Stable Higgs Boson as Dark Matter

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Okayama, Feb. 3, 2010

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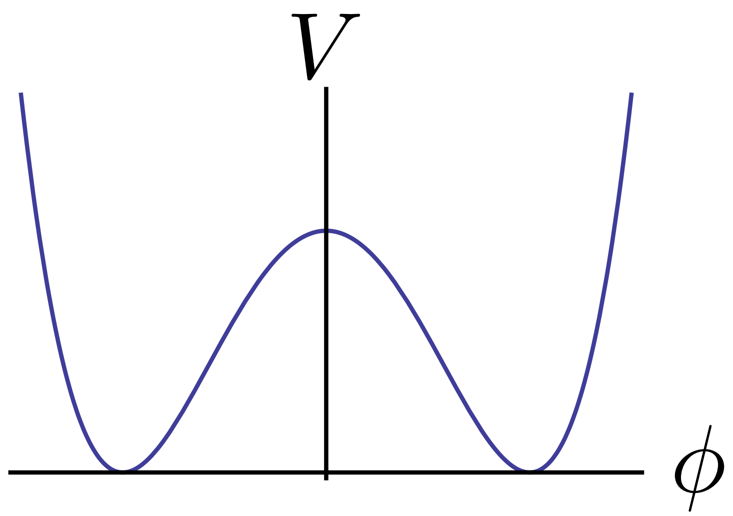
Introduction

Two big issues in particle physics

Electro-Weak Symmetry Breaking

Higgs mechanism:

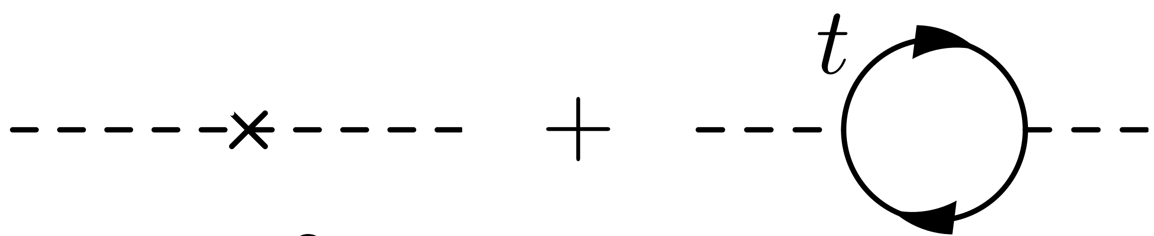
Not seen yet.



Naturalness and the hierarchy problem:

$\Lambda \sim M_{\rm Pl} \sim 10^{18}\,{\rm GeV}$ **vs** $M_{\rm weak} \sim 10^{3}\,{\rm GeV}$

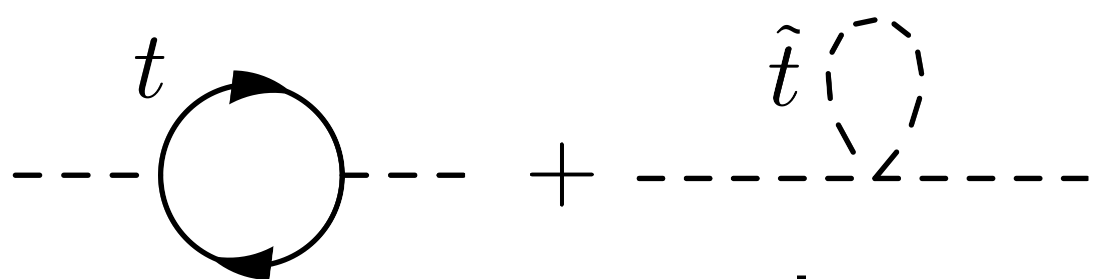
Radiative corrections to Higgs mass



m_0^2 $\qquad\qquad$ $\propto \Lambda^2$

$$\sim O((10^{18}\,\mathrm{GeV})^2) - O((10^{18}\,\mathrm{GeV})^2) \sim O((10^{3}\,\mathrm{GeV})^2)$$

A possible solution: Supersymmetry



$\sim \log \Lambda$

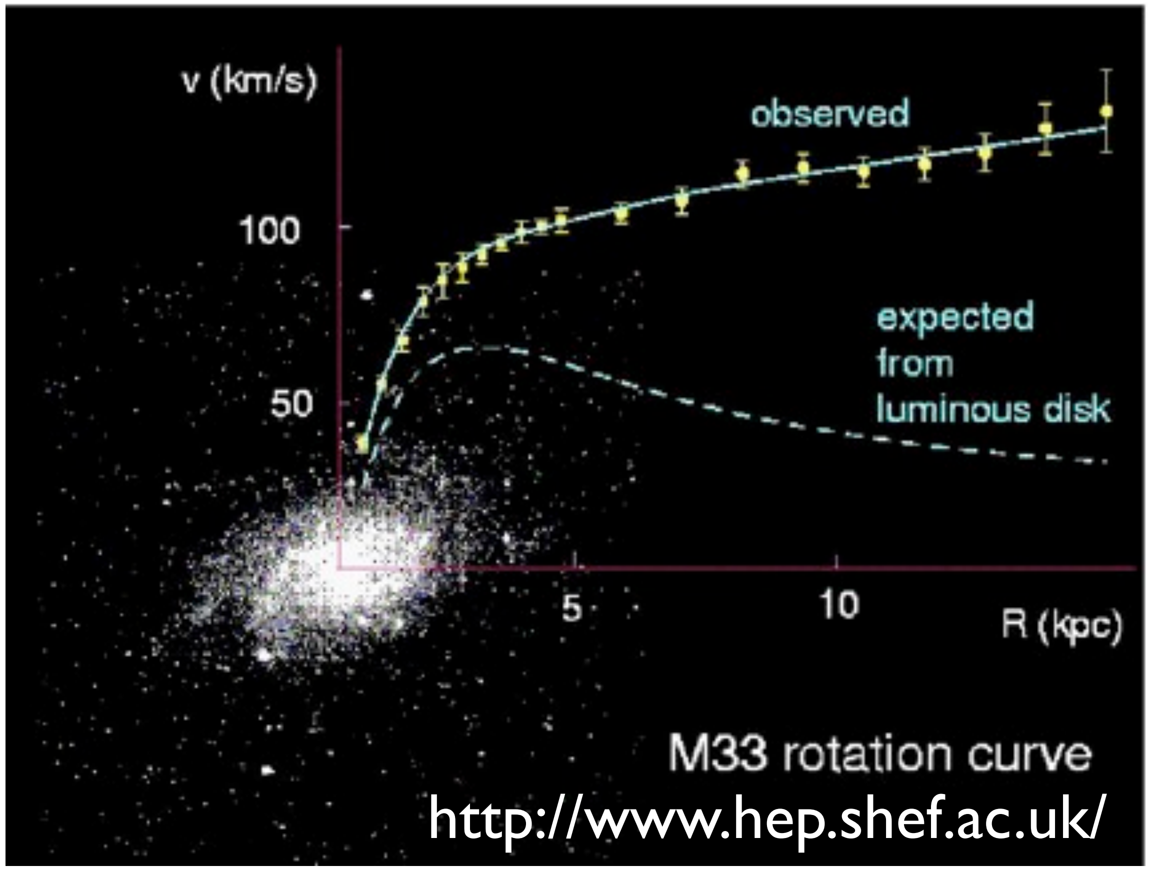
scalar top

An alternative solution:

Gauge-Higgs unification

Dark Matter

Rotation curves of galaxies: DM in galactic halo.

