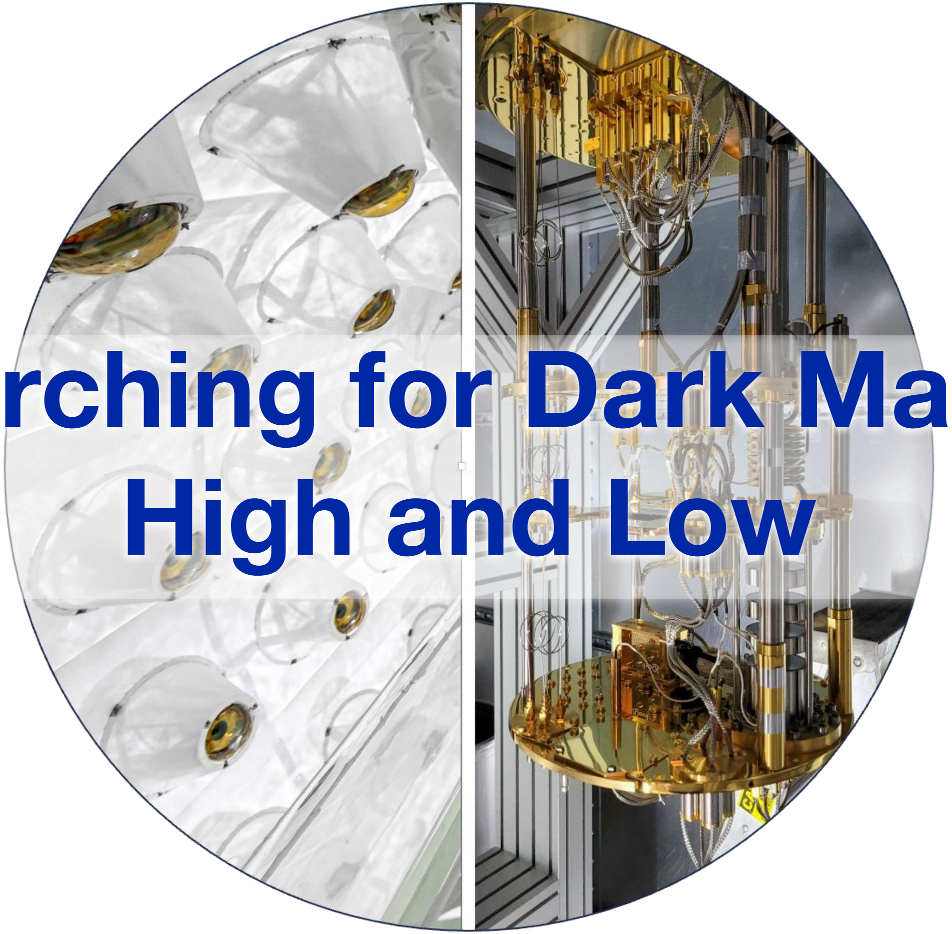
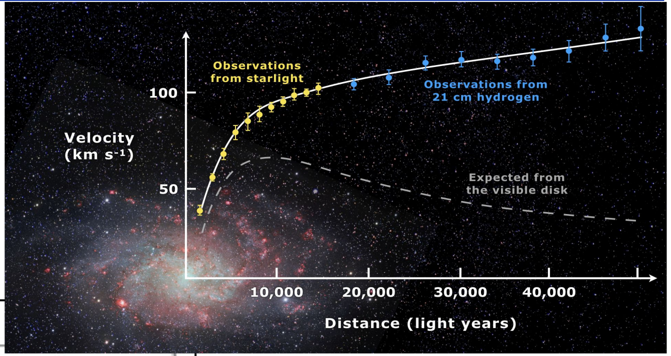
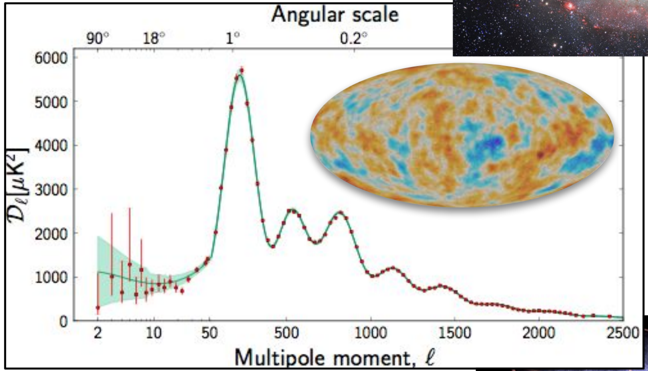
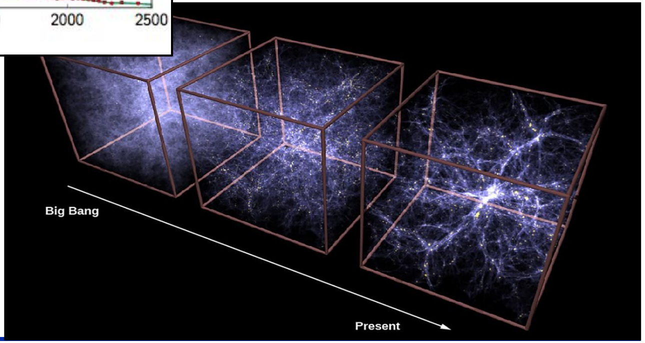


Searching for Dark Matter High and Low

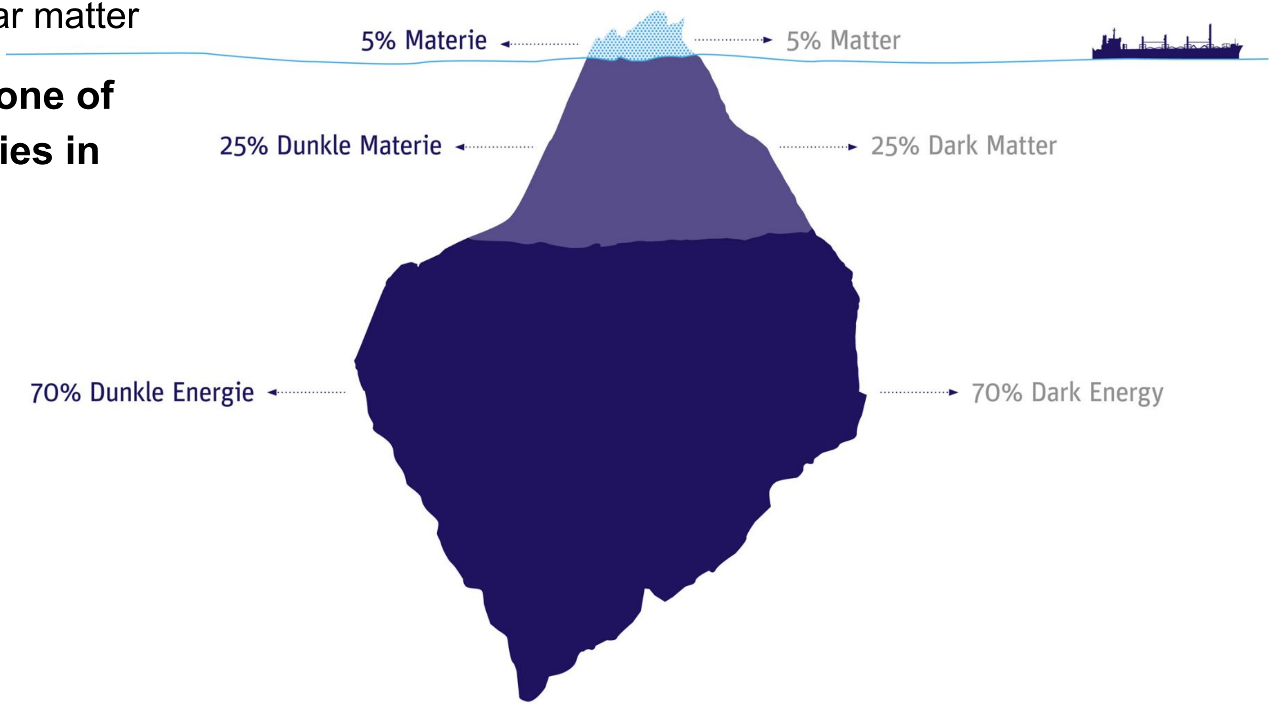
- **Dark Matter** (DM) is is the only theory that can **explain the Universe on all scales at at all times**
- Very **large body** of **evidence**
  - Galaxy rotation curves
  - Galaxy clustering
  - Cluster collision
  - Large-scale structures
  - CMB fluctuations
  - Gravitational lensing
- Global fit of cosmological parameters: $\Omega_\Lambda \approx 0.68$, $\boldsymbol{\Omega_{DM} \approx 0.27}$, $\Omega_b \approx 0.05$

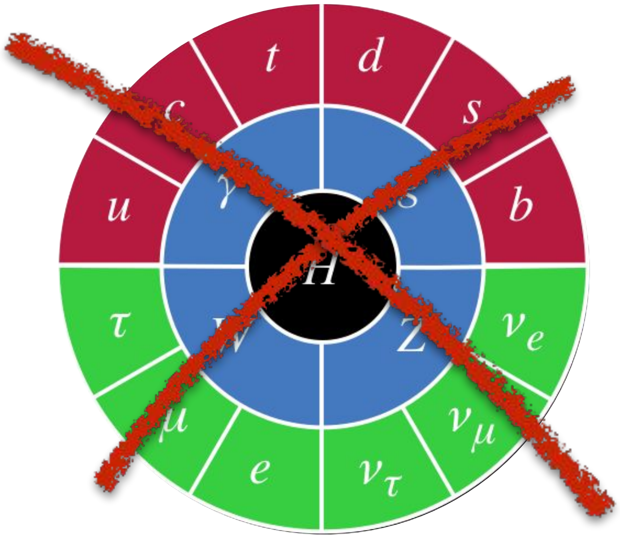




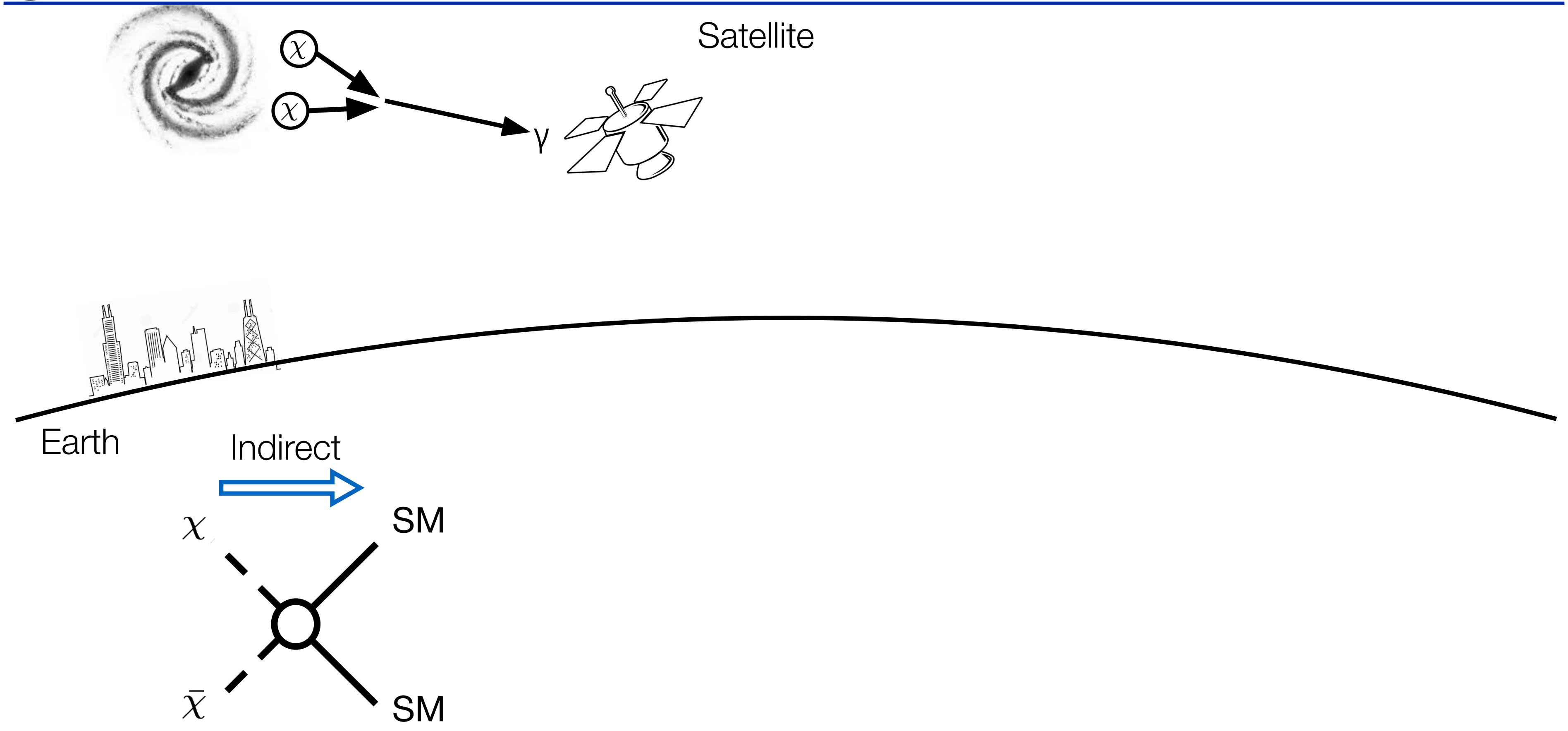


- **Five times more DM** than regular matter
- The **discovery of DM will be one of the most important discoveries in modern physics**

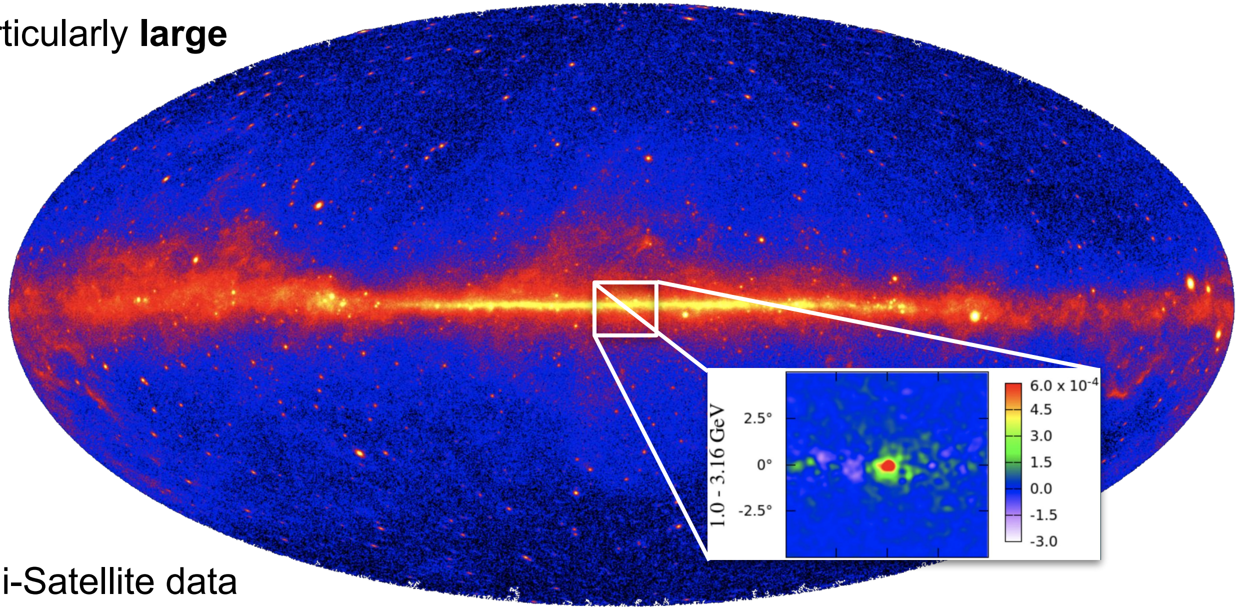


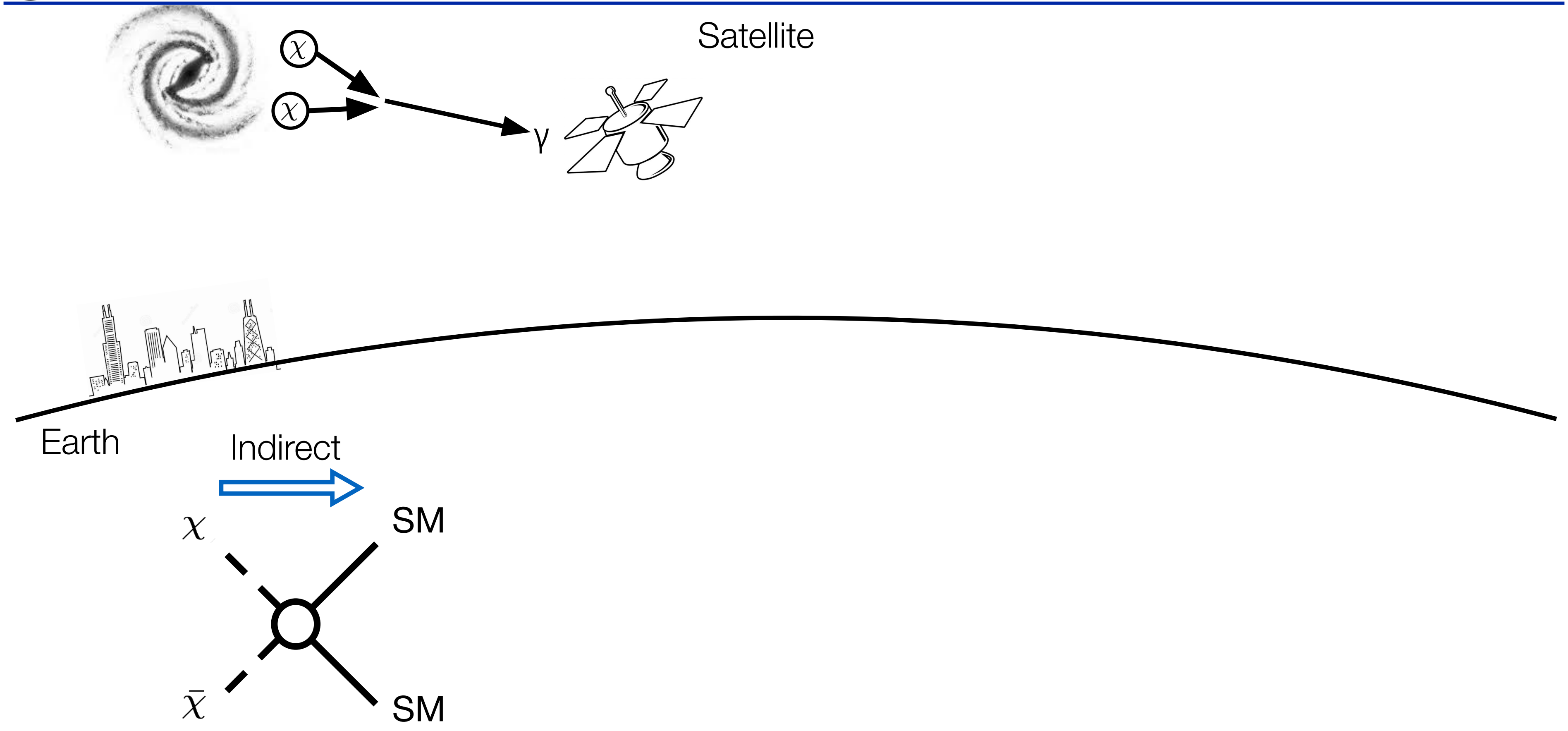


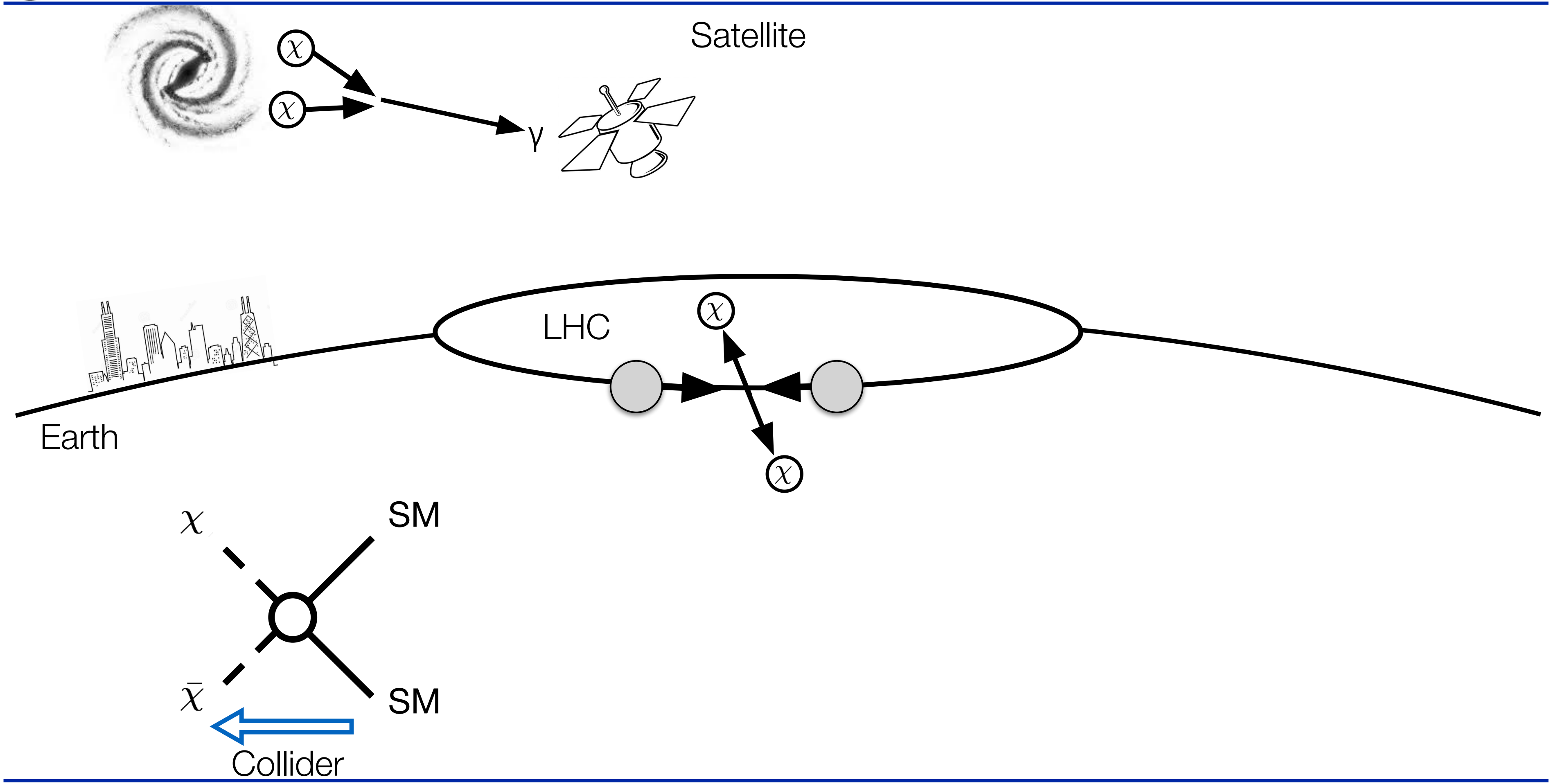
- Unfortunately, its detection has escaped us so far
- How to **catch such a specter**?


