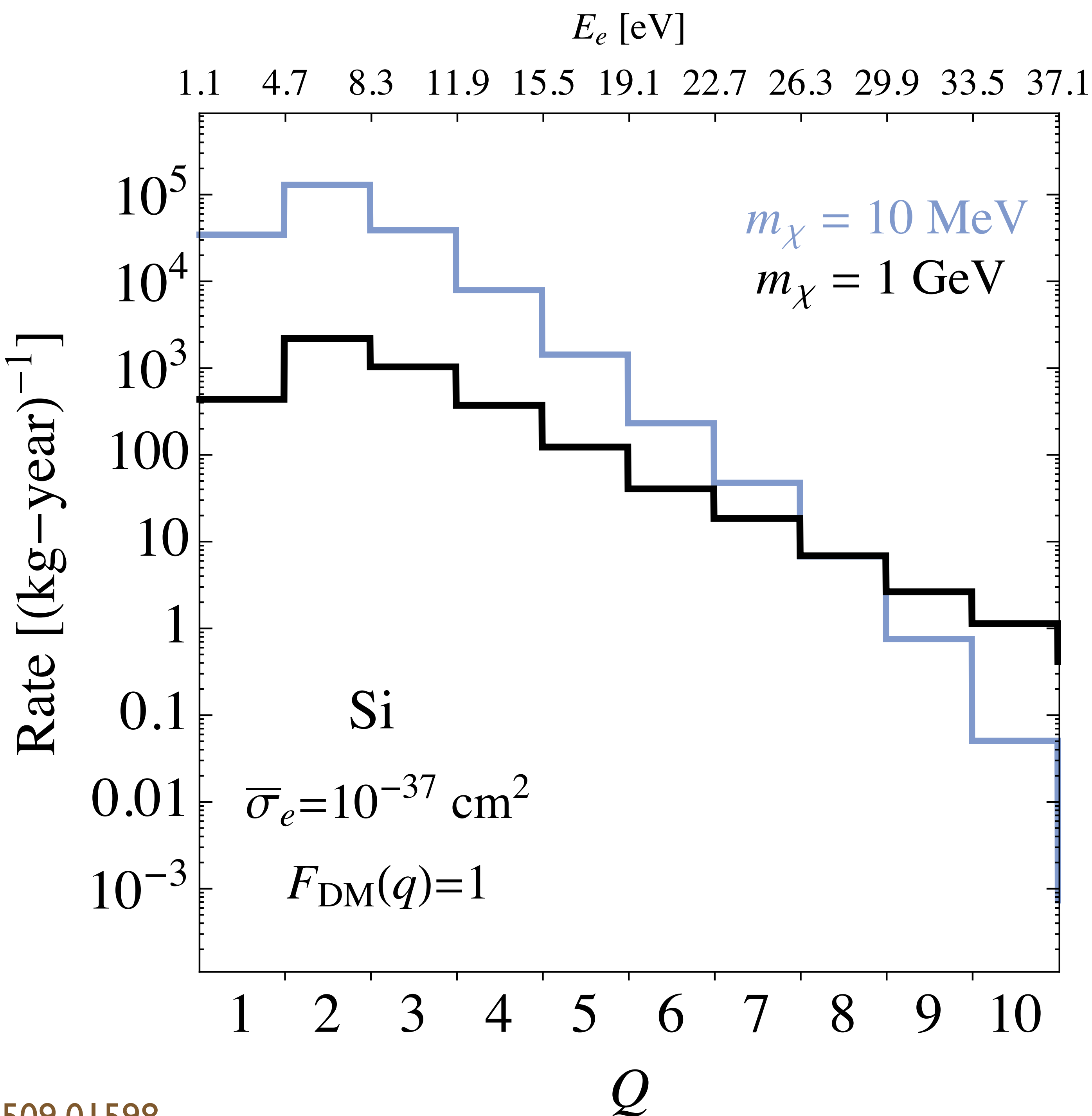


currently limited by readout noise (not backgrounds) to ~11 electrons

Lowering threshold gives *huge* increase in rate



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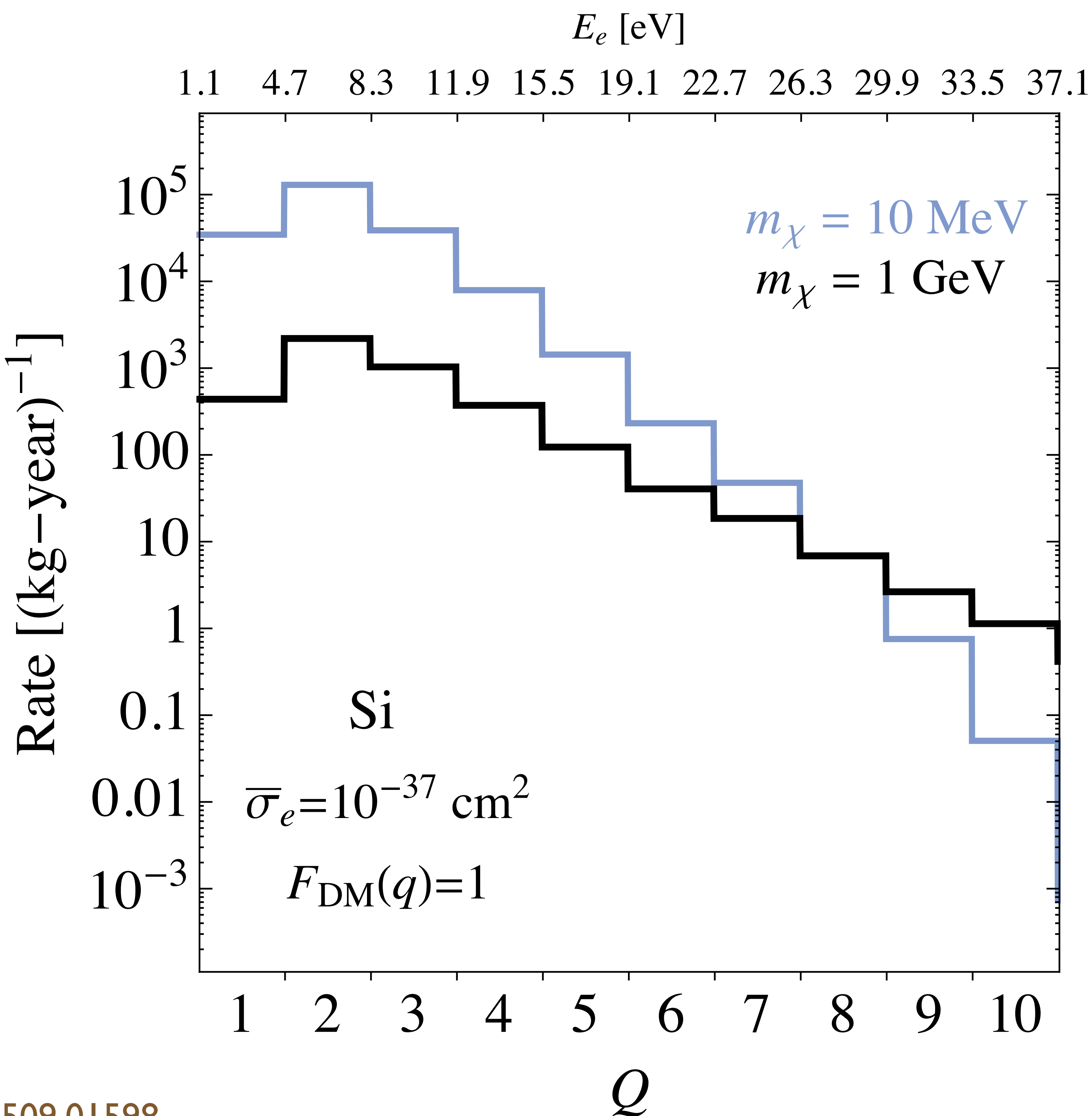

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Current thresholds, e.g.

CDMSlite: ~56 eV

(1509.02448)

DAMIC: ~40 eV

(1105.5191)

active R&D could reduce threshold to 1 or 2 e^-

How can we make a *discovery*?

