



University of
Zurich^{UZH}



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DARK MATTER

A detailed image of a spiral galaxy, likely M106, showing its characteristic spiral arms and central bright nucleus. The galaxy is set against a dark, star-filled background.

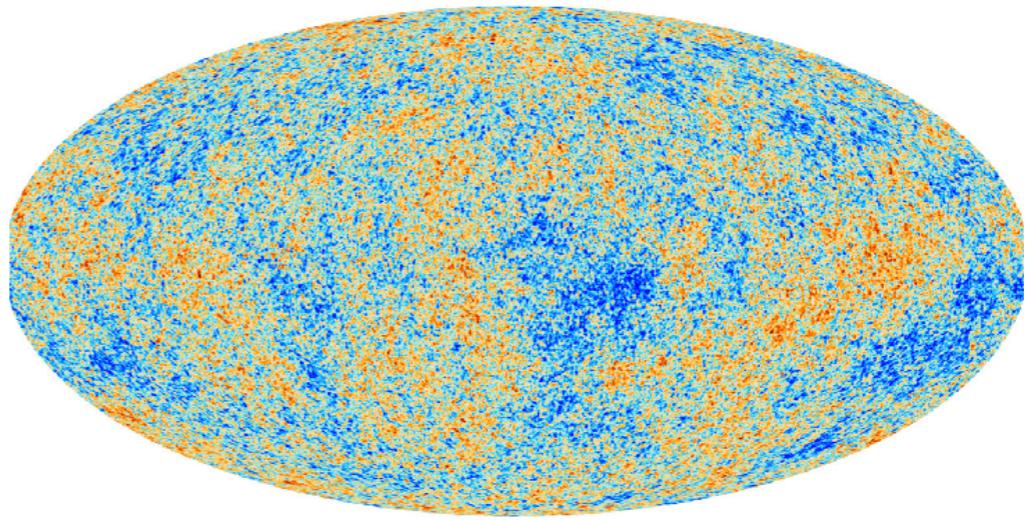
LAURA BAUDIS
UNIVERSITY OF ZURICH

LHCP2021
JUNE 12, 2021

MOST OF OUR UNIVERSE IS INVISIBLE

► The evidence for dark matter in the Universe is overwhelming

- Early and late cosmology (CMBR, LSS)
- Clusters of galaxies
- Galactic rotation curves
- Big Bang Nucleosynthesis
- ...



Planck (esa.int): "An almost perfect Universe"

► And Λ CDM describes all observations well

► *The fundamental nature of dark matter is still a mystery!*

- What is it, how does it interact?

100%

Dark energy
68%

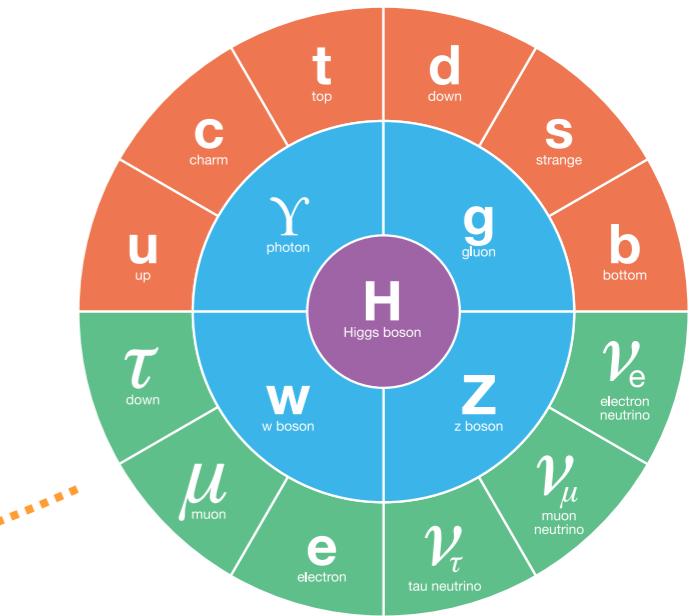
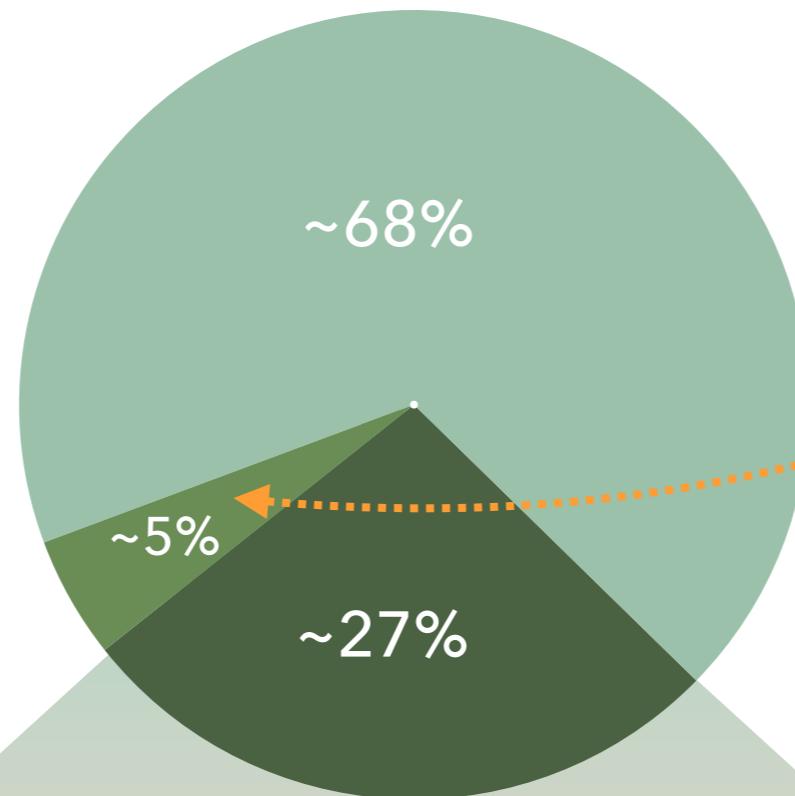
Dark matter
27%

Baryons
5%

WHAT IS THE DM?

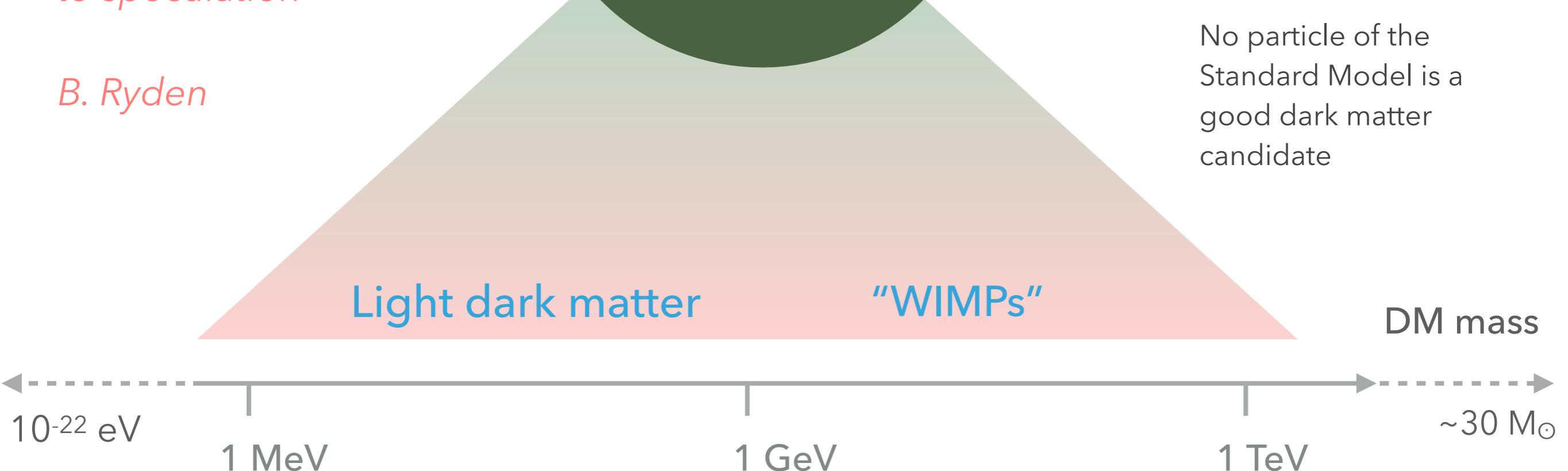
"A component of the universe that is totally invisible is an open invitation to speculation"

B. Ryden



"Known physics"

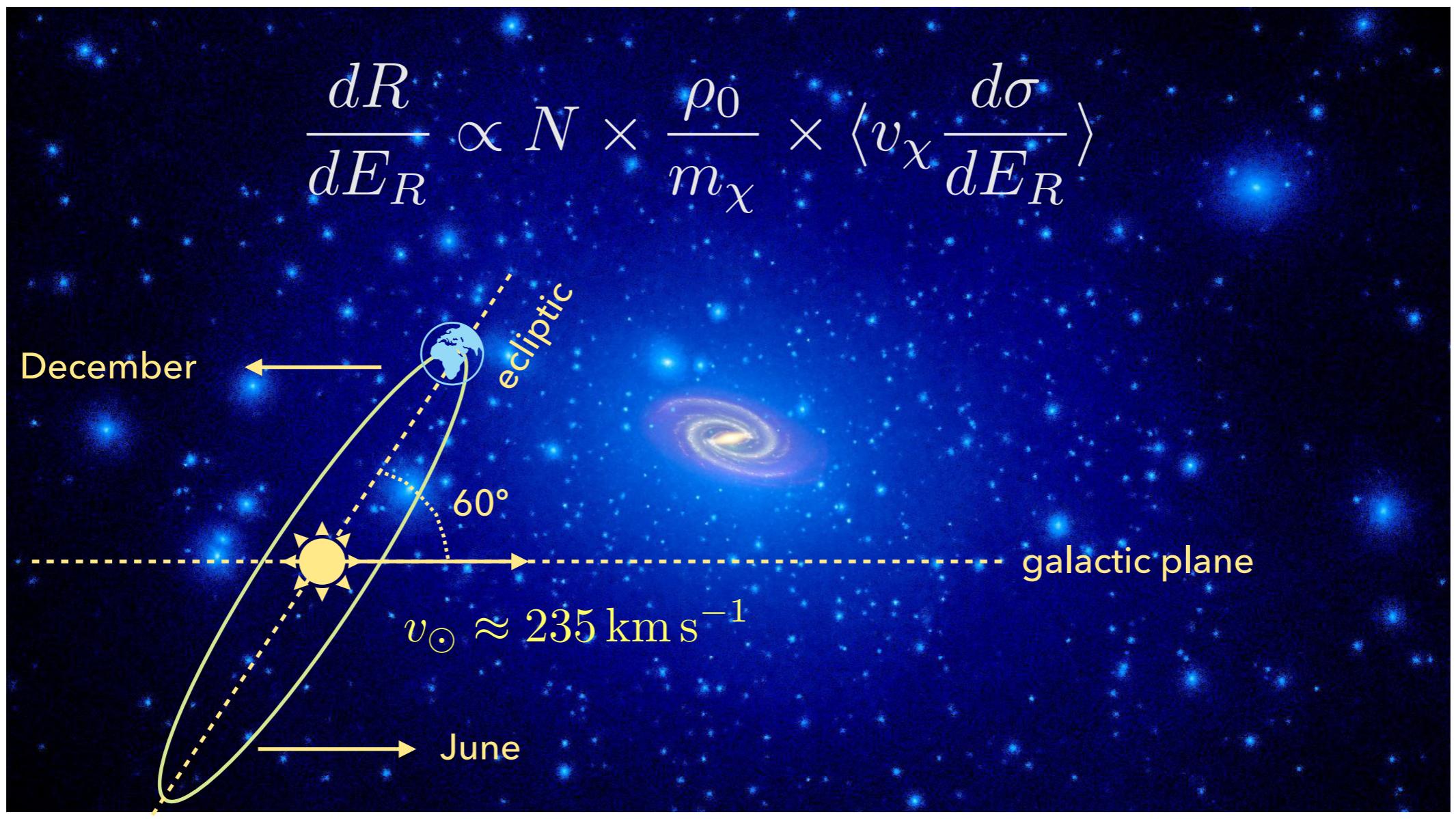
No particle of the Standard Model is a good dark matter candidate



~ 80 orders of magnitude in mass: a rather high number for the ratio of our ignorance-to-knowledge!

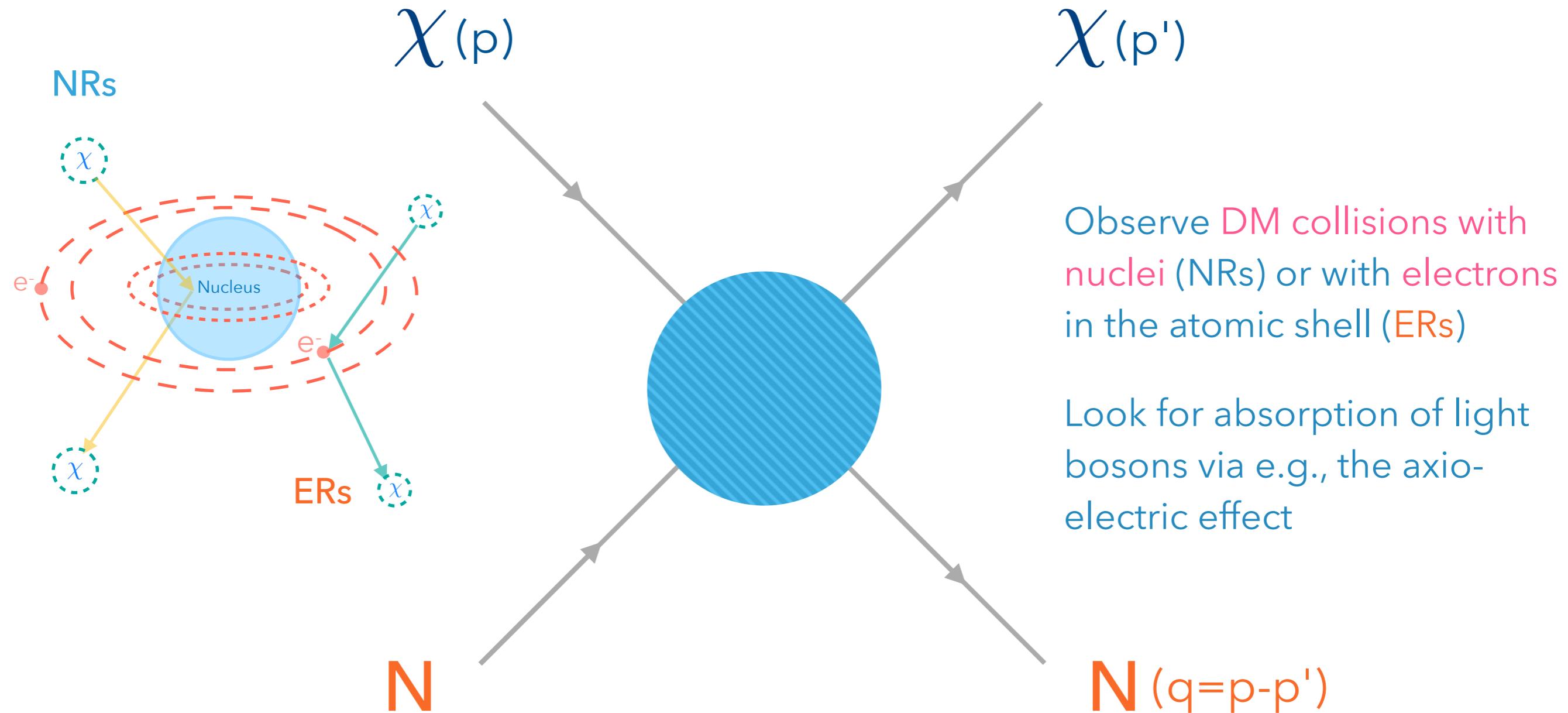
DARK MATTER IN THE MILKY WAY

- ▶ Look for scatters of *galactic dark matter particles* in terrestrial detectors



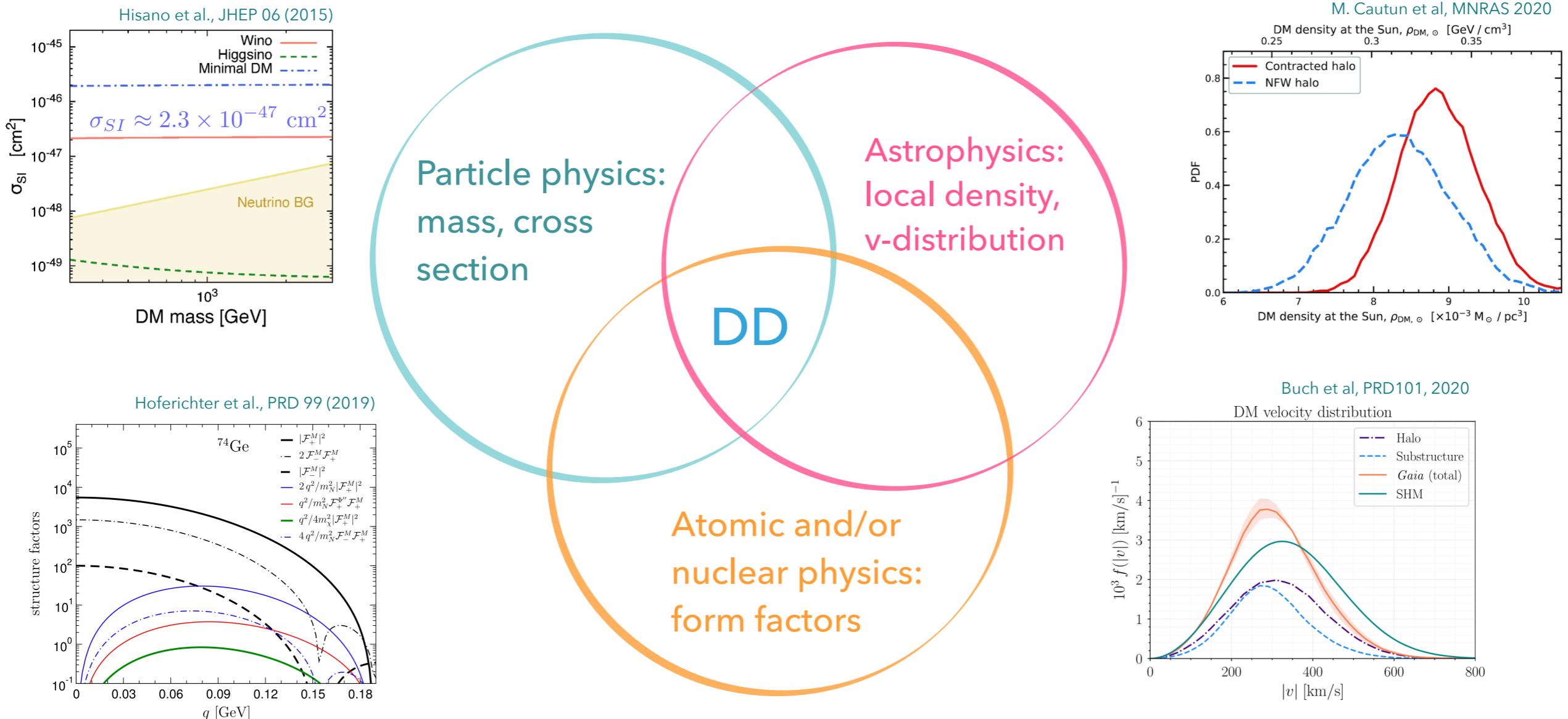
$R_{\text{halo}} \sim 300 \text{ kpc}$

DIRECT DARK MATTER DETECTION



DIRECT DARK MATTER DETECTION

- ▶ Main physical observable: a differential recoil spectrum
- Its modelling relies on several phenomenological inputs



KINEMATICS: DARK MATTER PARTICLE MASS

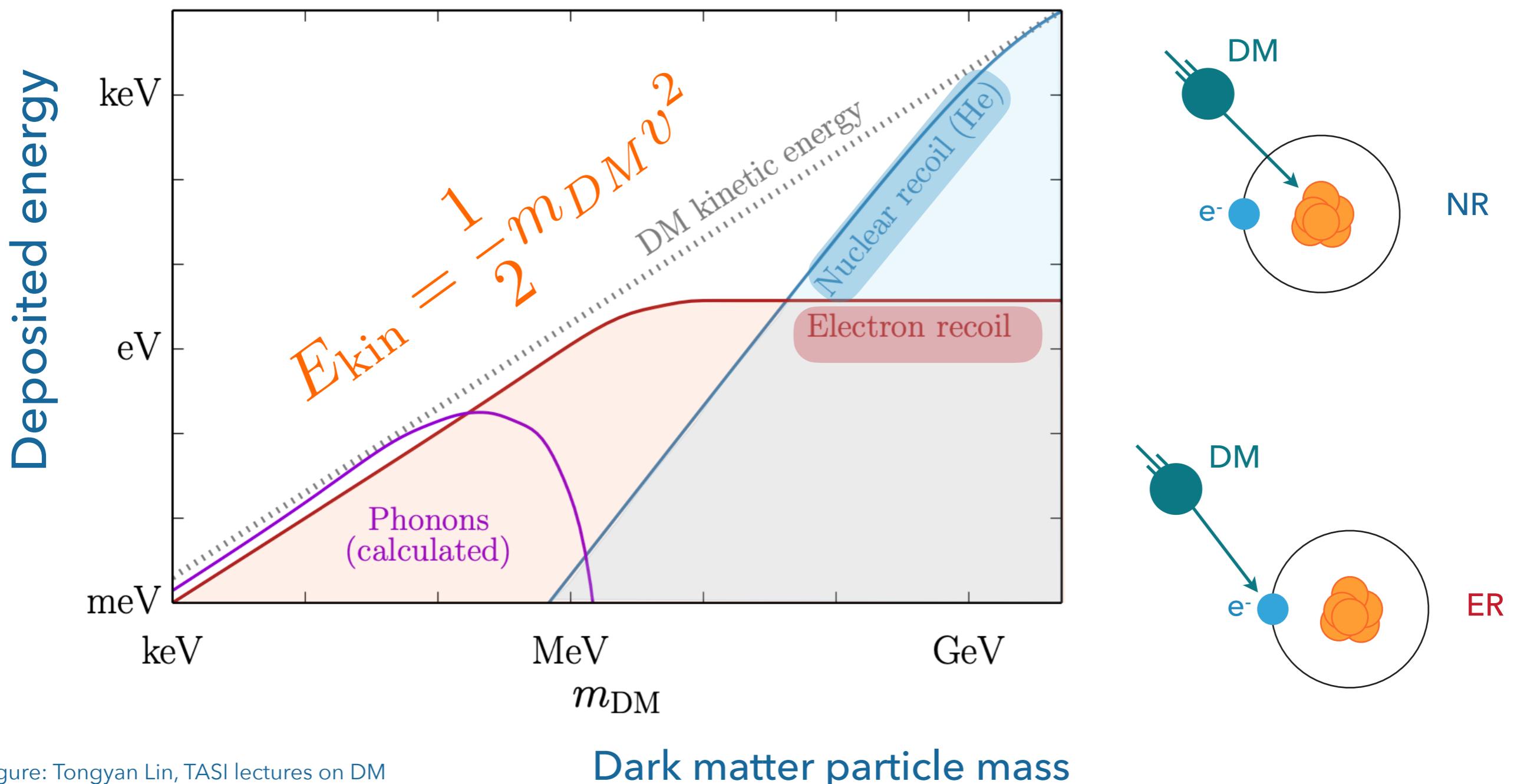
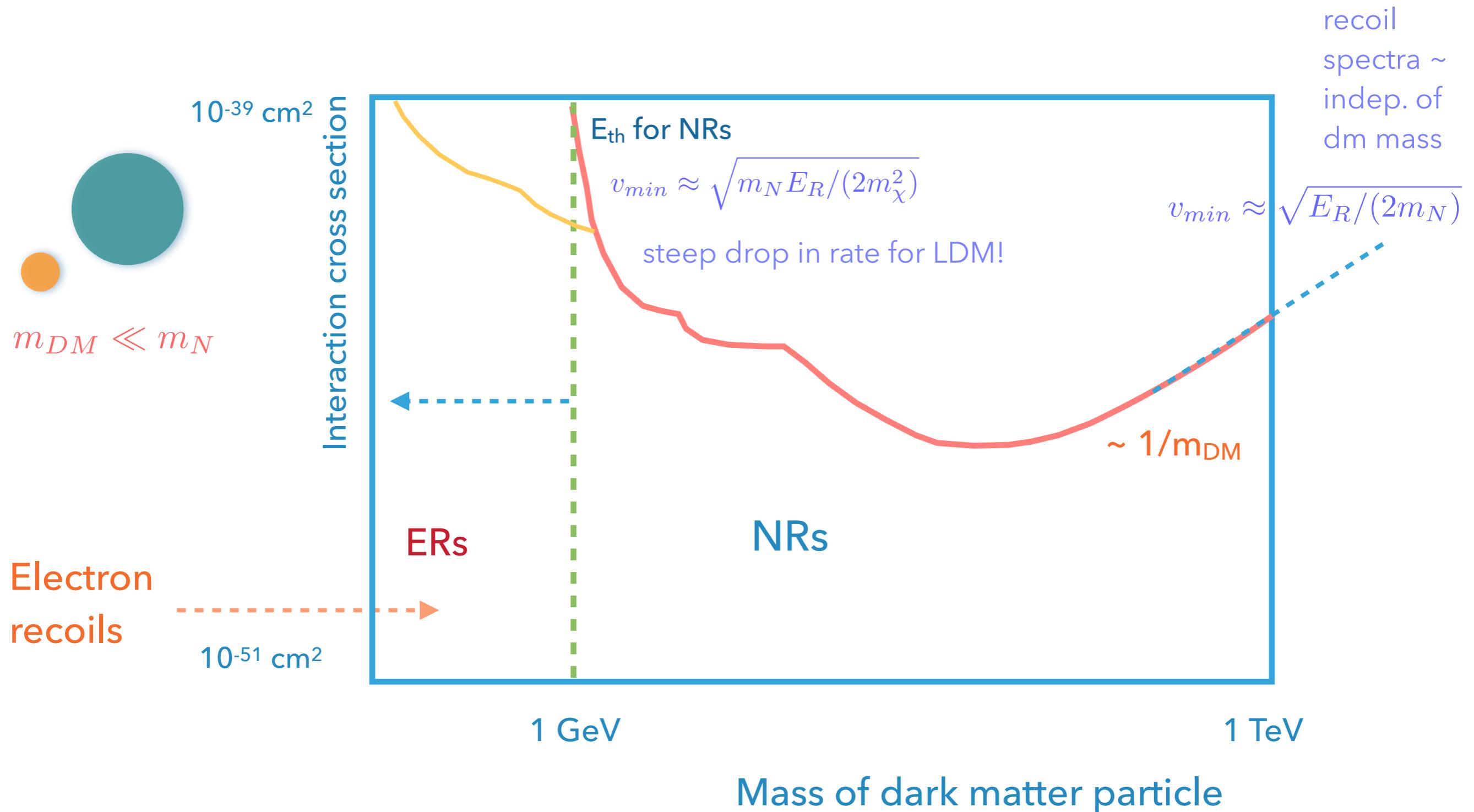


