Unification and Dark Matter in a Minimal Scalar Extension of the Standard Model

(arXiv:0704.2816)

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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

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

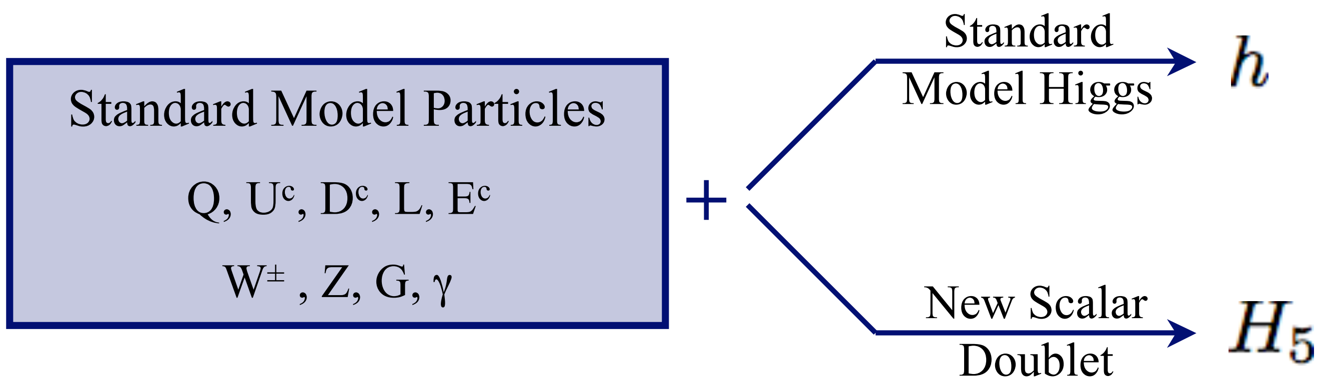
[Agrawal, Barr, Donoghue and Seckel]

- Dark Matter Mass

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

[Hellerman & Walcher; Tegmark et al.]

Six Higgs Doublet Model



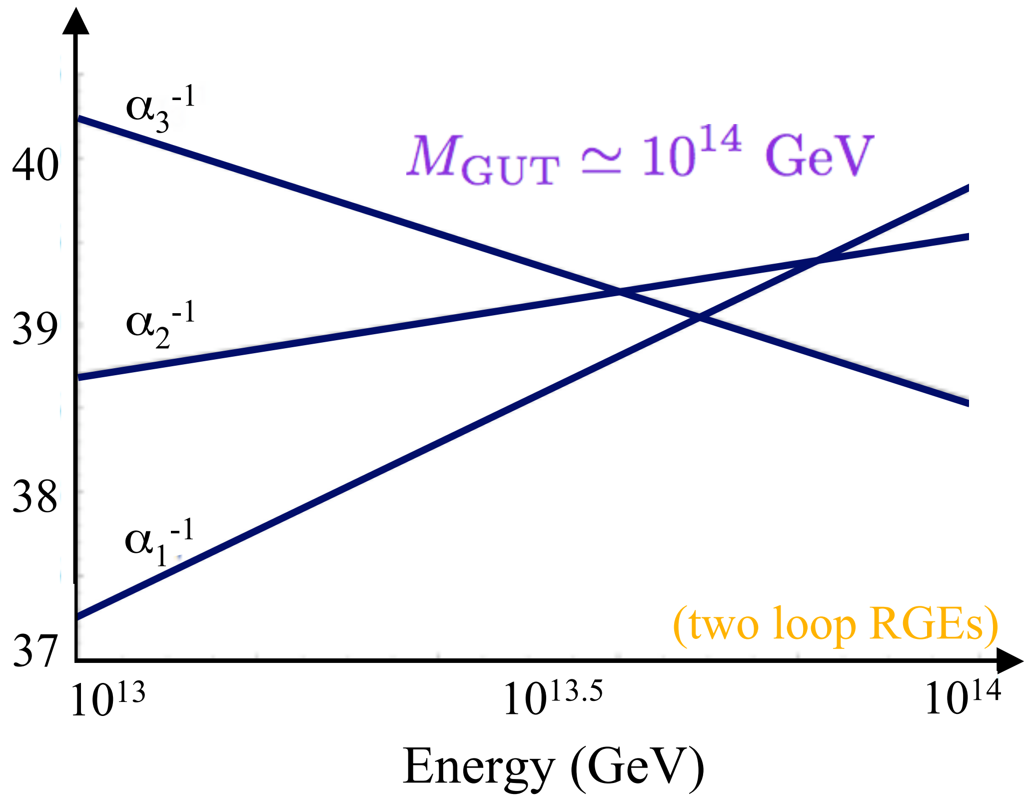
- H_5 charged under **5** representation of discrete symmetry group (i.e., S_6)
  - Standard Model particles are neutral under this symmetry

- 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



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

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

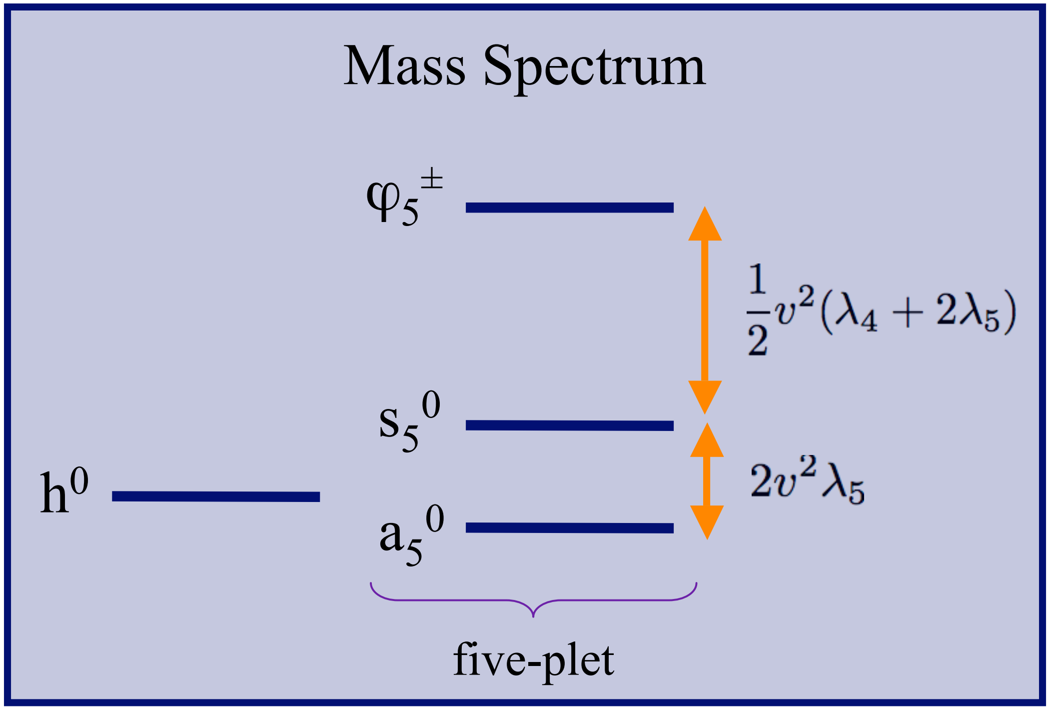
solutions: embed in 5D orbifold GUT, trinification,…

Mass Spectrum

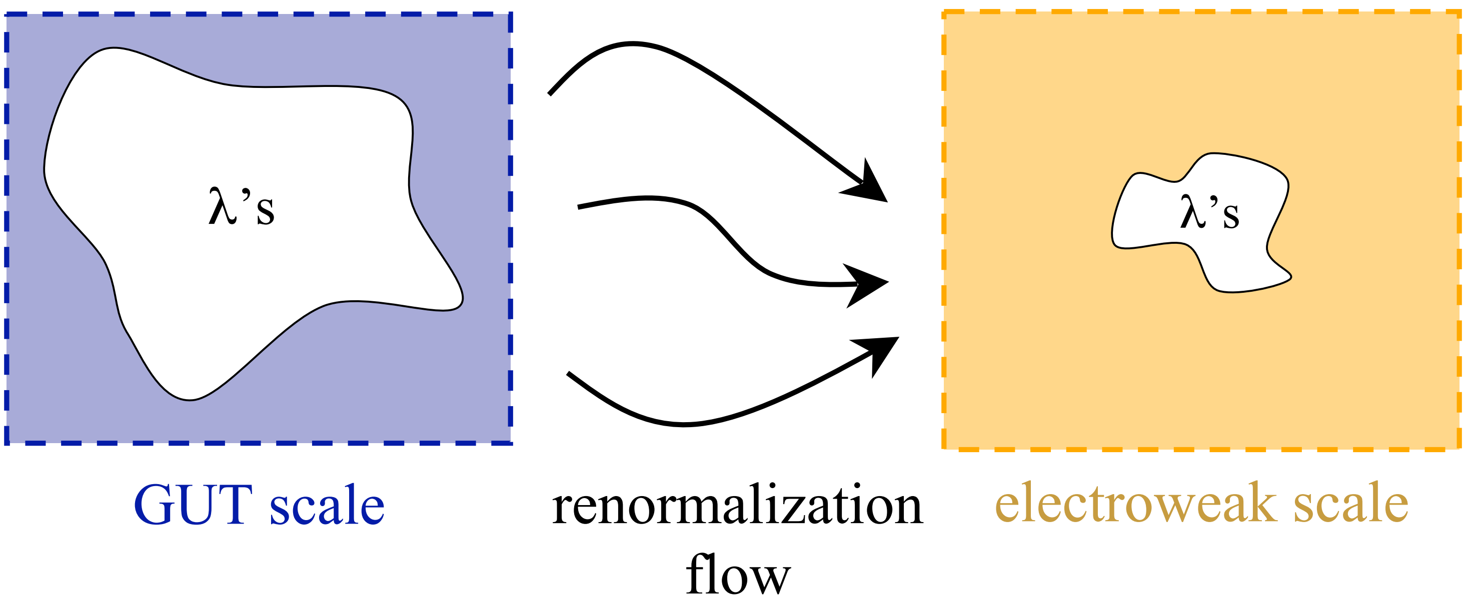
$$V \supset \underbrace{\lambda_1(|h|^2 - 2v^2)|h|^2}_{\text{Electroweak symmetry breaking}} + \lambda_4|h^\dagger H_n|^2 + \underbrace{\lambda_5((h^\dagger H_n)^2 + \text{h.c.})}_{\text{Breaks accidental U(1) symmetry}}$$

- 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



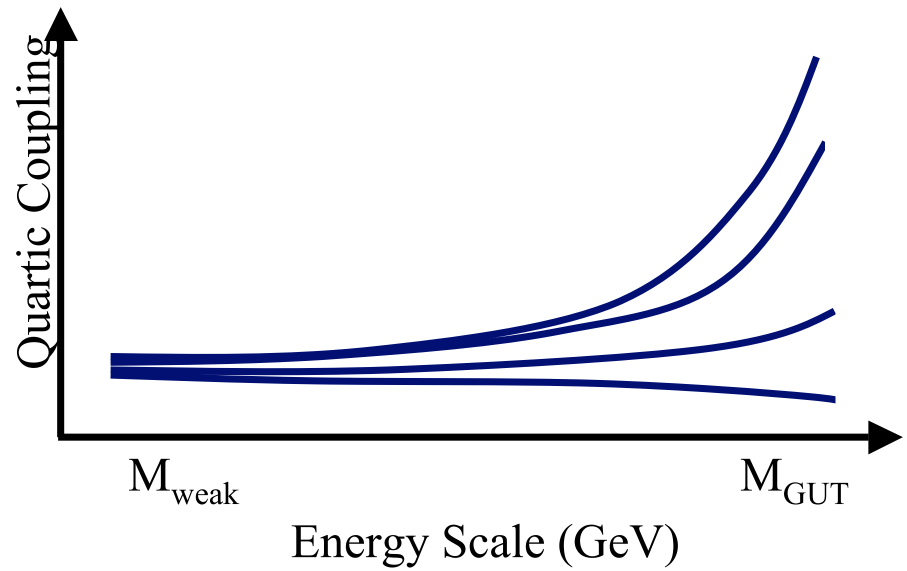
- Landscape gives many possibilities for couplings at GUT scale.
  What are the typical values in our neighborhood of vacua?

