ALL THE DARK WE CANNOT SEE

THE STATE-OF-THE-ART IN DIRECT SEARCHES FOR PARTICLE DARK MATTER

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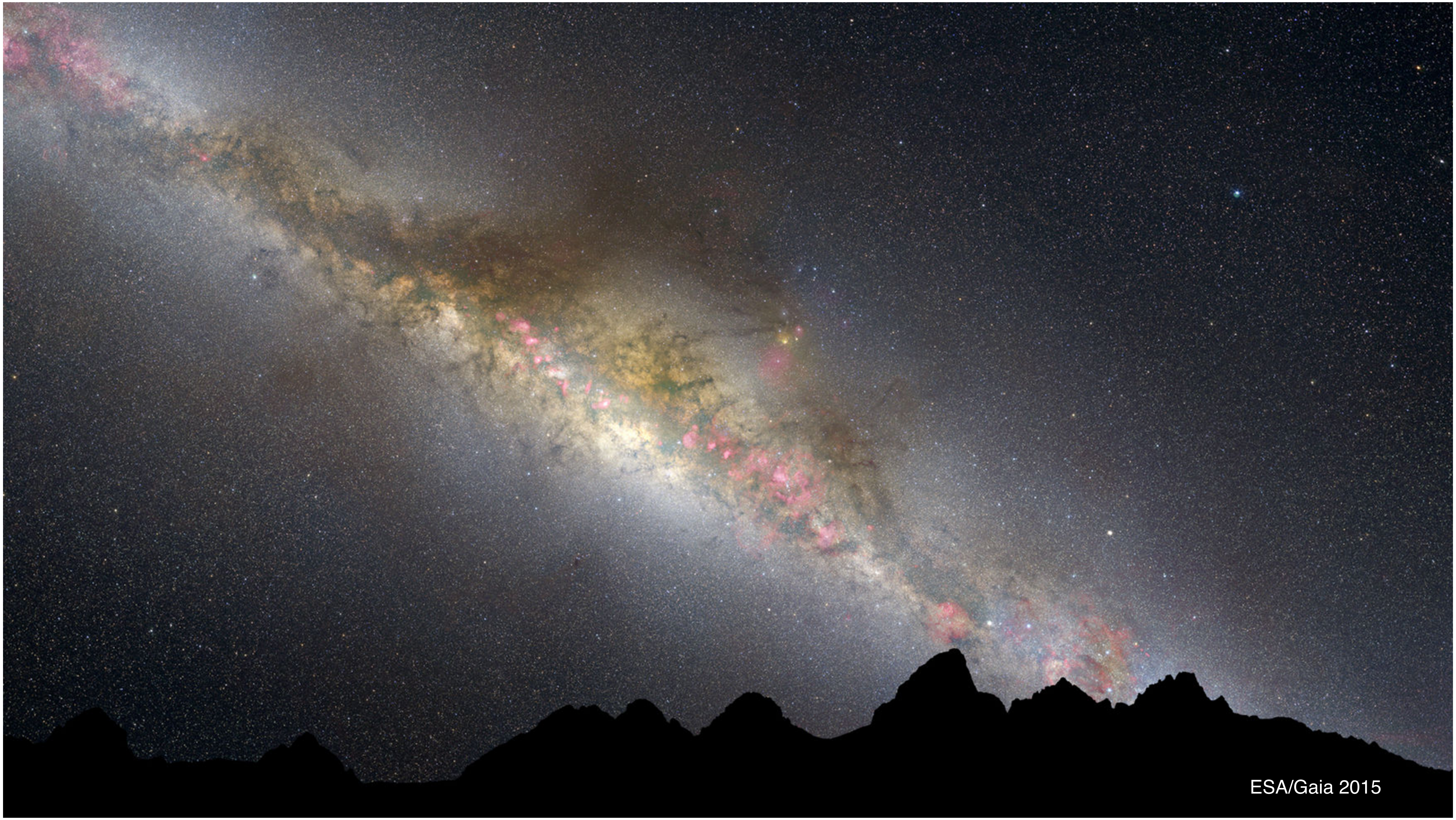
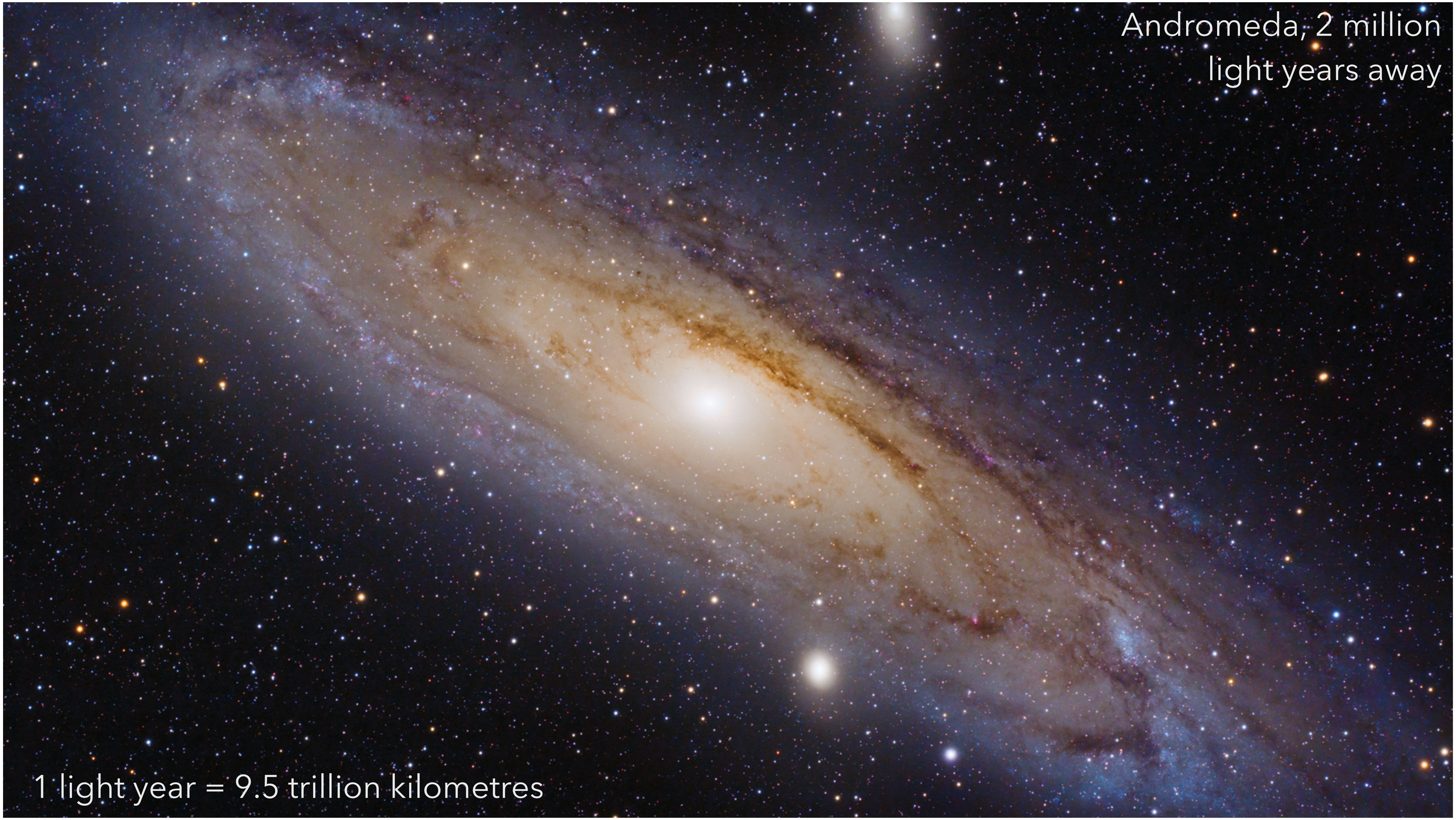
JUNE 23, 2021

WHEN YOU LOOK AT THE SKY IN A DARK, CLEAR NIGHT...



...YOU ARE MARVELLING AT A MINORITY OF MATTER IN THE UNIVERSE

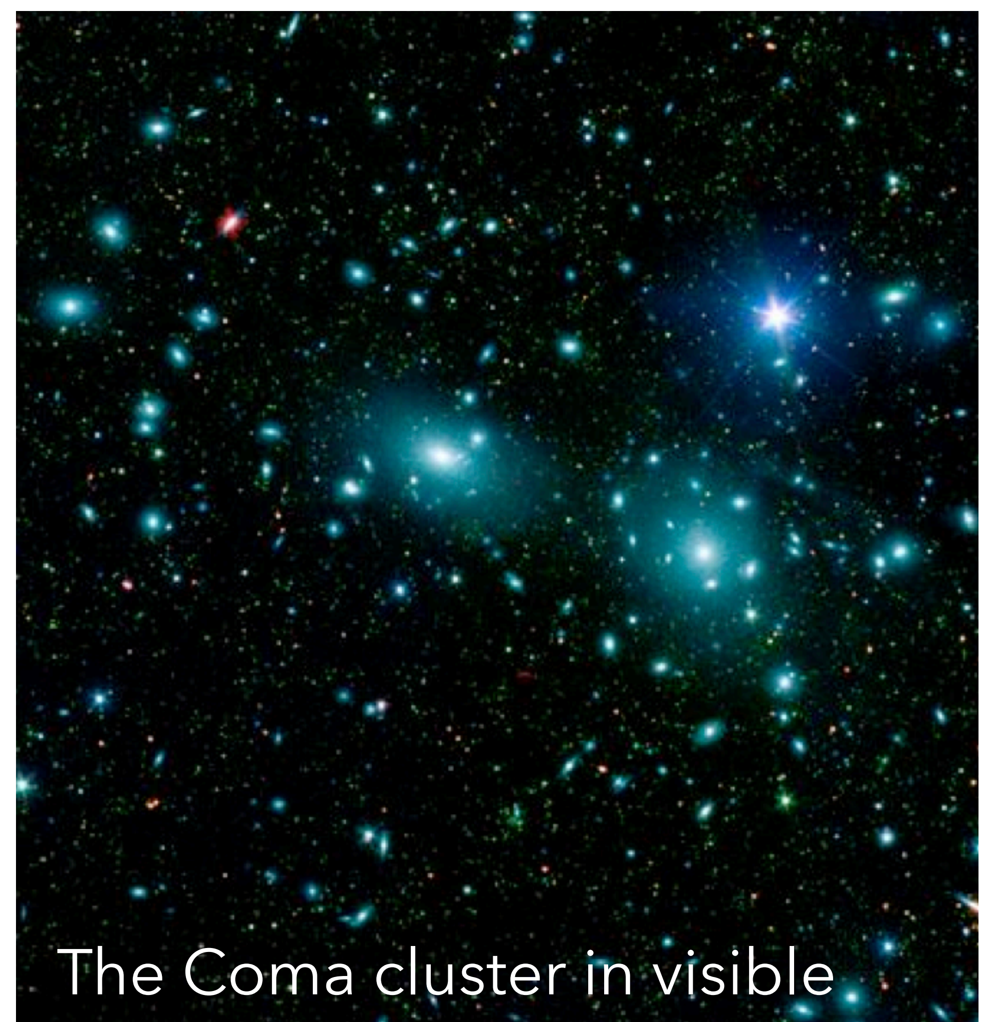


DARK MATTER IN GALAXY CLUSTERS

- Zwicky: first astronomer to make a compelling case for the existence of invisible, or dark matter
- Very large dispersion in the radial velocities of galaxies in the Coma cluster~ 1000 km/s
  - Not enough gravitational attraction from stars and gas within galaxies to keep the cluster together ⇒ "dunkle Materie"

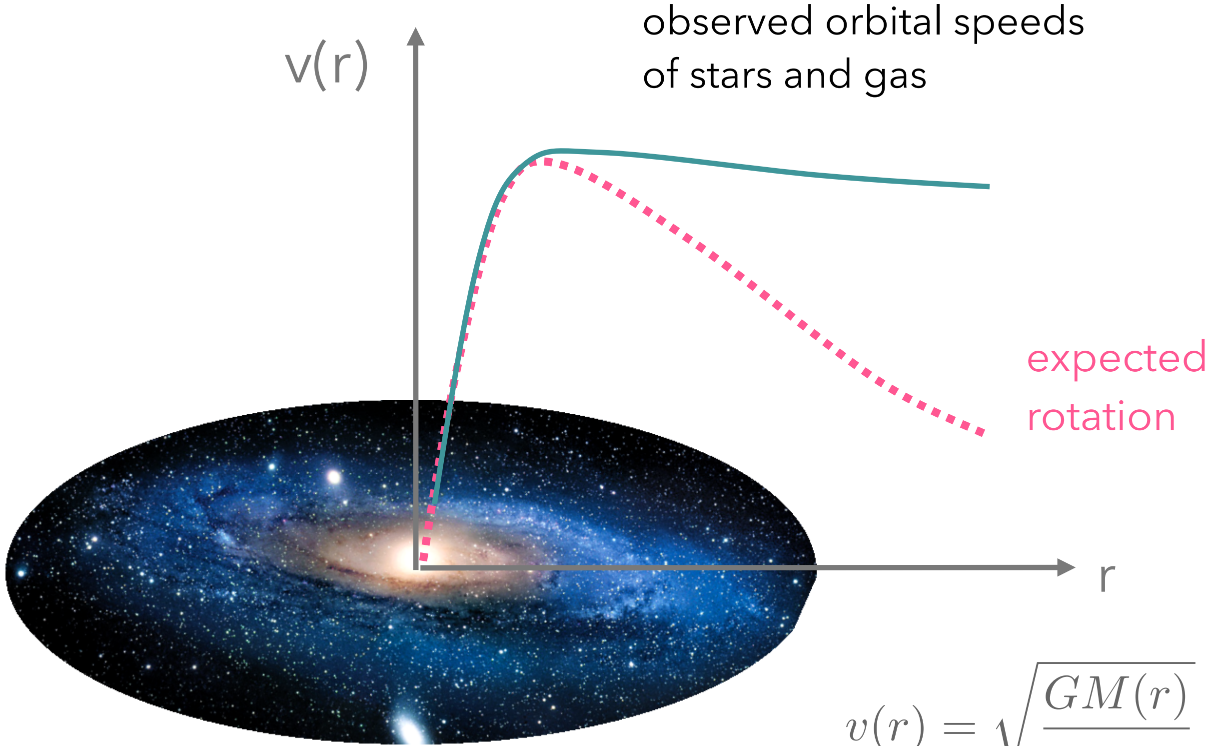
Fritz Zwicky, Helv. Phys. Acta, 1933, 110-127


Fritz Zwicky, 1933


The Coma cluster in visible

DARK MATTER IN SPIRAL GALAXIES

- No sign of a Keplerian decrease in the orbital speeds of stars and gas at large galactic radii!



$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

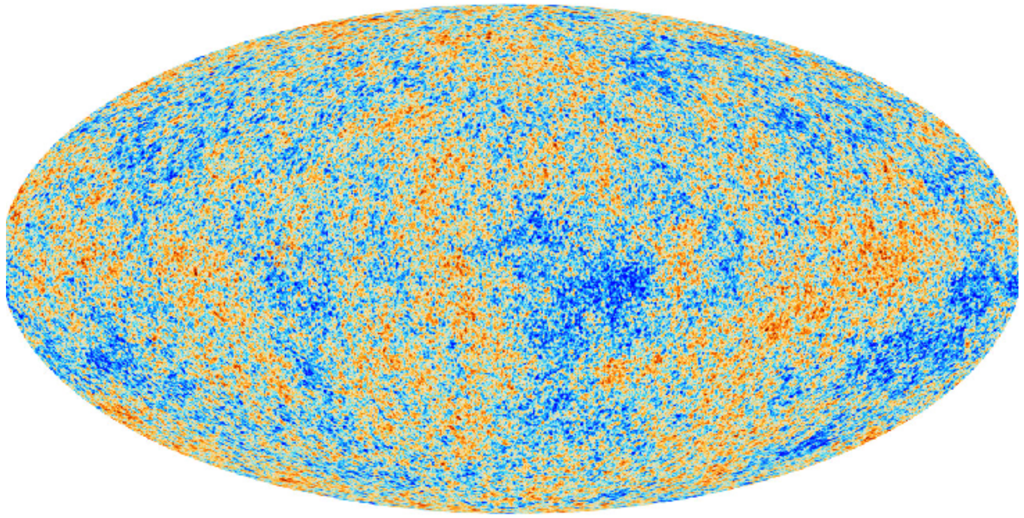
Vera Rubin, Kent Ford, Norbert Thonnard,
The Astrophysical Journal 1978

Vera Rubin:

"In a spiral galaxy, *the ratio of dark-to-light matter is about a factor of 10*. That's probably a good number for the ratio of our ignorance-to-knowledge. *We're out of kindergarten, but only in about third grade.*"

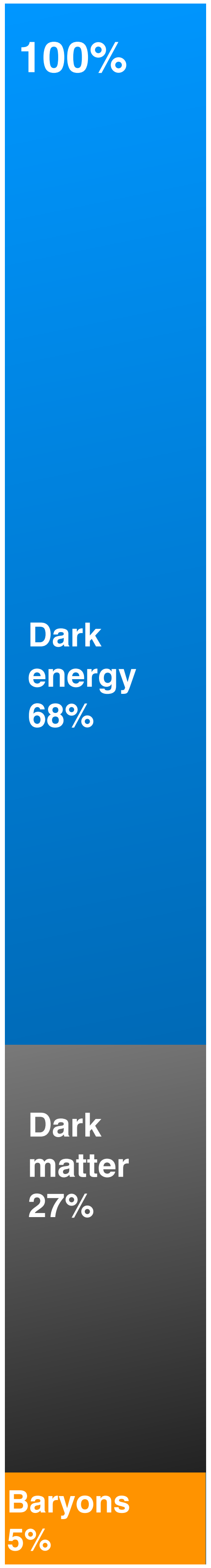
MOST OF OUR UNIVERSE IS INVISIBLE

- 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
  - ...



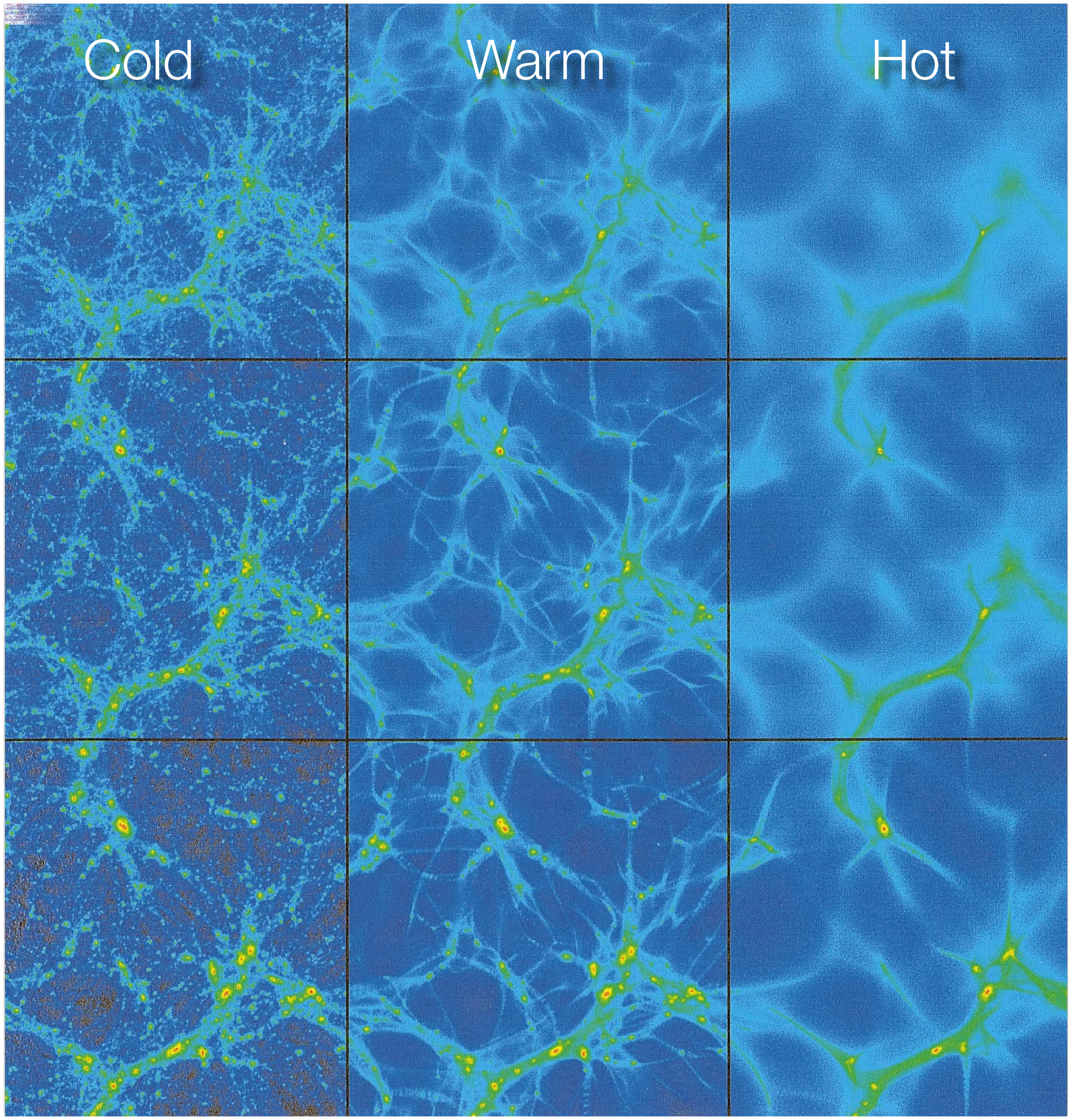
Planck (esa.int): "An almost perfect Universe"

- And ΛCDM describes all observations well
- *The fundamental nature of dark matter is still a mystery!*
  - What is it, how does it interact?



WHAT DO WE KNOW ABOUT DARK MATTER?

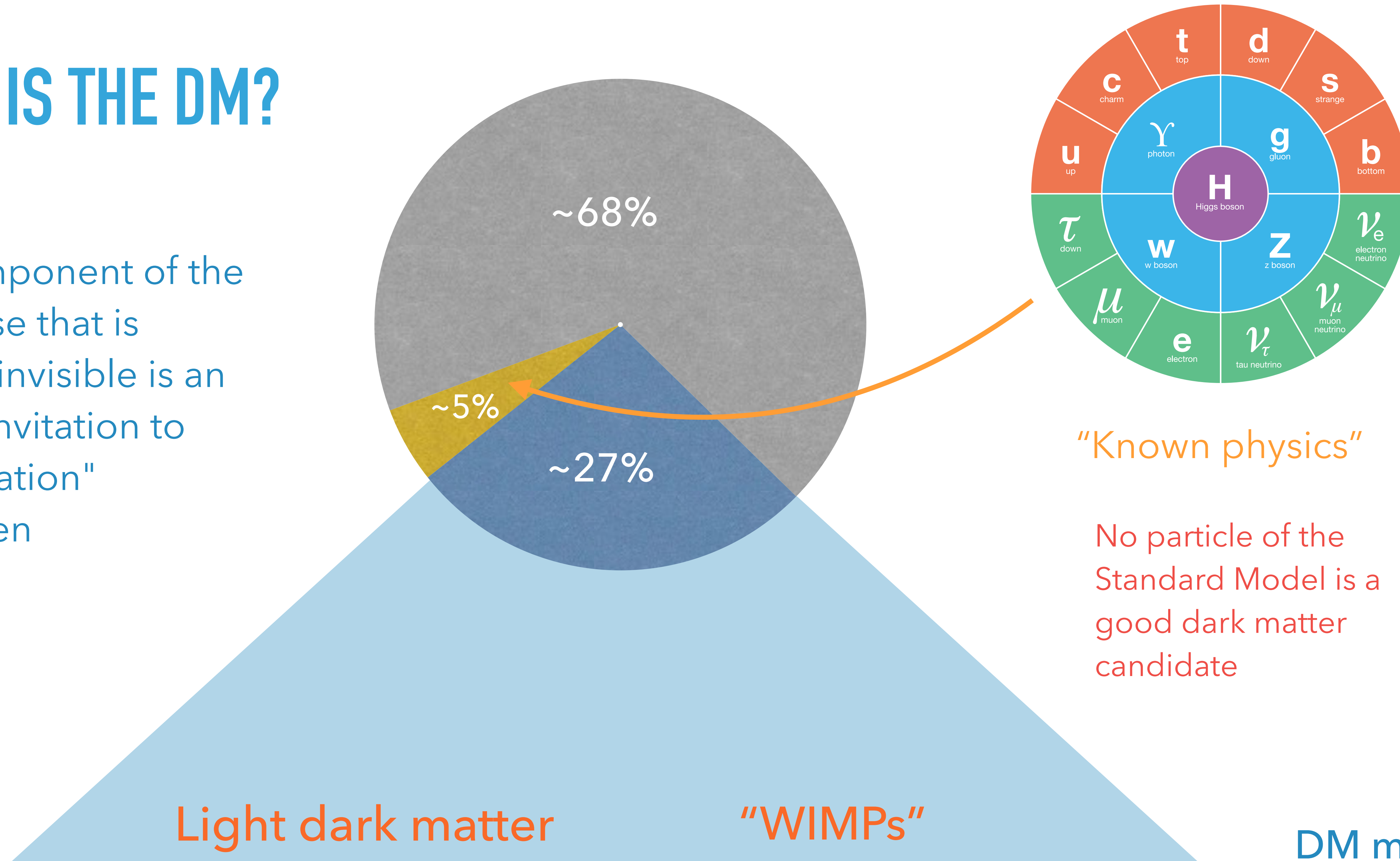
- Exists today and in the early Universe
- Constraints from astrophysics and from searches for new particles
  - No colour charge
  - No electric charge
  - No strong self-interaction
  - Slow-moving (NR) as LSS formed
- Stable, or very long lived



Probing dark matter through gravity

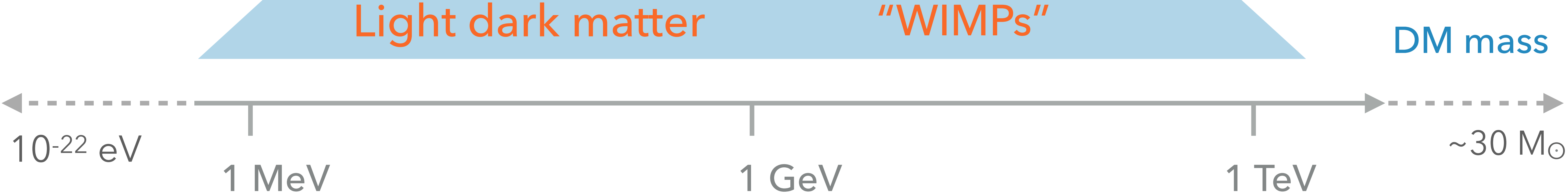
WHAT IS THE DM?

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



"Known physics"

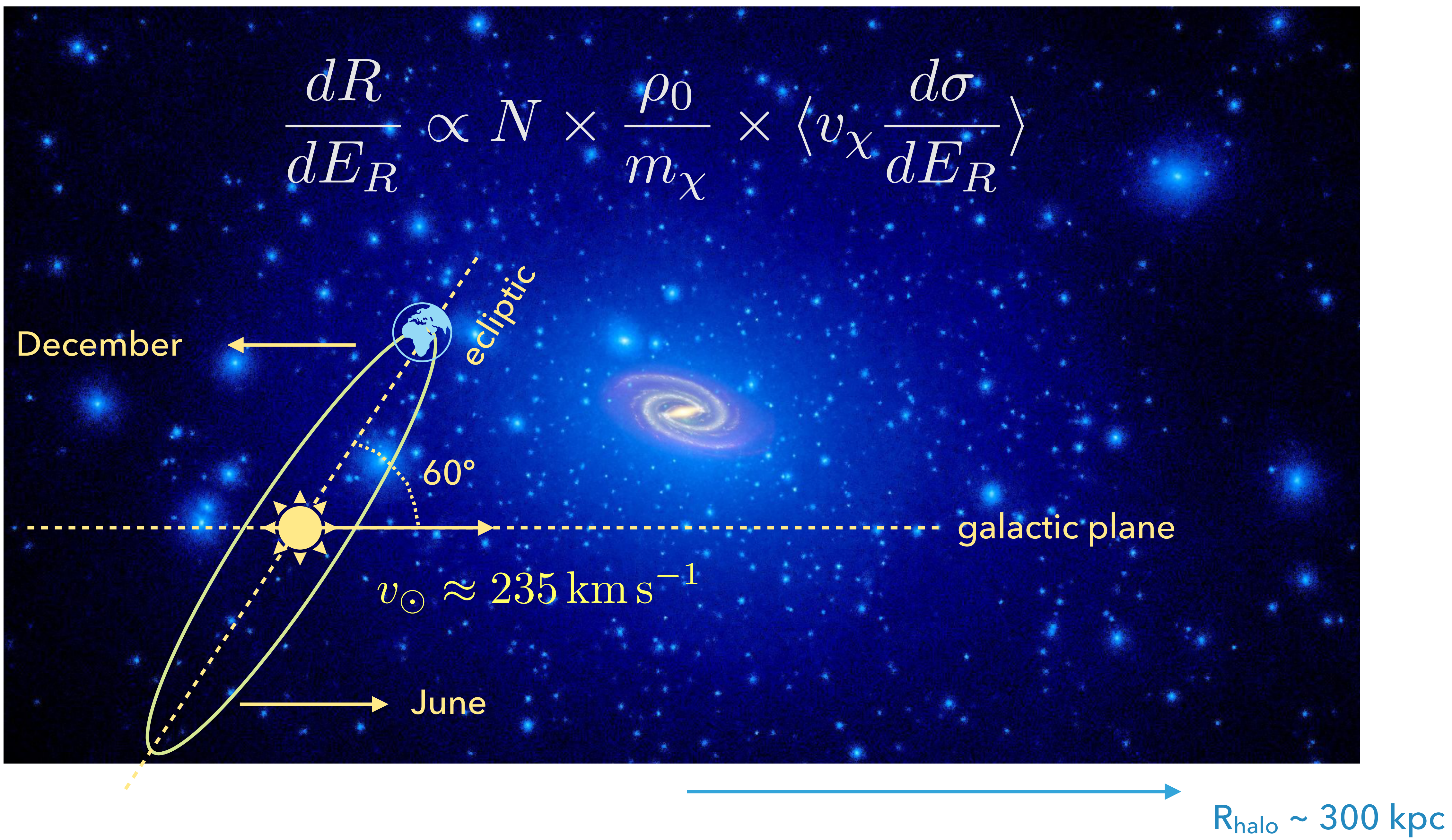
No particle of the Standard Model is a good dark matter candidate



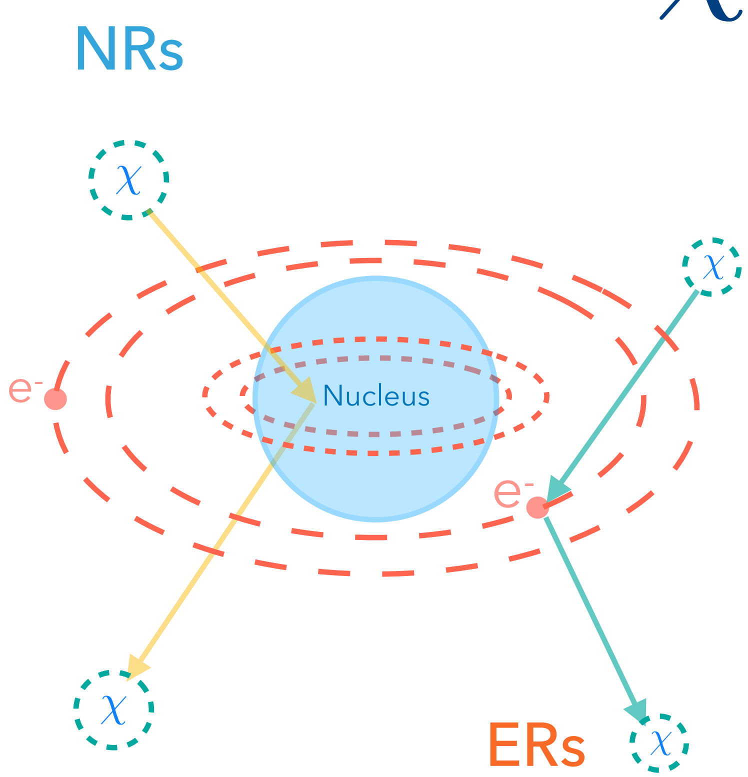
~ 80 orders of magnitude in mass: *a much higher number* for the ratio of our ignorance-to-knowledge!

