Direct Search Results of Light WIMP Dark Matter

- Grand Landscape
- Summary : Light DM Direct Search Results
- Selected Experiments -- Concept
- CDEX @ CJPL & Beyond
- Prospects: Anecdote from History

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May 2019

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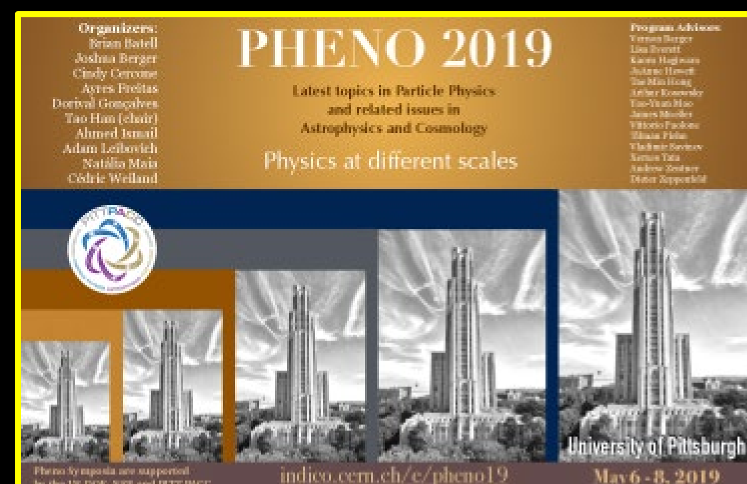
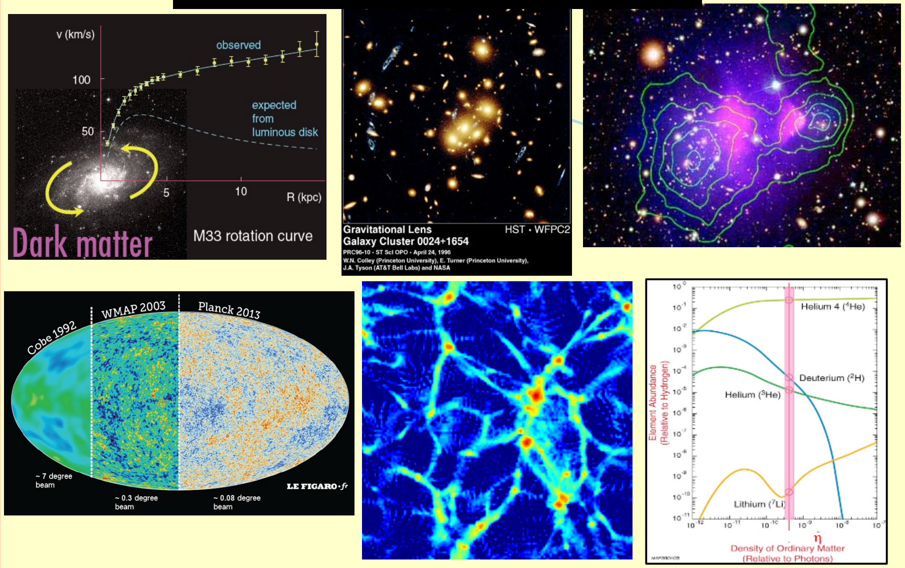
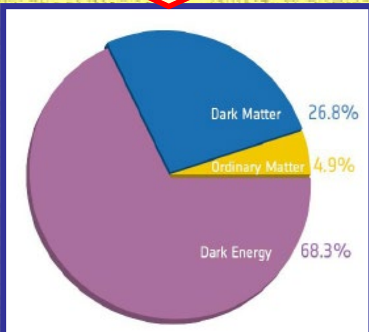
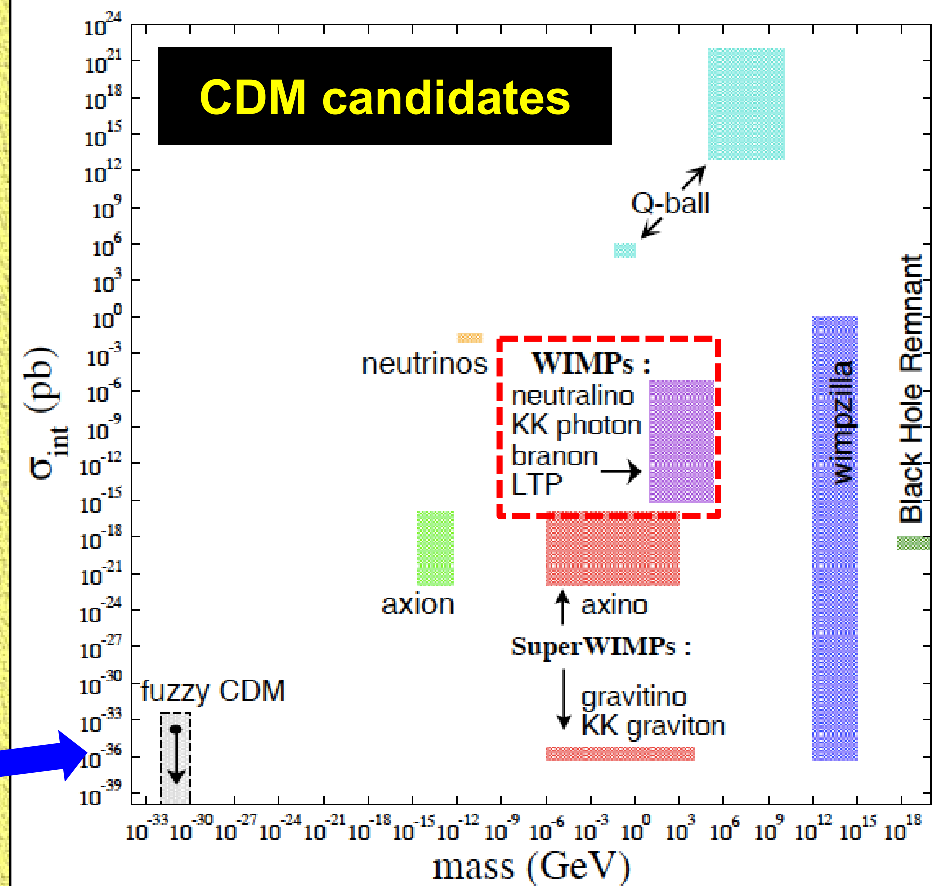


Evidence of Dark Matter







Most Experimental Programs focus on the Search of WIMPs *[∈CDM]*

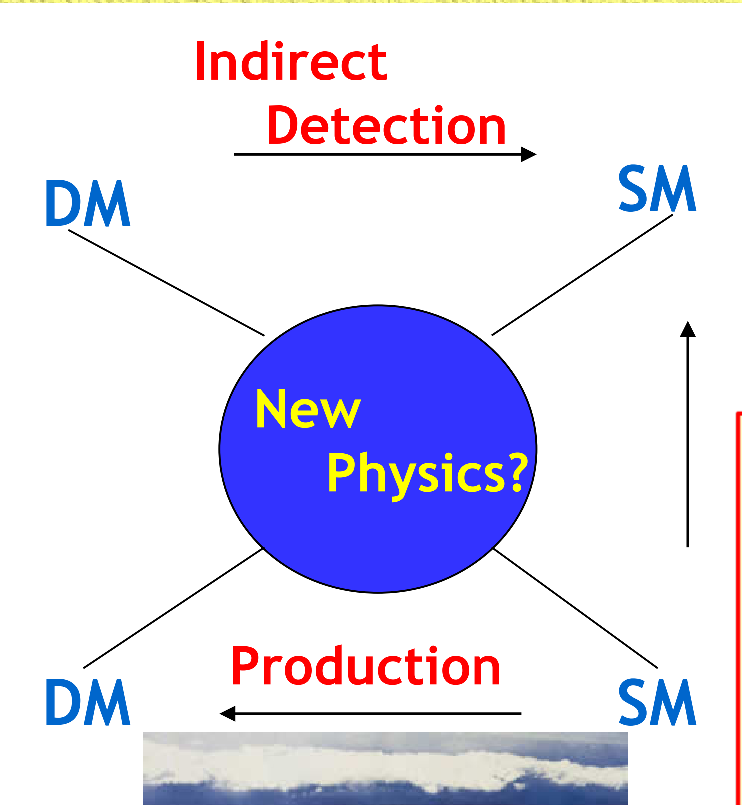
Key Variables: mass & cross-sections

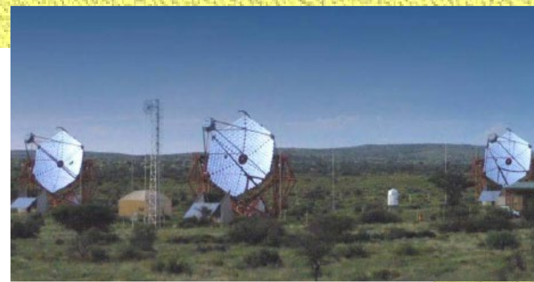
WHY this is *mainstream* ?

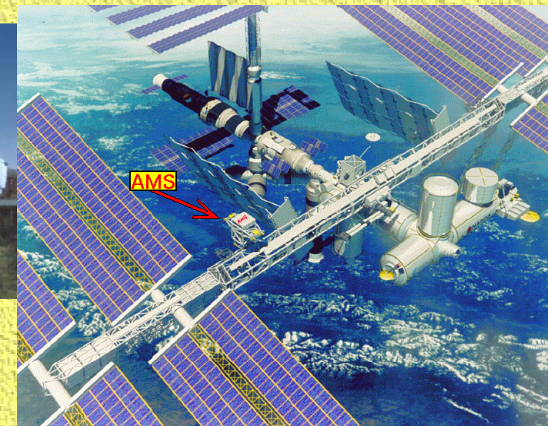
☑ **(Benefits or Burden) of Success of SM**

