XENON1T excess in local Z_2 DM models with light dark sector

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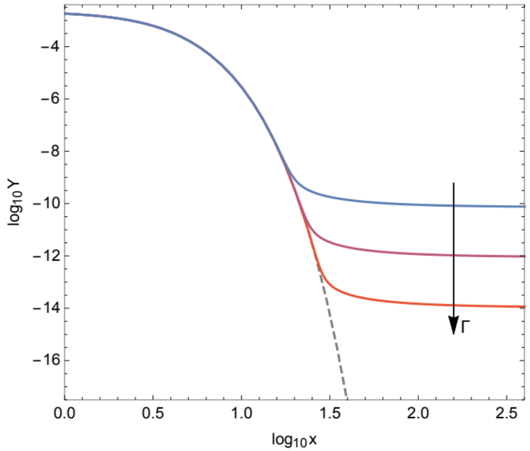
Thermal WIMP dark matter

- If the interaction between DM and SM is large enough
  - Thermal creation & destruction of DMs are efficient
  - **DM was in thermal equilibrium**

- Standard calculation for WIMP DM relic density
  - The Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\rm eq}^2\right)$$

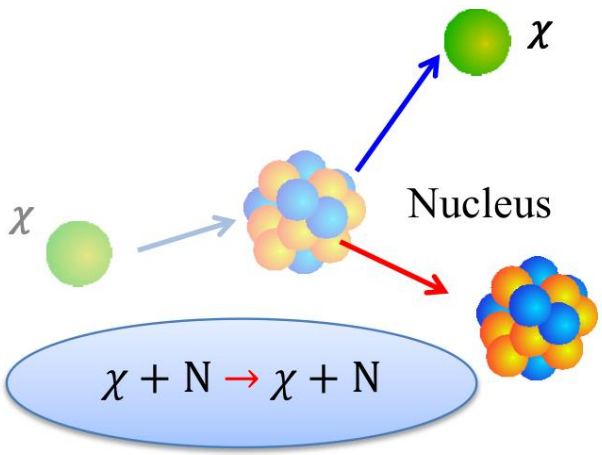
- **Relic density of WIMP DM**:
  - $0.1\,pb/\langle\sigma v\rangle \sim 0.12$
  - Interaction rate become effective, its relic abundance decreases



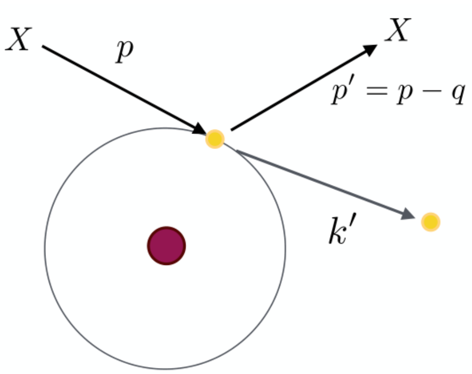
DM direct detection

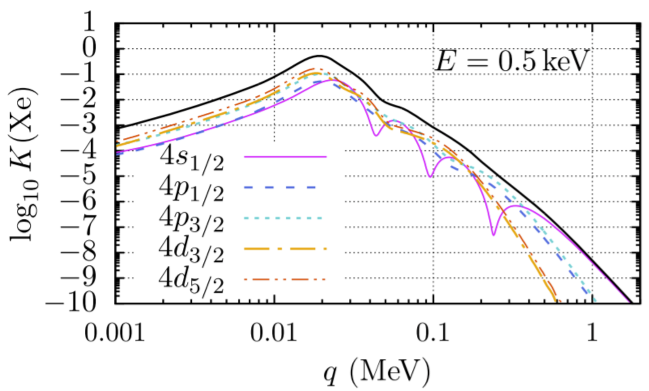
- Try to observe recoil energy coming from DM scattering process

- Nuclear Recoil (NR)
  - 1~100 keV



- Electronic Recoil (ER)
  - Ionization





XENON1T

PRL 121, 2018

- XENON1T utilizes a liquid xenon time projection chamber
  - The experiment detects scintillation **(S1)** and ionization **(S2)** produced when particles interact in the liquid xenon volume

