New Avenues to Search for sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

Stony Brook University

Berkeley DM workshop, 6/8/2015

Beyond the WIMP Paradigm

WIMPs are great!

But:

- 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")

Some challenges for WIMPs?

- Cusp-core — e.g. Navarro et al. 1997
- Missing satellites — e.g. Klypin et al. 1999; Moore et.al. 1999
- Too big too fail — Boylan-Kolchin et.al. 2011

Resolution?

- baryons?
- warm DM?
- self-interacting DM? — Spergel, Steinhardt 1999

Some challenges for WIMPs?

- Cusp-core — e.g. Navarro et al. 1997
- Missing satellites — e.g. Klypin et al. 1999; Moore et.al. 1999
- Too big too fail — Boylan-Kolchin et.al. 2011

Resolution?

- baryons?
- warm DM?
- self-interacting DM? — Spergel, Steinhardt 1999

requires new interactions

Beyond WIMPs:

MeV-to-GeV mass Dark Matter

(an old idea, e.g. Boehm, Fayet, …)

below conventional WIMP scale; above scale for which cosmological constraints can be important

natural, viable candidates exist

rich phenomenology
(like WIMPs)

Outline

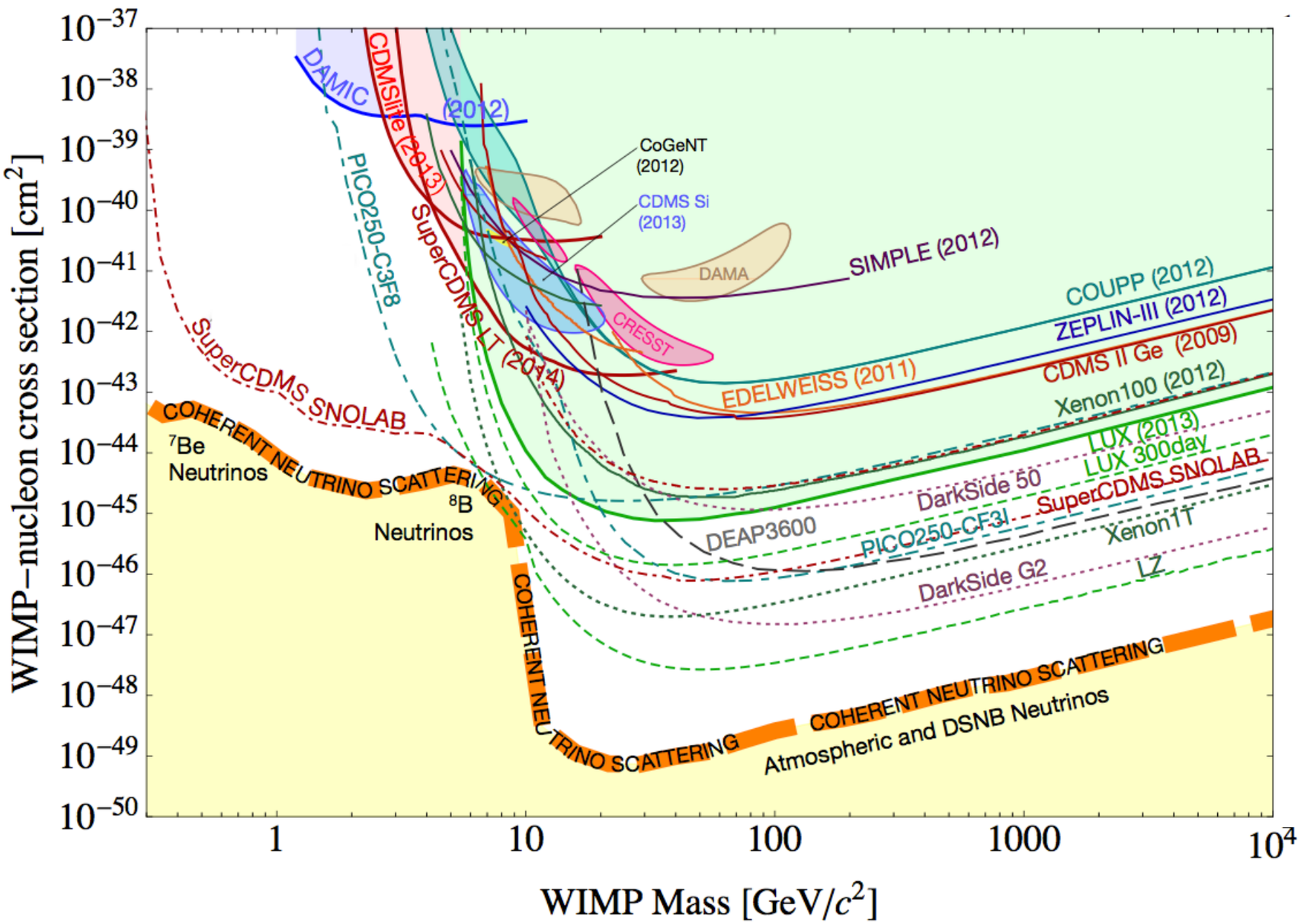
- direct detection
- colliders (e^+e^-)
- fixed-target (p & e^-)
- indirect detection

Outline

- direct detection
- colliders (e^+e^-)
- fixed-target (p & e^-)
- indirect detection

Direct Detection below 1 GeV?

conventional wisdom: no



Figueroa

Cannot use elastic nuclear recoils for detection

RE, Mardon, Volansky

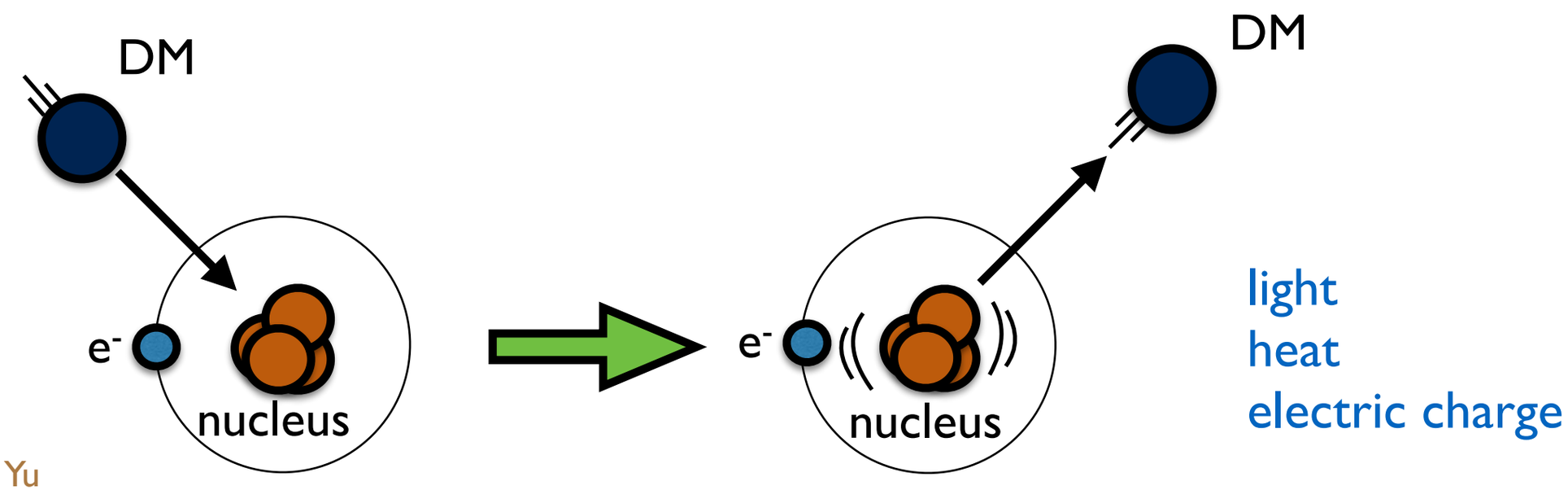
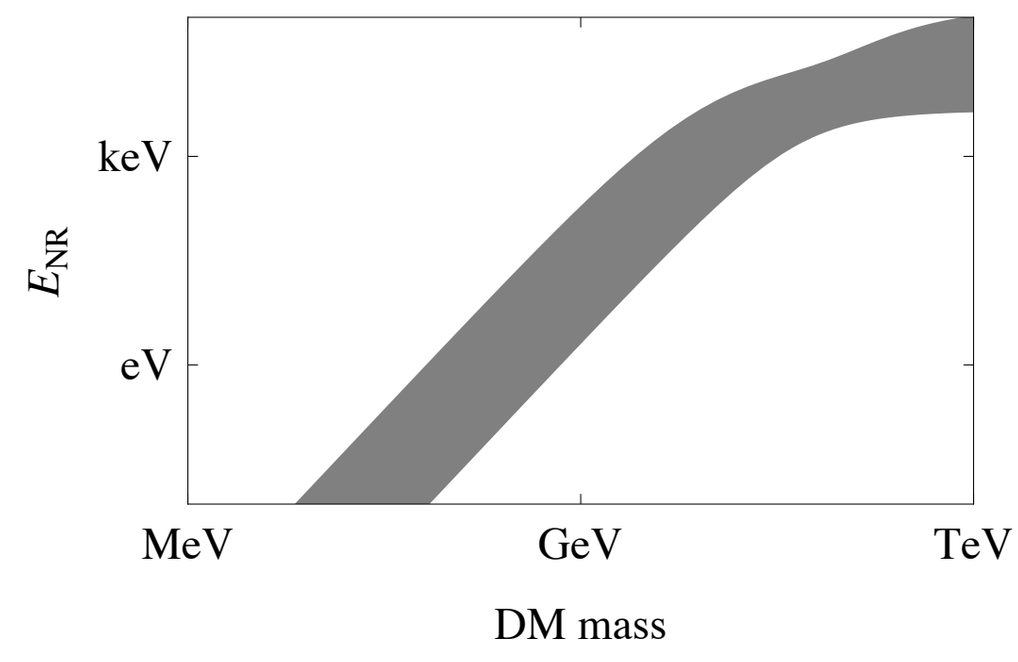


Fig credit: Tien-Tien Yu

recoiling nucleus has too little energy



But scattering off electrons works!

