Dark Matter Annual Modulation Analysis with Combined Nuclear & Electron Recoil Channels

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Dark matter annual modulation analysis with combined nuclear and electron recoil channels

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(TEXONO Collaboration)

Based On

Overview

- ❑ Introduction and Motivation
- ❑ Input Data
- ❑ Expected Spectra
- ❑ Cross Section
- ❑ Analysis
- ❑ Results and Interpretations
- ❑ Summary and Conclusions

Introduction & Motivation

Compelling Experimental Evidence (Cosmological Observations)

- One-quarter of Energy density of Universe == Composed of Dark Matter
- Exact Nature & Properties remain Unknown
  - Non-luminous & Non-baryonic
- Inferred Only from Gravitational Effects

Search Efforts

- Numerous Directions
- Diverse Techniques
- Intense areas of Fundamental Research
- Favored Candidate ⇒ WIMPs (χ)

Direct Experimental Search

- Assume Finite Interactions:: WIMPs with Electrons (χ_e) & Nuclei (χ_N)
- *Positive Signatures*::
  - Excess Events over known BKG [Measured Time-Integrated (TI) Energy Spectra]
    Sensitive to Uncertainties of BKG Modeling
  - Annual Modulation (AM) [Changes of Relative velocity between Earth & WIMPs in Galactic Halo]
    Only requires stable BKG with time & Independent of other details

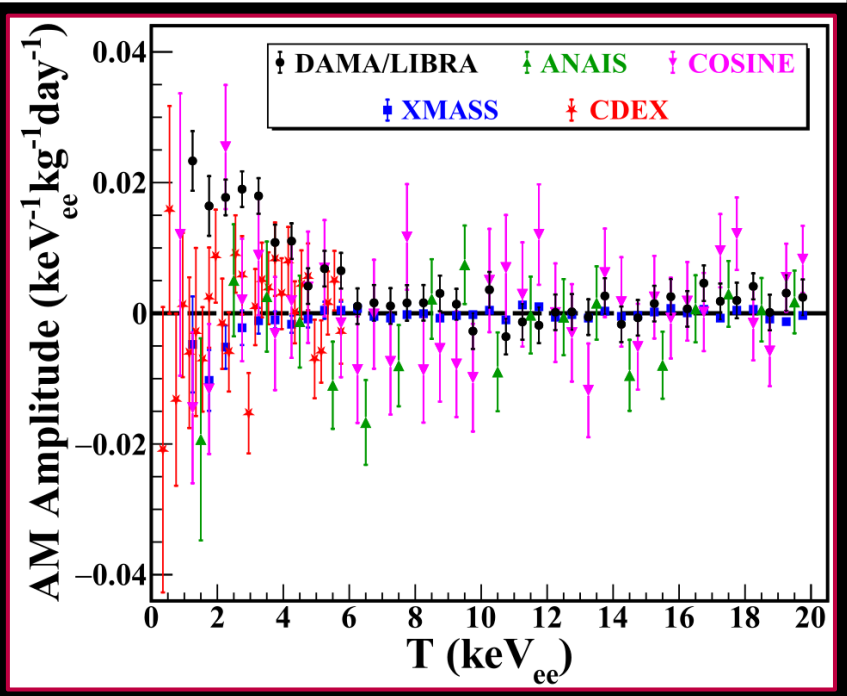
Decades of Experimental Efforts

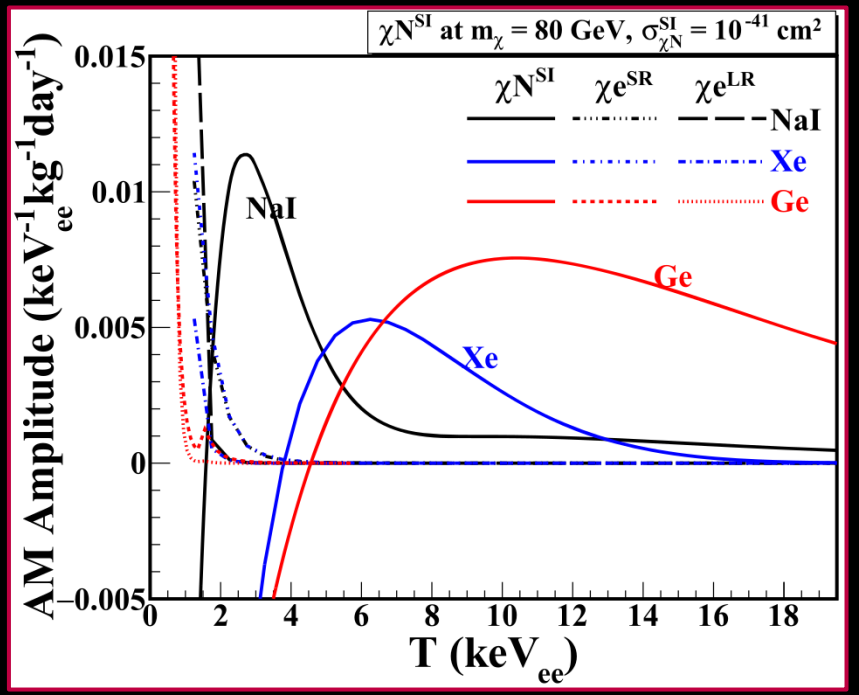
- Only Result:: Consistent with Positive WIMP Signatures is from AM analysis on χN from DAMA/LIBRA (DL) [NaI(Tl)]
- Challenged & Rejected:: Numerous Experiments + Variety of Targets
- Attempts to Explain:: Scenarios other than χN detection [e.g. complications in Analysis procedures]
- Present Study:: Analysis including both χe & χN interactions
- Three Interactions:: SI χN^{SI}, Long & Short-range χe^{LR} & χe^{SR}

