Scale Invariance as a Solution for Mass without Mass

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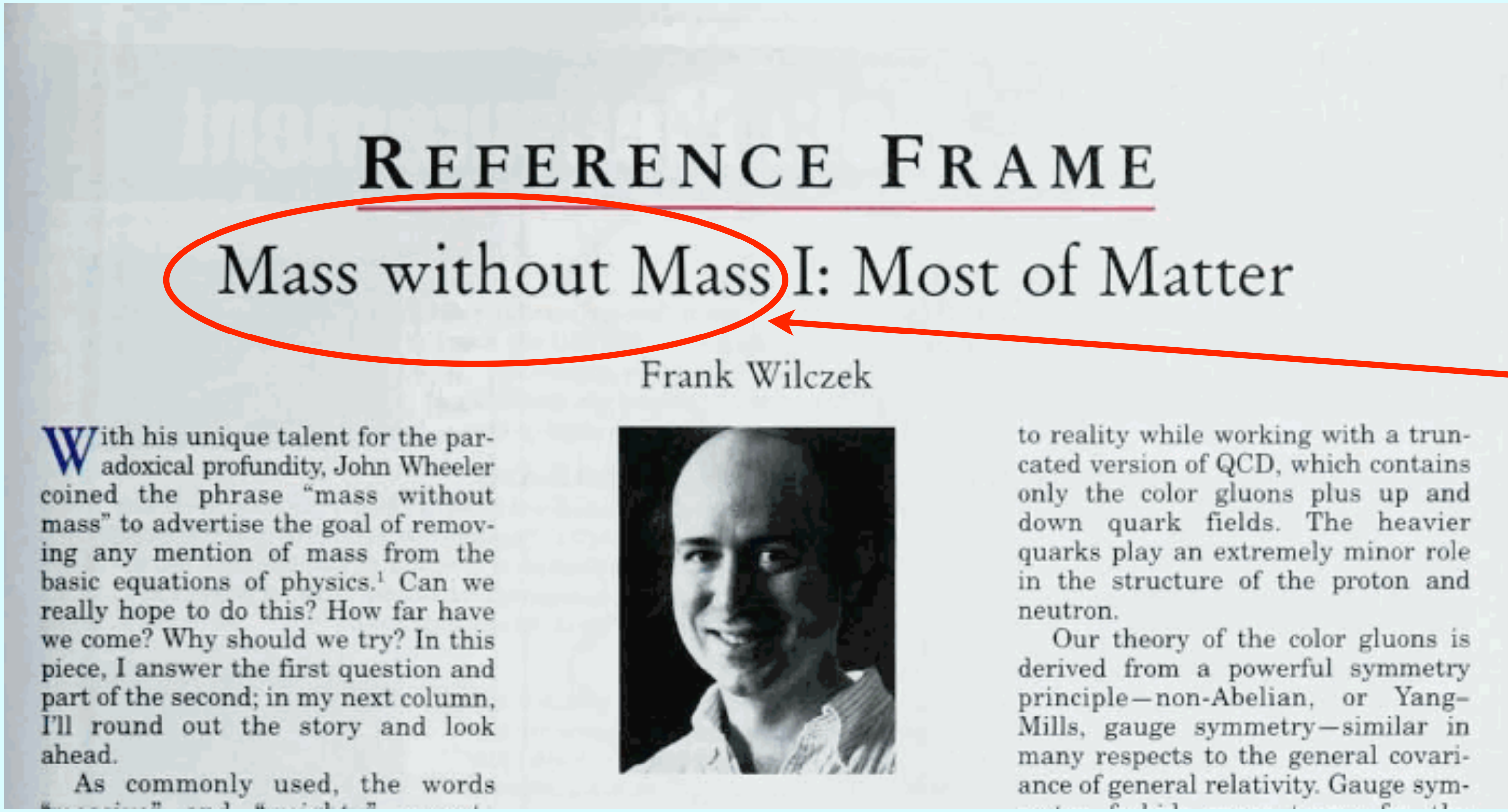
F. Wilczek



REFERENCE FRAME

Mass without Mass I: Most of Matter

Frank Wilczek

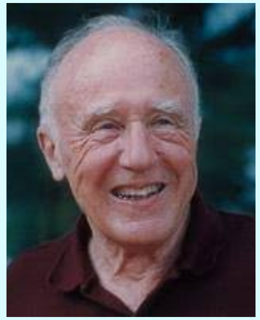
With his unique talent for the paradoxical profundity, John Wheeler coined the phrase “mass without mass” to advertise the goal of removing any mention of mass from the basic equations of physics.[1] Can we really hope to do this? How far have we come? Why should we try? In this piece, I answer the first question and part of the second; in my next column, I'll round out the story and look ahead.

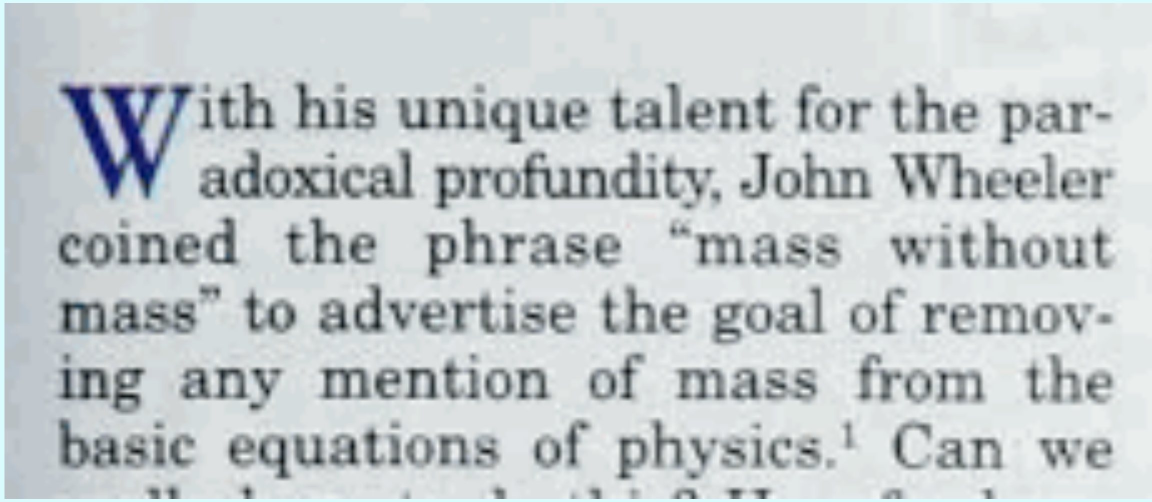
As commonly used, the words

... to reality while working with a truncated version of QCD, which contains only the color gluons plus up and down quark fields. The heavier quarks play an extremely minor role in the structure of the proton and neutron.

Our theory of the color gluons is derived from a powerful symmetry principle—non-Abelian, or Yang–Mills, gauge symmetry—similar in many respects to the general covariance of general relativity. Gauge sym-

J. Wheeler, 1962





With his unique talent for the paradoxical profundity, John Wheeler coined the phrase “mass without mass” to advertise the goal of removing any mention of mass from the basic equations of physics.[1] Can we

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

↓

The Lagrangian should not contain any dimensionful parameter.

↓

Scale Invariance

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Fundamental energy scales

Electroweak scale E_{EW} ,
Planck scale M_{Pl} ,
Cosmological constant Λ ,
etc

Shift the question of why E_{EW} / M_{Pl}
and Λ / M_{Pl} are so small (hierarchy problem)

↓

of where E_{EW}, M_{Pl} and Λ come from (their origin)

Scale invariance is hardly broken by scale anomaly.

Callan, '70; Symanzik,'70

However, scale anomaly can not directly generate mass gap.

To generate a mass gap, scale invariance has to be spontaneously broken.