☑ **Look where we are able to *Natural (and Human!)***

WIMP Dark Matter Detection

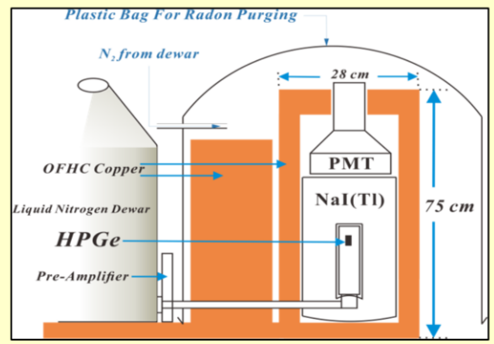




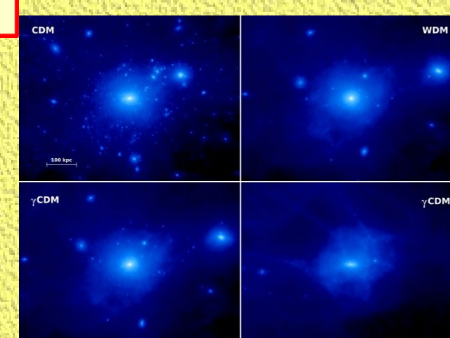


Direct
Detection

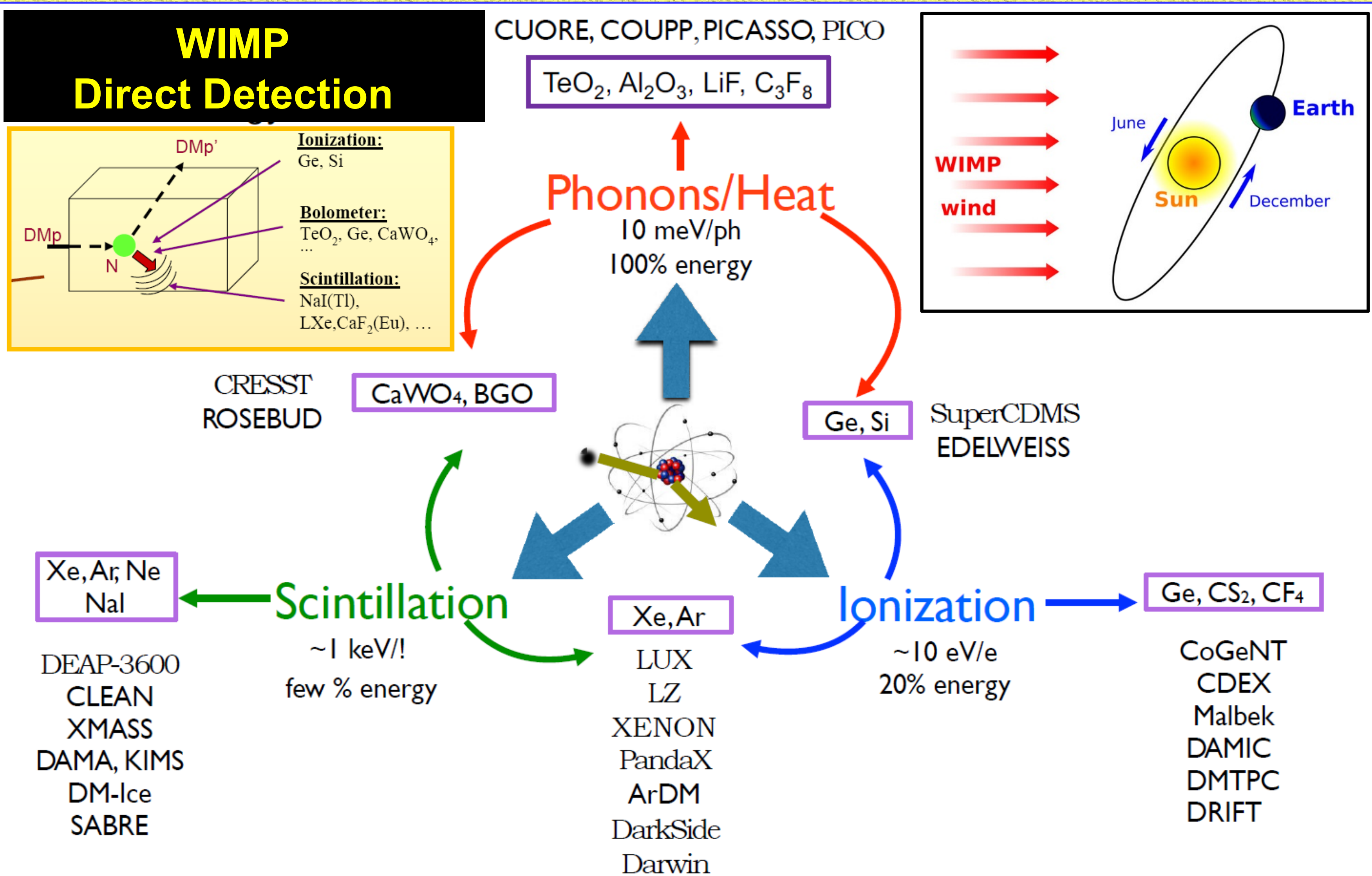
$\chi + A \rightarrow \chi + A$



+ Emerging : Probing DM Particle Physics Interactions with Astro/Cosmo/GW Data



WIMP Direct Detection

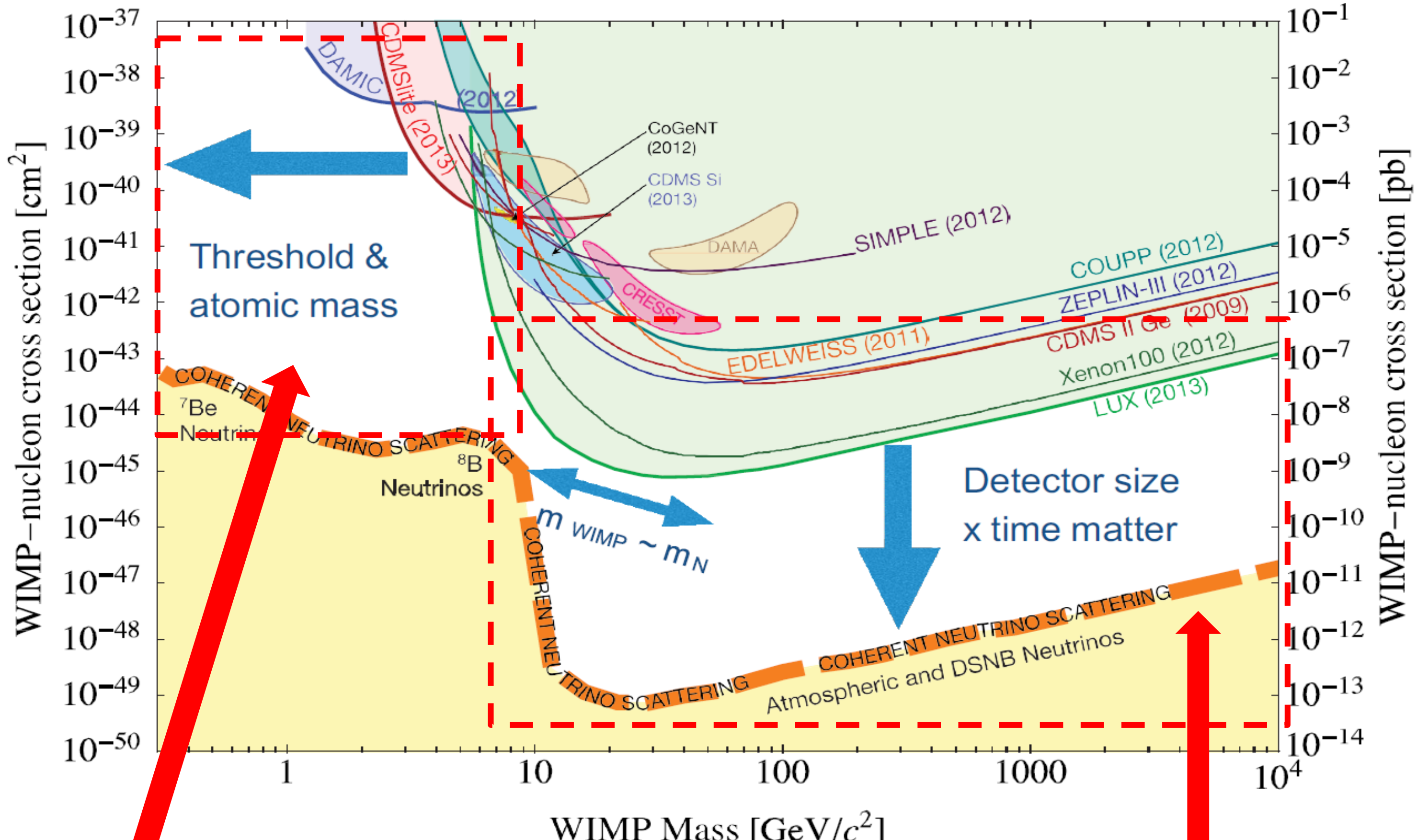


Signatures:

- ☑ **Annual Modulation effect due to Earth's rotation around the Sun**
- ☑ **Consistency among different nuclei/experiments**
- ☑ **Consistency among different methods**

Spin-Independent σ(χN) Exclusion Plot [~2013]

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



quality ← Detector requirements → mass

Semiconductor Experiments

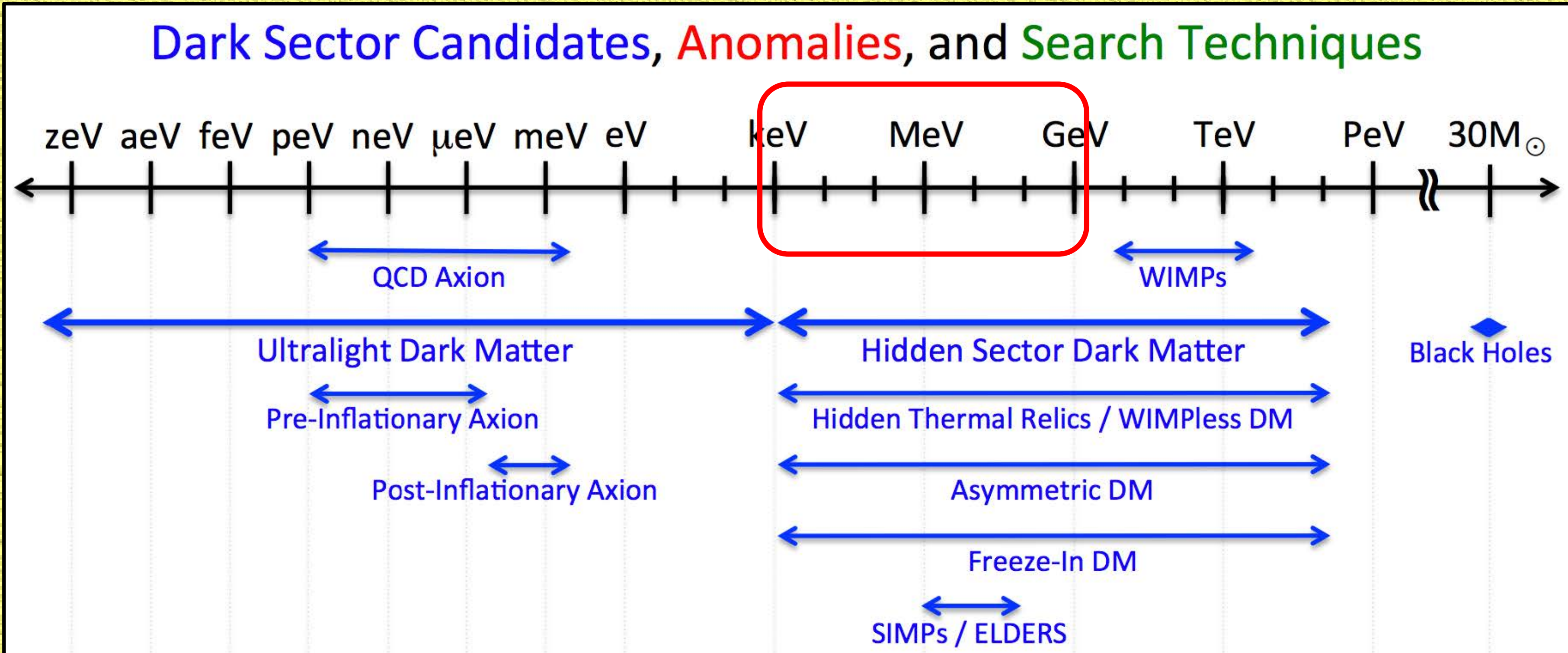
⇨ *Low Detector Threshold (→ 10-100 eV)*

… and Beyond for Future!! [T. Lin's Talk]

Liquid Noble Gas Experiments

⇨ *Large target mass (→ ton) with low (→ 0) Background*

Increase Activities to Scan Complete Mass Range and Explore New Models for DM

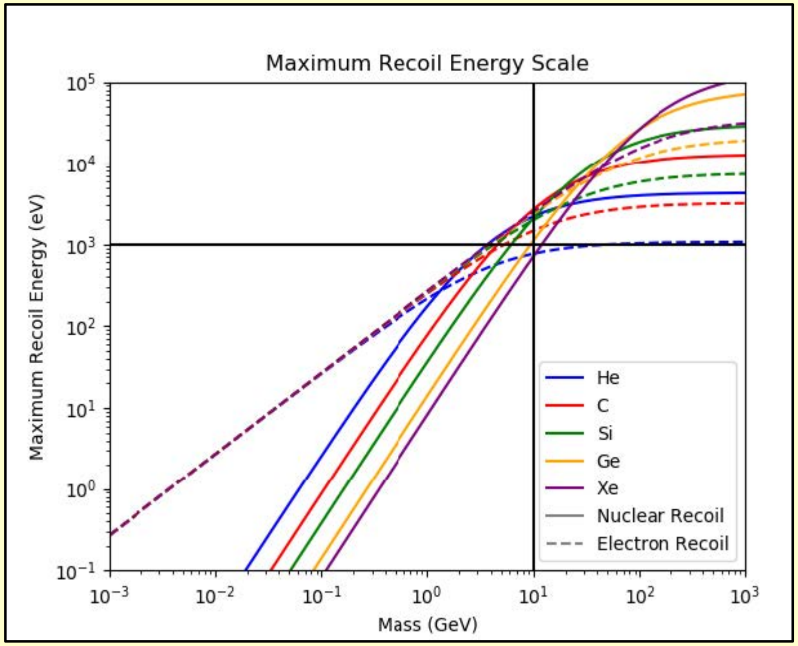


Why Light Dark Matter ?

- Some Models favor "Standard-Model like" with SM-scales *(electron-mass, QCD, proton-mass ….)* : Dark // Hidden // Mirror Sectors..
- Emerging **Experimental Accessibility** (Windows Opening) with **Novel Ideas** *[T. Lin's talk]* & **New Physics Detection Channels** *[Various Talks]*
- Complementarities with and Scrutinies from [with Model-Dependence] from **Accelerator** *[Gritsan&Outschoorn's Talks]* and **Astrophysics** constraints.

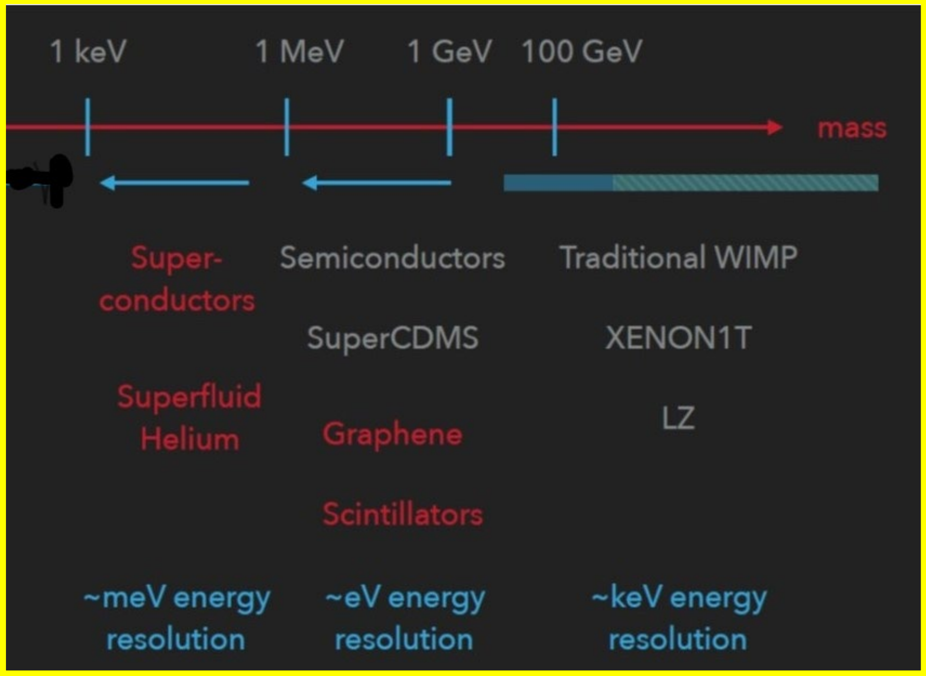
DM-Electron Scattering

Sensitive to lower m_{DM} at the same detector threshold (< keV)



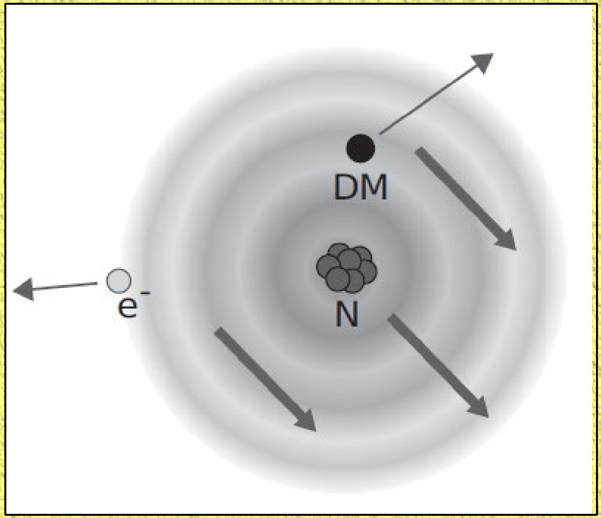
Novel Ideas & Intense efforts

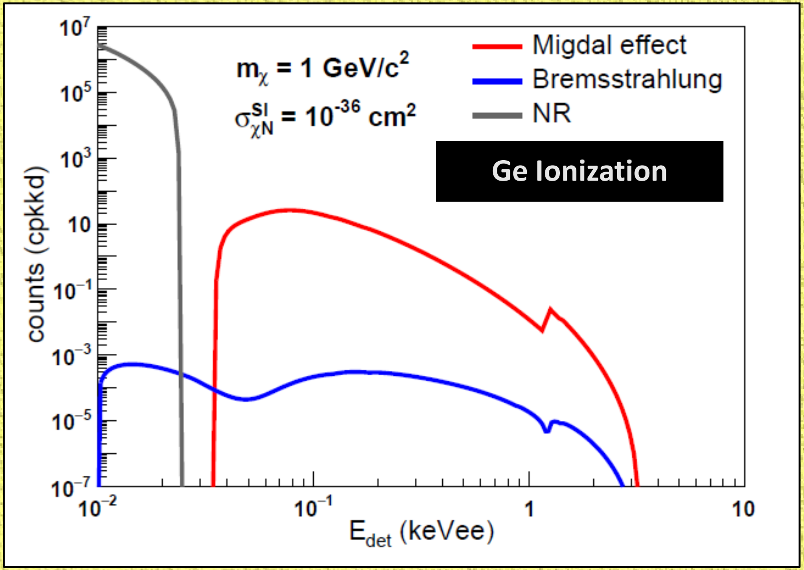
[T. Lin's Talk]



