SUCHE NACH DUNKLER MATERIE MIT XENON UND DARWIN

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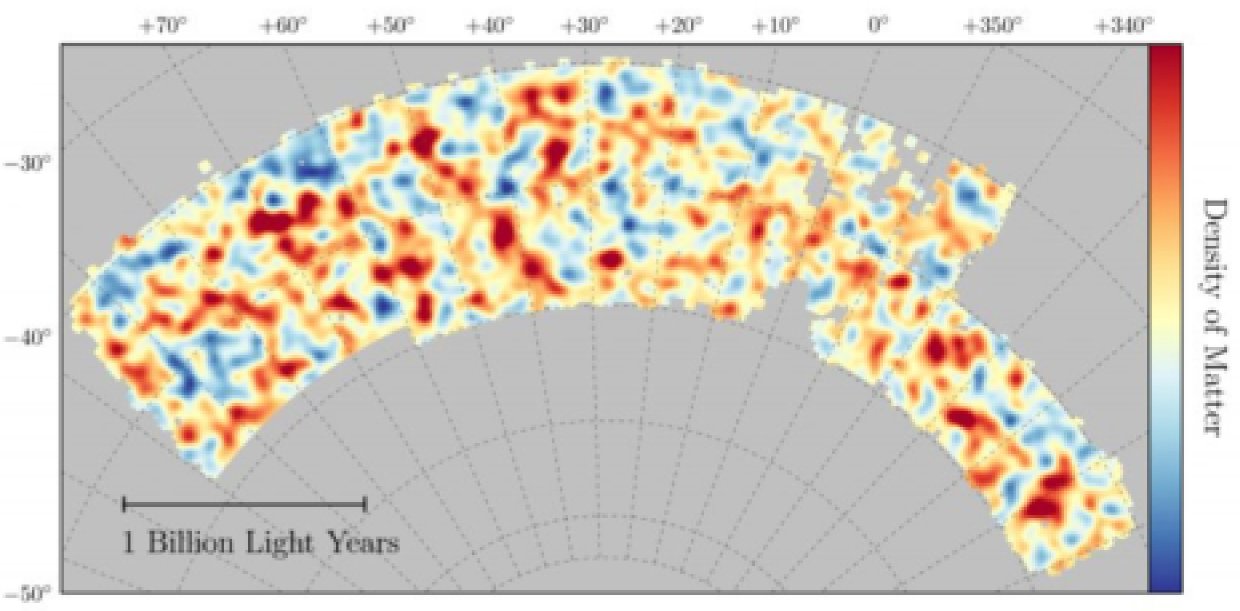
PHYSIKALISCHE GESELLSCHAFT ZÜRICH
8. NOVEMBER 2018

IN THE DARK…

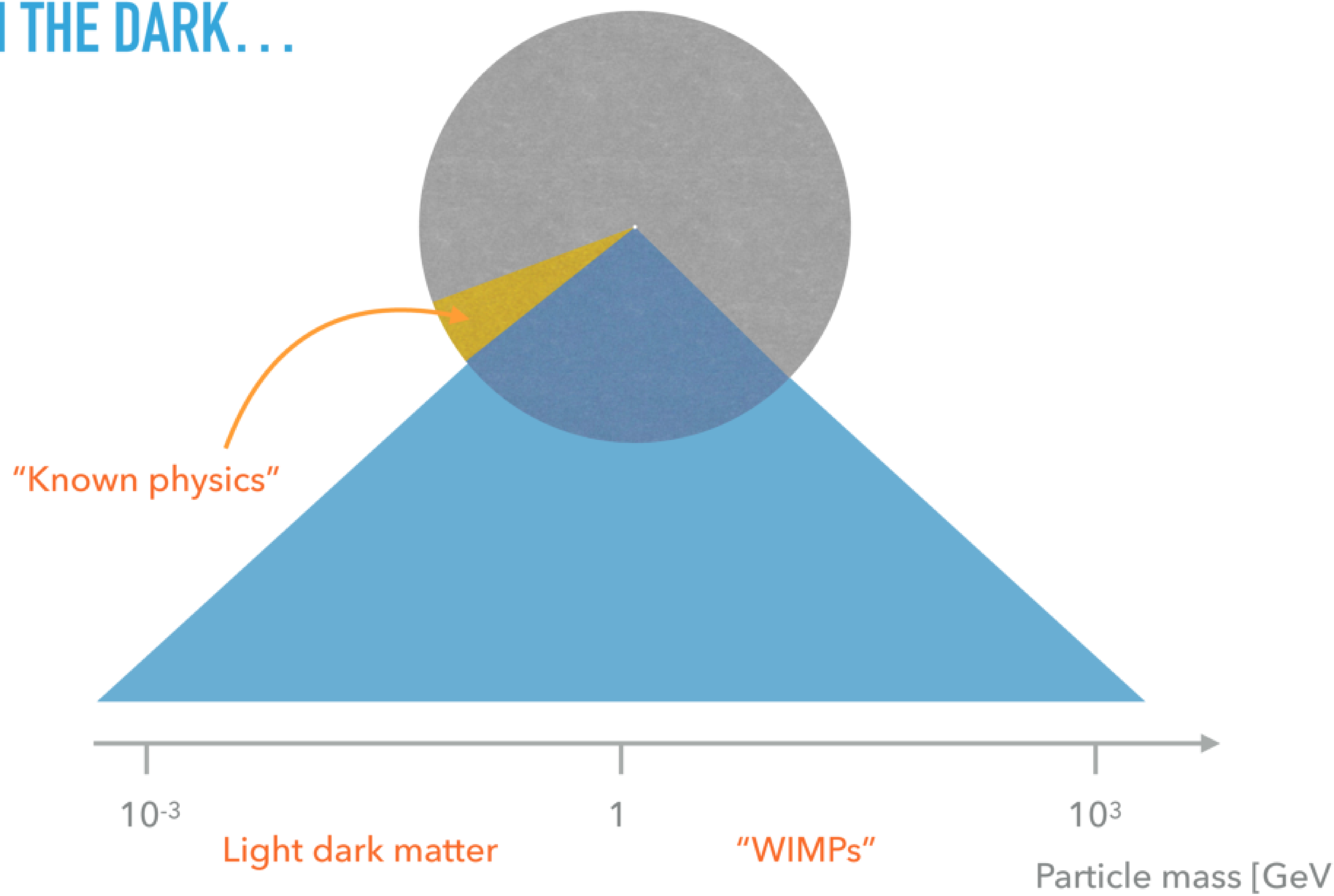
- The evidence for dark matter is overwhelming
  - Early and late cosmology (CMB, LSS)
  - Clusters of galaxies
  - Galactic rotation curves
  - BBN, …



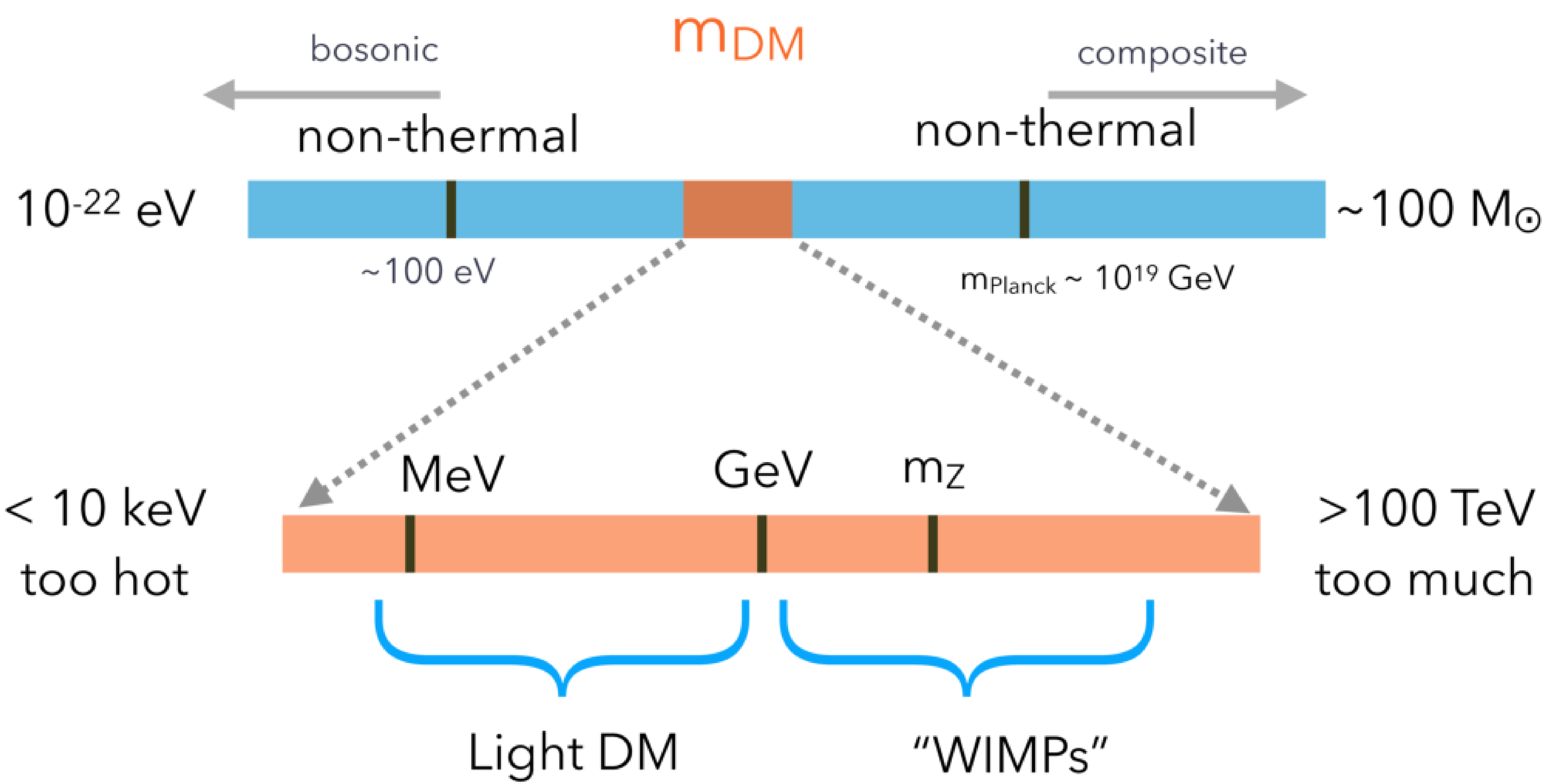
First DES dark matter results, 26×10^6 galaxies

- But - no idea about its composition at the particle level

IN THE DARK…


"Known physics"
10^{-3}
1
10^{3}
Light dark matter
"WIMPs"
Particle mass [GeV]

DARK MATTER CANDIDATES

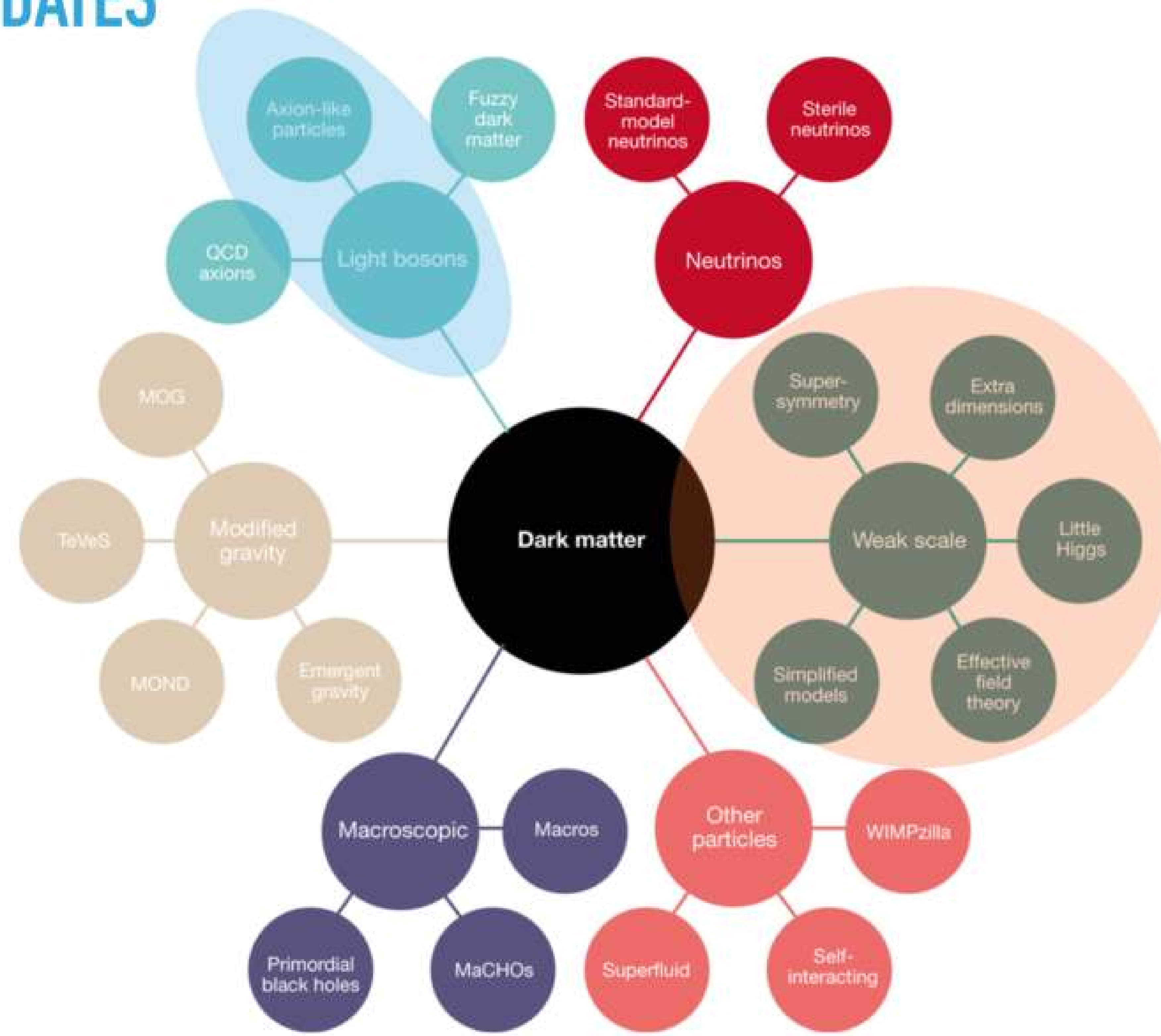


DARK MATTER CANDIDATES

Bertone and Tait, Nature 562, 51–56 (2018)

In this talk

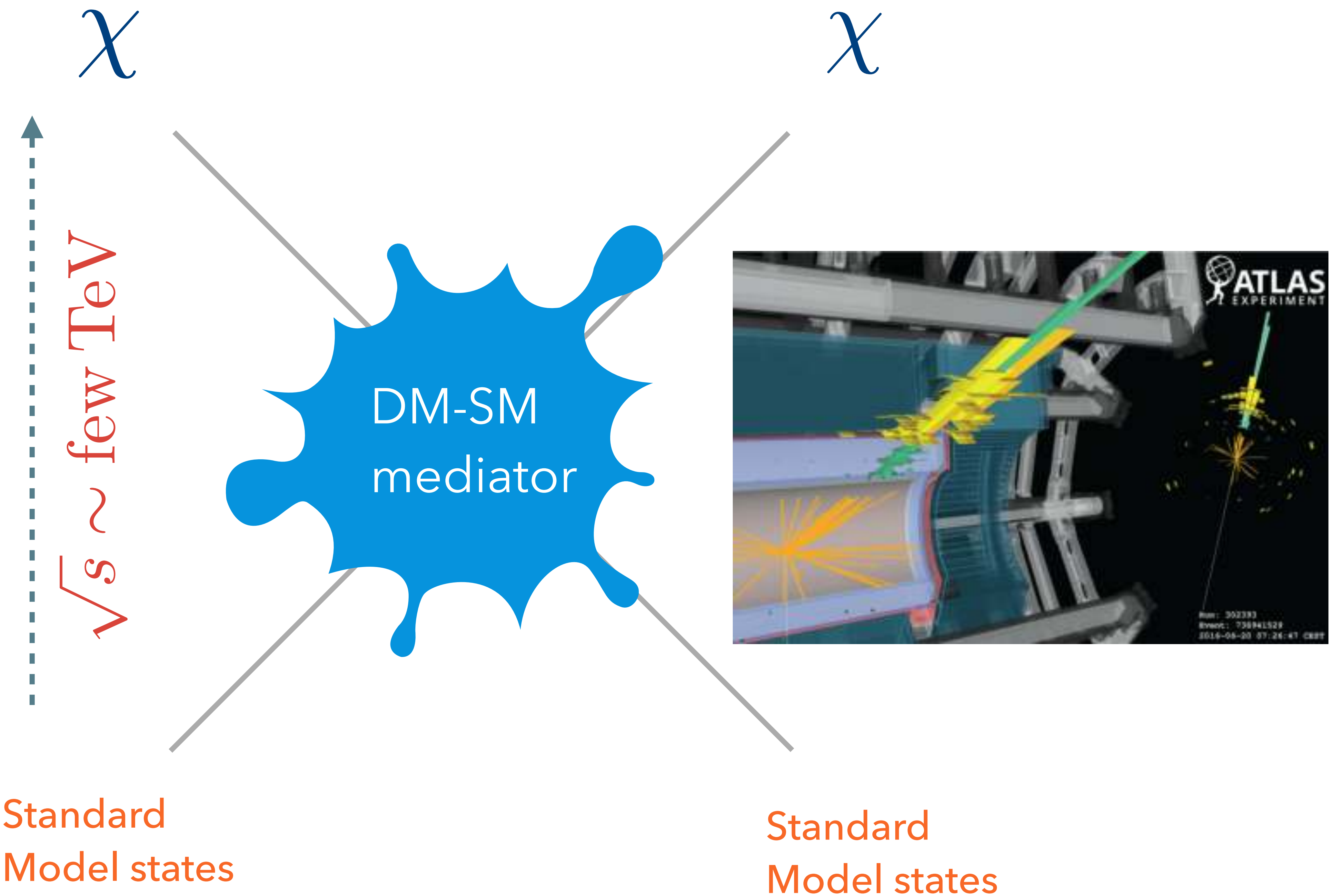
DARK MATTER CANDIDATES



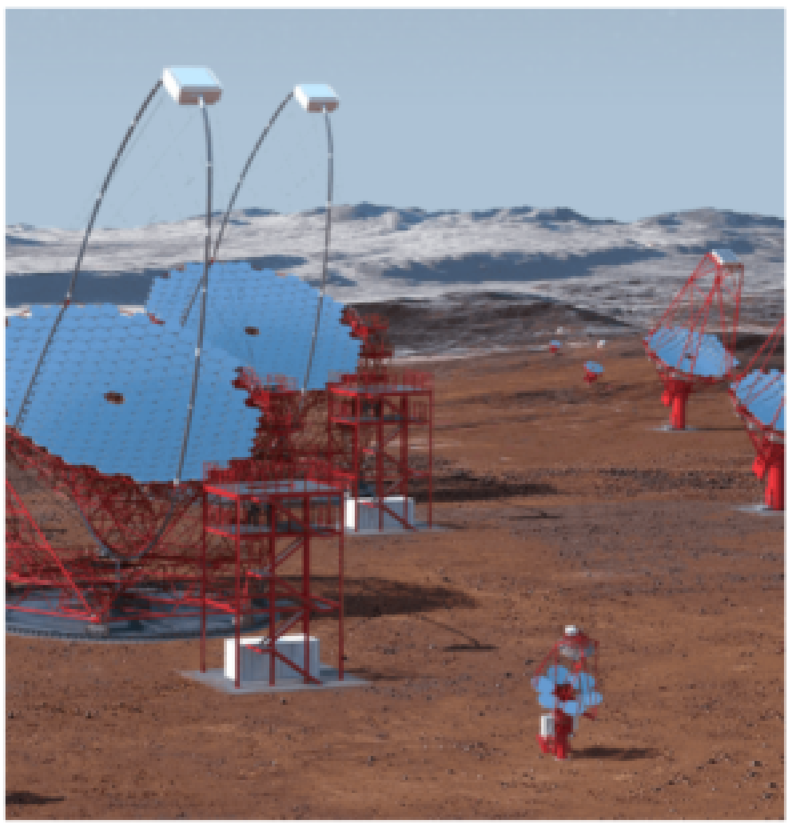
Bertone and Tait, Nature 562,
51–56 (2018)

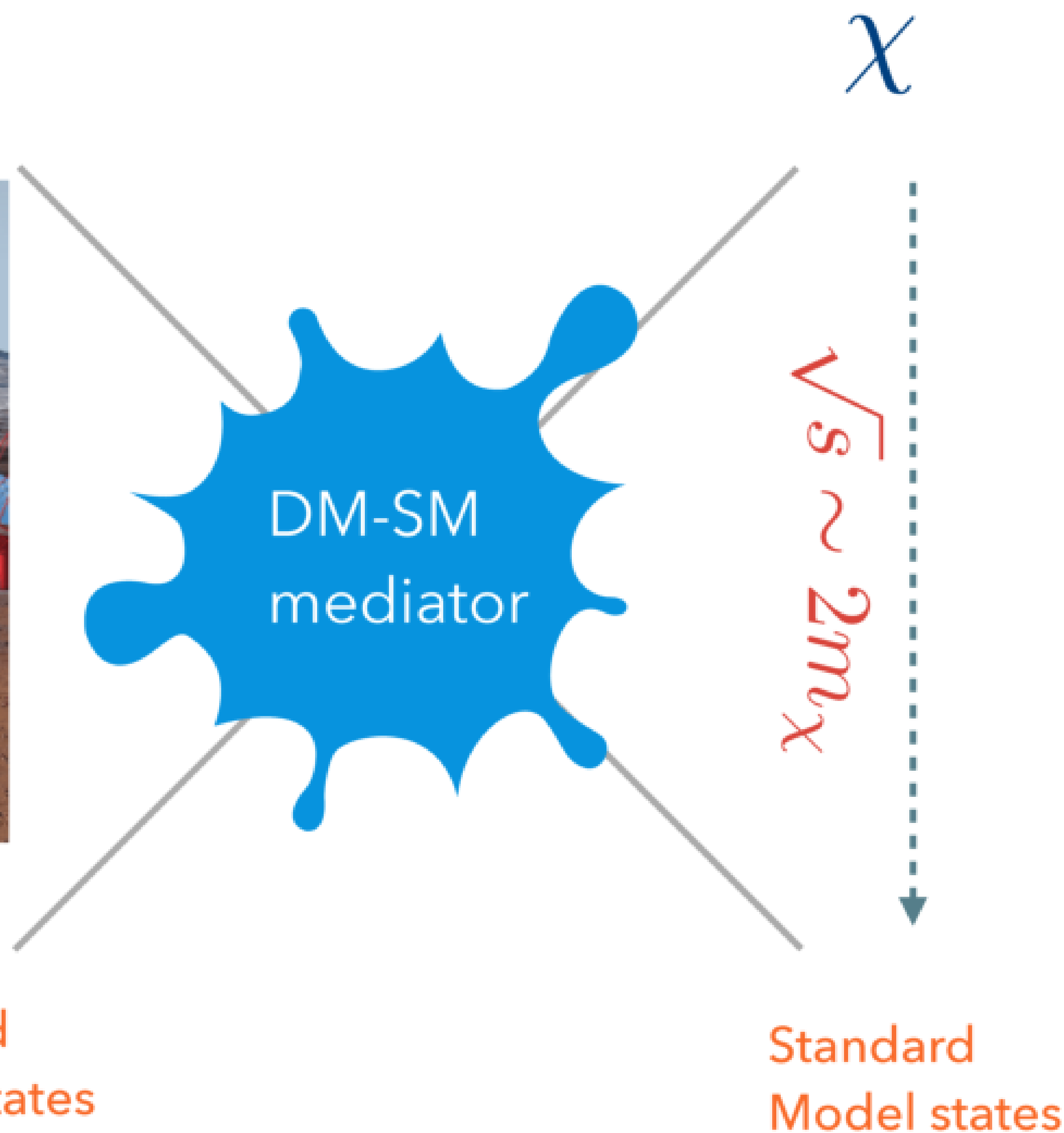
HOW TO SEE IN THE DARK?

- light dark matter searches at colliders, fixed target and beam dump experiments (new, light mediator) to probe the 'dark sector'



HOW TO SEE IN THE DARK?

