Unitarity and Dark Matter in the Private Higgs Model

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- Motivation
- Survey of the Model
- Perturbative Unitarity and the PH model
- Private Higgs Dark Matter (PHDM)
- Indirect Detection of PHDM

Motivation

- "Gi-normous" hierarchy in the fermion mass spectrum

- Quark sector: Top quark is 10^5 times heavier than up quark! (top special?)

- Only one Higgs doublet (e.g., SM):

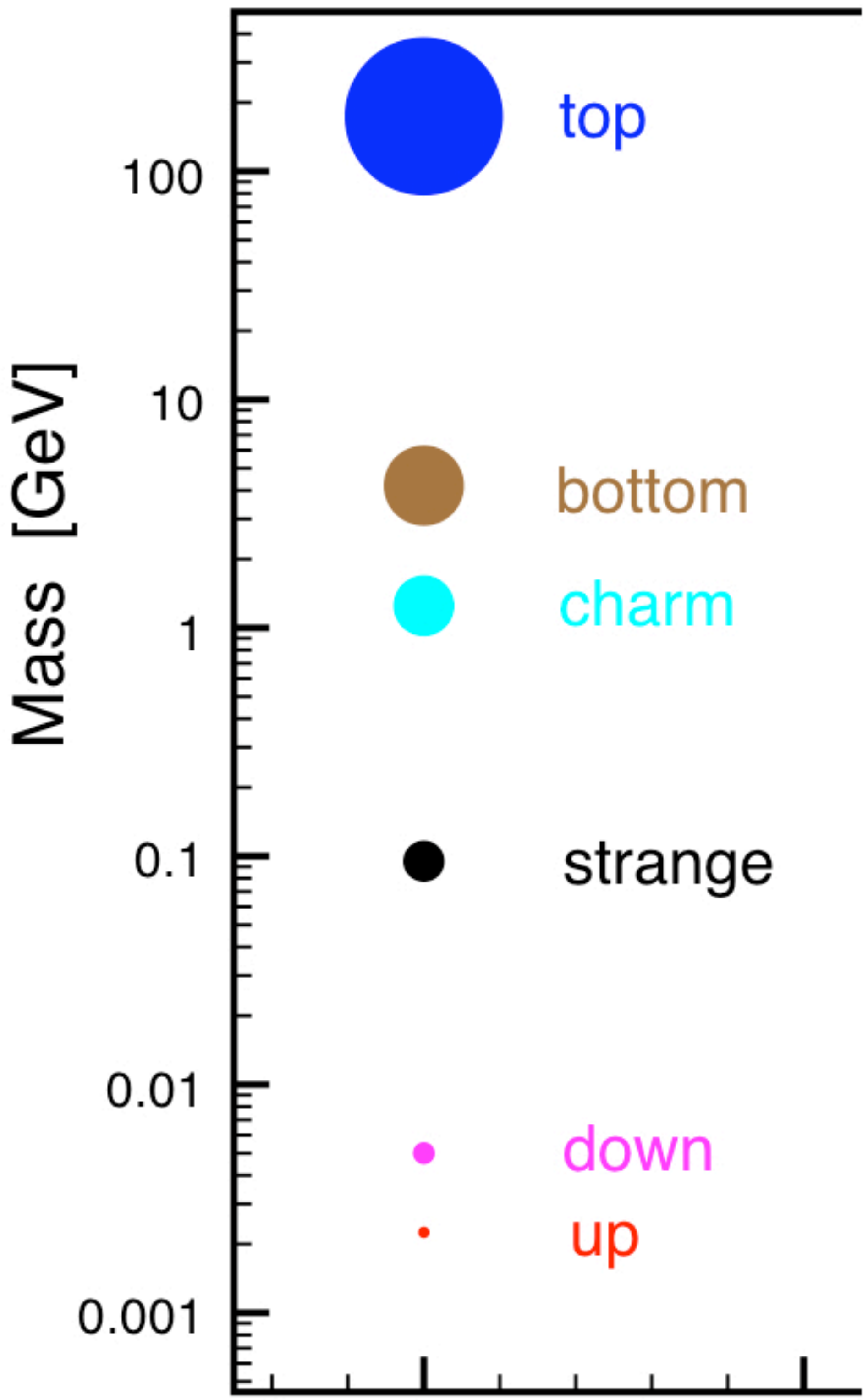
  mass hierarchy $\rightleftarrows$ Yukawa hierarchy

- Possible explanations?

  - SUSY: Yukawa unification in S0(10) GUTs

  - ExDim: "location, location, location, ..."

- Something simpler?



The Private Higgs (PH) Model

(Porto and Zee, arXiv:0712.0448)

- The Main Idea:
  - Introduce one "private" Higgs doublet per quark ("Democratic Higgs"?)
  - Construct SSB pattern s.t. *all* Yukawa couplings of order one
- PH doublets (φ_q) have same $SU(2) \times U(1)$ quantum numbers as SM Higgs
- Also, introduce a gauge singlet scalar S (for reasons given below)
- Impose set of six separate discrete symmetries K_q where:

$$U_R \to -U_R \ \ (D_R \to -D_R)\ ,\ \ \varphi_q \to -\varphi_q\ ,\ \ S \to -S$$

- Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM-H} - \sum_q (y_D^{PH}\,\overline{Q}_L \phi_D D_R + y_U^{PH}\,\overline{Q}_L \tilde{\phi}_U U_R) \\ + \partial_\mu S \partial^\mu S + \sum_q [(D_\mu \phi_q)^\dagger D^\mu \phi_q - V(S, \phi_q)]\,,$$

The PH Potential and EWSB

$$V(S,\phi_q) = \frac{\lambda_S}{4}\left(S^2 - \frac{v_d^2}{2}\right)^2 + \sum_q \left(\frac{1}{2}M_{\phi_q}^2 \phi_q^\dagger \phi_q + \lambda_q(\phi_q^\dagger\phi_q)^2 - g_{sq}S^2\phi_q^\dagger\phi_q\right)$$
$$- \sum_{q\neq q'}\left(\frac{\gamma_{qq'}}{\sqrt{2}}v_s S\phi_q^\dagger\phi_{q'} + a_{qq'}\phi_q^\dagger\phi_{q'}\phi_q^\dagger\phi_{q'} + b_{qq'}\phi_q^\dagger\phi_q\phi_{q'}^\dagger\phi_{q'} + c_{qq'}\phi_q^\dagger\phi_{q'}\phi_{q'}^\dagger\phi_q\right) + h.c.$$

- Top PH plays the role of the SM Higgs (i.e., responsible for m_W and m_Z)
- Use vev of S and g_{st} coupling to drive EWSB:

$$\tfrac{1}{2}M_{\phi_t}^2 - g_{st}v_s^2 \equiv \mu_t^2 < 0$$

- Non-top PH fields acquire vev's in slightly different manner
- Use vev's of S and top PH... along with cubic term $\gamma_{qq'}$:

$$\frac{1}{2}M_{\phi_q}^2\phi_q^\dagger\phi_q - \frac{\gamma_{qt}}{\sqrt{2}}\frac{v_h v_s^2}{2}\phi_q \longrightarrow \langle\phi_q\rangle = \frac{\gamma_{qt}}{\sqrt{2}}\frac{v_h v_s^2}{M_{\phi_q}^2} \equiv v_q$$

PH-enomenology

- Lighter the quark... heavier its PH partner ("up" PH ~ 10^2 - 10^3 TeV)
- To interest of LHC:
  - Two light scalars: h^0 and K^0
  - Heavy Scalar H^0, charged scalar $H^\pm$ and pseudoscalar A_b
- H^0, $H^\pm$ and pseudoscalar A_b all have masses ~ 1-2 TeV and O(1) Yukawa couplings to bottom quarks
- For small mixing between top PH and S (angle = β):
  - h^0 has same properties as SM Higgs
  - K^0 provides a good candidate for Dark Matter (DM)!

Perturbative Unitarity in the PH Model

- Requiring perturbative unitarity provides important constraints (e.g., in the SM, limits on m_h and/or scattering energy... see Lee, Quigg and Thacker '77)

- In models with extended scalar sectors, $hh \to hh$ probes self-interactions

- Analysis performed in terms of "partial waves", e.g. the J=0 partial wave:

$$a_0 = \frac{1}{16\pi s\beta^2}\int_{-s\beta^2}^{0} \mathcal{A}(h^0h^0 \to h^0h^0)dt$$

- In the PH model:

$$a_0 = -\frac{1}{32\pi}\Bigg\{g_{h^0h^0h^0h^0} + \frac{g^2_{h^0h^0h^0}}{s-m^2_{h^0}} + \frac{g^2_{h^0h^0K^0}}{s-m^2_{K^0}} + \frac{g^2_{h^0h^0H^0}}{s-m^2_{H^0}} - \frac{2}{s\beta^2}\Bigg[g^2_{h^0h^0h^0}\ln\left(\frac{s}{m^2_{h^0}}-3\right)$$

$$+g^2_{h^0h^0K^0}\ln\left(\frac{s-4m^2_{h^0}+m^2_{K^0}}{m^2_{K^0}}\right) + g^2_{h^0h^0H^0}\ln\left(\frac{s-4m^2_{h^0}+m^2_{H^0}}{m^2_{H^0}}\right)\Bigg]\Bigg\}.$$

Bounds on SM-like Higgs Mass

- To extract maximum Higgs mass consistent with PU, take $s \gg m^2$ limit:

$$\lim_{s\to\infty} a_0 = -\frac{1}{32\pi} g_{h^0h^0h^0h^0} \,.$$

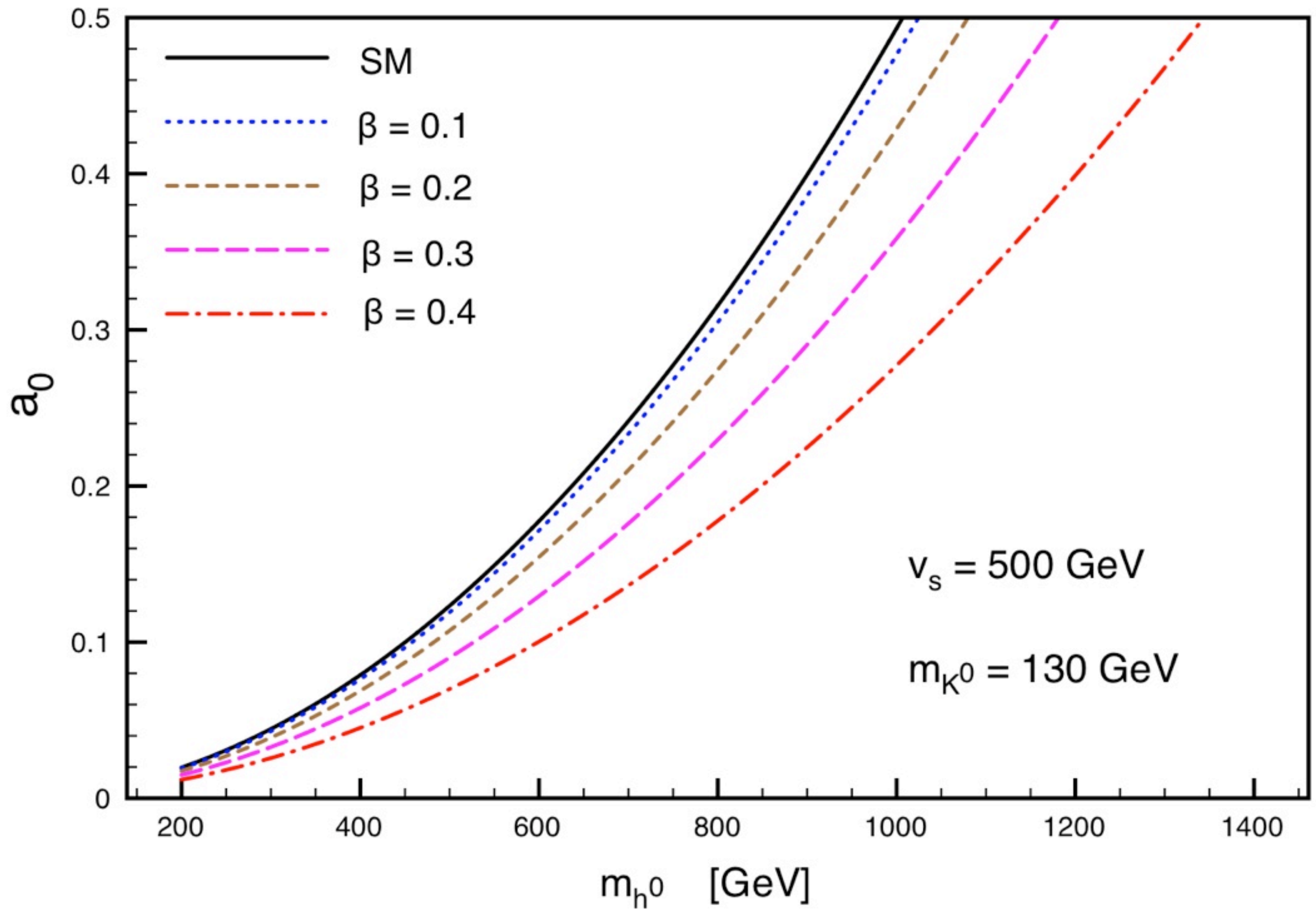
- SM Limit ($\beta \to 0$):

  $m_h \lesssim 1$ TeV

- PH = *softens* bounds

- Similar results for W_LW_L, Z_LZ_L, etc.

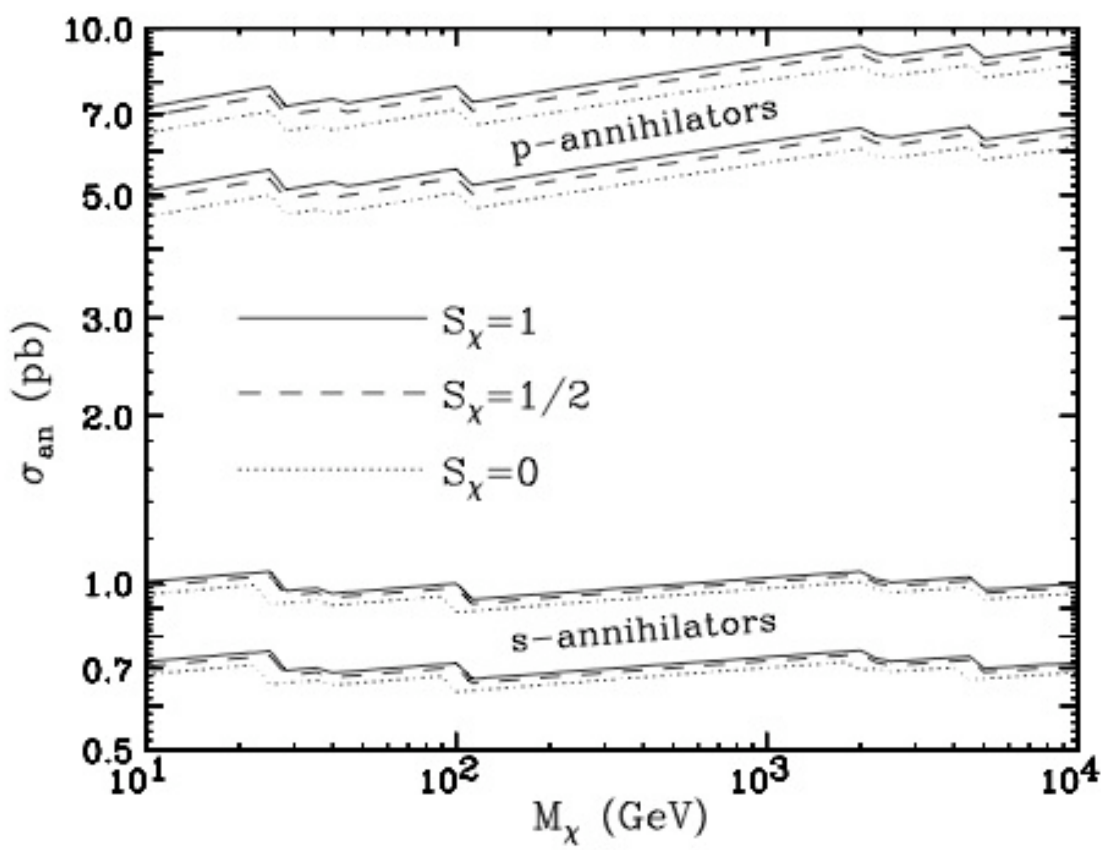
- Results nearly independent of m_K



Private Higgs Dark Matter (PHDM)

