Direct Detection of sub-GeV Dark Matter

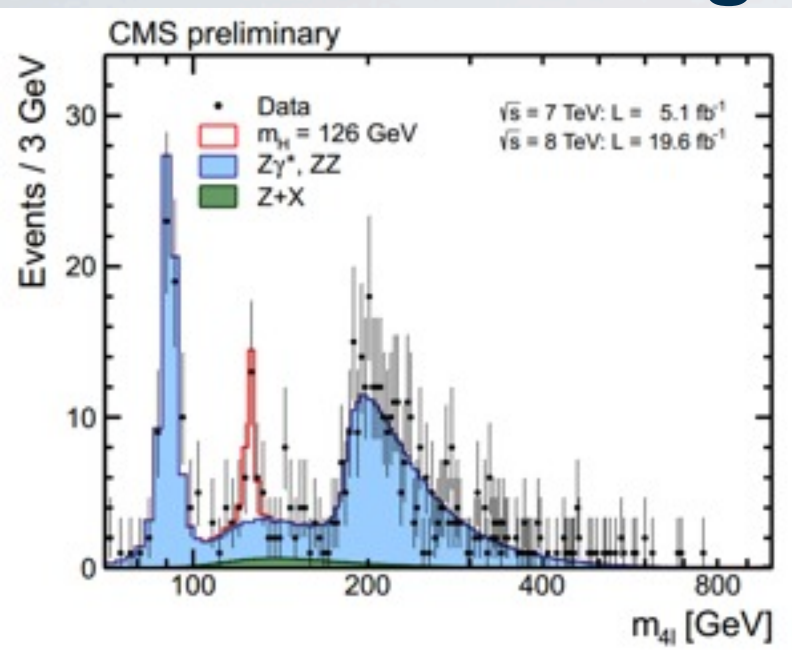
OVERVIEW AND STATUS

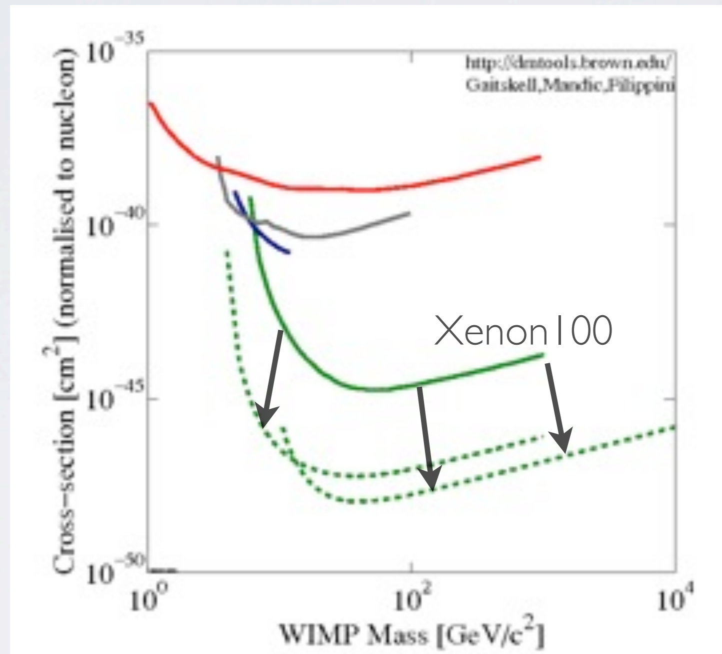
With T.Volansky, R. Essig
P. Sorensen, A, Manalaysay

Jeremy Mardon, SITP, Stanford

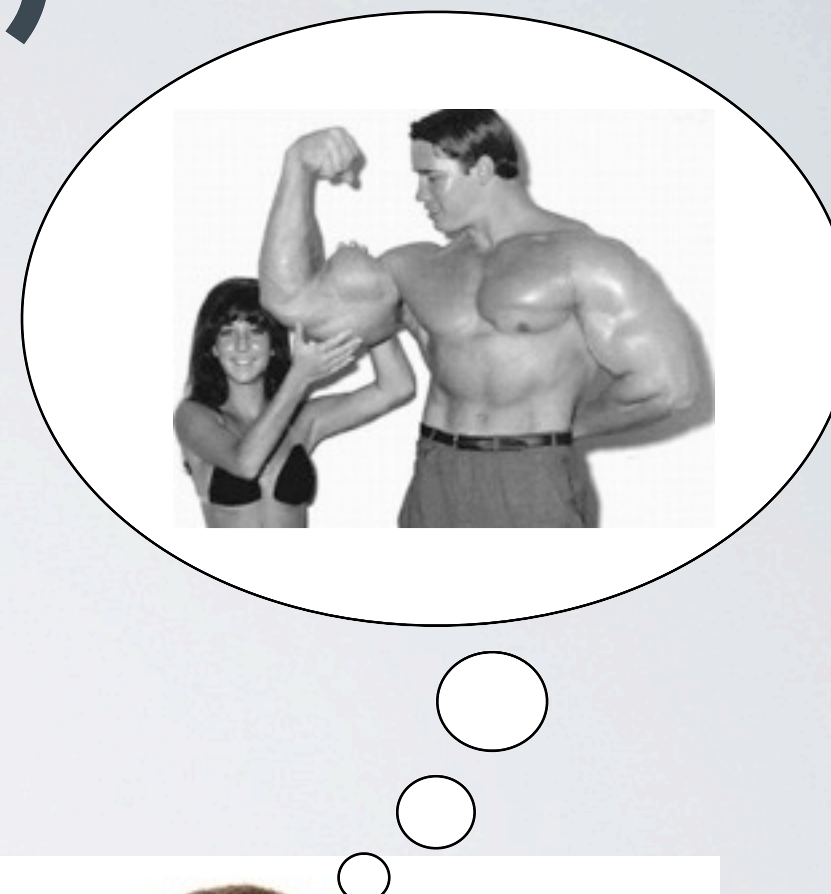
Have we put too much effort into the Weak scale? (an allegory)

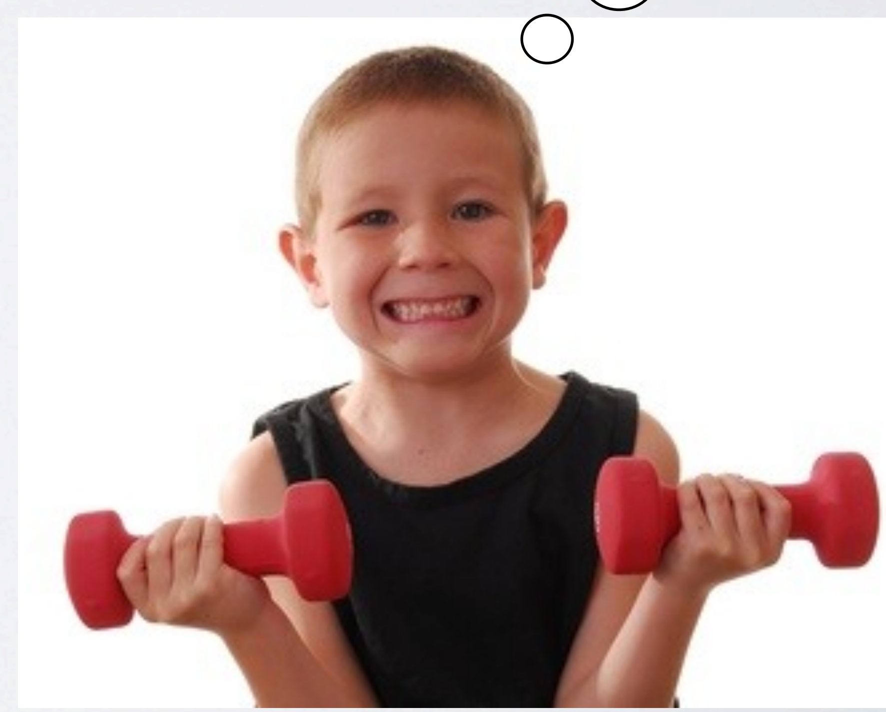
An amazing achievement





but where's the new physics?

