Scale Invariant Extension of the SM with QCD-like hidden sector and Composite Dark Matter

arXiv:1310.4423 to appear in JHEP.

on Dec. 20 at IPMU

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PLAN

I What have been the motivations to SUSY?

II Dark Technicolor model
- A scale invariant extension of the SM-

III The Nambu-Jona-Lasinio approach

IV The scale of the theory and the Higgs mass

V Dark Matter

VI Phase Transitions (PT) at finite Temperature

Conclusion

What have ebeen the motivations to SUSY

1. Maximal extension of the Poincare algebra.

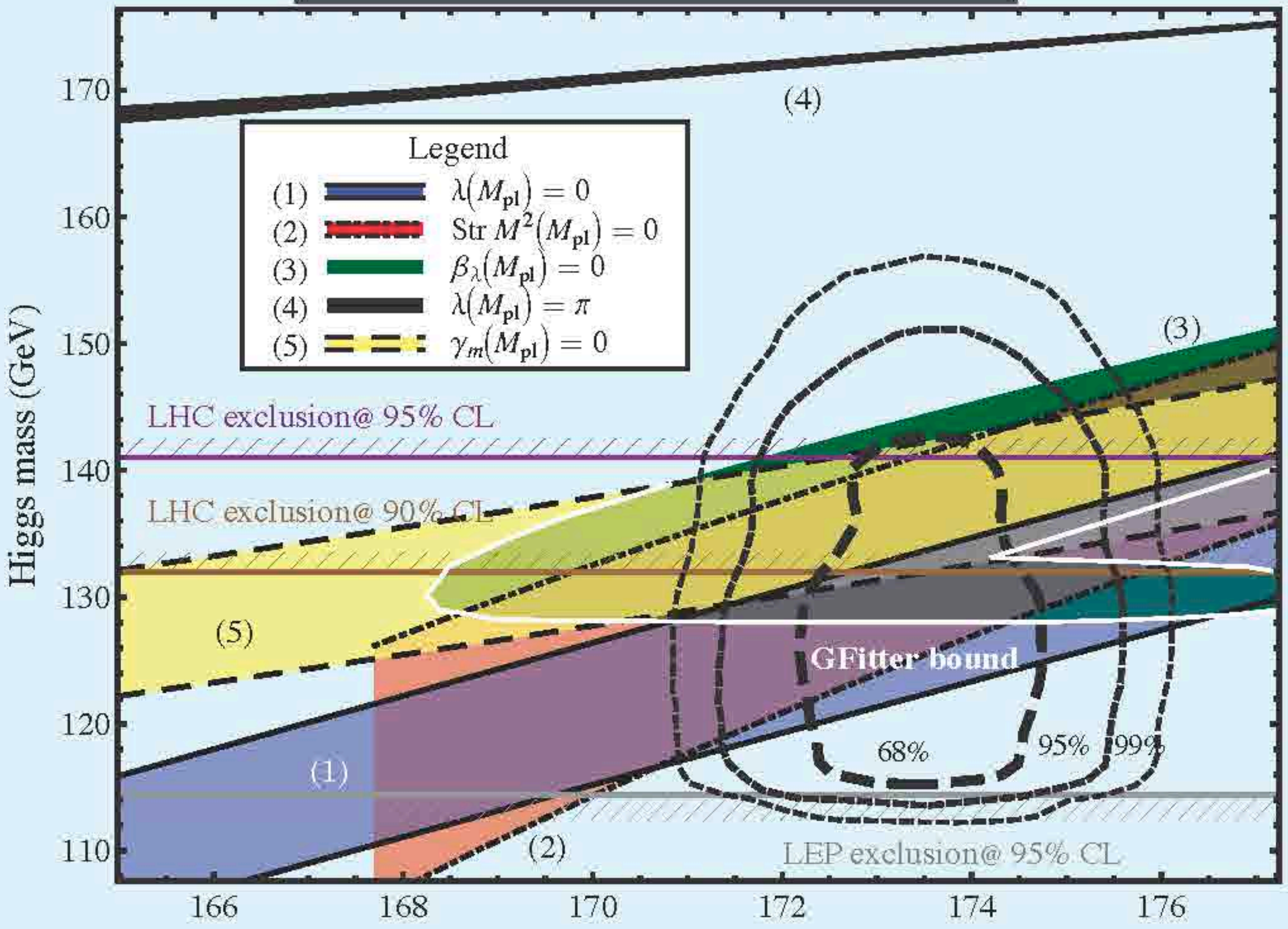
2. $\lambda_H \propto g^2$ so that λ_H does not blow up at high energy.

3. No quadratic divergence so that the fine tuning problem is softened.

4. Dark matter.

....

To 2 ($\lambda_H \propto g^2$):



$\lambda_H \propto g^2$ **is not needed!**

(Holthausen+Lee+Lindner`2012. See also Berzukov et al, 2012 and Haba,kaneta+Takahashi, 2013)

To 3 (No quadratic divergence):

$$m^2 \simeq m_0^2 - \Lambda^2/16\pi^2$$

What is actually Λ ?

Heavy particle mass of beyond the SM

M_H

or

Regulator mass Λ_{cut}

The regulator mass explicitly break the scale invariance, but does not appear in the trace of the energy momentum tensor.

(e.g. Adler+Collins+Duncan,`77, see also Meissner+Nicolai,`2009; Heikinheimo et al, 2013))

$$\Theta^{\mu}{}_{\mu} = \beta_i \ \mathcal{O}_i + M^2_{H_j} \ \mathcal{X}_j + \cancel{\Lambda^2_{\text{cut}}} \ \mathcal{Y}$$

$$\textbf{dim.}[\mathcal{O}] = 4 \ , \ \textbf{dim.}[\mathcal{X}] = 2$$

Or equivalently, anomalous WT identity (Callan-Symazik eq.)

$$\left(p_k \cdot \frac{\partial}{\partial p_k} - \beta_i \frac{\partial}{\partial g_i} + n(1+\gamma) - 4 \right) \Gamma(p_k^2, M_H^2, g_i) \propto M_H^2 \ \Gamma_{M_H^2}(p_k^2, M_H^2, g_i)$$

2 can be realized without susy.

3 can be realized without susy, if there is no large intermediate scale physics between the SM and the Planck scale.

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

Then, who orders the tinny SM scale?

A. Planck scale physics is responsible,

OR (e.g.Shaposhnikov+Wetterich,`2010)

B. ZERO at the Planck scale,
the low energy physics is responsible.

(e.g.Meissner+Nicolai,`2009;
Heikinheimo et al, 2013)

If B, how to generate the SM scale?

*Perurbatively a la Coleman-Weinberg
(Hempfling,`96;......)

*Non-Perurbatively
e.g. Dynamical Chiral Symmetry Breaking
(Technicolor, ...)

II Dark Technicolor model

(Hur, Jung, KO+Lee,arXiv:0709.1218+1103.2571; Heikinheimo,arXiv:1304.7006`76)

$$\mathcal{L}_{\rm H} = -\frac{1}{2}{\rm Tr}\ F^2 + {\rm Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

