Neutralino WIMP dark matter

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Based on the work with M. Baumgart and I.Z. Rothstein,

(PRL:114 (2015) 211301), M. Baumgart, I.Z. Rothstein, V.V
(JHEP:1504(2015) 106), M. Baumgart, I.Z. Rothstein, V.V
(ArXiv: 1510.02470), M. Baumgart and V.V

Outline

- Introduction to dark matter
- What are we calculating
- Why are we calculating what we are calculating
- How are we calculating it
- What do the calculations imply
- Summary and future work

Evidence for dark matter

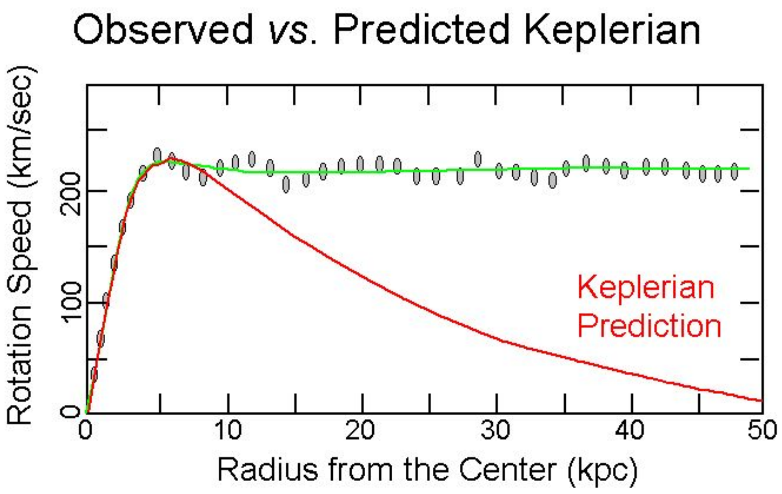
- Rotation curves of galaxies

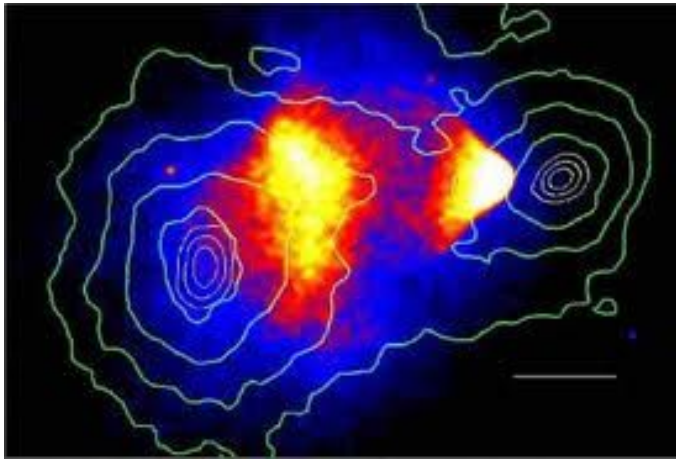
- Gravitational lensing from galactic clusters

- MACHO's?

- Cosmological evidence : Anisotropies in CMB are too small for observed structure

- Collision of Bullet cluster with cluster 1E 0657-56





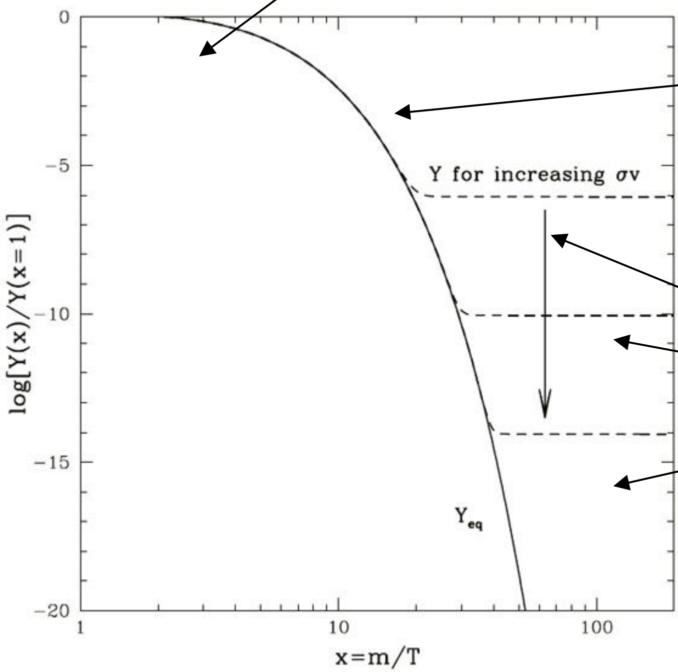
Dark Matter Candidates

- Massive particle that interacts gravitationally but only very weakly or not at all with SM particles (WIMP's)
- Neutrinos, Axions?
- Along came SUSY : naturalness problem, gauge coupling unification, natural dark matter candidate ->neutralino, sneutrino, gravitino?
- Neutralino : Massive cold dark matter, lightest super-symmetric partner(LSP) is stable by R parity conservation

The WIMP Miracle

Thermal Equilibrium

1. **Expanding Universe**
2. **Net annihilation**



Freeze -out, $\Gamma \sim H$

Thermal Relic density

- Relic Abundance calculation using Boltzmann equation for a weakly interacting particle ~ TeV scale WIMP

$$M_X \sim \mathrm{TeV}\left(10\sqrt{C}\alpha\right)\sqrt{\frac{\Omega_X h^2}{0.12}}$$

Assuming $\langle\sigma v\rangle \sim C\alpha^2/M_X^2$

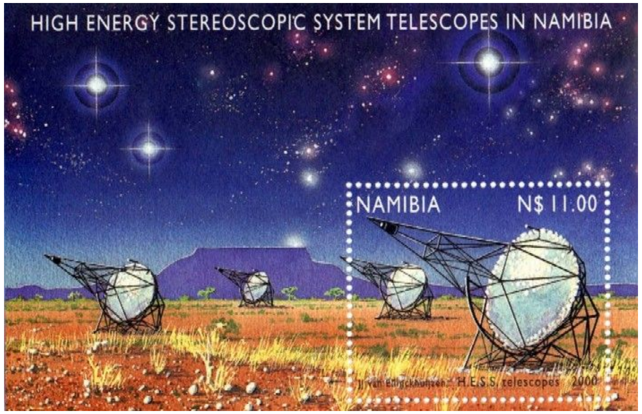
Direct detection

- Production at Colliders :LHC?
- Radioactively clean nuclei recoiling against a scatterd DM particle: XENON, LUX ..

Indirect Detection

Goal: Detect Gamma Ray lines at WIMP mass

- Air Cherenkov Telescope : HESS - High energy stereoscopic system , Namibia



What are we calculating

- Cold neutral dark matter at galactic center, v ~10^{-3} interacting weakly.

- Assuming that fermionic WIMP constitute the dark matter of the universe , Mass ~ TeV

- We want: annihilation cross section of the dark matter to monochromatic gamma rays at the WIMP mass

$$\chi^0\chi^0 \to \gamma + X$$

- A semi-inclusive cross section to a single high energy photon

WINO Dark matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}\left(i\not{D} + M_2\right)\chi$$

- $SU_L(2)$ triplet fermion χ, superpartner of weak gauge bosons, free mass parameter M_2 ~ TeV

