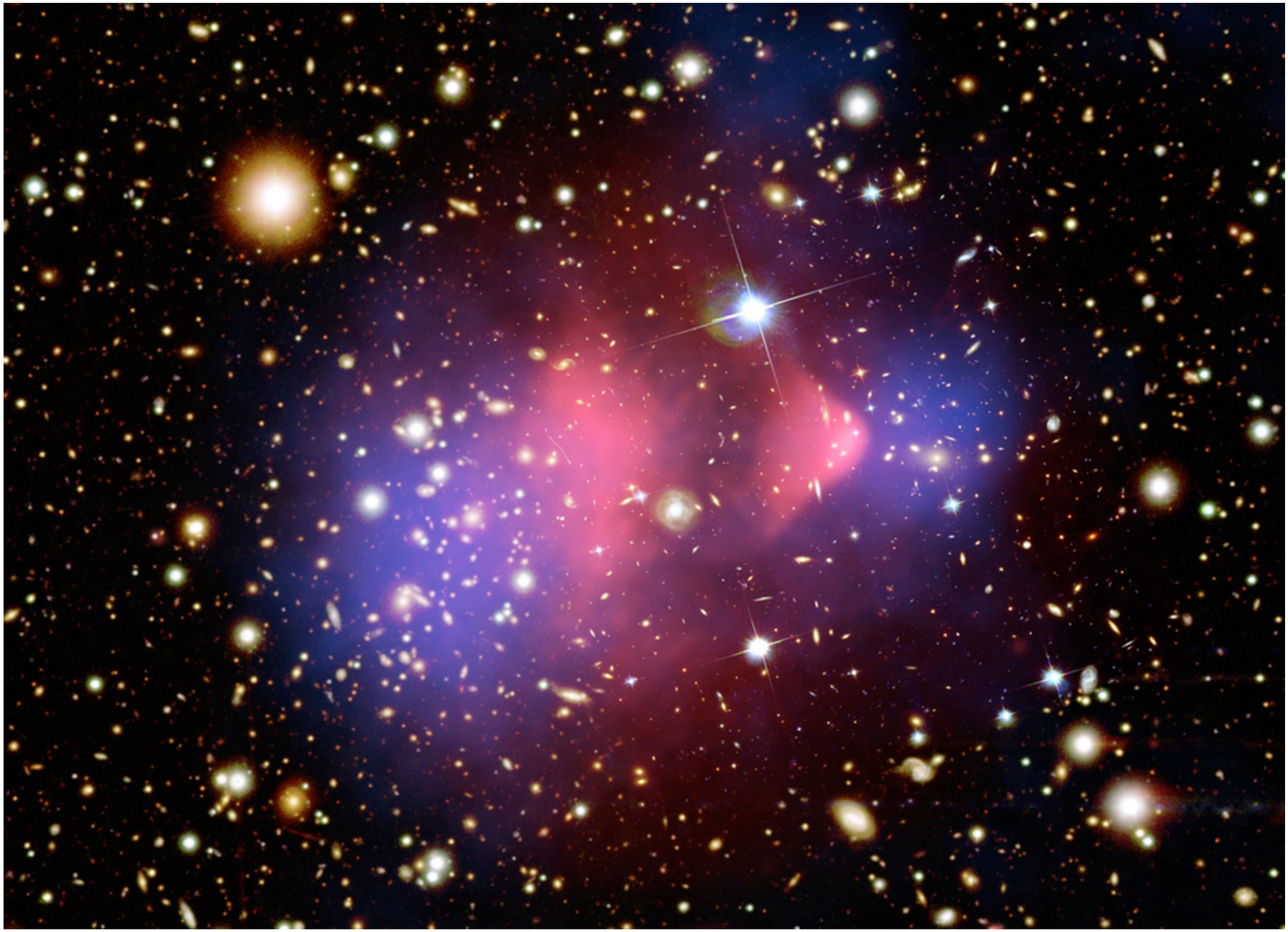
The Search for sub-GeV Dark Matter

Rouven Essig

C.N. Yang Institute for Theoretical Physics, Stony Brook

IPMU Seminar, Nov 15, 2013

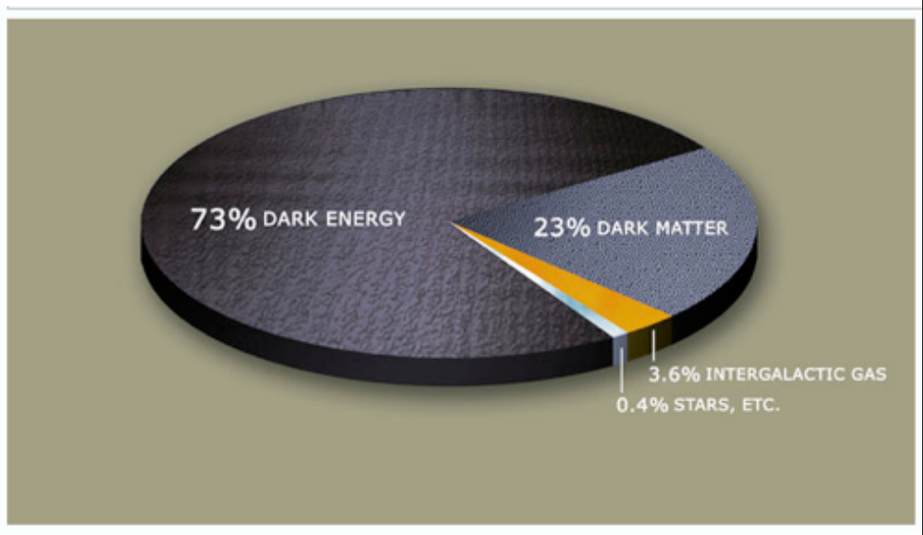
Lots of evidence for dark matter



X-ray: NASA/CXC/CfA/M.Markevitch et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

The Search for Dark Matter

- What is dark matter?
  $\Longrightarrow$ clearly, an important question…



- Major experimental efforts are underway
  $\Longrightarrow$ real chance of success in coming years…

But are we looking everywhere we can and should?

The Dark Matter Paradigm

The search for DM is dominated by the search for

Weakly Interacting Massive Particles (WIMPs)[1]

~ 5-1000 GeV

(1) axions and other DM candidates often only get mentioned as a footnote

Beyond The Paradigm

The intensive search for WIMPs is a no-brainer[(2)]

but let's make sure they don't get all the attention

- many new physics models have non-WIMP DM
- many other ways to get correct DM abundance
- no new physics at the LHC yet…

Many other well-motivated candidates exist that we can and should look for!

---

(2) ditto for axions, which should really get much more attention

sub-GeV Dark Matter

simple, well-motivated, viable candidates exist

very rich phenomenology,
plenty of room for new experimental investigation

opportunities are still being actively explored

This talk: broad, but biased, overview of:

- some constraints & models
- experimental opportunities

Outline

- some constraints & models
- experimental opportunities
  - direct detection
    - colliders (e^+e^-)
    - fixed-target (p & e^-)
    - indirect detection

Is sub-GeV DM allowed?

Yes, must avoid a few (model-dependent) constraints

Constraints from relic abundance

Lee-Weinberg bound: dark matter = heavy neutrino, interacting with weak-scale mediators

(1977)

$$\sigma \sim \frac{m_\chi^2}{M^4} \qquad \Omega_\chi \sim 0.2 \left(\frac{6\ \mathrm{GeV}}{m_\chi}\right)^2$$

too much DM for low masses

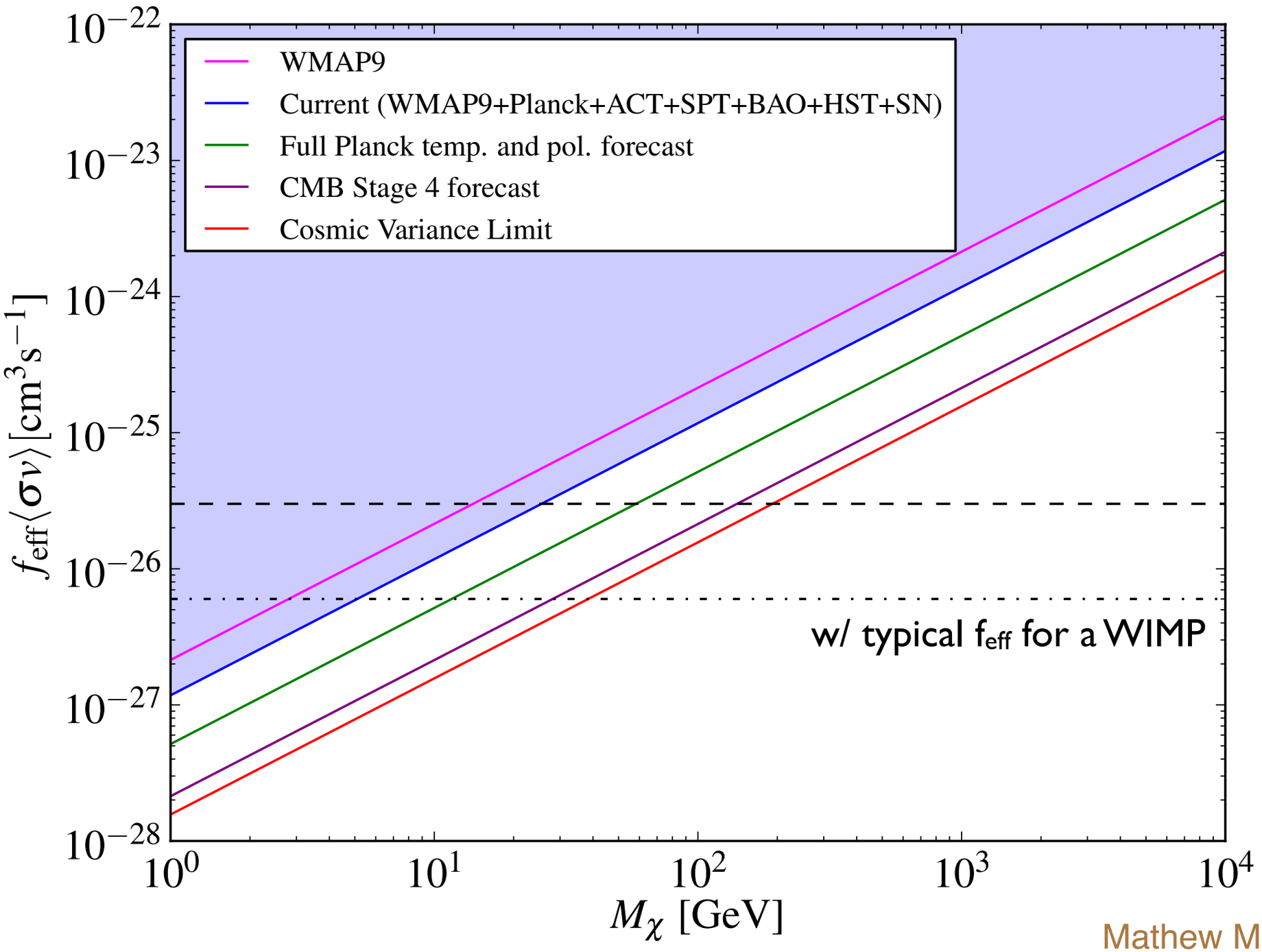
Easy to avoid w/ e.g. (new) light mediators:

e.g. Boehm, Fayet; …

$$\sigma \sim \frac{m_\chi^2}{M^4} \quad \text{or} \quad \sigma \sim \frac{1}{m_\chi^2}$$

small

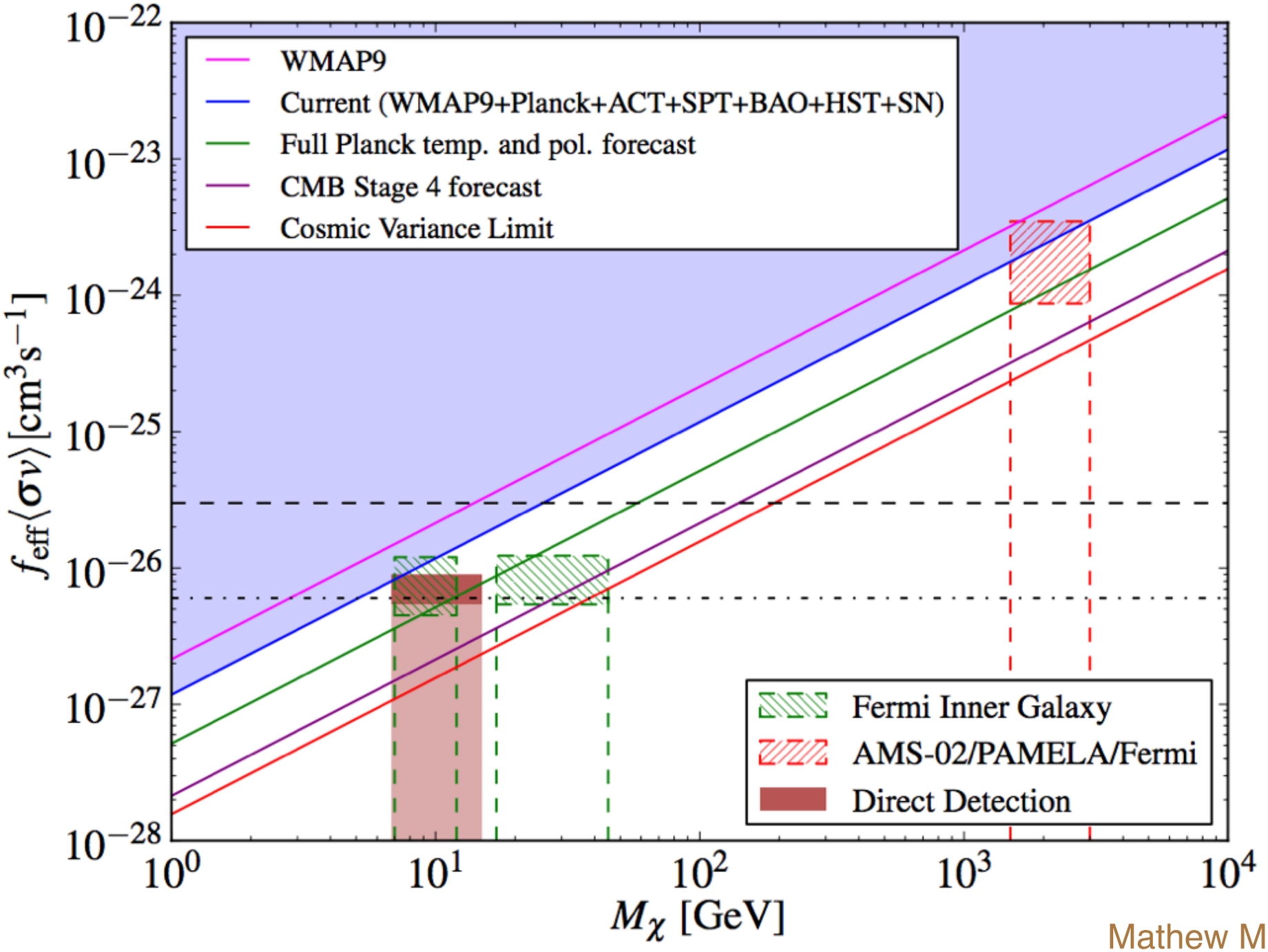
Constraints on DM annihilation from Cosmic Microwave Background



e.g. Galli et.al.; Slatyer, Padmanabhan, Finkbeiner; …

Mathew Madhavacheril, Neelima Sehgal, Tracy Slatyer (1310.3815)

Constraints on DM annihilation from Cosmic Microwave Background



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Mathew Madhavacheril, Neelima Sehgal, Tracy Slatyer (1310.3815)

sub-GeV Dark Matter

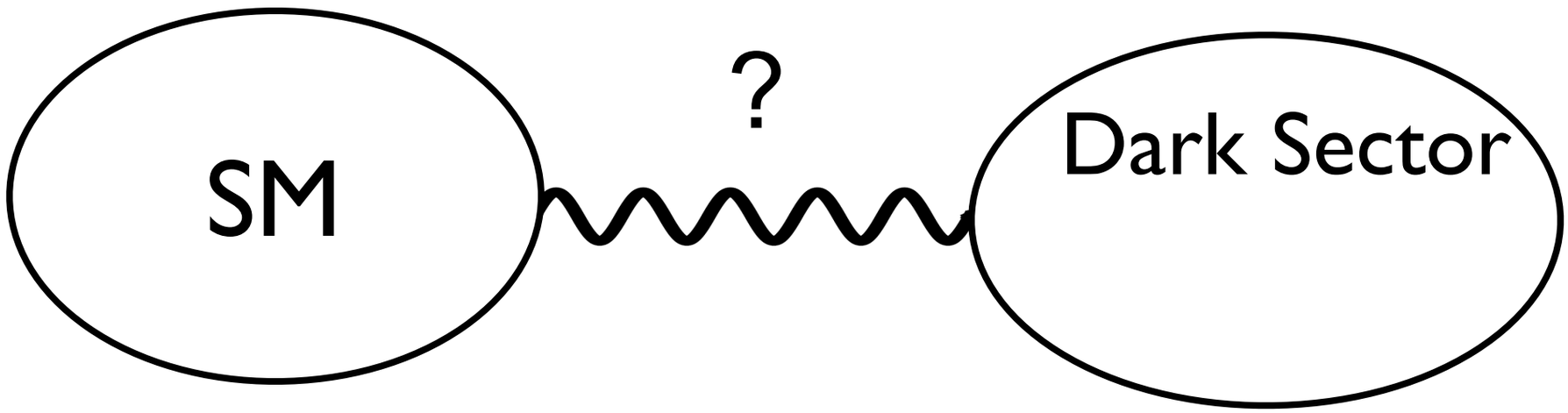
s-wave standard freeze out is disfavored below ~10 GeV

But constraints are model dependent & easy to avoid, e.g.

- p-wave suppressed
- non-thermal production — e.g. Kaplan, Luty, Zurek (2009), Falkowski et.al. (2011)
- asymmetric
- freeze-out with hidden-sector particles (WIMPless DM) — e.g. Feng & Kumar (2008)
- freeze-in — e.g. Hall et.al. (2009)
- sub-dominant
- …

A simplified model

Consider DM, χ, in a hidden sector

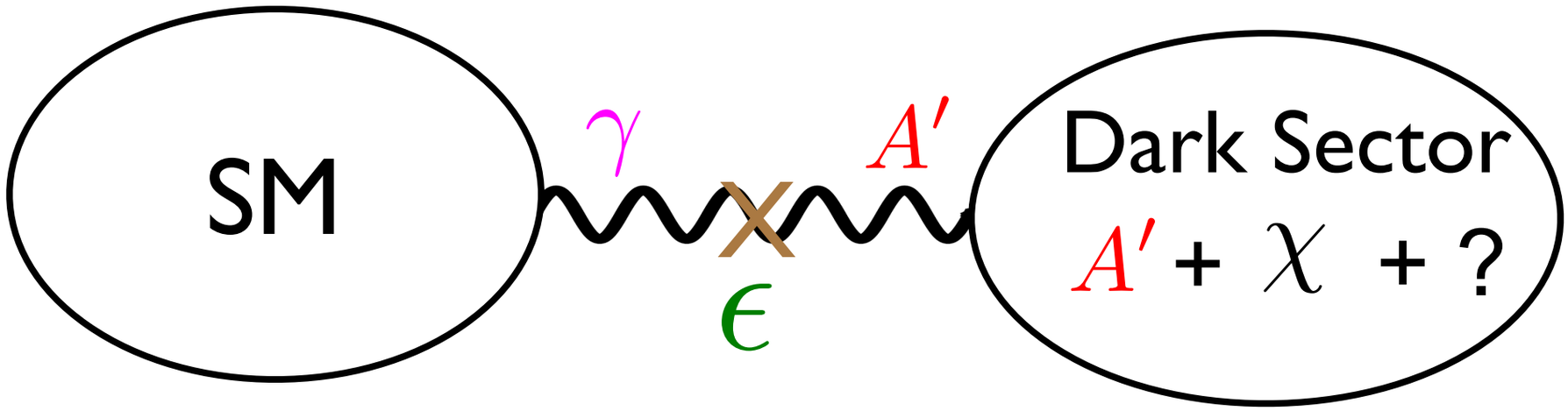


many possible mediators:

(pseudo-)scalar, (pseudo-)vector, …

A simplified model

Consider DM, χ, in a hidden sector



for concreteness, assume χ couples to dark photon A' that mixes with photon via *kinetic mixing*

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

Holdom;
Galison, Manohar

dark sector could be arbitrarily rich, but this is well-motivated and acts as a simplified model

sub-GeV scale can be generated naturally

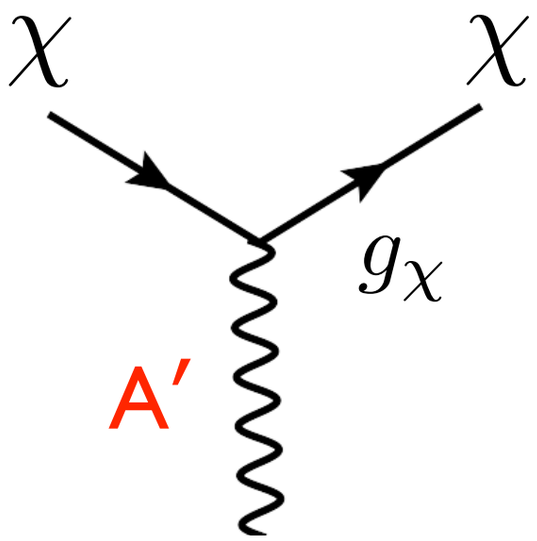
A simplified model

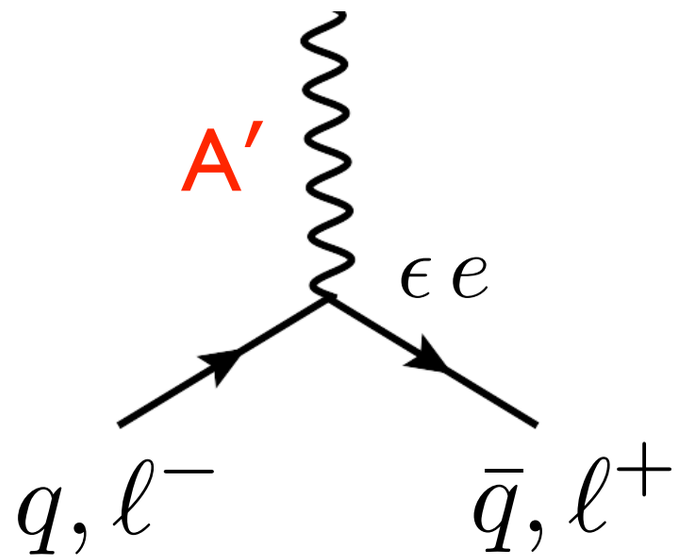
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$$m_\chi \sim m_{A'} \sim \mathrm{MeV} - 5\ \mathrm{GeV}$$

A′ mediates DM-SM interactions

(also DM-DM self-interactions)

