Direct-Detection of sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

Stony Brook University

Light Dark World 2016, 7/11/2016

An ongoing program

- "Direct Detection of sub-GeV Dark Matter", 1108.5383, PRD
  RE, Mardon, Volansky
- "First Direct Detection Limits on sub-GeV Dark Matter from XENON10", 1206.2644, PRL
  RE, Manalaysay, Mardon, Sorensen, Volansky
- "Direct Detection of sub-GeV Dark Matter with Semiconductor Targets", 1509.01598, JHEP
  RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
- "Direct Detection of sub-GeV Dark Matter with Scintillating Targets", submitted to PRL
  Derenzo, RE, Massari, Soto, Yu

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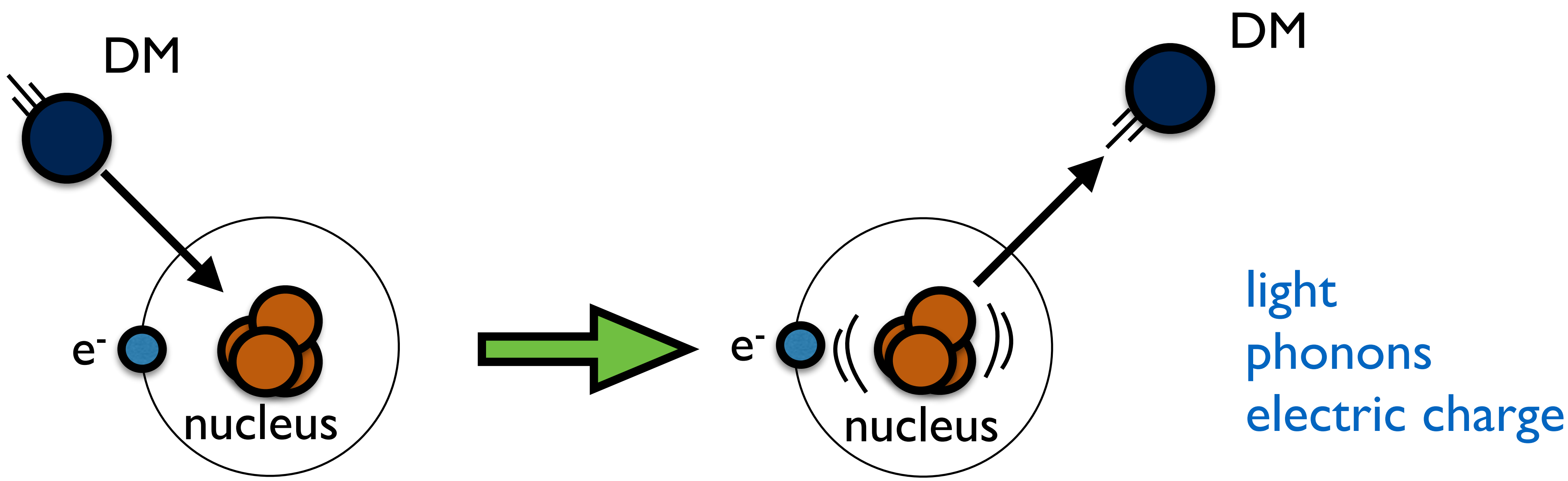
To appear:

- "Detection of Light Dark Matter and Solar Neutrinos via Chemical-Bond Breaking",
  RE, Mardon, Oren Slone, Volansky
- "Large Dark Matter-Electron Scattering Rates In Current Direct Detection Experiments",
  RE, Mardon, Volansky, Yu
- "Models probed by DM-electron recoil experiments",
  RE, Tobioka, Volansky, Yu
- "Direct(ional) Detection of sub-GeV Dark Matter with Semiconductor Targets",
  RE, Mardon, Adrian Soto, Volansky, Yu

Some related work

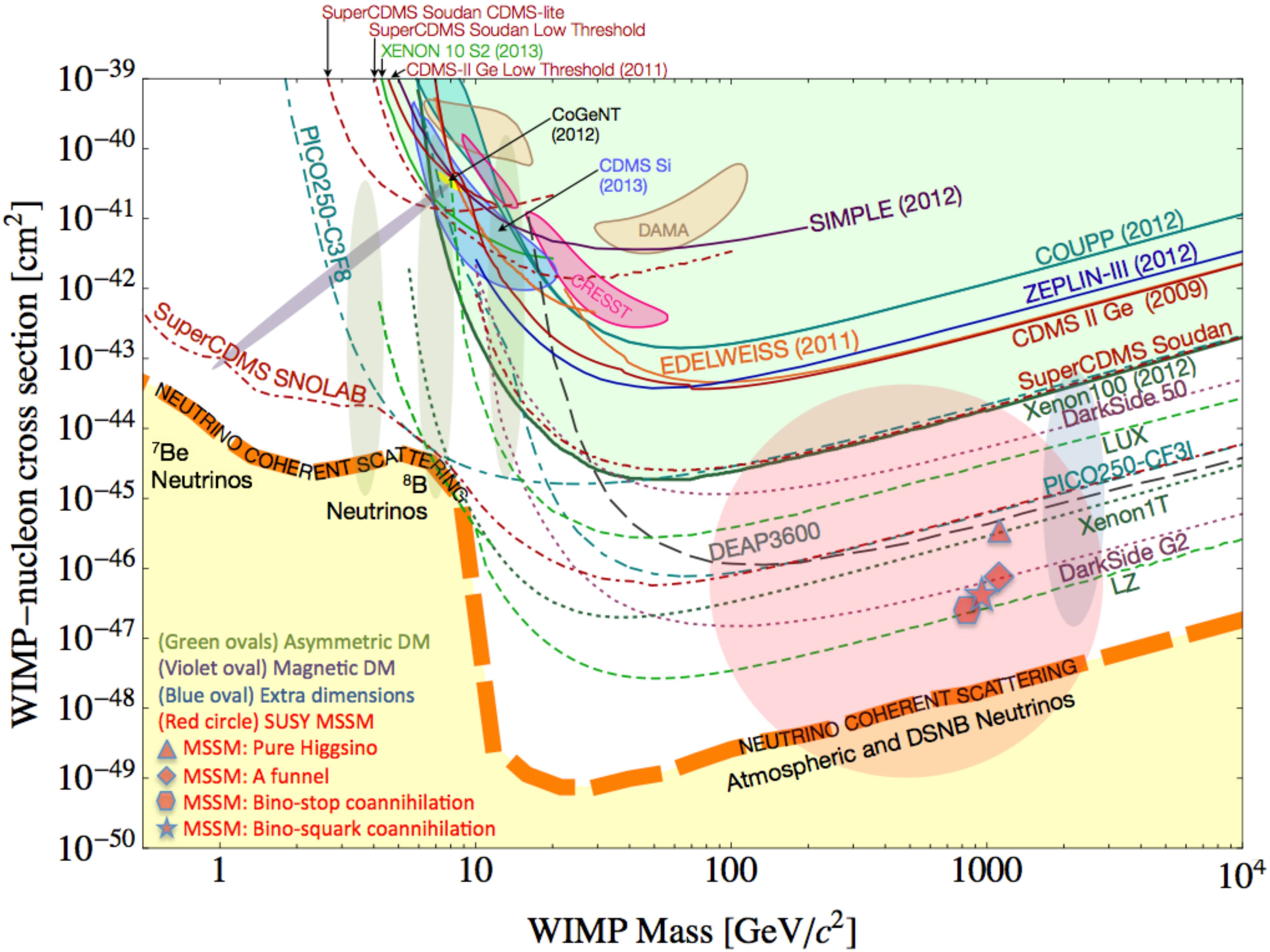
- Graham, Kaplan, Rajendran, Walters, “Semiconductor Probes of Light Dark Matter”, 1203.2531
- An, Pospelov, Pradler, “Dark Matter Detectors as Dark Photon Helioscopes”, 1304.3461
- An, Pospelov, Pradler, Ritz, “Direct Detection Constraints on Dark Photon Dark Matter”, 1412.8378
- Hochberg, Zhao, Zurek, “Superconducting Detectors for Super Light Dark Matter”, 1504.07237
- Lee, Lisanti, Mishra-Sharma, Safdi, “Modulation Effects in Dark Matter-Electron Scattering Experiments”, 1508.07361
- Hochberg, Pyle, Zhao, Zurek, “Superconducting Detectors for Super Light Dark Matter”, 1504.07237
- Dzuba, Flambaum, Pospelov, Roberts, Stadnik, “DM scattering on electrons: Accurate calculations…”, 1604.04559
- Hochberg, Lin, Zurek, “Detecting Ultralight Bosonic Dark Matter via Absorption in Superconductors”, 1604.06800
- Schutz, Zurek, “On the Detectability of Light Dark Matter with Superfluid Helium”, 1604.08206
- Hochberg, Kahn, Lisanti, Tully, Zurek, “Directional Detection of Dark Matter with 2D Targets”, 1606.08849

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

Beyond the WIMP Paradigm

- many other DM candidates exist
- no clear evidence for WIMPs (yet?)
- no new physics at the LHC (yet?)
- several challenges
  ("small-scale crisis of cold DM")

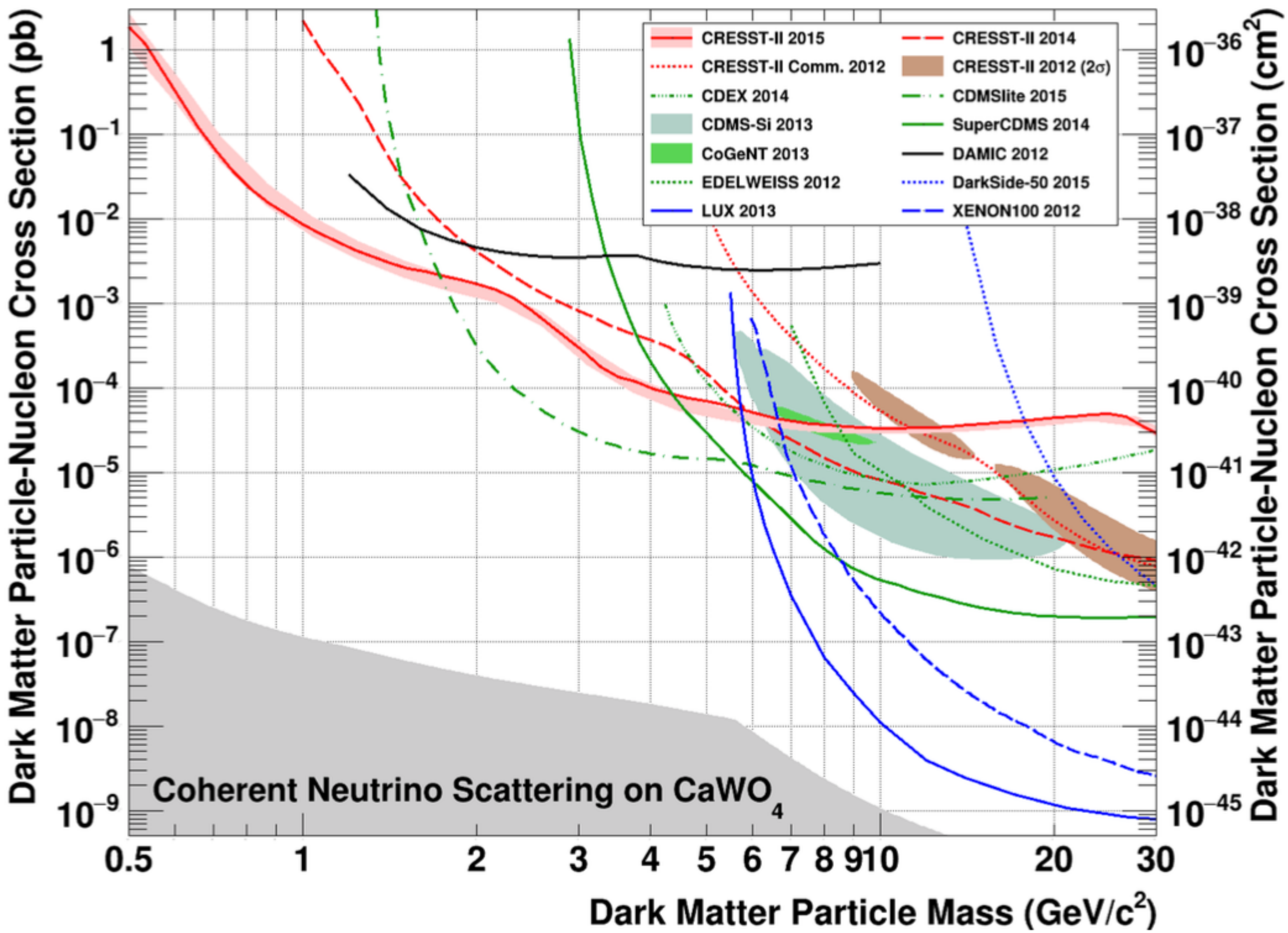
Must search broadly for DM!

focus on mass ~ MeV — GeV

(an old idea, e.g. Boehm, Fayet, …)

Direct Detection below 1 GeV?

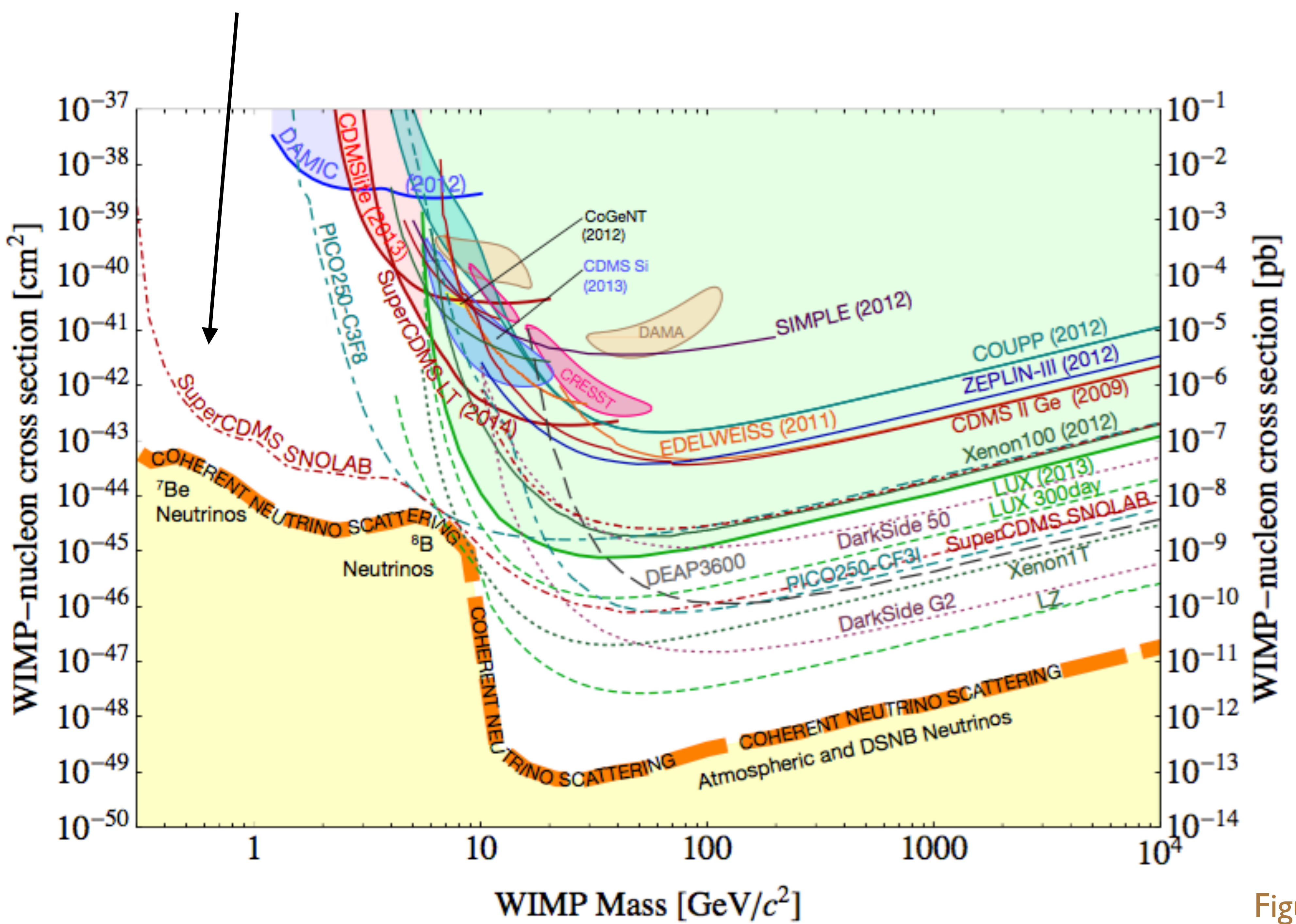
current best limit from CRESST II



1509.01515

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

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

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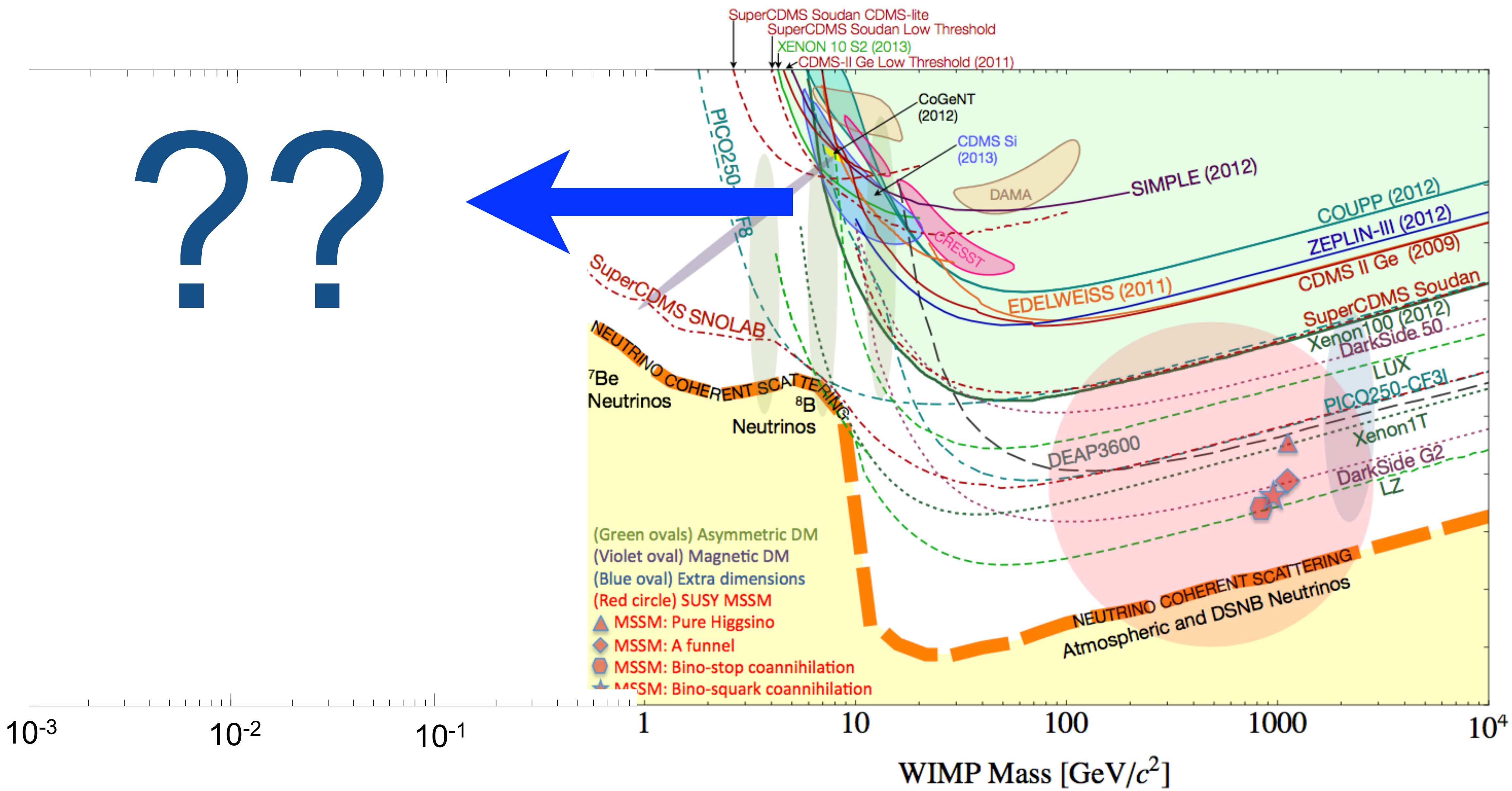
Exp	E_{th} (keV_{NR})	Ref
LUX	~3	1512.03506
DAMIC	~0.5	1510.00044
CDMSlite	~0.3	1509.02448
CRESST-II	~0.3	1509.01515

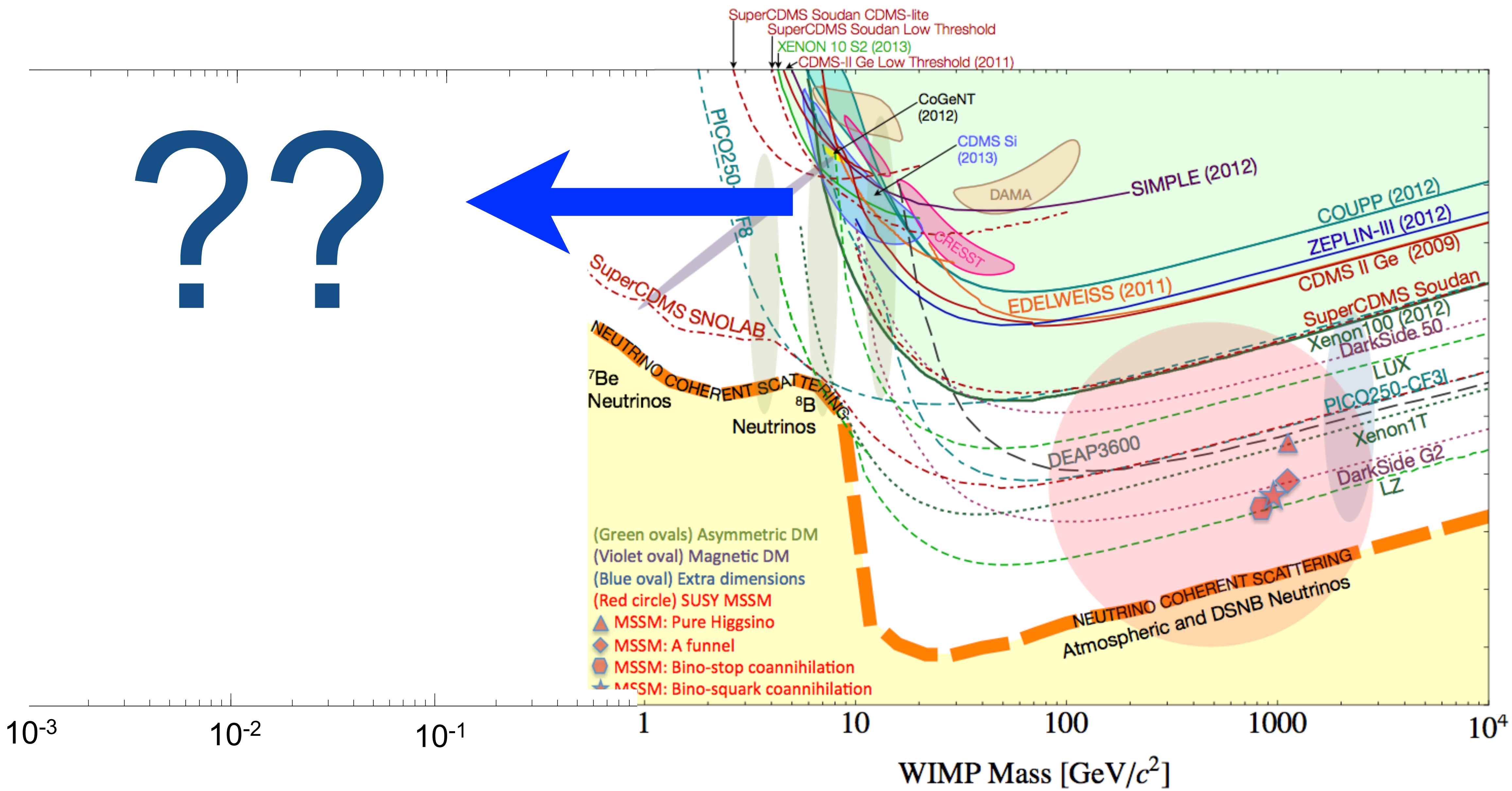
Can we go lower in DM mass?



and even lower??

Can we go lower in DM mass?

