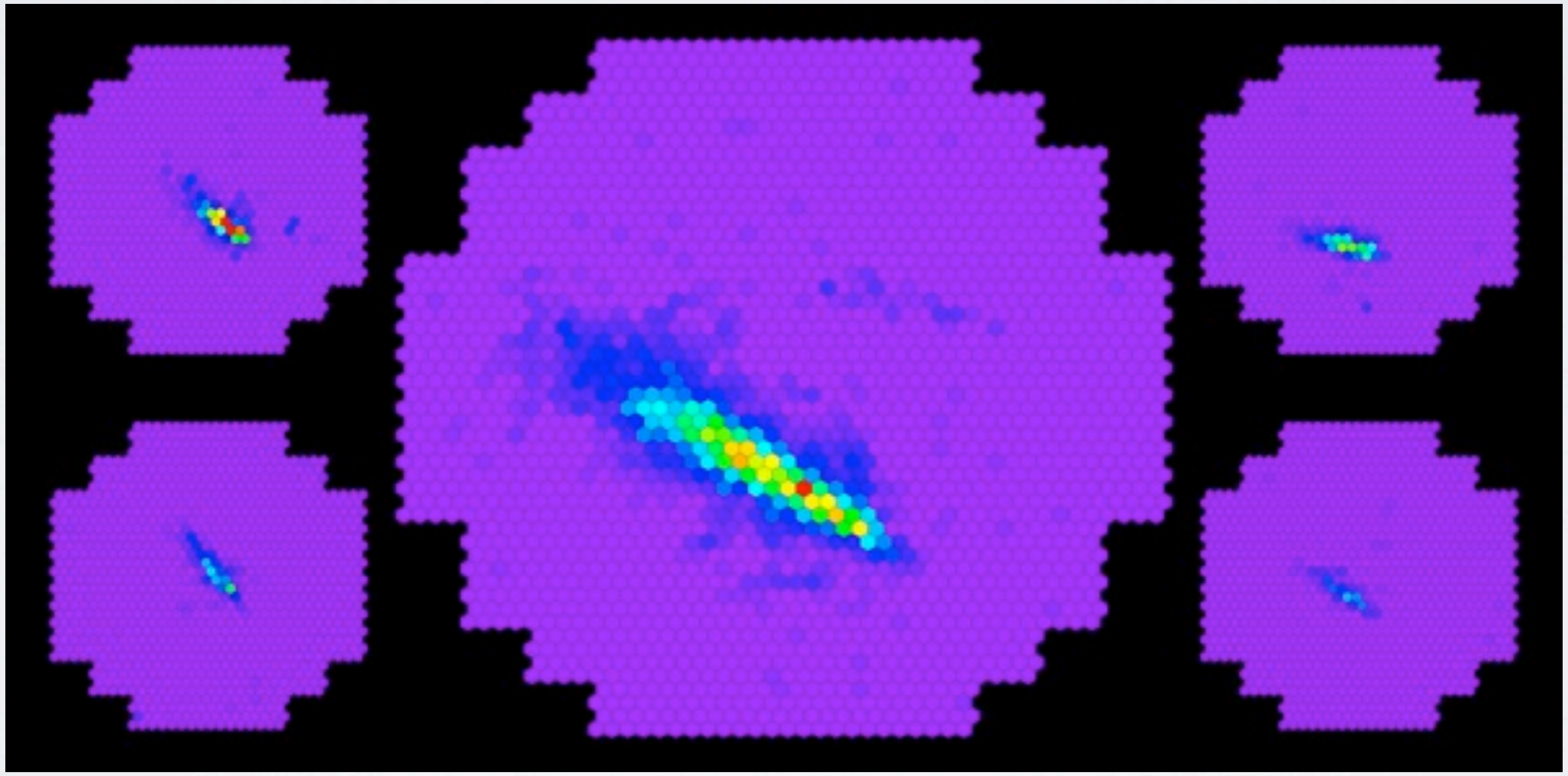
ON THE ANNIHILATION OF WIMPS

Matthew Baumgart (Carnegie Mellon U.)



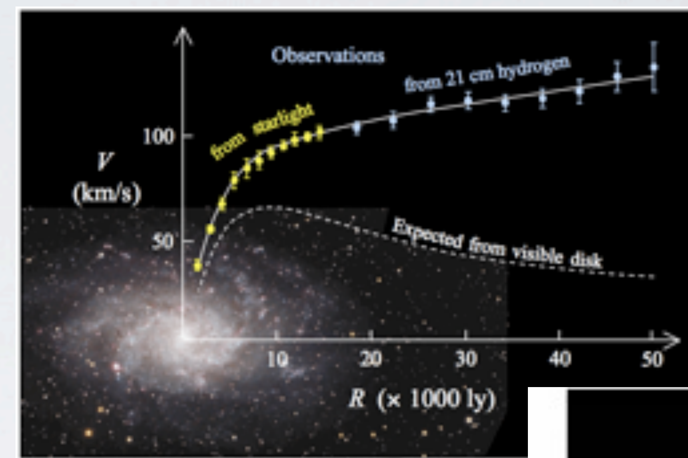
SCET Workshop 2015 - Santa Fe

3/27/2015

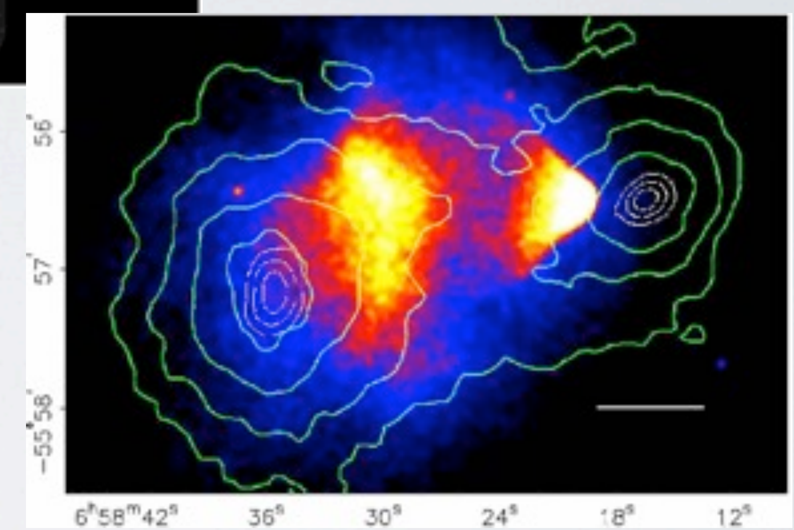
DARK MATTER

Dark Matter (DM) posited since 1930s (Zwicky, Oort, Rubin...) to explain variety of astrophysical anomalies

- Key questions about missing 27% of universe's energy
  - **Does it interact with us nongravitationally?**
  - **What are its quantum numbers?**
- Variety of motivated candidates (axions, asymmetric, sterile neutrinos...), but we focus on: Weakly-Interacting Massive Particles (WIMPs)



DM at 3 scales: Galaxy, Cluster, and Cosmological



Parameter	Planck Best fit	Planck 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020

WHY WIMPS?

- General consideration of particle DM in cosmology lead to "WIMP miracle"
- Particle freezes out when annihilation rate drops below cosmic expansion

$$n(T_f)\langle\sigma v\rangle \sim \left(H \sim \frac{T_f^2}{M_{Pl}}\right)$$

- Frozen out particle has density ratio to photons today as at freezeout

$$\frac{n_{X0}}{T_0^3} \simeq \frac{n(T_f)}{T_f^3}$$

- This lets us calculate relic density of dark matter...

$$\Omega_X h^2 \equiv \frac{\rho_{X0}}{\rho_c} h^2 \sim \frac{M_X}{T_f} \frac{1}{3 \times 10^4} \frac{1}{\langle\sigma v\rangle} \frac{1}{T_0 M_{Pl}} \sim \frac{1}{10^3 \langle\sigma v\rangle} \frac{1}{\mathrm{TeV}^2}$$

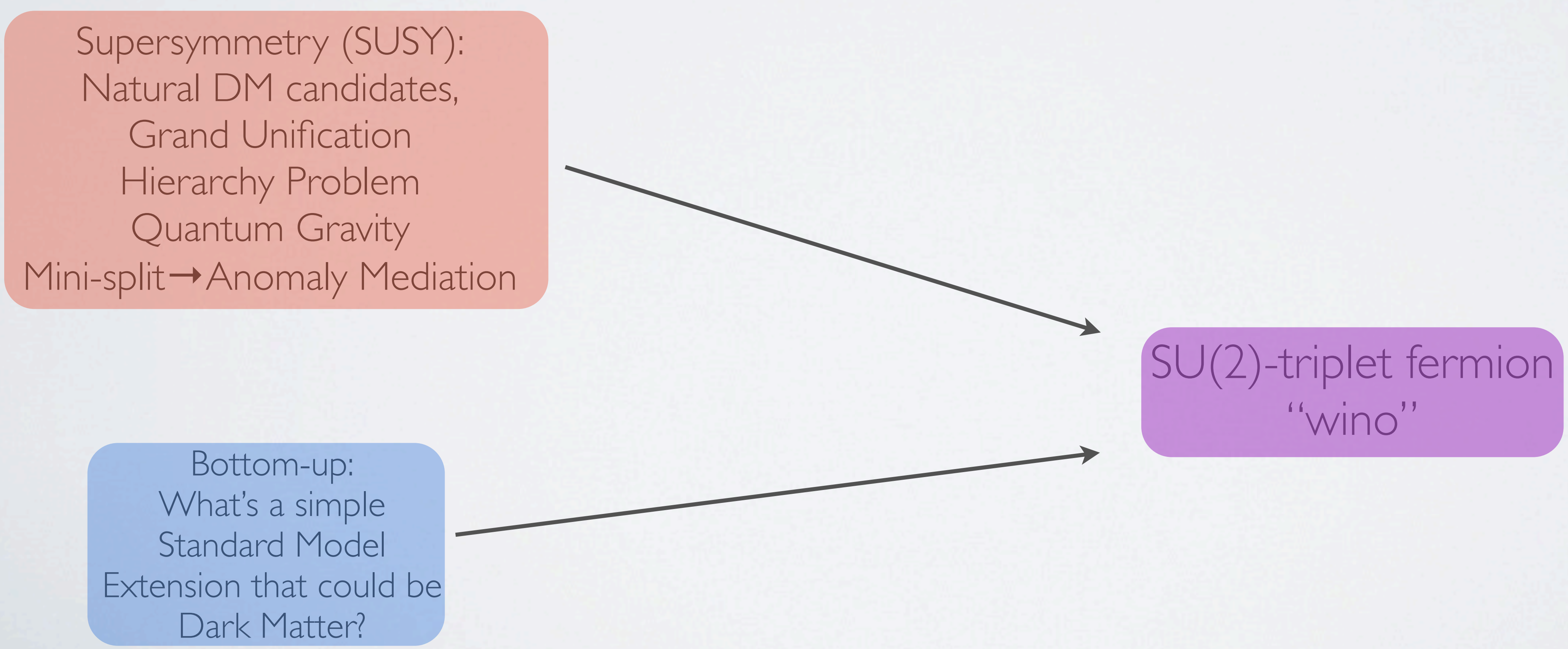
- ...and expected mass given a perturbative annihilation process $\langle\sigma v\rangle \sim C\, \alpha^2/M_X^2$

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

See Dimopoulos PLB 246(1990):347-52

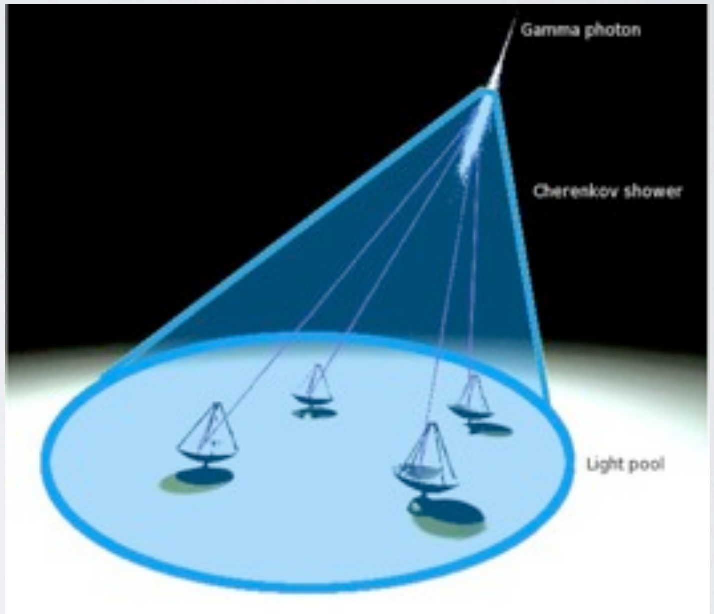
FROM WIMP TO WINO

- Without any input of electroweak physics, cosmology gives us Weak-scale (TeV) with weak couplings
- Tempting to connect Dark Matter to Hierarchy Problem as in SUSY
- What are motivated candidates and how do we find/exclude them?



HESS

- Probing TeV-scale winos in 2015 requires indirect detection ($\chi\chi \to$ observable)
- High Energy Steroscopic System (HESS)
- Atmospheric Cherenkov telescope
- Constrains photon lines. Our main interest...



