BSM search in KamLAND

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KamLAND/KamLAND-Zen Collaboration

~50 physicists work on this project

Collaboration meeting on Zoom, Mar. 2024

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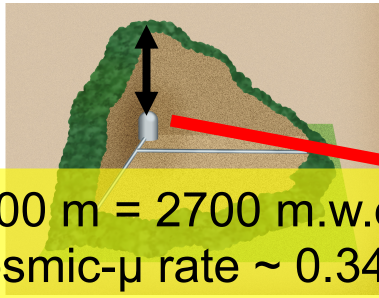
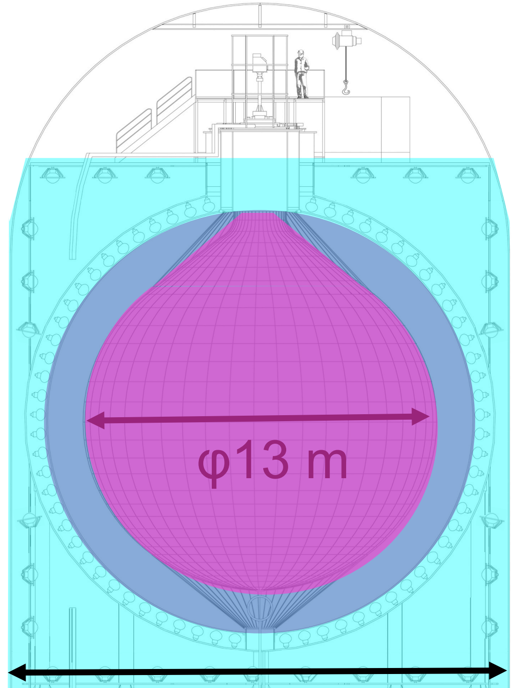
KamLAND



1000 m = 2700 m.w.e.
Cosmic-μ rate ~ 0.34 Hz

Water-Cherenkov Outer Detector:
Active cosmic-μ veto

3.2kton purified water
225(140), 20-inch PMTs



φ18 m

Scintillation Inner Detector:
Physics observation

1kton purified liquid scintillator (KamLS)

- $^{238}U \sim 5.0 \times 10^{-18}$ g/g
- $^{232}Th \sim 1.8 \times 10^{-17}$ g/g

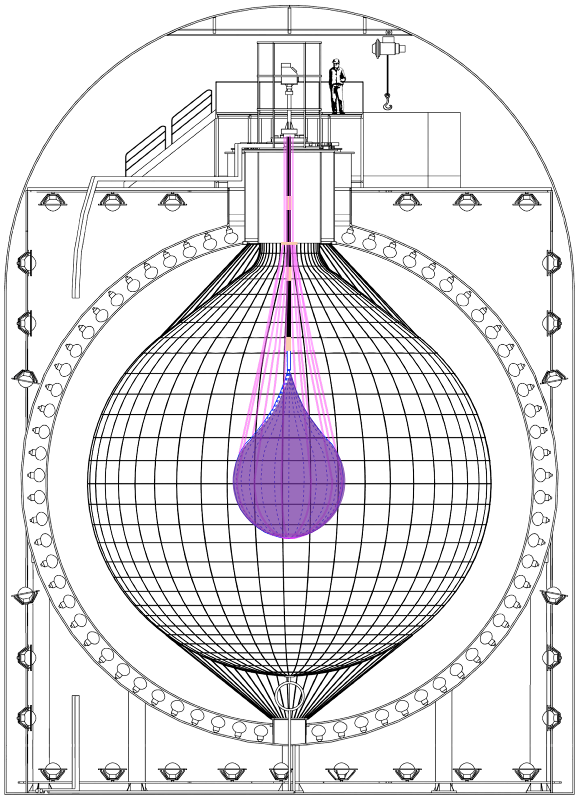
Buffer Oil
1879 PMTs
6.7%/√E, 13.7 cm/√E

Principal physics target of KamLAND experiment

- Reactor neutrinos
- Geoneutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Astrophysical neutrinos
- Proton decay

and more !

KamLAND-Zen



Xe loaded liquid scintillator(XeLS) in IB:

Xe loaded liquid scintillator

- 320-380 kg of Xenon for KLZ400
- 750 kg of Xenon for KLZ800
- ~90% ^{136}Xe + ~10% ^{134}Xe
- Dissolved into liquid scintillator 3%wt

Filled in ultra-clean inner-balloon(IB)

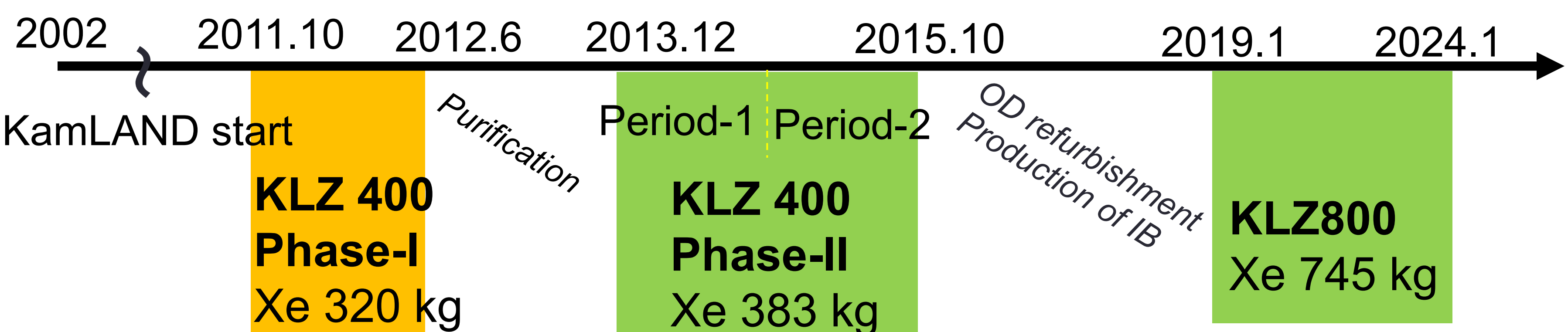
- Φ 3.8 m for KLZ800
- Φ 3.08 m for KLZ400

