Scale Invariant Extension
of the SM and NG Dark Matter

June 20 at FLASY2014.

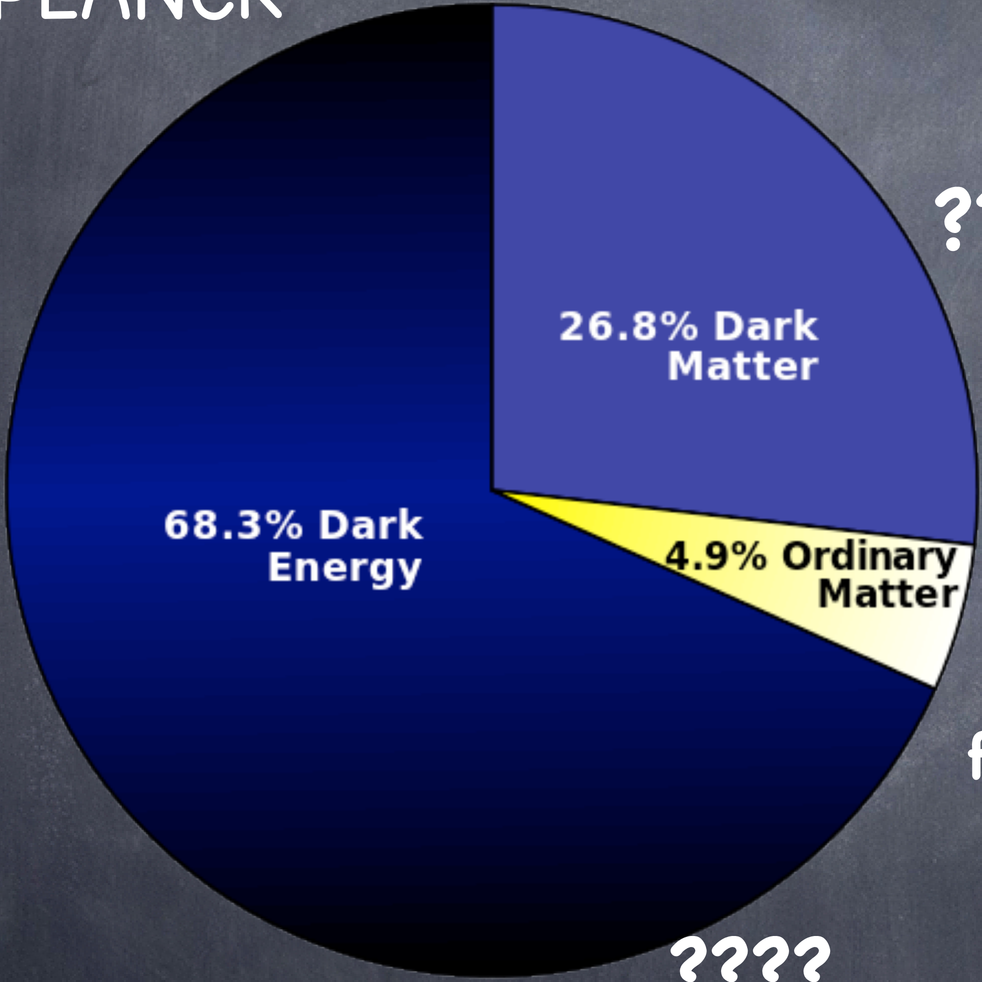
based on the collaboration with Martin Holthausen,
Kher Sham Lee and
Manfred Lindner
(MPI, Heidelberg)

by Jisuke Kubo,
Kanazawa University

**JHEP 1312 (2013) 076, arXiv:1310.4423 ;
arXiv:1403.4262 ; arXiv:1405.1052 ;**

The Cake of the Universe

PLANCK

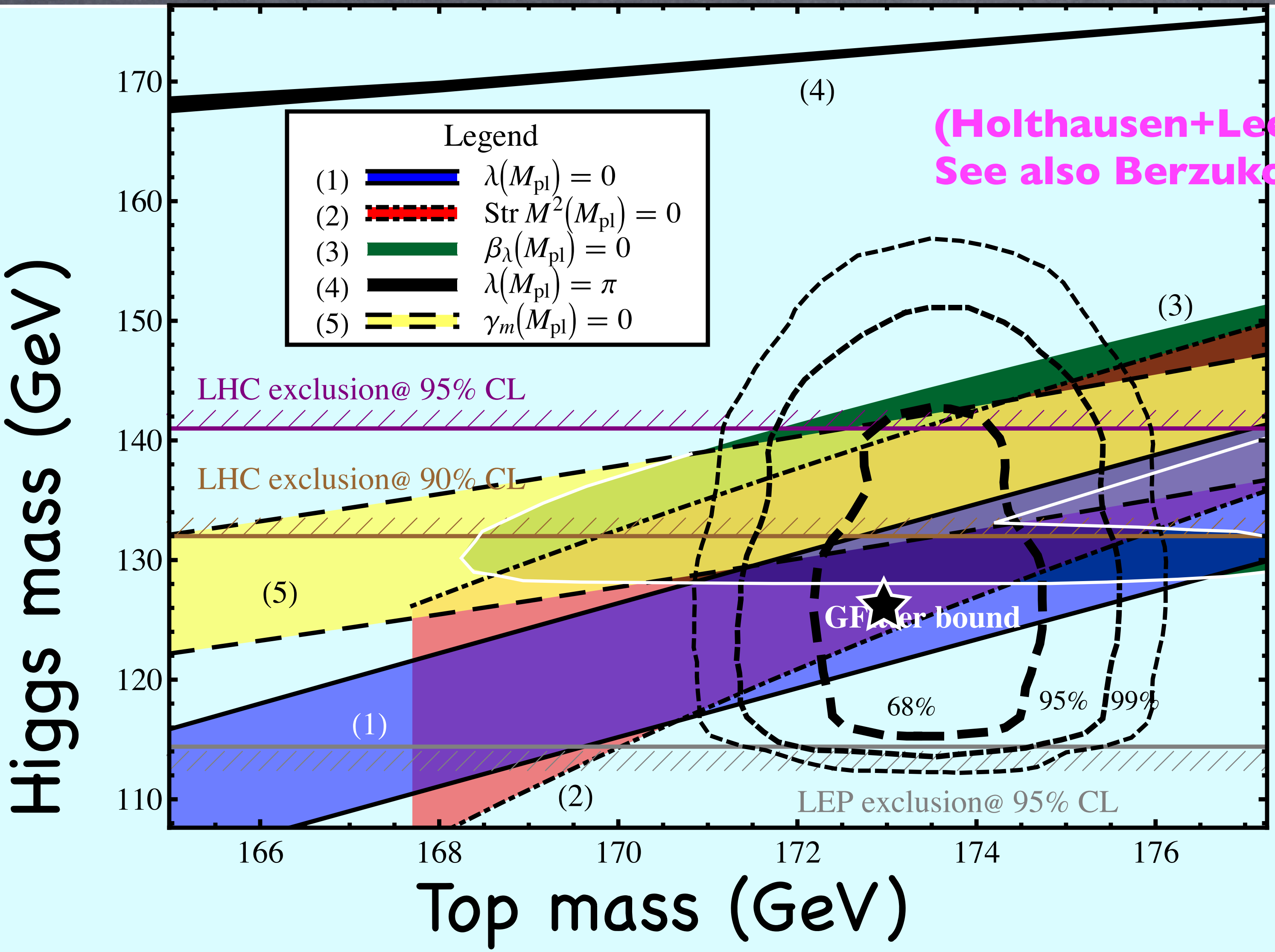


???