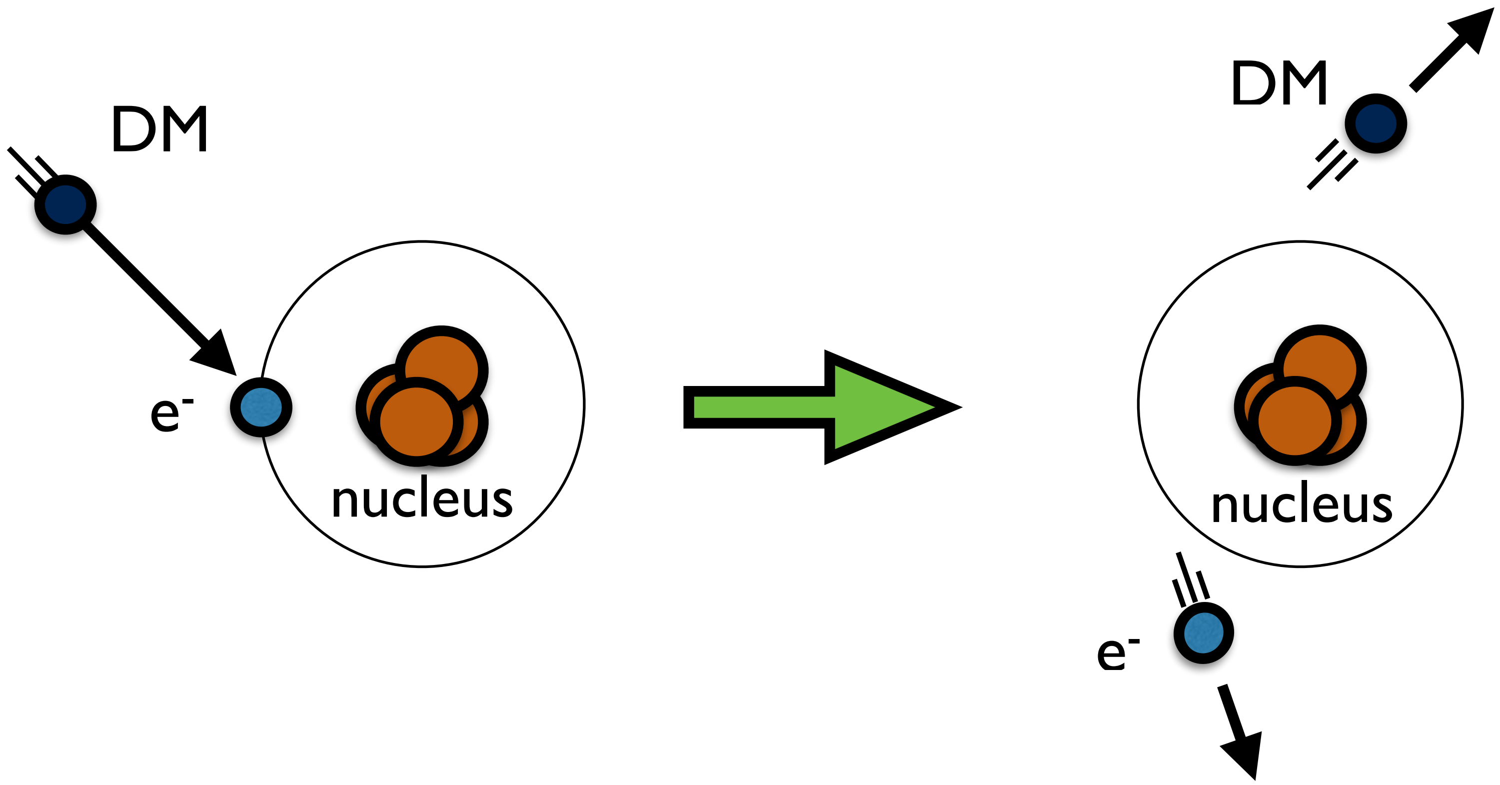
Yes!



and even lower??

DM-electron scattering

RE, Mardon, Volansky



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

DM-electron scattering can probe $\lesssim 1$ MeV

to overcome binding energy ΔE

need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

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

Typical momentum & energy transfer

bound e⁻ does not have definite momentum

Typical momentum transfer is set by e⁻ not DM

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

(for outer shell electron)

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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

Target materials?

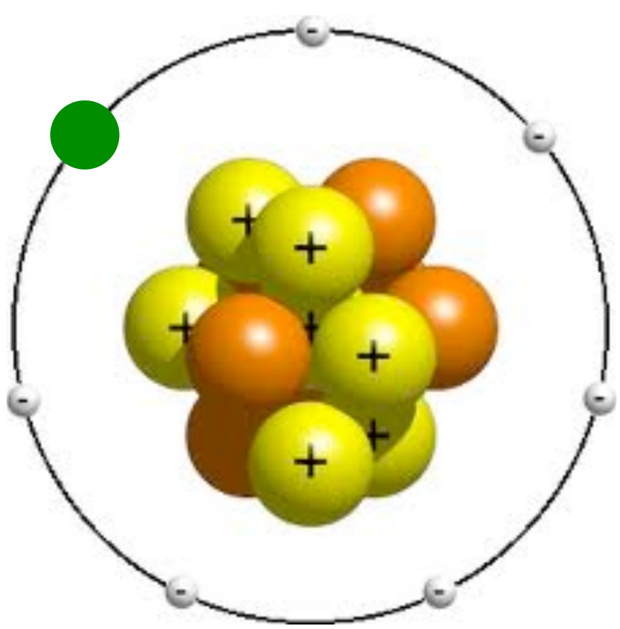
Target materials?

Type	Examples	E_{th} (eV)	$m_{DM,\, th}$ (MeV)	Status
Noble liquids	xenon argon helium	~10 eV (atom)	~5 MeV	Done w/ XENON10+100 data; improvements possible

RE, Mardon, Volansky

RE, Manalaysay, Mardon, Sorensen, Volansky

RE, Mardon, Volansky, Yu (to appear)



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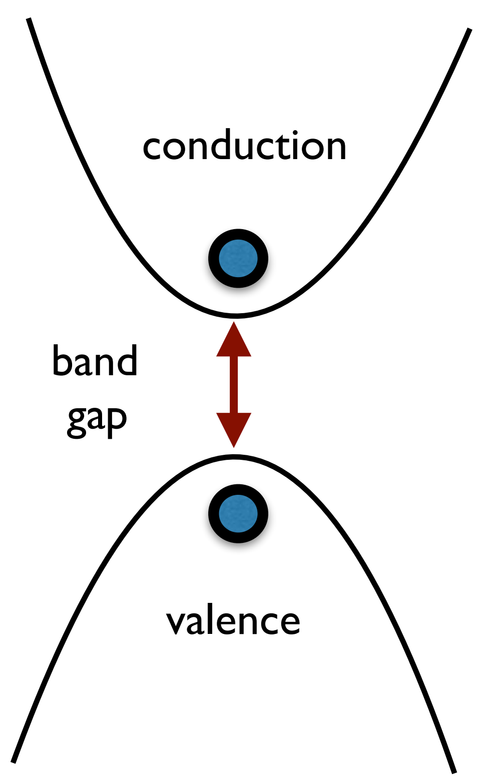

RE, Mardon, Volansky

Graham, Kaplan, Rajendran, Walters

Lee, Lisanti, Mishra-Sharma, Safdi

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Derenzo, RE, Massari, Soto, Yu

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Semiconductor & Scintillator bandgaps are near "typical" electron recoil energy — no wavefunction suppression

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Hochberg, Zhao, Zurek
Hochberg, Pyle, Zhao, Zurek

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superfluid helium, 2D graphene, … also possible targets

Schutz, Zurek

Hochberg, Kahn, Lisanti, Tully, Zurek

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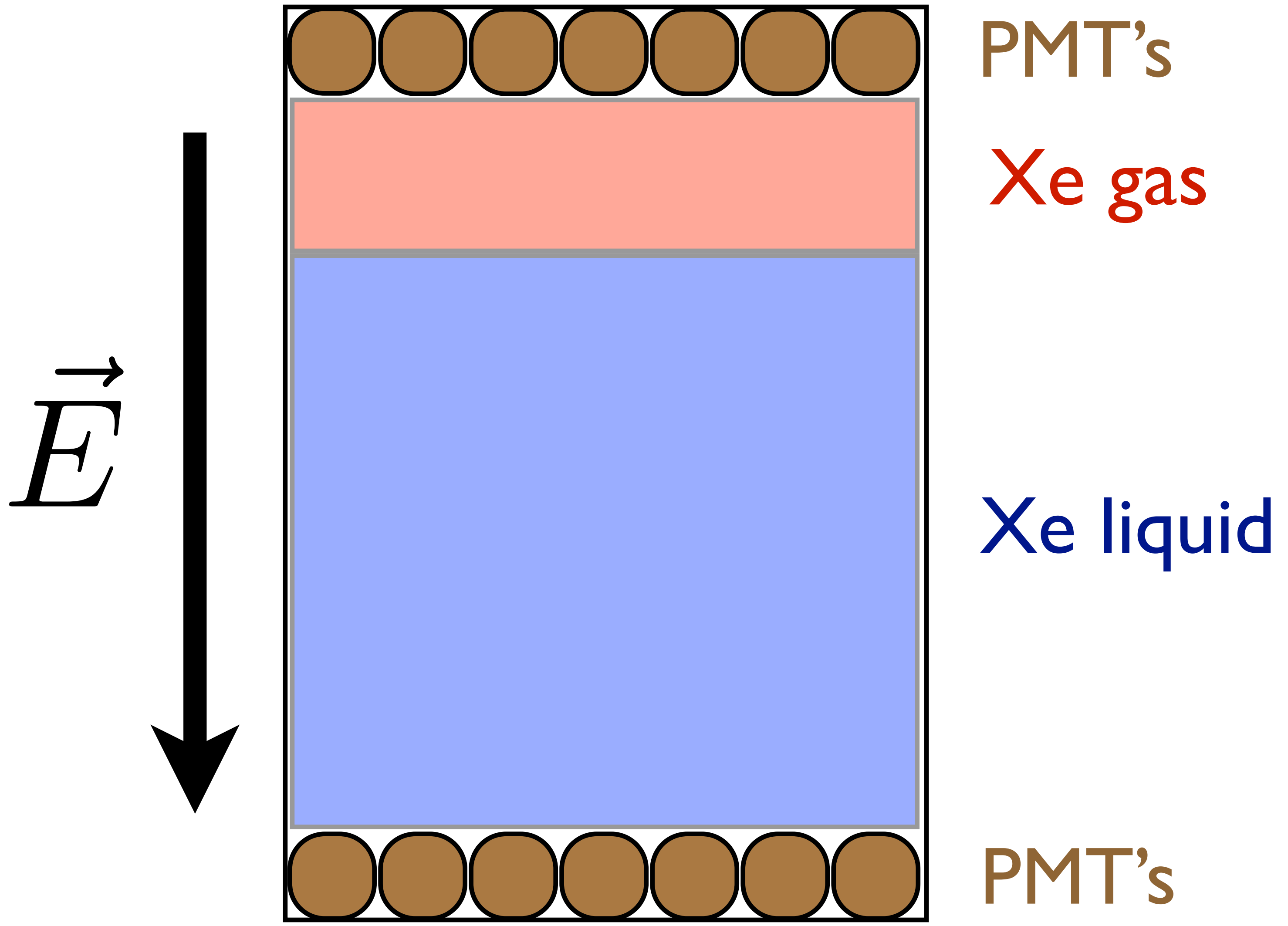
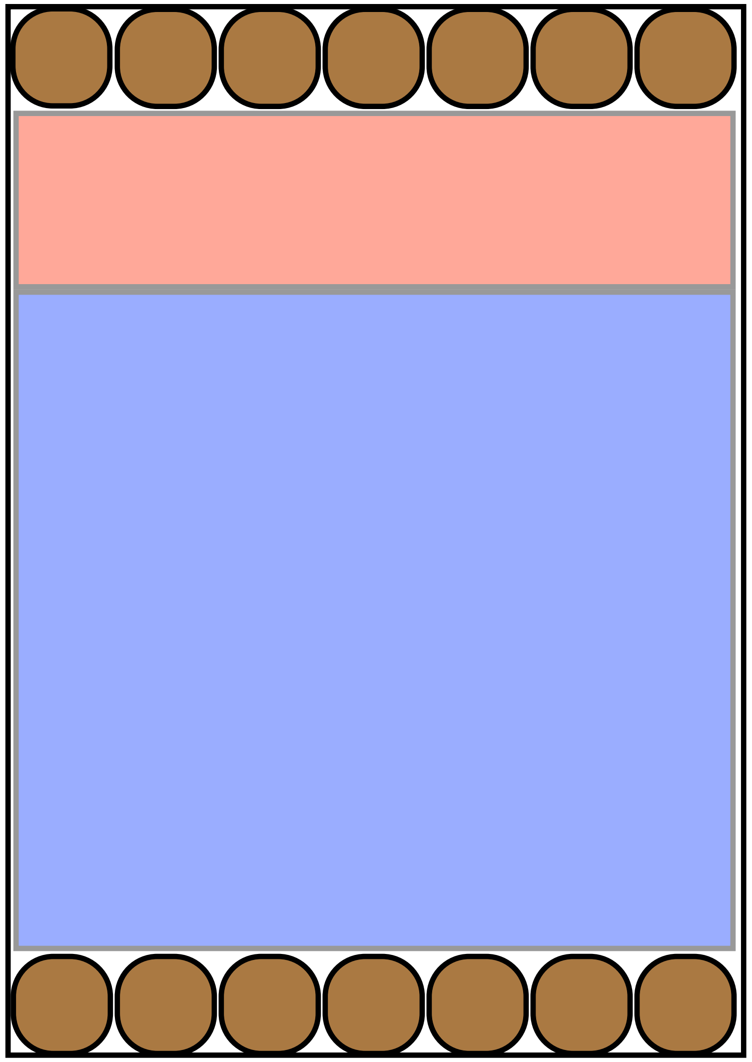
XENON10 detector schematic



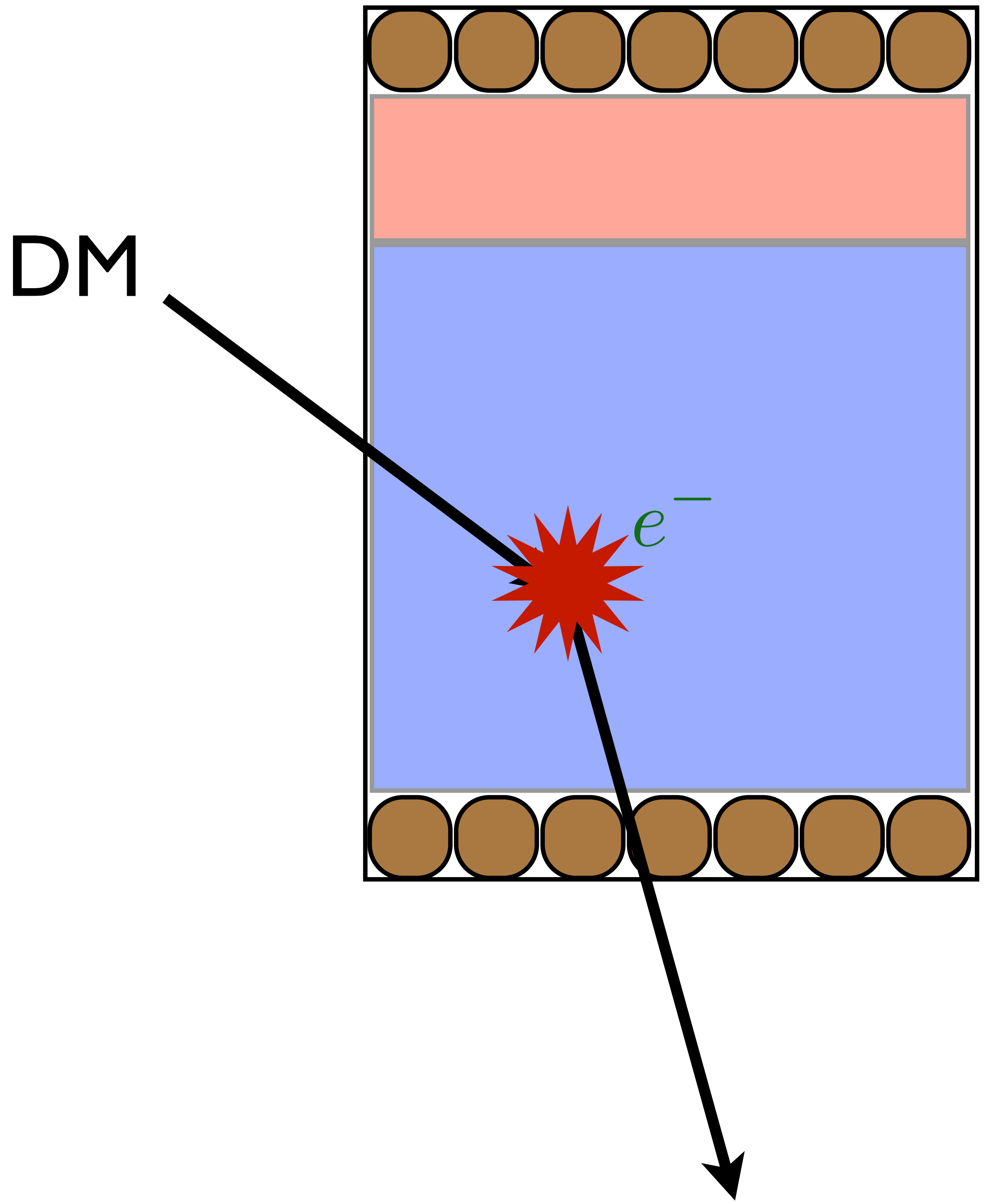
ran in 2006/2007, sensitive to single electrons!

Sub-GeV DM scattering off electrons

DM



Sub-GeV DM scattering off electrons



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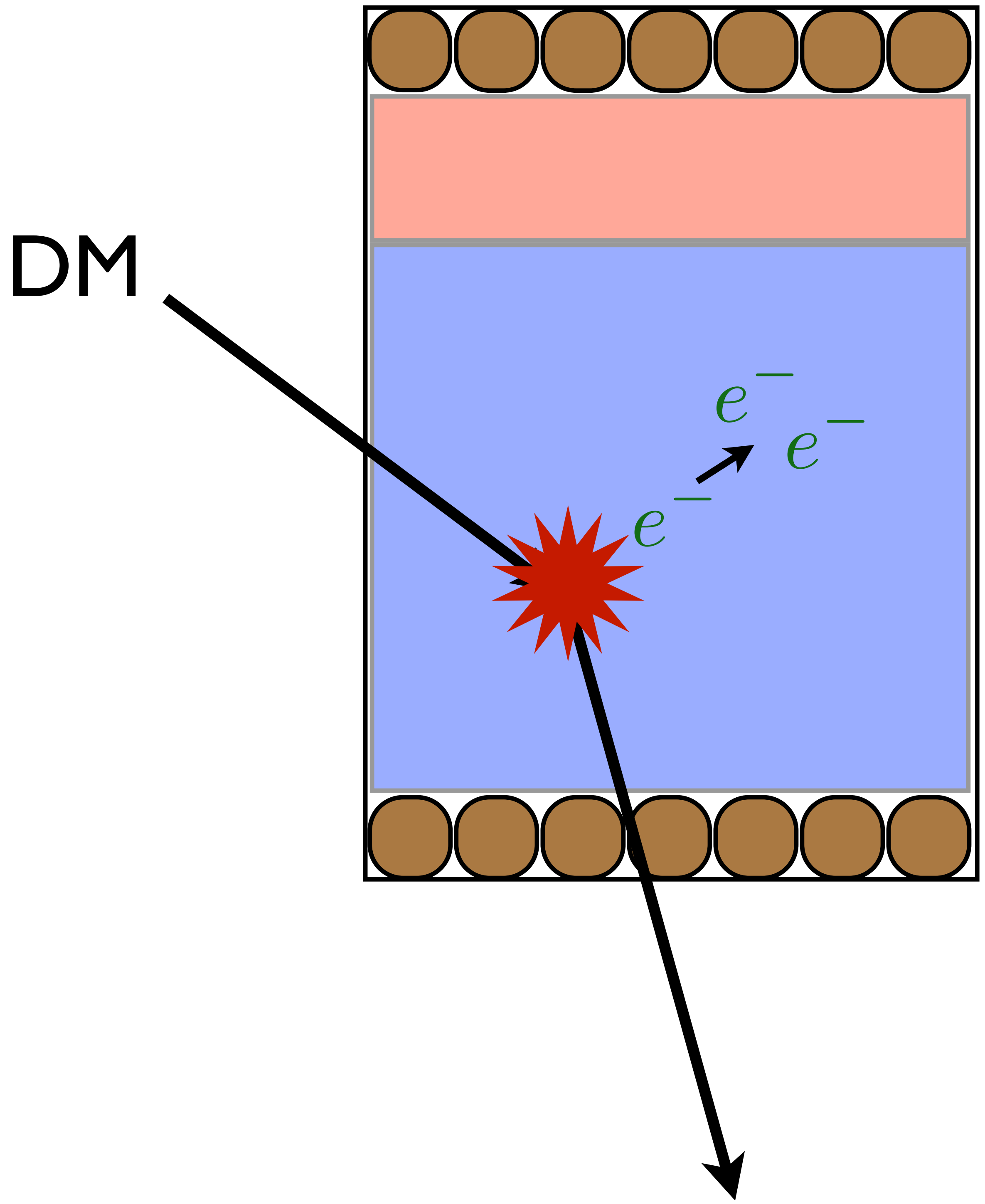

an energetic outgoing e^- can ionize other e^-'s

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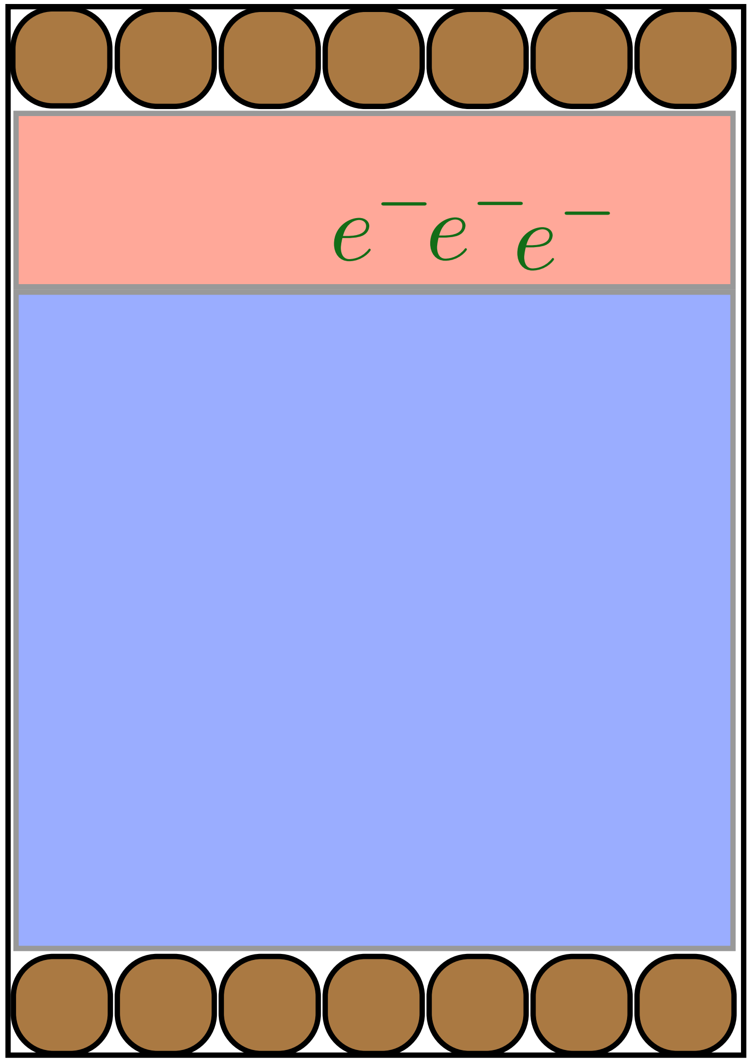