- PH provides a good candidate for a WIMP
- Scalar DM:
  "Gauge Singlet Scalar DM" (Zee et al., Davoudiasl et al., etc.)
  and "Inert Doublet Model" (Barbieri et al., etc.)
- Any form of DM is constrained by WMAP measurements:

$$\Omega_{DM}\, h^2 = 0.111 \pm 0.018$$



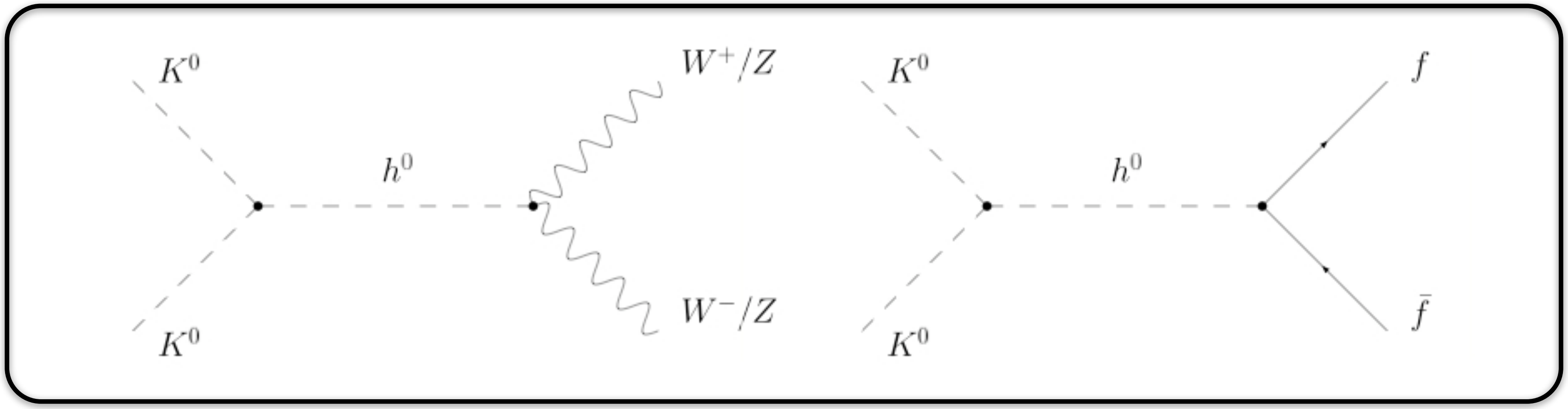
- Birkedal et al. (PRD70, 077701 (2004)): Limits on DM abundance translate into limits on annihilation cross section.
- For scalar "s-annihilator":

$$\sigma_{an} = 0.85 \pm 0.15 \text{ pb}$$

Constraining PHDM

- Focus on small values of mixing between top PH and *S* (to avoid copious decays into SM particles)

- Then, K^0 kept in equilibrium with cosmic fluid via:

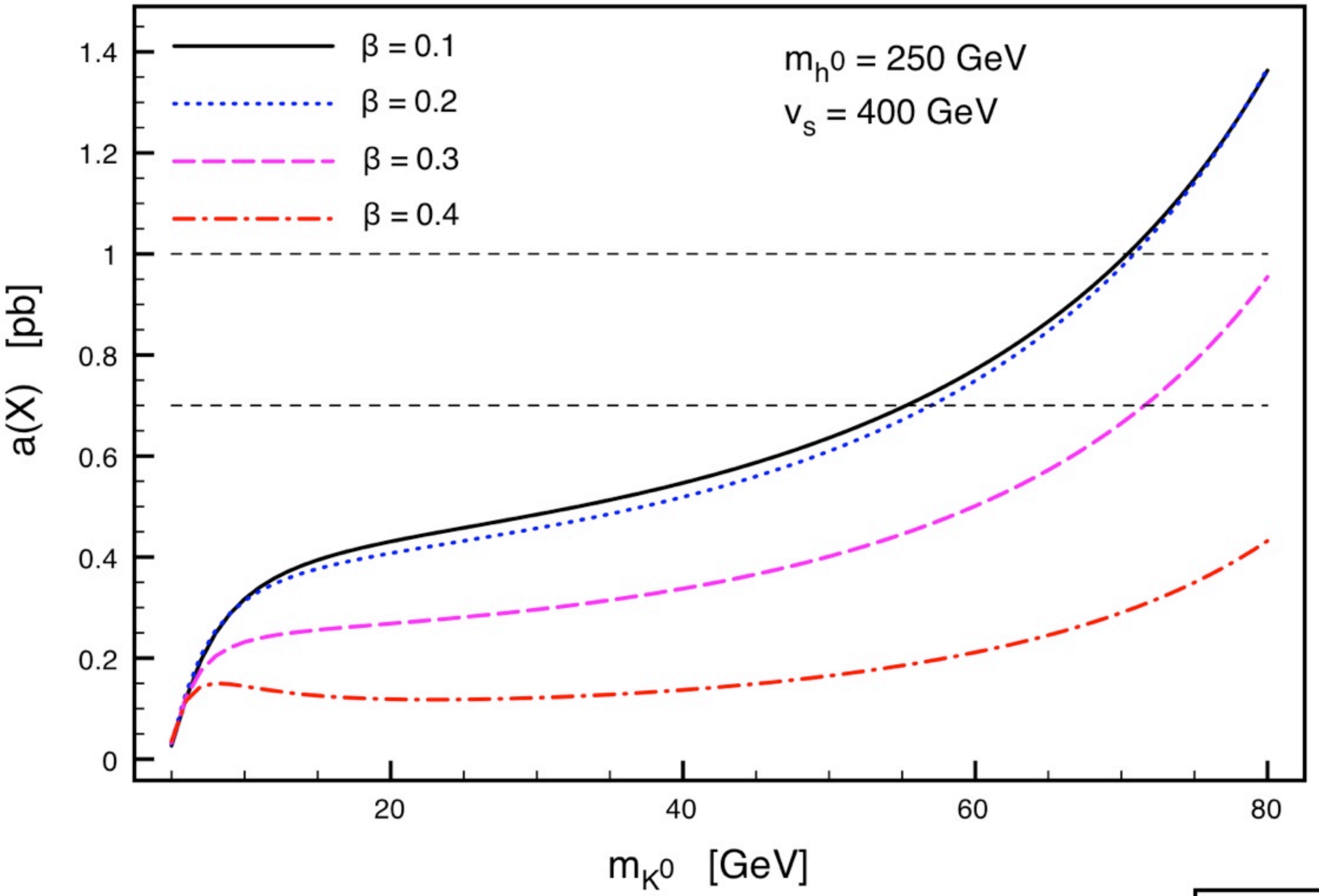


- Note: K^0 *s*-channel exchange suppressed by β^2, while *t*-channel diagrams are suppressed by β^4.

- Consider two scenarios:

  - "Light K^0" scenario: $m_K < m_W$ such that annihilation into *b*'s dominate

  - "Heavy K^0" scenario: $m_W < m_K < 2m_W$ s.t. annihiation into *WW*, *ZZ* pairs dominates