????

98% + 2%

from Dynamical Chiral SB (DχSB) in QCD



(Holthausen+Lee+Lindner`2012.
See also Berzukov et al, 2012)

The SM is perturbative
at least till the Planck scale.

The SM does not, by itself, has a fine tuning problem (Bardeen,`95).

Our conservative approach to BSM

* No large intermediate scale below the Planck scale.

* Low-energy physics is responsible for the origin of low energy scales.

Scale Invariant Extension of the SM

???

Scenario below the Planck Scale

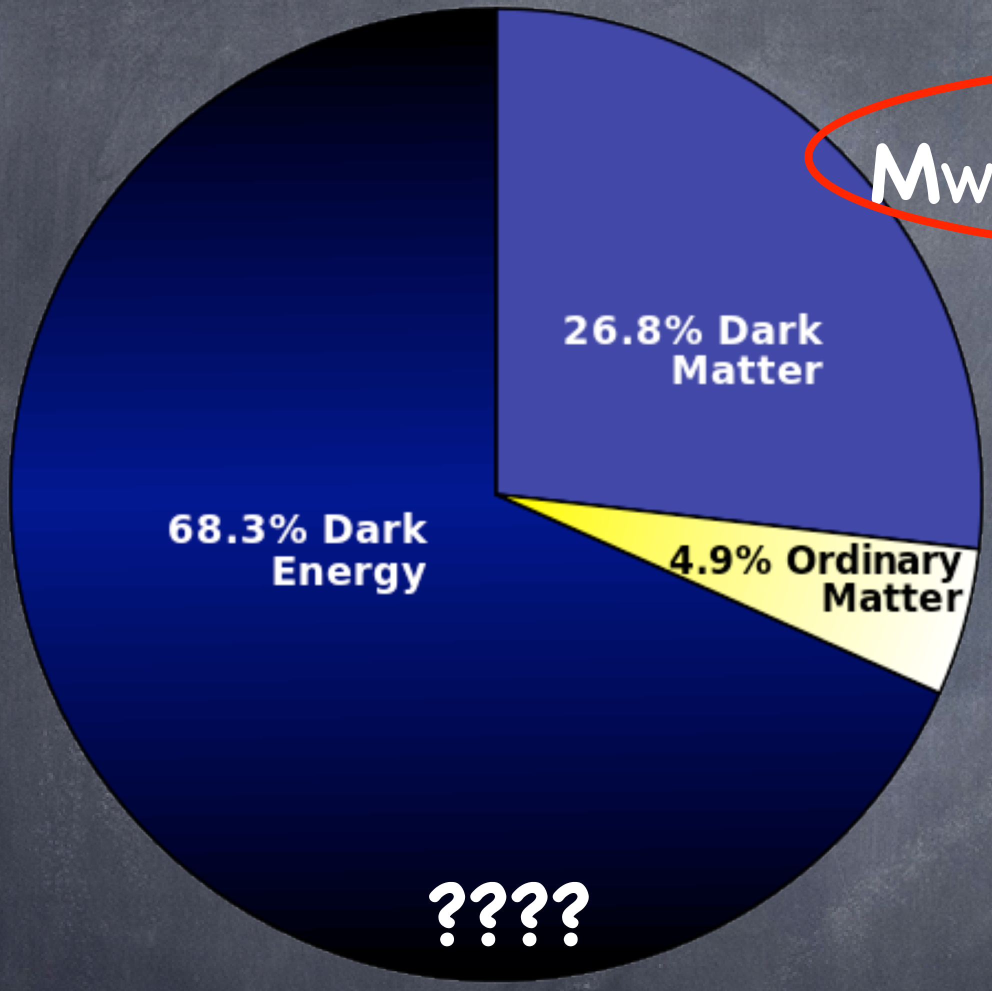
BSM:
cl. scale invariant,
renormalizable, perturbative theory

Dynamical chiral SB (DχSB)
in a hidden sector

EWSB

DχSB in QCD

The Cake of the Universe



$M_{\rm WIMP} \simeq 10$ GeV~few TeV

↑

from DχSB in a hidden QCD

↓

98% + 2%

↑

from DχSB in QCD

26.8%+4.9%=31.7% from DχSB

The model(s)

(Hur, Jung, Ko+Lee,arXiv:0709.1218+1103.2571; Heikinheimo,arXiv:1304.7006`76; Holthausen, Kubo, Lim, Lindner, arXiv:1310.4423; KLL, arXiv:1405.1052)

$$\mathcal{L}_{\rm H} = -\frac{1}{2}{\rm Tr}\ F^2 + {\rm Tr}\ \bar{\psi}(i\gamma^\mu\partial_\mu + gG_\mu + g'\overset{\substack{\text{Hypercharge}\\ \downarrow}}{Q}B_\mu - yS)\psi$$

$$V_{{\rm SM}+S} = \lambda_H(H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS}S^2(H^\dagger H)$$

