Self-Interacting Vector Dark Matter Via Freeze-In

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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 $\lesssim$ 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 region (v~30 km/s) to avoid the cluster constraints (v~1000 km/s)

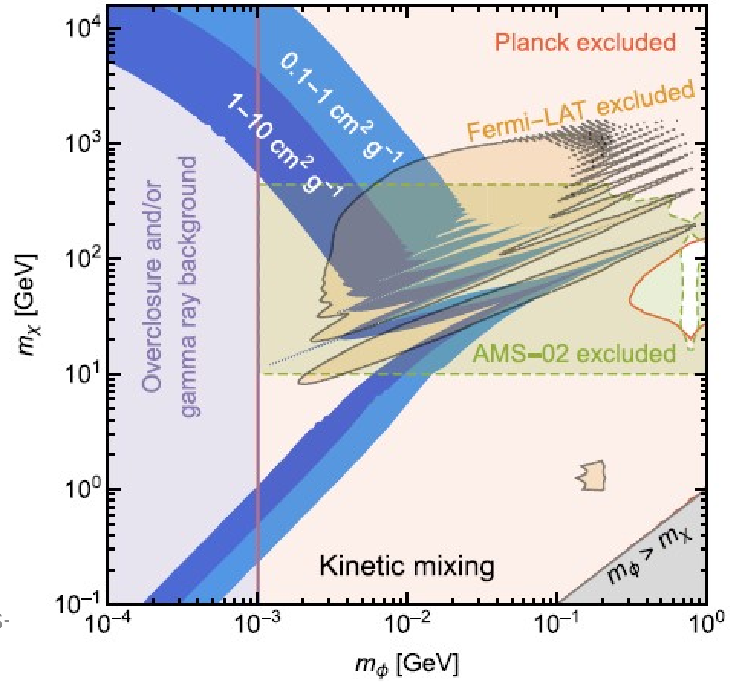
S. Tulin, et al, 2013;
M. Kaplinghat, et al. 2015

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

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

  T. Hambye, 0811.0172; O. Lebedev, et al., 1111.4482, Baeck et al. 1212.2131,;
  M. Duch, et al, 1506.08805; A. Karam & K. Tamvakis, 1508.03031, ….

- 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

- The non-Abelian version was studied by N. Bernal, et al, 2015

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:

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

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

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: $\begin{pmatrix} \phi_H \\ \phi_S \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$

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

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

Freeze-In Mechanism

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

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

where reaction densities γ_i for SM annihilations are defined as

$$\gamma(a\,b \to 1\,2) \equiv \int d\bar{p}_a d\bar{p}_b d\bar{p}_1 d\bar{p}_2 f_a^{\rm eq} f_b^{\rm eq} (2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2) |\mathcal{M}(a\,b \to 1\,2)|^2$$

$$= \frac{T}{32\pi^4} g_a g_b \int_{s_{\rm min}}^{\infty} ds \frac{[(s - m_a^2 - m_b^2)^2 - 4m_a^2 m_b^2]}{\sqrt{s}} \sigma(a\,b \to 1\,2) K_1\left(\frac{\sqrt{s}}{T}\right) ,$$

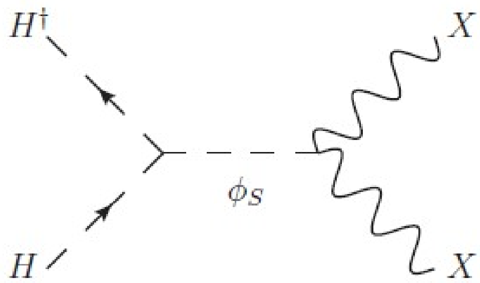
➢ $\gamma^D{}_h$ for SM-like Higgs decay h_1 → $X\,X$ is

$$\gamma_h^D \equiv \frac{1}{2\pi^2} m_{h_1}^2 \Gamma(h_1 \to XX) T K_1\left(\frac{m_{h_1}}{T}\right)$$

➢ Note that all γ's only depends on the Higgs portal κ and the VDM mass m_X

Freeze-In Mechanism

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



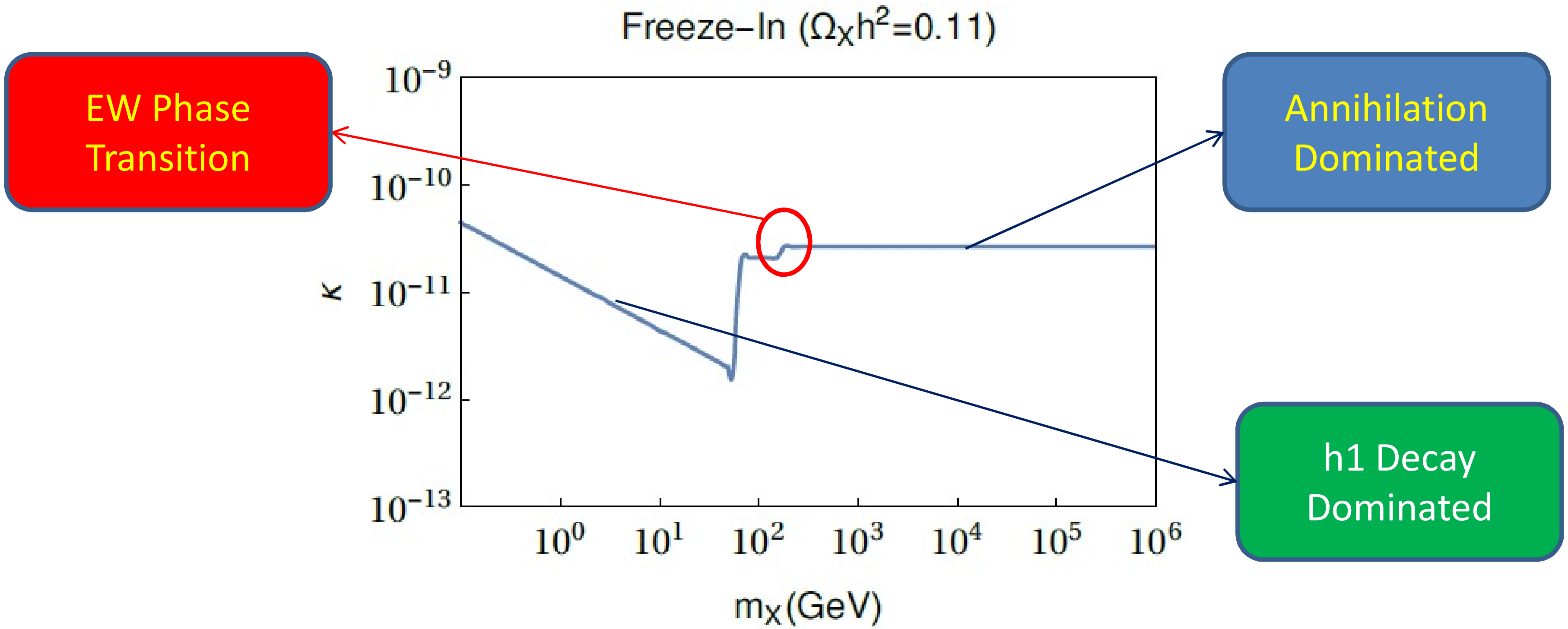
- Boltzmann Equation for Freeze-In is changed to

