The Story of Wino Dark matter

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Based on the work with M. Baumgart and I. Rothstein, 1409.4415 (PRL) & 1412.8698 (JHEP)

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

WINO Dark matter

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

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

- Mass eigenstates after electroweak breaking:

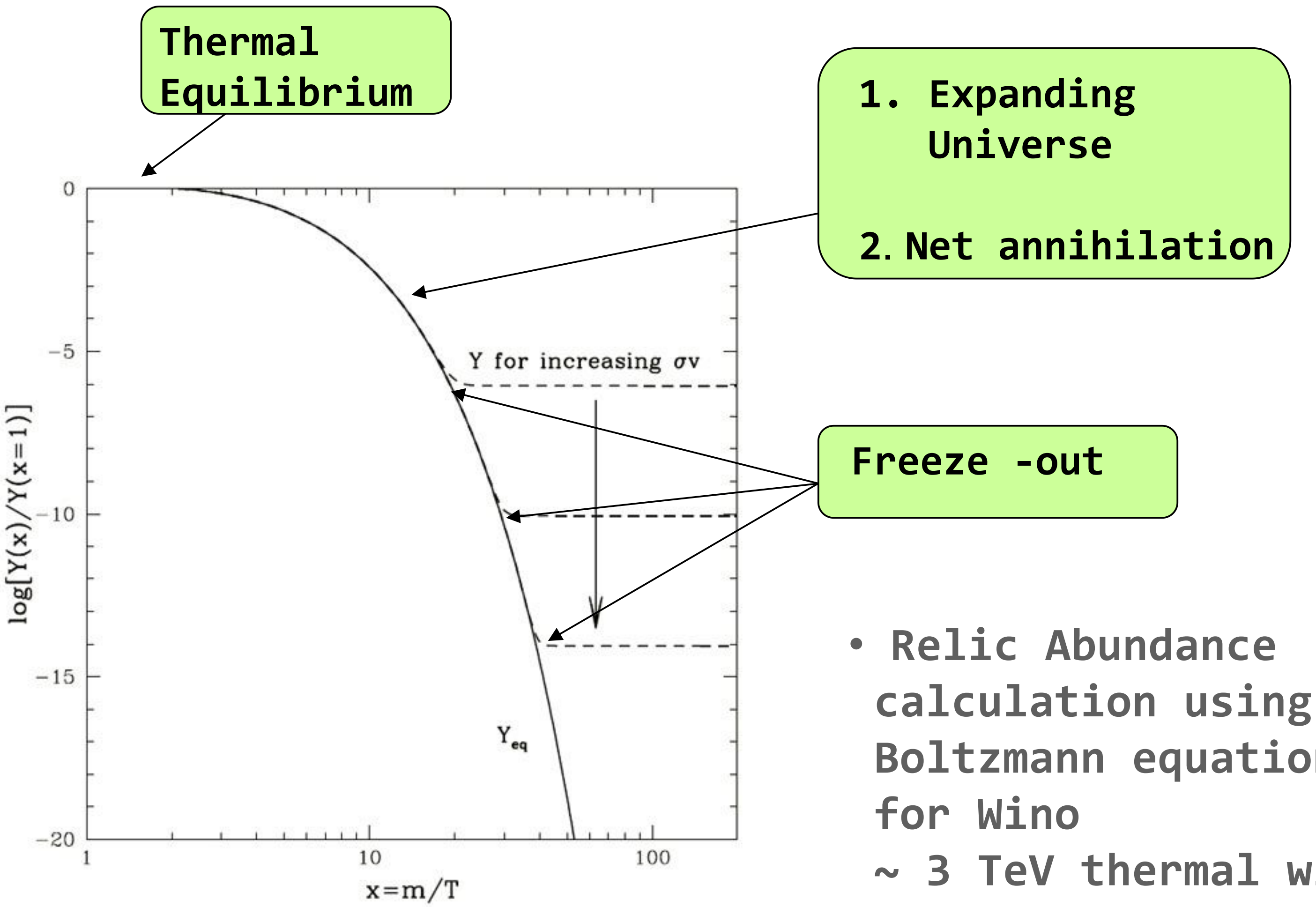
$$\chi^0 = \chi^3$$ Neutralino : Majorana fermion