- a priori, no reason why backgrounds should dominate at lowest energies, but the unknown can create challenges
- several ideas exist, e.g. annual modulation + work in progress

see WG talks for some new ideas
(e.g. Y. Kahn & T.-T. Yu)
+
discussion

Models

- DM w/ a light A' ($\sim m_{DM}$)
- DM w/ an ultralight A' ($\ll$ keV)
- A' DM ($\ll$ MeV)
- A' from Sun ($<$10 keV)

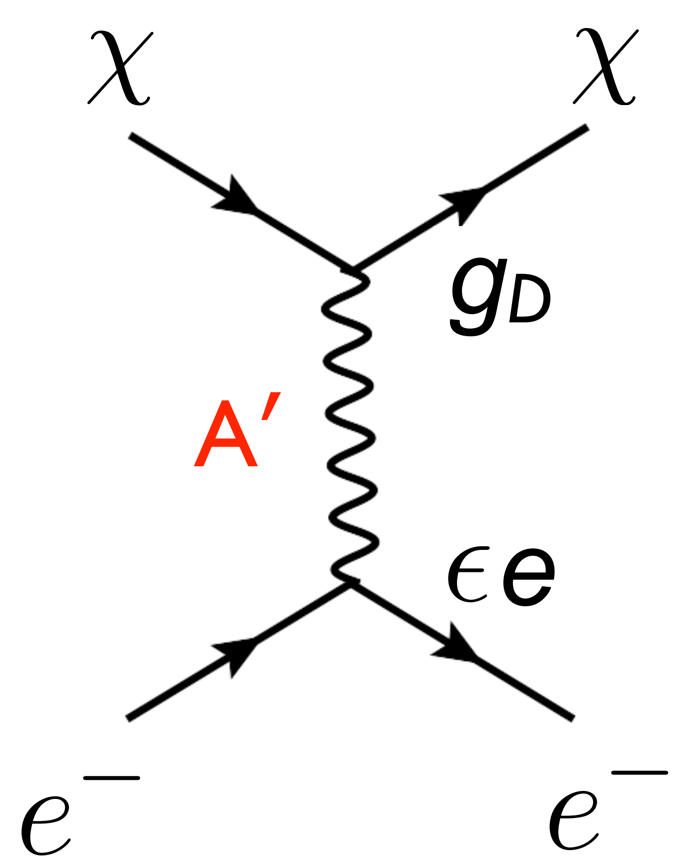
(won't discuss e.g. electric or magnetic dipole moment)

Models

- DM w/ a light A' ($\sim m_{DM}$)
- DM w/ an ultralight A' ($\ll$ keV)
- A' DM ($\ll$ MeV)
- A' from Sun (<10 keV)

see also Philip's talk

Direct Detection for $m_{A'} \sim m_{DM}$

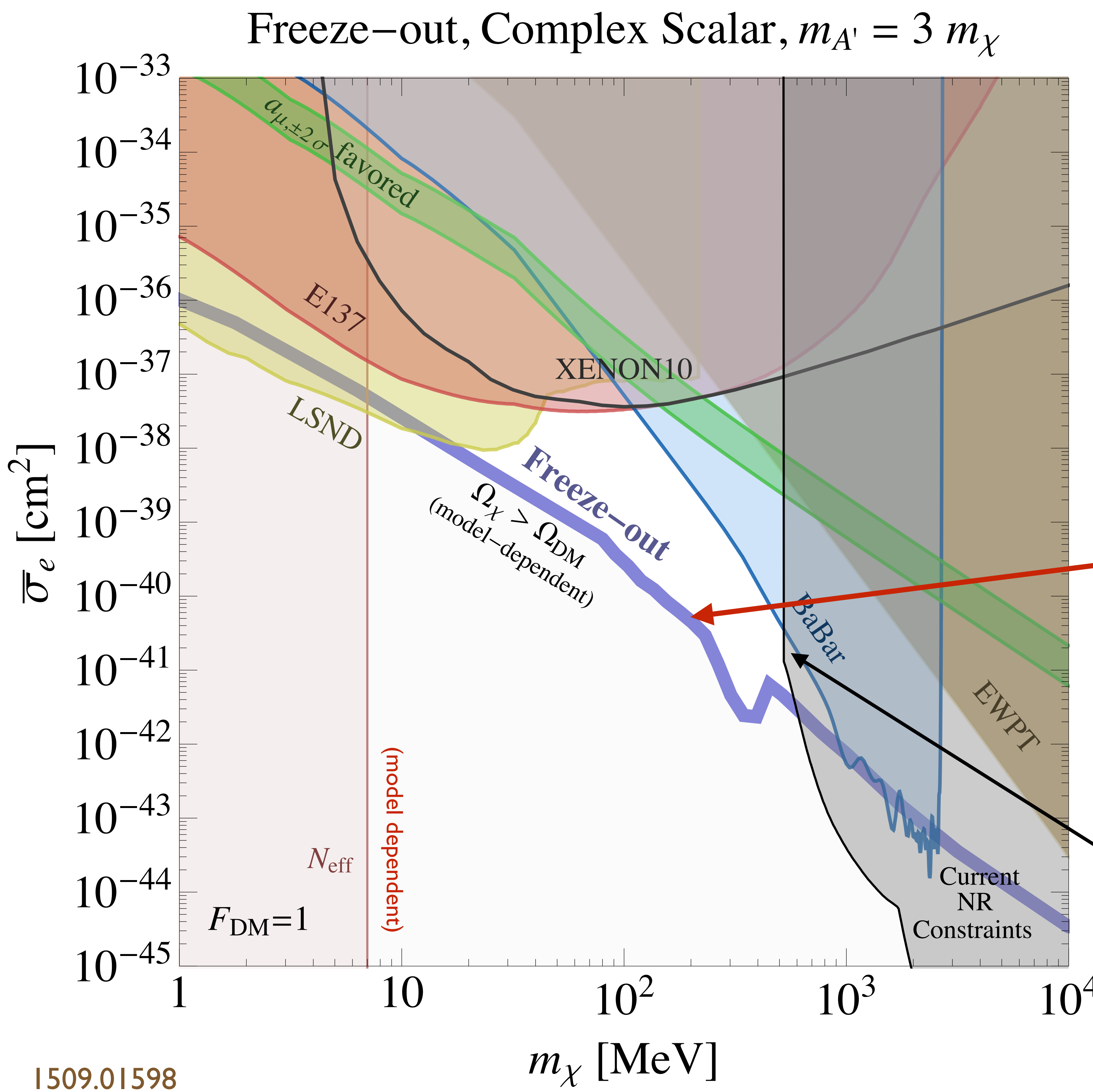


$$\bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} \mu_{\chi e}^2$$

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

Compare to definition of "y" in Philip's talk: $\bar{\sigma}_e = \dfrac{16\pi \mu_{\chi e}^2}{m_\chi^4} \times y$

Direct Detection, complex scalar, $m_{A'} > 2m_{DM}$



nice complementarity between DD and DMA

Please target me
(and more!)

