A BRIEF REVIEW ON UNDERGROUND EXPERIMENTAL PROJECTS UTILIZING ULTRA-LOW BACKGROUND TECHNIQUES

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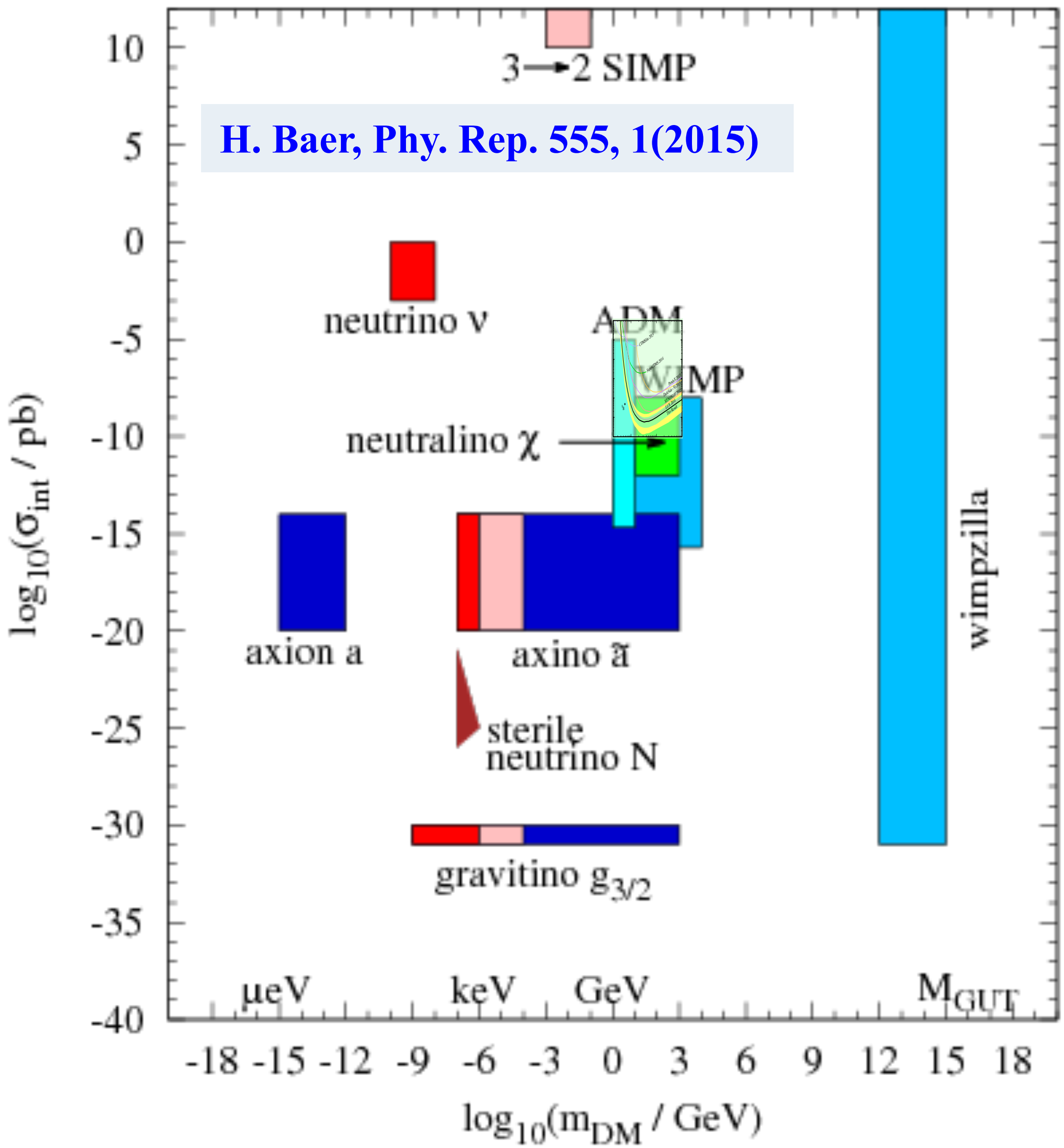
Contents

There are abundant candidates for DM



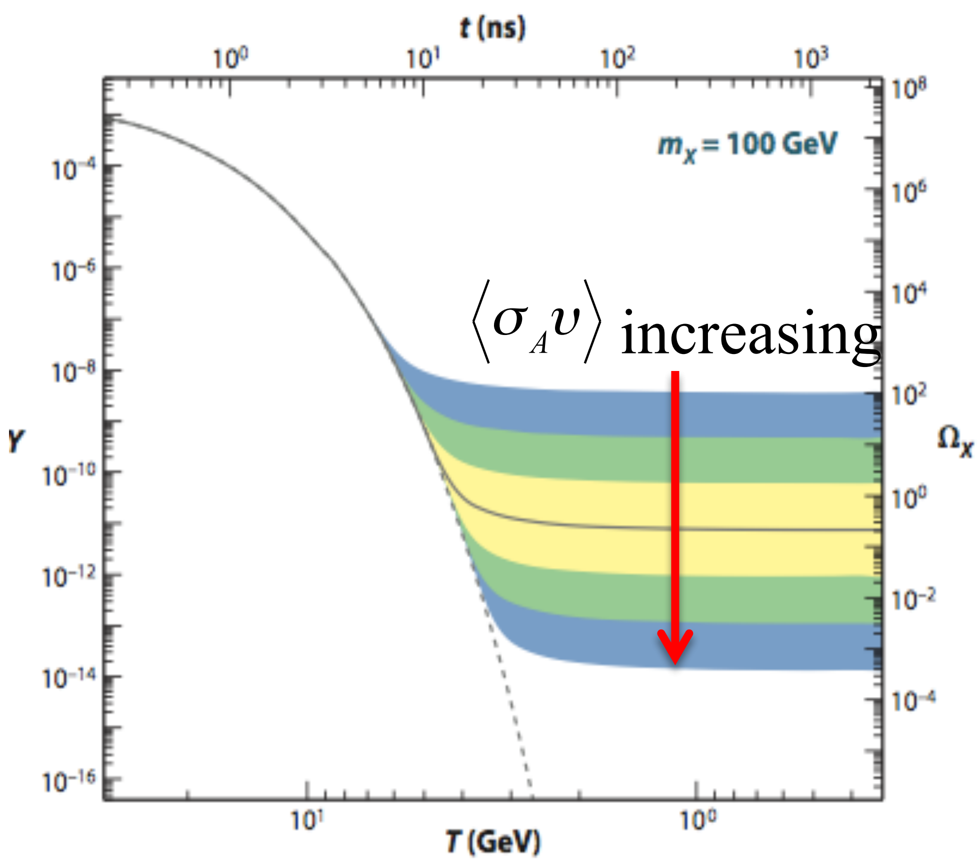
DM should be ;

1. Neutral
2. Stable or lifetime much longer than the Universe.
3. Massive enough for structure formation

Many candidates in many orders of magnitude of mass.

"WIMPs"

- The WIMP miracle is the fact that weak scale particles make good dark matter.
- It is at the heart of many expectations for connections between particle physics and cosmology and is the driving motivation behind most dark matter searches.



In early Universe, WIMPs (χ) are in thermal equilibrium at temperature $T \geq m_\chi$.

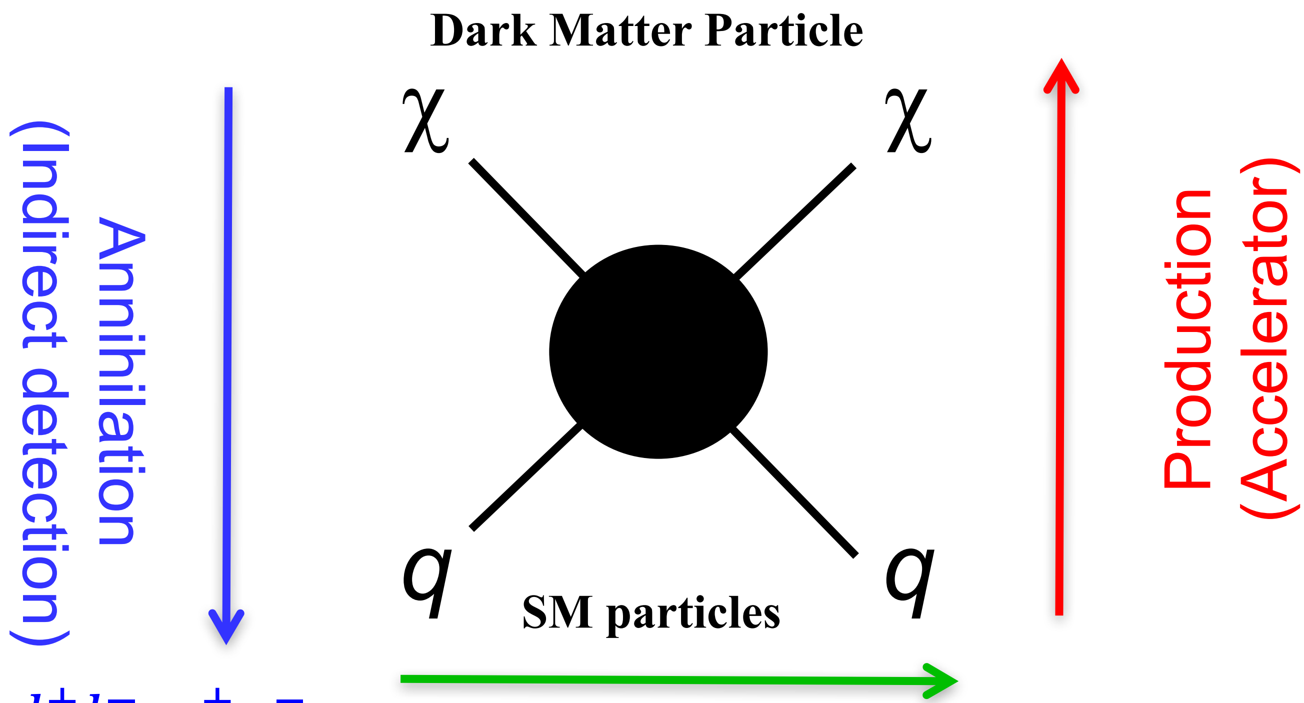
$$\Omega h^2 \approx \frac{3\times10^{-27} cm^3 s^{-1}}{\langle \sigma_{ann} v \rangle}$$

Estimation shows ;

$$\langle \sigma_{ann} v \rangle \sim 3\times10^{-26} cm^3 s^{-1}$$

General search methods for DM particles

DM particles can interact with SM particles, annihilate to SM particles, and can be produced in accelerator.



$$\chi\chi \rightarrow q\bar{q}, l^{+}l^{-}, \nu^{+}\nu^{-}$$
$$\rightarrow W^{+}W^{-},\ ZZ$$
$$\rightarrow \gamma\gamma, Z\gamma$$

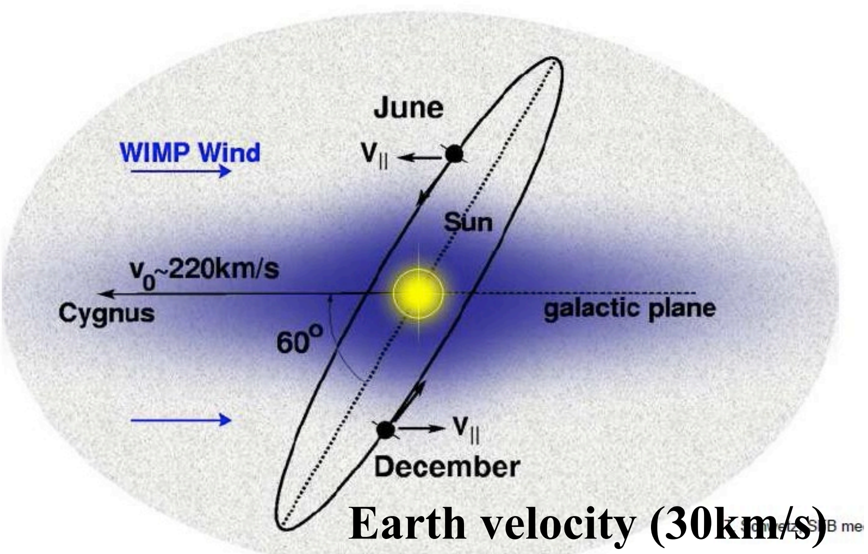
DM-SM Interaction
(Direct detection)

$$\chi + Nucleus \rightarrow \chi + Nucleus$$

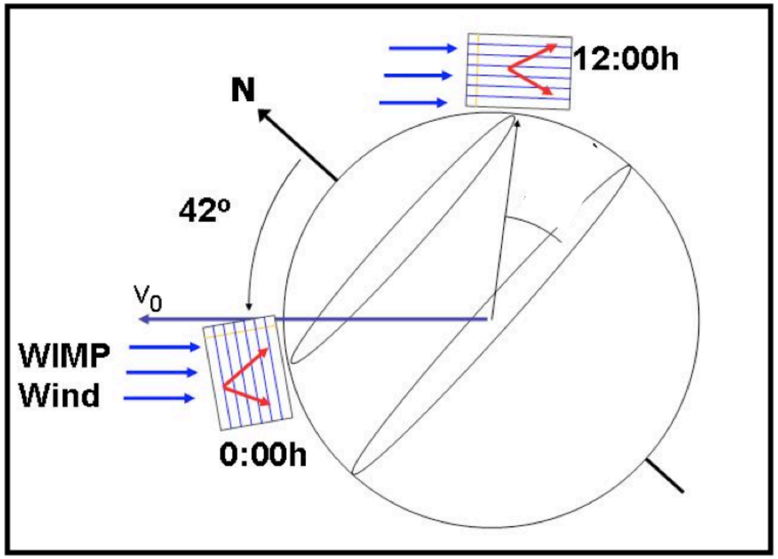
What is the direct detection signal for WIMPs ?

1. Recoil energy spectrum as expected at low energy.
2. Annual modulation.
3. Directional asymmetry.
4. A^2 dependence (Spin-independent)

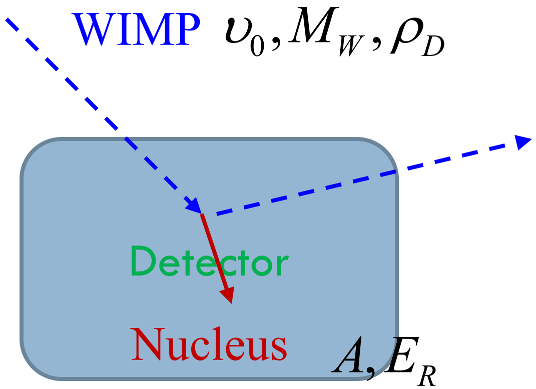
Yearly revolution → annual modulation



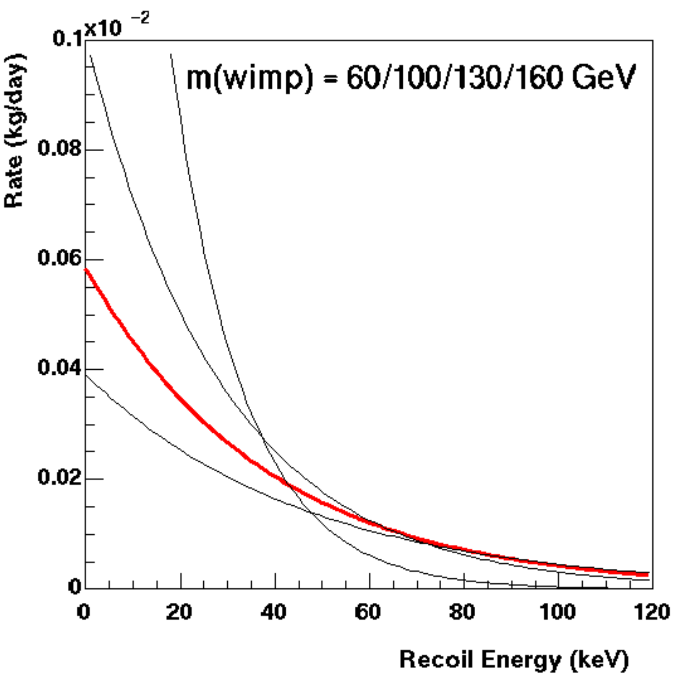
Daily rotation → direction change



Detection Principle of Direct Search



WIMP-Nucleus elastic scattering



Spin Independent(SD), Spin-Dependent(SI)