RE, Mardon, Volansky

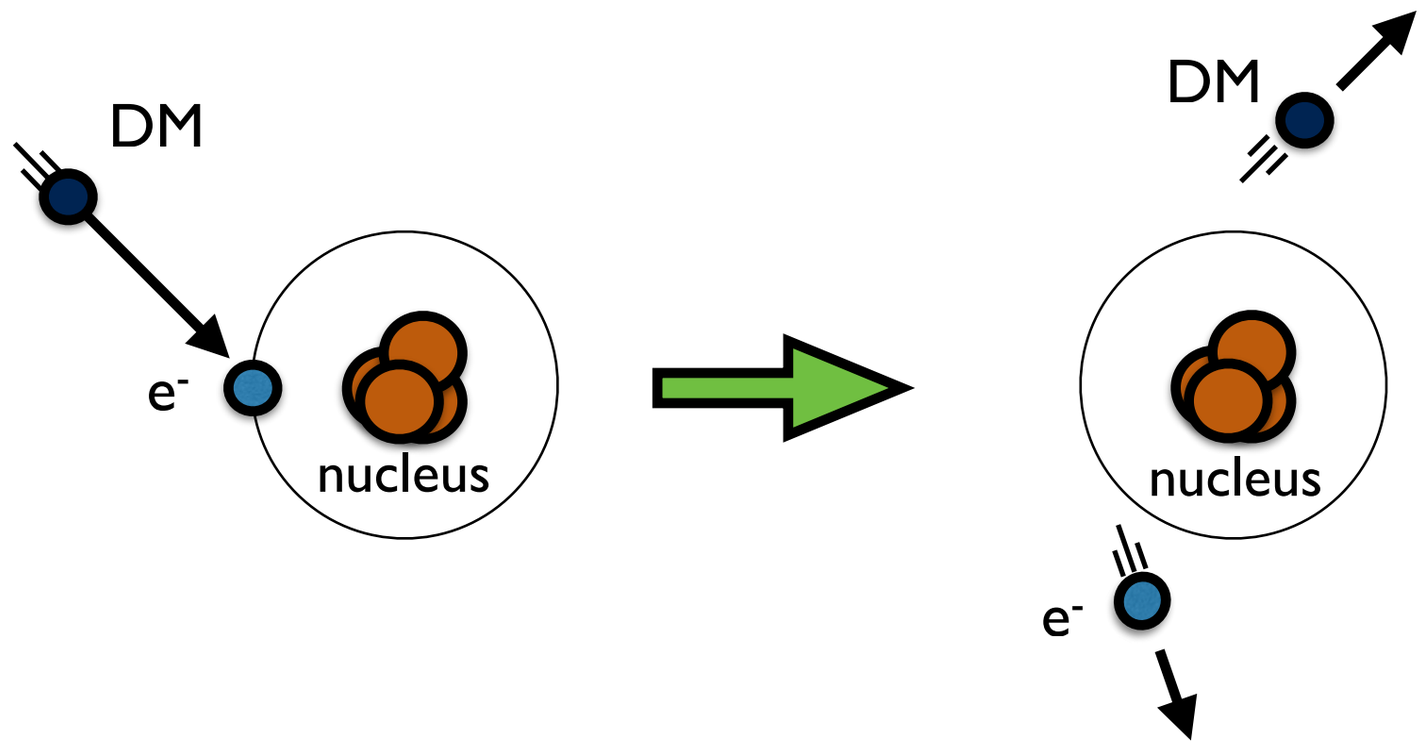
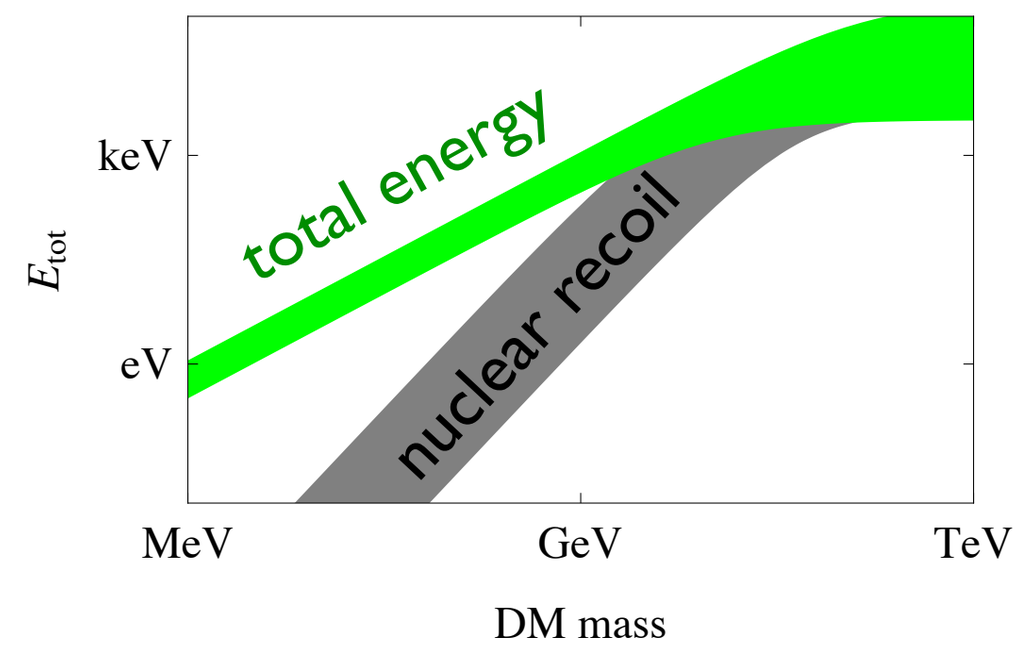
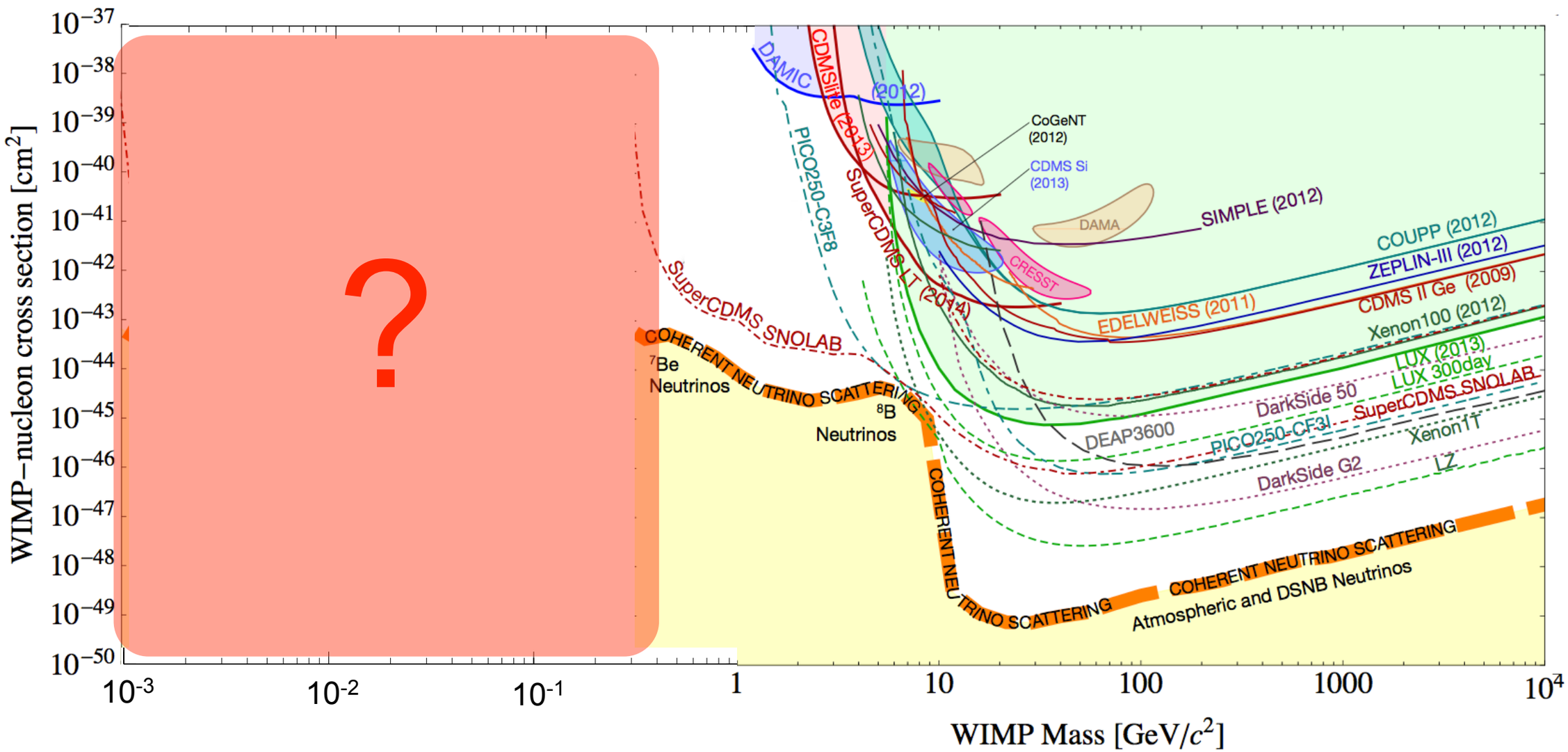


Fig credit: Tien-Tien Yu

most of DM energy can be transferred to electron



Allows Direct Detection down to ~1 MeV



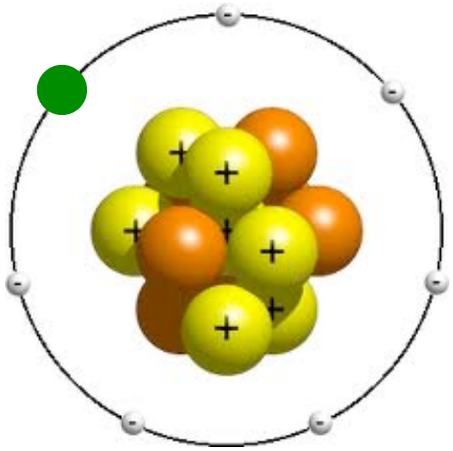
DM-electron scattering

- Noble liquids (xenon, argon, helium)

- Semiconductor targets (germanium, silicon)

DM-electron scattering

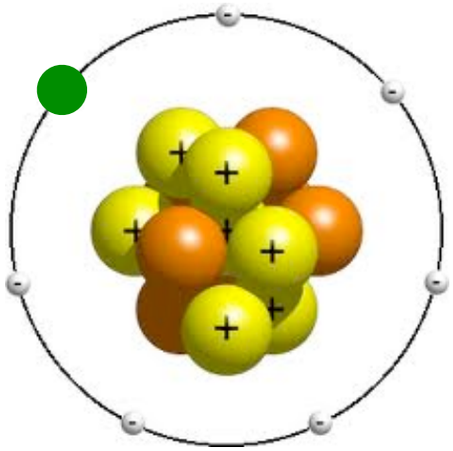
- Noble liquids (xenon, argon, helium)
  threshold ~ 10 eV



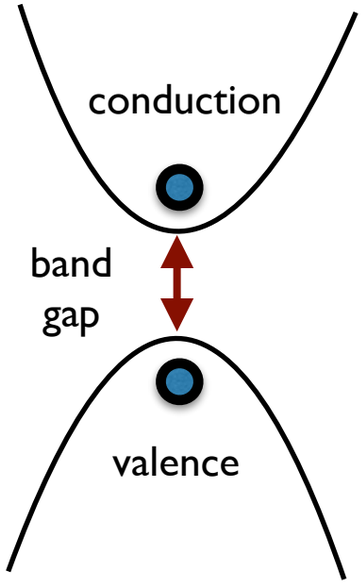
- Semiconductor targets (germanium, silicon)

DM-electron scattering

- Noble liquids (xenon, argon, helium)
  threshold ~ 10 eV



- Semiconductor targets (germanium, silicon)
  threshold ~ 1 eV (band gap)



DM-electron scattering

- Noble liquids (xenon, argon, helium)
  threshold ~ 10 eV

  sensitive to $m_{\mathrm{DM}} \sim 10\ \mathrm{MeV}$

- Semiconductor targets (germanium, silicon)
  threshold ~ 1 eV (band gap)

  sensitive to $m_{\mathrm{DM}} \sim 1\ \mathrm{MeV}$

DM-electron scattering

- Noble liquids (xenon, argon, helium)
  threshold ~ 10 eV

sensitive to $m_{\mathrm{DM}} \sim 10\ \mathrm{MeV}$

Done w/ XENON10 data!

But significant improvements possible

- Semiconductor targets (germanium, silicon)
  threshold ~ 1 eV (band gap)

sensitive to $m_{\mathrm{DM}} \sim 1\ \mathrm{MeV}$

Requires continued R&D to reach low threshold, but very promising

DM-electron scattering

- Noble liquids (xenon, argon, helium)
  threshold ~ 10 eV

sensitive to $m_{\mathrm{DM}} \sim 10\ \mathrm{MeV}$

Done w/ XENON10 data!

But significant improvements possible

- Semiconductor targets (germanium, silicon)
  threshold ~ 1 eV (band gap)

