Title: Exploring Dark Matter in a Leptophilic Two-Higgs-Doublet Model

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Abstract: A recent analysis of gamma rays from the centre of our galaxy has provided possible evidence for a dark matter annihilation signal, with the dark matter taking the form of low-mass WIMPs annihilating predominantly to taus. We study an extended Higgs model proposed to yield such a dark matter candidate. Scanning over parameter space in this model, we find suitable areas that feature fairly little fine-tuning. In favoured areas, the cross-sections for invisible decays of neutral Higgses are predicted to be too low for detection atcolliders. However, dark matter direct detection experiments are currently becoming relevant for constraining parameter space in the model.

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Exploring Dark Matter in a Lepton-Specific 2-Higgs-Doublet Model

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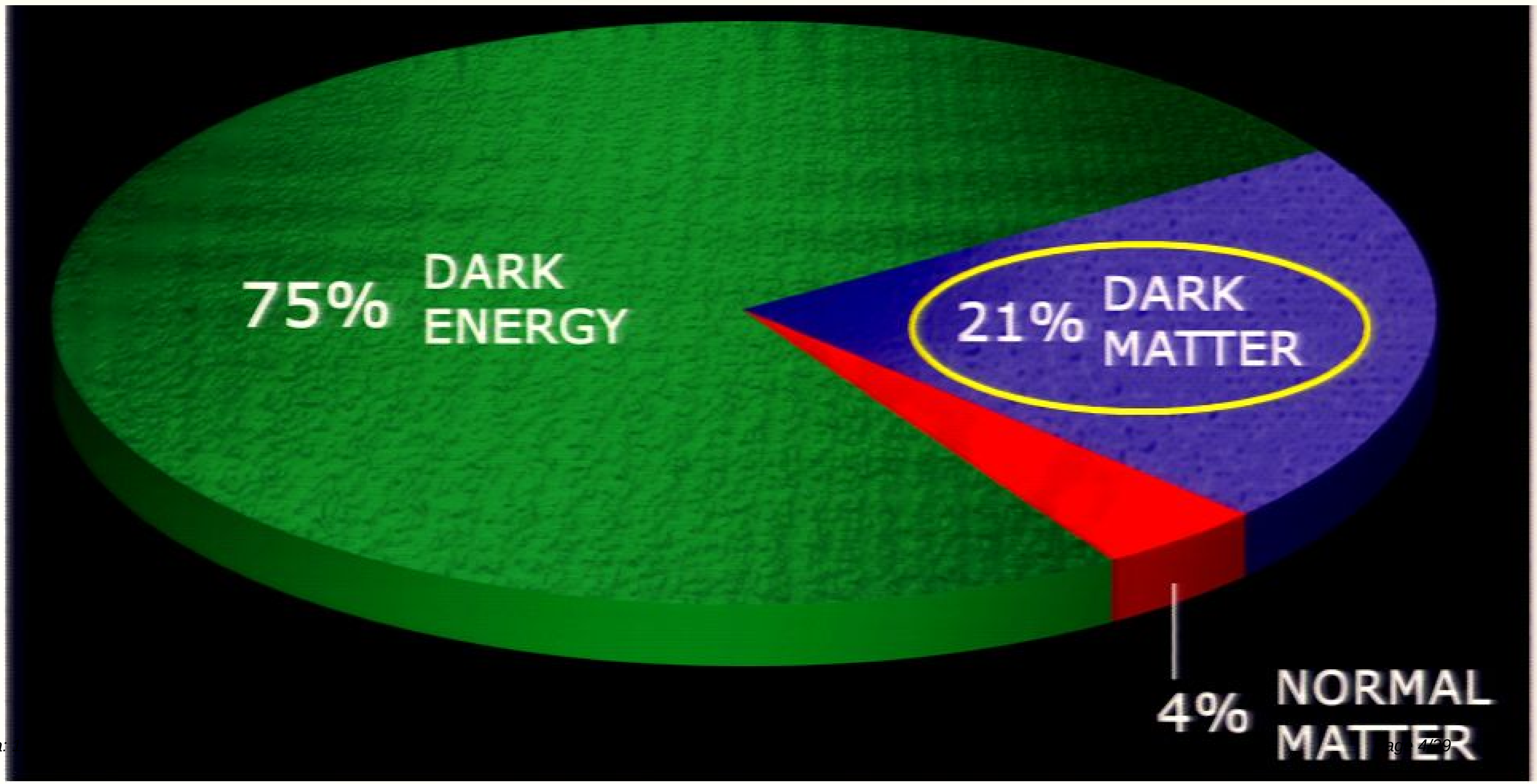
(S)pecial Thanks to Dr. Blair Grubb (University of Toledo)

Outline

- Dark Matter
  - Detection Experiments
  - Recent Results: DM Annihilation in Galactic Centre
- Higgs Models
  - Motivation and General Theory
  - Our 2HDM-L+S Model
- Computations: Selected Highlights
- Results
  - Scanning Parameter Space
  - Predictions in the 2HDM-L+S Model

