Self-Interacting Vector DM Through Freeze-In

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@Planck 2017

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Work still in progress

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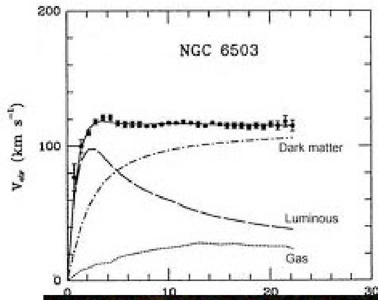
Motivation

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

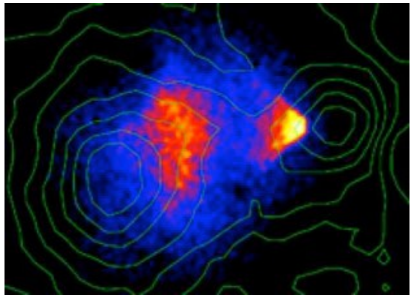


- Rotation Curves of Spiral Galaxies

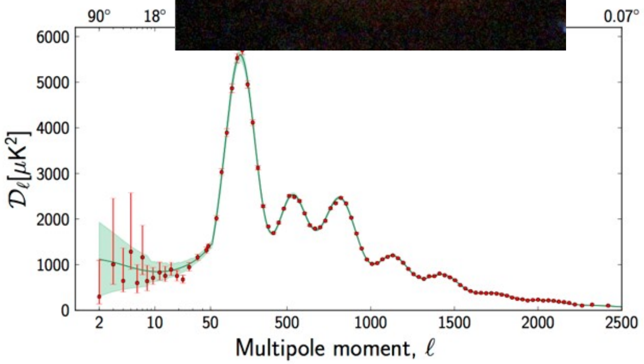
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980

- Gravitational Lensing

- CMB



- Bullet Clusters



But , they are all gravitational

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Motivation

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

- ➢ CCDM successfully explain 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
- Too Big to Fail Problem:

Motivation

- Possible Solutions: Introduction of DM Self-Interactions

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

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

- Constraints:

- Cluster Ellipticity

- Non-Evaporation of Galaxy halo in hot clusters

- Bullet Cluasters

- Typical Constraints: $\sigma_T/m_X \leq 1\ \mathrm{cm}^2/\mathrm{g}$

Motivation

- One intriguing mechanism is to consider the DM of broadly weak scale 1 GeV ~ 10 TeV, with a light mediator of mass to be 1~10 MeV.

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)

- We would like to study this scenario in a concrete DM model.

Motivation

- Usually, the standard WIMP mechanism to generate DM is through the freeze-out, in which DM is in thermal equilibrium with the SM particles at Big Bang, and freeze out at low temperatures $T \sim m_X/26$

- New Scenario: Freeze-In

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

Vector DM Model

- ➢ SM + Complex Scalar S + $U(1)_X$ Gauge Boson X + 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:

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

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

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

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

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

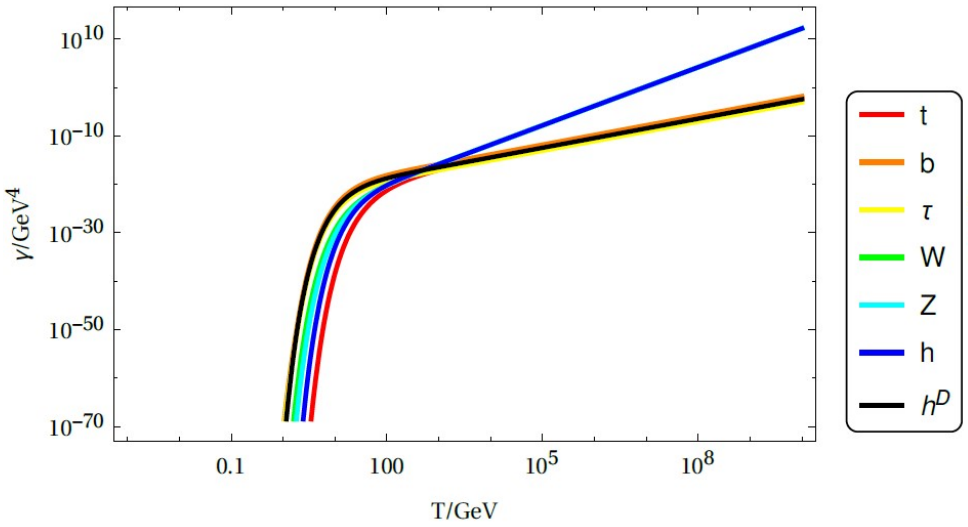
Freeze-In Mechanism

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

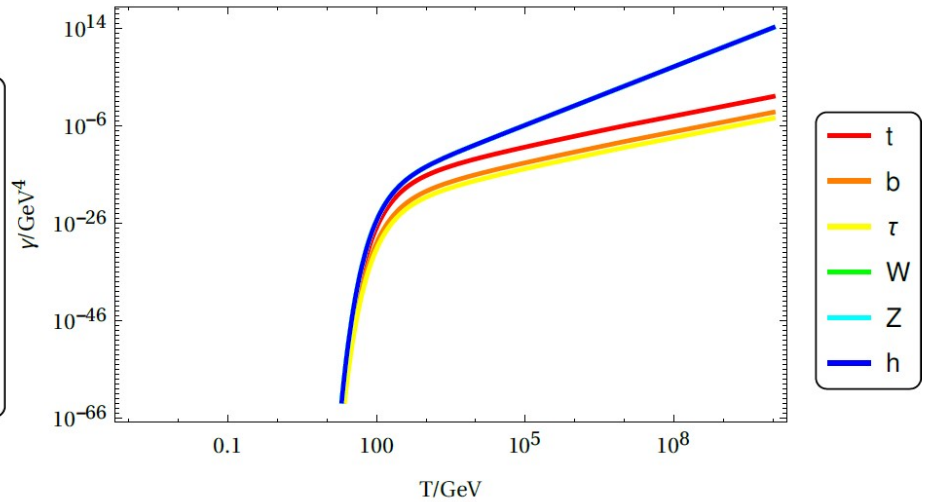
$$xHs\frac{dY_X}{dx} = \sum_f \gamma_f + \gamma_W + \gamma_h + \gamma_Z + \gamma_h^D .$$

Note that all γ's proportional to κ

$\boxed{m_X = 50 \text{ GeV}, \kappa = 1.15 \times 10^{-12}}$

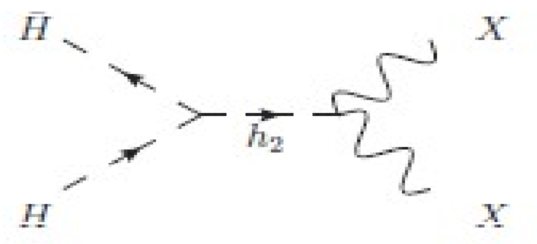


$\boxed{m_X = 100 \text{ GeV}, \kappa = 1.04 \times 10^{-11}}$



Freeze-In Mechanism

- At high temperature T>TEW = 160 GeV, the SM gauge symmetry is recovered, so only the SM Higgs doublet annihilations (HH→XX) contribute



- Boltzmann Equation for Freeze-In is changed to

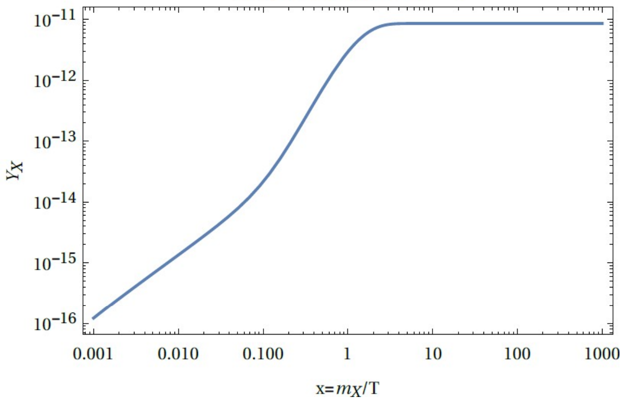
$$xHs\frac{dY_X}{dx} = \gamma_{H\bar{H}} \, .$$

