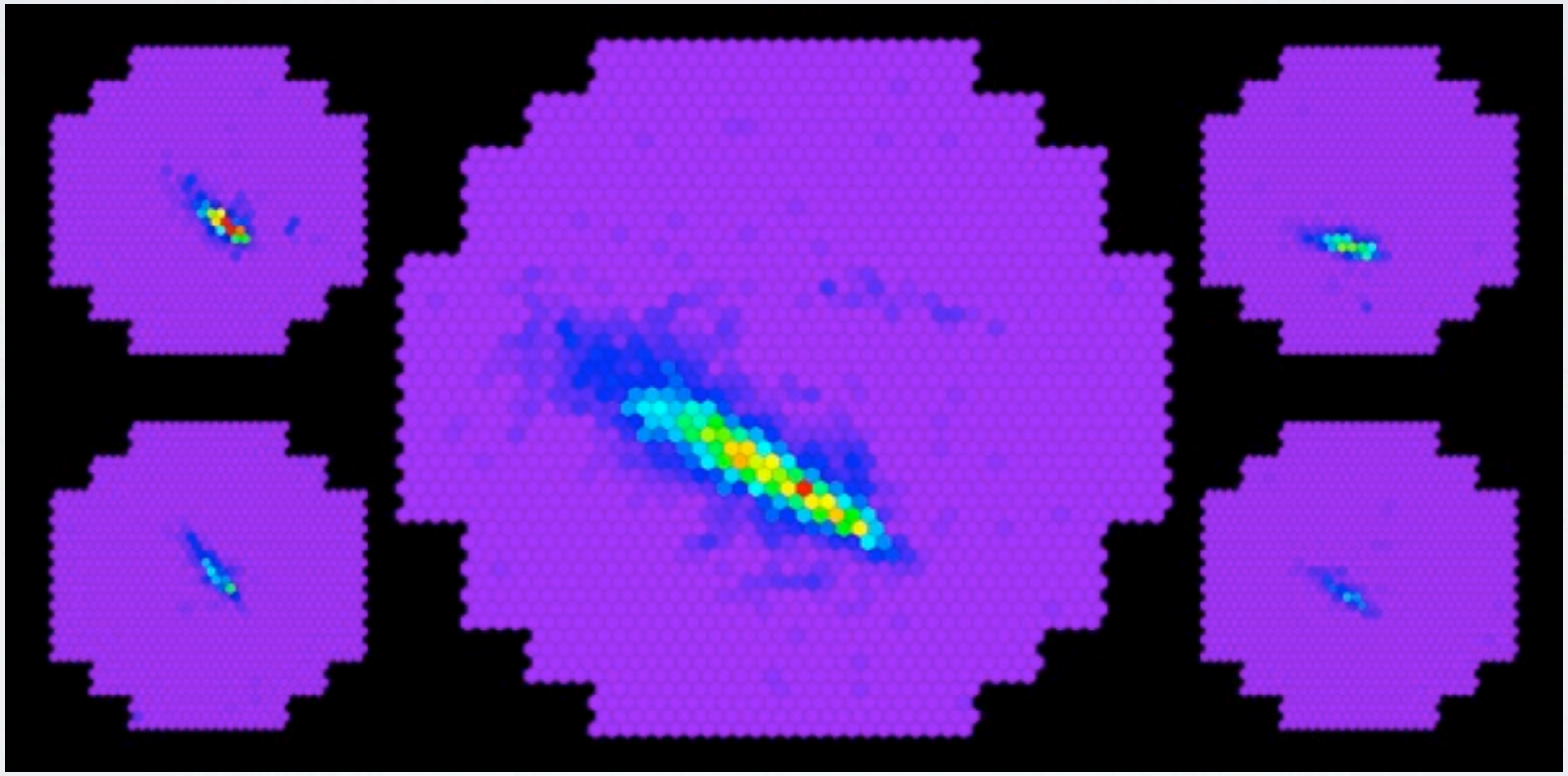
ON THE ANNIHILATION OF WIMPS

Matthew Baumgart (Carnegie Mellon U.)



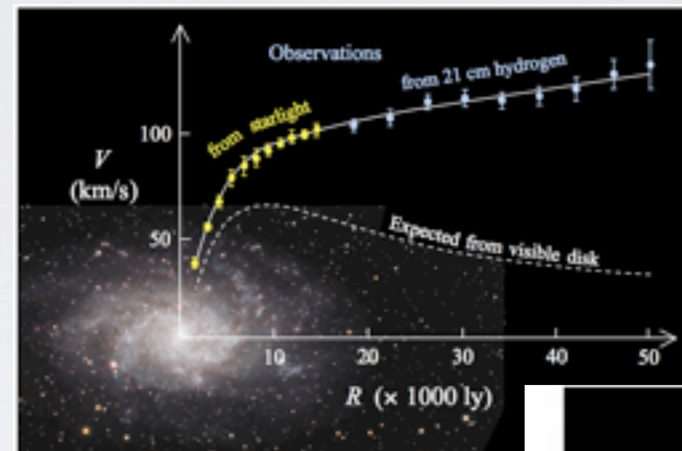
University of Massachusetts Amherst

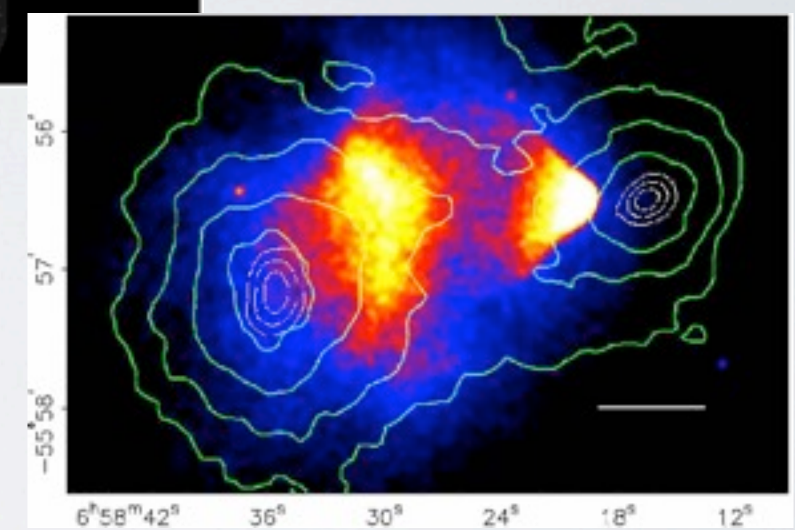
1/30/2015

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

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

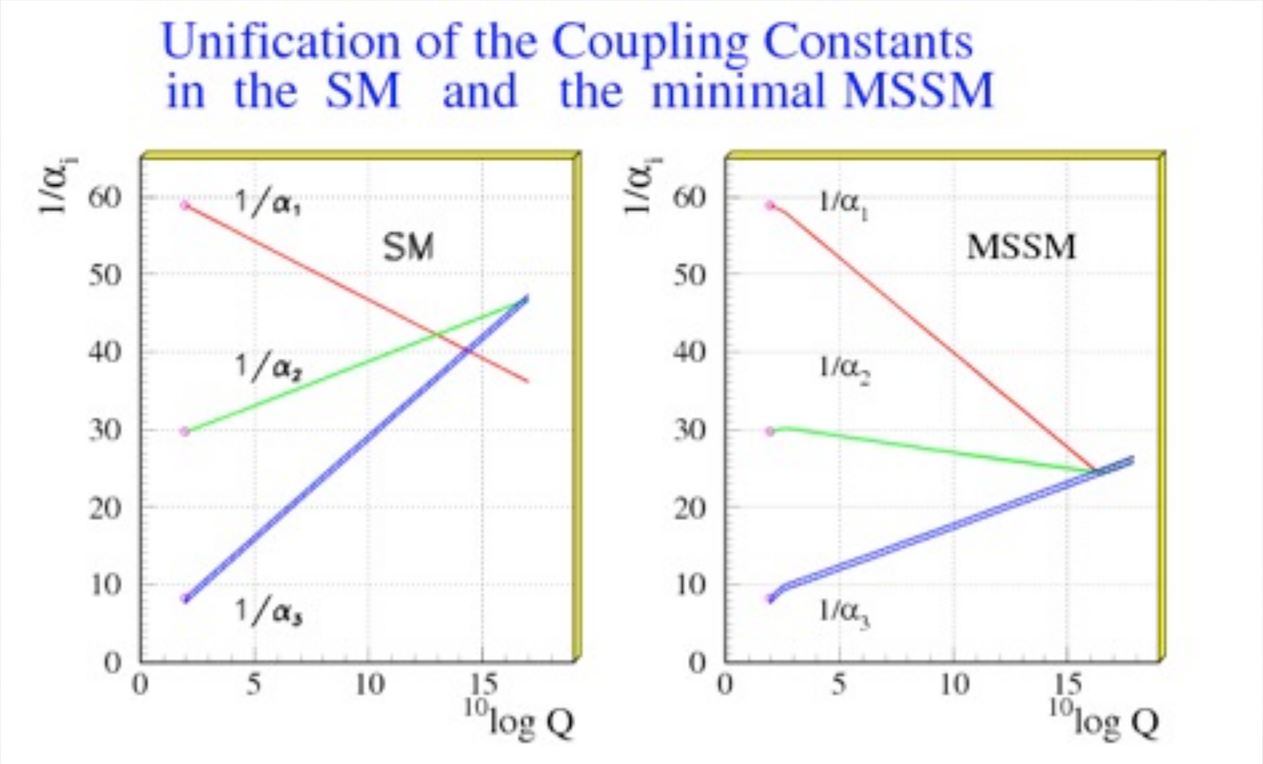
See Dimopoulos PLB 246(1990):347-52

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

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

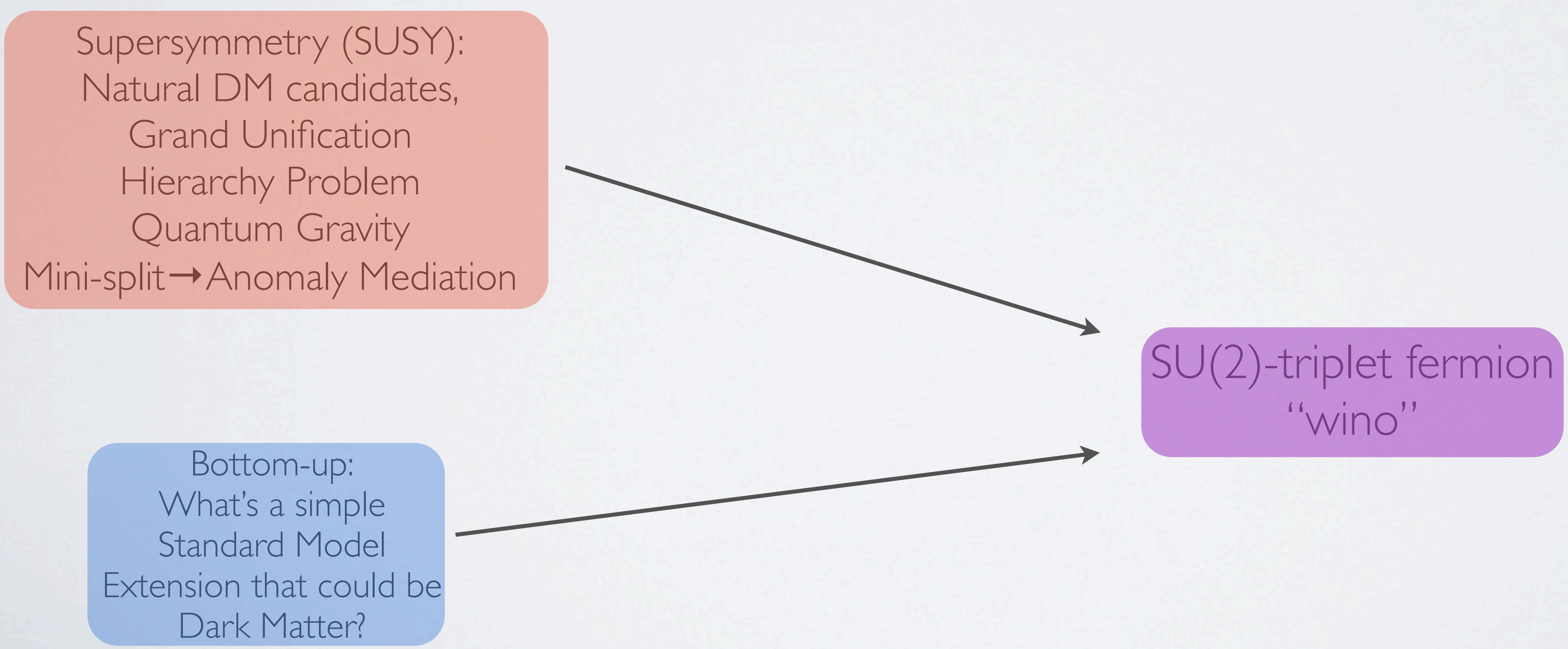
SUSY ties superpartner masses and weak scale in most of its parameter space