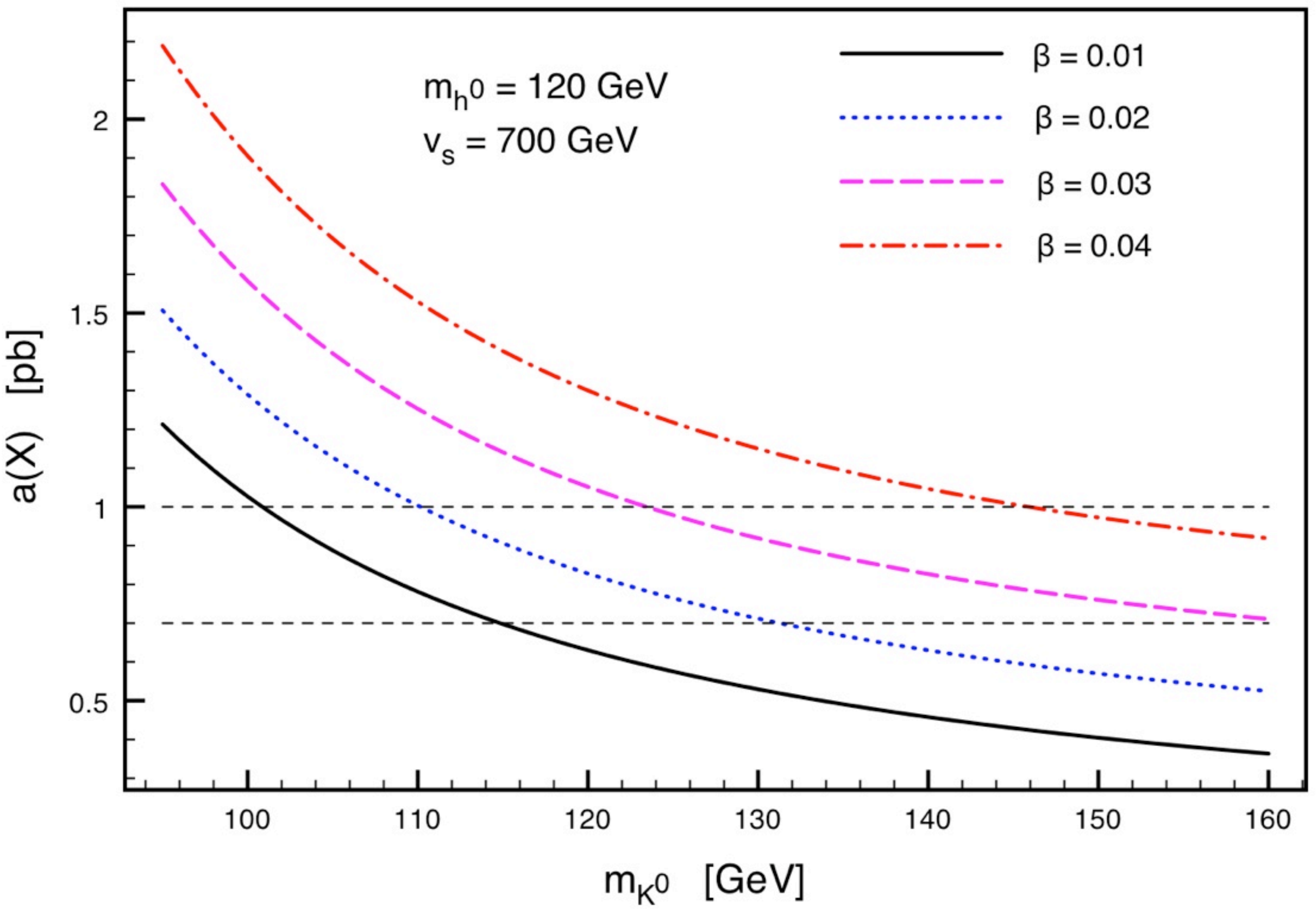


"Light K^0" Scenario:

- One "representative" point in parameter space... not a "full scan"
- Require $v_b \sim m_b$
- WMAP requires smaller mixing and masses ~ 50 - 75 GeV range

"Heavy K^0" Scenario:

- In general, easier to incorporate larger mass range
- Much smaller mixing angles
- Larger values of *S*'s vev

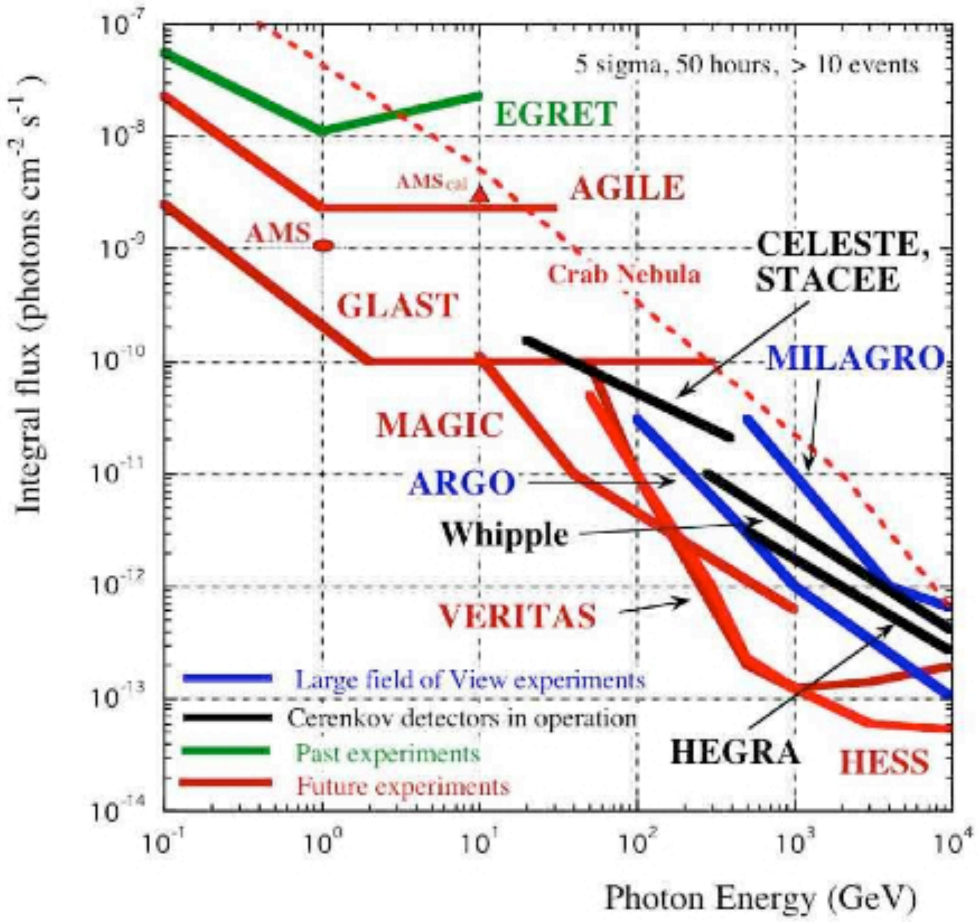


Indirect Detection of DM

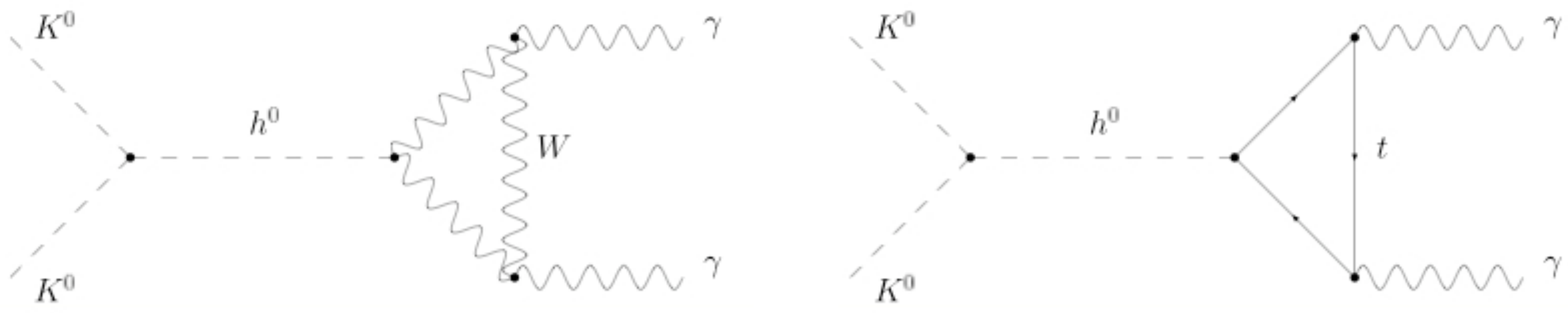
- Annihilation c.s. for DM ~ velocity-independent in non-relativistic regime
- DM collected in the galactic halo → anomalous cosmic rays