- Mass eigenstates after electroweak breaking:

$$\chi^0 = \chi^3$$

Neutralino : Majorana fermion

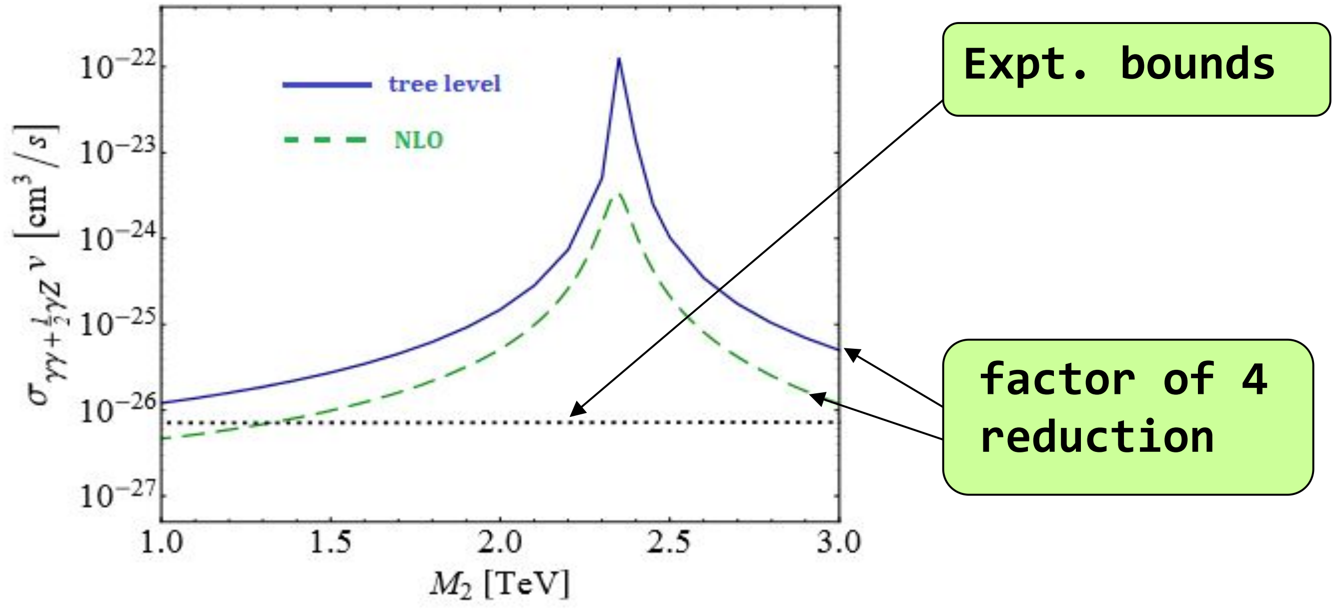
$$\chi^{\pm} = \frac{1}{\sqrt{2}}(\chi^1 \mp i\chi^2)$$

Chargino

- Mass splitting of 170 MeV from electroweak radiative corrections

- Neutral state χ^0 is the LSP -> Dark matter WINO

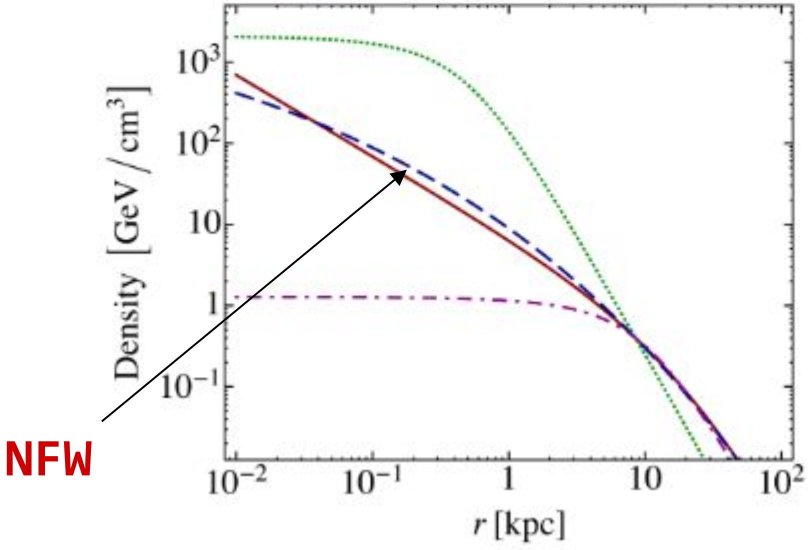
Wino Under Siege



- Previous results- fixed order, excludes the wino completely
- A suggestion that an NLO calculation can have a drastic impact on the cross section

Astronomical uncertainties

- Dark matter density ρ subject to large uncertainties
- A longstanding debate : Is the galactic DM halo cusped or cored?
- Flux of photons coming from Galactic center proportional to ρ^2



- A cored profile reduces the photon flux and hence can save the WINO

Imperative to have a good handle on theoretical errors

Exclusive vs Semi-inclusive

- Other complementary calculations : two body exclusive process $\chi\chi \to \gamma\gamma + 1/2\gamma Z$, an observed photon recoiling against an unseen photon or Z

- Missing channels in exclusive calculation :

  1. There is no restriction on the nature of recoil particles.

  2. The observed photon can be accompanied by soft radiation which lies below the detector energy resolution.

- Current detector resolution (HESS) ~ 15% of WIMP mass from 1-19 TeV. => ΔE > 150 GeV

Annihilation to photon

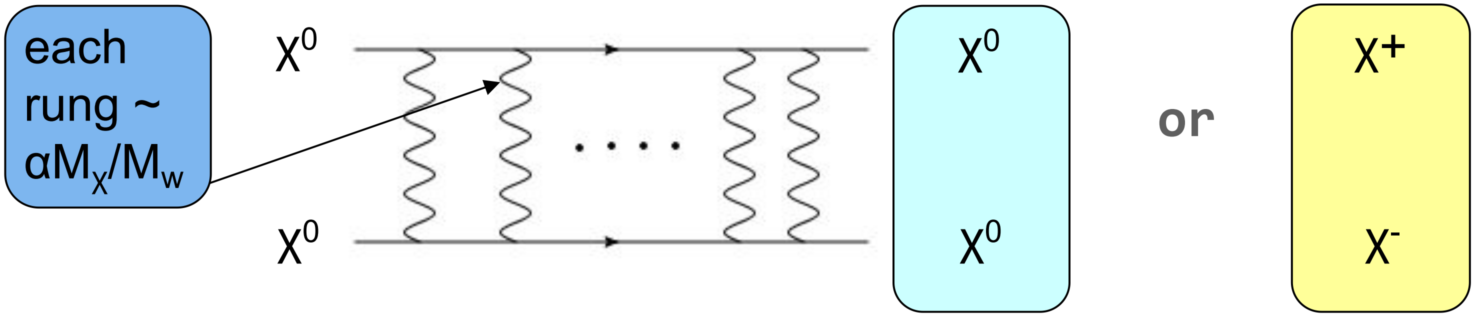
$$\chi^0\chi^0 \to \gamma + X$$

- Semi- inclusive cross section of annihilation to a hard photon .

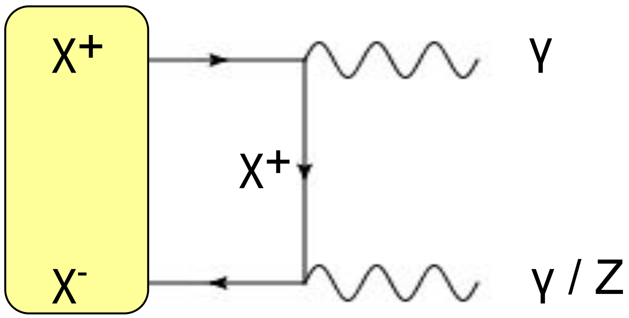
- The wino's are non relativistic , v ~ 10^{-3}

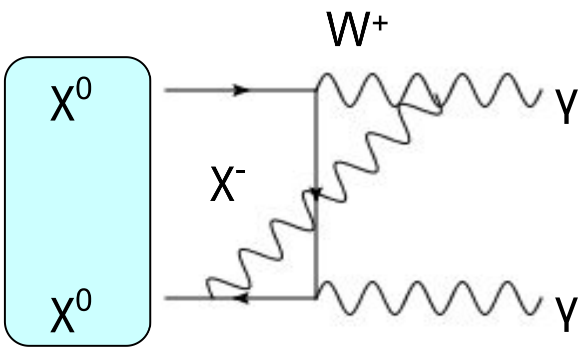
- Interaction has two contributions :

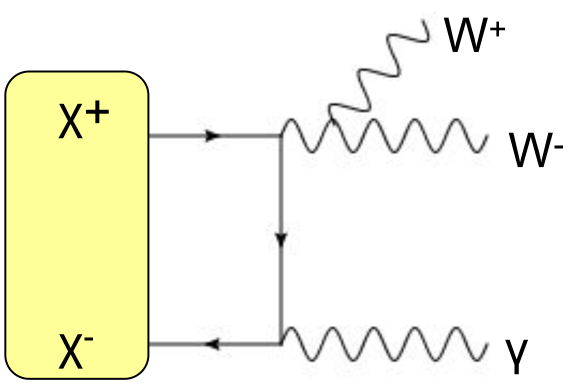
Phase 1 : Well separated (r ~ 1/Mw), slow moving fermions interact via gauge boson exchange