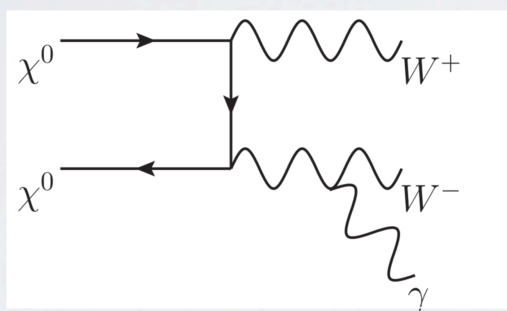
O(TeV) γ leads to O(10^4m) light pool on ground

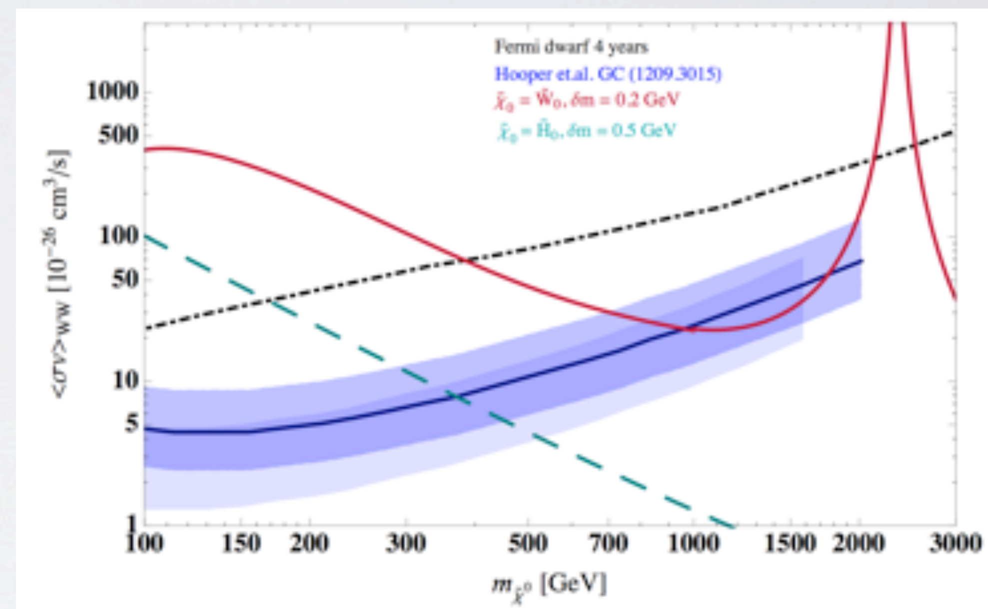
Schematic of air shower observed by Cherenkov Telescope (spie.org)

HESS in Namibia

INDIRECT DETECTION

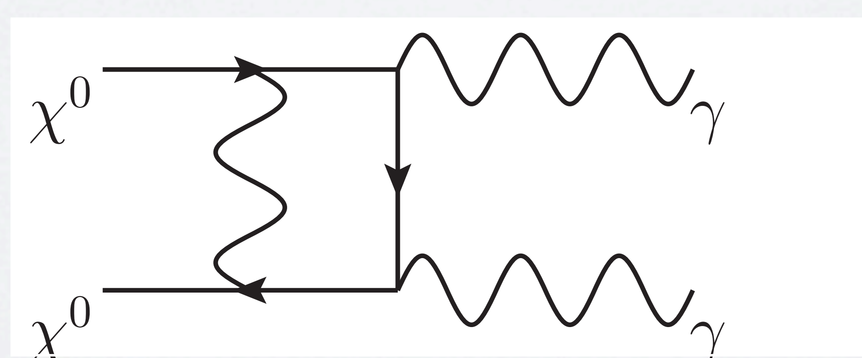
- Continuum (χχ→W⁺W⁻→photons) useful for sub-TeV limits (Fermi)





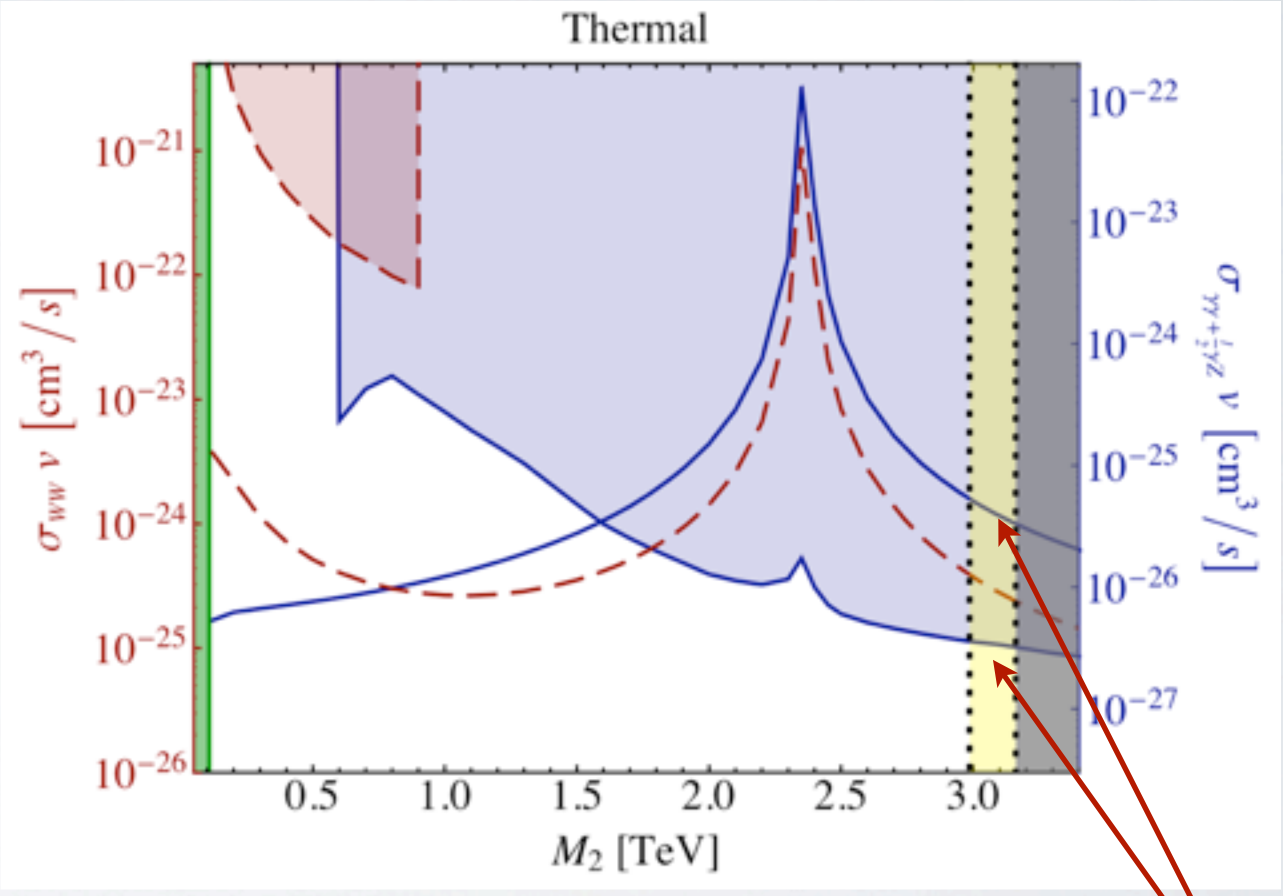
J. Fan & M. Reece: 1307.4400

- Line (χχ→γ+X) extends to multi-TeV range



"WINO DARK MATTER UNDER SIEGE"*

- SM gauge couplings + Boltzmann Equation → M≈3 TeV thermal relic
- Has our beautiful, simple model been shot dead by HESS?
- Navarro-Frank-White (cusped) halo profile assumed



From 1307.4082:
Blue line: Wino annihilation rate
Blue shade: Exclusion from HESS
Yellow shade: All DM is thermal wino

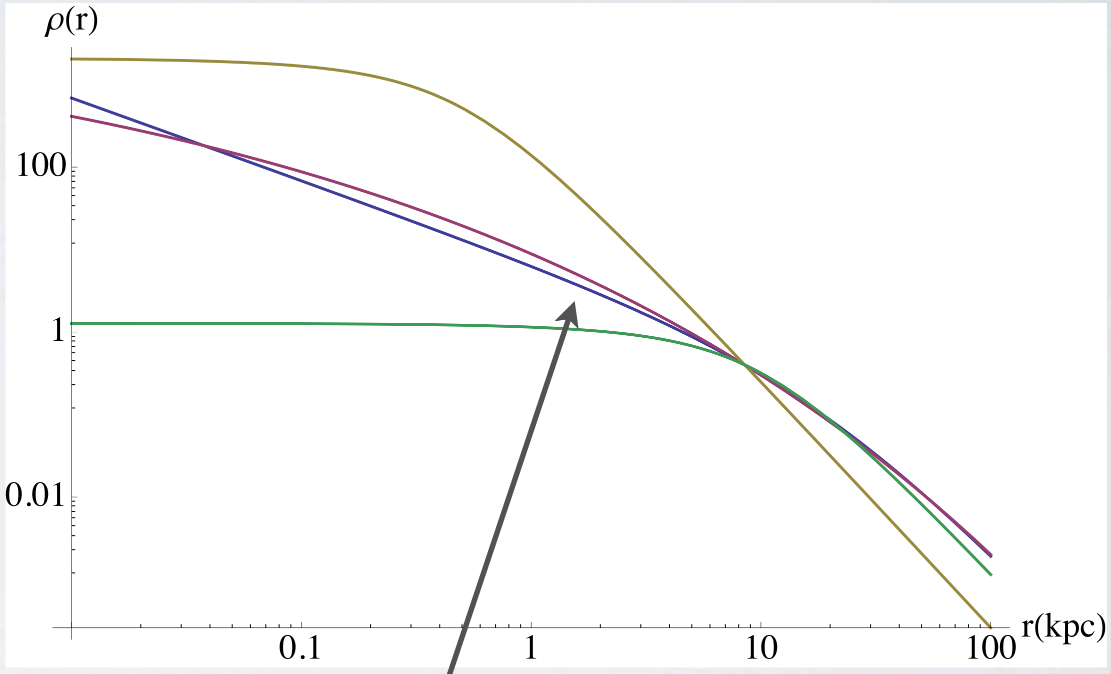
Ruled out by 16x?

*1307.4082: Cohen, Lisanti, Pierce, and Slatyer; see also "In Wino Veritas", 1307.4400: Fan & Reece

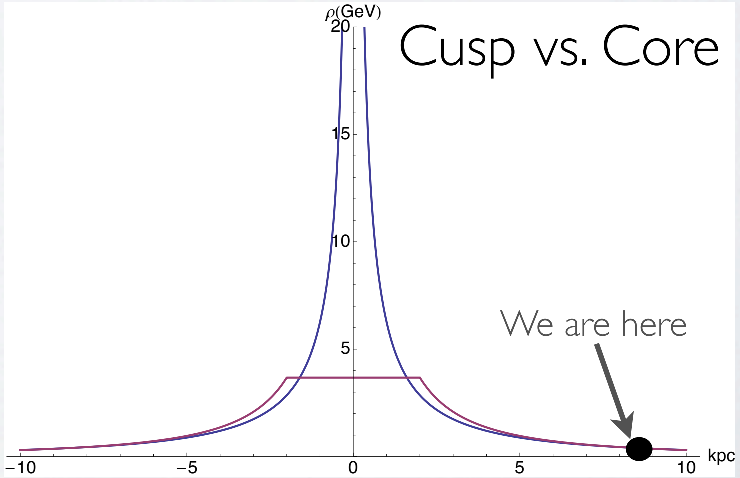
THE HALO LOOPHOLE

- Indirect detection searches suffer from large astrophysical uncertainties from unknown form of DM halo.
- Observation only constrains possible core < 10 kpc (Nesti & Salucci 1304.5127)
- Flux of photons observed by HESS proportional to integrated ρ^2
- Dwarf galxies evince corings, but simulation, even with baryons, finds **cusps down to 1 kpc***

*1208.4844, 1305.5360, 1306.0898



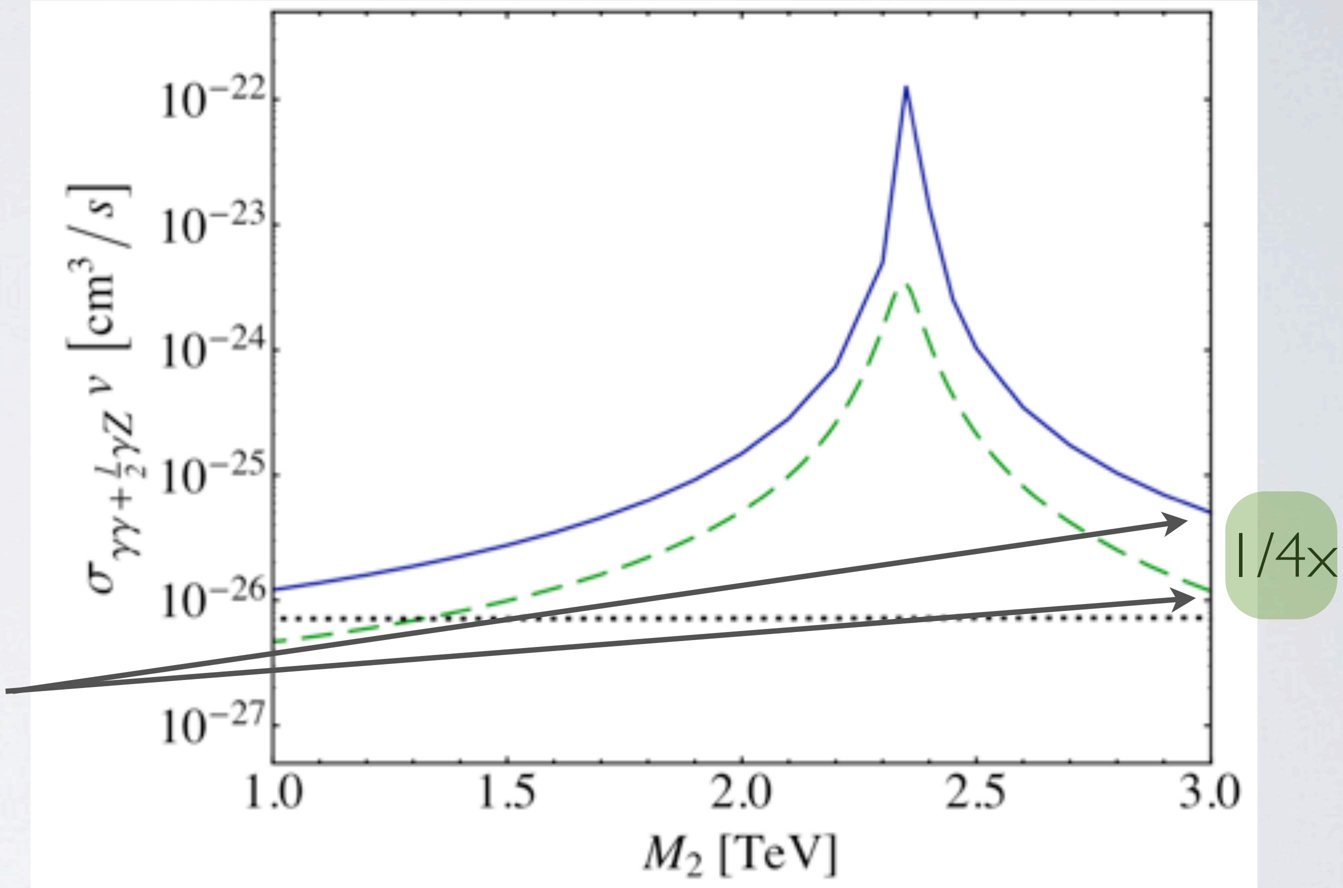
Blue (NFW), Red (Einasto), Yellow (Burkert-0.5), Green (Burkert-10) fixed to local density (8.5 kpc) of 0.4 GeV/cm^3



WHAT COULD SAVE THE WINO?