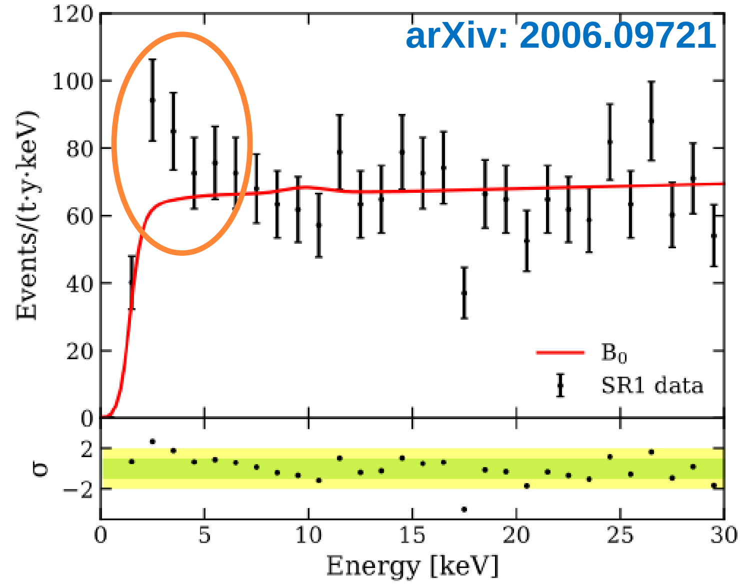
- The energy region of interest
  - [1.4, 10.6] keV_{ee}
  - [4.9, 40.9] keV_{nr}

2016-2018
2 ton – 1m drift
$\sigma \sim 10^{-47} cm^2$

- XENON1T features
  - Low background (<100events/tonne/year/keV_{ee})
  - Low energy threshold (~1keV_{ee})
  - Large exposure (~1tonne*year)

XENON1T excess

- Excess between 1 - 7keV
  - Expectation: 232±15
  - Observation: 285
  - Deviated from 3.5σ

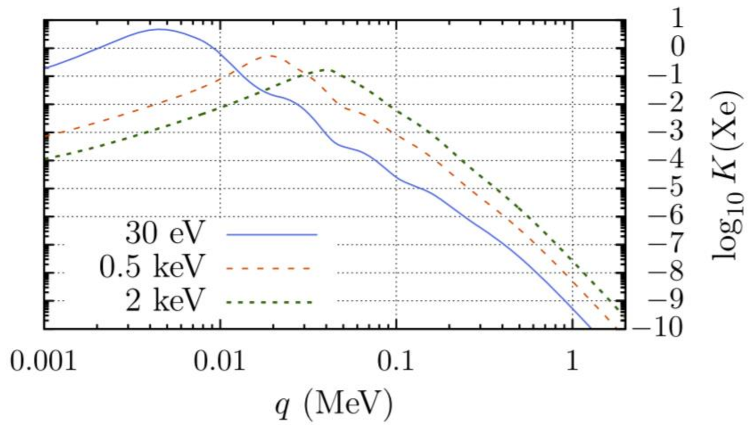


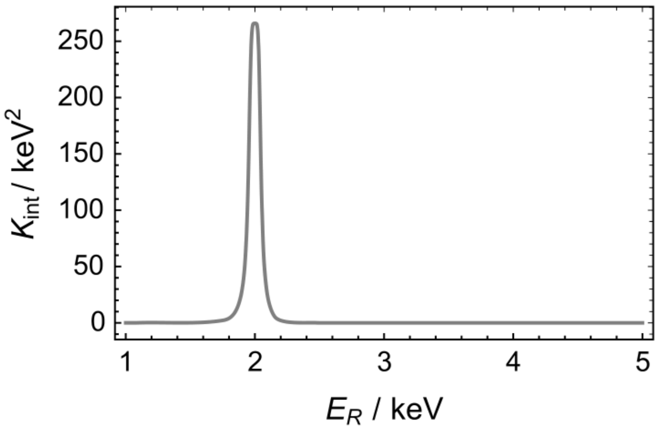
- Tritium contamination
  - Long half life (12.3 years)
  - Abundant in atmospheric & cosmogenically produced in xenon
- Solar axions
  - Produced in the Sun
  - Favored over background @ 3.5σ
- Neutrino magnetic dipole moment / NSI
  - Favored 3.2 σ

XENON1T excess from XDM

- Inelastic down-scattering off an electron

$$\frac{d\sigma v}{dE_R} = \frac{\sigma_e}{2m_e v}\int_{q_-}^{q_+} a_0^2 q\,dq\,K(E_R,q) \;\Rightarrow\; \frac{dR}{dE_R} = n_T n_R \frac{d\sigma v}{dE_R}$$





- The enhancement is determined by
  - $E_R \sim \delta = m_{XDM} - m_{DM}$
- Inelastic exothermic DM scattering
  - $\mathrm{XDM} + e_{atomic} \rightarrow \mathrm{DM} + e_{free}$ **with a kinetic mixing**

K. Kannike et al,
K. Harigaya et al,
H.M. Lee,
J. Bramante et al,
…

Exothermic DM models

- Exothermic DM models
  - **The mass difference** between DM & XDM is often introduced **by hand** in terms of dim-2 (3) operators
  - Local gauge symmetry is broken explicitly & softly
  - Introducing **dark photon Z'** would be theoretically **inconsistent**