- **Low threshold requires new detector techniques**
- **Electron-Recoil signatures : Background more severe than Nuclear-Recoils**
- **Measureable differential spectra require incorporation of atomic physics effects**

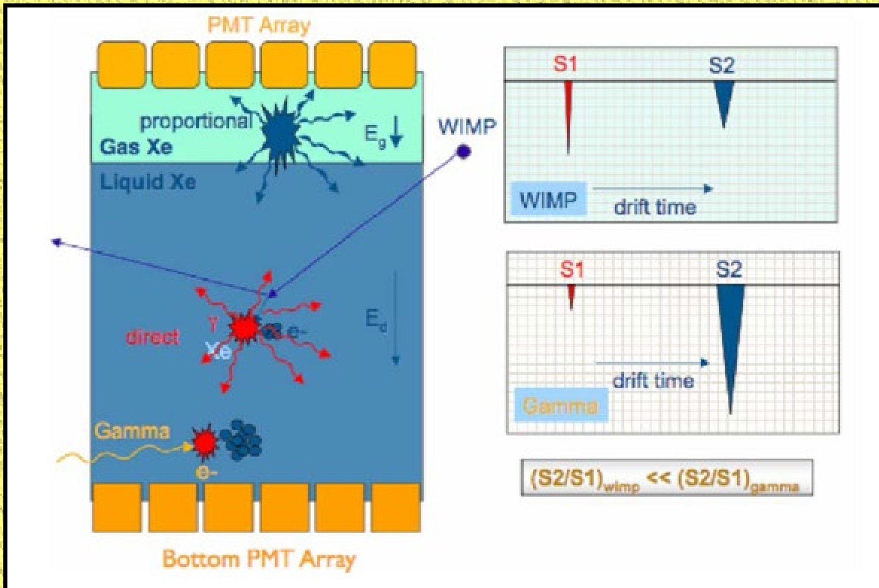
Migdal (& Bremsstrahlung) Effects *[J.Dent's Talk]*

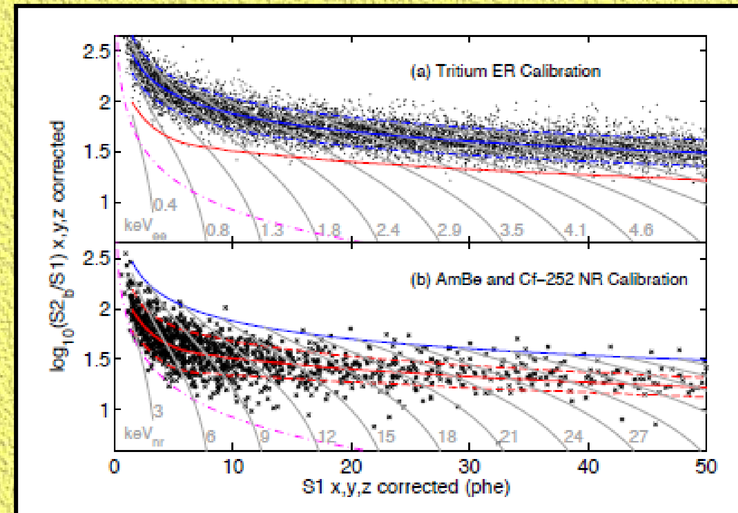


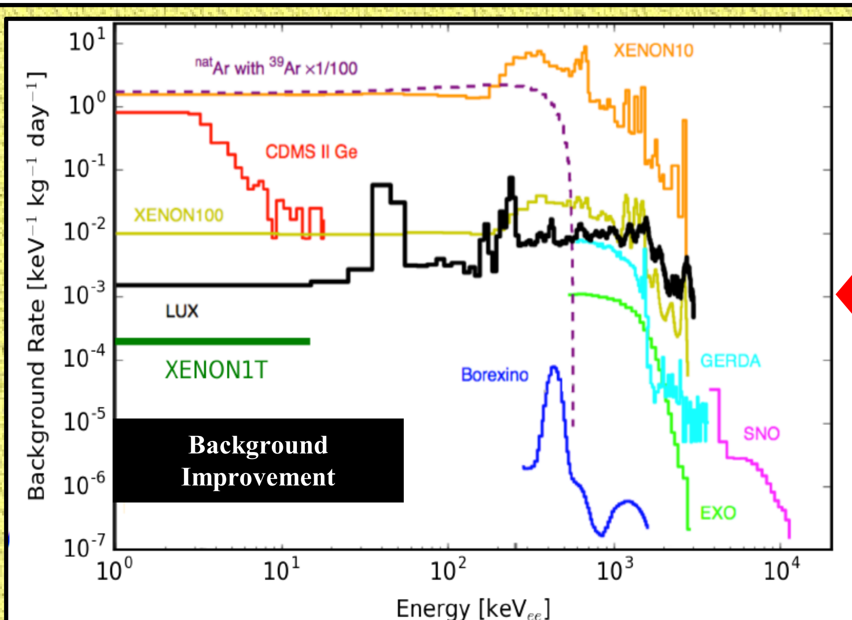


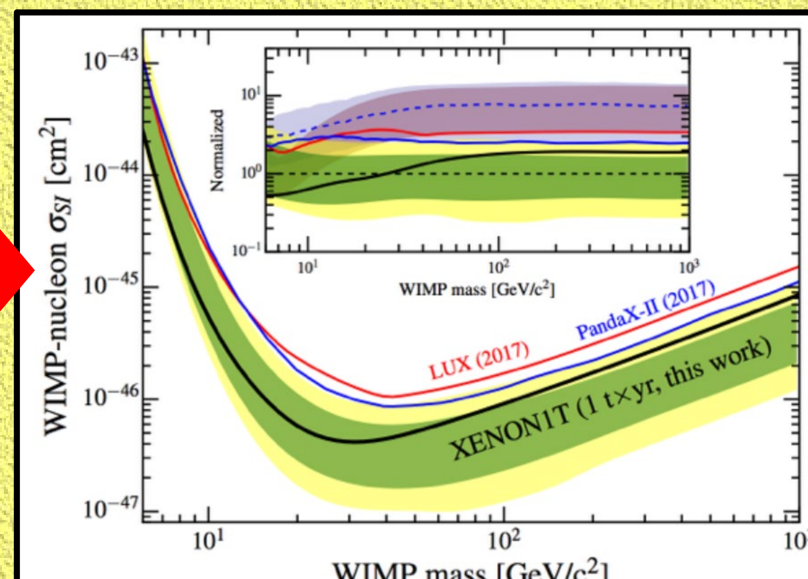
- ☑ Atomic electrons do not follow instantaneously the motion of recoiling nucleus in **DM+N scattering**
- ☑ Finite time necessary for electrons to "catch up", resulting in possible **ionization** and **excitation** in that atom ⇒ **inelastic processes**
- ☑ Energy loss E_{EM} with electromagnetic signatures, in addition to E_{NR} for nuclear recoil.
- ☑ Small probability but **enhance total energy loss** to above detector threshold for light DM
- ☑ Energy boost esp. significant for E_{ER} with quenched signals.

Two-Phase Liquid Xenon Techniques Dominates the $\sigma_{\chi N}$(SI) Sensitivity Plots at m_χ > 10 GeV *[J. Howlett's Talk]*



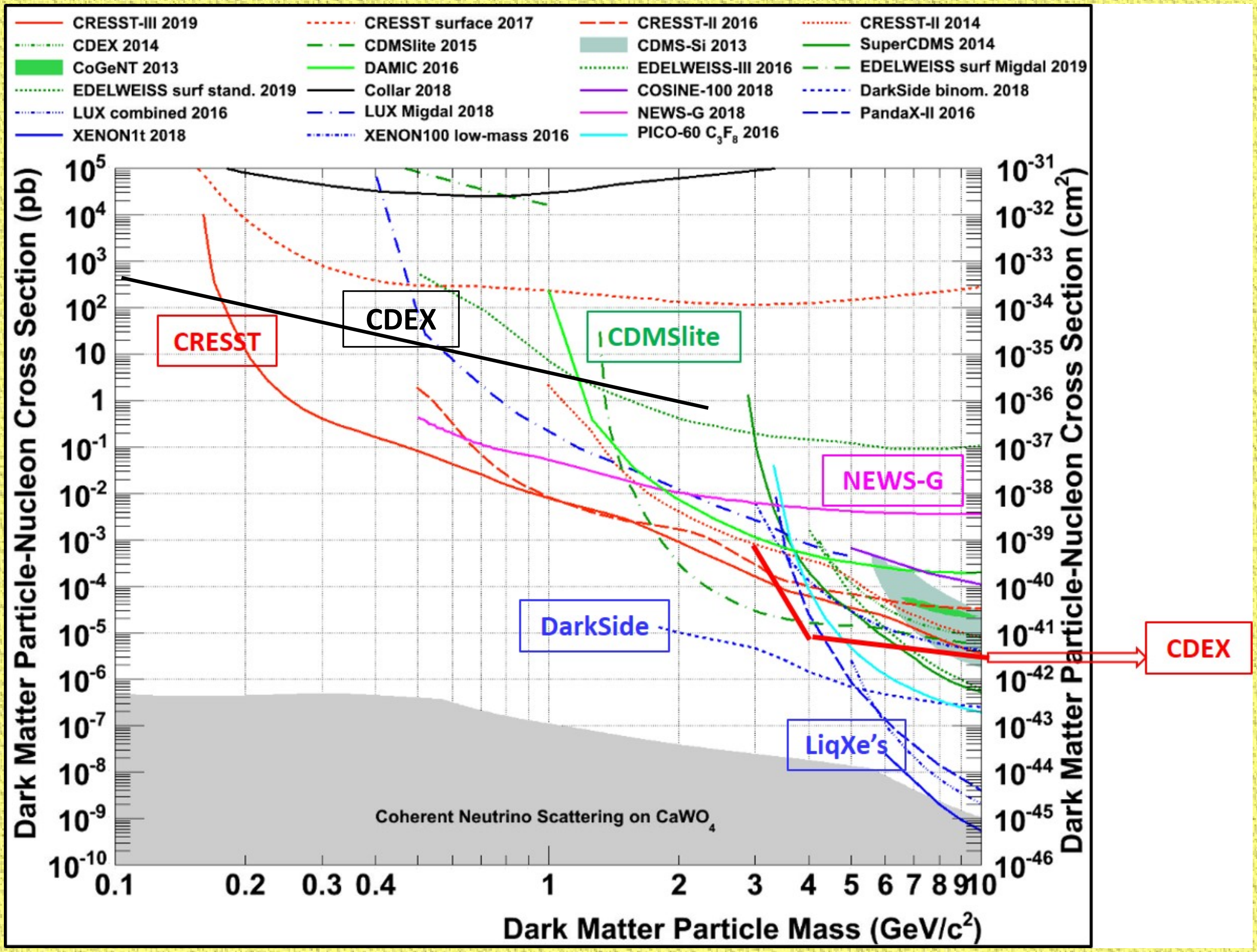






Light DM Spin-Independent $\sigma(\chi N)$ Exclusion Plot

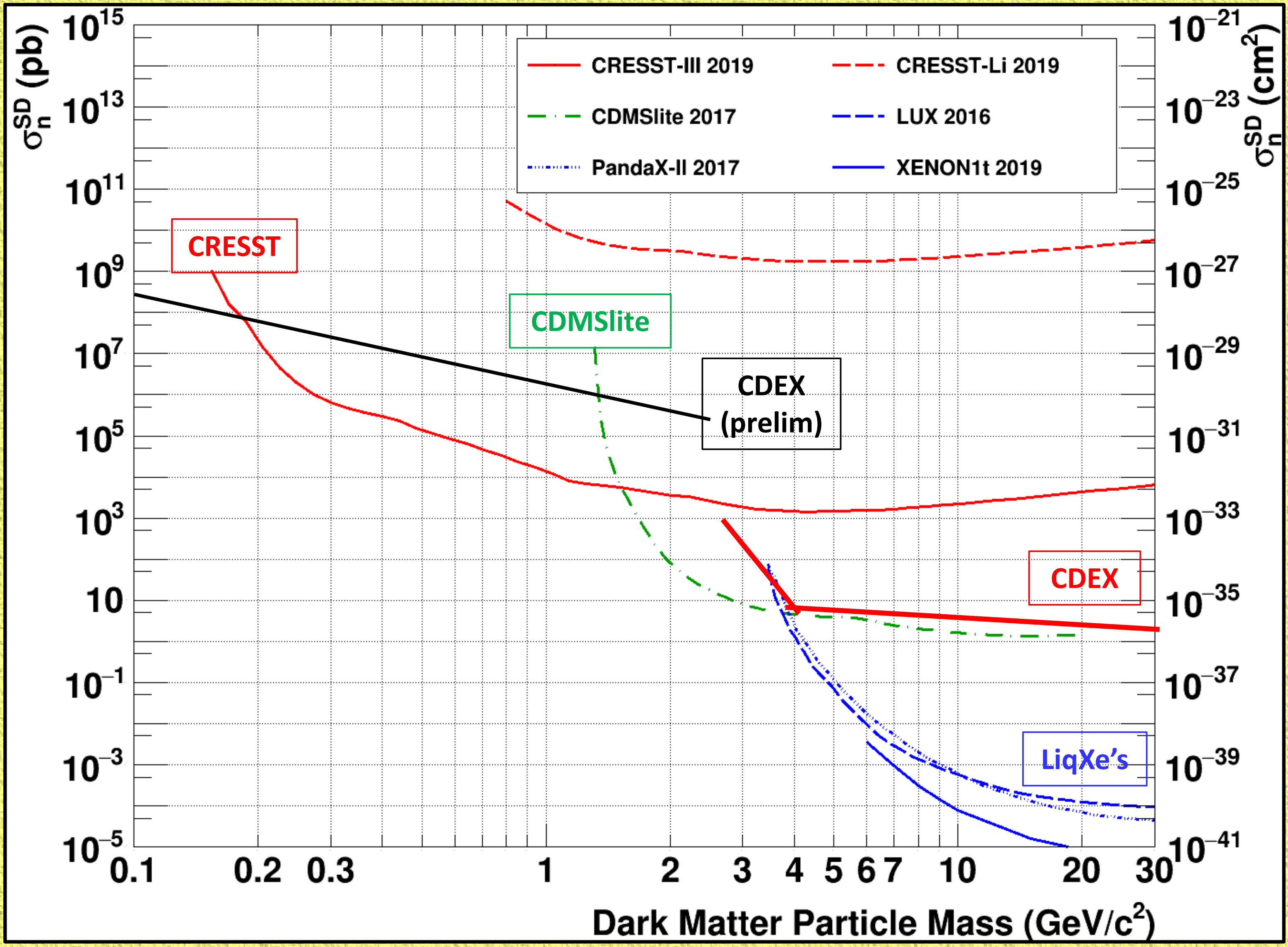
[*arXiv: 1904.00498* , CRESST]