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} F^2(q)$$

$$R_0 = \frac{2\upsilon_0}{\sqrt{\pi}} \frac{N_0}{A} \frac{\rho_D}{M_W} \sigma_{WA}^{SI(SD)}$$

$$\sigma_{WA}^{SI} = \frac{\mu_A^2}{\mu_p^2} A^2 \sigma_{Wp}^{SI}, \quad \sigma_{WA}^{SD} = \frac{\mu_A^2}{\mu_p^2} \frac{4}{3} \frac{J+1}{J} \langle S_{n,p} \rangle^2 \sigma_{Wp}^{SI}$$

Experiment
Measure this

Nuclear Physics

SUSY models

- E_R < 100 keV

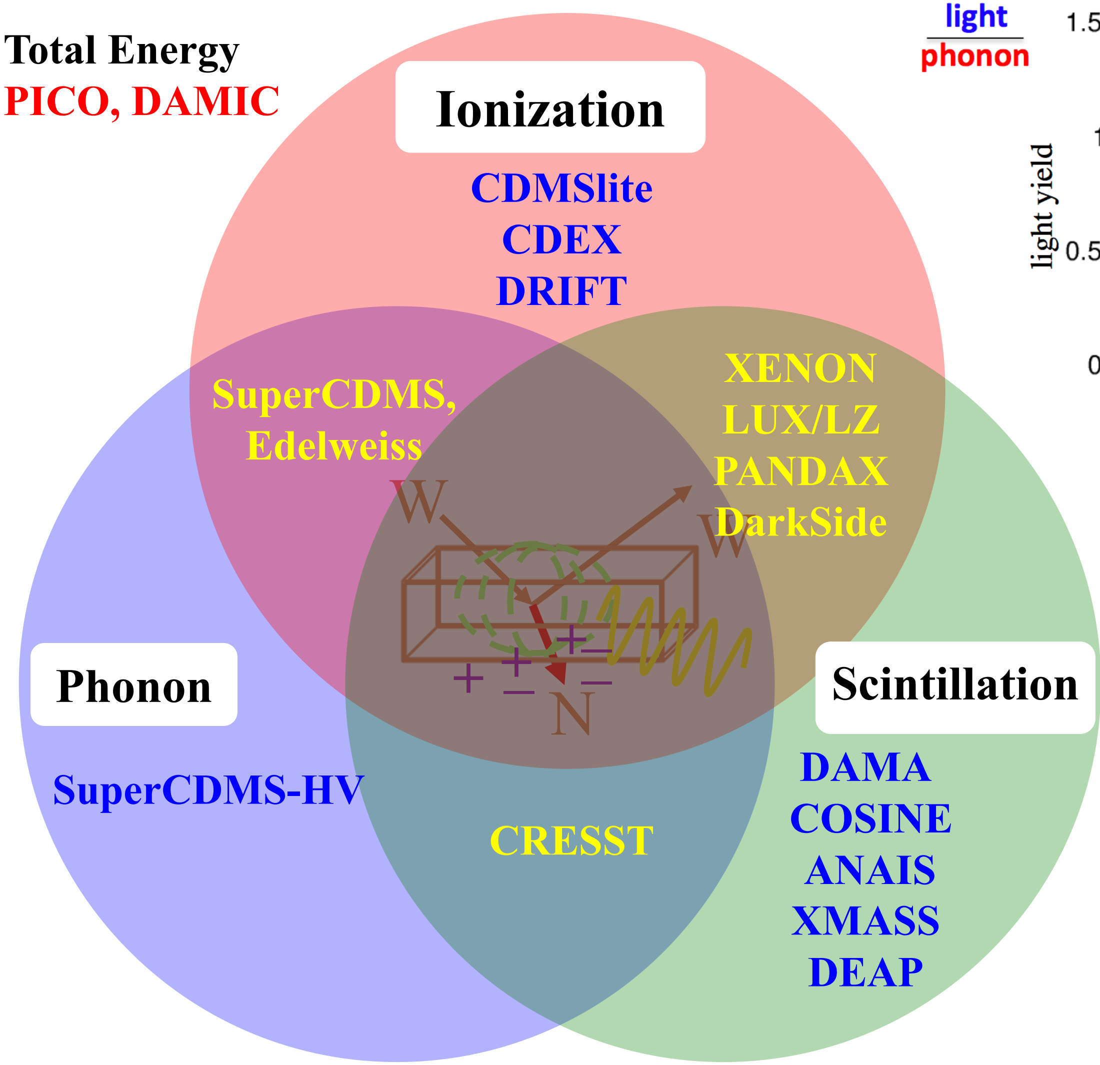
$\sigma(\tilde{\chi}_1^0 N \to \tilde{\chi}_1^0 N)$ <~ 10^{-10} pb

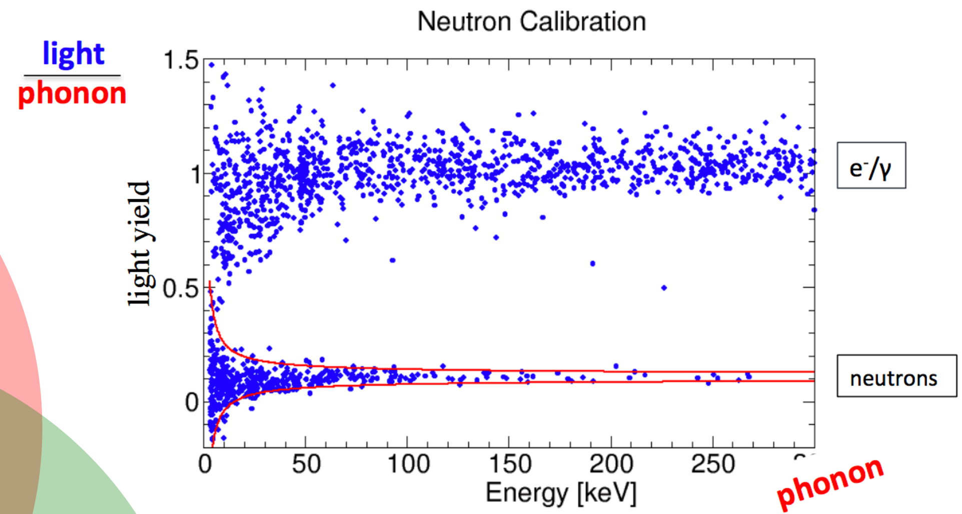
Expected event rate
<< 1/kg/day

Detector Techniques for direct detection

WIMP-Nucleus interaction can be separated by Dual Parameter Measurements.

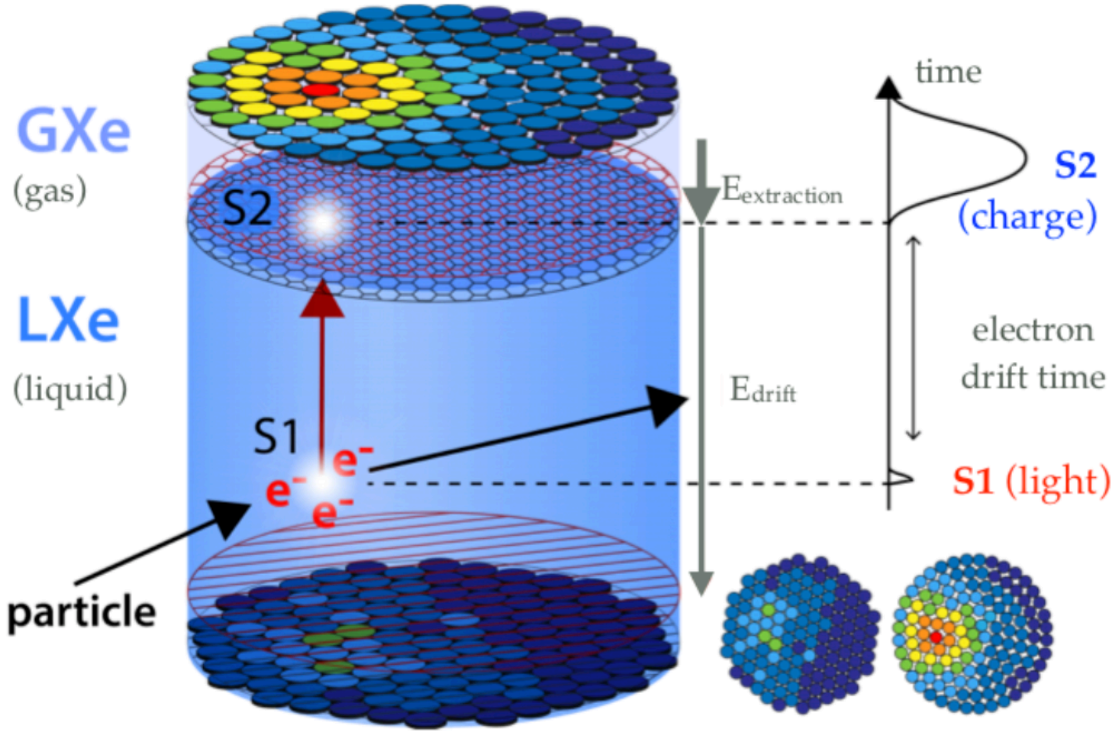
Total Energy
PICO, DAMIC

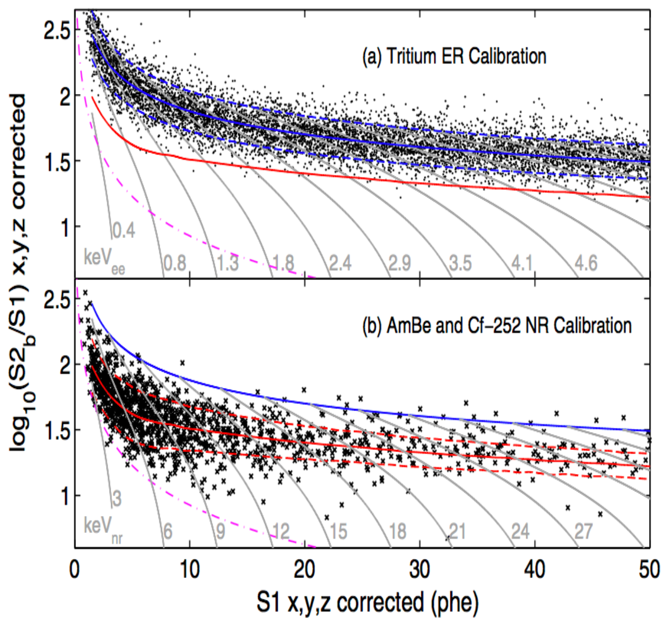




One example of Dual parameter detector, CRESST, Scintillation vs Phonon

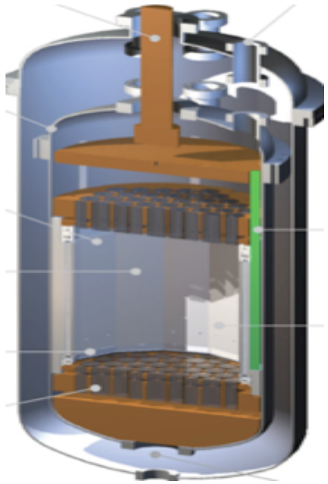
Dual phase Liquid TPC - Principle

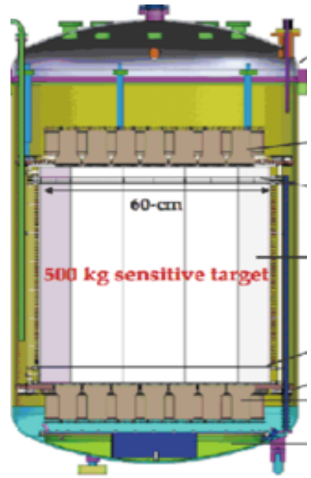


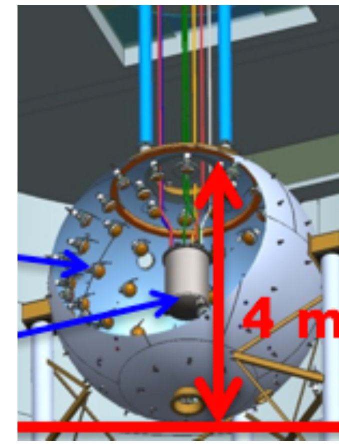


Real ionizing signal will generate scintillation signal (S1) followed by ionizing signal (S2). The ratio S1/S2 depends on the particle type, nuclear or electron recoil.
→ Powerful discrimination between WIMP signal and gamma backgrounds.

Current Running Exp

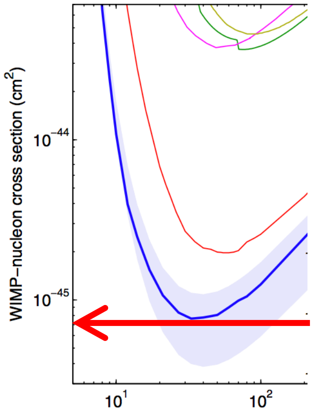




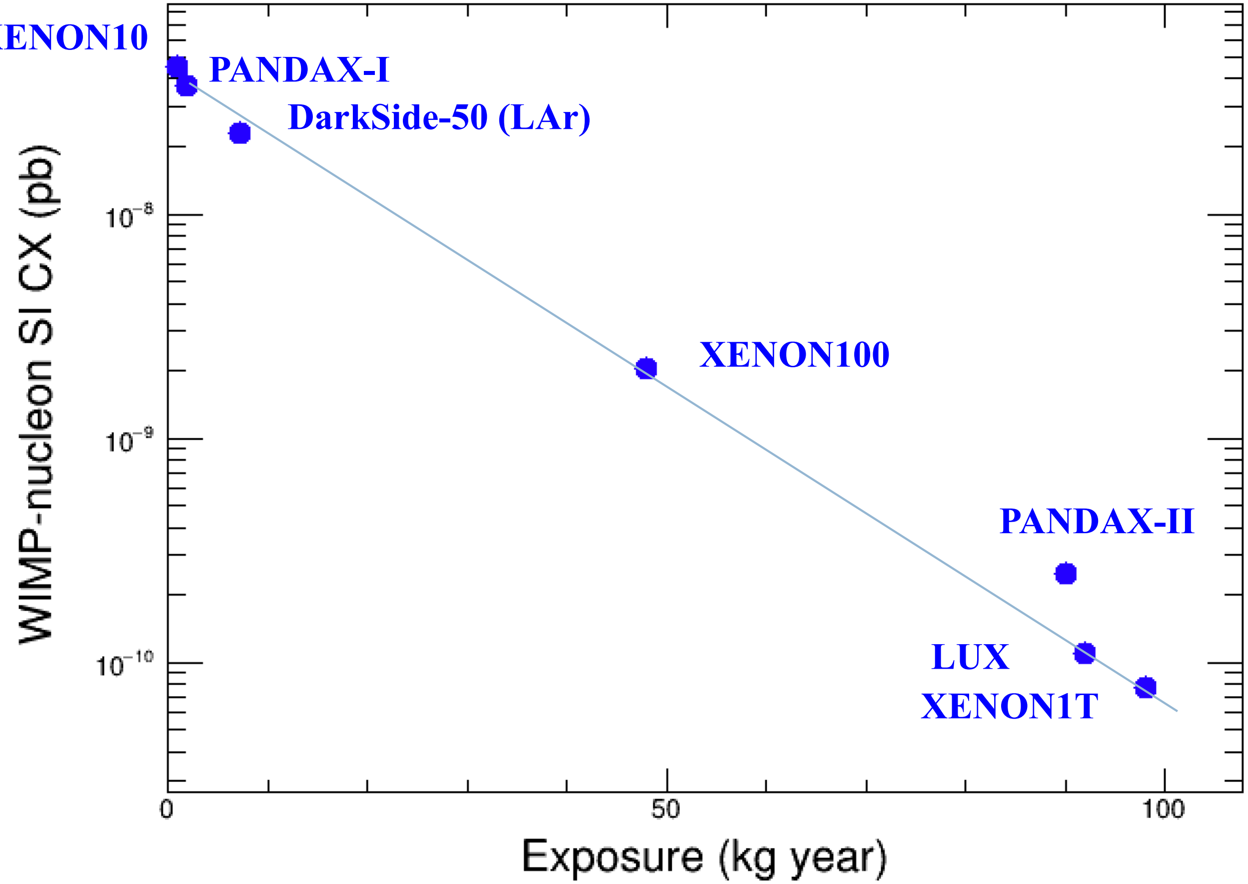


EXP	LUX	PANDAX-II	XENON1T	DarkSide-50
Mat.	LXe	LXe	LXe	LAr
Total (kg)	350	500	3200	50
Fiducial (kg)	104	329	1042	37
Exposure (kg year)	92	90	98	7.2
Pub. Year month	17 01	16 09	17 05	16 04
Limit (cm^2)	1.1×10^{-46}	2.5×10^{-46}	7.7×10^{-47}	2×10^{-44}

WIMP limits vs Exposure



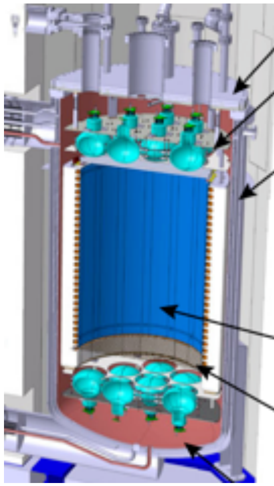
Y-axis : lowest cross section

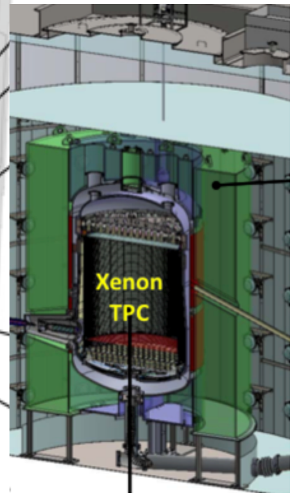


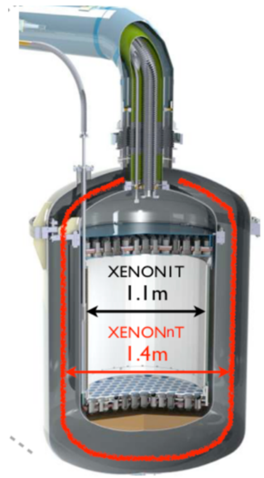
= Fiducial mass X Data Time

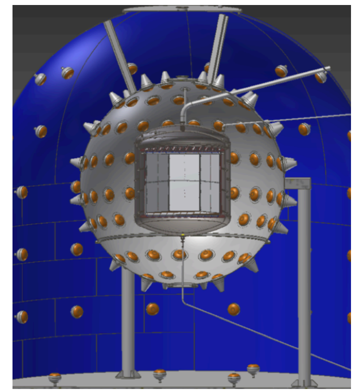
A good correlation between exposure and published lowest limits in WIMP-nucleon cross section. PANDAX-II data is a little off.
Detector performances are uniformly well maintained.
Currently, 100 kg year is the largest exposure !!

