Above-Ground Direct Searches for WIMPS

Motivation (SIMPs)

Constraints for high-mass DM particle

Constraints from Direct Searches for sub-GeV DM particles

Jules Gascon
(IPNLyon, Université Lyon 1 + CNRS/IN2P3)

Strong DM interactions?

- Main focus of direct DM searches so far: DM-nucleon cross-sections below 10^{-31} cm^2:
  - Shielding from Earth + atmosphere can be neglected.
  - Deep underground sites, to reduce cosmic-ray induced backgrounds

- But strong interactions of ~GeV DM particles are relevant
  - O(10^{-24}) cm^2 DM-DM cross-section of ~GeV DM particles *[cf: <0.57 cm^2/g, JI Read, ALPS2019]* could actually help CDM problems at small-scale (DM halo, satellites...) *[Spergel+Steinhardt PRL 84 3760 (2000)]*
  - Natural extension to test for O(10^{-24}) cm^2 DM-nucleon interactions *[e.g. Chen et al, PRD 65 123515 (2002)]*

Strongly Interacting Massive Particles

- No exclusive definition of SIMPs (yet):
  - Strong self-interactions limited to Hidden sector (e.g. Models with $3 \rightarrow 2$ processes during freeze-out *[Hochberg, PRL 115 021301 (2015)]*
  - ... or extended to interactions with nucleons/e^-/γ (... millicharge) *[e.g. Davidson et al, JHEP05,03 (2000); Chang et al, JHEP09 051 (2018)]*
  - Or (in the context of direct DM searches): strong force interaction with nucleons

This talk...

SIMP interactions with Earth + atmosphere

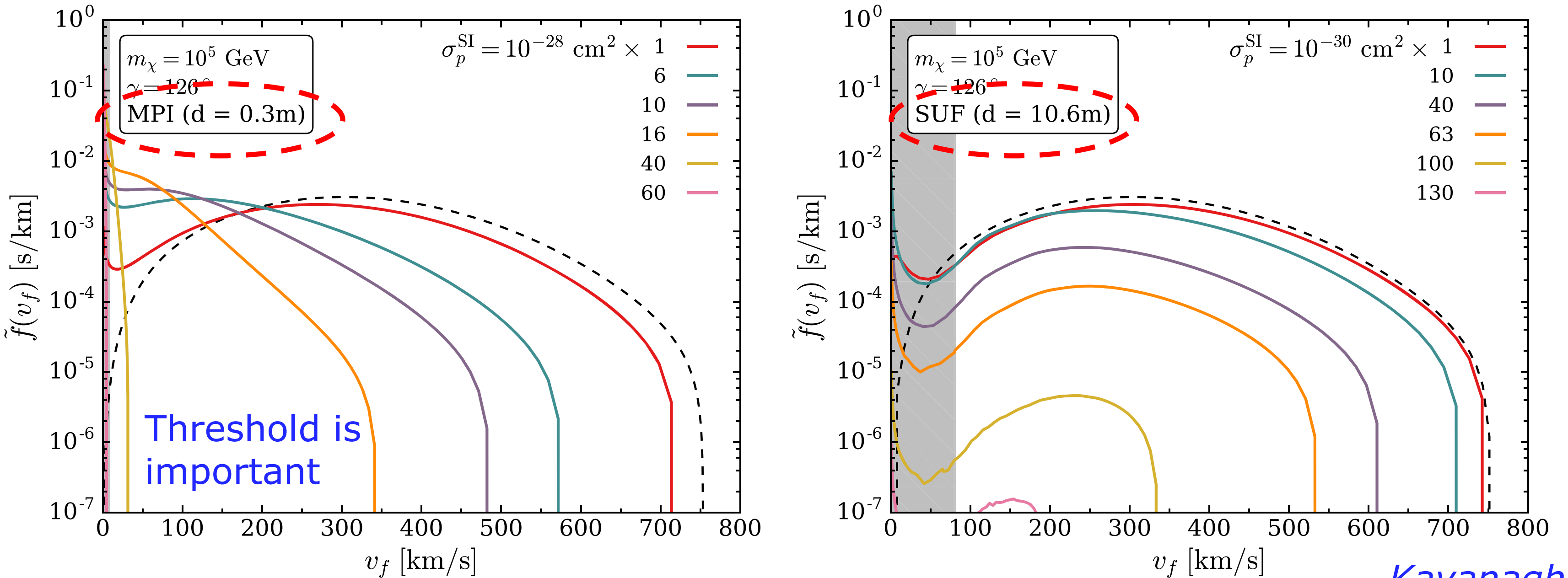
Many recent papers, see e.g.

- *Hooper+McDermott, PRD 97 115006 (2018)*
- *Emken+Kouvaris, PRD 97 115047 (2018)*
- *Kavanagh, PRD 97 123013 (2018)*
- *Kavanagh+Catena+Kouvaris, JCAP 01(2017)012*