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

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

Freeze-In Mechanism

- Parameter Space for the right VDM relic density



Freeze-In Mechanism

➢ Non-Thermalization Condition: In order for the freeze-in to work, the dark sector is required to neither thermalize by itself nor with the SM sector.

- Due to a tiny κ, VDM cannot reach an equilibrium with SM.

- The non-equilibrium between VDM and h_2 is encoded by

$$\langle \sigma(XX \to h_2 h_2) v \rangle n_X \leq H \,,$$

where all of the quantities are defined at T_{FI}.

DM Self-Interactions

- In order to generate large enough DM Self Interactions, we focus on the parameter space m_X ~ 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 $k = \mu v$

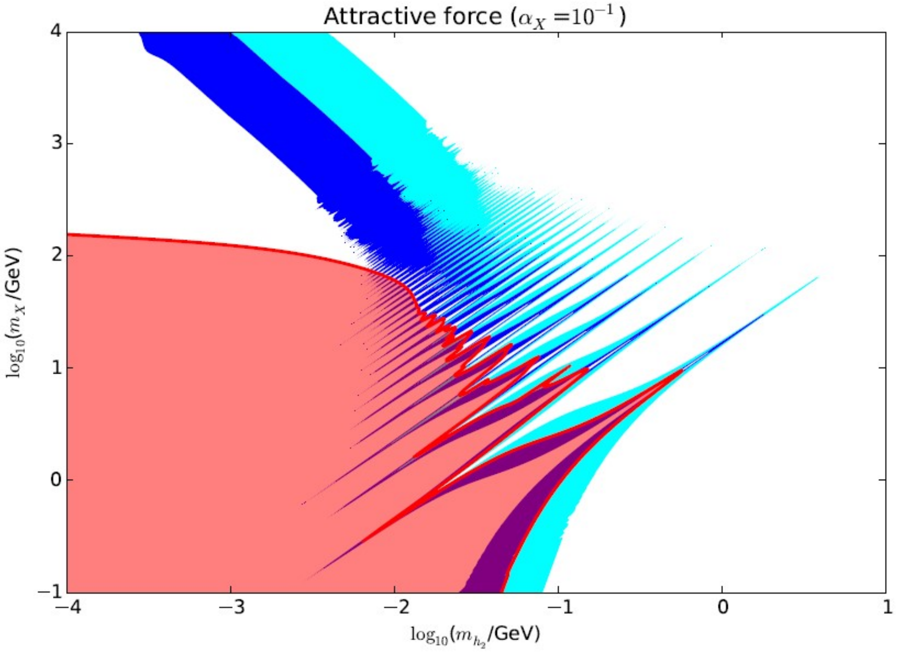
DM Self-Interactions

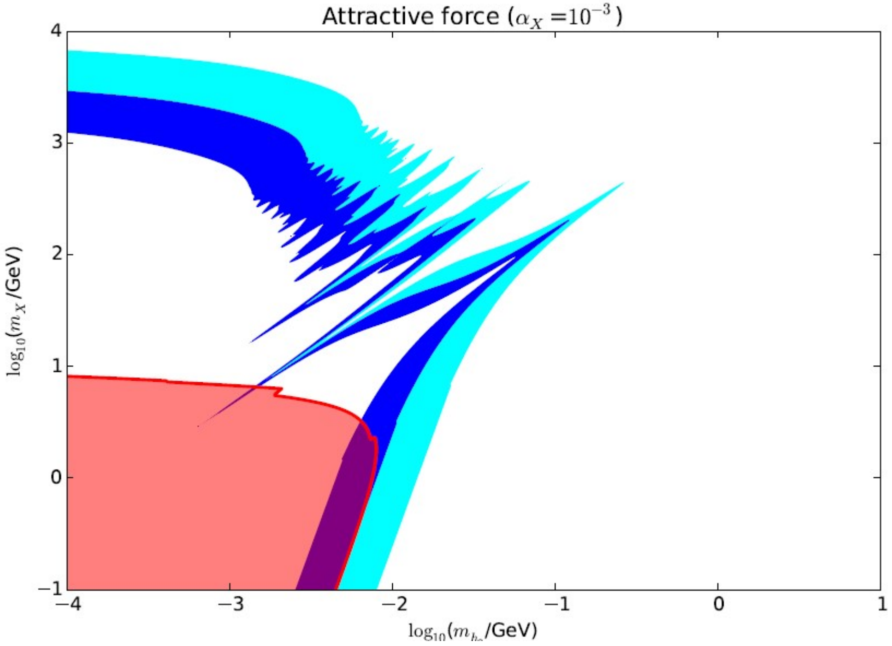
➢ Numerical Results

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

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

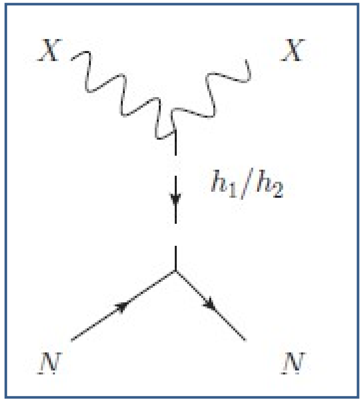
Red: Excluded by Cluster constraints





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

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

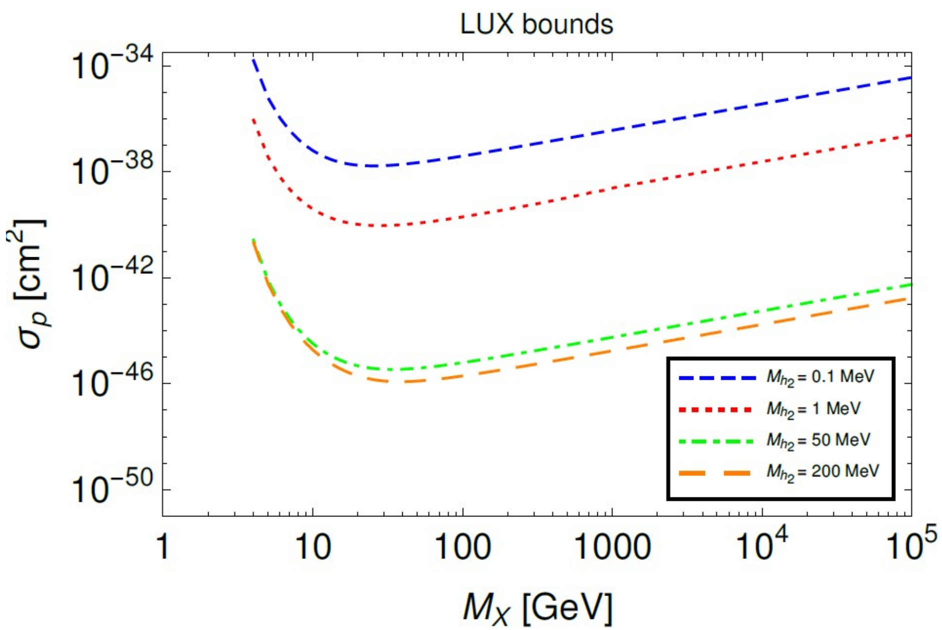
where

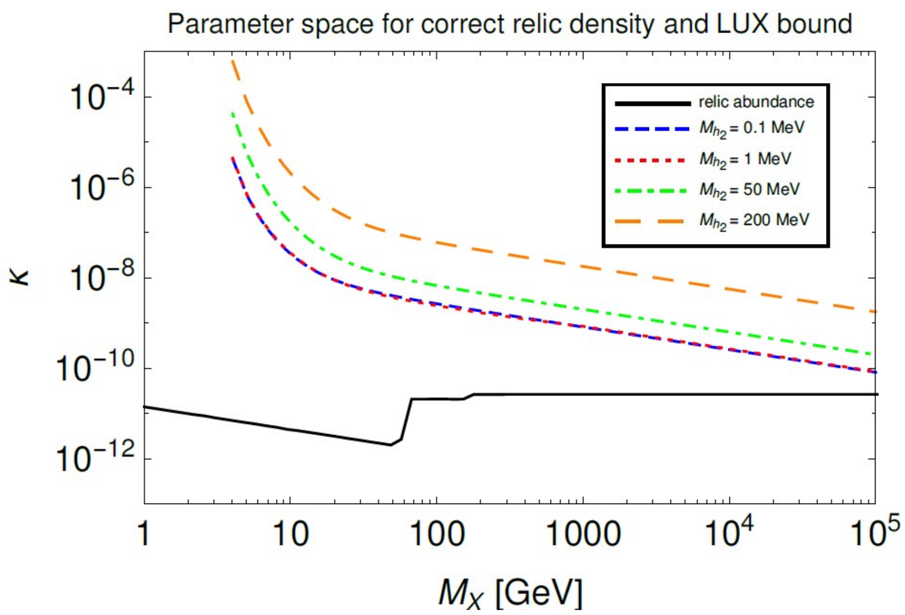
$$G(q^2) = \frac{m_{h_2}^2 (m_{h_2}^2 + 4\mu_{XN}^2 v^2)}{(q^2 + m_{h_2}^2)^2}$$

