Perturbative Unitarity Constraints On (non-)SUSY Higgs Portals

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arXiv:1310.8286

and in collaboration with K. Betre and S. El Hedri (to appear)

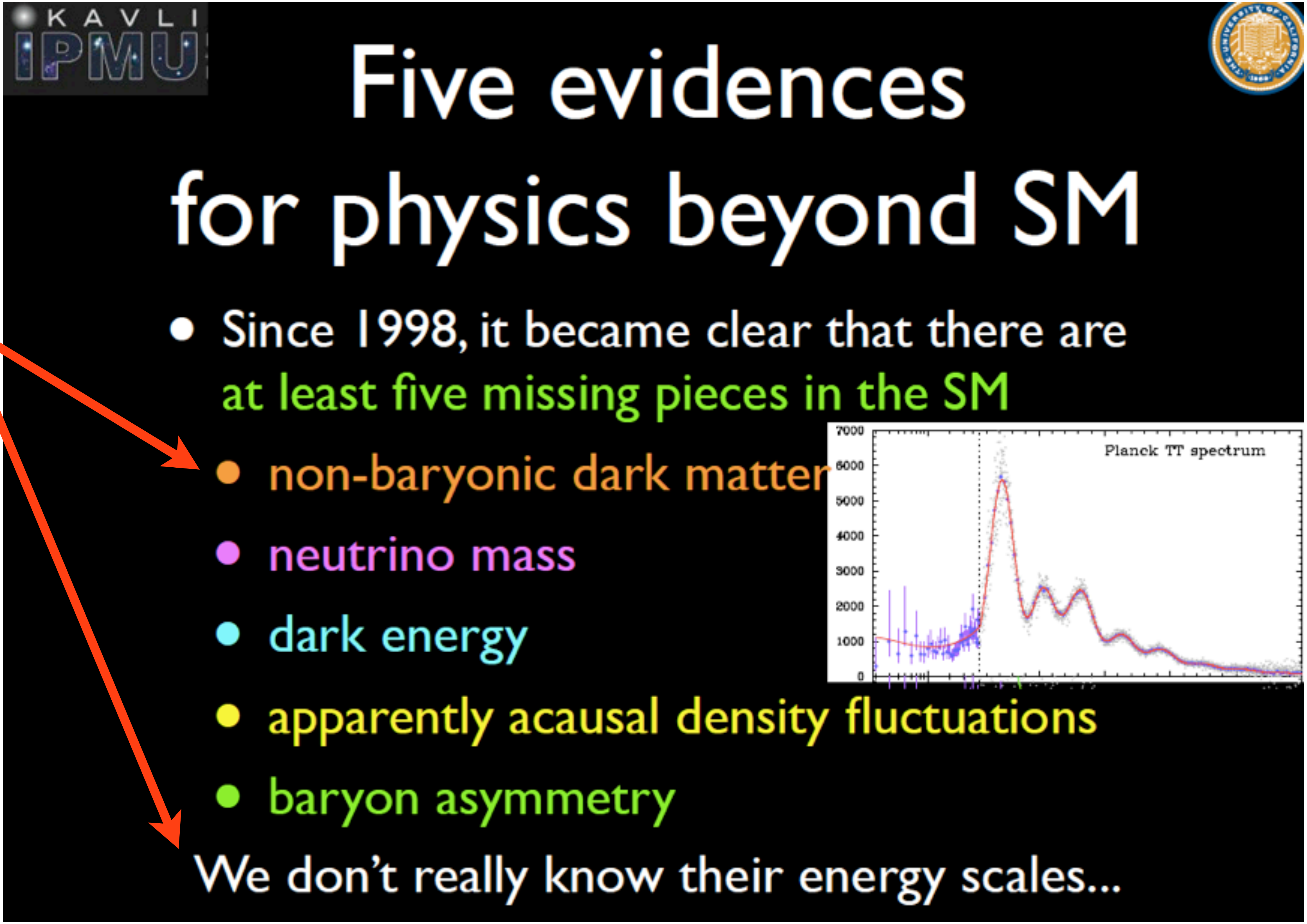
A Brief History of New Physics

- Historically perturbative unitarity arguments have reliably indicated when new, perturbative physics will appear:

Fermi theory: Dimension six operators violate unitarity around 350 GeV. Rescued: W boson at 80 GeV.

Light pion effective theory: Pion scattering violates unitarity around 1.2 GeV. Rescued: Axial and vector resonances at 800 MeV.

Electroweak theory: WW scattering requires new physics around 1.2 TeV. Rescued: SM Higgs boson at 125.5 GeV. A primary motivation for 14 TeV LHC!



Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

We don't really know their energy scales...

!

H. Murayama, LP2013

- Today: Use perturbative unitarity constraints and the thermal dark matter hypothesis to place bounds on Higgs portal dark matter as well as the visible particles needed for annihilation.

(Aside: Essentially, trying to replace naturalness arguments with more rigorous perturbative unitarity arguments to get a better understanding of when new physics will appear.)

Today’s Talk

- Basic Philosophy
- A (Non-SUSY) Higgs portal
  - Two models with fermionic dark matter
  - Perturbative unitarity arguments/relic abundance
  - Bounds/Signatures
- NMSSM Higgs portal
  - NMSSM review
  - Perturbative unitarity arguments/relic abundance
  - Mass/bounds on SUSY Breaking scales
  - Some Signatures
- Conclusions

Basic Philosophy

Basic Philosophy

- For the basic philosophy, consider a generic Higgs portal:

1. A dark Higgs that couples directly to dark matter.
2. The dark and the SM Higgses mix to facilitate dark matter annihilations.

Basic Philosophy

- Now consider simple WW scattering amplitudes:

$$
\begin{aligned}
\mathcal{M}_{\text{gauge}} &= \frac{g^2}{4\,m_W^2}(s+t) \\
\mathcal{M}_{\text{SM higgs}} &= -\frac{g^2}{4\,m_W^2}(s+t)\,\cos^2\theta \\
\mathcal{M}_{\text{dark higgs}} &= -\frac{g^2}{4\,m_W^2}(s+t)\,\sin^2\theta
\end{aligned}
$$

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Both higgses needed to unitarize WW scattering because of the mixing.

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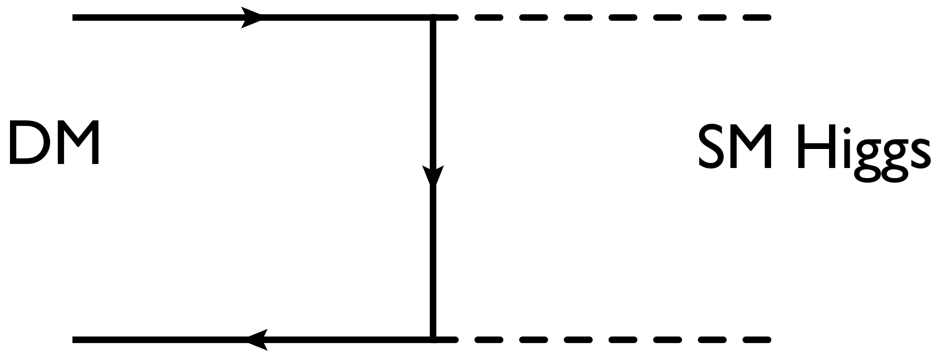
\end{aligned}$$

Both higgses needed to unitarize WW scattering because of the mixing.

- As the dark Higgs mass is raised, one is forced to set the mixing angle to zero to satisfy unitarity.

Basic Philosophy

- However, (in the decoupled dark Higgs limit) the relic abundance prevents $\sin\theta \rightarrow 0$.



$$\langle \sigma |v| \rangle \sim \frac{\sin^4\theta}{m_\chi^2}$$

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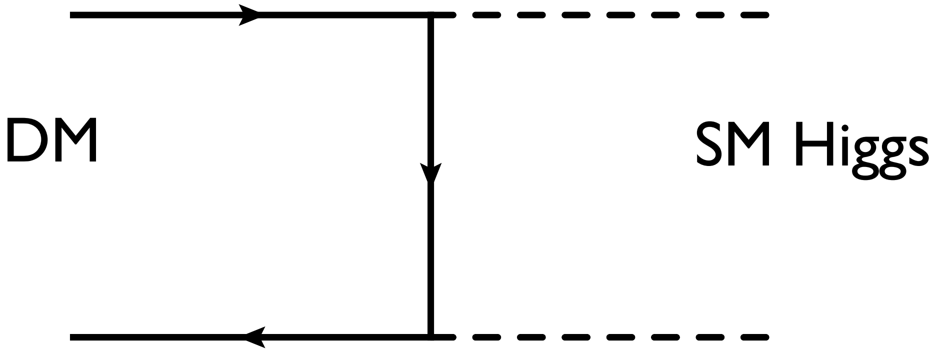

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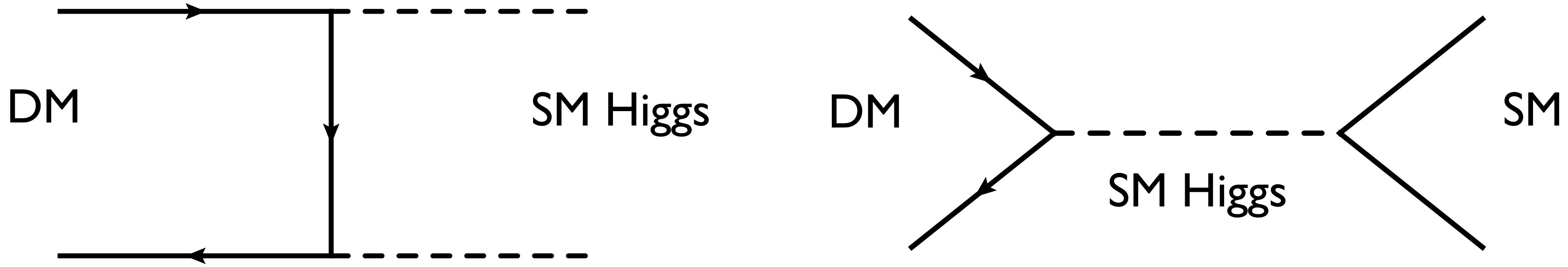

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- The dark Higgs mass cannot completely decoupling.

Basic Philosophy

- General Philosophy:

  Generate tension between unitarity and low-energy observables (e.g. relic abundance) to produce upper bounds on new particles.

- Basic claim:

  Relic abundance constraints (WIMP dark matter) +

  SM Higgs mass constraints +

  Unitarity constraints = New (tighter) Physics Bounds

A (non-SUSY) Higgs Portal

A (non-SUSY) Higgs Portal

- A Higgs portal:

$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^2 - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^2 - \frac{u^2}{2}\right)$$

$$\mathcal{L} = \overline{\chi}\left(\lambda_{\chi_V} + i\,\lambda_{\chi_A}\gamma_5\right)\Phi\,\chi$$

A (non-SUSY) Higgs Portal

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mixing term

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dark matter

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dark matter

Pseudo-scalar coupling for Model 2.
Important for dark matter annihilation channels.

- Two models: **Model 1:** $\lambda_{\chi\,A} = 0$,

  Model 2: $\lambda_{\chi\,A}$ and $\lambda_{\chi\,V}$ are non-zero

A (non-SUSY) Higgs Portal

- Masses and mixings:

$$\begin{pmatrix} h' \\ \rho' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix}$$

$$\begin{aligned} m_h^2 &= 2\,\lambda_1 v^2 \left(1 - \frac{\lambda_3^2}{4\,\lambda_1 \lambda_2} + \ldots\right) \\ m_\rho^2 &= 2\,\lambda_2\, u^2 \left(1 + \frac{\lambda_3^2}{4\,\lambda_2^2} \frac{v^2}{u^2} + \ldots\right) \end{aligned}$$

$$\sin\theta \sim \frac{\lambda_3\, v}{2\lambda_2\, u}$$

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dark Higgs

mixing angle

- Interested in the limit where the dark Higgs is heavy but the mixing angle is non-trivial.

Relic Abundance

- **t-channel annihilation:**

  (heavy dark Higgs limit)

$$\langle\sigma|v|\rangle \;=\; \frac{\sin^4\theta}{4\pi\;\left(2\,m_\chi^2-m_h^2\right)^2}\sqrt{1-\frac{m_h^2}{m_\chi^2}}\left(m_\chi^2\,(\lambda_{\chi A}^4+6\,\lambda_{\chi A}^2\lambda_{\chi V}^2+\lambda_{\chi V}^4)-m_h^2\,(\lambda_{\chi A}^2+\lambda_{\chi V}^2)^2\right)+\ldots$$

- **s-channel annihilation:**

  (heavy dark Higgs limit)

$$\langle\sigma|v|\rangle_{\bar{f}f} \;=\; \frac{\lambda_{\chi A}^2\sin^2\theta\cos^2\theta}{4\pi}\sum_{f=u,d,c,s,t,b,e,\mu,\tau}\sqrt{1-\frac{m_f^2}{m_\chi^2}}\left(\frac{g\,m_f}{m_W}\right)^2\left(\frac{m_\chi^2-m_f^2}{\left(4\,m_\chi^2-m_h^2\right)^2}\right)+\ldots$$

$$\langle\sigma|v|\rangle_{VV} \;=\; \frac{\lambda_{\chi A}^2\,m_W^2\,\sin^2\theta\cos^2\theta}{8\,\pi}\sum_{V=W,Z}\sqrt{1-\frac{m_V^2}{m_\chi^2}}\left(\frac{g_{Vh}^2}{m_V^4\,\left(4m_\chi^2-m_h^2\right)^2}\right)\left(3\,m_V^4-4m_V^2\,m_\chi^2+4\,m_\chi^4\right)+\ldots$$

$$\langle\sigma|v|\rangle_{hh} \;=\; \frac{\lambda_{h^3}^2\,\lambda_{\chi A}^2\,\sin^2\theta}{2\,\pi}\sqrt{1-\frac{m_h^2}{m_\chi^2}}\frac{9\,u^2}{\left(4\,m_\chi^2-m_h^2\right)^2}+\ldots$$

Relic Abundance

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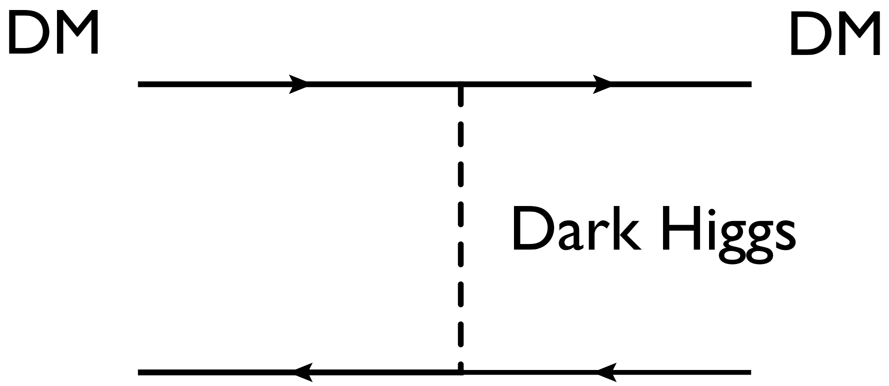
Proportional to
pseudo-scalar
coupling

*Lopez-Honorez, Schwetz and Zupan,
Phys. Lett. B 716, 179

Unitarity Considerations

- Dark matter/dark matter scattering:
  (Similar to unitarity bounds* on heavy 4th generation fermions)



* Furman, Hinchliffe and Chanowitz,
Nuclear Physics B153, 402; Physics Letters B78, 285

Full Unitarity Considerations

(Goldstone Boson Limit)

$$\left(W_L^+W_L^-,\ \frac{Z_LZ_L}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ \frac{\rho\rho}{\sqrt{2}},\ h\rho,\ hZ_L,\ \rho Z_L\right)$$

$$\mathcal{M}_I^{(0)} = -\frac{\lambda_1}{4\pi}\begin{pmatrix} 1 & \frac{1}{\sqrt{8}} & \frac{c^2}{\sqrt{8}} & \frac{s^2}{\sqrt{8}} & \frac{sc}{2} & 0 & 0 \\ \frac{1}{\sqrt{8}} & \frac{3}{4} & \frac{c^2}{4} & \frac{s^2}{4} & \frac{sc}{\sqrt{8}} & 0 & 0 \\ \frac{c^2}{\sqrt{8}} & \frac{c^2}{4} & \frac{3c^4}{4} & \frac{3s^2c^2}{4} & \frac{3\,sc^3}{\sqrt{8}} & 0 & 0 \\ \frac{s^2}{\sqrt{8}} & \frac{s^2}{4} & \frac{3\,s^2c^2}{4} & \frac{3s^4}{4} & \frac{3\,cs^3}{\sqrt{8}} & 0 & 0 \\ \frac{sc}{2} & \frac{sc}{\sqrt{8}} & \frac{3\,sc^3}{\sqrt{8}} & \frac{3\,cs^3}{\sqrt{8}} & \frac{3\,c^2s^2}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{c^2}{2} & \frac{sc}{2} \\ 0 & 0 & 0 & 0 & 0 & \frac{sc}{2} & \frac{s^2}{2} \end{pmatrix} - \frac{\lambda_3}{4\pi}\begin{pmatrix} 0 & 0 & \frac{s^2}{\sqrt{32}} & \frac{c^2}{\sqrt{32}} & -\frac{sc}{4} & 0 & 0 \\ 0 & 0 & \frac{s^2}{8} & \frac{c^2}{8} & \frac{-sc}{\sqrt{32}} & 0 & 0 \\ \frac{s^2}{\sqrt{32}} & \frac{s^2}{8} & \kappa & \delta & \xi & 0 & 0 \\ \frac{c^2}{\sqrt{32}} & \frac{c^2}{8} & \delta & \alpha & \beta & 0 & 0 \\ -\frac{sc}{4} & -\frac{sc}{\sqrt{32}} & \xi & \beta & \eta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{s^2}{4} & -\frac{sc}{4} \\ 0 & 0 & 0 & 0 & 0 & -\frac{sc}{4} & \frac{c^2}{4} \end{pmatrix}$$

Full Unitarity Considerations

(Goldstone Boson Limit)

dark higgs

$$\left(W_L^+W_L^-,\ \frac{Z_LZ_L}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ \frac{\rho\rho}{\sqrt{2}},\ h\rho,\ hZ_L,\ \rho Z_L\right)$$

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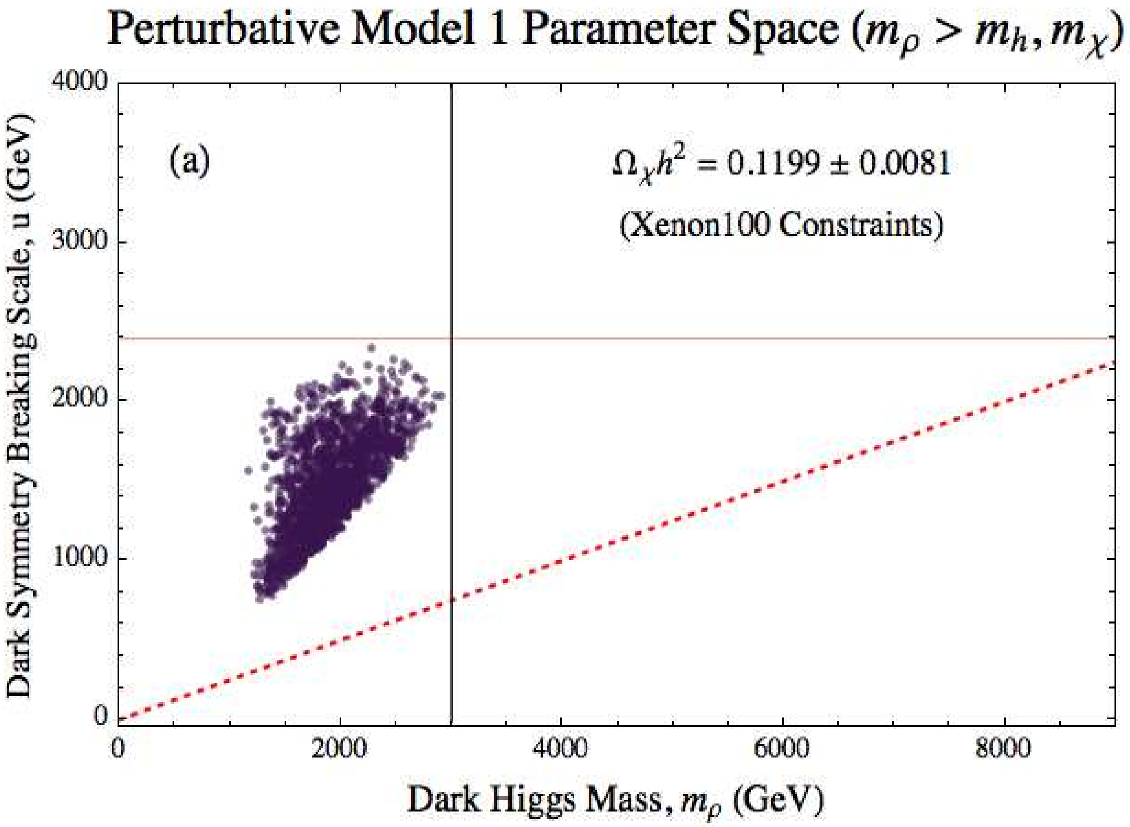
Perturbative Corrections

