

New developments *in dark matter direct detection experiments*

Christopher McCabe

SLAP!, Kasteel Woerden - 11th October 2017



Outline

Why direct detection?

New developments with...

**Large
detectors**



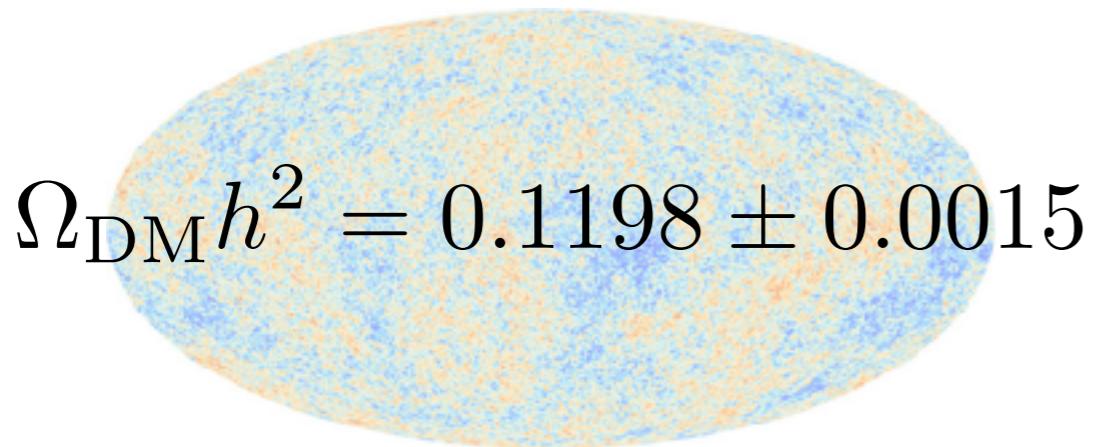
Small
detectors

Why direct detection?

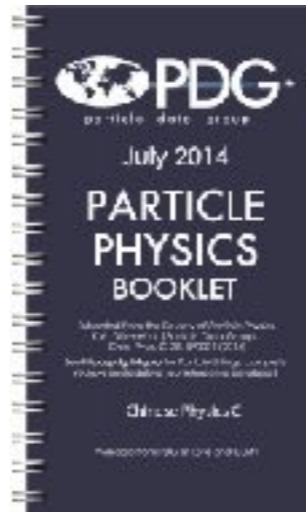
“Up to a point the stories of cosmology and particle physics can be told separately. In the end though, they will come together.”

Steven Weinberg

Cosmology



Particle Physics



$$\begin{aligned}\mathcal{L} = & \mathcal{L}_{\text{SM}} \\ & + \frac{m_q}{\Lambda^3} \bar{\chi} \chi \bar{q} q \\ & + \dots\end{aligned}$$

Suggests DM - matter interactions should be present
&

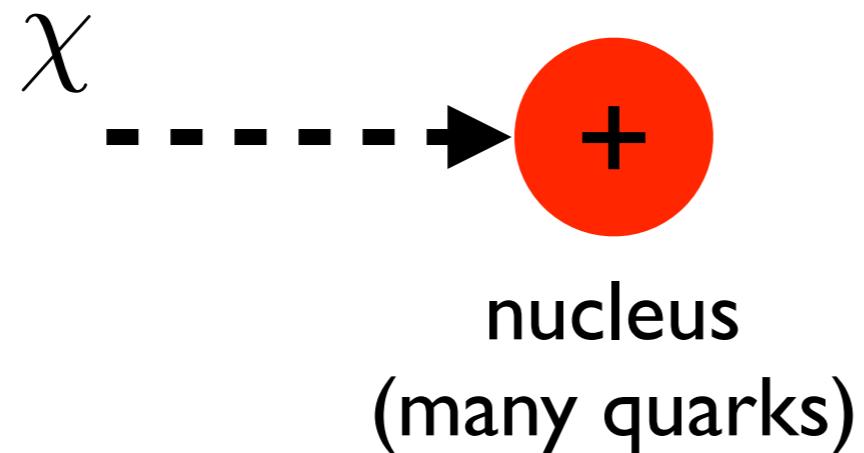
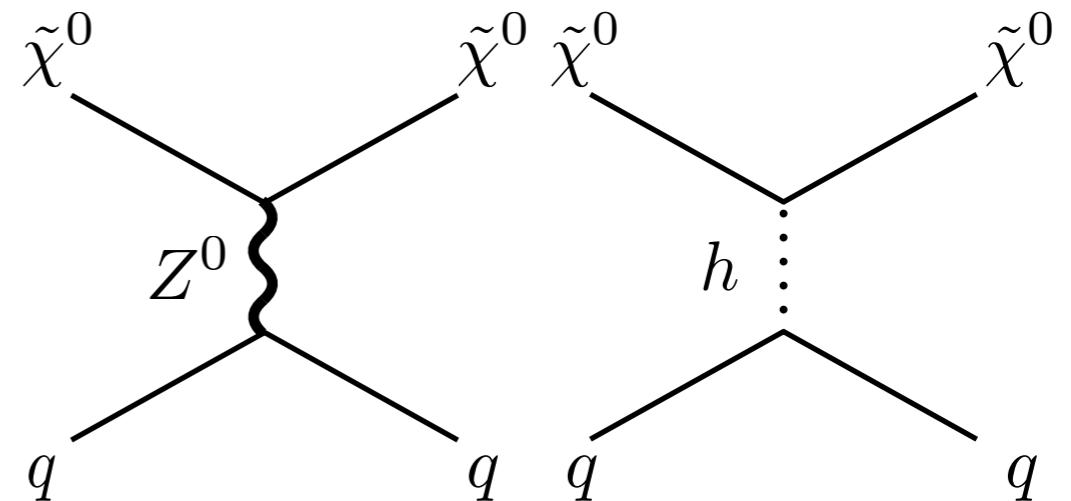
informs and limits the possible interactions

Classic example: SUSY WIMPs

Thermal freeze-out gives
the abundance

&

We know the
interactions

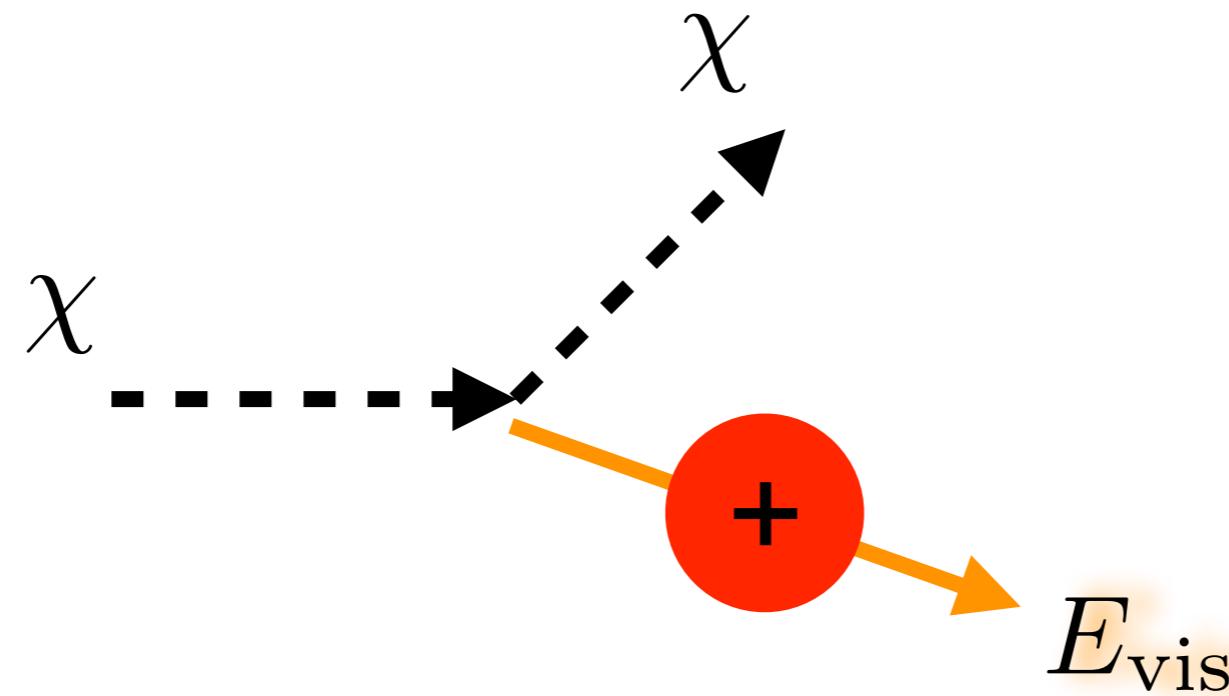
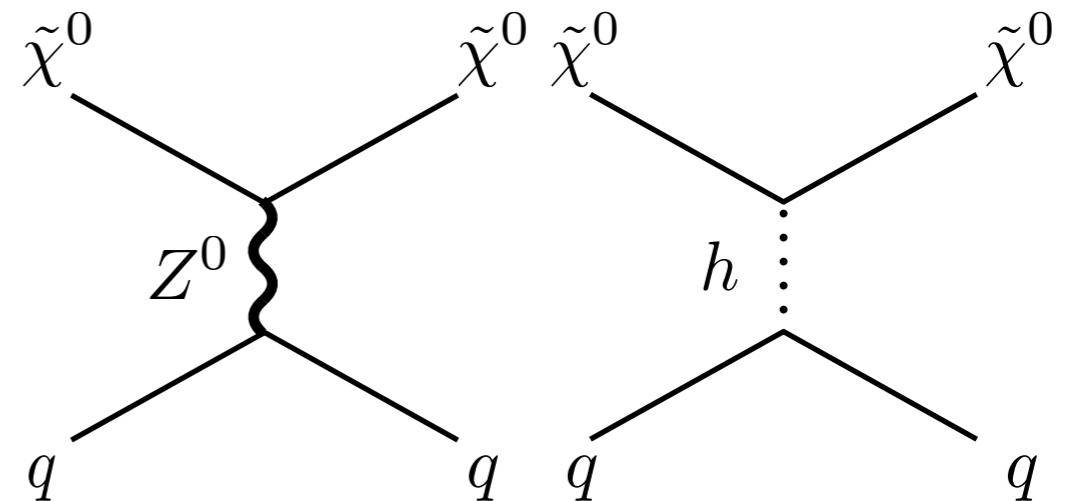