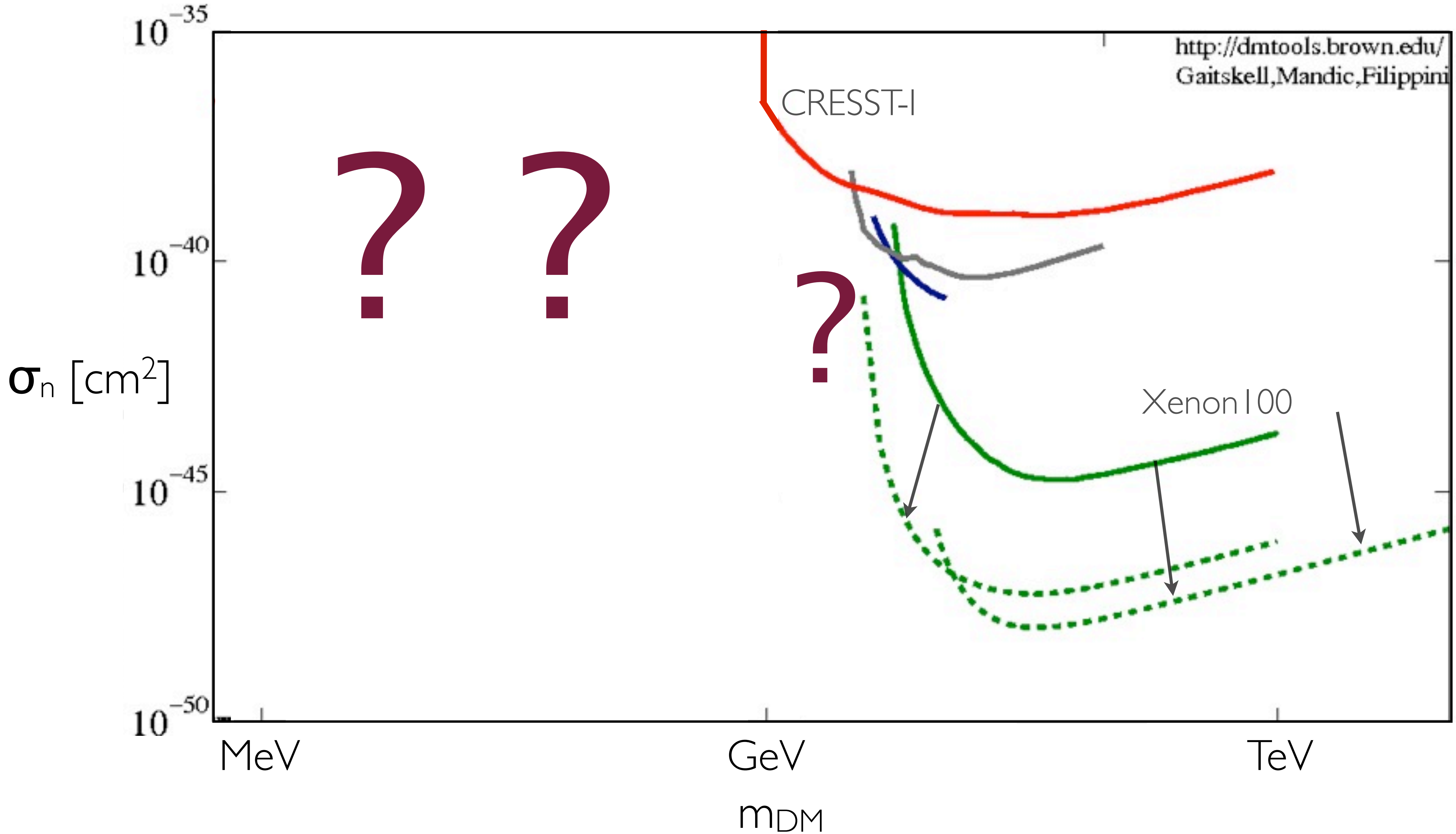


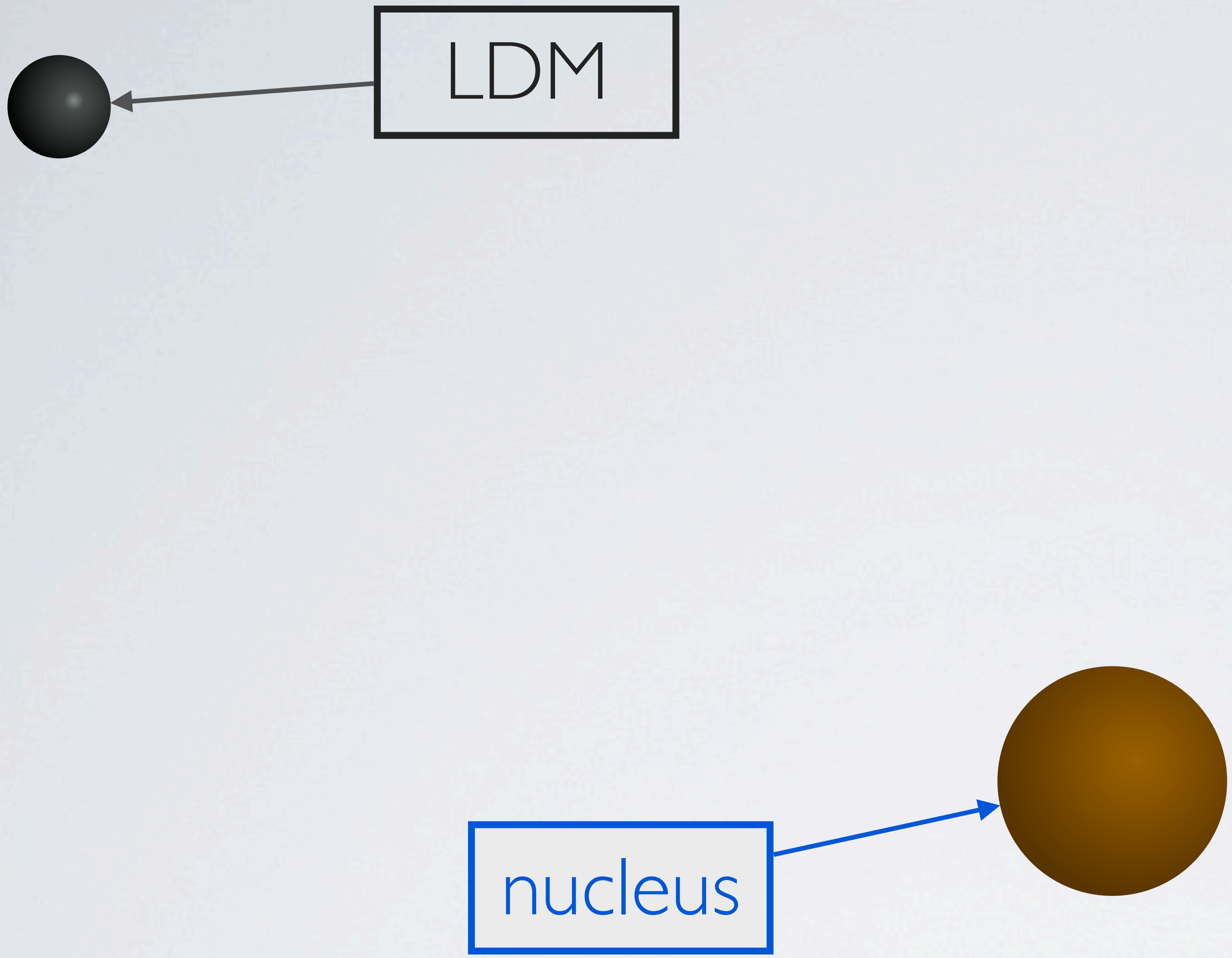


30 years ago

THE DANGERS OF AN IMBALANCED WORKOUT

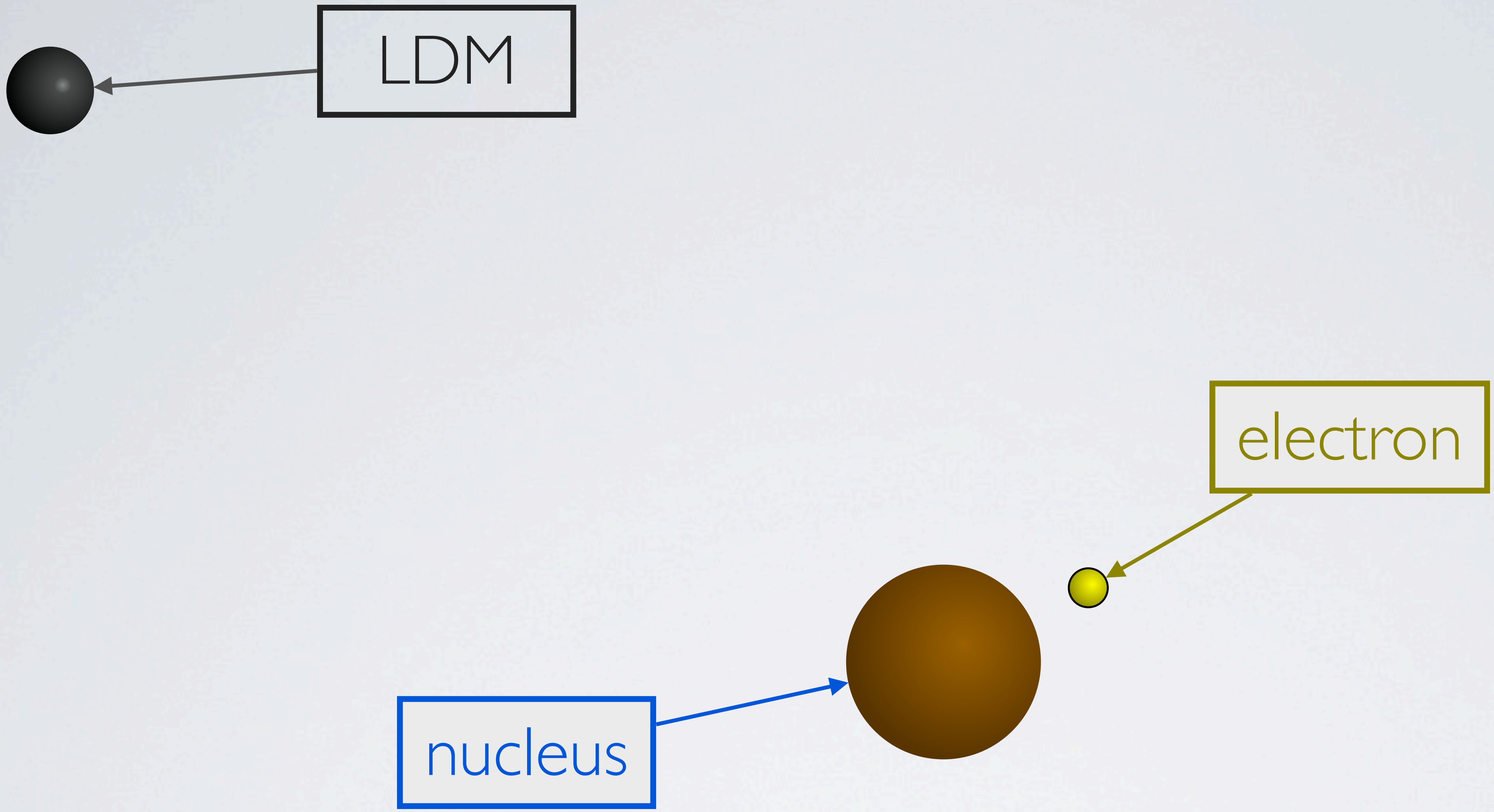
LIMITATIONS OF DIRECT DETECTION





Nuclear scattering transfers only ~(m_{DM}/m_N) of energy

(no ionization, sub-eV phonon energy: undetectable)



Energy available ≈ eV (m_{DM}/MeV)

Electron scattering can transfer most of energy

(ionizes an electron)

Strategy:

Search for DM scattering with electrons

Signal is a single (or a few) ionized electrons

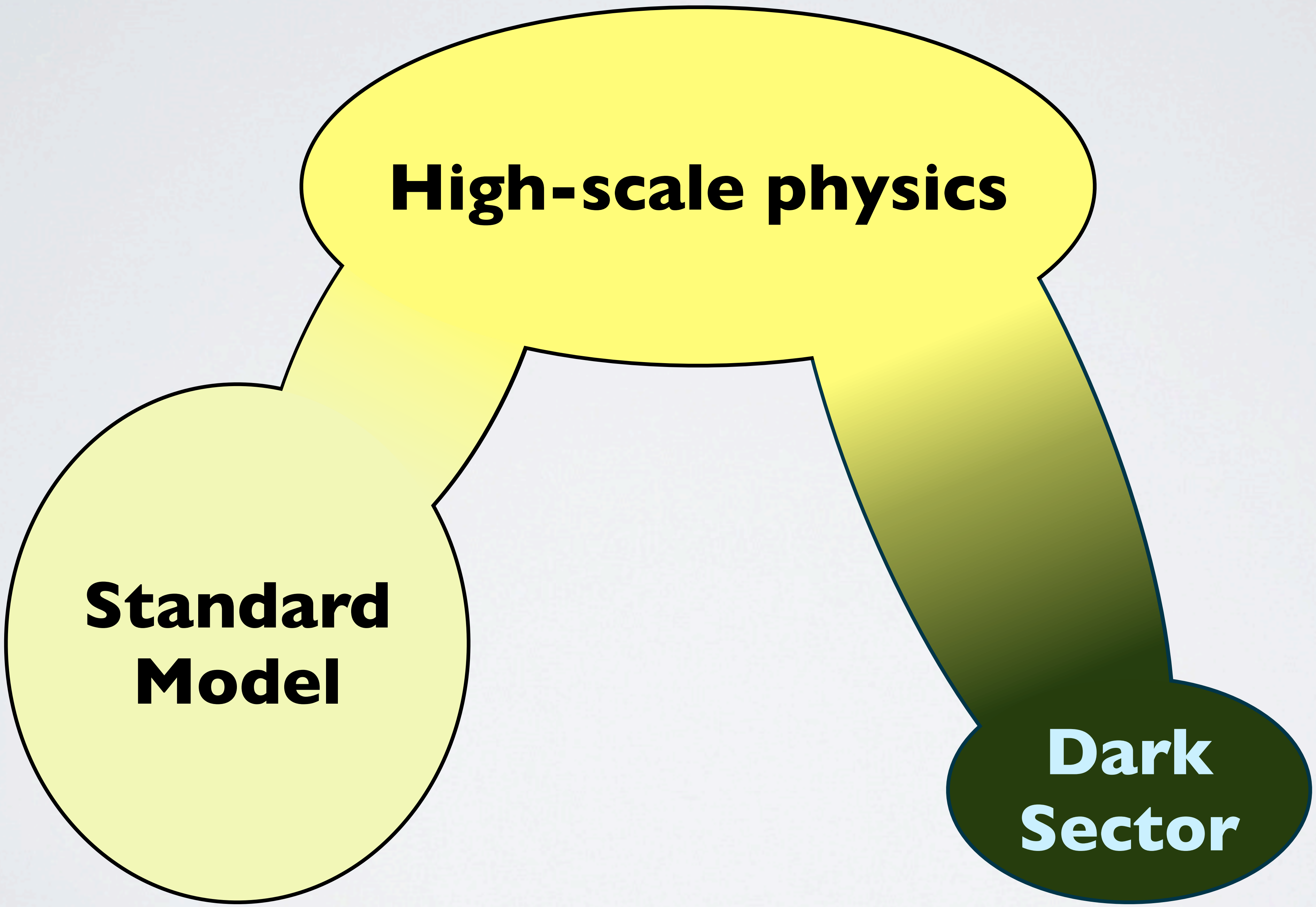
Sensitivity down to MeV scale

"Direct Detection of Sub-GeV Dark Matter"
Essig, Mardon & Volansky
arXiv:1108.5383

see also Graham, Kaplan, Rajendran & Walters 1203.2531

VARIETIES OF SUB-GEV DM

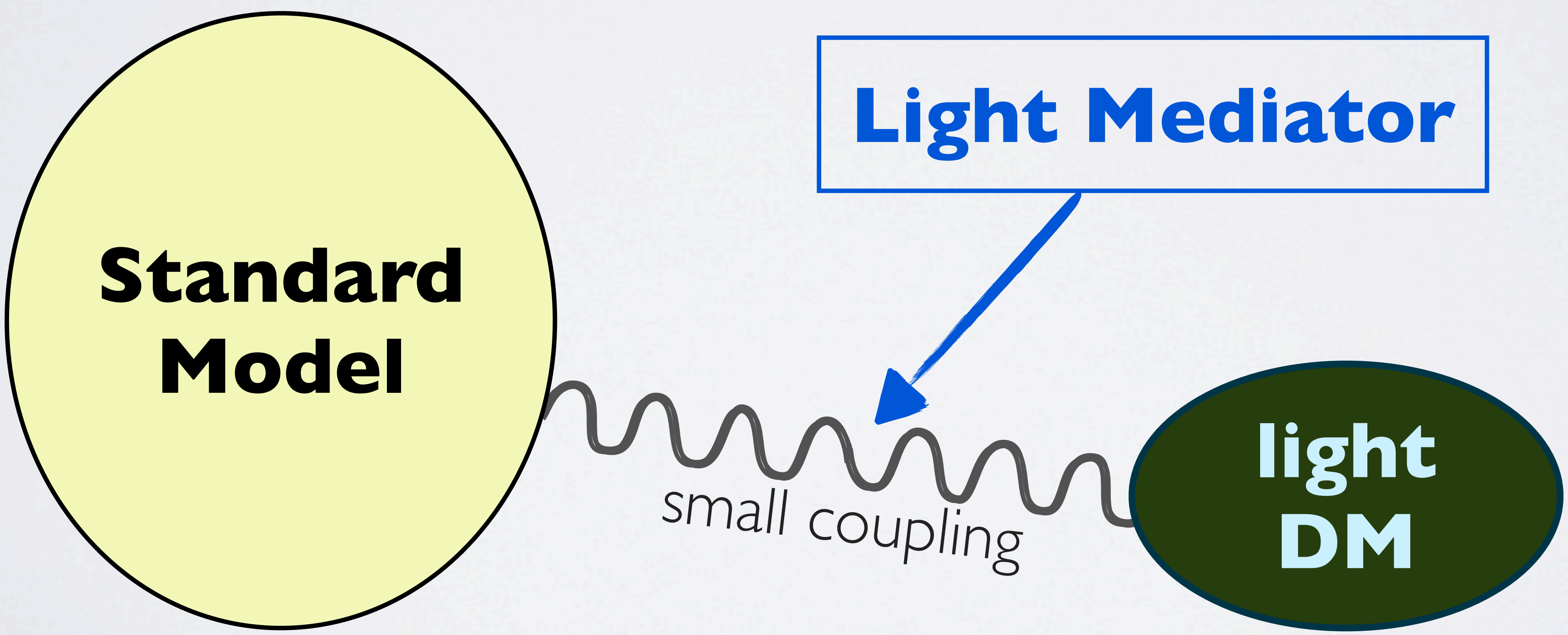
(an illustrative example)



VARIETIES OF SUB-GEV DM

(an illustrative example)

Low-energy effective theory



See e.g. 1108.5383, 1111.0293, 1112.0493, 1203.2531, 1203.4854, 1302.3898

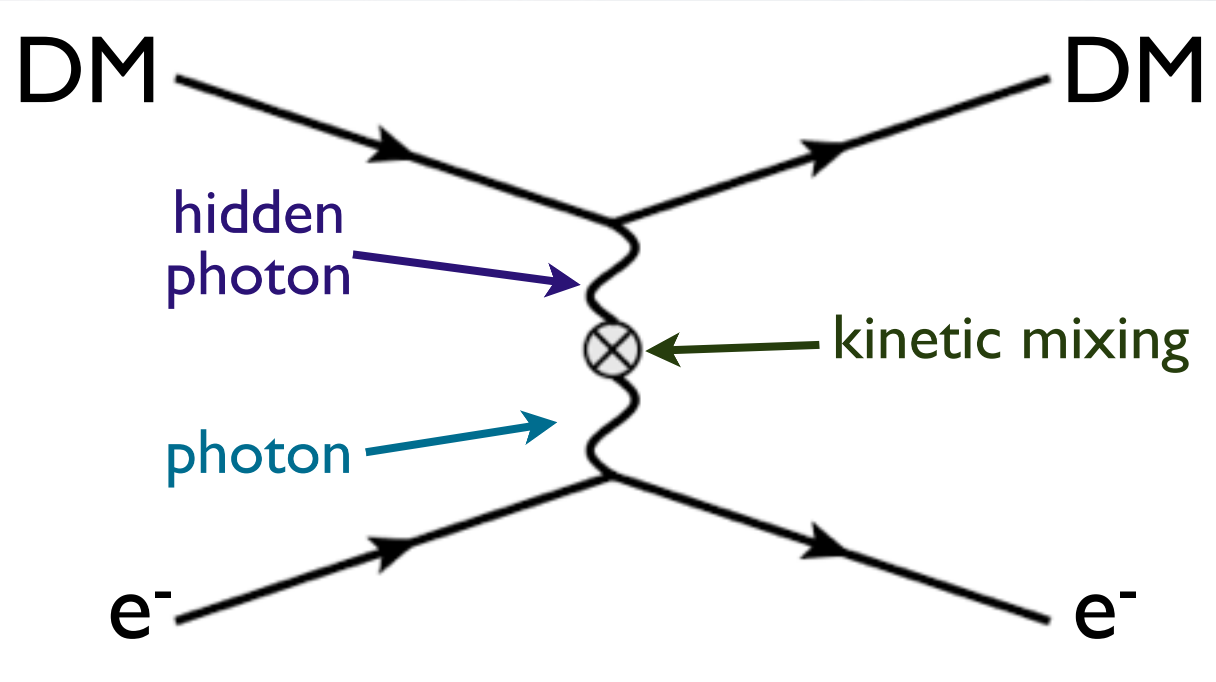
BENCHMARK MODELS

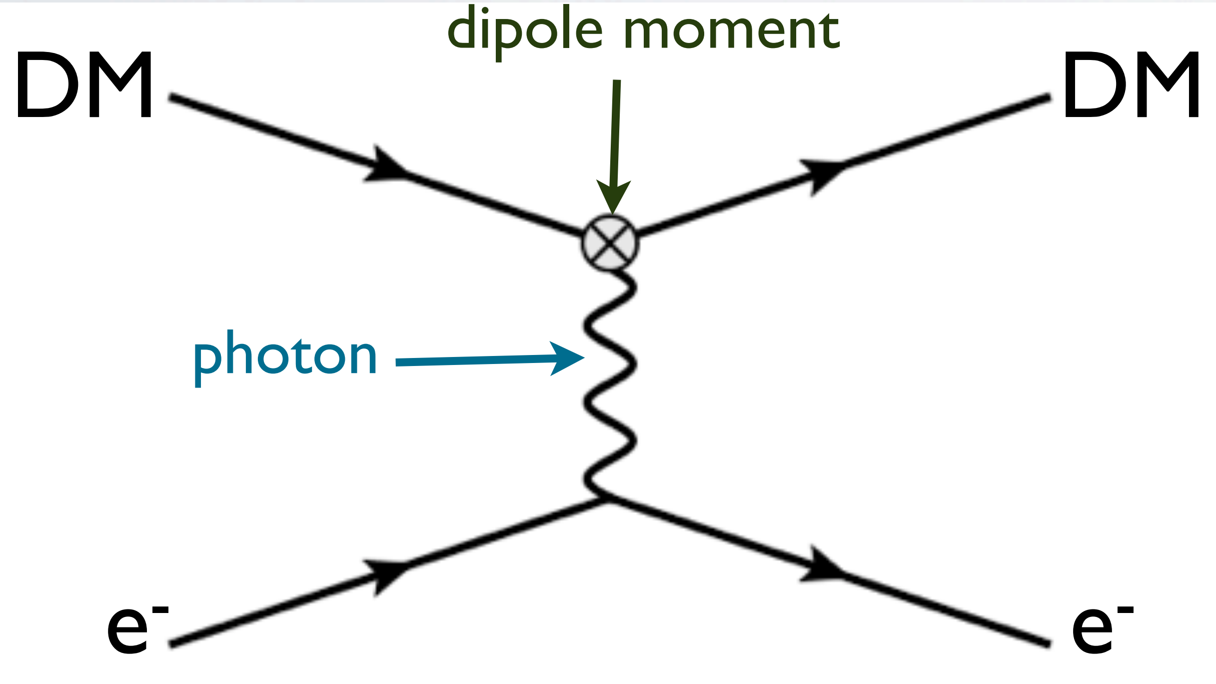
DM coupled to a *hidden photon* mediator (aka A′ boson)