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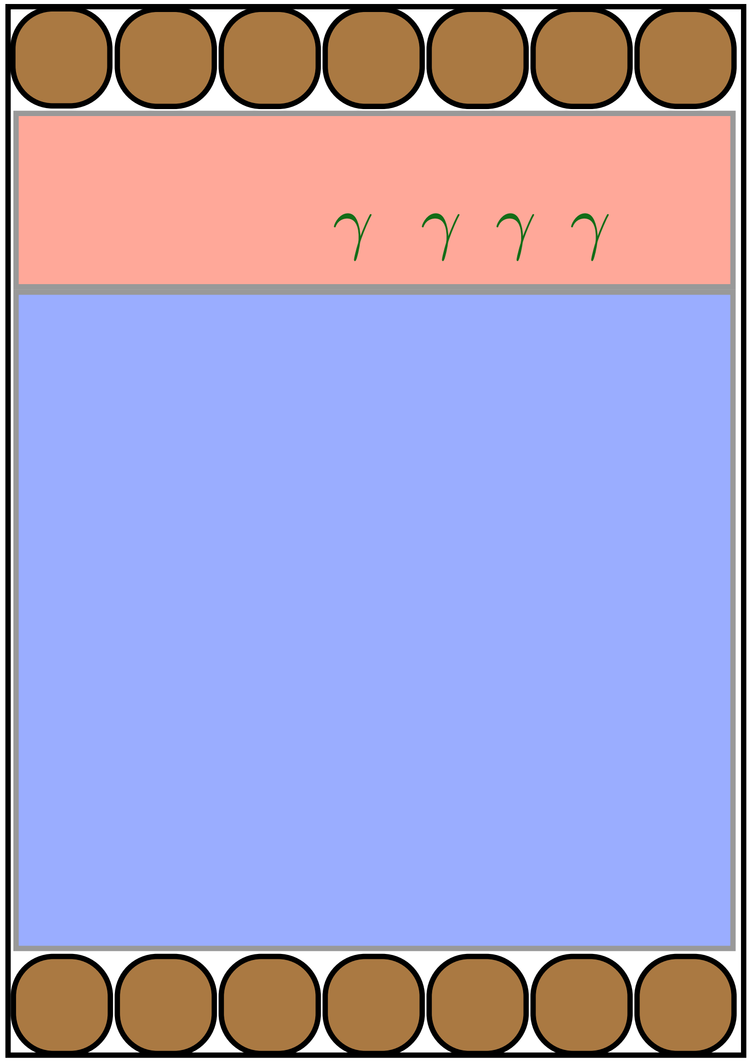

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one e^- produces ~27 detected photons
("S2-signal")

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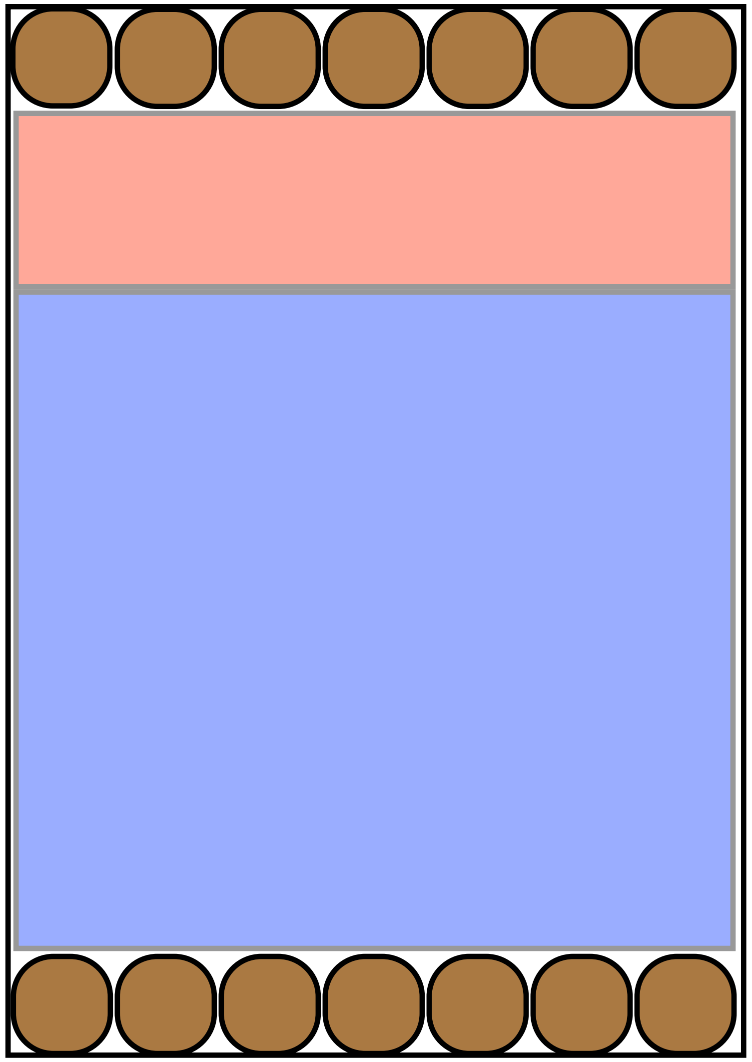

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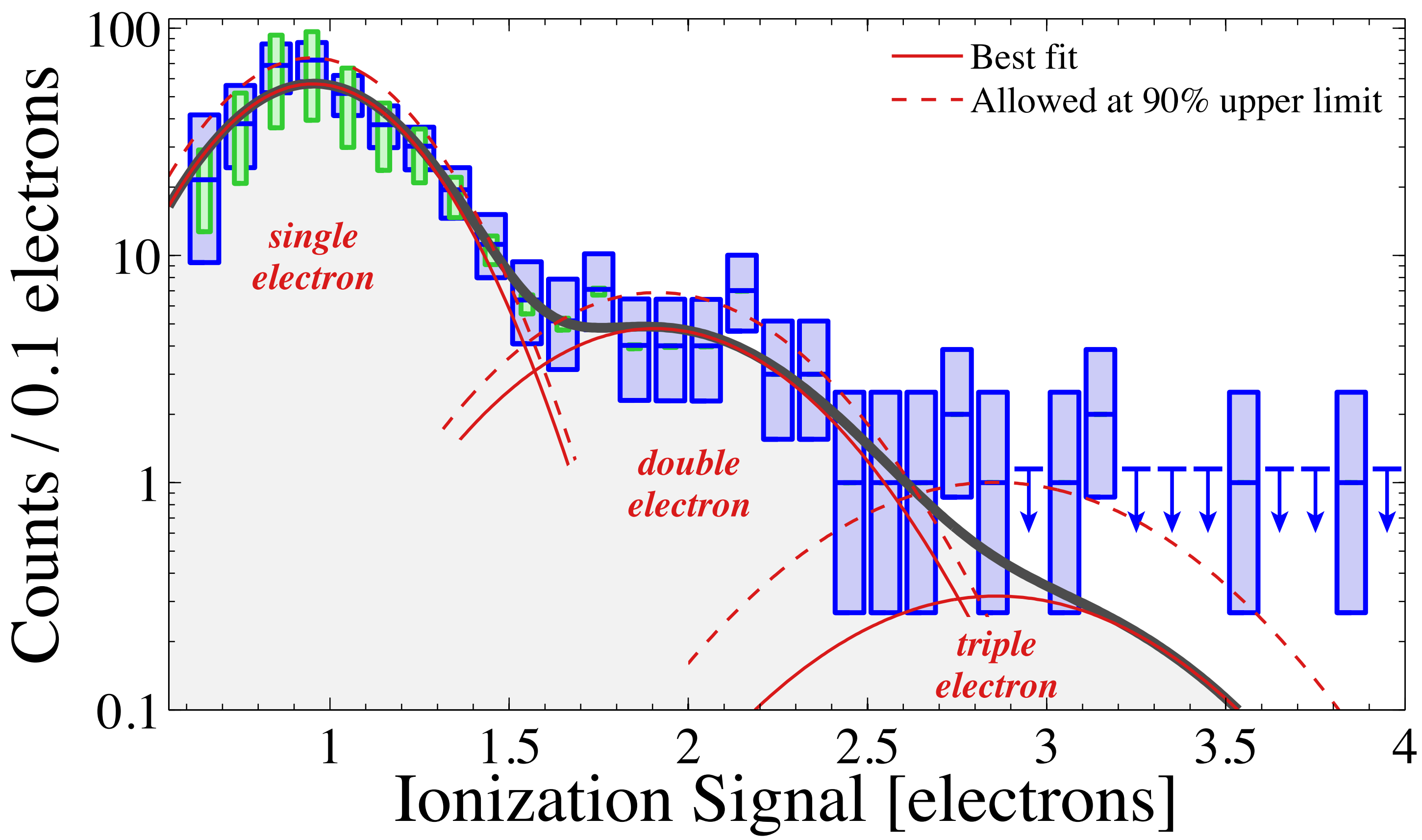
The XENON10 data

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, 2012

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  - Not a general "physics" background, but seems specific to dual-phase detectors (also present in XENON100, LUX), 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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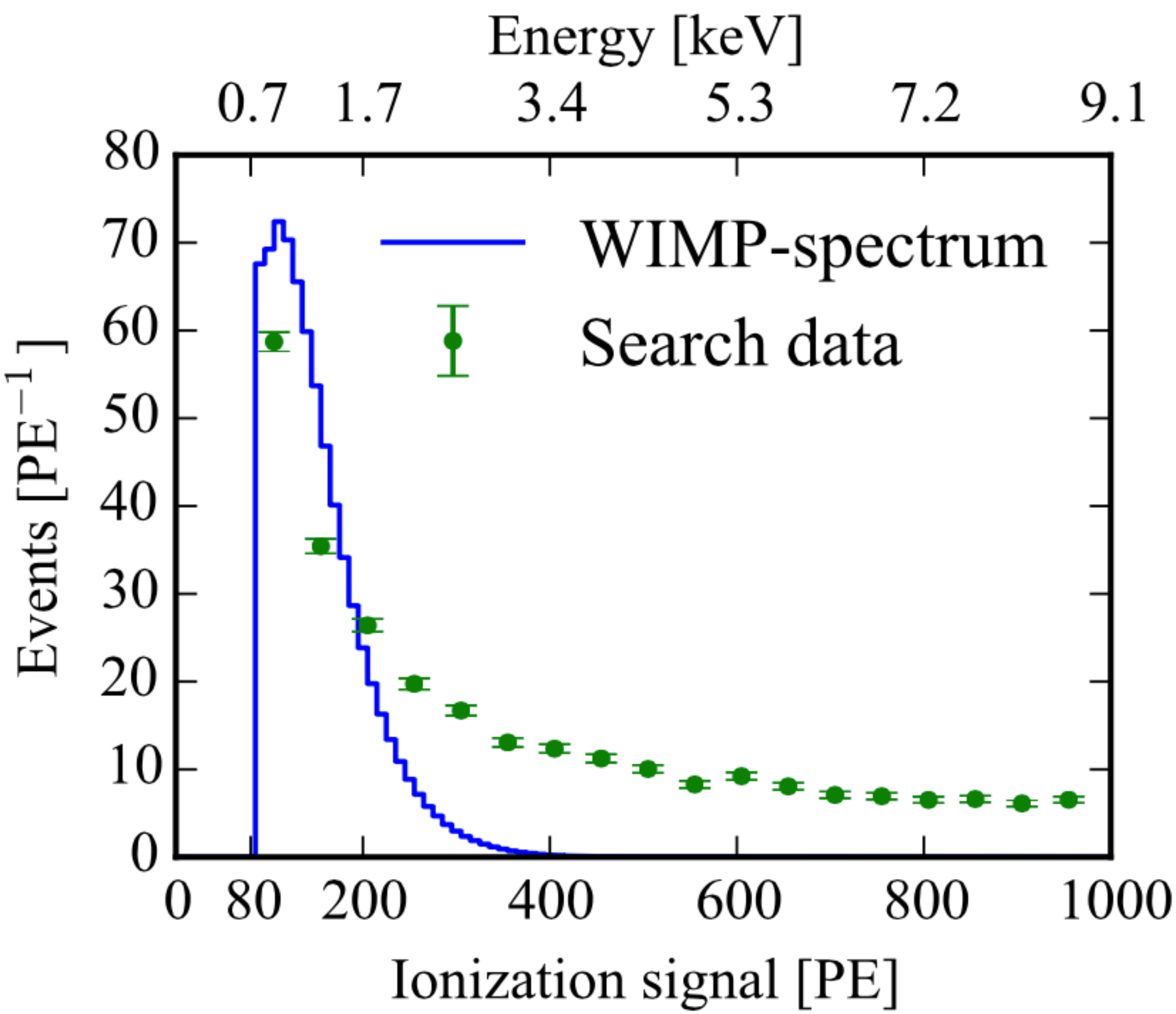
    - e^- emission by cathode
- Could some events be DM?
  - Yes (more later)

Recent XENON100 S2-only data sets new limits!

RE, Mardon, Volansky, Yu (to appear)



from 1605.06262

spectrum for $\geq$4 electrons

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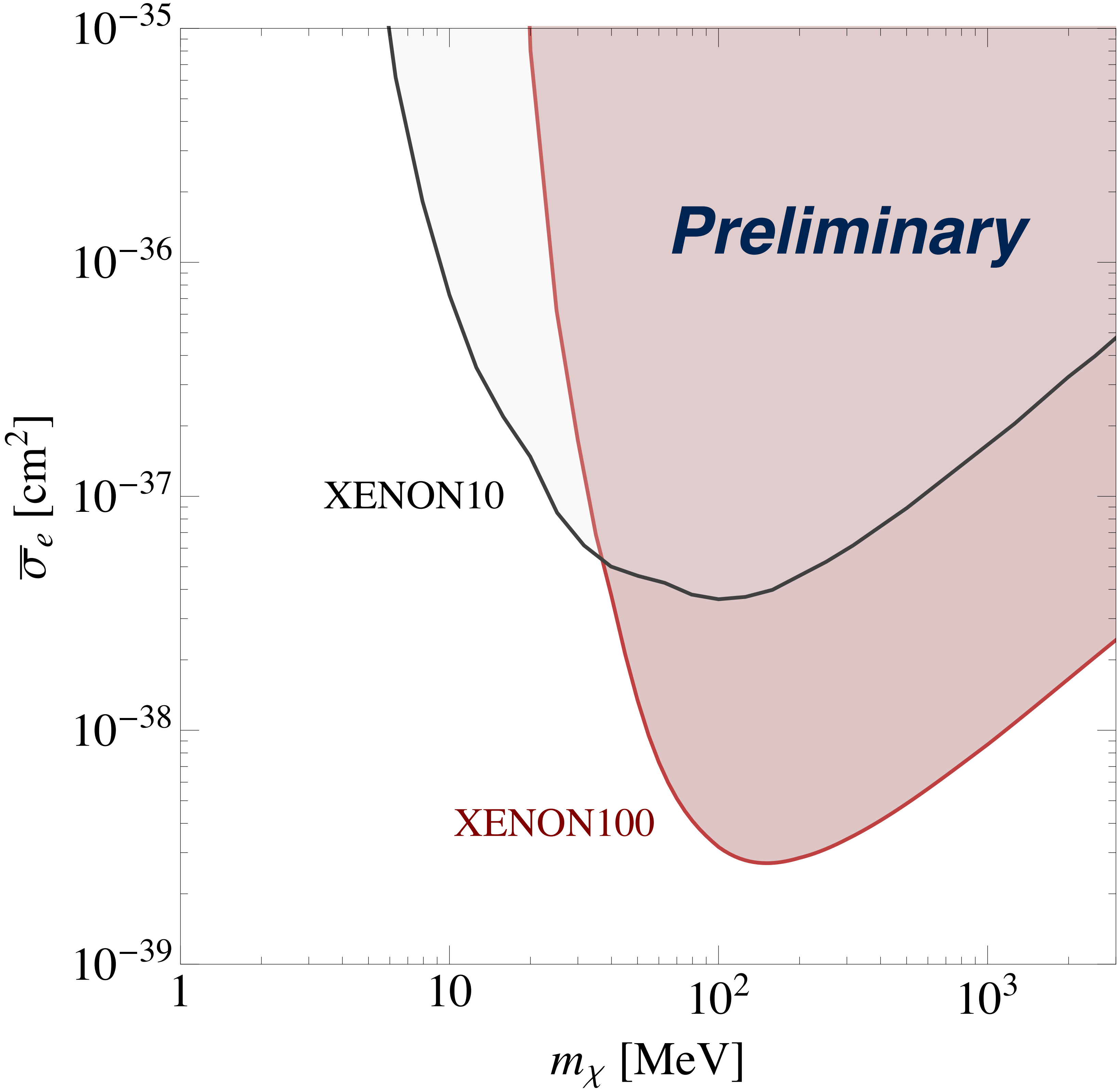

XENON10+100 & beyond

clever cuts could significantly reduce backgrounds

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large exposures of LUX, XENON1t, LZ could compensate for uncertain backgrounds (e.g. look for annual modulation)

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

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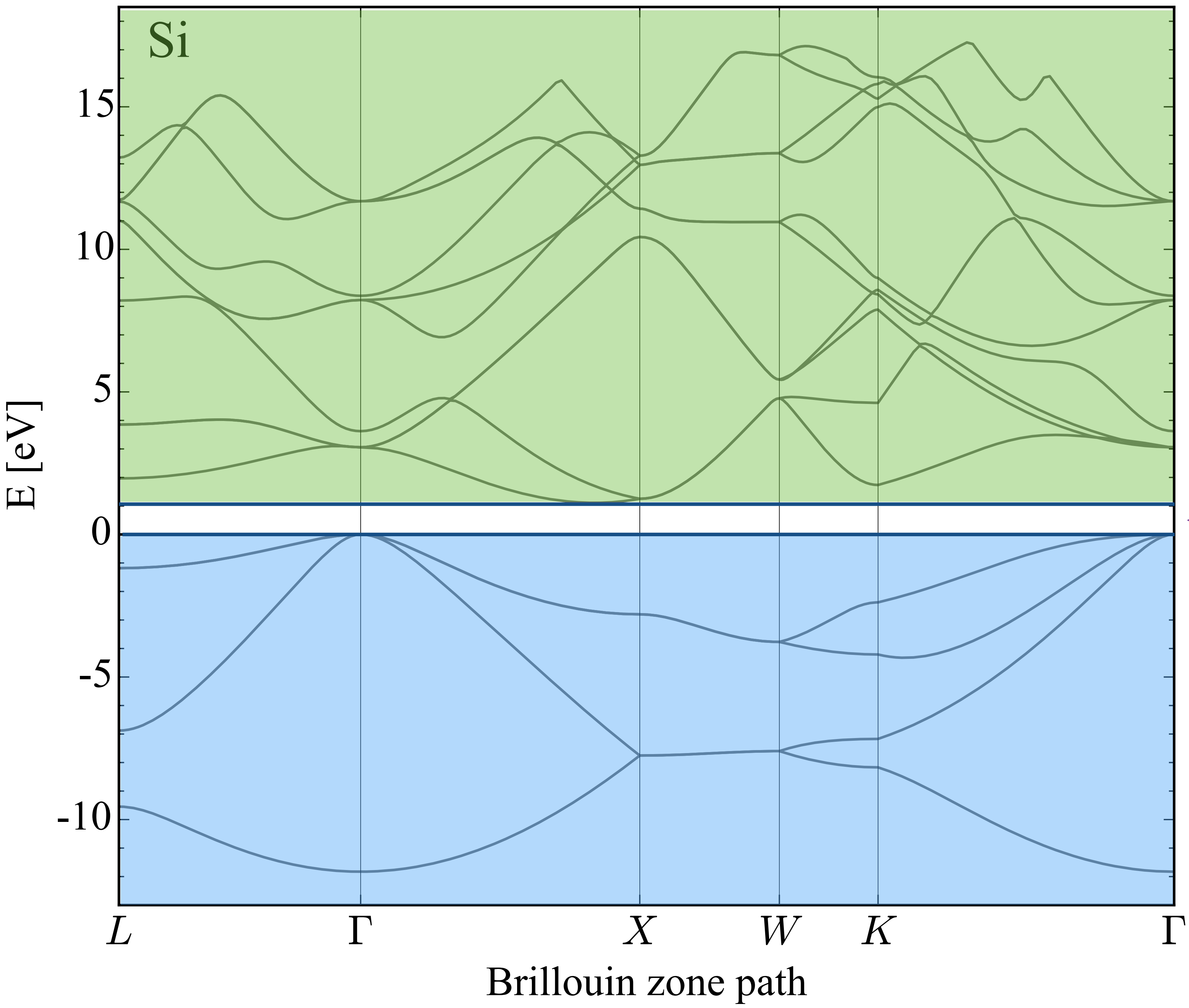
large exposures of LUX, XENON1t, LZ could compensate for uncertain backgrounds (e.g. look for annual modulation)

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

focus here on semiconductors & scintillators, since technologies should be available over next few years

Semiconductors & Scintillators (schematic)

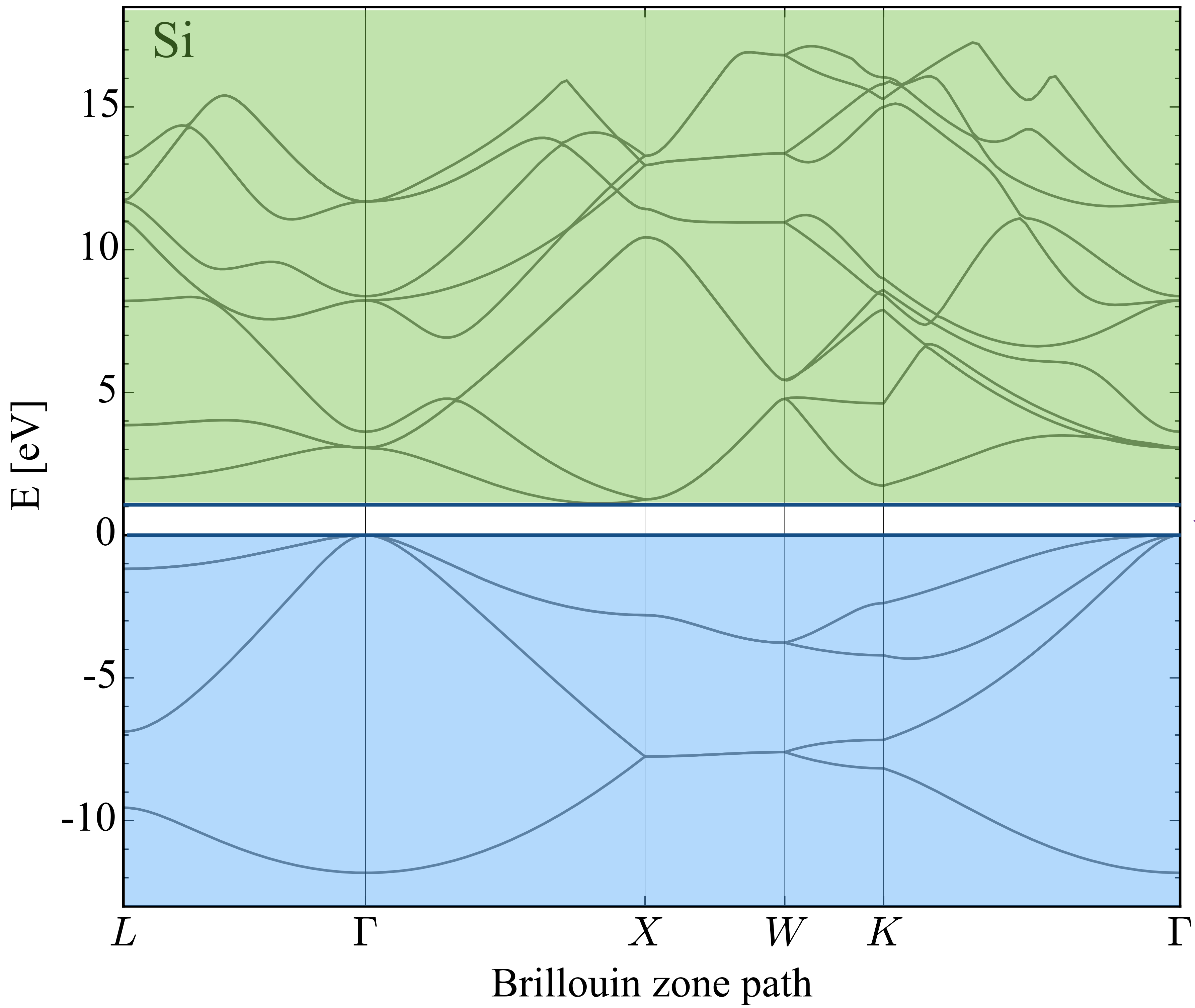


empty conduction band

band gap

filled valence band

Semiconductors & Scintillators (schematic)



band gap

	[eV]
Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

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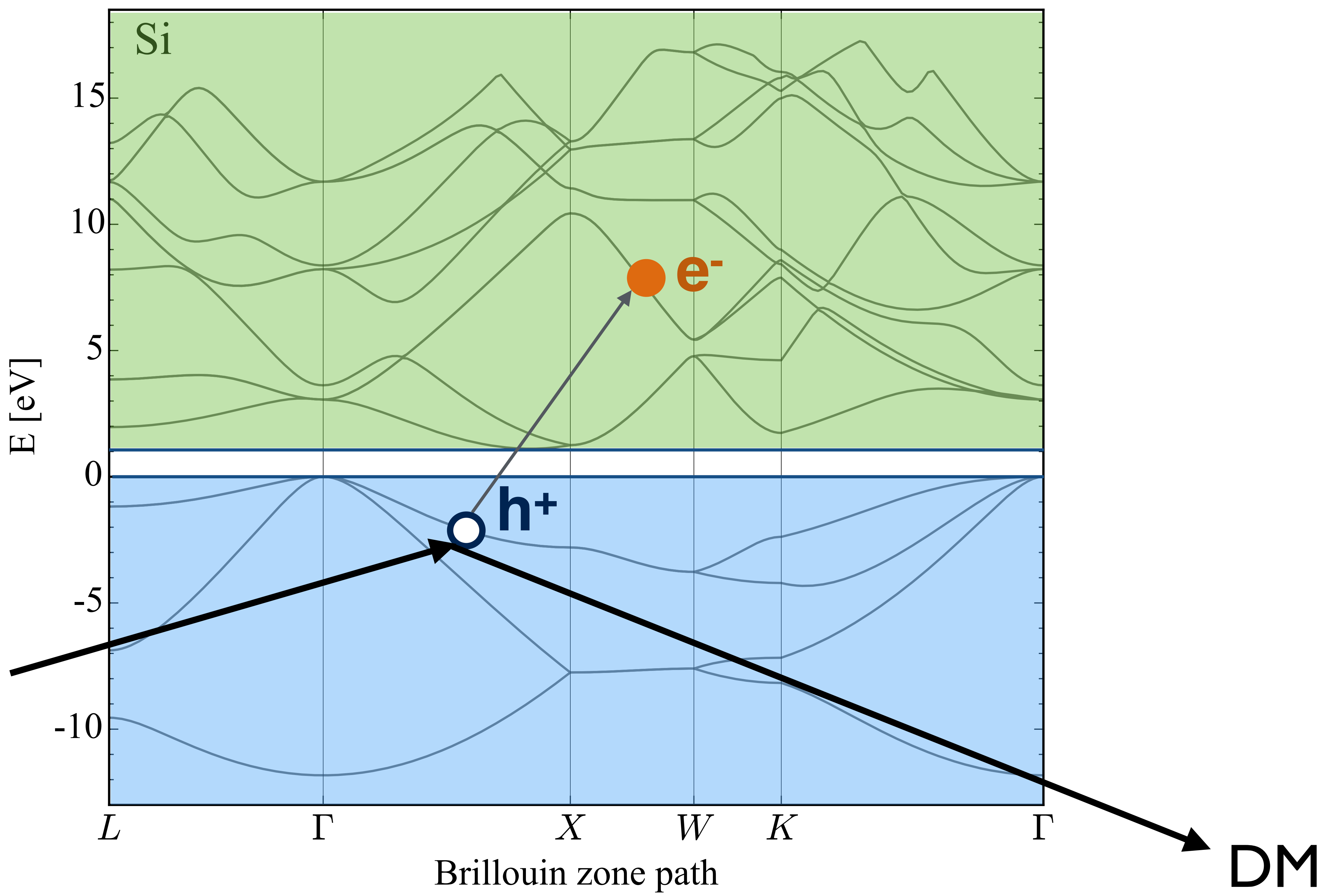

