Self-Interacting Vector Dark Matter Via Freeze-In

Da Huang

FUW-UW

@Matter to the Deepest

In collaboration with B. Grzadkowski and M. Duch

Work still in progress

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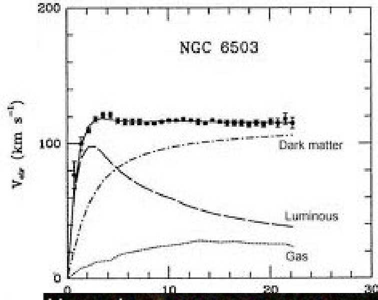
Motivation

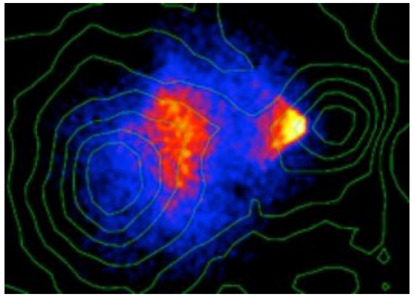
➢ There are already many established evidences for the existence of dark matter

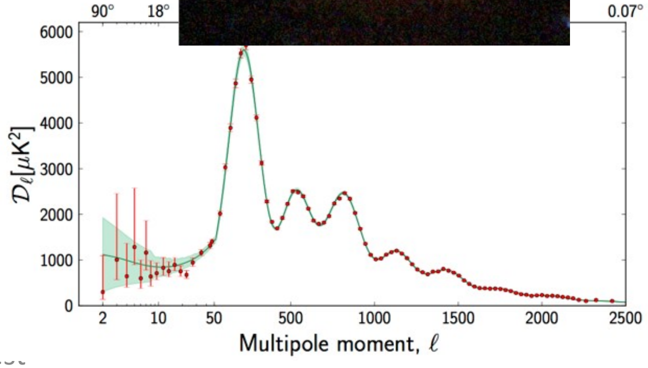


- Rotation Curves of Spiral Galaxies
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980

- Gravitational Lensing

- CMB Planck Collaboration, 2015





- Bullet Clusters

But , they are all gravitational

Motivation

- Currently, the benchmark Dark Matter model is the Collisionless Cold Dark Matter (CCDM)

- CCDM successfully explains all of the above observations, especially for the large scale structure in our Universe

- CCDM meets difficulty in interpreting small scale structures

- Cusp-Core Problem: Dwarf Galaxies

  B. Moore, 1994, R. A. Flores & Primack, 1994, S.H. Oh, et al. 2011, M.G. Walker & J. Penarrubia, 2011

- Too Big to Fail Problem

  M. Boylan-Kolchin, et al, 2011,

Motivation

- Possible Solutions: Introduction of DM Self-Interactions

  A.A. de Laix, et al, 1995, D.N. Spergel & P. J. Steinhardt, 2000

$$0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma_T/m_X < 10\ \mathrm{cm}^2/\mathrm{g}$$

where transfer cross section $\sigma_T = \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$

- Constraints:

● Cluster Ellipticity N. Yoshida et al., 2000, J. Miralda-Escude, 2002, M. Rocha, et al, 2012, A. Peter ,et al. 2012

● Non-Evaporation of Galaxy halo in hot clusters

O. Y. Gnedin & J.P. Ostriker, 2000

● Bullet Clusters S.W. Randall, et al, 2008

- Typical Constraints: $\sigma_T/m_X \leq 1\ \mathrm{cm}^2/\mathrm{g}$ M. Vogelsberger et al., 2012

Motivation

- One intriguing mechanism is to consider the DM of broadly weak scale 1 GeV ~ 100 TeV, with a light mediator of mass to be < 100 MeV.

A. Loeb & N. Weiner, 2011; J.L. Feng, et al, 2010; S. Tulin, et al, 2013; L.G. van den Aarssen et al. 2012; F. Y. Cyr-Racine, et al, 2016