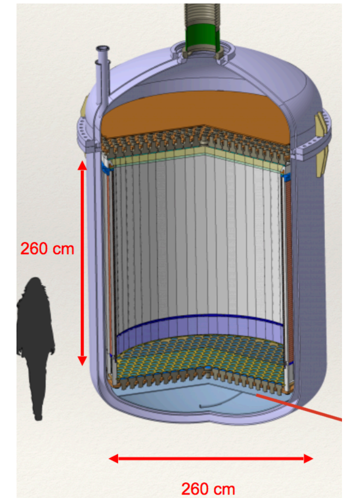
Future Liquid Detectors







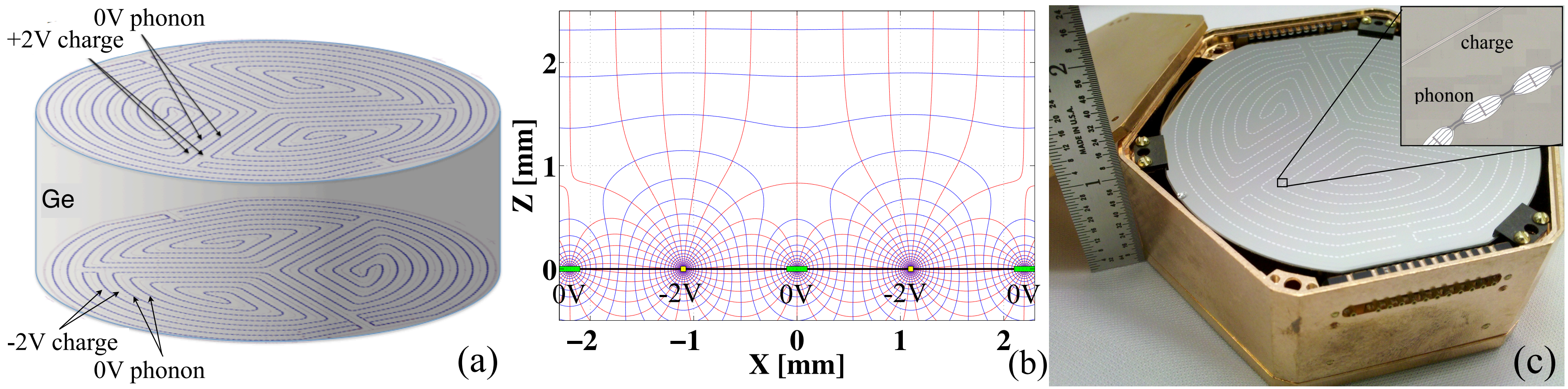




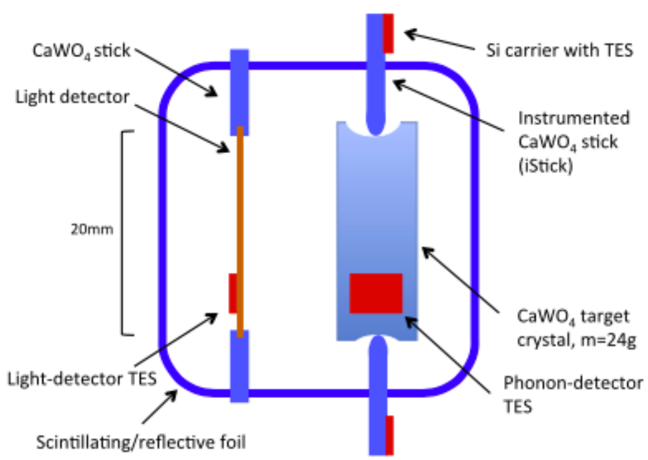
EXP	ArDM	LZ	XENONnT	DarkSide-20k	Darwin
Mat.	LAr	LXe	LXe	LAr	LXe
Total (ton)	850	10000	8000		50000
Fiducial (ton)		5600	5000	20000	30000
Limit (cm^2)		10^{-48}	10^{-48}	$7x10^{-49}$	10^{-49}

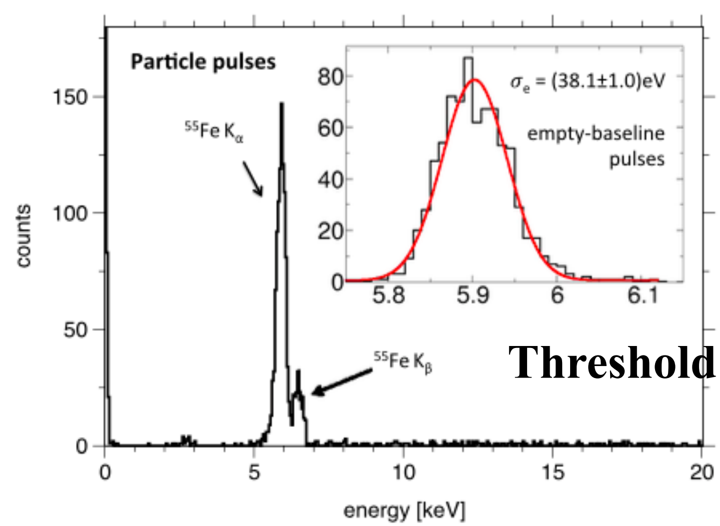
Cryogenic detectors for low mass WIMPs

SuperCDMS : Charge vs Phonons



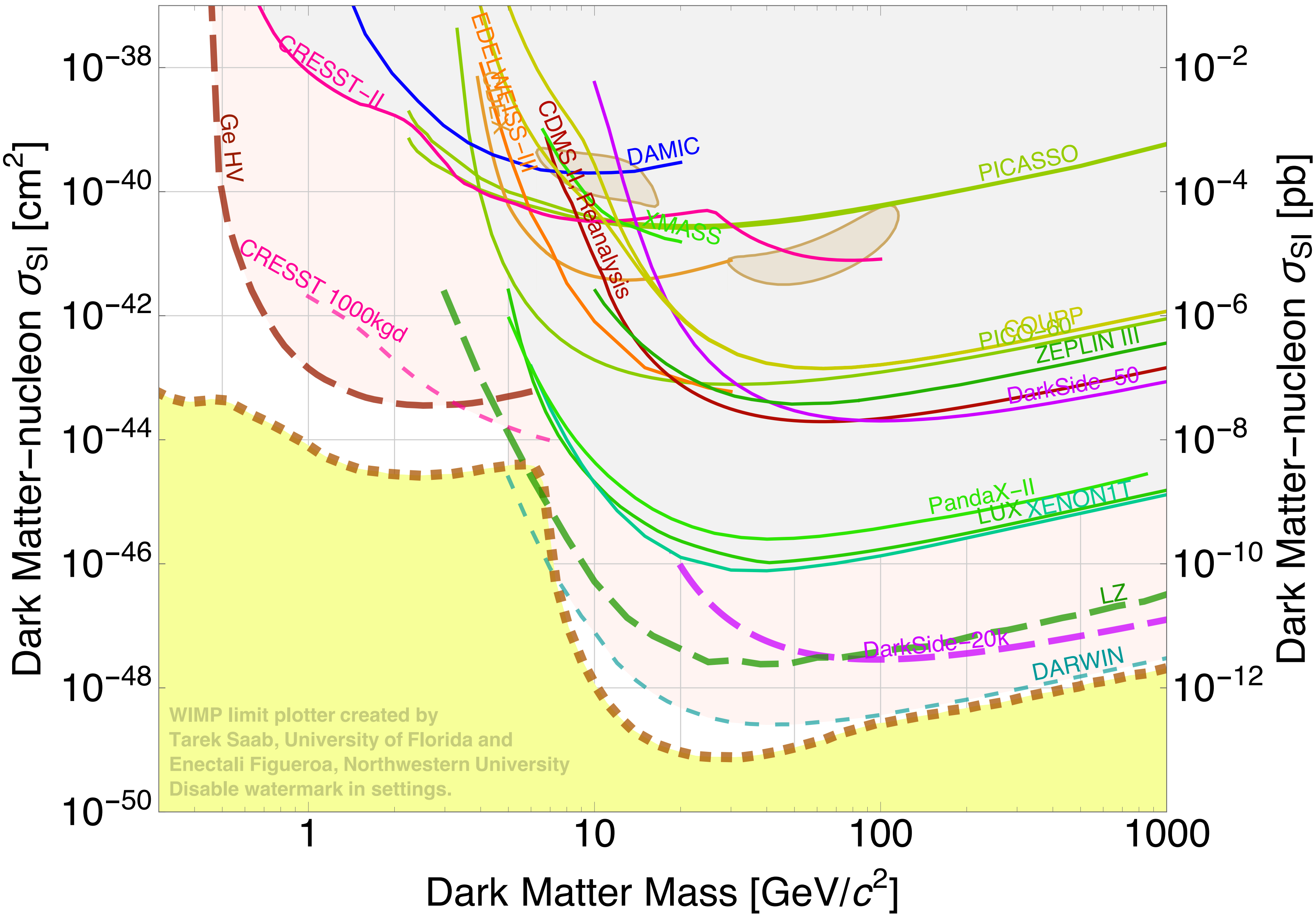
CRESST-III : Light vs Phonons





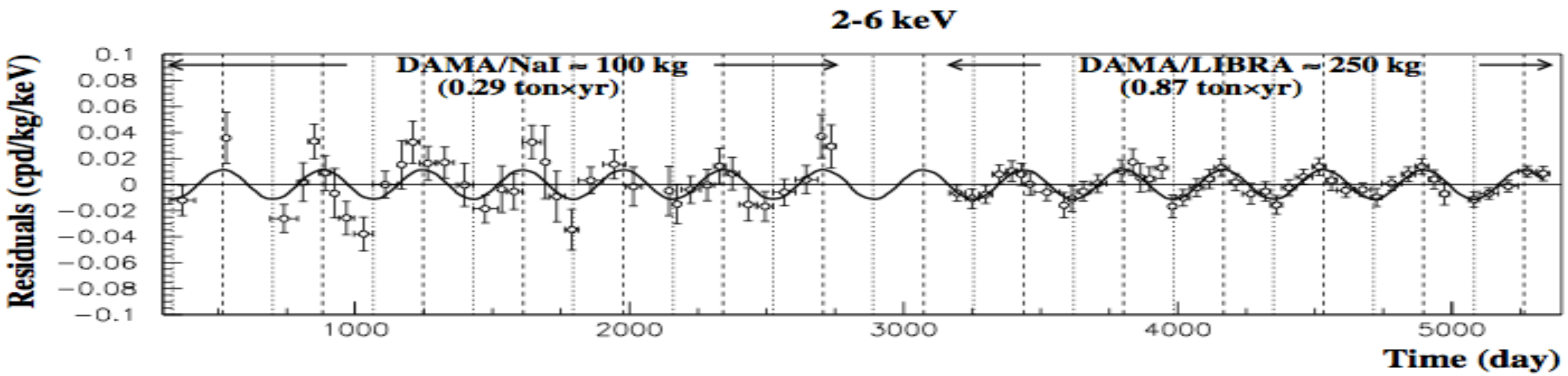
Threshold ~ 190eV

Current limits of Spin-independent



DAMA conundrum should be clarified !

- DAMA group reported modulation for 14 years consistently. → "DAMA anomaly"

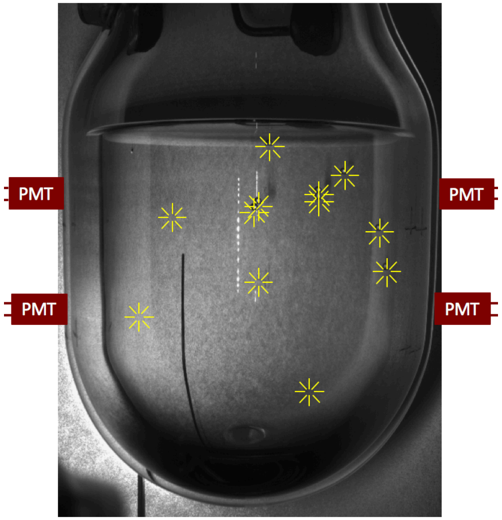


- **A lot of theoretical speculations …….**
- **Dual experiments are preferred always.**

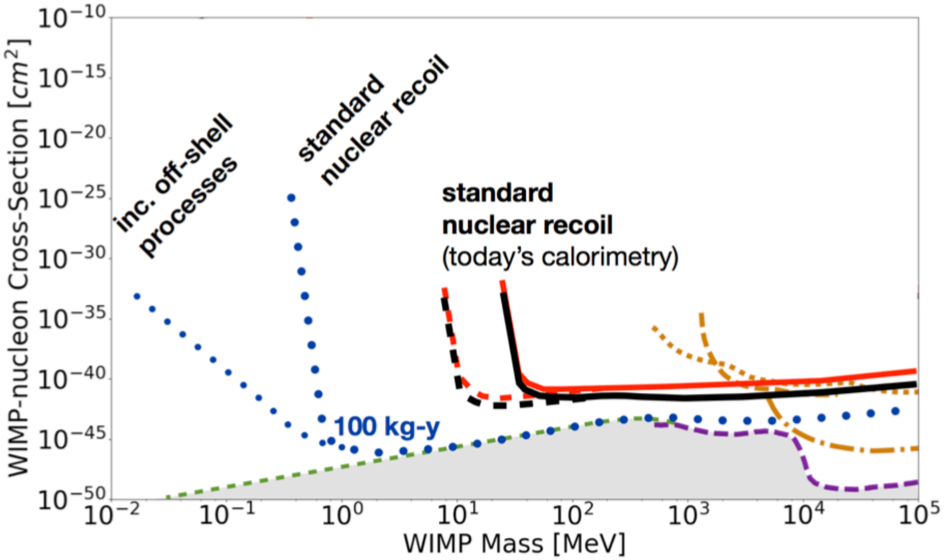
- **You will hear DAMA and COSINE talks tomorrow.**

New detectors, techniques for low mass WIMPs

Scintillating Bubble Chamber
-Use LXe instead of CF_3I



Superfluid He
w/ ultra-low threshold



A lot of parameter space is not explored yet, specially for
1 keV < m_X < 1 GeV.

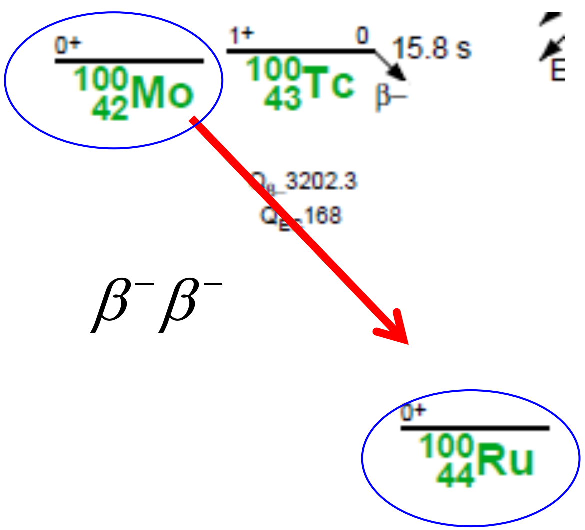
Neutrino Properties known & still to be determined.