note current nuclear recoil constraint from CRESST-II

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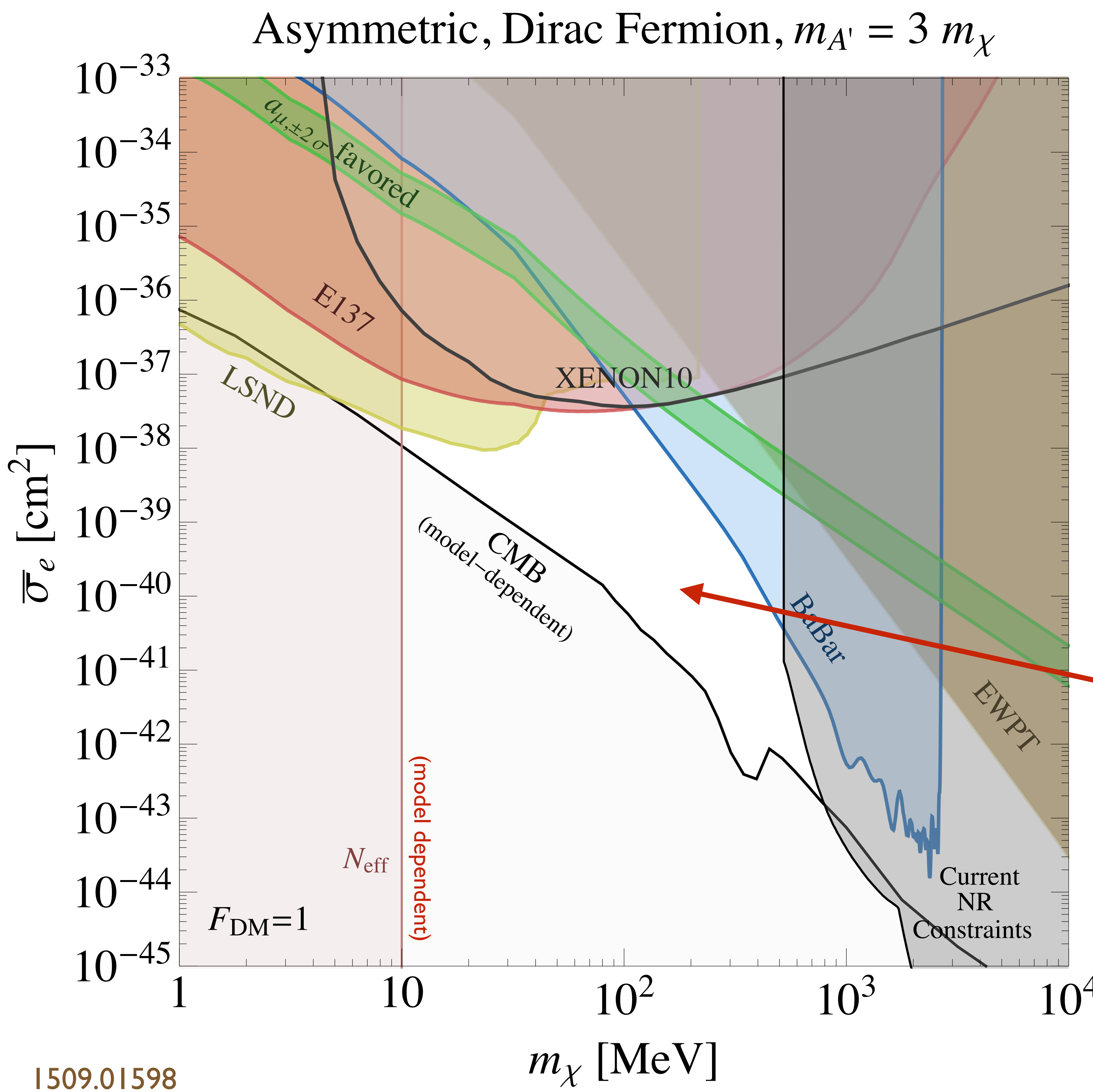
Direct Detection, Dirac fermion, $m_{A'}>2m_{DM}$



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asymmetric DM

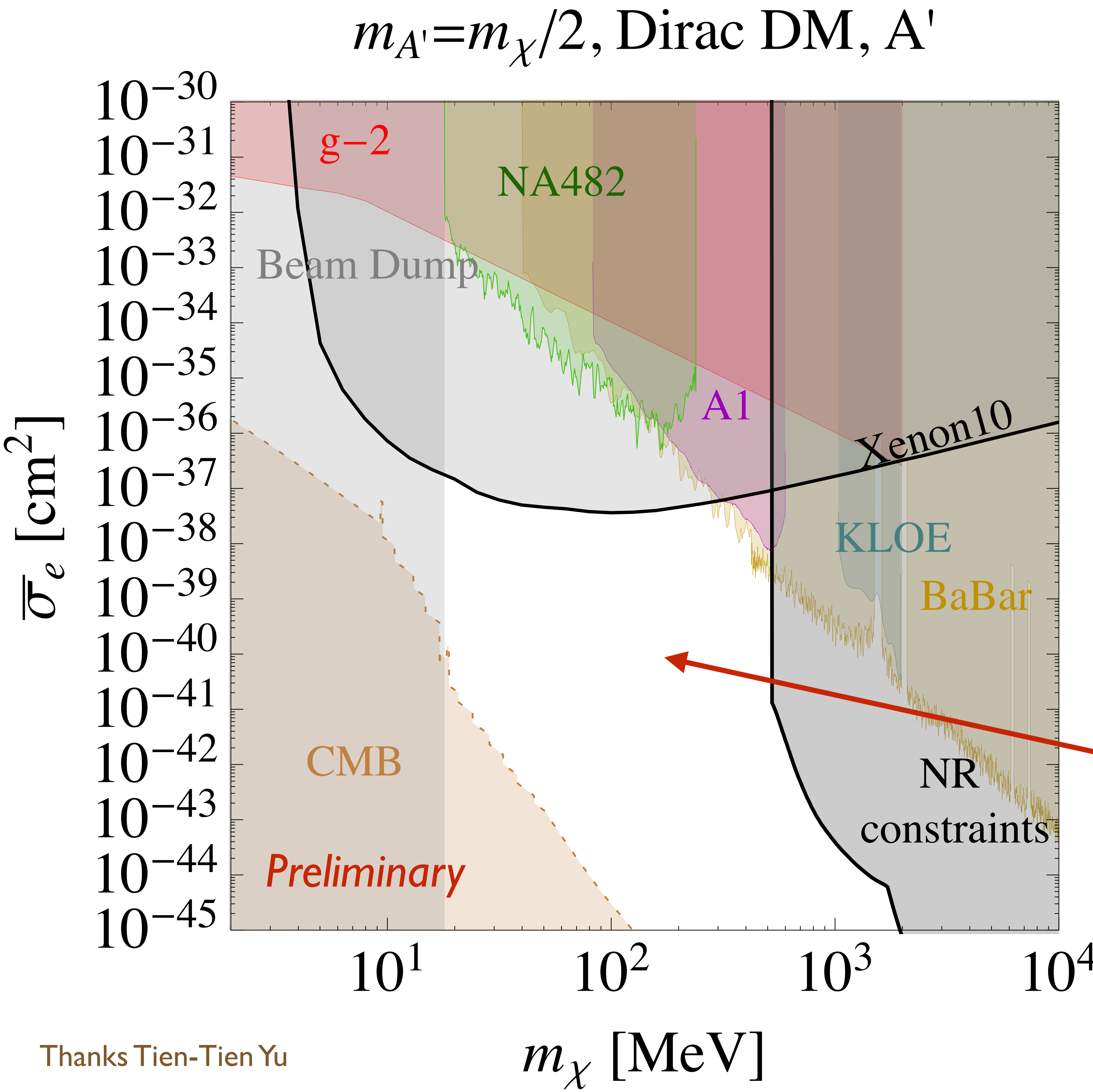
(generate correct DM relic density via an initial asymmetry)

e.g. Kaplan, Luty, Zurek (0901.4117)
Lin, Yu, Zurek (1111.0293)

Please target me

(and more!)

Direct Detection, Dirac fermion, $m_{A'} < m_{DM}$



asymmetric DM

here DD, visible A′, and invisible A′ searches are important!