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

Freeze-In Mechanism

- Solution to Boltzmann Equations

$\boxed{m_X = 50\ \mathrm{GeV}, \kappa = 1.15 \times 10^{-12}}$



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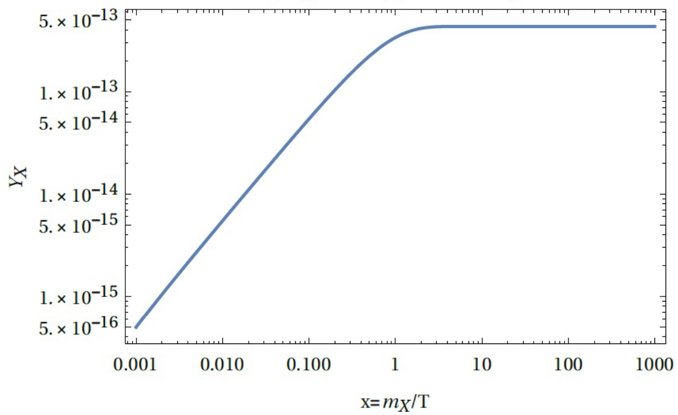
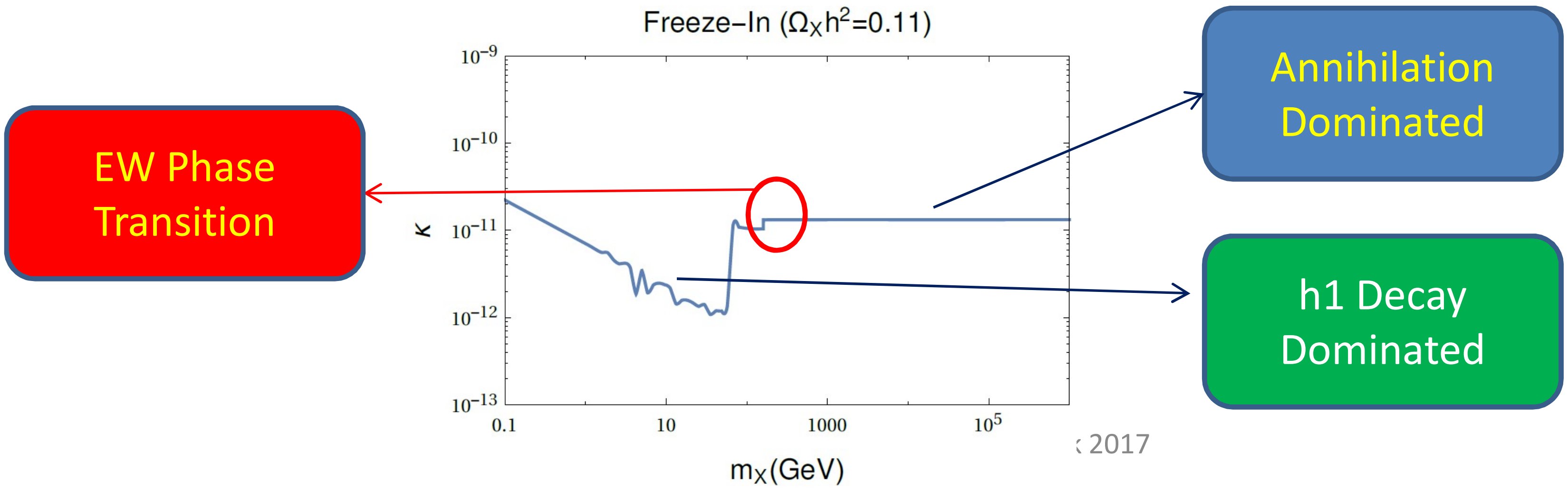