Satellite
χ
χ
γ
Earth
Indirect
χ
χ̄
SM
SM

- **Indirect Searches** search for DM where we know it exists: In the Universe
- Look at places where we expect particularly **large amounts of DM**, e.g:
  - Center of the Galaxy
  - Galaxies which are DM dominated
  - Objects with massive gravity like the sun
- So far '**no smoking gun**' but some intriguing excesses
- **Galactic center** excess in γ-rays between 0.1 and 10 GeV from Fermi-Satellite data
  - Spherically symmetric within < 10° × 10° around the Galactic Center
  - Foreground modeling very difficult, open debate




Satellite
χ
χ
γ
Earth
Indirect
χ
$\bar{\chi}$
SM
SM


Satellite
χ
χ
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LHC
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χ
Earth
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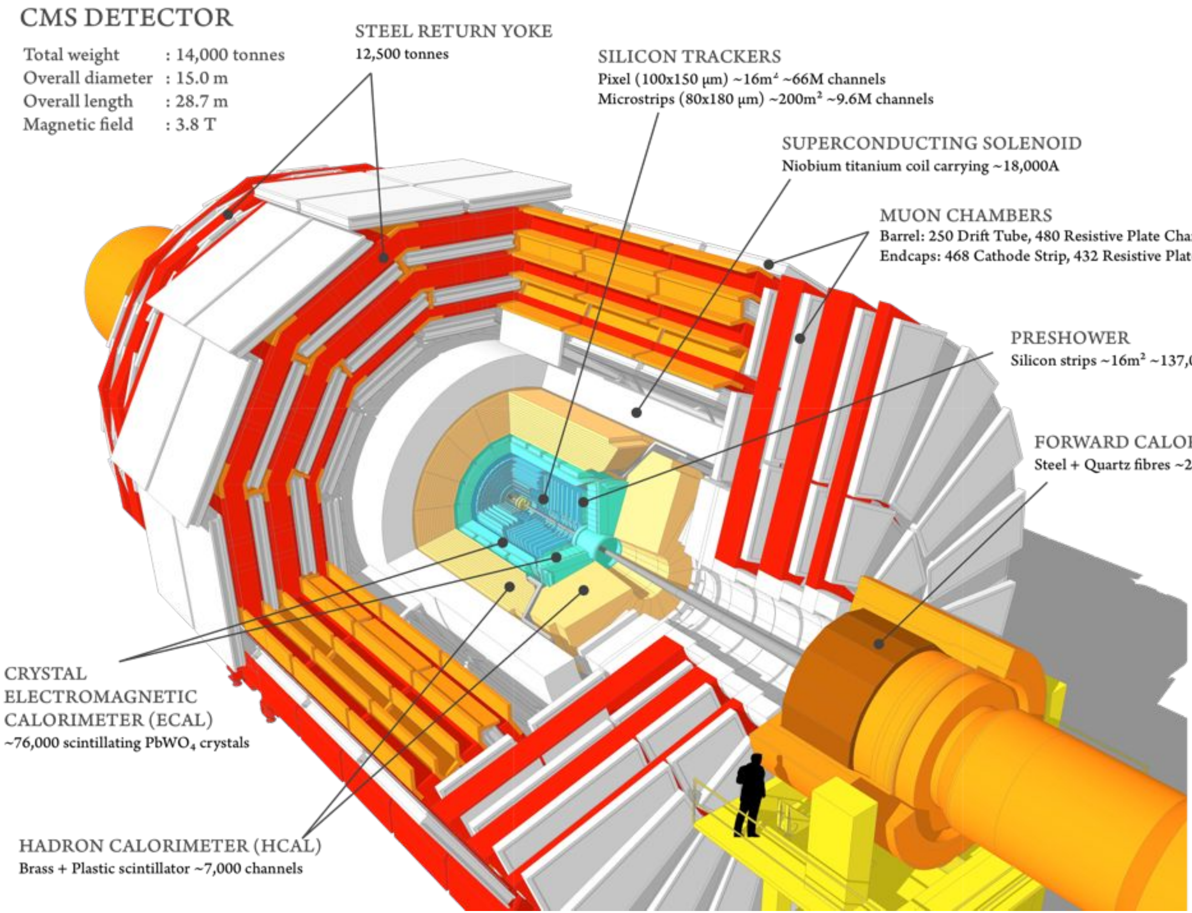
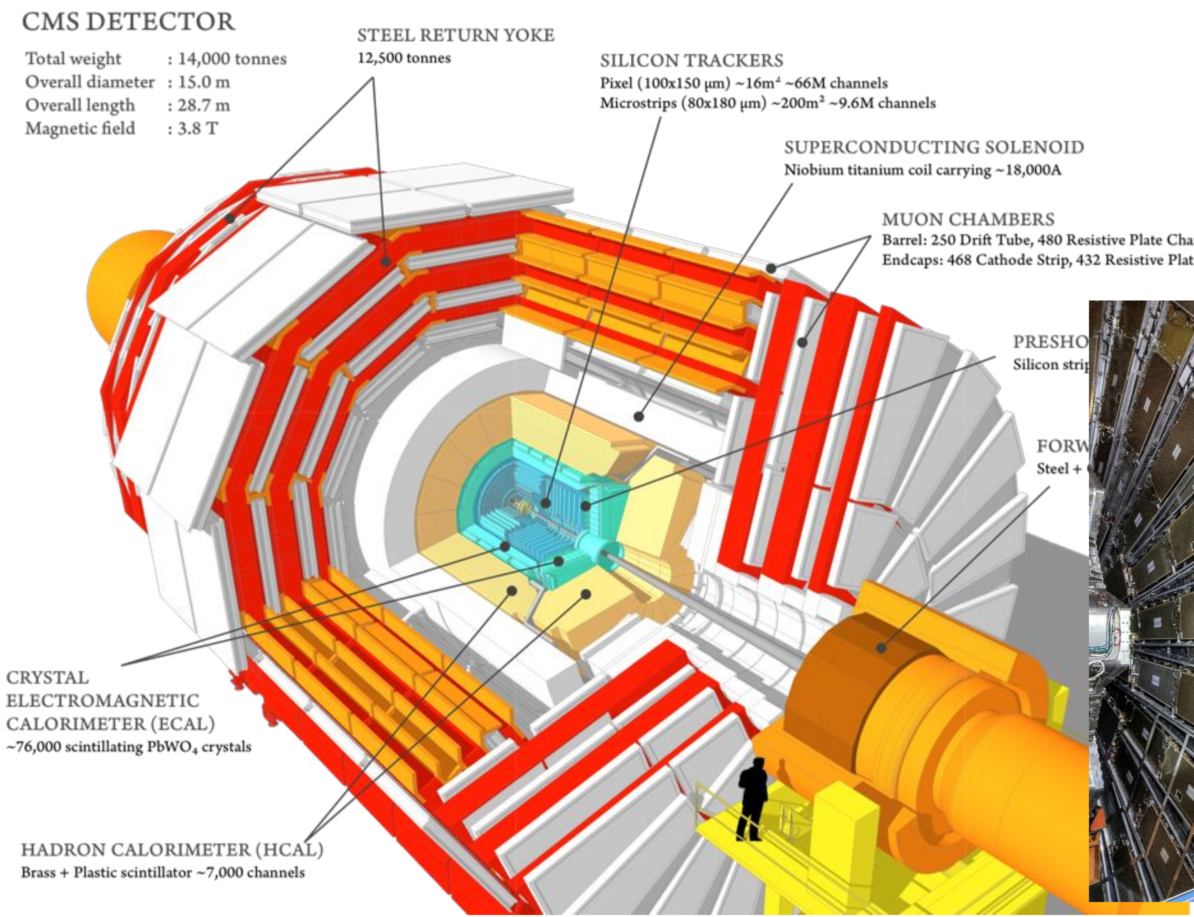
$\bar{\chi}$
SM
Collider


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels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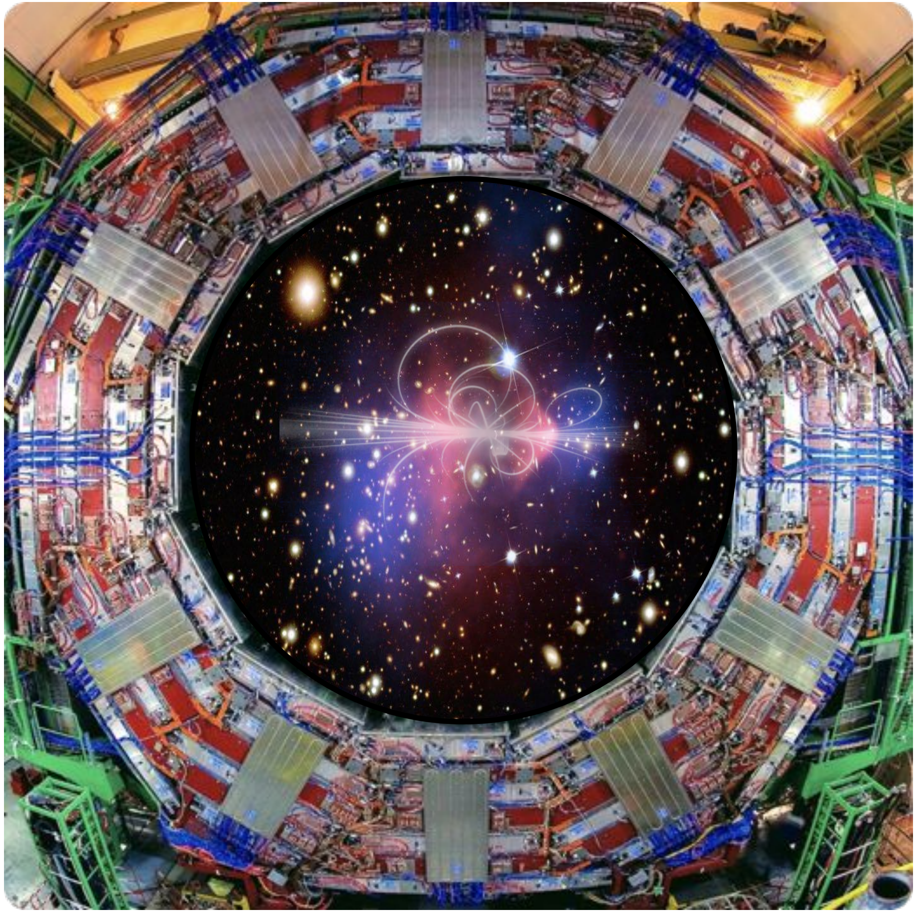
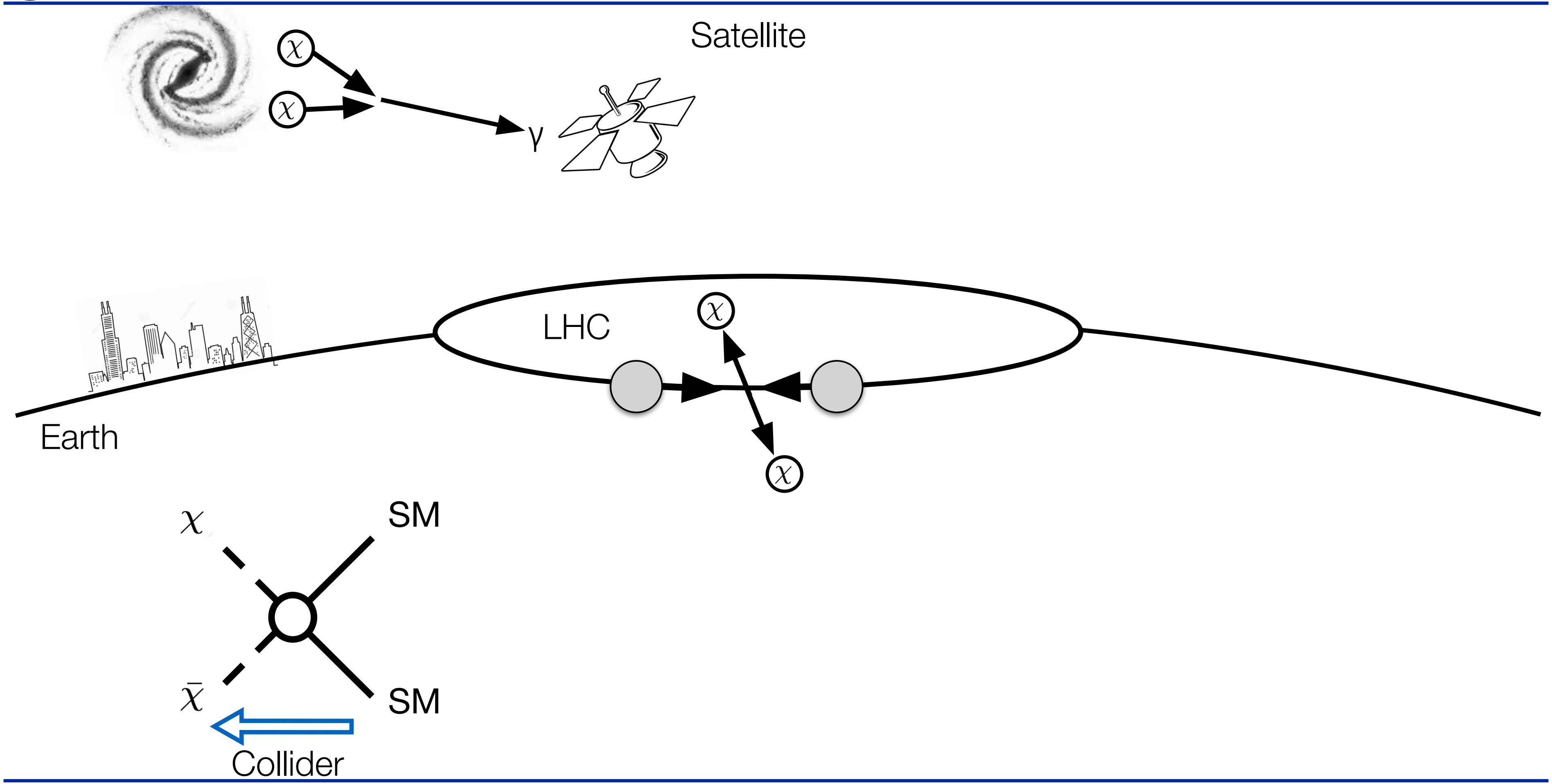
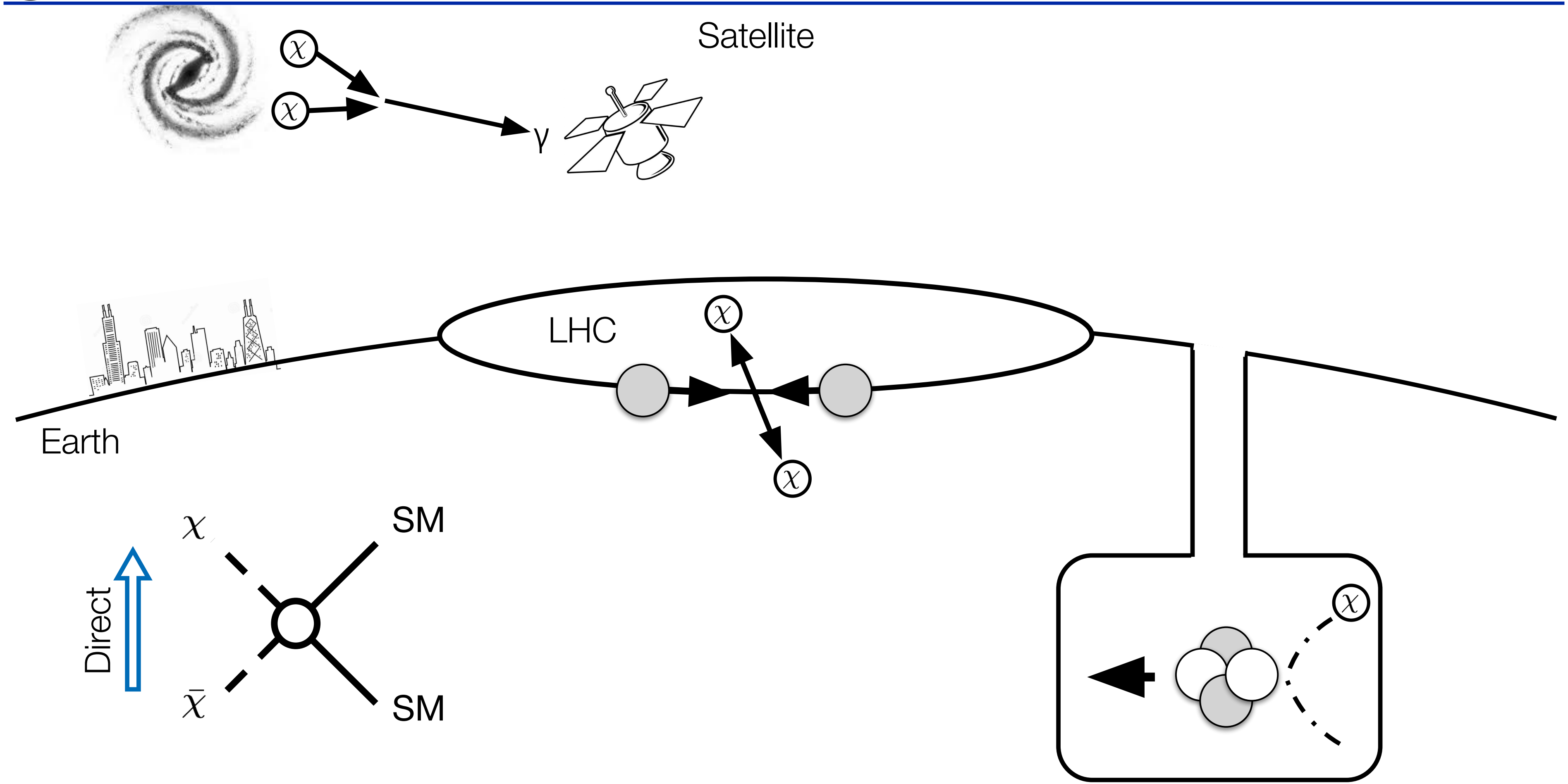
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

- If all evidence of DM is gravitational, why should we look for it at collider (particularly hadron)?
  - Well motivated,**'WIMP paradigm**' predicts particles approximate EW scale
  - **Complementarity**: Collider have different strengths and uncertainties
- But
  - DM has to be kinematically accessible: ~1-1000 GeV
  - We haven't seen it yet



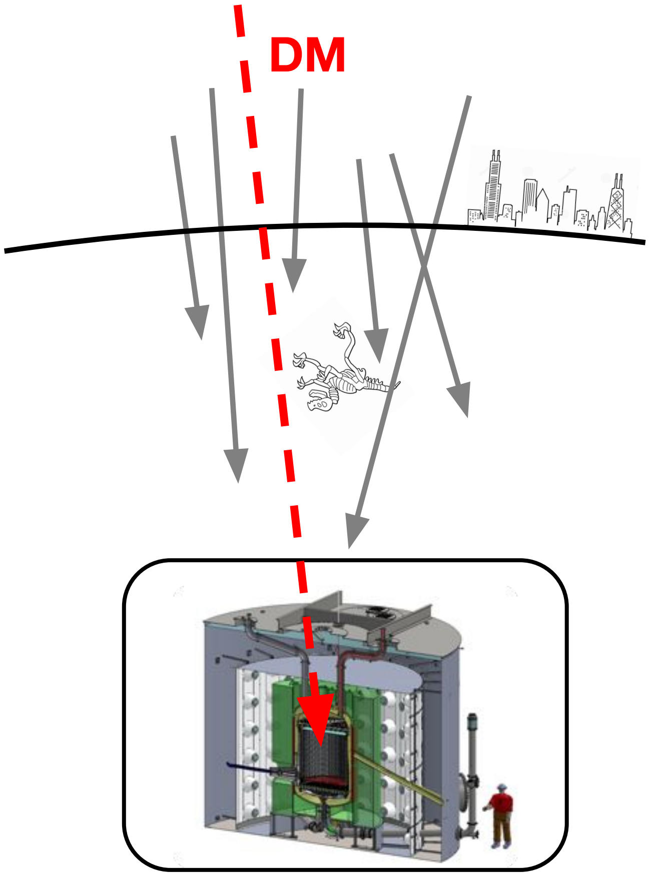

Satellite
γ
LHC
Earth
SM
SM
Collider


Satellite
χ
χ
γ
LHC
χ
χ
Earth
χ
$\bar{\chi}$
SM
SM
Direct
χ

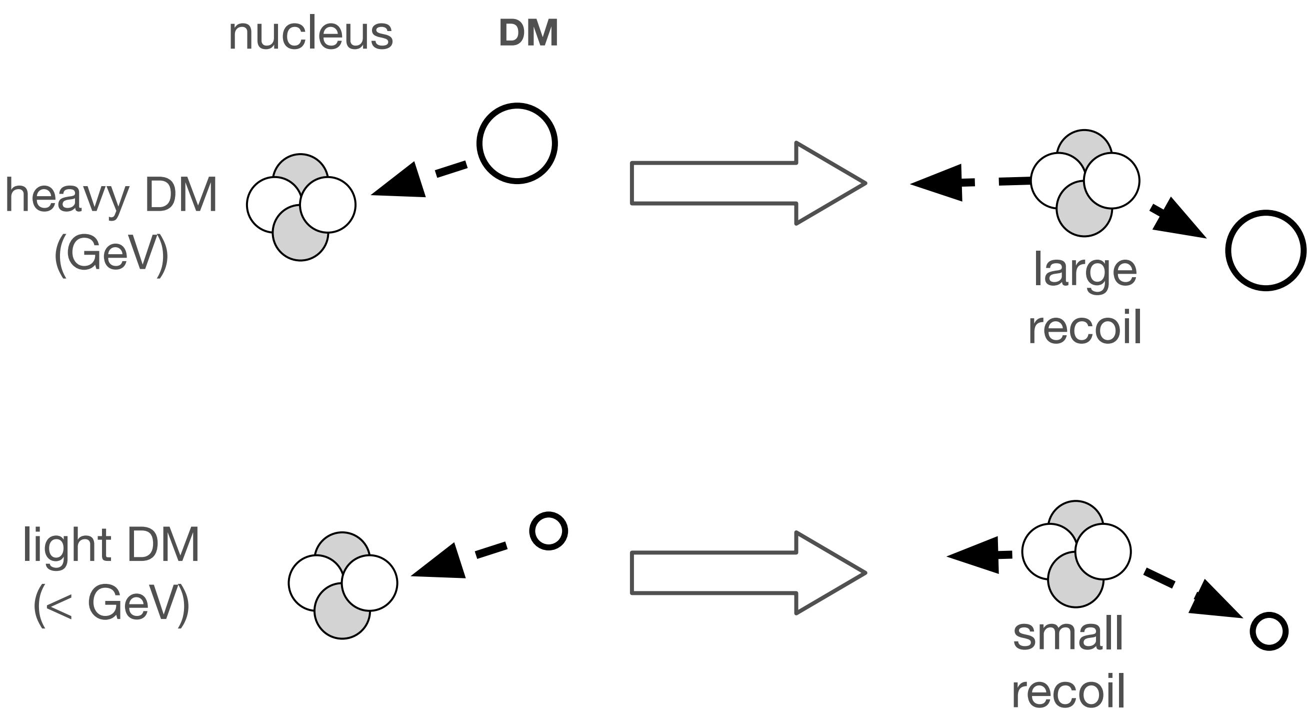
- Detect DM as our solar system passes through the galactic halo
  - $v \sim 10^{-3}$ c
  - Kinetic energy ~ 100 keV
- Detected by recoils off **ultra-sensitive detectors** deep underground
- Roughly 1 interaction per kg per year