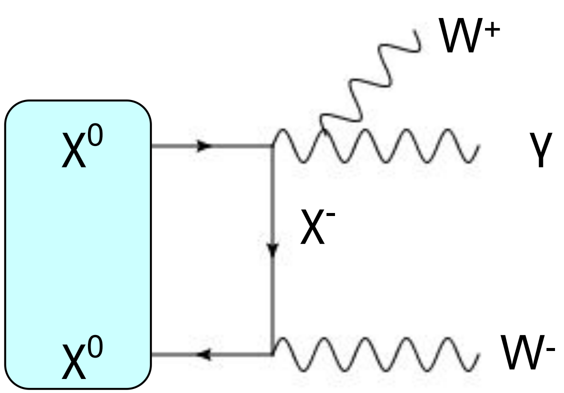


- Hard scattering at short distance ($r \sim 1/M_X$): Two channels available for semi -inclusive cross section









Chargino contribution begins at tree level

Neutralino only begins at one loop

Bloch Nordsieck violation

- IR safe observable -> final state should be a sum over indistinguishable (dangerous) states

- In Unbroken Electroweak theory, IR divergences due to semi-inclusive nature of cross section

- Gauge boson masses turn IR divergences to sudakov logs $\alpha_w \ln^2(M_X/M_W)$

$$\frac{\alpha_W}{\pi}\log(M_{\rm wino}^2/m_W^2)^2 \approx 0.6$$

- Resummation becomes important to save perturbation theory.

EFT for WIMP Annihilation

- Factorize the long distance non perturbative physics from short distance annihilation process.

$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = F_{00}|\psi_{00}(0)|^2 + F_{\pm}|\psi_{+-}(0)|^2 + F_{0\pm}(\psi_{00}\psi_{+-} + \text{h.c.})$$

$\psi_{00}(0)$, $\psi_{+-}(0) \longrightarrow$ Neutralino, Chargino two body wavefunction enhancement factor due to long range gauge boson exchange

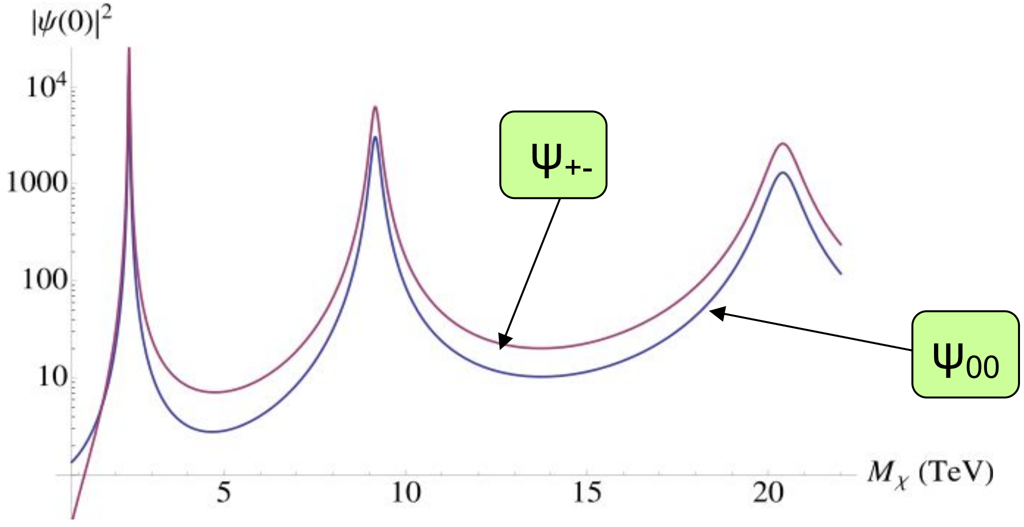
F_{00} , $F_{\pm}$, $F_{0\pm} \longrightarrow$ Short range hard annihilation to photon

Sommerfeld enhancement

- Effect captured by solving Schrodinger equation with effective potential

$$V(r) = \begin{pmatrix} 2\delta M - \frac{\alpha}{r} - \alpha_W c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}, \quad \psi = \begin{pmatrix} \psi_{+-} \\ \psi_{00} \end{pmatrix}$$

- Sommerfeld enhancement for two channels



EFT for annihilation

- Hybrid "NRQCD" - SCET II theory with expansion parameter $\lambda = M_W/M_X$

WIMP's ~ ($E \sim \lambda^2$, $p \sim \lambda$) → Initial state

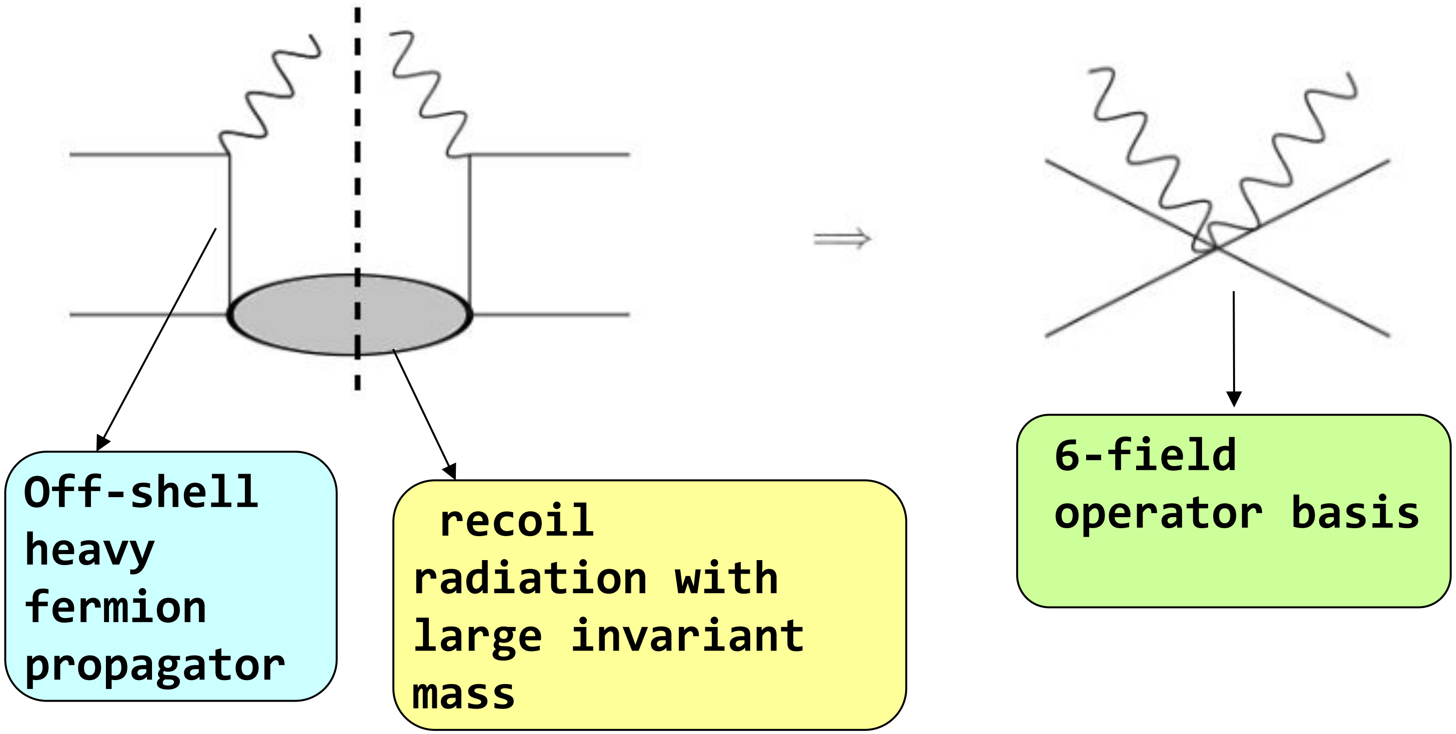
Potential ~ ($E \sim \lambda^2$, $p \sim \lambda$) → Long range Gauge boson exchange