Dark Matter

- DM: unseen matter that interacts gravitationally



Dark Matter

- Many cosmological observations point to the existence of DM
  - Rotation curves of galaxies
  - Modulation of gravitational lensing around galaxies
  - Baryon fraction inside individual galaxy clusters
  - WMAP constraints on baryon and matter abundance

Dark Matter

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  - Baryon fraction inside individual galaxy clusters
  - WMAP constraints on baryon and matter abundance
- WIMPs (Weakly Interacting Massive Particles): naturally yield correct "relic density"
  - By cosmologically-estimated abundance:
    $<\sigma v_{rel}> \approx 3 \times 10^{-26}\ cm^3/s$
- Today, WIMPs would still be annihilating with each other in collisions

Dark Matter: Detection Experiments

- Indirect methods
  - Look for products of DM annihilations (neutrinos, positrons, anti-protons, synchrotron radiation, γ rays …)
  - e.g. Fermi Gamma-ray Space Telescope (FGST)

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  - Look for products of DM annihilations (neutrinos, positrons, anti-protons, synchrotron radiation, γ rays …)
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- Direct methods
  - Watch for events where DM particles scatter off target nuclei
  - e.g. XENON100

Dark Matter: FGST Results

- Independent analysis by Hooper & Goodenough
- Analyze γ rays to search for signal from DM annihilations
  - DM halo of Milky Way would be densest at galactic centre
  - Energy and angular dependence
  - Determined by DM density, mass, annihilation cross-section, annihilation spectrum, ...
- Within 1.25° of Galactic Centre, excess of 600MeV - 6GeV emissions appeared
  - Astrophysical backgrounds subtracted, and fits performed

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Dark Matter: FGST Results

- Possibly due to DM with:
  - Mass of 7.3 – 9.2 GeV
  - Annihilation primarily to taus (with at most 10-20% of annihilations proceeding to bottom pairs or charm pairs)
  - $\langle \sigma v \rangle = 3.3 \times 10^{-27} - 1.5 \times 10^{-26}$ cm^3/s

Dan Hooper and Lisa Goodenough. Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope. *Phys. Lett.*, B697:412–428, 2011. 1010.2752.

Dark Matter: FGST Results

- Possibly due to DM with:
  - Mass of 7.3 – 9.2 GeV
    - Fairly low-mass!
  - Annihilation primarily to taus (with at most 10-20% of annihilations proceeding to bottom pairs or charm pairs)
    - Something here is leptophilic?
  - $<\sigma v> = 3.3 \times 10^{-27} - 1.5 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
    - A little low… but a lot of uncertainties are involved in this area

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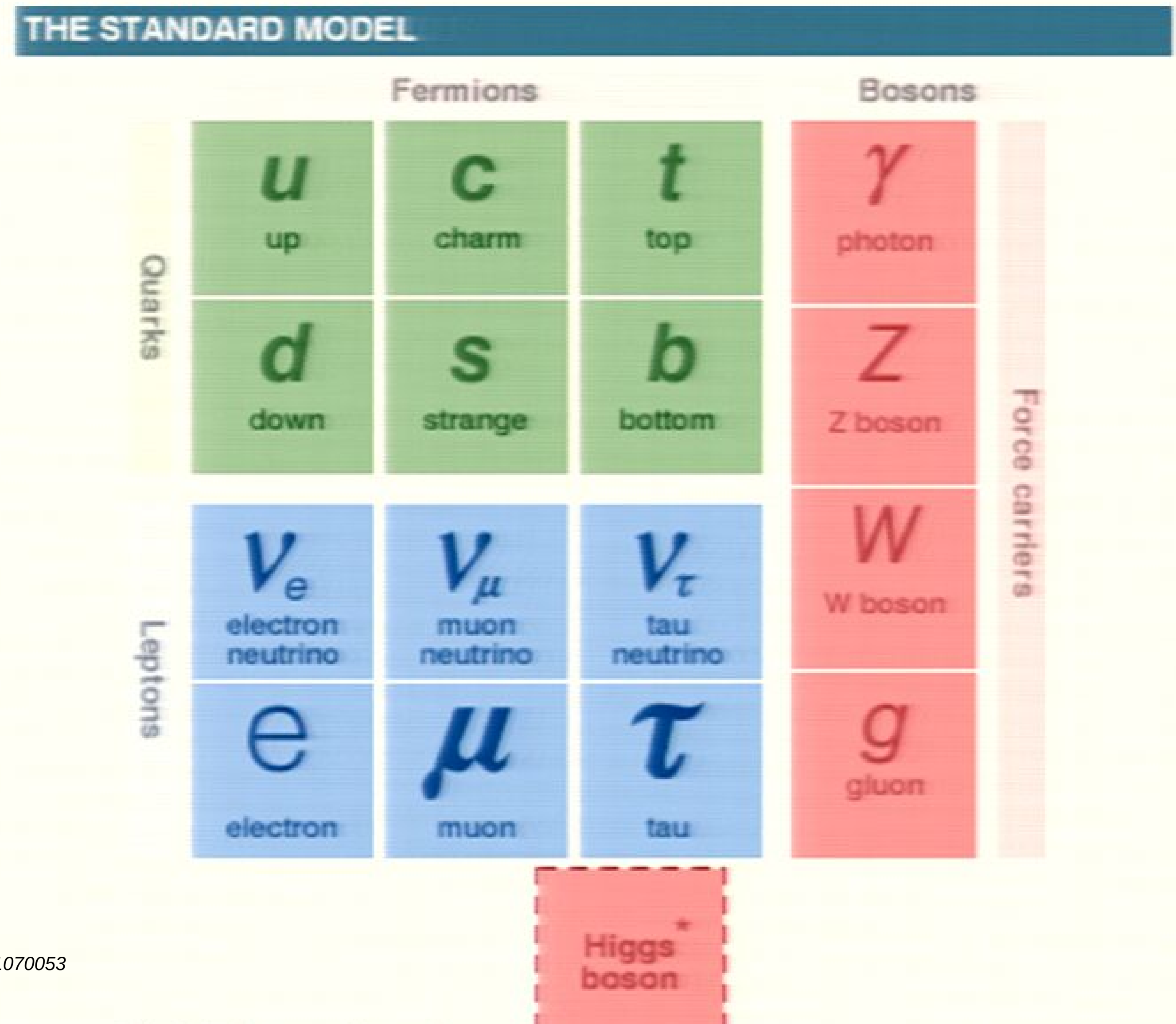
Higgs Models: Motivation



