Unification and Dark Matter

in a

Minimal Scalar Extension of the Standard Model

(arXiv:0704.2816)

Mariangela Lisanti and Jay G. Wacker

SLAC, Stanford University

July 28, 2007

Outline

I. Unnatural Models

II. Six Higgs Doublet Model

III. Renormalization Group Influence on Low Energy Spectrum

IV. Dark Matter Discovery

Environmental Selection

• Galactic Principle

No galaxies if cosmological constant larger than (~100 times) observed value

[Weinberg]

• Atomic Principle

No complex chemistry if Higgs vev larger than (~5 times) observed value

$$m_{\mathrm{neutron}} - m_{\mathrm{proton}} \propto v$$

[Agrawal, Barr, Donoghue and Seckel]

• Dark Matter Mass

Halo formation (& star/galaxy formation) fix dark matter density to within an order of magnitude

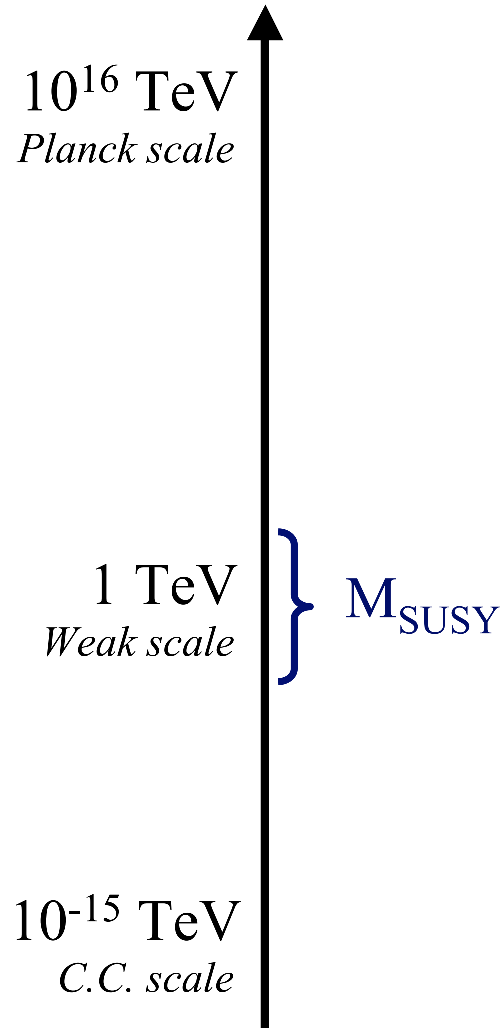
[Hellerman & Walcher; Tegmark et al.]

Environmental Selection

Landscape provides a natural framework for environmental selection

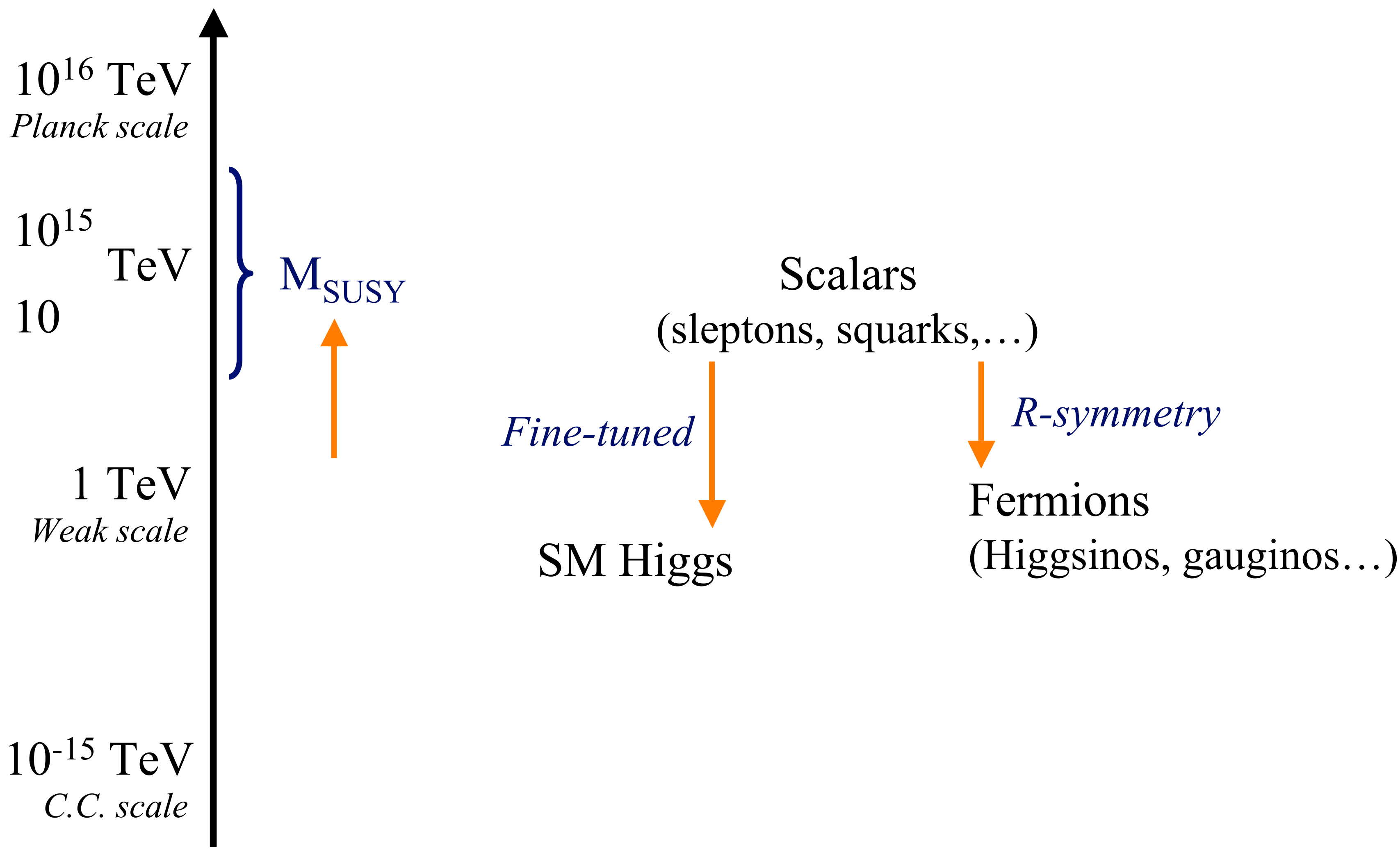
Consider models with unnatural parameters

Split Supersymmetry



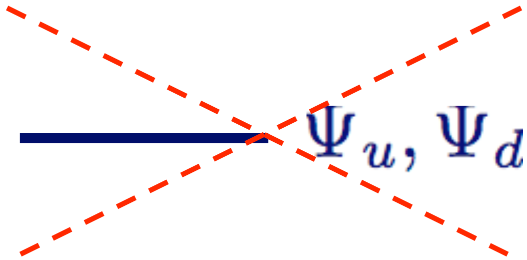
[Arkani-Hamed & Dimopoulos]

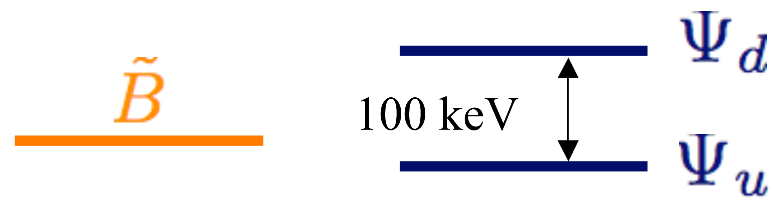
Split Supersymmetry



[Arkani-Hamed & Dimopoulos]

Minimal Model





Standard Model plus two 'Higgsinos'

$\Rightarrow$ gauge coupling unification

Add 'bino' to split mass

$\Rightarrow$ direct detection okay

Minimal Model

- Unification
- Dark matter mass:

  100 GeV - 2 TeV

- 2 fine-tunings:

  Higgs mass & C.C.

[Mahbubani & Senatore; Cirelli, Fornengo & Strumia]

Technical Naturalness

Technical naturalness invoked to keep fermionic dark matter light

Split SUSY: R-symmetry

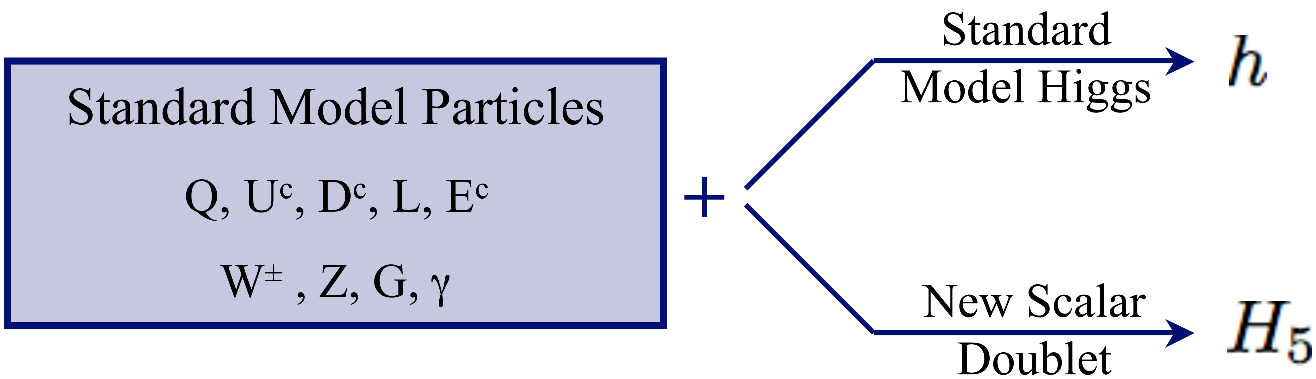
$\Rightarrow$ How is R-symmetry breaking explicitly communicated to fermions?

Minimal model: Ad hoc dynamical mechanism

$\Rightarrow$ What is the high energy theory?

Use of technical naturalness might be misleading for relevant couplings that determine large-scale structure of the Universe

Six Higgs Doublet Model



- H_5 charged under **5** representation of discrete symmetry group (i.e., S_6)
  - Standard Model particles are neutral under this symmetry

- H_5 does not acquire a vev: $h = \begin{pmatrix} 0 \\ v + h^0/\sqrt{2} \end{pmatrix}$ $\quad H_5 = \begin{pmatrix} \phi_5^+ \\ (s_5^0 + i a_5^0)/\sqrt{2} \end{pmatrix}$

- H_5 interacts with Standard Model gauge bosons, but not fermions

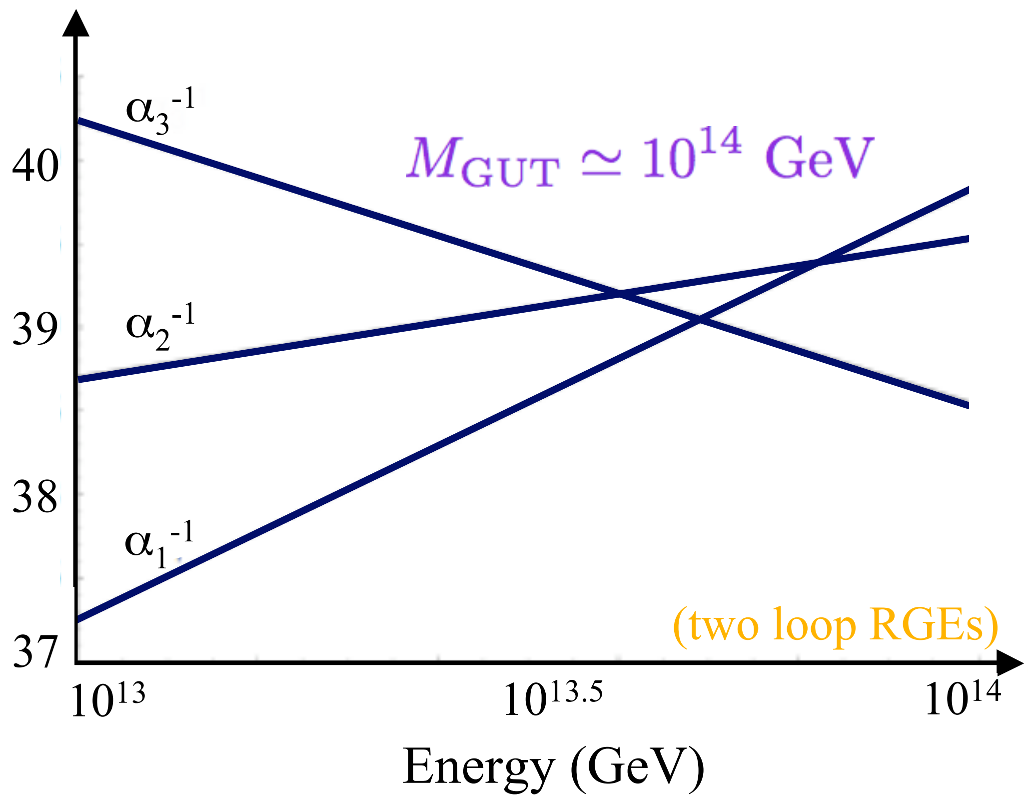
Unification

- Unification is key motivation for introducing the five-plet H_5

- Threshold correction

  $m_2/m_3 \sim 30$ 6 Higgs

  $m_3/m_2 \sim 20$ MSSM



- Proton decay too rapid in SU(5) GUT:

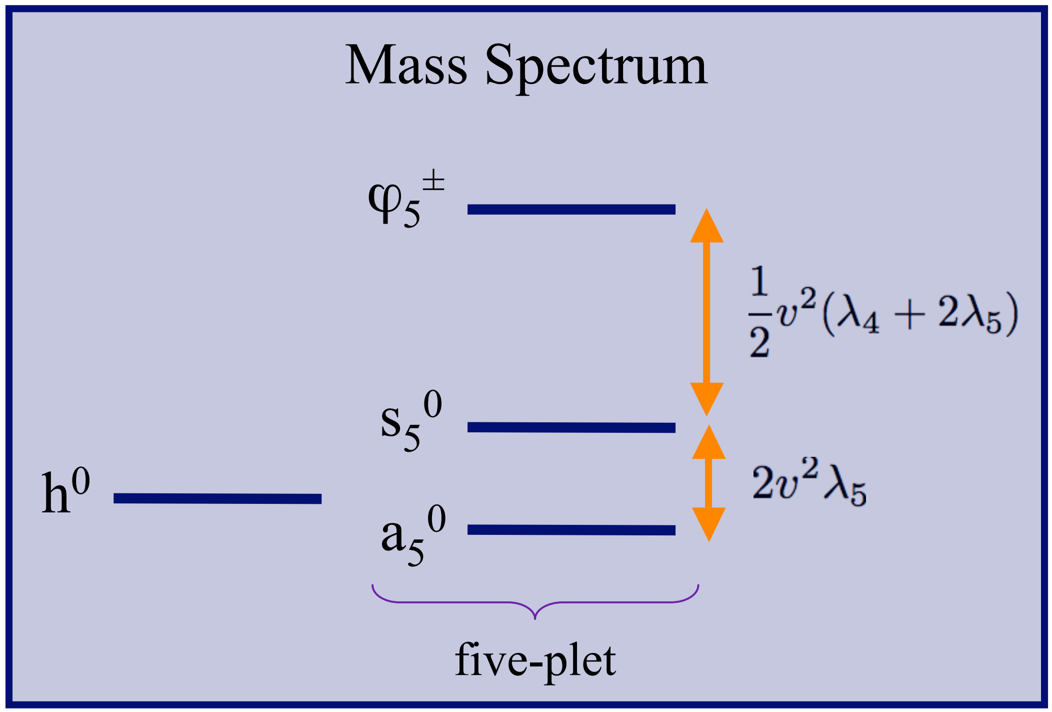
$$\Gamma(p \to e^+\pi^0) \simeq \frac{\alpha_{\rm GUT}^2 m_p^5}{M_{GUT}^4} \simeq 10^{-28}\ {\rm yr}^{-1}$$

Mass Spectrum

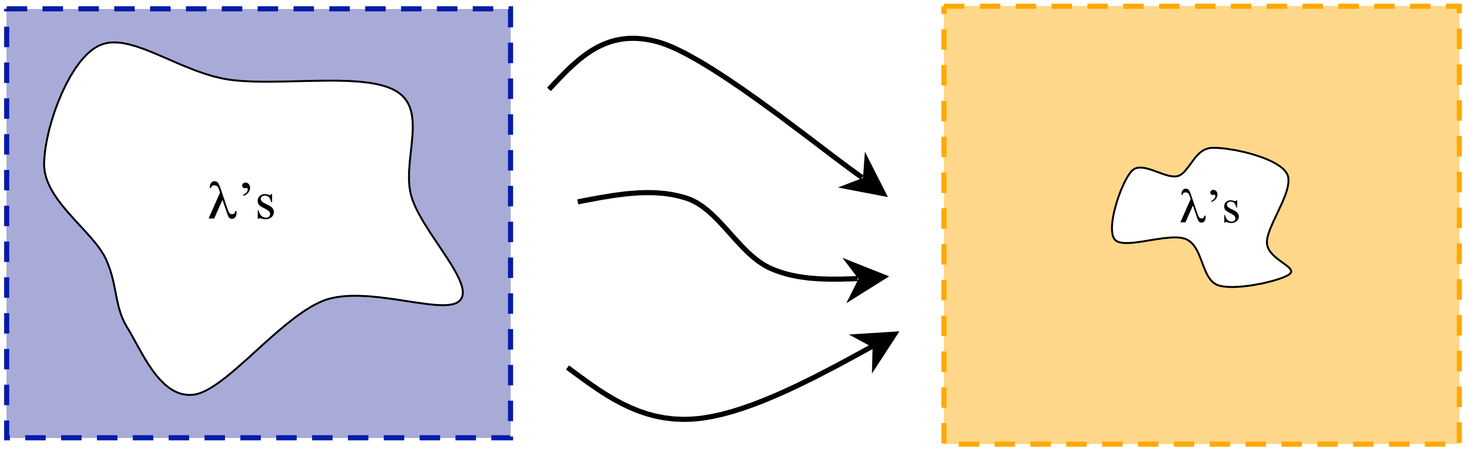
$$V \supset \underbrace{\lambda_1(|h|^2 - 2v^2)|h|^2}_{\text{Electroweak symmetry breaking}} + \lambda_4 |h^\dagger H_n|^2 + \underbrace{\lambda_5((h^\dagger H_n)^2 + \text{h.c.})}_{\text{Breaks accidental U(1) symmetry}}$$

- λ_4 and λ_5 determine scalar mass splittings

- a_5 is lightest neutral particle and serves as the dark matter candidate



Renormalization Group Effects



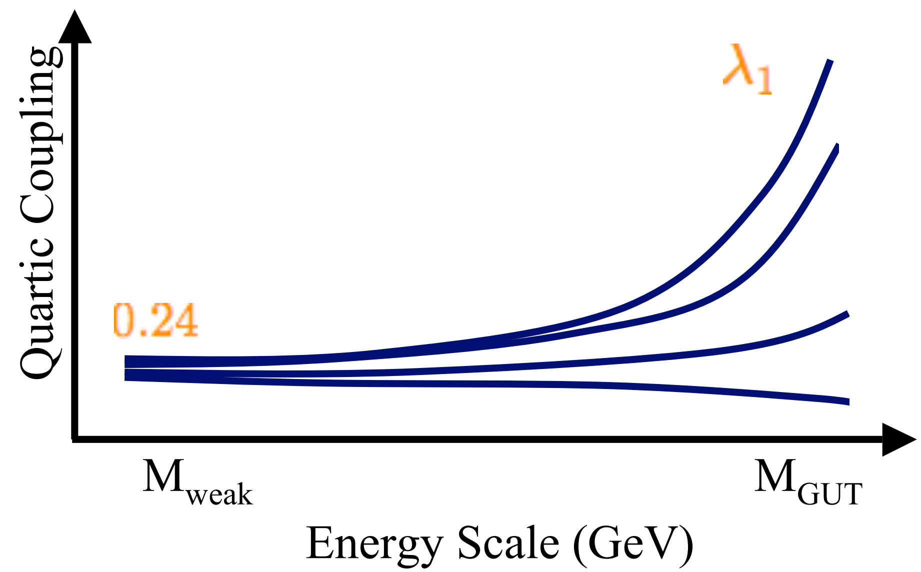
- Landscape gives many possibilities for couplings at GUT scale.
  What are the typical values in our neighborhood of vacua?

- Distribution of couplings is a UV sensitive question
  - Large range of couplings at high energies is compressed at low energies

Parameter Space Democracy

All couplings at GUT scale are equally likely

- Allowed region for quartics at electroweak scale is small:
    - perturbativity
    - positive SM Higgs mass
    - vacuum stability