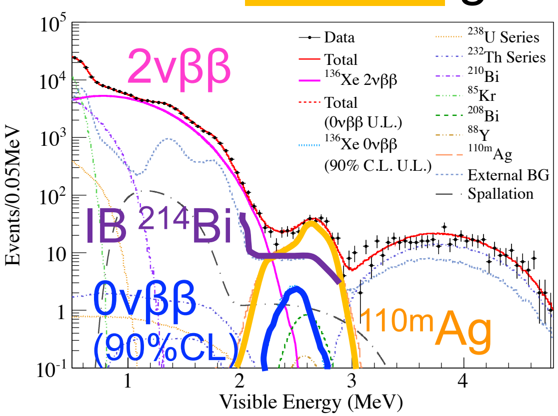
<u>Principal physics target of KamLAND-Zen</u>

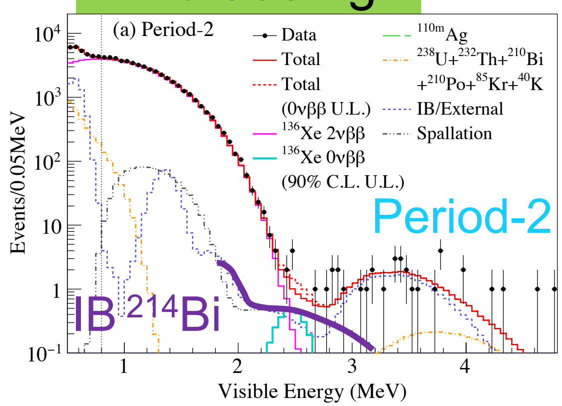
- Neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe
- Double beta decay ($2\nu\beta\beta$) of ^{136}Xe

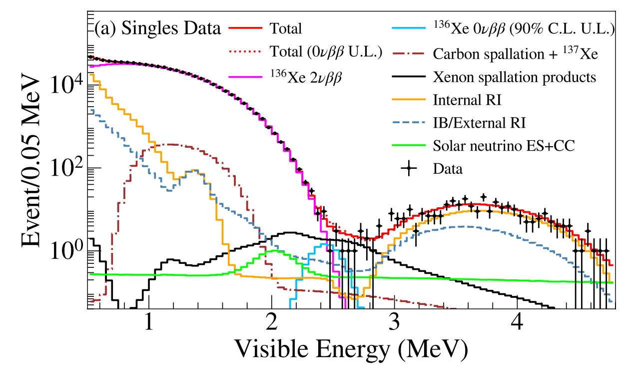
and more !!

History of KamLAND-Zen









✓ **Reduced ^{110m}Ag by purification**

✓ **Successfully produced a low-BG IB (~1/10)**

✓ **Double Xe**

An experiment with great potential to take advantage of the low BG environment and work on other physics exploration.

BSM search in KamLAND

1. Neutrinoless double beta decays
2. Majoron Emission in $0\nu\beta\beta$
3. Charged exited stats of dark matter

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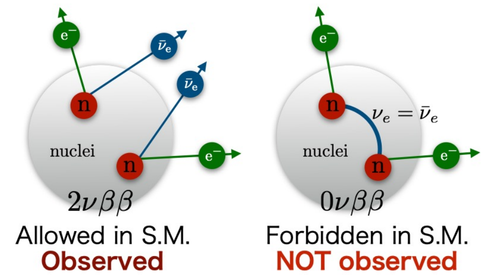
Neutrinoless double beta decays ($0\nu\beta\beta$)

Neutrino can be **Majorana Neutrino ($\nu = \bar{\nu}$)**

- Lepton number violation (BSM)
- Majorana neutrino is key of
  - ✓ Tiny neutrino mass (via Seesaw mechanism)
  - ✓ Matter dominant universe (via Leptogenesis)



Neutrinoless mode ($0\nu\beta\beta$) is allowed only when the neutrino is the Majorana particle:

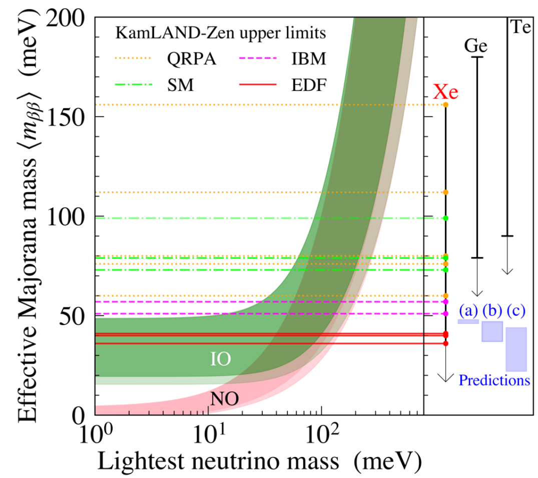
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

KLZ searches for $0\nu\beta\beta$ with ^{136}Xe

$T^{0\nu}{}_{1/2} > 2.3\times10^{26}$ yr (90% C.L.)

→ Effective Majorana mass $\langle m_{\beta\beta} \rangle < 36 - 156$ meV

The first search in inverted mass ordering !!



We completed KamLAND-Zen 800 DAQ on Jan. 11, 2024.
Data analysis with full dataset is in progress.

Next generation of KLZ: KamLAND2-Zen

Next-generation detector R&D is now in progress

Film BG

Scintillation balloon film

Enlarge sensitive volume by tagging $^{214}Bi \rightarrow ^{214}Po$ sequential decay on the film

$2\nu\beta\beta$ decay

Enhance detector energy resolution (4%→2% @2.6 MeV)

High QE PMT & Light guide mirror

Improve light collection efficiency and photo coverage

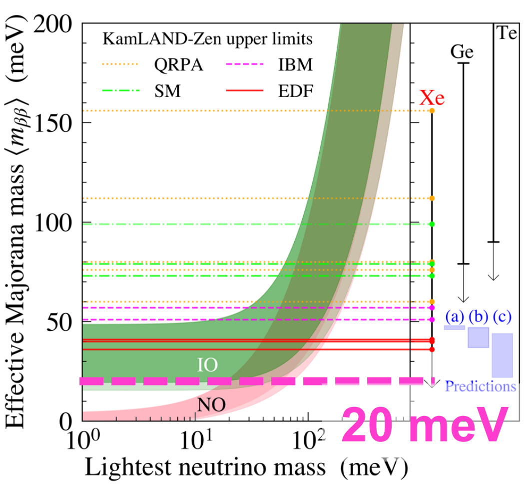
Brighter LS

Higher light yield and transmittance

Xe spallation products

New Dead-time free electronics

Collect all the neutron information from the noisy period



Target $\langle m_{\beta\beta} \rangle$~20 meV (5yrs)

KamLAND2-Zen will be the first search to cover the Inverted-Ordering band !!