Halo Model	Radiative Corrections
Flatten distribution in galactic center (core)	Claim in literature of 75% reduction at NLO
Core needed: **1.5 kpc**	Core needed: **0.5 kpc**

Simulations with baryons show **cusped profiles down to 1 kpc** (1208.4844, 1305.5360, 1306.0898)



From Cohen et al. 1307.4082

Factor of few at stake, need state of the art calculation to determine

MB, Ira Rothstein, & Varun Vaidya: 1409.4415 (PRL) & 1412.8698 (JHEP)

SOMMERFELD ENHANCEMENT

- Wino annihilation subject to 2 effects beyond perturbation theory*
  - Sommerfeld Enhancement
  - Sudakov double logs
- Quantum-Mechanically, short-distance annihilation rate modified by wavefunction-at-origin in presence of potential:

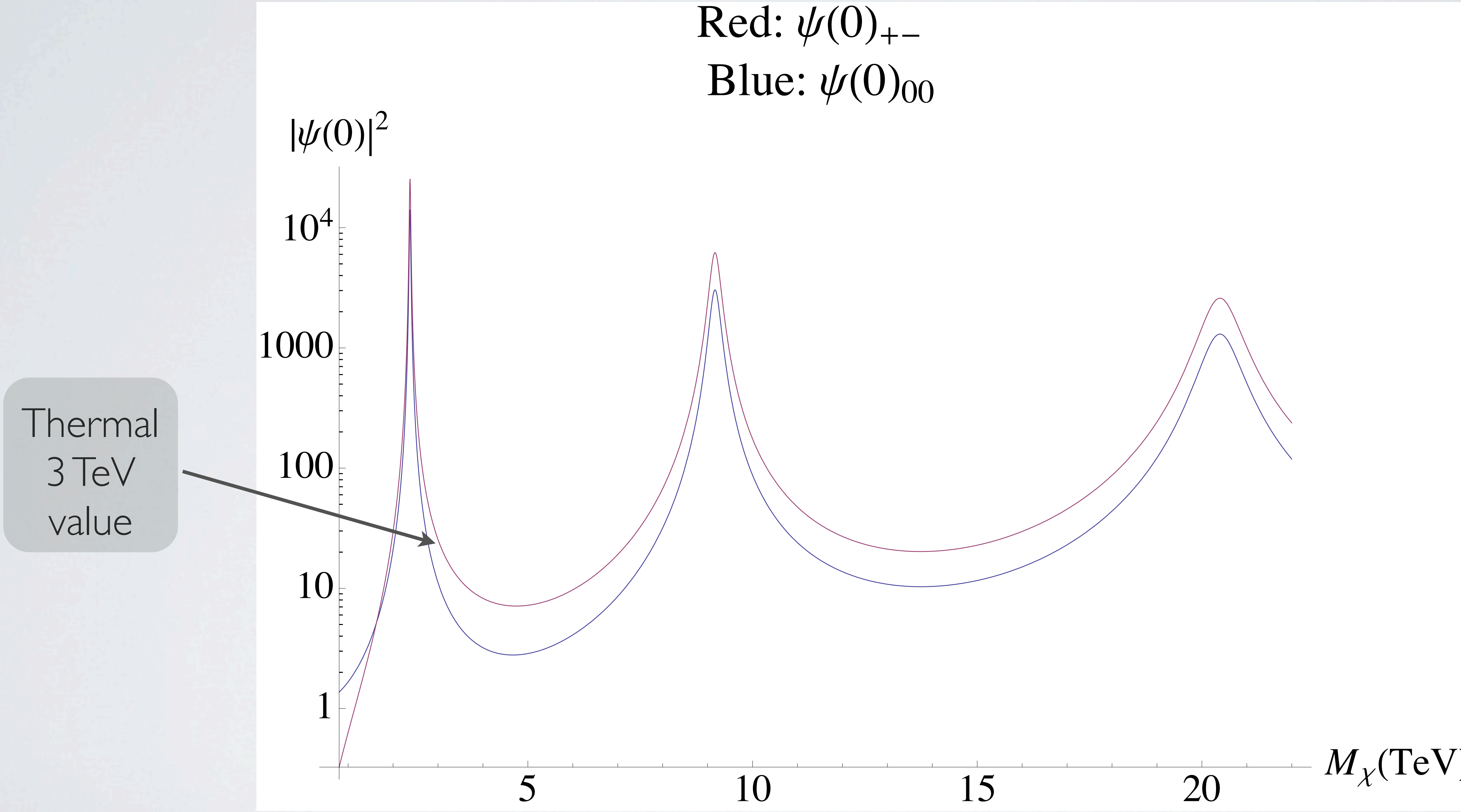
$$\langle \sigma v \rangle = |\psi(0)|^2 \, \Gamma_{\text{pert.}}$$

In absence of gravitation, capture radius is geometric, R

Turning on gravity, cross section grows for slower projectile: $b_{\text{capture}} = R\sqrt{1 + \frac{2GM}{v^2 R}}$

*See also 1409.7392: M. Bauer et al,; 1409.8294: G. Ovanesyan et al.

WINO SOMMERFELD FACTORS



Solving Schrodinger equation for v = 10^{-3} gives us resonance regions with $O(10^4)$ enhancement

MODES & FACTORIZATION

- Large logs → disparate scales ($\lambda \sim m_W/M_{wimp}$) → factorization
- Factorization lets us separate 2 nontrivial behaviors (Sommerfeld and Sudakov) in hybrid NRQCD/SCET-2 theory*
- Setting up EFT requires list of relevant modes

Soft Higgs couplings are power-suppressed; Collinear Higgses only run Fragmentation Functions

$$\mathrm{WIMPs}\,(\chi) : (E \sim \lambda^2,\, p \sim \lambda)$$

$$\mathrm{Potential} : (E \sim \lambda^2,\, p \sim \lambda)$$

$$\mathrm{Collinear}\,(B^{\mu\perp}) : (k_+ \sim 1,\, k_- \sim \lambda^2,\, k_\perp \sim \lambda)$$

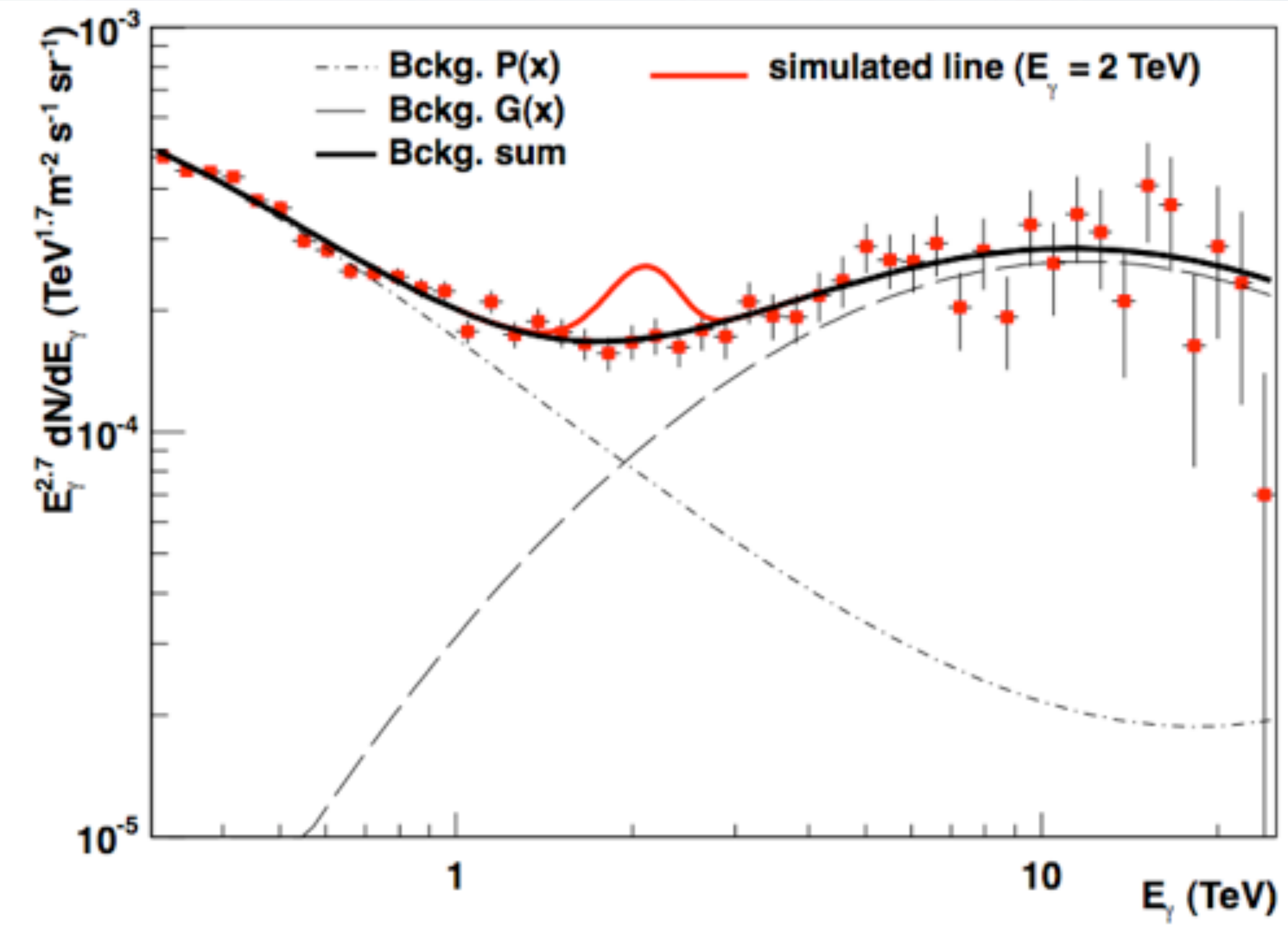
$$\mathrm{Soft}\,(S_{ab}) : (k_+ \sim \lambda,\, k_- \sim \lambda,\, k_\perp \sim \lambda)$$

These are all just W field in full theory (→ Potential, Collinear, Soft)

*See also Fleming, Leibovich, Mehen hep-ph/0607121 for photon spectrum for quarkonium decays

SEMI-INCLUSIVE ANNIHILATION

- Our interest is in setting limits from indirect detection
- HESS is an air Cherenkov telescope that observes photons colliding with the atmosphere
- Therefore, we compute $\chi\chi \to \gamma + X$



From HESS collaboration 1301.1173

at 3 TeV, energy resolution is ~400 GeV

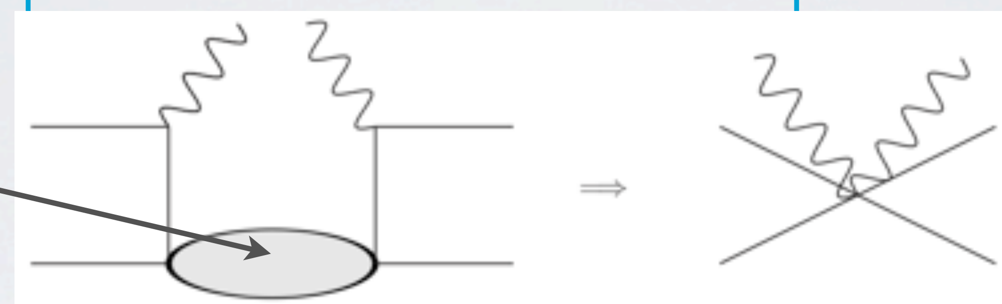
E_γ (soft W)=M_χ-m_W/2

E_γ (collinear Ws) = M_χ-m_W^2/M_χ

OPERATOR BASIS

- Since our interest is semi-inclusive processes, it is useful to work with the Operator Product Expansion (OPE)

General recoil state has virtuality λM_X^2 so we integrate out



- Matching tree level with one-loop running, we generate:

$$O_1 = (\bar{\chi}\gamma^5\chi)\,|0\rangle\langle 0|\,(\bar{\chi}\gamma^5\chi)\,B^{\mu A\perp}B_\mu^{A\perp}$$

$$O_2 = \frac{1}{2}\Big\{(\bar{\chi}\gamma^5\chi)\,|0\rangle\langle 0|\,(\bar{\chi}_A\gamma^5\chi_B) + (\bar{\chi}_A\gamma^5\chi_B)\,|0\rangle\langle 0|\,(\bar{\chi}\gamma^5\chi)\Big\}B_\mu^{\perp A}B^{\mu B\perp}$$

$$O_3 = (\bar{\chi}_C\gamma^5\chi_D)\,|0\rangle\langle 0|\,(\bar{\chi}_D\gamma^5\chi_C)\,B^{\mu A\perp}B_\mu^{A\perp}$$

$$O_4 = (\bar{\chi}_A\gamma^5\chi_C)\,|0\rangle\langle 0|\,(\bar{\chi}_C\gamma^5\chi_B)\,B_\mu^{\perp A}B^{\mu B\perp}$$

Vacuum projectors for WIMPs guarantee large momentum in process needed for OPE

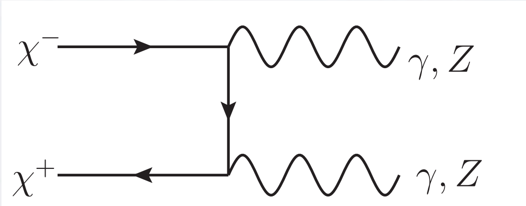
We implicitly work with SU(2) adjoint, so basis reduced by having Majorana fermion

Spin-singlets by Fermi statistics up to O(v) corrections

Collinear boson fields in symmetric limit

WILSON COEFFICIENTS

- We have four operators, but controlled by one tree-level matching coefficient
  - Just two dimension-five operators in "square root" of OPE, $\chi\chi B_n B_{\underline{n}}$ and $\chi^C\chi^D B_n^C B_{\underline{n}}^D$ and
  - Their coefficients equal and opposite to cancel, e.g. $\chi^3\chi^3 \rightarrow W^3W^3$



