Search for Charged Excited States of Dark Matter with KamLAND-Zen

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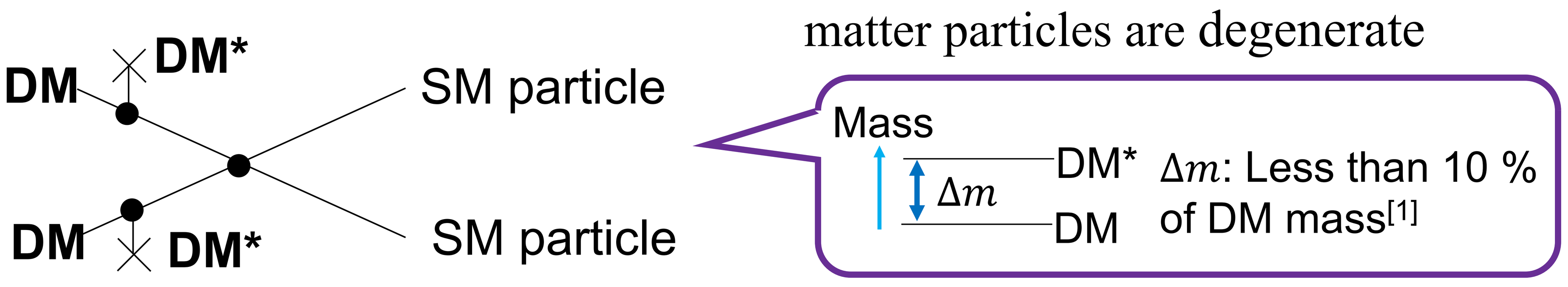
WIMPs and co-annihilation

The standard WIMP scenario assumes thermal equilibrium between DM and SM particles in the early stages of the Universe.
→ ⟨σv⟩, explaining the current dark matter abundance is $3\times10^{-26}\mathrm{cm^3/s}$.

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

Co-annihilation: the masses of dark matter particles are degenerate



Charged exited states of Dark Matter

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

[2]