https://github.com/temken/damascus

https://github.com/bradkav/verne

- Depth-dependent reduction of velocity + attenuation of flux



Kavanagh

SIMP interactions with Earth + atmosphere

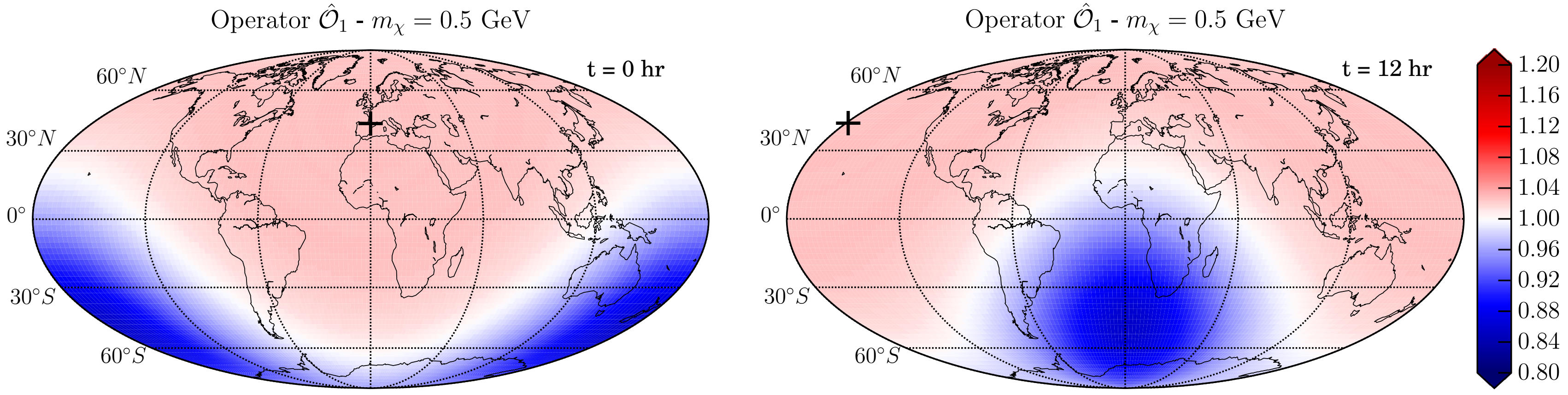
Many recent papers, see e.g.

- *Hooper+McDermott, PRD 97 115006 (2018)*
- *Emken+Kouvaris, PRD 97 115047 (2018)*
- *Kavanagh, PRD 97 123013 (2018)*
- *Kavanagh+Catena+Kouvaris, JCAP 01(2017)012*

https://github.com/temken/damascus

https://github.com/bradkav/verne

- Depth-dependent reduction of velocity + attenuation of flux
- Anisotropy due to Earth shielding + sun velocity vector



... some days may be better than others for SIMP searches

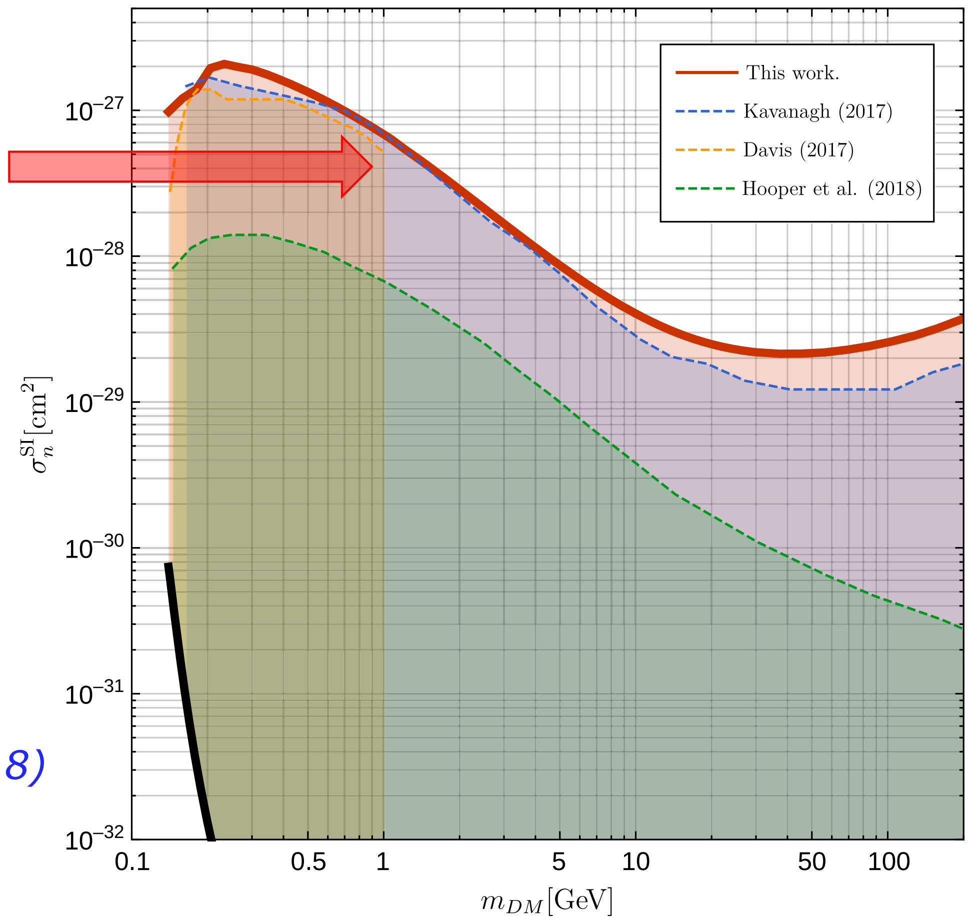
Monte Carlo vs analytical calculations

- Depth-dependent energy spectrum + abrupt cut-off: determining σ_{max} requires a scan with a fine granularity, especially at low mass
- Monte Carlo vs analytical calculation comparisons

Analytical:
Davis, PRL 119, 211302 (2017)
Hooper+McDermott, PRD97 115006 (2018)
Kavanagh, PRD 97 123013 (2018)