- Couplings approach tracking solution very quickly

Example: λ_1 large at GUT scale, self-coupling term dominates at low energy

$$\lambda_1^{\max} \simeq \frac{16\pi^2}{24 t_{\rm GUT}} \sim 0.24$$

Supersymmetry

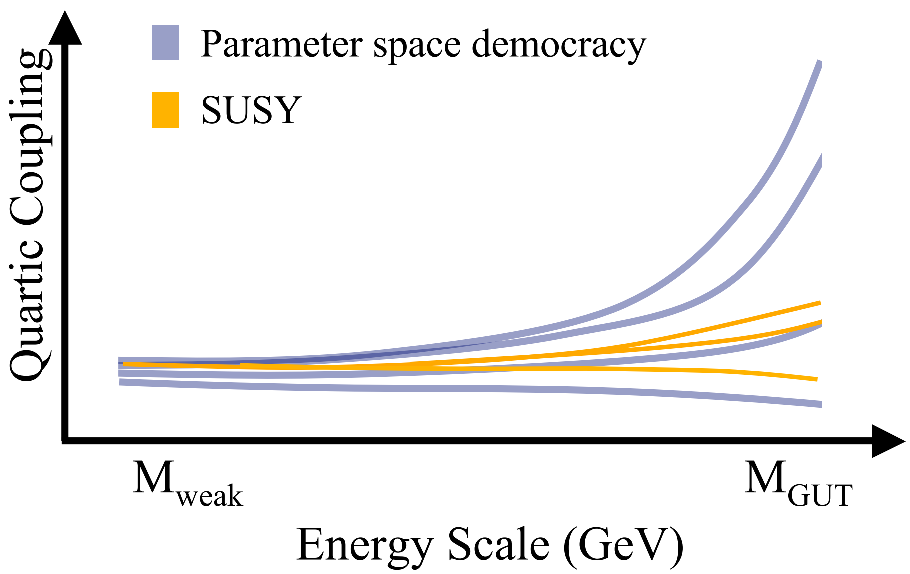
Quartic couplings arise from D-terms

• Each low-energy Higgs doublet comes from chiral superfield

$$\Phi_h| = c_\beta h - s_\beta \tilde{h}$$

• Two angles β and β_5 give orientation of scalars within superfield

$$\Phi_{H_5}| = c_{\beta_5} H_5 - s_{\beta_5} \tilde{H}_5$$



• Smaller couplings at high energies as compared to parameter space democracy

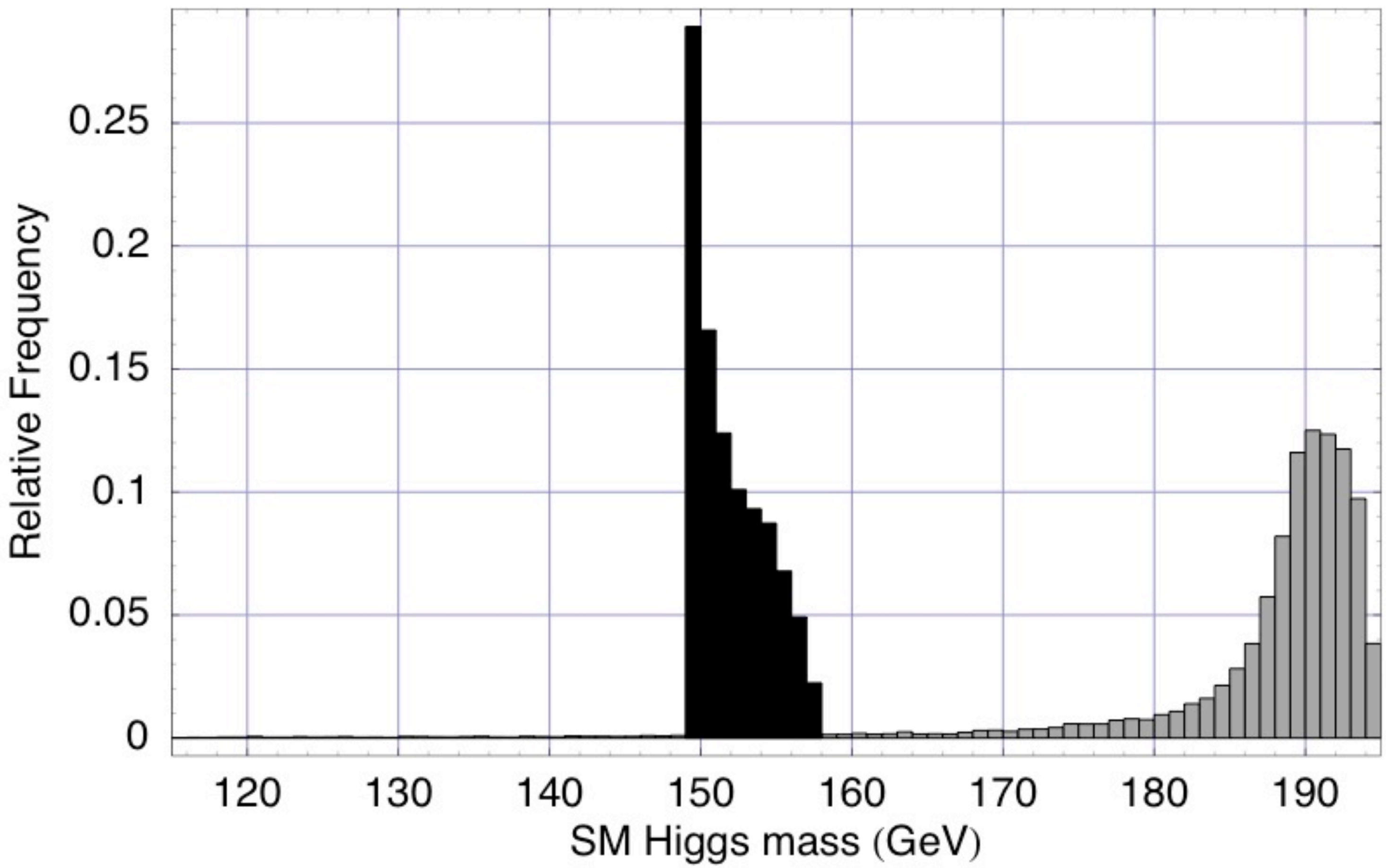
  • Even smaller range at low energy

Renormalization Effects

■ Parameter space democracy ■ SUSY

PSD: Large range, peaked at 200 GeV

SUSY: Small range ~ 155 GeV



Outline

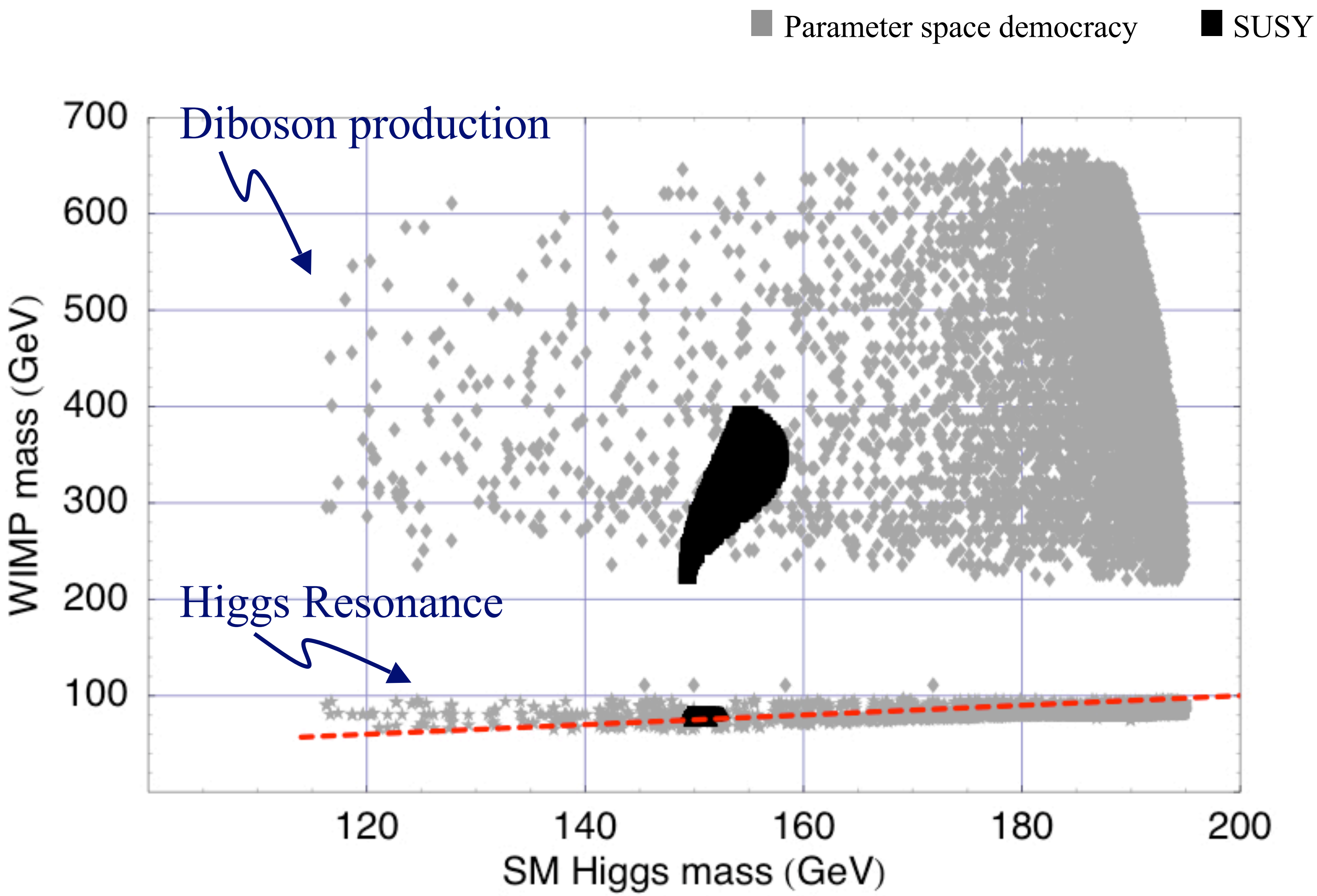
I. Unnatural Models

II. Six Higgs Doublet Model

III. Renormalization Group Influence on Low Energy Spectrum

IV. Dark Matter Discovery

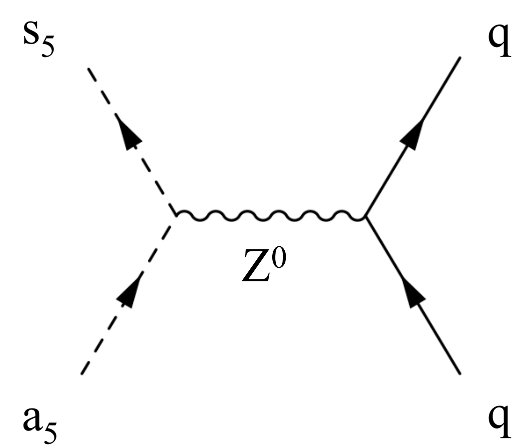
Relic Abundance



Direct Detection

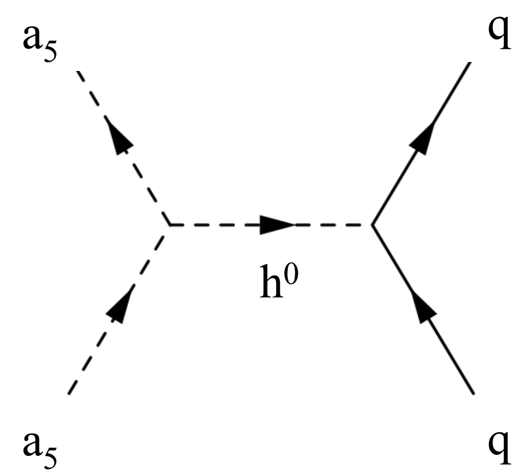
• Inelastic scattering between a_5 and s_5 bounds mass splitting

$$\Delta m_{s^0 a^0} \simeq 100 \text{ keV}$$

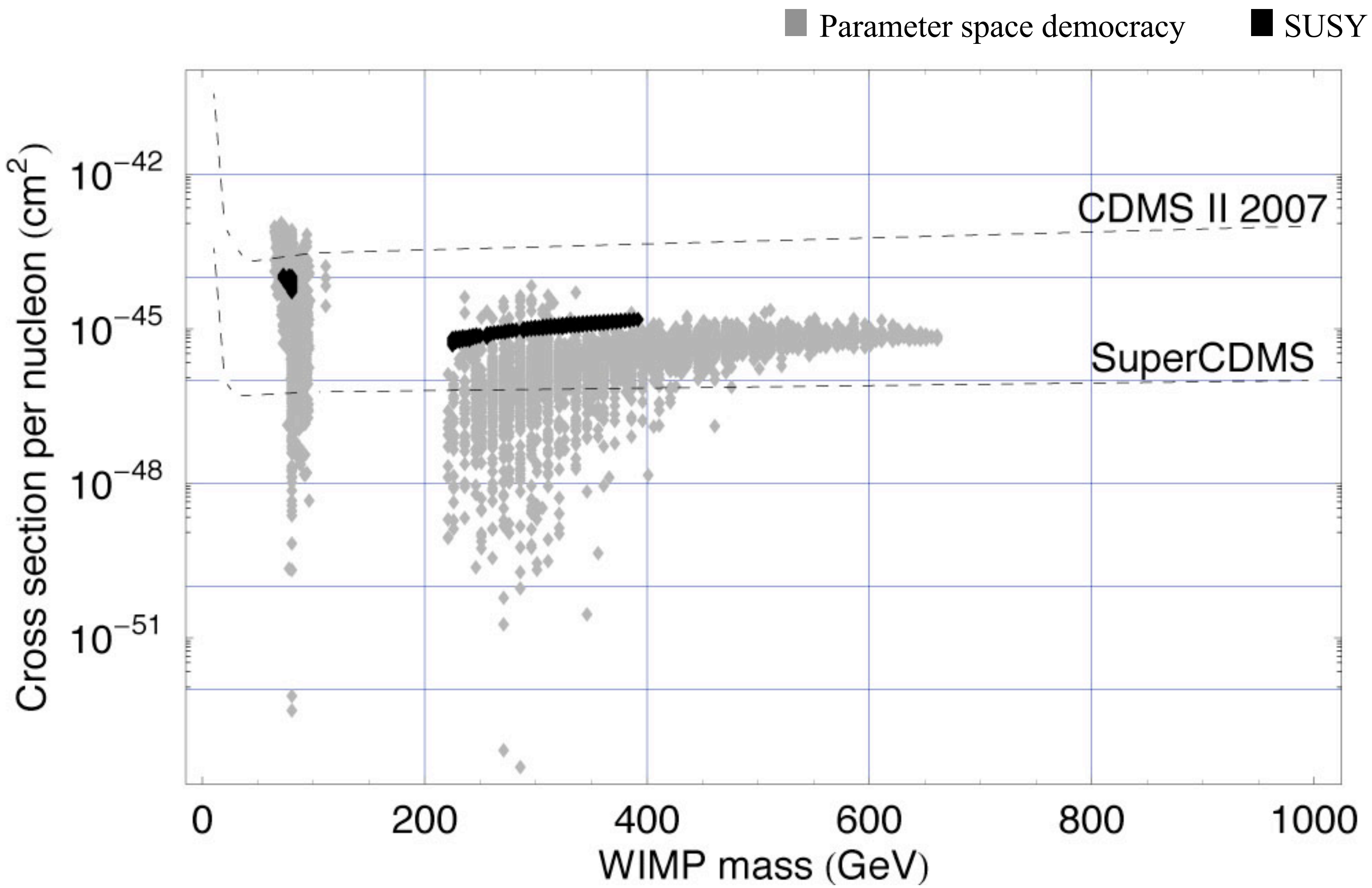


• Elastic scattering between a_5 and a_5 dominates spin-independent contribution

$$\sigma_n = 2 \times 10^{-9} \text{ pb} \left(\frac{\lambda_{\text{eff}}}{0.4}\right)^2 \left(\frac{350 \text{ GeV}}{m_{a^0}}\right)^2 \left(\frac{200 \text{ GeV}}{m_{h^0}}\right)^4$$



Direct Detection



Indirect Detection

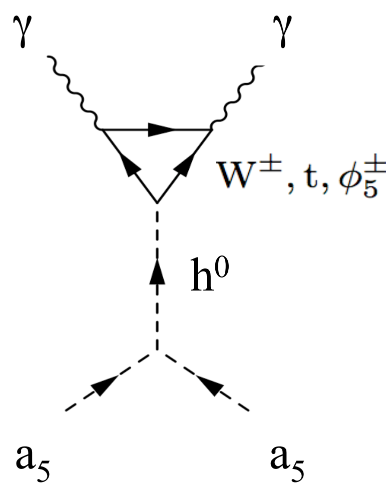
Monochromatic photons produced by WIMP annihilation

• Flux observed by a telescope with a field of view $\Delta\Omega$ and line of sight $\Psi(\theta,\phi)$:

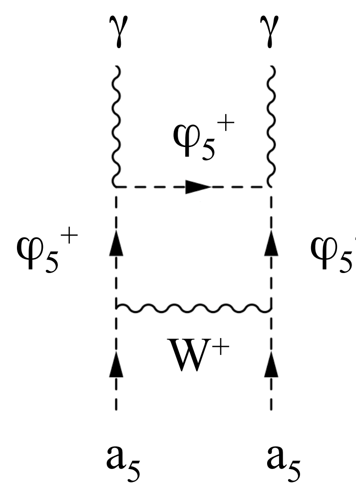
$$\Phi \propto \underbrace{\left(\frac{\sigma_{\gamma\gamma}u}{1\mathrm{p}b}\right)\left(\frac{100\mathrm{G}eV}{m_{a^0}}\right)^2}_{\text{“Particle physics”}} \underbrace{\bar{J}(\Psi,\Delta\Omega)\Delta\Omega}_{\text{“Astrophysics”}}$$

“Particle physics” “Astrophysics”

Low-mass dark matter (~80 GeV)

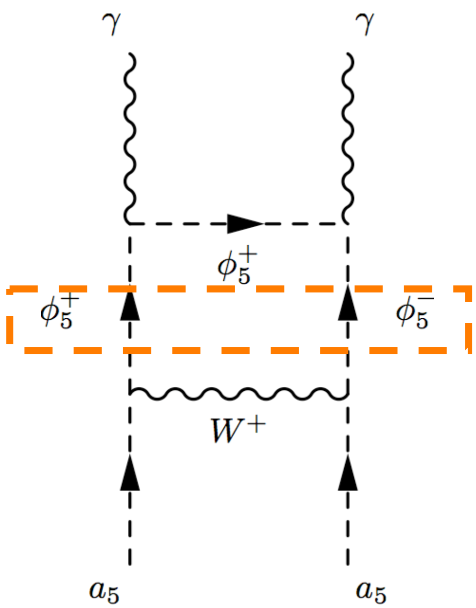


High-mass dark matter (≥ 200 GeV)