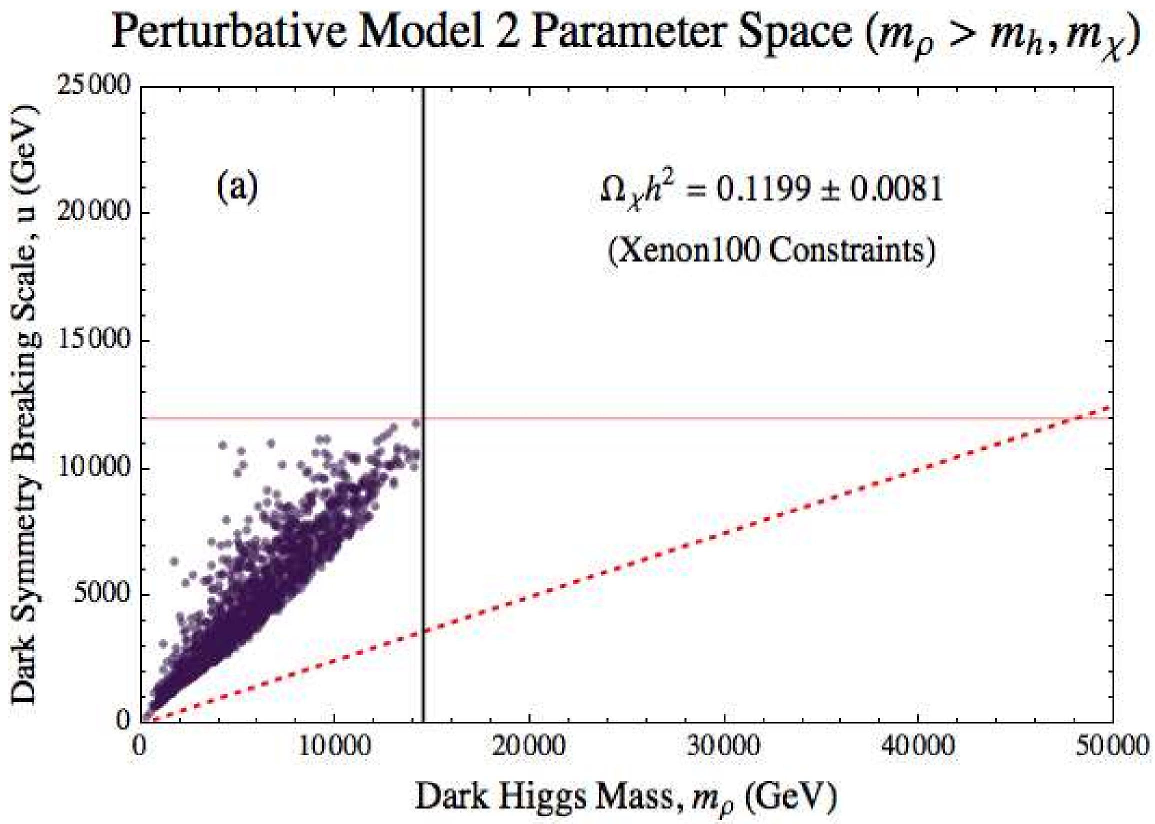
- Tree-level unitarity constraints are not enough to get an accurate scale of new physics.*
- In addition require the next order correction not to generate a 30% correction larger than the tree-level correction**. (no Landau poles)
- More (fuller explanation) on this in the next section.

*See Aydemir, Anber and Donoghue, arXiv:1203.5153, for a similar conclusion using chiral perturbation theory.

**See Barbieri, Hall and Rychkov, arXiv:0603188.

A (non-SUSY) Higgs Portal





(Walker, arXiv:1310.1083)

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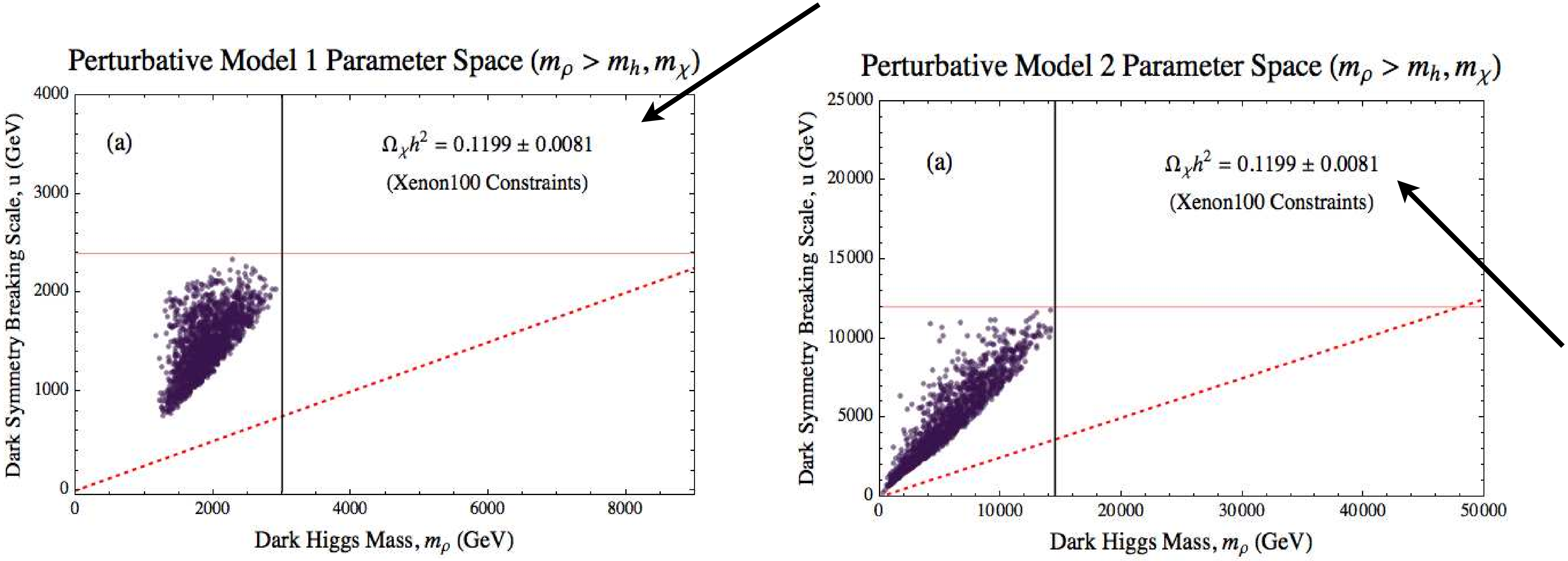

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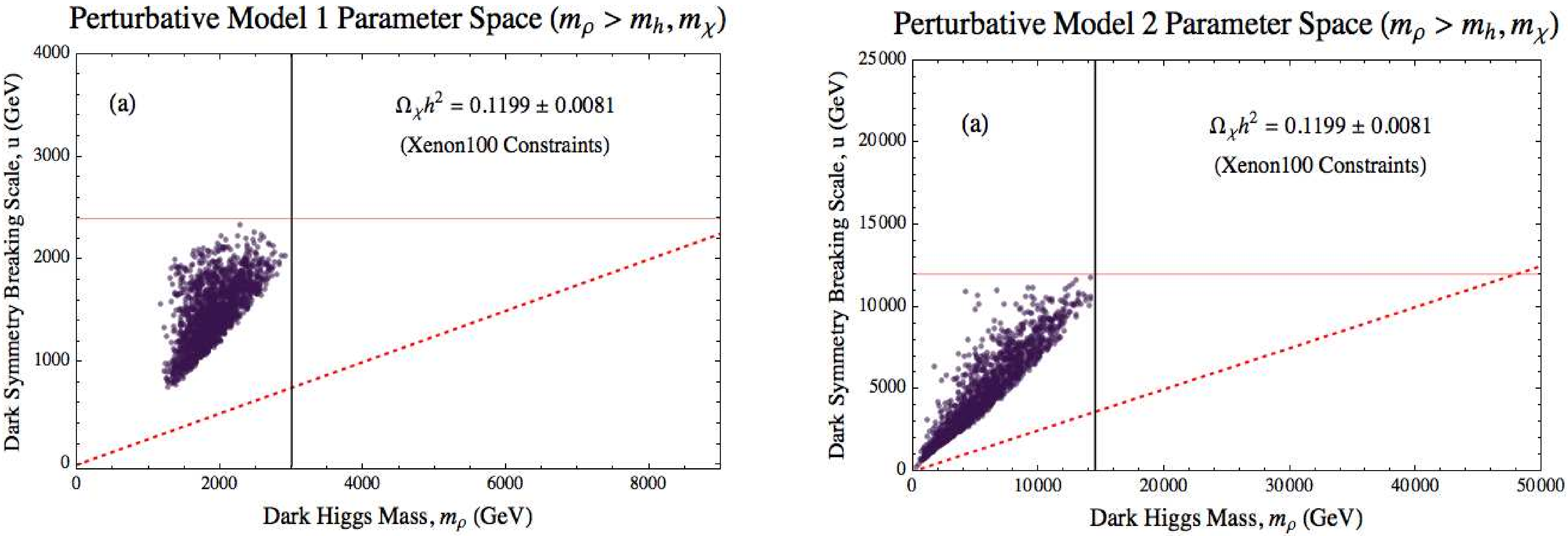
- Points which satisfy (or give smaller) relic abundance.

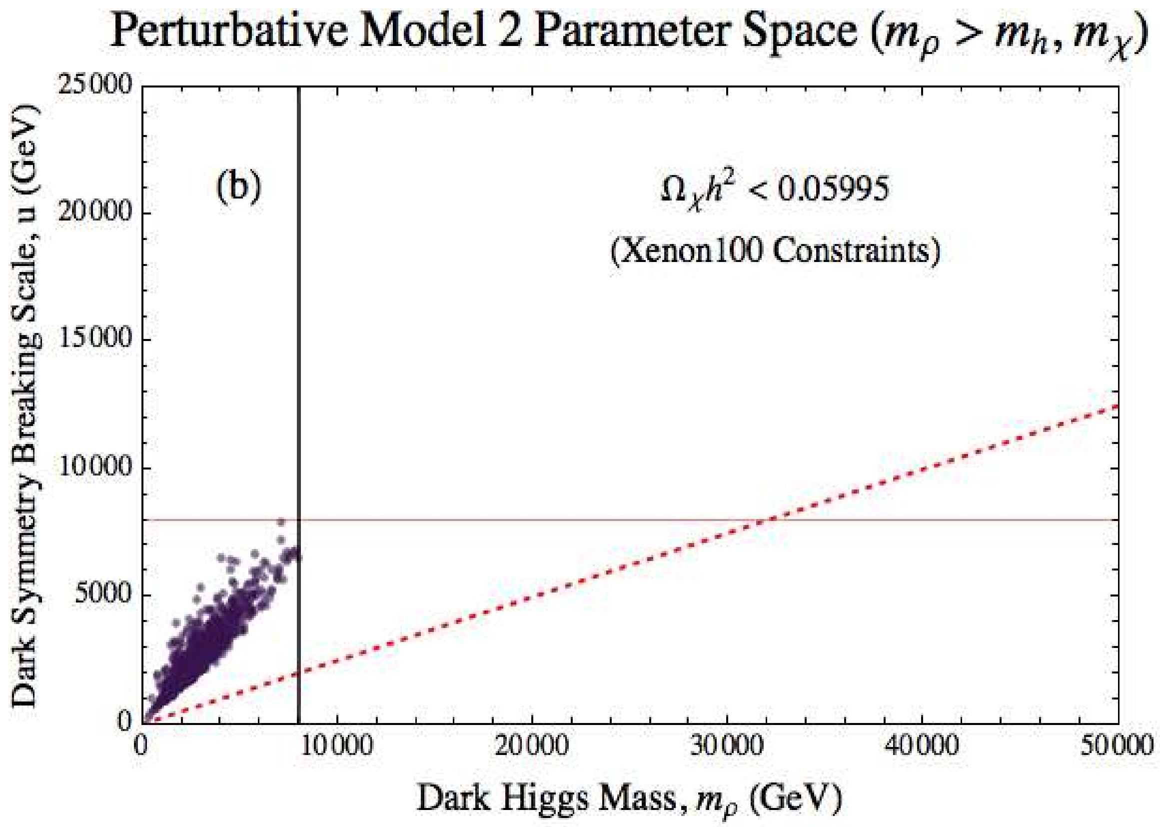
A (non-SUSY) Higgs Portal



(Walker, arXiv:1310.1083)

- 1T direct detection searches are sensitive to all of the above points.

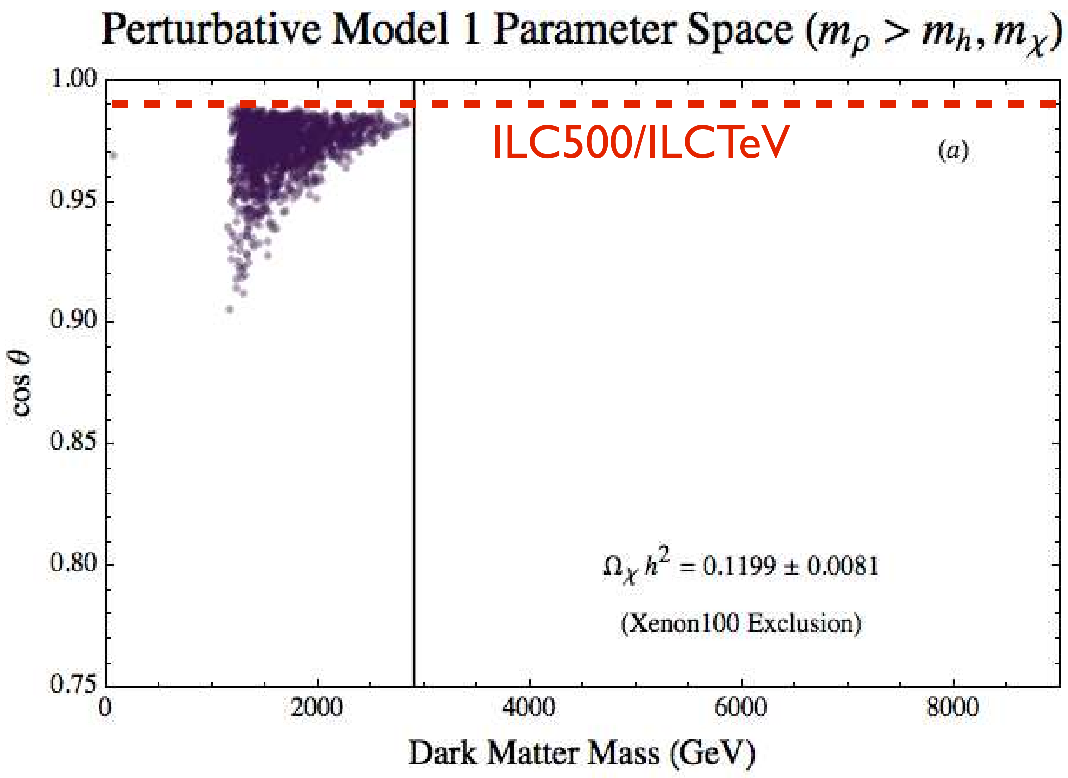
A (non-SUSY) Higgs Portal

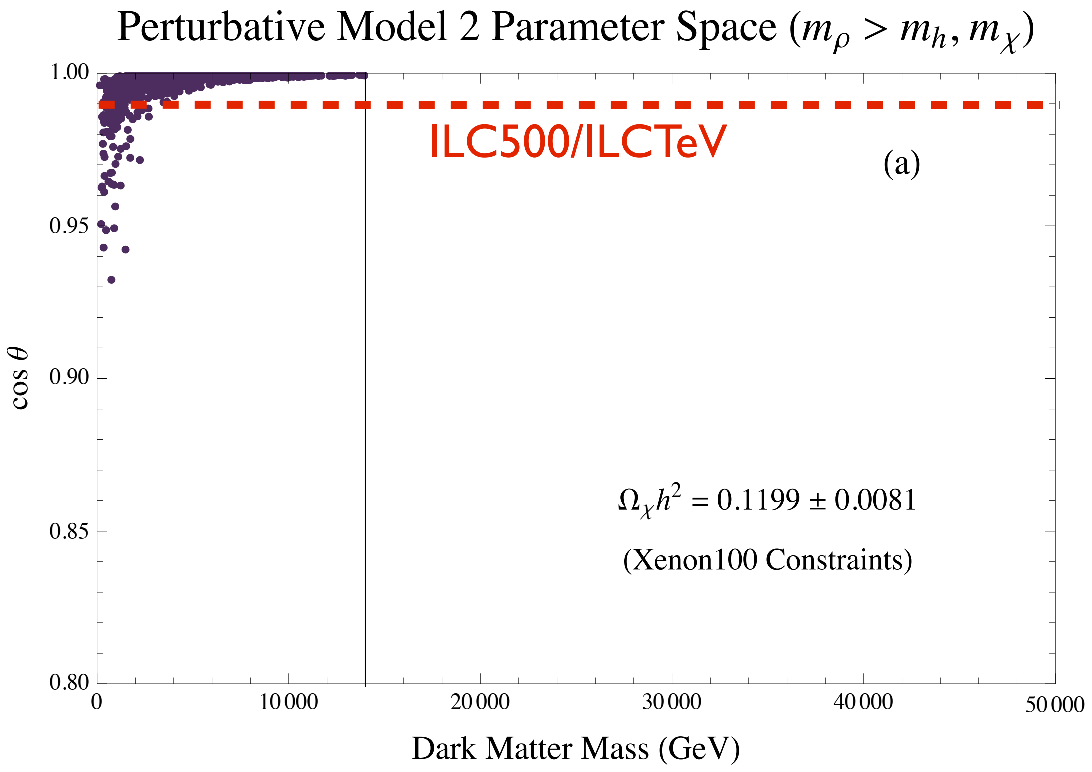


(Walker, arXiv:1310.1083)

- Points which satisfy (or give smaller) half of measured relic abundance.

Philosophy from (non-SUSY) Higgs Portals





(Walker, arXiv:1310.1083)

- Precisely measuring deviation from the SM Higgs decays to WW and ZZ can severely constrain the parameter space.