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

No dimensional parameters

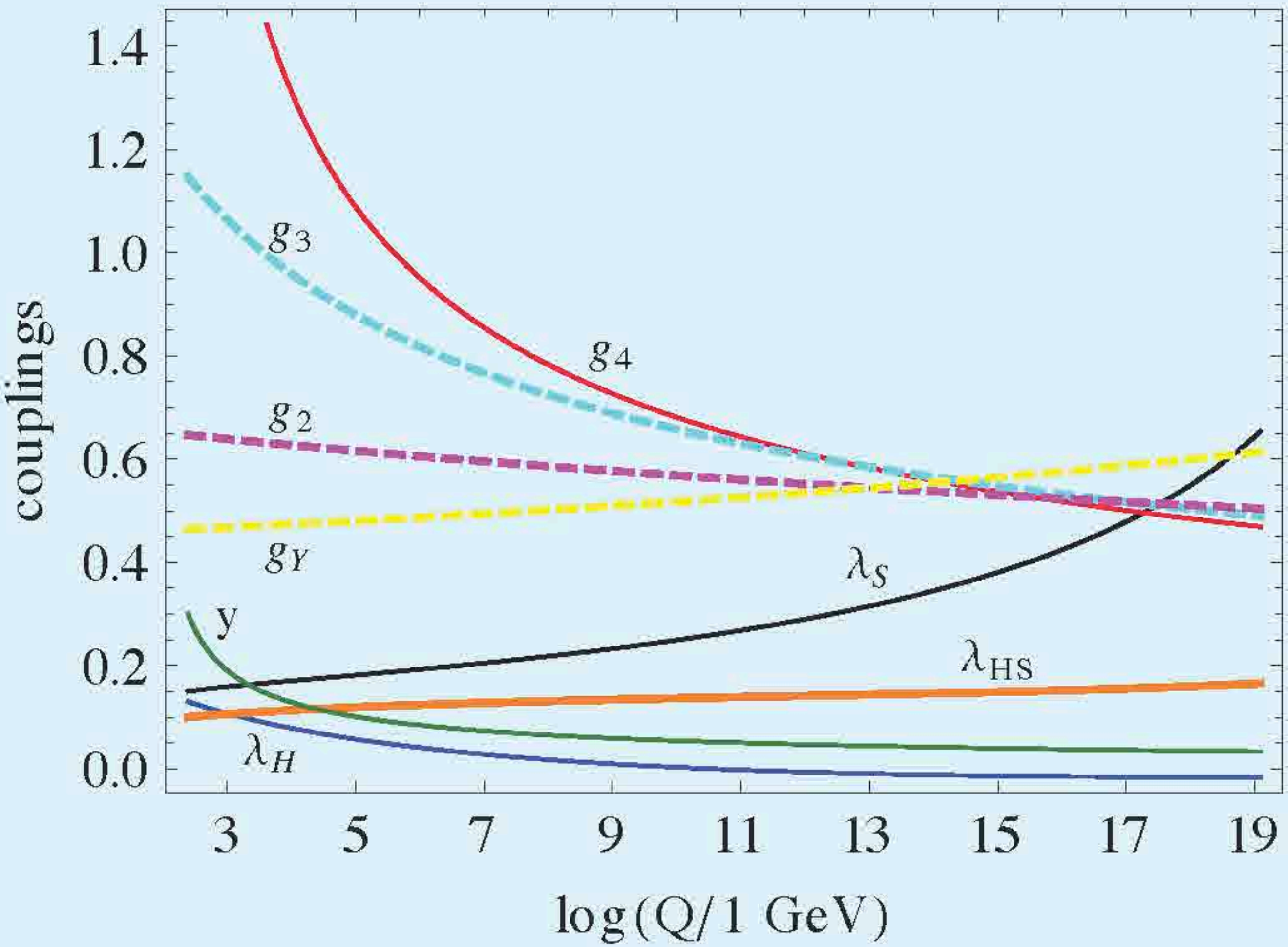
▼

Classically scale invariant

▼

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

Running of couplings



$$\mathcal{L}_{\rm H} = -\frac{1}{2}{\rm Tr}\ F^2 + {\rm Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

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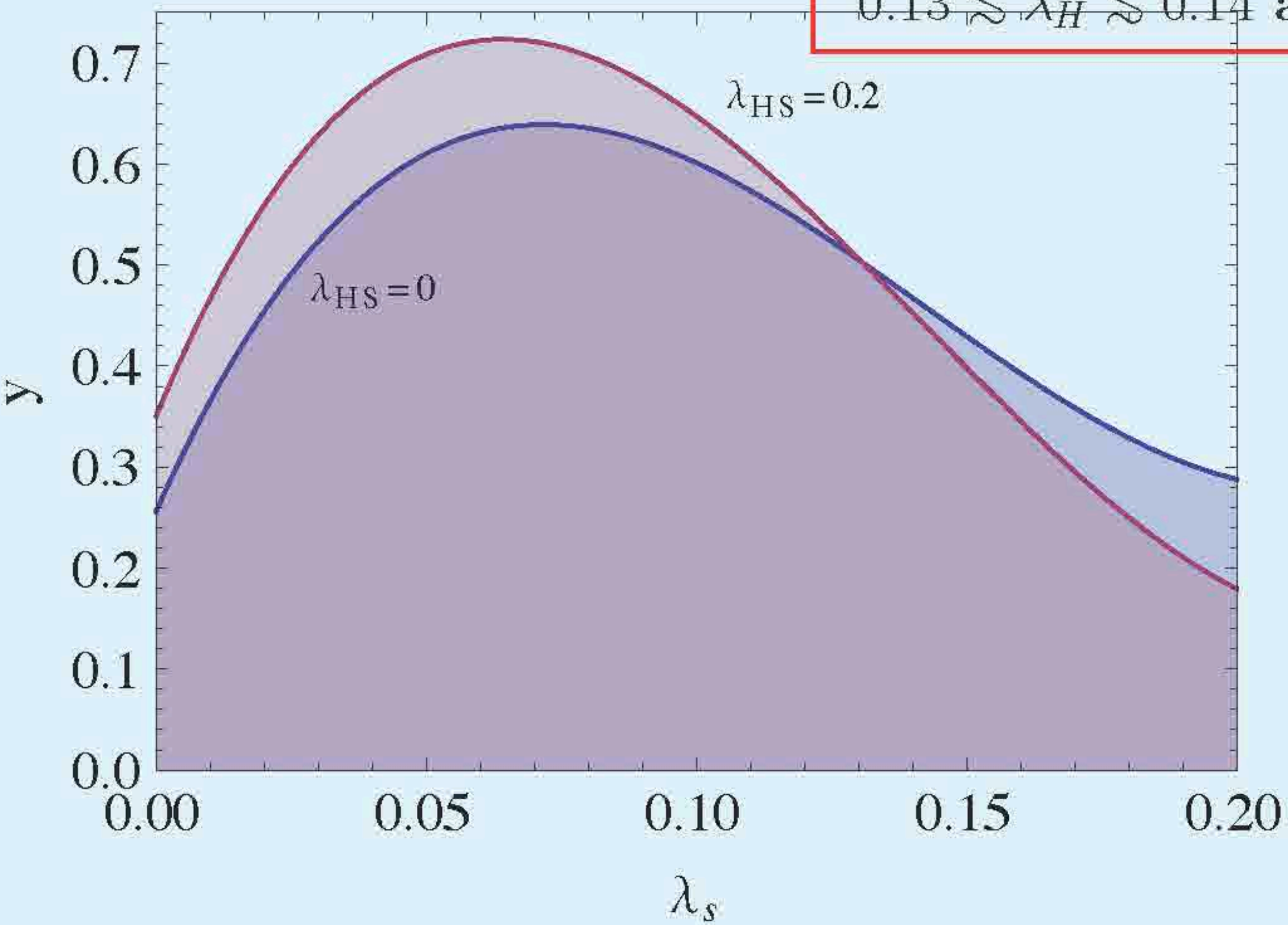
Landau pole constraint

$$\alpha_h = g_h^2/4\pi \lesssim 1 \textbf{ at } 1 \textbf{ TeV}$$

$$0.13 \lesssim \lambda_H \lesssim 0.14 \textbf{ at } 1 \textbf{ TeV}$$



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

At low energy:

Dynamical Chiral Symmetry Breaking in the hidden sector (Dχ~~Sym~~metry)

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

The NJL model can describe the basic feature of

χ Symmetry breaking in QCD.

DχSy~~m~~metry: $\boxed{SU(3)_L \times SU(3)_R \rightarrow SU(3)_V}$

generating the mass for the fermions and hence a mass scale from ZERO.

The important relations such as the Goldberger-Treiman and Gell-Mann-Oakes-Renner relations are satisfied.

4-fermi 6-fermi

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

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

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

The same global symmetry

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

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

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

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

III NJL in the mean field approximation

(For a review: Hatsuda+Kunihiro, PR.`94)

1. Go from the conventional vacuum $|0\rangle$ to the "BCS" vacuum $|\text{"BCS"}\rangle = |\sigma, \pi, K, \cdots\rangle$, where $\sigma, \pi, K, \cdots$ are identified with $\langle\text{"BCS"}|\ \mathrm{Tr}\ \overline{\psi}\lambda^a(1, \gamma_5, \cdots)\psi\ |\text{"BCS"}\rangle$.
   This is the definition as well as the self-consistency condition.

2. Express $\mathcal{L}_{NJL} = \mathcal{L}_0 + \mathcal{L}_I$, where

   (a) $\mathcal{L}_I$ is normal-ordered with respect to $|\text{"BCS"}\rangle$, i.e. $\langle\text{"BCS"}|\ \mathcal{L}_I |\ \text{"BCS"}\rangle = 0$.

   (b) $\mathcal{L}_0$ is at most quadratic in fermions, where the ferimon bilinears are NOT normal-ordered.

3. Compute diagrams with external mean fields (mesons) to predict the meson properties by integrating out the fermions. But at the lowest order of the approximation, $\mathcal{L}_I$ does not contribute.

$$\mathcal{L}_0 = \mathrm{Tr}\bar{\psi}(i\gamma^\mu\partial_\mu - yS)\psi + 2G\mathrm{Tr}(\varphi^\dagger\Phi + h.c) - 2G\mathrm{Tr}\varphi^\dagger\varphi - 2G_D(\det\varphi + h.c.)$$
$$+ G_D\left(\mathrm{Tr}\varphi^2\Phi - \mathrm{Tr}\varphi\Phi\ \mathrm{Tr}\varphi - \frac{1}{2}\mathrm{Tr}\varphi^2\mathrm{Tr}\Phi + \frac{1}{2}\mathrm{Tr}\varphi^2\mathrm{Tr}\Phi + h.c.\right)\ ,$$

$$\mathcal{L}_I = 2G : \mathrm{Tr}\Phi^\dagger\Phi : + G_D : (\det\Phi + h.c) :$$
$$+ G_D : \left(\mathrm{Tr}\varphi\Phi^2 - \mathrm{Tr}\varphi\Phi\ \mathrm{Tr}\Phi - \frac{1}{2}\mathrm{Tr}\Phi^2\mathrm{Tr}\varphi + \frac{1}{2}\mathrm{Tr}\Phi^2\mathrm{Tr}\varphi + h.c.\right) :$$

where

$$\varphi = \langle\text{“}\mathbf{BCS}\text{”}|\Phi|\text{“}\mathbf{BCS}\text{”}\rangle = -\frac{1}{4G}\left(\mathbf{diag}(\sigma,\sigma,\sigma) + i(\lambda^a)^T\phi_a\right)$$
$$\Phi_{ij} = \bar{\psi}_i(1-\gamma_5)\psi_j$$

Finally

$$
\begin{aligned}
\mathcal{L}_0 = {} & i\ \mathrm{Tr}\bar{\psi}\gamma^\mu\partial_\mu\psi - \left(\sigma + yS - \frac{G_D}{8G^2}\sigma^2\right)\mathrm{Tr}\bar{\psi}\psi \\
& + \frac{G_D}{8G^2}\left(-(2/3)\eta_0^2\ \mathrm{Tr}\bar{\psi}\psi - \mathrm{Tr}\bar{\psi}\phi^2\psi + \sum_{a=1}^{8}\phi_a\phi_a\mathrm{Tr}\bar{\psi}\psi + \sqrt{2/3}\eta_0\mathrm{Tr}\bar{\psi}\phi\psi\right) \\
& - i(\sqrt{2/3})\bar{\psi}\gamma_5\eta_0\psi - i\mathrm{Tr}\bar{\psi}\gamma_5\phi\psi + \frac{G_D}{8G^2}\left(-i2\sqrt{2/3}\sigma\eta_0\ \mathrm{Tr}\bar{\psi}\gamma_5\psi + i\sigma\ \mathrm{Tr}\bar{\psi}\gamma_5\phi\psi\right) \\
& - \frac{1}{8G}\left(3\sigma^2 + 2\eta_0\eta_0 + 2\sum_{a=1}^{8}\phi_a\phi_a\right) + \frac{G_D}{16G^3}\left(\sigma^3 + \sigma\sum_{a=1}^{8}(\phi_a)^2 - 2\sigma\ (\eta_0)^2\right),
\end{aligned}
$$

where $\eta_0 = \phi_0$.