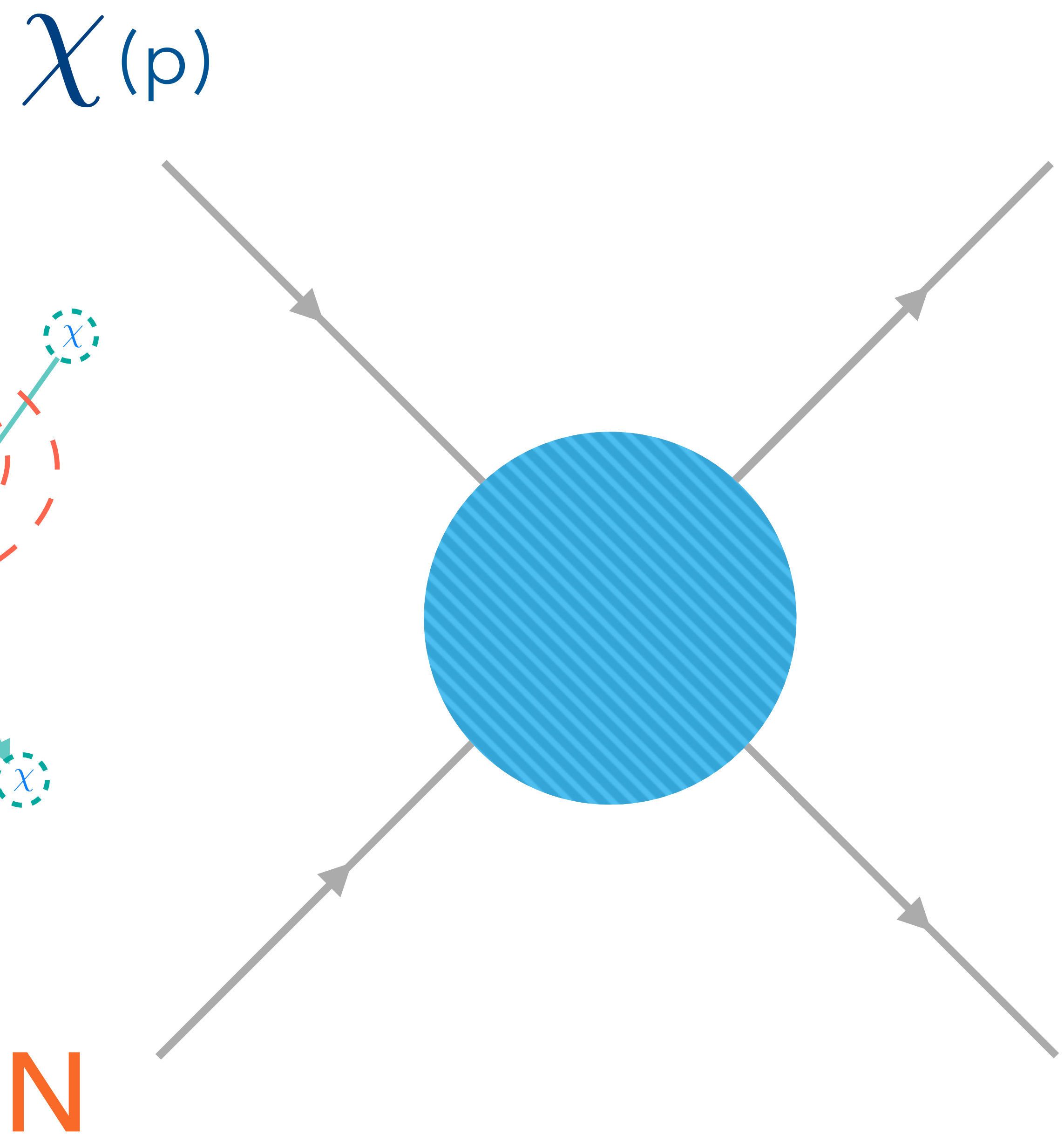
DARK MATTER IN THE MILKY WAY

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



DIRECT DARK MATTER DETECTION



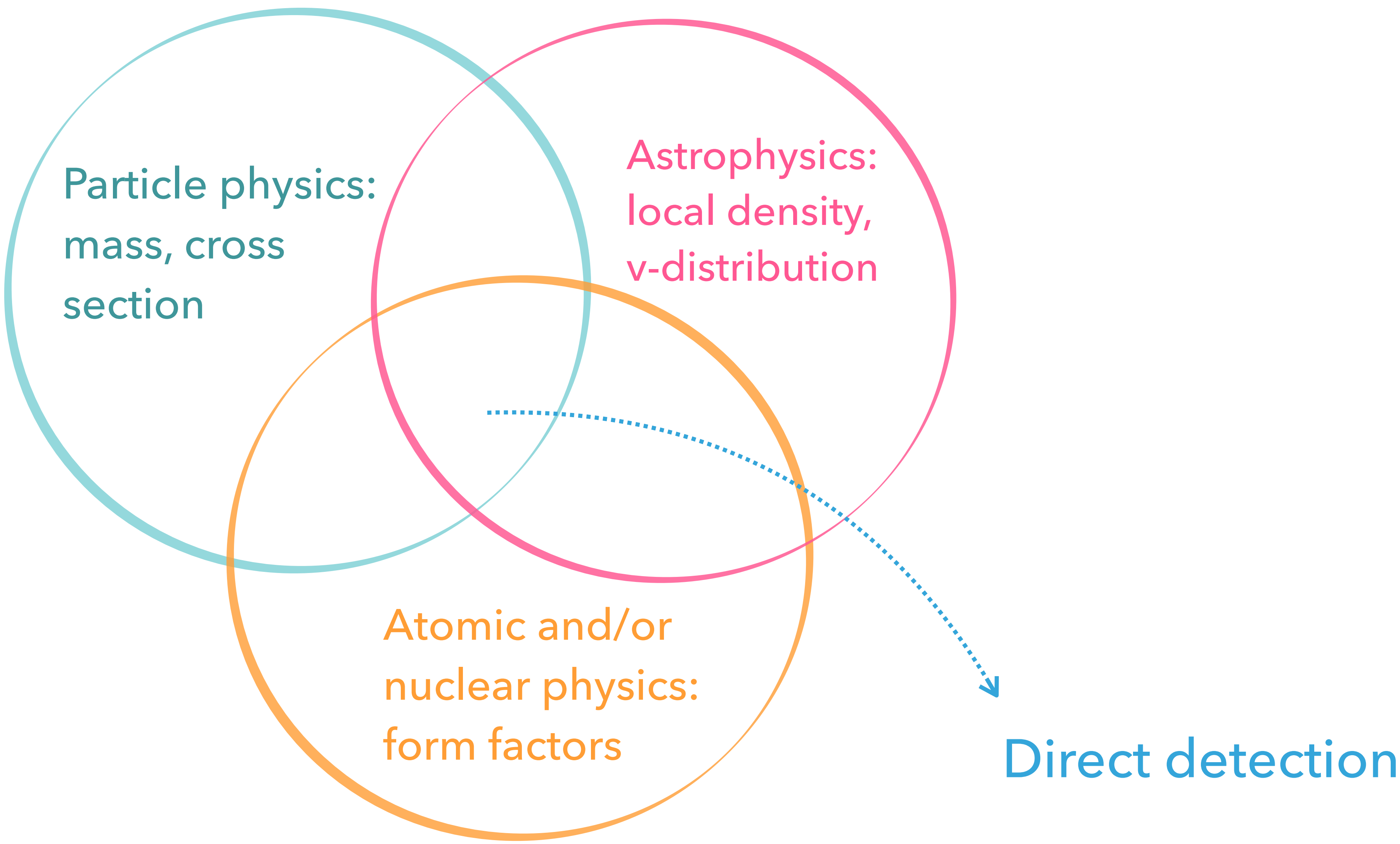


Observe DM collisions with nuclei (NRs) or with electrons in the atomic shell (ERs)

Look for absorption of light bosons via e.g., the axio-electric effect

DIRECT DARK MATTER DETECTION

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

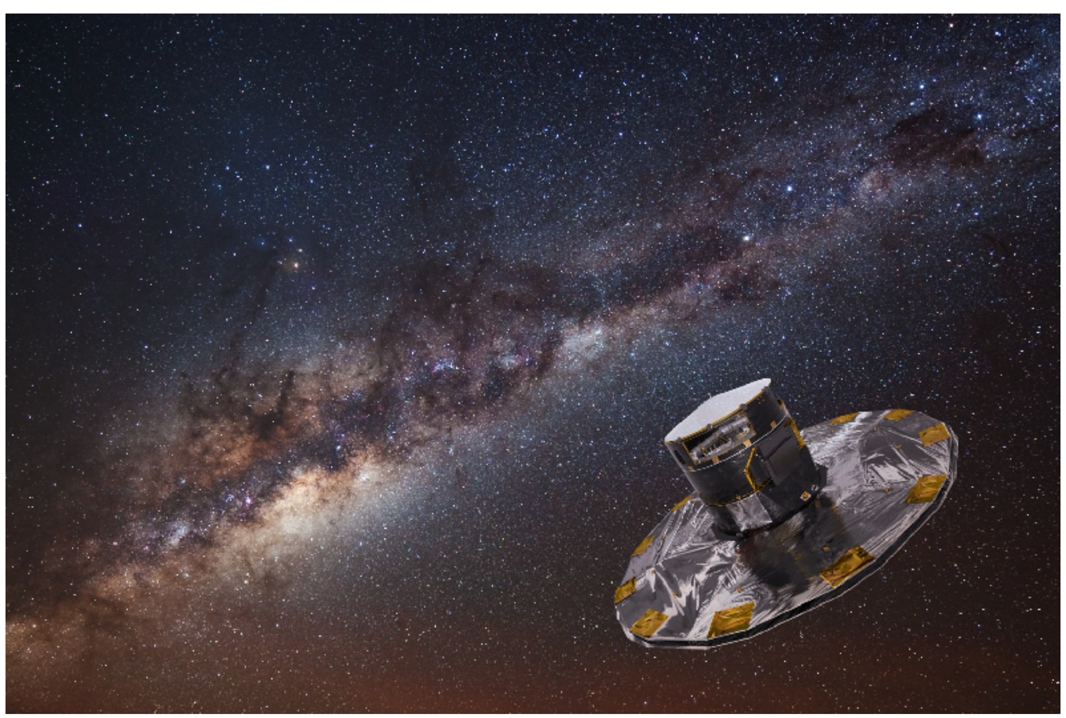


ASTROPHYSICS: LOCAL DARK MATTER DENSITY

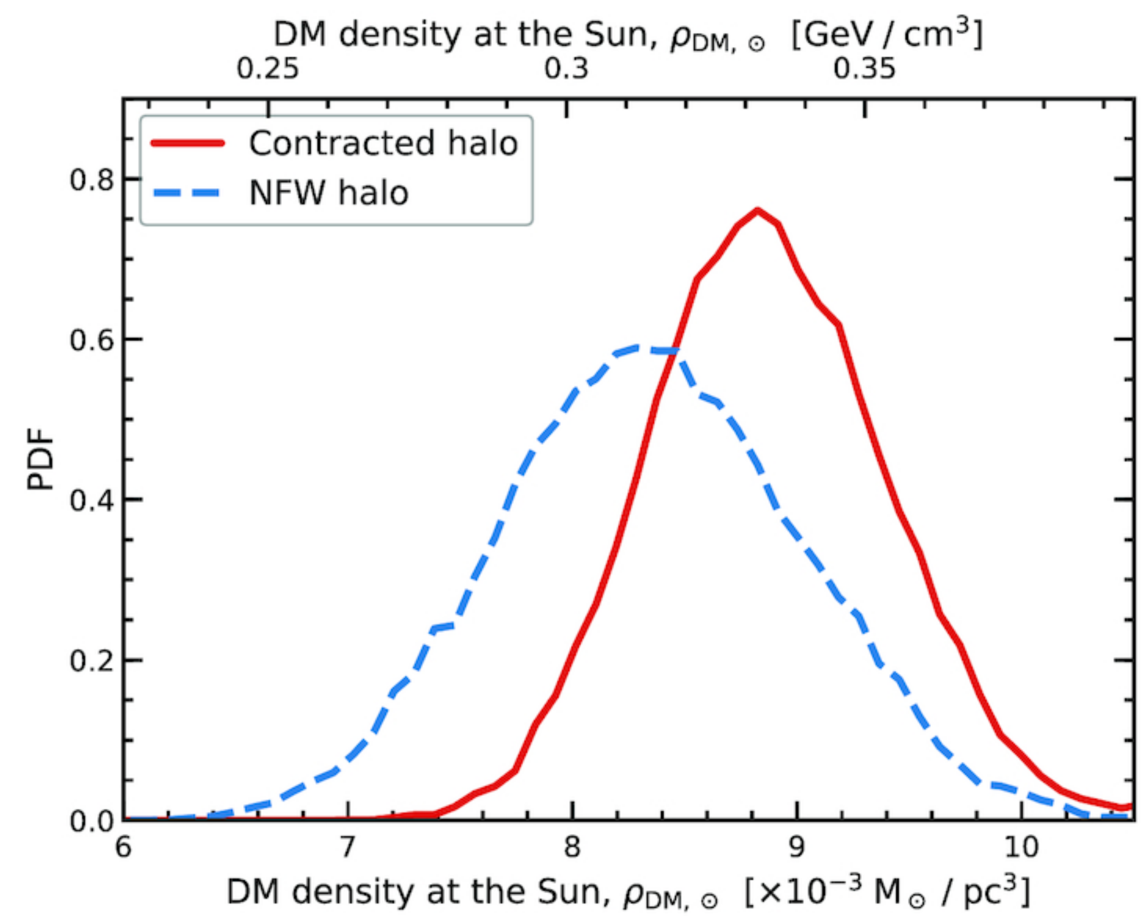
- Local measures: vertical kinematics of stars near Sun as 'tracers' (smaller error bars, stronger assumptions about the halo shape)
- Global measures: extrapolate the density from Milky Way's rotation curve derived from kinematic measurements of gas, stars… (larger errors, fewer assumptions)

See review by Justin Read, Journal of Phys. G 41 (2014)

Major source of uncertainty: contribution of baryons (stars, gas, stellar remnants, …) to the local dynamical mass



Gaia DR3 2020: positions, parallaxes, and proper motions for 2.5 x 10^9 stars



M. Cautun et al, MNRAS 494 (2020) 3, using Gaia DR2

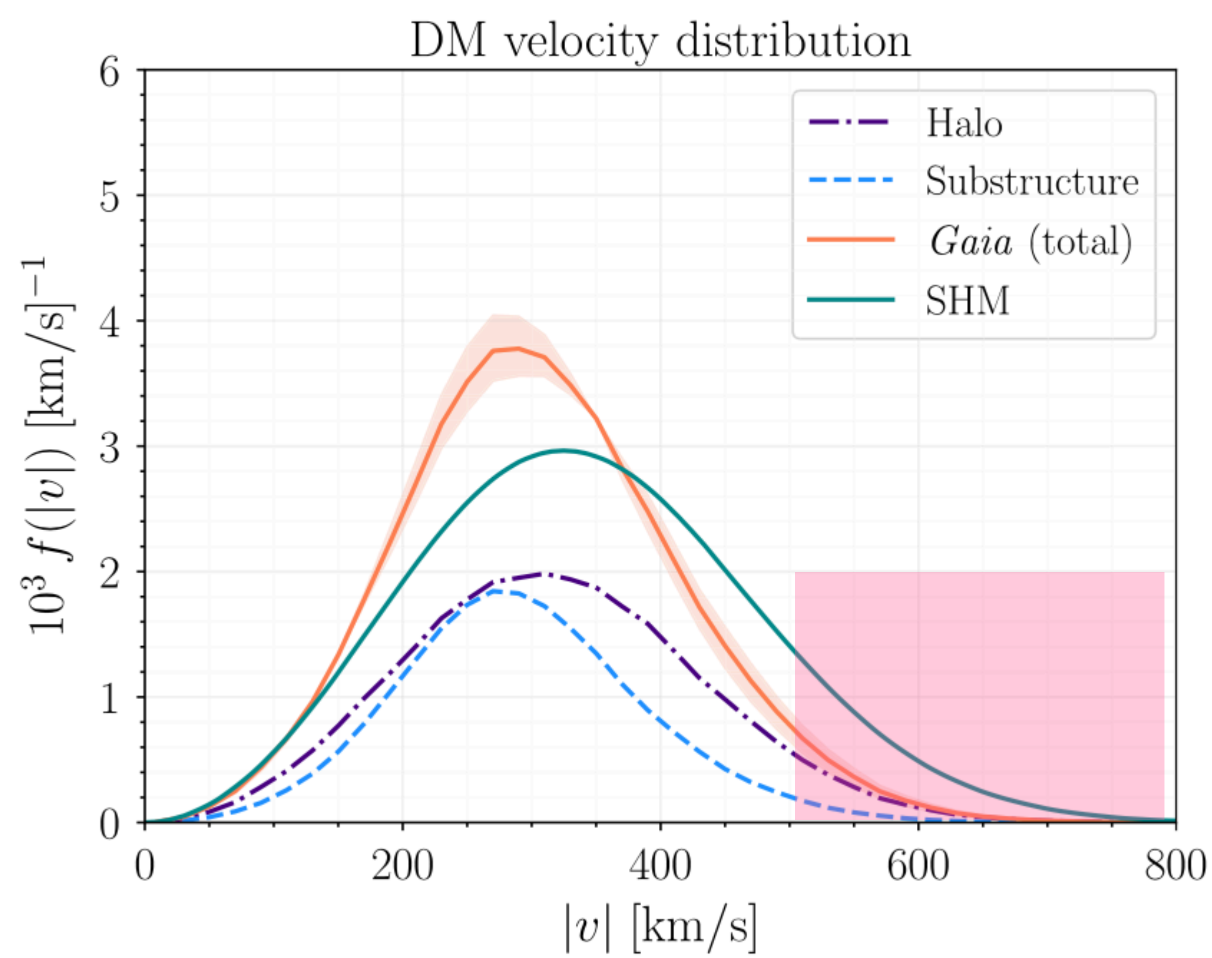
ASTROPHYSICS: DARK MATTER VELOCITY DISTRIBUTION

- Standard halo model: Maxwellian distribution (isotropic velocities)

$$\rho(r) \propto r^{-2}$$

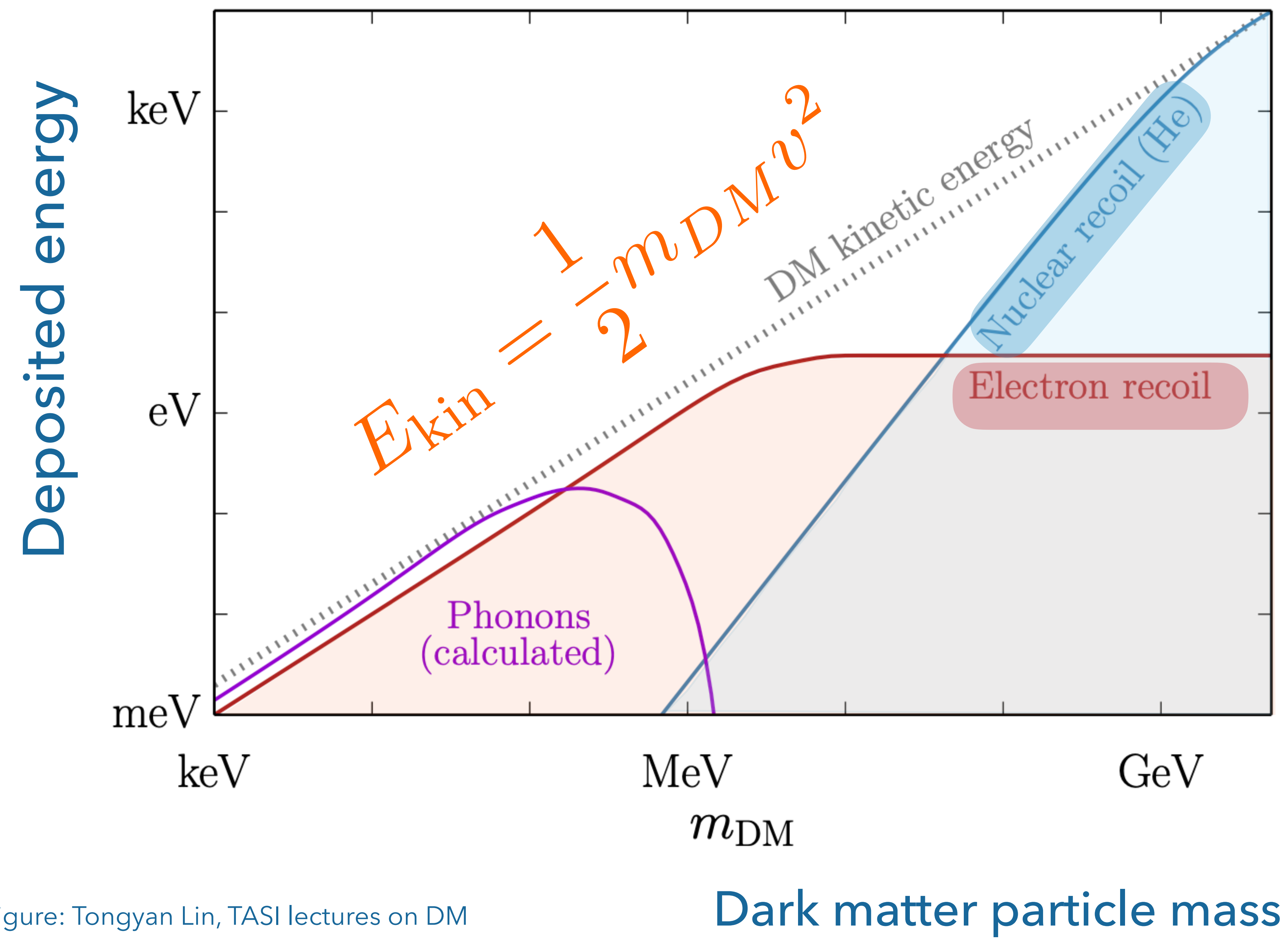
- Goal: determine f(v) from observation (e.g., motion of stars that share kinematics with DM)
- Recent studies: some deviations from SHM, due to anisotropies in the local stellar distribution (in Gaia data)
- These arise from accretion events, where the "Gaia-sausage" seems to be the dominant merger in the solar neighbourhood
- Effects for direct detection: relevant mostly at low dark matter masses

Necib, Lissanti, Belorukov 2018, Evans, O'Hare, McCabe, PRD99, 2019; Buch, Fan, Leung, PRD101, 2020; and others



Normalised Gaia DM velocity distribution in heliocentric frame

KINEMATICS: DARK MATTER PARTICLE MASS



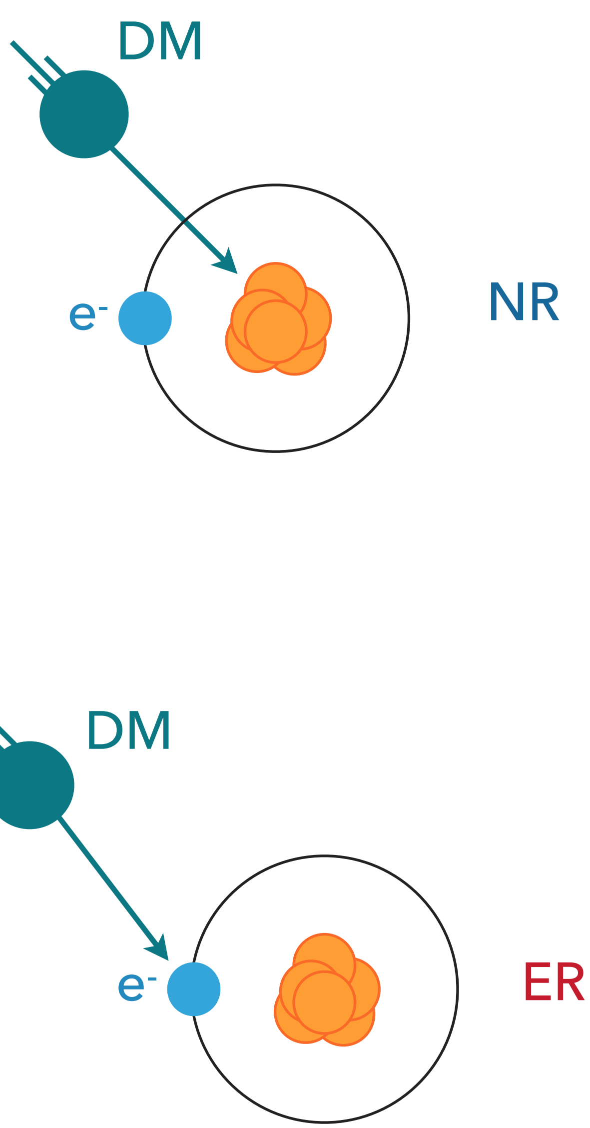
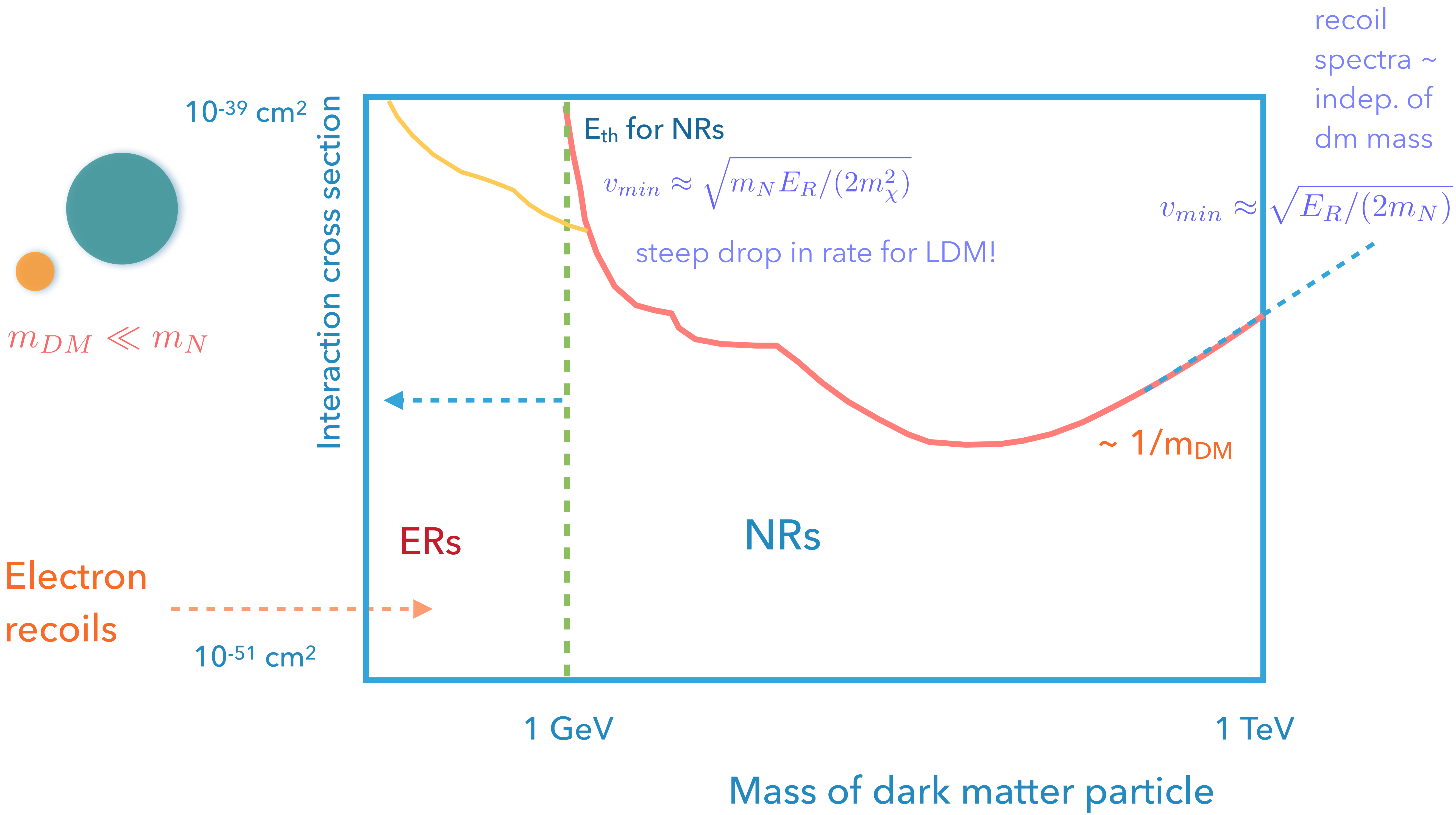


