Electroweak scale genesis by dynamical scale symmetry breaking and strong scale phase transition in the early Universe

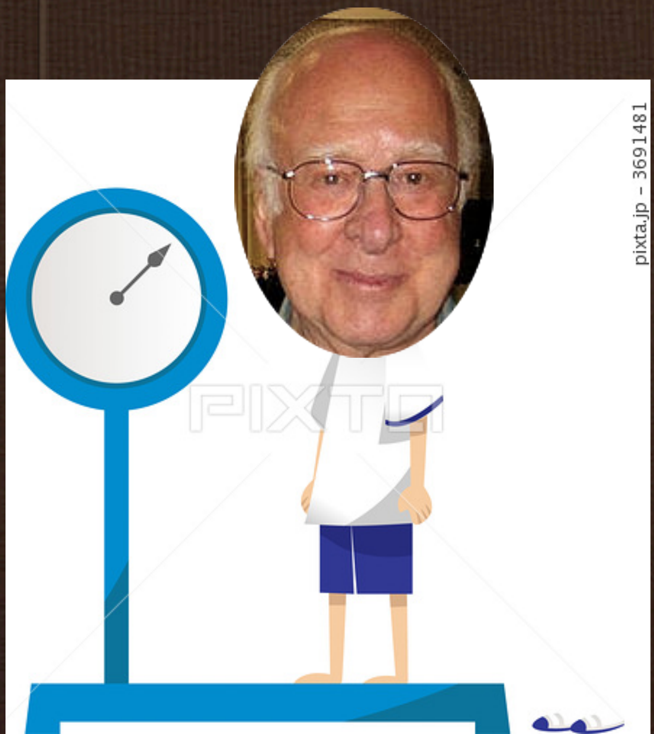
CosPA2016, Sydney

by Jisuke Kubo,
Kanazawa University

based on:
J.Kubo and M. Yamada,
PRD93 (2016) 075016;
PTEP 2015 093B01;
arXiv:1610.02241 (JCAP).

**The mass of the SM particles is provided by our „God Particle“ Higgs.

**But who is responsible for the mass of the Higgs?



It is the mass term μ in the Higgs potential.

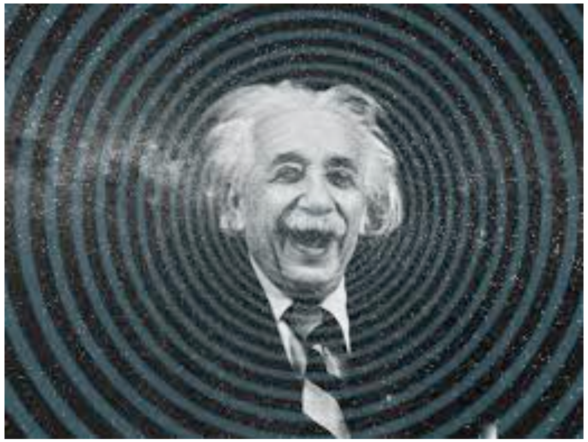
Without μ the SM would be scale invariant at the classical level.

We propose a scenario of scale genesis creating from nothing:

We propose a scenario of scale genesis creating from nothing:

Dark Matter

and also



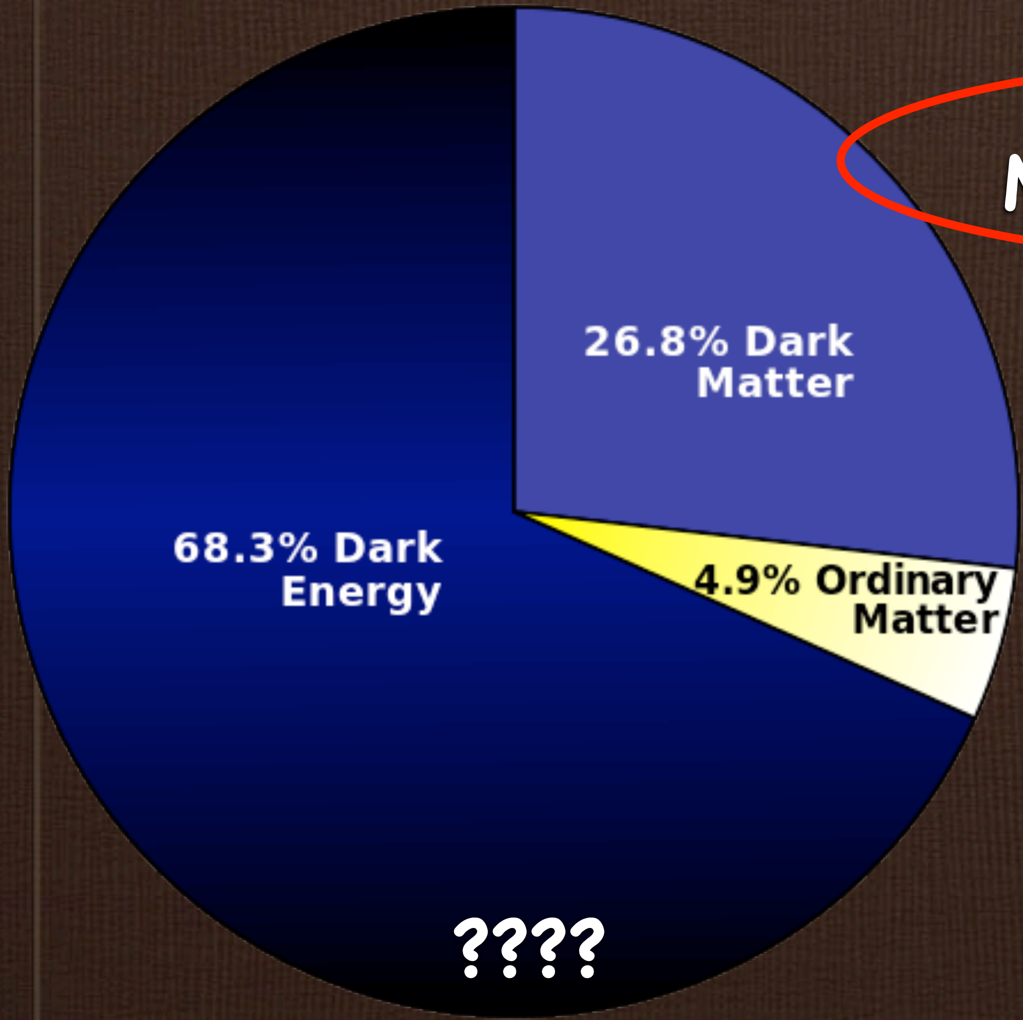
If we start with a theory containing a mass from the beginning, we have no chance to explain its origin.

↓

Scale Invariant Extension of the SM

We assume:
Low-energy physics is responsible for the origin of low energy scales.

The Cake of the Universe



$M_{\rm WIMP} \simeq$ few 100 GeV

from DSSB in a hidden sector

98% + 2% ($\leftarrow$ Higgs)

from DχSB in QCD

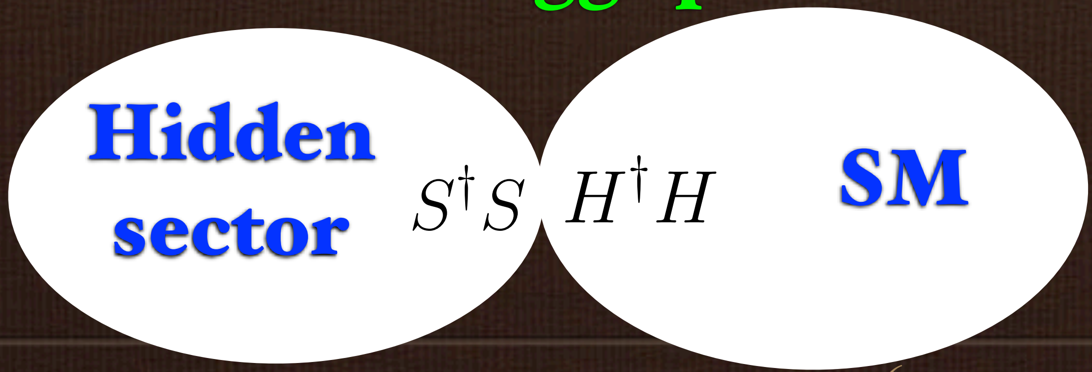
26.8%+4.9%=31.7% from DχSB+DSSB

Model

J.Kubo and M. Yamada,
PRD93 (2016) 075016;
PTEP (2015) 093B01.