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

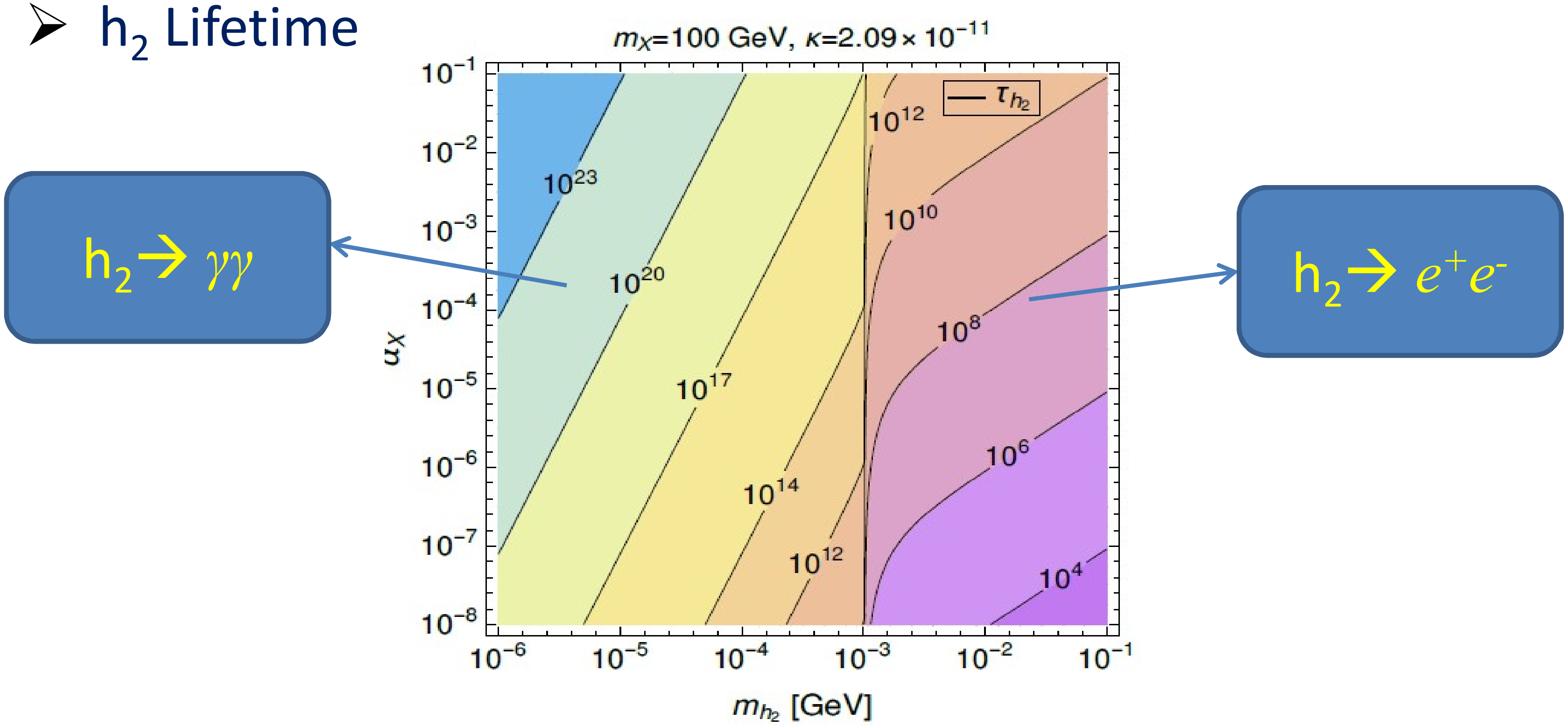




DM Indirect Detection

➢ The phenomenology of VDM indirect detections strongly depends on the properties of h_2.

➢ h_2 Lifetime



➢ The density of h_2 before its decay is determined by freeze-in

BBN Constraints

- Since $\tau_{h2} \gtrsim 10^4$s, h_2 behaves as a decaying DM from the BBN perspective.

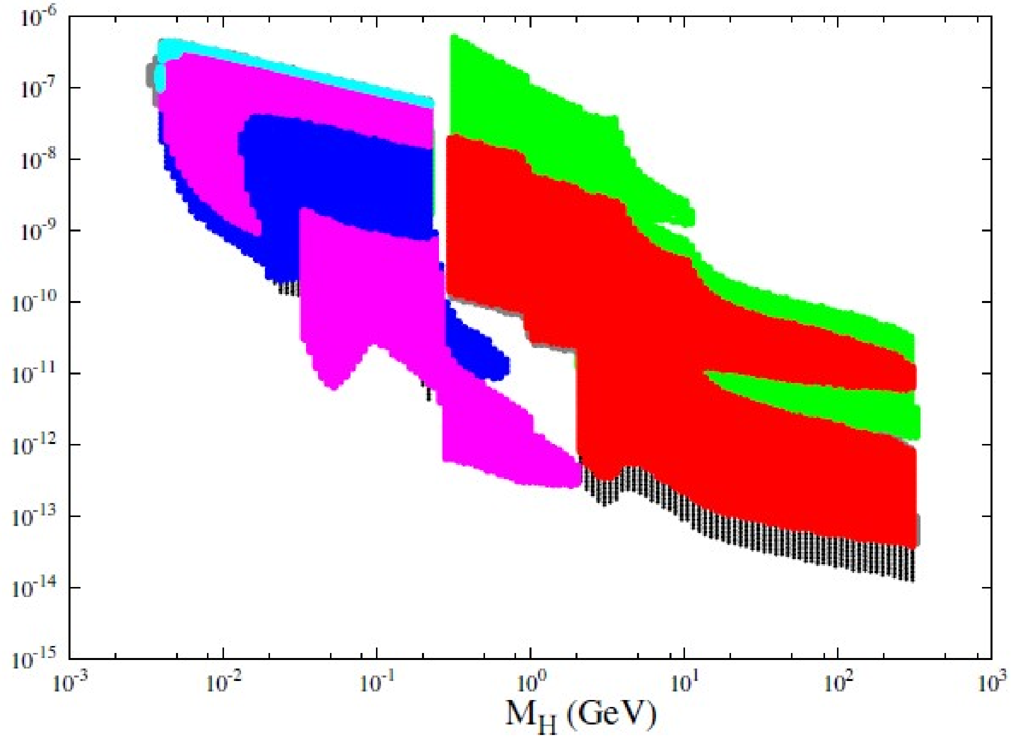
- The electromagnetic energy injections from the h2 decay would change the yields of various elements.

- From J. Berger et al. 2016, the BBN constraint is:

  for 1 MeV< m_{h2} < 100 MeV,

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

  while for m_{h2} < 1 MeV, there are no constraints.



