# Dark matter outlook

GDR DUPhy kick-off meeting

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# Outline

· Three brief comments on direct searches for WIMPy dark matter

For more information *cf* talk by Geneviève Bélanger

· Freeze-in dark matter and Feebly Interacting Massive Particles (FIMPs)

· Axions and Axion-Like Particles (ALPs)

· The low mass frontier

· Outlook of Outlook

# Brief comments on WIMP searches

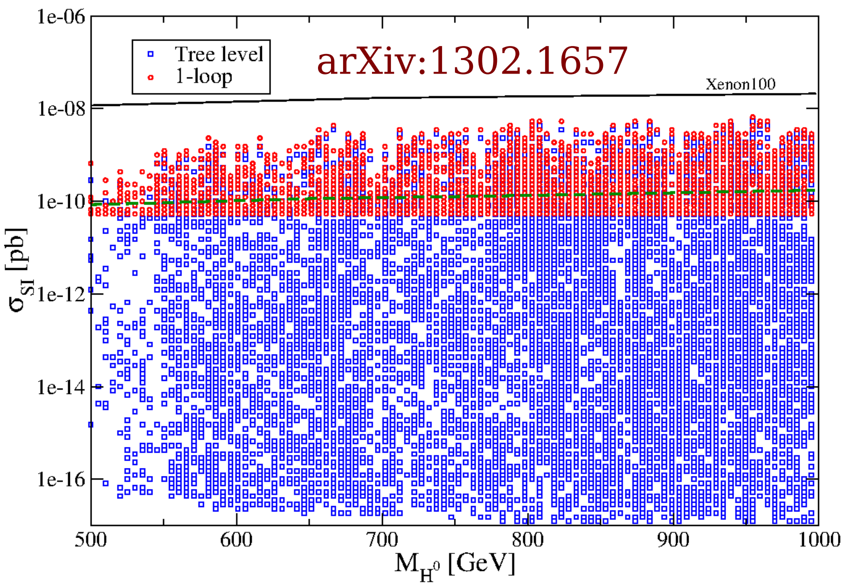
# Brief comments on WIMPs

Standard direct detection experiments have excelled in testing WIMP dark matter scenarios :

· The favourite models of the past few decades have been excluded also thanks to the efforts of the direct detection community.

Thermal freeze-out cannot be excluded in full generality, *cf* talk by G. Bélanger

· In some models, direct detection is probing higher-order corrections which cannot always be tuned away by adjusting parameters.




· Noble target detectors will continue dominating the GeV – TeV mass range.

What about other candidates ? Other masses ?

# Freeze-in and Feebly Interacting Massive Particles

# The freeze-in alternative

arXiv:hep-ph/0106249
arXiv:0911.1120

The freeze-in mechanism relies on two basic premises :

· Dark matter interacts *very* weakly ("feebly") with the Standard Model.

· It has a negligible initial abundance: $f_\chi(t = 0) \sim 0$ and $(1 \pm f_\chi) \sim 1$ .

In this context $t = 0$ corresponds, *e.g.*, to the end of inflation

Then, if we consider a process as $B_1 + B_2 \leftrightarrow X + \chi$

$B_1$, $B_2$: bath particles, $\chi$ is a FIMP

$$\dot{n}_\chi + 3Hn_\chi =$$

Small, ignore

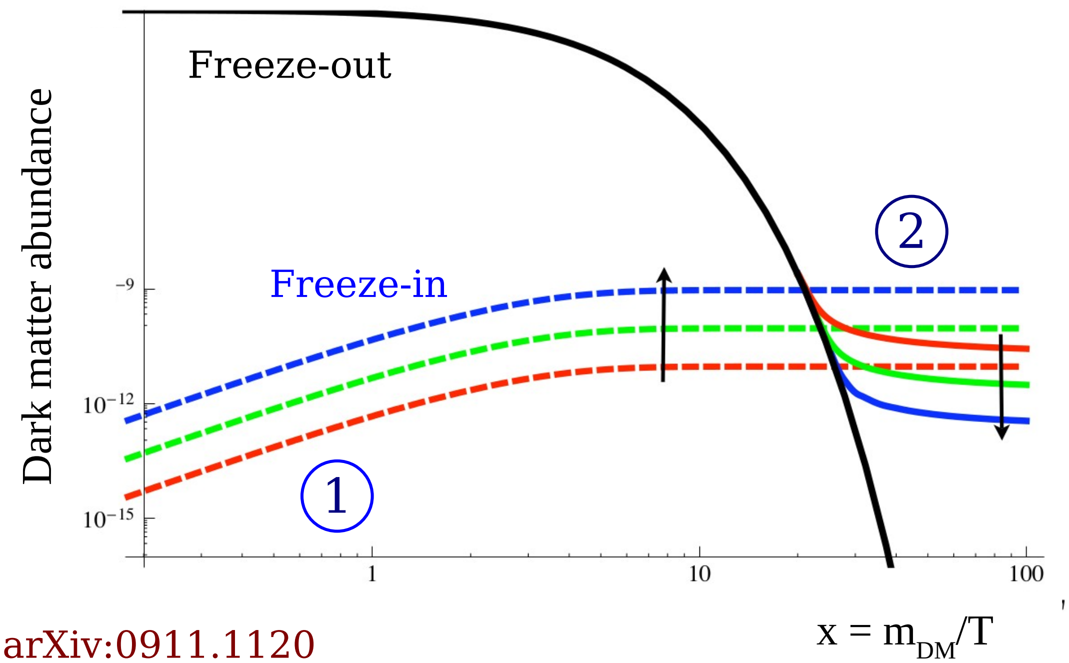
$$- \sum_{\text{spins}} \int \left[ f_\chi f_X \left(1 \pm f_{B_1}\right)\left(1 \pm f_{B_2}\right) \left|\mathcal{M}_{\chi X \to B_1 B_2}\right|^2 - f_{B_1} f_{B_2} \left(1 \pm f_\chi\right)\left(1 \pm f_X\right) \left|\mathcal{M}_{B_1 B_2 \to \chi X}\right|^2 \right]$$