$$\mathcal{L}_{\rm H} = -\frac{1}{2}\,{\rm tr}F^2 + ([D^\mu S_i]^\dagger D_\mu S_i) - \hat{\lambda}_S(S_i^\dagger S_i)(S_j^\dagger S_j)$$
$$- \hat{\lambda}'_S(S_i^\dagger S_j)(S_j^\dagger S_i) + \hat{\lambda}_{HS}(S_i^\dagger S_i)H^\dagger H - \lambda_H(H^\dagger H)^2 + \mathcal{L}'_{\rm SM}$$

Higgs portal



$N_c = \#$of the hidden colors

$i, j = 1, \ldots, N_f$

$\boxed{U(N_f)\ \text{flavor symmetry}}$

At some low energy the SU(Nc) gauge interaction becomes so strong that the SU(Nc) invariant scalar bilinear forms dynamically a U(Nf) invariant condensate:

$$\langle (S_i^\dagger S_j) \rangle = \langle \sum_{c=1}^{N_c} S_i^{c\dagger} S_j^c \rangle \propto \delta_{ij}$$

which is nothing but the μ term.

$$\lambda_{HS}(S_i^\dagger S_i) H^\dagger H$$

J.K, K-S. Lim and M. Lindner, PRL 113 (2014) 091604

But this is a non-perturbative effect.

How to deal with this non-perturbative effect ?

*Direct approach: Lattice gauge theory

*Effective theory approach:

In the case of dynamical chiral symmetry breaking, e.g.

Sigma models

. . . .

We follow the idea of

Nambu-Jona-Lasinio (NJL)

NJL	Our approach

1. Integrating out the gauge fields.

2. Global symmetries

$\boxed{SU(3)_L \times SU(3)_R \times U(1)_V \times U(1)_A}$ $\boxed{U(N_f) \times \text{Scale invariance}}$

Anomalous

3. Mean fields and excitations

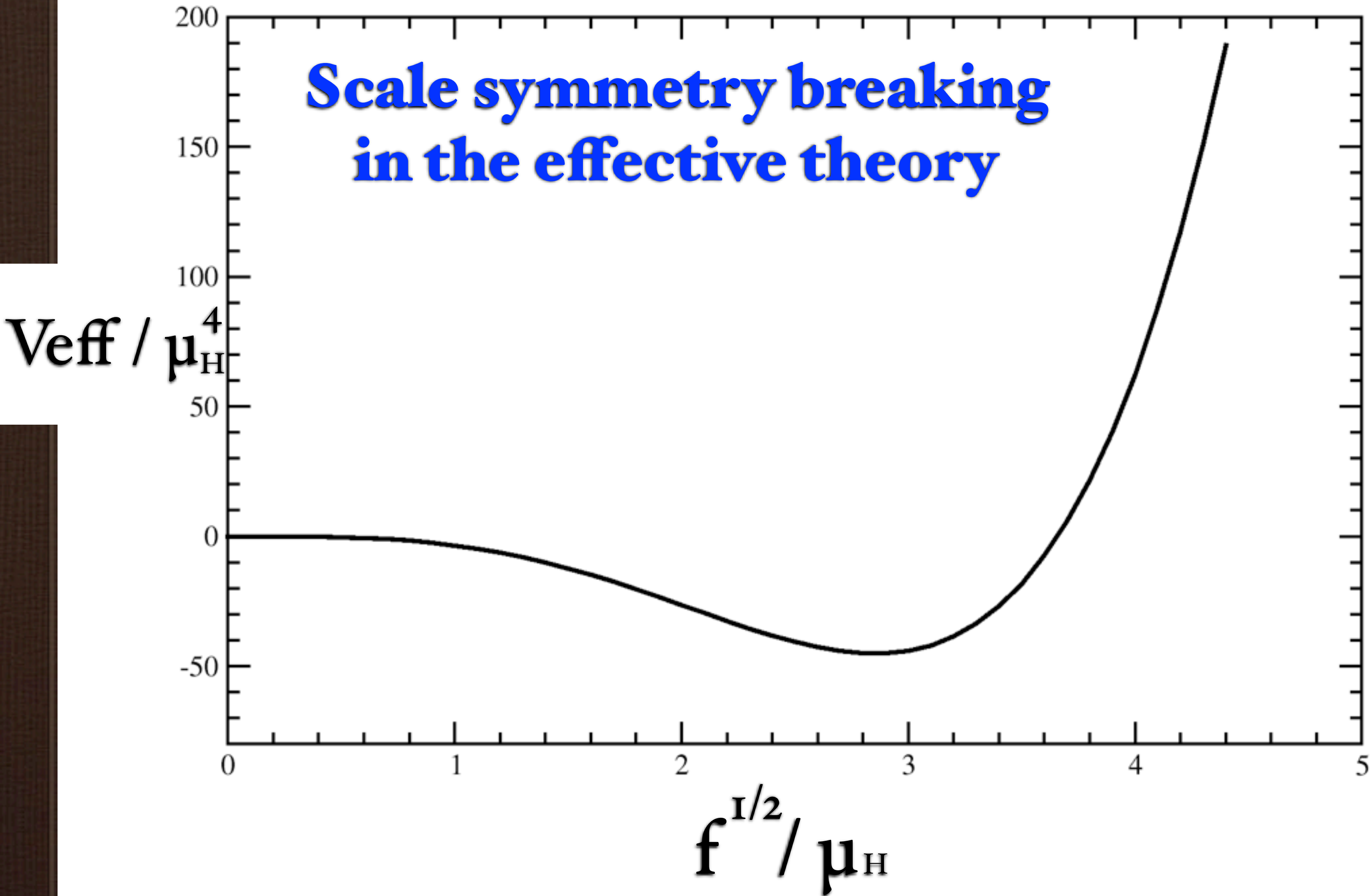
$\boxed{\bar{\psi}_i(1-\gamma_5)\psi_j \propto \delta_{ij}\sigma + i t^a_{ji}\, \pi^a}$ $\boxed{S^\dagger_i S_j \propto \delta_{ij} f + i t^a_{ji}\, \phi^a}$

Condensate

4. Effective potential from

integrating out ψ integrating out δS around $\bar{S}$

$\lambda_S = \lambda'_S = 1, N_f = 2, N_c = 6$
$\lambda_{HS} = 0$



$$S_i^\dagger S_j = \delta_{ij} f$$

In the case of scale symmetry breaking:

* Higgs mass

$$
\begin{aligned}
m_{h0}^2 &= |\langle H\rangle|^2 \left(\frac{16\lambda_H^2(N_f\lambda_S+\lambda_S')}{G}+\frac{N_cN_f\lambda_{HS}^2}{8\pi^2}\right)\\
&= \langle f\rangle \frac{N_f\lambda_{HS}}{2\lambda_H}\left(\frac{16\lambda_H^2(N_f\lambda_S+\lambda_S')}{G}+\frac{N_cN_f\lambda_{HS}^2}{8\pi^2}\right)
\end{aligned}
$$

$$G \equiv 4N_f\lambda_H\lambda_S - N_f\lambda_{HS}^2 + 4\lambda_H\lambda_S' \quad > 0$$