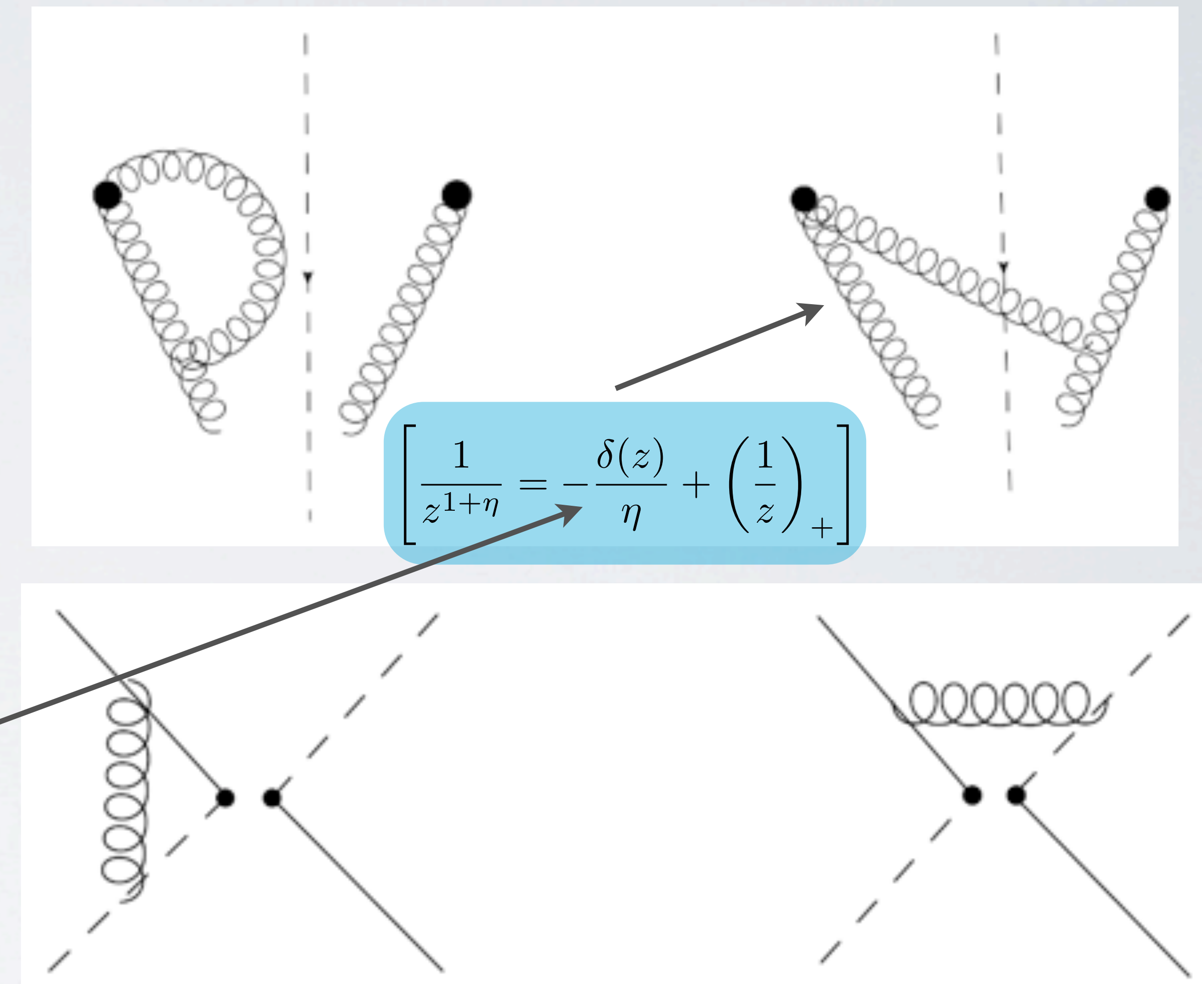
  - Squaring in OPE gives trivial color contraction, so

$$C_1 \equiv C \quad C_2 = -2C$$
$$C_3 = 0 \quad C_4 = C$$

$$C(M_\chi) = \frac{\pi\alpha_W^2 \sin^2\theta_W}{2M_\chi^3}$$

ANOMALOUS DIMENSIONS

- Compute soft & collinear anomalous dimensions separately
- Real process only contributes double log for zero-energy emission
- Thus, real & virtual corrections to $\chi\chi \rightarrow \gamma + X$ will appear as loops



$$\left[\frac{1}{z^{1+\eta}} = -\frac{\delta(z)}{\eta} + \left(\frac{1}{z}\right)_+\right]$$

Above: Collinear contributions O_c^a (real & virtual)
Below: Interactions between soft Wilson lines O_s^a (solid - timelike; dashed - lightlike)
$O_{1,3}$ have trivial color structure and thus 0-anomalous dimension

ANOMALOUS DIMENSION RESULTS

- For the collinear and soft sectors of our operators, (a - nonsinglet and b - singlet)

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

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

Note ν dependence drops out in soft-collinear sum

- Resum logs from Renormalization Group equation (2,4 - nonsinglet and 1,3 - singlet)

$$\mu\frac{d}{d\mu}C_{2,4}(\mu) = -(\gamma^c_{aa} + \gamma^s_{aa})C_{2,4}$$

$$\mu\frac{d}{d\mu}C_{1,3}(\mu) = -(\gamma^c_{ba} + \gamma^s_{ba})C_{2,4}.$$

Logs minimized for (μ,ν)
soft: (m_W, m_W)
collinear: (M_χ, m_W)

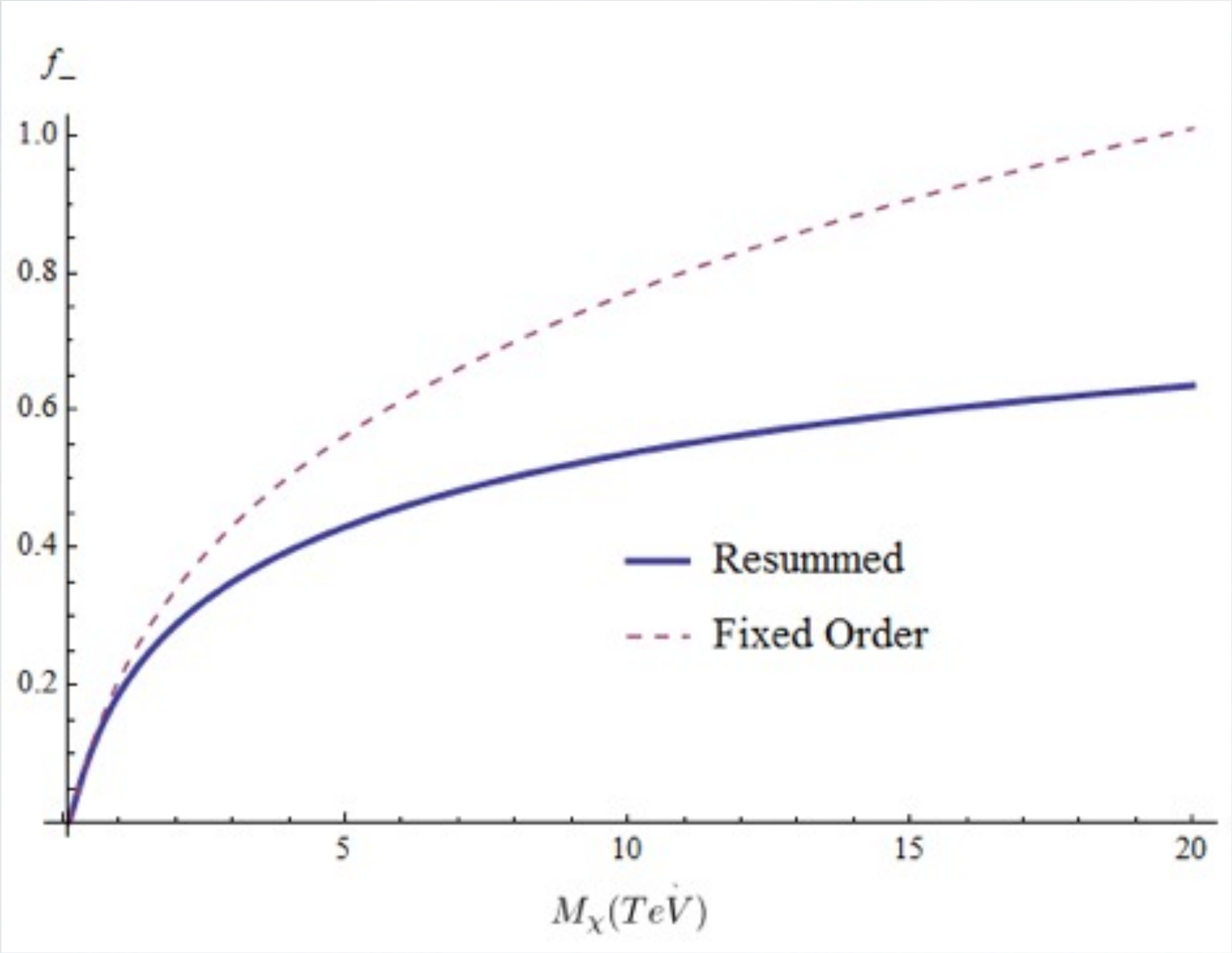
TOTAL RATE

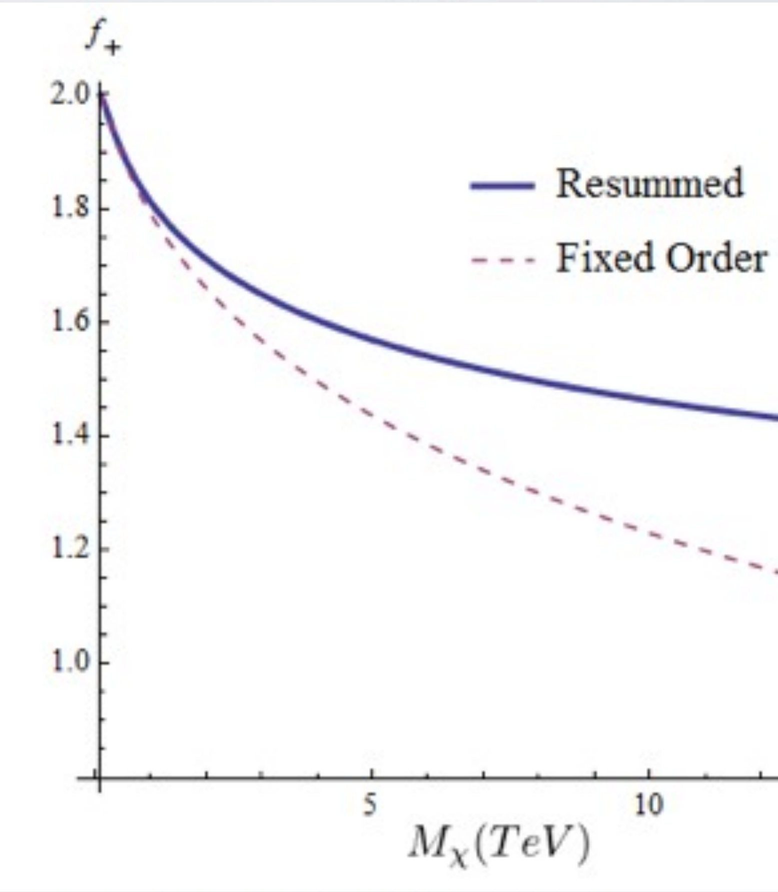
$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = \frac{C_1(\mu = E_\gamma)}{4M_\chi^2\, v}\delta(E_\gamma - M_\chi)\left[\frac{2}{3}f_-\,|\psi_{00}(0)|^2 + 2f_+\,|\psi_{+-}(0)|^2 + \frac{2}{3}f_-(\psi_{00}\psi_{+-} + \text{h.c.})\right]$$

- The ψ-factors quantify the Sommerfeld enhancement for annihilating state
- The f-factors arise from running Wilson coefficients and resum Sudakov double-logs

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

RESUMMATION





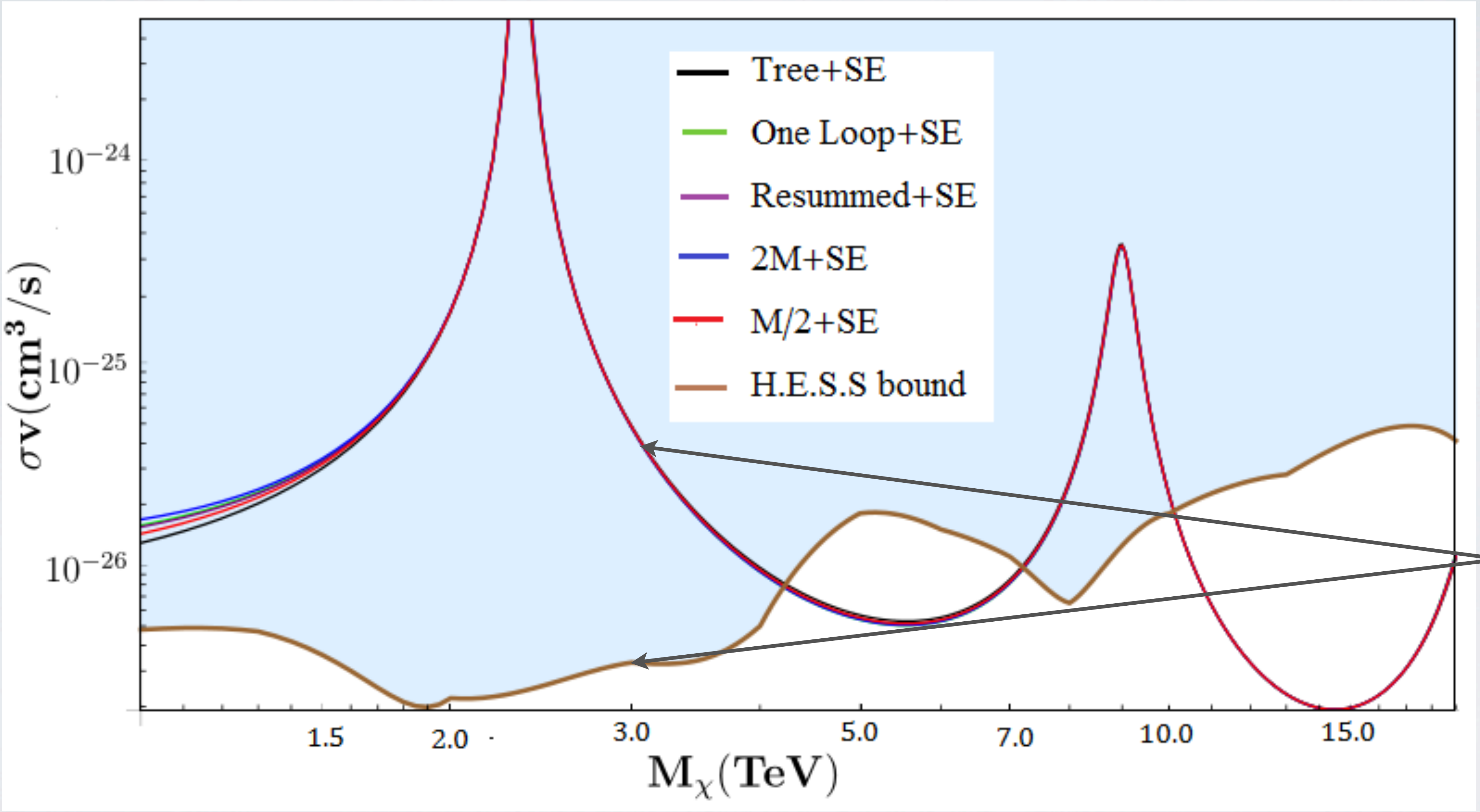
f^+ term generally larger, allowing quick estimate of higher orders