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

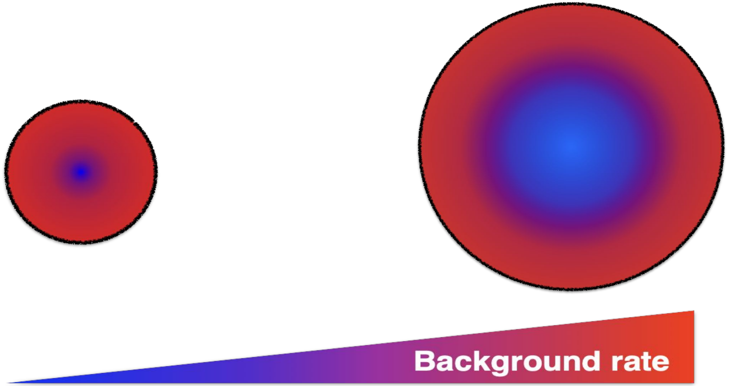
- Very stringent cleanliness and background rejection requirements
- **Variety of detection methods**

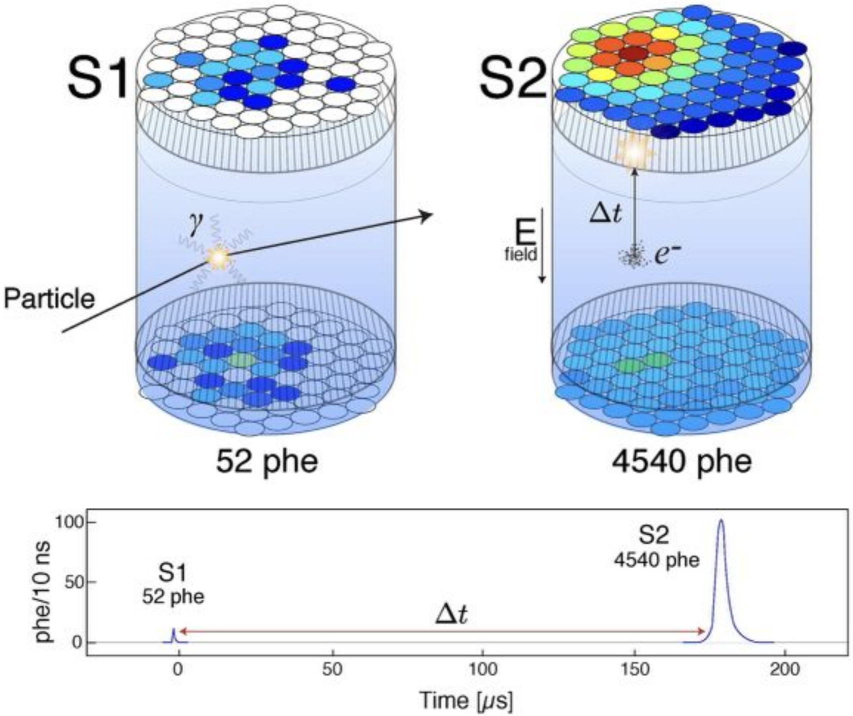


- Momentum transfer crucial
- Low mass difficult
- **LXe dual-phase TPCs** demonstrated best sensitivity

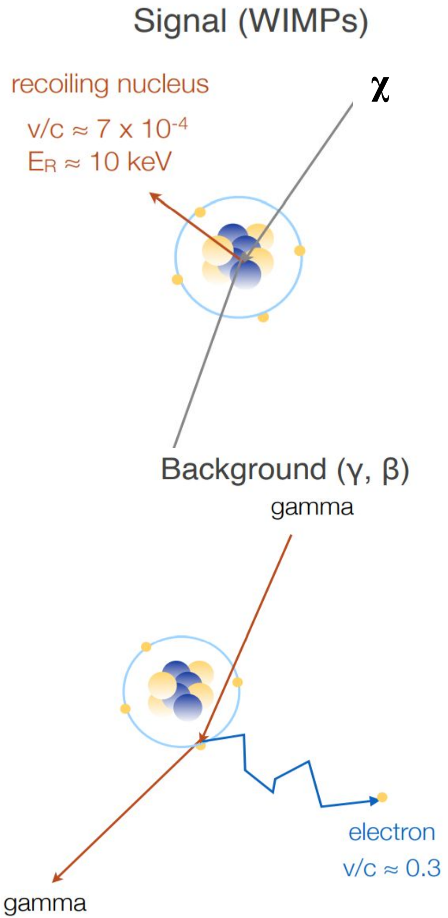


- **Dual phase TPC**, two signals
  - Prompt scintillation light (S1)
  - Prop. charge signal amplified in gas (S2)
- **Depth** (z) from time difference between S1/S2 and light pattern provides (x, y) **position**
- Allows to define a **fiducial volume**
- LXe is dense and **shelf-shielding**

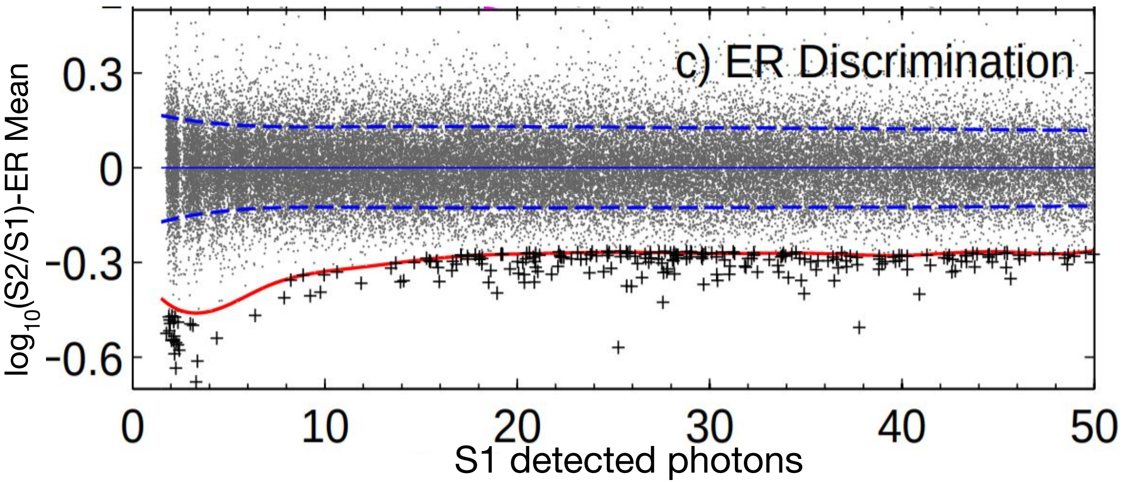




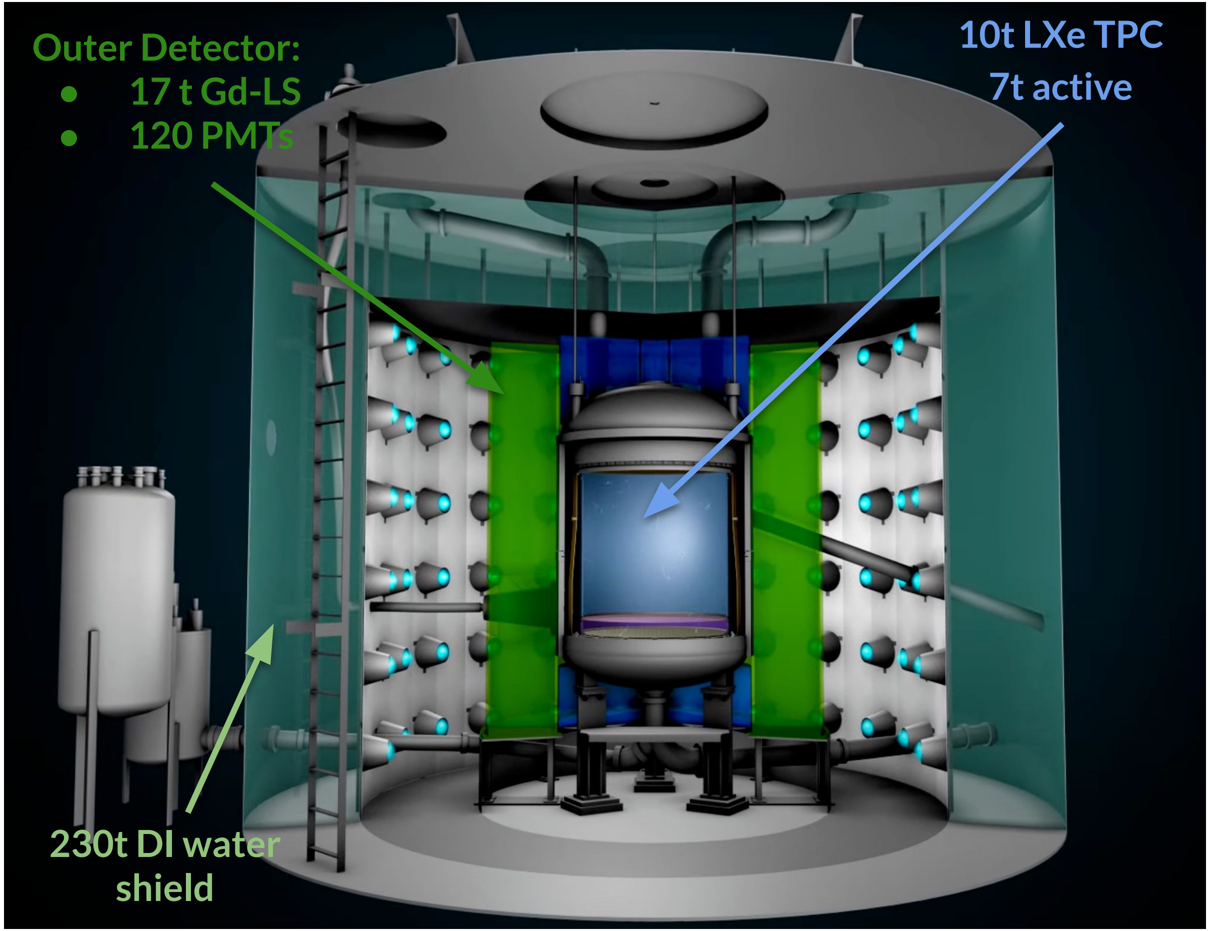
Signal Discrimination



- Ionization/excitation (charge/light) depends on dE/dx
- Signal ratio allows to **discriminate particles**
  - **Electron** scatter tend to produce **more charge**
  - **Neutron** scatter create **more light**
- Excellent discrimination of signal and most backgrounds: **99.5%** discrimination before statistical methods

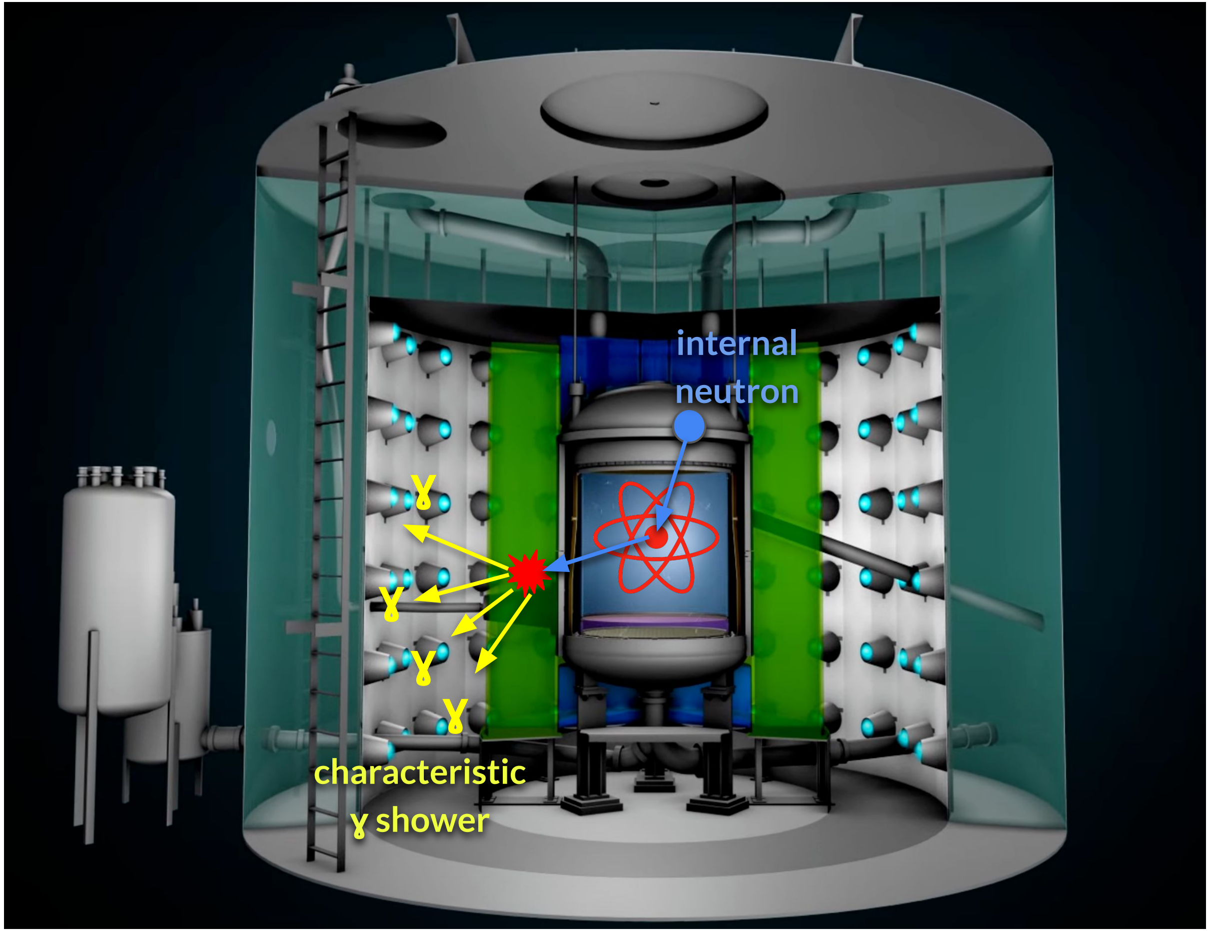


- 10t LXe target mass
- Surrounded hermetically by veto detectors
- Operating since Christmas 2021

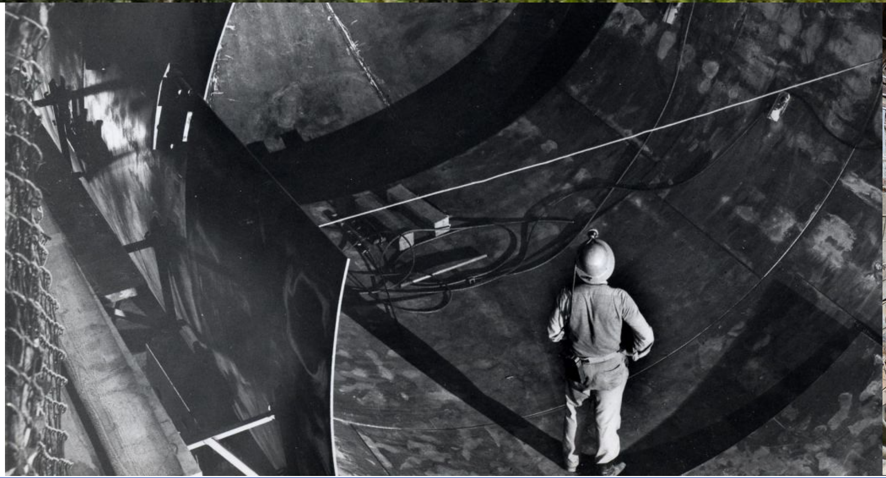


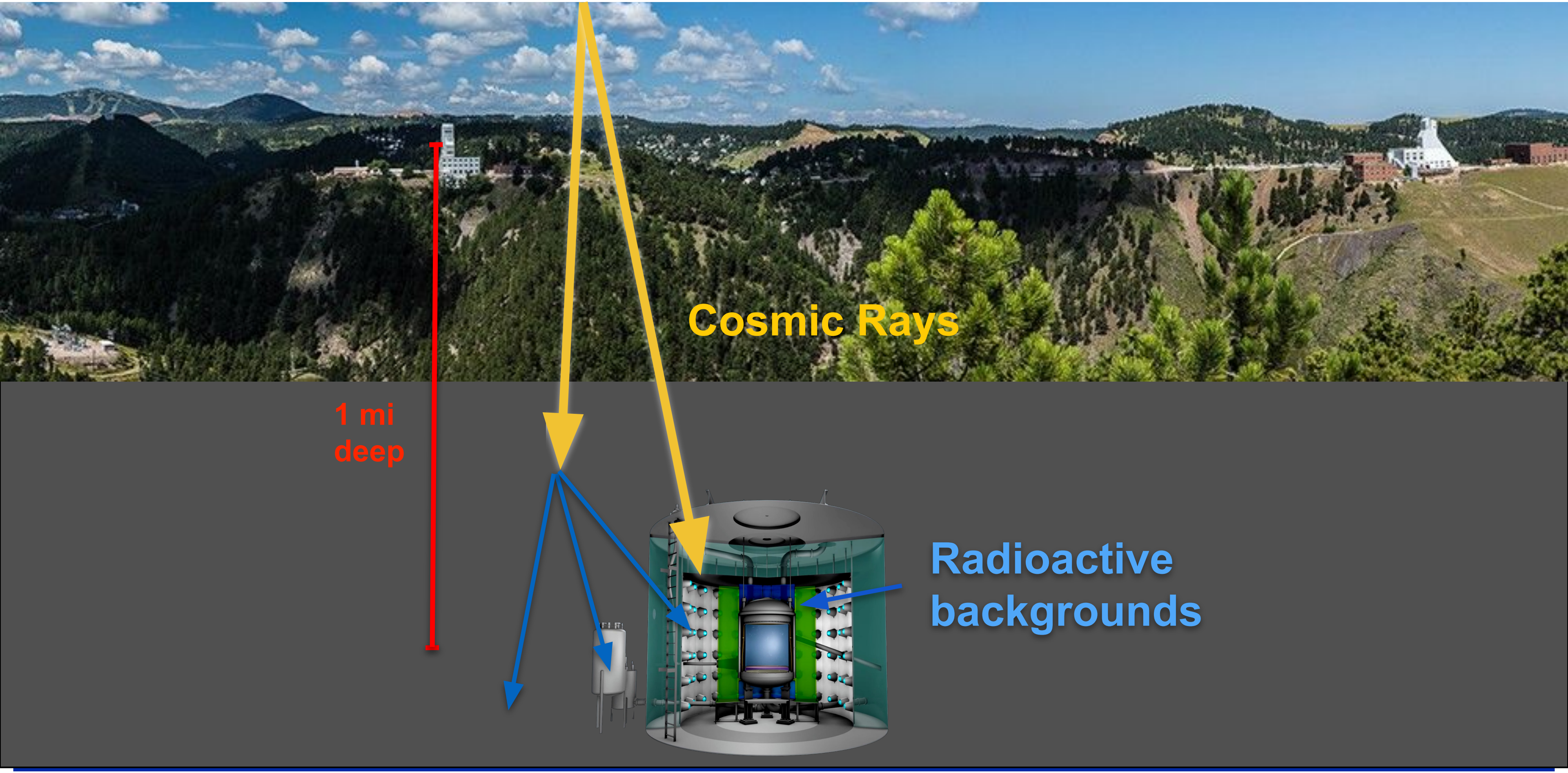
The Outer Detector

- The **Outer Detector** encloses hermetically the TPC
- Using Gadolinium based liquid scintillator (**Gd-LS**)
- OD views Gd-LS using 120 8”-PMTs, surrounded by reflector system and mechanical support in aggressive environment
- Capturing neutron created 7.9 MeV cascades of about 3-4γ
- About **doubles** the **fiducial volume**



- LZ is located at SURF 1 mile deep
- Historic (and future) place
- Permanent presence at SURF

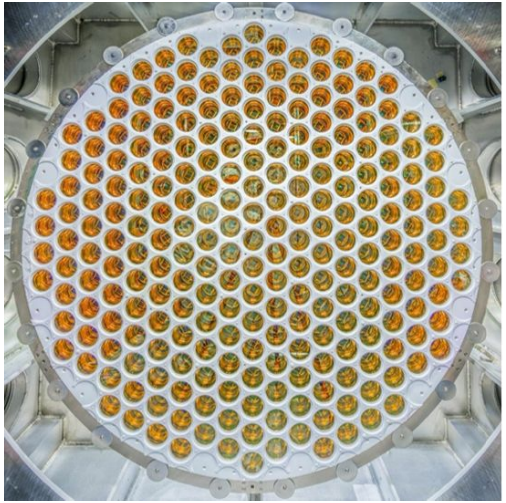



Cosmic Rays
1 mi deep
Radioactive backgrounds

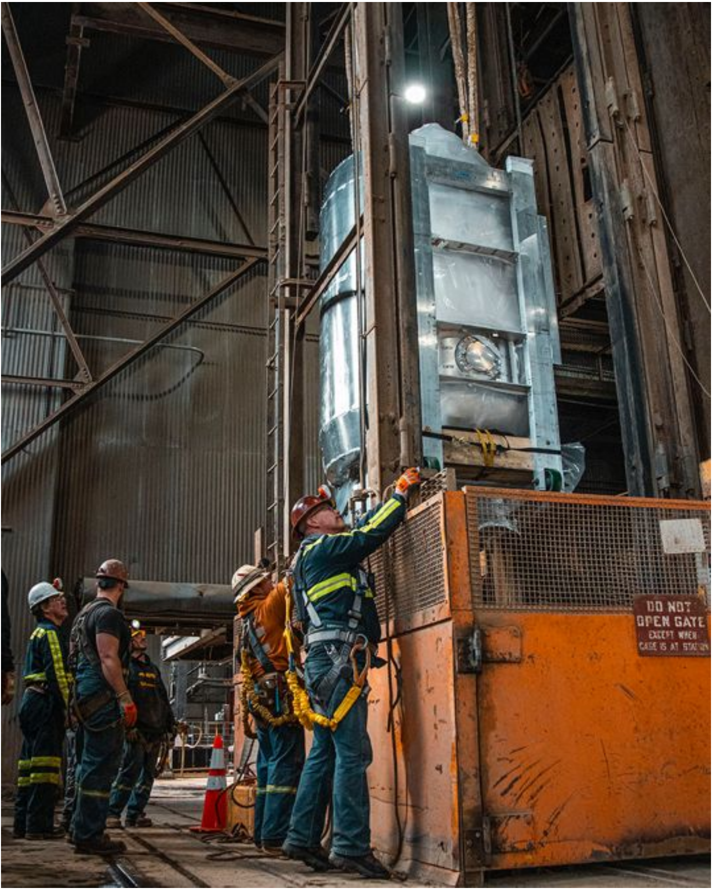
1 Banana = 15 Bq

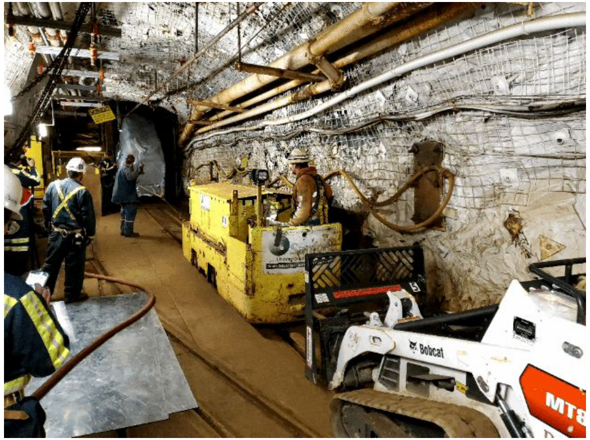
- Bananas are actually somewhat radioactive due to potassium
  - **15Bq/Banana**
- Our target activity in the Xe: 2 µBq/kg - **1/750,000 Bananas**
- Cleaning, cleaning, cleaning, cleaning!