$$\times \left(2\pi\right)^4 \delta^4 \left(p_\chi + p_X - p_{B_1} - p_{B_2}\right) \times \prod_{i=\chi, X, B_1, B_2} \left( \frac{d^3 p_i}{\left(2\pi\right)^3 2E_i} \right)$$

*i.e.* we can ignore dark matter depletion and focus on production processes.

# The freeze-in alternative: result

The previous discussion amounts, schematically, to the following picture :




arXiv:0911.1120

1. Starting from a negligible initial density, DM is produced from decays or annihilations of other particles.

2. DM production disfavoured, abundance “freezes-in”.

MicrOMEGAs 5: Freeze-in dark matter abundance in *generic* extensions of the Standard Model, arXiv:1801.03509

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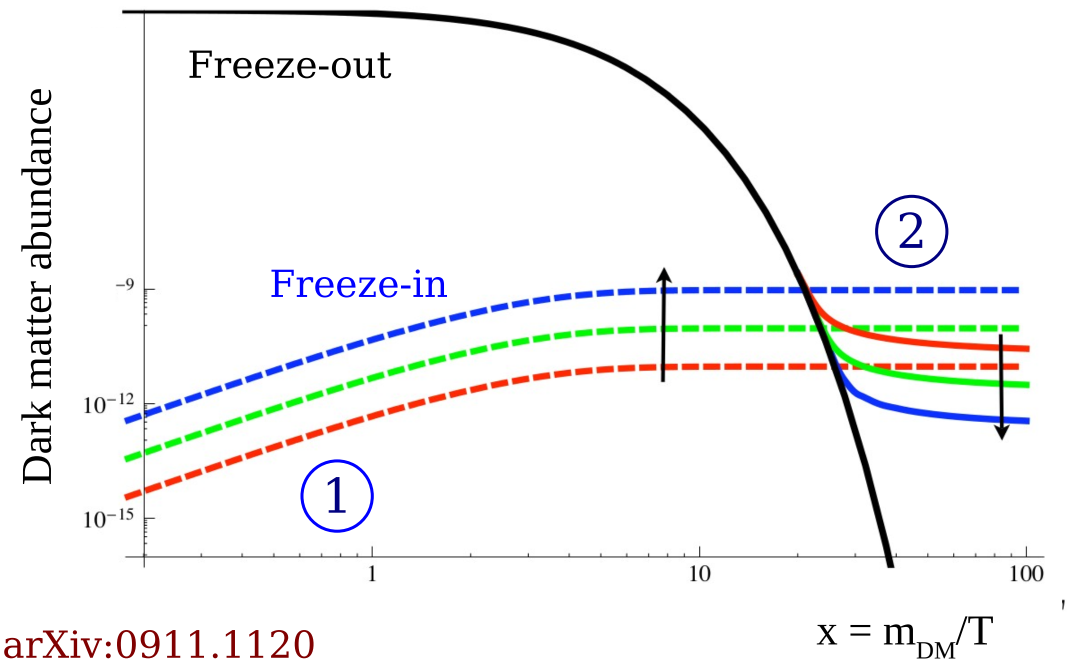