- 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

Supersymmetry

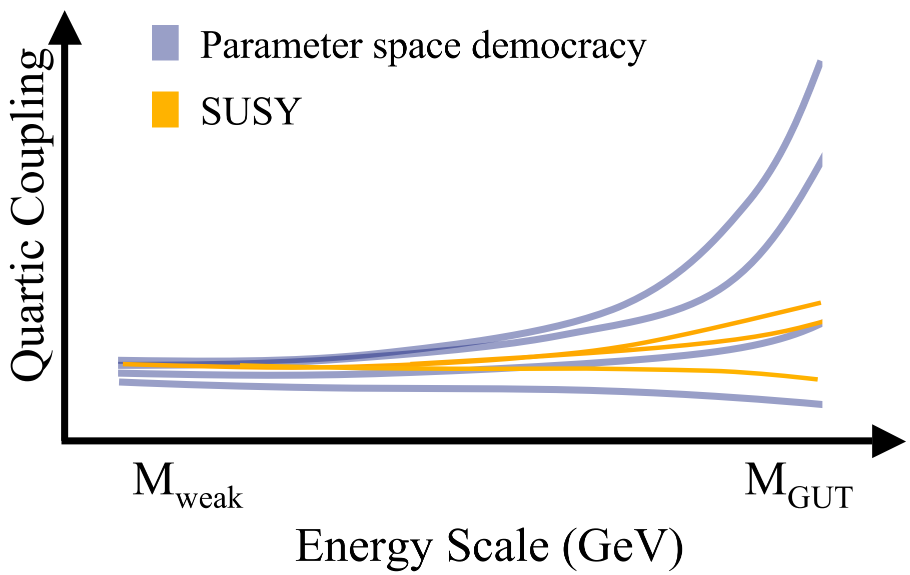
Quartic couplings arise from D-terms

• 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

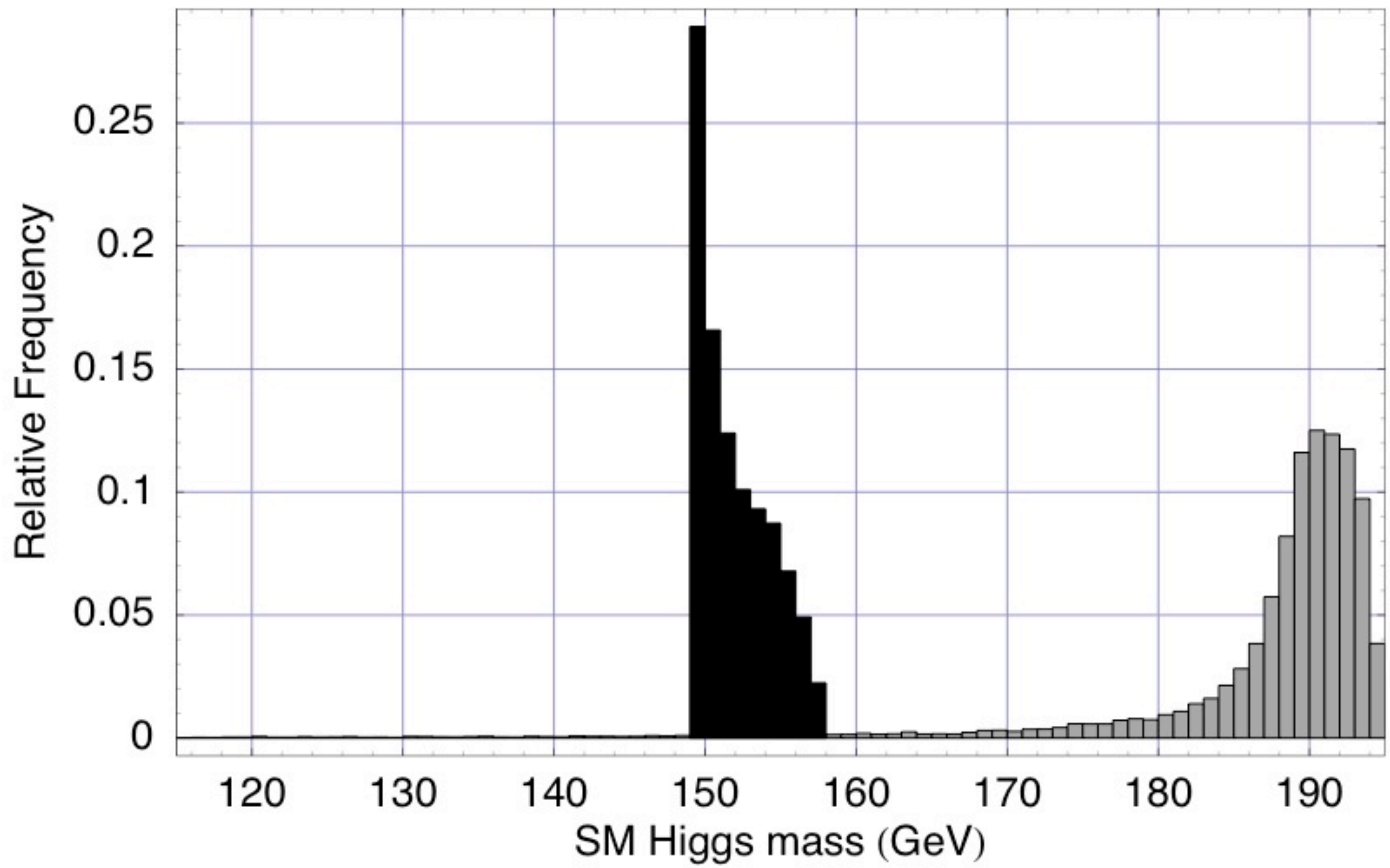
- Even smaller range at low energy

Renormalization Effects

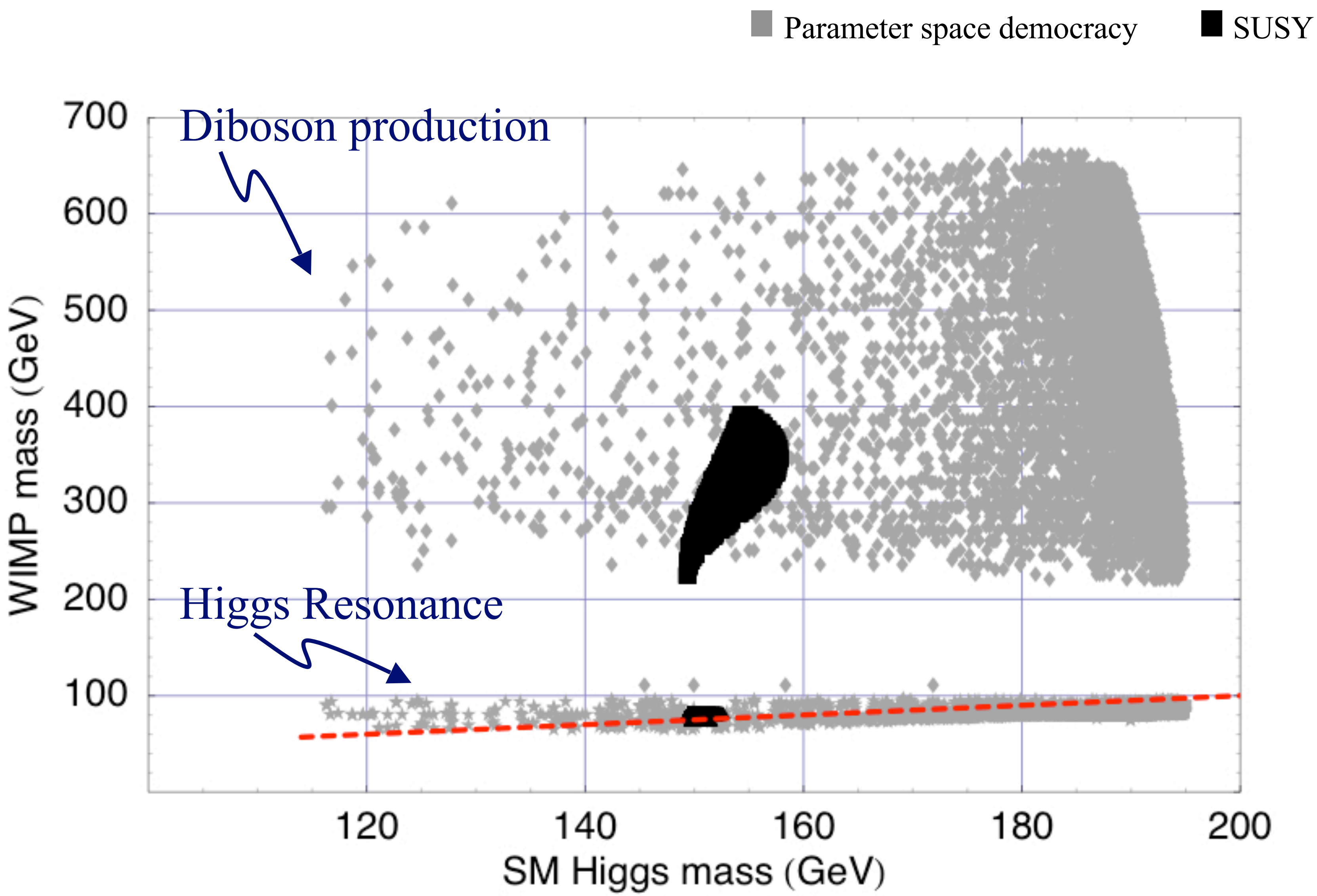
Parameter space democracy ■ SUSY

PSD: Large range, peaked at 200 GeV

SUSY: Small range ~ 155 GeV



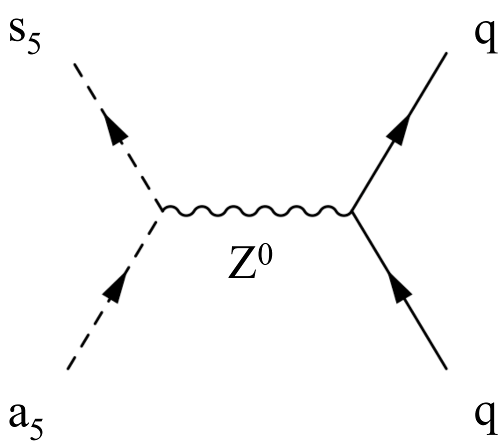
Relic Abundance



Direct Detection

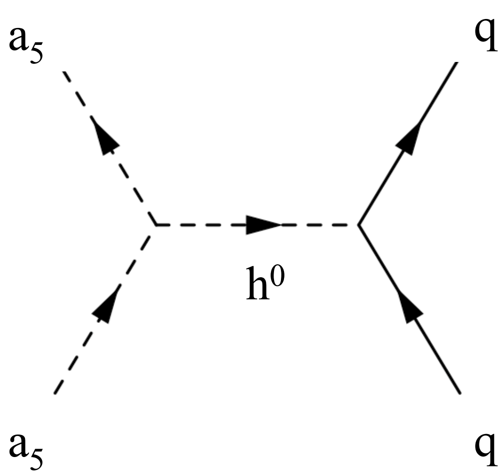
• Inelastic scattering between a_5 and s_5 bounds mass splitting