BSM search in KamLAND

1. Neutrinoless double beta decays
2. Majoron Emission in $0\nu\beta\beta$
3. Charged exited stats of dark matter

Majoron Emission in $0\nu\beta\beta$ $(0\nu\beta\beta J)$

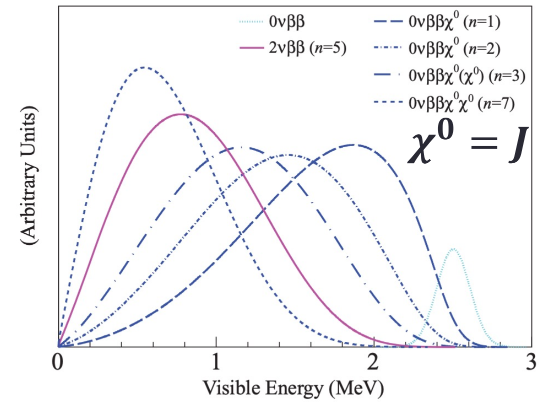
Majorana neutrino violates B−L. How is it violated?

Global $U(1)_{B\text{-}L}$ symmetry violation is one possible.

→ New Nambu-Goldstone boson **"Majoron"** appears.

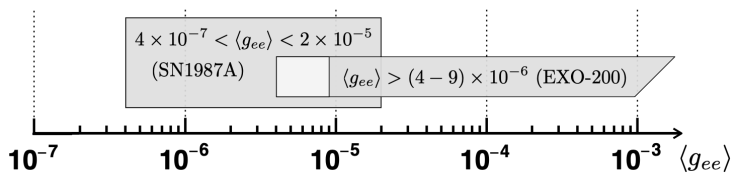
There are some models in which a $0\nu\beta\beta$ decay emission one or two **Majorons**:

$$(Z, A) \rightarrow (Z + 2, A) + 2e^{-} + \boldsymbol{J}\ (+\boldsymbol{J})$$



Massless :

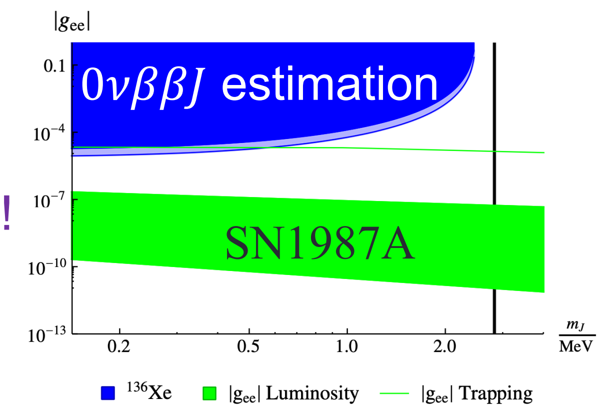
- Supporting SN1987A's constrain



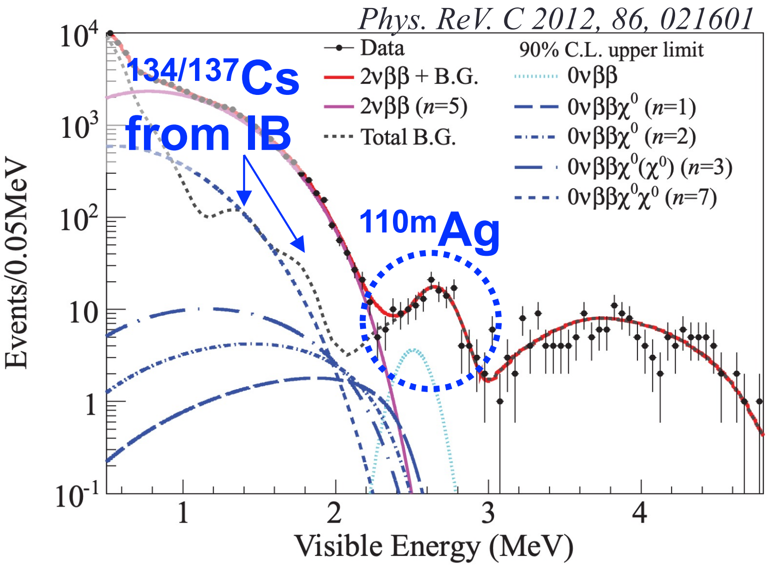
Massive :

Majoron is usually massless but it can have mass and it brings more new physics!

- $0\nu\beta\beta$ experiment has never been searched yet.
- There is the gap between SN limit and $0\nu\beta\beta J$ estimation limit. → This must be filled !



Search for $0\nu\beta\beta J$



Massless-*J* has been studied in KLZ400 Phase-I

- An exposure of 112.3 days with 125 kg of ^{136}Xe
- $T^{0\nu J}{}_{1/2} > 2.6\times10^{24}$ yr (90% C.L.) (spectral index n=1)

→ The effective $\nu - J$ coupling $\langle g_{ee} \rangle > (0.8 - 1.6)\times10^{-5}$

KLZ800 is expected to improve several times over!

✓ High statistic :

- Livetime ~ 4.7 times
- Fiducial volume expansion & amount of Xe ~ 5 times

✓ Low BG :

- Successfully created a low-BG IB ~ 1/10 times

KLZ800 will perform the first search for massive majoron emission in the world.