} **NRQCD**

Collinear ~ ($k^+ \sim 1$, $k^- \sim \lambda^2$, $k_\perp \sim \lambda$) → Final state photon + jet

Soft ~ ($k^+ \sim \lambda$, $k^- \sim \lambda$, $k_\perp \sim \lambda$)

} **SCET**



- Soft gauge invariance fixes the position of soft wilson lines required to reproduce IR physics

- Majorana condition reduces the operator basis to 4

$$O_1 = (\bar{\chi}\gamma^5\chi)(\bar{\chi}\gamma^5\chi)\, B^A B^A$$

$$O_3 = (\bar{\chi}_C\gamma^5\chi_D)(\bar{\chi}_D\gamma^5\chi_C)\, B^A B^A$$

Color-singlet collinear sector , Trivial soft sector

$$O_2 = \frac{1}{2}\left\{(\bar{\chi}\gamma^5\chi)(\bar{\chi}_{A'}\gamma^5\chi_{B'}) + (\bar{\chi}_{A'}\gamma^5\chi_{B'})(\bar{\chi}\gamma^5\chi)\right\} B^{\tilde{A}} B^{\tilde{B}}\, S^{\top}_{vA'A}\, S_{vBB'}\, S^{\top}_{n\tilde{A}A}\, S_{nB\tilde{B}}$$

$$O_4 = (\bar{\chi}_{A'}\gamma^5\chi_C)(\bar{\chi}_C\gamma^5\chi_{B'})\, B^{\tilde{A}} B^{\tilde{B}}\, S^{\top}_{vA'A}\, S_{vBB'}\, S^{\top}_{n\tilde{A}A}\, S_{nB\tilde{B}}$$

SCET building blocks

$$B^A B^B \equiv \sum_X B_\mu^{\perp A} \mid \gamma + X\rangle\langle\gamma + X \mid B^{\mu B\perp}$$

$$(\bar{\chi}_{A'}\gamma^5\chi_C)(\bar{\chi}_C\gamma^5\chi_{B'}) \equiv (\bar{\chi}_{A'}\gamma^5\chi_C)|0\rangle\langle 0|(\bar{\chi}_C\gamma^5\chi_{B'})$$

$$B_\mu^{A\perp} \equiv f^{ABC}\, W_n^T (D_\mu^\perp)^{BC}\, W_n$$

$$W_n^{BC} = P\left(e^{g\int_{-\infty}^{0} n\cdot A_n^A(n\lambda) f^{ABC} d\lambda}\right)$$

$$S_{(v,n)bc} = P\left[e^{g\int_{-\infty}^{0} (v,n)\cdot A^a((v,n)\lambda) f^{abc} d\lambda}\right]$$

Cross section :

$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = \frac{1}{4M_\chi^2 v}\langle 0|O_s^a|0\rangle\Bigg[\int dn\cdot p\Big\{C_2(M_\chi, n\cdot p)\langle p_1p_2 \mid \frac{1}{2}\Big\{(\bar{\chi}\gamma^5\chi)\,(\bar{\chi}_{A'}\gamma^5\chi_{B'})$$

$$+ (\bar{\chi}_{A'}\gamma^5\chi_{B'})(\bar{\chi}\gamma^5\chi)\Big\}(0)\mid p_1p_2\rangle + C_4(M_\chi, n\cdot p)\langle p_1p_2 \mid (\bar{\chi}_{A'}\gamma^5\chi_C)\,(\bar{\chi}_C\gamma^5\chi_{B'})(0)\mid p_1p_2\rangle\Big\}F^\gamma_{\tilde{A}\tilde{B}}\left(\frac{2E_\gamma}{n\cdot p}\right)\Bigg]$$

$$+\Bigg[\int dn\cdot p\Big\{C_1(M_\chi, n\cdot p)\langle p_1p_2 \mid (\bar{\chi}\gamma^5\chi)\,(\bar{\chi}\gamma^5\chi)(0)\mid p_1p_2\rangle + C_3(M_\chi, n\cdot p)$$

$$\times\langle p_1p_2 \mid (\bar{\chi}_C\gamma^5\chi_D)\,(\bar{\chi}_D\gamma^5\chi_C)(0)\mid p_1p_2\rangle\Big\}F_\gamma\left(\frac{2E_\gamma}{n\cdot p}\right)\Bigg],$$

$$F^\gamma_{\tilde{A}\tilde{B}}\left(\frac{n\cdot k}{n\cdot p}\right) = \int\frac{dx_-}{2\pi}e^{in\cdot p x_-}\langle 0\mid B^{\perp\mu}_{\tilde{A}}(x_-)\mid\gamma(k_n)+X_n\rangle \times\langle\gamma(k_n)+X_n\mid B^{\perp}_{\mu\tilde{B}}(0)\mid 0\rangle,$$

$$F_\gamma = F^\gamma_{\tilde{A}\tilde{B}}\delta_{\tilde{A}\tilde{B}}.$$

} Fragmentation functions

$$O_s^a = S^T_{vA'A}S_{vBB'}S^T_{n\tilde{A}A}S_{nB\tilde{B}} \qquad O_s^b = \mathbb{1}\,\delta_{\tilde{A}\tilde{B}}\delta_{A'B'}$$

} **Soft Operators**

$$O_c^a = B^\perp_{\tilde{A}}\mid\gamma(k_n)+X_n\rangle\langle\gamma(k_n)+X_n\mid B^\perp_{\tilde{B}}$$

$$O_c^b = B^\perp_{\tilde{D}}\mid\gamma(k_n)+X_n\rangle\langle\gamma(k_n)+X_n\mid B^\perp_{\tilde{D}}\delta_{\tilde{A}\tilde{B}}.$$

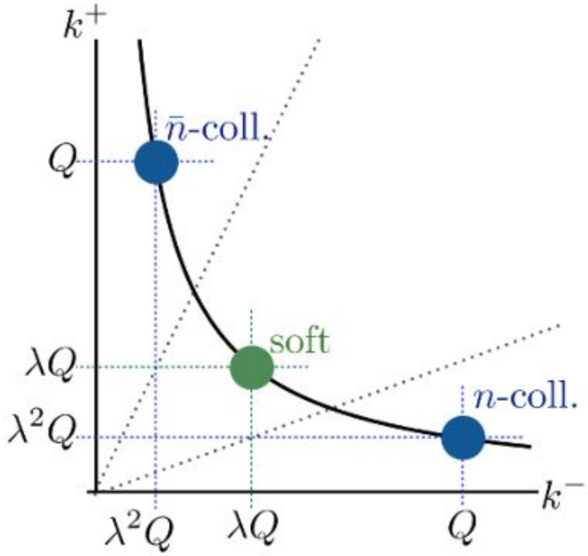
} **Collinear Operators**

Rapidity renormalization group

$$\mu\frac{d}{d\mu}\begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix} = \begin{pmatrix} \gamma_{\mu,aa}^{c,s} & \gamma_{\mu,ab}^{c,s} \\ \gamma_{\mu,ba}^{c,s} & \gamma_{\mu,bb}^{c,s} \end{pmatrix}\begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix}$$

$$\nu\frac{d}{d\nu}\begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix} = \begin{pmatrix} \gamma_{\nu,aa}^{c,s} & \gamma_{\nu,ab}^{c,s} \\ \gamma_{\nu,ba}^{c,s} & \gamma_{\nu,bb}^{c,s} \end{pmatrix}\begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix}$$

Rapidity renormalization group equations



New divergences due to Factorization: usually regulated by dim. reg.

Rapidity divergences due to separation of the soft and collinear regions: a new regulator is needed that breaks residual boost invariance

Anomalous Dimensions

$$\gamma^c_{\mu,aa} = \frac{3\alpha_W}{\pi}\log\left(\frac{\nu^2}{4M_\chi^2}\right) + \frac{\alpha_W}{2\pi}\left(\beta_0 - 2\int_{z_{cut}}^1 dz\, P^*_{gg}(z)\right),$$

$$\gamma^c_{\mu,ab} = -\frac{\alpha_W}{\pi}\log\left(\frac{\nu^2}{4M_\chi^2}\right) + \frac{\alpha_W}{\pi}\int_{z_{cut}}^1 dz\, P^*_{gg}(z),$$

$$\gamma^c_{\mu,bb} = \frac{\alpha_W}{\pi}\left(\frac{\beta_0}{2} + 2\int_{z_{cut}}^1 dz\, P^*_{gg}(z)\right).$$

- Operator mixing in each sector for μ and ν anomalous dimensions.