A: hidden photon mass ~ 10 MeV

B: hidden photon mass << keV

e.g. Essig et al 1108.5383, Lin et al 1111.0293, Chu et al 1112.0493
Hall et al 0911.1120





DM with an *electric* or *magnetic dipole moment*

Sigurdson et al Phys.Rev. D70 (2004) 083501 + Erratum-ibid.
Graham et al 1203.2531

BENCHMARKS: ABUNDANCE

Basic freeze-out ruled out by CMB for DM lighter than 10 GeV

e.g. Galli et al 0905.0003
Giesen et al 1209.0247

Hidden photon mass ~ 10 MeV: Asymmetric

Essig, JM & Volansky 1108.5383
Lin, Yu & Zurek 1111.0293

Hidden photon mass << keV: Freeze-In

Hall et al 0911.1120
Essig, JM & Volansky 1108.5383
(but see also An, Pospelov & Pradler 1304.3461)

MDM/EDM: generically overabundance problem

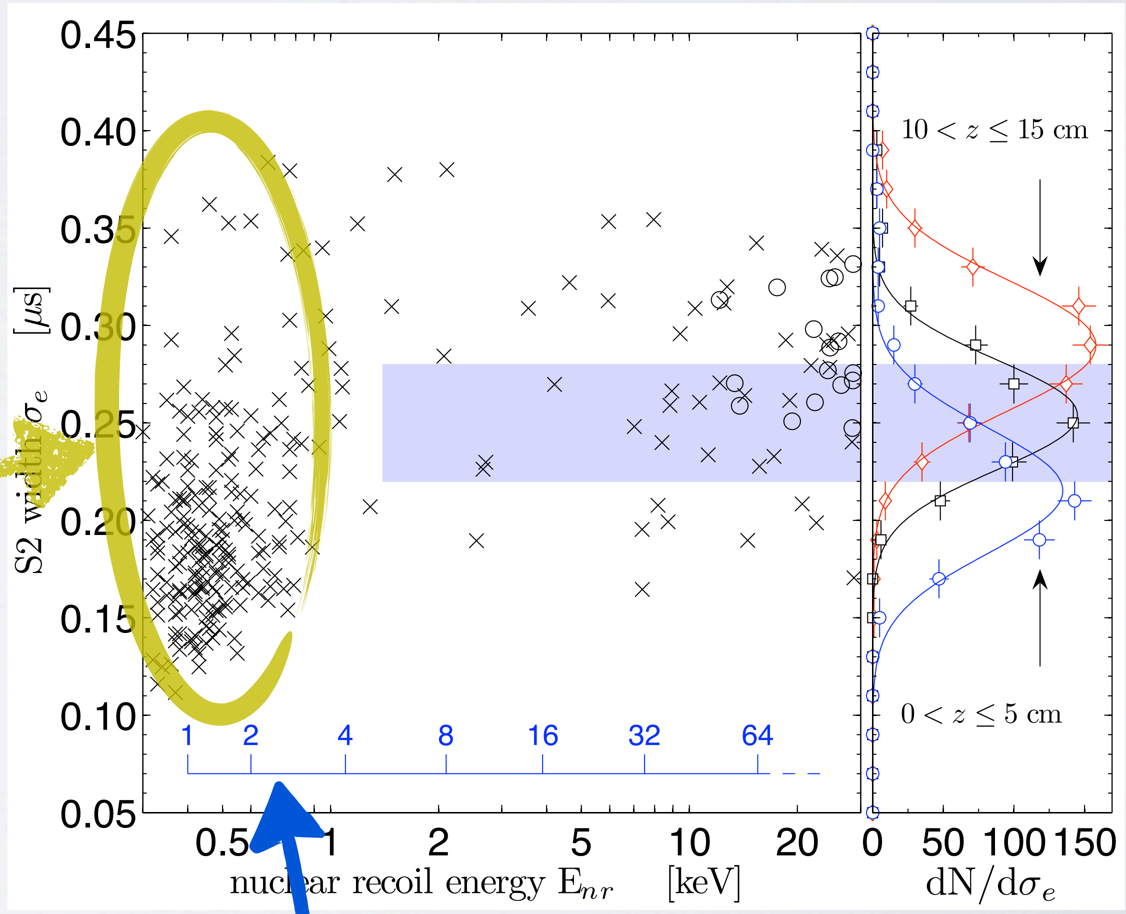
PROOF OF PRINCIPLE: XENON10

XENON10:

- Incredible sensitivity: could measure single electrons
- Hardware trigger only recorded single electrons during a 15 kg-day exp. in 2006

"A search for light dark matter in XENON10 data"
1104.3088

single/few-electron events
(background events)



number of ionized electrons

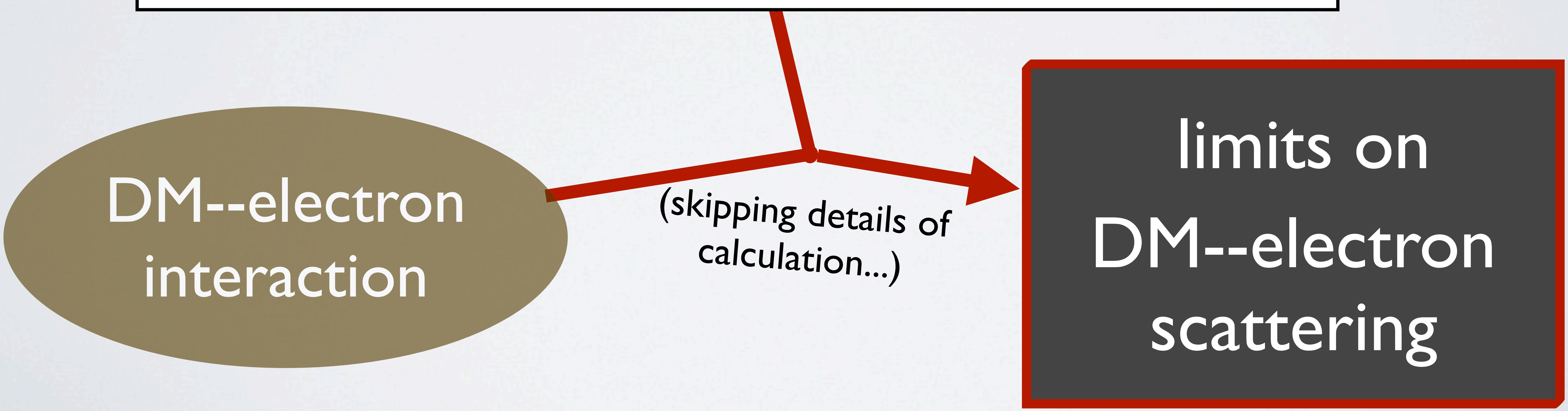
PROOF OF PRINCIPLE: XENON10

Extracting limits on 1-, 2-, and 3-electron rates:

(skipping many important details...)

limits: R1 < 39, R2 < 4.7, R3 < 1.1 counts per kg-day

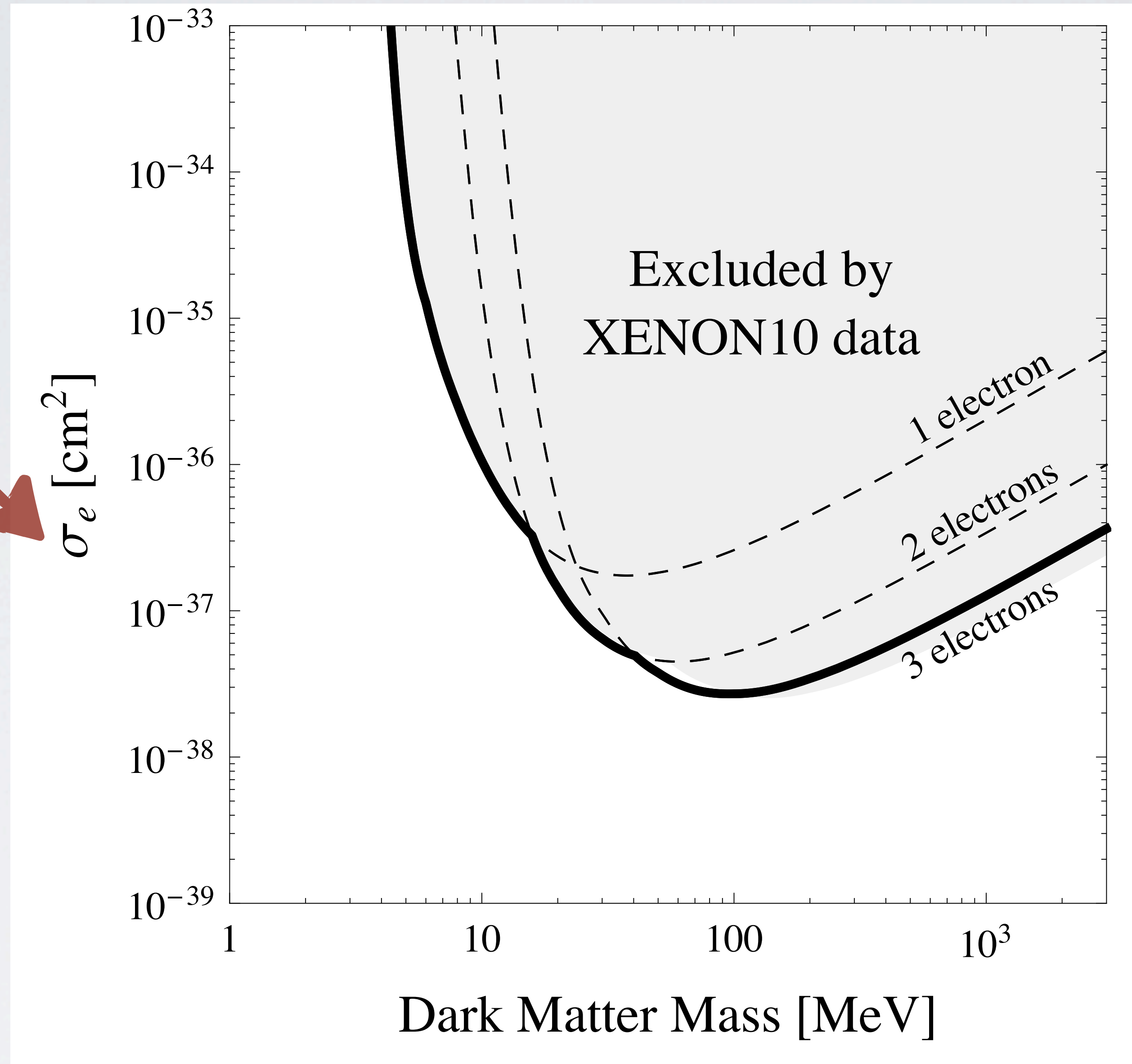
at 90% CL



Essig, Manalaysay, JM, Sorensen & Volansky. 1206.2644

PROOF OF PRINCIPLE: XENON10

cross-section to scatter with free electron



"First Direct Detection Limits on sub-GeV DM"

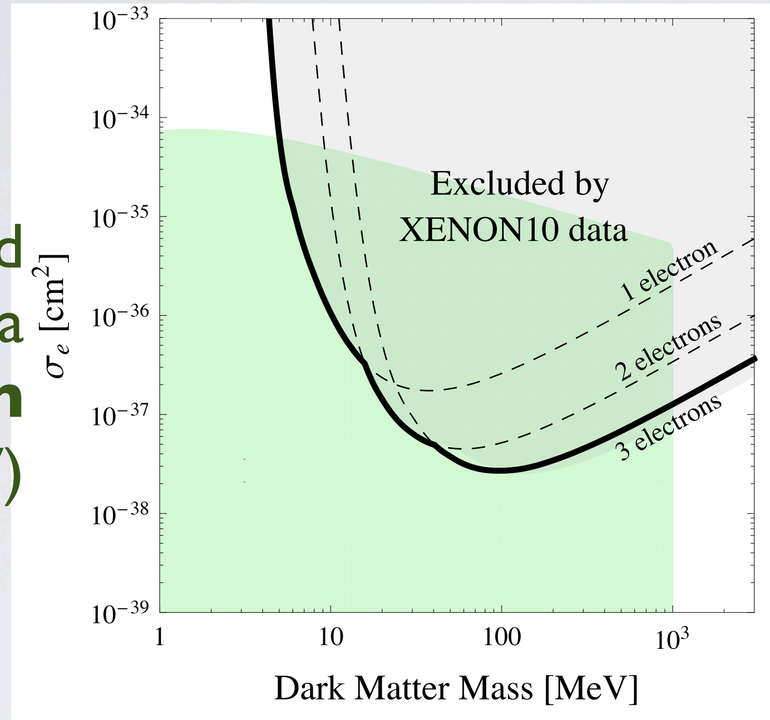
Essig, Manalaysay, Mardon, Sorensen & Volansky

arXiv:1206.2644

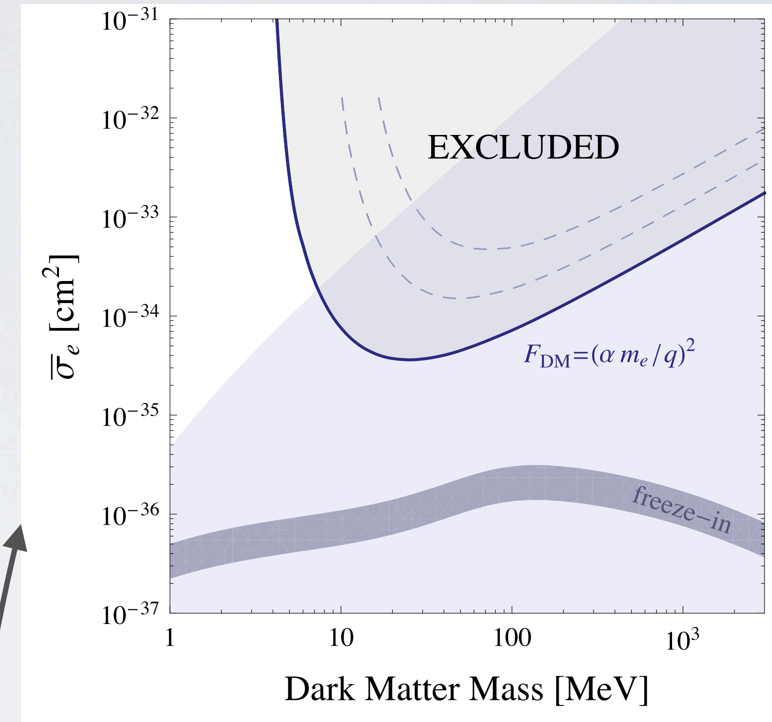
HOW DOES THIS COMPARE TO BENCHMARKS?