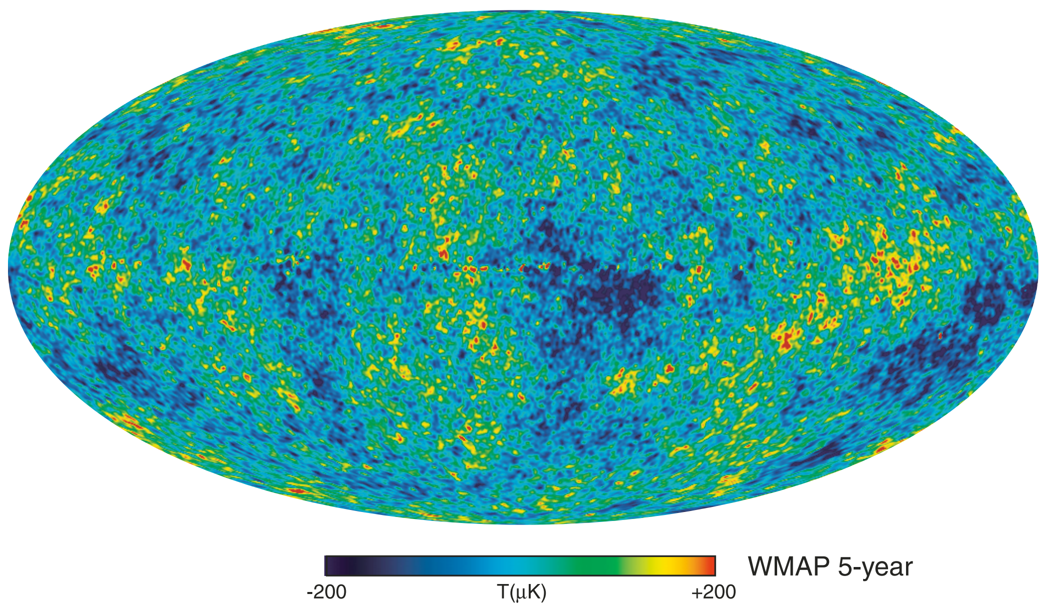


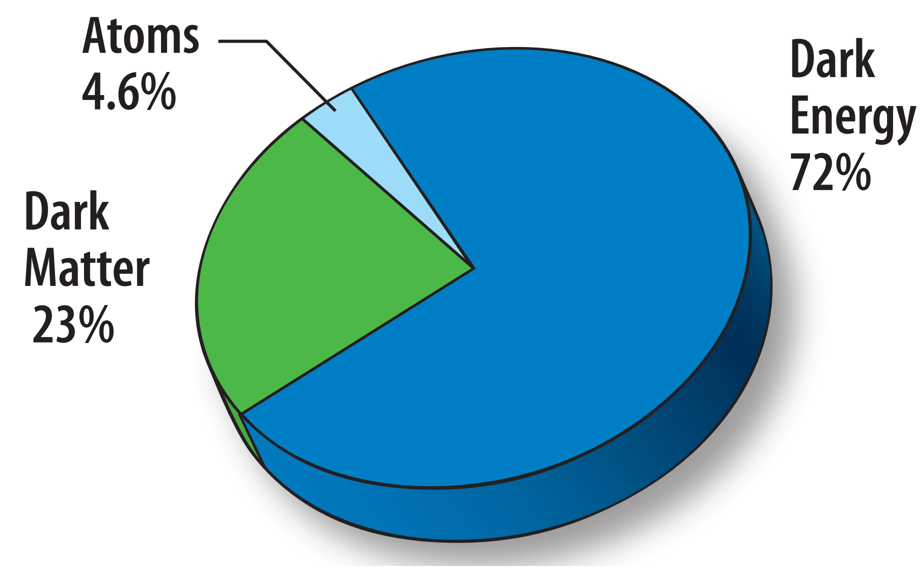
Other evidences:

cluster gas, gravitational lensing,
colliding clusters

Cosmic microwave background:

WMAP $\Omega_{\rm CDM}h^2 = 0.1131 \pm 0.0034$





http://map.gsfc.nasa.gov/

How particle physics explains the dark matter?

Supersymmetry → Neutralino

Gauge-Higgs unification → ?

Stable Higgs as Dark Matter (Dark Higgs scenario)

謎の2粒子 正体は同じ!?

宇宙構成の定説覆す可能性

ノーベル賞学者、南部陽一郎博士の理論から存在が予測された粒子「ヒッグス」が、宇宙を満たす謎の物質「ダークマター（暗黒物質）」と同じものであるという新理論を、大阪大の細谷裕教授がまとめた。この〝2粒子〟は素粒子物理の最重要テーマで、世界中で発見が競われている。ダークマターは安定で壊れないが、ヒッグスは素粒子の基本法則「標準理論◎」ではすぐに壊れるとされ、新理論は従来の宇宙の成り立ちを説明する定説を覆すもの。証明されれば宇宙は5次元以上あることになり、人工ブラックホールの創出も可能になるかもしれない。

「暗黒物質はヒッグス」

南部博士が1960年に提唱し、授賞理由になった「対称性の自発的破れ」を基にヒッグスが提唱されたが未発見。宇宙誕生直後にでき、他粒子はヒッグスに衝突して動きにくくなり質量を持つとされる。一方、宇宙は光を出さず安定なダークマターで満ちていると予想されている。

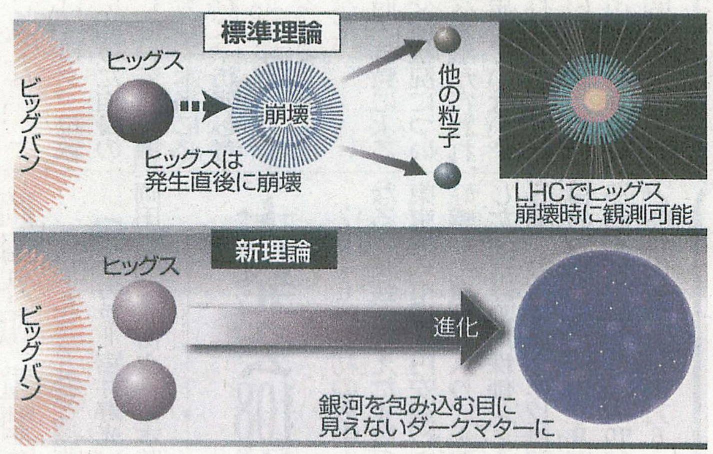
阪大教授 新理論

細谷教授は、宇宙が時間と3次元空間の4次元ではなく、5次元以上であると考え、様々な粒子が力を及ぼしあう理論を考えた。その結果、ヒッグスは崩壊せず、電荷を持たない安定した存在」となった。

欧州にある世界最大の加速器（LHC）では最大の課題としてヒッグスの検出実験が行われる。標準理論では「観測可能」だが、細谷理論では観測不能。新たな実験手法で検証が可能になるという。一方、ダークマターも09年末、発見の可能性が報告されたが、細谷理論と矛盾しないという。

細谷教授は09年秋、来日した南部博士に新理論を説明。南部博士は「今まで誰も気づかなかったヒッグス粒子に対する見方は十分あり得る」と評価したという。

小林富雄・東京大教授（素粒子実験）の話「美しく素晴らしいアイデア。数年で新理論を検証できる可能性もある」



◎標準理論　物質の成り立ちや力の働き方を説明する素粒子理論。宇宙の四つの力のうち重力を除いた電磁気力と弱い力、強い力を説明する。南部博士の理論などが基礎になっている。

Yomiuri newspaper, the front page on Jan. 5, 2010.

Questions on the dark Higgs scenario

How is it realized?

a gauge-Higgs unification model

Does it explain the relic abundance?

a constraint on Higgs mass

How do we confirm it?

collider phenomenology

Gauge-Higgs Unification

Gauge field in higher dimensions

Five-dimensional space-time: $x^M = (x^\mu, y)$

$x^\mu = (x^0, x^1, x^2, x^3)$

Gauge field: $A_M = (A_\mu , A_y)$

A_μ → 4D vector

A_y → 4D scalar ∋ Higgs

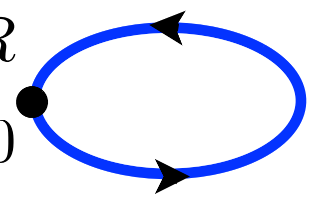
5D gauge inv. → Massless A_M

A potential solution to the naturalness problem!

Dynamical symmetry breaking

4D Higgs field: Wilson line (AB) phase

$M^4 \times S^1$ (multiply connected)



$$\hat{\theta}_H(x) \sim g \int_0^{2\pi R} A_y \, dy$$

$\langle \hat{\theta}_H \rangle \neq 0$ at quantum level.

Nontrivial $V_{\text{eff}}(\hat{\theta}_H)$ at 1-loop.

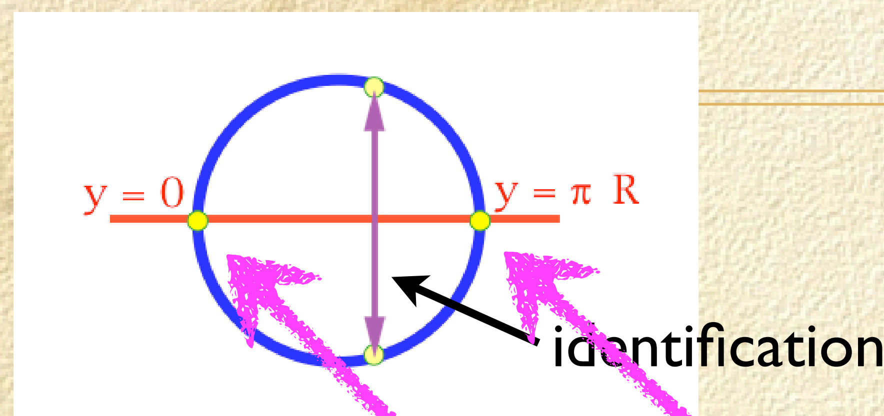
Hosotani mechanism, 1983

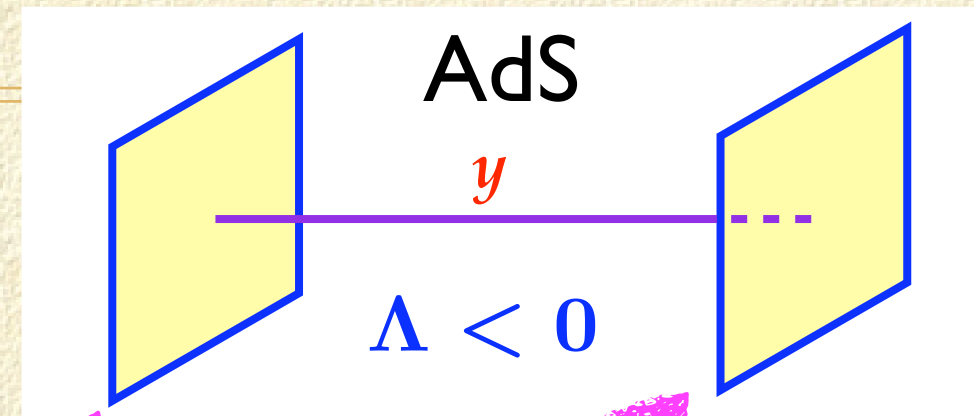
Gauge symmetry is dynamically broken.

