Dark Matter with Dipole Moment

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Magnetic Dipole (MDM) and Electric Dipole Moment (EDM) of Dark Matter (DM)

- Many DM models expect the dominate DM interaction is weak interaction.
- V. Barger, WY. Keung, D. Marfatia (2010) proposed the DM can have MDM and EDM, that DM can have interaction with photon.
- The DM (χ)-photon vertex are

  $$V_{\gamma\chi\bar{\chi}}(MDM) = \frac{e}{\Lambda_{MDM}}\sigma^{\mu\alpha}P_\mu \ , \quad V_{\gamma\chi\bar{\chi}}(EDM) = \frac{e}{2\Lambda_{EDM}}\sigma^{\mu\alpha}\gamma^5 P_\mu \ ,$$

  where $\mu_\chi = \frac{e}{\Lambda_{MDM}}$ and $d_\chi = \frac{e}{\Lambda_{EDM}}$.

- For MDM, the DM-nuclear differential cross section is

$$\frac{d\sigma^{MDM}}{dE_R} = \frac{e^2\mu_\chi^2}{4\pi E_R}\frac{S+1}{3S}\left[Z^2\left(1-\frac{E_R}{2m_A v_r^2}-\frac{E_R}{m_\chi v_r^2}\right)G_E^2(E_R)\right.$$
$$\left.+\frac{I+1}{3I}\left(\frac{\mu_{Z,A}}{\frac{e}{2m_p}}\right)^2\frac{m_A E_R}{m_p^2 v_r^2}G_M^2(E_R)\right] .$$

- For EDM, the DM-nuclear differential cross section is

$$\frac{d\sigma^{EDM}}{dE_R} = \frac{e^2 d_\chi^2}{4\pi}Z^2\left(\frac{S+1}{3S}\right)\frac{1}{v_r^2}\frac{1}{E_R}G_E^2(E_R) .$$

- Comparing with the conventional Spin-Independent (SI) DM-nuclear cross section

$$\frac{d\sigma_A^{SI}}{dE_R} = \frac{G_F^2 m_A}{2\pi v_r^2}\left[Zf_p+(A-Z)f_n\right]^2 G_E^2(E_R) .$$

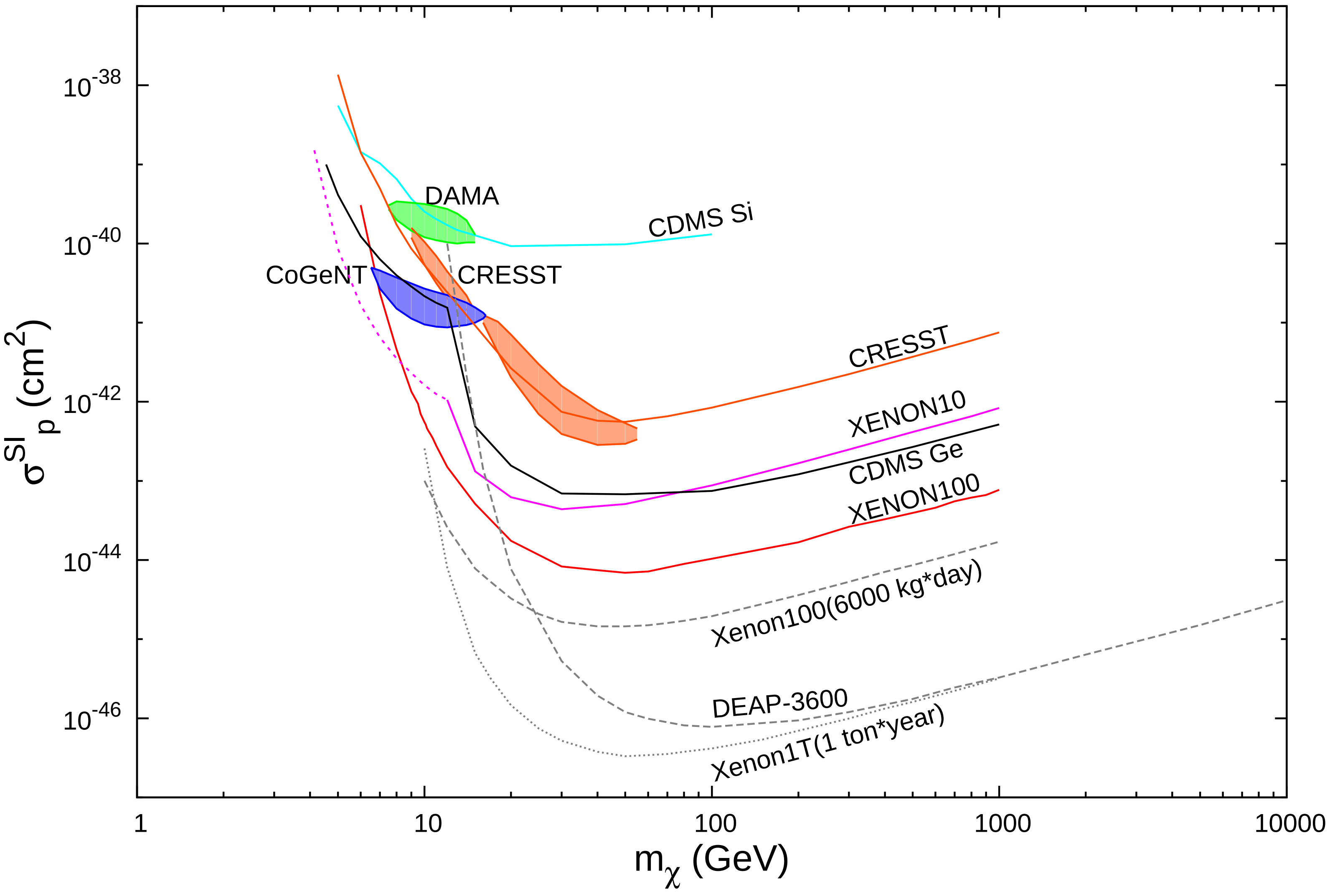
- We defined the DM-proton cross section for MDM by