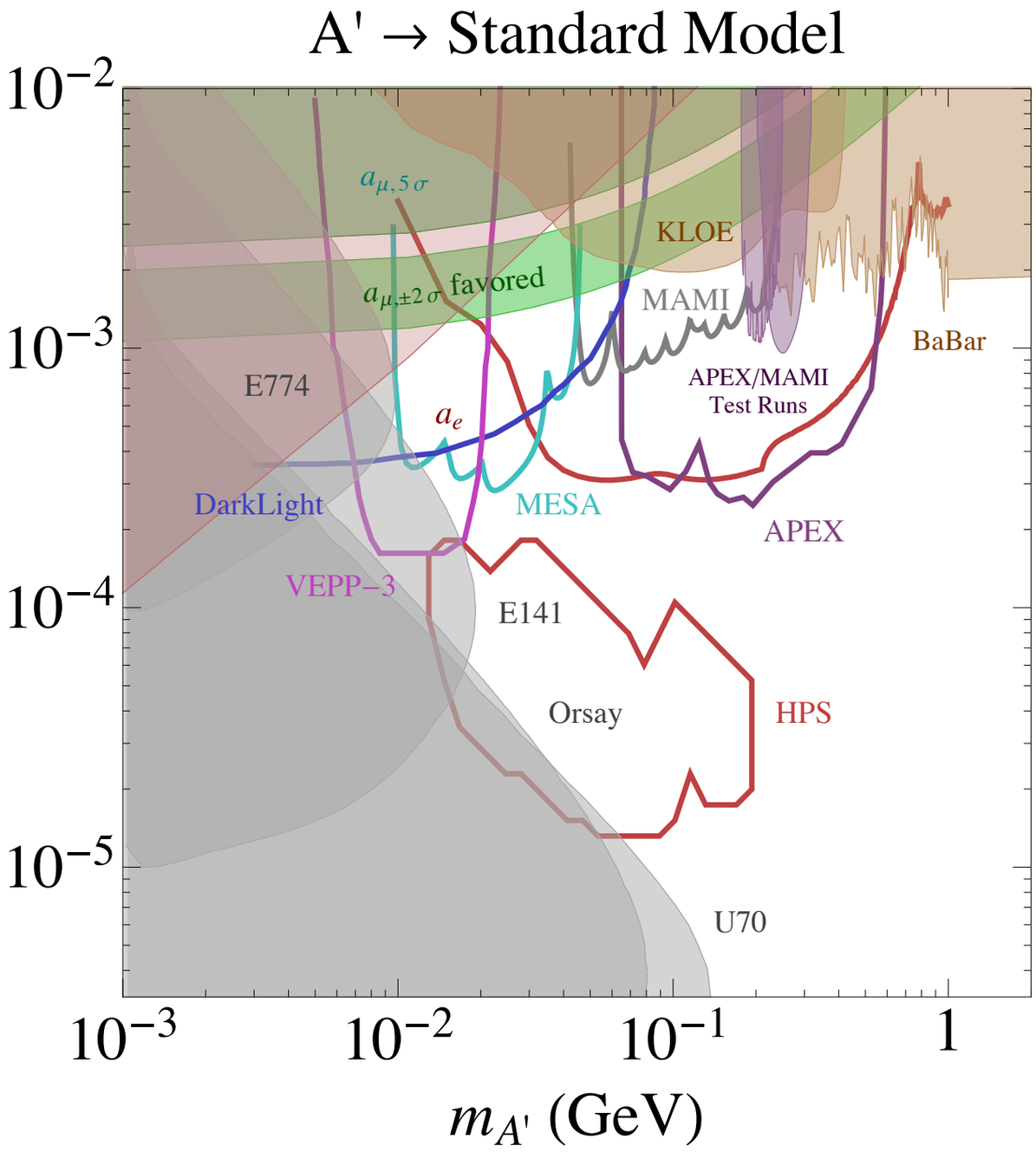


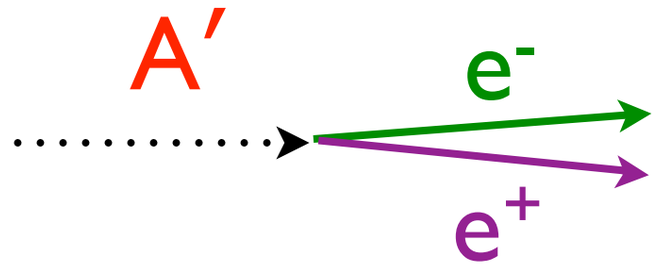


(we're agnostic about how DM abundance is generated)

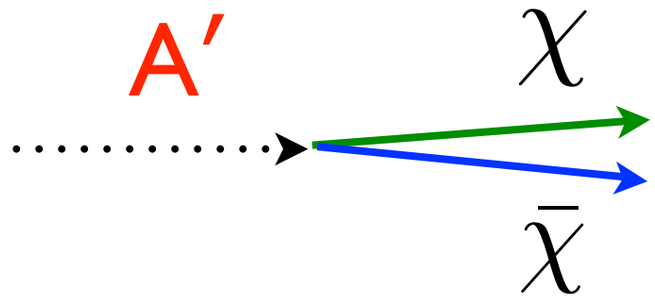
Constraints + prospects on visible A′ decays

If $m_{A'} < 2\,m_\chi$ then A′ decays *visibly*, e.g.





What if A′ decays *invisibly*, to DM?



will come back to this later…

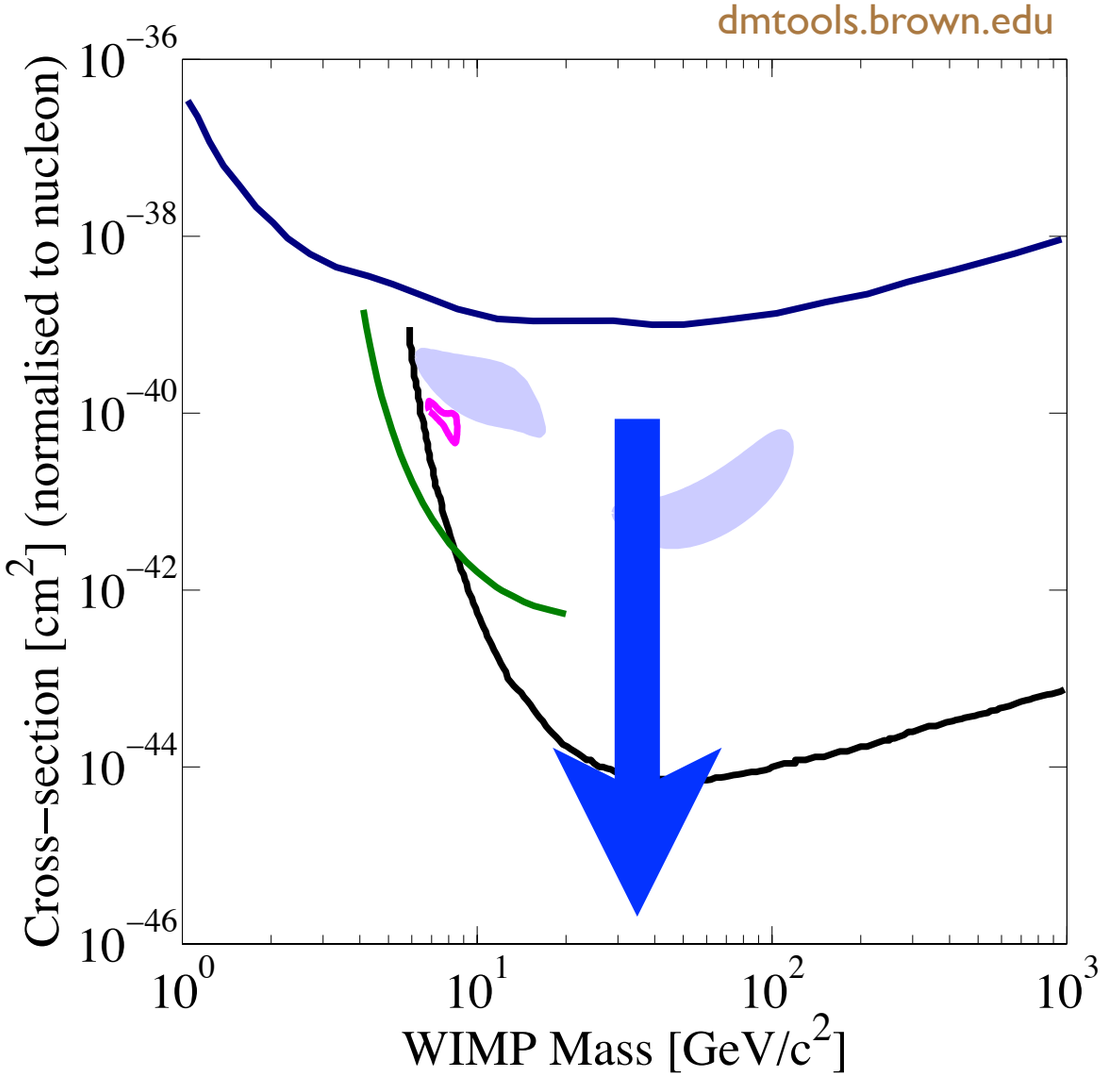
Outline

- some constraints & models
- experimental opportunities
  - direct detection
    - colliders (e^+e^-)
    - fixed-target (p & e^-)
    - indirect detection

The Future of Direct Detection

push lower in cross-section w/ bigger detectors

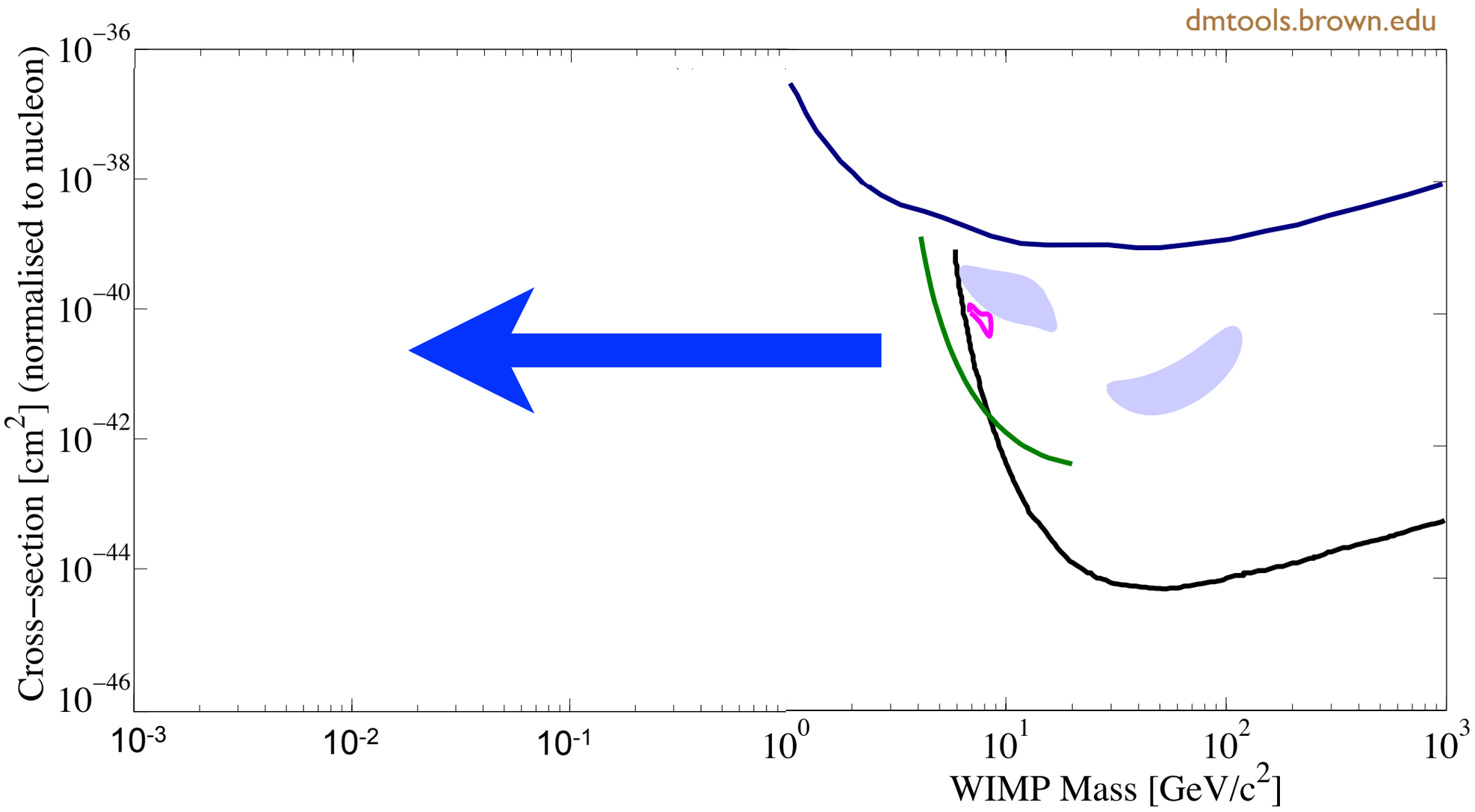
around 2020, this important program will have reached it's full potential



The Future of Direct Detection

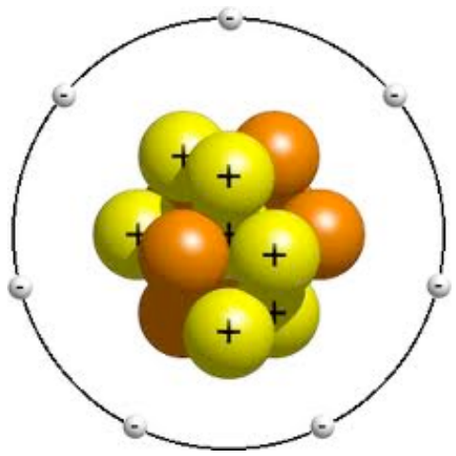
RE, Mardon, Volansky

push *much* lower in mass by considering
DM scattering off *electrons* or *molecules*



Cannot use elastic nuclear recoils for detection

Recall: Heavy DM

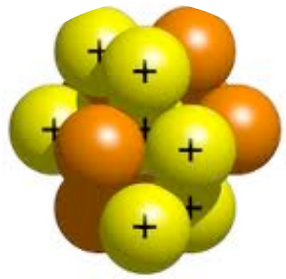


Atom

Cannot use elastic nuclear recoils for detection

Recall: Heavy DM

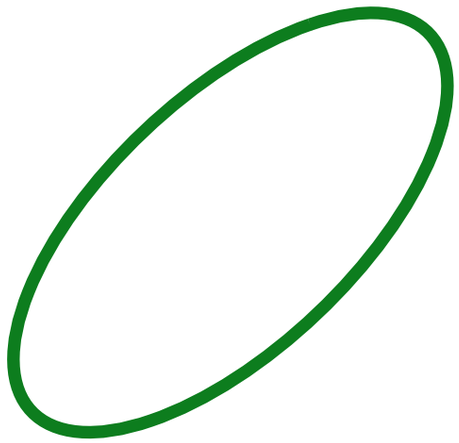
DM



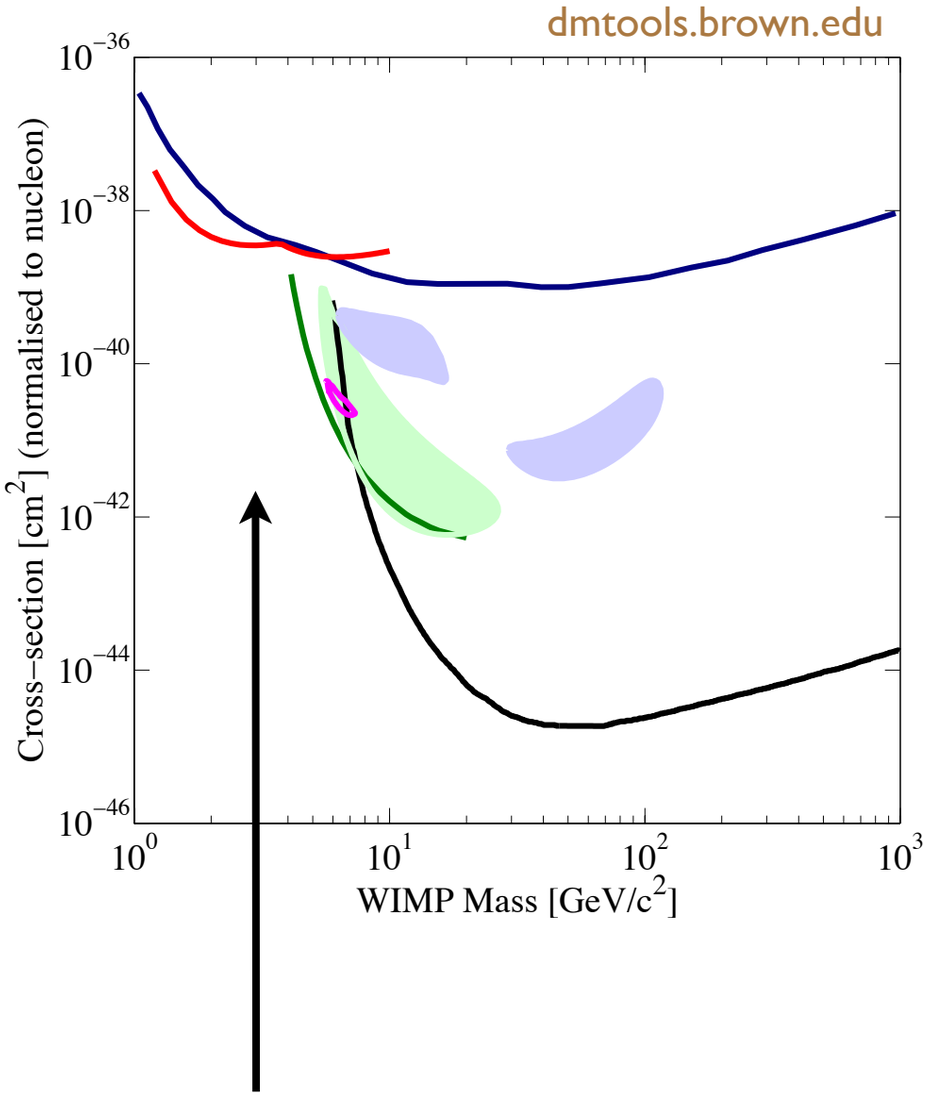
large recoil…
“no problem”

Cannot use elastic nuclear recoils for detection

nuclear recoil energy

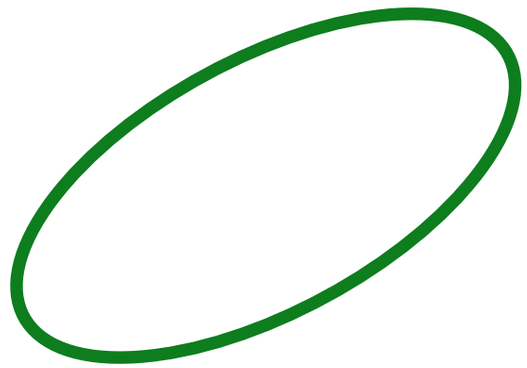


for sub-GeV DM, nuclear recoil energy is too small to produce visible scintillation, ionization, or phonon signal



limits absent below ~few GeV

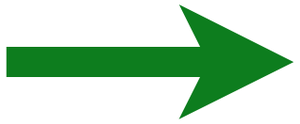
But, total energy available is much larger:



enough energy to excite or ionize an atom,
or dissociate molecules

(just not from nuclear recoils!)

How to detect sub-GeV DM



- ionization

  (DM-electron scattering)

- excitation

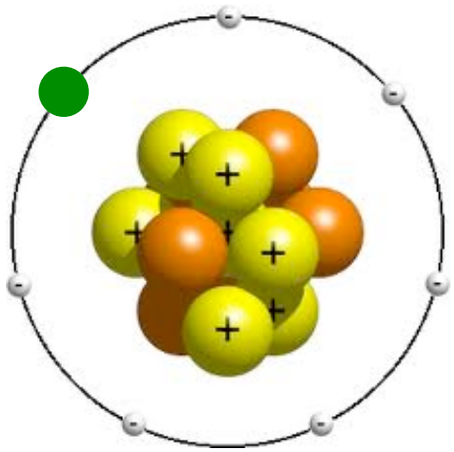
  (DM-electron scattering)

- molecular dissociation

  (DM- or ν-nucleon scattering)

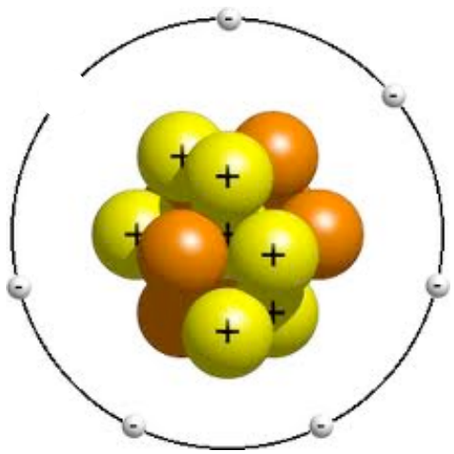
Ionization: DM scattering off electron

DM



Atom

Ionization: DM scattering off electron



Atom

threshold ~ 10 eV

Signal: single (or few) electron events

XENON10/100, LUX, DarkSide, … could detect this!

A Proof of Principle

(for ionization signal)

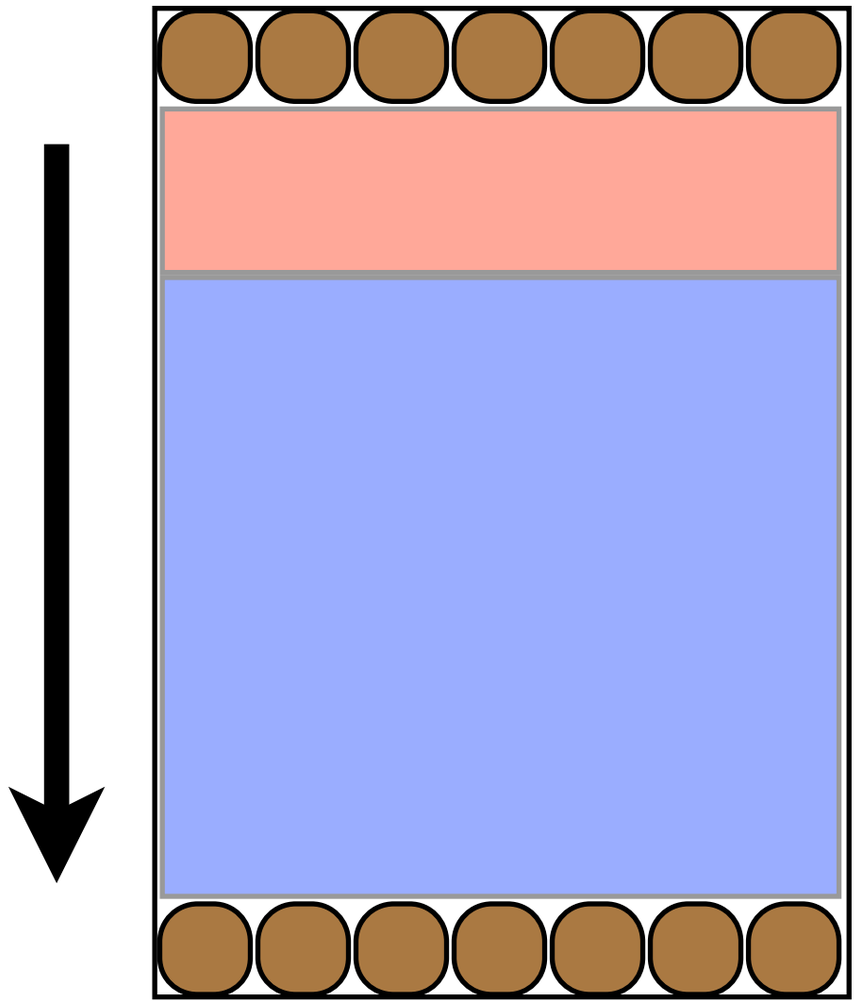
"First direct detection limits on sub-GeV Dark Matter from XENON10"

RE, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky

(1206.2644, PRL)