(PREVIOUSLY ALLOWED REGIONS ARE SHADED)

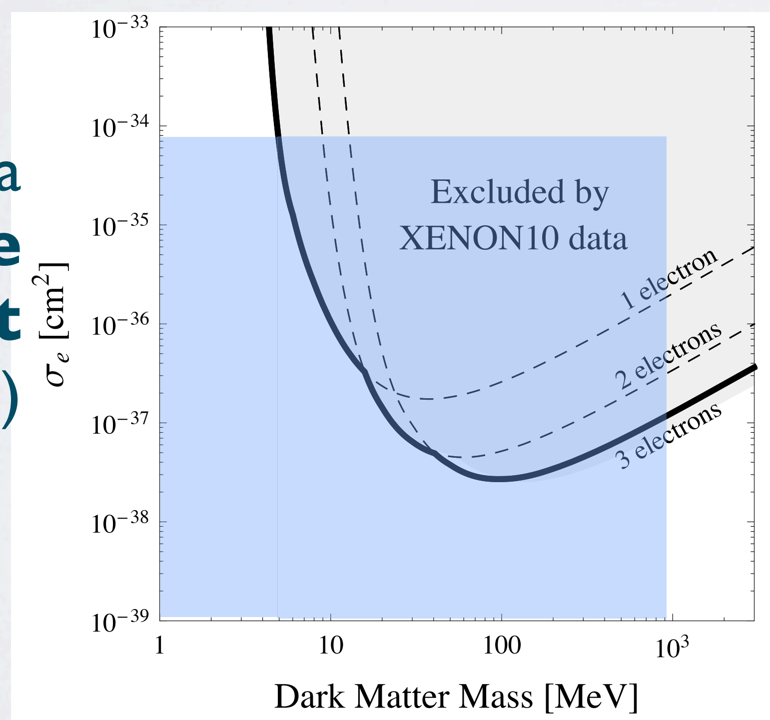
DM coupled via a **hidden photon** (mass~10 MeV)



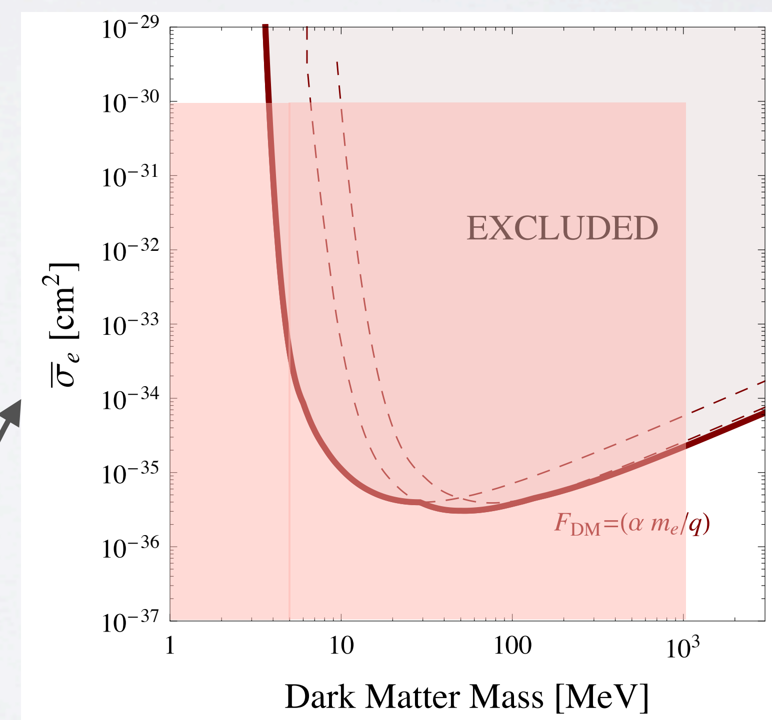
DM coupled via an **ultra-light hidden photon** (mass<< keV)



DM with a **magnetic dipole moment** (μ<TeV^{-1})



DM with an **electric dipole moment** (d< TeV^{-1})



different momentum-dependence of DM coupling

Essig, Manalaysay, Mardon, Sorensen & Volansky. 1206.2644

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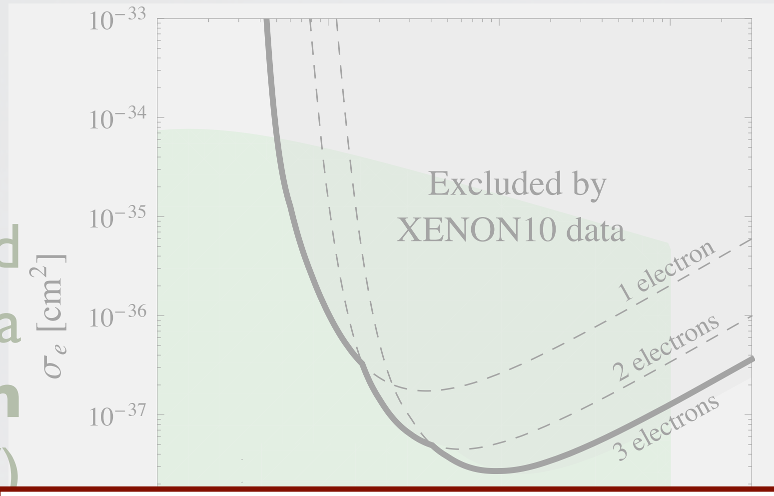

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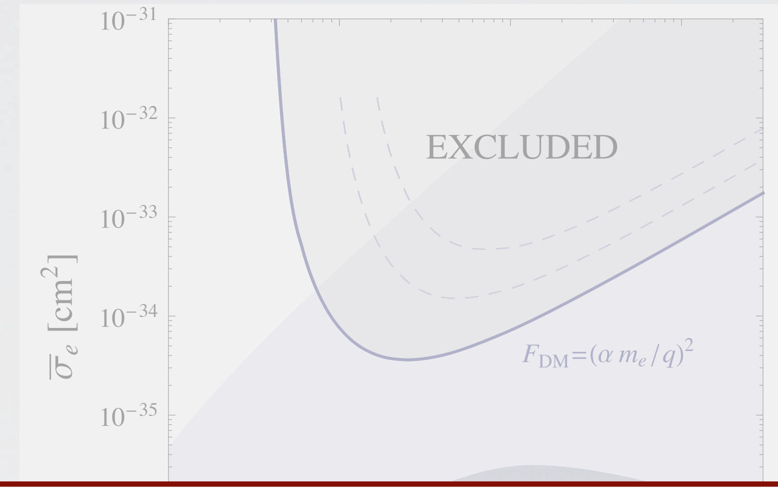
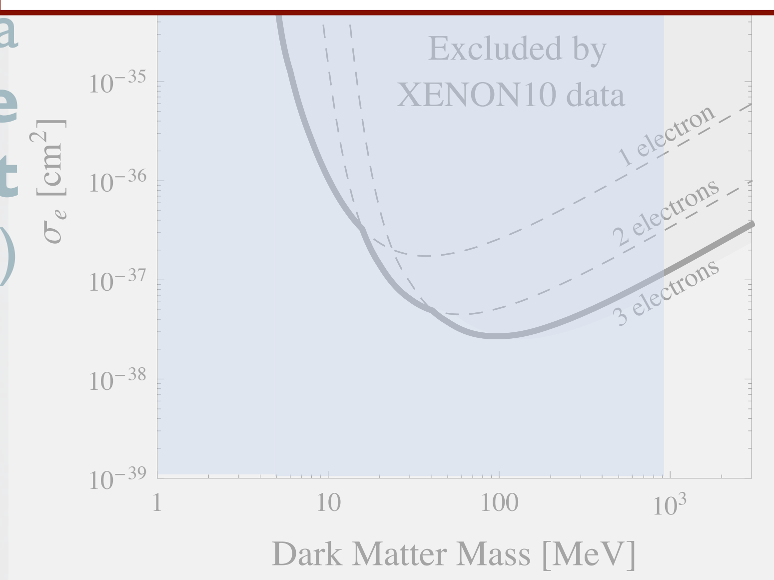


This is just a proof of principle

(with a lucky, small dataset)

DM with a **magnetic dipole moment** (μ<TeV^{-1})



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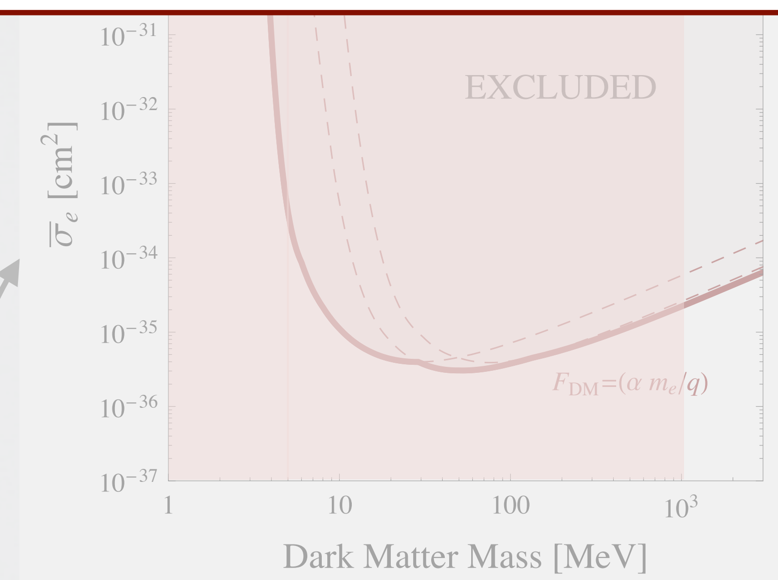

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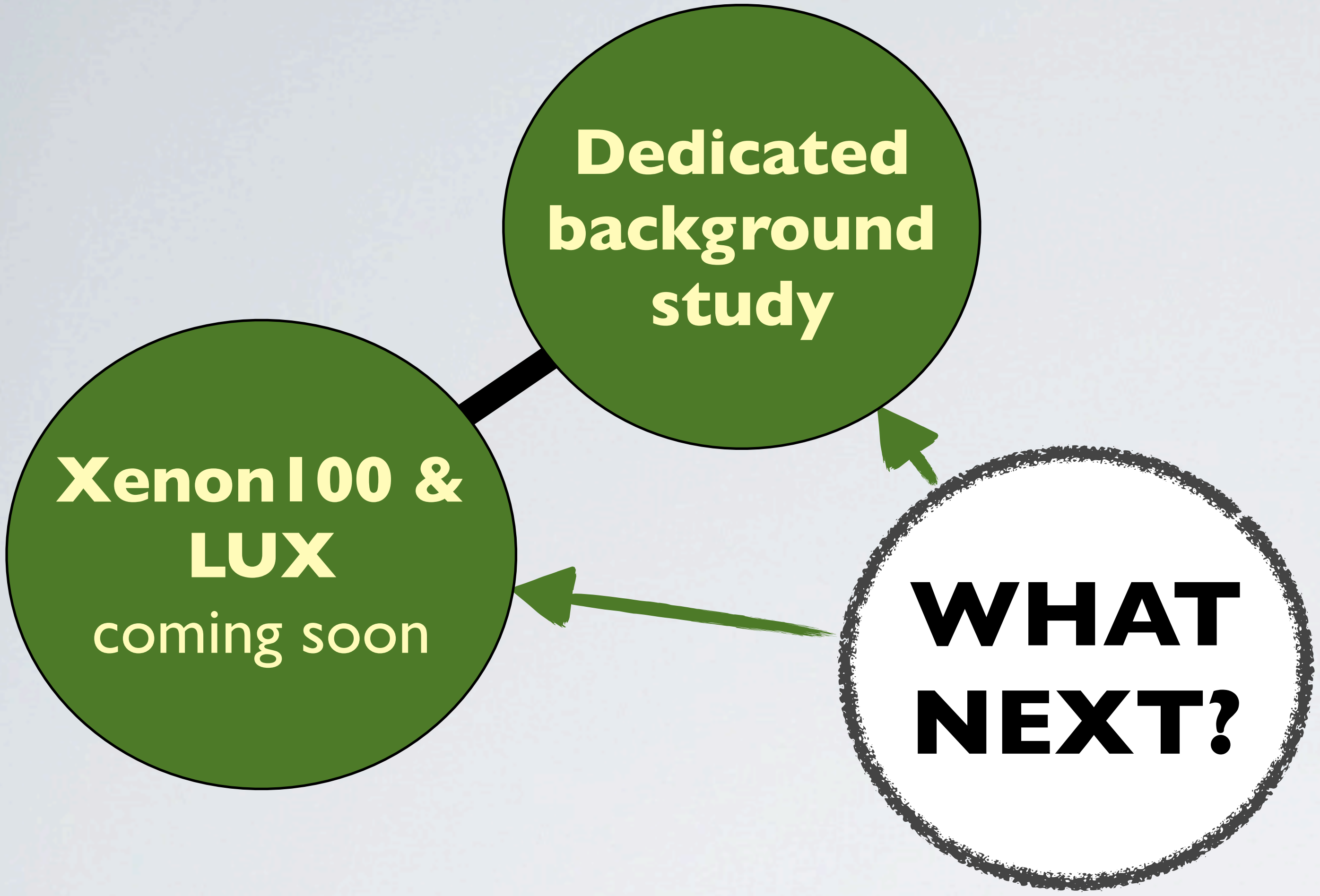
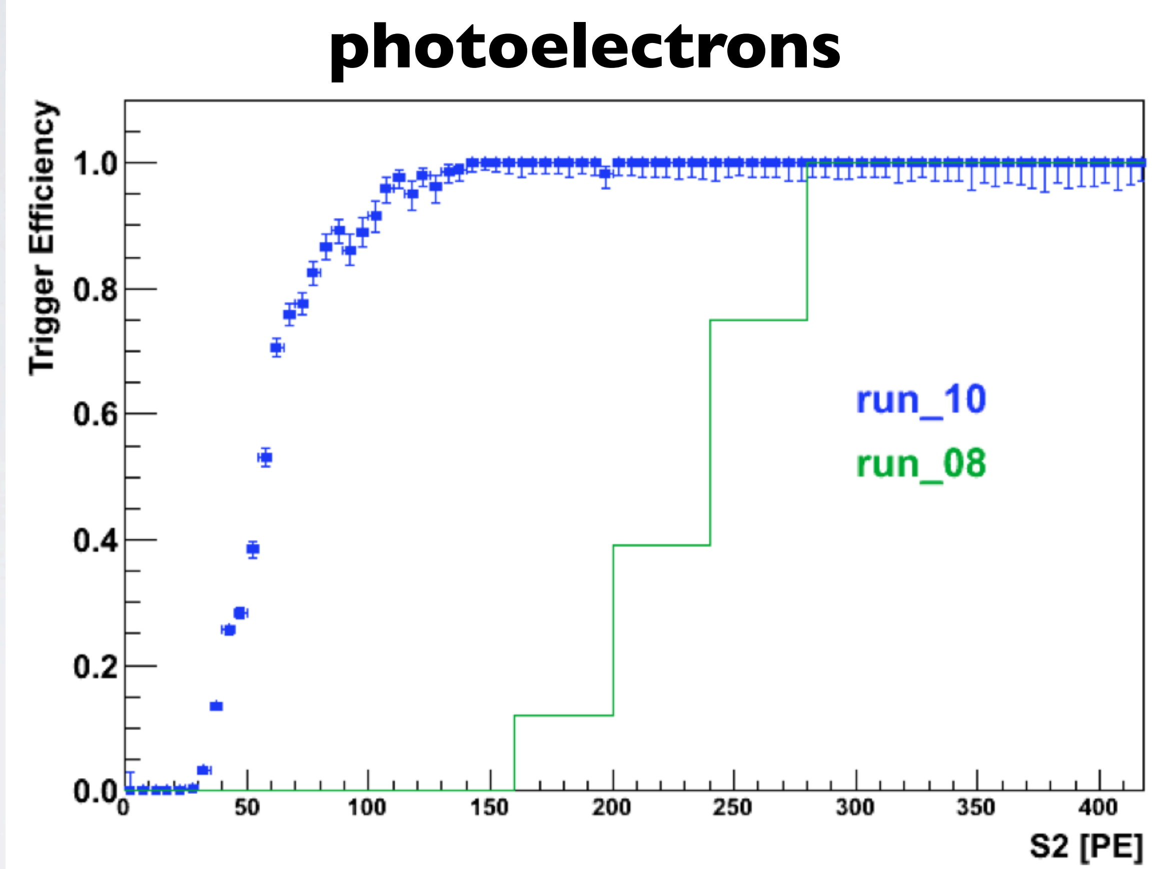
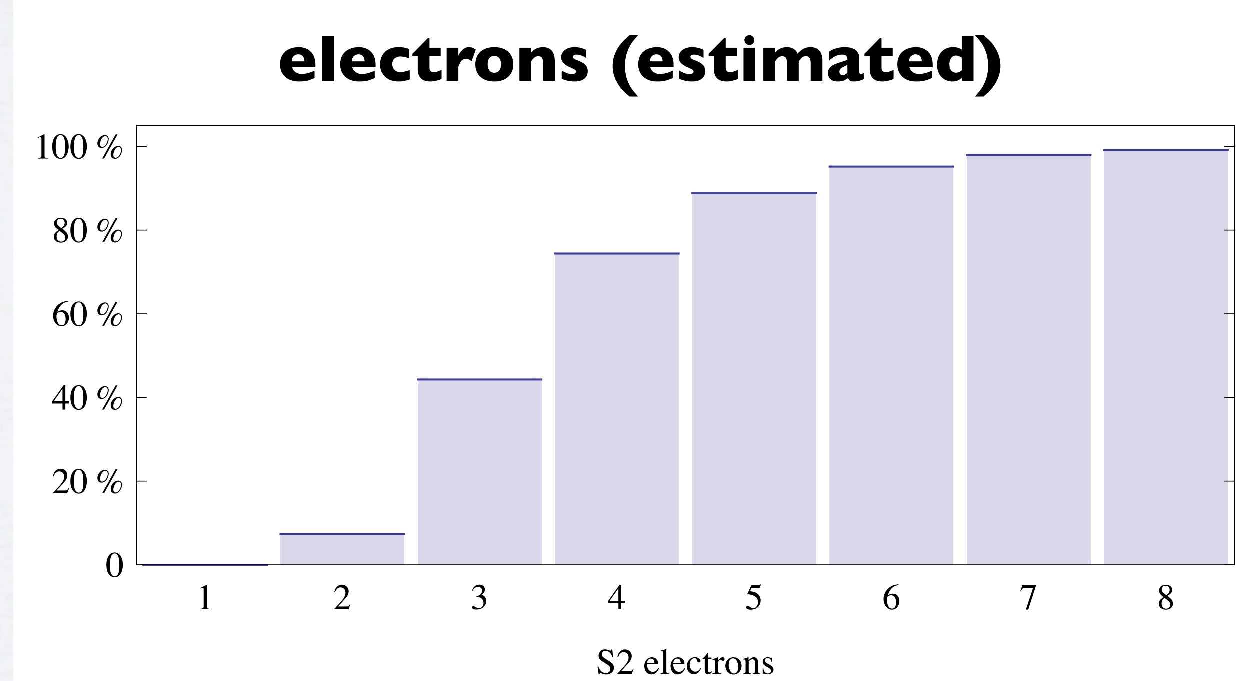