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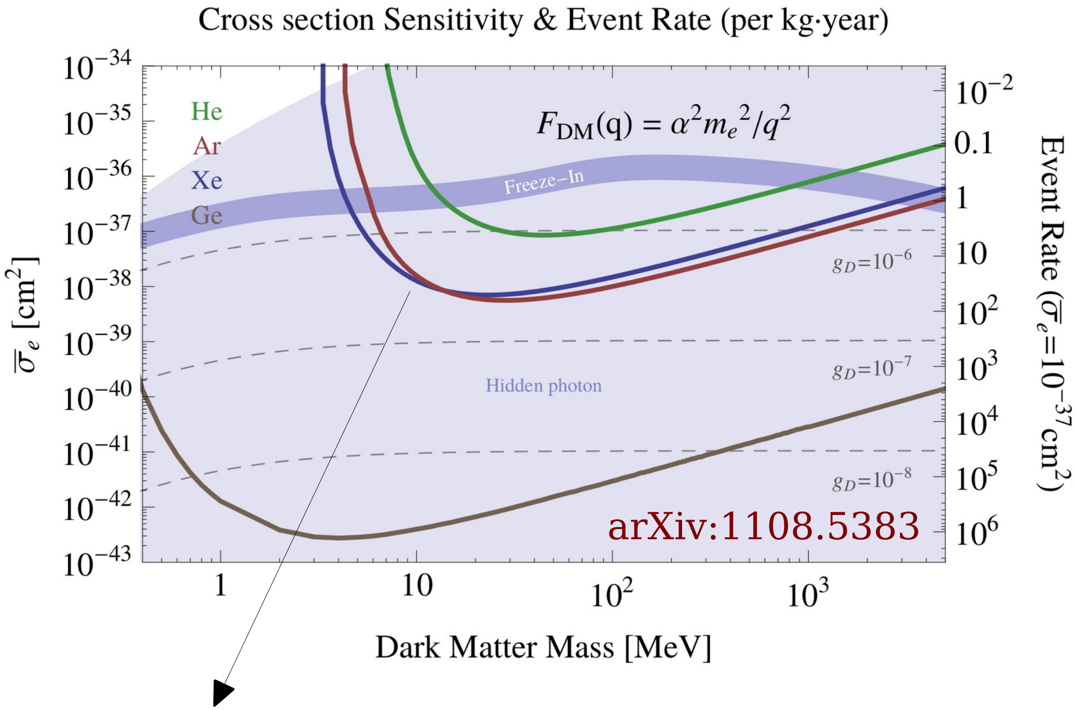
**Can we detect a particle that interacts extremely weakly with ordinary matter?**

· Many ideas, most of them related to searches for long-lived particles, but direct detection can also play a role!

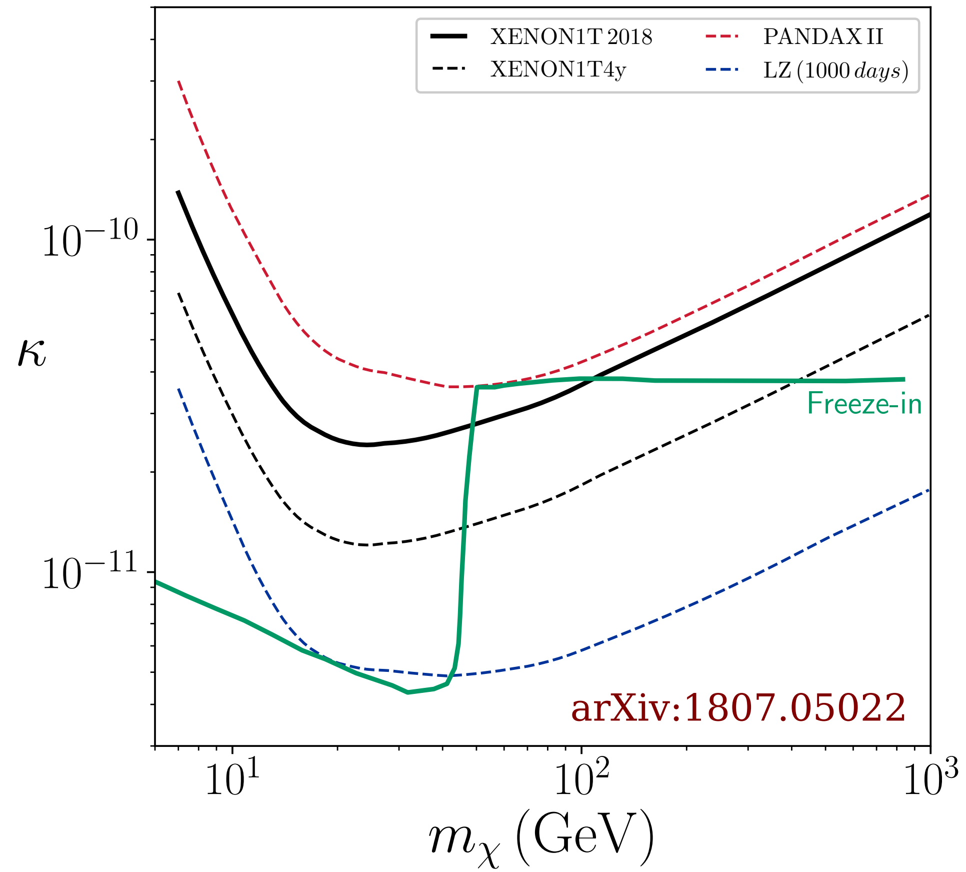
# Direct detection of FIMPs

It turns out that there is one limit in which direct detection experiments *can*, actually, probe FIMPs: if they interact with the SM through very light mediators.

*Cf* also talk by J-P Zopounidis for leptonic case




Probing dark gauge couplings of ***O***$(10^{-7})$!




· Scattering cross-section massively enhanced thanks to $\sim 1/q^2$ dependence, can overcome suppression due to feeble nature of interactions.