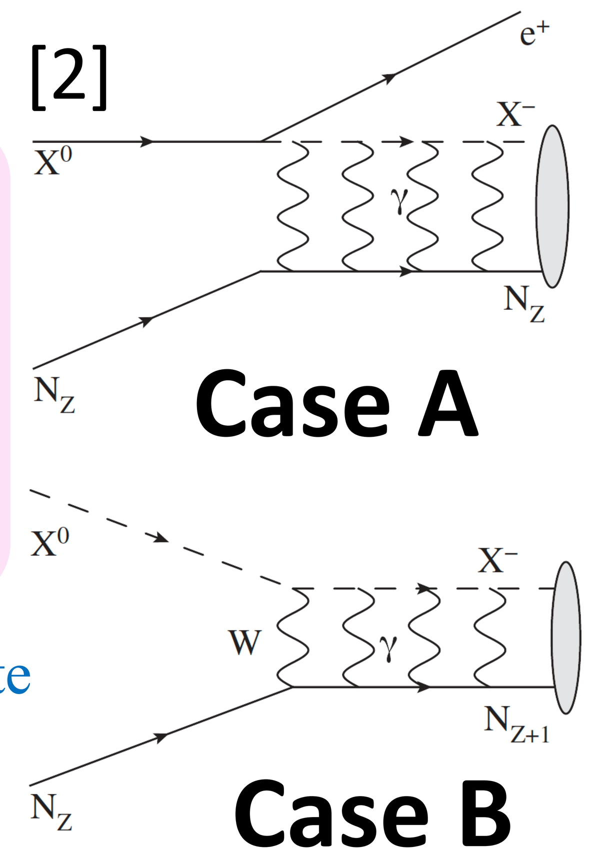
Case A: positron is emitted

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

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

Annihilation γ

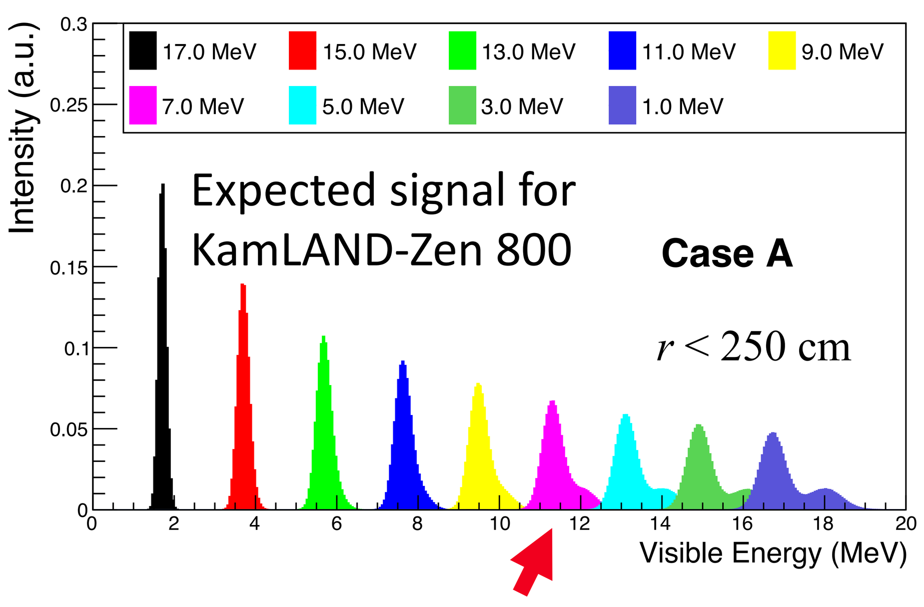
$$E_{tot} = \begin{cases} E_b^{(0)} - \Delta m + m_e\ (\textbf{Case A})\ (= E_{e^+} + E_\gamma + 2m_e) \\ E_b^{(0)} - \Delta m + m_Z - m_{Z+1}\ (\textbf{Case B})\ (= E_\gamma) \end{cases}$$

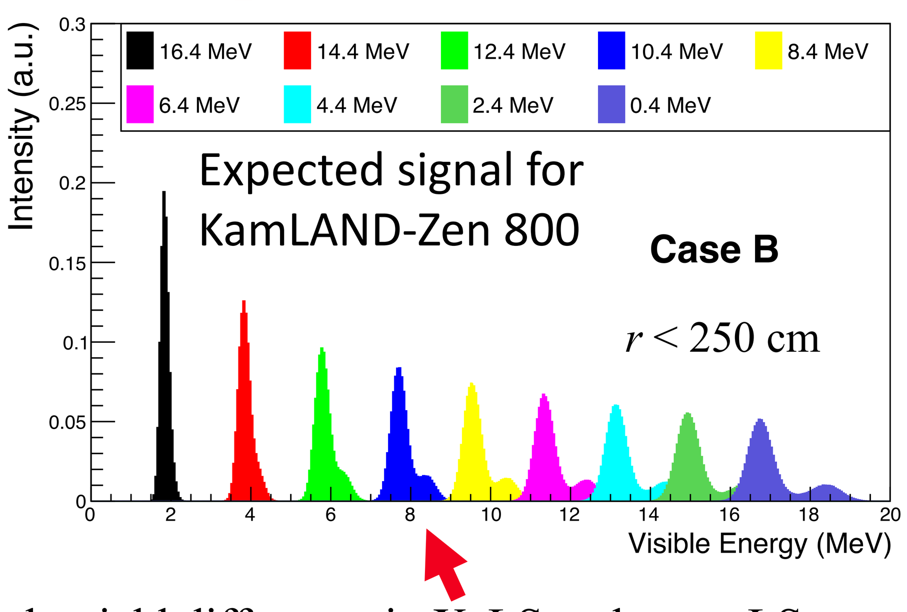
$E_b^{(0)}$: the binding energy of the ground state of the bound states with the nucleus (depends on the target nucleus: O(1-10 MeV), **18.4 MeV for Xenon**)