BSM search in KamLAND

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3. Charged exited stats of dark matter

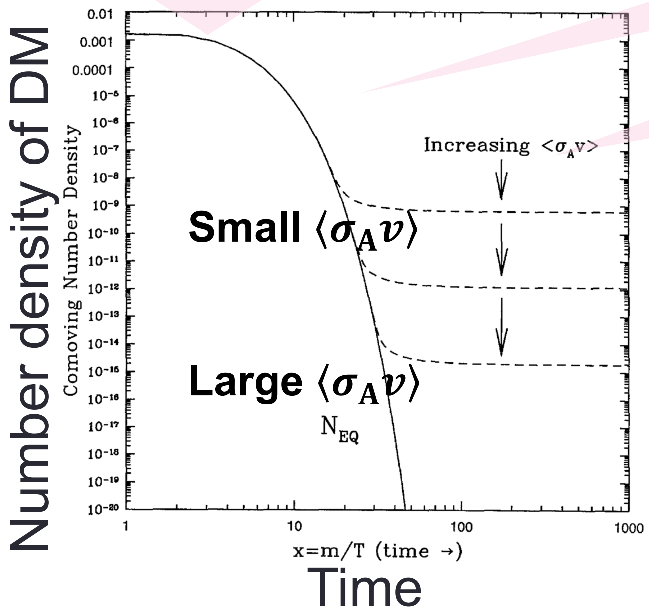
Weakly Interacting Massive Particles (WIMP)

- Elementary particles predicted by BSM model SUSY
- Heavy neutral particle (O(100 GeV-TeV)) with Weakly interaction
- Residual particles from thermal equilibrium in the early universe

Being produced and annihilating
$$\chi\chi \rightleftarrows ff'$$

The temperature decreases as the universe expands.
→ DM production was suppressed

Freeze-out:
Convergence to current DM abundance



Considering mass O(100 GeV-TeV) and weakly scale interactions
→ Explain current DM abundance (**WIMP Miracle**)

$$\langle\sigma_A v\rangle \sim 3\times10^{-26}\ \mathrm{cm^3/s}$$

→ **DM has been actively explored in O(GeV-TeV) mass range.**

Coannihilation

In $\langle \sigma v \rangle < 3\times10^{-26}$ cm^3/s, the WIMP scenario cannot explain the current DM abundance...?

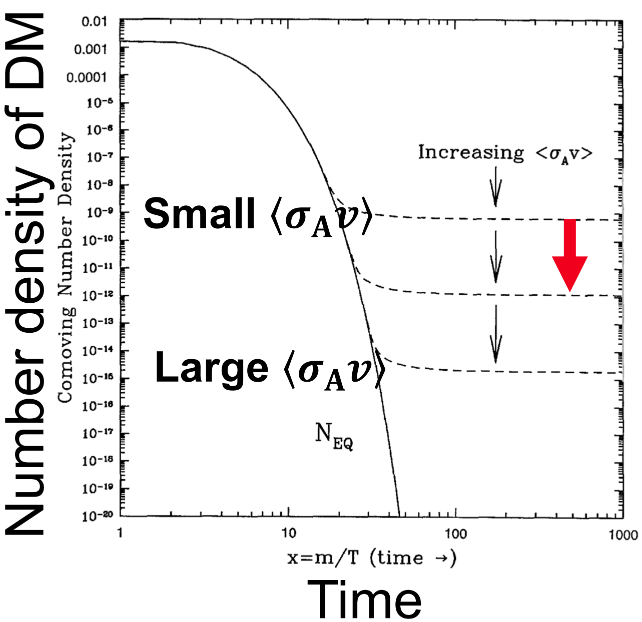
Coannihilation

In $\langle\sigma v\rangle < 3\times10^{-26}$ cm³/s, the WIMP scenario cannot explain the current DM abundance...?

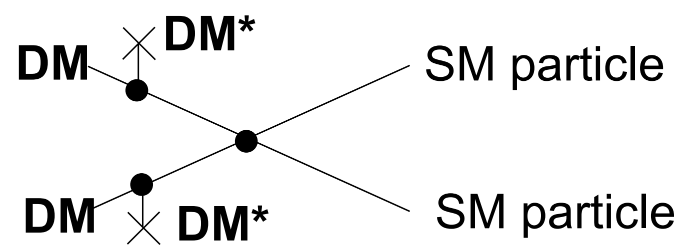
There are exceptions.

If the co-annihilation cross-section is large,
$\langle\sigma v\rangle < 3\times10^{-26}$ cm³/s can still explain the current DM abundance.

Co-annihilation: the masses of DM particles are degenerate



Co-annihilation can reduce the abundance.

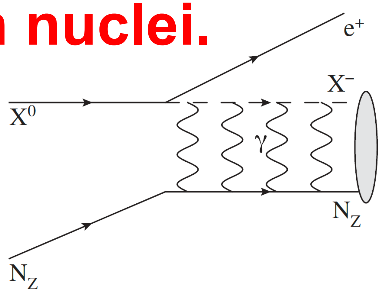


[1] K. Griest, D. Seckel, Three exceptions in the calculation of relic abundances, Phys. Rev. D 43 (1991) 3191.

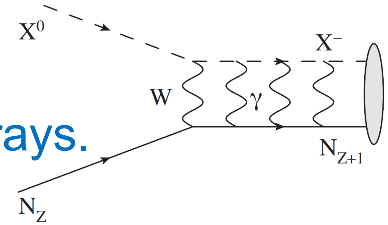
In this case, we need DM search in $\langle\sigma_A v\rangle < 3\times10^{-26}$ cm³/s !

Charged exited states of Dark Matter

If the mass difference between the WIMP and the excited state **$\Delta m (= m_{X^-} - m_{X^0}) < 20$ MeV, the negatively charged excitation of the WIMP can form a stable bound state with nuclei.** [2]



Case A



Case B

Case A: positron is emitted

$$N_z + X^0 \rightarrow (N_z X^-) + e^+$$

Case B: neutron is converted to a proton

$$N_z + X^0 \rightarrow (N_{z+1} X^-)$$

N_z: the target nucleus with atomic number Z
$X^0 (X^-)$: the WIMP ground (excited) state

NX^- is formed in an excited state and will de-excite by emitting γ-rays.

- Expected signal

$$E_{tot} = \begin{cases} E_b^{(0)} - \Delta m + m_e \ (\textbf{Case A}) \ (= K_{e^+} + E_\gamma + 2m_e) \\ E_b^{(0)} - \Delta m + m_Z - m_{Z+1} \ (\textbf{Case B}) \ (= E_\gamma) \end{cases}$$

Annihilation γ-rays

$E_b^{(0)}$: the binding energy of the ground state of the bound states with the nucleus (depends on the target nucleus : O(1-10 MeV))

[2] H. An, M. Pospelov, J. Pradler, Direct constraints on charged excitations of dark matter, PRL 109 (2012) 251302

Requirements for Experiments

✓ **Target nuclei with large $E_b^{(0)}$**

- Xenon nuclei are good targets that increase the $E_b^{(0)}$ value and expand the Δm region that can be explored!!