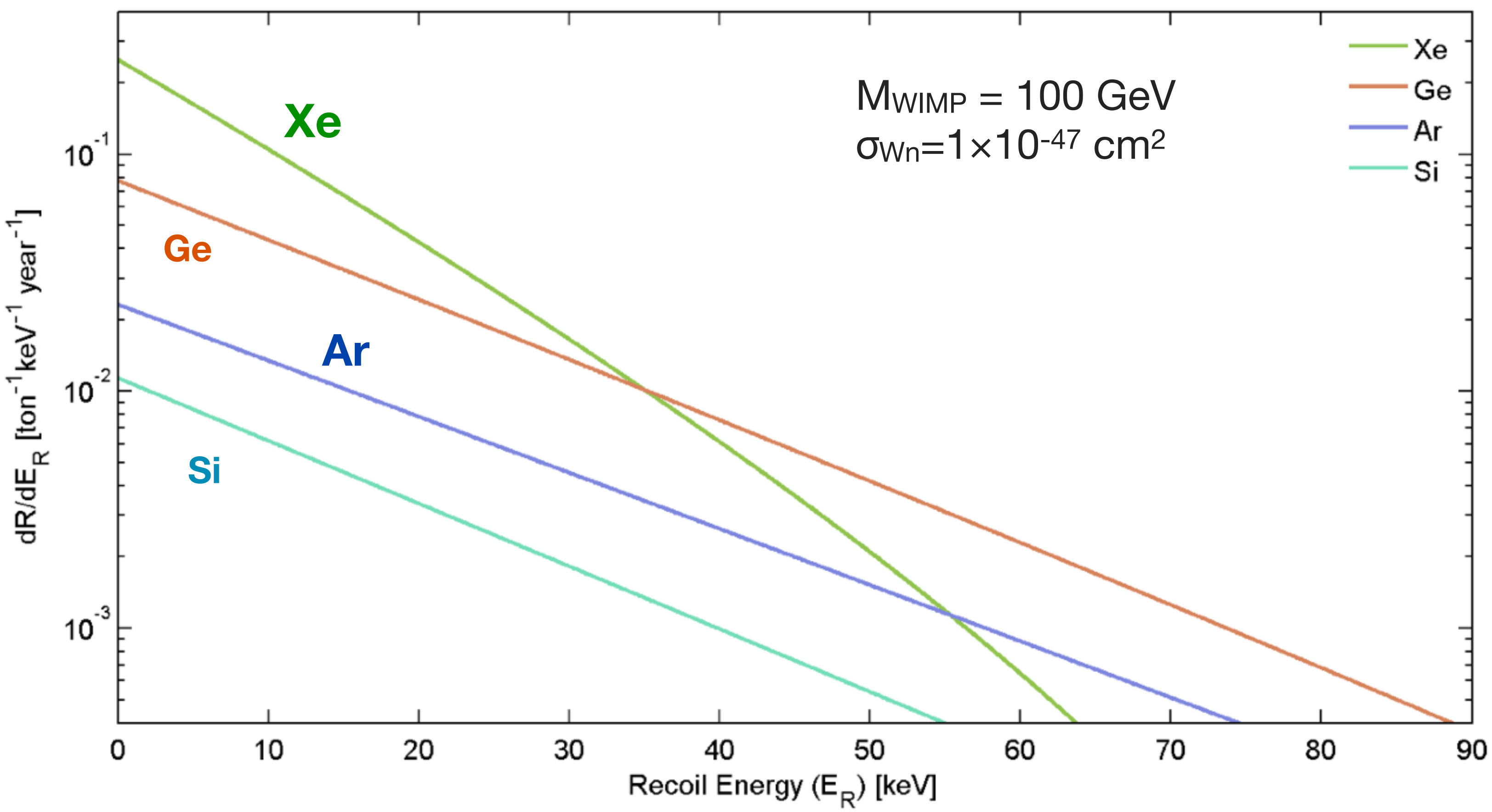
Figure: Tongyan Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

INTERACTION CROSS SECTION VS MASS



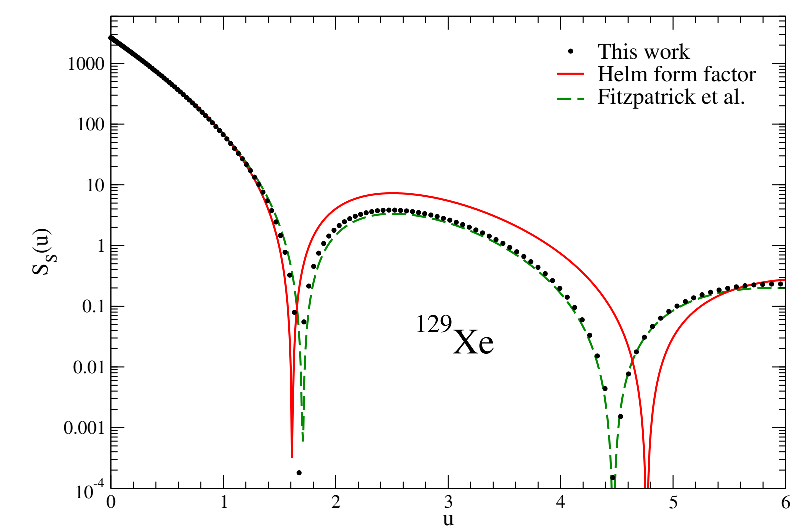
INTERACTION RATES: DM-NUCLEUS SCATTERING

$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}}\left[\frac{A}{100}\times\frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2}\times\frac{\langle v\rangle}{220\,\text{km}\,\text{s}^{-1}}\times\frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}}\right]$$

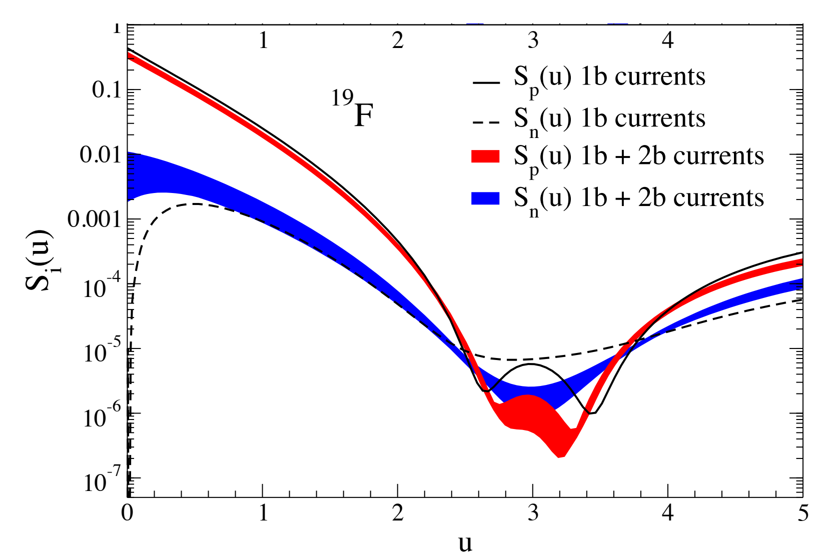


Spin-independent (SI) nuclear recoil spectrum

L. Vietze, W. Haxton et al., Phys.Rev. D91 (2015)



SI



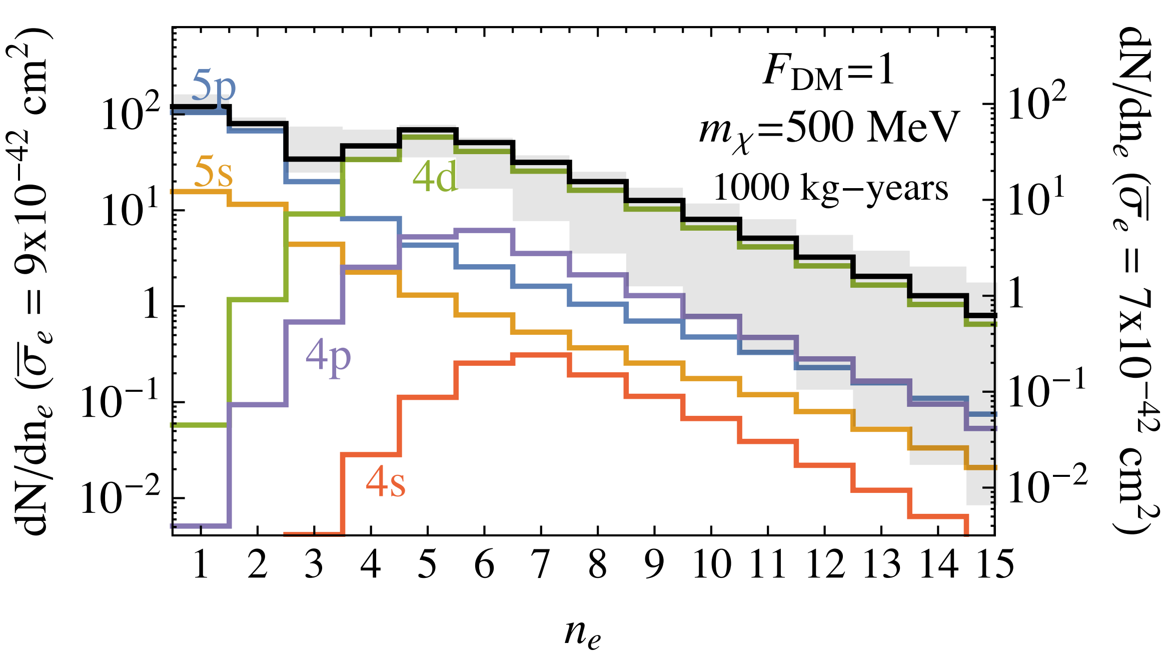
SD

P. Klos et al., PRD 88 (2013)

INTERACTION RATES: DM-ELECTRON SCATTERING

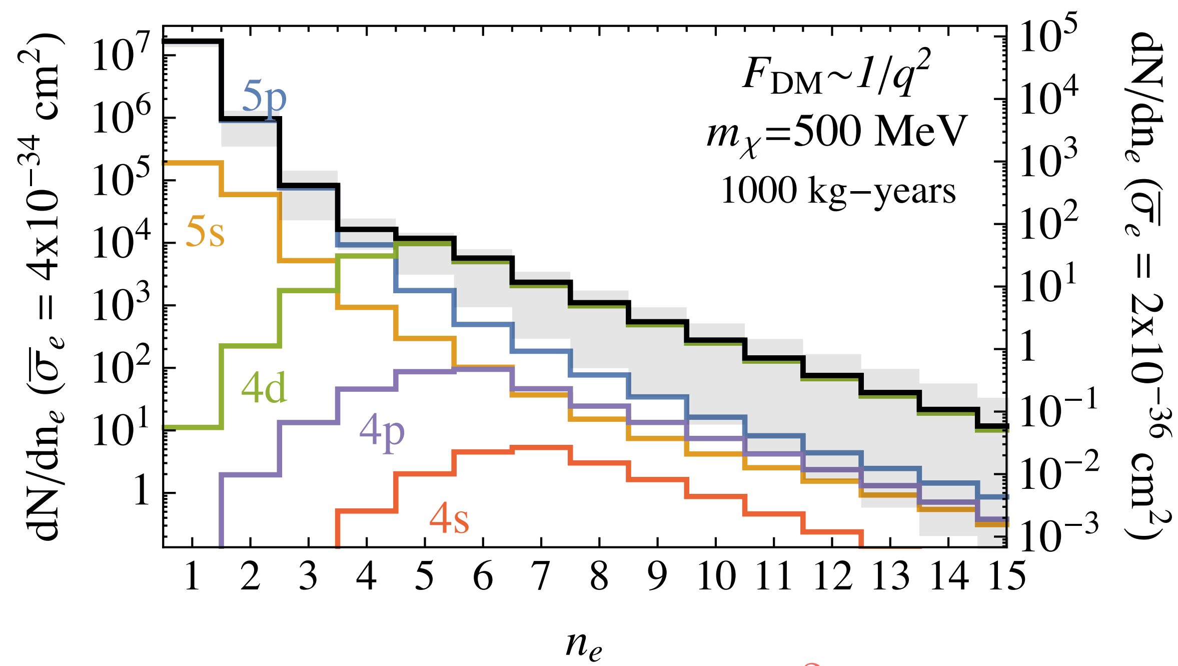
$$\frac{dR_{ion}}{d\ln E_R} = \frac{6.2}{A}\left(\frac{\rho_0}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\sigma_e}{10^{-40}\mathrm{cm^2}}\right)\left(\frac{10\,\mathrm{MeV}}{m_{\mathrm{DM}}}\right)\times\frac{d\langle\sigma_{ion}v\rangle/d\ln E_R}{10^{-3}\sigma_e}\,\frac{\mathrm{events}}{\mathrm{kg\,d}}$$

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



$$F_{DM} = 1$$

Heavy dark photon A' mediator



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

Ultra-light dark photon A' mediator

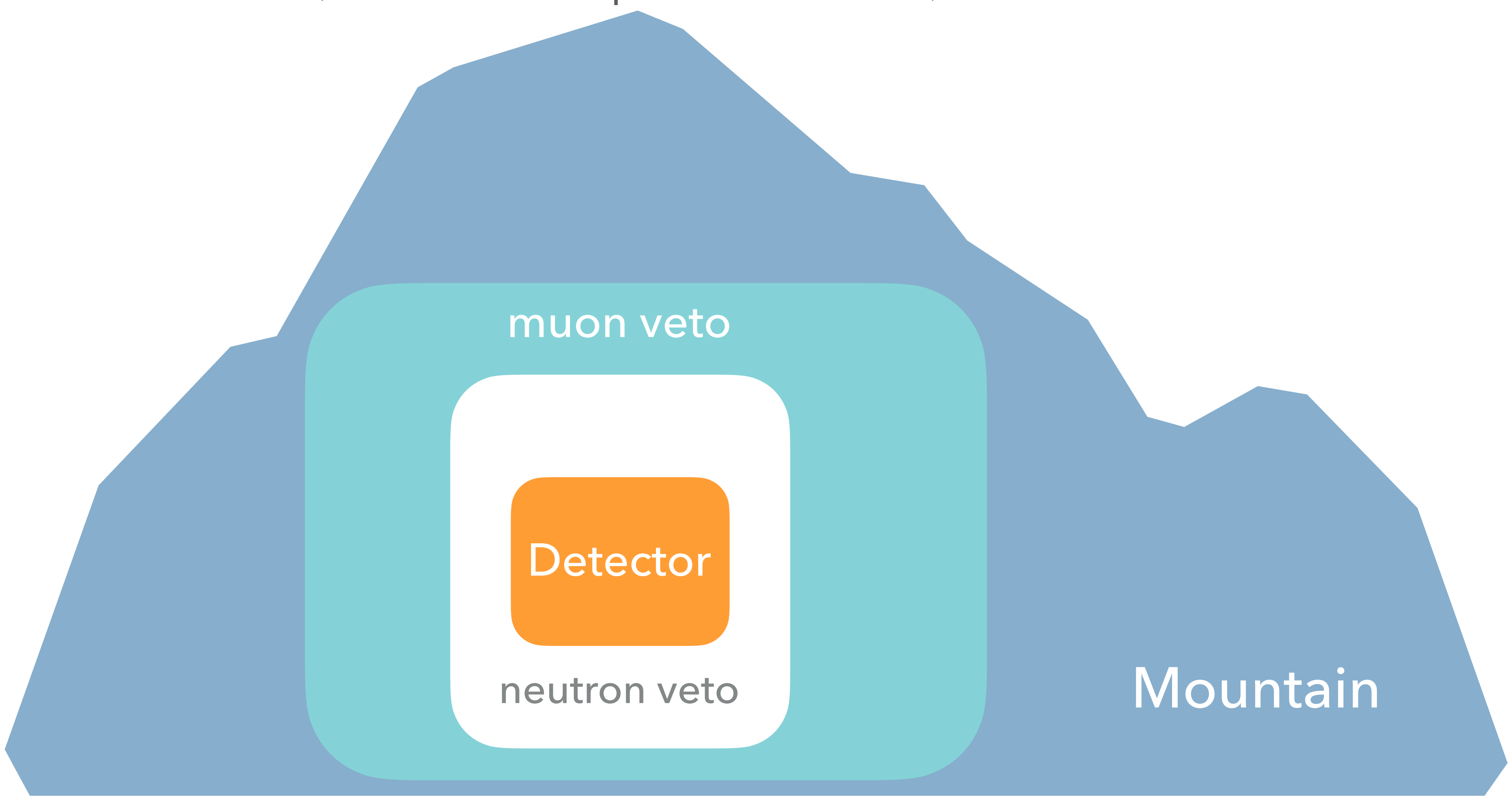
Essig, Volanski, Yu, PRD 96, 2017

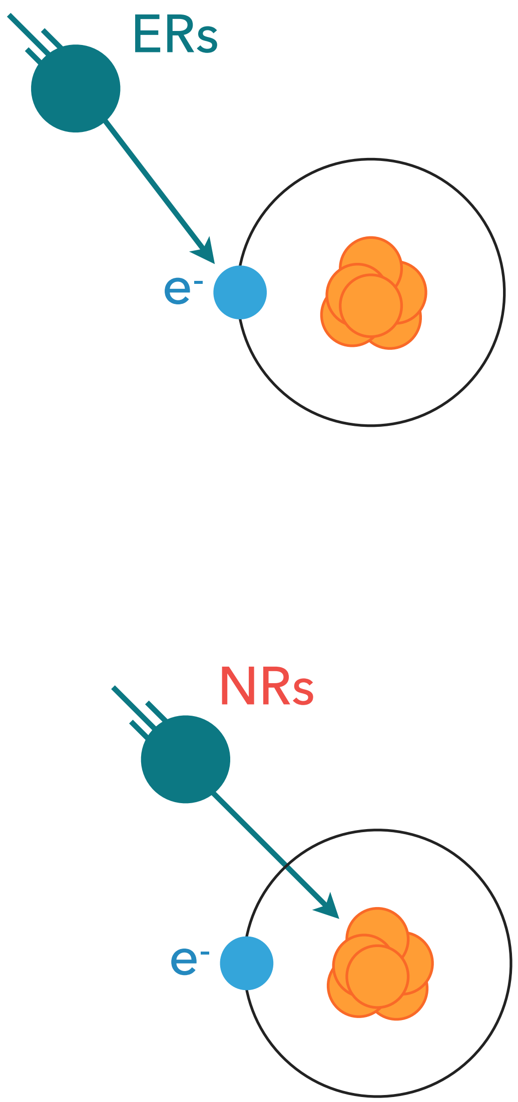
MAIN EXPERIMENTAL CHALLENGES TOWARDS THE "NEUTRINO FOG"

- 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 x higher rates → deep underground & low-radioactivity materials

BACKGROUNDS: OVERVIEW

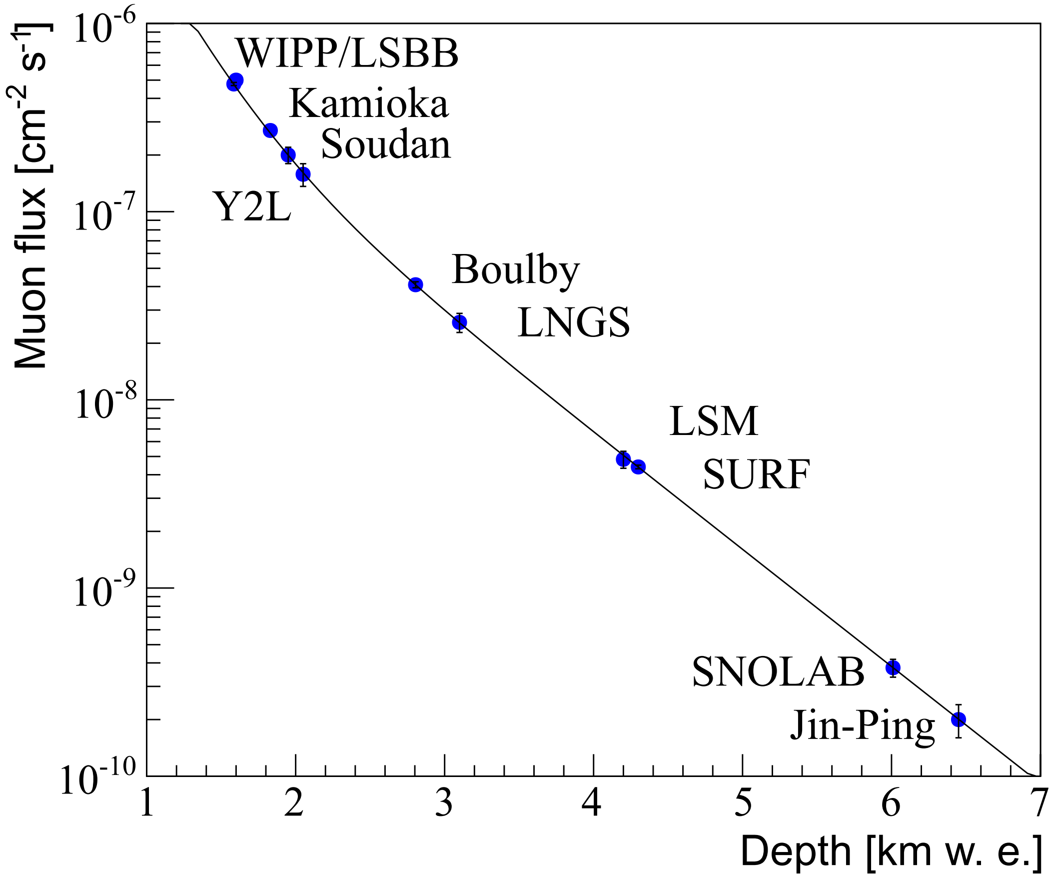
- Muon-induced neutrons: NRs
- Cosmogenic activation of materials/targets (^{3}H, ^{32}Si, ^{60}Co, ^{39}Ar): ERs
- Radioactivity of detector materials (n, γ, α, e^-): NRs and ERs
- Target intrinsic isotopes (^{85}Kr, ^{222}Rn, ^{136}Xe, ^{39}Ar, etc): ERs
- Neutrinos (solar, atmospheric, DSNB): NRs and ERs

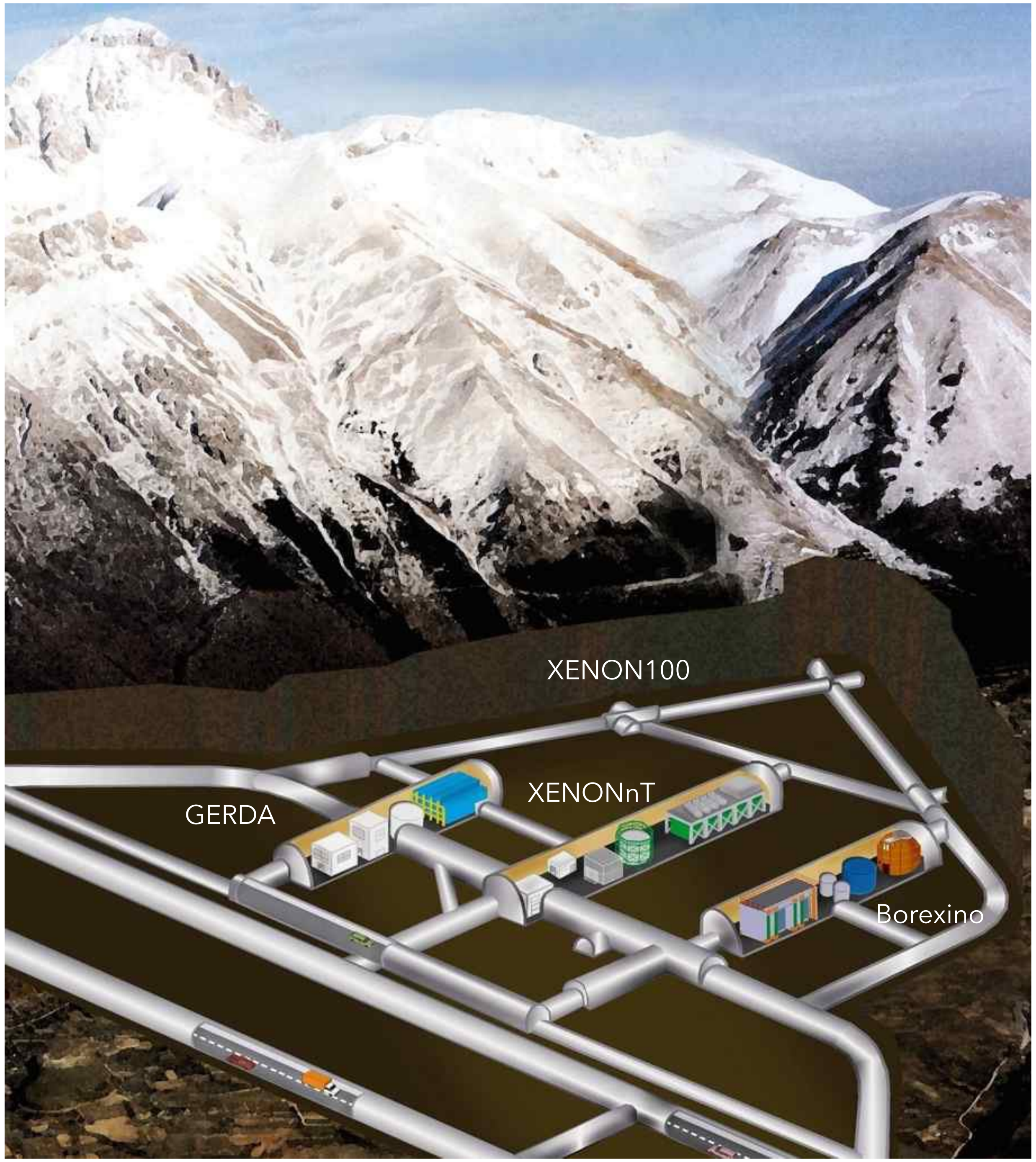




BACKGROUNDS AND SHIELDS

- Go deep underground
  - However, can't shield neutrinos
  - On the bright side: possible signals (pp, ^{7}Be, ^{8}B, SN,…)