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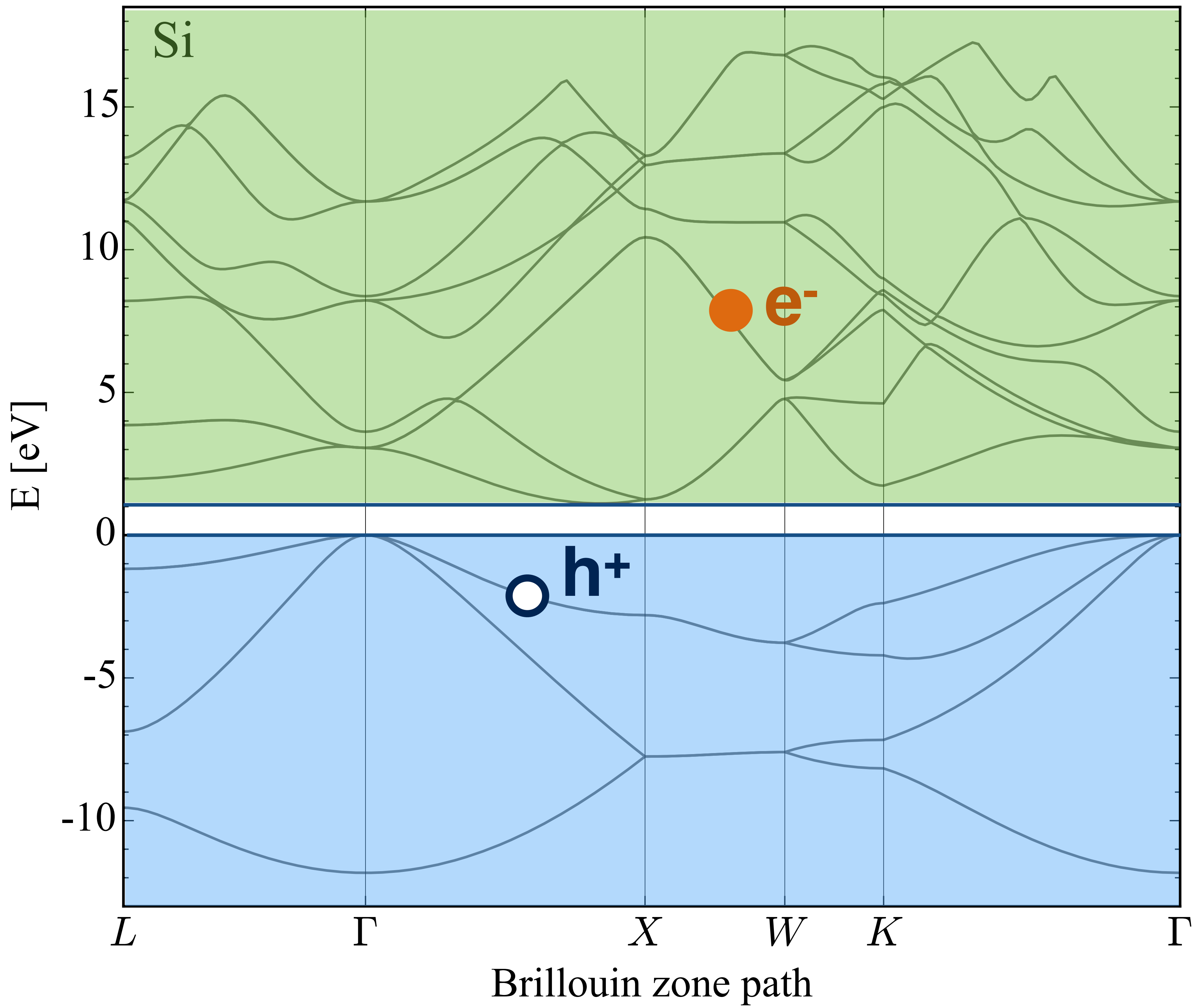
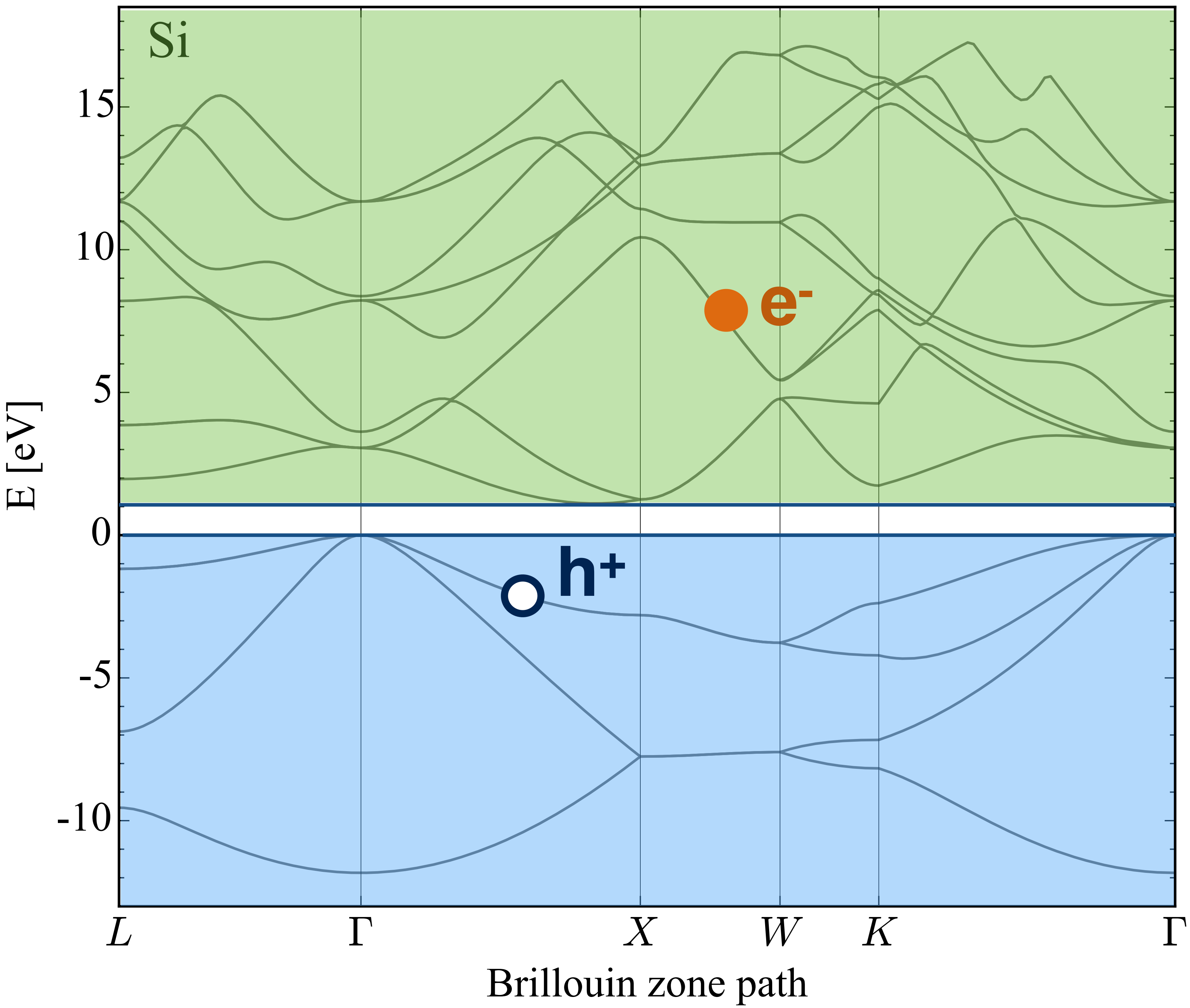


recoiling e^- can create additional e^-/h^+ pairs

e.g. one pair for each 2.9 eV (3.6 eV) in Ge (Si)

Semiconductors & Scintillators (schematic)



semiconductor:
apply electric field to measure electrons (ionization)

scintillator:
e.g. e^-/h^+ can recombine to produce photons (no E-field needed)

Possible advantages & challenges for scintillators

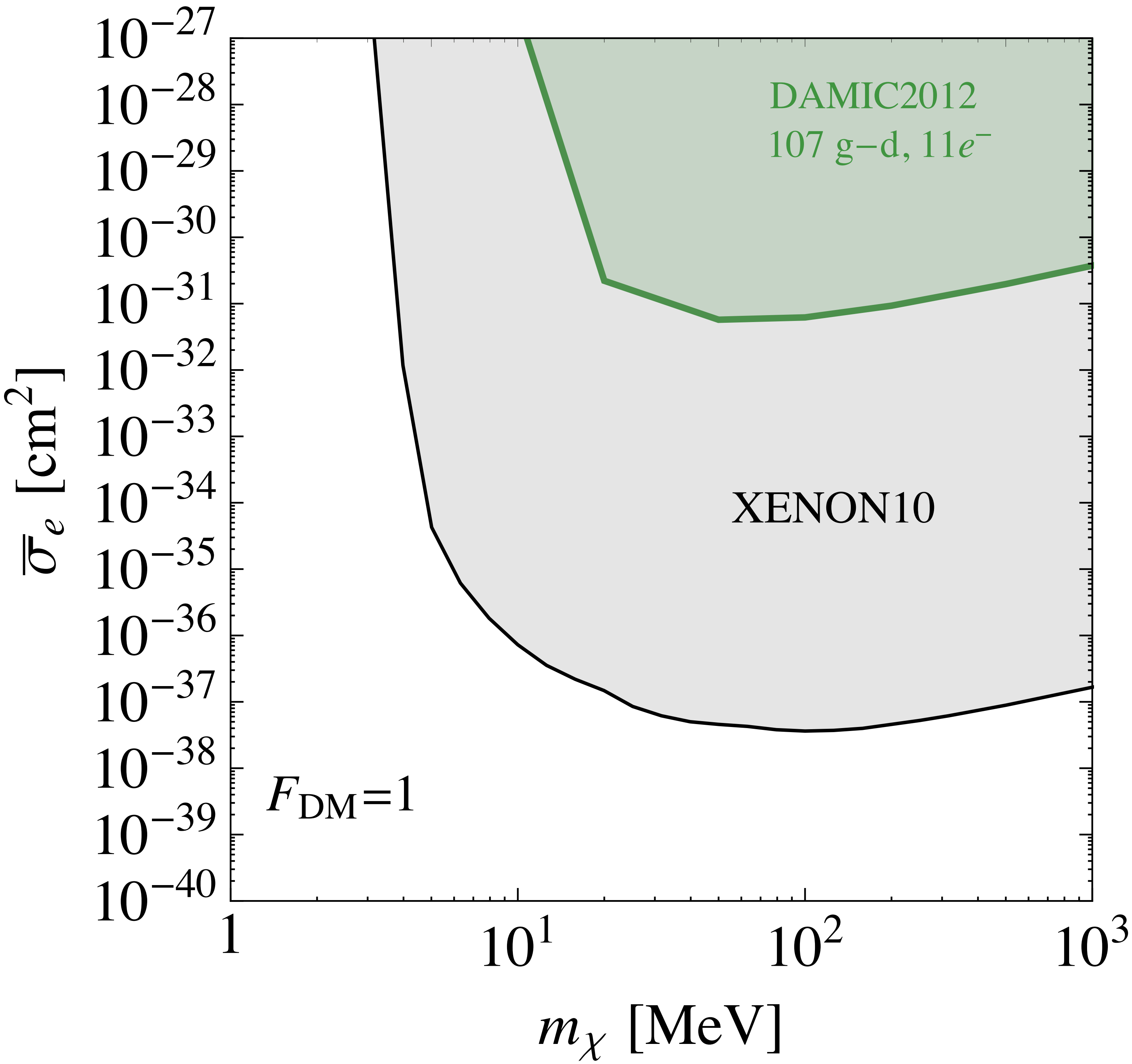
Derenzo, RE, Massari, Soto, Yu
(submitted to PRL)

- Single photons easier to detect than single electrons?
  (photodetectors under development by e.g. M. Pyle et.al.)
- No electric field, so no dark counts?
- A possible challenge: "afterglow"?

more R&D needed

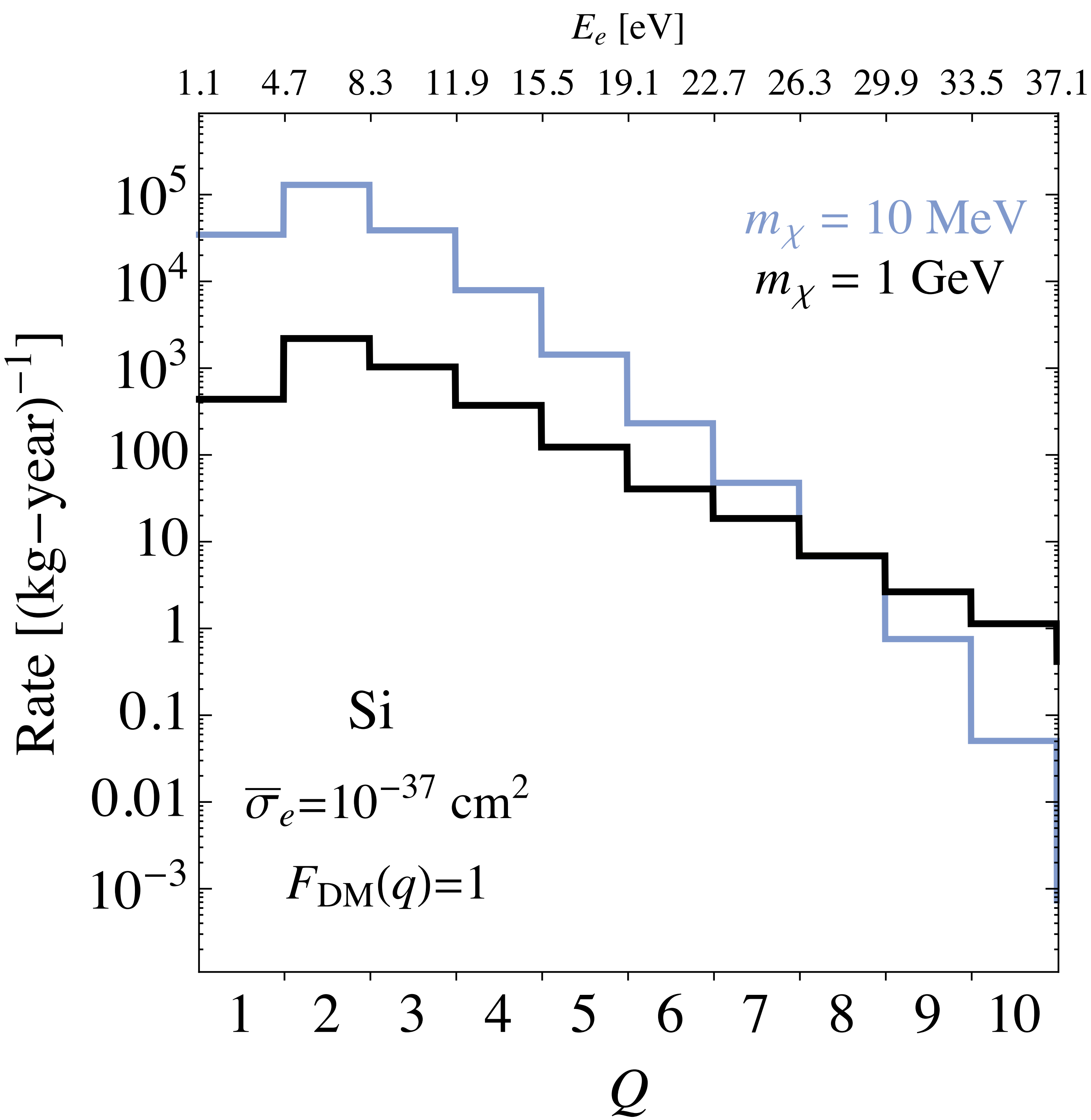
Current best limit from a semiconductor (DAMIC, Si)

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu



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

Rates increase dramatically for lower thresholds



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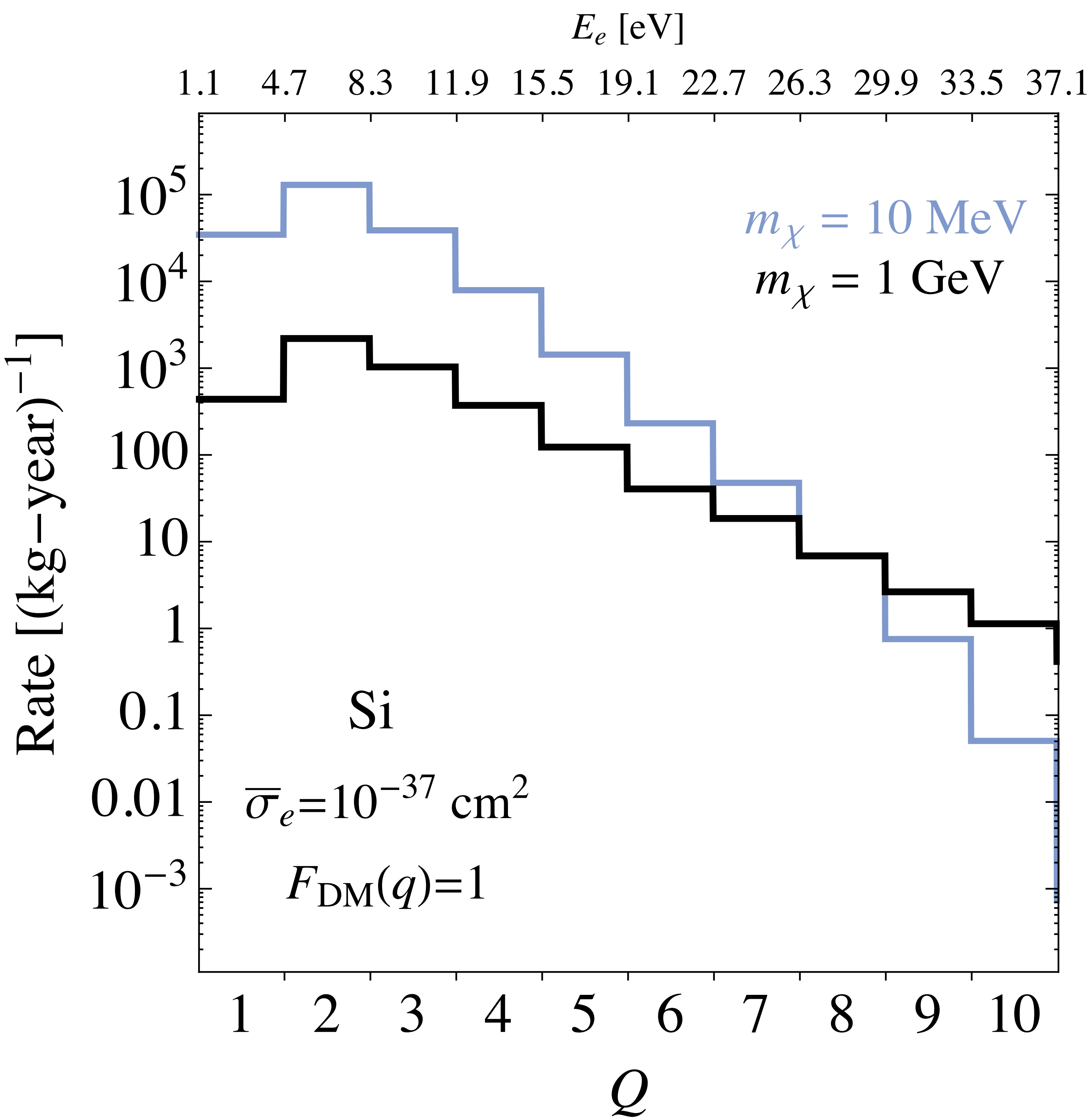


Current thresholds, e.g.

CDMSlite: ~56 eV

(1509.02448)

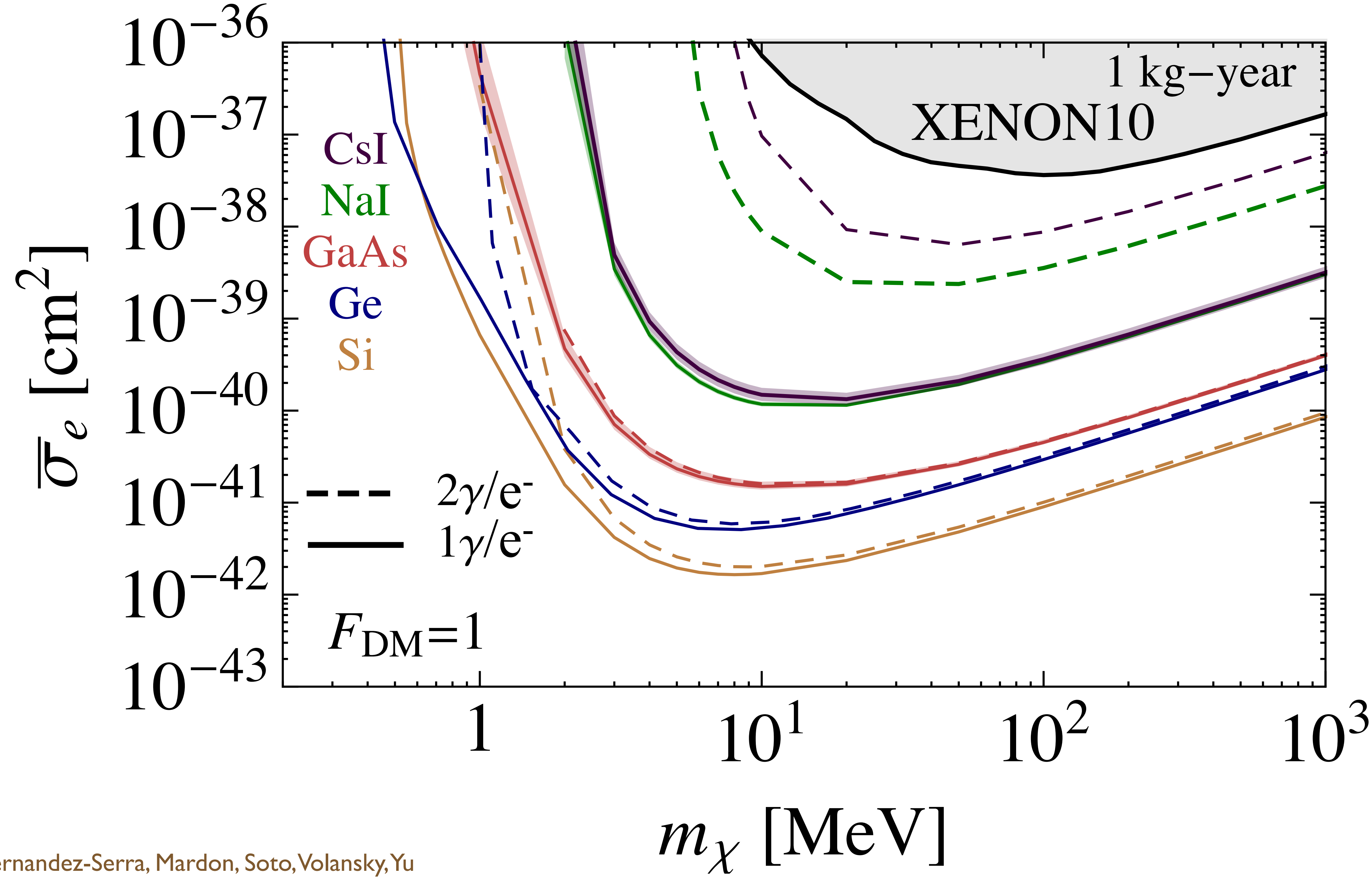
DAMIC: ~40 eV

(1105.5191)

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

Prospects?