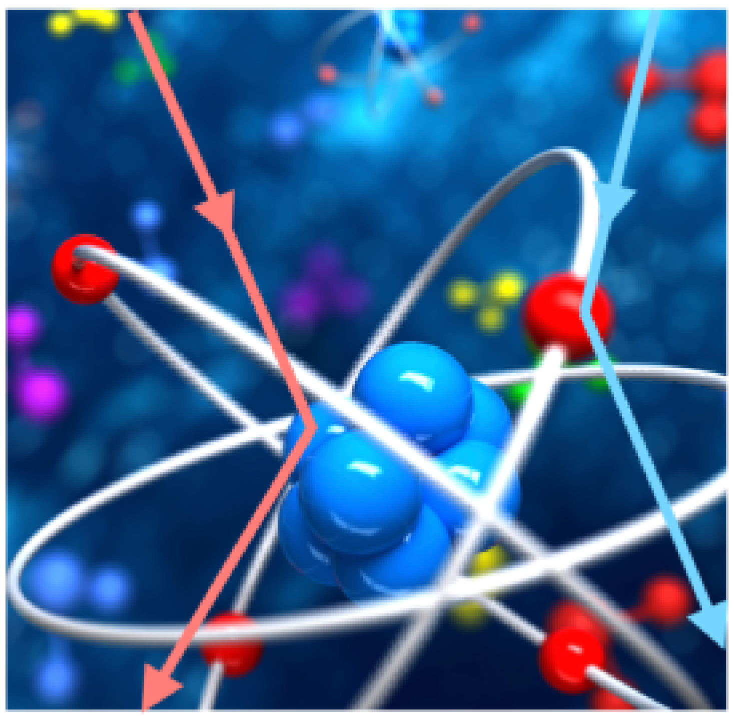


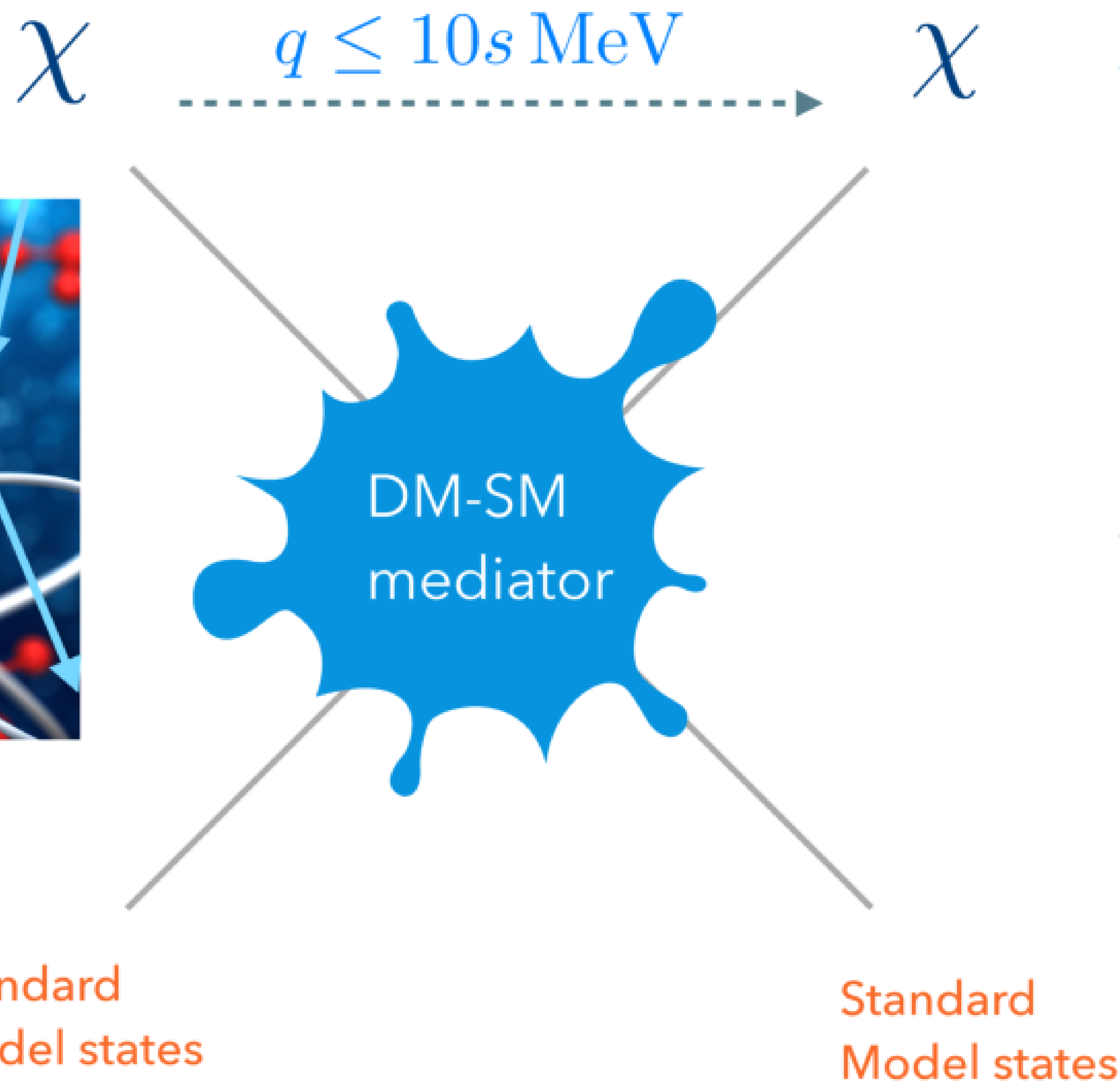


- astrophysical probes, e.g. observations of structures on small scales/ comparison with simulations
- early Universe annihilation, e.g., constraints from CMB

see M. Buckley and A. Peter for recent review 1712.06615

HOW TO SEE IN THE DARK?



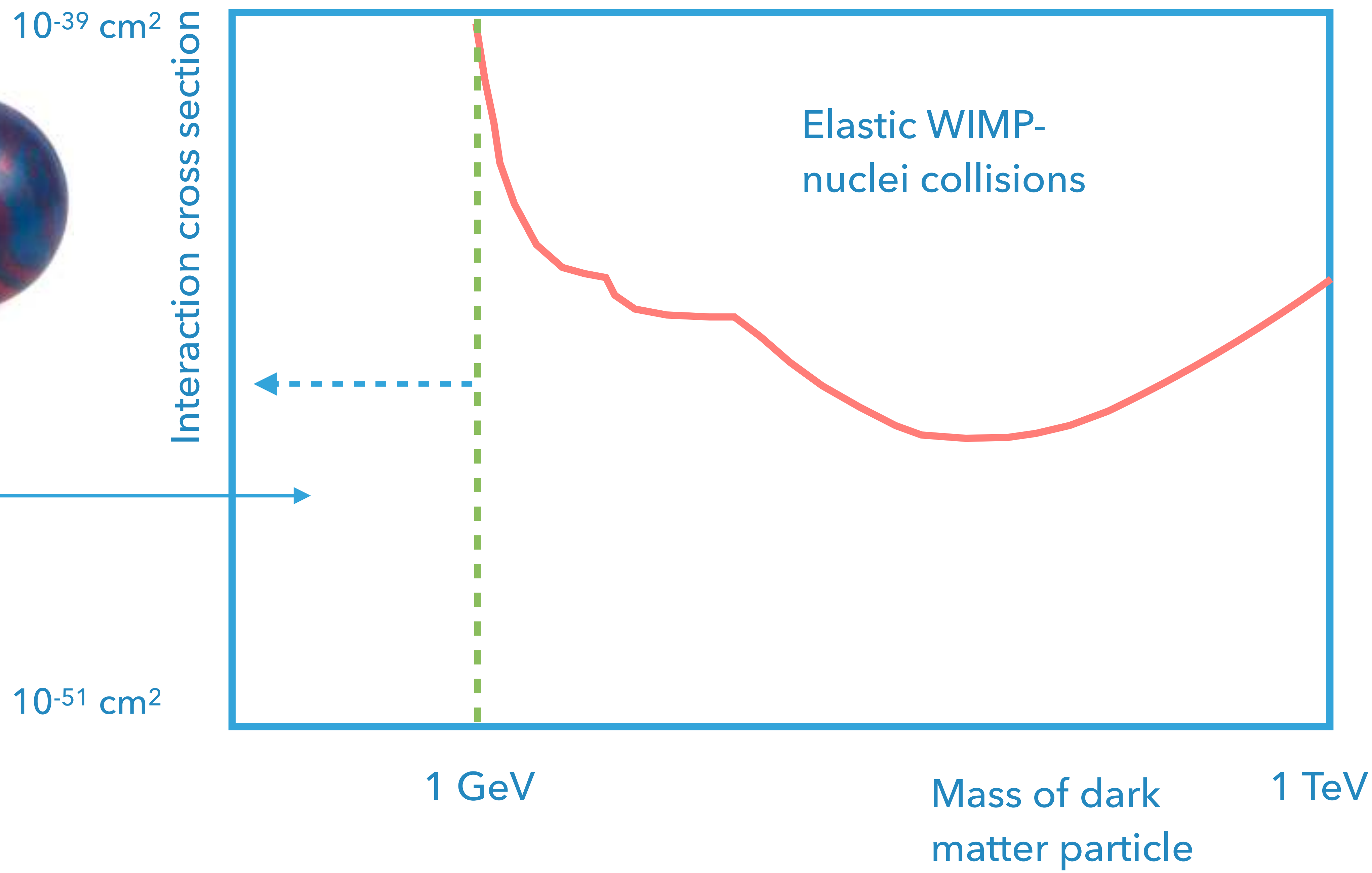


- collisions with electrons in the atomic shell, or absorption of light bosons via the so-called axio-electric effect
- Bremsstrahlung from polarised atoms; e$^-$ emission due to so-called Migdal effect

see Kouvaris, Pradler, McCabe; M. Ibe et al.

DARK MATTER PARTICLE INTERACTIONS

Electron recoils and additional signal from shell e^- from the recoiling nuclei



WHAT TO EXPECT IN AN EARTH-BOUND DETECTOR?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Detector physics

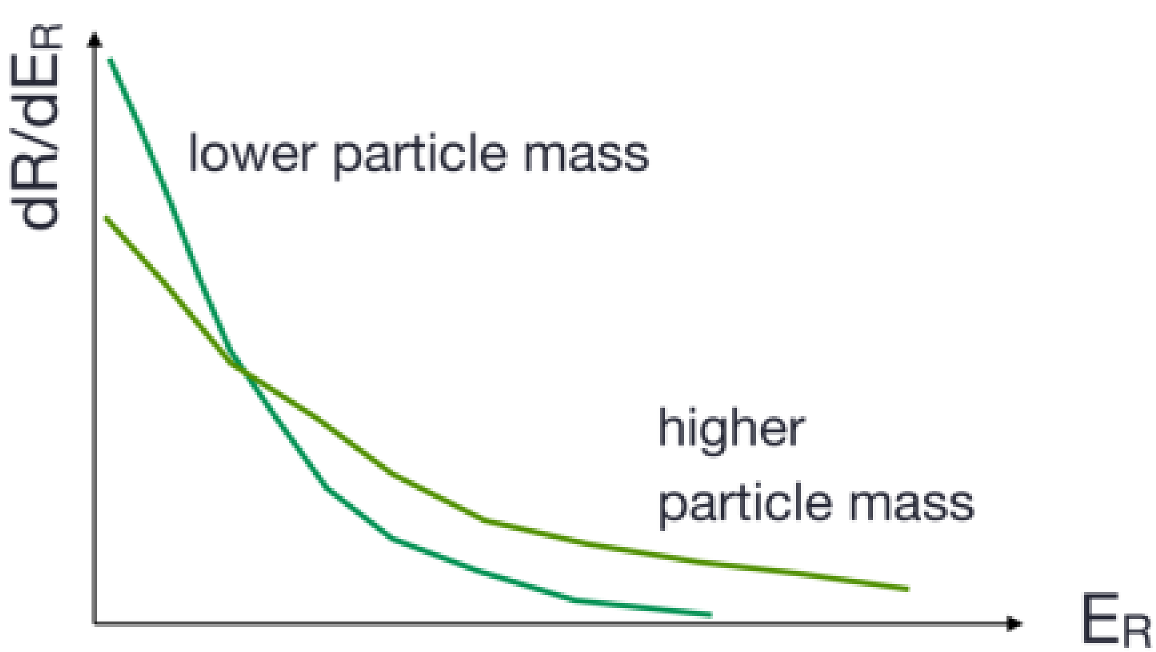
N_N, E_{th}

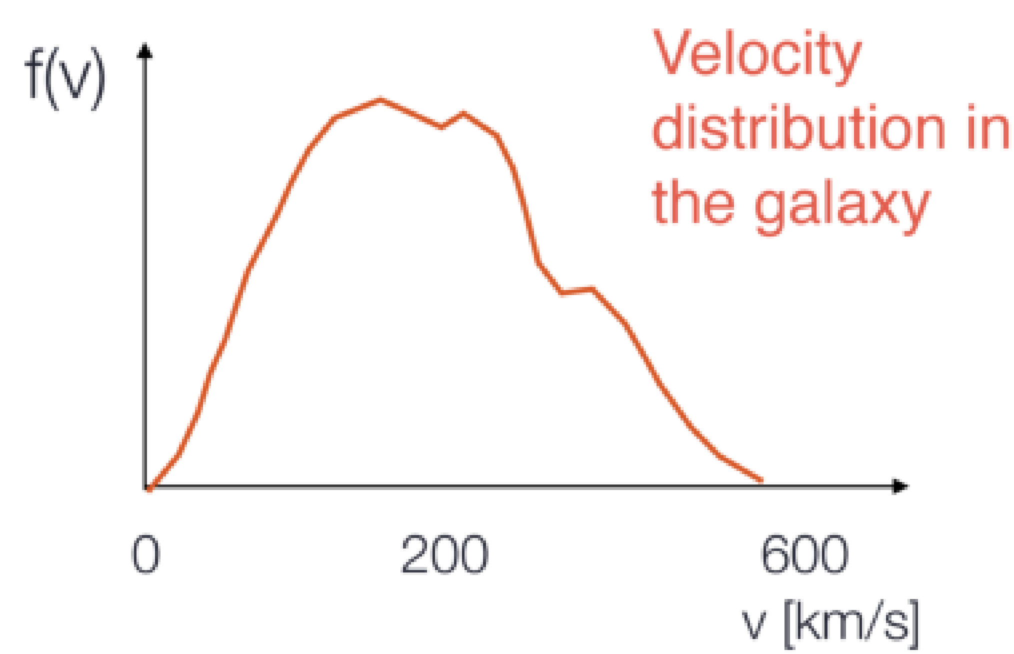
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$





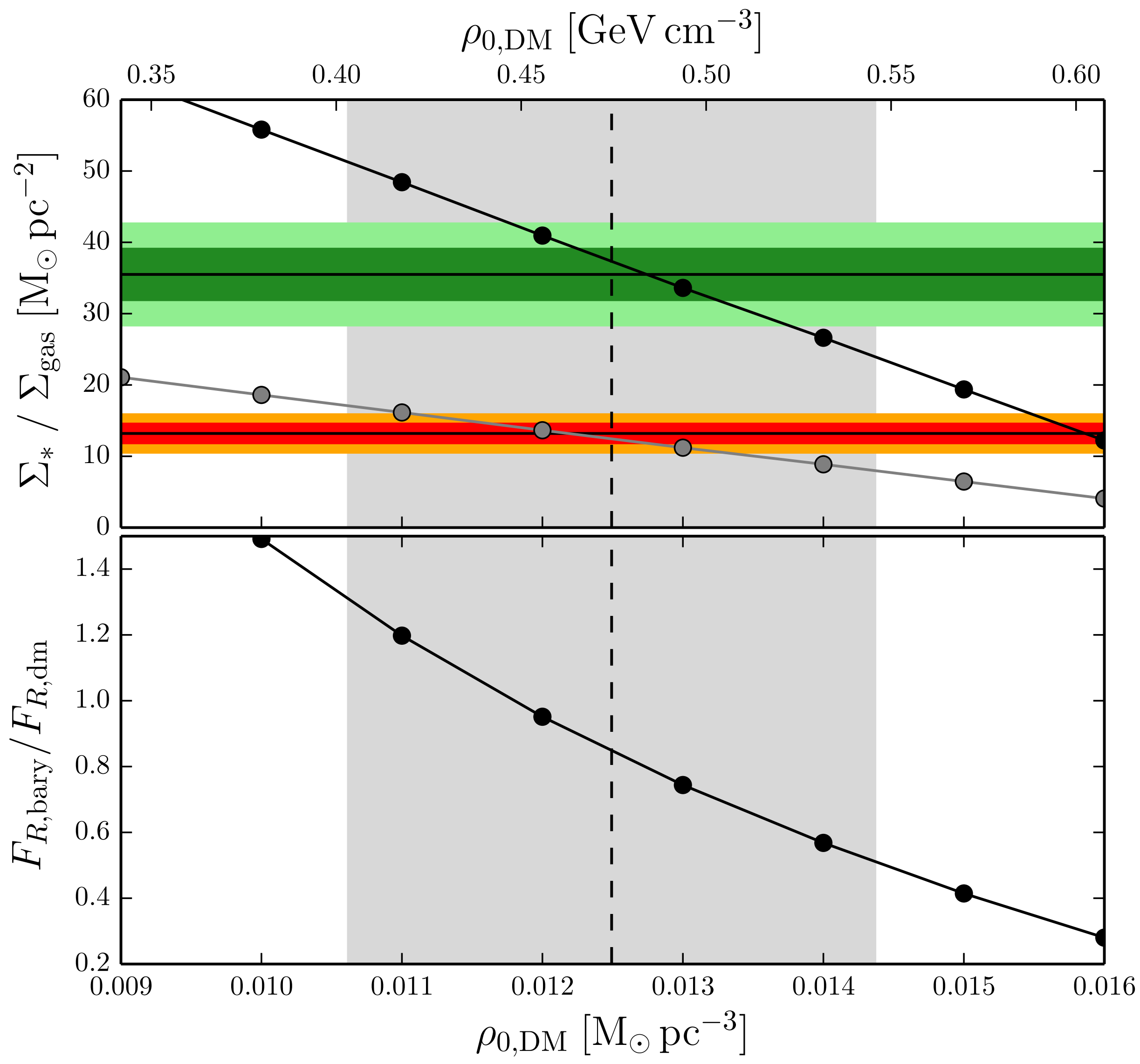
LOCAL DARK MATTER DENSITY

- Local measures: vertical kinematics of starts near Suns as 'tracers' (smaller error bars, stronger assumptions about the halo shape)
- Global measures: extrapolate the density from the rotation curve (larger errors, fewer assumptions)

Gaia mission: data from 1.4 x 10^9 stars

Piffle et al, 2014, MNRAS 445. 3133

see also
J. Hagen & A. Helmi, A&A 615, 2018 for somewhat higher dark matter densities (0.018 M_o/pc^3)



DARK MATTER VELOCITY DISTRIBUTION

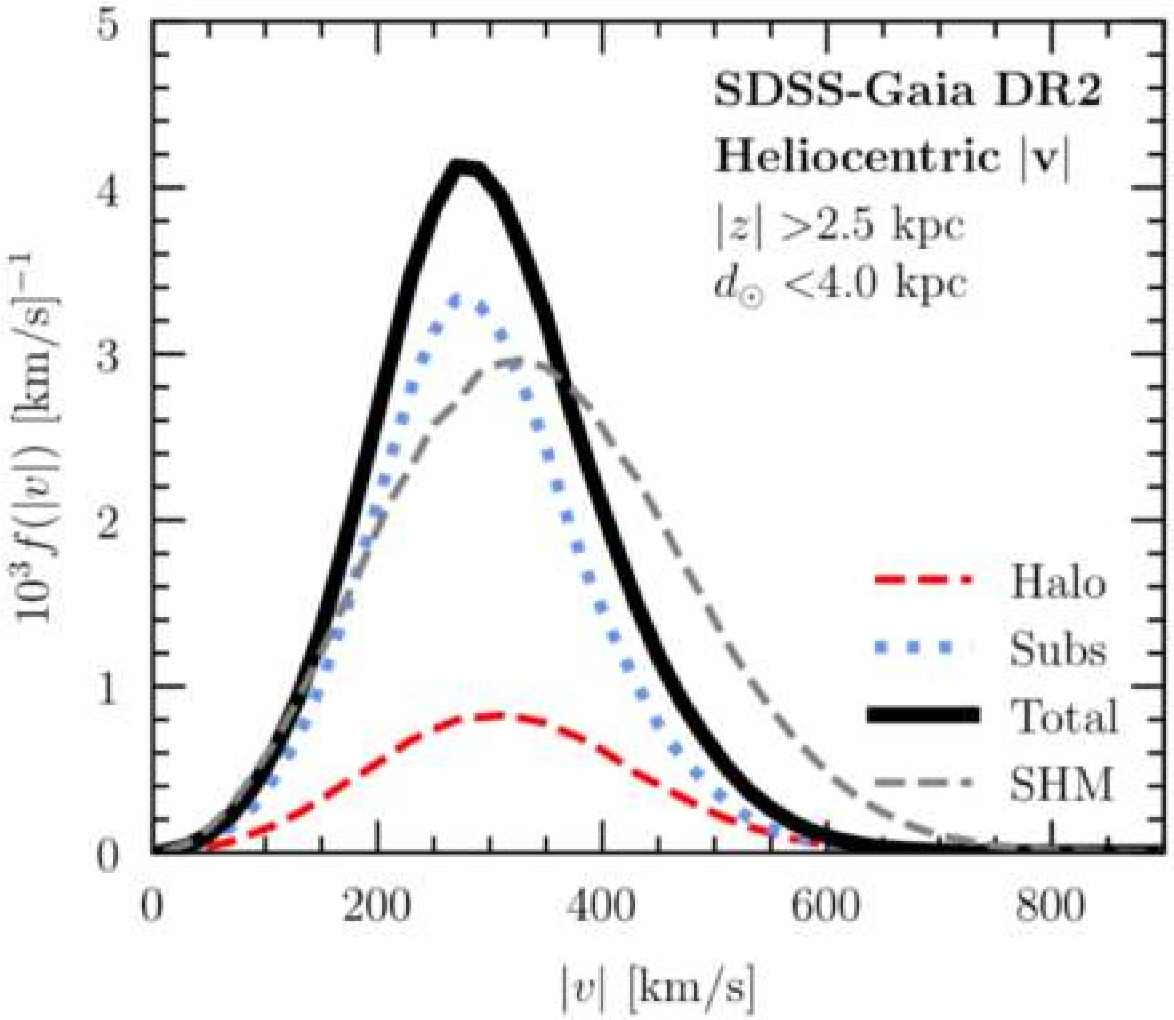
- Standard halo model: Maxwellian distribution
- Recent studies: deviations from simple SHM

Gaia mission: data from 1.4 x 10^9 stars

Necib, Lisanti and Belokurov, arXiv: 1807.02519

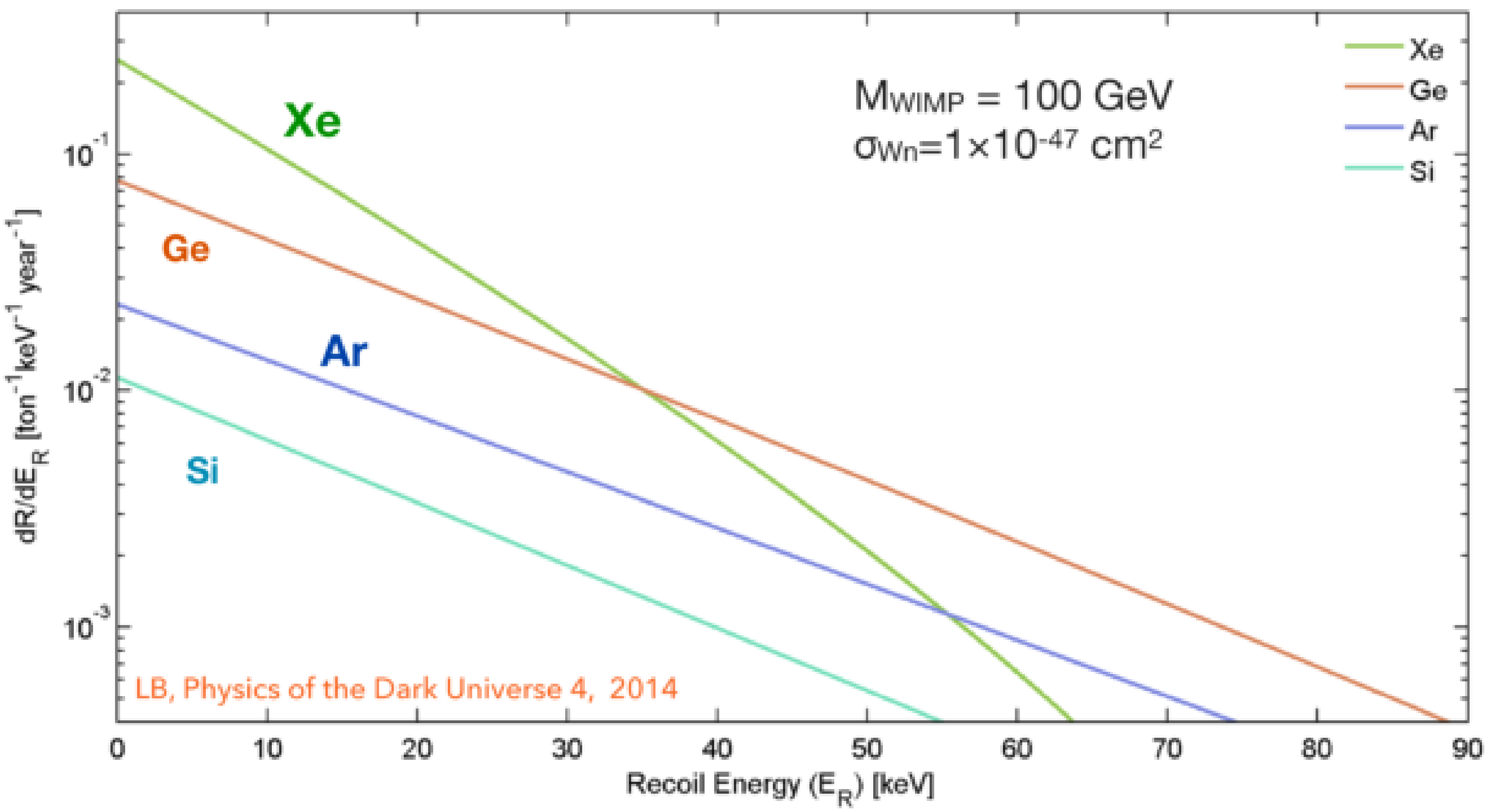
Accreted stars trace their dark matter counterparts

"It seems that we live in a huge debris flow"