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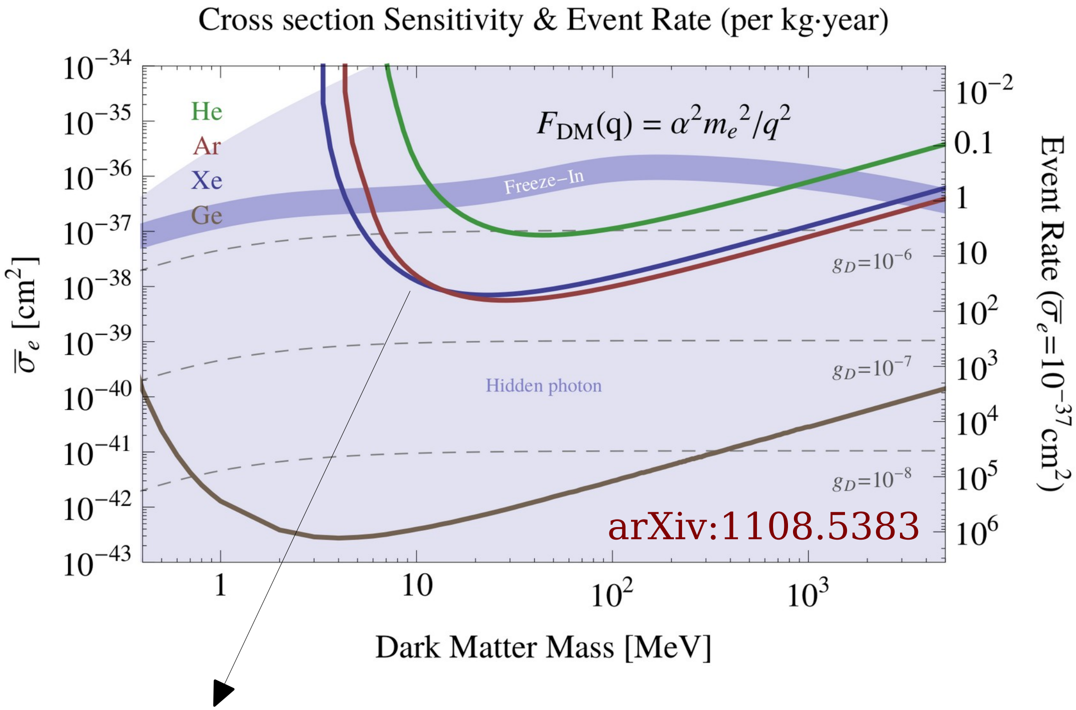
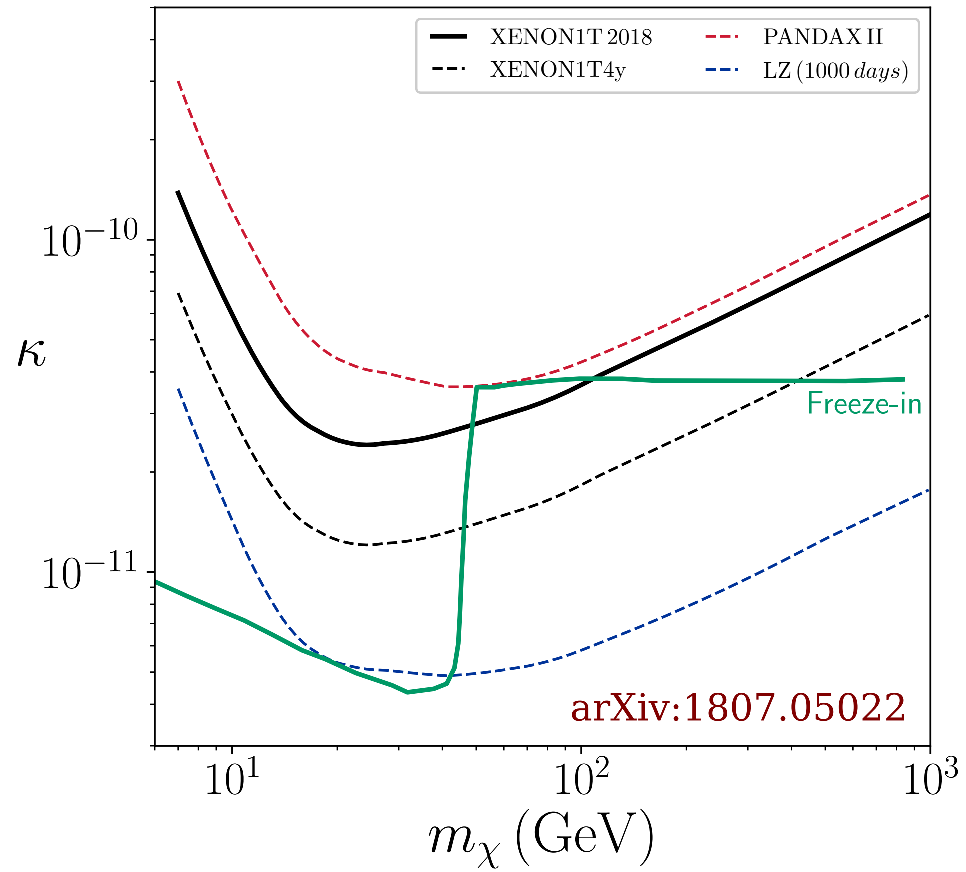



Probing dark gauge couplings of $\boldsymbol{O}(10^{-7})$!

