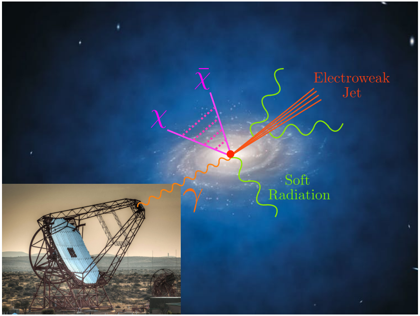
Hunting for Heavy Winos in the Galactic Center with Effective Field Theory

Ian Moult
Berkeley/LBL



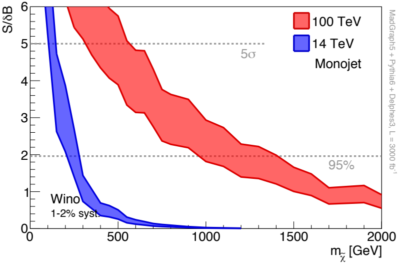
arXiv:1712.07656, 1808,04388, 1808.08956

with M. Baumgart, T. Cohen, N. Rodd, T. Slatyer, M. Solon, I. Stewart, V. Vaidya, and Lucia Rinchiuso, Emmanuel Moulin

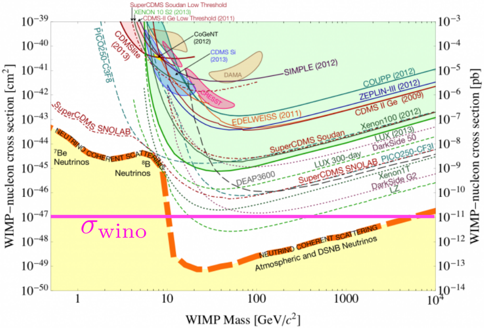
TeV Scale DM

- Weakly Interacting Massive Particles (WIMPs) are economic and simple models.
    - Wino: 3TeV (This talk)
    - Higgsino: 1TeV
    - Minimal DM SU(2) Quintuplet: 10TeV
- Difficult to probe directly.

Monojet Wino Limit



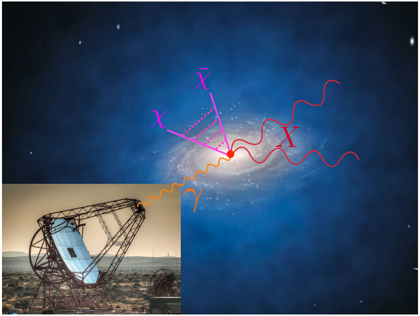
Summary of Direct Detection Limits



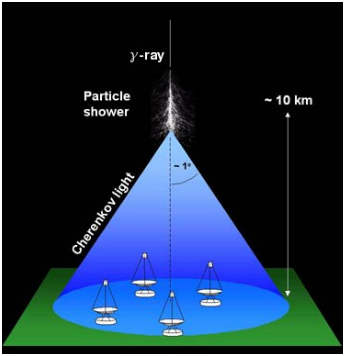
Indirect Detection

- High mass DM can be probed through annihilation to photons!

Indirect Detection



Air Shower



HESS

- Can probe DM up to 20 – 100 TeV scale.
- Gamma ray line provides clean signal.

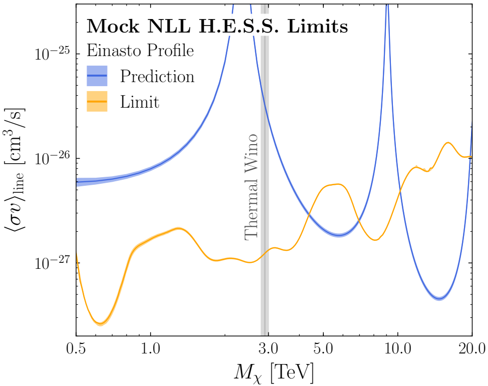
Indirect Detection

- Line searches put strong constraints on TeV scale DM.

[Cohen, Lisanti, Pierce, Slatyer]

[Fan, Reece]

H.E.S.S. Limits

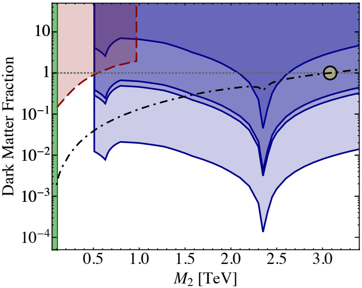


- For uncored profiles, Thermal Wino well excluded.
- Large number of current and future experiments will push this further.

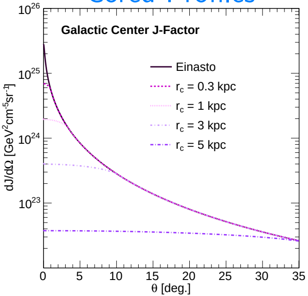
Coring

- Limits can be evaded by coring.

HESS Limit



Cored Profiles

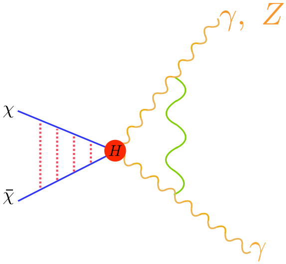


[Cohen, Lisanti, Pierce, Slatyer]
[Fan, Reece]

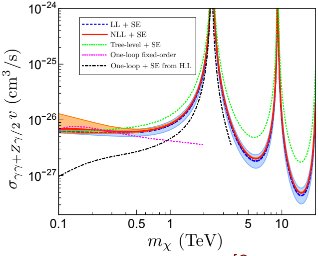
- We are now in a regime where limits probe core sizes comparable with simulation/ observational constraints
  $\Longrightarrow$ factors of 5 matter for interpretation.
- Can we conclusively exclude the thermal wino (Higgsino)?