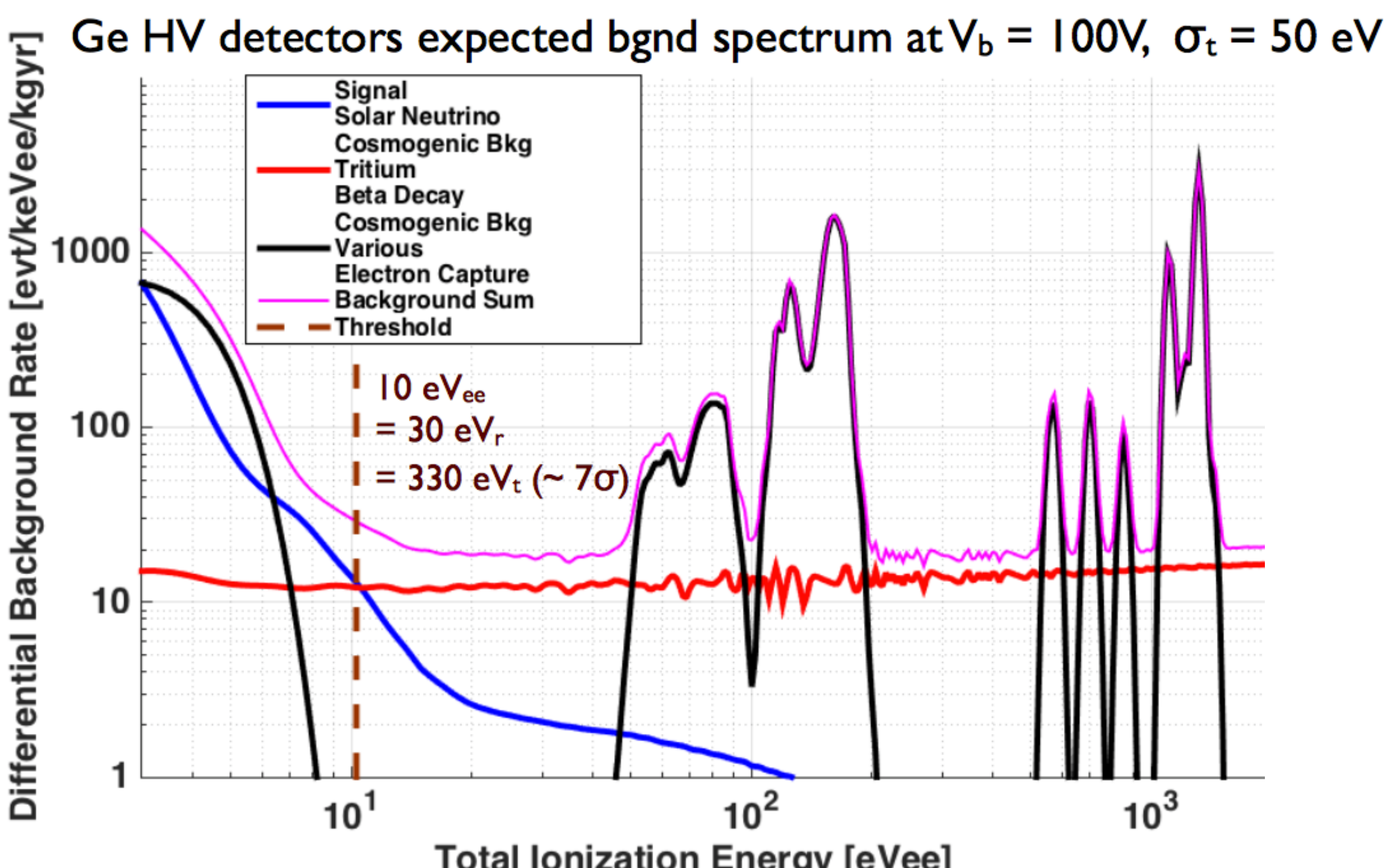
95% c.l. for zero background (i.e. 3.6 DM events)



RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu

Backgrounds?

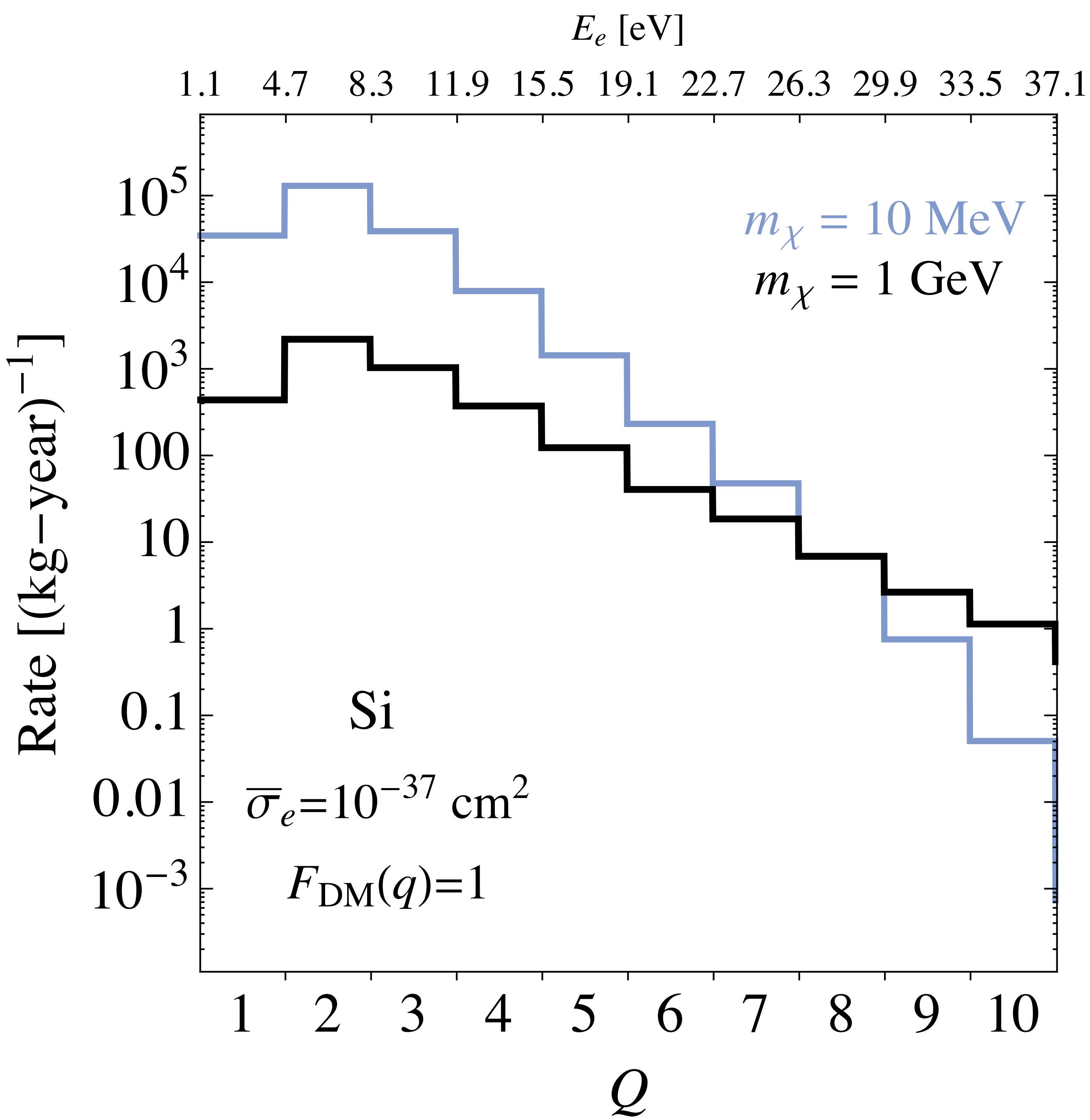
- “traditional” backgrounds (radioactivity etc.) < few/kg/year/eV (likely not important)
- understanding & controlling detector & unknown backgrounds is much more important



talk by S. Golwala, UCLA DM 2016

Handles to distinguish signal from backgrounds

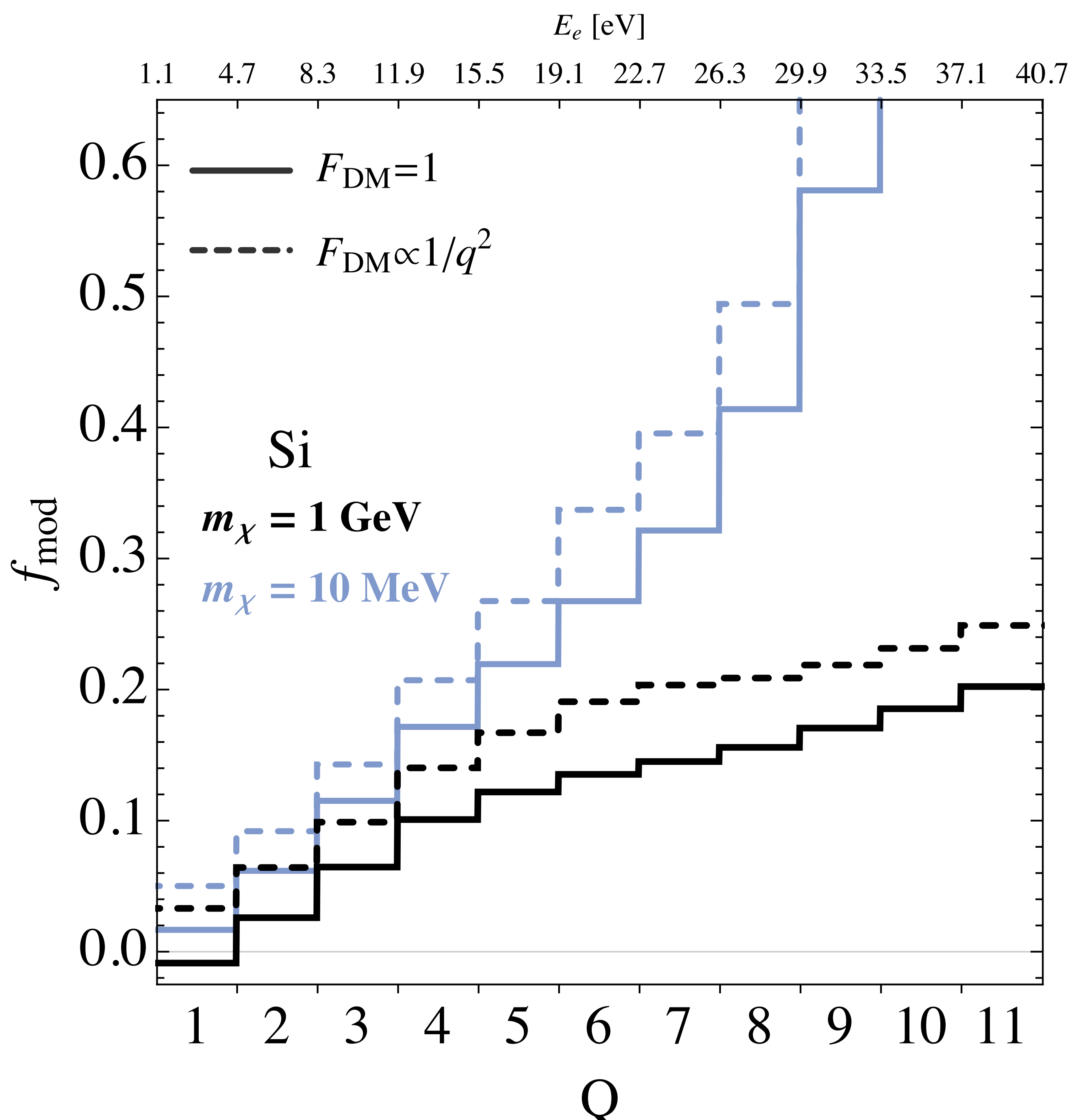
1. distinctive shape of recoil spectrum



RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

Handles to distinguish signal from backgrounds

2. large annual modulation

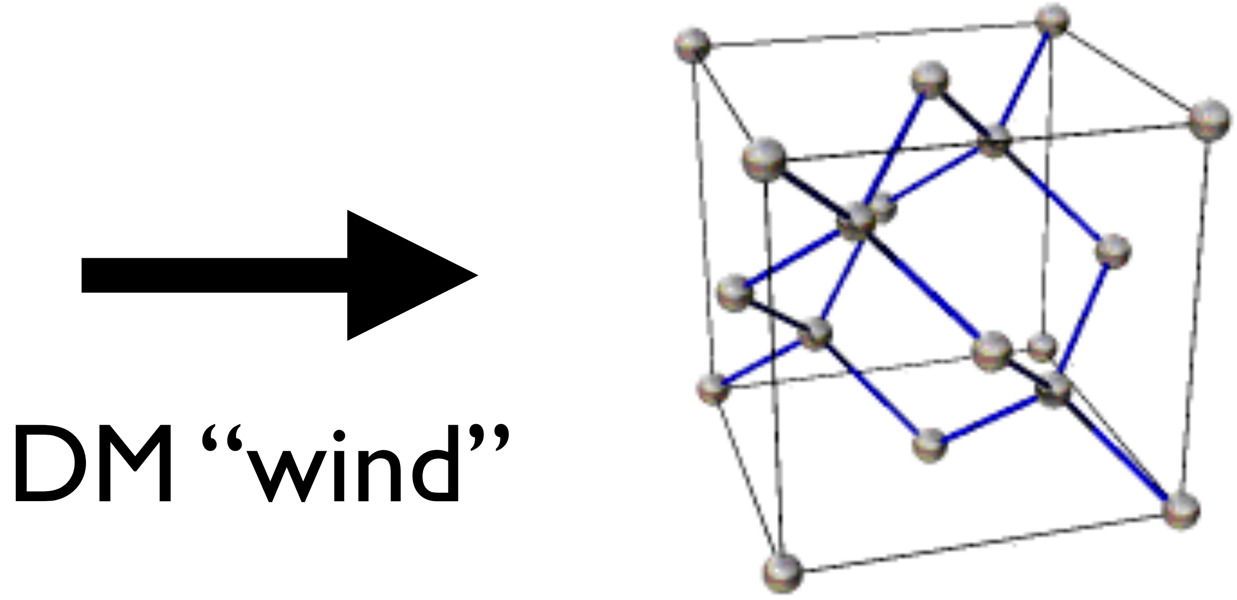


RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

Handles to distinguish signal from backgrounds

3. directional dependence of DM wrt crystal axes

RE, Mardon, Soto, Volansky, Yu (in progress)



http://butane.chem.uiuc.edu/pshapley/GenChem2/C4/1.html

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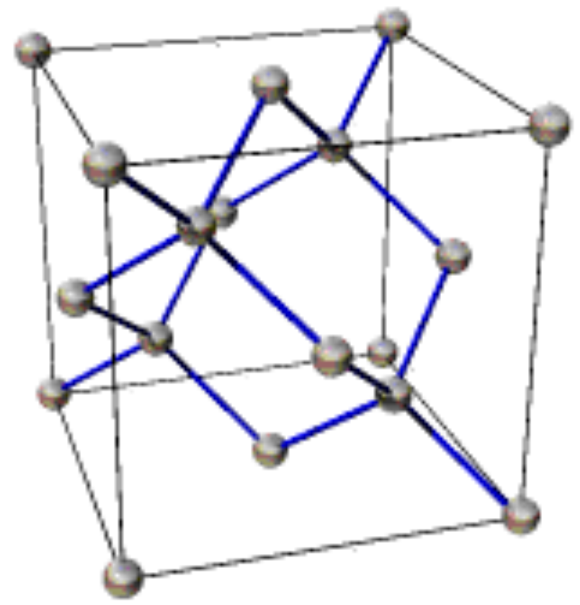


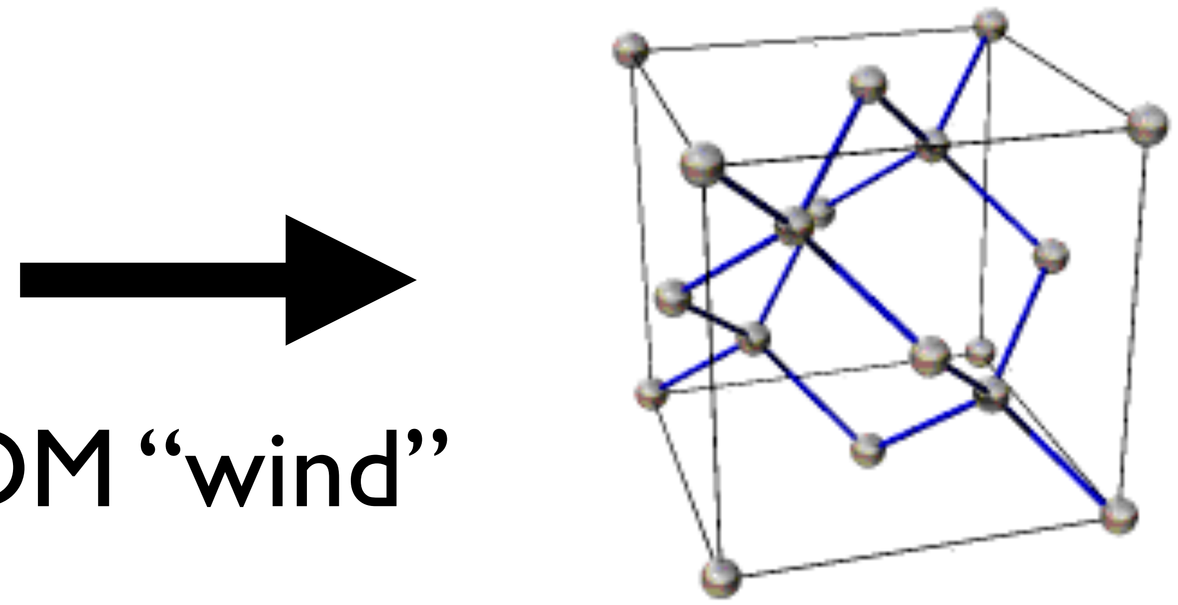
http://butane.chem.uiuc.edu/pshapley/GenChem2/C4/1.html

Handles to distinguish signal from backgrounds

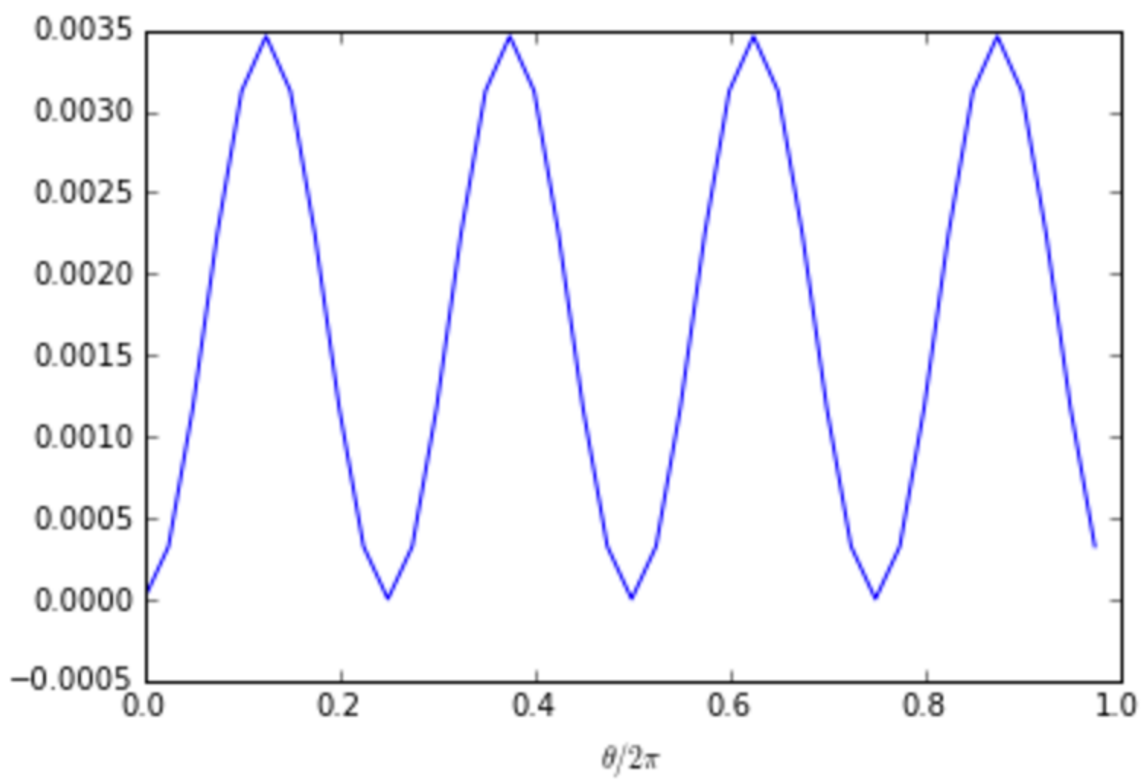
3. directional dependence of DM wrt crystal axes

RE, Mardon, Soto, Volansky, Yu (in progress)

DM "wind"



http://butane.chem.uiuc.edu/pshapley/GenChem2/C4/1.html



preliminary: Si/Ge very symmetric (<1% variation);

other crystal targets (e.g. GaAs) under investigation

Handles to distinguish signal from backgrounds

4. Ptolemy setup w/ 2D graphene sheets

(challenging to get large mass)

Hochberg, Kahn, Lisanti, Tully, Zurek

5. gravitational focusing can give energy-dependent modulation phase

Lee, Lisanti, Mishra-Sharma, Safdi

6. other ideas?

maybe you?

Models?

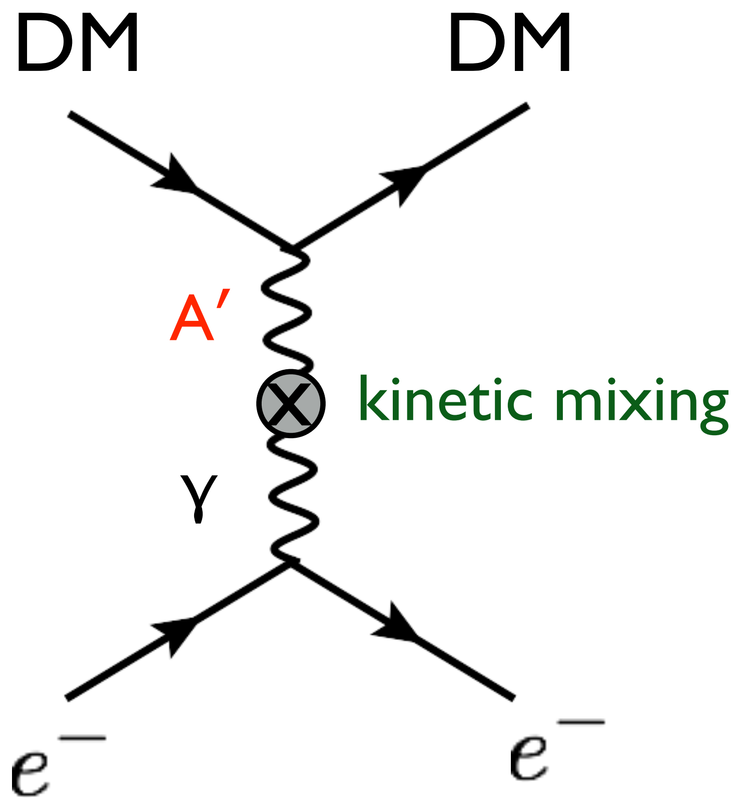
DM-e^- scattering can probe lots of models!