Origin of the Higgs mass

Dark Matter phenomenology

Since SU(Nf) is unbroken,

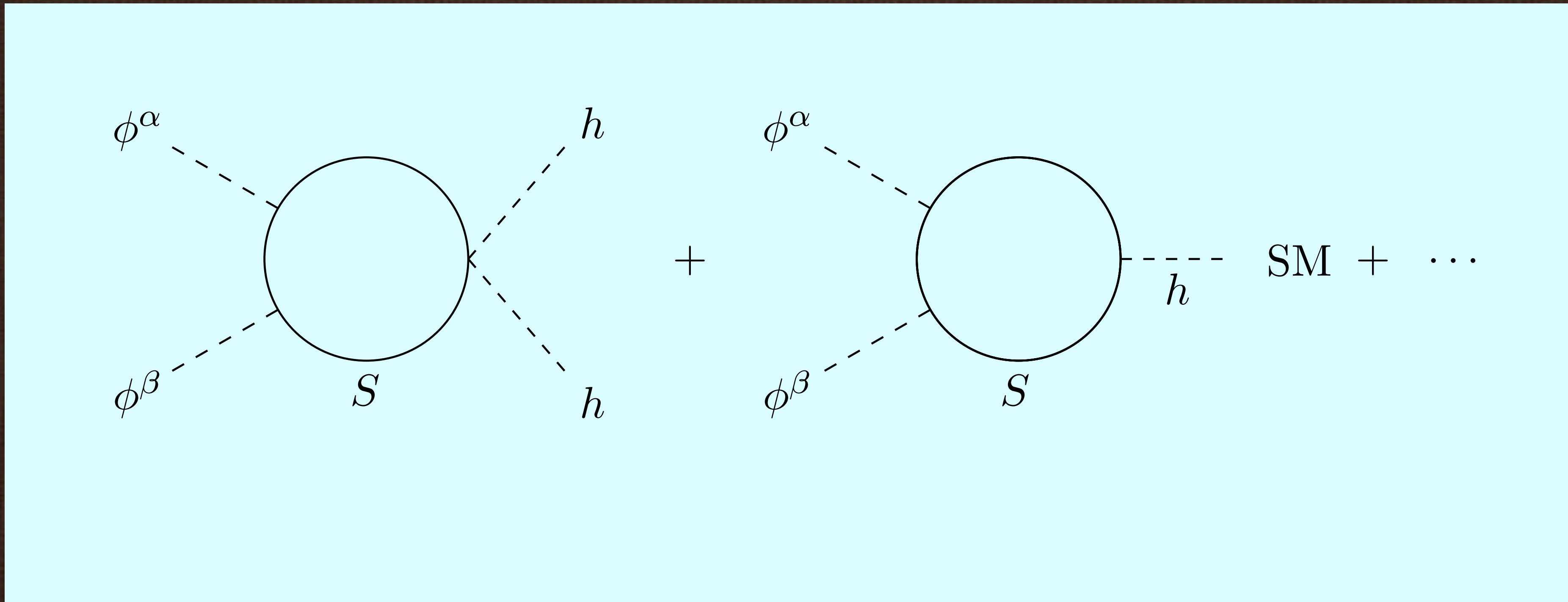
ϕ^a **is stable and can be a DM candidate.**

$$S_i^\dagger S_j = \delta_{ij} f + \delta_{ij} Z_\sigma^{1/2} \sigma + Z_\phi^{1/2} t_{ji}^a \phi^a$$

$$\text{Independent parameters} : \lambda_S \ , \ \lambda'_S \ , \ \lambda_{HS} \ , \ \lambda_H \ , \ \Lambda_H = e^{3/4} \mu_H$$

$$\text{Input} : v_h = 246 \text{ GeV} \ , \ m_h = 126 \text{ GeV} \ , \ \Omega_{\text{DM}} h^2 = 0.120 \pm 0.005$$

*Dark Matter annihilation into the SM particles

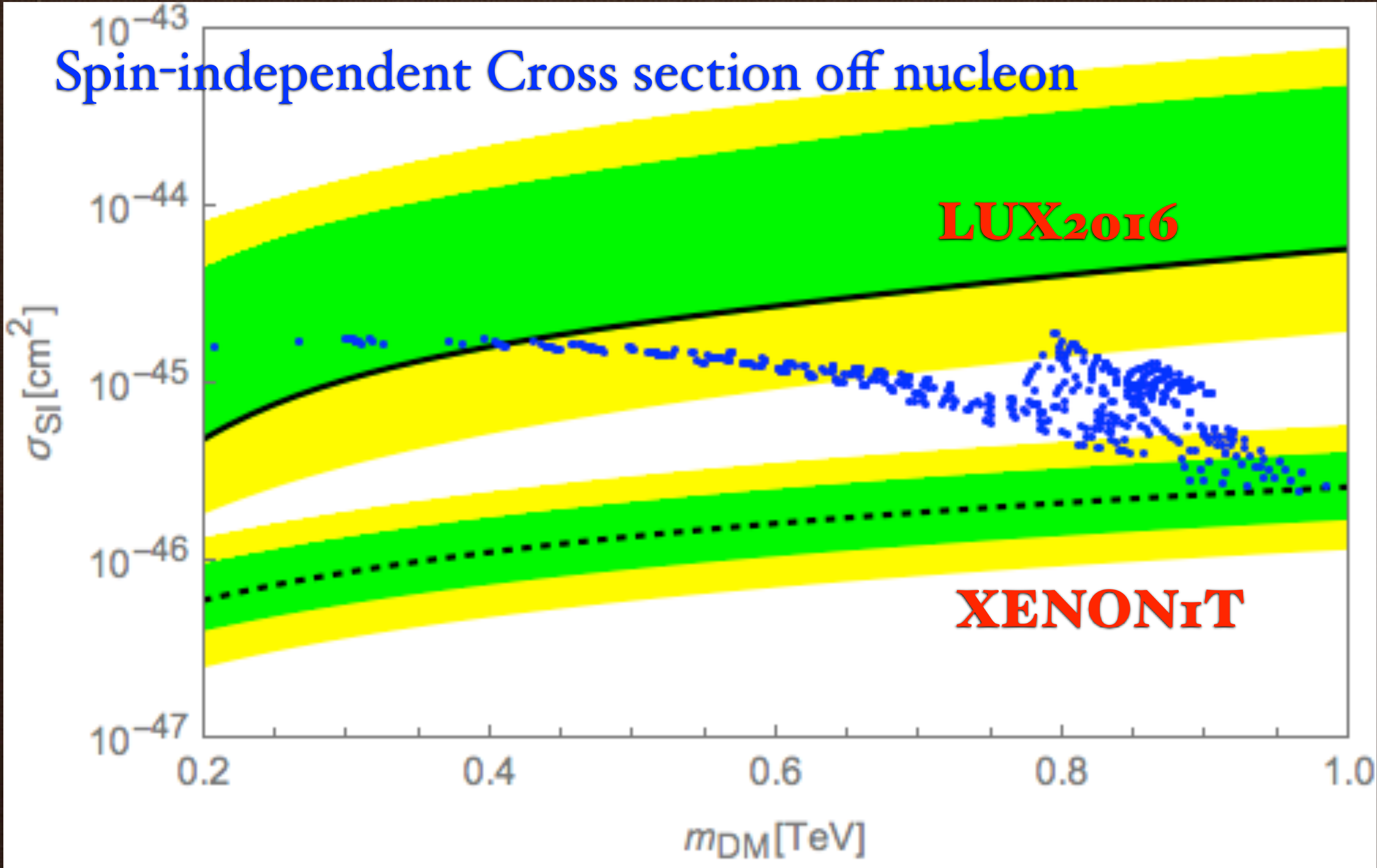


Relic abundance $\Omega_{\rm DM}h^2$ and direct detection

Direct detection

$N_f = 2, N_c = 6$

$\Omega_{\rm DM} h^2 = \Omega_{\rm PLANCK} h^2$ with 2σ



Phase Transitions (PT) and Gravitational Waves (GW)