DM Indirect Detections

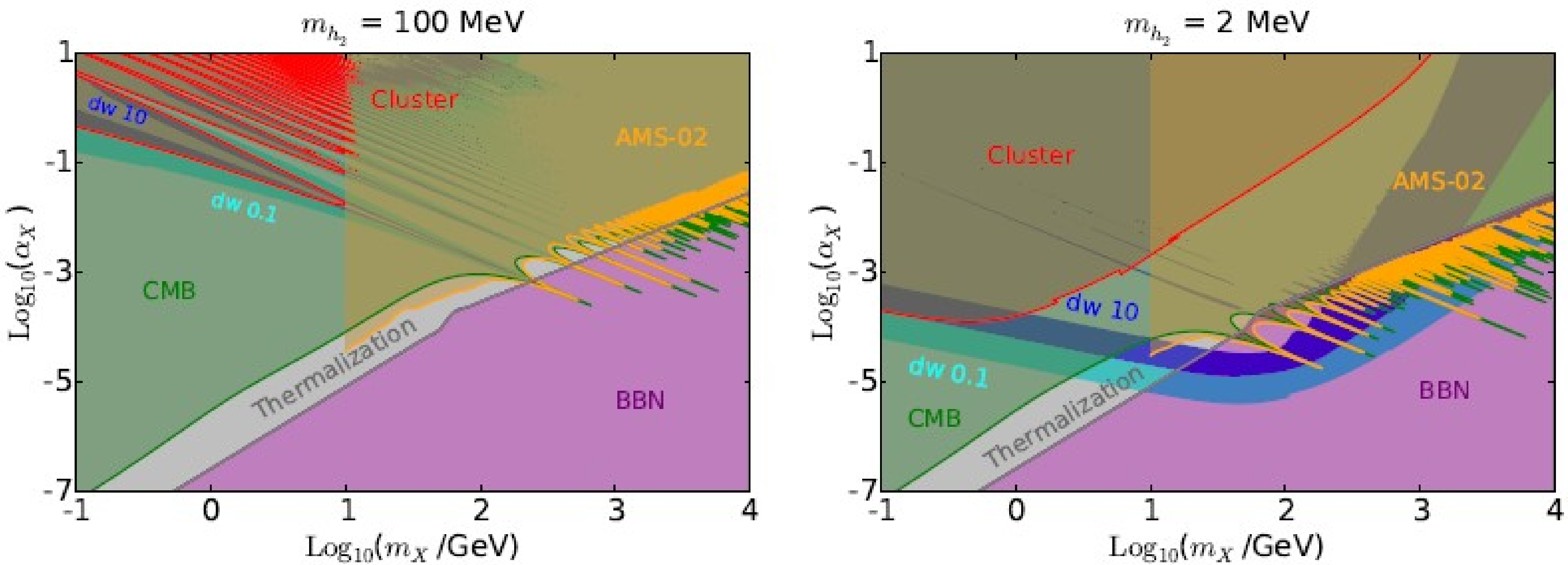
- mh2 > 1 MeV
  - Dominant Decay Channel: e^+e^- pair
  - Typical Lifetime: 10^4 s < τ_{h2} < 10^{12} s
  - Constraints on $XX \rightarrow h_2 h_2$ followed by h_2 decays
- Constraints: CMB, AMS-02, Fermi-LAT. G. Elor et al. 2016
  - CMB: modification of cosmological ionization history
  - AMS-02: positron flux excess in local region
  - Fermi-LAT: gamma ray signals from dwarf galaxies
- This process corresponds to the 1-step cascade annihilation , already been studied by G. Elor et al. 2016.
- It was shown that the Fermi-LAT constraint is typically weaker than AMS-02 and CMB, and thus neglected.

DM Indirect Detections

- Due to the mass hierarchy, the $XX \rightarrow h_2 h_2$ suffers a large Sommerfeld enhancement

$$\sigma v = S \times (\sigma v)_0 ,$$

where $(\sigma v)_0$ denotes the perturbative cross section, and S the s-wave Sommerfeld factor.



DM Indirect Detections

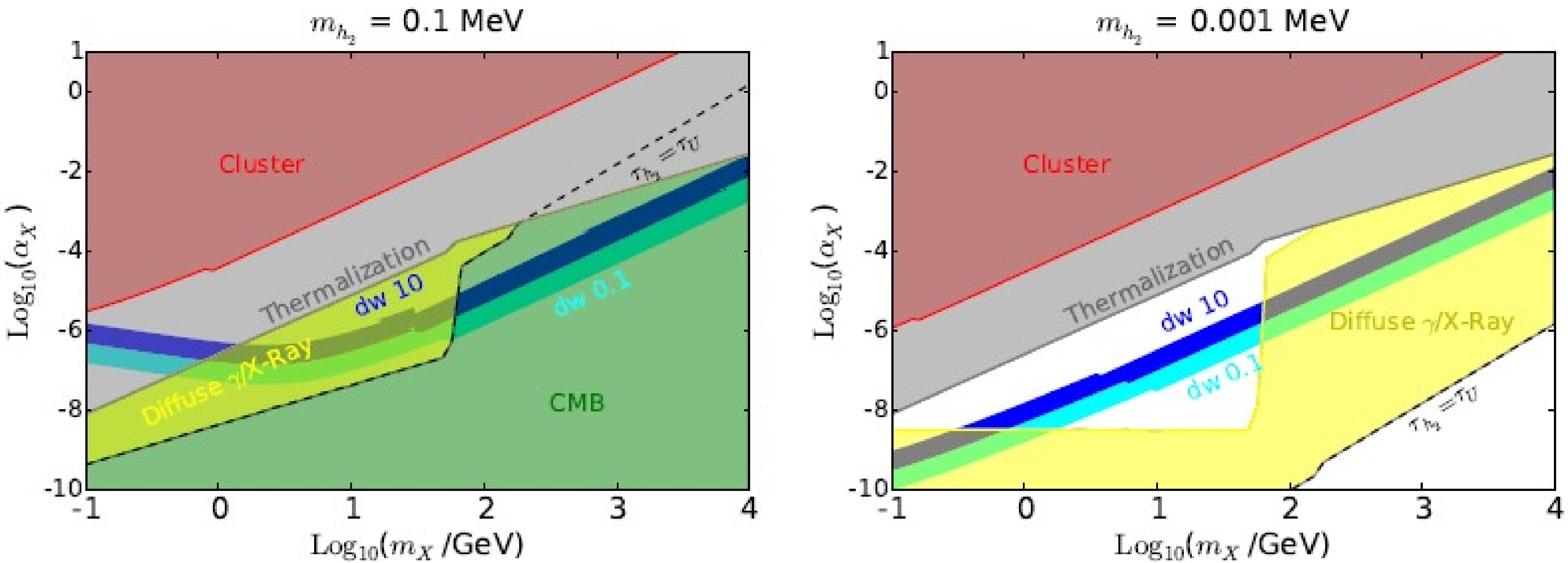
- $m_{h2} < 1$ MeV
  - Dominant Decay Channel: diphotons
  - Typical Lifetime: $\tau_{h2} > 10^{12}$ s
  - Constraints: CMB, diffuse γ/X-ray