No dimensional parameters

▼

Classically scale invariant

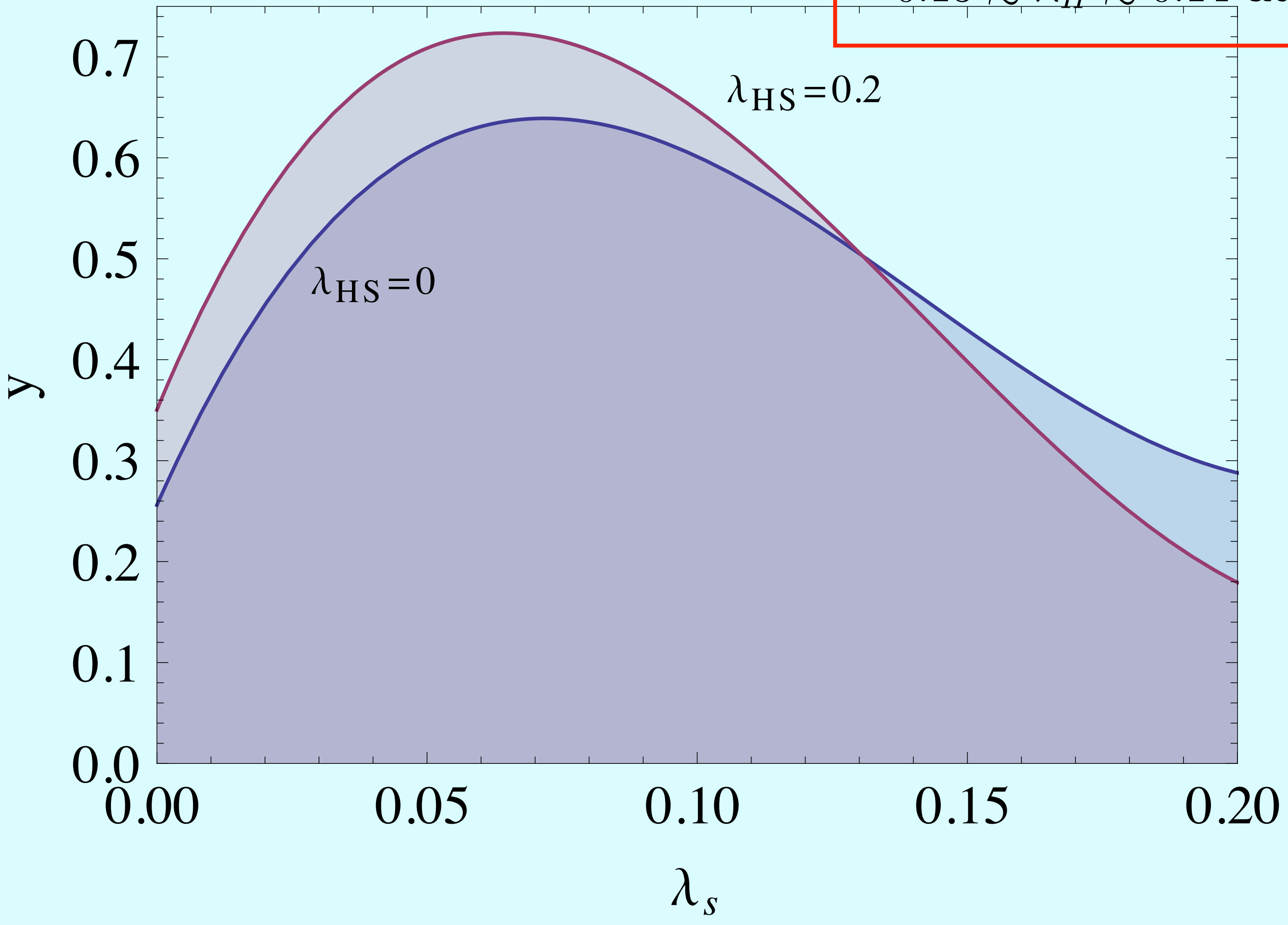
▼

Perturbatively renormalizable, and vertex functions for non-exceptional momenta exist. **(Poggio+Quinn,`76, see also Loewenstein +Zimmermann,`76)**

Landau pole constraint（Q=0）

$\alpha_4 = g_4^2/4\pi \sim 1$ **at** 1 **TeV**

$0.13 \lesssim \lambda_H \lesssim 0.14$ **at** 1 **TeV**



$$V_{\rm SM+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

At low energy:

Dynamical Chiral Symmetry Breaking in the hidden sector (DχSB)

How to deal with this nonperturbative effect ?

***<u>Direct approach</u>: Lattice gauge theory**

***<u>Effective theory approach</u>:**

Sigma models

・・・・

Nambu-Jona-Lasinio (NJL)model

$\mathcal{L}_{\mathrm{H}}$

4-fermi 6-fermi

$$\rightarrow \mathcal{L}_{\mathrm{NJL}} = \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu\partial_\mu + g'Q\gamma^\mu B_\mu - yS)\psi + 2G\ \mathrm{Tr}\ \Phi^\dagger\Phi + G_D\ (\det\Phi + h.c.)$$

$$\boxed{(N_F = N_C = 3)}$$

$$\Phi_{ij} = \bar{\psi}_i(1-\gamma_5)\psi_j = \frac{1}{2}\lambda^a_{ji}\mathrm{Tr}\ \bar{\psi}\lambda^a(1-\gamma_5)\psi$$

The same global symmetry

The Yukawa: $U(3)_L \times U(3)_R \to U(3)_V$

The 6-fermi (anomaly term): $U(1)_A \to Z_3$

(Kobayashi+Maskawa,`70, Shifman, Vainshtein, Zakharov,`80, t Hooft, `86)

Finally: $SU(3)_V \times U(1)_V$

The parameters of the hidden sector of NJL

Assume that the QCD NJL parameters, up to an overall scale, remain the same even in the absence of the current quark masses and in the presence of the Yukawa coupling for the hidden sector NJL.

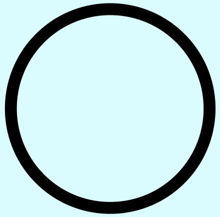
$$G\Lambda^2 = 4.02 \ , \ \ G_D\Lambda^5 = 42.3$$

Λ **is free.**

of the parameters in the L_{NJL} is the same as in L_H.

The scale of the theory and the Higgs mass

$$V_T(h,S,\sigma) = V_{\mathrm{SM+S}} - \frac{3}{8G}\sigma^2 + \frac{G_D}{16G^3}\sigma^3 +$$



constituent fermion

$$< h > \quad , \quad < S > \quad , \quad < \sigma >$$

$$< h >= 246\ \mathbf{GeV} \quad \Rightarrow \quad \Lambda$$

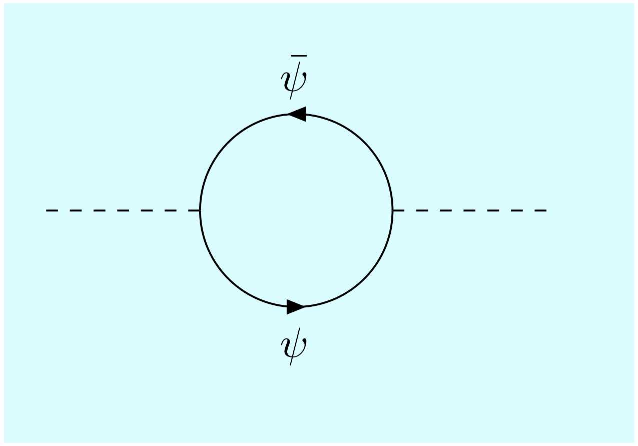
for $y = 0.0052$, $\lambda_H = 0.13$

$\lambda_{HS} = 0.01$, $\lambda_S = 0.19$

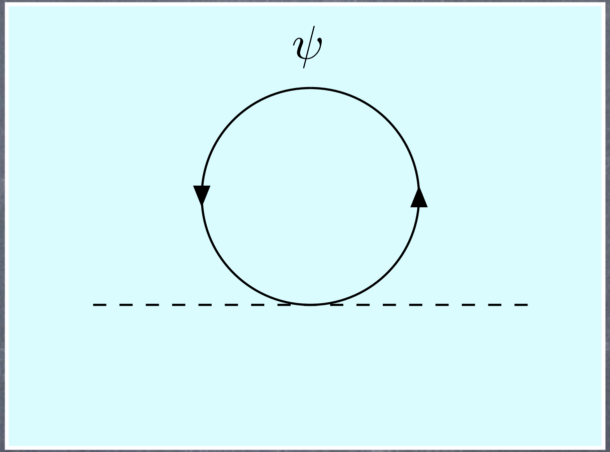
$$\Lambda \simeq 11\ \mathbf{TeV}$$

The Higgs mass can be obtained by solving the mixing among $h\ ,\ S$ **and** σ

at fermion one-loop:



and



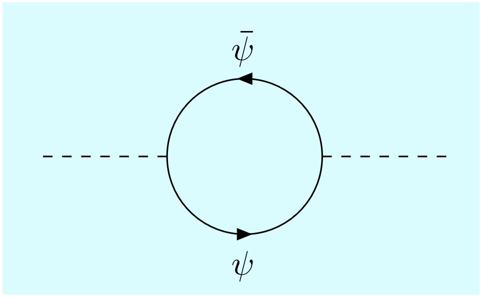
Only three of $y\ ,\ \lambda_H\ ,\ \lambda_{HS}\ ,\ \lambda_S$ **are independent.**

Dark Matter

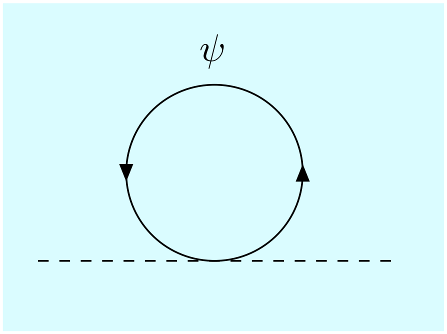
Because of $SU(3)_V$ the hidden pions are stable and hence can be dark matter.

Global symmetry: $SU(3)_V \times U(1)_V$

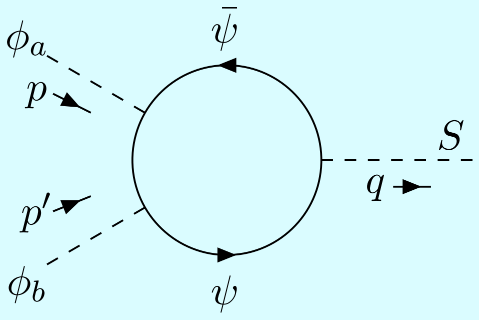
*Dark Matter mass

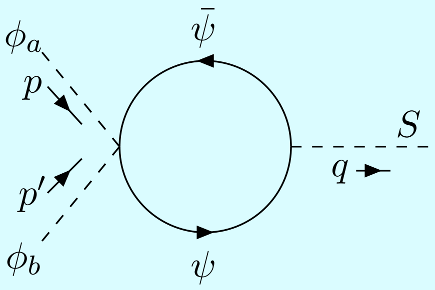


and



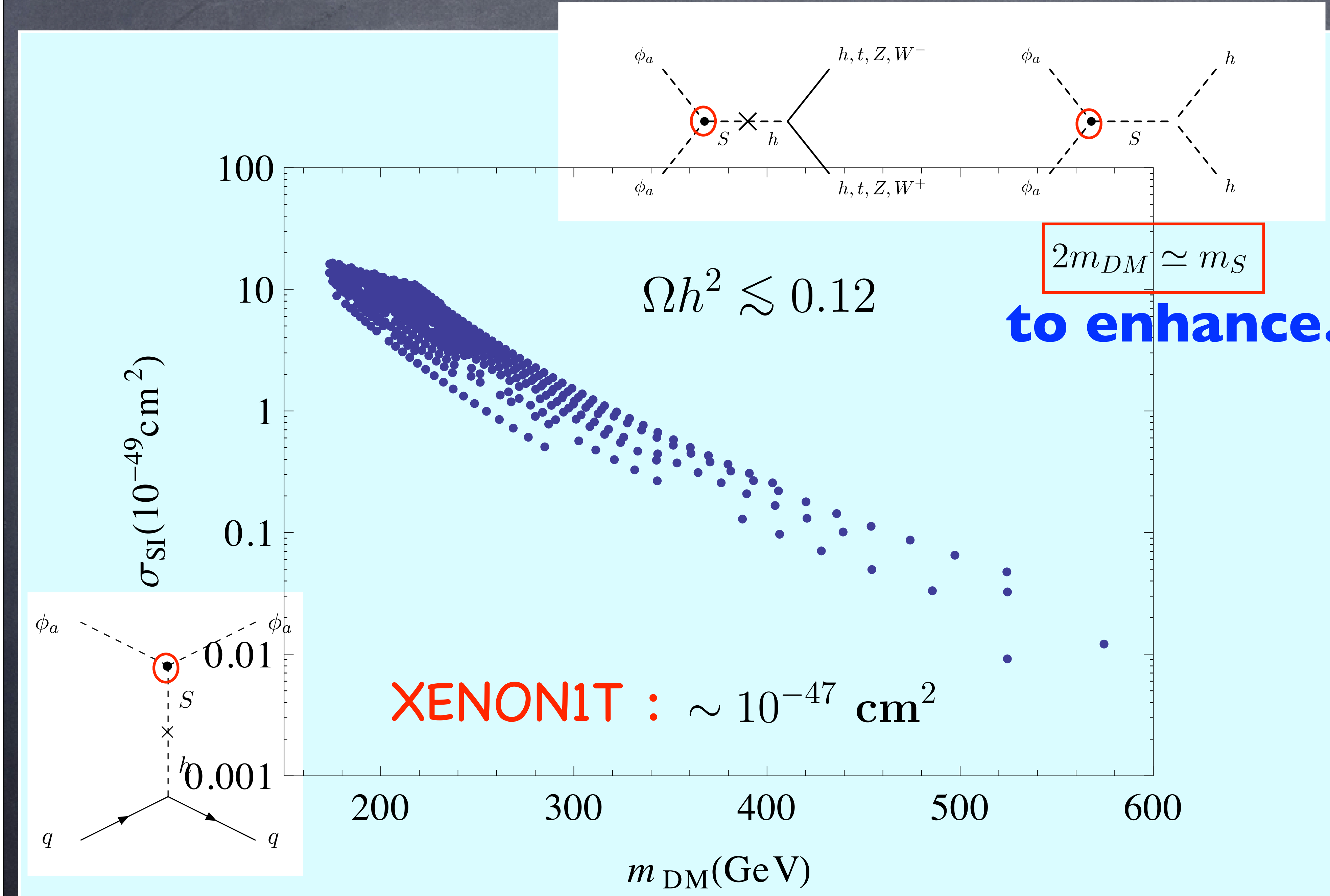
*Dark Matter coupling to the singlet S





$$= \kappa \sim 2.4 \ \mathrm{GeV}$$

Direct detection (Q=0)