Input

1. Published AM Amplitudes Data !

- [NaI(Tl)]:: [DL, ANAIS, COSINE], [Xe] XMASS, [Ge] CDEX
- Complementary in Strength:: Probe Different Parameter Space

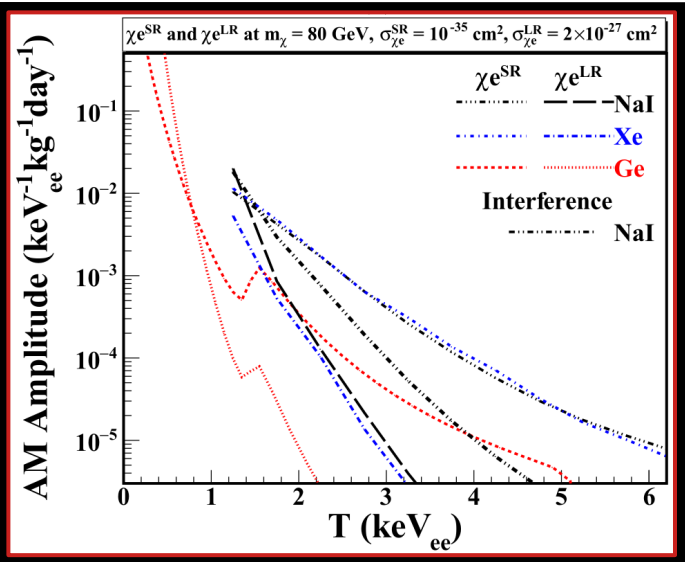


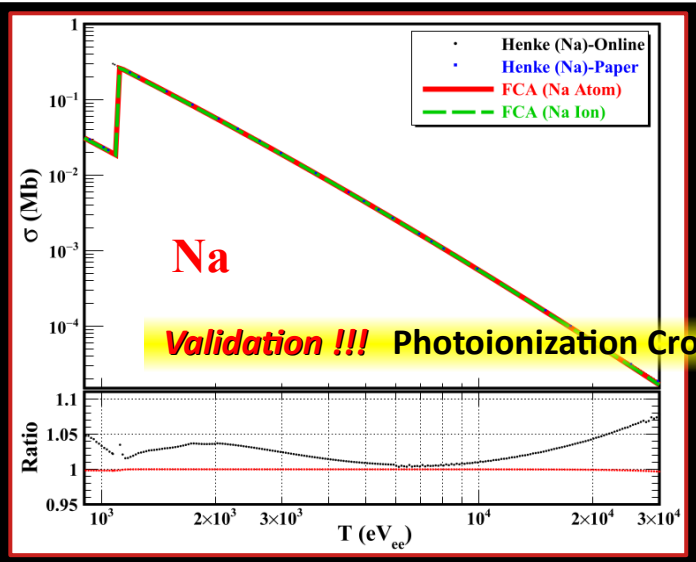


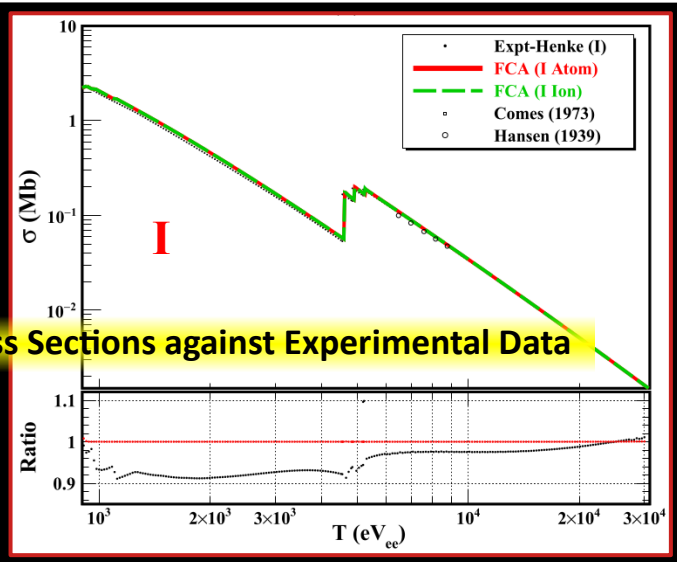
2. Expected Differential Spectra [χN^{SI}]

- Origin:: Differences in χ-velocity relative to Earth
- Maximum (minimum) Amplitudes :: June 1 (December 2)
- Feature :: Drop from Enhancement to Deficit at LE
- Turning Point ⇒ m_χ-dependent

Input







Validation !!! **Photoionization Cross Sections against Experimental Data**

3. Differential AM Spectra [χe^{LR} & χe^{SR}]

- ❒ χe Recoil Energy
  - I. Rapidly Rising Spectra
  - II. Only Data < 4 keVee ➡ Contribute to Analysis
- ❒ χe^{LR} Interactions has Additional $1/q^2$ term
  - I. Rise More Steeper @ Low Recoil Energy
  - II. Favor experiments with Lower Detection Threshold
- ❒ Very Different Response at LE from χN^{SI}