Sudakov factor vs. Dark Matter mass

Resummation is modest ~5% affect for thermal Wino (3 TeV)

More important effect that we looked at semi-inclusive instead of two-body annihilation

TOTAL RATE & EXCLUSION

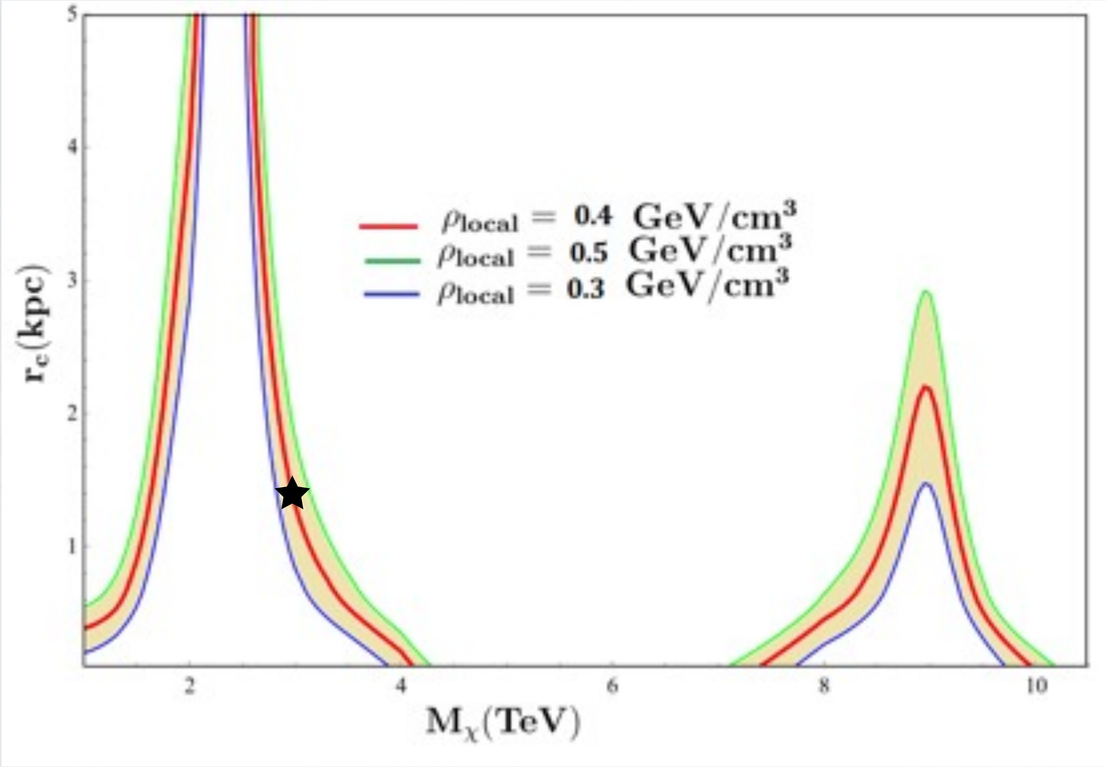


Wino escape at higher orders foiled by more accurate calculation

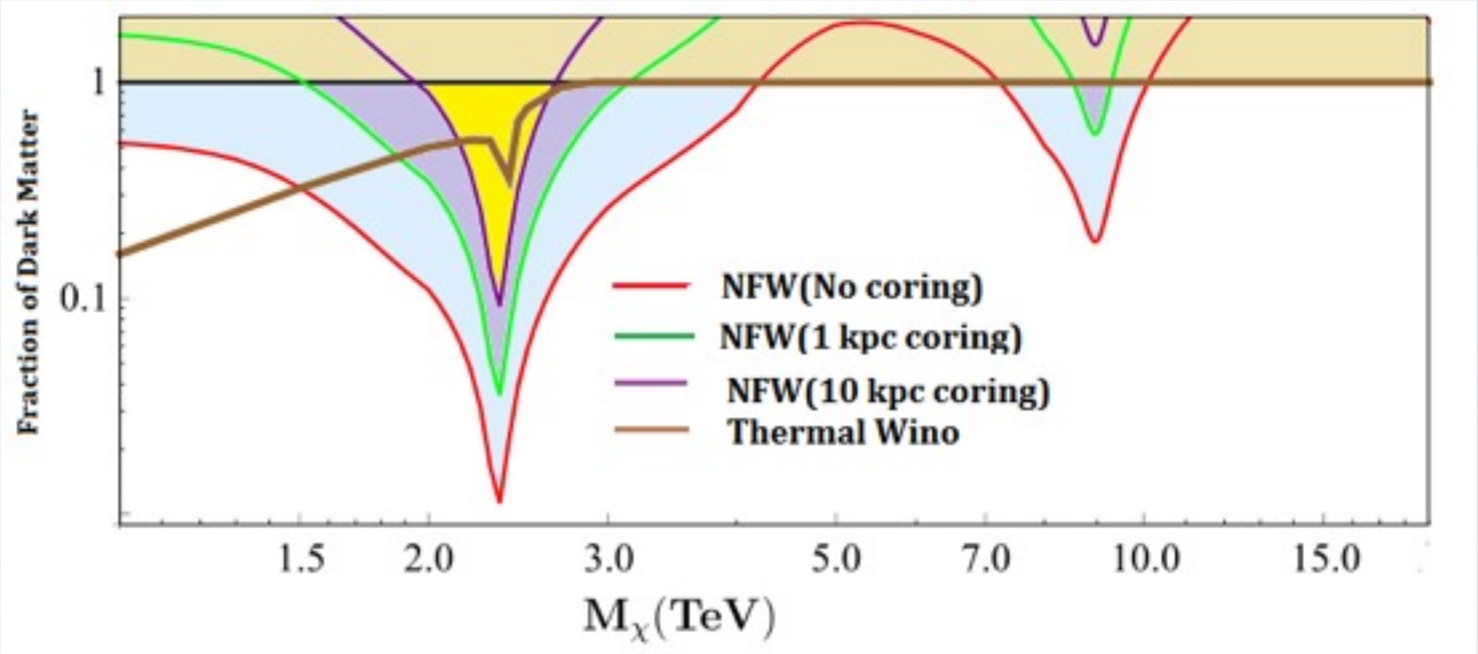
Exclusion curve taken from Ovanesyan, Slatyer, and Stewart (1409.8294); HESS data with NFW profile

WINO VIABILITY

Initial motivation for Wino stressed its simplicity,
but perhaps its role in Dark Matter is more involved, including
a non-thermal history, multi-component DM, mixing with other EW states



Imposing a constant density below a given radius for NFW (core), at what point does wino become viable total DM?



Possibility for the wino to make up some fraction of DM with NFW profile flattened to a constant core at some radius

CONCLUSION

- When computing observationally relevant semi-inclusive rate, NLO effects are small (~few%)
- Semi-Inclusive → Leading Log operator mixing → 1±Exp[-Log^2].
- Viability of thermal wino dark matter requires profile in tension with simulation (core ~ 1.5 kpc)
- Discovery of wino would have huge implications for astrophysical Dark Matter

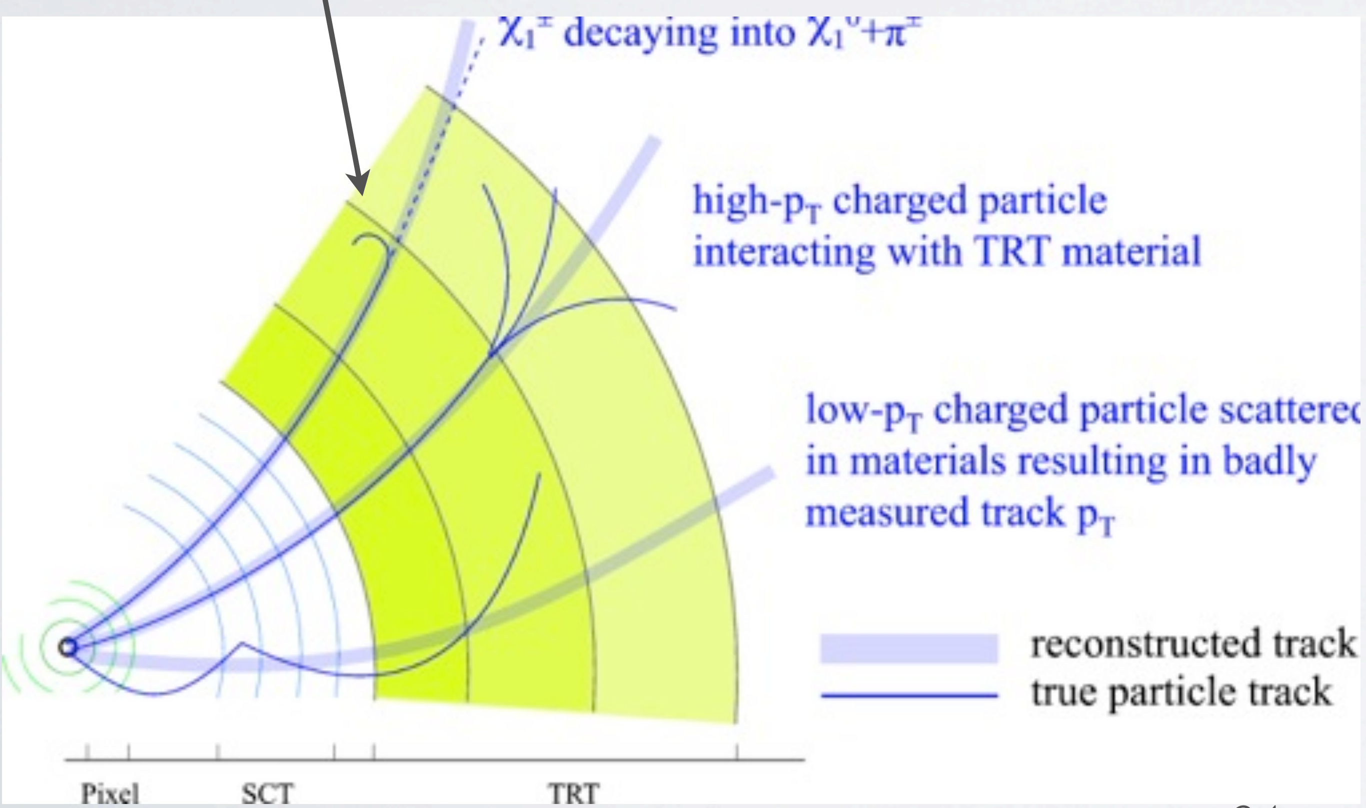
SUSY & DARK MATTER

- The Minimal Supersymmetric Standard Model (MSSM) comes with several natural WIMP dark matter candidates
  - Bino: Generic LSP in many SUSY-breaking scenarios. Overcloses universe unless nearly degenerate slepton provides co-annihilation ($\Delta M/M \sim 5\%$)
  - Wino: Generic LSP in Anomaly Mediated Supersymmetry Breaking (AMSB)
  - Higgsino: Pure Higgsino ruled out by direct detection, but bino/wino admixture possible*
  - Sneutrino: Ruled out by direct detection, but could be possible in extension
  - Gravitino: LSP of low-scale Gauge Mediation, very light O(100 keV), with overclosure and Big Bang Nucleosynthesis problems

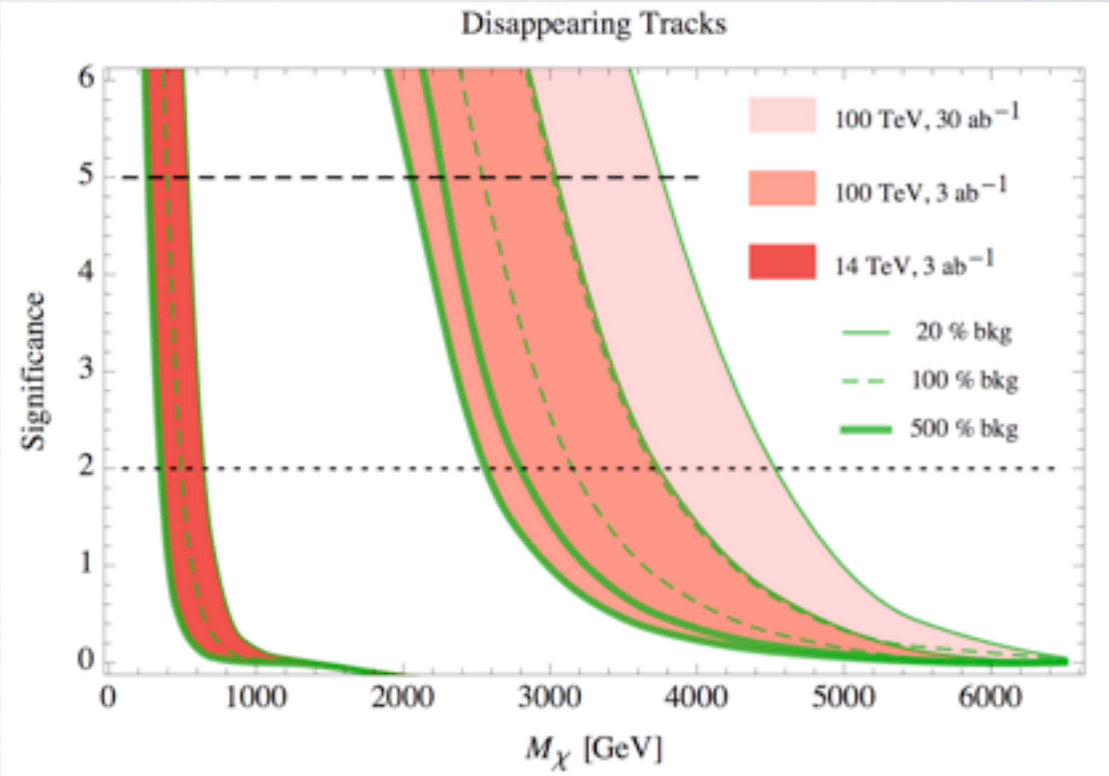
*See "The Well-Tempered Neutralino" Arkani-Hamed et al. hep-ph/0601041