- We explore **local Z_2 scalar & fermion DM models with dark Higgs mechanism**

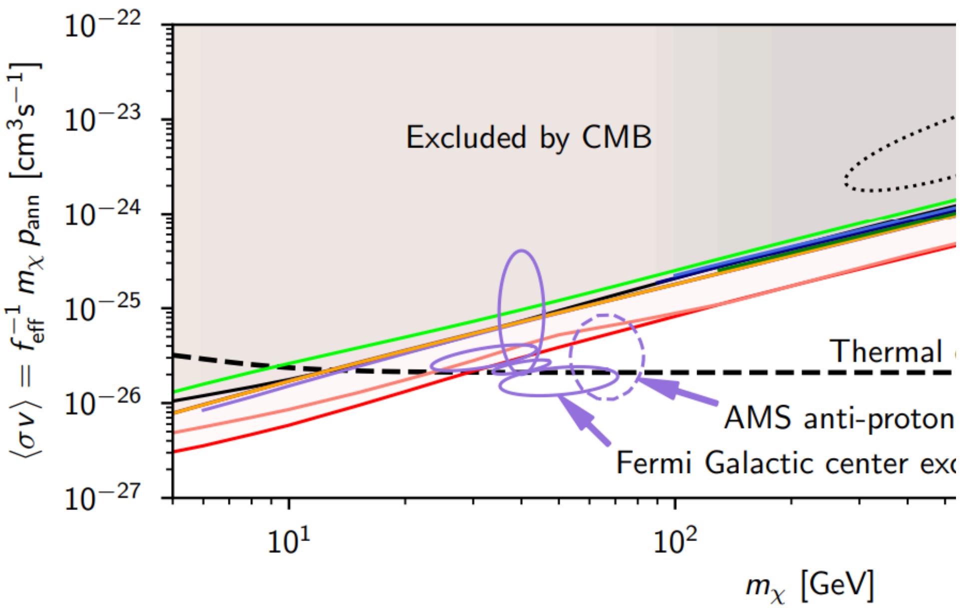
- **DM thermal relic density** and the **XENON1T electron recoil excess** could be **simultaneously accommodated** if dark Higgs boson is light enough

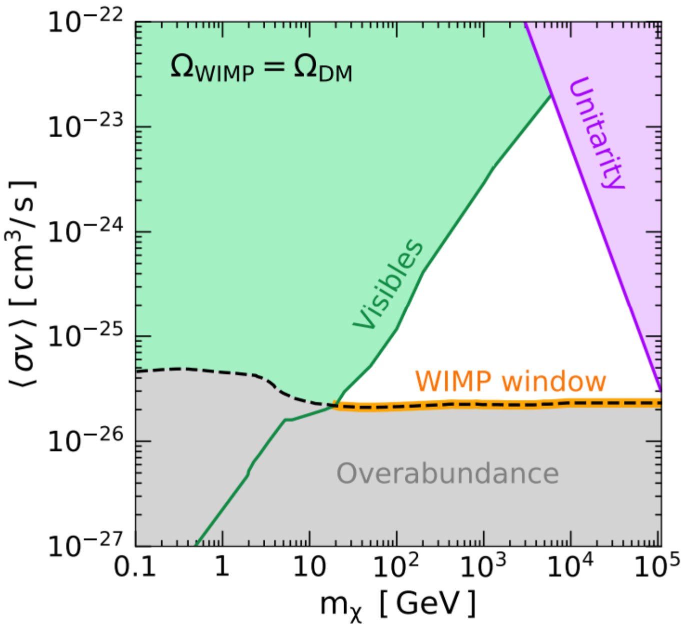
Exothermic DM models

- To evade the direct detection bound from NR
  - **sub-GeV DM**
- CMB bound excludes the thermal DM freeze-out determined by s-wave annihilation
  - DM annihilation should be mainly in **p-wave**

$\langle \sigma v \rangle \sim a + b\, v^2$

Planck 2018,
R. K. Leane et al, PRD 2018





Local Z_2 scalar DM model

S. Baek et al, PLB 2015

- Dark sector has a gauged $U(1)_X$ symmetry

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D^\mu\phi^\dagger D_\mu\phi + D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi$$
$$-\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H$$
$$-\mu\left(X^2\phi^\dagger + H.c.\right),$$