[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

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

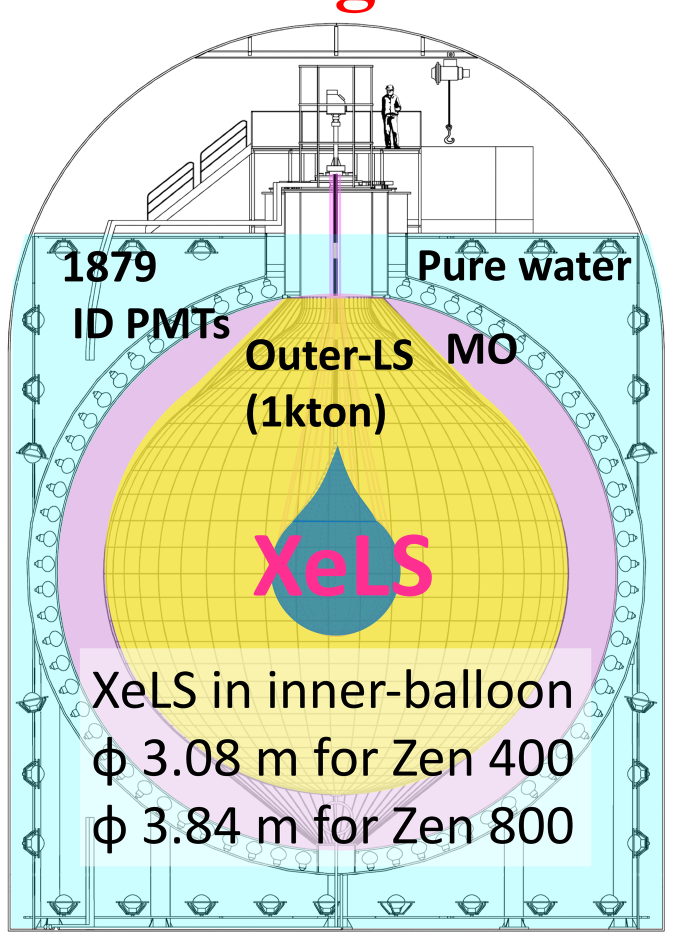




The non-Gaussian distributions are due to the light yield difference in XeLS and outer-LS.