- CMB: h_2 seems a decaying DM generated via freeze-in, so photons from h2 decays would be constrained.

T.R. Slatyer & C.L. Wu, 2016

- When $\tau_{h2} > \tau_U$, h2 is a true DM component. Its decays lead to diffuse γ/X-ray excesses. S. Riemer-Srensen et al, 2015

DM Indirect Detections



- 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 a substantial role.

- We focus on the freeze-in region, in which $m_X \sim 1$ 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

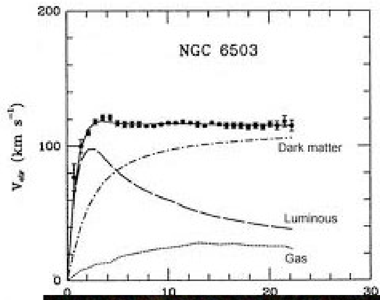
- We find that direct detections do not constrain the model much, but the indirect detections restrict m_{h2} should be of or smaller than O(keV)

THANKS FOR YOUR ATTENTION!

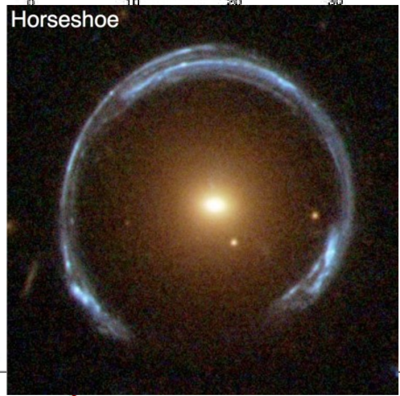
BACK-UP SLIDES

Motivation

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

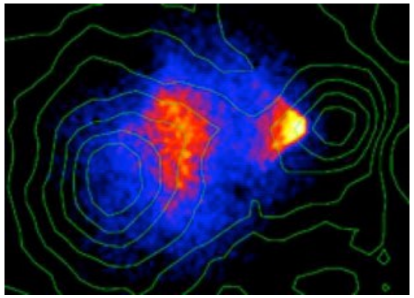


- Rotation Curves of Spiral Galaxies
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980