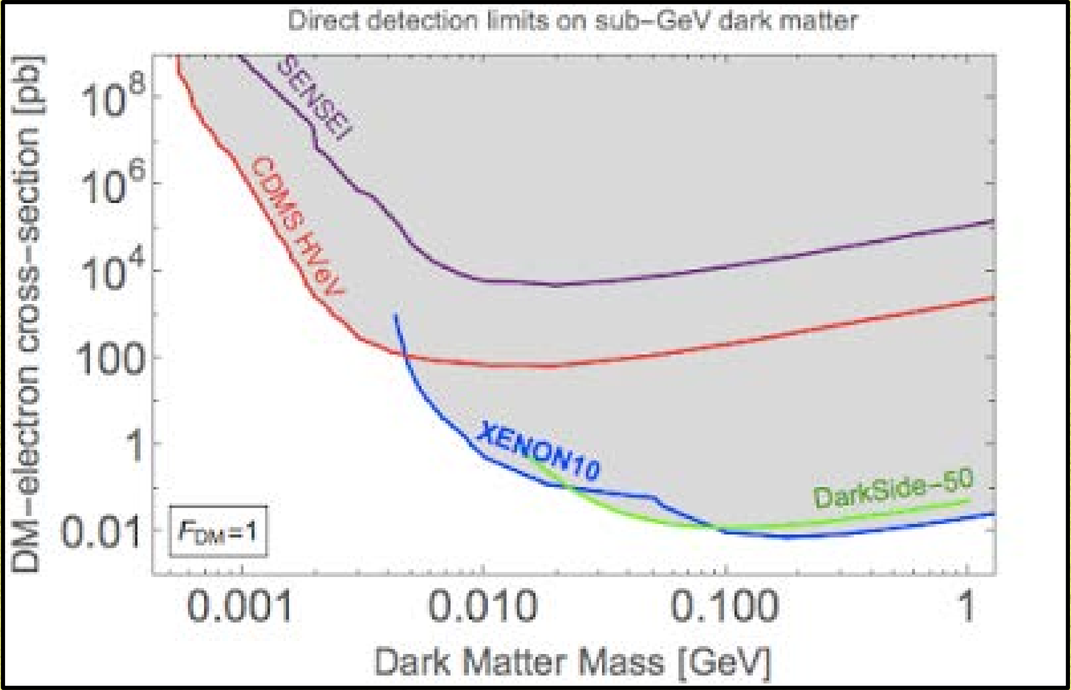
Nuclear Vs Electron Recoils Distinction -- Inefficient or Absent !!

Light DM Spin-Dependent σ(χN) Exclusion Plot

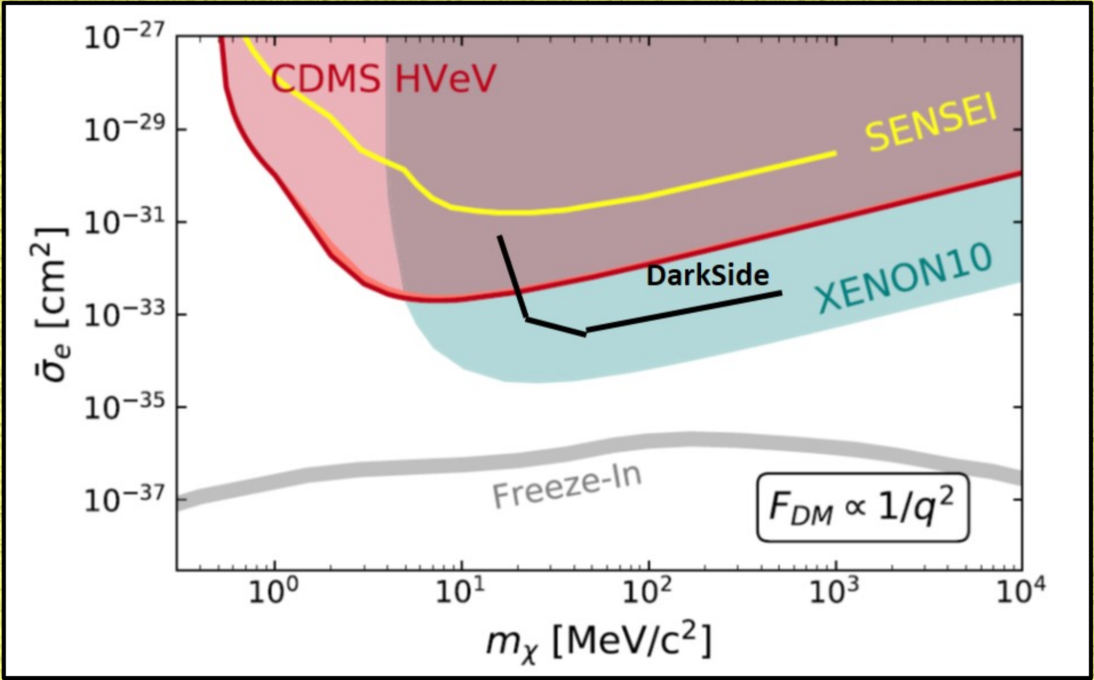
[arXiv: 1904.00498 , CRESST]



Light DM σ(χ–e) Exclusion Plot



Light Mediator (Long Range Interaction)

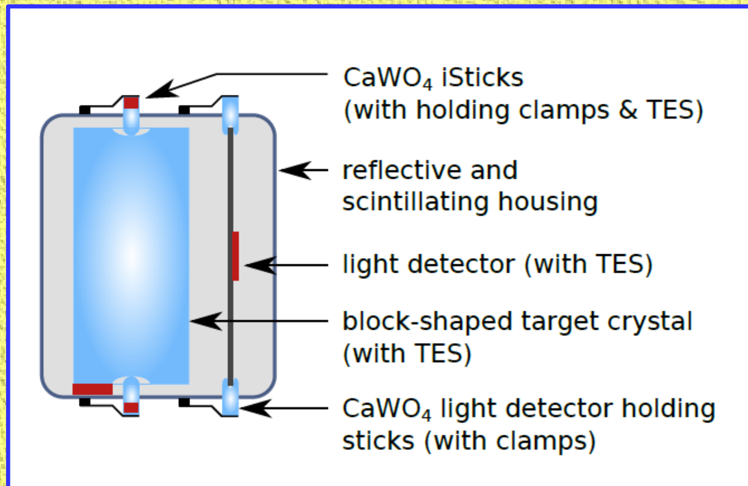


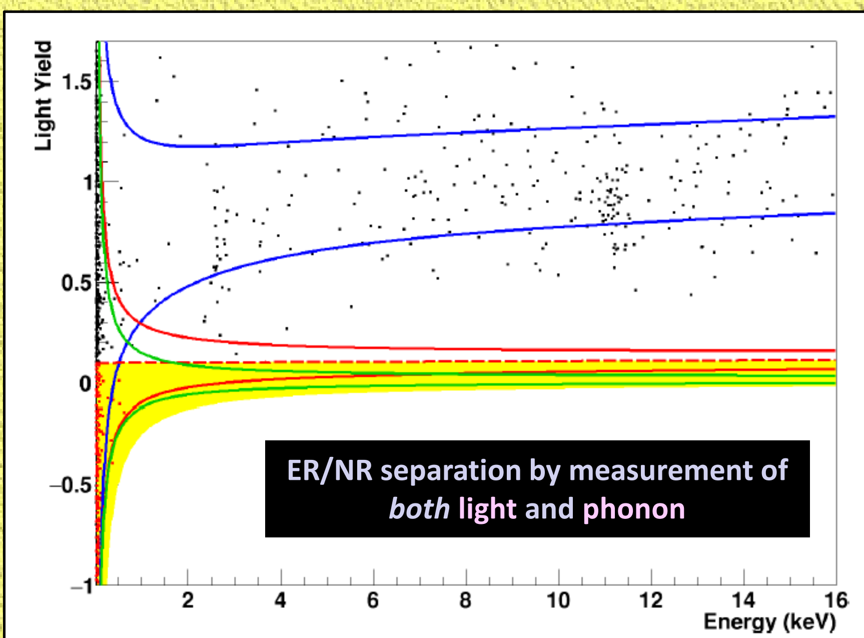
Heavy Mediator (Short Range Interaction)

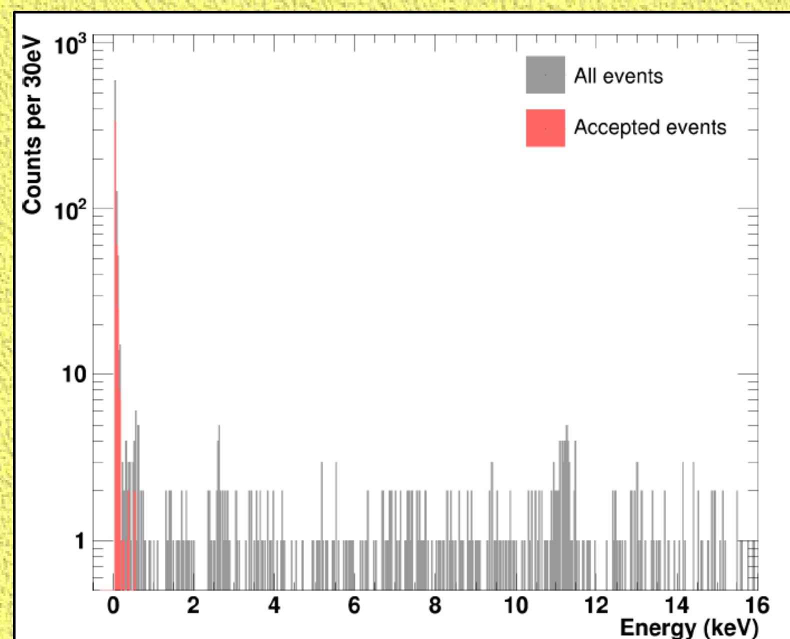
$$F_{\rm DM}(q) = \frac{{m_{A'}}^2 + \alpha^2 {m_e}^2}{{m_{A'}}^2 + q^2} \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 {m_e}^2}{q^2}, & m_{A'} \ll \alpha m_e, \end{cases}$$

CRESST @ Gran Sasso

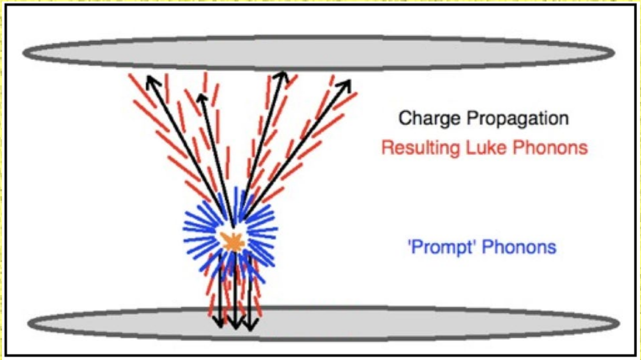
- $CaWO_4$ @ O(10 mK)
- Latest Results *[arXiv:1904]*:
  - ☑ 24 g target, 2.39 kg-d
  - ☑ Detector threshold ~30 eV
  - ☑ Lead sensitivity m_{DM}~0.15-1.5 GeV

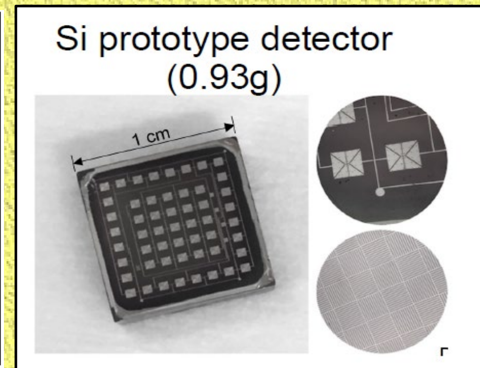


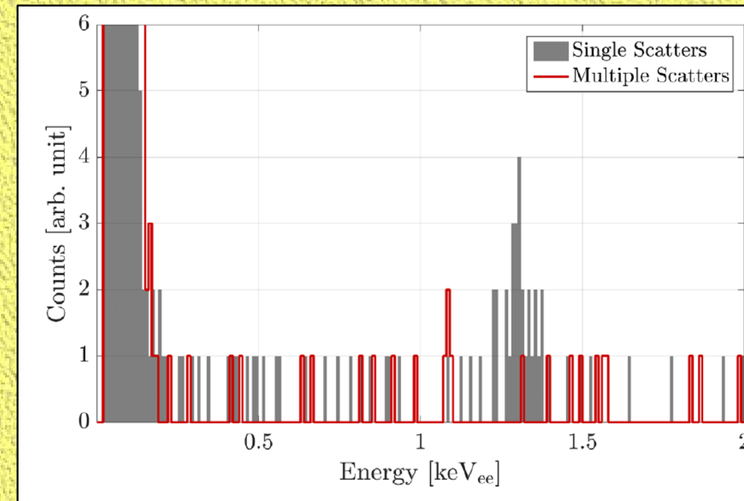




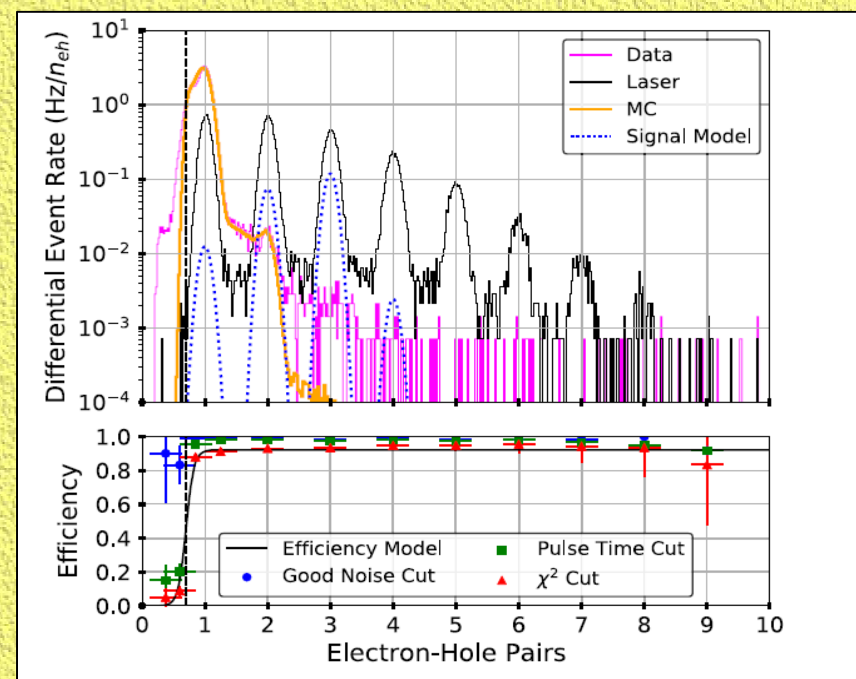
SuperCDMS [“Neganov-Trofimov-Luke Effects” (Bolometric Amplification)]