	X	ϕ
Q_X	1	2

- Spontaneously broken down to discrete Z_2, X becomes the DM candidate

K. Babu et al, PRD 1998

- $X = \frac{1}{\sqrt{2}}(X_R + iX_I)$: Complex scalar → two real scalars

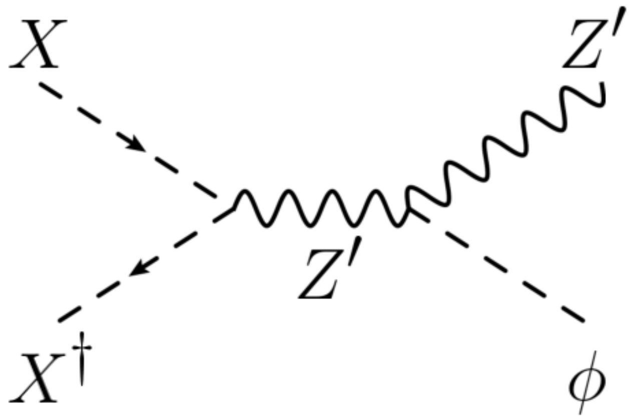
$$\mathcal{L} \supset g_X Z'^\mu\left(X_R\partial_\mu X_I - X_I\partial_\mu X_R\right) - \epsilon e c_W Z'_\mu\bar{e}\gamma^\mu e - \frac{\mu}{\sqrt{2}}\phi\left(X_R^2 - X_I^2\right)$$

Thermal relic abundance

- Local Z_2 scalar DM
  - Suppress the $XX^\dagger \to Z'Z'$ when $m_{DM} < m_{Z'}$
  - Make $XX^\dagger \to H_2H_2$ subdominant

- Mass spectrum: $\boldsymbol{m_{DM} < m_{Z'}\ \&\ m_{Z'} + m_\phi < 2m_{DM}}$

- Main annihilation channel for the relic density



Local Z_2 fermion DM model

P. Ko et al, arXiv:2019.04311

- Dark sector has a gauged $U(1)_X$ symmetry

	χ	Φ
Q_X	1	2

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi$$
$$- \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

- Φ breaks the dark $U(1)_X$ symmetry into a dark Z_2 symmetry
- Dirac field is split into two Majorana fields

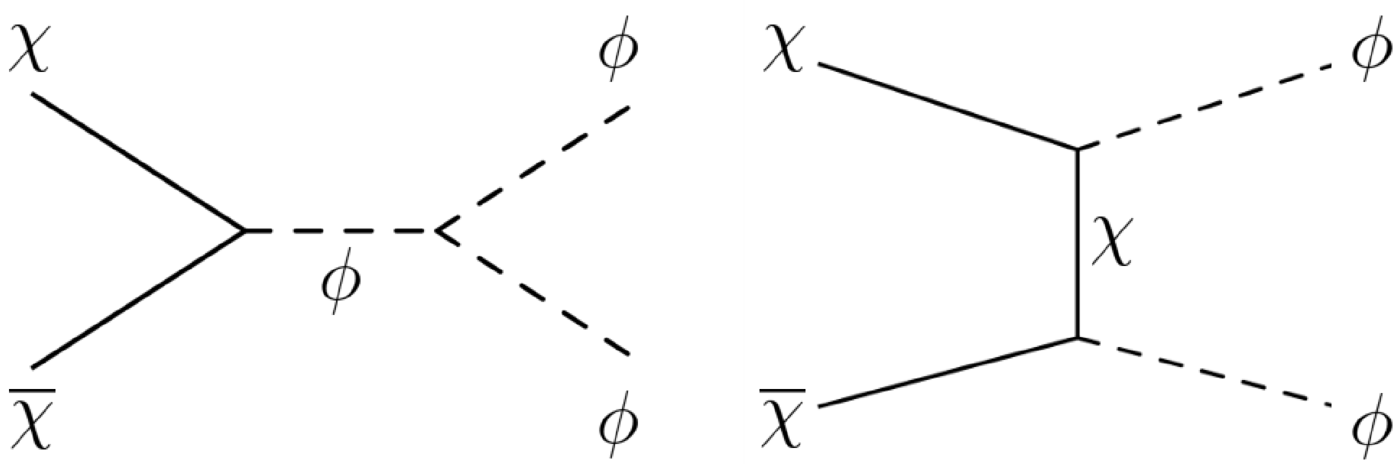
$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I), \quad \chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I)$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right)$$
$$- \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),$$

Thermal relic abundance

- Fermion Z_2 DM
  - To evade the CMB constraint we suppress the s-wave annihilation by $m_{DM} < m_{Z'}$ & $2m_{DM} < m_{Z'} + m_{\phi}$

- Main annihilation channel for the relic density



XDM decay mode

- Due to kinetic mixing between Z' and B,
  - XDM decays mainly via the SM Z-mediating $\chi_R \to \chi_I \nu \overline{\nu}$

$$\mathcal{L} \supset -\frac{i}{2}\epsilon s_W g_X Z_\mu (\overline{\chi}_R \gamma^\mu \chi_I - \overline{\chi}_I \gamma^\mu \chi_R) - \frac{1}{2} g_Z Z_\mu \overline{\nu}_L \gamma^\mu \nu_L$$

$$\Gamma \simeq \frac{\epsilon^2 \alpha_X s_W^2}{5\sqrt{2}\pi^2} \frac{G_F \delta^5}{m_Z^2} \simeq 1.9 \times 10^{-49}\,\mathrm{GeV} \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{\alpha_X}{0.078}\right) \left(\frac{\delta}{2\,\mathrm{keV}}\right)^5 .$$