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

- Mass splitting of 170 MeV from electroweak radiative corrections

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

Thermal WIMP



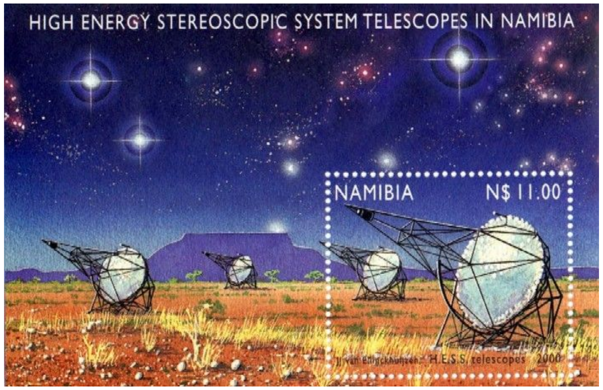
Thermal Relic density

- Relic Abundance calculation using Boltzmann equation for Wino
  ~ 3 TeV thermal wino

Indirect Detection

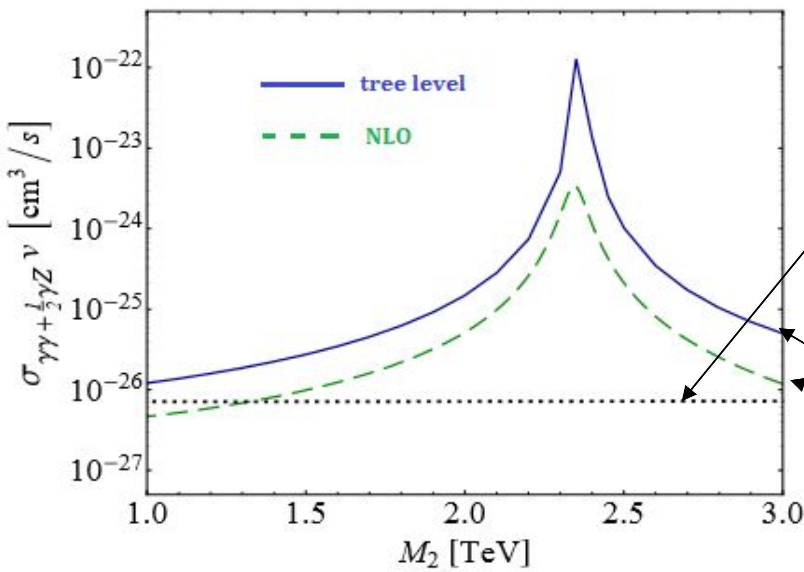
Goal: Detect Gamma Ray lines at WIMP mass

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



- **HAWC: High altitude water Cherenkov Observatory, Mexico**

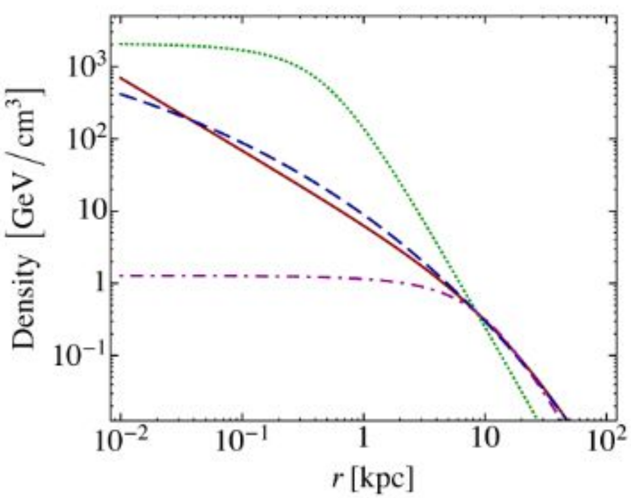
Wino Under Siege $\chi^0\chi^0 \to \gamma + X$



Expt. bounds

factor of 4 reduction

Previous results- fixed order, excluded important channels



- Indirect detection bounds plagued by uncertainties in galactic dark matter profiles