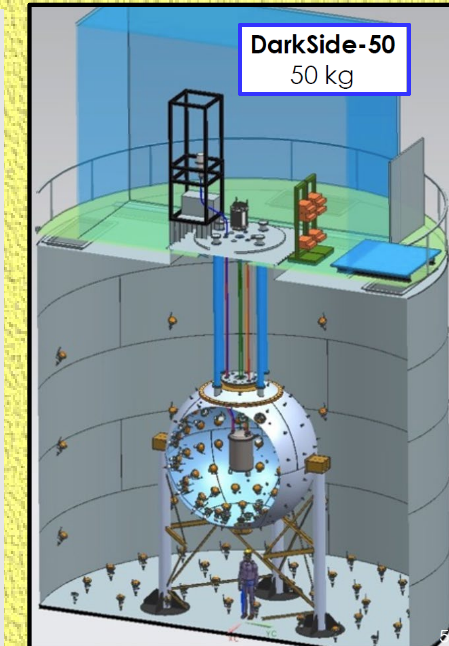


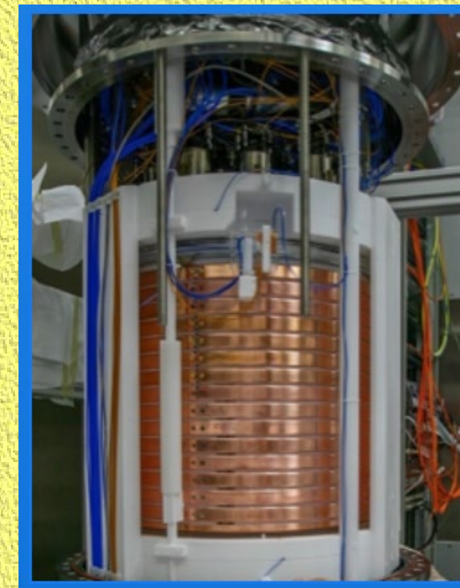
- **CDMSlite @ Soudan** ***[PRD18]***
  - ☑ **600 g Ge target,**
  - ☑ **R2: 70.1 kg-d**
  - ☑ **DM-N Threshold ~56 eVee**
- **HVeV @ SNOLab** ***[PRL18]***
  - ☑ **0.93 g Si @ 33 mK, 140 V**
  - ☑ **0.49 g-d data**
  - ☑ **Threshold~1 eh (3 eV)**
  - ☑ **DM-electron scattering Probe**
    m_{DM}~1 MeV
  - ☑ ***Also dark photon constraints***

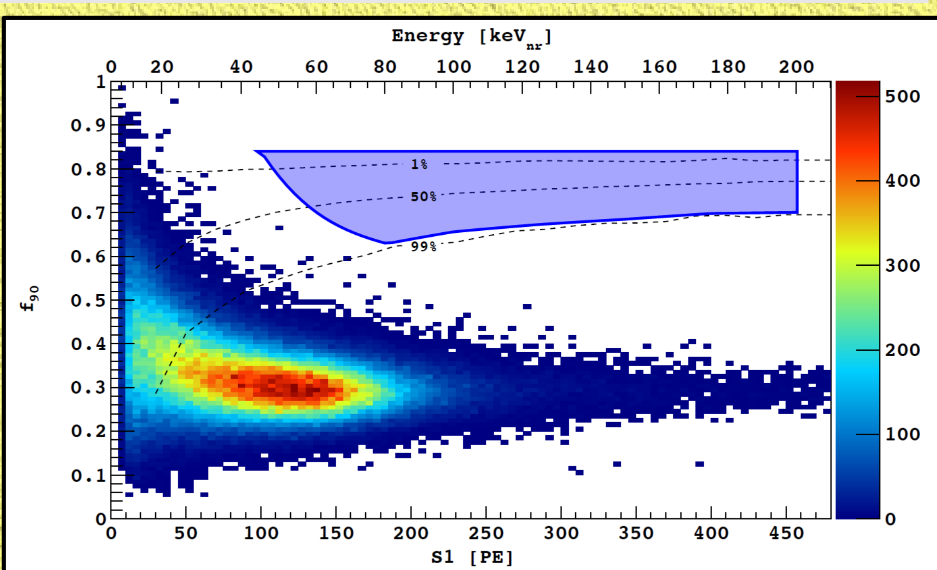


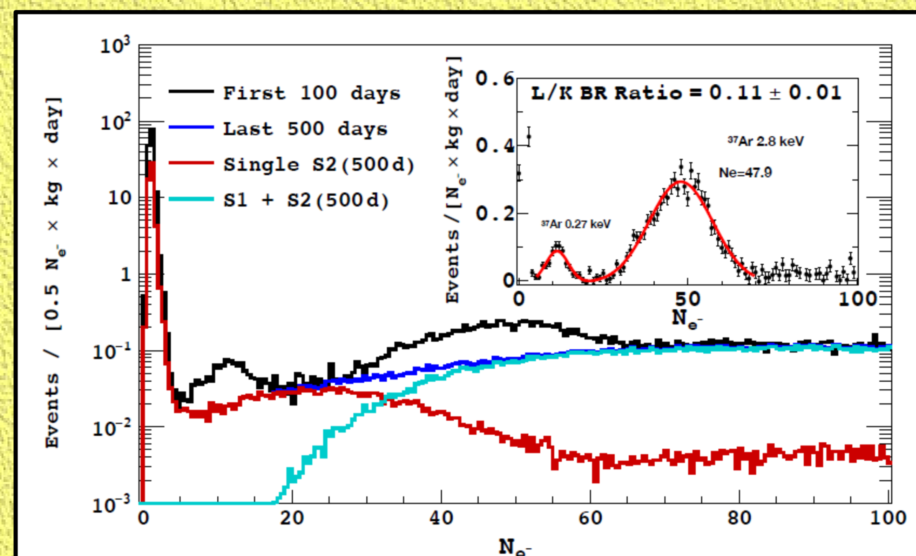
DarkSide @ Gran Sasso

- Dual-Phase LiqAr for ER/NR separation
- 50 kg fiducial target
- Depleted radioactive Ar39
- Latest Results *[PRL18]*:
  - ☑ S2 (ionization only),
  - ☑ threshold 0.4 keVnr,
  - ☑ 6786 kg-d
  - ☑ Lead sensitivity m_{DM}~1.8-6 GeV



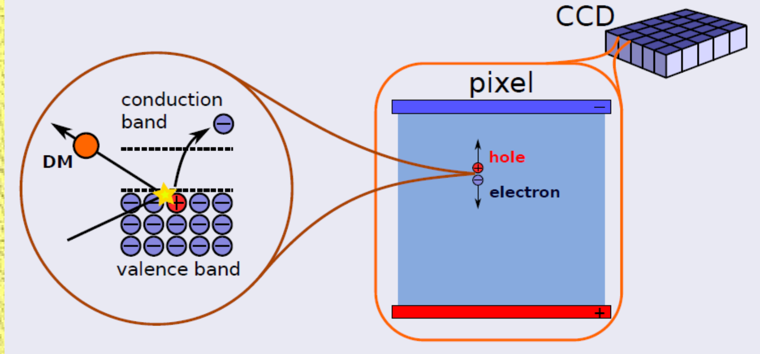


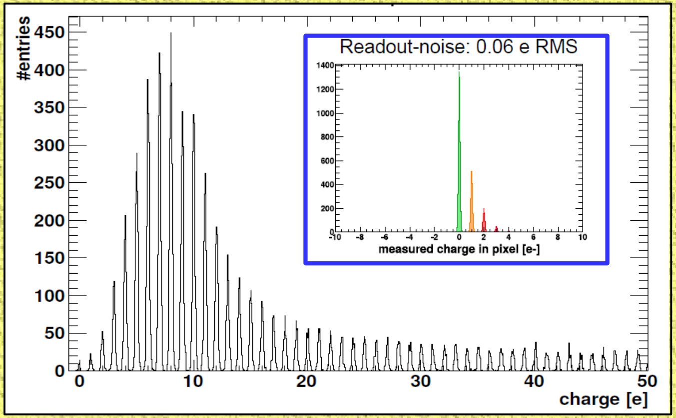




SENSEI @ FNAL *[D. Gift's Talk]*

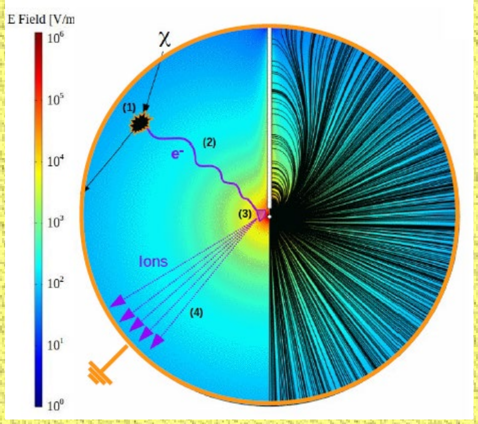
- Skipper CCD, multiple sampling
- 0.06 e RMS noise
- Threshold Si-band gap 1.2 eV
- Latest Results *[arXiv1901]*:
  - ☑ 0.177 g-d
  - ☑ Probe DM-e to m_{DM}>1 MeV

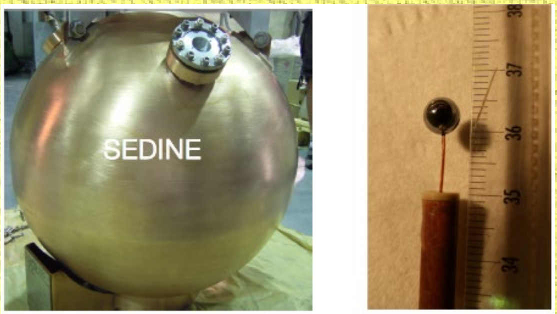




NEWS-G @ Modane

- Spherical Proportional Chamber
- First Results *[Astropart 17]*:
  - ☑ 0.284 g Ne+CH4 target;
  - ☑ 9.6 kg-d
  - ☑ Threshold ~500 eVee
  - ☑ Sensitivity m_{DM} > 0.5 GeV



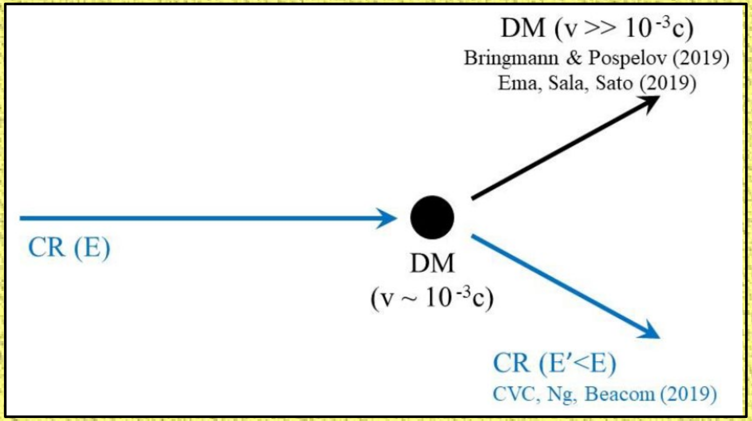


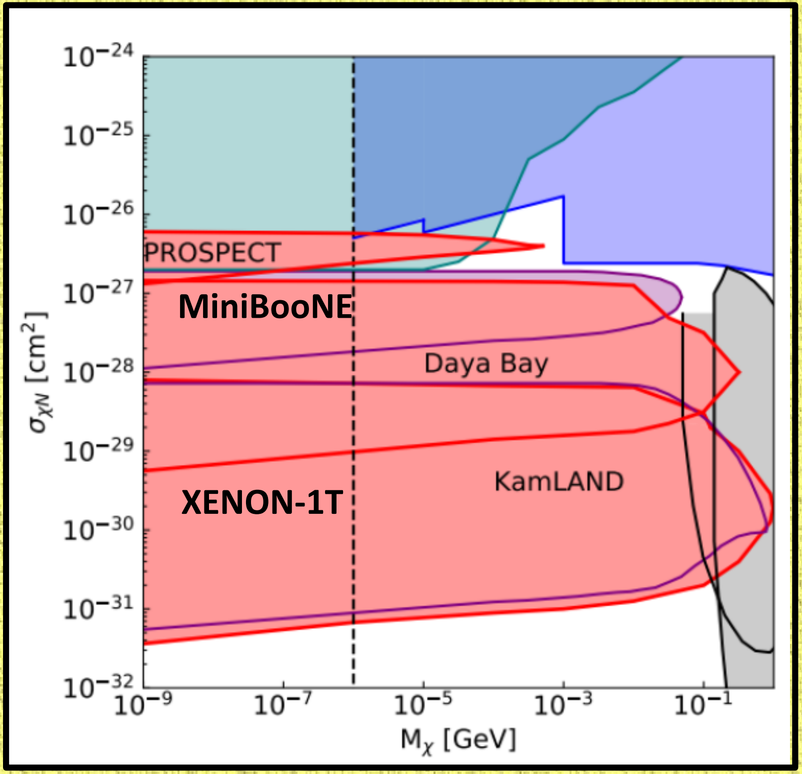
Vessel
60 cm ∅ NOSV Copper

Sensor
6.3 mm ∅

Up-scattering by Cosmic-Rays *[C.Cappiello 's Talk]*

- ☑ Cosmic-Ray DM scattering boosting DM-kinetic energy
- ☑ DM-Detector interactions provide (much) larger deposited energy
- ☑ Large target mass neutrino detectors can place constraints
- ☑ Can probe very low mass
  m_{DM} < keV