- The lifetime of χ_R is much longer than the age of the Universe
  - Guarantee χ_R is as good a DM as χ_I
  - **Equal number density** → $n_R = n_I$

Cosmological bound

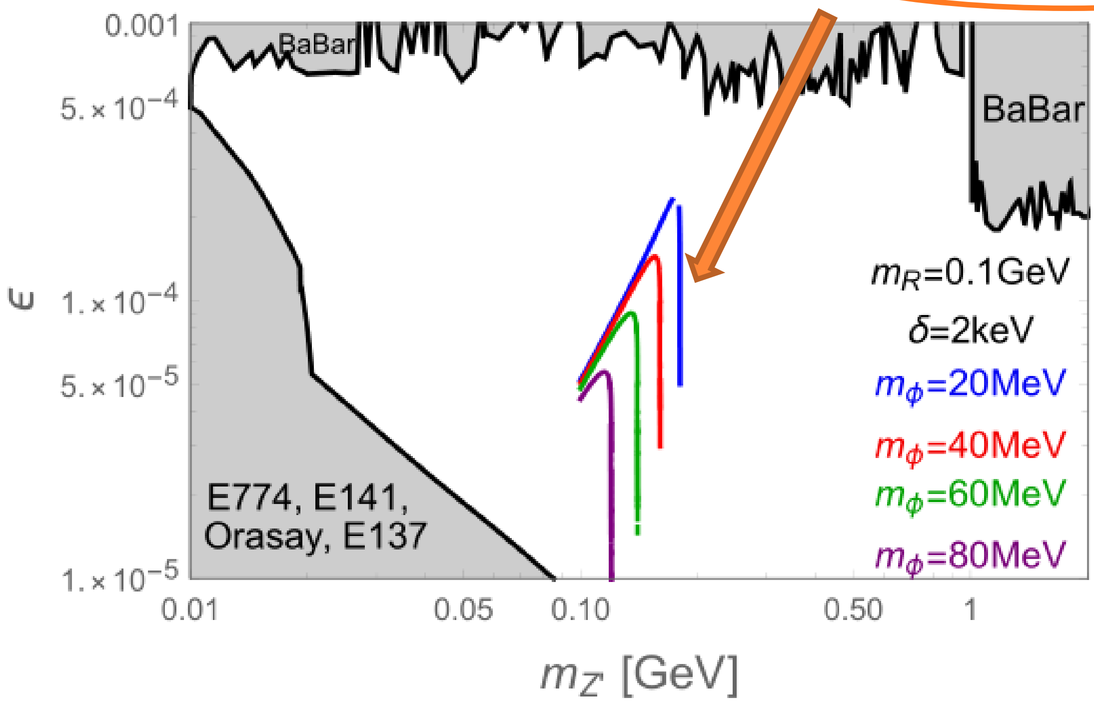
S. Matsumoto et al, JHEP 2019

- Constraint from **BBN**
  - $\Gamma(\phi \to \bar{\ell}\ell) \approx (1.1\times10^{16}\mathrm{sec}^{-1})\alpha_H^2\left(m_\phi/1\mathrm{GeV}\right)$
  - $\Gamma(Z' \to \bar{\ell}\ell) \approx 1.87\times10^{-11}\mathrm{GeV}(\epsilon/10^{-4})^2(m_{Z'}/1\mathrm{GeV})^2$
  - The light mediator Z' & dark Higgs decay before 1sec

- Constraint from N_{eff} @ T_{CMB}
  - If light dark Higgs & Z' masses are lighter than T_{dec}^{ν}~1MeV
  - The light dark Higgs & Z' mainly decays into $e^{\pm}$ or γ
  - Light particles make the difference between T_γ & T_ν larger than the one given by the standard cosmology by imparting its entropy only to γ → $\Delta N_{eff} \neq 0$
  - Avoid this problem: $m_\phi, m_{Z'} > 1\mathrm{MeV}$