$\Omega h^2 \lesssim 0.12$

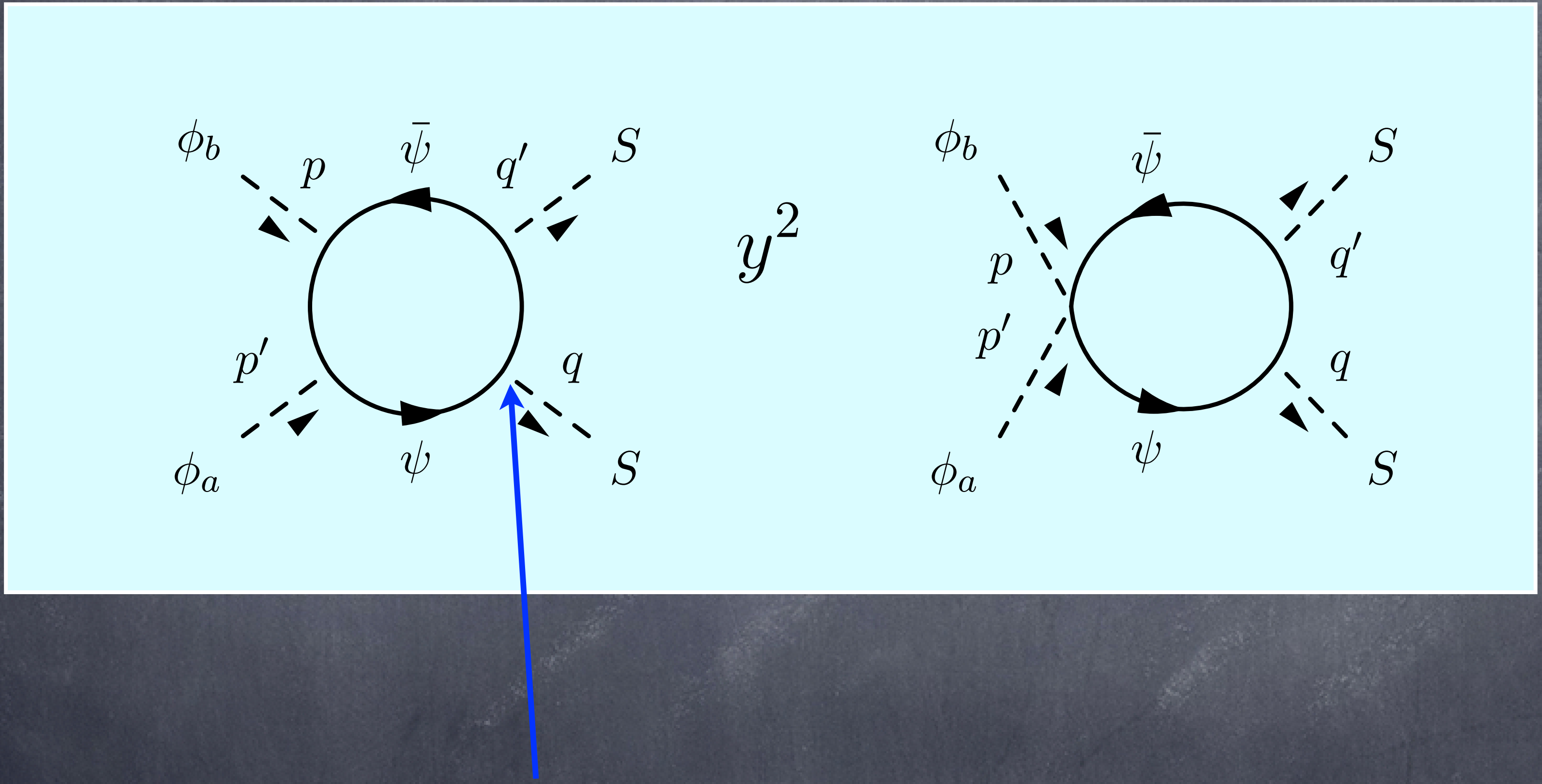
$\boxed{2m_{DM} \simeq m_S}$

to enhance.

XENON1T : $\sim 10^{-47}$ **cm**^{2}

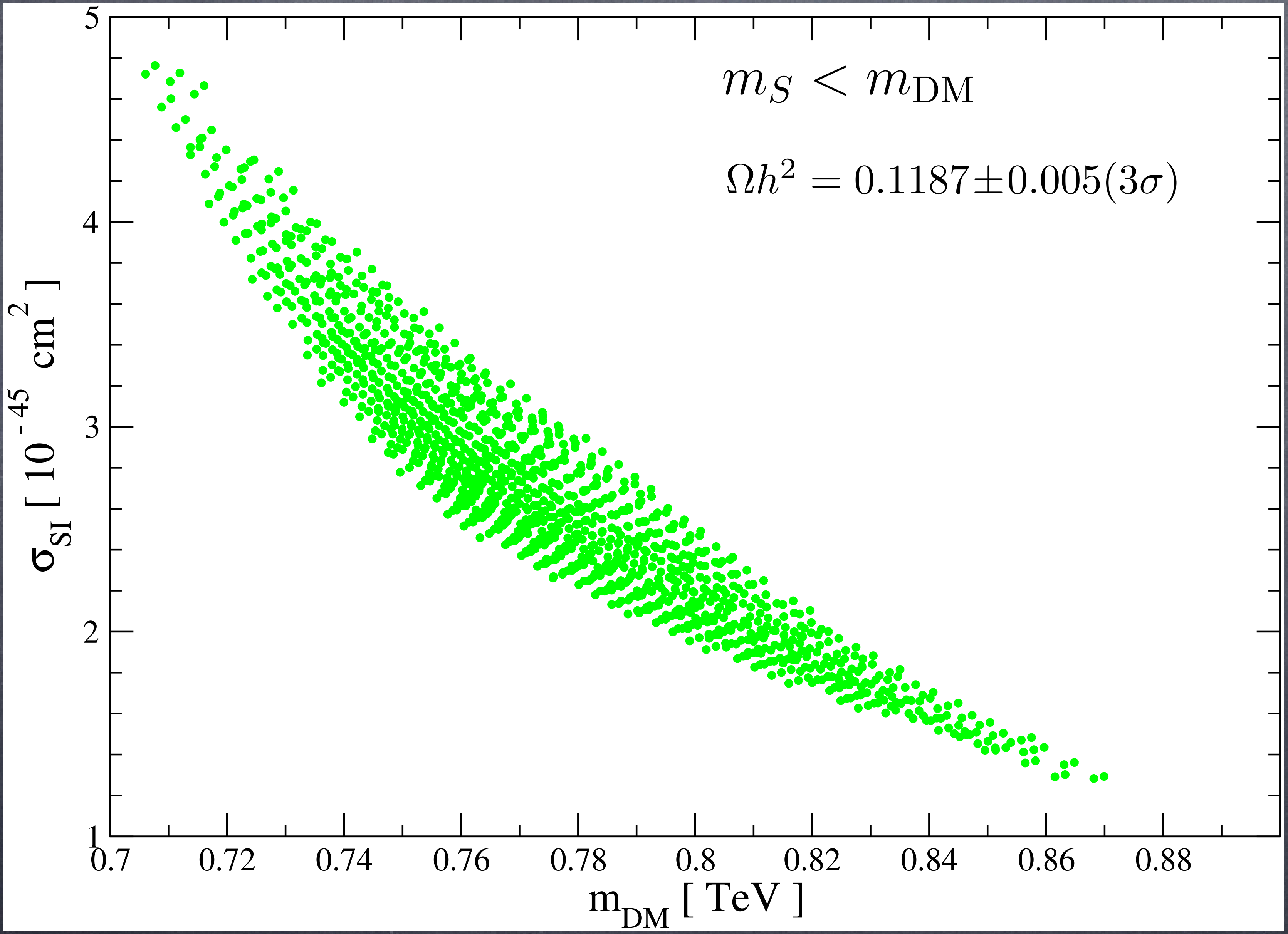
*If the singlet S is lighter than Dark Matter:

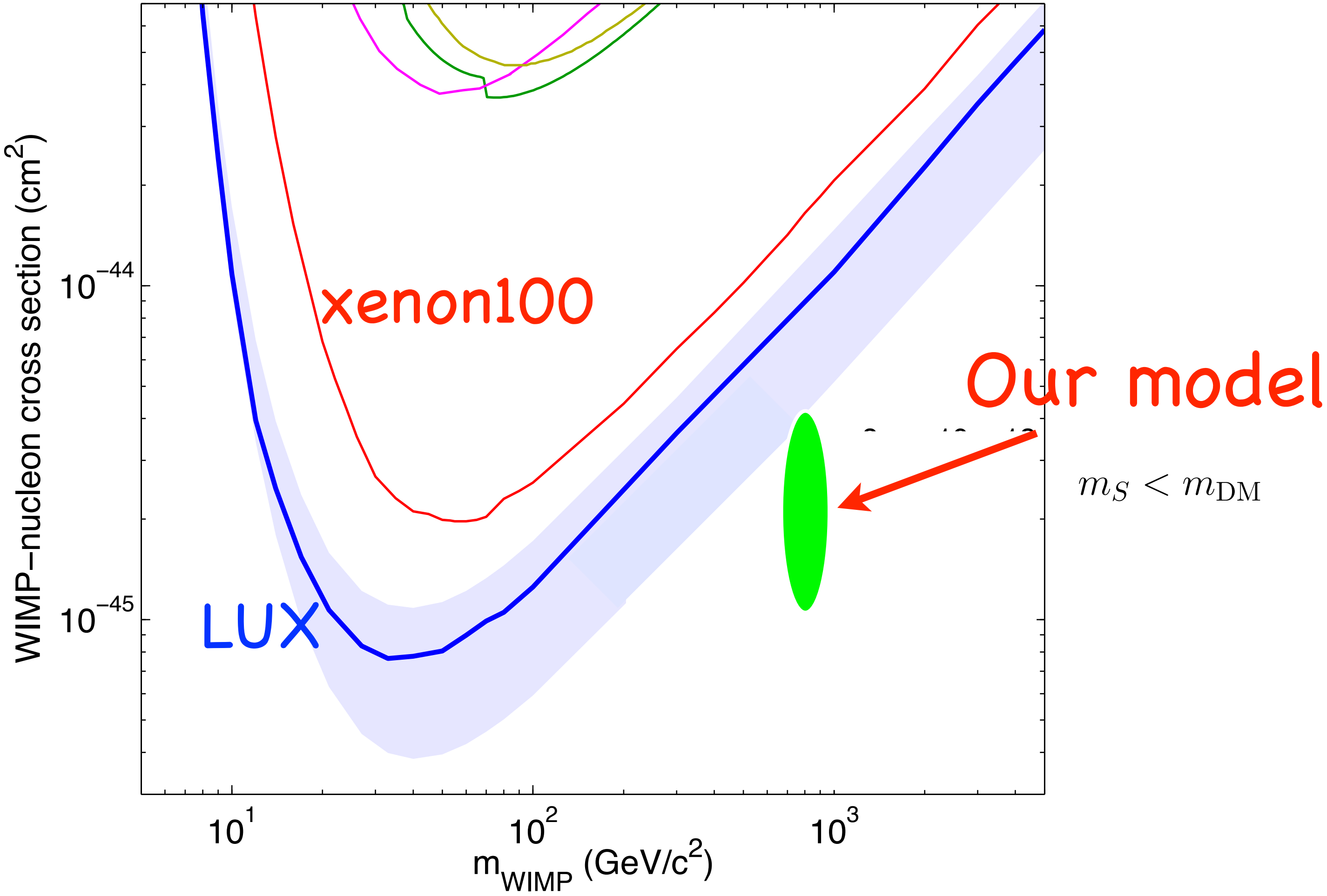
$m_{DM} > m_S$



A large Yukawa y means a heavy DM.