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

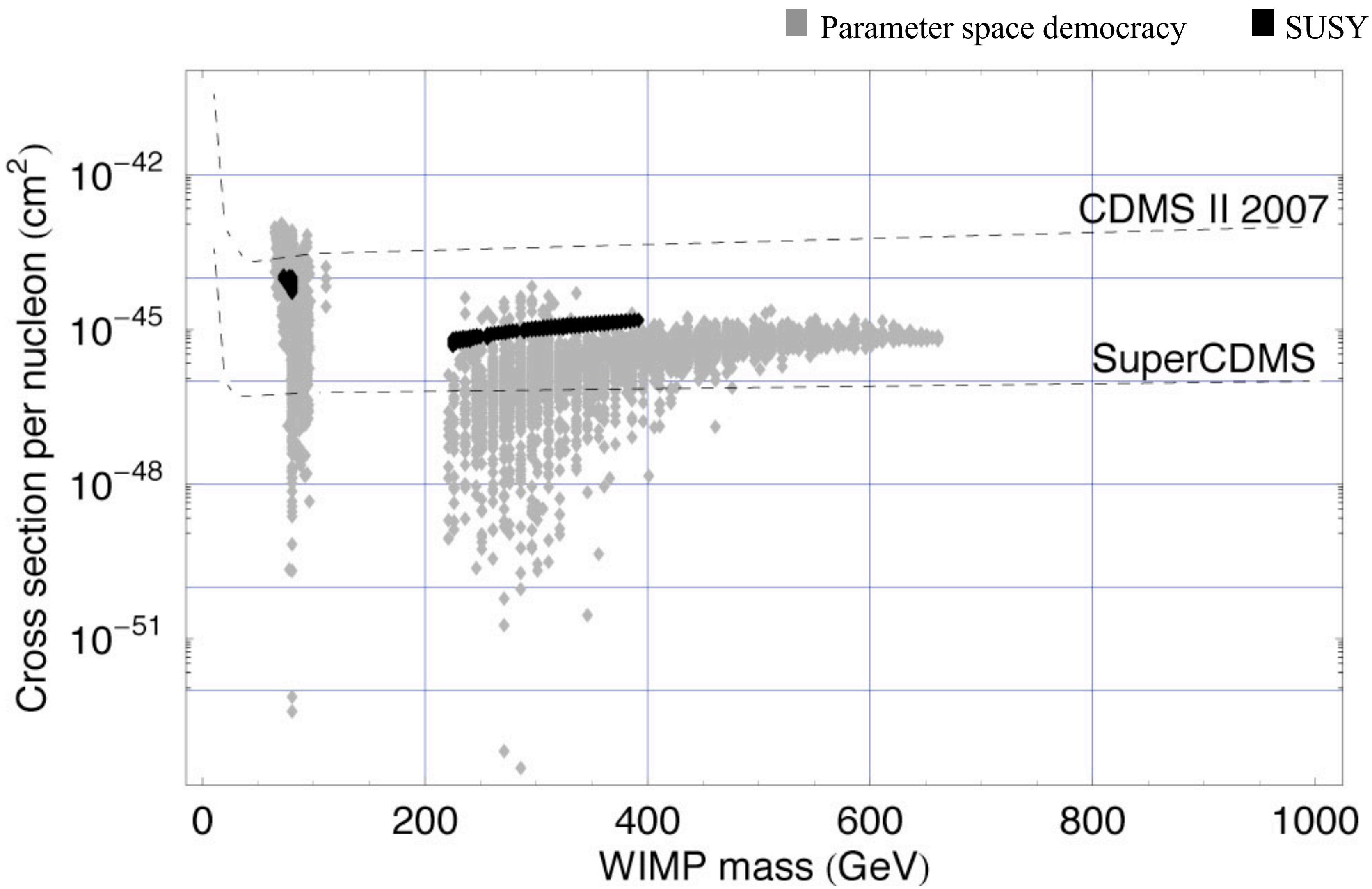


• Elastic scattering between a_5 and a_5 dominates spin-independent contribution

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



Direct Detection



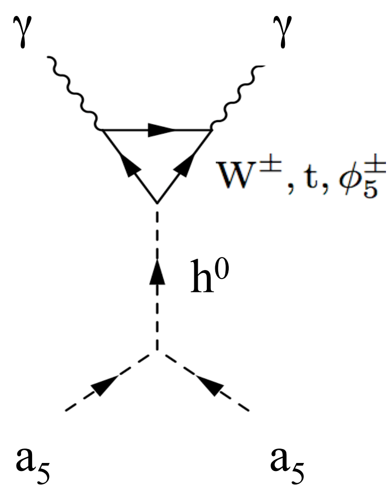
Indirect Detection

Monochromatic photons produced by WIMP annihilation

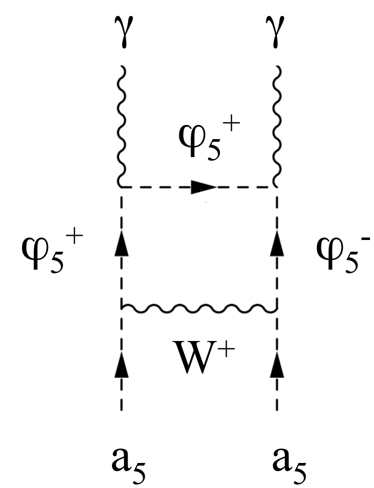
- Flux observed by a telescope with a field of view $\Delta\Omega$ and line of sight $\Psi(\theta,\phi)$:

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

Low-mass dark matter (~80 GeV)

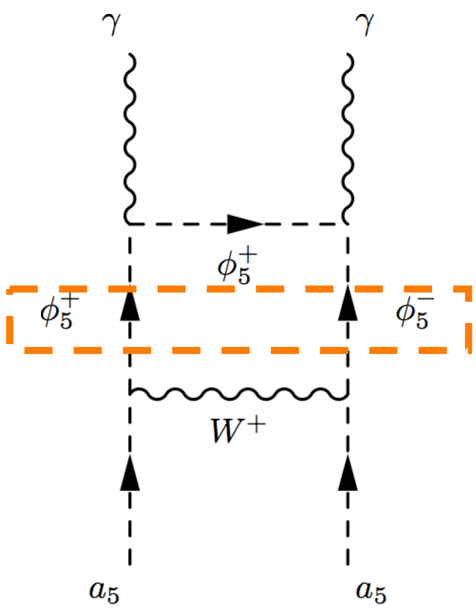


High-mass dark matter (≥ 200 GeV)



Indirect Detection

High-mass dark matter (≥ 200 GeV)



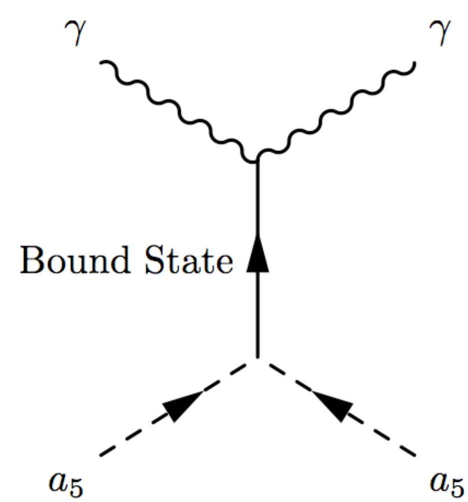
When $m_a \sim m_\varphi$, there is an effective Yukawa force between the $\varphi_5^+ \varphi_5^-$ pair:

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

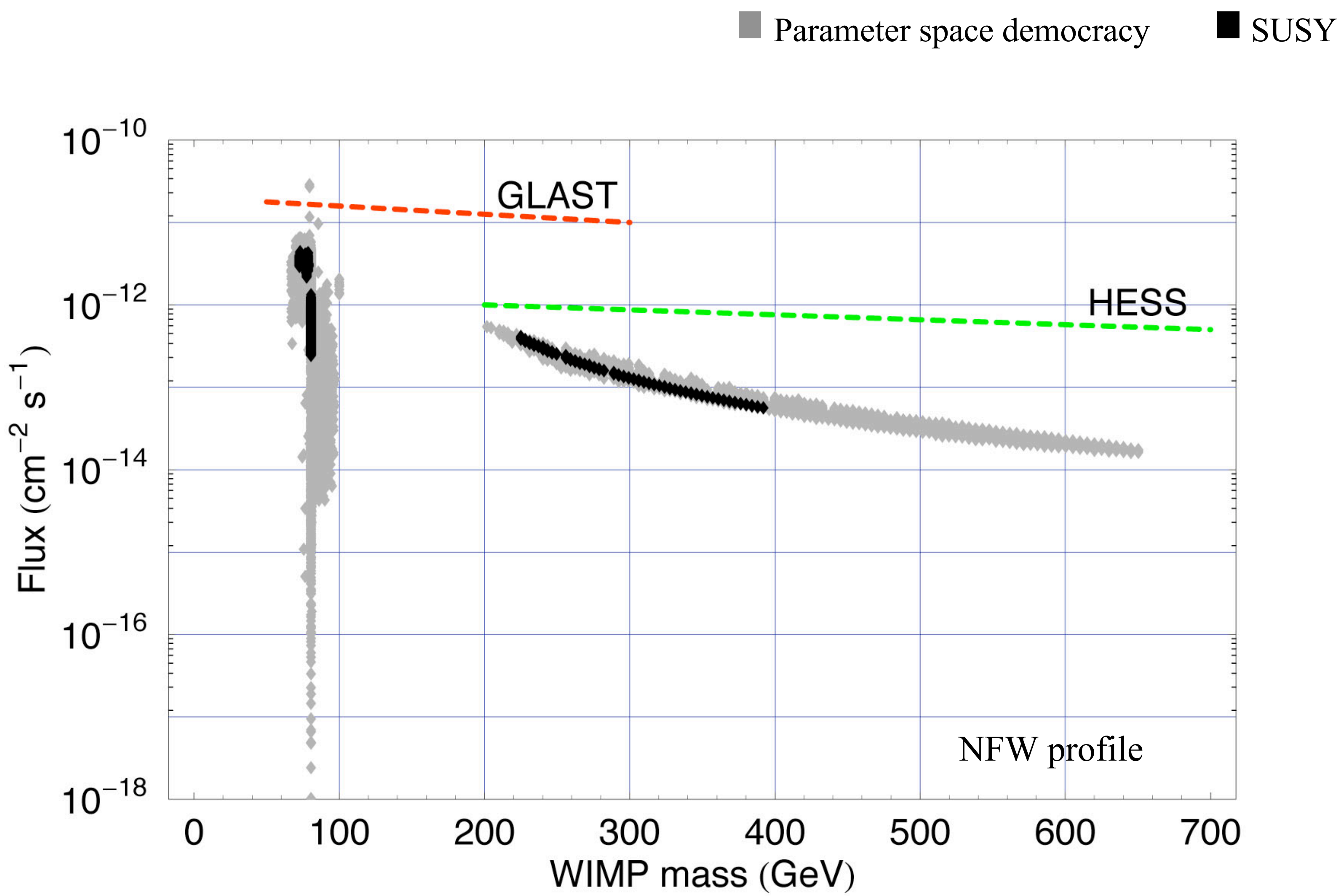
Charged scalars form a bound-state solution to the non-relativistic Schrodinger equation.

$$\sigma(a_5 a_5 \to \gamma\gamma)u = \left[\sigma(a_5 a_5 \to \mathrm{BS})u\right]\Gamma(\mathrm{BS} \to \gamma\gamma)$$

$$\sim \frac{\alpha^2 \alpha_2^2}{N_h M_{\mathrm{w}}^2}\left(1 + \sqrt{\frac{2 m_a \Delta m_{\phi a}}{M_{\mathrm{w}}^2}}\right)$$