$$\sigma_{sc} = \frac{2}{E^{Max}} \int_0^{E^{Max}} \frac{d\sigma}{dE_R} E_R dE_R \ ,$$

where $E^{Max} = \frac{2m_{rA}^2 v_r^2}{m_A}$.
These cross sections can let us easier to see the difference between the experiment results of MDM DM and conventional SI DM.

The Event Rate of Direct Detection Experiments

- The Direct Detection Experiments (SI: XENON100, CDMS, CoGeNT, DAMA, CRESST,$\cdots$ etc. SD: PICASSO, KIMS, COUPP,$\cdots$ etc.)
- The CoGeNT, DAMA, and CRESST observed the DM signal. However because there are no DM signal in the other experiments, these signal region been rule out by XENON100 in the conventional SI DM case.


10^-38
10^-40
10^-42
10^-44
10^-46
σ^SI_p (cm^2)
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10
100
1000
10000
m_χ (GeV)
DAMA
CDMS Si
CoGeNT
CRESST
CRESST
XENON10
CDMS Ge
XENON100
Xenon100(6000 kg*day)
DEAP-3600
Xenon1T(1 ton*year)

- The event rate per unit detector mass

$$R = \frac{\rho_0}{m_\chi}\frac{1}{m_A} \int_{E_{Rmin}}^{E_{Rmax}} dE_R \int_{v_{min}}^{v_{esc}+v_E} dv_r v_r f_1(v_r) \frac{d\sigma}{dE_R} \ ,$$