sensitive to $m_{\mathrm{DM}} \sim 1\ \mathrm{MeV}$

Requires continued R&D to reach low threshold, but very promising

First limits

RE, Manalaysay, Mardon, Sorensen, Volansky

2012

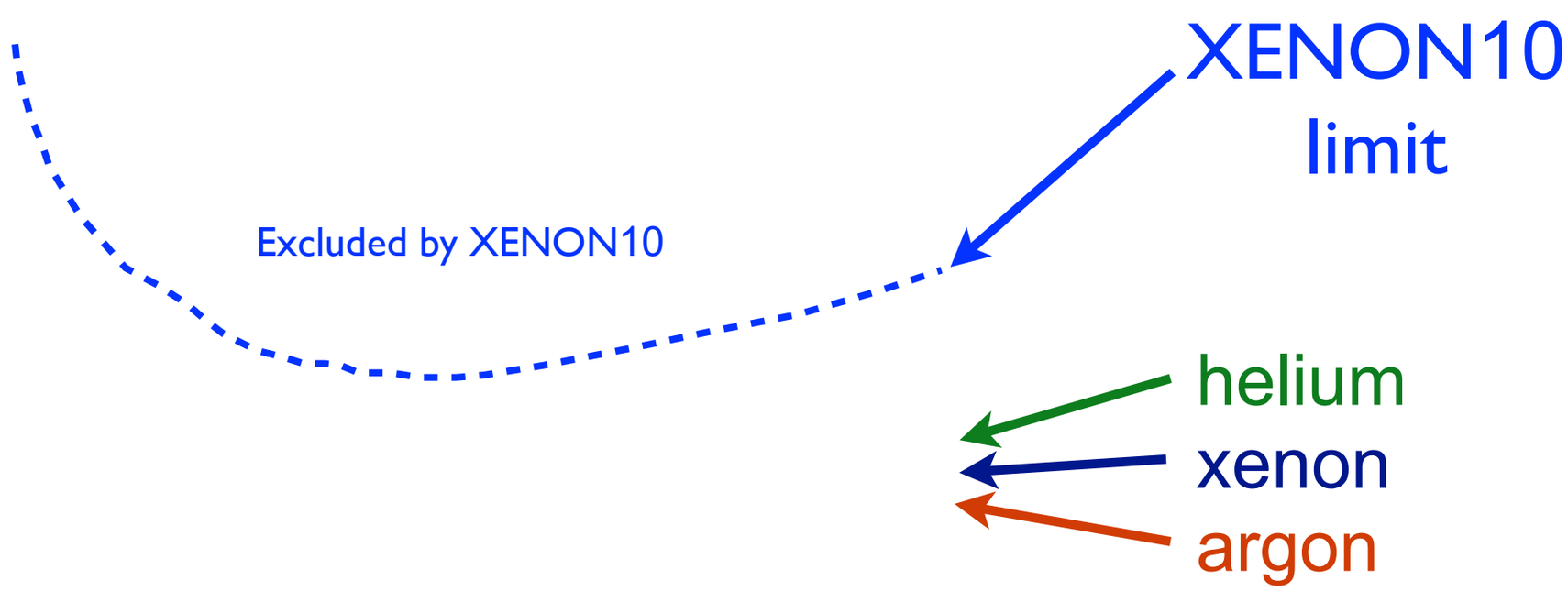
Prospects for noble liquids

RE, Mardon, Volansky

1 kg-year

Prospects for noble liquids

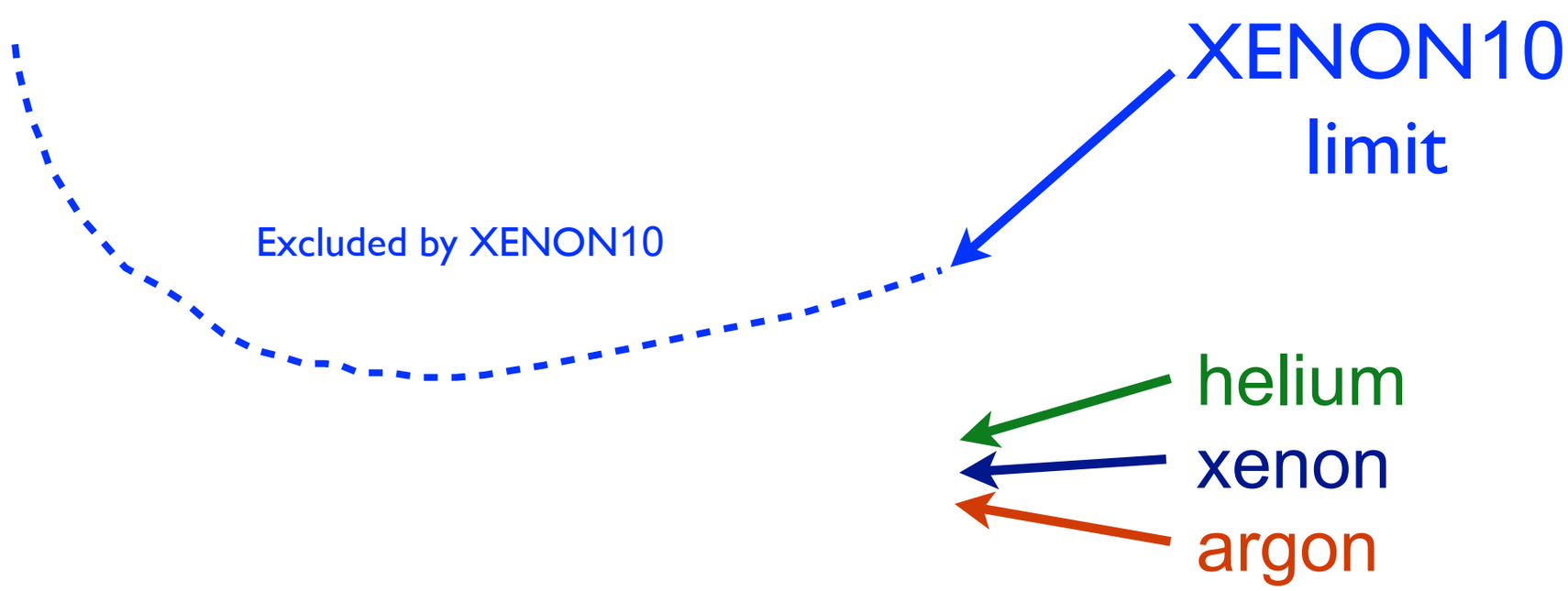
RE, Mardon, Volansky



1 kg-year

Prospects for noble liquids

RE, Mardon, Volansky



1 kg-year

possible improvements by XENON100, LUX, …

Prospects for semiconductors

RE, Mardon, Volansky

see also Graham, Kaplan, Rajendran, Walters

semiconductors
(Ge, but Si similar)

1 kg-year

band gap (~1 eV) < atomic ionization energy (~10 eV)

$\Longrightarrow$ can *potentially* reach *very* low masses!

Calculating Rates

$$\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\,dq\left|f^i_{ion}(k',q)\right|^2\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})$$

$$v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

Calculating Rates

$$\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\,dq\,\underline{\left|f^i_{ion}(k',q)\right|^2}\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})$$

$$v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

ionization form factor

$$|f(q)|^2 \sim \sum_{\rm degeneracies} \left|\langle\psi_{\rm out}|e^{i\vec{q}\cdot\vec{r}}|\psi_{\rm bound}\rangle\right|^2$$

Calculating Rates

$$\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\,dq\,\underline{\left|f^i_{ion}(k',q)\right|^2}\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})$$

$$v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

ionization form factor

$$|f(q)|^2 \sim \sum_{\rm degeneracies} \left|\langle\psi_{\rm out}|e^{i\vec{q}\cdot\vec{r}}|\psi_{\rm bound}\rangle\right|^2$$

Challenging to calculate, especially for semiconductors!

- analytic approximation — how accurate?

Graham et.al. (1203.2531)

Lee, Lisanti, Mishra-Sharma, Safdi (to appear)

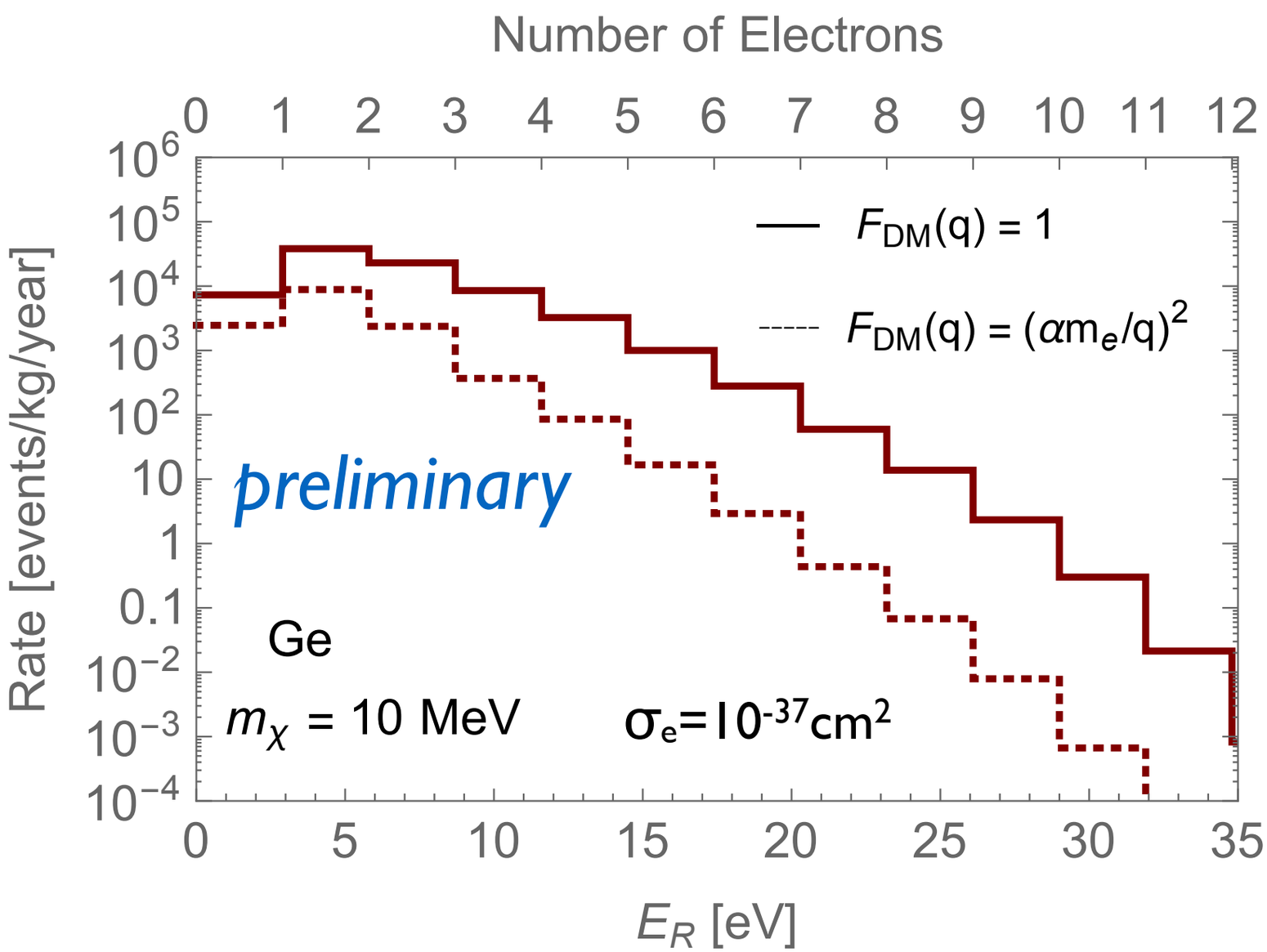
- numerical: adapt existing solid-state codes

RE, Mardon, Volansky (1108.5383)

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)

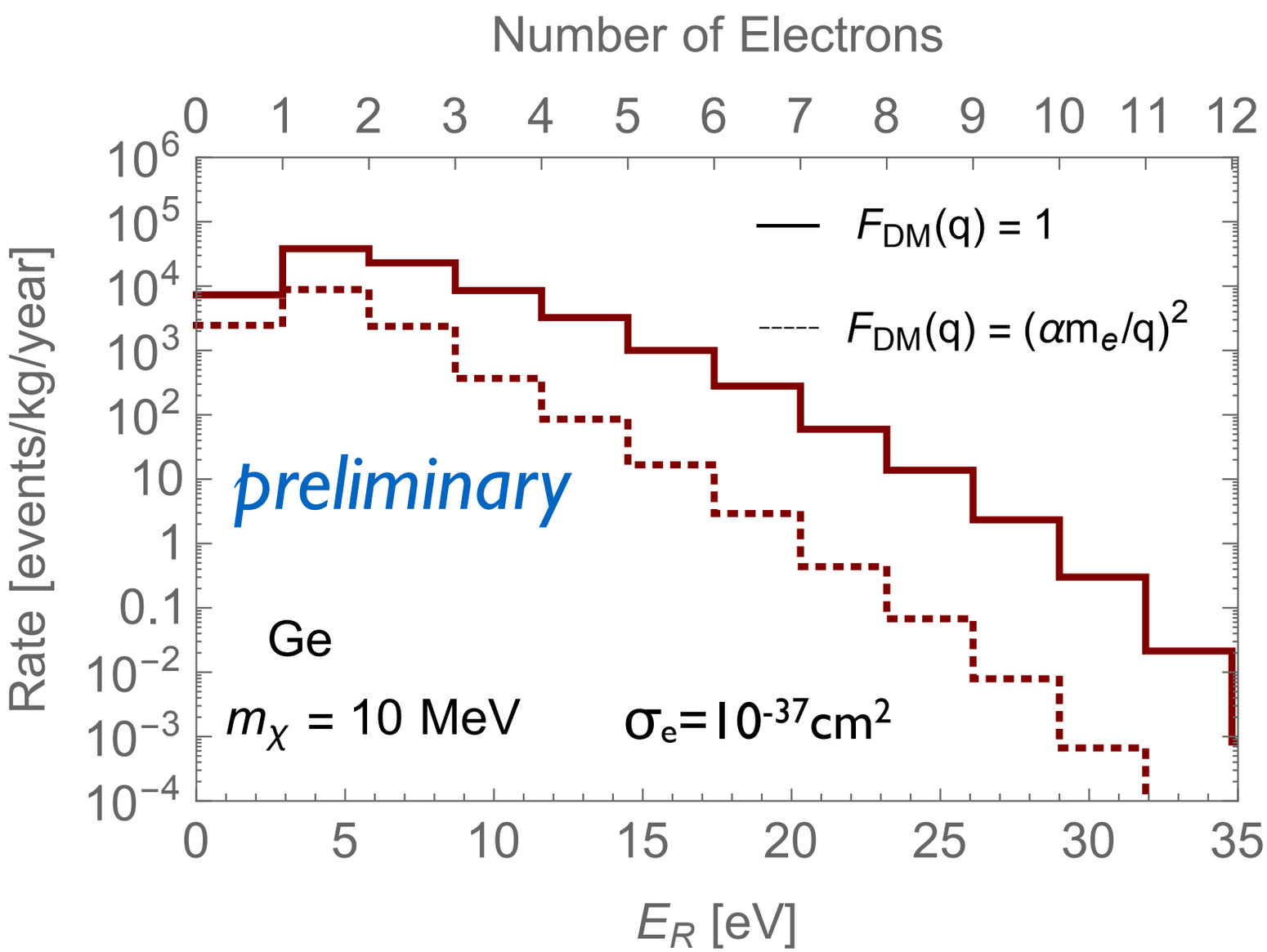
Recoil energy spectrum

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)



Recoil energy spectrum

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)



Current thresholds, e.g.