NJL
QCD

	Ours	Hatsuda+Kunihiro, `94
$(2G)^{-1/2}$	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
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
$< \bar{\psi}_1 \psi_1 >^{NP}$	$-(250\ \ \mathrm{MeV})^3$	$-(245\ \ \mathrm{MeV})^3$
$< \bar{\psi}_3 \psi_3 >^{NP}$	$-(221\ \ \mathrm{MeV})^3$	$-(226\ \ \mathrm{MeV})^3$

NJL: $(2G)^{-1/2}$, $(-G_D)^{-5}$, Λ

Input: m_π, f_π, m_K

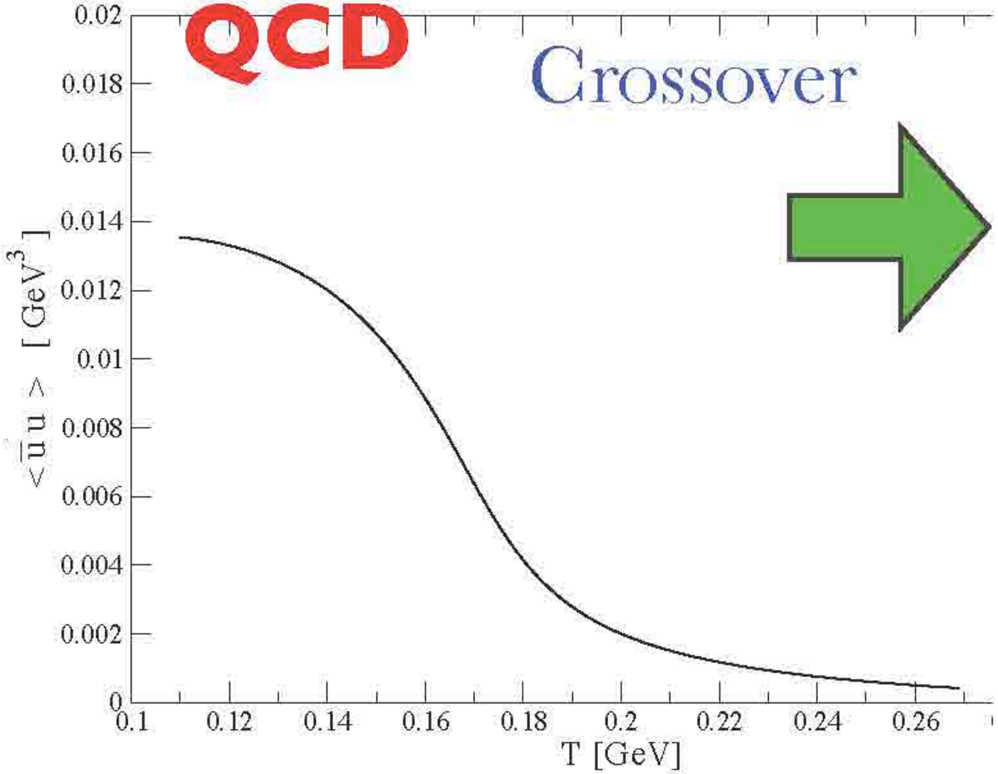
NJL
QCD

Hatsuda+Kunihiro, '94

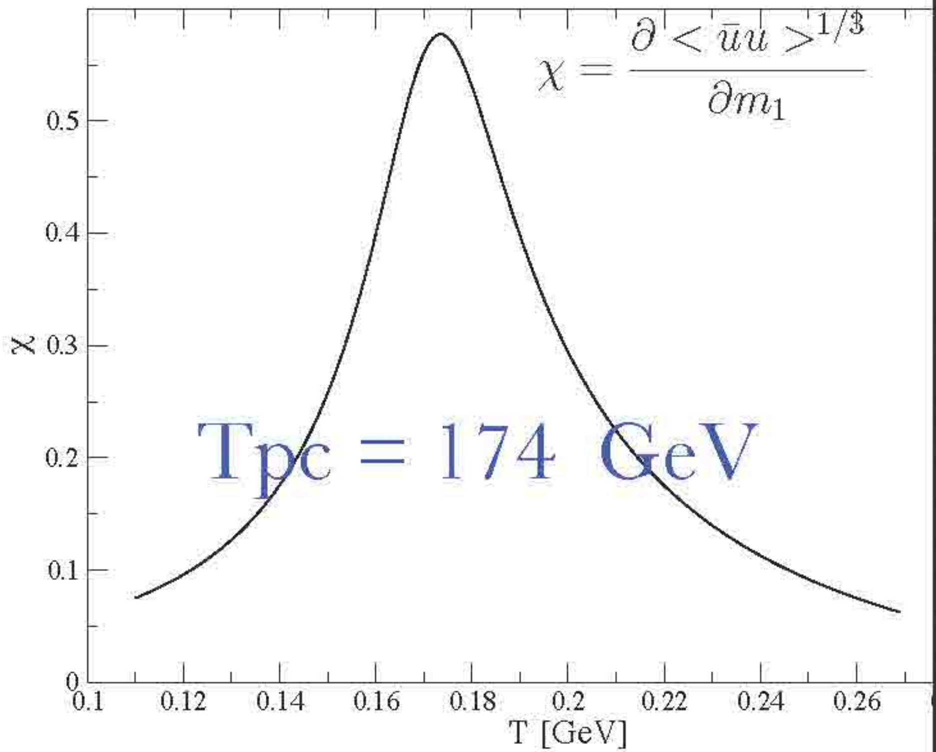
Table 3.2
Comparison of the theoretical estimates and the experimental/empirical values of the basic physical quantiti
the quantity used as input.

	Theory	Experimental/empirical va
M_u (M_s)	335 (527)	336 (540) MeV
$\langle \bar{u}u \rangle^{NP}$	$-(245)^3$	$-(225 \pm 25)^3$ MeV^3
$\langle \bar{s}s \rangle^{NP} / \langle \bar{u}u \rangle^{NP}$	0.78	0.8 ± 0.1
m_π (m_K)	138* (496*)	138 (496) MeV
m_η ($m_{\eta'}$)	487 (958*)	549 (958) MeV
m_σ ($m_{\sigma'}$)	668 (1348)	$\sim$ 700 ($\sim$ 1400) MeV
$\Gamma_{\sigma \to 2\pi}$	$\sim$ 900	$\sim$Re m_σ
f_π (f_K)	93.0* (97.7)	93 (113) MeV
f_η ($f_{\eta'}$)	94.3 (90.8)	93±9 (83±7) MeV
θ_η (φ_σ)	$-21°$ ($-6.8°$)	$\sim -20°$ (–)
$G_{\pi q}$ (G_{Kq})	3.5 (3.6)	$\sim$ 3.5 (–)
$G_{\pi N}$ ($G_{\sigma N}$)	12.7 (7–10)	13.4 ($\sim$10.0)