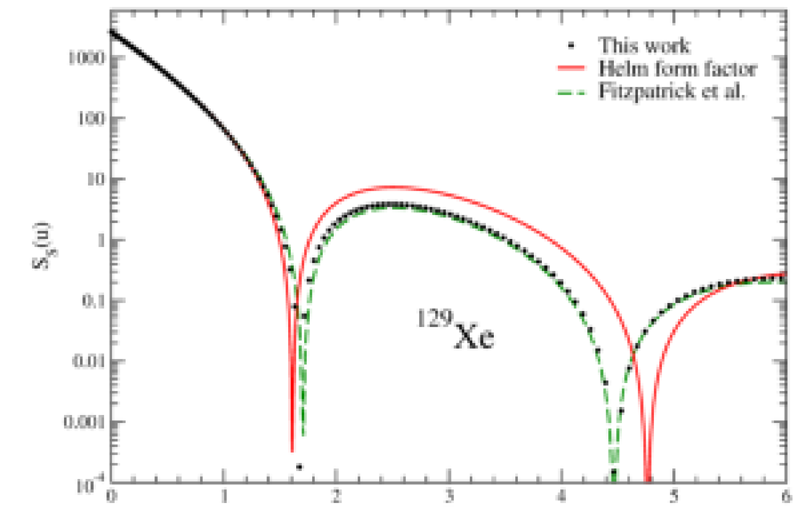


INTERACTION RATES

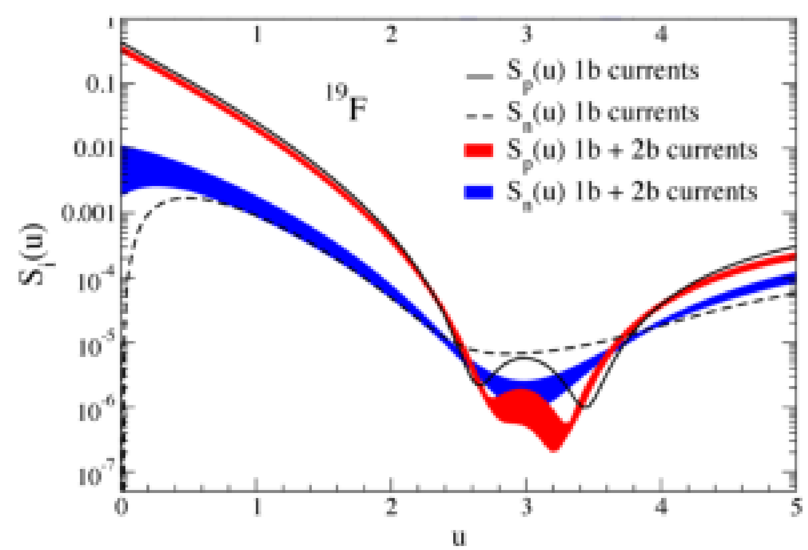
$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Spin-independent (SI) nuclear recoil spectrum



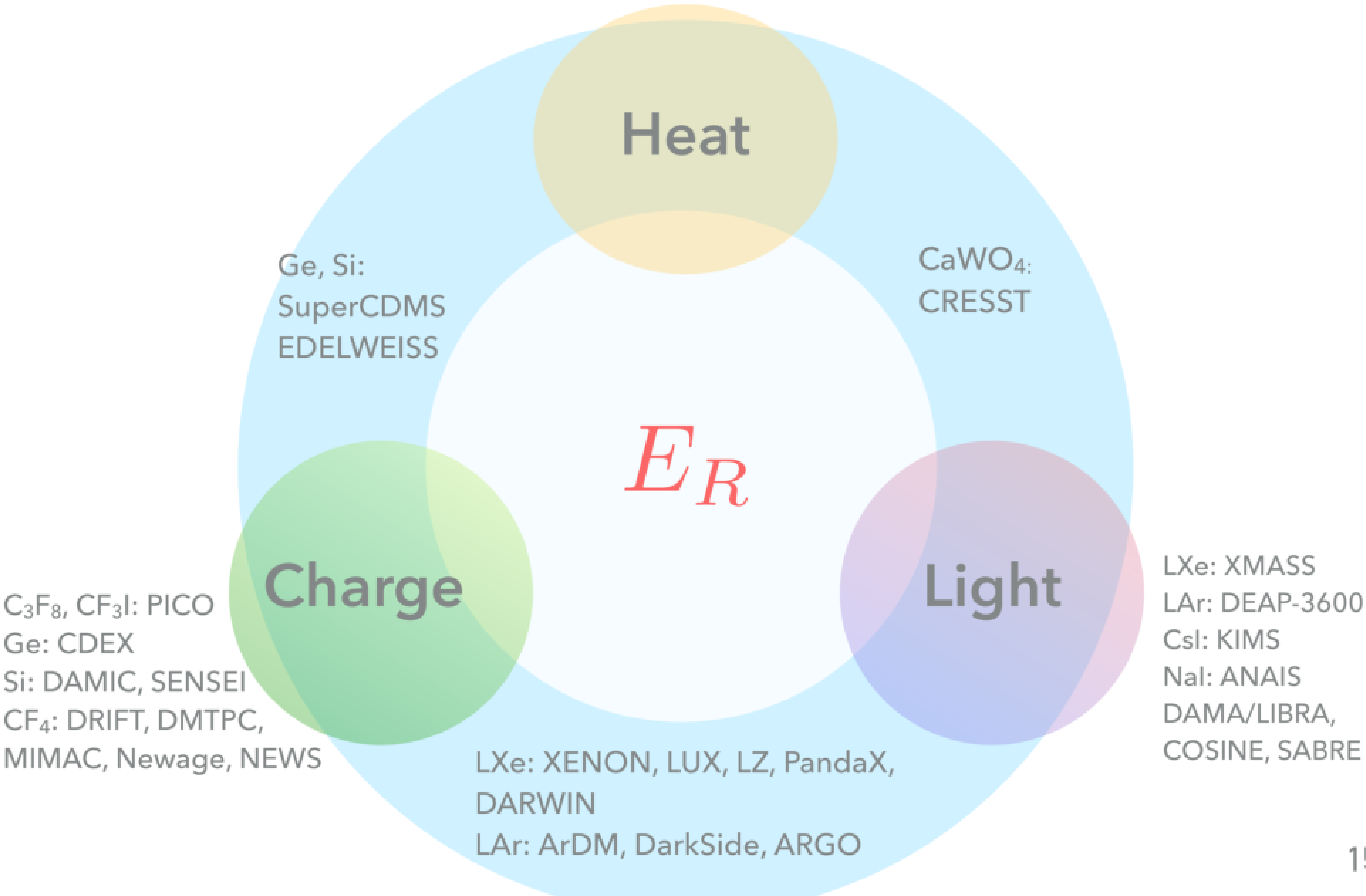
SI



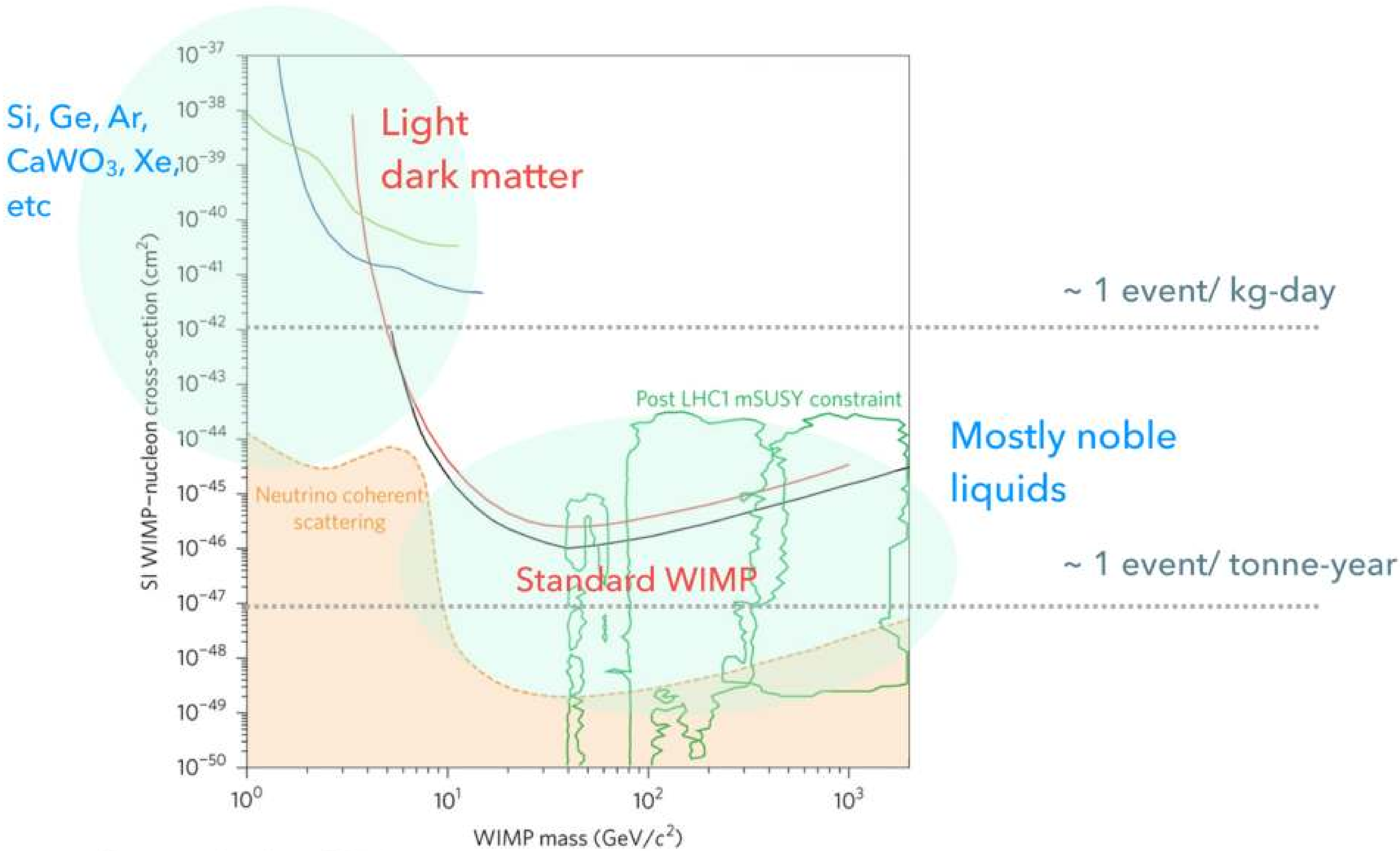
SD

A. Schwenk et al

DIRECT DETECTION SIGNATURES



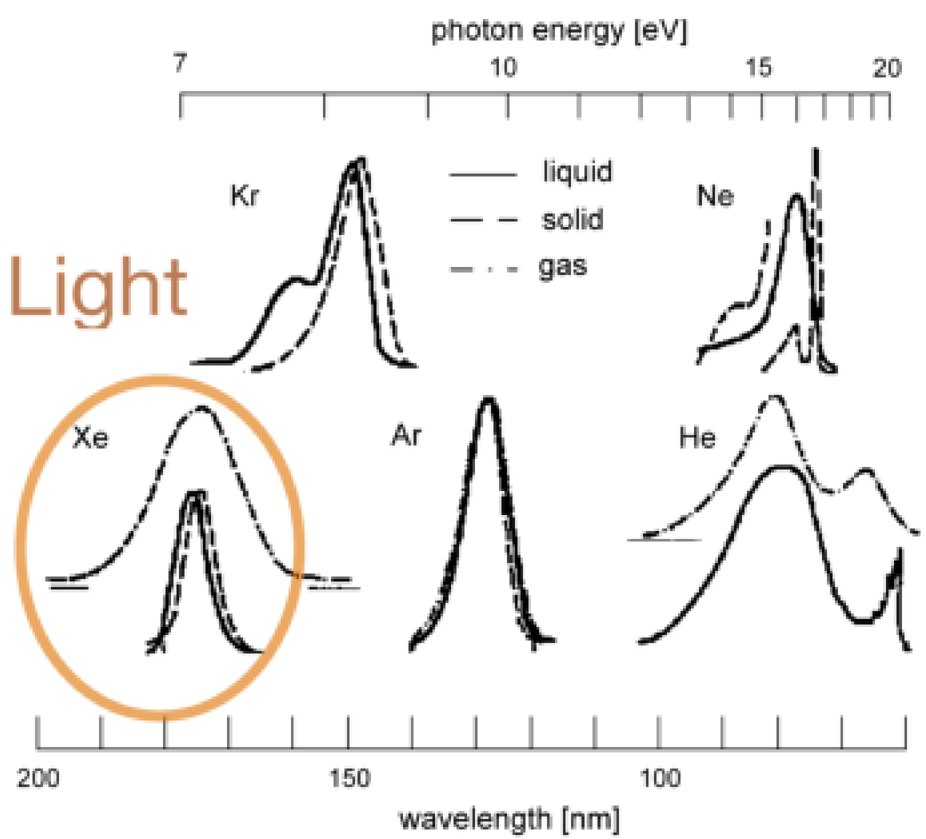
THE WIMP LANDSCAPE ABOUT ONE YEAR AGO

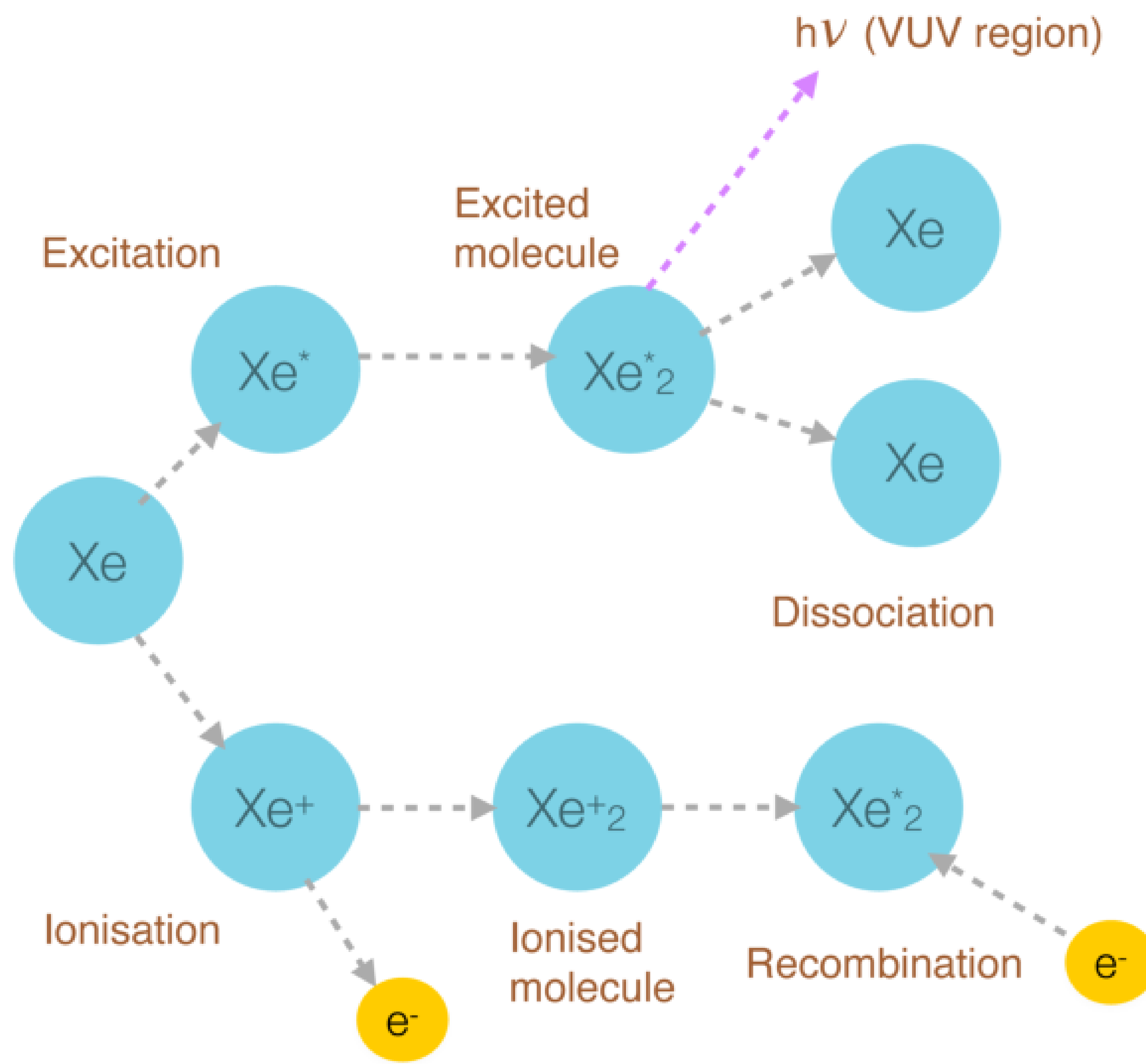


Nature physics, 2017

XENON ("THE STRANGE ONE") AS A NOBLE GAS

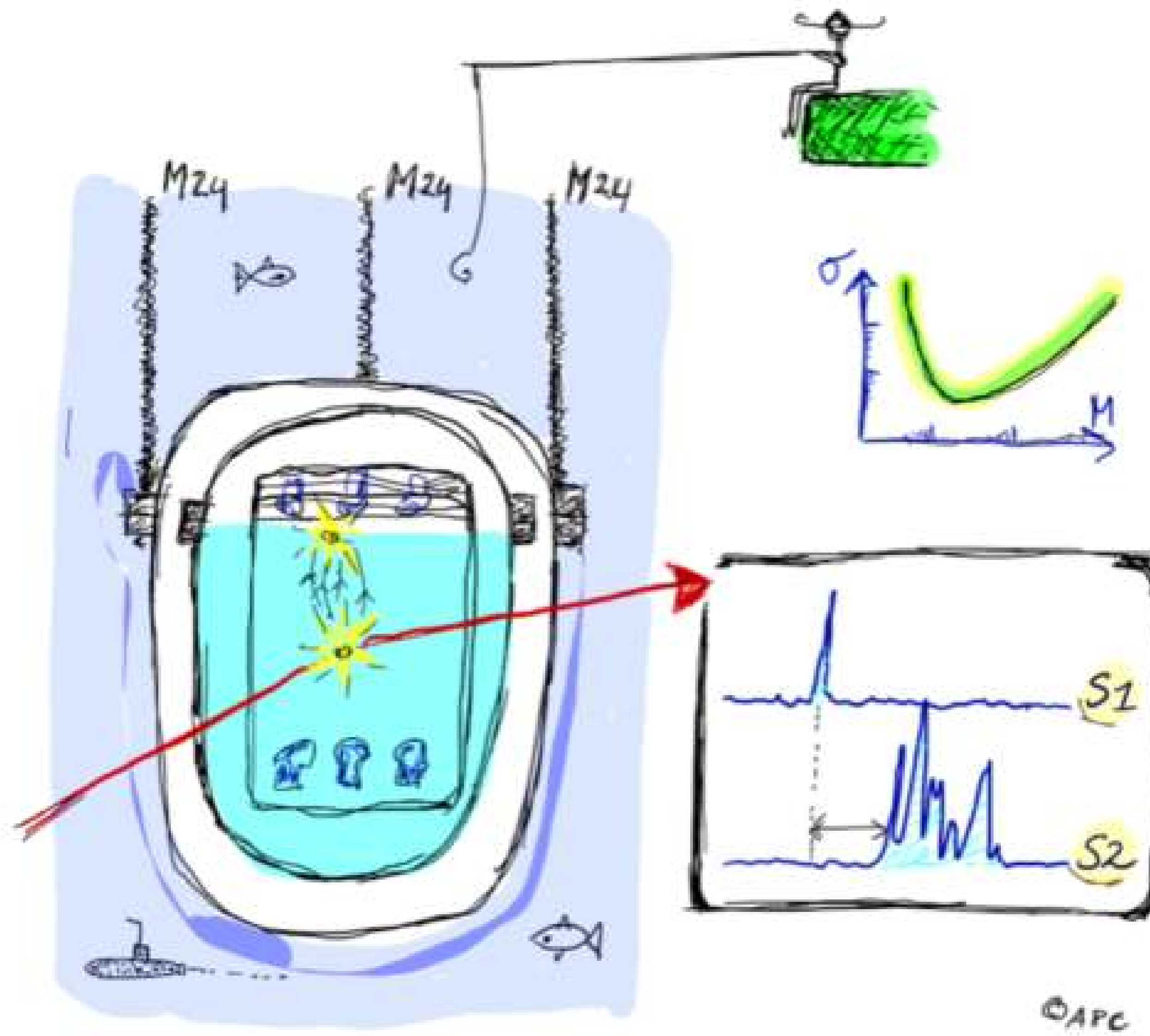
- Discovered by William Ramsay, student of Bunsen & professor at UCL
- Nobel prize 1904 in Chemistry





A XENON TIME PROJECTION CHAMBER

- 3D position resolution via light (S1) and charge (S2) signals
- S2/S1 depends on particle ID
- Fiducialisation
- Single versus multiple interactions



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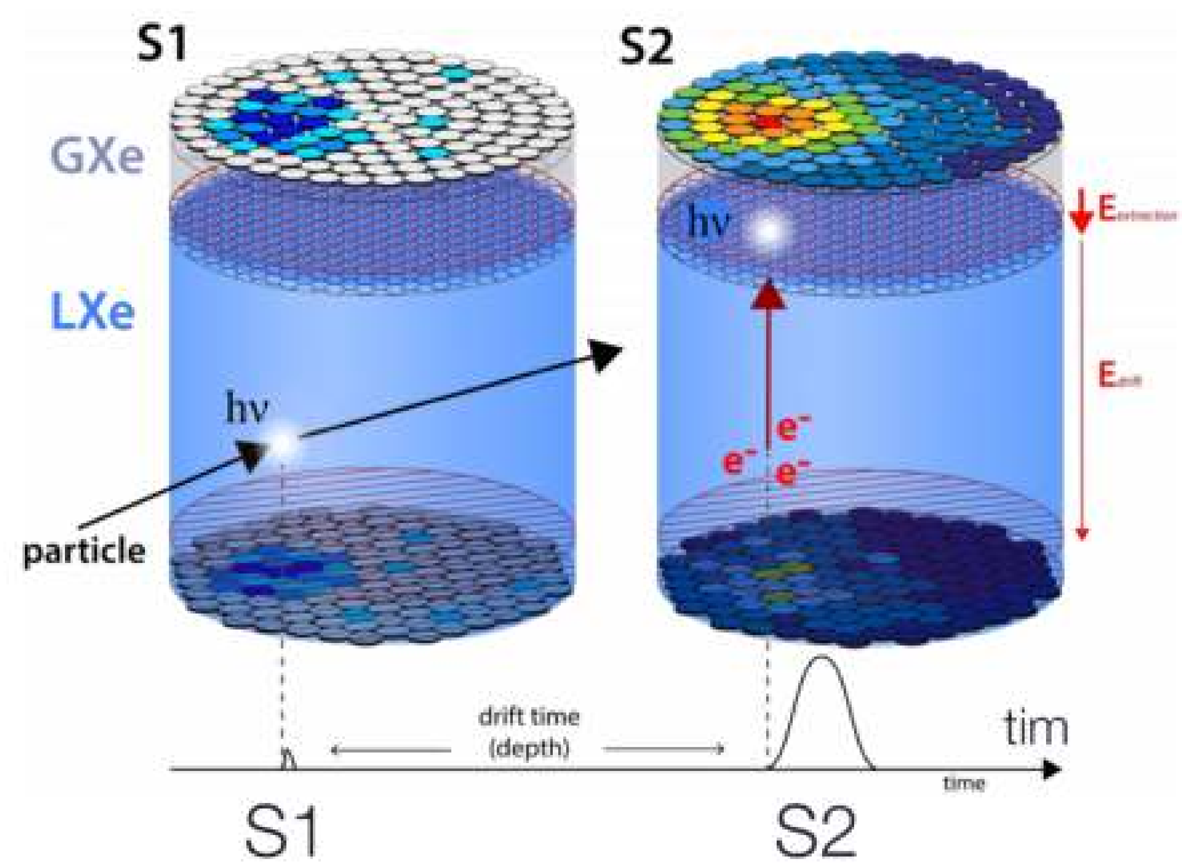
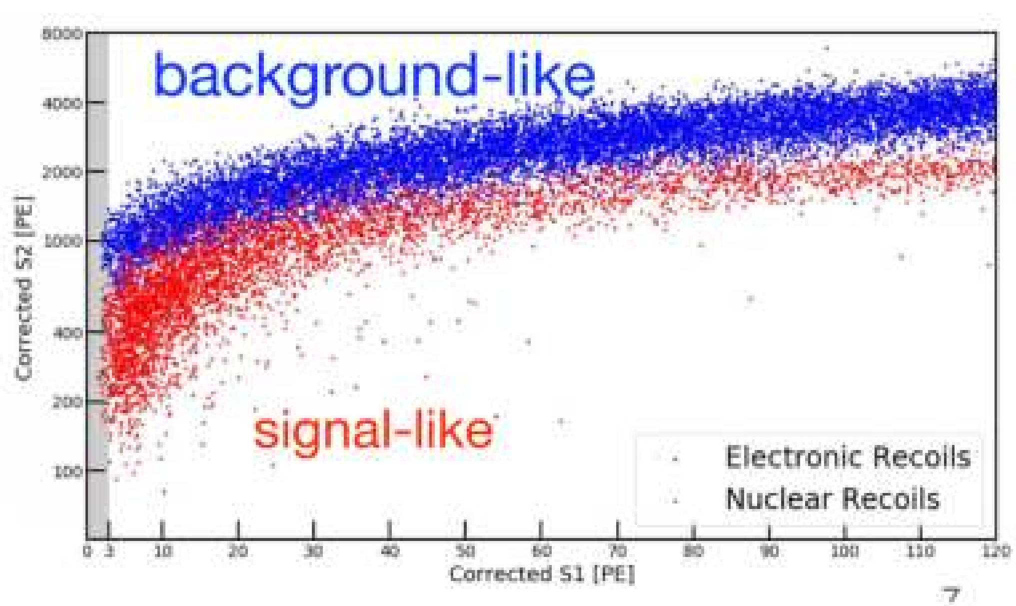
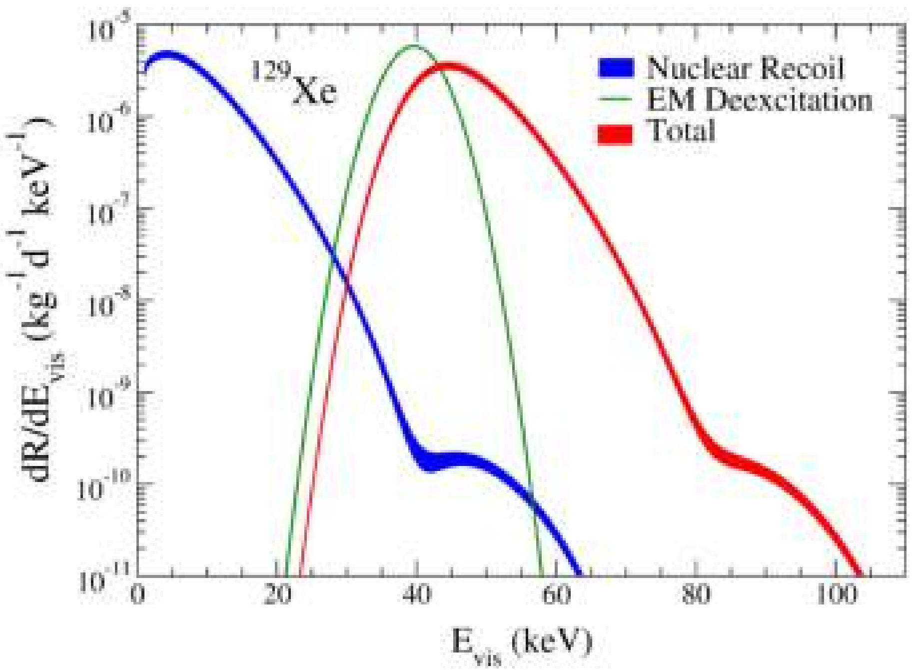