Multiple Scales

- Particle physics predictions complicated by the presence of hierarchical scales: $m_W \ll M_\chi$.
- Line cross section requires all orders resummation:
  - Sommerfeld Effect: $(\alpha_w \, M_\chi / m_w)^k$
  - Sudakov double logarithms: $\alpha_w \log^2(M_\chi / m_w)$



Resummed Line Spectrum



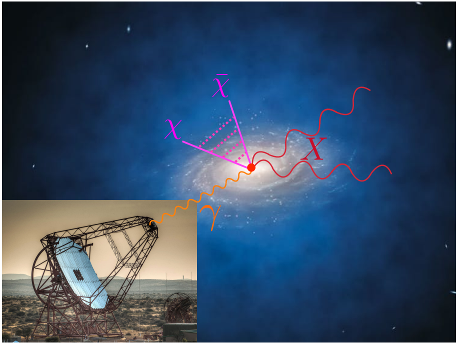
[Ovanesyan, Slatyer, Stewart]

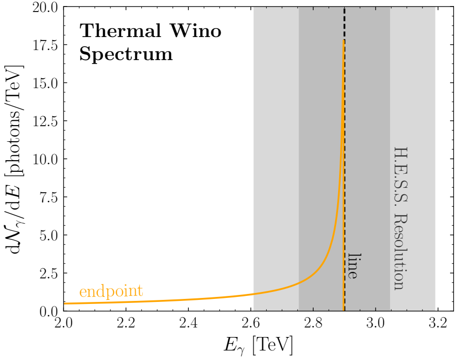
[Bauer, Cohen, Hill, Solon]

- Line cross section successfully analyzed using EFT techniques.

Indirect Detection

- In reality, the situation is not so simple!
- Experiments cannot fully constrain recoiling state.

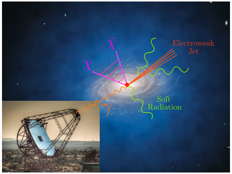


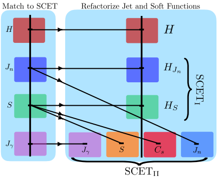


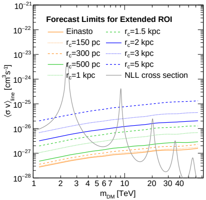
- Realistic prediction for experiment requires energy spectrum
  $\Longrightarrow$ significantly more involved field theory setup.

Outline

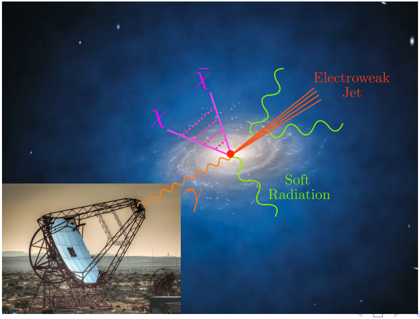
- Kinematics and Effective Field Theories
- Factorization Formula for the Endpoint Region
- H.E.S.S. Forecast and Core Constraints





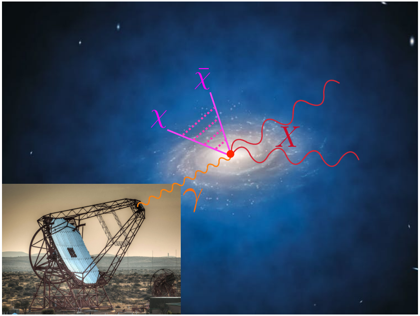


Kinematics and Effective Field Theories



Kinematics

- We are interested in $\chi\bar{\chi} \to \gamma + X$
- X is final state other than observed photon.



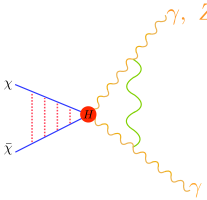
- Use a dimensionless variable z to characterize the final state.

$$E_\gamma = M_\chi \, z \, , \qquad m_X^2 = 4 \, M_\chi^2 (1 - z)$$

Three Different Regimes

- z measures the additional radiation in the final state.

$z = 1$

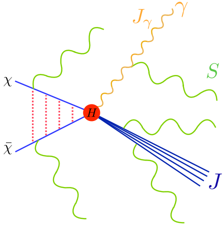


Exclusive

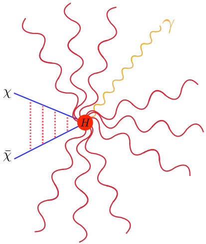
[Ovanesyan, Slatyer, Stewart]

[Bauer, Cohen, Hill, Solon]

$z \to 1$



$(1 - z) \sim 1$



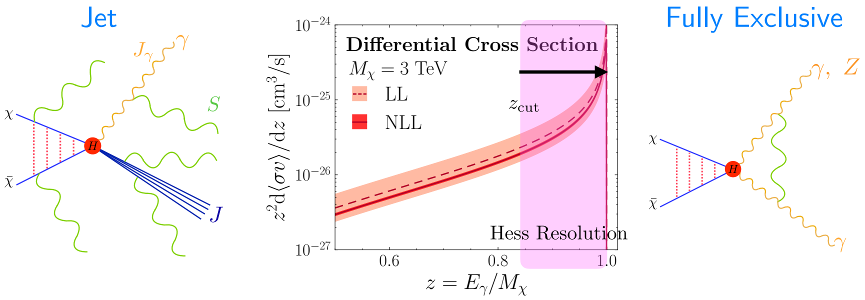
Inclusive

[Baumgart, Vaidya, Rothstein]

- Exclusive and Inclusive cases considered in literature.