NJL
QCD

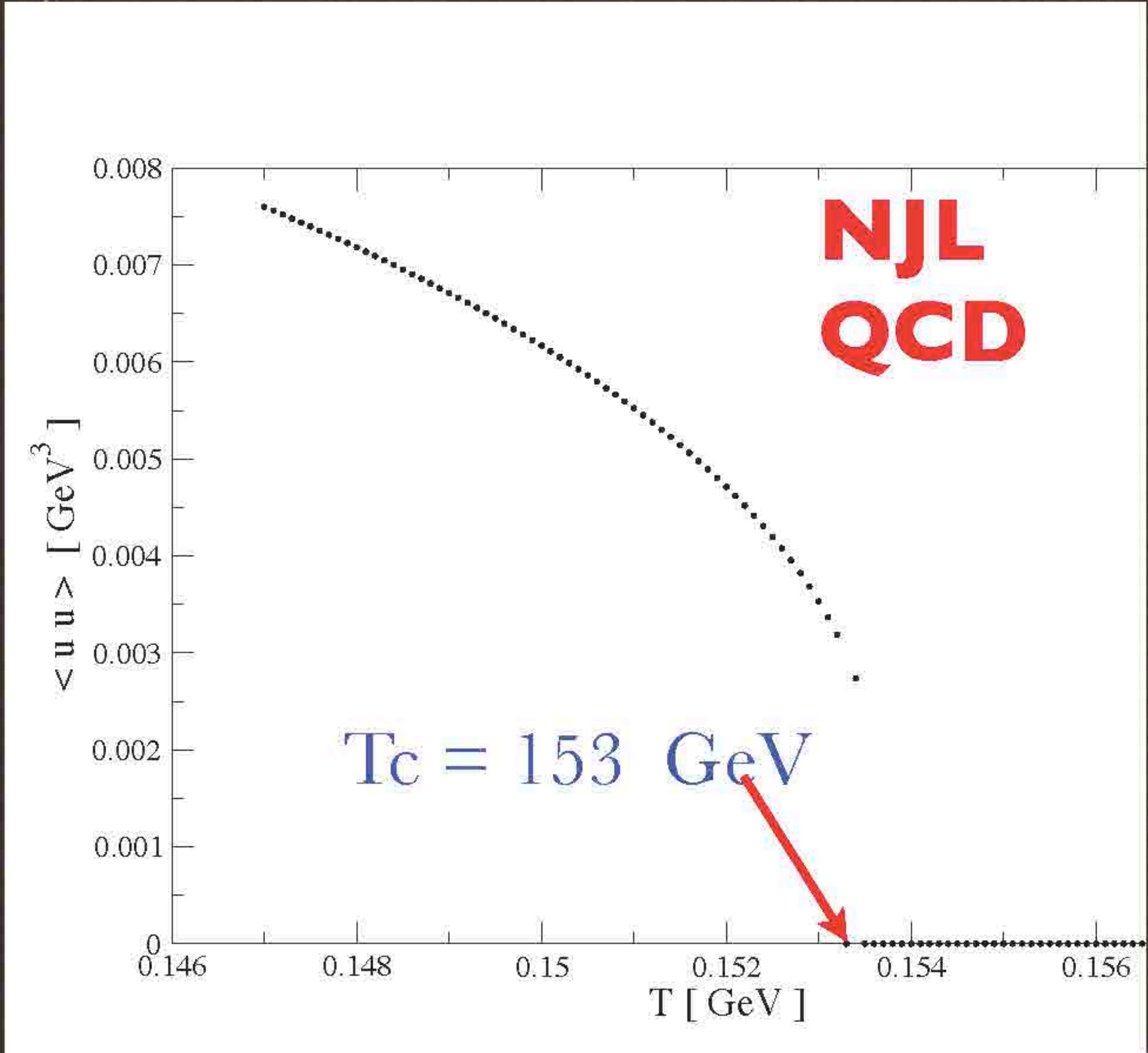


Susceptibility



$\boxed{T_{pc} \simeq 0.164 \text{ GeV}}$ **(LQCD and TWQCD, 2011)**

First order phase transition for $m_u = m_d = m_s = 0$



$\boxed{T_c \simeq 0.154 \text{ GeV}}$ **(LQCD and TWQCD, 2011)**

The parameters of the hidden sector of NJL

Assume that the QCD NJL parameters, up to the 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.

IV The scale of the theory and the Higgs mass

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

current fermion loop with

$$M = \sigma + yS - \frac{G_D}{8G^2}\sigma^2$$

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

$$<h> = 246 \;\mathbf{GeV} \Longrightarrow \Lambda$$

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

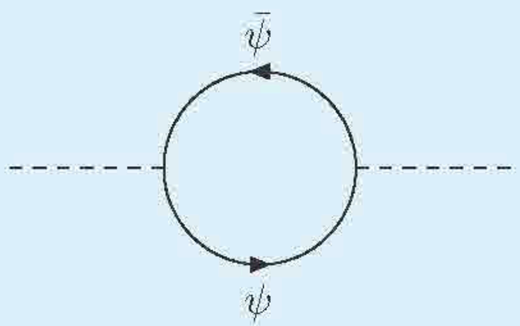
$\lambda_{HS} = 0.01$, $\lambda_S = 0.19$

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

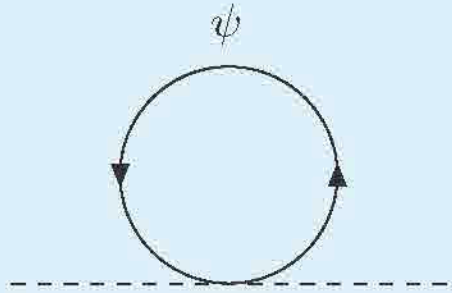
The Higgs mass can be obtained by solving the mixing among

$$h\ ,\ S \text{ and } \sigma$$

at fermion one-loop:



and



$$\begin{pmatrix} h \\ S \\ \sigma \end{pmatrix} = \begin{pmatrix} \xi_1^{(1)} & \xi_1^{(2)} & \xi_1^{(3)} \\ \xi_2^{(1)} & \xi_2^{(2)} & \xi_2^{(3)} \\ \xi_3^{(1)} & \xi_3^{(2)} & \xi_3^{(3)} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

$$\tilde{m}_1 = m_h = 125.4\,\mathrm{GeV},$$
$$\tilde{m}_2 = m_S = 946.4\,\mathrm{GeV},$$
$$\tilde{m}_3 = m_\sigma = 6833\,\mathrm{GeV},$$

for $y = 0.0052\ , \lambda_H = 0.13\ ,\ \lambda_{HS} = 0.01\ ,\ \lambda_S = 0.19\ .$

$$m_h = 126\ \mathbf{GeV}$$

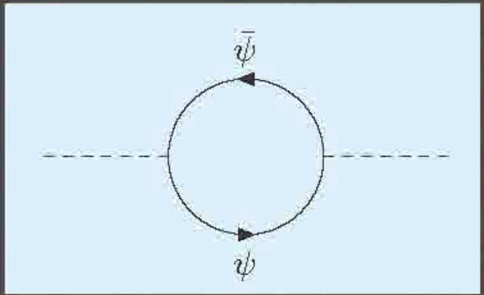
Only three of $y\ ,\ \lambda_H\ ,\ \lambda_{HS}\ ,\ \lambda_S$ **are independent.**

∨ Dark Matter

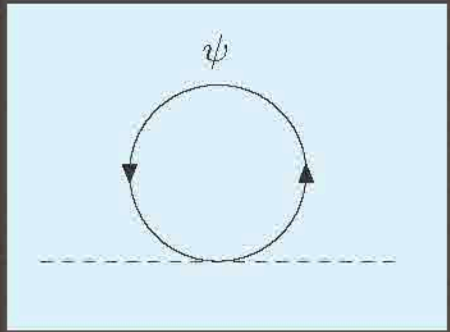
Because of $SU(3)_V$ the hidden pions are stable and hence can be dark matter.