CDMSlite: ~170 eV

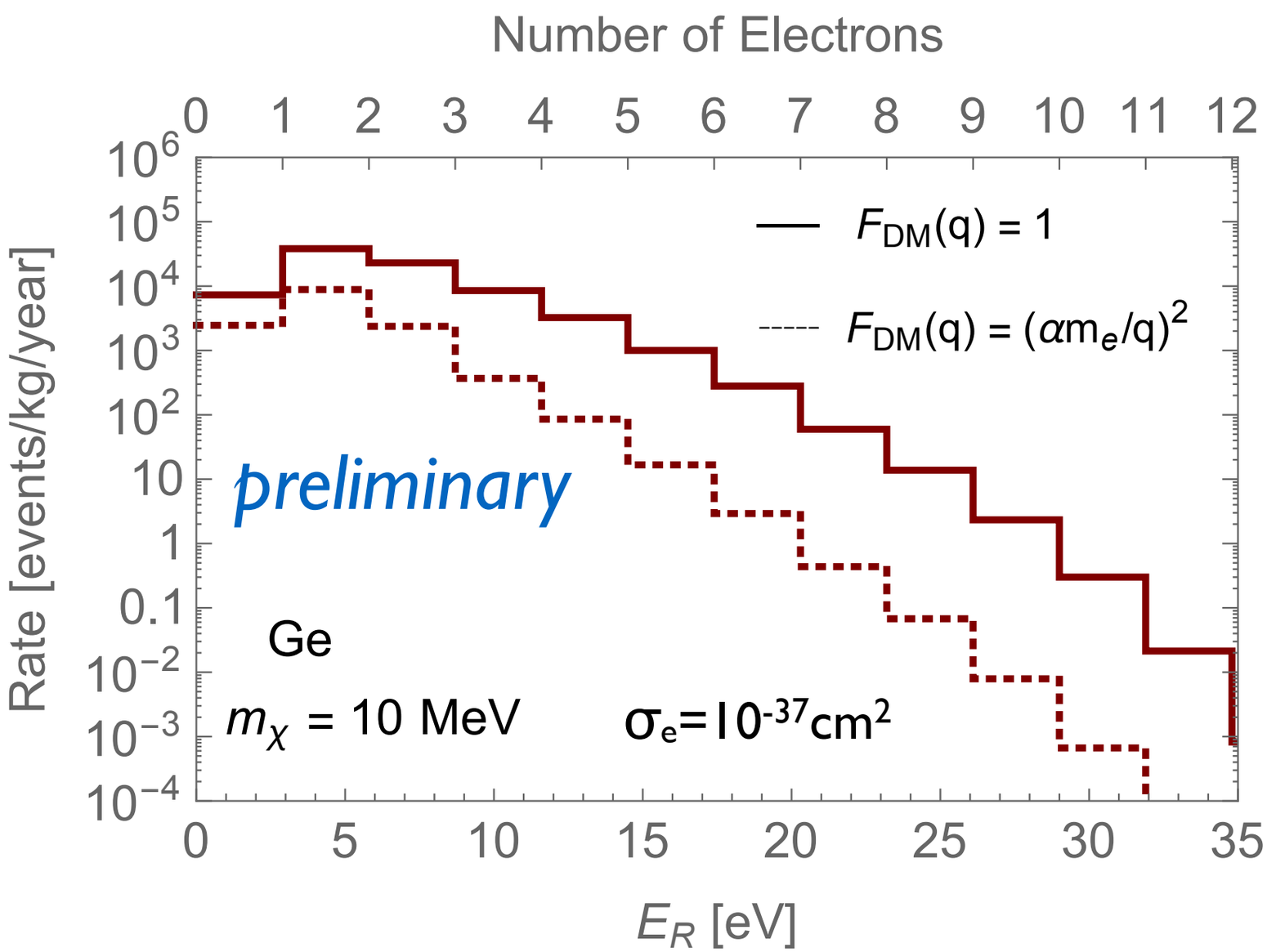
(1309.3259)

DAMIC: ~50 eV

(1105.5191)

Recoil energy spectrum

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)



Current thresholds, e.g.

CDMSlite: ~170 eV

(1309.3259)

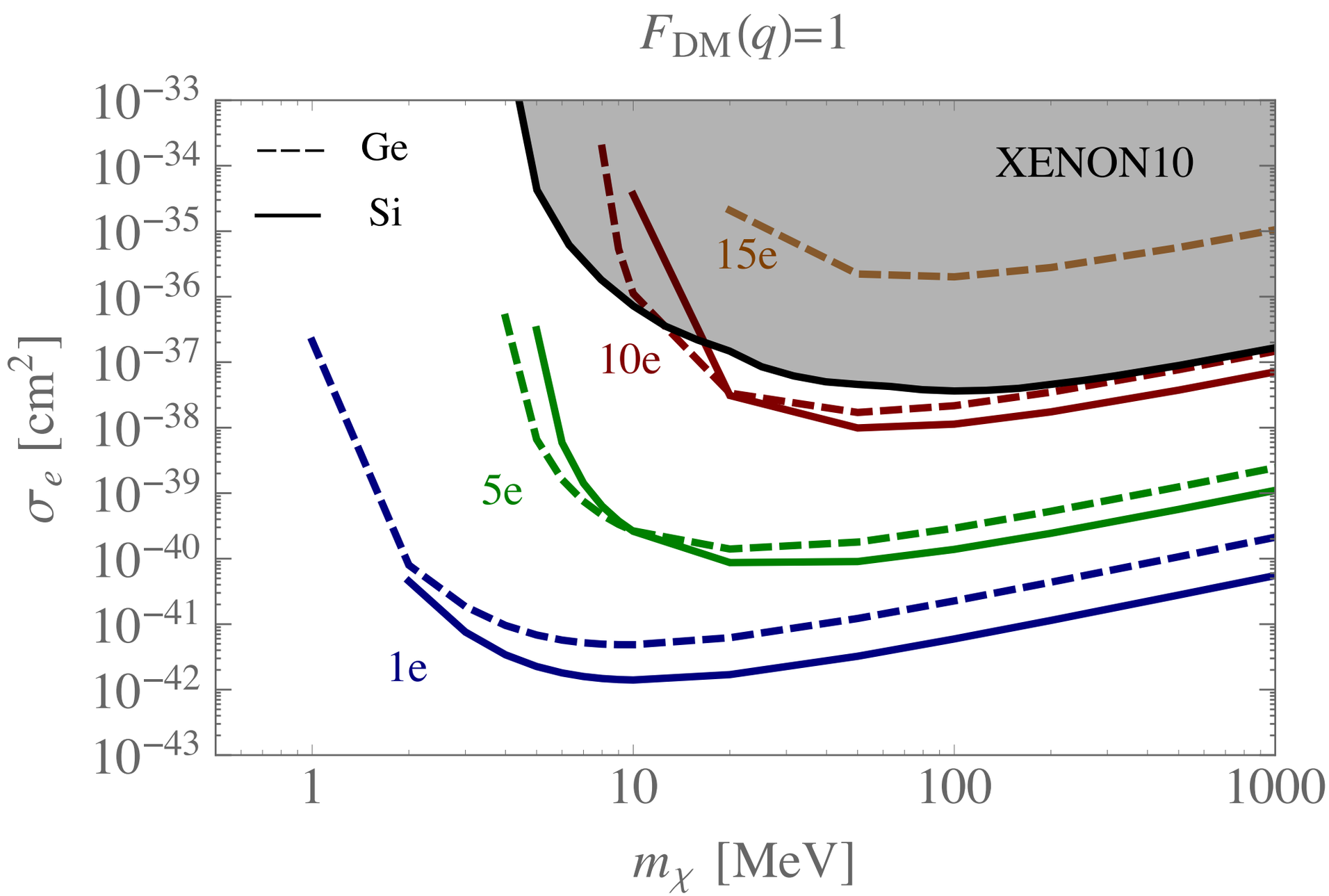
DAMIC: ~50 eV

(1105.5191)

Lowering threshold gives *HUGE* increase in rate

Prospects for semiconductors

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)



preliminary

Other direct detection avenues for sub-GeV DM

✔ • ionization

• excitation

RE, Mardon, Volansky
+Andrea Massari, Tien-Tien Yu

• molecular dissociation

RE, Mardon, Oren Slone, Volansky

see also Va'vra

Other direct detection avenues for sub-GeV DM

✔ • ionization

→ (briefly) • excitation

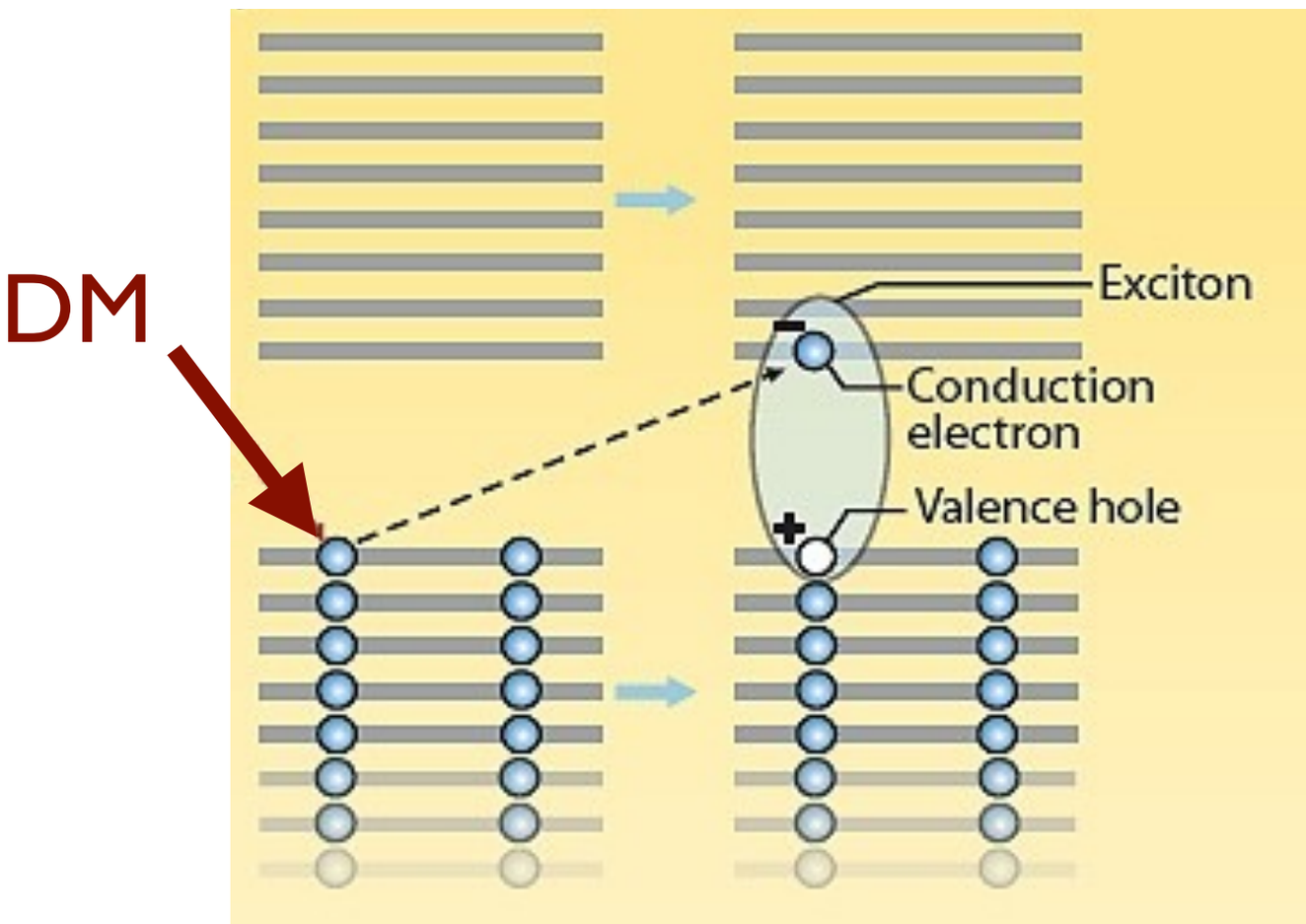
RE, Mardon, Volansky
+Andrea Massari, Tien-Tien Yu

• molecular dissociation

RE, Mardon, Oren Slone, Volansky

see also Va'vra

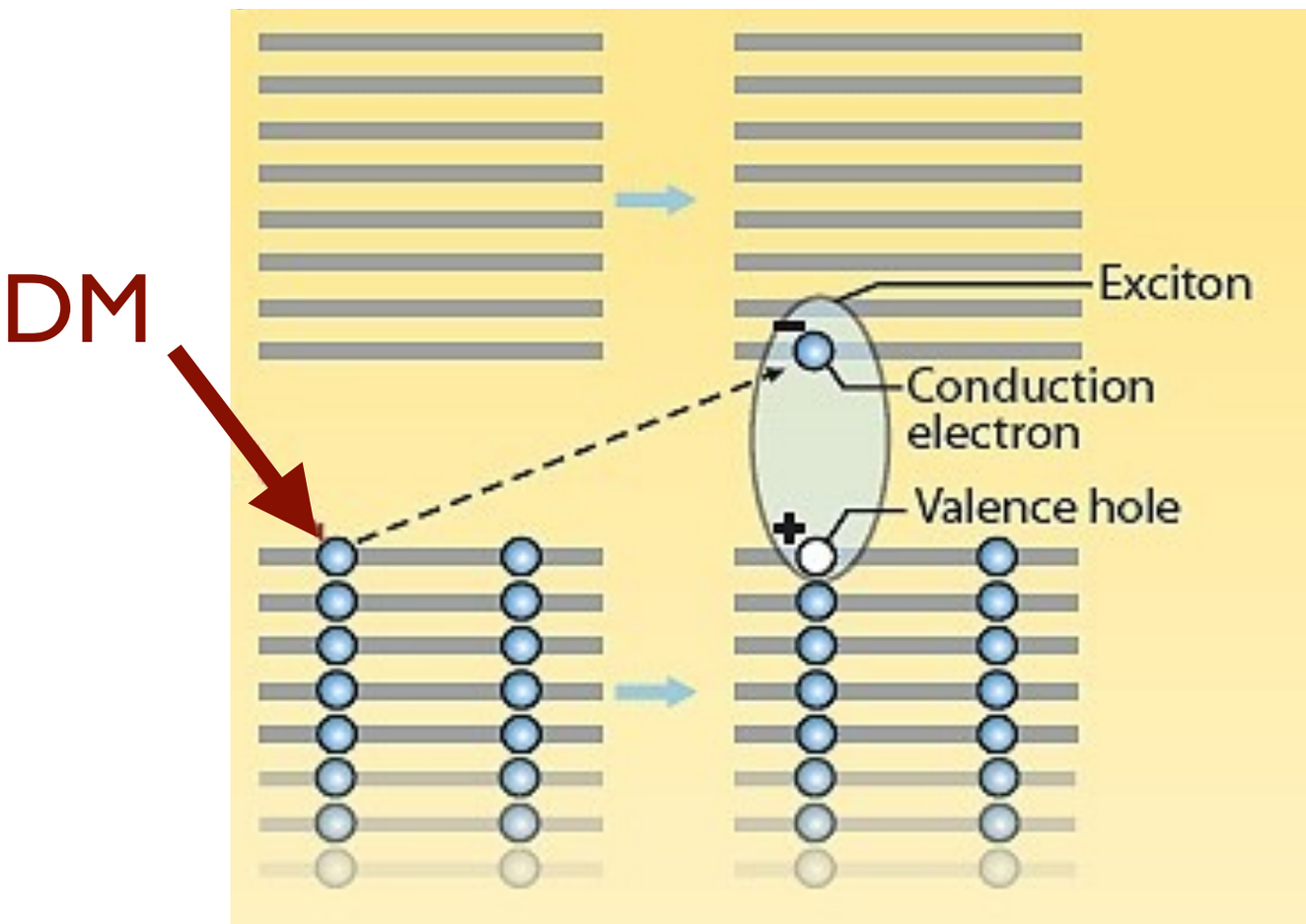
Example: Excitons in scintillating crystals?