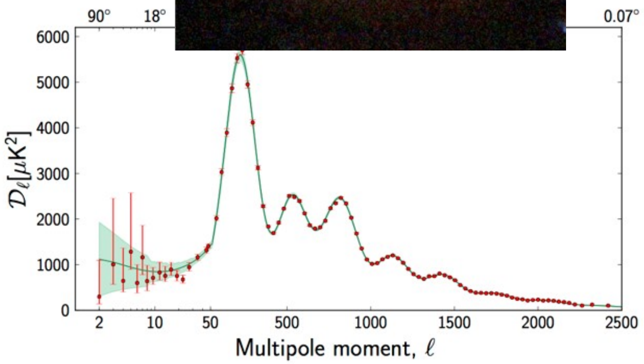


- Gravitational Lensing

- CMB Planck Collaboration, 2015



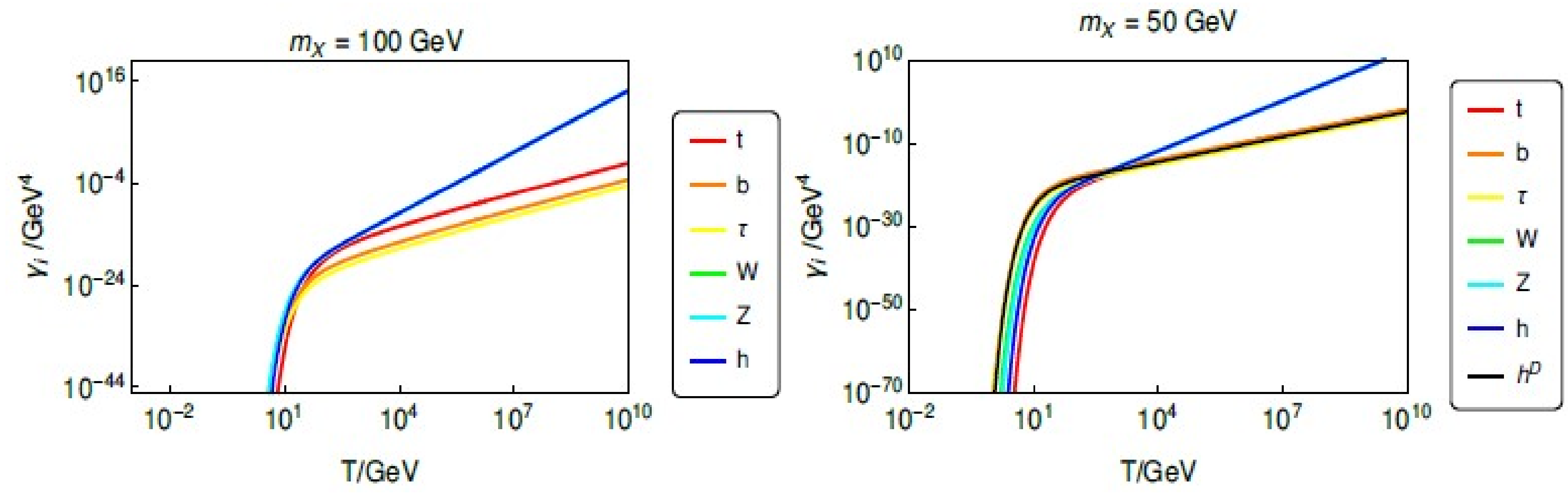
- Bullet Clusters



But , they are all gravitational

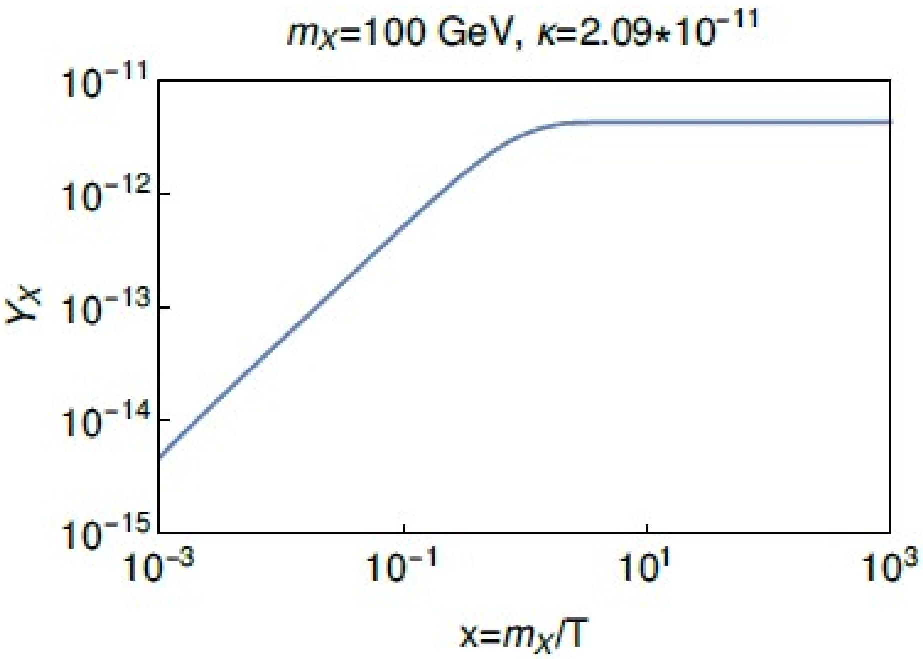
Freeze-In Mechanism

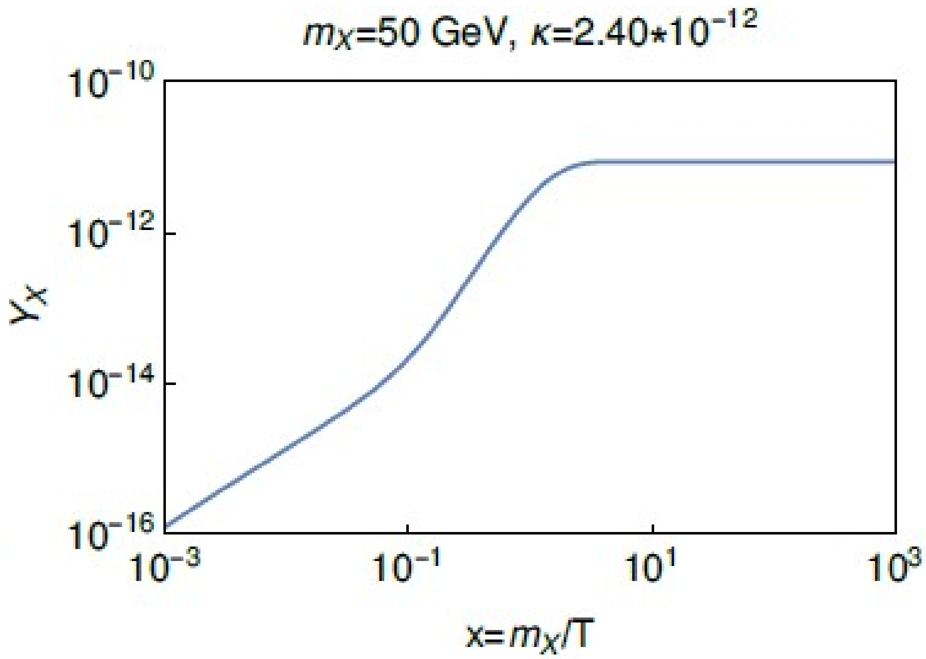
➢ Evolutions of γ's (SM Symm. Broken phase):



Freeze-In Mechanism

➢ Evolutions of VDM Yield (SM Symm. Broken phase):