γ rays → information on DM

- Experiments:
  - Ground-based (atmospheric cerenkov telescopes):VERITAS, HESS, etc.
  - Space-based: GLAST
- Typical reach for DM searches:
  - ACT's ~ 10^{-11} - 10^{-12} cm^{-2} s^{-1}
  - GLAST ~ 10^{-10} cm^{-2} s^{-1}



Indirectly Detecting PHDM

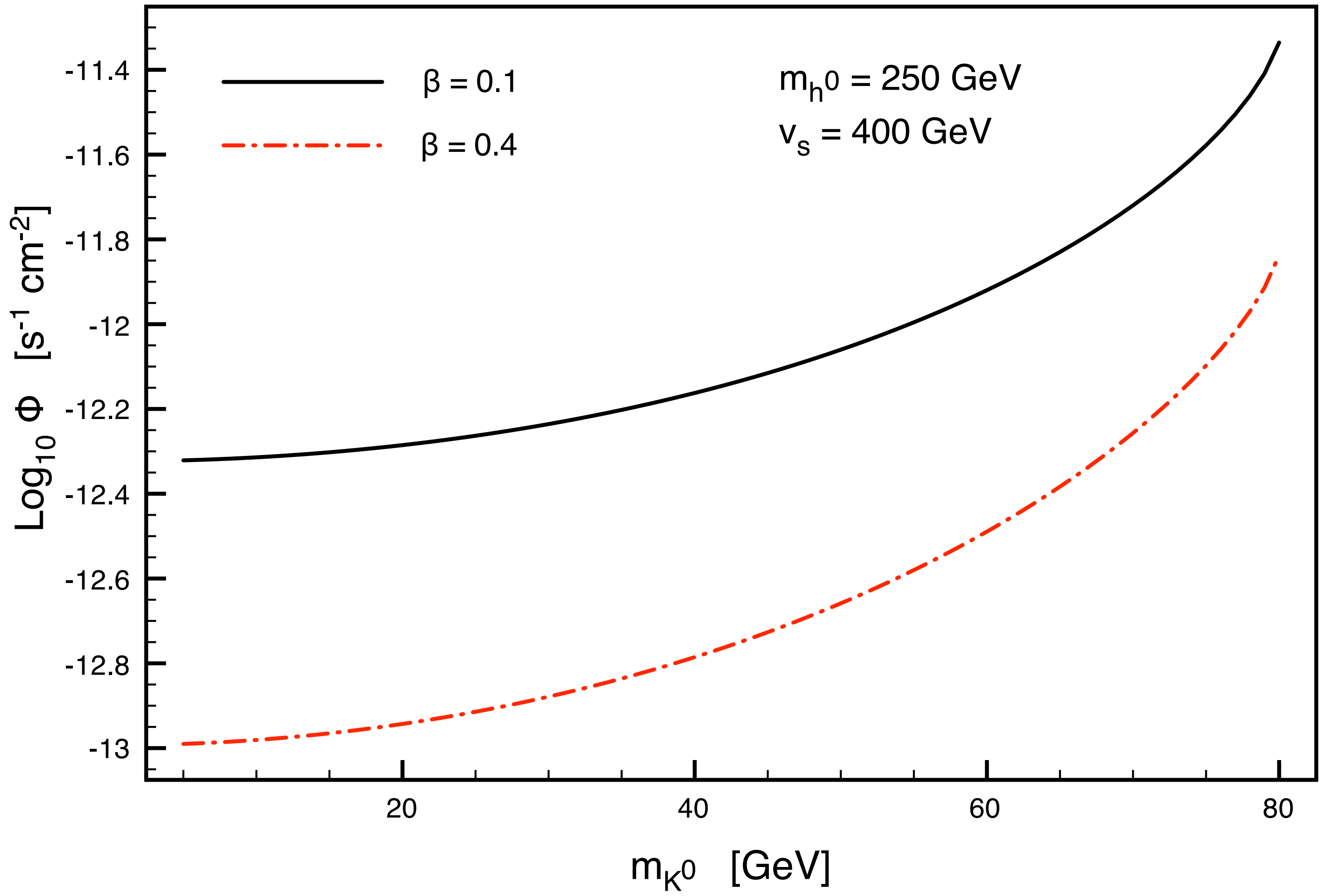


- The flux of photons observed with a line of sight Ψ(θ,φ) and f.o.v. ΔΩ:

$$\Phi = (1.1 \times 10^{-9}\,\mathrm{s}^{-1}\mathrm{cm}^{-2})\left(\frac{\sigma_{\gamma\gamma}u}{1\ \mathrm{pb}}\right)\left(\frac{100\ \mathrm{GeV}}{m_{K^0}}\right)\bar{J}(\Psi,\Delta\Omega)\Delta\Omega\,,$$