Long Range Force

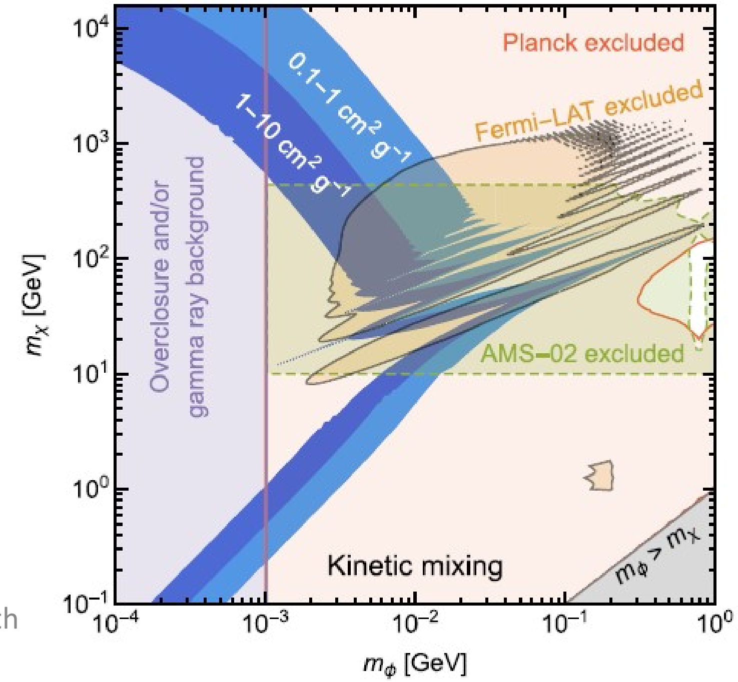
- Advantage: Velocity-Dependent Xection, so it is easy for dwarf signal (v~30 km/s) to avoid the cluster constraints (v~1000 km/s) S. Tulin, et al, 2013; M. Kaplinghat, et al. 2015

Motivation

➢ Usually, the standard WIMP mechanism to generate DM is through the thermal freeze-out. L. Ackerman et al, 2009; M.R. Buckley & P. J. Fox, 2009; A. Loeb & Weiner, 2011; S. Tulin, et al. 2013

➢ However, the dark freeze-out mechanism to generate SIDM is excluded by the DM indirect searches, such as BBN, AMS-02, Fermi-LAT, and CMB.

T. Bringmann et al. 2017,
F. Kahlhoefer, et al. 2017



Motivation

➢ In our work, we consider the case in which the self-interacting DM are generated by freeze-in mechanism.

➢ Features of freeze-in scenario:

J. McDonald, 2002

L. J. Hall, et al. 2010

- Negligible Initial Distribution
- Feeble couplings to SM
- IR dominated: predictability as FO

➢ Question: Can such SIDMs be allowed by current DM detections?

Vector DM Model

M. Duch, B. Grzadkowski and M. McGarrie, 2015

- SM + $U(1)_X$ Gauge Boson X + Complex Scalar S + Z_2 Symm.

- S: Unit Charge under $U(1)_X$, but Neutral under SM

- Z_2 Symmetry: Charge Conjugate Symmetry in Dark Sector

$$X_\mu \to -X_\mu \,, S \to S^* \,,$$

forbids terms $X_\mu B^\mu$ or $X_{\mu\nu} B^{\mu\nu}$.

- After SSB, X is massive and stable due to Z_2 → DM Candidate

Vector DM Model

- Dark Sector Lagrangian:

$$\mathcal{L}_{\rm d} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu S)^\dagger D^\mu S + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4 - \kappa|S|^2|H|^2,$$

$$\boxed{D_\mu S \equiv (\partial_\mu + i g_X X_\mu) S}$$

κ : Higgs Portal

- After SSB:

$$\langle H \rangle \equiv (0, v_H/\sqrt{2})^T \qquad \langle S \rangle \equiv v_S/\sqrt{2}$$

$$\boxed{v_H^2 = \frac{2(\mu_H^2 \lambda_S - \mu_S^2 \kappa)}{\lambda_S \lambda_H - \kappa^2}, \qquad v_S^2 = \frac{2(\mu_S^2 \lambda_H - \mu_H^2 \kappa)}{\lambda_S \lambda_H - \kappa^2}.}$$

Vector DM Model

- After SSB:
- Gauge Boson Mass: $m_X = g_X v_S$
- $$H = \begin{pmatrix} H^+ \\ (v_H + \phi_H + i\sigma_H)/\sqrt{2} \end{pmatrix}, \qquad S = \frac{1}{\sqrt{2}}(v_S + \phi_S + i\sigma_S)\,.$$
- $(\phi_H, \phi_S)^T$ Mass Matrix $\mathcal{M}^2 = \begin{pmatrix} \lambda_H v_H^2 & \kappa v_H v_S \\ \kappa v_H v_S & \lambda_S v_S^2 \end{pmatrix}$
- Physical Mass Eigenstates: $\begin{pmatrix} \phi_H \\ \phi_S \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$

$$\kappa = \frac{(m_{h_1}^2 - m_{h_2}^2)s_{2\theta}}{2v_H v_S}, \quad \lambda_H = \frac{m_{h_1}^2 c_\theta^2 + m_{h_2}^2 s_\theta^2}{v_H^2}, \quad \lambda_S = \frac{m_{h_2}^2 c_\theta^2 + m_{h_1}^2 s_\theta^2}{v_S^2}.$$