Global symmetry: $SU(3)_V \times U(1)_V \times Z_3$

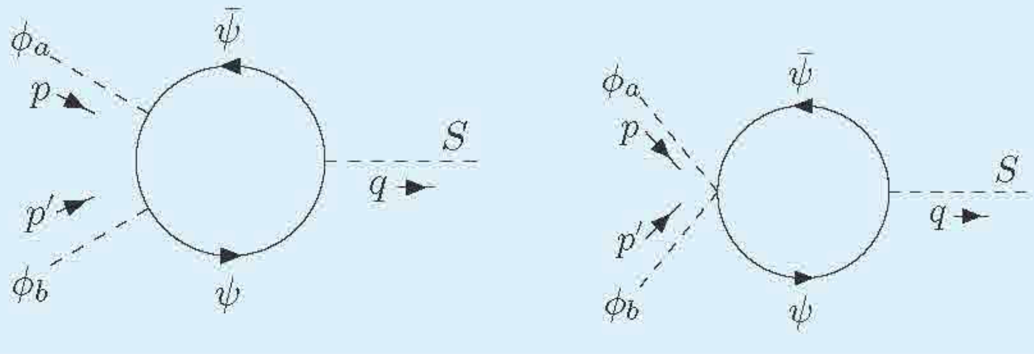
*Dark Matter mass



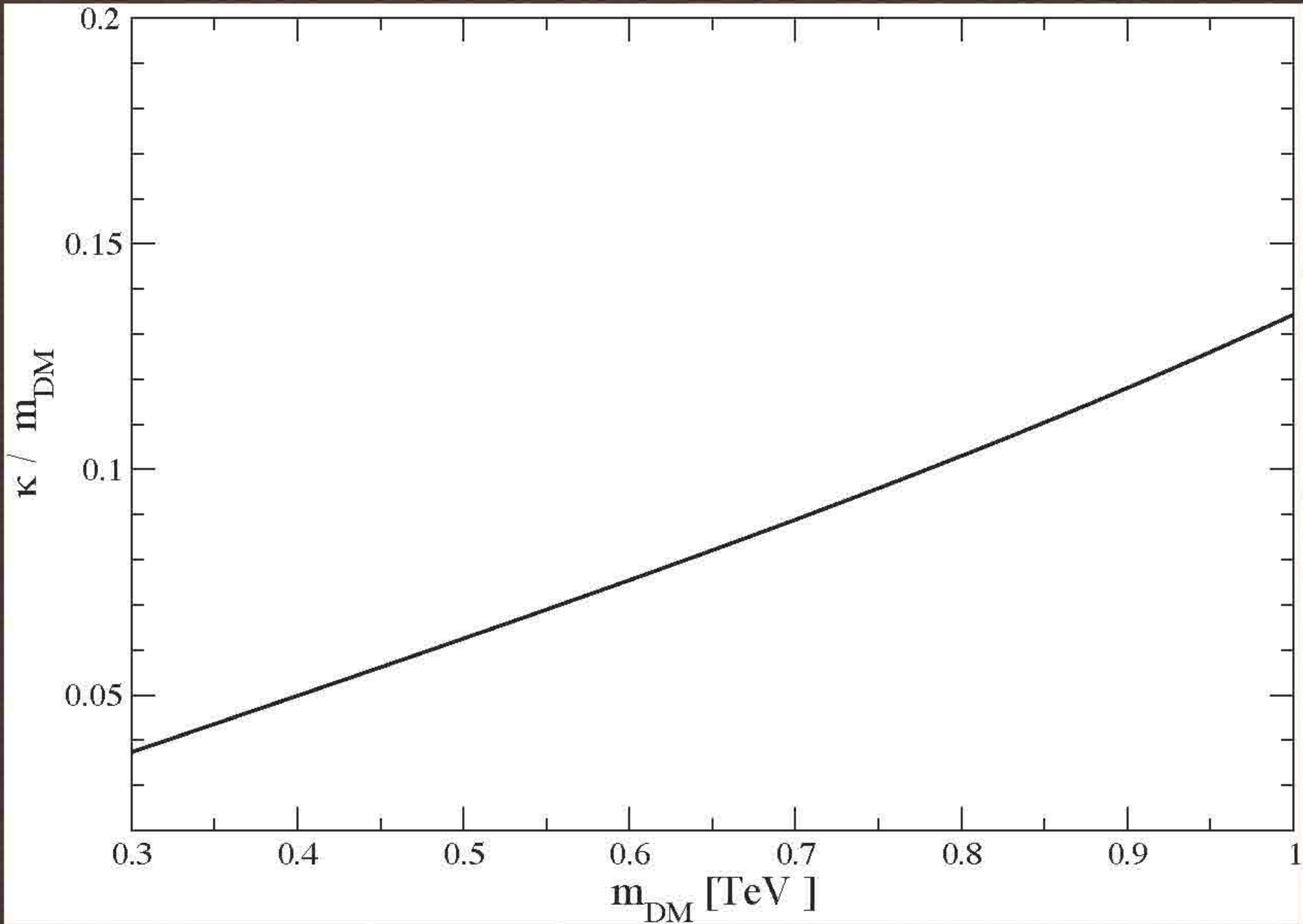
and



*Dark Matter coupling to the singlet S

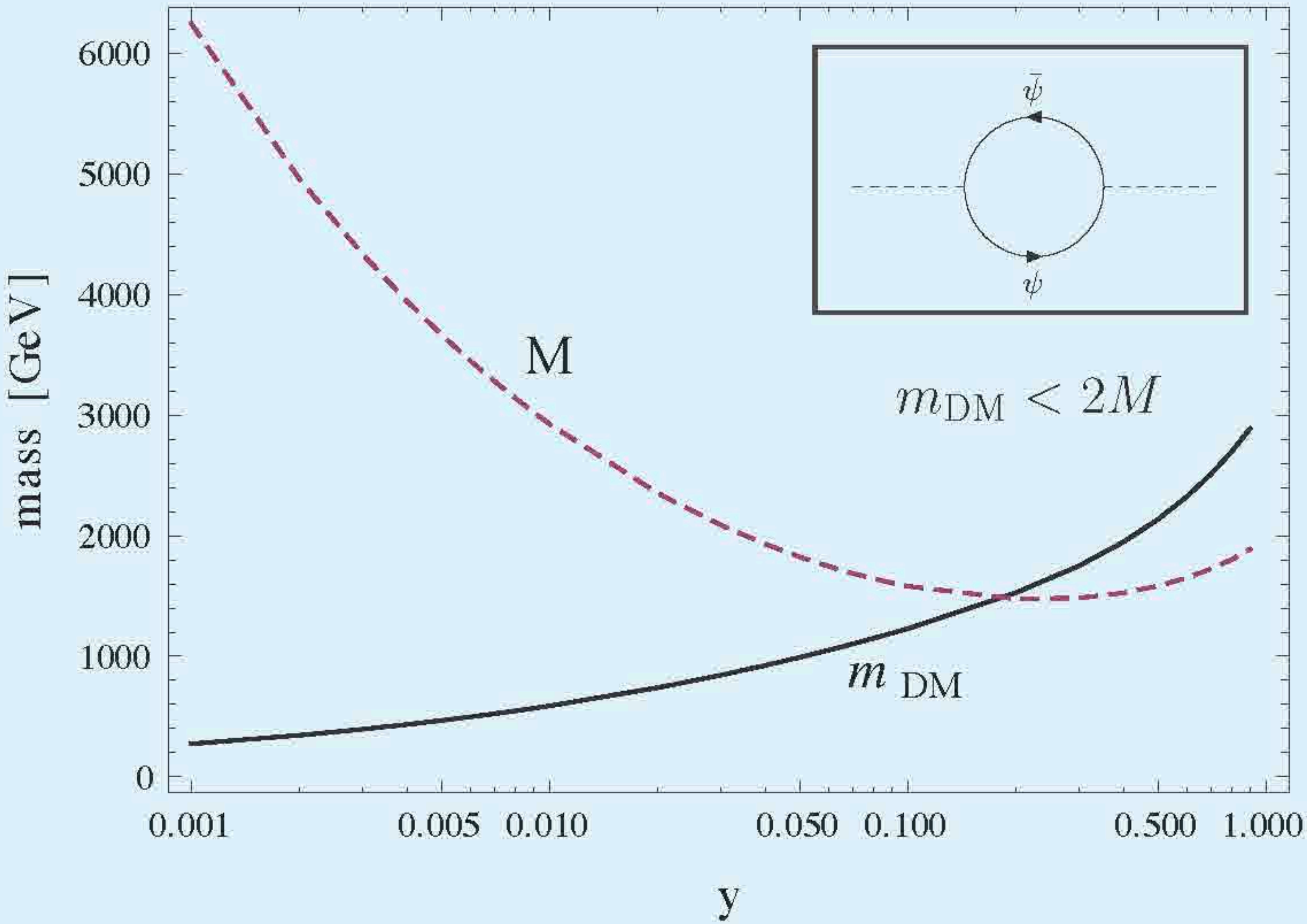


$$= \kappa \sim 2.4\ \mathrm{GeV}$$

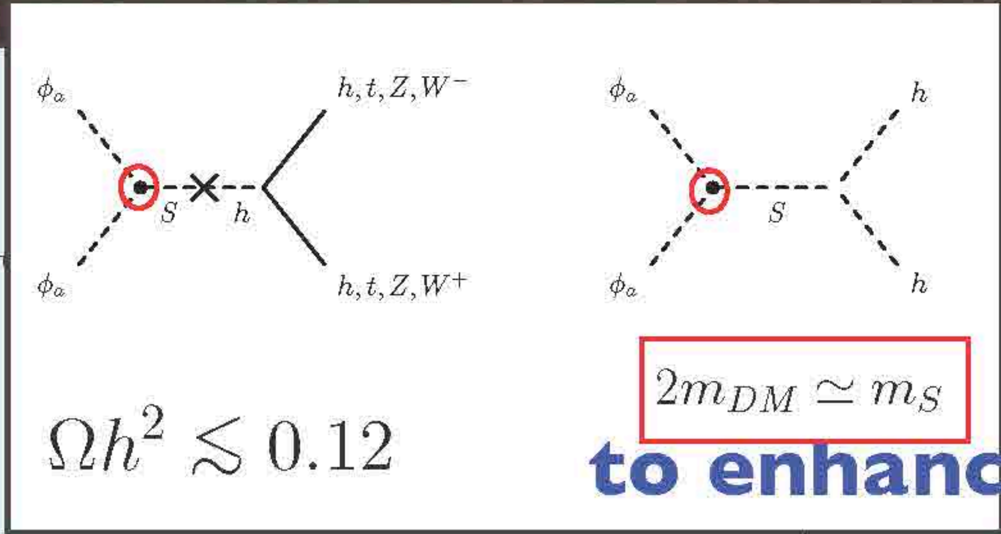

0.2
0.15
0.1
0.05
κ / m_DM
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m_DM [TeV]

Dark Matter and constituent fermion mass

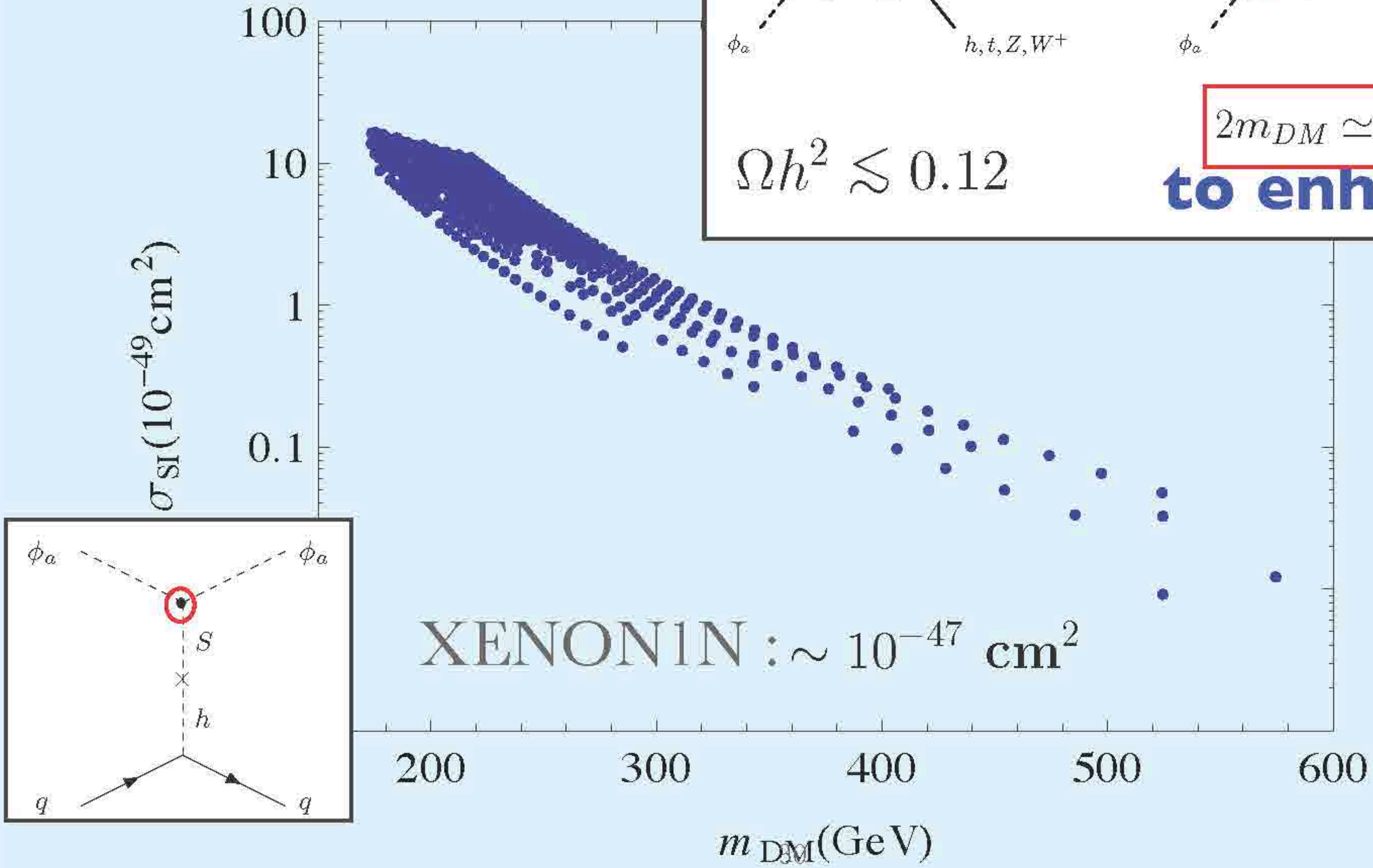
for $\lambda_H = 0.13\ ,\ \lambda_{HS} = 0.01\ ,\ \lambda_S = 0.19$