Classic example: SUSY WIMPs

Thermal freeze-out gives
the abundance

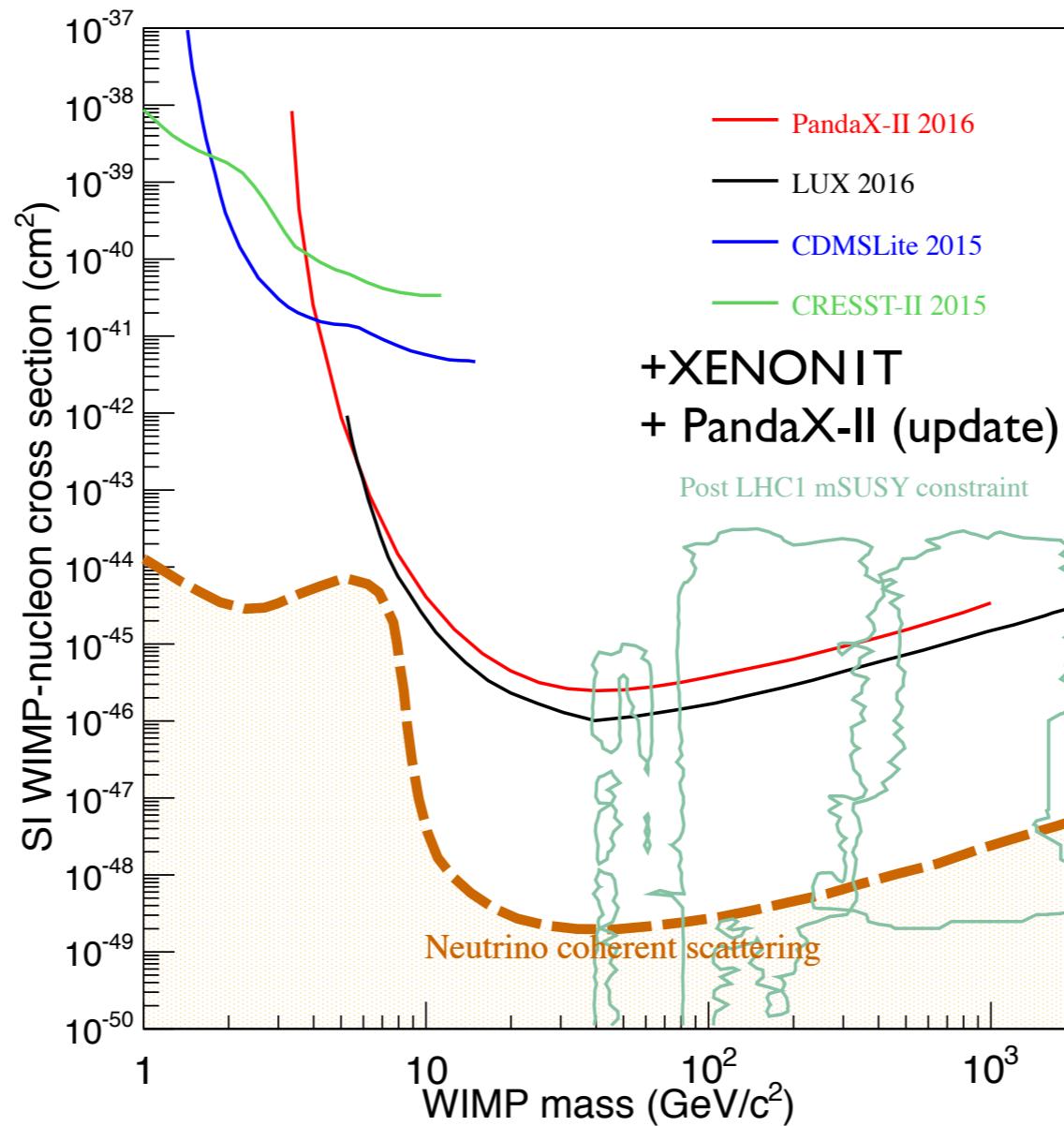
&

We know the
interactions



measure recoil energy
of the nucleus

Where are we?

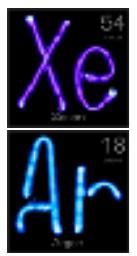


What next?
Keep pushing down
...and look for other things!



New signals in Large Detectors

*Large = {multi-tonne, established technology}



XENON1T

XENONnT, LZ, PandaX-III: 5-10t

DARWIN, PandaX-IV: 50t

DEAP3600

DarkSide-20t

ARGO: 300t

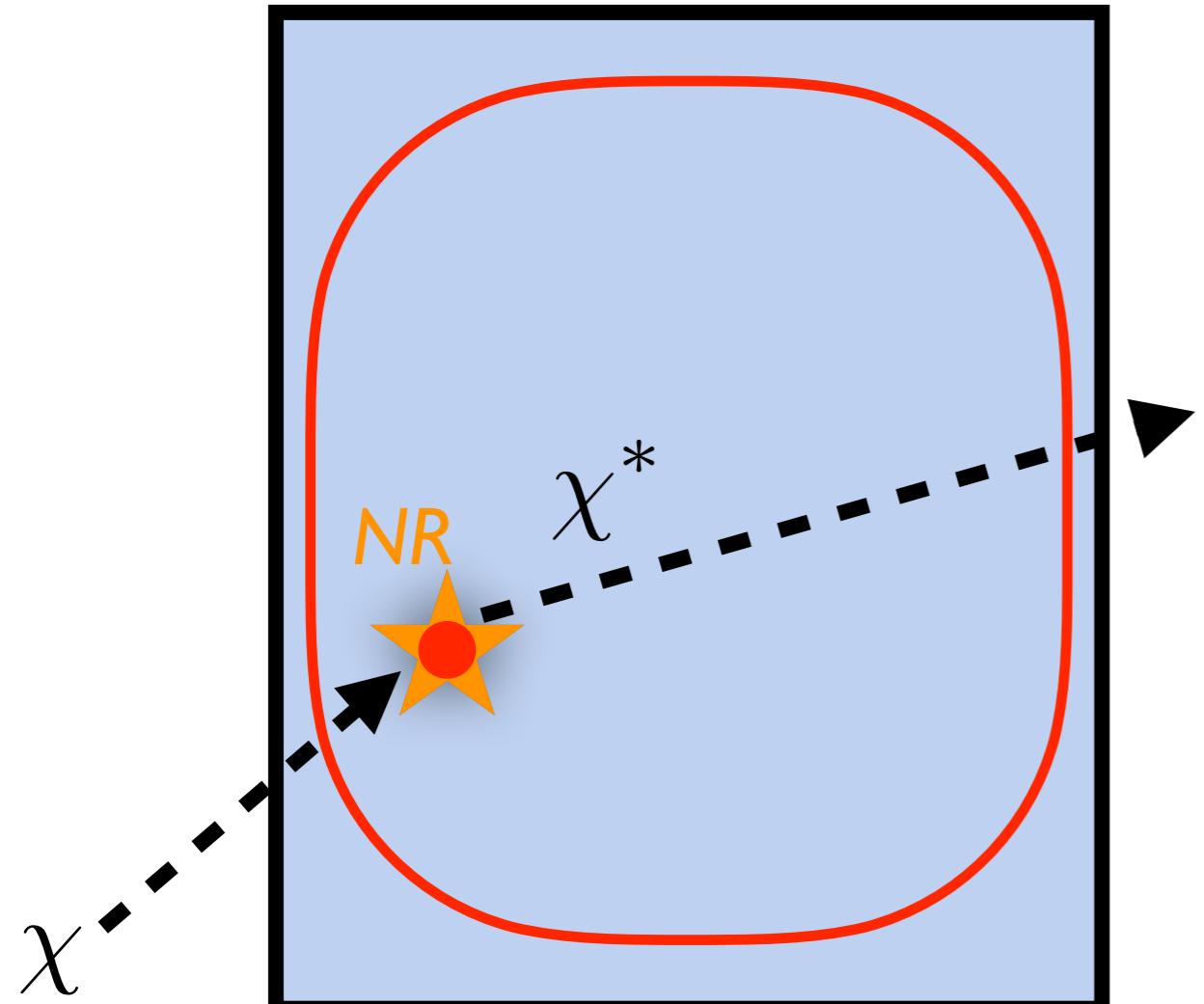
Today

2020

2025+



I. Excite



Idea of inelastic scattering has been around for some time

Tucker-Smith, Weiner, arXiv:0101138

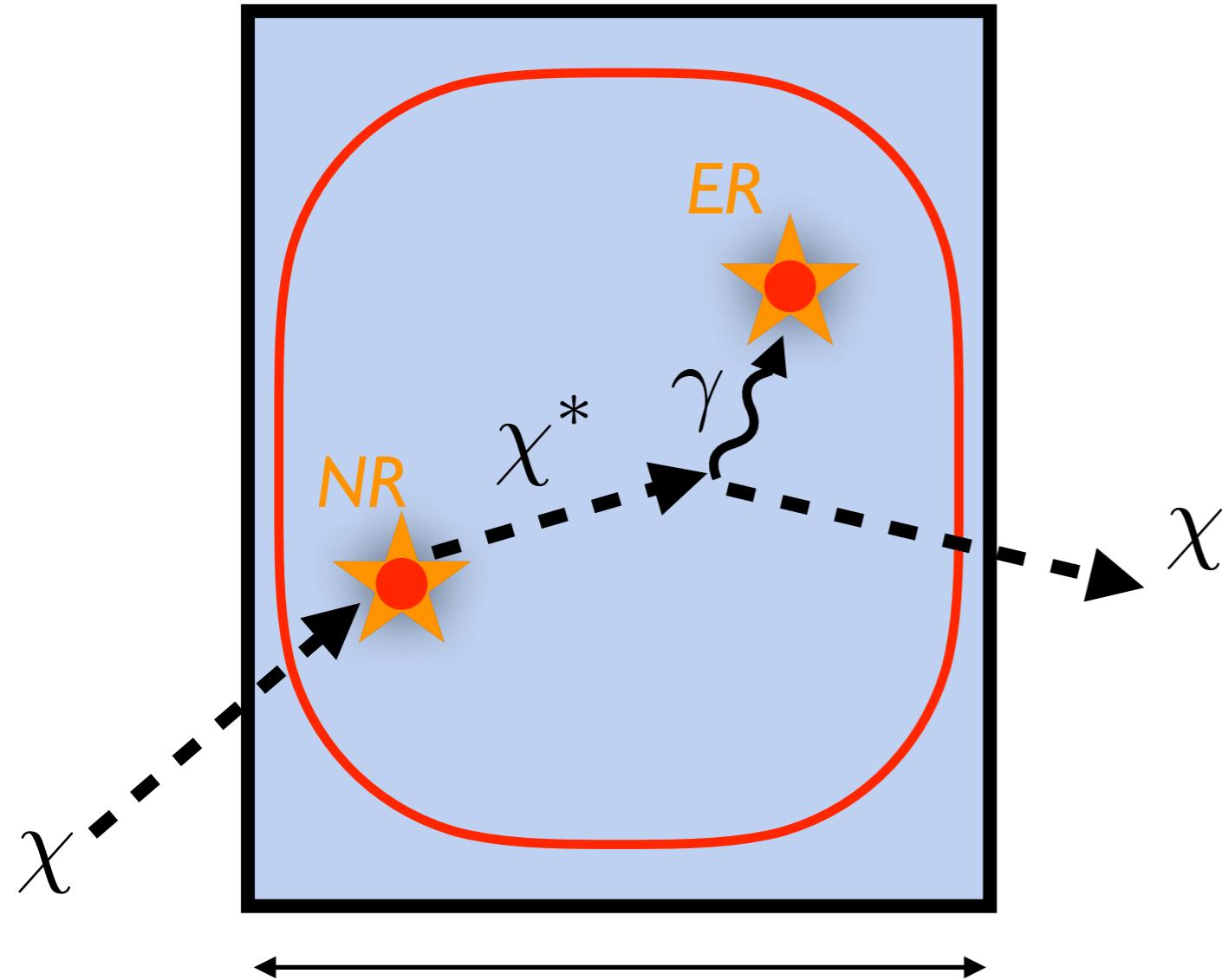
Can up-scatter so long as

$$m_{\chi^*} - m_\chi \lesssim 200 \text{ keV}$$

(and you have a model for it)



I. Excite and decay



XE100 30cm; XEIT 100cm; LZ 150cm

New: can look for decays
with large detectors

e.g. *magnetic dipole interaction*

$$\mathcal{L} \supset \mu_\chi \bar{\chi}^* \sigma_{\mu\nu} \chi F^{\mu\nu}$$

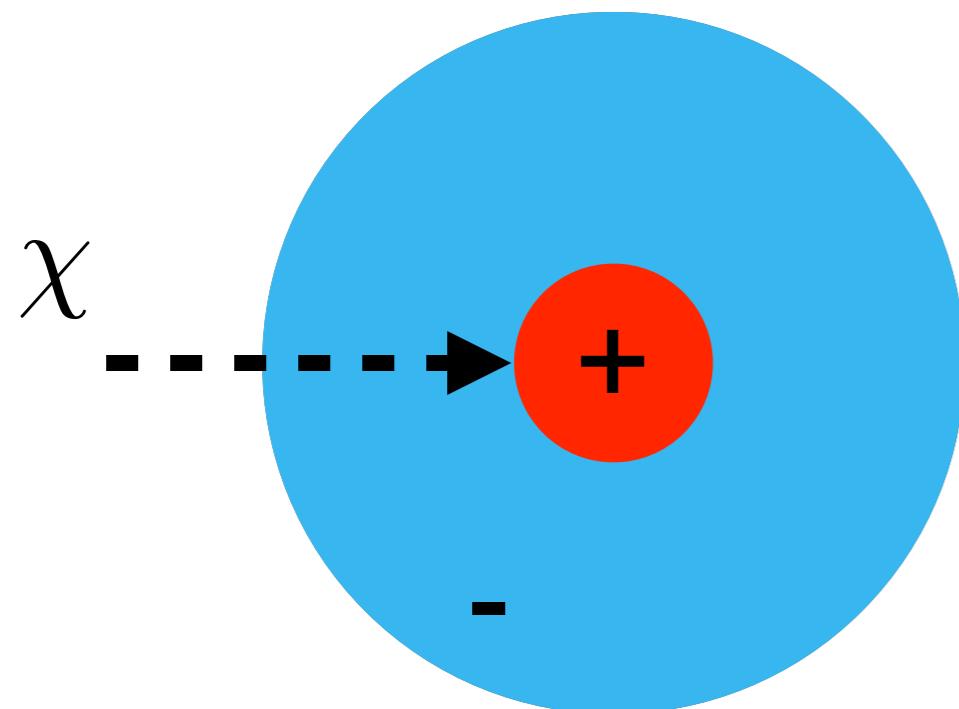
$$\tau_{\chi^*} \sim \mu\text{s} \sim 30\text{cm}$$