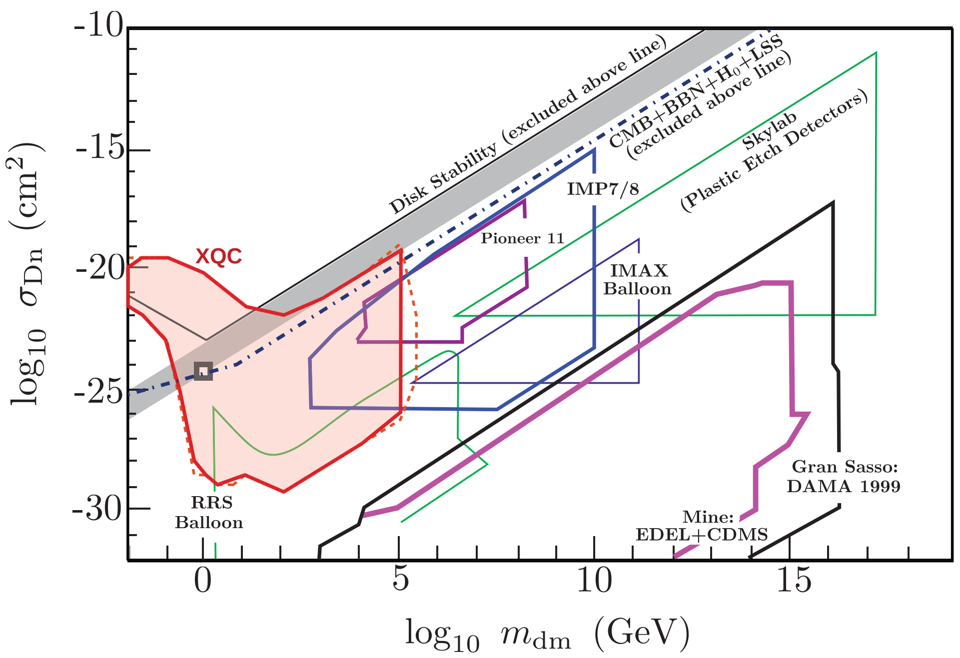
Monte Carlo:
Emken+Kouvaris, PRD 97 115047 (2018)

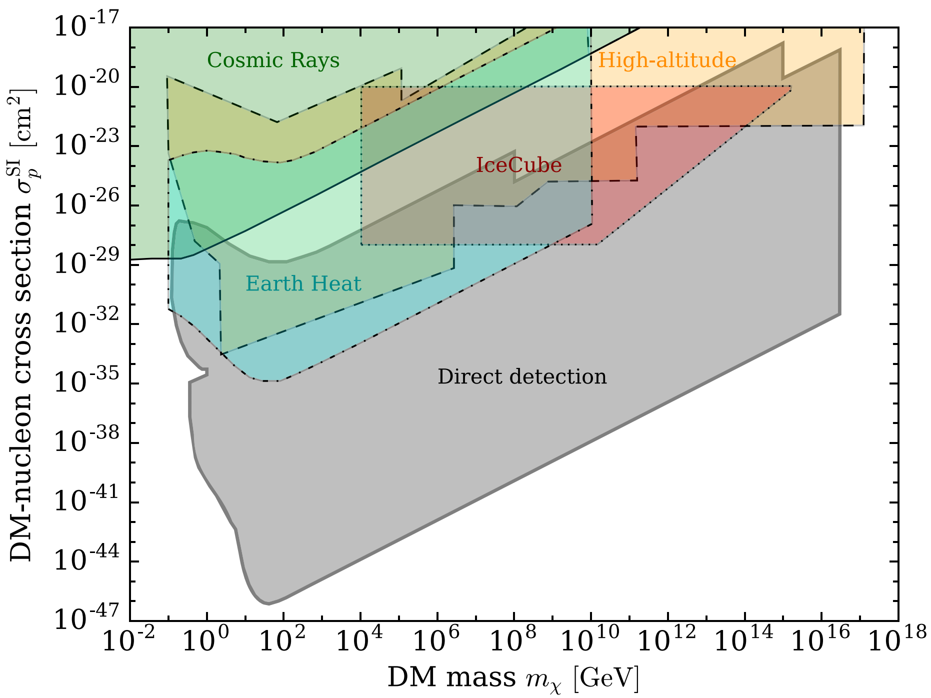
Emken+Kouvaris



Constraints at high mass

- Large cross sections excluded by CMB + large scale structures + BBN
- Gap between CMB and deep underground searches *[e.g. Albuquerque + Baudis, PRL91 229903 (2003)]* filled by balloon experiments + space experiments + IceCube + Earth heat flux