Indirect Detection

High-mass dark matter (≥ 200 GeV)

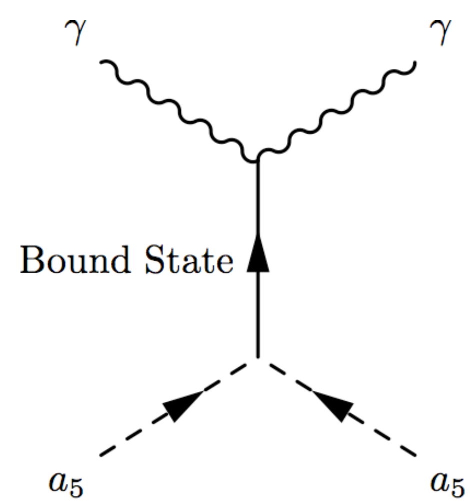


When $m_a \sim m_\varphi$, there is an effective Yukawa force between the $\varphi_5^+ \varphi_5^-$ pair:

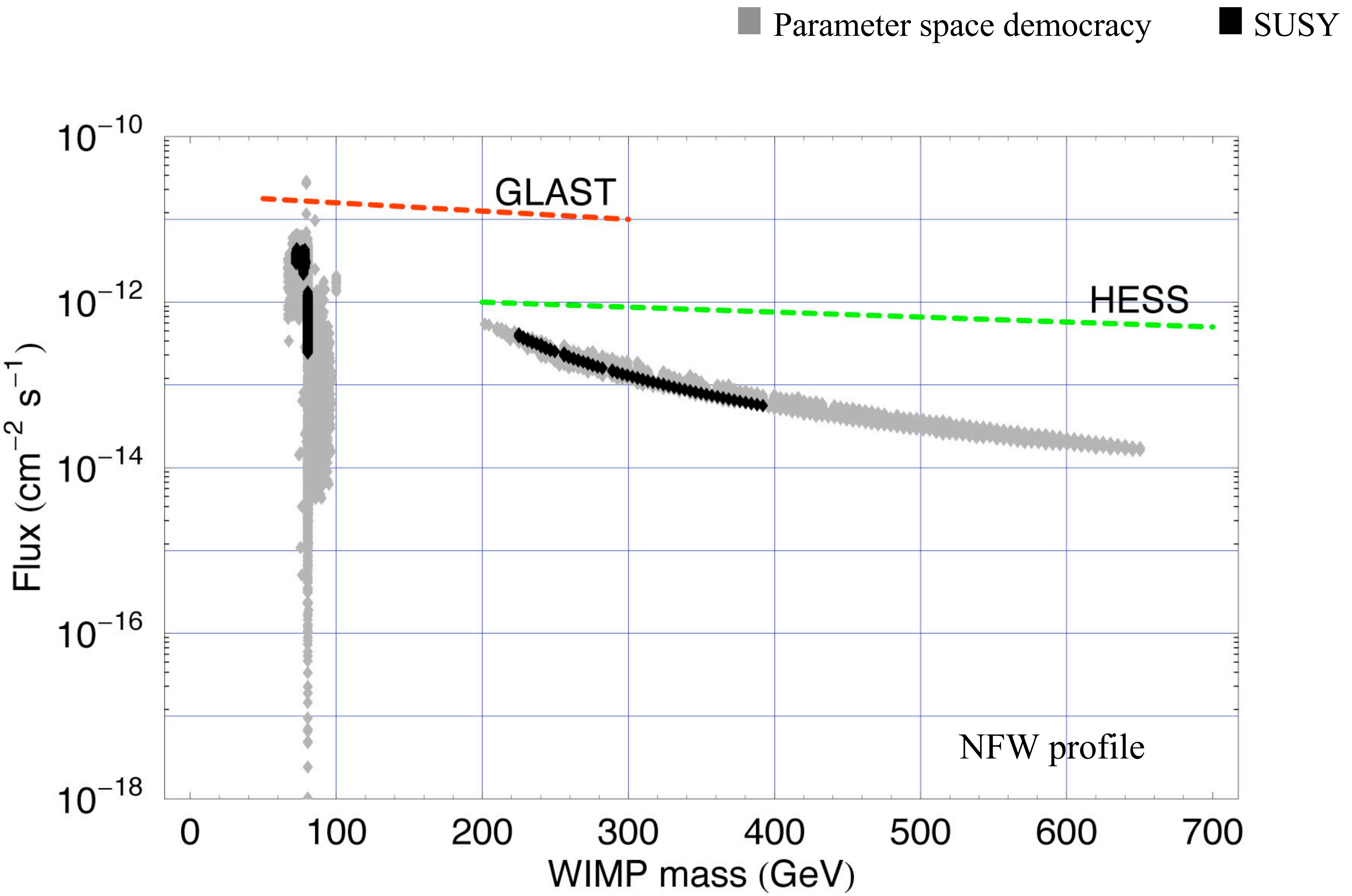
$$V(r) \sim -\alpha_2 \frac{e^{-M_w r}}{r}$$

Charged scalars form a bound-state solution to the non-relativistic Schrodinger equation.

$$\sigma(a_5 a_5 \to \gamma\gamma)u = \left[\sigma(a_5 a_5 \to \mathrm{BS})u\right]\Gamma(\mathrm{BS} \to \gamma\gamma)$$
$$\sim \frac{\alpha^2 \alpha_2^2}{N_h M_{\mathrm{w}}^2}\left(1 + \sqrt{\frac{2m_a \Delta m_{\phi a}}{M_{\mathrm{w}}^2}}\right)$$

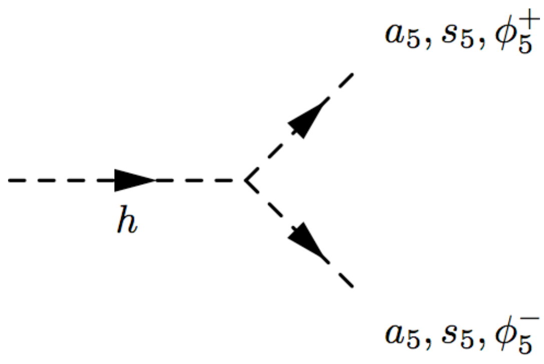


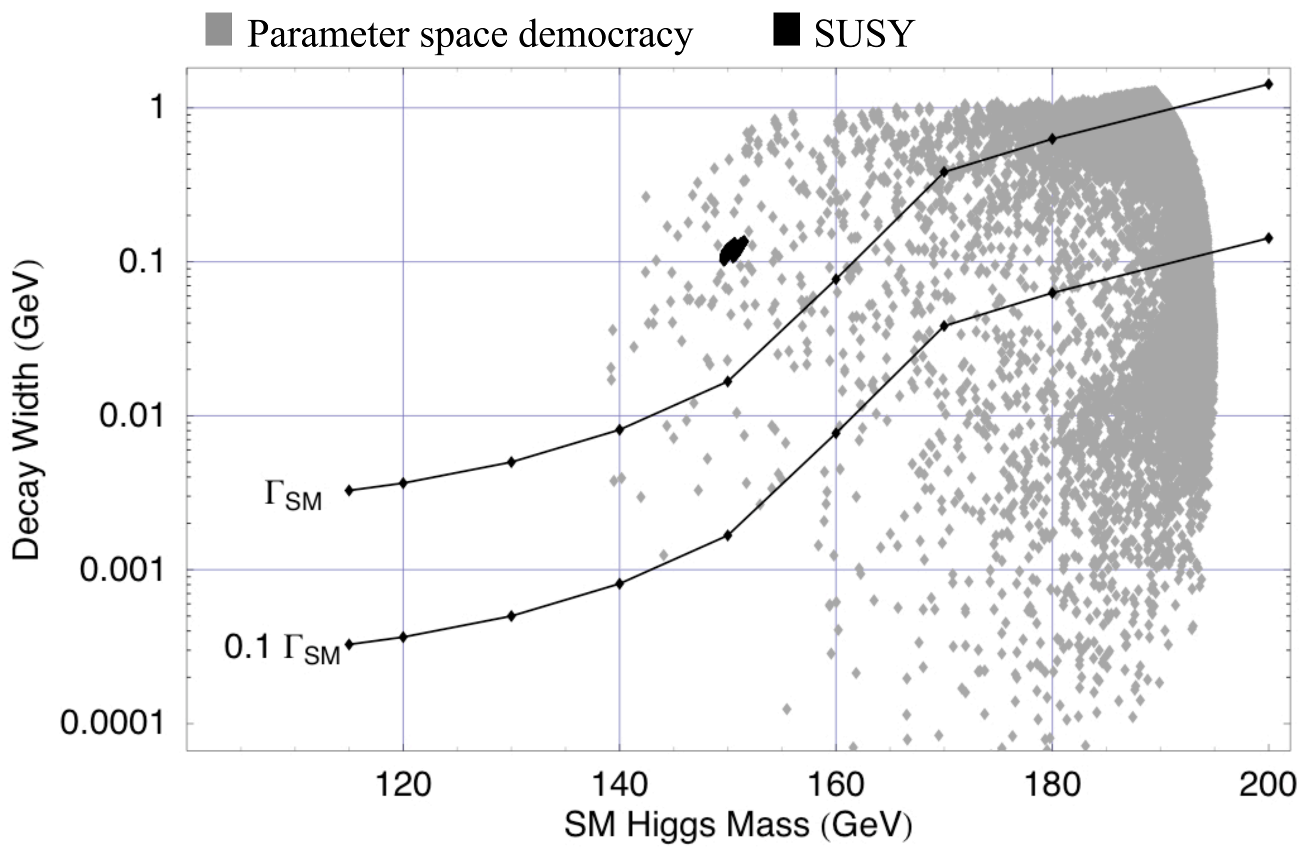
Indirect Detection



Decay of the Standard Model Higgs

- New invisible decay modes for SM Higgs
- One of the most promising discovery channels

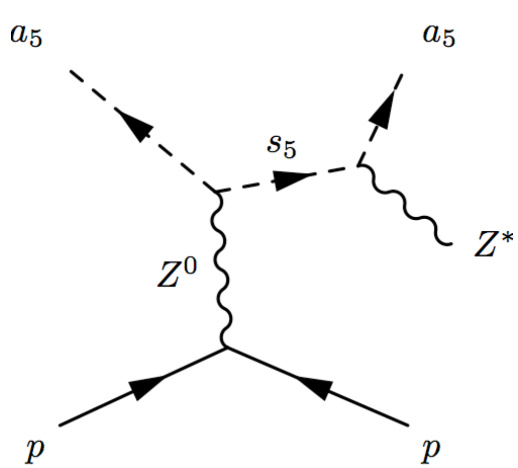




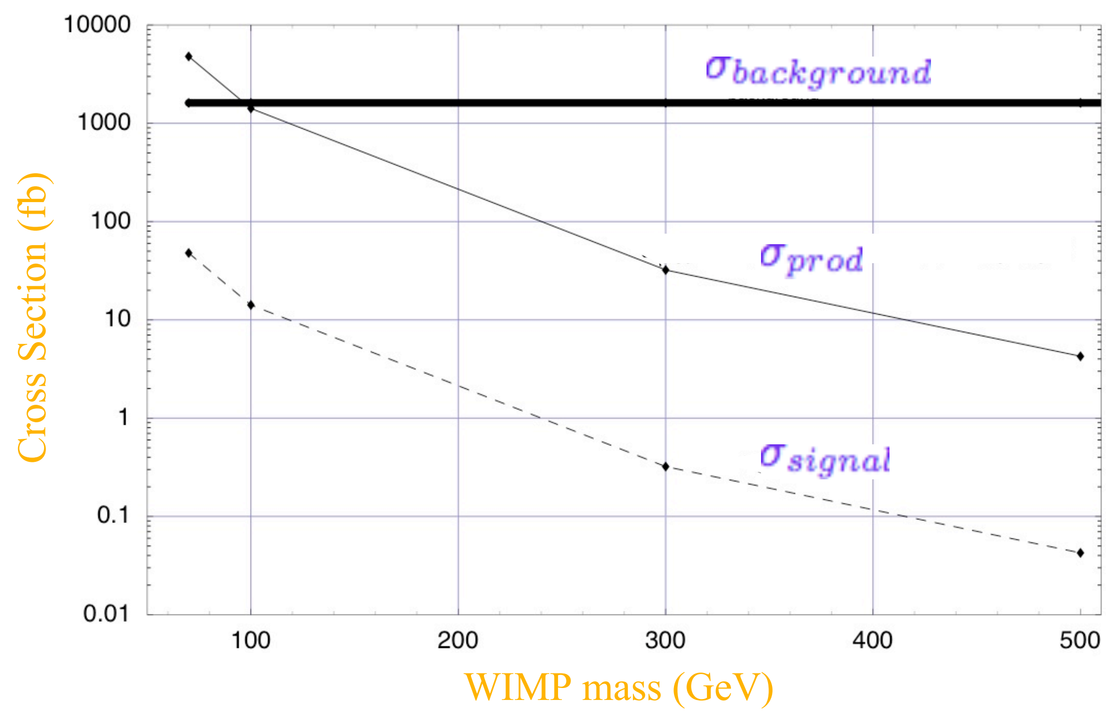
Signatures at the LHC

Estimate signal for sample point in parameter space

- Choose leptonic branching channels for off-shell gauge bosons
- With cuts, may be possible to detect signal for low-mass dark matter



$$\sigma_{\text{prod}} = \sigma(pp \to a_5 s_5) + \sigma(pp \to \phi_5^+ \phi_5^-)$$