Flat space and warped space

$M^4 \times (S^1/Z_2)$

Randall-Sundrum





$$ds^2 = dx_\mu dx^\mu + dy^2 \quad \Rightarrow \quad ds^2 = e^{-2k|y|} dx_\mu dx^\mu + dy^2$$

Y. Hosotani

warp factor

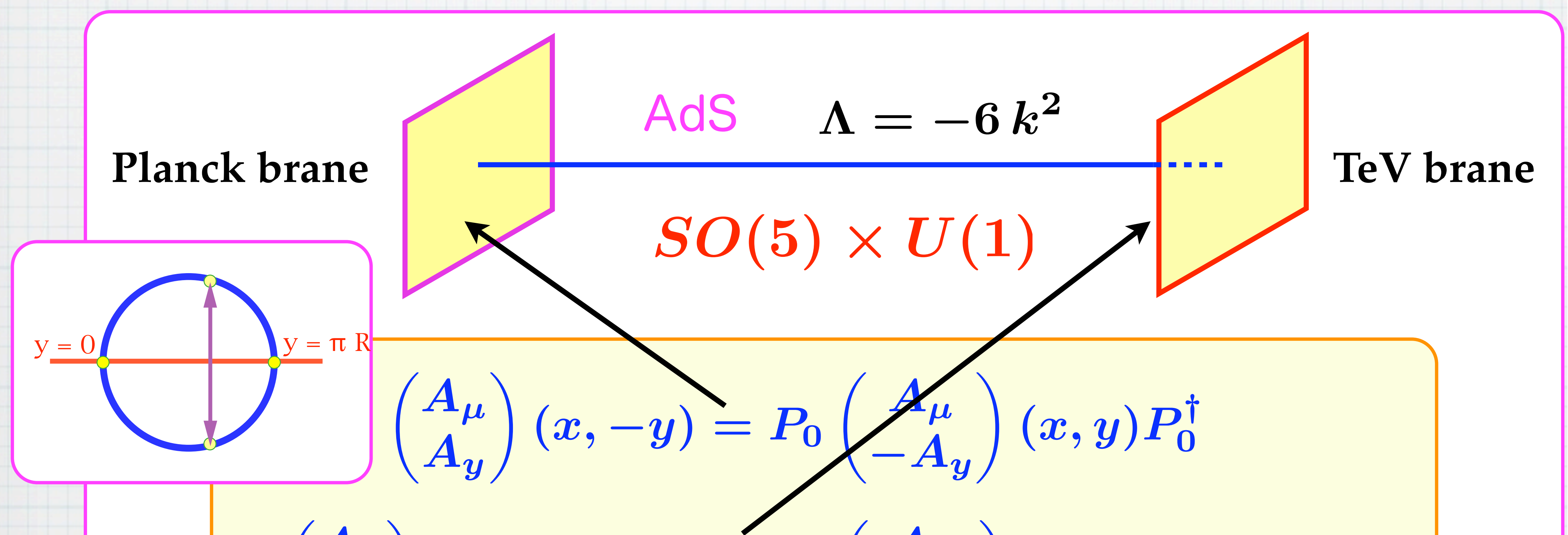
$e^{-k\pi R} \sim 10^{-15}$

Two fixed points: $y = 0,\ y = \pi R$ → Two branes.

RS warped space → Realistic spectrum

An SO(5)xU(1) model on RS warped space

Agashe, Contino, Pomarol, 2005. Hosotani, Sakamura, 2006.
Medina, Shah, Wagner, 2007. Hosotani, Oda, Ohnuma, Sakamura, 2008.



$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, -y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, y) P_0^\dagger$$

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, \pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, \pi R + y) P_1^\dagger$$

Orbifold BC : $P_0\ ,\ P_1$

Y. Hosotani, ICFP2009, 25 September 2009 - 5

Origin of the Higgs doublet

$$P_0 = P_1 = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & +1 \end{pmatrix}$$

W Z γ

$A_\mu \sim$

$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)$

Higgs

$A_y \sim$ ϕ_1 ϕ_2 ϕ_3 ϕ_4

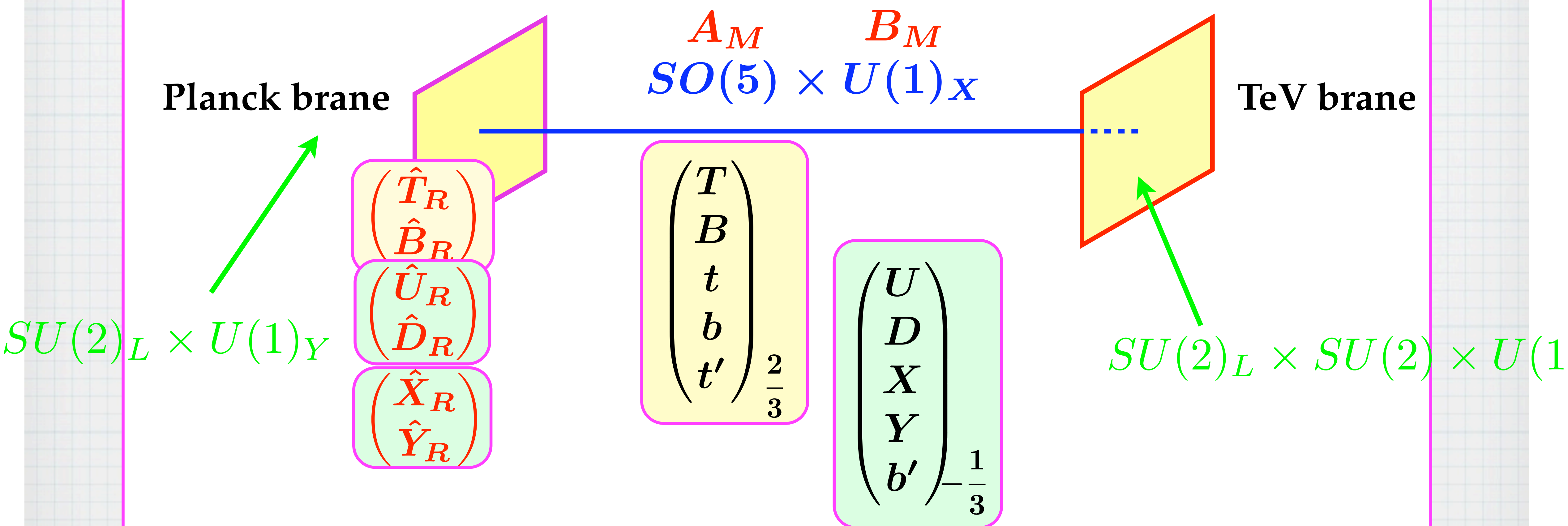
$$\Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

Y. Hosotani, ICFP2009, 25 September 2009 - 6

$$A_y(x^\mu, y) \sim \hat{\theta}_H(x^\mu) h_0(y) \hat{T}^4 + \cdots \qquad h_0(y) = h_0(-y)$$

SO(5)xU(1) Model on RS

YH, Oda, Ohnuma, Sakamura 2008
(YH, Noda, Uekusa 2009)



At low energies γ , W , Z $\begin{pmatrix} t_L \\ b_L \end{pmatrix}$ t'_R b'_R $\cdots$

H

Y. Hosotani, 物理学会, 12 September 2009 - 2

Discrete symmetries

EWSB by Hosotani mechanism

4D Higgs field: Wilson line (AB) phase, $\hat{\theta}_H(x)$

→ Periodicity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + 2\pi)$

Bulk fermions: vectors (and/or tensors) of SO(5),

no spinors.

→ Reduction of period: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + \pi)$

Mirror reflection symmetry

$$y \to -y\,, \ A_y \to -A_y\,, \ \Psi \to \gamma_5 \Psi$$

→ Parity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(-\hat{\theta}_H)$

Effective Lagrangian at the Weak Scale

$$\mathcal{L}_{\text{eff}} = -V_{\text{eff}}(\hat{\theta}_H) - \textstyle\sum_f m_f(\hat{\theta}_H)\bar{f}f$$
$$+m_W^2(\hat{\theta}_H)W^{+\mu}W_\mu^- + \frac{1}{2}m_Z^2(\hat{\theta}_H)Z^\mu Z\mu$$

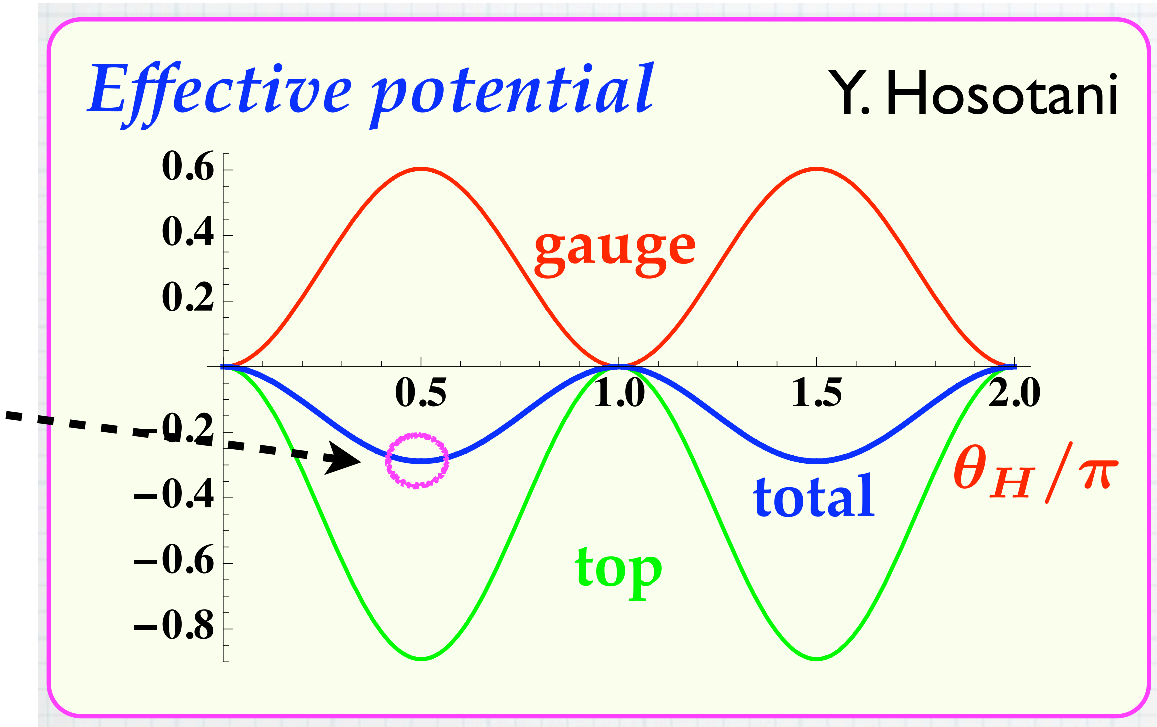
Symmetry implications:

$$V_{\text{eff}}(\hat{\theta}_H + \pi) = V_{\text{eff}}(\hat{\theta}_H) = V_{\text{eff}}(-\hat{\theta}_H)\,,$$
$$m_{W,Z}^2(\hat{\theta}_H + \pi) = m_{W,Z}^2(\hat{\theta}_H) = m_{W,Z}^2(-\hat{\theta}_H)\,,$$
$$m_f(\hat{\theta}_H + \pi) = -m_f(\hat{\theta}_H) = m_f(-\hat{\theta}_H)\,.$$