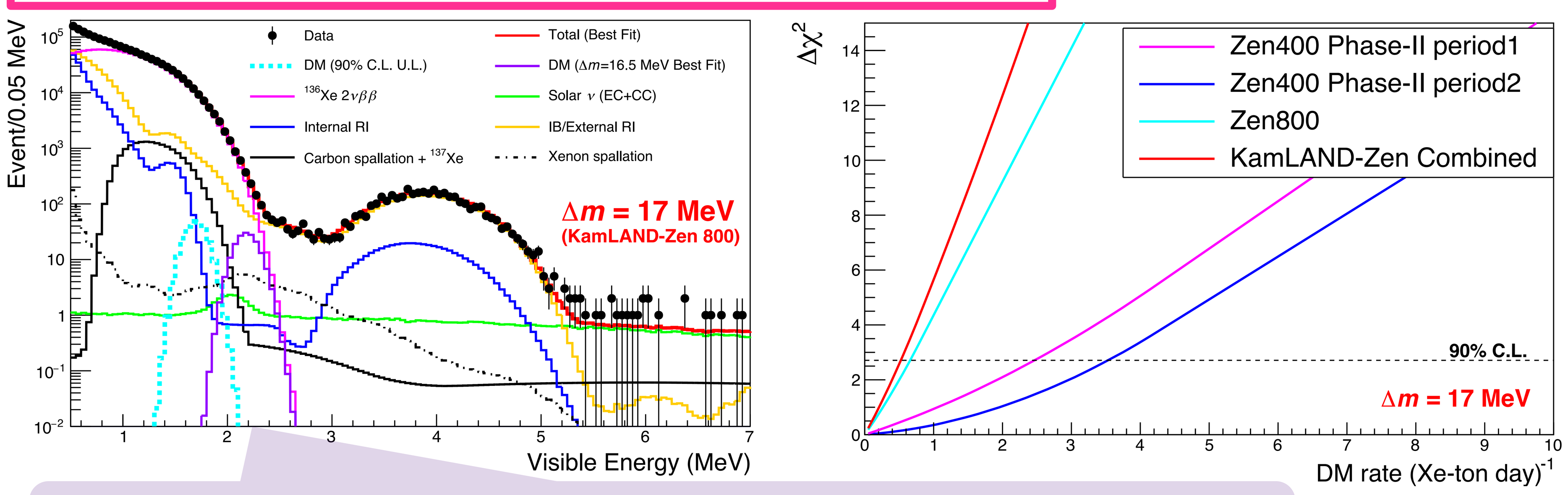
KamLAND-Zen Experiment

KamLAND-Zen is the suitable detector to search the charged exited state of DM

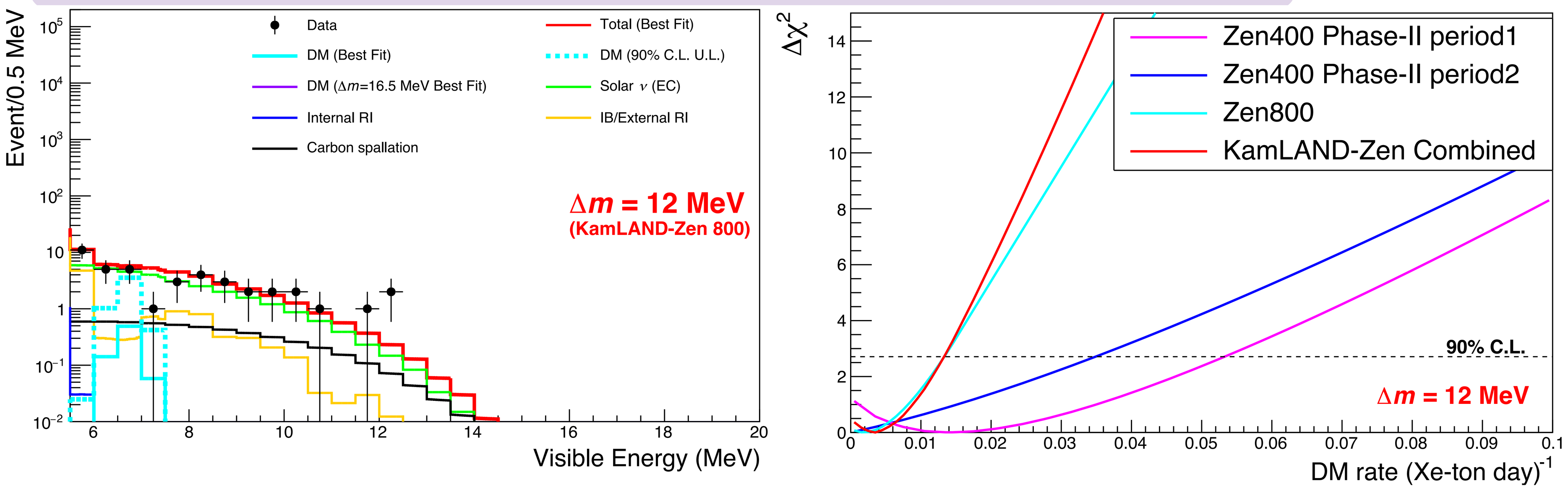


- ✓ **Sensitive to O(1-10) MeV energy range**
- ✓ Low-BG environment
- ✓ Large volume liquid scintillator detector with Xenon nuclei
  - **383 kg in KamLAND-Zen 400 Phase-II**
  - **745 kg in KamLAND-Zen 800**