The XENON10 experiment

detector schematic



two-phase xenon time projection chamber

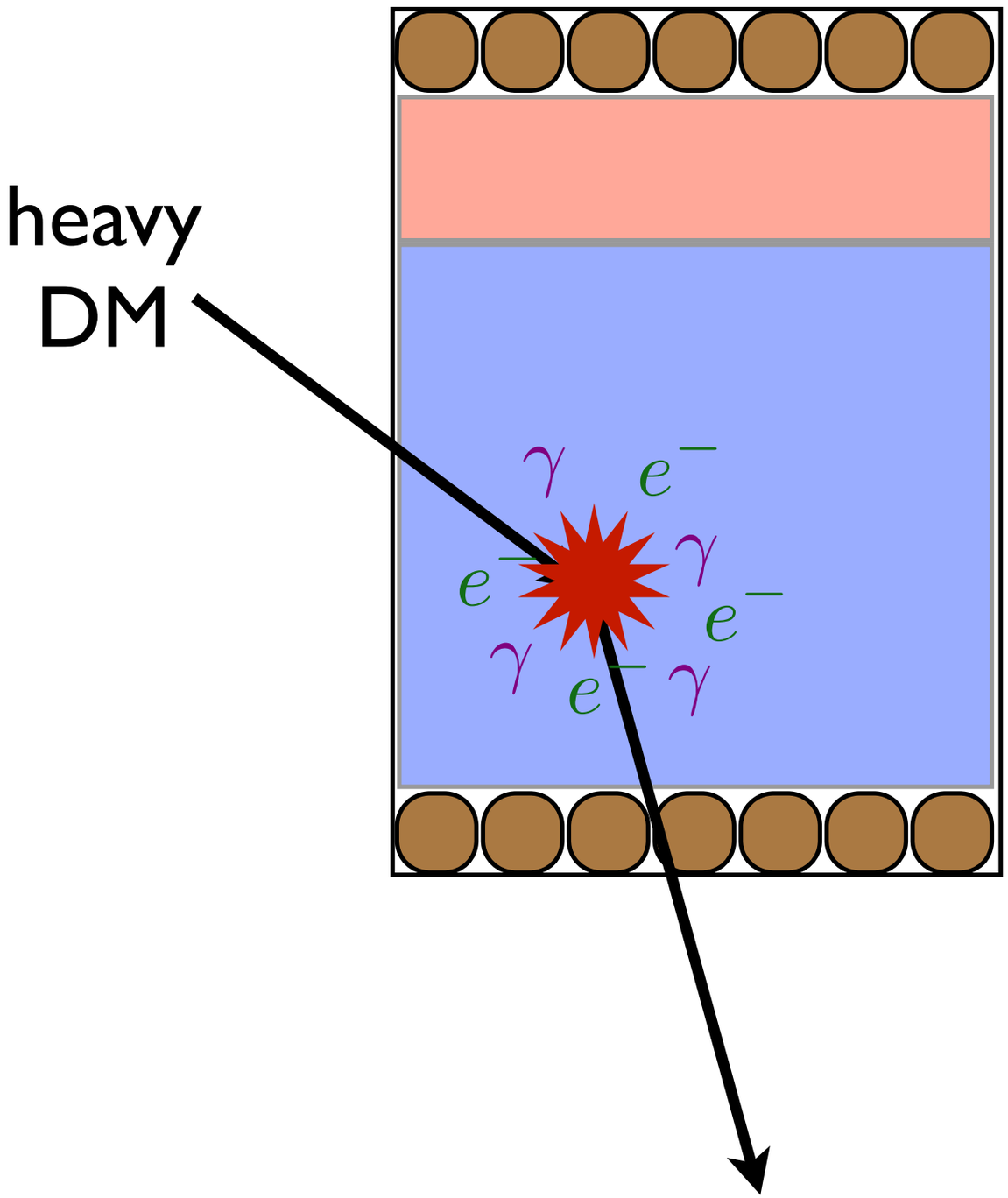
operated for ~1 year in 2006/2007

How to detect usual WIMPs

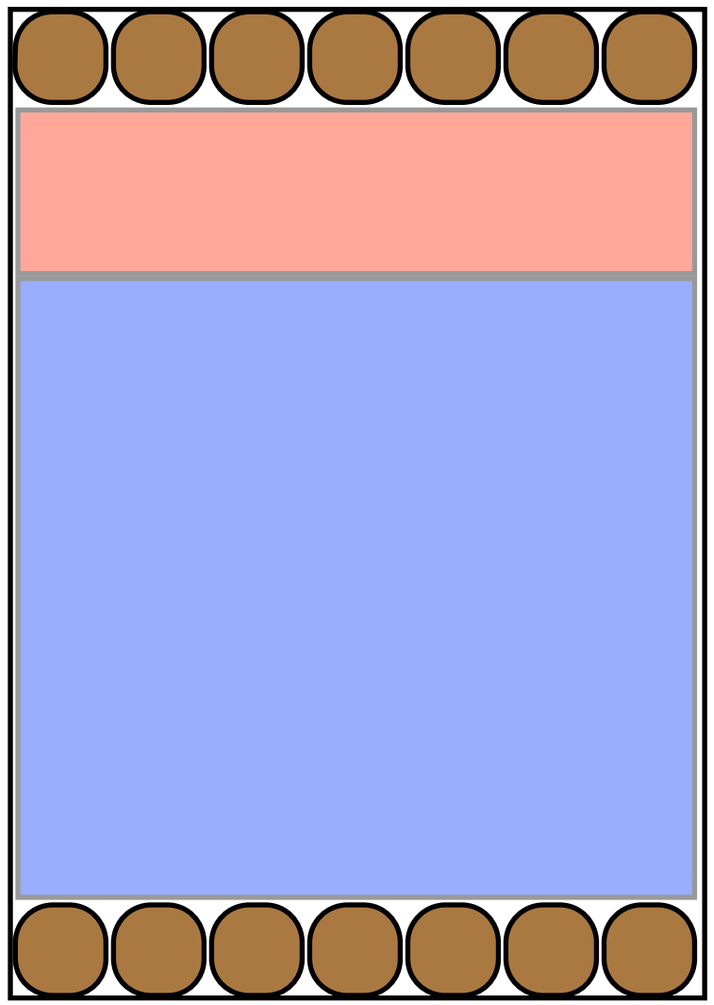
$$\mathrm{Xe} \rightarrow \mathrm{Xe}^{*}, \mathrm{Xe}^{+}$$

produces photons and electrons

Two types of signal:



How to detect usual WIMPs



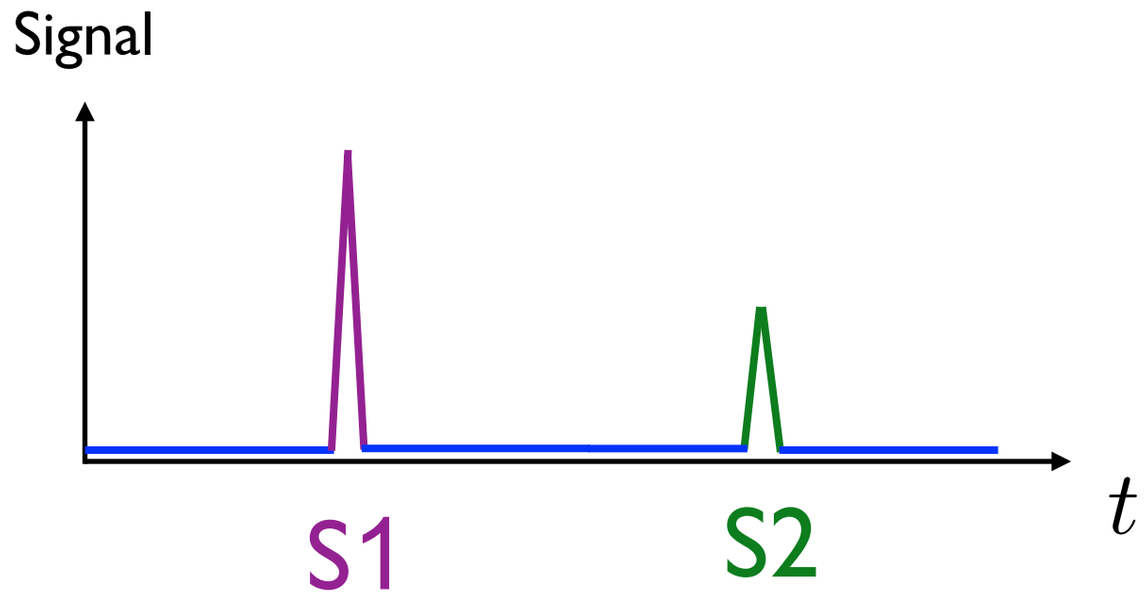
$$\mathrm{Xe} \rightarrow \mathrm{Xe}^{*}, \mathrm{Xe}^{+}$$

produces photons and electrons

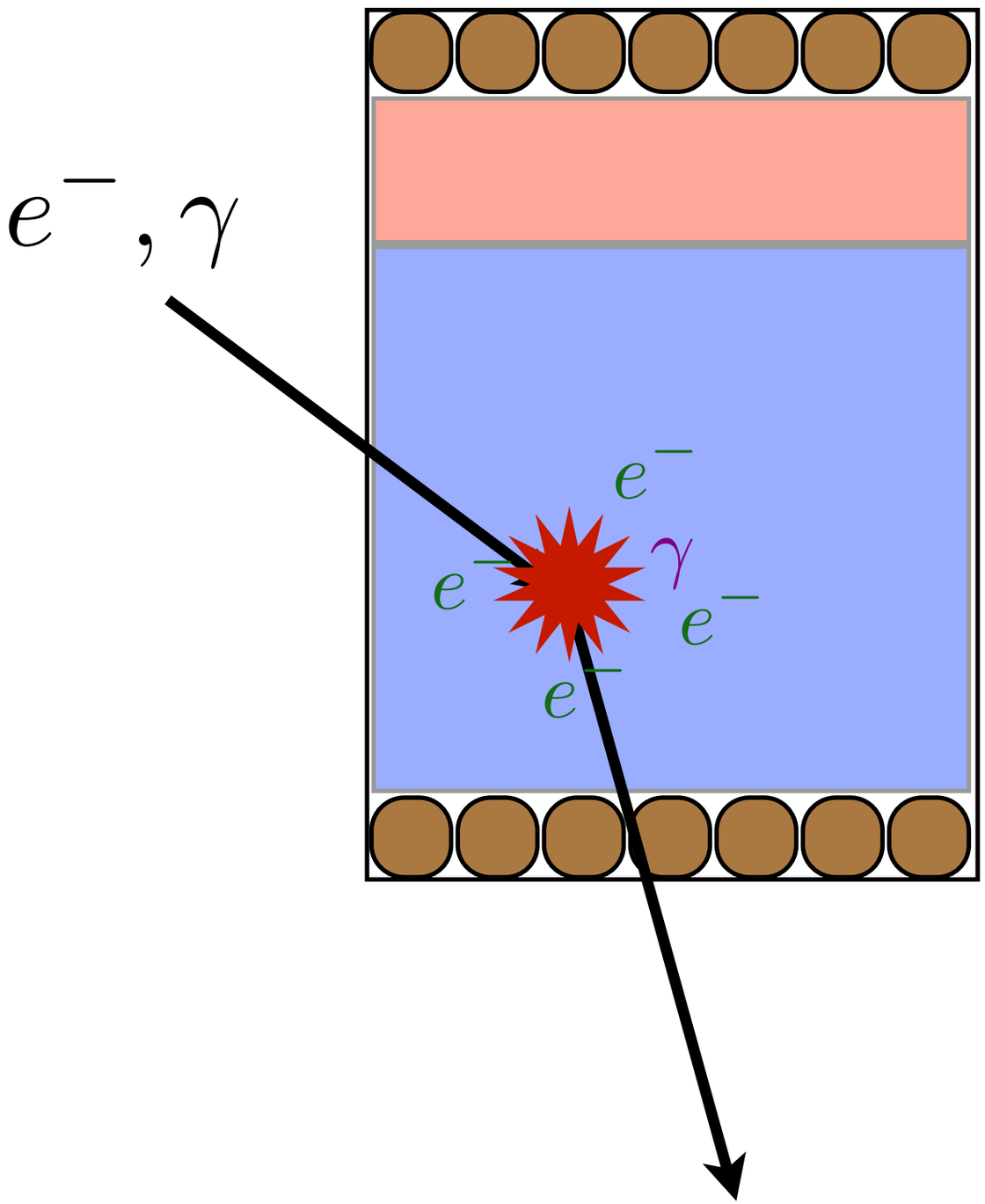
Two types of signal:

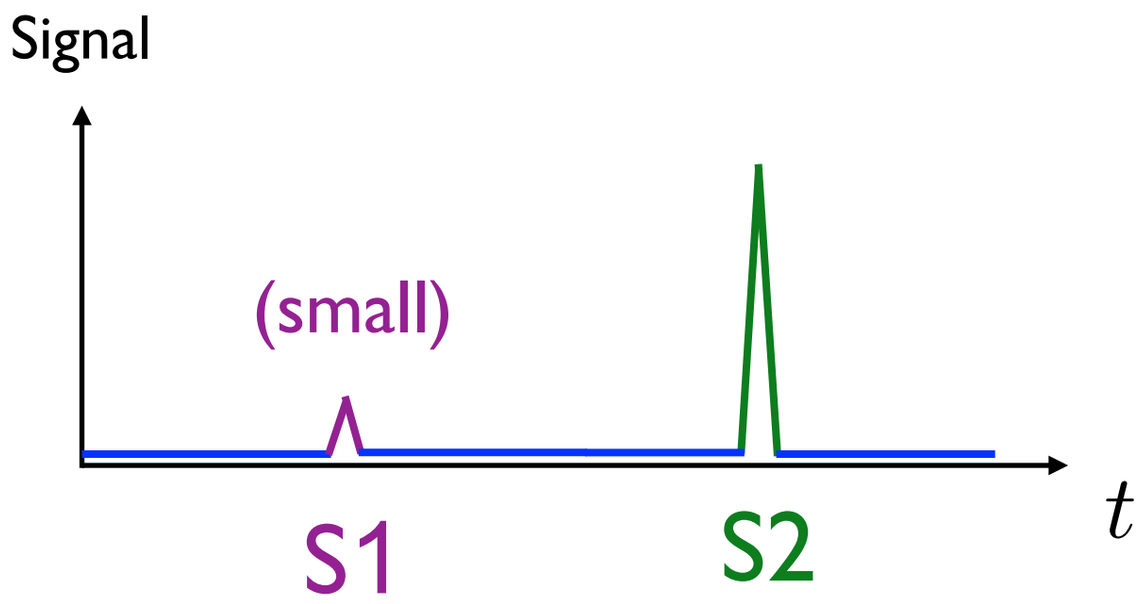
S1: prompt scintillation

S2: proportional scintillation (from ionization)

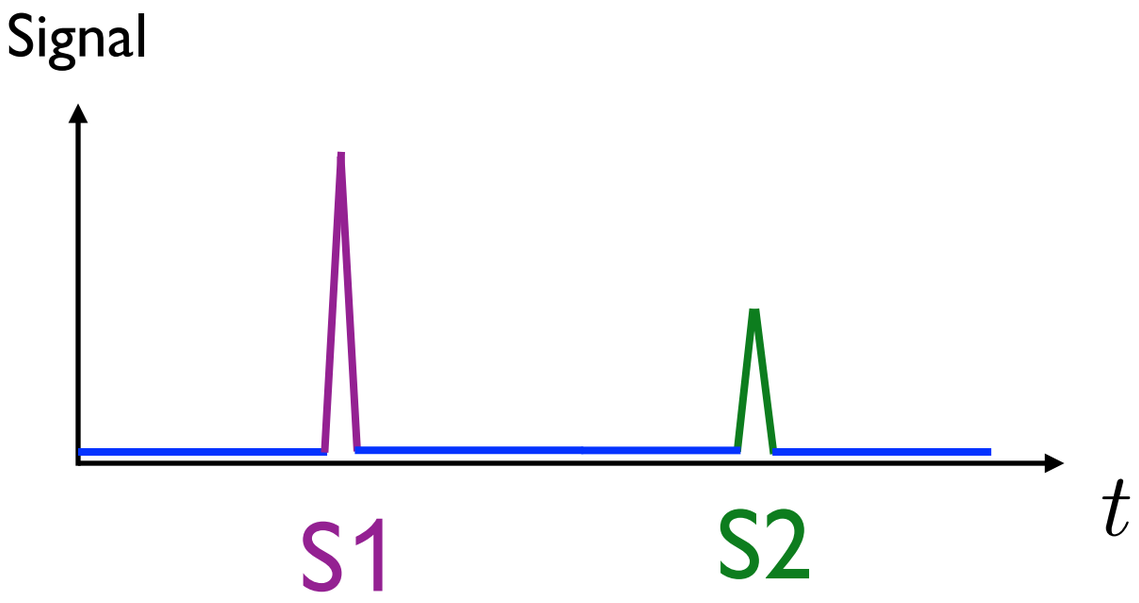


Background events

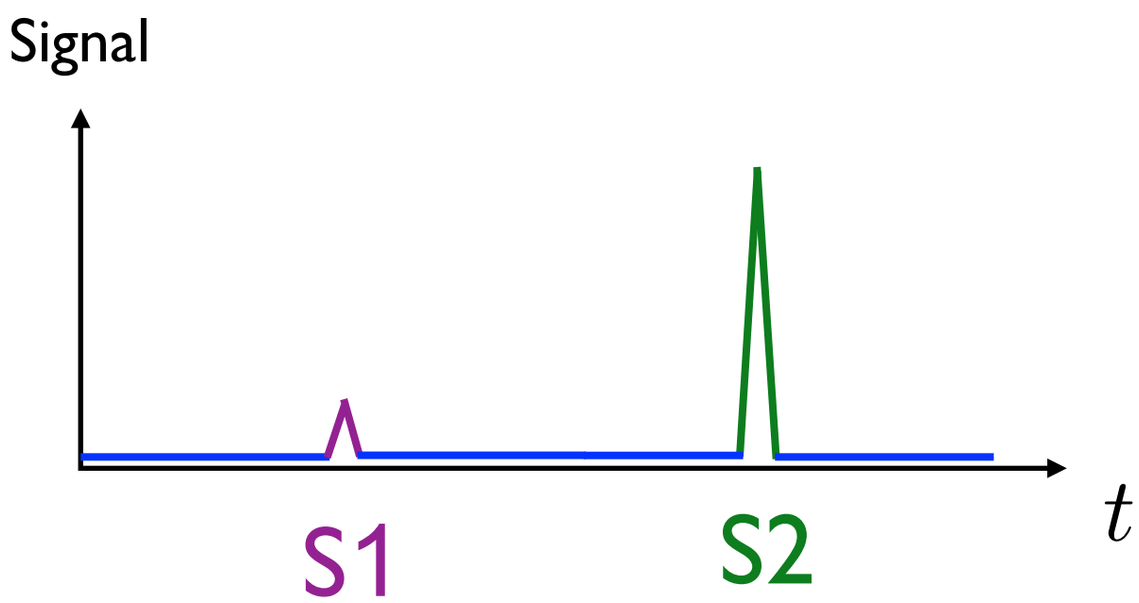




Usual WIMP searches



WIMP

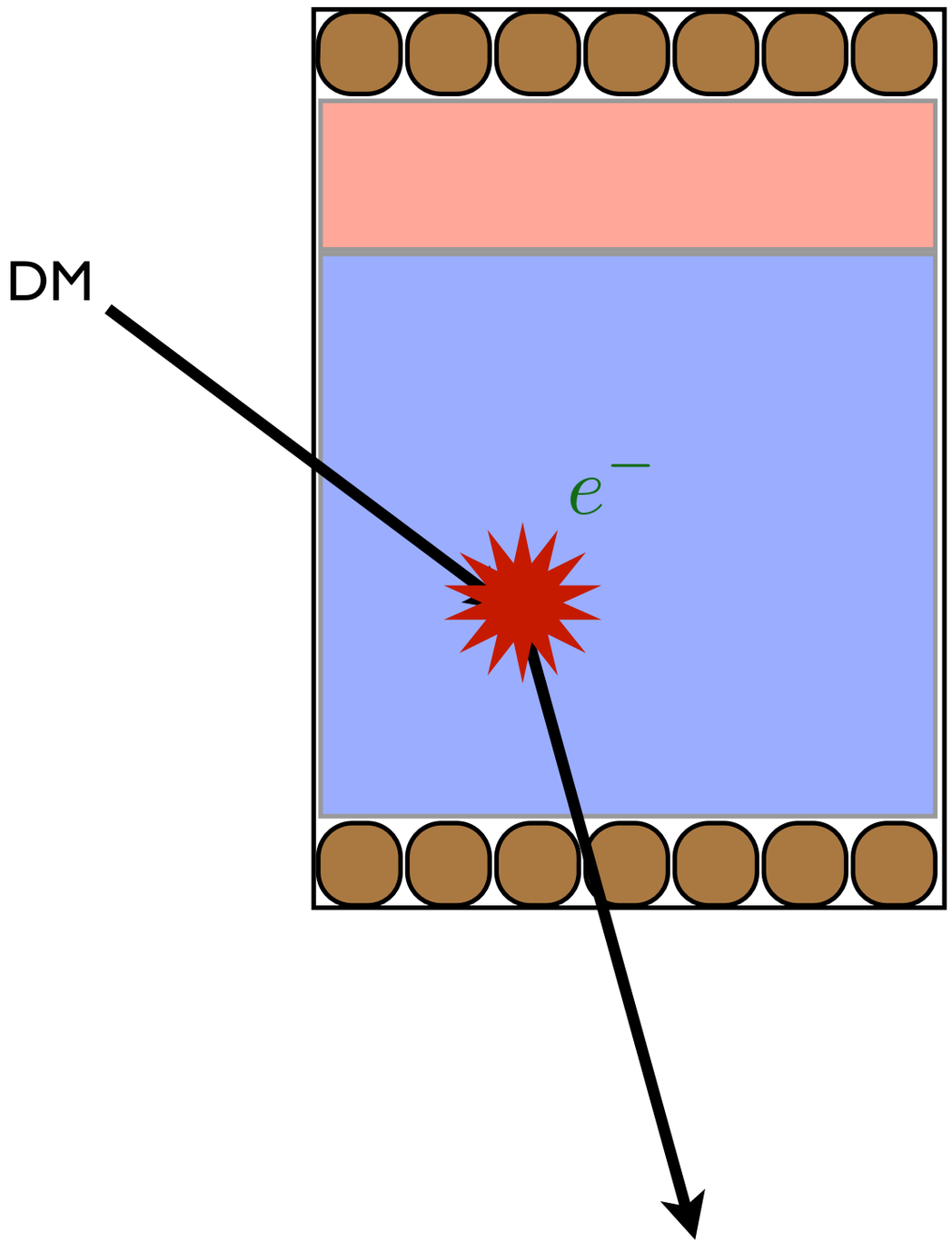


background

$$\left(\frac{S_2}{S_1}\right)_{\mathrm{WIMP}} \ll \left(\frac{S_2}{S_1}\right)_{\gamma}$$

What about light DM ?