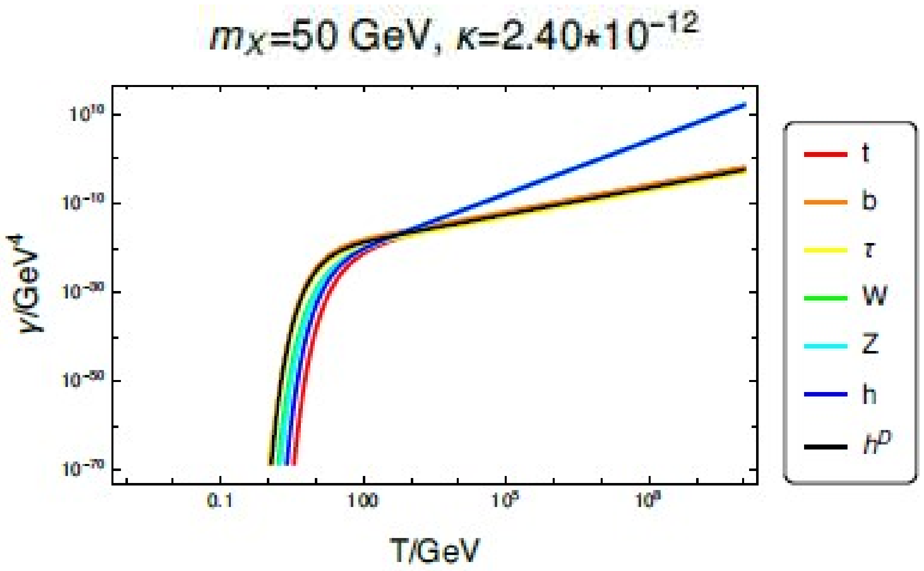
- Parameters: $(m_X,\, m_{h_2},\, \kappa,\, g_X)$

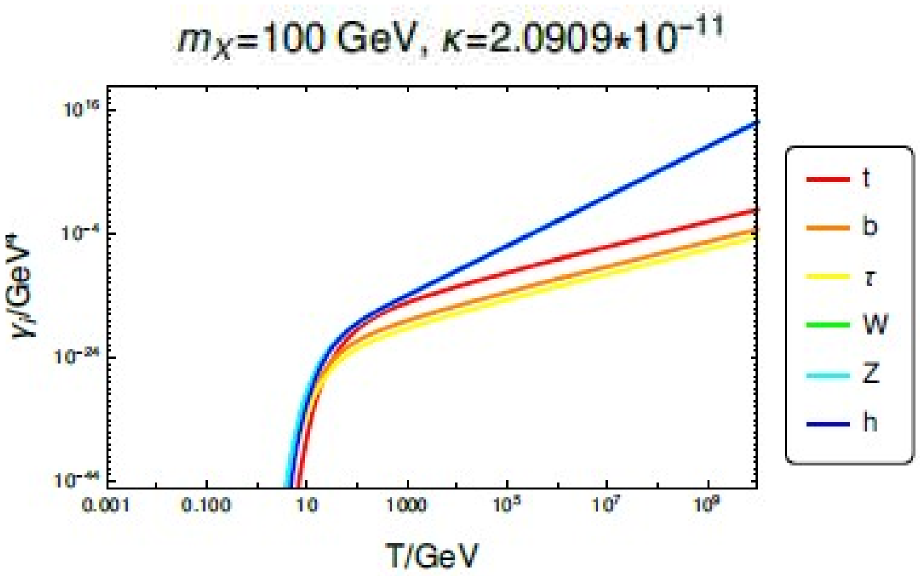
Freeze-In Mechanism

- Boltzmann Equation for Freeze-In (SM Symm. Broken phase) :

$$xHs\frac{dY_X}{dx} = \sum_f \gamma_f + \gamma_W + \gamma_h + \gamma_Z + \gamma_h^D \,.$$

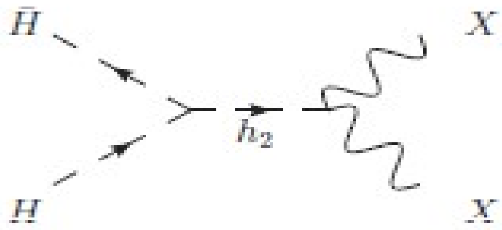
Note that all γ's are proportional to κ





Freeze-In Mechanism

- At high temperature $T>T_{EW}$ = 160 GeV, the SM gauge symmetry is recovered, so only the SM Higgs doublet annihilations ($HH \rightarrow XX$) contribute