TO FIND A TEV WINO

- **LHC:** Small mass splitting between $\chi^{\pm}$ and χ^{0} (ΔM=165 MeV) makes disappearing track O(10cm)
  Current limit M_χ>270 GeV



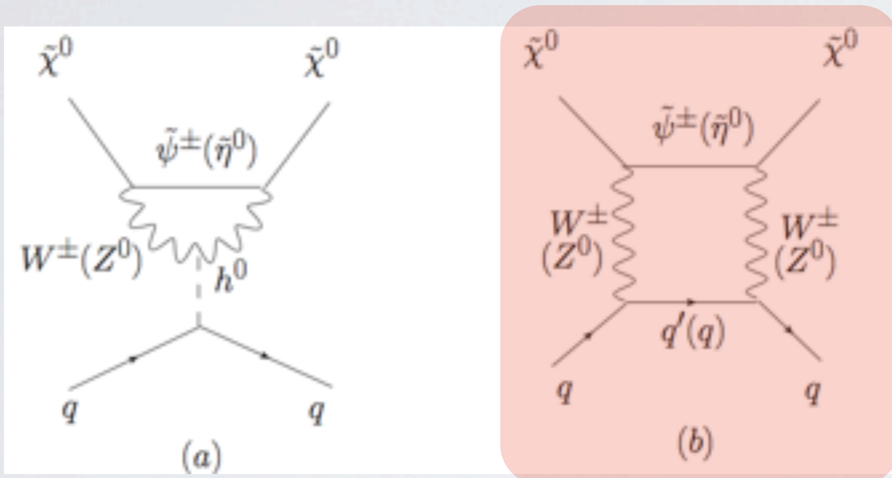
1202.4847 (ATLAS)



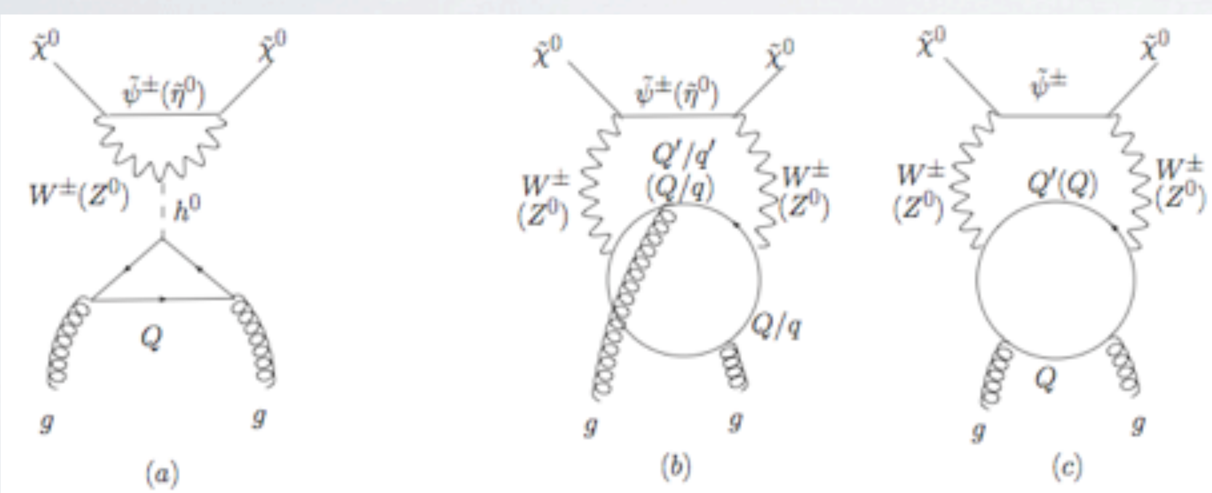
From Cirelli et al. 1407.7058

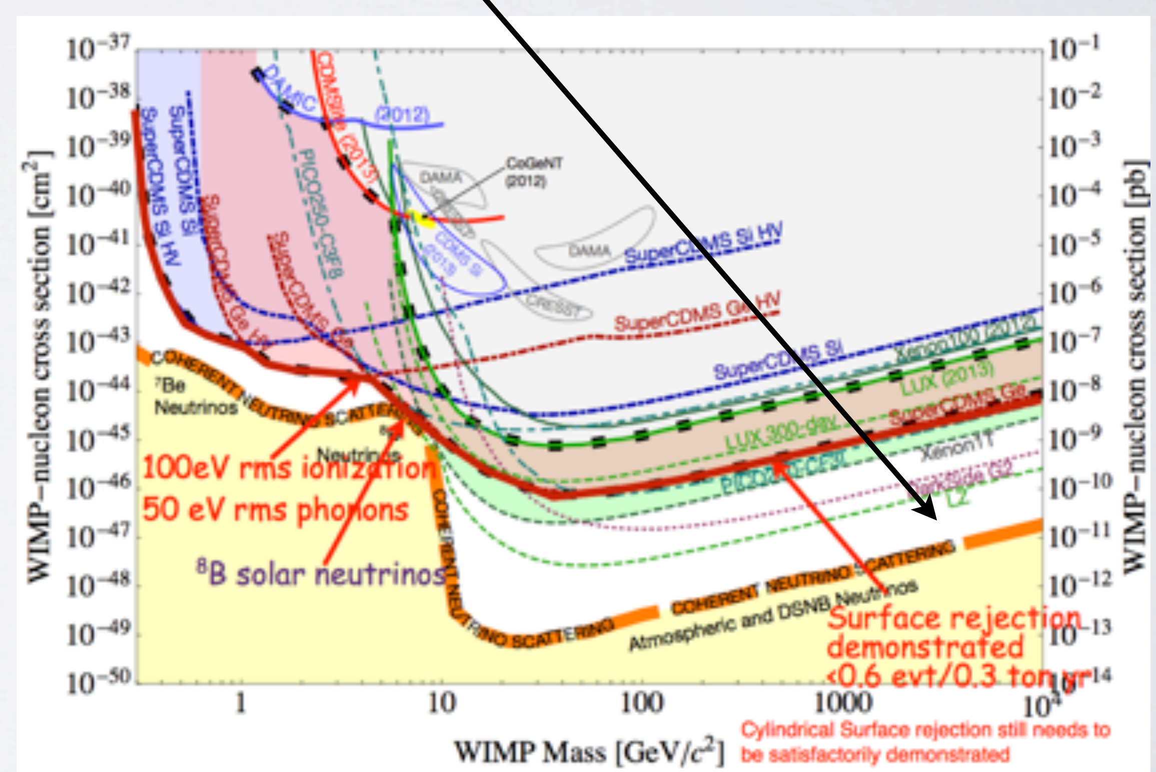
TO FIND A TEV WINO

Direct Detection: Wino has no renormalizable couplings to Z-boson or Higgs
Cross section proceeds through loops, which partially cancel for $m_h = 125$ GeV



Highlighted diagram gives negative contribution, all others positive, $\sigma \sim 10^{-47}$ cm^2





* Hisano et al. 1104.0228

From Rick Gaitskell (LUX) talk via Resonaances

WINOS BEYOND PERTURBATION THEORY*

- There are reasons to think wino annihilation in the present-day may receive large higher-order corrections:
  - Slowly-moving ($v \sim 10^{-3}$) winos' annihilation rate subject to **Sommerfeld Enhancement**. Higher perturbative order brings in new channel.
  - **Sudakov double-logarithms**: Large in electroweak physics, even in inclusive observables. Can't trust fixed order. We must resum logs.

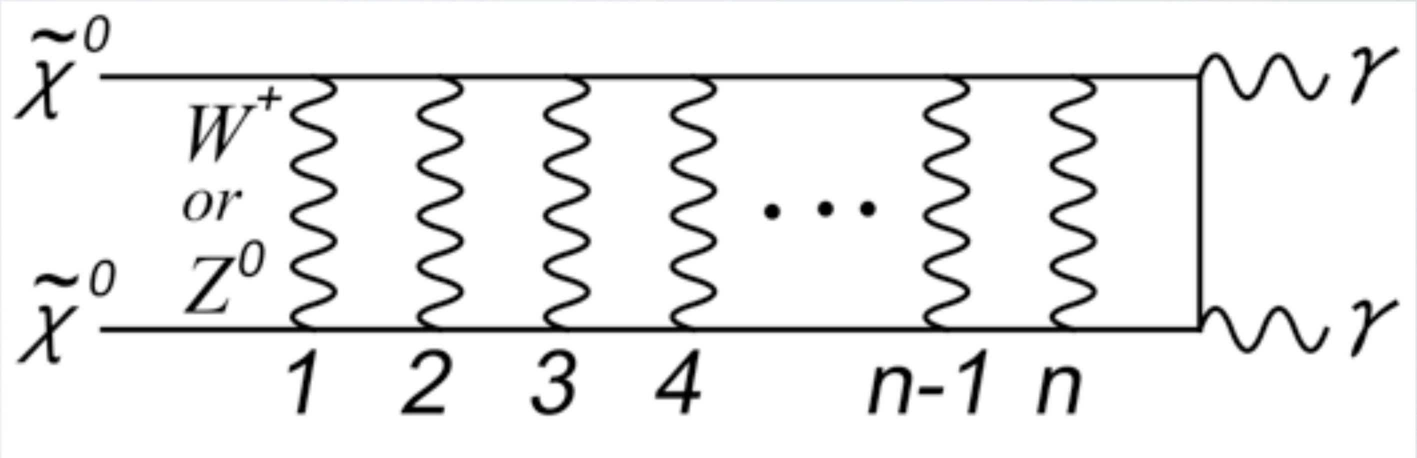
*MB, Rothstein, I and Vaidya, V: 1409.4415 & 1412.8698

SOMMERFELD & FIELD THEORY

Corrections at $O(v^2)$ to potential and $O(\alpha)$ from running couplings

- In nonrelativistic regime, summing infinite ladder exchange → solving Schrodinger equation for appropriate potential
- W-exchanges flip between $\chi^0\chi^0$ and $\chi^+\chi^-$ states
- Ladder exchanges unsuppressed

$$\mathcal{A}_n \simeq \alpha \left(\frac{\alpha_2 M}{m_W} \right)^n$$



From Hisano et al. hep-ph/0412403, see also Arkani-Hamed et al.: 0810.0713, Slatyer: 0910.5713

ELECTROWEAK POTENTIAL*

- Potential accounts for Yukawa exchange of Ws, Zs, Coulomb exchange of γs, and χ^+ - χ^0 mass splitting = (0.17 GeV)

$$\begin{pmatrix} 2\delta M - \frac{\alpha}{r} - \alpha_W c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

Mass splitting means +- state decays exponentially

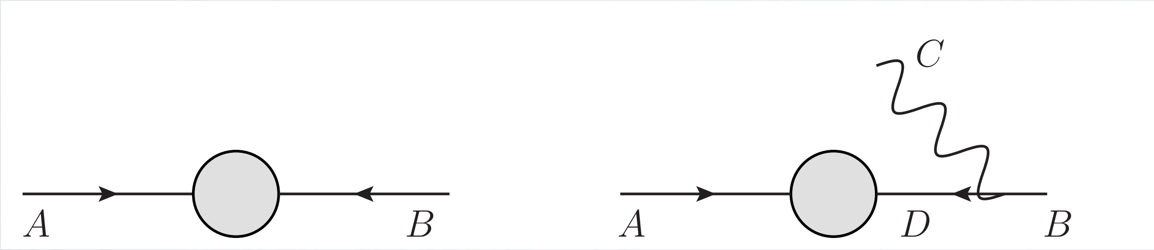
- Between the two-body $^1S_0$ states with interpolating fields:

$$\frac{1}{\sqrt{2}}\chi^+(\vec{x} - \vec{r}/2)\chi^-(\vec{x} - \vec{r}/2) \qquad \frac{1}{2}\chi^0(\vec{x} - \vec{r}/2)\chi^0(\vec{x} - \vec{r}/2)$$

*See also Hisano et al.: hep-ph/0412403

BLOCH-NORDSIECK THEOREM VIOLATION*

- Electroweak physics has infrared divergences, even in fully inclusive observables



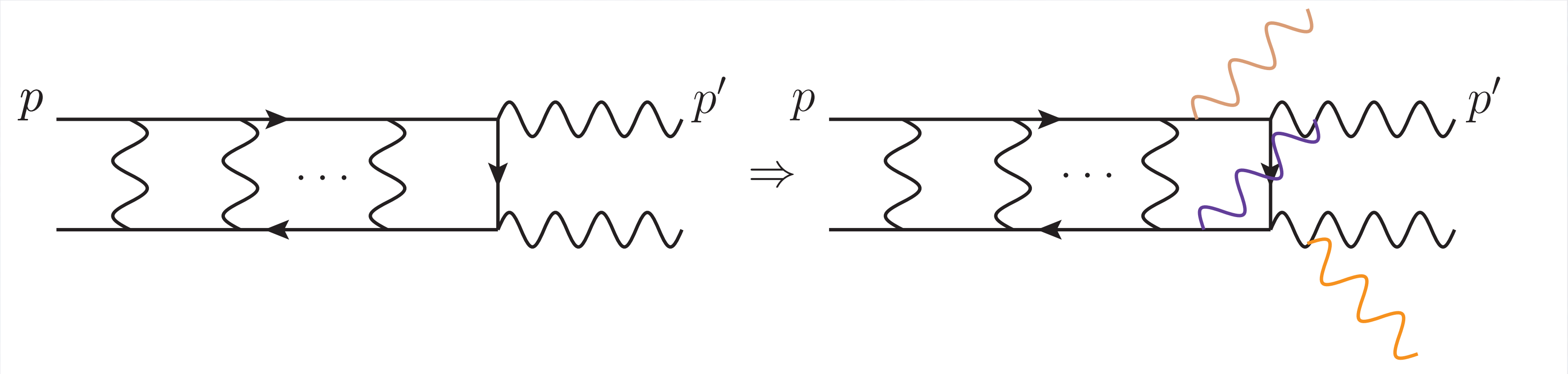
$\sigma_{AB} \neq \sigma_{AD}$, virtual corrections only cancel emission upon color averaging