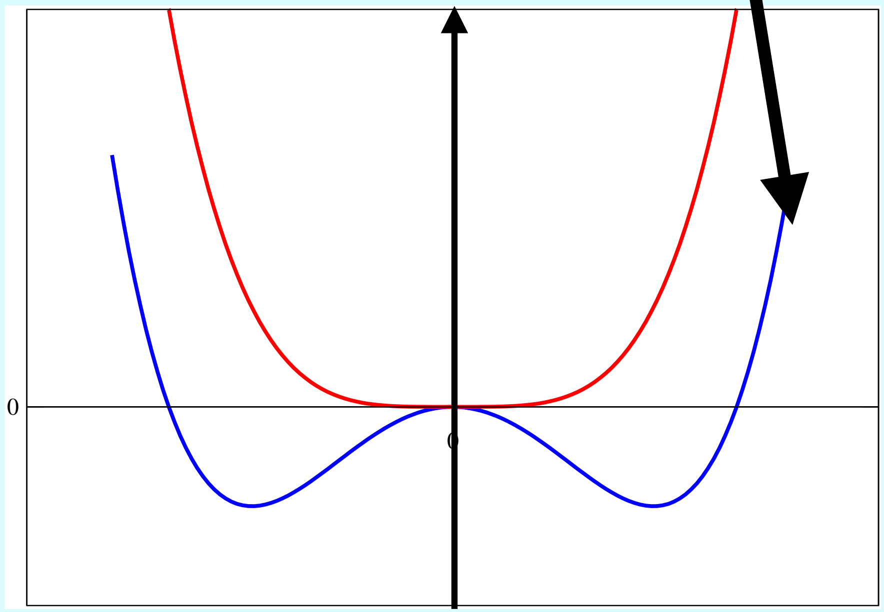
Dynamical generation of E_{EW}

Coleman+Weinberg, '73

with $\mu_H^2 = 0$: if $m_{\rm top}$ = 0

Higgs potential

Scale anomaly



Unfortunately: $m_H \sim 10 \text{ GeV}$

Dynamical generation of M_{Pl}

Induced gravity

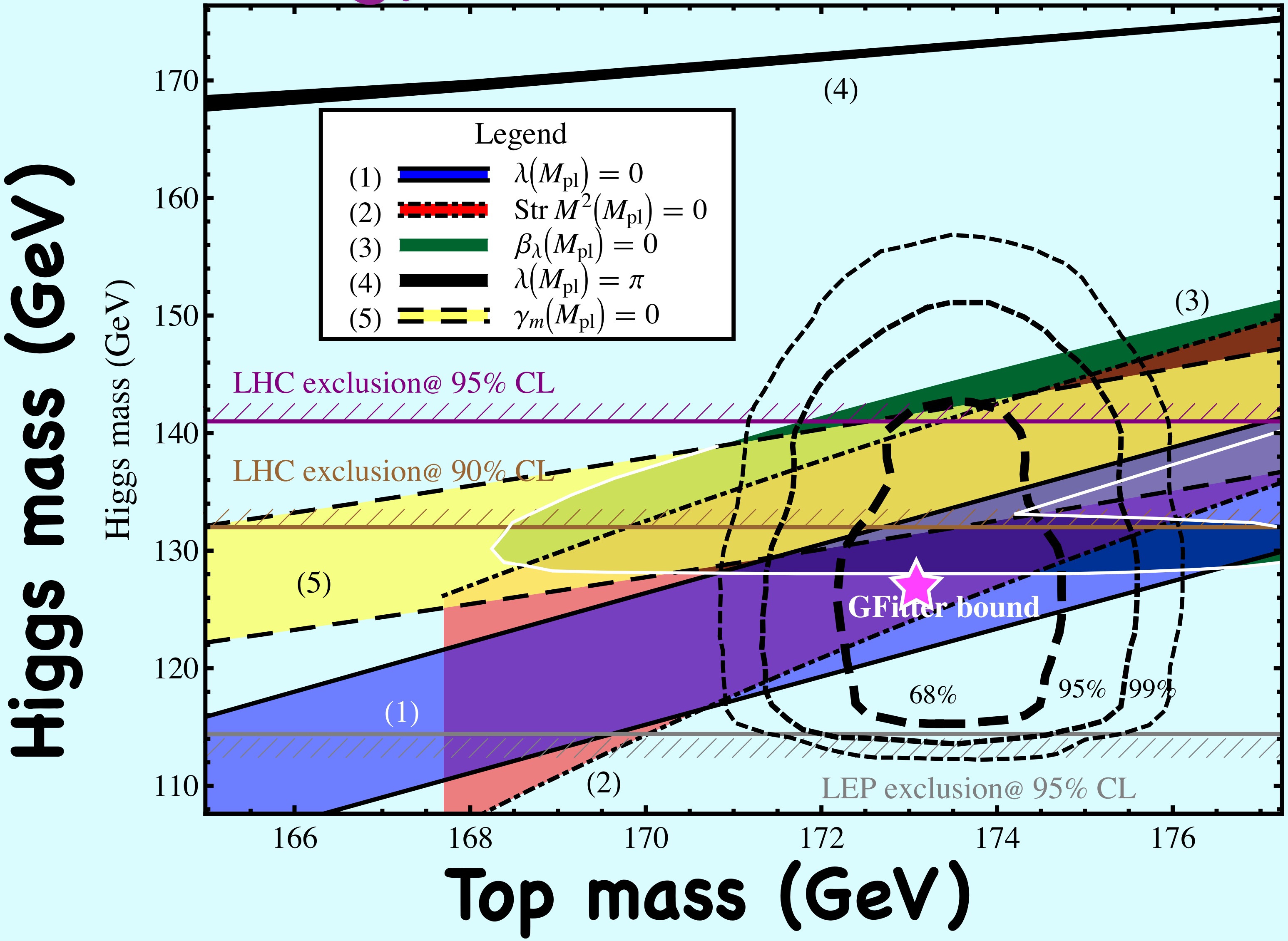
with scalars

*Fujii '74
*Minkowski, '77
*Englert, Gunzig, Truffin+Windey,'75
*Minkowski, '77
*Chundnovsky,'78
*Fradkin+Vilkovisky,'78
*Zee,'79
*Smolin,'79
*Terazawa,'81
*Nieh, '82
....