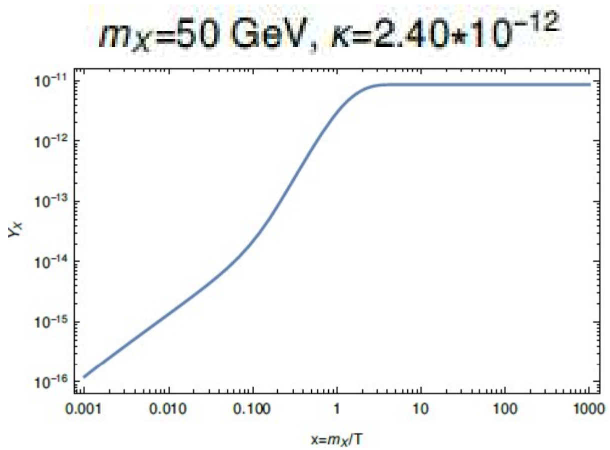
- Boltzmann Equation for Freeze-In is changed to

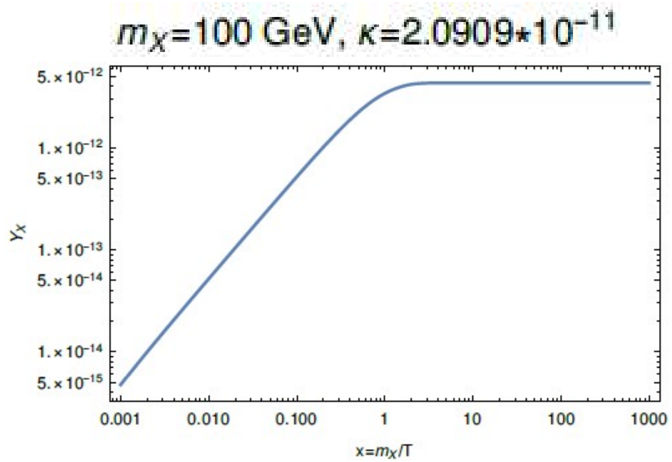
$$xHs\frac{dY_X}{dx} = \gamma_{H\bar{H}}\,.$$

- The EW phase transition effect is important for DM with its mass greater than T_{EW}.

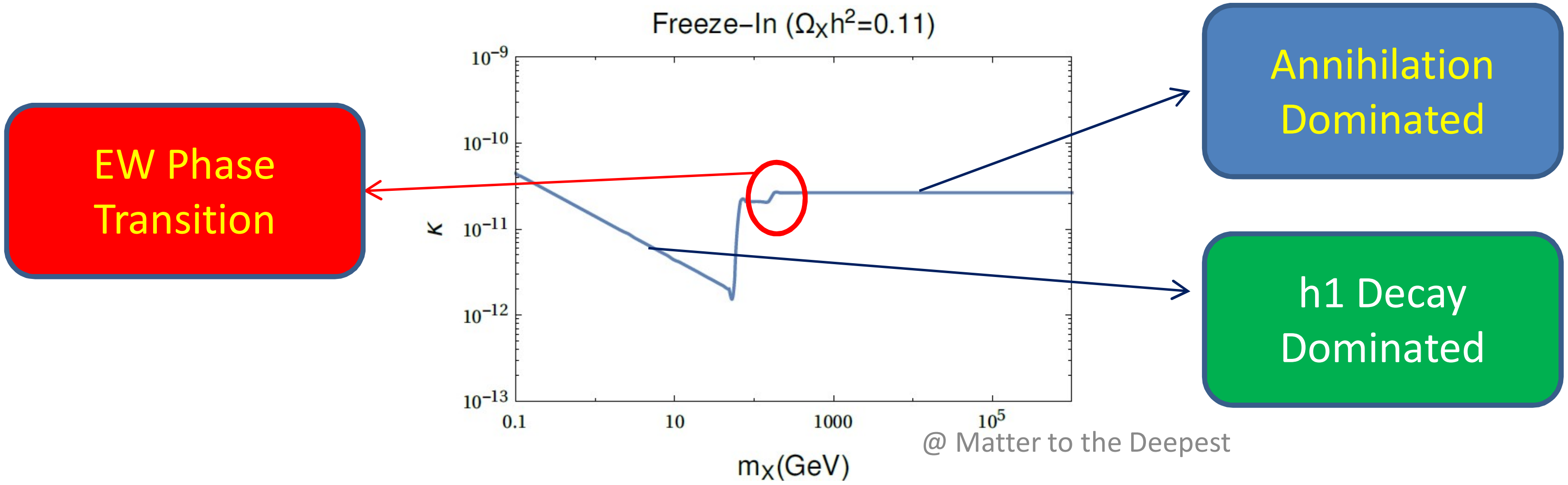
Freeze-In Mechanism

- Solution to Boltzmann Equations





- Parameter Space



DM Self-Interactions

- In order to generate large enough DM Self Interactions, we focus on the parameter space $m_X \sim 1$ GeV – 100 TeV and $m_{h2} \leq 100$ MeV, so h_2 acts as the light mediator

