Singlet extension of the MSSM as a solution to the small cosmological scale anomalies

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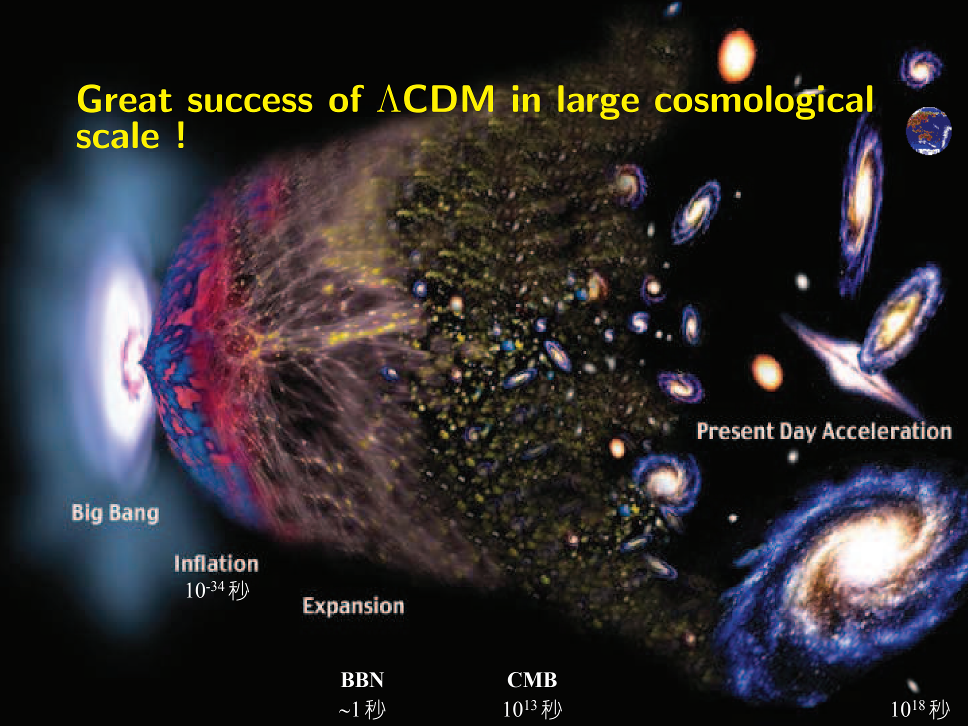
OUTLINE:

- Dark matter interactions
  - The transfer and viscosity cross sections of self-interacting dark matter
  - Summary of DM interactions
- Can self-interacting dark matter scenario be realized in the NMSSM ?
  - The next to minimal supersymmetric standard model
  - Allowed parameter space and dark matter self scattering in the NMSSM
- Can self-interacting dark matter scenario be realized in the GMSSM ?
  - Dark matter and Higgs bosons in the GMSSM
  - Allowed parameter space and dark matter self scattering in the GMSSM
- Conclusion

Great success of ΛCDM in large cosmological scale !



Anomalies of ΛCDM in small cosmological scale

- *missing satellites* – The DM halo of the Milky Way (MW) should contain many more dwarf-sized subhalos (satellites) than observed.
- *cusp vs core* – Low surface brightness and dwarf galaxies seem to have cored inner density profiles, at odds with CDM cusps predicted by simulations.
- *too big to fail* – The observed brightest satellites of the MW attain their maximum circular velocity at a too large radii in comparison with the densest and most massive satellites simulations.

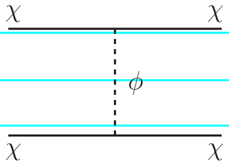
These anomalies need:

$$\sigma/m_\chi \sim 0.5\mathrm{cm}^2/\mathrm{g}$$

at Dwarf (DW), milky way (MW) and cluster (CL) scales. This much larger than the requirement of the relic density!

see Phys. Rev. Lett. **110**, 111301 (2013) for detail.