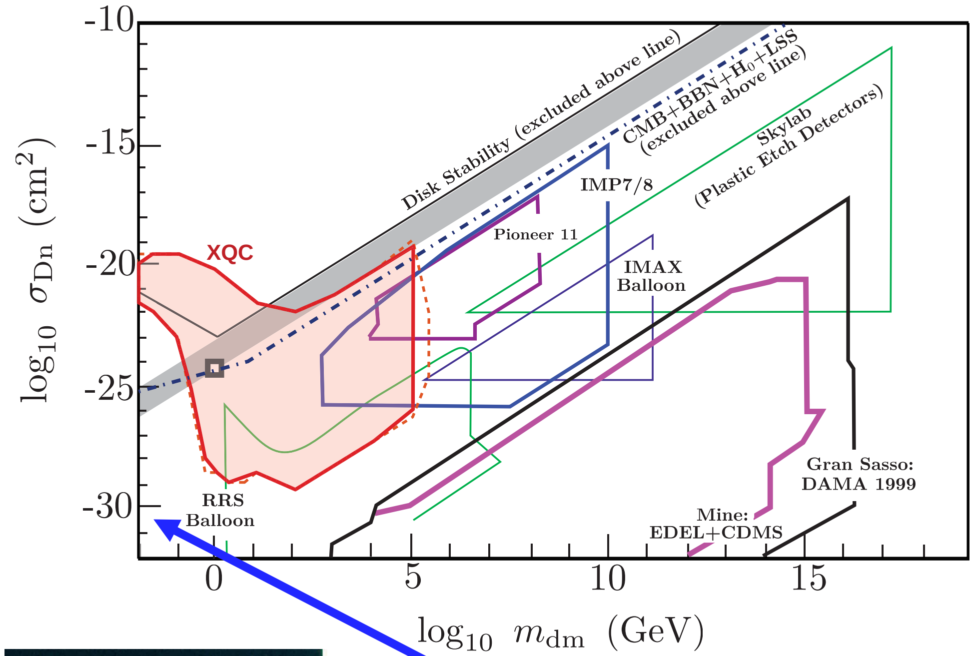




Erickeck et al, PRD 76 042007 (2007)

Kavanagh 2018

Limits at lower mass



RRS balloon

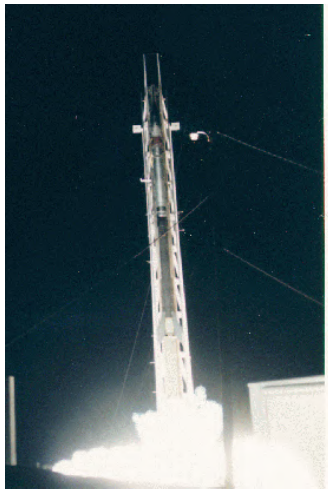
[J. Rich et al, PLB194 173 (1987)]

- 0.5 g Si ionization detector
- 50 km above ground
- 0.4 keV_{ee} threshold (~2 keV recoil)

XQC rocket

[Erickeck et al, PRD 76 042007 (2007)]

- Si calorimeter @ 60 mK: ~30 eV threshold
- 200 km above ground
- 100 s of data (3×10^{-6} kgd!)



Remaining domain:

Gap below 1 GeV

<1 GeV SIMP search experiments

- Above-ground Liquid Scintillator [Collar, PRD98 023005 (2018)]
  - 10^{-31} cm^2 limits obtained with aggressive subtraction of single-e^- PM noise
- Reanalysis of DM search data from shallow sites? (...>1 GeV/c^2)
  - DAMIC 2011 (100 m rock) [*Hooper+McDermott, PRD97 115006 (2018)*]
  - CDMS-I SUF (10.3 m rock) [*Kavanagh, PRD 97 123013 (2018)*]
- Above-ground: CRESST - ν-cleus
  - 0.49 g Al_2O_3, phonon signal
  - 20 eV (phonon) threshold
  - ~10^5 evt/g/day at 100 eV
- Above-ground: EDELWEISS-surf
  - 33 g Ge, phonon signal
  - 60 eV (phonon) threshold
  - ~200 evt/g/day at 100 eV

<1 m overburden

No problem with quenching effects
(+resolution: minimal distortion of signal shape)

No background assumptions

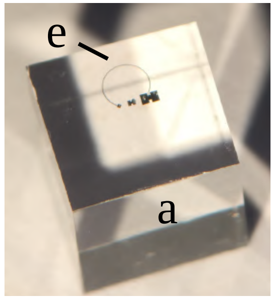
Detector developments for both DM & coherent elastic neutrino-nucleon scattering

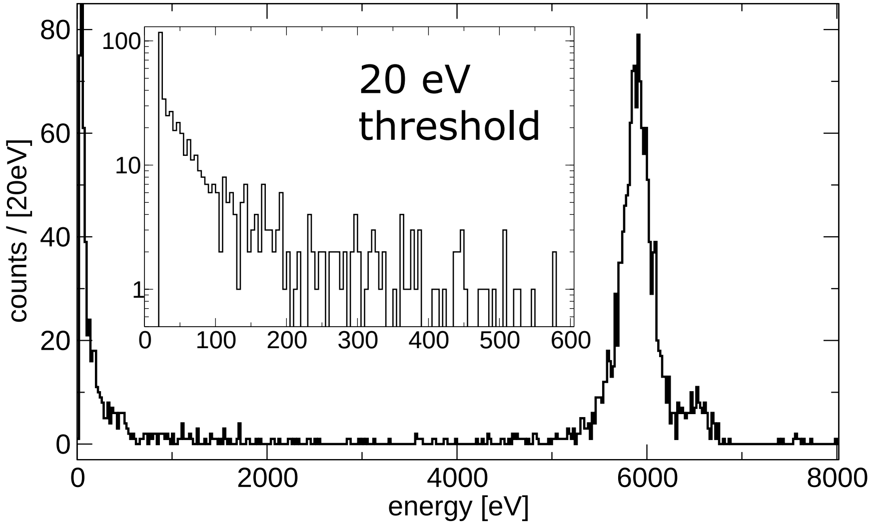
Experimental data

CRESST-ν-cleus

- 0.49 g Al_2O_3
- TES phonon sensor
- Upper limits from Yellin optimal interval method

Angloher et al, EPJC77 637 (2017)
+ Davis, PRL119, 211302 (2017)