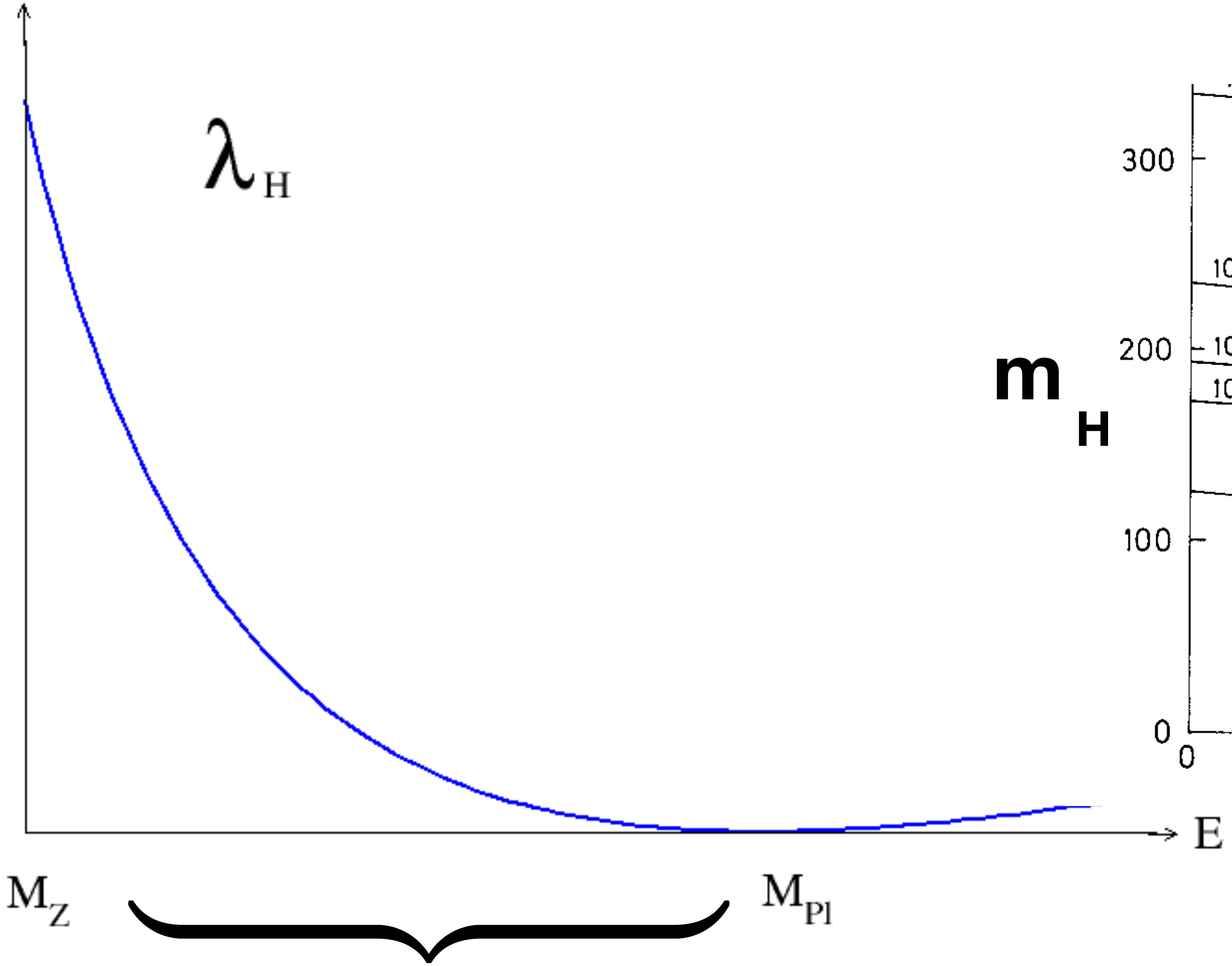
without scalars

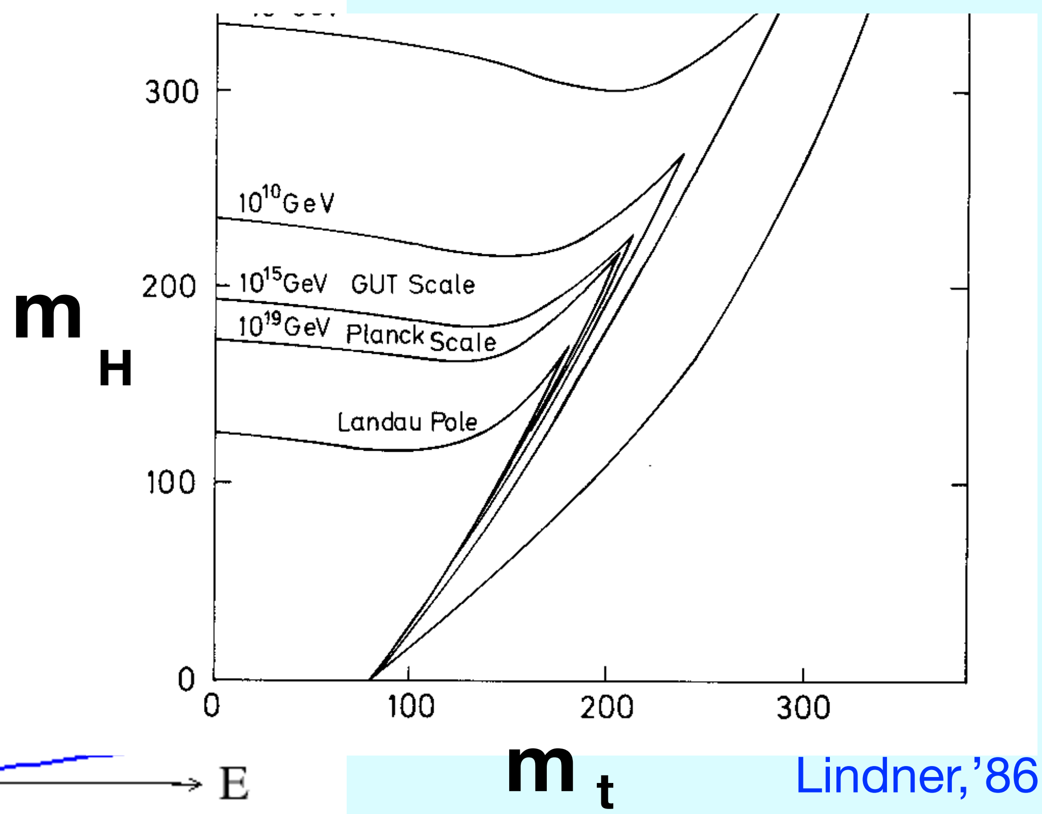
*Akama, Chikashige+ Matsuki,'78
*Adler,'80
*Zee,'81
....

Indications for Scale Invariance: At low energy



Holthausen+Lee+Lindner, '12. See also
Berzukov et al, '12; Degrassi et al '12, Buttazzo et al, '12





Lindner,'86

Desert => Scale invariance is broken only by anomaly if μ_H = 0.

Bardeen,'95

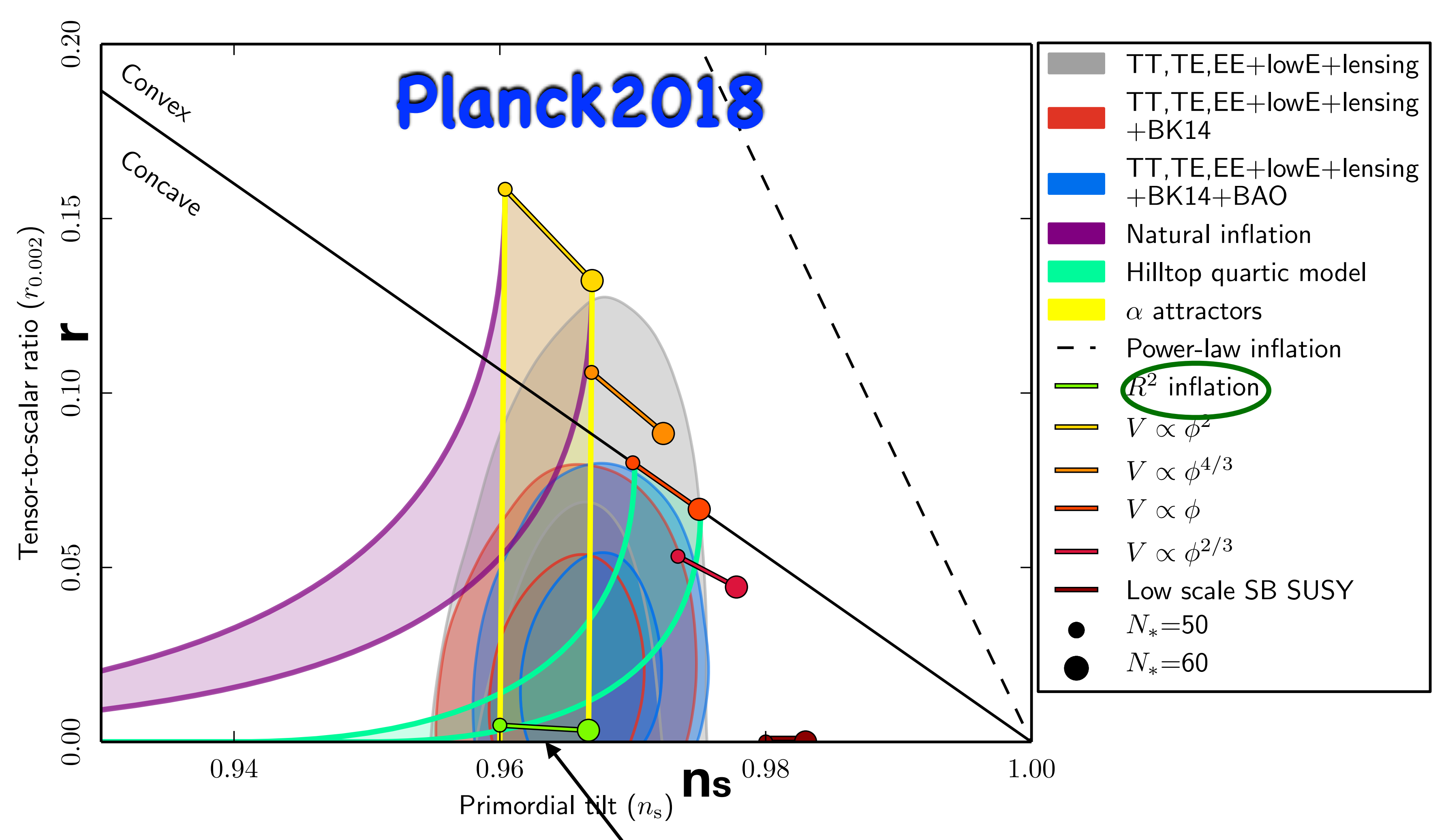
$\{\lambda_H \ , \ y_t \ , \ g_3\}$ - system is asymptotically free.