HESS Resolution

- HESS performs line searches, but has a finite resolution.
- To constrain to a single recoiling Z at $M_\chi = 500\text{GeV}$ (10 TeV) would require $z \simeq 0.99(0.9999)$
- Resolution of HESS in these energies is equivalent to $z = 0.83 - 0.89$



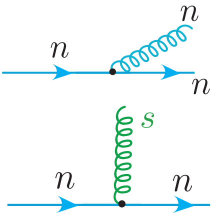
- Recoiling final state is a jet!

Soft and Collinear Radiation

- For HESS resolution, $(1-z) \ll 1 \implies$ mass of unobserved final state is small.
- To have small invariant mass, $m_X^2 = 4\,M_\chi^2(1-z)$, the final state X can consist of radiation that is either
  - Collinear: $m_X^2 \sim M_\chi^2\theta^2 \equiv 4\,M_\chi^2(1-z)$

    $\implies \theta \sim \sqrt{1-z}$
  - Soft: $m_X^2 \sim M_\chi E_s \equiv M_\chi^2(1-z)$

    $\implies \frac{E_s}{M_\chi} \sim (1-z)$

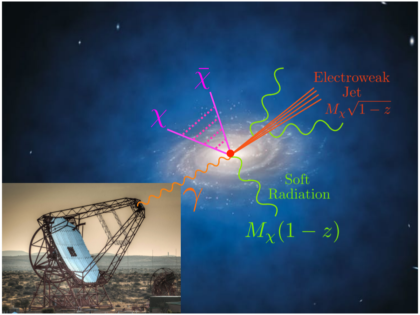


- HESS resolution forces recoiling state into soft and collinear limits.

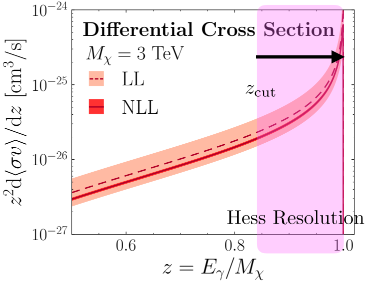
Jets

- Heavy WIMP annihilation produces jets.
- A jet is a spray of collimated (electroweak) radiation.
- Perturbative Sudakov double logarithms appear: $\alpha_W \log^2(1-z)$

Electroweak Jet from WIMP Annihilation



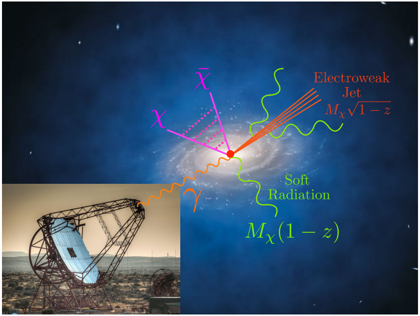
Spectrum



- Need to be resummed to all orders to understand energy spectrum.
- Previous approaches only have $\delta(1-z)$.

Summary of Scales

- Indirect detection is a complicated multi-scale problem:

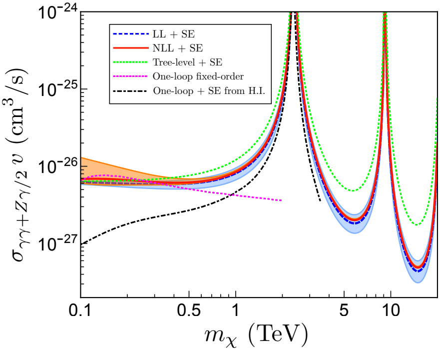


- Sommerfeld: $(\alpha_W\, M_\chi/m_W)^k$
- Electroweak: $\alpha_W \log^2(M_\chi/m_W)$
- Resolution: $\alpha_W \log^2(1-z)$

- Ideal for Effective Field Theory and Factorization!

Summary of Scales

- Are all numerically large effects

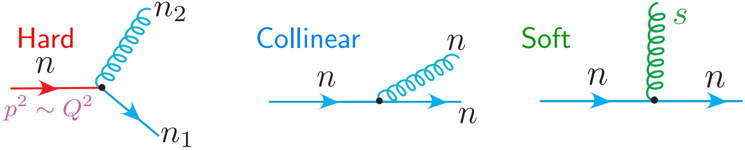


- Sommerfeld: $(\alpha_W M_\chi / m_W)^k$
- Electroweak: $\alpha_W \log^2(M_\chi / m_W)$
- Resolution: $\alpha_W \log^2(1 - z)$

- Want to understand how to disentangle and incorporate at the level of the spectrum.
- Once perturbative series has been reorganized (resummed), good behavior of electroweak perturbation theory will be restored.

Effective Field Theory

- Approach of Effective Field Theory:
  - Focus on relevant degrees of freedom.
  - Integrate out irrelevant degrees of freedom.