➢ Freeze-in Temperature:

- $T_{FI} \simeq m_X$, for mX $\geqslant m_{h1}/2$: only SM annihilations contribute
- $T_{FI} \simeq m_{h1}$, for mX $\leqslant m_{h1}/2$: h1 decay dominates

DM Indirect Detection

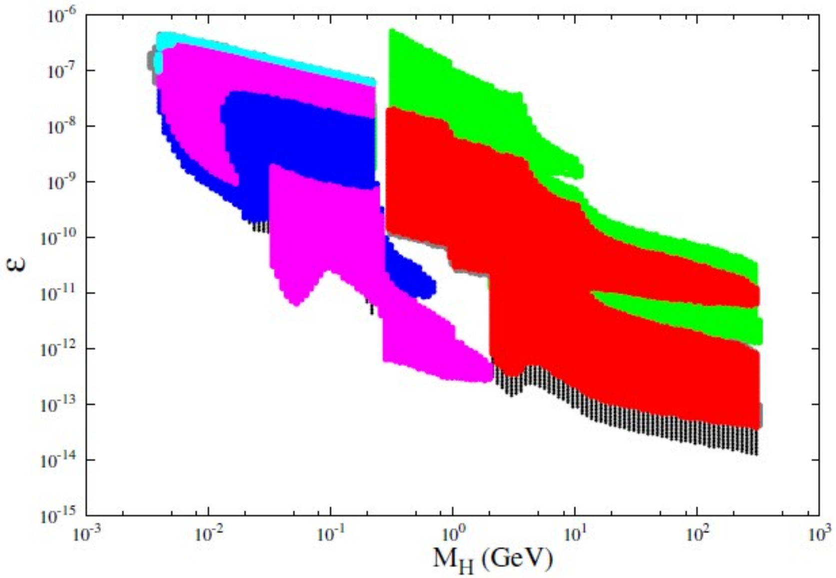
- For DM indirect detection, we use the data from BBN, Fermi-LAT dwarf galaxy gamma-ray observation, AMS-02 e^+e^-, and recent Planck data on the CMB power spectrum