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

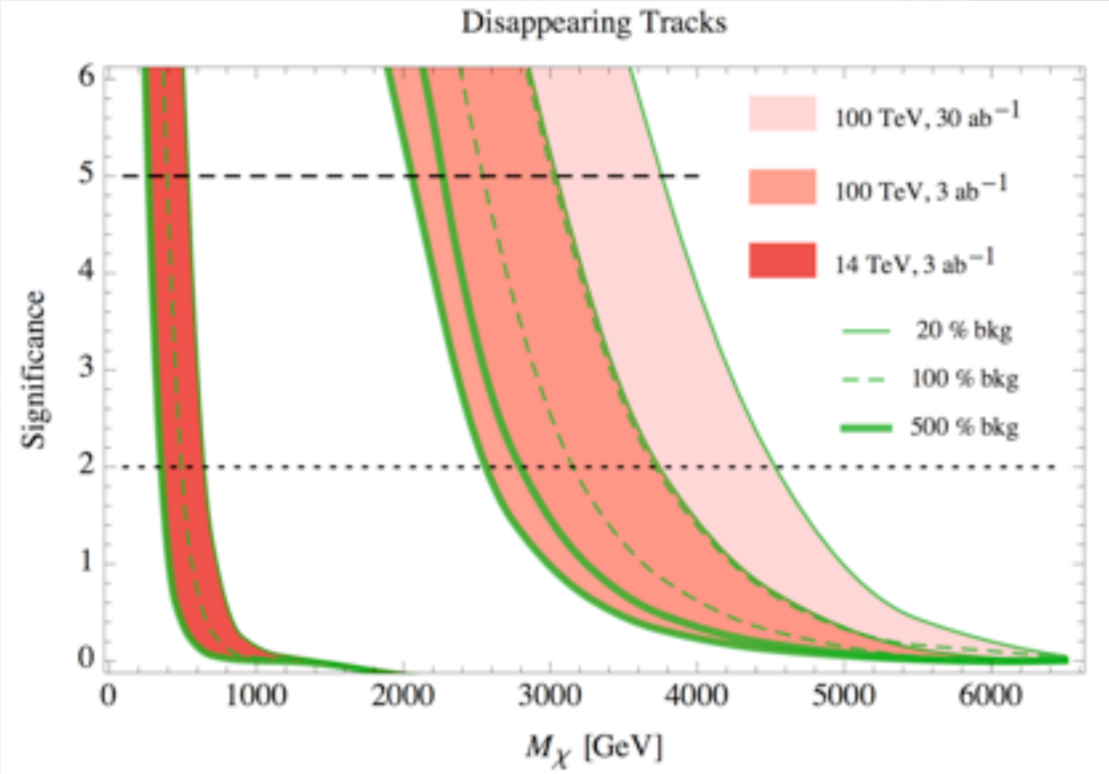
FROM WIMP TO WINO

- 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?

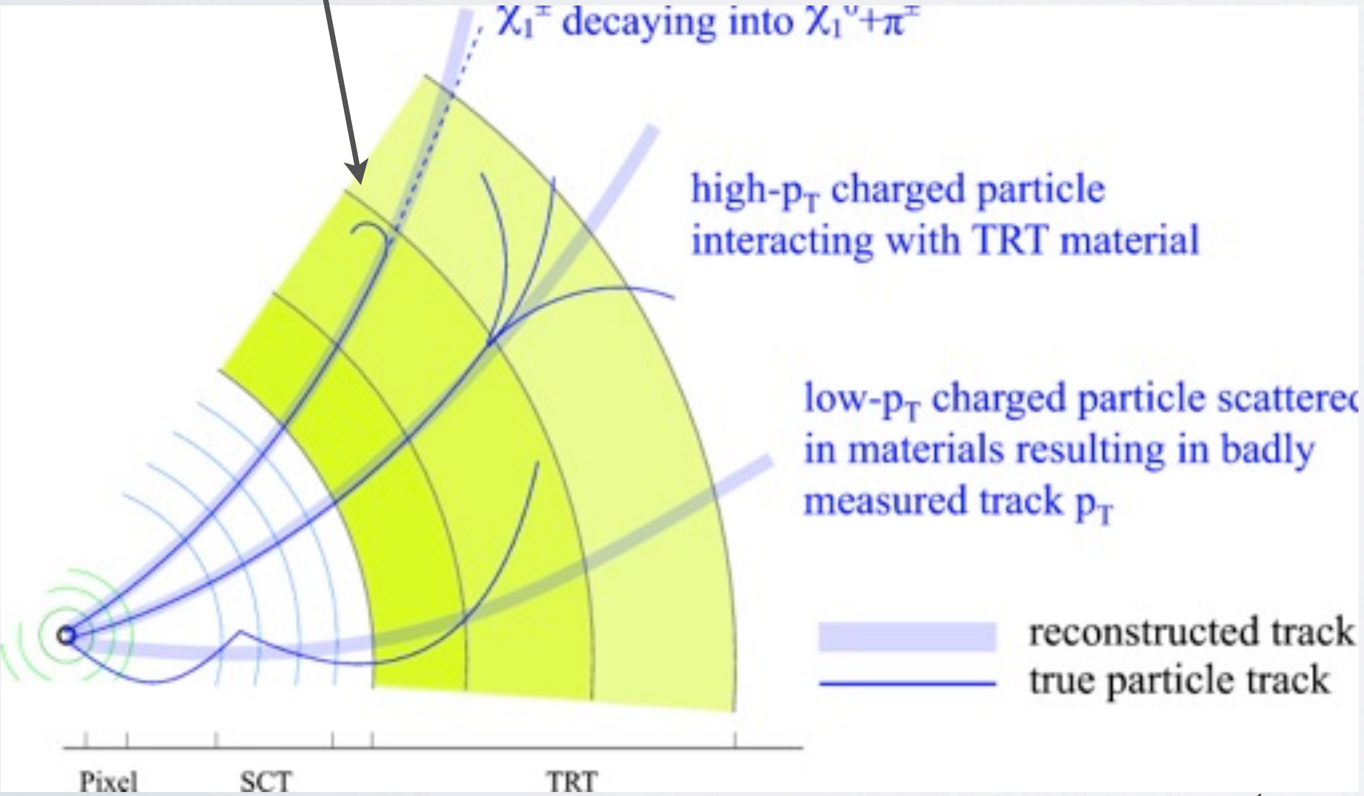


TO FIND A TEV WINO

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



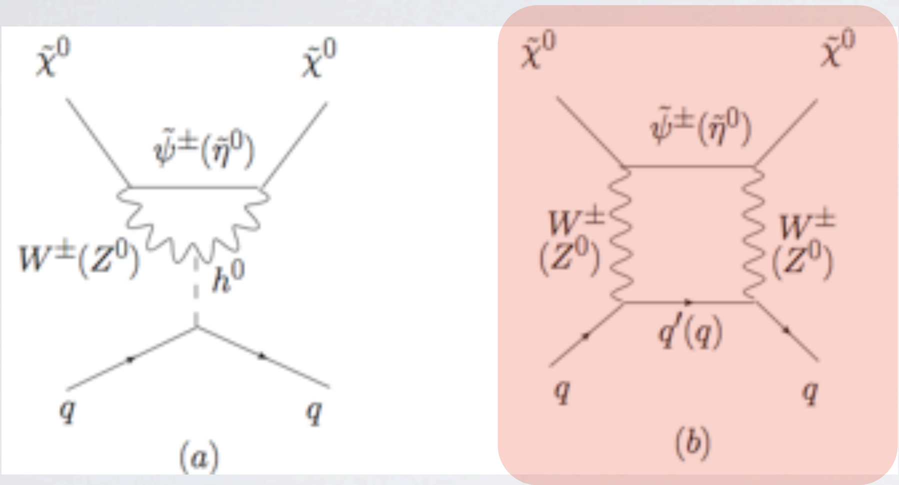
From Cirelli et al. 1407.7058



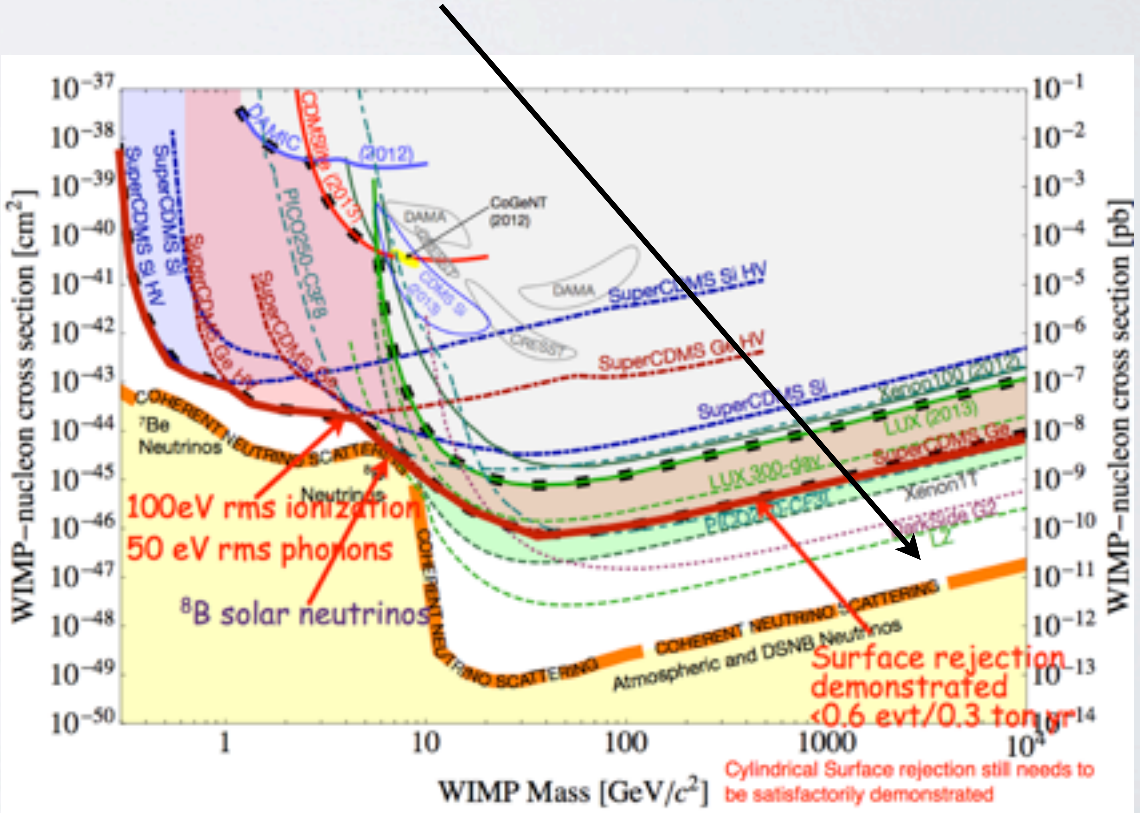
1202.4847 (ATLAS)