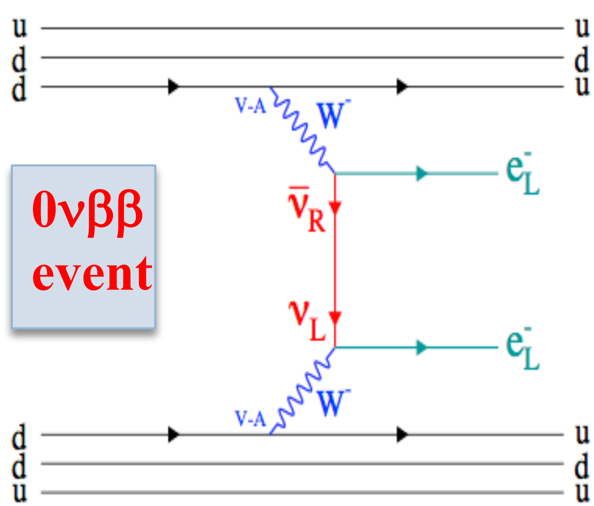
- Neutrinos are massive.
- Neutrinos are from Sun and Supernova
- Neutrinos are mixed and oscillates. All mixing angles and mass differences are measured.
- Mass Hierarchy ?
- CP violation in lepton sector ? → Leptogenesis
- Mass scale ?
- Majorana nature ? – See-Saw mechanism.
- Sterile Neutrinos ? → Dark Matter
- Cosmic Neutrino Backgrounds (CNB) ?

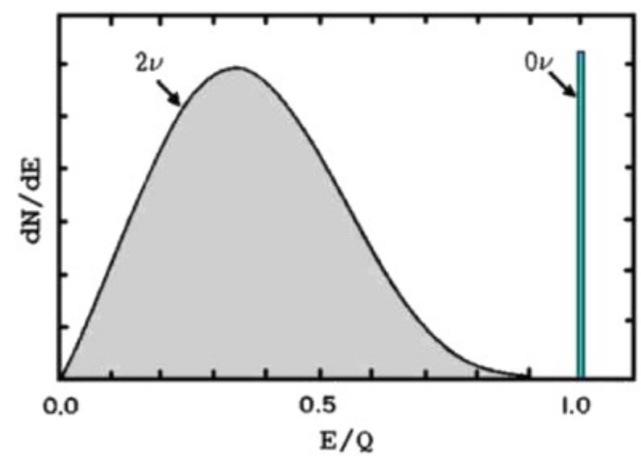
Search for Neutrinoless double beta decay (0νββ)

- **Observation of 0νββ will confirm**
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.
- **Observation of 0νββ will support more on**
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

$$m_\nu \approx \frac{m_D^2}{m_N}$$

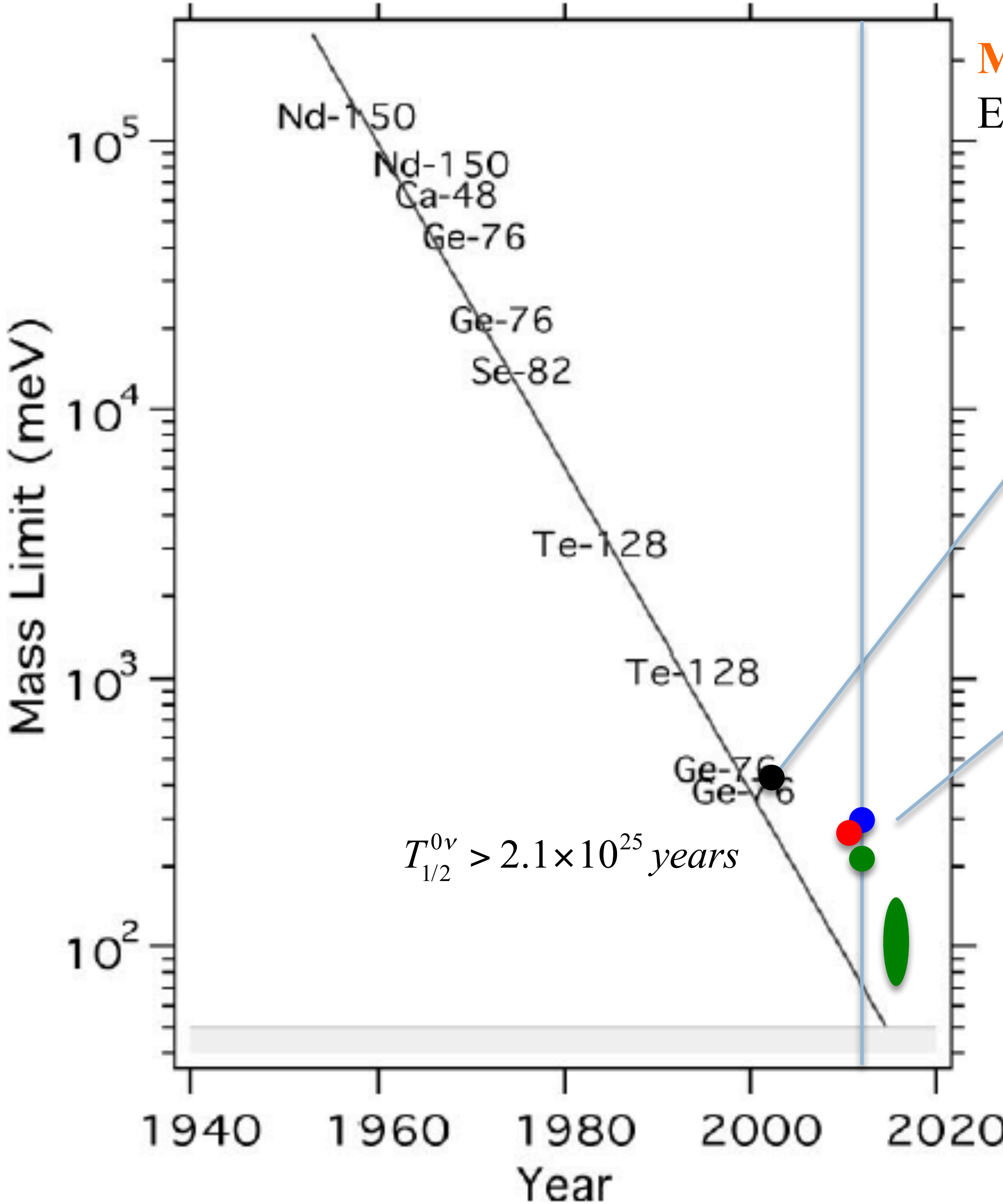


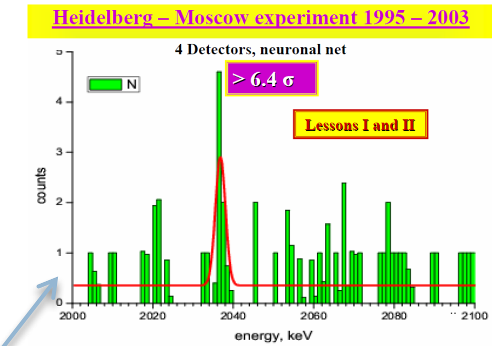


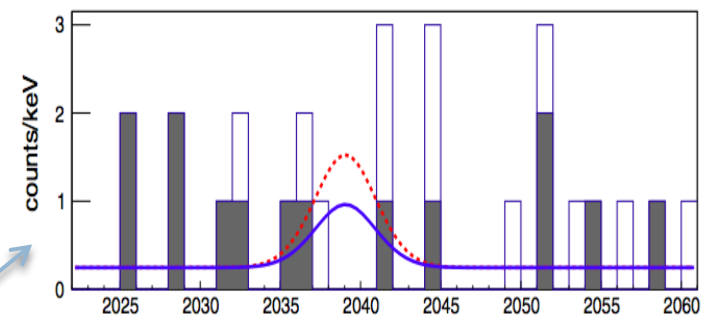


Moore's law for 0νββ ?

Elliott & Vogel, Ann, Phys. (2002)







^{76}Ge, Gerda (0.3) 2013.9

^{136}Xe, EXO (0.26) 2012.7

^{136}Xe, KAMLAND-ZEN, 2013.2

^{136}Xe, KAMLAND-ZEN, 2016.5 !!!

Neutrino mass from 0νββ experiment

- **Half-lifves of 0νββ depends on phase factor, matrix element and effective neutrino mass.**
- **Effective neutrino mass depends on mass hierachy.**

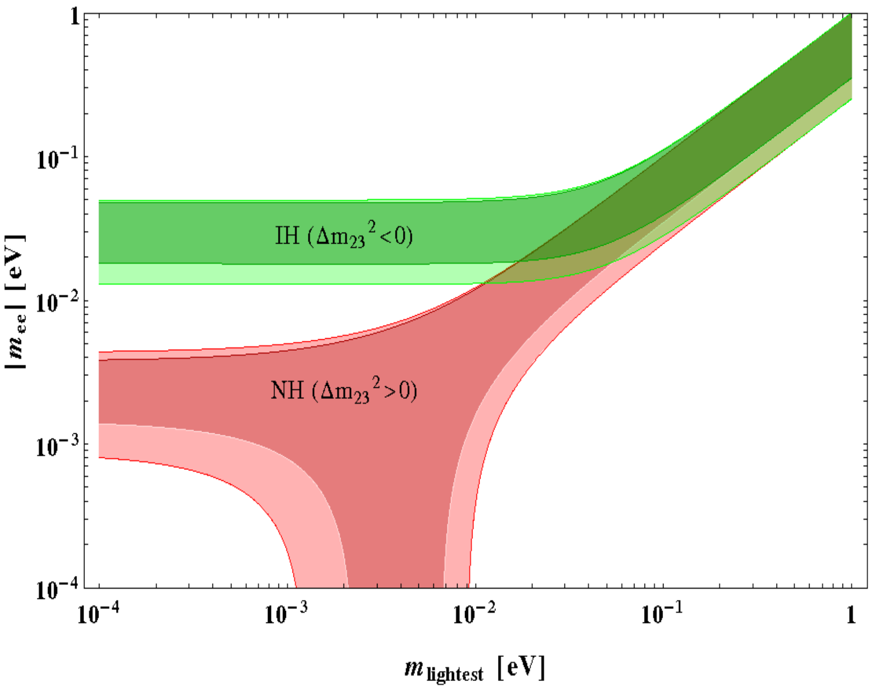
Phase factor

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life Measured **Nuclear Matrix Element** **Neutrino Mass**

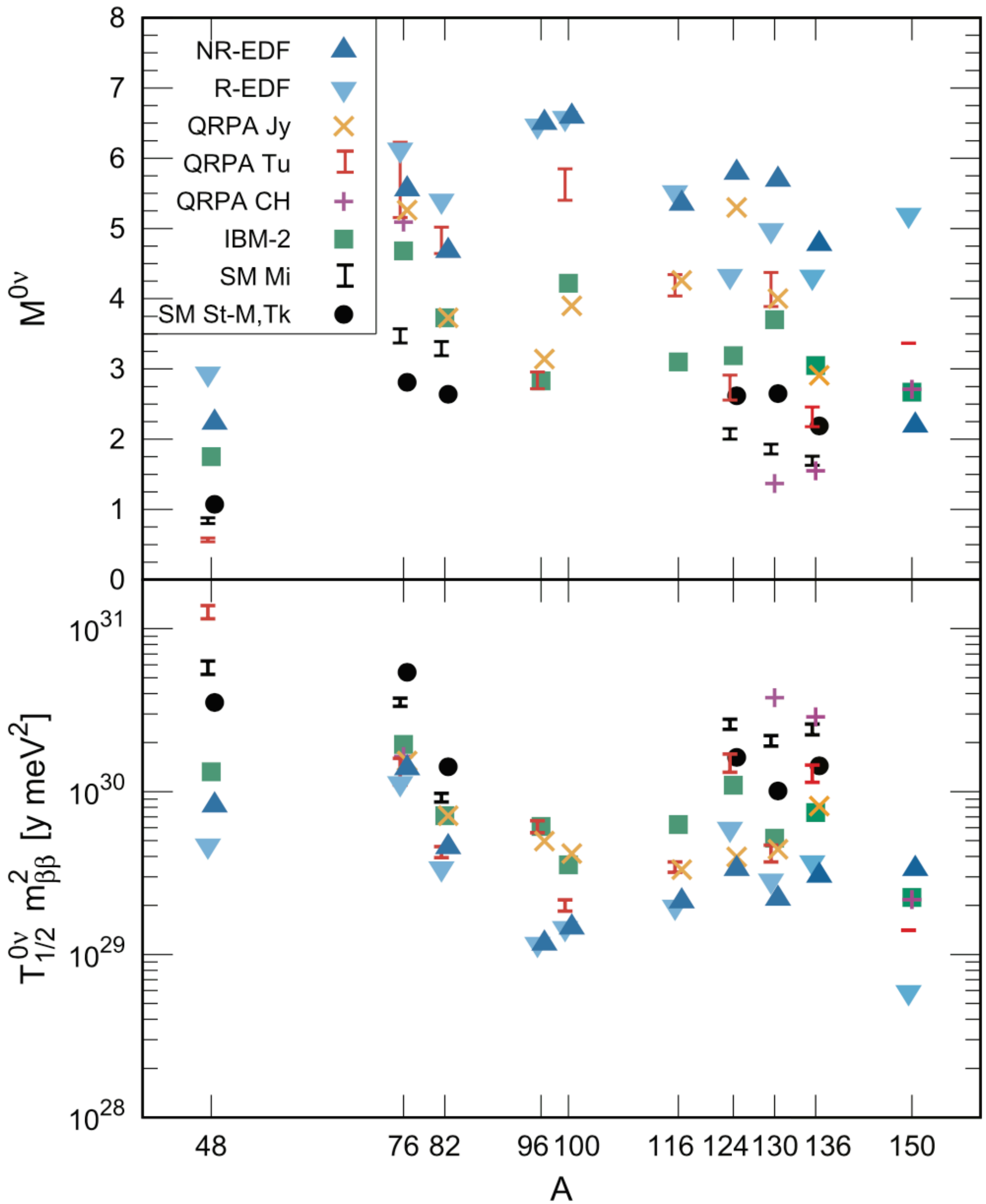
$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$$

$$T_{1/2}^{0\nu} \rightarrow m_{\beta\beta}$$



Matrix Elements

Engel, 2016



- An uncertainty of a factor of three in the matrix element corresponds to nearly an order of magnitude uncertainty in the amount of material required.
- The expected lifetime for neutrinoless DBD differs about factor up to 5 with average values of different models.