4. Cross-Section

[Talk: Prof. Cheng-Pang Liu → ID 359 *!*]

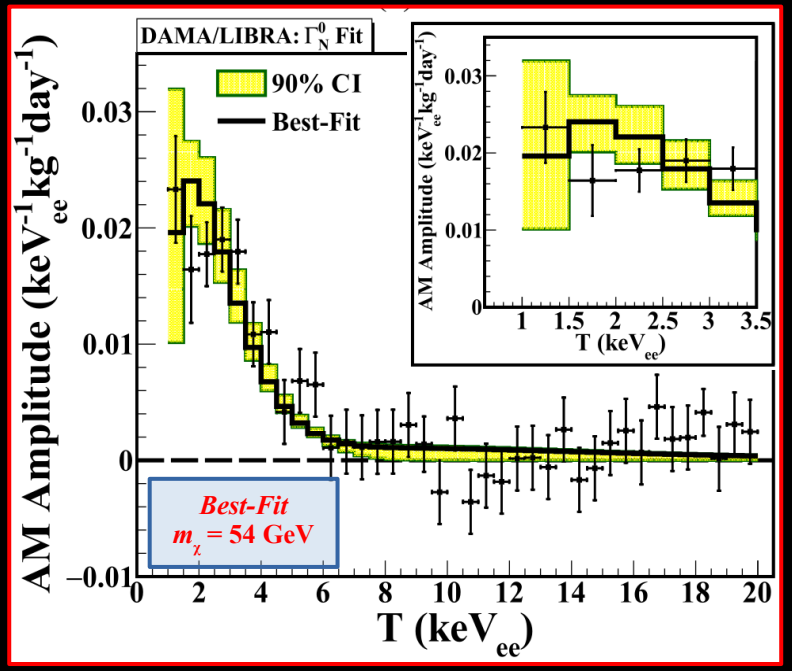
- ■ χe Detection Channel ➡ $\chi + A \rightarrow \chi + e^- + A^+$
- ■ Frozen Core Approximation (FCA) — PRD 102,123025 (2020)
  - I. Experience on Ge & Xe ➡ Extend same approach to Na & I
  - II. Consistency Within ~ 5% [Across Energy Range of 1-30 keVee]
  - III. Identical Results [Whether Targets treated as Atoms or Ions]
  - IV. Indicates:: Reliable Modeling to Interactions of χ with Atoms

Analysis

Best-fit Estimate Cross Sections @ Given m_χ

$$\chi^2 = \sum_i \frac{1}{\Delta_i^2}\{n_i - [\sigma^{SI}_{\chi N}\phi^{SI}_{\chi N}(T_i) + \sigma^{LR}_{\chi e}\phi^{LR}_{\chi e}(T_i) + \sigma^{SR}_{\chi e}\phi^{SR}_{\chi e}(T_i) + 2\sqrt{\sigma^{LR}_{\chi e}\sigma^{SR}_{\chi e}}\phi^{int}_{\chi e}(T_i)]\}^2$$

n_i & Δ_i [AM Amplitudes & Uncertainties], ϕ [Normalized Spectral Functions]



DL Data::

I. Positive AM Signatures & Reject Null Hypothesis [@ Large Significance]

II. Best-fit Spectra only with χN-channel [Γ^0_N: $\sigma^{LR}_{\chi e} = \sigma^{SR}_{\chi e} = 0$]

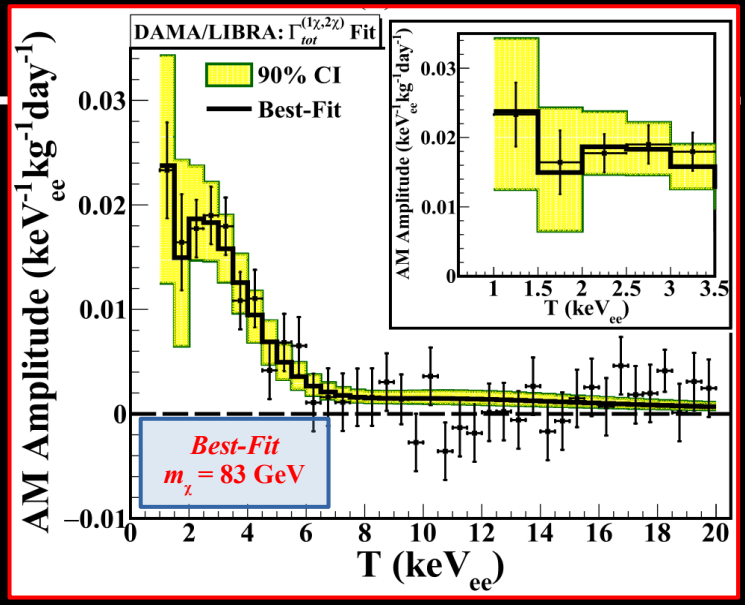
III. Analysis Expands :: All Three Channels as free fitting variables

Two DM Scenarios::

1. Parametrized by f_χ as DM Relic Density Fraction from χ interacting via χe
2. $\Gamma^{1\chi}_{tot}$ → Both χN & χe Interactions are due to a single χ ($f_\chi = 1$)
   [Same constraints on m_χ apply to All Channels]
3. $\Gamma^{2\chi}_{tot}$ → Case of Independent constraints
   [Two different χ with fractional density f_χ & $(1 - f_\chi)$ interact separately via χe & χN]
4. Limiting Case ($f_\chi = 0$) → Corresponds to Baseline Γ^0_N