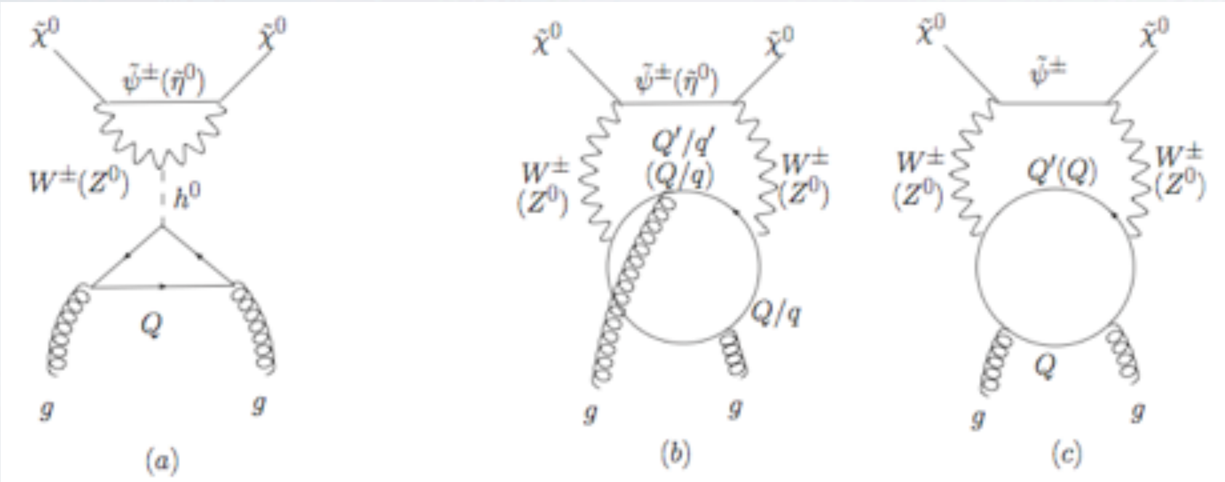
TO FIND A TEV WINO

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



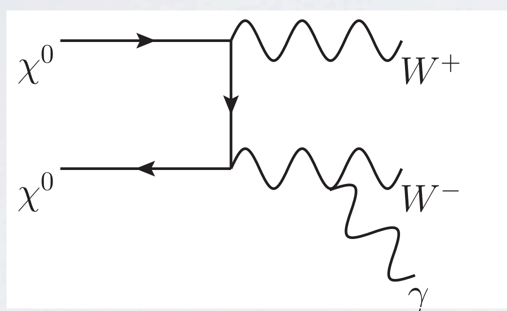


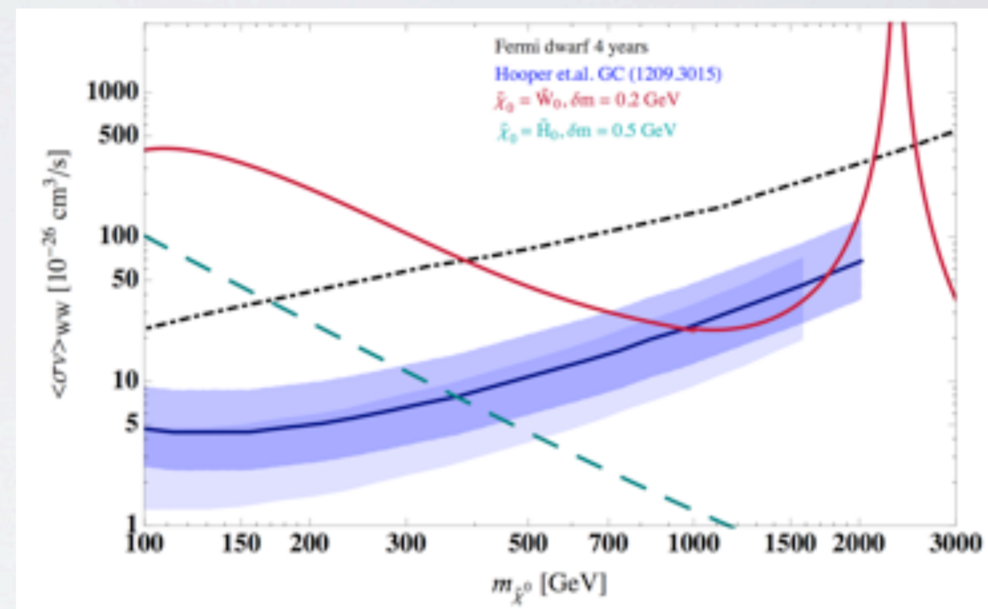
* Hisano et al. 1104.0228

From Rick Gaitskell (LUX) talk via Resonaances

INDIRECT DETECTION

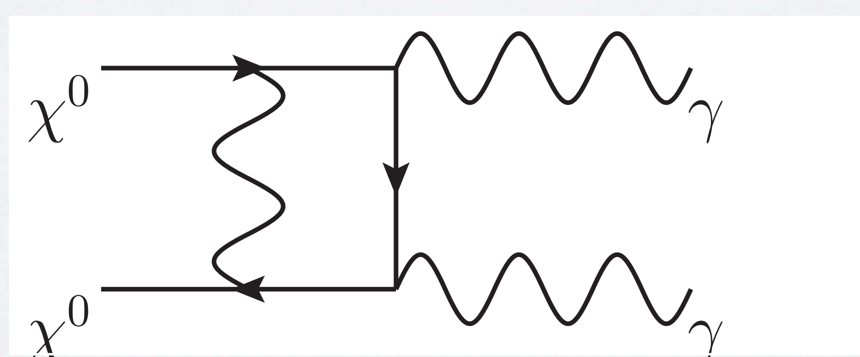
- Continuum ($\chi\chi \to W^+W^- \to$ photons) useful for sub-TeV limits (Fermi)





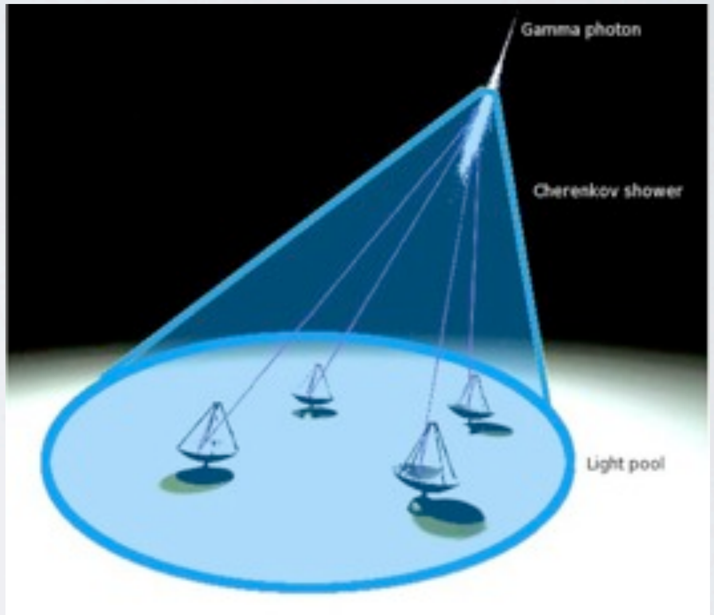
J. Fan & M. Reece: 1307.4400

- Line ($\chi\chi \to \gamma + X$) extends to multi-TeV range



HESS

- High Energy Steroscopic System (HESS)
- Atmospheric Cherenkov telescope
- Constrains photon lines. Our main interest...



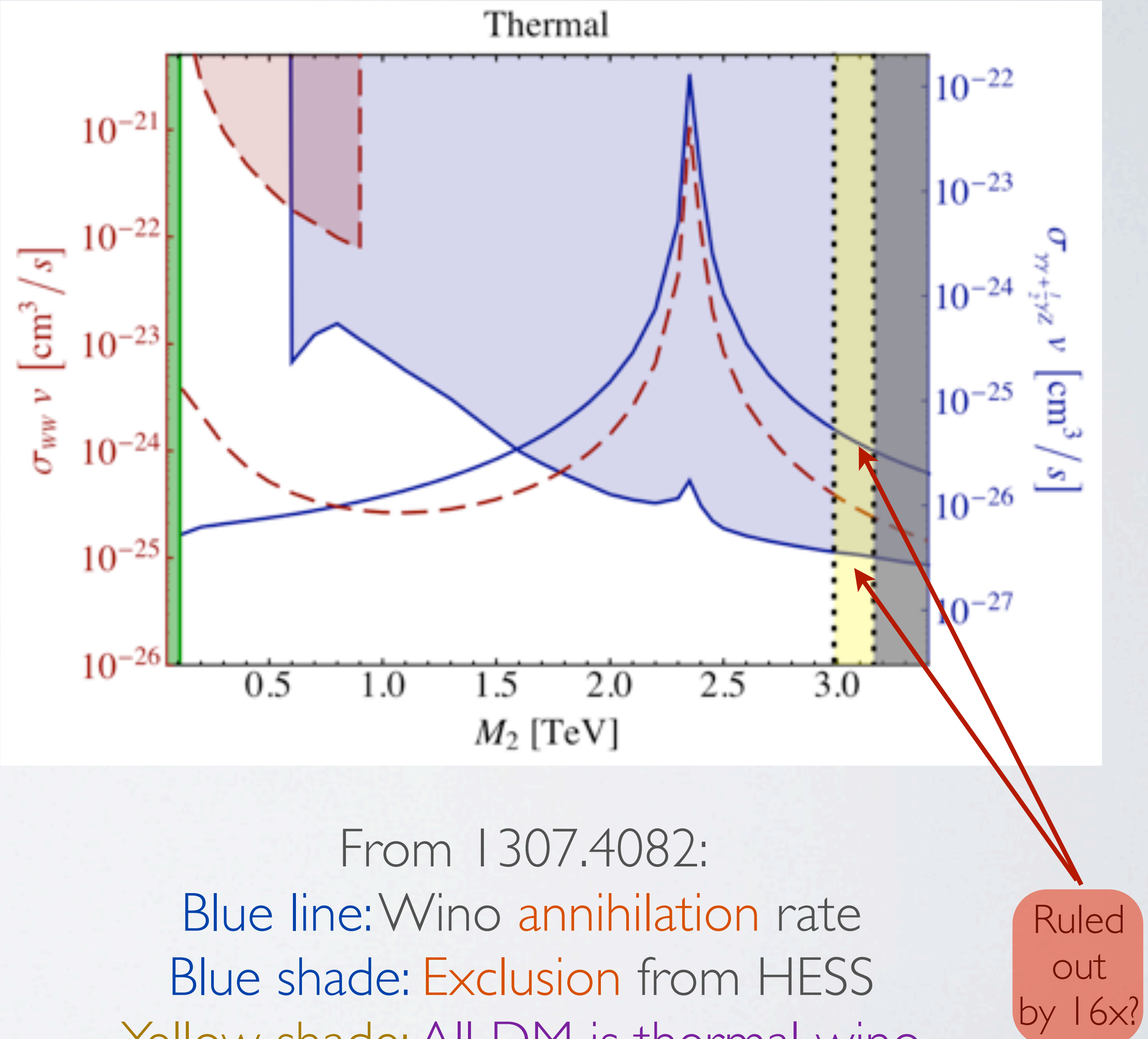
O(TeV) γ leads to $O(10^4 m)$ light pool on ground

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

HESS in Namibia

"WINO DARK MATTER UNDER SIEGE"*

- Annihilation of neutral wino, χ, through gauge interactions to SM states (e.g. χχ→γγ) gives M≈3 TeV
- Has our beautiful, simple model been shot dead by HESS?
- Navarro-Frank-White (cusped) halo profile assumed



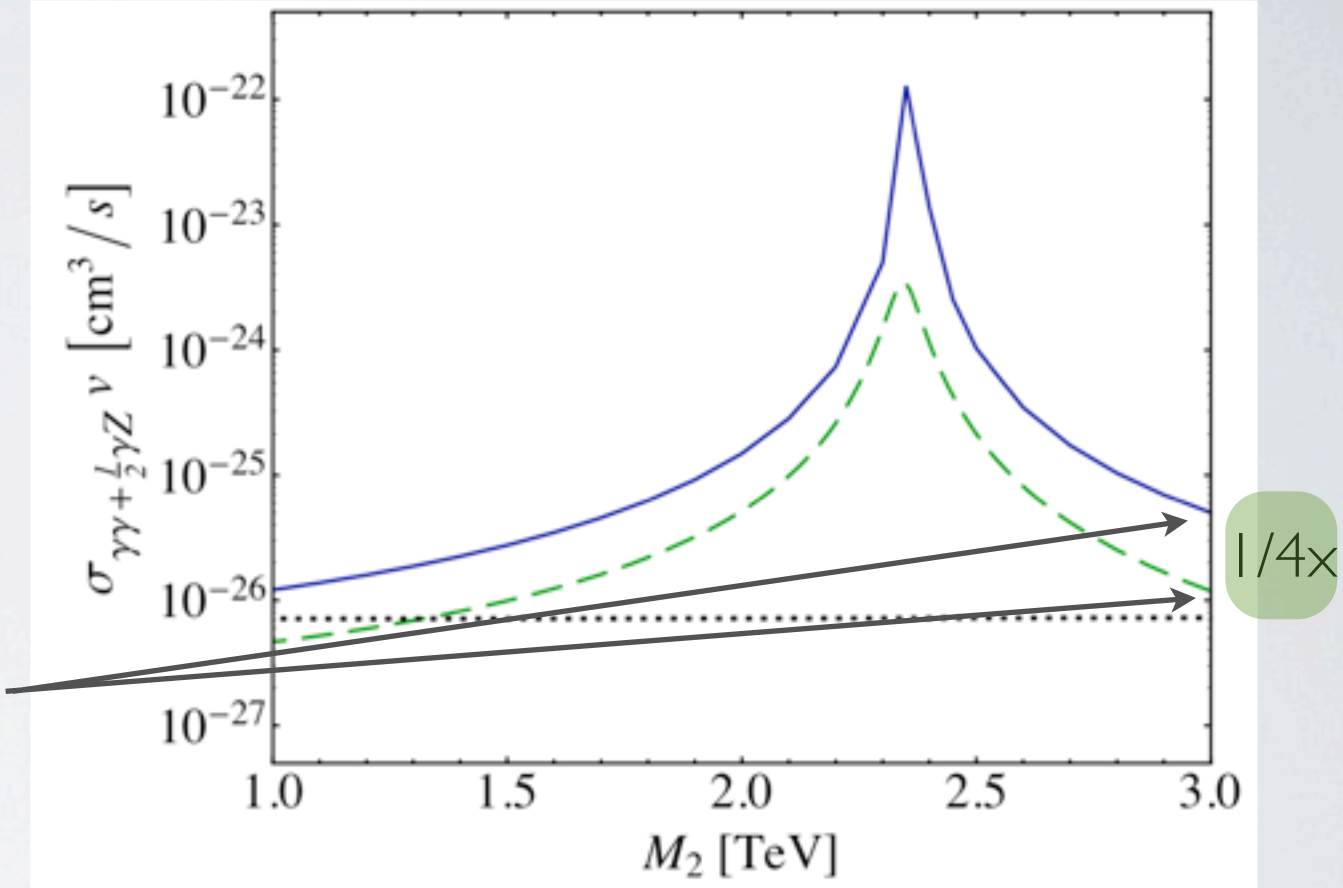
From 1307.4082:
Blue line: Wino annihilation rate
Blue shade: Exclusion from HESS
Yellow shade: All DM is thermal wino

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

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

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.

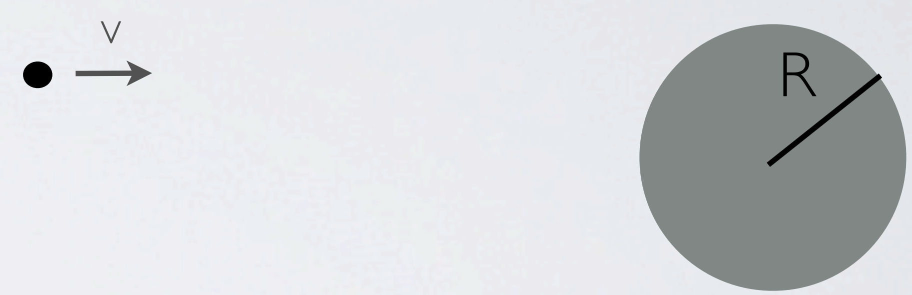
  - **Sudakov double-logarithms**: Large in electroweak physics, even in inclusive observables. Can't trust fixed order. We must resum logs.