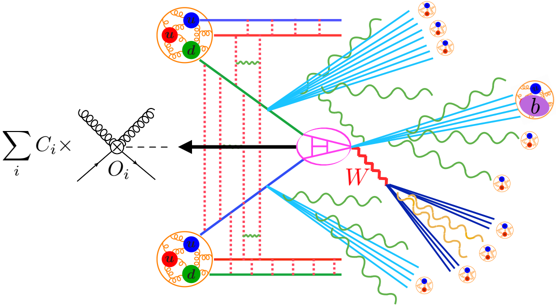


- Effective theory for long wavelength dynamics of soft and collinear radiation in the presence of a hard scattering source
  $\Longrightarrow$ Soft Collinear Effective Theory [Bauer, Fleming, Pirjol, Stewart]
  - Separate fields for collinear $\mathcal{B}^{\mu}_{n_i\perp}$ and soft A^{μ}_{us} gauge bosons.
- Extended to Electroweak theory [Chiu, Fuhrer, Kelley, Manohar]

Soft Collinear Effective Theory

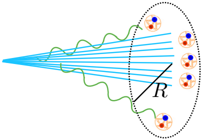
[Bauer, Fleming, Pirjol, Stewart]

- Hard scattering is described by operators in EFT



- Long wavelength dynamics of soft and collinear radiation described by Lagrangian

$\mathcal{L}_{\text{dyn}}$:



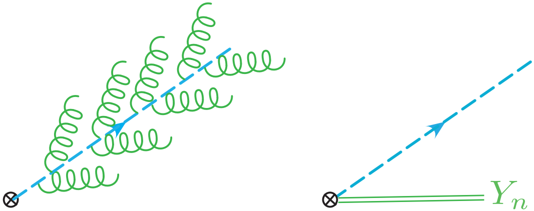
Field Redefinitions and Wilson Lines

[Bauer, Fleming, Pirjol, Stewart]

- Leading power soft-collinear interactions can be decoupled by field redefinition:

$$\mathcal{B}^{a\mu}_{n\perp} \to \mathcal{Y}^{ab}_n \mathcal{B}^{b\mu}_{n\perp}, \qquad \chi^\alpha_n \to Y^{\alpha\beta}_n \chi^\beta_n$$

$$Y^{(r)}_n(x) = \mathbf{P}\exp\left[ig\int_0^\infty ds\, n\cdot A^a_{us}(x+sn)\,T^a_{(r)}\right]$$



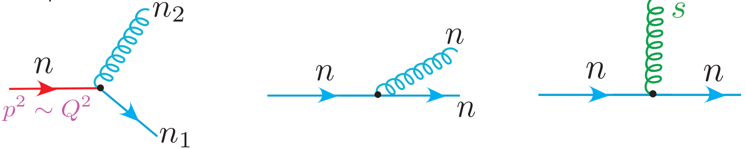
- Soft dynamics described by matrix elements of Wilson lines.
- Lagrangian and States factorize:

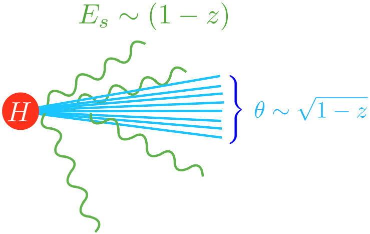
$$\mathcal{L}^{(0)} = \mathcal{L}^{(0)}_n + \mathcal{L}^{(0)}_s \implies |X\rangle = |X_n\rangle|X_s\rangle$$

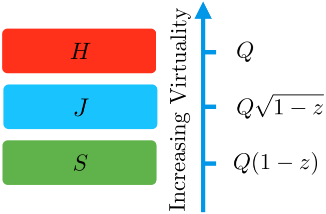
Factorization

[Bauer, Fleming, Pirjol, Stewart]

- After decoupling interactions, can write cross section as a product of hard, collinear and soft matrix elements







$$\frac{d\sigma}{dz} = H(Q^2) \int dz_J dz_S \delta\Big(z - z_J - z_S\Big) J(z_J) S(z_S)$$

Factorization and Renormalization

- Factorization allows cross section to be written as a product (convolution) of simple single scale functions:

$$\frac{d\sigma}{dz} = H(Q^2) \int dz_J dz_S \delta\Big(z - z_J - z_S\Big) J(z_J) S(z_S)$$

- Each function can be easily computed by itself (often in an expanded limit).
- All logarithms predicted by renormalization group evolution:

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} F(z;\mu) = \int \mathrm{d}z' \, \gamma_F^\mu(z - z';\mu) F(z';\mu)$$

- Offers powerful approach to multi-scale problems

Aside: Natural Scales

- All single scale functions have a natural μ scale at which all logarithms in their expansion vanish. e.g.

$$F(\mu; M_\chi) = 1 - \alpha_W \log^2\left(\frac{\mu}{M_\chi}\right) + c_1\alpha_W + \mathcal{O}(\alpha_W^2)$$

- At the natural scale, the function is a pure expansion in α_W:

$$F(\mu = M_\chi; M_\chi) = 1 + c_1\alpha_W + \mathcal{O}(\alpha_W^2)$$

- Scalings we worked out earlier are natural scalings:
  - Hard: $\mu \sim M_\chi$
  - Jet: $\mu \sim M_\chi\sqrt{1-z}$
  - Soft: $\mu \sim M_\chi(1-z)$

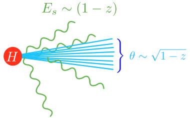
$$\mu\frac{d}{d\mu}F = -\alpha_W \log\left(\frac{\mu^2}{(M_\chi)^2}\right)F$$

$$\implies F(m_W) = \exp\left(-\alpha_W \log^2\left(\frac{m_W}{M_\chi}\right)\right)F(M_\chi)$$

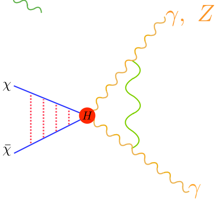
- Logarithms which invalidate the perturbative expansion are resummed to all orders by RG evolution.

A Complication

- Standard SCET can deal with a single measurement.
- Two cases considered previously in literature:
  - Constraint on massless final state radiation.