Two order parameters:

$$\langle h \rangle \qquad\qquad \langle f \rangle$$

EWPT $\rightarrow \langle h \rangle$

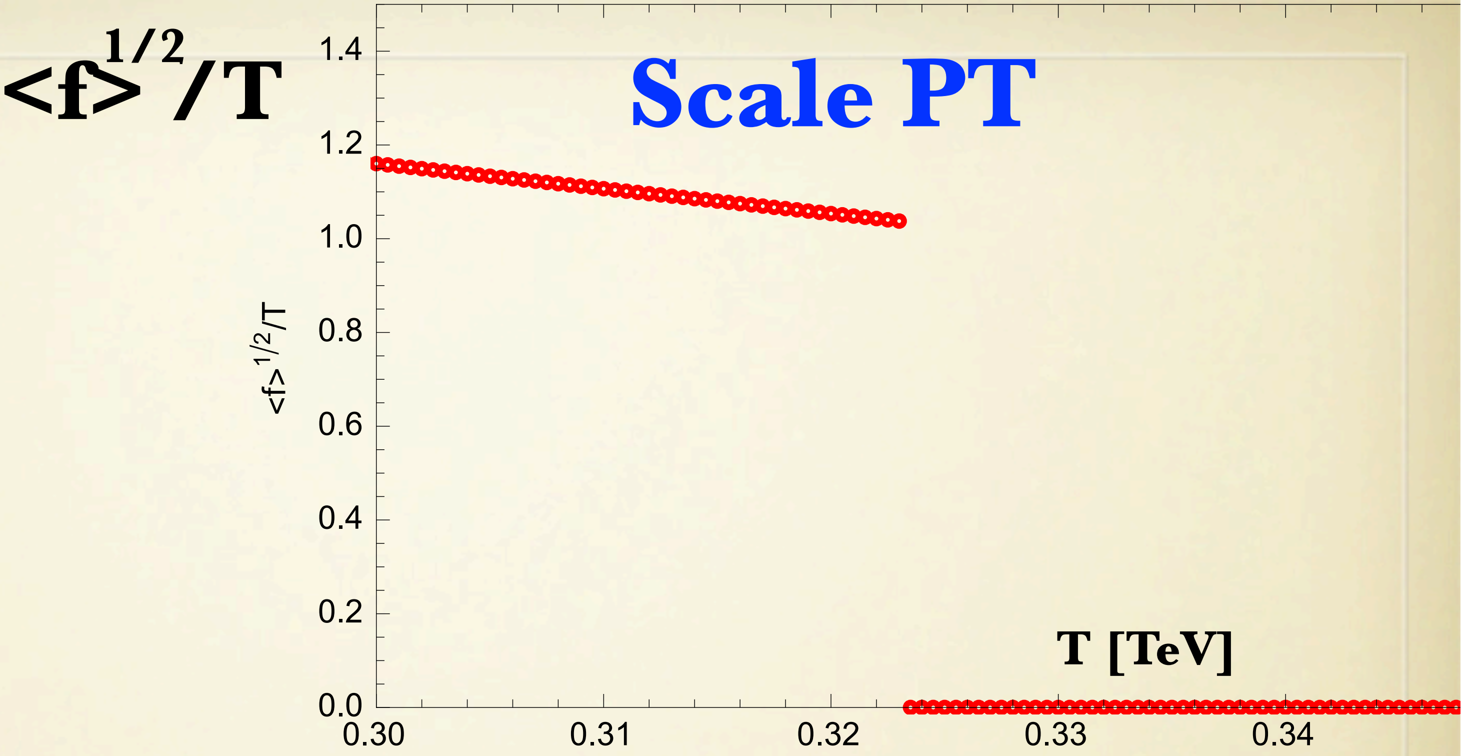
Scale PT $\rightarrow \langle f \rangle$