EWSB

Vacuum: Minimize $V_{\rm eff}(\theta_H)$

$\theta_H = \pi/2\,.$



Physical Higgs:

$$\hat\theta_H(x) = \frac{\pi}{2} + \frac{H(x)}{f_H}\,.$$

$$f_H = 246\,\mathrm{GeV}\;(\Leftarrow m_W = g f_H/2)$$

A new dynamical parity, H-parity,

$$\frac{\pi}{2} + \frac{H}{f_H} \xrightarrow[\hat\theta\to-\hat\theta]{} -\frac{\pi}{2} - \frac{H}{f_H} \xrightarrow[\hat\theta\to\hat\theta+\pi]{} \frac{\pi}{2} - \frac{H}{f_H}$$

$$H(x) \to -H(x)\,.$$

Effective Interactions

Integrating out KK modes,

$$m_W(\hat{\theta}_H) \sim \cos\theta_W m_Z(\hat{\theta}_H) \sim \frac{1}{2} g f_H \sin\hat{\theta}_H \ ,$$

$$m_a^F(\hat{\theta}_H) \sim \lambda_a \sin\hat{\theta}_H \ ,$$

$$\mathcal{L}_{\rm int} = -\frac{m_W^2}{f_H^2} H^2 W^{+\mu} W_\mu^- - \frac{m_Z^2}{2 f_H^2} H^2 Z^\mu Z_\mu + \sum_f \frac{m_f}{2 f_H^2} H^2 \bar{f} f + \cdots .$$

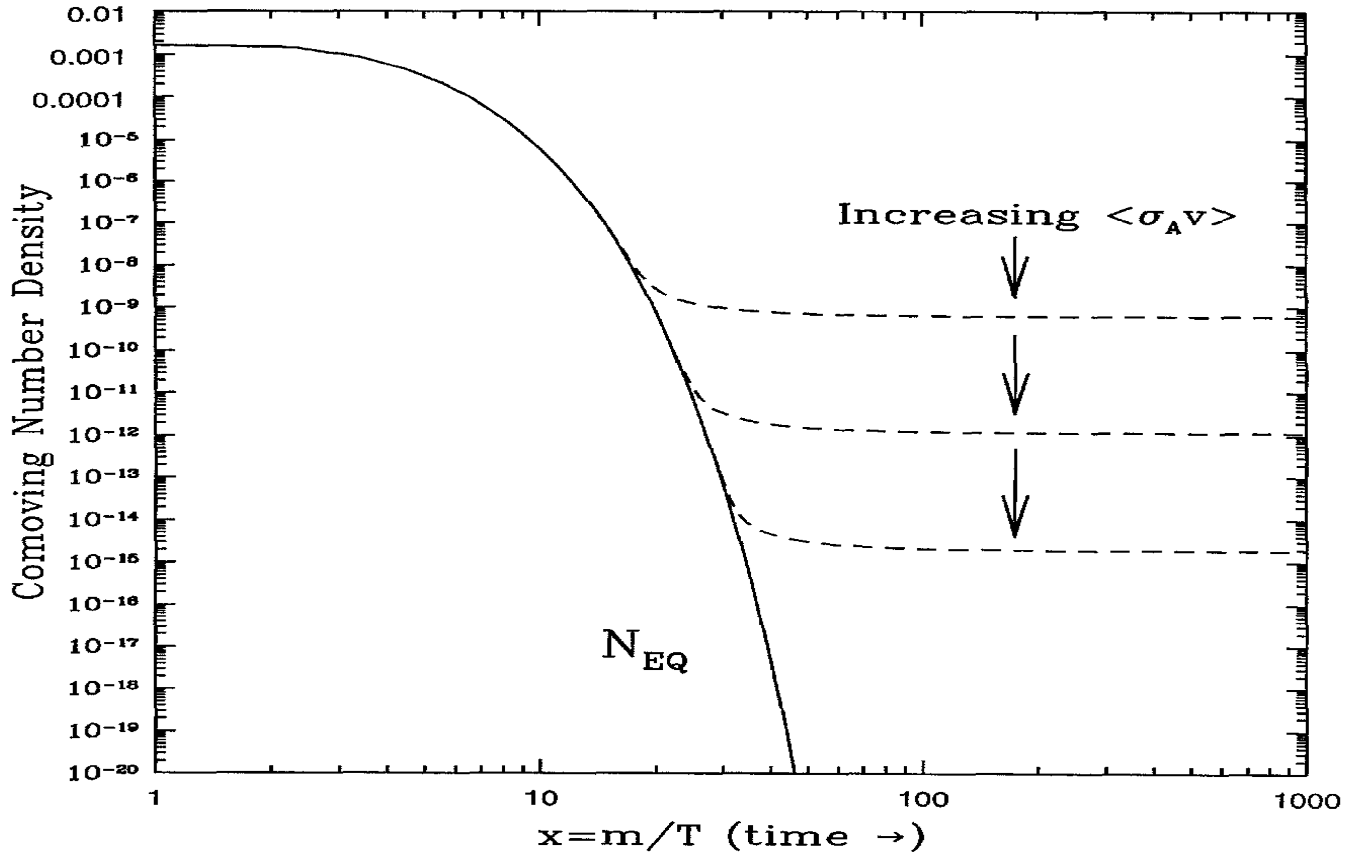
No odd powers of H .

Higgs is STABLE!

A good candidate for WIMP DM.