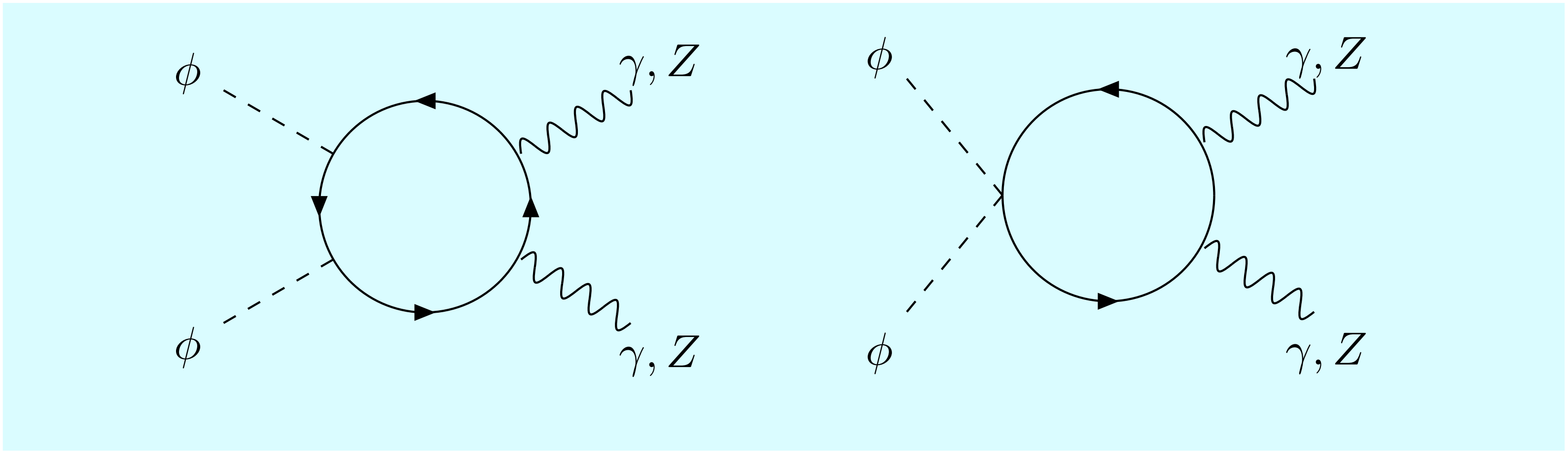
Direct detection





$m_S < m_{\rm DM}$

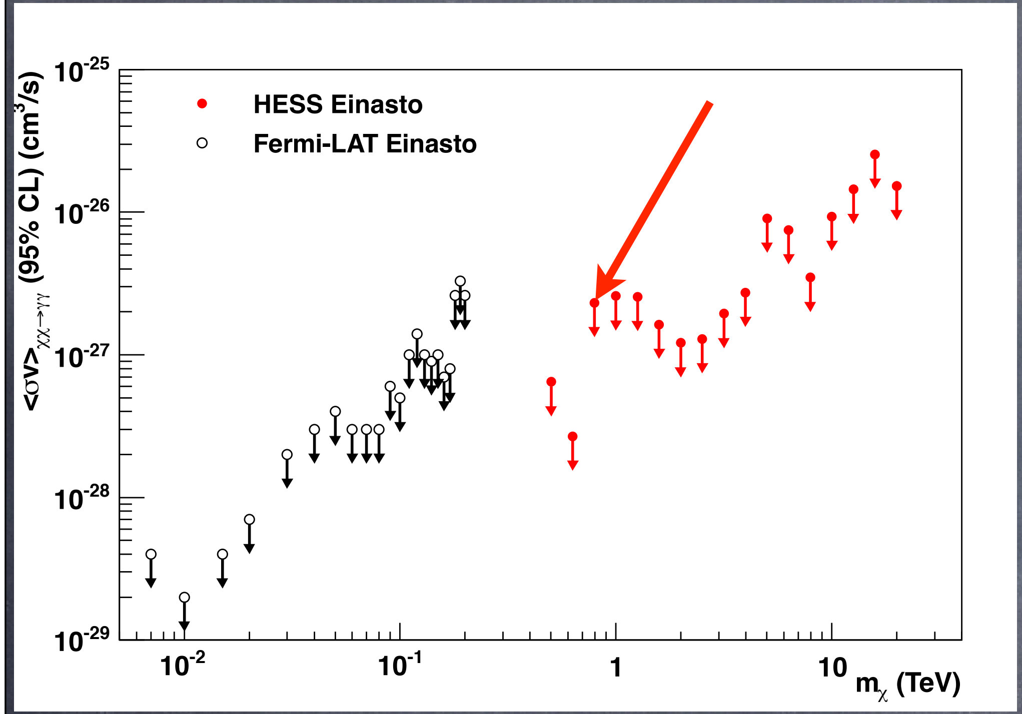
XENON100 [53] and LUX [55] limits are $\sim 10^{-44}\,\mathrm{cm}^2$ for $m_{\rm DM} = 0.7\,\mathrm{TeV}$

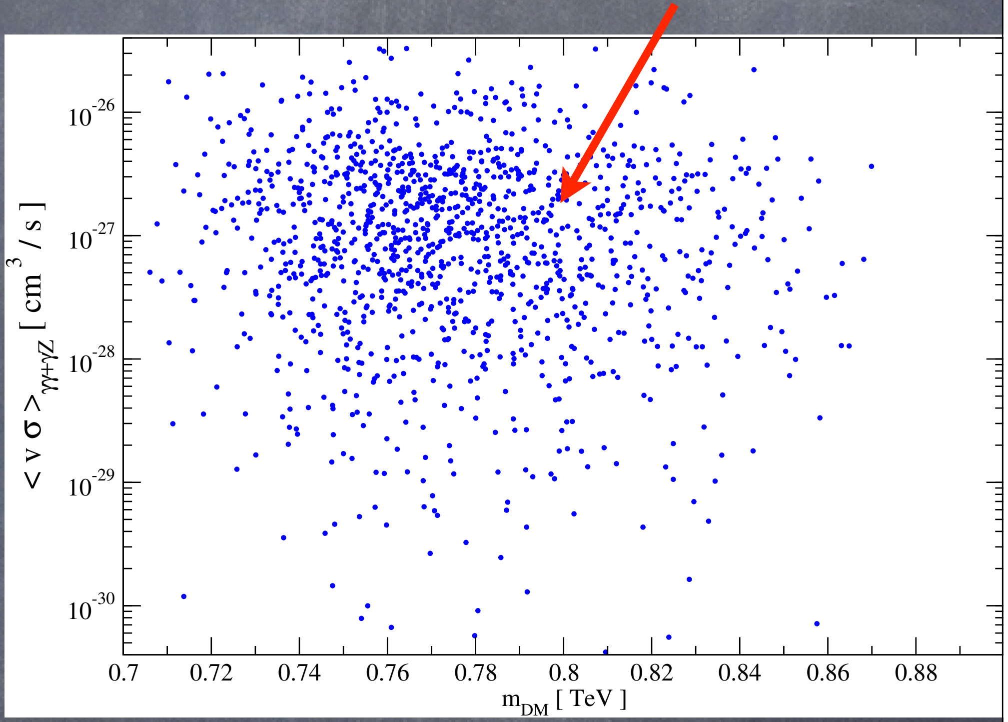


Monochromatic Gamma Ray Line
800 GeV from DM annihilation

$$\frac{d\Phi}{dE_\gamma} \propto \langle v\sigma\rangle_{\gamma\gamma+\gamma Z}\, \delta(E_\gamma - m_{\rm DM})$$

$m_{DM} > m_S$





Constraints from FermiLAT and HESS

Prediction with Q=1/3

Target for GAMMA400 and CTA

Phase Transitions (PT) at finite Temperature

Three order parameters:

$$< h > \ , \quad < S > \ , \quad < \sigma >$$

EWPT

Chiral PT

EW Baryogenesis

(Kuzmin+Rubakov+Shaposhnikov,`85;
Klinkhamer+Manton,`84;
....)