Xenon100 S2 trigger:



Aprile, DarkAttack 2012

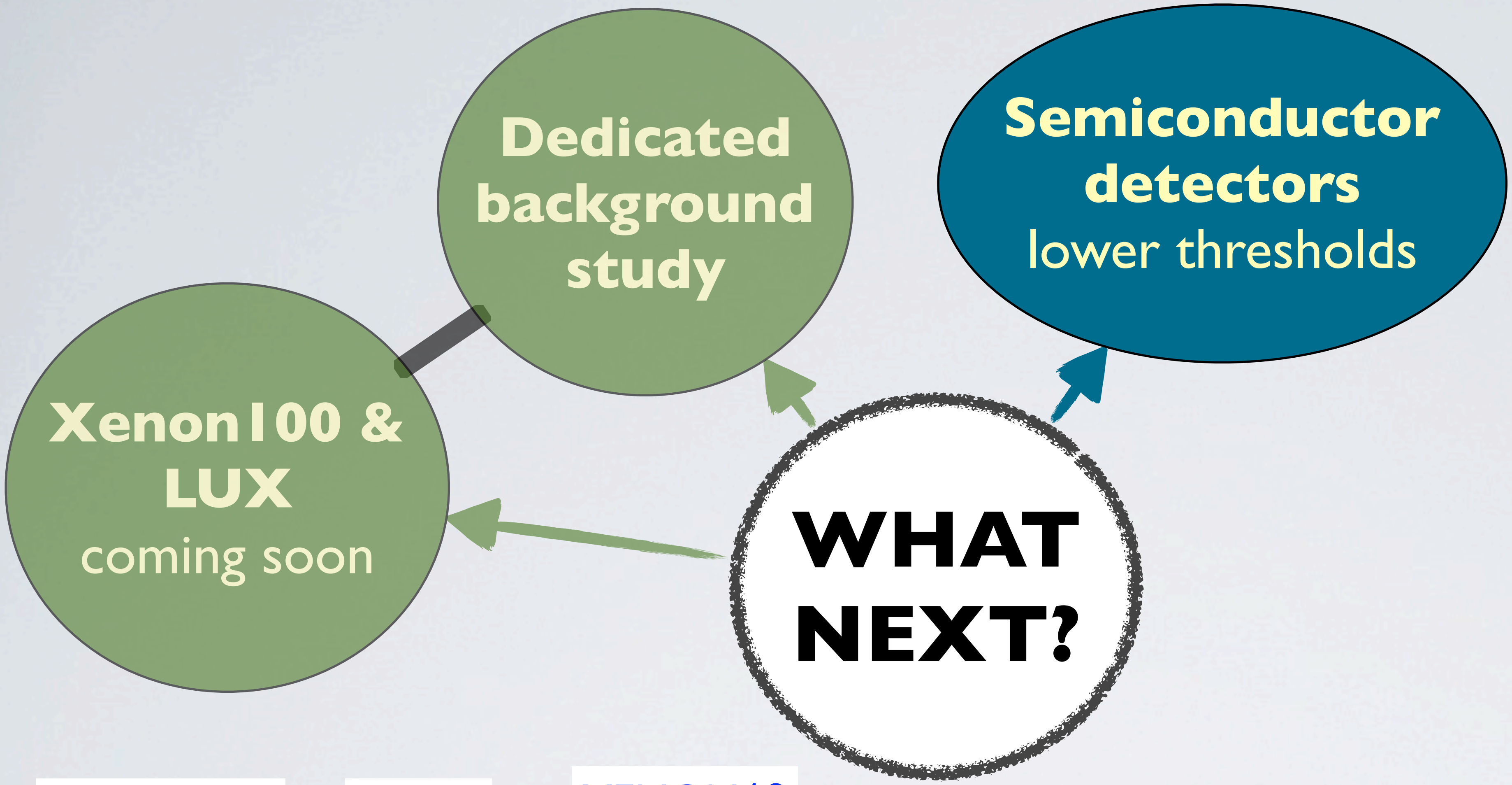


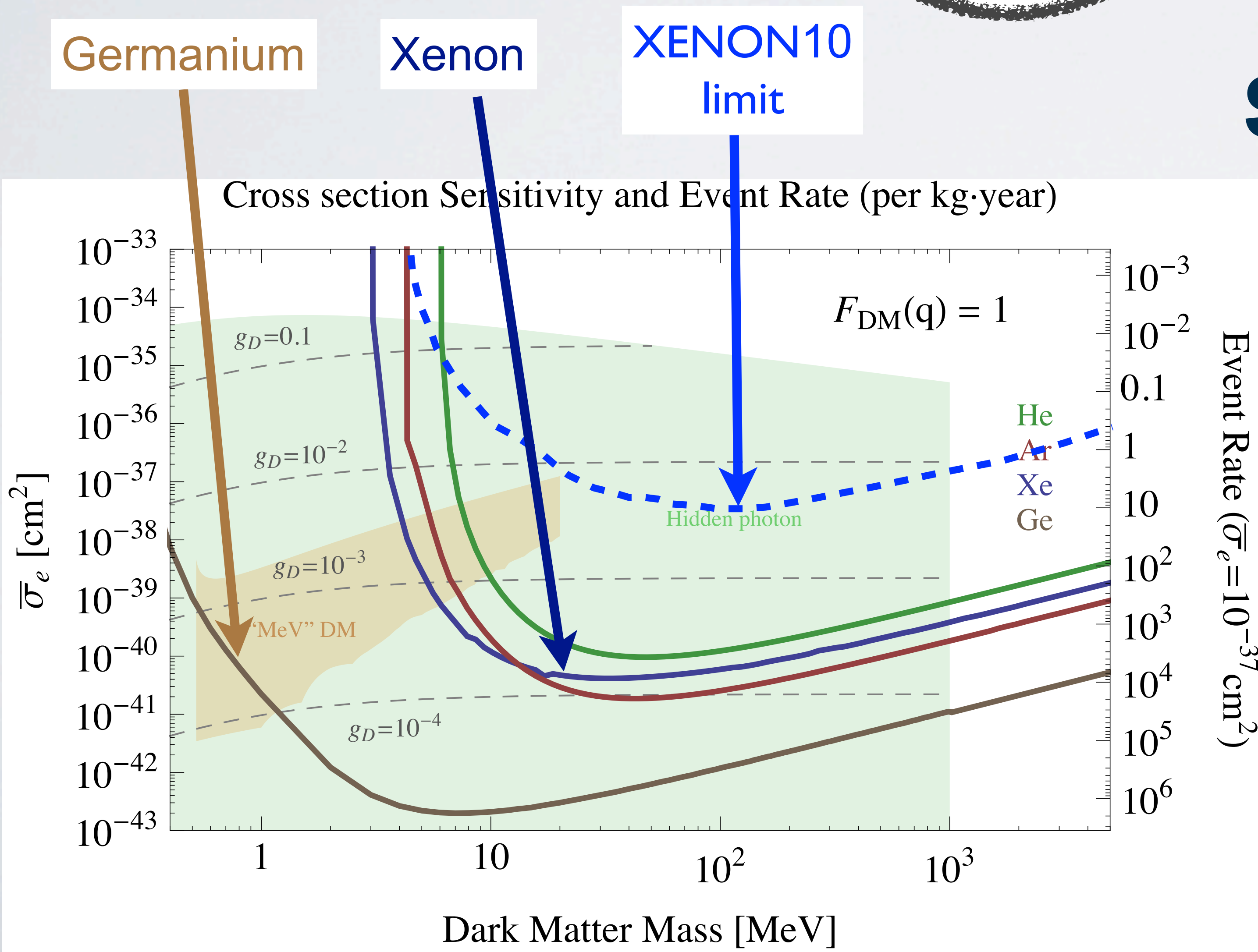
Dual phase xenon

- Xenon100 study underway
- LUX coming soon
- needs low trigger thresholds!

1st priority is backgrounds

- what causes them?
- how can they be reduced?





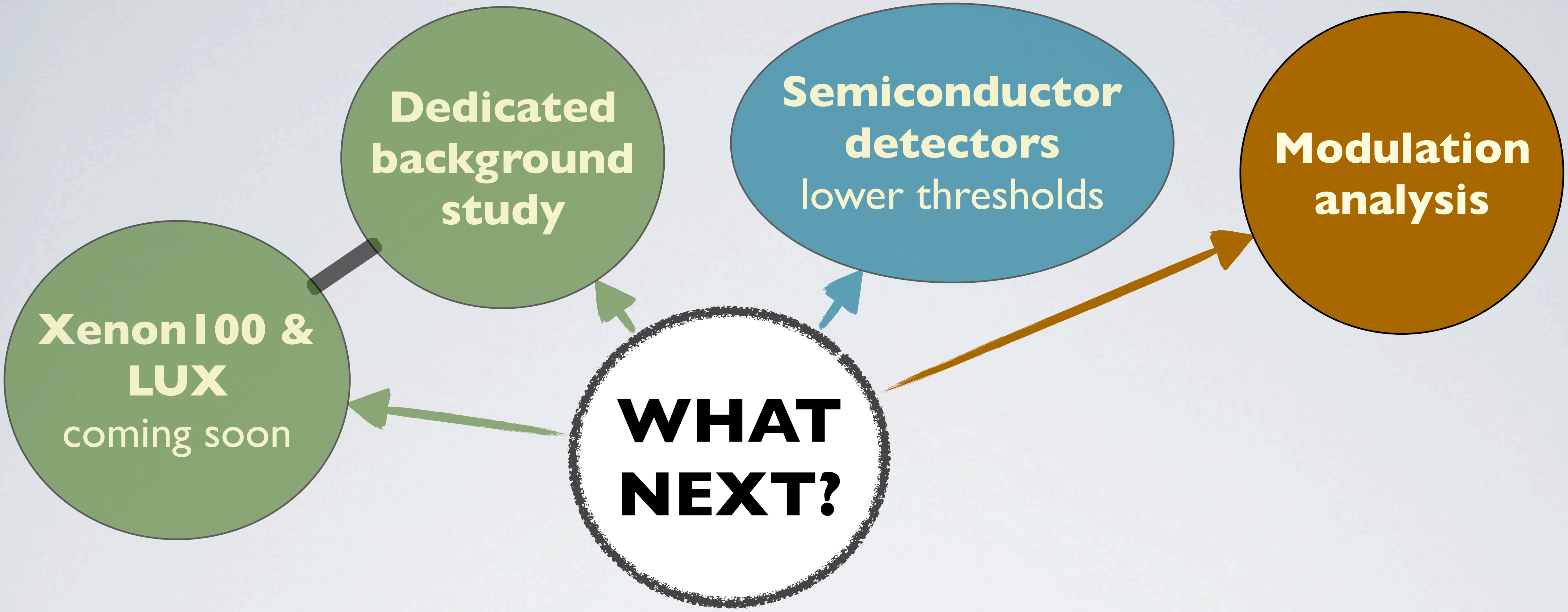
Semiconductor detectors

- lower threshold (~1eV)

- technology being developed by CDMS and DAMIC

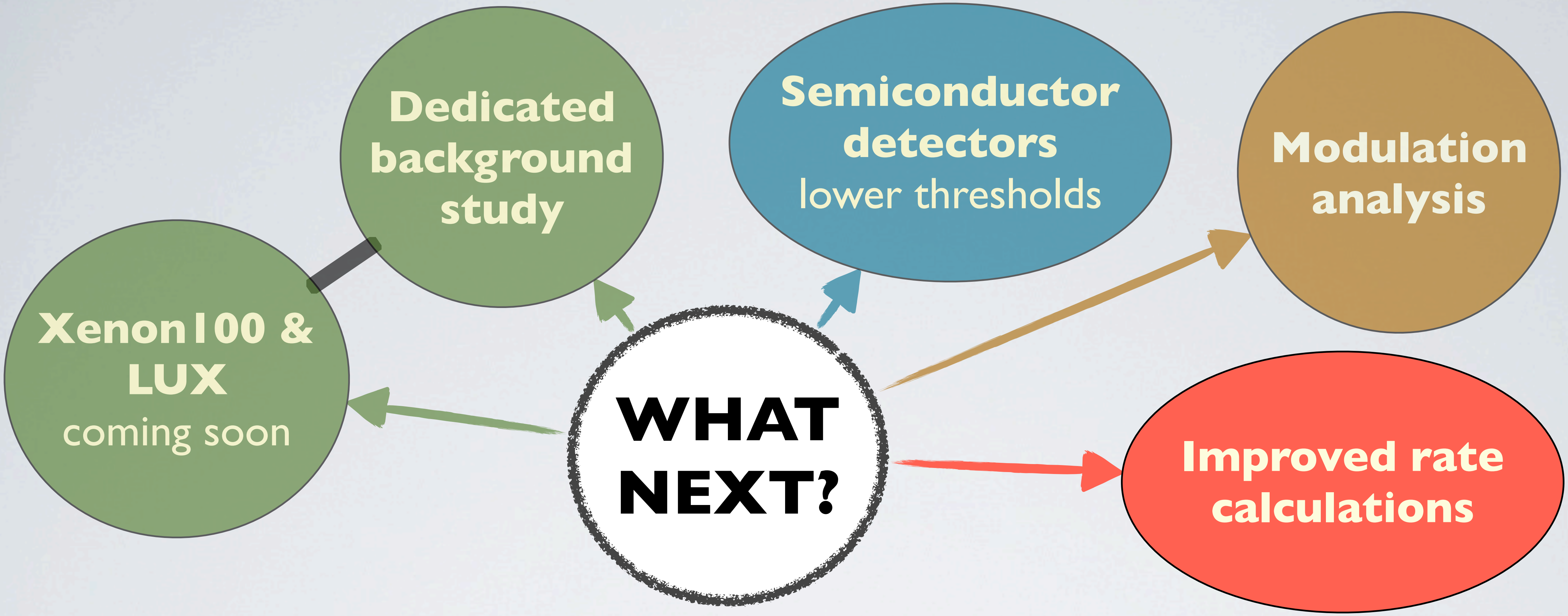
- lower backgrounds?