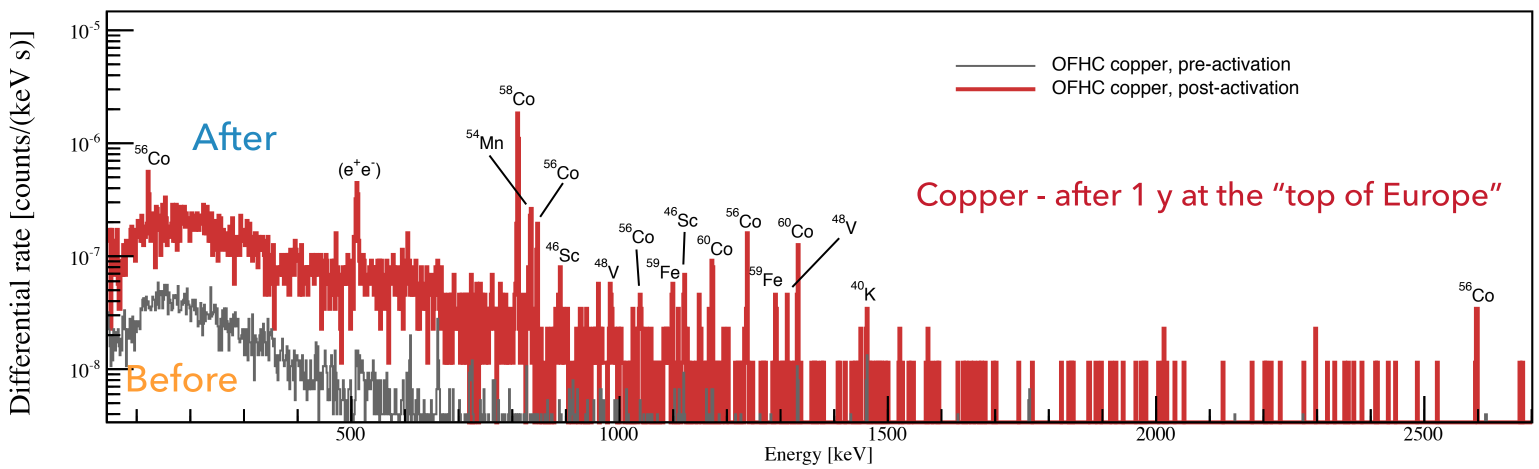




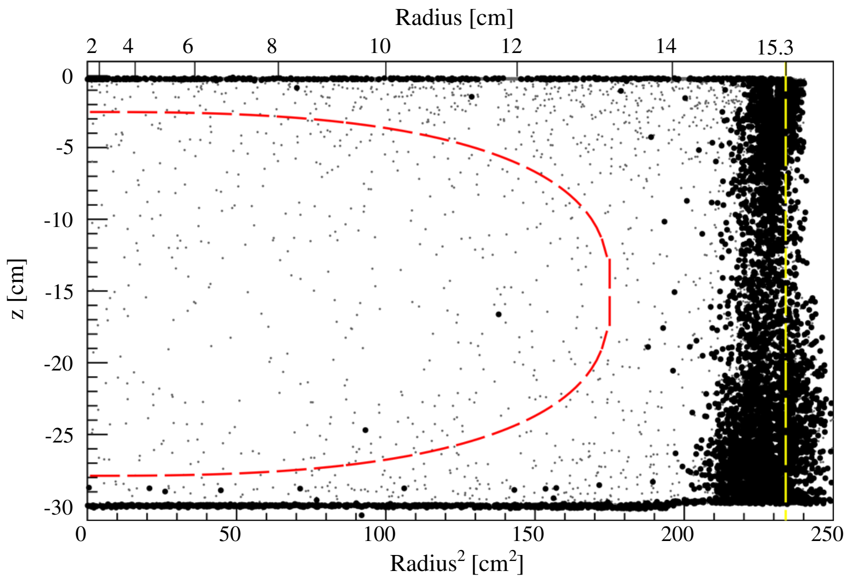
FURTHER BACKGROUND REDUCTION

- Avoid cosmic activation

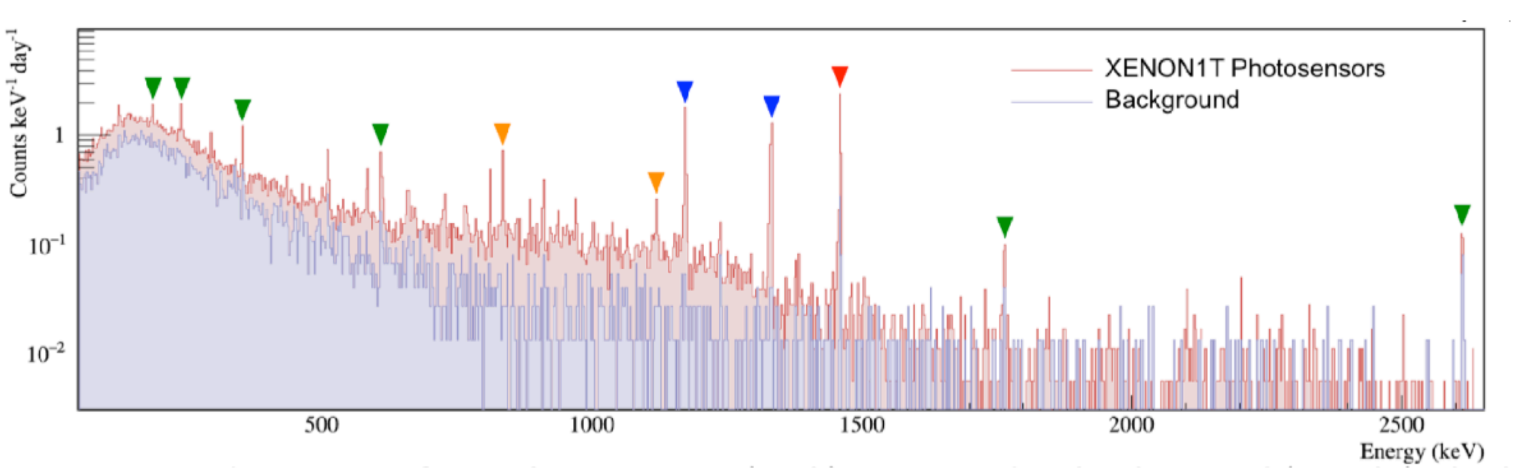
LB et al., Eur. Phys. J. C75 2015



- Fiducialise

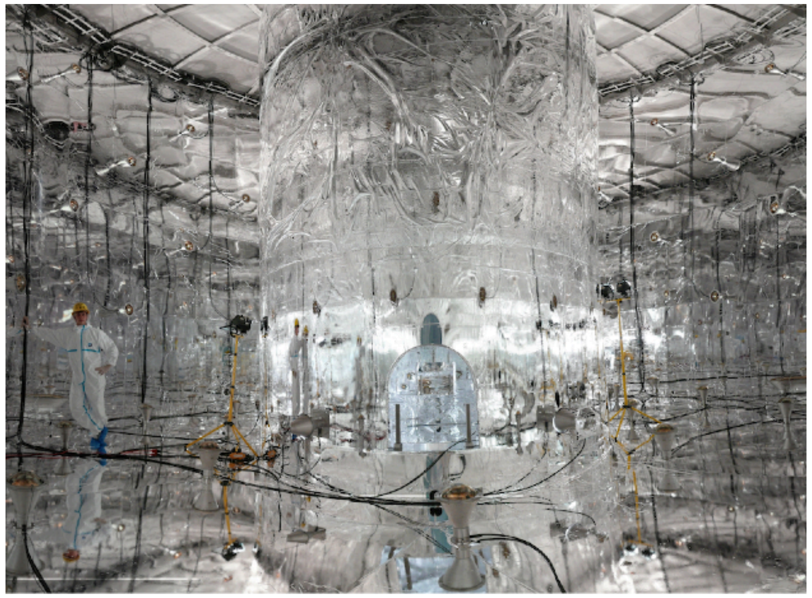


- Select low-radioactivity materials



XENON collaboration, EPJ-C 75 (2015) 11

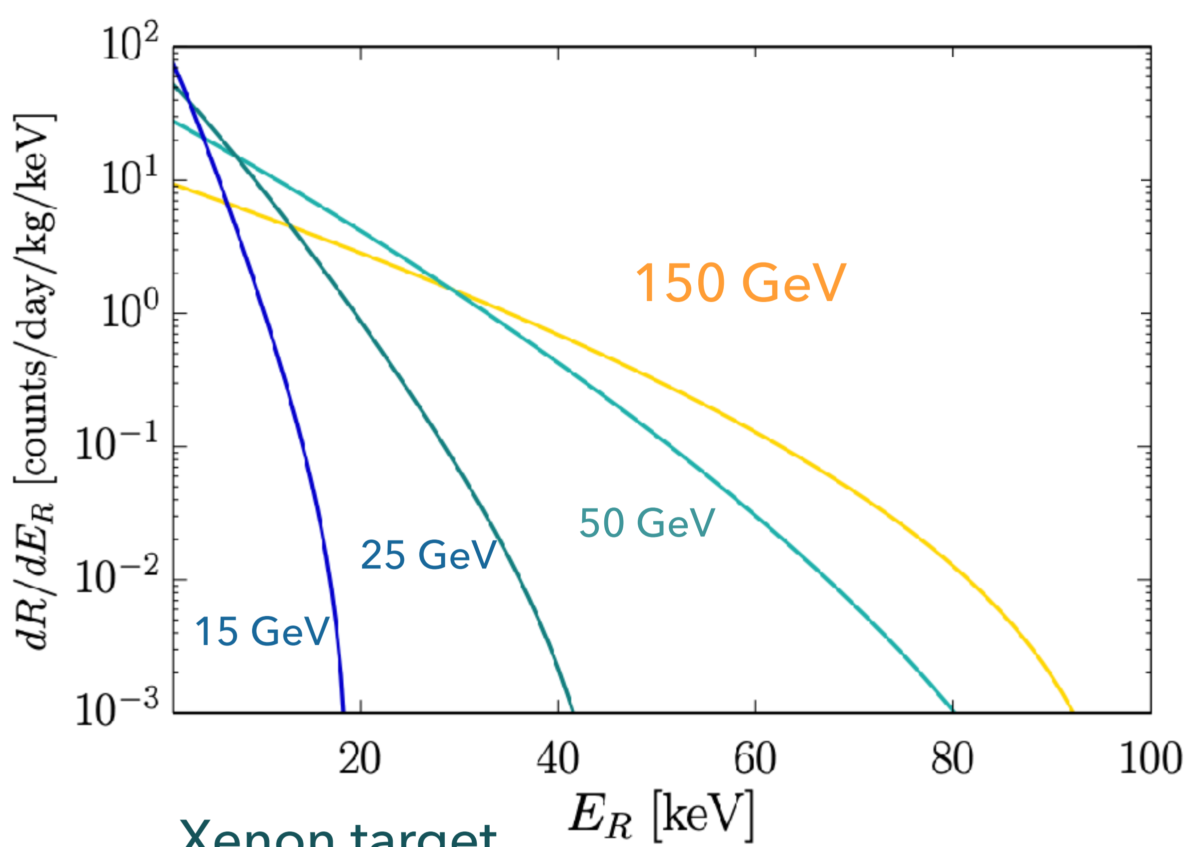
- Use active shields



DARK MATTER SIGNATURES

Rate and shape of recoil spectrum depend on:

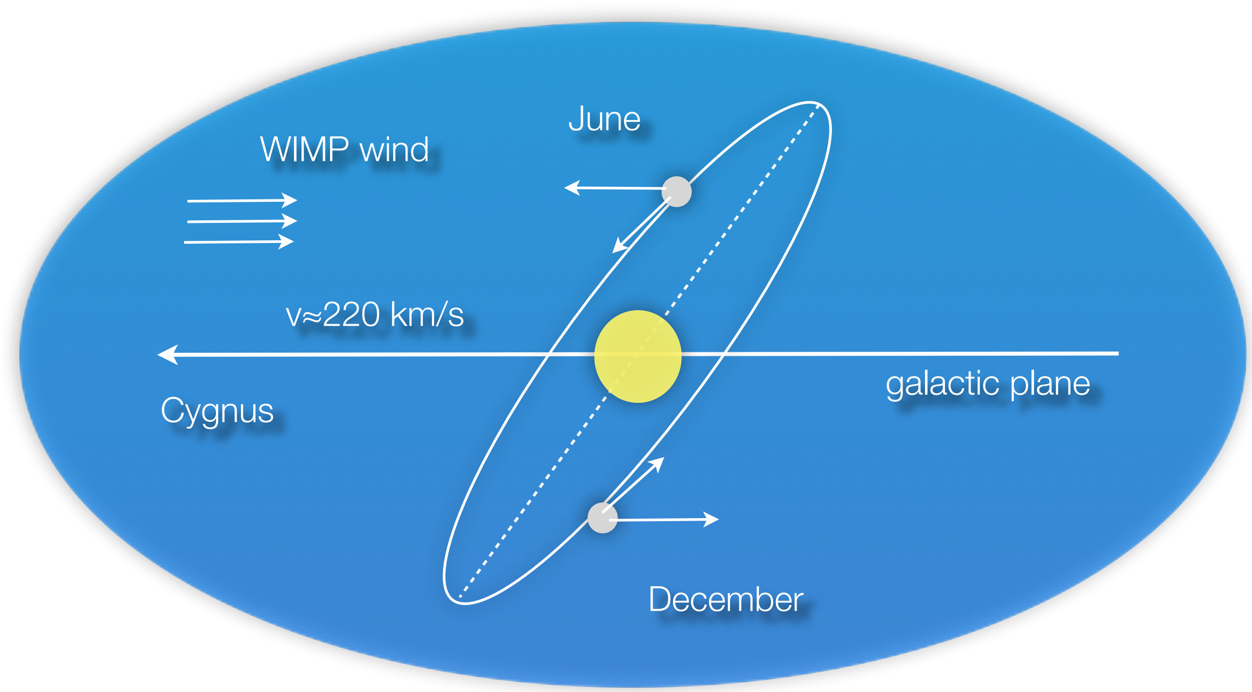
- DM particle mass
- Target material



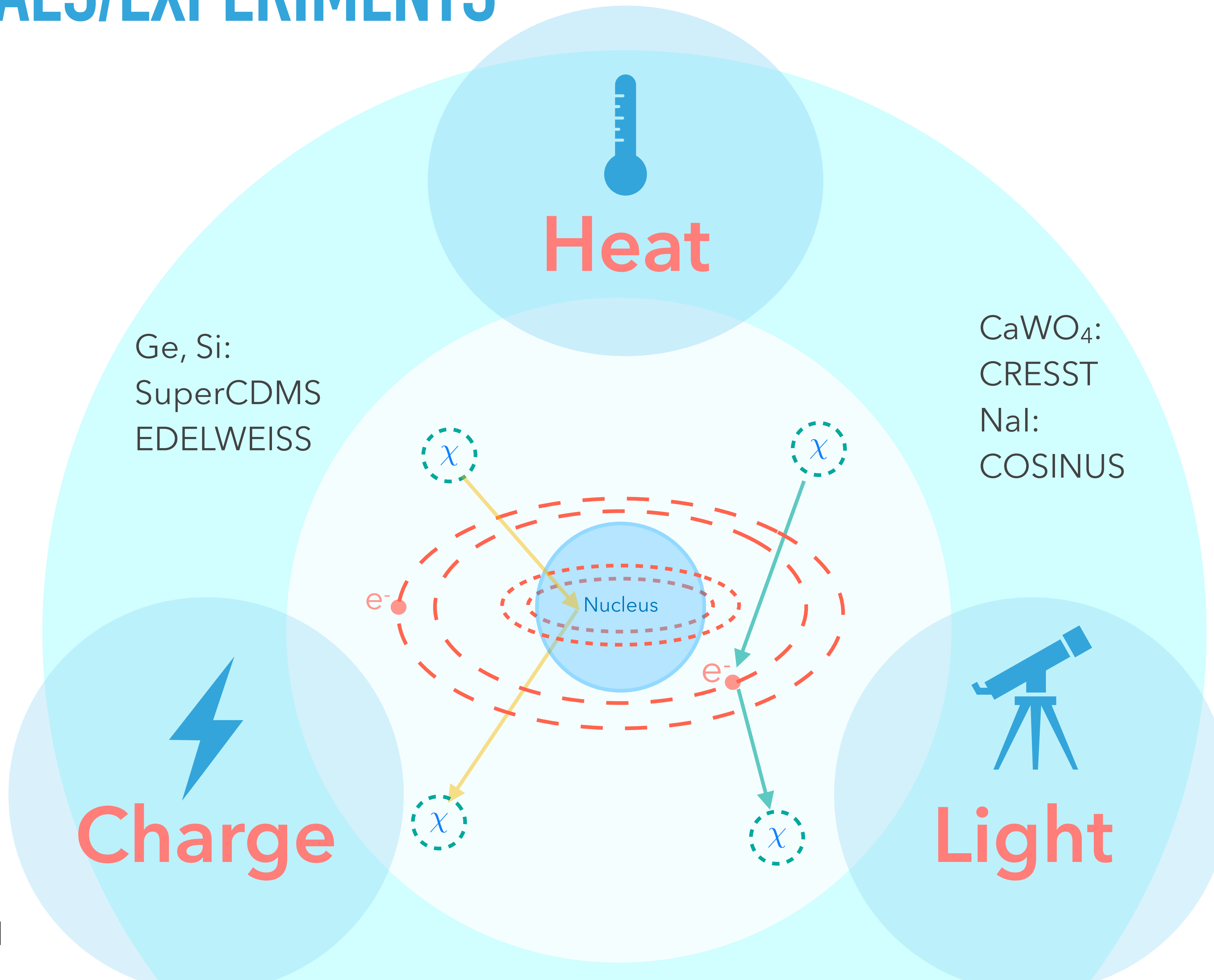
Xenon target

Motion of Earth causes:

- Annual event rate modulation: June - December asymmetry ~ 2-10%
- Sidereal directional modulation: asymmetry ~20-100% in forward-backward event rate



DD SIGNALS/EXPERIMENTS



Ge, Si:
SuperCDMS
EDELWEISS

$CaWO_4$:
CRESST
NaI:
COSINUS

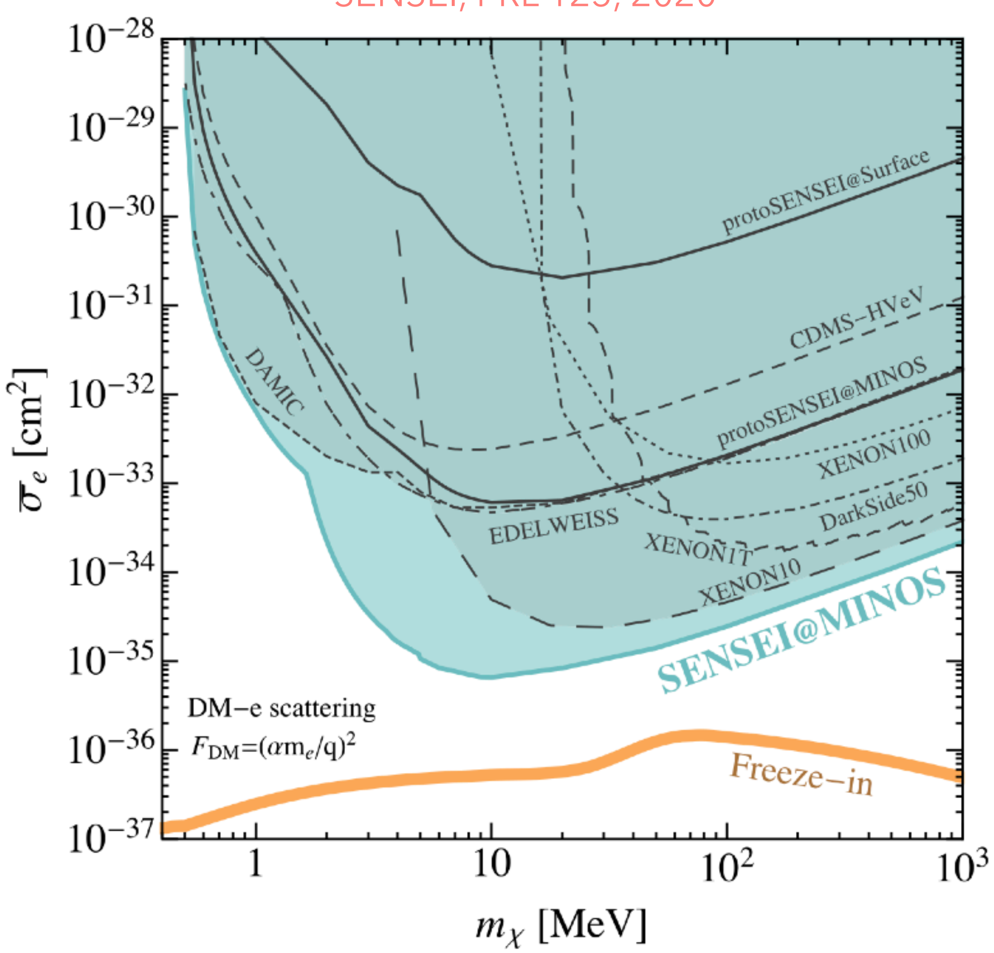
C_3F_8: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF_6: CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO
He: ALETHEIA, HeRALD (R&D)

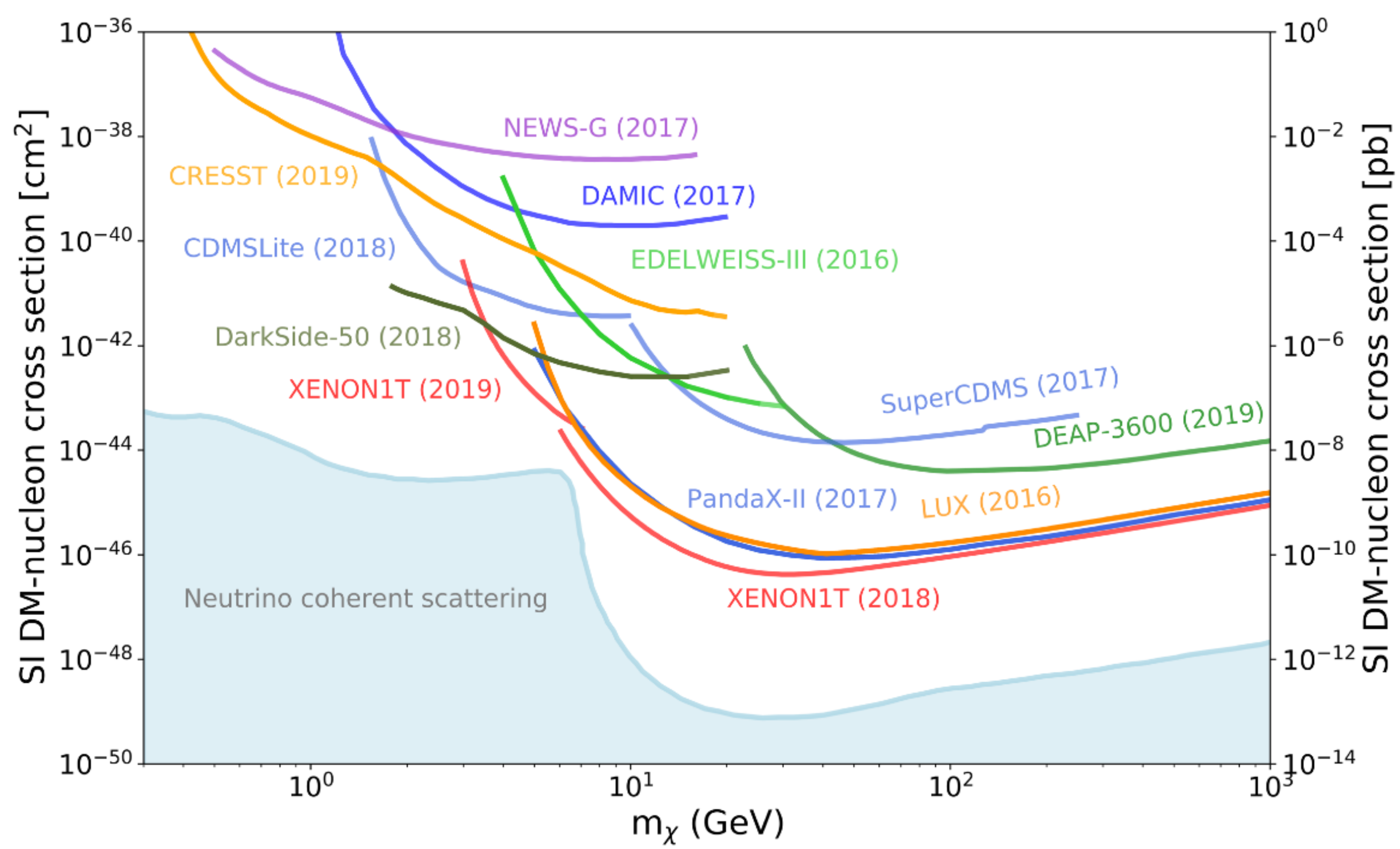
Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

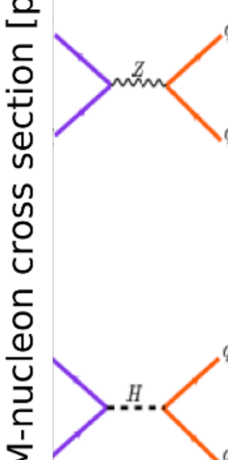
THE DIRECT DETECTION LANDSCAPE

SENSEI, PRL 125, 2020



PDG 2020



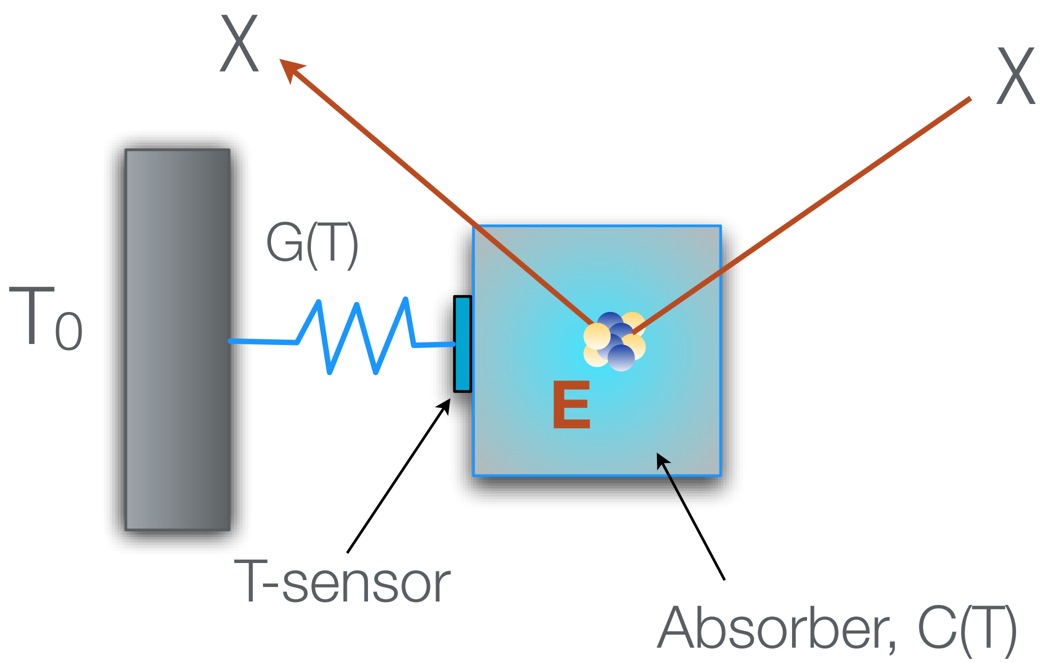


Scattering off electrons

Scattering off nuclei

CRYOGENIC EXPERIMENTS

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



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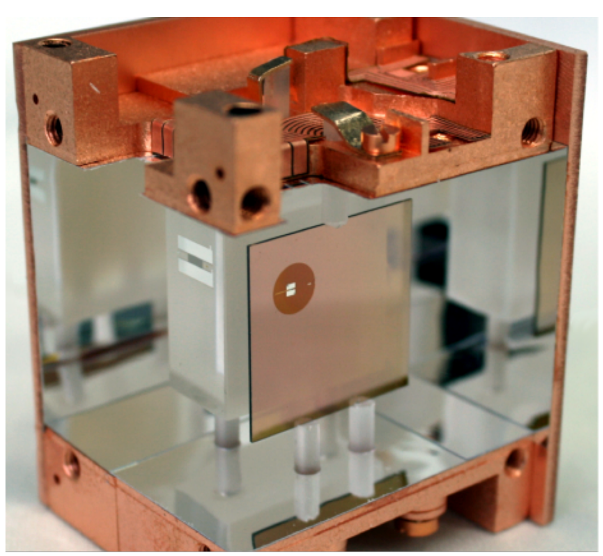
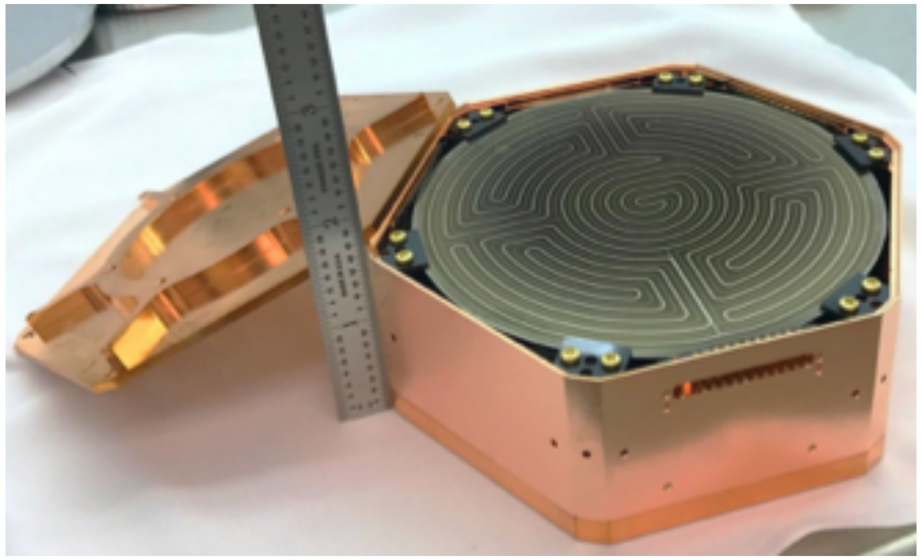


EDELWEISS

Super-CDMS



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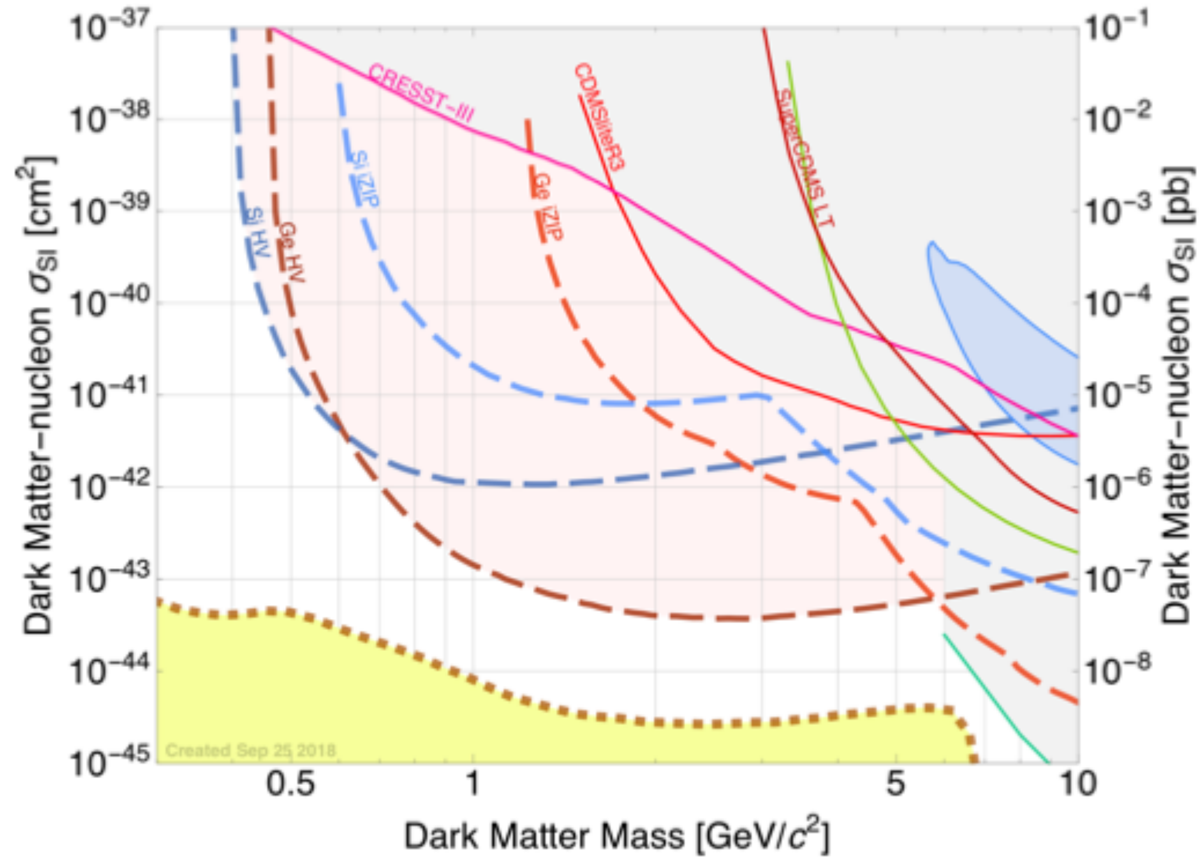

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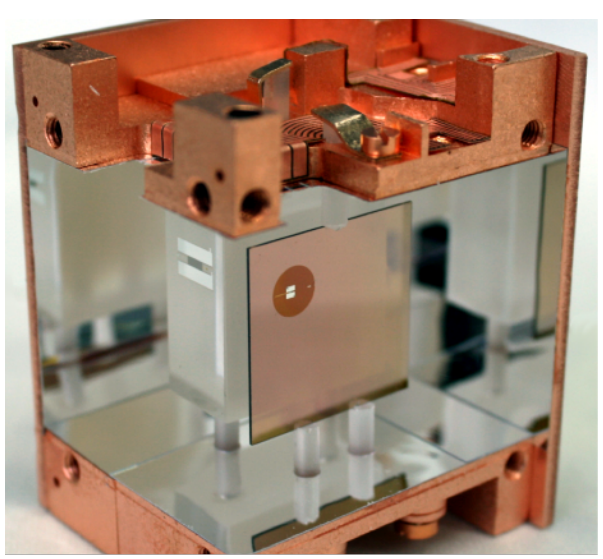