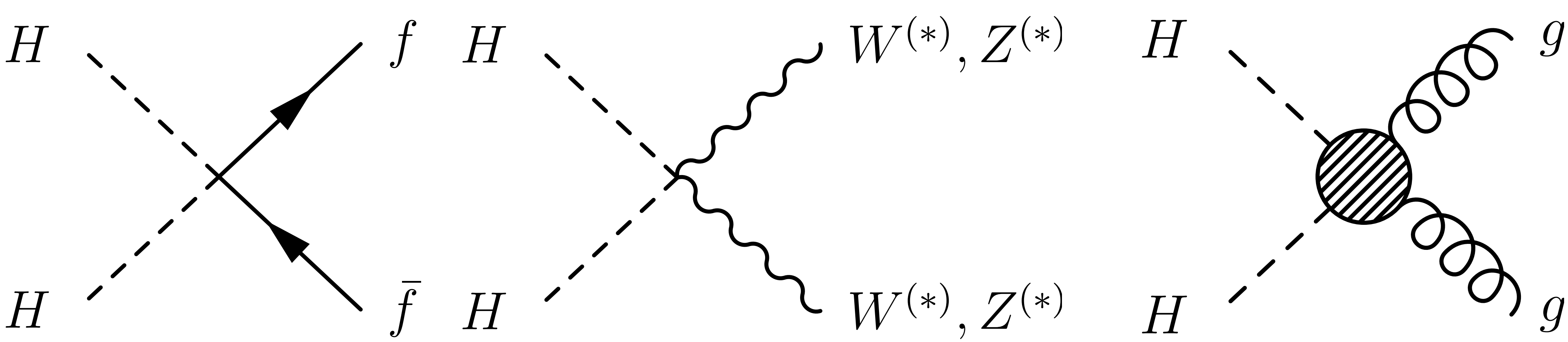
Dark Higgs

Relic Abundance

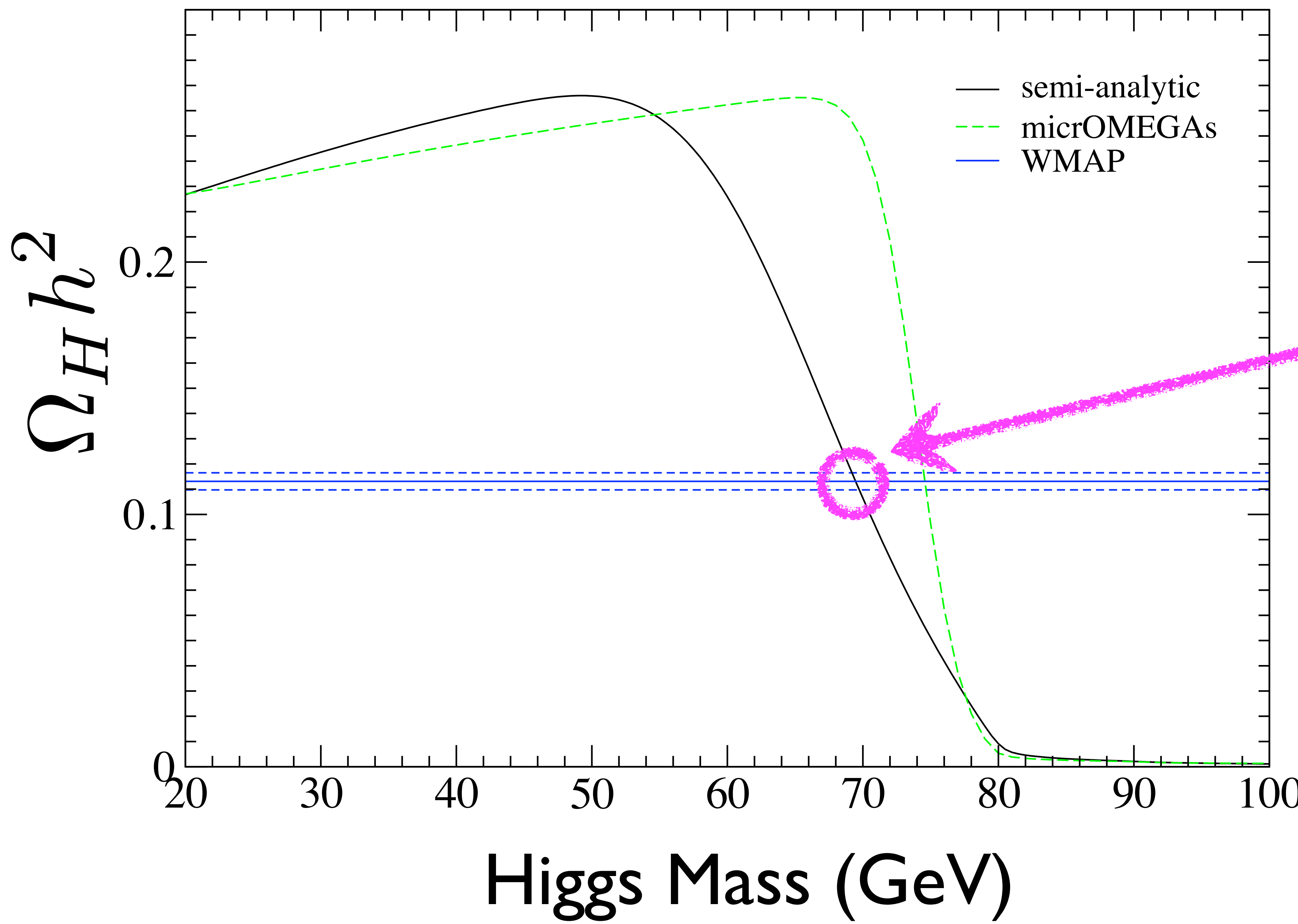


Kolb and Turner, 1989

Annihilation processes:



Relic Abundance

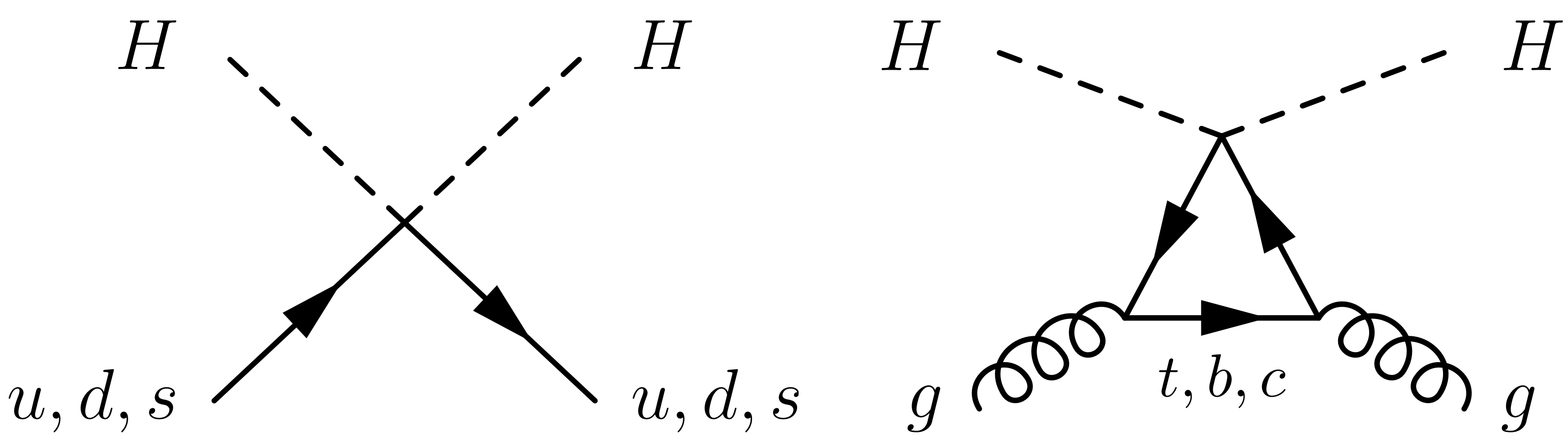


$m_H \sim 70\,\mathrm{GeV}$ favored.

$T_f \sim 3\,\mathrm{GeV}$

$10^{-27}\mathrm{cm}^3/\mathrm{s}$	$b\bar{b}$	$W^{(*)}W^{(*)}$	$Z^{(*)}Z^{(*)}$
$\sigma v\|_{v\to 0}$	7.3	11	1.5

Direct Detection $HN \to HN$



$$\mathcal{L}_{\rm eff} \simeq \frac{H^2}{2f_H^2}\left[\sum_{q=u,d,s} m_q \bar{q} q - \frac{\alpha_s}{4\pi} G^a_{\mu\nu} G^{a\,\mu\nu}\right]$$

$$\mathcal{L}_{HN} \simeq \frac{2+7f_N}{9}\,\frac{m_N}{2f_H^2}\,H^2 \bar{N} N$$

$$f_N = \sum_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle / m_N \simeq 0.1 \sim 0.3$$

Spin-Independent Cross Section

CDMS II

arXiv:0912.3592

Local DM density

$$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$$

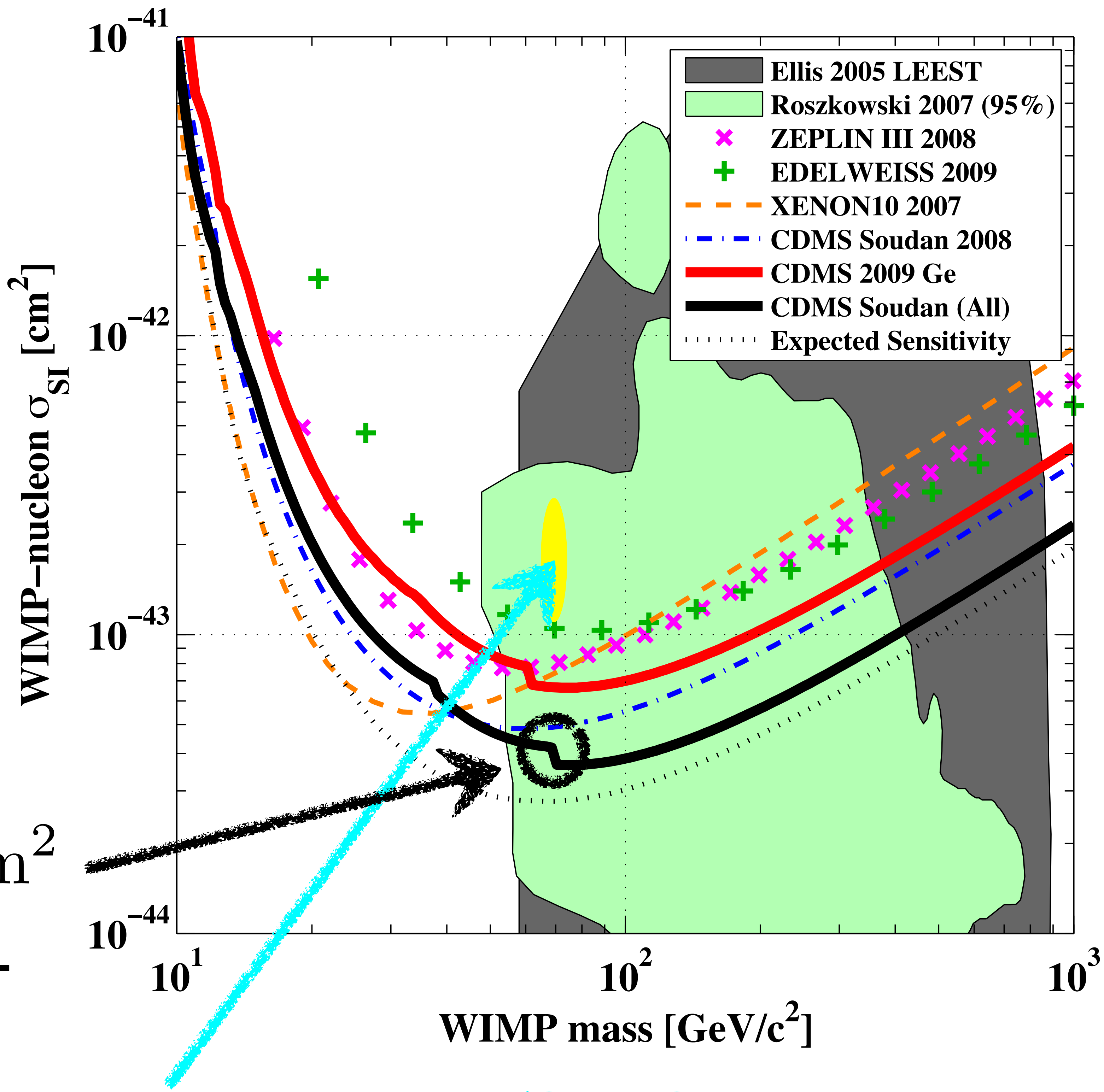
assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