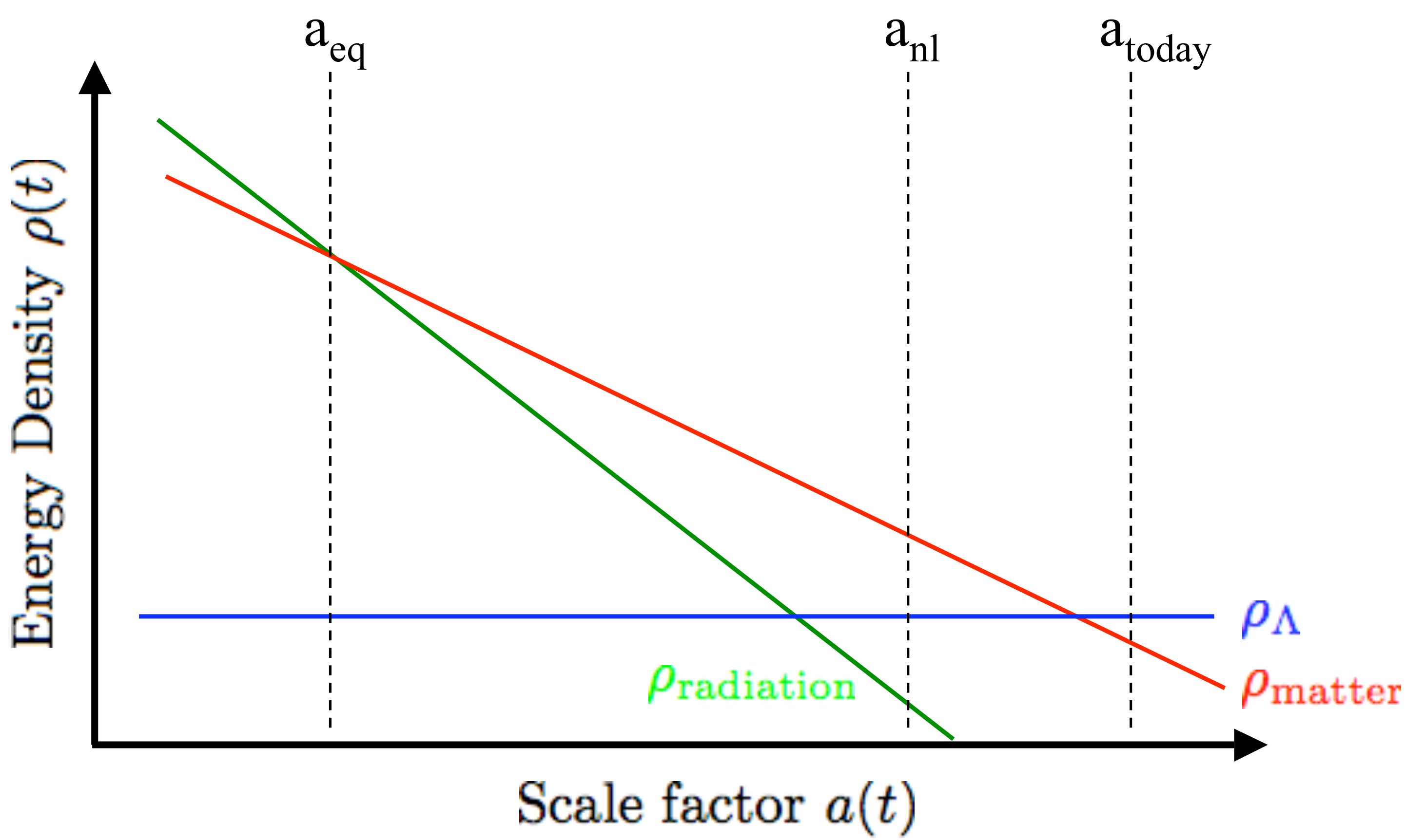
$$\left[\ \sigma_{background} = \sigma(pp \to WW)\text{Br}(W \to l\nu)^2 + \sigma(pp \to ZZ)\text{Br}(Z \to l^+ l^-)\text{Br}(Z \to \nu\nu)\ \right]$$

Conclusions

- Introduce electroweak doublet with discrete symmetry to Standard Model
    - Unification & dark matter
- Two ranges for dark matter mass: light (~ 80 GeV) and heavy (> 200 GeV)

	Light $m_a \sim 80$ GeV	Heavy $m_a > 200$ GeV
Direct Detection	CDMS II	SuperCDMS
Indirect Detection	GLAST, HESS	GLAST, HESS
SM Higgs Decay	Tevatron, LHC	No luck
Direct Production	LHC	ILC?

Galactic Principle



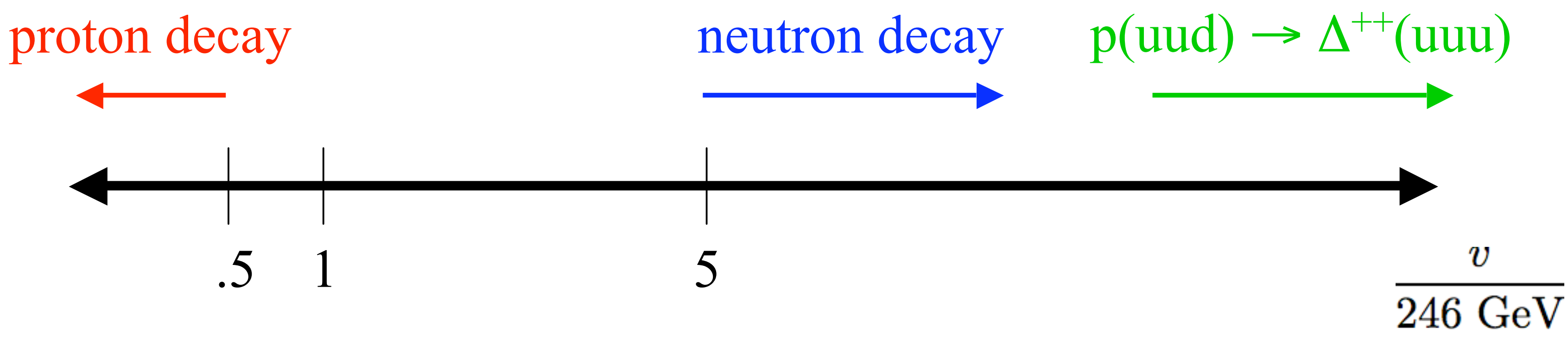
$$\rho_\Lambda \lesssim \rho_{\text{nl}}$$

No galaxies if C.C. larger than (~100 times) observed value

[Weinberg]

Atomic Principle

$$m_n - m_p = \underbrace{(m_d - m_u)}_{\propto v} - \underbrace{E_{em}}_{1.7\ \text{MeV}}$$



Complex chemistry if Higgs vev ~ factor of 5 of its observed value

[Agrawal, Barr, Donoghue and Seckel]

Dark Matter Bound

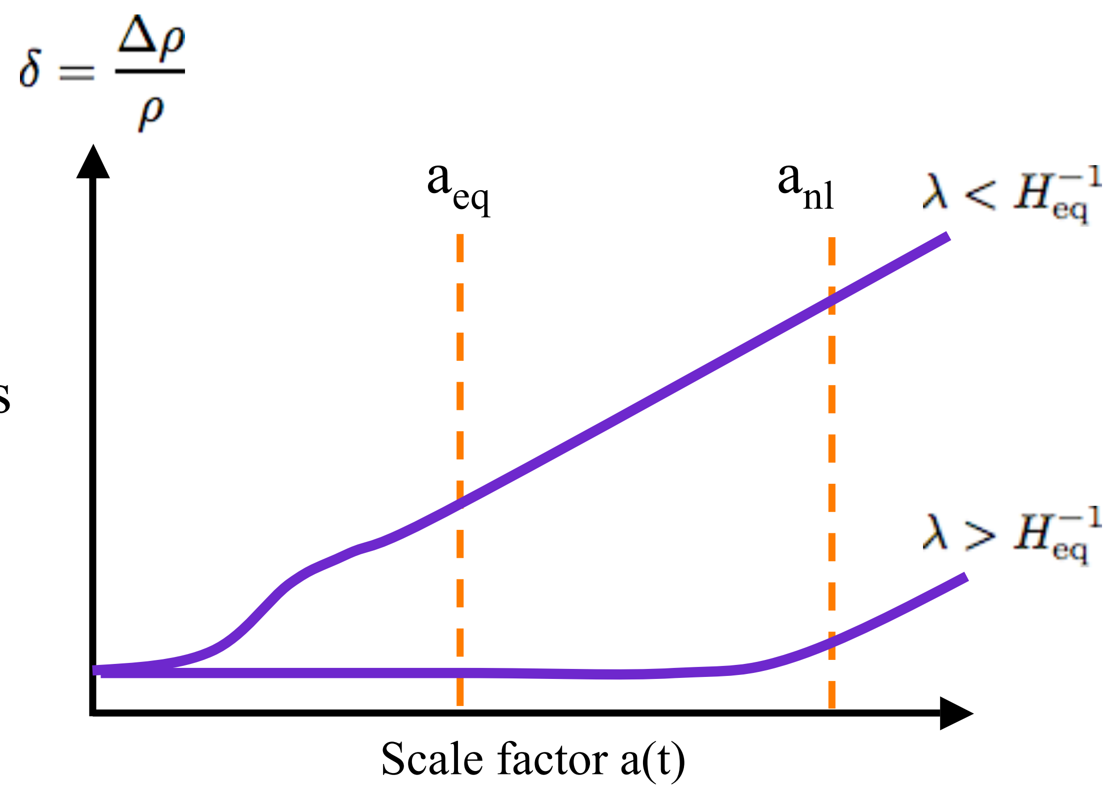
Environmental selection bounds on $\xi = \rho_{\rm dm}/\rho_{\rm b}$?

Nonlinear regime should set in before C.C. expansion takes over: $\rho_\Lambda \lesssim \rho_{\rm nl}$

$\delta \propto a$

when matter density dominates

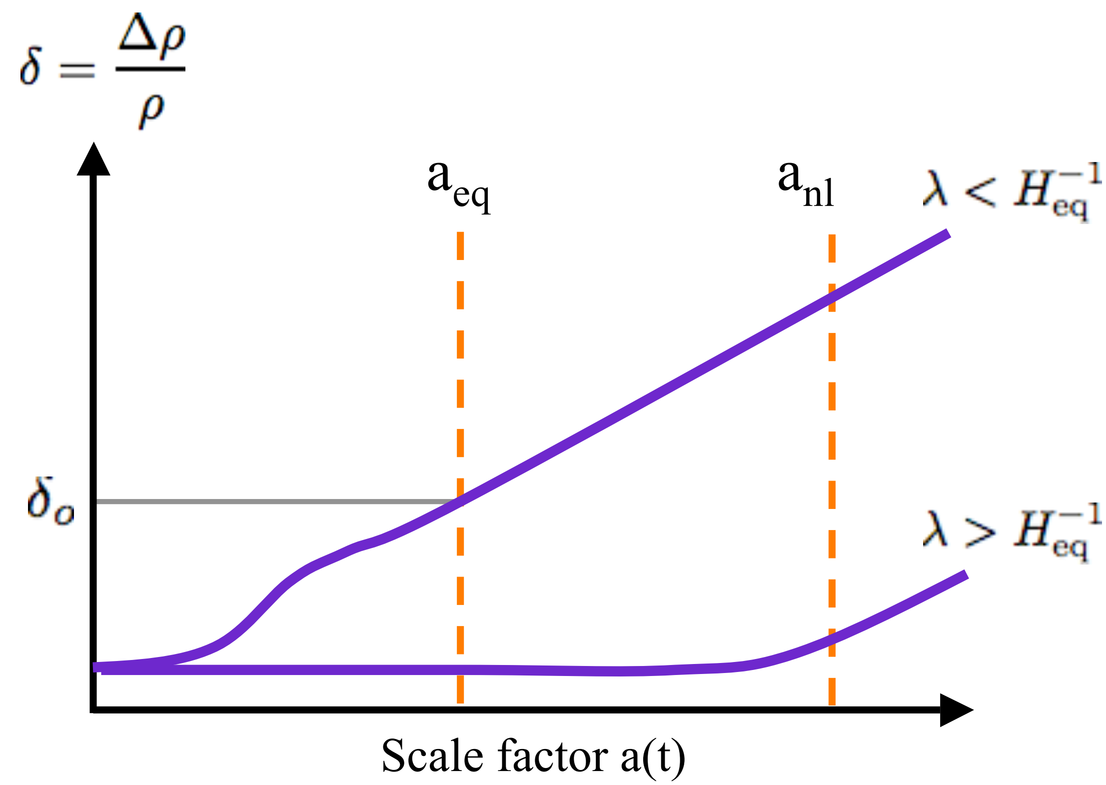
$$\rho_{\rm nl} = \rho_{\rm eq}\left(\frac{a_{\rm eq}}{a_{\rm nl}}\right)^3 = \rho_{\rm eq}\delta_{\rm eq}^3$$