The max. value of $y_t^2/\lambda_H \quad \rightarrow \quad m_t^2/m_H^2 \simeq 1.9 \left(\left[m_t^2/m_H^2 \right]_{\text{exp}} \simeq 2.0 \right)$

JK, Sibold, Zimmermann, '85;'88

Indications for Scale Invariance:
At high energy

Planck Collaboration: Constraints on Inflation

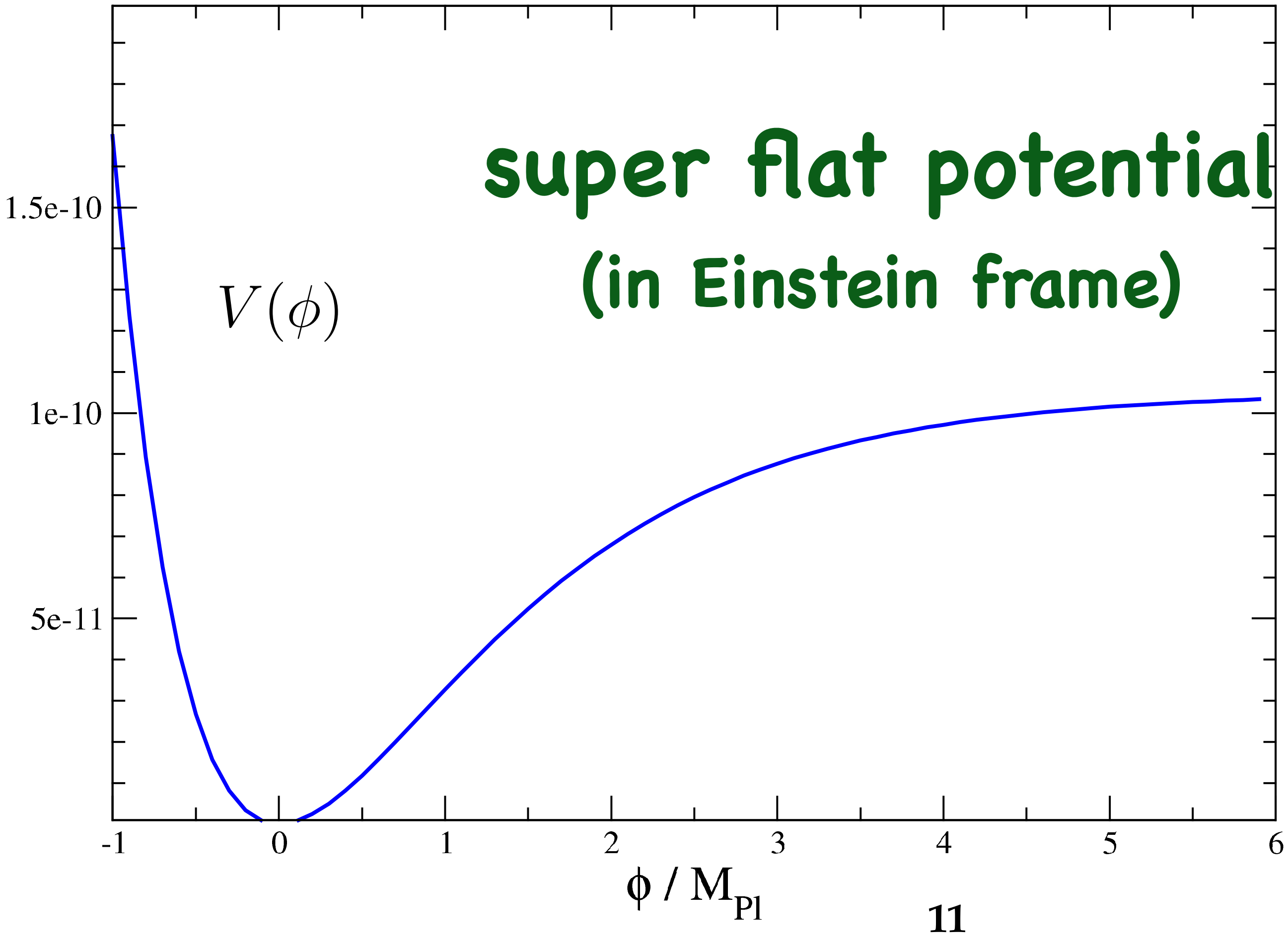


R^2 inflation

scale invariant

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{M_{\rm Pl}^2}{2}R + \begin{cases} \gamma R^2 \quad (\gamma \sim 10^9) \\ \beta |H|^2 R - \lambda_H |H|^4 \quad (\beta \sim 10^4) \end{cases}$$

for $\begin{cases} R^2 \text{ inflation, Starobinsky, '80} \\ \text{Higgs inflation, Bezrukov and Shaposhnikov, '08.} \end{cases}$



$$r \propto \left(\frac{V'(\phi)}{V(\phi)}\right)^2$$

Scenarios for scalegenesis

* Perturbative scenario

$\langle \phi \rangle \neq 0$ by CW   Coleman+Weinberg,'73; Gildener+Weinberg,'76

* Nonperturbative scenario

$\langle \bar{\psi}\psi \rangle \neq 0$ Nambu+Jona-Lasinio,'60;'61

$\langle S^\dagger S \rangle \neq 0$ Osterwalder+Seiler, 78; Fradkin+Shenker,'79

* By boundary condition

(Inertial spontaneous scale symmetry breaking)

Ferreira,Hill+Ross,'16;'18

Nonperturbative scenario

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*Weinberg, '76;79
*Susskind,'79

••
*Hur,Jung,Ko,Lee,'07
*Hur,Ko,'11
*Heikinheimo et al,'13

*JK,Holthausen,Lim,Lindner,'13
JK,Lim,Lindner,'14
*JK, Yamada,'15
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*
....

Perturbative scenario

*Coleman -Weinberg, '73
*Gildener -Weinberg, '76

*Hempfling,'96
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*Meissner,Nicolai,'07,
*Chang,Ng,Wu,'07
*Foot,Kobakhidze,Volkas,'07
*Espinosa,Quiros,'07
*Iso,Okada,Orisaka,'09
*Holthausen,Lindner, Schmidt,'09
....
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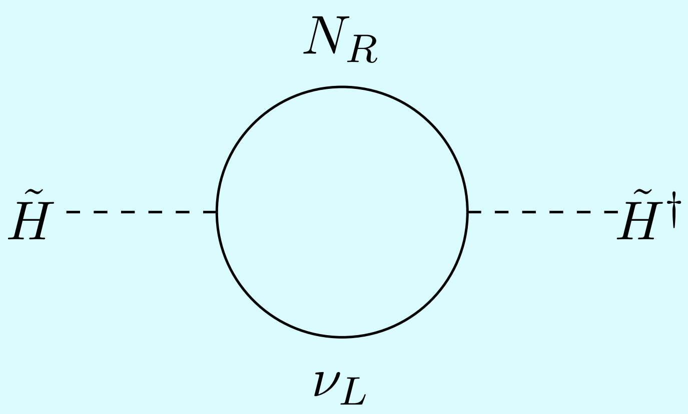
*Jung, Lee+Nam,'19;
*Wetterich, 19;
*Salvio, 20 for reviews

Application to the neutrino option

Brivo+Trott ,'17



$$|\Delta\mu_H^2| \sim \frac{y_\nu^2 m_N^2}{4\pi^2}$$

Vissani,'97; Casa et al,'99;
Clarke et al,'15; Bambhaniya et al,'16

Use it to trigger EW symmetry breaking

Brivo+Trott ,'17

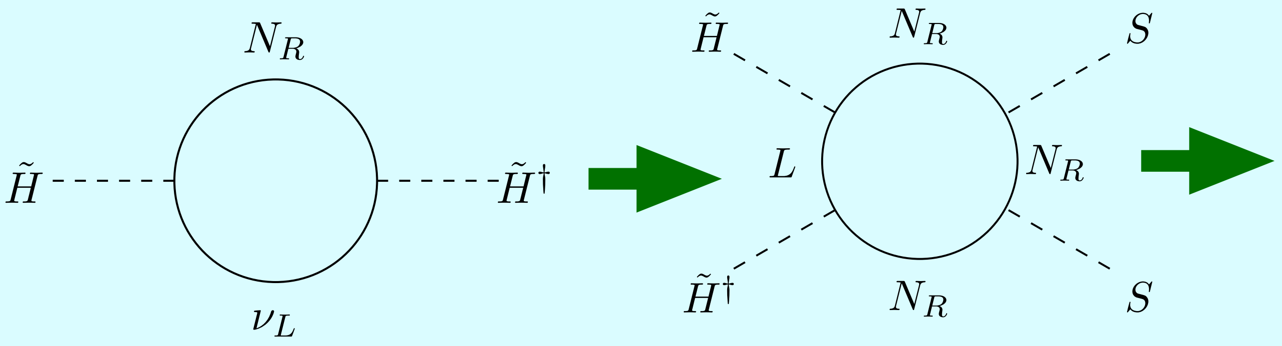
$$|\Delta\mu_H^2| \sim \frac{y_\nu^2 m_N^2}{4\pi^2}$$ ~ (100 GeV)^2

if $m_N \sim 10^7$ GeV and type I seesaw is used.