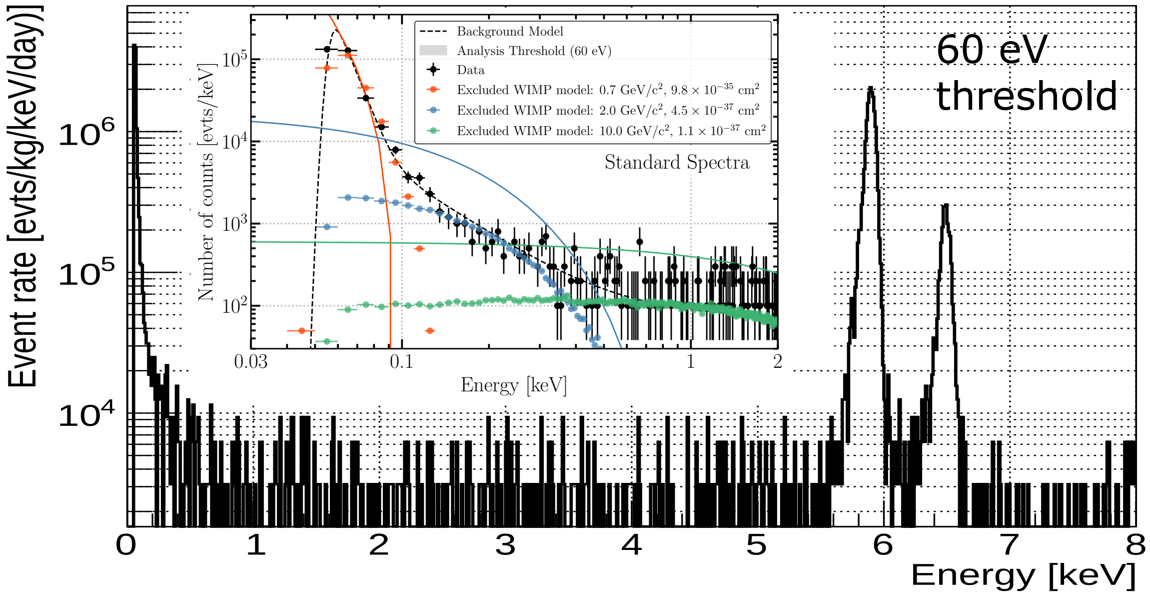




EDELWEISS-surf

- 33 g Ge
- GeNTD phonon sensor
- Max. Poisson rate in blindly-determined energy intervals

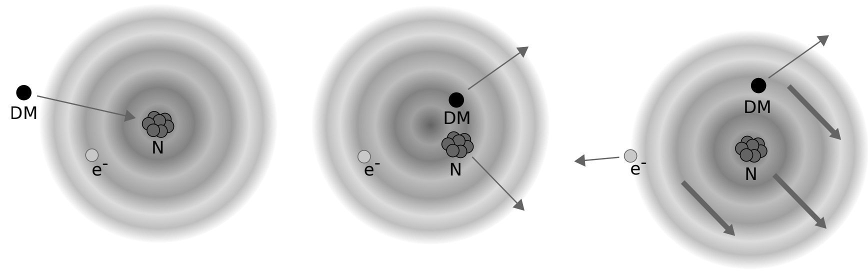
Armengaud et al, PRD99 082003 (2019)



Migdal effect

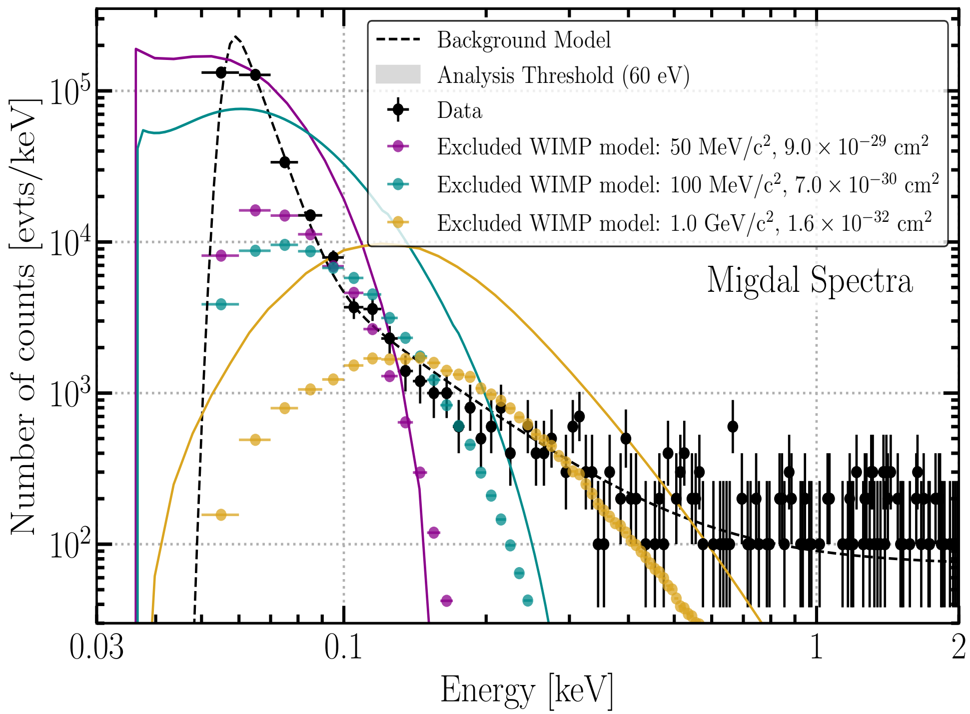
- Consider ionization effects of e⁻ cloud (n=3 shell) due to sudden boost of nucleus in DM collision