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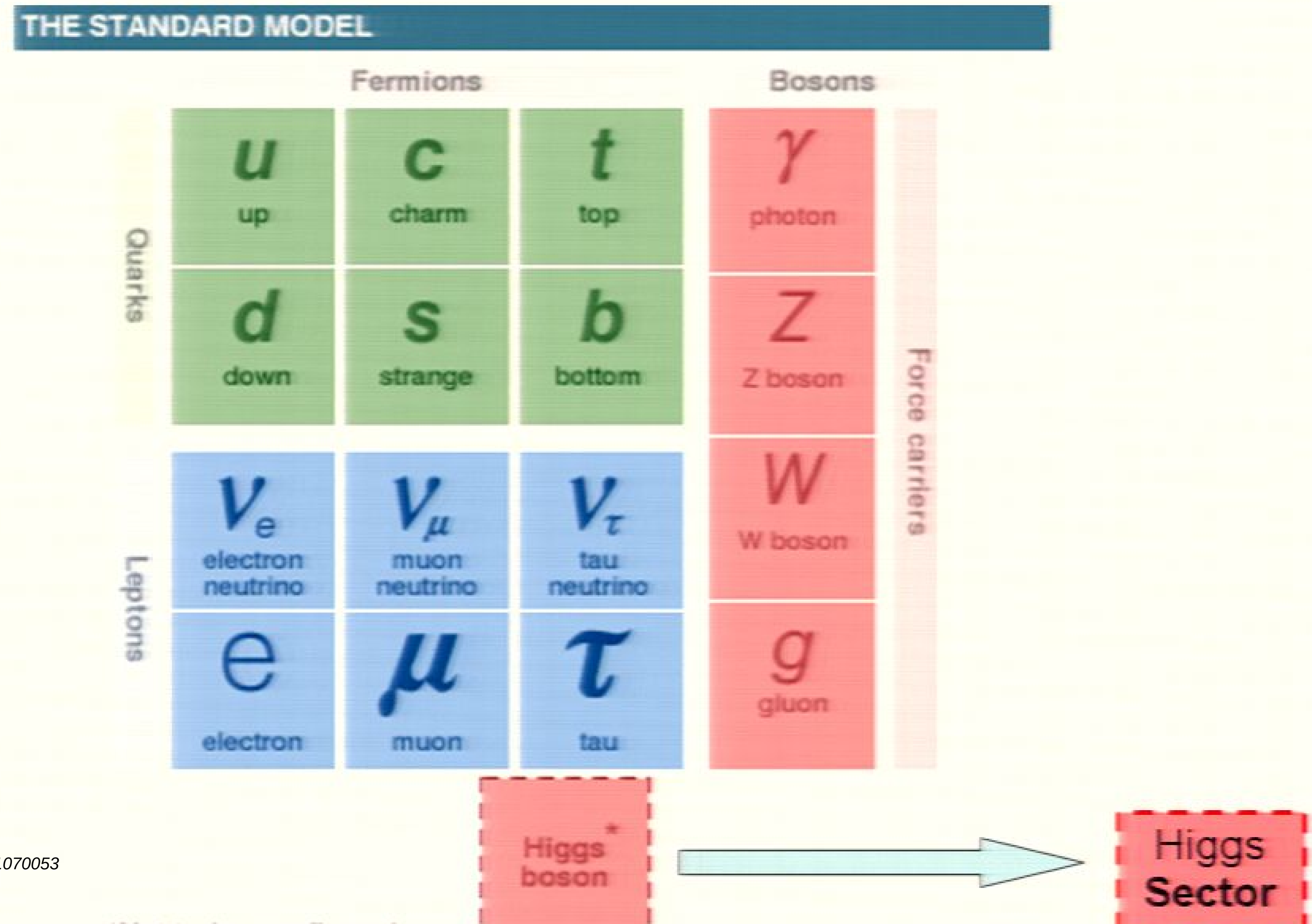