Analysis

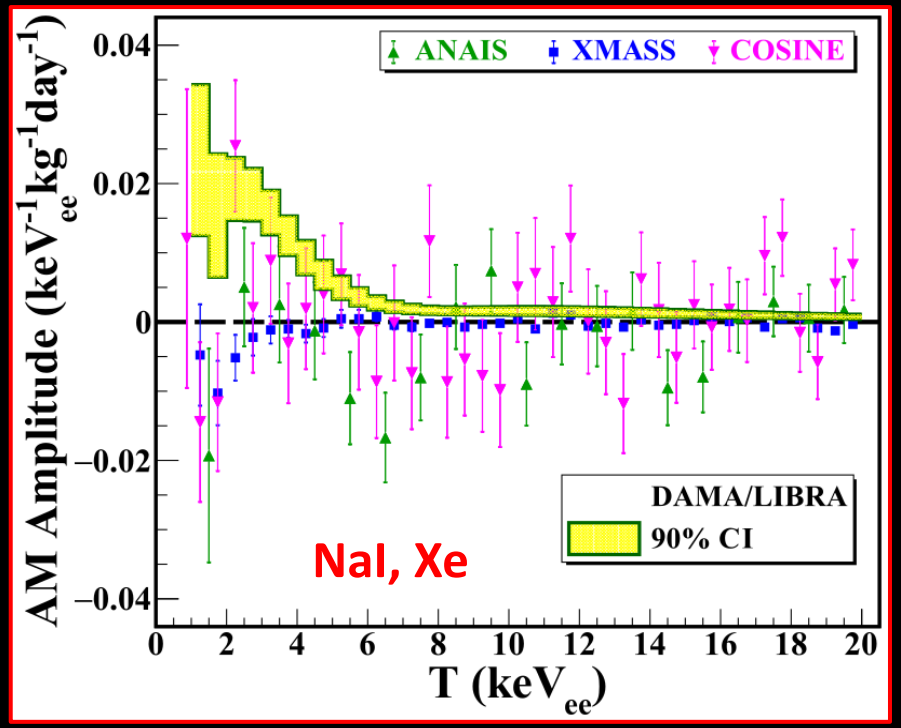
- Combined best-fit in $\Gamma^{1\chi}_{tot}$ == Spectra for $\Gamma^{2\chi}_{tot}$
  - ☞ Shifted m_χ from 54 GeV in Γ^{0}_{N} to 83 *GeV in* $\Gamma^{1\chi}_{tot}$
- Addition of χe-Channels ⇒ *Better Description* data < 4 keVee
- Interpretation of DL data incorporating $\Gamma^{(1\chi,\,2\chi)}_{tot}$::
  - I. Statistical Significance higher than Γ^{0}_{N} alone
  - II. LE data (1-4 keVee) gives p-values of 0.52 for $\Gamma^{(1\chi,\,2\chi)}_{tot}$ but only 0.07 for Γ^{0}_{N}
    - ☞ χN^{SI} Channel as Sole Physics scenario cannot Explain LE data
  - III. Differences in χ^2/d.o.f. between Γ^{0}_{N} & $\Gamma^{(1\chi,\,2\chi)}_{tot}$ ⇔ p-values of 0.02 & 0.008
    - ☞ Implies Additional physical processes (χe^{LR} & χe^{SR}) to Explain AM spectrum
  - IV. For Complete 1-20 keV dataset :: χ^2/d.o.f. in $\Gamma^{(1\chi,\,2\chi)}_{tot} < 1$
    - ☞ Suggests a Scenario ⇒ Published uncertainties are overestimated
  - V. TEST Case :: Uncertainties of DL data Uniformly reduced by 20%
    - ☞ Resulting in p-value = 0.5
    - ☞ Tension against Γ^{0}_{N} as a Valid Hypothesis is Stronger
    - ☞ $\Gamma^{(1\chi,\,2\chi)}_{tot}$ shows a Perfect Agreement with Data