- Parameter Space



DM Self-Interactions

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

- 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 $k = \mu v$

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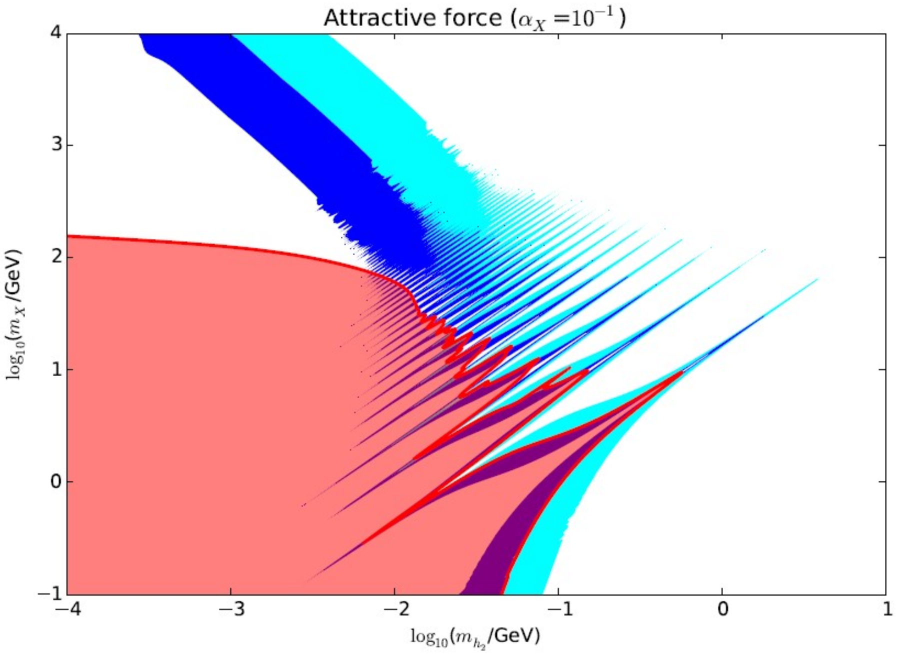
DM Self-Interactions

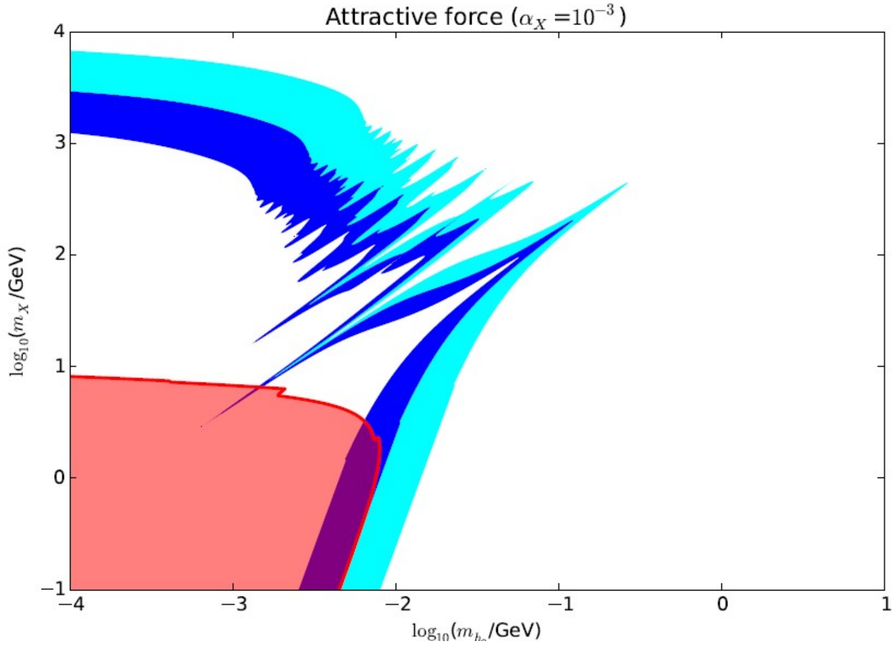
- Numerical Results

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





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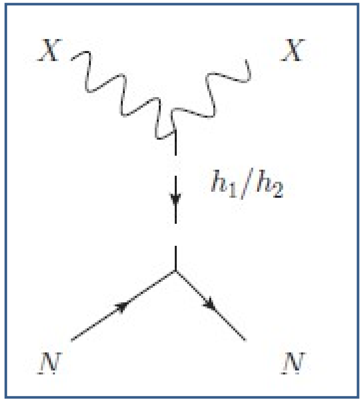
DM Direct Detection