Higgs Models: Motivation

- Gauge theories with massless force carriers (gluons, photons) are fairly straightforward
- But weak gauge bosons ($W^{+/-}$, Z) have mass!
- Solution: modify the theory by adding Higgs
  - Weak gauge bosons receive masses via Higgs mechanism
  - SM quarks and charged leptons receive masses through Yukawa interactions
- "Minimal" form of Higgs sector ("SM Higgs") has one doublet, so one Higgs particle
- Many "beyond the SM" candidates predict extended Higgs sectors (multiple Higgs particles)

Higgs: Our 2HDM-L+S Model

- 2HDM: Two isospin doublet scalar fields (Φ_1 and Φ_2)
- 2HDM-L: all quarks couple to Φ_q while charged leptons couple to Φ_l, with Z_2 symmetry broken only softly in Higgs potential
- Doublet representation:

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ \frac{1}{\sqrt{2}}(\phi_j^{0,\Re} + v_j + i\phi_j^{0,\Im}) \end{pmatrix}$$ where $v_q^2 + v_l^2 = v_{SM}^2$ and $\tan\beta \equiv \frac{v_q}{v_l}$

- Yukawa Lagrangian:

$$\mathcal{L}_{\text{Yuk}} = -\sum_{i,j=1}^{3} \left[y_{ij}^u \overline{u}_{Ri} \tilde{\Phi}_q^\dagger Q_{Lj} + y_{ij}^d \overline{d}_{Ri} \Phi_q^\dagger Q_{Lj} + y_{ij}^\ell \overline{e}_{Ri} \Phi_\ell^\dagger L_{Lj} \right] + \text{h.c.}.$$

where

$$Q_{Li} = (u_{Li}, d_{Li})^T$$
$$L_{Li} = (\nu_{Li}, e_{Li})^T$$

and

$$\tilde{\Phi}_q \equiv i\sigma_2 \Phi_q^* = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(\phi_q^{0,r} + v_q - i\phi_q^{0,i}\right) \\ -\phi_q^- \end{pmatrix}$$

2HDM-L+S: Add a gauge-singlet real scalar field S (odd under unbroken Z_2 symmetry)

This adds the following to the potential:

$$V_S = \frac{1}{2} m_3^2 S^2 + \frac{\lambda_q}{2} S^2 \Phi_q^\dagger \Phi_q + \frac{\lambda_\ell}{2} S^2 \Phi_\ell^\dagger \Phi_\ell + \lambda_S S^4$$

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Zoo!

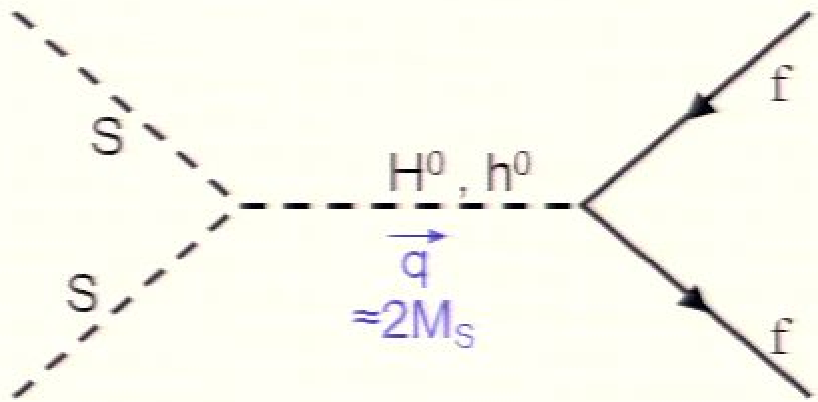
(Physical) Particle Content:

- A : pseudoscalar
- H+ / H- : "charged" Higgs
- h^0 : "SM-like" Higgs
- H^0 : another neutral Higgs
- S: stable due to Z_2 symmetry; the DM candidate!