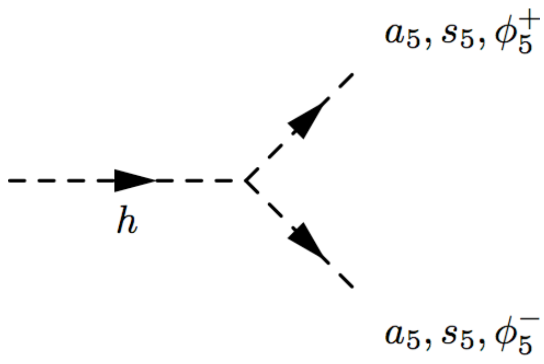


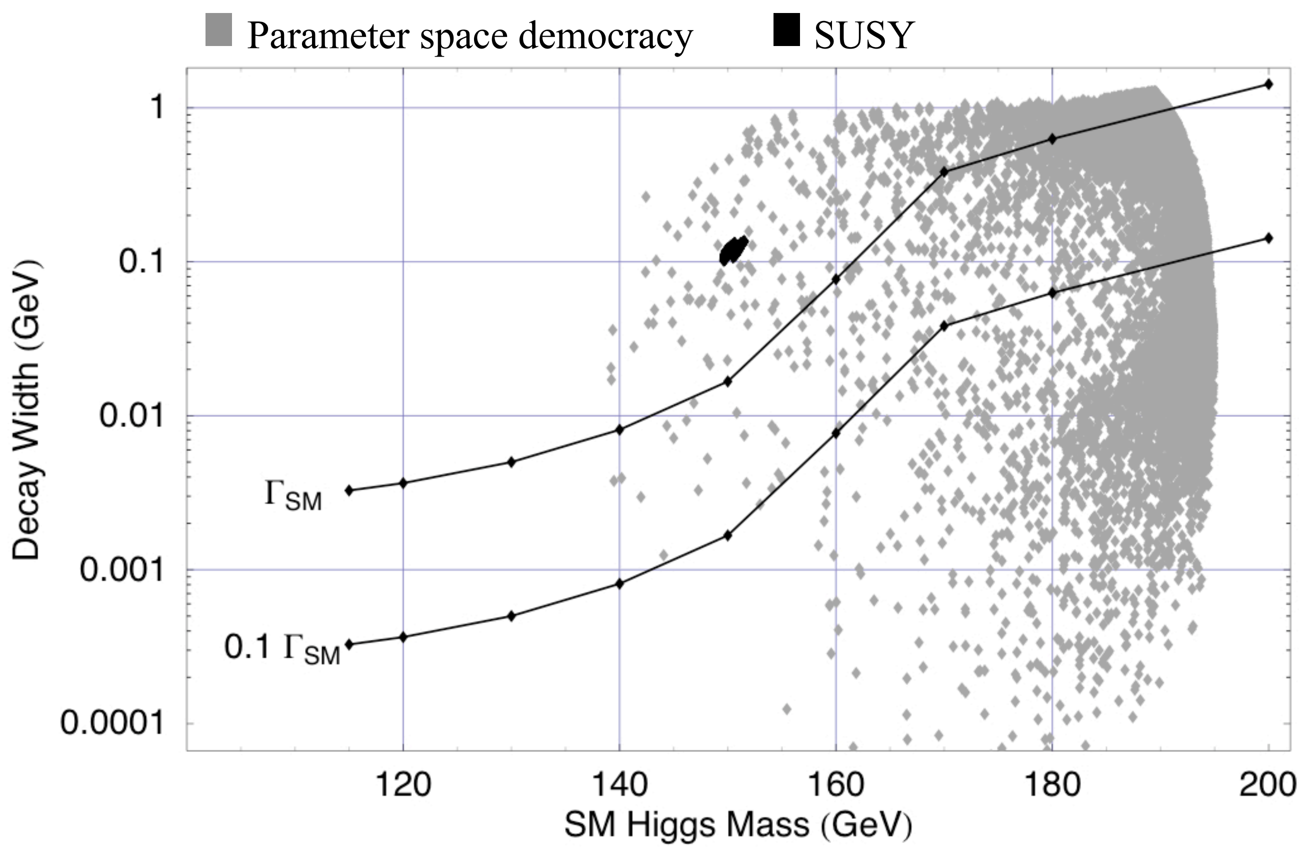
Indirect Detection



Decay of the Standard Model Higgs

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

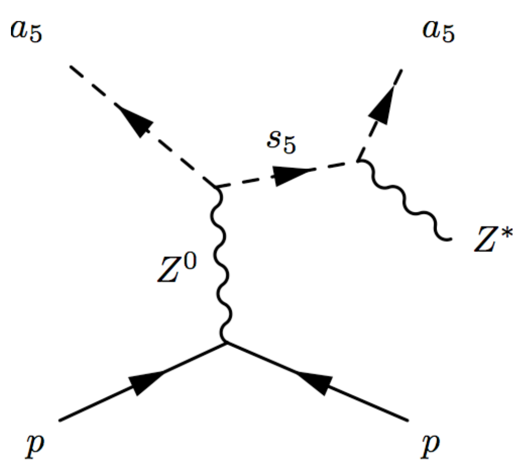




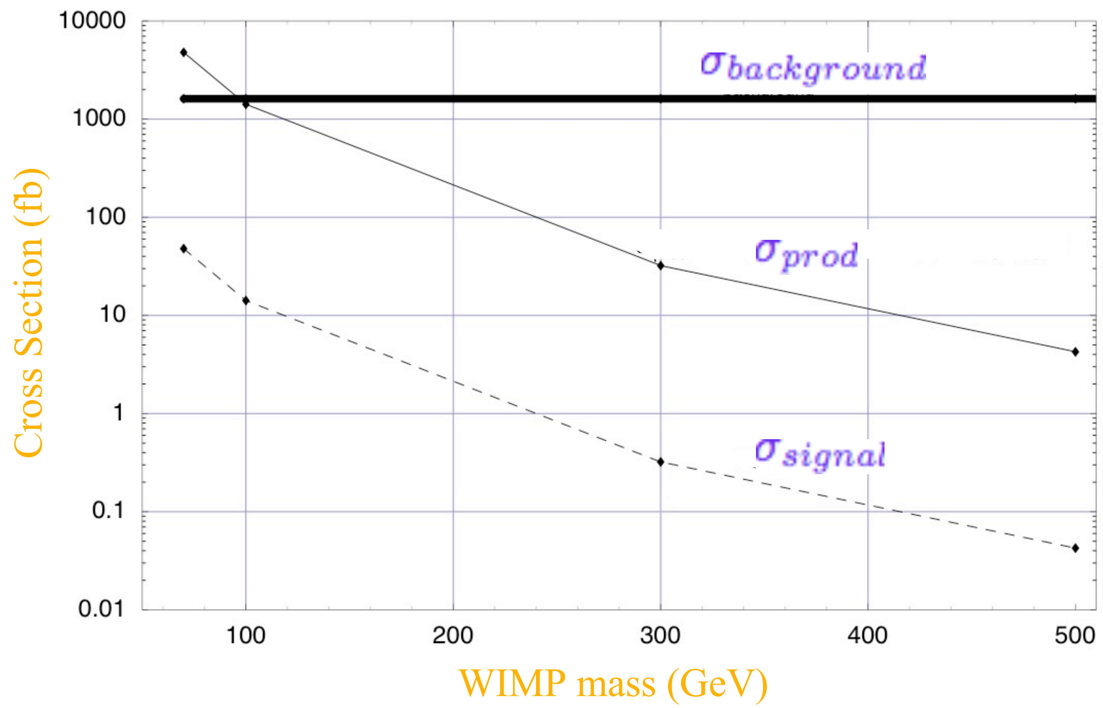
Signatures at the LHC

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



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



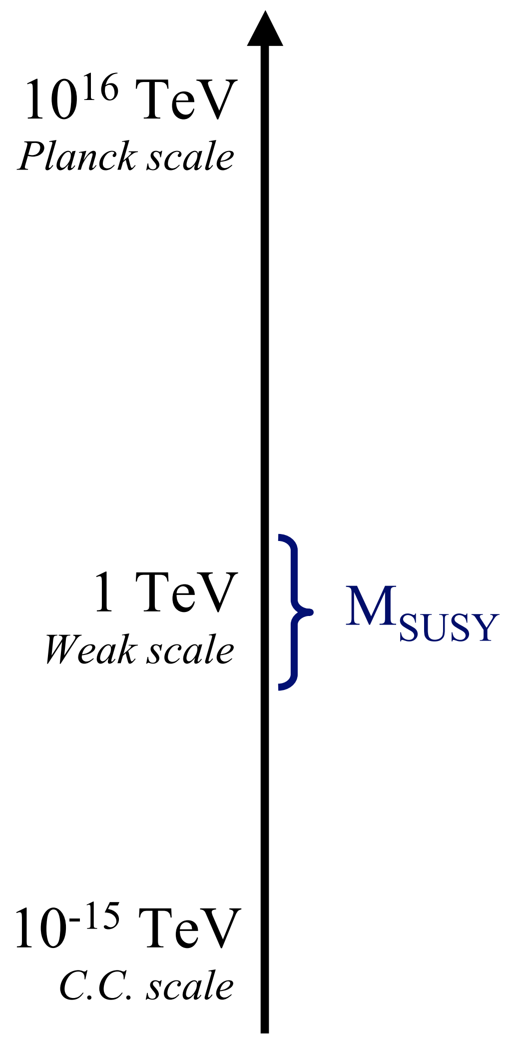
$$\left[\ \sigma_{background} = \sigma(pp \to WW){\rm Br}(W \to l\nu)^2 + \sigma(pp \to ZZ){\rm Br}(Z \to l^+ l^-){\rm Br}(Z \to \nu\nu)\ \right]$$

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)

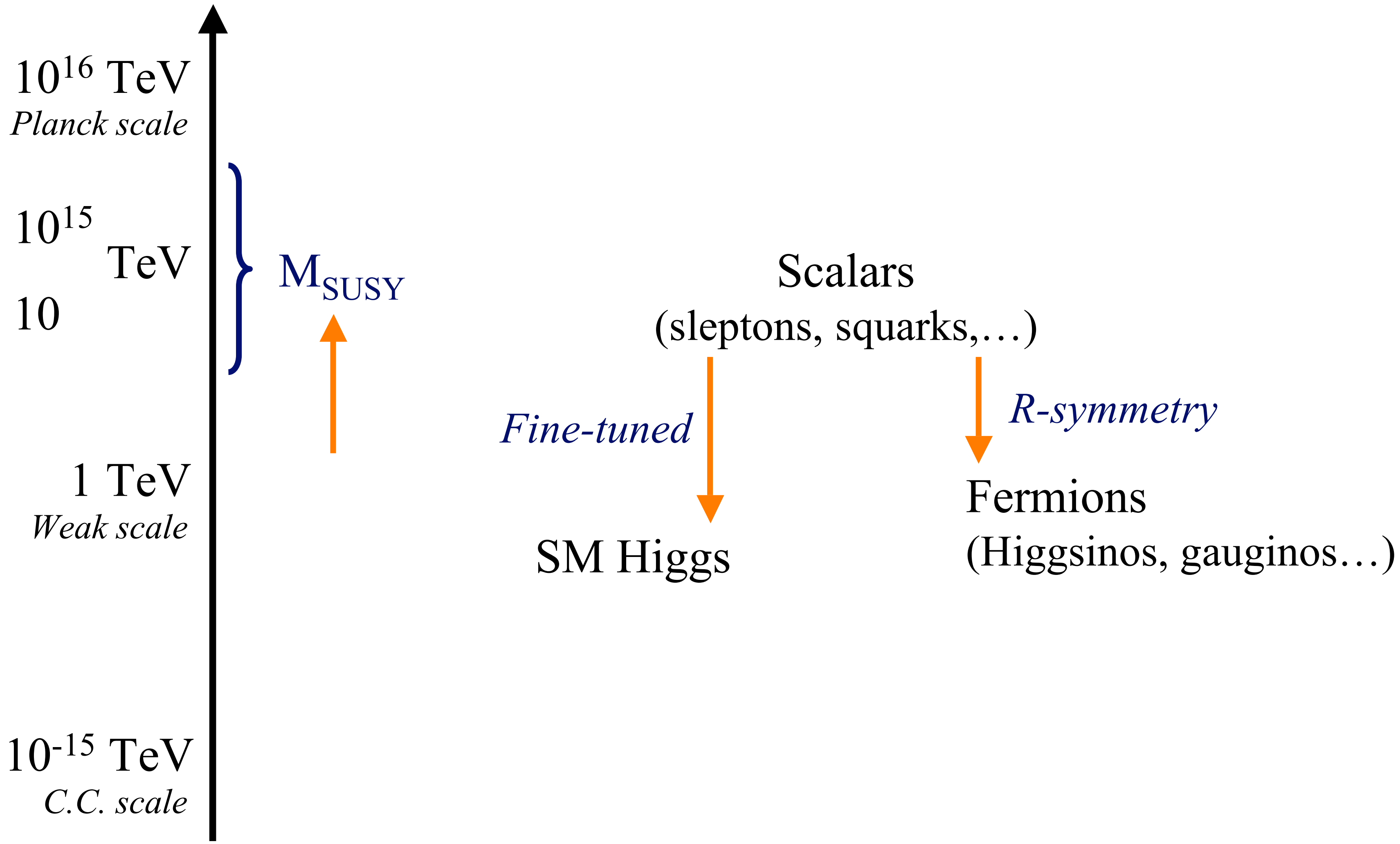
	Light $m_a \sim 80$ GeV	Heavy $m_a > 200$ GeV
Direct Detection	CDMS II	SuperCDMS
Indirect Detection	GLAST, HESS	GLAST, HESS
SM Higgs Decay	Tevatron, LHC	No luck
Direct Production	LHC	ILC?