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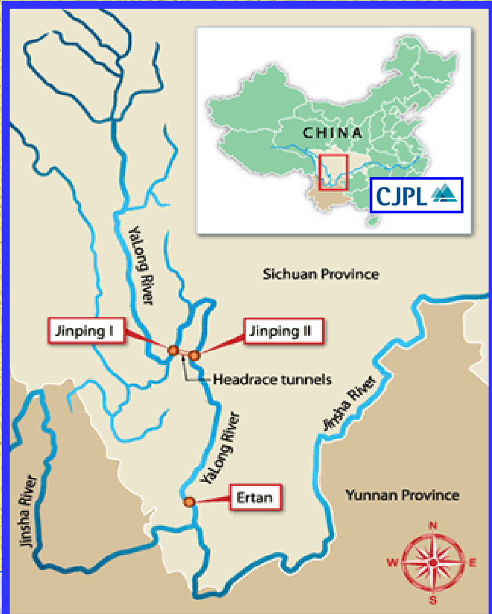
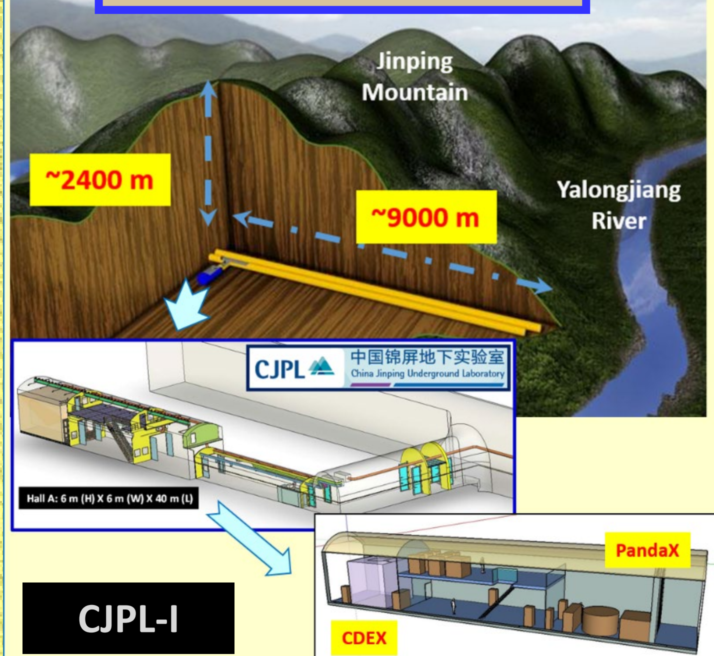
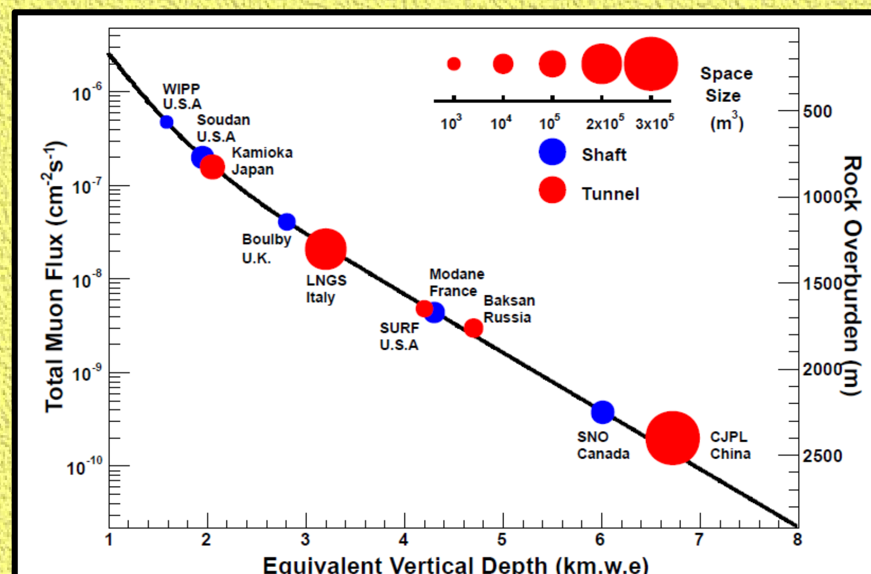
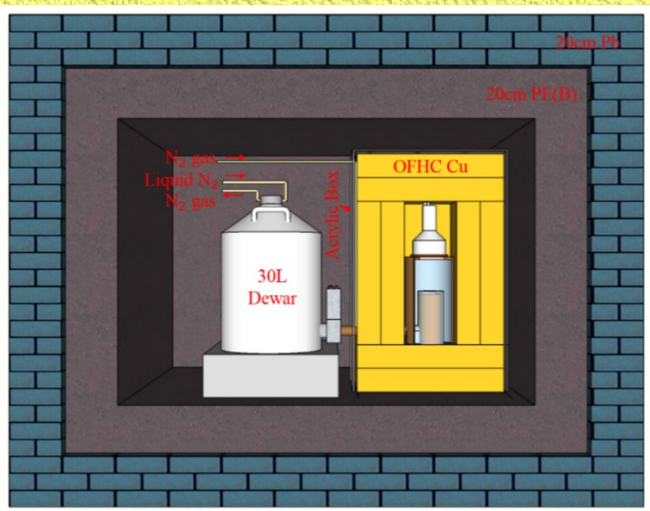


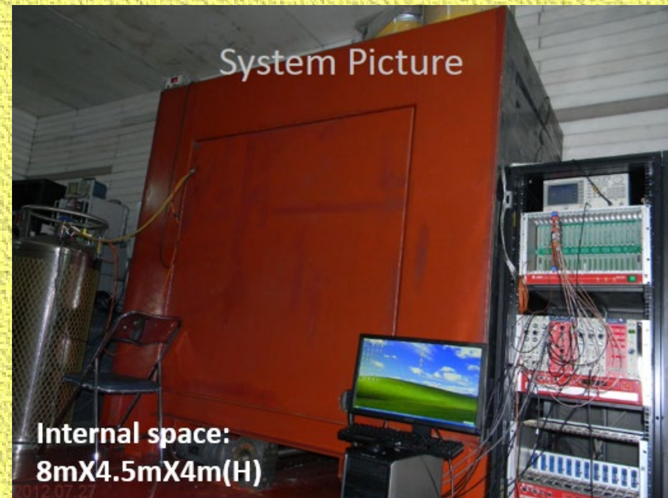


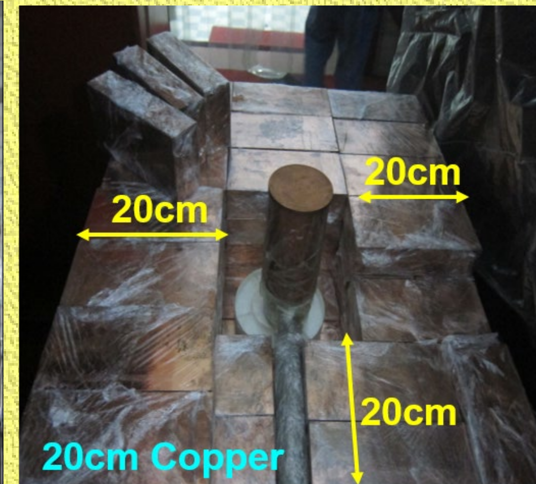
- **Merits: 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures**
- **CJPL-I (2010): *6X6X40 m* cavern**
- ***CJPL-II (2018+) : [4X(14X14X130 m) Halls] + Pits***
- **CDEX Dark Matter Program**
  - ☑ ***Foundation catalyzed by TEXONO-reactor neutrino + sub-keV Ge detector***
  - ☑ ***May well evolve back into neutrino physics***



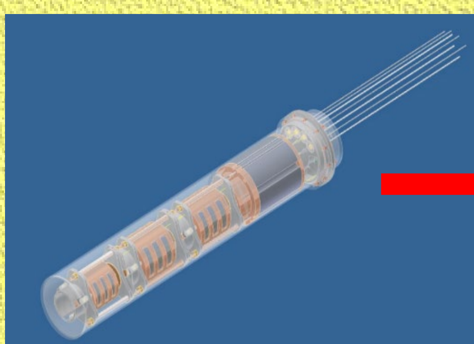
CDEX-1

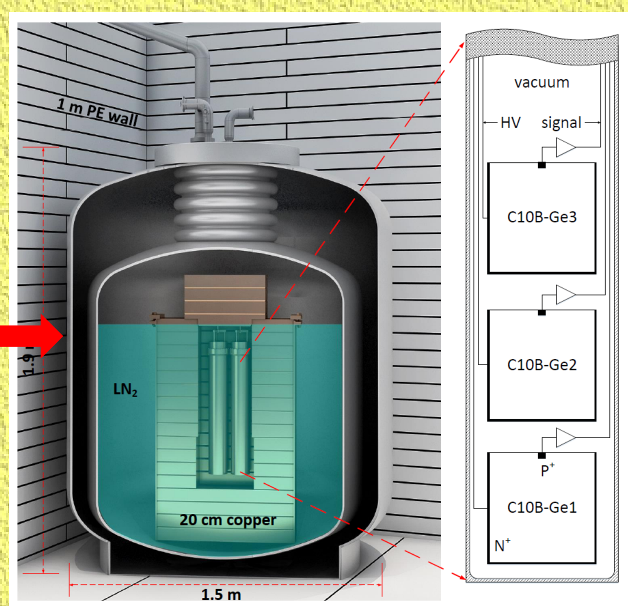






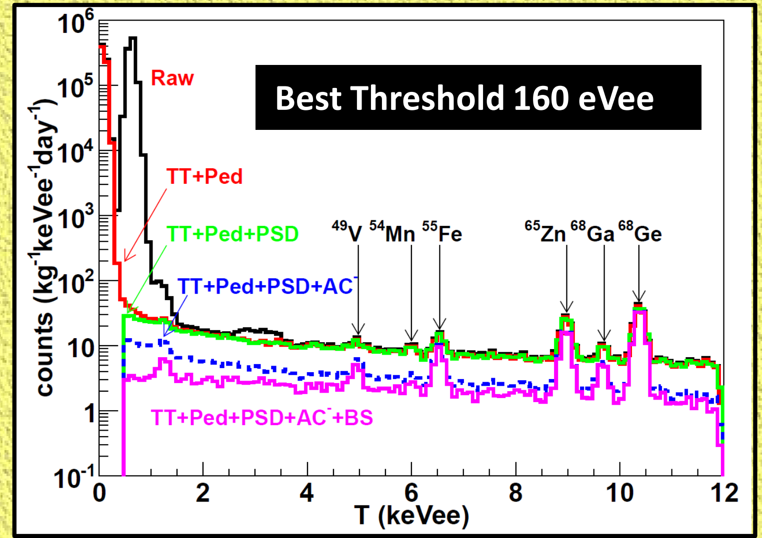
CDEX-10

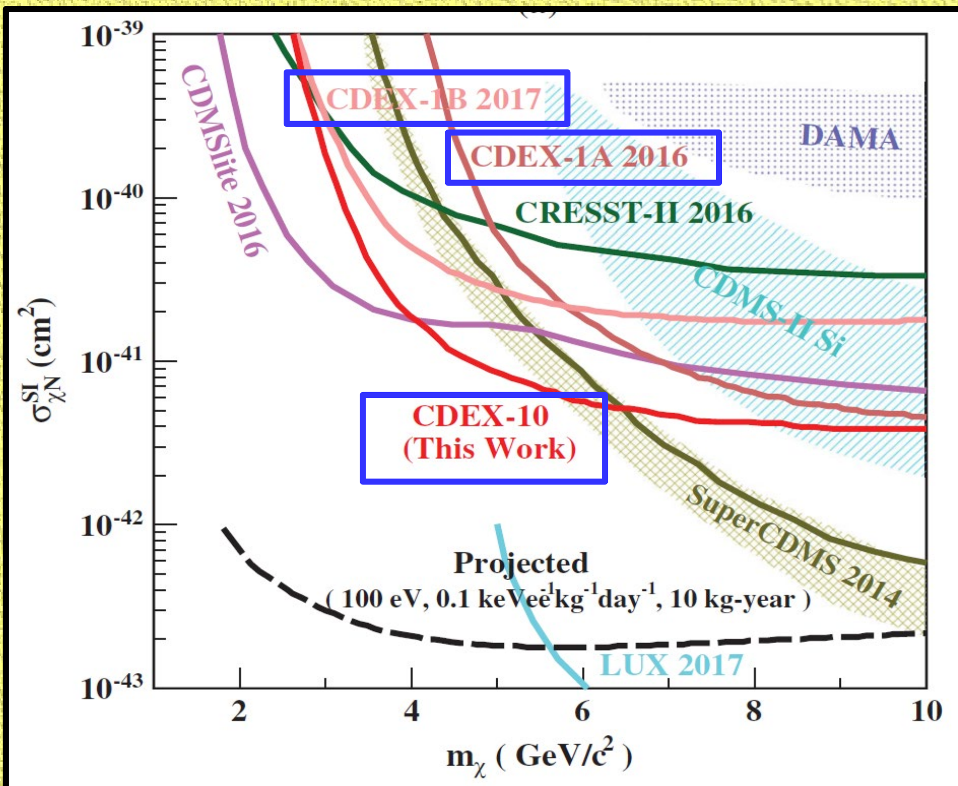




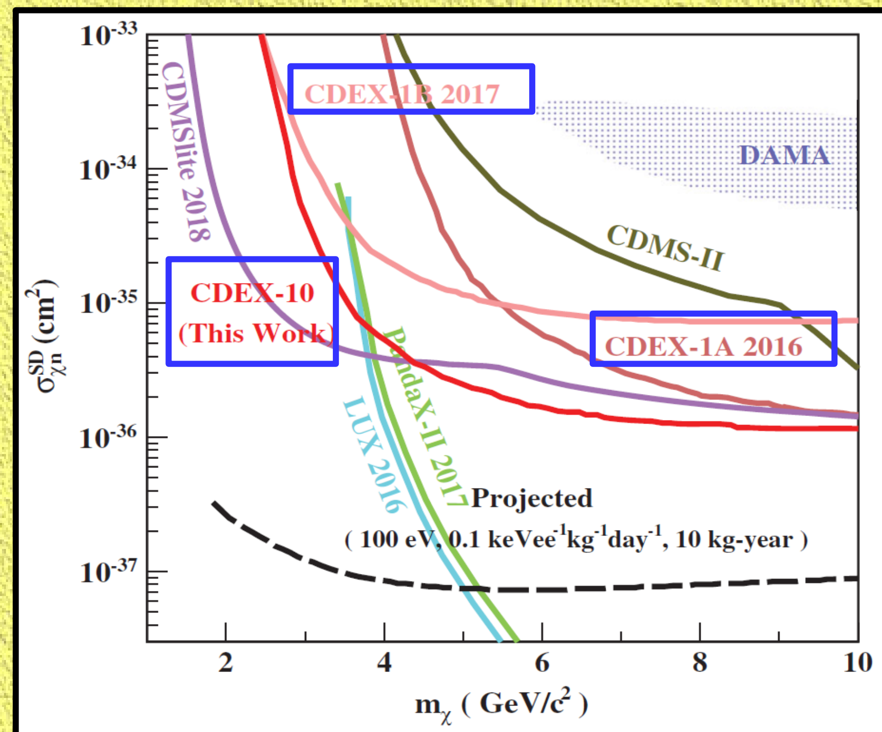
- ☑ **As Ge-Array -- important stage towards large-scale Ge experiment**
- ☑ **Novel -- Directly immersed into liquid nitrogen for cooling;**