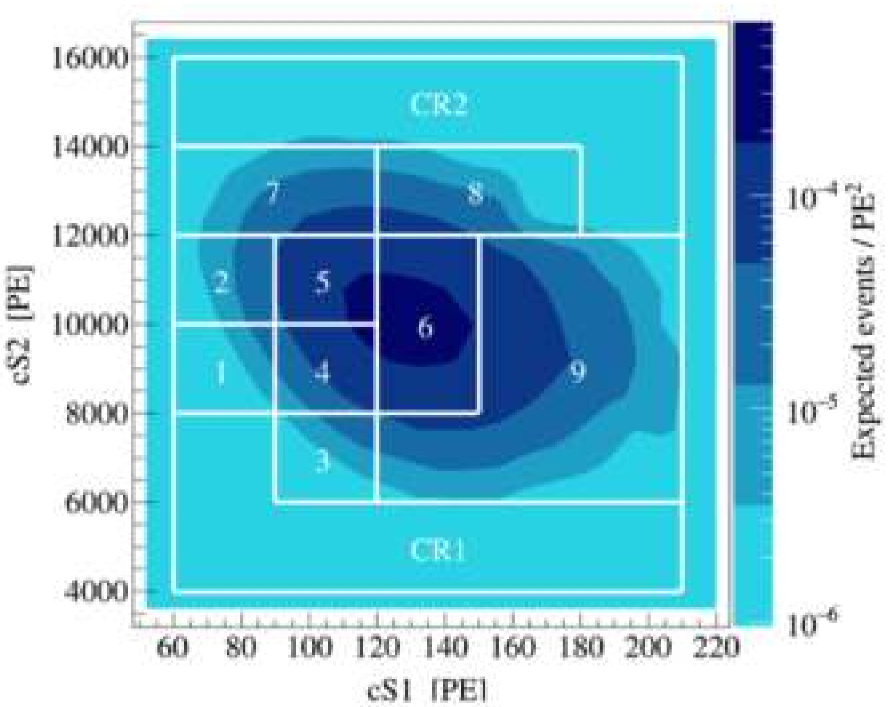


WIMP PHYSICS WITH XENON NUCLEI

- SI elastic scatters ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.9%)
- SD elastic scatters ^{129}Xe (26.4%), ^{131}Xe (21.2%)
- Inelastic, SD scatters: $\chi +^{129,131} Xe \rightarrow \chi +^{129,131} Xe^* \rightarrow \chi +^{129,131} Xe + \gamma$



L. Baudis et al, Phys. Rev. D 88, 2013

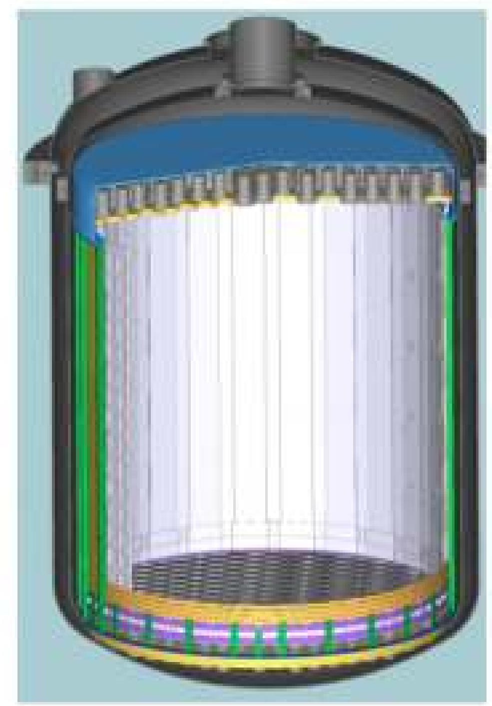
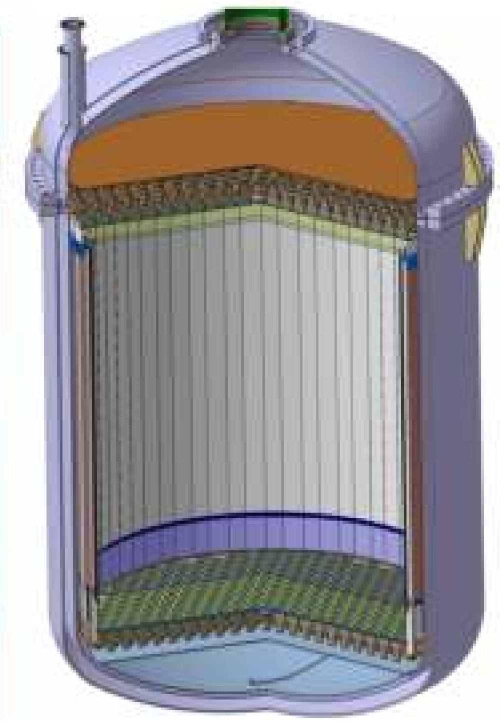


XENON collaboration, Phys. Rev. D 96, 2017

THE XENON & DARWIN TIMELINE

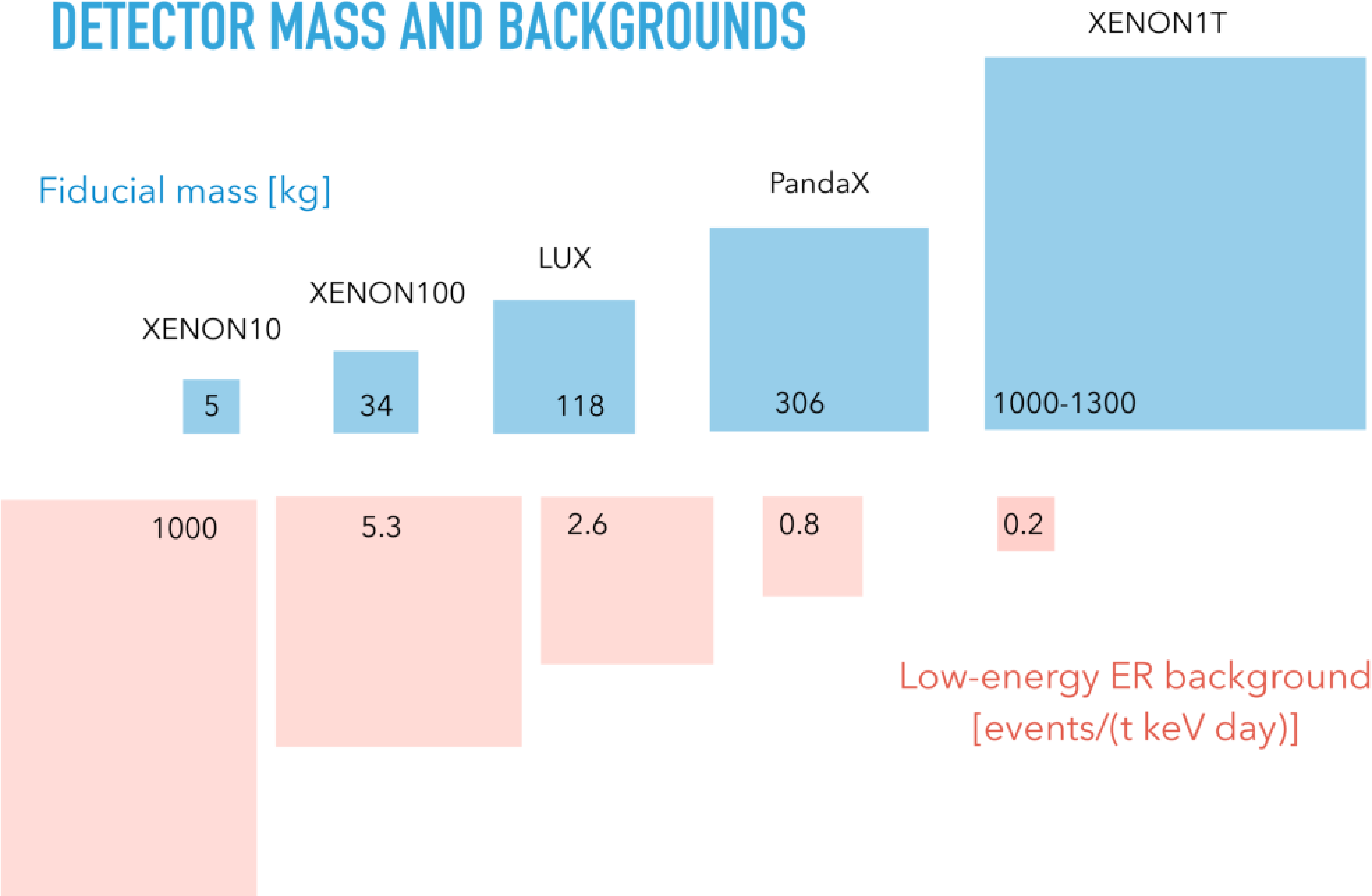
XENON10 XENON100 XENON1T XENONnT DARWIN



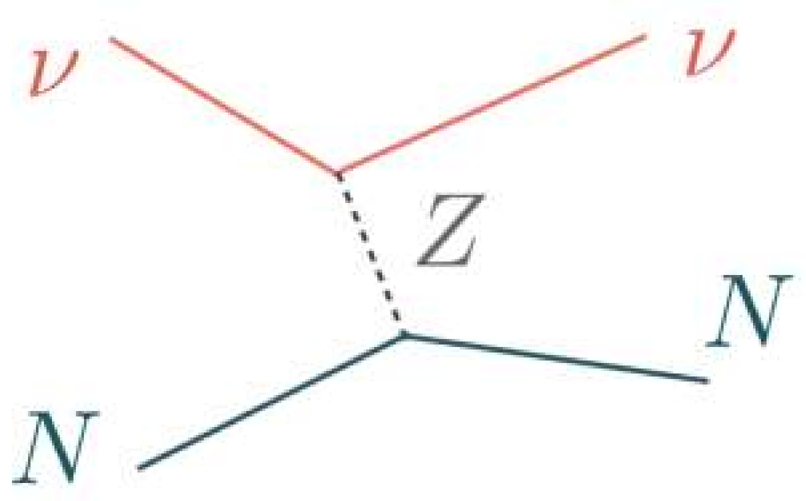
2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

DETECTOR MASS AND BACKGROUNDS

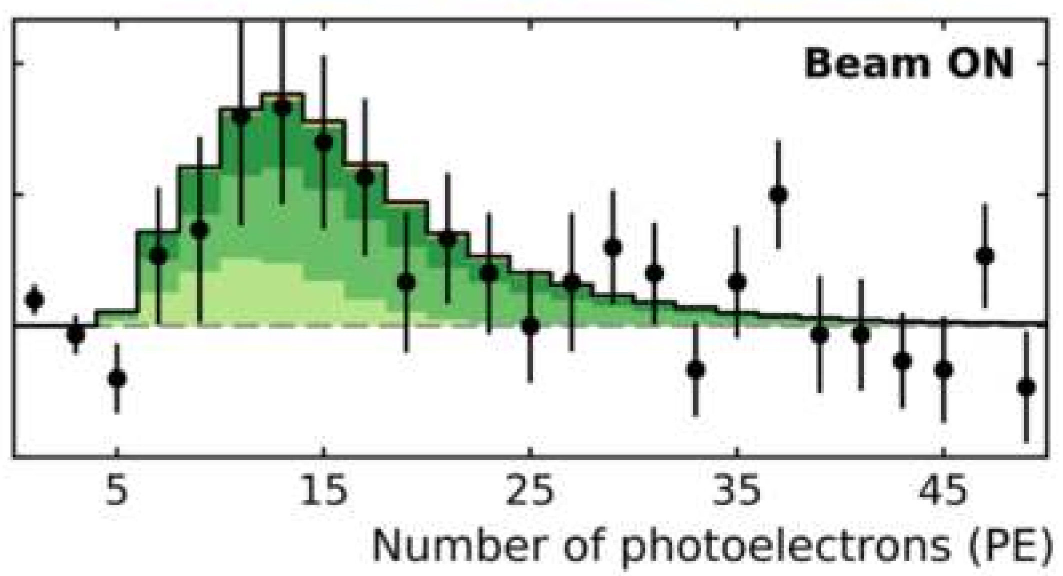


BACKGROUNDS

- In the ideal case: below the expected signal
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural and anthropogenic radioactivity
  - Neutrinos! Coherent neutrino-nucleus scattering was observed



COHERENT, Science, August 3, 2017



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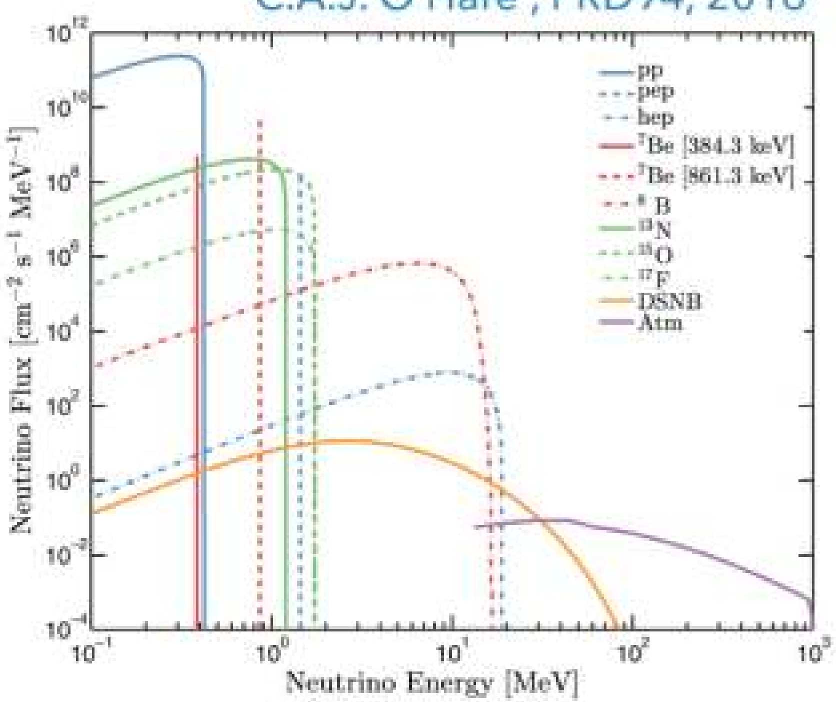
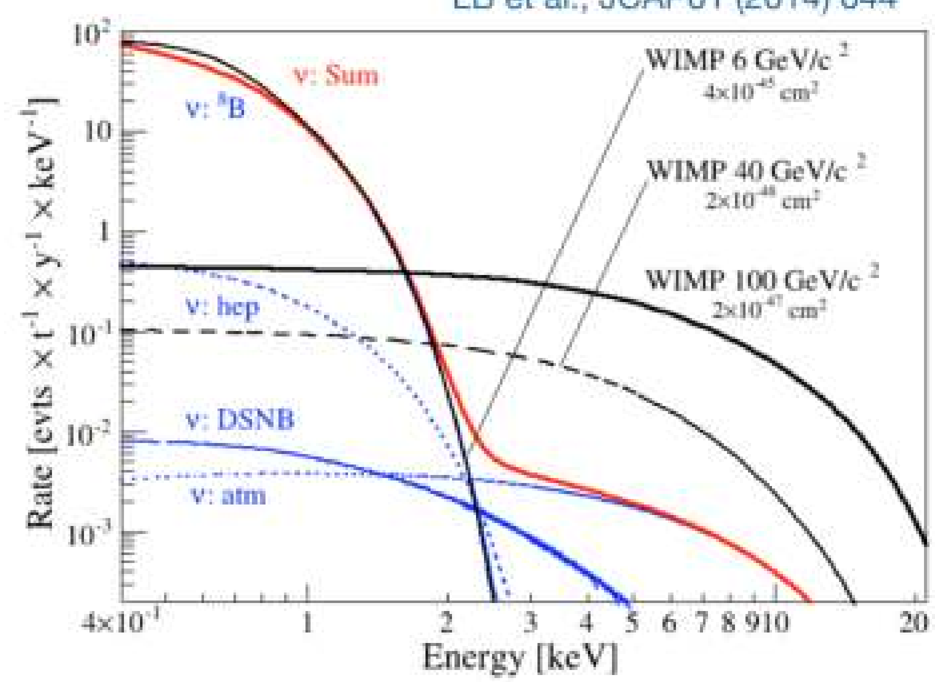
C.A.J. O'Hare , PRD94, 2016



LB et al., JCAP01 (2014) 044



GO UNDERGROUND

- Bad news: you can't shield neutrinos
- Good news: eventually these will be one of your signals

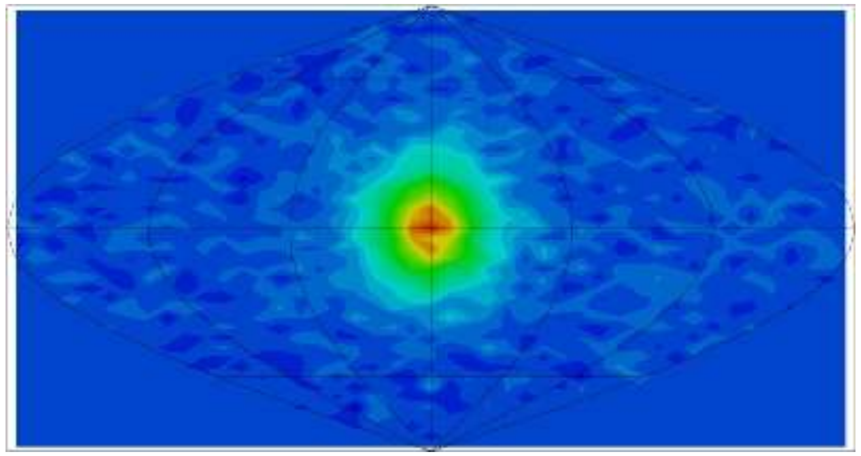
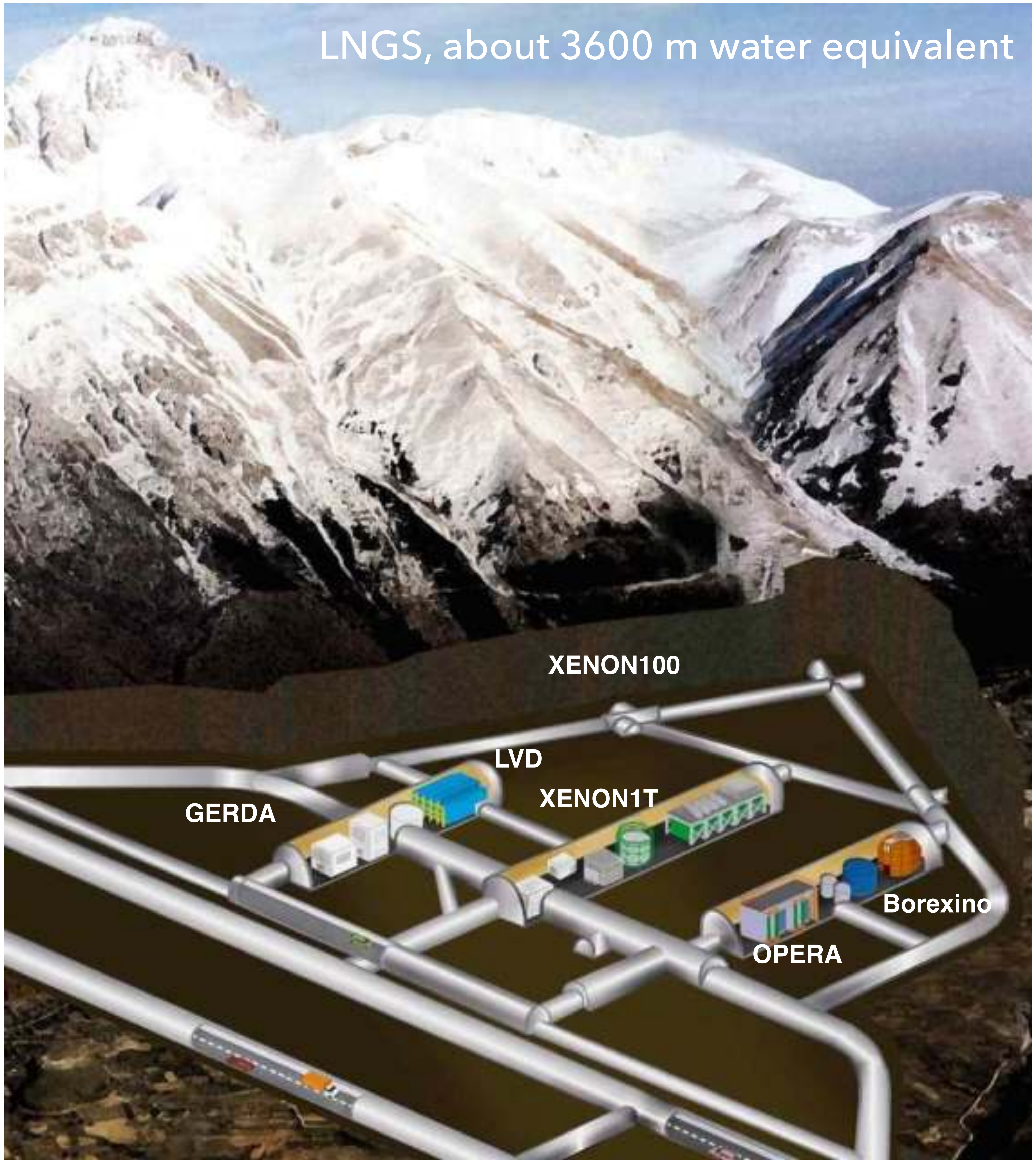