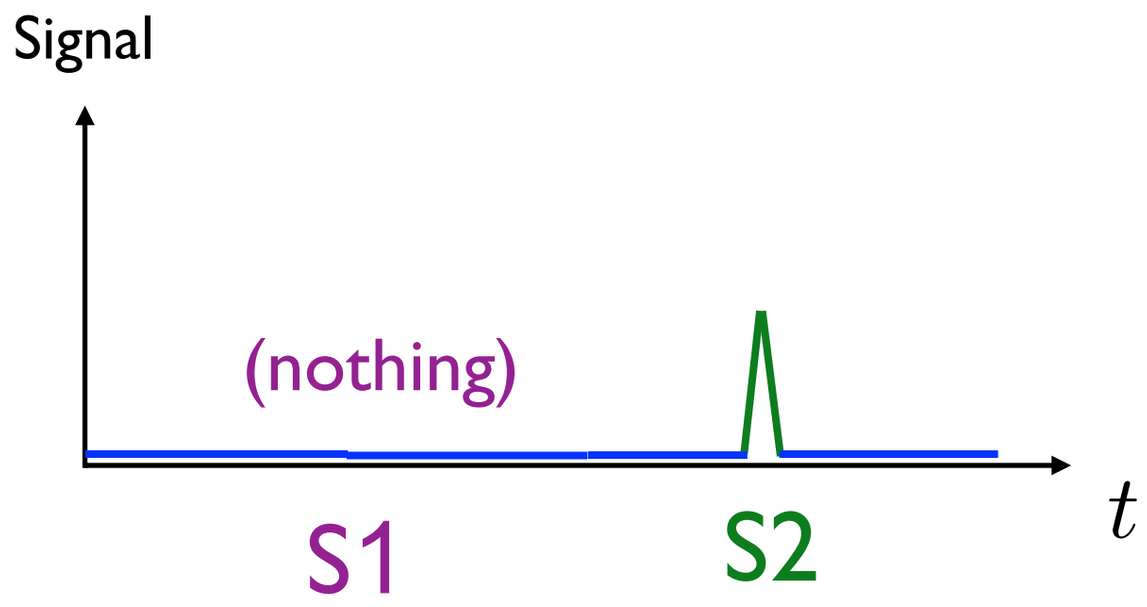
Light Dark Matter hitting an electron



on average, a single electron
produces about 27
detected photo-electrons

S1: not measurable

S2: small signal

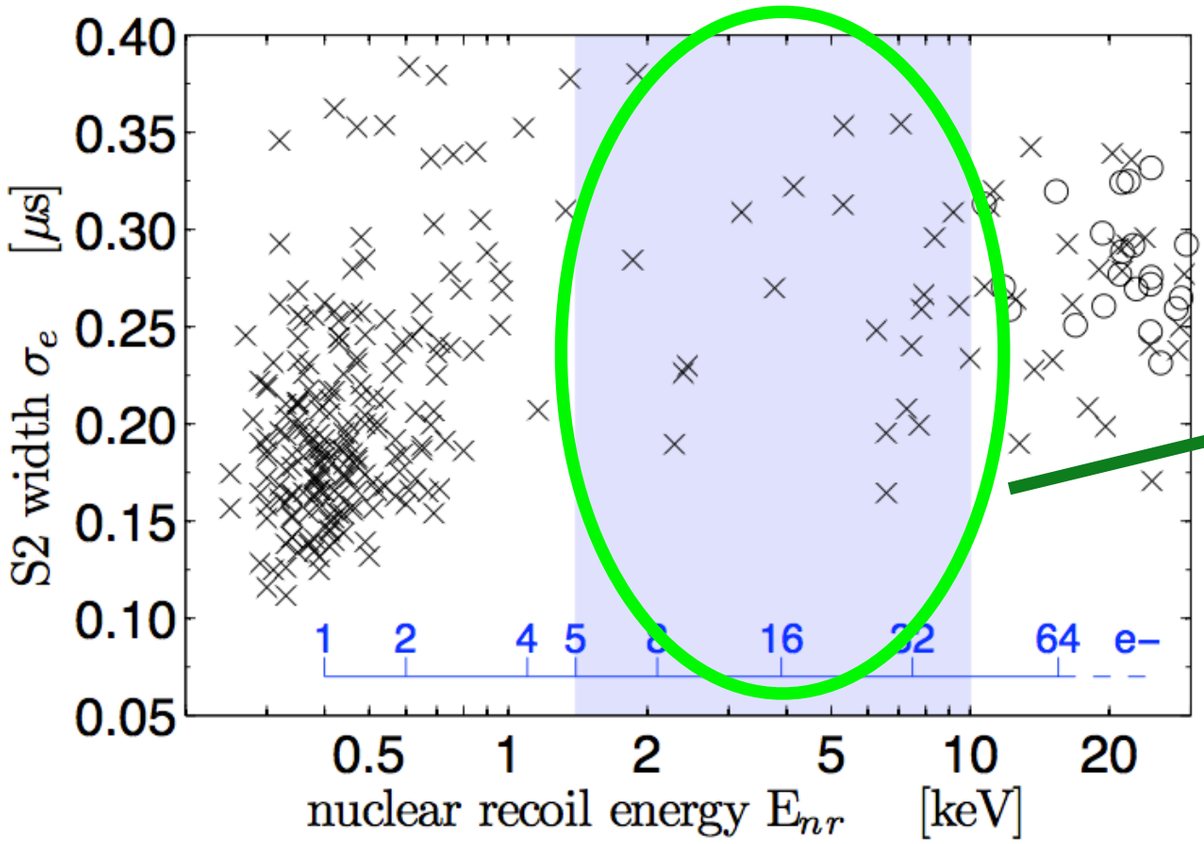


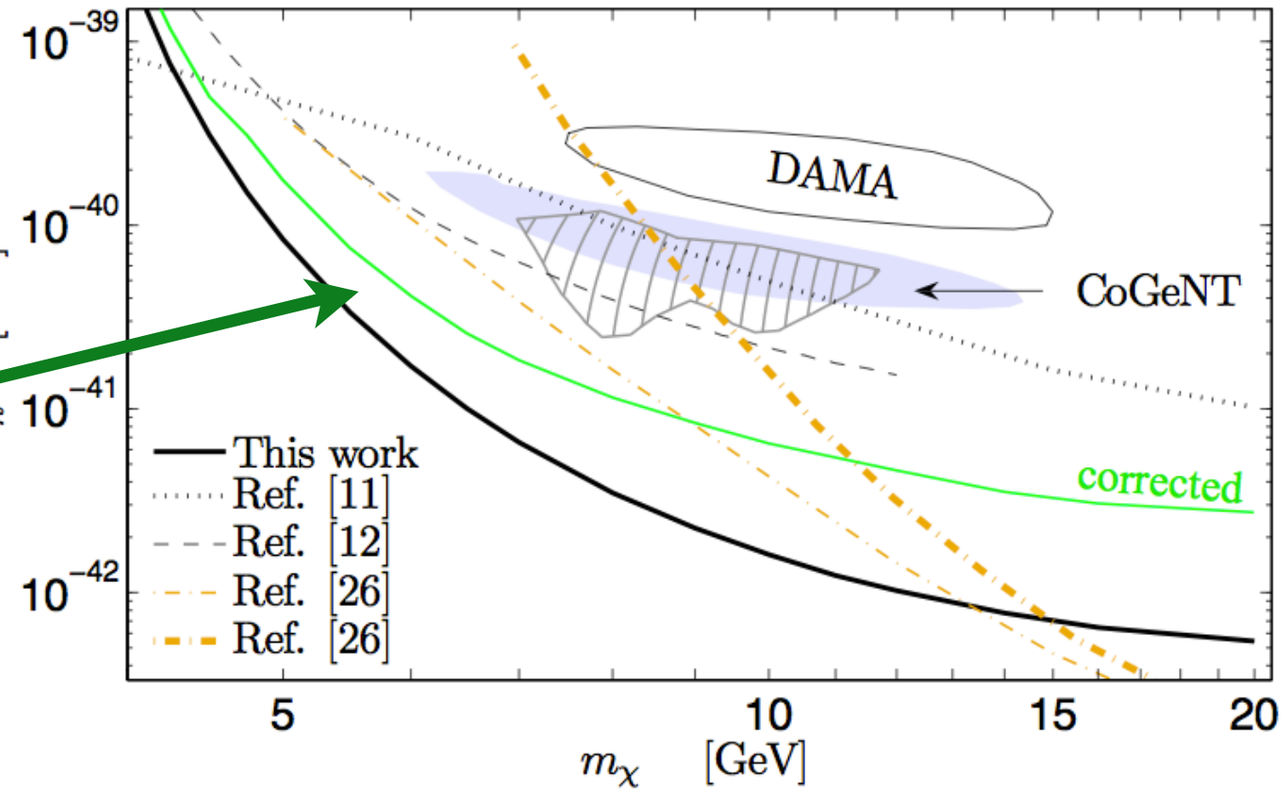
The XENON10 data

XENON10 was set-up to trigger on single e^- events (with S1 = 0) for *only 12.5 days* in 2006

Can use this data to set the first direct detection limits on sub-GeV DM

The XENON10 data

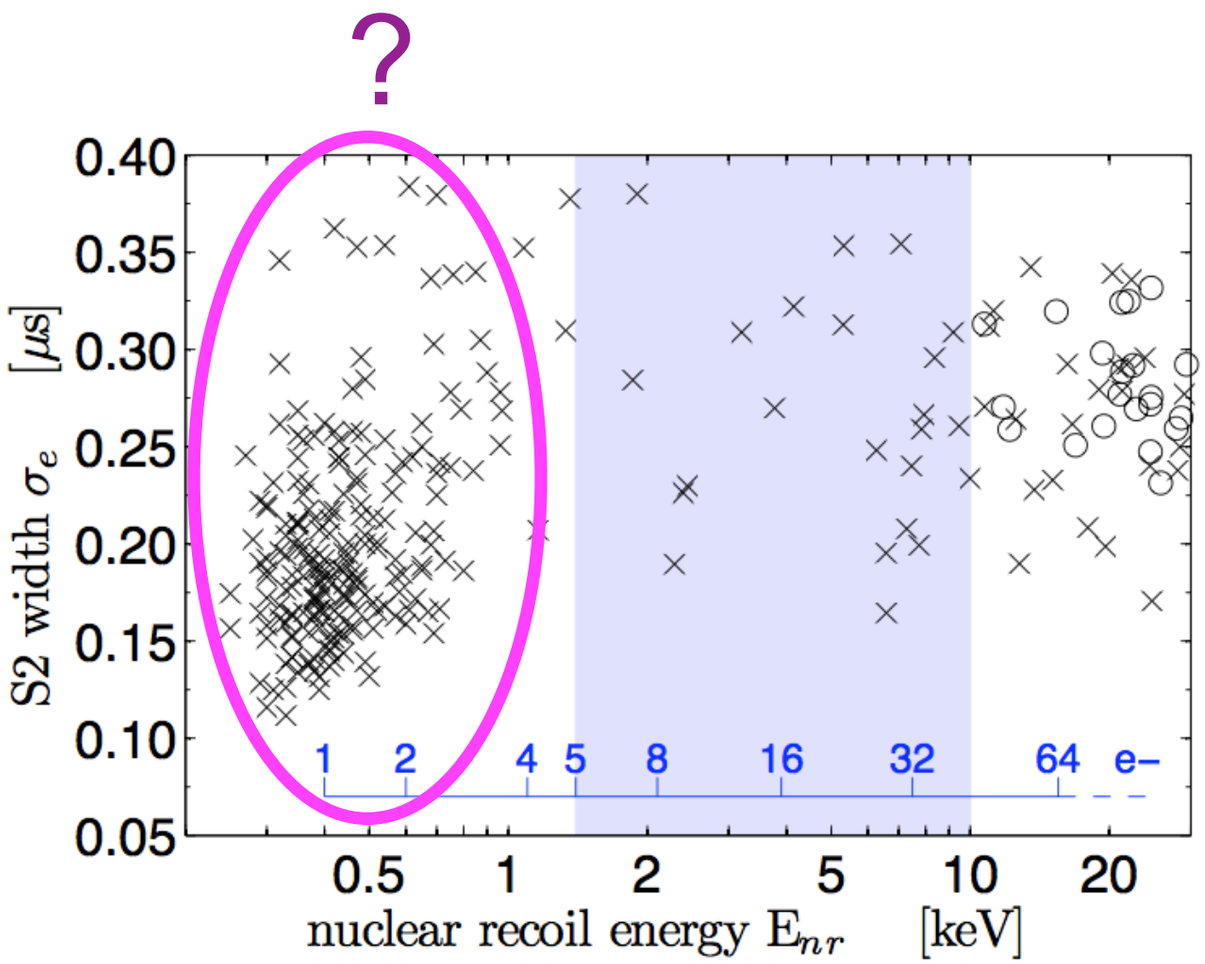


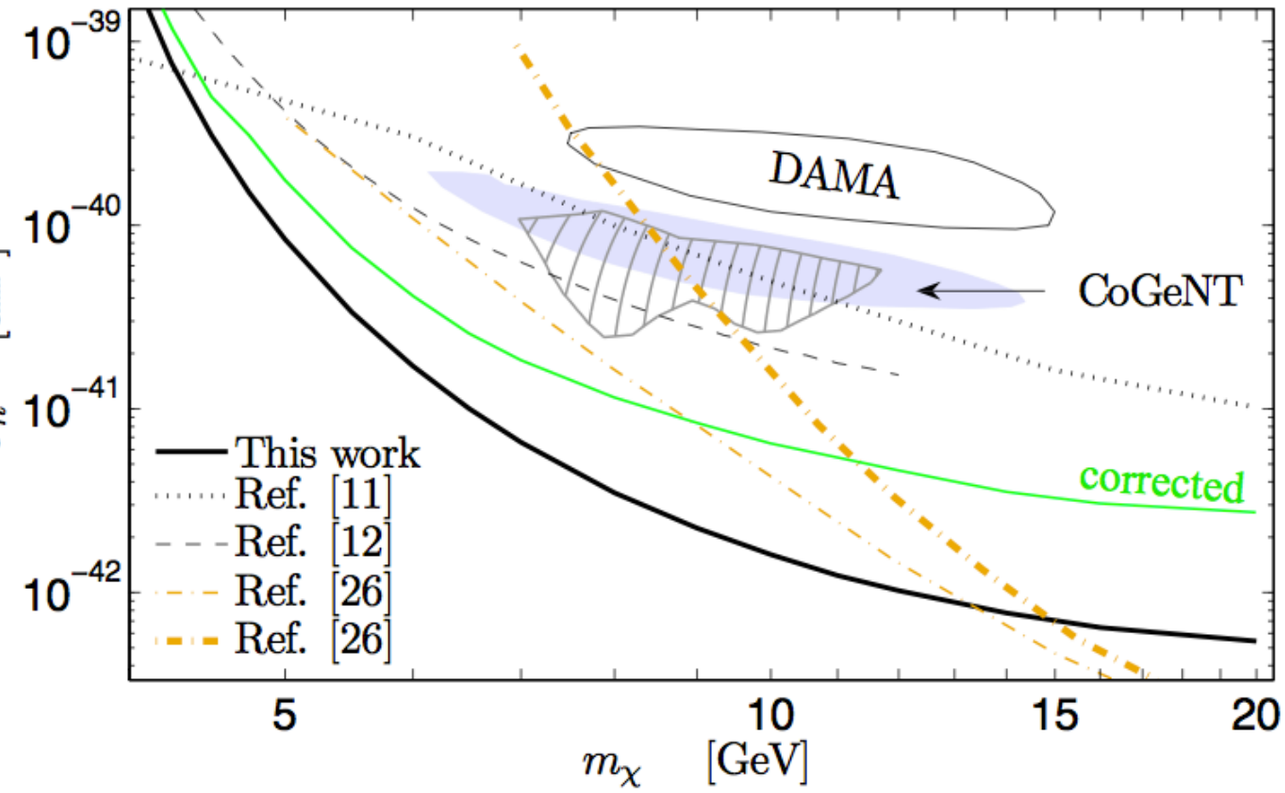


XENON10 used this data to set limits on ~10 GeV DM from *nuclear recoils*, constraining DAMA/CoGeNT region

(2011)

The XENON10 data



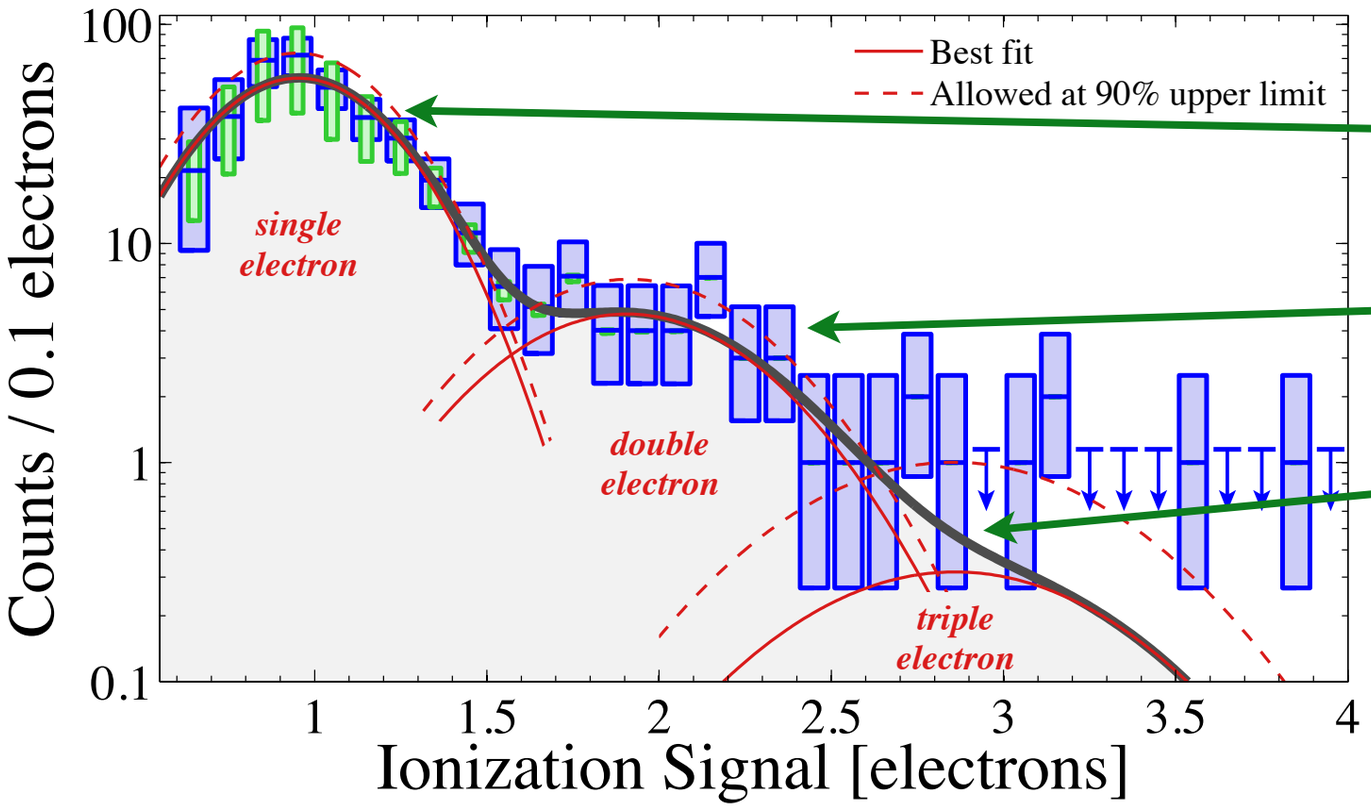


XENON10 used this data to set limits on ~10 GeV DM from *nuclear recoils*, constraining DAMA/CoGeNT region

(2011)

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



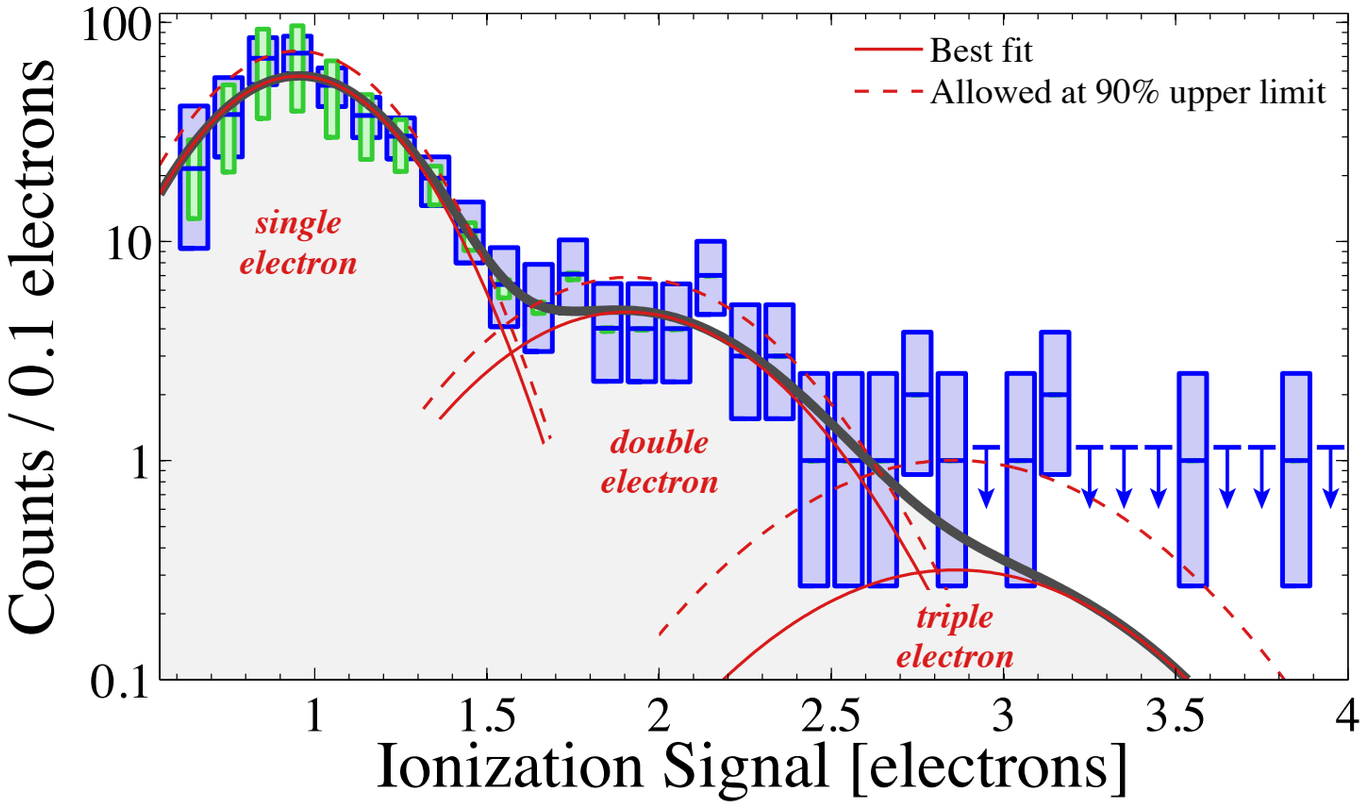
1-electron events

2-electron events

3-electron events

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed

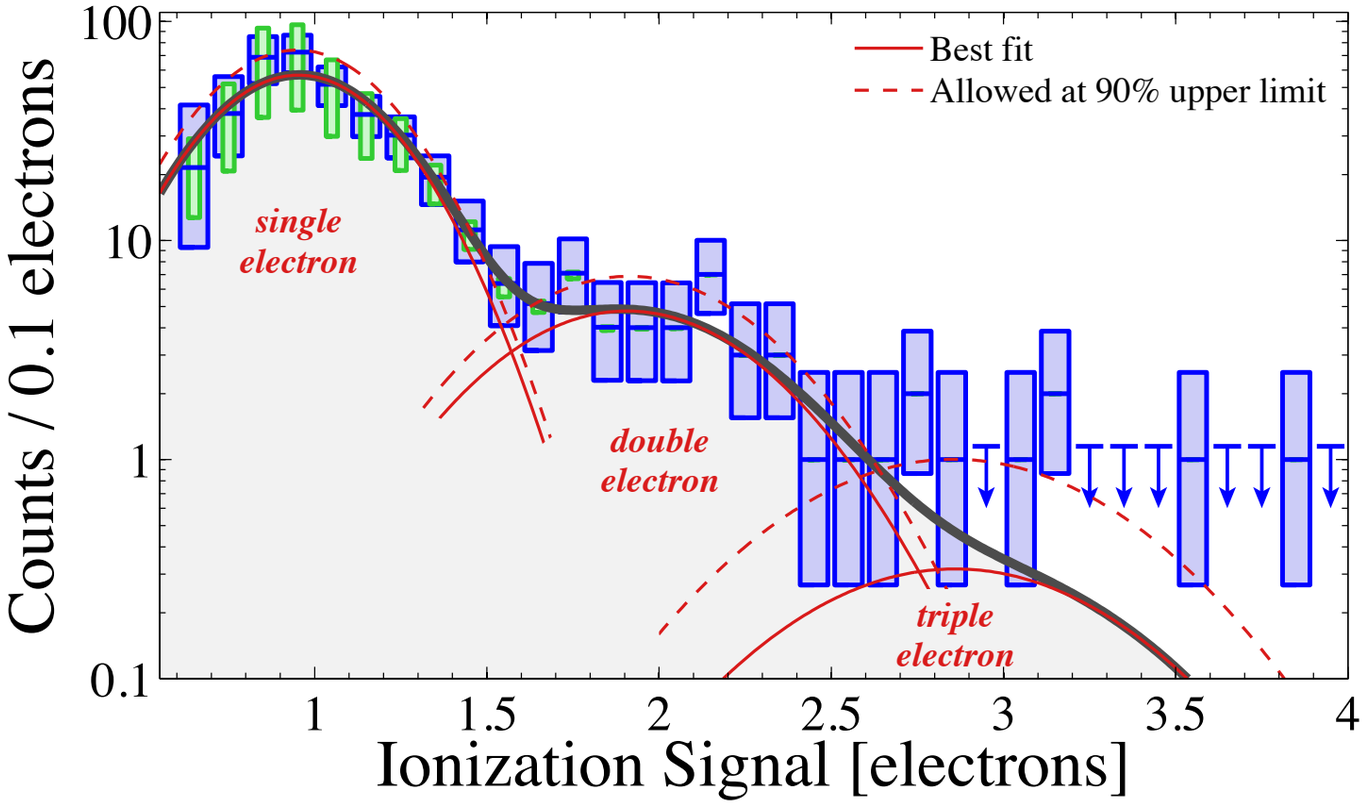


What *are* these events ?