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

SOMMERFELD ENHANCEMENT

- Slowly-moving objects in a potential can have much larger cross section than perturbative treatment suggests
- Quantum-Mechanically, short-distance annihilation rate modified by wavefunction-at-origin in presence of potential:

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



In absence of gravitation, capture radius is geometric, R

Turning on gravity, cross section grows for slower projectile:

$$b_{\mathrm{capture}} = R\sqrt{1 + \frac{2GM}{v^2 R}}$$

SOMMERFELD & FIELD THEORY

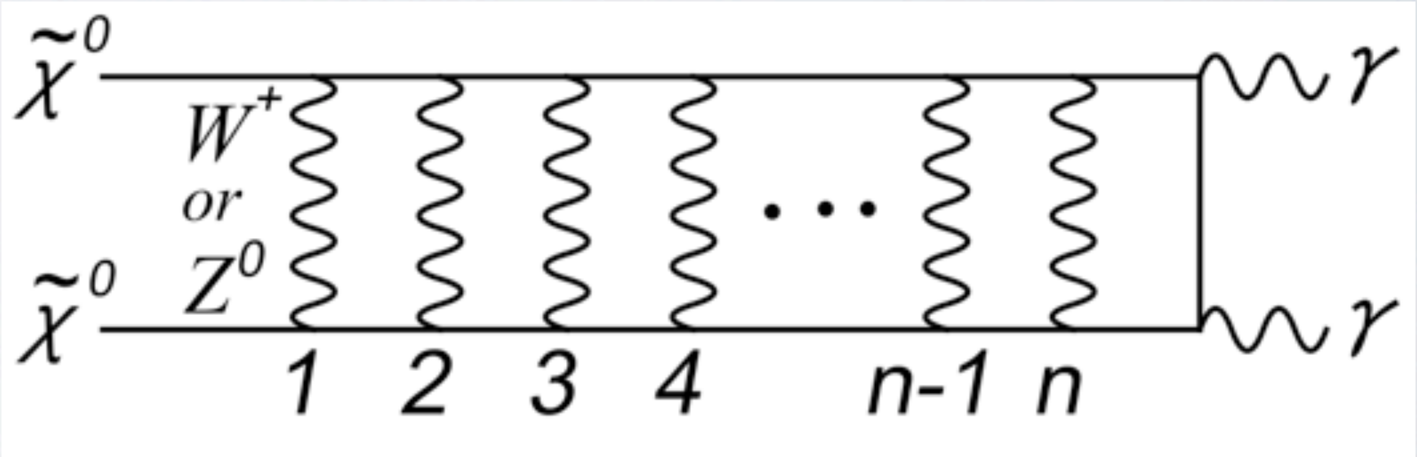
Crossing lines leads to O(v) suppression compared to ladder

- In nonrelativistic regime, summing infinite ladder exchange equivalent to solving Schrodinger equation for appropriate potential

- W-exchanges flip between $\chi^0\chi^0$ and $\chi^+\chi^-$ states

- Ladder exchanges unsuppressed

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



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)

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

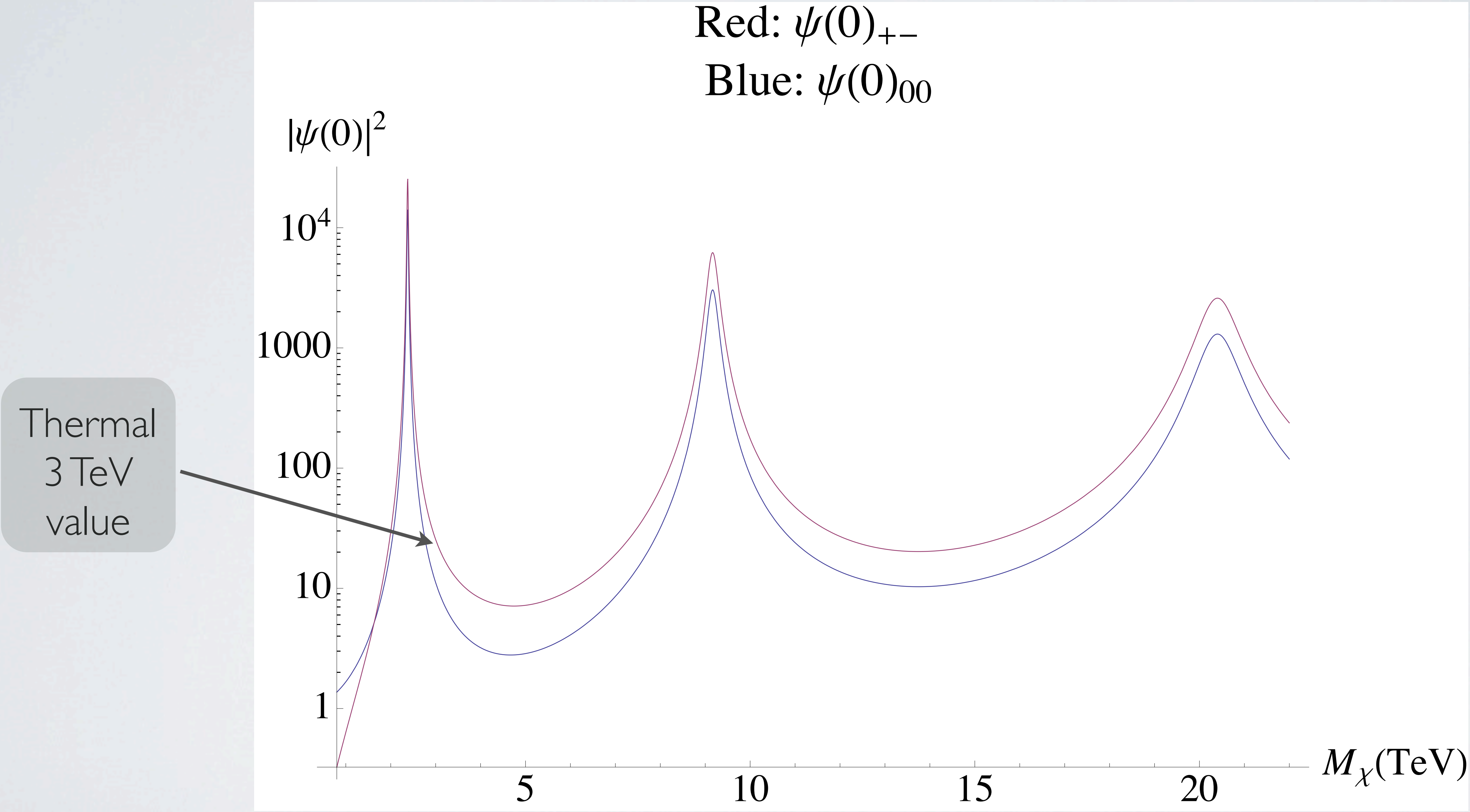
Mass splitting means +- state decays exponentially

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

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

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

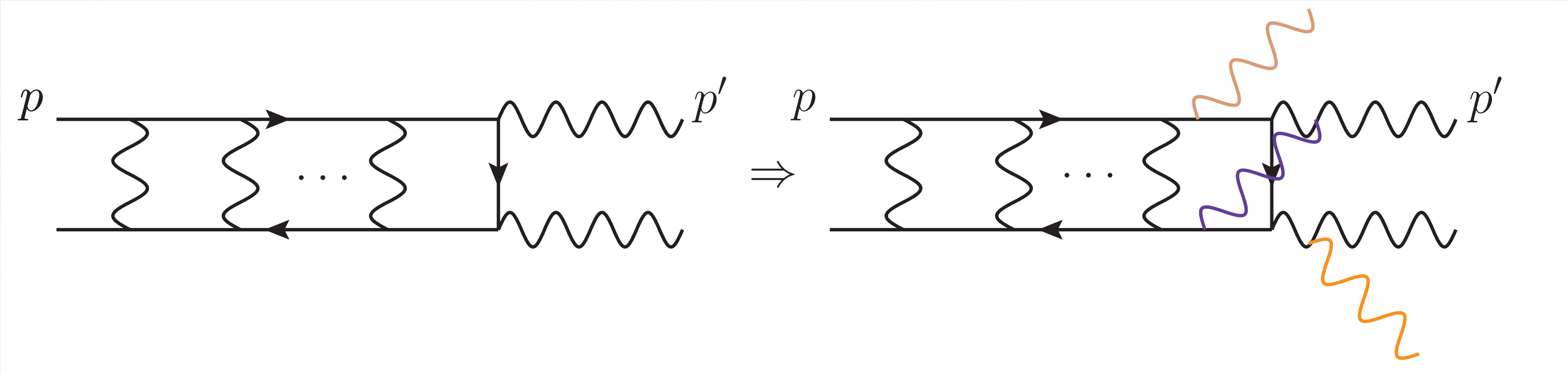
WINO SOMMERFELD FACTORS



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

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** $\frac{\alpha_W}{\pi}\log(M^2_{\rm wino}/m^2_W)^2 \approx 0.6$

EFFECTIVE FIELD THEORY

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

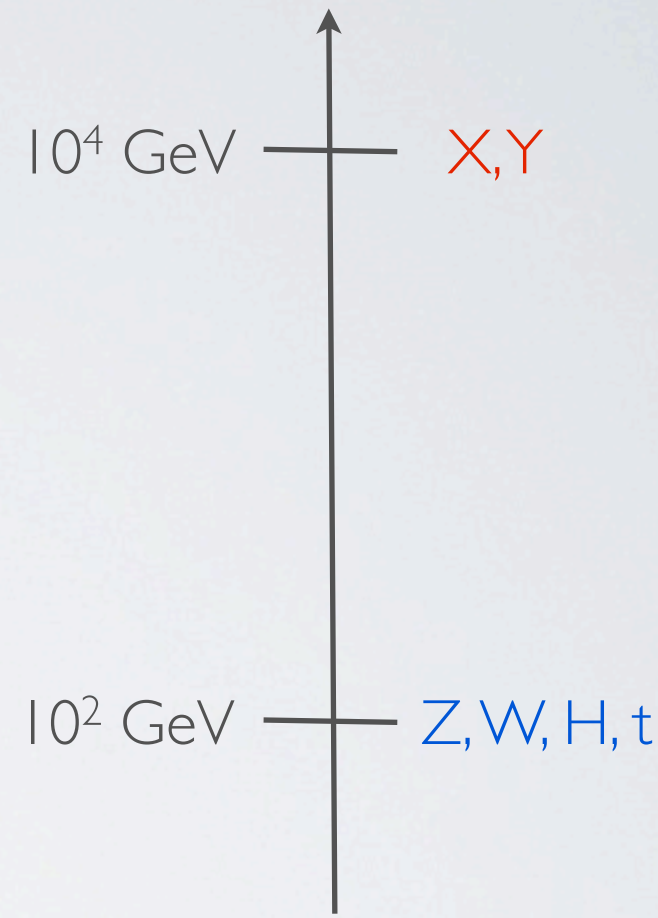
- Essential tool of the modern, phenomenological field theorist

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

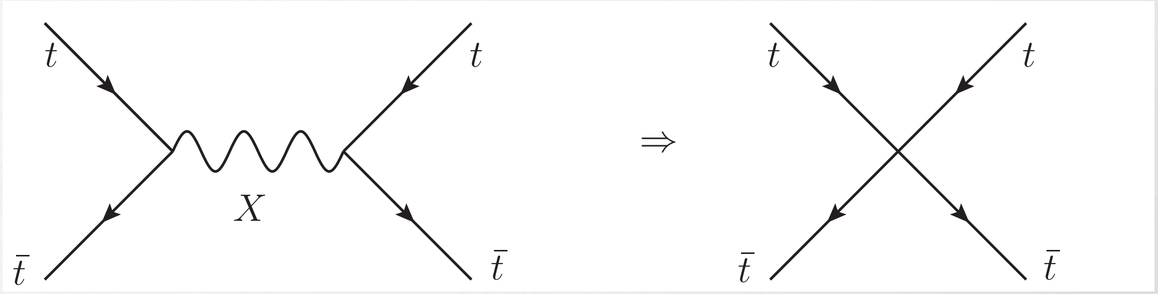
$$Z[\phi]_{\Lambda-\Delta\Lambda} = \int_{k\in(\Lambda-\Delta\Lambda,\Lambda)} \mathcal{D}\phi \exp[iS(\phi)]$$

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

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



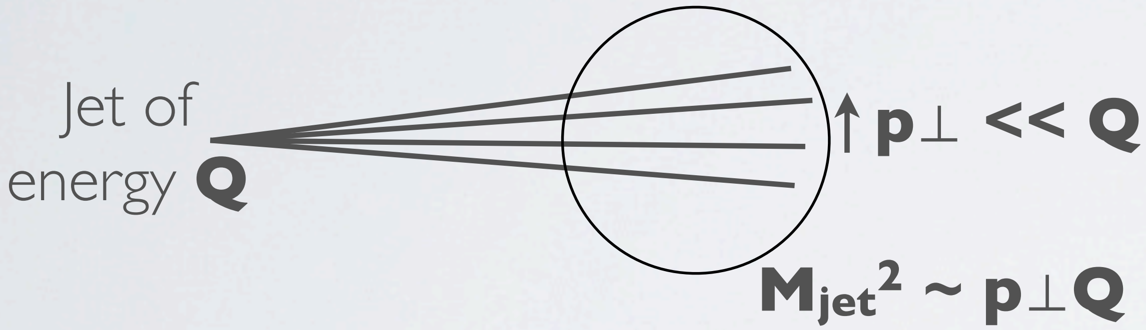
Schematic for simple EFT, where X,Y integrated out to generate new interactions for SM fields