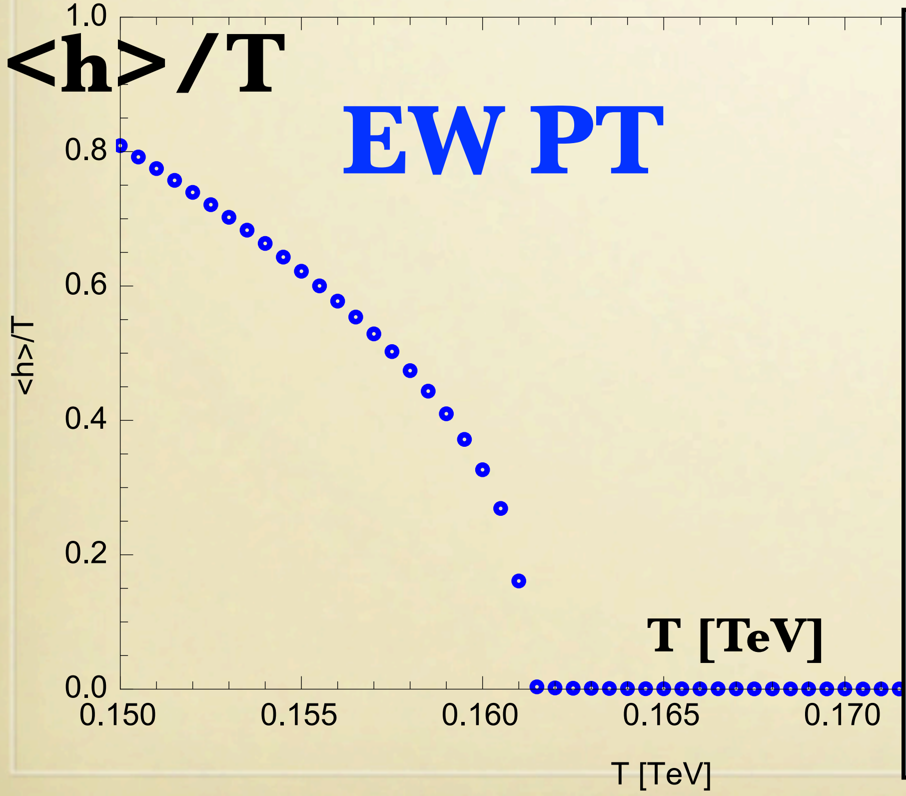
EW Baryogenesis

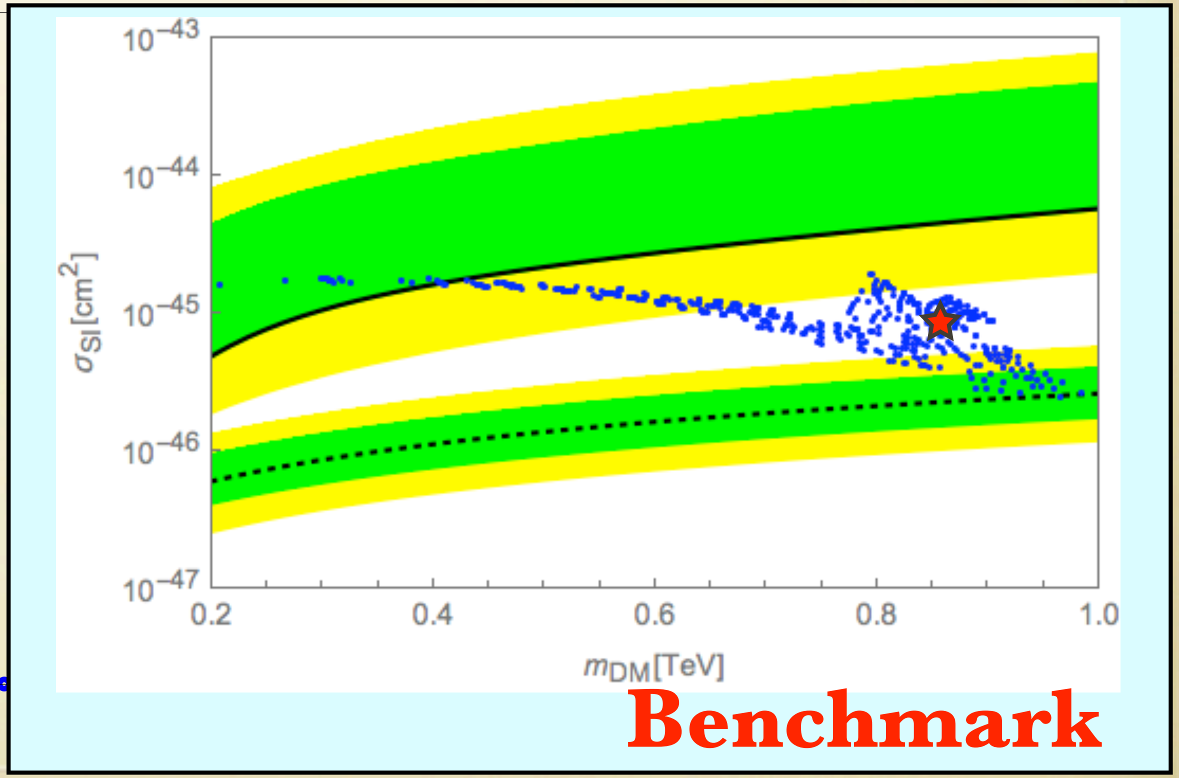
Gravitational wave BG

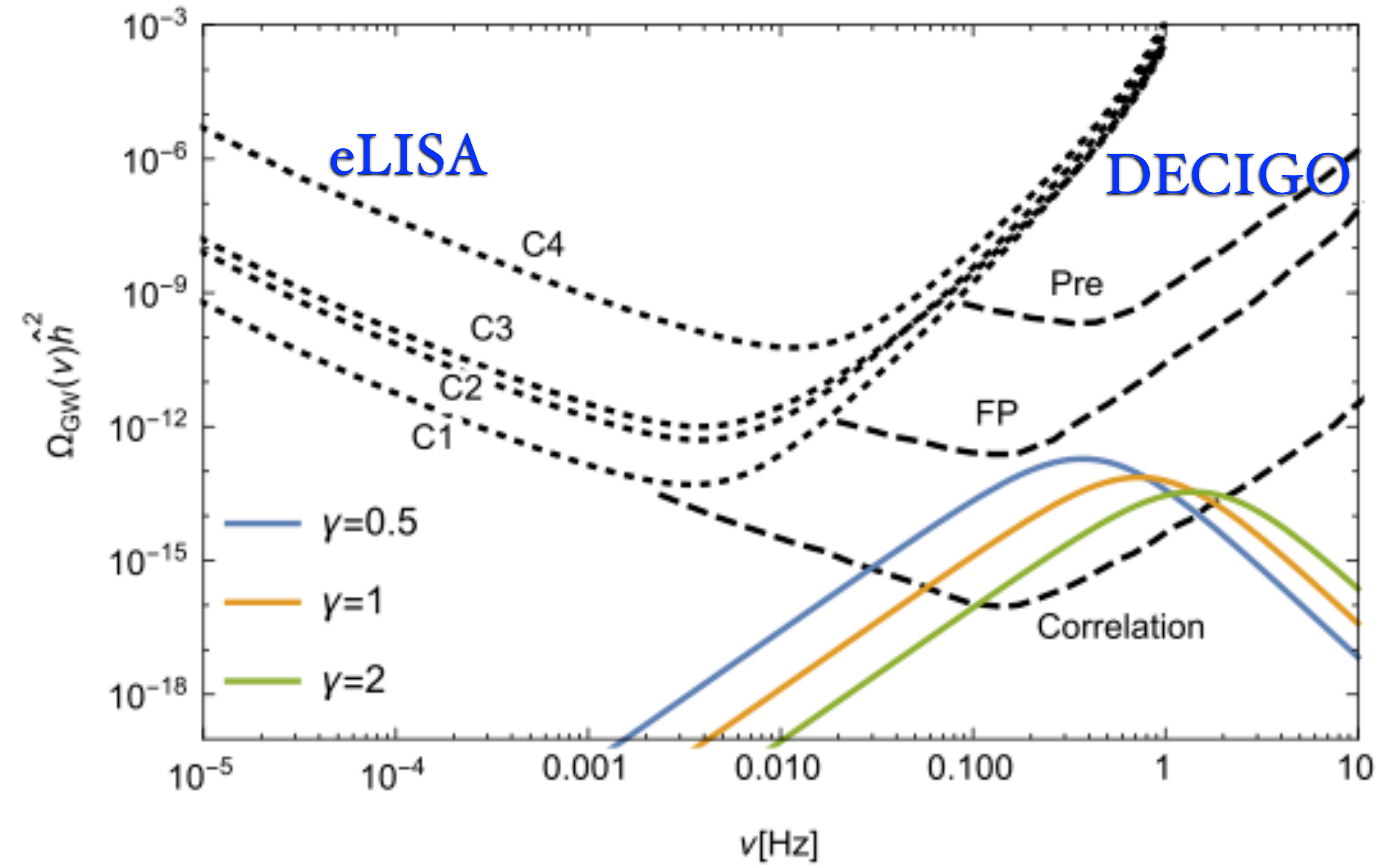
(Hogan,`83; Witten,`84; ....)

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


$\langle f \rangle^{1/2}/T$
Scale PT
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\langle f \rangle^{1/2}/T$
T [TeV]
0.30
0.31
0.32
0.33
0.34


$\langle h \rangle/T$
EW PT
1.0
0.8
0.6
0.4
0.2
0.0
$\langle h \rangle/T$
T [TeV]
0.150
0.155
0.160
0.165
0.170
T [TeV]


10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
$\sigma_{SI}[cm^2]$
0.2
0.4
0.6
0.8
1.0
m_{DM}[TeV]
Benchmark



γ	T_t [TeV]	$S_3(T_t)/T_t$	α	$\tilde{\beta}$	$\tilde{\Omega}_{\rm sw}h^2$	$\tilde{\nu}_{\rm sw}$ [Hz]
0.5	0.300	149	0.070	3.7×10^3	1.9×10^{-13}	0.37
1.0	0.311	145	0.062	7.0×10^3	7.4×10^{-14}	0.73
2.0	0.316	146	0.059	13×10^3	3.4×10^{-14}	1.4

J.Kubo and M. Yamada, ***arXiv:1610.02241***(JCAP).

Conclusion

EW scale genesis
through scalar bi-linear condensation
in a strongly interacting hidden sector
may be tested

at DECIGO in > 10 years.

THANK YOU VERY MUCH FOR YOUR ATTENTION.

$$\mathcal{L}_{\mathrm{H}} = -\frac{1}{2}\ \mathrm{tr} F^2 + ([D^\mu S_i]^\dagger D_\mu S_i) - \hat{\lambda}_S (S_i^\dagger S_i)(S_j^\dagger S_j)$$
$$- \hat{\lambda}'_S (S_i^\dagger S_j)(S_j^\dagger S_i) + \hat{\lambda}_{HS}(S_i^\dagger S_i) H^\dagger H - \lambda_H (H^\dagger H)^2 + \mathcal{L}'_{\mathrm{SM}}$$

J.Kubo and M. Yamada, ***PRD93 (2016) 075016***.

$$\mathcal{L}_{\mathrm{eff}} = ([\partial^\mu S_i]^\dagger \partial_\mu S_i) - \lambda_S (S_i^\dagger S_i)(S_j^\dagger S_j) - \lambda'_S (S_i^\dagger S_j)(S_j^\dagger S_i) + \lambda_{HS}(S_i^\dagger S_i) H^\dagger H - \lambda_H (H^\dagger H)^2 + \mathcal{L}'_{\mathrm{SM}}$$

U(Nf) flavor symmetry and classical scale invariance

1 Introduce the auxiliary fields.

$$S_i^\dagger S_j = \delta_{ij} f + \delta_{ij} Z_\sigma^{1/2} \sigma + Z_\phi^{1/2} t_{ji}^a \phi^a \quad \textbf{with} \quad \langle \sigma \rangle = \langle \phi^a \rangle = 0$$

2 Integrate out the fluctuation of S to get:

$$V_{\mathrm{eff}}(f, \bar{S}, H)$$
$$= M^2 (\bar{S}_i^\dagger \bar{S}_i) + \lambda_H (H^\dagger H)^2 - N_f (N_f \lambda_S + \lambda_S') f^2 + \frac{N_c N_f}{32\pi^2} M^4 \ln \frac{M^2}{\Lambda_H^2}$$

$$M^2 = 2(N_f \lambda_S + \lambda_S') f - \lambda_{HS} H^\dagger H.$$

$$\Lambda_H = \mu e^{3/4}$$

With a (current) mass of S, but without H

→ Kobayashi+Kugo, PTP 1537 (1975)