  Calculated in Ibe et al, JHEP 03 (2018) 194



Dolan et al, PRL 121, 101801 (2018)

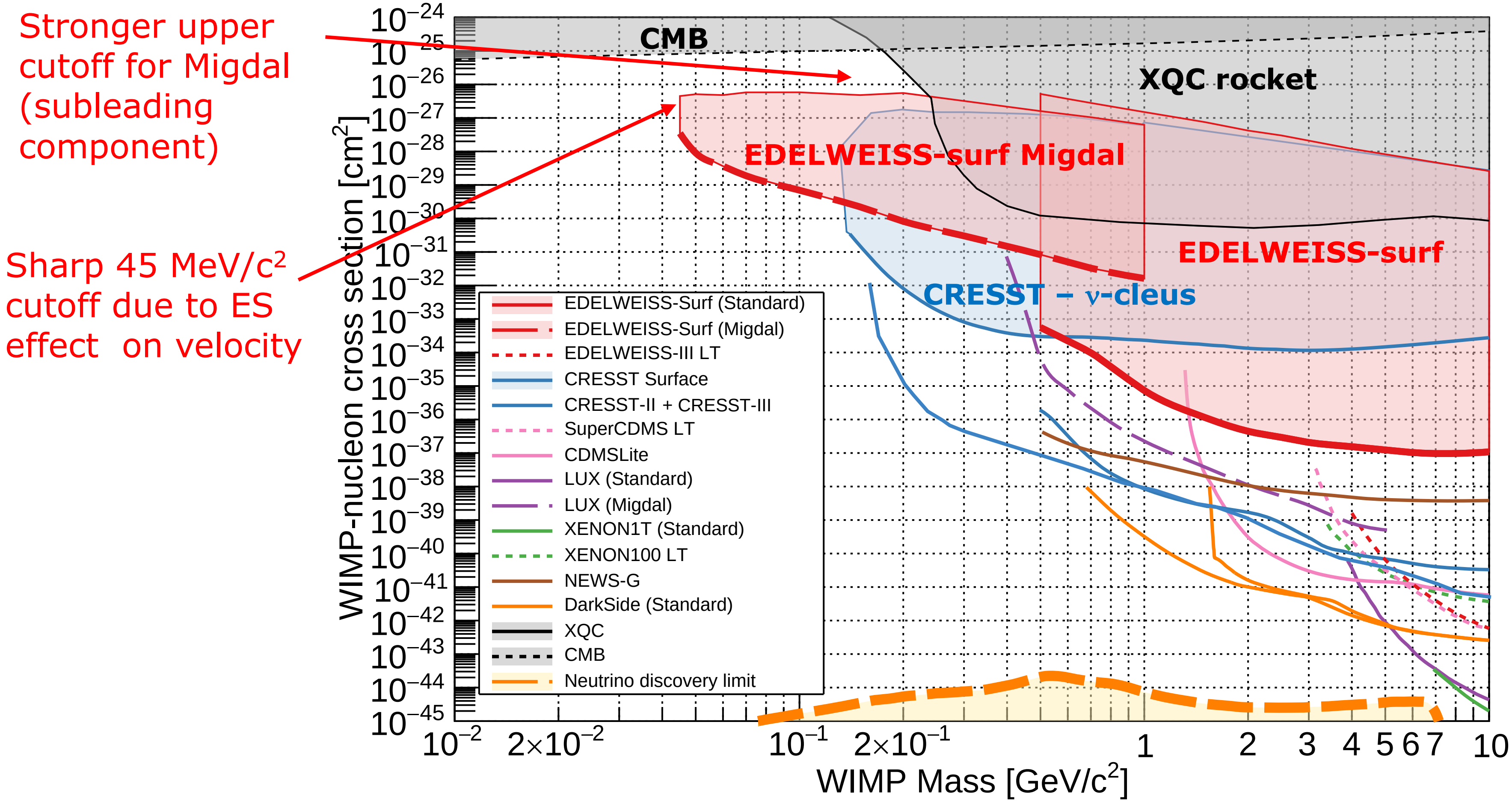
- Injection of electronic energy in the sub-keV to keV range
  - <1% probability
  - Negligible for >10 GeV/c² WIMPs
  - Major contribution for light DM particles, especially if nuclear recoil contribution is quenched
  - ***Robust signal >100 eV even for DM masses <0.1 GeV/c²***