several possibilities exist, but virtually no attempt was made to understand their origin

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



90% c.l. upper bounds on rates:

1 e^-: 34.5 counts/kg/day

2 e^-: 4.5 counts/kg/day

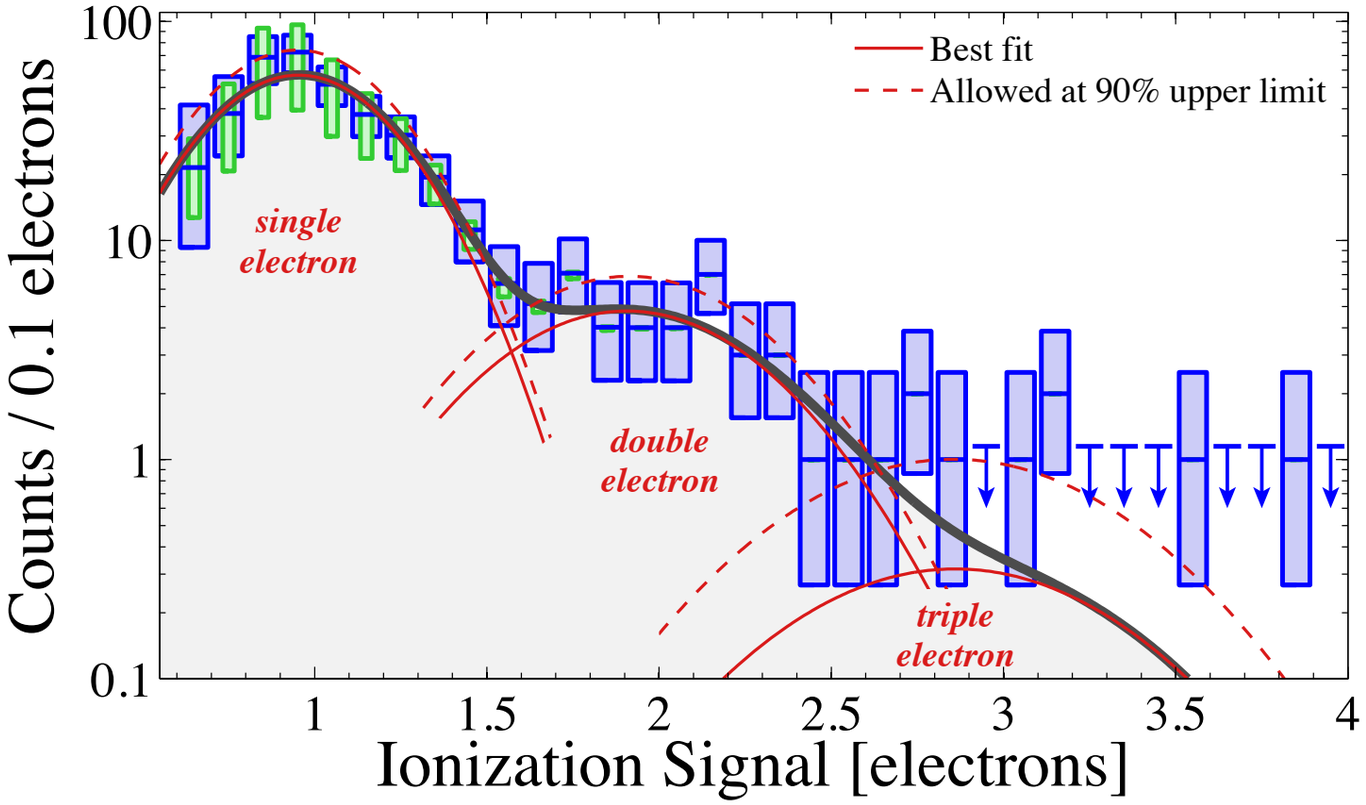
3 e^-: 0.83 counts/kg/day

Note: DM *can* give rise to 2- and 3-electron events:

- outgoing e^- can ionize further e^-'s
- ionizing an inner-shell e^- gives a de-excitation photon that can ionize other e^-'s

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



90% c.l. upper bounds on rates:

1 e^-: 34.5 counts/kg/day

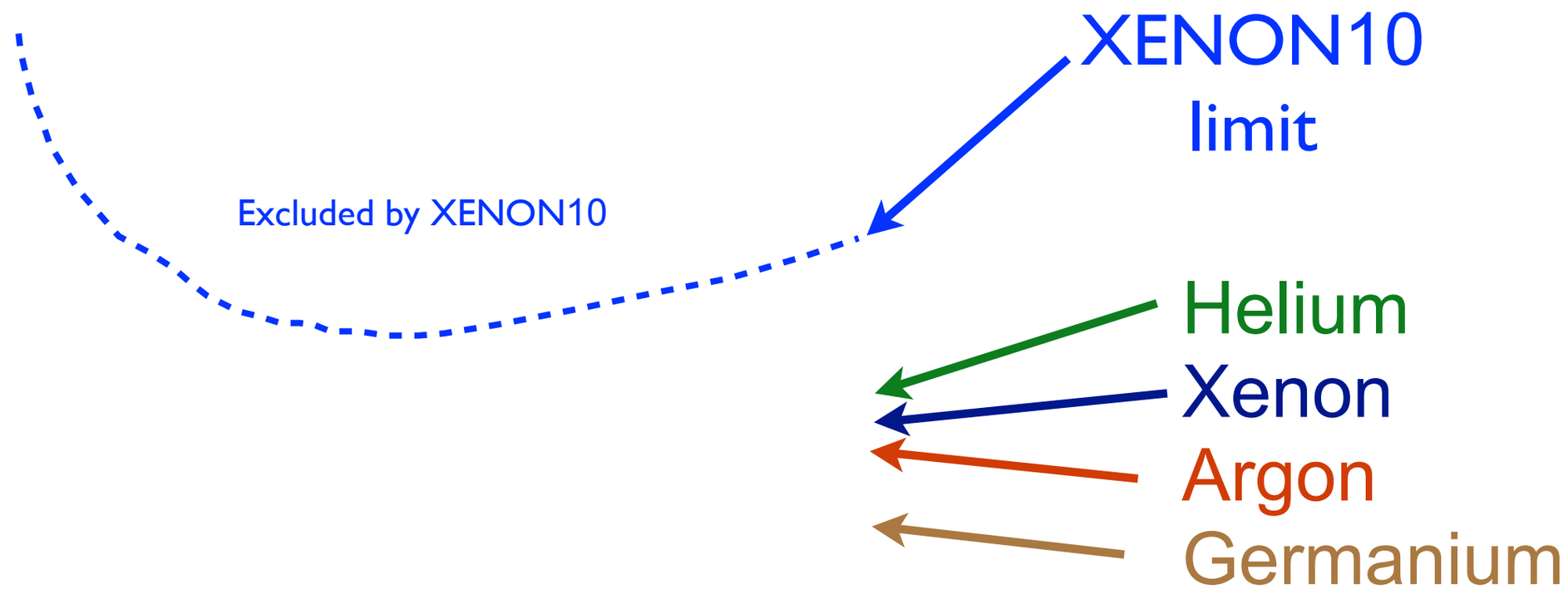
2 e^-: 4.5 counts/kg/day

3 e^-: 0.83 counts/kg/day

since number of 3-electron events is so small, this sets the best limit for somewhat heavier DM

First direct detection limits on sub-GeV DM

Future?



1 kg-year

XENON100 & LUX can do this analysis!

A proposal was submitted to XENON100

XENON100 (Budnik) w/ RE, Mardon, Volansky

Possible sensitivity, assuming 0.02 events kg^{-1} day^{-1}

dashed: annual modulation

realistic???

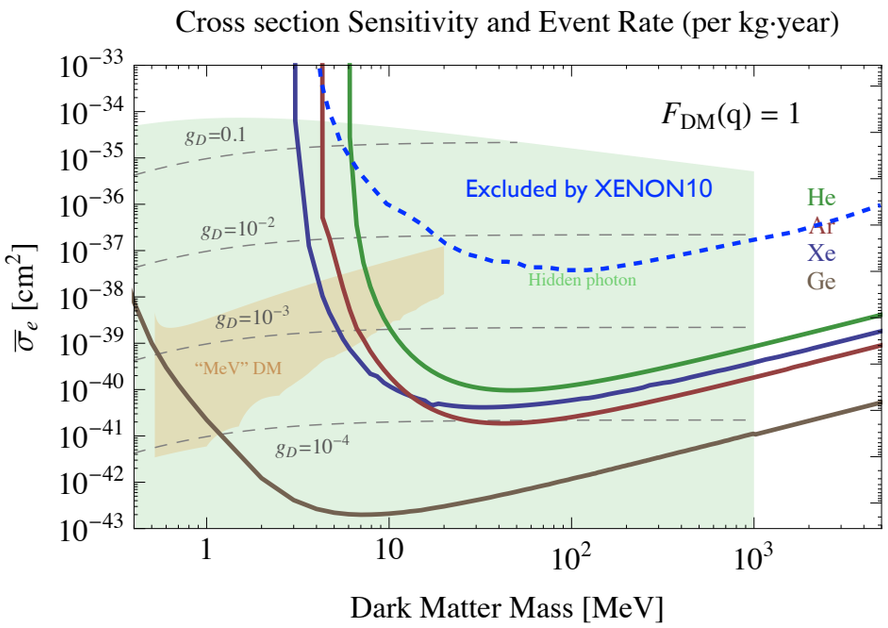
need to do analysis to know!

Future?

1 kg-year

NB: semi-conductors (e.g. Ge)

$\Longrightarrow$ reach to *very* low masses !



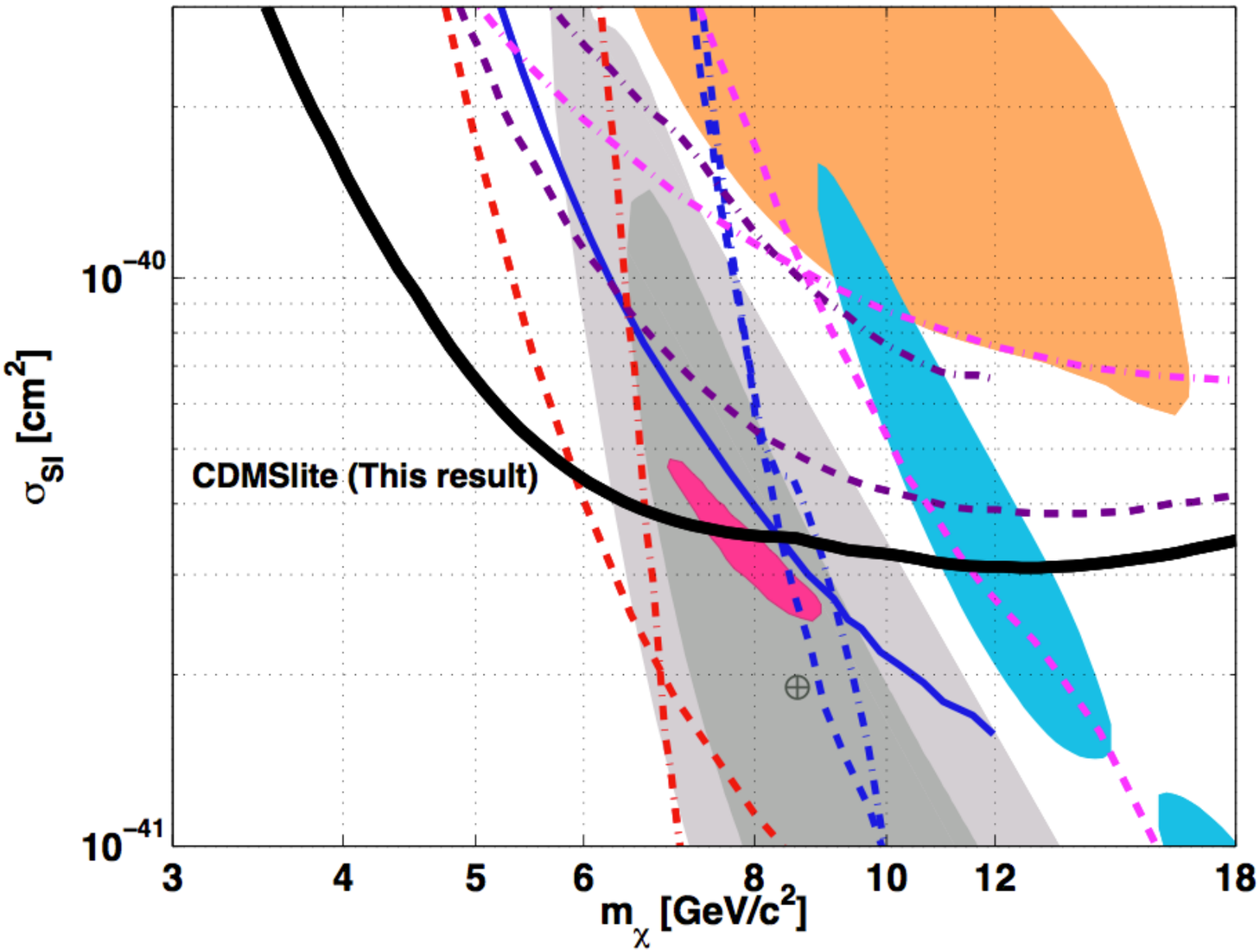
RE, Mardon, Volansky

see also Graham, Kaplan, Rajendran, Walters

NB: semi-conductors (e.g. Ge)

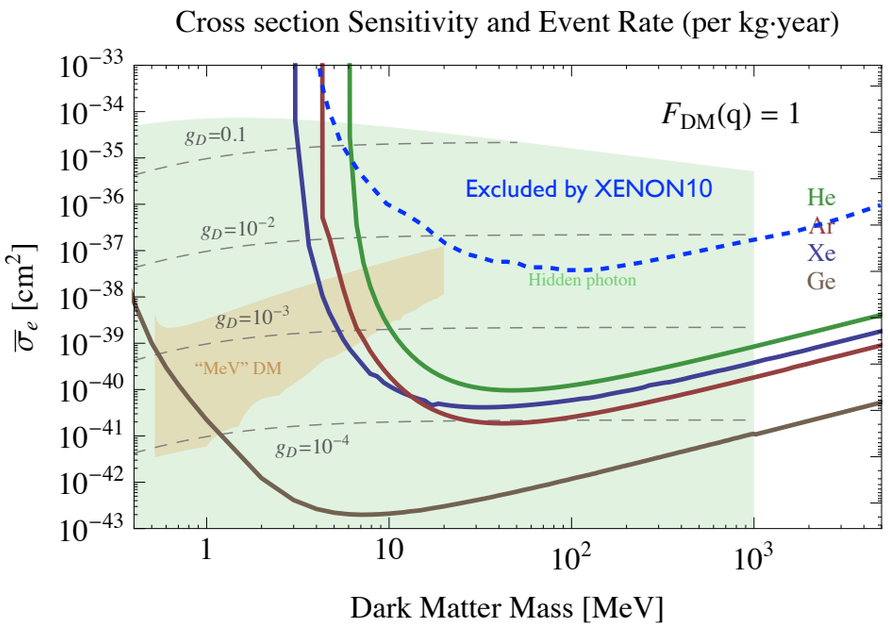
$\Longrightarrow$ reach to *very* low masses !

- band-gap only ~ 1 eV (much lower than Xe!)
- current thresholds:
  - CDMS: ~300 e^-
  - "CDMSlite" (increase voltage)



CDMSlite result, 170 eV_{ee}

1309.3259



RE, Mardon, Volansky

see also Graham, Kaplan, Rajendran, Walters

NB: semi-conductors (e.g. Ge)

$\Longrightarrow$ reach to *very* low masses !

- band-gap only ~ 1 eV (much lower than Xe!)
- current thresholds:
  - CDMS: ~300 e^-
  - "CDMSlite" (increase voltage)
  - DAMIC (Si, CCD's): current threshold ~40 eV (1105.5191)
    future: ~4 eV ?

Field developing fast!
exciting potential

How to detect sub-GeV DM

- ionization

  (DM-electron scattering)

- excitation

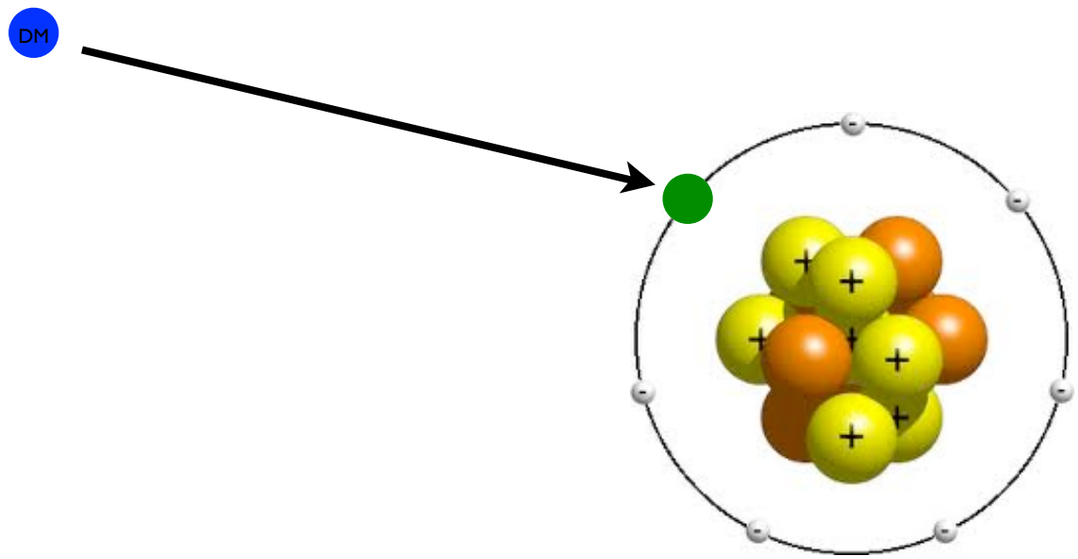
  (DM-electron scattering)

- molecular dissociation

  (DM-nucleon or scattering)

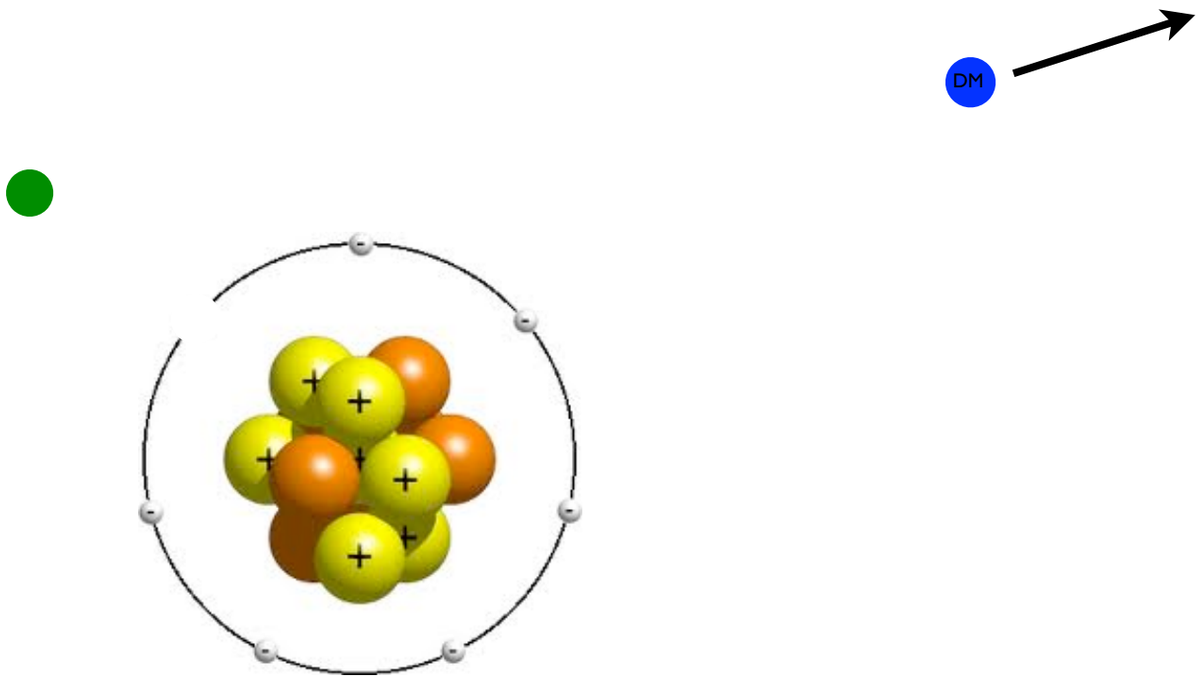
} Danger: work in progress!

Excitation: DM scattering off electron



Atom

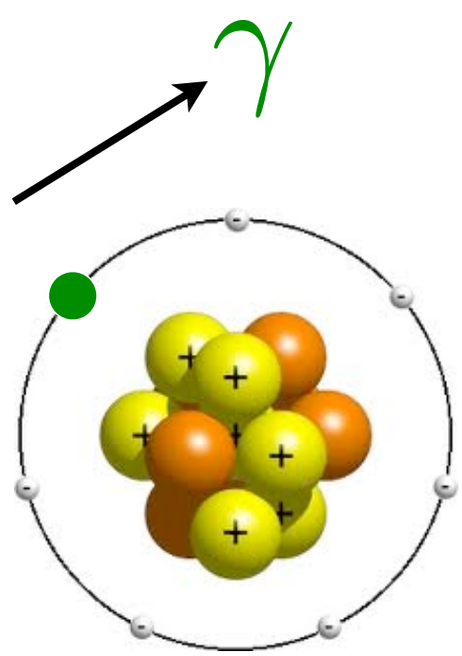
Excitation: DM scattering off electron



Atom

Excite atom…

Excitation: DM scattering off electron



Atom

threshold <O(10 eV)

Excite atom…& look for de-excitation photon

Signal: photons

Use Microwave Kinetic Inductance Detectors (MKIDs) to detect these photons?