Models?

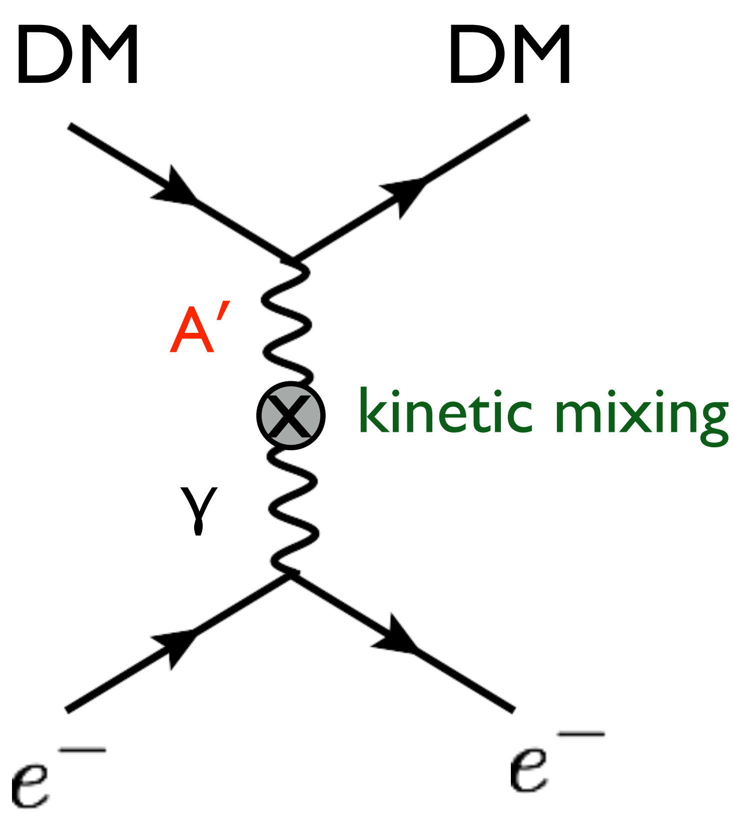
DM-e^- scattering can probe lots of models!

- DM w/ a light A' ($\sim m_{DM}$)
- DM w/ an ultralight A' ($\ll$ keV)
- A'/scalar/pseudoscalar DM ($\ll$ MeV)
- Electric or magnetic dipole moment
- SIMP, ELDER
- inelastic DM
- A'/scalar/pseudoscalar from Sun (<10 keV)
- …

DM w/ dark photon (A′) mediator



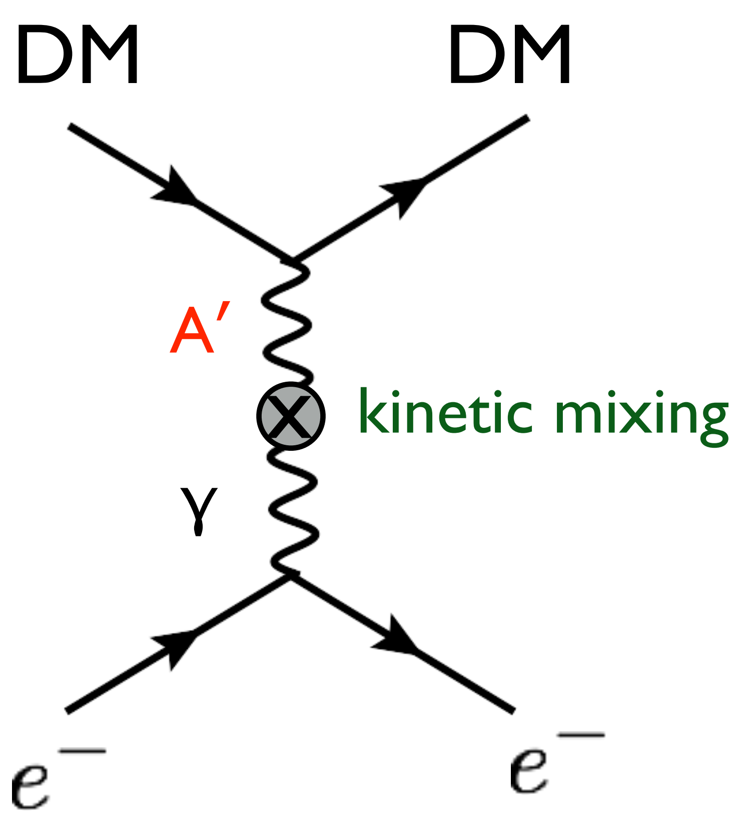
DM w/ dark photon (A′) mediator



- light A′ (~m$_{DM}$) $\quad F_{\rm DM} = 1$
- ultra-light A′ (≪keV) $\quad F_{\rm DM} \propto 1/q^2$

simple & predictive

DM w/ dark photon (A′) mediator

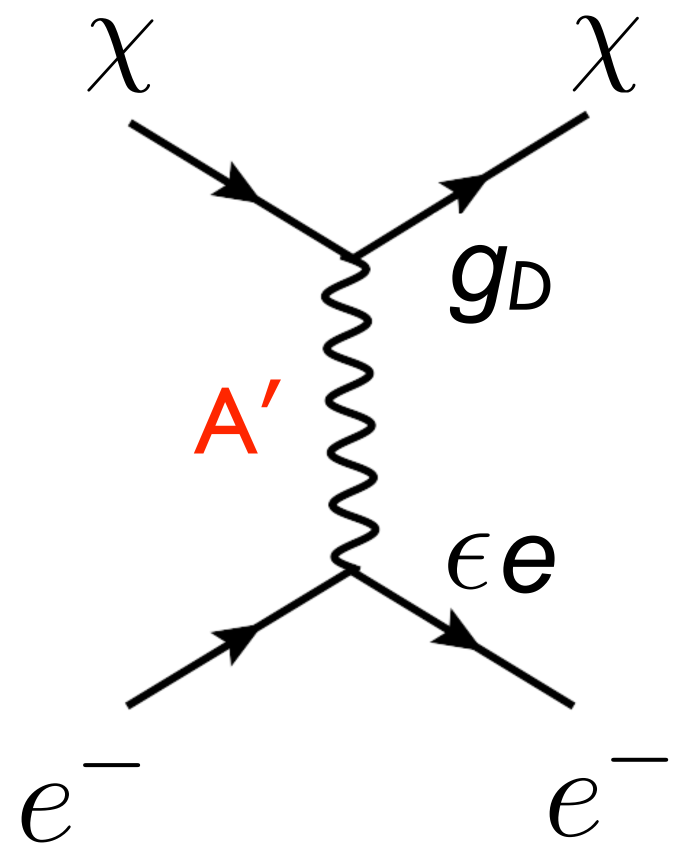


- light A′ (~m_{DM}) $F_{\rm DM} = 1$
- ultra-light A′ ($\ll$keV) $F_{\rm DM} \propto 1/q^2$

simple & predictive

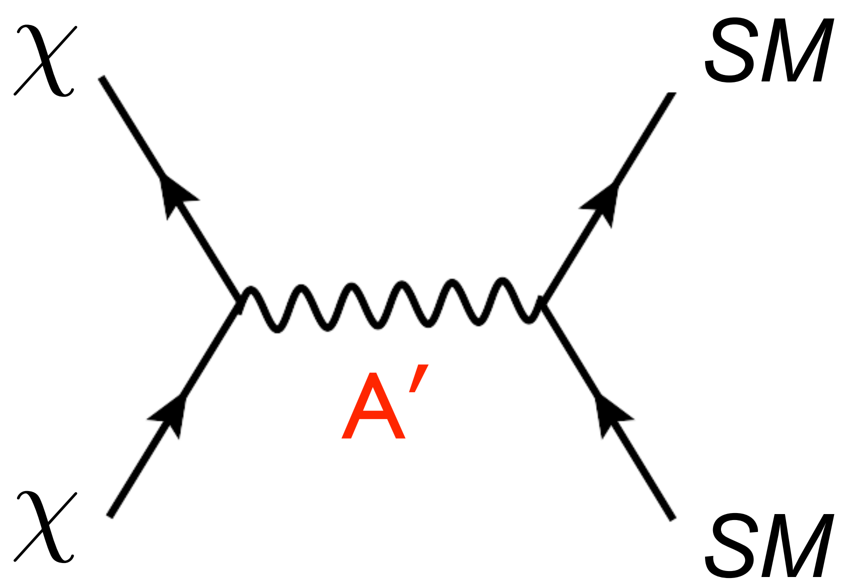
see e.g. Arkani-Hamed et.al.; Weiner et.al.; Pospelov & Ritz; RE, Kaplan, Schuster, Toro; RE, Mardon, Volansky; Lin, Yu, Zurek; Chu, Hambye, Tytgat; Hall, Jedamzik, March-Russell, West; Boehm, Fayet; Borodatchenkova, Choudhury, Drees; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; …

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



$$\bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} \mu_{\chi e}^2 \qquad F_{\rm DM} = 1$$

Thermal freeze-out

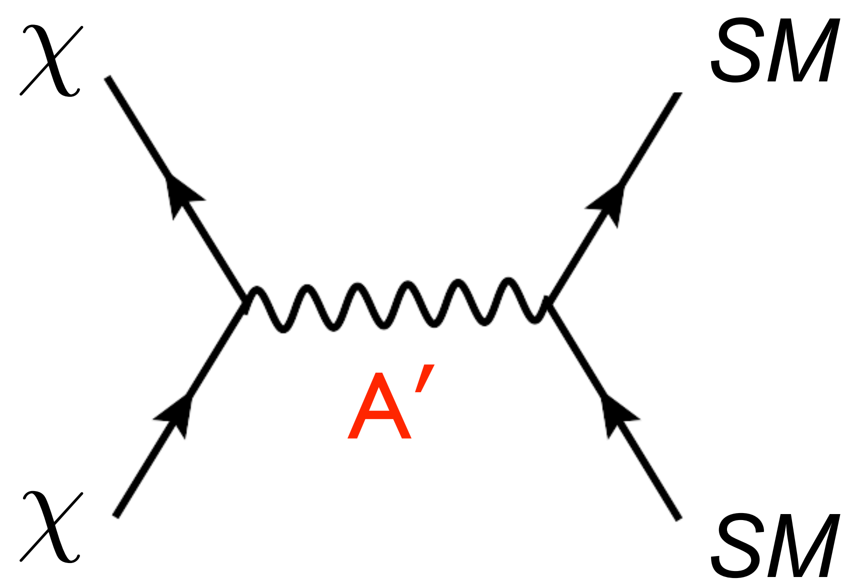


$m_{A'} > 2m_\chi$

(very predictive)

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005);
Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Thermal freeze-out



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

(very predictive)

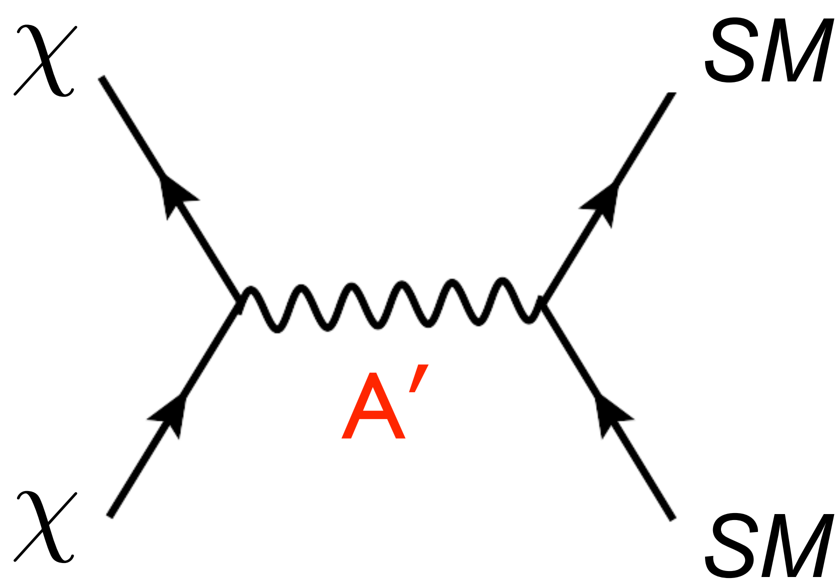
scalar χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 v^2$$

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

similar combination of parameters as direct detection!

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Thermal freeze-out



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

(very predictive)

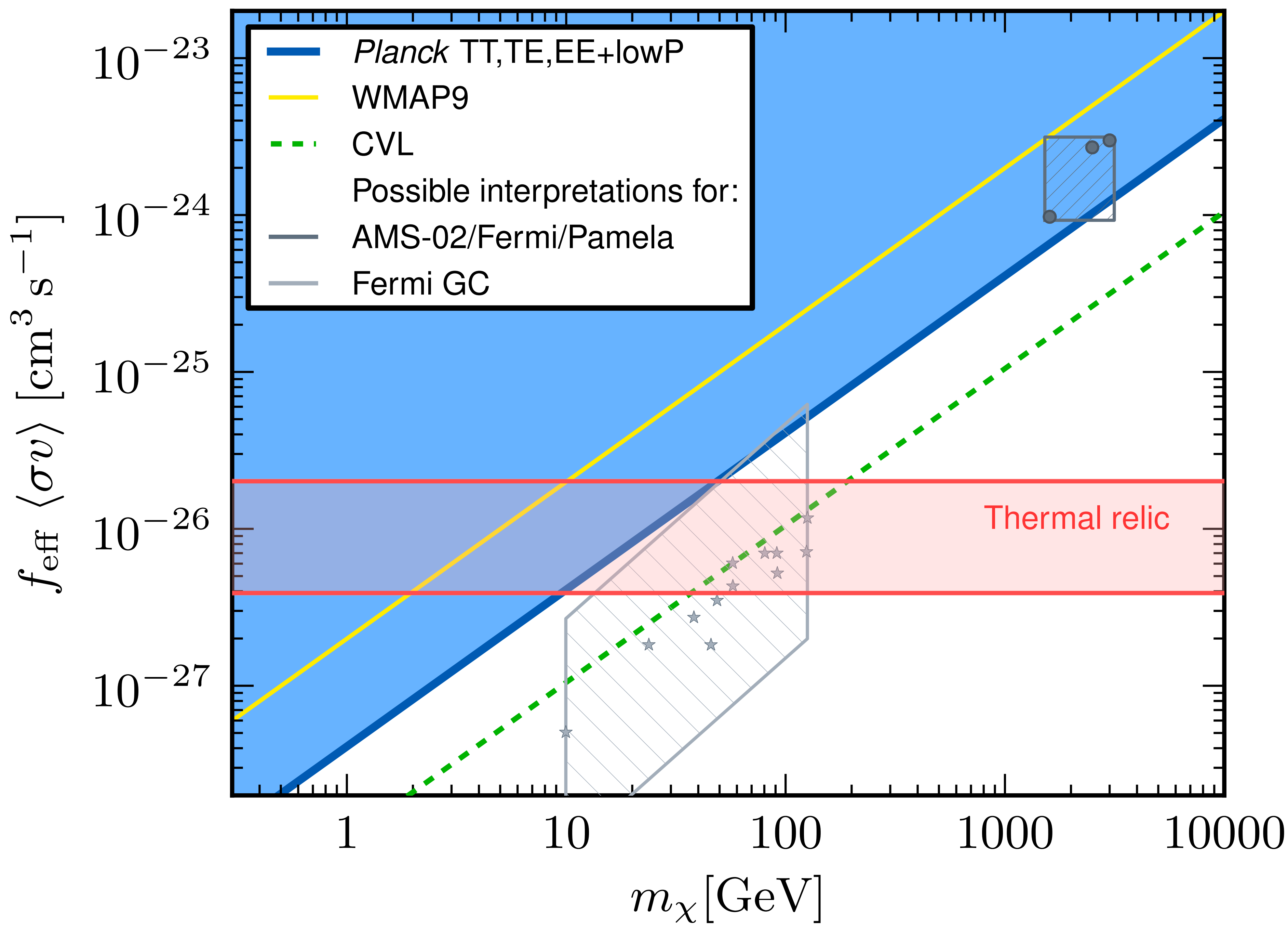
scalar χ: $\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 v^2$ p-wave

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

similar combination of parameters as direct detection!

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005);
Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Constraints from CMB



standard s-wave freeze-out disfavored <10 GeV

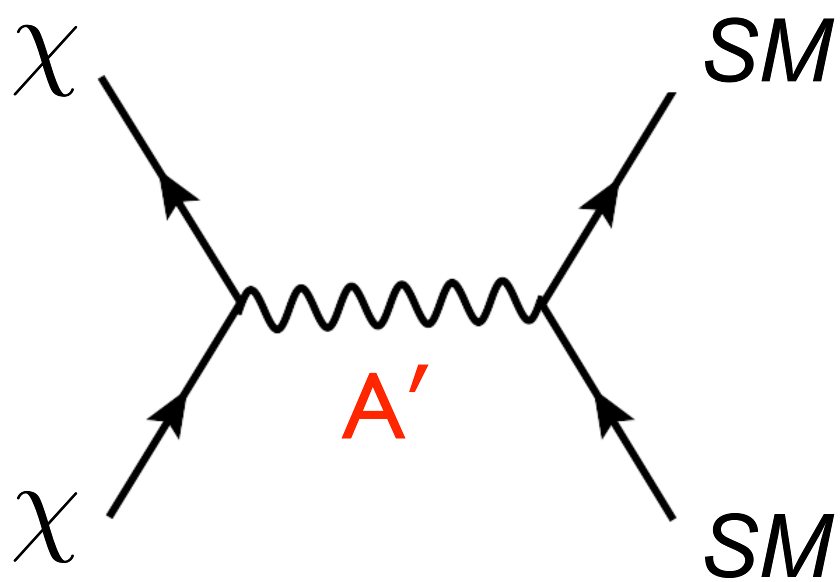
but p-wave or asymmetric is ok

Planck

see also e.g. Galli et.al.; Slatyer, Padmanabhan, Finkbeiner; Madhavacheril, Sehgal, Slatyer

for γ-ray constraints see e.g. RE, Kuflik, McDermott, Volansky, Zurek; 1309.4091

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

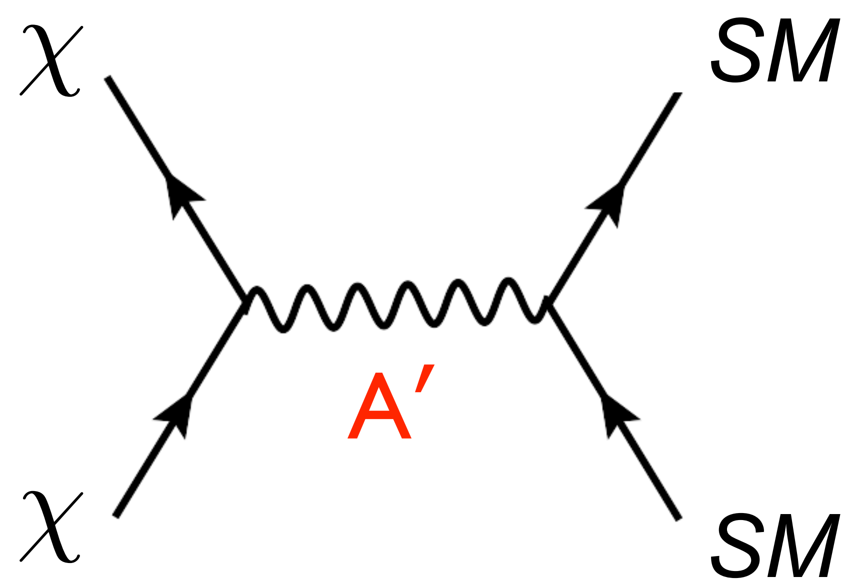
Dirac fermion χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2$$

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

CMB sets *lower* bound on σv

e.g. Kaplan, Luty, Zurek; Lin, Yu, Zurek

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***

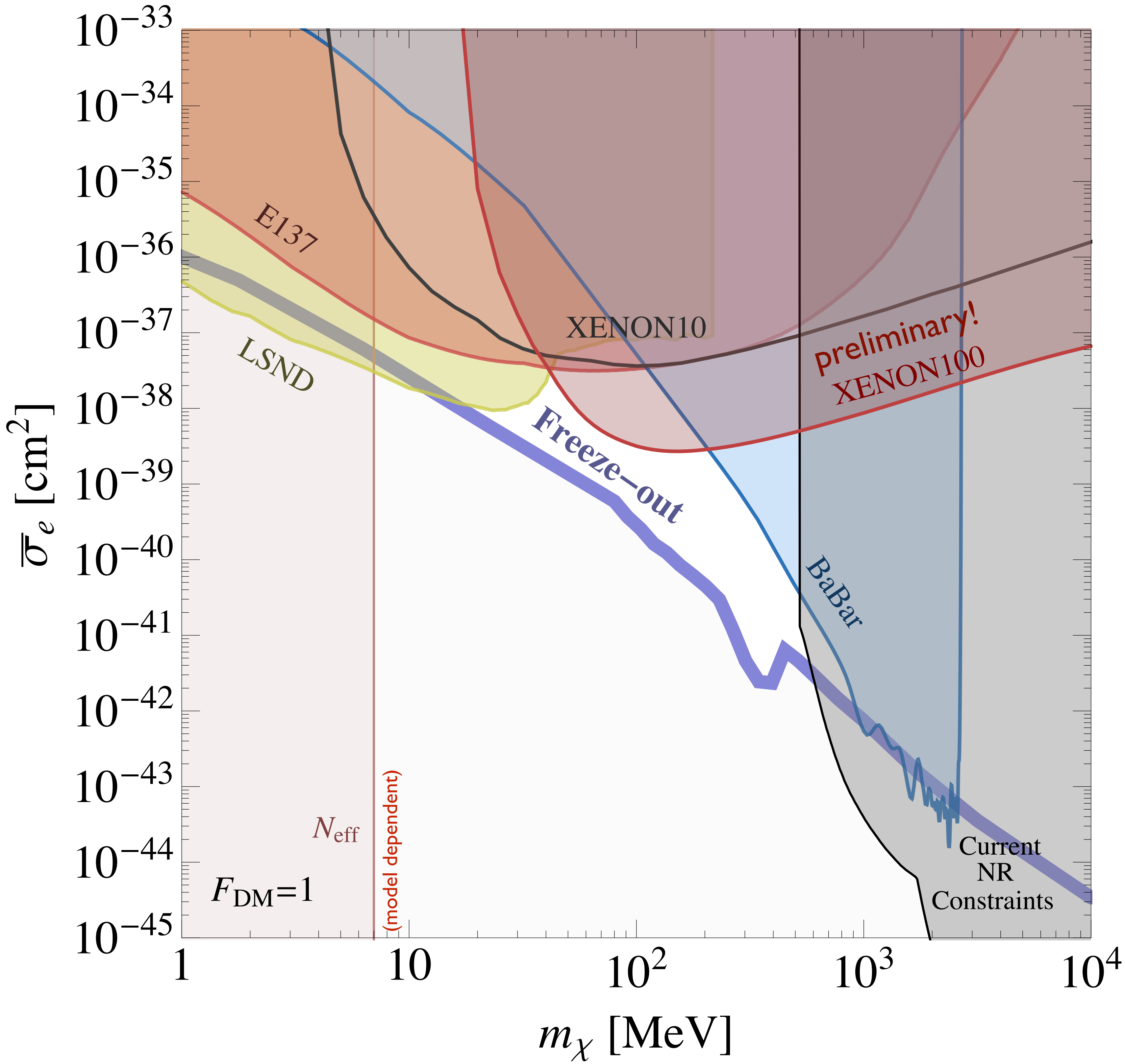
CMB sets *lower*

bound on σv

provides nice targets for direct detection experiments!