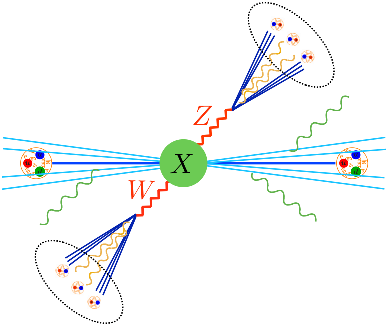
  - Virtual corrections for massive gauge bosons.
    [Chiu, Fuhrer, Kelley, Manohar]



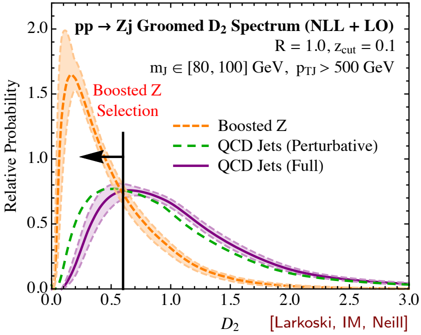
- Our situation is more complicated: Constraint on massive final state radiation.
- Must simultaneously consider two measurements: $(1-z)$ and m_W.

Borrowing from Jet Substructure

- Must extend SCET to deal with multiple measurements.
- Similar problem has appeared in jet substructure.



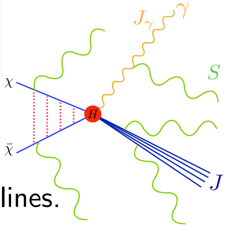
Groomed D_2 Distribution



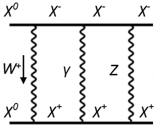
[Larkoski, IM, Neill]

- Can apply recent advances in field theories for jet substructure!

Non-Relativistic DM EFT



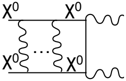
- Incoming DM particles are slow, $v \leq 10^{-3}$.
- Describe interactions using non-relativistic EFT.
- Interactions with soft radiation decoupled via Wilson lines.
- Leads to standard non-relativistic Lagrangian



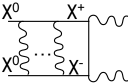
$$\mathcal{L}^{(0)}_{\mathrm{NRDM}} = \chi_v^\dagger \left(i\, v \cdot \partial + \frac{\vec{\nabla}^2}{2\, M_\chi} \right) \chi_v + \hat{V}[\chi_v, \chi_v^\dagger](m_{W,Z})$$

- Sommerfeld effect described by matrix elements:

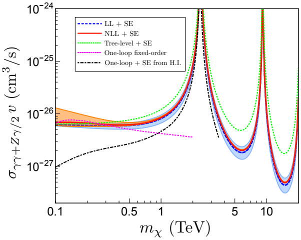
$$\left\langle 0 \middle| \chi_v^{3\,T}\, i\sigma_2\, \chi_v^3 \middle| (\chi^0\chi^0)_S \right\rangle = 4\sqrt{2}\, M_\chi\, s_{00}\,,$$



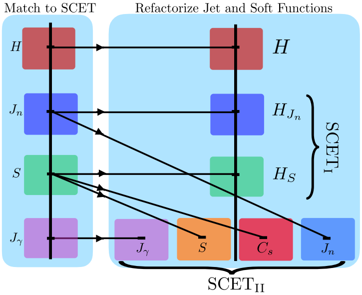
$$\left\langle 0 \middle| \chi_v^{+\,T}\, i\sigma_2\, \chi_v^- \middle| (\chi^0\chi^0)_S \right\rangle = 4\, M_\chi\, s_{0\pm}$$



- Decouples into a multiplicative factor.
- Resonances when $\alpha_W M_\chi \sim n^2 m_W$

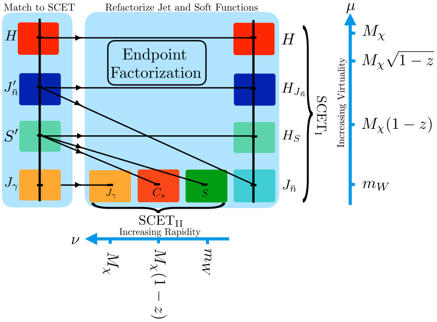


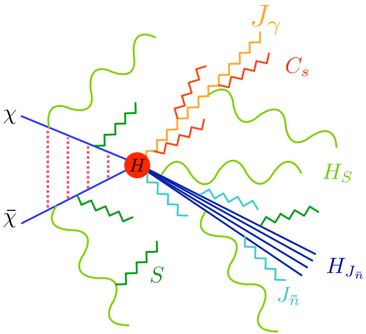
Factorization Formula for the Endpoint Region



The Factorization Formula

- Full factorization derived through a multistage matching procedure.





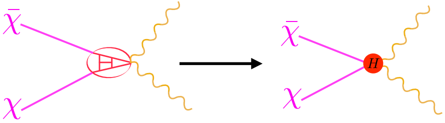
- Provides an all orders description, and operator definitions

$$\frac{d\hat\sigma^{LL}}{dz} = H(M_\chi,\mu)\,J_\gamma(m_W,\mu,\nu)\,J_{\bar n}(m_W,\mu,\nu)\,S(m_W,\mu,\nu)\times$$
$$H_{J_{\bar n}}(M_\chi,1-z,\mu)\otimes H_S(M_\chi,1-z,\mu)\otimes C_S(M_\chi,1-z,m_W,\mu,\nu)$$