Self-interacting DM can solve these anomalies



- ϕ can be a vector or scalar $V(r) = \pm\frac{\alpha_\chi}{r}e^{-m_\phi r}$
- $\frac{d\sigma}{d\Omega}$ is used in the simulation. to do estimation in particle physics, the total cross section can be defined as

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

for distinguished dark matter

$$\sigma_V = \int d\Omega\sin^2\theta\frac{d\sigma}{d\Omega}$$

for identical dark matter

Calculation of the cross sections

Solve the schrödinger equation of scattering

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

for the Dirac dark matter

$$f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}P_\ell(\cos\theta)\sin\delta_\ell\,.$$

The differential scattering cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left|\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}P_\ell(\cos\theta)\sin\delta_\ell\right|^2,$$

the transfer cross section is

$$\frac{\sigma_T k^2}{4\pi} = \sum_{\ell=0}^{\infty}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)\ .$$

For the Majorana DM

$$\frac{d\sigma_{VS}}{d\Omega} = |f(\theta)+f(\pi-\theta)|^2 = \frac{1}{k^2}\left|\sum_{\ell(\text{EVEN number})}^{\infty}(2\ell+1)(\exp(2i\delta_l)-1)P_\ell(\cos\theta)\right|^2$$

$$\frac{d\sigma_{VA}}{d\Omega} = |f(\theta)-f(\pi-\theta)|^2 = \frac{1}{k^2}\left|\sum_{\ell(\text{ODD number})}^{\infty}(2\ell+1)(\exp(2i\delta_l)-1)P_\ell(\cos\theta)\right|^2$$

Then the viscosity cross sections are

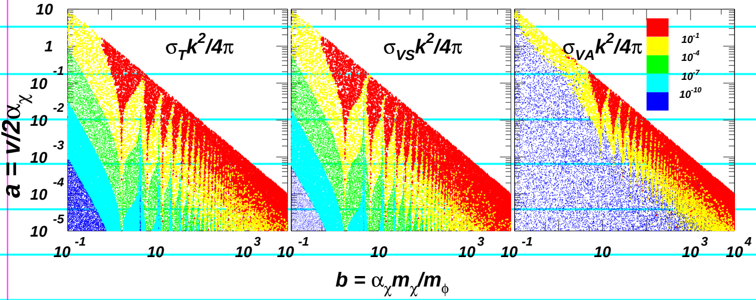
$$\frac{\sigma_{VS}k^2}{4\pi} = \sum_{\ell(\text{EVEN number})}^{\infty} 4\sin^2(\delta_{\ell+2}-\delta_\ell)(\ell+1)(\ell+2)/(2\ell+3),$$

$$\frac{\sigma_{VA}k^2}{4\pi} = \sum_{\ell(\text{ODD number})}^{\infty} 4\sin^2(\delta_{\ell+2}-\delta_\ell)(\ell+1)(\ell+2)/(2\ell+3).$$

we assume that the DM scatters with random orientations, thus

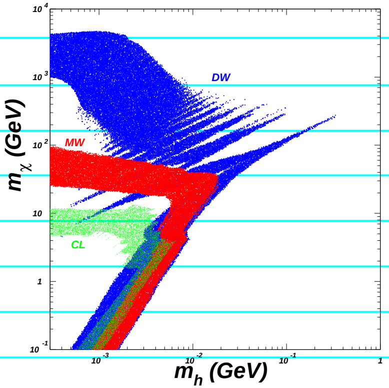
$$\sigma_V = \frac{1}{4}\sigma_{VS} + \frac{3}{4}\sigma_{VA}\ .$$

The transfer and viscosity cross sections



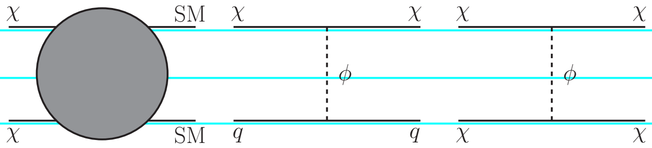
- There are the resonance regions ($b \gtrsim 1$ and $ab \lesssim 0.5$) in which all the cross sections exhibit patterns of resonance, making the cross section much complicated. Self-interacting DM scenario and in this paper works around the resonance regions.