The vacuum

$$0 = \frac{\partial}{\partial \bar{S}_i^a} V_{\mathrm{MFA}} \longrightarrow \langle \bar{S}_i^a \rangle \langle M^2 \rangle = 0$$

+two other gap equations

(i) $\langle \bar{S}_i^a \rangle \neq 0$ and $\langle M^2 \rangle = 0$

<Veff>=0

(End point solution of Bardeen+Moshe,'83)

(ii) $\langle \bar{S}_i^a \rangle = 0$ and $\langle M^2 \rangle = 0$

<Veff>=0

(iii) $\langle \bar{S}_i^a \rangle = 0$ and $\langle M^2 \rangle \neq 0$

<Veff> < 0 (Kobayashi+Kugo,'75)

$$\boxed{V_{\mathrm{eff}}(f, \bar{S}, H) = M^2 (\bar{S}_i^\dagger \bar{S}_i) + \lambda_H (H^\dagger H)^2 - N_f (N_f \lambda_S + \lambda_S') f^2 + \frac{N_c N_f}{32\pi^2} M^4 \ln \frac{M^2}{\Lambda_H^2}}$$

(iii)

$$\langle V_{\mathrm{MFA}}\rangle = -\frac{N_c N_f}{64\pi^2}\Lambda_H^4 \exp\left(\frac{64\pi^2\lambda_H}{N_c G} - 1\right) < 0.$$

$$G \equiv 4N_f\lambda_H\lambda_S - N_f\lambda_{HS}^2 + 4\lambda_H\lambda'_S > 0$$

* **VEV**

$$|\langle H\rangle|^2 = \frac{v_h^2}{2} = \frac{N_f\lambda_{HS}}{G}\Lambda_H^2 \exp\left(\frac{32\pi^2\lambda_H}{N_c G} - \frac{1}{2}\right)$$

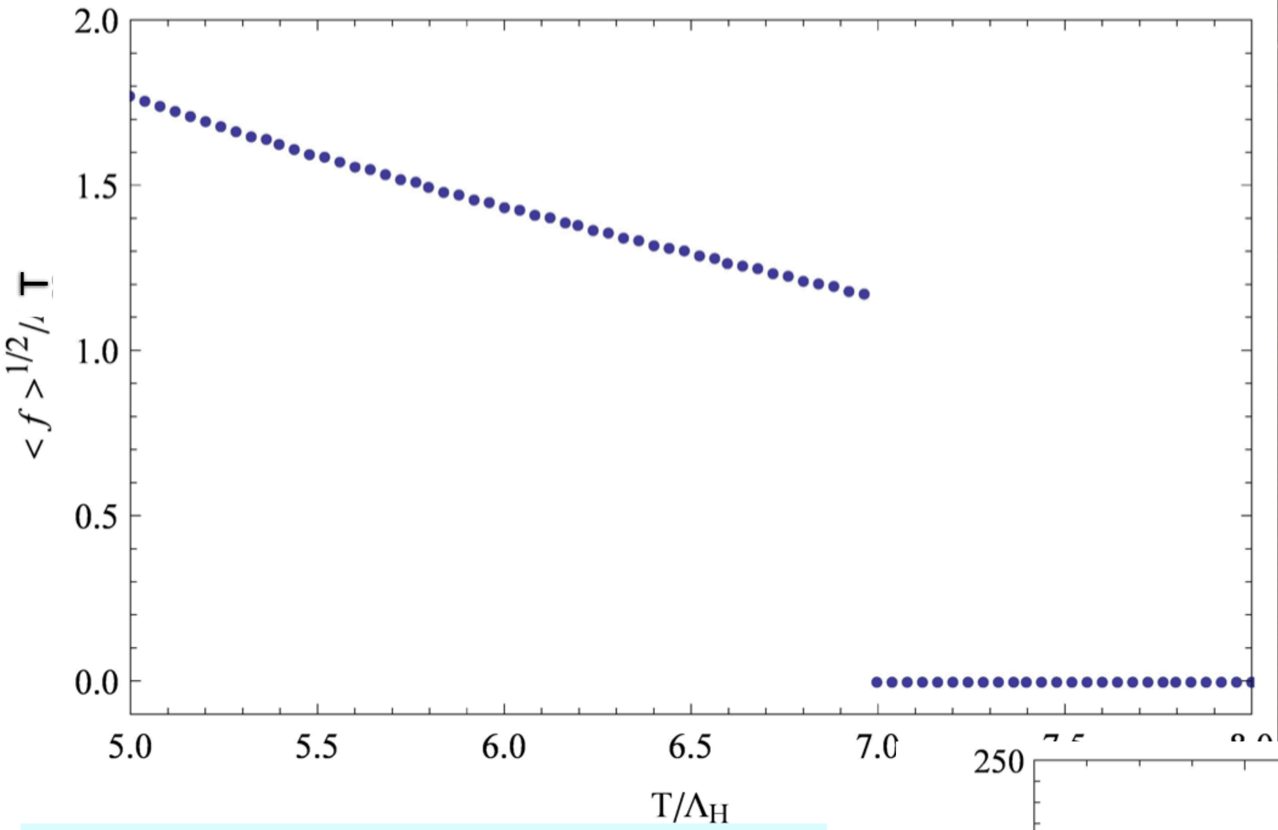
* **Constituent mass**

$$\langle M^2\rangle = M_0^2 = \frac{G}{N_f\lambda_{HS}}|\langle H\rangle|^2$$

* **Higgs mass**

$$\begin{aligned} m_{h0}^2 &= |\langle H\rangle|^2 \left(\frac{16\lambda_H^2(N_f\lambda_S + \lambda'_S)}{G} + \frac{N_c N_f \lambda_{HS}^2}{8\pi^2}\right) \\ &= \langle f\rangle \frac{N_f\lambda_{HS}}{2\lambda_H}\left(\frac{16\lambda_H^2(N_f\lambda_S + \lambda'_S)}{G} + \frac{N_c N_f \lambda_{HS}^2}{8\pi^2}\right) \end{aligned}$$

Origin of the Higgs mass

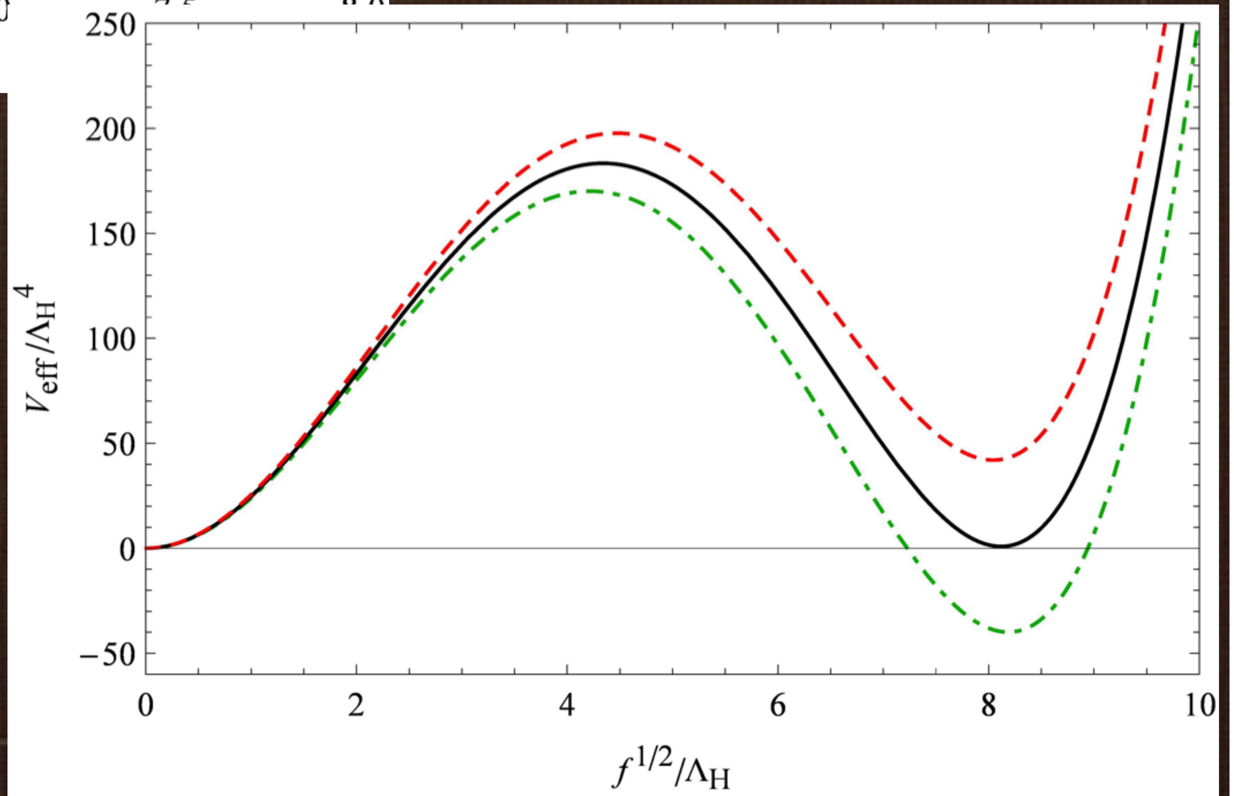


Scale PT is 1st order.