Split Supersymmetry



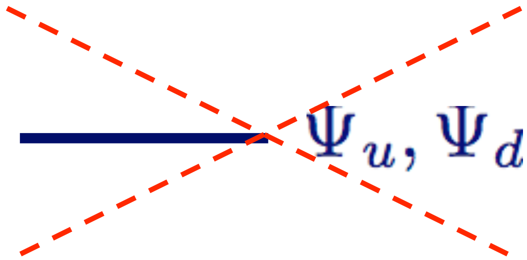
[Arkani-Hamed & Dimopoulos]

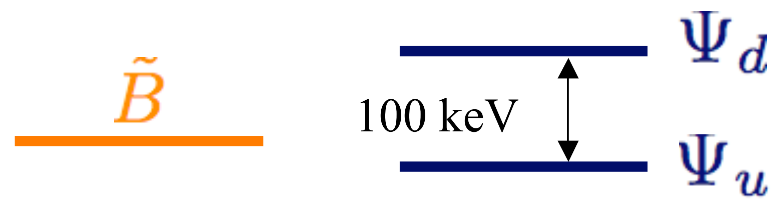
Split Supersymmetry



[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

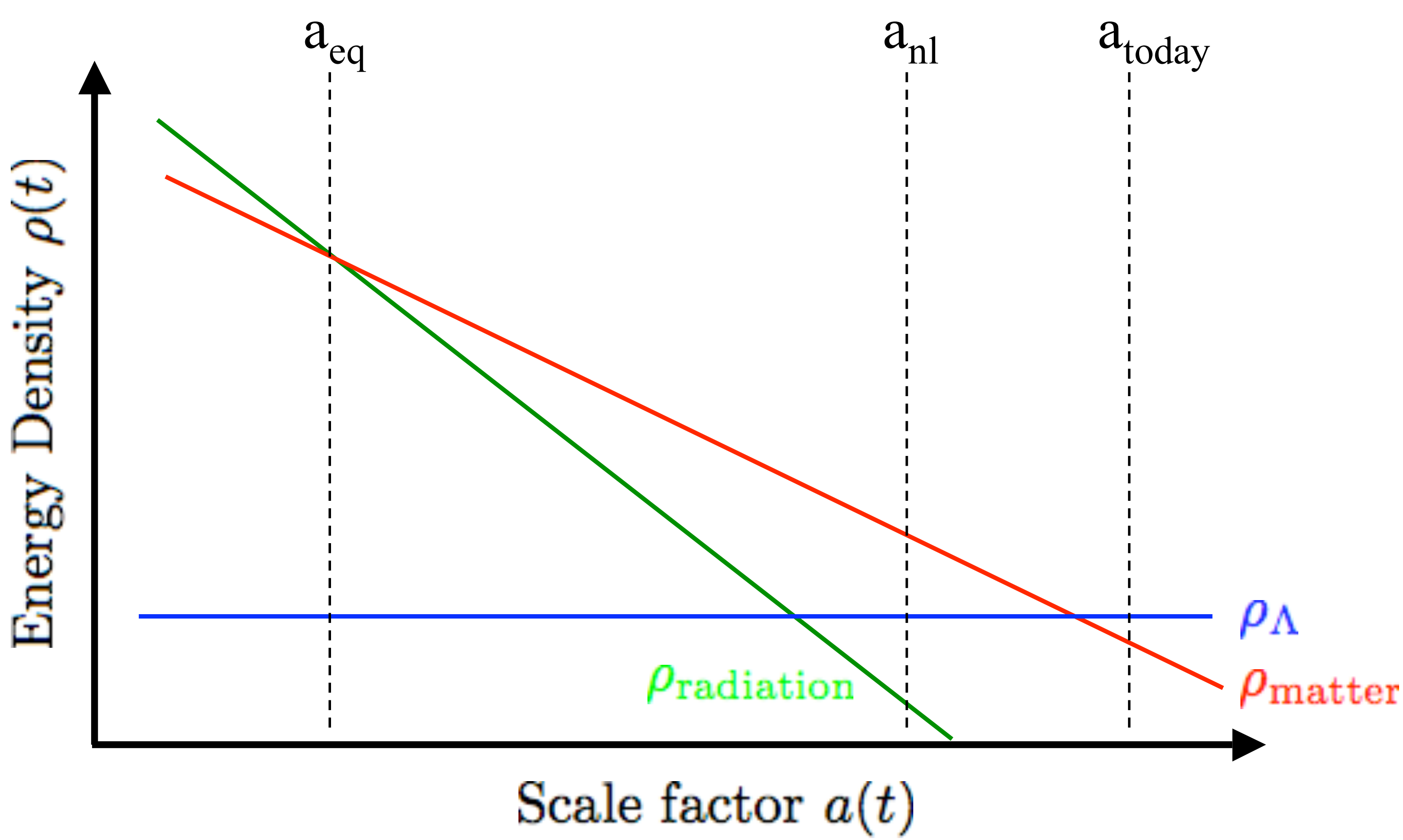
- Unification
- Dark matter mass:

  100 GeV - 2 TeV
- 2 fine-tunings:

  Higgs mass & C.C.

[Mahbubani & Senatore; Cirelli, Fornengo & Strumia]

Galactic Principle



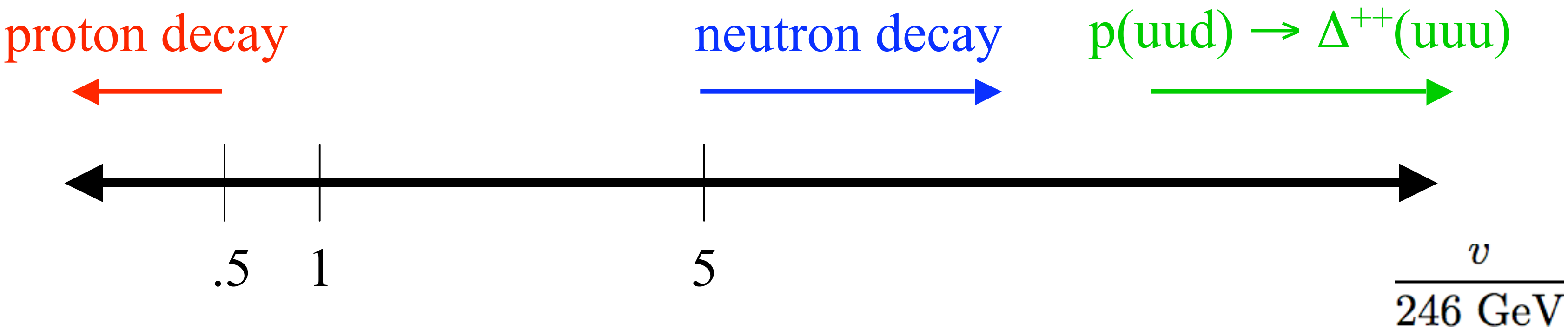
$$\rho_\Lambda \lesssim \rho_{nl}$$

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

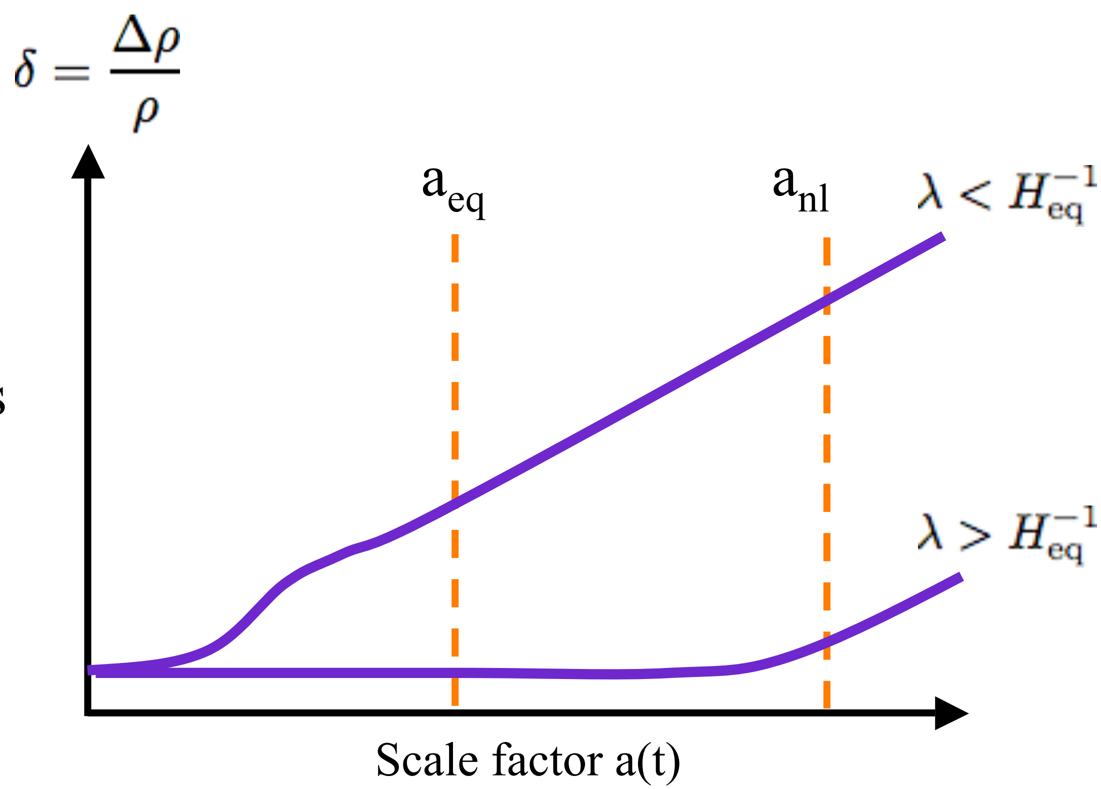
Environmental selection bounds on $\xi = \rho_{\rm dm}/\rho_{\rm b}$?

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

$\delta \propto a$

when matter density dominates

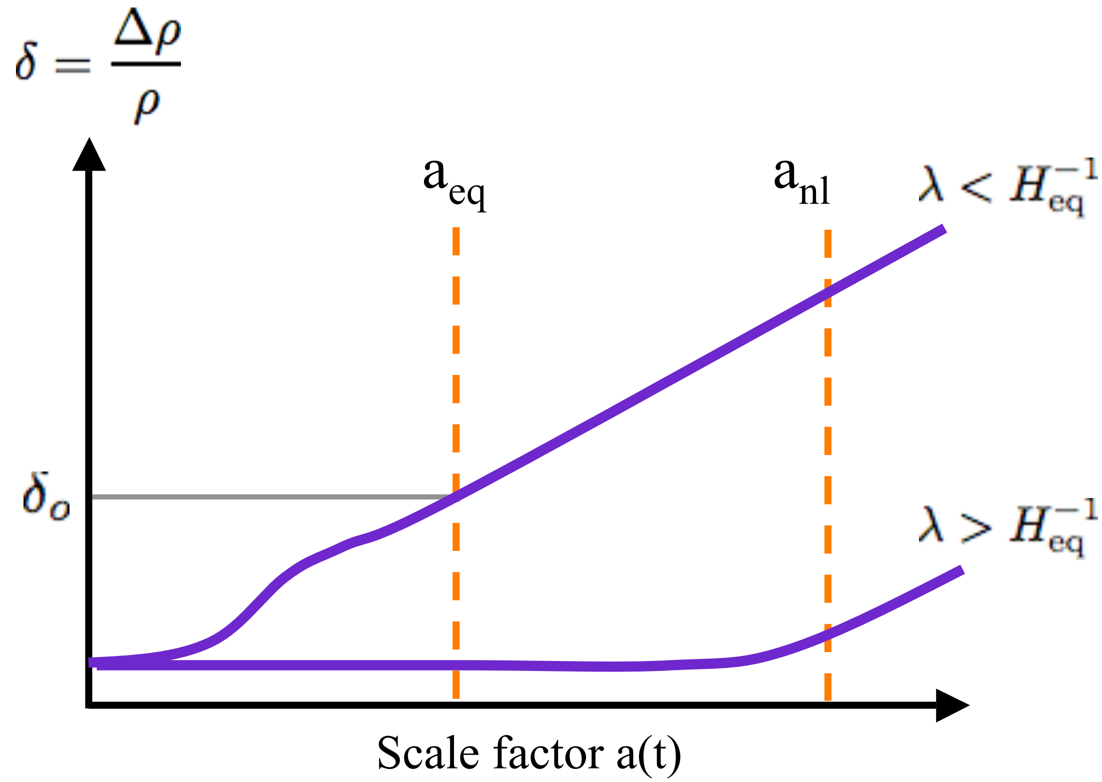
$$\rho_{\rm nl} = \rho_{\rm eq}\left(\frac{a_{\rm eq}}{a_{\rm nl}}\right)^3 = \rho_{\rm eq}\delta_{\rm eq}^3$$