One loop Cusp

One loop non-cusp

$$\gamma^s_{\mu,aa} = -\frac{3\alpha_W}{\pi}\log\left(\frac{\nu^2}{\mu^2}\right) + \frac{3\alpha_W}{\pi},$$

$$\gamma^s_{\mu,ab} = \frac{\alpha_W}{\pi}\log\left(\frac{\nu^2}{\mu^2}\right) - \frac{\alpha_W}{\pi}.$$

$$\gamma^c_{\nu,aa} = \frac{3\alpha_W}{\pi}\log\left(\frac{\mu^2}{M_W^2}\right), \quad \gamma^s_{\nu,aa} = -\frac{3\alpha_W}{\pi}\log\left(\frac{\mu^2}{M_W^2}\right),$$

$$\gamma^c_{\nu,ab} = -\frac{\alpha_W}{\pi}\log\left(\frac{\mu^2}{M_W^2}\right), \quad \gamma^s_{\nu,ab} = \frac{\alpha_W}{\pi}\log\left(\frac{\mu^2}{M_W^2}\right).$$

$$P^*_{gg}(z) = 2\left[z(1-z) + \frac{z}{(1-z)^+} + \frac{1-z}{z}\right]$$

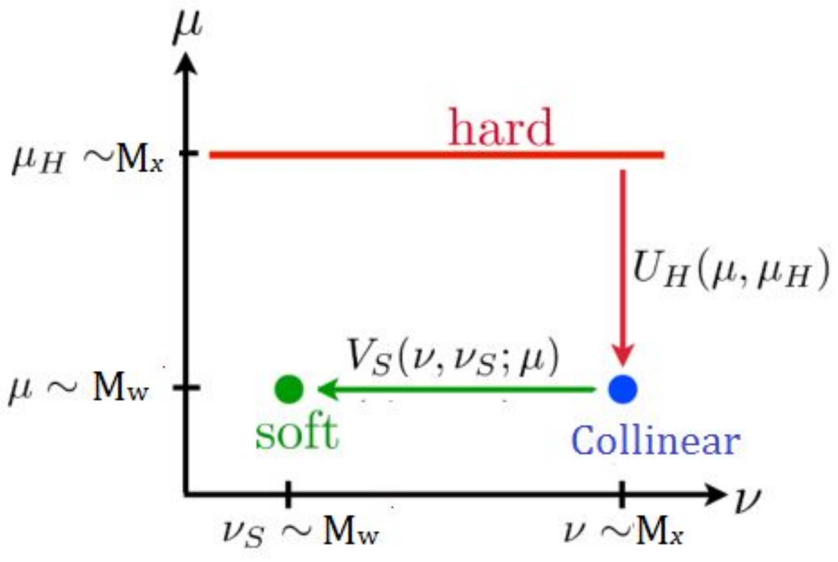
- ν anomalous dimension cancels between soft and collinear sectors.

Resummation at LL'

Power counting at LL' :

$\alpha_W \ln^2(M_X/M_W) \sim 1$ resummed to all orders,
$\alpha_W \ln(M_X/M_W) \ll 1$, included only at leading order

Net result: All terms of the form $\alpha_W^{n+1} \ln^{2n+1}(M_X/M_W)$



Resummation of logs by choosing a path in μ, ν space

Total rate

- Resummed cross section

$$\sigma v = \frac{\pi \alpha_W^2 \sin^2\theta_W}{8M_\chi^4}\left\{\frac{4}{3}f'_-|\psi_{00}(0)|^2 + 4f'_+\,|\psi_\pm(0)|^2 + \frac{4}{3}f'_-\left(\psi_{00}(0)\psi_\pm^*(0) + \text{h.c.}\right)\right\},$$

Ψ_{00} , Ψ_{+-} → **Sommerfeld enhancement factors**

Sudakov factors

$$f'_\pm = (1 \pm E_1) + (LP_g + \Pi_{\gamma\gamma}) \pm E_1\left(P'_g L + \Pi_{\gamma\gamma}\right) \mp 2E_1\frac{\alpha_W}{\pi}L^2\left(\frac{\alpha_W}{2\pi}\beta_0 L + \Pi_{\gamma\gamma}\right).$$

$\Pi_{\gamma\gamma}$ → **photon self energy at Mw**

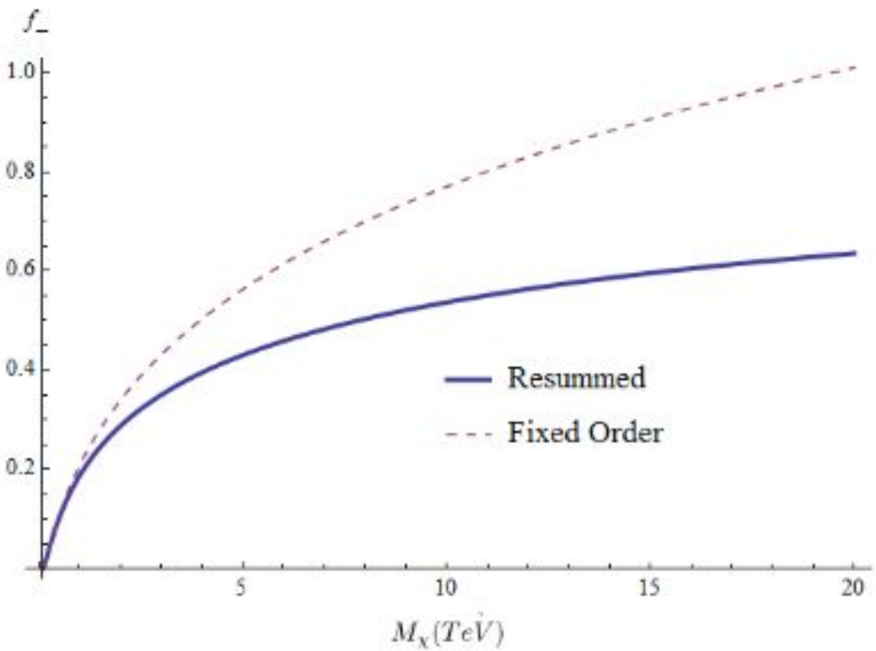
$$P_g = \frac{\alpha_W}{\pi}\left(\frac{\beta_0}{2} + 2\int_{z_{cut}}^1 dz\, P_{gg}^*(z)\right),$$

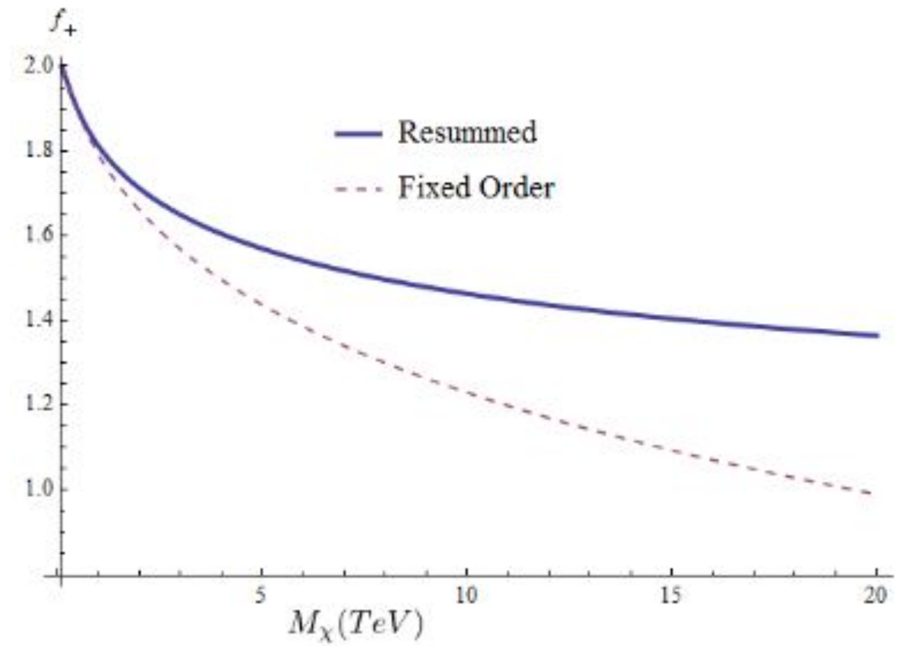
$$E_1 = \exp\left[-\frac{3\alpha_W}{\pi}\log^2\left(\frac{2M_\chi}{M_W}\right)\right],$$