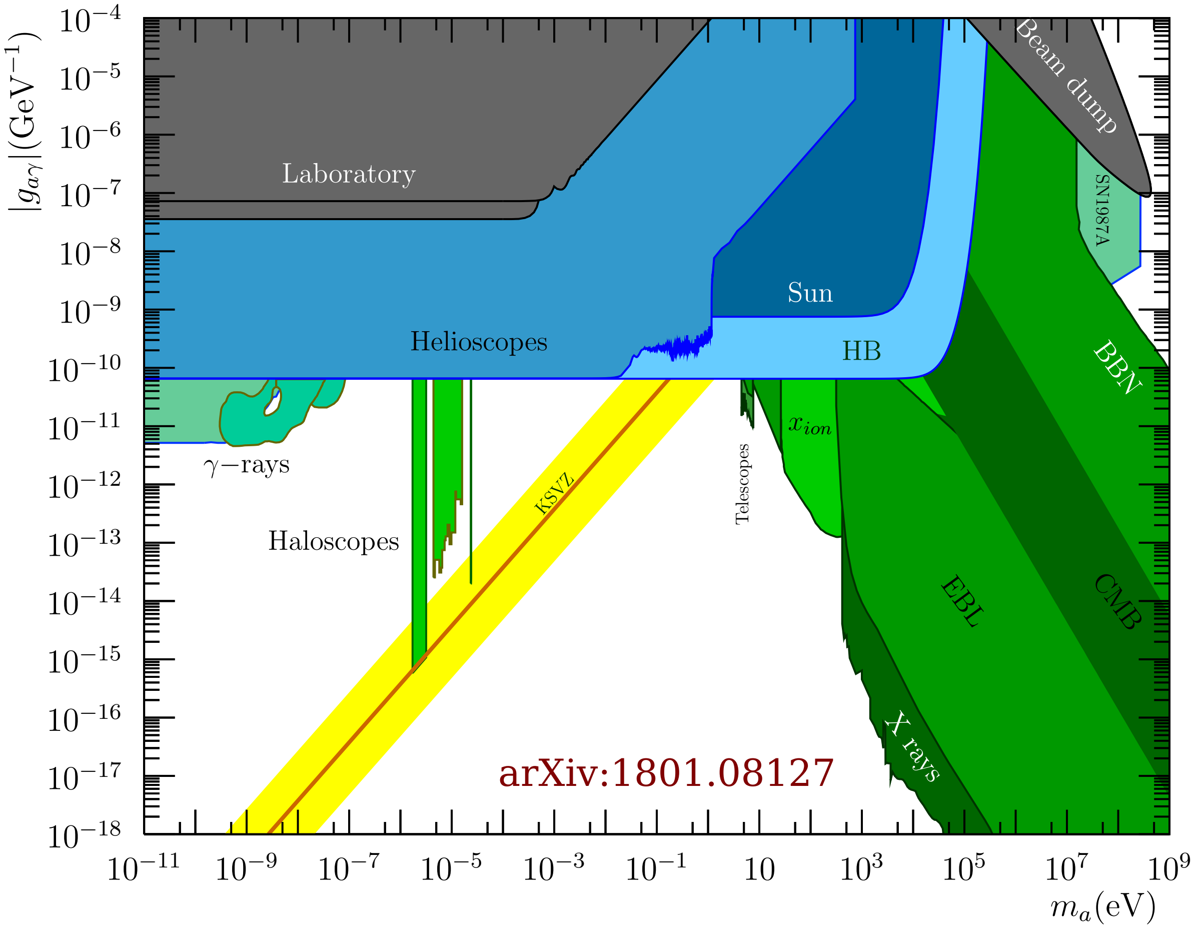



**Direct detection experiments *can* probe some FIMP dark matter models!**

# Axions and ALPs

# Axions: general aspects

Originally introduced as part of the Peccei-Quinn solution to the strong CP problem.




R. D. Peccei, H. R. Quinn, PRL (1977)
S. Weinberg, PRL (1978)
F. Wilczek, PRL (1978)

· Typically very light, *extremely* cold dark matter candidates.

· DM abundance depends on axion mass, decay constant and initial misalignment.