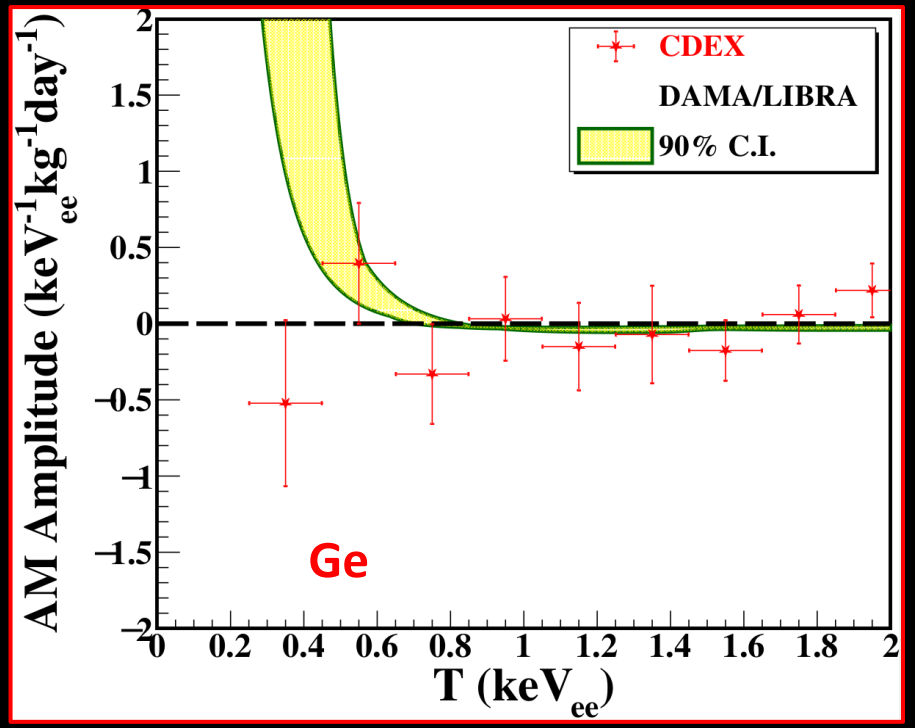


Data (keVee)	Γ^{0}_{N}:: χN^{SI}	$\Gamma^{(1\chi,2\chi)}_{tot}$:: $\chi N^{SI} + \chi e^{LR} + \chi e^{SR}$	Compare
	χ^2/d.o.f. (p-value)		$\Delta\chi^2$/d.o.f. (p-value)
Published Data			
1-20	32.06/36 (0.66)	22.40/34 (0.94)	9.66/2 (0.008)
1-4	8.6/4 (0.07)	1.3/2 (0.52)	7.26/2 (0.02)
Test Case (Effects or reduced uncertainties)*			
1-20	48.1/36 (0.086)	**33.33/34 (0.50)***	14.8/2 (0.0006)
1-4	12.8/4 (0.012)	1.94/2 (0.38)	10.86/2 (0.0044)

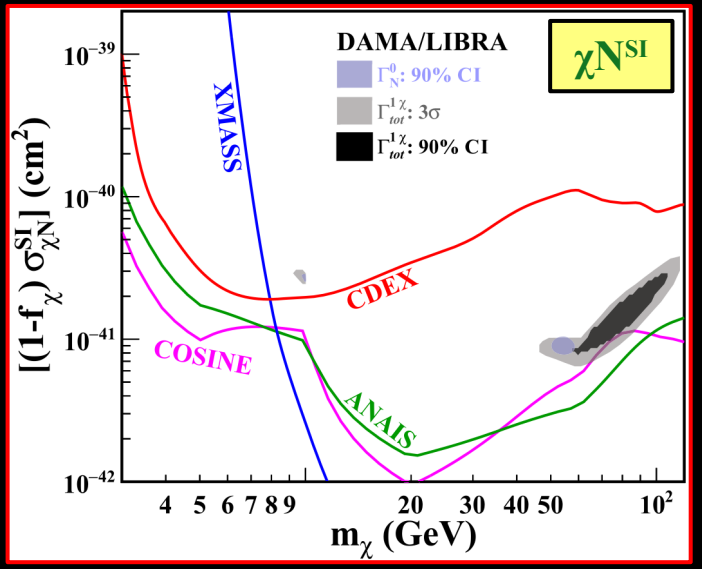
Analysis

- **No AM Signatures Observed:: COSINE, ANAIS, XMASS, CDEX**
  - ☞ Data consistent with Null Hypothesis
- **Predicted Spectra for Null AM Experiments**
  - ☞ Due to $\Gamma^{(1\chi,2\chi)}_{tot}$ best-fit values of (χN^{SI}, χe^{LR}, χe^{SR}) derived from DL AM data
  - ☞ Shows:: Incompatibility of DL best-fit values with Null AM Experiments