How to detect sub-GeV DM

- ionization

  (DM-electron scattering)

- excitation

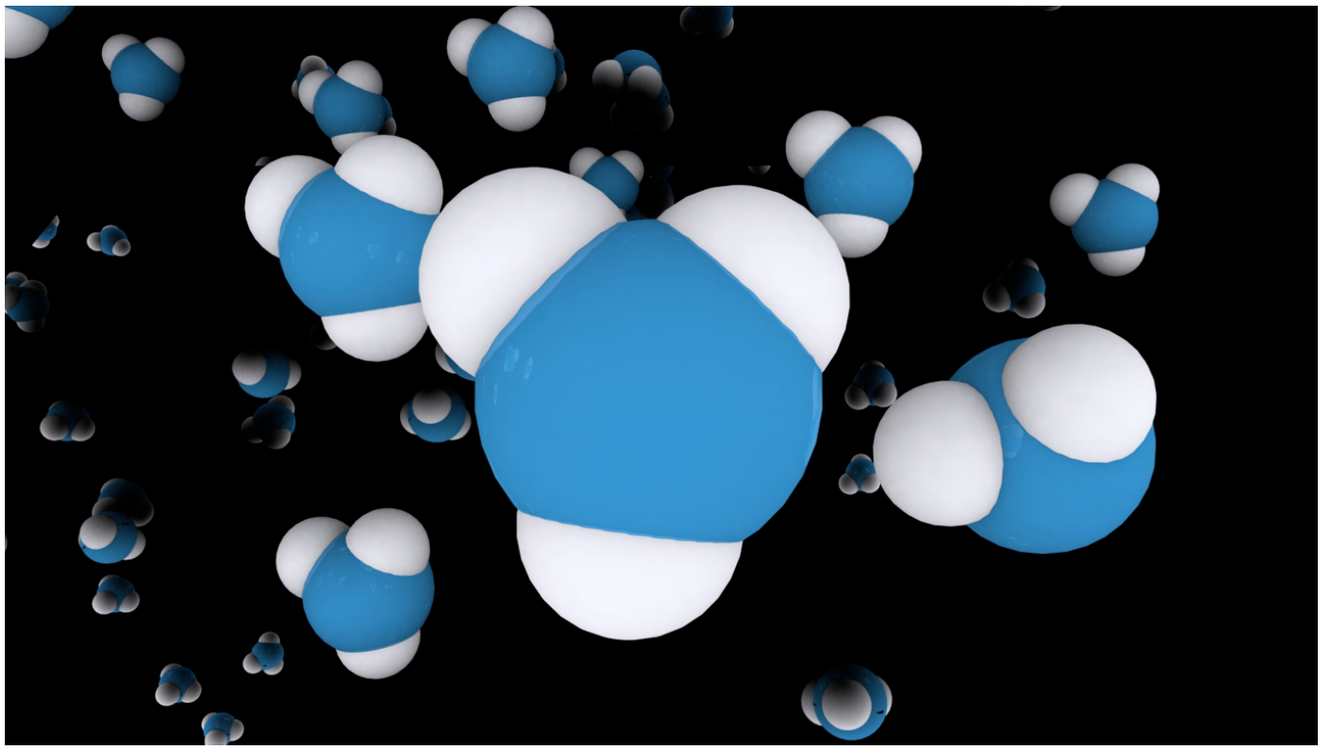
  (DM-electron scattering)

- molecular dissociation

  (DM-nucleon scattering)

Molecular Dissociation: DM or ν scattering off nuclei

RE, Mardon, Oren Slone, Volansky etc.
work in progress



threshold ~ few eV

Signal: various possibilities under investigation

We are calculating rates & talking w/ several experimentalists/chemists to investigate feasibility…

Outline

- some constraints & models
- experimental opportunities
  - direct detection

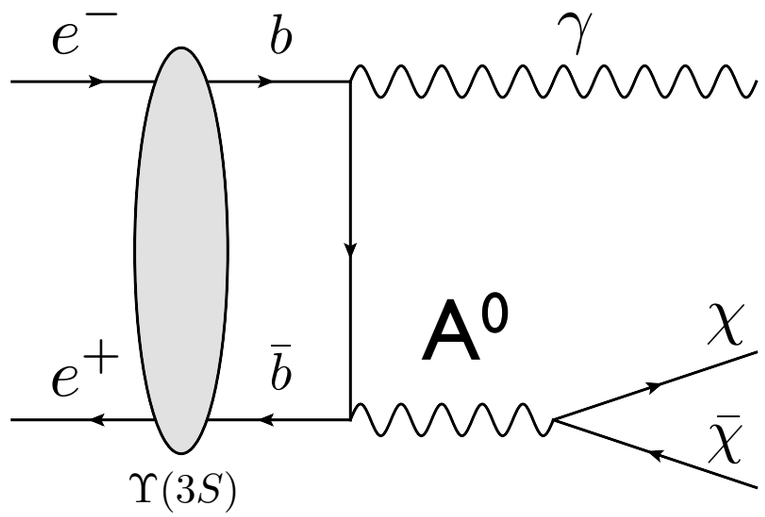
  - colliders (e^+e^-)
  - fixed-target (p & e^-)
  - indirect detection

O(GeV) DM & mediators best probed at low-energy e^+e^- coliders

- huge luminosity at e.g. B-factories
- large cross sections $\sigma \propto \frac{1}{E_{\rm cm}^2}$
- signal: mono-photon events

Existing BaBar analysis

- BaBar searched for: $\Upsilon(3S) \to \gamma + A^0 \to \gamma + \text{invisible}$

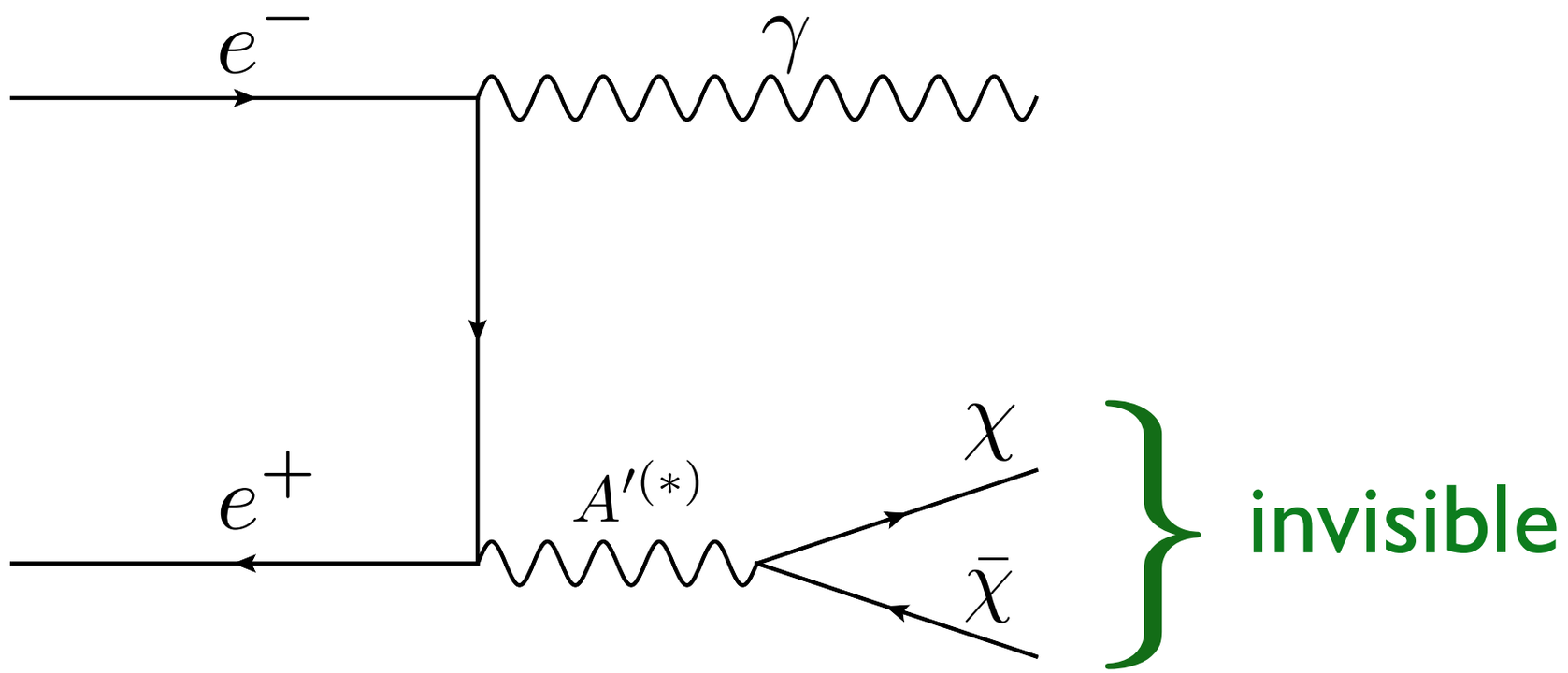


- Analysis appeared in a conference proceeding (0808.0017), improvements + paper expected soon

- mono-photon trigger for only 30/fb on Υ(3S)

Sensitive to DM production in e^+e^- collisions

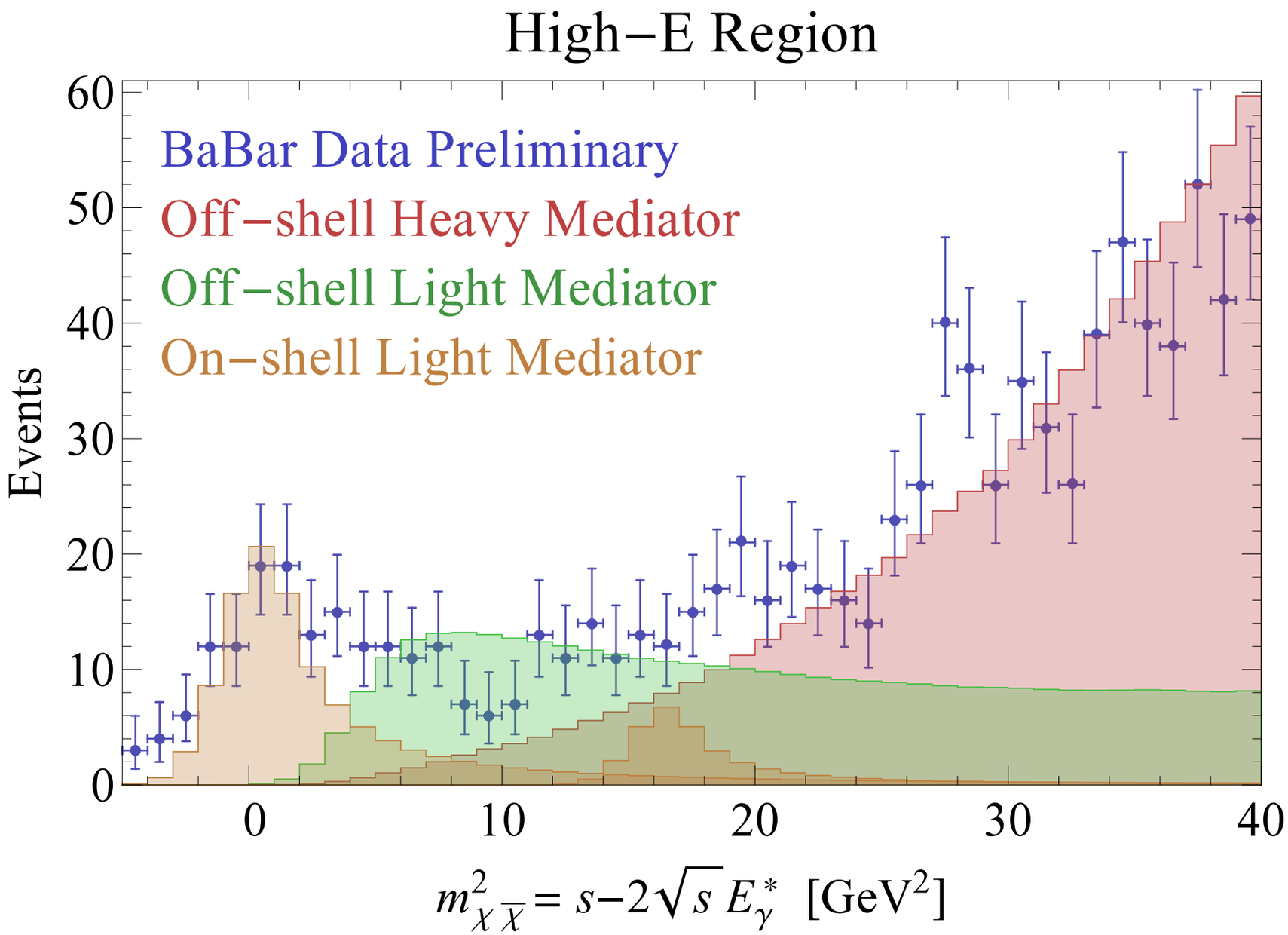
RE, Mardon, Papucci, Volansky, Zhong
(see also Izaguirre, Krnjaic, Schuster, Toro; Fayet; Borodatchenkova et.al., …)



A′ can be on- or off-shell

if A′ on-shell, get a bump!

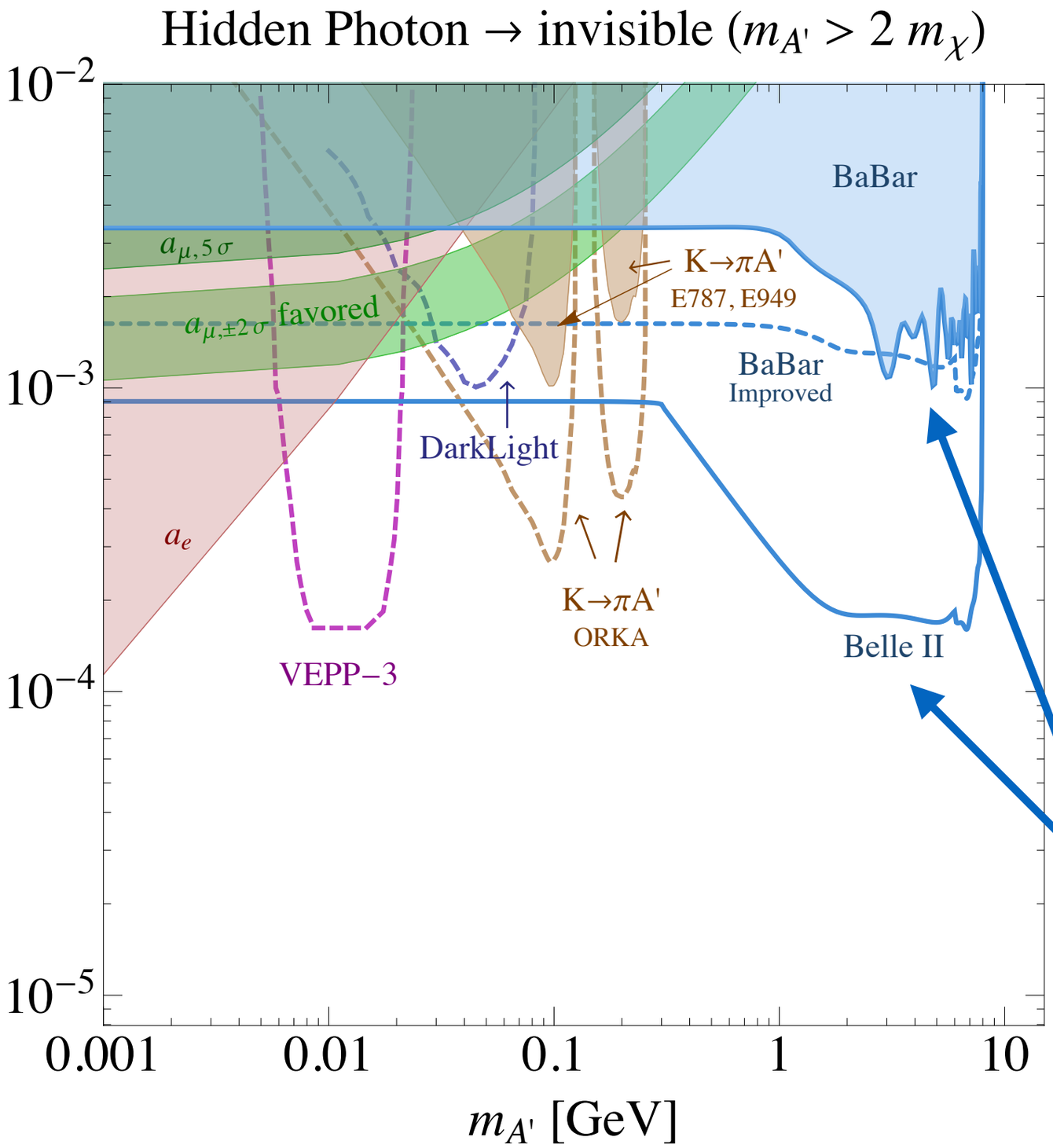
The BaBar Data



$3.2\ \text{GeV} < E^*_\gamma < 5.5\ \text{GeV}$

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

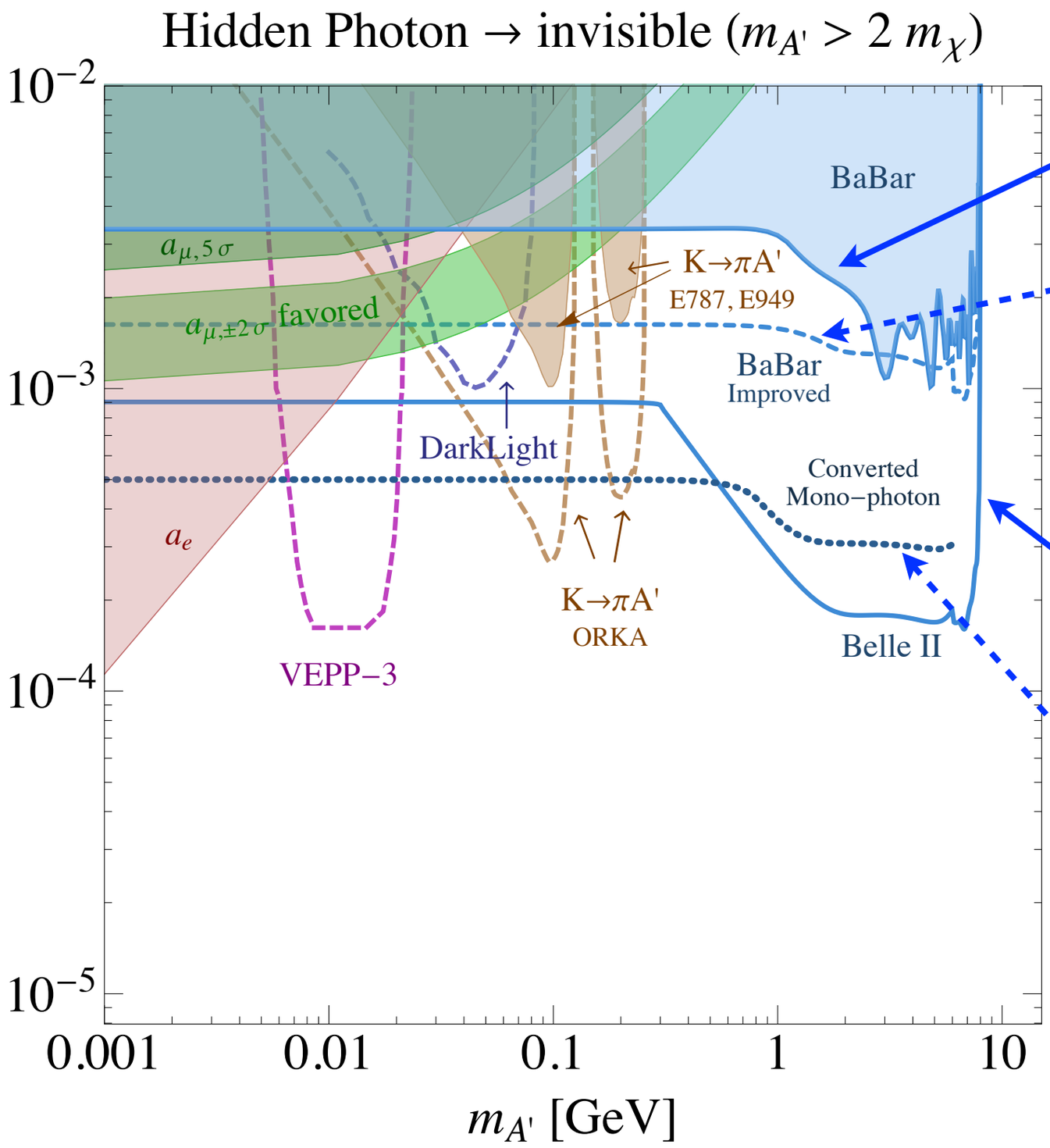
RE, Mardon, Papucci, Volansky, Zhong



- 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

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

RE, Mardon, Papucci, Volansky, Zhong



- existing data
- potential improvement from reducing $\gamma\not{\gamma}$ background (private communication)
- projected Belle II
  50/ab, better resolution
- potential improvement using converted photons

Belle II working on implementing mono-photon trigger…

Outline

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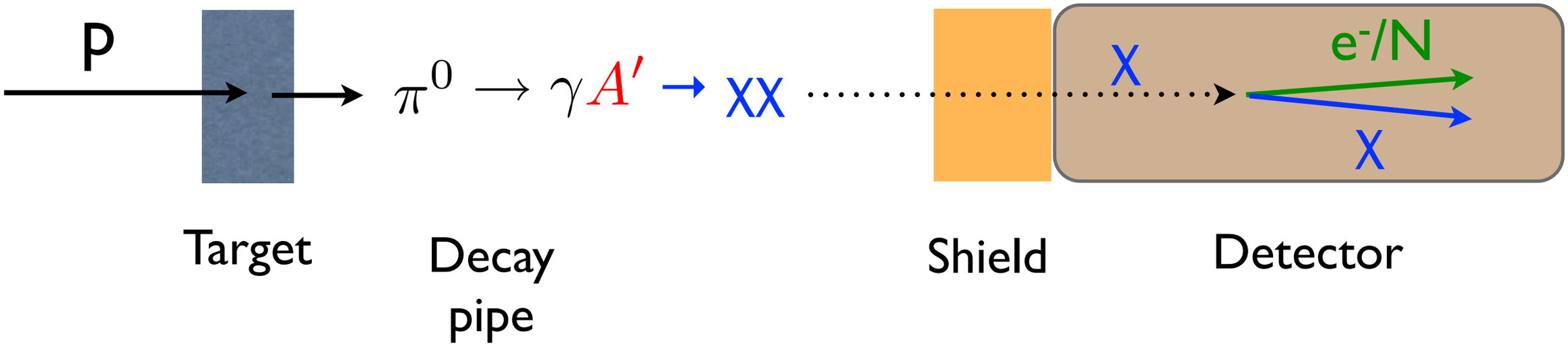
Proton-beam fixed target experiments

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

Produce DM in a proton dump via

$$A' \to \bar{\chi}\,\chi$$

χ recoils of e^-/nucleon in detector



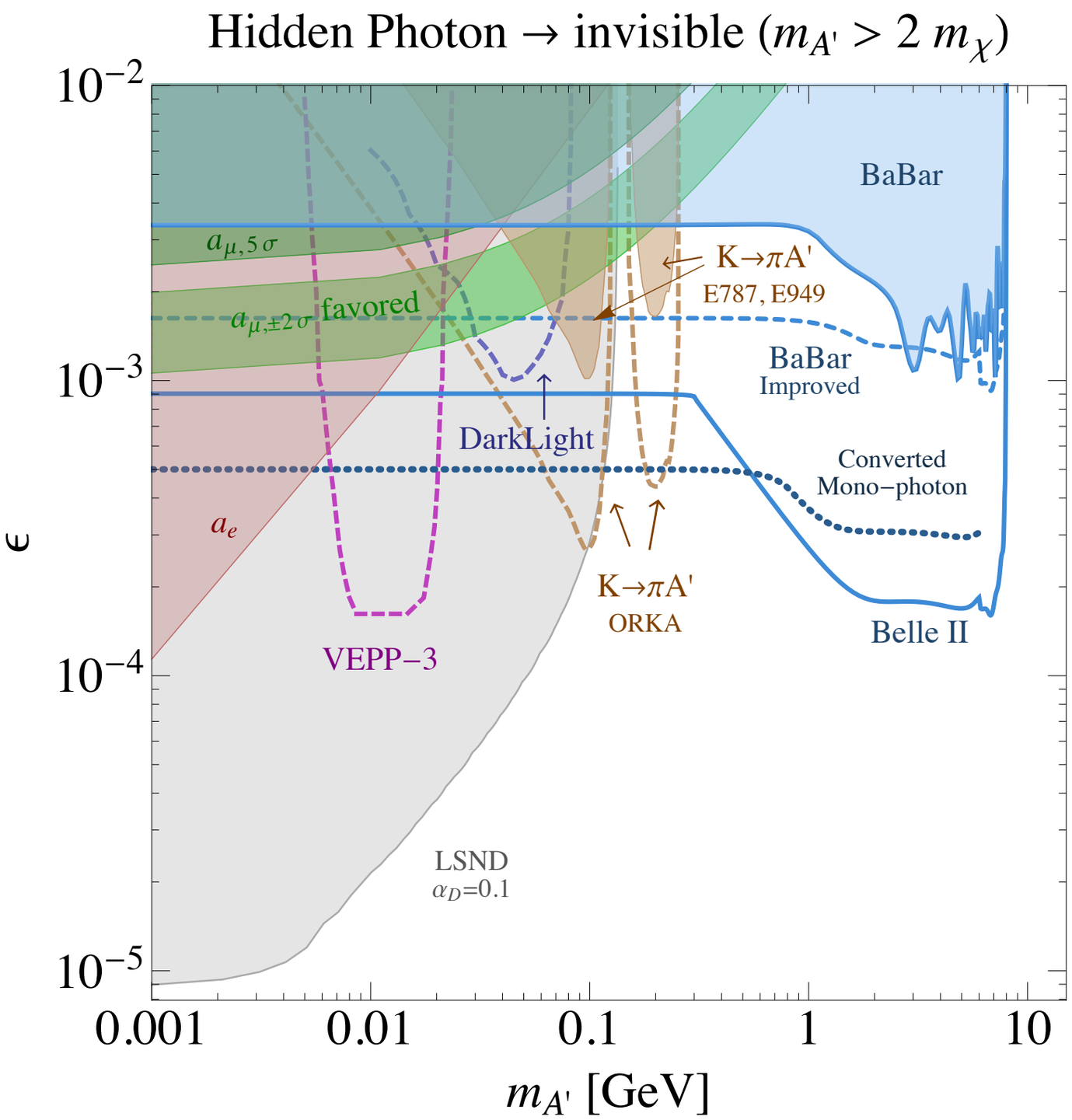
plenty of room for future exploration at neutrino facilities, e.g.

LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …

LSND sets powerful limits for $m_{A'} > 2\, m_X$

deNiverville, Pospelov, Ritz

plot from RE, Mardon, Papucci, Volansky, Zhong



- limit depends on $\alpha_D = \dfrac{g_D^2}{4\pi}$

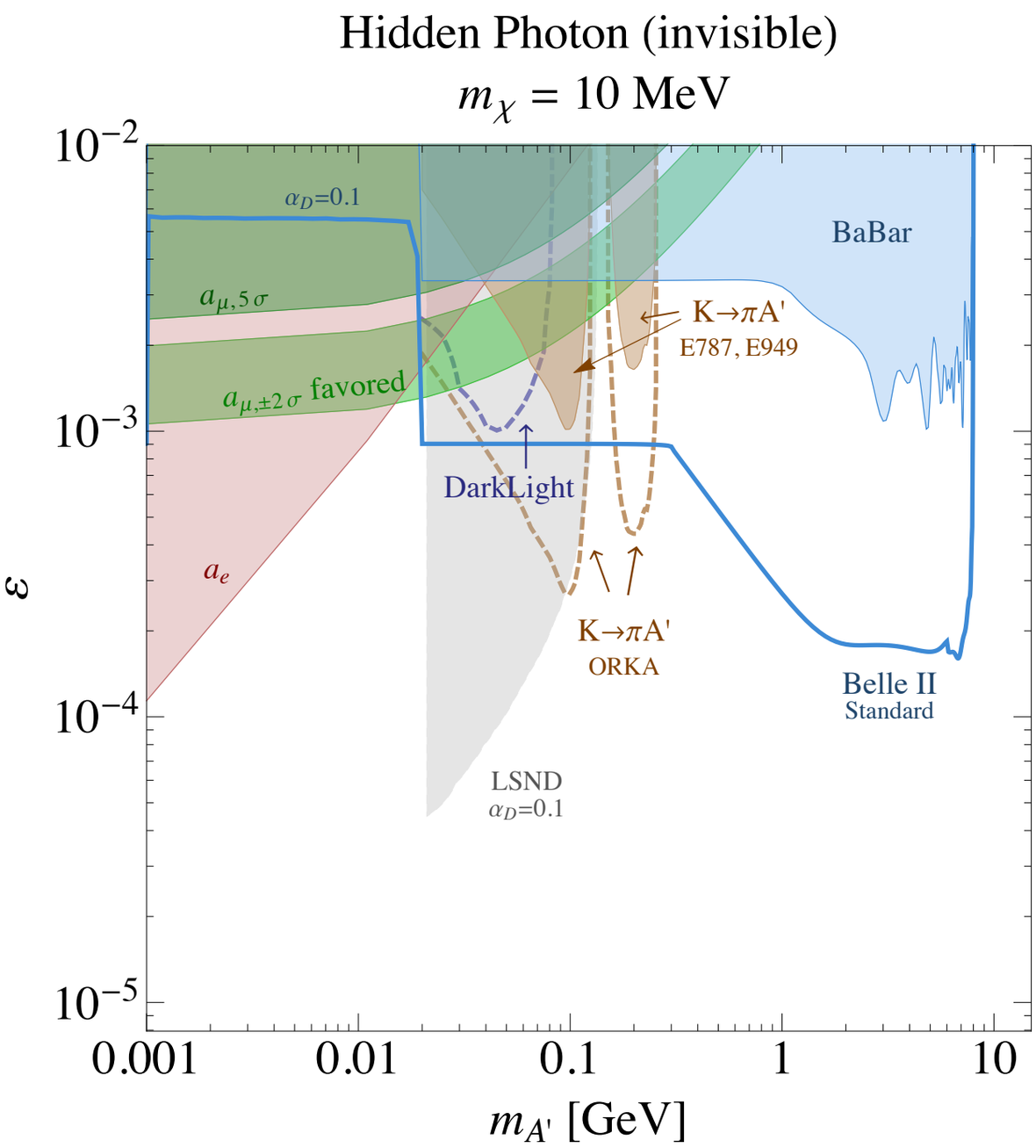
- a proposal has also been submitted to MiniBoONE

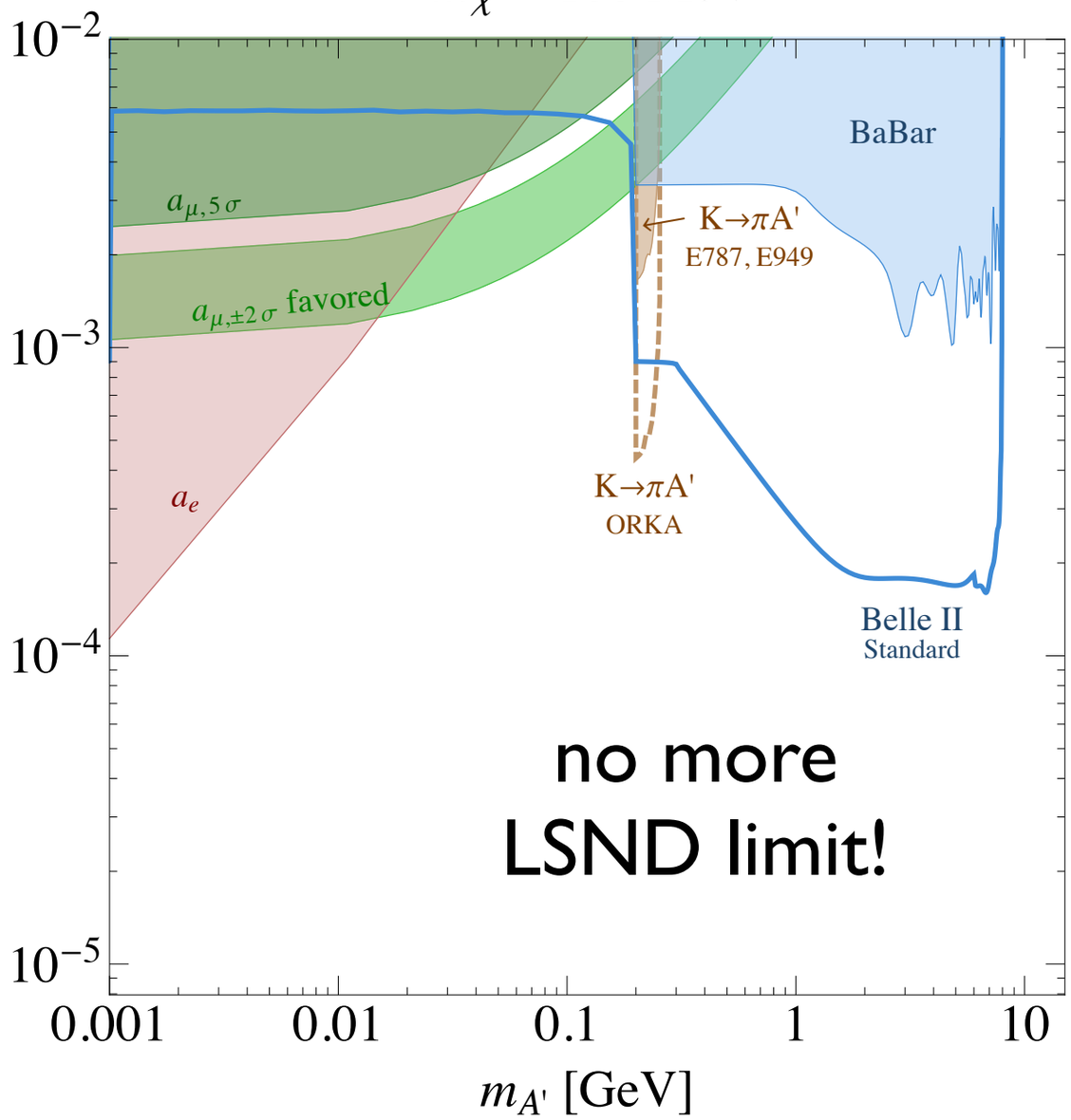
Aguilar-Arevalo et.al.

Limits depend on mx

Batell, Pospelov, Ritz

plot from RE, Mardon, Papucci, Volansky, Zhong





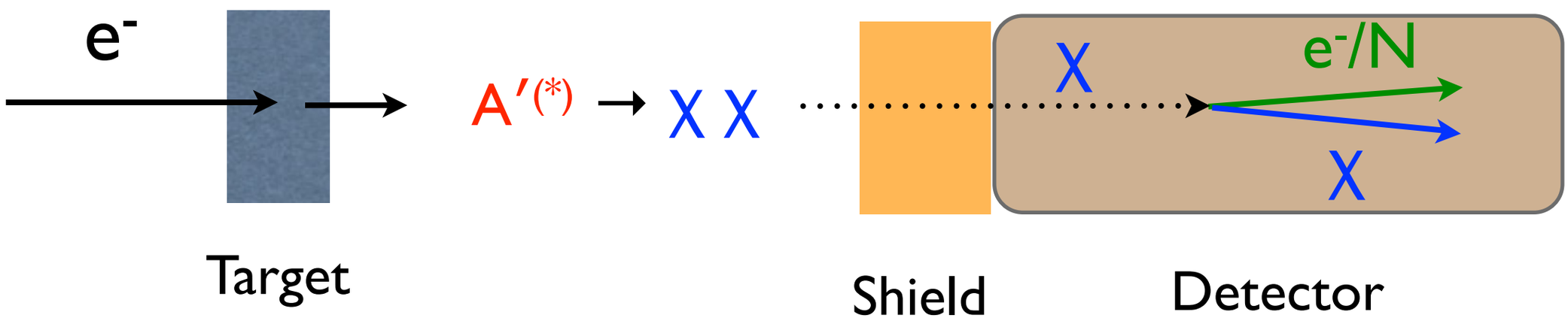
Electron-beam fixed target experiments

Gordan Krnjaic, Eder Izaguirre, Schuster, Toro

Gordan & Eder are at workshop

Example: produce χ directly from on/off-shell A'

χ recoils of e^-/nucleon in detector

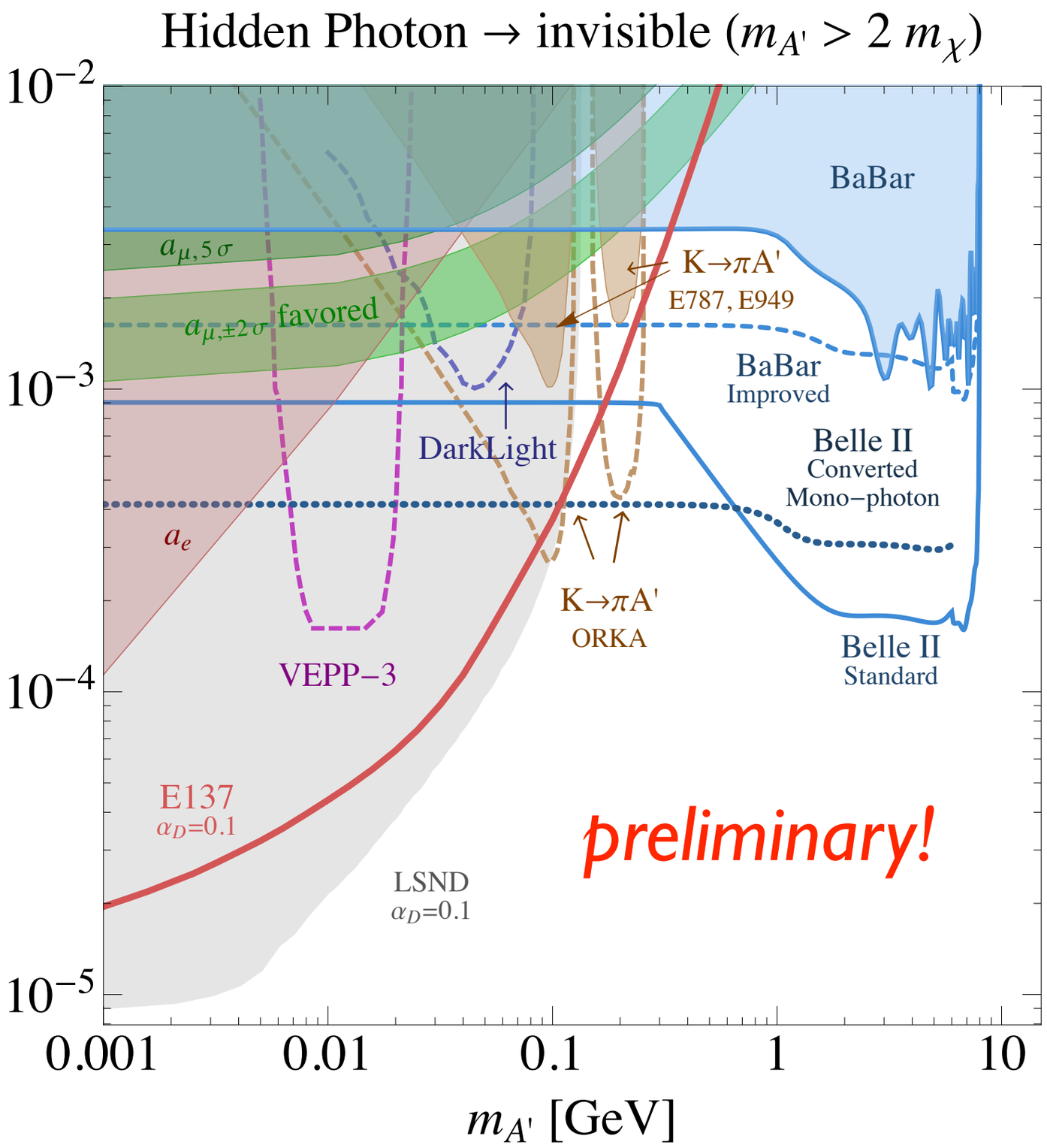


new parasitic experiments possible at

e.g. JLab, Mainz, SLAC, SuperKEK, ILC, …

Constraint from past SLAC beam dump E137

Brian Batell, RE, Ze'ev Surujon
(work in progress)



E137 Bjorken et.al.

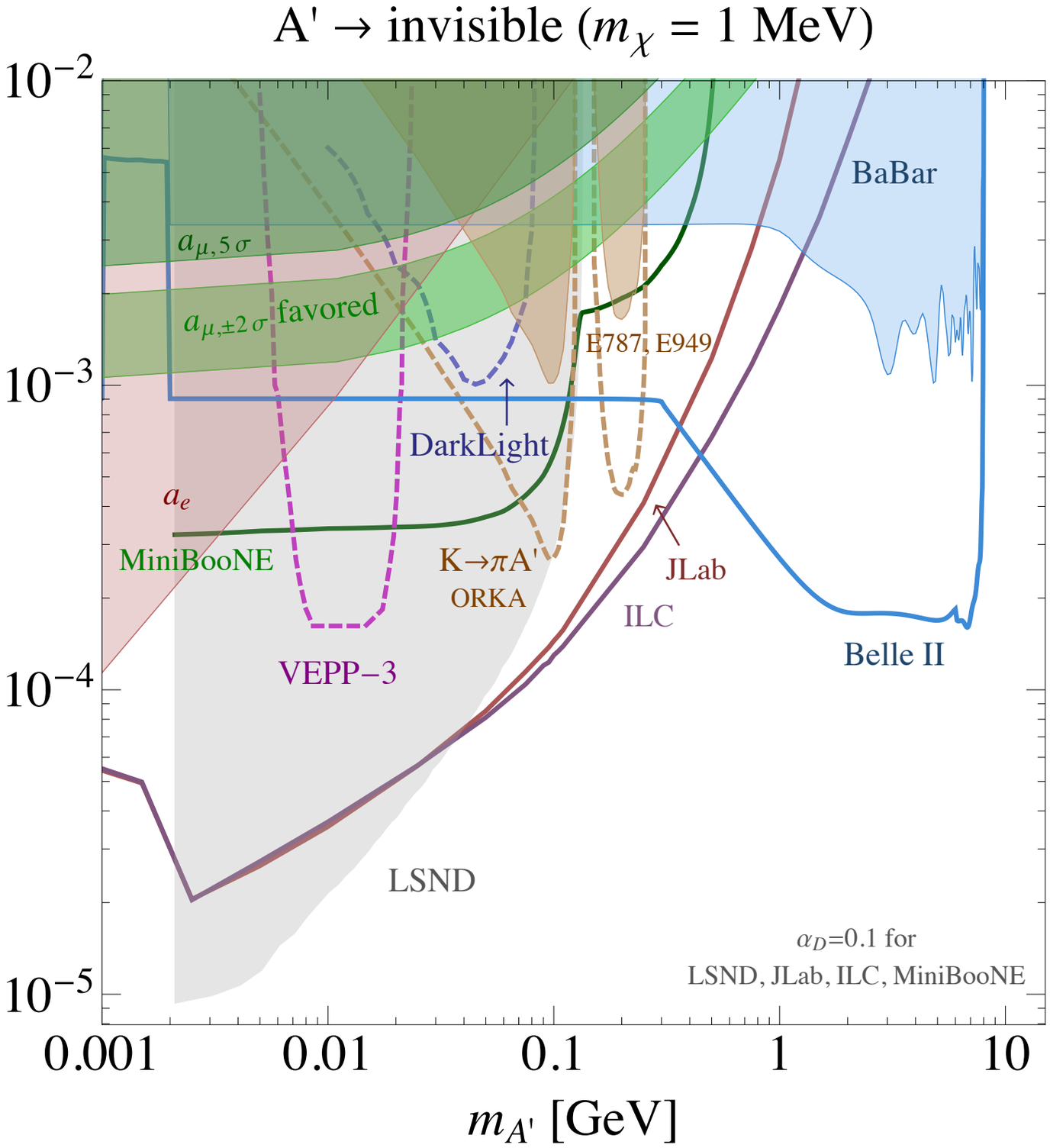
Constraint (not shown) also exists from SLAC milli-charge experiment

Diamond, Schuster
1307.6861

Examples of all constraints/prospects

see e.g. NLWCP Snowmass report

collection of work by B. Batell, P. deNiverville, E. Izaguirre, G. Krnjaic, J. Mardon, M. Papucci, M. Pospelov, A. Ritz, T. Volansky, Y. Zhong, Philip, Natalia, RE (probably forgot someone!)



not shown:

- SLAC mQ — Diamond, Schuster
- E137 — Batell, RE, Surujon (work in progress)

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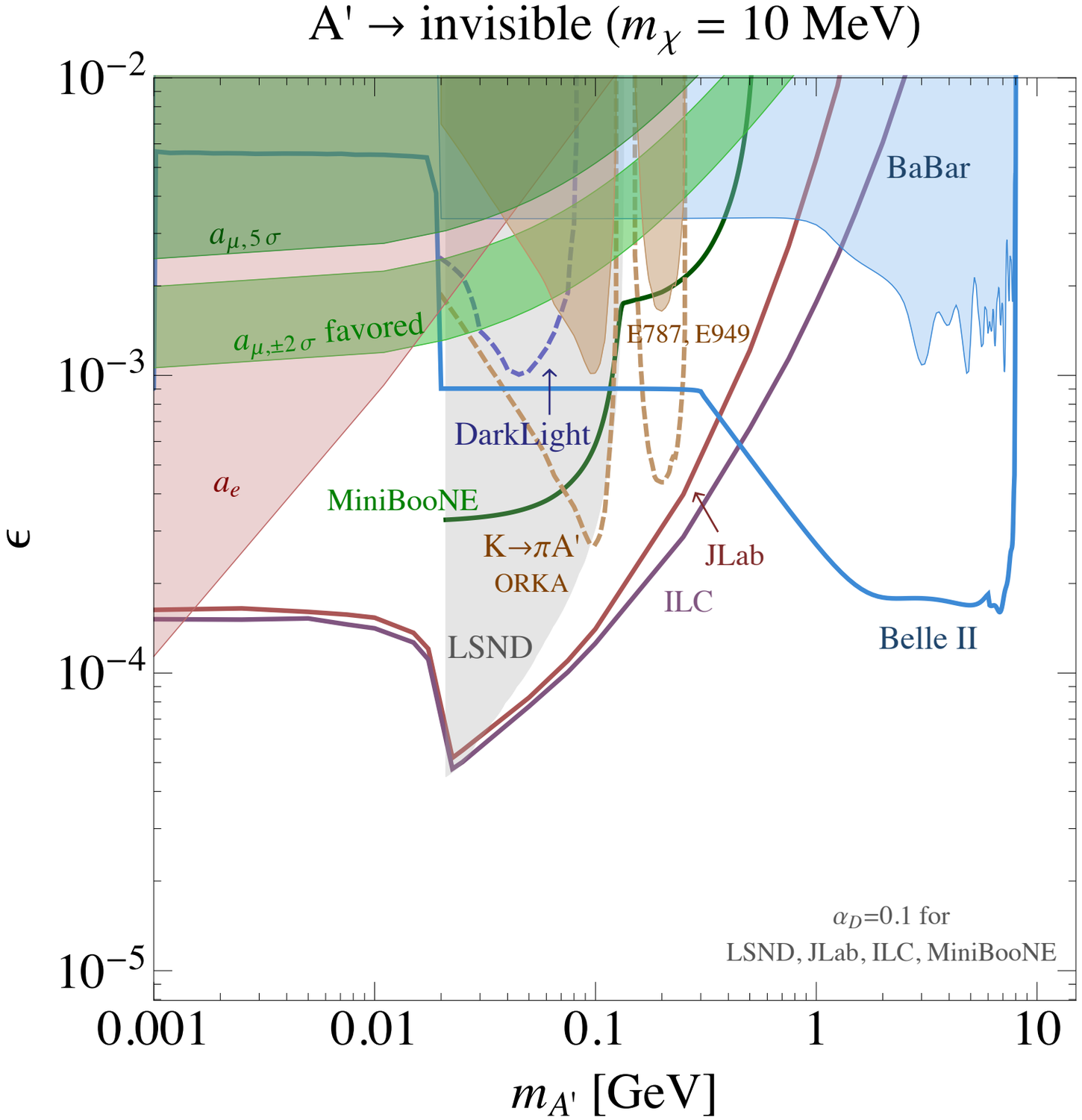