At least in pre-inflationary scenario

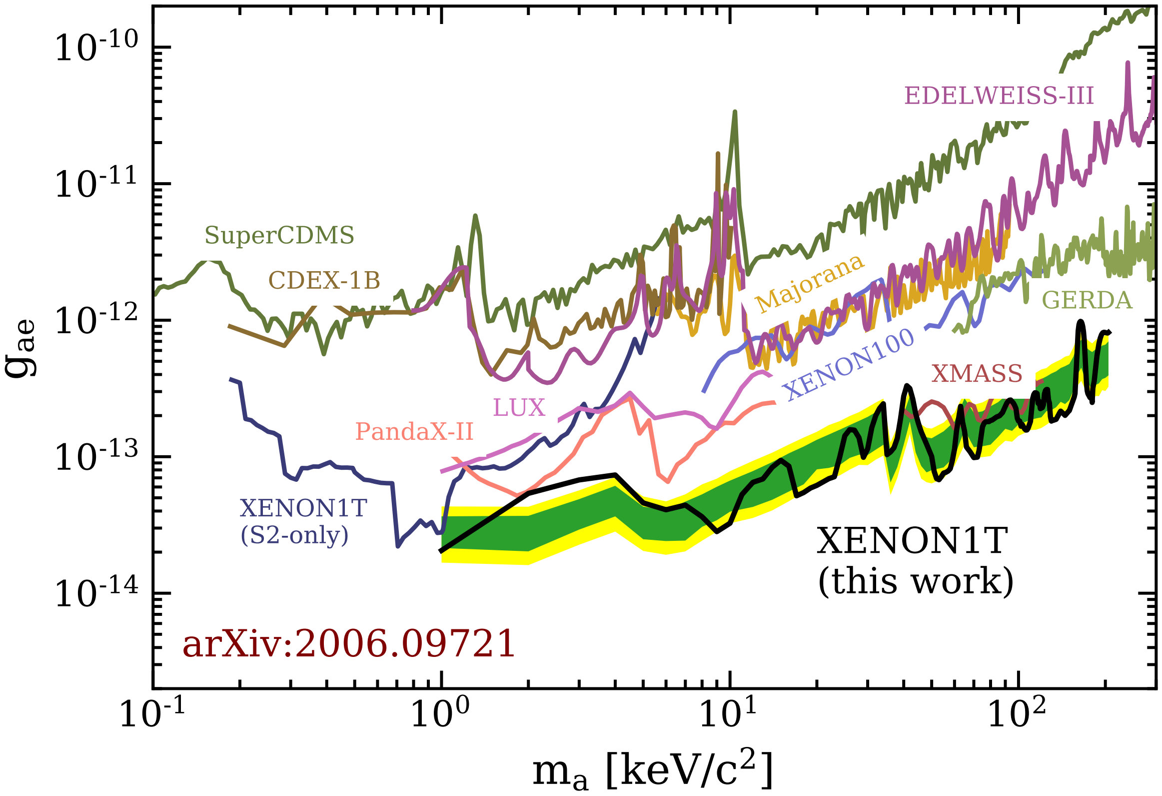
· A rich experimental axion search programme already exists.

Do direct dection experiments have a role to play in axion searches?

# Axions: role of direct detection ?

A lot of excitement generated last year by the observation of excess electron recoil events in XENON1T.

arXiv:2006.09721




· Numerous models proposed in order to explain the excess of events, including ALPs.

· General statements rather hard to make, models often in tension with other constraints.

· In any case, we see that axions can produce observable signals in direct detection experiments.

Direct dection experiments are sensitive to ALPs!

Similar remarks apply to dark photons

# The low mass frontier

# The low mass frontier

General approach: find (as well understood as possible) processes in nature with a very low energy threshold. A fully non-exhaustive list of ideas includes:

· Semiconductors

Many

· Superconductors

arXiv:1504.07237

· Superfluid He

arXiv:1604.08206

· Dirac materials

arXiv:1708.08929

· Molecular bond breaking

· ...

# MeV – GeV range

For lighter DM, expect smaller momentum transfer. Ideas include:

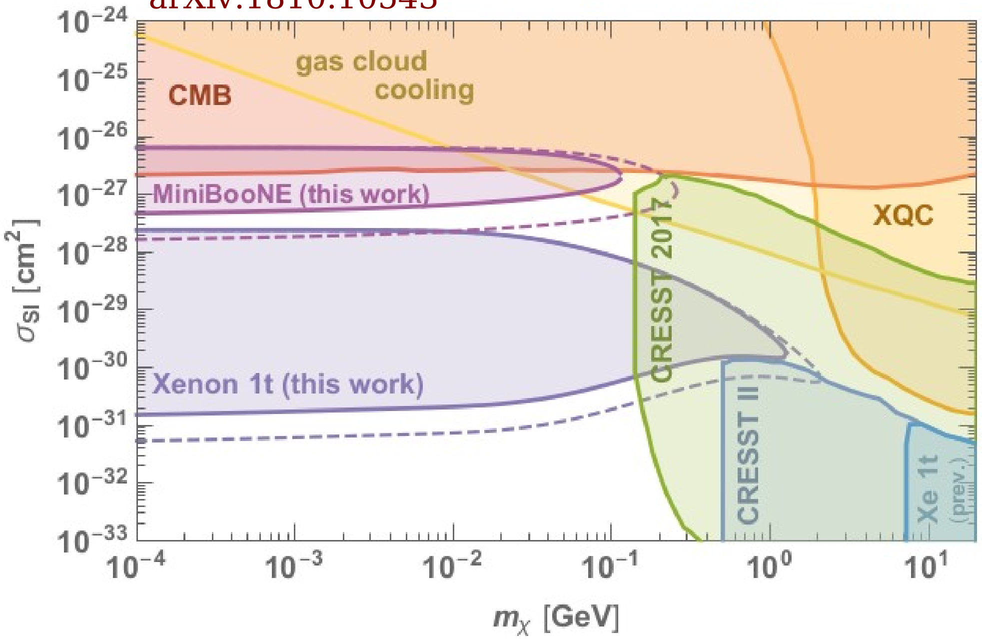
· Radiative processes (Bremsstrahlung, Migdal)