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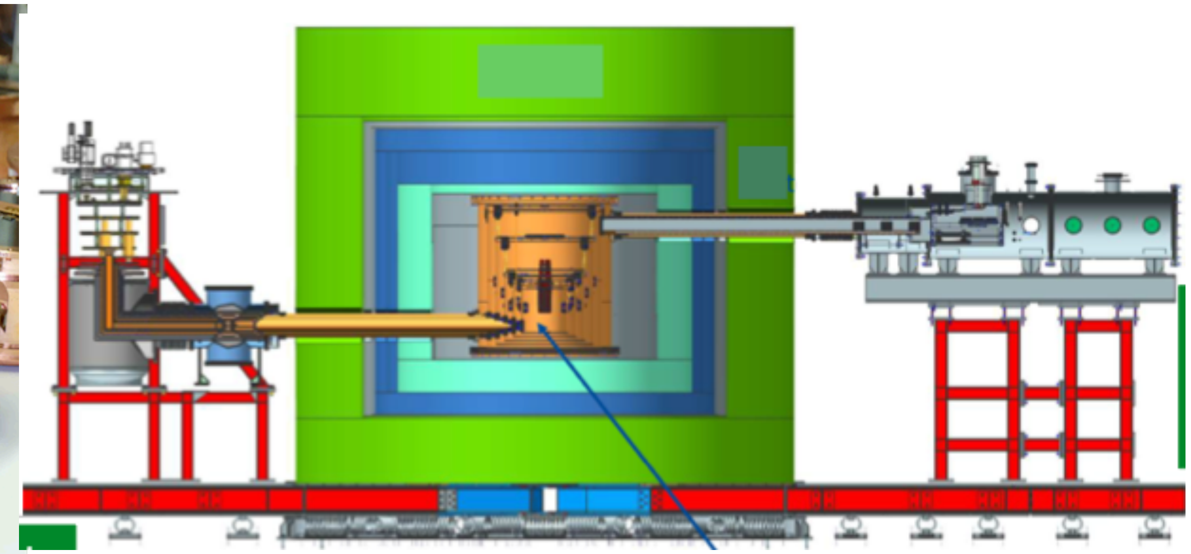
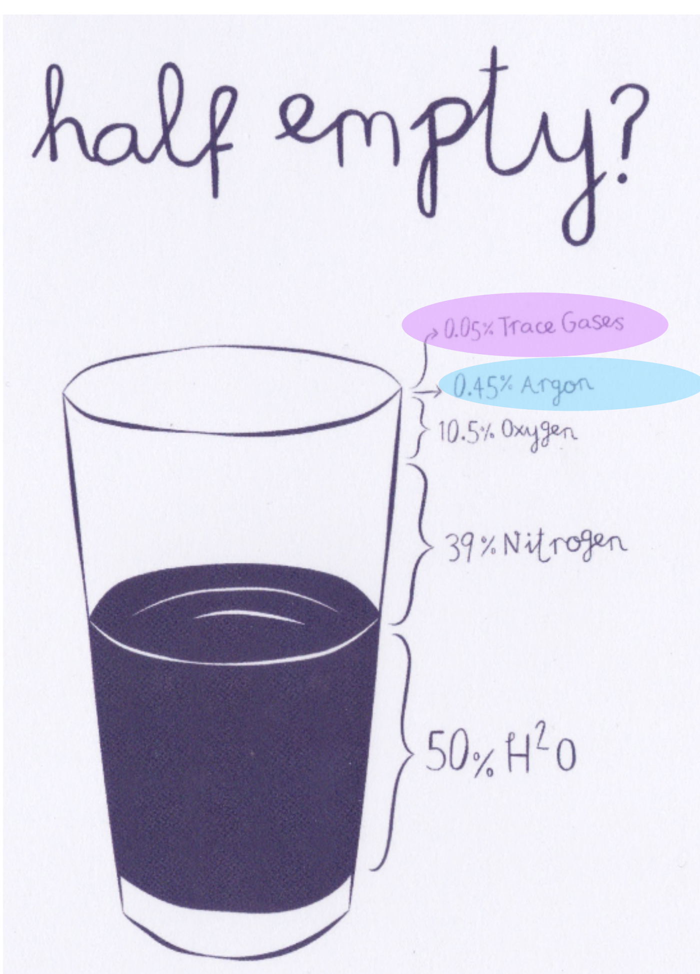
Super-CDMS at SNOLAB



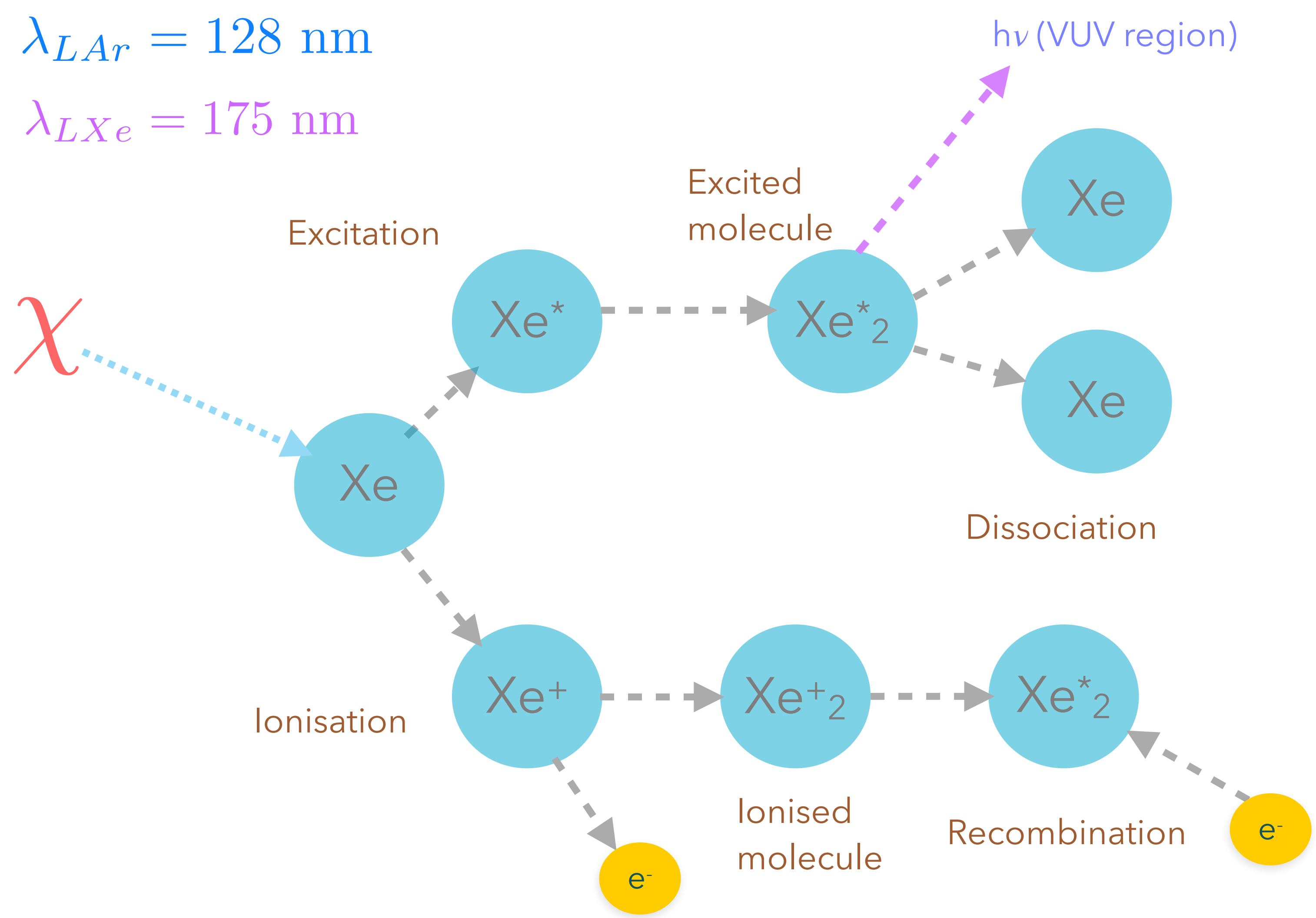
ARGON AND XENON DETECTORS

- Use a large amount of clean liquid argon or xenon target & detect ionisation and excitation from particle interactions
- Argon, "the inactive one", xenon, "the strange one", concentration in the atmosphere: 0.934% and 0.87 ppb (by volume)



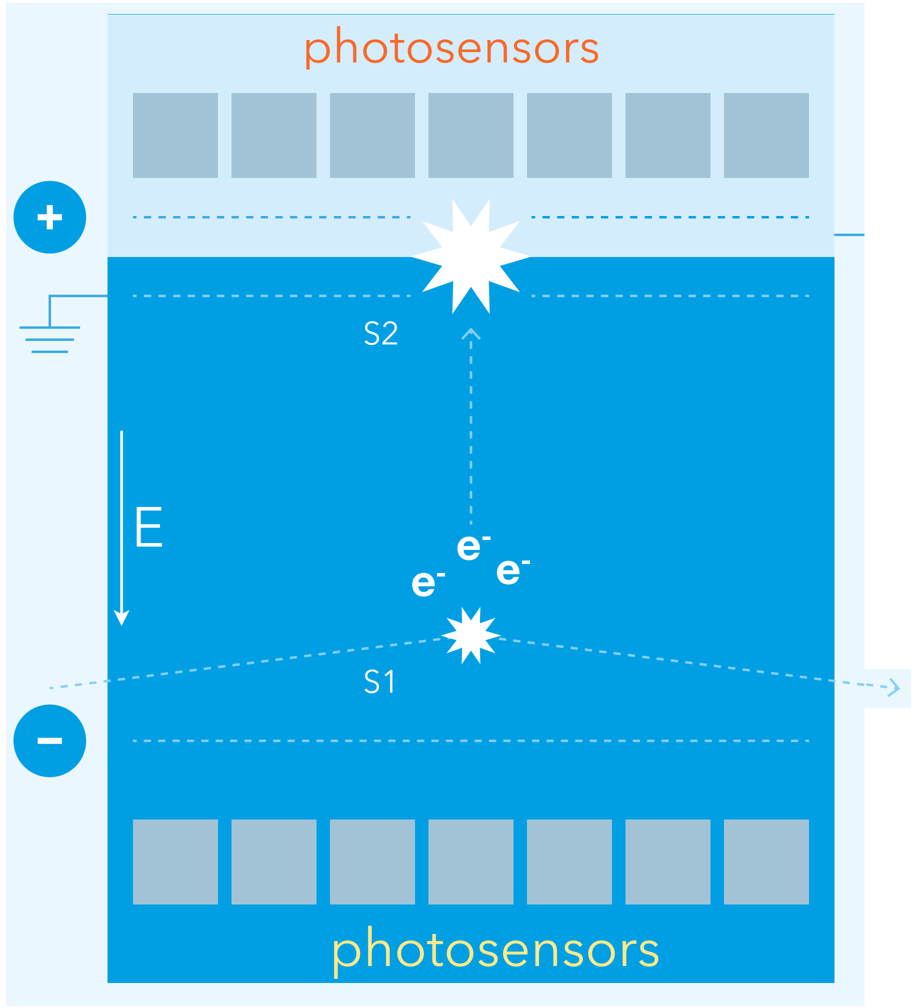
$\lambda_{LAr} = 128 \text{ nm}$

$\lambda_{LXe} = 175 \text{ nm}$



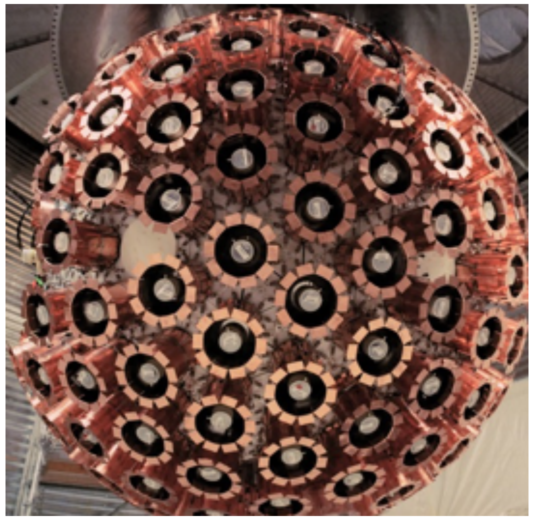
LIQUEFIED NOBLE GASES

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

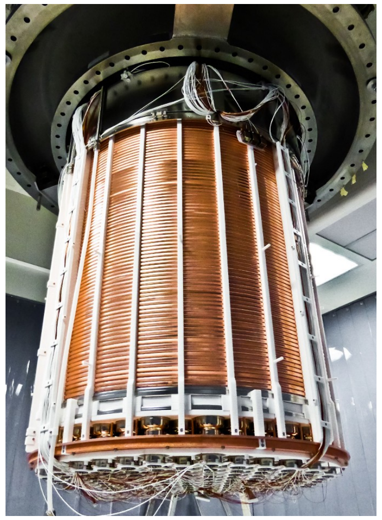


XMASS

DEAP-3600



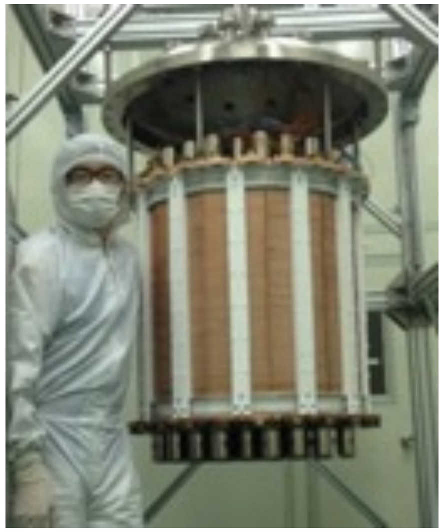
XENON1T



LUX

DarkSide-50

PandaX-II

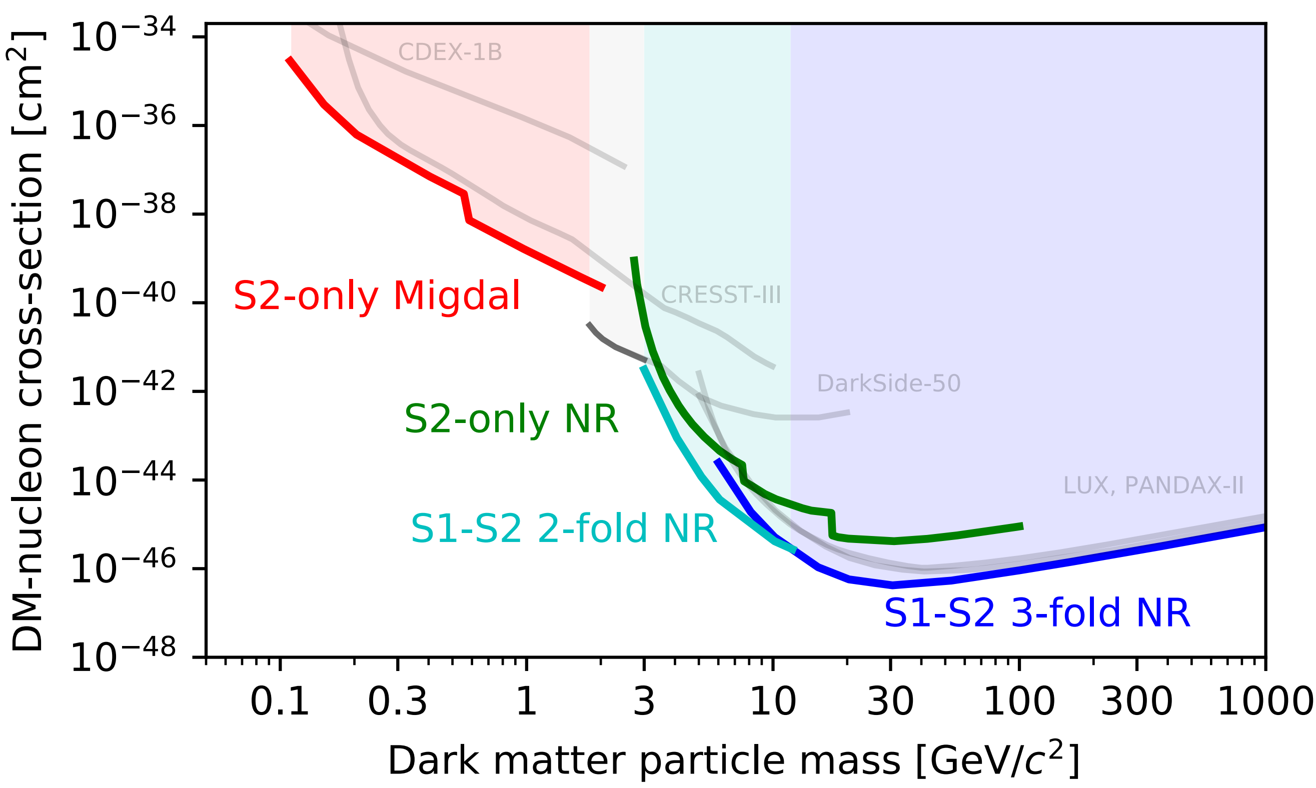


LIQUEFIED NOBLE GASES

No excess of nuclear recoil events observed so far

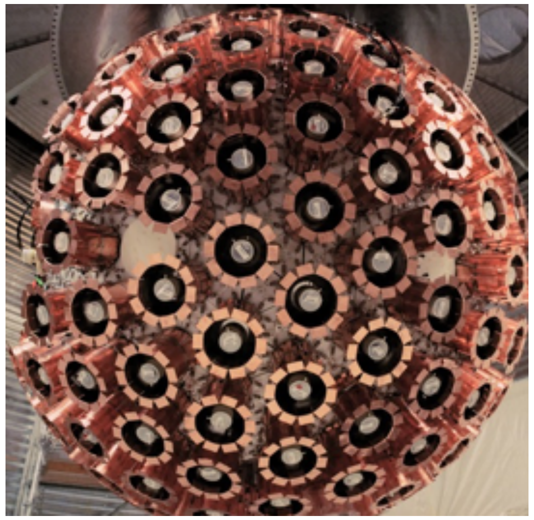
- Single and two-phase Ar & Xe detectors
- Time projection chambers:
  - energy determination, 3D position resolution via light (S1) & charge (S2): fiducialisation
  - S2/S1⇒ ER/NR discrimination
  - Single versus multiple interactions

$\sigma_{SI} < 4.1 \times 10^{-47} \mathrm{cm}^2$ at $30\,\mathrm{GeV/c}^2$

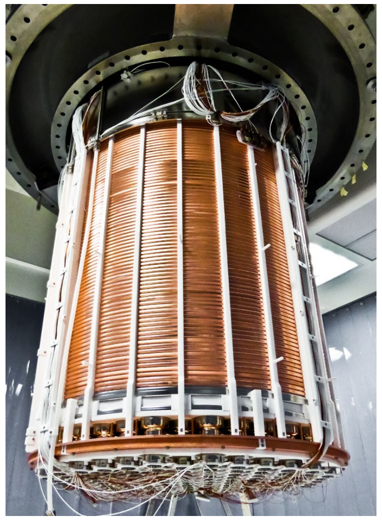


XMASS

DEAP-3600



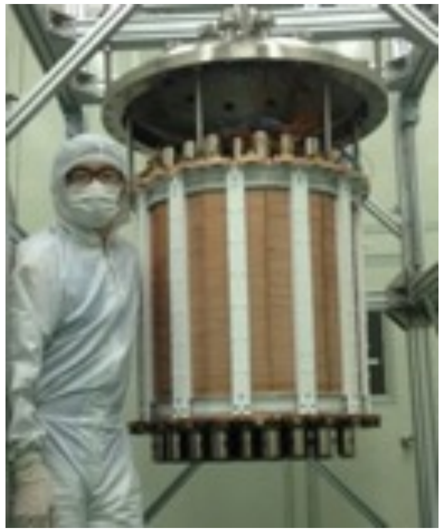
XENON1T



LUX

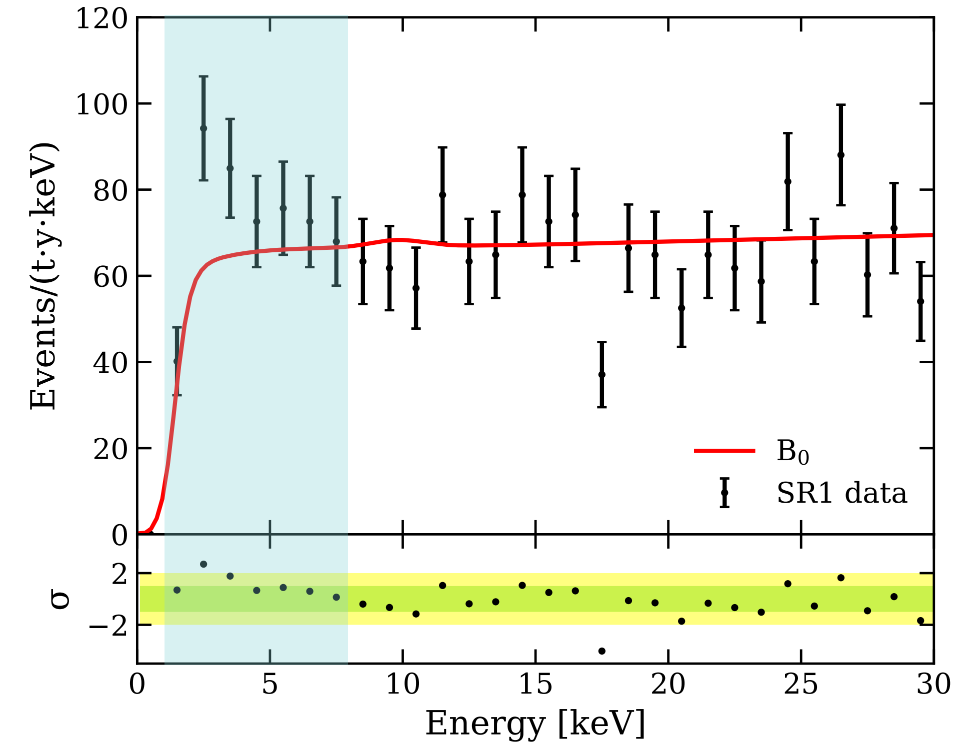
DarkSide-50

PandaX-II

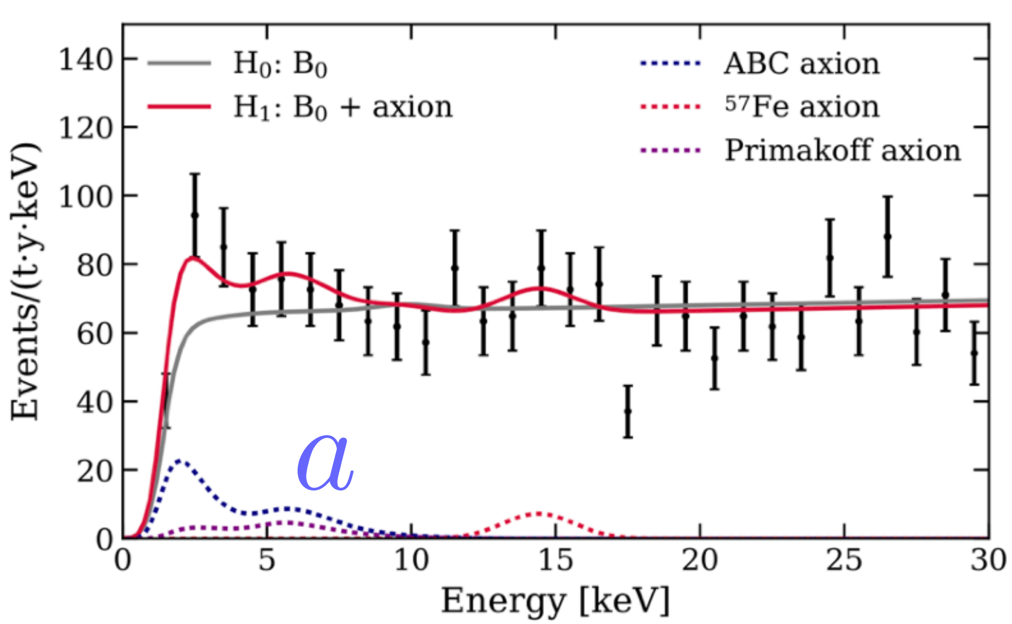


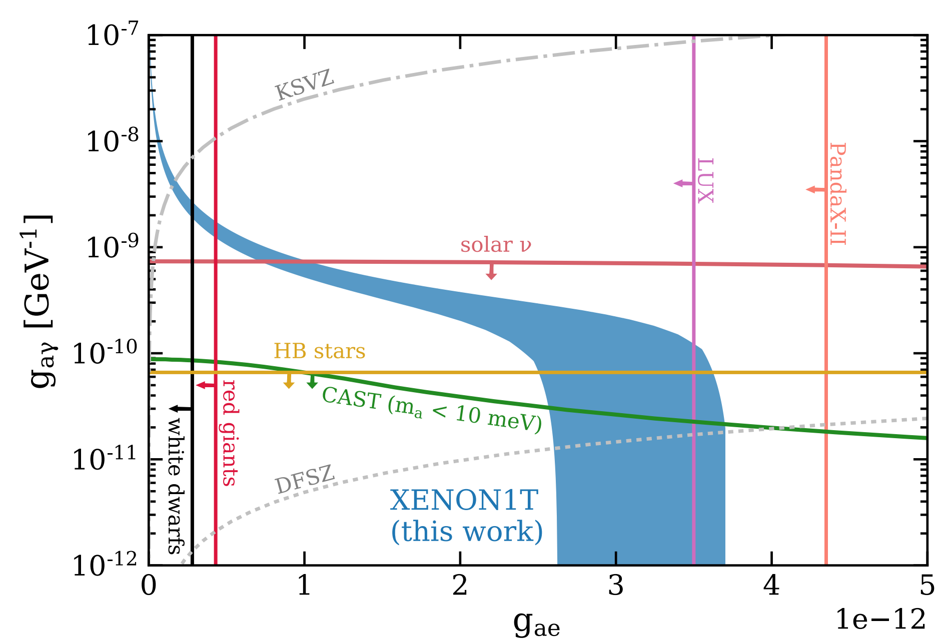
XENON1T: ELECTRONIC RECOIL EXCESS

XENON Collab., Phys. Rev. D 102, 2020



- 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?

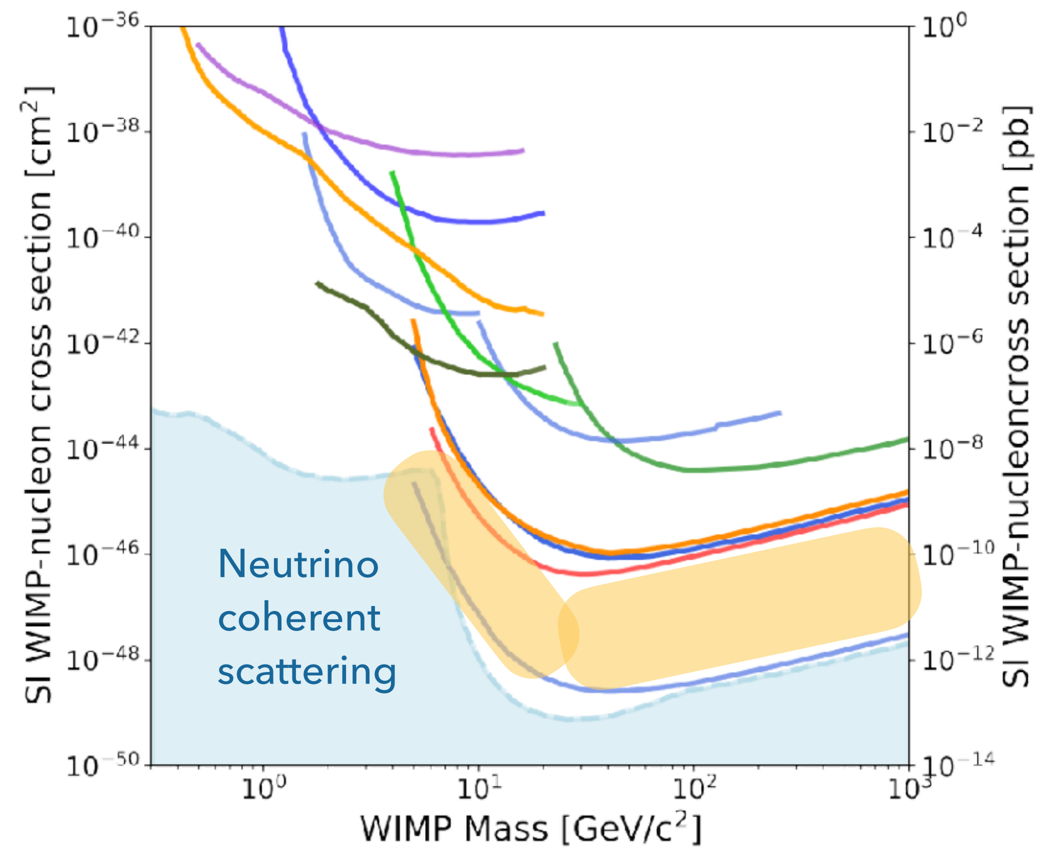


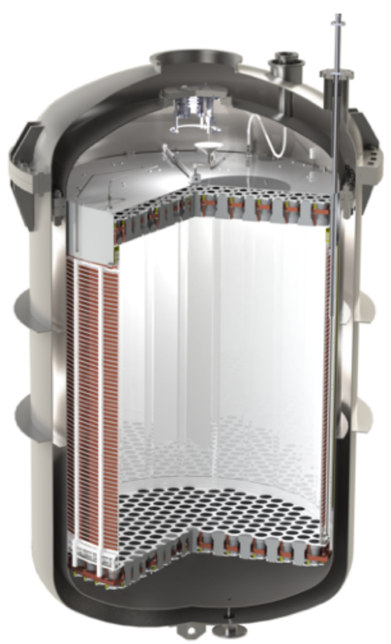


Solar axion favoured over background-only at 3.4 σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487); Tritium favoured over background-only at 3.2 σ $\widehat{=}$ to (6.2 ± 2) x 10^{-25} mol/mol