Annihilation to photon

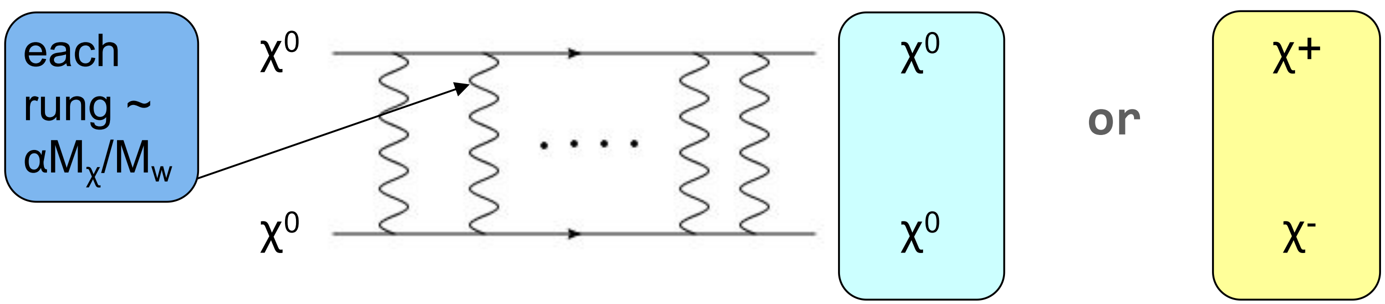
$$\chi^0\chi^0 \to \gamma + X$$

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

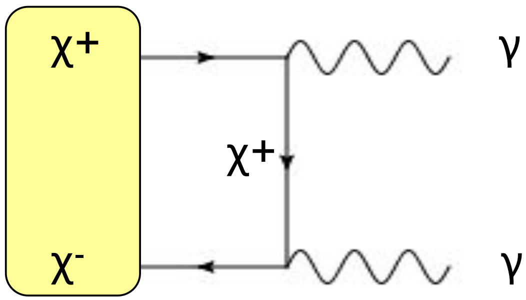
- The wino's are non relativistic , v ~ 10^{-3}

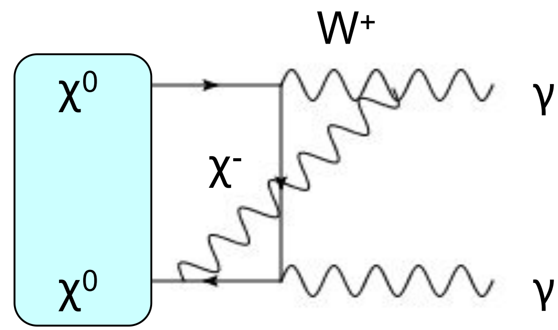
- Interaction has two contributions :

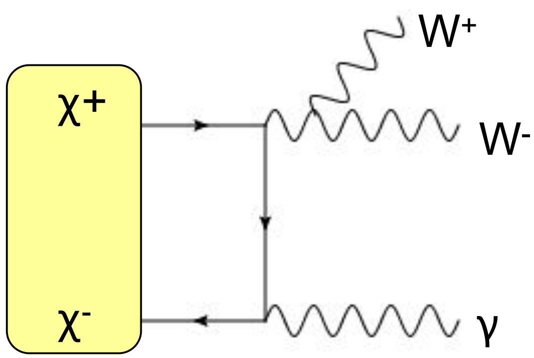
Phase 1 : Well separated slow moving fermions interact via gauge boson exchange

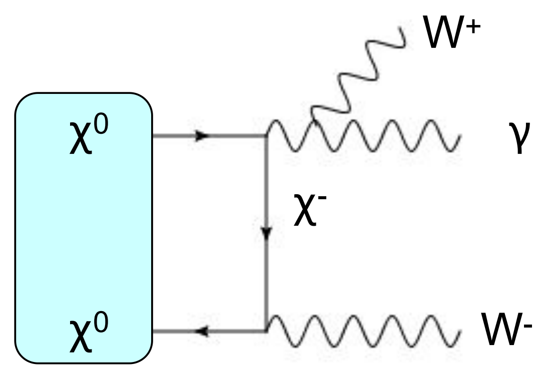


- Hard scattering at origin : Two channels available for semi -inclusive cross section









Chargino contribution begins at tree level

Neutralino only begins at one loop

- IR safety -> suitable sum over indistinguishable (initial and final) states.

- IR divergences cut off by gauge boson mass-> **Sudakov double logs** $\alpha_w \ln^2(M_\chi/M_W)$

- Resummation becomes important to save perturbation theory.