CDEX-1(10) Results on $\sigma_{\chi N}$ SI/SD *[PRD14,PRD16,CPC18,PRL18]*





Spin-Independent χN

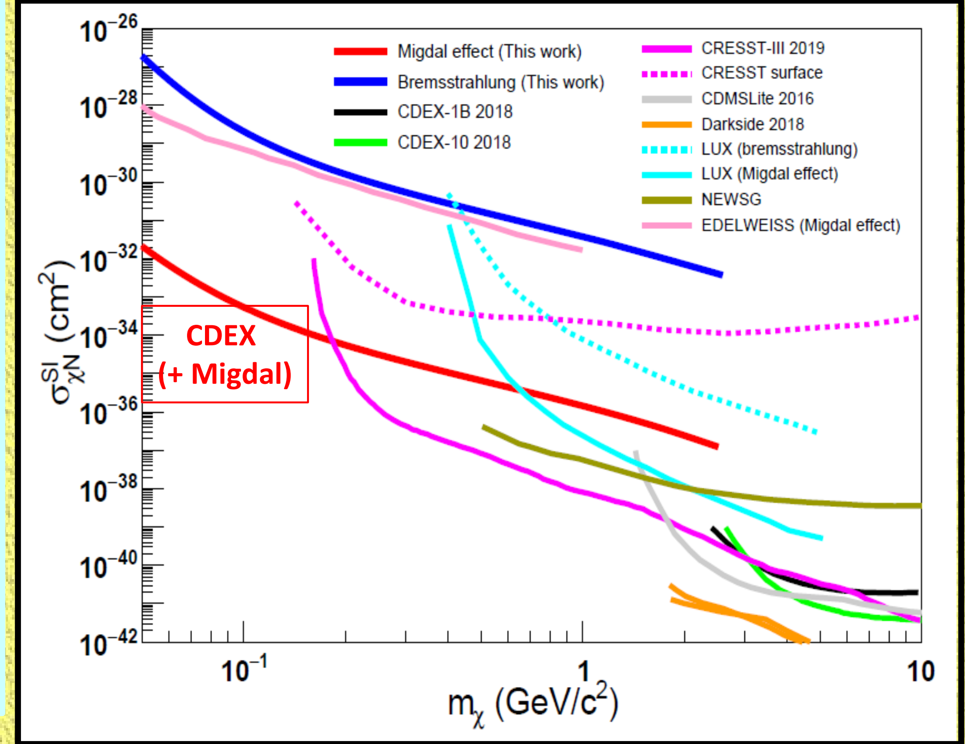


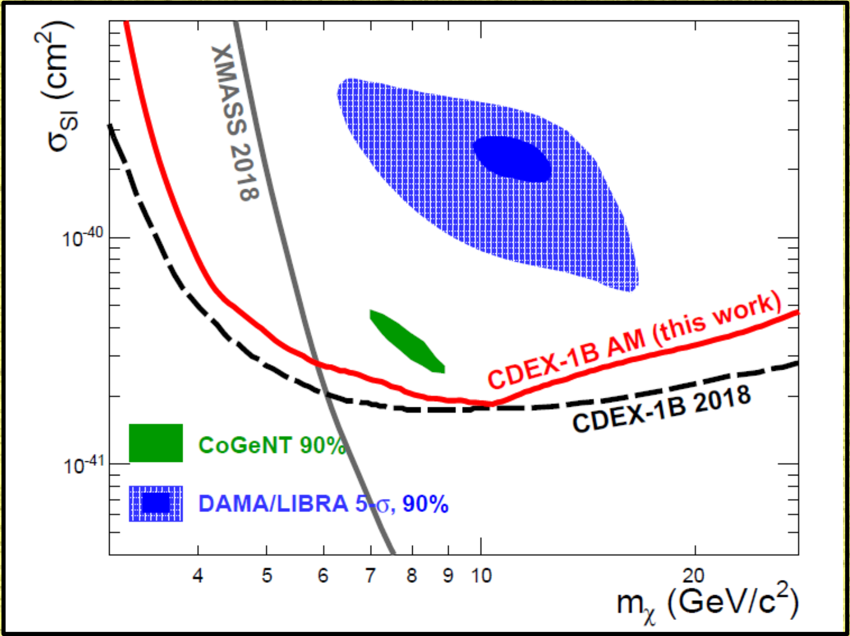
Spin-Dependent χN

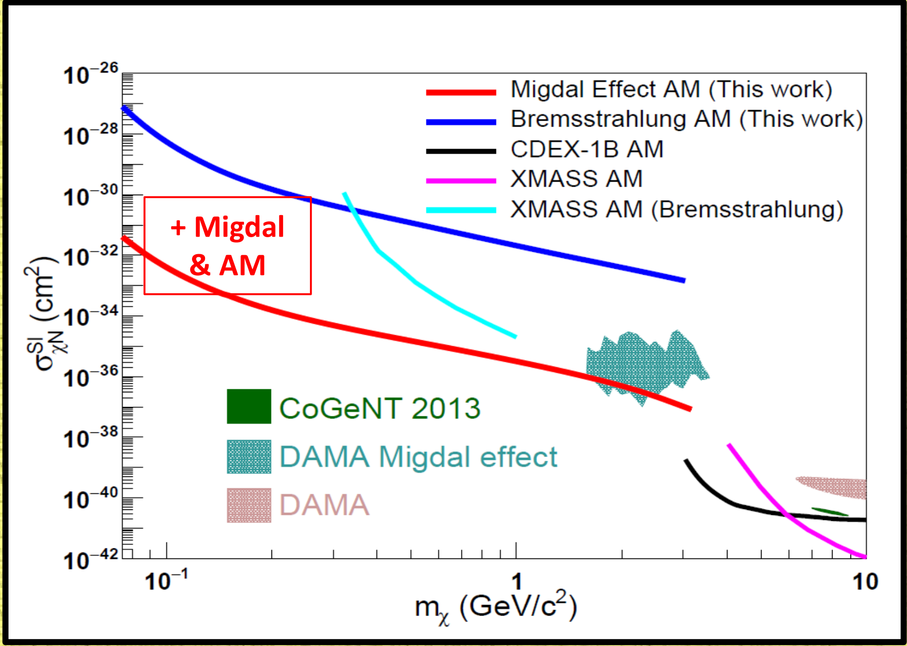
CDEX-1 Results *[arXiv1905 x2]*

$\sigma_{\chi N}$ SI *[+ Migdal & AM]*

- **Time-Integrated Analysis with Migdal: 737.1 kg-d ; 160 eVee threshold**
- **AM Analysis: 1107.5 kg-d ; 250 eVee threshold.**
- **Lead sensitivity in m_{DM}~50-180 MeV**