✓ **Sensitive to *O*(1-10) MeV energy range**

- Experiments with xenon sensitive to energies up to about 20 MeV would cover a wider Δm range.

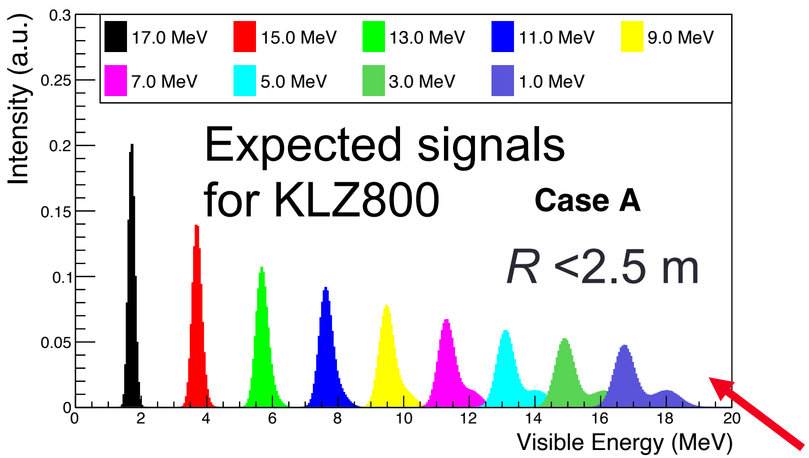
✓ **Large amount of target**

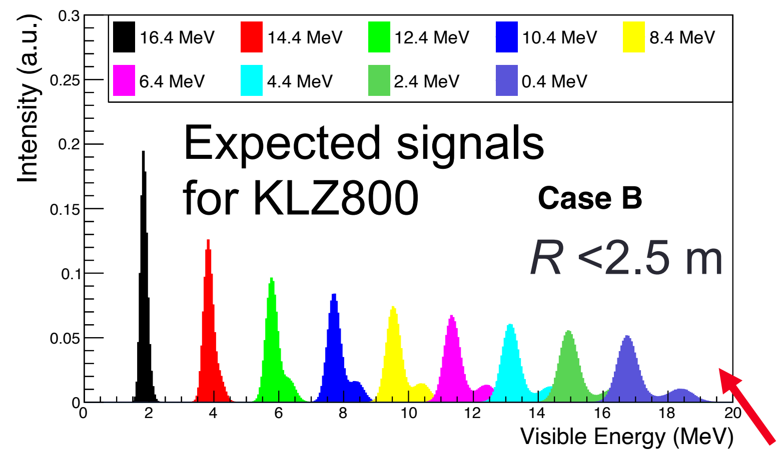
✓ **Low-BG environment**

[2]

Exps.	EXO-200/ Kaml.-Zen/ Xe100	DAMA NaI(Tl)	SNO NaCl	Bore-xino
Nucleus	Xe	I	Cl	C
$E_b^{(0)}$ (MeV)	18.4	18.2	6.3	2.7
MT (kg yr)	40/30/0.9	7.5	1274	1.3×10^5

KamLAND-Zen combines all of these things!



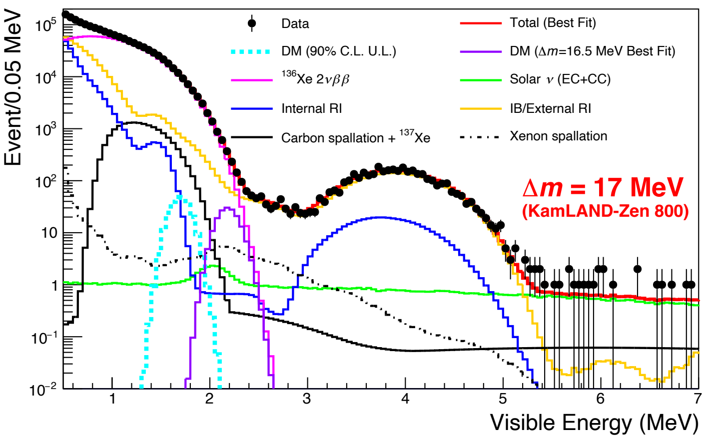


*The non-Gaussian distributions are due to the light yield difference in XeLS and KamLS.

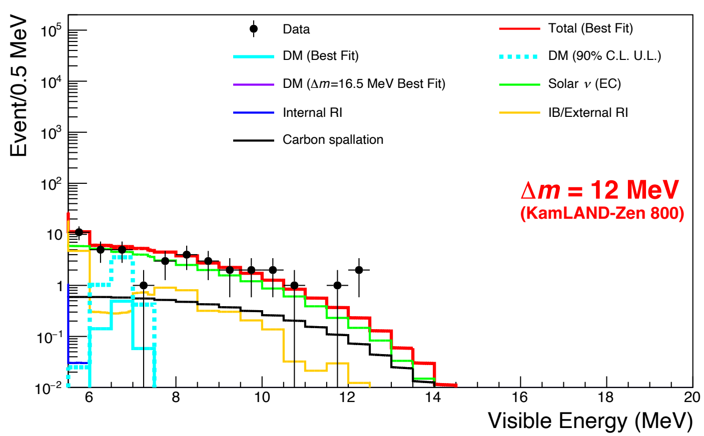
[2] H. An, M. Pospelov, J. Pradler, Direct constraints on charged excitations of dark matter, PRL 109 (2012) 251302

Dominant Backgrounds for DM search

◆Low energy region



◆High energy region



Double-beta decay of ^{136}Xe

- Inevitable BG source below 2.6 MeV

Cosmic-ray muon spallation products

- Carbon spallation + ^{137}Xe (short-lived)
- Xenon spallation (long-lived)

Radioactive impurities(XeLS, IB+KamLS)

- ^{238}U, ^{232}Th, ^{40}K, ^{85}Kr etc.