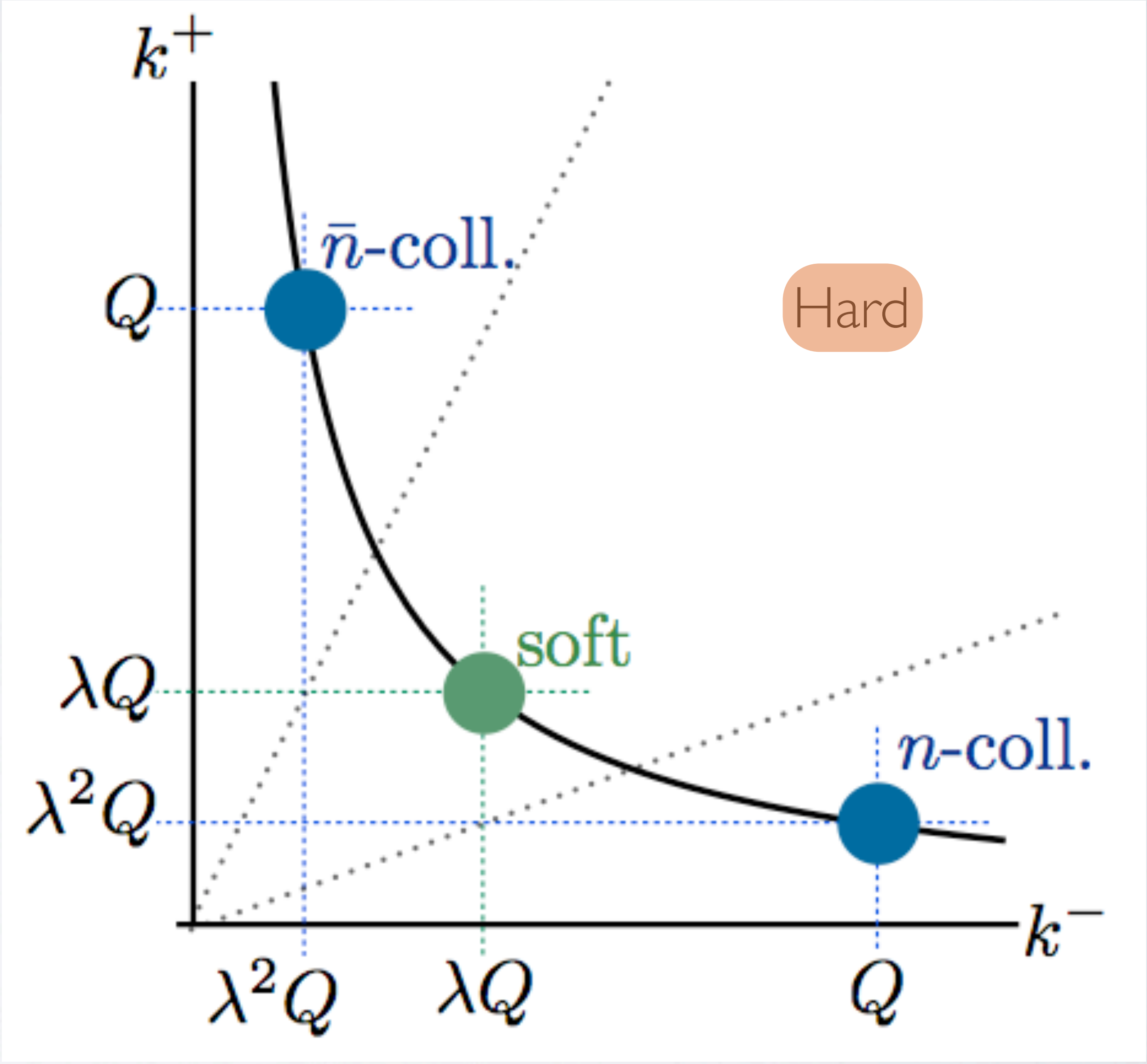
SOFT-COLLINEAR EFFECTIVE THEORY

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

- Large scale-hierarchies can arise within one field



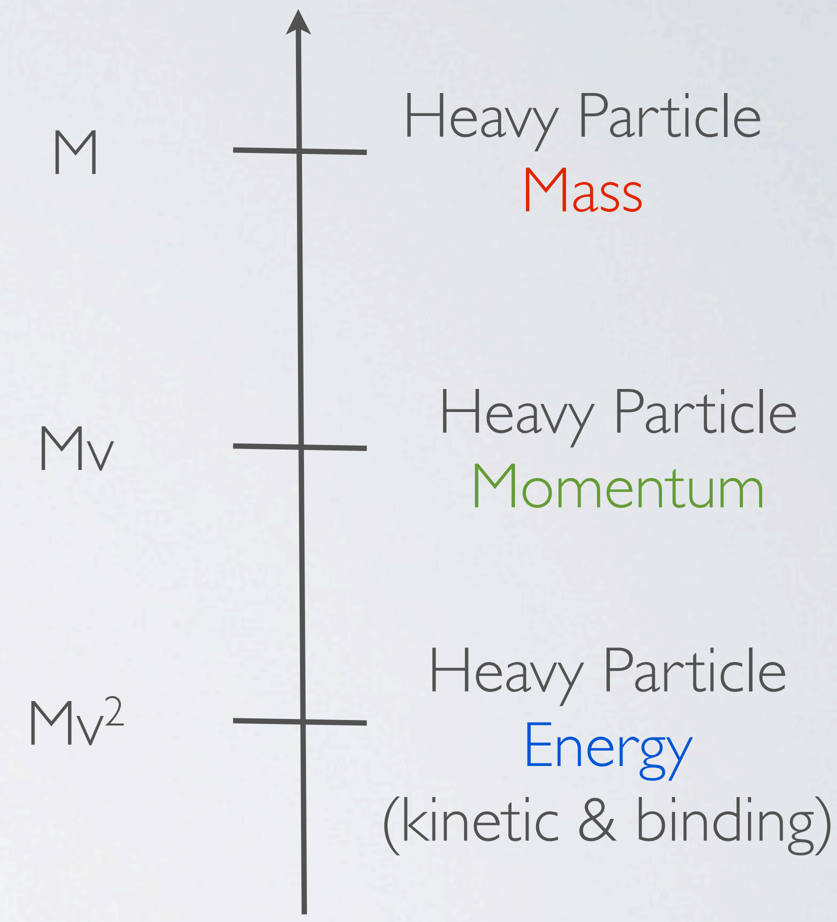
- We can use Renormalization Group to resum kinematic logs



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

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

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 theory*
- Setting up EFT requires list of relevant modes

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

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

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

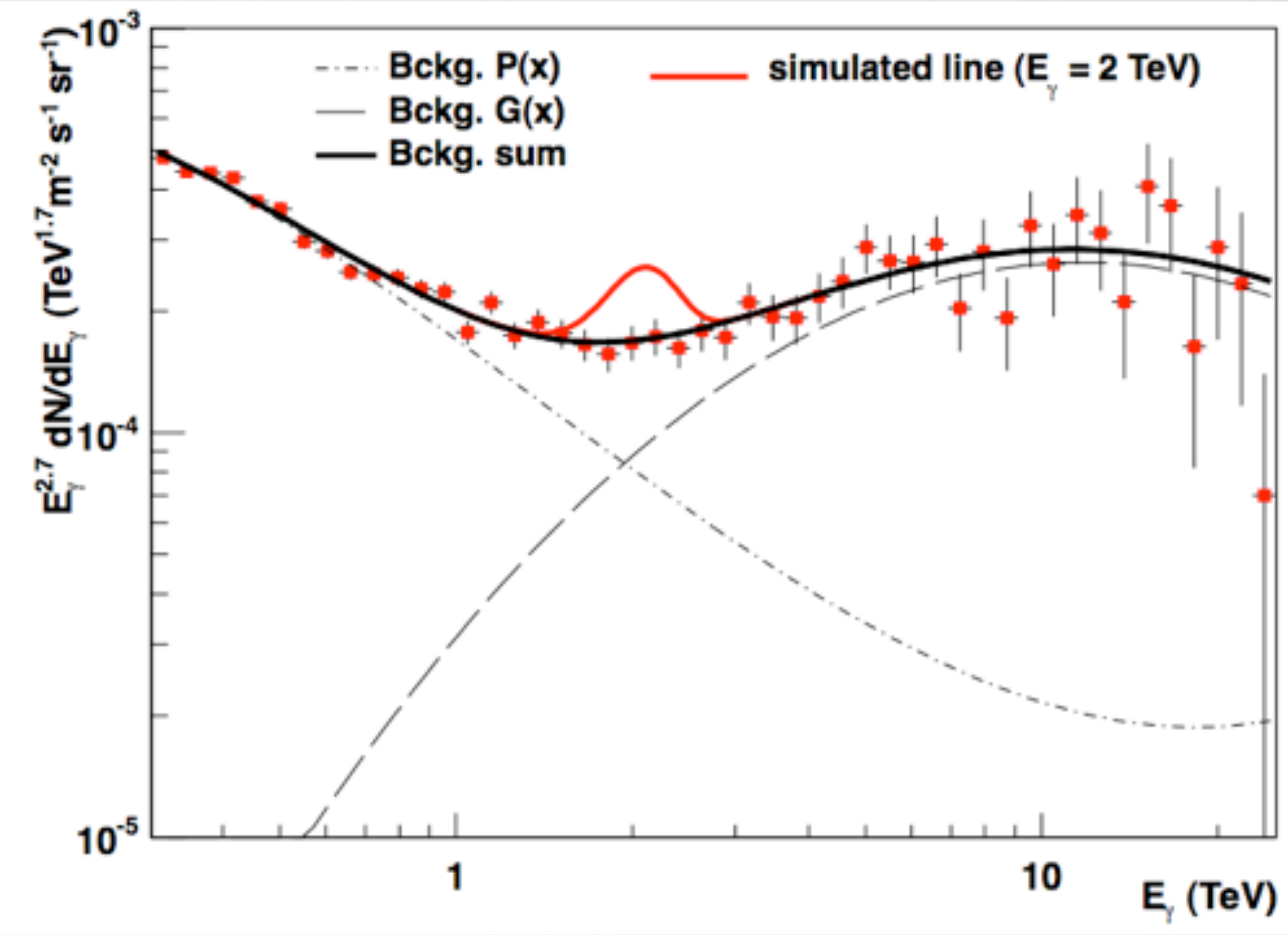
$$\text{Soft}\,(S_{ab}) : (k_+ \sim \lambda,\, k_- \sim \lambda,\, k_\perp \sim \lambda)$$

These are all just W field in full theory

*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 $\chi\chi \rightarrow \gamma + X$



From HESS collaboration 1301.1173

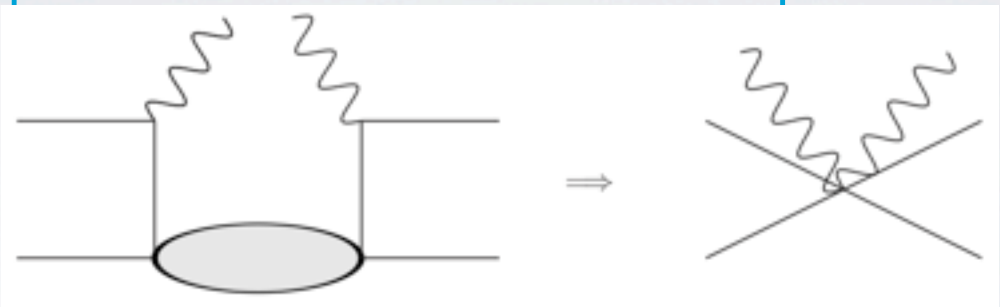
at 3 TeV, energy resolution is ~400 GeV

E_γ (soft W) $= M_\chi - m_W/2$

E_γ (collinear Ws) $= M_\chi - m_W^2/M_\chi$

OPERATOR BASIS

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



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

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

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

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

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

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 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)