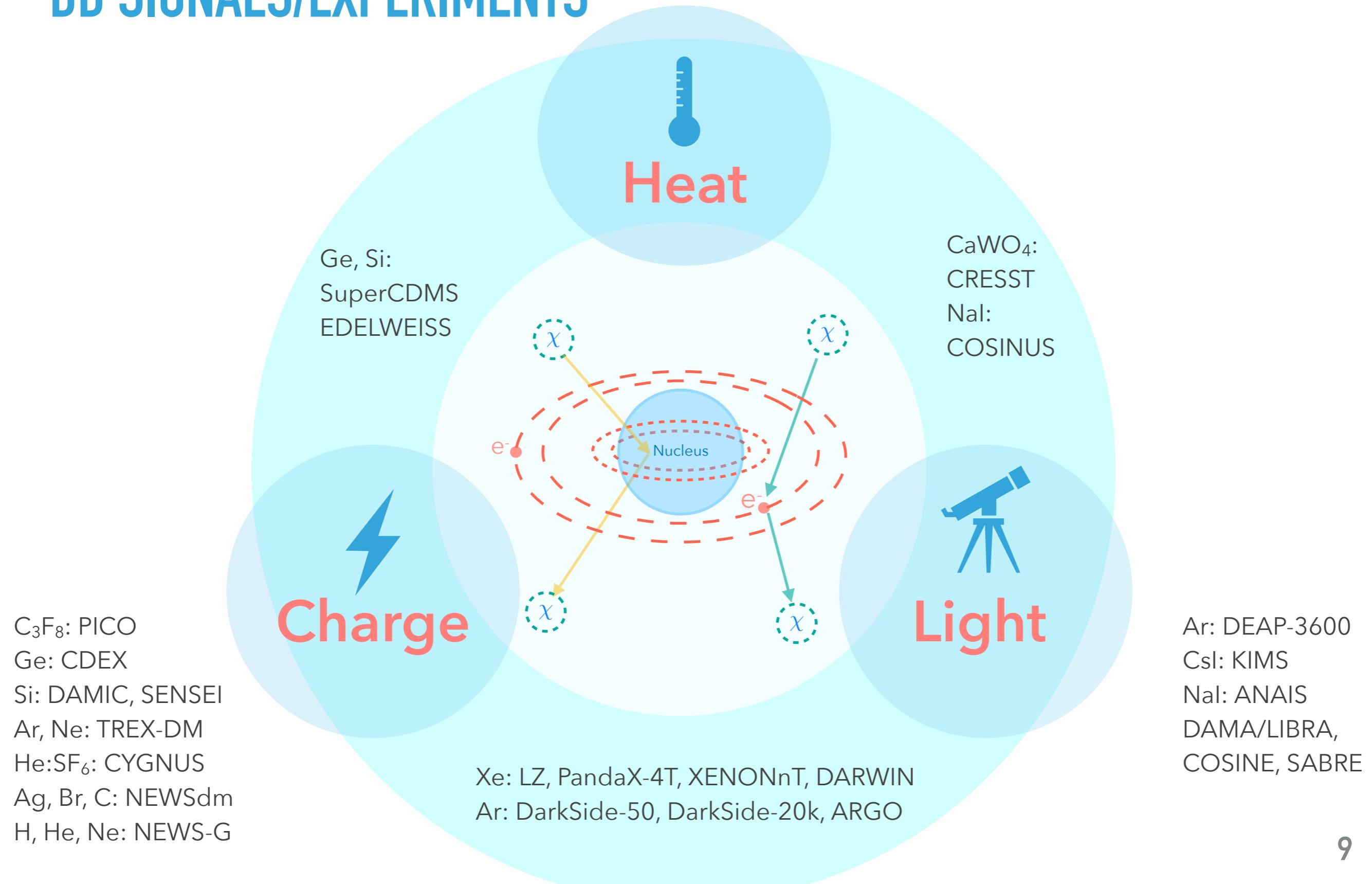
Figure: Tongyan Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

Dark matter particle mass

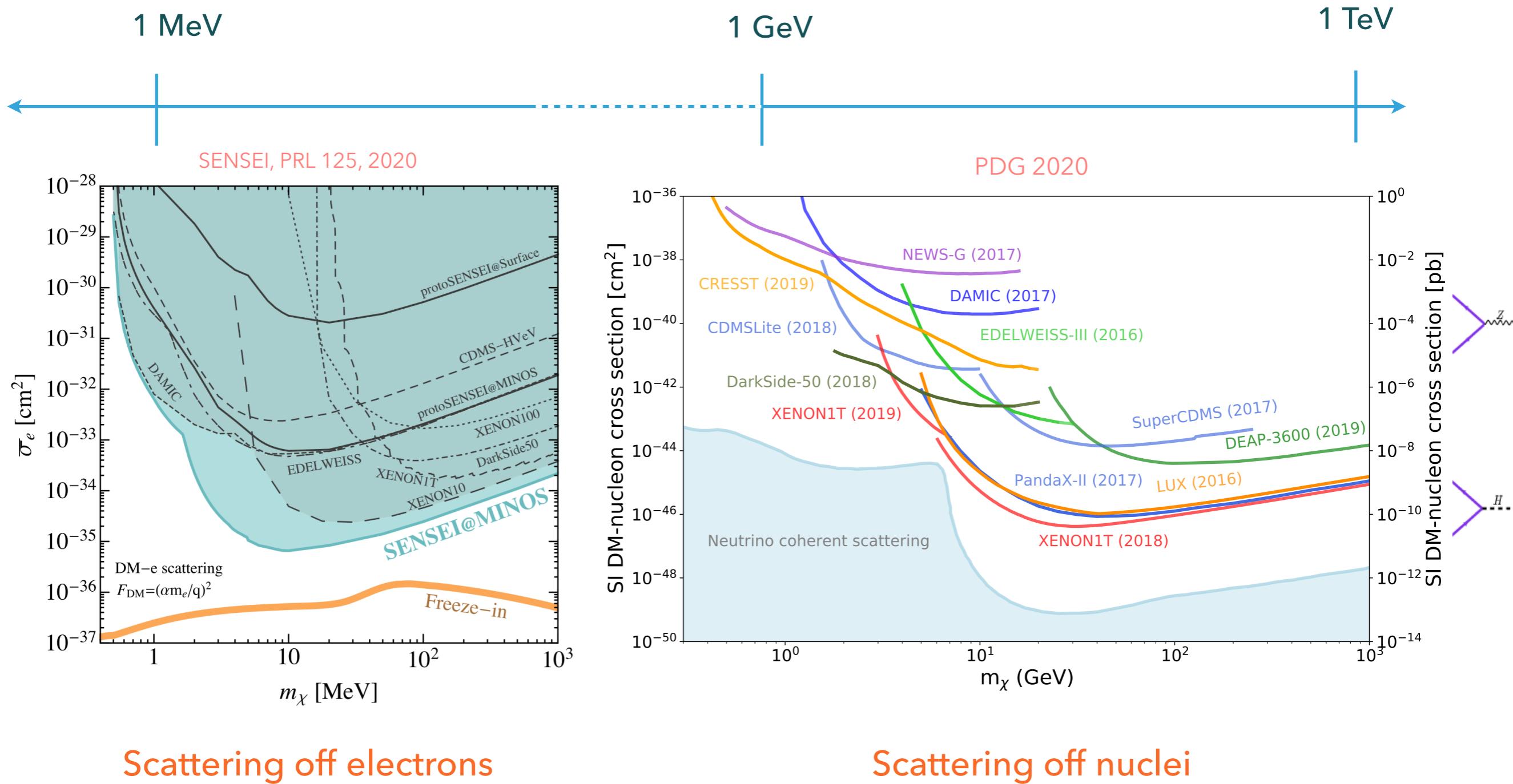
INTERACTION CROSS SECTION VS MASS



DD SIGNALS/EXPERIMENTS

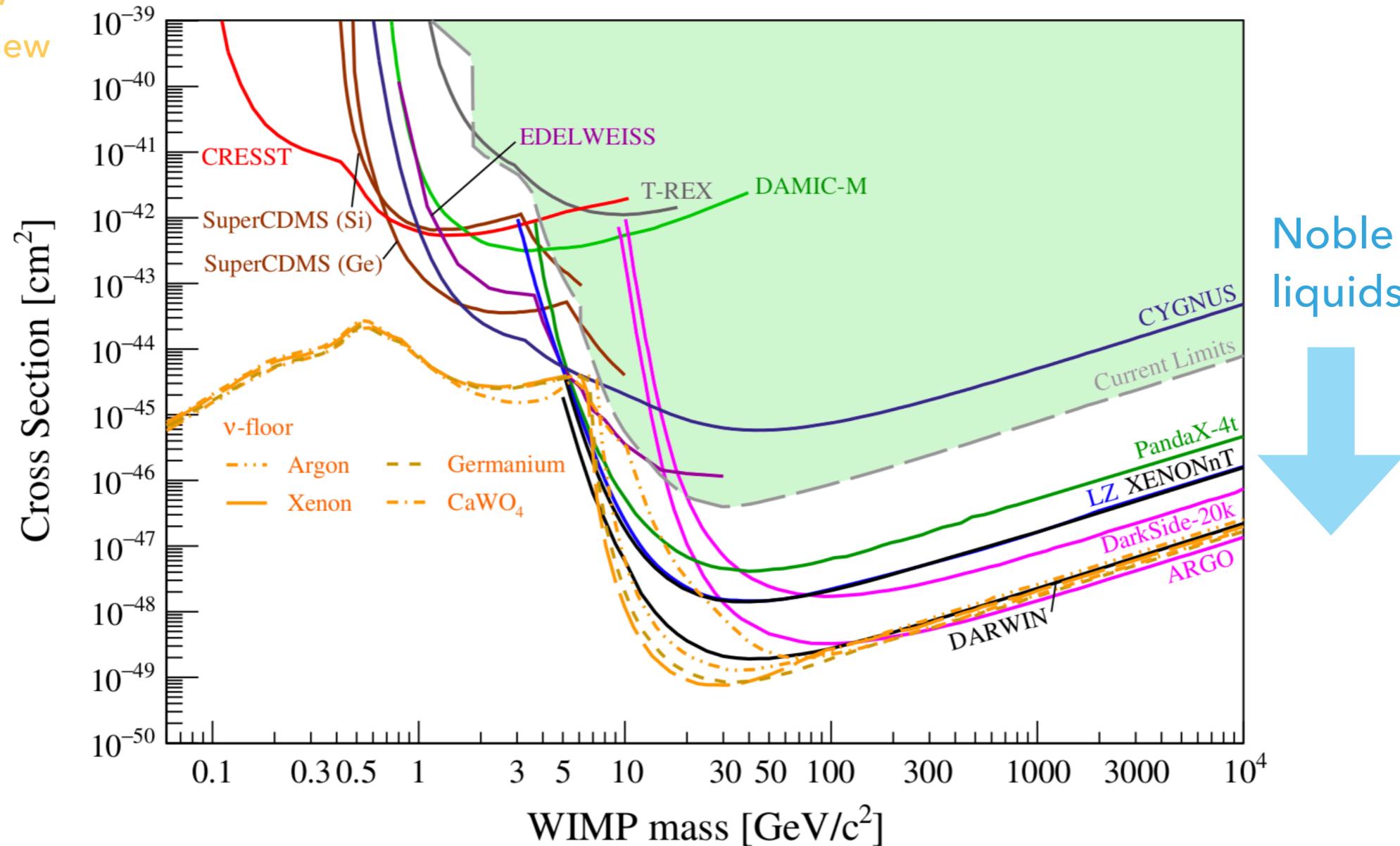
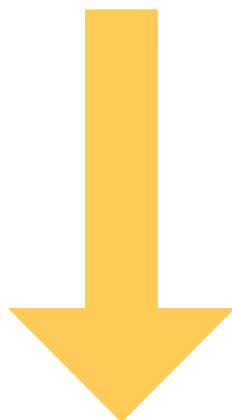


THE DIRECT DETECTION LANDSCAPE



THE DIRECT DETECTION LANDSCAPE: PROJECTIONS

Bolometers,
CCDs (plus new
technologies)



Noble
liquids



Scattering off nuclei

Figure: APPEC DM Report, <https://indico.cern.ch/event/982757/overview>

MAIN EXPERIMENTAL CHALLENGES TOWARDS THE "NEUTRINO FOG"

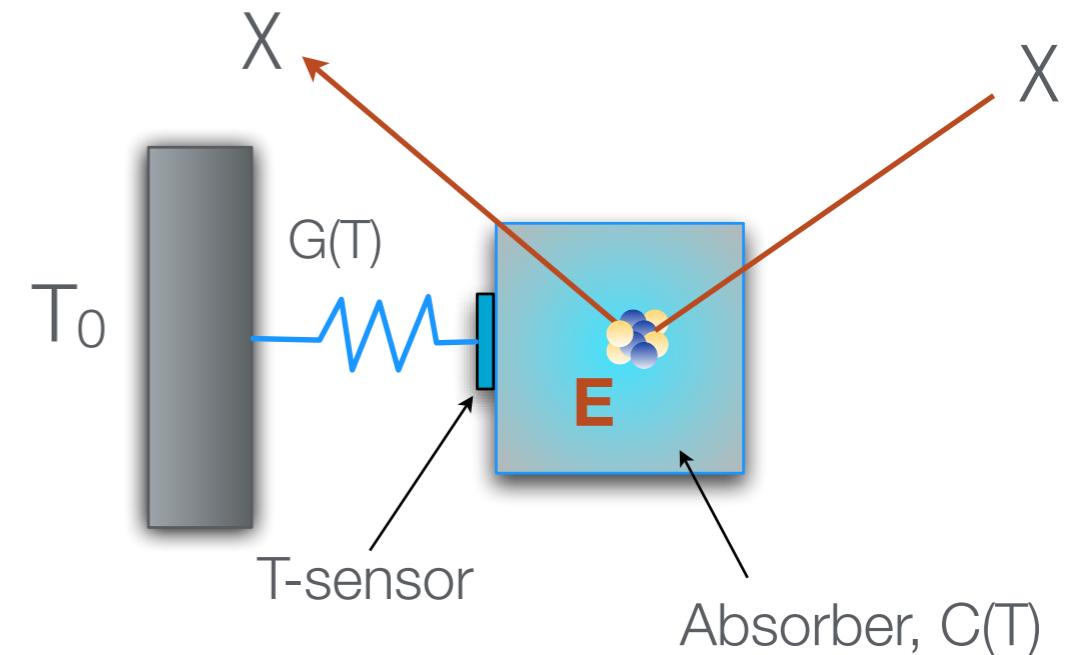
► To observe a signal which is:

- very small → low recoil energies: ~eV to keV (perhaps even meV)
- very rare → <1 event/(kg y) at low masses and < 1 event/(t y) at high masses
- buried in backgrounds with $> 10^6 \times$ higher rates → deep underground & low-radioactivity materials

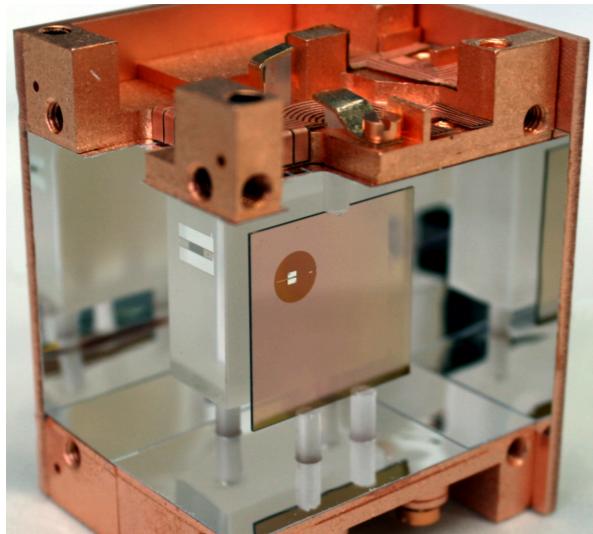


CRYOGENIC EXPERIMENTS

- ▶ Sub-keV (< 100 eV) energy thresholds
- ▶ Cryogenic detectors: phonons and/or ionisation/light \Rightarrow background discrimination
- ▶ Probe light dark matter



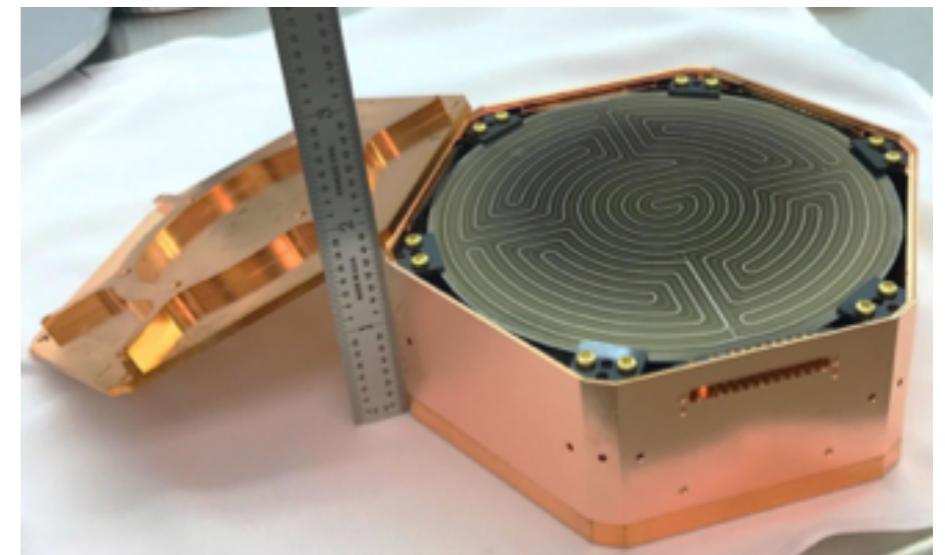
CRESST



EDELWEISS

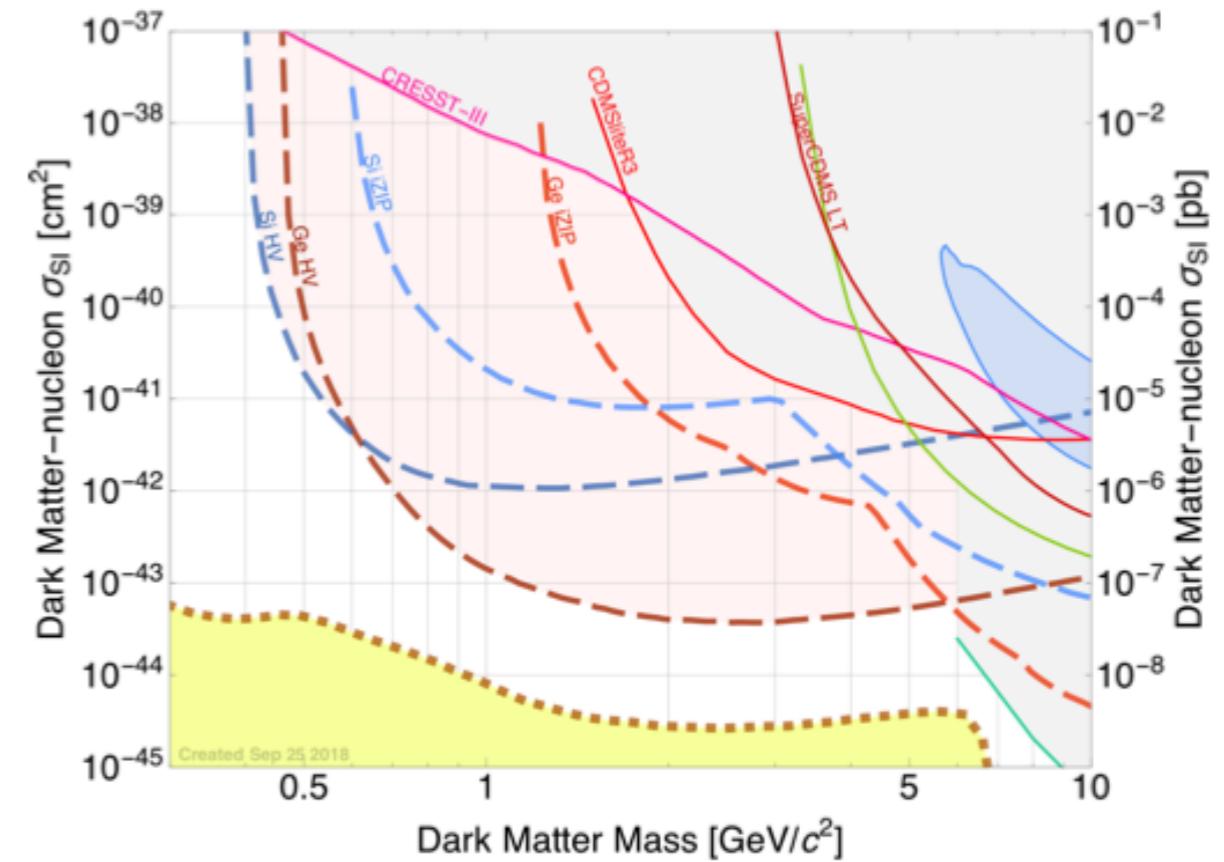


Super-CDMS

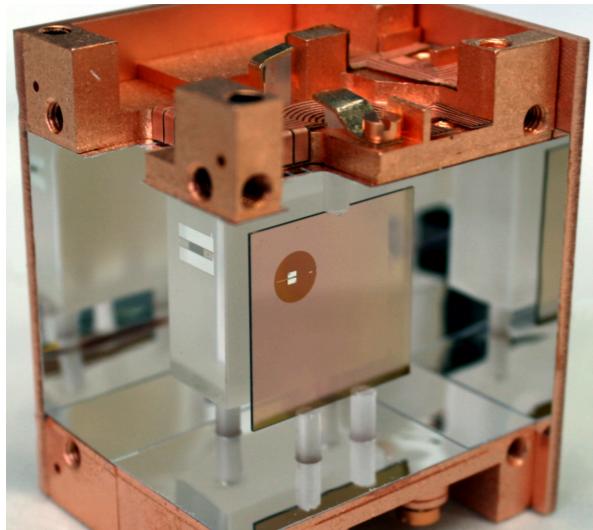


CRYOGENIC EXPERIMENTS

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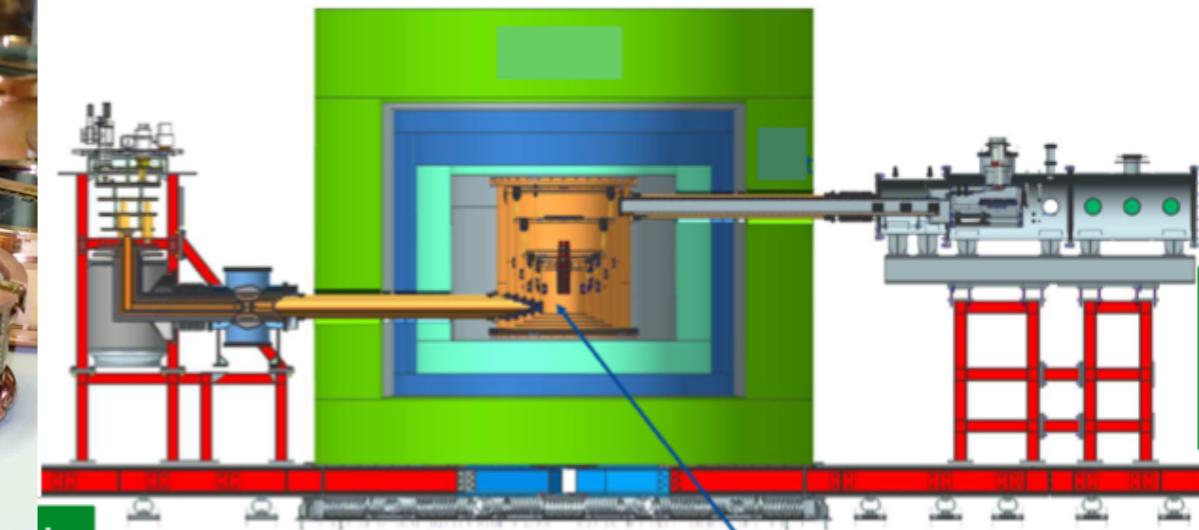
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EDELWEISS

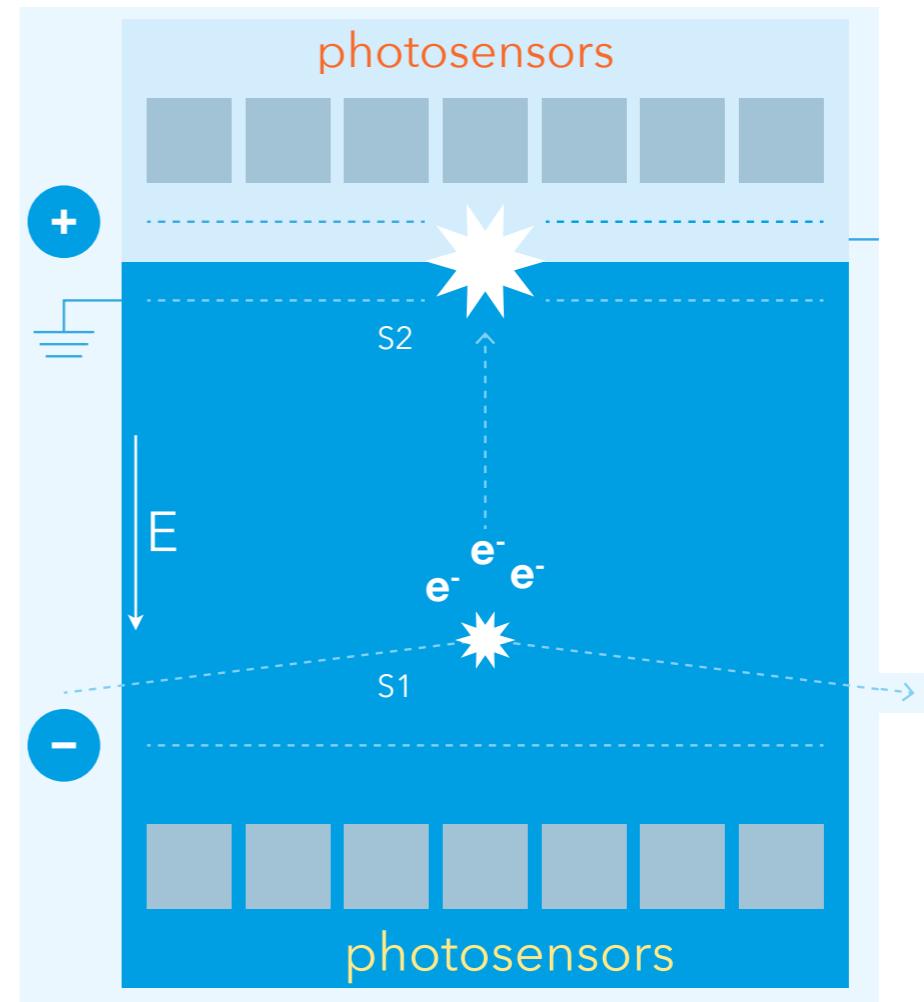


Super-CDMS at SNOLAB



LIQUEFIED NOBLE GASES

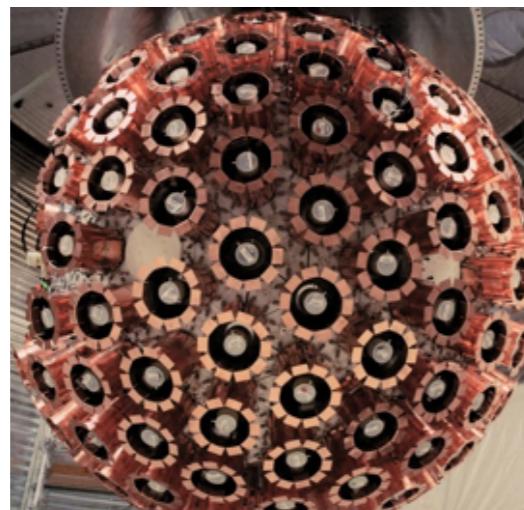
- ▶ Single and two-phase Ar & Xe detectors
- ▶ Time projection chambers:
 - energy determination, 3D position resolution via light (S1) & charge (S2): fiducialisation
 - S2/S1 \Rightarrow ER/NR discrimination
 - Single versus multiple interactions