Dark Matter Bound

$$\rho_{\rm nl} = \rho_{\rm eq}\left(\frac{a_{\rm eq}}{a_{\rm nl}}\right)^3 = \rho_{\rm eq}\delta_{\rm eq}^3$$

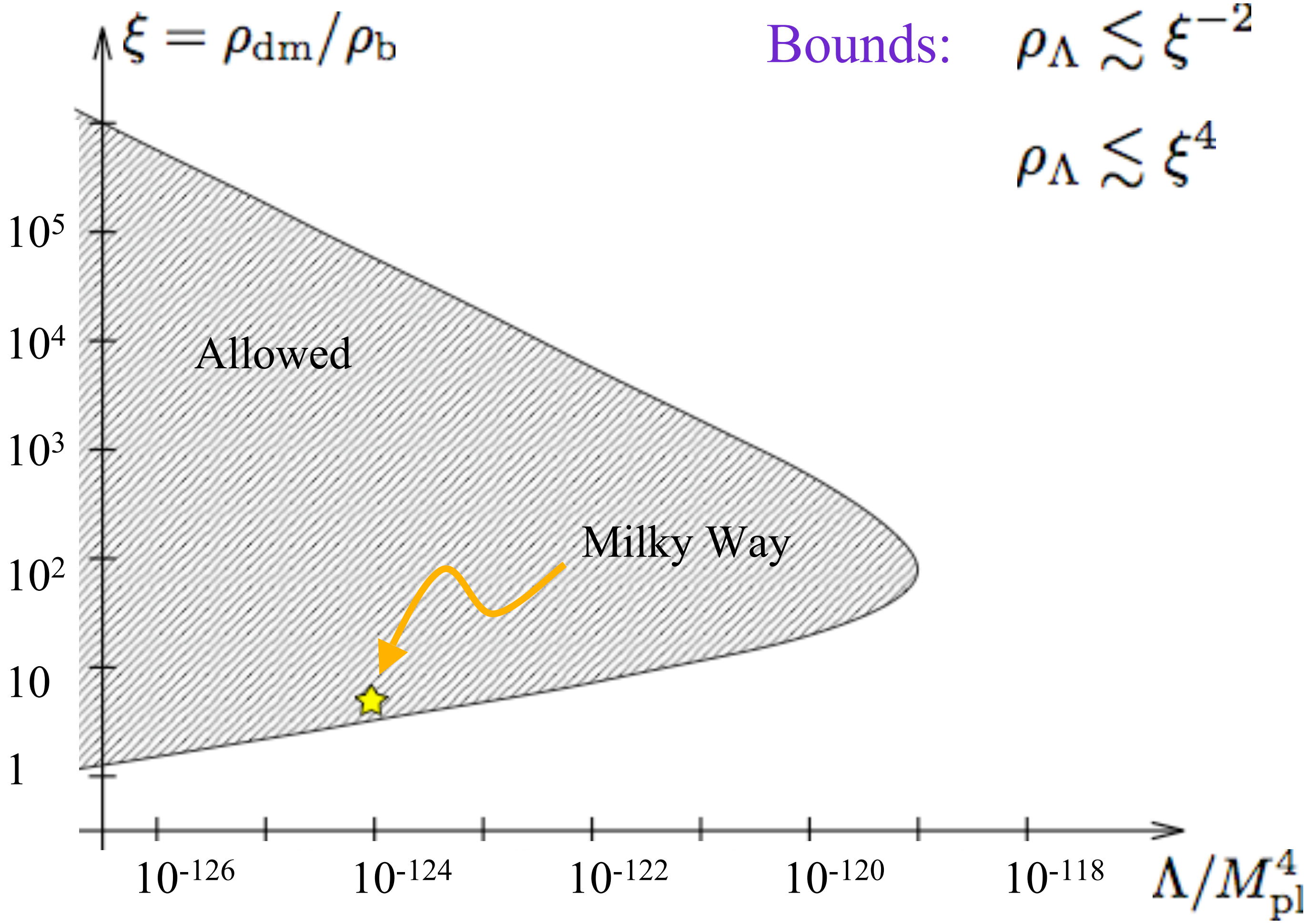
$$\rho_{\rm eq} = T_{\rm eq}^4 \sim \xi^4$$



δ_{eq} suppressed for large-scale modes

$$\delta_{\rm eq} \sim \delta_o\left(\frac{\lambda}{H_{\rm eq}^{-1}}\right)^{-2} \sim \delta_o\xi^{-8}$$

Dark Matter Bound



Bounds: $\rho_\Lambda \lesssim \xi^{-2}$

$\rho_\Lambda \lesssim \xi^4$

[Hellerman & Walcher]

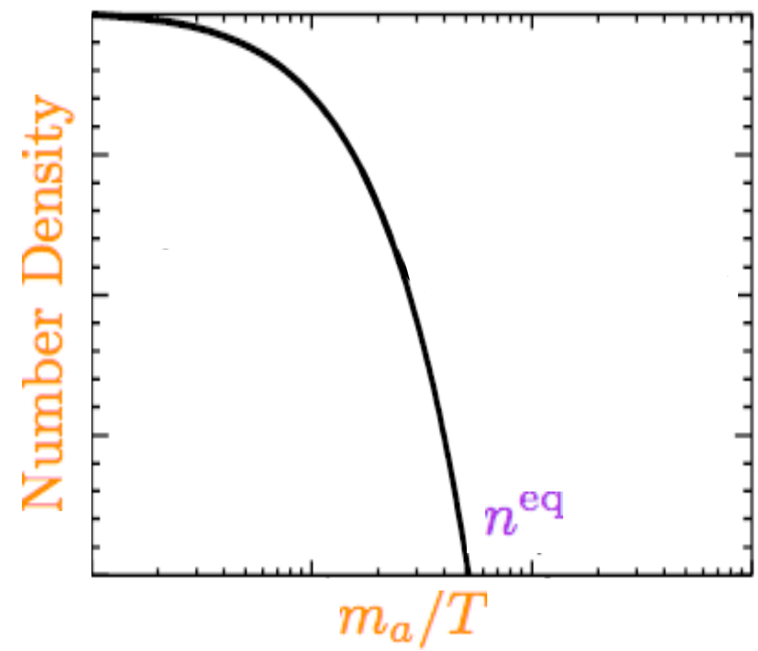
Dark Matter Bound

- Annihilation cross section for WIMPs

$$\langle \sigma v \rangle \sim \frac{\alpha_w^2}{m_{\rm wimp}^2}$$

- Interaction rate of WIMPs

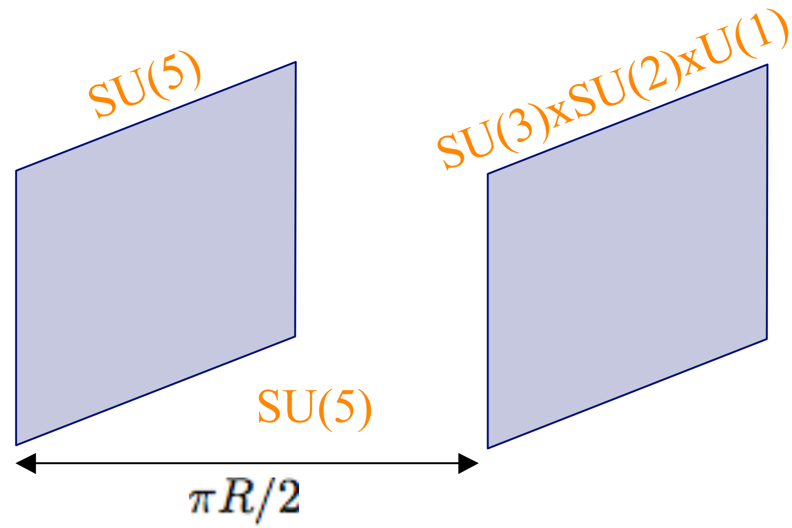
$$\Gamma = \langle \sigma v \rangle n_{\rm wimp} = \langle \sigma v \rangle \frac{\rho_{\rm dm}}{m_{\rm wimp}}$$



Unification

Potential mechanisms for suppressing proton decay rate

- Embed theory in 5D orbifold GUT
  - configuration of fields in extra dimensions can suppress proton decay



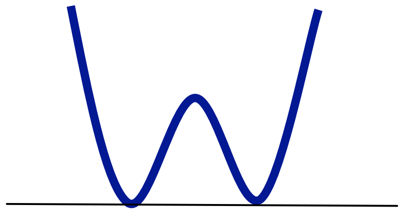
- Trinification: $SU(3)_C$x $SU(3)_L$x $SU(3)_R$ broken ~ 10^{14} GeV
  - proton decay via gauge bosons is forbidden

[Mahbubani & Senatore; de Rújula, Georgi, & Glashow]

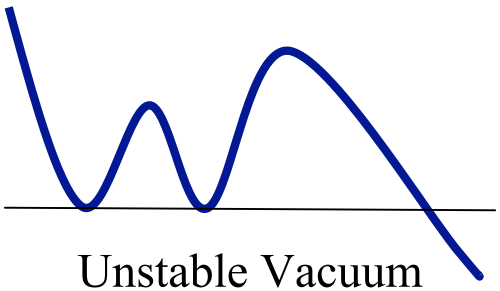
Constraints on Quartics

• Stability of potential in all field directions at all energy scales:

$$V(\mu) > 0$$



Stable Vacuum



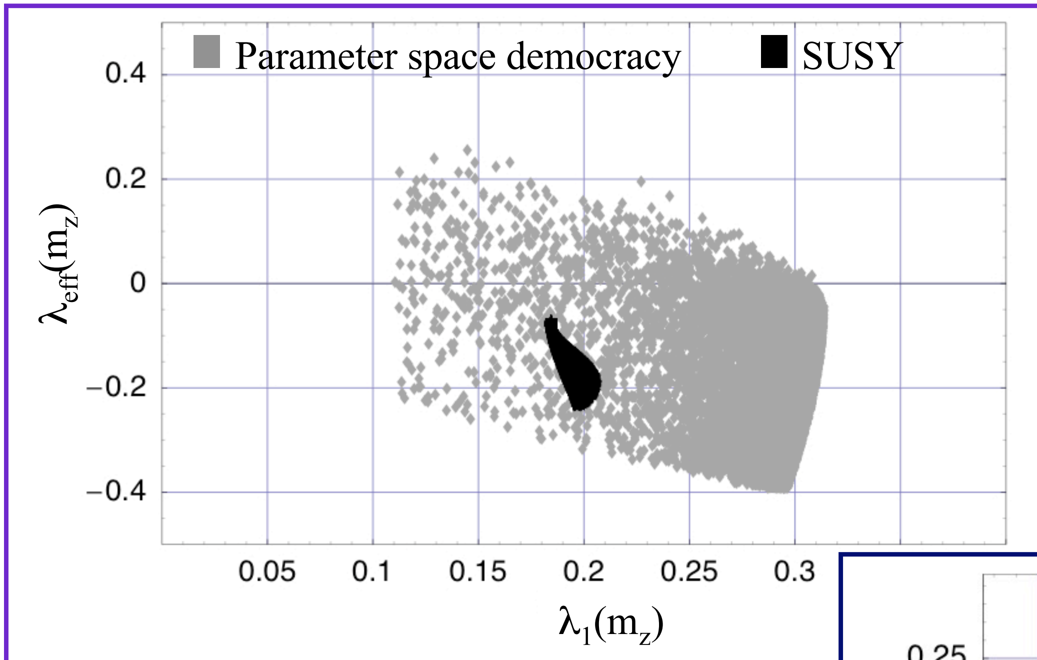
Unstable Vacuum

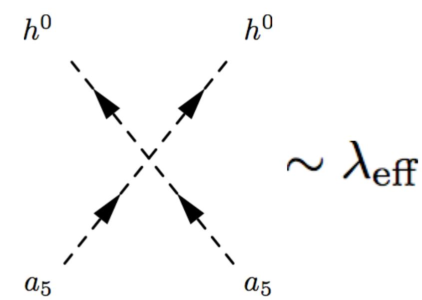
• Direct detection bound: $|\lambda_5| \gtrsim 10^{-6}$