Solving the anomalies



- Numerical results of σ_T allowed by solving the small cosmological scale anomalies (dwarf, Milky Way and cluster) with their corresponding characteristic velocities. We can see that σ_T/m_χ can satisfy simultaneously the requirements to solve the small scale anomalies.

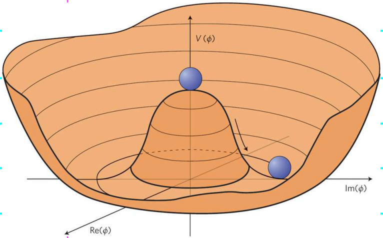
Summary of DM interactions



1. The annihilation to the SM particles whose cross section at high energy determines the relic density of dark matter and whose cross section at low energy is being probed by the indirect detection experiments.
2. The elastic scattering off the SM particles which is being probed by various direct detection experiments.
3. The non-relativistic self-scattering where $l = 0$ in the partial wave expansion gives the Sommerfeld enhancement relative to the relativistic annihilation while $l \lesssim 25$ can account for the anomalies in the small cosmological scales.

Can self-interacting dark matter scenario be realized in the NMSSM ?

To solve μ problem of MSSM



$$\mu_{eff} = \lambda < S >$$

Table: MSSM and several of its extensions.

Model	Symmetry	Superpotential	CP-even	CP-odd	Charged
MSSM	–	$\mu \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0	A_2^0	$H^\pm$
NMSSM	$\mathbb{Z}_3$	$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0	$H^\pm$
nMSSM	$\mathbb{Z}_5^R, \mathbb{Z}_7^R$	$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F M_n^2 \hat{S}$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0	$H^\pm$
UMSSM	$U(1)'$	$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0, H_3^0	A_2^0	$H^\pm$
sMSSM	$U(1)'$	$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$	$H_{1,2,3,4,5,6}^0$	$A_{1,2,3,4}^0$	$H^\pm$

DM scenarios of the NMSSM

- Bino-dominant DM. Under current collider and DM relic density constraints, the SI cross section can exclude a large part of parameter space, leaving only a bino-dominant DM candidate below TeV.
- Higgsino-dominant DM. The higgsino-dominant DM candidate around 1.1 TeV can satisfy all the constraints, including the relic density and current DM direct detections.
- Singlet-dominant DM. showed that in the Peccei-Quinn limit there can exist three light singlet-like particles (0.1-10 GeV): a scalar, a pseudoscalar and a singlino-like DM candidate. For a certain parameter window, through annihilation into the light pseudoscalar the singlino DM can give the correct relic density, and through exchanging the light scalar in scattering off the nucleon a large cross section suggested by CoGeNT and DAMA/LIBRA can be attained.

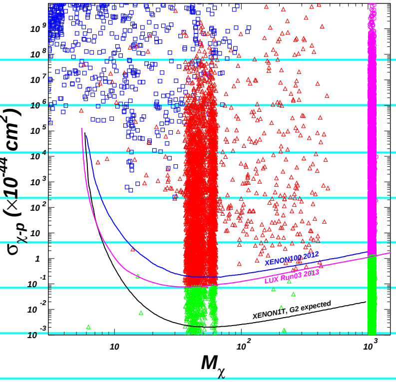
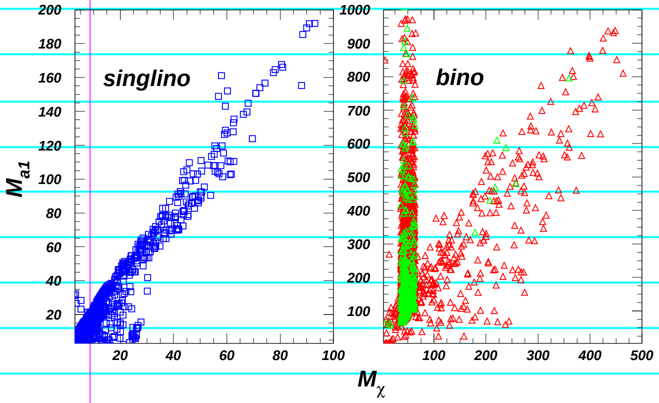