XENON1T + Relic density

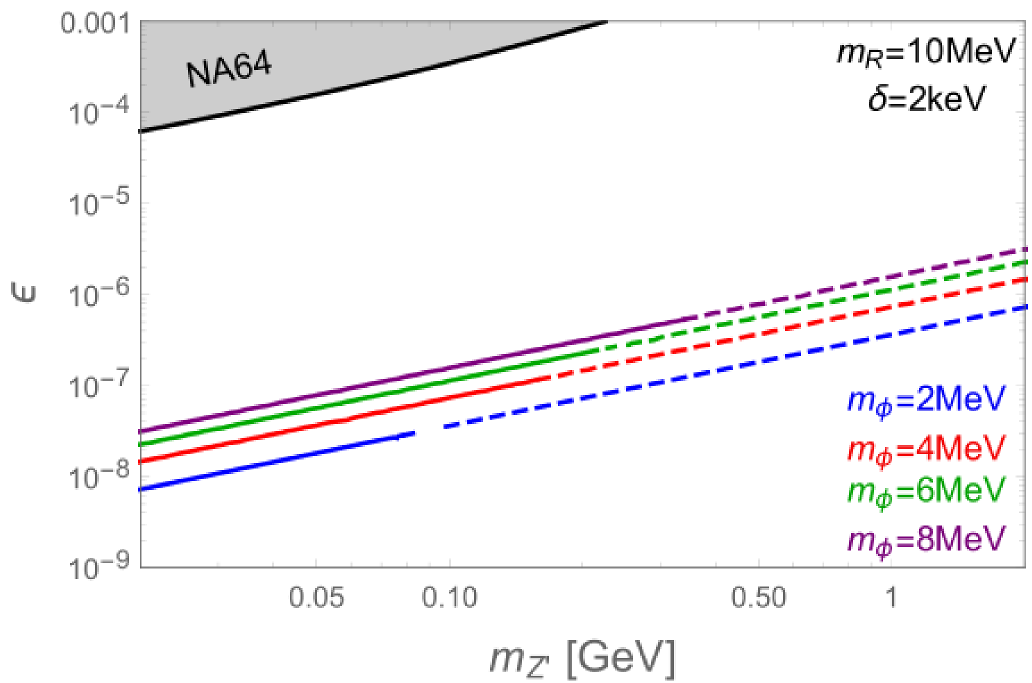
- Local Z_2 scalar DM: $m_{DM} < m_{Z'}$ & $m_{Z'} + m_\phi < 2m_{DM}$



- Gray areas are excluded by various experiments
  - Assuming $Z' \to \chi_R \chi_I$ is kinematically forbidden

XENON1T + Relic density

- Local Z_2 fermion DM: $m_\phi < m_{DM} < m_{Z'}$& $2m_{DM} < m_{Z'} + m_\phi$



- Gray region: ruled out by NA64
  - assuming $Z' \to \chi_R \chi_I$
- Dashed lines: g_X violates perturbativity condition

Conclusions

- We showed that the electron recoil excess reported by XENON1T Collaboration could be accounted for by exothermic DM scattering on atomic electron in Xe, with sub-GeV light DM

- The exothermic scattering in inelastic Z_2DM models within standard freeze-out scenario can explain the XENON1T excess without modifying early Universe cosmology.

- **The existence of dark Higgs** is **crucial** for us to get the desired DM phenomenology to explain the XENON1T excess with the correct thermal relic density in case of both DM models.

Conclusions

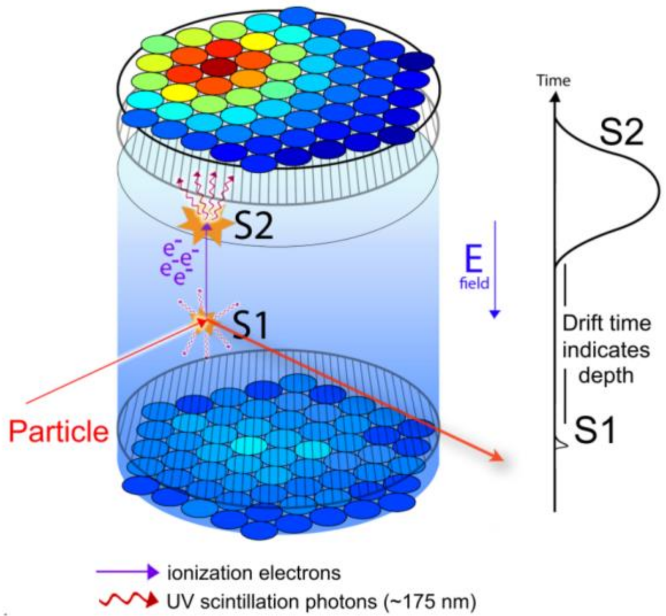
- We showed that the electron recoil excess reported by XENON1T Collaboration could be accounted for by exothermic DM scattering on atomic electron in Xe, with sub-GeV light DM

Thank you.

- **The existence of dark Higgs** is **crucial** for us to get the desired DM phenomenology to explain the XENON1T excess with the correct thermal relic density in case of both DM models.