$$P'_g = \frac{\alpha_W}{\pi}\left(\frac{\beta_0}{2} - \int_{z_{cut}}^1 dz\, P_{gg}^*(z) + 3\right)$$

$$L = \log\left(\frac{2M_\chi}{M_W}\right)$$

$$P_{gg}^*(z) = 2\left[z(1-z) + \frac{z}{(1-z)^+} + \frac{1-z}{z}\right]$$



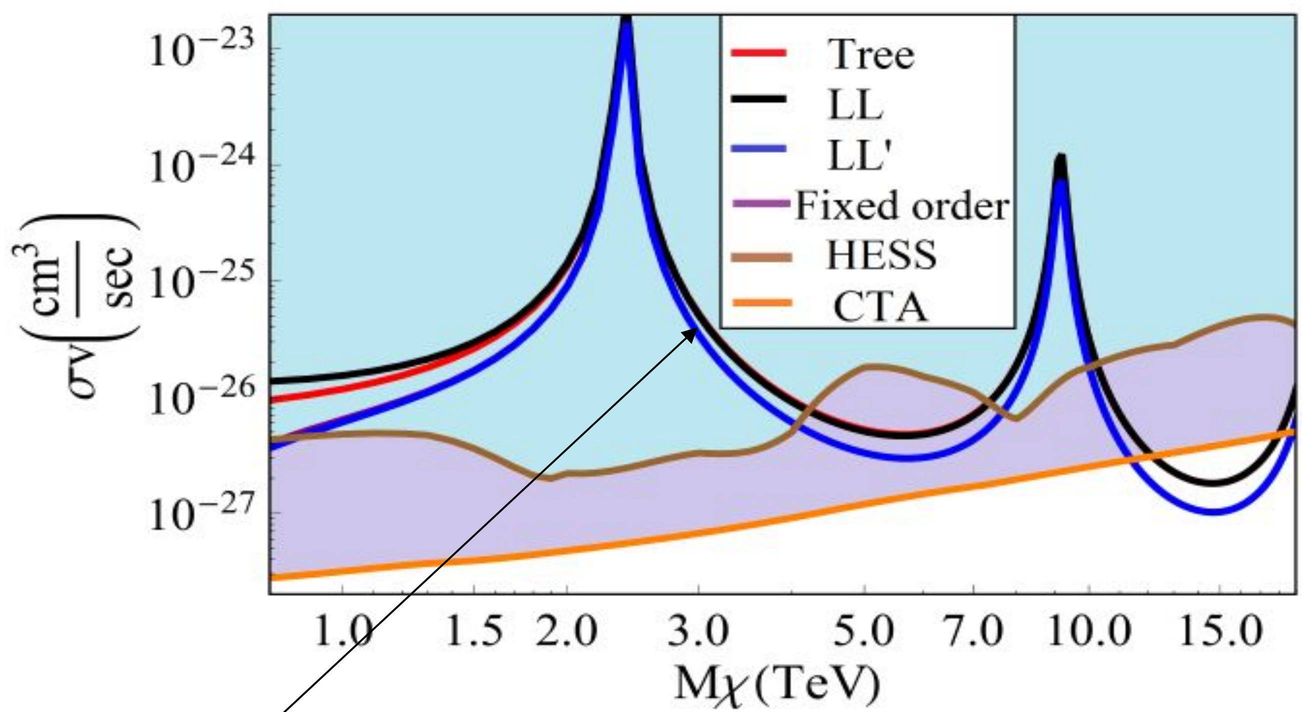


- Sudakov factors as a function of WIMP mass
- ~ 5 % effect for 3 TeV thermal WINO from the dominant ($\chi^+\chi^-$) channel

Effect of resummation is small due to semi-inclusive nature of cross section

The Wino-ing

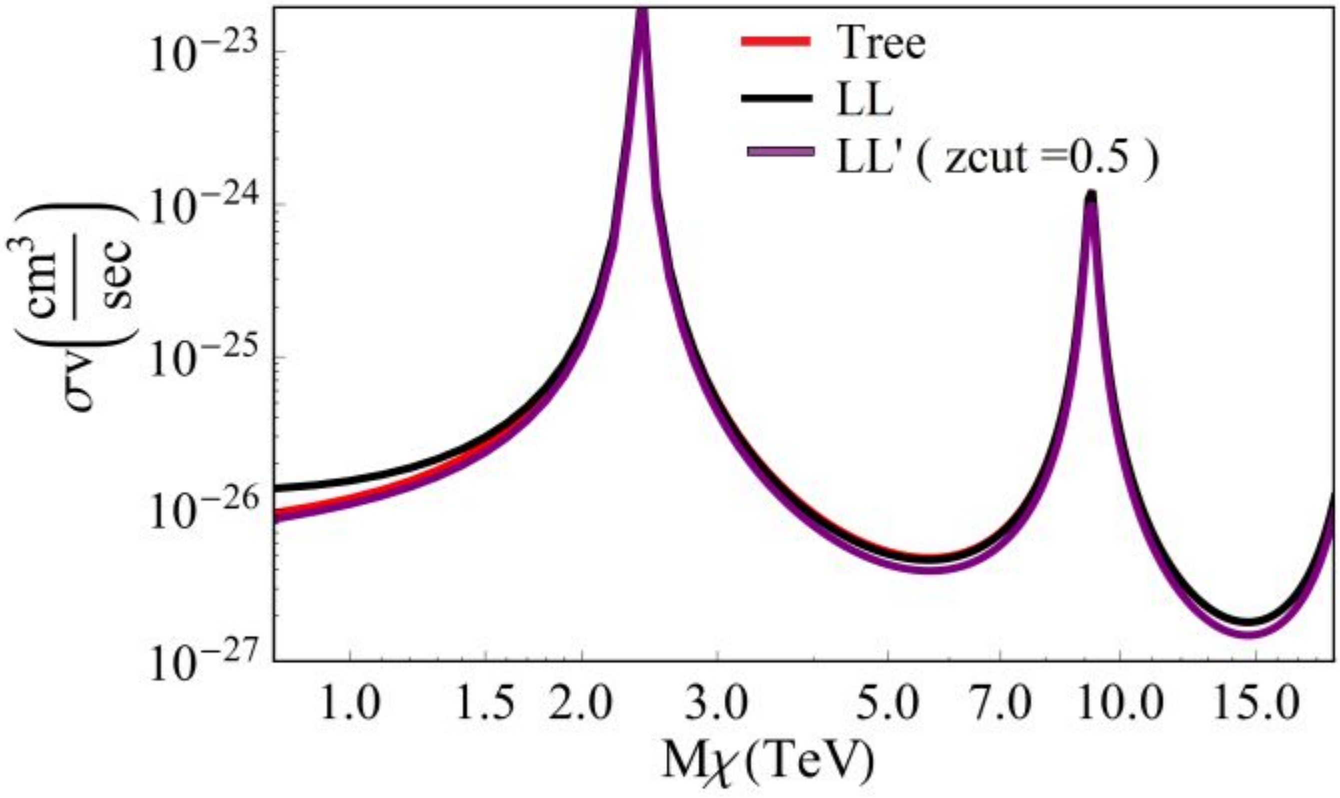
Total Rate : Sommerfeld + Sudakov



Thermal Wino in a lot of trouble !