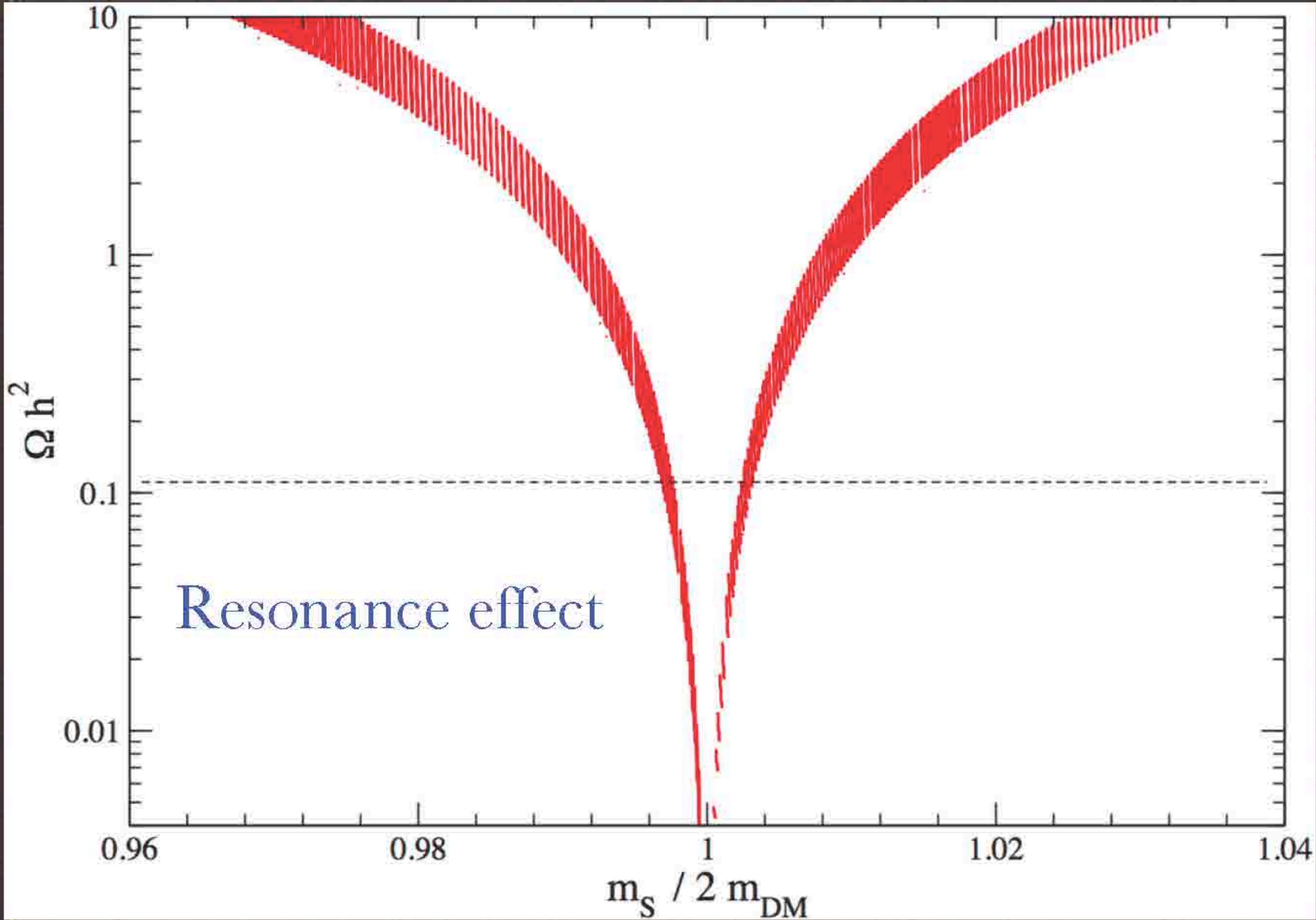


Direct detection and relic abundance



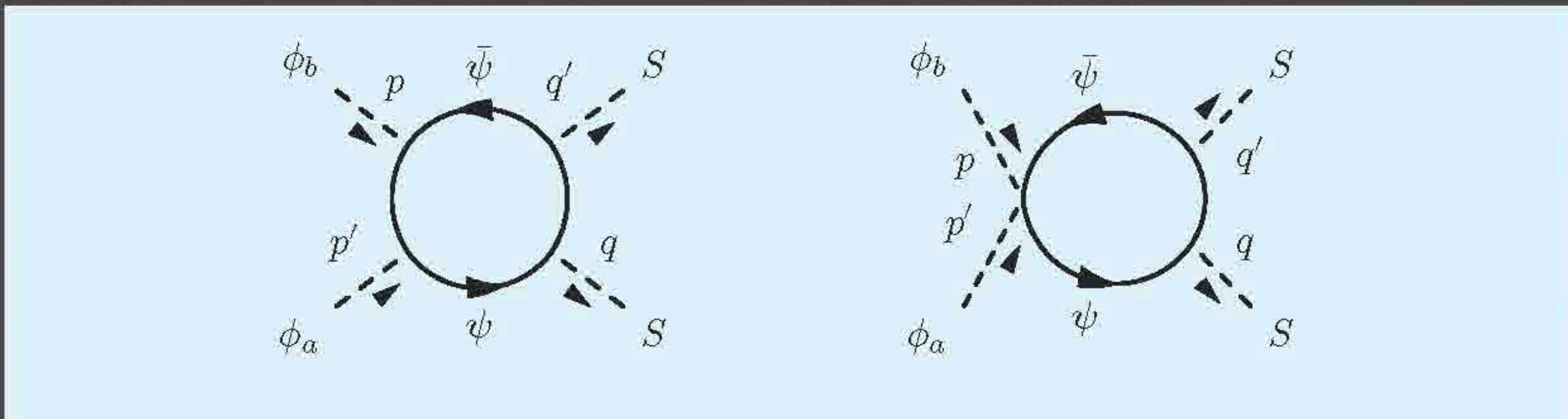
to enhance.