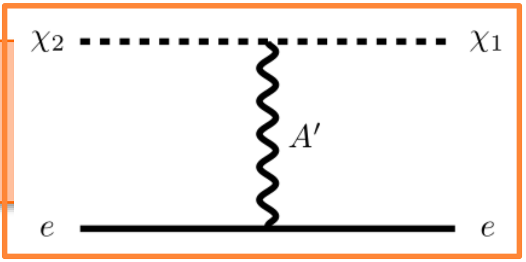
XENON1T

- XENON1T detectors are basically two-phase time projection chambers PRL 121, 2018



- A prompt S1 signal coming from a scintillation process
- A delayed scintillation signal S2 coming from the ionized and drifted electron

XENON1T excess



- scattering cross section

$$\sigma_e = \frac{16\pi\epsilon^2\alpha_{\rm em}\alpha_X c_W^2 m_e^2}{m_{Z'}^4} \Rightarrow \frac{d\sigma v}{dE_R} = \frac{\sigma_e}{2m_e v}\int_{q_-}^{q_+} a_0^2 q dq K(E_R, q)$$

- Integration limits

$$q_\pm \simeq m_R v \pm \sqrt{m_R^2 v^2 - 2m_R(E_R - \delta)}, \quad \text{for } E_R \geq \delta,$$

$$q_\pm \simeq \pm m_R v + \sqrt{m_R^2 v^2 - 2m_R(E_R - \delta)}, \quad \text{for } E_R \leq \delta.$$

- Event rate

$$R \approx 3.69 \times 10^9\, \epsilon^2\, g_X^2 \left(\frac{1\text{GeV}}{m_R}\right)\left(\frac{1\text{GeV}}{m_{Z'}}\right)^4 /\text{ton}/\text{year}.$$

WIMP DM with Z_2 symmetry

- The required longevity of DM can be guaranteed by a symmetry
  - If the symmetry is global,

$$-\mathcal{L}_{\text{decay}} = \begin{cases} \dfrac{\lambda_{X,\text{non}}}{M_P} X F_{\mu\nu} F^{\mu\nu} & \text{for bosonic DM } X \\ \dfrac{\lambda_{\psi,\text{non}}}{M_P} \overline{\psi} \left(\not{D} \ell_{Li} \right) H^\dagger & \text{for fermionic DM } \psi \end{cases}$$

- $\tau_{\text{DM}} \gtrsim 10^{26-30}\text{sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10)\text{keV} \\ m_\psi \lesssim \mathcal{O}(1)\text{GeV} \end{cases}$

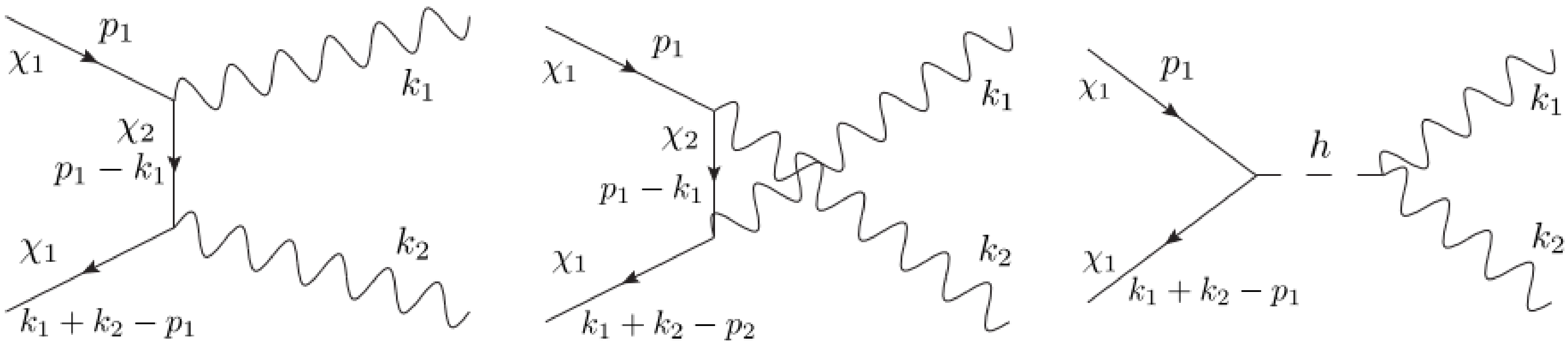
M. Ackermann et al, PRD 86, 2012

  - **WIMP DM is unlikely to be stable**
  - It looks natural and may need to **consider a gauge symmetry in dark sector, too**

Local Z_2 fermion DM model

P. Ko et al, arXiv:2019.04311

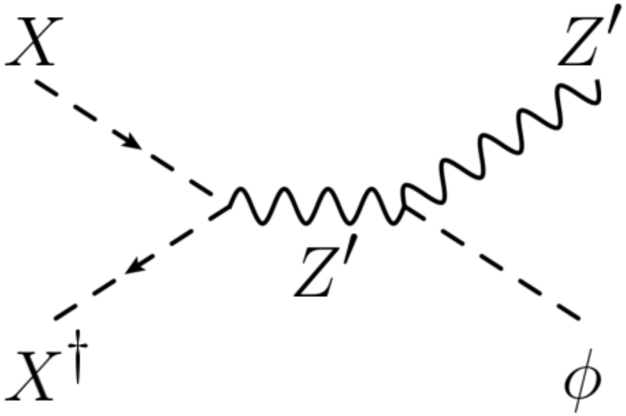
- Importance of dark Higgs



- Without dark Higgs, the sum of the **first 2 Feynman diagrams** shows a bad high energy behavior like in the SM without Higgs
- Including the dark Higgs (the **last Feynman diagram**), this bad behavior is cured, and the theory becomes healthy