- **Need also to avoid all type of internal contaminants**
  - Use purest materials obtainable, screen all materials
  - Build everything in clean room, reduce dust on surfaces to **O(ng/cm^2)**
  - Keep circulating and purifying target material: aim Xenon contaminants to **O(0.015 ppt)**

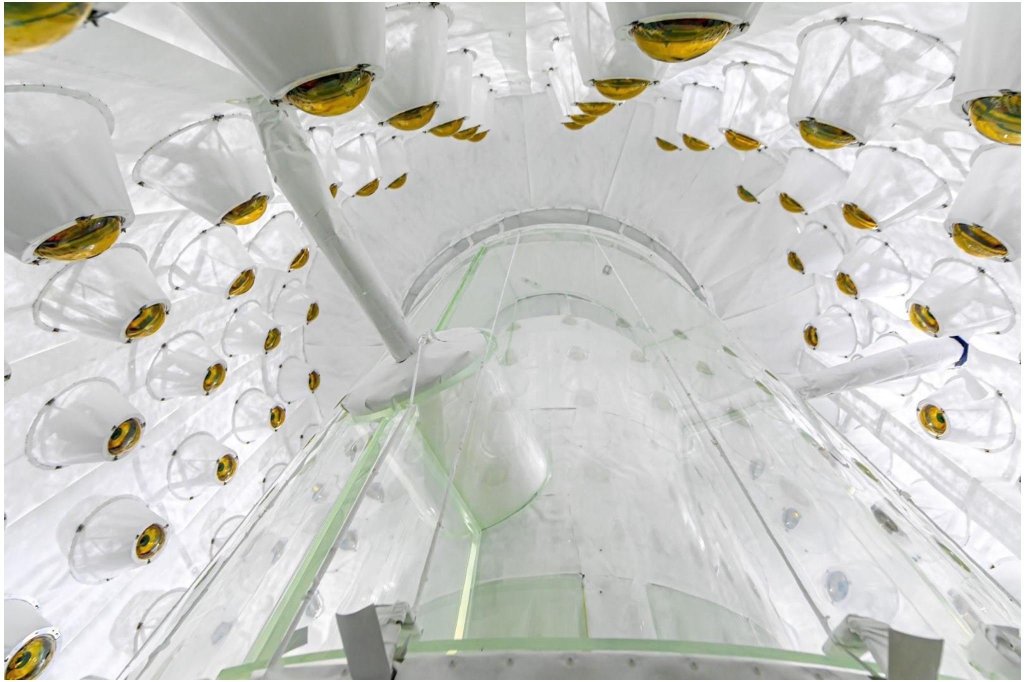


Underground Transport

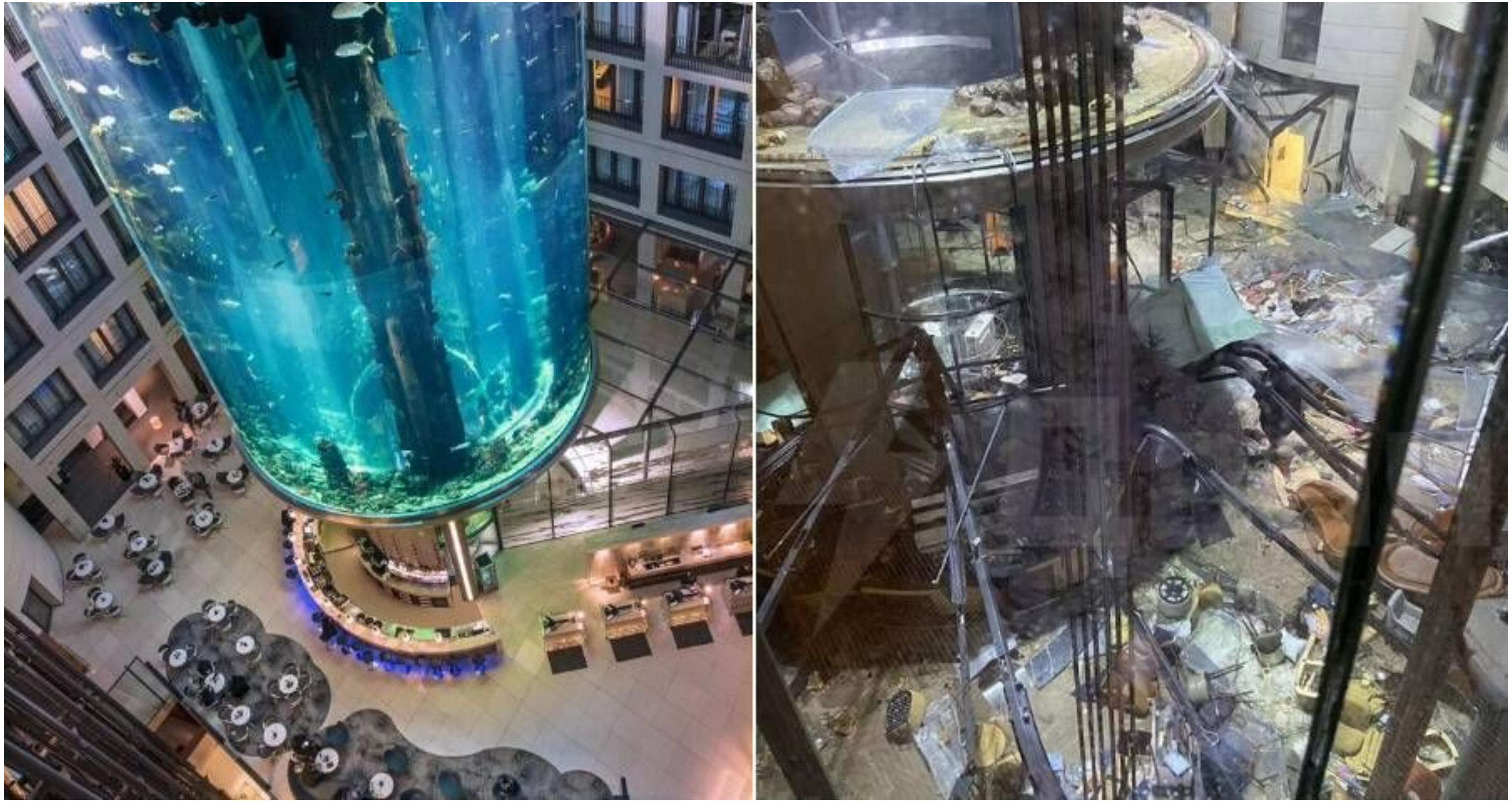




Outer Detector



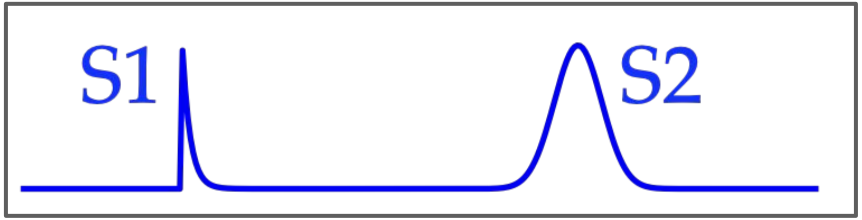
Outer Detector

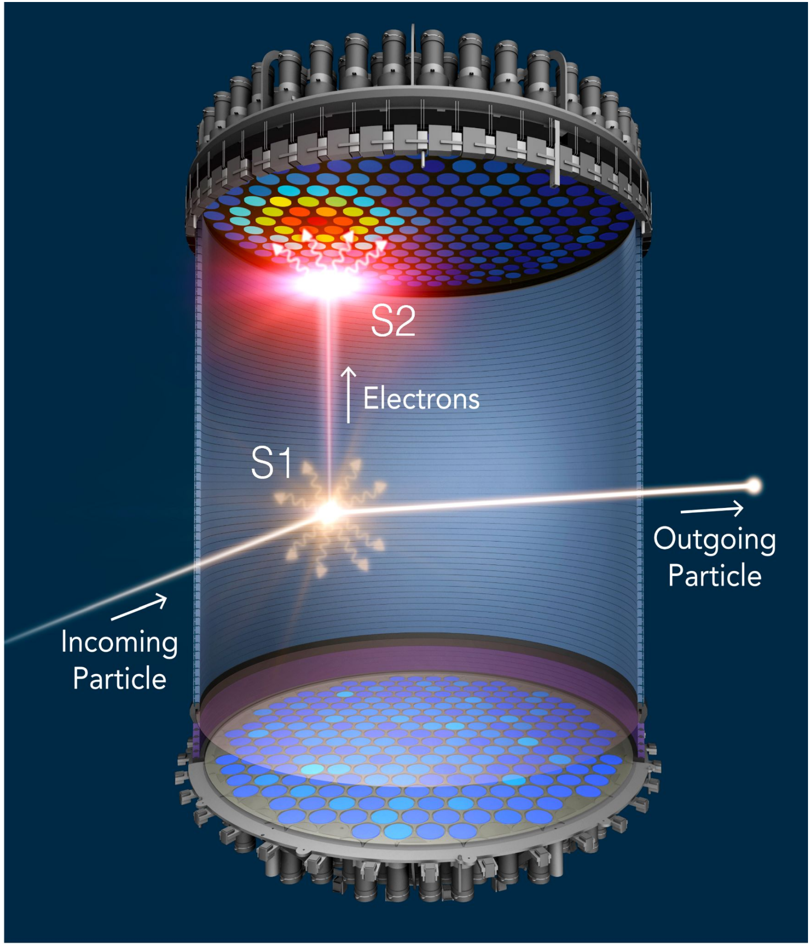


Those tanks look familiar…

Let’s look at some Data!

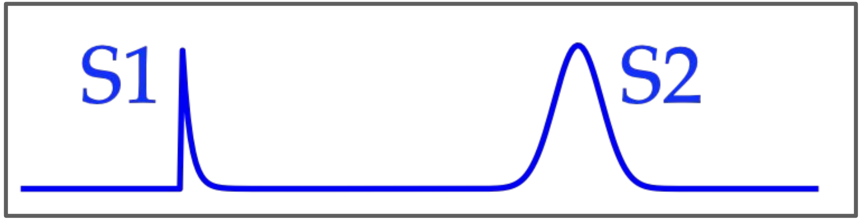
- Cartoon waveform:



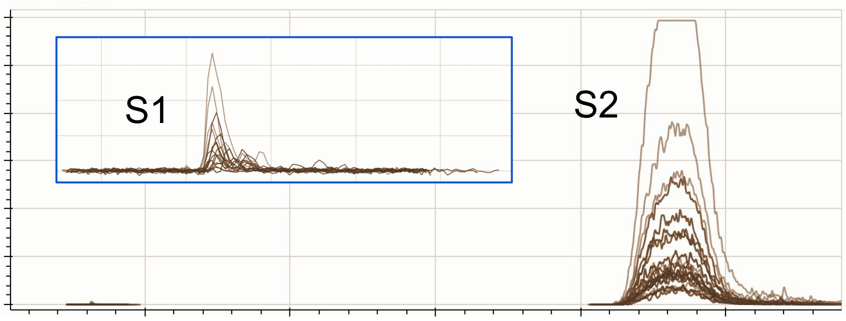


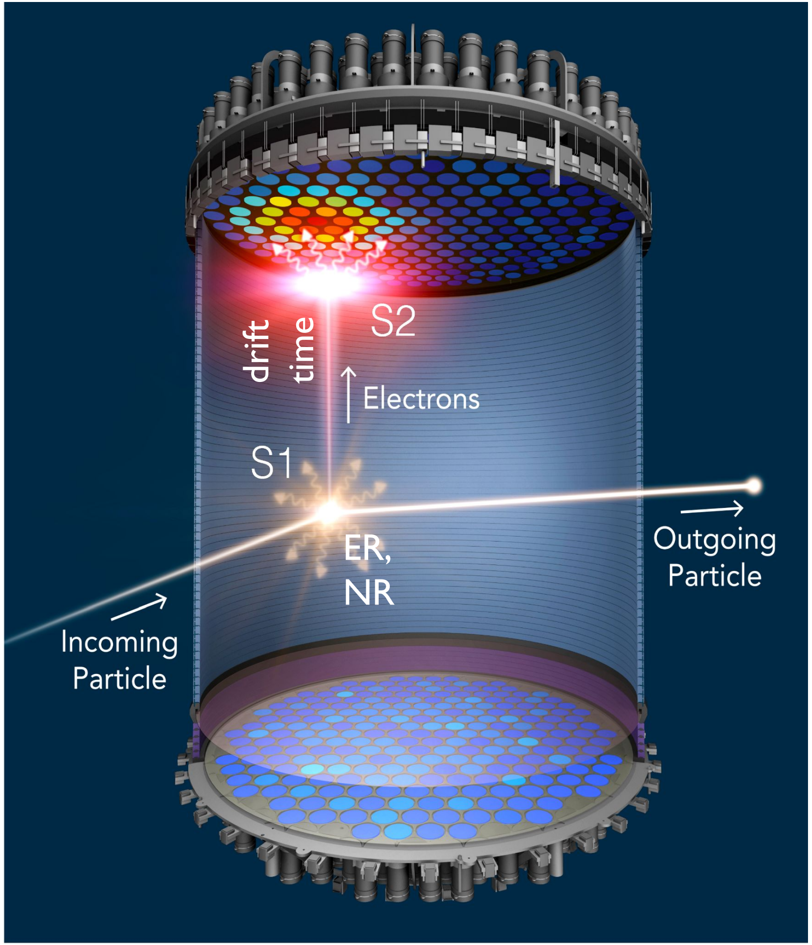
An Event in the TPC

- Cartoon waveform:

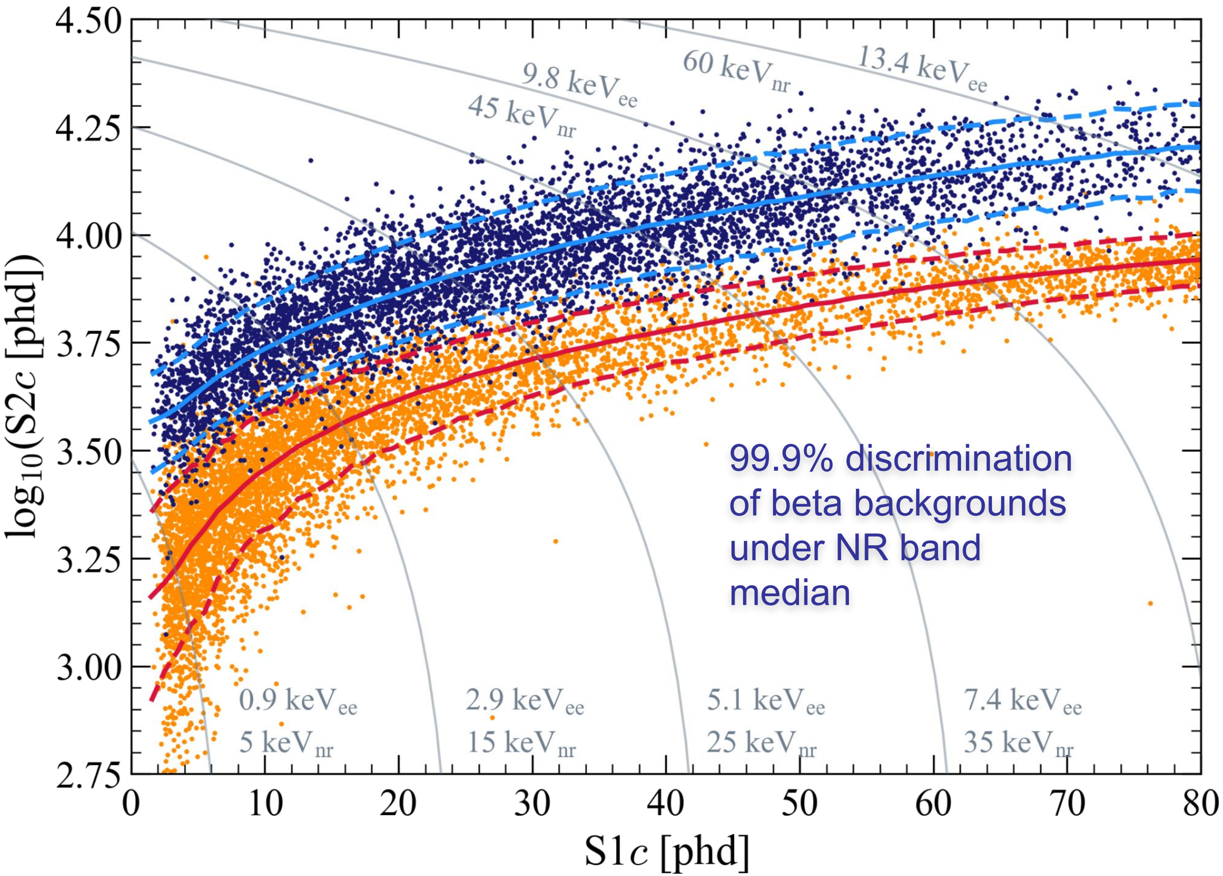


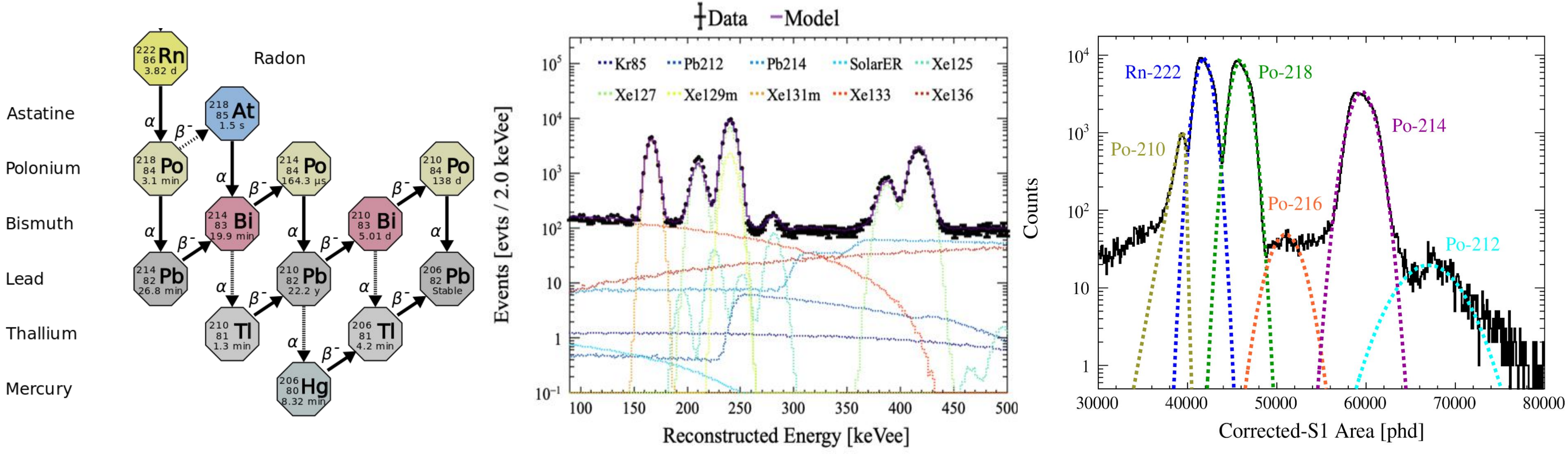
- Actual waveform:



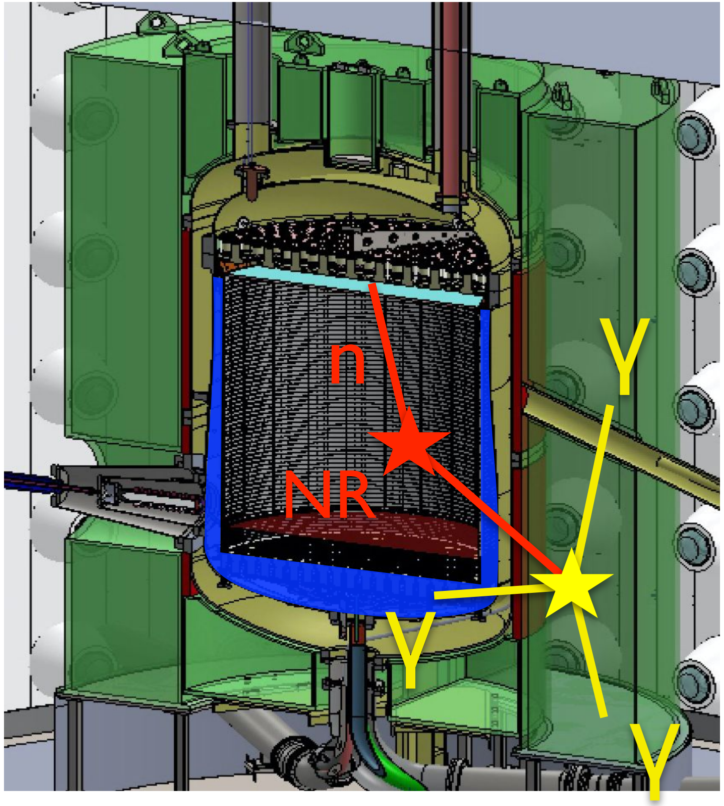


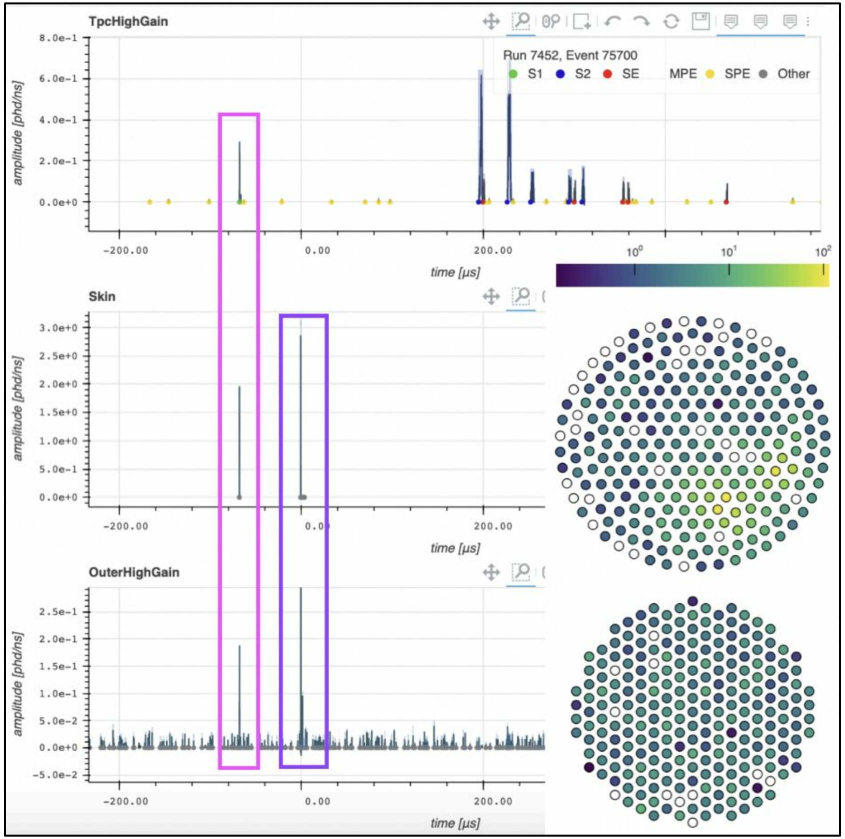
- Backgrounds predominantly ERs, WIMPs produce NRs
- **ER band**: Tritiated methane (CH3T) injection, spatially homogeneous β source
- **NR band**: DD neutron generator (NR band), Monoenergetic 2.45 MeV neutrons





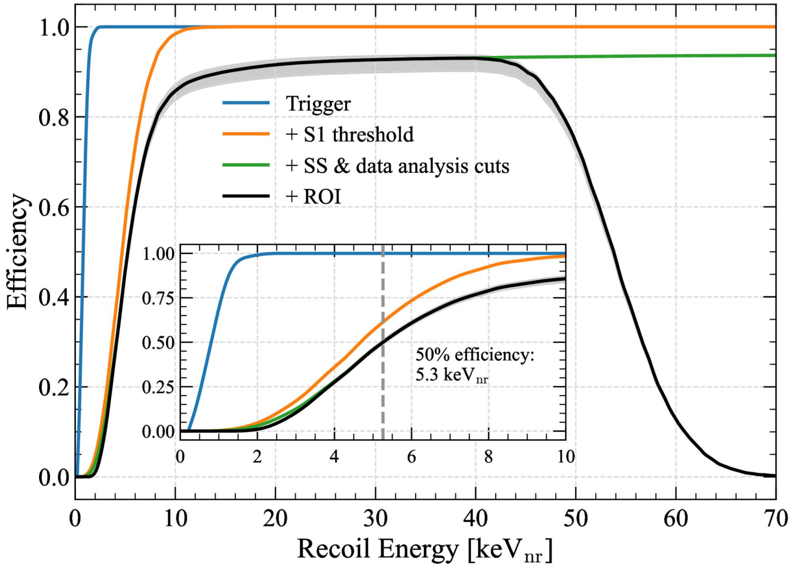
- ‘Naked’ ^{214}Pb β-decays (no-γ) from Rn emanated in Xe are the main ER background
- Constrain β-decay rate by bracketing with Rn-chain α-tagging & spectral fit of all internal BGs
- ^{222}Rn activity within assay expectation



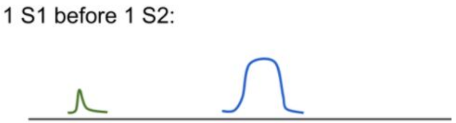


- We actually observed more NR background than expected, successfully vetoed by the OD

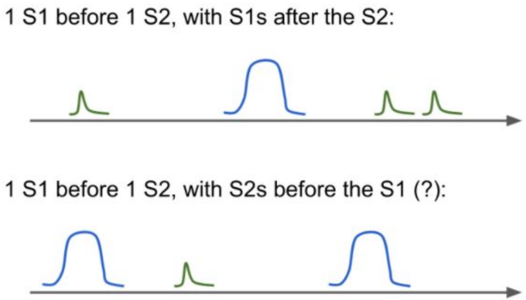
- **Event selections:**
  - S1/S2 shape and topology selection
  - Veto detector, anti-coincidence
  - Fiducial Volume, ROI, single scatter cuts



Single Scatter

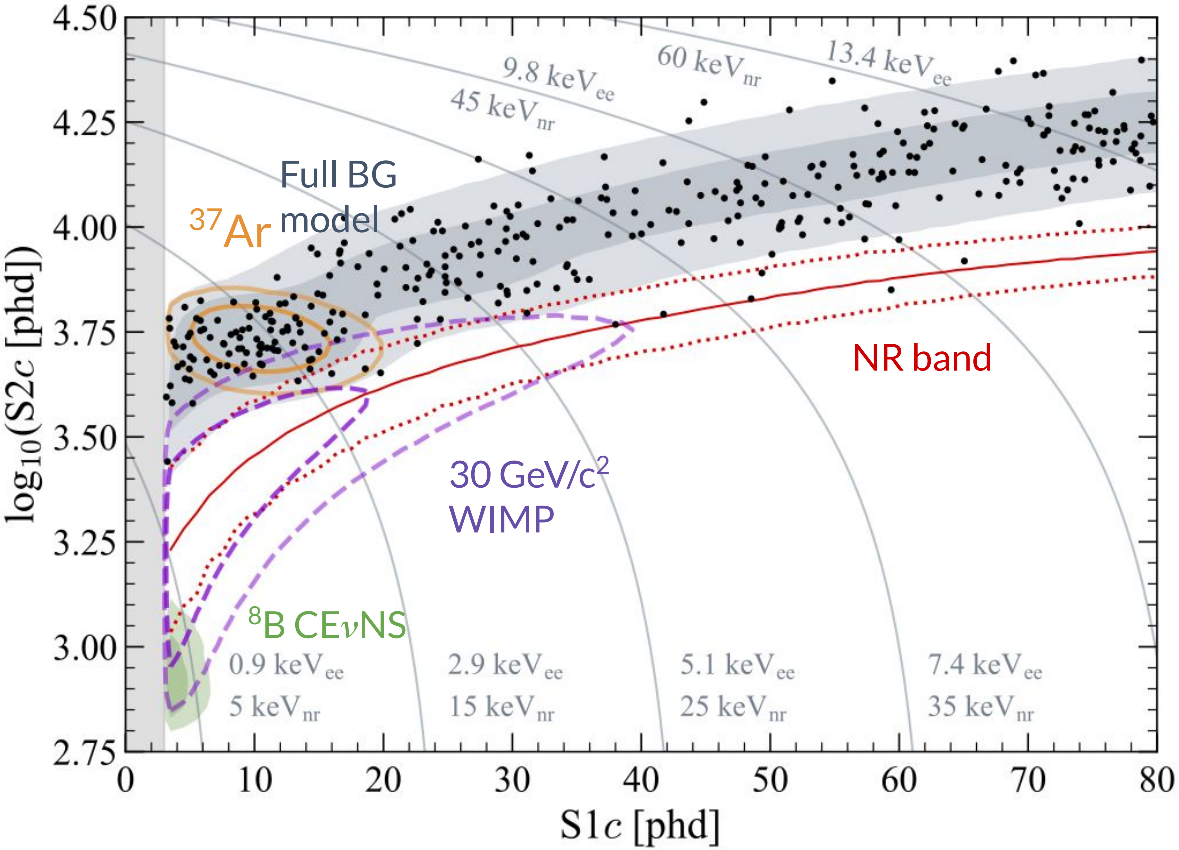


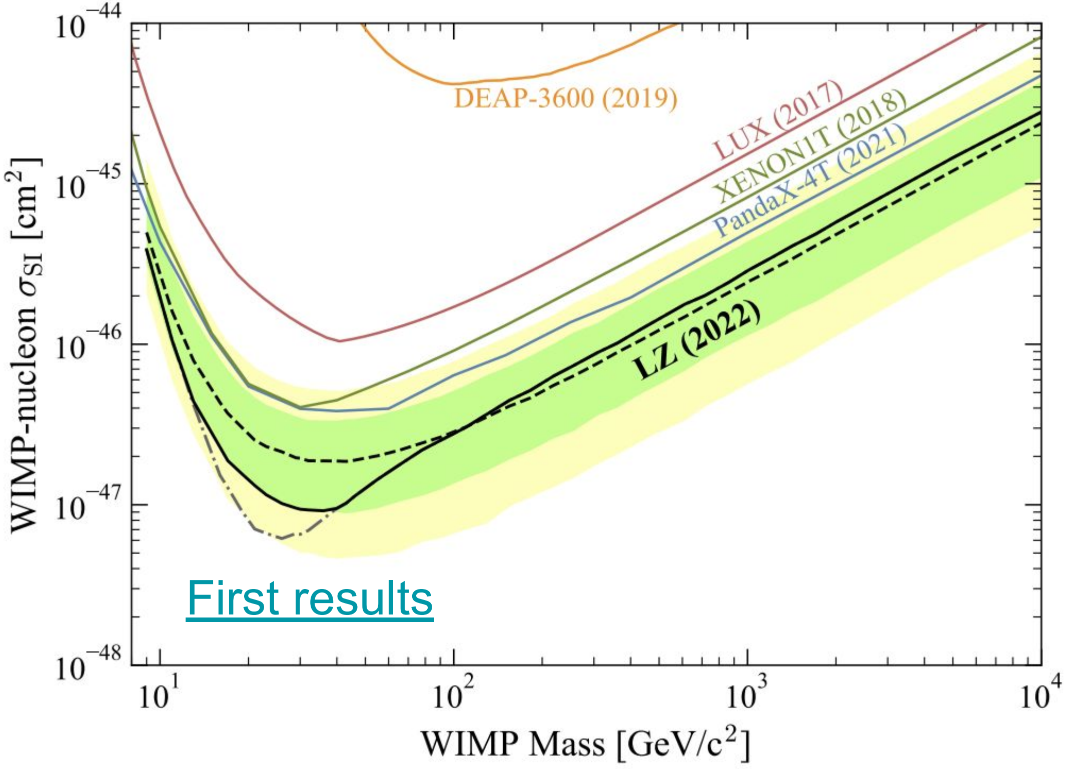
Multiscatter



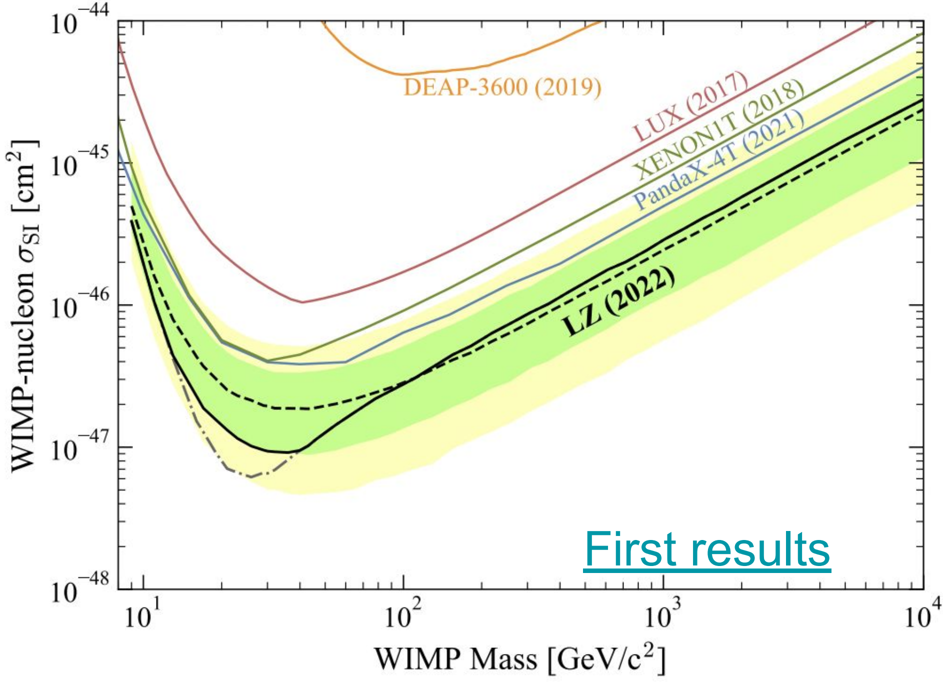
- Selection criteria developed on non-WIMP ROI background & calibration data
- Rejection of live time with detector instabilities, high TPC pulse rates
- **Key numbers**:
  - 60 live days
  - 5.5 T of fiducial volume

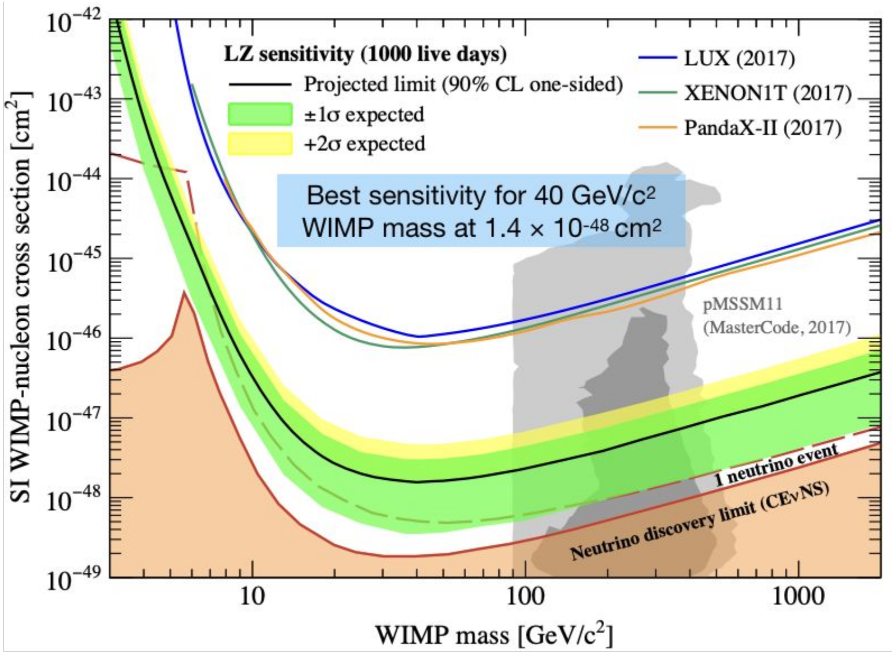
- **Region-of-interest**:
  - 3 phd < S1*c* < 80 phd, S1 coincidence ≥3
  - S2 > 600 phd (6e⁻), S2*c* < 10^5 phd
- 335 events in final dataset
- 60 live days, 5.5 ± 0.2 tonne FV





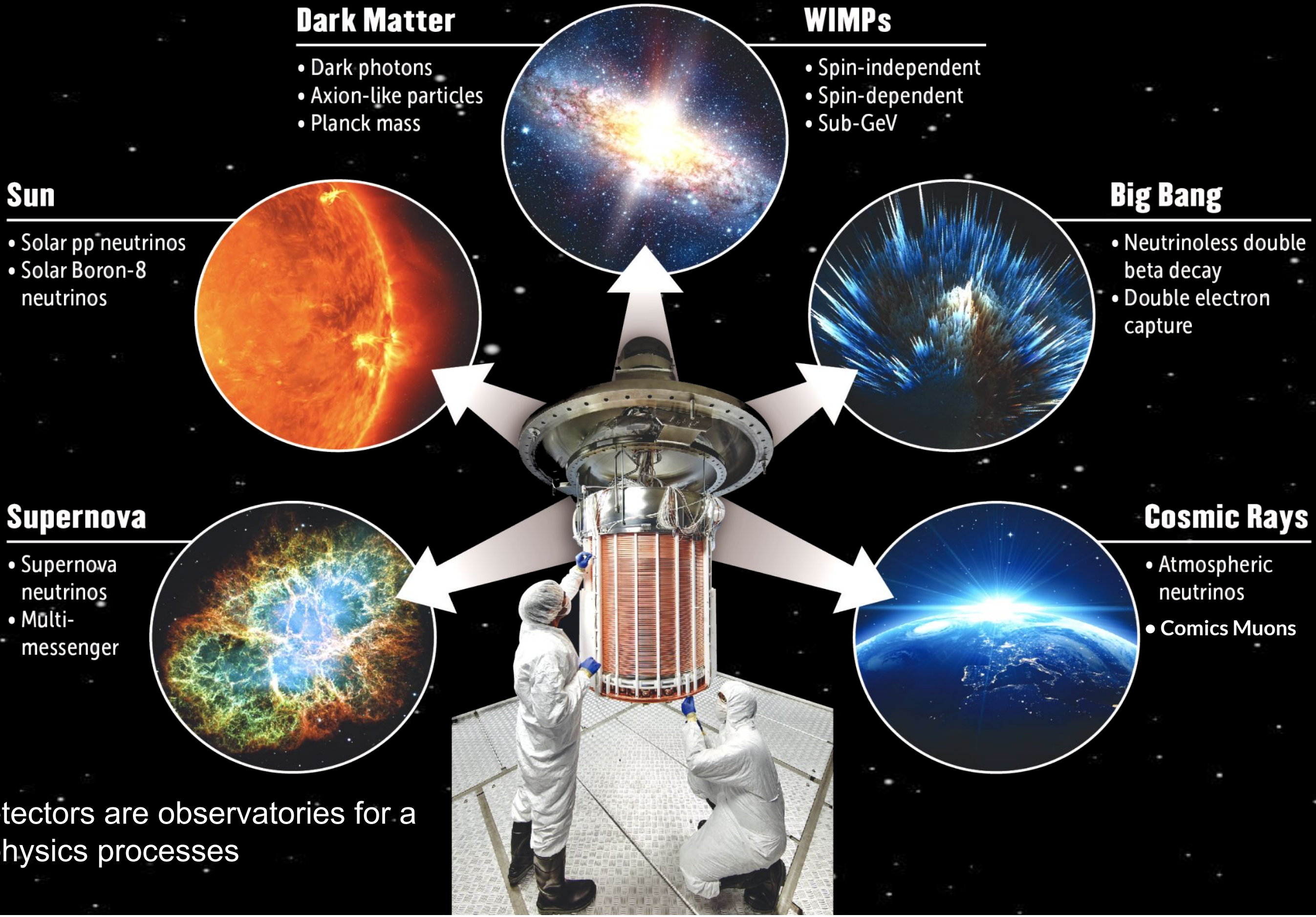
- LZ presently **world strongest result**





- LZ presently **world strongest result**
- Only **60 days out of a 1000 days** exposure published, considering extension to 2028

What's Next?



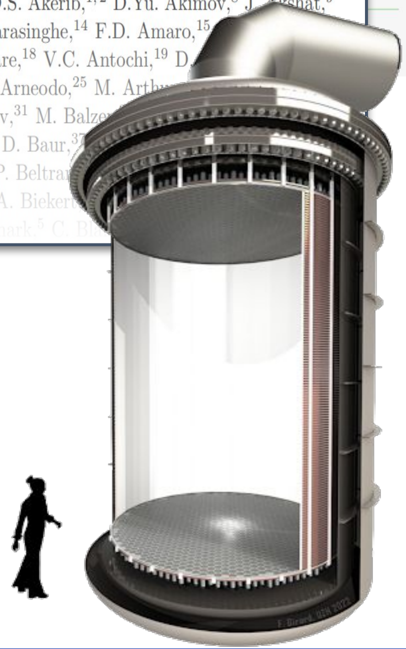
- Modern LXe detectors are observatories for a wide range of physics processes

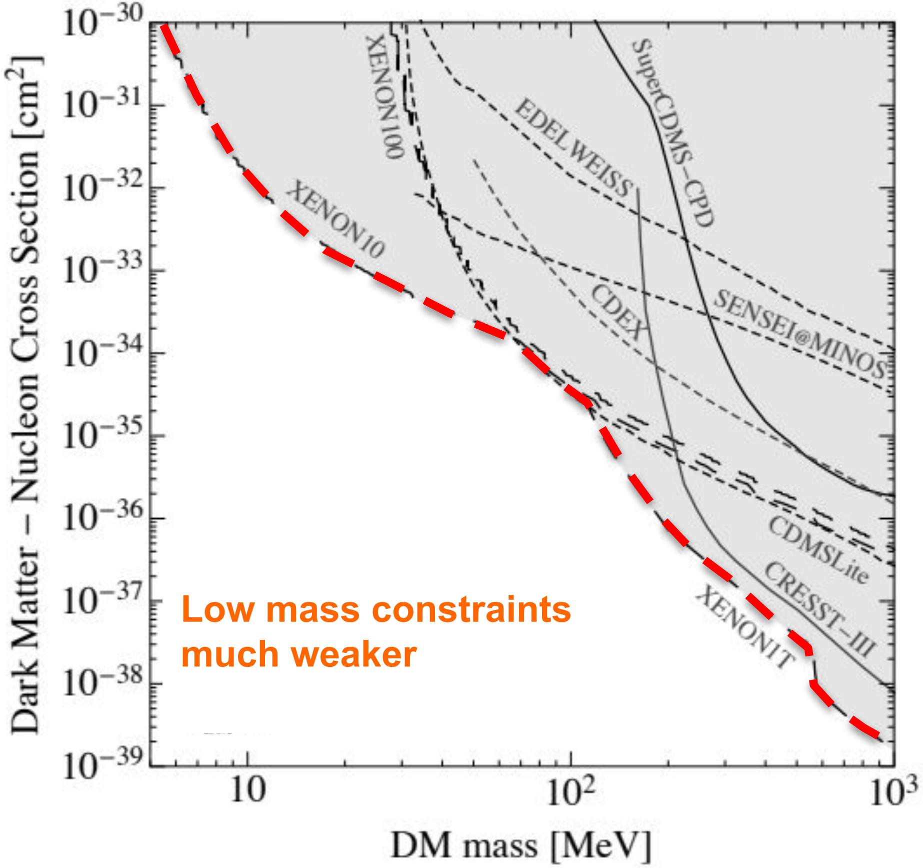
- MOU between LZ, XENON, DARWIN
- Had first meetings in Germany and LA
  - https://xlzd.org/
  - White paper (2203.02309)

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] ...
A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] ...
T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] ...
B. Antunovic,[21,22] E. Aprile,[23] H.M. Araújo,[16] J.E. Armstrong,[24] F. Arneodo,[25] ...
S. Baek,[27] X. Bai,[28] D. Bajpai,[29] A. Baker,[16] J. Balajthy,[30] S. Balashov,[31] ...
J. Bang,[34] E. Barberio,[35] J.W. Bargemann,[36] L. Baudis,[5] D. Bauer,[16] D. Baur, ...
M. Bazyk,[39] K. Beattie,[40] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltra...
E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert...