Current best results for 0νββ

2017. 1. 13

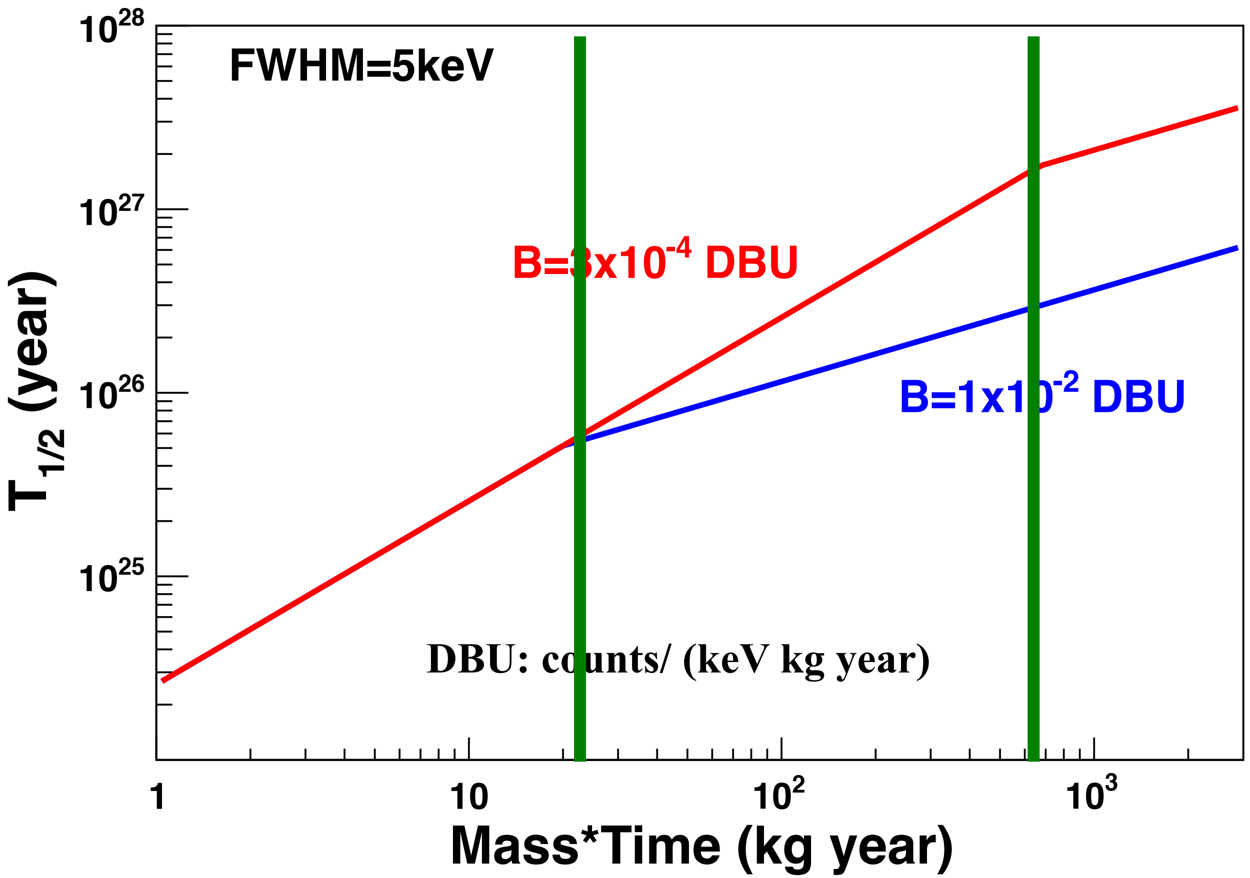
Mother	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T_{1/2}$ (10^{24} Y)	Ref.
^{48}Ca	4270.0	0.187	0.44	ELEGANT VI	> 0.058	
^{76}Ge	2039.1	7.8	15	GERDA-II	>21	DBD2016
^{82}Se	2997.9	9.2	0.92	NEMO-3	> 0.36	
^{100}Mo	3034.4	9.6	0.07	NEMO-3	>1.1	PRD89, 111101 (2014)
^{116}Cd	2813.4	7.6	0.29	Solotvina	> 0.17	
^{130}Te	2527.5	34.5	9.1	CUORE-0	> 4.0	PRL115, 102502 (2015)
^{136}Xe	2458.0	8.9	21	EXO-200 KamLAND-Zen	> 11 > 107	Nature 510, 229 (2014) PRL117, 082503 (2016)
^{150}Nd	3371.4	5.6	0.08	NEMO-3	> 0.018	

“zero” Backgrounds

- If “zero” backgrounds in ROI(Region of Interests), the half-life limits are proportional to the detector mass and DAQ time. If finite backgronds, sqrt (MT).

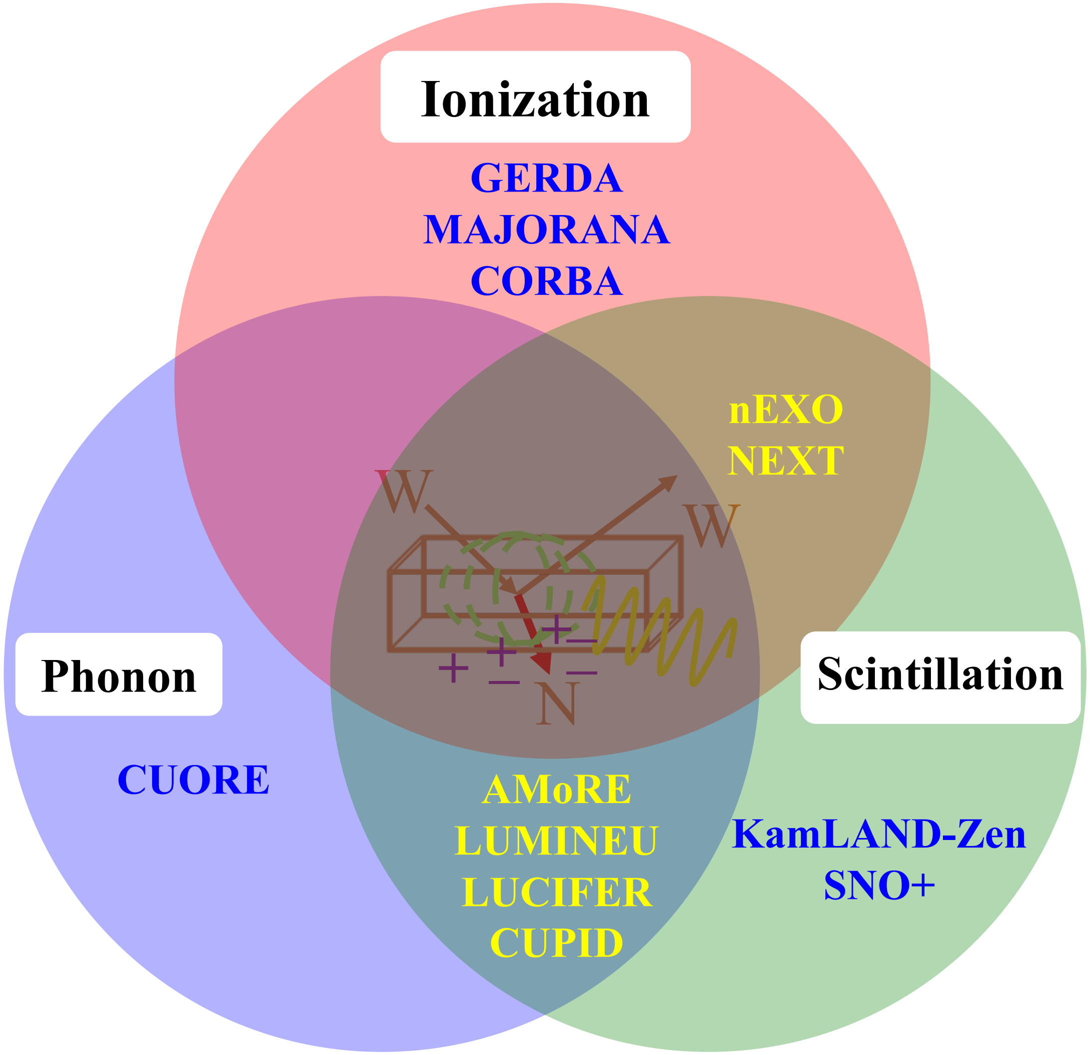
$T^{0\nu}_{1/2} \propto MT\ (for\ zero\ backgronds)$

$T^{0\nu}_{1/2} \propto \sqrt{\frac{MT}{b\Delta E}}$(for finite backgrounds)



Detector Techniques for 0νββ

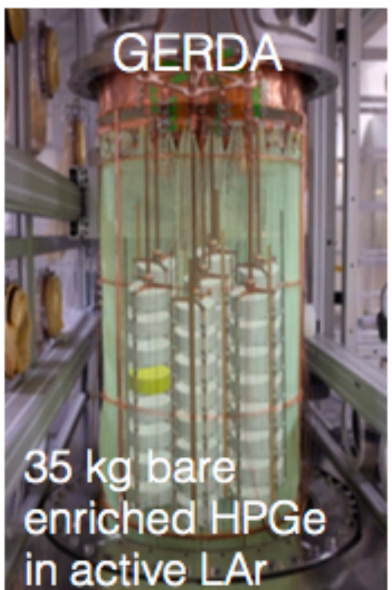
Similar techniques are used as direct dark matter experiments



You will hear about KamLAND-Zen, CUORE, AMoRE on Wednesday.

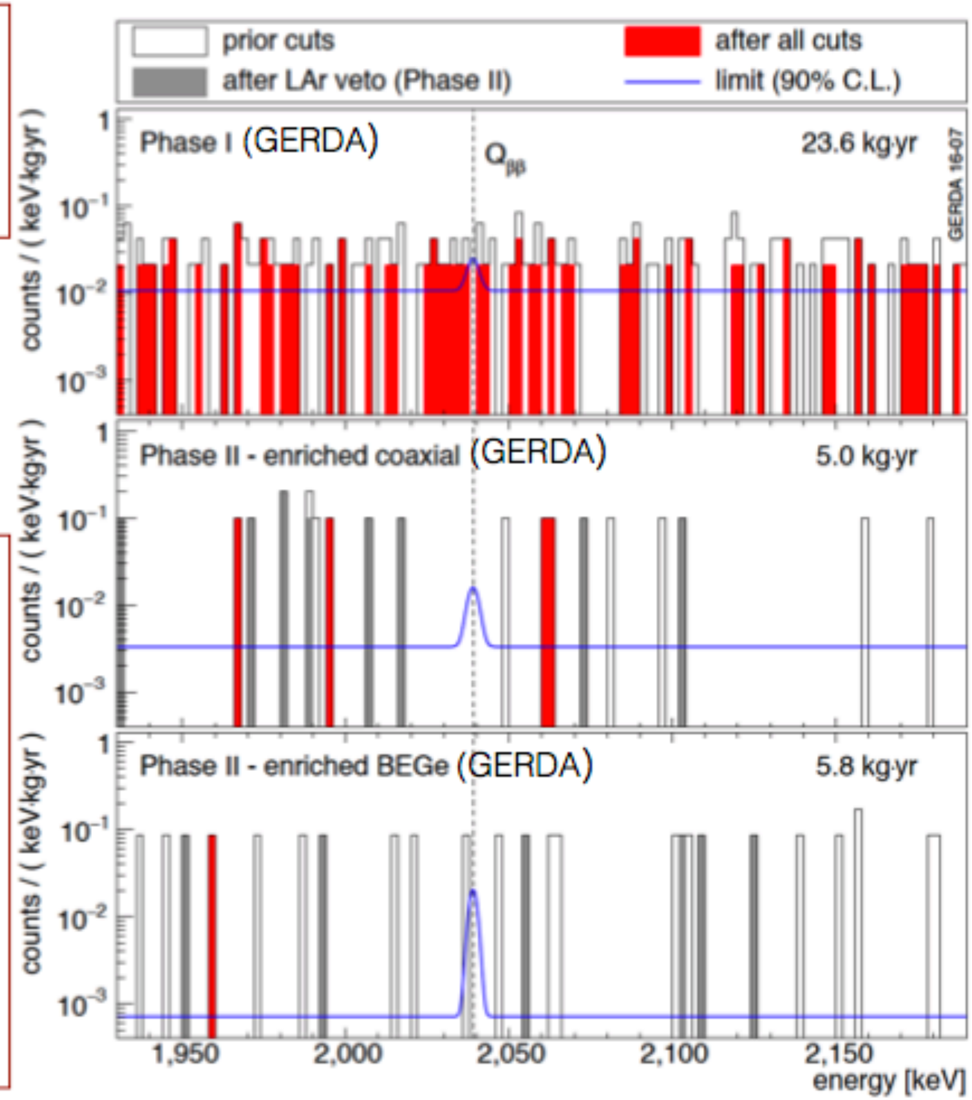
Ge-Experiments: MJD & GERDA

TAUP 2017
BI: $1.8^{+3.2}_{-1.1} \times 10^{-3}$
cts /(keV kg yr)
ROI: 2.8 keV



Nature 554 (2017)
47-52
BI: $0.7^{+1.1}_{-0.5} \times 10^{-3}$
cts /(keV kg yr) for
enr BEGe's

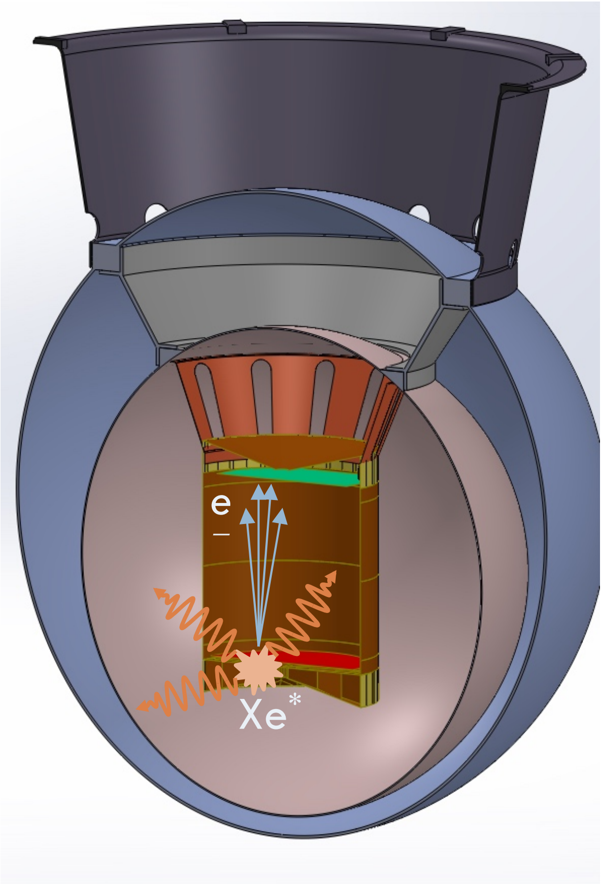
$T_{1/2}^{0\nu} > 5.3 \times 10^{25}$ yr
(90% C.L.)
Sensitivity:
$T_{1/2}^{0\nu} > 4.0 \times 10^{25}$ yr



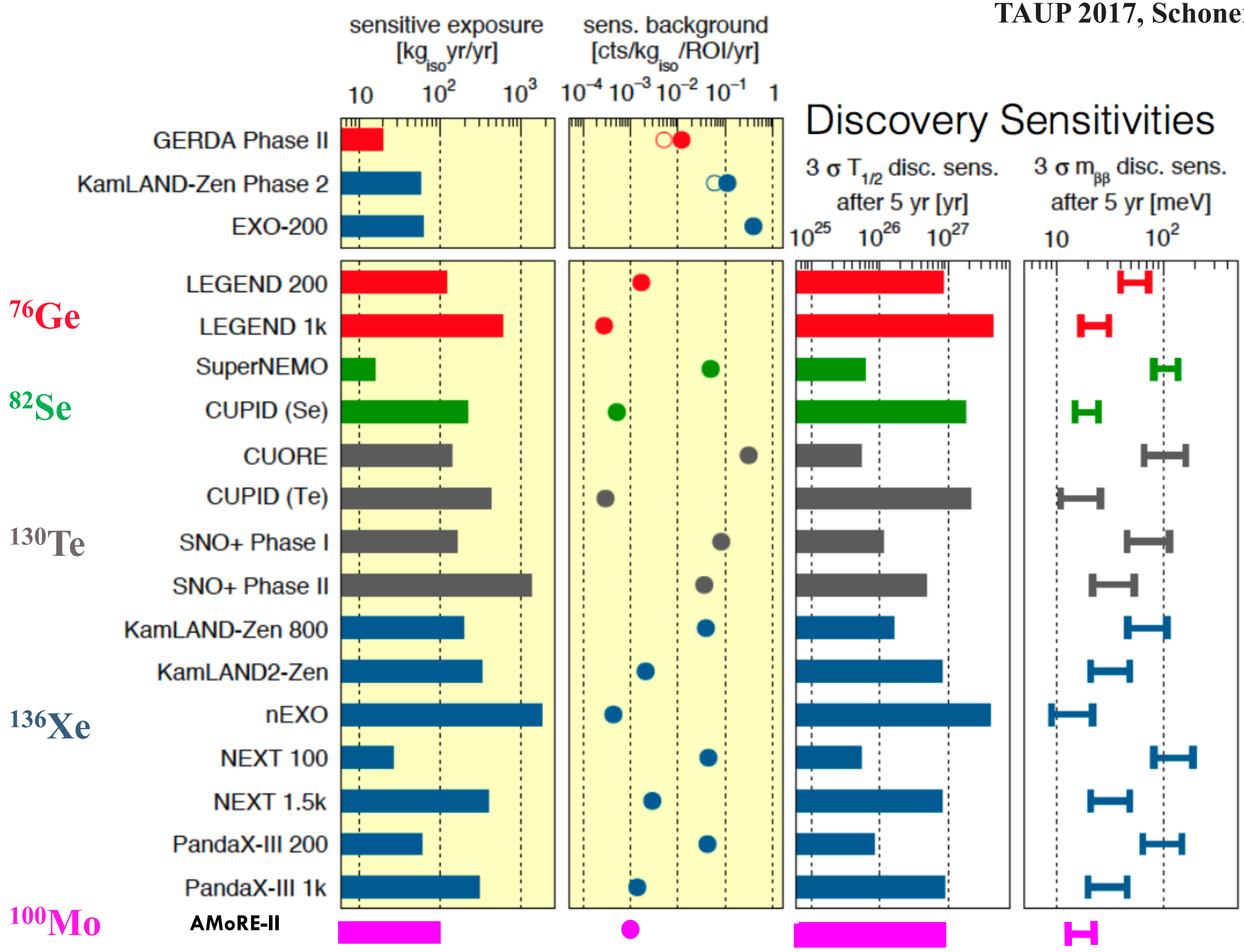
"**Background free search** for neutrinoless double-β decay with GERDA"

5t Homogeneous nEXO Concept

- Cold (in LXe) front end electronics.
- Spherical carbon fiber cryostat (lighter than copper).
- 3 mm^2 charge readout pads (anode).
- 4 m^2 SiPM staves lining the inside of the barrel.
- Reflective cathode.
- Liquid cryogen (HFE-7000).
- 1.3 m diameter.
- 1.3 m maximum drift length.