Search with KamLAND-Zen



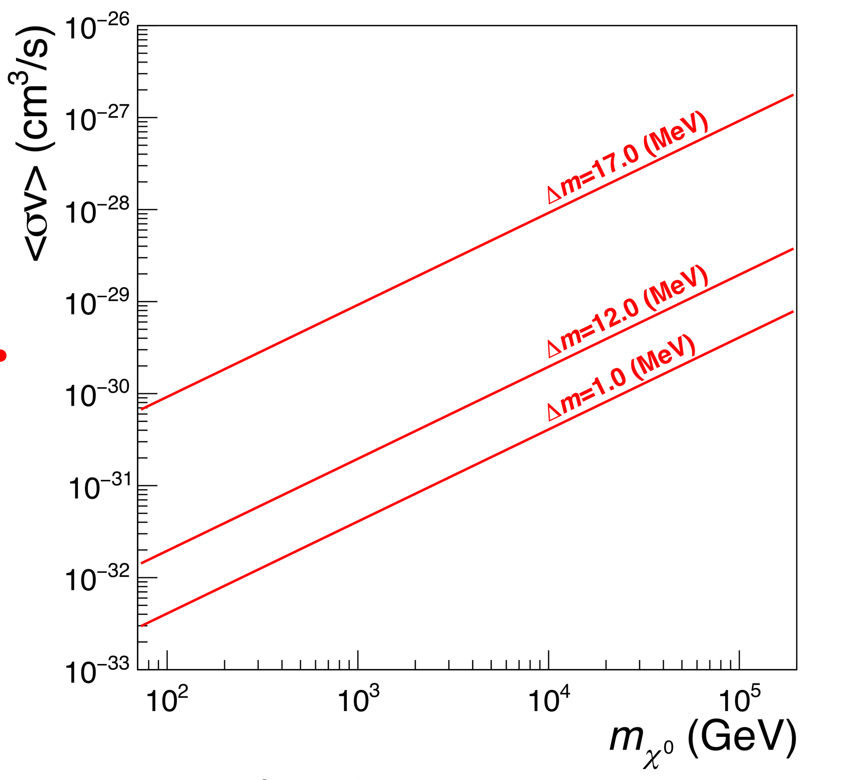
3.4σ local significance for Δm = 16.5 MeV
→ 2.2σ global significance when accounting for the look elsewhere effect



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

The limit for WIMP-nucleus recombination cross section ⟨σv⟩ was set by DM event rate.

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



⟨σv⟩ can be converted to other physical parameters.

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

Contribution from capture into state (n,l)

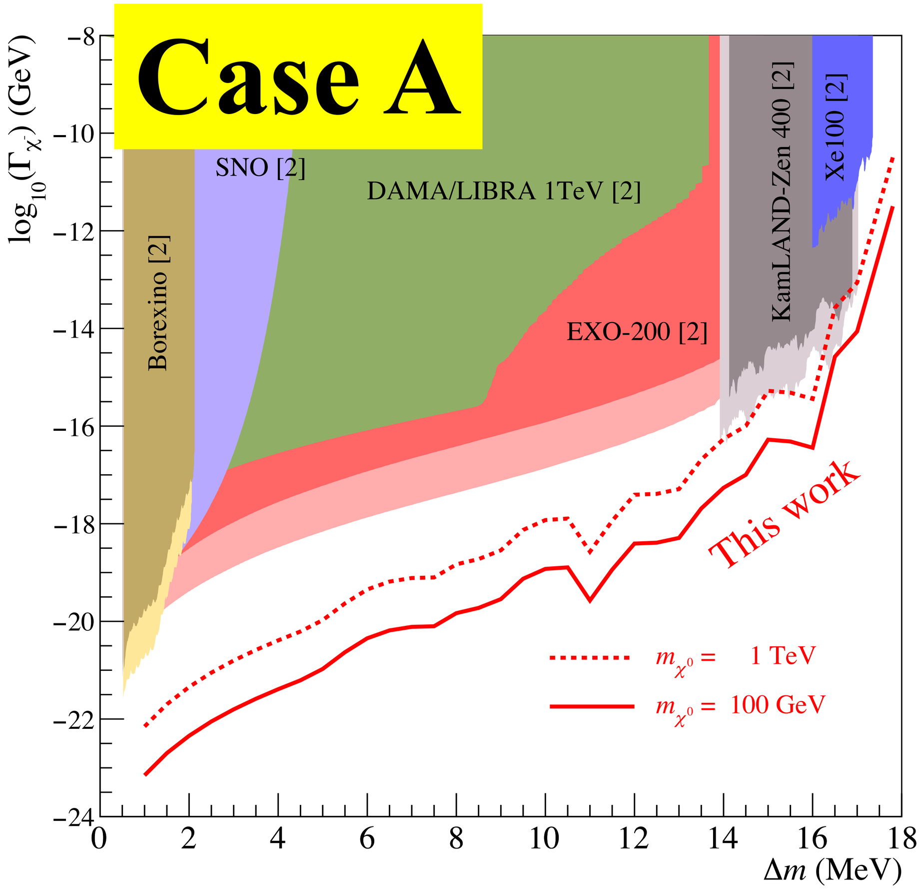
$$\langle\sigma v\rangle \approx \left(|g_{eL}|^2 + |g_{eR}|^2\right) \big/ (8\pi m_{\chi^0}) \times \sum_{n,l} B_{n,l}$$