NMSSM Higgs Portal

NMSSM Higgs Sector

- Focus on the NMSSM Higgs sector

  (only higgsino/singlino dark matter)

- Superpotential/soft-breaking terms:

$$\mathcal{W}_{\text{NMSSM}} = -\lambda \hat{S}\hat{H}_1 \cdot \hat{H}_2 + \frac{1}{3}\kappa \hat{S}^3$$

(scale invariant NMSSM)

$$V_{\text{soft}} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + m_S^2 S^\dagger S - \left(\lambda A_\lambda S H_1 \cdot H_2 - \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right)$$

NMSSM Higgs Sector

- Focus on the NMSSM Higgs sector

  (only higgsino/singlino dark matter)

- Six free parameters:

  (after requiring the correct electroweak vacuum)

$$\lambda, \quad \kappa, \quad \tan\beta, \quad \mu, \quad A_\lambda, \quad A_\kappa$$

NMSSM Higgs Sector

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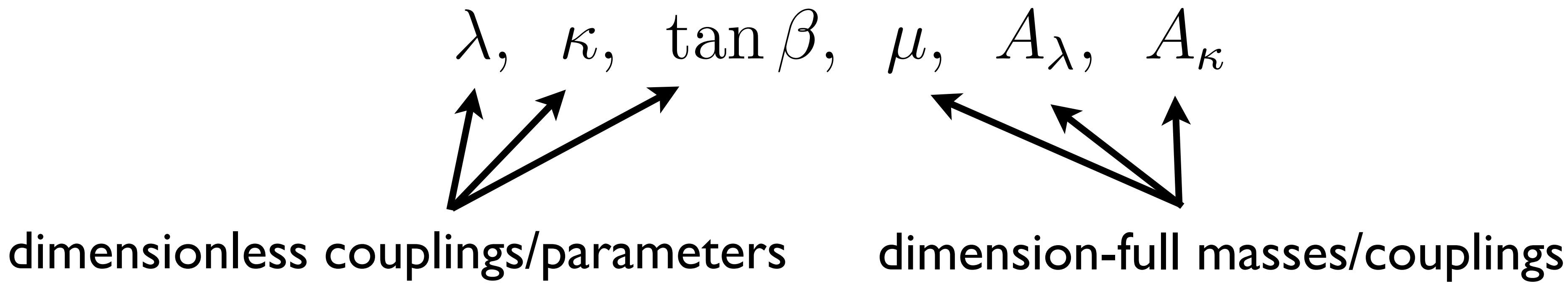


$$\lambda, \quad \kappa, \quad \tan\beta, \quad \mu, \quad A_\lambda, \quad A_\kappa$$

dimensionless couplings/parameters

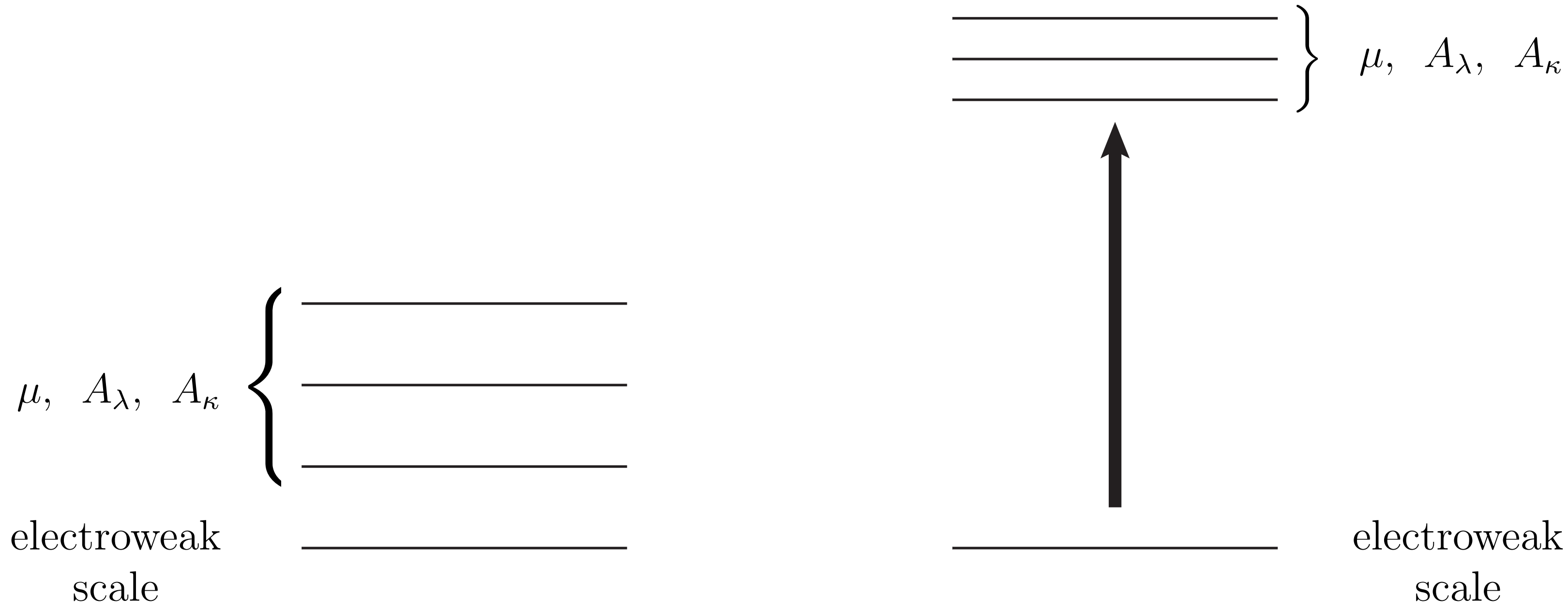
dimension-full masses/couplings

NMSSM Higgs Sector

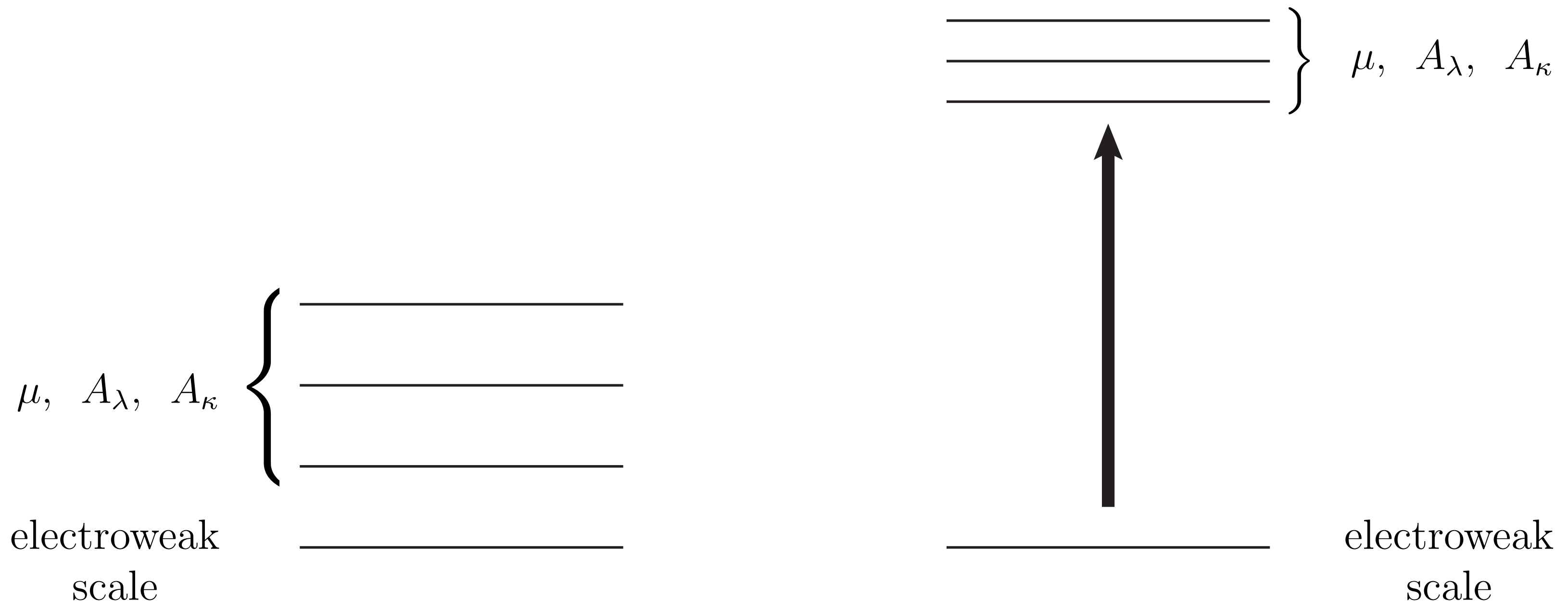
Want to generate tension by decoupling the NMSSM SUSY breaking scales.

(analogous to decoupling the dark Higgs in the non-SUSY Higgs portal)

NMSSM Higgs Sector



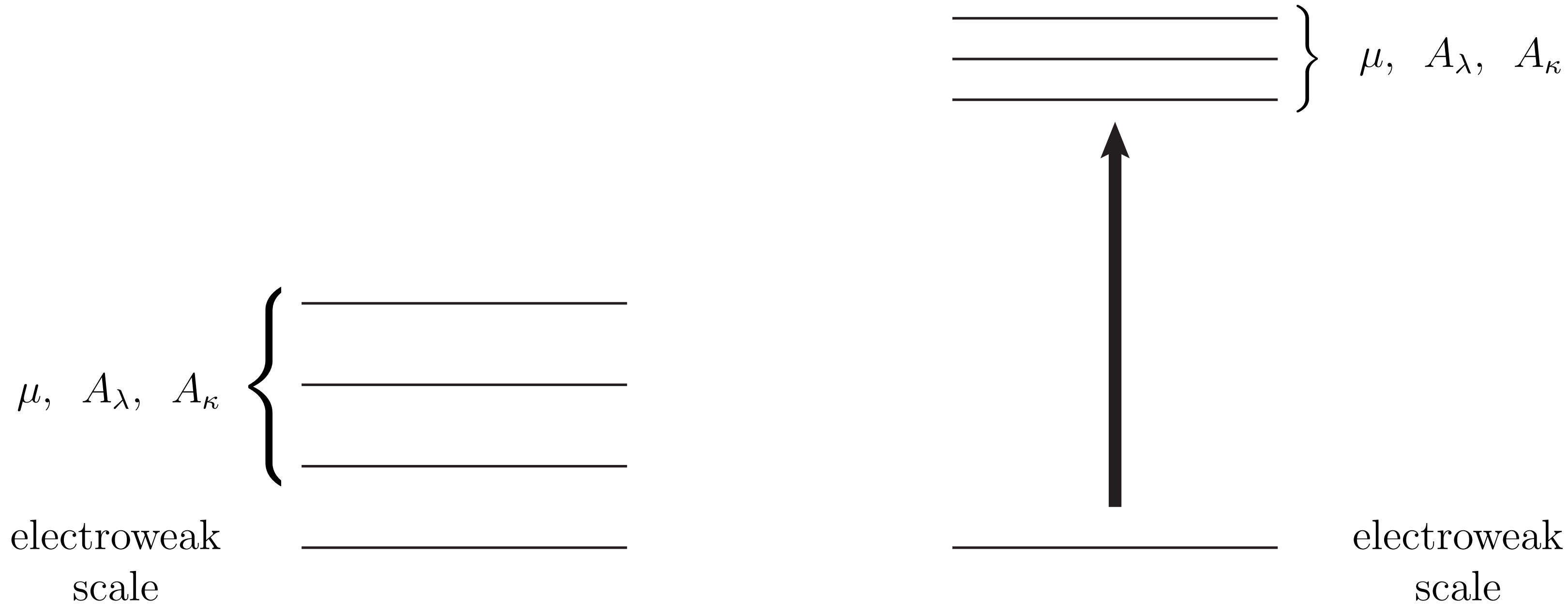
NMSSM Higgs Sector



- SM Higgs mass constrains λ modulo β :

$$m_{\rm SM}^2 = m_{H_1}^2 < m_Z^2 \left(\cos^2(2\beta) + \frac{2|\lambda|^2 \sin^2(2\beta)}{g_1^2 + g_2^2} \right)$$

NMSSM Higgs Sector

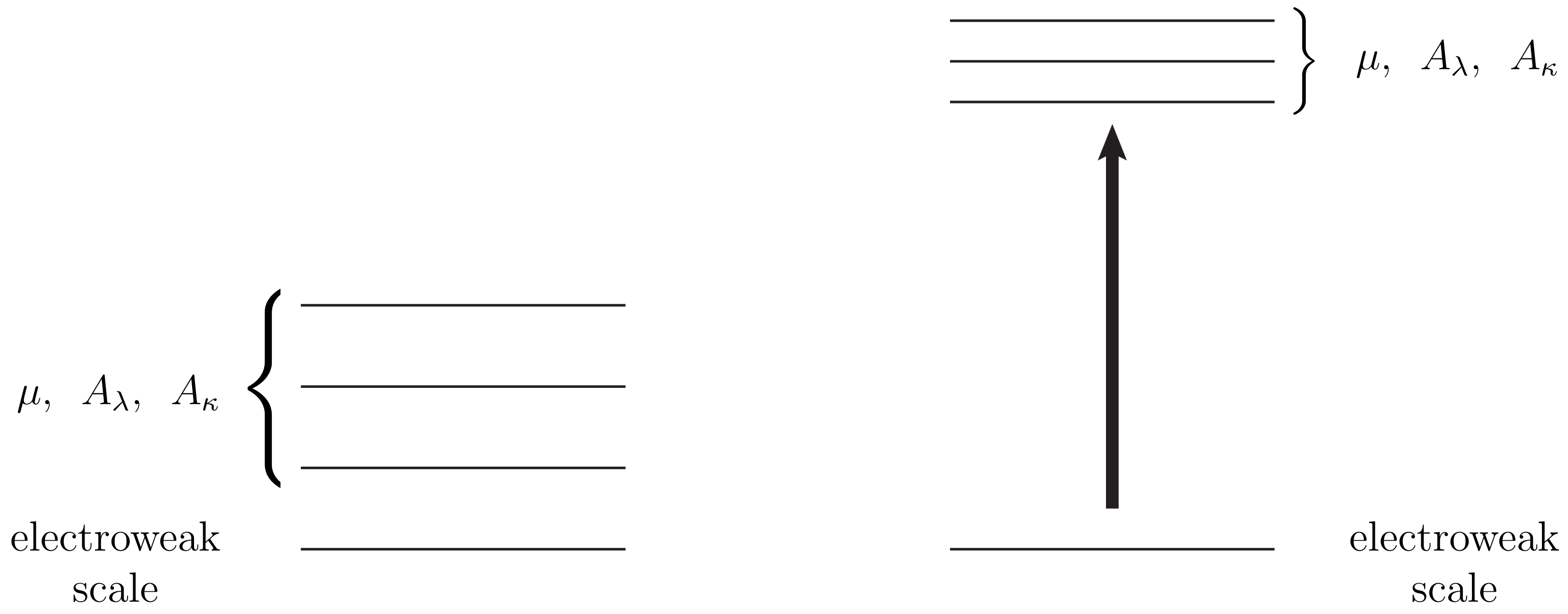


- Vacuum constrains*: $\lambda, \quad \kappa, \quad \tan\beta, \quad \mu, \quad A_\lambda, \quad A_\kappa$

   1. **Forbid** D-flat directions in the MSSM potential.
   2. **Forbid** directions where only one MSSM Higgs or singlet gets a vev.

*See, e.g., Kanehata, Kobayaski, Konishi, Seto and Shimomura, arXiv:1103.5109

NMSSM Higgs Sector

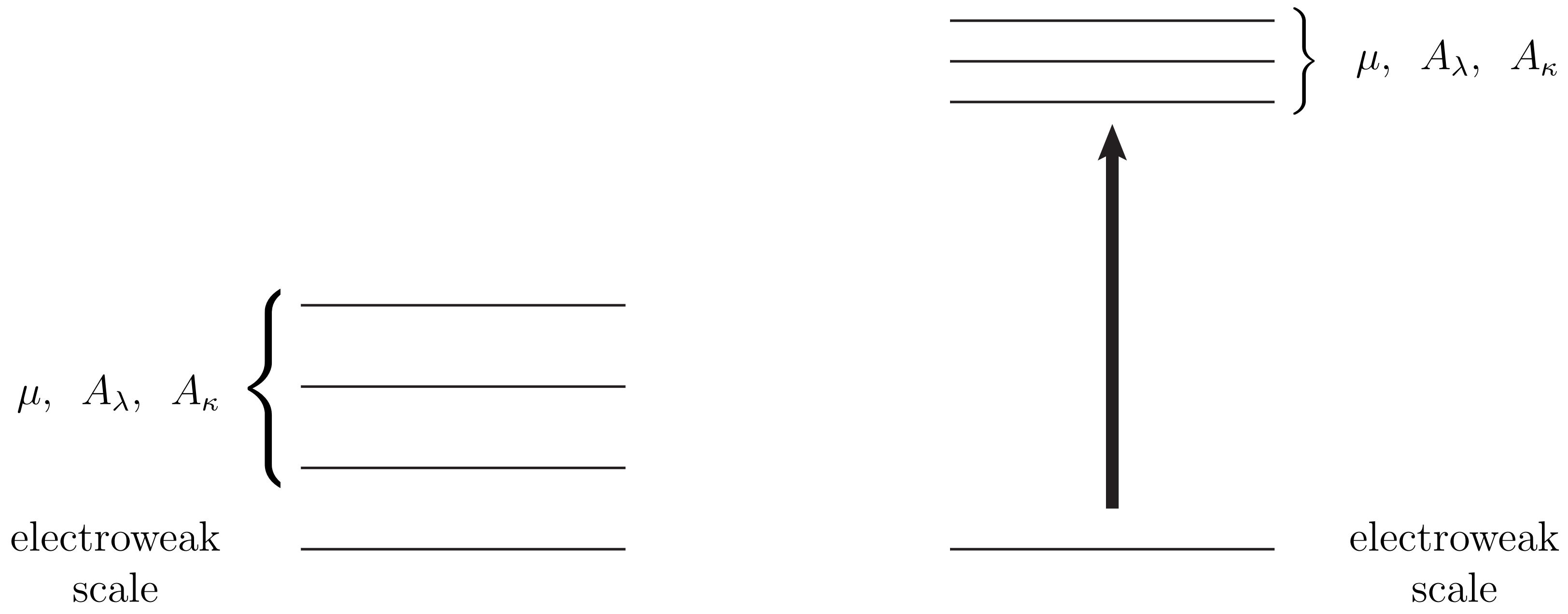


- Mass spectrum (in the decoupling limit):

$$\begin{aligned} m_{\tilde{H}_1} &= \mu + \mathcal{O}(v) \\ m_{\tilde{H}_2} &= \mu + \mathcal{O}(v) \\ m_{\tilde{S}} &= \sqrt{2}\,\kappa\,\mu/\lambda + \mathcal{O}(v) \\ m_{\tilde{H}^{+/-}} &= \mu + \mathcal{O}(v) \end{aligned}$$

$$\begin{aligned} m_{H_1^0} &= m_h \\ m_{H_2^0} &\sim f(\mu, A_\lambda) \\ m_S &\sim g(\mu, A_\kappa) \\ m_{A_1} &\sim h(\mu, A_\lambda) \\ m_{A_2} &\sim h'(\mu, A_\kappa) \\ m_{H^{+/-}} &\sim h(\mu, A_\lambda) \end{aligned}$$

NMSSM Higgs Sector



- Mass spectrum (in the decoupling limit):

$$\begin{aligned} m_{\tilde{H}_1} &= \mu + \mathcal{O}(v) \\ m_{\tilde{H}_2} &= \mu + \mathcal{O}(v) \\ m_{\tilde{S}} &= \sqrt{2}\,\kappa\,\mu/\lambda + \mathcal{O}(v) \\ m_{\tilde{H}^{+/-}} &= \mu + \mathcal{O}(v) \end{aligned}$$

$$\begin{aligned} m_{H_1^0} &= m_h \\ m_{H_2^0} &\sim f(\mu, A_\lambda) \\ m_S &\sim g(\mu, A_\kappa) \\ m_{A_1} &\sim h(\mu, A_\lambda) \\ m_{A_2} &\sim h'(\mu, A_\kappa) \\ m_{H^{+/-}} &\sim h(\mu, A_\lambda) \end{aligned}$$

All non-SM masses increase
with decoupling.

Perturbative Unitarity Arguments

Perturbative Unitarity Arguments

- Use perturbative unitarity on both the dimensionless and dimension-full parameters to estimate when perturbativity will break down.

$$\lambda, \quad \kappa, \quad \mu, \quad A_\lambda, \quad A_\kappa$$

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- Performed the standard analysis to bound the scalar quartic couplings when $s \to \infty$.