Computations: Selected Highlights

- S Annihilation Cross-Sections:
  - Into fermion-antifermion pair:

$$\sigma v_{rel} = \frac{N_c m_f^2 C_f^2}{4\pi}\left(1 - \frac{m_f^2}{M_S^2}\right)^{3/2}$$



with

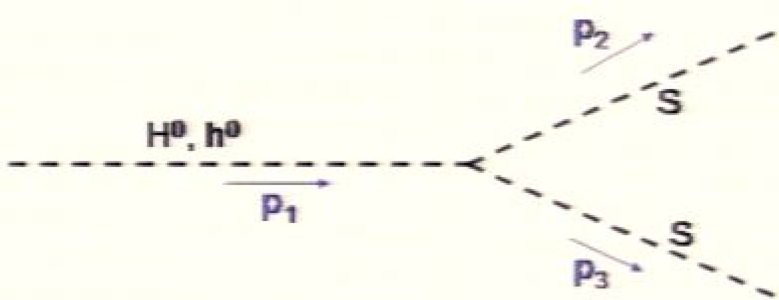
$$C_l = \frac{(\lambda_q \tan\beta\cos\alpha - \lambda_l \sin\alpha)\sin\alpha}{4M_S^2 - M_{h^0}^2} - \frac{(\lambda_q \tan\beta\sin\alpha + \lambda_l \cos\alpha)\cos\alpha}{4M_S^2 - M_{H^0}^2}$$

$$C_q = \frac{-(\lambda_q \cos\alpha - \lambda_l \cot\beta\sin\alpha)\cos\alpha}{4M_S^2 - M_{h^0}^2} - \frac{(\lambda_q \sin\alpha + \lambda_l \cot\beta\cos\alpha)\sin\alpha}{4M_S^2 - M_{H^0}^2}$$

  - We're particularly interested in annihilation into tau pair, bottom pair, charm pair

Computations: Selected Highlights

- Decay Widths of Neutral Higgses
  - Invisible Decay (where ϕ = H^0 or h^0):



$$\Gamma(\phi \to SS) = \frac{\lambda_\phi^2 v_{SM}^2}{32\pi M_\phi}\sqrt{1 - \frac{4M_S^2}{m_\phi^2}}$$

$$\lambda_{h^0} = \lambda_q \sin\beta\cos\alpha - \lambda_l \cos\beta\sin\alpha$$

$$\lambda_{H^0} = \lambda_q \sin\beta\sin\alpha + \lambda_l \cos\beta\cos\alpha$$

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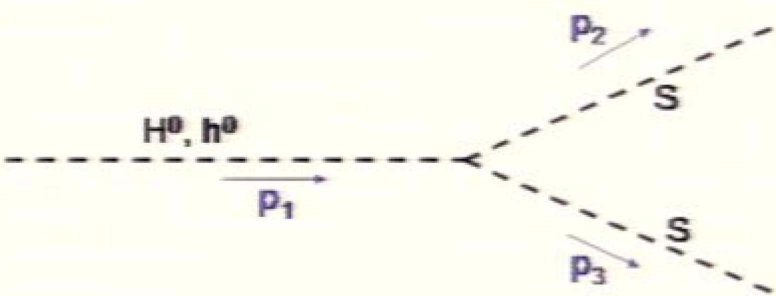

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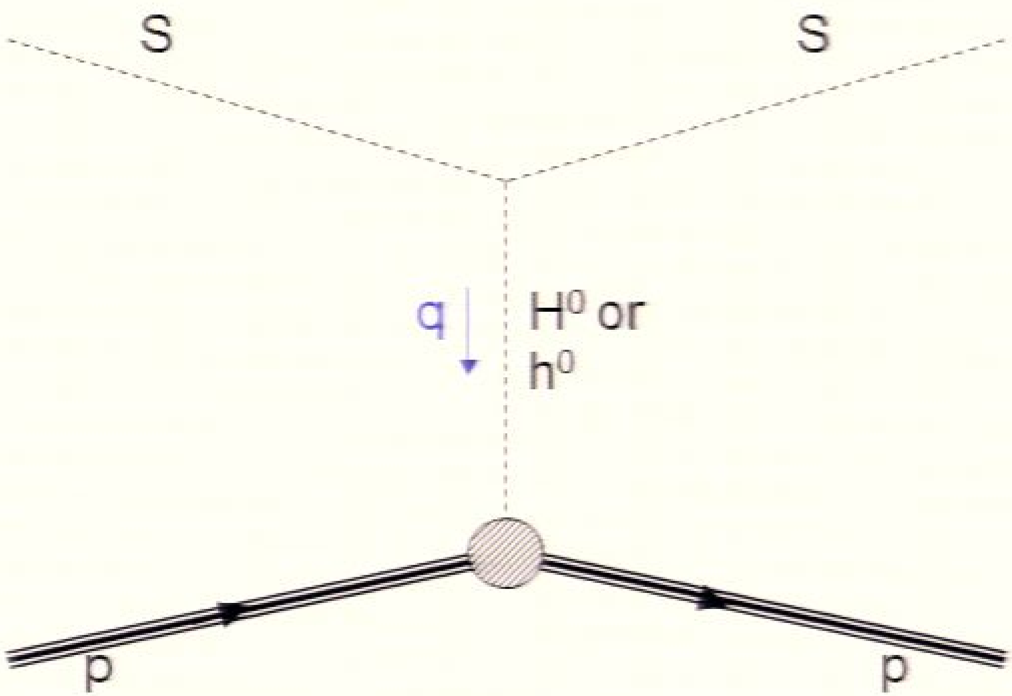
  - Total Width: Partial decay width to each of $b\overline{b}, c\overline{c}, \tau\tau, \mu\mu, gg, \gamma\gamma, Z\gamma, WW$, and ZZ is decay width for SM Higgs multiplied by appropriate scaling factor