Figure: The spin-independent cross section of DM scattering off the proton versus the DM mass in different scenarios in the NMSSM. □ denotes singlino-dominant DM scenario, most of which are excluded by the DM direct detection limits; △ denotes bino-dominant DM scenario, among which the red ones are excluded while the green ones survive; ○ (around 1 TeV) denotes the higgsino-dominant DM scenario, among which the pink ones are excluded while the green ones survive. All the samples satisfy the DM relic density constraints.



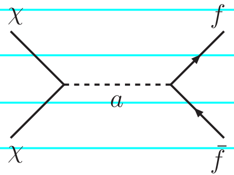
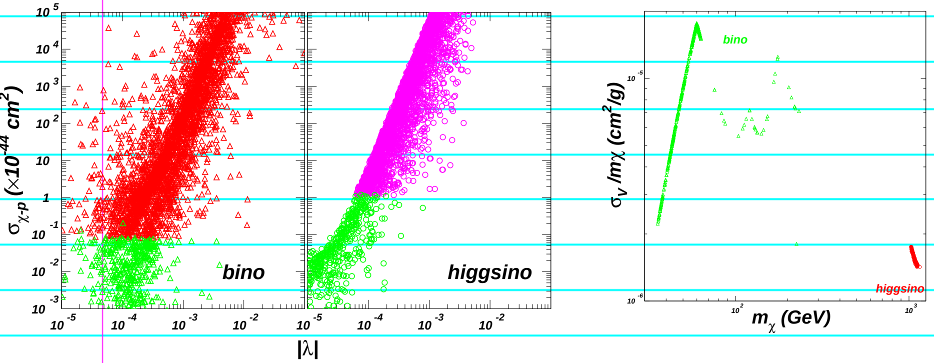


Figure: Feynman Diagram of DM annihilation to SM fermions through a pseudo-scalar a.

- The SI cross section has the inverse quartic power dependence on the mediated scalar mass. Though the coupling of $h_1 f \bar{f}$ is suppressed by a small λ, the cross section will be enhanced greatly when the mass of h_1 is below GeV.



- The singlino-dominant DM scenario is almost excluded because of the λ-value correlation between relic density and DM-nucleon SI cross section
- Some parameter space still survived the SI cross section limits in the bino-dominant and higgsino-dominant DM scenarios. but the the DM are almost the free interacting thus can not solve the small cosmological anomalies.

Can self-interacting dark matter scenario be realized in the GMSSM ?

Reason of failure of the NMSSM in solving the small cosmological scale anomalies is

- $$\lambda S H_u \cdot H_d$$

  to solve the μ problem, then give a too small λ (constrained by DM-nucleon SI cross section limits), which determines the coupling strength of $h_1 \chi\chi$ in DM self-interaction.

So, We should extend the MSSM with a singlet generally (GMSSM)

$$W = \mu \widehat{H}_u \cdot \widehat{H}_d + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \eta \widehat{S} + \frac{1}{2} \mu_s \widehat{S}^2 + \frac{1}{3} \kappa \widehat{S}^3$$

λ can set as Zero, the singlet will be a dark sector and sufficient for the self-interacting DM scenario.