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

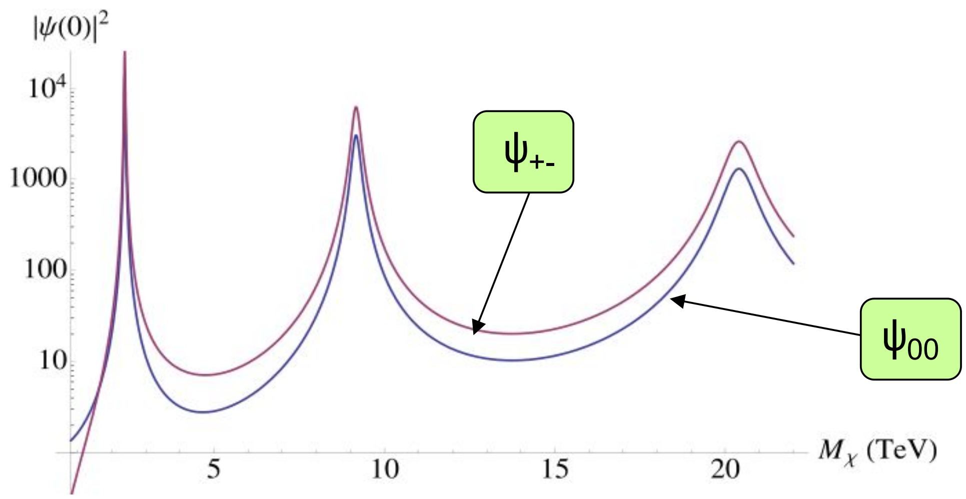
$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = F_{00}|\psi_{00}(0)|^2 + F_{\pm}|\psi_{+-}(0)|^2 + F_{0\pm}(\psi_{00}\psi_{+-} + \text{h.c.})$$

Sommerfeld enhancement

- **Effect captured by solving Schrodinger equation with effective potential**

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

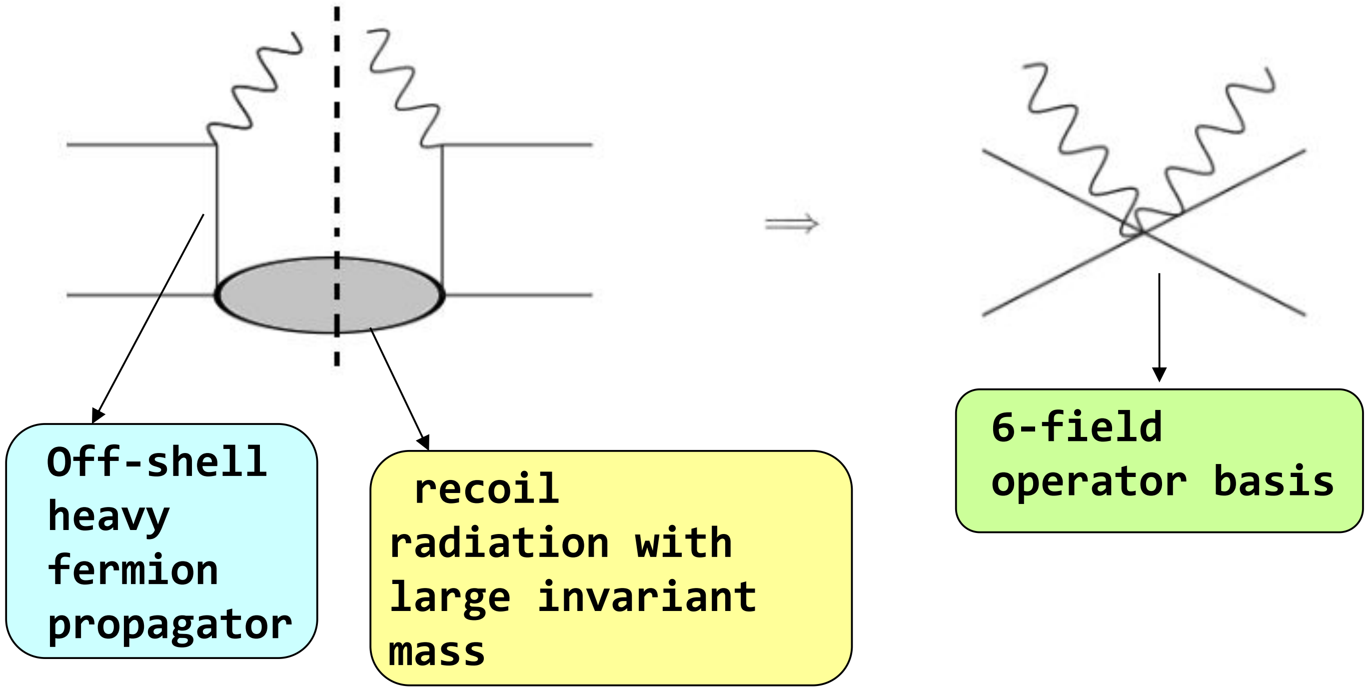
- **Sommerfeld enhancement for two channels**