Please target me

Thanks Tien-Tien Yu

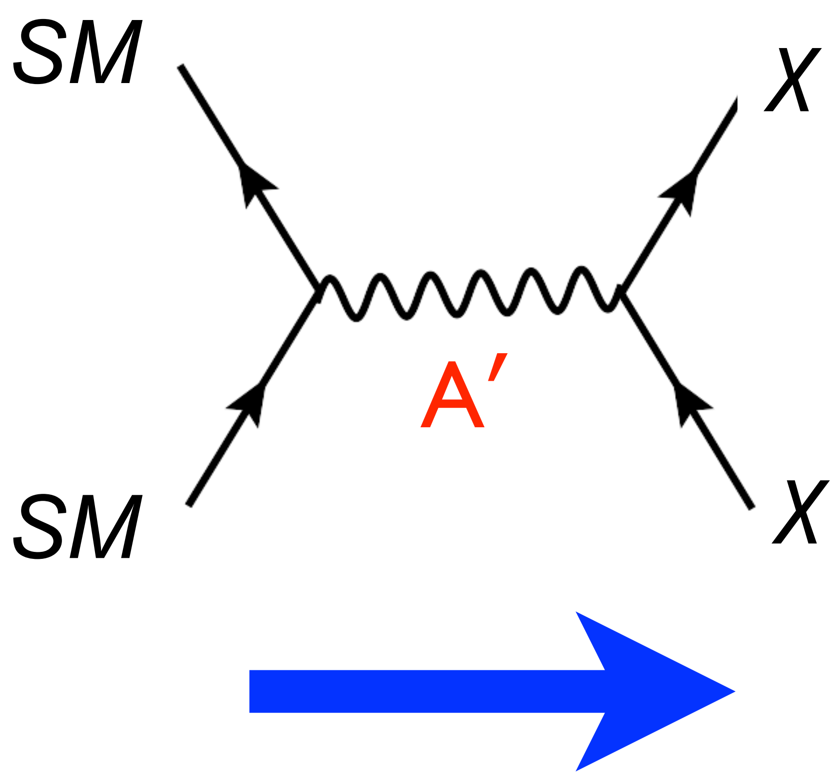
Models

- DM w/ a light A' ($\sim m_{DM}$)
- DM w/ an ultralight A' ($\ll$ keV)
- A' DM ($\ll$ MeV)
- A' from Sun (<10 keV)

“Freeze-in”

can generate correct DM relic density by “freeze-in”

Hall et.al. (0911.1120)



build up DM abundance as Universe cools

1108.5383

1112.0493

"Freeze-in"

can generate correct DM
relic density by "freeze-in"

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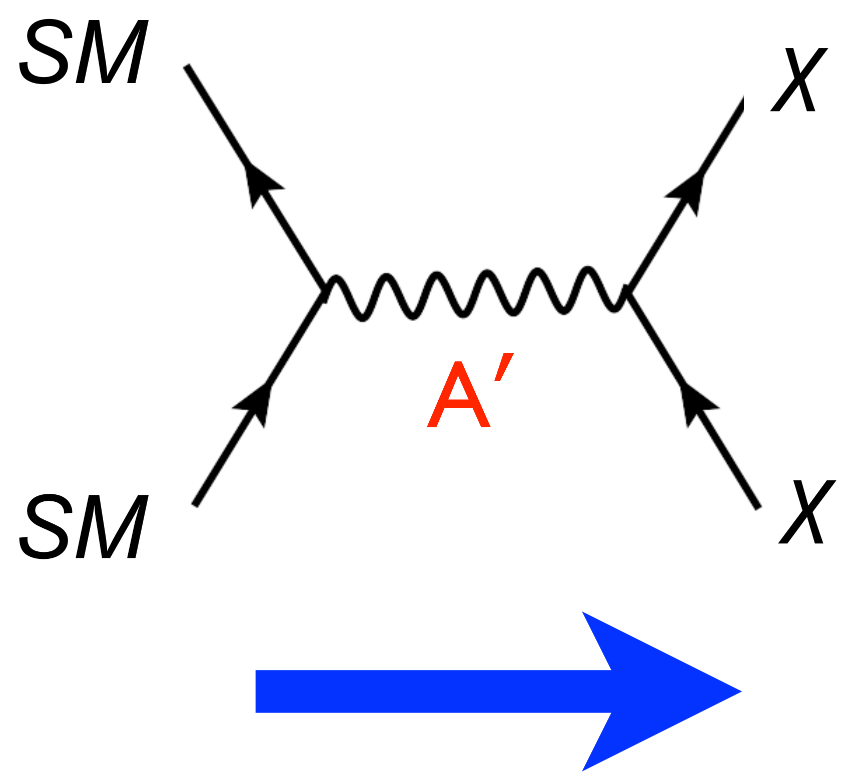


build up DM
abundance as
Universe cools

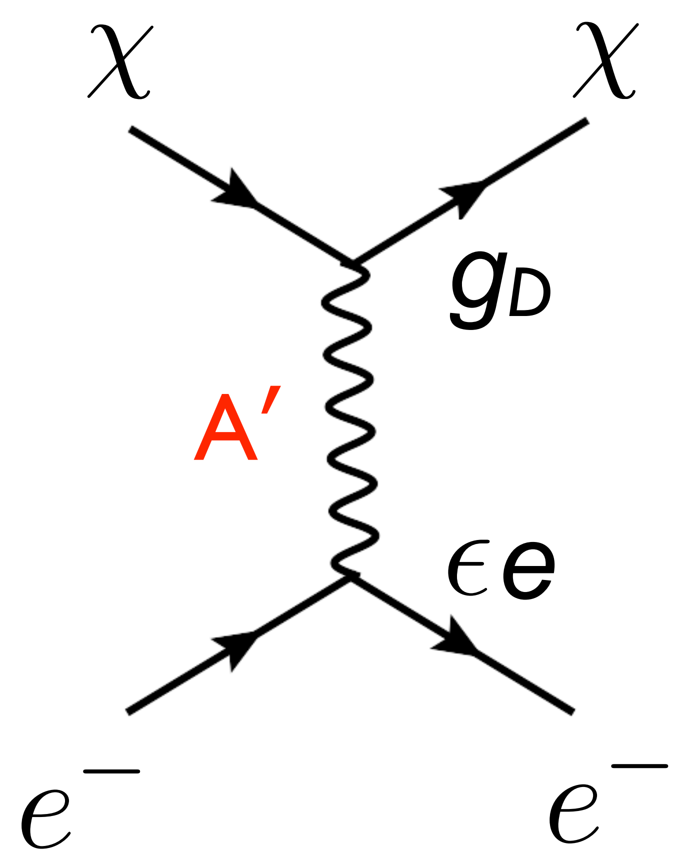
1108.5383

1112.0493

e.g. m_X = 100 MeV, correct relic abundance for $\alpha_D \epsilon^2 \sim 3 \times 10^{-24}$

(~independent of $m_{A'}$)

Direct Detection w/ ultralight A′ (≪ keV)



$$\sigma \propto \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D\epsilon^2}{q^4} = \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D\epsilon^2}{(\alpha^2 m_e^2)^2} \times \left(\frac{\alpha^2 m_e^2}{q^2}\right)^2$$

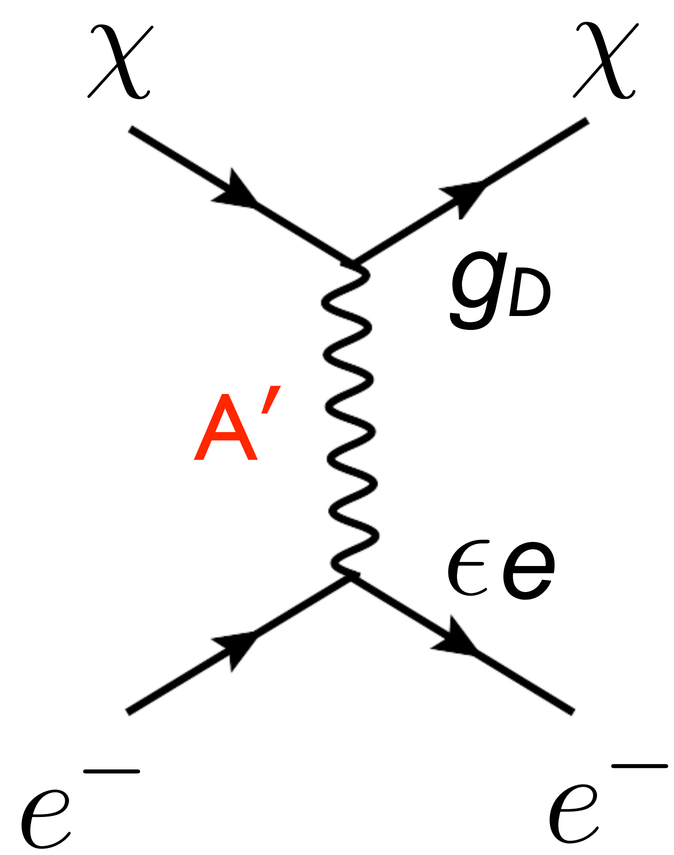
assume

$m_{A'} \ll \alpha\, m_e$

$\sim \mathrm{keV}$

enhanced at low q^2 !