Essig, Mardon & Volansky. 1108.5383



Making a discovery

- no way to discriminate signal events from background events(?)
- there's always annual modulation



particle physics → free cross-section

atomic quantum mechanics → atomic form-factor

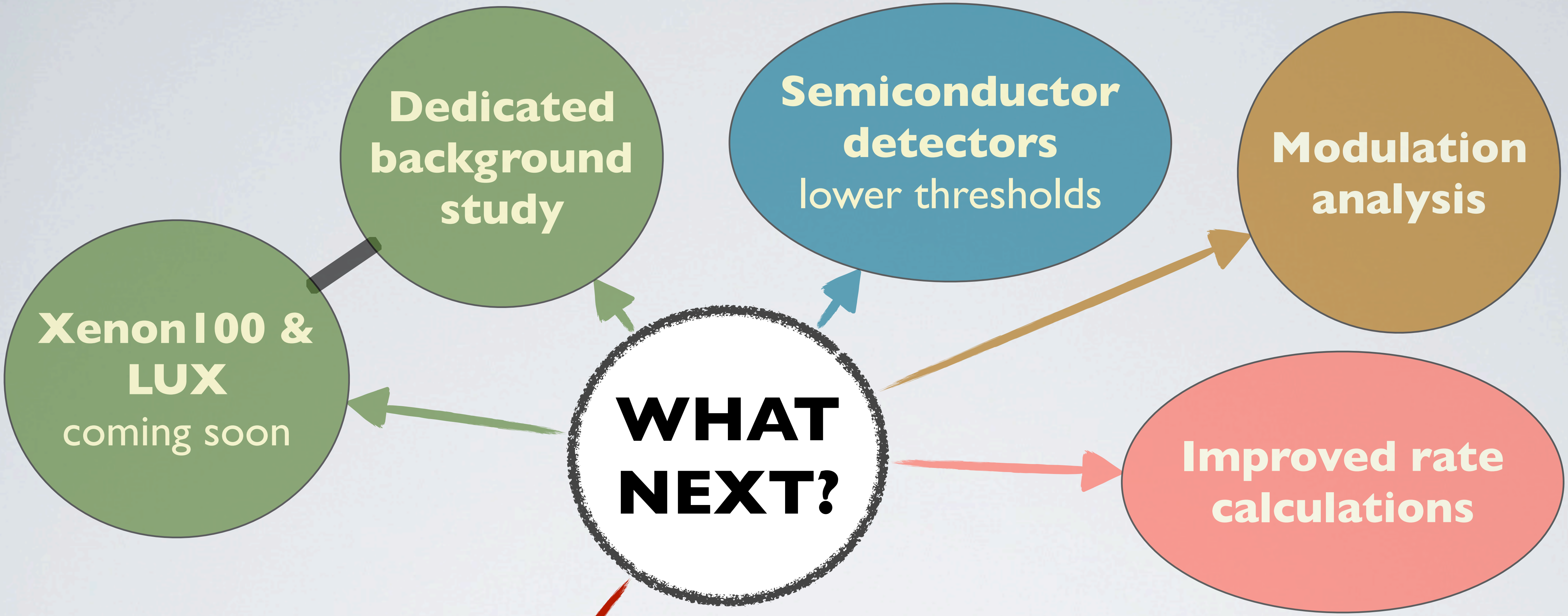
semi-empirical model → secondary scattering probability

Event rate = free cross-section x atomic form-factor x secondary scattering probability

- current error O(1) (not O(10))

- biggest uncertainty is in size of S2

- can this be calibrated experimentally?



SOMETHING NEW?

Dedicated experiment?

New ideas?

... e.g. molecular dissociation

- detect nuclear recoil with ~eV threshold
- could this ever be detected?
- with T. Volansky, R. Essig & others

CONCLUSION

We may have paid too much attention to the Weak scale and WIMP DM

Direct detection can probe DM masses down to the <u>MeV</u> scale via electron scattering

Need to understand and reduce backgrounds

- **XENON100 study underway**
- **LUX coming soon**

New single-electron detectors?

- **CDMS & DAMIC**

There's room for new ideas!

BACK UP SLIDES

SUB-GeV DARK MATTER

Jeremy Mardon, SITP, Stanford

Is anything wrong with sub-GeV DM

Warm DM?

- too light --- moves too fast --- washes out small-scale structure
- **typically only a problem for masses below ~10keV**

Self-interactions?

- lighter DM --- more numerous --- more self scattering
- In conflict with e.g. Bullet Cluster and halo ellipticity

Markevich et.al. 2003
Miralda-Escude 2000
Feng et.al. 0905.3039

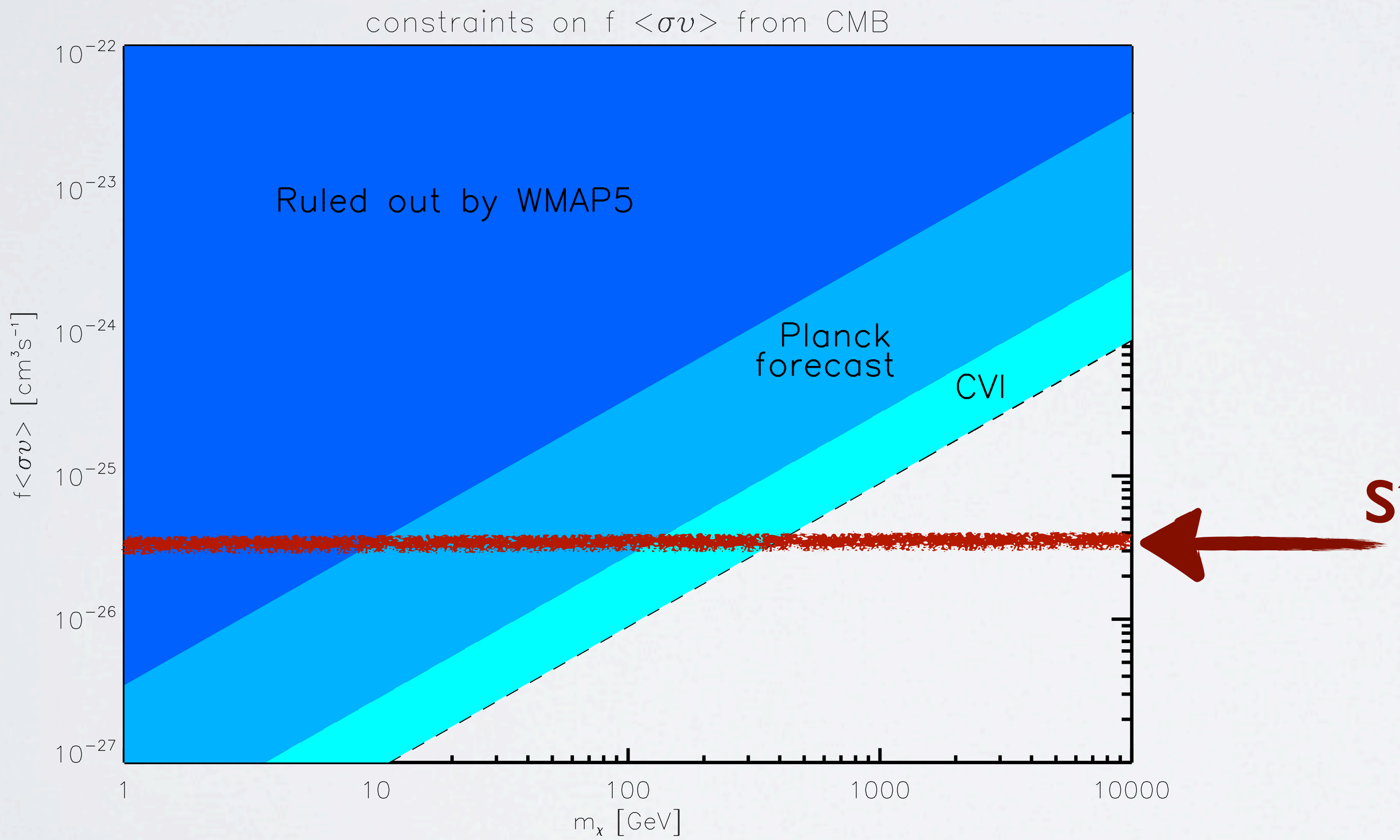
- **constrains couplings for DM lighter than ~GeV**

IS ANYTHING WRONG WITH SUB-GEV DM

Annihilation distorts CMB

- DM annihilation into EM-interacting particles delays recombination
- would be observable in CMB

Galli et.al. 0905.0003



standard freeze-out cross-section

Standard freeze-out is ruled out below ~10 GeV

Jeremy Mardon, SITP, Stanford

IS ANYTHING WRONG WITH SUB-GEV DM

Abundance:

- Asymmetric DM
  - e.g. SUSY (at some scale) + inflation + accidental symmetry

    --> generic matter asymmetry

    Dine, Randall & Thomas 1995

- Freeze-in

  Hall et.al. 0911.1120

- Freeze out within hidden sector

  Feng & Kumar 0803.4196

VARIETIES OF SUB-GEV DM

Contact interactions

- e.g. $\frac{\overline{\chi}\gamma^{\mu}\chi\ \overline{e}\gamma_{\mu}e}{\Lambda^2}$

Constrained by LEP (gamma + M.E.)

Fox et al 1103.0240

$\Lambda > \mathcal{O}(500\text{GeV})$

LEP

Light mediator exchange

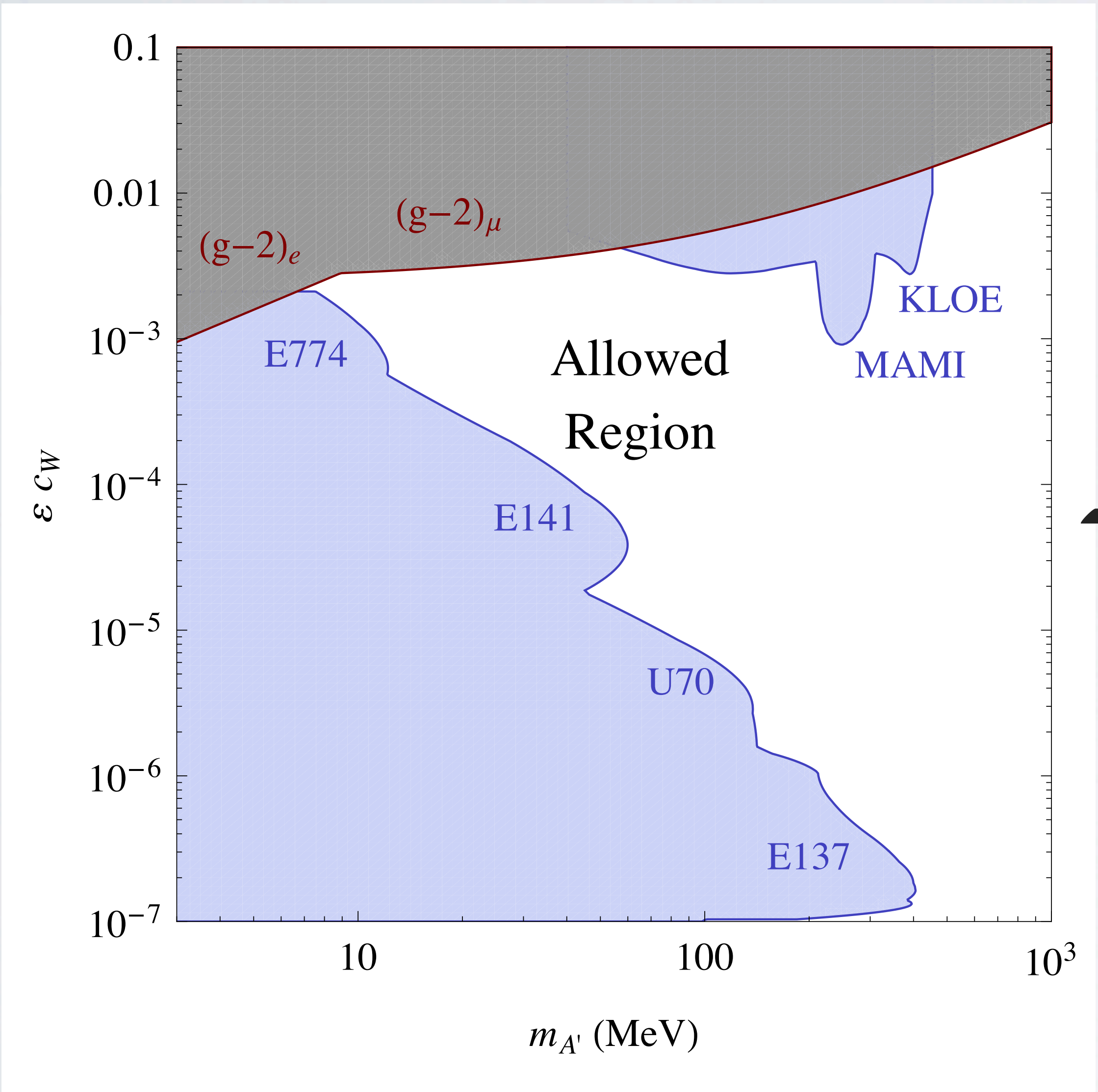
$m_{\text{mediator}} \ll \mathcal{O}(100\text{GeV})$