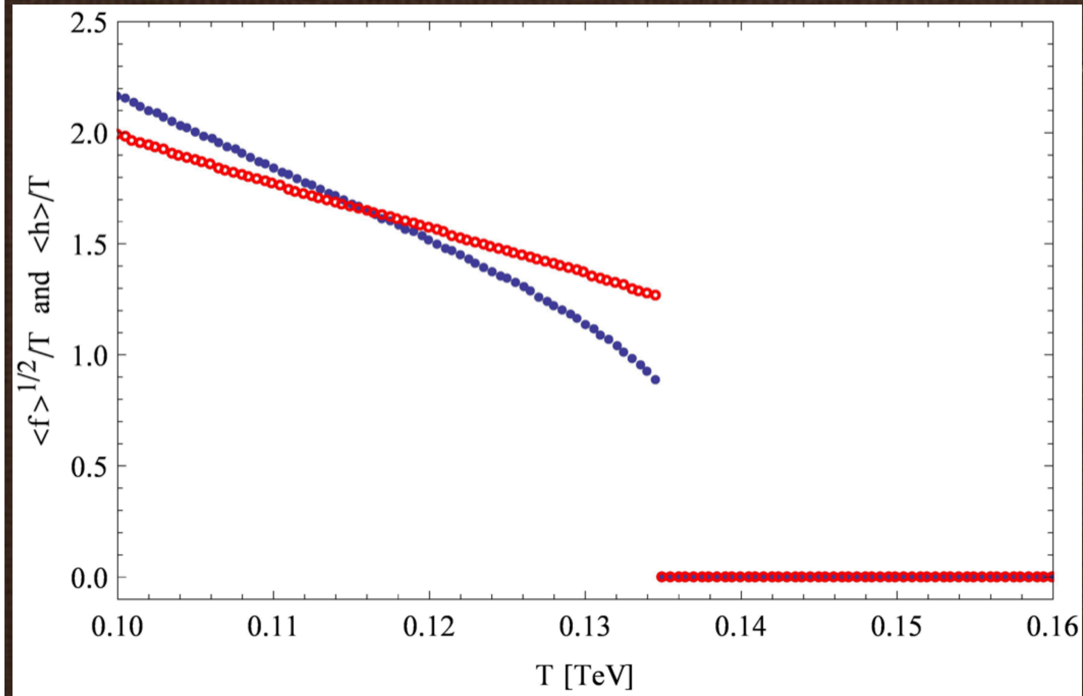
$N_f = 1,\ N_c = 6,\ \lambda_S + \lambda_S' = 2.083$

$\lambda_{HS} = 0$

The portal is closed.