Direct Detection w/ ultralight A′ (≪ keV)



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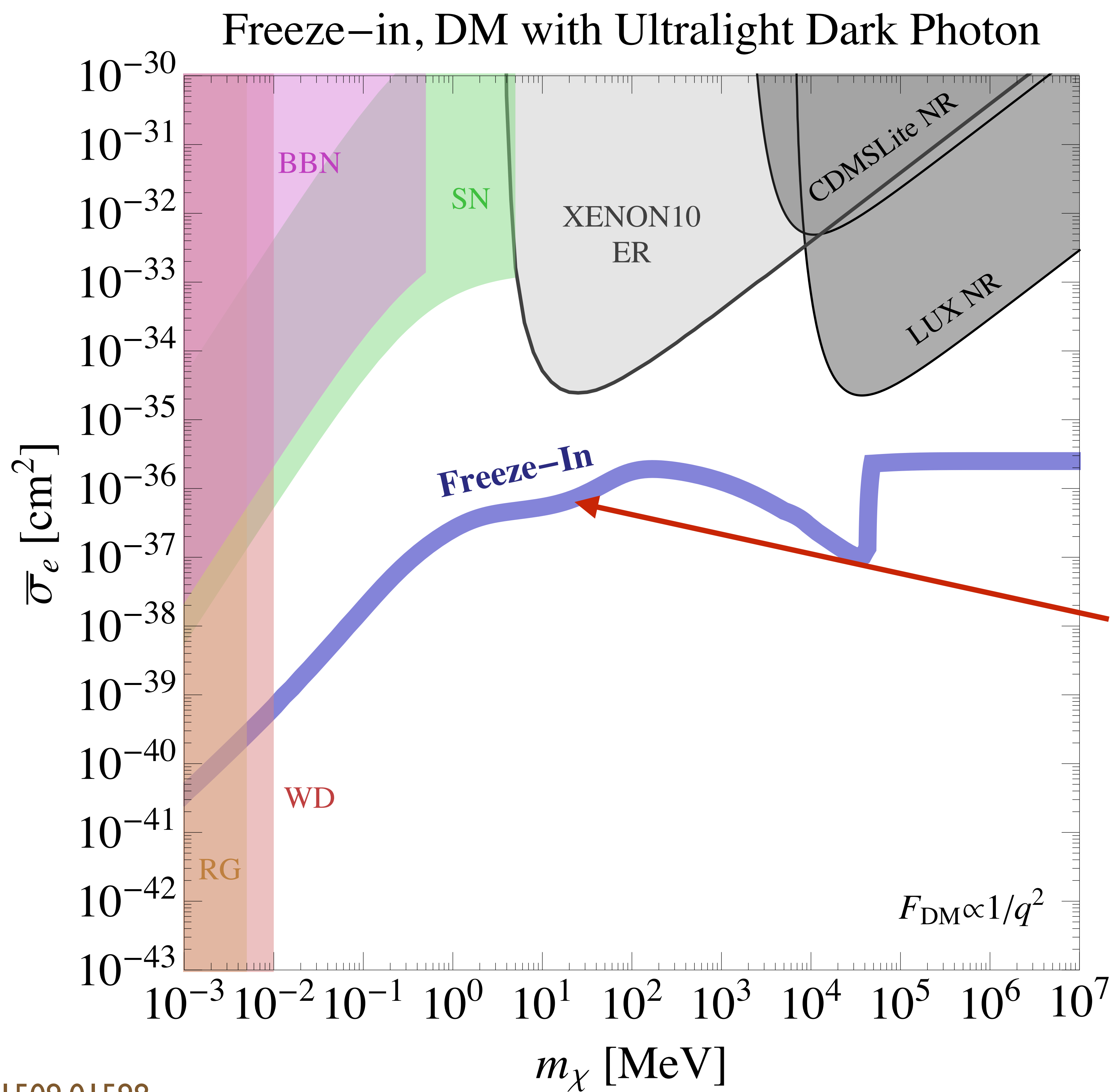
$$\equiv \bar{\sigma}_e \times (F_{\rm DM}(q))^2$$

assume $m_{A'} \ll \alpha\, m_e$ $\sim \mathrm{keV}$

enhanced at low q^2 !

Direct Detection w/ ultralight A′ (≪keV)



DD (electron recoils!) very powerful due to ~$1/q^4$ enhancement

Please target me
(and more!)

note bounds on millicharged particles; DMA bounds weak

1509.01598

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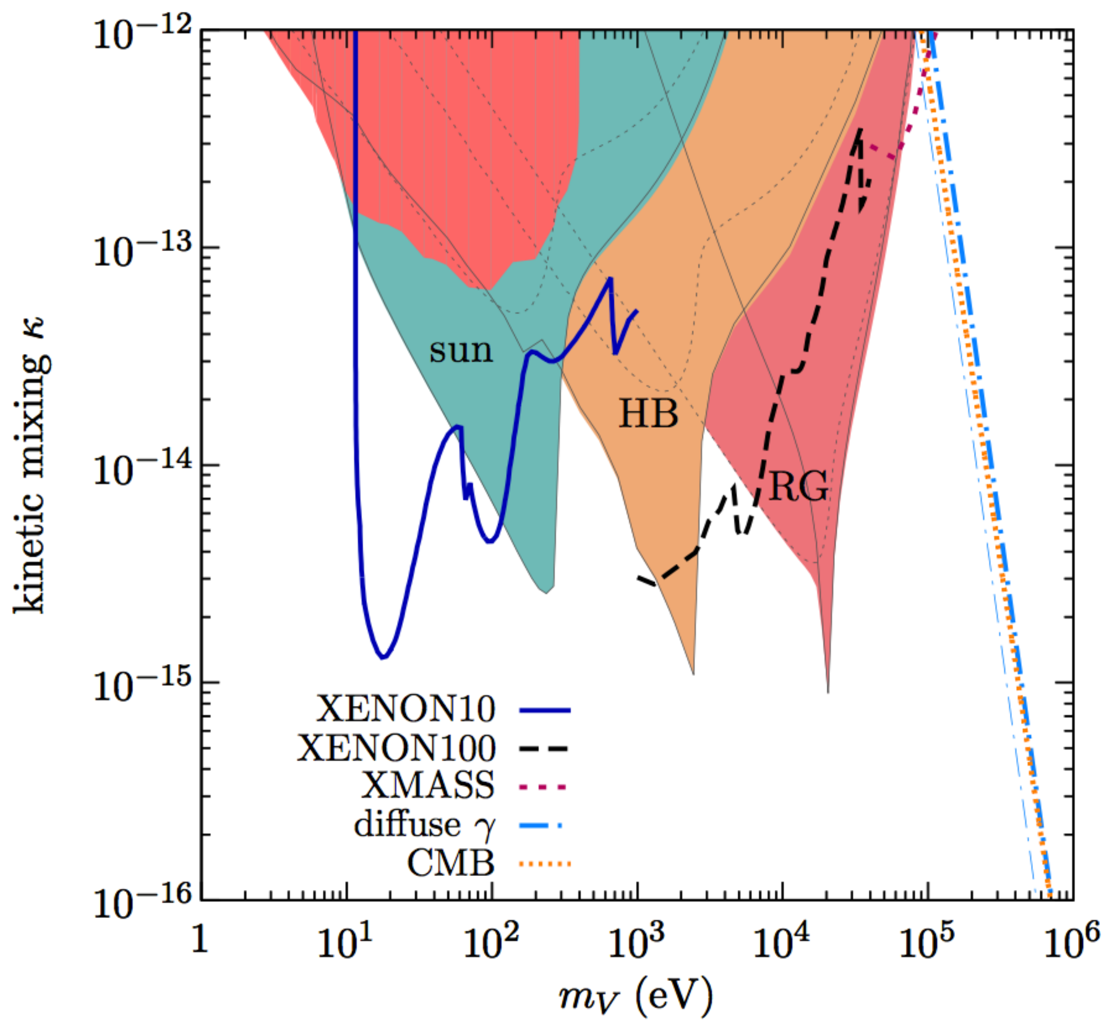
A′ DM