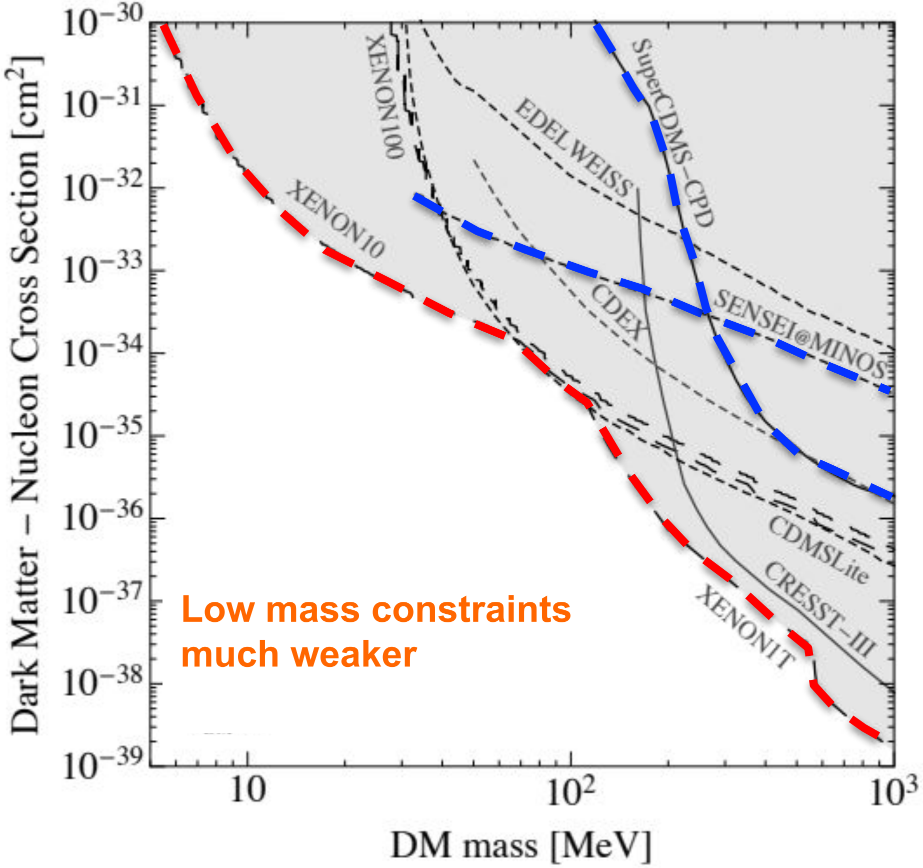


- **We want to go lower & deeper!**

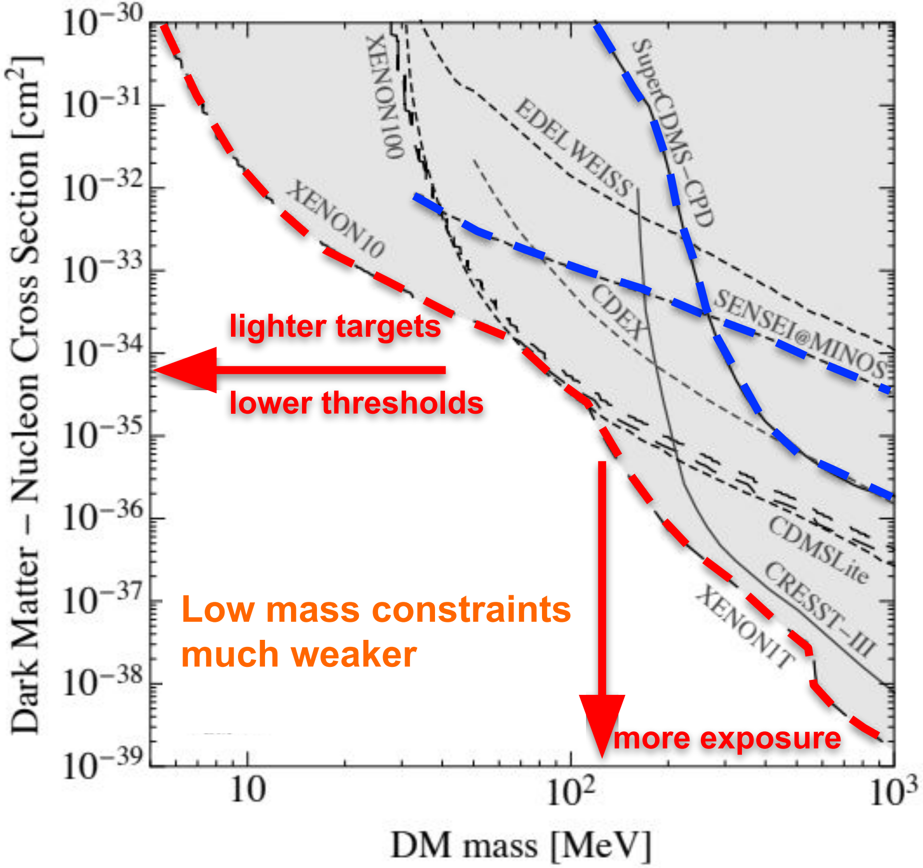
Low Mass DM

$$R = \sigma n_{\rm DM} N_{exp} = \sigma \frac{\rho_{\rm DM}}{m_{\rm DM}} N_{exp}$$

Exposure: Rate scales inversely with dark matter mass

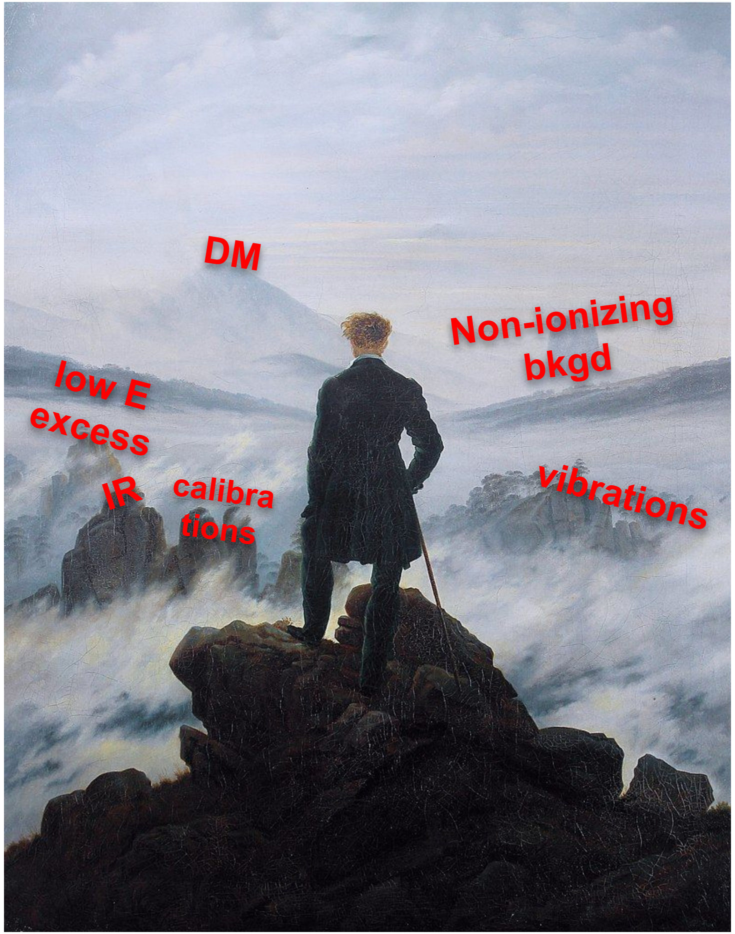


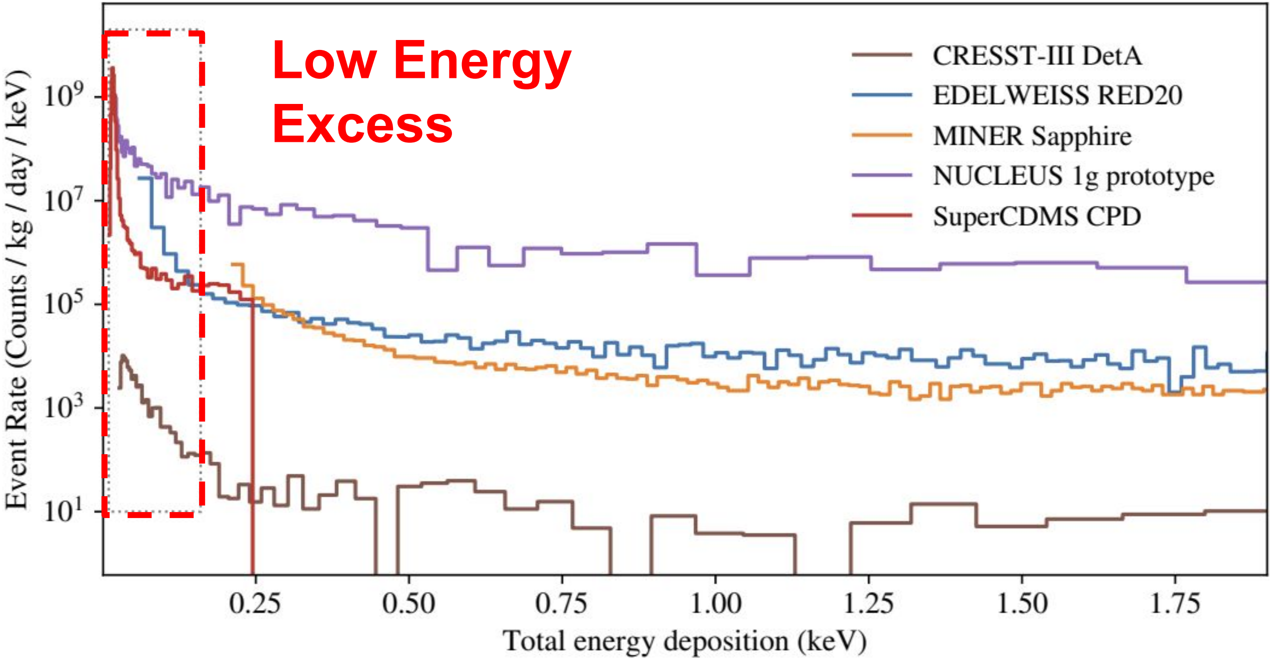
- Compare ton scale LXe with gram scale low mass DM experiments



- Lower mass searches require **light targets** and **very low energy thresholds**

- Facing **new landscape**
- **Nuclear backgrounds**: Exists but less significant due to small ROI
  - **γ down-scatter** to low E, can also **induce NR** via Thomas-Delbrück
  - Epithermal **neutrons**
- **Novel backgrounds**:
  - Sensors sensitive to **smallest energies**
  - **IR** backgrounds, **parasitic power**, **phonons**, **vibrations**, **transition radiation** etc
- New **calibrations** necessary
- We know some of the challenges we're facing, but **some cliffs** are probably still **hidden in the fog**

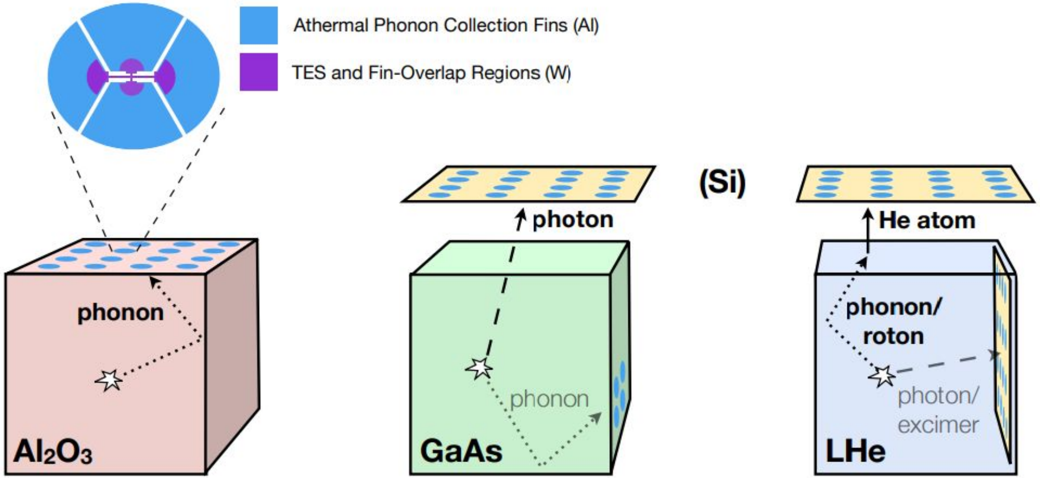


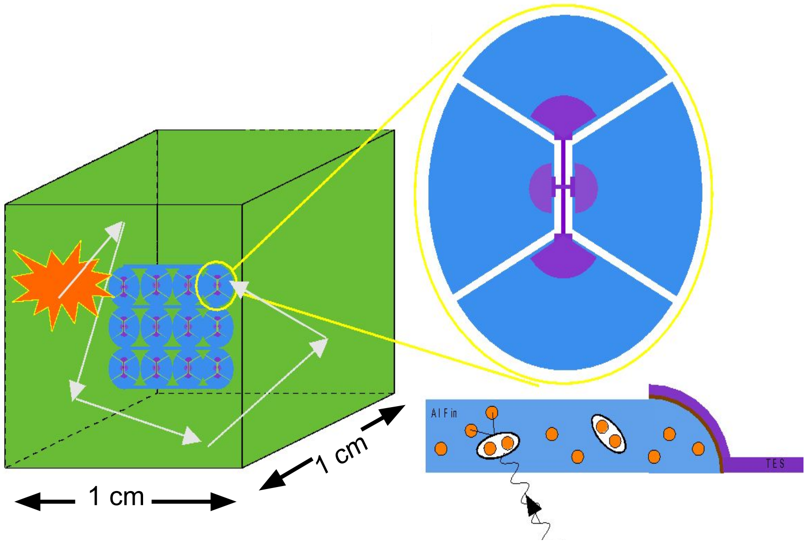


- Low energy excess, observed in many experiments: SuperCDMS, Edelweiss, Nucleus, DAMIC, SENSEI etc
  - Primary characteristic energy Scale: **eV**?
  - Probably more than one origin

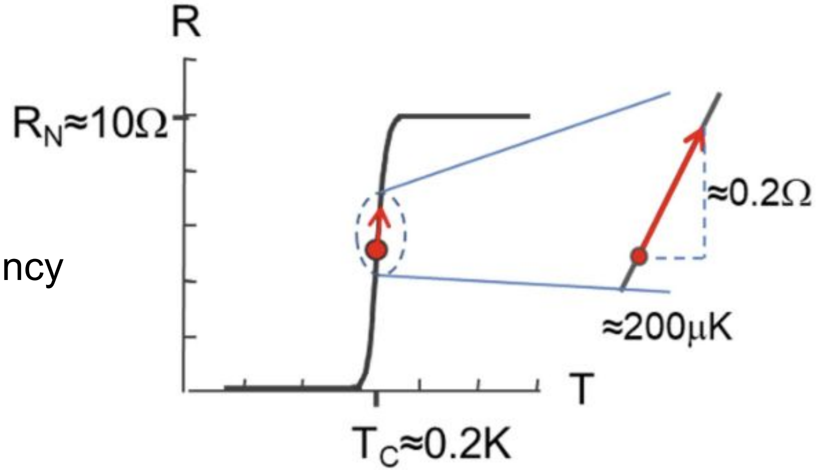
- What we need:
  - Low energy threshold
  - Scalable
  - Minimize backgrounds
  - Ability to discriminate and understand remaining and novel backgrounds

- **Tesseract**: Use different targets that probe different DM models and affected by different backgrounds
- **Energy sensitivity** is primary driver for low mass DM → need detectors with thresholds of 1-100 meV
- All targets read out using **Transition Edge Sensor** (TES) readouts, no E-field (no dark-currents)

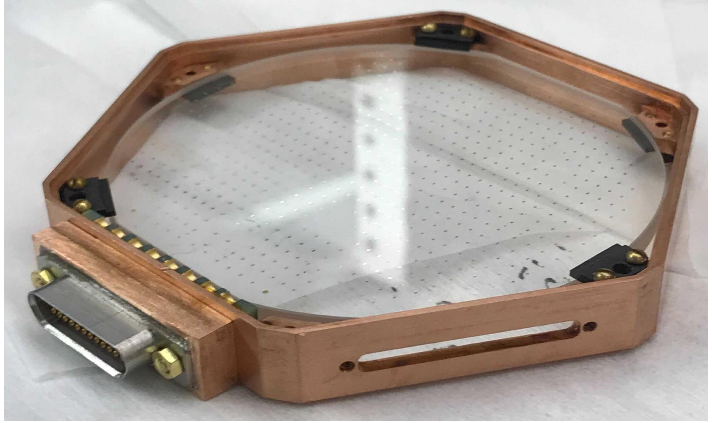


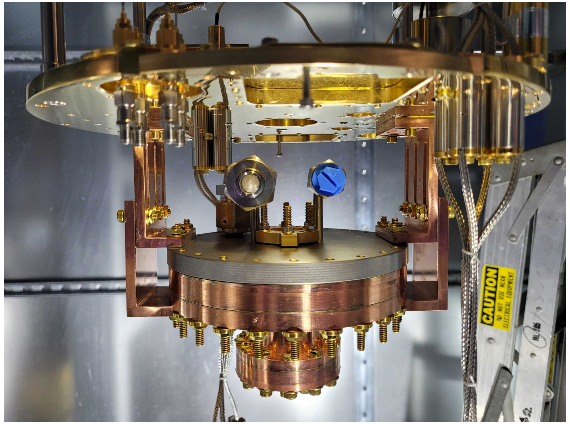


- Collect and concentrate athermal phonon energy into Al fins
  - Phonons break Al cooper pairs
  - Quasiparticles are absorbed by W TES connected to Al fin



- Large collection area without the drawback of the heat capacity of a large sensor
  - Signal is degraded by low phonon collection efficiency
- **Readout of all targets identical** except the substrate
- More **DM science doesn't increase cost** significantly!





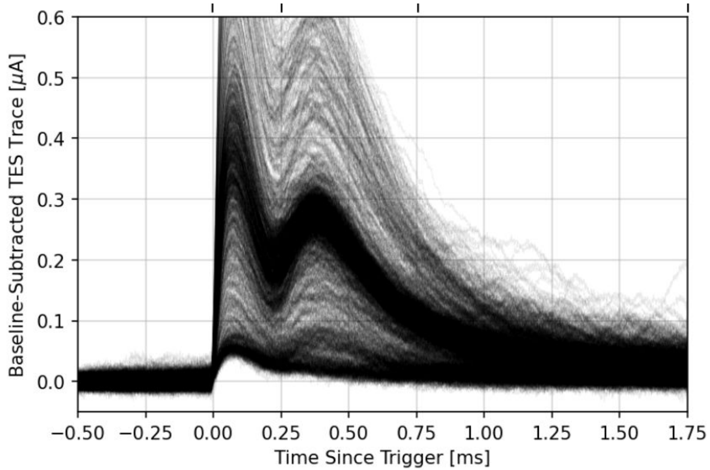
- **Sapphire** (Al_2O_3): Many optical phonon modes that are kinematically well-matched to low-mass DM, high dark photon sensitivity
- **GaAs**: polar crystal, band gap matched well to low mass region. Reduce backgrounds via photons and phonons ratio/coincide
- **Superfluid helium** provides low mass NR sensitivity and multiple signal channels

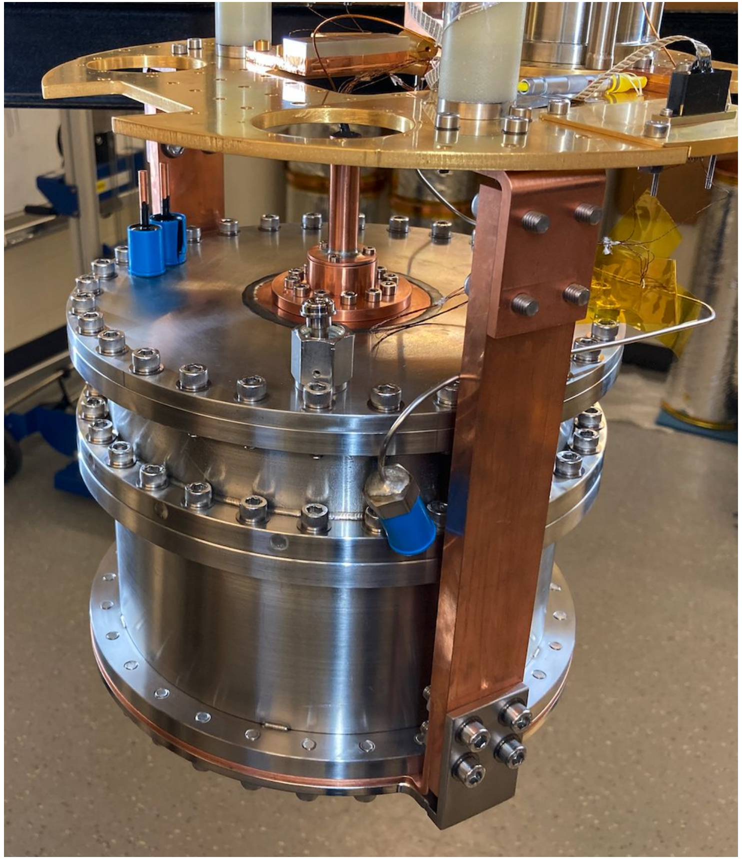
- All **sensors operating** in demonstrator setups and are delivering physics
- **Novel & challenging backgrounds** due to femto and attoWatts sensitivity in TES
- **Advantage of Tesseract**: Ability to discriminate and characterize these backgrounds