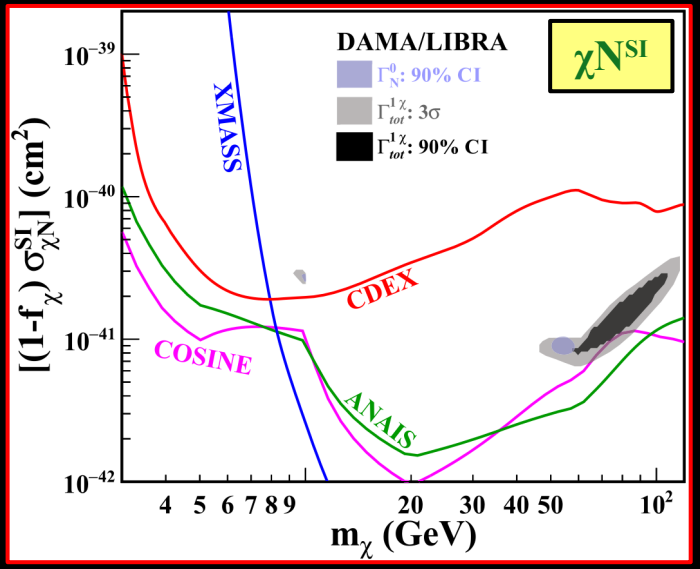


Results & Interpretations:: Case of $\Gamma^{1\chi}_{tot}$

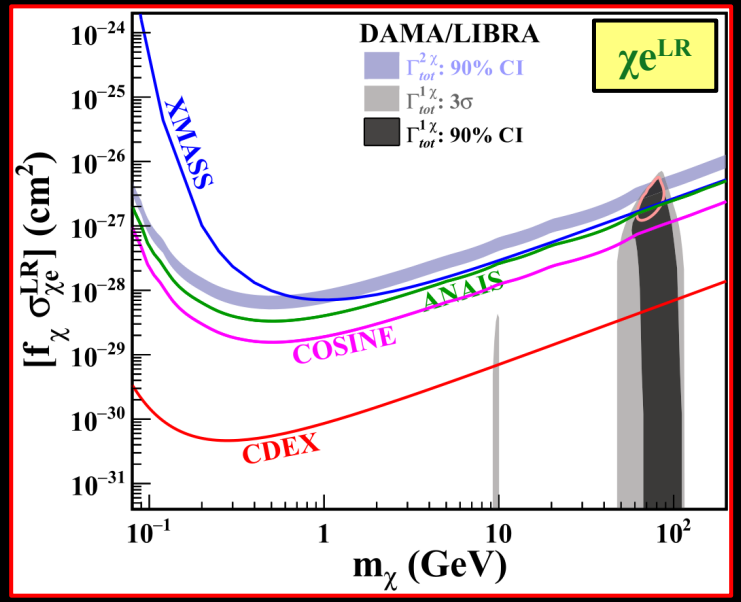


- Two Allowed Regions in Γ^0_N::
  @ Low & High m_χ ➡ Na & I-recoils
- With χe^{LR} & χe^{SR} Added in $\Gamma^{1\chi}_{tot}$::
  Only high m_χ Region [I-recoils] ➡ Allowed
  @ Same Significance
- Best-fit Solution of m_χ::
  Shifted from 54 GeV in Γ^0_N to 83 GeV in $\Gamma^{1\chi}_{tot}$

Results & Interpretations:: Case of $\Gamma^{1\chi}_{tot}$



- **Dominance::**
  - I. χe-Channels ➡ [Near-Threshold behavior]
    Highly Correlated & Share Strength @ LE
  - II. χN ➡ HE (> 3 keVee) Spectra
- **Limiting Case of Best-fit value::**
  @ $\sigma^{SR}_{\chi e} = 0$ ➡ Light Red Circle [Allowed Region]
- **Weaker bounds in $\sigma^{LR}_{\chi e}$ Originates::**
  - I. Sharper Rise of AM Spectra [$1/q^2$] Dependence
  - II. Low threshold CDEX ➡ Strong Constraints



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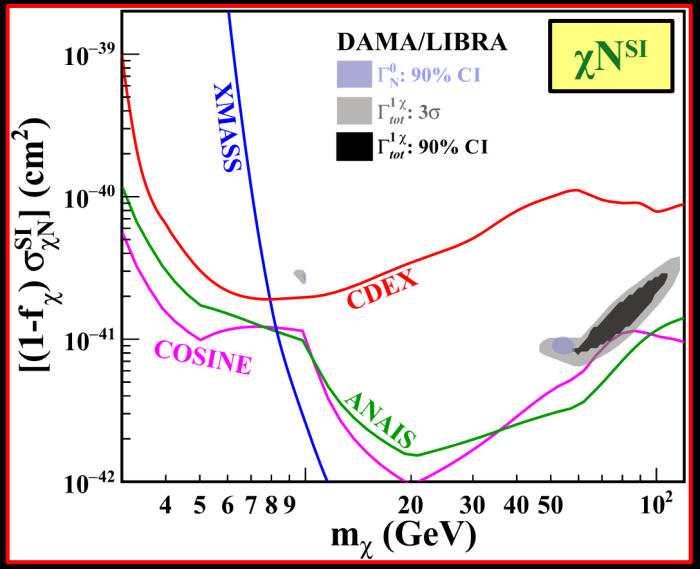

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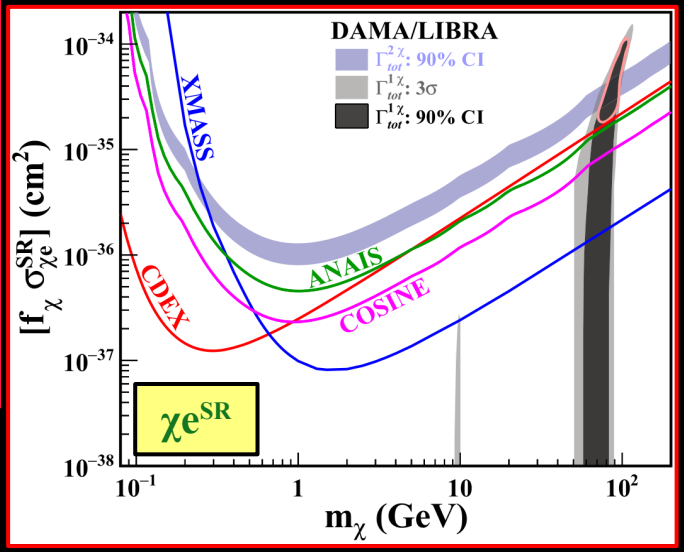
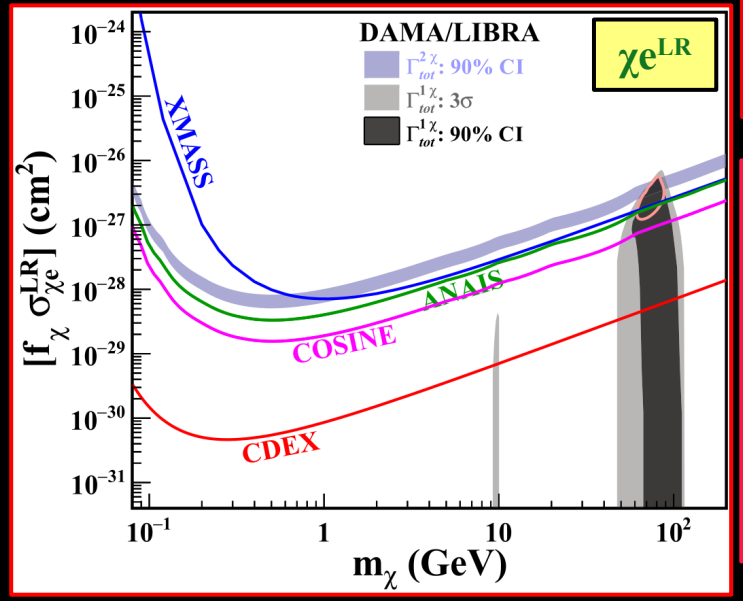