XMASS



DEAP-3600



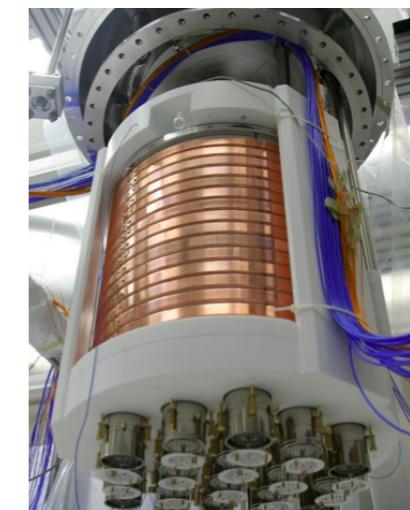
XENON1T



LUX



DarkSide-50



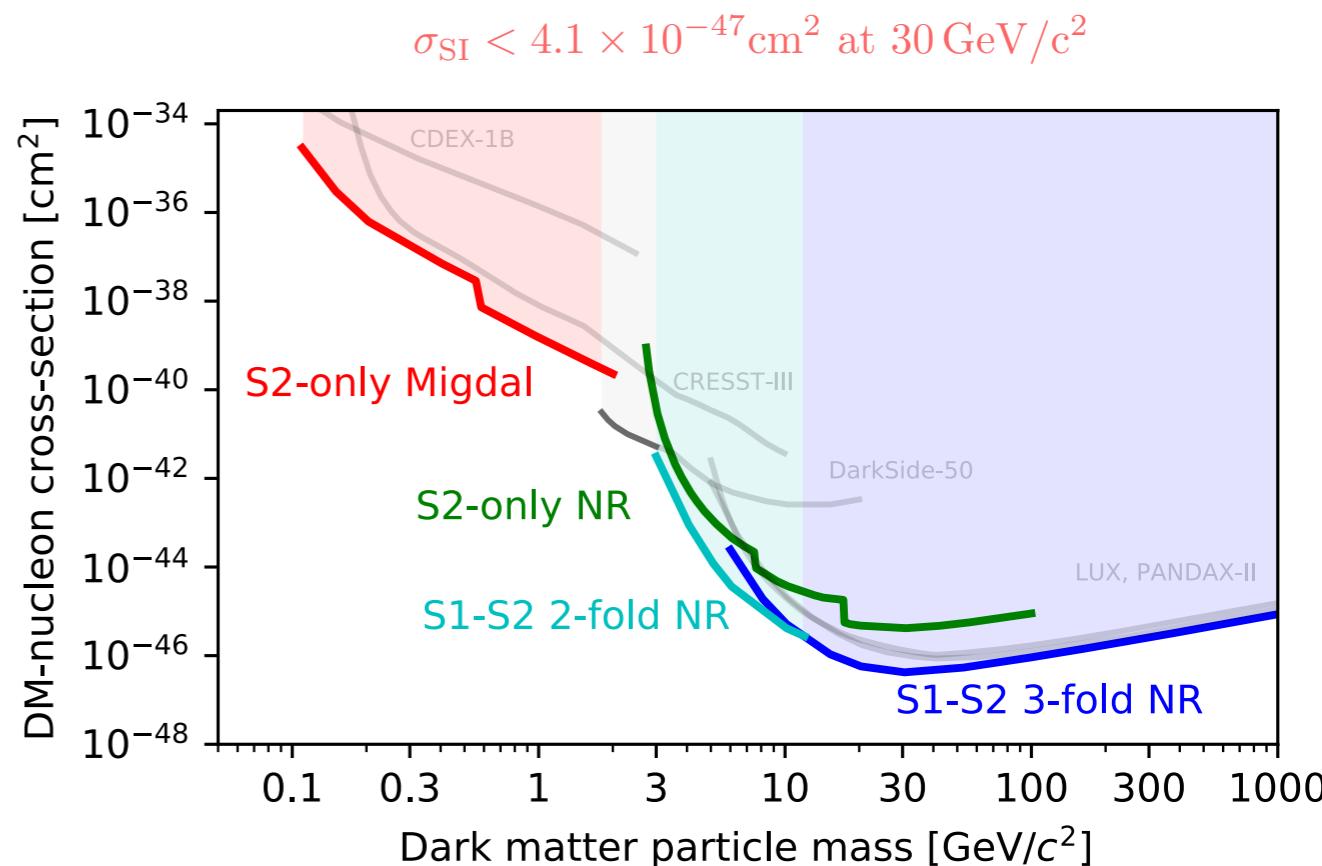
PandaX-II



LIQUEFIED NOBLE GASES

- ▶ Single and two-phase Ar & Xe detectors
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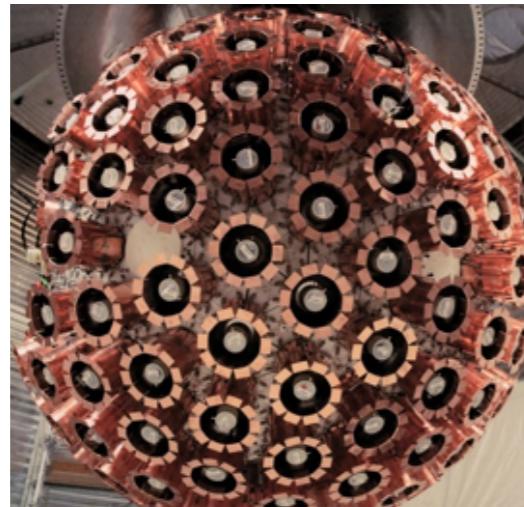
No excess of nuclear recoil events observed so far



XMASS



DEAP-3600



XENON1T



LUX



DarkSide-50

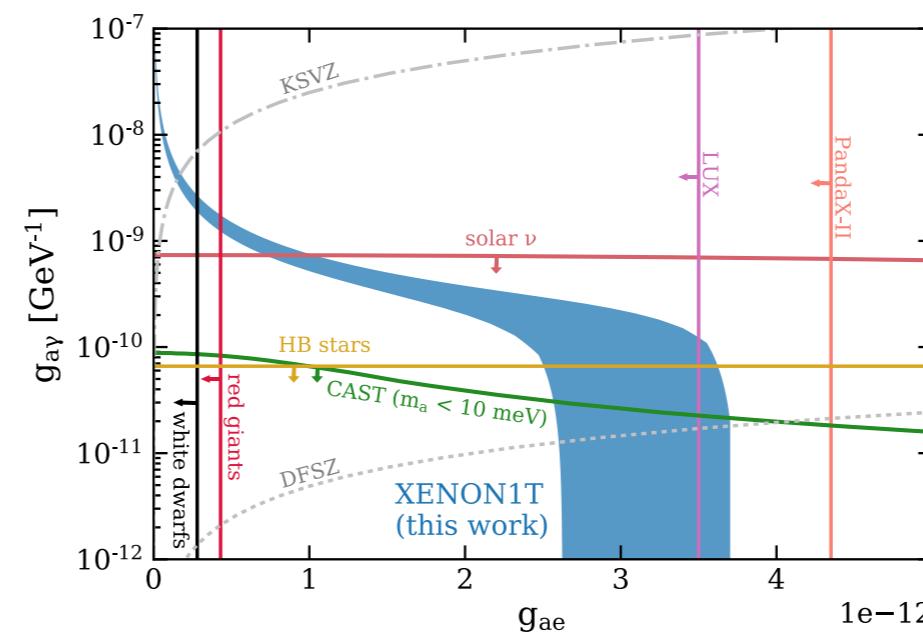
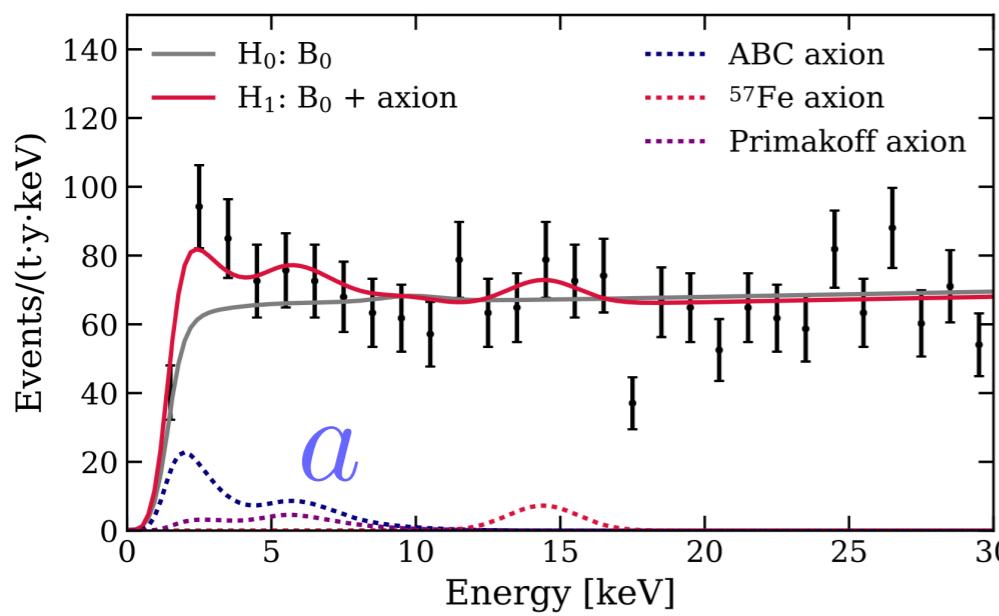
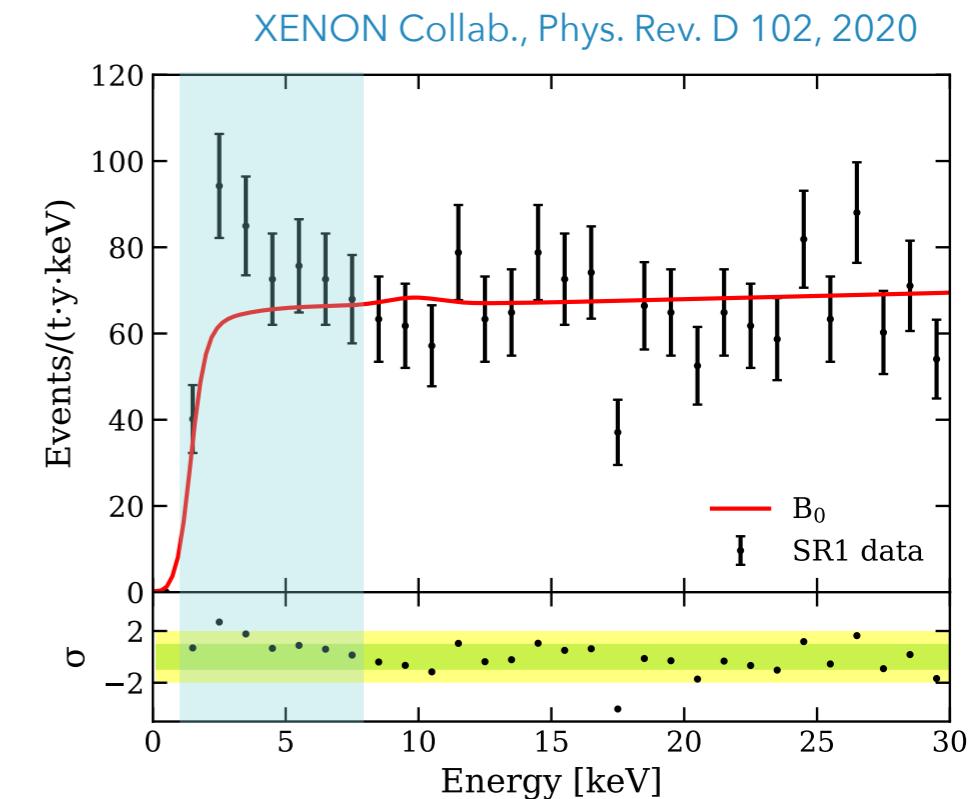


PandaX-II



XENON1T: ELECTRONIC RECOIL EXCESS

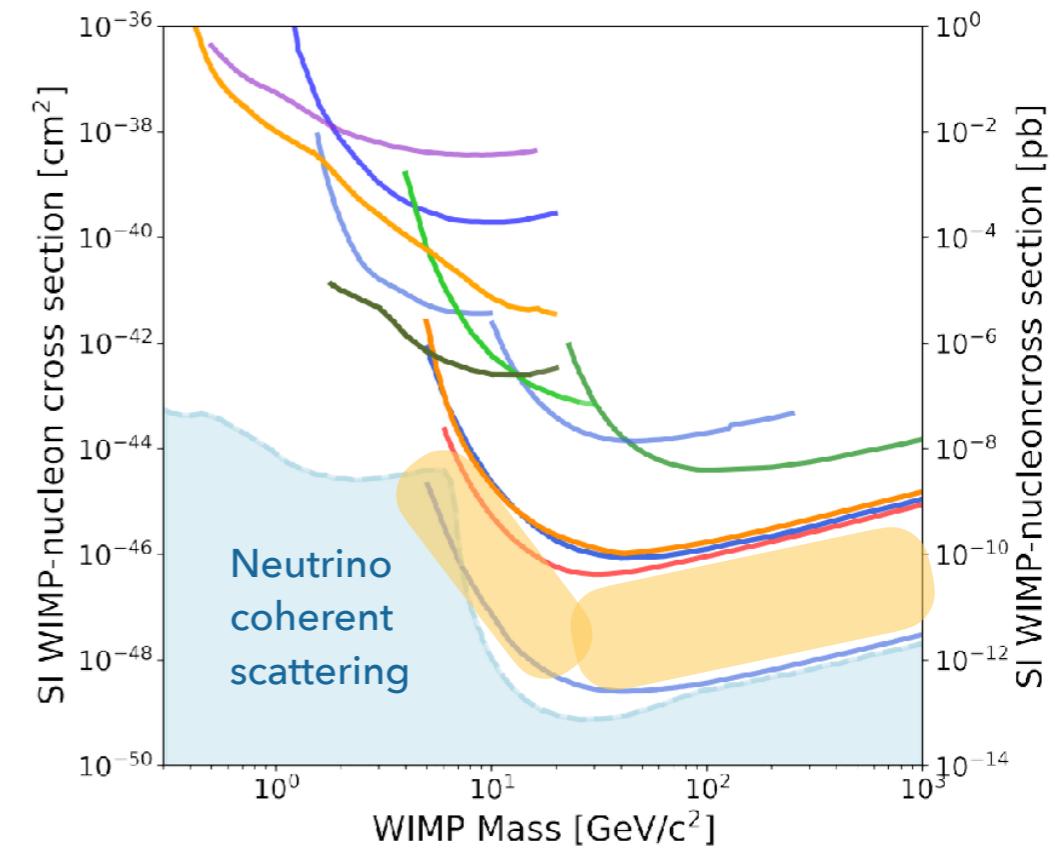
- Excess between (1,7) keV; number of observed events: 285, expected from background: (232 ± 15) events
- Unknown origin: tritium, solar axions, ALPs, dark photons, something else?



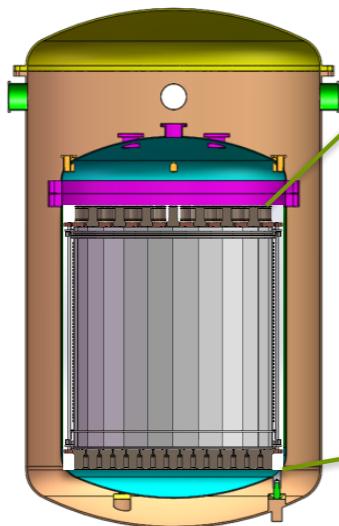
Solar axion favoured over background-only at 3.4σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487); Tritium favoured over background-only at 3.2σ $\hat{\equiv}$ to $(6.2 \pm 2) \times 10^{-25} \text{ mol/mol}$

FUTURE: LIQUEFIED NOBLE GASES

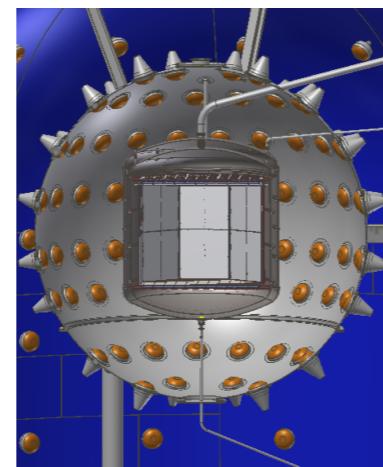
- ▶ In construction, commissioning or first data taking:
 - ▶ LUX-ZEPLIN, XENONnT, PandaX-4t, DarkSide-20k
- ▶ Planned (design and R&D stage)
 - ▶ DARWIN (50 t LXe), ARGO (300 t LAr)



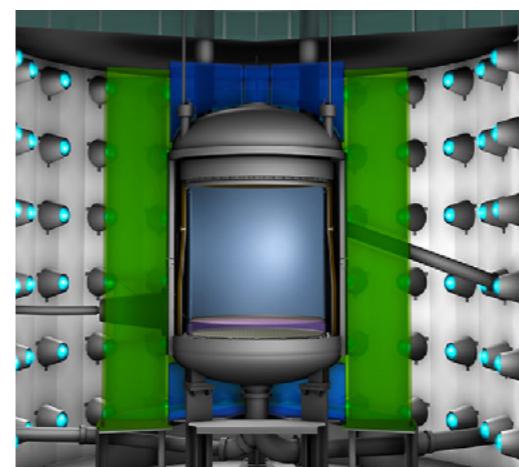
XENONnT: 8.6 t LXe
Data taking 2021



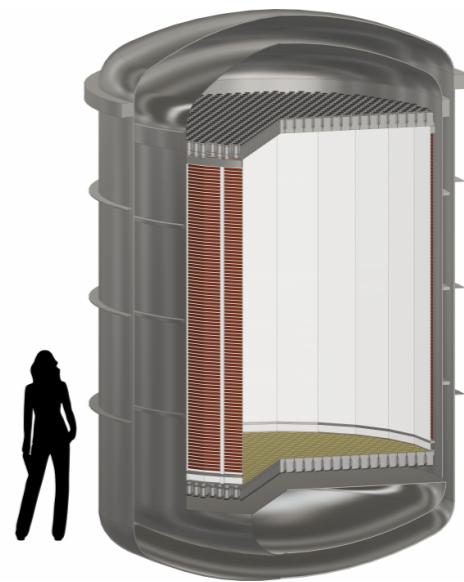
PandaX-4t LXe
Data taking 2021



DarkSide: 20 t LAr
Data taking 2023



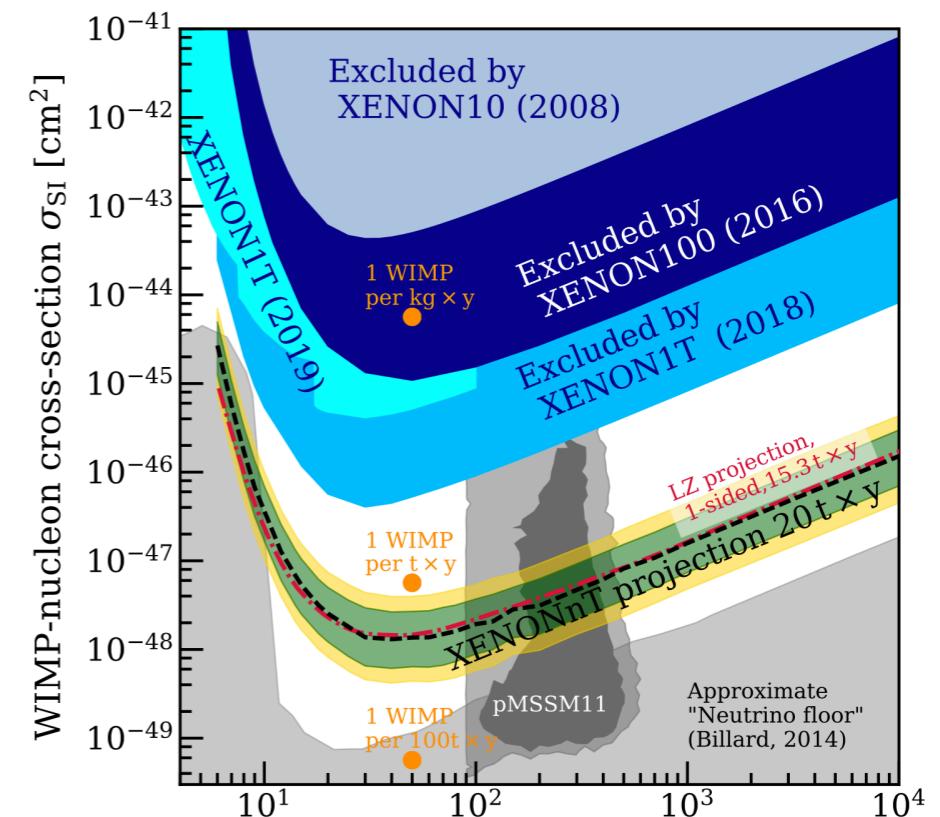
LUX-ZEPLIN: 10 t LXe
Data taking 2021



DARWIN: 50 t LXe
Data taking ~2027/28

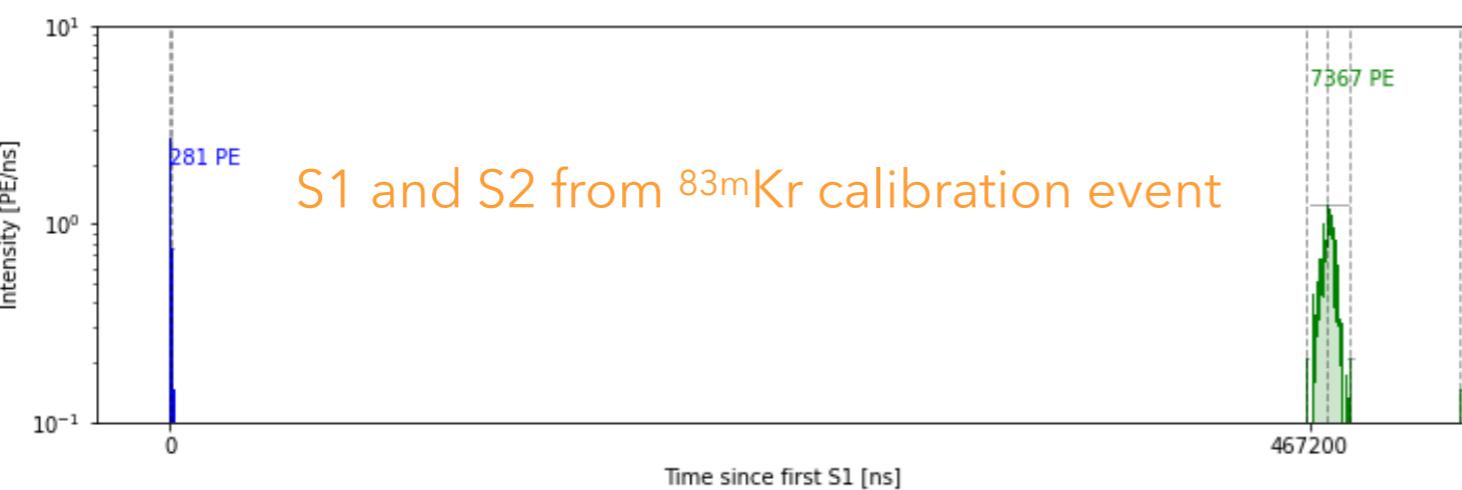
LUX-ZEPLIN AND XENON-NT

- ▶ Scale: 10 t and 8.6 t LXe in total
 - TPCs with 494 3-inch PMTs
 - Kr and Rn removal (different techniques)
 - Neutron (Gd-loaded LS and Gd-loaded water) & muon vetos
 - External and internal calibration sources
- ▶ Commissioning at SURF and LNGS
- ▶ XENONnT: calibration runs in progress

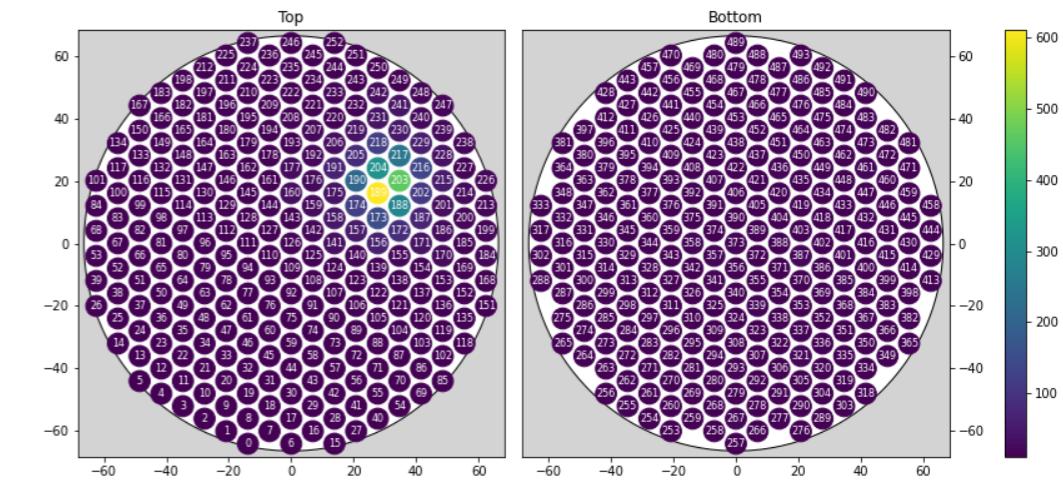
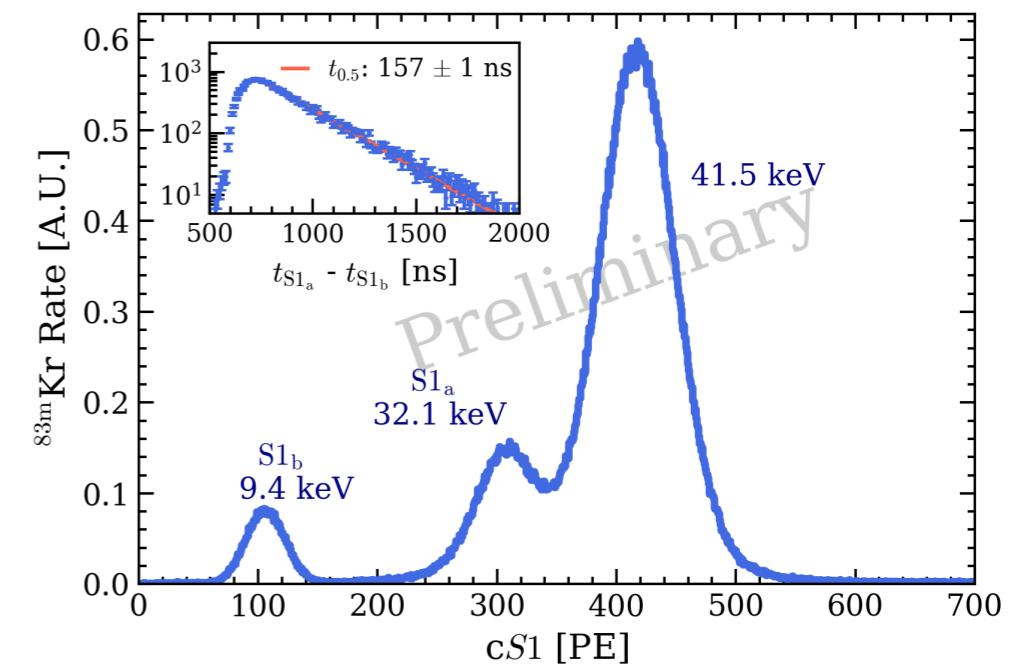


XENON-NT FIRST LIGHT

- ▶ All new systems (TPC, liquid purification system, neutron veto, radon distillation column) commissioned
 - First ^{83m}Kr calibration data with S1 and S2
 - Electron lifetime*: 7 ms (0.6 ms in XENON1T)
 - ^{222}Rn reduction factor due to distillation column ≥ 3.6
- ▶ Start a first science run in June 2021



*e⁻-lifetime: a measure of the charge that is lost during e⁻-drift to liquid/gas interface



DARWIN: DESIGN AND R&D



- ▶ Detector, Xe target, background mitigation, photosensors, etc
- ▶ Two large-scale demonstrators (in z & in x-y) supported by ERC grants: demonstrate electron drift over 2.6 m, operate 2.6 m Ø electrodes
- ▶ Demonstrators (Xenoscope, 2.6 m tall & Pancake, 2.6 m diam TPCs) in commissioning stage