• Experimental bound on Higgs mass: $\lambda_1 \gtrsim 0.107$

• Require that WIMP remains neutral: $\lambda_4 - 2|\lambda_5| < 0$

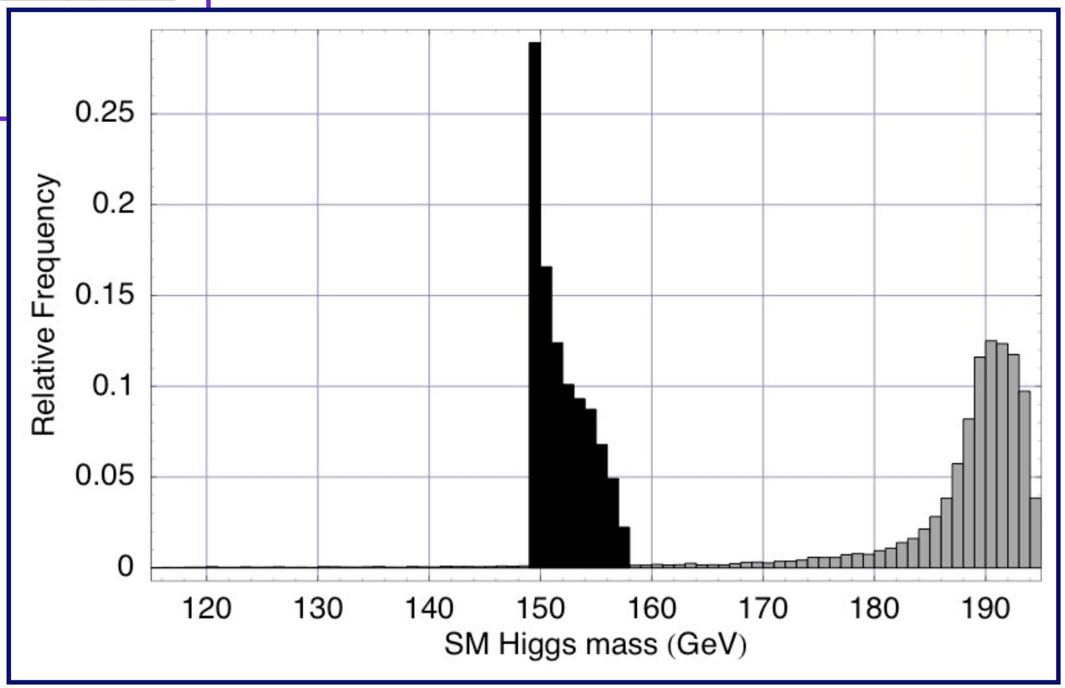
Parameter Space Democracy



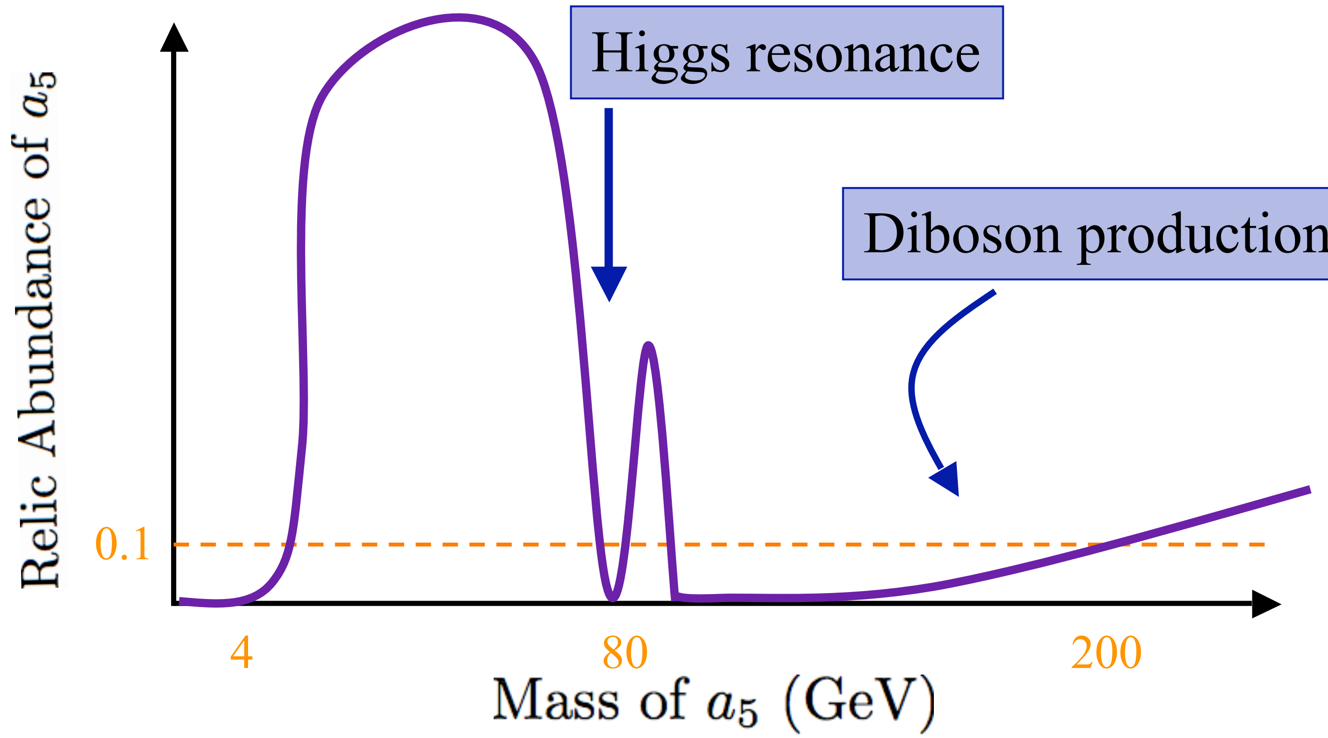


SM Higgs Mass

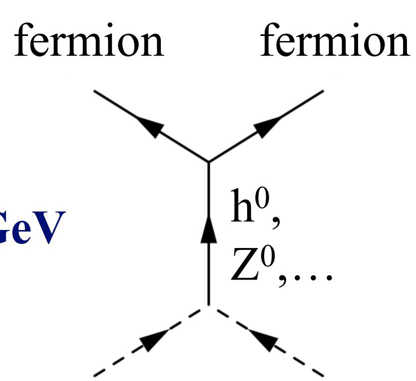
Large range, peaked at ~ 200 GeV



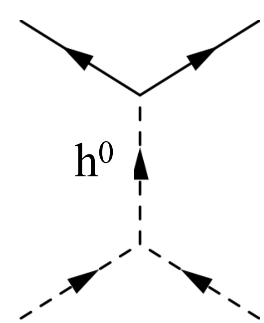
Coannihilation



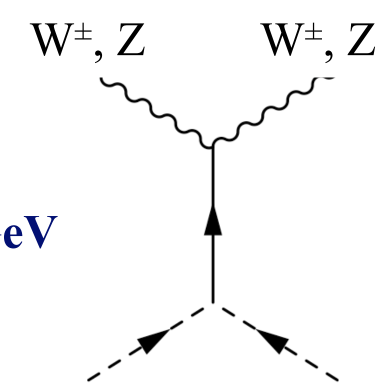
m_a < 80 GeV



m_a ~ 80 GeV



m_a > 80 GeV



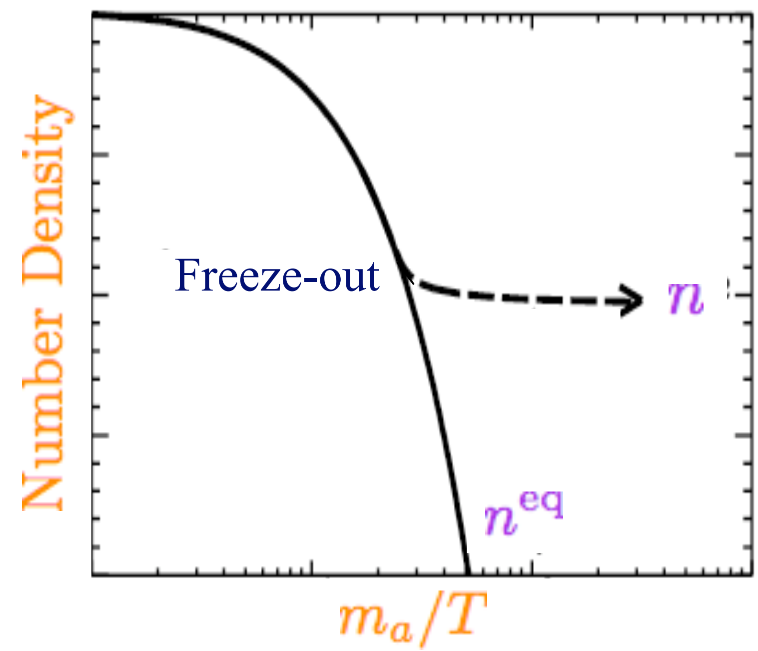
Coannihilation

- Boltzmann equation is

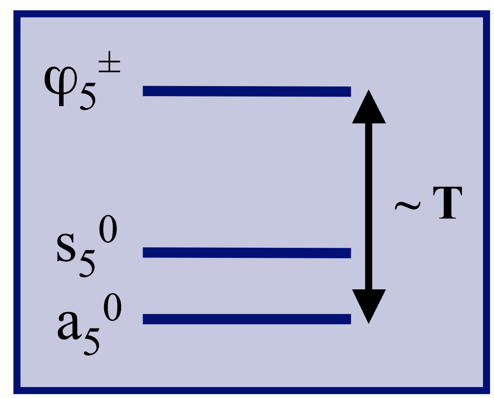
$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle [n^2 - (n^{eq})^2]$$

Particle annihilation

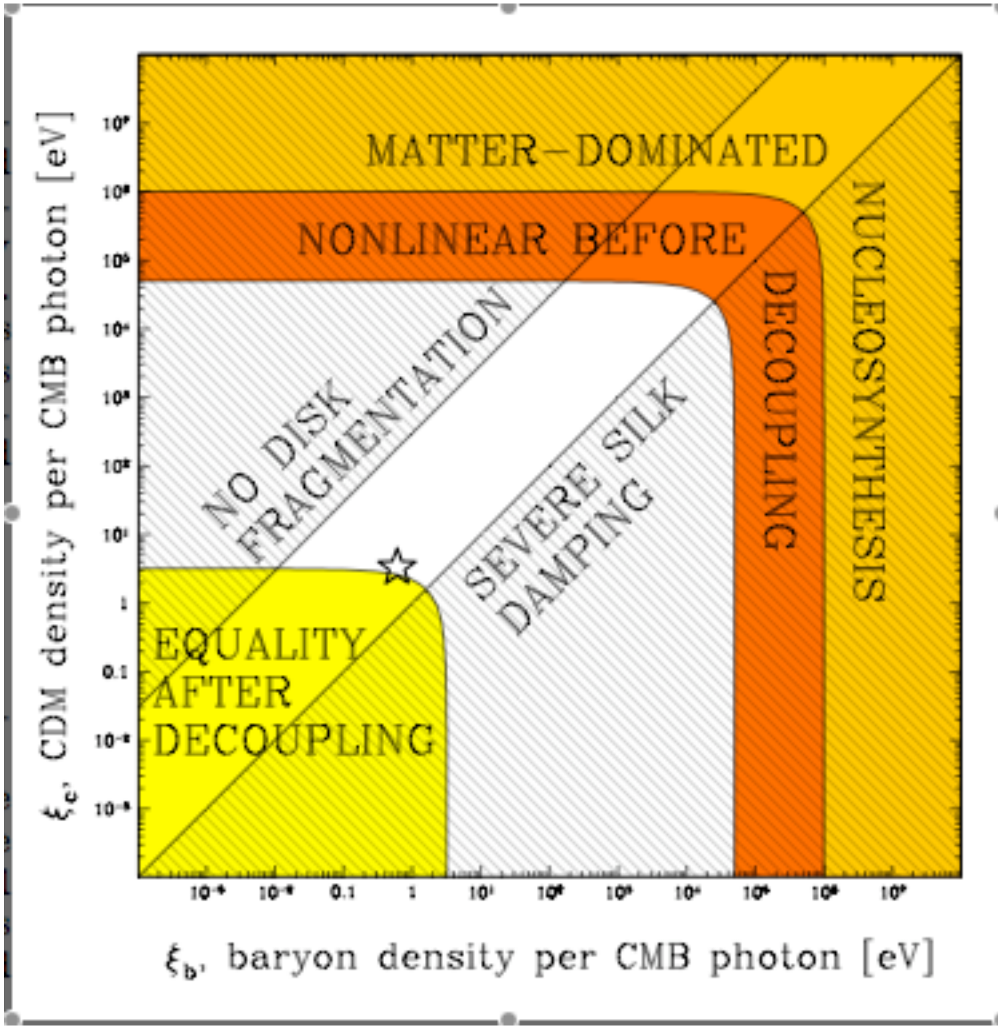
Dilution from expansion of universe



- When temperature is on the order of the mass splittings,
  - interactions including s_5 and $\varphi_5^{\pm}$ can become important in determining relic density of a_5