Thermal relic abundance

- Scalar Z_2 DM model

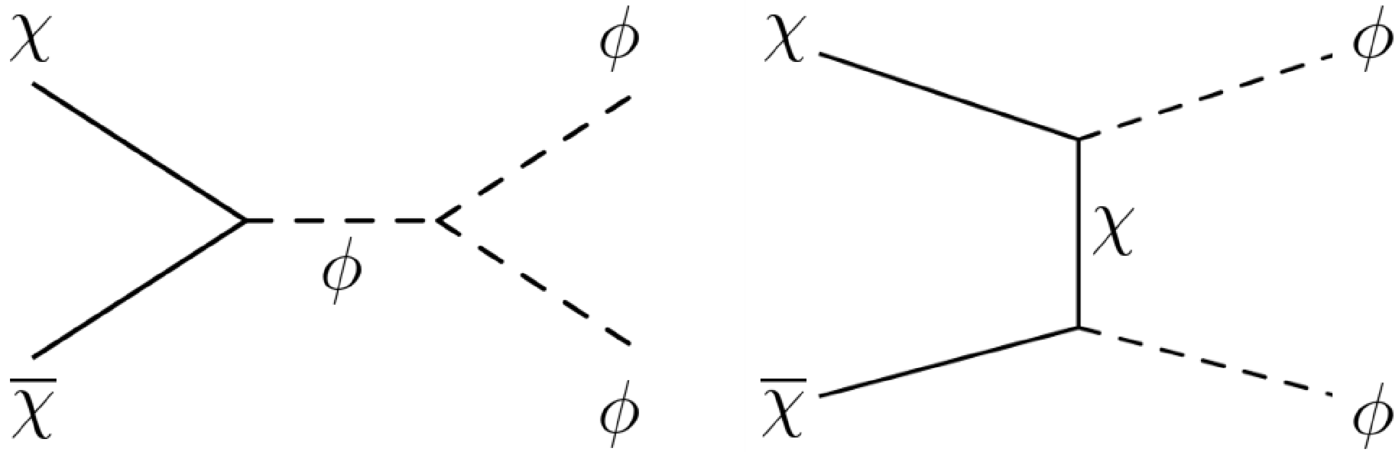


$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16 m_X^4 + m_{Z'}^4 + m_\phi^4 + 40 m_X^2 m_{Z'}^2 - 8 m_X^2 m_\phi^2 - 2 m_{Z'}^2 m_\phi^2\right)$$

$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4),$$

Thermal relic abundance

- Fermion Z_2 DM model

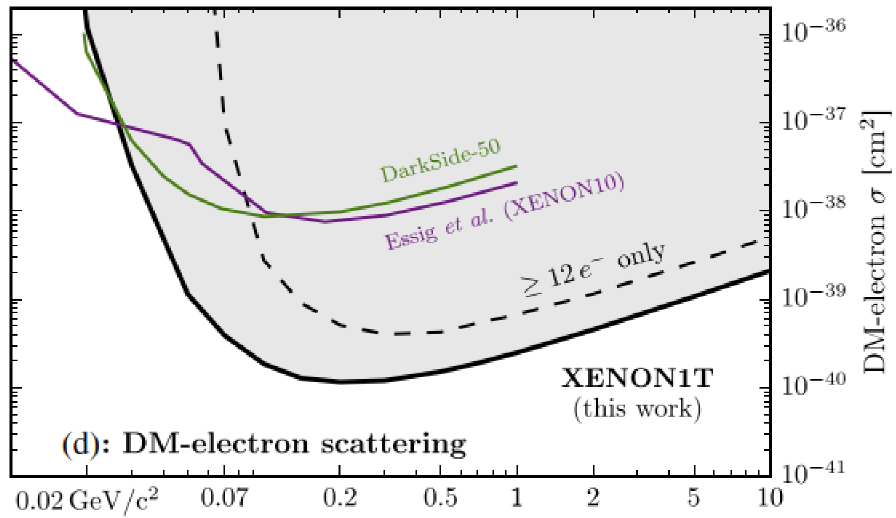


$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi}\left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2(9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4}\right] + \mathcal{O}(v^4)$$

XENON1T scattering bounds

- DM-electron scattering

PRL 123, 2019



- DM-nucleon scattering

PRL 121, 2018