First search by XE100
(no signal) [arXiv:1704.05804](https://arxiv.org/abs/1704.05804)

Bonus: *directional detection
with head-tail information*

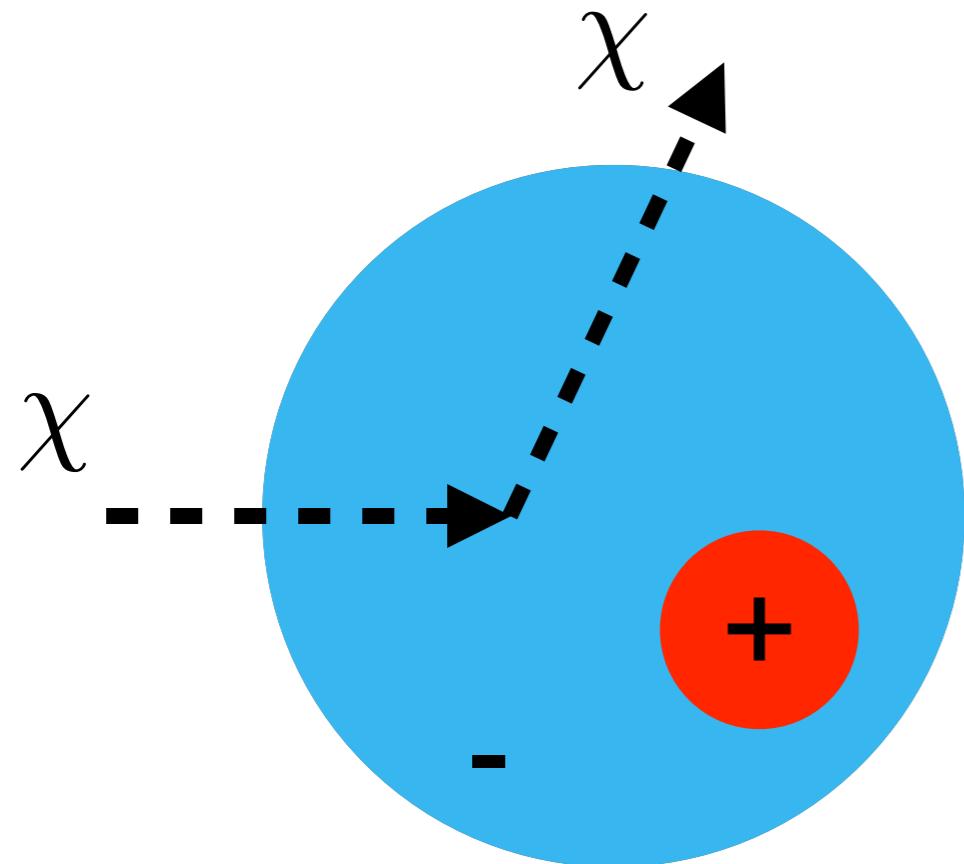
Lin, Finkbeiner, arXiv:1011.3052

2. Shake the atom



xenon atom
(ground state)

2. Shake the atom



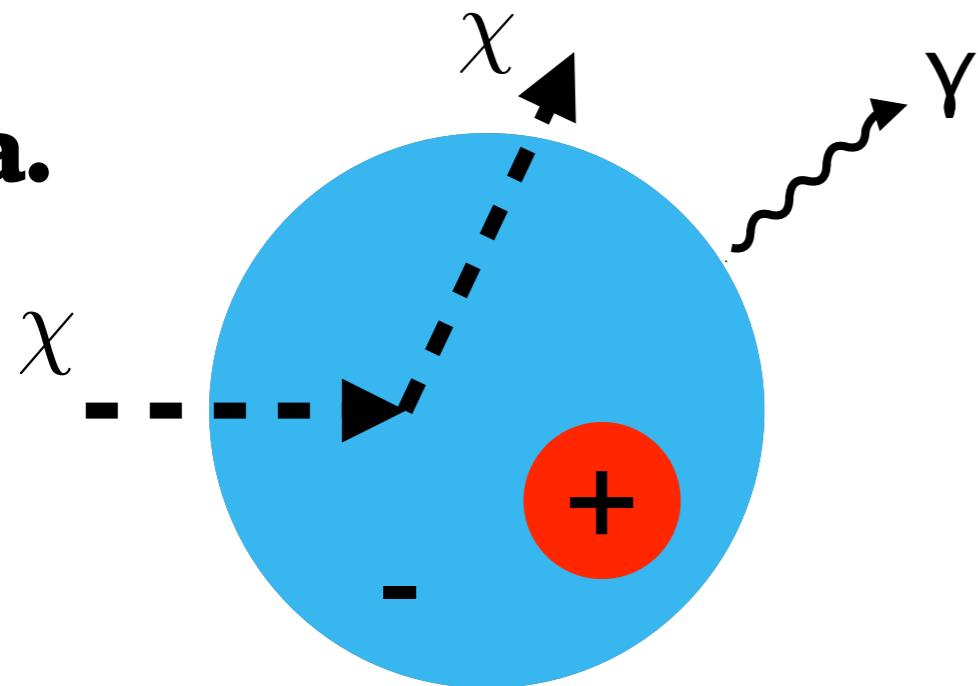
nucleus gets a nudge

$$E_{\text{recoil}} \lesssim 0.1 \text{ keV}$$



2. Shake the atom

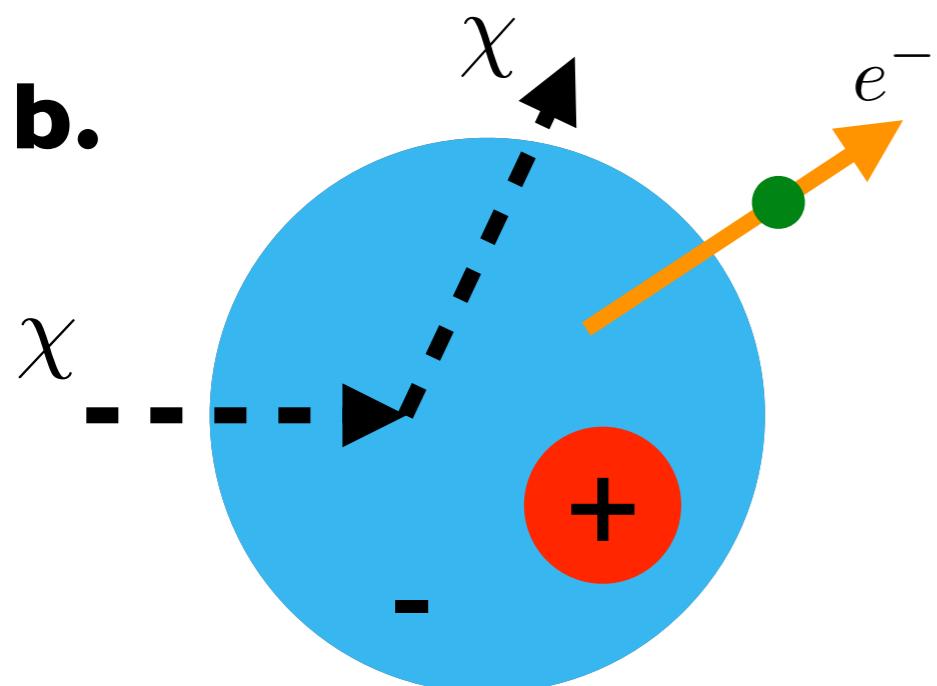
a.



Polarised atom emits a photon
Suppression factor $\sim 10^{-8}$

Kouvaris & Pradler
arXiv:1607.01789
CM arXiv:1702.04730

b.



Atom emits an electron (Migdal effect)

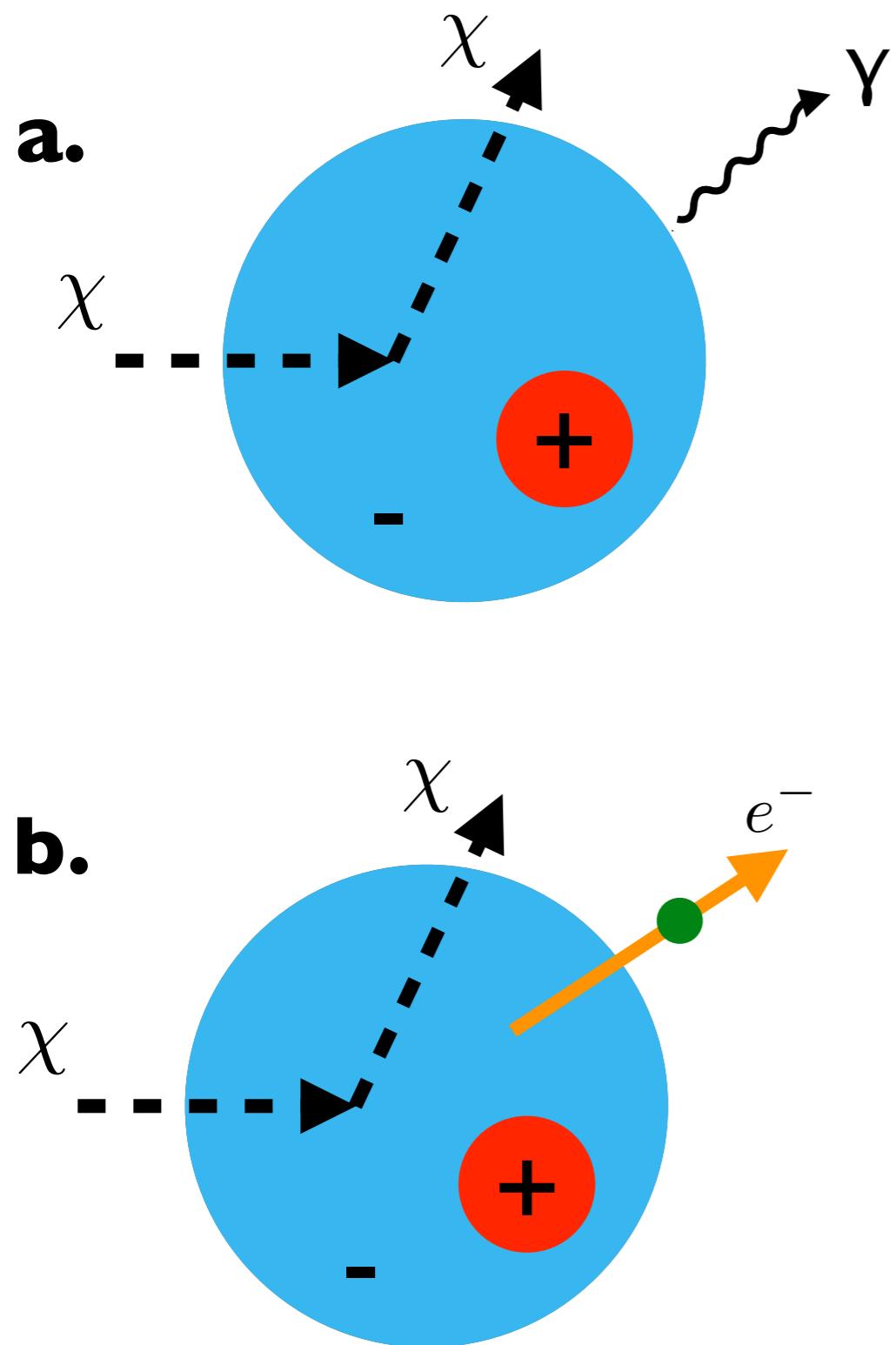
“...it takes some time for the electrons to catch up, which causes ionisation of the atom”