EFT for hard annihilation

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

WIMP's	$\sim (E \sim \lambda^2, p \sim \lambda)$ → Initial state	}	NRQCD
Potential	$\sim (E \sim \lambda^2, p \sim \lambda)$ → Long range Gauge boson exchange	}	NRQCD
Collinear	$\sim (k^+ \sim 1, k^- \sim \lambda^2, k_\perp \sim \lambda)$ → Final state photon + jet	}	SCET
Soft	$\sim (k^+ \sim \lambda, k^- \sim \lambda, k_\perp \sim \lambda)$	}	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

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

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

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

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

SCET building blocks

$$B^{A\perp}_{\mu} \equiv f^{ABC}\, W^T_n (D^{\perp}_{\mu})^{BC}\, W_n.$$

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

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

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

Soft Operators

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

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

Collinear Operators

- 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

$$\mu \frac{d}{d\mu} \begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix} = \begin{pmatrix} \gamma^{c,s}_{\mu,aa} & \gamma^{c,s}_{\mu,ab} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix}$$

$$\nu \frac{d}{d\nu} \begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix} = \begin{pmatrix} \gamma^{c,s}_{\nu,aa} & \gamma^{c,s}_{\nu,ab} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} O_a^{c,s} \\ O_b^{c,s} \end{pmatrix}$$

Rapidity renormalization group equations

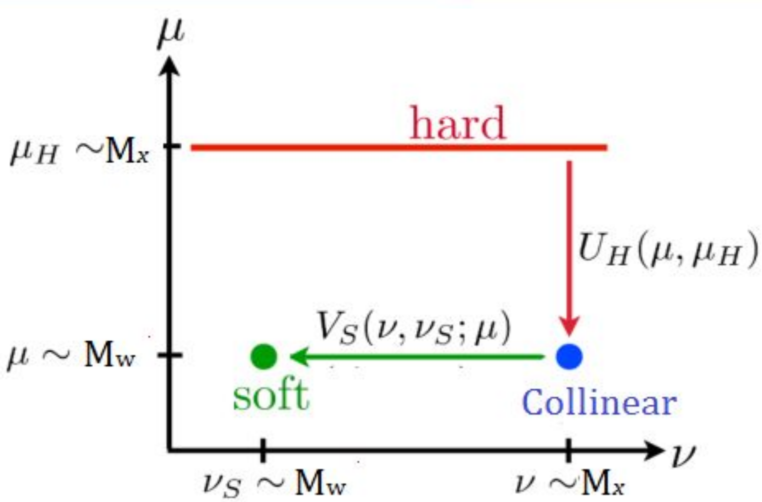
$$\gamma^c_{\mu,aa} = \frac{3g^2}{4\pi^2}\log\left(\frac{\nu^2}{4M_\chi^2}\right), \qquad \gamma^s_{\mu,aa} = \frac{-3g^2}{4\pi^2}\log\left(\frac{\nu^2}{\mu^2}\right),$$

$$\gamma^c_{\mu,ba} = \frac{-g^2}{4\pi^2}\log\left(\frac{\nu^2}{4M_\chi^2}\right), \qquad \gamma^s_{\mu,ba} = \frac{g^2}{4\pi^2}\log\left(\frac{\nu^2}{\mu^2}\right).$$

$$\gamma^c_{\nu,aa} = \frac{3g^2}{4\pi^2}\log\left(\frac{\mu^2}{M_W^2}\right), \qquad \gamma^s_{\nu,aa} = \frac{-3g^2}{4\pi^2}\log\left(\frac{\mu^2}{M_W^2}\right),$$

$$\gamma^c_{\nu,ba} = \frac{-g^2}{4\pi^2}\log\left(\frac{\mu^2}{M_W^2}\right), \qquad \gamma^s_{\nu,ba} = \frac{g^2}{4\pi^2}\log\left(\frac{\mu^2}{M_W^2}\right).$$