▪ Cross-Section for S Scattering off Protons:

Spin-Independent ($\sigma_{SI,p}$)

$$\sigma_{SI,p} = \frac{m_p^4}{2\pi(m_p + M_S)^2} C_q'^2 (f_{proton-up} + f_{proton-down} + f_{proton-strange} + \frac{2}{9} f_{proton-gluon})^2$$



Form-Factors:

- $f_{proton-up} = 0.02$
- $f_{proton-down} = 0.026$
- $f_{proton-strange} = 0.118$
- $f_{proton-gluon} = 0.836$

Computations: Selected Highlights

- Naturalness:

$$M_S^2 = m_3^2 + \frac{v_{SM}^2}{2}(\lambda_q \sin^2\beta + \lambda_l \cos^2\beta)$$

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~246 GeV

~8 GeV

  - We let $b = \frac{|m_3^2|}{M_S^2}$
  - *b* is a measure of "how much fine-tuning is in the model"
  - *b* < 10: relatively little fine-tuning
  - *b* > 100: large cancellations are at play

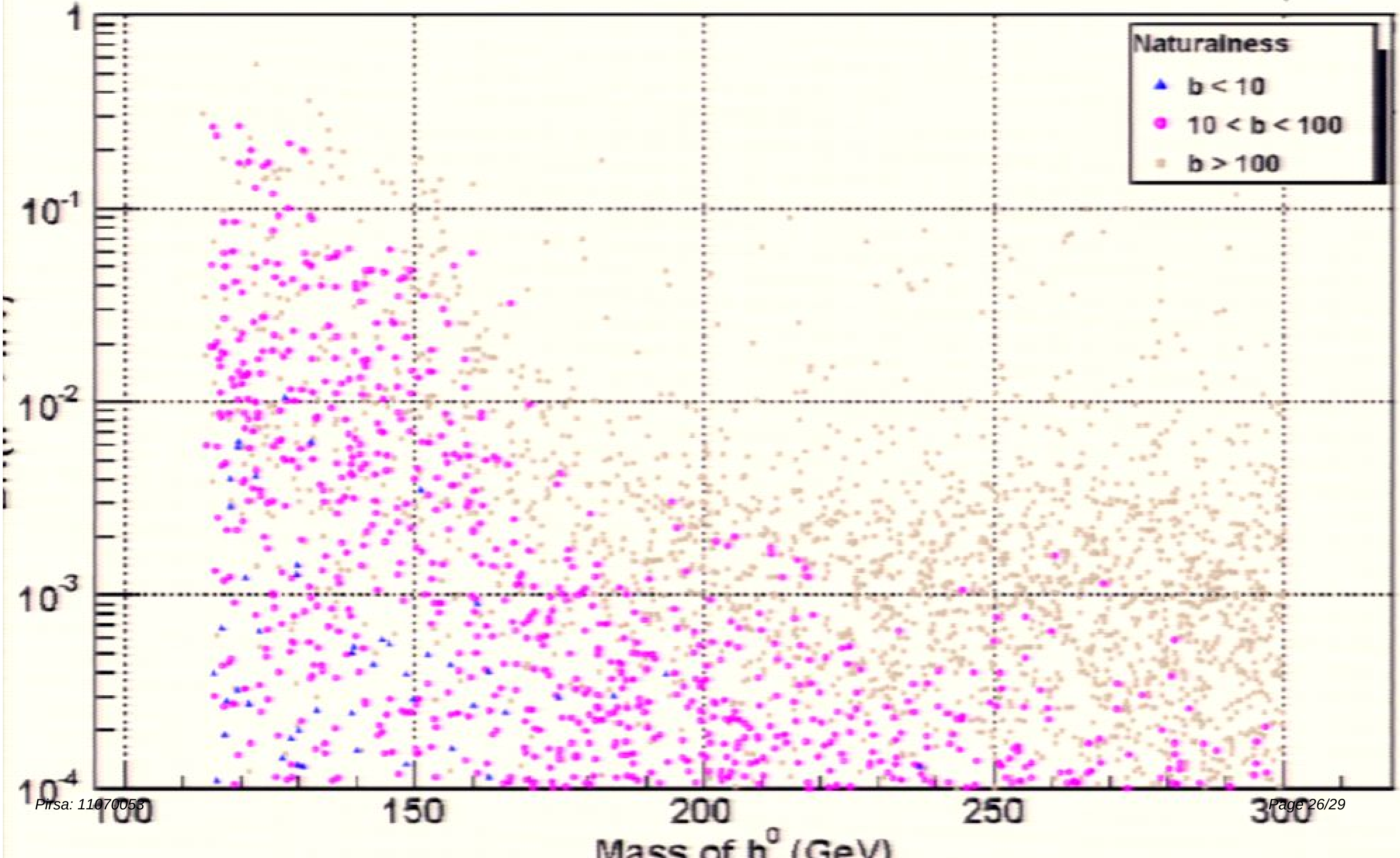
Results: Scanning Parameter Space

- Generated 50000 points in parameter space

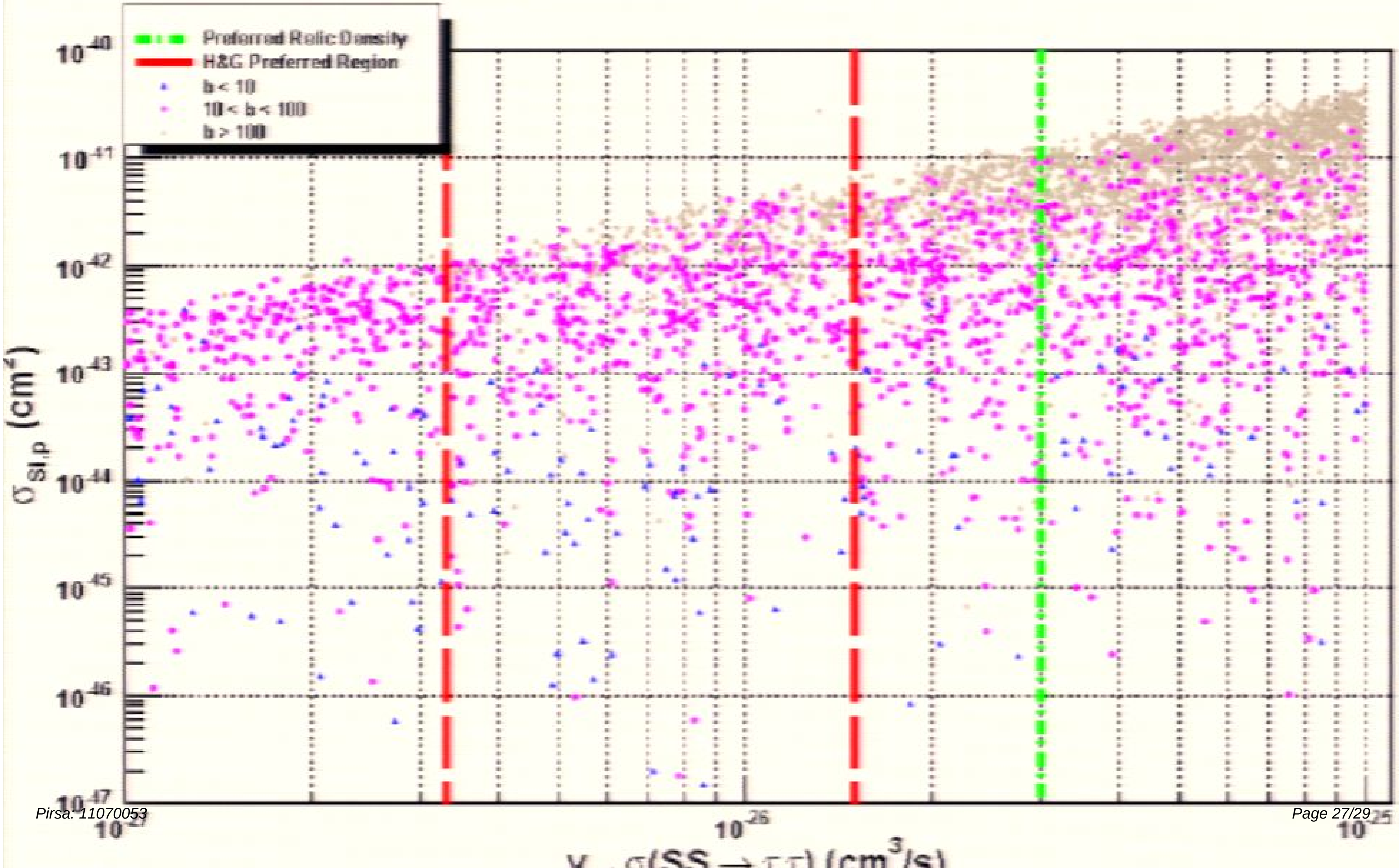
Parameter	Range
M_S	7.3 - 9.2 GeV
M_{ho}	10 - 300 GeV
M_{H0}	10 - 300 GeV
λ_q	
λ_l	0 - λ_{max}
$\tan\beta$	1 - 50
α	$\beta - \frac{3\pi}{4} \leq \alpha \leq \beta - \frac{\pi}{4}$