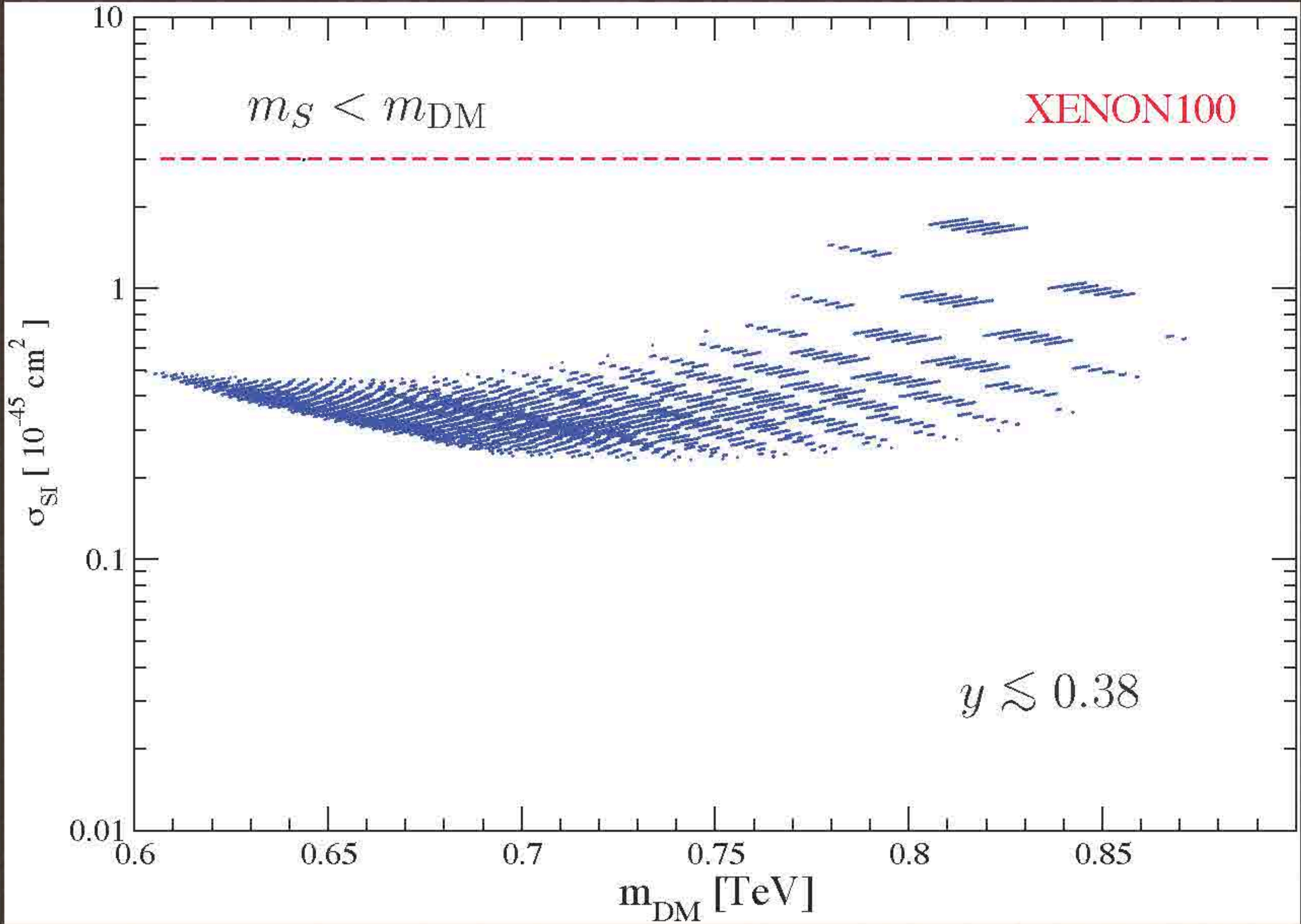


Resonance effect
10
1
0.1
0.01
0.96
0.98
1
1.02
1.04
Ωh^2
$m_S / 2 m_{DM}$

*If the singlet S is lighter than Dark Matter,



A large Yukawa y means a heavy DM.

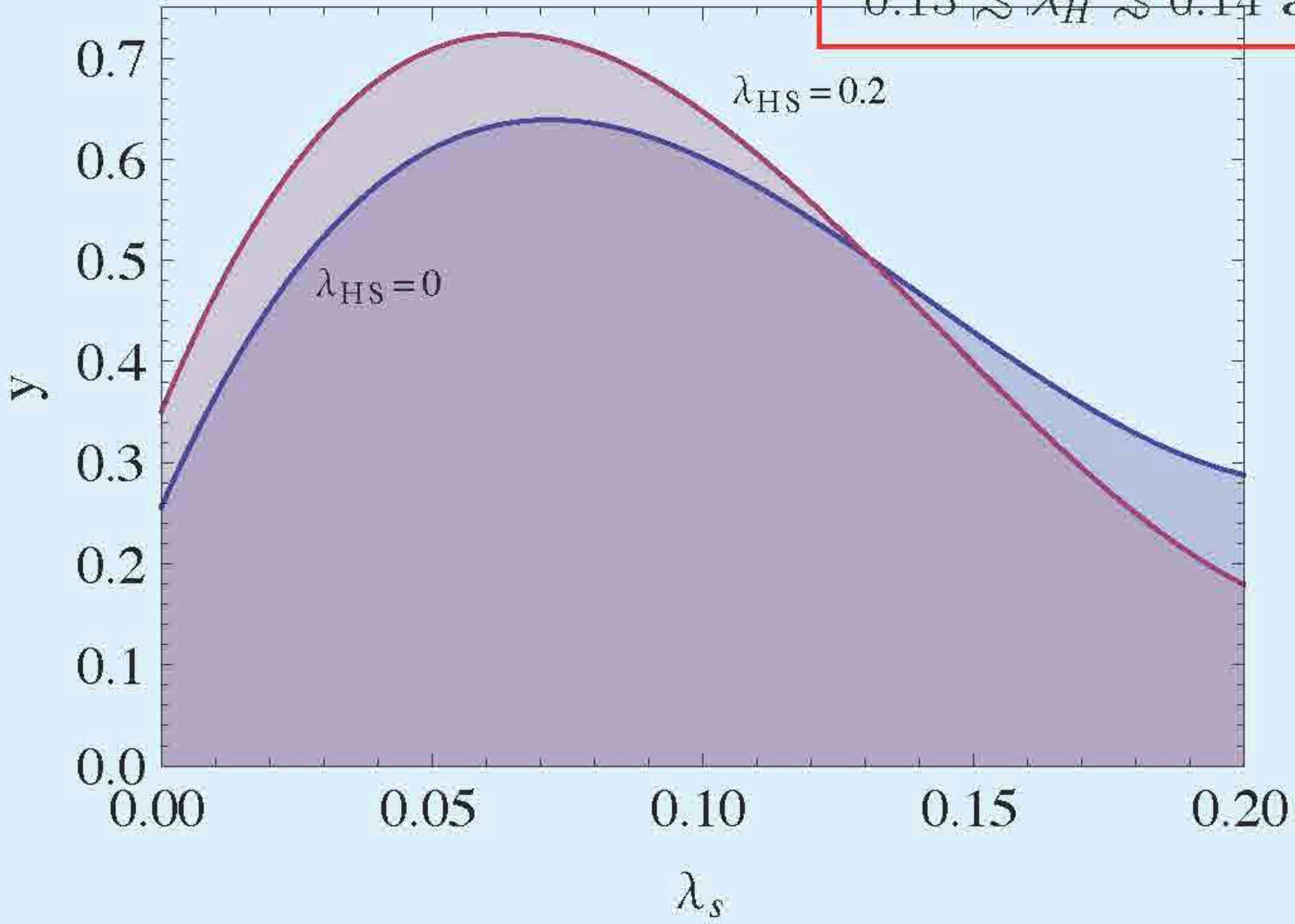


$m_S < m_{\rm DM}$
XENON100
$y \lesssim 0.38$
$\sigma_{\rm SI}$ [10^{-45} cm^2]
$m_{\rm DM}$ [TeV]
10
1
0.1
0.01
0.6
0.65
0.7
0.75
0.8
0.85

Landau pole constraint

$\alpha_h = g_h^2/4\pi \lesssim 1$ **at** 1 **TeV**

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



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

VI Phase Transitions (PT) at finite Temperature

Three order parameters:

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

EWPT $\rightarrow < h >$

Chiral PT $\rightarrow < \sigma >$

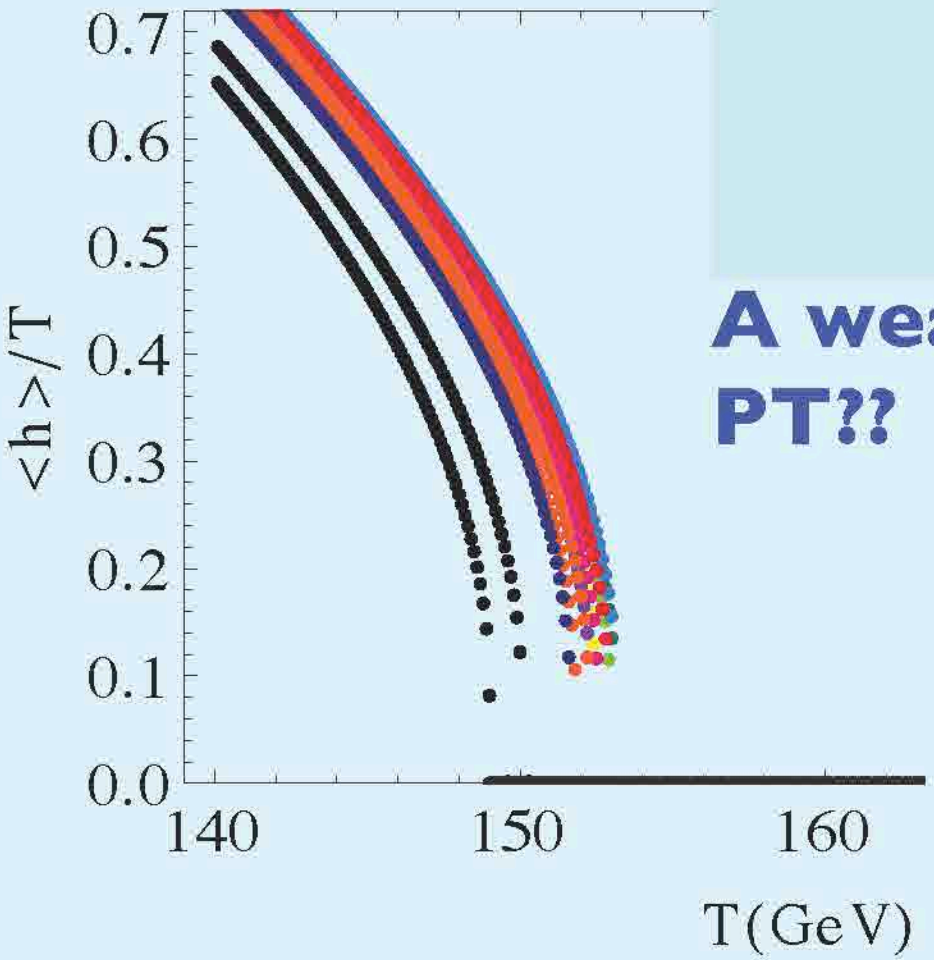
EW Baryogenesis

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

Gravitational wave BG

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

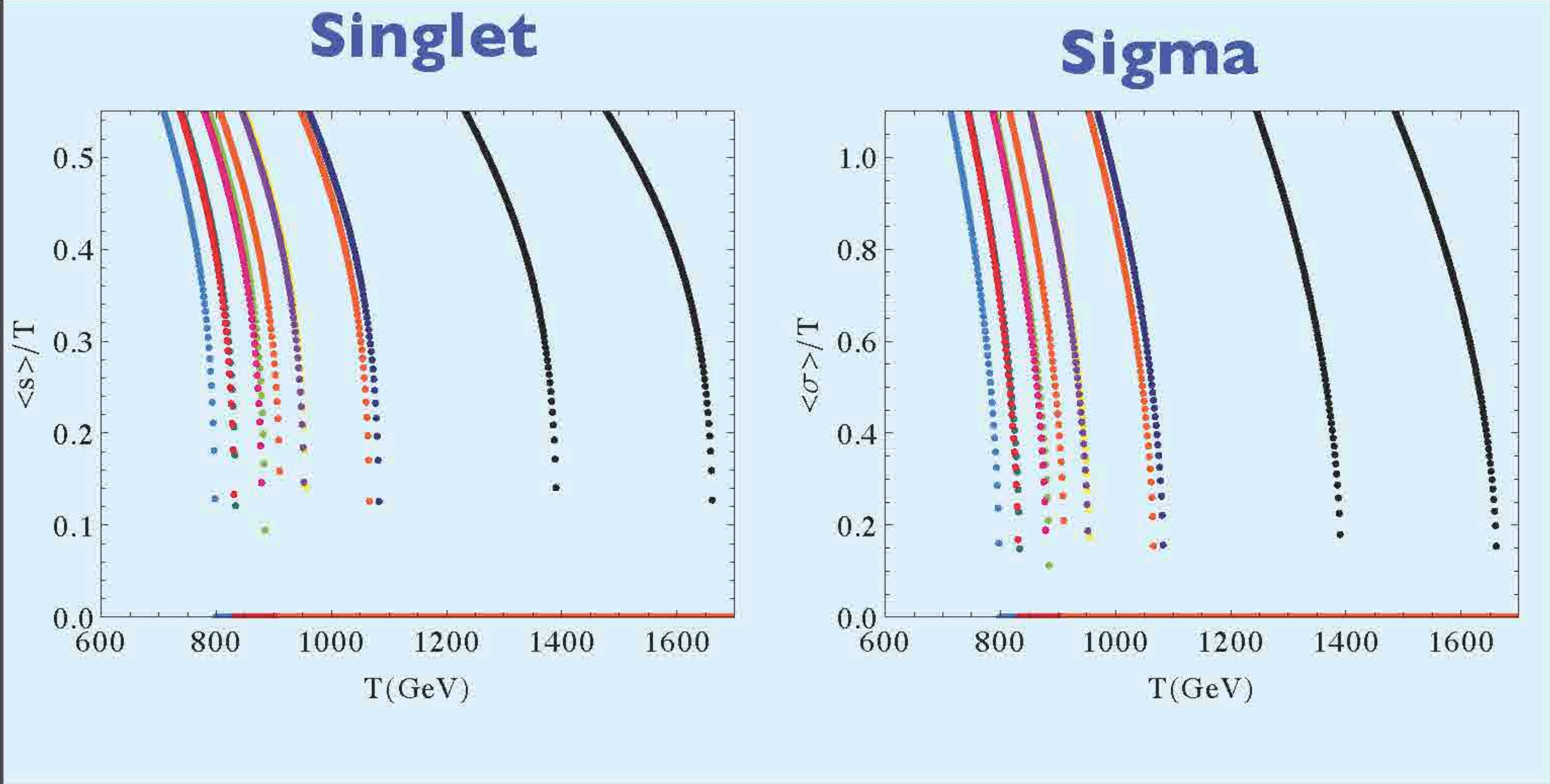
EWPT in the mean field approximation:



A weak 1st order PT??

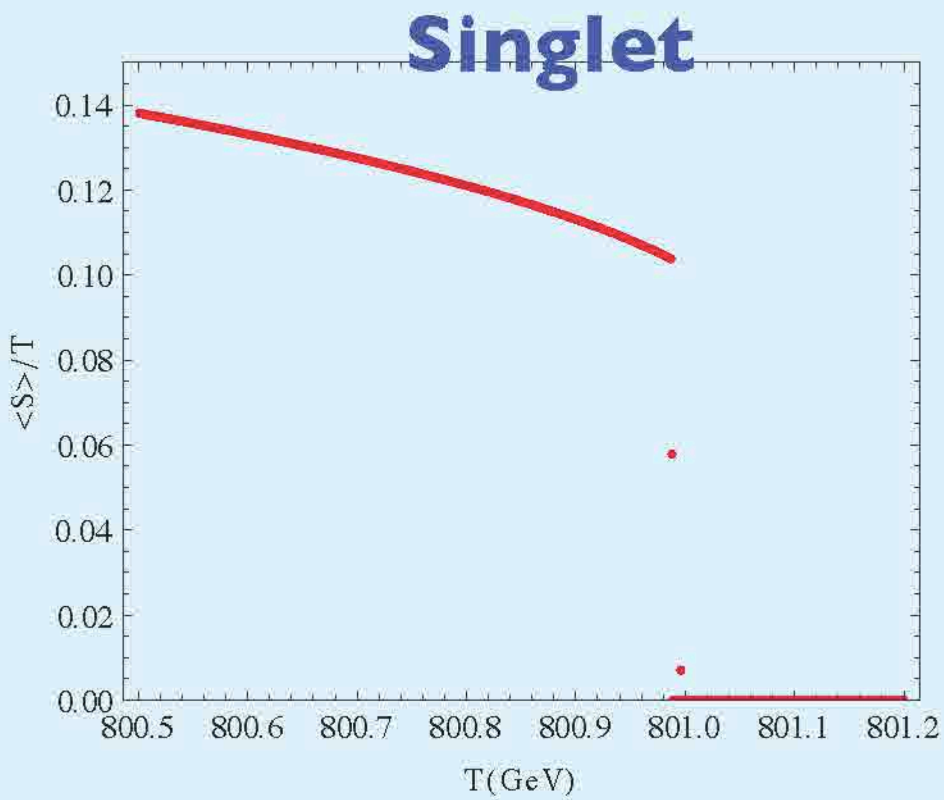
can however be considerably different from the lattice calculation (e.g. Kajantie+Lane+Rummukainen +Shaposhnikov,`96)

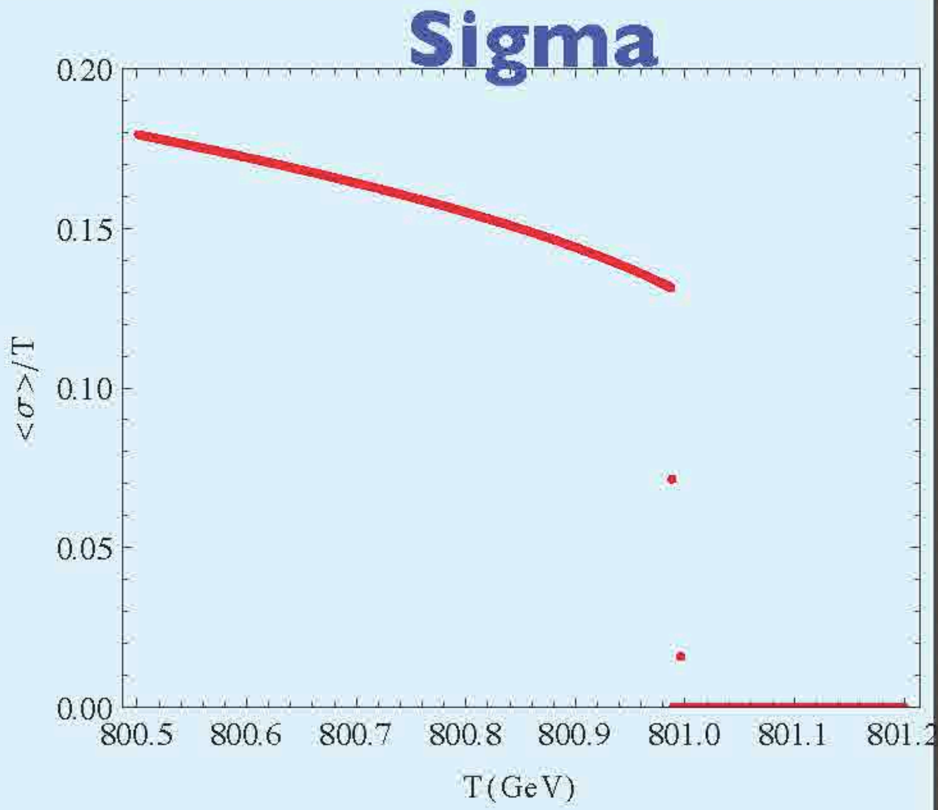
Chiral PT in the mean field approximation:



look like weak 1st oder PT.

Near the transition point:





can be considerably different from the lattice result.

Conclusion

* Dark Technicolor model
  is an attractive scale invariant extension of the SM

* The NJL method is applied to analyze the model:

- Dark pions are Dark matter, but a fine tuning $\boxed{2m_{DM} \simeq m_S}$ is needed.
- The ChPT seems to be a weak 1st order PT.
- No EW Baryogenesis, but there will be many possibilities to modify the model!

Thank You !