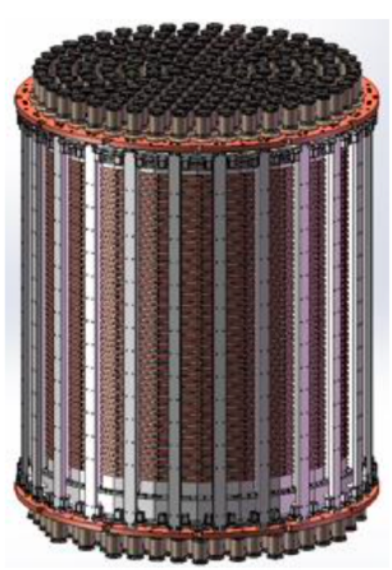
FUTURE: LIQUEFIED NOBLE GASES

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

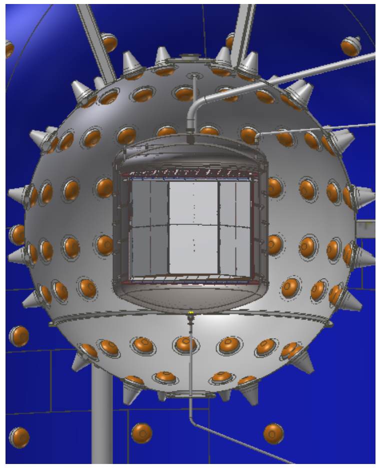




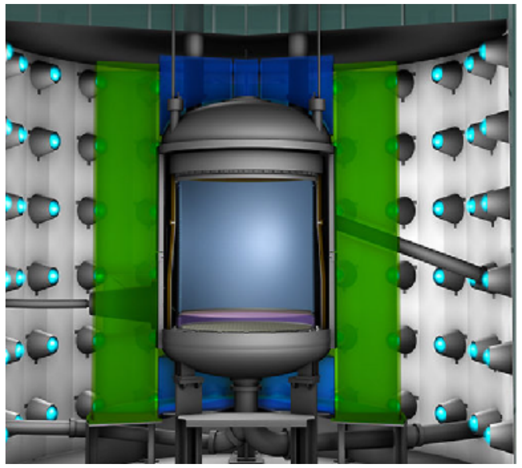
XENONnT: 8.6 t LXe
Data taking 2021



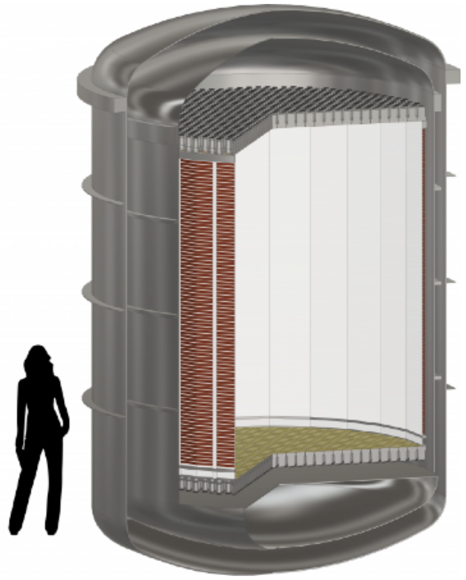
PandaX-4T LXe
Data taking 2021



DarkSide: 20 t LAr
Data taking 2023



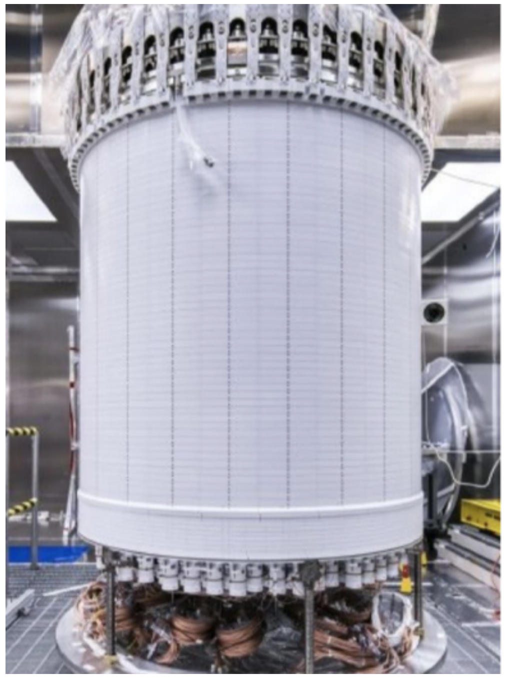
LUX-ZEPLIN: 10 t LXe
Data taking 2021

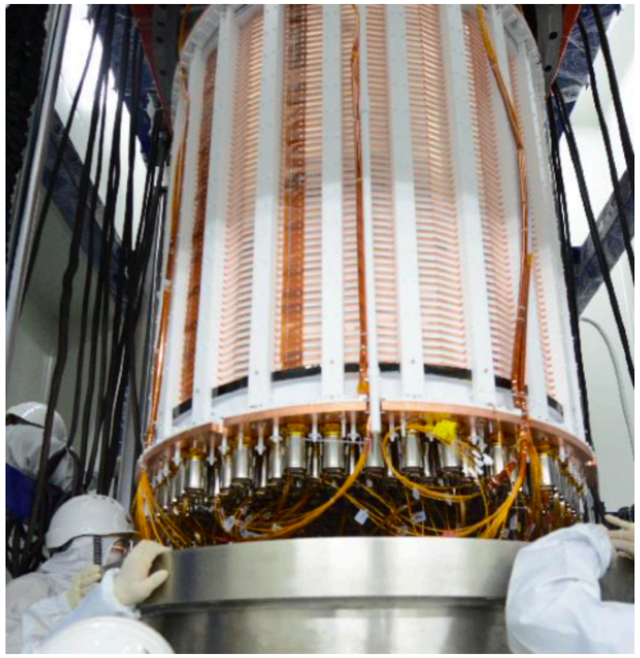


DARWIN: 50 t LXe
Data taking ~2027/28

LUX-ZEPLIN, PANDAX-4T, AND XENON-NT

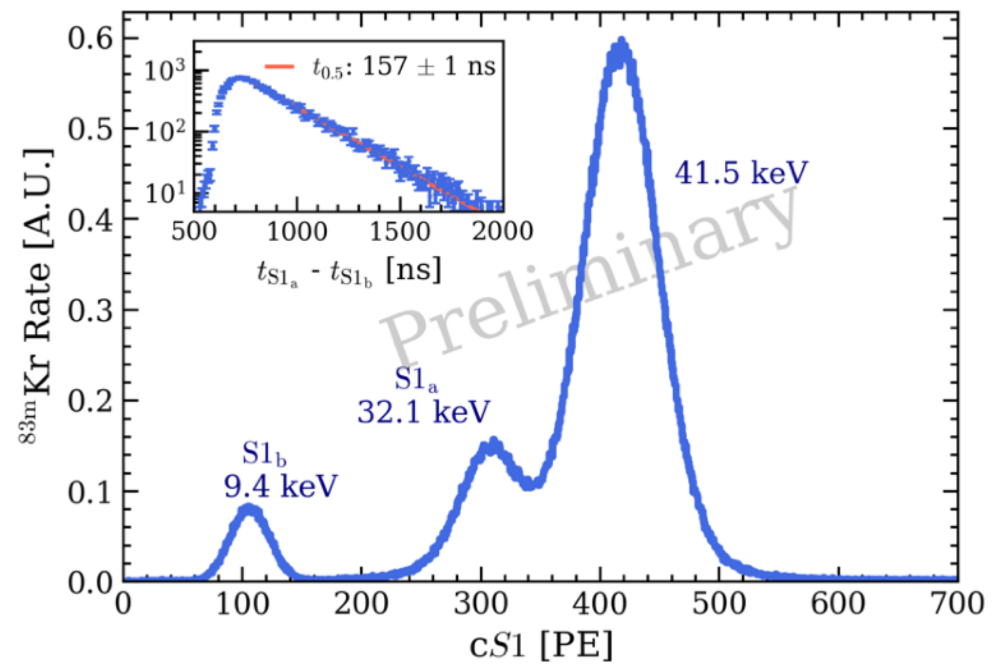
- Scale: 10 t, 6 t and 8.6 t LXe in total
  - TPCs with 2 arrays of 3-inch PMTs
  - Kr and Rn removal techniques
  - Ultra-pure water shields; neutron & muon vetos (LZ, XENON-nT)
  - External and internal calibration sources
- Status: commissioning at SURF, Jinping and LNGS

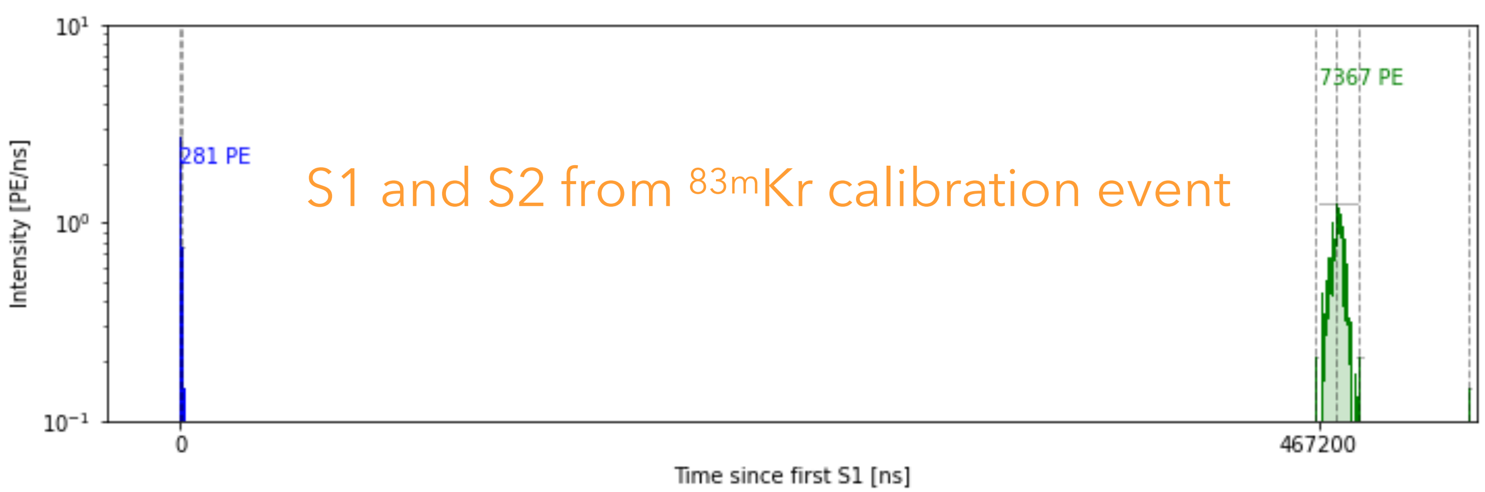




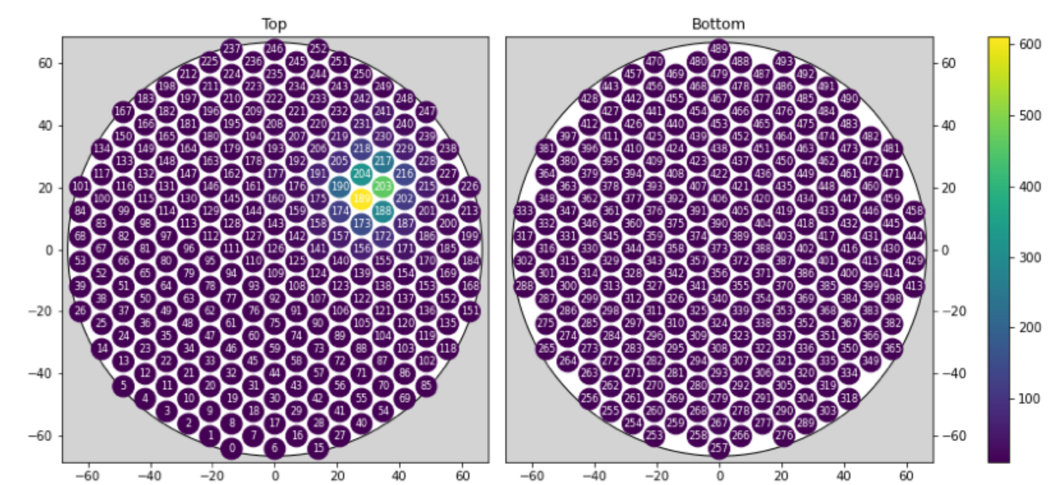
XENON-NT FIRST LIGHT

- 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





S1 and S2 from ^{83m}Kr calibration event



*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

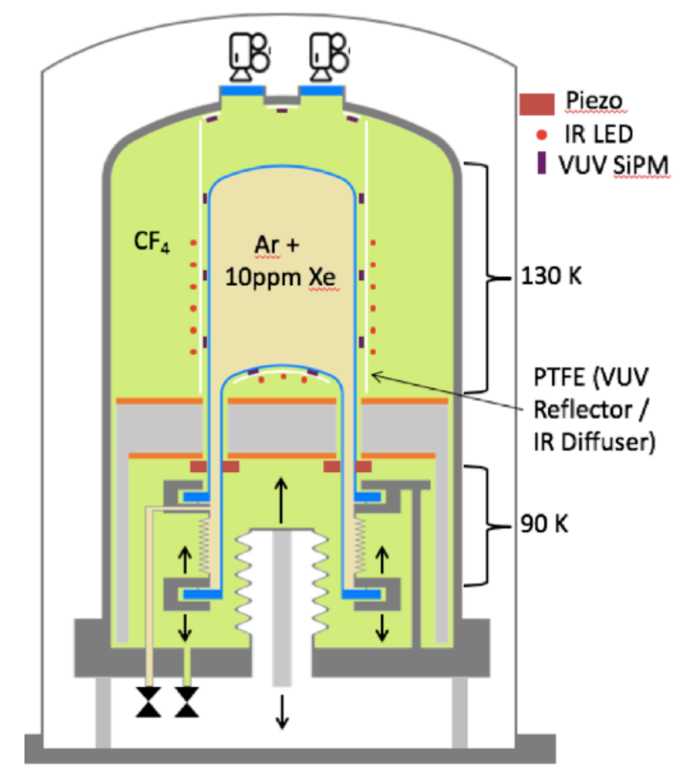
Test e- drift over 2.6 m (purification, high-voltage)

Test electrodes with 2.6 m diameter

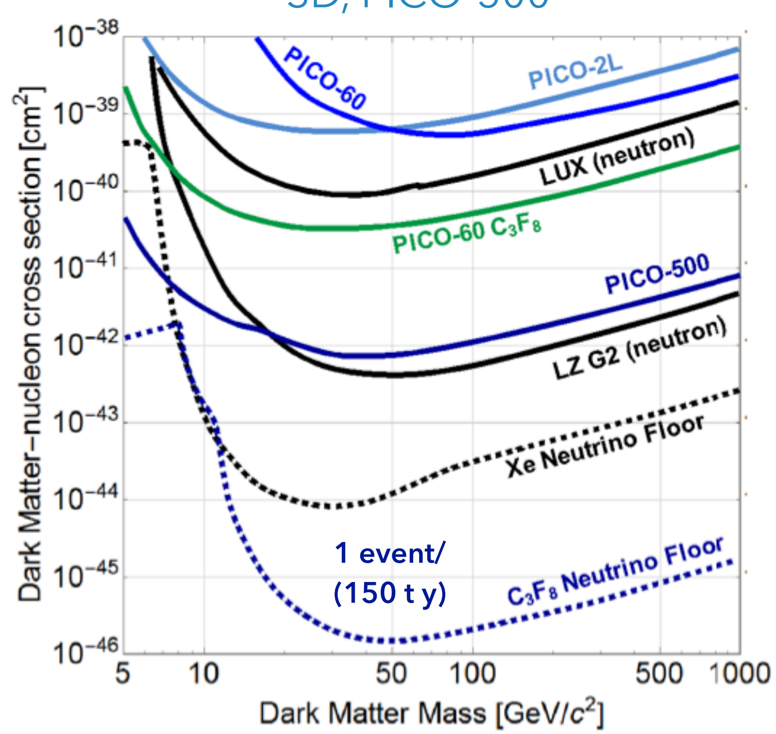
BUBBLE CHAMBERS

- 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

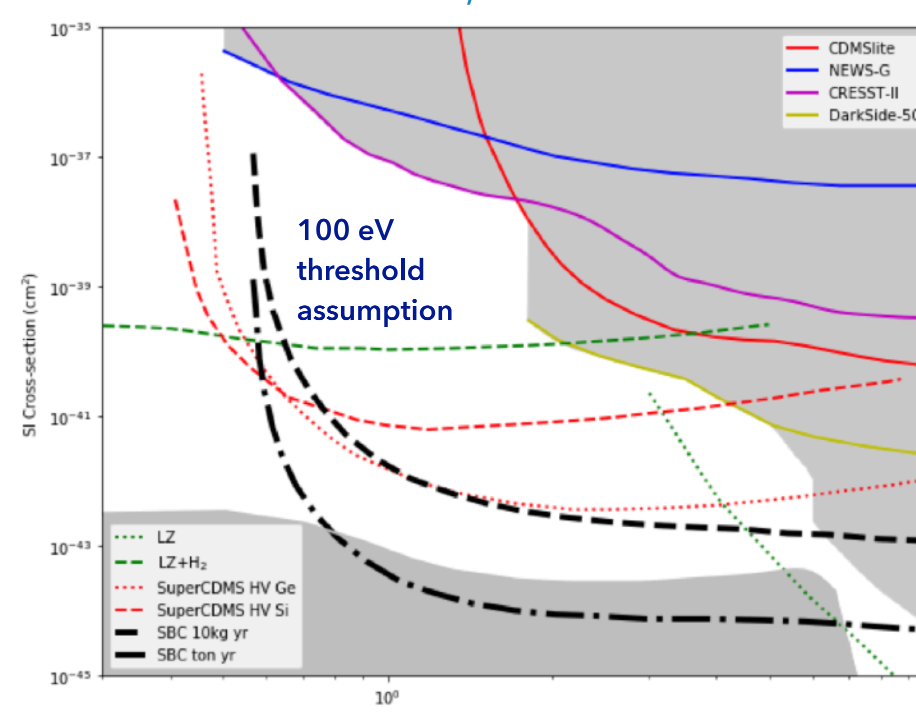
SBC



SD, PICO-500



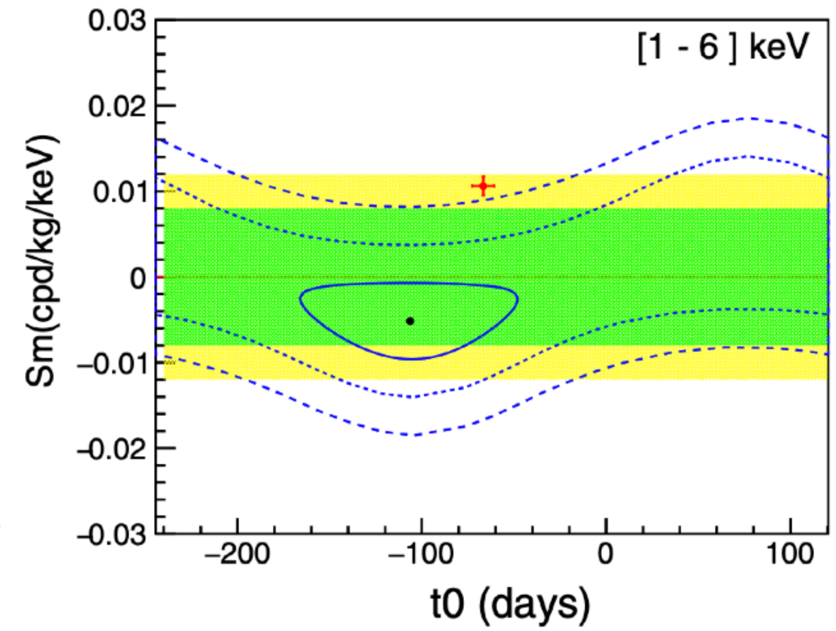
SI, SBC

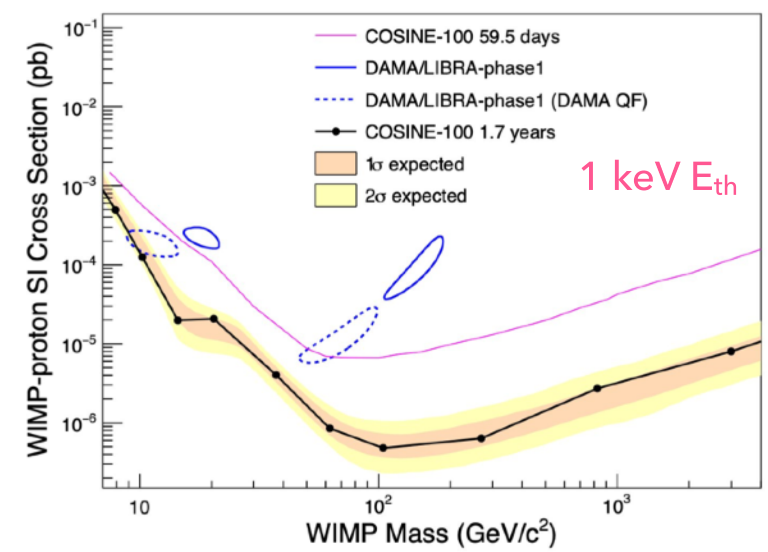


SODIUM IODIDE EXPERIMENTS

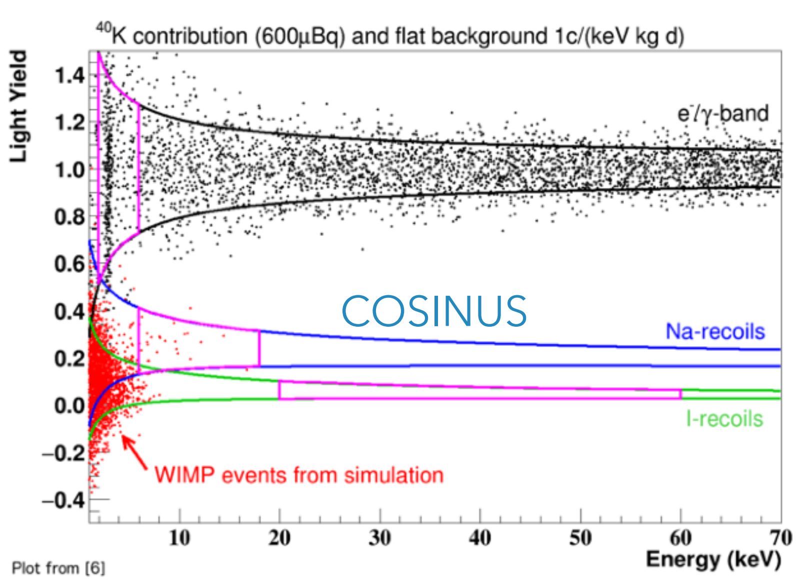
- Test the DAMA/LIBRA annual modulation anomaly with sodium iodide crystals: NaI(Tl)
- So far, no evidence for annual modulation from ANAIS-112 (3 y of data) and COSINE-100 (1.7 y of data)
- New experiment COSINUS: detects also phonons in undoped NaI (apart from scintillation) at few mK, for active background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

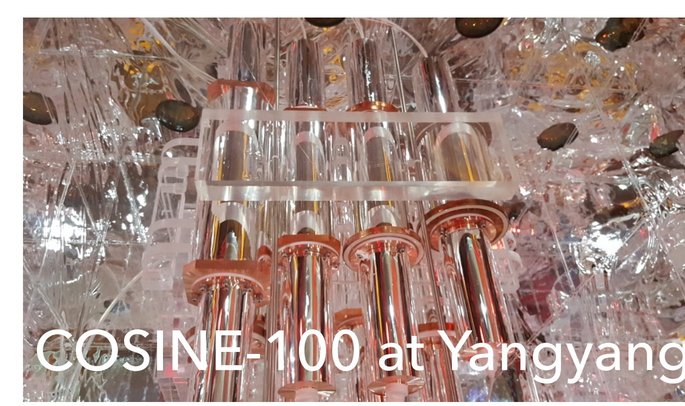
ANAIS, PRD 103, 2021





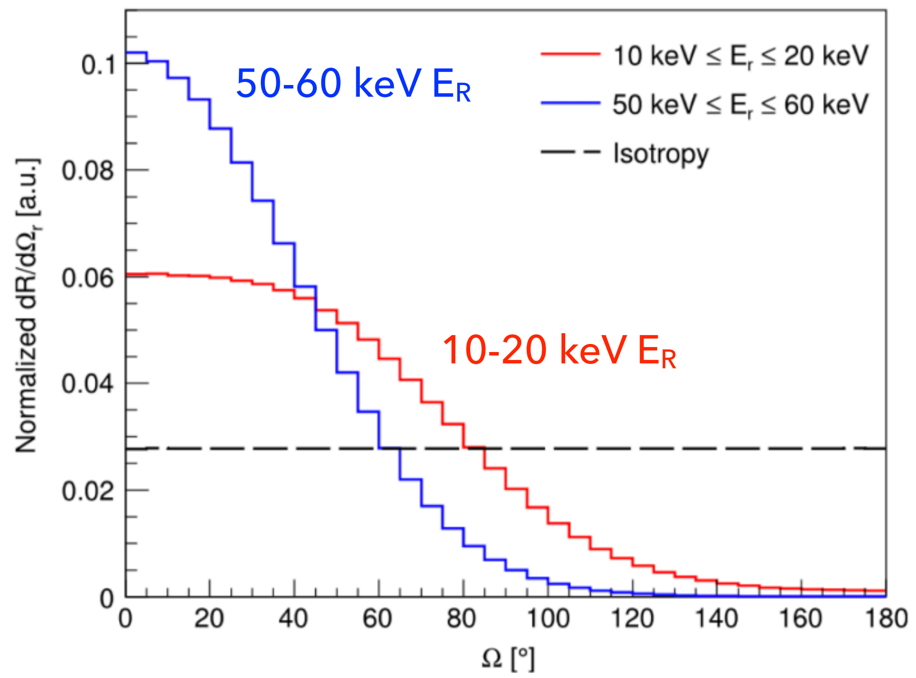
COSINE-100, arXiv:2104.03537



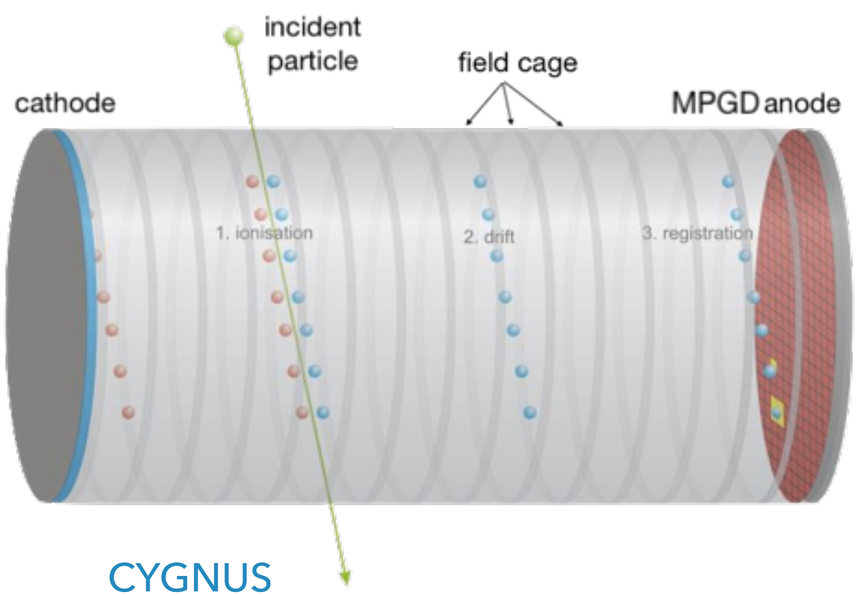


DIRECTIONAL DETECTORS

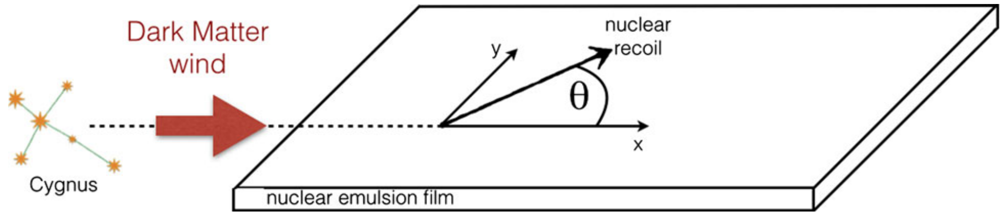
F. Mayet et al., Physics Reports 627(2016)



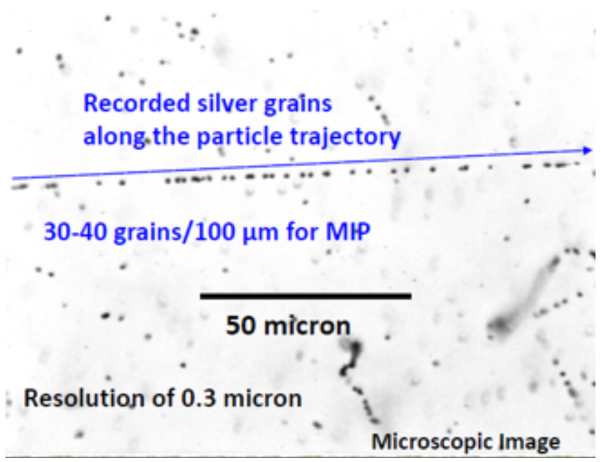
- Low-pressure gas, nuclear emulsion and graphene detectors to measure the recoil direction (30° & 13° res) correlated to galactic motion towards Cygnus
- Challenge: good angular resolution plus head/tails at low recoil energies
- Cygnus: proto-collaboration to coordinate R&D efforts for gas based (He-CF_4) TPCs with ~ 1 keV threshold



CYGNUS



NEWSdm
nuclear emulsions

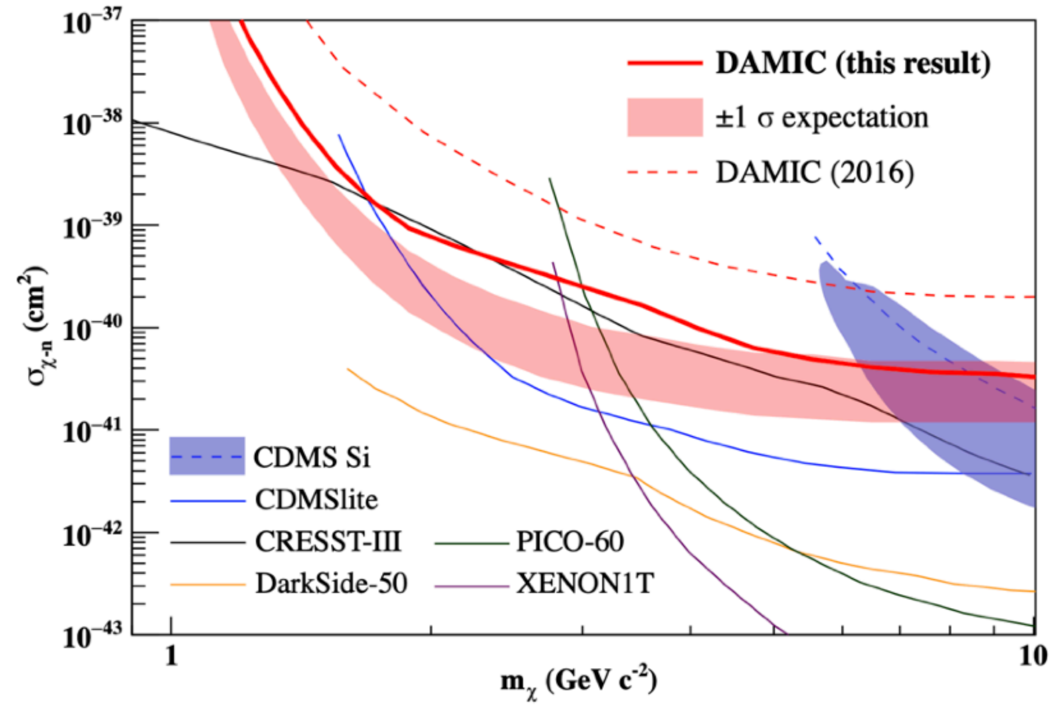


NEWSdm, EPJ-C 78, 2018

IONISATION DETECTORS

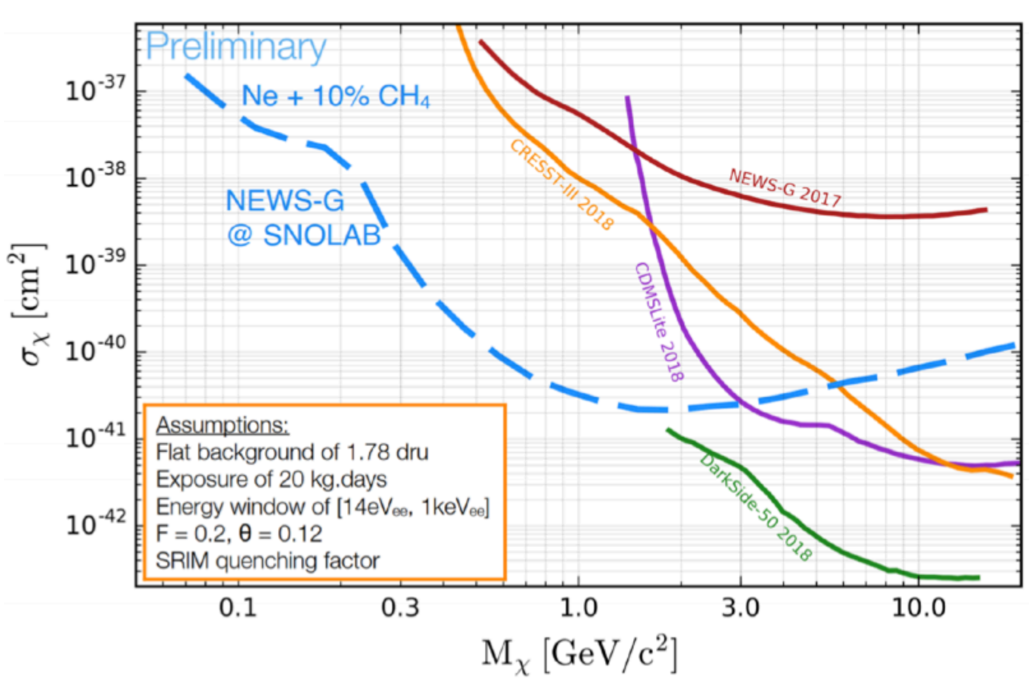
- Point contact HPGe detectors: low energy threshold and (potentially) large total mass (CDEX)
- Si CCDs: low ionisation energy, low noise, and particle tracks for background reduction ⇒ particle ID (DAMIC-M, SENSEI)
- NEWS-G: spherical proportional counter, light targets (H, He, Ne), pulse shape discrimination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