- Process: XN→ XN



- Total Cross Section

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

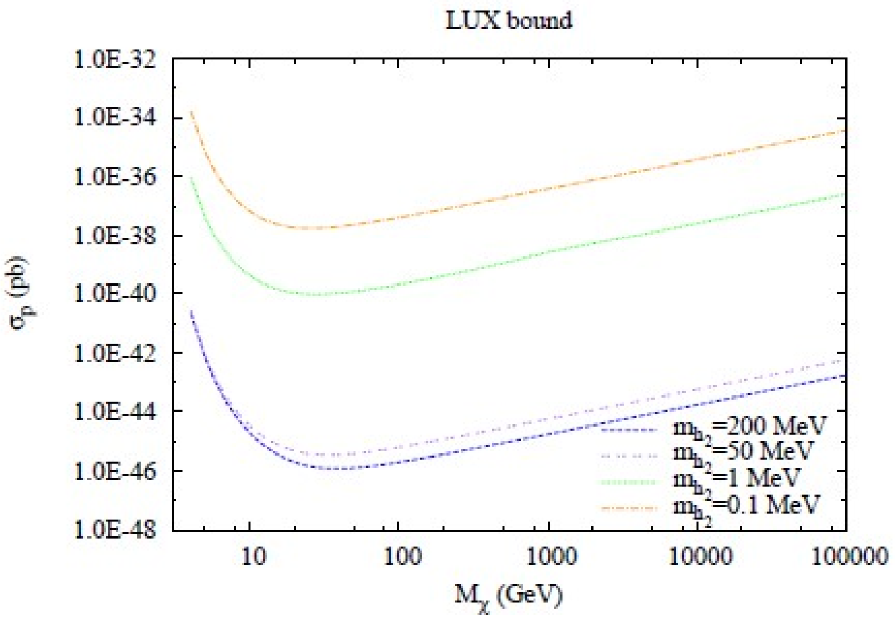
- Differential Cross Section

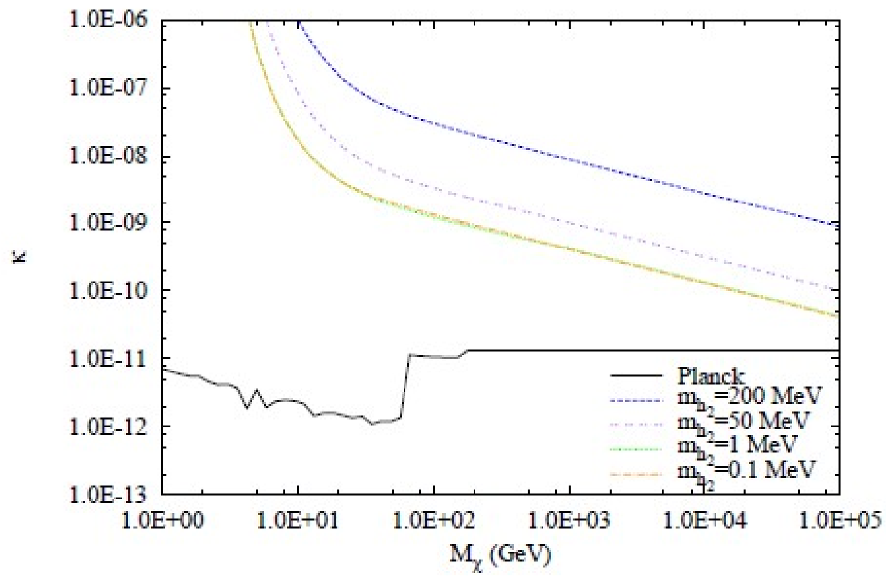
$$\frac{d\sigma_{XN}}{dq^2} = \frac{\sigma_{XN}}{4\mu_{XN}^2 v^2} G(q^2)$$