S. Tulin, et al. 2013

- Effective Yukawa Potential

$$V(r) = -\frac{\alpha_X}{r} e^{-m_{h_2} r}$$

- Schrodinger Equation for Partial Waves

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{dR_\ell}{dr}\right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right) R_\ell = 0$$

with boundary condition $\lim_{r\to\infty} R_\ell(r) \propto \cos\delta_\ell\, j_\ell(kr) - \sin\delta_\ell\, n_\ell(kr)$

- Transfer Xection: $\frac{\sigma_T k^2}{4\pi} = \sum_{\ell=0}^{\infty} (\ell+1)\sin^2(\delta_{\ell+1} - \delta_\ell)$ with $k = \mu v$

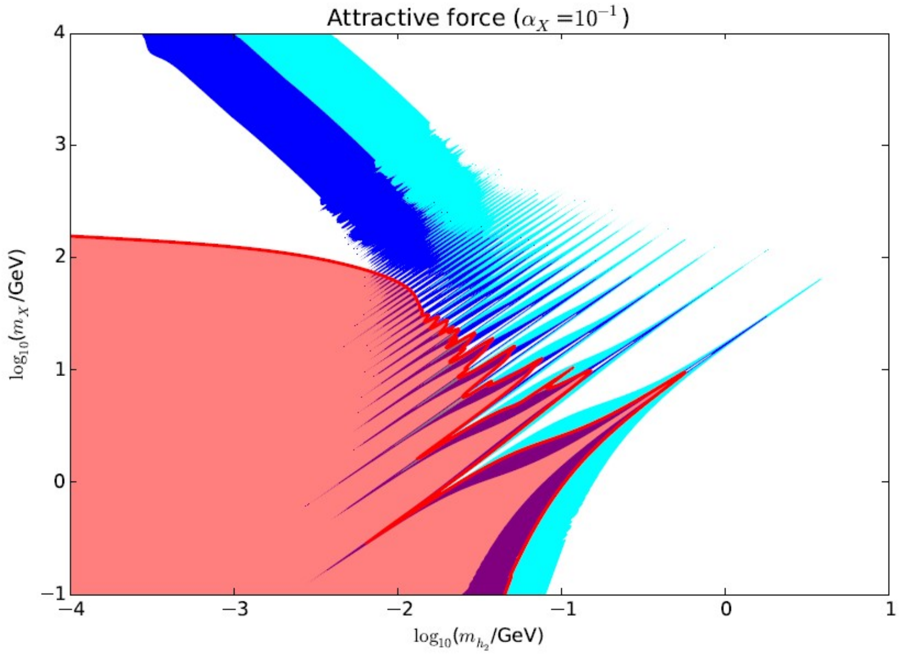
DM Self-Interactions

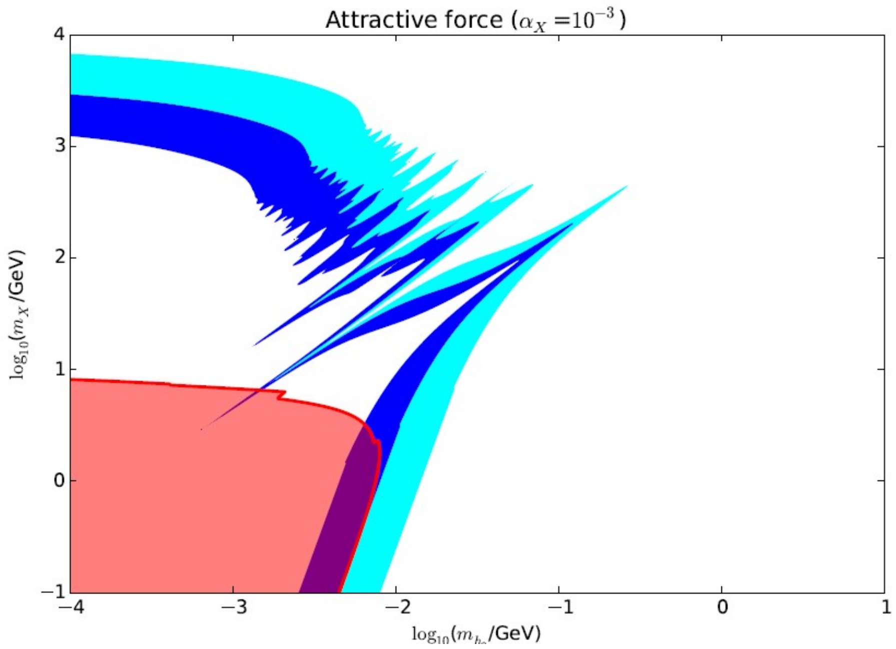
➢ Numerical Results

Cyan : $0.1\ \mathrm{cm^3/g} < \sigma_T/mX < 1\ \mathrm{cm^3/g}$