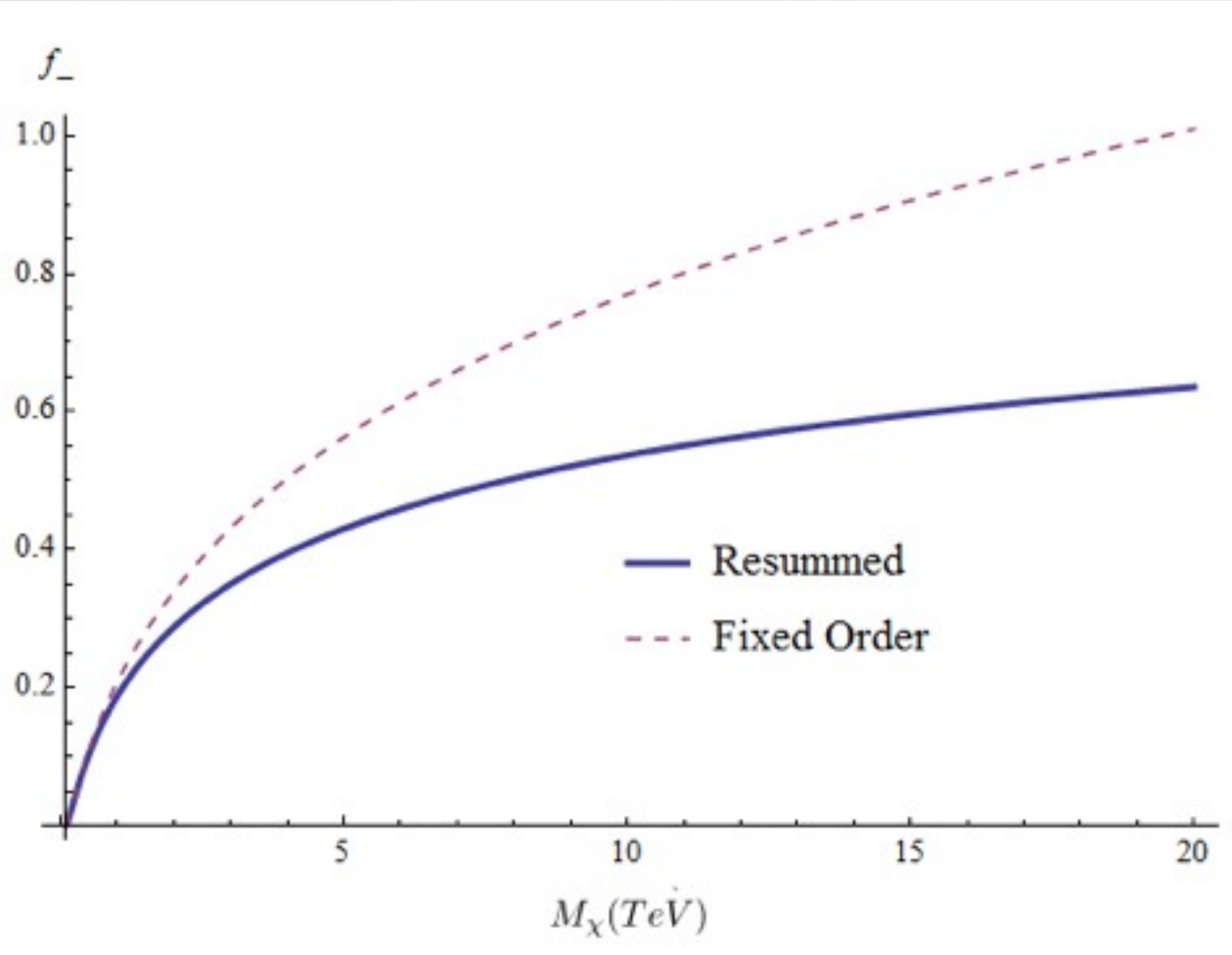
TOTAL RATE

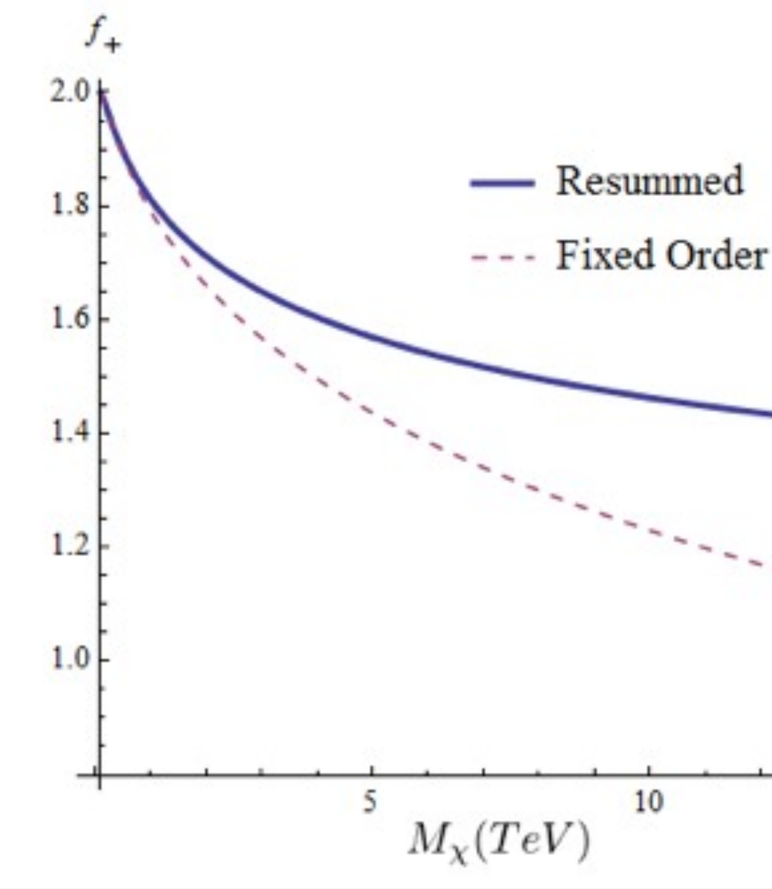
$$\frac{1}{E_\gamma}\frac{d\sigma}{dE_\gamma} = \frac{C_1(\mu = E_\gamma)}{4M_\chi^2\, v}\delta(E_\gamma - M_\chi)\left[\frac{2}{3}f_- \,|\psi_{00}(0)|^2 + 2f_+\,|\psi_{+-}(0)|^2 + \frac{2}{3}f_-(\psi_{00}\psi_{+-} + \mathrm{h.c.})\right]$$

- 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





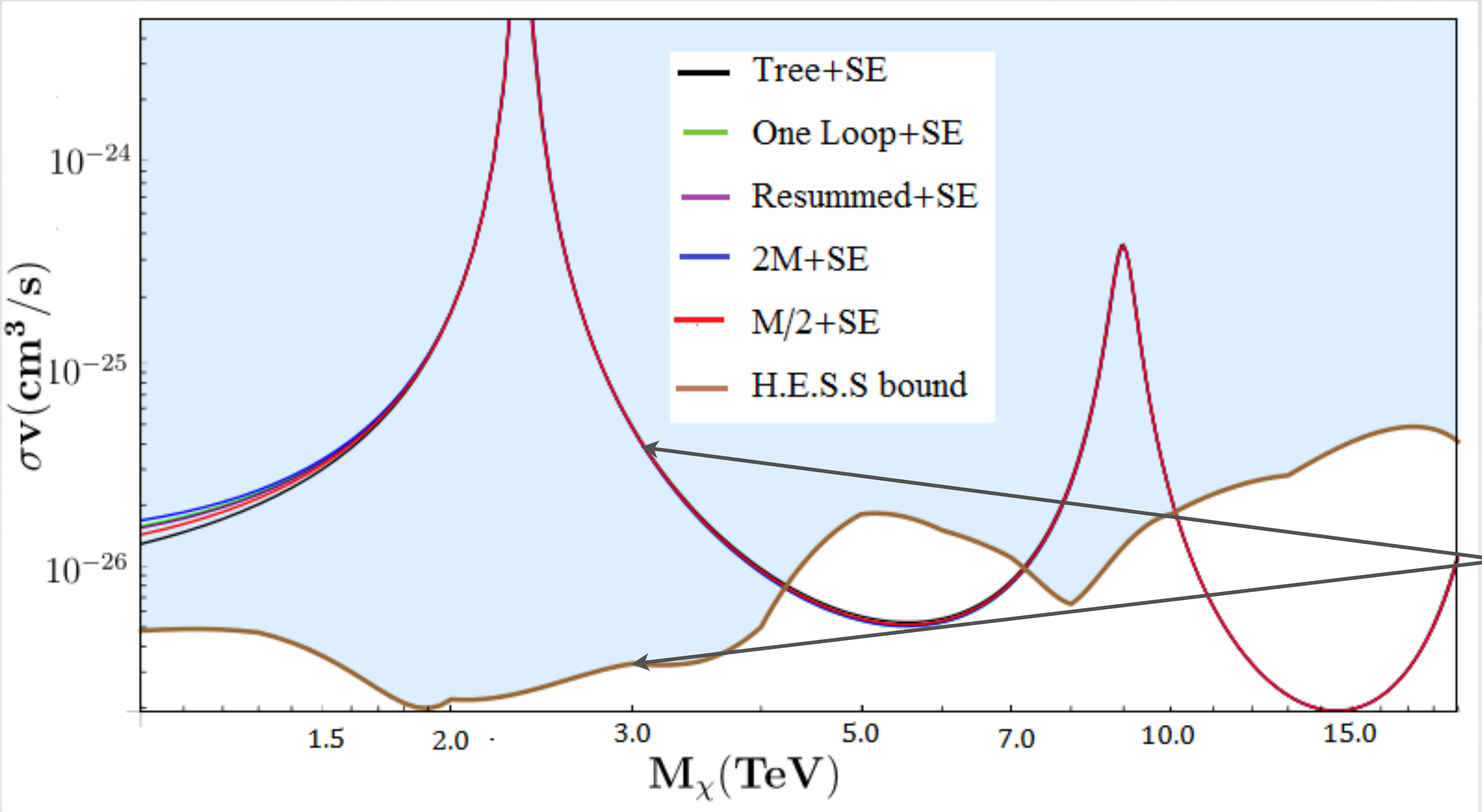
f^+ term generally larger, allowing quick estimate of higher orders

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

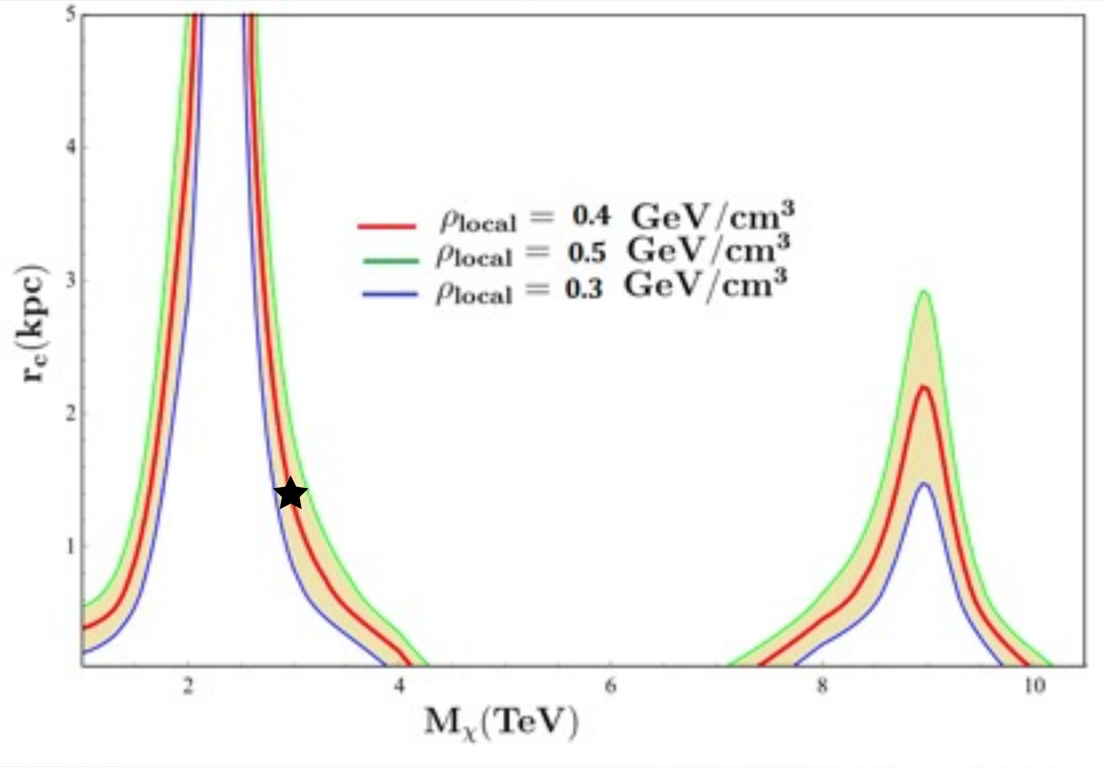


Wino escape at higher orders foiled by more accurate calculation

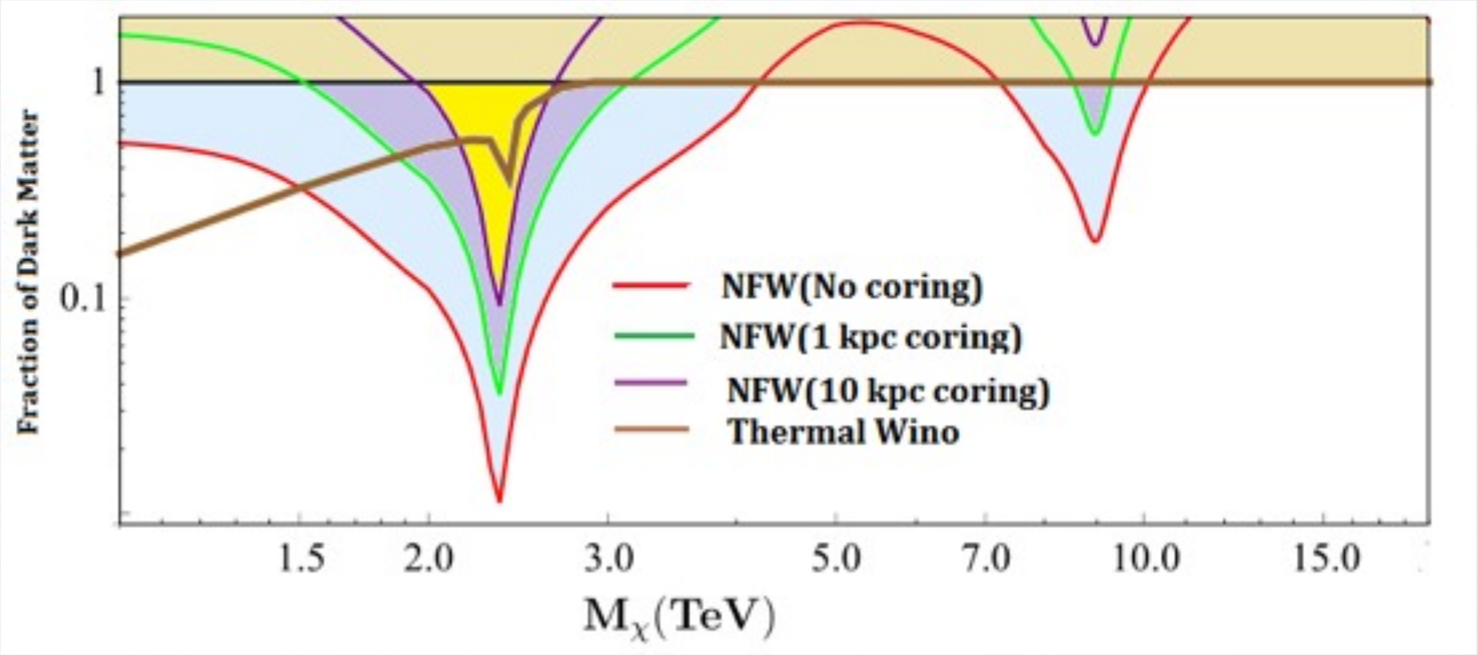
Exclusion curve taken from Ovanesyan, Slatyer, and Stewart (1409.8294); HESS data with NFW profile

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

WINO CONCLUSION

- When computing observationally relevant semi-inclusive rate, NLO effects are small (~few%) compared to ~50% found in exclusive analyses: Ovanesyan et al. (1409.8294); Bauer et al. (1409.7392)

  - Semi-Inclusive → Leading Log operator mixing → 1+Exp[-Log^2].