- an ultralight A′ itself can be the DM and get absorbed by atom in underground detector:

e.g. in xenon: $Xe + A' \to Xe^* + e^-$



An, Pospelov, Pradler, Ritz (1412.8378)

(also works for scalar or pseudoscalar)

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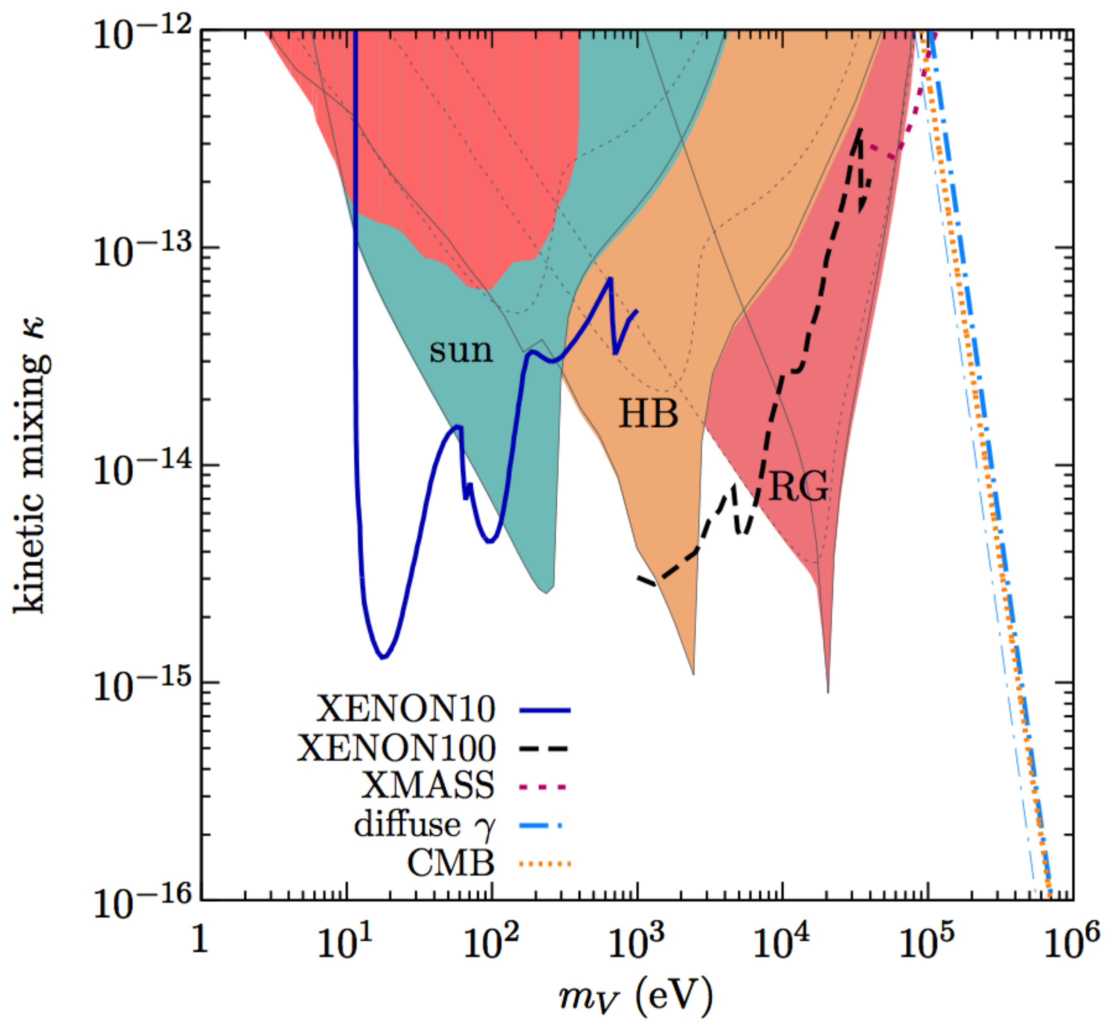


We'll have WG talks on:

superconductors (T. Lin)

Hochberg, Lin, Zurek (1604.06800)

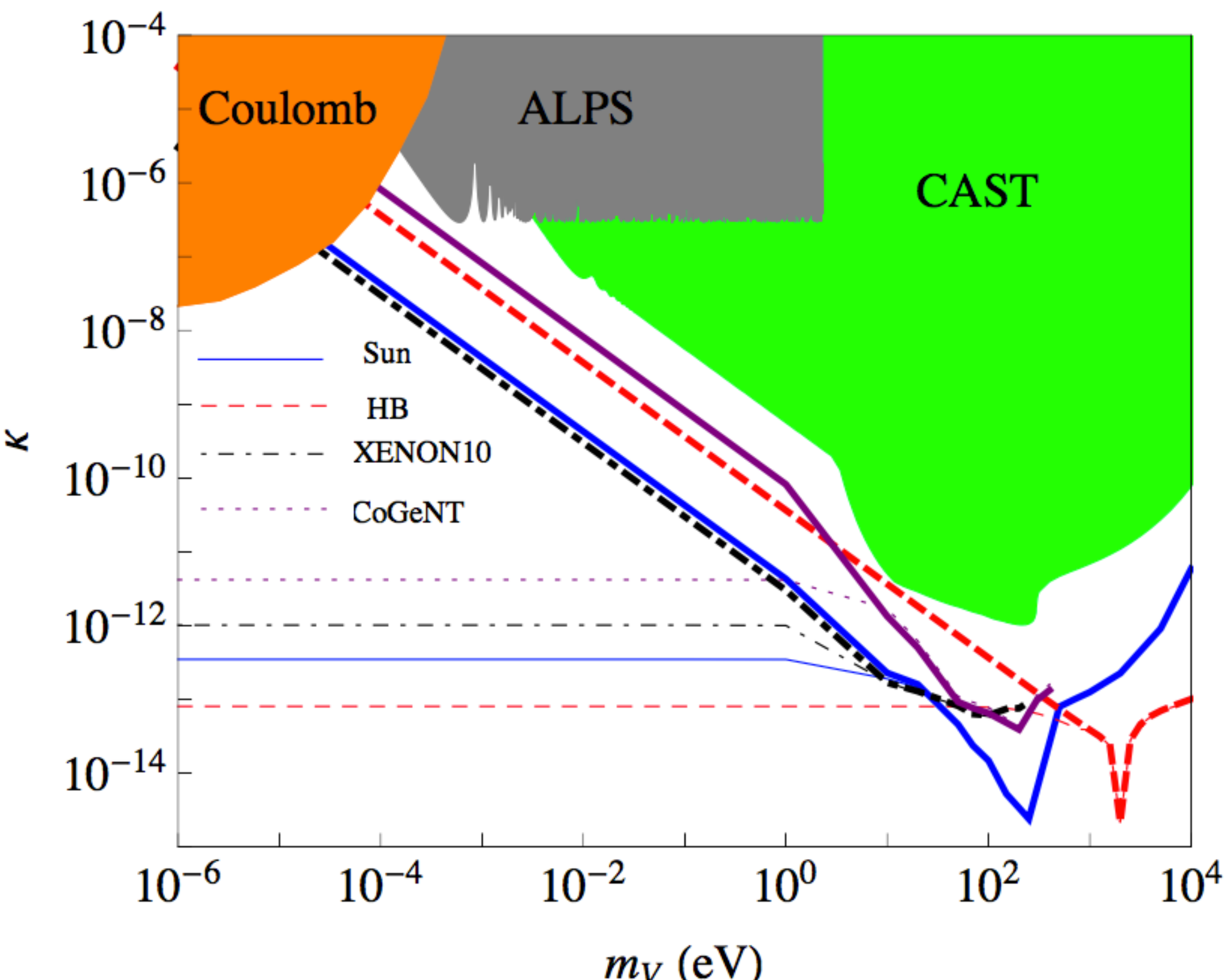
& semiconductors (T. Yu)

An, Pospelov, Pradler, Ritz (1412.8378)   (also works for scalar or pseudoscalar)