- Dependence of flux on DM density distribution is contained in J
  - Value of J very model-dependent
  - Many models predict large spike in neighborhood of galactic center
  - J ≈ 10^3 - 10^7 for ΔΩ = 10^{-3} sr (typical for ACTs)

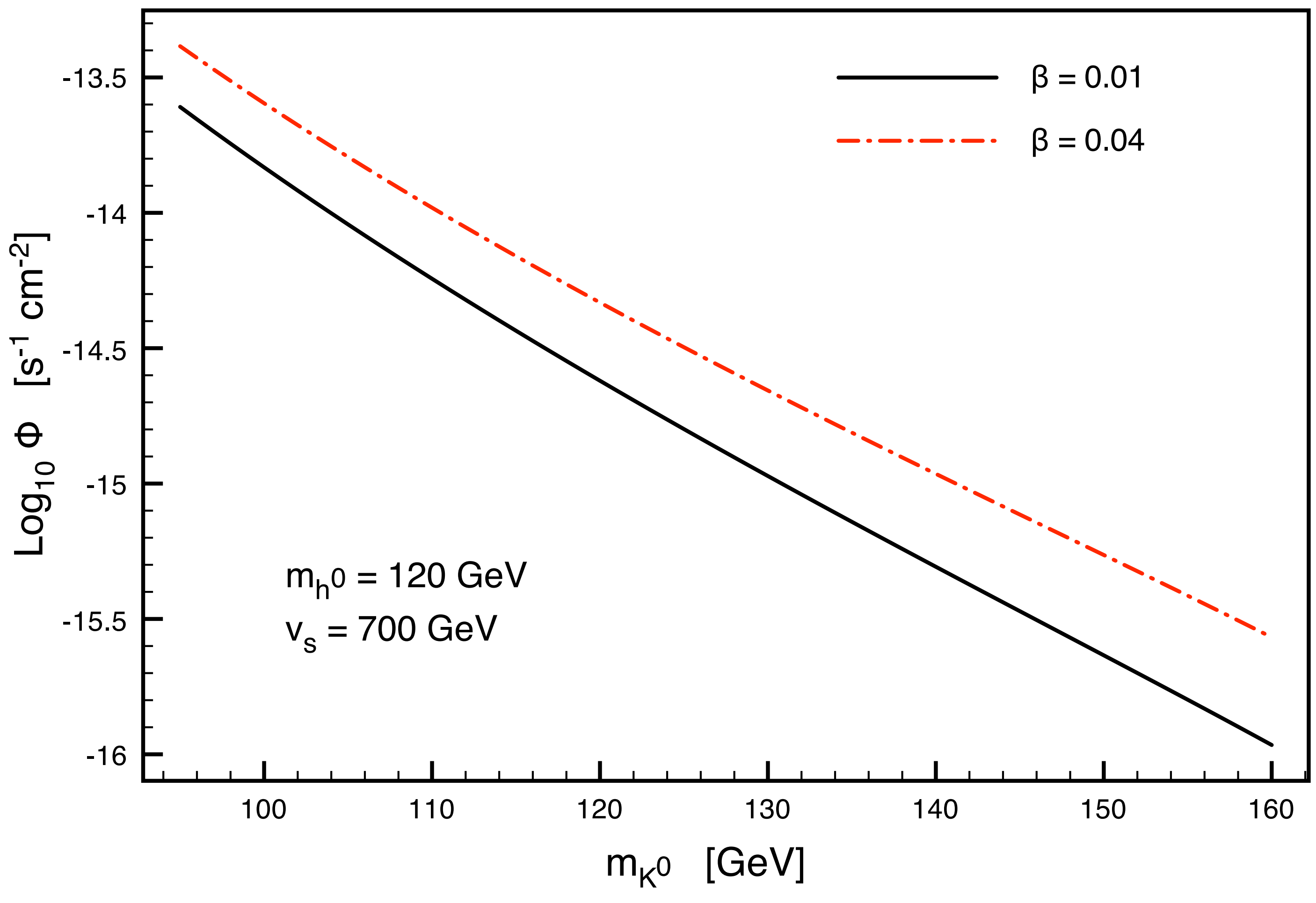
"Light K^0" Scenario:



- Assume no significant clumping (i.e., $J(\Psi,\Delta\Omega)\ \Delta\Omega = 1$)
- Beyond the reach of GLAST (reach = 10^{-10} cm^{-2} s^{-1})
- With considerable clumping (e.g., $J(\Psi,\Delta\Omega)\ \Delta\Omega = 10^2$), observation at ACTs possible

"Heavy K^0" Scenario:

- Tough to detect for larger masses
- Still possible at ACTs for larger values of clumping
- Full scan needed, though



Conclusions

- Private Higgs model provides a simple way to account for large hierarchy observed in the fermion mass spectrum
- Idea: Introduce one Higgs doublet per fermion + discrete symmetries
- Induce EWSB via vev of a gauge singlet scalar S
- PH-enomenology consists of a handful of scalars below ~ TeV and a possible DM candidate
- Perturbative Unitarity: PH sector softens bounds on SM-like Higgs mass
- Private Higgs Dark Matter (PHDM):
    - Easily account for relic abundance of DM with “natural” values of parameters
    - If PHDM clumps in the region of the galactic core, observation with gamma ray telescopes is possible