Dark Matter Bound

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

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



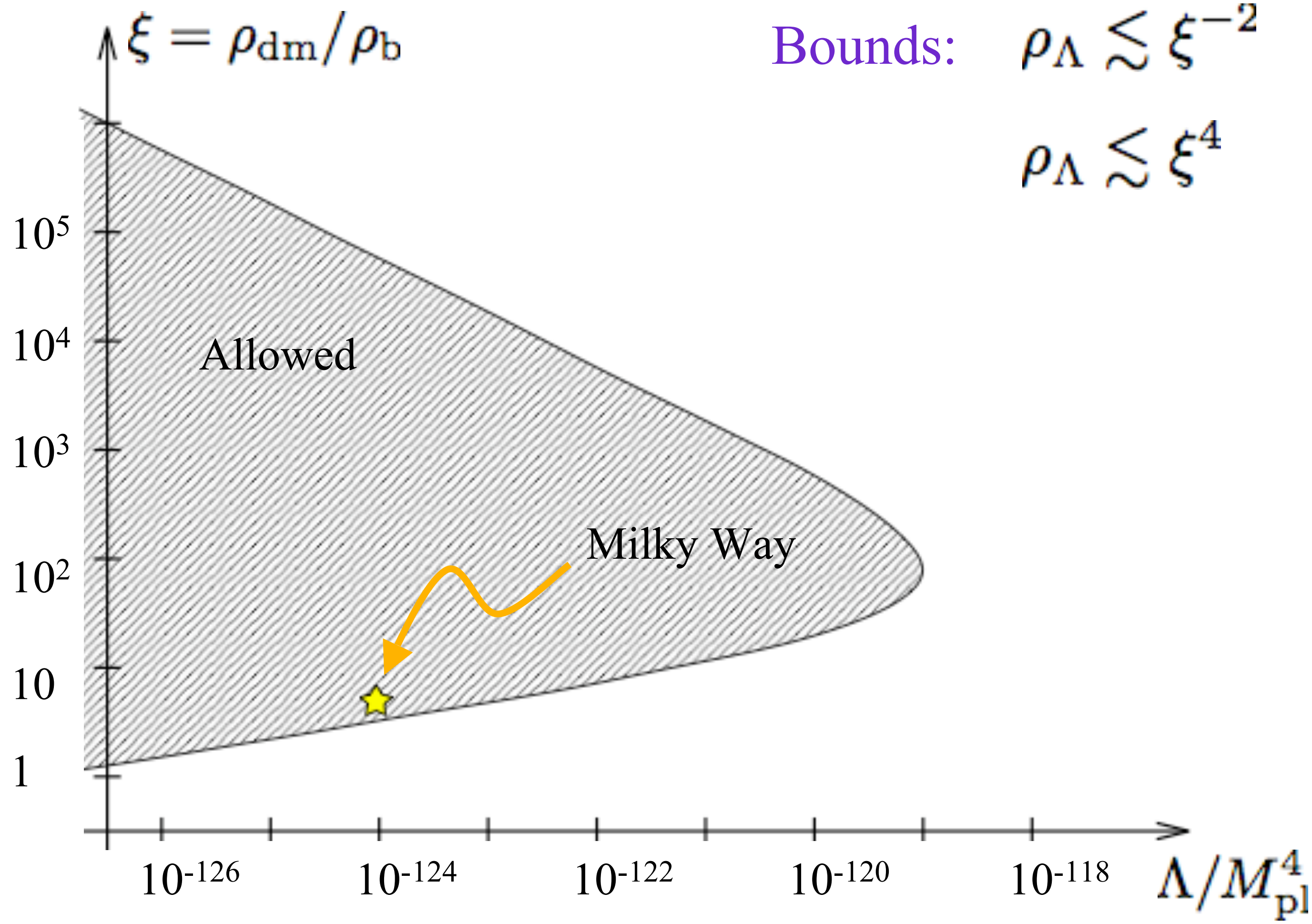
δ_{eq} suppressed for large-scale modes

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

Dark Matter Bound

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

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



[Hellerman & Walcher]

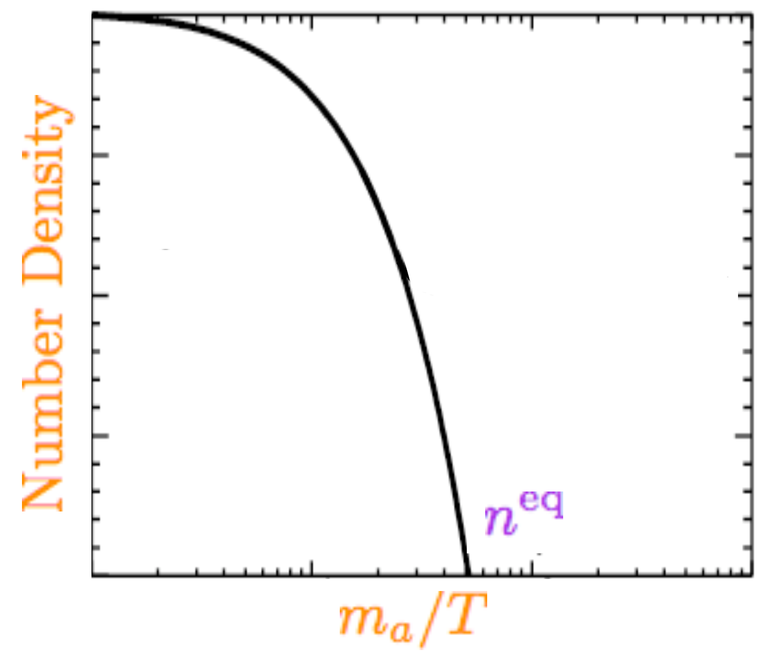
Dark Matter Bound

- Annihilation cross section for WIMPs

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

- Interaction rate of WIMPs

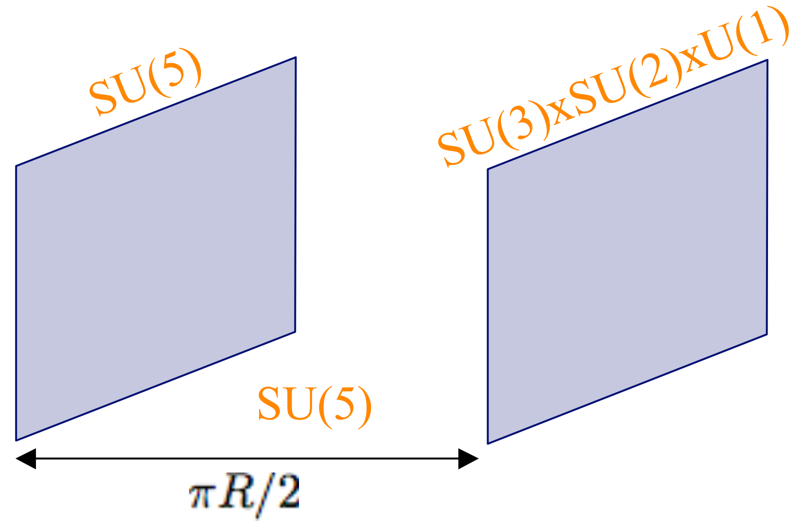
$$\Gamma = \langle \sigma v \rangle n_{\rm wimp} = \langle \sigma v \rangle \frac{\rho_{\rm dm}}{m_{\rm wimp}}$$



Unification

Potential mechanisms for suppressing proton decay rate

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



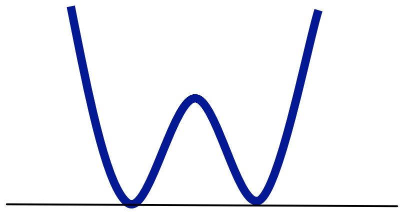
- Trinification: $SU(3)_C$x $SU(3)_L$x $SU(3)_R$ broken ~ 10^{14} GeV
  - proton decay via gauge bosons is forbidden

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

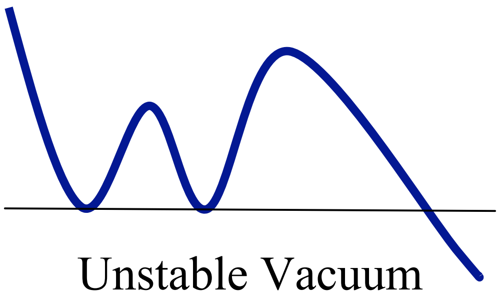
Constraints on Quartics

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

$$V(\mu) > 0$$



Stable Vacuum



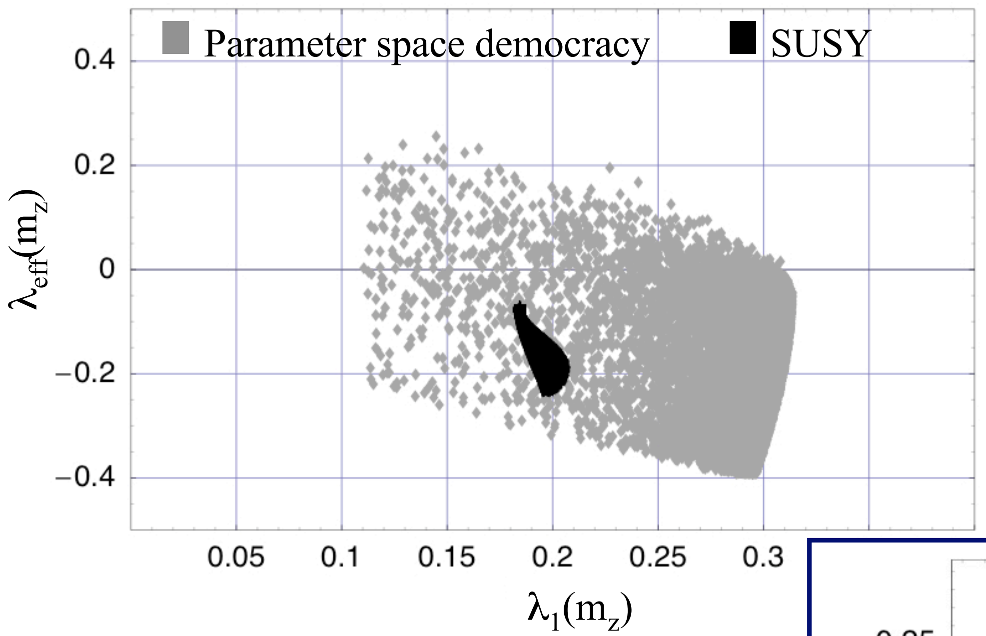
Unstable Vacuum

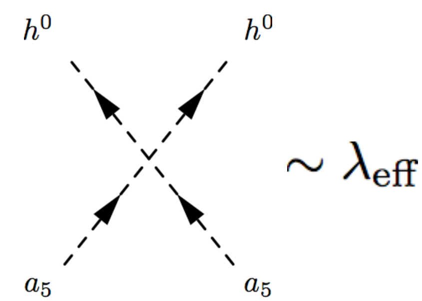
- Direct detection bound: $|\lambda_5| \gtrsim 10^{-6}$