Figure by SuperKamiokande

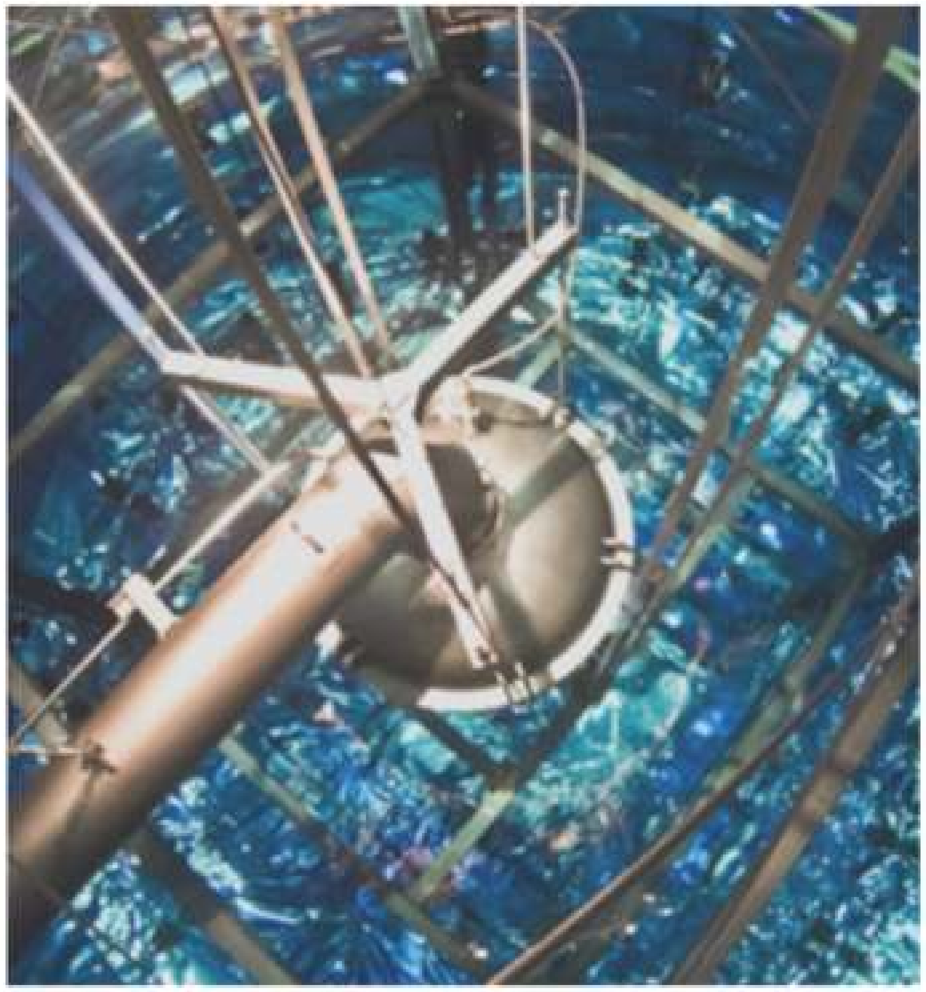


SHIELD, SHIELD, SMARTER SHIELD

XENON10

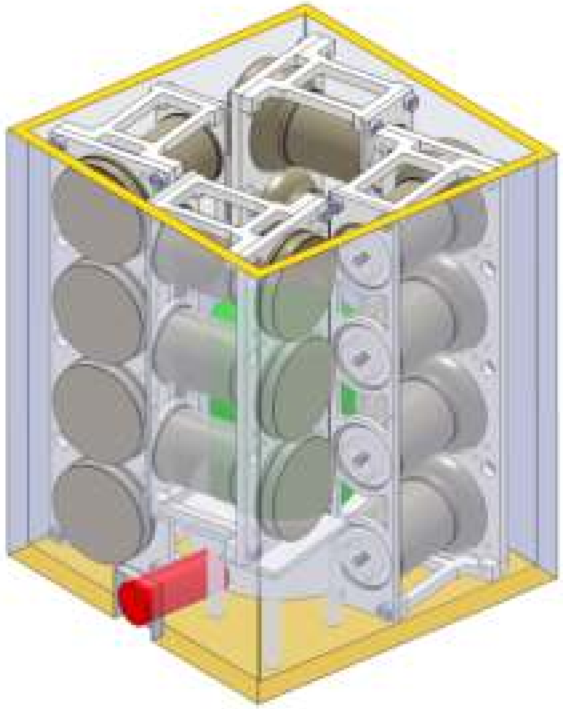
XENON100

XENON1T

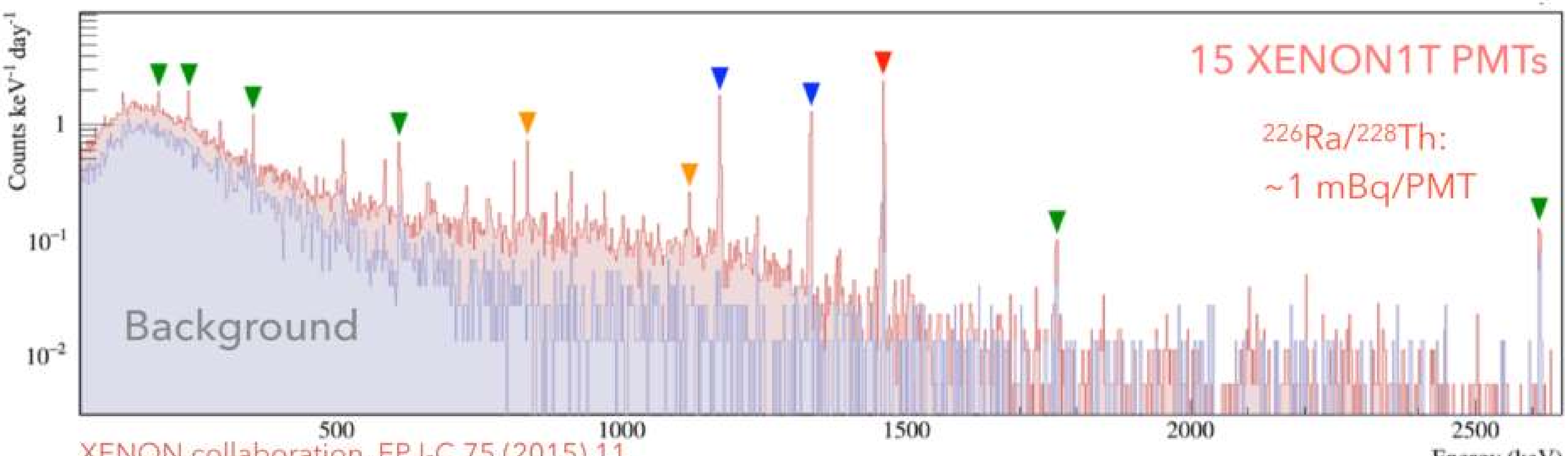


MATERIAL SCREENING AND SELECTION

- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



L. Baudis et all, JINST 6, 2011

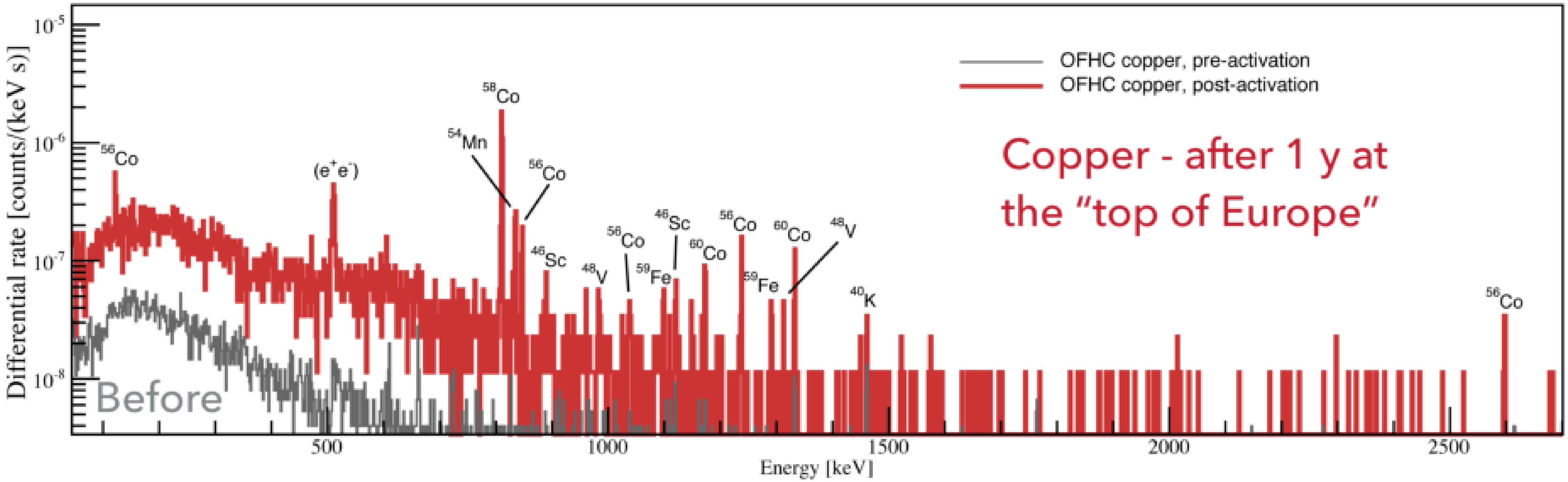


XENON collaboration, EPJ-C 75 (2015) 11

AVOID EXPOSURE TO COSMIC RAYS

- Spallation reactions can produce long-lived isotopes
- Activate and compare with predictions (Activia, Cosmo, etc)

L. Baudis et al., Eur. Phys. J. C75 2015



XENON collaboration, EPJ-C 77 (2017) 12

XENON1T AT THE GRAN SASSO LABORATORY

XENON1T AT THE GRAN SASSO LABORATORY

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

Cryogenics pipe (cables, xenon)

Cryogenics and purification

Data acquisition and slow control

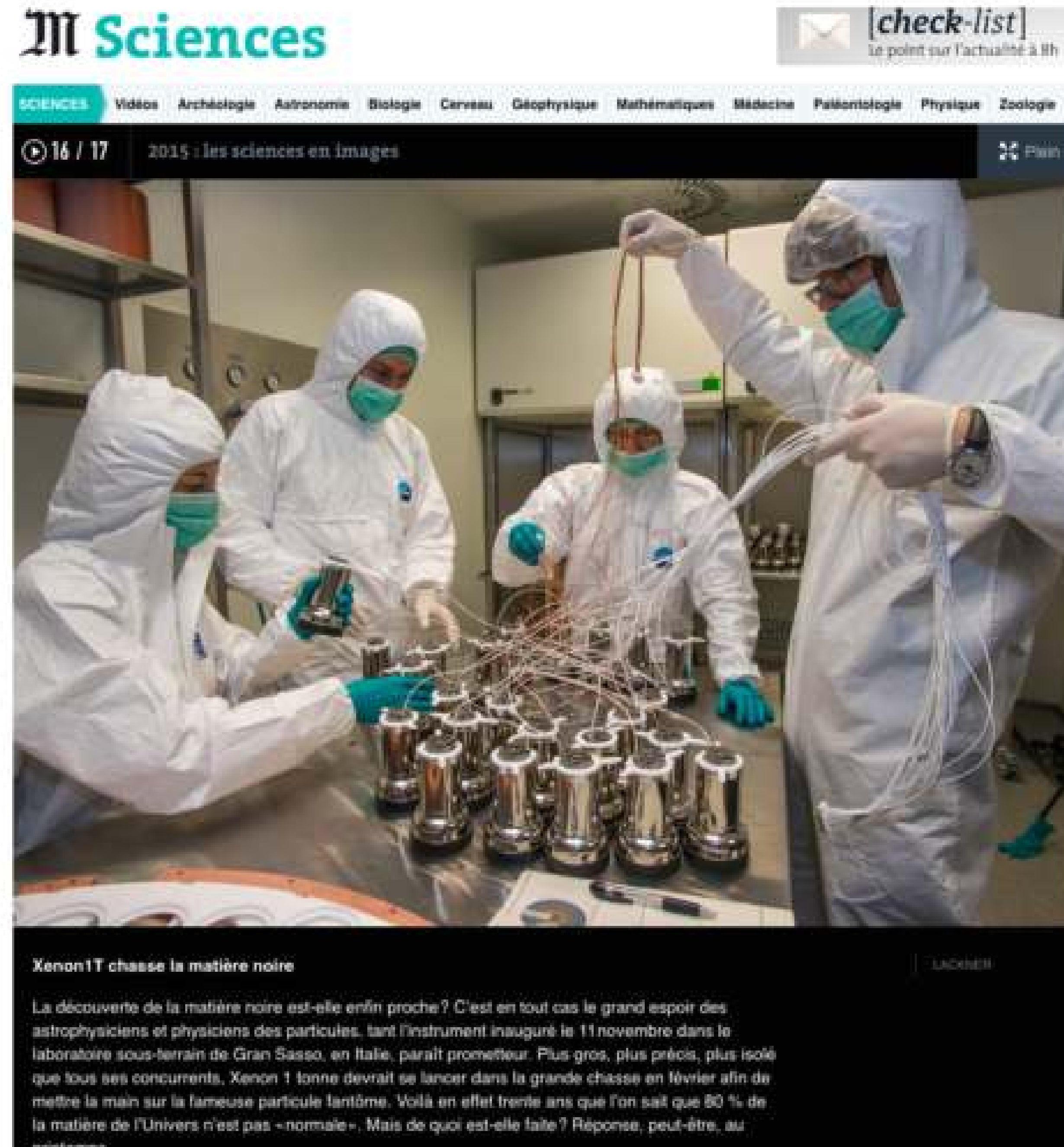
Xenon storage, handling and Kr removal via cryogenic distillation

160 scientists

27 institutions

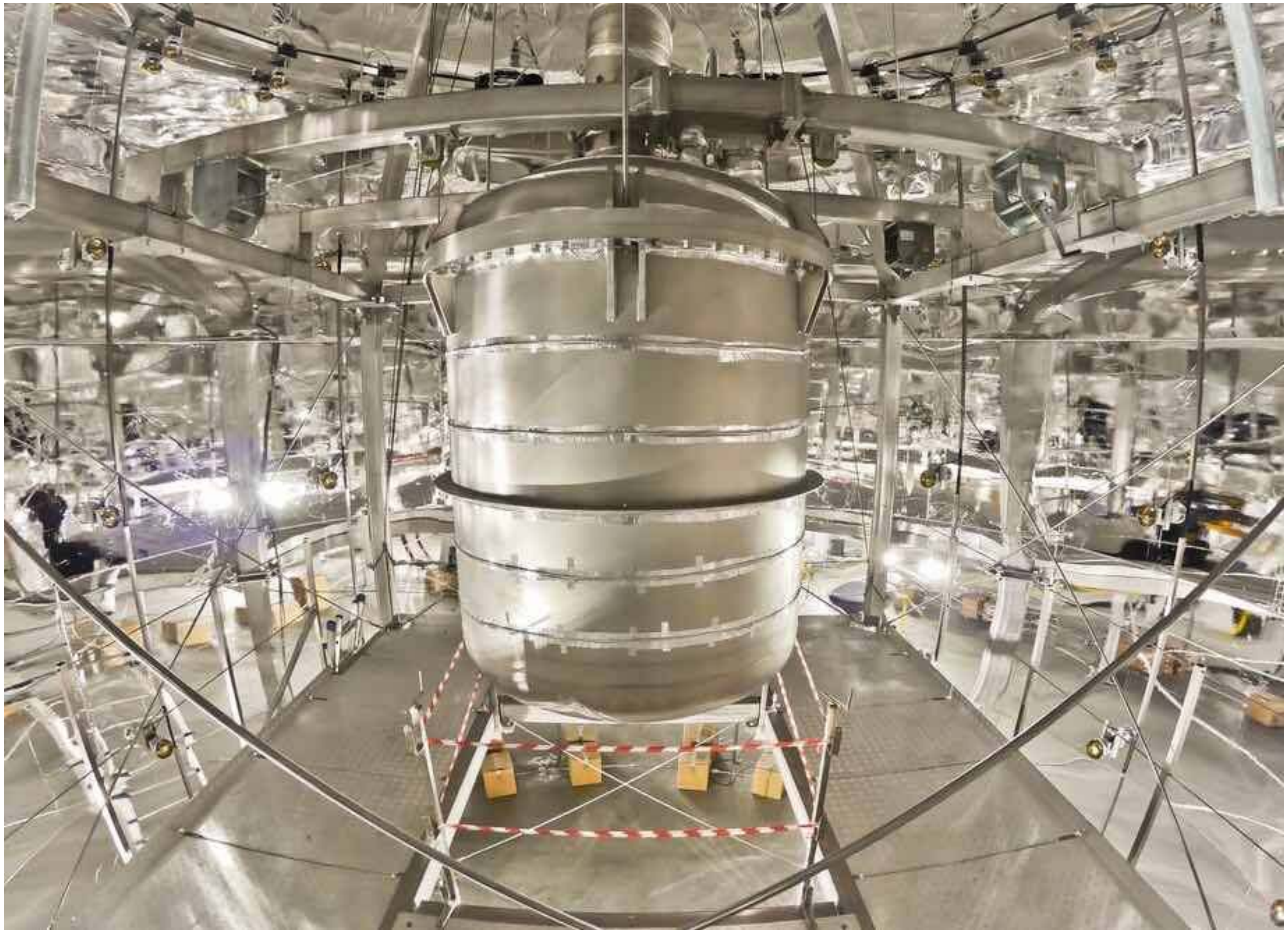
11 countries

TPC AND PMT ARRAYS FIRST ASSEMBLY & TESTS



THE XENON1T TPC IN THE CLEANROOM AT LNGS

CRYOSTAT AND WATER CHERENKOV SHIELD



CRYOSTAT AND WATER CHERENKOV SHIELD

THE TIME PROJECTION CHAMBER

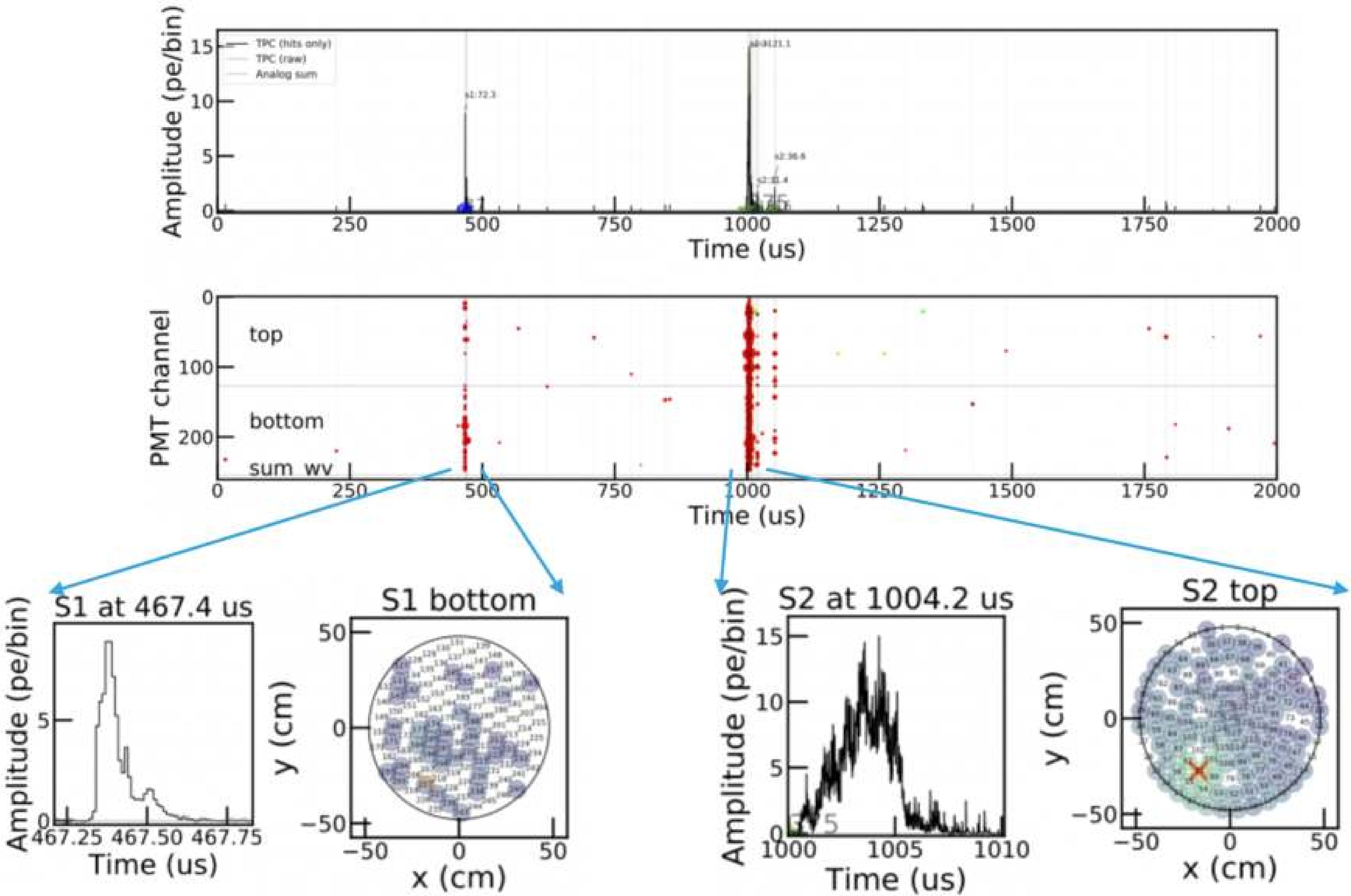
- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs
- 74 Cu field shaping rings, 5 electrodes, 4 level meters

127 PMTs top array

121 PMTs bottom array

THE EYES OF THE DETECTOR

EXAMPLE OF A LOW-ENERGY EVENT IN THE TPC

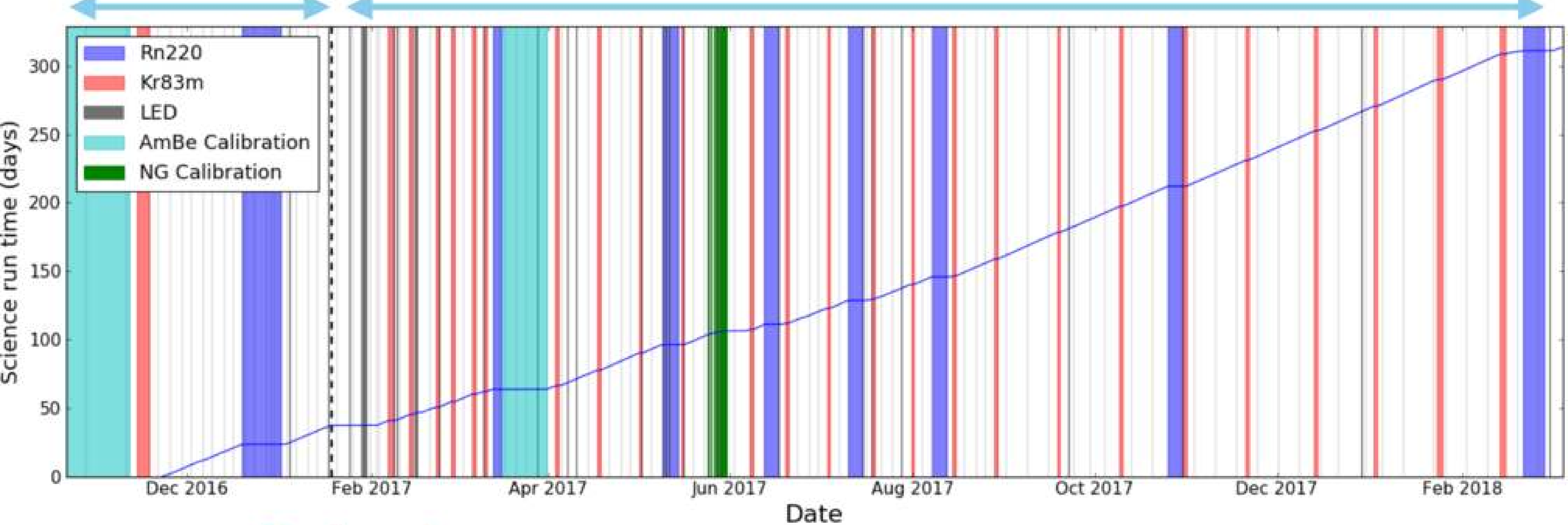


DATA OVERVIEW

- First science run: Oct 2016 - Jan 2017
- Second science run: Feb 2017 - Feb 2018

SR0: 31.2 live days

SR1: 246.7 live days



PRL 118, 2017

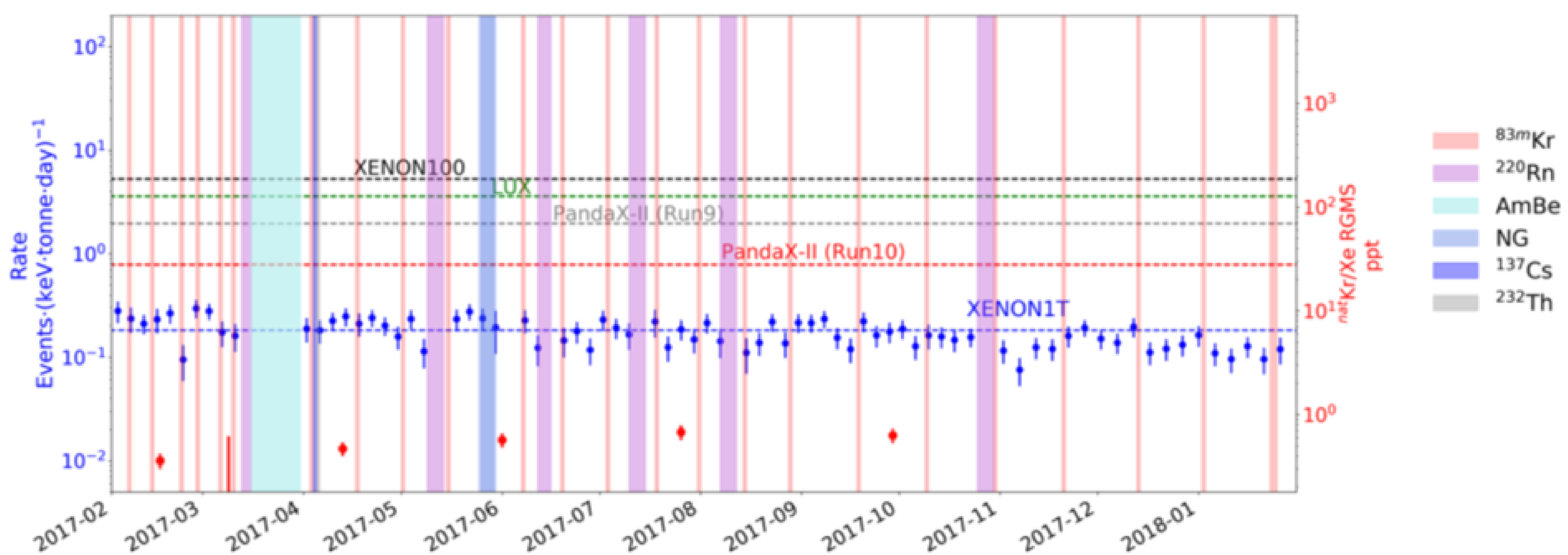
Earthquake mag 5.7

PRL 121, 2018

BACKGROUND PREDICTIONS AND DATA

- ER rate: (82±3) events/(keV t y), in 1.3 t and below 25 keV_{ee}
- Lowest background in a dark matter detector

^{nat}Kr: ~0.45 ppt ; ^{222}Rn: ~ 10 μBq/kg

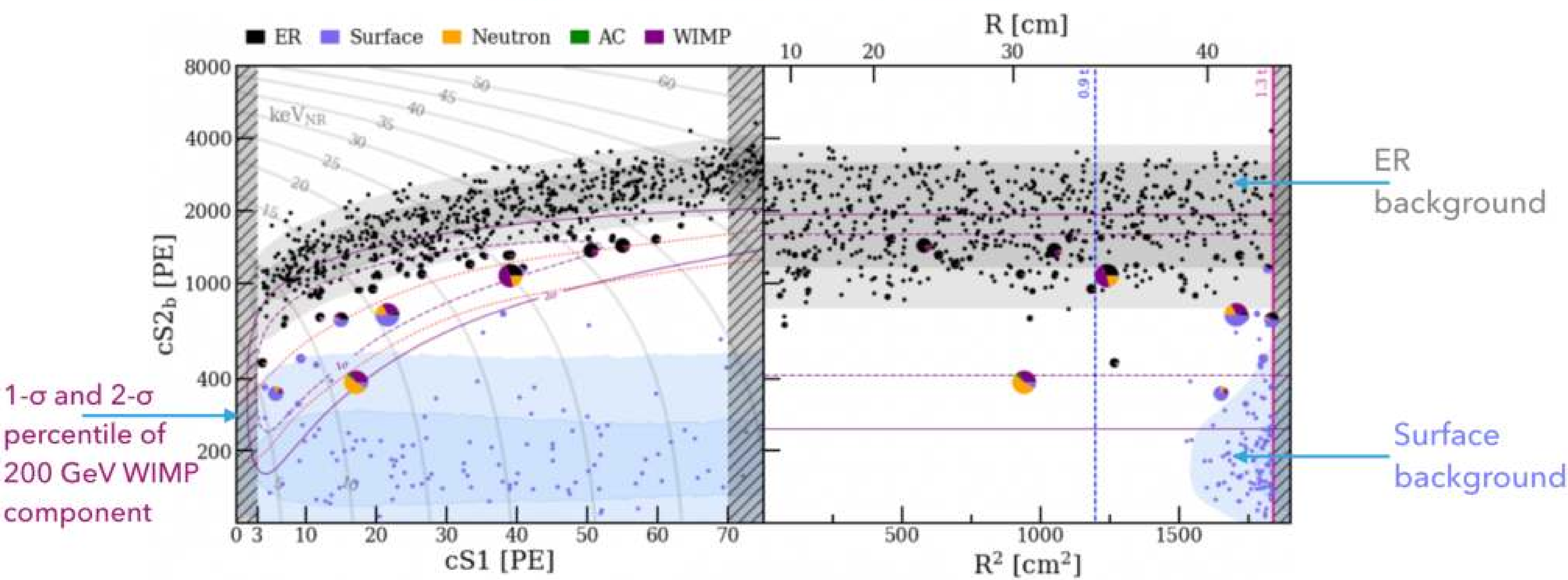


^{222}Rn: 85.4%, ^{85}Kr: 4.3%, solar ν: 4.9%, materials: 4.1%, ^{136}Xe: 1.4%

DARK MATTER SEARCH RESULTS

- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Piecharts: relative PDF from the best fit of 200 GeV WIMPs with 4.7×10^{-47} cm^2