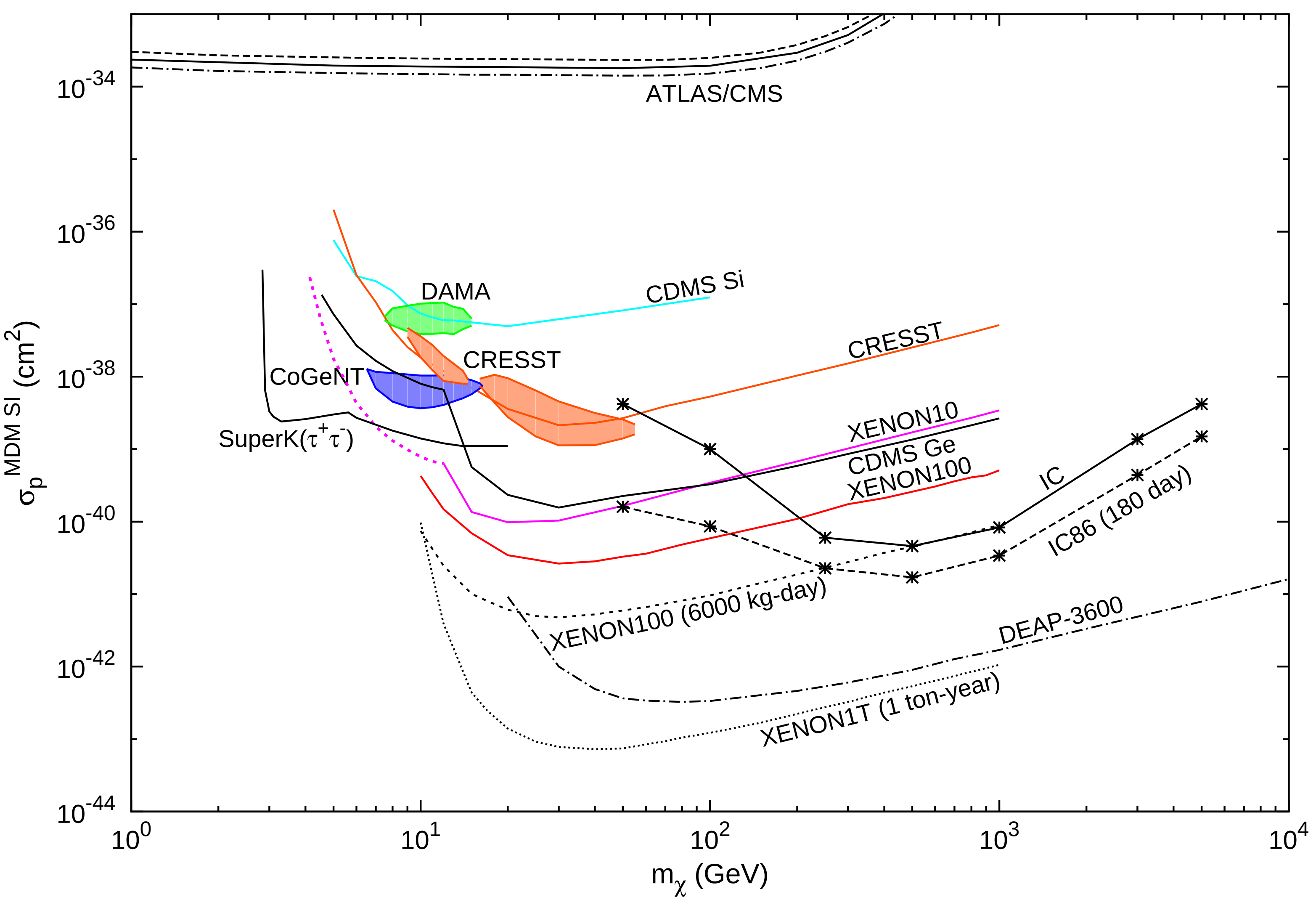
  where v_r is the DM velocity, $v_{min} = \sqrt{\frac{m_A E_R}{2m_{rA}^2}}$, $v_{esc} \approx 600km/s$ is the escape velocity of our galaxy, $v_E = 244km/s$ is the velocity of the Sun relative to the halo.

- $v_{min} < v_{esc} + v_E$. Therefore experiment with smaller E_{Rmin} and lighter nuclear are more sensitive to the light DM.

- The DM velocity distribution in the halo is Maxwellian distribution. $f_1(v_r)$ is the DM velocity distribution in Solar frame.

- The $\frac{d\sigma}{dE_R}$ of MDM and EDM is proportional to $\frac{1}{E_R}$. The event rate will dominately come from the low recoil energy. If the E_{Rmin} of one experiment is small relative to others, that experiment is more sensitive to MDM and EDM DM.

- Because XENON100 has a relatively large E_{Rmin} and heavy Xe, the constraint from XENON100 been mitigated in MDM and EDM case (factor 2.5 for MDM, factor 7 for EDM). XENON10 constraint also been reduced.
- The 2nd interest result is the three signal region from CoGeNT, DAMA, CRESST are closer to each other in MDM and EDM case.