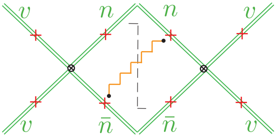
The Factorization Formula

$$\frac{d\hat{\sigma}^{LL}}{dz} = H(M_\chi,\mu)\, J_\gamma(m_W,\mu,\nu)\, J_{\bar{n}}(m_W,\mu,\nu)\, S(m_W,\mu,\nu)\times$$
$$H_{J_{\bar{n}}}(M_\chi, 1-z,\mu) \otimes H_S(M_\chi, 1-z,\mu) \otimes C_S(M_\chi, 1-z, m_W,\mu,\nu)$$

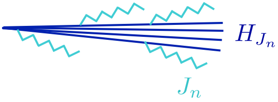
- Hard:



- Soft:

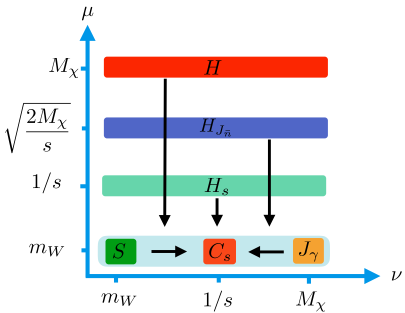


- Jet:



Renormalization Group Evolution

- All large logarithms are resummed by renormalization group evolution
- Compute all functions at their natural scale: $F = 1 + c_1 \alpha_W + \cdots$
- RG evolve to a common scale (s Laplace conjugate to $M_\chi(1-z)$).



- e.g. Hard function: $\mu \frac{d}{d\mu} H = -8\, C_A\, \tilde{\alpha}_W \log\left(\frac{\mu^2}{(2\,M_\chi)^2}\right) H$

$$\implies H\,(m_W) = \exp\left(-8\, C_A\, \tilde{\alpha}_W \log^2\left(\frac{m_W}{2\,M_\chi}\right)\right) H(2M_\chi)$$

Resummed Spectrum at LL

- Obtain simple analytic formula for leading logarithmic spectrum:

$$\left(\frac{d\sigma}{dz}\right)^{\mathrm{LL}} = 4\,|s_{0\pm}|^2\,\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}\,\delta(1-z) + \frac{2\,\alpha_W}{\pi}\frac{\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}}{1-z}\,e^{\frac{4\,\alpha_W}{\pi}\,L_J^2(z)}\left\{F_1\Big(3\,L_S(z)-2\,L_J(z)\Big)e^{\frac{-3\,\alpha_W}{\pi}\,L_S^2(z)}-2\,F_0\,L_J(z)\right\}.$$

- Non-trivial combination of perturbative logarithms and Sommerfeld factors.

- Formula at higher logarithmic orders remains functions of logarithms and Sommerfeld factors (but much less compact).

Resummed Spectrum at LL

- Obtain simple analytic formula for leading logarithmic spectrum:

$$\left(\frac{d\sigma}{dz}\right)^{\mathrm{LL}} = 4\,|s_{0\pm}|^2\,\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}\,\delta(1-z) + \frac{2\,\alpha_W}{\pi}\,\frac{\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}}{1-z}\,e^{\frac{4\,\alpha_W}{\pi}\,L_J^2(z)}\left\{F_1\left(3\,L_S(z)-2\,L_J(z)\right)e^{\frac{-3\,\alpha_W}{\pi}\,L_S^2(z)} - 2\,F_0\,L_J(z)\right\}.$$

- Perturbative Logarithms:

$$\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}} = \frac{\pi\,\alpha_W^2\,\sin^2\theta_W}{2\,m_{\mathrm{DM}}^2\,v}\exp\left[-\frac{4\,\alpha_W}{\pi}\,\ln^2\left(\frac{m_W}{2\,m_{\mathrm{DM}}}\right)\right]$$

$$L_J(z) = \ln\left(\frac{m_W/m_{\mathrm{DM}}}{2\sqrt{1-z}}\right)\Theta\left(1-\frac{m_W^2}{4\,m_{\mathrm{DM}}^2}-z\right),$$

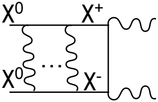
$$L_S(z) = \ln\left(\frac{m_W/m_{\mathrm{DM}}}{2\,(1-z)}\right)\Theta\left(1-\frac{m_W}{2\,m_{\mathrm{DM}}}-z\right),$$

Resummed Spectrum at LL

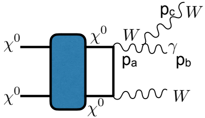
- Obtain simple analytic formula for leading logarithmic spectrum:

$$\left(\frac{d\sigma}{dz}\right)^{\mathrm{LL}} = 4\,|s_{0\pm}|^2\,\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}\,\delta(1-z)$$
$$+\frac{2\,\alpha_W}{\pi}\,\frac{\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}}{1-z}\,e^{\frac{4\,\alpha_W}{\pi}\,L_J^2(z)}\left\{F_1\left(3\,L_S(z)-2\,L_J(z)\right)e^{\frac{-3\,\alpha_W}{\pi}\,L_S^2(z)}-2\,F_0\,L_J(z)\right\}.$$

- Sommerfeld Effects:



$s_{0\pm} \implies$ Pure Endpoint



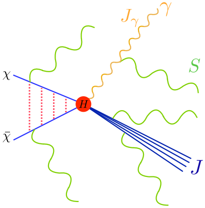
$$F_0 = \frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 + \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right),$$

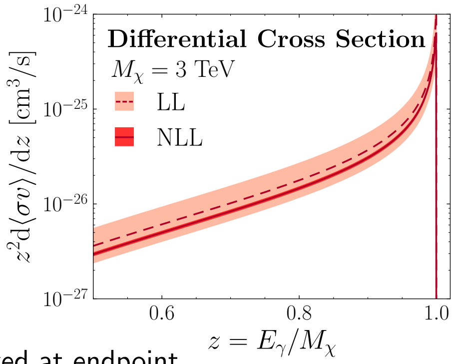
$$F_1 = -\frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 - \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right)$$

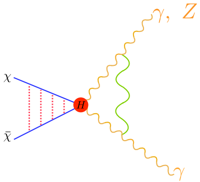
Energy Spectrum

- Provides first resummed prediction for the energy spectrum for heavy WIMP annihilation.