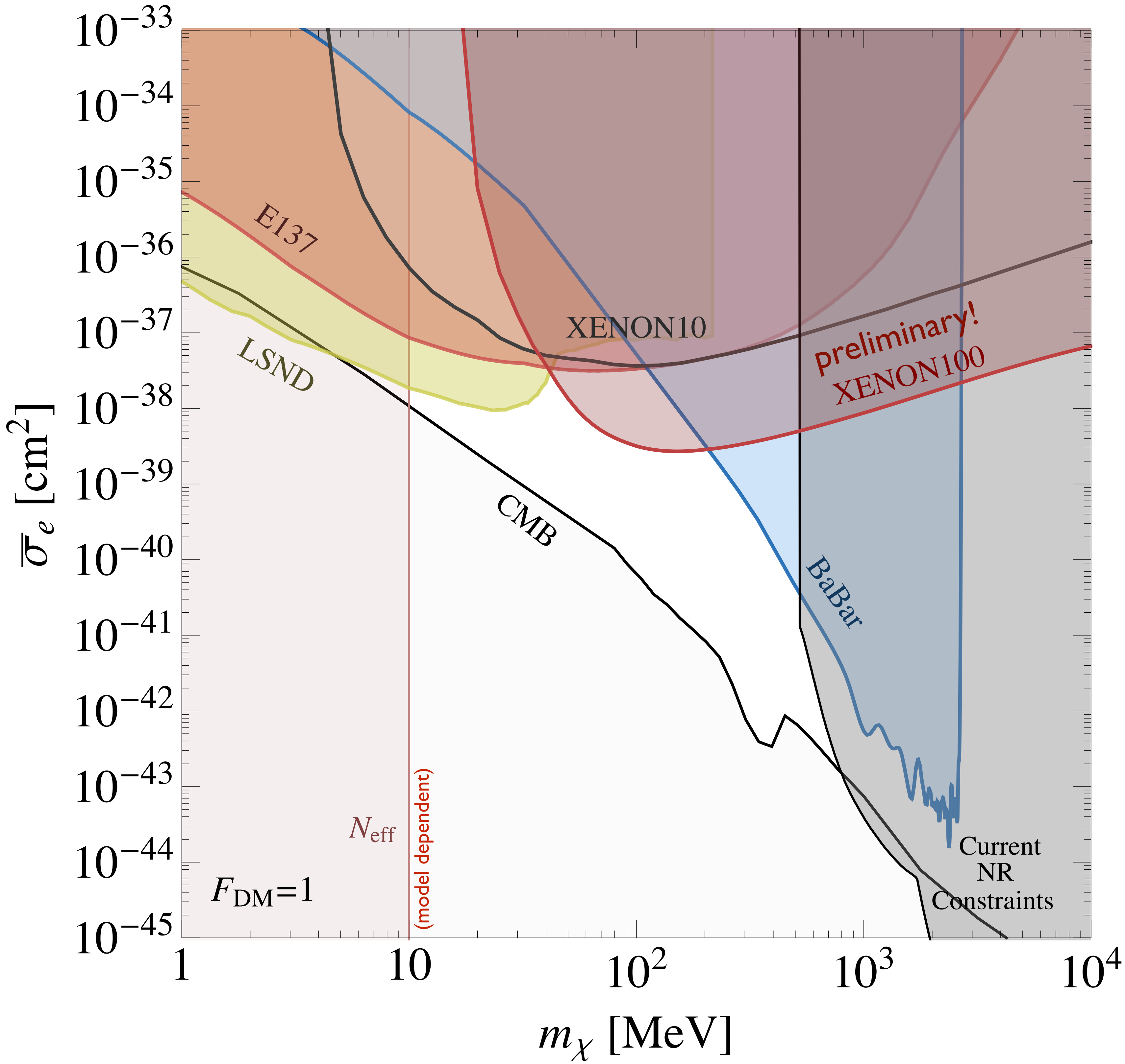
e.g. Kaplan, Luty, Zurek; Lin, Yu, Zurek

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



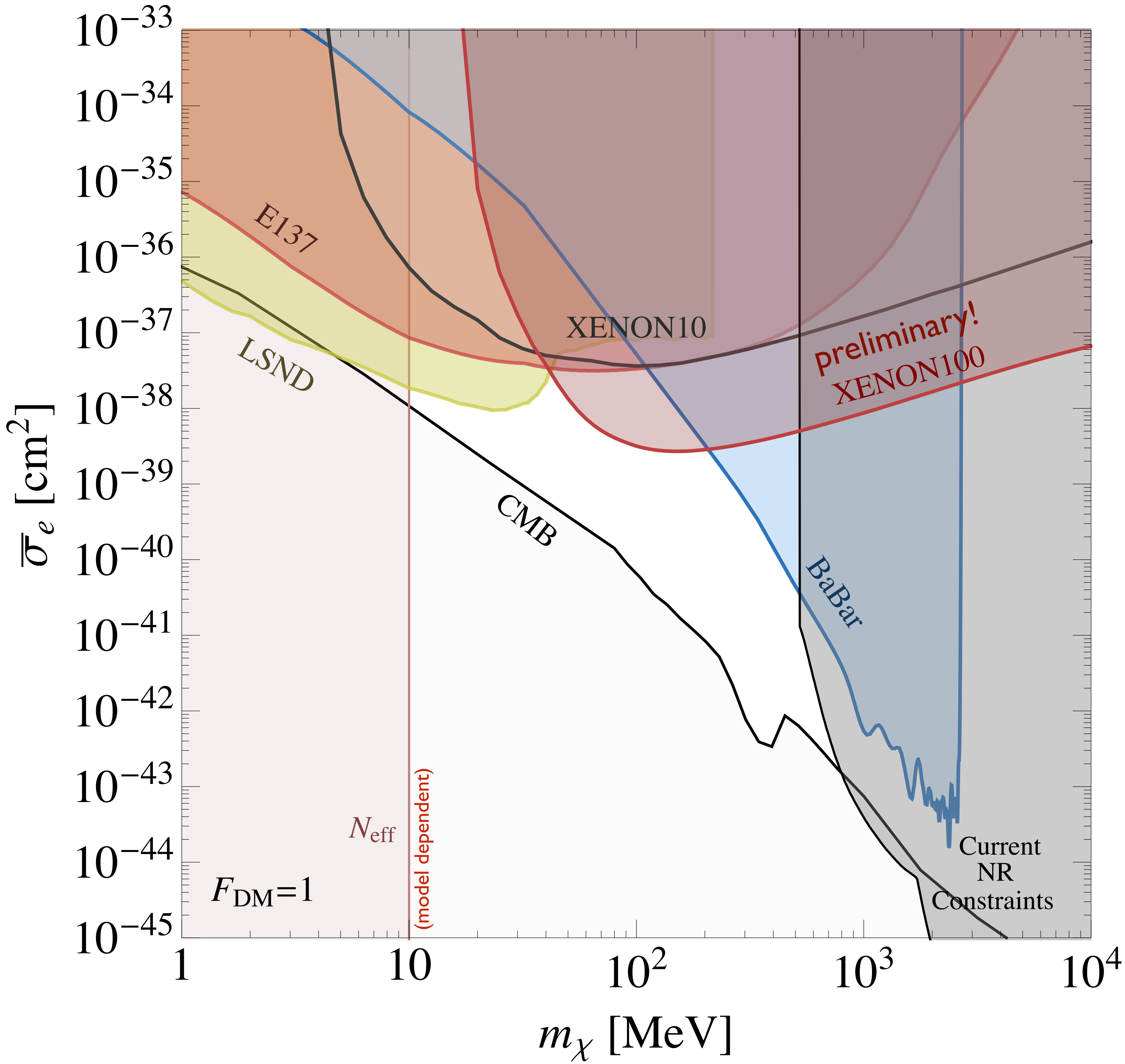
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

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



RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

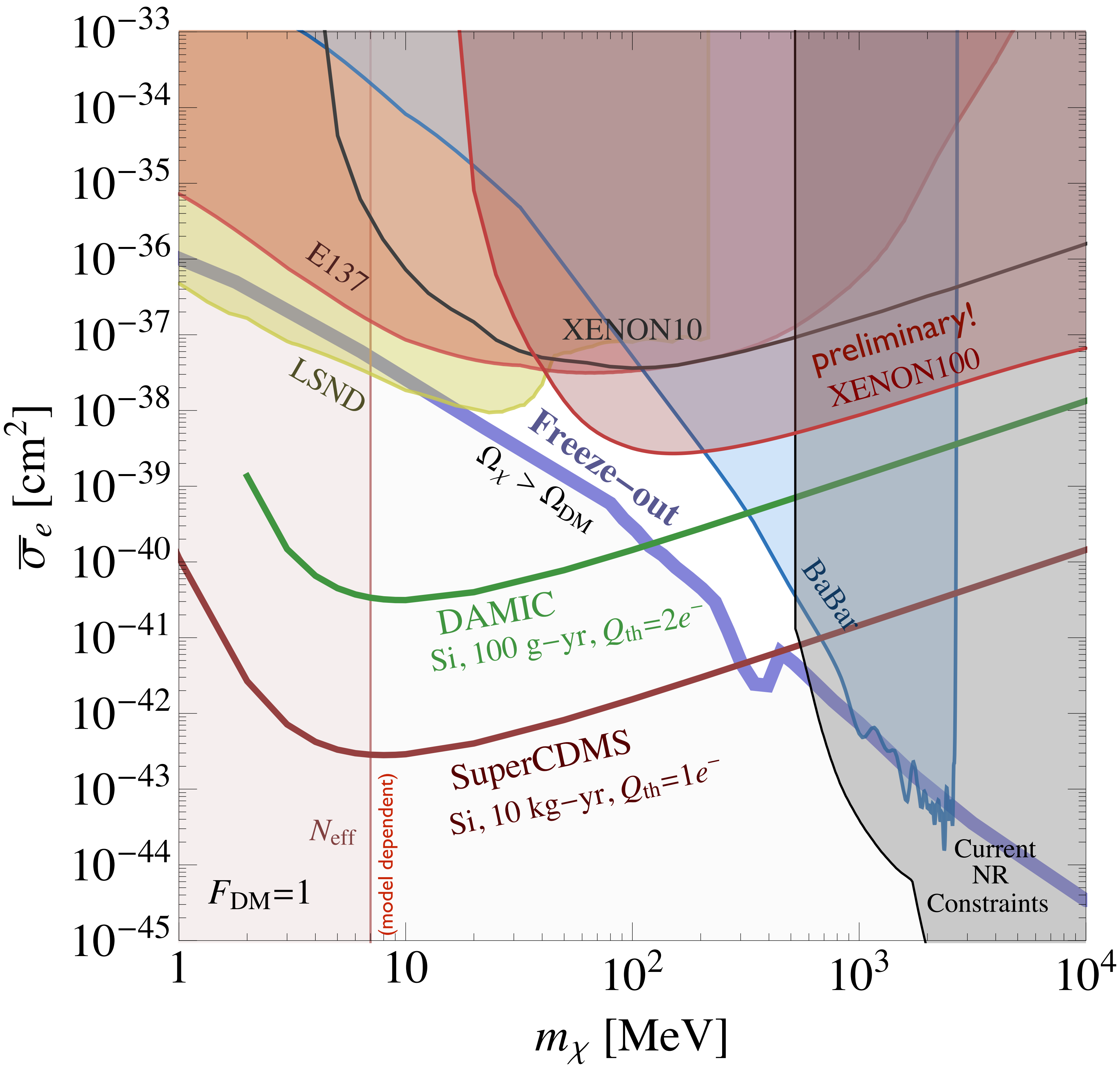
Direct Detection, Dirac fermion, $m_{A'} > 2m_{DM}$



probably no time to discuss constraints…

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

Semiconductor prospects

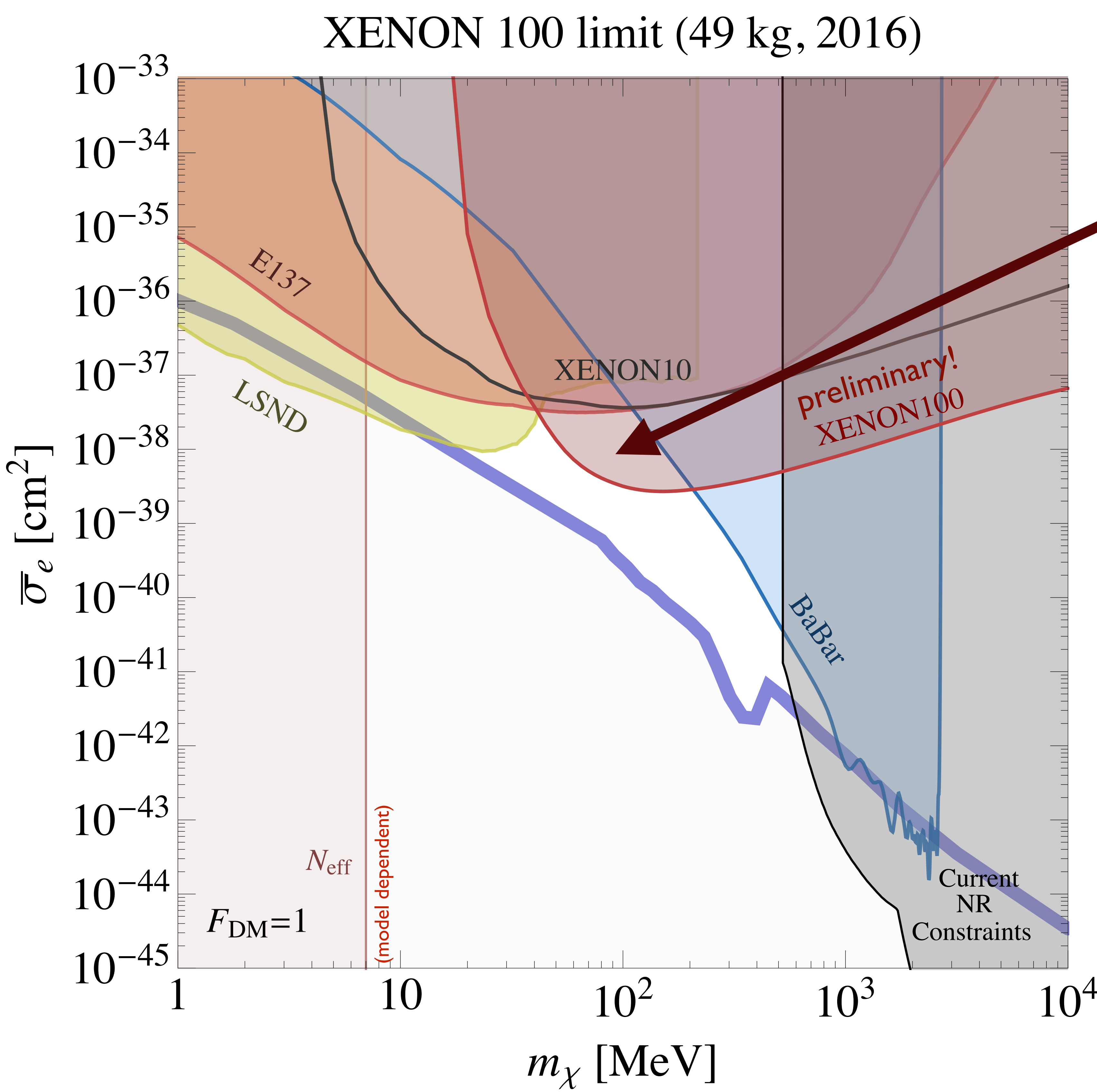


95% c.l., assuming zero background (i.e. 3.6 events)

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

XENON100

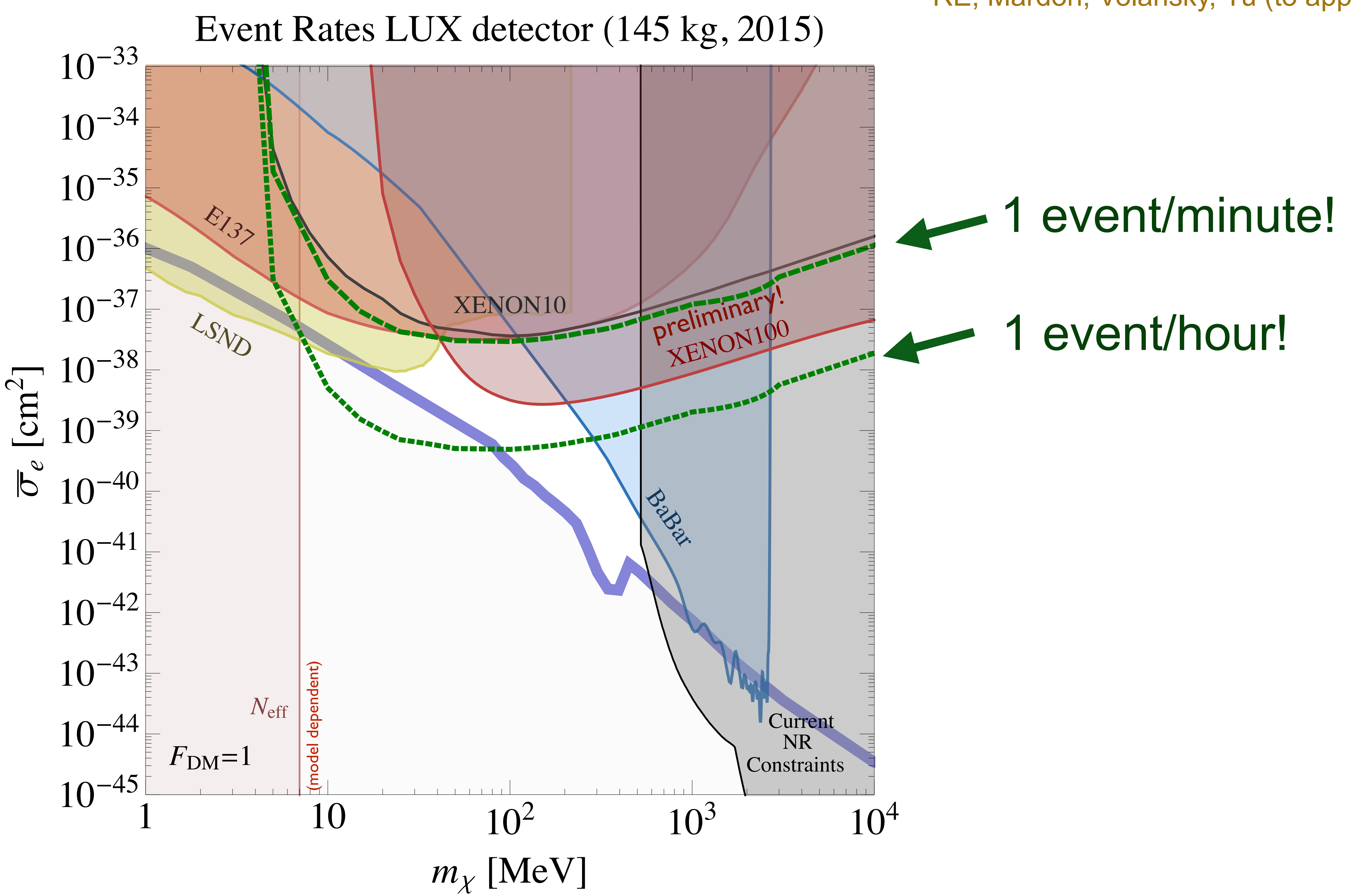
RE, Mardon, Volansky, Yu (to appear)



XENON100 events could be mostly DM…

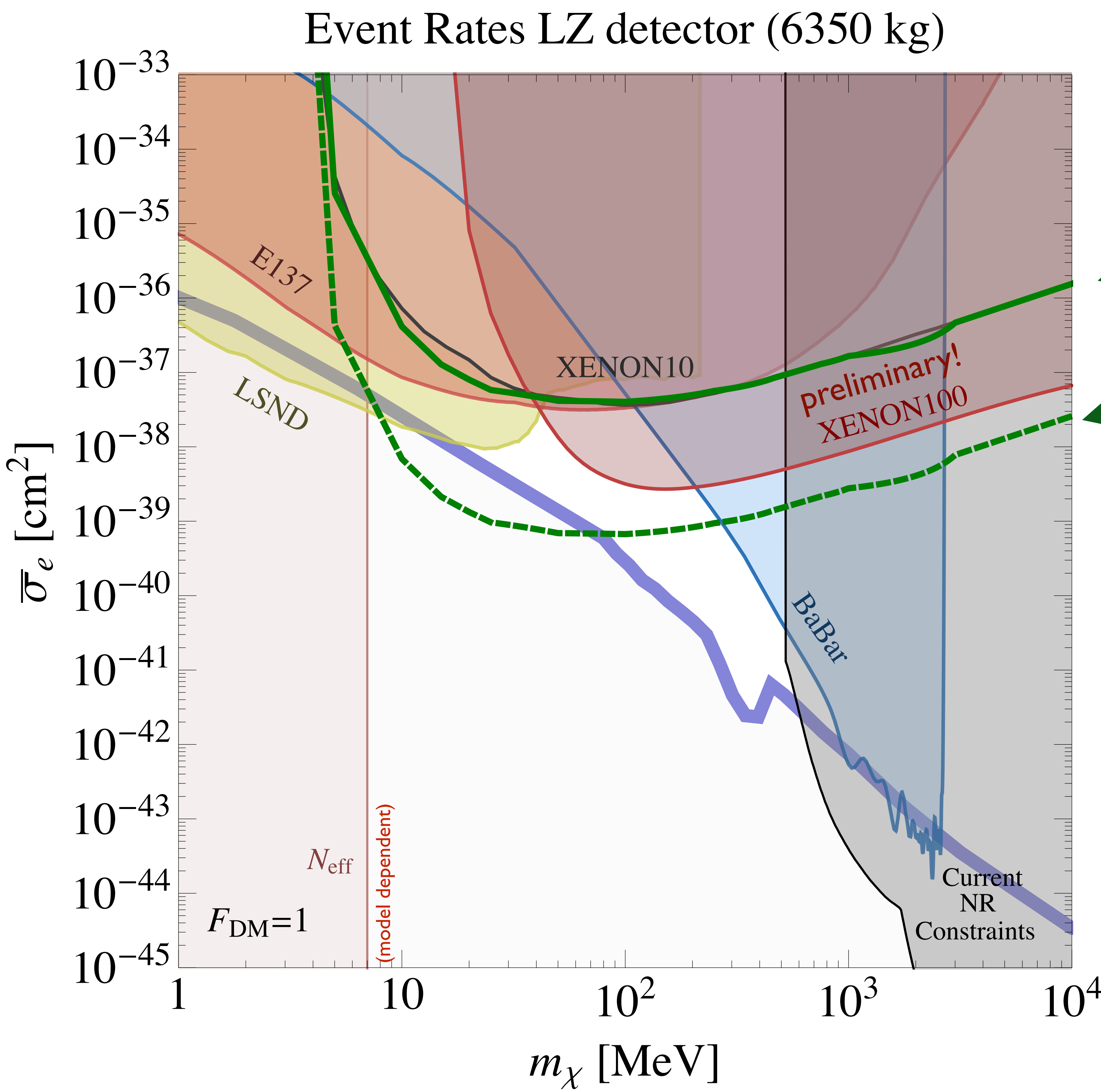
LUX prospects

RE, Mardon, Volansky, Yu (to appear)



LZ prospects

RE, Mardon, Volansky, Yu (to appear)



1 event/second!

1 event/minute!

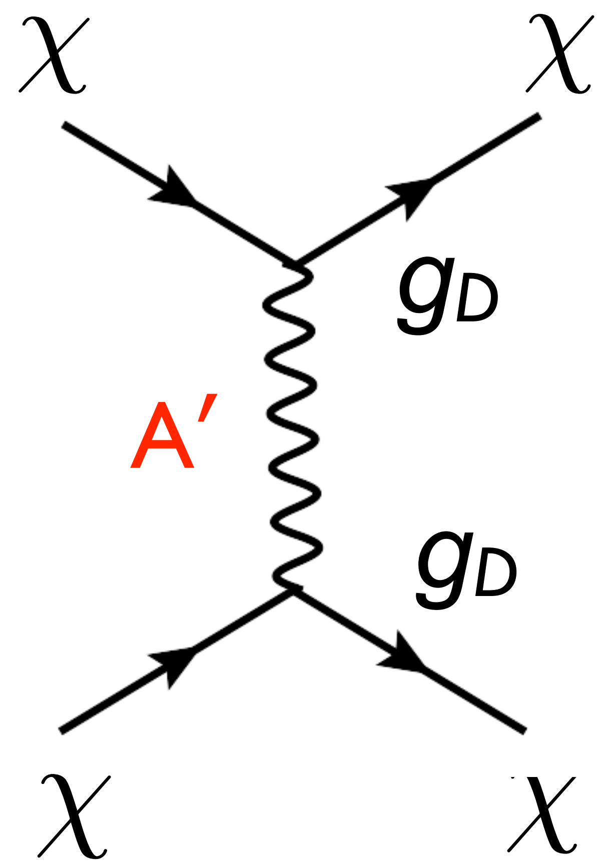
Message to XENON100/1t/ LUX/LZ:

analyzing observed S2-only events is time well-spent!