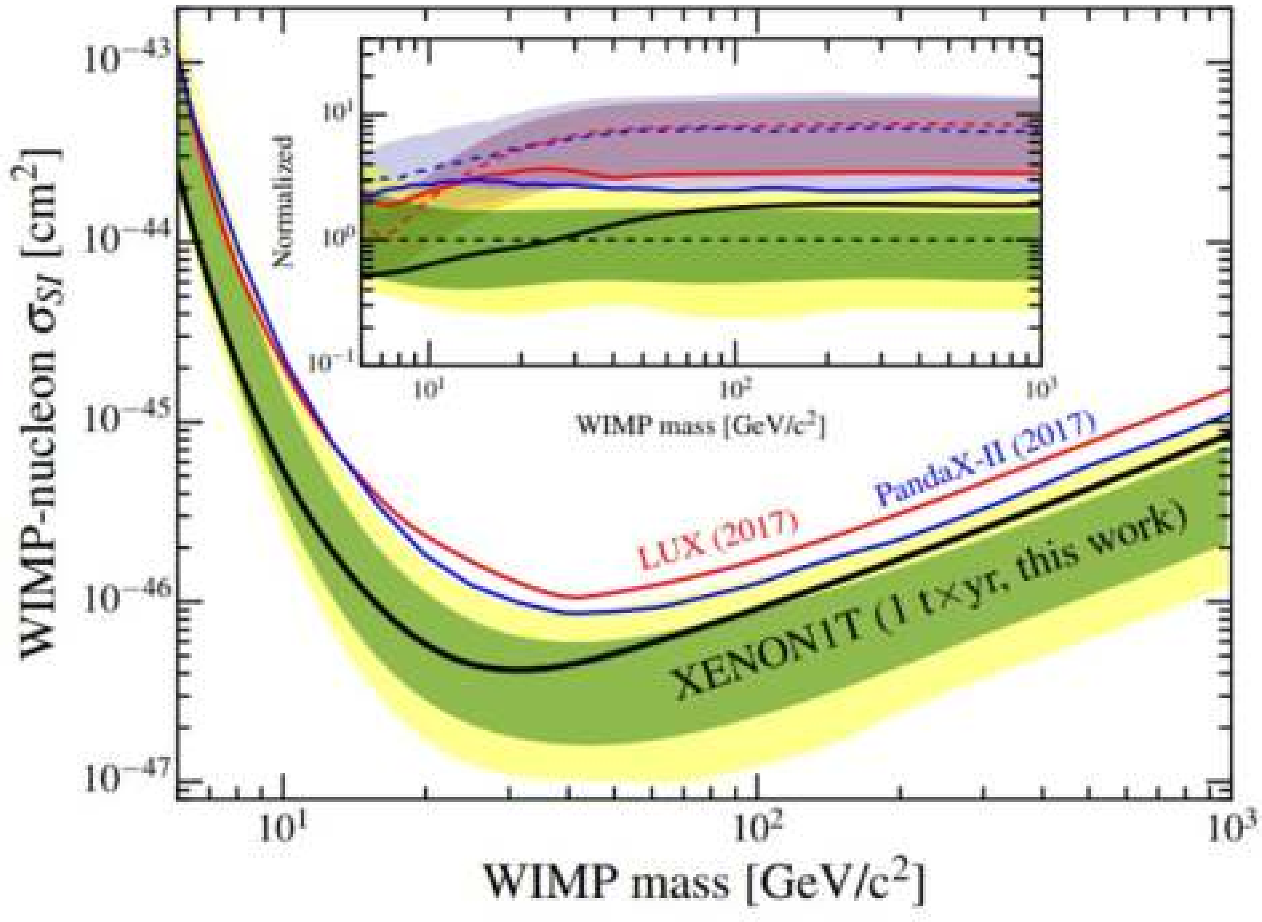
Larger charts: larger WIMP probability



NEW CONSTRAINTS ON WIMP INTERACTIONS

- Strongest upper limit (at 90% CL) on SI WIMP-nucleon cross sections > 6 GeV
- Median sensitivity: factor 7 higher than for previous experiments (LUX, PandaX-II)
- 1-σ fluctuation at higher WIMP masses could be due to background or signal

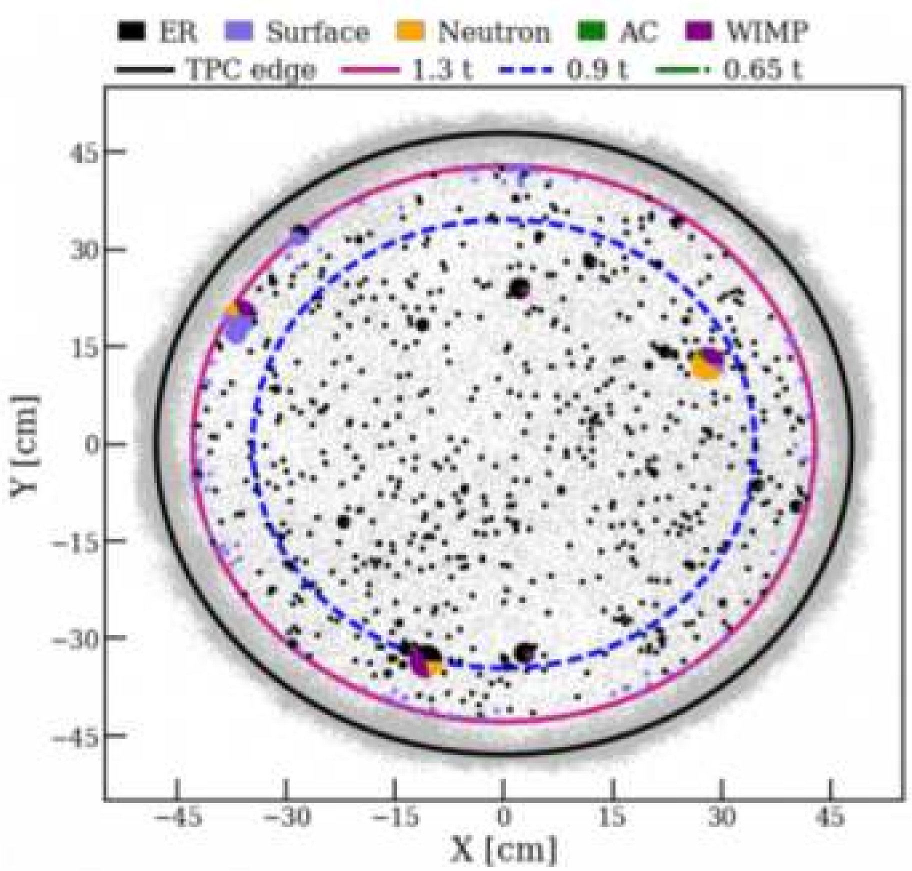
PRL 121, 2018

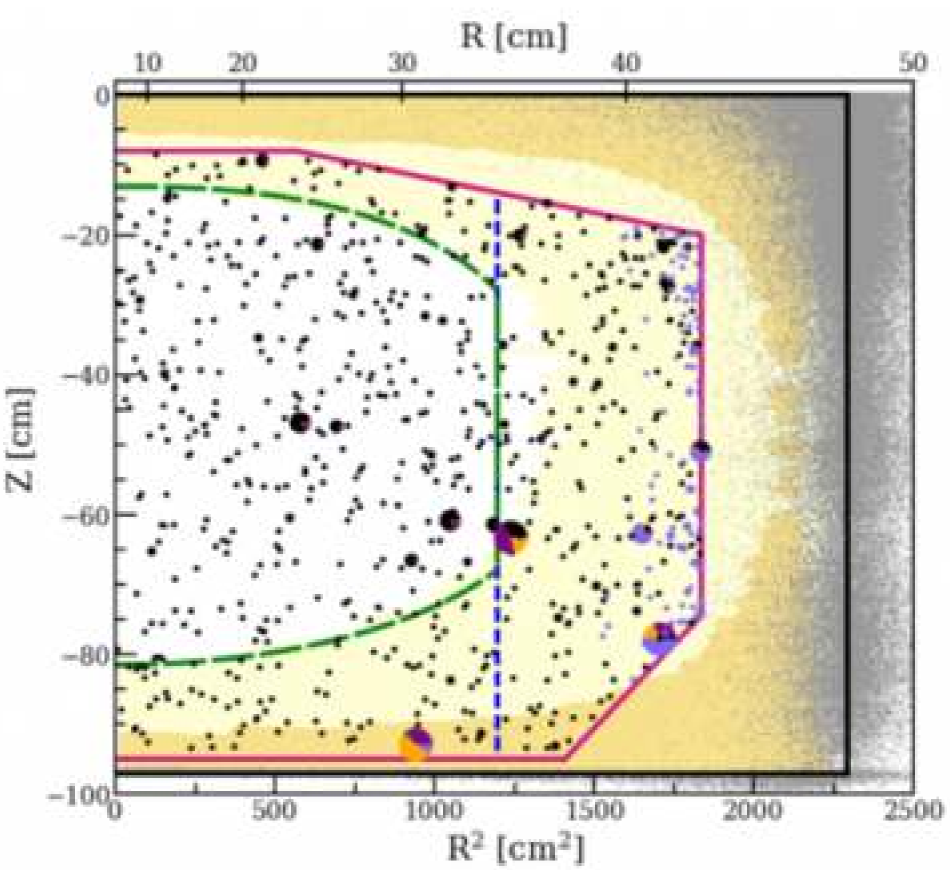


$$\sigma_{\mathrm{SI}} < 4.1 \times 10^{-47}\mathrm{cm}^2 \text{ at } 30\,\mathrm{GeV}/\mathrm{c}^2$$

SPATIAL DISTRIBUTION OF EVENTS

- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Core volume: to distinguish WIMPs over neutron background



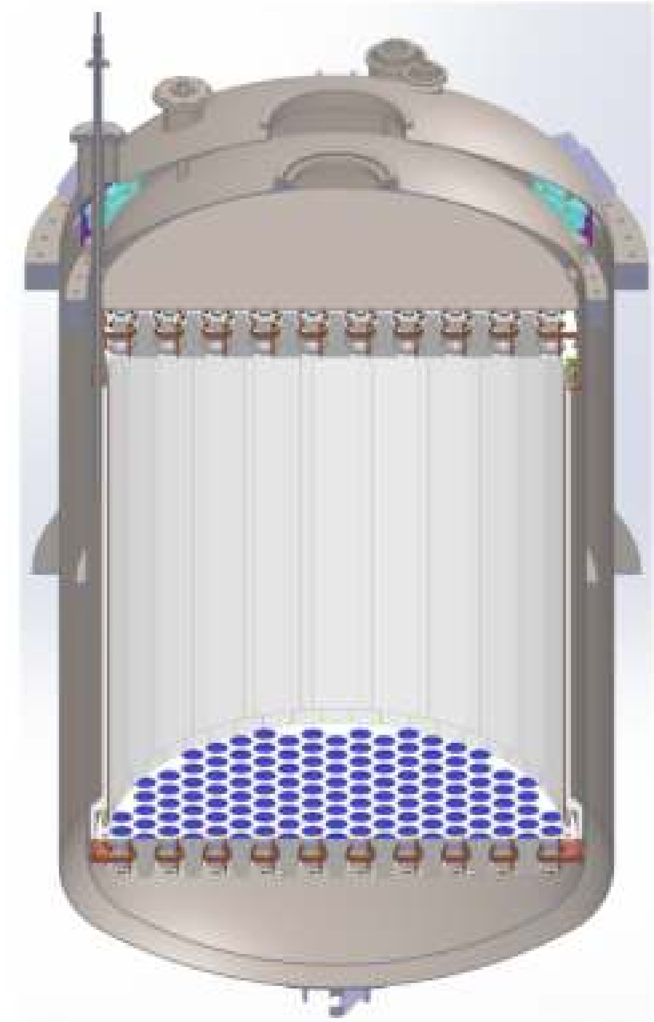


Events passing all selection criteria:

pie charts → relative probabilities of background and signal components for each event *under the best fit model* (assuming 200 GeV WIMP and σ_{SI} = 4.7e-47 cm^2)

XENONNT

- Rapid upgrade to 8.4 t total mass, 6 t in the TPC
- Most sub-systems in place from XENON1T
- New inner cryostat, new TPC, 476 PMTs (most of these tested & screened)
- Neutron veto, Rn removal tower, additional storage system
- Installation at LNGS scheduled to start in spring 2019, commissioning in late 2019

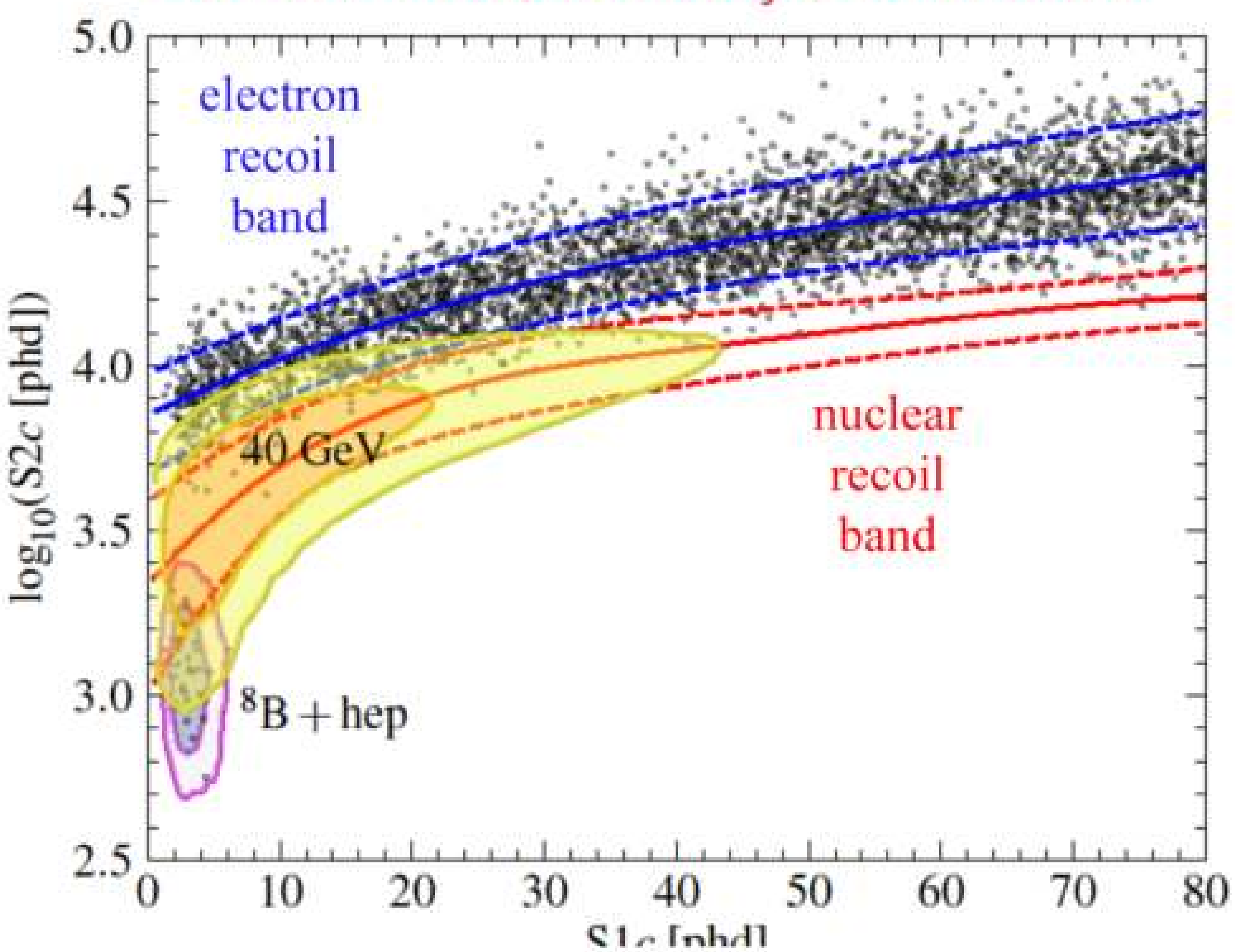


Pizza slice tests in Zurich

LUX-ZEPLIN

- Experiment at SURF, USA; TPC field cage assembly in fall 2018
- Starts operation April 2020; 5 (3) σ for 6.7 (3.8) x 10^{-48} cm^2

40 GeV WIMP, 1000 days, 5.6 t fiducial



DARWIN

European Research Council
Established by the European Commission

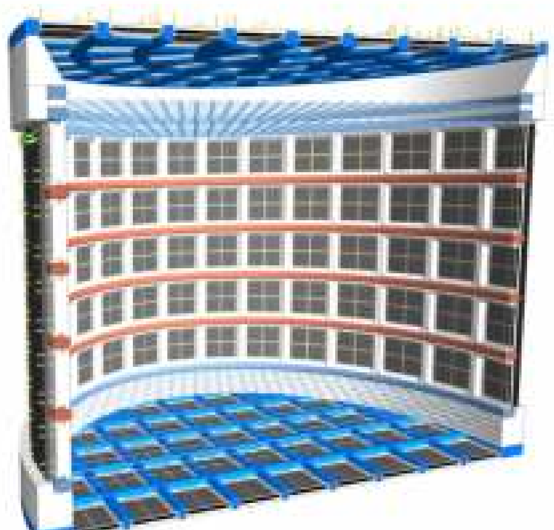
darwin-observatory.org

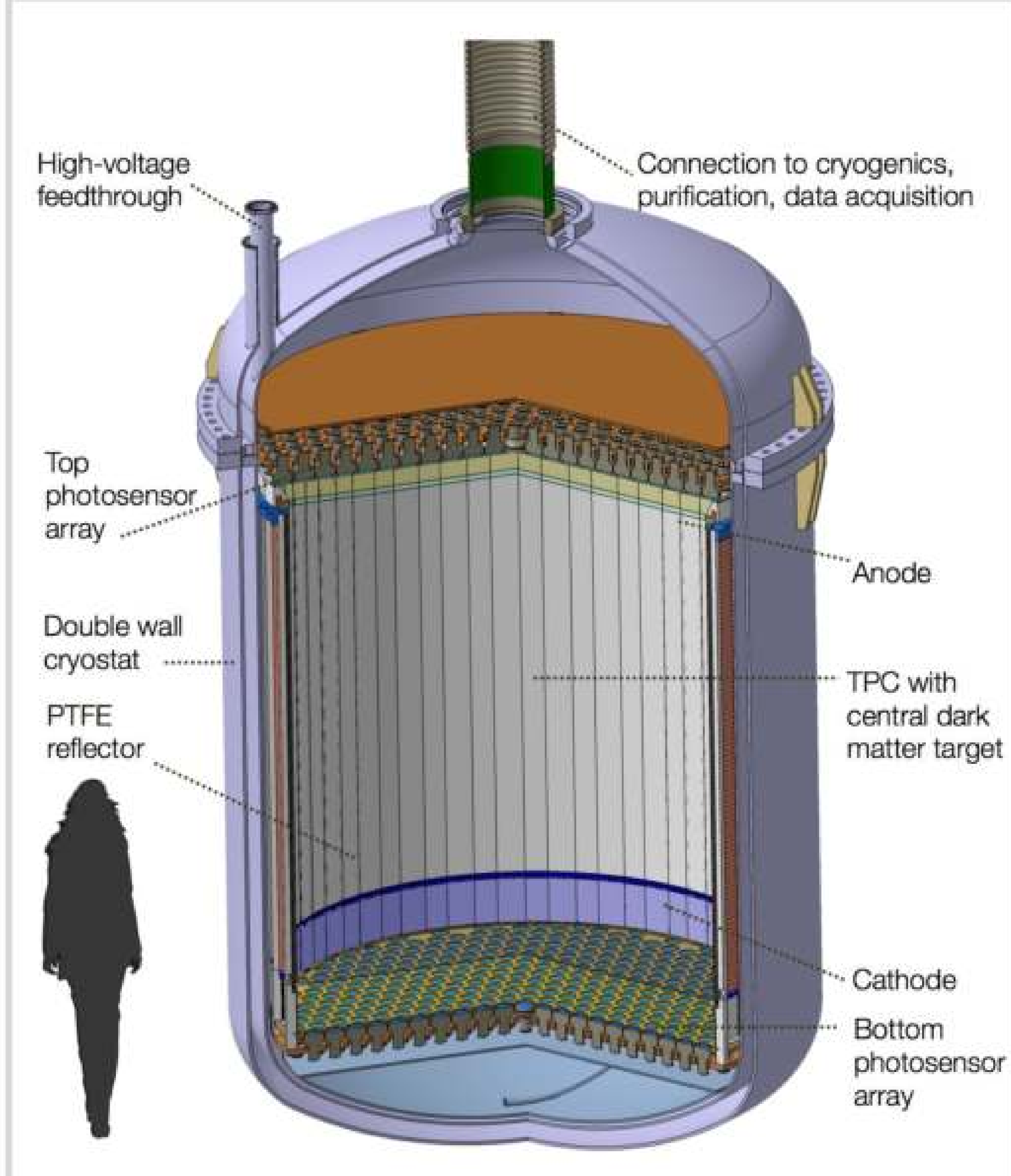
DARWIN collaboration, JCAP 1611 (2016) 017

"Ultimate" WIMP detector

50 tonnes liquid xenon

R&D and prototypes supported by two ERC grants: Ultimate (Freiburg) and Xenoscope (Zürich)





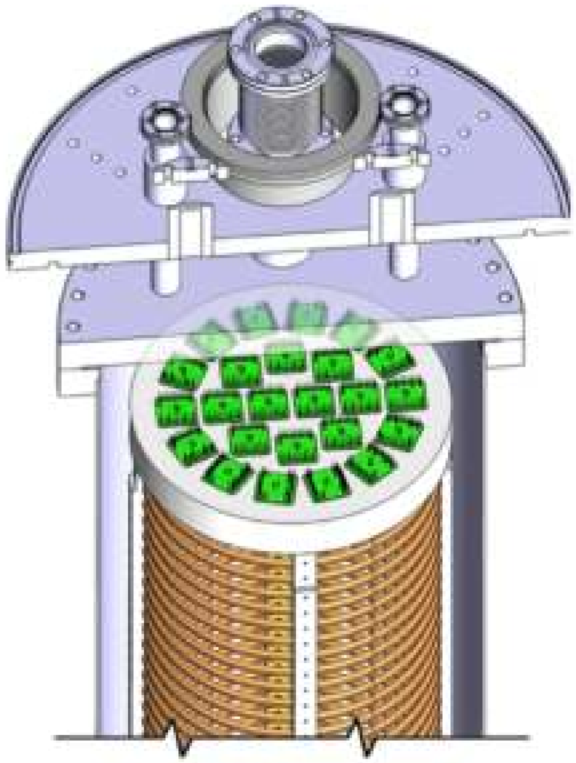
DARWIN

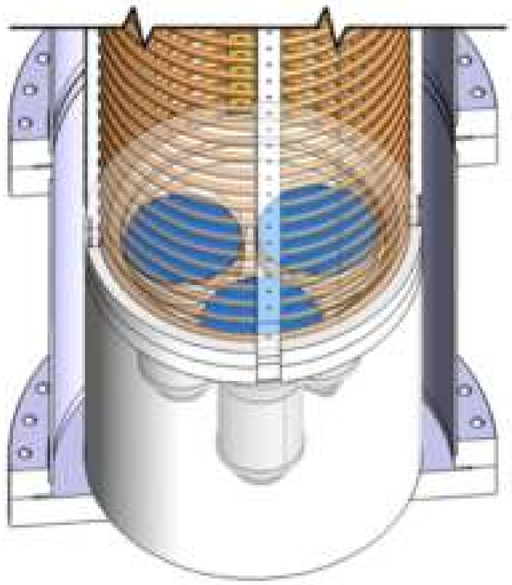
European Research Council
Established by the European Commission