adapted from www.lanl.gov/science/1663/june2010/story2a.shtml

- DM creates exciton

Example: Excitons in scintillating crystals?



adapted from www.lanl.gov/science/1663/june2010/story2a.shtml

- DM creates exciton
- Exciton de-excites

Signal:
one (or a few) photons

Backgrounds?

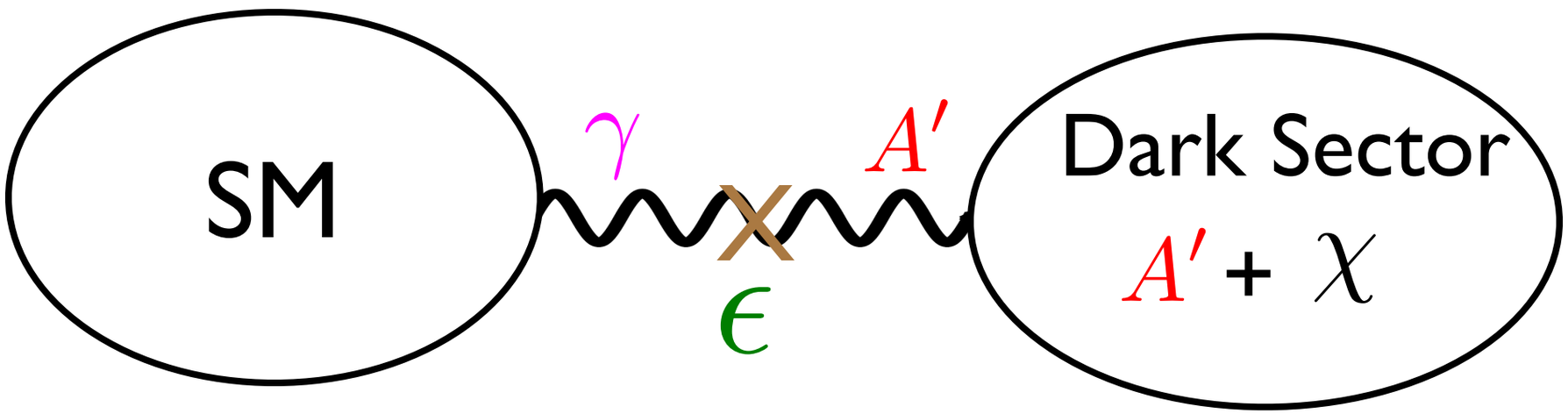
Outline

illustrate w/ simple model

- direct detection
- colliders (e^+e^-)
- fixed-target (p & e^-)
- indirect detection

A simple, predictive model

χ: scalar or Dirac fermion

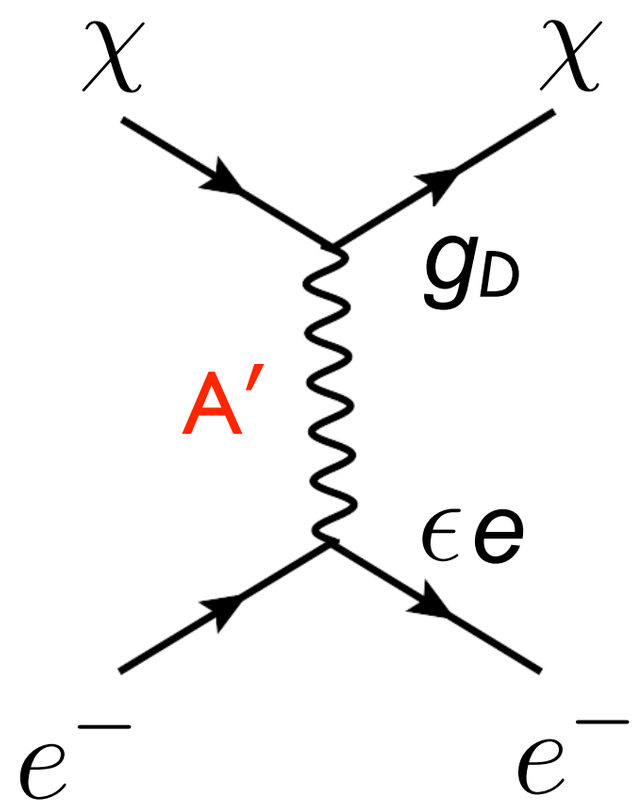


Kinetic mixing: $$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Holdom;
Galison, Manohar

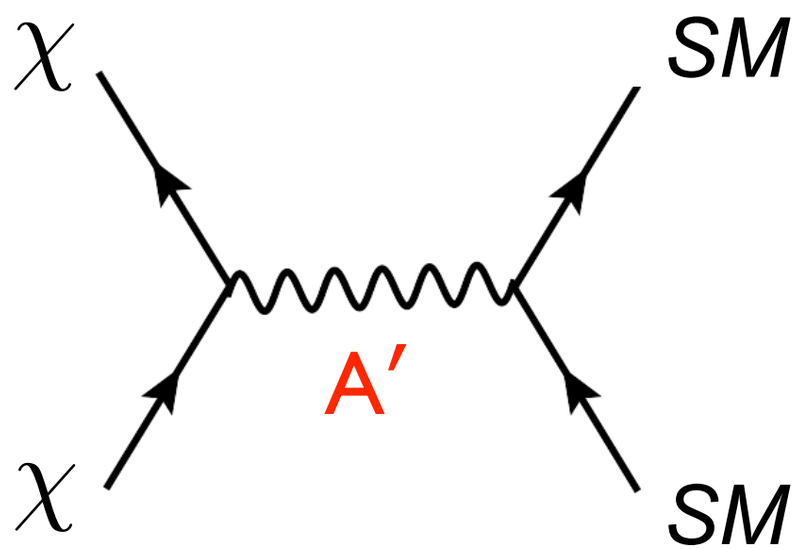
see also e.g.
Boehm, Fayet; Pospelov, Ritz, Voloshin;
Batell, Pospelov, Ritz; Lin, Yu, Zurek;
Izaguirre, Krnjaic, Schuster, Toro; …

Direct Detection



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

Thermal freeze-out

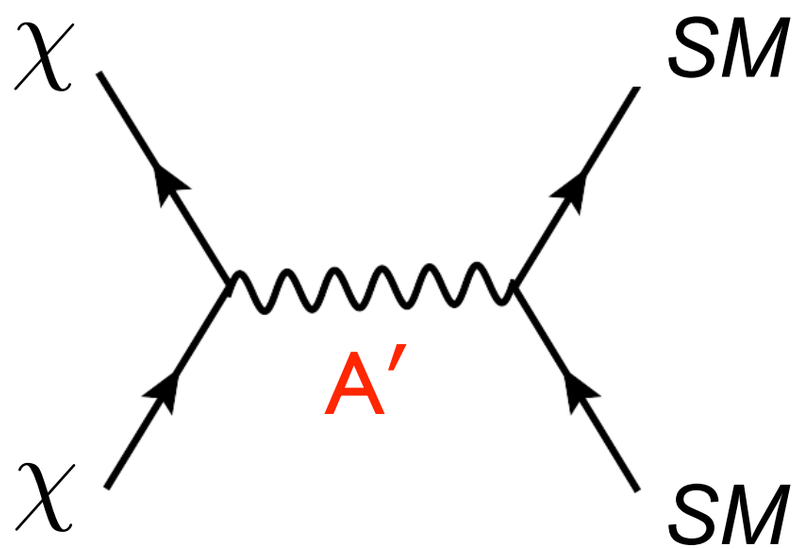


$m_{A'} > 2m_\chi$

(very predictive!)

see also Izaguirre, Krnjaic, Schuster, Toro, 2015

Thermal freeze-out



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

(very predictive!)

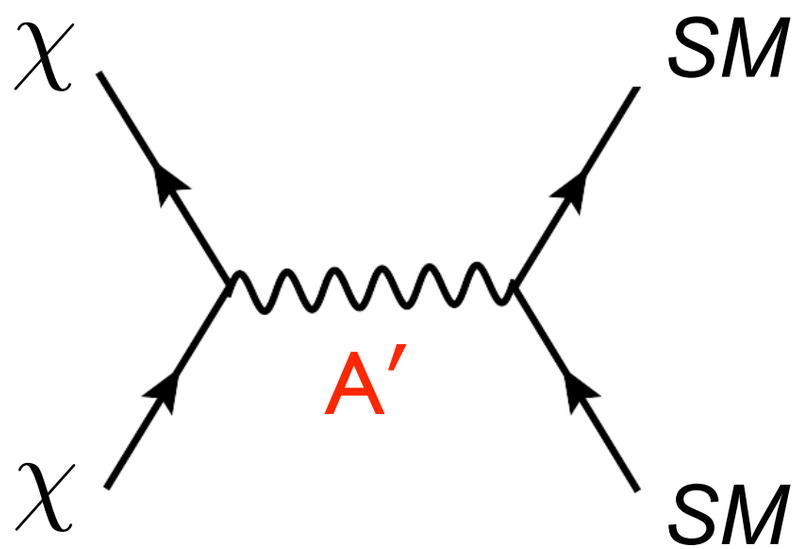
see also Izaguirre, Krnjaic, Schuster, Toro, 2015

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!

Thermal freeze-out



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

(very predictive!)

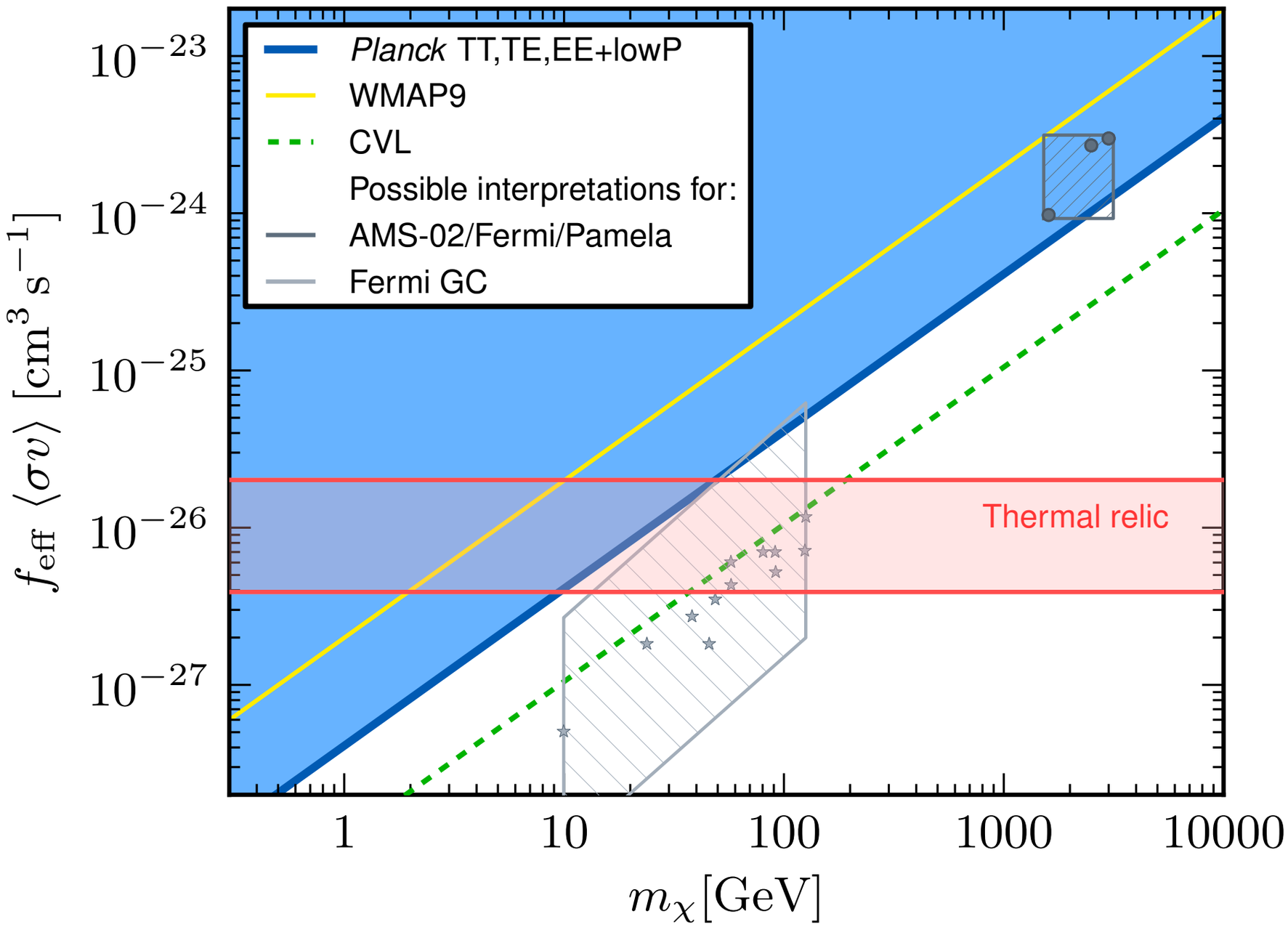
see also Izaguirre, Krnjaic, Schuster, Toro, 2015

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!