Suppression factor $\sim 10^{-5}$

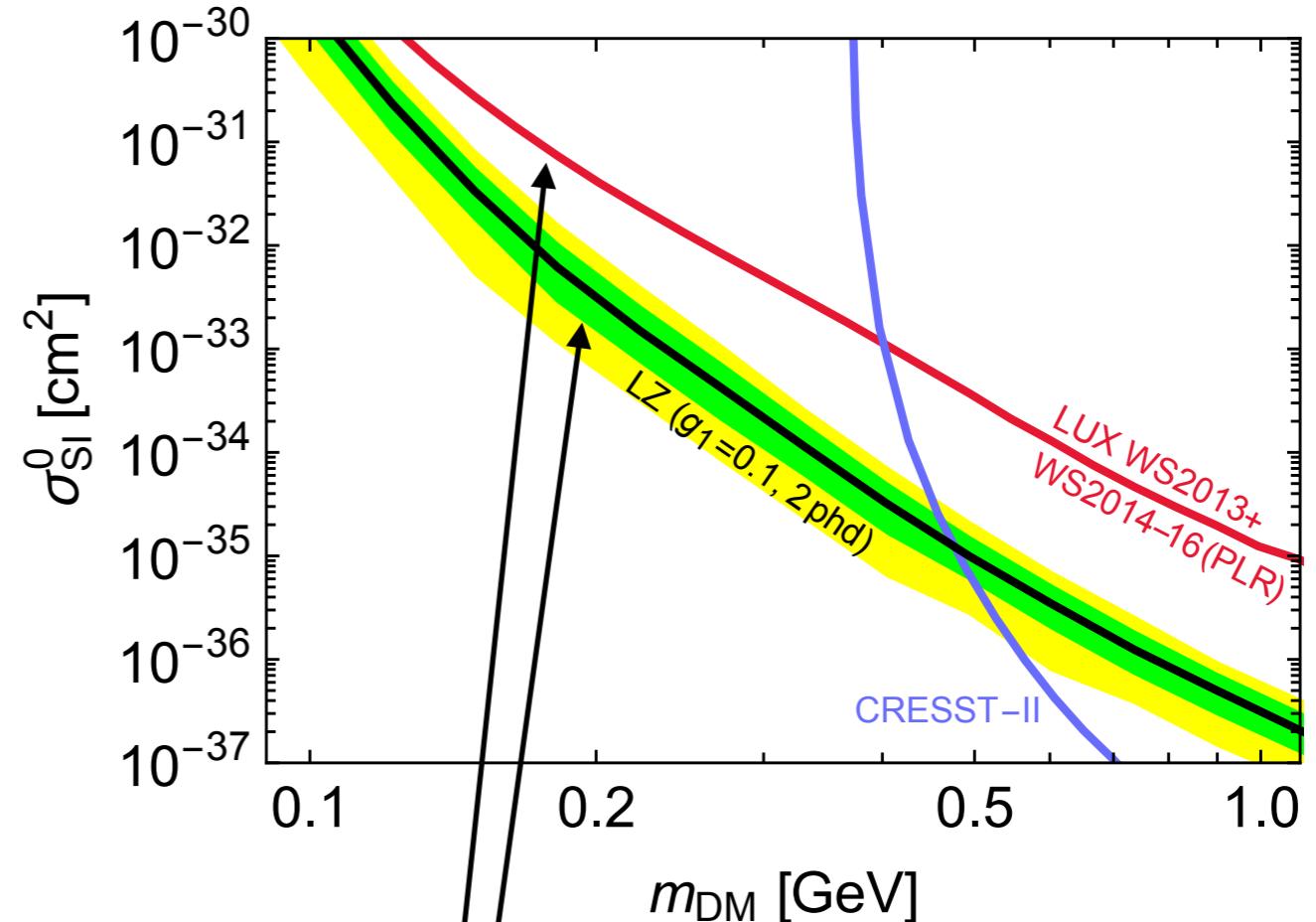
Ibe et al
arXiv:1707.07258



2. Shake the atom



Large detectors overcome suppression
Photon & electrons easy to detect!



A new probe of sub-GeV DM

3. Supernova neutrino detection



Energy:

$\sim 10^{53}$ erg released

$\sim 99\%$ is emitted by all neutrino flavours

Neutrino energy ~ 15 MeV

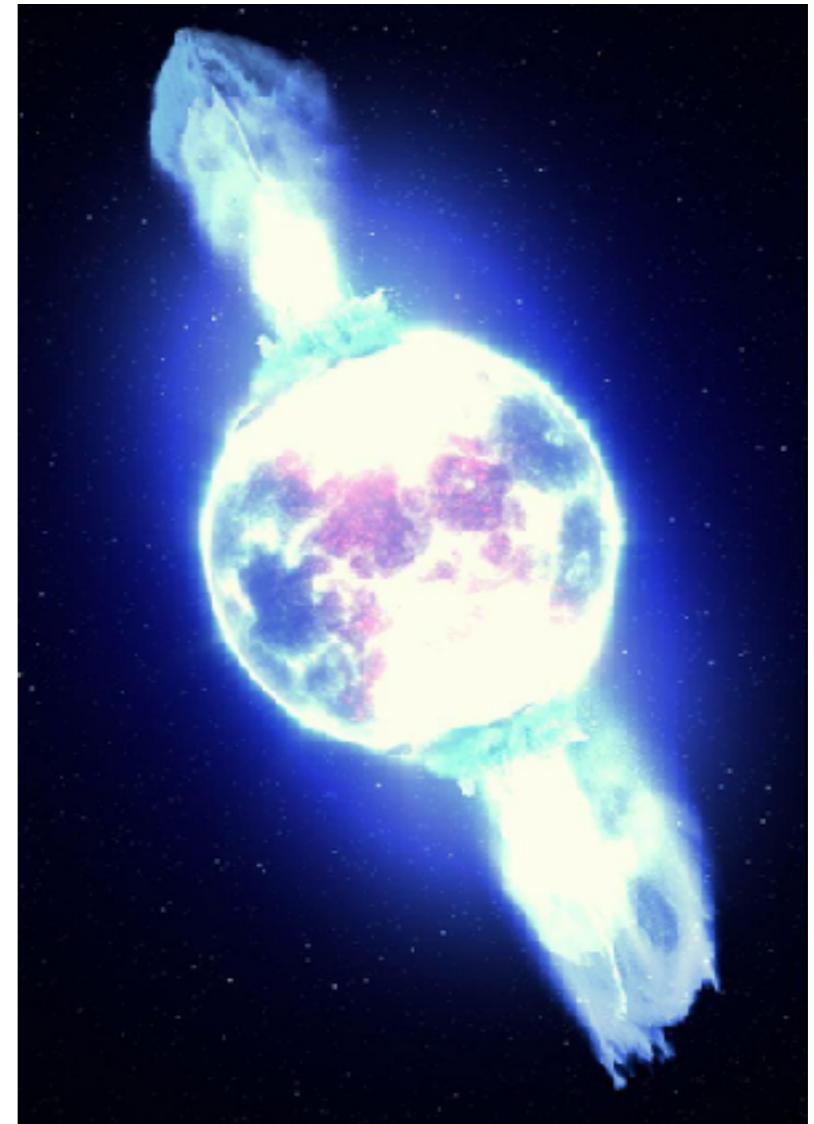
Time:

Neutrino emission lasts ~ 10 s

When/where:

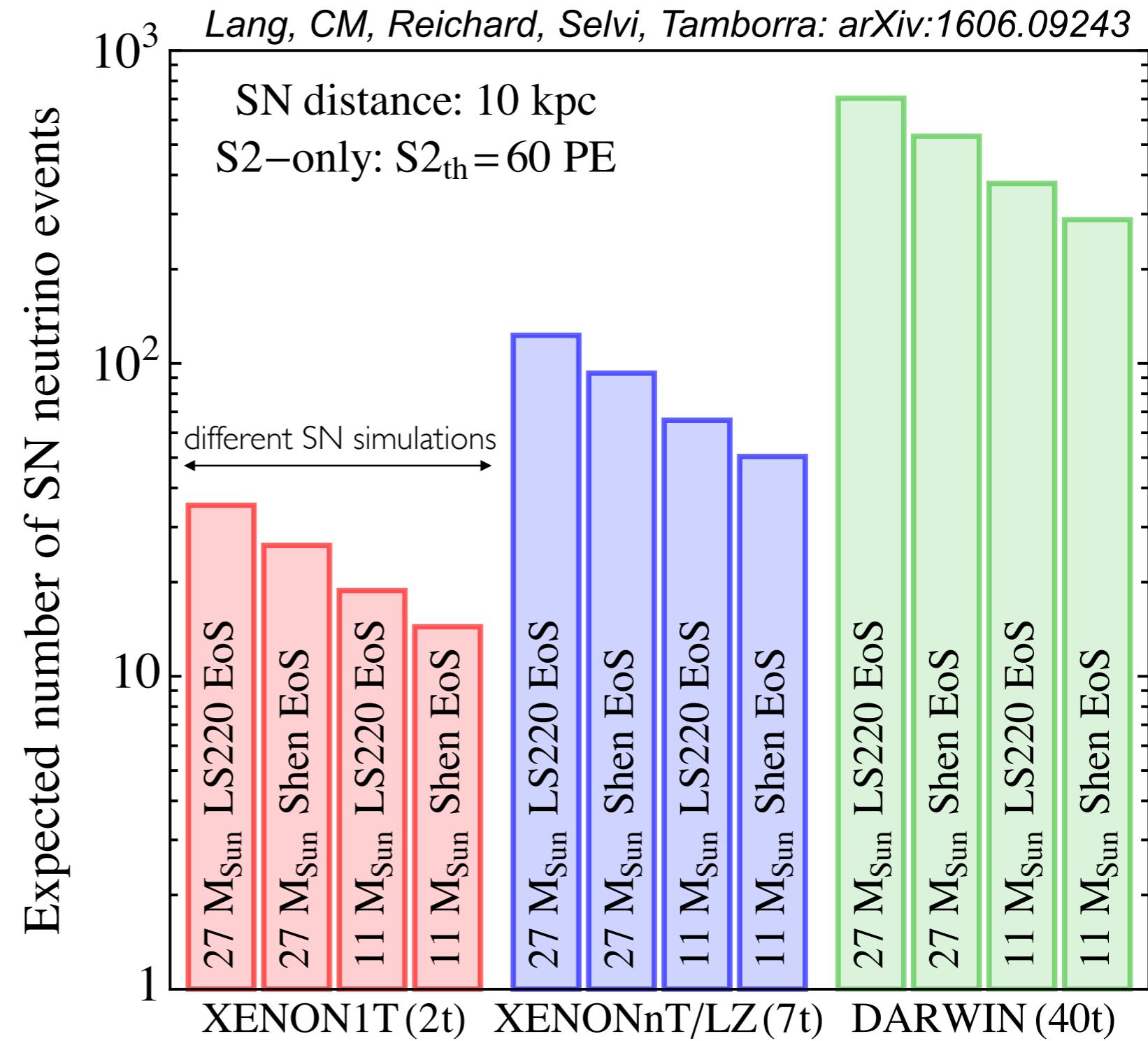
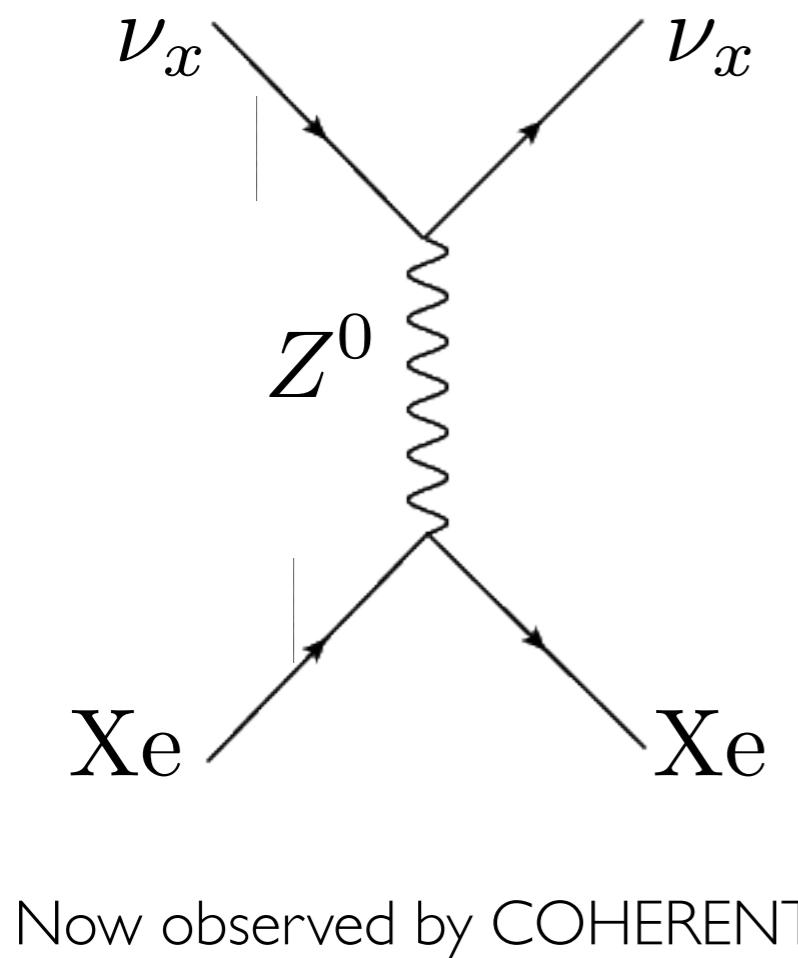
$\sim 1-3$ SN/century in our galaxy