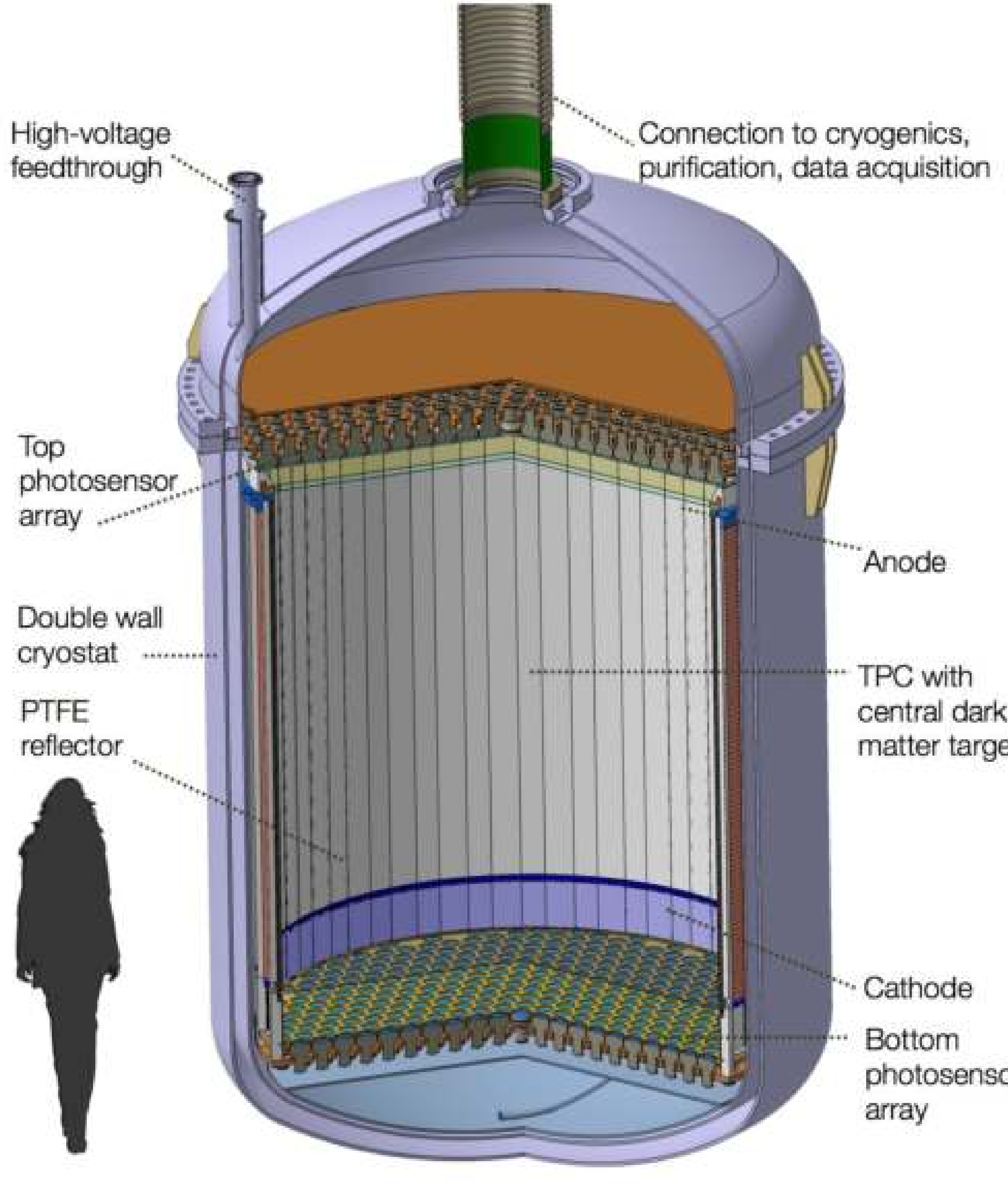
darwin-observatory.org

DARWIN collaboration, JCAP 1611 (2016) 017

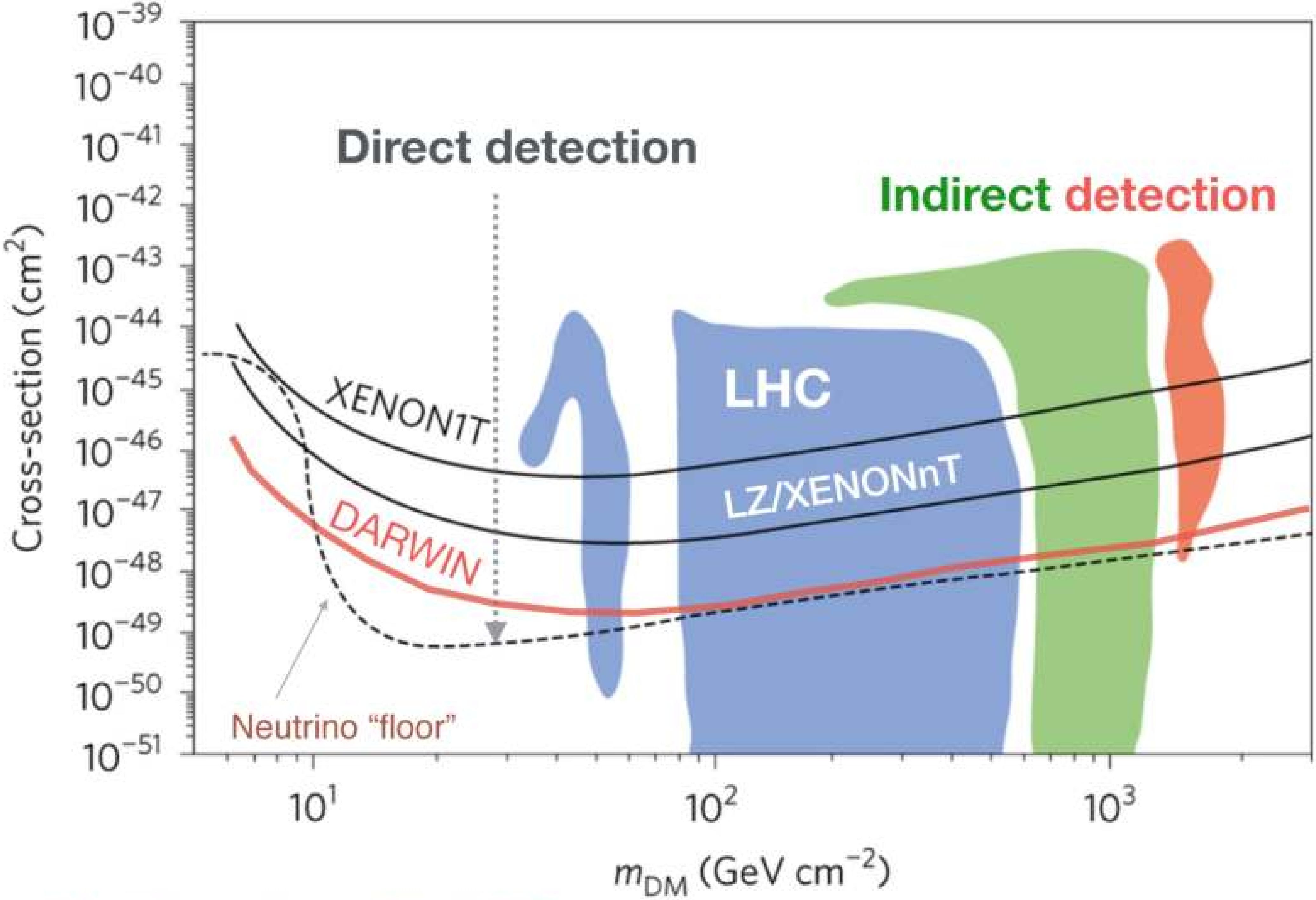
- Physics goals: WIMP-nucleon interactions; solar neutrinos; neutrinoless double beta decay of ^{136}Xe and DEC of ^{124}Xe; coherent neutrino-nucleon interactions; axions and ALPs







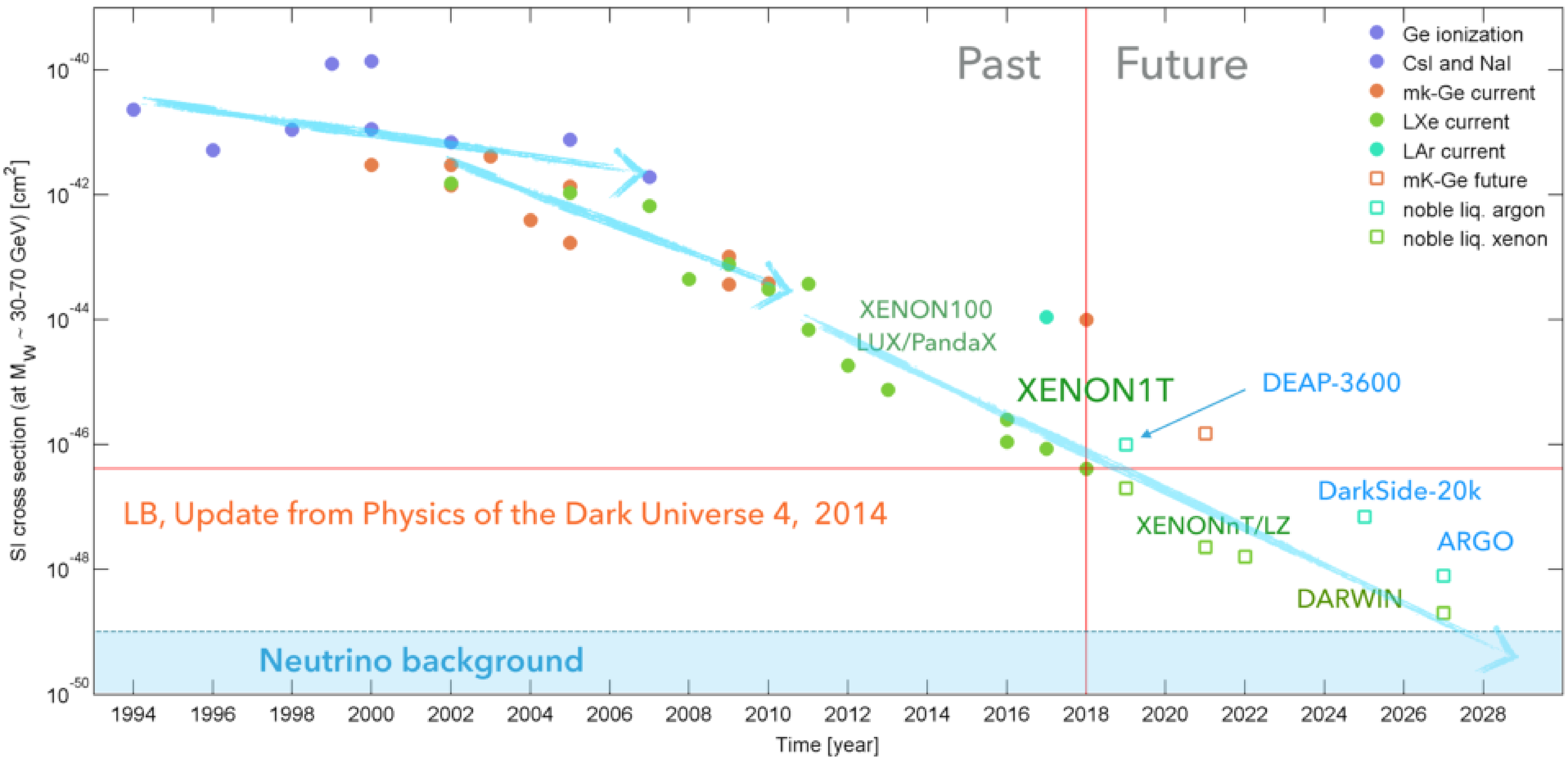
WIMP Physics: Direct, indirect detection, and LHC



After Nature physics, March 2017

SPIN-INDEPENDENT CROSS SECTION

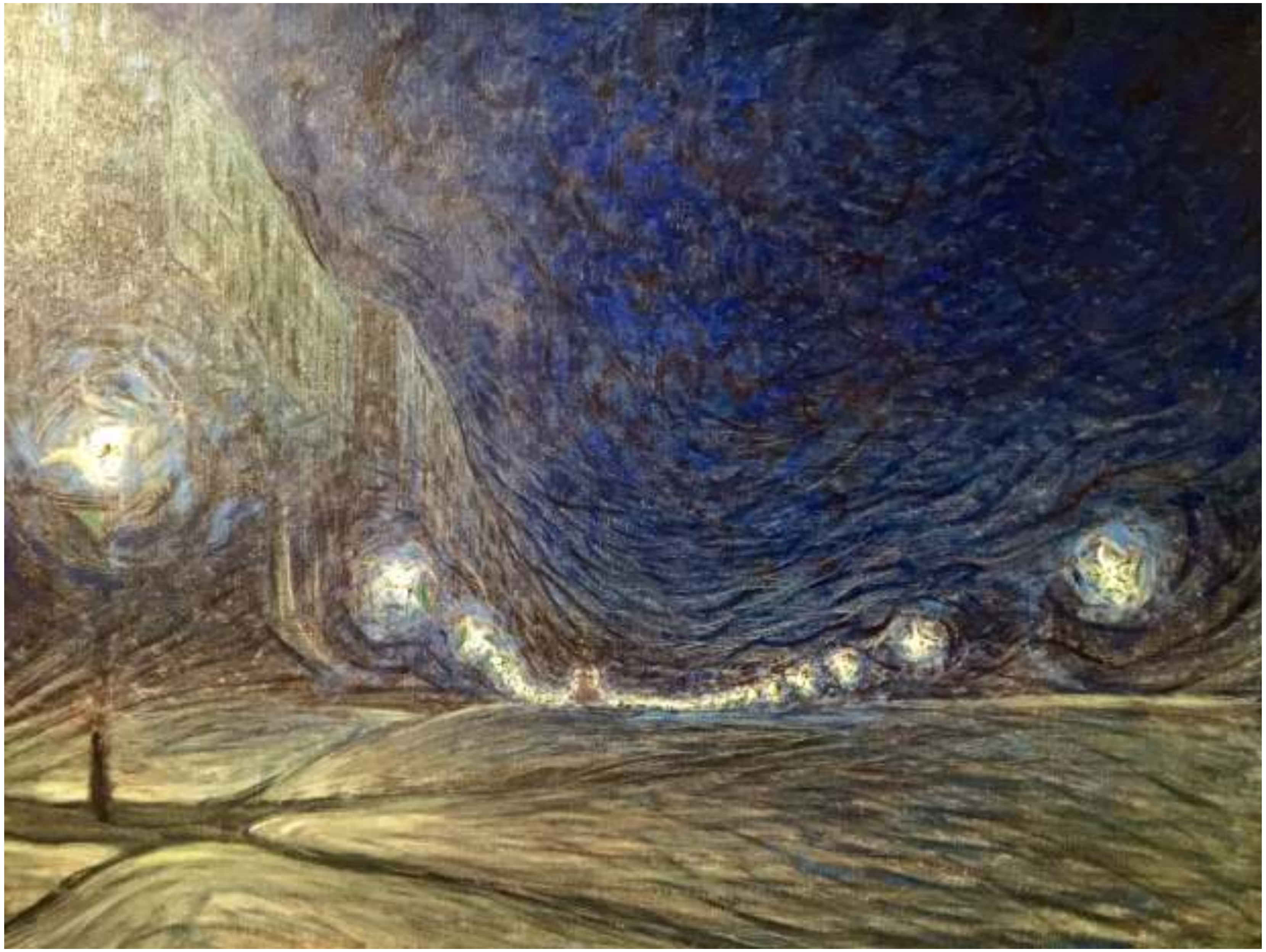
- Sensitivity increase: ~ factor 10 every 2 years



SUMMARY AND OUTLOOK

- The first multi-ton scale LXe-TPC was operated > 1 y
- Achieved the lowest background in a dark matter detector
- Result from an analysis of 1 tonne year exposure: the strongest upper limit on SI WIMP-nucleon cross sections for masses > 6 GeV, with 4.1×10^{-47} cm^2 at 30 GeV
- XENON1T acquires more data until its upgrade, XENONnT, is ready for installation at LNGS
- Many analyses in the pipeline (DEC, $0\nu\beta\beta$-decay, annual modulation, low-mass WIMPs, bosonic SuperWIMPs, etc)
- XENONnT and DARWIN are designed for a factor 10 and 100 increase in sensitivity, respectively

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



THE END

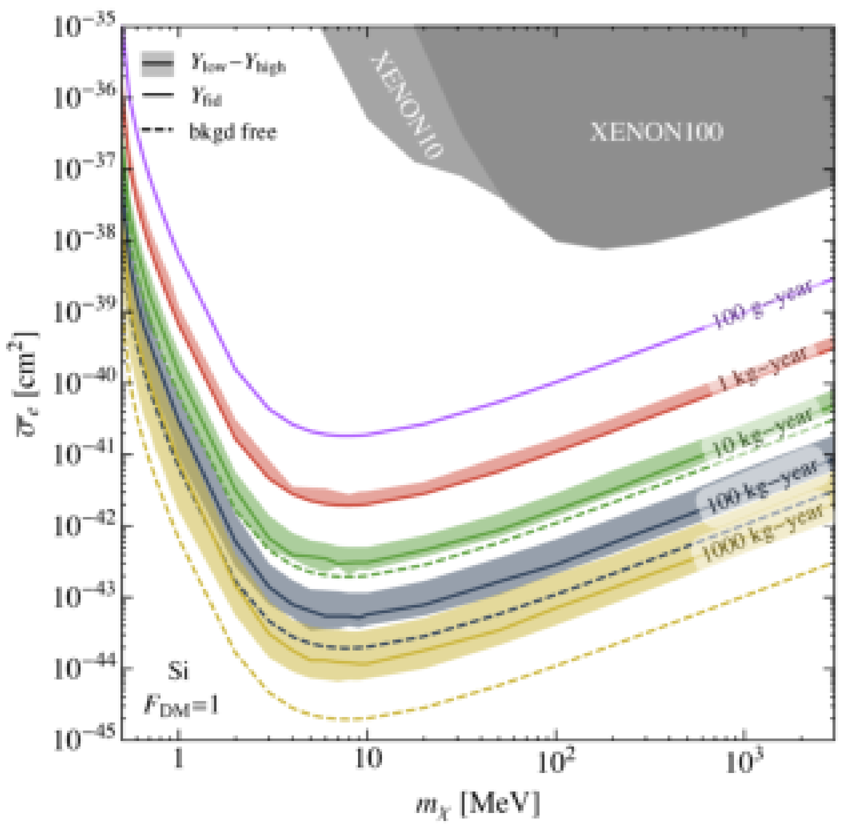
SUMMARY & OUTLOOK

- 'Thermal dark matter' particles 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*… so we have been narrowing down the options; but, tremendous progress over the past decades, and expected for next
- Pragmatic goal: broaden the searches & probe the experimentally accessible parameter space
- Rich non-WIMP physics programme (neutrinos, axions/ALPs, dark photons, etc) & remember that today's background might be tomorrow's signal

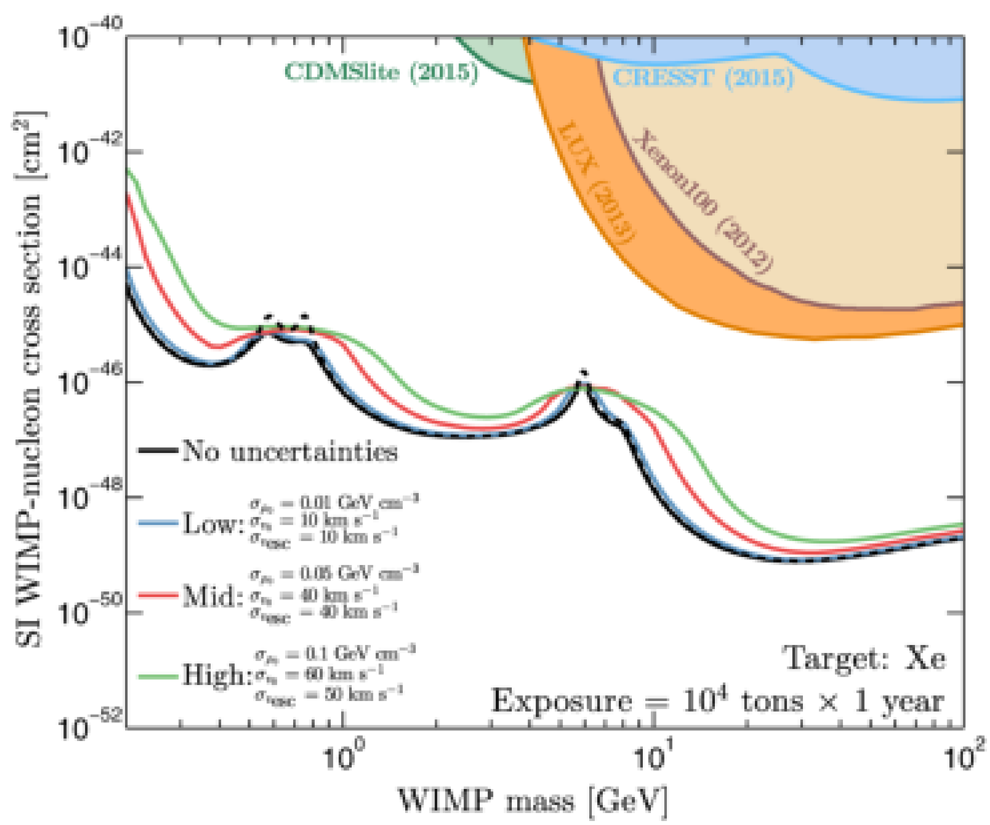
NEUTRINO BACKGROUNDS

- 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 dependance, inelastic DM-nucleus scatters, etc

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



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

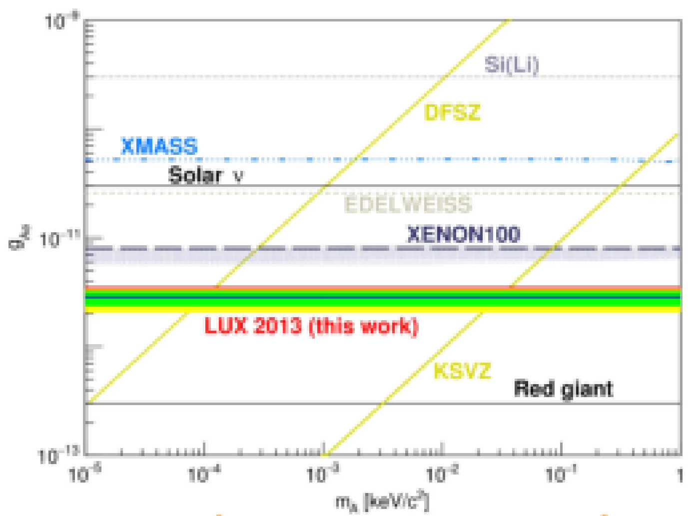


DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)

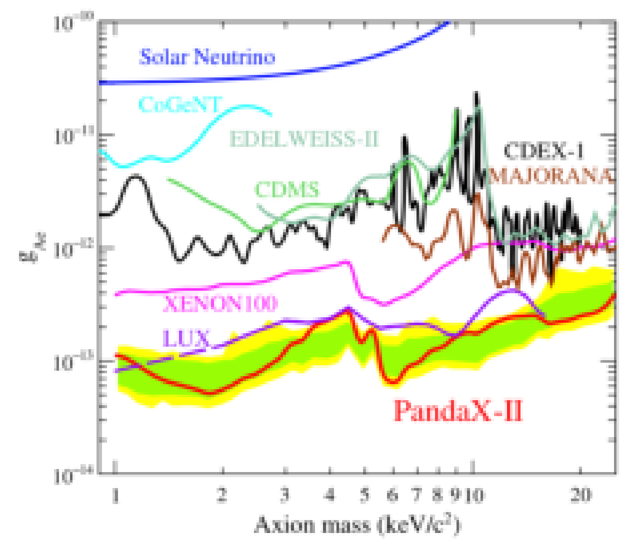
AXIONS, AXION-LIKE PARTICLES AND DARK PHOTONS

- Absorption via axio-electric effect; peak at particle mass

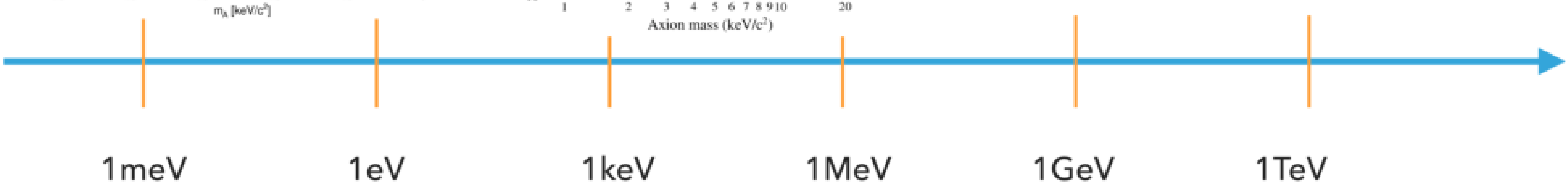
Solar axions, PRL 118, 2017



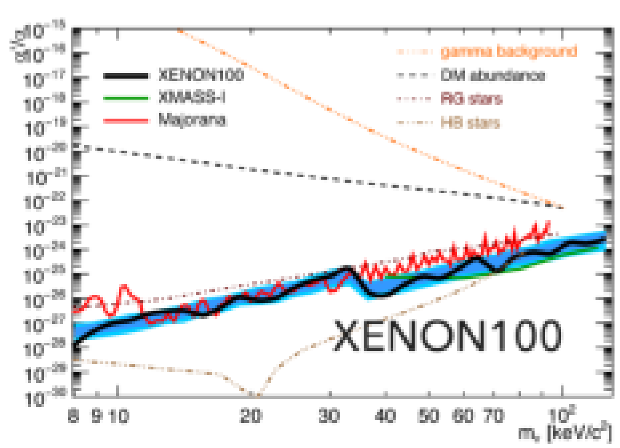
Pseudo-scalar; PRL 119, 2017



$$R \simeq \frac{4\times 10^{23}}{A}\frac{\alpha'}{\alpha}\left(\frac{\mathrm{keV}}{m_v}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$