Scale invariant extension by

Brdar, Emonds, Helmboldt+Lindner,'19

(talk by Rezacek)



$$|\Delta\mu_H^2| \sim \frac{y_\nu^2 m_N^2}{4\pi^2}$$

quadratic corr. => logarithmic corr.

to $\lambda_{HS} S^2 \, H^\dagger H$ with $\lambda_{HS} << \frac{y_\nu^2 y_N^2}{4\pi^2} \sim O(10^{-12})$!!

Higgs naturalness => Naturalness of λ_{HS}

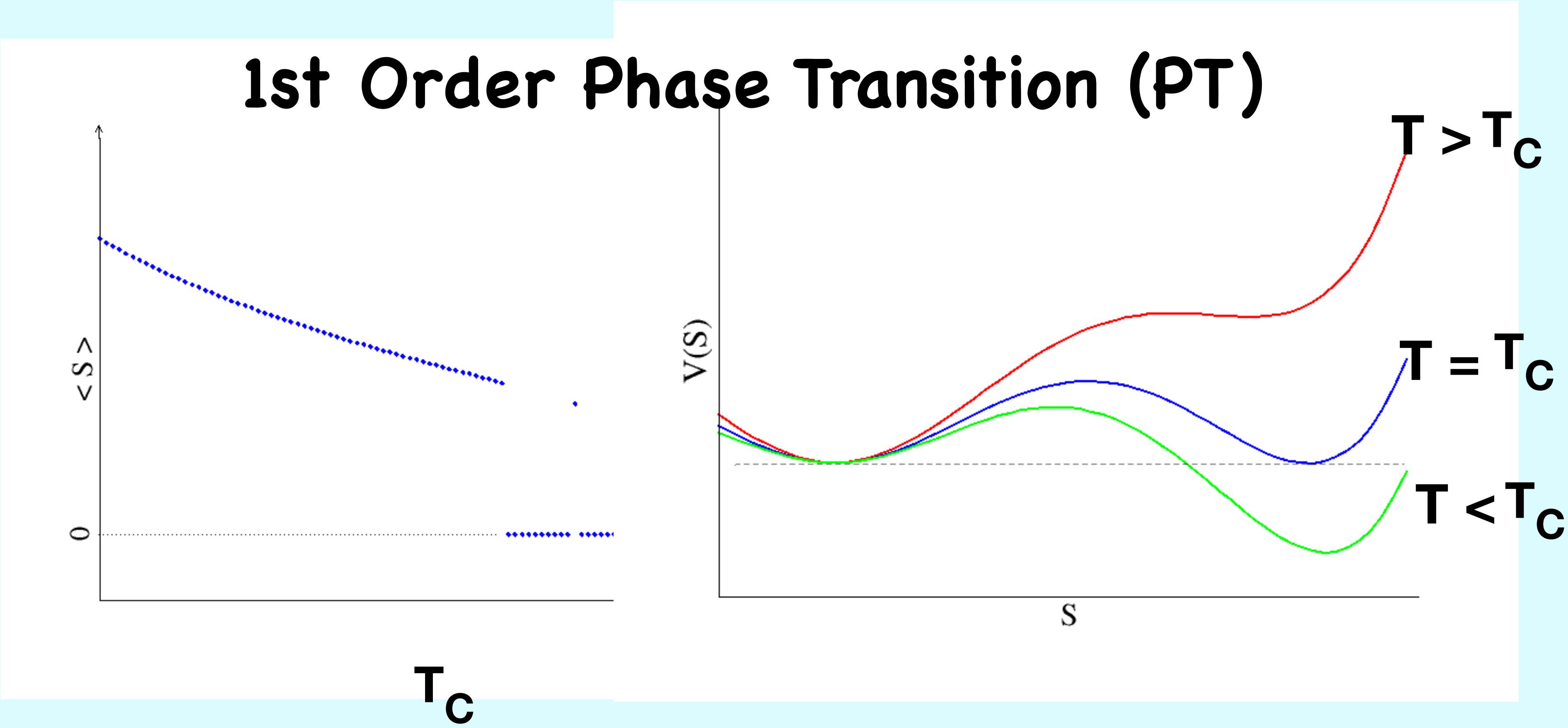
Related topics: GW, Leptogenesis, etc

Brdar, Helmboldt+JK,'19;
Brivo+Trott,'19, '20;Brdar, Helmboldt, Iwamoto+Schmitz ,'19;
Brivo, Moflat, Pascoli+Turner,'20Aoki, Brdar+JK,'20

Characteristics

of spontaneous scale symmetry breaking at finite temperature

1st Order Phase Transition (PT)



at the laboratory (H=0)

In the expanding Universe

Nucleation rate

$\Gamma \simeq H^4$ **for PT to start =>** $T_n < T_C$

(n=nucleation)

$$\Gamma(T) \simeq T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} \exp(-S_3/T)$$

Linde,'83

(talk by Gonzalez)

$$\simeq \Gamma(T_n) e^{-\beta \Delta t} \text{ for } T \sim T_n$$

$(S_3 = 3 - d \text{ Euclidean action})$

$$\frac{S_3}{T_n} \sim 140$$

$1/\beta$ duration of PT

$$\frac{\beta}{H} = T \frac{d}{dT}\left(\frac{S_3}{T}\right) |_{T=T_n}$$

$$\frac{\beta}{H} \sim S_3/T_n \sim O(100)$$ Hogan,'83; Witten,'84

In scale invariant theories:

β/H

- $\sim O(10)$ for Coleman-Weinberg

  Konstandin+Serpico,'11; Marzola,Racioppi+Vaskonen,'17; Brdar,Helmboldt+JK,'18; Prokopec,Rezacek+Swiezewska,'19;….

- $\sim O(10^{3\sim4})$ for $\langle\bar{\psi}\psi\rangle \neq 0$ or $\langle S^\dagger S\rangle \neq 0$

  JK+Yamada,'16; Helmboldt,JK+van der Woude,'19; Aoki+JK,'19

Coleman-Weinberg scenario

β /H is small => long lasting PT => $T_n \ll T_C$

Supercooled PT

If $T_n < T_{EW}$, T_n > or < T_{QCD},
a new cosmological history has to be drawn:

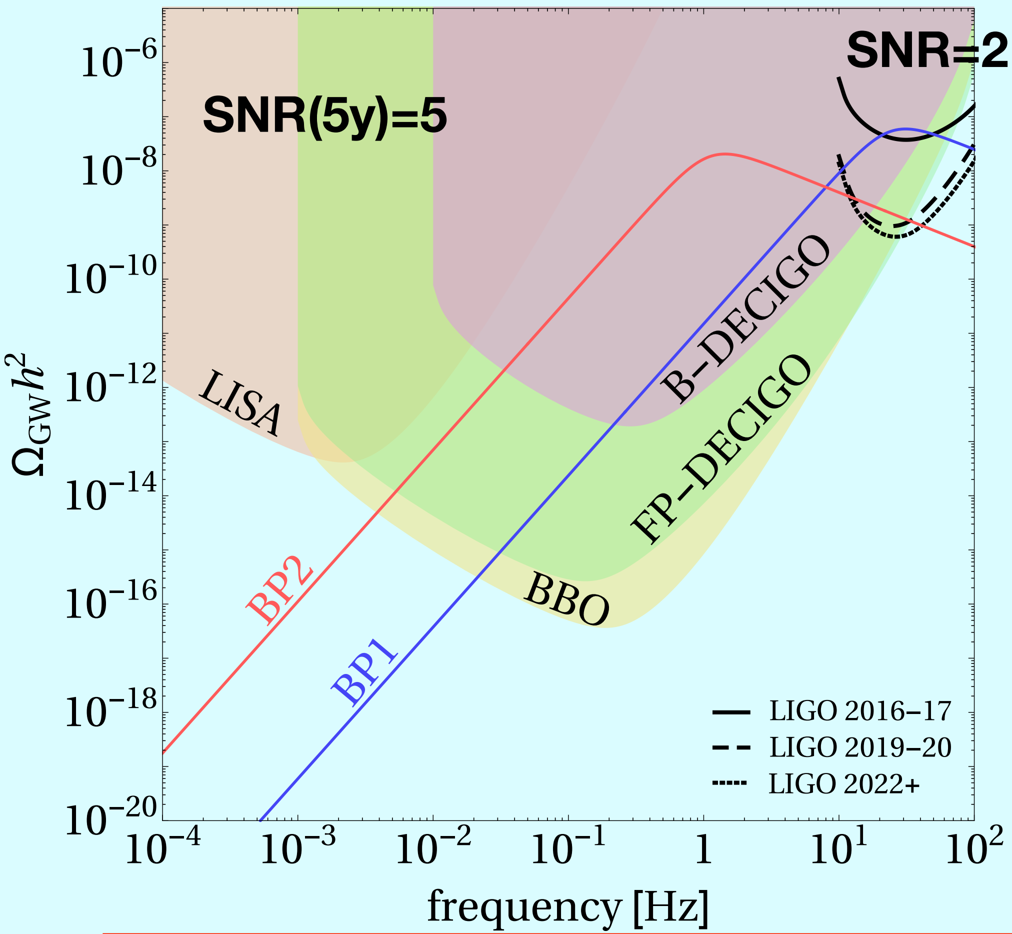
* DM production
* Baryogenesis
* EW PT
* Reheating etc