Constraints from CMB



standard s-wave freeze-out disfavored <10 GeV

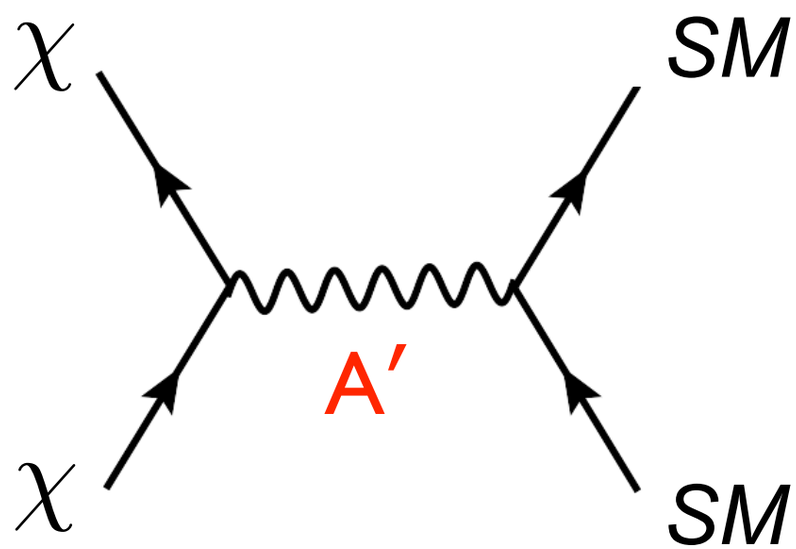
easy to avoid, e.g. p-wave or asymmetric

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



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

(very predictive!)

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

p-wave

unconstrained by CMB

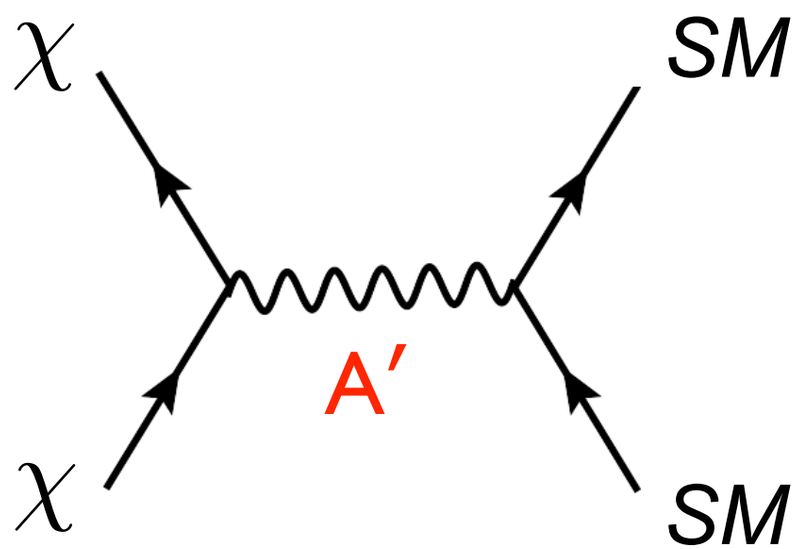
Dirac fermion χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2$$

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

CMB sets *lower* bound on σv

e.g. Lin, Yu, Zurek

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

unconstrained by CMB

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

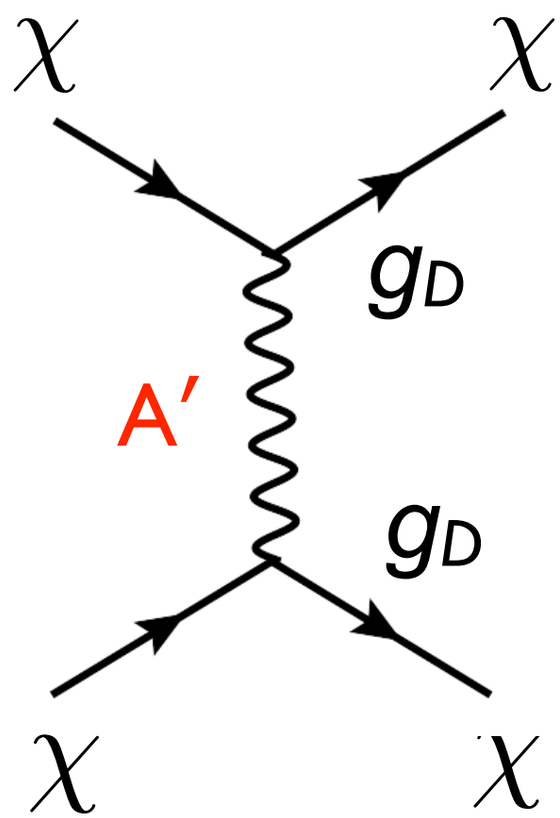
s-wave $\Longrightarrow$ *asymmetric*

CMB sets *lower* bound on σv

e.g. Lin, Yu, Zurek

provides nice targets for direct detection experiments!

Self-interactions



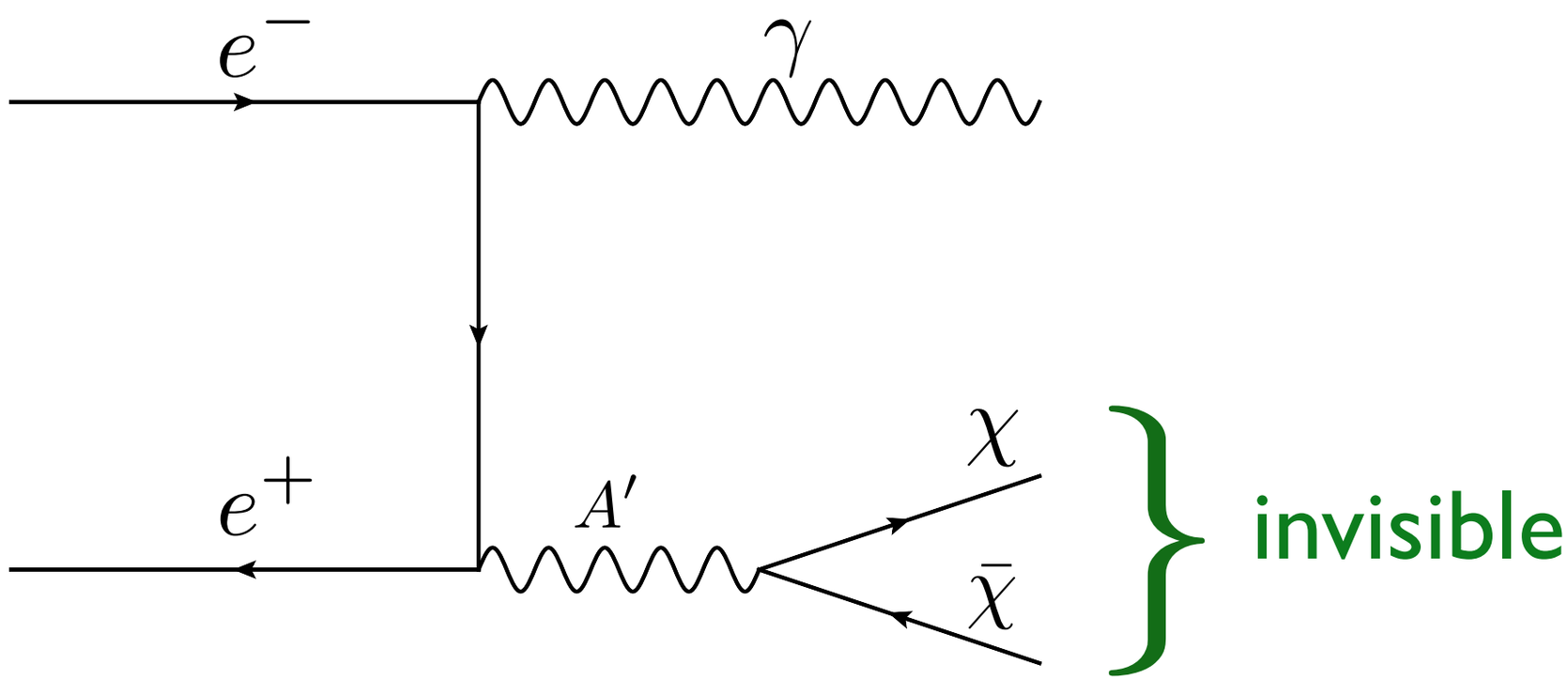
constraint from bullet cluster etc.

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

sets upper bound on α_D

e^+e^- colliders

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



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

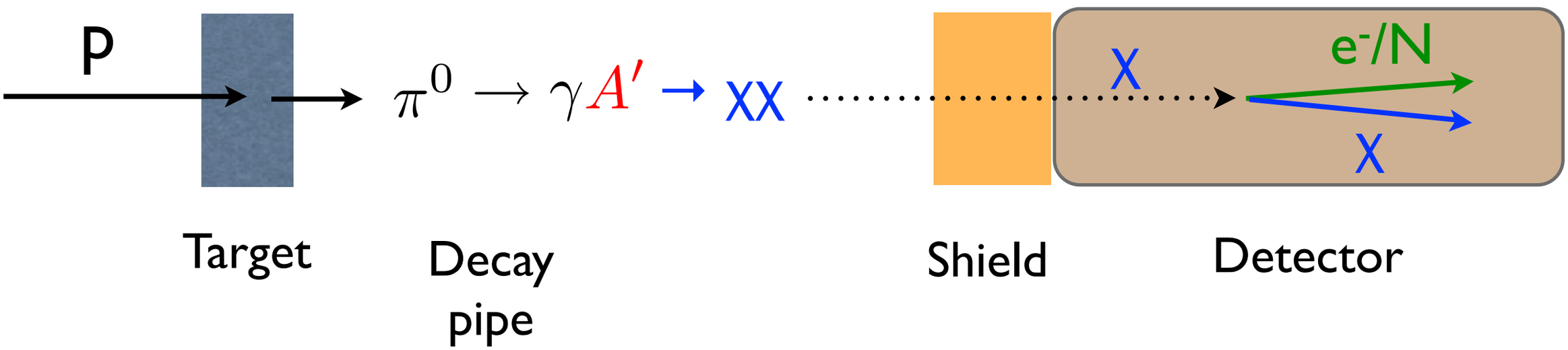
Constrained from 30/fb @BaBar

Exciting prospects @Belle-2

(needs mono-photon trigger)