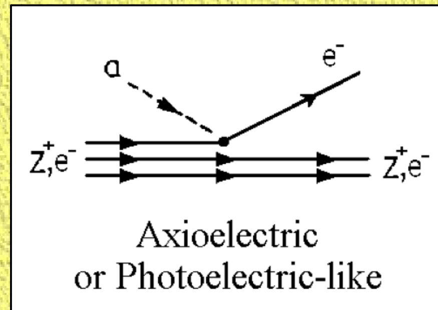


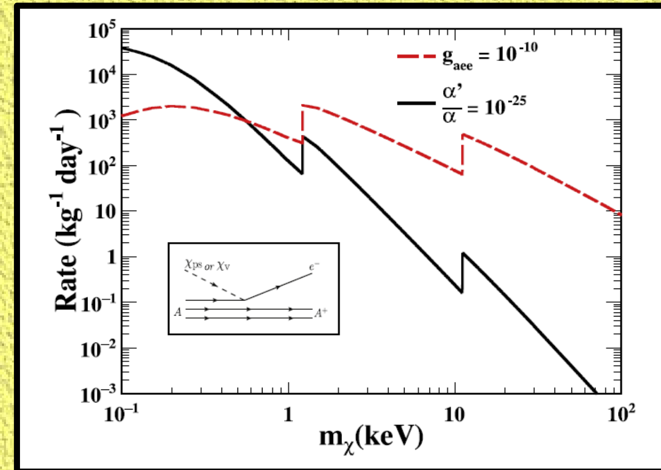


Axion-Like-Particles (ALP) & Bosonic Vector DM *[PRD17 ; CJP19]*

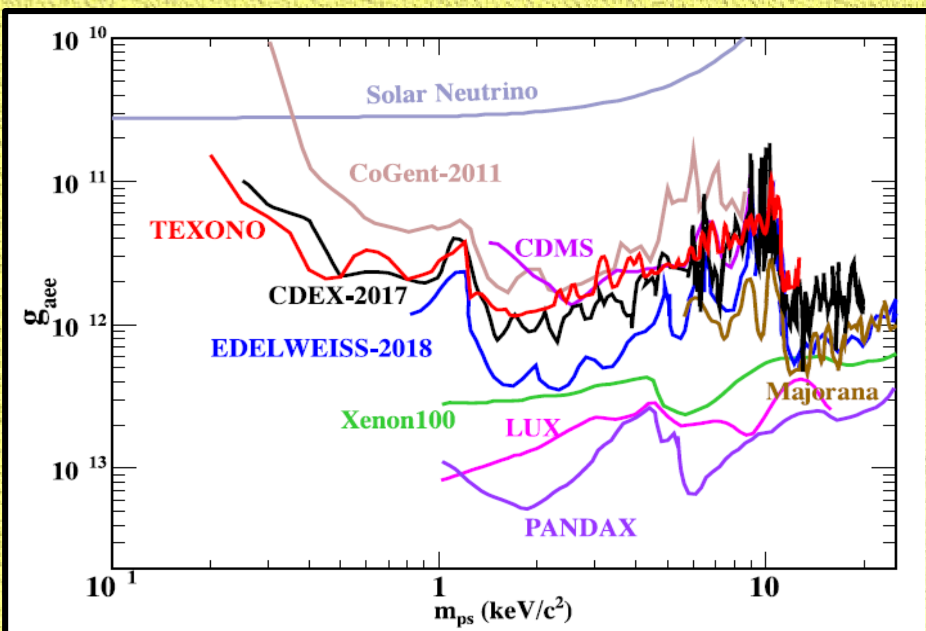
axioelectric effect

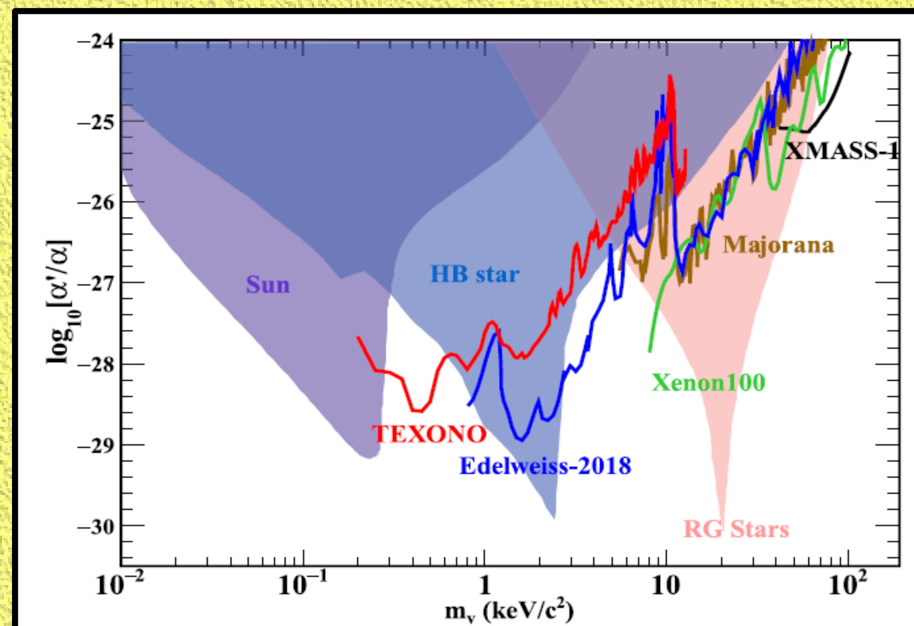
$\alpha + A \rightarrow A^{+} + e^{-}$





Leading sensitivities in sub-keV mass

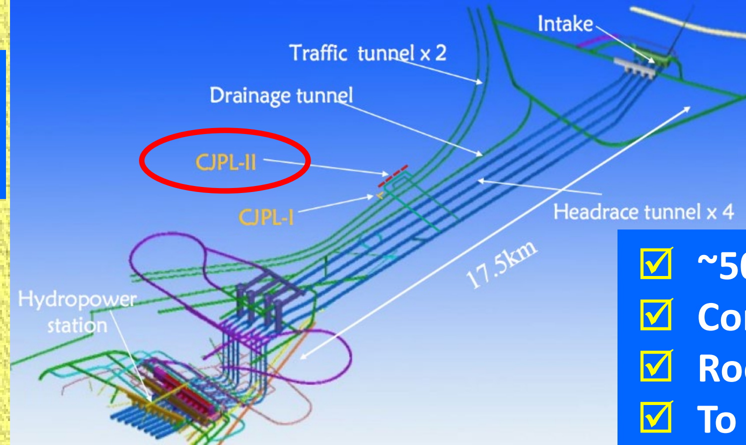




Dark Matter ALP-Electron Coupling

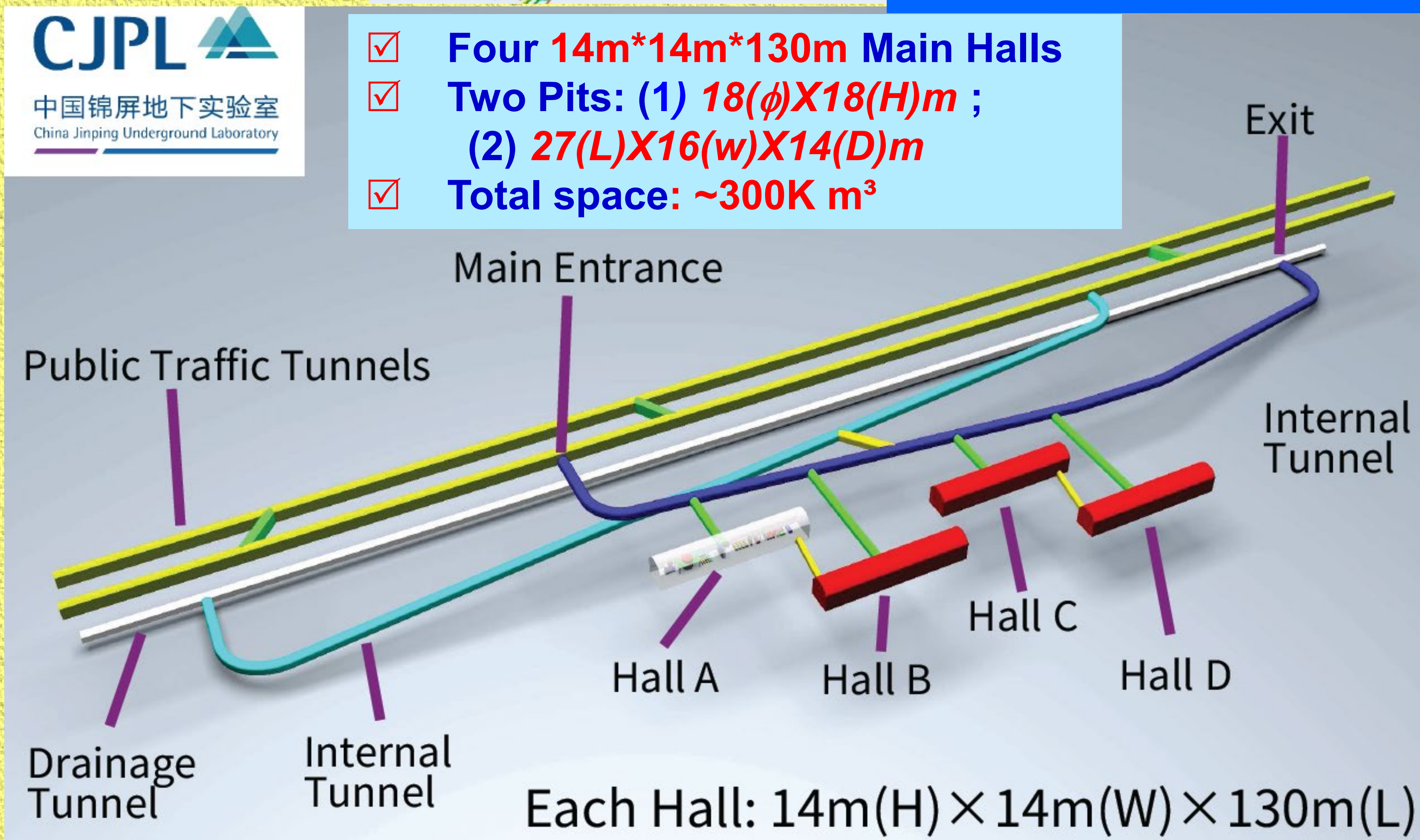
Bosonic Vector Dark Matter Electromagnetic Coupling

CJPL-II



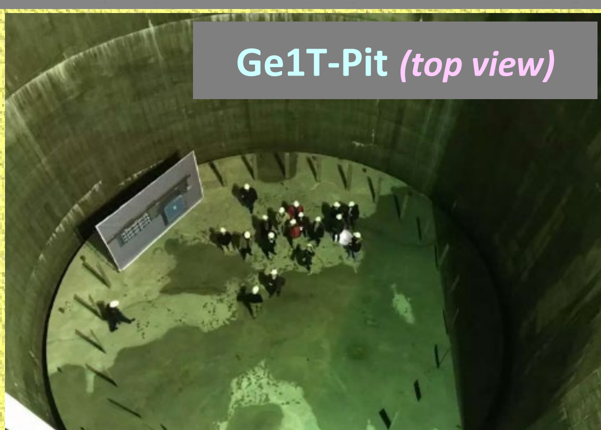
- ☑ ~500m west to CJPL-I
- ☑ Construction started 2014
- ☑ Rock Excavation completed May 2016
- ☑ To be Commissioned *Soon…*

- ☑ Four 14m*14m*130m Main Halls
- ☑ Two Pits: (1) *18(ϕ)X18(H)m* ;
  (2) *27(L)X16(w)X14(D)m*
- ☑ Total space: ~300K m³



Future Prospects @ CJPL-II: CDEX-Ge1T ($0\nu\beta\beta$+DM) Project

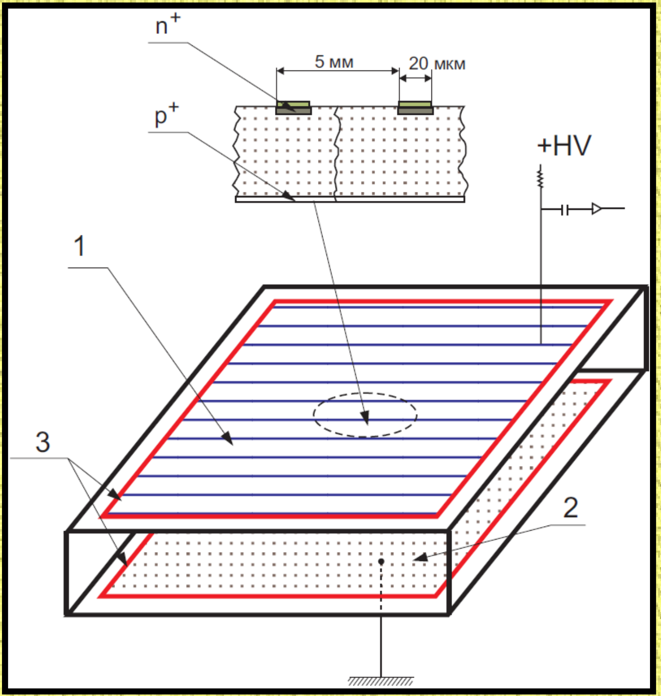
- **LEGEND-1T is a natural and excellent candidate for Ge1T@CJPL2**



R&D on Ge-Ionization with Charge Amplification

GEMADARC
Germanium Materials and Detectors Advancement Research Consortium

- ☑ **Partnership within NSF-PIRE-GEMADARC**
- ☑ **Ge-IA, following concept paper of *[Starostin & Beda 2000]* on Ge planar strip detectors, extend to point-contact design.**
- ☑ **Expect Charge multiplication @ 10^5 V/m E-field**
- ☑ **Potentials: O(10 eVee) threshold, with Ge-Ionization, LN2 operation, fast ~μs signals**
- ☑ **Applications: νA_{el} & other ν-physics at reactor, dark matter searches**
- ☑ **Groups: *USD (US), AS (Taiwan), THU (China), BHU (India) ….***
- ☑ **Opportunity for Future CJPL-CDEX-DM**



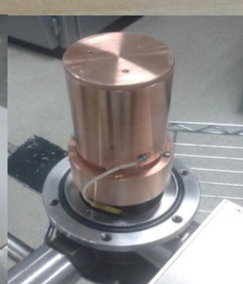
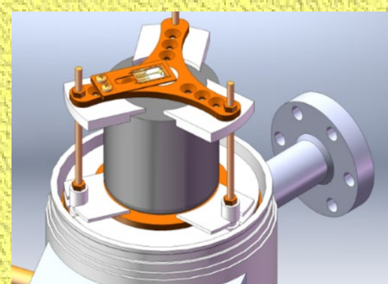
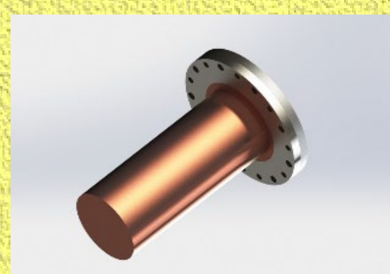
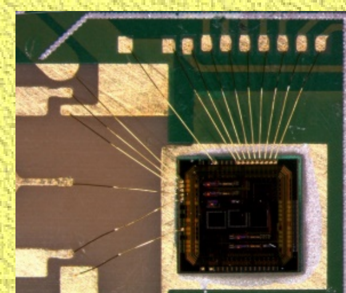
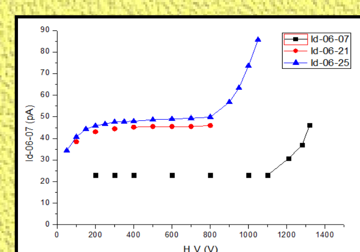
Starostin & Beda 2000

- **Avalanche with V=4000 V ; E~105 V/m at O(10 mm)**

Mastering Key Technologies towards Ge-1T

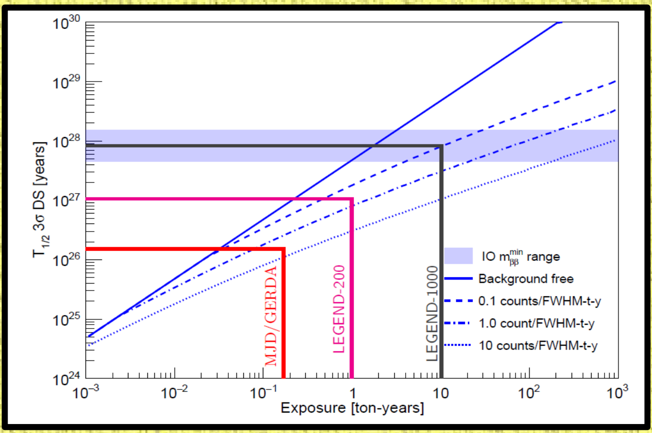
- ☑ Ge purification and crystal growth;
- ☑ HPGe detector fabrication;
- ☑ Ultra-low background VFE and FADC;
- ☑ Ultra-pure Cu for structure and cables;
- ☑ Large-volume cooling tank "cryostat"




LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Sensitivity for 3σ signal discovery

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

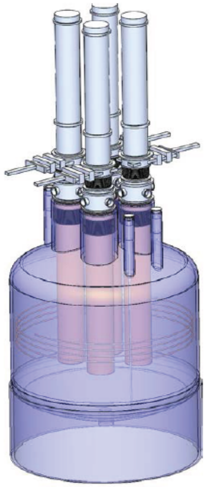
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

- up to 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:

- staged 1000 kg
- timeline connected to U.S. DOE down select process
- BG: goal 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation



☑ **Towards Ton-scale enriched-Ge76 experiment for neutrinoless double beta decay experiment to cover the "Inverted Hierarchy"**

☑ **Main Cast : mainly GERDA, Majorana, CDEX groups**

CDEX groups – exploring scenarios of hosting L1T at CJPL-II

Recall Lessons from History

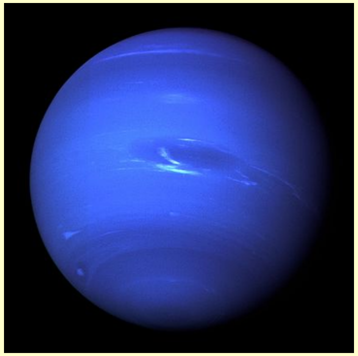
- Anomalies in *"Precision Measurements"* in Planetary Orbits Vs Newton's *"Standard Model"* Theory of Gravitation in the 19th Century

☑ **Irregularities of Uranus's Orbit**

Solution *[Alphabet]*

⇨ Prediction *[1845, Verrier, Adams]* *AND THEN*

Observation *[1846, Galle ….]* of Neptune



☑ **Anomalous Perihelion Precession of Mercury** *[1859, Verrier]*

Solution *[Grammar]*

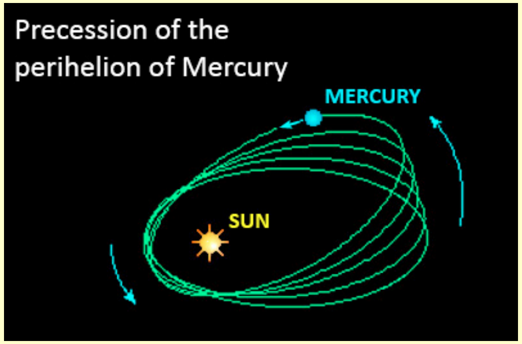
⇨ General Relativity *[1915, Einstein]*

Vs "Vulcan (Hypothetical Inner Planet) Theory" [~1860, Verrier]

and ……

World-Wide Searches … +

Multi Observation Claims & Refutations [1859-1908]



[Natural & Human !!!]

Prospects & Outlook

- Missing Energy Density [$\Omega_{SM} < \Omega_{Total}$] Problem is compelling. Solution…s are natural (best-efforts/intentioms) extensions of our tools. Surprising development likely … Stay Tuned & Get Prepared.
- Intense (+ *intellectually captivating & engaging*) world-wide activities on Dark Matter searches.
- CDEX program @ CJPL have contributed to light WIMP & axion searches + sub-keV Ge technologies
- CJPL @ China [+ expanding communities] add to the world's arsenal of low-background facility ; Gathering momentum for a future Ge1T project for $0\nu\beta\beta$ (+DM)