Test e- drift over 2.6 m (purification, high-voltage)



Test electrodes with 2.6 m diameter

FUTURE: DARWIN-LZ COLLABORATION

- ▶ Future merger of DARWIN and LZ collaborations to build/operate next-generation liquid xenon experiment
 - new, stronger international collaboration
 - comes after LZ and XENONnT are done ~ 2026
- ▶ Paving the way now
 - first joint and very successful DARWIN LZ meeting April 26-27: <https://indico.cern.ch/event/1028794/>
 - MoU in progress



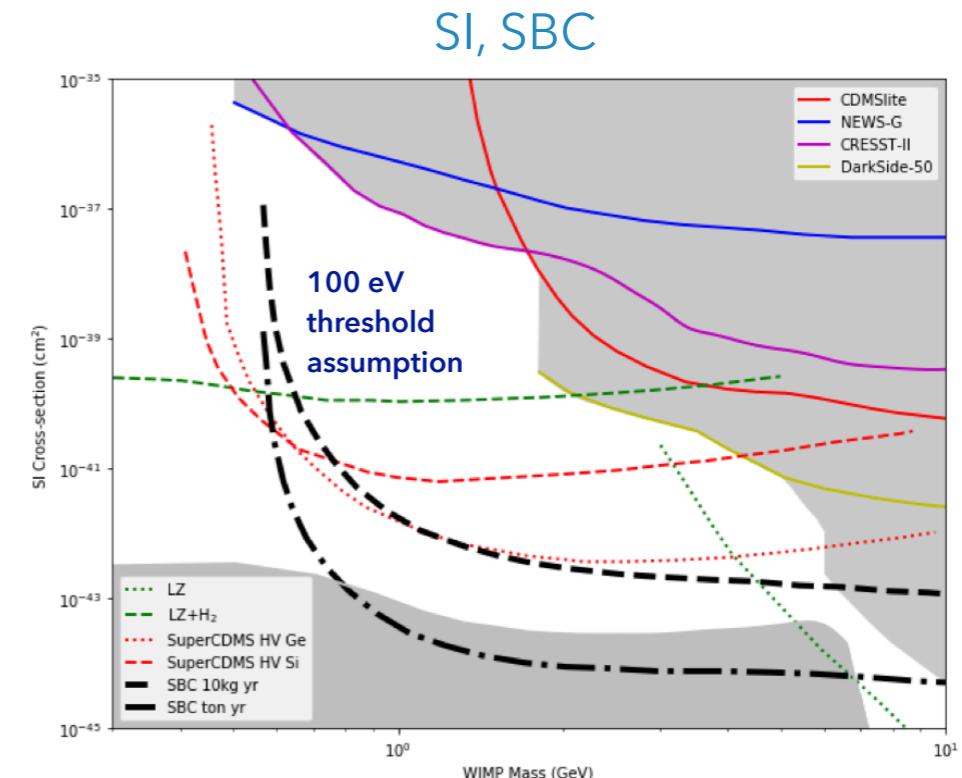
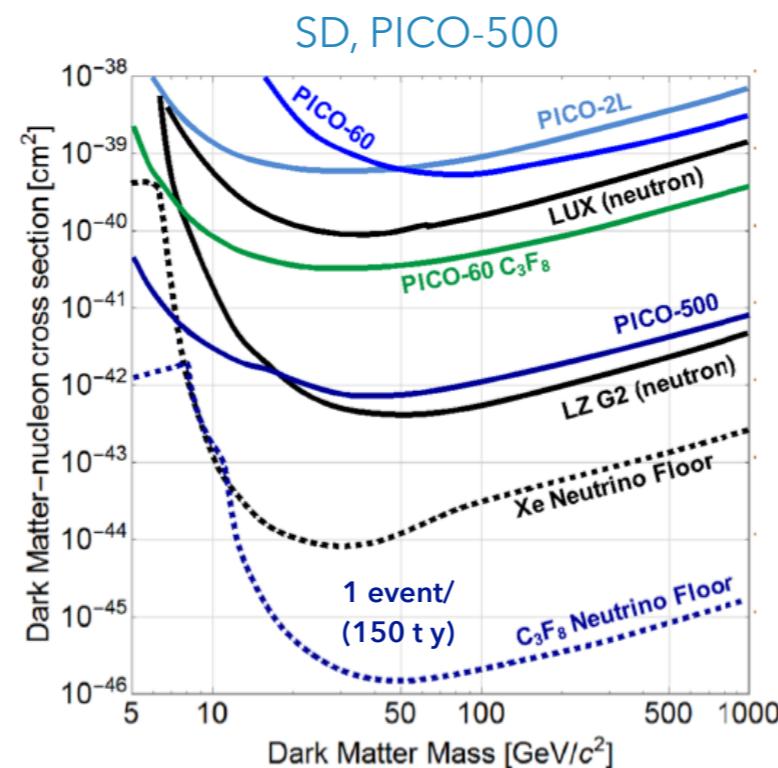
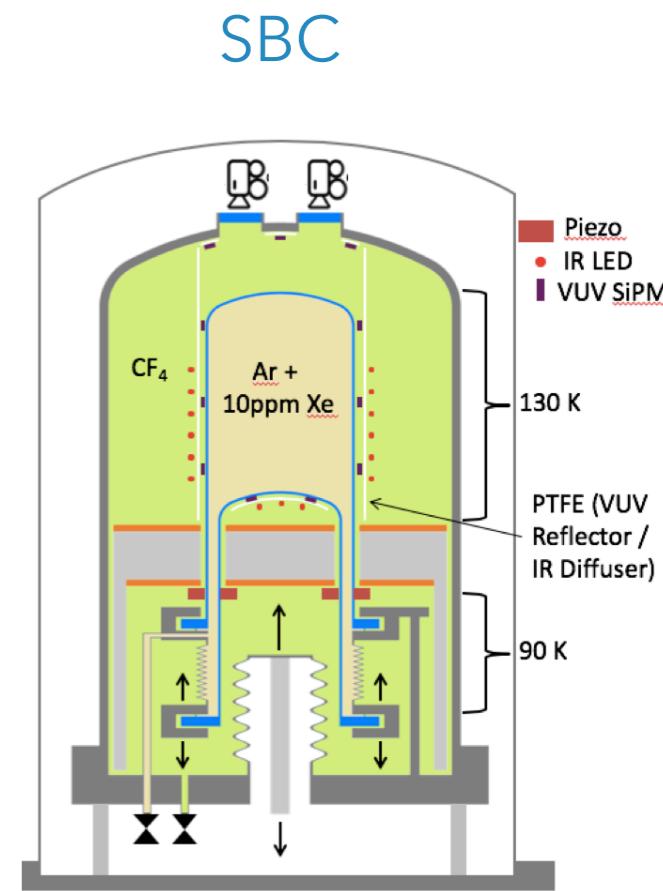
BUBBLE CHAMBERS

► PICO: superheated liquid C_3F_8 octafluoropropane

- Acoustic + visual readout : impressive background rejection
- PICO-500 at SNOLAB: under design, installation/data in 2022/23

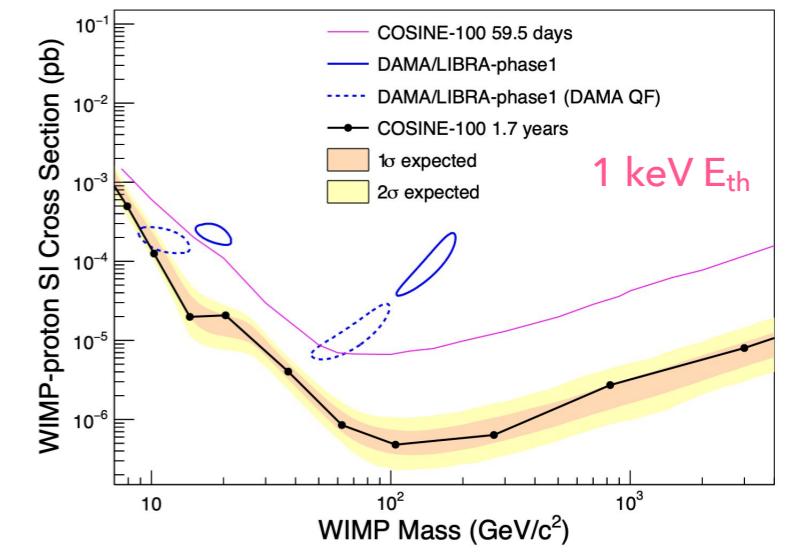
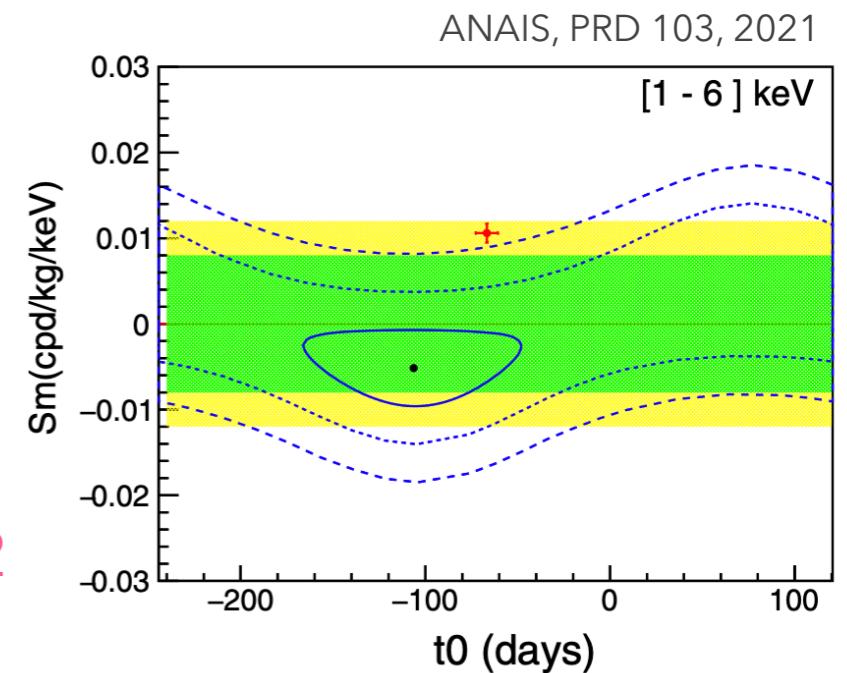
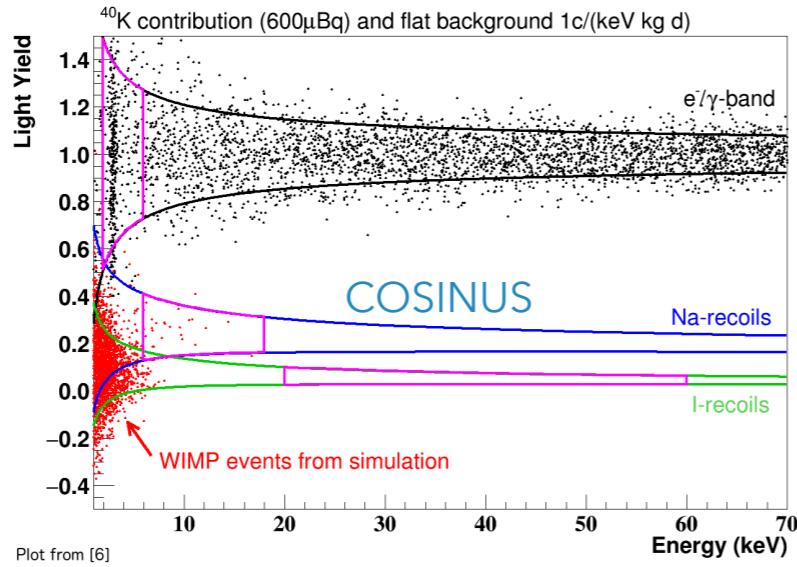
► New detector: the scintillating bubble chamber (SBC)

- ▶ superheated 10 kg Xe-doped LAr, cooled to 130 K, piezoelectric sensors + cameras readout + SiPMs for scintillation signal



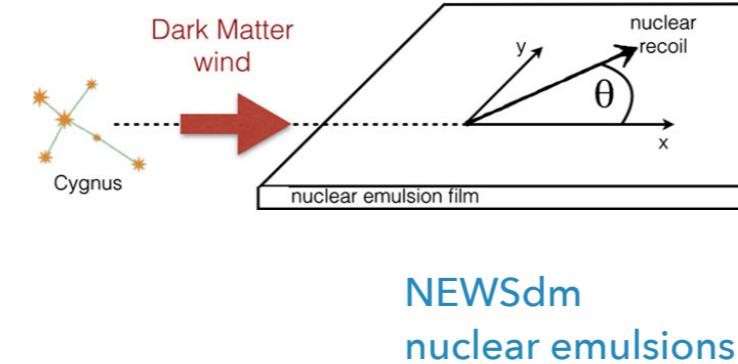
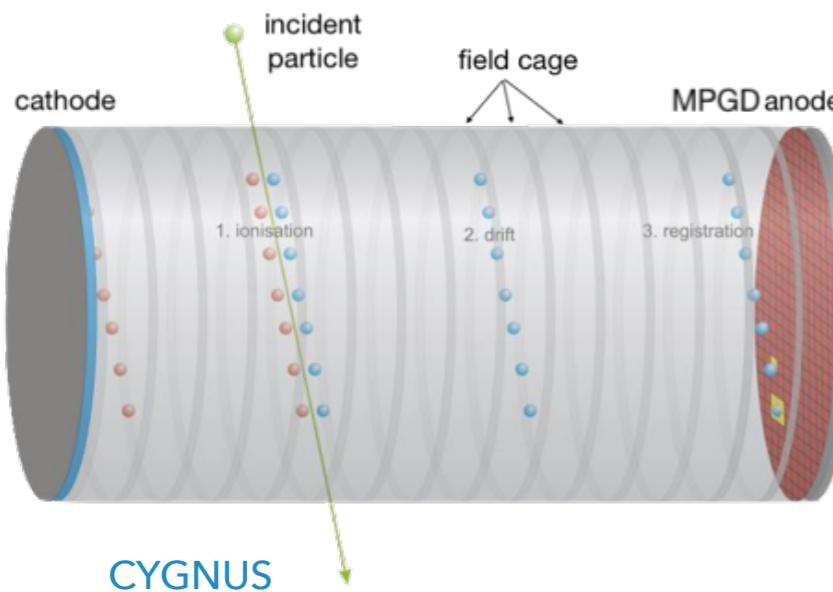
SODIUM IODIDE EXPERIMENTS

- ▶ Test the DAMA/LIBRA annual modulation anomaly with sodium iodide crystals: NaI(Tl)
- ▶ So far, no evidence for annual modulation from ANAIS-112 (3 y of data) and COSINE-100 (1.7 y of data)
- ▶ New experiment COSINUS: detects also phonons in undoped NaI (apart from scintillation) at few mK, for active background rejection; [construction/data at LNGS 2022/23](#)

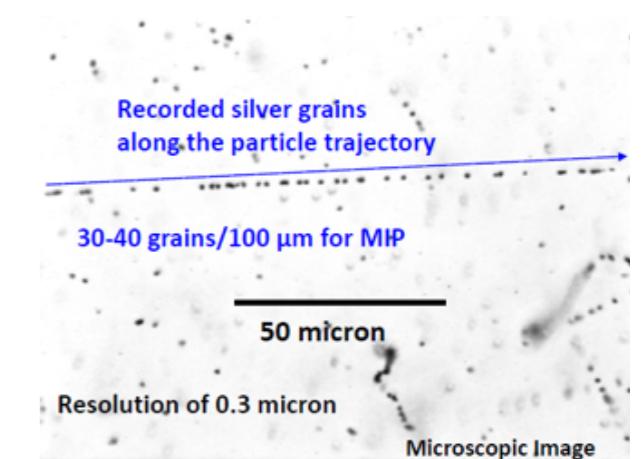
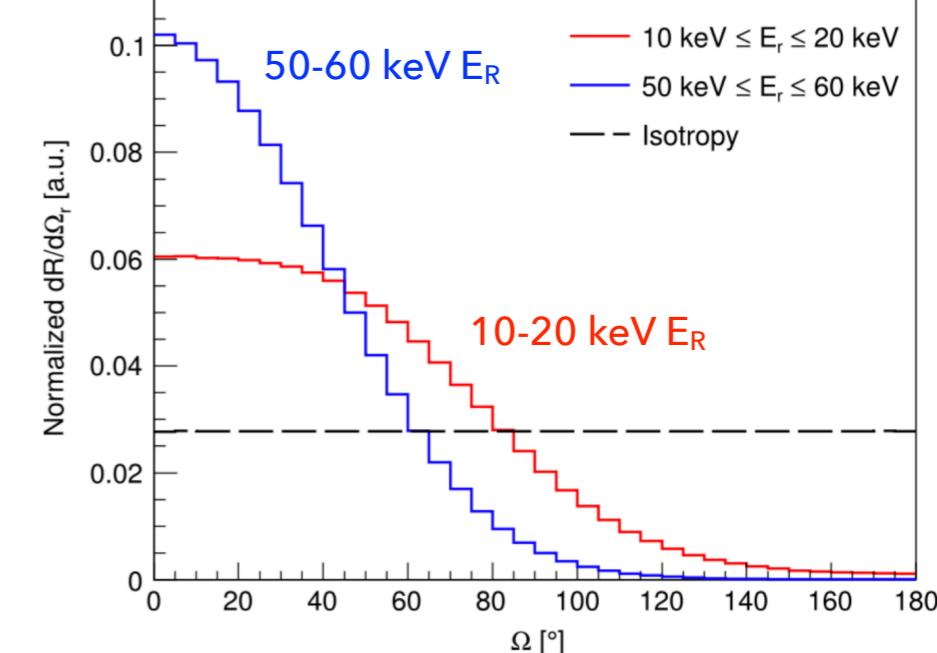


DIRECTIONAL DETECTORS

- ▶ Low-pressure gas, nuclear emulsion and graphene detectors to measure the recoil direction (30° & 13° res) correlated to galactic motion towards Cygnus
- ▶ Challenge: good angular resolution plus head/tails at low recoil energies
- ▶ Cygnus: proto-collaboration to coordinate R&D efforts for gas based (He-CF₄) TPCs with ~ 1 keV threshold



NEWSdm
nuclear emulsions



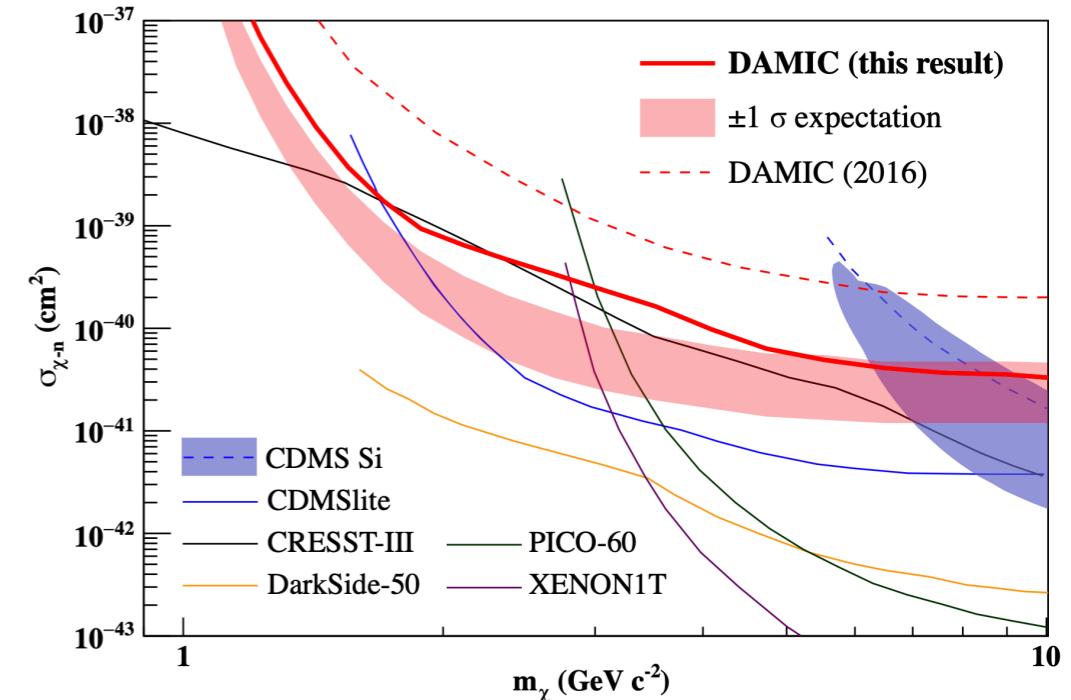
NEWSdm, EPJ-C 78, 2018

F. Mayet et al., Physics Reports 627(2016)

IONISATION DETECTORS

- ▶ Point contact HPGe detectors: low energy threshold and (potentially) large total mass (CDEX)
- ▶ Si CCDs: low ionisation energy, low noise, and particle tracks for background reduction ⇒ particle ID (DAMIC-M, SENSEI)
- ▶ NEWS-G: spherical proportional counter, light targets (H, He, Ne), pulse shape discrimination against surface events, low energy threshold (very low capacitance)