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

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





DM Indirect Detection

- BBN Constraints: successful prediction of element abundance requires either very short h2 lifetime or very small density of h2 when BBN due to h2 decay

- Previous Fitting shows that

$$\tau_{h_2} < 10^{-4}\ \mathrm{s} \quad \text{or} \quad \Omega_{h_2} h^2 < 10^{-5}$$

- Our model predicts lifetime of h2 is always larger than 10^{-4} s when mh2 < 100 MeV, so only the densityoption can be realized

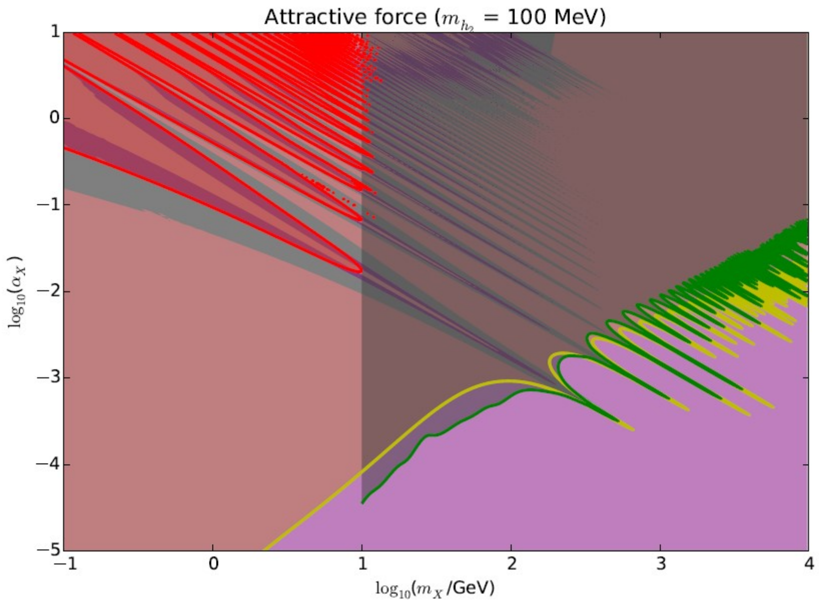
DM Indirect Detection

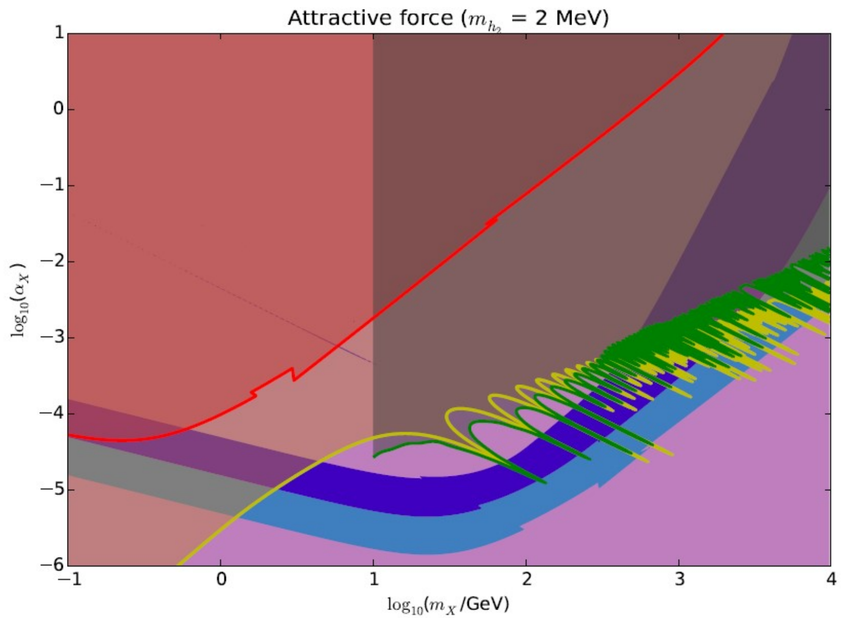
- For DM Indirect Detection, we use the data from Fermi-LAT dwarf galaxy gamma-ray observation, AMS-02 e+e-, and recent Planck data on the CMB power spectrum