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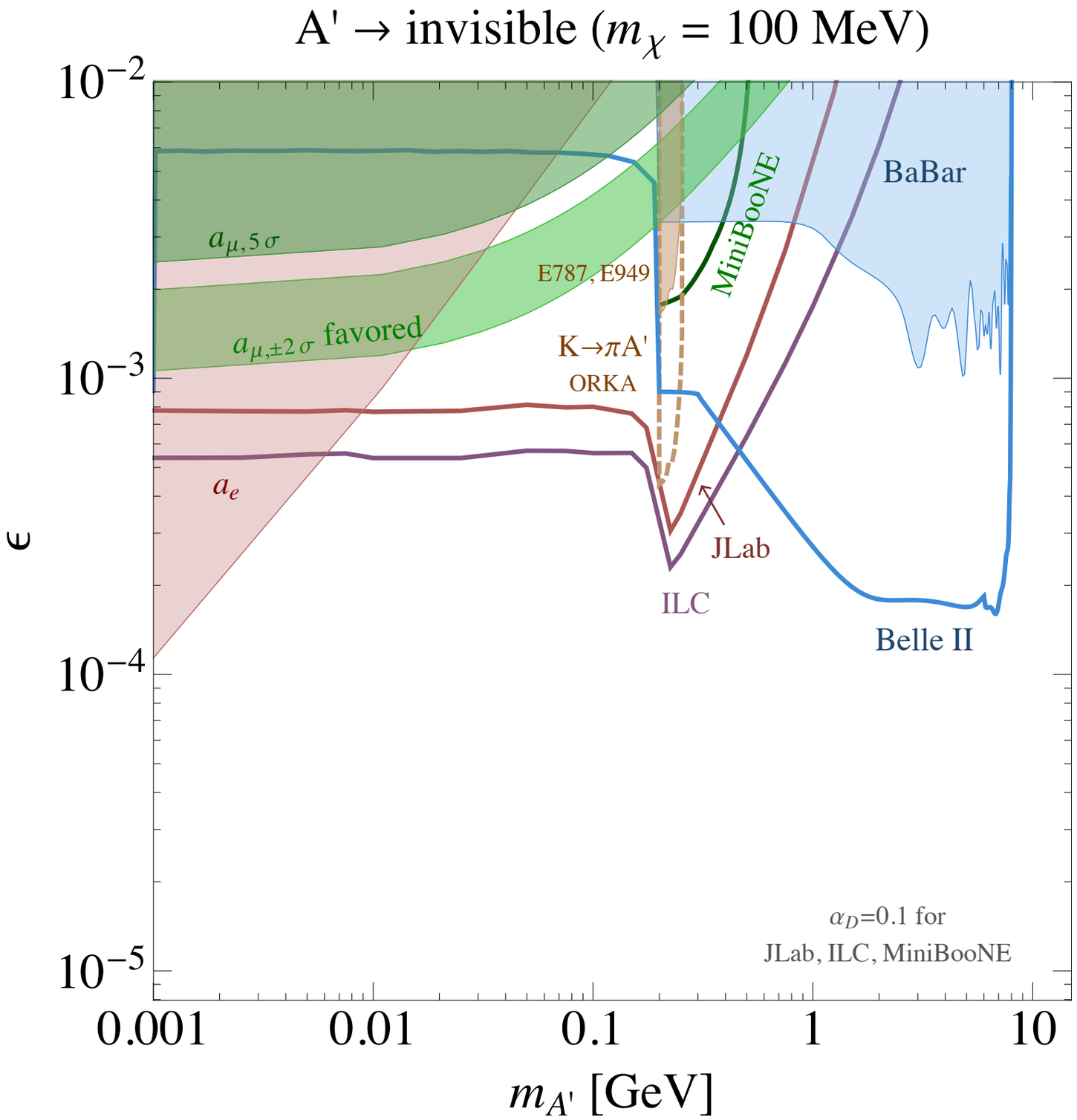
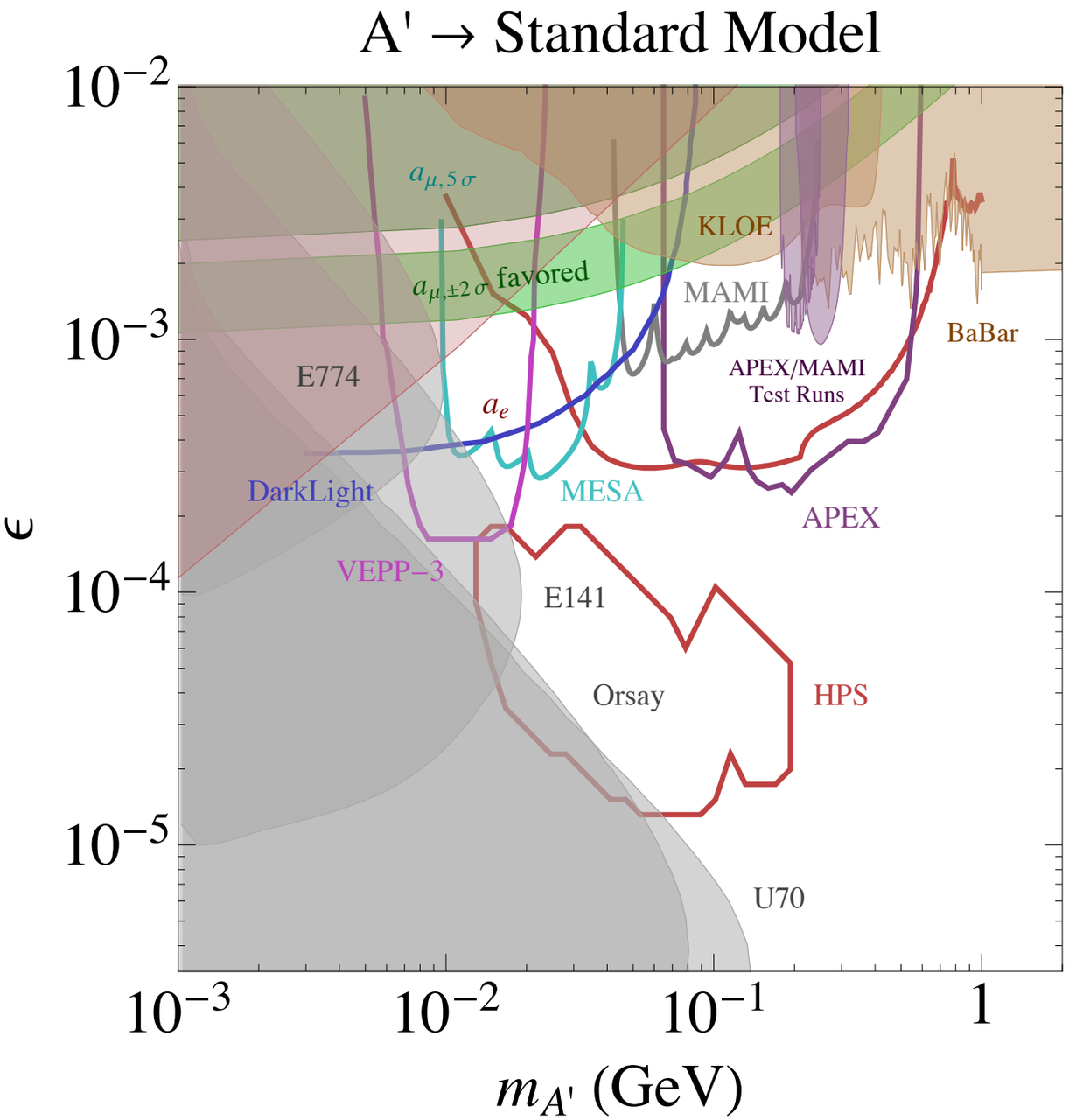
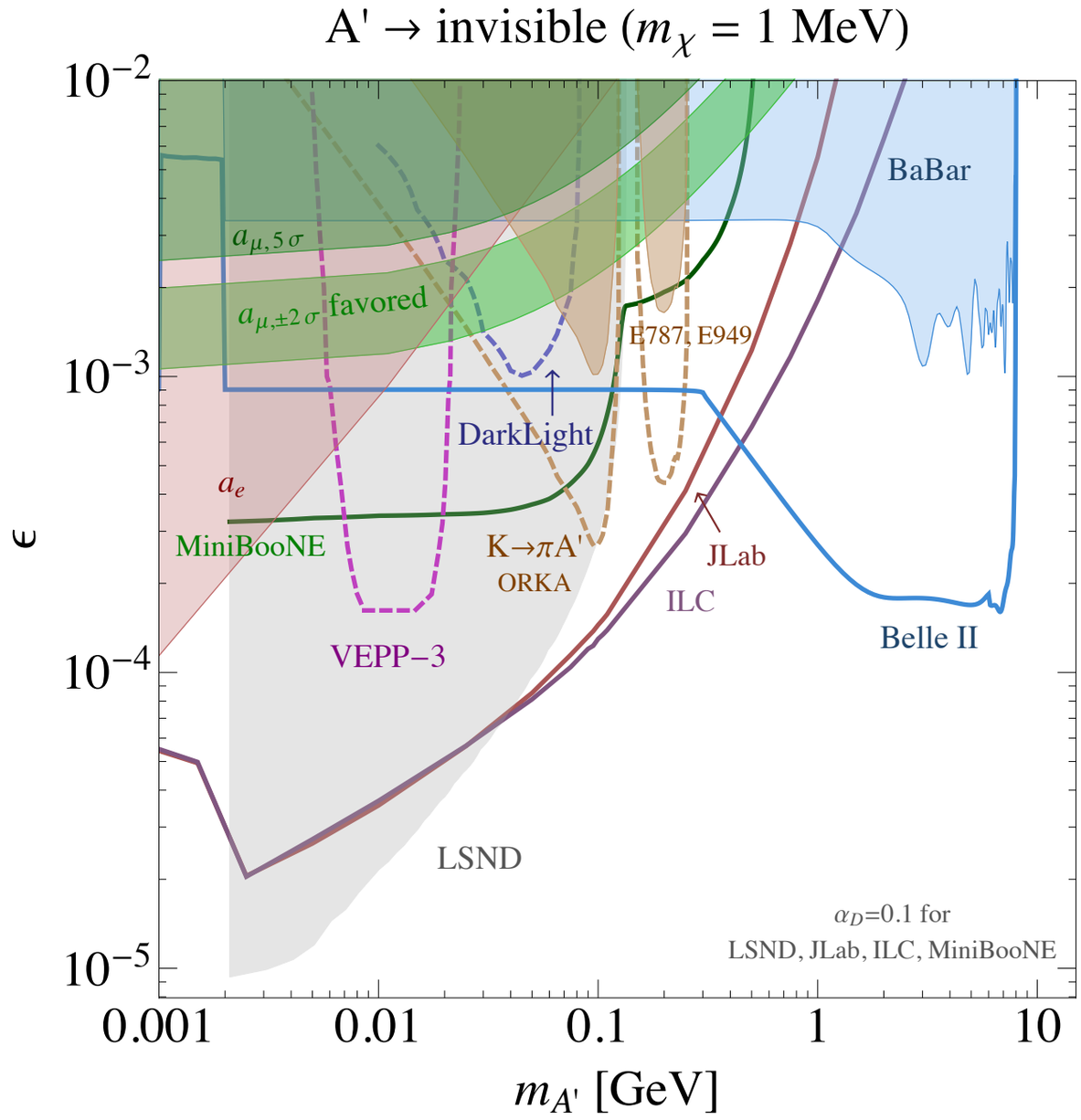


not shown:

- SLAC mQ — Diamond, Schuster
- E137 — Batell, RE, Surujon (work in progress)

Various proposals now exist to probe both visible and invisible A′ decays





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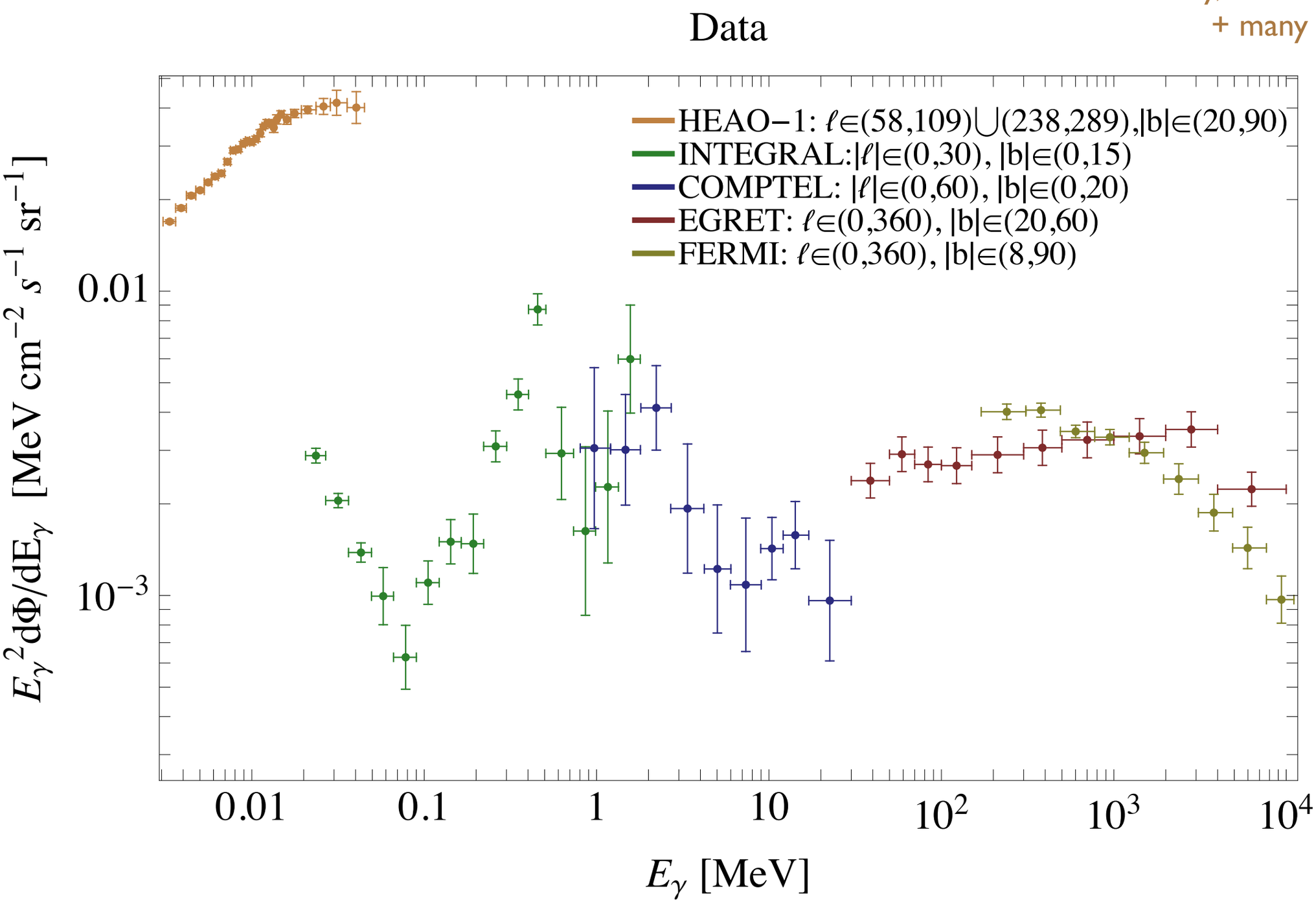
  - direct detection
    - colliders (e^+e^-)
    - fixed-target (p & e^-)
    - indirect detection

RE, Eric Kuflik, Sam McDermott, T. Volansky, K. Zurek; 1309.4091

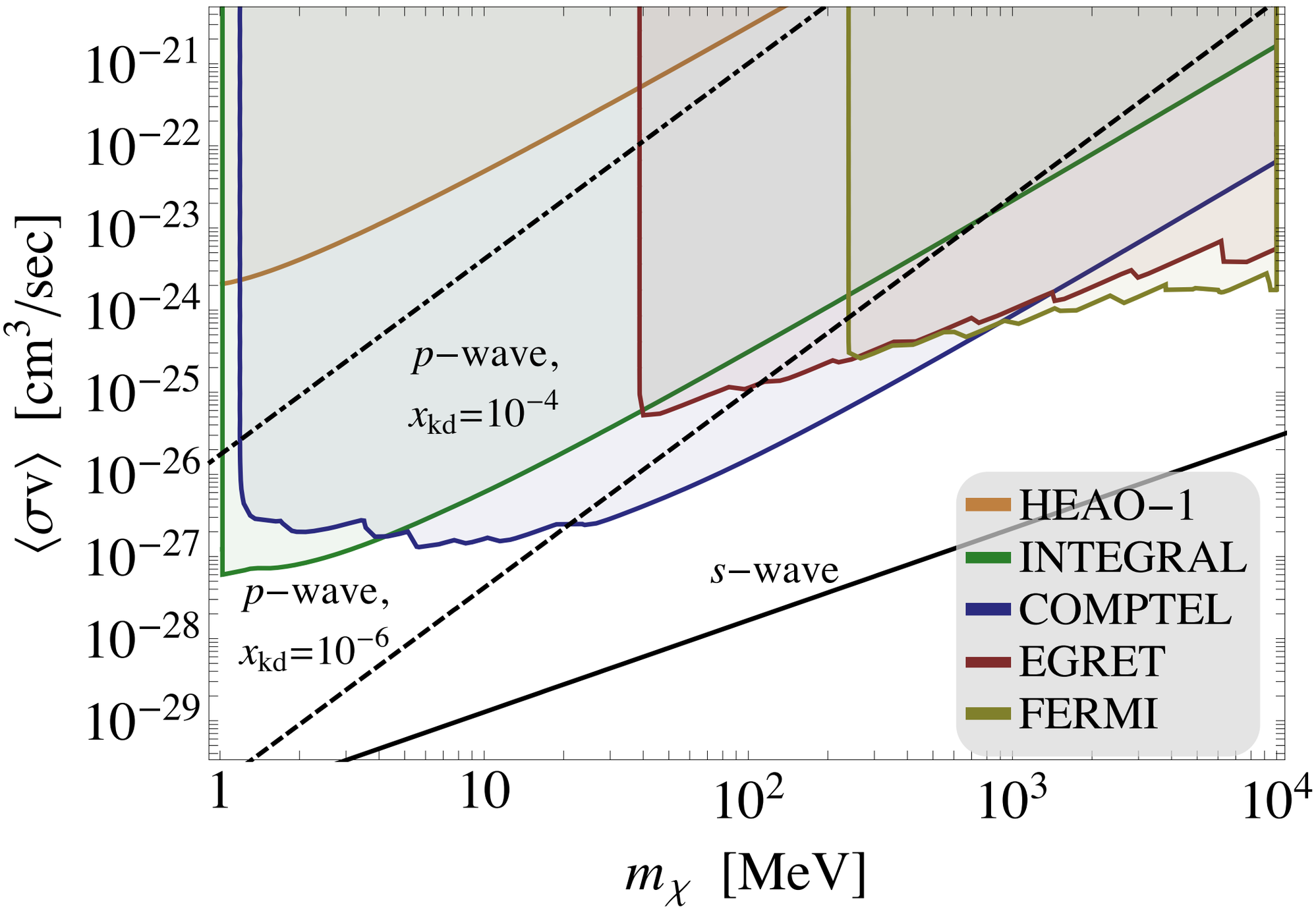
There is lots of X-ray & γ-ray data!

RE, Eric Kuflik, Sam McDermott, T. Volansky, K. Zurek; 1309.4091
+ many others



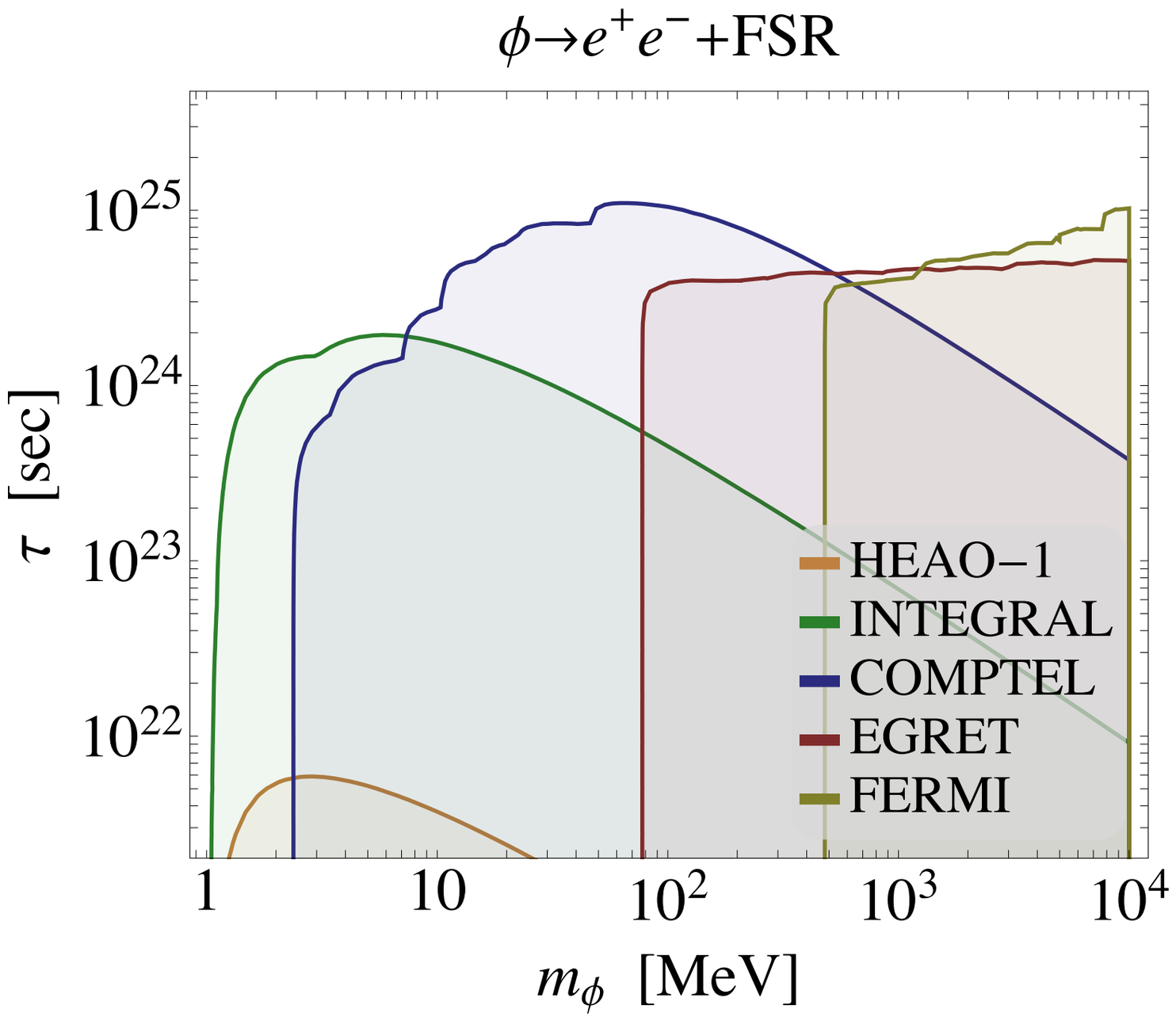
set conservative constraints on specific and simplified models

DM annihilation



galactic constraints can be stronger than CMB for p-wave suppression

DM decay (example)



opportunities exist for collaborations
to optimize data analysis for DM

Summary

- many simple, well-motivated, viable candidates of sub-GeV DM exist
- rich phenomenology: direct, indirect, colliders, fixed-target
- many opportunities for new experiments