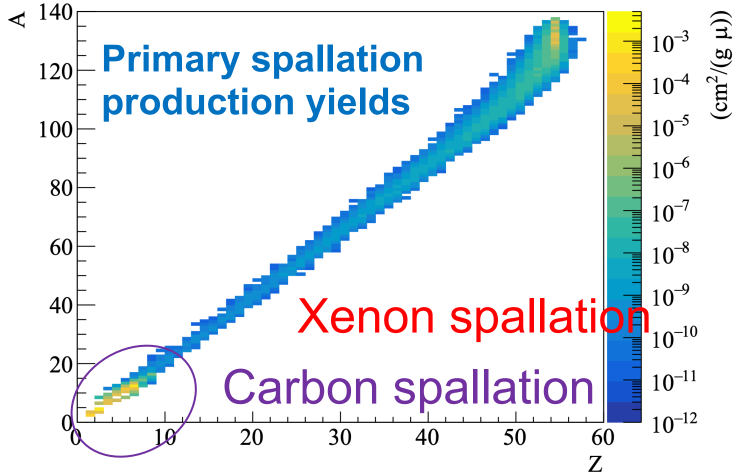
Neutrinos

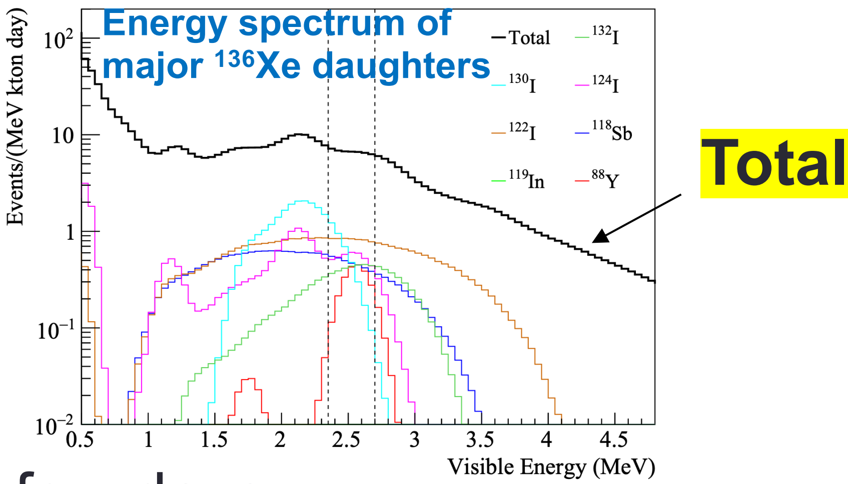
- Interactions by solar neutrinos

External gamma-rays

- The origins are the rock, PMTs, and the other detector components

Xenon spallation products

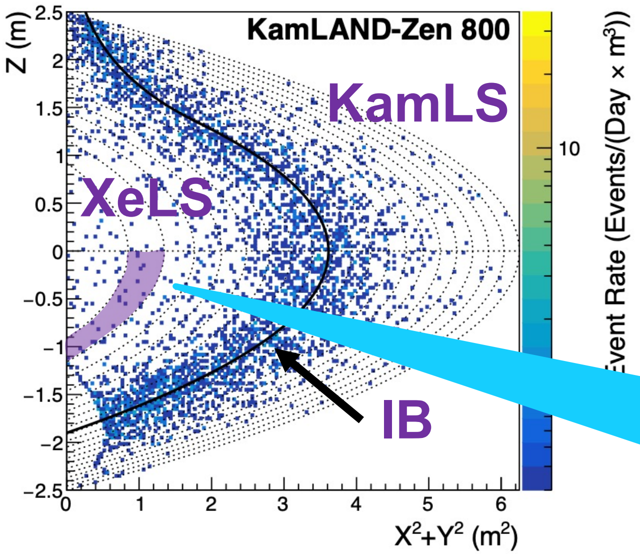




- Long life-time: a few hours or a few days
- Reject with a likelihood method (LL-veto)
  - Parameters: ① time difference from muon, ② distance between Xe-spallation and neutron capture gamma, ③ effective number of neutron
  - Rejection efficiency : 42.0 +/- 8.8 %

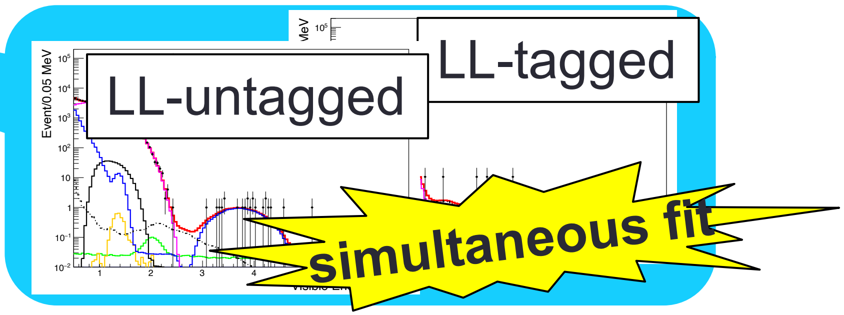
- Rejected data-set is also used for DM analysis (next page)
  - Events after the LL-veto (LL-untagged) : **DM candidates**
  - Rejected events (LL-tagged) : **xenon spallation candidates**

Method of DM analysis



Fiducial volume : *R* < 2.5 m

1. Separated dataset into **LL-untagged (DM candidates)** and **LL-tagged**
2. Simultaneous fit of 2 datasets with:
- some energy bins
- some equal-volume bins



The fitting condition is divided into two categories because of the main BG's distribution:

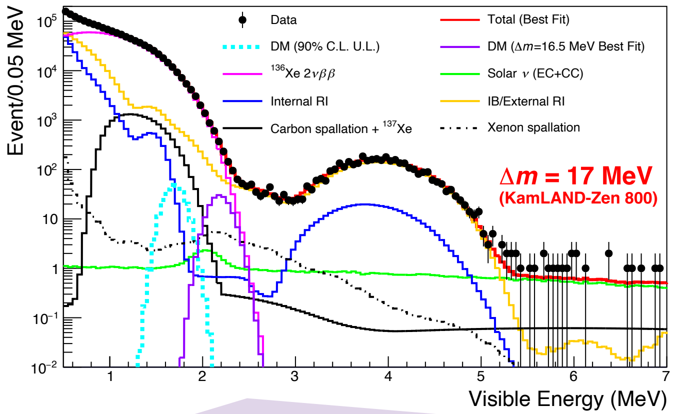
1. $\Delta m > 12$ MeV:

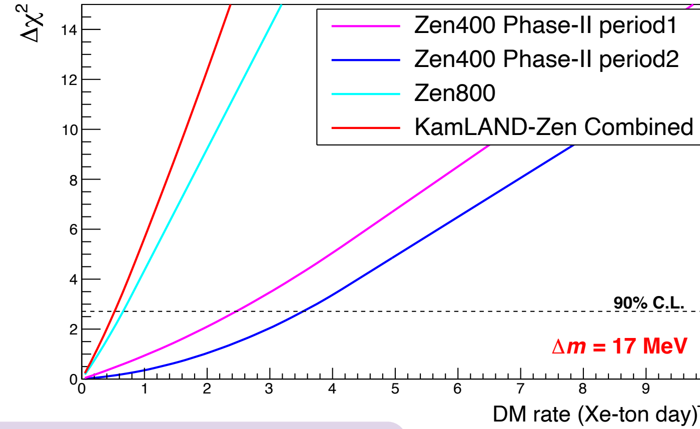
Complex BG distribution due to IB
- 130 energy bins (0.5—7.0 MeV)
- 40 equal-volume bins

2. $\Delta m \leq 12$ MeV:

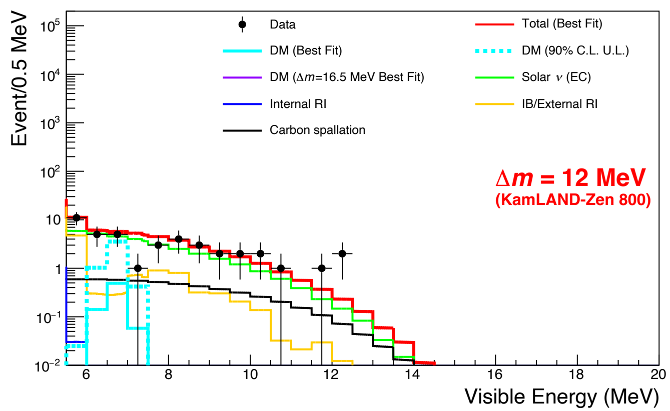
Uniform BG distribution
- 29 energy bins (5.5—20 MeV)
- 4 equal-volume bins

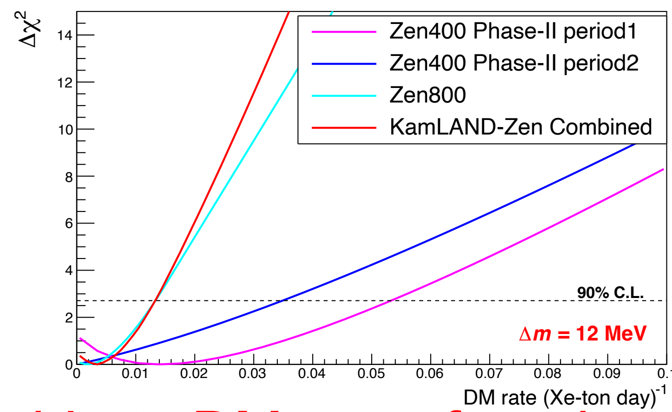
Search with KamLAND-Zen





3.4σ local significance for Δm = 16.5 MeV
→ 2.2σ global significance when accounting for the look elsewhere effect

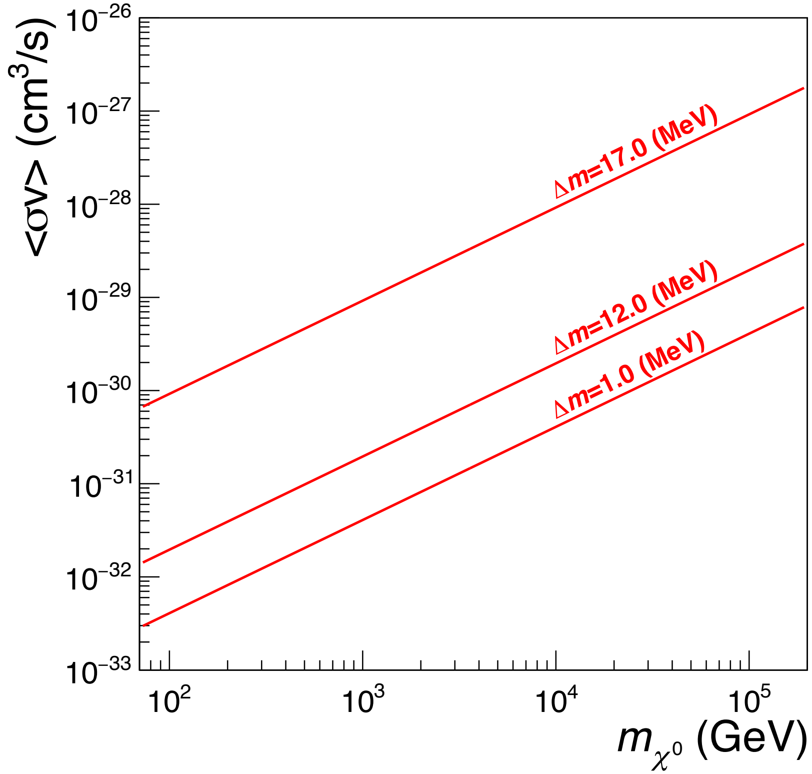




No significant excess of events attributable to DM were found.
The upper limits was set at 90% confidence level.