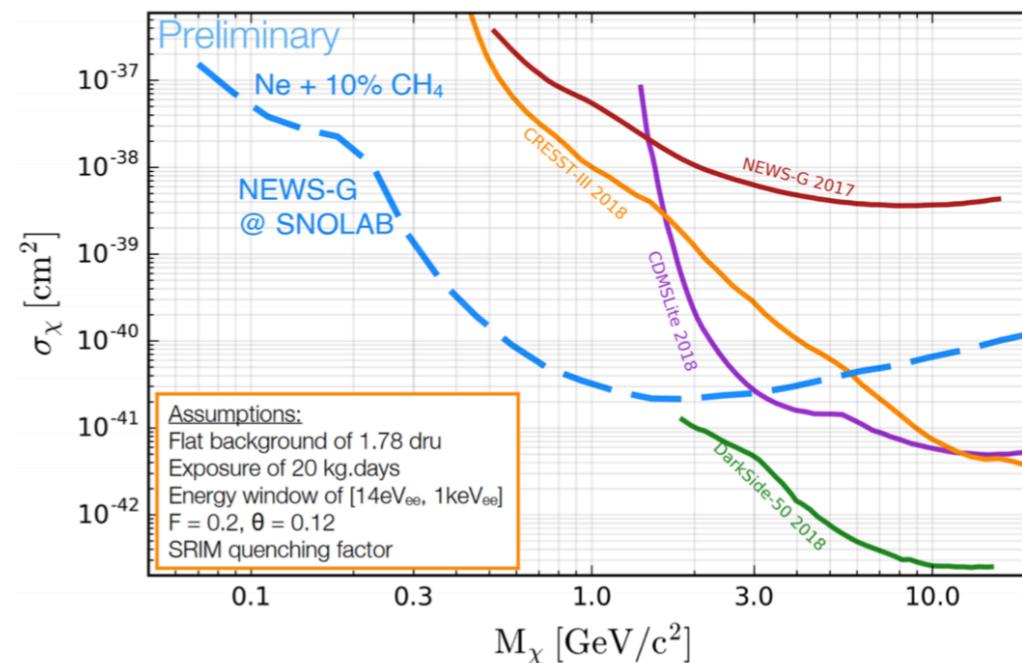
DAMIC, Phys. Rev. Lett. 125, 2020



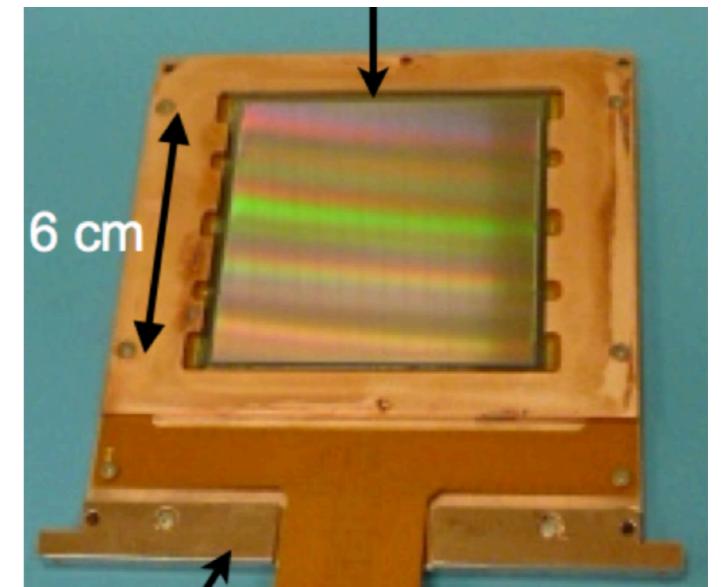
NEWS-G



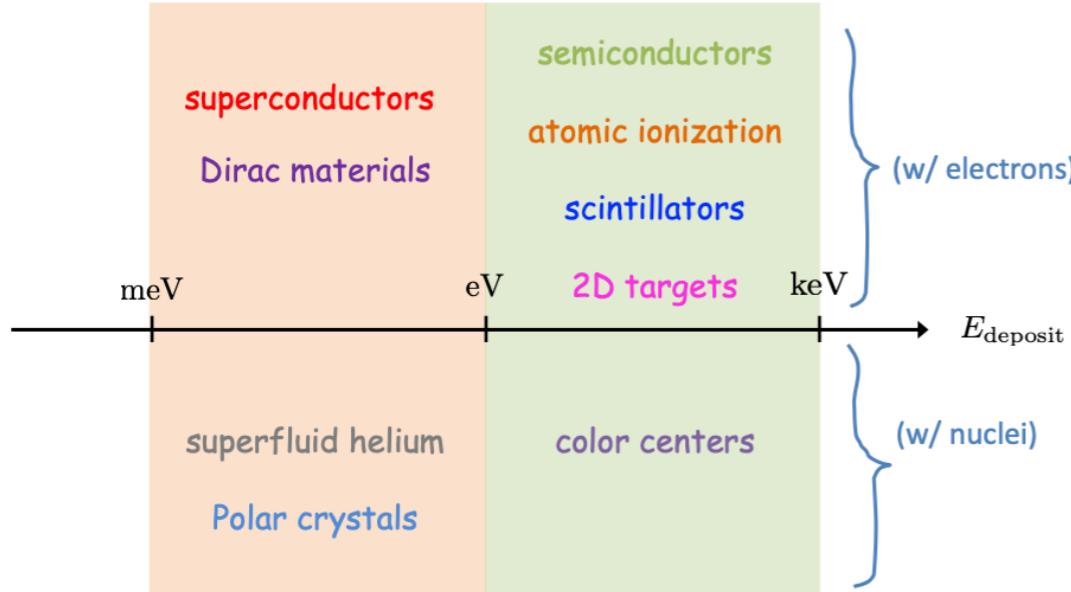
Reach of NEWS-G at SNOLAB



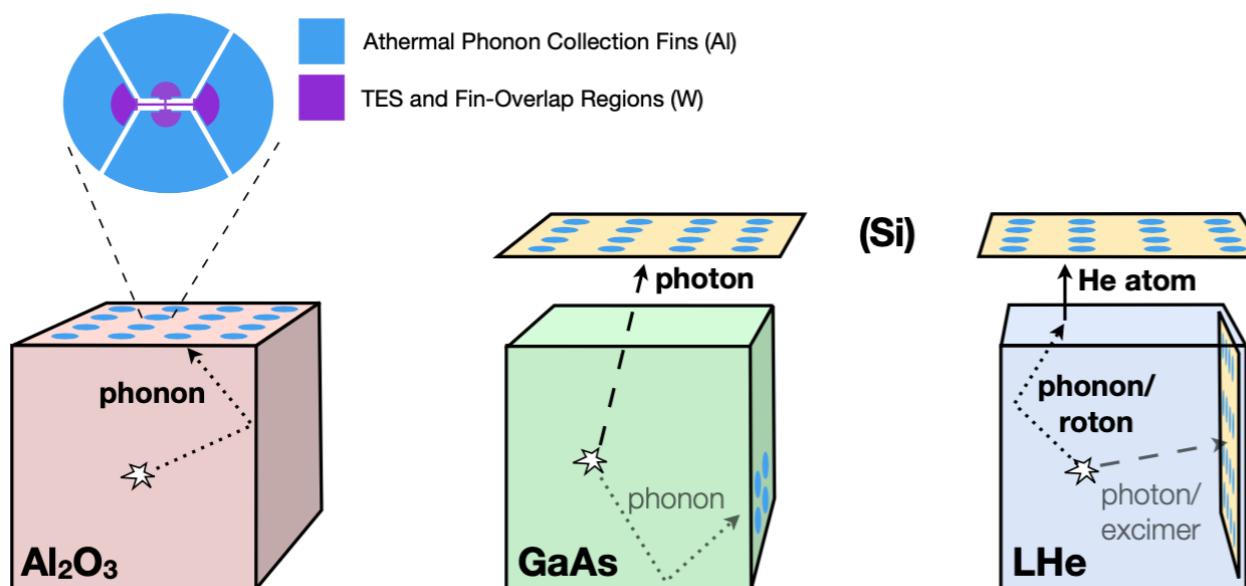
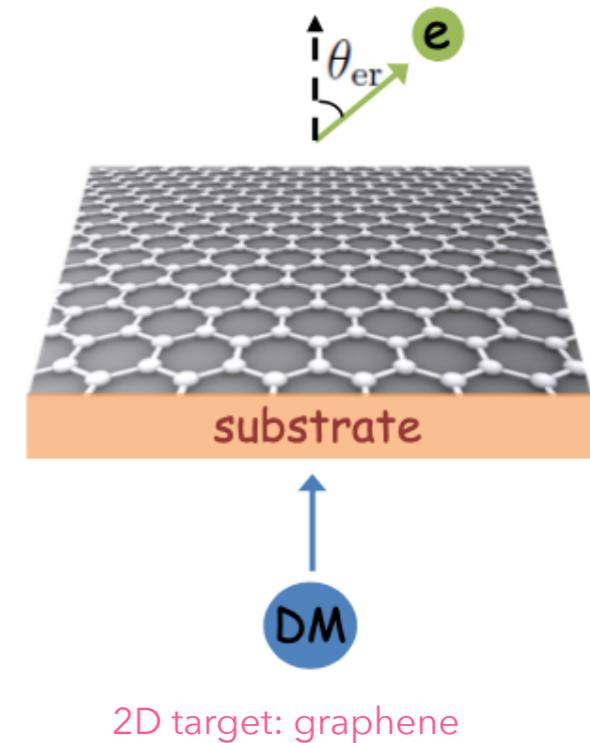
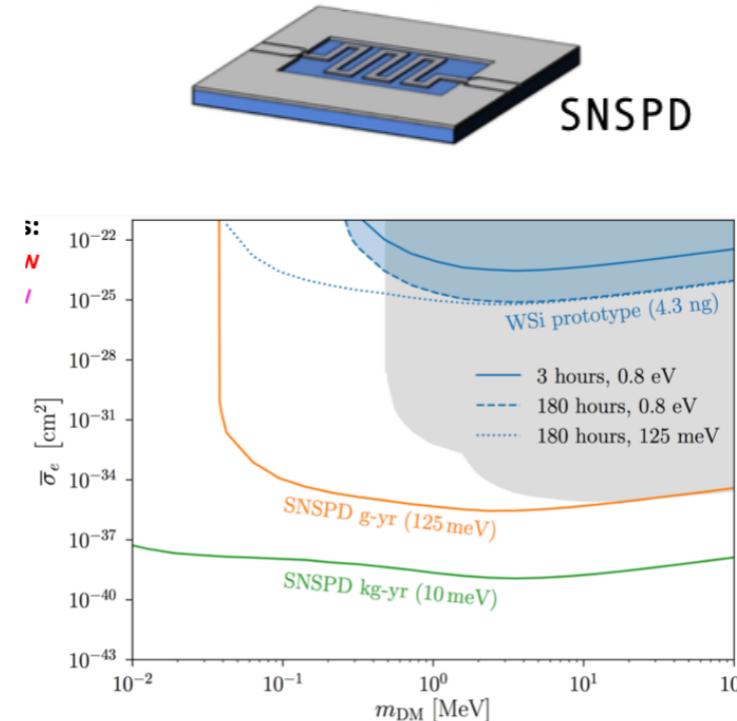
DAMIC



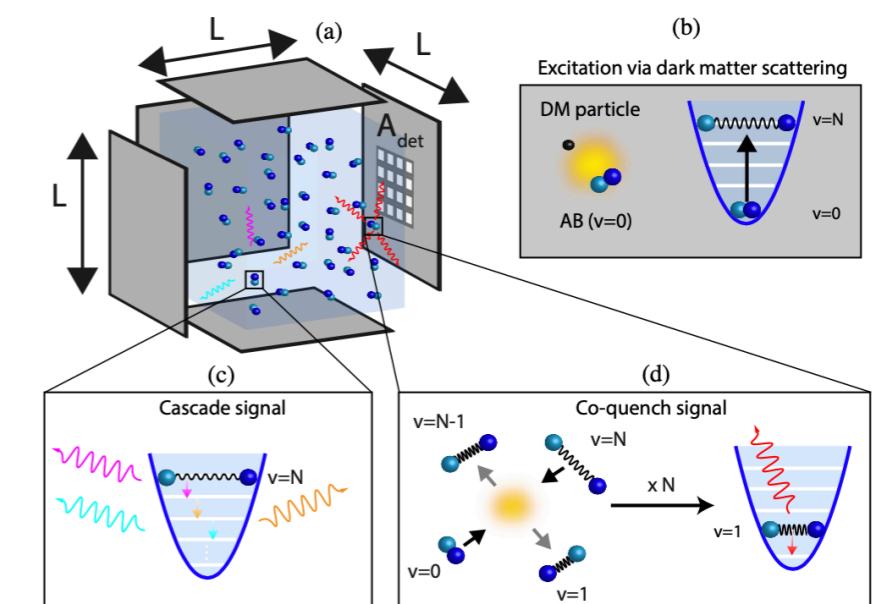
MANY NEW TECHNOLOGIES AND PROPOSALS...



See talk by Yonit Hochberg, Invisibles 2021



Matt Pyle, Dan McKinsey, et al., GaAs + Sapphire; liquid He



K. Berggren, R. Essig et al. low P, low T molecular gas target (e.g. CO), ro-vibrational molecule excitation

DD EXPERIMENTS: PAST, PRESENT, FUTURE

- Example: spin-independent cross section upper limits at 60 GeV WIMP mass

10^{-41} cm^2 in ~1998 to few $\times 10^{-47} \text{ cm}^2$ in ~2018

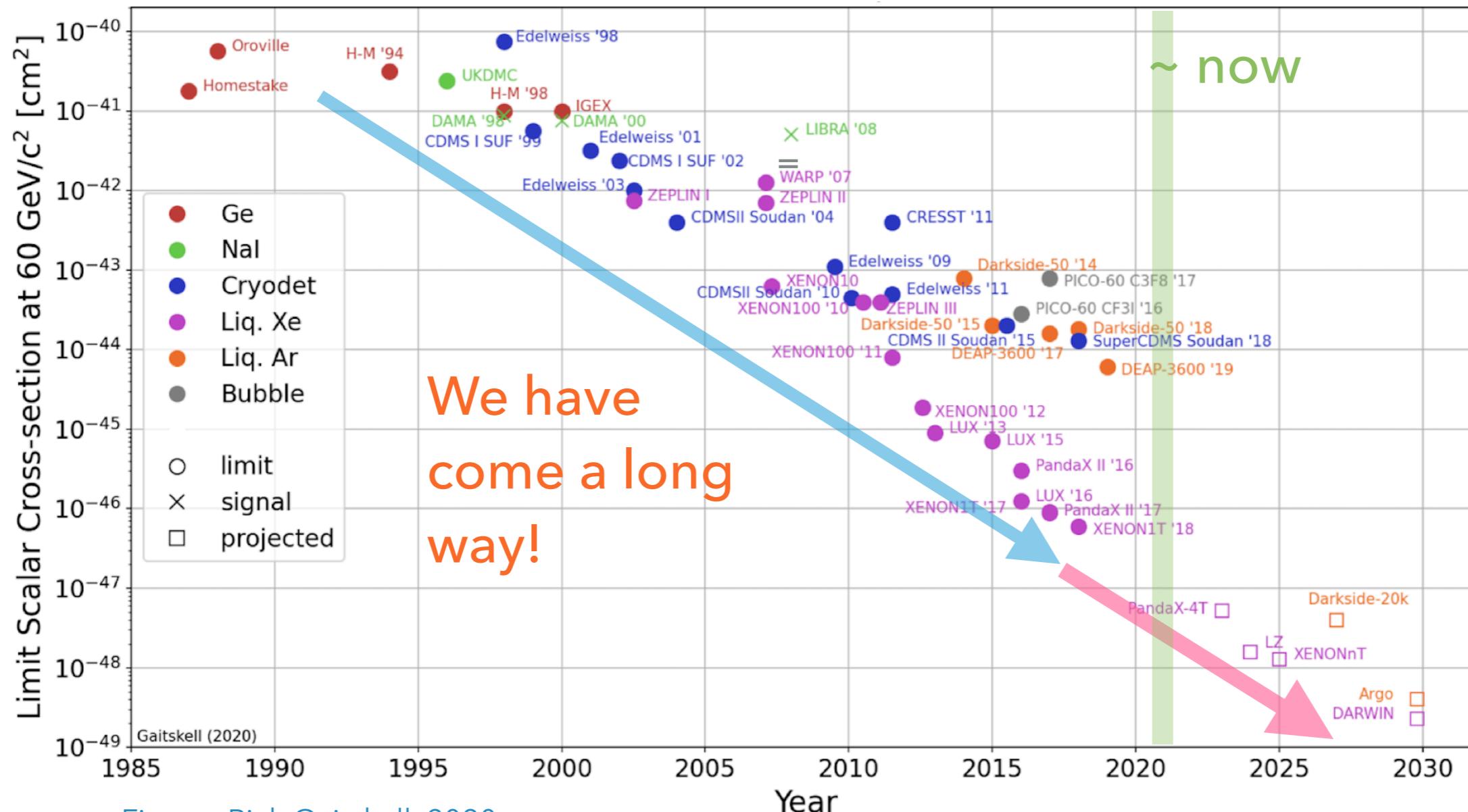


Figure: Rick Gaitskell, 2020

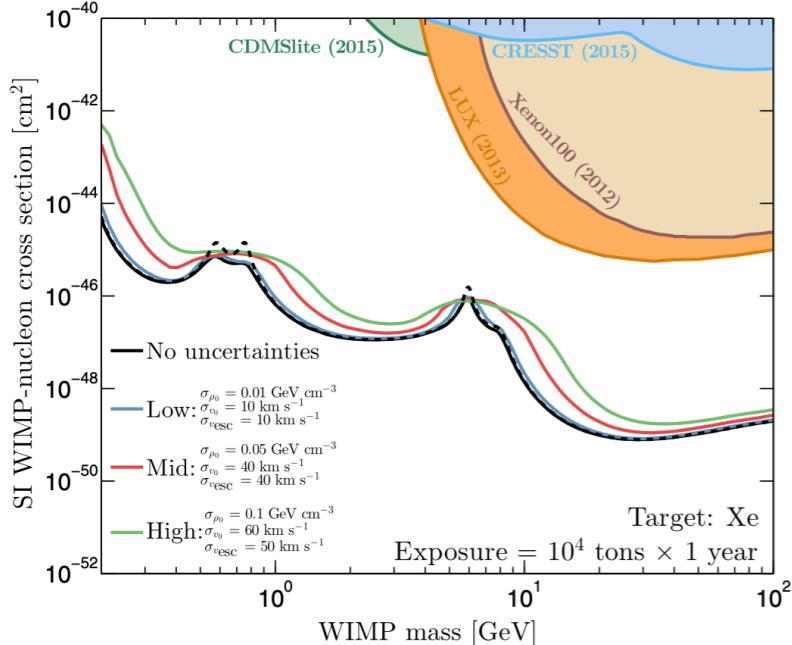
SUMMARY & OUTLOOK

- ▶ Direct dark matter detection experiments must cover an enormous range in dark matter masses & cross sections
- ▶ Principal challenges: reduce energy thresholds further (with existing and new technologies & materials), reduce/understand backgrounds, increase target masses
- ▶ Main goals: discover a new, dark species & explore the parameter space until solar and cosmic neutrinos will dominate event rates
- ▶ Explore a variety of dark matter candidates (WIMPs, LDM, ALPs, dark photons, etc) & break new grounds in neutrino physics, solar axions, etc
- ▶ Be prepared for a discovery & the unexpected ;-)

THE END

BACKGROUNDS: THE NEUTRINO FOG

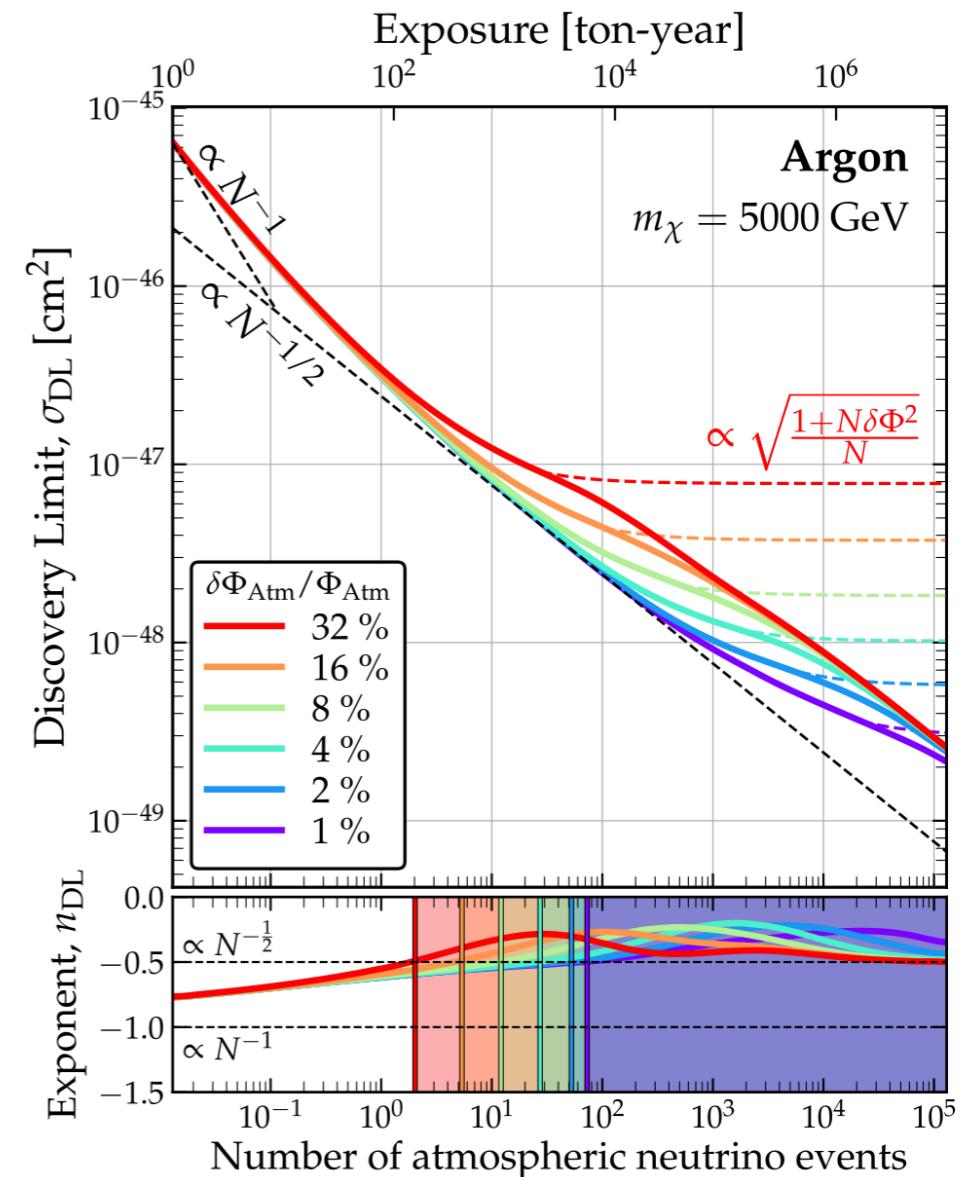
- ▶ Sensitivity of DDNR experiments: **eventually limited by the neutrino backgrounds**
- ▶ **Discovery of a signal:** only possible if excess in events > stat. fluctuations in the background
- ▶ **The "neutrino fog" depends on**
 - systematic uncertainty in neutrino fluxes ($\sim 2\%$ in ${}^8\text{B}$, $\sim 20\%$ for atmospheric neutrinos)
 - nuclear and astro inputs for the DM signal



C. A. J. O'Hare PRD 94, 2016

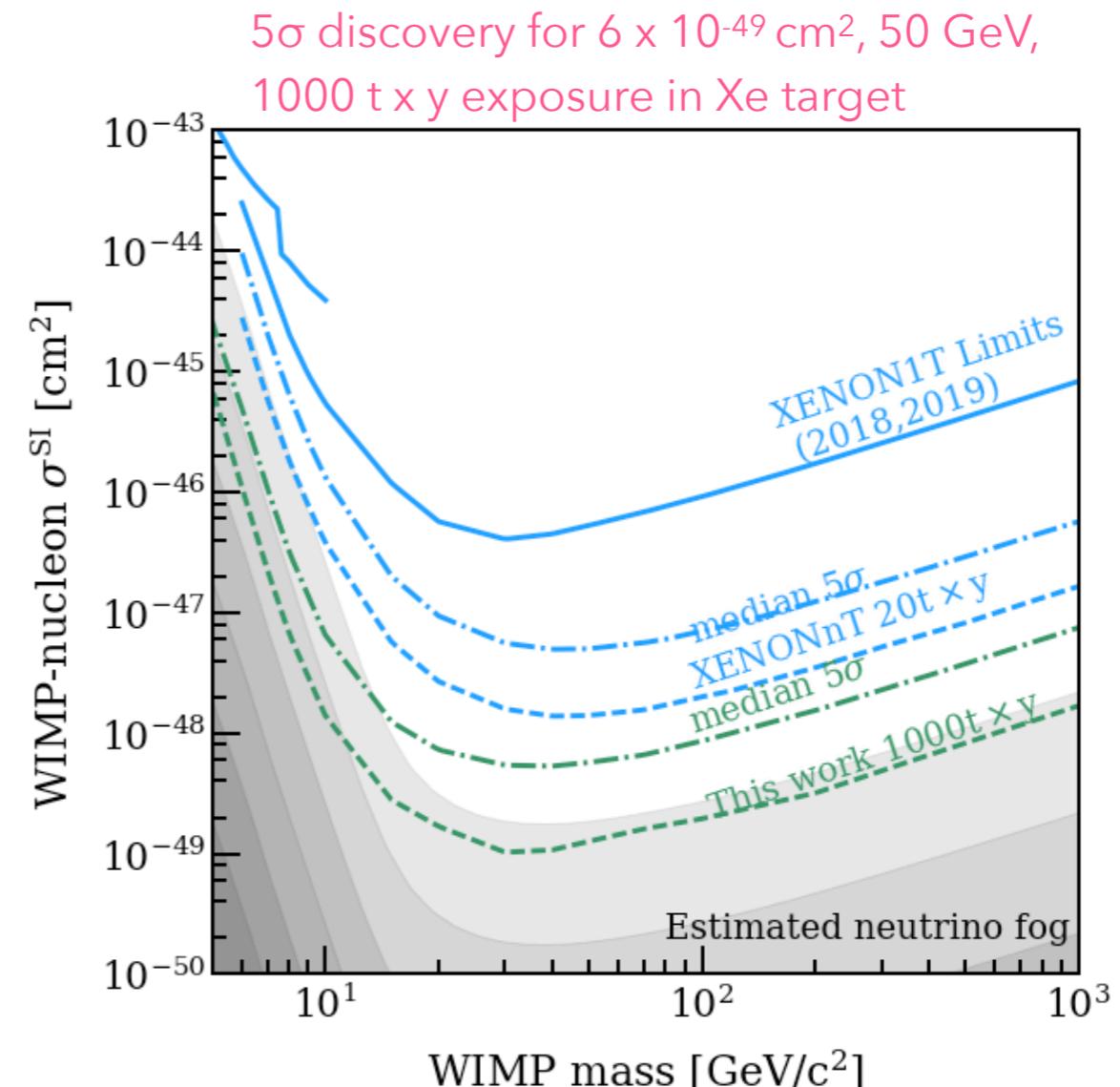
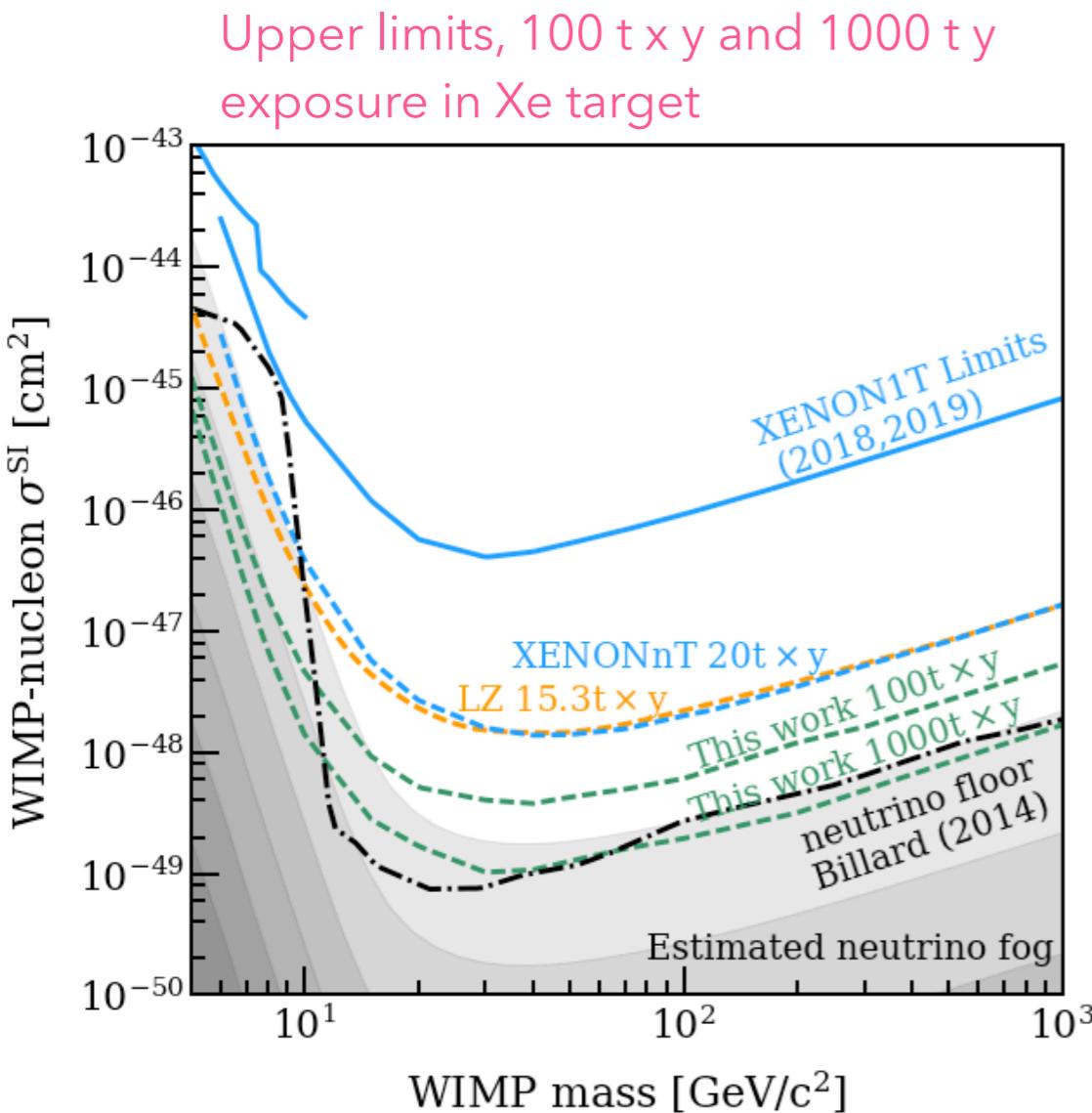
Neutrino "floor" for 3 sets of 1- σ uncertainties on the local density, speed and escape velocity for a xenon target

C. A. J. O'Hare PRD 102, 2020



Discovery limit of a 5 TeV WIMP in an argon target, as a function of the atm. neutrino event N and fract. uncertainty on the atm v flux: $\delta\Phi_{\text{atm}}/\Phi_{\text{atm}}$

BACKGROUNDS: THE NEUTRINO FOG



Figures: Knut Mora

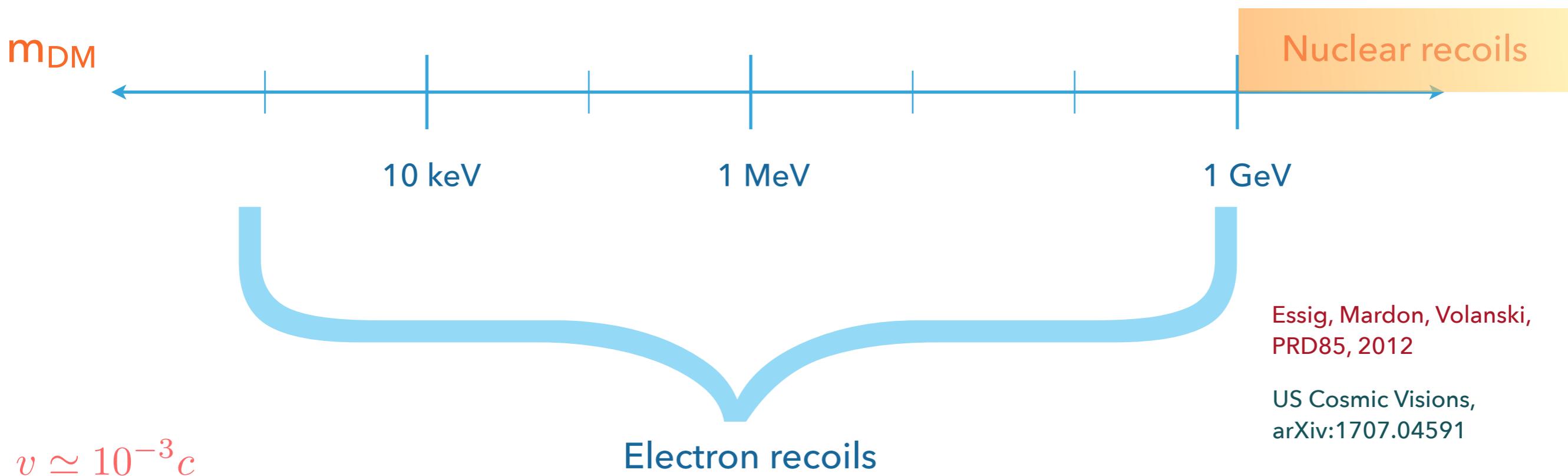
Shaded grey areas: the “neutrino fog” \rightarrow the lightest area shows the WIMP cross-section where more than 1 ν event is expected in the 50% most signal-like (S1, S2) region; subsequent shaded areas: 10-fold increases of the ν expectation

KINEMATICS: DARK MATTER PARTICLE MASS

- ▶ Light DM: nuclear recoil energy - well below the threshold of most experiments
- ▶ Total energy in scattering: larger, and can induce inelastic atomic processes → visible signals

$$E_e \leq \frac{m_{DM}v^2}{2} \leq 3 \text{ eV} \times \frac{m_{DM}}{1 \text{ MeV}}$$

$$E_{NR} = \frac{q^2}{2m_N} \simeq 1 \text{ eV} \times \left(\frac{m_{DM}}{100 \text{ MeV}} \right)^2 \times \frac{10 \text{ GeV}}{m_N}$$