Perturbative Unitarity Arguments

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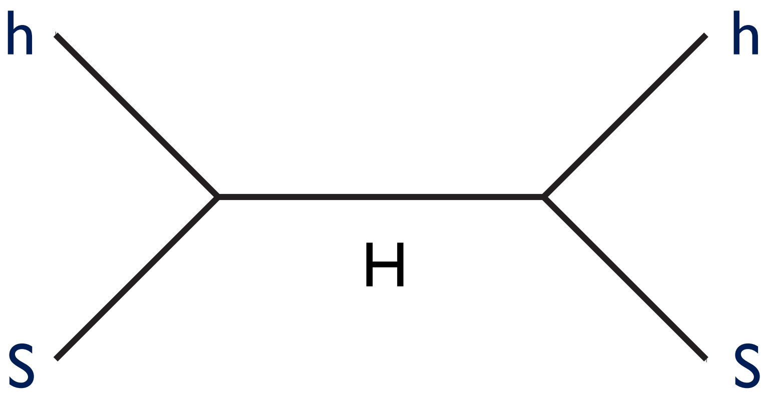
$$\lambda, \quad \kappa, \quad \mu, \quad A_\lambda, \quad A_\kappa$$

- SUSY is a perturbative theory. Trilinear and dimensionless couplings cannot be too large.
- Performed the standard analysis to bound the scalar quartic couplings when $s \to \infty$.
- Claim: Perturbative unitarity also has sensitivity to ratios of the dimension-full parameters.

Perturbative Unitarity Arguments

- Sensitivity to ratios:



$$\mathcal{M} \sim \frac{A_\lambda^2}{s - m_H^2}$$

Code scans over s. Selects a optimized value of s, where the amplitude can be maximized.

Perturbative Unitarity Arguments

- Review:

Unitarity of the S-matrix requires

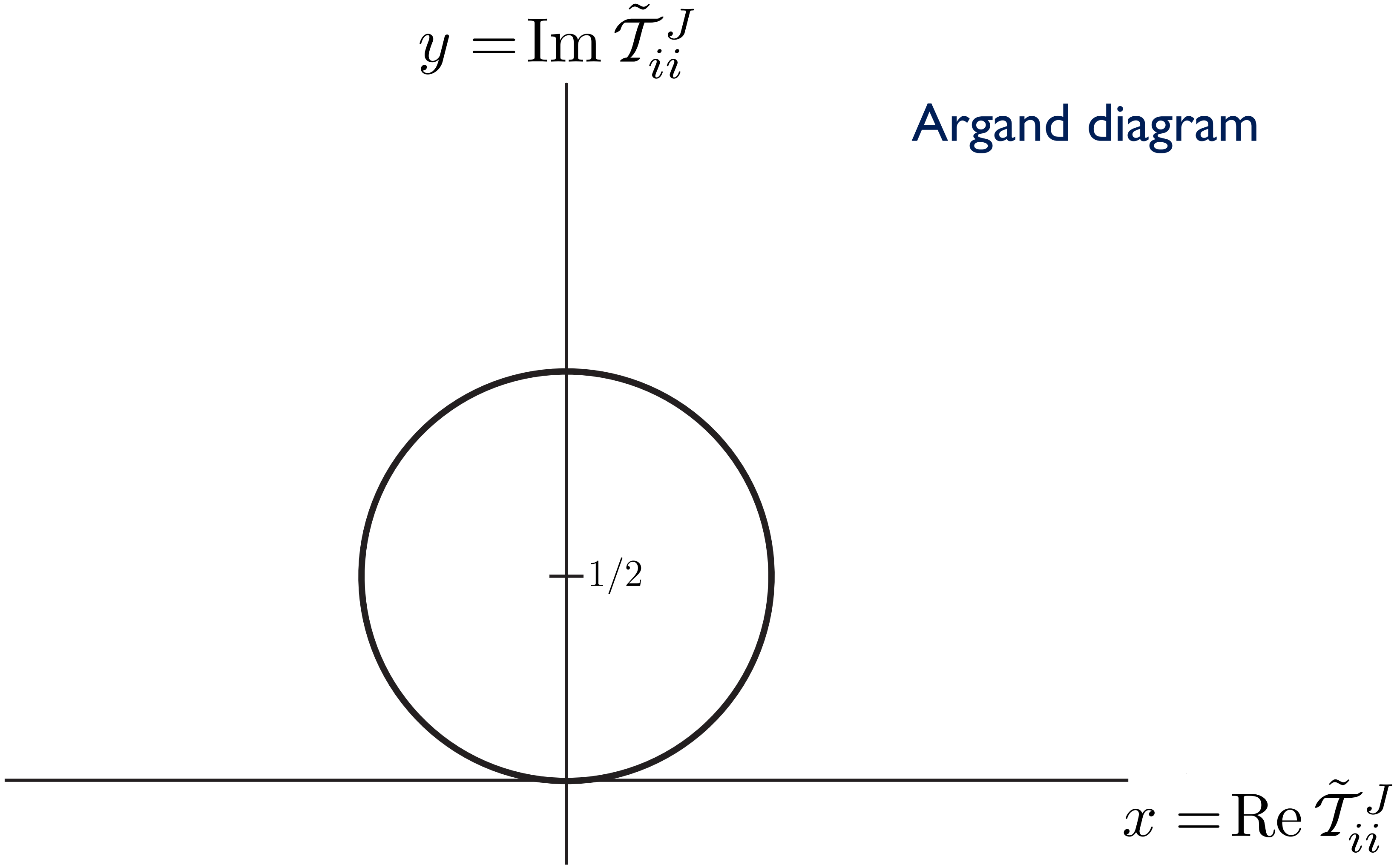
$$-\mathrm{i}\left(T - T^\dagger\right) = T^\dagger T \qquad\qquad \frac{1}{2\mathrm{i}}\left(\mathcal{T}^J_{fi} - \mathcal{T}^{J*}_{if}\right) \cong \sum_h \mathcal{T}^{J*}_{hf}\,\mathcal{T}^J_{hi}$$

where

$$\mathcal{T}^J_{fi} = \frac{1}{2}\,\frac{\lambda_f^{1/4}\lambda_i^{1/4}}{16\pi\, s}\int_{-1}^{1} \mathrm{d}\cos\theta\, \hat{\mathcal{T}}_{fi}(\sqrt{s}, \cos\theta)\, P_J(\cos\theta)$$

Perturbative Unitarity Arguments

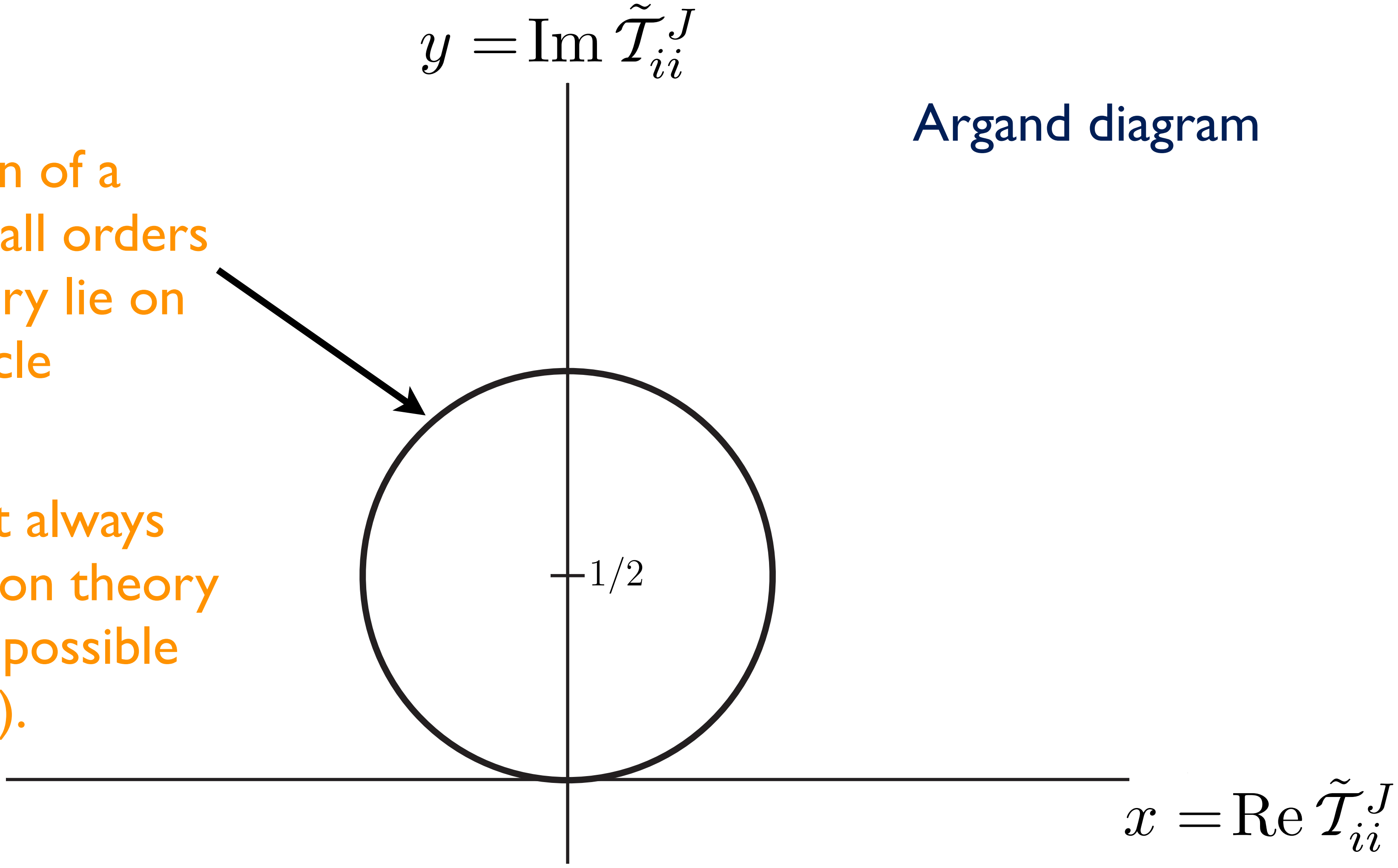
- Our approach:



Argand diagram

Perturbative Unitarity Arguments

- Our approach:



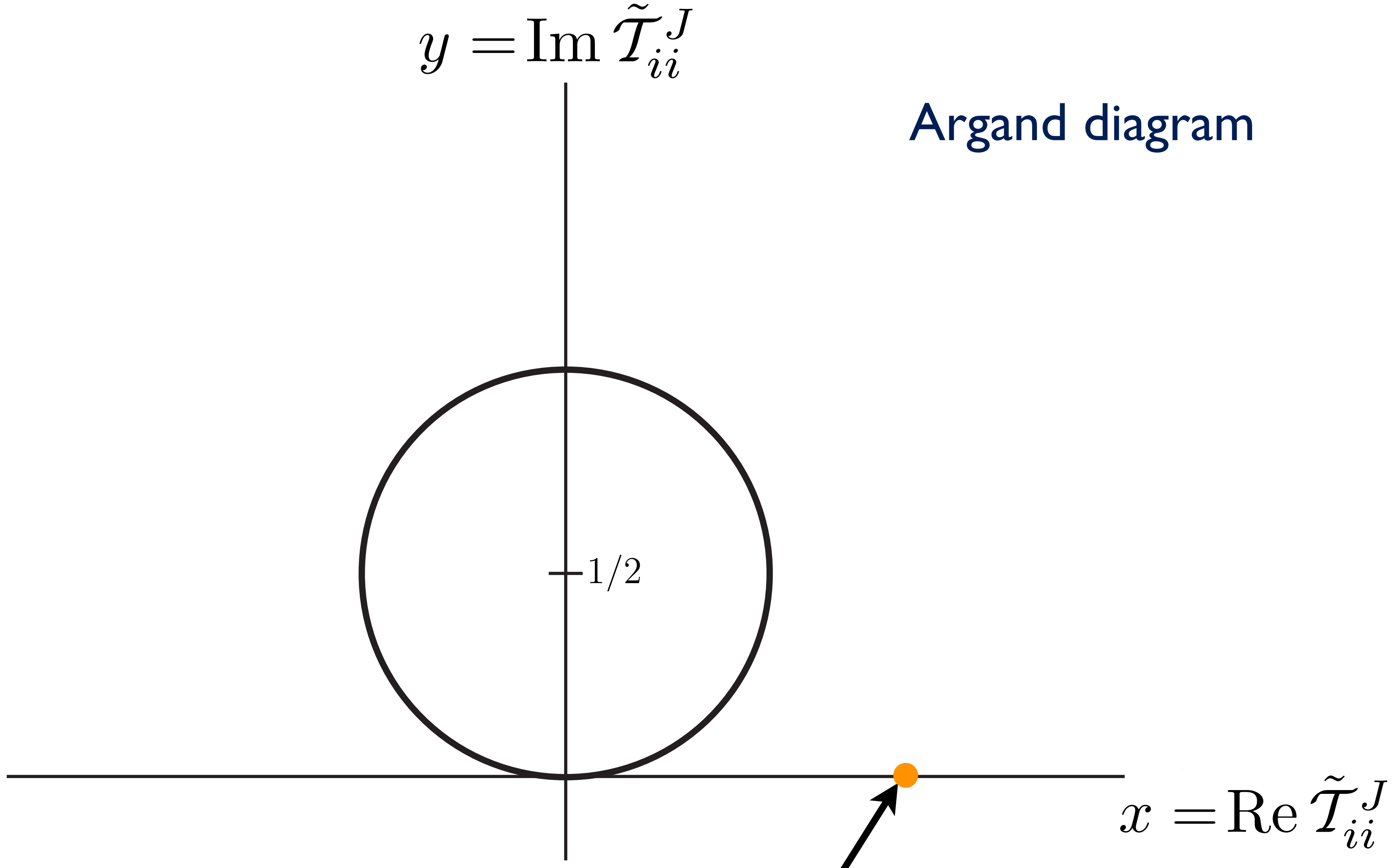
Argand diagram

Exact computation of a scattering process to all orders of perturbation theory lie on the Argand circle

However, we almost always compute in perturbation theory to the **lowest order** possible (off the circle).

Perturbative Unitarity Arguments

- Our approach:

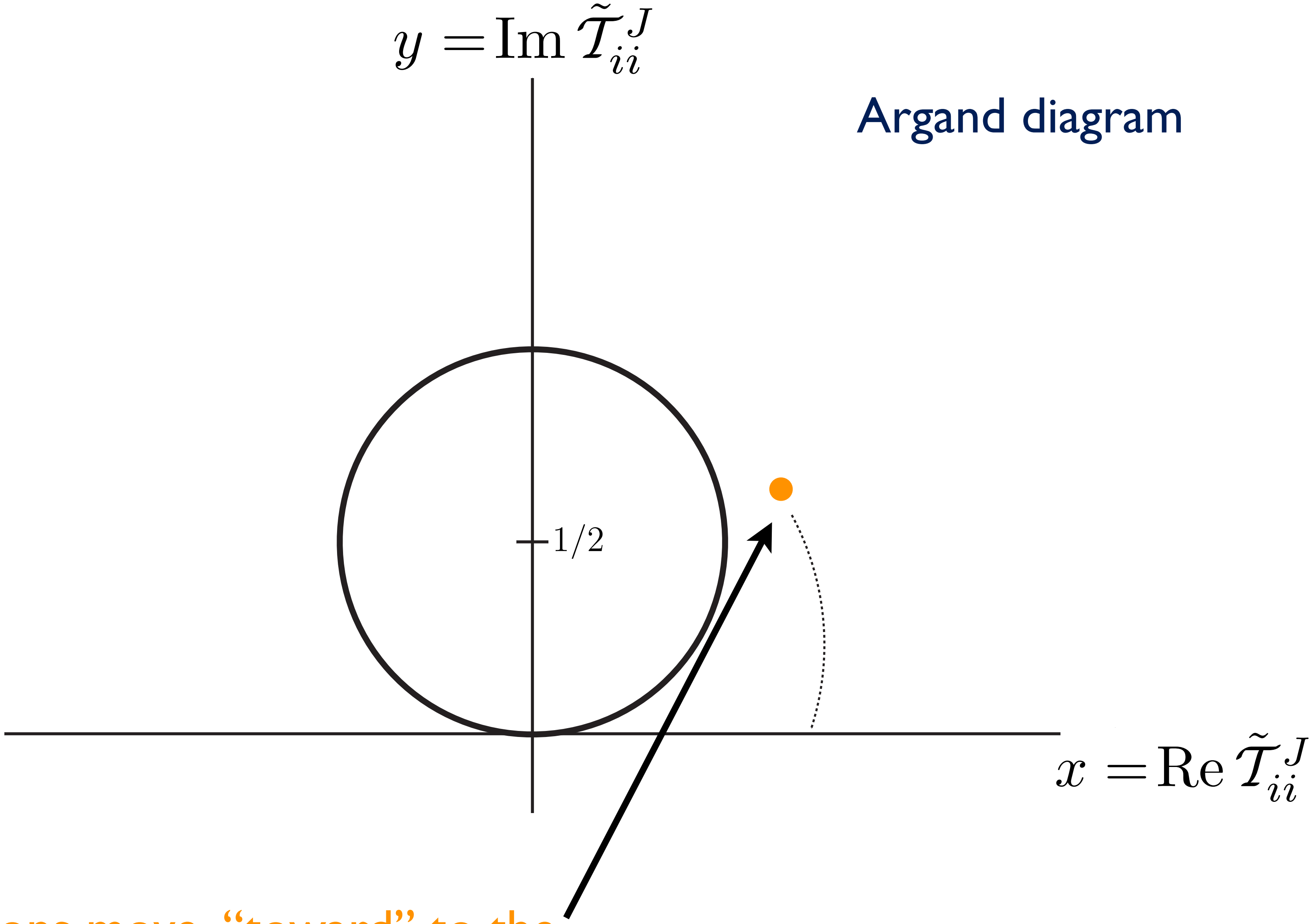


Argand diagram

Unitarity computations in the tree-level, Born approximation appear on the x-axis.

Perturbative Unitarity Arguments

- Our approach:

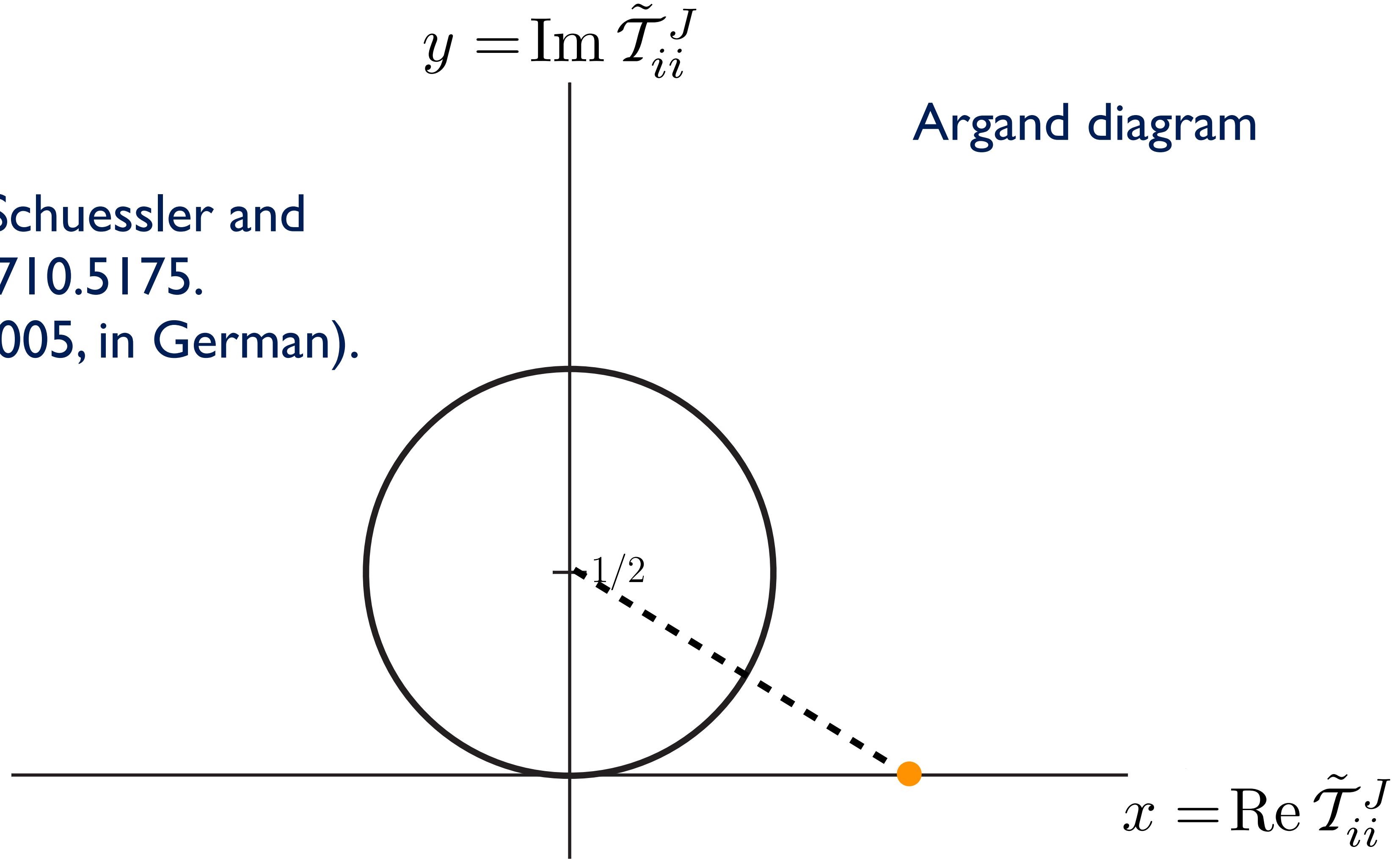


Higher-order corrections move “toward” to the Argand circle. However, a circuitous route is possible* depending on the size of the correction.