ATLAS/CMS
DAMA
CDMS Si
CRESST
CRESST
CoGeNT
SuperK(τ+τ-)
XENON10
CDMS Ge
XENON100
IC
IC86 (180 day)
XENON100 (6000 kg-day)
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σ_p^MDM SI (cm^2)
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10^-36
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10^0
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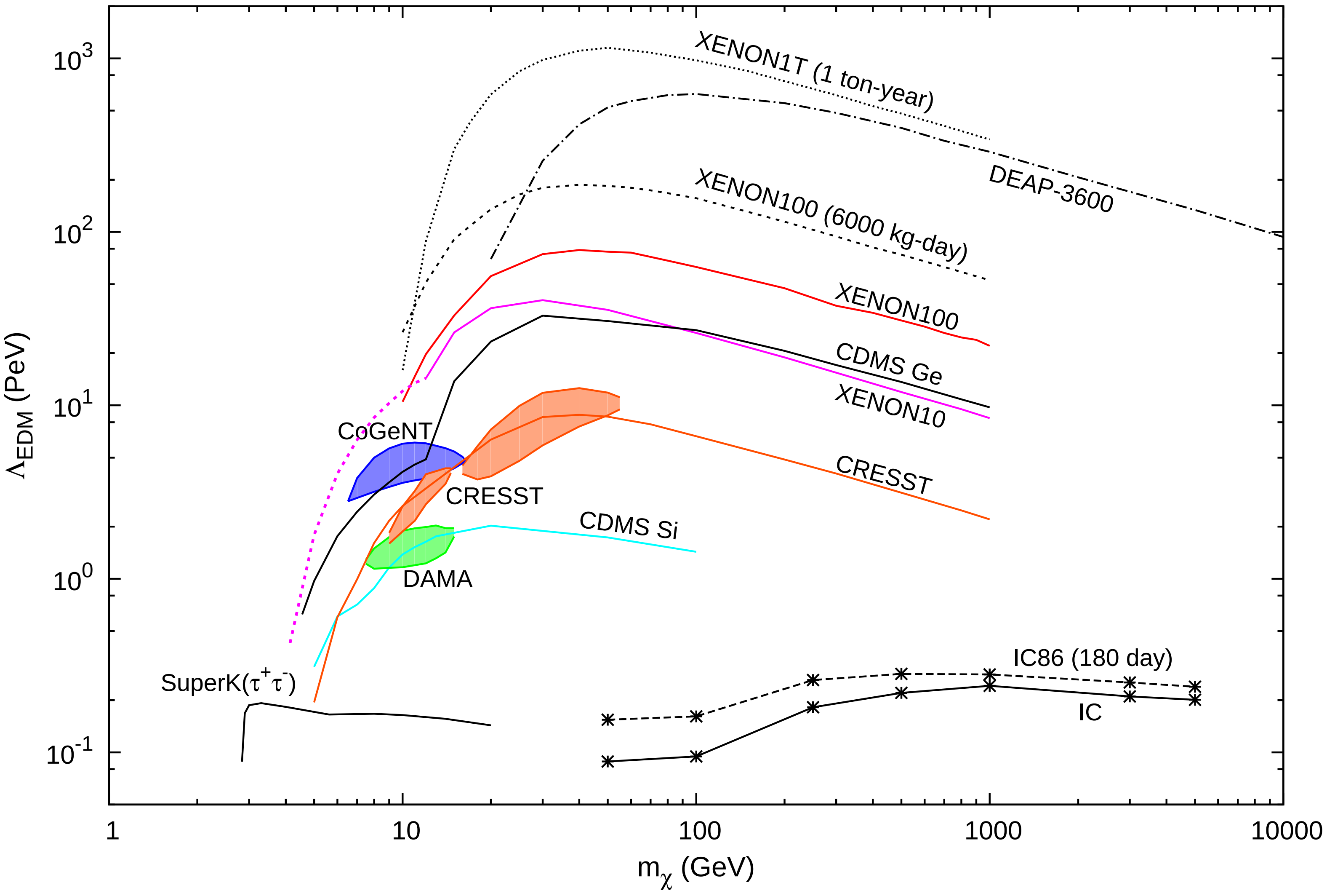
m_χ (GeV)