THE DIFFERENTIAL NUCLEAR RECOIL SPECTRUM

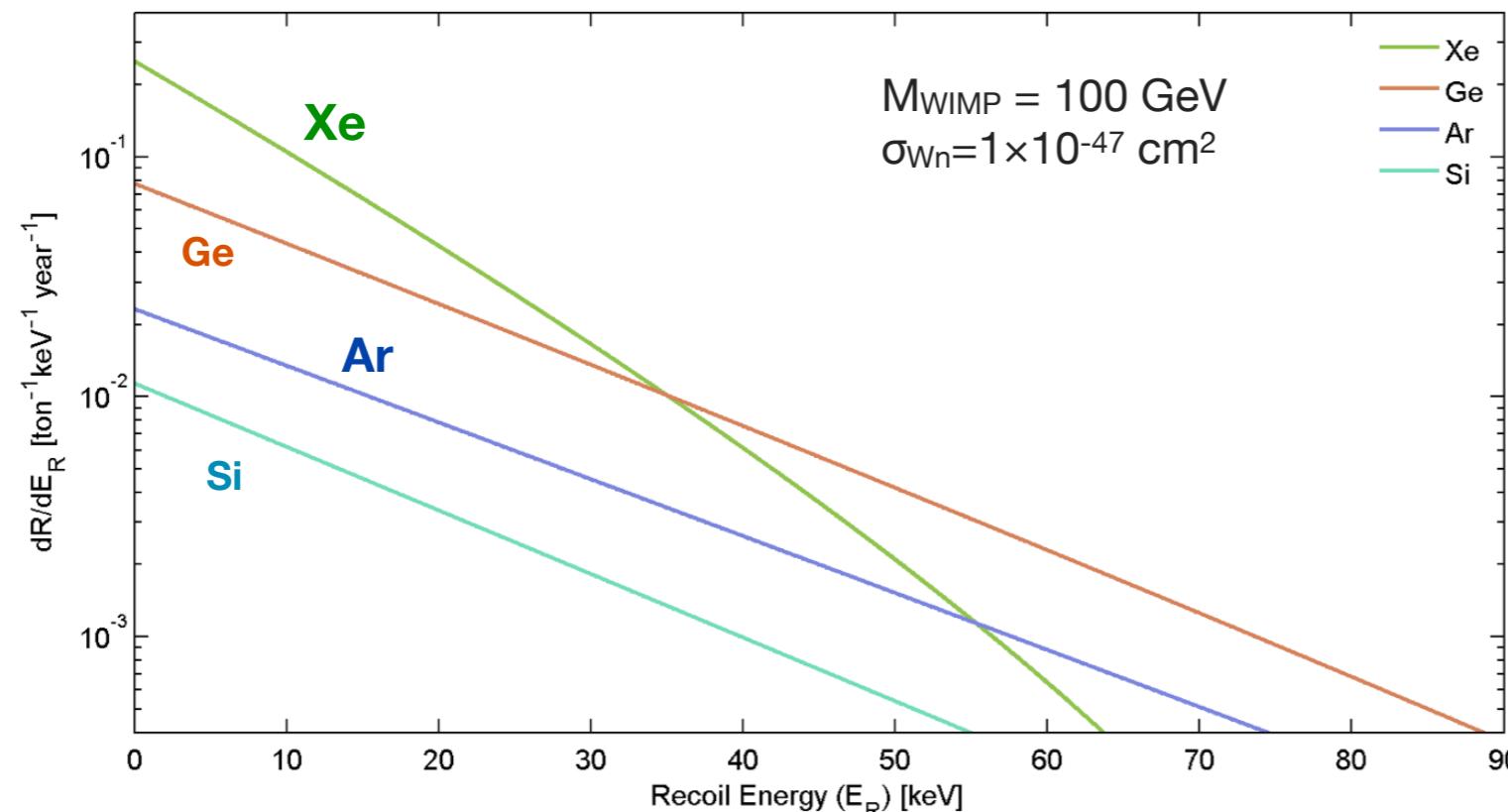
$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_\chi} \int_{v > v_{min}}^{\infty} \frac{d\sigma}{dE_R} v f(\vec{v}) d^3 \vec{v}$$

$v_{min} = \sqrt{m_N E_R / 2 \mu_{\chi N}^2}$

Detector physics
 N_N, E_{thr}

Particle/nuclear physics
 $m_\chi, d\sigma/dE_R$

Astrophysics
 $\rho_0, f(\vec{v})$

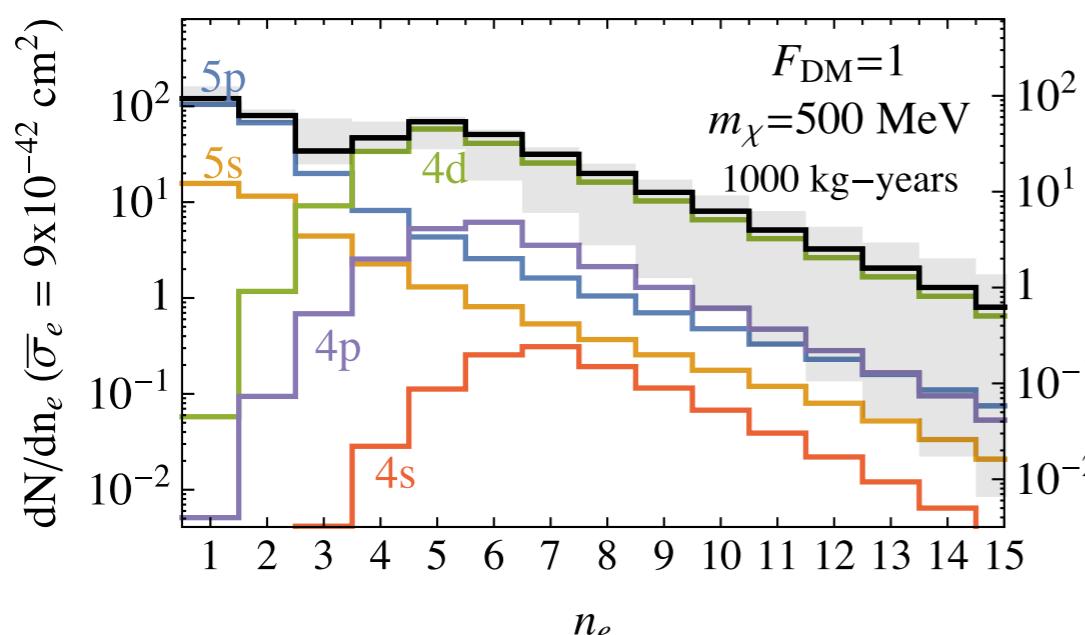


Spin-
independent
NR spectrum

INTERACTION RATES: DM-ELECTRON SCATTERING

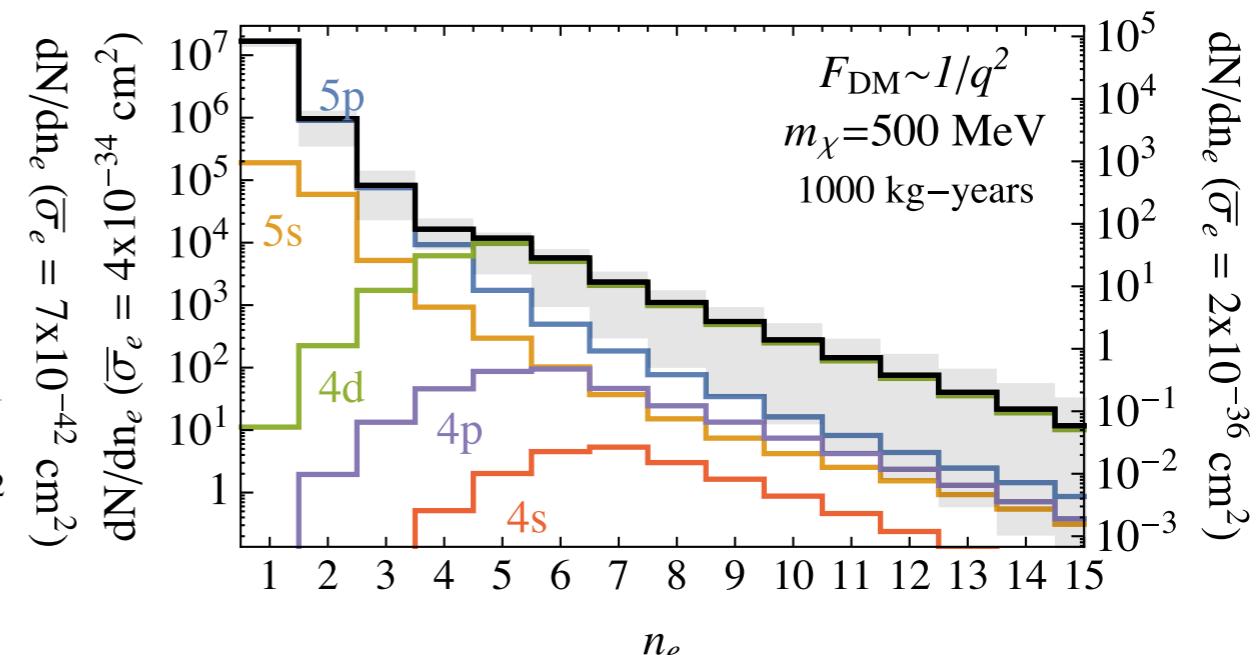
$$\frac{dR_{ion}}{d \ln E_R} = \frac{6.2}{A} \left(\frac{\rho_0}{0.4 \text{ GeV cm}^{-3}} \right) \left(\frac{\sigma_e}{10^{-40} \text{ cm}^2} \right) \left(\frac{10 \text{ MeV}}{m_{\text{DM}}} \right) \times \frac{d\langle \sigma_{ion} v \rangle / d \ln E_R}{10^{-3} \sigma_e} \frac{\text{events}}{\text{kg d}}$$

Expected number of events for a xenon detector with 1 tonne year exposure



$$F_{\text{DM}} = 1$$

Heavy dark photon A' mediator



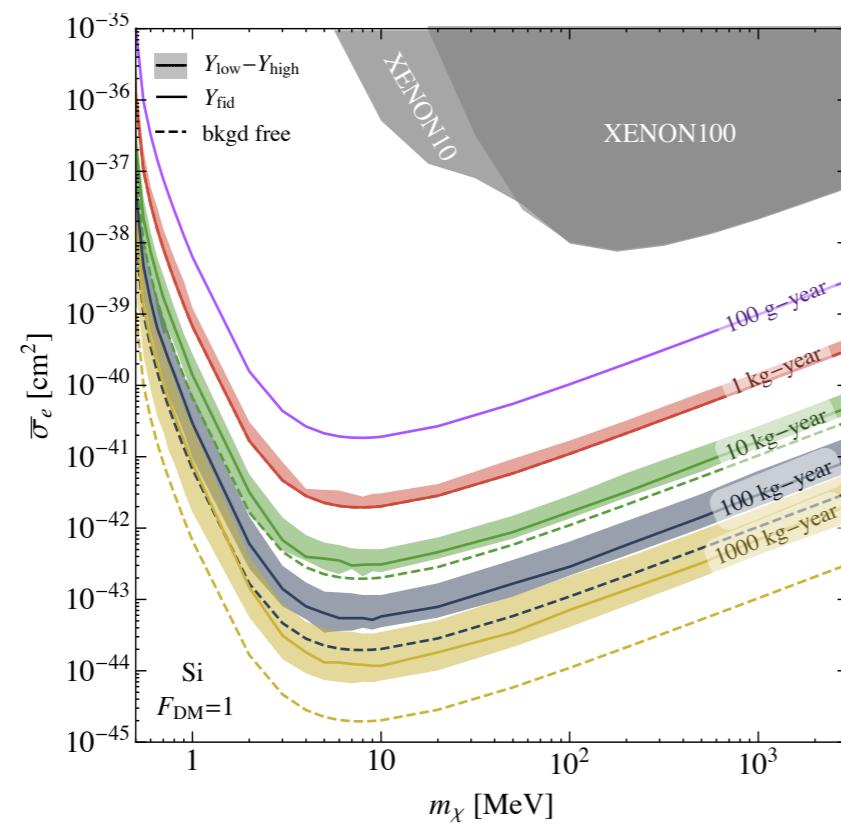
$$F_{\text{DM}} = \alpha^2 \frac{m_e^2}{q^2}$$

Ultra-light dark photon A' mediator

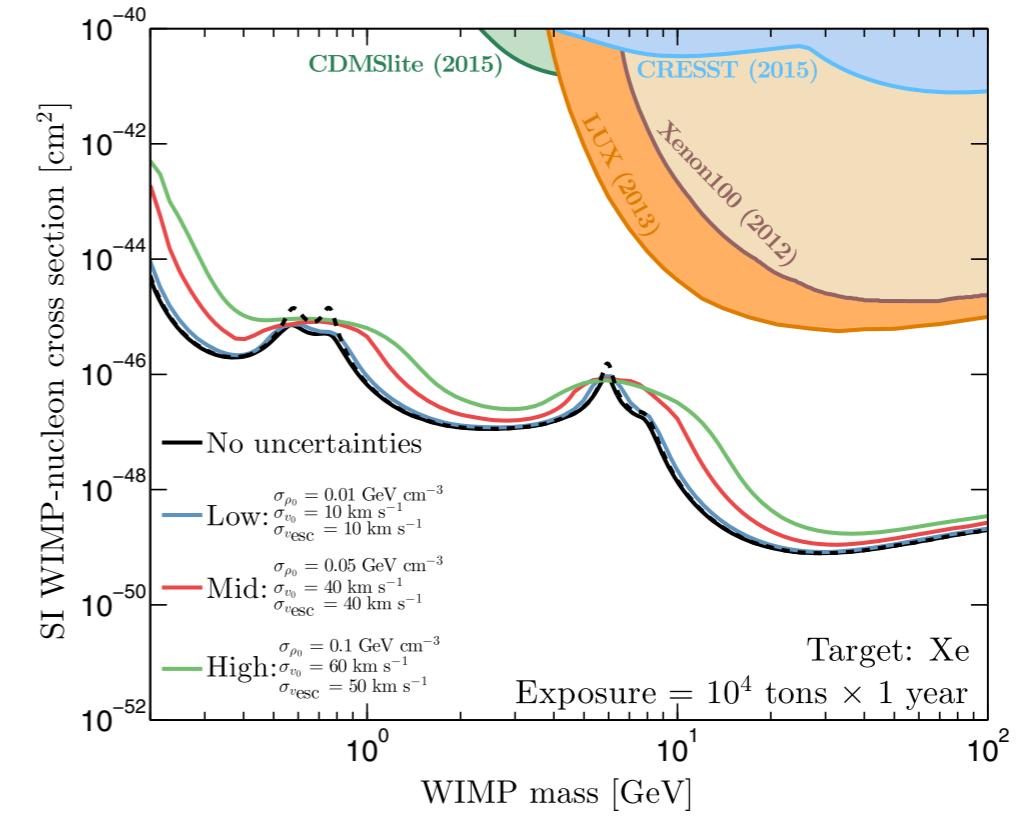
NEUTRINO BACKGROUNDS

- ▶ Low mass region: limit at ~ 0.1 - 10 kg year (target dependent)
- ▶ High mass region: limit at ~ 10 ktonne year
- ▶ But: annual modulation, directionality, momentum dependence, inelastic DM-nucleus scatters, etc

Discovery limits
(2- σ) for various
ionisation
efficiencies Y ,
solar v
background
only



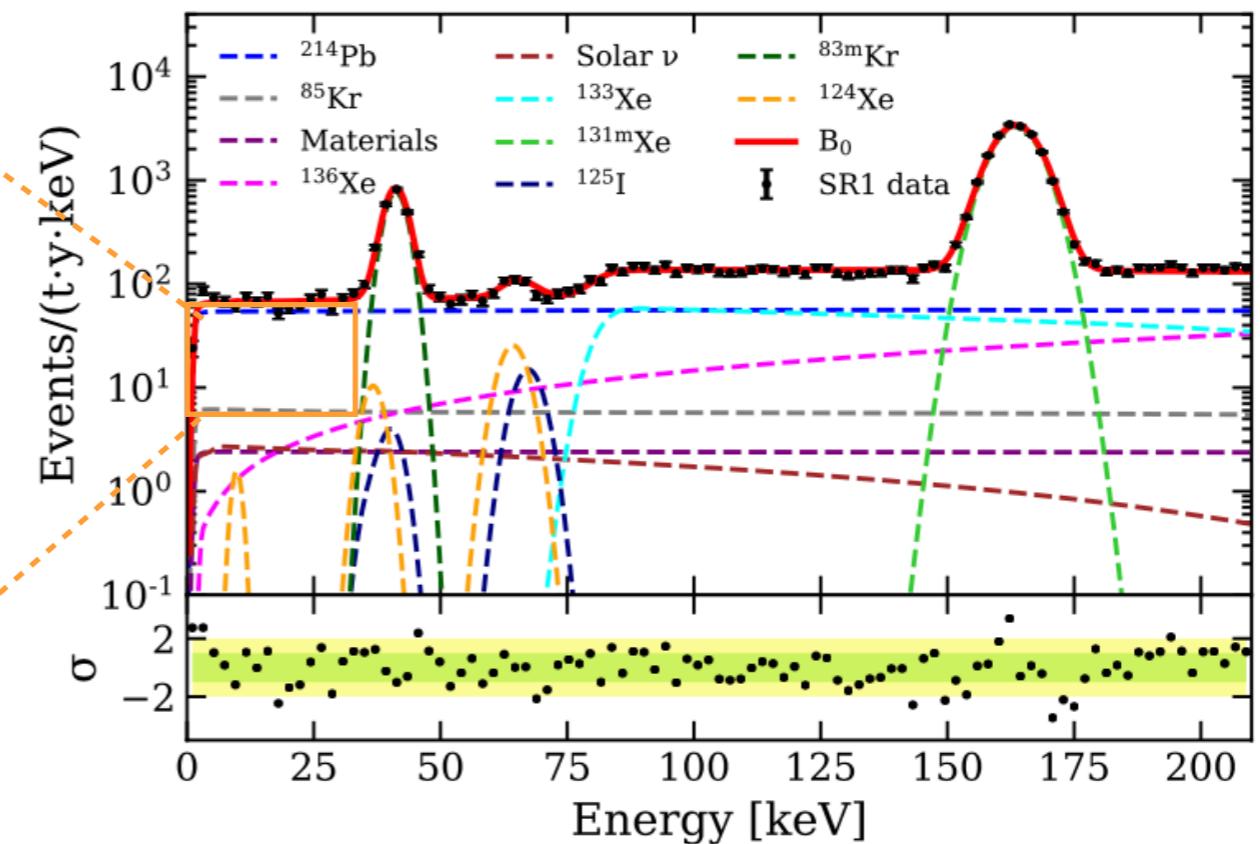
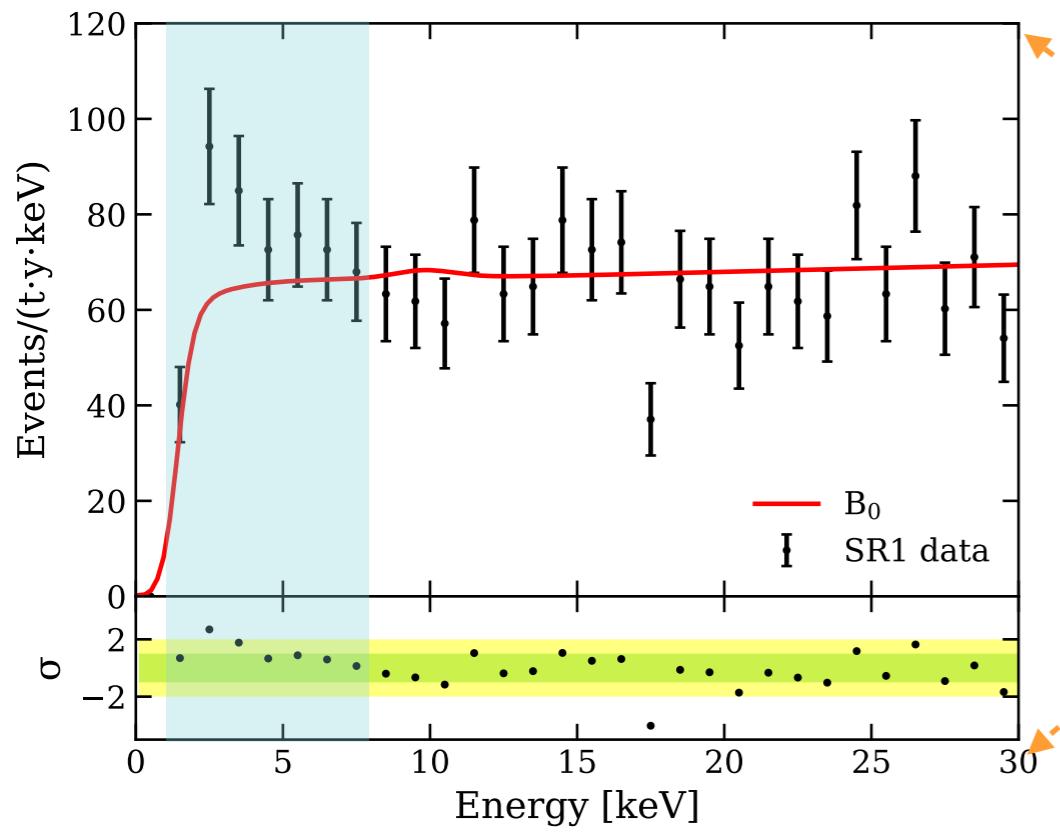
DM-electron scatters (R. Essig et al, PRD97, 2018)



DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)

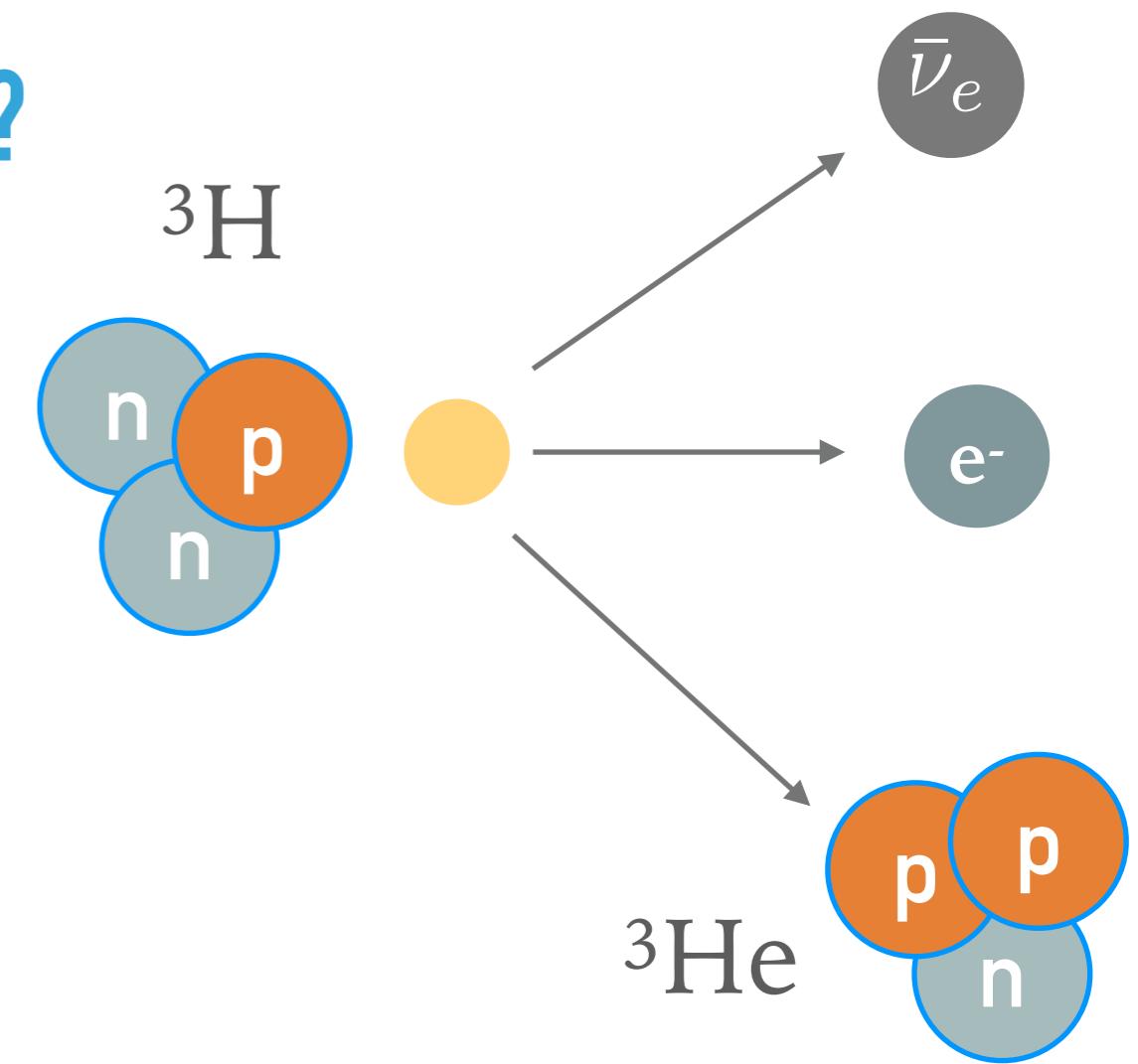
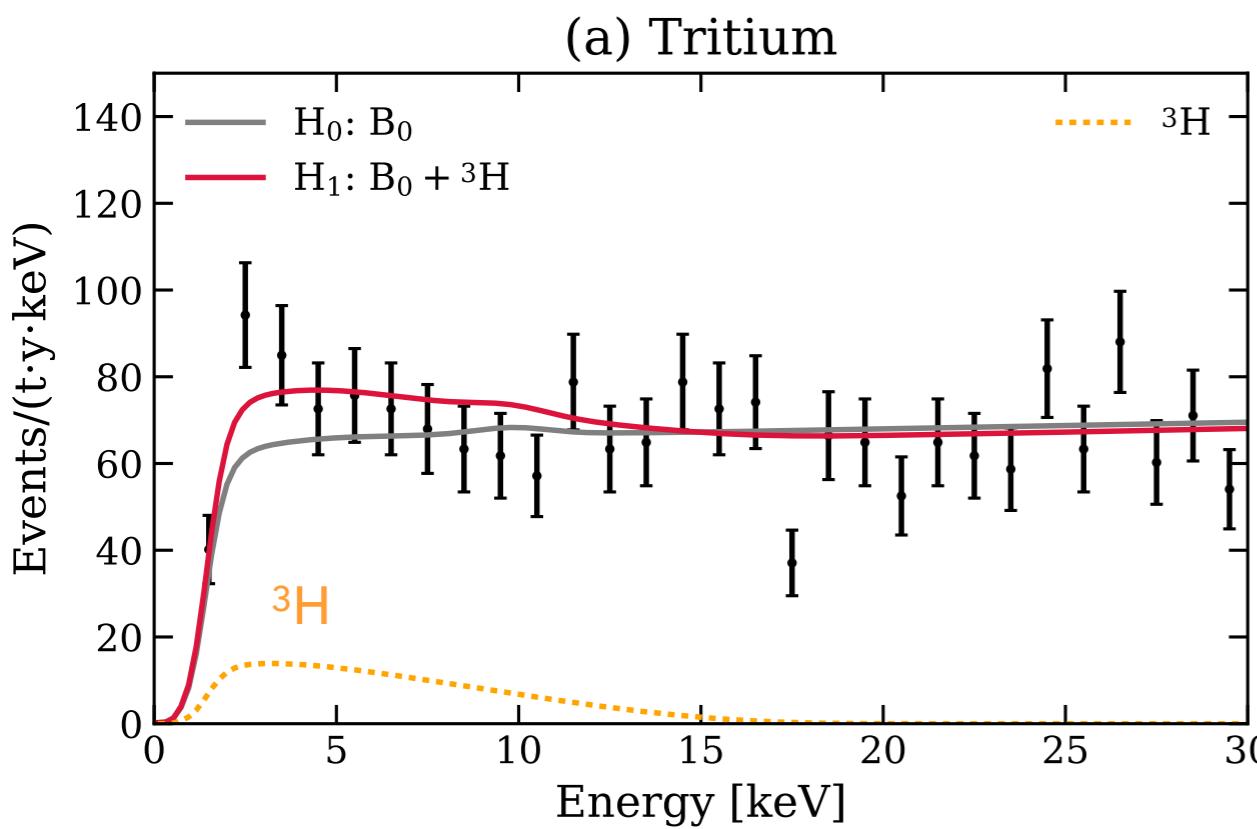
BACKGROUND MODEL AND DATA

- ▶ Good fit over most of the energy region
- ▶ Excess between (1,7) keV
- ▶ Number of observed events: 285, expected from background: (232 ± 15) events



NEW BACKGROUND: TRITIUM DECAYS?