distance ~ 10 kpc





3. Supernova neutrino detection



Small Detectors



US Cosmic Visions: New Ideas in Dark Matter 2017 :
Community Report

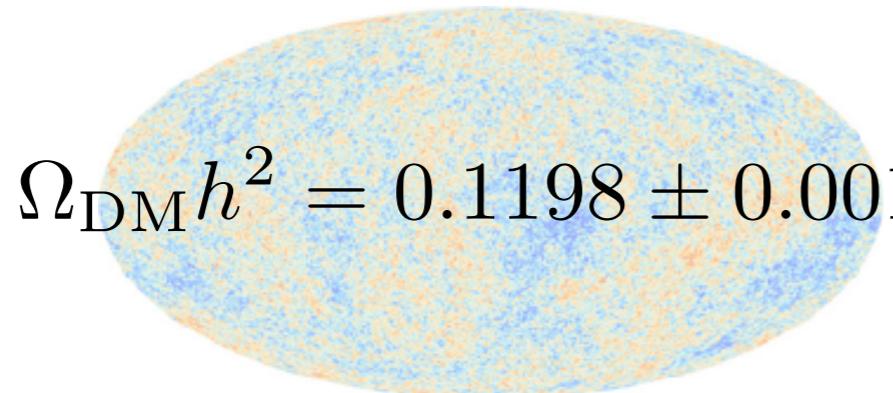
arXiv:1707.04591v1

*Small = {< kg, new technology}

Why go small?

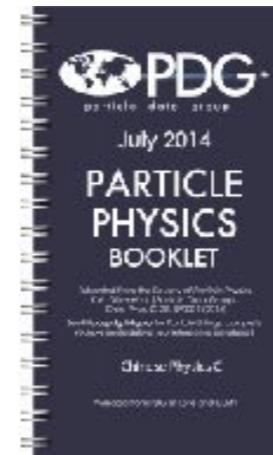


Cosmology



$$\Omega_{\text{DM}} h^2 = 0.1198 \pm 0.0015$$

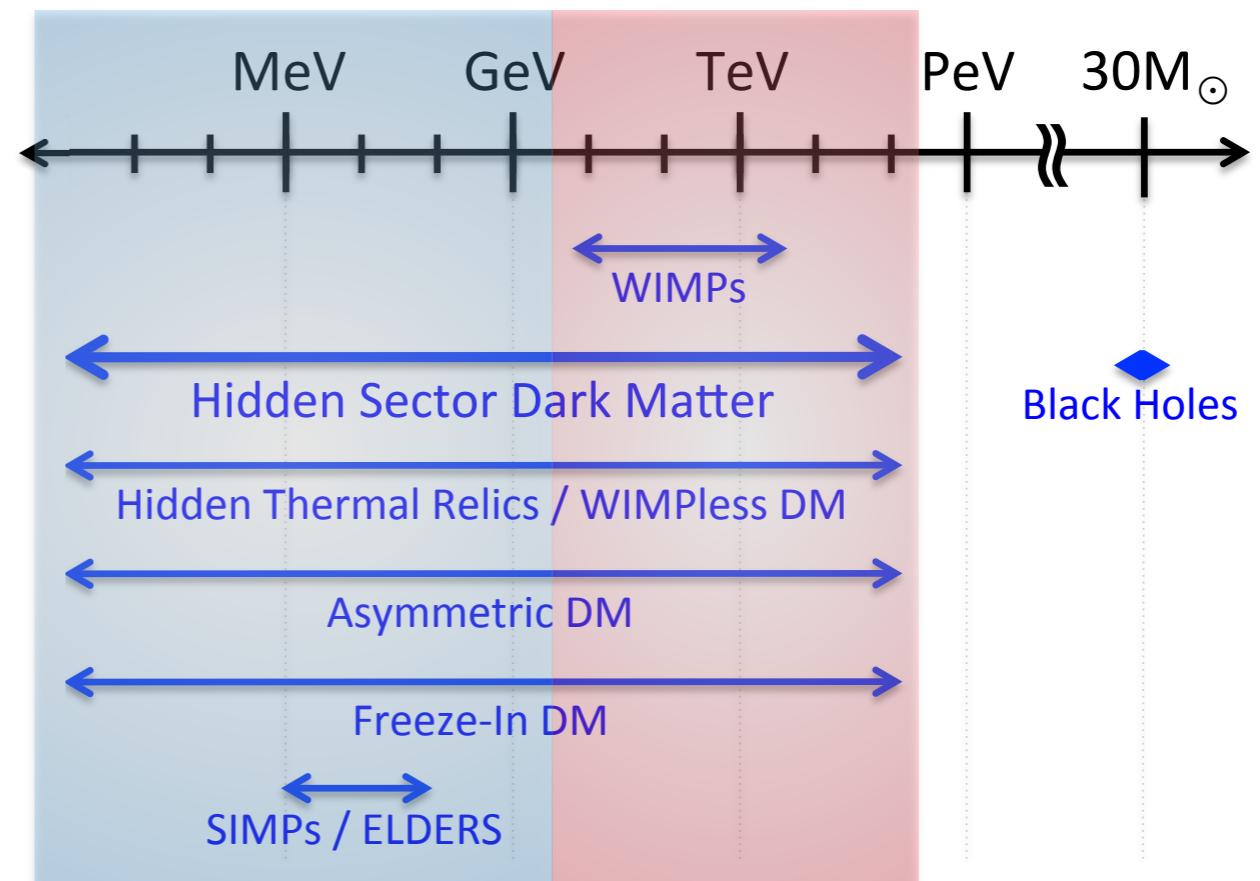
Particle



$$\begin{aligned}\mathcal{L} = & \mathcal{L}_{\text{SM}} \\ & + \frac{m_q}{\Lambda^3} \bar{\chi} \chi \bar{q} q \\ & + \dots\end{aligned}$$

Many other DM production mechanisms

how can we probe them?



Lots of activity (all in USA?)

18 proposed experiments
results in 2yrs?

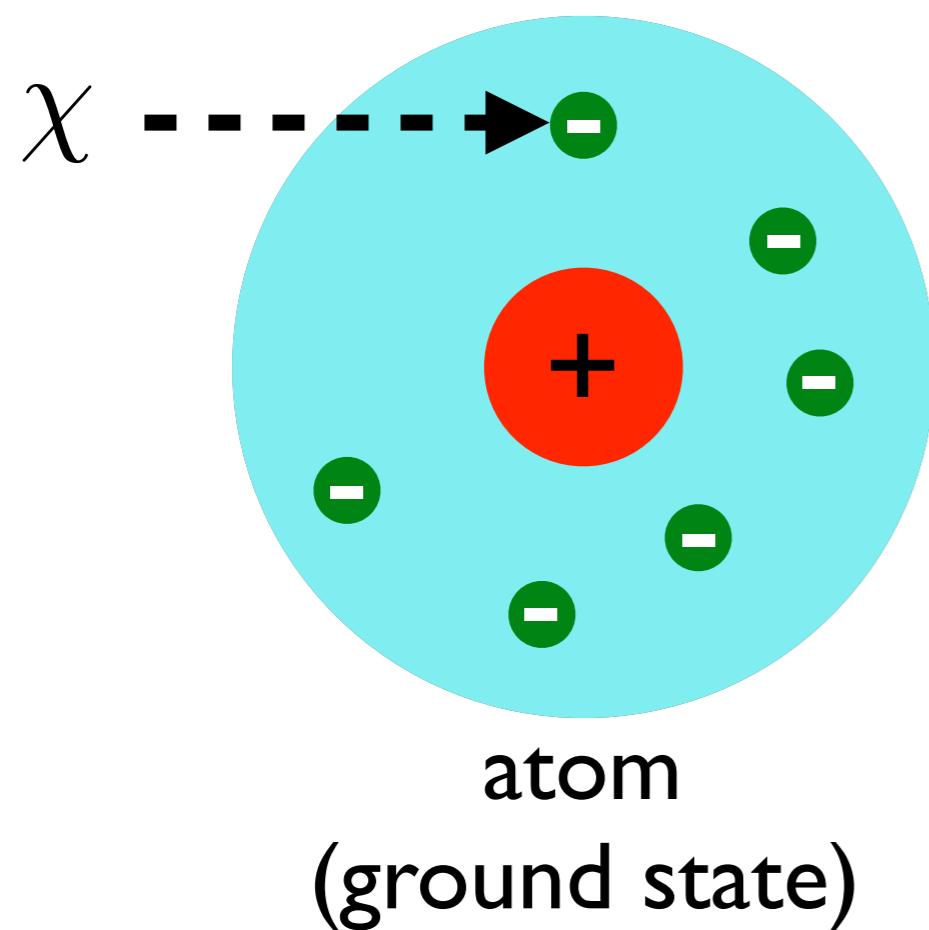
US Cosmic Visions: New Ideas in Dark Matter 2017 :
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arXiv:1707.04591v1