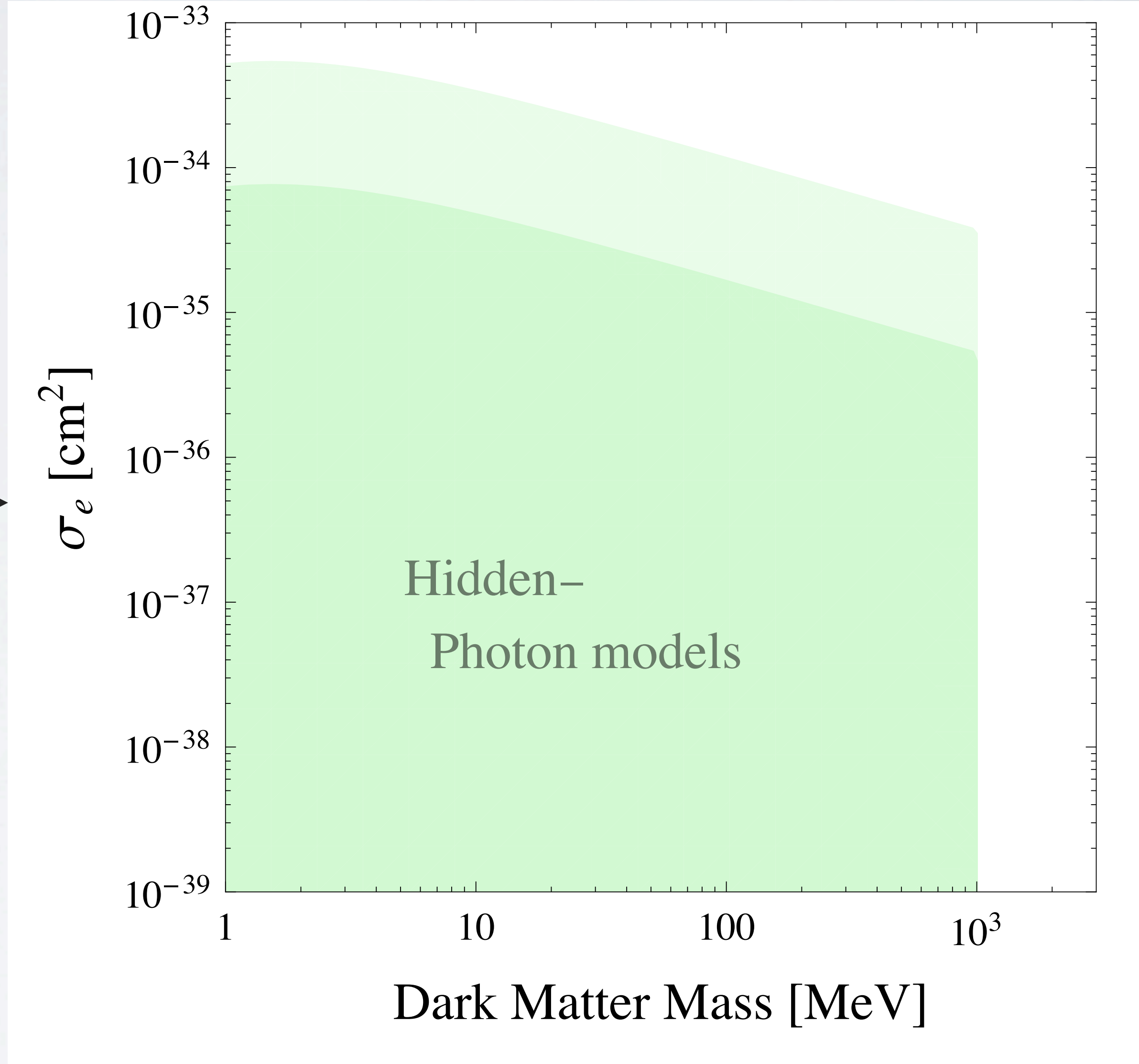
- light hidden photon
- *the* photon
- ~~axion / pseudo NGB~~

m_e-suppressed

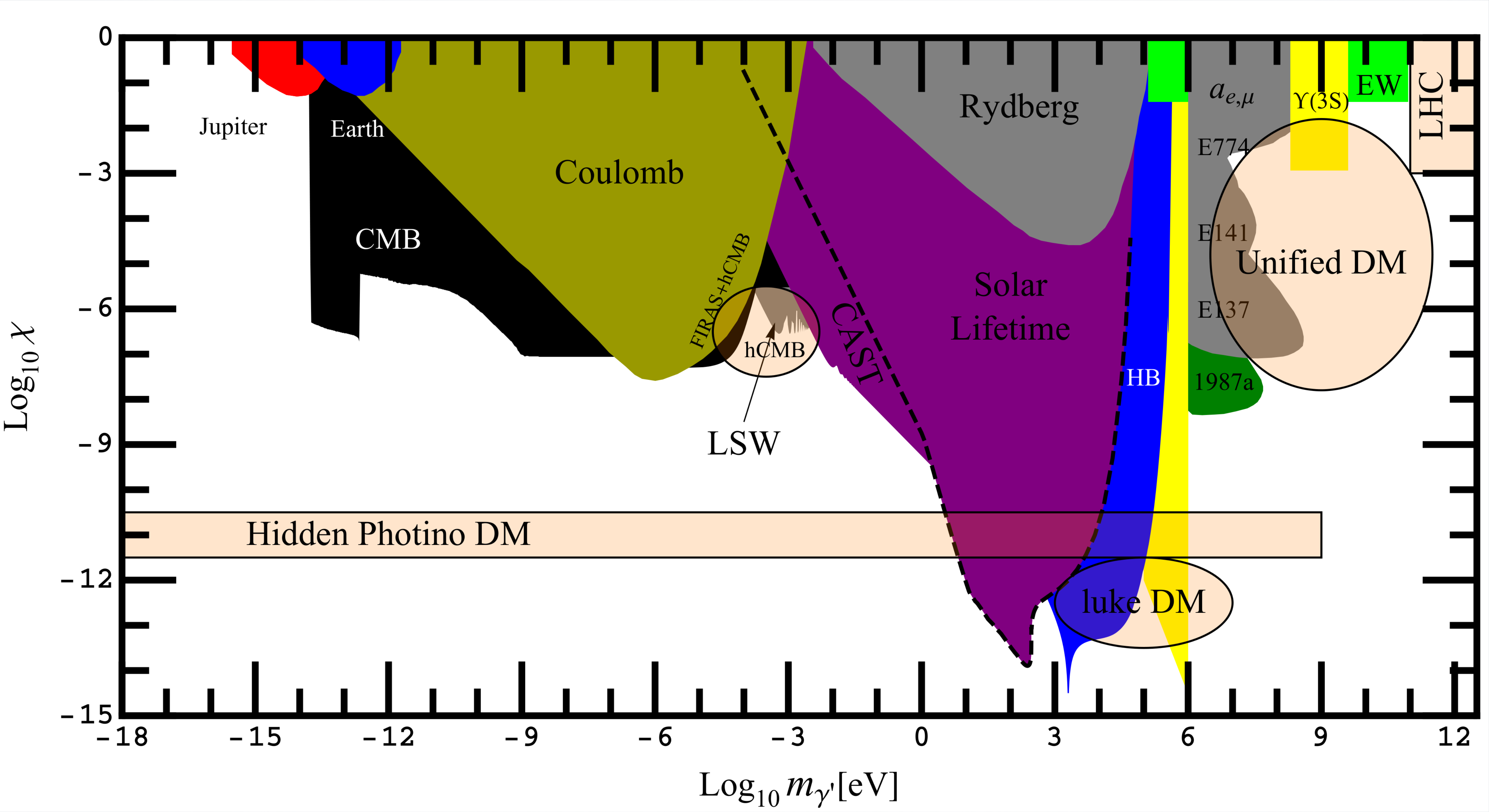
Not well constrained by LEP

HIDDEN PHOTON MODELS





Hidden Photon Models



Jaeckel & Ringwald, 1002.0329

Other possible signals?

Scattering with electrons → atomic exitation → individual photons?

- single-photon detection is currently *far* too noisy

Ionization → let deposited energy thermalize → phonons?

- may reach phonon thresholds of ~10s of eV in Germanium

Formaggio et.al.: 1107.3512

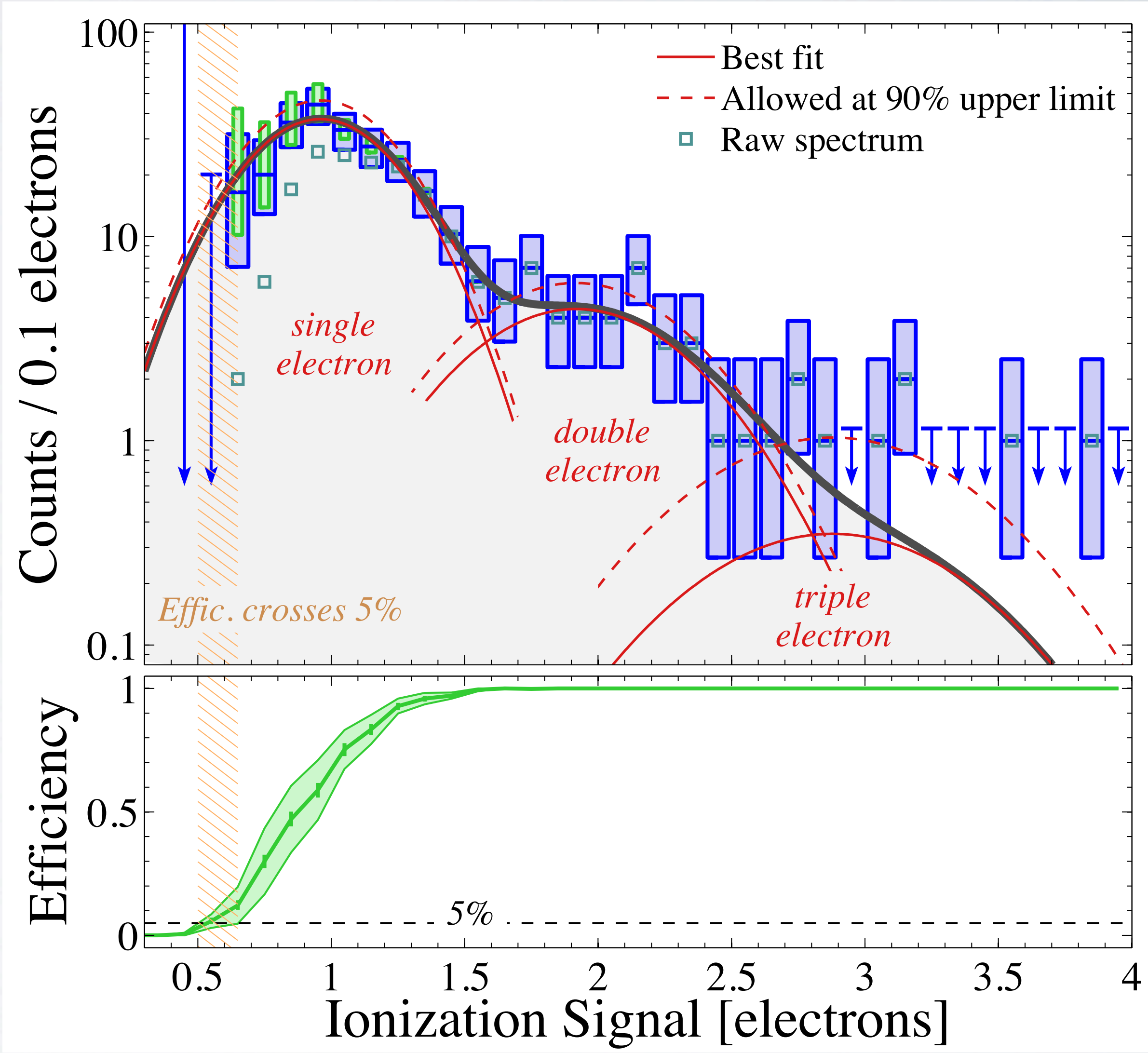
Scattering with nuclei in molecules → break molecular binding energy → collect individual ions?

- could probe nuclear coupling as well as electron coupling
- technology hasn't even been imagined yet

SINGLE ELECTRON EVENTS IN XENON10

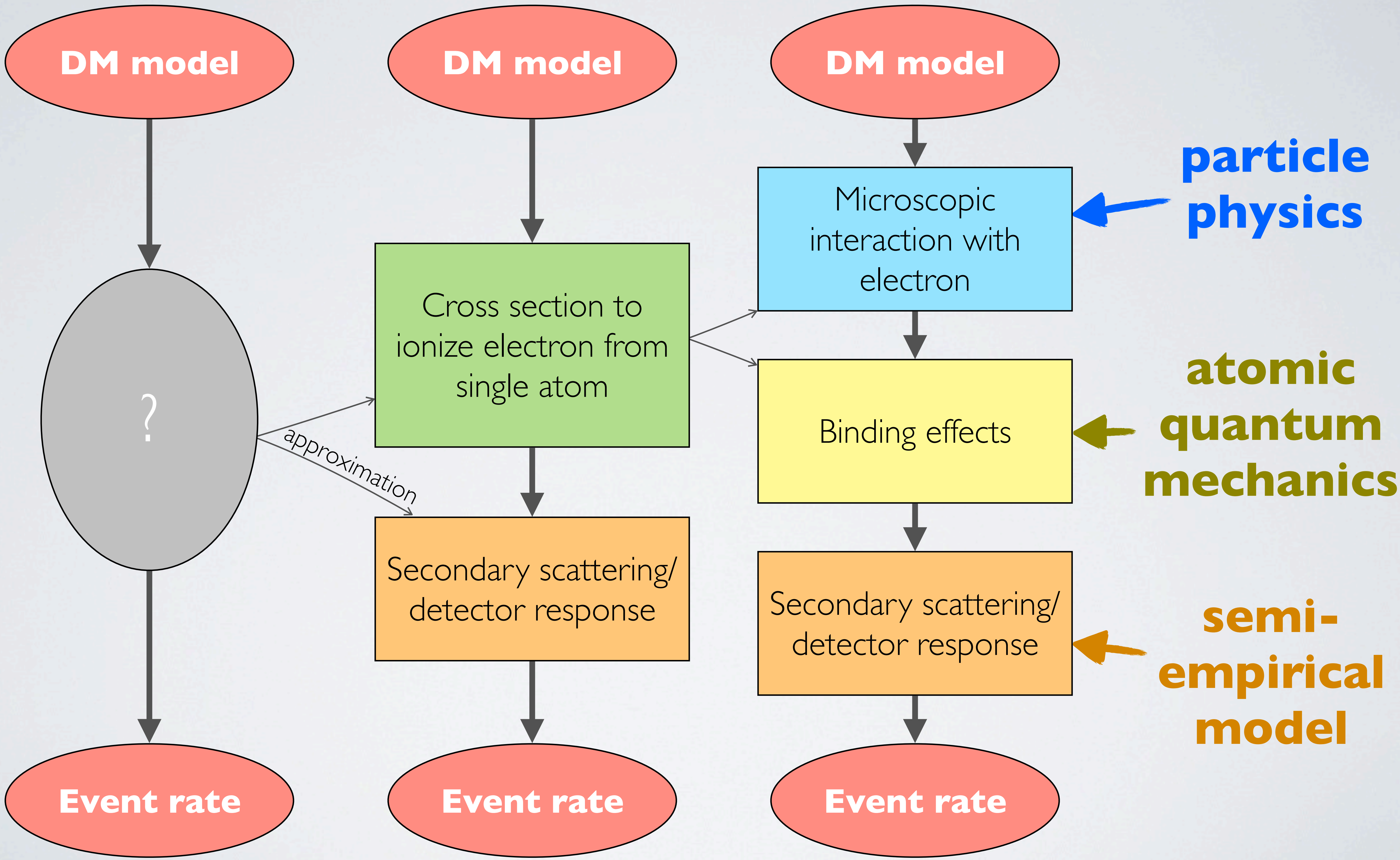
Understanding the events

- study single electrons seen in other event records
- Monte Carlo simulation of trigger efficiency
- produce 90% CL upper limits on 1-, 2- and 3-electron rates