10^3
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Λ_{EDM} (PeV)
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m_χ (GeV)
XENON1T (1 ton-year)
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The DM Capture Rate and Annihilation Rate in the Sun

- The Sun will sweep across the DM in halo and collider with DM. After the collision, if the velocity of the DM is less than the escape velocity of the Sun $v_{esc,\odot}$, DM will be trapped and accumulate in the Sun.
- The DM capture rate by the Sun is

$$\frac{dC_{C,\odot}}{dV} = \frac{\rho_\chi \rho_{\odot,A}(r)}{m_\chi m_A} \times$$

$$\int_0^\infty \frac{v_r^2 + v_{esc,\odot}^2(r)}{v_r} f_1(v_r) dv_r \int_{E_{R,min}}^{E_{R,max}} \frac{d\sigma_A}{dE_R} |F(E_R)|^2 dE_R \ ,$$

where $E_{R,min} = \frac{1}{2} m_\chi v_r^2$ and $E_{R,max} = \frac{2m_{rA}^2}{m_A}[v_r^2 + v_{esc,\odot}^2(r)]$.

- The DM accumulation in the Sun will increase the DM density. DM will annihilat and the annihilation rate is

$$C_A = \frac{C_C}{2} tanh^2\left(t/\tau\right) \ ,$$

$$t/\tau = 330 \left[\frac{C_C}{s^{-1}} \frac{\langle \sigma_{ann} v \rangle}{cm^3 s^{-1}} \left(\frac{m_\chi}{10\ GeV} \right)^{0.75} \right]^{\frac{1}{2}} \ ,$$

  where τ is the solar life time, σ_{ann} is the DM annihilation cross section.

- If $t/\tau \gg 1$, the DM capture rate and annihilation rate are equilibrium $C_A = C_C/2$. (s-wave annihilation, i.e $b = 0$)

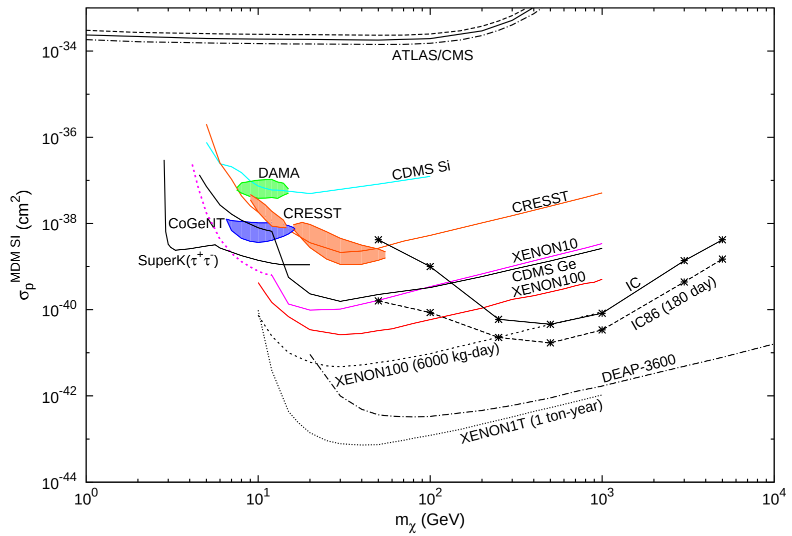
- If $\langle \sigma_{ann} v \rangle$ is small (p-wave annihilation, i.e $a = 0$), the DM capture rate and annihilation rate are not equilibrium $C_A < C_C/2$.

$$\sigma_{ann} v = a + bv$$

- If the DM annihilate into final state $\tau^+\tau^-$, W^+W^-,$\cdots$ etc. There final state particles will decay into neutrino. These neutrino from the direction of Sun can be detected by IceCube and Super-Kamiokande.