Target	NRDM	ERDM (> 1 MeV)	ERDM (keV - MeV)	Absorption	Background rejection
Al2O3/SiO2					
GaAs					
Superfluid helium					

- Targets relatively cheap, hence we consider several
- **Al_2O_3** sensitivity across the board. One type of signal (phonon), multiple readouts to reduce instrumental background
- **GaAs** and **superfluid helium**: Advantages in background rejection: multiple signal channels and multipixel coincidence-based instrumental background rejection

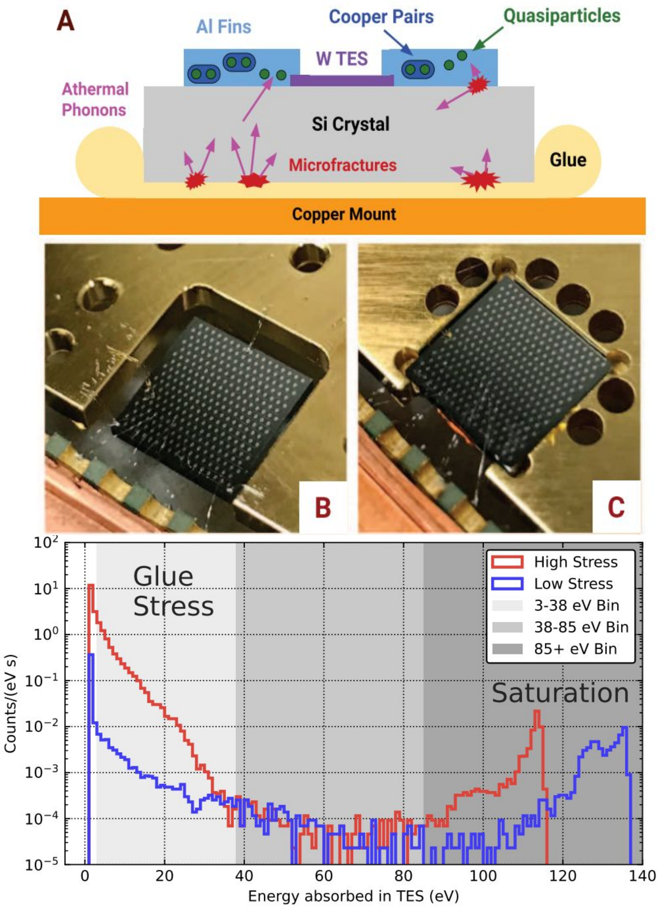
- Measurement of ^{4}He light yield of ER and NR and HeRALD proof of concept
    - arXiv:2108.02176, arXiv:2307.11877
- Good **agreement** with an **empirical model**
- High **NR light yield,** measurement of quantum evaporation gain
- Offers **ER/NR discrimination** via photon/roton ratio

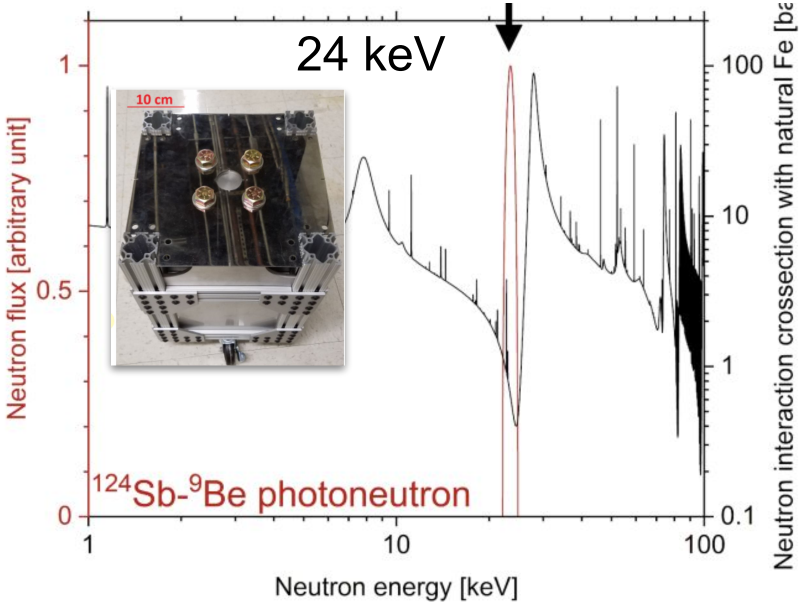




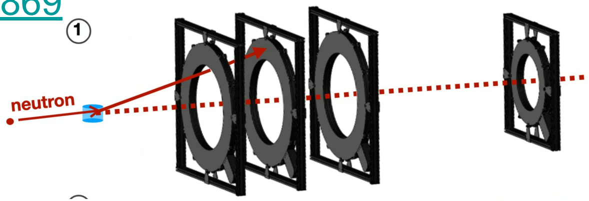
Recent Process - Stress

- Two **identical detectors** (as possible)
  - One glued
  - One suspended from wire bonds
- **TES based readout** measures athermal phonon pulses in substrate
- Successful mitigation of mounting stress
  - **Two orders** of magnitude difference in rate → stress is major source of LEE
- **Investigating** other sources: stress from sensor films, crystal and IR leakage
- See arXiv:2208.02790

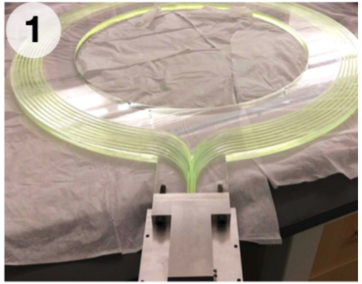


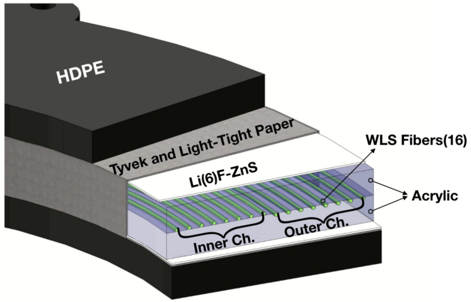


- **SbBe photoneutron + Fe** shield
- Fe transparent to neutron, serves as collimator and very efficient gamma shield
    - 124SbBe neutron energy: 23.47 keV
    - Fe n-transmission resonance: 24.54 keV
- See arXiv:2302.03869

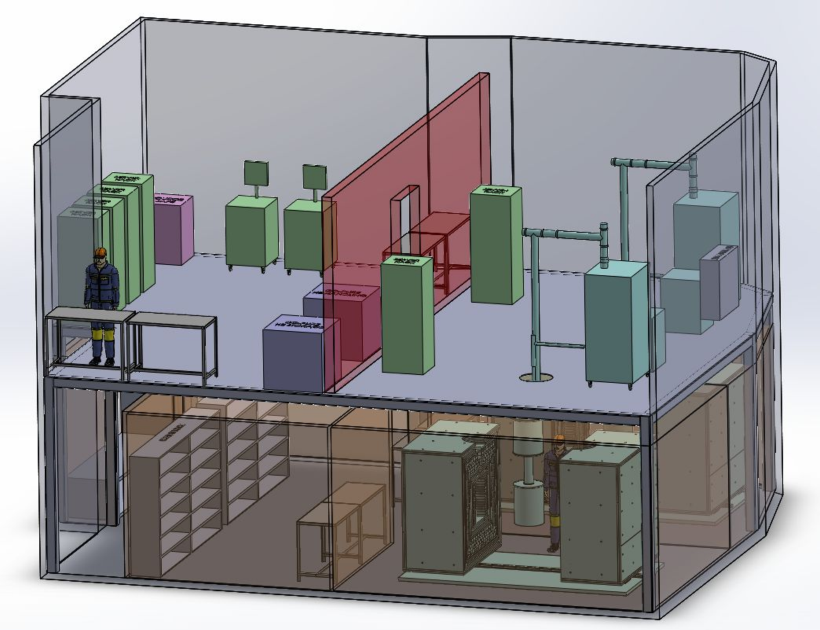


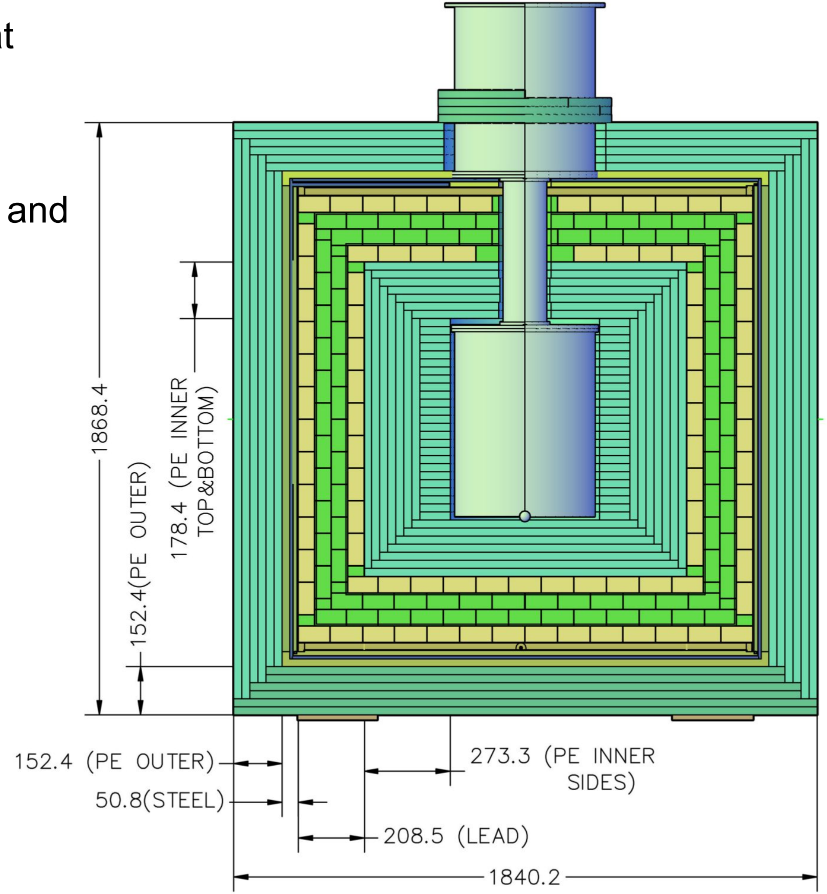
- Scattering of neutron of known energy, tag its scattering angle
- Large arge **keV Neutron backing** detector for low energy NR calibrations
- See arXiv:2203.04896

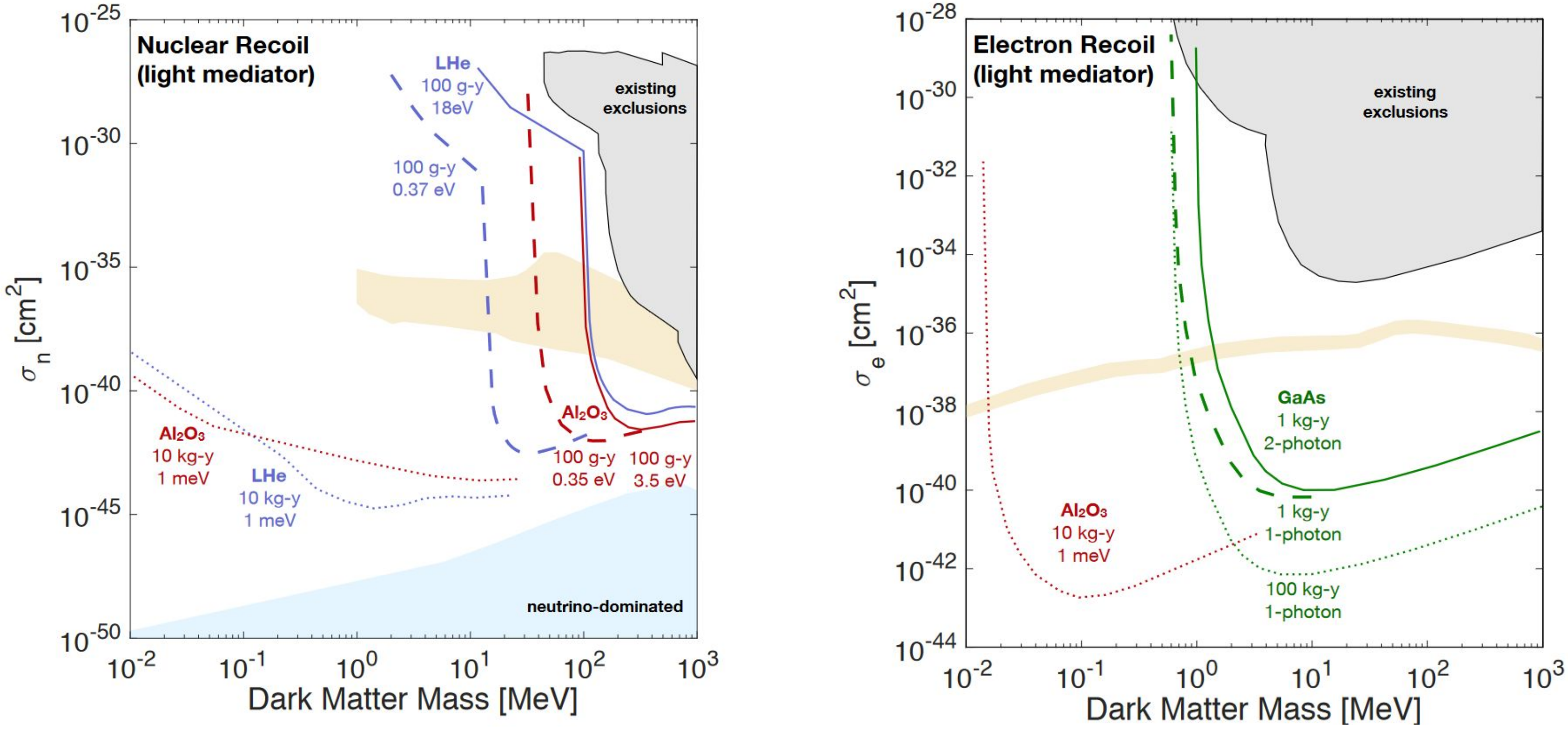




- Developed a low background shield (1.2 DRU@1 keV) that can be opened to **swap detectors quickly**
    - Building prototype right now at Kamioka
- Experiment will be hosted in **Modane**, established the site and close collaboration with France last year





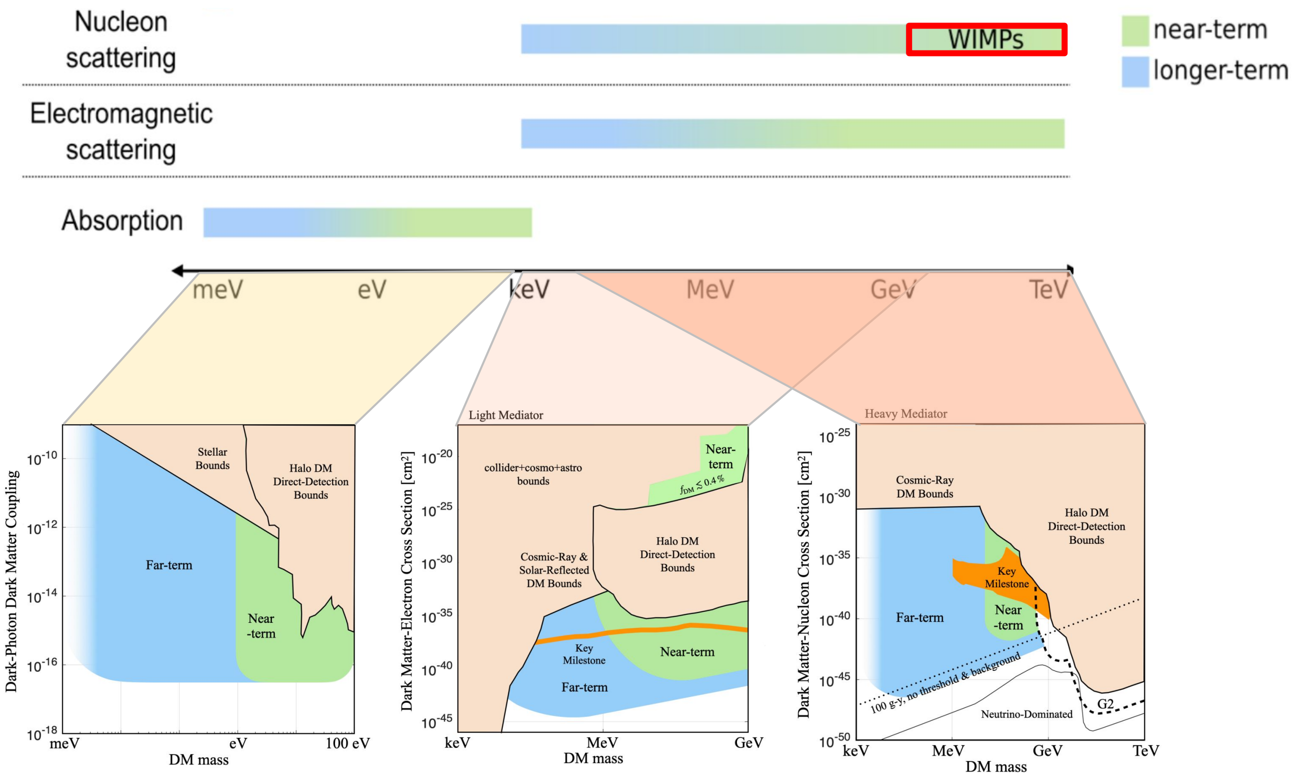


- Tesseract will **probe multiple unexplored DM parameter spaces** in a few years
- UZH will leads construction, operation and physics of Tesseract
- Data taking as early as **2026**

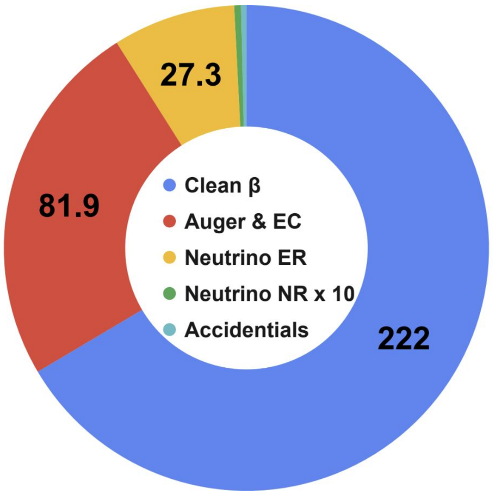
- **DM is out there** and will transform our understanding of the universe
- **LZ** has **60 out of 1000 days** of data published, many publications and potential discoveries soon
- **Tesseract demonstrated to work,** funded and growing, first physics results already published
- The field is being transformed right now:
  - **Xenon TPCs are the most sensitive detector** today
  - **Tesseract** will within a few years push sensitivities to yet **entirely unprobed energies**
  - **XLZD** preparing **to explore to the neutrino fog**
- These experiments will provide the **best sensitivity for dark matter for years to come**
- Continuous **interplay between hardware and physics** provides great training & opportunities

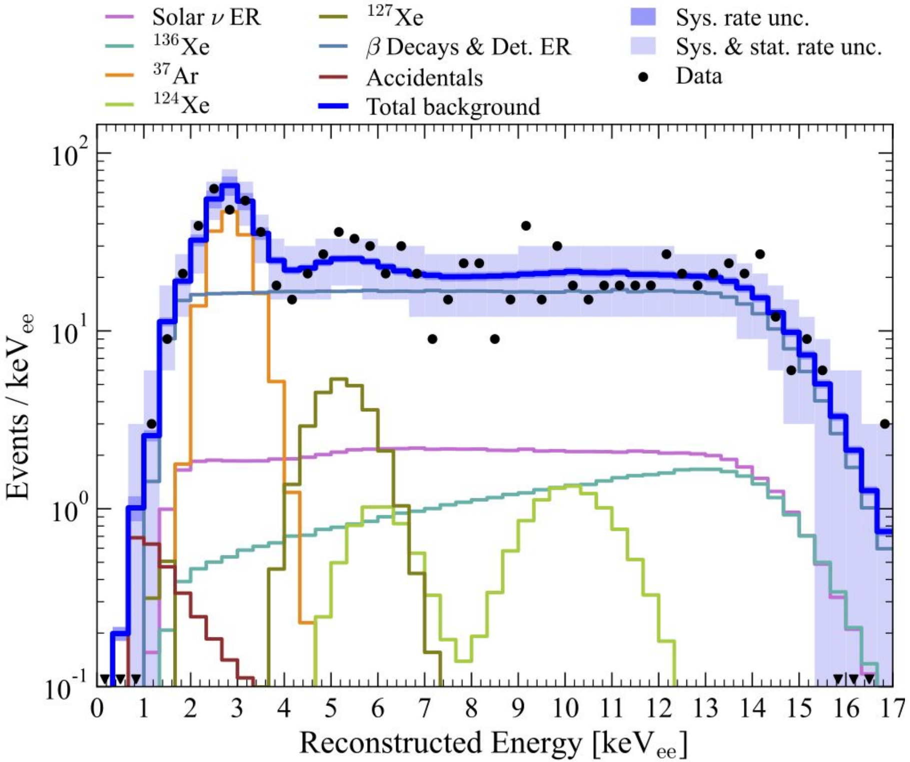
Backup

Low Mass Dark Matter



- Sub-Gev (low mass) DM barely explored
- DM masses in the **MeV regime** and cross sections approaching or below **10^{-40} cm^2** in reach

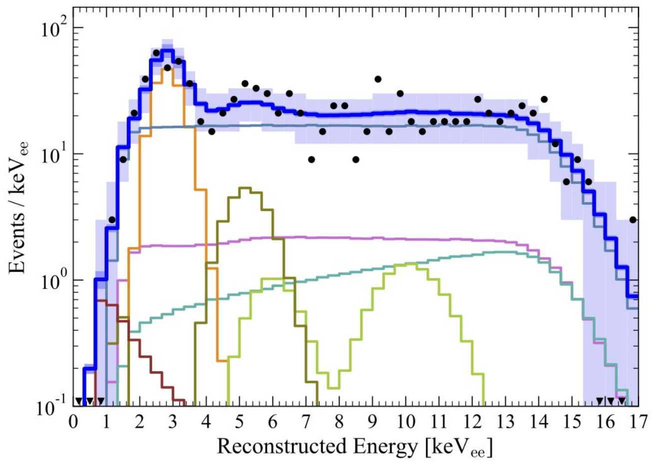


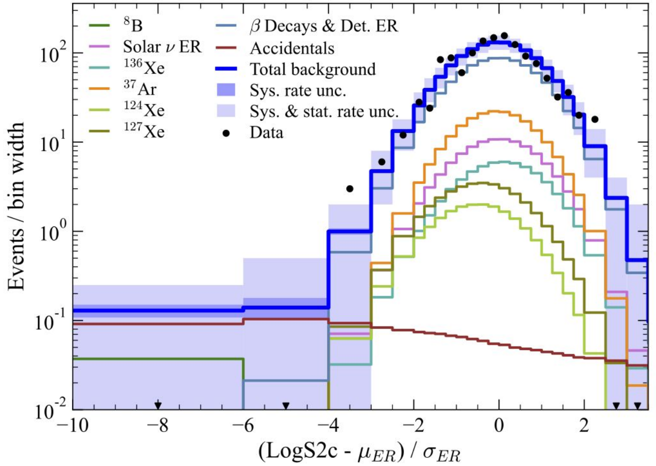


- Electron energy equiv. distribution, systematics are blue band
- Best fit with no WIMP signal