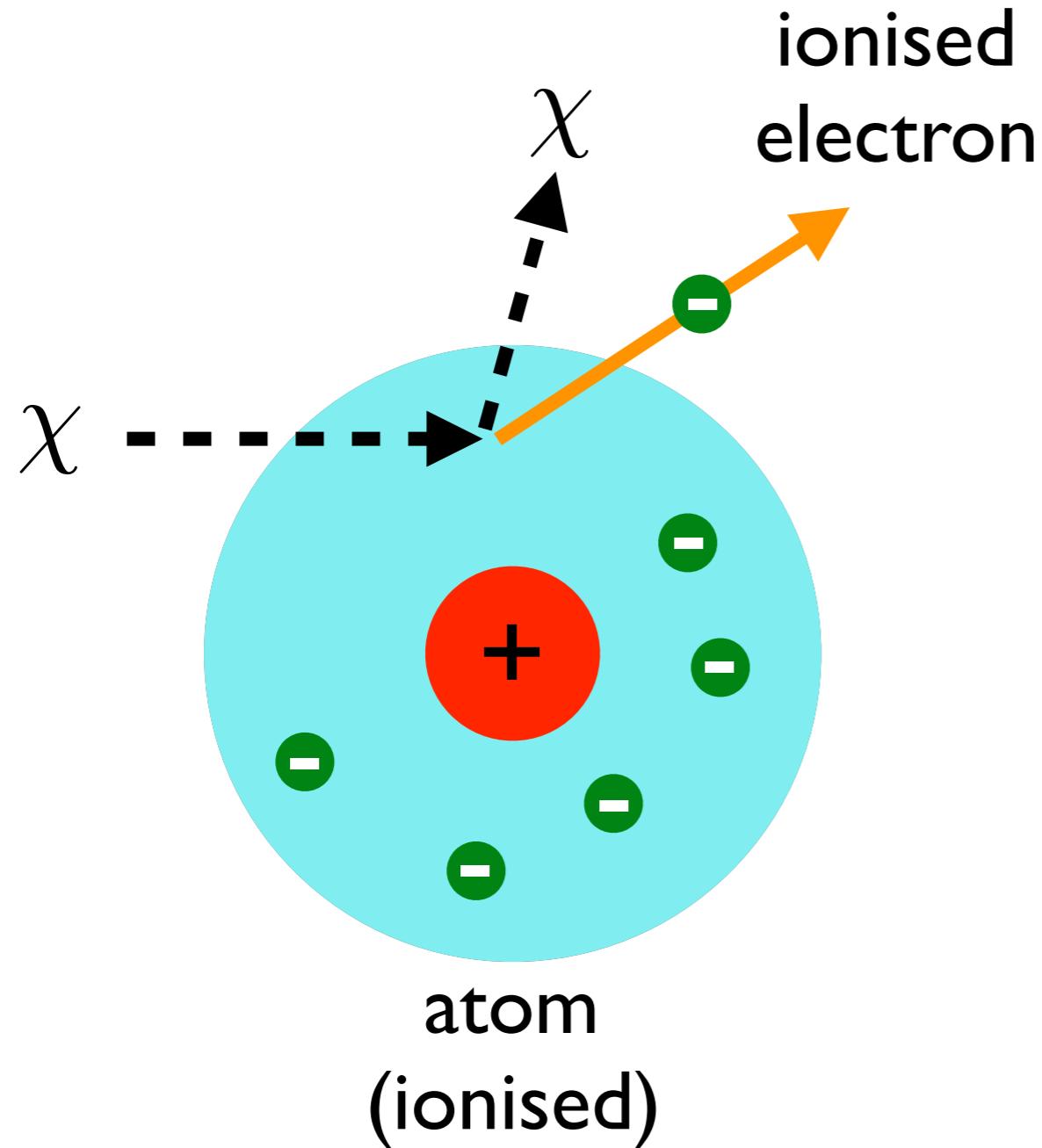


Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA'(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
Sub-GeV Dark Matter (Nucleon Interactions)	supercond. Al cube	Al	heat	10+ yr program
	Superfluid helium with TES readout	He	heat, light	1 yr R&D; 2018 ready to start project; 2022 run
	Evaporation & detection of He- atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing
Searches down to Neutrino Floor for $\mathcal{O}(\text{GeV})$ Dark Matter	SuperCDMS-G2+	Ge	heat, ionization	3 yr R&D; 1 yr fabrication; 2022 start running
	NEWS-G	H, He	charge	140cm sphere installed at SNOLAB in 2018
	NEWS-dm	Si, Br, I, C, O, N, H, S	charge directionality	R&D phase complete. Now technical test
	CYGNUS HD-10	SF ₆ , He flexible	charge directionality	1 yr R&D; 1 yr 1 m ³ ; 2 yr 10 m ³
	Scintillating bubble chamber	Xe, Ar C ₆ F ₆ , H ₂ O	light heat(bubble)	2 yr program; test 10kg Xe chamber with CENNS
	Spin-Dependent (Proton) Interactions	PICO bubble chambers	wide range heat(bubble)	40 l chamber now PICO 500 l next

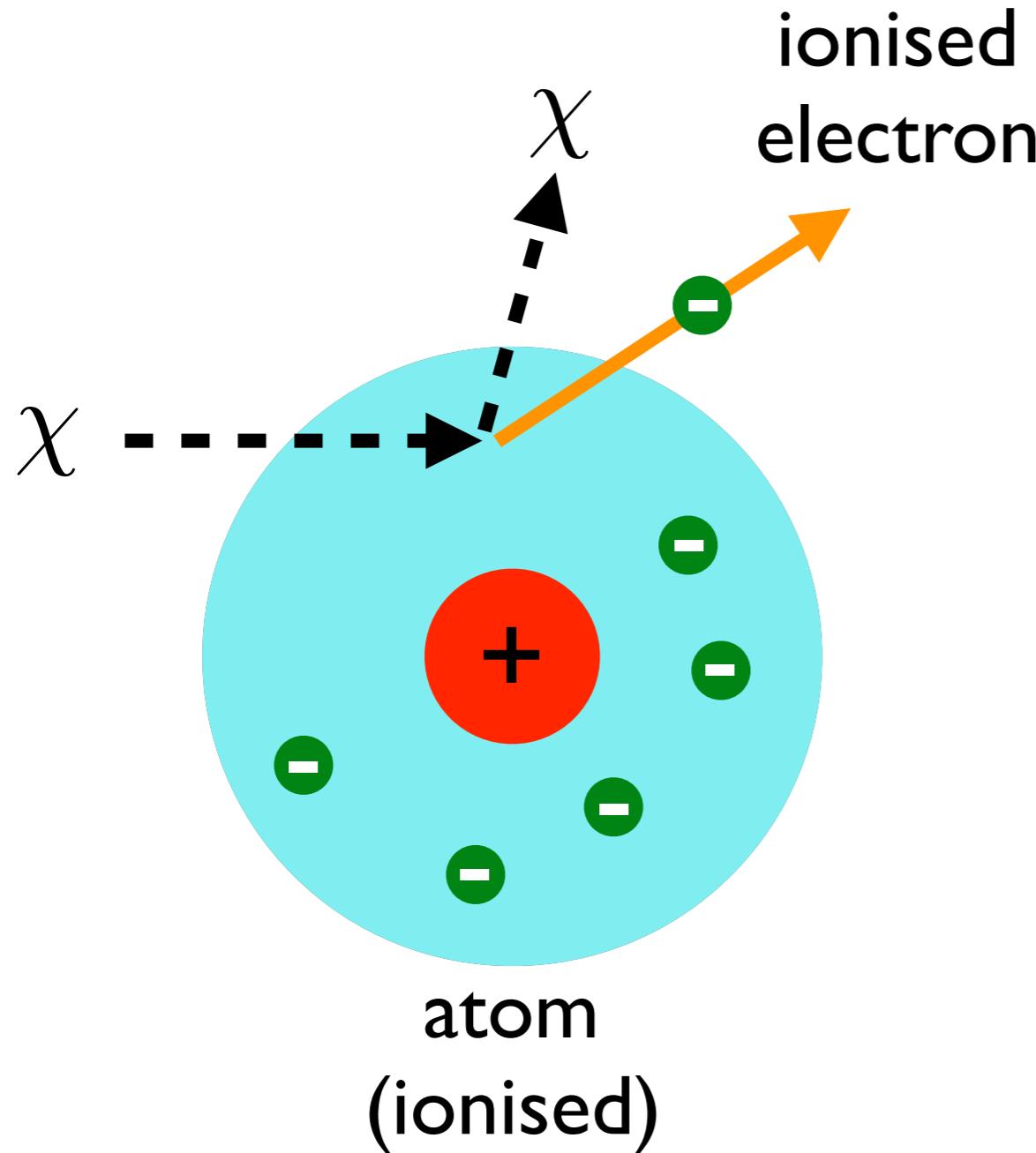
Technique I: ionise electrons



Ionise electrons



Ionise electrons



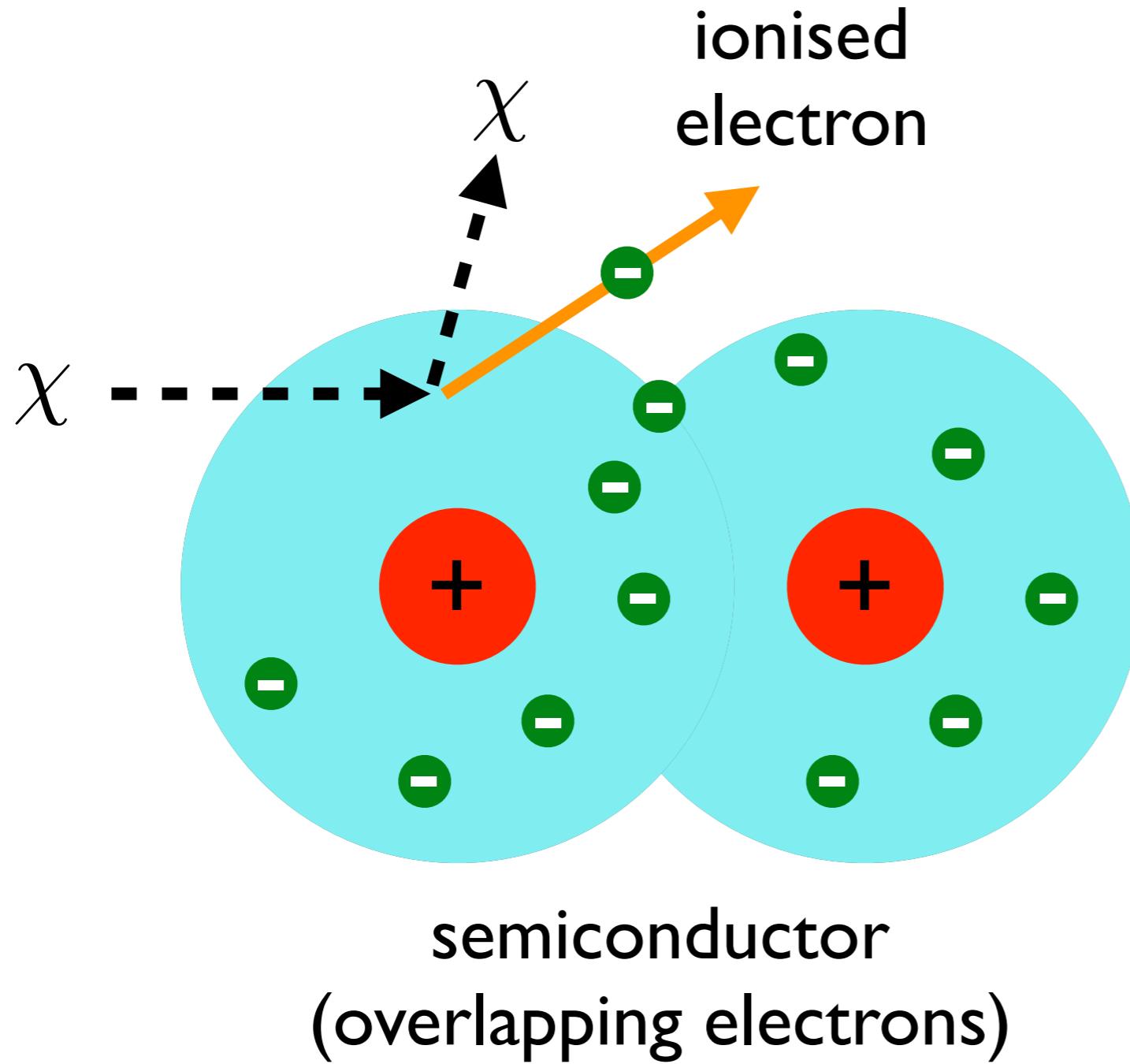
$$\frac{1}{2}m_{\text{DM}}v^2 \simeq E_{\text{binding}}$$

Atoms:

$E_{\text{binding}} \sim 10 \text{ eV}$

$m_{\text{DM}} \gtrsim 10 \text{ MeV}$

Ionise electrons



$$\frac{1}{2}m_{\text{DM}}v^2 \simeq E_{\text{binding}}$$

Atoms:

$E_{\text{binding}} \sim 10 \text{ eV}$

$m_{\text{DM}} \gtrsim 10 \text{ MeV}$

Semi-conductors:

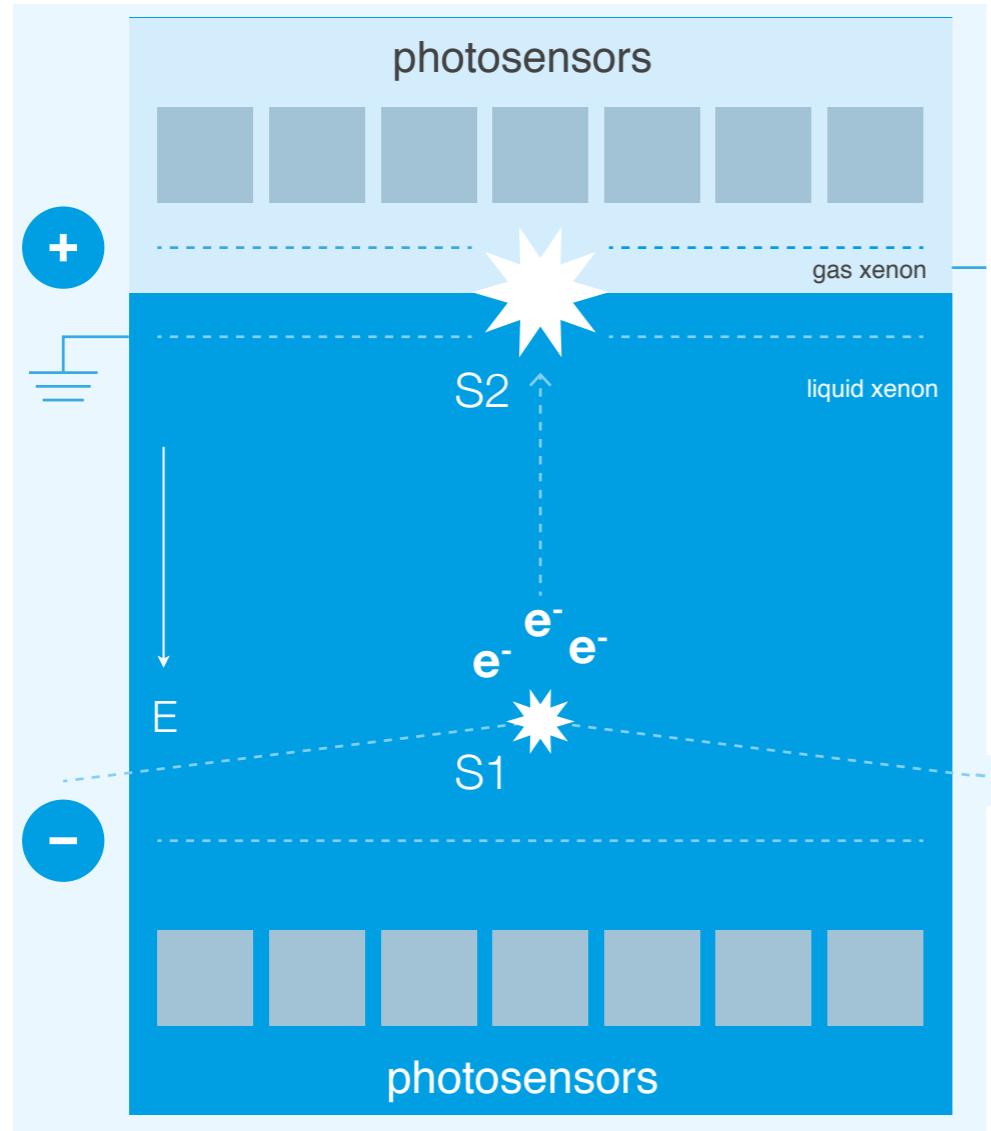
$E_{\text{binding}} \sim 1 \text{ eV}$

$m_{\text{DM}} \gtrsim 1 \text{ MeV}$

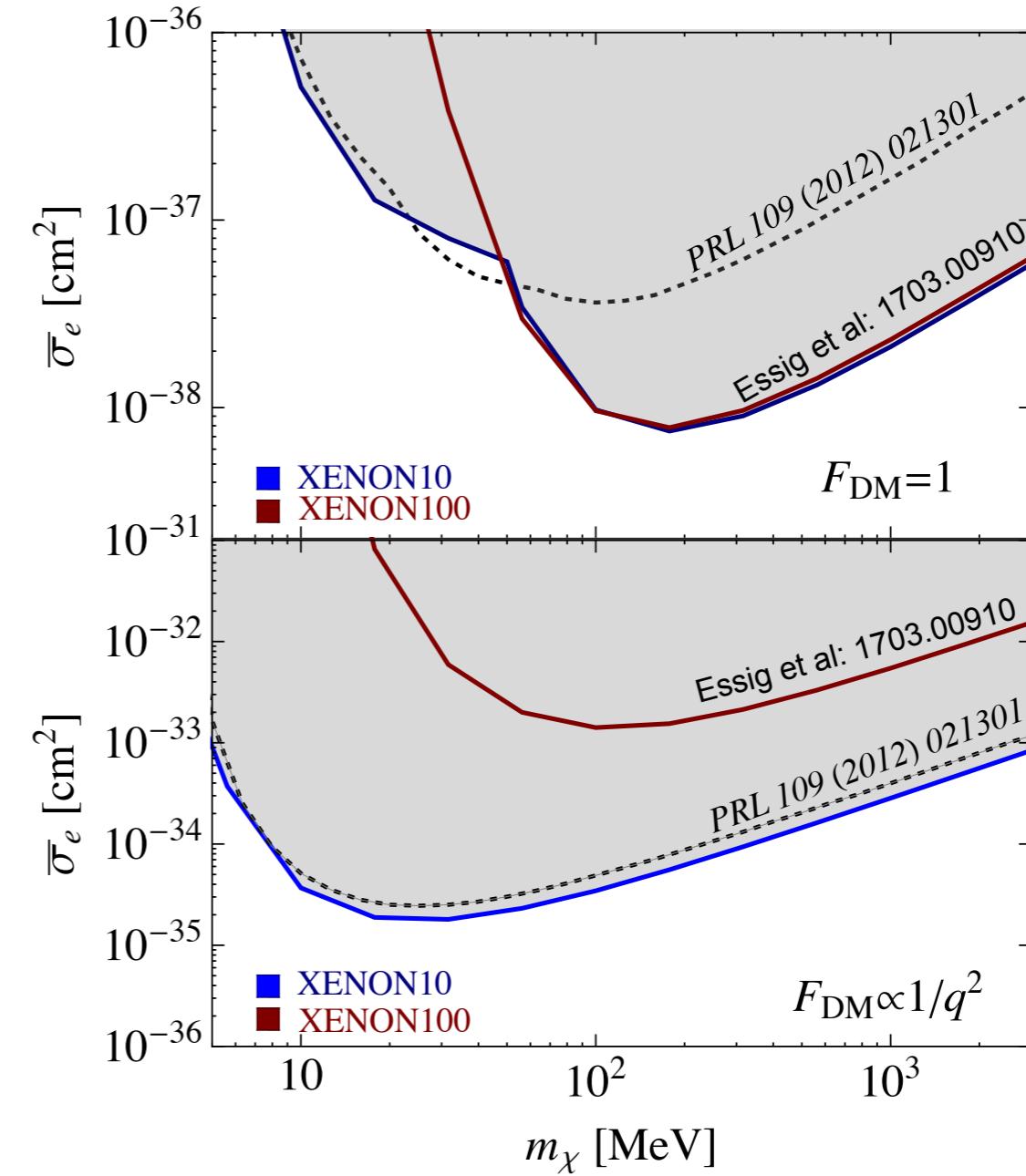
Proof-of-concept



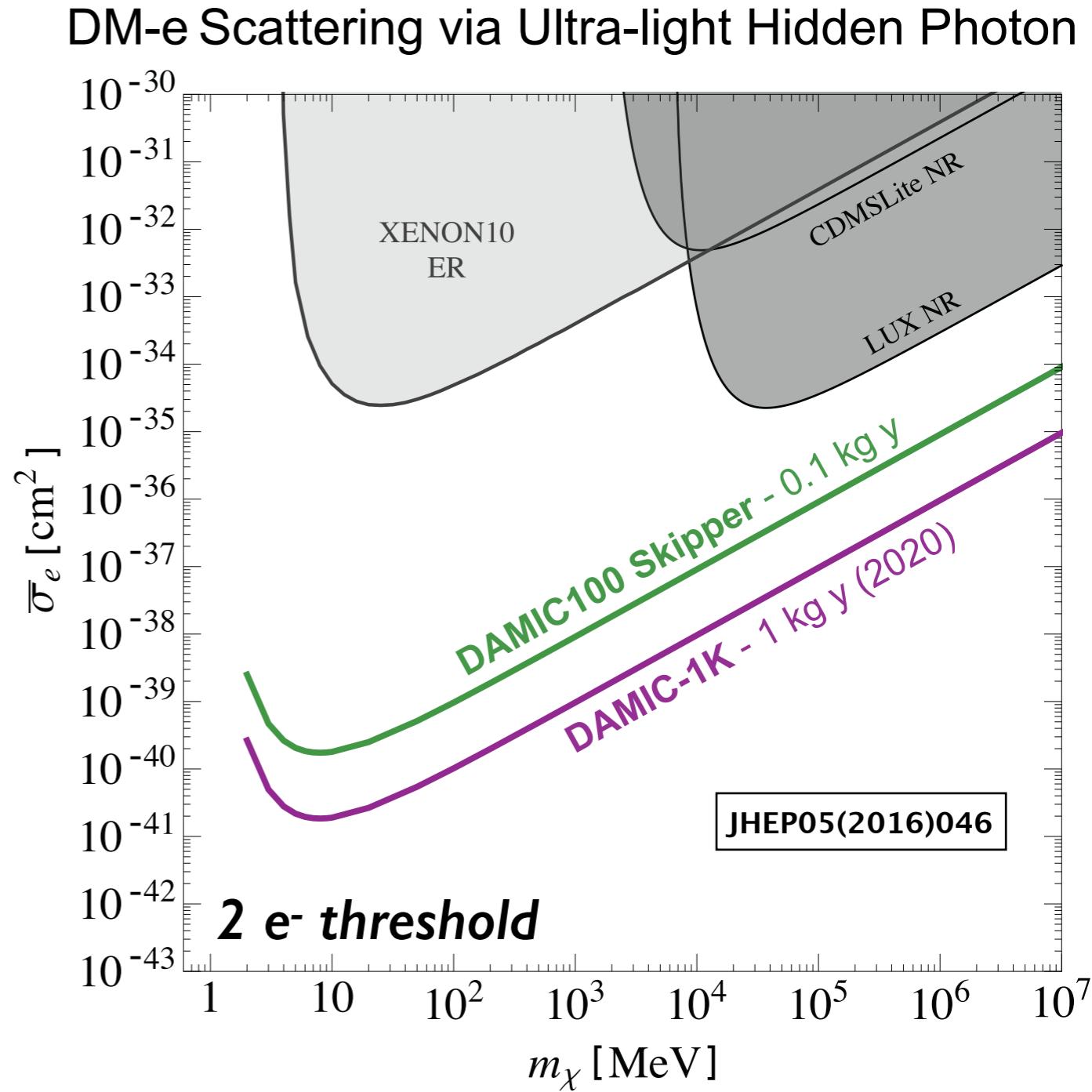
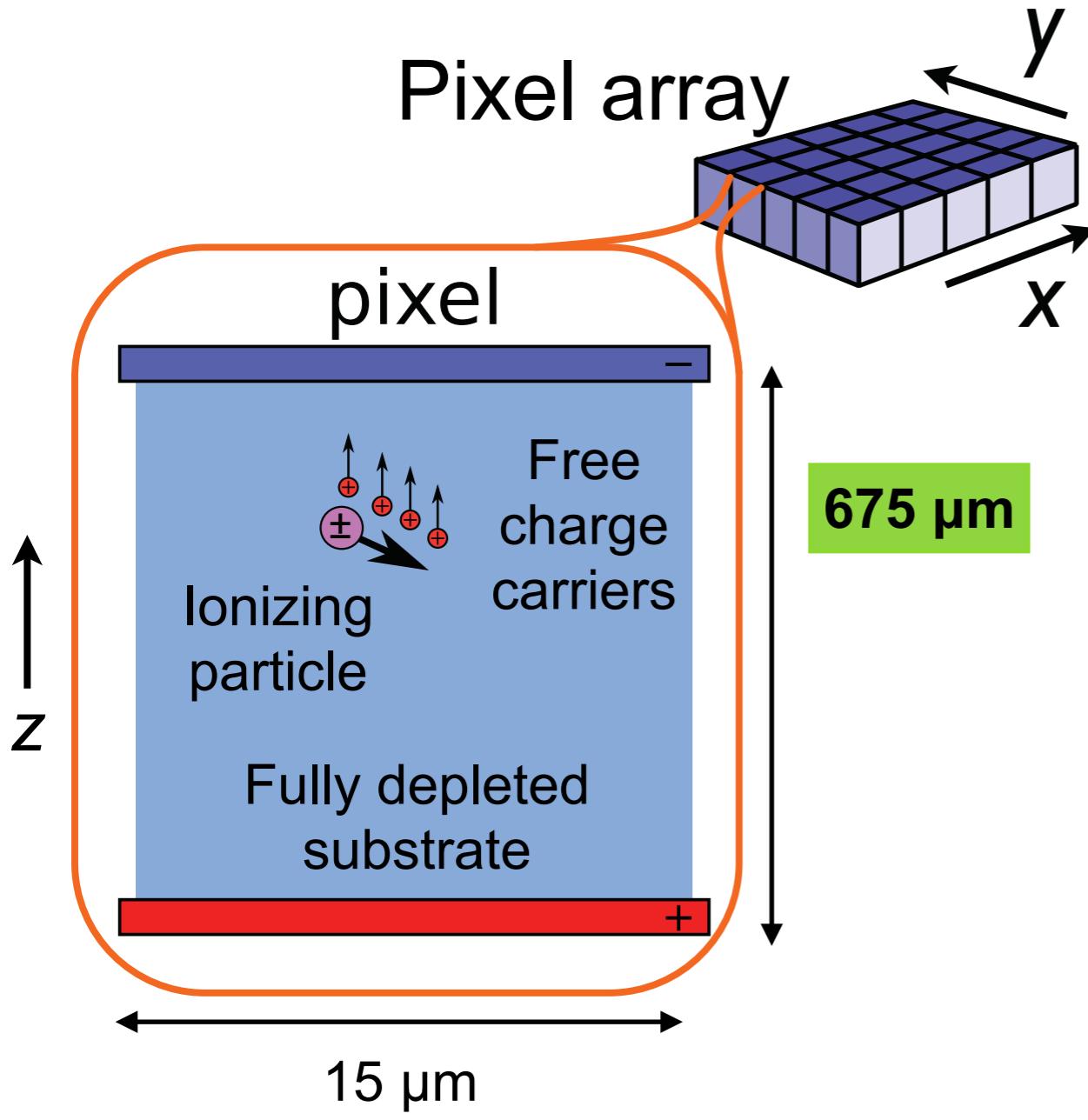
Ionised atom search performed with XE10,100 data