Ideas in arXiv:1607.01789 and 1707.07258, XENON1T results in arXiv:1907.12771

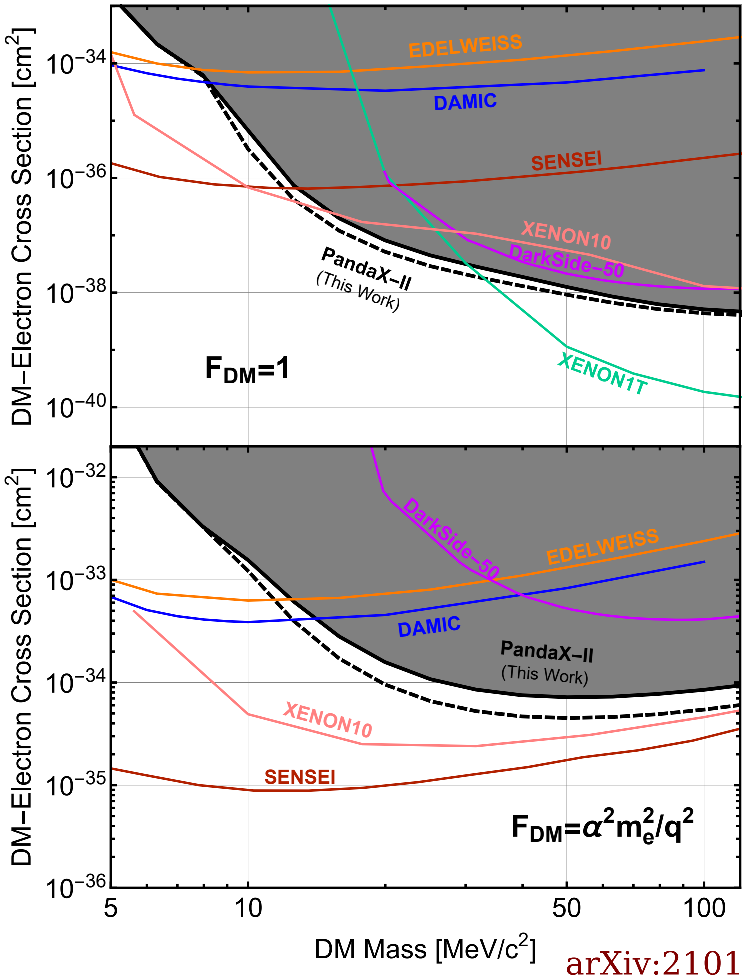
· Fast DM accelerated by scattering off cosmic rays