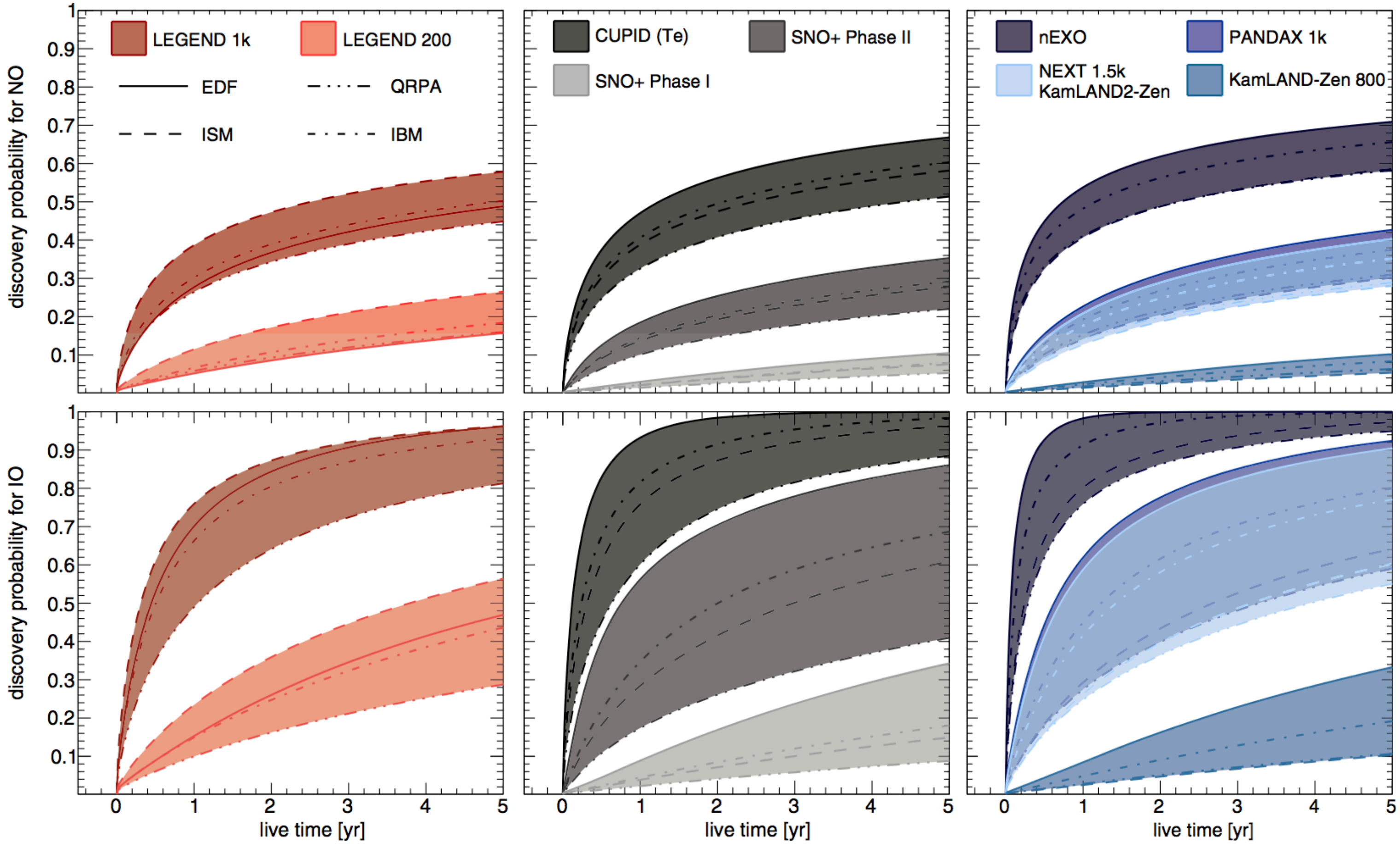
TAUP 2017, Schonert



Discovery probability

- Discovery probability for NO and IO assuming logarithmic mass distribution and flat in the angles and phases.
- Even normal hierarchy, the probability is high ~ 50% in 5 years for next generation experiments.

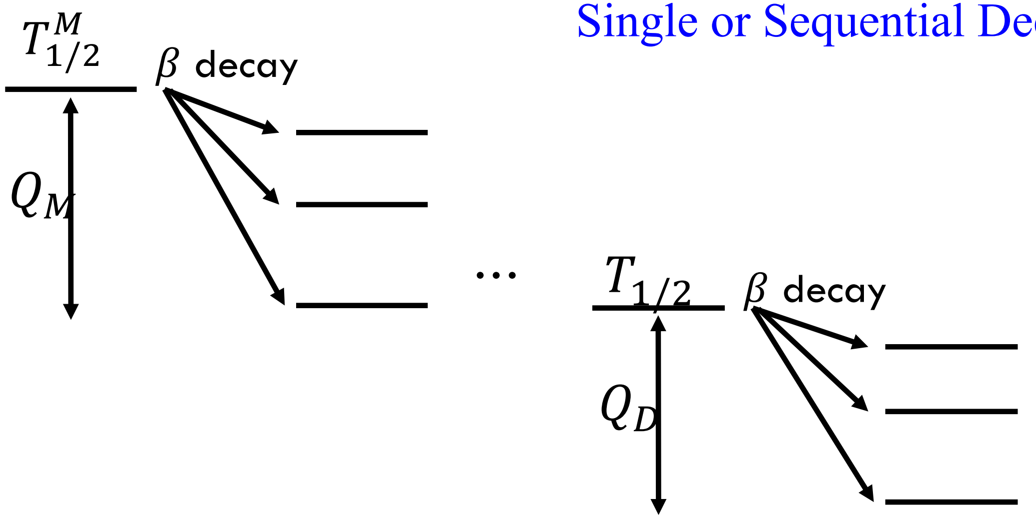
Agostini, PRD 96, 053001 (2017)



"Events" dangerous to DBD

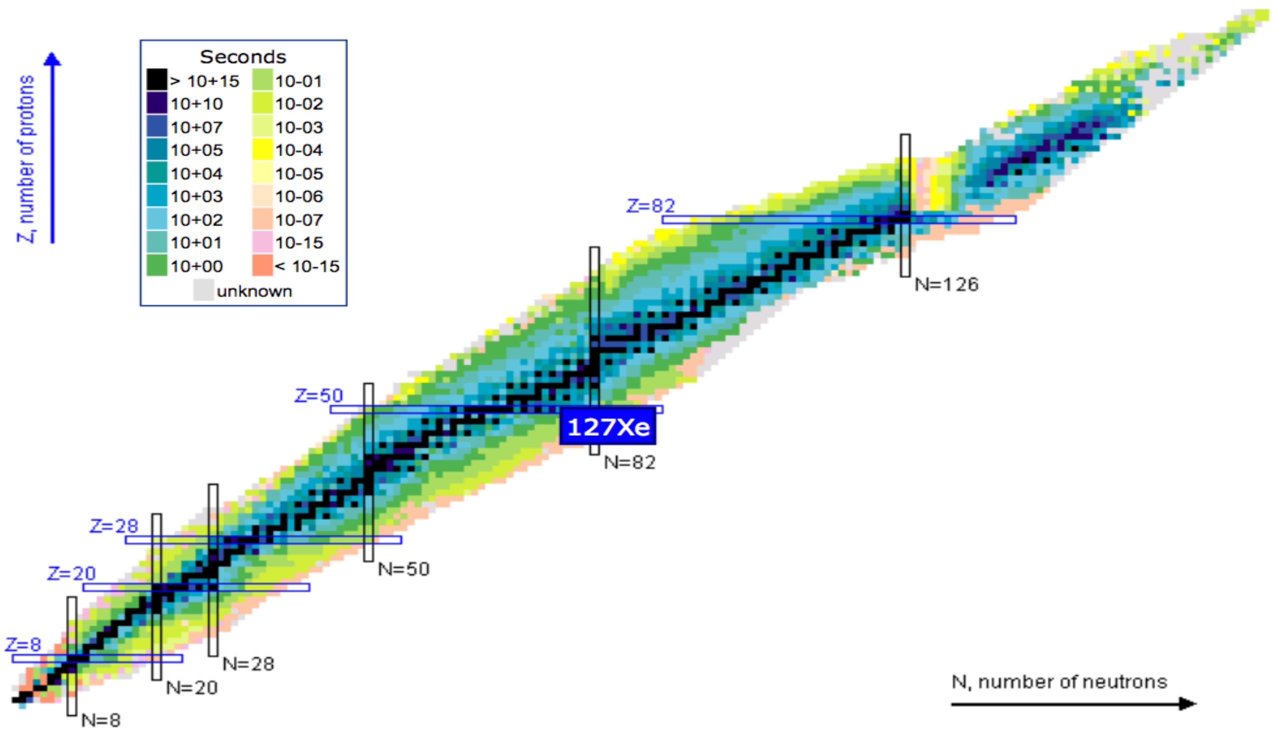
- **There is no localized "event" with energy release > 2MeV other than nuclear decay, passing muons, and entering hadrons and gammas.**
- 2 conditions to be "dangerous nuclei" for ^{100}Mo experiment.
  1) 30 days < $T_{1/2}^{M}$ < 10^{11} years.
  2) β *decay with* Q_M or Q_D > 3.02MeV
- Go through all nuclei including isomers.

Single or Sequential Decay



Nuclear Chart

- How many nuclei are dangerous among ~ 3000 nuclei ? Go through all the nuclei to find potential dangerous nuclei.



Results

El	Decay	$T_{1/2}$	Q	Mother	Chain	Comment
			MeV	N/A		
^{26}Al	EC	$7.4x10^5$y	4.004	N/A		Long lifetime
^{56}Co	EC	0.21y	4.567	N/A		Short lifetime
^{88}Y	EC	0.29y	3.623	^{88}Zr (0.23 y)		Short lifetime
^{106}Rh	B-	30s	4.004	^{106}Ru(1.02y)		
^{126}Sb	B-	12.5d	3.670	^{126}Sn($2.3x10^5$y)		Long lifetime
^{146}Eu	EC	4.61d	3.878	^{146}Gd (0.13 y)		Short lifetime
^{208}Tl	B-	3.05m	4.999	^{228}Th (1.91 y)	Th232	Main
^{209}Tl	B-	2.16m	3.970	^{233}U(159200y)	U233	2.1% branching
^{210}Tl	B-	1.3m	5.482	^{226}Ra(1600y)	U238	0.02% branching
^{214}Bi	B-	19.9m	3.269	^{226}Ra(1600y)	U238	Main

- Only Thorium and Uranium natural radioactivity are dangerous for Q> 3.02MeV. → Great advantage to run high Q-value nuclei !
- ^{110m}Ag(3010.5 keV) doesn't contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.

Strategy for zero backgrounds for high Q exp.

1. Develop to measure ^{238}U, ^{232}Th, ^{226}Ra, ^{228}Th at lowest level and confirm that these are below the required level.
2. Reduce two neutrino events pile-up backgrounds : rising time.
3. Minimize the surface contamination.
4. Any external background < ^{100}Mo $2\nu\beta\beta$.
5. Should minimize exposure at ground level.
6. In-situ muons : Water tank shielding.

→ Expecting "zero" background is in principle possible with this strategy before starting experiment.

→ New technique need to measure ^{232}Th level down to 0.1 ppt in the detector isotopes.

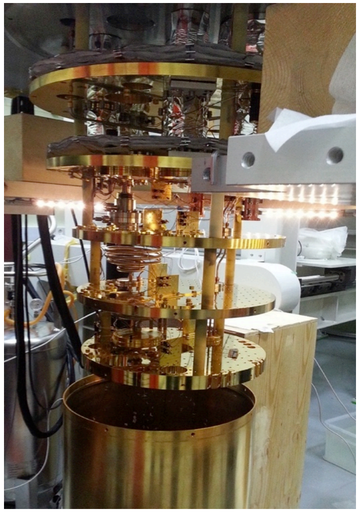
Projects at Center for Underground Physics

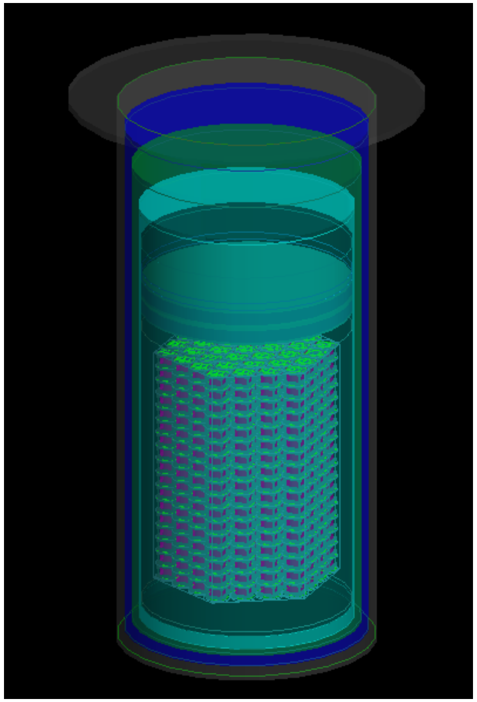
COSINE (Collaboration Of Sodium IodiNe Experiments) to check DAMA/LIBRA results.

Center for Underground Physics

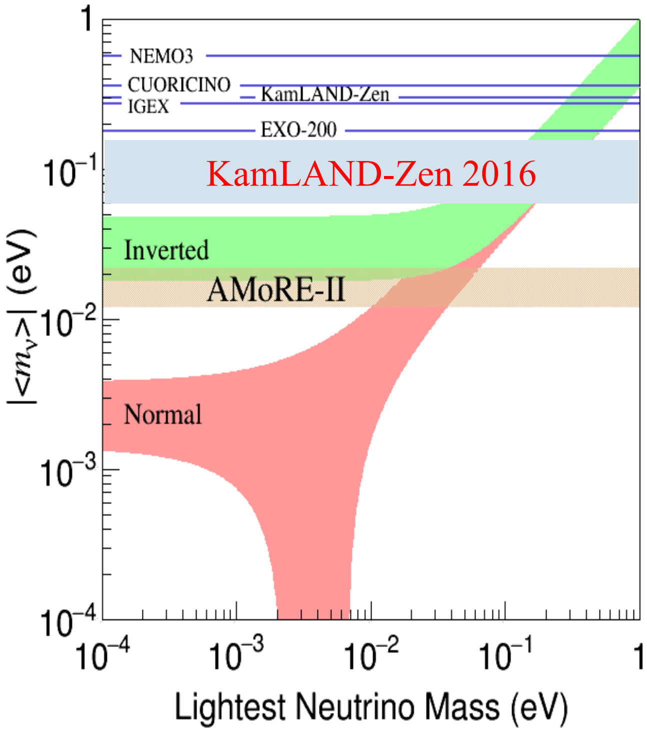
AMoRE ββ experiment

100 kg ^{100}Mo double beta decay experiment, largest experiment Q> 2614 keV





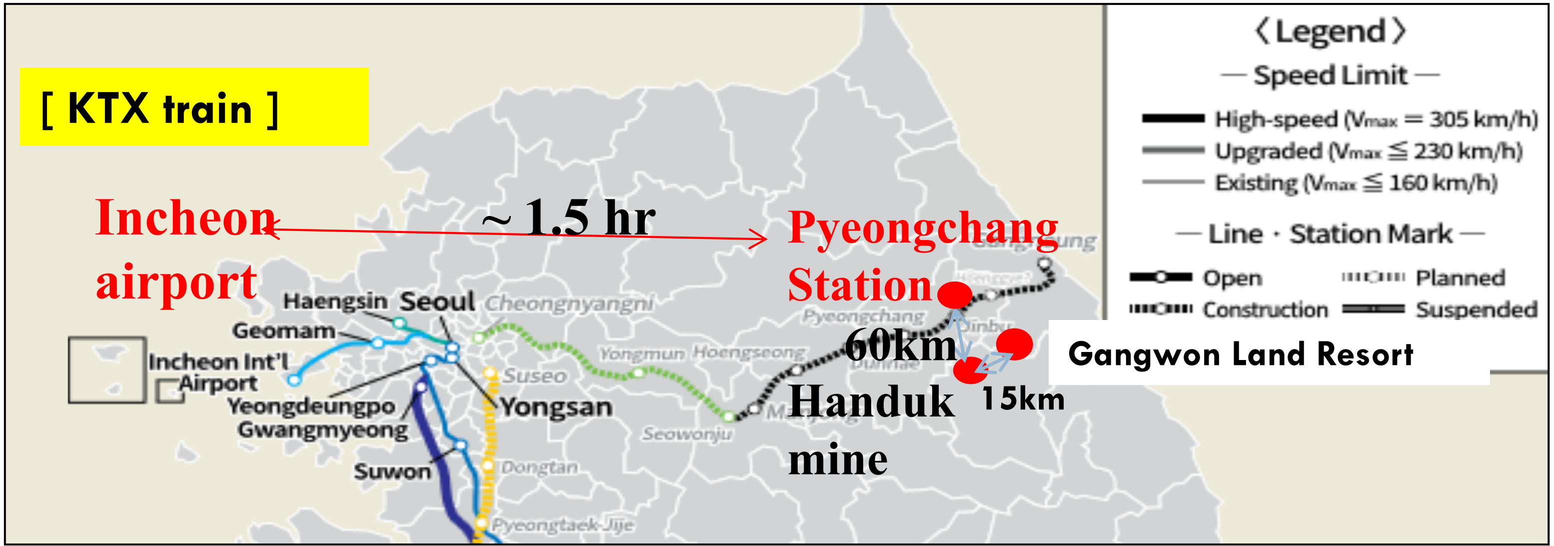
AMoRE-II



IBS is building a new underground lab.