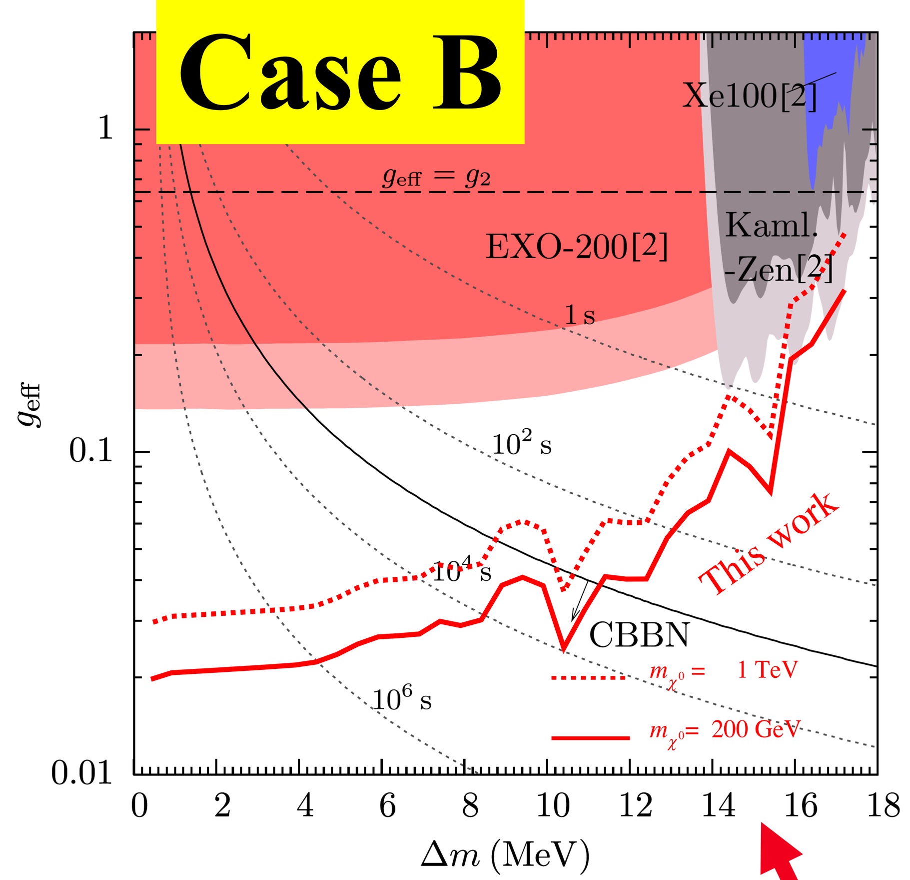
Yukawa couplings

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

Case B: the effective coupling g_{eff}

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





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

* Filled regions are expected sensitivity [2].

Summary

- KamLAND-Zen performed searches for the bound state formation of a xenon nucleus and the electrically charged WIMP state.
- The most stringent limits were obtained.

Ref::[1] K. Griest, D. Seckel, PRD 43 (1991) 3191, [2] H. An, et al., PRL 109 (2012) 251302.