(+ annual modulation)

Other constraints?
(probably skip due to lack of time)

Self-interactions



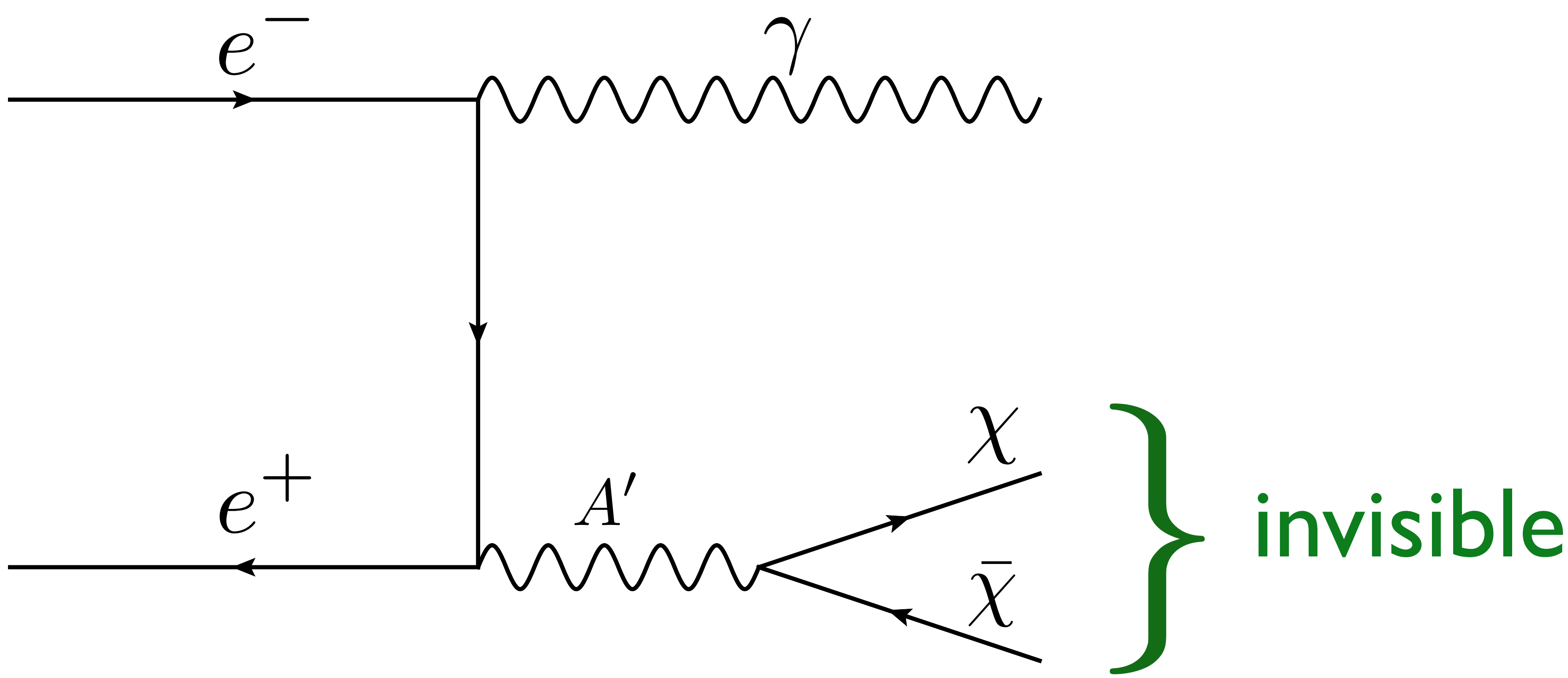
constraint from bullet cluster etc.

$$\sigma \propto \frac{\alpha_D^2}{m_{A'}^4} m_\chi^2$$

sets upper bound on α_D

e⁺e⁻ colliders

RE, Mardon, Papucci, Volansky, Zhong
Izaguirre, Krnjaic, Schuster, Toro;
Fayet; Borodatchenkova et.al.



$$\sigma \propto \frac{\epsilon^2}{E_{\rm CM}^2}$$

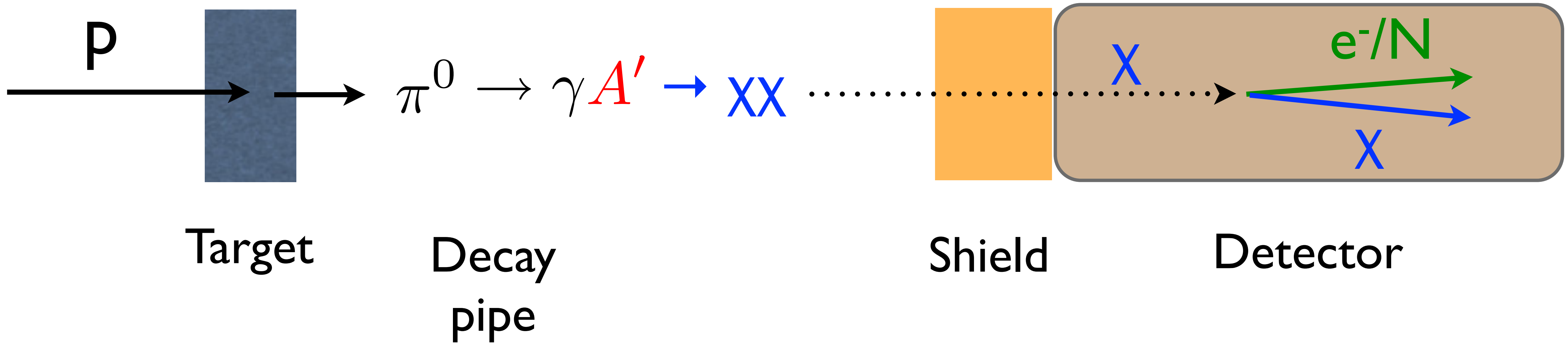
Constrained from 30/fb @BaBar

Interesting prospects @Belle-2

(need mono-photon trigger)

Proton-beam dumps

Batell, Pospelov, Ritz
Deniverville, Pospelov, Ritz
Deniverville, McKeen, Ritz
Aguilar-Arevalo et.al.



$$N_{\rm obs} \propto \frac{\epsilon^4 \alpha_D}{m_{A'}^2}$$

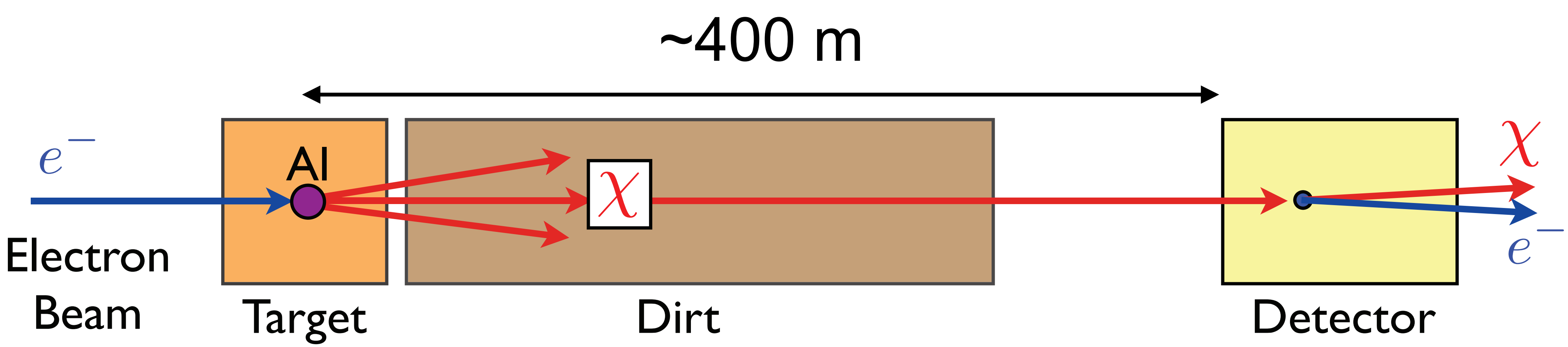
constrained by LSND

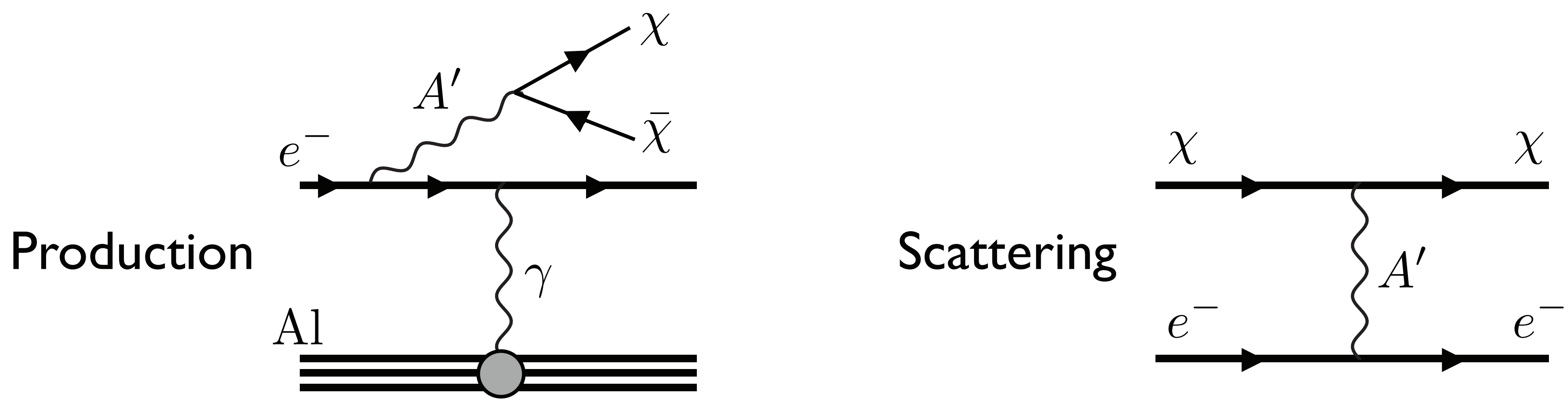
MiniBooNE search underway

plenty of room for future exploration, see SLAC Dark Forces workshop, 2016

Electron-beam dumps: e.g. SLAC's E137

Bjorken et.al.
Batell, RE, Surujon



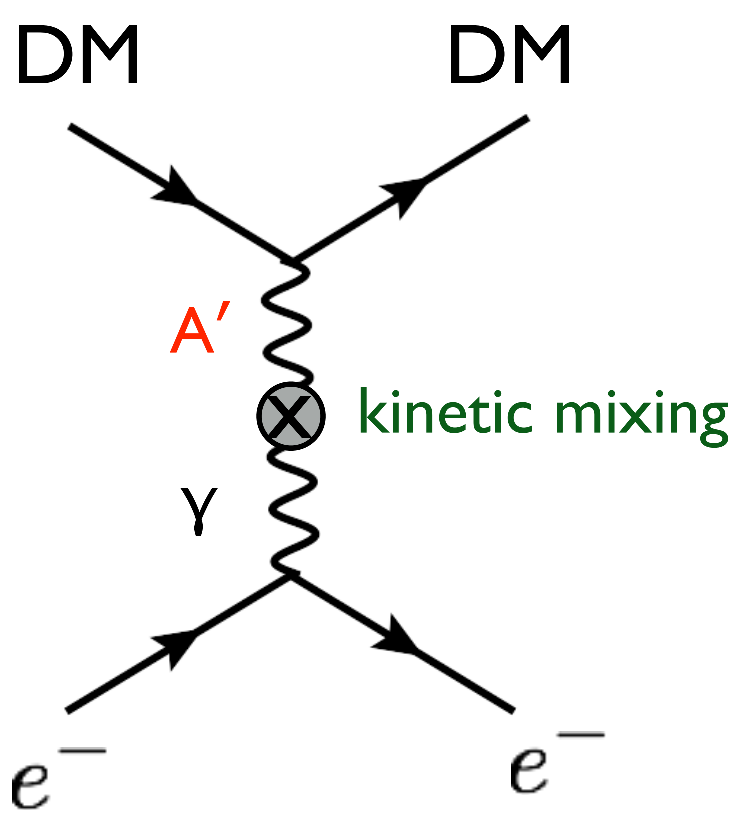


plenty of room for future exploration, see SLAC Dark Forces workshop, 2016

see Izaguirre, Krnjaic, Schuster, Toro; Diamond, Schuster; Battaglieri et.al.

End of constraints

DM w/ dark photon (A′) mediator

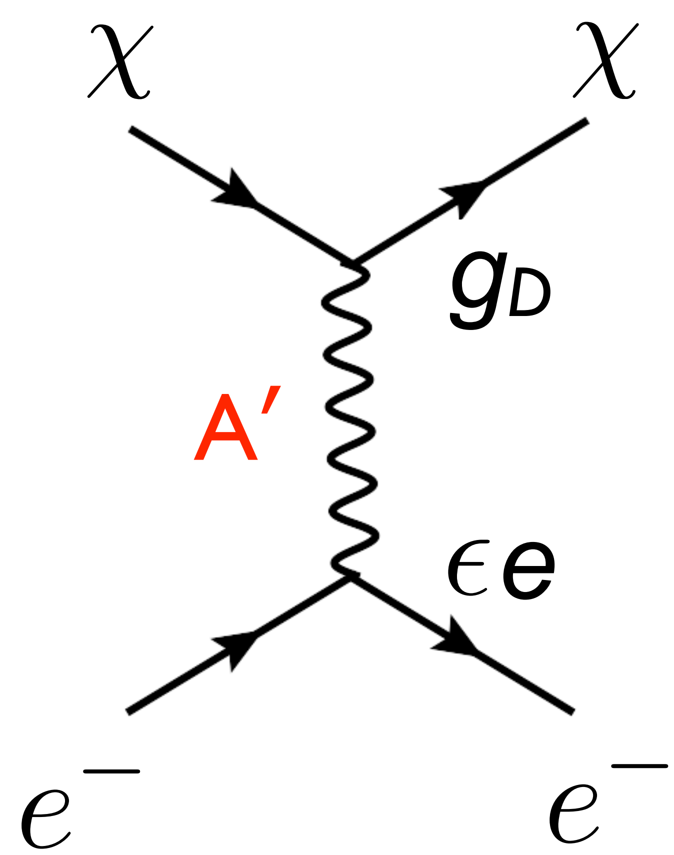


- light A′ (~m$_{DM}$) $\quad F_{\rm DM} = 1$
- ultra-light A′ (≪keV) $\quad F_{\rm DM} \propto 1/q^2$

simple & predictive

see e.g. RE, Mardon, Volansky; Chu, Hambye, Tytgat; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu;

Direct Detection w/ ultralight A′ (≪ keV)



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

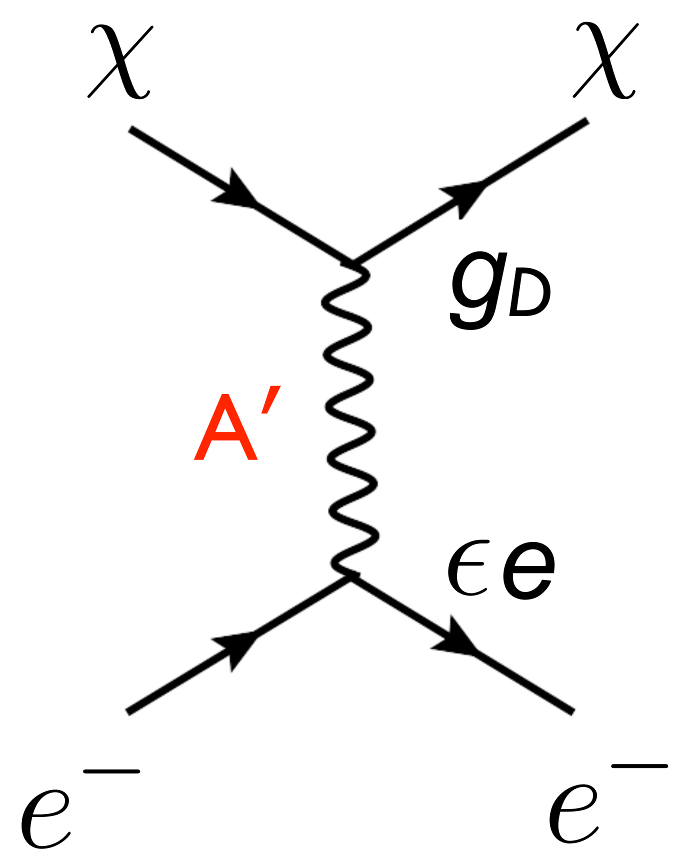
assume

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

$\sim \mathrm{keV}$

enhanced at low q^2 !

Direct Detection w/ ultralight A′ ($\ll$ keV)



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

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

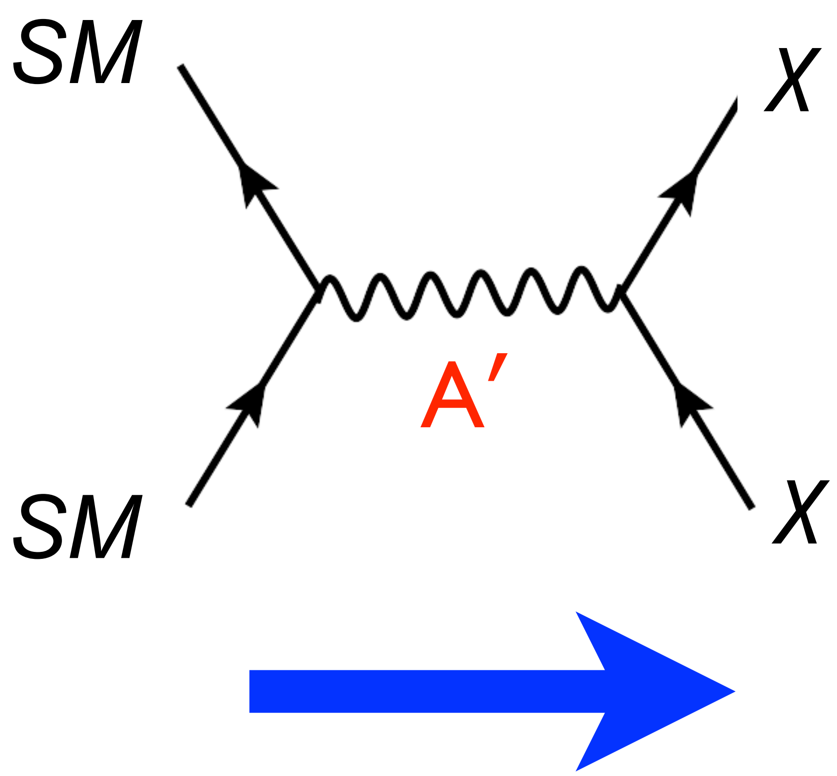
assume $m_{A'} \ll \alpha\, m_e$ $\sim$ keV

enhanced at low q^2 !

"Freeze-in"

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

Hall et.al. (0911.1120)

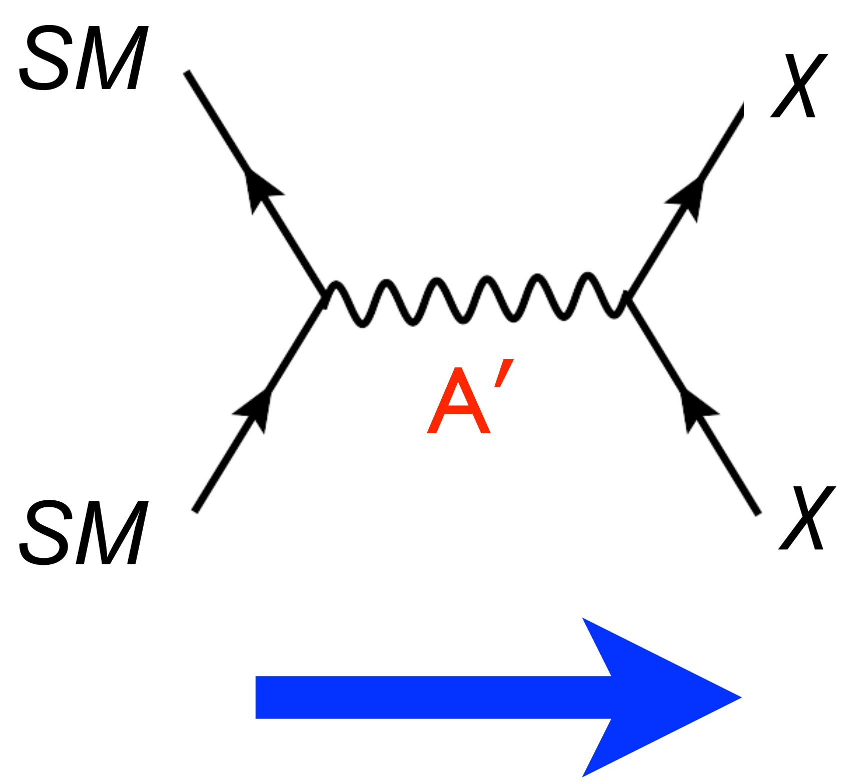


build up DM
abundance as
Universe cools

“Freeze-in”

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

Hall et.al. (0911.1120)



build up DM abundance as Universe cools

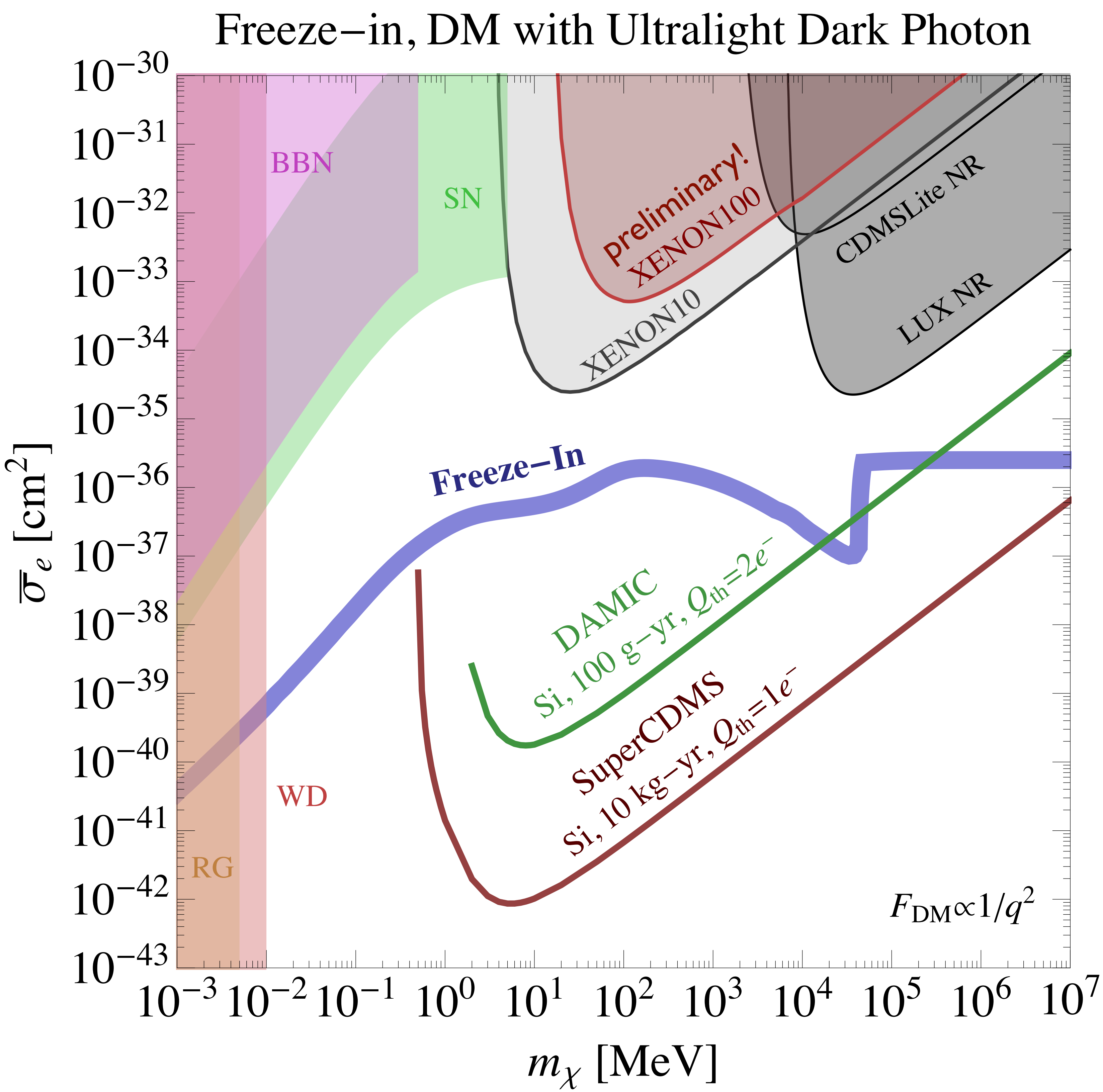
e.g. m_X = 100 MeV, correct relic abundance for $\alpha_D \epsilon^2 \sim 3 \times 10^{-24}$

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

RE, Mardon, Volansky

Chu, Hambye, Tytgat

Direct Detection w/ ultralight A′ (≪keV)



DD powerful due to ~$1/q^4$ enhancement

note bounds on millicharged particles; accelerator-based searches very weak

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

Summary

- DD of DM to $\lesssim$1 MeV is possible w/ e^- recoils
- noble-liquid experiments have demonstrated sensitivity & large exposures (significant improvements possible if backgrounds can be controlled or understood)
- semiconductors & scintillators (& other ideas) have great potential, but further R&D needed
- many opportunities for significant progress in next few years!