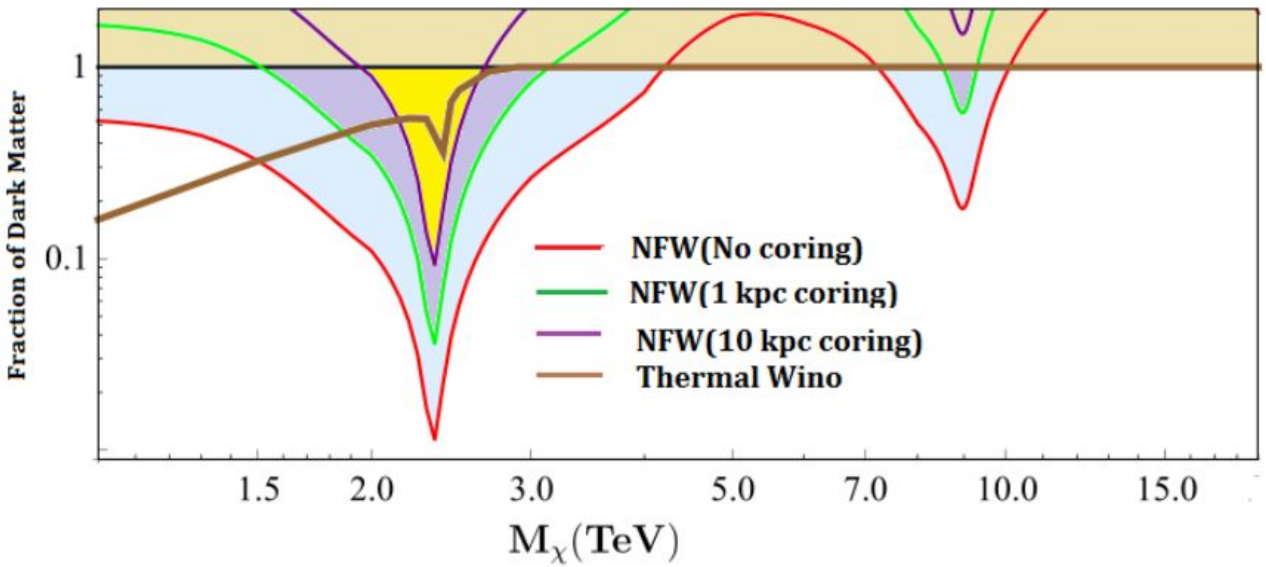
Exclusion plot using HESS with NFW profile

End point effects

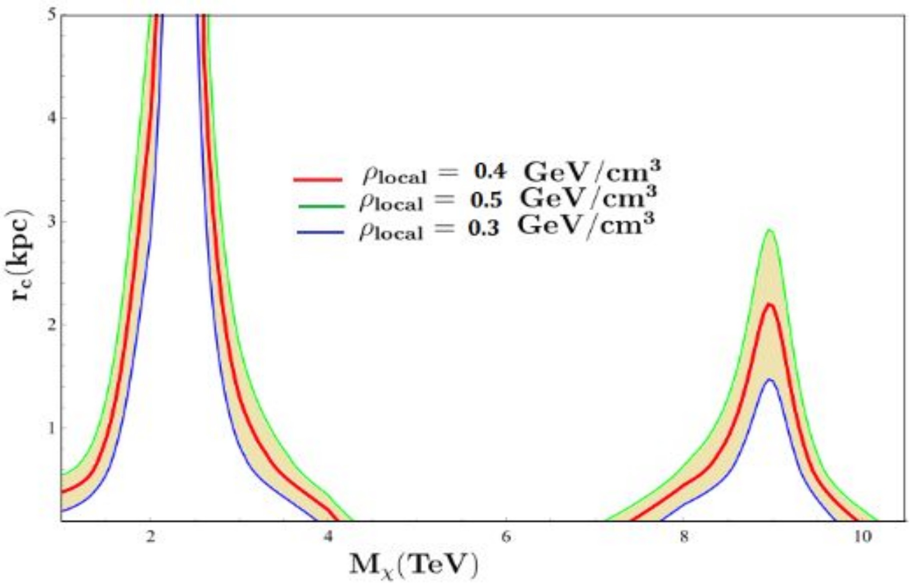


$$\log(1 - z_{cut})^2 = \log(2M_\chi/M_W)$$

$M_\chi \approx 1.4$ TeV.



Viability of the Wino fraction of DM for different galactic profiles



Coring needed for the Wino to avoid exclusion

Higgsino Dark matter

Higgsino basis

$$O_1 = g^2 g'^2 \left[(\bar{\chi}\,\gamma^5 \tau^a \chi)(\bar{\chi}\,\gamma^5 \tau^a \chi) + \frac{\tan\theta_W^2}{4} (\bar{\chi}\,\gamma^5 \chi)(\bar{\chi}\,\gamma^5 \chi) \right] B\, B$$

Hypercharge

$$O_2 = \frac{g^4}{4} (\bar{\chi}\,\gamma^5 \chi)(\bar{\chi}\,\gamma^5 \chi)\, B^A\, B^A$$

$$O_3 = g^2 g'^2 (\bar{\chi}\,\gamma^5 \tau^A \chi)(\bar{\chi}\,\gamma^5 \tau^B \chi)\, B^A\, B^B$$

SU(2) gauge bosons

$$O_4 = \left(\frac{g^3 g' + g g'^3}{2} \right) \left[(\bar{\chi}\,\gamma^5 \tau^A \chi)(\bar{\chi}\,\gamma^5 \chi)\, B^A\, B + (\bar{\chi}\,\gamma^5 \chi)(\bar{\chi}\,\gamma^5 \tau^A \chi)\, B\, B^A \right]$$

$$O_5 = (\bar{\chi}\,\gamma^5 \tau^A \chi)(\bar{\chi}\,\gamma^5 \tau^A \chi)\, B^B\, B^B.$$

$$\bar{\chi} = \begin{pmatrix} -\epsilon\,\tilde{h}_d & \tilde{h}_u^* \end{pmatrix} \qquad \chi \equiv \begin{pmatrix} \tilde{h}_u \\ \epsilon\,\tilde{h}_d^* \end{pmatrix}$$

Two SU(2) doublets instead of a single triplet
State charged under hypercharge

Mass Eigenstates

LSP

$$\chi_1^0 = \frac{1}{\sqrt{2}}\left(h_d^0 - h_u^0\right)$$

$$\chi_2^0 = -\frac{i}{\sqrt{2}}\left(h_d^0 + h_u^0\right),$$

Neutralino majorana fermions

$$\chi^{+\top} = (\tilde{h}_u^+ \; \tilde{h}_d^{-*}).$$

Charged Dirac fermion

Remarkably we have exactly the SAME operators in the collinear and soft sectors as in the case of the WINO despite the different representation.