- ▶ Low energy β -decay with 18.6 keV endpoint, $T_{1/2} = 12.3$ y
- ▶ Cosmogenic production in xenon & emanation of HTO and HT from detector materials
 - Removed by continuous gas purification



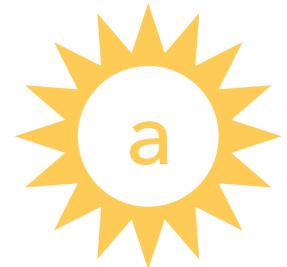
Best fit: (159 ± 51) events/(t y)

${}^3\text{H}:\text{Xe}$ concentr.: $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol

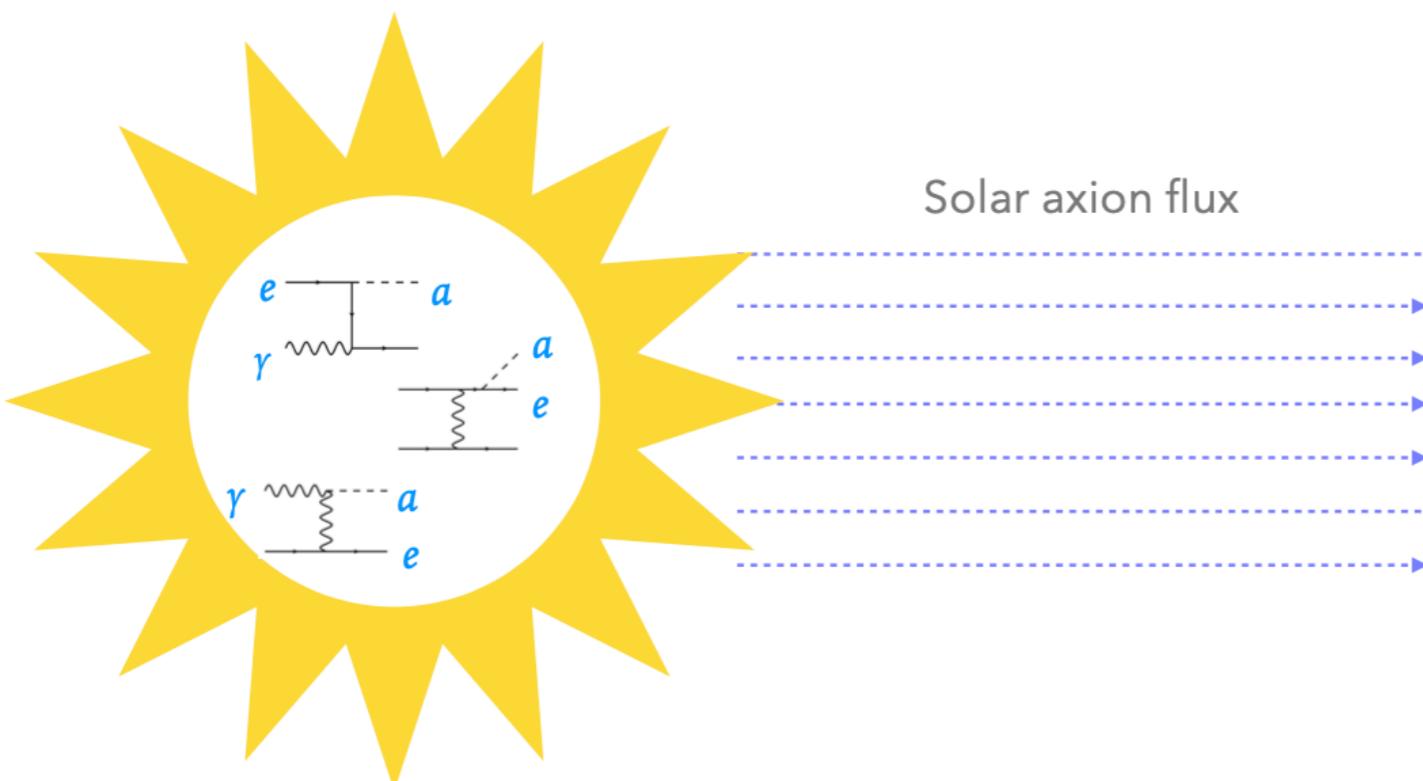
< 3 ${}^3\text{H}$ atoms per kg of xenon

Tritium favoured over background-only fit at 3.2σ

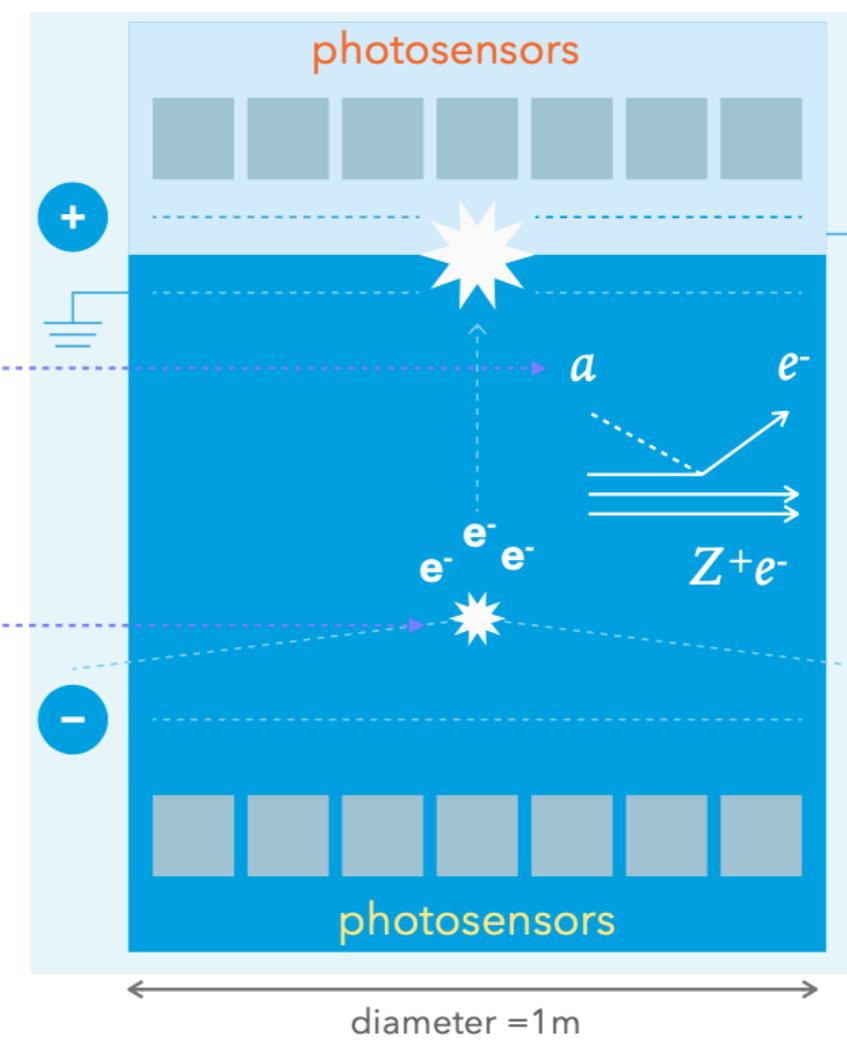
SIGNAL: SOLAR AXIONS?



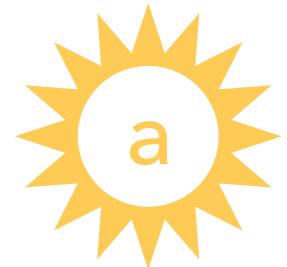
- ▶ Axion could be produced in the Sun with \sim keV kinetic energies
- ▶ They can travel to Earth and be detected in the XENON1T TPC
- ▶ Several production mechanisms in the Sun



$$\text{For QCD axions: } m_a \simeq 6 \times \frac{10^9 \text{ GeV}}{f_a} \text{ meV}$$



SIGNAL: SOLAR AXIONS?



- ▶ Axion could be produced in the Sun with \sim keV kinetic energies
- ▶ They can travel to Earth and be detected in the XENON1T TPC
- ▶ Several production mechanisms in the Sun

ABC: atomic recombination & de-excitation, bremsstrahlung & Compton interactions

g_{ae}

axion-electron

Primakoff effect

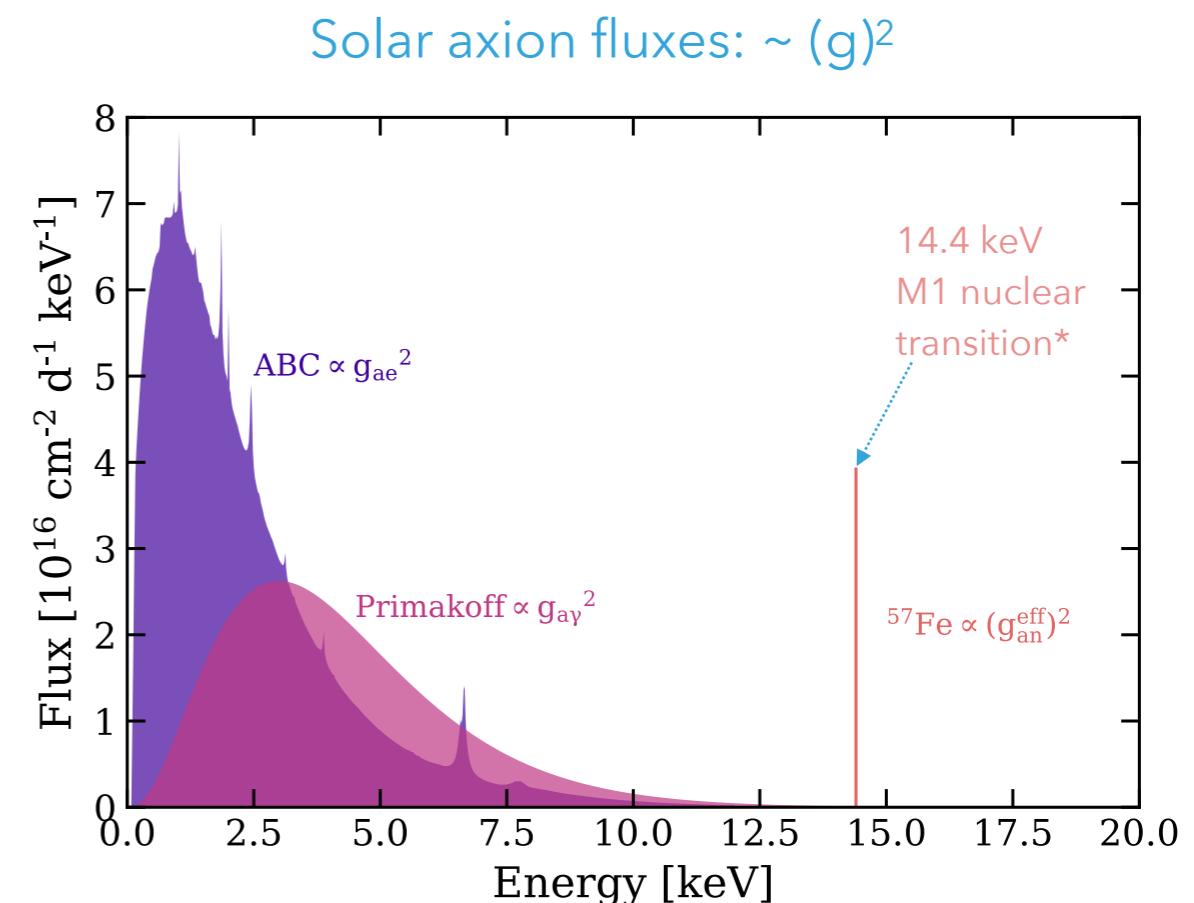
$g_{a\gamma}$

axion-photon

Nuclear de-excitation

g_{an}

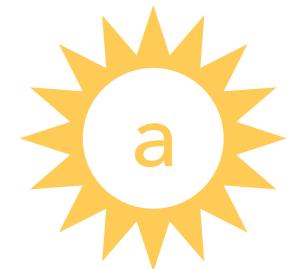
axion-nucleon



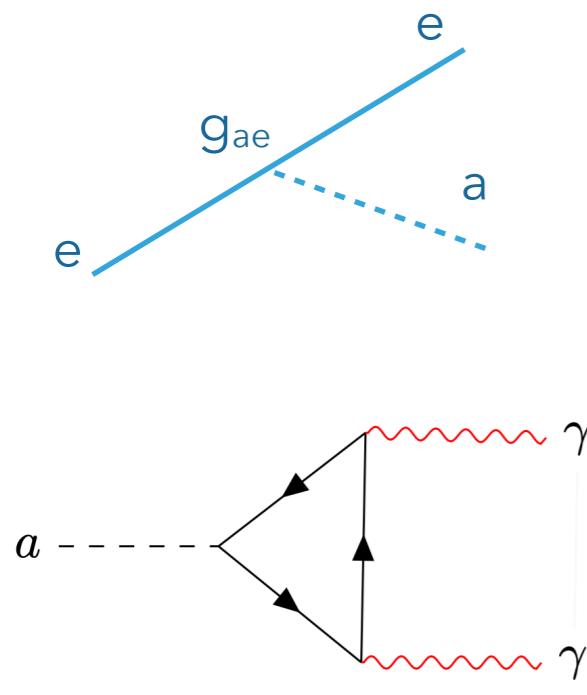
* W. Haxton & K. Lee, PRL66, 1991, S. Moriyama, PRL 75, 1995

J. Redondo, JCAP 12, 2013, ABC flux

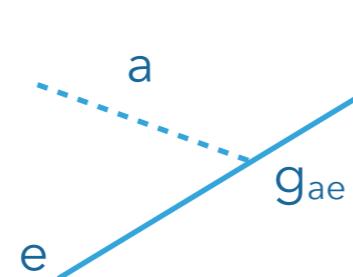
SOLAR AXIONS



Production
Solar physics

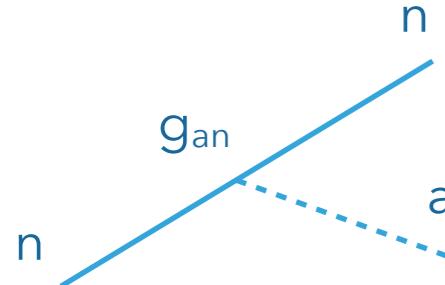


Detection:
Axioelectric effect

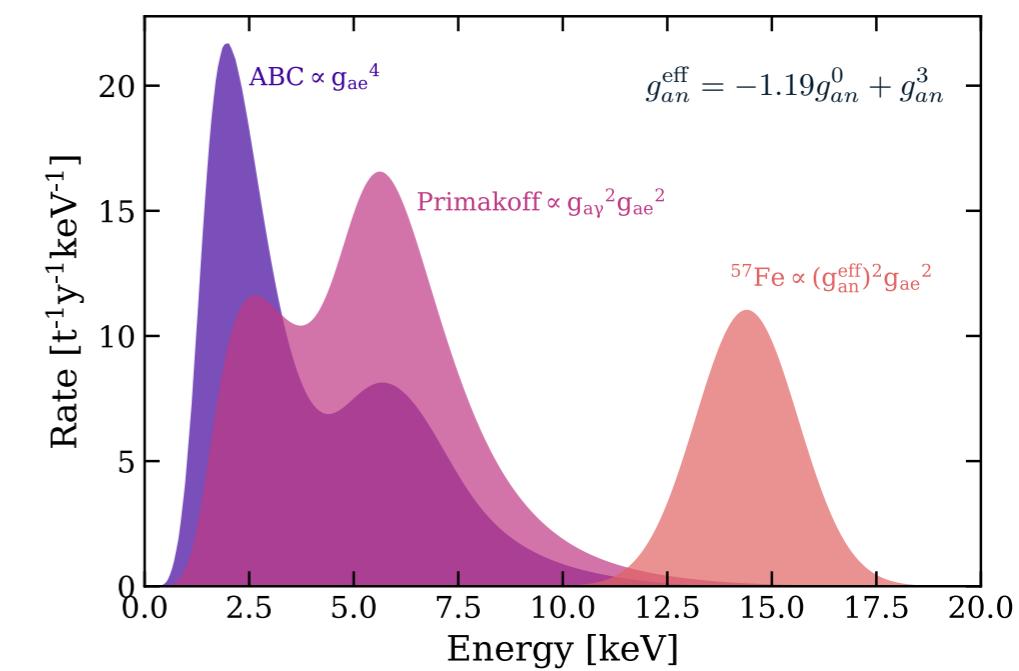


σ for detection, analogous to
photoelectric effect

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

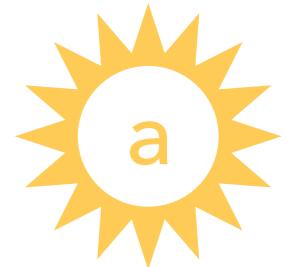


Reconstruction
XENON1T resolution, efficiency

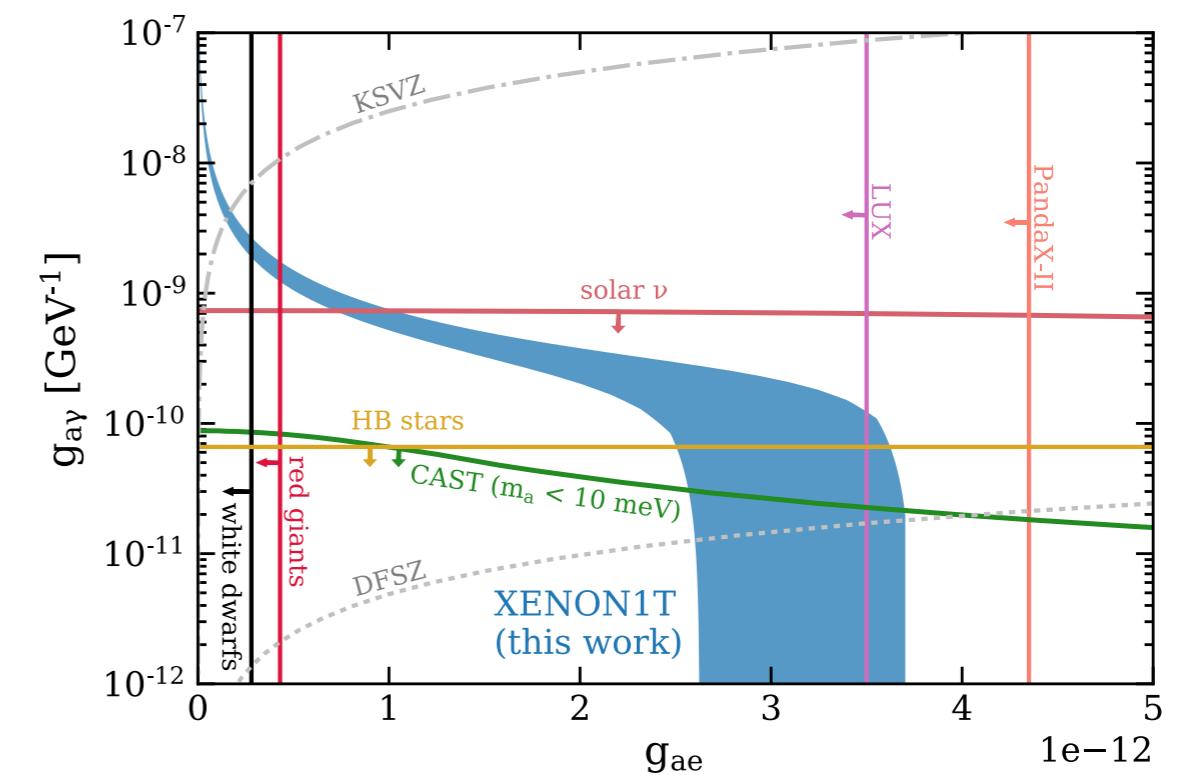
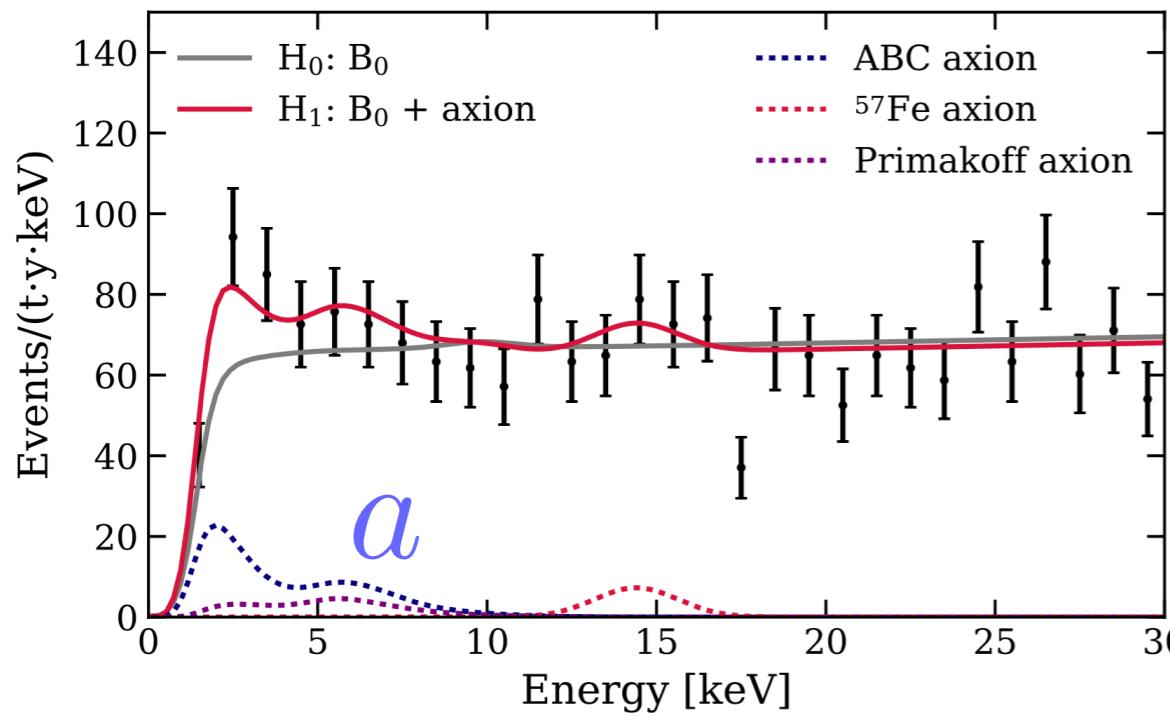


- Production & detection: constrain $|g_{ae}|$, $|g_{ae}g_{an}|$, $|g_{ae}g_{ay}|$
- No axion model assumed in the analysis, the 3 fluxes considered independent of one another (couplings left unconstrained in the fit)

SOLAR AXIONS



- ▶ Solar axion favoured over background-only at 3.4σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487)
- ▶ Tritium favoured over background-only at $3.2\sigma \stackrel{\text{def}}{=} (6.2 \pm 2) \times 10^{-25}$ mol/mol
- ▶ Solar axion + ^3H favoured at 2.0σ over ^3H hypothesis



INTERACTION RATES: DM ABSORPTION

- ▶ Absorption of bosonic DM (ALPs, dark photons) via the "axioelectric" effect
- ▶ Rates $\sim \phi \times \sigma \sim \rho \times v/m \times \sigma$ (here $\rho = 0.3 \text{ GeV/cm}^3$)

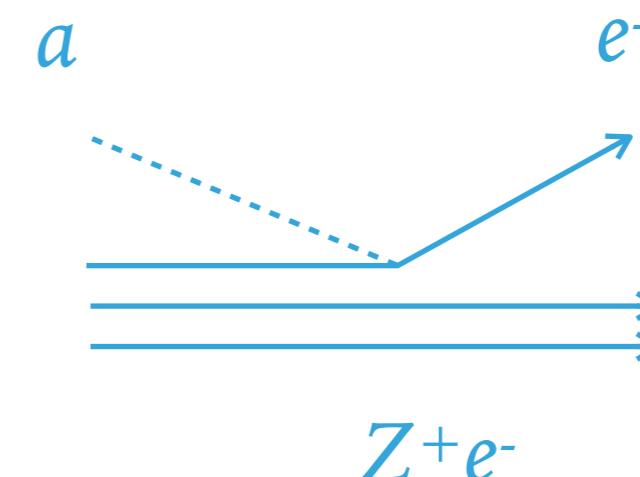
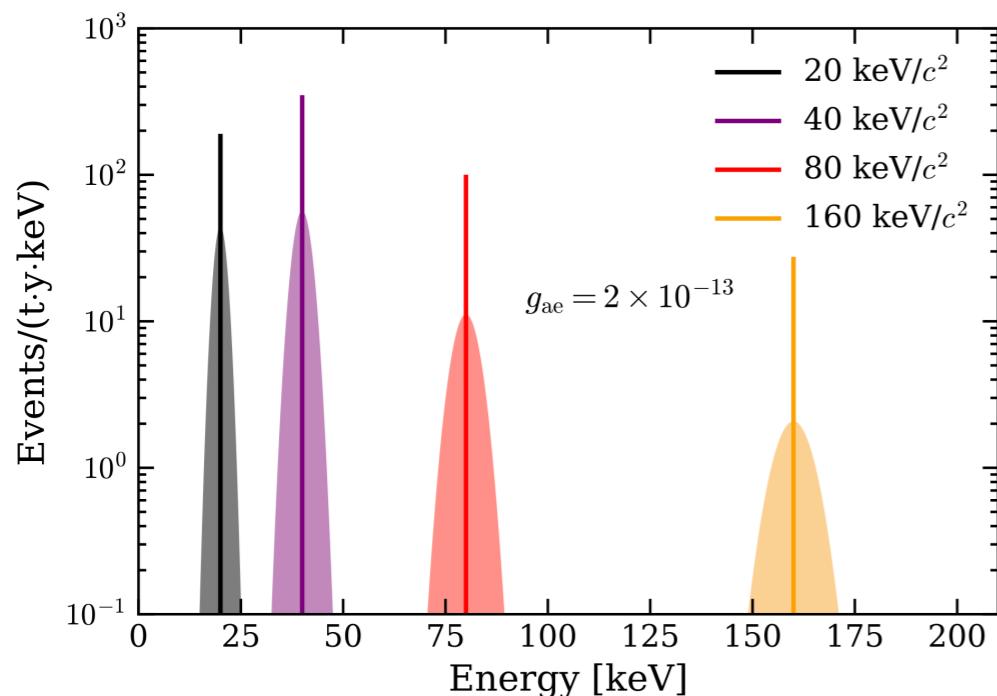
$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\text{keV}} \right) \left(\frac{\sigma_{pe}}{b} \right) \text{kg}^{-1}\text{d}^{-1}$$

$$R \simeq \frac{4.7 \times 10^{23}}{A} \kappa^2 \left(\frac{\text{keV}}{m_V} \right) \left(\frac{\sigma_{pe}}{b} \right) \text{kg}^{-1}\text{d}^{-1}$$