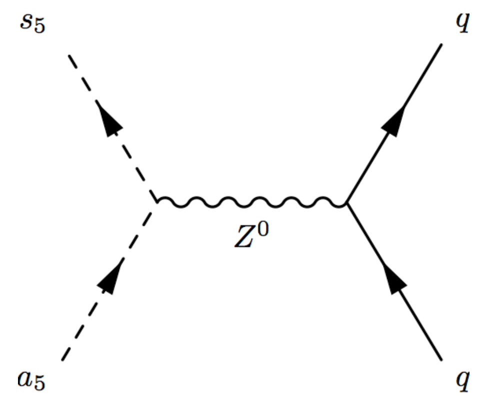
Dark Matter Bounds

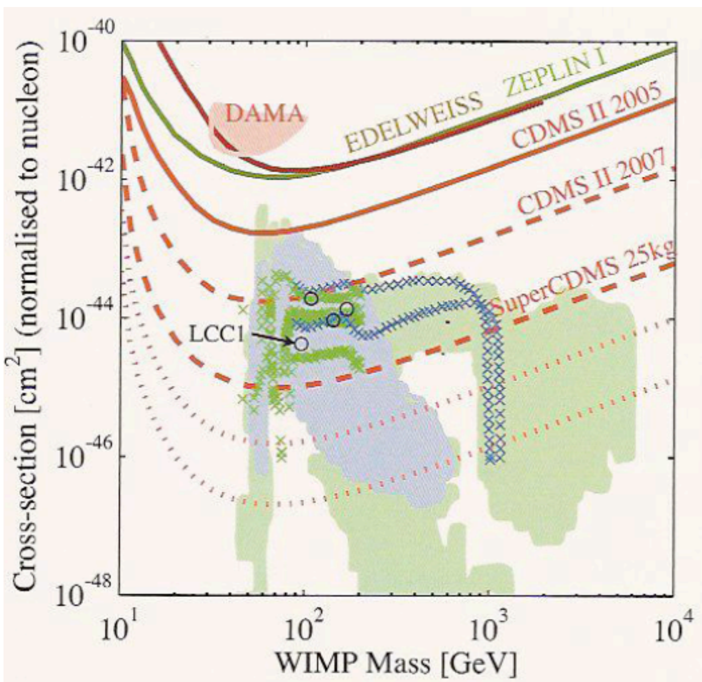


Inelastic Scattering

• Inelastic scattering between nearly-degenerate a_5 and s_5 may also contribute to spin-independent cross section

$$\Delta m_{s^0 a^0} \simeq 100 \text{ keV}$$





• Inelastic scattering may reconcile conflicting results from DAMA and CDMS

$$\Delta m_{s^0 a^0} < \frac{\beta^2 m_{a^0} m_{\mathrm{N}}}{2(m_{a^0} + m_N)}$$

• m_N larger for DAMA → higher cutoff for mass splittings that can be observed

[Smith & Weiner]

Electroweak Precision Tests

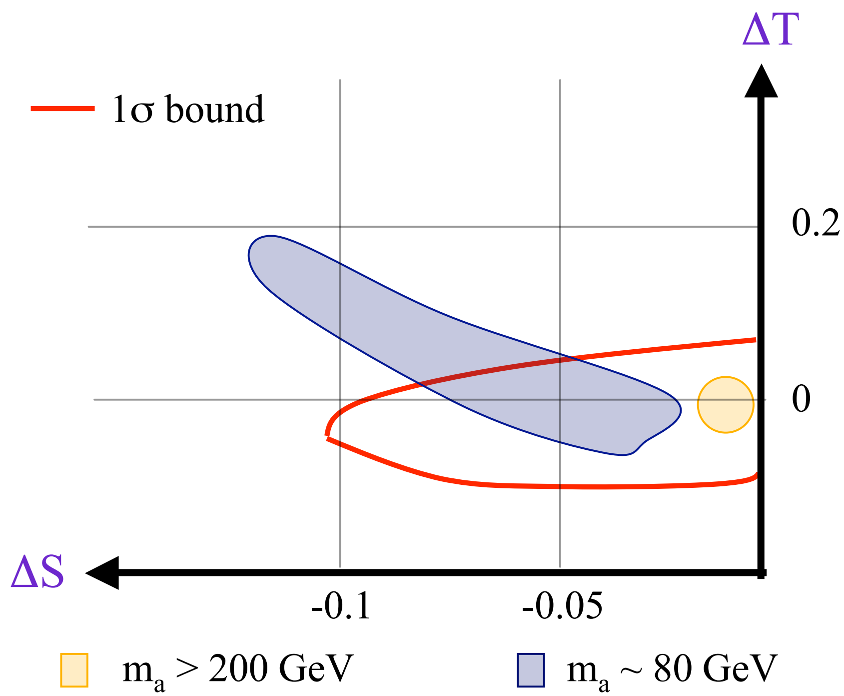
Are masses and quartics consistent with electroweak data?

• For small mass differences, corrections to S and T parameters are

$$\Delta T \propto \frac{5}{m_a \alpha v^2}(m_{\phi^\pm} - m_a)(m_{\phi^\pm} - m_s) \qquad \Delta S \propto \frac{5v^2}{m_a^2}\lambda_4$$

• Heavy dark matter fits well within the experimental bound

• Some of the light dark matter region excluded experimentally



Signatures at the LHC

H_5 scalars may be produced at the LHC

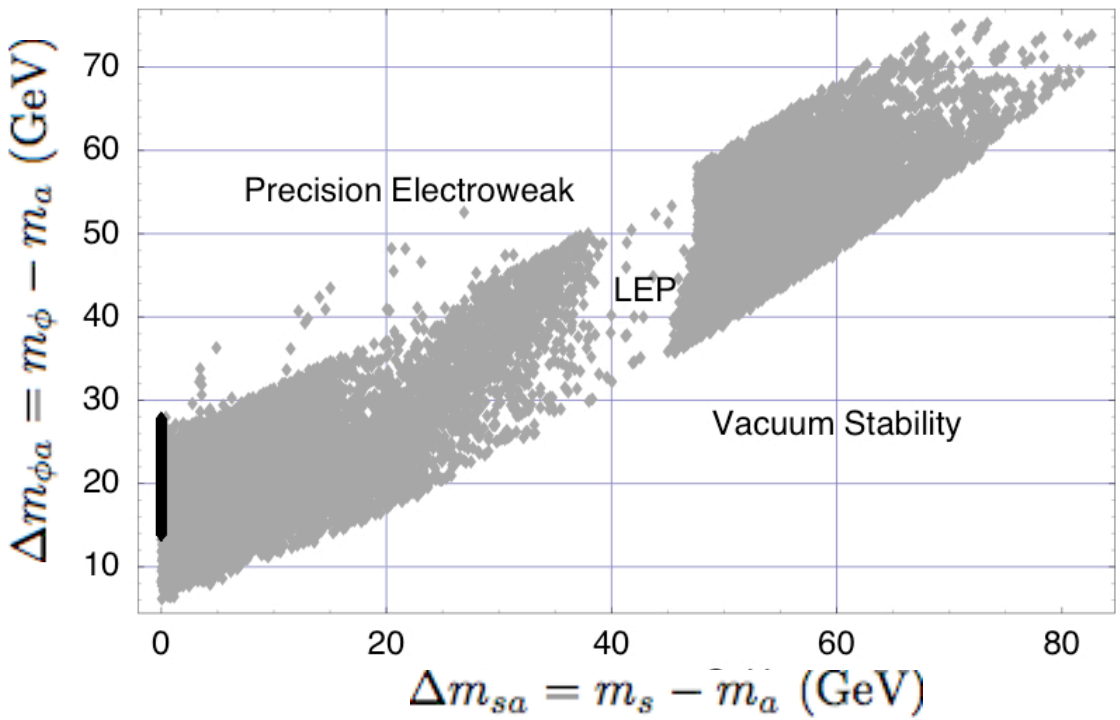
$p\,p \rightarrow a_5^0\, s_5^0$
↳ $Z^0\, a_5^0$

$p\,p \rightarrow a_5^0\, \varphi_5^\pm$
↳ $W^\pm\, a_5^0$

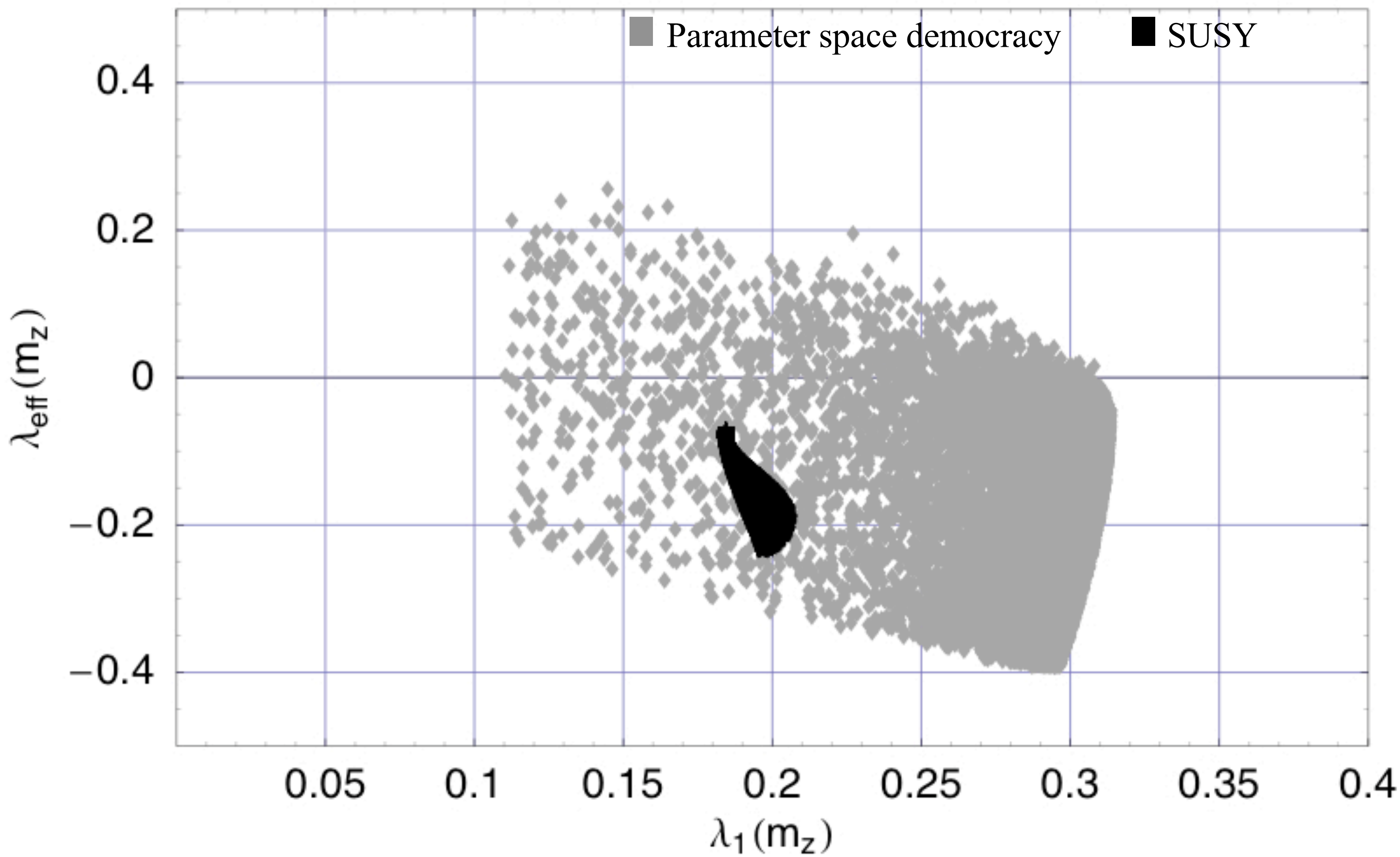
$p\,p \rightarrow s_5^0\, \varphi_5^\pm$
↳ $Z^0\, W^\pm\, 2a_5^0$

$p\,p \rightarrow \varphi_5^\pm\, \varphi_5^\pm$
↳ $2W^\pm\, 2a_5^0$

- Gauge bosons are always off-shell
  - Opposite-sign leptons + $\not\!\!E_T$



Direct Detection

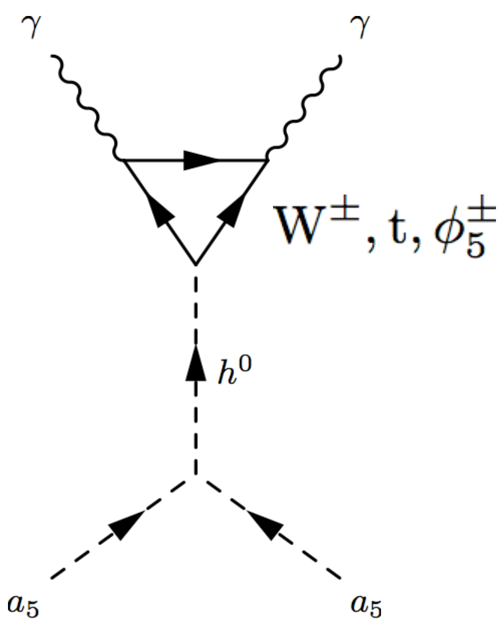


$$\sigma_n = 2 \times 10^{-9}\ \text{pb}\left(\frac{\lambda_{\text{eff}}}{0.4}\right)^2\left(\frac{350\ \text{GeV}}{m_{a^0}}\right)^2\left(\frac{200\ \text{GeV}}{m_{h^0}}\right)^4$$

Indirect Detection

Low-mass dark matter (~80 GeV)

s-channel Higgs exchange dominates over box diagrams



$$\sigma(a_5 a_5 \to \gamma\gamma) u \simeq \frac{1}{N_h} \frac{v^2 \lambda_{eff}^2}{(s - m_{h^0}^2)^2 + m_{h^0}^2 \Gamma_{h^0}^2} \frac{\Gamma(h^0 \to \gamma\gamma)}{\sqrt{s}}$$