Energy Spectrum for Wino Annihilation





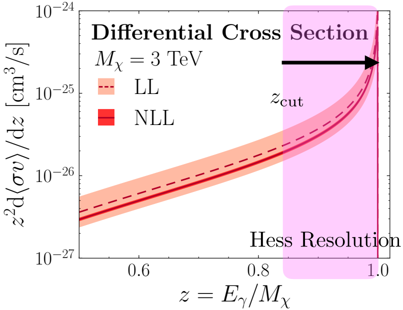


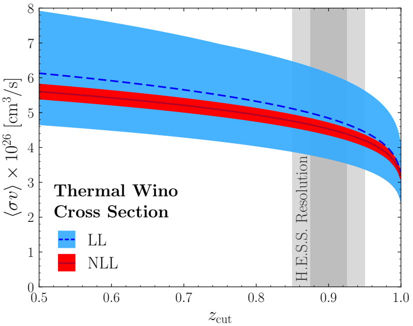
- Strongly peaked at endpoint.
- Non-trivial spread due to additional radiation.
- Once resummed, EW perturbation theory converges very well.

Energy Spectrum

- HESS resolution much larger than line width
  $\implies$ integrates flux over a window.

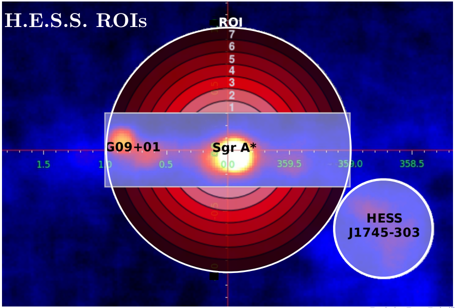
Energy Spectrum | **Integrated Cross Section**





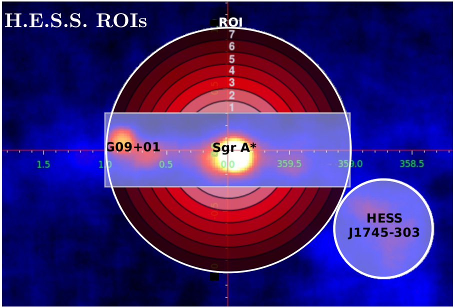
- Significant contribution from non-line photons.
- Additional photons can be used to strengthen limits.
- Allows real experimental resolution function to be used.

H.E.S.S. Forecast

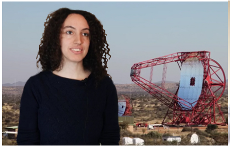


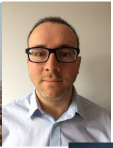
H.E.S.S. Analysis

- We* performed a realistic H.E.S.S. forecast using our prediction for the photon spectrum.



*Our H.E.S.S. collaborators Lucia Rinchiuso and Emmanuel Moulin





- Goals:
  - Effect of the full endpoint spectrum on constraints.
  - Using a wider ROI to improve sensitivity to core size.

Review: Computing the Flux

- Quick Review:
  - Flux at the detector can be written

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E} = J \, \frac{\langle \sigma v \rangle}{8\,\pi\, M_\chi^2} \, \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

  - DM density enters as J-factor:

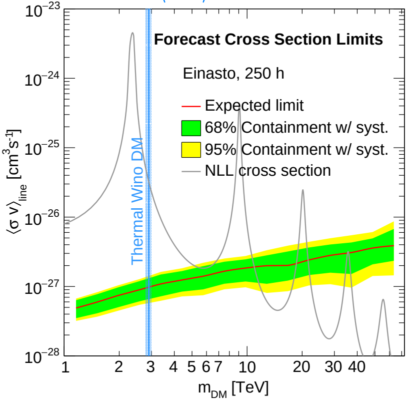
$$J = \frac{\int_{\mathrm{ROI}} \mathrm{d}s \, \mathrm{d}\Omega \, \rho^2_{\mathrm{DM}}(s, \Omega)}{\int_{\mathrm{ROI}} \mathrm{d}\Omega}$$

- Can place limits on EITHER
  - $\langle \sigma v \rangle$ for a fixed profile.
  - J-factor.

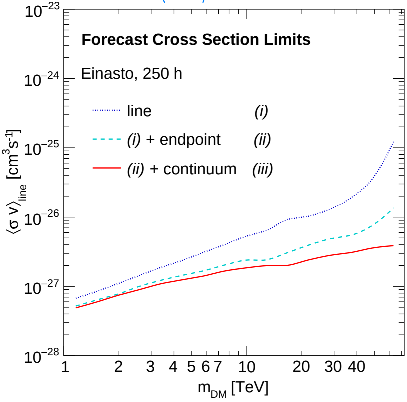
Cross Section Limits

- Provide updated limits using our spectrum.