- Only kept points where:
  - DM annihilation is <20% to bottoms/charms
  - 1.0×10^{-27} cm^3/s < $v_{rel}\sigma(SS \to \tau\tau)$ < 1.0×10^{-25} cm^3/s
  - Not ruled out by existing searches (public code HiggsBounds)

Results: Neutral Higgs Invisible Branching Ratios



Results: Proton Scattering Cross-Section



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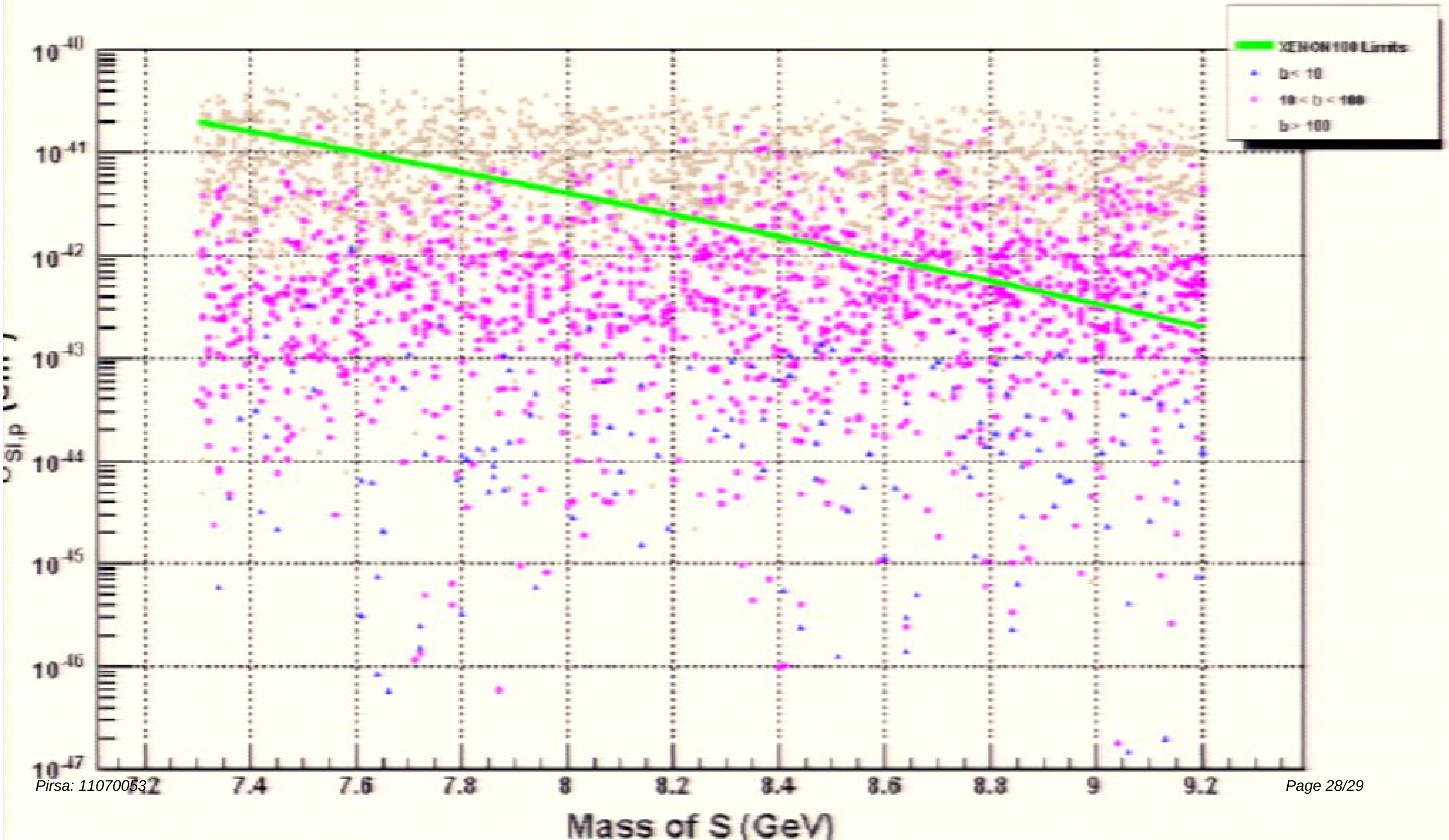

Conclusions

- Given recent analysis of FGST data that may be interpreted as evidence for annihilating DM, 2HDM-L+S model yields interesting DM candidate
- A scan of parameter space in this model yielded many promising points, compatible with FGST observations and with cosmologically measured relic abundance
- Invisible Higgs decay searches look unpromising
- Direct detection searches starting to constrain parameter space