- Operator mixing in each sector for μ and ν anomalous dimensions.
- ν anomalous dimension cancels between soft and collinear sectors.



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

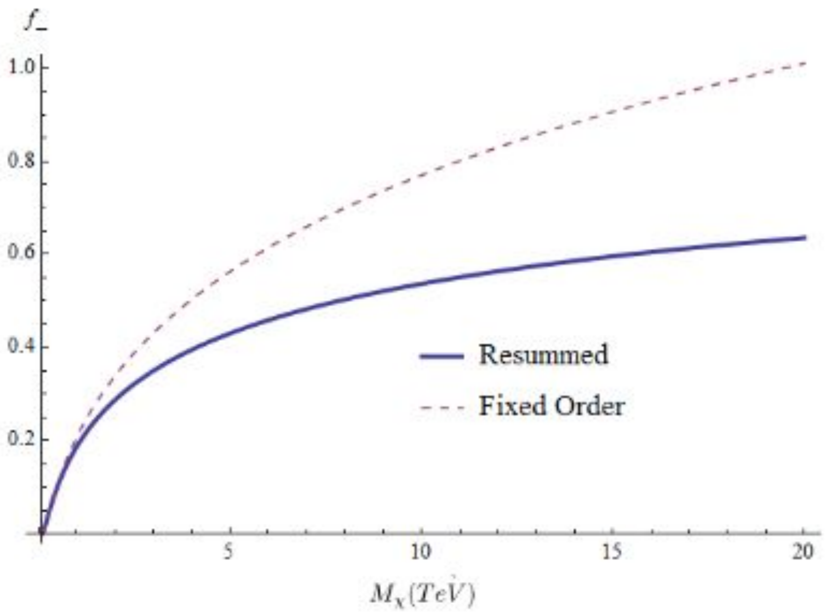
Total rate

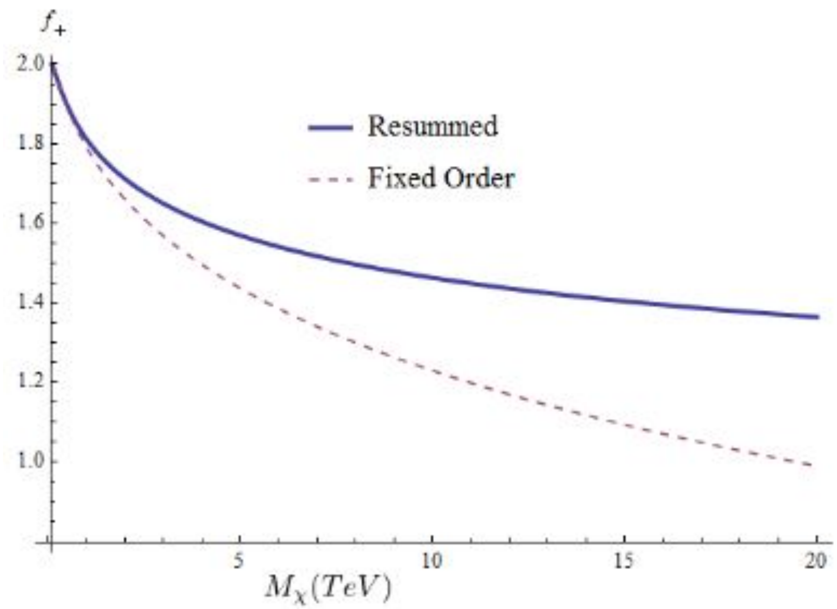
- Resummed cross section

$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = \frac{C_1(\mu = E_\gamma)}{4M_\chi^2 v}\delta(E_\gamma - M_\chi)\left[\frac{2}{3}f_- \,|\psi_{00}(0)|^2 + 2f_+ \,|\psi_{+-}(0)|^2 + \frac{2}{3}f_-(\psi_{00}\psi_{+-} + \text{h.c.})\right]$$