The IceCube and Super-Kamiokande constraint of Solar neutrino flux

- IceCube is located in the south pole, and Super-Kamiokande is in Japan.
- They measure the up-going neutrino from the Sun. They measue the neutrino, when the Sun is underground.
- The neutrino will interact with earth and produce μ. The μ in the ice or water with $v \approx c$ will produce Cherenkov radiation. By measuring the Cherenkov radiation, they derive the direction that the neutrino come from.
- The IceCube and Super-Kamiokande did not measure excess of solar neutrino flux, thus they give a constraint for DM annihilation rate of the Sun C_A.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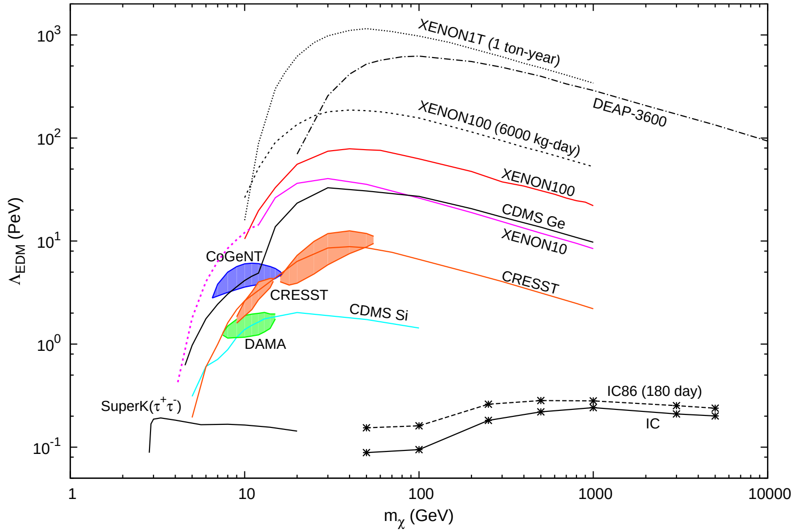
m_χ (GeV)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10^0
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m_χ (GeV)

- For MDM, it is s-wave annihilation dominate. So the solar capture and annihilation rate is equilibrium $C_A = C_C/2$. The limits from IceCube and Super-Kamiokande are strong for MDM.

- For MDM, the limit from Super-Kamiokande can rule out the favored region of CoGeNT, DAMA, and CRESST.

- For MDM with $m_\chi > 200 GeV$, the limit from IceCube is stronger than the XENON100 constraint.

- It is becuase when $m_\chi > 200 GeV$, the MDM DM almost 100% annihilate into W^+W^-. The neutrino spectrum from W^+W^- is harder than that from $\tau^+\tau^-$.

- For EDM, it is p-wave annihilation. The annihilation cross section is very small and produce less neutrino. So, $C_A < C_C/2$. The limits from IceCube and Super-Kamiokande are almost no constaint for EDM.

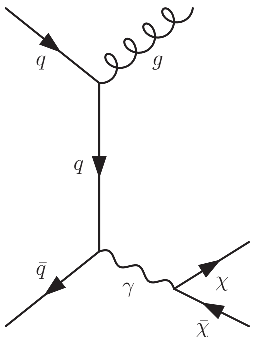
The Constraints from Monojet + missing $\not{E}_T$ of ATLAS and CMS

- The luminosity of the Monojet + missing $\not{E}_T$ data of ATLAS and CMS are $1fb^{-1}$ and $4.7fb^{-1}$, respectively.
- The event number from the experiment and SM prediction are consistant with each other

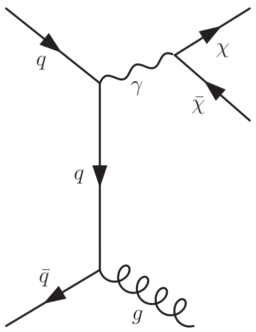
$$N_{obs},\ N_{SM}\pm\sigma_{SM} = 167, 193\pm 25 \qquad ATLAS\ ,$$

$$N_{obs},\ N_{SM}\pm\sigma_{SM} = 1142, 1224\pm 101 \qquad CMS\ .$$

- The MDM and EDM production come from these Feynman Diagrams ($q\bar{q} \to g\chi\bar{\chi}$, and $qg \to q\chi\bar{\chi}$)



a.