    Exclusive calculation → no mixing → simply Exp[-Log^2]

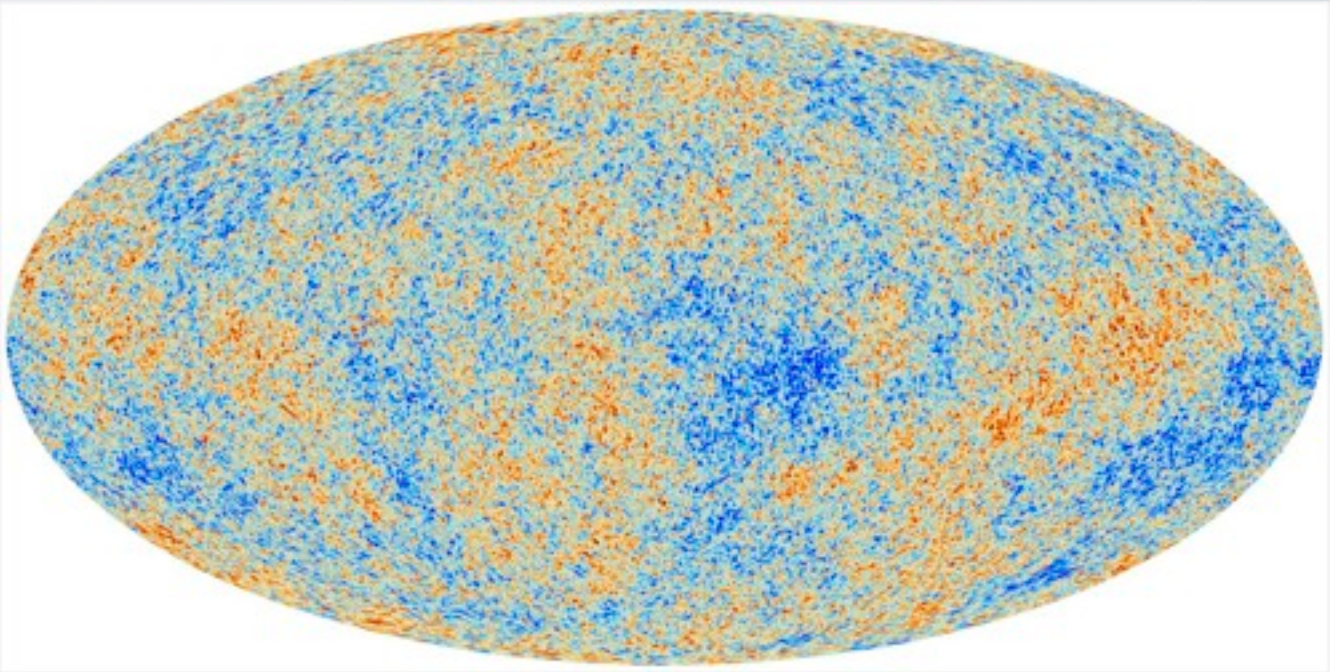
- Viability of thermal wino dark matter requires profile in tension with simulation (core ~ 1.5 kpc)

- Discovery of wino would have huge implications for astrophysical Dark Matter

THE RUTHLESS HUNT FOR NEW PHYSICS

- Understanding TeV-scale would be a great triumph of science
  - Electroweak symmetry breaking
  - WIMP dark matter
- Q: Is that enough?

  A: Would the rich like to be richer?
- To understand physics at M >>TeV, we will need the **particle accelerator universe** → observables of inflation



Temperature anisotropy map from Planck satellite
Experiment confirms nearly **$1/k^3$ power spectrum** expected from a quasi-De Sitter geometry,

UNDERSTANDING PERTURBATION THEORY IN DE SITTER

- In 1940s and 1950s, theorists worked to understand QED to all orders → Deep insight into Renormalization Group

No matter how small λ, eventually overwhelmed

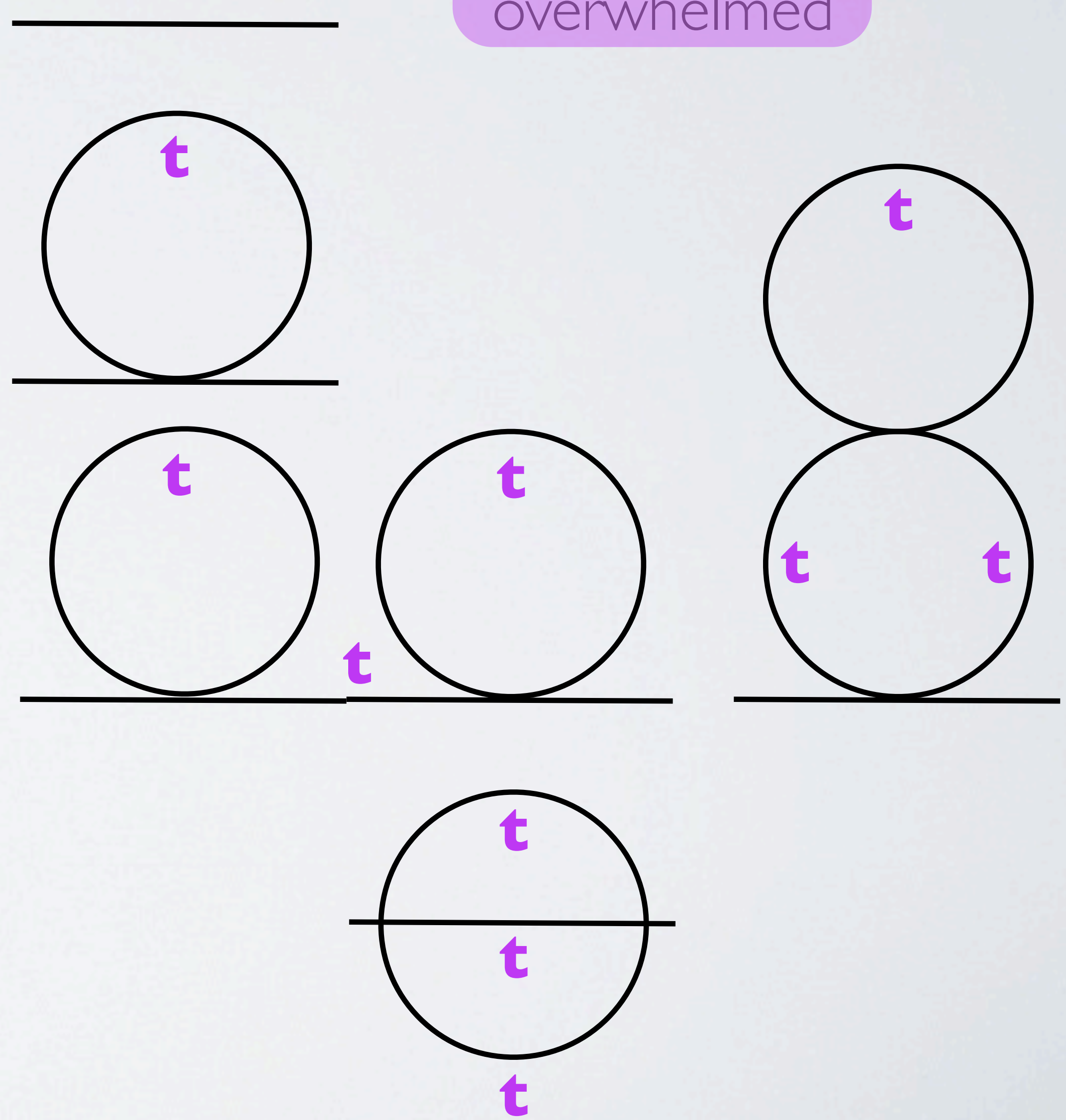
- Inflation successful, but it raises conceptual problems, what is grammar for QM on cosmological scales?

- For clues, use pure DS as theoretical laboratory massless field contains IR pathology

$$\langle \phi_k \phi_{-k} \rangle \sim \frac{H^2(1+k^2\eta^2)}{k^3} \qquad \langle \phi(x)\phi(y) \rangle \sim \int \frac{dk}{k} \sim \log(k_{UV}) - \log(k_{IR})$$

- Can regulate IR, but at cost of linear-in-t growth of propagator

$$\langle \phi(x)\phi(y) \rangle \sim H^2 \log(a = e^{Ht}) = H^3 t$$



IR OF DE SITTER ↔ IR OF QCD

- Just as in gauge theory (QCD, electroweak), we have poorly behaved infrared
- Problem demands novel EFT methods, but morally similar to SCET, divide field into modes, carefully treat IR and resum

$$\psi[\{\phi_1\}; t+\Delta t]_{IR} = \psi_{BD,\, Ha'>k>Ha}[\phi_{1k}, t+\Delta t]$$
$$\times \int \mathcal{D}\phi_{0q} \text{``}\delta[\phi_{0q} - \phi_{\rm cl}(\phi_{1q}; t, t+\Delta t)]\text{''}$$
$$\times\, \psi_{\rm soft}[\{\phi_{0q}\}; t] e^{iS_{\rm soft,\,cl}[\phi_{1q}, \phi_{0q}; t, t+\Delta t]}$$

Modes redshift from perturbative UV

Soft modes obey first-order stationary phase approximation

- Update equation for wavefunctional in path integral gives simple evolution for wavefunctional mod-squared:*

$$\dot{p}(\phi, t) = \frac{1}{3H}\partial_\phi[V'(\phi)\, p(\phi, t)] + \frac{H^3}{8\pi^2}\partial_\phi^2 p(\phi, t)$$

$$p(\phi, t) = N e^{-\frac{8\pi^2}{3H^4}V} + \sum_{n=1}^{\infty} \Phi_n(\phi) e^{-\Gamma_n t}$$

- DS/Parton Shower correspondence? Leading IR physics takes us to: Markovian evolution, flow equation, UV fixed point...

*MB and R. Sundrum 1503.xxxxx
"Stochastic Inflation" Starobinsky (1986)

EFFECTIVE FIELD THEORY UNIVERSE

- Effective Field Theory can simply mean integrating out heavy particles and is useful for parametrizing Beyond the Standard Model physics

MB: 0706.1380 (dimension-6 operators in deconstructed, composite Higgs Models)
MB & B. Tweedie: 1212.4888: (top quark spin observables for higher-dimension operators)
J. Adelman et al.: 1308.5274: (top quark rate observables for higher-dimension operators)

- EFT is much richer formalism to understand wide variety of systems with intrinsic scale hierarchies (jets from hard collisions, bound states, long-lived inflationary universe), often involving the same field

MB, C. Marcantonini, & I. Stewart: 1007.0758 (NLL parton shower from SCET)
MB & A. Katz: 1204.6032 (Higgs decays via new physics to NRQCD bound states)
MB et al.: 1406.2295 (NRQCD bound states in jets analyzed with SCET to understand quarkonium polarization puzzle)
MB, I. Rothstein & V. Vaidya: 1409.4415 (SCET+NRQCD formalism to resum wino annihilation logs)
MB, I. Rothstein & V. Vaidya: 1409.8696 (SCET+NRQCD calculation of wino annihilation rate)
MB & R. Sundrum: 1503.xxxxx (Resummation of time for light scalars in DS)

- **Pushing ever-forward in energy, understanding disparate-scale systems will be crucial to answering our deepest questions.**

Top and other heavy particle observables, including spin
Irrelevant operator analysis of new models

Resumming electroweak logs at colliders
Seeing color of partons in jets
Identifying Dark Matter
Understanding Quantum Field Theory in De Sitter

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

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

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

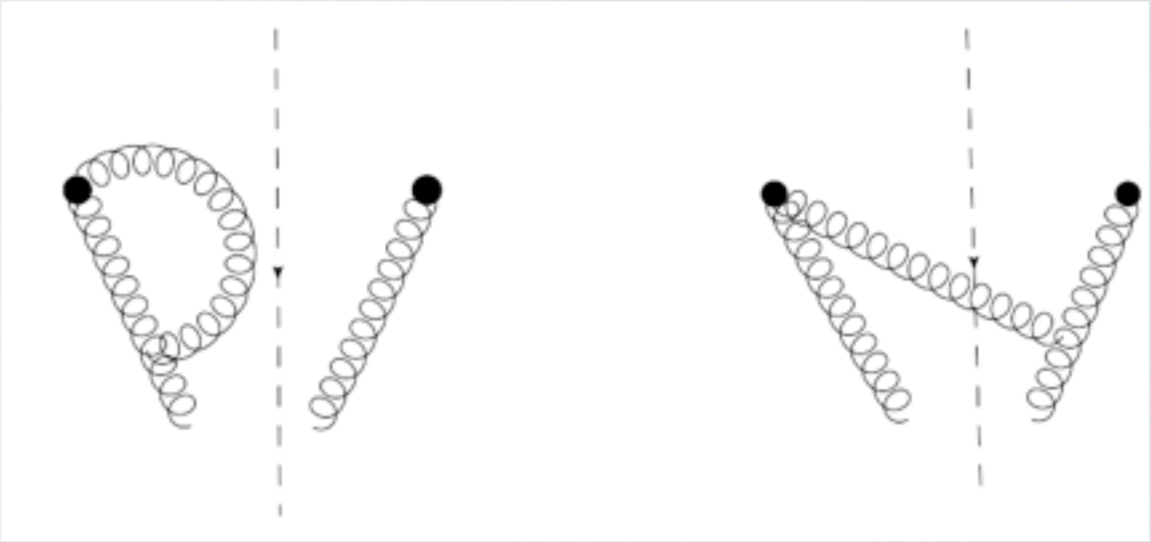
- Soft&Collinear-gauge-boson structure is therefore