*See Aydemir, Anber and Donoghue, arXiv:1203.5153, for a similar analysis of chiral perturbation theory.

Perturbative Unitarity Arguments

- Our approach:



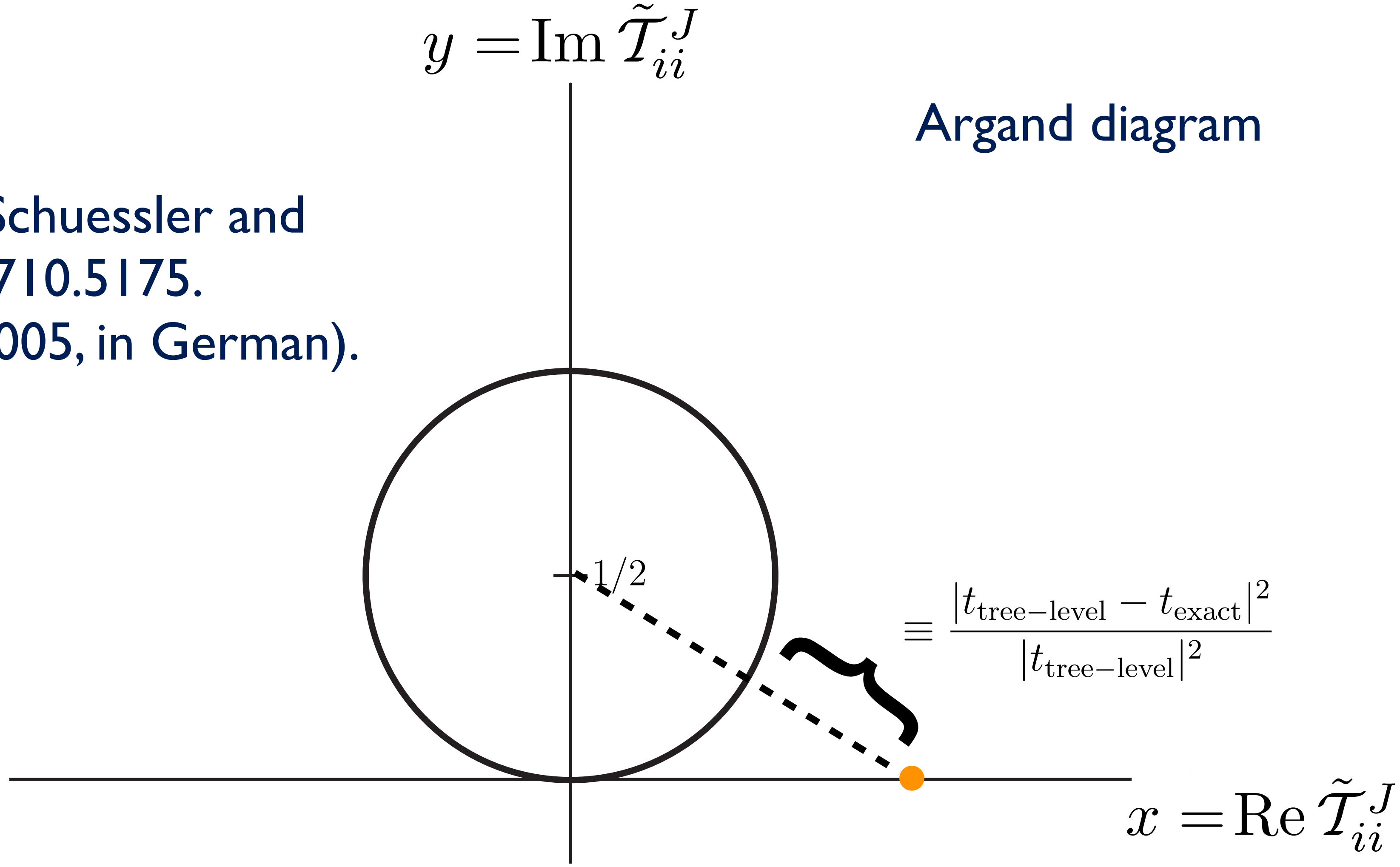
Argand diagram

*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).

To conservatively estimate the perturbative corrections, take the tree-level computation and draw a straight line to the nearest point* on the circle.

Perturbative Unitarity Arguments

- Our approach:



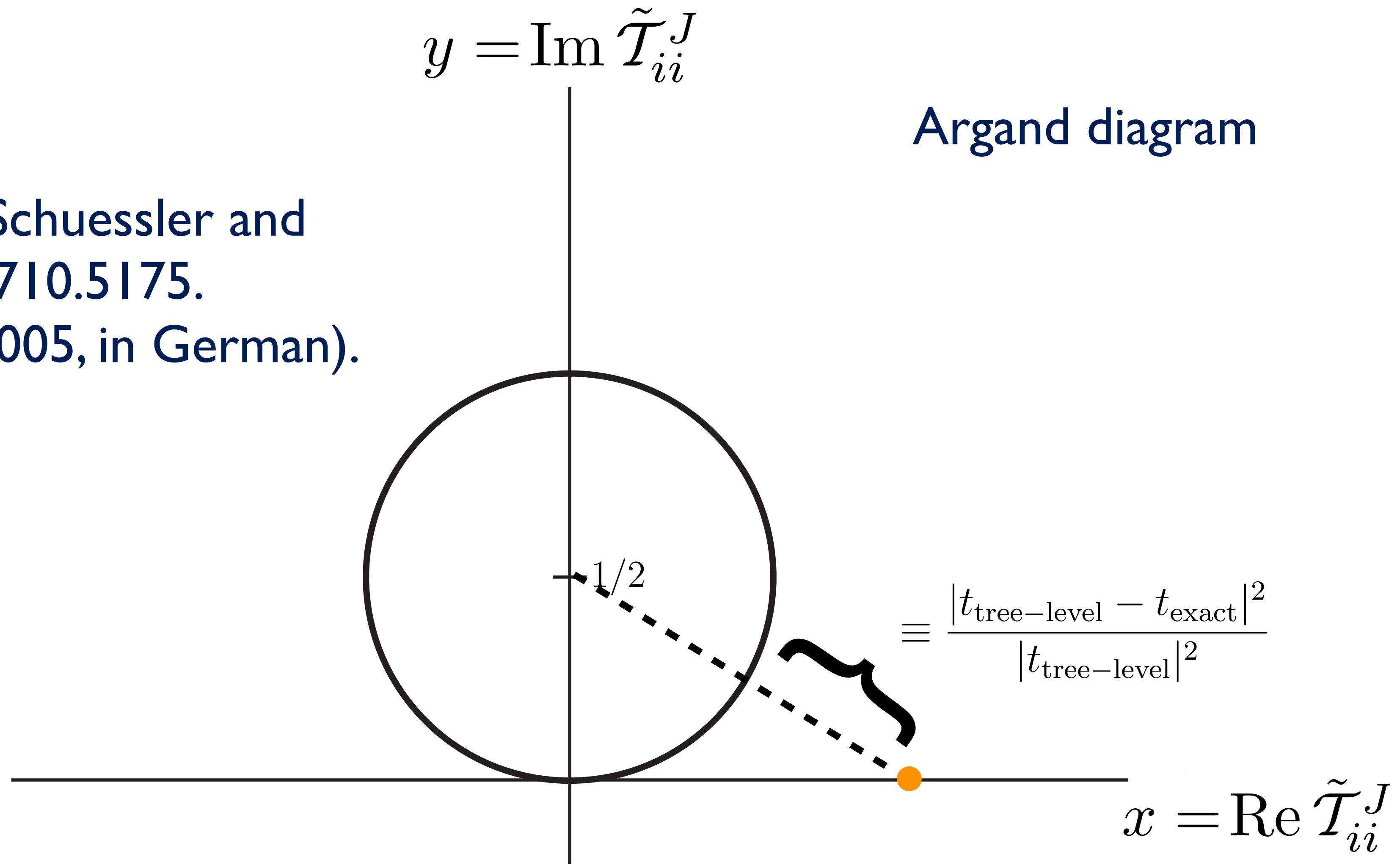
Argand diagram

*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).

This distance corresponds to the minimum perturbative correction needed to correct the tree-level amplitude*.

Perturbative Unitarity Arguments

- Our approach:



*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).

We scan over $\sqrt{s}$ to give the maximum value of tree-level amplitude. We only allow points in the parameter space that correspond to less than a 20% correction* to the amplitude.

Relic Abundance

NMSSM Relic Abundance

- Relic abundance “anchors” the NMSSM spectrum. Same for the non-SUSY Higgs portal.
- Roughly, raising the dark matter mass means larger couplings to get the right relic abundance*.

*A moral of Griest and Kamionkowski, Phys. Rev. Lett. 64, 615.

NMSSM Relic Abundance

- Require relic abundance to be less than or equal to the Planck central value.

$$h^2\Omega_c \leq 0.1199$$

- Used MicrOmegas and NMSSMTools*.

*MicroOmegas authors: Bélanger, Boudjema, Pukhov and Semenov
NMSSM Tools authors: Das, Ellwanger, Gunion, Hugonie, Jean-Louis and Teixeria

NMSSM SUSY Mass Spectrum

NMSSM SUSY Mass Spectrum

- Analysis: Scan over the NMSSM parameters:

  1. SUSY mass parameters: $|A_i|, |\mu| \leq 40 \text{ TeV}$
  2. Dimensionless parameters: $|\lambda|, |\kappa| \leq 4$

- Apply constraints:

  a) Perturbative unitarity constraints
  b) Relic abundance
  c) Vacuum and other NMSSM consistency constraints.

- Result is a bounded NMSSM spectra

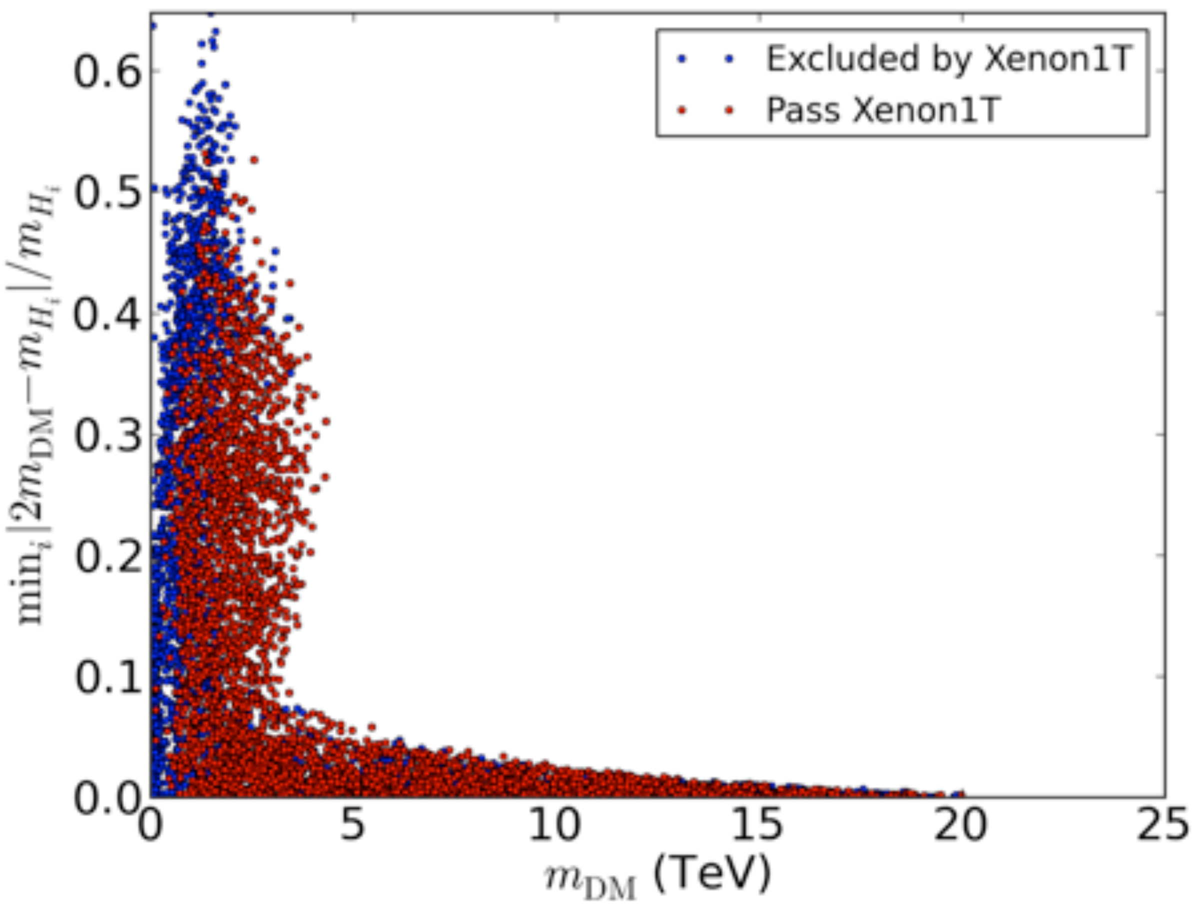
NMSSM SUSY Mass Spectrum

- Dark matter and Heaviest CP Even, Neutral Higgs Mass vs. Resonant Fine-Tuning Parameter:

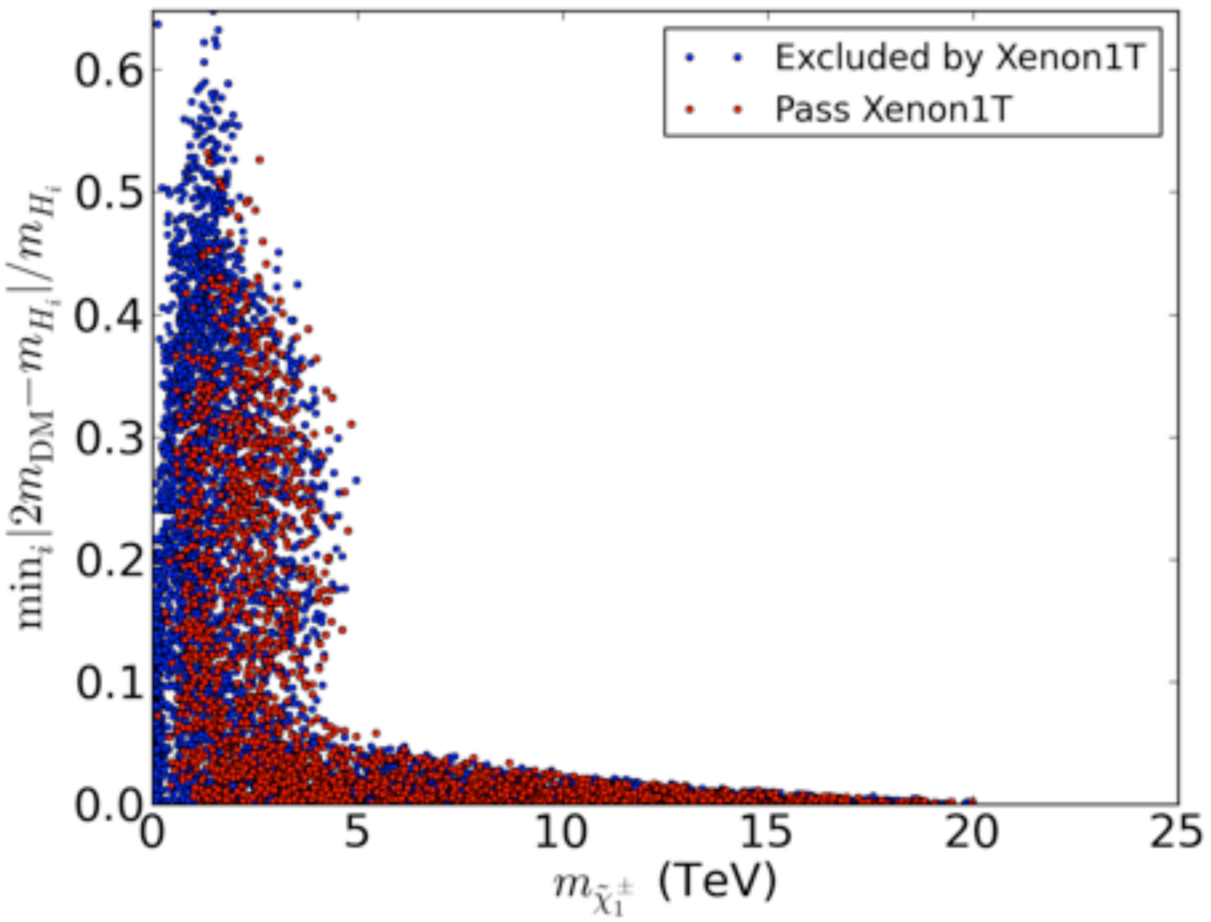
Resonant annihilation fine-tuning parameter:

$$R = \mathrm{min_i}\left|2\,m_{\mathrm{DM}} - m_{H_i}\right|/m_{H_i}$$

Red - Xenon 1T projected exclusion



Dark Matter Mass



Chargino Mass

NMSSM SUSY Mass Spectrum

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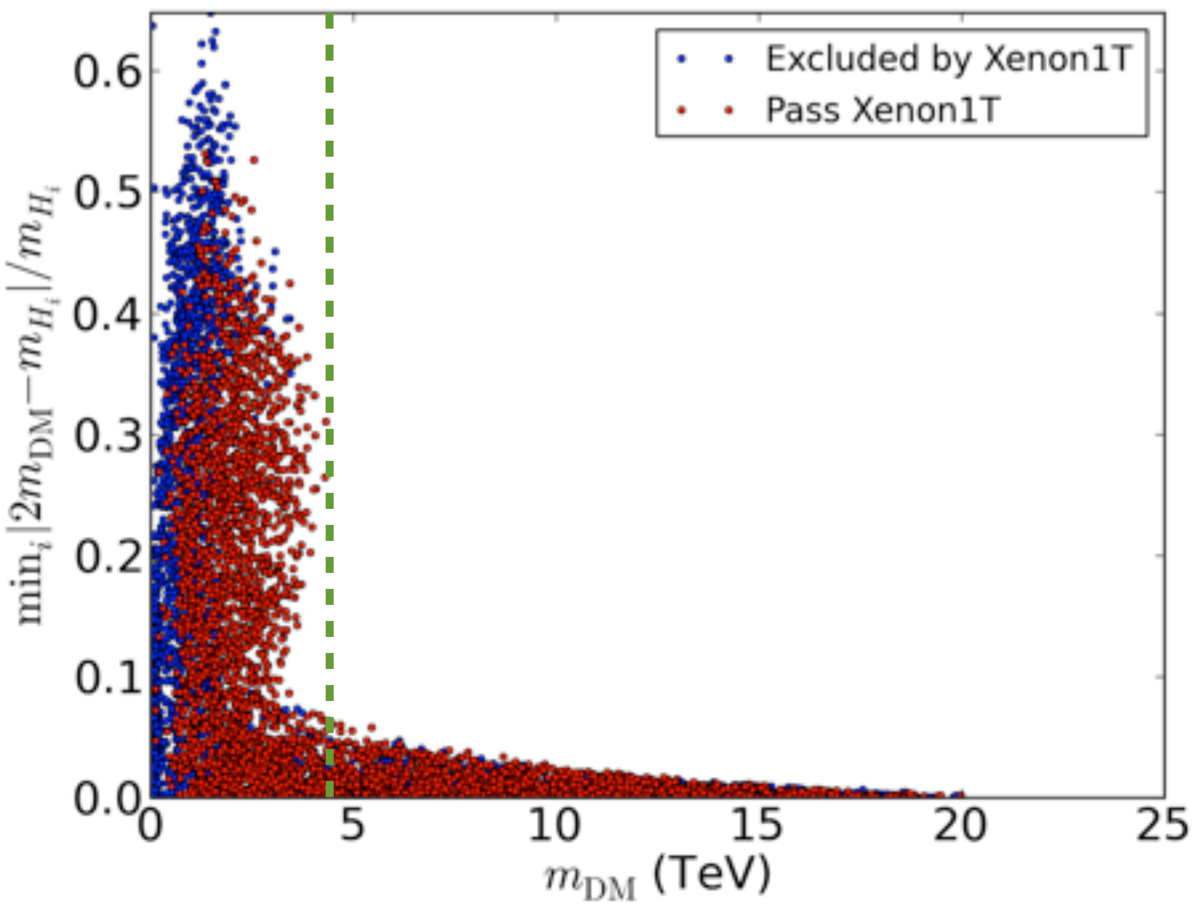
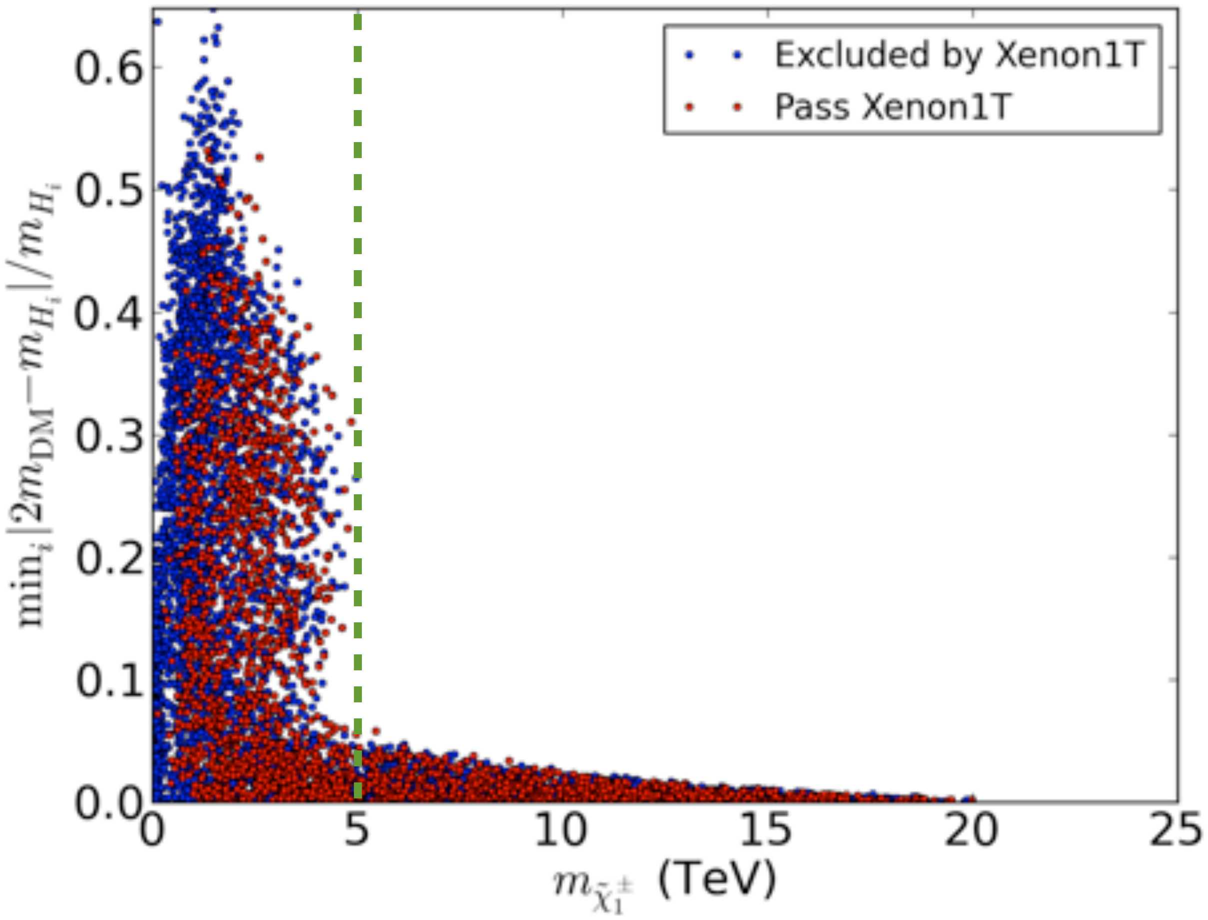


Dark Matter Mass



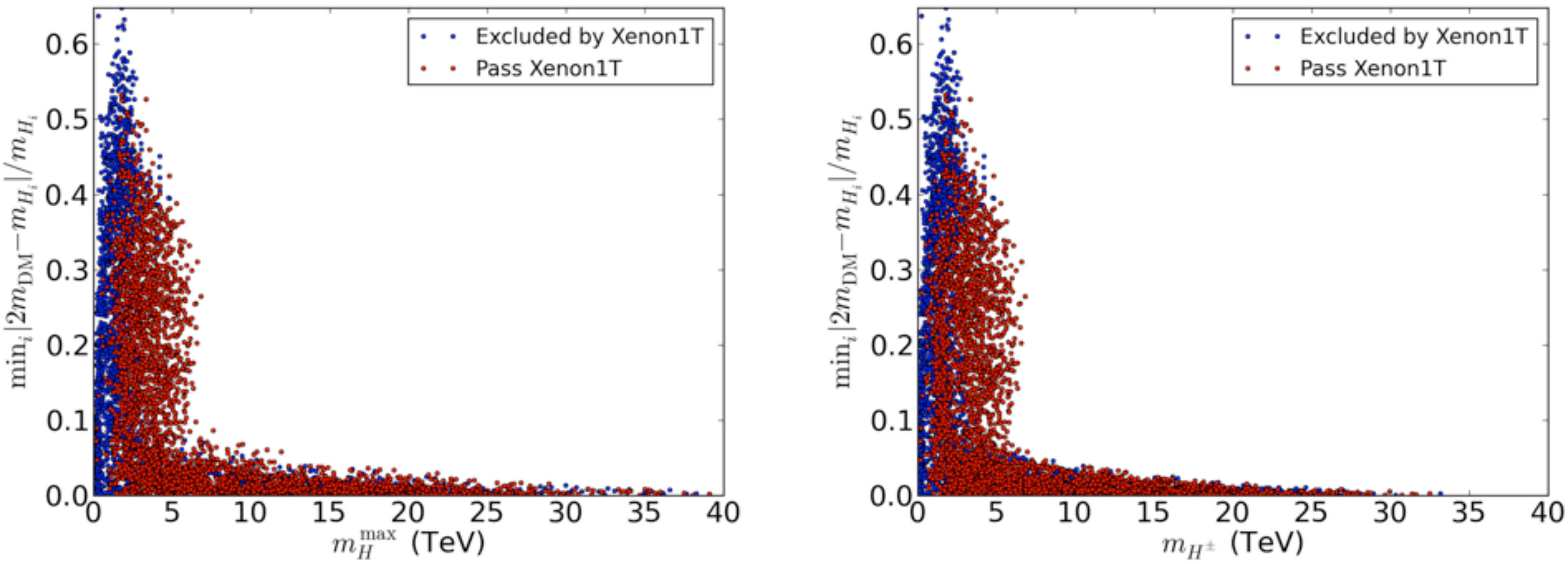
Chargino Mass

NMSSM SUSY Mass Spectrum

- Heaviest CP Even, Neutral and Charged Higgs Mass vs. Resonant Fine-Tuning Parameter:

Resonant annihilation fine-tuning parameter: $R = \mathrm{min_i} \left| 2\, m_{\mathrm{DM}} - m_{H_i} \right| / m_{H_i}$

Red - Xenon 1T projected exclusion



Heaviest CP Even, Neutral Higgs Mass

Charged Higgs Mass

NMSSM SUSY Mass Spectrum

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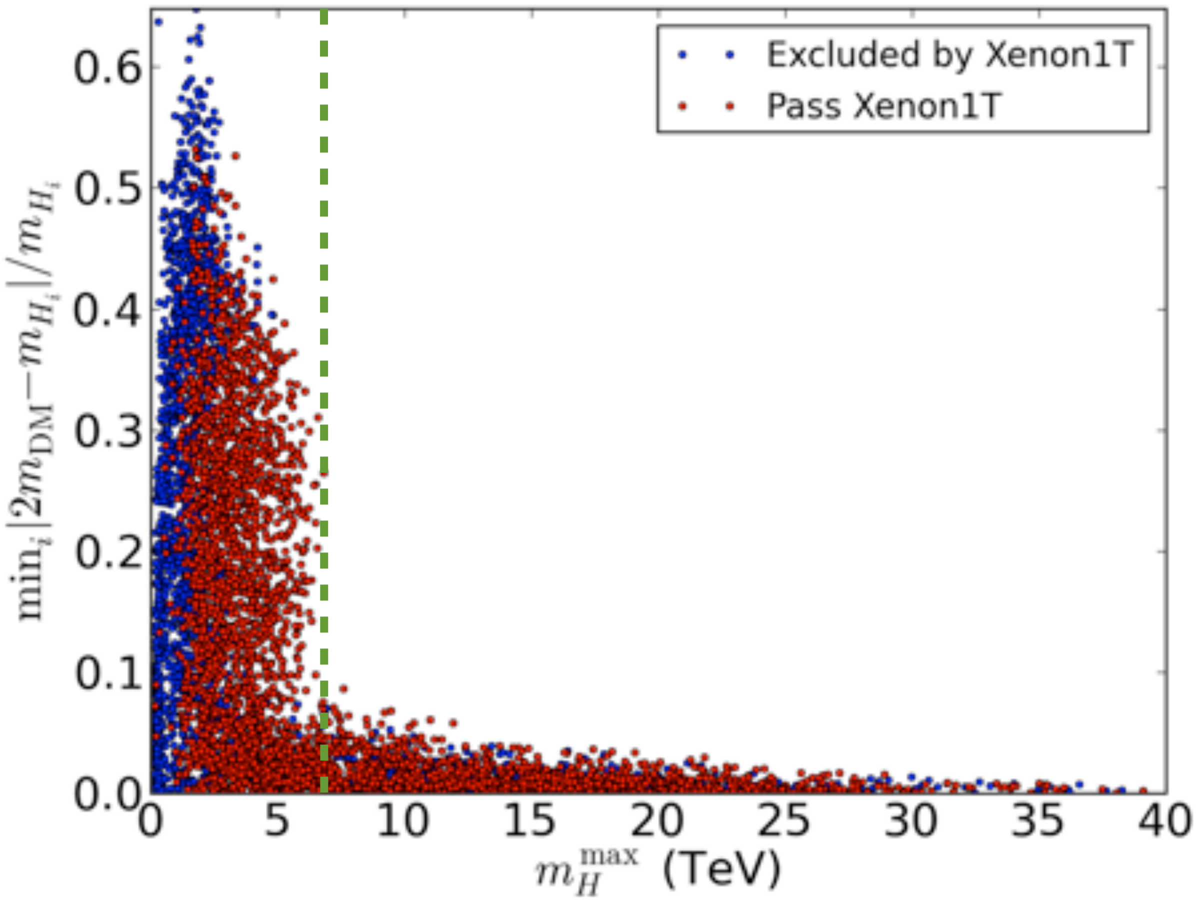
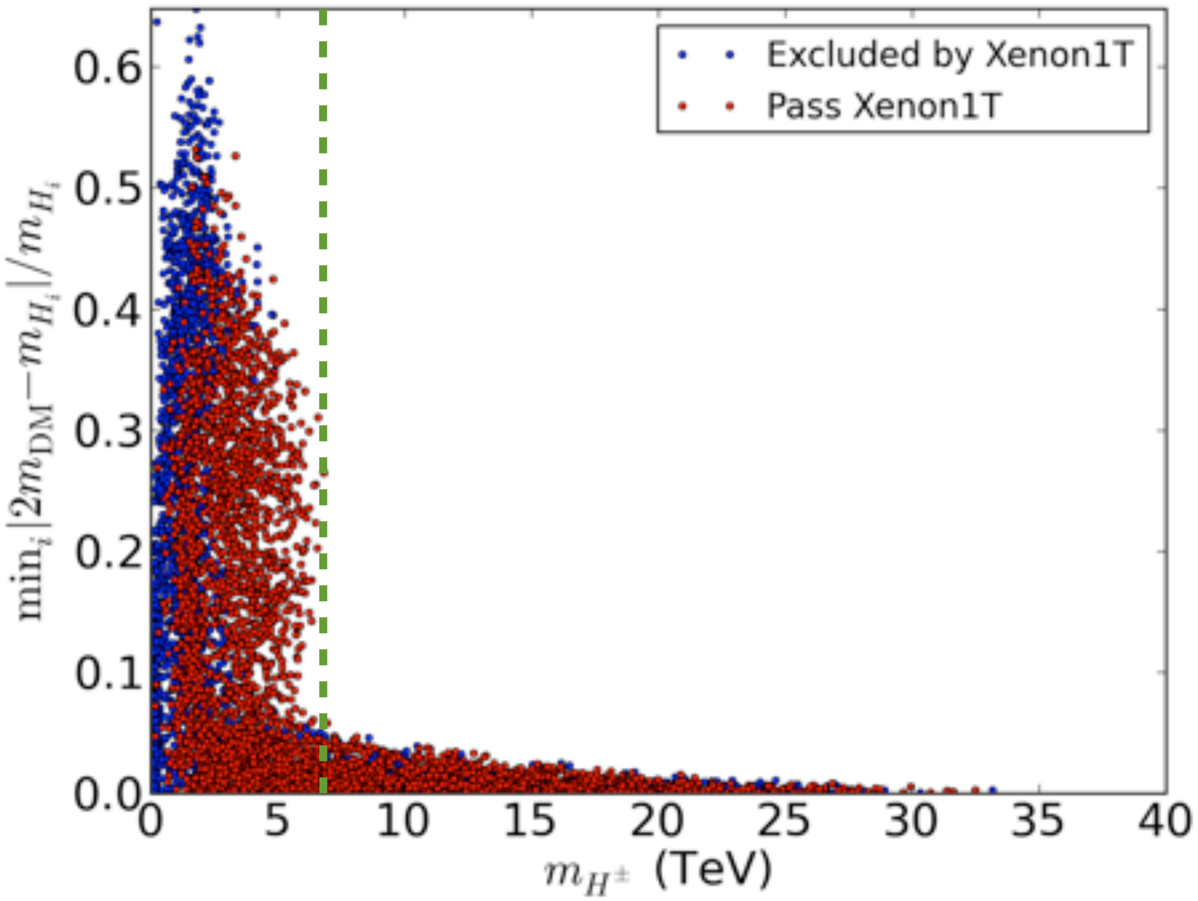
Red - Xenon 1T projected exclusion



Heaviest CP Even, Neutral Higgs Mass

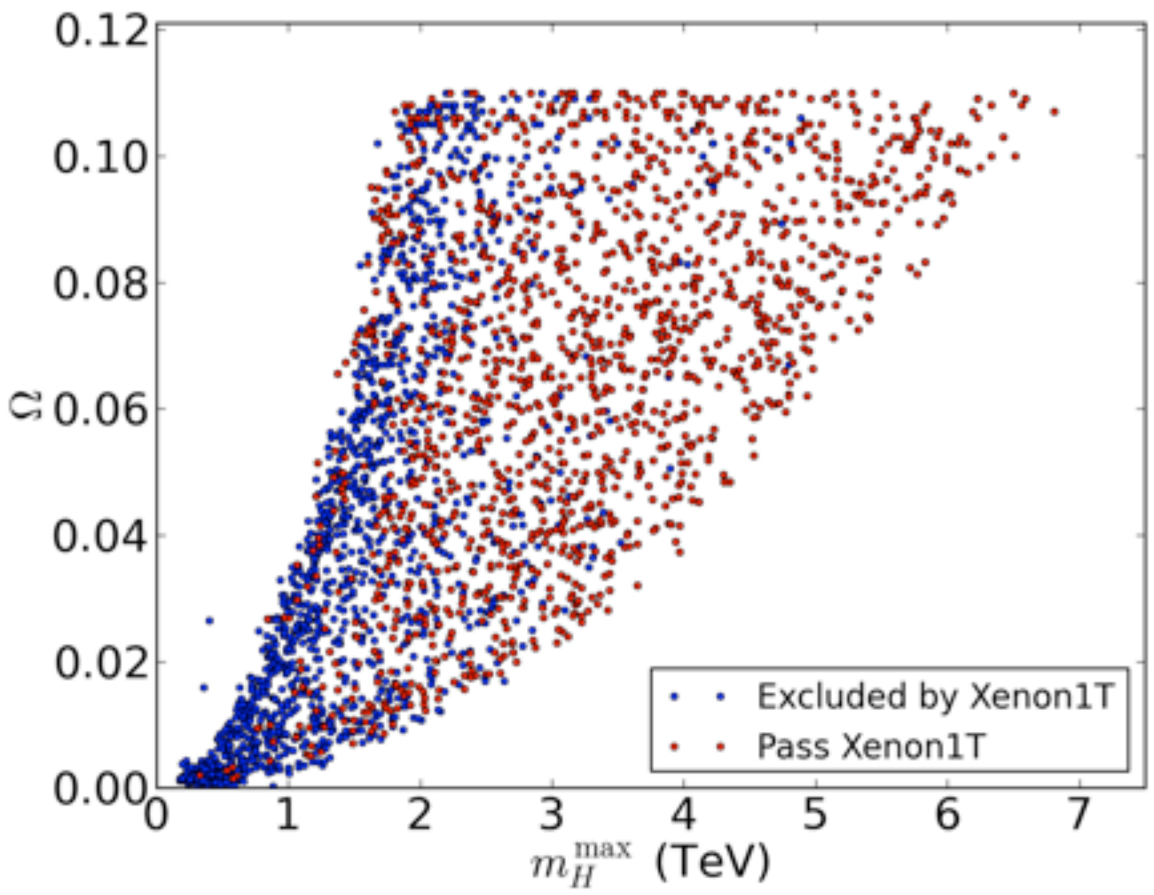


Charged Higgs Mass

NMSSM SUSY Mass Spectrum

- Heaviest CP Even, Neutral Higgs Mass vs. Relic Abundance:

Red - Xenon 1T projected exclusion



Heaviest CP Even, Neutral Higgs Mass

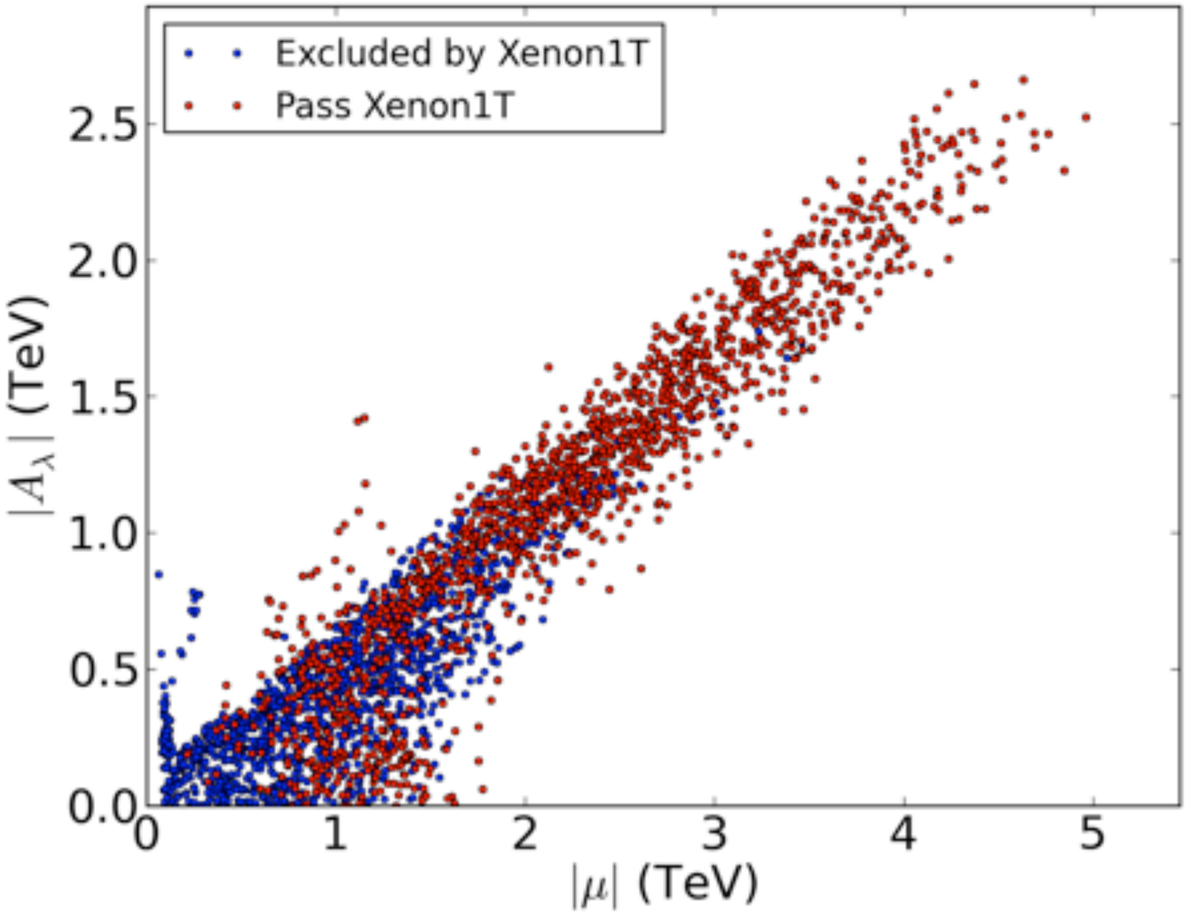
Fine-tuning cutoff resonant annihilation fine-tuning parameter at 10%:

$$R = \min_{\mathrm{i}} \left| 2\, m_{\mathrm{DM}} - m_{H_i} \right| / m_{H_i}$$

NMSSM SUSY Mass Spectrum

- μ parameter vs. Aλ

Red - Xenon 1T projected exclusion



μ parameter

Fine-tuning cutoff resonant annihilation fine-tuning parameter at 10%:

$$R = \mathrm{min_i}\left|2\,m_{\mathrm{DM}} - m_{H_i}\right|/m_{H_i}$$

Some Signatures

- Phenomenology is just starting:

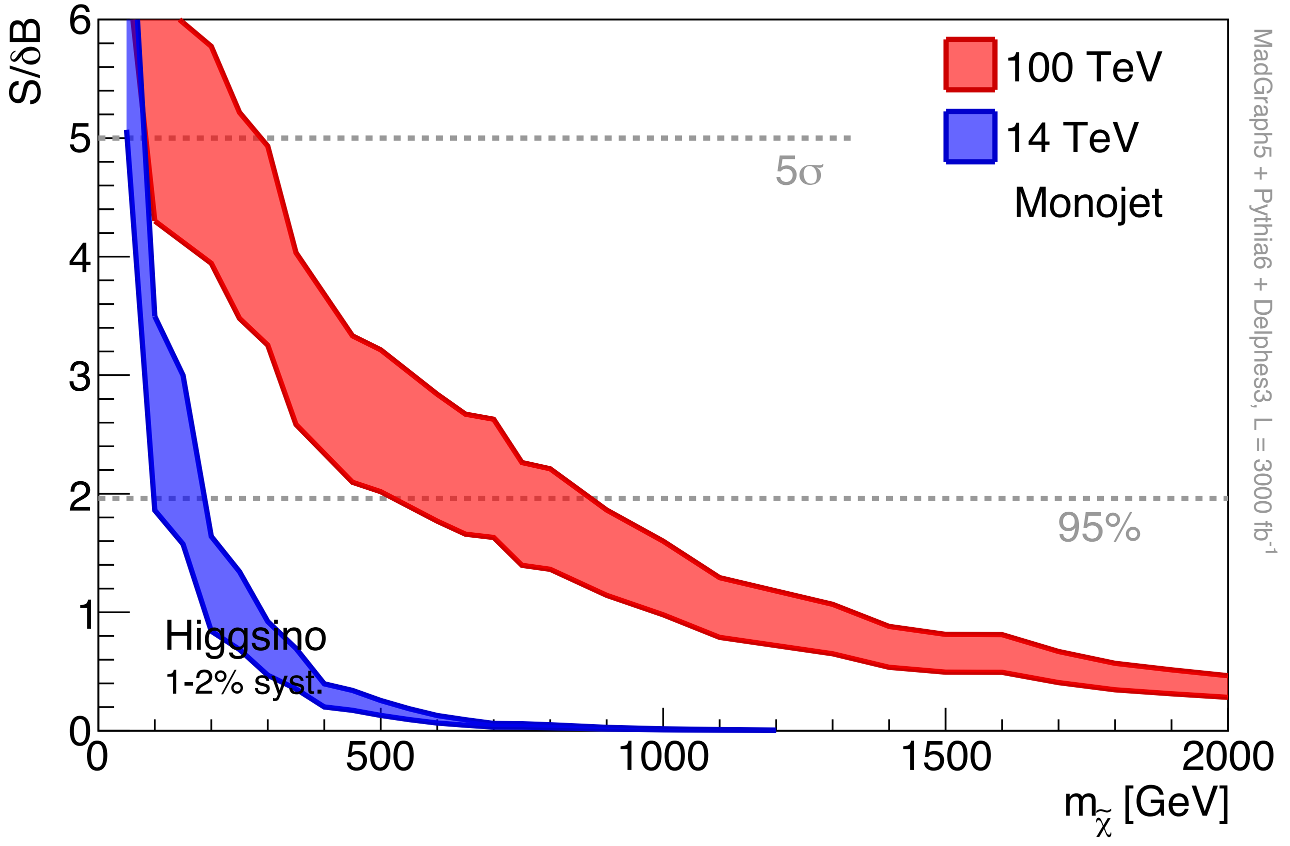
  Much that needs to be done to be sensitive to the full range of parameter space.

Some Signatures

- That said...
  - Proposed indirect search experiments like CTA (Cherenkov Telescope Array) uses very high energy gamma-rays to search for heavy LSPs.
  - Like the LHC, production of heavy colored particles that decay to the Higgses/dark matter is compelling.

Some Signatures

- Work on searching for pure Higgsinos with mono-jet searches in the MSSM* @ 100 TeV:



$$\text{Significance} = \frac{S}{\delta B} = \frac{S}{\sqrt{B + \lambda^2 B^2 + \gamma^2 S^2}}$$

λ and γ parameterize the systematic uncertainty on the background and signal, respectively

Our work: NMSSM couplings likely will be stronger at larger scales.

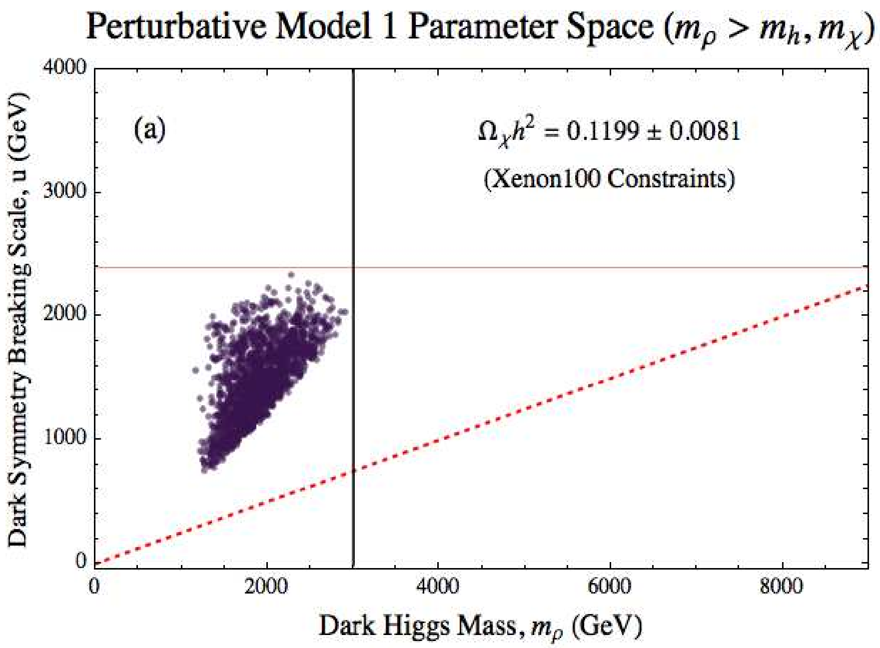
*Low and Wang, arXiv: 1404.0682

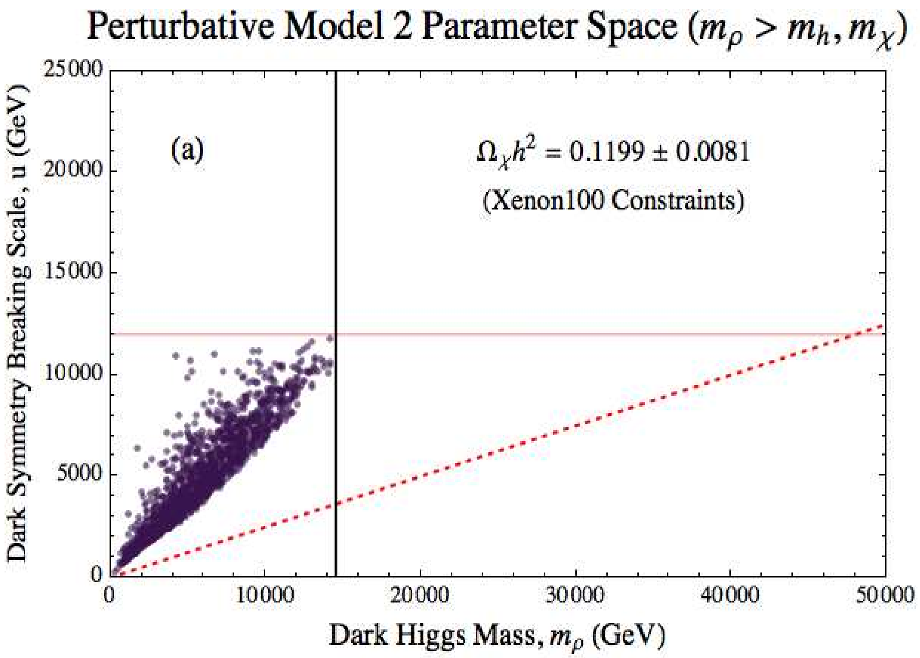
Conclusions

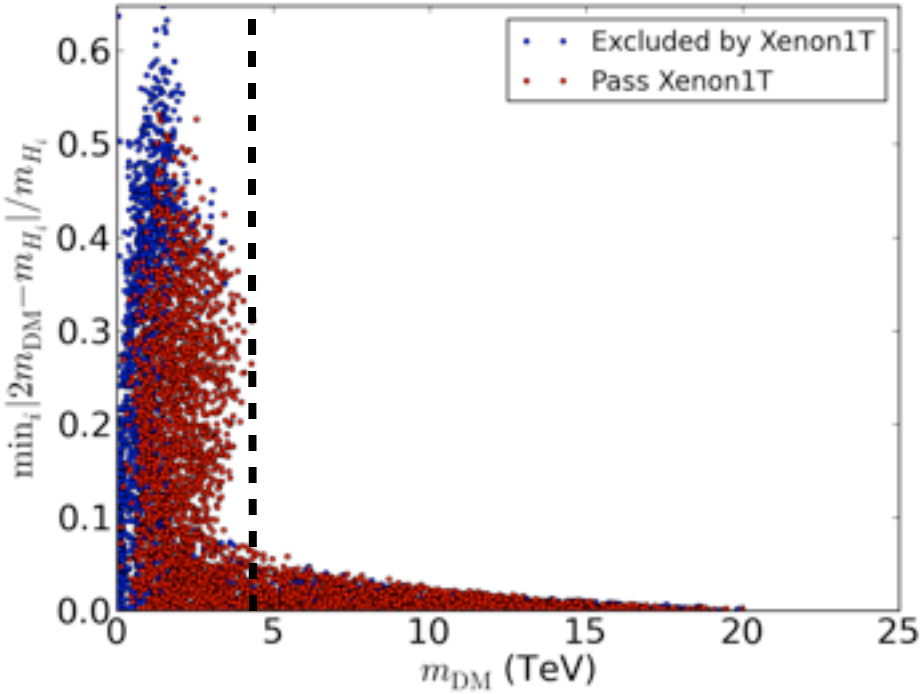
Conclusions

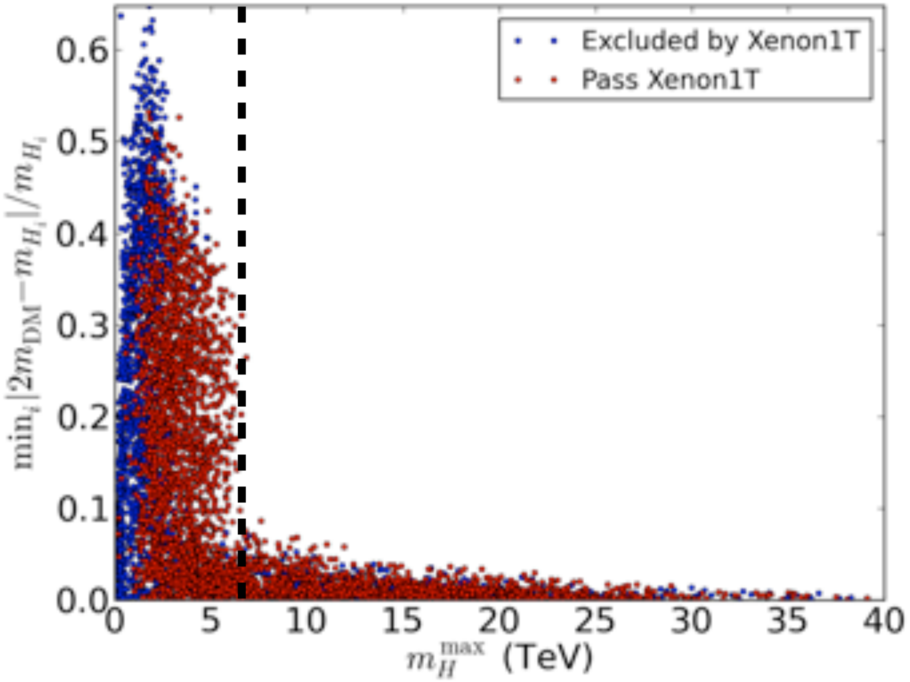
We used a combination of perturbative unitarity constraints and the relic abundance to generate upper bounds on two different Higgs portals.

Thank you ACFI!

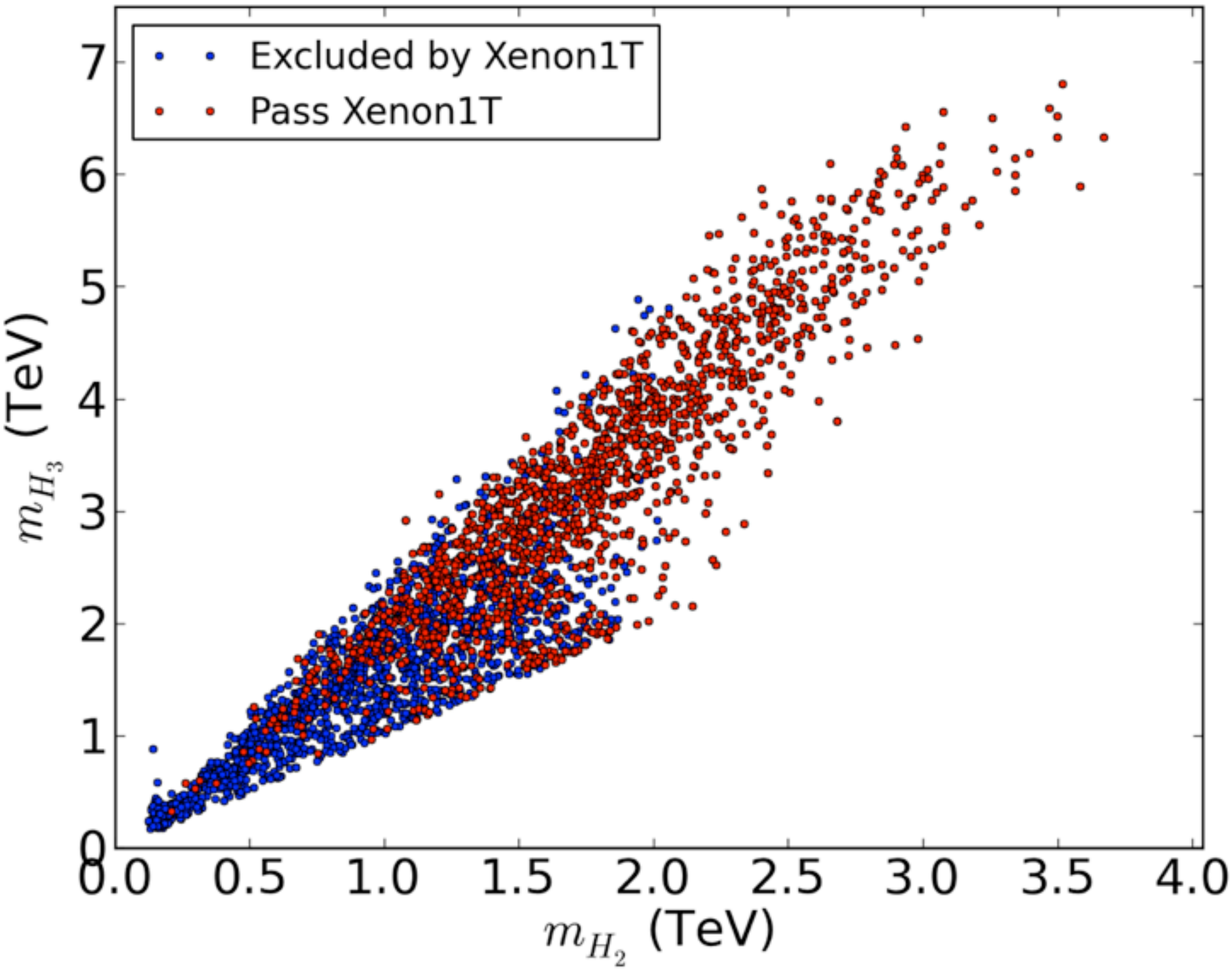

Perturbative Model 1 Parameter Space ($m_\rho > m_h, m_\chi$)


Perturbative Model 2 Parameter Space ($m_\rho > m_h, m_\chi$)