Proton-beam dumps

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



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

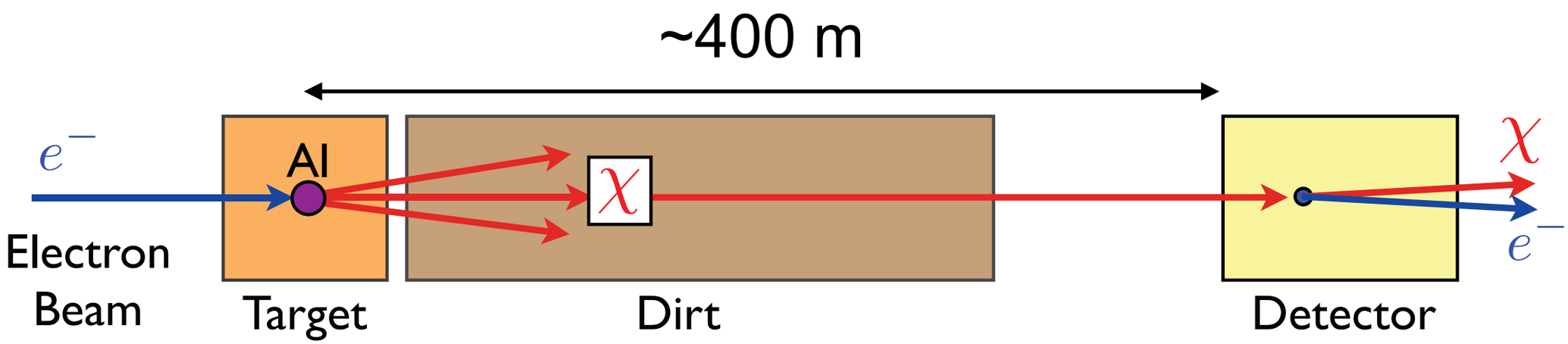
constrained by LSND

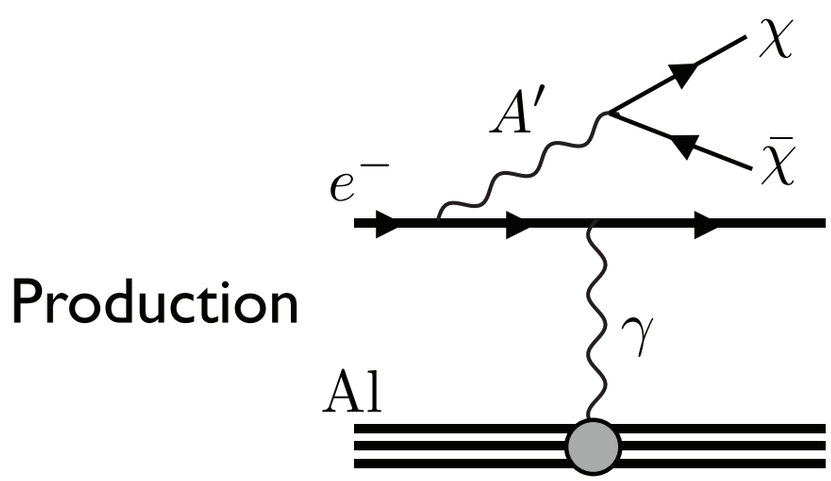
MiniBooNE search underway

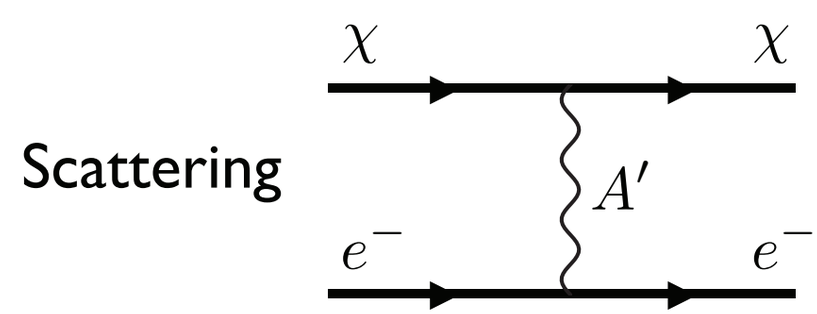
plenty of room for future exploration

Electron-beam dumps: SLAC's E137

Bjorken et.al.
Batell, RE, Surujon

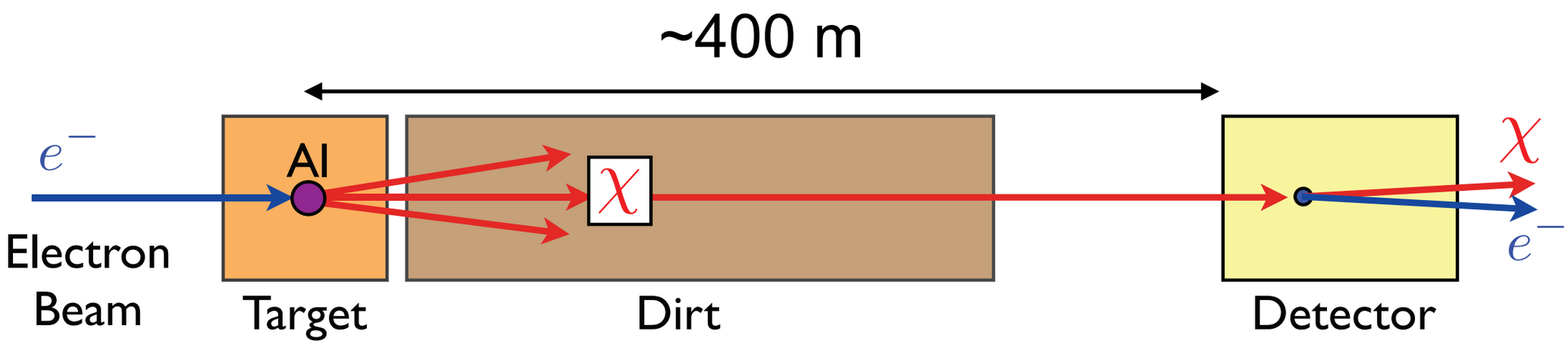


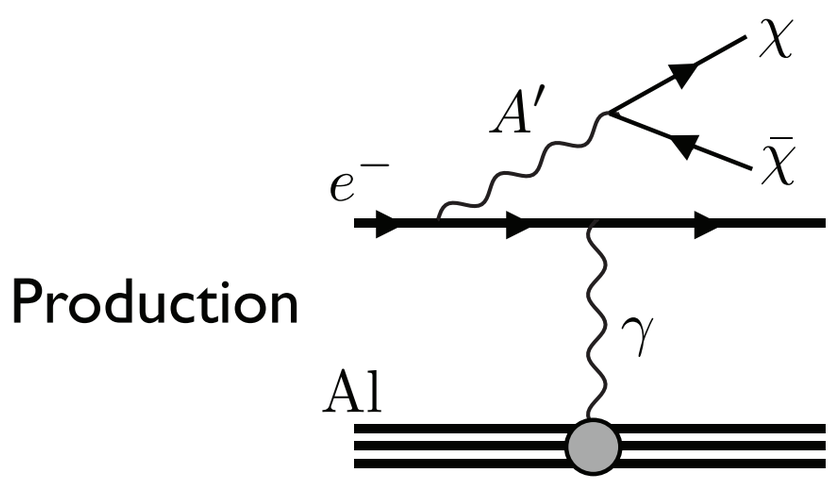


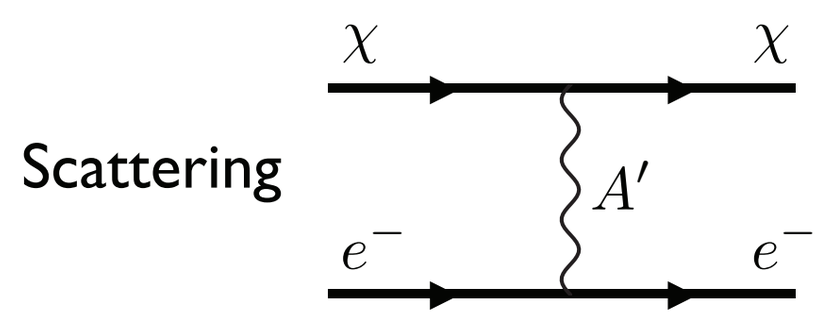


Electron-beam dumps: SLAC's E137

Bjorken et.al.
Batell, RE, Surujon







but plenty of room for future exploration, e.g. w/ BDX

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

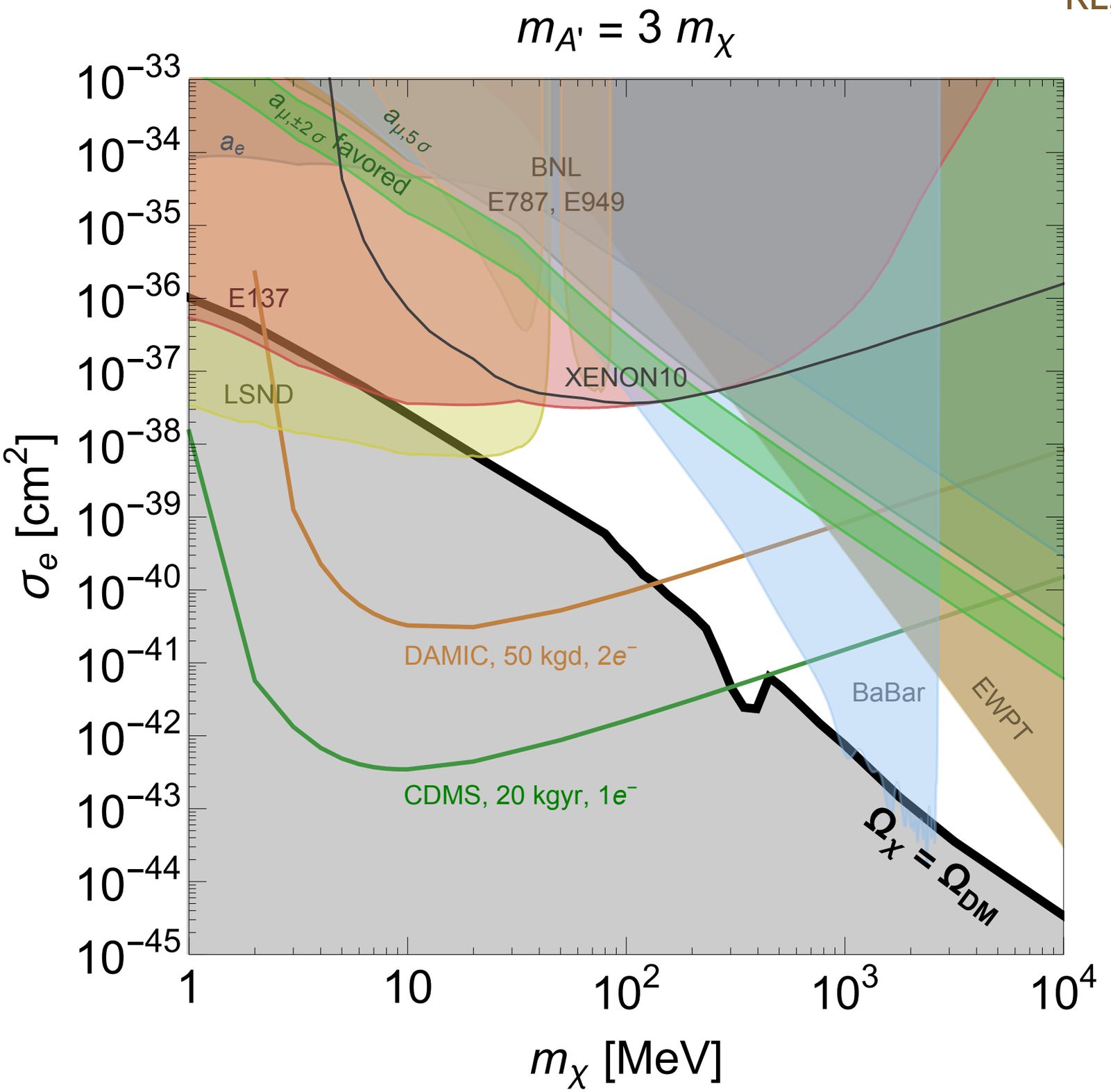
see also proposals for "missing momentum search" Izaguirre, Krnjaic, Schuster, Toro

putting it all together…

(w/ a few additional constraints that I didn’t discuss)

Direct Detection Prospects (scalar χ)

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)

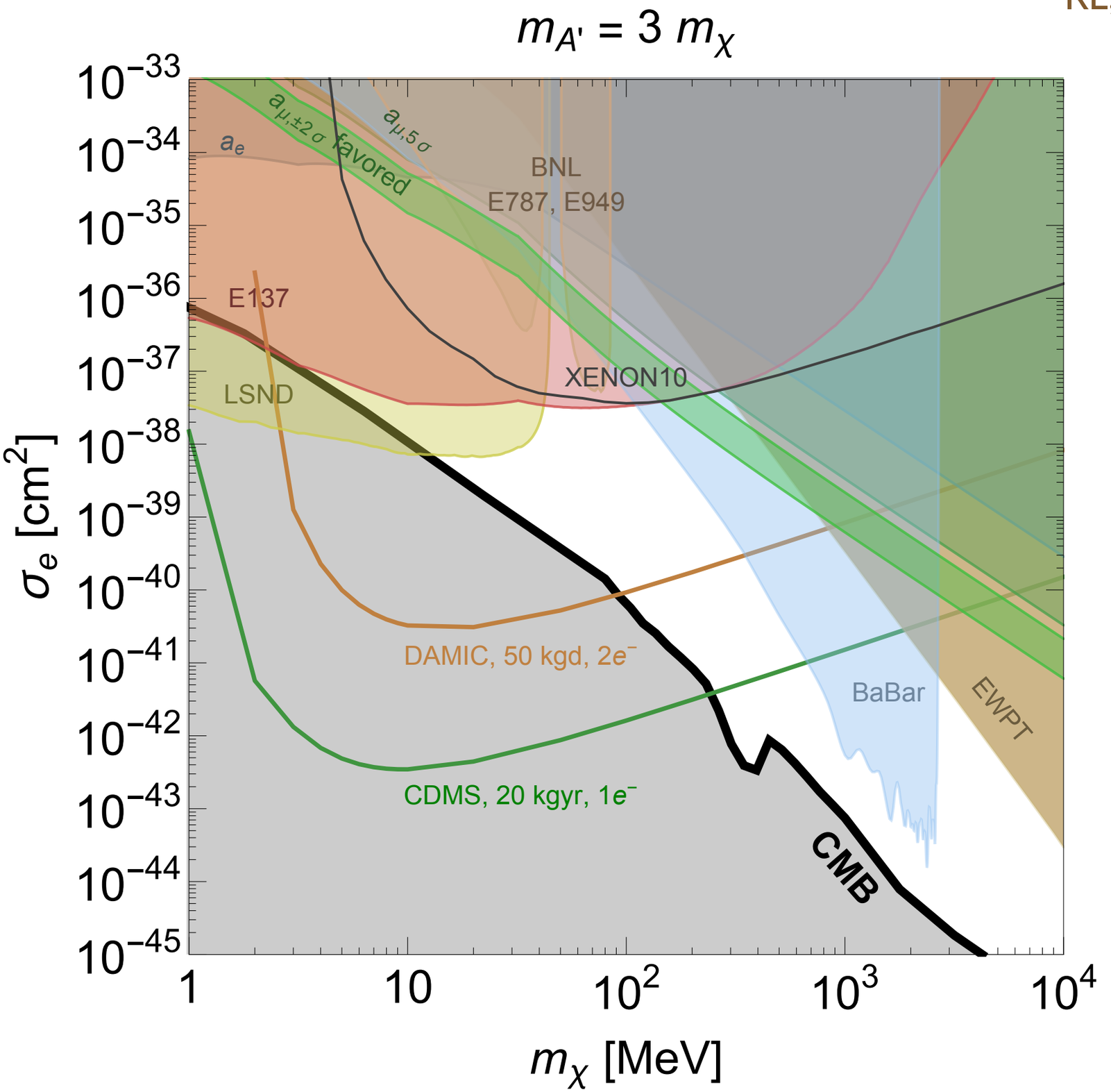


preliminary

of course, prospects depend on (unknown) backgrounds!