Gravitational wave BG

(Hogan,`83; Witten,`84;
....)

Conclusion

* **QCD-like hidden sector is an attractive scale invariant extension of the SM.**

- **Dark pions can be realistic CDM.**
- **For $m_S < m_{DM}$, the model can be tested soon.**
- **With $Q \neq 0$ the hidden sector is no longer dark:**
  Monochromatic gamma lines can be produced, and
  hidden hadron could be probed at collider experiments, opening hidden Hadron Physics.

THANK YOU VERY MUCH FOR YOUR ATTENTION.

NJL in the mean field approximation

NJL

QCD

		Ours	Hatsuda+Kunihiro, `94
NJL	$(2G)^{-1/2}$	326 MeV	330 MeV
	$(-G_D)^{-5}$	437 MeV	404 MeV
	Λ	924 MeV	631 MeV
	m_1	6.6 MeV	5.5 MeV
	m_3	127 MeV	136 MeV
Input	m_π	138 MeV	138 MeV
	f_π	93 MeV	93 MeV
	m_K	496 MeV	496 MeV
	$M_u = M_1$	337 MeV	335 MeV
	$M_s = M_3$	503 MeV	527 MeV
	$< \bar{\psi}_1 \psi_1 >^{NP}$	$-(250\ \ \mathrm{MeV})^3$	$-(245\ \ \mathrm{MeV})^3$
	$< \bar{\psi}_3 \psi_3 >^{NP}$	$-(221\ \ \mathrm{MeV})^3$	$-(226\ \ \mathrm{MeV})^3$

But gauge invariance is broken by cutoff!!

↓

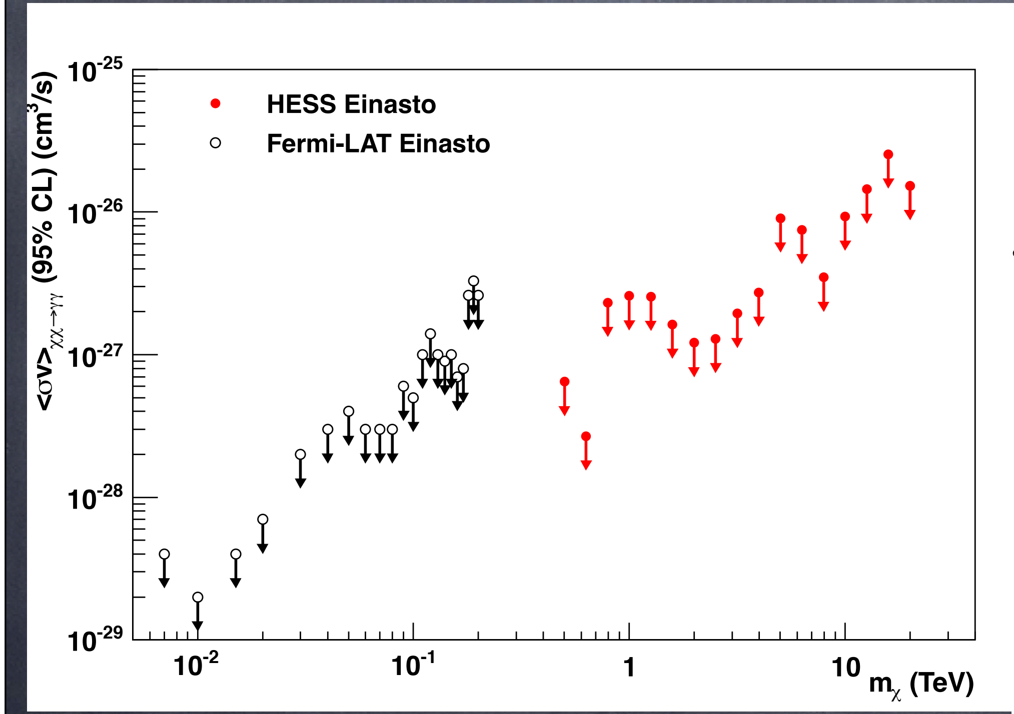
Least Subtraction Procedure
to restore Gauge Invariance

Kubo, Lee+Lindner, arXiv:1405.1052 ;

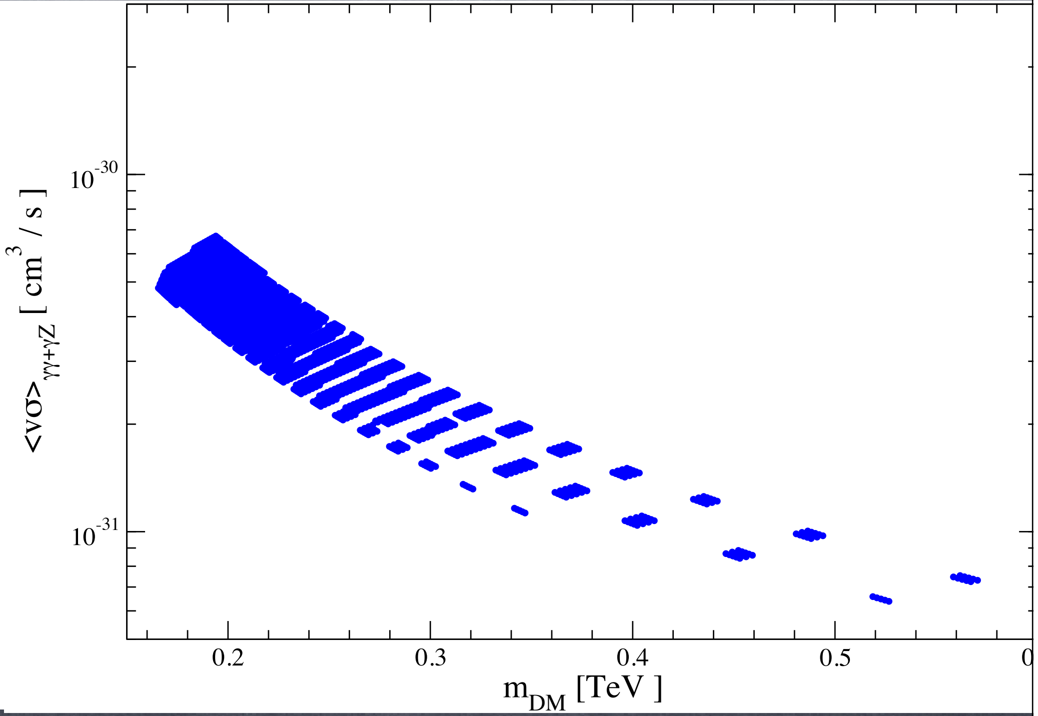
Subtraction to the minimum necessary.

$< v\sigma > (\mathrm{DMDM} \to \gamma\gamma)$ against m_{DM}

$m_{\mathrm{DM}} < m_S$



Constraints from FermiLAT and HESS



Prediction with Q=1/3