Blue : $1\ \mathrm{cm^3/g} < \sigma_T/mX < 10\ \mathrm{cm^3/g}$

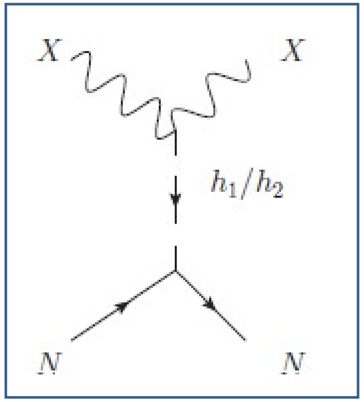
Red: Excluded by Cluster constraints





DM Direct Detection

- Process: XN→ XN



- Total Cross Section

$$\sigma_{XN} = \frac{\kappa^2 f_N^2 m_X^2 m_N^2 \mu_{XN}^2}{\pi m_{h_1}^4 m_{h_2}^2 (m_{h_2}^2 + 4\mu_{XN} v^2)}$$

- Differential Cross Section

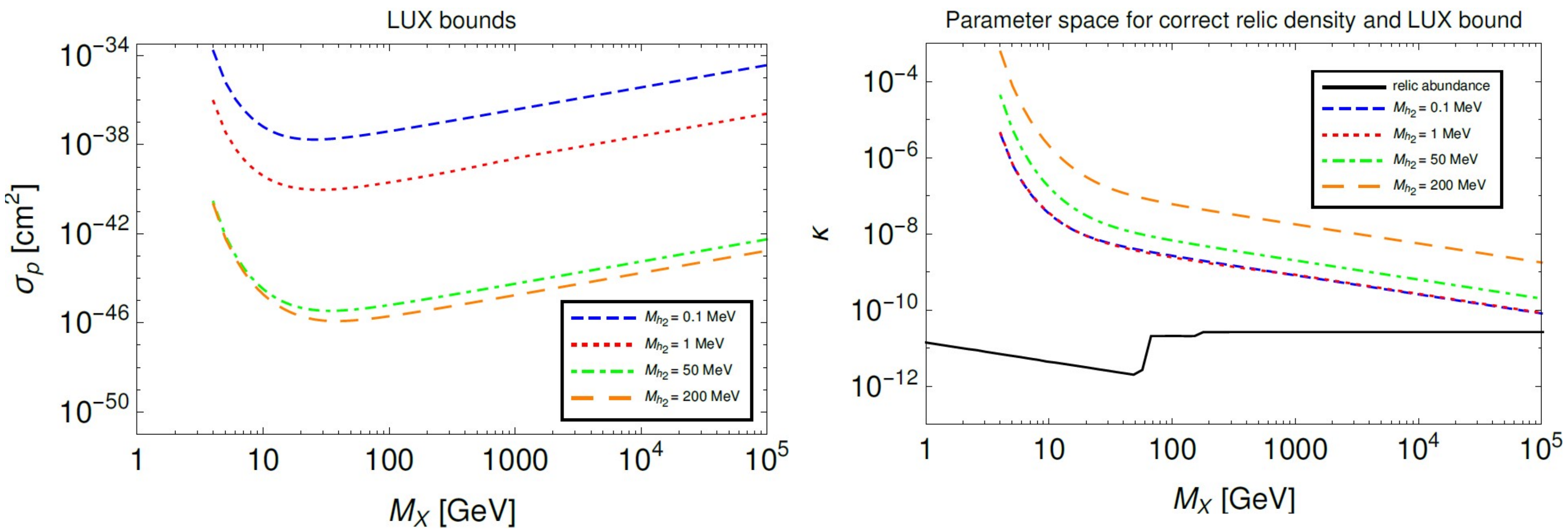
$$\frac{d\sigma_{XN}}{dq^2} = \frac{\sigma_{XN}}{4\mu_{XN}^2 v^2} G(q^2)$$

where $$G(q^2) = \frac{m_{h_2}^2 (m_{h_2}^2 + 4\mu_{XN}^2 v^2)}{(q^2 + m_{h_2}^2)^2}$$

DM Direct Detection

- The strongest constraints are given by LUX, PandaX-II and XENON1T, the bounds of which are of similar order.