Exp. bound:

$$\sigma_{\rm SI} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$$

90% CL



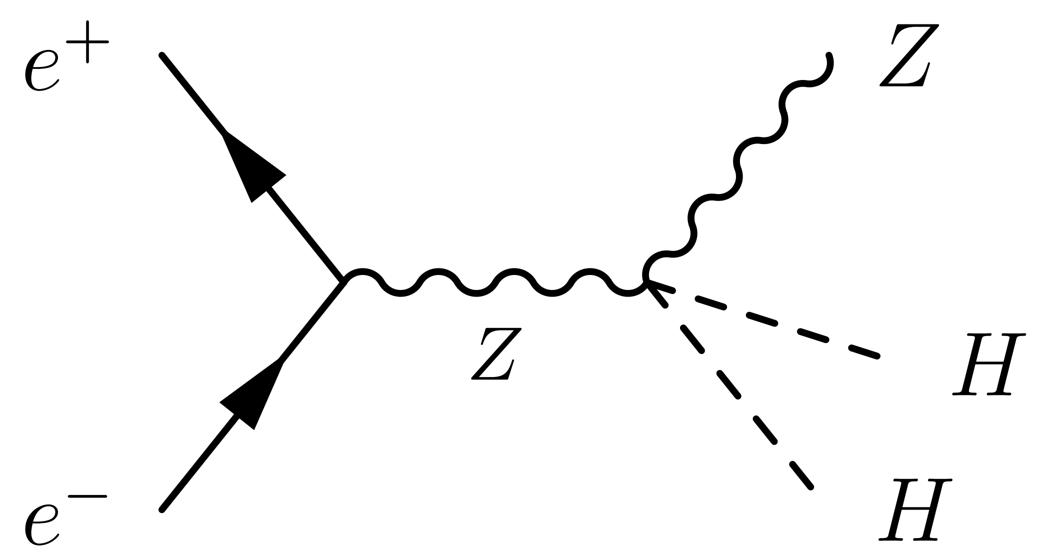
Dark Higgs

Prediction: $\sigma_{\rm SI} \simeq (1.2 - 2.7) \times 10^{-43}\,\mathrm{cm}^2$

Collider Signals

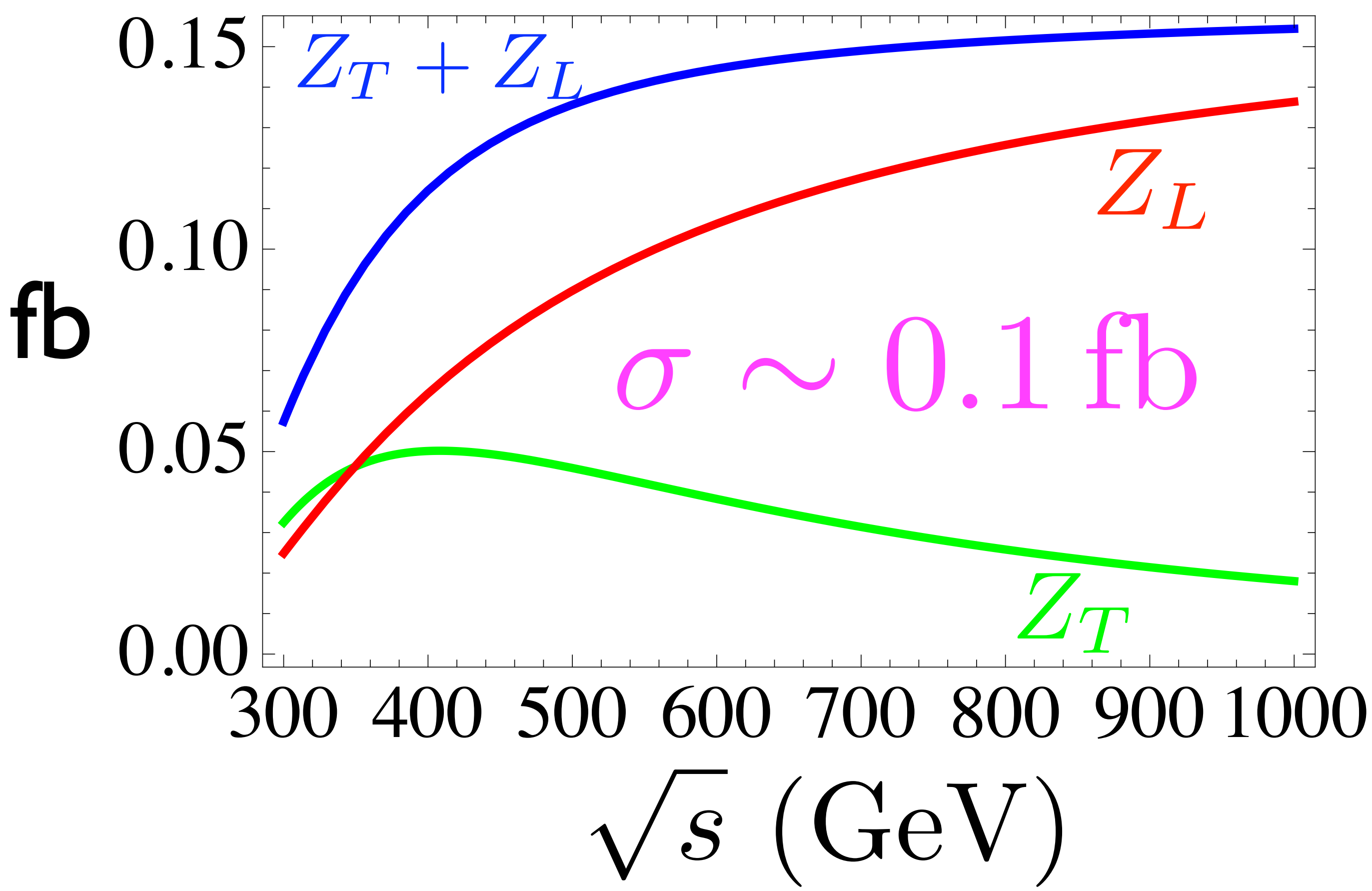
Linear Collider

Signal: $e^+e^- \to ZHH$



H's are missing.

total cross section for $m_H = 70\,\mathrm{GeV}$



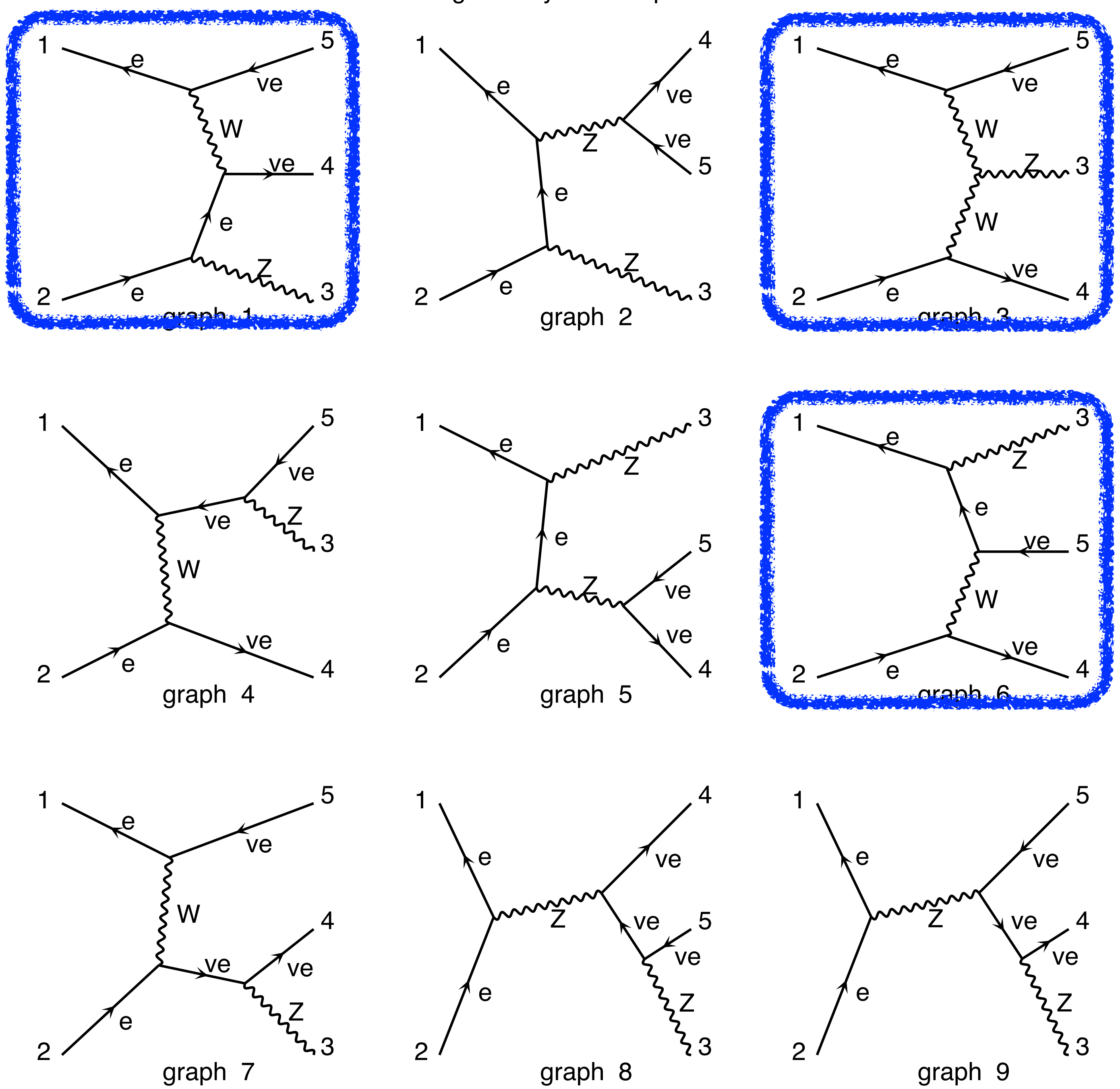
Z_L violates the unitarity unless $s/m_{\mathrm{KK}}^2 \ll 1$.