A′ from Sun

- an ultralight A′ can be produced in Sun and get absorbed by atom in underground detector:

e.g. in xenon: $Xe + A' \to Xe^* + e^-$



An, Pospelov, Pradler (1304.3461)

Summary

- DD of DM to ~MeV and perhaps much lower is feasible
- proof-of-principle exists; expect continued improvements; new ideas emerging rapidly
- DD and DMA are very complementary — we don't know what DM is, so need a multitude of approaches!
- Major discussion items of WG include novel ideas, how to make a convincing discovery, and how to deal with backgrounds

Suggested specific challenge questions for DD WG

- What are the limiting backgrounds? How much can shielding help? What about (internal) radioactive backgrounds? Surface events? Comptons? Which technologies suffer from which backgrounds?
- Current generation DM-nuclear recoil searches usually rely on two signals to reject signal from backgrounds. Can we think of two distinguishing signals for DM-electron recoils?
- The annual modulation signal is larger for DM-electron scattering that for typical WIMP scattering. If one were to see a signal, what would it take to convince oneself that it is real? How can one verify it?
- What other options exist to distinguish signal from background events?
- What technologies are needed to probe below the 100's of keV scale?
- Complementarity between direct detect and DMA?
- + more general questions (see next talk!)

Back-up

Typical energy & momentum transfer

The e$^-$ (not DM) sets typical momentum transfer

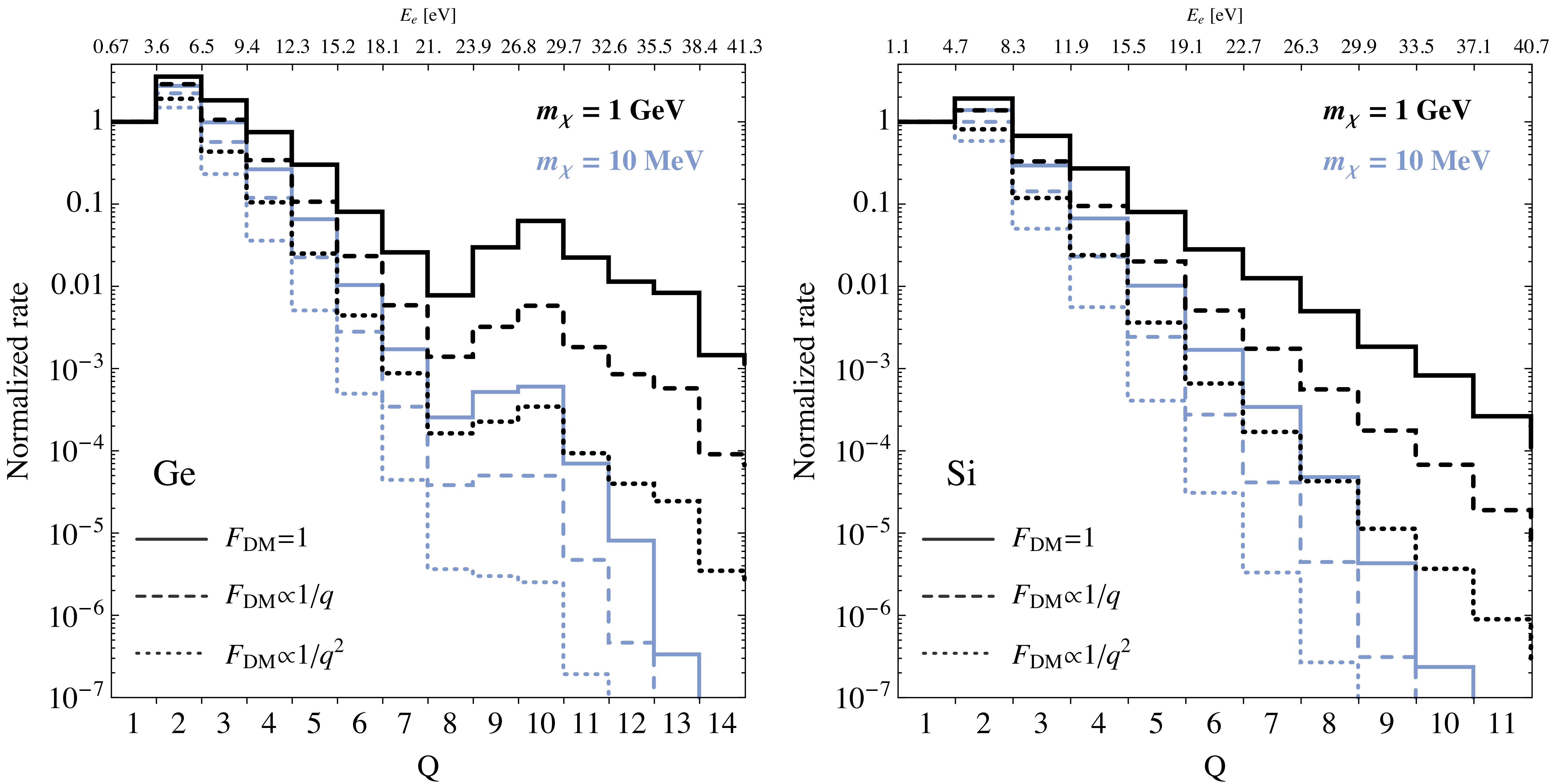
typically $v_e \sim \alpha \gg v_{\rm DM} \sim 10^{-3}$ (for outer shell electron)

$$q_{\rm typ} \simeq \mu_{\chi e} v_{\rm rel} \sim \alpha m_e \sim 4 \text{ keV}$$

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$

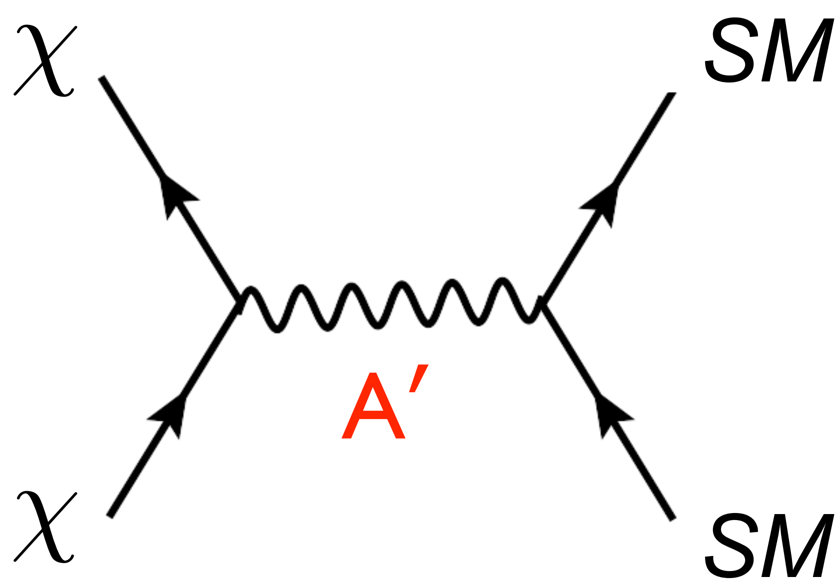
minimum *q* to obtain ΔE: $q \gtrsim \dfrac{\Delta E}{v_{\rm DM}} \sim \dfrac{\Delta E}{4 \text{ eV}} \times q_{\rm typ}$

$\Delta E \gtrsim 4$ eV requires *q* on tail of e$^-$ wavefunction or DM velocity



E_e [eV]
0.67 3.6 6.5 9.4 12.3 15.2 18.1 21. 23.9 26.8 29.7 32.6 35.5 38.4 41.3
m_χ = 1 GeV
m_χ = 10 MeV
Normalized rate
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Ge
$F_{DM}=1$
$F_{DM} \propto 1/q$
$F_{DM} \propto 1/q^2$
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Q
E_e [eV]
1.1 4.7 8.3 11.9 15.5 19.1 22.7 26.3 29.9 33.5 37.1 40.7
m_χ = 1 GeV
m_χ = 10 MeV
Normalized rate
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Si
$F_{DM}=1$
$F_{DM} \propto 1/q$
$F_{DM} \propto 1/q^2$
1 2 3 4 5 6 7 8 9 10 11
Q