- Must keep EM backgrounds as low as possible

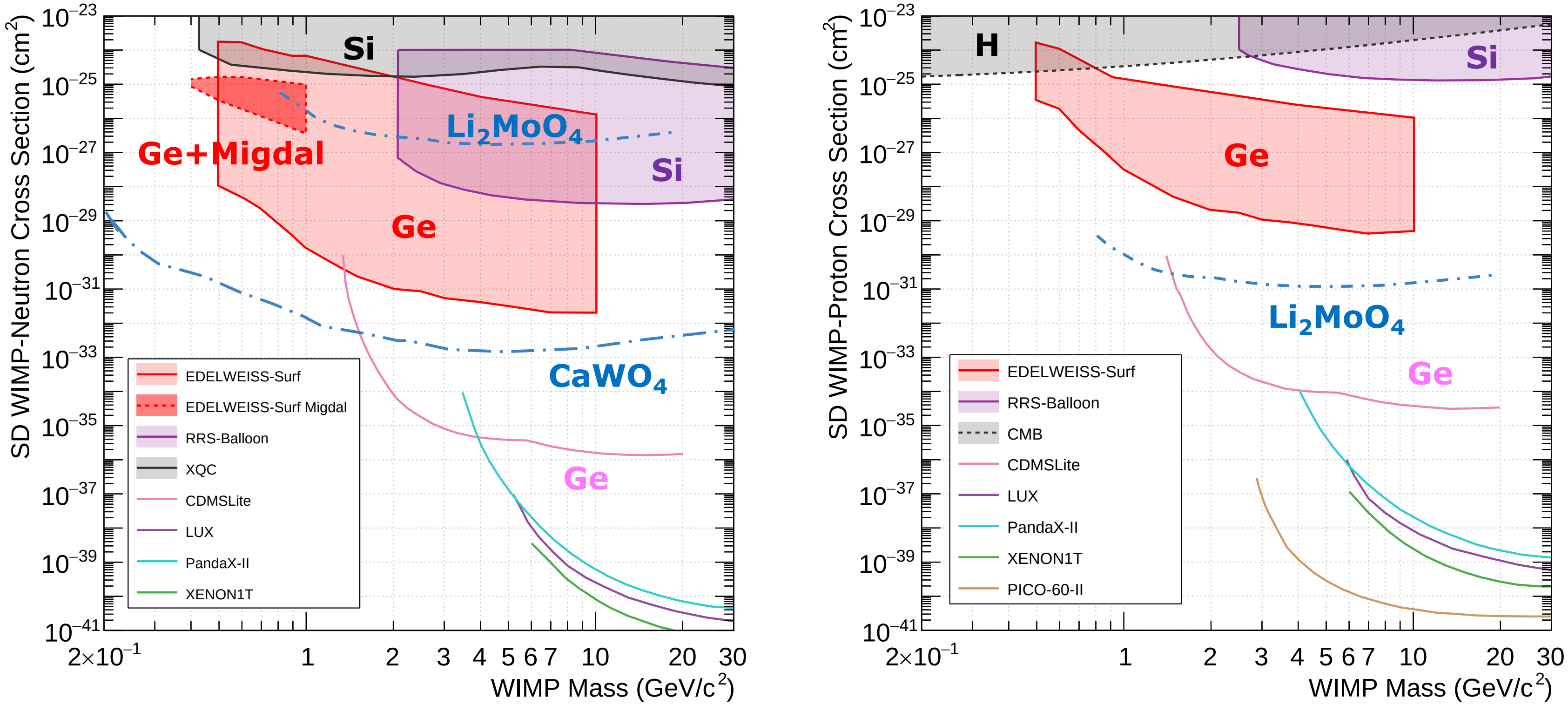
Starting to fill the SubGeV gap...

- Shaded regions: full Earth-Shielding (ES) calculation
- Lines: underground limits (w/o ES calculation, ok for $<10^{-31}$ cm^2)



Spin-dependent cases

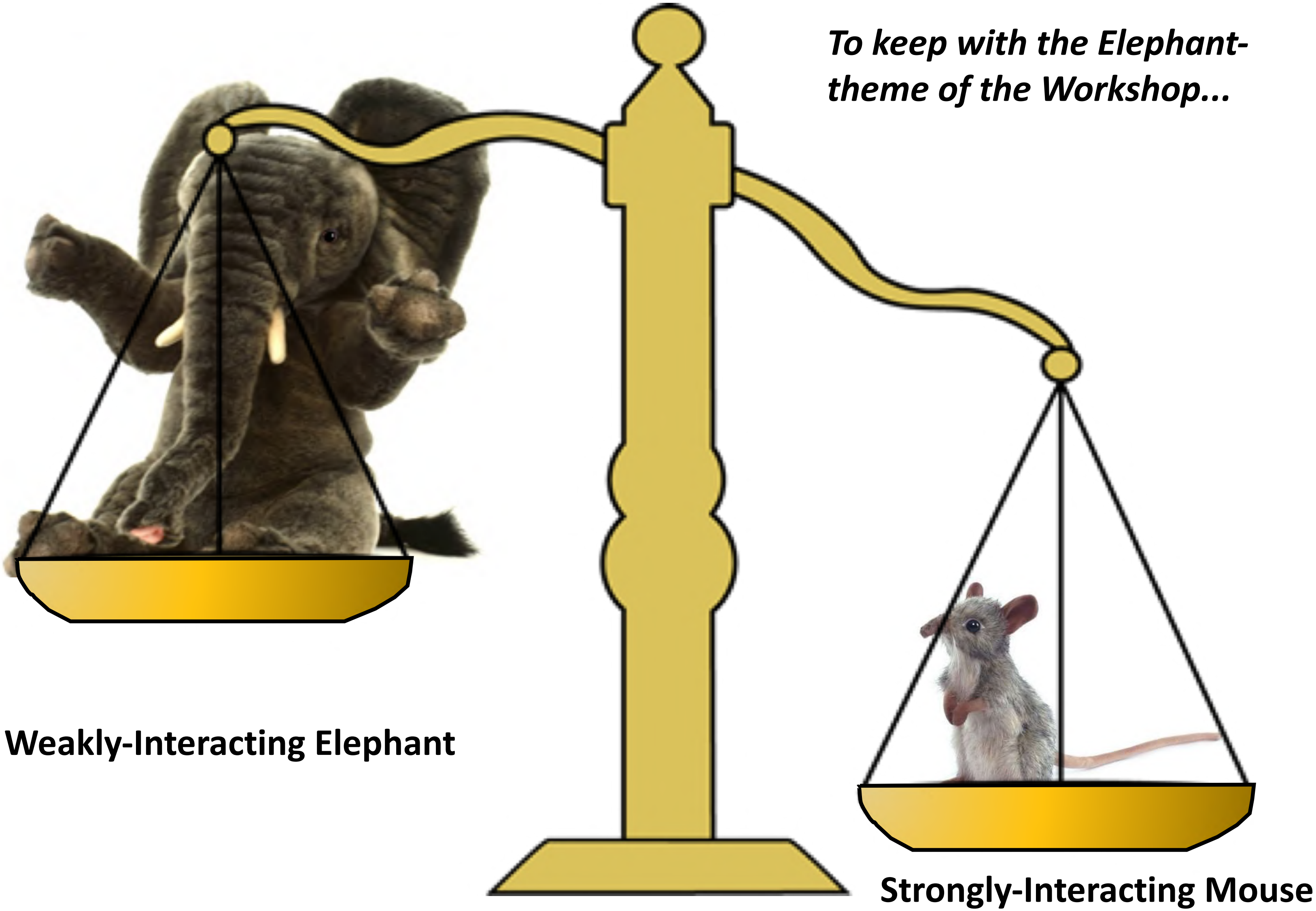
- Unfortunately, ^{14}N has both p and n spin: *shielding from atmosphere*
- Large cross-section → dramatic ES effects (especially on Migdal limits)
- Blue dot-dashed: CRESST surface Li_2MoO_4 [arXiv:1902.07587] and underground $CaWO_4$ [arXiv:1904.00498] – SIMP contour calcs. underway