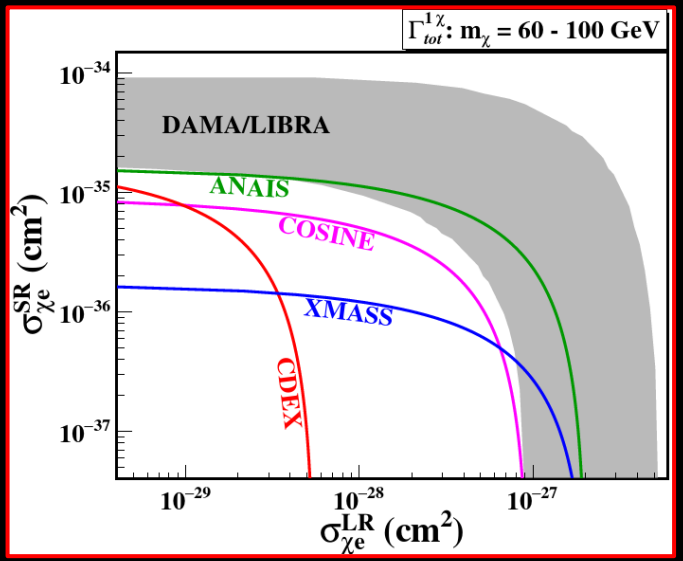
- **Two Allowed Regions in Γ^{0}_{N}::**
  @ Low & High m_χ ⇒ Na & I-recoils
- **With χe^{LR} & χe^{SR} Added in $\Gamma^{1\chi}_{tot}$::**
  Only high m_χ Region [I-recoils] ⇒ Allowed
  @ Same Significance
- **Best-fit Solution of m_χ::**
  Shifted from 54 GeV in Γ^{0}_{N} to 83 GeV in $\Gamma^{1\chi}_{tot}$

- **Limiting Case of Best-fit value::**
  @ $\sigma^{LR}_{\chi e} = 0$ ⇒ Light Red Circle [Allowed Region]
- **Interdependent Allowed Regions::**
  - I. Low Cross Section Portion of [$\sigma^{LR}_{\chi e}$, $\sigma^{SR}_{\chi e}$]
    Allowed Regions remains Unprobed
  - II. Correlation Allowed Space::
    Correlated with High Cross Section Region of its Counterparts ⇒ ***Rejected by Null AM Experiments***

Results & Interpretations:: Case of $\Gamma^{1\chi}_{tot}$

- **Correlations::**
  - I. Combined Constraints of $[\sigma^{SR}_{\chi e}, \sigma^{LR}_{\chi e}]$
  - II. Null AM experiments ⇒ *Reject Entire DL Allowed region in* $\Gamma^{1\chi}_{tot}$
- **Exclusion Margins::**
  Particularly Large through Combined constraints of CDEX & XMASS

Case of $\Gamma^{1\chi}_{tot}$



Results & Interpretations:: Case of $\Gamma^{2\chi}_{tot}$

- **Correlations::**
  - I. Combined Constraints of $[\sigma^{SR}_{\chi e}, \sigma^{LR}_{\chi e}]$
  - II. Null AM experiments ➡ *Reject Entire DL Allowed region in $\Gamma^{1\chi}_{tot}$*
- **Exclusion Margins::**
  Particularly Large through Combined constraints of CDEX & XMASS

❒ $\Gamma^{2\chi}_{tot}$:: χN & χe Interactions [Two Different χ]

☞ **Independent Constraints** ➡ High & Low Energy AM Spectral Components

☑ HE Component Define ➡ DL χN^{SI} Allowed Regions ➡ Excluded by Null Expts.