- Numerical Results for the LUX upper bounds: Poisson Statistics by assuming no candidate nucleus recoil events



DM Indirect Detection

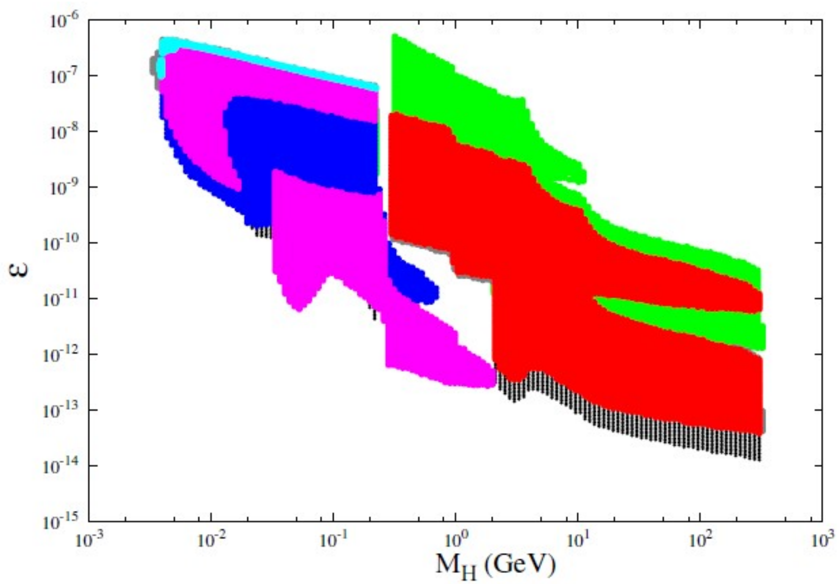
- For DM indirect detection, we use the data from BBN, Fermi-LAT dwarf galaxy gamma-ray observation, AMS-02 e^+e^-, and recent Planck data on the CMB power spectrum

- When h2's lifetime is longer than the age of the Universe, we also consider the diffuse gamma-ray constraints

- Since τ_{h2} > 1s, the BBN bounds cannot be avoided. From J. Berger et al. 2016, the BBN constraint is:

$$s_\theta < 5 \times 10^{-12}$$

for 1 MeV< m_{h2} < 100 MeV



Numerical Result

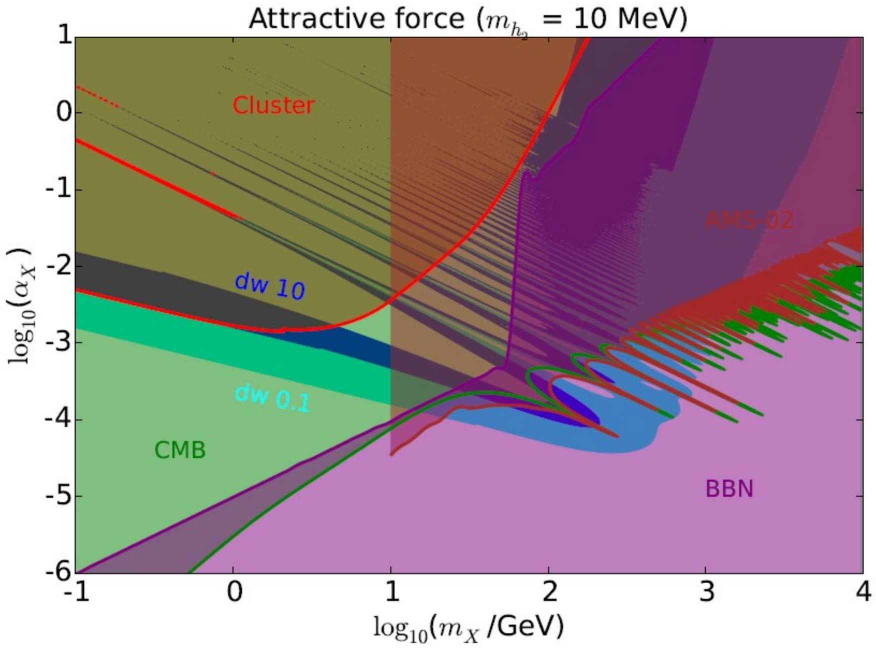
- mh2 > 1 MeV
  - Dominant Decay Channel: e+e- pair
  - Typical Lifetime: 10^4 s< t_{h2} < 10^{12} s
  - Constraints: Cluster, BBN, AMS-02, CMB.