WIMP-nucleus recombination cross section

The limit for WIMP-nucleus recombination cross section $\langle \sigma v \rangle$ was set by DM event rate.



$$N_{tot} = \frac{MT\ N_T \rho_{DM} \langle \sigma v \rangle}{2 m_{\chi^0}} \epsilon_{det}$$

MT. : exposure (s kg)

N_T. : Number of target nuclei (/kg)

ρ_{DM} : DM local density (= 0.3 GeV/cm^3)

m_{χ^0} : WIMP mass

ϵ_{det} : Detection efficiency (%)

$\langle\sigma v\rangle$ can be converted to other physical parameters

Case A [2] **:** a decay width of a new particle $\boldsymbol{\Gamma_{\chi^-}}$

$$\langle\sigma v\rangle \approx \underbrace{\left(|g_{eL}|^2 + |g_{eR}|^2\right)}_{\text{Yukawa couplings}} \Big/ \left(8\pi m_{\chi^0}\right) \times \sum_{n,l} B_{n,l}$$

Contribution from capture into state (n,l)

$$\boldsymbol{\Gamma_{\chi^-}} = \tau_{\chi^-}^{-1} \approx \frac{\sqrt{\Delta m^2 - m_e^2}}{4\pi m_{\chi^0}} \left(\Delta m + m_e\right) \left(|g_{eL}|^2 + |g_{eR}|^2\right)$$

Case B [2]**:** the effective coupling $\boldsymbol{g_{\mathrm{eff}}}$

$$\langle\sigma v\rangle \approx \frac{g_{eff}^4 m_p^2}{8M_w^4} \int d^3r \rho_n(\vec{r}) \int_{m_n}^{m_n + \frac{p_{nF}^2}{2m_n}} \frac{dp_n^0}{\frac{4}{3}\pi p_{pf}^3} \sqrt{\left(-V(r) - \Delta m + p_n^0\right)^2 - m_p^2} \sqrt{{p_n^0}^2 - m_n^2}$$
$$\times \theta\left(-V(r) - \Delta m + p_n^0 - m_p - \frac{p_{pF}^2(N_{Z+1})}{2m_p}\right)$$

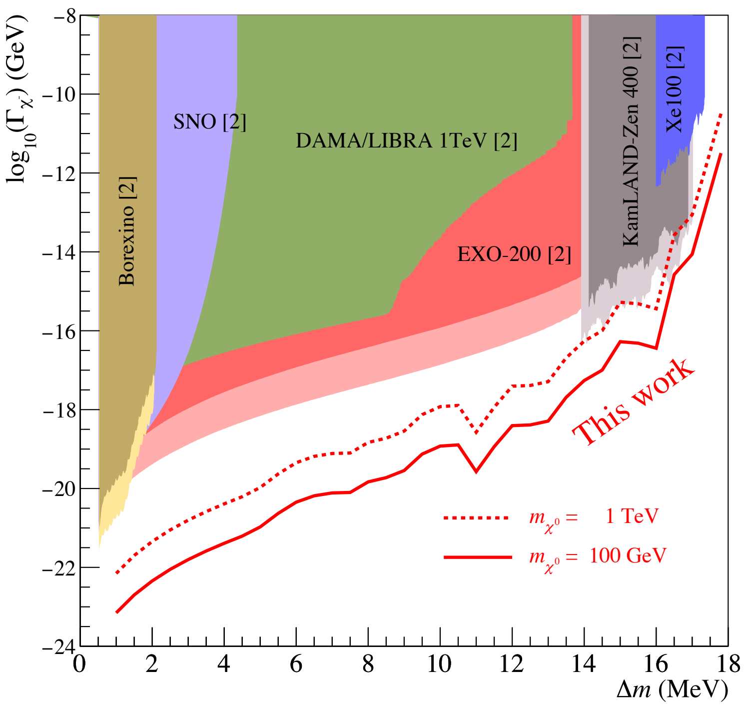
[2] H. An, M. Pospelov, J. Pradler, Direct constraints on charged excitations of dark matter, PRL 109 (2012) 251302

Results

arXiv:2311.09676v1

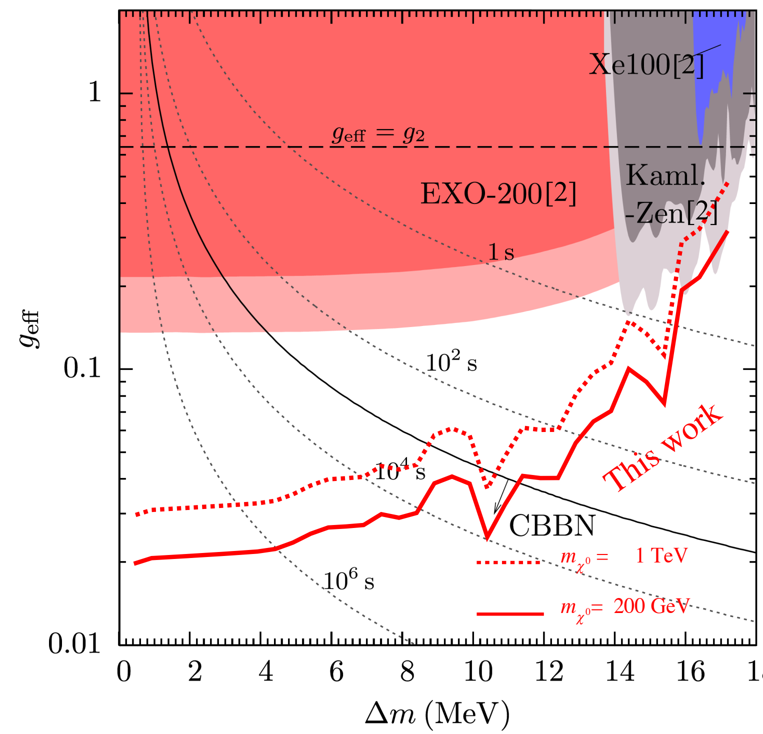
Case A [2] :

a decay width of a new particle Γ_{χ^-}



Case B [2] :

the effective coupling g_{eff}



The most stringent limits on the charged excited states of DM!!

* Filled regions are expected sensitivity [2].

[2] H. An, M. Pospelov, J. Pradler, Direct constraints on charged excitations of dark matter, PRL 109 (2012) 251302

Summary

- KamLAND-Zen is an experiment that searches for $0\nu\beta\beta$ of ^{136}Xe with xenon loaded liquid scintillator.

- BSM at KamLAND-Zen:
  - $0\nu\beta\beta$:
    - KLZ set limit $\langle m_{\beta\beta} \rangle < 36 - 156$ meV
    - The target of KL2-Zen is $\langle m_{\beta\beta} \rangle = 20$ meV

  - Majoron Emission in $0\nu\beta\beta$:
    - KLZ800 is expected to improve several times over of KLZ400 result and will perform the first search for massive majoron emission in the world.

  - Charged exited stats of DM :
    - KLZ set the most stringent limits.