$m_{\mathrm{KK}} \sim 1.5\,\mathrm{TeV}$

$\sqrt{s} = 500\,\mathrm{GeV}$ in the following.

LC background $e^+e^- \to Z\nu\bar{\nu}$

Diagrams by MadGraph



BG cross section with $M_{\text{miss}} \geq 120\,\text{GeV}$

$\sigma_{\text{BG}} \simeq 311\,\text{fb}$

Need polarizations!

beams and Z

LC with polarizations

Ideal case: $e_L^+ e_R^- \to Z_L HH\,,\ Z_L \nu\bar{\nu}$

$\sigma_{\text{signal}} \simeq 0.12\,\text{fb}$ vs $\sigma_{\text{BG}} \simeq 0.42\,\text{fb}$

$|\cos\theta| < 0.6$ is applied.

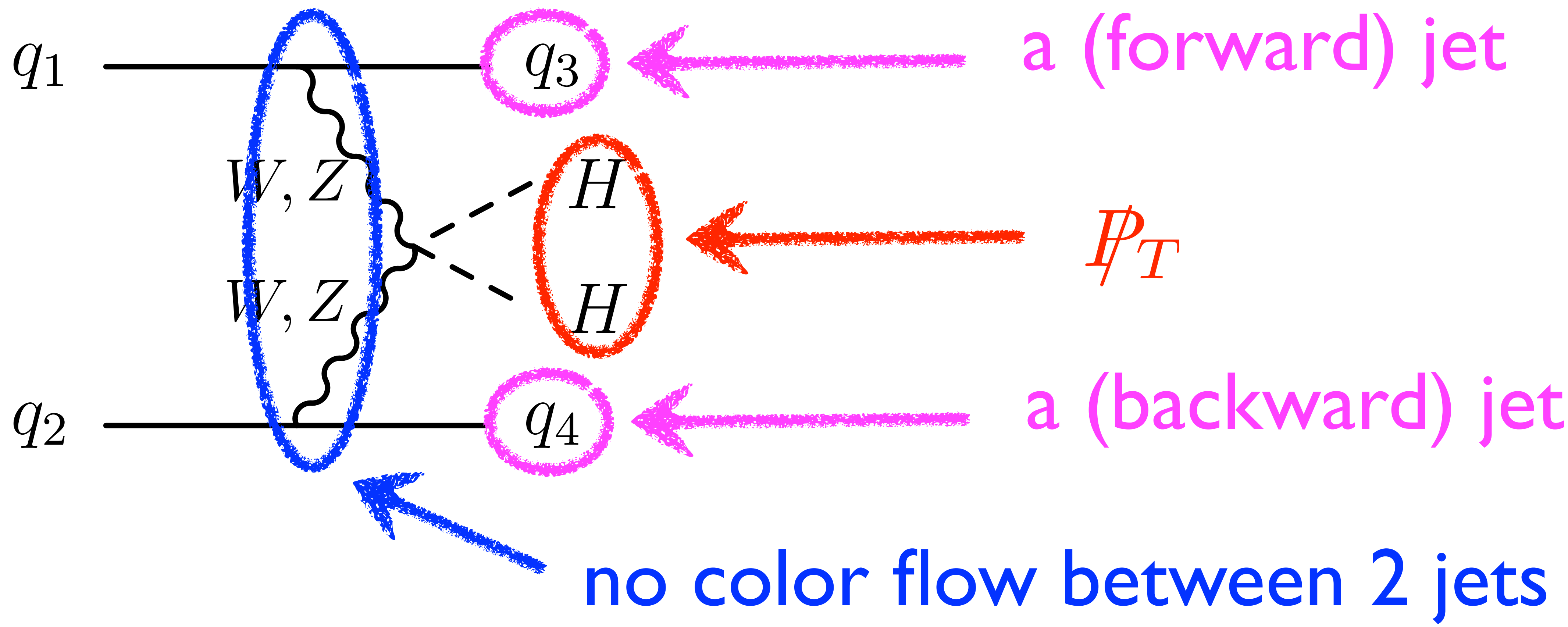
Significance: $\mathcal{S} \equiv \dfrac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{BG}}}}$

$$\mathcal{S} = 1.4\sqrt{L/100\,\text{fb}^{-1}}$$

A few (or more) ab^{-1} is required!

LHC

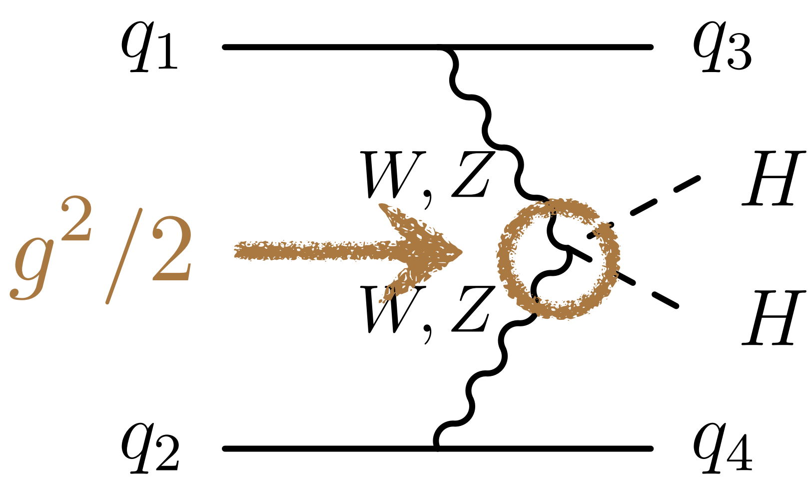
Signal: Weak boson fusion

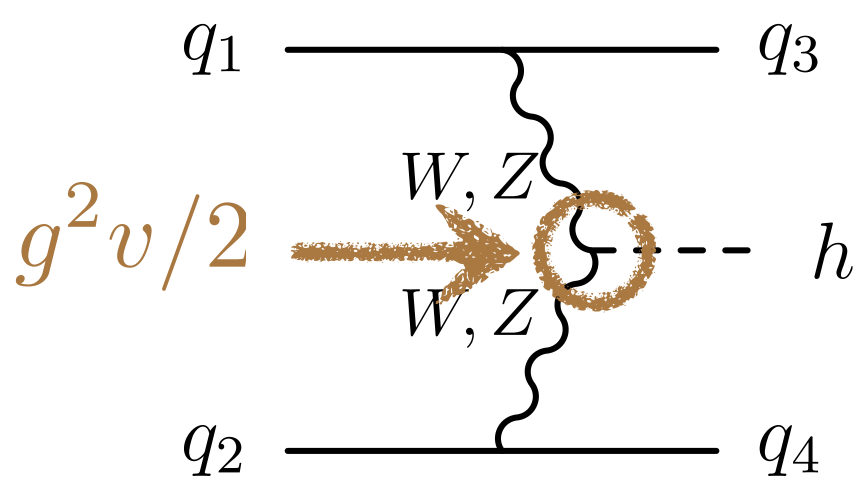


Background: Wjj, Zjj, jjj

→ Similar as invisible Higgs search

Signal cross section at LHC





$$\frac{d\sigma_{HH}}{dm^2_{HH}} = \frac{\bar{\beta}_f}{32\pi^2 v^2} \sigma_h \Big|_{m_h^2 = m^2_{HH}}$$

in the SM

$$\sigma_{HH} \sim 1.5\,\mathrm{fb}$$

$$\sigma_{BG} \simeq 167\,\mathrm{fb}$$

$$\mathcal{S} \sim 1.2\sqrt{L/100\,\mathrm{fb}^{-1}}$$

Éboli, Zeppenfeld

$p_T^j > 40$ GeV, $\quad |\eta_j| < 5.0,$

$|\eta_{j1} - \eta_{j2}| > 4.4, \quad \eta_{j1} \cdot \eta_{j2} < 0,$

$\not{p}_T > 100$ GeV.

$M_{jj} > 1200$ GeV, $\quad \phi_{jj} < 1.$

Summary

- Stable Higgs in gauge-Higgs unifiction is a viable candidate of dark matter.

  Dark Higgs scenario

- $m_H \sim 70\,\mathrm{GeV}$ is predicted.
- Direct detection is likely.

  Exp. limits depend on the local DM density, ρ_0 .

  $\rho_0 \simeq 0.04 \sim 0.6\,\mathrm{GeV/cm^3}$

- We need a few ab^{-1} or more.