After extensive study, we finally decided to build a new underground lab at an active iron mine, Handuk.

- **For 2018 Winter Olympic, construction of a high-speed train between airport to east has started.**
- **~ 3 hour from Incheon airport to Handuk mine.**

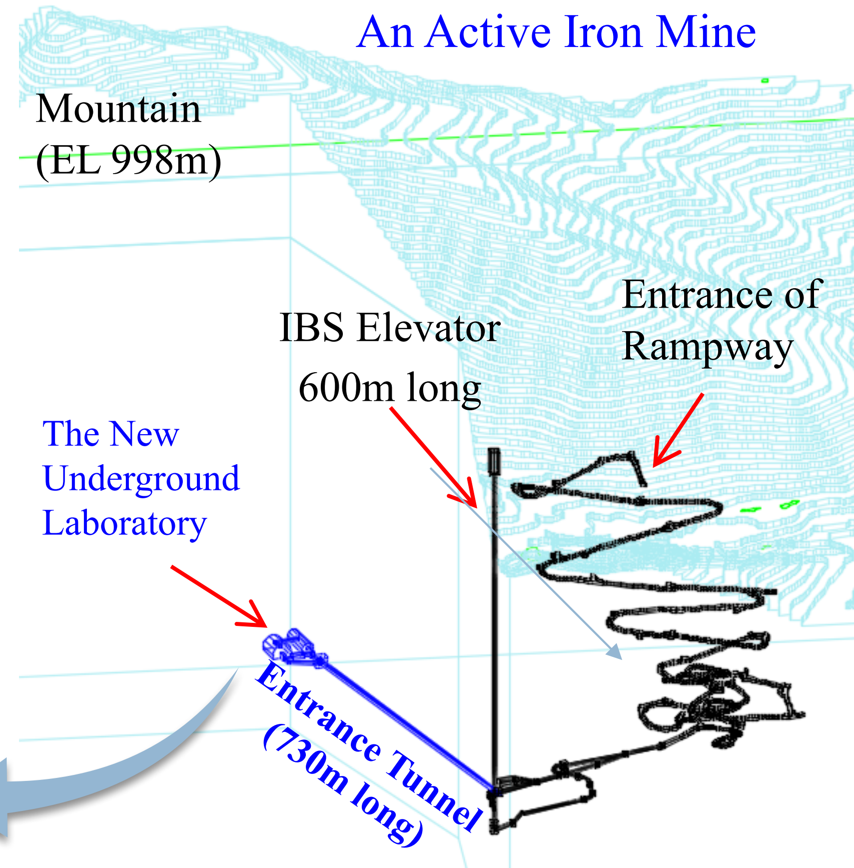


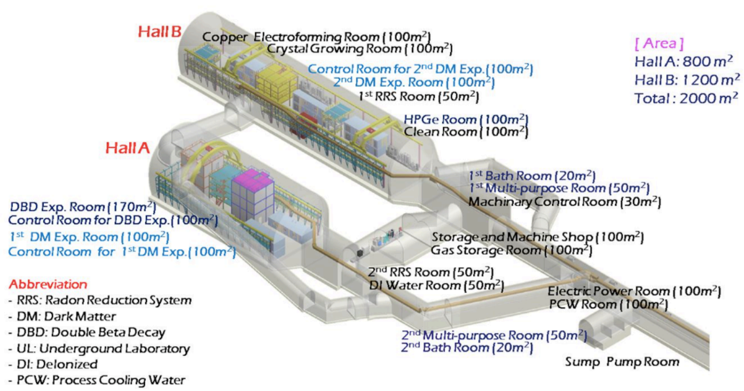
Overview of the new underground laboratory

- **Will have an independent entrance (human vertical elevator) from mine activity.**
- **The constructions start this year and completed end of 2019.**

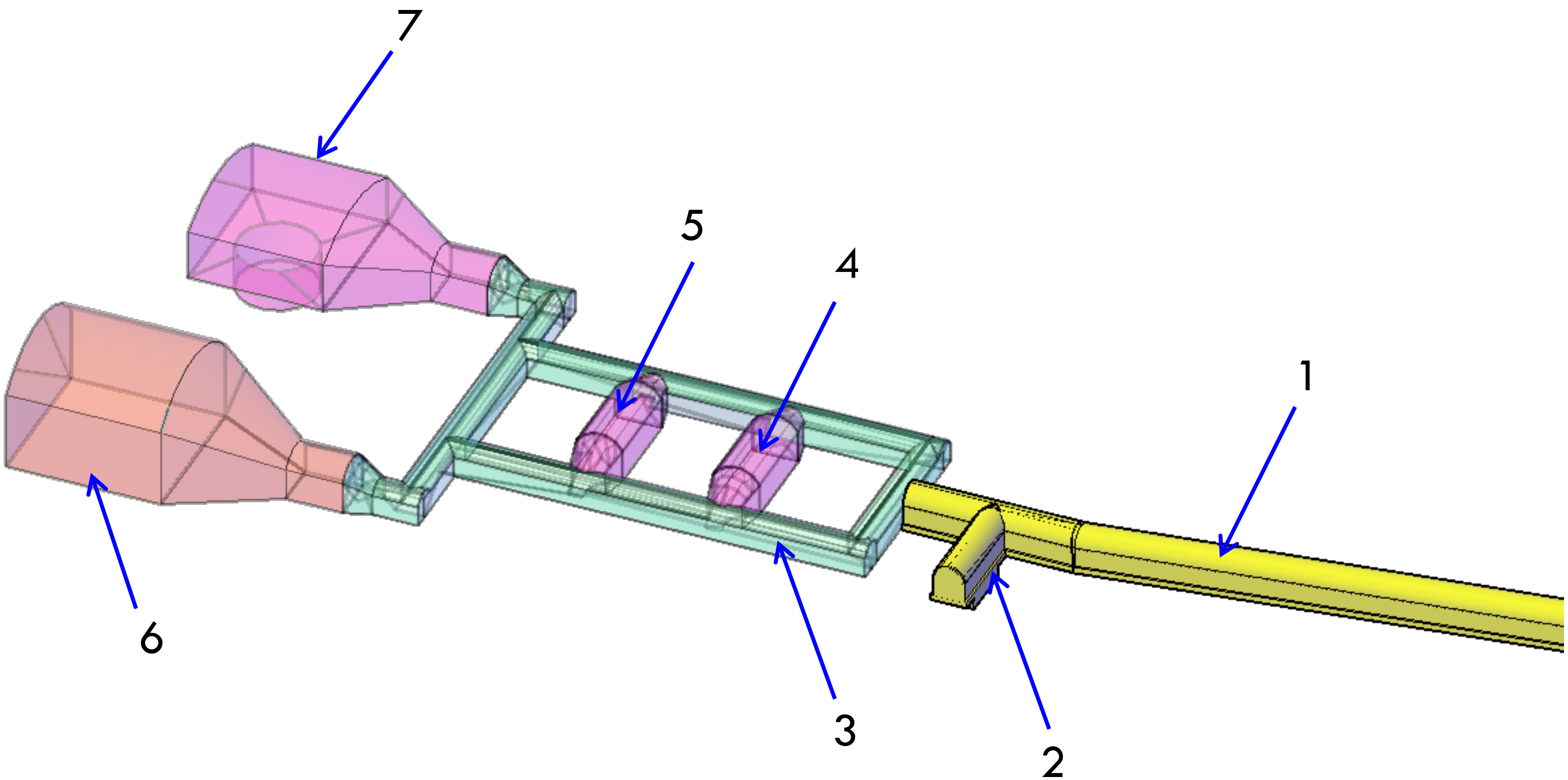
Bird view of Handuk Iron Mine

Handuk mine, ~ 0.7milion tons iron ore a year





Large (>2000m^2), deeper (1100m depth)



	Area (m^2)	Volume (m^3)
Access tunnel	3650	18000
Expr. Halls + hallway	2000	32000

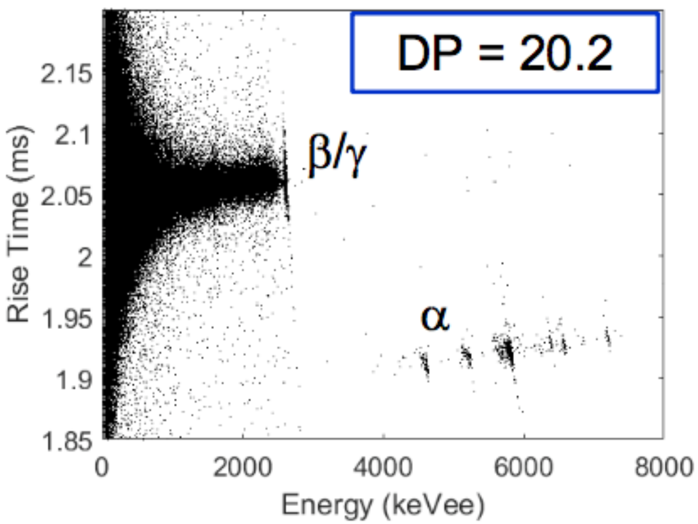
1	Access tunnel	5(W)x5(H)x730(L) m^3
2	Sump	In design
3	Hallway	In design
4	Expr. hall 1	In design
5	Expr. hall 2	In design
6	AMoRE hall	In design
7	LSC hall	In design

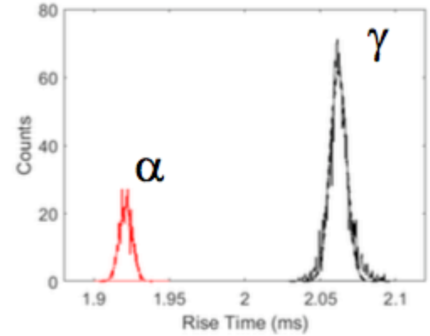
Summary

- DM candidates are more diverse, 10^{-22} eV – 10^{25} eV, including FDM, Dark Photon, ADM, SIMP etc…
- We have to search DM more broadly.
- For WIMPs, high mass will be pursued with larger LXe, LAr detectors, ~ 50 tons. Lower mass needs lower threshold, and new techniques are developed.
- DAMA conumdrum should be closed in.
- Double beta decay experiments are rapidly increasing the sensitivity for discovery for next generation experiments.
- CUP are working on both critical dark matter and neutrinoless double beta decay searches.

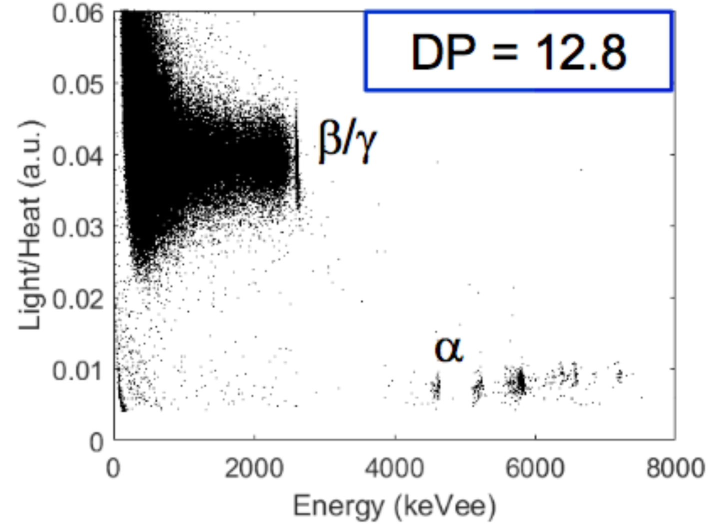
Backup Slides

Particle discrimination in run-5 (preliminary)





$$DP = \frac{x_{\beta/\gamma} - x_{\alpha}}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}$$



β/γ and α particles can be distinguished using pulse shape discrimination via pulse rise time or mean time

The use of the light/heat ratio for particle discrimination also shows excellent results.

Crystals	DP Light/Heat	DP Mean Time	DP Rise Time
SB28 (0.20 kg)	12.8	22.0	20.2
S35 (0.25 kg)	18.8	11.3	9.4
SS68 (0.35 kg)	16.2	6.0	5.7
SE01 (0.35 kg)	15.7	21.8	19.3
SB29 (0.40 kg)	14.1	8.6	9.8
SE02 (0.34 kg)	9.6	20.5	18.1

Sterile Neutrinos

The present relic density is estimated to be ;

$$\Omega_s \simeq 0.2\ \text{GeV} \left(\frac{\sin^2\theta}{3\times10^{-9}}\right)\left(\frac{m_s}{3\ \text{keV}}\right)^{1.8}$$

Thus, if the mass of the sterile neutrino is around keV, then they can become a rea listic candidate for warm dark matter.

The lifetime of sterile neutrino DM via three body decay gives a constraint on the mixing angle. The decay into photon gives an even stronger bound on the mixing from X-ray observations as

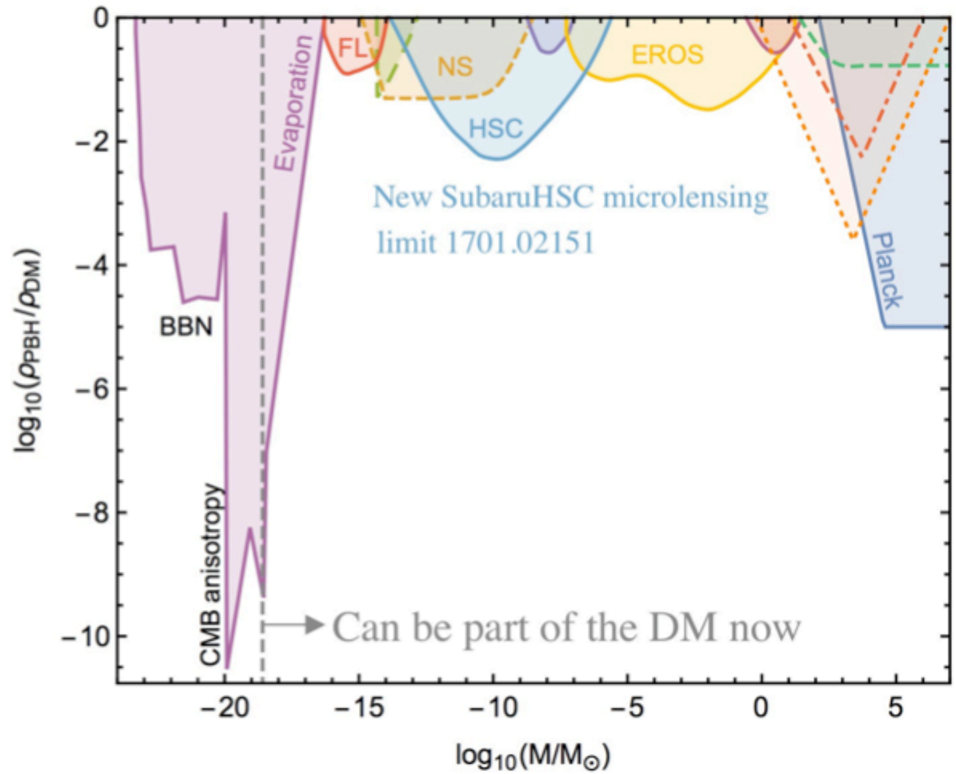
$$\sin^2 2\theta < 2.5\times10^{-18}\left(\frac{0.86\ \text{MeV}}{m_s}\right).$$

Graciela Gelmini-UCLA

Dark Matter: could be Primordial Black Holes (PBH)?