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3} \right)$$

$$\sigma_v \simeq \frac{\sigma_{pe}}{\beta} \kappa^2$$

strength of kinetic mixing
between photon and dark photon

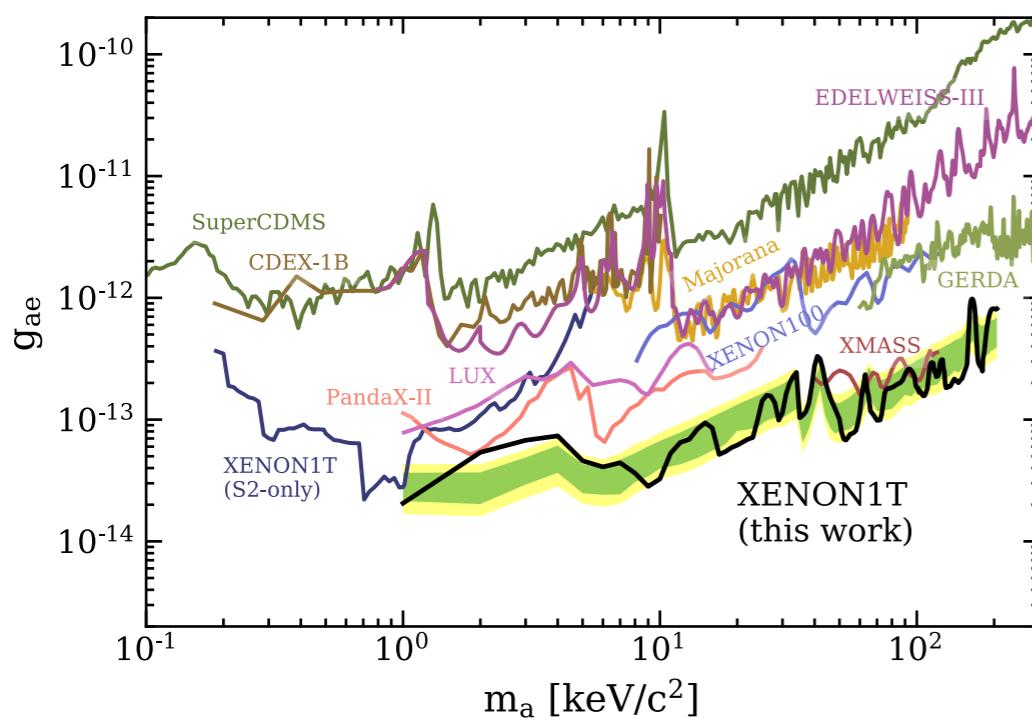


Pospelov, Ritz, Voloshin, PRD 78,
2008; An, Pospelov, Pradler, Ritz,
PLB747, 2015

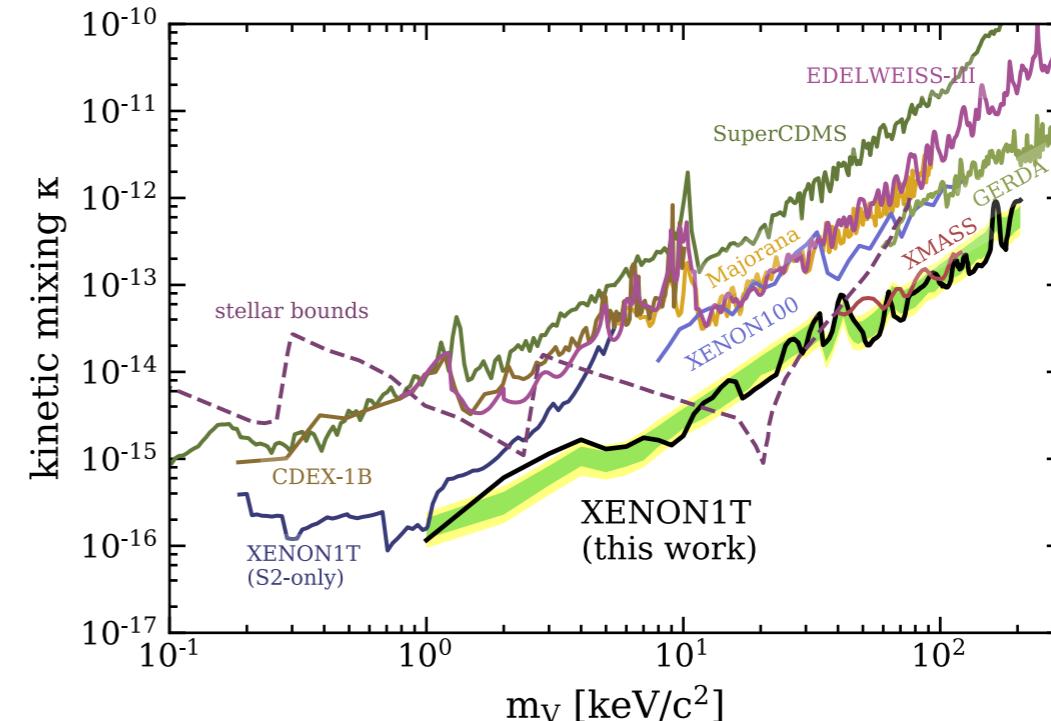
ALPS AND DARK PHOTONS

- ▶ Constraints on couplings for bosonic pseudoscalar DM with (fixed) masses [1, 210] keV
- ▶ No global significance above 3- σ under the background model
- ▶ ALPs and dark photons: 90% CL upper limits and sensitivities

Upper limits on g_{ae} versus ALP mass

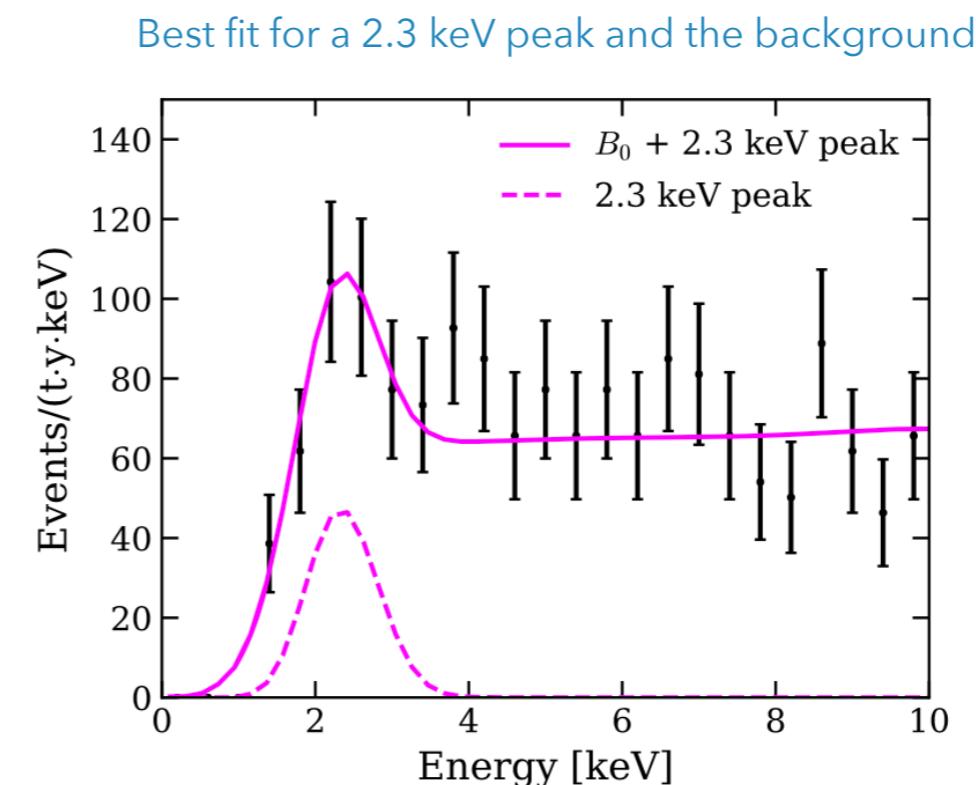
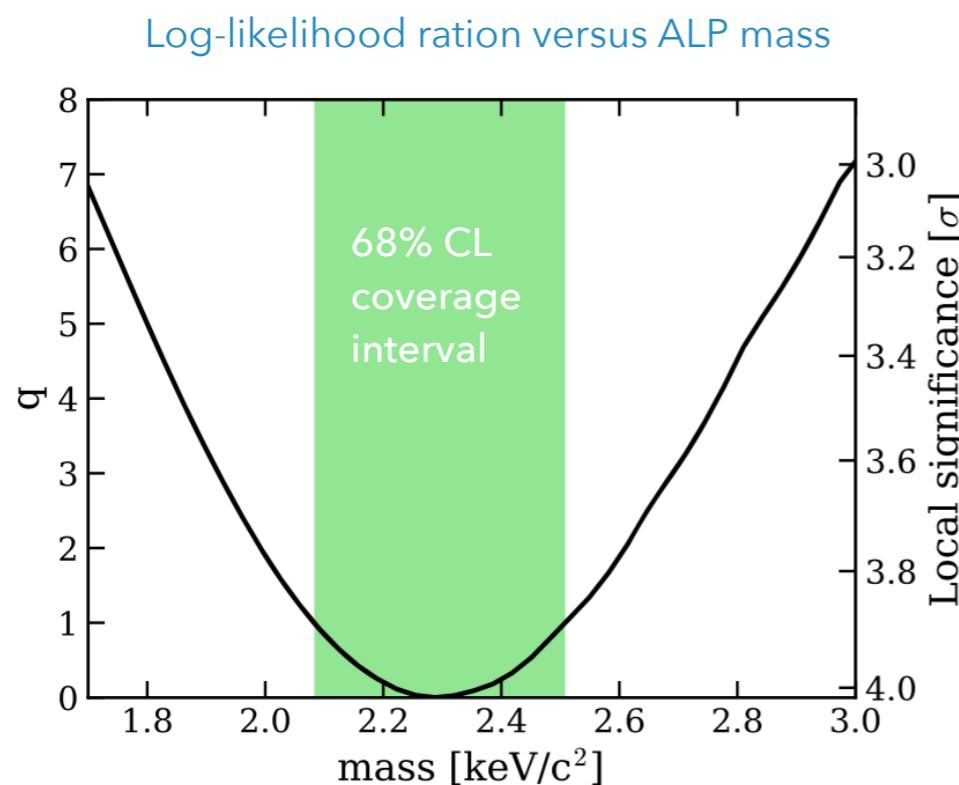


Upper limits on κ versus dark photon mass



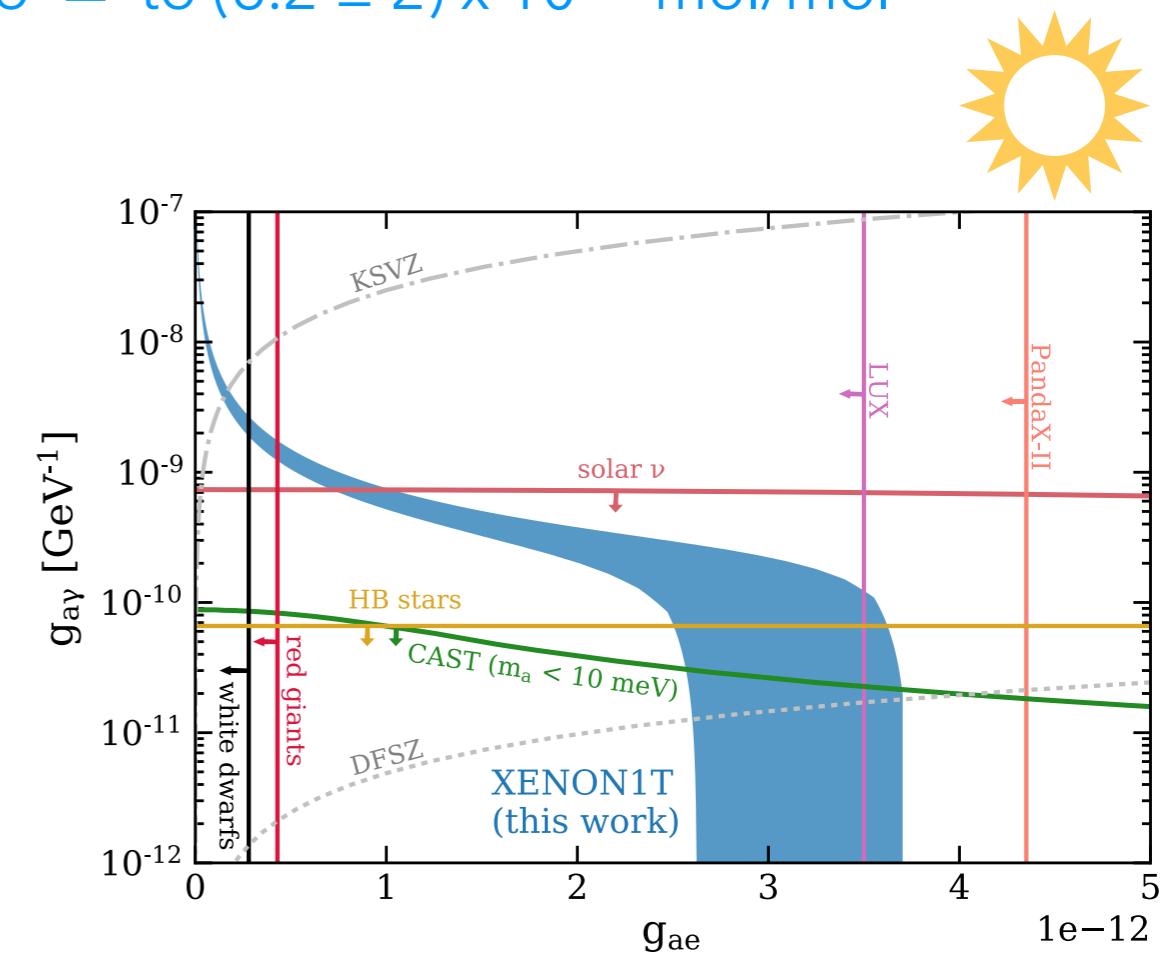
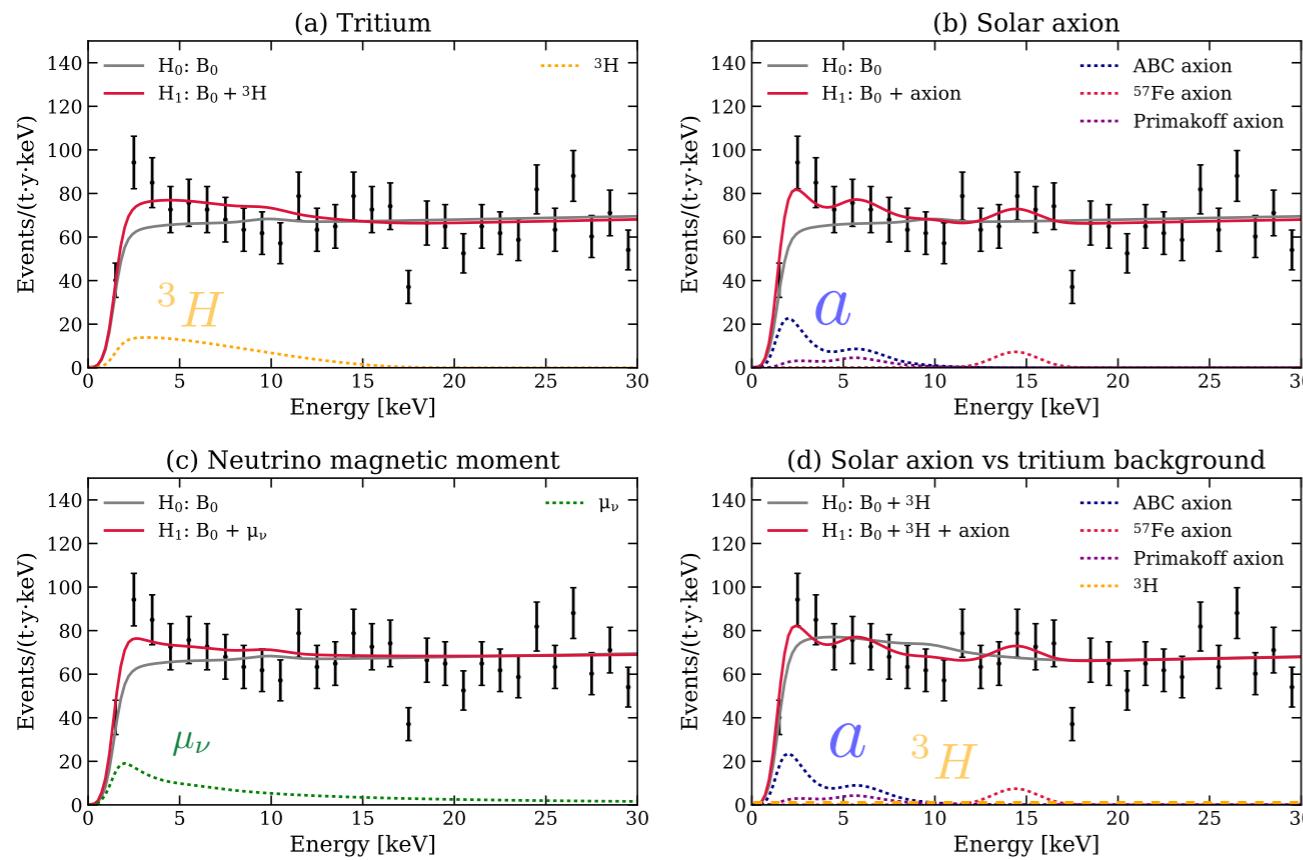
ALPS AND DARK PHOTONS

- ▶ Constraints on couplings for bosonic pseudoscalar DM with (fixed) masses [1, 210] keV
- ▶ No global significance above 3- σ under the background model
- ▶ A 3- σ global (4- σ local) significance for a peak at (2.3 ± 0.3) keV (68% CL)



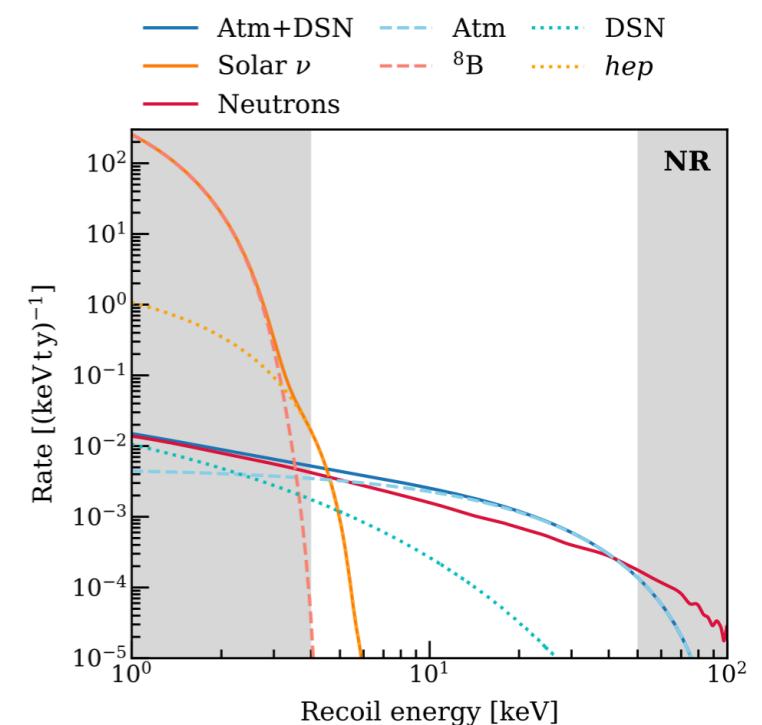
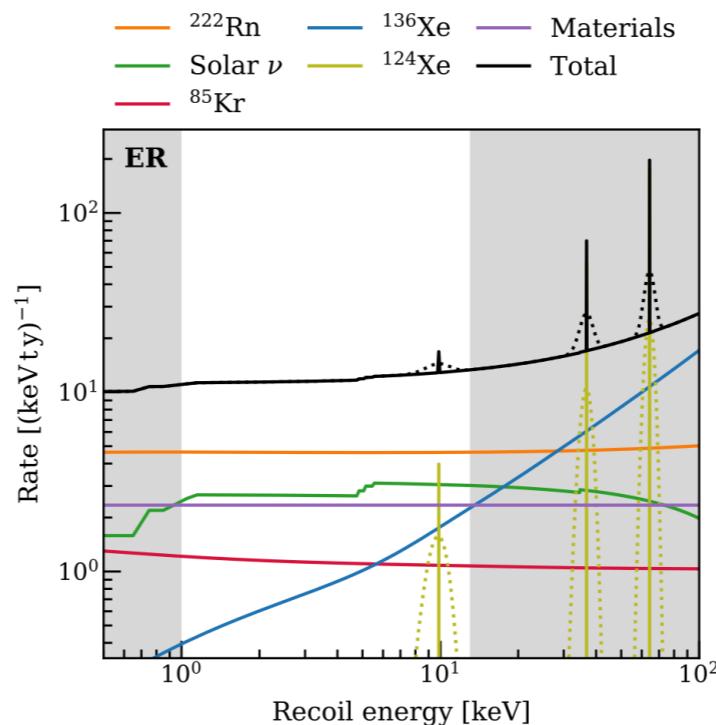
SEARCHES FOR SOLAR AXIONS, ALPS, DARK PHOTONS...

- ▶ Considered “signals”: ${}^3\text{H}$ β -decay, solar axions, neutrino magnetic moment
- ▶ Solar axion and neutrino magnetic moment favoured over background-only at 3.4σ and 3.2σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487)
- ▶ Tritium favoured over background-only at $3.2 \sigma \hat{=}$ to $(6.2 \pm 2) \times 10^{-25} \text{ mol/mol}$



XENON-NT: BACKGROUND PREDICTIONS

| Source | Rate $[(\text{t yr})^{-1}]$ |
|----------------------------|--------------------------------|
| ER background | |
| Detector radioactivity | 25 ± 3 |
| ^{222}Rn | 55 ± 6 |
| ^{85}Kr | 13 ± 1 |
| ^{136}Xe | 16 ± 2 |
| ^{124}Xe | 4 ± 1 |
| Solar neutrinos | 34 ± 1 |
| Total | 148 ± 7 |
| NR background | |
| Neutrons | $(4.1 \pm 2.1) \times 10^{-2}$ |
| CE ν NS (Solar ν) | $(6.3 \pm 0.3) \times 10^{-3}$ |
| CE ν NS (Atm+DSN) | $(5.4 \pm 1.1) \times 10^{-2}$ |
| Total | $(1.0 \pm 0.2) \times 10^{-1}$ |

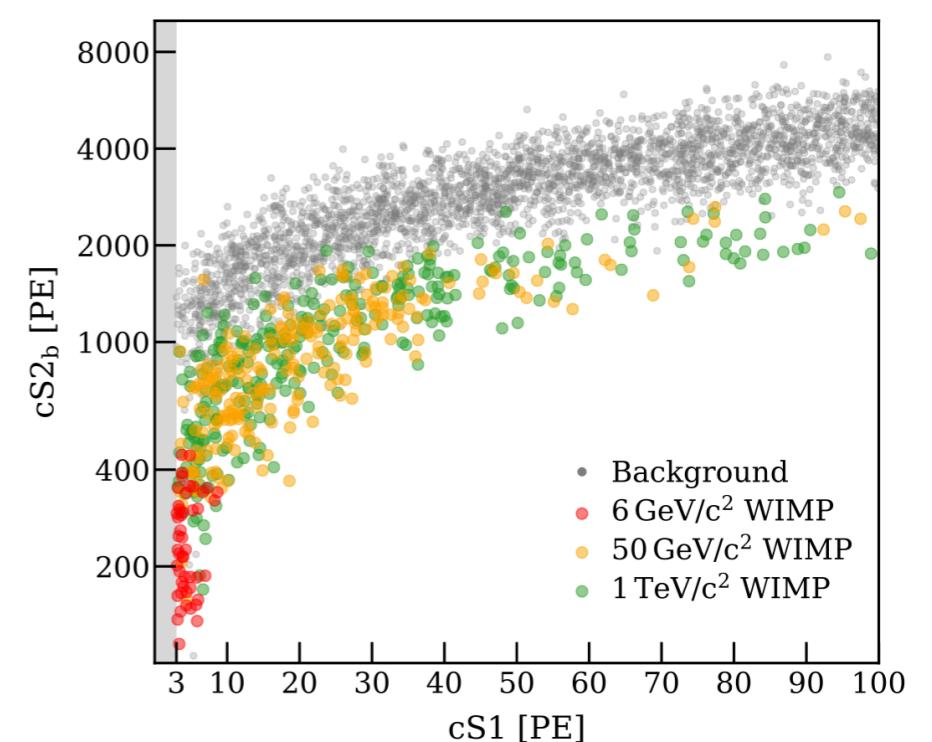
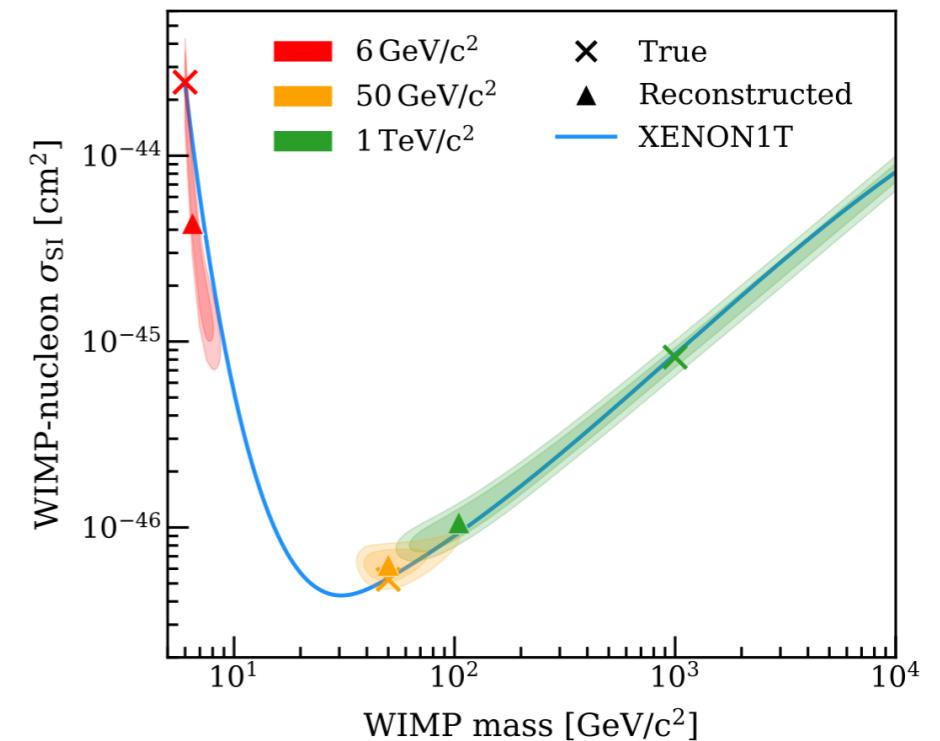


rates in a fiducial mass of 4 t of LXe, 1-13 keV ER, 4 - 50 keV NR energy range

XENON-NT: BACKGROUND PREDICTIONS

| Model component | Expectation value (μ) in 20 t y | | Rate uncertainty (ξ) |
|---|---------------------------------------|-------------------------|----------------------------|
| | Observable ROI | Reference signal region | |
| Background | | | |
| ER | 2440 | 1.56 | |
| Neutrons | 0.29 | 0.15 | 50% |
| CE ν NS (Solar ν) | 7.61 | 5.41 | 4% |
| CE ν NS (Atm+DSN) | 0.82 | 0.36 | 20% |
| WIMP signal | | | |
| 6 GeV/c 2 ($\sigma_{\text{DM}} = 3 \times 10^{-44} \text{ cm}^2$) | 25 | 19 | |
| 50 GeV/c 2 ($\sigma_{\text{DM}} = 5 \times 10^{-47} \text{ cm}^2$) | 186 | 88 | |
| 1 TeV/c 2 ($\sigma_{\text{DM}} = 8 \times 10^{-46} \text{ cm}^2$) | 286 | 118 | |

Number of events in the ROI and in a reference WIMP signal region for an exposure of 20 t years



XENON-NT: SCIENCE REACH