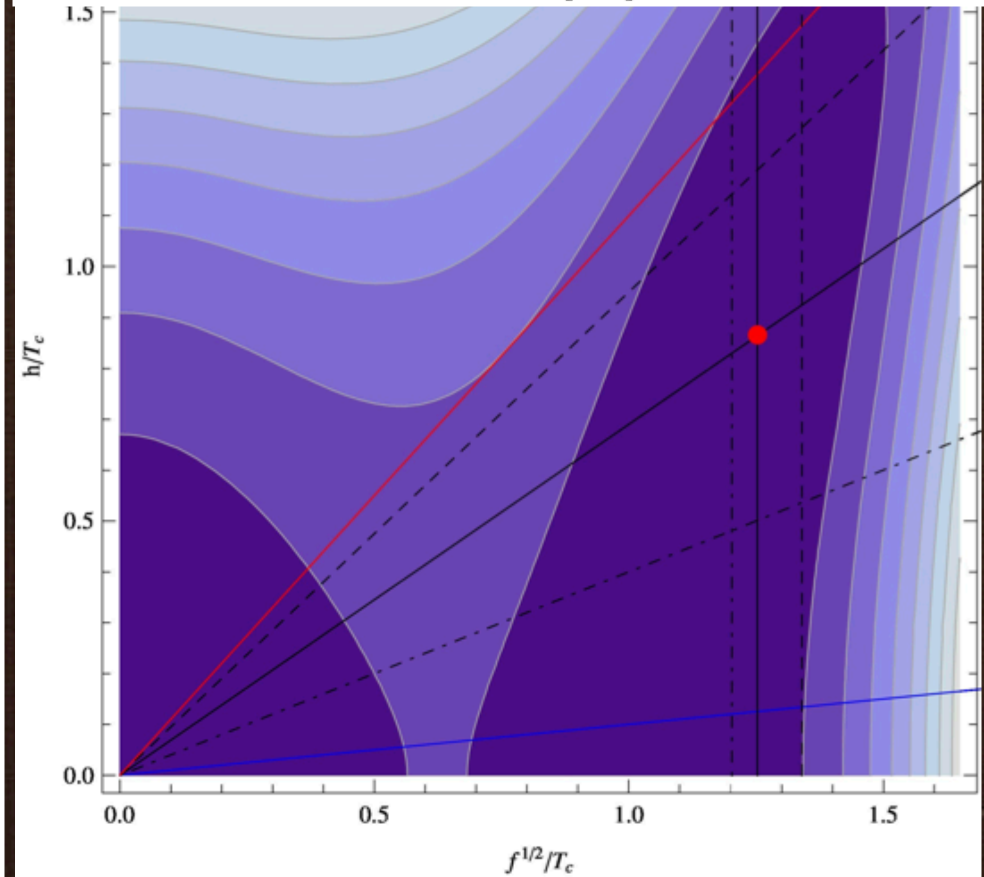
Strong 1st-order EW and Scale PT

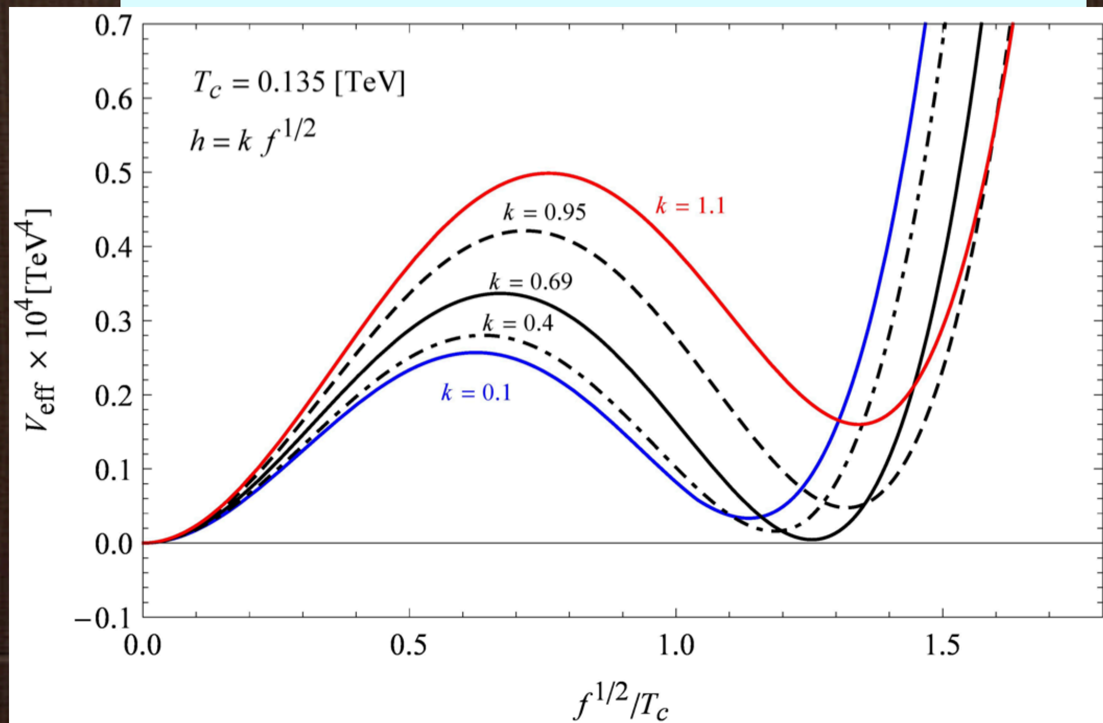


No DM

$$N_f = 1,\ N_c = 6,\ \lambda_S + \lambda'_S = 2.083,$$

$$\lambda_{HS} = 0.296,\ \lambda_H = 0.208.$$





J.Kubo and M. Yamada, *arXiv:1610.02241*.

$$\mathcal{L}_3 = \frac{1}{4f} Z^{-1} \partial_i f \partial_i f + V_{\text{eff}}(f, T)$$

$$= \gamma Z^{-1} \partial_i \chi \partial_i \chi + V_{\text{eff}}(\gamma\chi^2, T)$$

$$\boxed{f = \gamma\chi^2 \quad (\dim[\chi] = 1)}$$

(Z=0 at the tree level.)

Serious problems

1. $S_E(T)$ of a non-abelian GT
   $\wr\!|$??
   $S_3(T)/T$ of the effective theory
2. A strongly 1st order PT for f (i.e.$\langle f \rangle^{1/2}/T_S \sim 1$) is no longer strongly 1st order for χ if γ is large.

Our assumptions:

1. V_{eff} is OK.
2. The kinetic term for χ is canonically normalized if $\gamma \sim O(1)$.

The latent heat with $N_c = 3, N_f = 1$ and $\lambda_{HS} = \lambda_H = 0$ just below Ts.

$$\frac{\epsilon(T)}{T^4} = \begin{cases} 0.70 \\ 0.55 \\ 0.43 \end{cases} \quad \text{for} \quad \lambda_S + \lambda_S' = \begin{cases} 3 \\ 4 \\ 5 \end{cases}$$

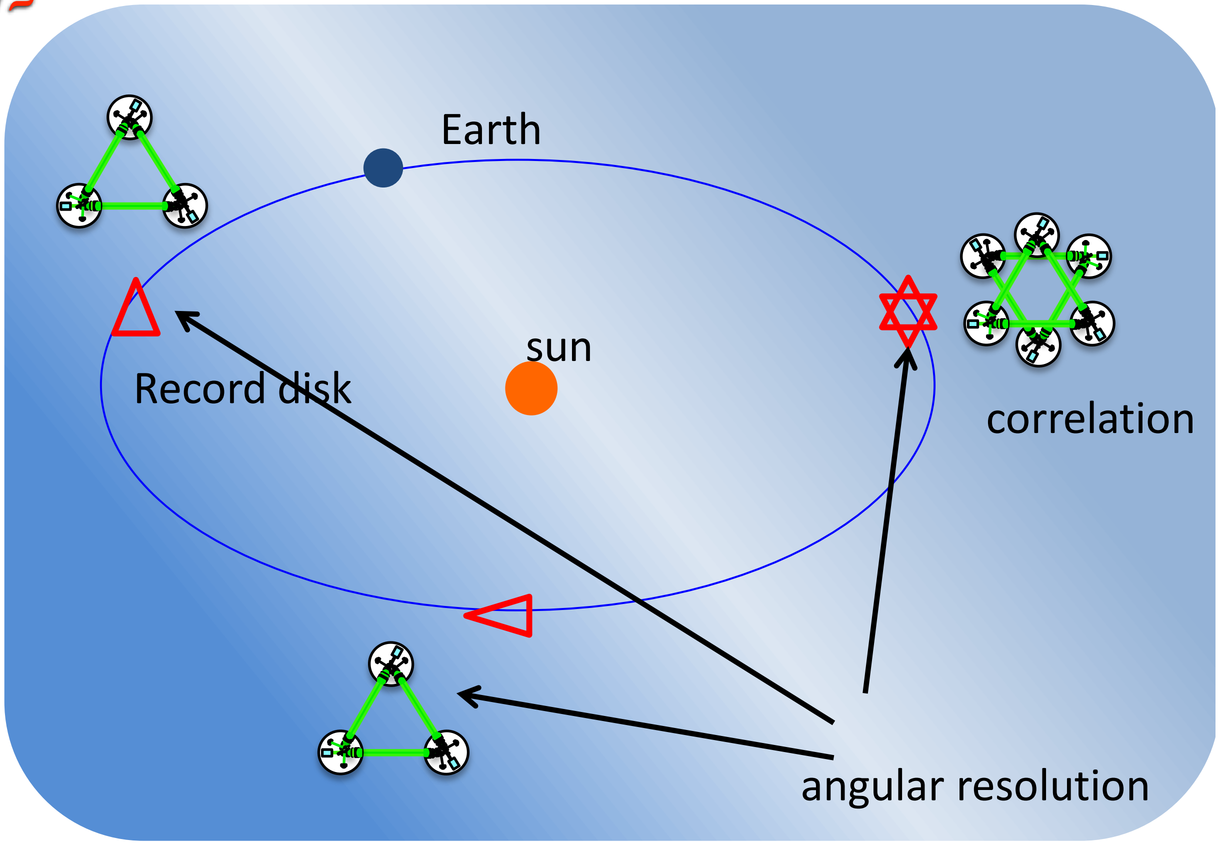
The lattice QCD value:

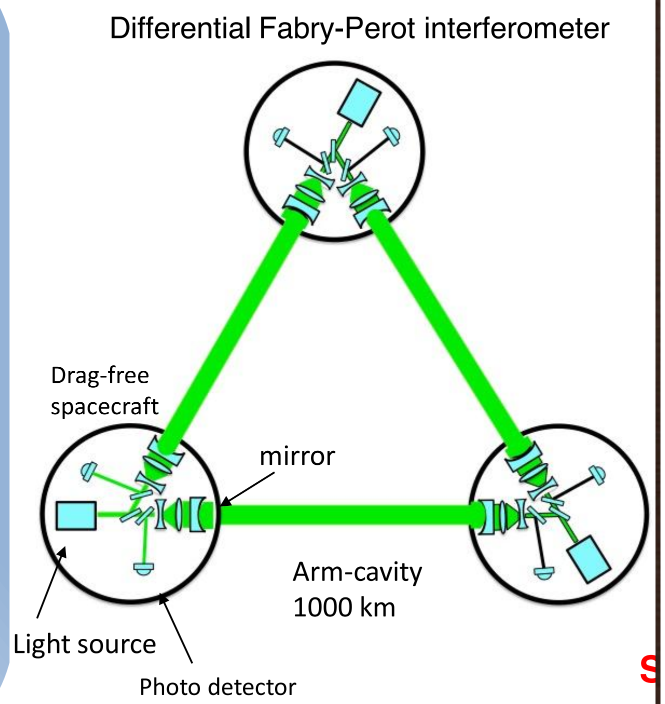
$$\epsilon(T)\,/T^4 = 0.75 \pm 0.17$$

(Shirogane, Ejiri, Iwami,Kanaya+Kitazawa, 2016)

DECIGO : pre-conceptual design

2027-





Orbit : record disk around the sun

Constellation :

4 interferometer units

- 2 overlap units : cross correlation for stochastic background
- 2 separated units : increase angular resolution