ψ_{00} , ψ_{+-} ⟶ **Sommerfeld enhancement factors**

$f_\pm \equiv 1 \pm \exp[-\frac{3\alpha_W}{\pi}\log^2(\frac{M_W}{E_\gamma})]$; ⟶ **Sudakov factors**





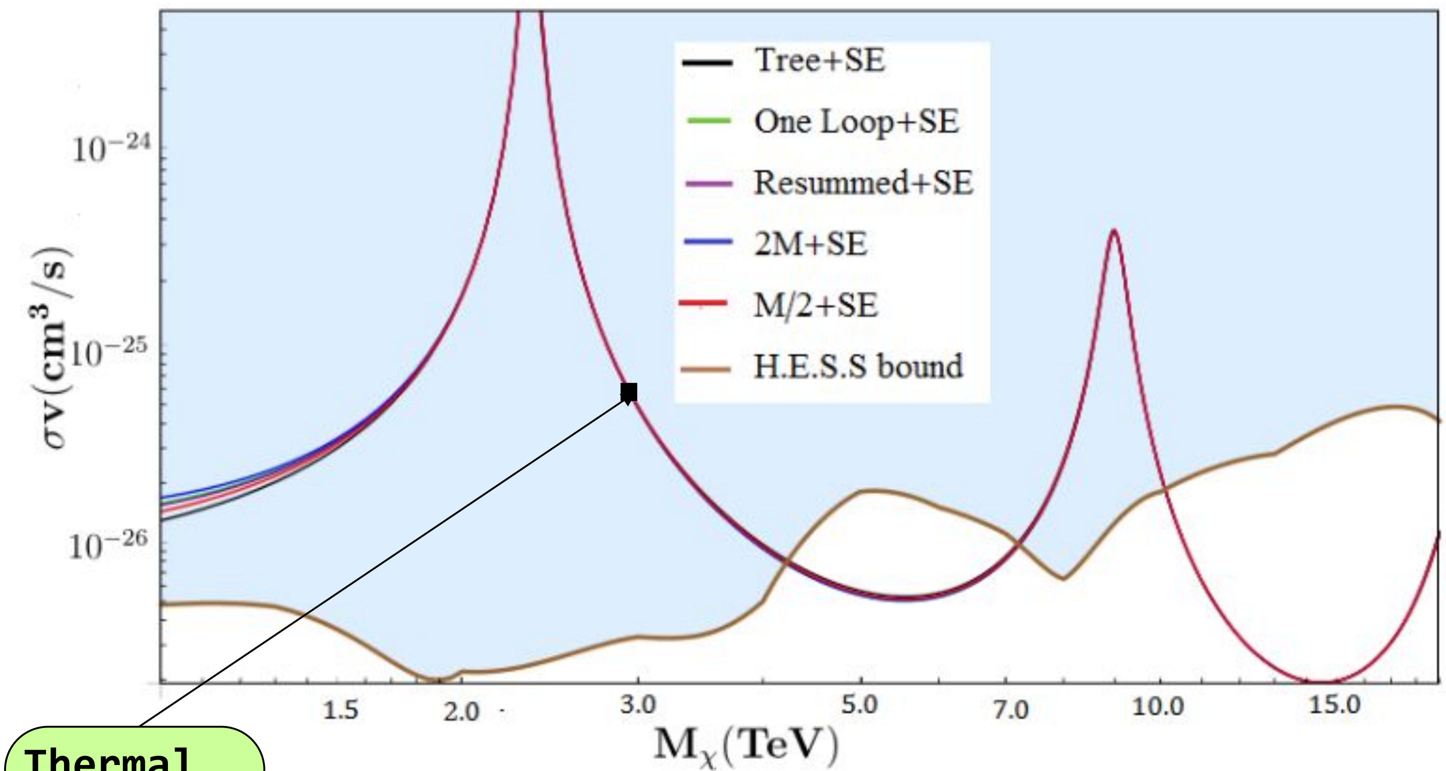
- Sudakov factors as a function of WIMP mass