Backup Slides


Excluded by Xenon1T
Pass Xenon1T
m_{H_3} (TeV)
m_{H_2} (TeV)
0
1
2
3
4
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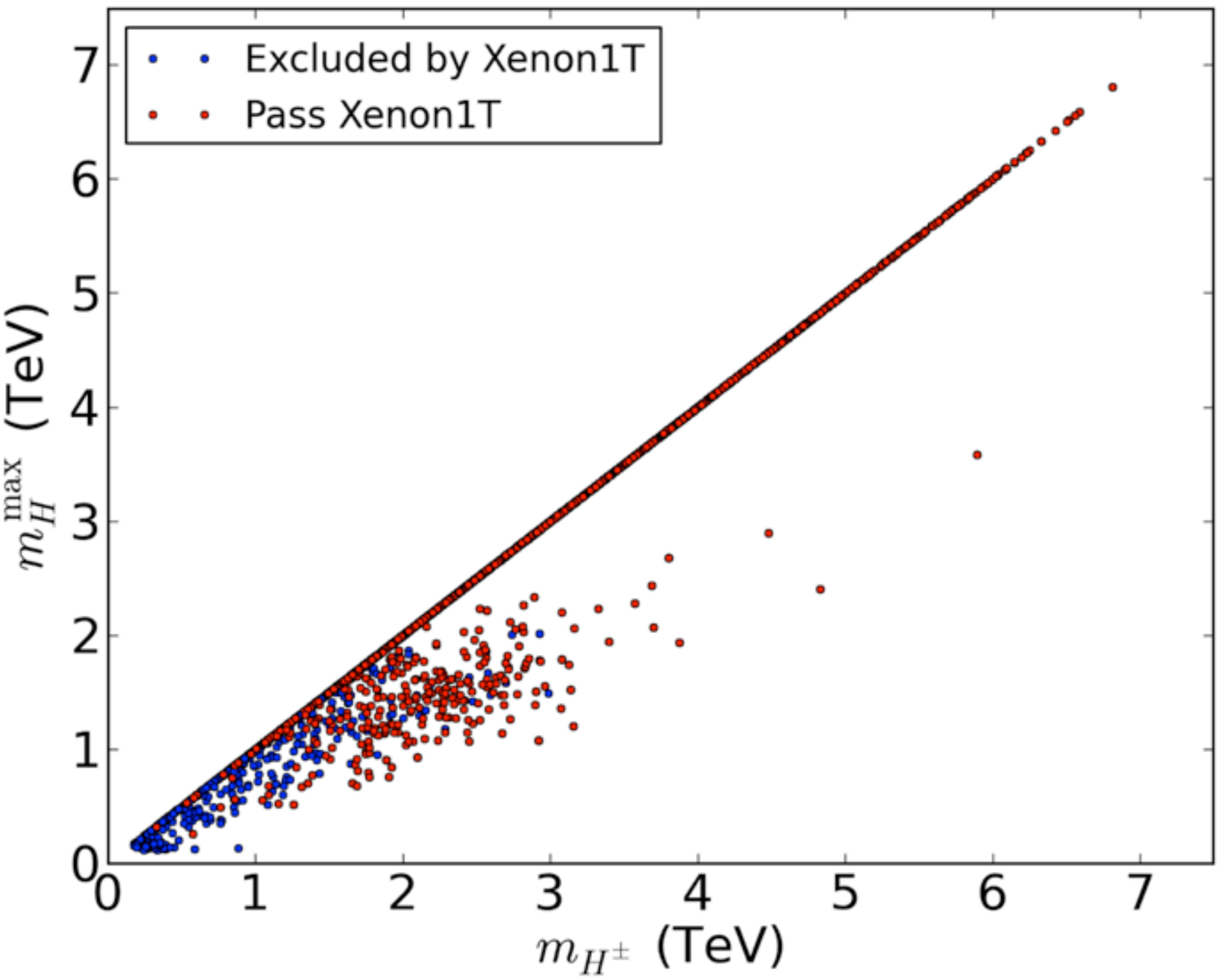
6
7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Excluded by Xenon1T
Pass Xenon1T
$m_H^{\max}$ (TeV)
$m_{H^\pm}$ (TeV)
0
1
2
3
4
5
6
7
0
1
2
3
4
5
6
7

NMSSM Bounds

- How do dimensional unitarity constraints compare to vacuum constraints?

$$A^2 < 3\left(m_{\phi_1}^2 + m_{\phi_2}^2 + m_{\phi_3}^2\right)$$

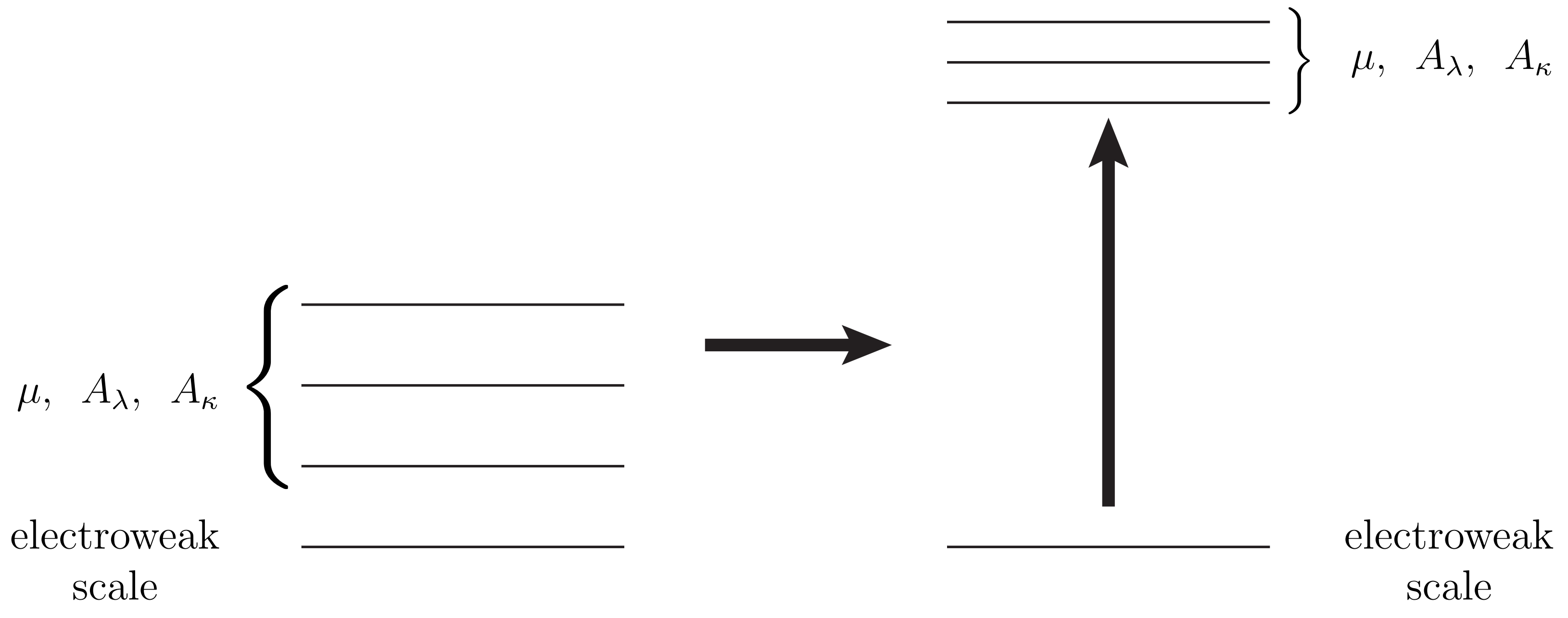
Generic Constraint from
Superpotential with three superfields

$$m_S^2 \lesssim \frac{1}{9} A_\kappa^2$$

From limit where: $V_S(S) = \kappa^2 S^4 + \frac{2}{3}\kappa A_\kappa S^3 + m_S^2 S^2 + \ldots$

- The ratios are better at constraining the SUSY breaking masses.

NMSSM Higgs Sector



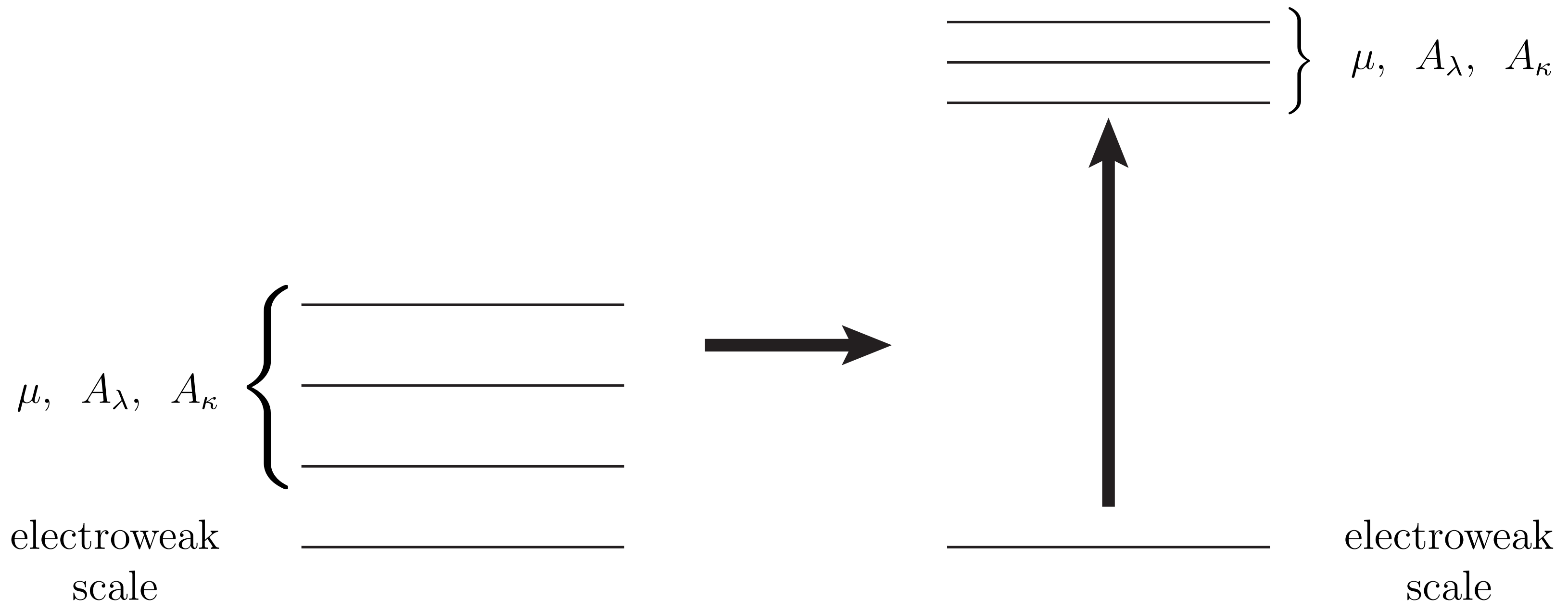
- Neutralino mass spectrum (in the decoupling limit):

Decoupled

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z & 0 \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z & 0 \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\lambda v_s/\sqrt{2} & -\lambda v_u/\sqrt{2} \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\lambda v_s/\sqrt{2} & 0 & -\lambda v_d/\sqrt{2} \\ 0 & 0 & -\lambda v_u/\sqrt{2} & -\lambda v_d/\sqrt{2} & \sqrt{2}\kappa v_s \end{pmatrix}$$

Relatively small.
Effectively no neutralino mixing

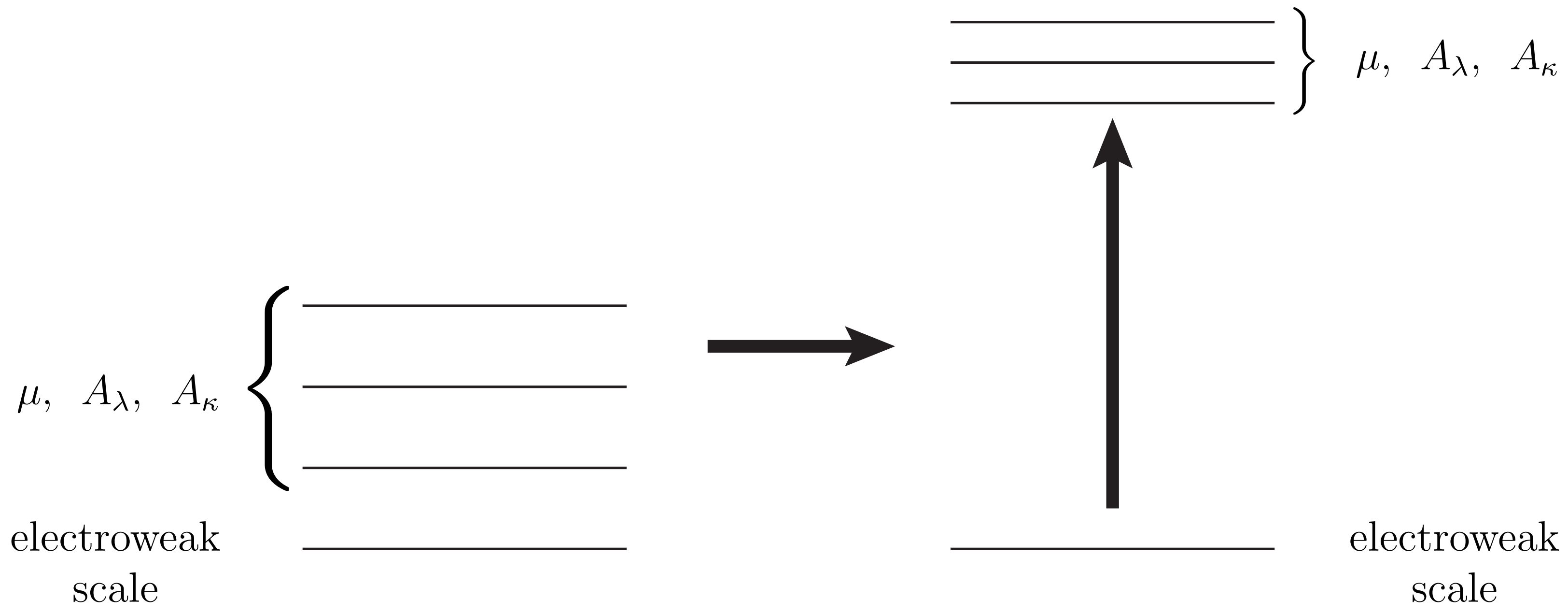
NMSSM Higgs Sector



- Chargino mass spectrum (in the decoupling limit):

$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix} \qquad \mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta \, m_W \\ \sqrt{2} c_\beta \, m_W & \mu \end{pmatrix}$$

NMSSM Higgs Sector



- Chargino mass spectrum (in the decoupling limit):

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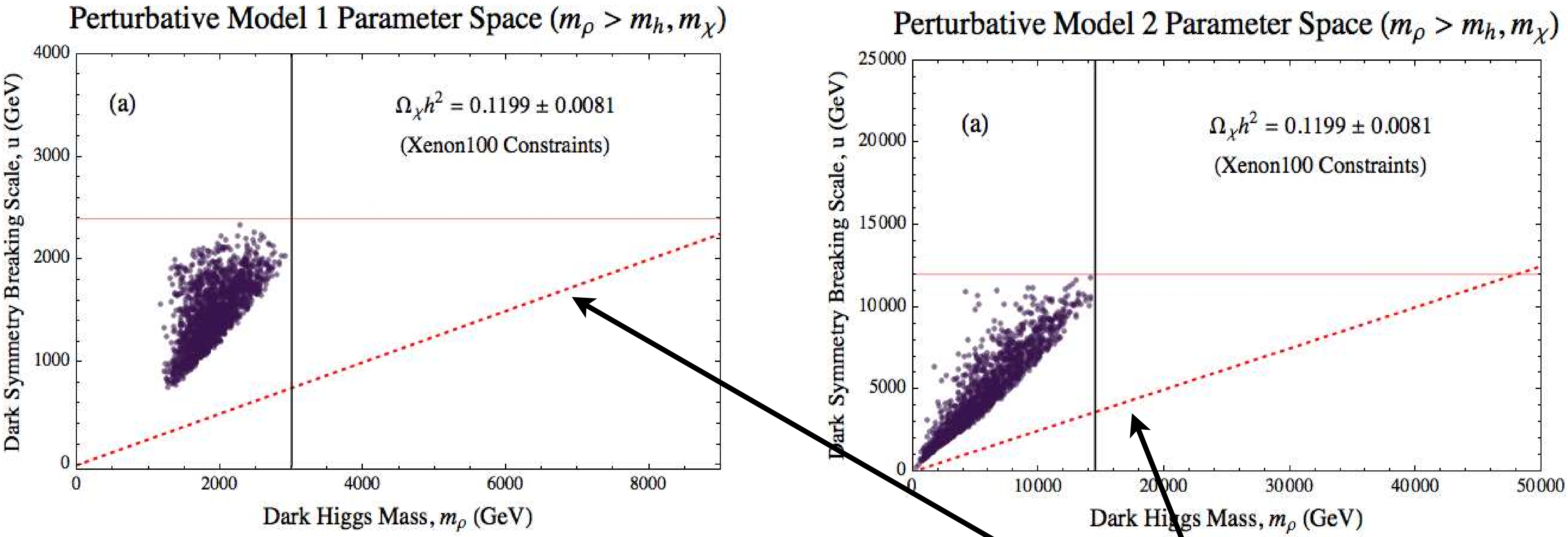
$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix} \qquad \mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta \, m_W \\ \sqrt{2} c_\beta \, m_W & \mu \end{pmatrix}$$

Scales with SUSY breaking scales.

Philosophy from (non-SUSY) Higgs Portals


Perturbative Model 1 Parameter Space ($m_\rho > m_h, m_\chi$)

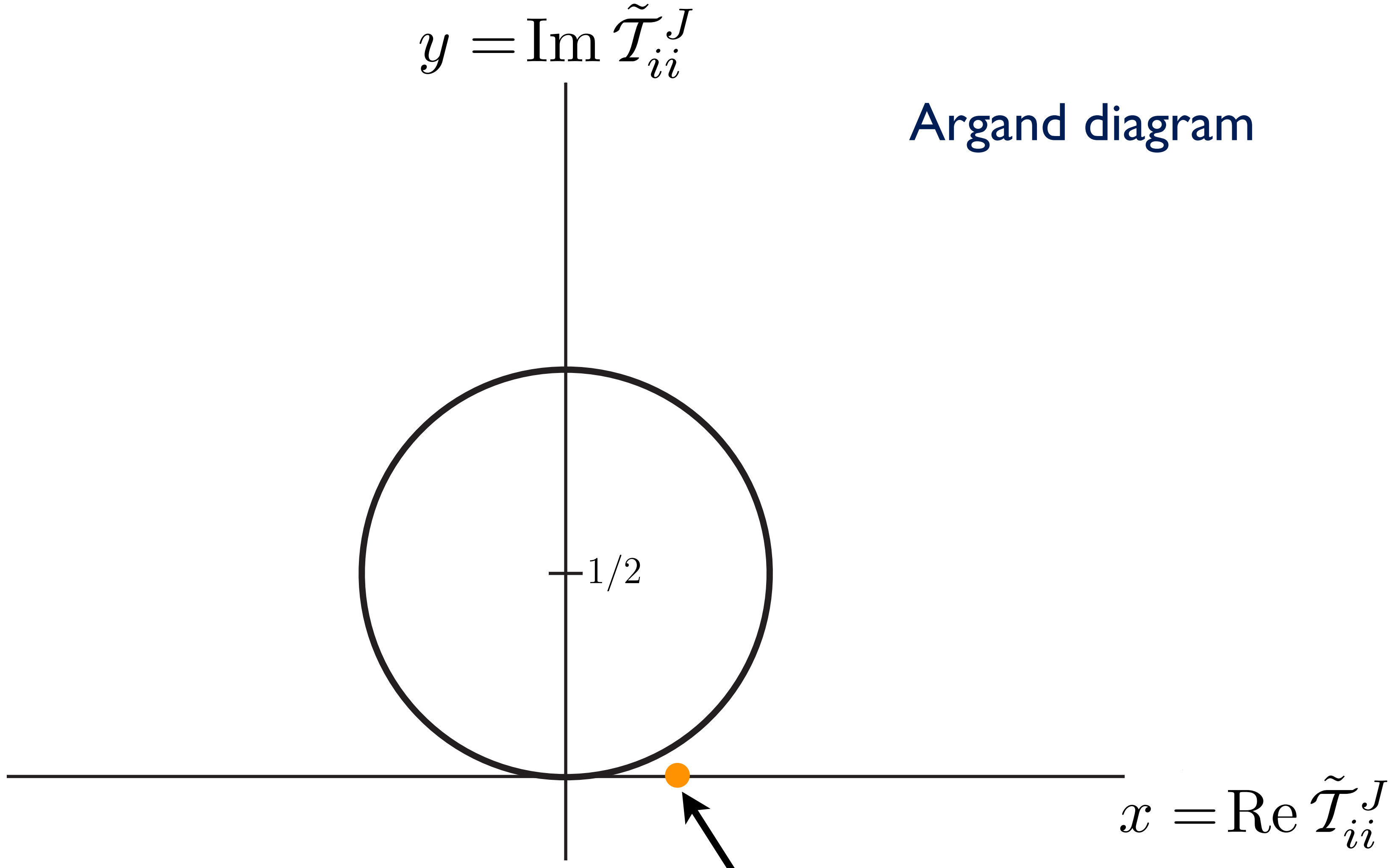
Perturbative Model 2 Parameter Space ($m_\rho > m_h, m_\chi$)

(Walker, arXiv:1310.1083)

Generalized Lee, Quigg, Thacker unitarity bound for dark Higgses.
(For v ~ 246, $m_{h\text{ bound}} \sim 1.2\text{ TeV}$)

Perturbative Unitarity Arguments

- Our approach:



Argand diagram

Note: Lee, Quigg and Thacker works because $g_i^2 \ll 1$.
This x is close to the Argand circle.