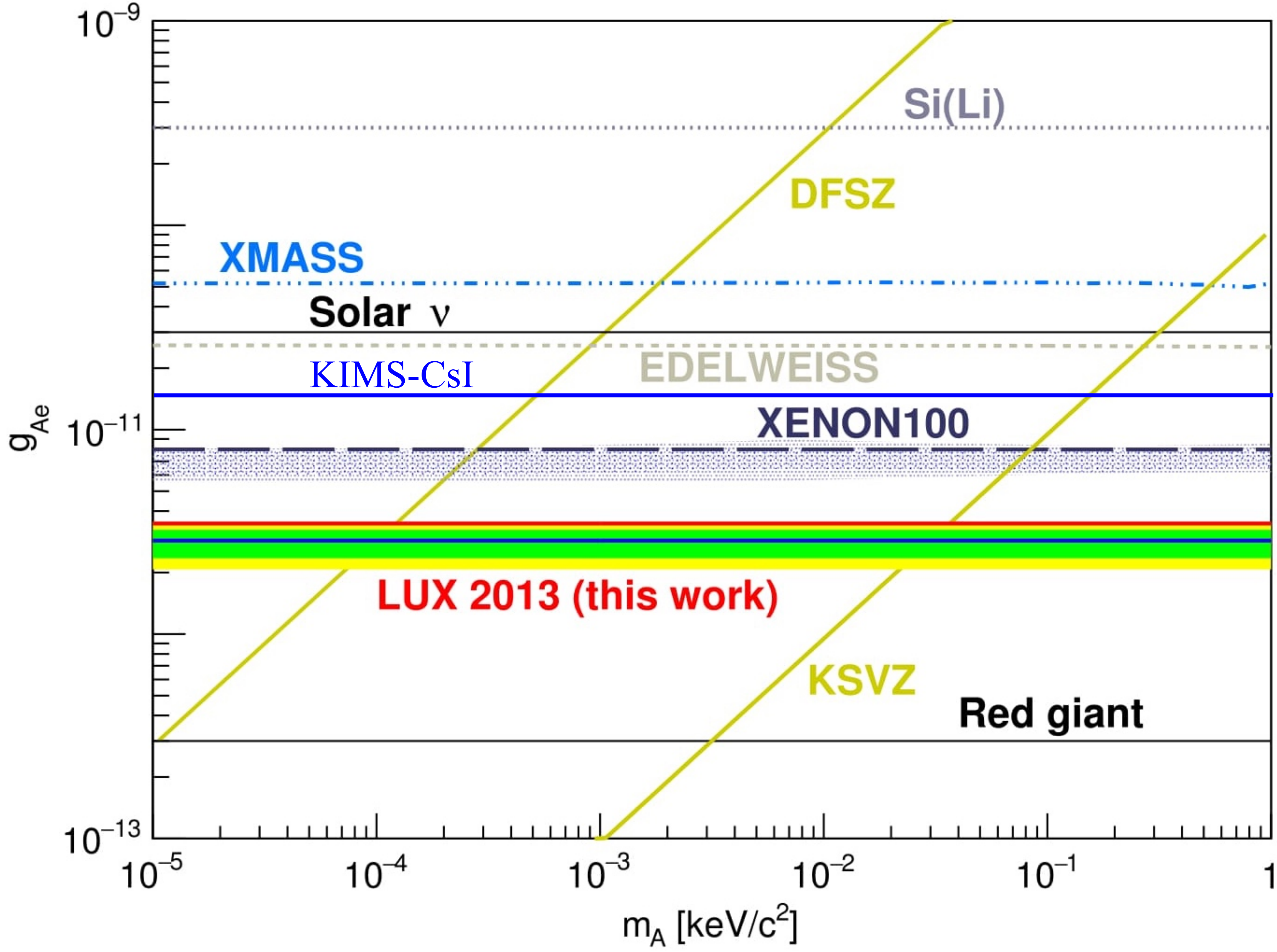
compilation of bounds on PHB/DM density fraction f for monochromatic PHB mass function (dashed can be avoided with special assumptions)

Carr, Tenkanen and Vaskonen 1706.03746



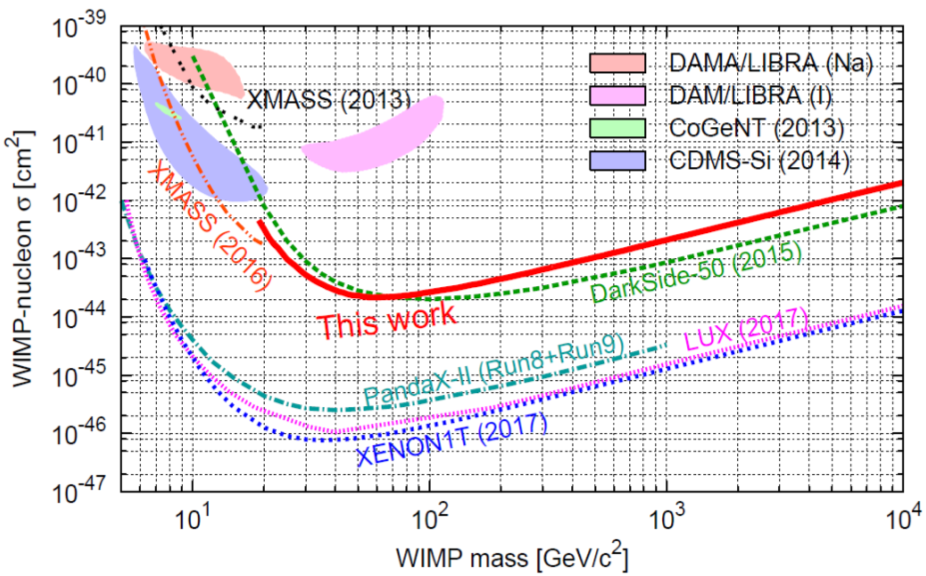
Only narrow windows may remain for PBH weakening some constraints, e.g. just below the MACHO microlensing limit $10^{-13} M_\odot$ or in MACHO "window" 10 $M_\odot$-100 $M_\odot$

Could LIGO BH ~10's $M_\odot$ be most of the DM? Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234, 1501.07565

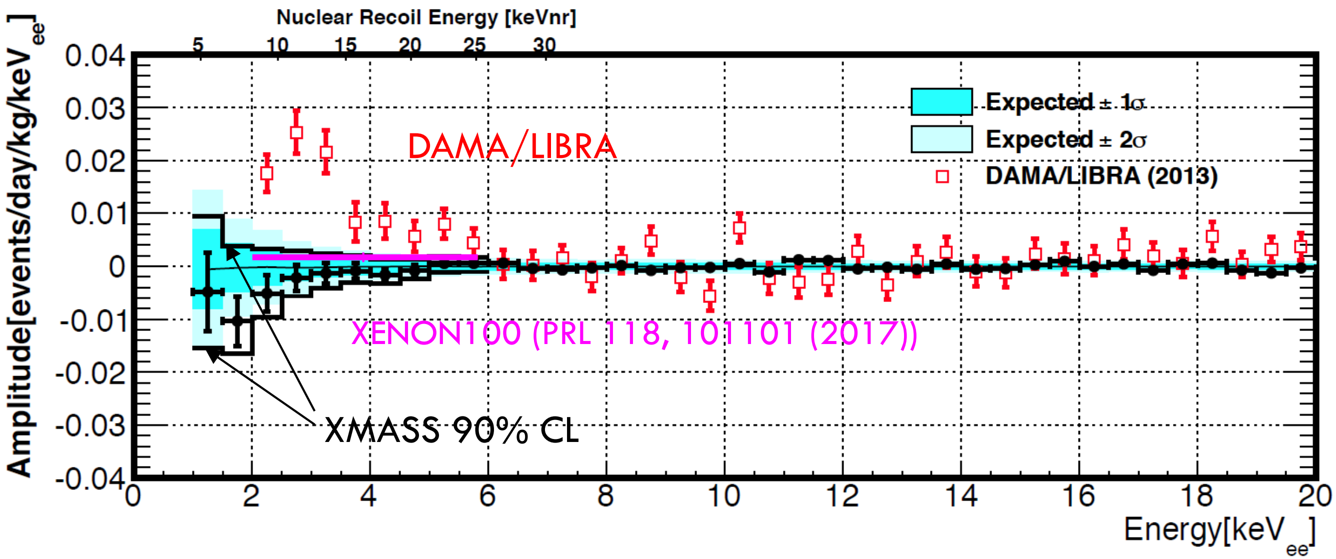


Si(Li)
DFSZ
XMASS
Solar ν
EDELWEISS
KIMS-CsI
XENON100
LUX 2013 (this work)
KSVZ
Red giant
g_{Ae}
10^{-9}
10^{-11}
10^{-13}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_A [keV/c^2]

Single phase liquid Xenon



XMASS has a largest exposure, (200 kg year)
XMASS obtained the lowest backgrounds in single phase detector, but limited by PSD and vertex localization.



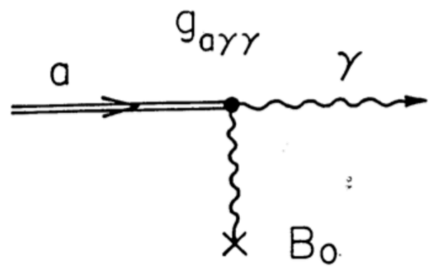
Axion & Axion-lke particles (ALP) searches

- Axion is the particle for spontaneous symmetry breaking of PQ symmetry.
- Axion is light.

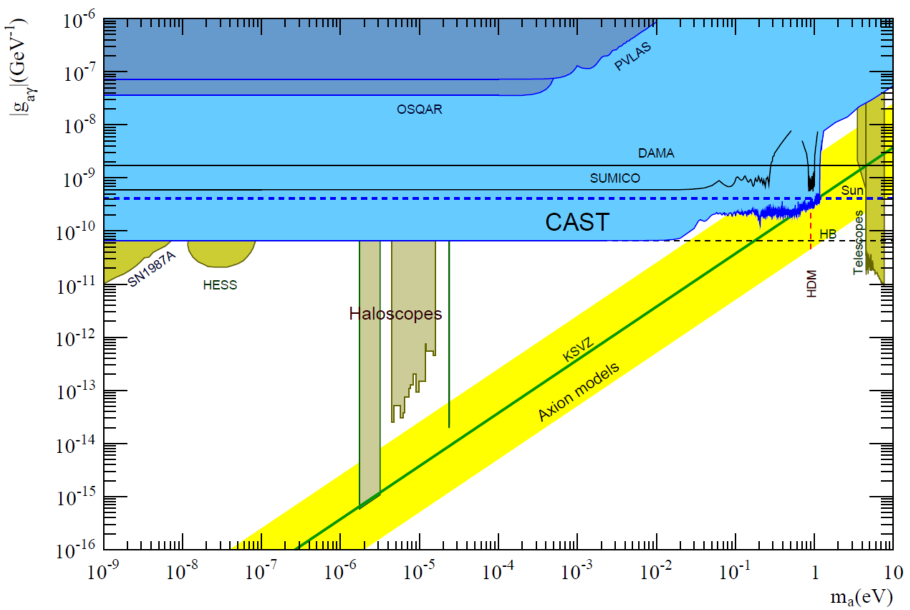
$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 0.6\,\mathrm{eV}\left(\frac{10^7\,\mathrm{GeV}}{f_a}\right);$$

- Axion-photon conversion in the presence of EM fields (Primakoff effect) is used most of Axion searches.

$$g_{a\gamma\gamma} = \left(1.3\times 10^{-15}\ \mathrm{GeV}^{-1}\right)\frac{m_a}{10^{-5}\ \mathrm{eV}}$$

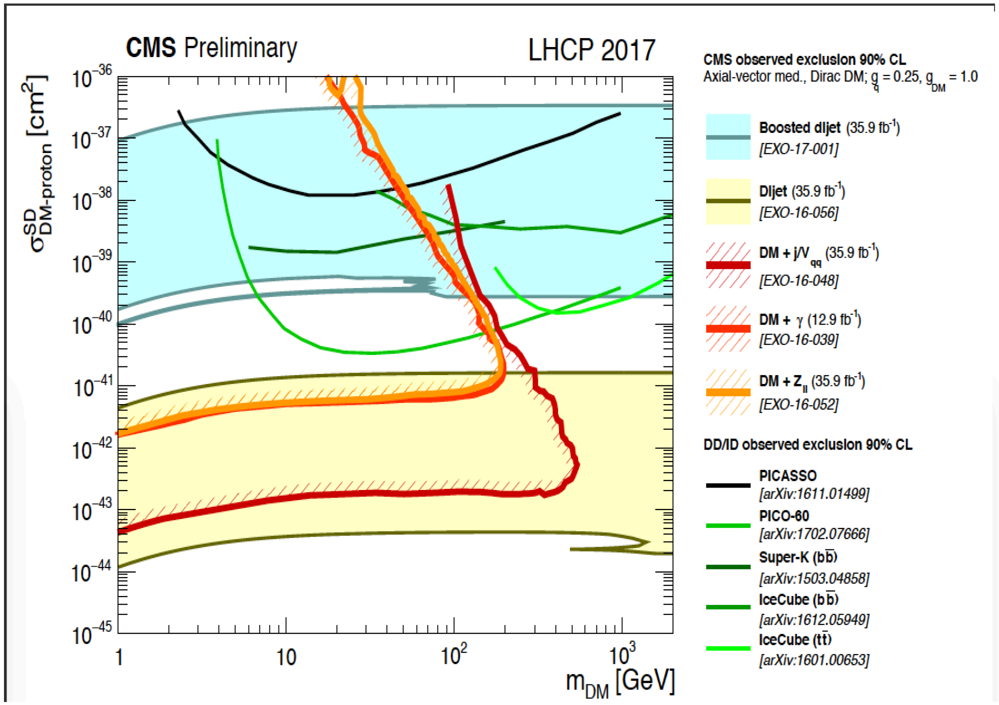


- For axions, interaction strength is fixed by mass.
- For axion-like particles (ALPs), coupling and mass are independent.

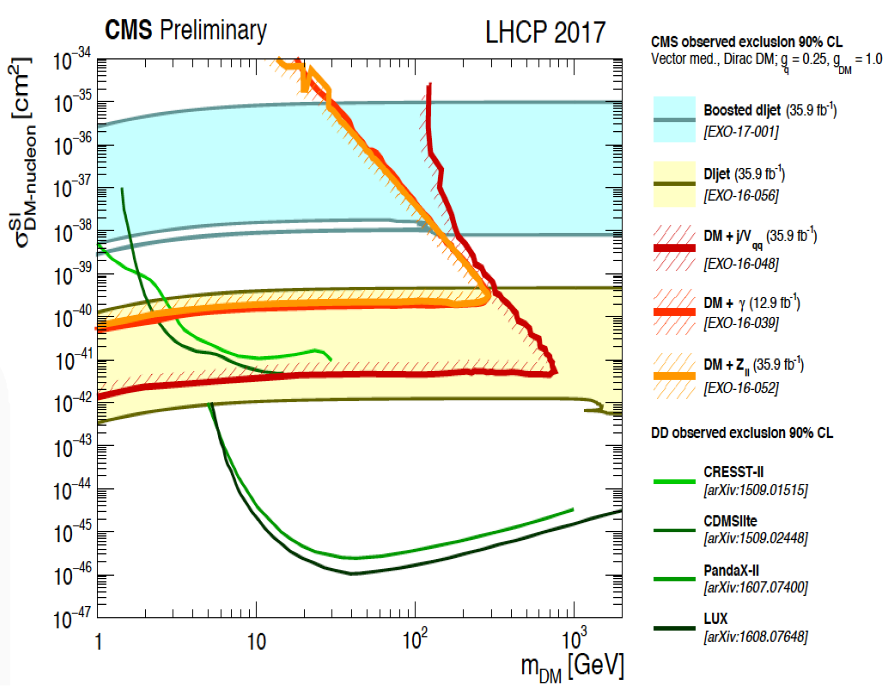


Limits for direct DM searches.

Spin dependent limit



Spin independent limit



No direct DM evidence.

Also no SUSY particles indication below ~ 400 GeV

Albert De Roeck, ICRC2017