- ~ 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

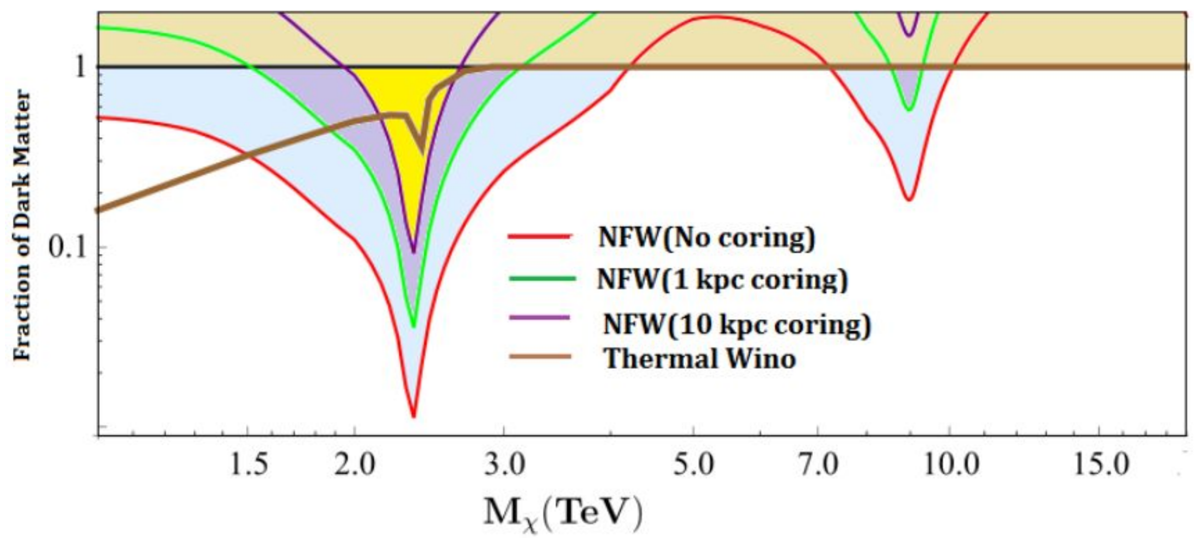
The Wino-ing

Total Rate : Sommerfeld + Sudakov

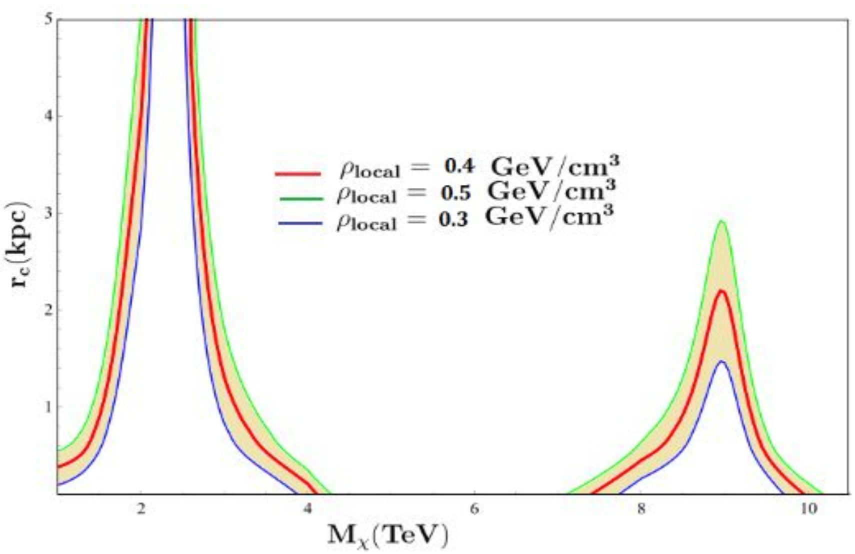


Thermal Wino in a lot of trouble !

Exclusion plot using HESS with NFW profile



Viability of the Wino fraction of DM for different galactic profiles



Coring needed for the Wino to avoid exclusion

Summary

- A complete calculation for semi-inclusive annihilation cross section of Wino dark matter
- Sommerfeld enhancement- a huge non-perturbative effect, puts the wino in trouble
- Impact of resumming Sudakov logs is minimal
- 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