DAMIC, Phys. Rev. Lett. 125, 2020

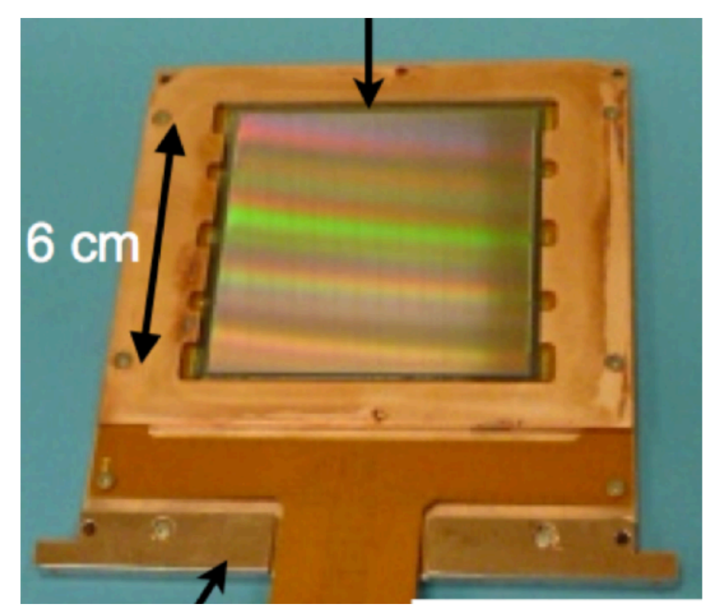


NEWS-G

Reach of NEWS-G at SNOLAB



DAMIC



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 x 10^{-47} cm^2 in ~2018

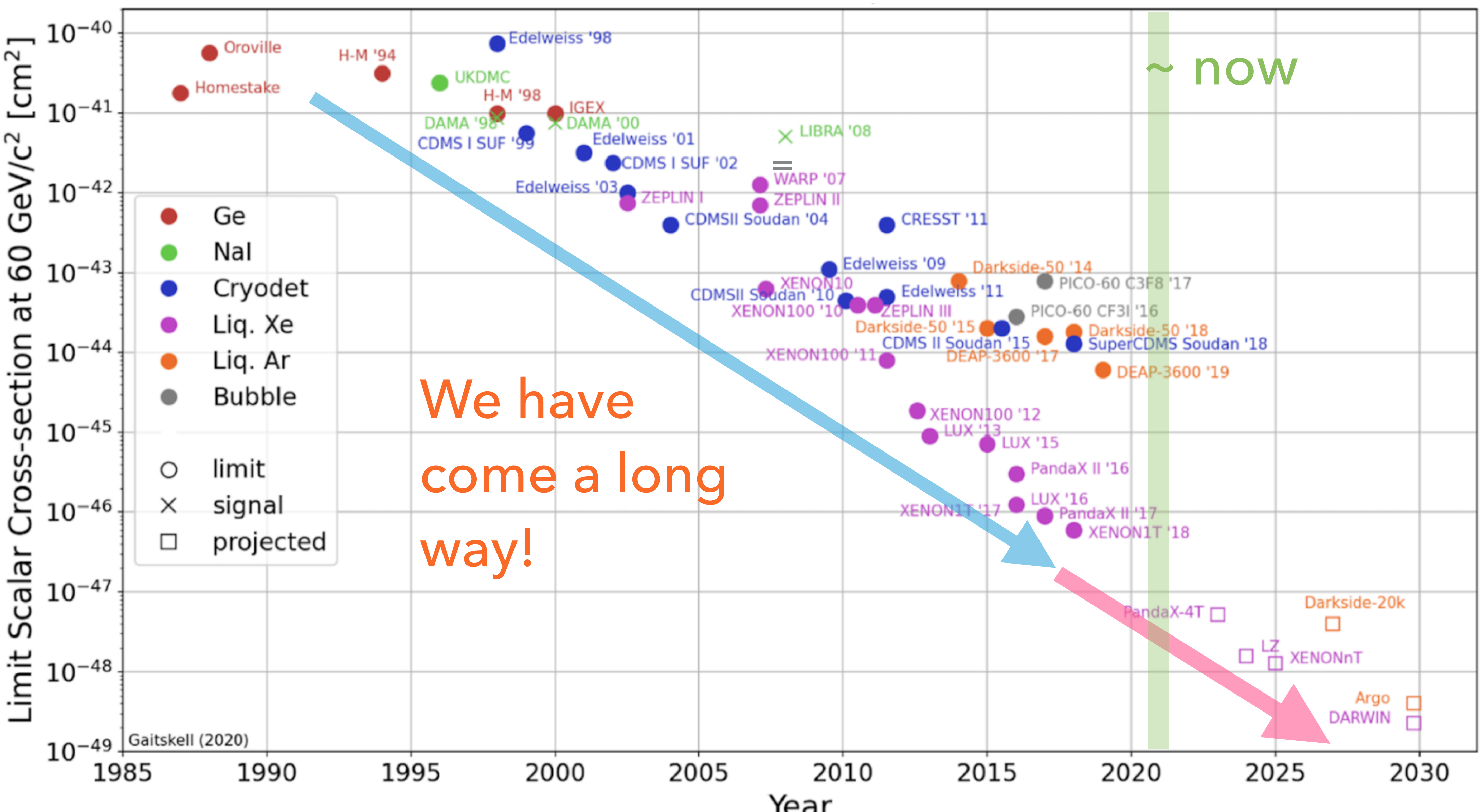
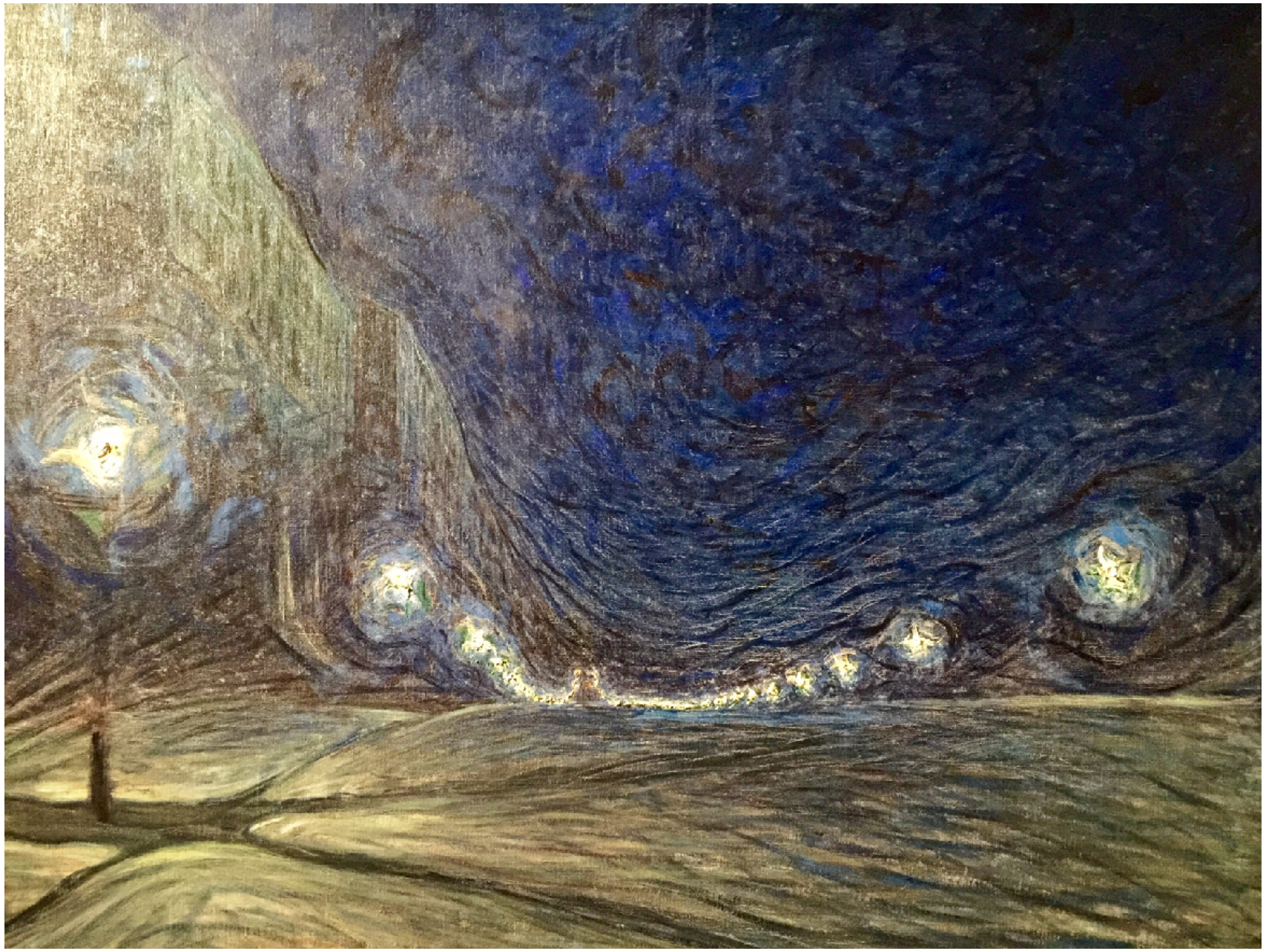


Figure: Rick Gaitskell, 2020

SUMMARY & OUTLOOK

- Dark matter particle candidates cover large mass & cross section range
- A variety of technologies employed for their detection & many new ideas
- So far: we have mostly learned what dark matter is not… we have been narrowing down the options
- However, tremendous progress over the past decades & expected for next
- Pragmatic goal: broaden the searches & probe the experimentally accessible parameter space
- Rich non-WIMP physics programme: neutrinos, solar axions, ALPs, dark photons…
- Remember that yesterday's background might be today's signal ;-)

Of course, "the probability of success is difficult to estimate, but if we never search, the chance of success is zero" G. Cocconi & P. Morrison, Nature, 1959



Eugene Jansson
Hornsgatan Nattetid, 1902

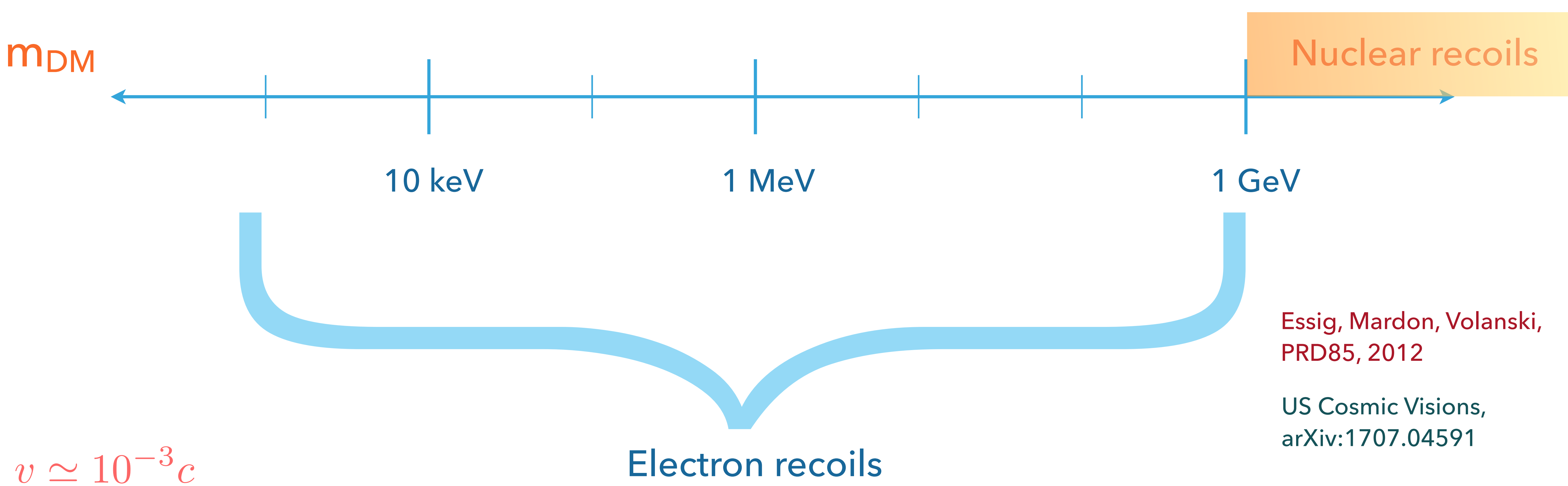
ADDITIONAL MATERIAL

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

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

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



Essig, Mardon, Volanski, PRD85, 2012

US Cosmic Visions, arXiv:1707.04591

$v \simeq 10^{-3} c$

INTERACTION RATES: DM ABSORPTION

- Absorption of bosonic DM (ALPs, dark photons) via the "axioelectric" effect
- Rates ~ φ x σ ~ ρ x v/m x σ (here ρ = 0.3 GeV/cm³)

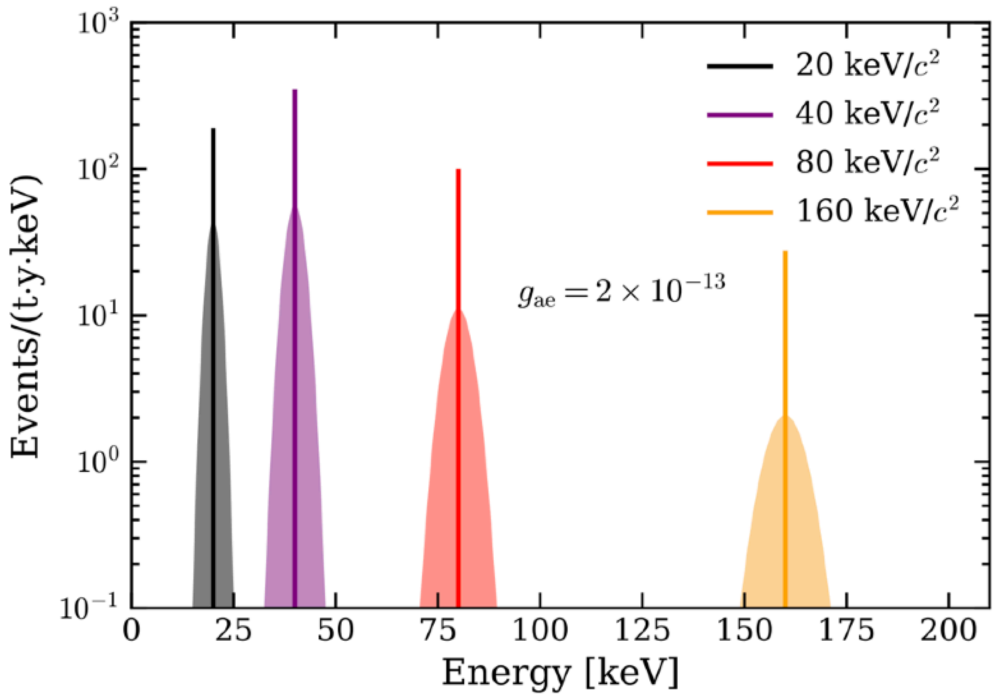
$$R \simeq \frac{1.5\times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

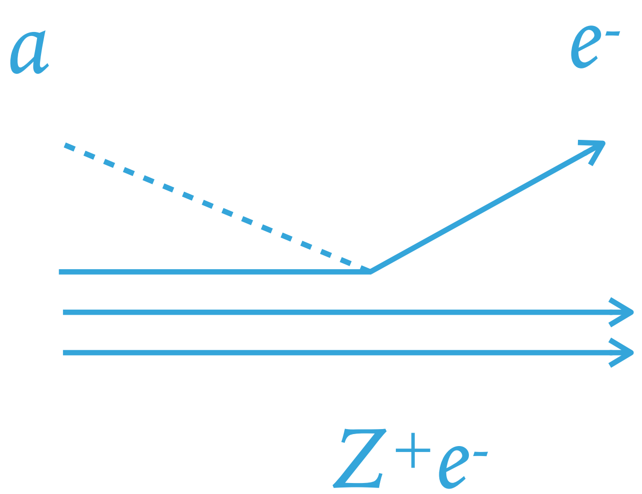
$$\sigma_{ae} = \sigma_{pe}\frac{g_{ae}^2}{\beta}\frac{3E_a^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

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

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

strength of kinetic mixing between photon and dark photon

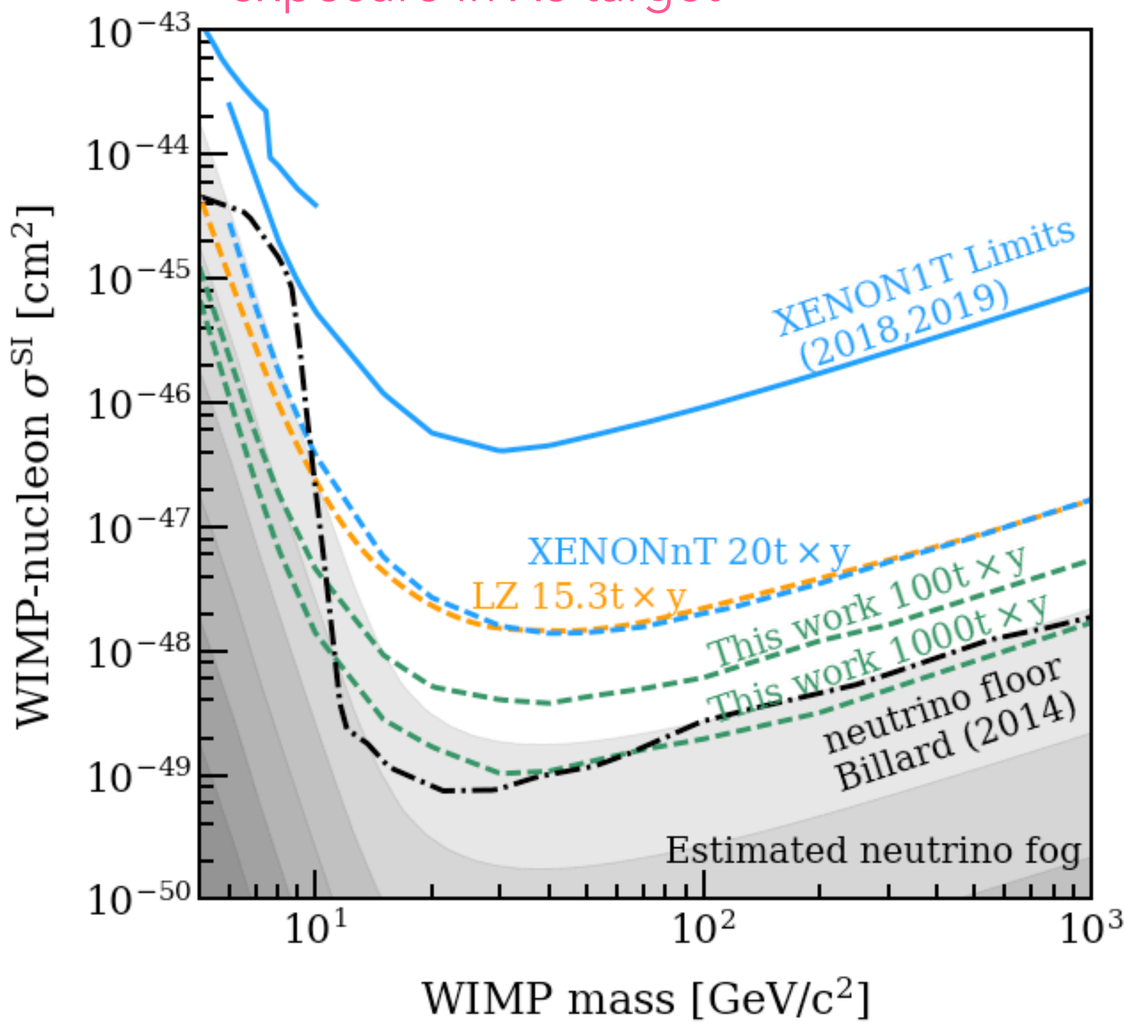




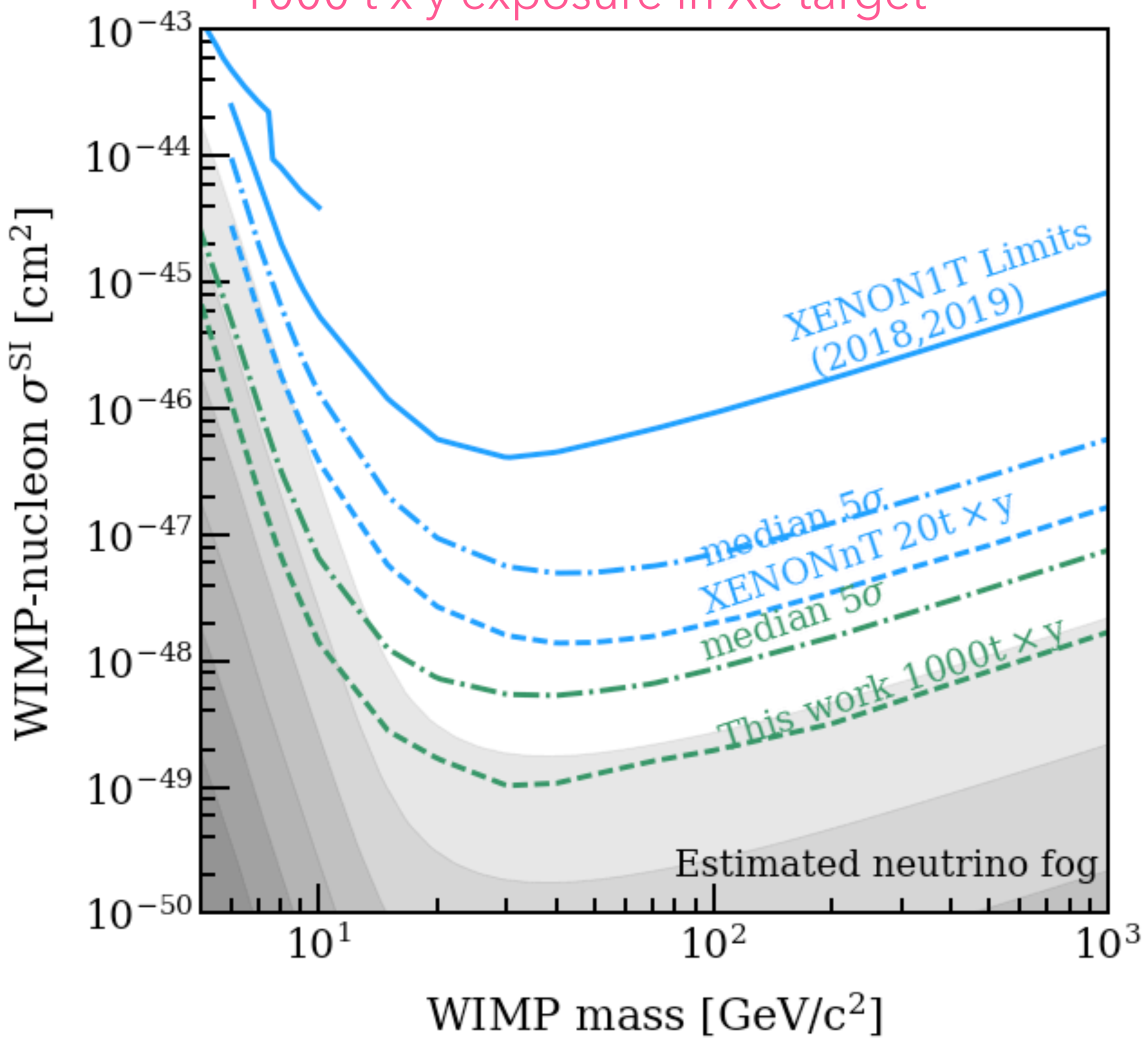
Pospelov, Ritz, Voloshin, PRD 78, 2008; An, Pospelov, Pradler, Ritz, PLB747, 2015

BACKGROUNDS: THE NEUTRINO FOG

Upper limits, 100 t x y and 1000 t y exposure in Xe target



5σ discovery for 6 x 10^{-49} cm^2, 50 GeV, 1000 t x y exposure in Xe target



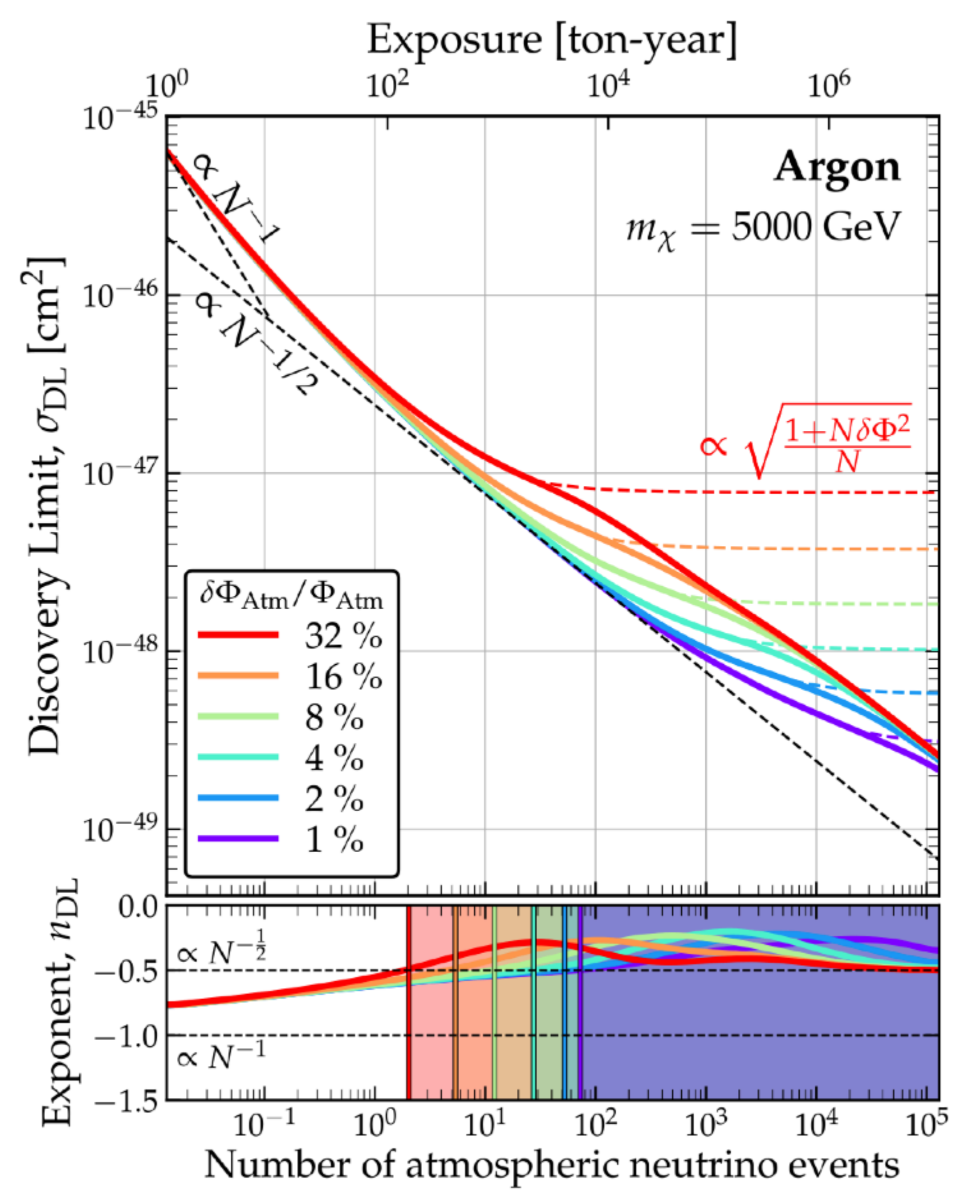
Figures: Knut Moraa

Shaded grey areas: the "neutrino fog" -> 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

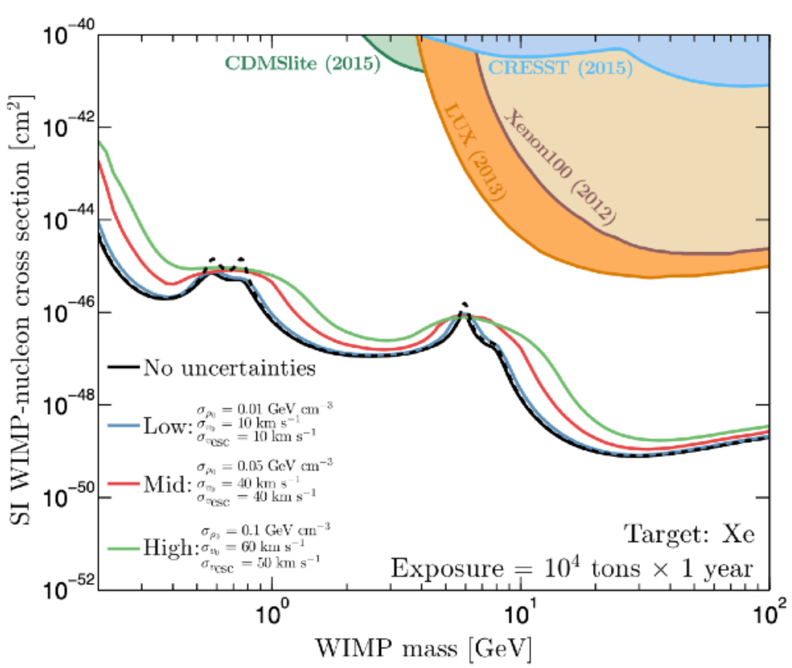
BACKGROUNDS: THE NEUTRINO FOG

- 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 (~2% in ^8B, ~20% for atmospheric neutrinos)
  - nuclear and astro inputs for the DM signal