Konstandin+Servant,'11; Iso,Shimada+Serpico,'17;Hambye,Strumia+Teresi,'18, Jinno et al,'19; Brdar,Helmbolt+Lindner,'20; Döring et al,'21.....(talk by Döring)

Gravitational Waves

β /H is small => long lasting PT => T_n<< T_C
=> <S>/ T_n >>1 => strong PT => strong GW signal

Marzola,Racioppi+Vaskonen,'17;
Prokopec,Rezacek+Swiezewska,'19;
Marzo,Marzola+Vaskonen,'19;
Mohamednejad,'19;Ellis,Lewicki+No,'19;
Ellis,Lewicki+Vaskonen,'20,…..



Scale invariant ext. of Neutrino Option

Brdar,Helmboldt+JK,'18

$$T_C \simeq 2\times 10^8\ \text{GeV}\ ,\ T_n \simeq 4\times 10^4\ \text{GeV}\ ,\ \beta/H \simeq 10$$ **for B1**

Non-perturbative scenario

$$\frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3}{T}\right)|_{T=T_n} \sim \frac{S_3}{T} \sim O(100) \rightarrow f \sim 10^{-8}\ \mathrm{Hz}$$

Witten,'84

No 1st principle calculation of S_3 / T

on going project ,USQCD, ,19

Analysis based on EFTs

Helmboldt,JK+van der Woude,'19

- Nambu-Jona-Lasinio (NJL)
- Polyakov-NJL (PNJL)
- Linear Sigma Model (LSM)

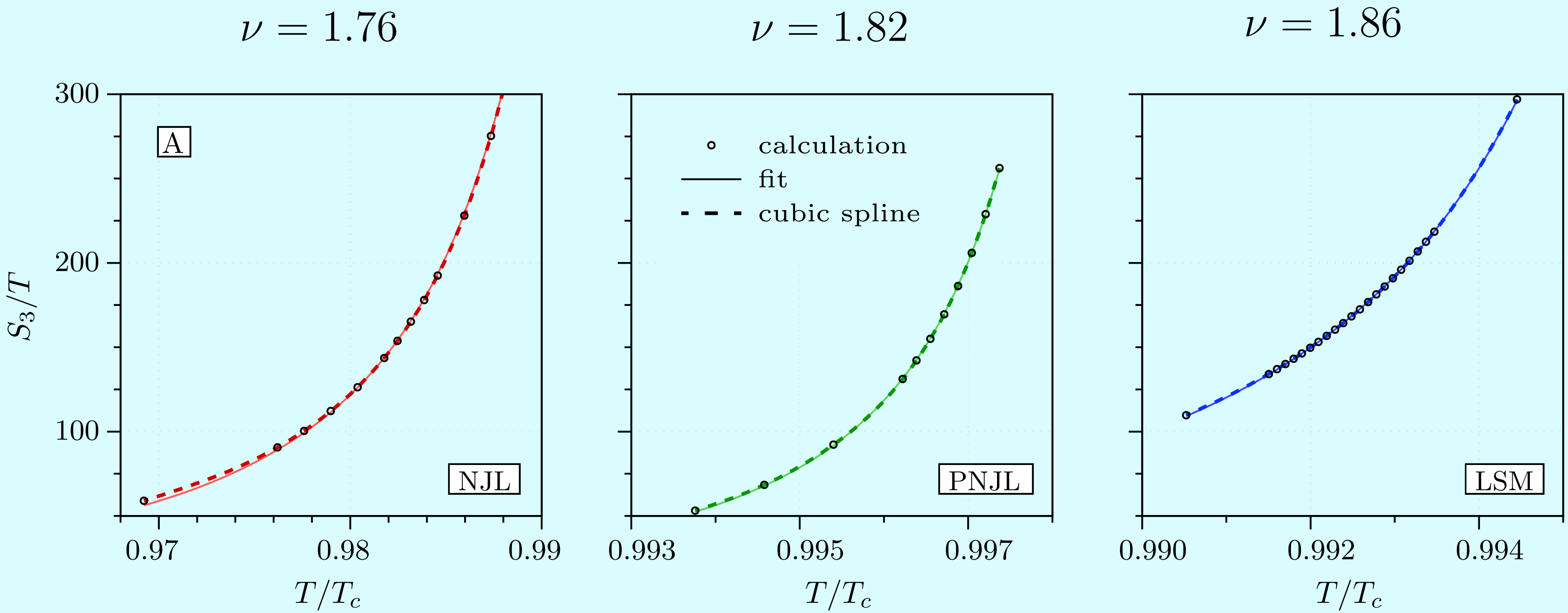
Tsumura,Yamada+Yamaguchi,'17;
Croon,Houtz+Sanz,'19

Holographic QCD, talk by Schwaller

Critical-Phenomena-like behavior of S_3 / T

$$\frac{S_3}{T} \propto \left(1 - T/T_C\right)^{-\nu}$$

anticipated by Hogan,'83



Helmboldt,JK+van der Woude,'19

But $\beta/H \sim 10^{(3\sim4)}$

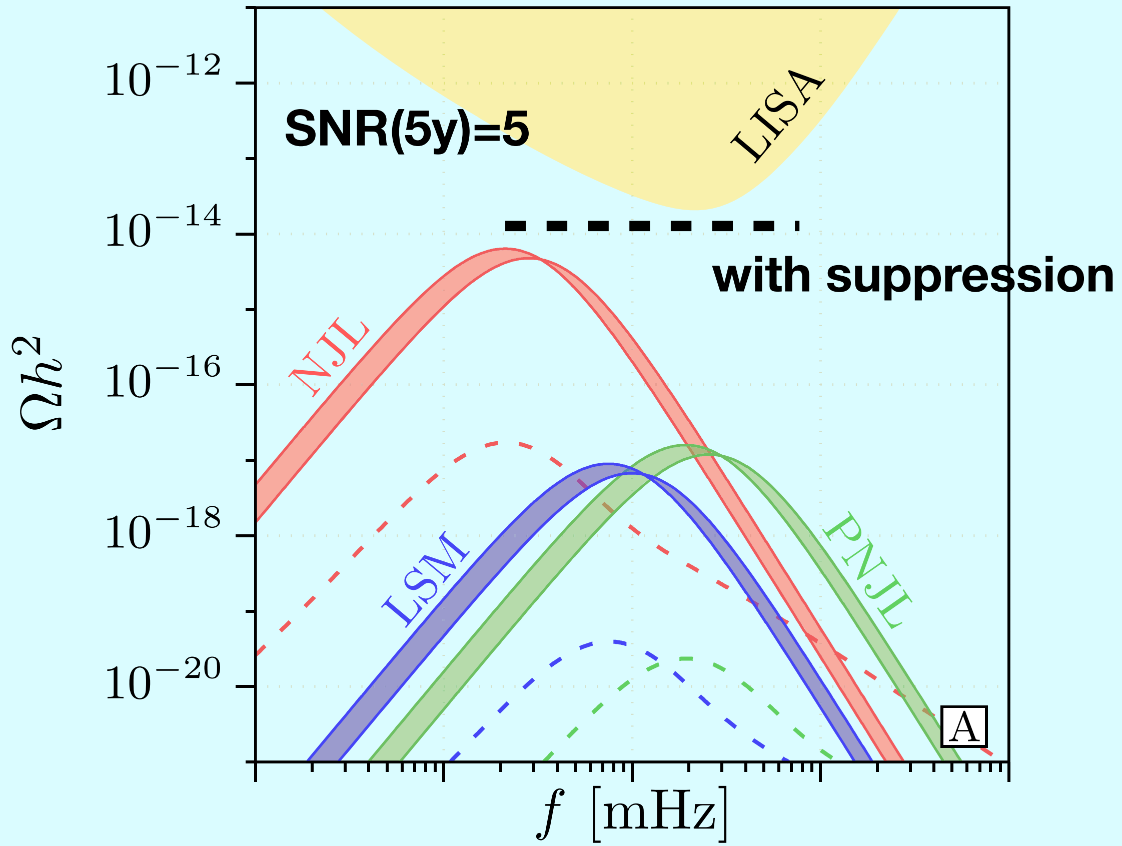
=> $f \sim 10^{-3}$ Hz ($\sim 10^{-8}$ Hz by Witten,'84)