S₂ sensitive to
single electrons

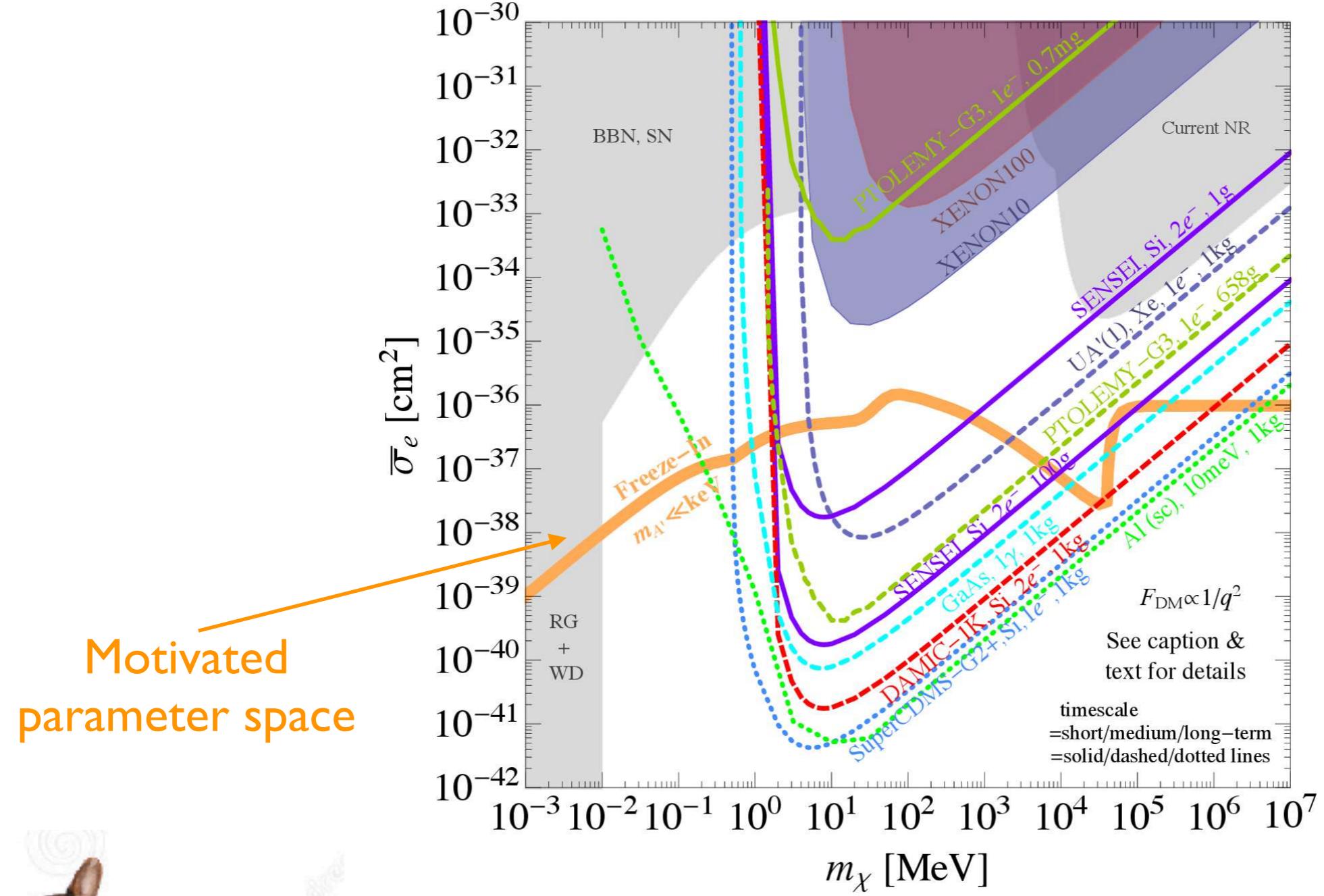


Room for improvement e.g. DAMIC



(Skipper = lower noise design)

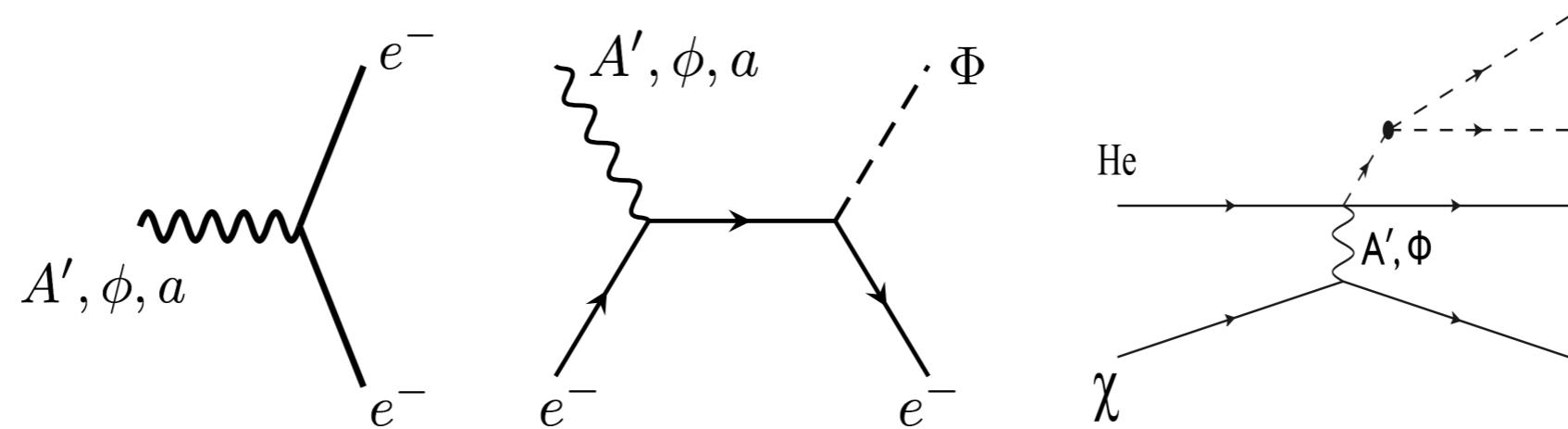
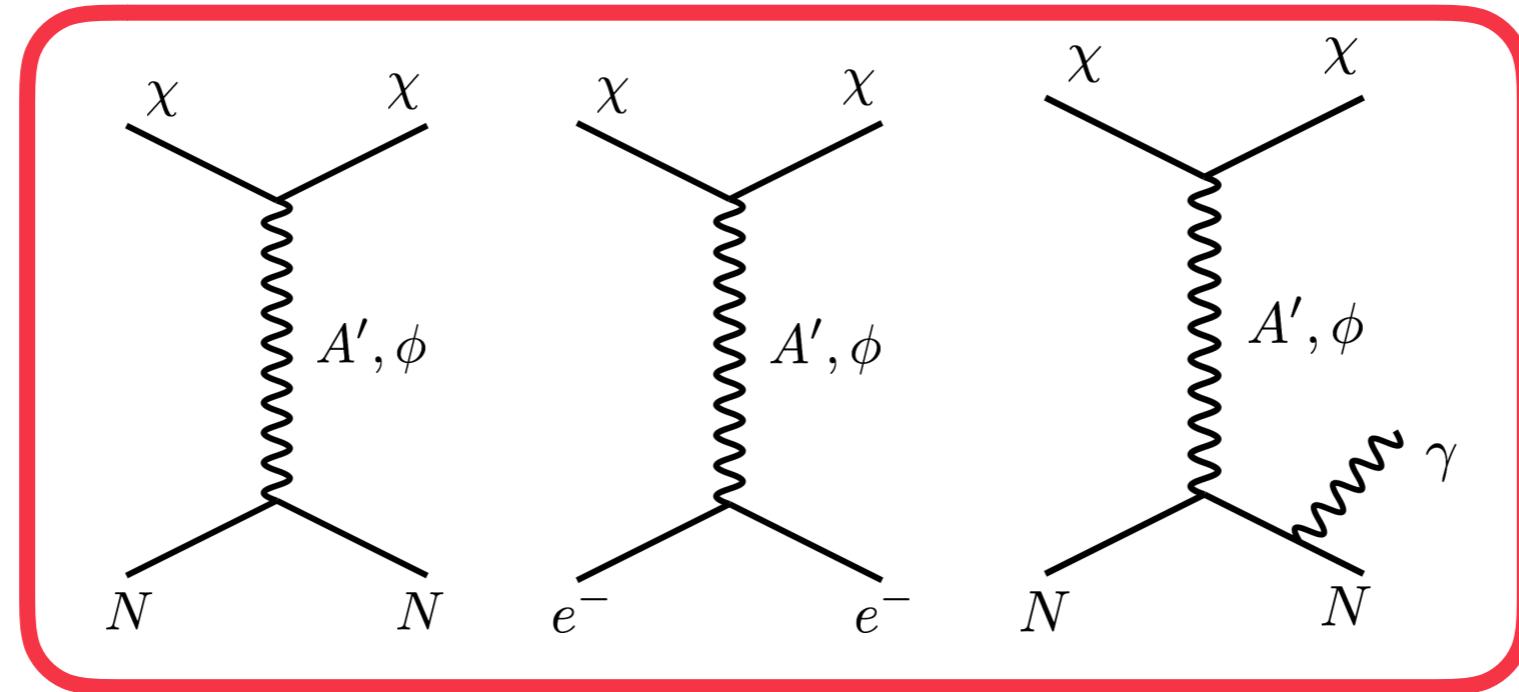
Many proposals...



Other ideas



covered these processes



absorption

absorption
&
phonons

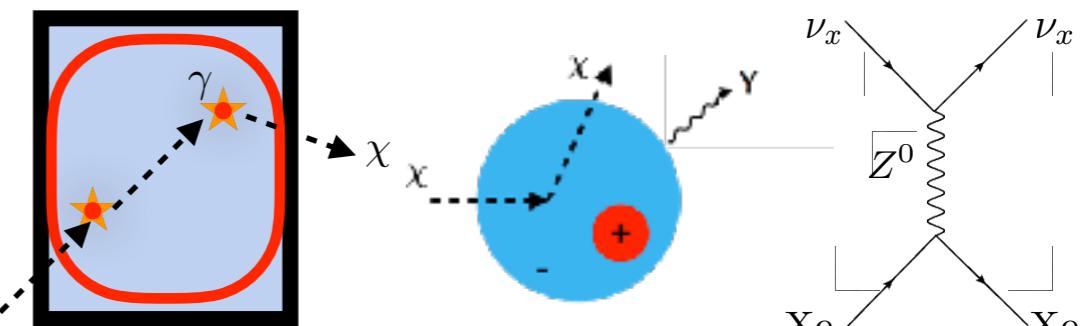
scatter
&
phonons

+
more

Conclusions

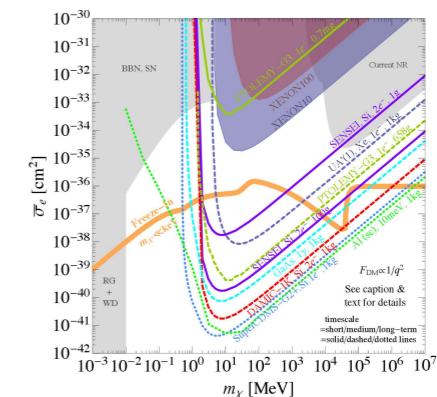
We should search for dark matter along every feasible avenue

Large detectors



new signals are possible

Small detectors



vast regions of unexplored parameter space

Thanks



Science & Technology
Facilities Council
10 Years of Impact and Inspiration