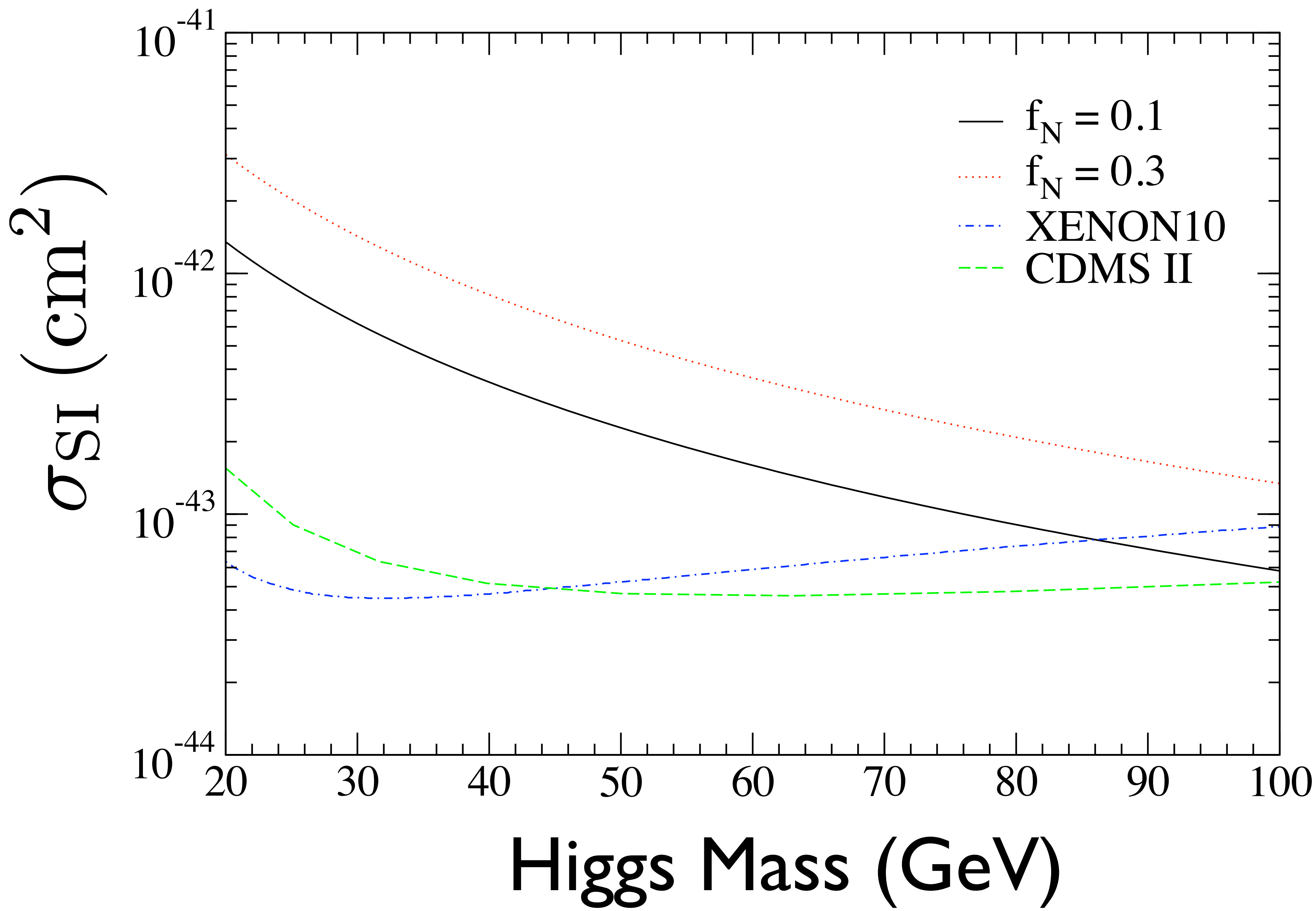
  both for LHC and LC.

- Signals in KK mode production should be studied.

  $m_{\mathrm{KK}} \sim 1.5\,\mathrm{TeV}$ Higher energy colliders?
  Lowering KK mass?

Backup Slides

Spin-Independent Cross Section



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assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

Prediction: $\sigma_{SI} \simeq (1.2 - 2.7) \times 10^{-43}\,\mathrm{cm}^2$

Exp. bound: $\sigma_{SI} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$

Uncertainties in the direct detection

Local density of CDM (not measured)

$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

assumed in the experiments.

$\rho_0 = 0.2 \sim 0.6\,\mathrm{GeV/cm^3}$

reasonable for smooth halo.

$\rho_0 \sim 0.04\,\mathrm{GeV/cm^3}$ (Kamionkowski and Koushiappas)

possible for non-smooth halo.

Effective Higgs coupling $HH\bar{f}f$

may be altered in more general models.

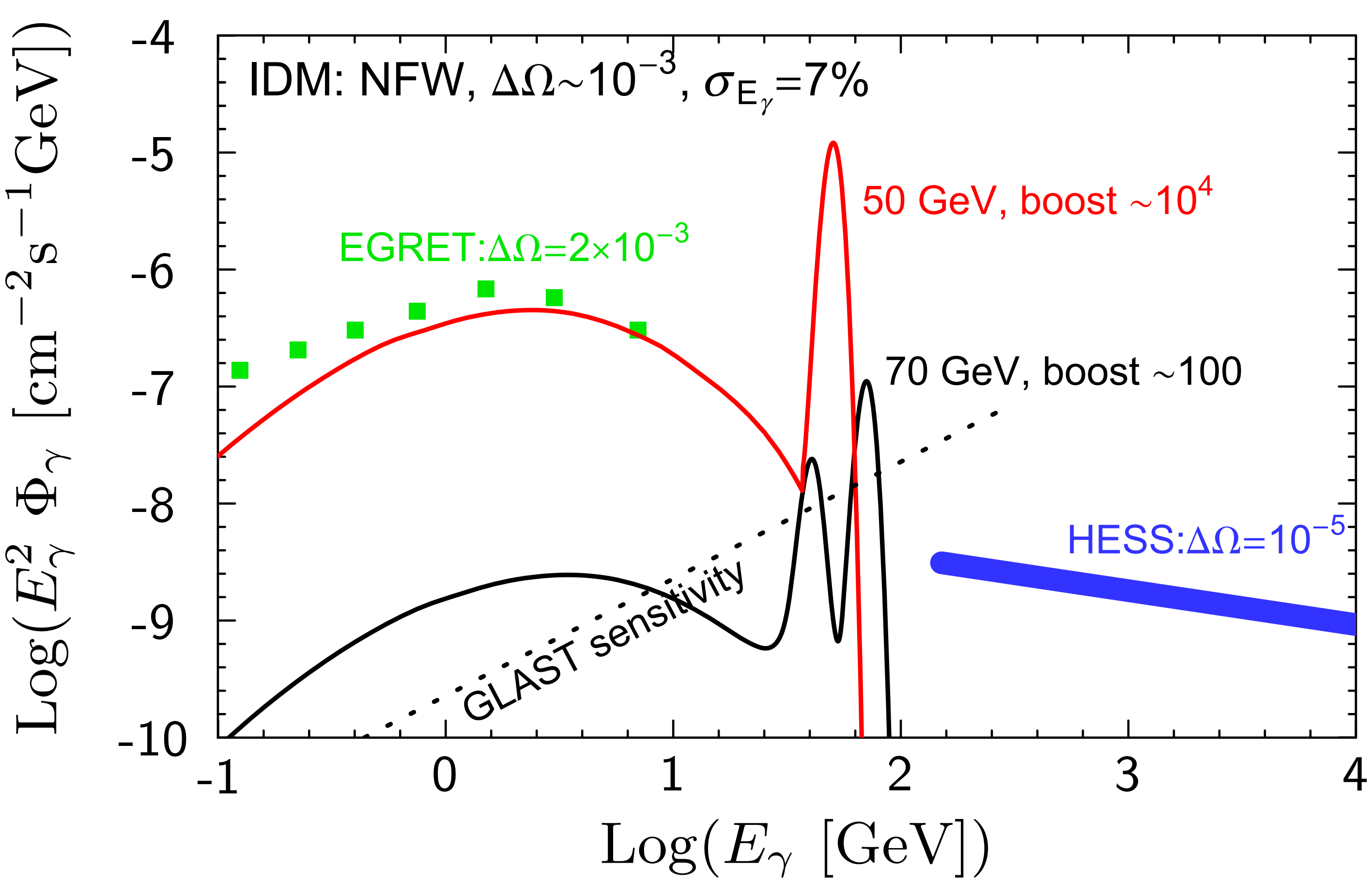
Astrophysical Signals

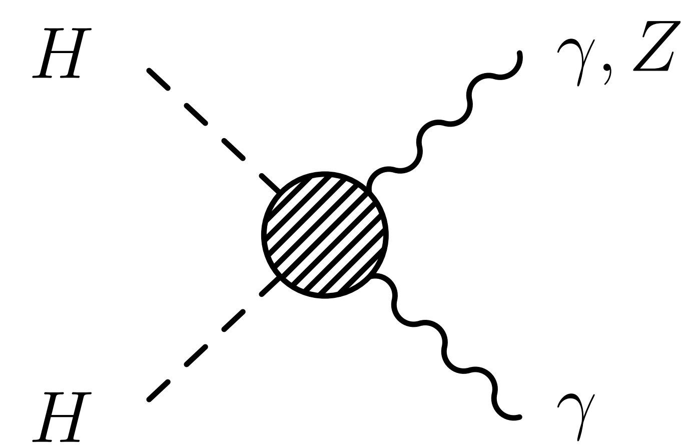
$HH \to \gamma\gamma,\ \gamma Z$ in the Galactic halo.

Two (nearly) monochromatic gamma lines.

$$E_\gamma = m_H (\simeq 70\mathrm{GeV}) \,, m_H - m_Z^2/(4m_H)(\simeq 40\mathrm{GeV})$$

$$\sigma_{\gamma\gamma(\gamma Z)}\, v|_{v\to 0} \simeq 4.3(5.4)\times 10^{-29}\mathrm{cm}^3/\mathrm{s}$$





cf. Inert Doublet Model

← Gustafsson et al.