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



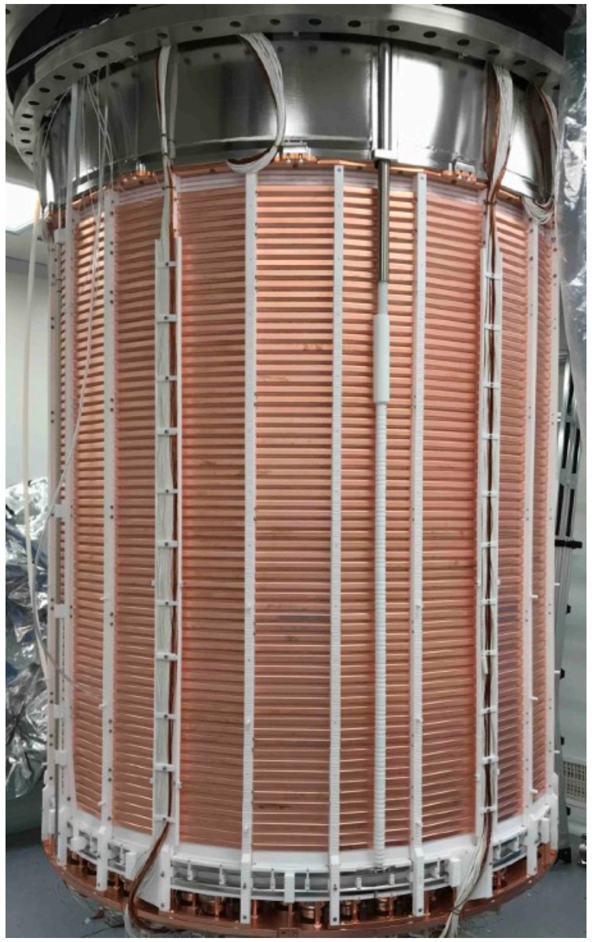
Discovery limit of a **5 TeV WIMP in an argon target**, as a function of the atm. neutrino event N and fract. uncertainty on the atm ν flux: $\delta\Phi_{atm}/\Phi_{atm}$



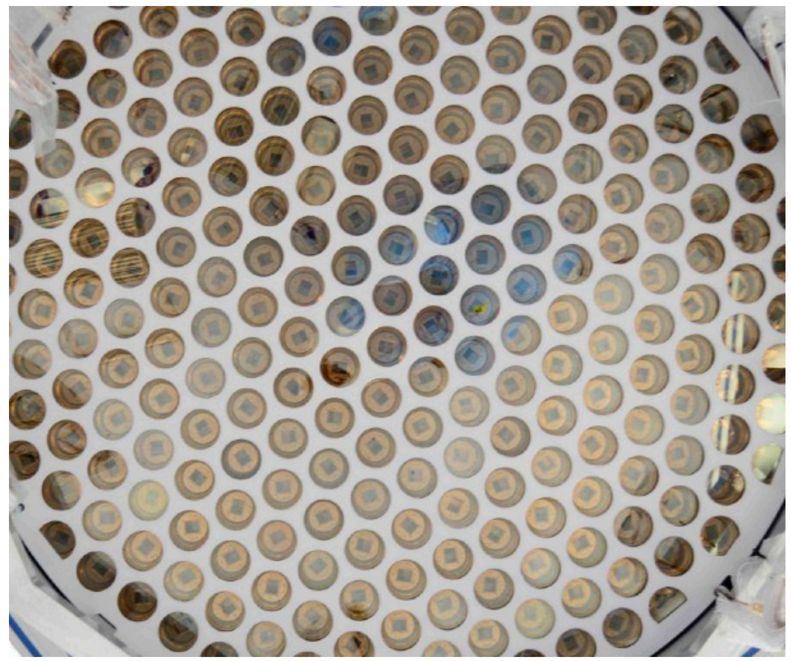
C. A. J. O'Hare PRD 94, 2016

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

XENON-NT

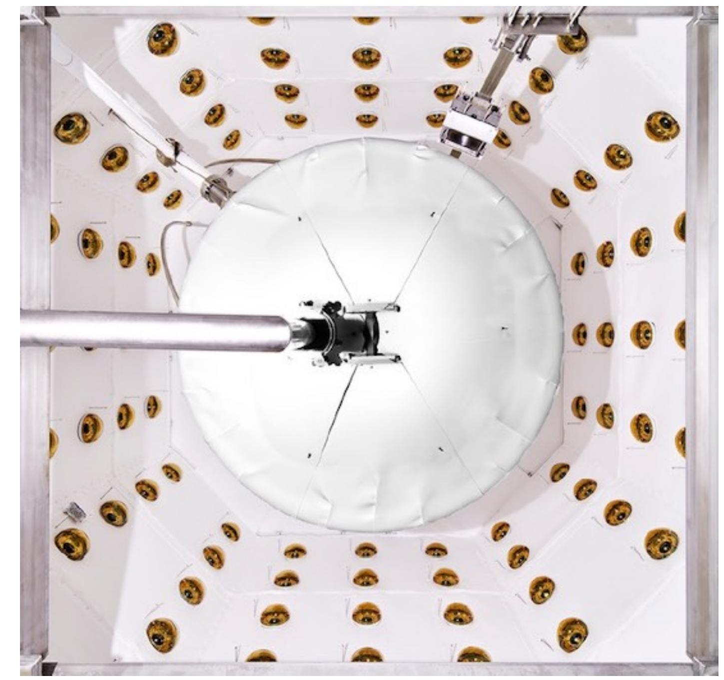


TPC (5.9 t LXe, 4 t fiducial), 1.3 m diameter, 1.5 m tall



PMT array (494 PMTs in total, in 2 arrays)

Neutron veto (120 additional PMTs, Gd doped (0.5% $Gd_2(SO_4)_3$))

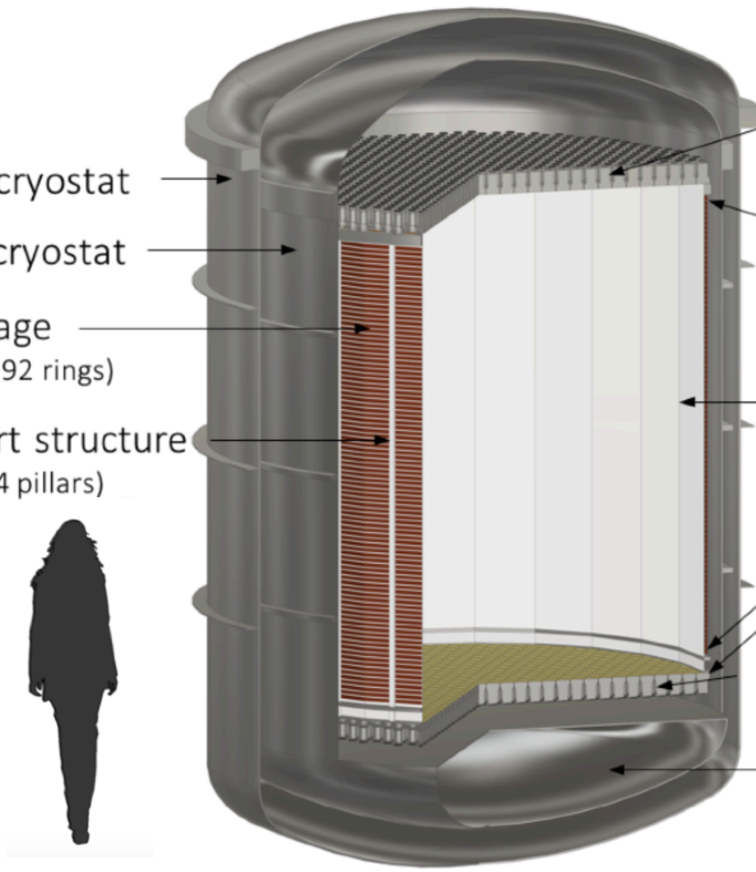


LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm)

Rn distillation column (reduce ^{222}Rn - hence also ^{214}Bi - from pipes, cables, cryogenic system)

THE DARWIN PROJECT

- Two-phase Xe TPC: 2.6 m ø, 2.6 m height
- 50 t (40 t) LXe in total (in the TPC)
- Two arrays of photosensors (e.g., 1800 3-inch PMTs)
- PTFE reflectors and Cu field shaping rings
- Low-background, double-walled titanium cryostat
- Shield: Gd-doped water, for μ and n

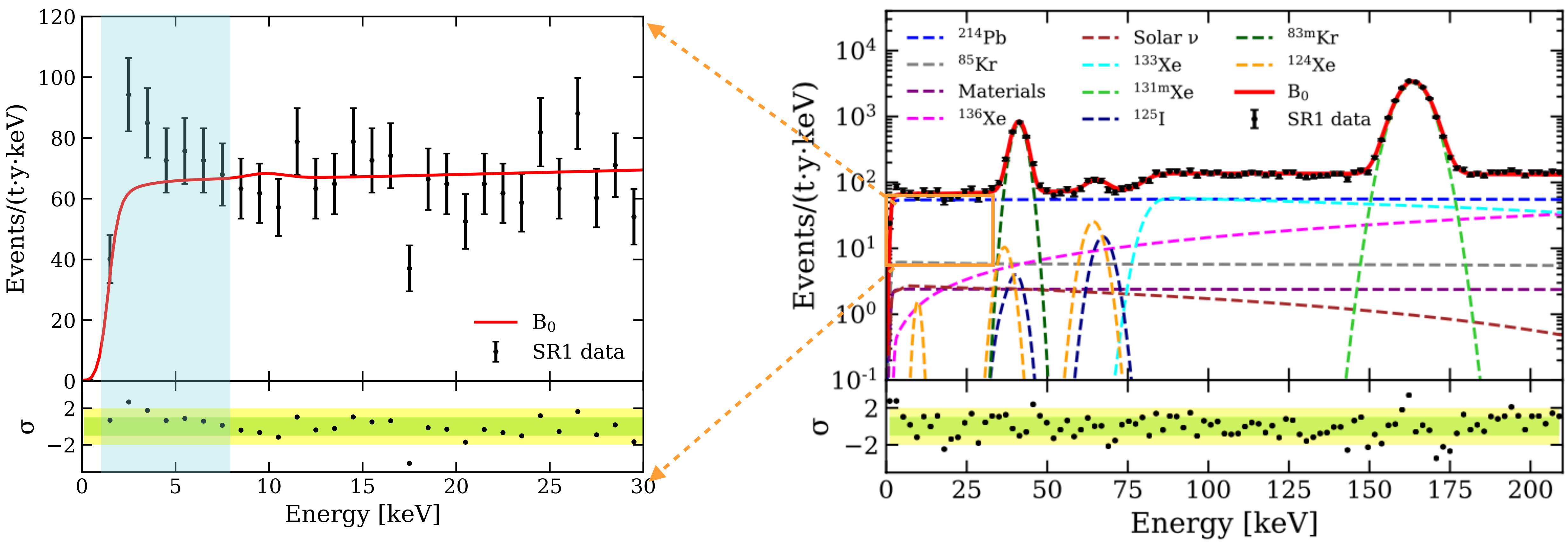


DARWIN collaboration, JCAP 1611 (2016) 017

Alternative TPC designs, photosensors etc under study

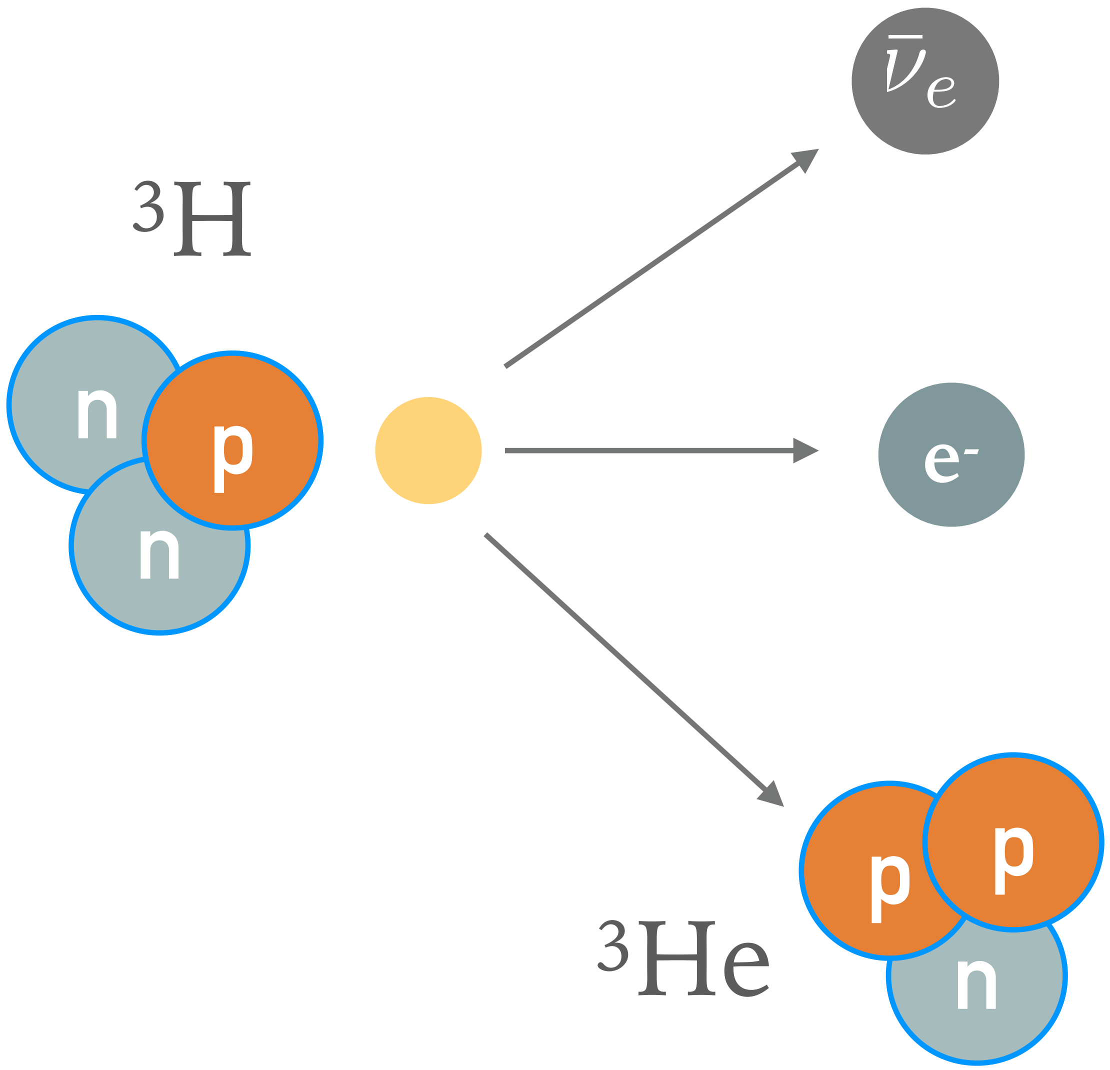
BACKGROUND MODEL AND DATA

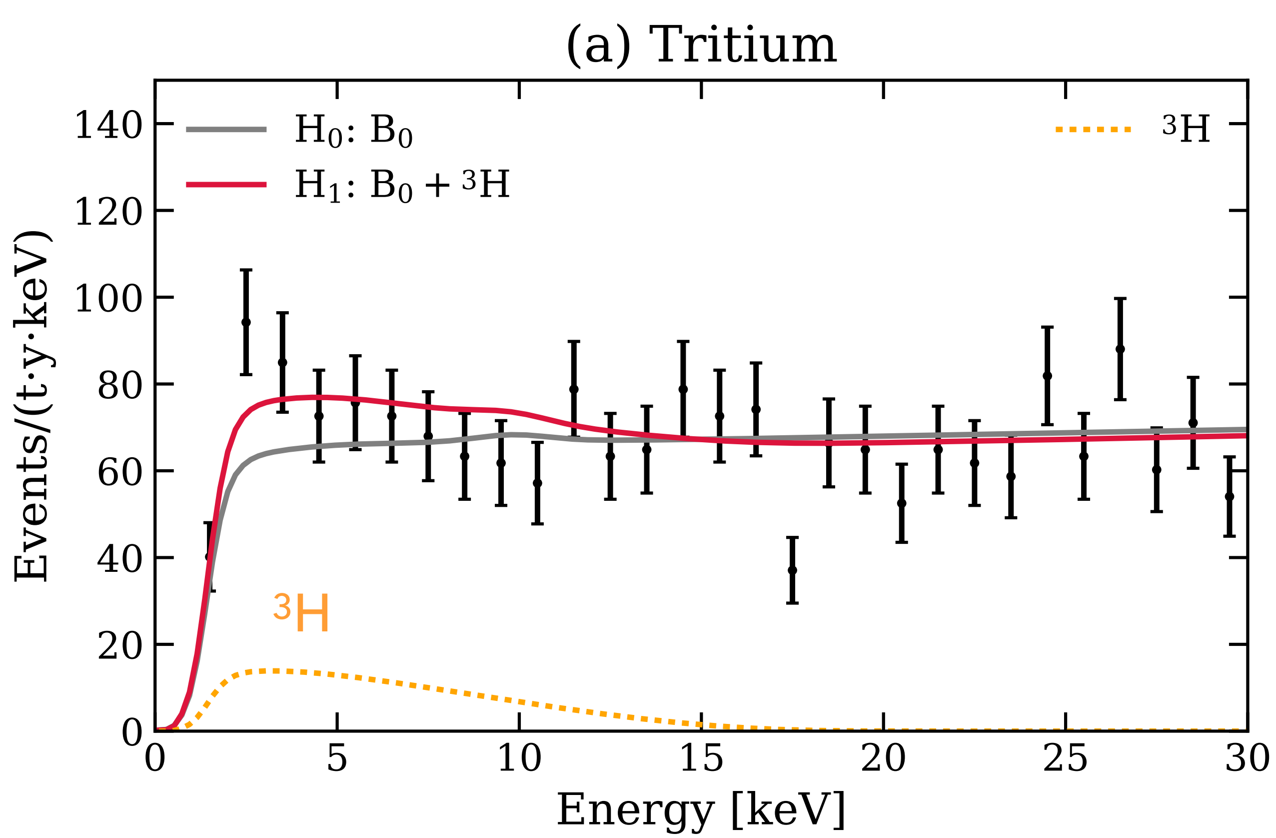
- Good fit over most of the energy region
- Excess between (1,7) keV
- Number of observed events: 285, expected from background: (232±15) events



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)

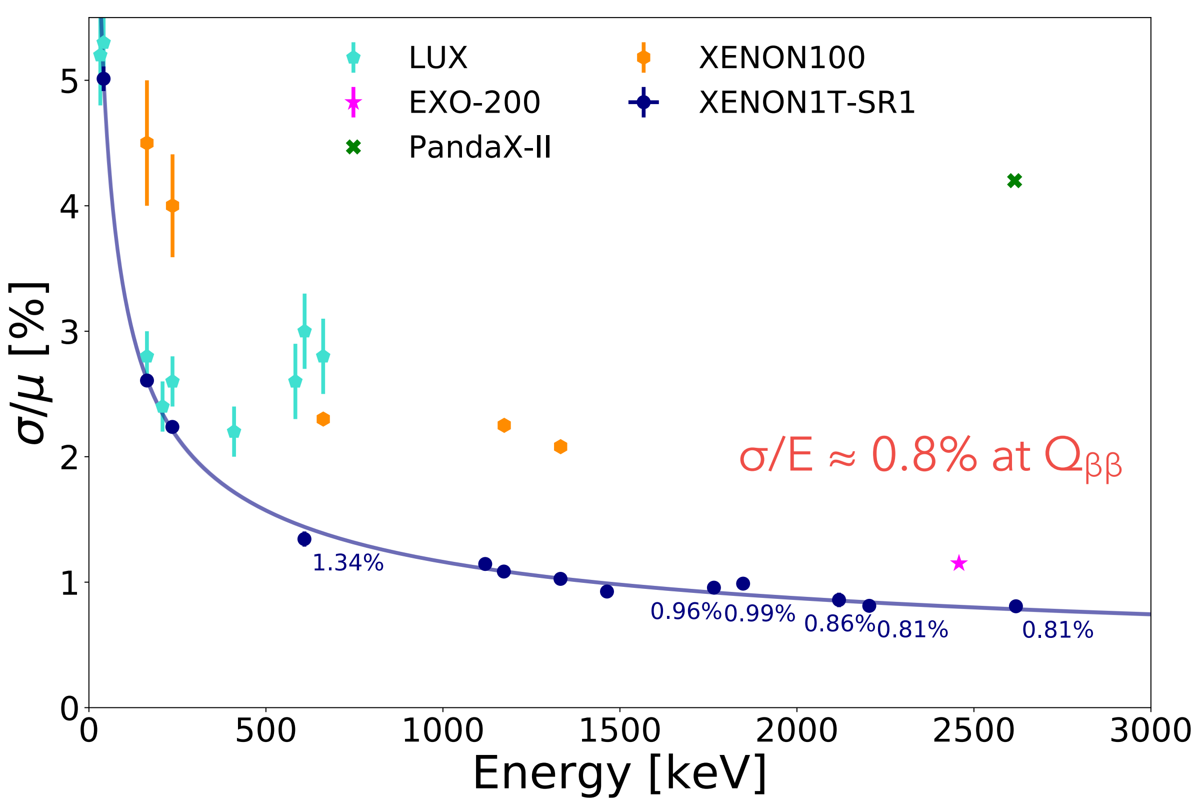
^{3}H:Xe concentr.: (6.2 ± 2.0) x 10^{-25} mol/mol

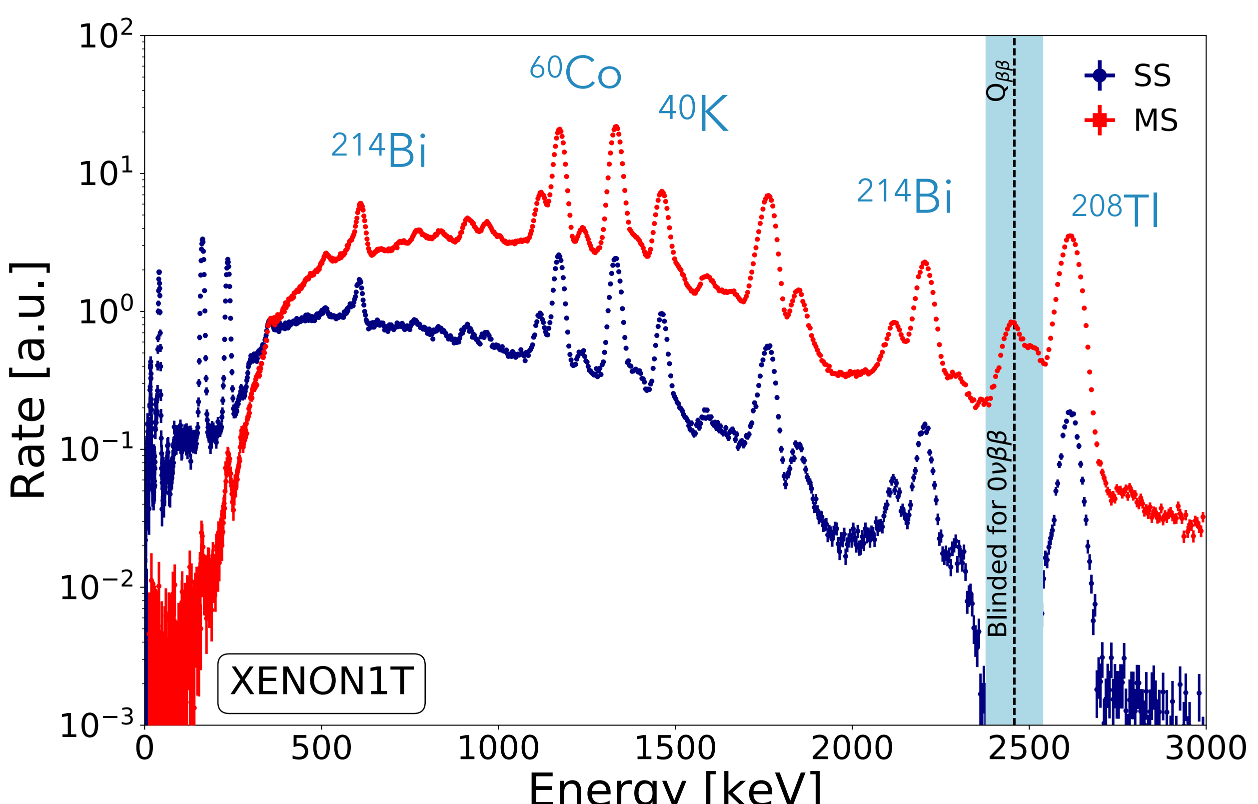
< 3 ^{3}H atoms per kg of xenon

Tritium favoured over background-only fit at 3.2 σ

HIGH–ENERGY ANALYSIS FOR A DOUBLE BETA SEARCH OF ^{136}XE

- Motivation: search for $0\nu\beta\beta$-decay of ^{136}Xe, at $Q_{\beta\beta}$= (2457.83±0.37) keV, understand background rate and spectrum at high energies
- Correct for signal saturation, determine event multiplicity, energy scale, resolution
- Achieved σ/E ~0.8%; $0\nu\beta\beta$-decay data analysis and data/MC matching in progress

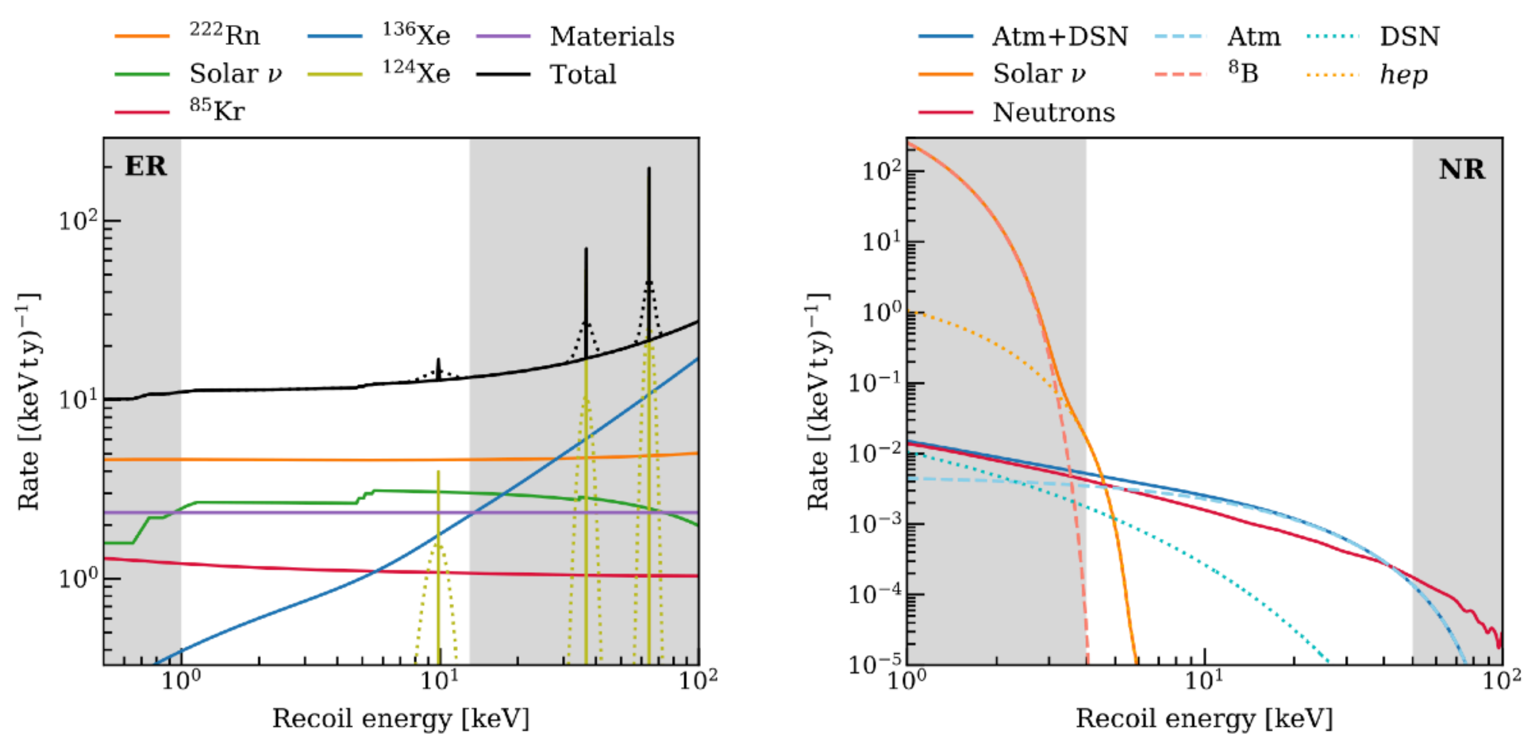




XENON collaboration, EPJ-C 80, 2020

XENON-NT: BACKGROUND PREDICTIONS

Source	Rate $[(\mathrm{t\,y})^{-1}]$
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	$(4.1 \pm 2.1) \times 10^{-2}$
CEνNS (Solar ν)	$(6.3 \pm 0.3) \times 10^{-3}$
CEνNS (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
	Observable ROI	Reference signal region	(ξ)
Background			
ER	2440	1.56	
Neutrons	0.29	0.15	50%
CEνNS (Solar ν)	7.61	5.41	4%
CEνNS (Atm+DSN)	0.82	0.36	20%
WIMP signal			
$6\,\mathrm{GeV/c^2}$ ($\sigma_{\mathrm{DM}} = 3 \times 10^{-44}\,\mathrm{cm^2}$)	25	19	
$50\,\mathrm{GeV/c^2}$ ($\sigma_{\mathrm{DM}} = 5 \times 10^{-47}\,\mathrm{cm^2}$)	186	88	
$1\,\mathrm{TeV/c^2}$ ($\sigma_{\mathrm{DM}} = 8 \times 10^{-46}\,\mathrm{cm^2}$)	286	118	

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