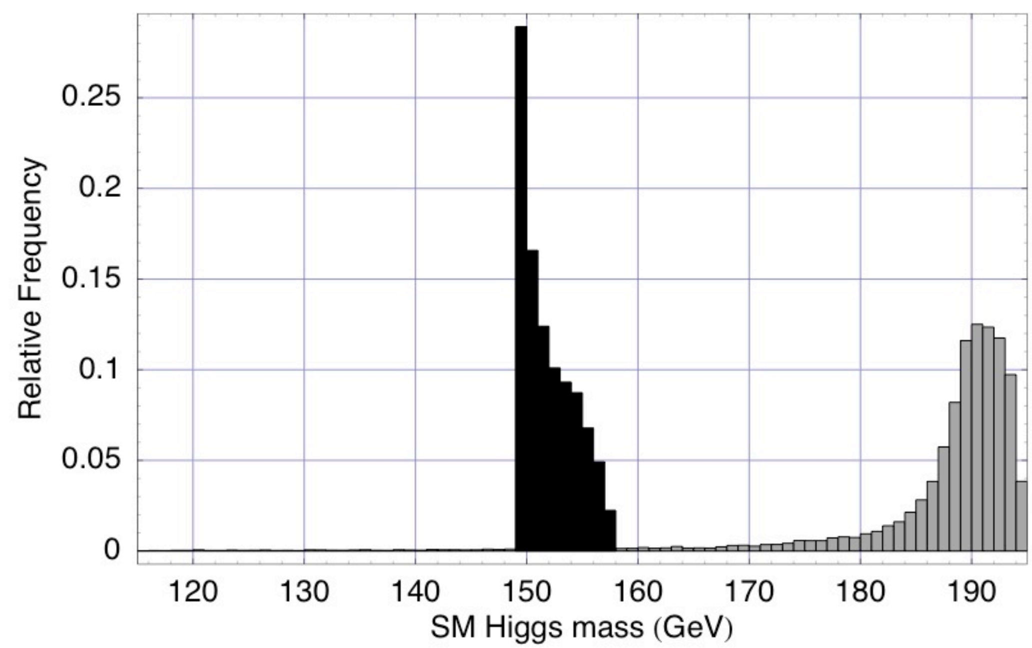
- Experimental bound on Higgs mass: $\lambda_1 \gtrsim 0.107$

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

Parameter Space Democracy



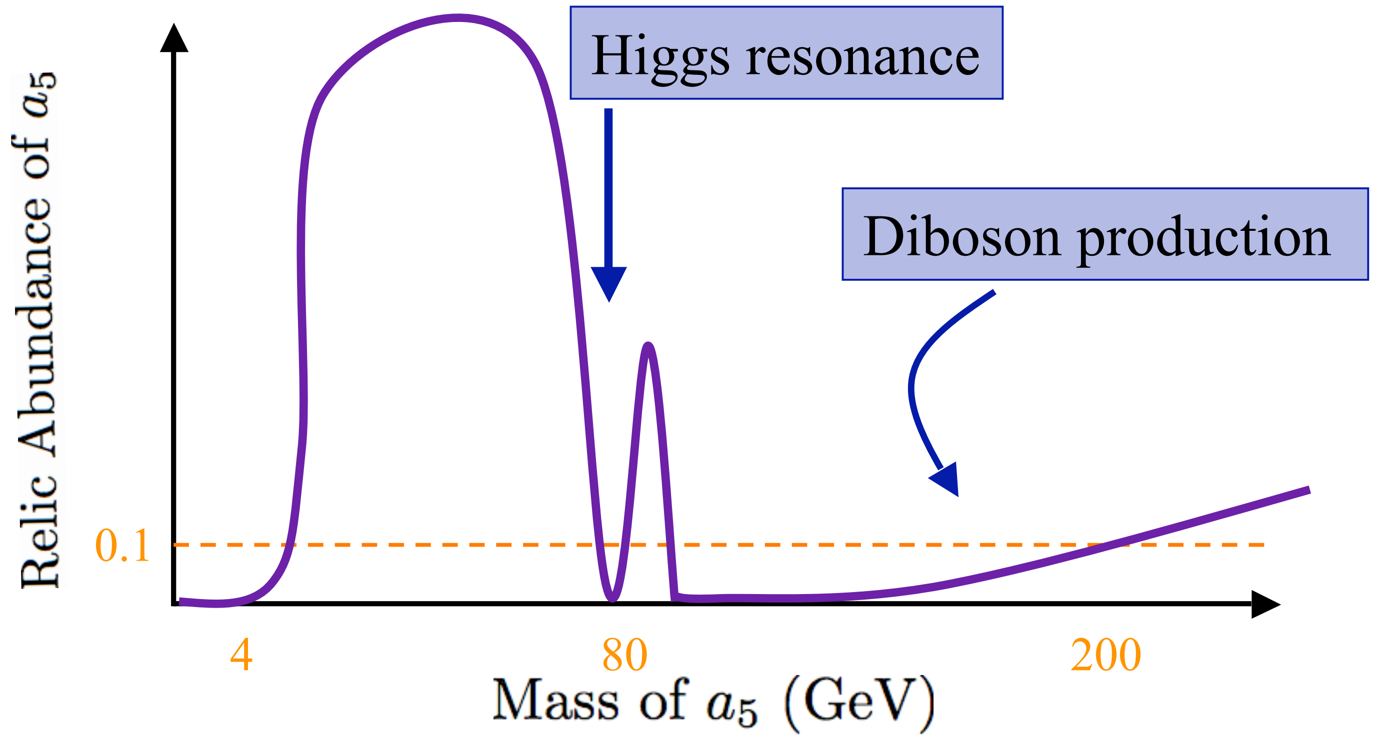


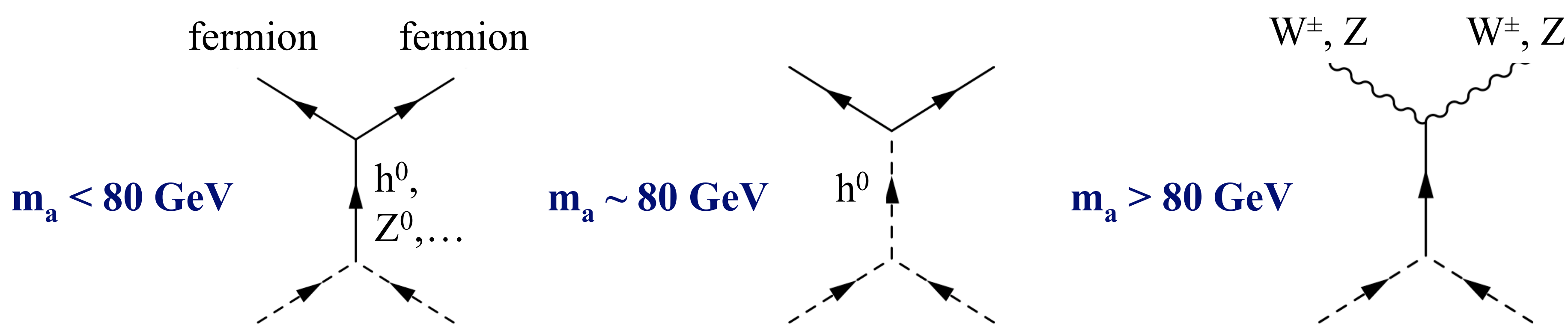


SM Higgs Mass

Large range, peaked at ~ 200 GeV

Coannihilation





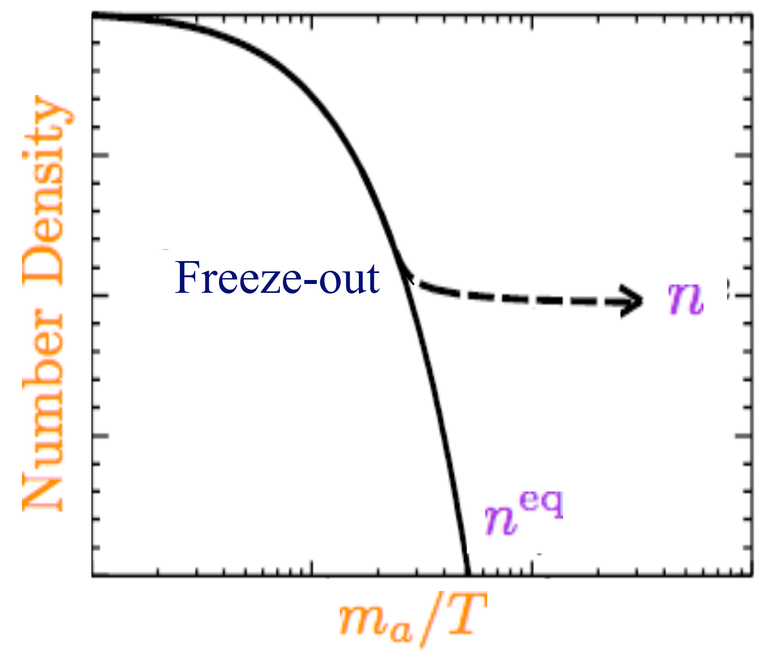
Coannihilation

- Boltzmann equation is

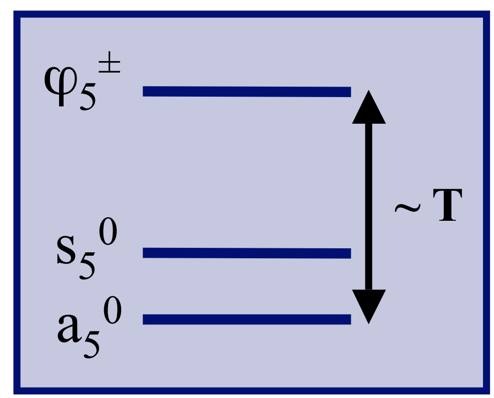
$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle[n^2 - (n^{\rm eq})^2]$$