Vector; PRD 96, 2017

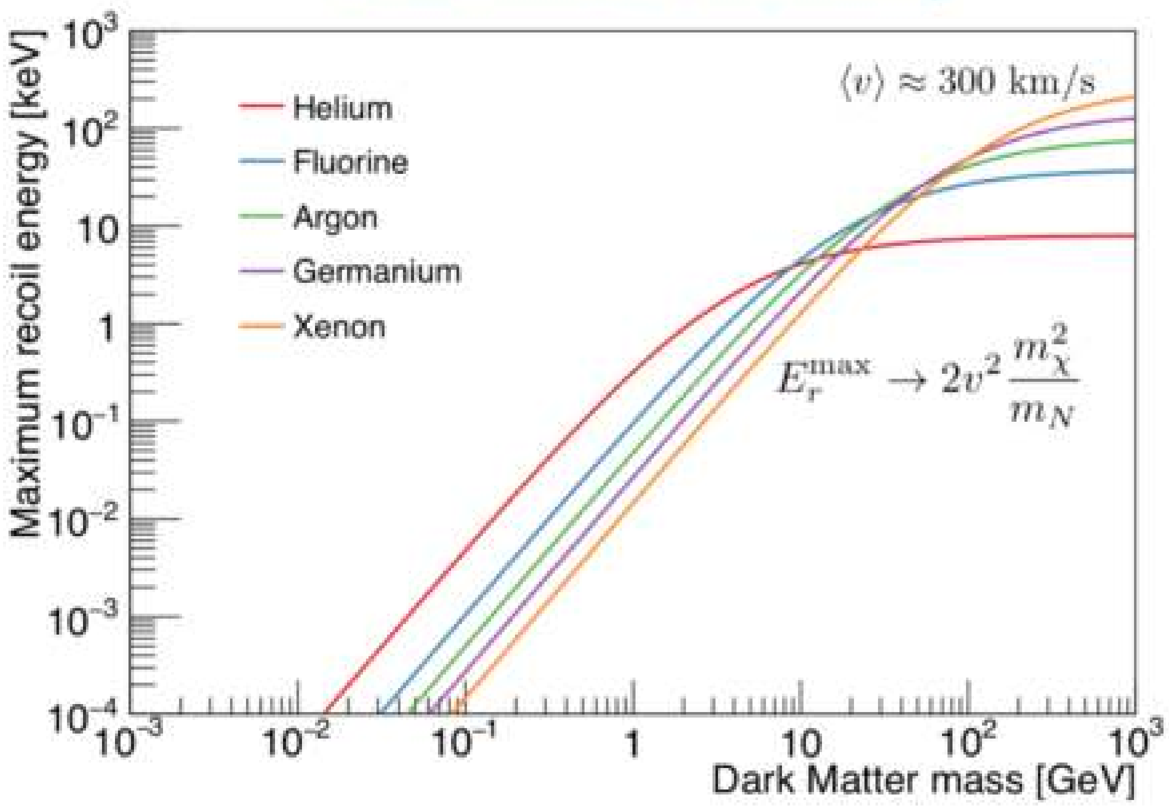


$$R \simeq \frac{1.29\times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

LOW-MASS DARK MATTER

- Once the mass of the dark matter particle is much smaller than the nuclear mass, the transfer of kinetic energy becomes very inefficient
- Thus, exploit *dark matter - electron scattering*

DM-nucleus scattering



+ electronic recoil

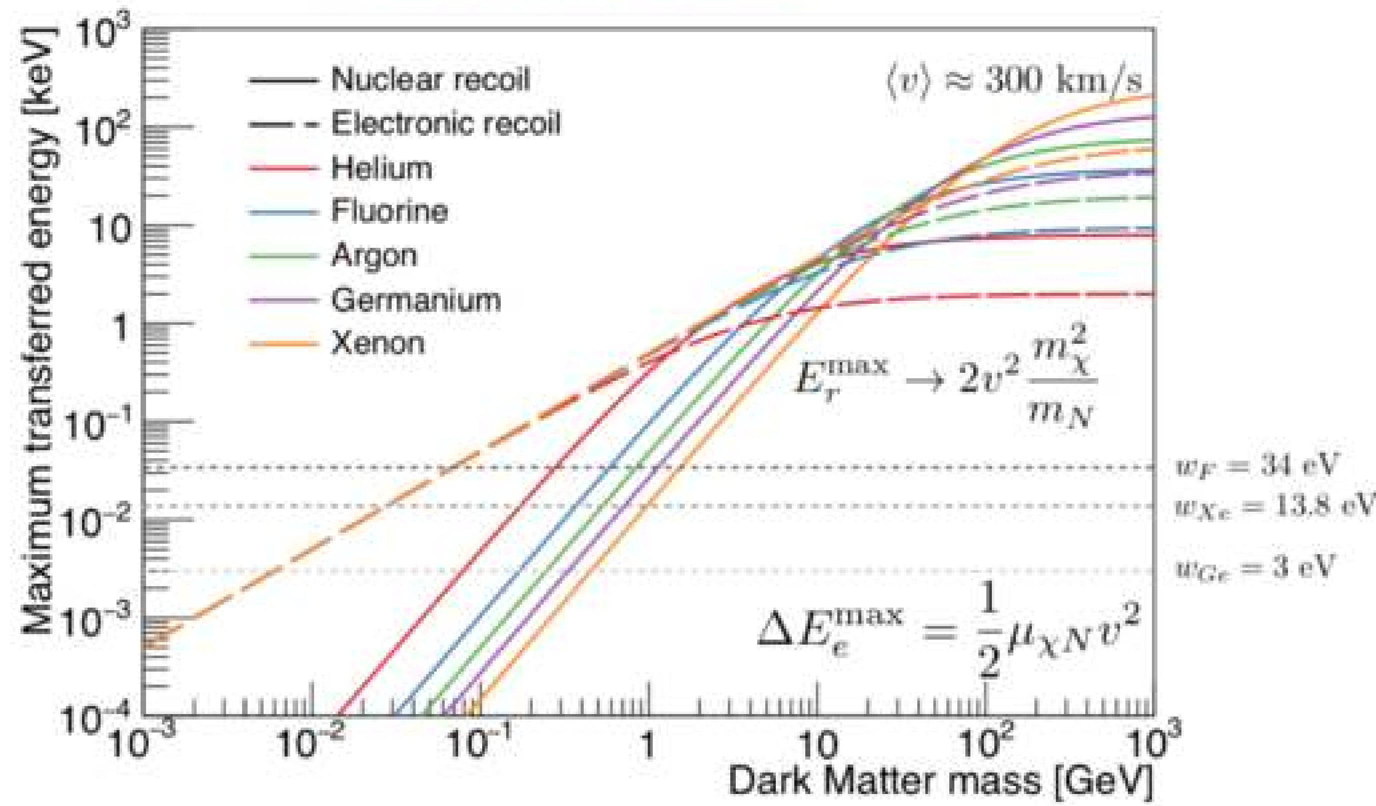
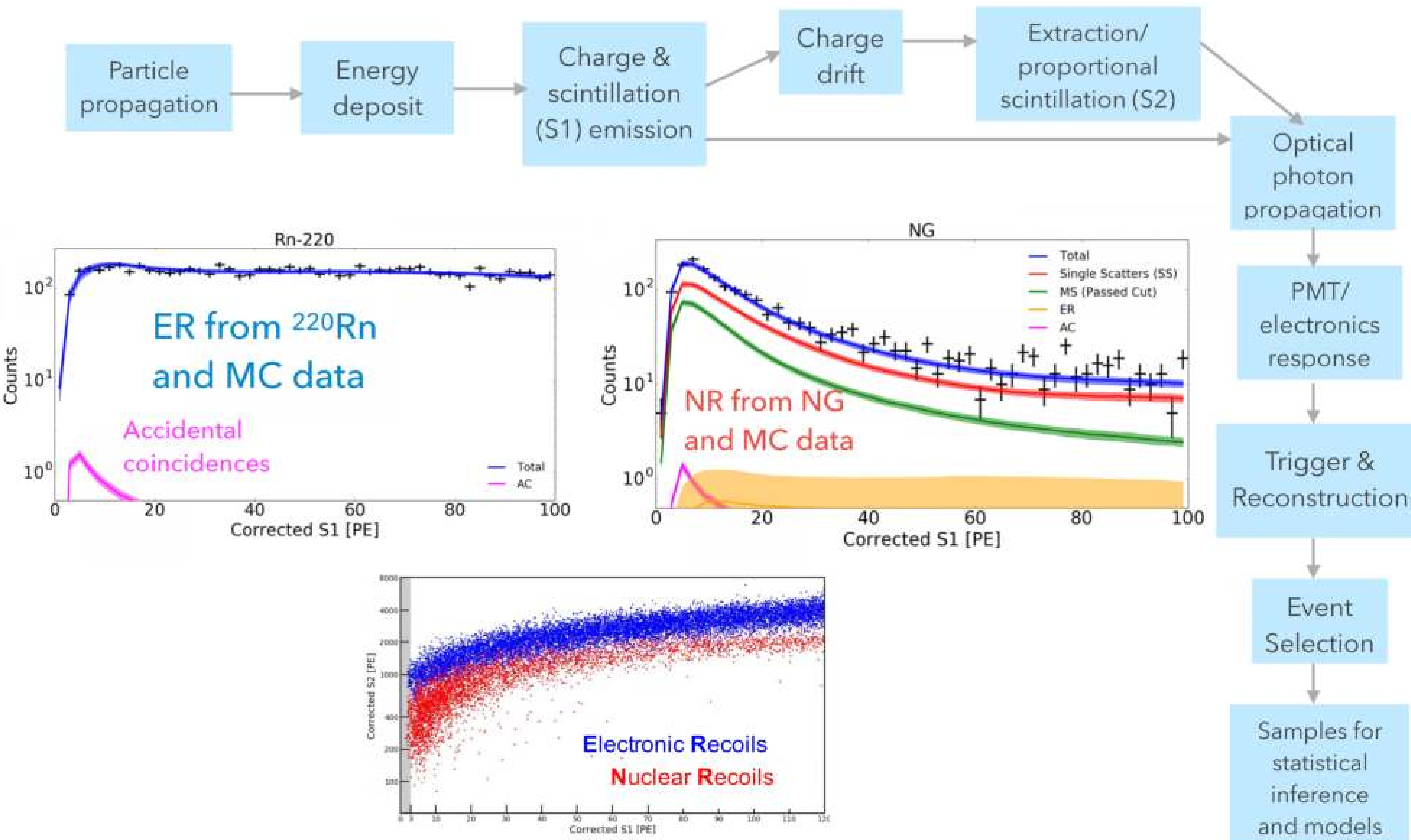


Fig. shown by Silvia Scorza, PPC2018, Zurich

SIGNAL AND BACKGROUND MODELLING

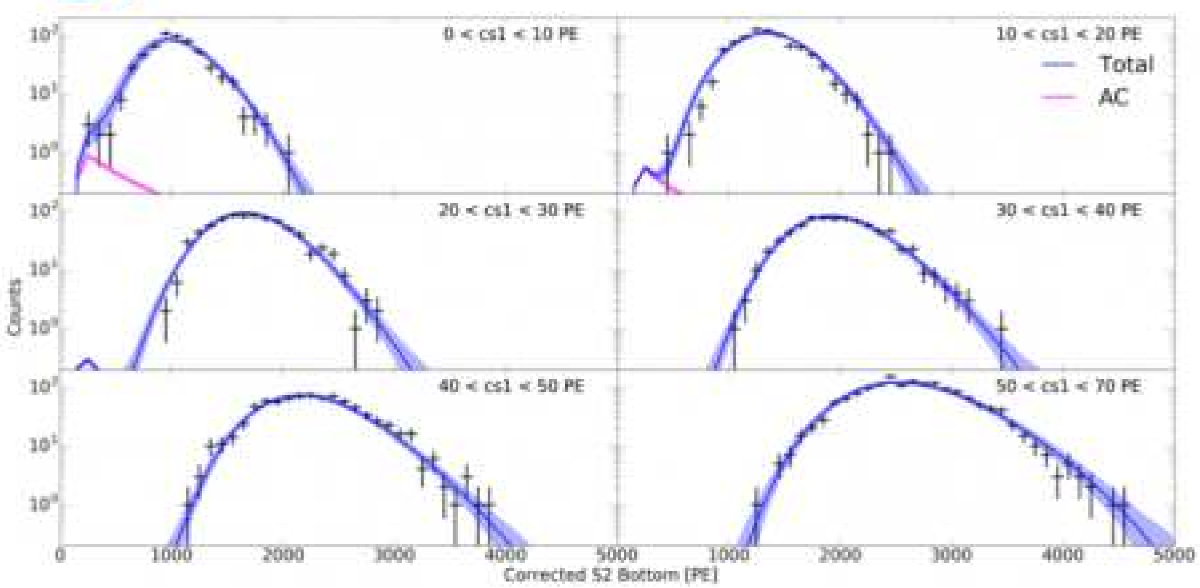


SIGNAL AND BACKGROUND MODELLING

Particle propagation → Energy deposit → Charge & scintillation (S1) emission → Charge drift → Extraction/ proportional scintillation (S2) → Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Event Selection → Samples for statistical inference and models

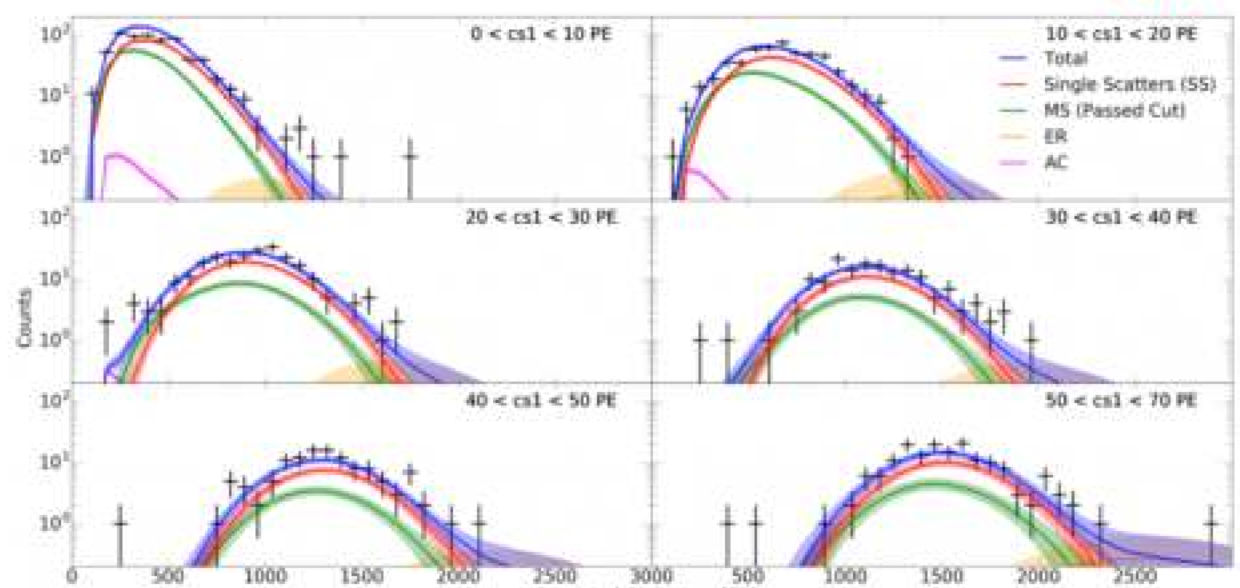
(Charge & scintillation (S1) emission → Optical photon propagation)

ER



Slice in S1 & project onto S2

NR



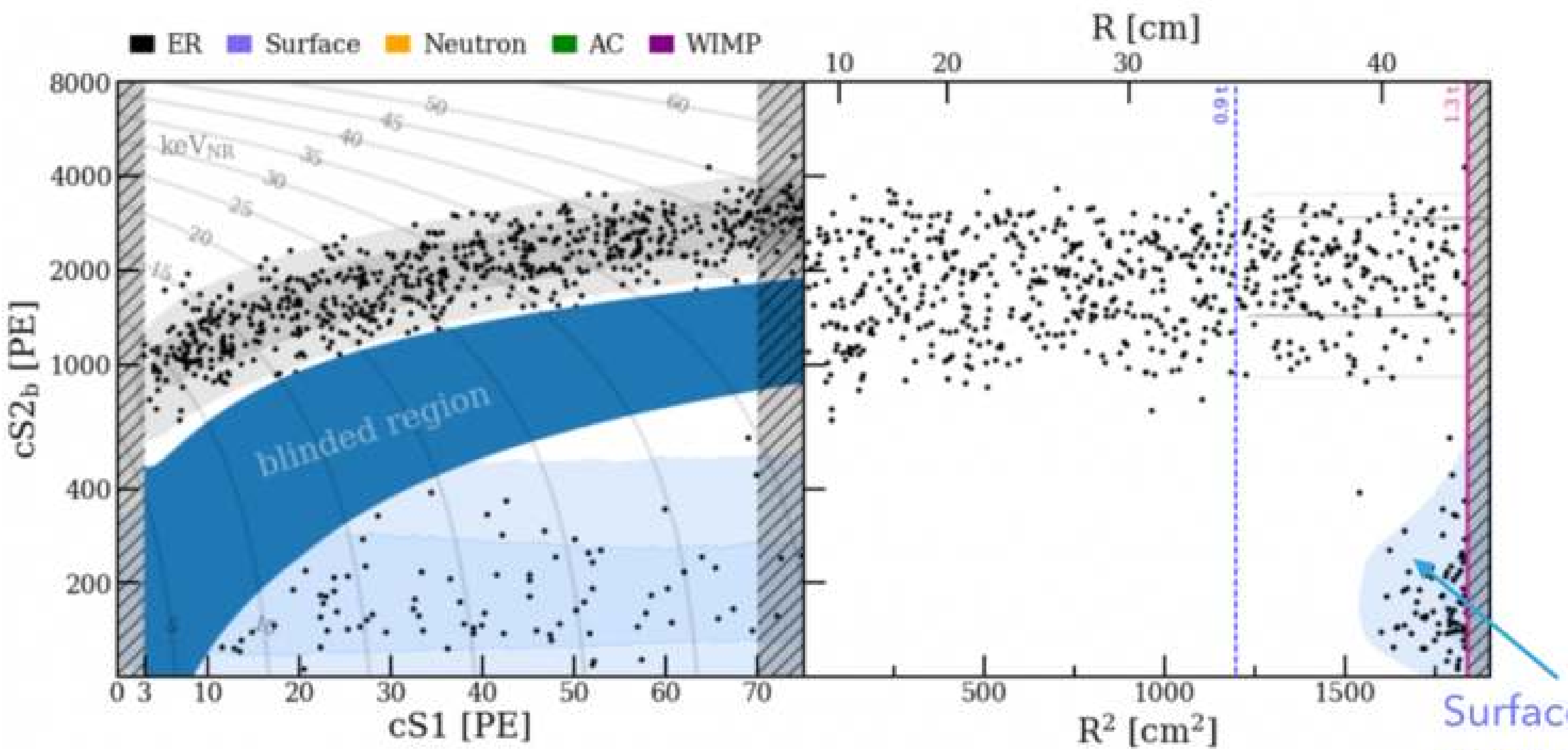
Each component (S, B) is modelled as a probability density function in ($S1$, $S2_b$, r, z)

DARK MATTER SEARCH DATA

- Blinded: avoid bias in event selection and S/B modelling
- Salted: protect against post-unblinding tuning of cuts and background models

Blinded region:

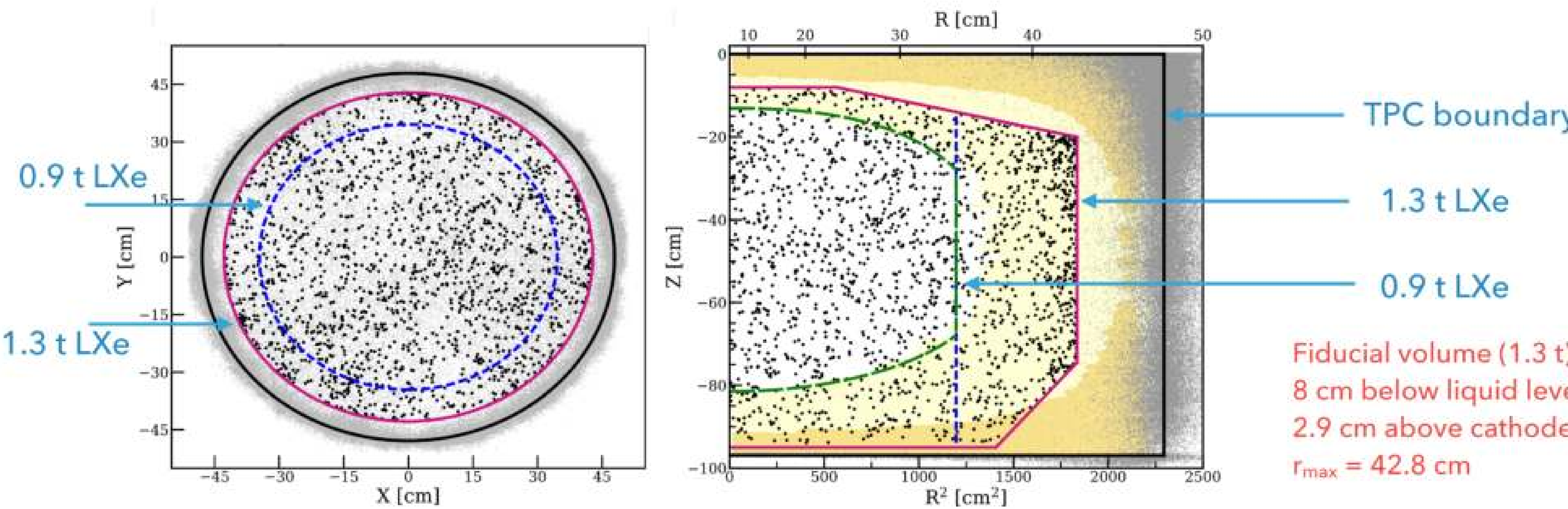
- S2 > 200 PE
- below the ER -2σ quantile in $S2_b$ versus S1 space



Surface component

FIDUCIAL VOLUME SELECTION

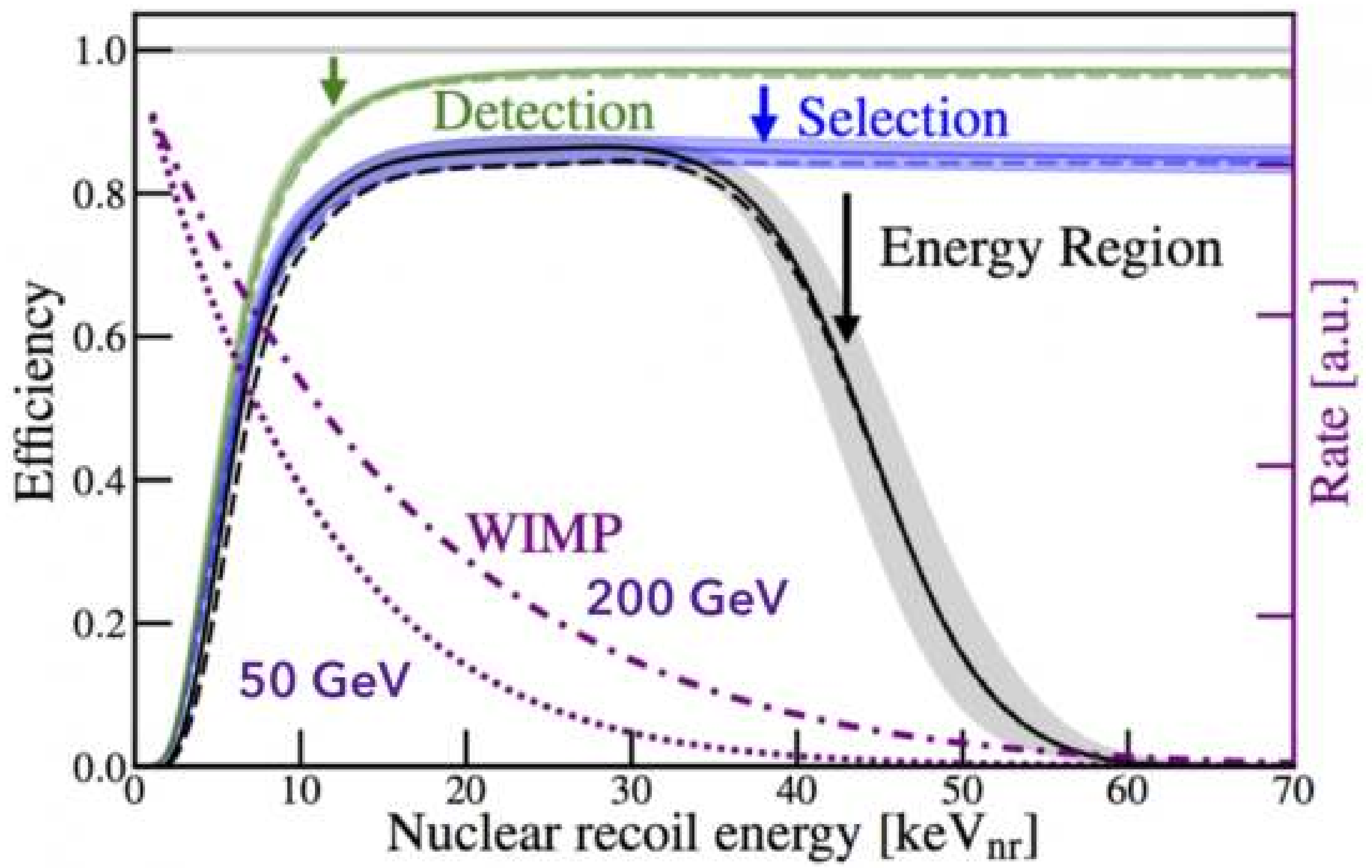
- Optimised prior to unblinding to reduce materials and surface background: 1.0 t → (1.3±0.01) t
- Included radius r in statistical inference due to surface background model; analysis in (S1, $S2_b$, r, z)-space



Fiducial volume (1.3 t):
8 cm below liquid level,
2.9 cm above cathode;
r_{max} = 42.8 cm

EVENT SELECTION AND DETECTION EFFICIENCY

- Detection efficiency: due to 3-fold PMT coincidence requirement
- Selection efficiencies: from MC and data control samples
- Dark matter search region: [3-70] PE in S1



Bands: 68% credible regions

ROI: [3 - 70] PE corresponds to

ER: [1.4 - 10.6] keV$_{ee}$

NR: [4.9 - 40.9] keV$_{nr}$

DARK MATTER AND THE CMB