$$O_s^c = S_{vA'A}^{\top} S_{n\tilde{A}A}^{\top}.$$

$$O_c^c = B_{\tilde{A}} B + B B_{\tilde{A}}$$

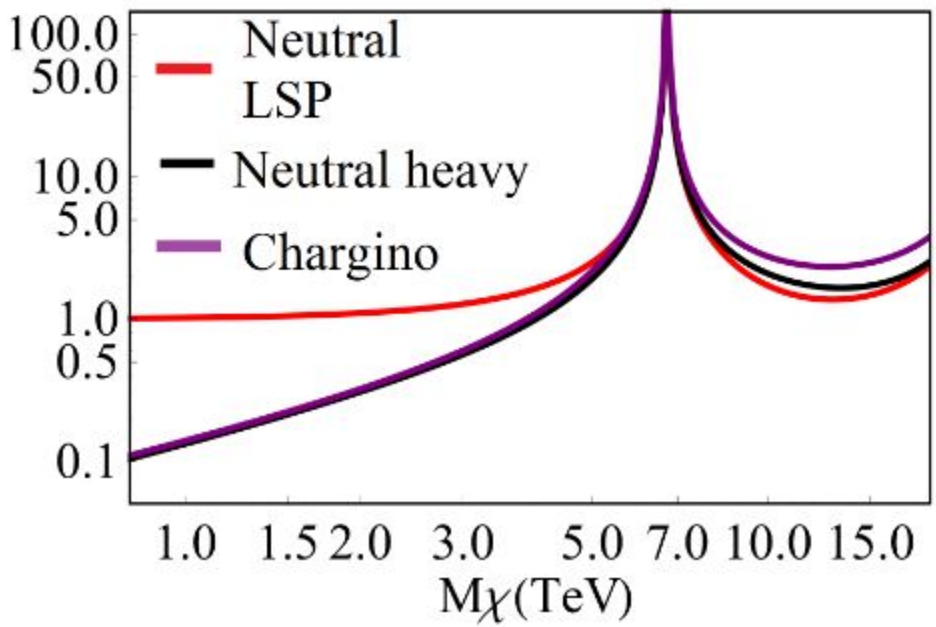
$$O_c^d = B\, B$$

Three new operators due to the hypercharge field

Sommerfeld factors

$$V(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \frac{\alpha_W(1-2c_W^2)^2}{4c_W^2}\frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_W\frac{e^{-m_W r}}{r} & -\sqrt{2}\alpha_W\frac{e^{-m_W r}}{4r} \\ -\sqrt{2}\alpha_W\frac{e^{-m_W r}}{4r} & 0 & -\frac{\alpha_W e^{-m_Z r}}{4c_W^2 r} \\ -\sqrt{2}\alpha_W\frac{e^{-m_W r}}{4r} & -\frac{\alpha_W e^{-m_Z r}}{4c_W^2 r} & 2\delta m_N \end{pmatrix}$$

$$\psi = \begin{pmatrix} \psi_\pm \\ \psi_{00}^1 \\ \psi_{00}^2 \end{pmatrix}$$



$\Delta M_+ = 350$ MeV.

$\Delta M = 200$ keV

Total Rate

$$\sigma v = \frac{\pi\,\alpha_W \alpha'}{16\,M_\chi^4}\Bigg[\frac{1}{4}\left[|\psi^1_{00}(0)|^2 + |\psi^2_{00}(0)|^2 + (\psi^1_{00}\,\psi^{2*}_{00} + \text{c.c.})\right] \times$$

$$\Bigg\{(1-E_2)\bigg\{1 + \left(\frac{\alpha_W}{\pi} + \frac{\alpha_W}{4\pi}\beta_0 + \frac{\alpha'}{4\pi}\beta'_0\right)L + \Pi_{\gamma\gamma}\bigg\} - \frac{s_W^2}{3}(1-E_1)(1 + P'_g L + \Pi_{\gamma\gamma})$$

$$- c_W^2\frac{\alpha_W}{\pi}\left\{1 - \int_{z_{cut}}^1 dz\, P^*_{gg}(z)\right\}L + (E_2 - s_W^2 E_1)\left(\frac{2\alpha_W}{3\pi}\right)L^2\left(\frac{\alpha_W\beta_0}{2\pi}L + \Pi_{\gamma\gamma}\right)\Bigg\}$$

$$+ |\psi_\pm(0)|^2 \times$$

$$\Bigg\{(1+E_2)\bigg\{1 + \left(\frac{\alpha_W}{\pi} + \frac{\alpha_W}{4\pi}\beta_0 + \frac{\alpha'}{4\pi}\beta'_0\right)L + \Pi_{\gamma\gamma}\bigg\} - \frac{s_W^2}{3}(1-E_1)(1 + P'_g L + \Pi_{\gamma\gamma})$$

$$- c_W^2\frac{\alpha_W}{\pi}\left\{1 - \int_{z_{cut}}^1 dz\, P^*_{gg}(z)\right\}L - (E_2 + s_W^2 E_1)\left(\frac{2\alpha_W}{3\pi}\right)L^2\left(\frac{\alpha_W\beta_0}{2\pi}L + \Pi_{\gamma\gamma}\right)\Bigg\}$$

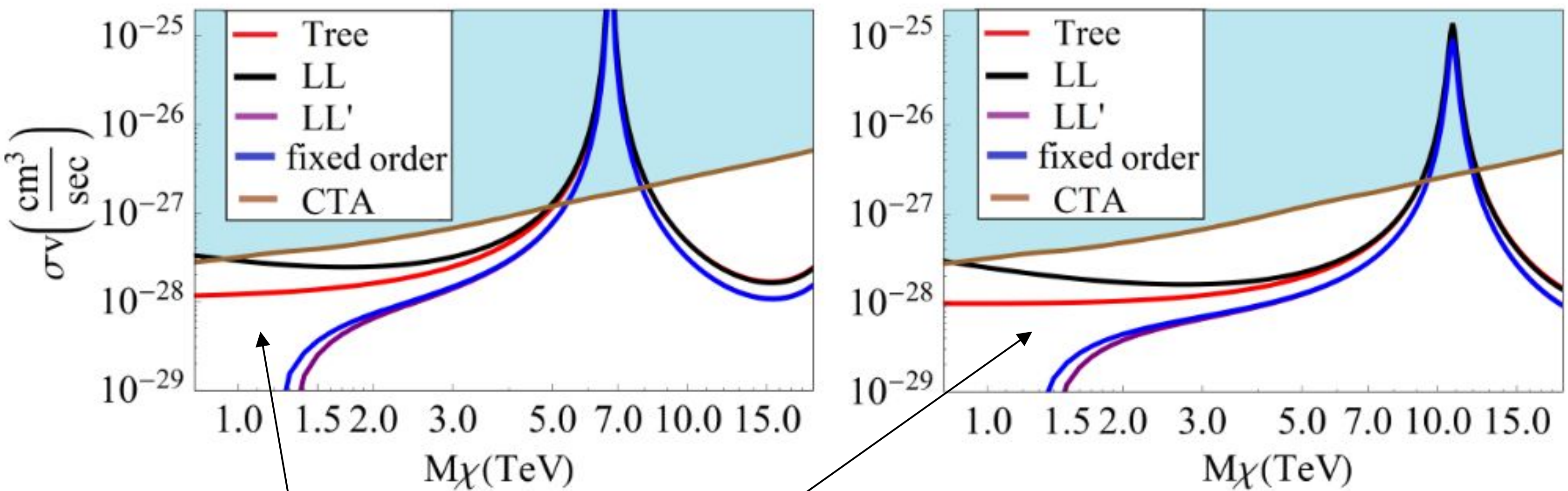
$$+ \frac{1}{2}\left(\psi^1_{00}\,\psi^*_\pm + \psi^2_{00}\,\psi^*_\pm + \text{c.c.}\right) \times$$

$$\Bigg\{\frac{s_W^2}{3}(1-E_1)(1 + P'_g L + \Pi_{\gamma\gamma}) - s_W^2\frac{\alpha_W}{\pi}L - (s_W^2 - c_W^2)\left\{\frac{\alpha_W}{4\pi}\beta_0 - \frac{\alpha'}{4\pi}\beta'_0\right\}L$$

$$+ c_W^2\frac{\alpha_W}{\pi}\left\{\int_{z_{cut}}^1 dz\, P^*_{gg}(z)\right\}L + s_W^2 E_1\left(\frac{2\alpha_W}{3\pi}\right)L^2\left(\frac{\alpha_W\beta_0}{2\pi}L + \Pi_{\gamma\gamma}\right)\Bigg\}\Bigg],$$

Rate at LL

Higgsino bounds at LL'



δM_N= 200 keV, δM_+=350 MeV,

δM_N= 2 GeV, δM_+=480 MeV.

Unstable at low mass

z_{cut}=0.85.

Summary

- A complete EFT calculation for semi-inclusive annihilation cross section to a photon of Wino/Higsino dark matter at LL'
- Sommerfeld enhancement- a huge non-perturbative effect, puts the neutralino in trouble
- Impact of resumming Sudakov logs is minimal due to **semi-inclusive** nature of calculation
- Either we need enough coring~ 1.5 kpc to save the thermal Wino or look for non-thermal history
- Reciprocally, the discovery of such a particle would impact astrophysical observations

End point corrections are important at low masses, needs further analysis

Evidence for dark matter

- Rotation curves of galaxies
- Gravitational lensing from galactic clusters
- Cosmological evidence : Anisotropies in CMB
- Collision of Bullet cluster with cluster 1E 0657-56

Dark Matter Candidates

Massive particle that interacts gravitationally and (possibly) weakly with SM particles (WIMP's):

- Neutrinos, Axions
- SUSY :sneutrino, gravitino, neutralino

Cold dark matter, (LSP) is stable by R parity conservation