Particle annihilation

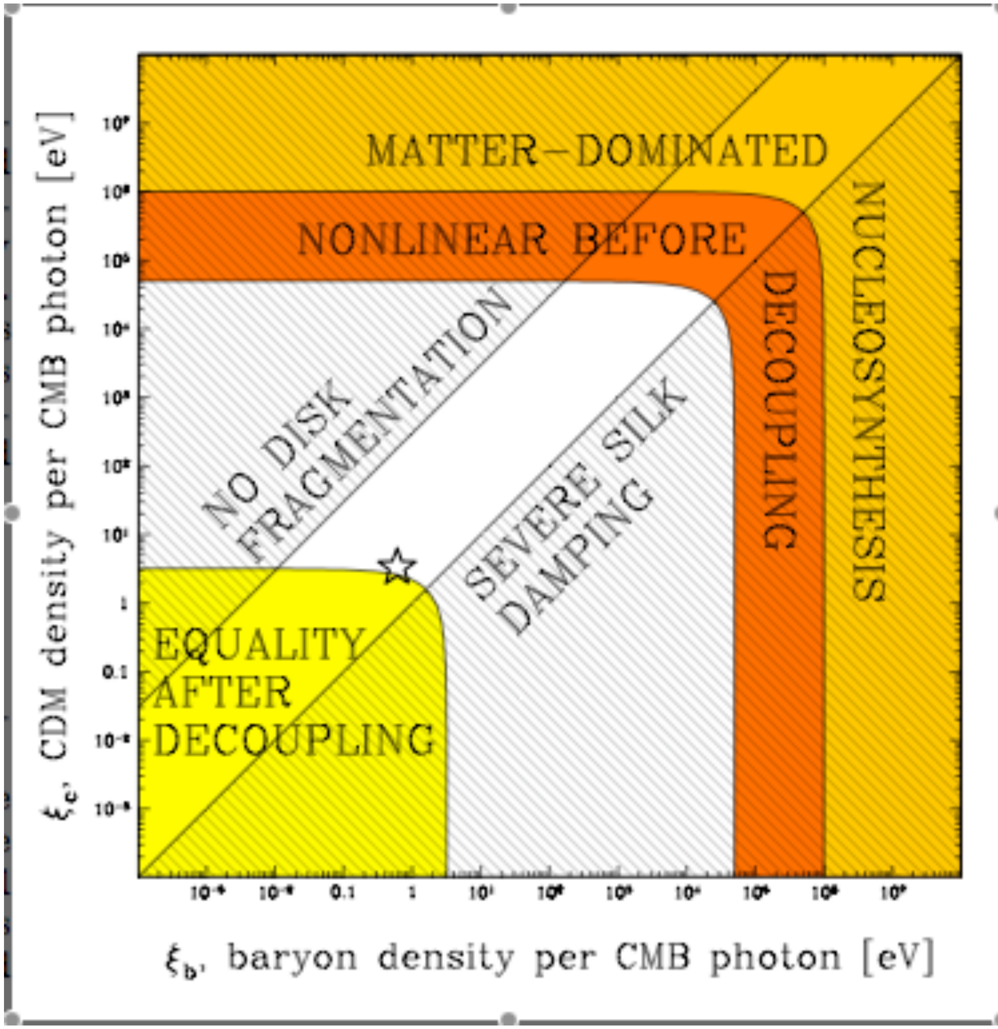
Dilution from expansion of universe



- 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



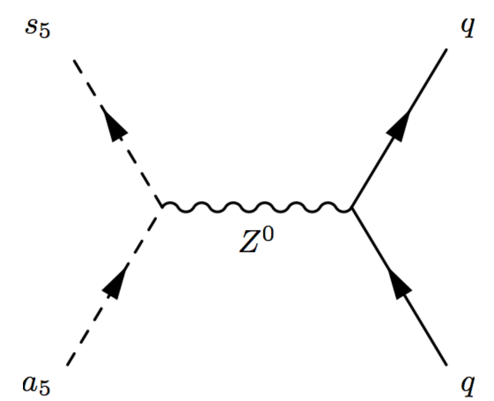
Dark Matter Bounds

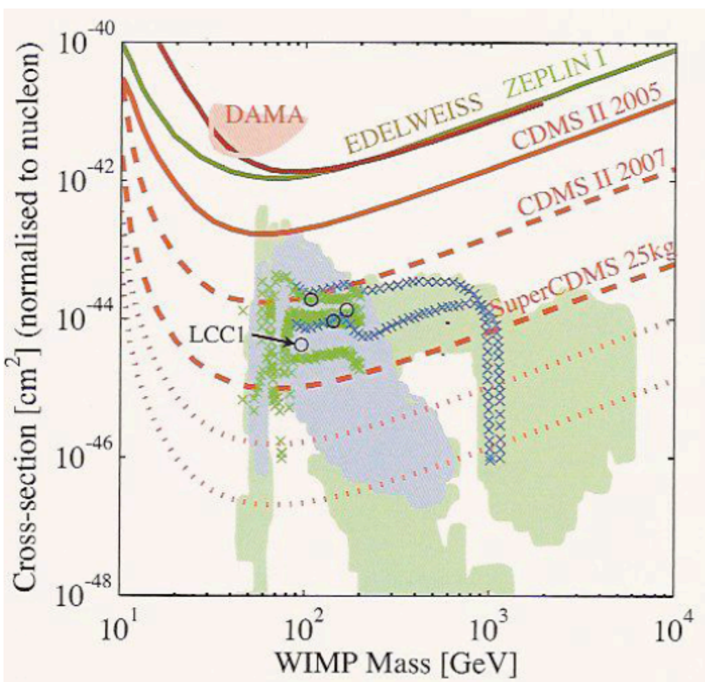


Inelastic Scattering

• 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

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

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

[Smith & Weiner]

Electroweak Precision Tests

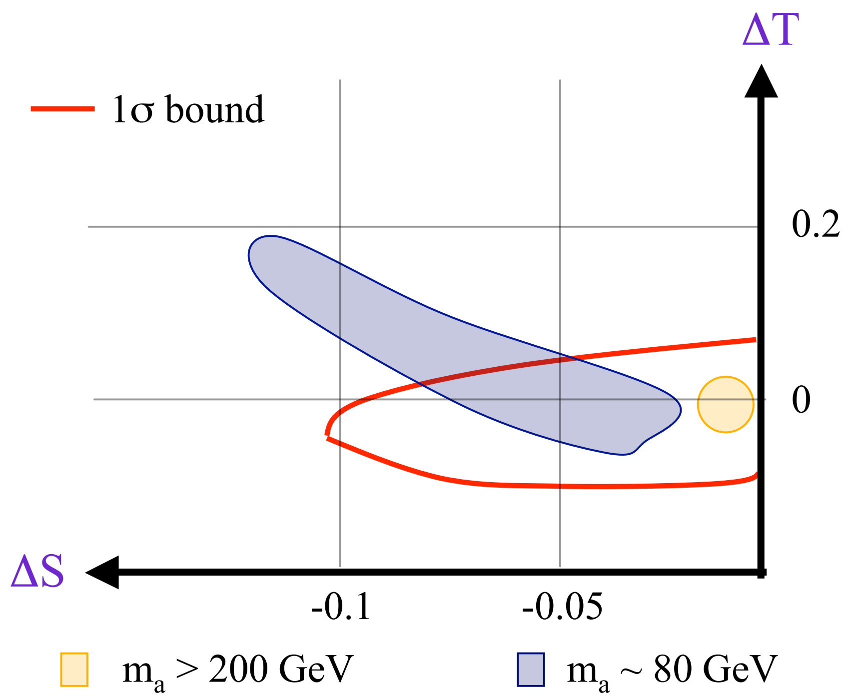
Are masses and quartics consistent with electroweak data?

• 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

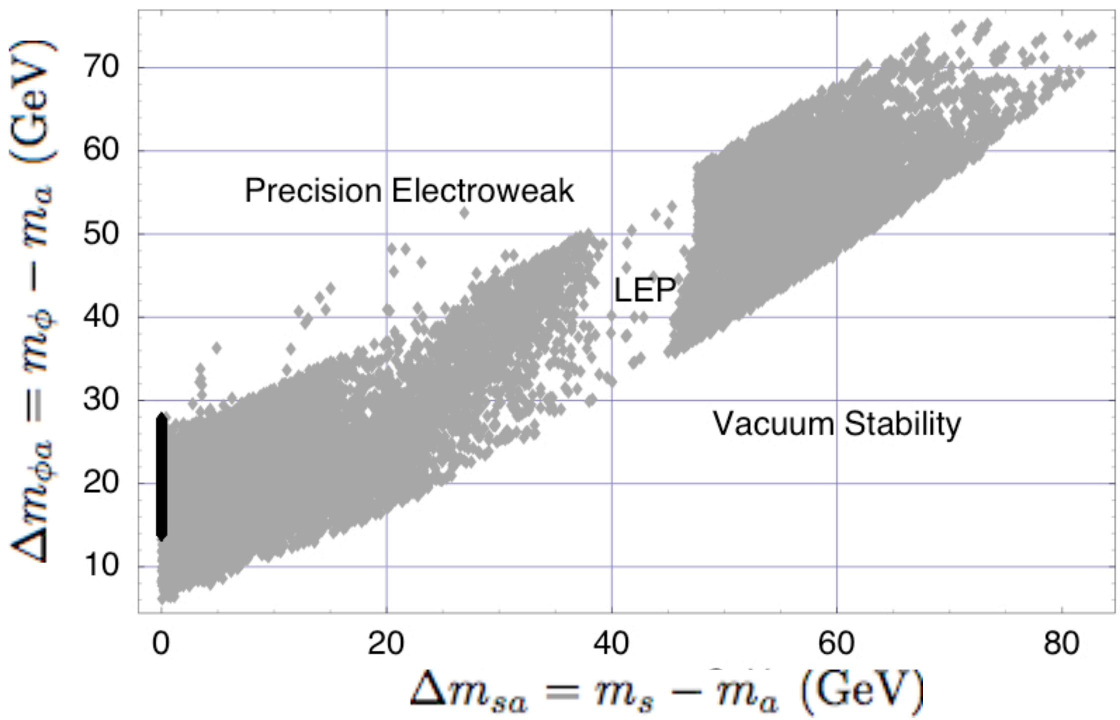
$p\,p \to a_5^0\, s_5^0$
↳ $Z^0\, a_5^0$

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

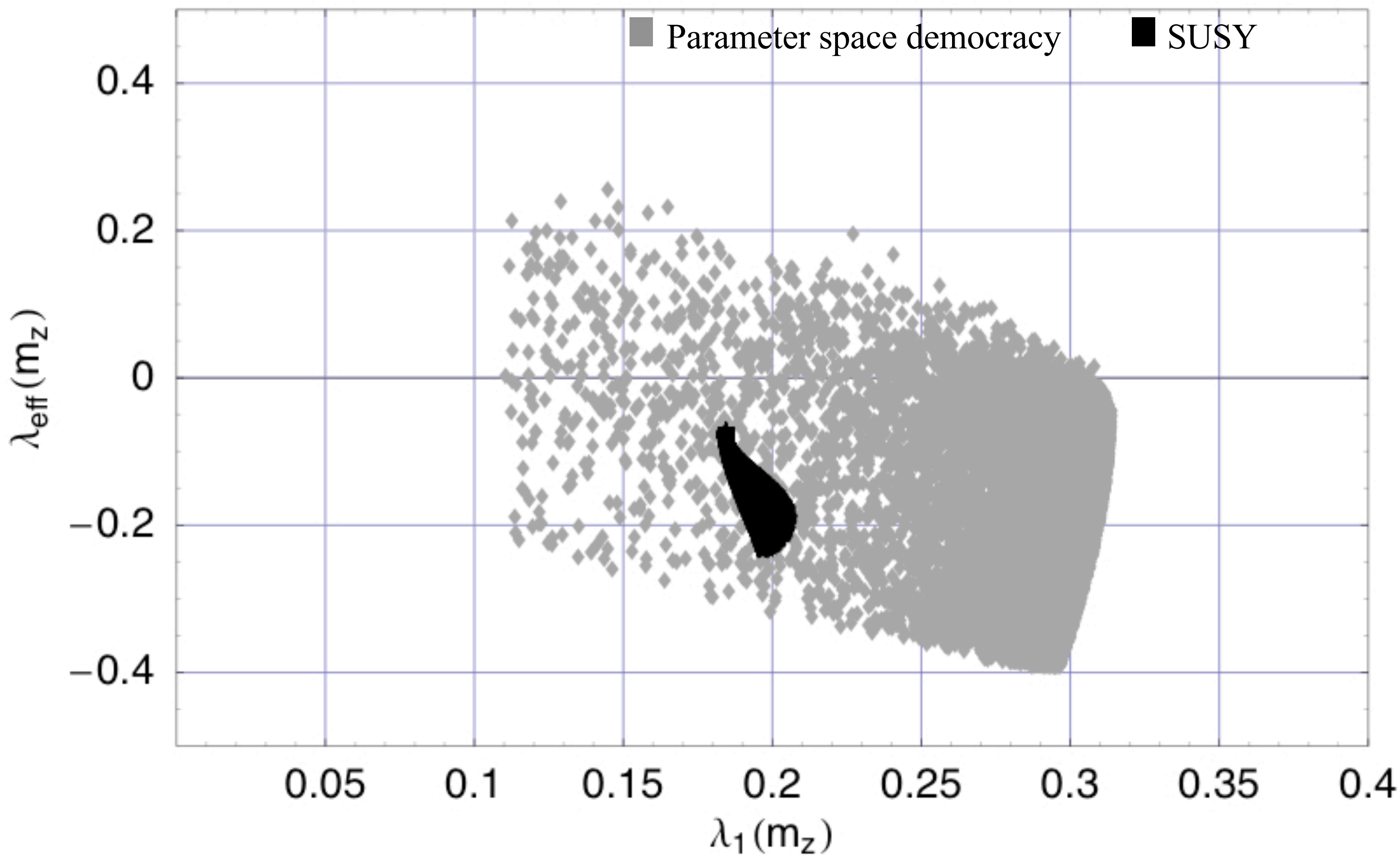
$p\,p \to s_5^0\, \varphi_5^\pm$
↳ $Z^0\, W^\pm\, 2a_5^0$

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

- Gauge bosons are always off-shell
  - Opposite-sign leptons + $\not{E}_T$



Direct Detection

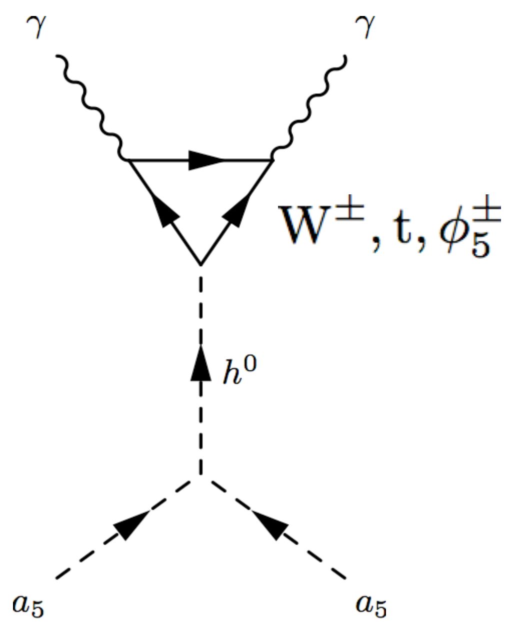


$$\sigma_n = 2 \times 10^{-9}\ \text{pb}\ \left(\frac{\lambda_{\text{eff}}}{0.4}\right)^2 \left(\frac{350\ \text{GeV}}{m_{a^0}}\right)^2 \left(\frac{200\ \text{GeV}}{m_{h^0}}\right)^4$$

Indirect Detection

Low-mass dark matter (~80 GeV)

s-channel Higgs exchange dominates over box diagrams



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