- We avoid pathology because
  - QED: Emission doesn't change particle identity → real/virtual cancellation → Bloch-Nordsieck
  - QCD: Singlets let us average over initial colors, factorization isolates IR sensitivity (e.g. PDFs)
  - Electroweak: Gauge boson masses cut off divergence, but allow for $\log(Q^2/m_W^2)^2$

*hep-ph/0001142: Ciafaloni, Ciafaloni, & Comelli; hep-ph/0103315: Ciafaloni

SUDAKOV LOGARITHMS

- Emission of soft or collinear radiation can lead to infrared divergences



- Accounting for extra emission enters multiplicatively as Sudakov double logarithm

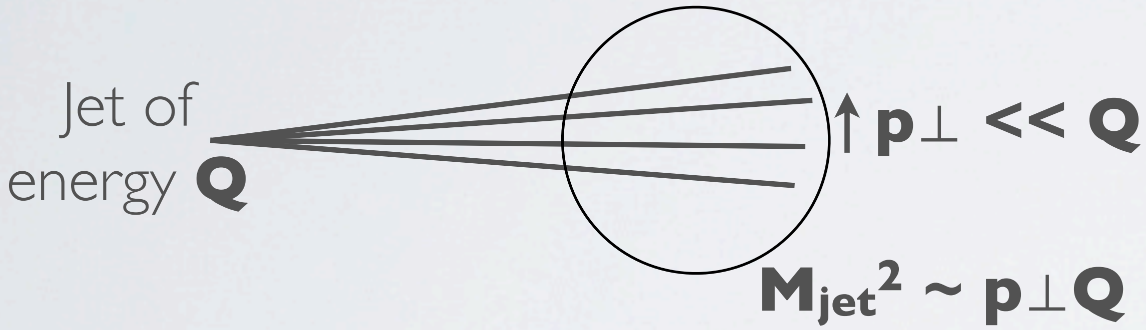
$$d\sigma(p \to p' + \gamma) = d\sigma(p \to p')\frac{\alpha}{\pi}\log\left(Q^2/\mu^2\right)\log\left(Q^2/m^2\right)$$

- For wino annihilation at the thermal mass (3 TeV), another **challenge for perturbation theory** $\frac{\alpha_W}{\pi}\log(M_{\text{wino}}^2/m_W^2)^2 \approx 0.6$

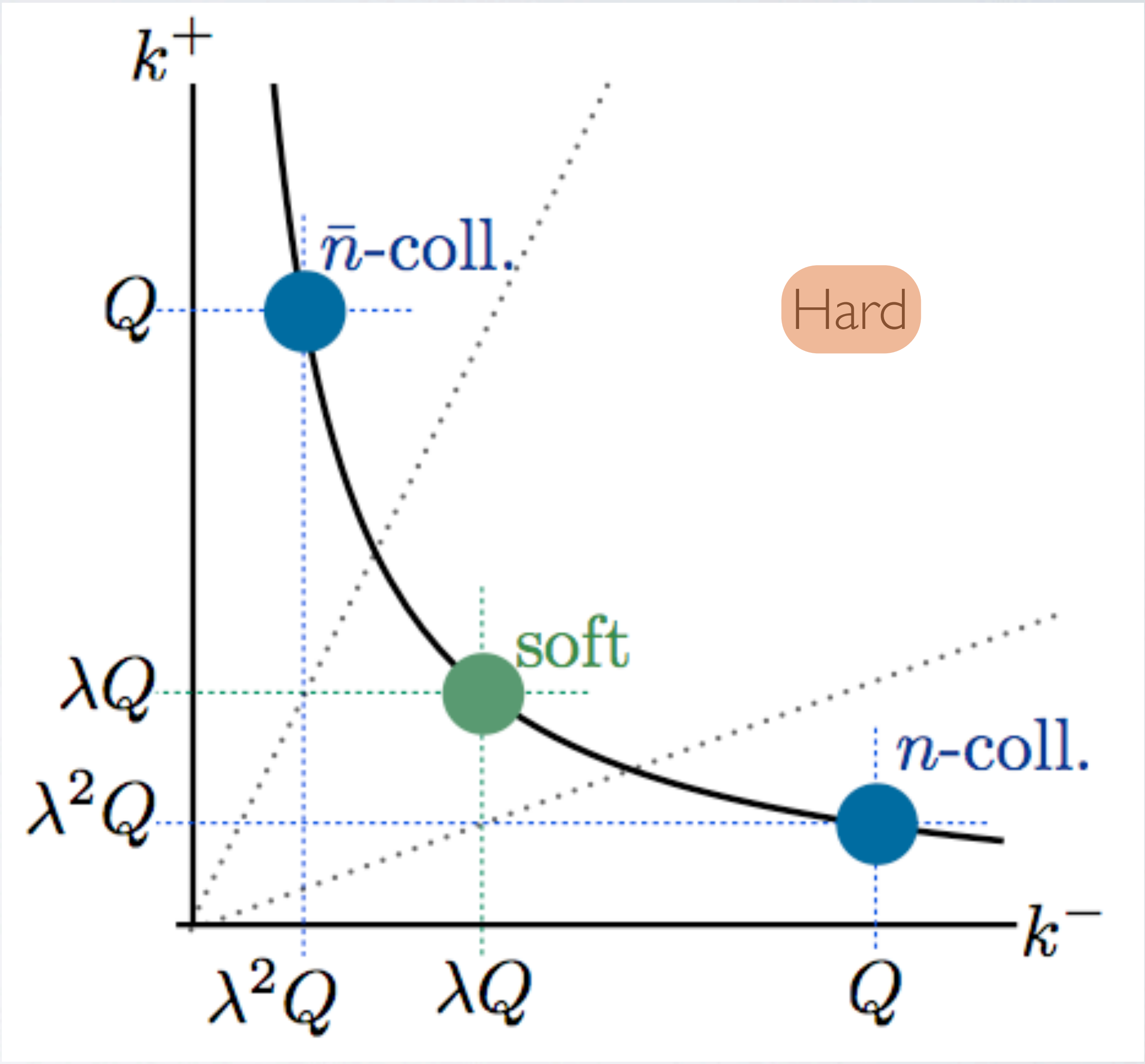
SOFT-COLLINEAR EFFECTIVE THEORY

Lightcone momenta
$k^+ = k^0 + k^3$
$k^- = k^0 - k^3$

- Large scale-hierarchies can arise within one field



- We can use Renormalization Group to resum kinematic logs

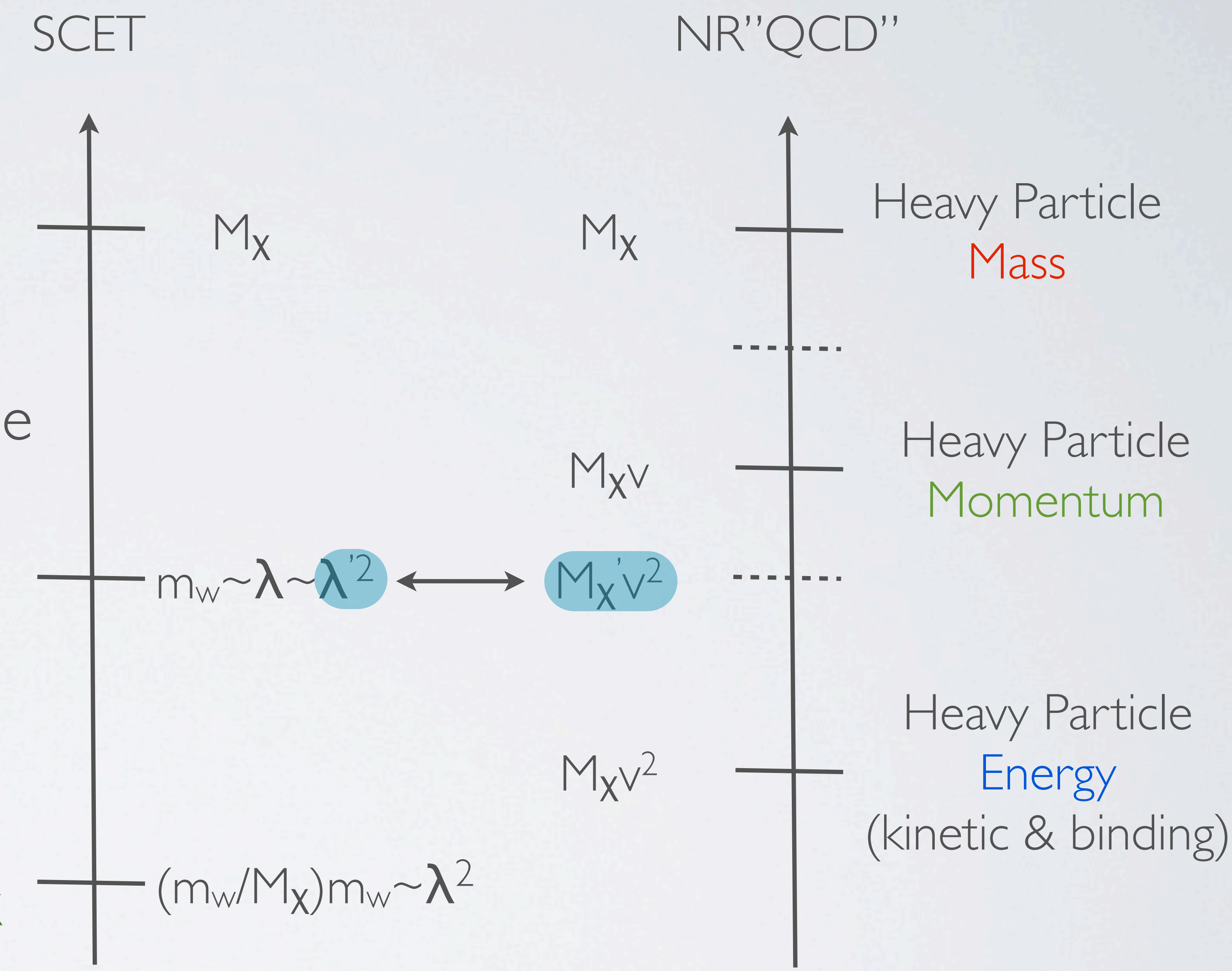


Integrate out hard gauge boson modes, but keep those collinear to null directions and soft fields

METHOD OF DESCENT

- Interactions in full theory couple SCET soft modes to WIMPs, collinear Ws, and NR ultrasofts
- Instead of matching directly, we raise M_χ to fictitious value, M_χ'
- On SCET side, we work in SCET-1 with $\lambda' = (m_W/M_\chi)^{1/2}$
- After field redefinition, we send M_χ back to its value of interest, and lower to SCET-2 with $\lambda = m_W/M_\chi$

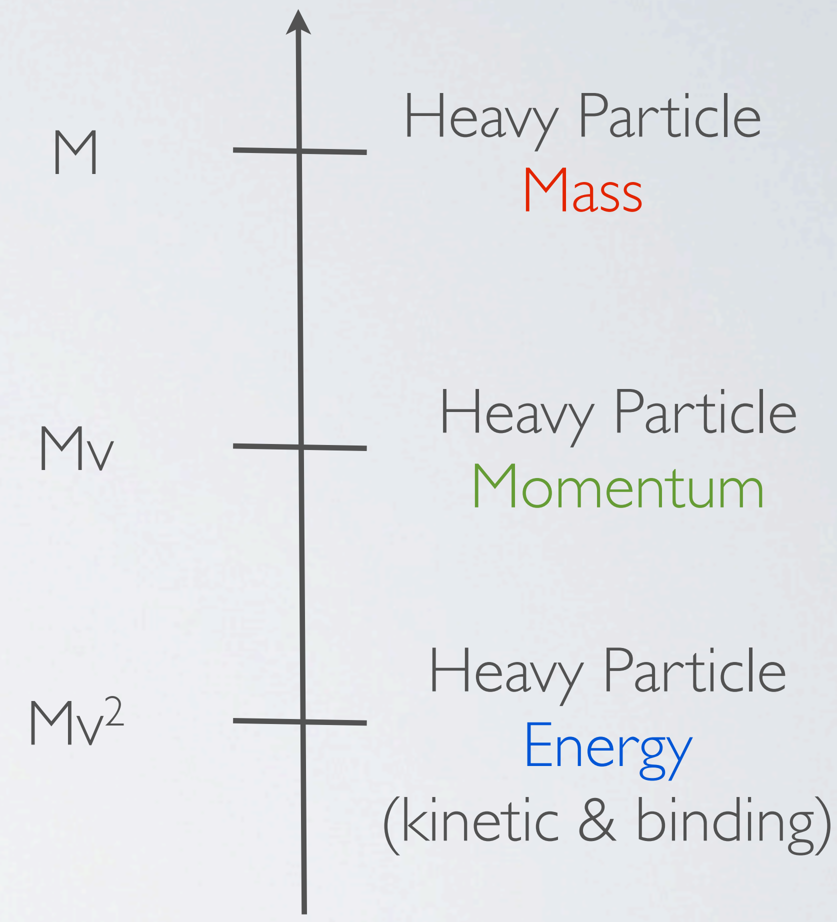
$$\chi \to S_v \chi$$
$$B \to S_n B$$



*Original development for SCET-1 to SCET-II matching hep-ph/0211069: Bauer, Pirjol, Stewart

NR"QCD" FOR WIMPS

- Nonrelativistic EFTs handle separation of scales in bound-state problems*
- Unsuppressed ladder-exchange of potential bosons ($E \sim Mv^2$, $p \sim Mv$) → Sommerfeld
- WIMPs heavy, but Renormalization Group resums soft-scale logs