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

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

ANOMALOUS DIMENSIONS

- Compute soft & collinear anomalous dimensions separately
- OPE converts amplitude-squared to operator whose expectation value gives rate
- Thus, real & virtual corrections to $\chi\chi \to \gamma + X$ will appear as loops



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

RAPIDITY RG

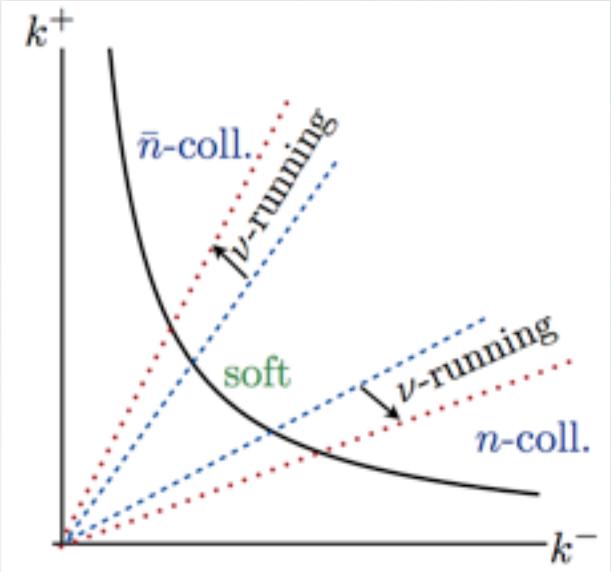
- SCET is a "modal" theory

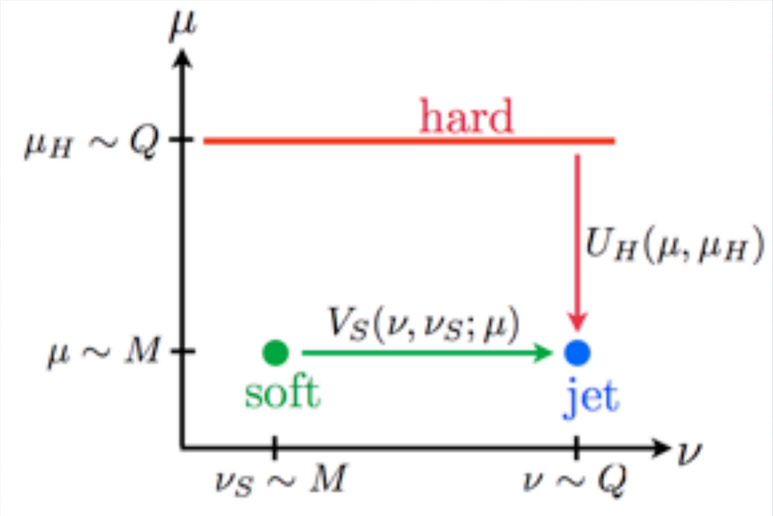
$$A_\mu = A_\mu^{c,n} + A_\mu^{c,\bar{n}} + A_\mu^{soft} + \dots$$

- 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

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

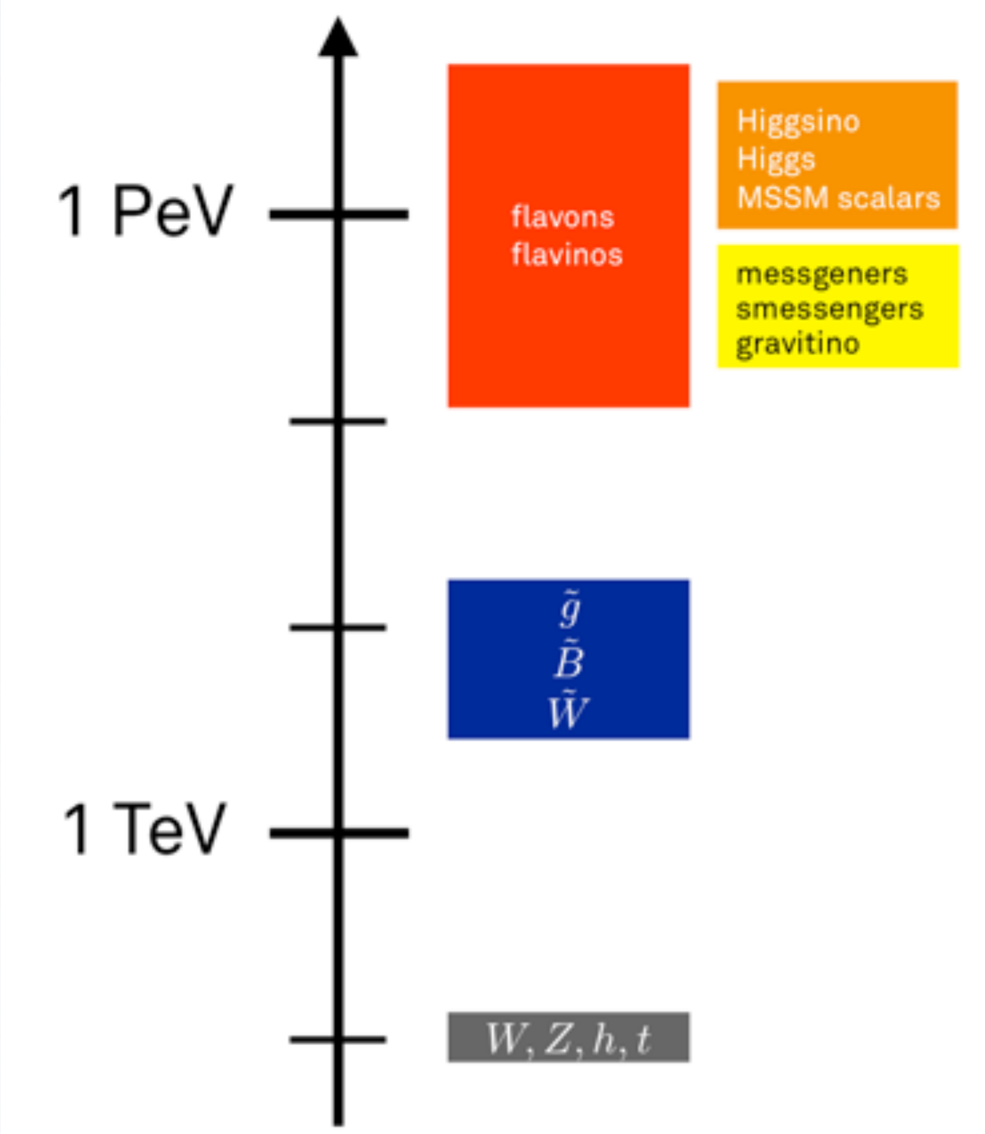




From Chiu et al. 1202.0814: In SCETII, soft and collinear modes have same virtuality
ν-running lets us minimize log between soft & collinear scales

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



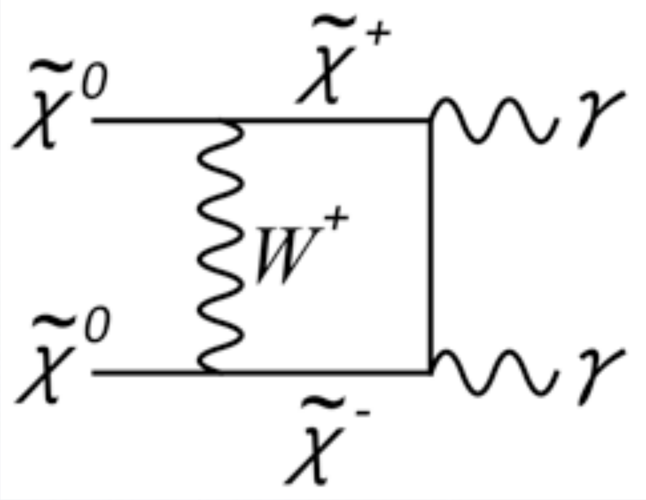
From 1403.6118: MB, Stolarski, and Zorawski
Mini-split SUSY allows a radiative generation of flavor hierarchies
and allows for thermal WIMP-DM

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



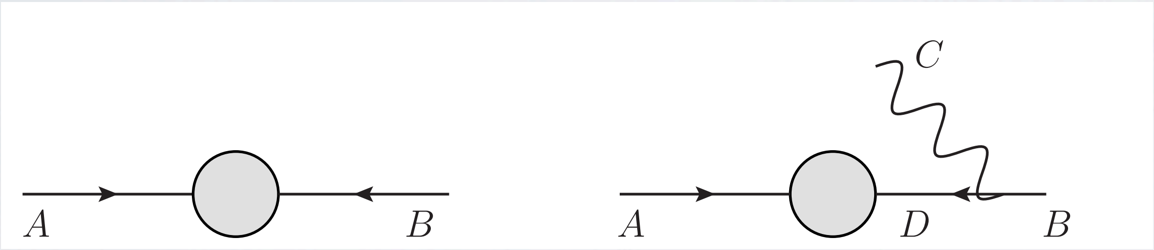
$$\sigma_{\mathrm{one-loop}} v = \frac{4\pi\alpha^2\alpha_W^2}{m_W^2}$$

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

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

BLOCH-NORDSIECK THEOREM VIOLATION*

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



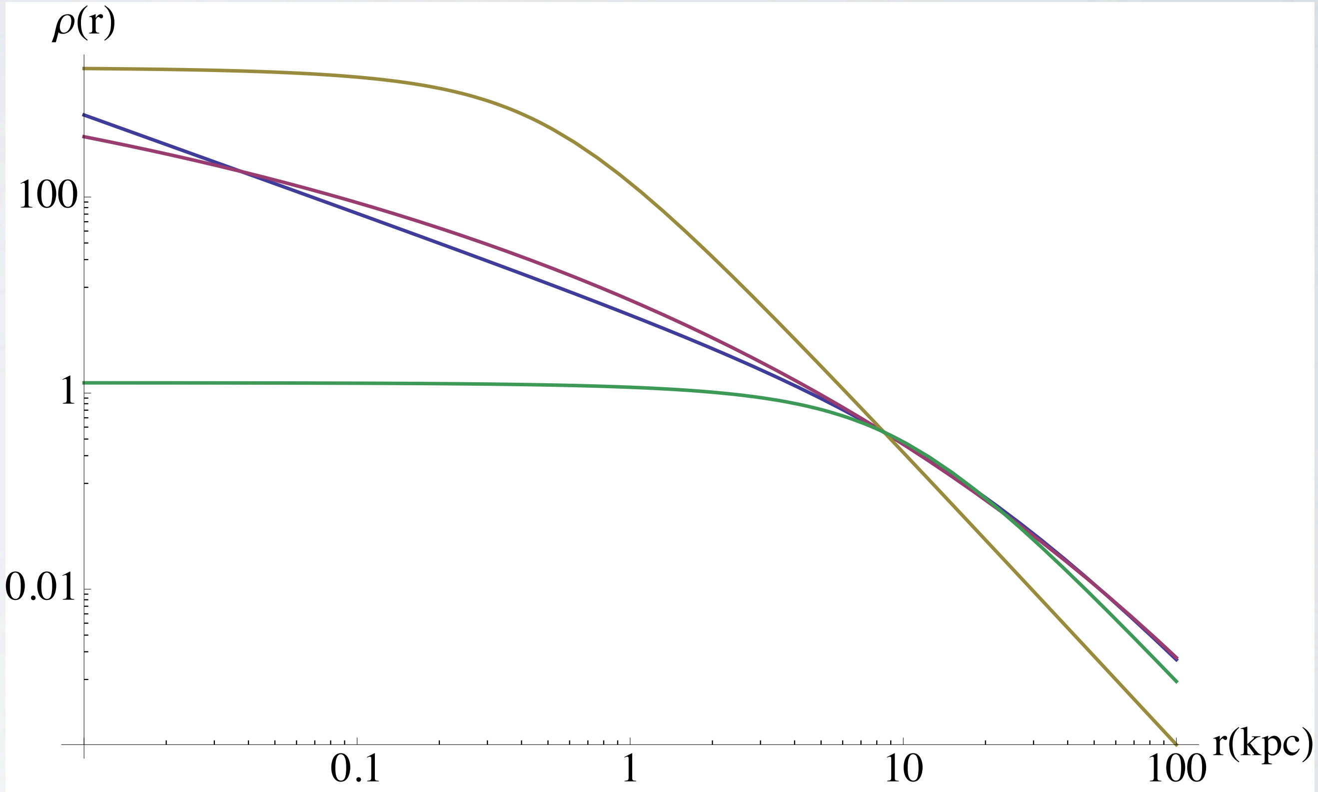
$\sigma_{AB} \neq \sigma_{AD}$, virtual corrections only cancel emission upon color averaging

- 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

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*



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

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{(r/20{\rm kpc})(1+r/20{\rm kpc})^2}$$

$$\rho_{\rm Burk.}(r) = \frac{\rho_0}{(1+r/r_c)(1+r/r_c)^2}$$

*1208.4844, 1305.5360, 1306.0898