Spectrum and feynman rules:

$$m_\chi = 2\kappa s + \mu_S, \quad (1)$$

$$m_h^2 = \kappa s(4\kappa s + A_\kappa + 3\mu_S) - C_\eta \eta/v, \quad (2)$$

$$m_a^2 = -2B_s\mu_s - \kappa s(3A_\kappa + \mu_S) - C_\eta \eta/s, \quad (3)$$

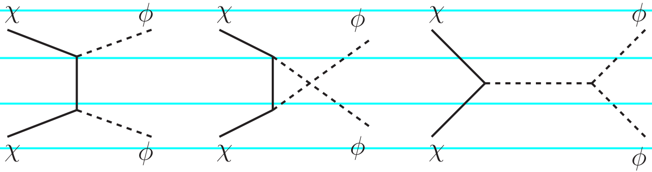
$$V_{hhh} = -4ik(6\kappa s + A_\kappa + 3\mu_S) = -4i\kappa(3m_\chi + A_\kappa), \quad (4)$$

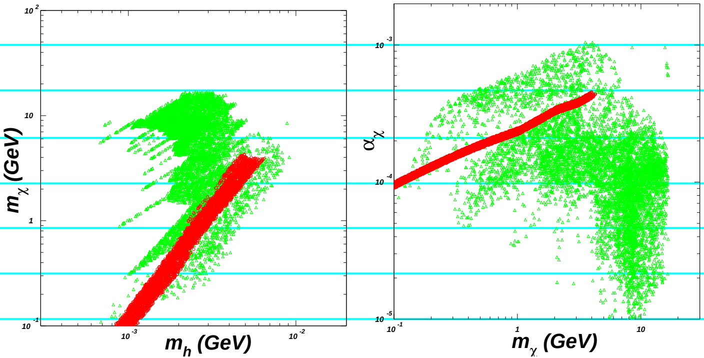
$$V_{haa} = -4i\kappa(2\kappa s - A_\kappa + \mu_S) = -4i\kappa(m_\chi - A_\kappa), \quad (5)$$

$$V_{h\chi\chi} = -4i\kappa, \quad (6)$$

$$V_{a\chi\chi} = -4\kappa\gamma^5. \quad (7)$$

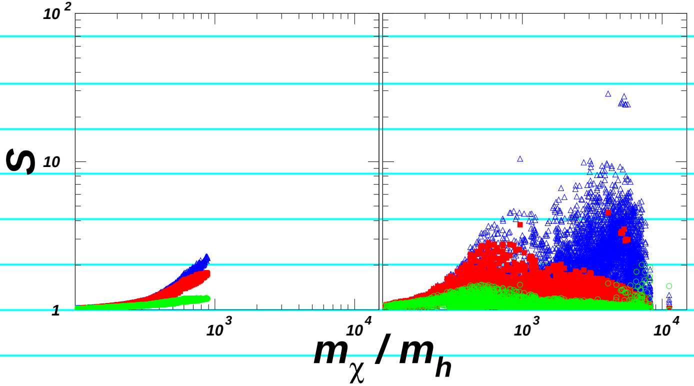
The annihilation of DM





The GMSSM has a larger parameter space to solve the anomalies of all three small scales. The reason is that in the DM self-interaction model DM can only annihilate into hh via t-channel and u-channel while in the GMSSM DM can annihilate into hh, ha and aa via t-channel, u-channel and s-channel.

Sommerfeld enhancements in the two models



The GMSSM allows for a larger m_χ/m_h and thus can give a larger Sommerfeld enhancement factor. The ongoing indirect detections of DM can probe the DM annihilation rate (shed light on the Sommerfeld enhancement factor) and thus help to distinguish different DM self-interaction models.

Conclusions

1. If the DM is Majorana fermion, we must viscosity cross section for the DM simulations. there are two the viscosity cross sections: σ_{VS}, σ_{VA}.
2. The correlation between annihilation rate and SI cross section strongly constrains the NMSSM, making it impossible to realize the self-interaction DM scenario.
3. It easy to realize self-interacting DM scenario is the general singlet extension of the MSSM.
4. The singlet of the GMSSM can give appropriate enhancement.

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Thank you !