Hierarchy of scales for nonrelativistic particles interacting with potential

*Classic treatment of NRQCD in Bodwin, Braaten, LePage hep-ph/9407339

RAPIDITY RG

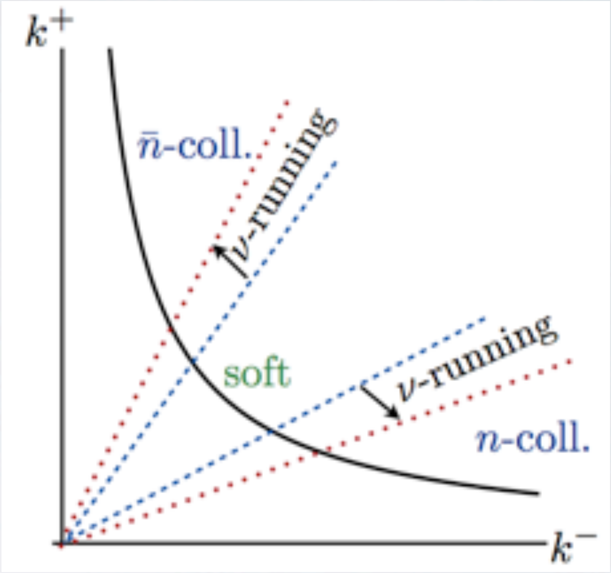
- SCET is a "modal" theory

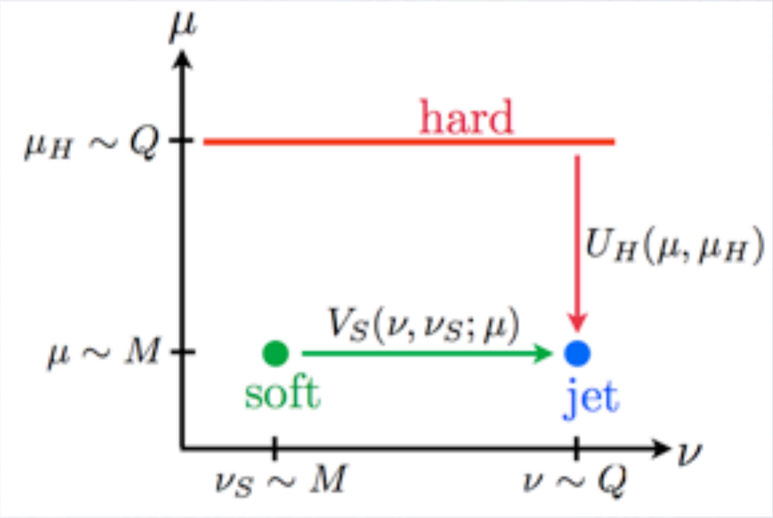
$$A_\mu = A_\mu^{c,n} + A_\mu^{c,\bar{n}} + A_\mu^{soft} + \ldots$$

- We can get divergences when integrals invade other sectors. Soft-collinear overlap requires boost-violating regulator

- Regulating sets up RG for resumming these rapidity logs

$$W_n = \sum_{\text{perms}} \exp\left[-\frac{g}{\bar{n}\cdot P}\frac{\nu^\eta}{|\bar{n}\cdot P|^\eta}\bar{n}\cdot A_n\right]$$





From Chiu et al. 1202.0814: In SCETII, soft and collinear modes have same virtuality
ν-running lets us minimize log between soft & collinear scales

WILSON LINES, GAUGE INVARIANCE, SOFTS

- SCET has rich gauge structure (separate for soft and collinear sectors) and collinear fields contain implicit collinear Wilson lines

$$B_\mu^{a\perp} \equiv f^{abc}\, W_n^T (D_\mu^\perp)^{bc}\, W_n$$

- We have soft Wilson lines for both WIMP and collinear fields

$$S_{(v,n)} = P[e^{ig\int_{-\infty}^{0}(v,n)\cdot A((v,n)\lambda)d\lambda}]$$

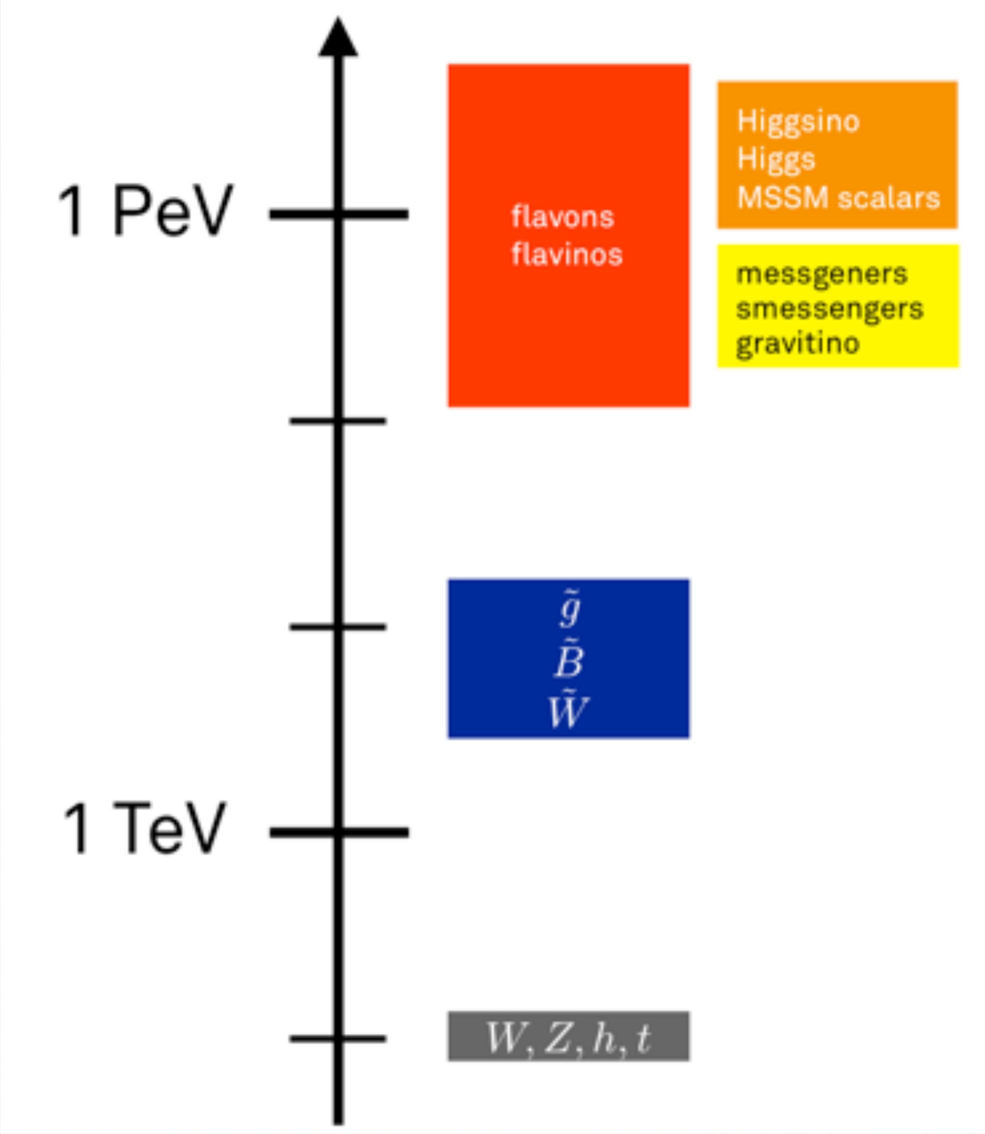
- Soft&Collinear-gauge-boson structure is therefore

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

$$O_c^a = B^\perp_{\tilde{A}} B^\perp_{\tilde{B}} \qquad O_c^b = B^\perp \cdot B^\perp \delta_{\tilde{A}\tilde{B}}$$

POST-HIGGS SUSY

- For all its virtues, SUSY is famously unobserved
- Higgs + nothing else means?
  - SUSY to eliminate most fine-tuning? 10^{-8} instead of 10^{-32}
  - Higgs mass (125 GeV > m_Z) and flavor physics point to sfermions at 100-1000 TeV
  - Simpler SUSY model building (Gravity +Anomaly mediation)
  - Gauginos (w/ wino LSP) at right scale for WIMP Miracle



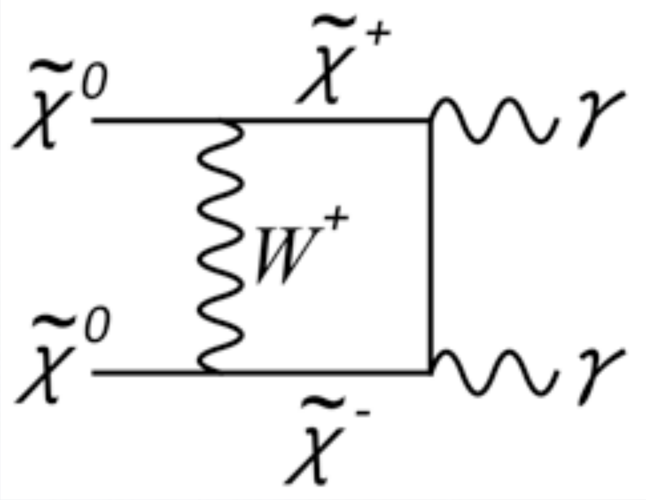
From 1403.6118: MB, Stolarski, and Zorawski
Mini-split SUSY allows a radiative generation of flavor hierarchies
and allows for thermal WIMP-DM

Mini-split SUSY: 1112.2462: Ibe & Yanagida, 1210.0555: Arvanitaki et al., 1210.2395: Hall, Nomura, & Shirai, 1212.6971: Arkani-Hamed et al.

Also see Altmannshofer et al. 1409.2522 for radiative flavor

CHARGED & NEUTRAL STATES

- Perturbative annihilation proceeds through either charged (tree) or neutral (one-loop) channels



$$\sigma_{\rm one-loop} v = \frac{4\pi\alpha^2\alpha_W^2}{m_W^2}$$

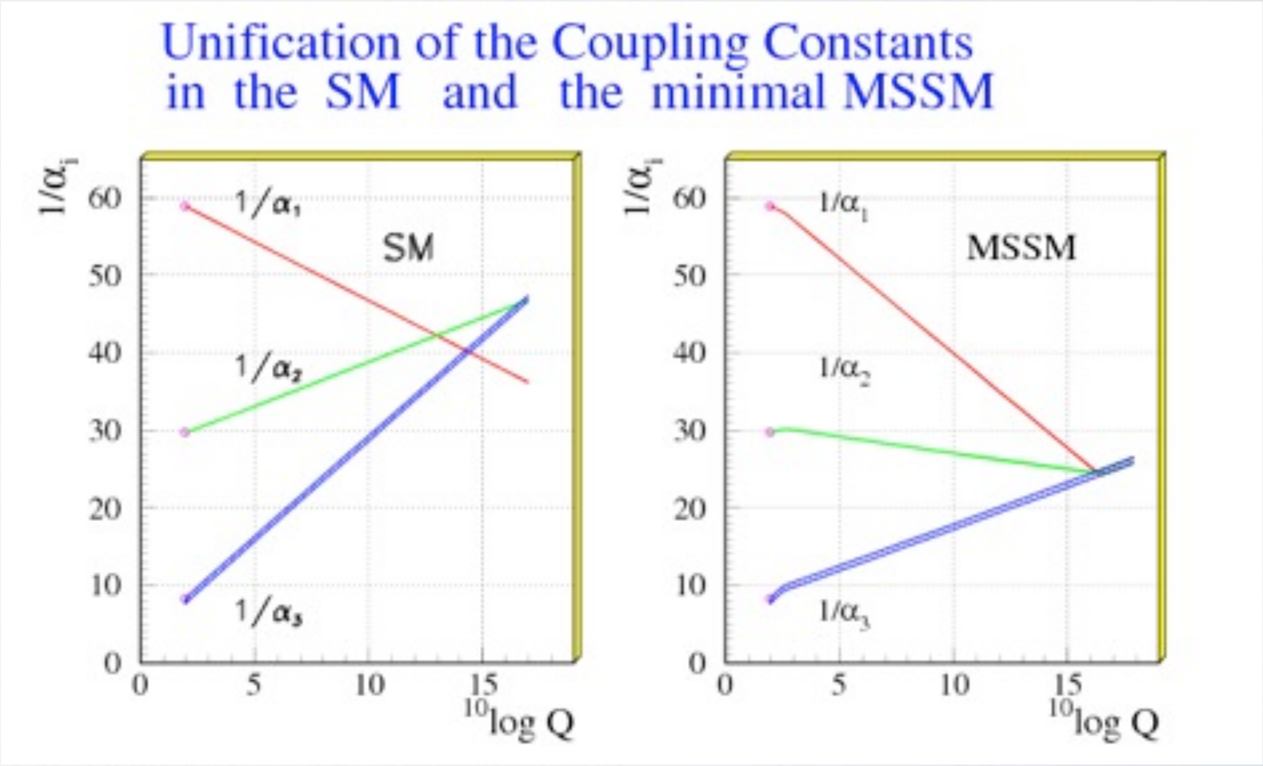
- For asymptotic neutral state (Dark Matter), we compute amplitude for charged or neutral state at origin

$$\begin{aligned}\psi_{00} &= \langle 0|\bar{\chi}^0\gamma^5\chi^0|\chi^0\chi^0\rangle_S \\ \psi_{\pm} &= \langle 0|\bar{\chi}^+\gamma^5\chi^+|\chi^0\chi^0\rangle_S\end{aligned}$$

SUPERSYMMETRY

- Supersymmetry: Unique extension of global spacetime symmetries of special relativity*
- Posits bosonic partner for all fermions with same quantum numbers (and vice versa)
- Discrete symmetry to protect proton (R-parity) provides a new stable particle (LSP)
- Connecting SUSY to weak scale thus gives natural WIMP dark matter

SUSY ties superpartner masses and weak scale in most of its parameter space



Strongest indirect evidence for weak-scale SUSY possibly the unification of gauge couplings

*Haag et al. NPB 88(1975): 257-74

EFFECTIVE FIELD THEORY

- Stuck with large log, we must resum $\alpha \log^2$ to $\mathrm{Exp}[C\, \alpha \log^2]$

- Essential tool of the modern, phenomenological field theorist

- Systematically decouple high-energy degrees of freedom to answer low-energy questions as in Wilsonian-RG

$$Z[\phi]_{\Lambda-\Delta\Lambda} = \int_{k\in(\Lambda-\Delta\Lambda,\Lambda)} \mathcal{D}\phi \, \exp[iS(\phi)]$$

- Match amplitudes as expansion in $1/M_X^2$, α

  Resum logs $\log(M_X/m_t)$ by running in EFT

Schematic for simple EFT, where X,Y integrated out to generate new interactions for SM fields