Results Fit

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



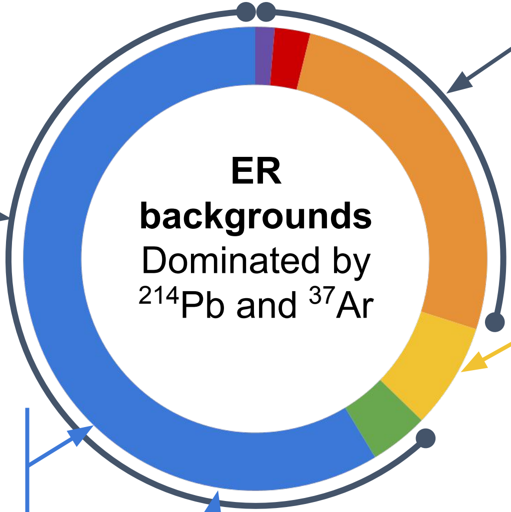


Best fit with zero WIMP events for all masses

- Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar
- Total expected **NR** counts in ROI in first run: **0.15**

Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

Dissolved β-emitters
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe (2νββ)



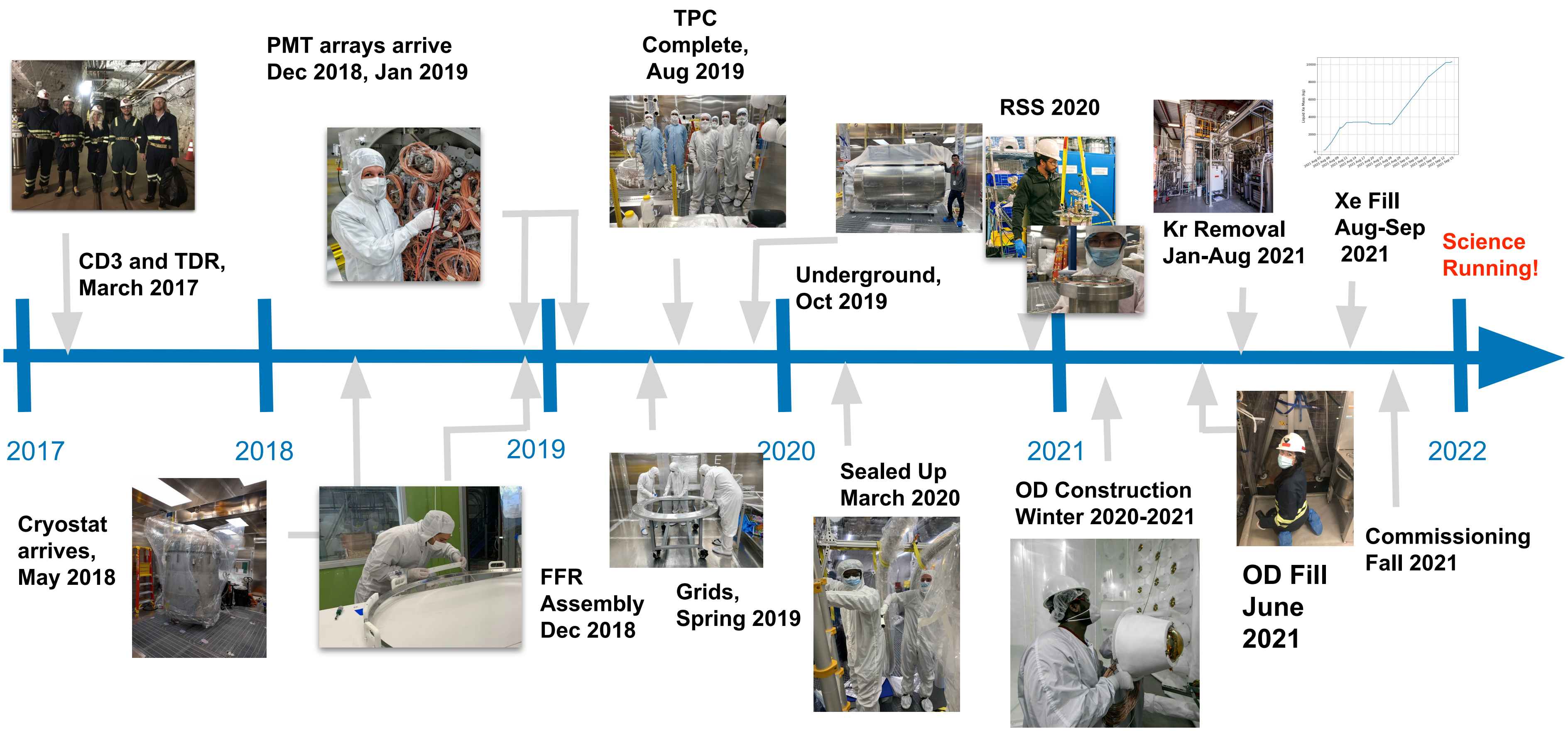
Solar neutrinos (ER)
- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials
- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

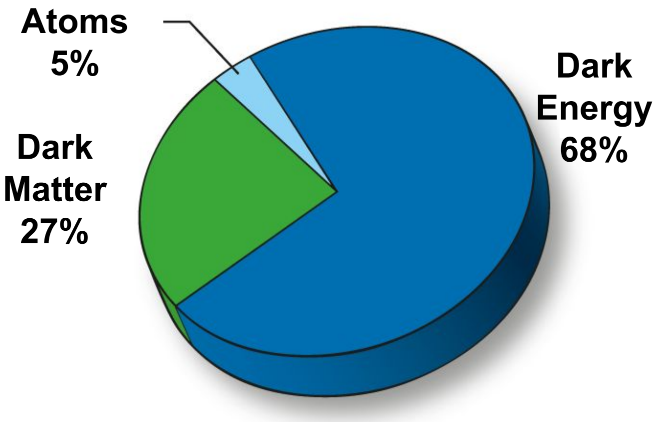
Flat-spectrum (in ROI) ERs

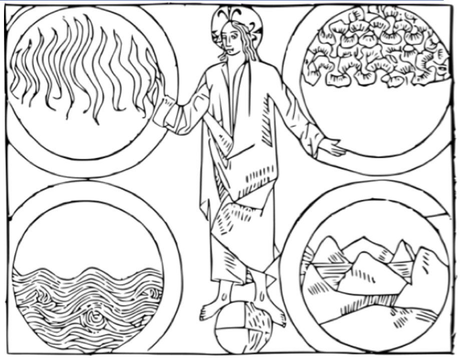
NR backgrounds:
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

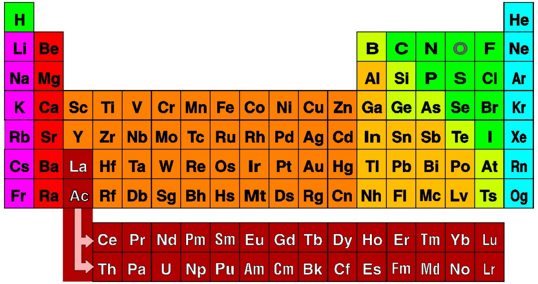
Accidental coincidence backgrounds

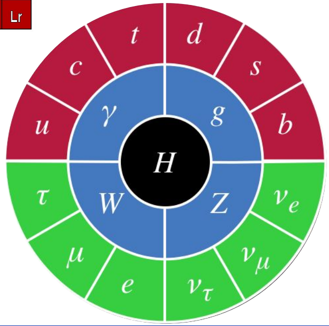

PMT arrays arrive
Dec 2018, Jan 2019
TPC
Complete,
Aug 2019
RSS 2020
CD3 and TDR,
March 2017
Underground,
Oct 2019
Kr Removal
Jan-Aug 2021
Xe Fill
Aug-Sep
2021
Science
Running!
2017
2018
2019
2020
2021
2022
Cryostat
arrives,
May 2018
FFR
Assembly
Dec 2018
Grids,
Spring 2019
Sealed Up
March 2020
OD Construction
Winter 2020-2021
OD Fill
June
2021
Commissioning
Fall 2021

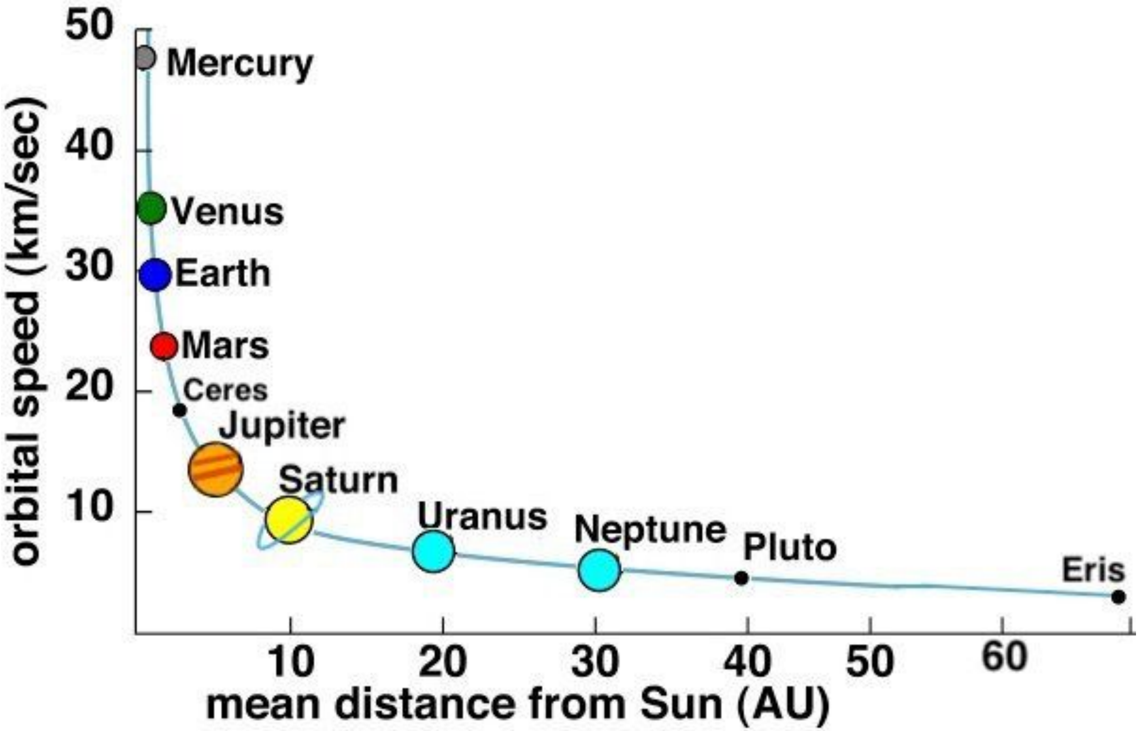
- It took a few **hundred years**
- With the discovery of the **Higgs boson** the **Standard Model has been completed**
- However, this is just the **tip of the iceberg**





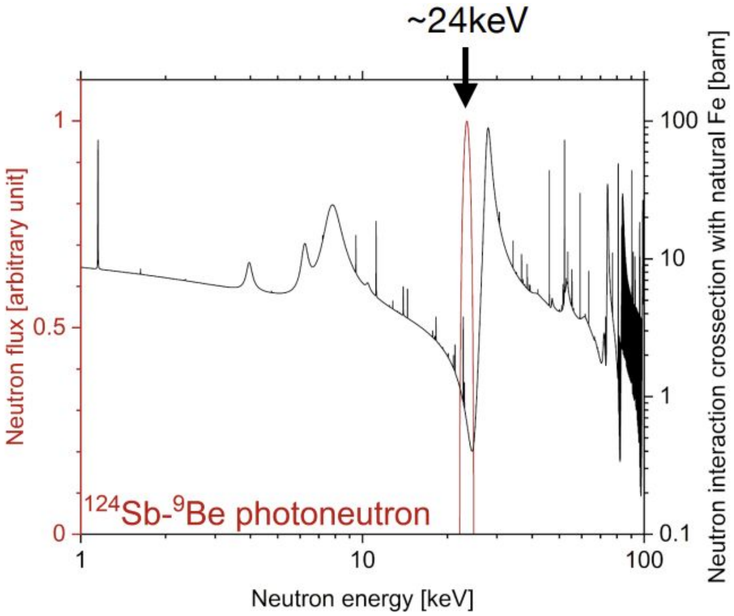




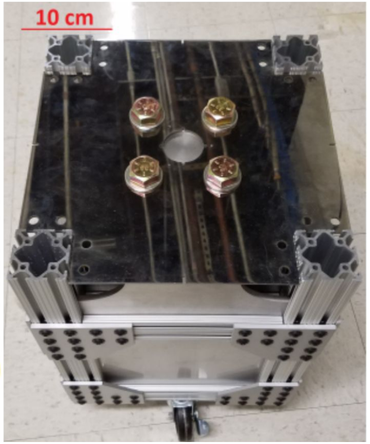


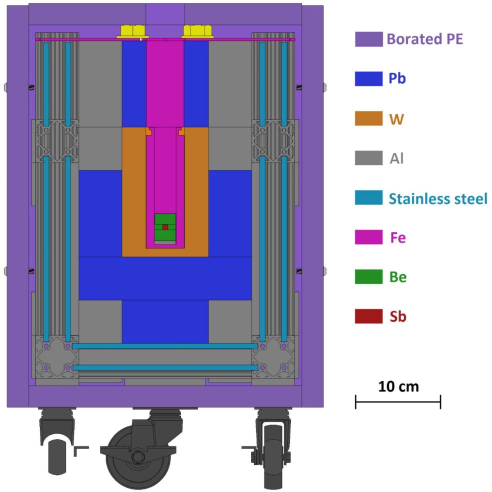
- We know exactly the speeds of orbiting objects, such as planets around the sun

  ...or stars around the galactic center



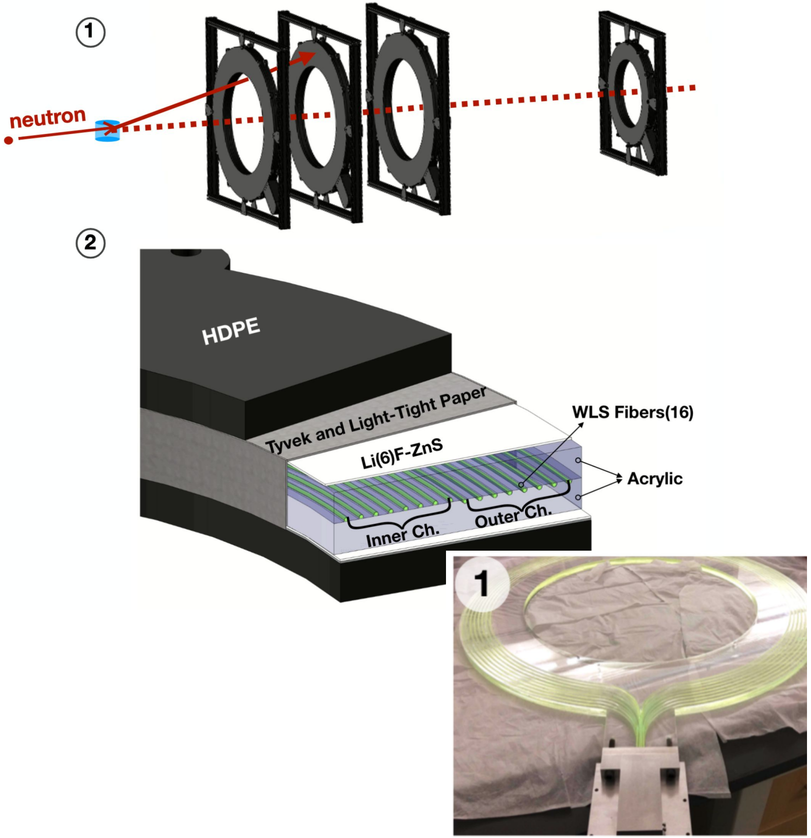
- **SbBe photoneutron + Fe** shield
- Remarkable coincidence:
  - ^{124}SbBe **neutron energy**: 23.47 keV
  - Fe n-**transmission resonance**: 24.54 keV
- Fe transparent to neutron, serves as collimator and very efficient gamma shield



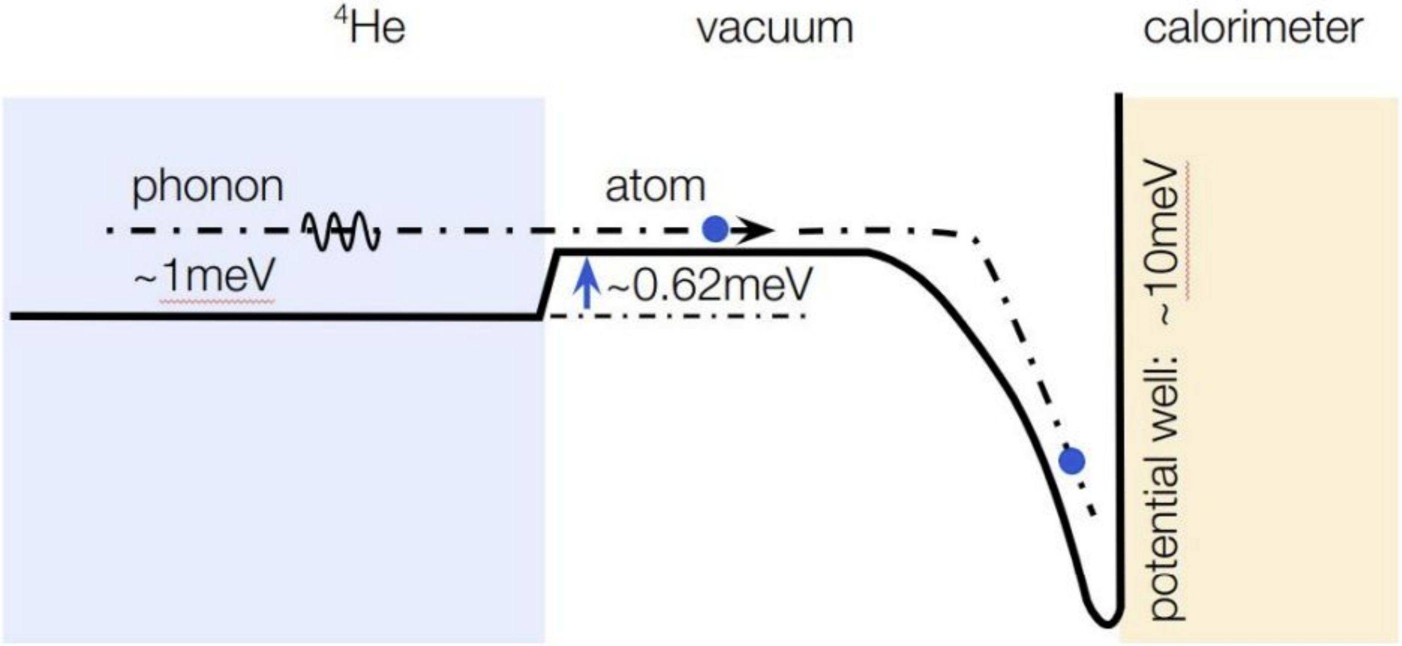


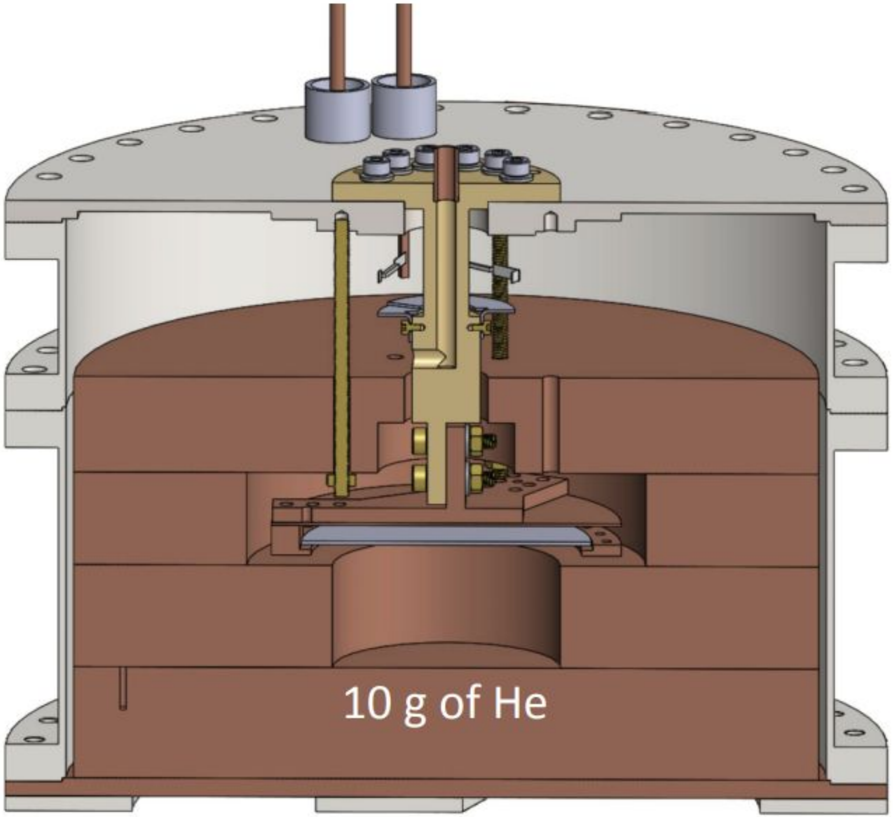
- Source built & works
- Favorable **n flux**: ~5 $cm^{-2}s^{-1}$
- Portable, ideal for **CEνNS** and **light DM** experiments
- See arXiv:2302.03869

- Developed a low energy neutron source
  - Scattering of neutron of known energy, tag its scattering angle
- Large arge **keV Neutron backing** detector for low energy NR calibrations
- ^{6}Li + Scintillator + Reflector + WS fiber + SiPM
- Eff: 25% eff. & affordable
- See arXiv:2203.04896



Amplification of evaporation signal via Van der Waals acceleration




10 g of He

- Inner 5.5 tonne fiducial volume (FV) is lowest background and uniform
- **Skin and OD vetoes**:
    - Removes γ background
    - Tag neutron capture (main DM background)
- Provides in situ constraint on neutron BG:
    - $0^{+0.2}$ neutron events in SR1