$\langle \sigma v \rangle$ vs. m_{DM}



$\langle \sigma v \rangle$ vs. r_c

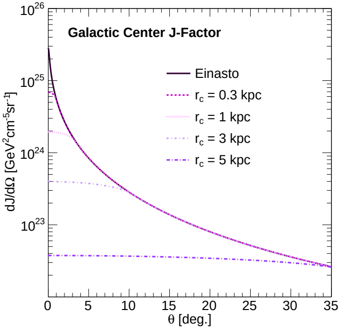


- Inclusion of endpoint photons strengthens limits.

Core Size Constraints

- Can reinterpret as core size constraints for cored Einasto profile.

$$\rho_{\mathrm{DM}}(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

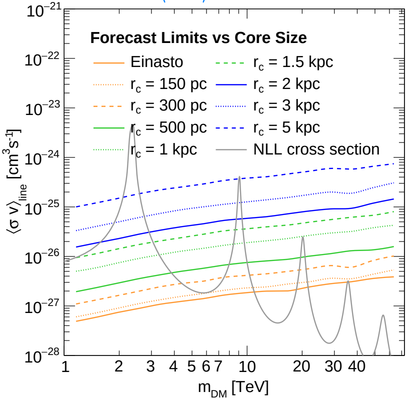


- Simulations give flattened cores of $\mathcal{O}(1)$ kpc for Milky-Way sized galaxies [e.g. Chan et al. 2015]
- Observations of stellar motion suggest ≤ 2 kpc core [e.g. Hooper 2017]

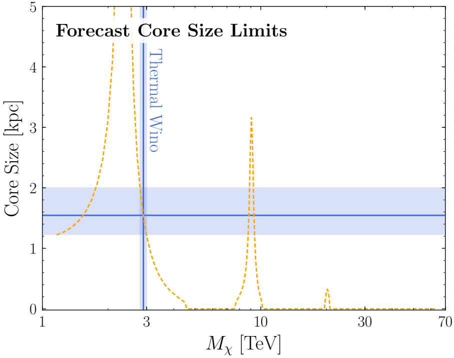
Core Size

- Due to Sommerfeld enhancement, for Thermal Wino DM, probe cores of $\mathcal{O}(1.5)$ kpc.

$\langle \sigma v \rangle$ vs. m_{DM}



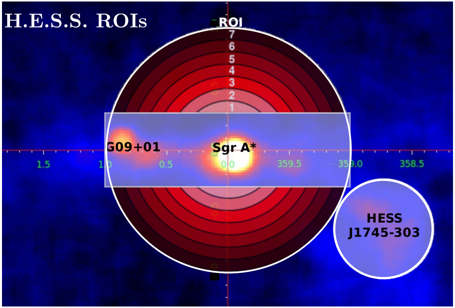
$\langle \sigma v \rangle$ vs. r_c

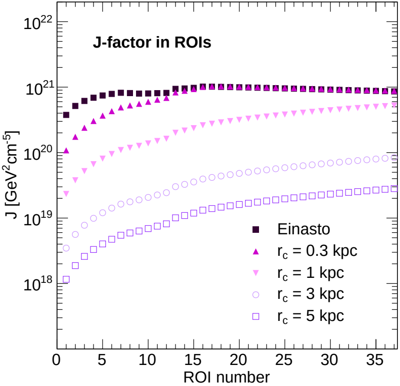


- Beginning to enter interesting region!

Extended R.O.I.

- To improve sensitivity to core size, we performed a forecast with an extended R.O.I.
- Extend from 1° → 4°, but use standard H.E.S.S. analysis.

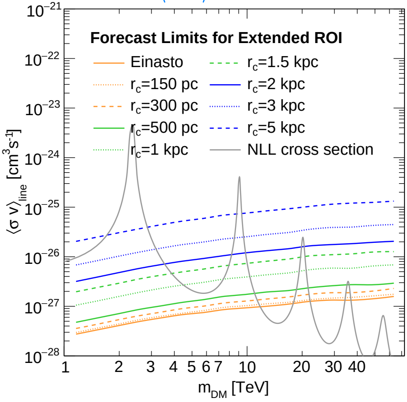




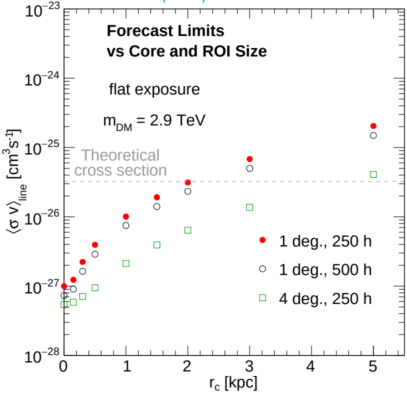
Extended R.O.I.

- Extended R.O.I. significantly improves reach for core size.

$\langle \sigma v \rangle$ vs. m_{DM}



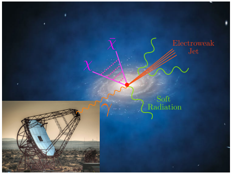
$\langle \sigma v \rangle$ vs. r_c

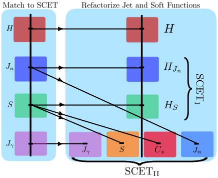


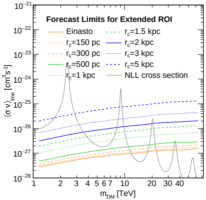
- Probes cores of $\mathcal{O}(5)$ kpc for Thermal Wino DM!

Conclusions

- EFTs provide powerful techniques for complicated multiscale problems.
- Derived factorized description allowing first calculation of resummed spectrum for indirect detection.
- HESS forecast with increased ROI allows to probe ~ 5 kpc cores.








Thanks!