Thermal freeze-out



$m_{A'} > 2m_\chi$

scalar χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 v^2$$

p-wave

unconstrained by CMB

Dirac fermion χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2$$

s-wave $\Longrightarrow$ ***asymmetric***

CMB sets *lower* bound on σv

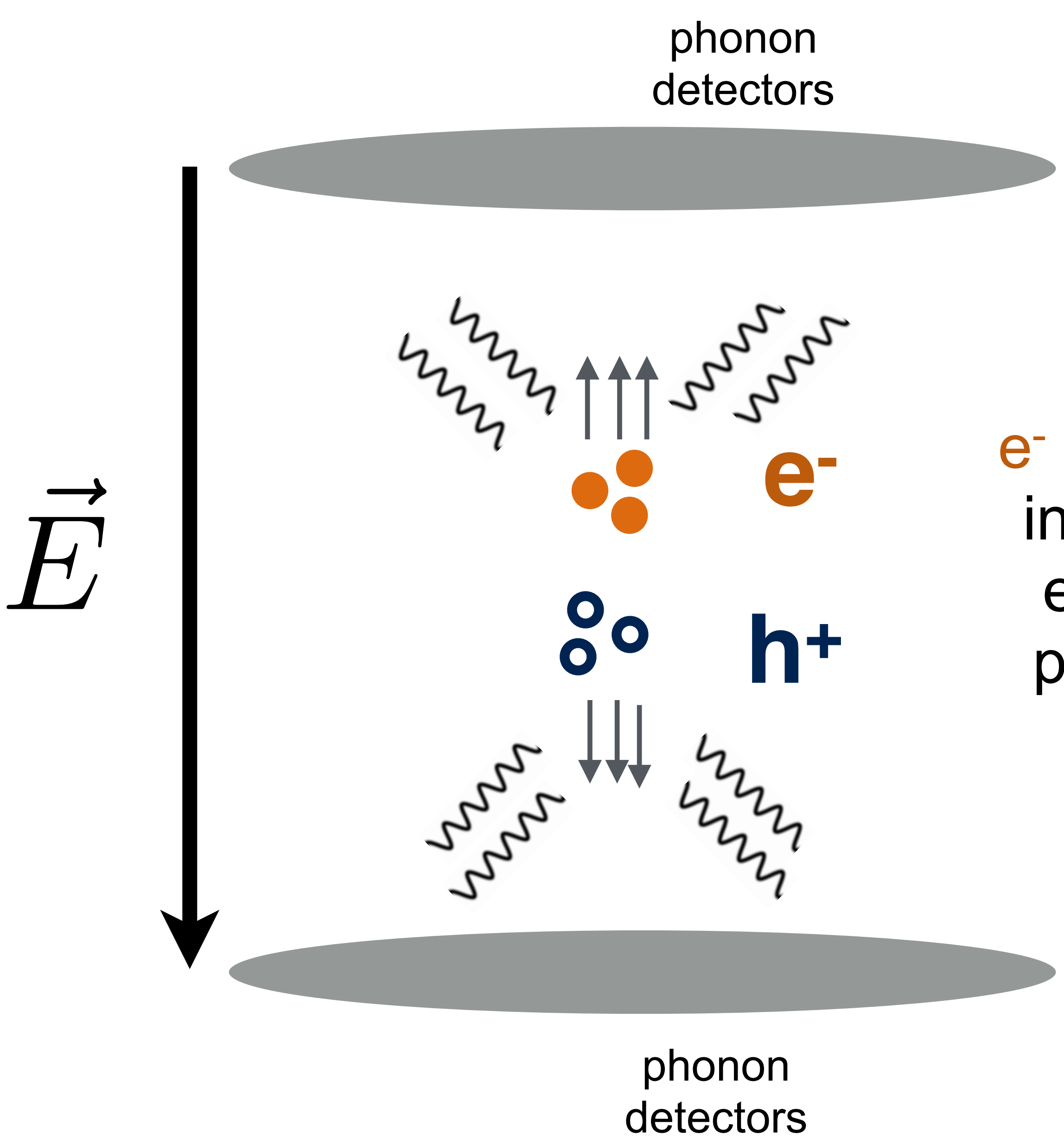
provides nice targets!

e.g. Lin, Yu, Zurek

1. How detect electrons?

amplify phonons by drifting charge

e.g. CDMSlite, SuperCDMS



e^- & h^+ drift in E-field, emitting phonons

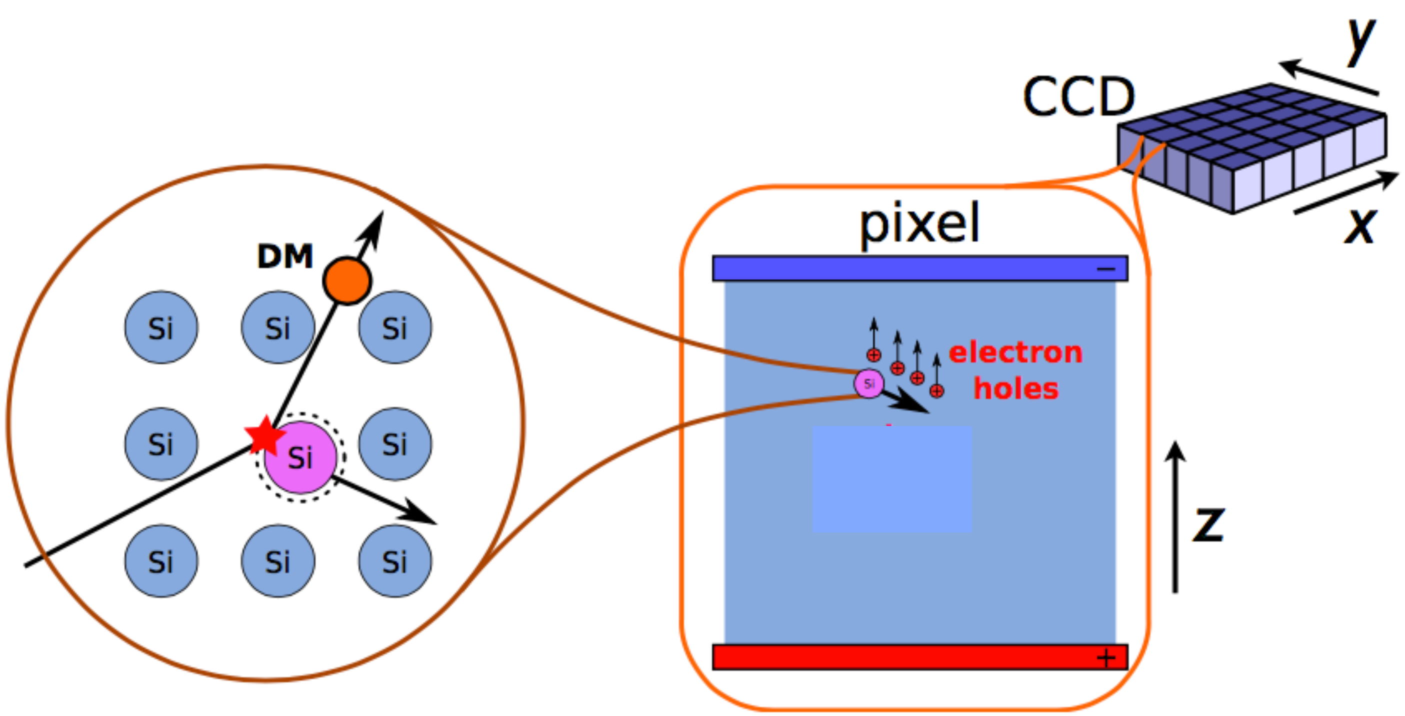
single/few e^- sensitivity being developed over next few years

backgrounds?
(likely much smaller than xenon)

2. How detect electrons?

use CCDs as target: drift and measure charge directly

e.g. DAMIC



1407.0347

current threshold ~11 e^-
(limited by readout noise)

successful
Fermilab LDRD:

~2e^- sensitivity feasible
over next few years
(limited by dark currents)