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

- Since $\tau_{h2} > 1s$, 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

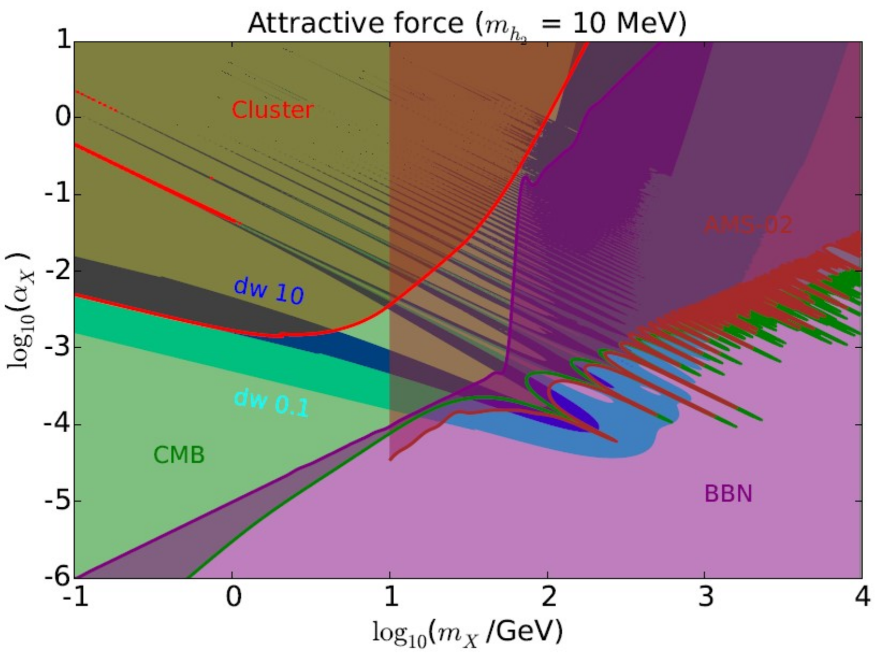
- mh2 > 1 MeV
  - Dominant Decay Channel: e+e- pair
  - Typical Lifetime: 10^4 s< t_{h2} < 10^{12} s
  - Constraints: Cluster, BBN, AMS-02, CMB.

- 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

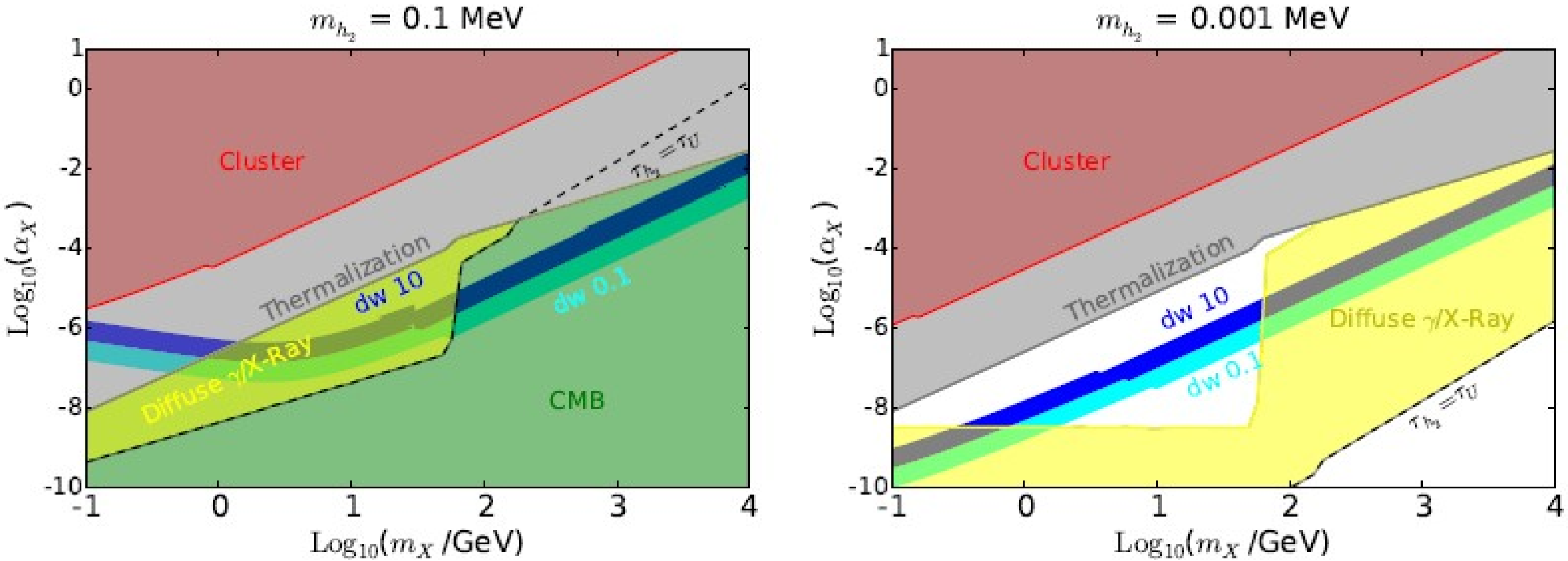
- All the parameter space is excluded



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