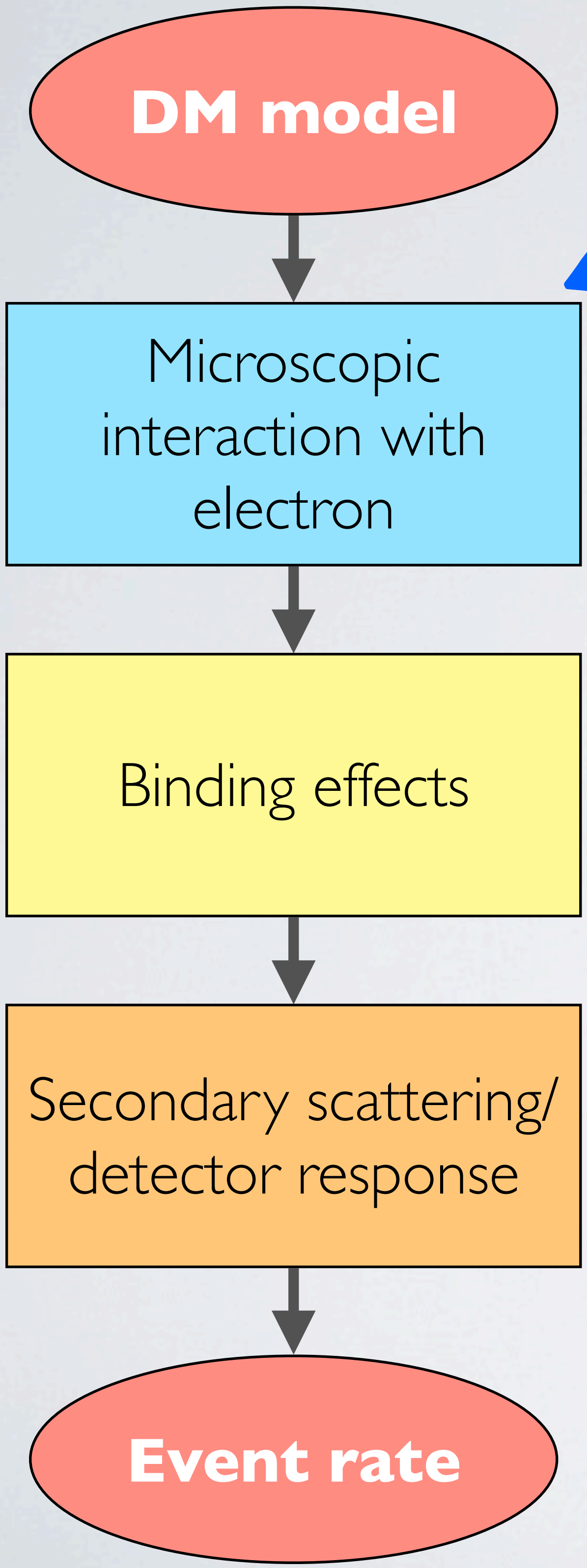
CALCULATING RATES

CALCULATING EVENT RATES



Essig, Mardon & Volansky. 1108.5383

CALCULATING EVENT RATES



particle physics

parametrize theory with:

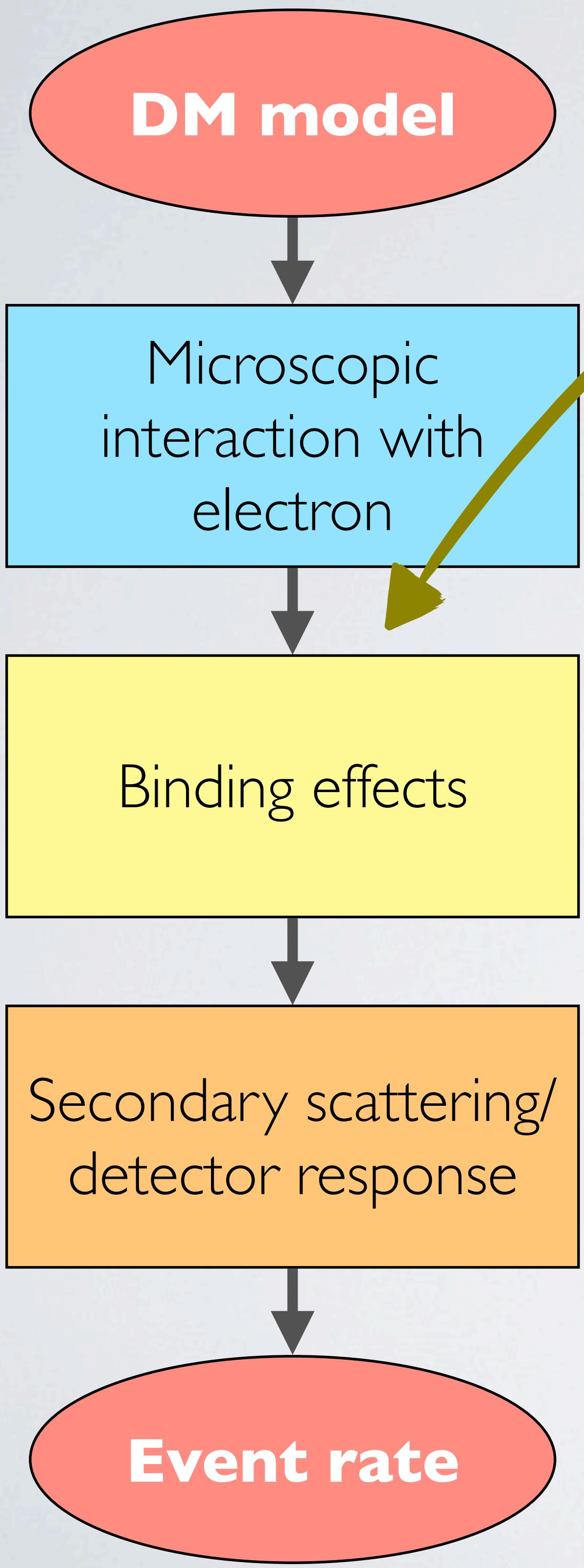
cross-section to scatter with a *free* electron: $\overline{\sigma_e}$

and

"DM form-factor" containing q-dependence of microscopic interaction: $F_{\rm DM}(q)$

Essig, Mardon & Volansky. 1108.5383

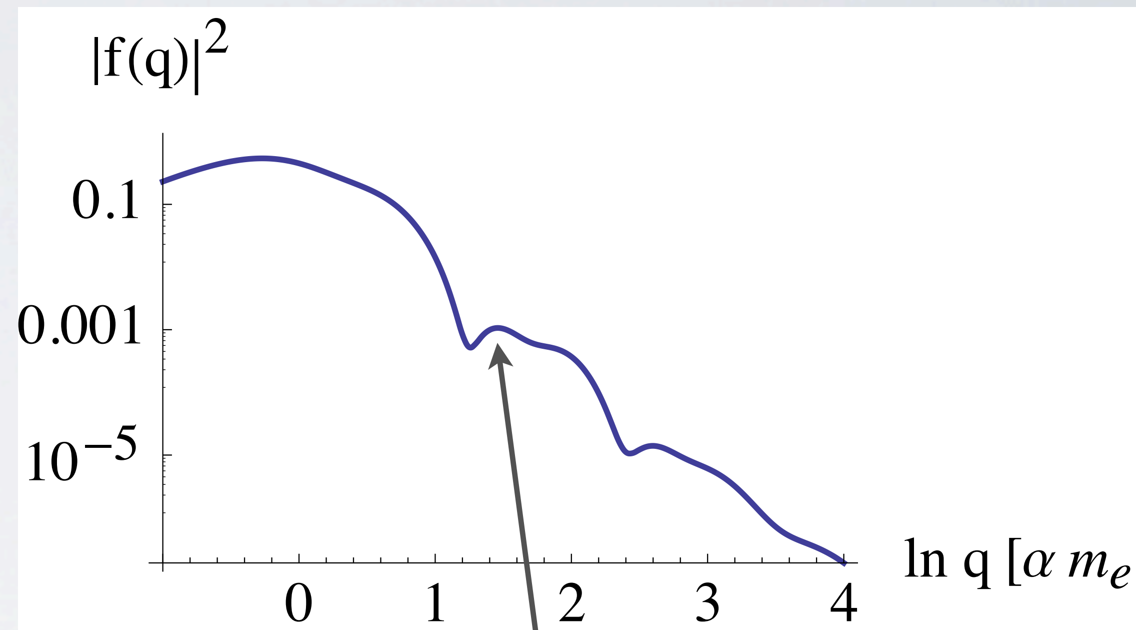
CALCULATING EVENT RATES



atomic quantum mechanics

scattering amplitude
=
microscopic amplitude
x
atomic form-factor

typical atomic form factor



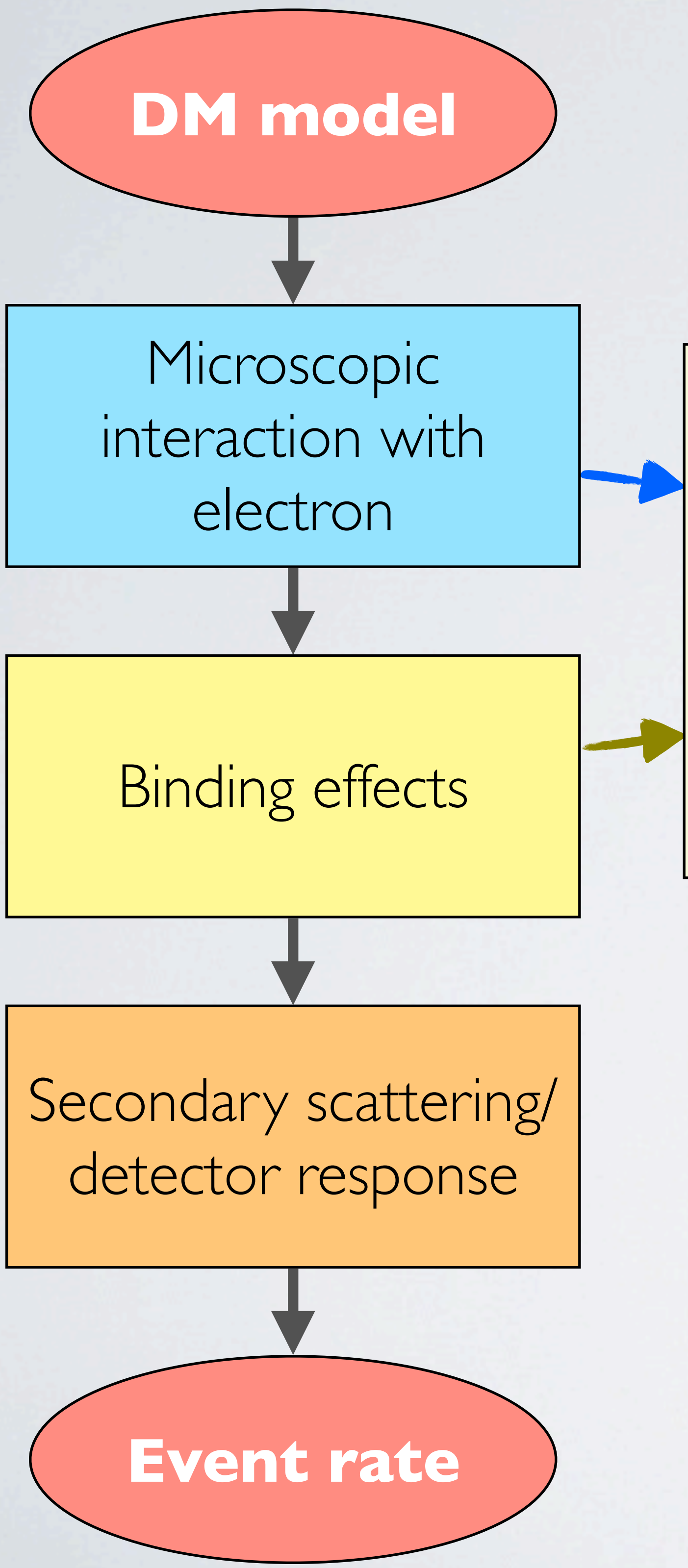
suppressed for $q \gtrsim \alpha m_e$

wavefunctions computed numerically
Bunge et.al. A.D.N.D.T. 53, 113

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

Essig, Mardon & Volansky. 1108.5383

CALCULATING EVENT RATES

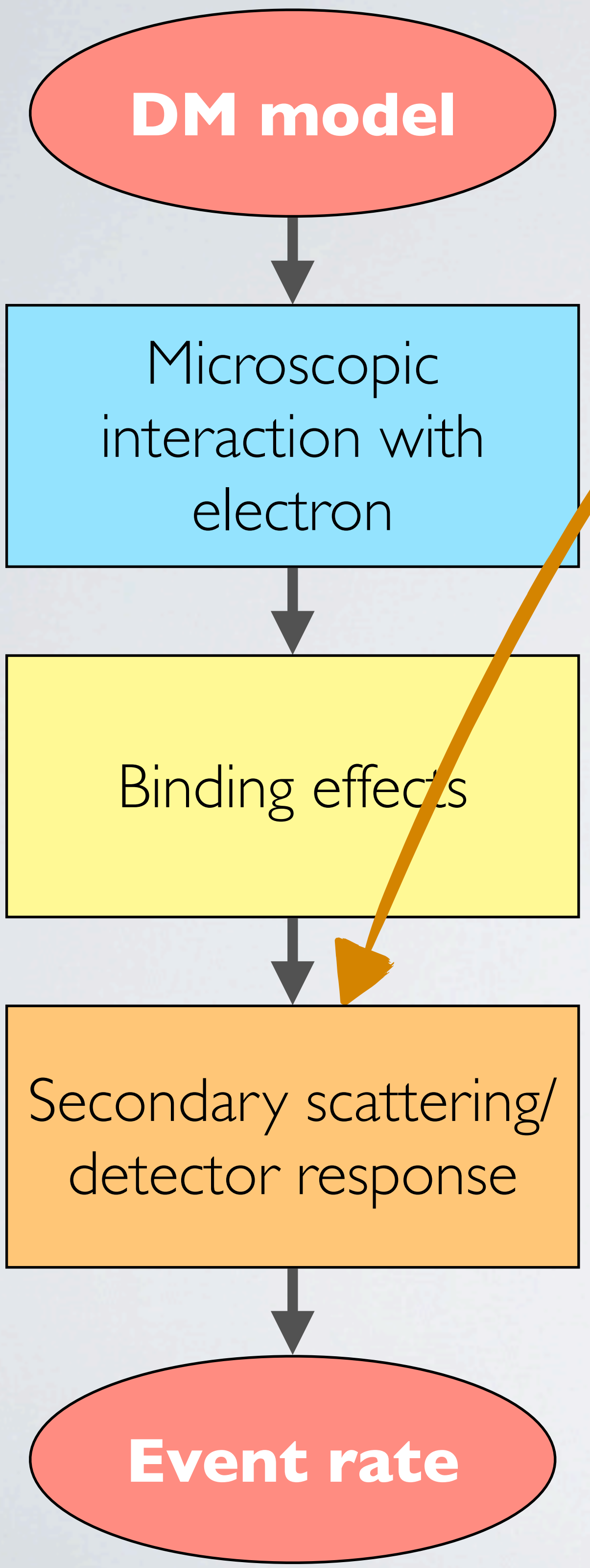


$$\frac{d\langle\sigma^{nl}v\rangle}{d\ln E_R} = \overline{\sigma}_e \int \frac{q\,dq}{8\mu_{\chi e}^2} \left|f^{nl}(E_R,q)\right|^2 \left|F_{\rm DM}(q)\right|^2 \eta(v_{\rm min}(q))$$

$$v_{\rm min} = \frac{|E^{nl}_{\rm binding}| + E_R}{q} + \frac{q}{2m_{\rm DM}}$$

Essig, Mardon & Volansky. 1108.5383

Calculating Event Rates



semi-empirical model

How many electrons do we see?

- It's complicated...

- Use probabilistic model to distribute the recoil energy between electrons (which we see) and photons/heat (which we don't)

- O(1) uncertainty --- but not O(10)!

- good enough for now

Essig, Mardon & Volansky. 1108.5383
Essig, Manalaysay, Mardon, Sorensen & Volansky. 1206.2644