- AMS-02 and CMB constrain the DM annihilations:

  X X → h2 h2

  In which the Sommerfeld enhancements should be taken into account. G. Elor et al. 2016

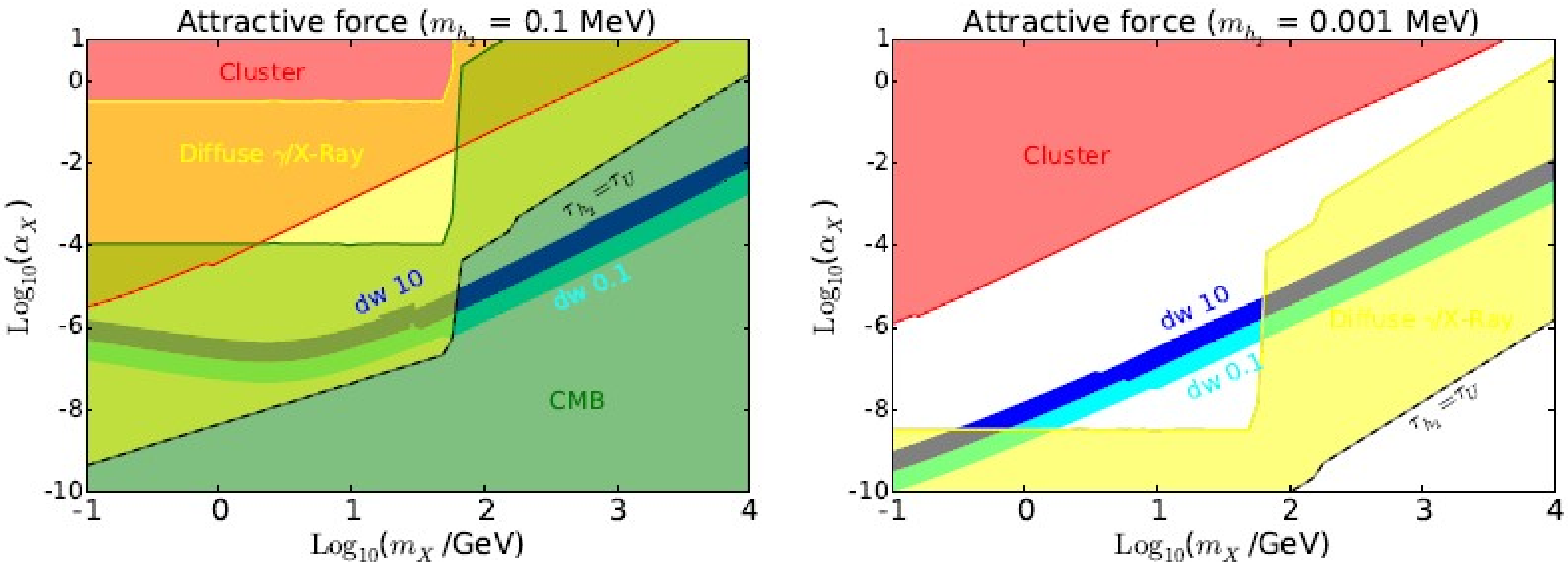
- All the parameter space is excluded



Numerical Result

- $m_{h2} < 1$ MeV
  - Dominant Decay Channel: diphotons
  - Typical Lifetime: $t_{h2} > 10^{12}$ s
  - Constraints: Cluster, CMB, Diffuse Gamma

T.R. Slatyer & C.L. Wu, 2016
S. Riemer-Srensen et al, 2015



- Only when $m_{h2}\sim$ keV, we find regions satisfying all constraints

Summary

- The VDM model via the Higgs portal is investigated, and we find that EWPT plays an important role.

- We focus on the freeze-in region, in which $m_{\chi} \sim 1$ GeV – 100 TeV and $m_{h2} <= 100$ MeV, so dark Higgs can act as the light mediator to enhance the DM self interactions and solve the cosmological small scale problem

- We find that direct detections do not constrain the model much, but the indirect detections restrict mh2 should be of or smaller than O(keV)

THANKS FOR YOUR ATTENTION!

BACK-UP SLIDES

DM Indirect Detection

- DM ID strongly depends on the properties of h2

- h2 lifetime