Conclusions

- *Recent above-ground direct searches for <GeV/c^2 DM particles interacting with nucleons help cover a relevant domain of the (M_{DM}, σ) parameter space*

- *Thresholds and backgrounds are key factors*
  - Technological developments for both surface DM & coherent elastic neutrino-nucleon scattering experiments *(RICOCHET & ν-cleus)*
  - Small cryogenic detectors have low and well-defined thresholds (eg: resolution, quenching effects)
  - *Challenge 1:* further background reductions without increasing the external shielding
  - *Challenge 2:* further improvements in thresholds
  - Migdal effect helps reduce thresholds → this stresses the importance to get a direct measurement of this effect (with cryogenic Ge?)


To keep with the Elephant-theme of the Workshop...
Weakly-Interacting Elephant
Strongly-Interacting Mouse

BACKUP

SIMP interactions with Earth + atmosphere

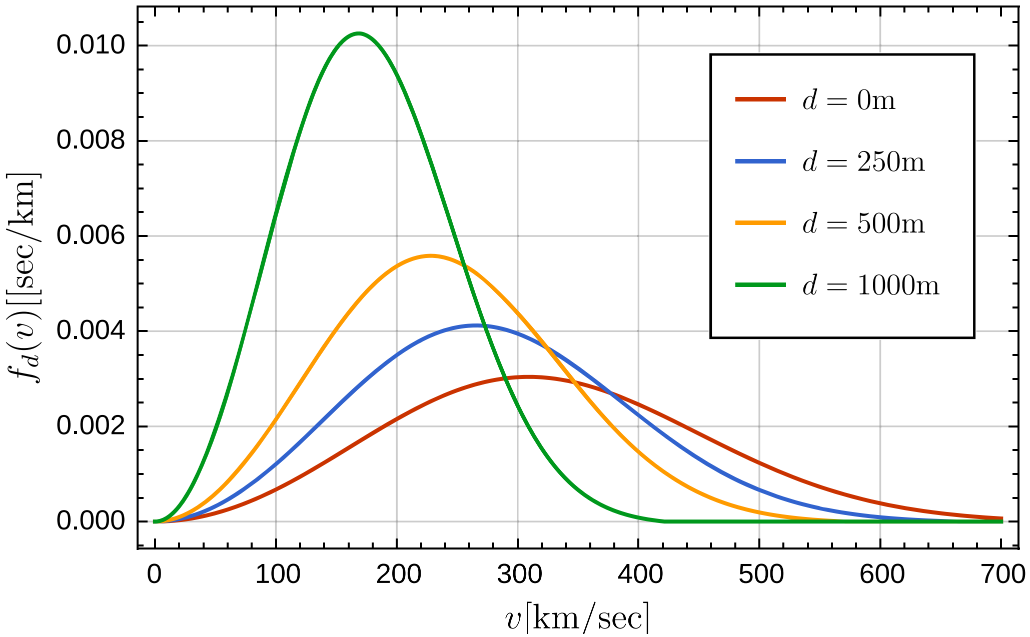
See e.g.

- *Hooper+McDermott, PRD 97 115006 (2018)*
- *Emken+Kouvaris, PRD 97 115047 (2018)*
- *Kavanagh, PRD 97 123013 (2018)*
- *Kavanagh+Catena+Kouvaris, JCAP 01(2017)012*

https://github.com/temken/damascus

https://github.com/bradkav/verne

- Depth-dependent reduction of velocity + attenuation of flux



1 GeV/c^2 DM velocity attenuation vs depth

Emken+Kouvaris

Liquid Scintillator experiment

JI Collar, PRD 98, 023005 (2018)

- 2 liquid scintillators EJ-301
- PSD, veto timing (but not relevant for low energy)
- Aggressive subtraction of single-electron dark current
- Earth/atmosphere shielding effects not taken into account