☑ LE Component Dominated by χe Channels ➡ Different χ Unconstrained in m_χ

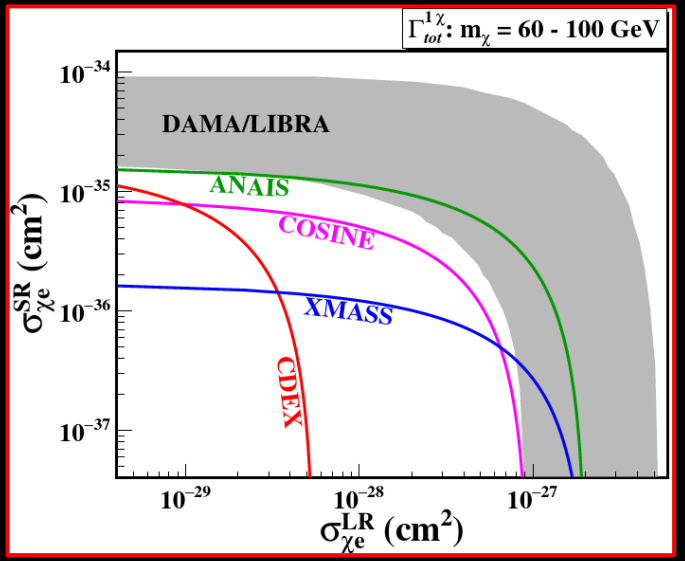
☑ Yields Allowed Regions in $\Gamma^{2\chi}_{tot}$ ➡ Light blue bands $[\sigma^{LR}_{\chi e}, \sigma^{SR}_{\chi e}]$

❒ $\Gamma^{2\chi}_{tot}$ Scenario ➡ **Excluded by Null AM Expts.** ➡ Independently in $[\sigma^{LR}_{\chi e}, \sigma^{SR}_{\chi e}]$

☑ CDEX [Severe Constraints on $\sigma^{LR}_{\chi e}$] → $1/q^2$ dependence → Favors Low Threshold Expts.

☑ XMASS → Sensitive to $\sigma^{SR}_{\chi e}$ → Large Exposure

Case of $\Gamma^{1\chi}_{tot}$

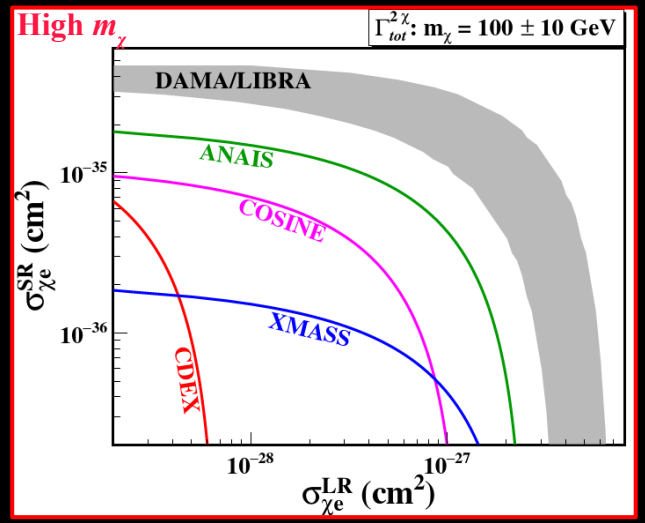


■ **Correlation $[\sigma^{SR}_{\chi e}$ & $\sigma^{LR}_{\chi e}]$::**
- I. Allowed Region from DL
- II. Null AM Experiments

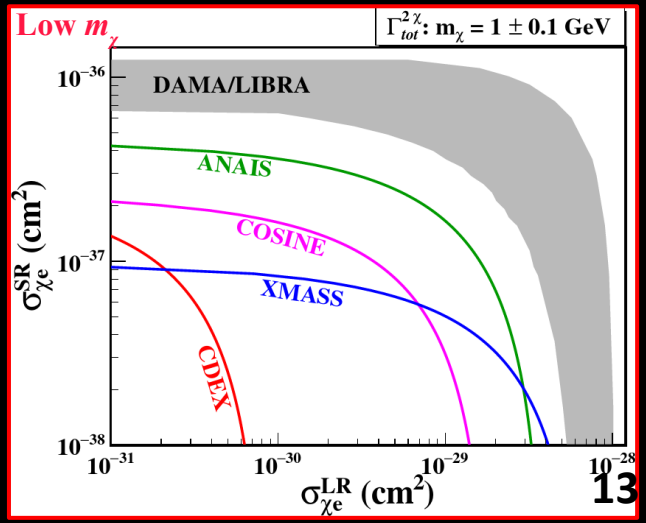
Complementary Roles of Experiments

Probing Parameter Space

High m_χ



Low m_χ



Summary and Conclusions

"First analysis":: Explores How χe AM can Play a Role in DL AM

■ Present Study:: Expand Investigations

- ☞ Addition of χe^{LR} and χe^{SR} Interactions to χN
  - ☑ Using Frozen Core Approximation
- ☞ Considered Two scenarios
  - ☑ χN & χe Processes:: Single χ ($\Gamma^{1\chi}_{tot}$) or Two Different χ ($\Gamma^{2\chi}_{tot}$)
- ☞ Combined fits [χN & χe] Provides
  - ☑ Stronger significance to DL AM data
  - ☑ Compatible with Presence of Additional Physical Effects
  - ☑ Beyond χN Alone

■ All DL AM Allowed Parameter Spaces::

☞ χN & χe Channels under both $\Gamma^{1\chi}_{tot}$ & $\Gamma^{2\chi}_{tot}$

⇩

Ruled out @ 90% CL by Combined null AM results

■ Projection::

☞ Very Little Room is Left

⇩

To account for DL AM data with WIMP-induced χN + χe Effects

Acknowledgments

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Dr. Shuvadeep Karmakar

Prof. Henry Tsz-King Wong

Thank You ! 谢谢