· Rely on WIMP – electron scattering

arXiv:1810.10543




Constraints in complementary region to Bremsstrahlung/Migdal one




arXiv:2101.07479

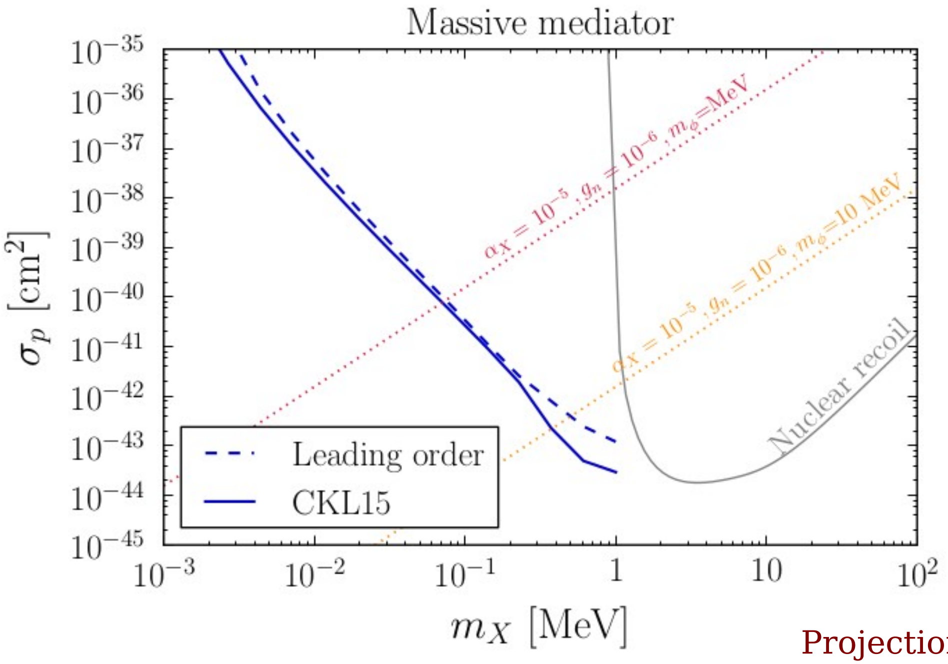
# Superfluid He

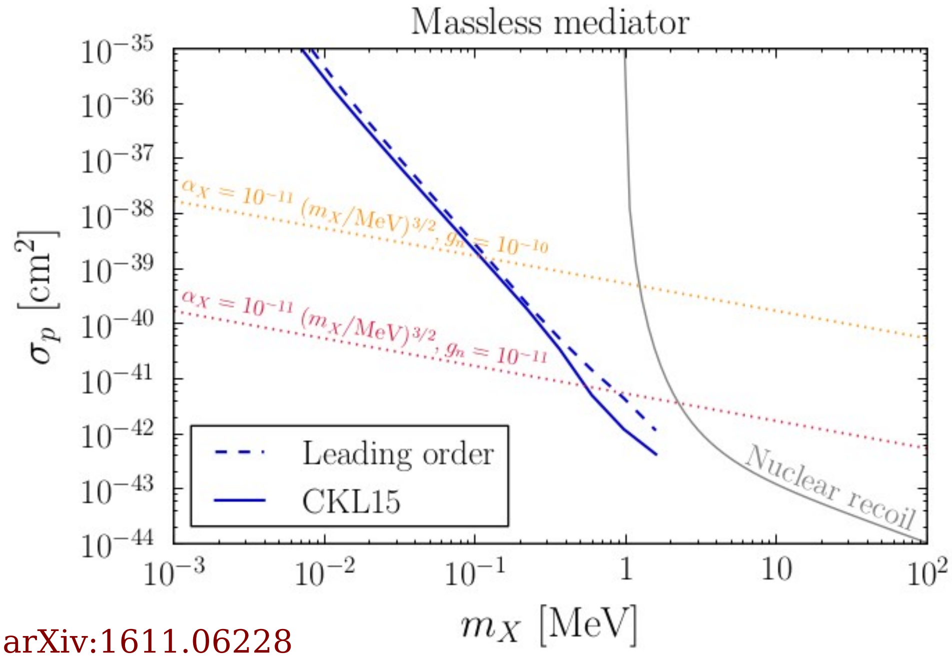
arXiv:1604.08206

General idea: probe the DM-nucleon coupling based on DM scattering – induced collective excitations (*e.g.* phonons).

· For keV – MeV dark matter, expect momentum transfer $O$(eV -  keV), experiments may go as low as ~ keV in DM mass

· Callibrations performed using neutron scattering and simulations (issue: not for identical kinematical regions).



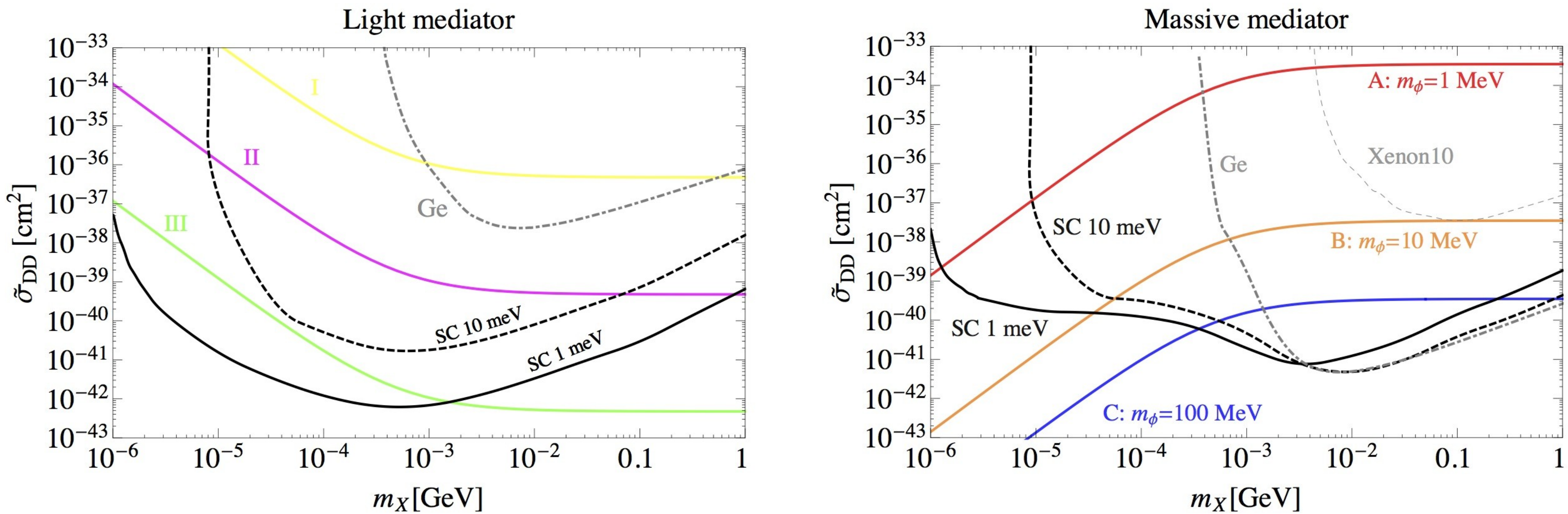




Projections from arXiv:1611.06228

# Superconductors

General idea: probe the DM-electron coupling based on DM – induced breaking of Cooper pairs.

arXiv:1504.07237




Projections from arXiv:1512.04533

· Technique inefficient for light, kinetically mixed dark photons due to in-medium – induced mass.

# Summary and outlook

· Conventional direct detection experiments *can test* and *are testing* non-WIMP dark matter candidates.

· This often means employing the same detectors in different ways (*e.g.* electron scattering in experiments originally intended for WIMP-nucleon scattering).

· At the same time, some limitations do exist, notably when it comes to low mass dark matter candidates → Important to develop new technologies, input from TH also needed.

+ not covered in this talk, candidates below the $\nu$ floor.
Main option: directional detection, *cf* relevant talks on first day.

· Until recently, our perceptions on the mechanism of dark matter genesis informed our approaches on how to detect it. As conventional detectors push the limits, an opposite tendency also starts to appear. In my view, this two-way communication is the way to go forward.

Thank you!