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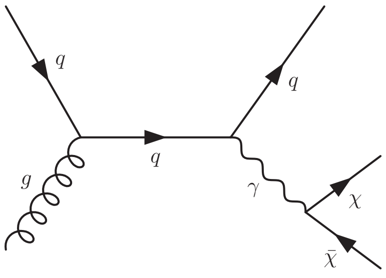

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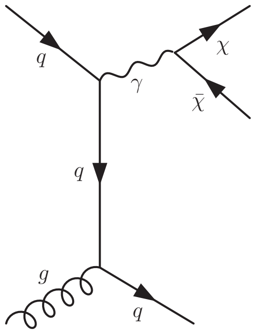
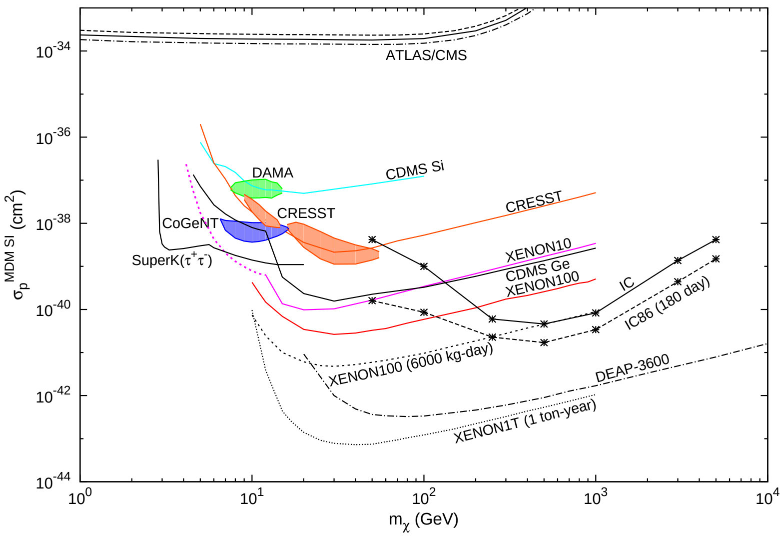


d.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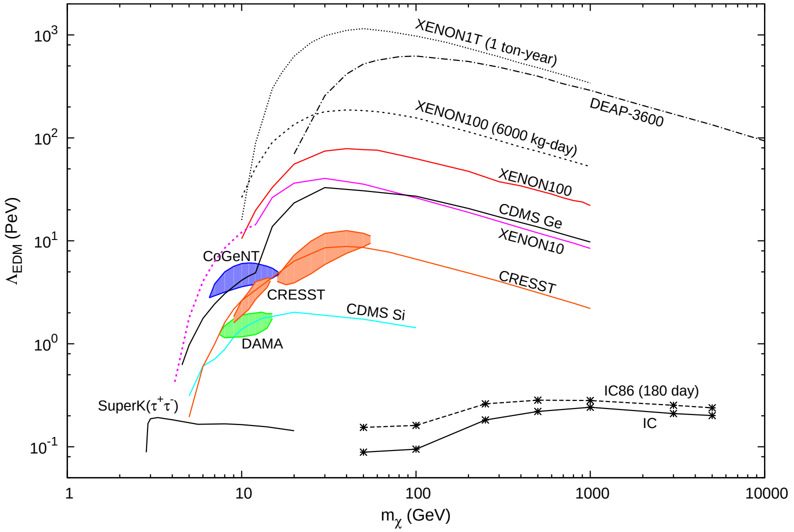
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- For MDM, the collider constraints are very weak by comparing with direct detection and solar neutrino experiment.
- For EDM, the collider constraints are even weaker than MDM case.
- If the m_χ $3GeV$, the Monojet + missing $\not\!\!E_T$ of collider have the largest potential to find or rule out this DM.

Summary

- We study DM with magnetic and electric dipole moment and various kinds of experimental conatraints.
- Direct detection: The MDM and EDM DM can move three favored regions (CoGeNT, DAMA, CRESST) closer and mitigate XENON100 constraint.
- Solar neutrino: For MDM, the constraint from Super-Kamiokande can rule out three favored regions. The constraint from IceCube is stronger than XENON100 limit for $m_\chi > 200GeV$.
  For EDM, the capture and annihilation rate are not equilibrium, so there are almost no constraint from IceCube and Super-Kamiokande.
- The constraints from Monojet + missing $\not{E}_T$ data of ATLAS and CMS are important only when $m_\chi < 3GeV$.

Thanks your attention!