Direct Detection Prospects (Dirac χ)

RE, Fernandez-Serra, Mardon, Adrian Soto, Volansky, Tien-Tien Yu (to appear)

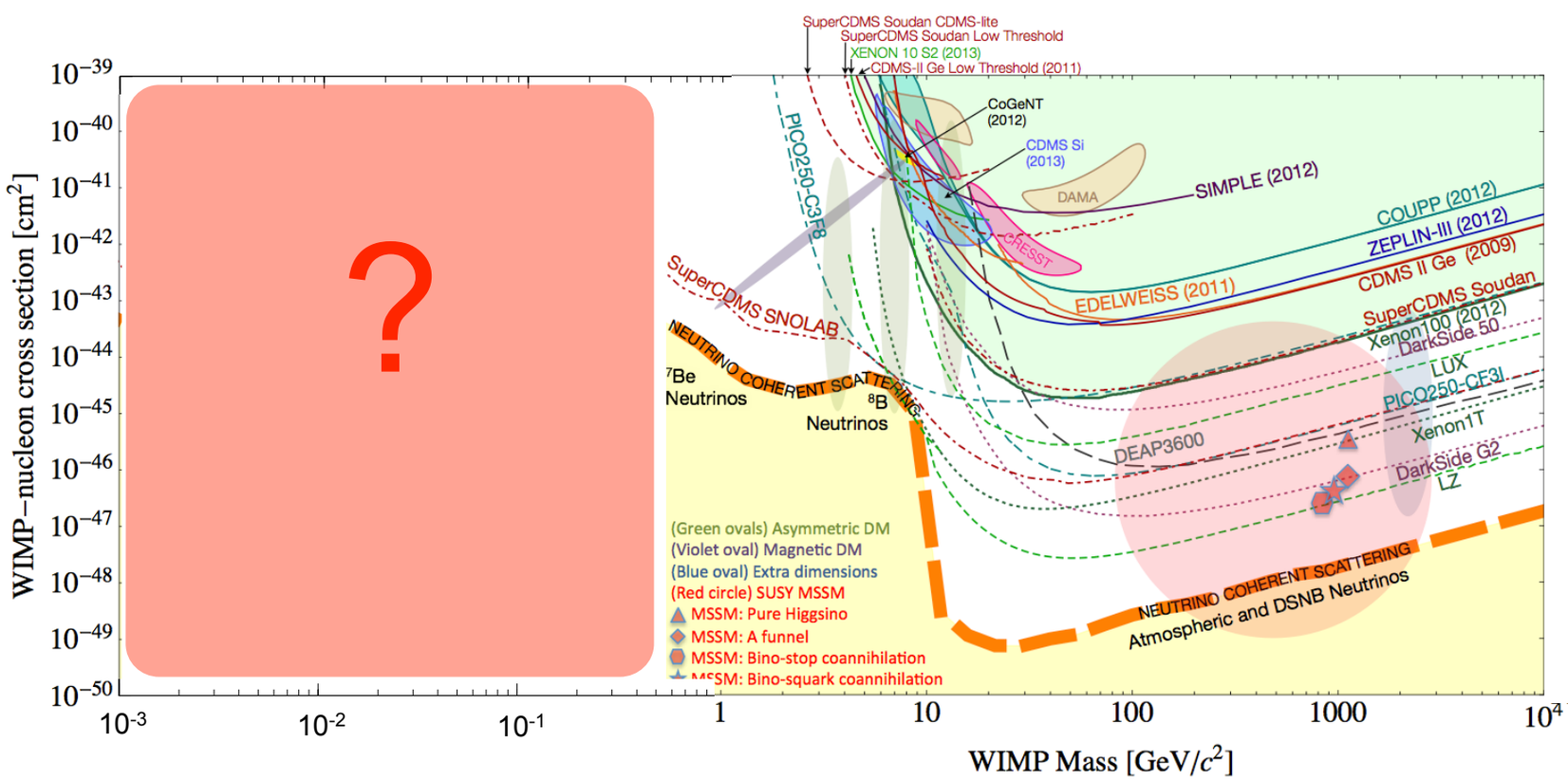


preliminary

of course, prospects depend on (unknown) backgrounds!

Summary

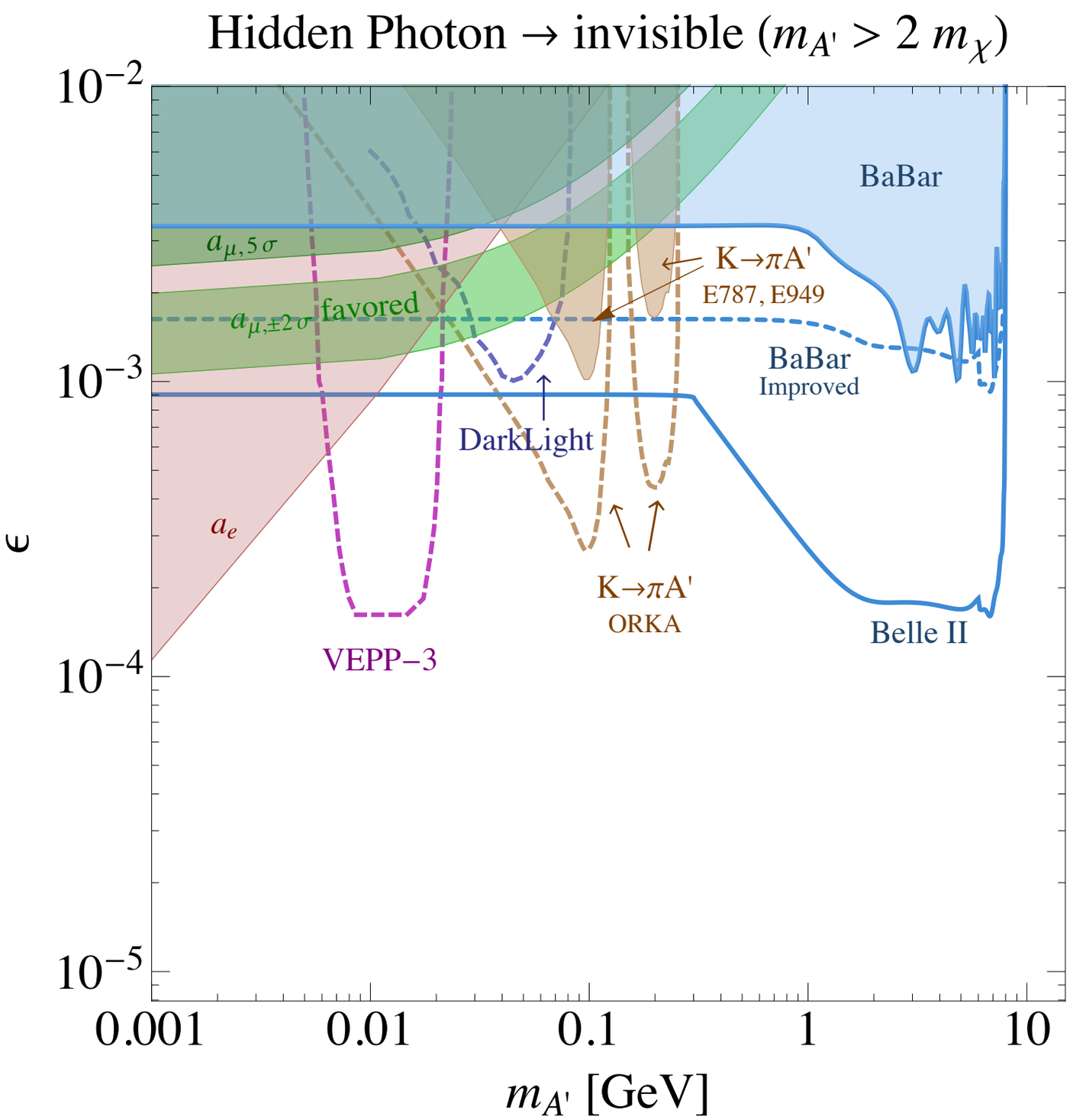
- sub-GeV DM is a motivated, viable possibility
- rich phenomenology: direct, indirect, colliders, fixed-target
- many opportunities for significant progress over next few years



Back-up

On-shell A′ w/ decays to any invisible state(s)

RE, Mardon, Papucci, Volansky, Zhong



- g-2 regions

  Pospelov

- VEPP-3 & DarkLight

  Wojtsekhowski, Nikolenko, Rachek

  Kahn, Thaler

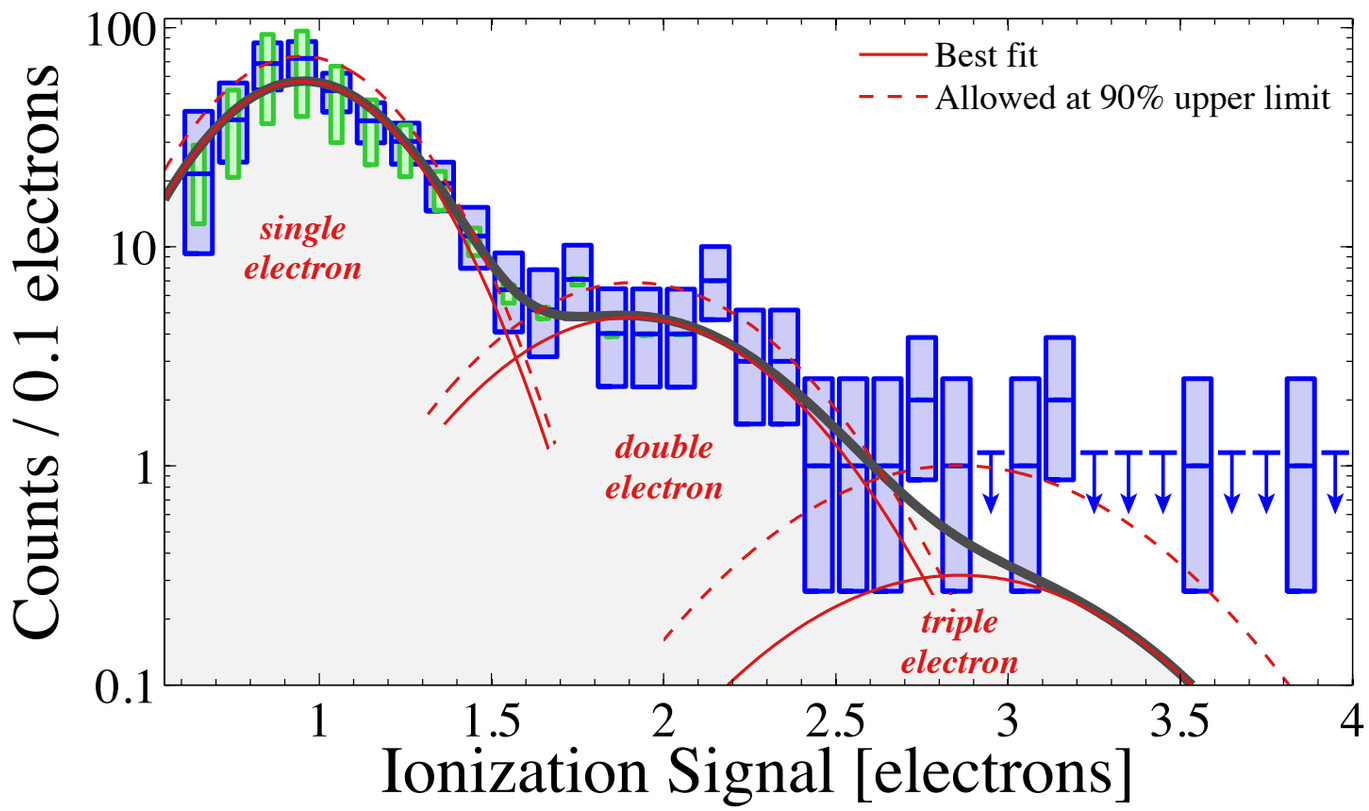
- rare Kaon decays

  see also deNiverville, Pospelov, Ritz

- BaBar and Belle II best at higher masses

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