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

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

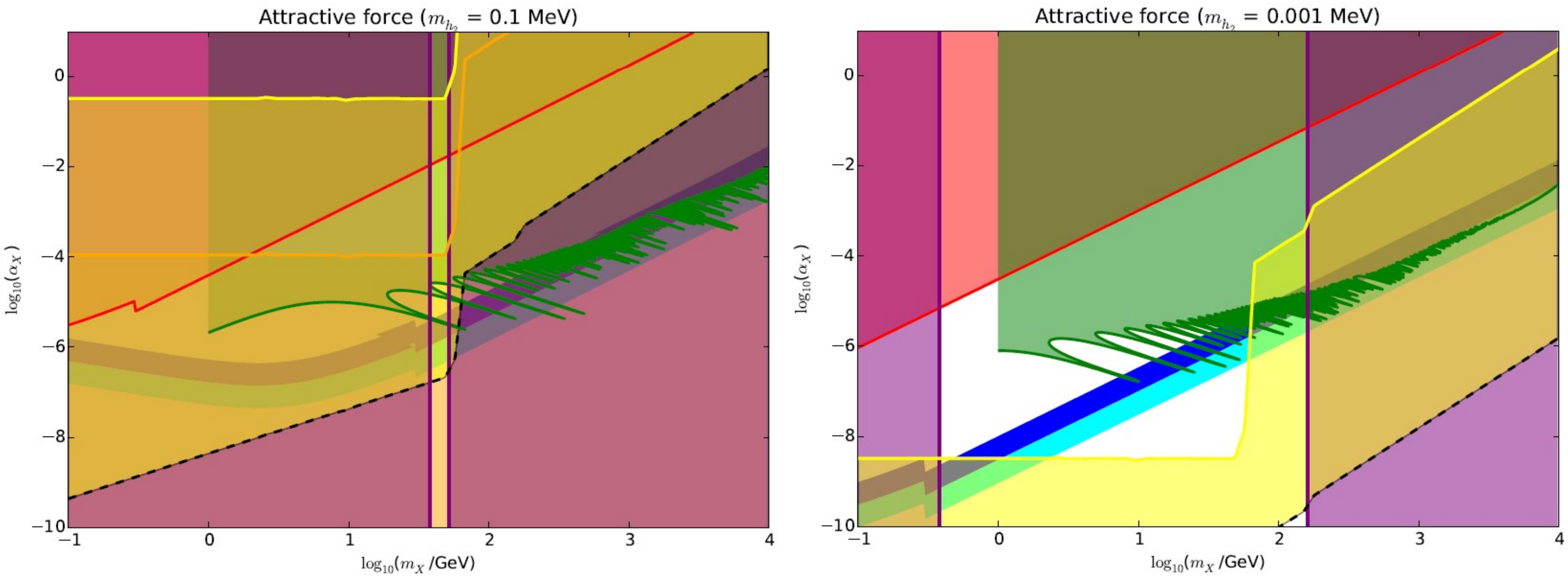




- All the parameter space is excluded by BBN

Numerical Result

- mh2 < 1 MeV
  - Dominant Decay Channel: diphotons
  - Typical Lifetime: $t_{h2} > 10^{12}$ s
  - Constraints: Cluster, BBN, Fermi-LAT, CMB, Diffuse Gamma



- Only when mh2~ keV, we find regions satisfying all constraints

Summary

- The VDM model via the Higgs portal is invesigated

- We focus on the freeze-in region, in which m_X ~ 1 GeV – 1 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)