=> short PT

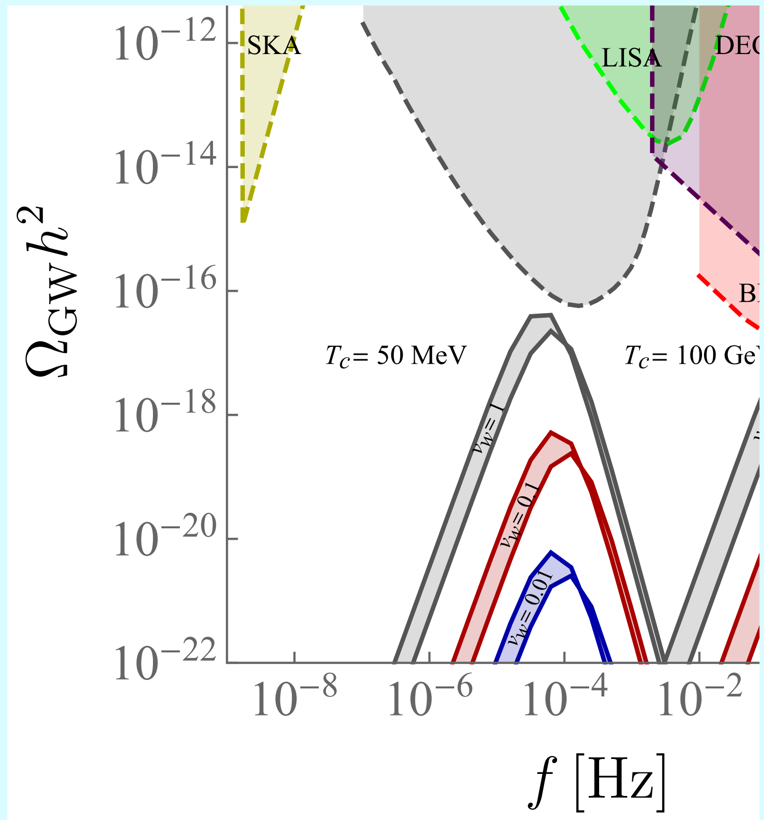
=> suppression of GW (sound wave)

The result is academic, because m_q =0.

Ellis,Lewicki+No,'18;'19



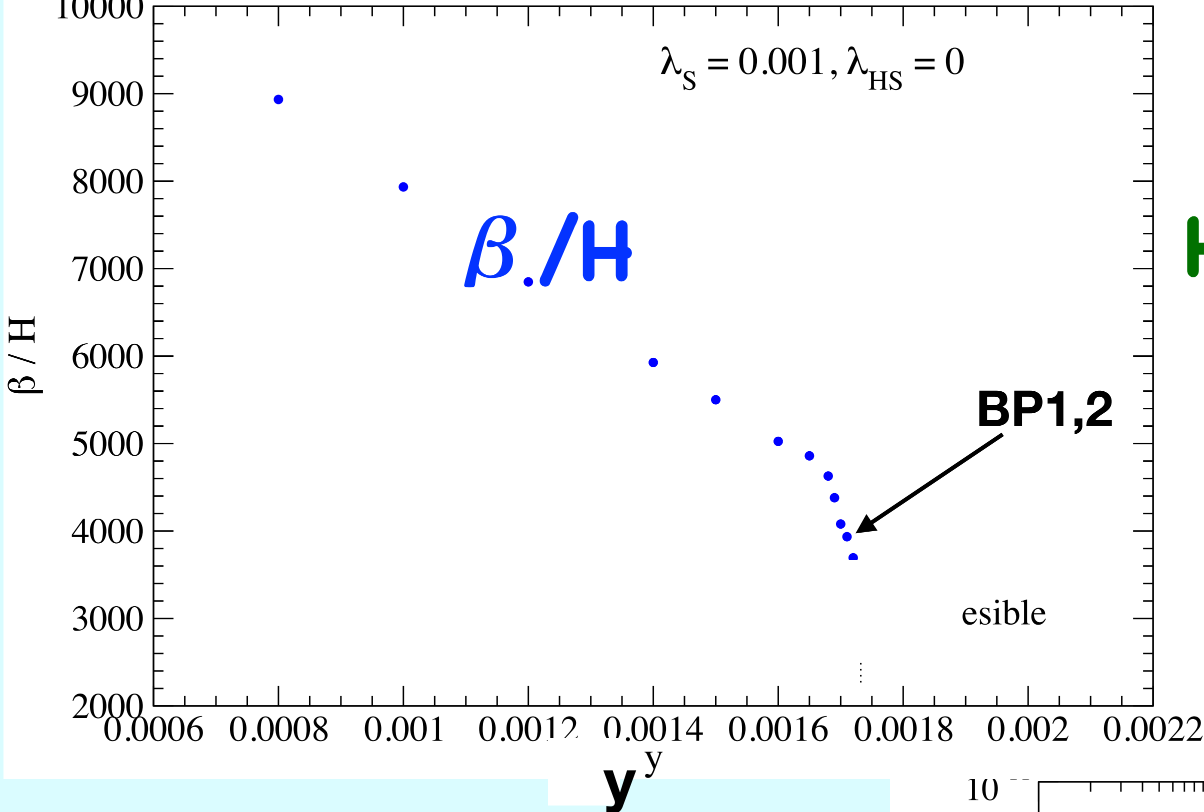
Helmboldt,JK+van der Woude,'19



from Schwaller's talk

Hidden QCD-like model

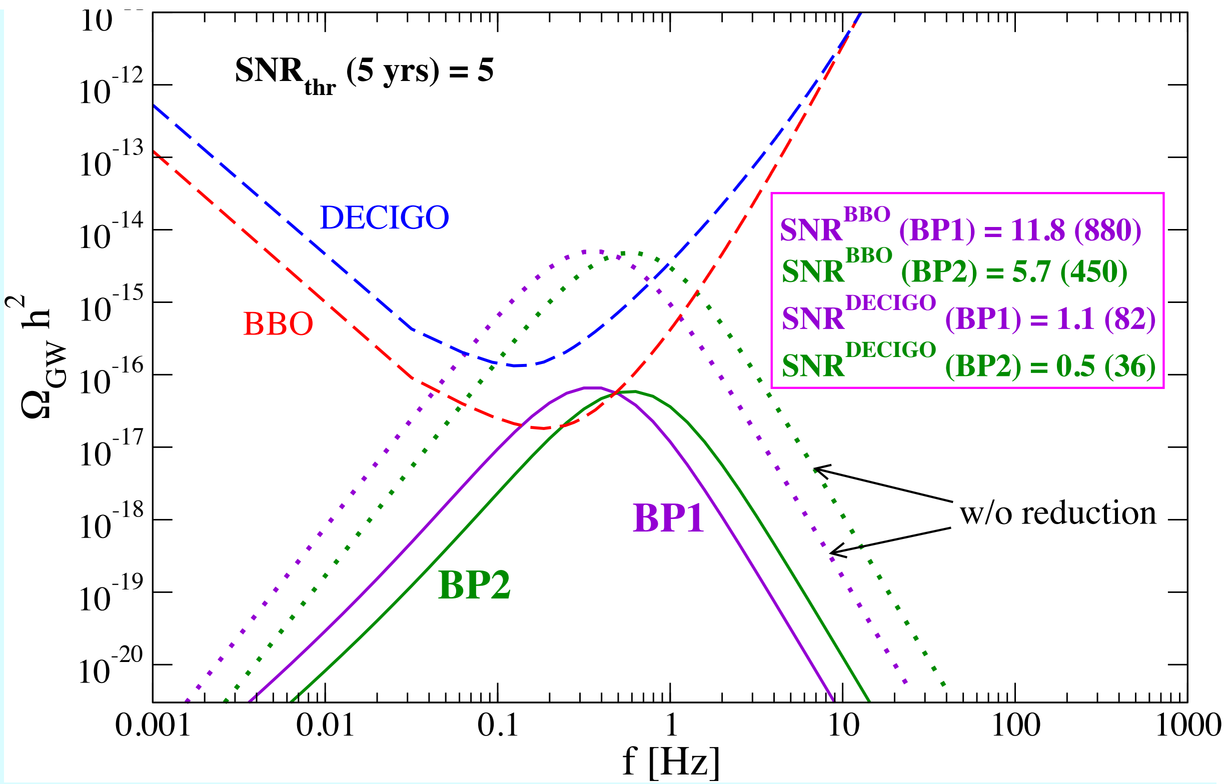
Aoki+JK, ,19



- - - - - - - without suppression

$$y\, S\, \bar{\psi}\psi$$

Hidden fermion



Including Gravity

Spontaneous generation (SG) of M_{Pl}

= SG of Einstein-Hilbert theory

The economic and simple way:

$$\frac{\xi_S}{2} S^2 R \to \frac{\xi_S}{2} \langle S \rangle^2 R \to \frac{M_{\rm Pl}^2}{2} R$$

$$M_{\rm Pl} = \sqrt{\xi_S} \langle S \rangle$$

Brans+Dicke,'61; Fujii,'74; Englert+Truffin+Grastmans,'76; Minkowsky,'77;……

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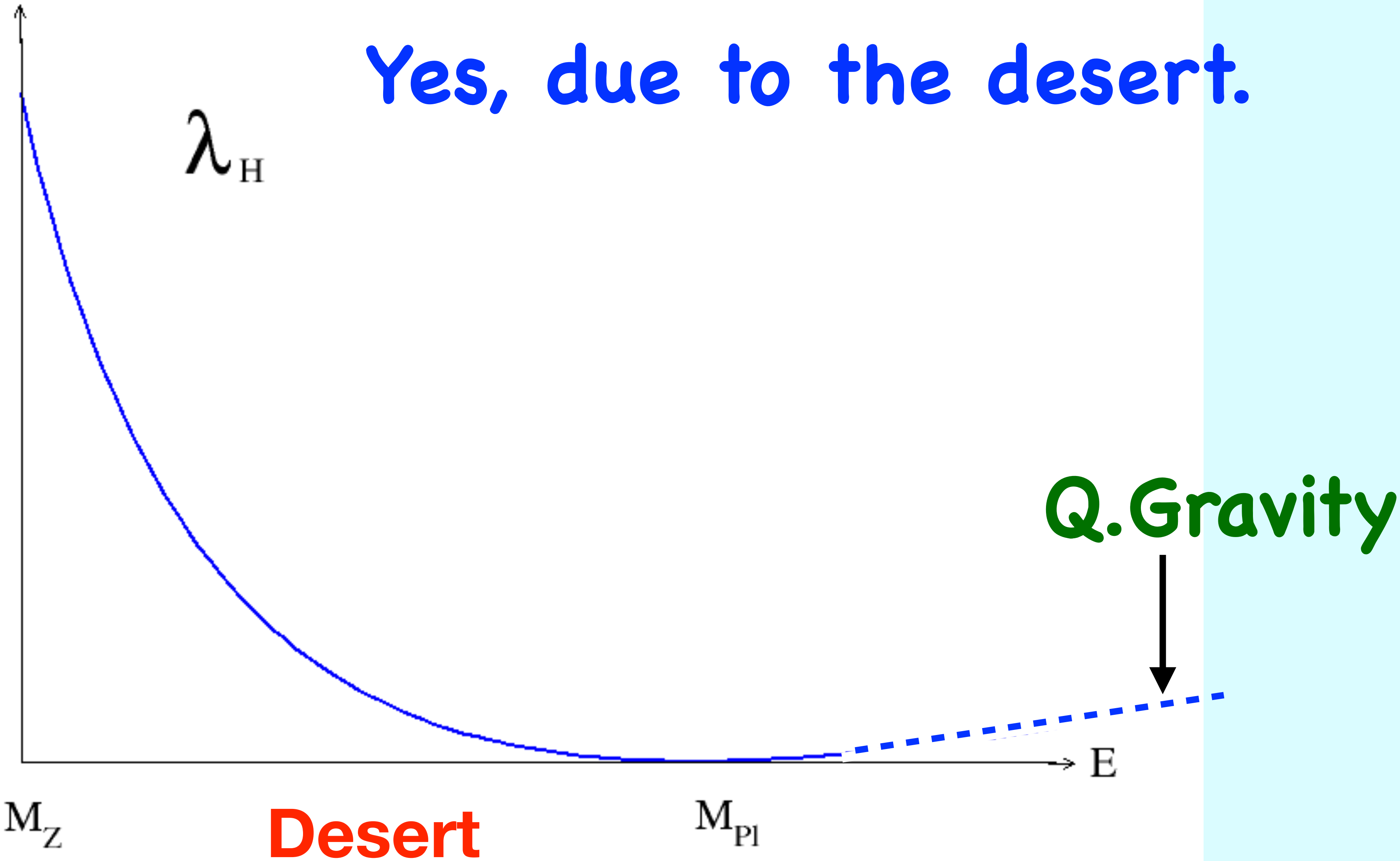
(NJL,'60+'61; CW,'73)

Is the spontaneous generation of M_{Pl} related to SM?

Yes, due to the desert.



Q.Gravity

Non-perturbative scenario: Fixed Point (asymptotic safety)

Weinberg,’78; Reuter,98; Don+Percacci,’98; Souma,’99;…….; Shapshnikov+Wetterich,’10; ..,,Wetterich,’19… (talk by Gutierrez)

Perturbative senario

‘t Hooft+Veltman,’74; Deser+van Nieuwenhuizen,’74; Stelle,’77;Fradkin+Tseytlin,’82; ……;Salvio+Strumia,’14; ’18; Salvio,’20

Strings …… (talk by Dvali, Ibanez)

Perturbative scenario

Salvio+Strumia,’14; ’18; Salvio,’20

based on renormalizability of Quadratic Gravity (QG)

Stelle,’77

Quantum corrections can be controlled.

QG includes:

$$-\frac{1}{2}\xi_{ab}\,\phi_a\phi_b\,R+\gamma\,R^2-\kappa\,W^2$$

$W=$ Weyl tensor

Origin of massive spin-two ghost (discussed by Koshelev)

Naturalness of λ_{HS}

$$M_{\rm Pl}^2 = \xi_S \langle S \rangle^2 \to \lambda_{HS} \langle S \rangle^2 H^\dagger H \to \lambda_{HS} \langle S \rangle^2 \lesssim O(m_H^2)$$

$$\lambda_{HS}/\xi_S \lesssim M_{\rm Pl}^2/m_H^2 \sim 2.5 \cdot 10^{-33} \;!!$$

Renormalizability + scale invariance

The naturalness may be achieved

Salvio+Strumia,'14;'18

$$\mathcal{L} \supset -(\beta_H H^\dagger H + \frac{1}{2}\beta_S S^2) R + \gamma R^2 - \kappa W^2$$

$$\mu \frac{d\lambda_{HS}}{d\mu} = -\frac{\xi_S}{(4\pi)^2}\Big(\frac{5\xi_H}{4}\kappa^{-2} + \frac{\xi_H}{36}\gamma^{-2}(1+6\xi_H)(1+6\xi_S) \Big) + O(\lambda_{HS})$$

Salvio+Strumia,'14;'18

$\lesssim 2.5 \cdot 10^{-33}\, \xi_S$ **0** $\infty \times 0 =$ **??**

$$\begin{cases} \kappa^{-1} \to 0 \\ \gamma^{-1} \to \infty \\ \xi_{H,S} \to -1/6 \end{cases} \quad \text{as} \quad \mu \to \infty$$

Fradkin+Tseytlin,'82; Avramidi,'95

Elizalde et al,'96; Yoon+Yoon,'97;Buchbinder,'92; Shapiro, '20

Even μ around M Pl

$$\Delta\lambda_{HS} \lesssim 2.5 \cdot 10^{-33}\, \xi_S$$

Strong constraints on $\xi_{H,S}$, γ and κ

$$\xi_{H,S} \;,\; \gamma \;,\; \kappa$$

I. responsible for the naturalness of λ_{HS}

and at the same time

II. control the slow-roll parameters of inflation

γ **for R^2 Inflation**

Starobinsky,'80

ξ_H **for Higgs inflation**

Bezrukov+Shaposhnikov,'07

κ **contributes to r**

Baumann,H.Lee+Pimentel,'15; Salvio,'19

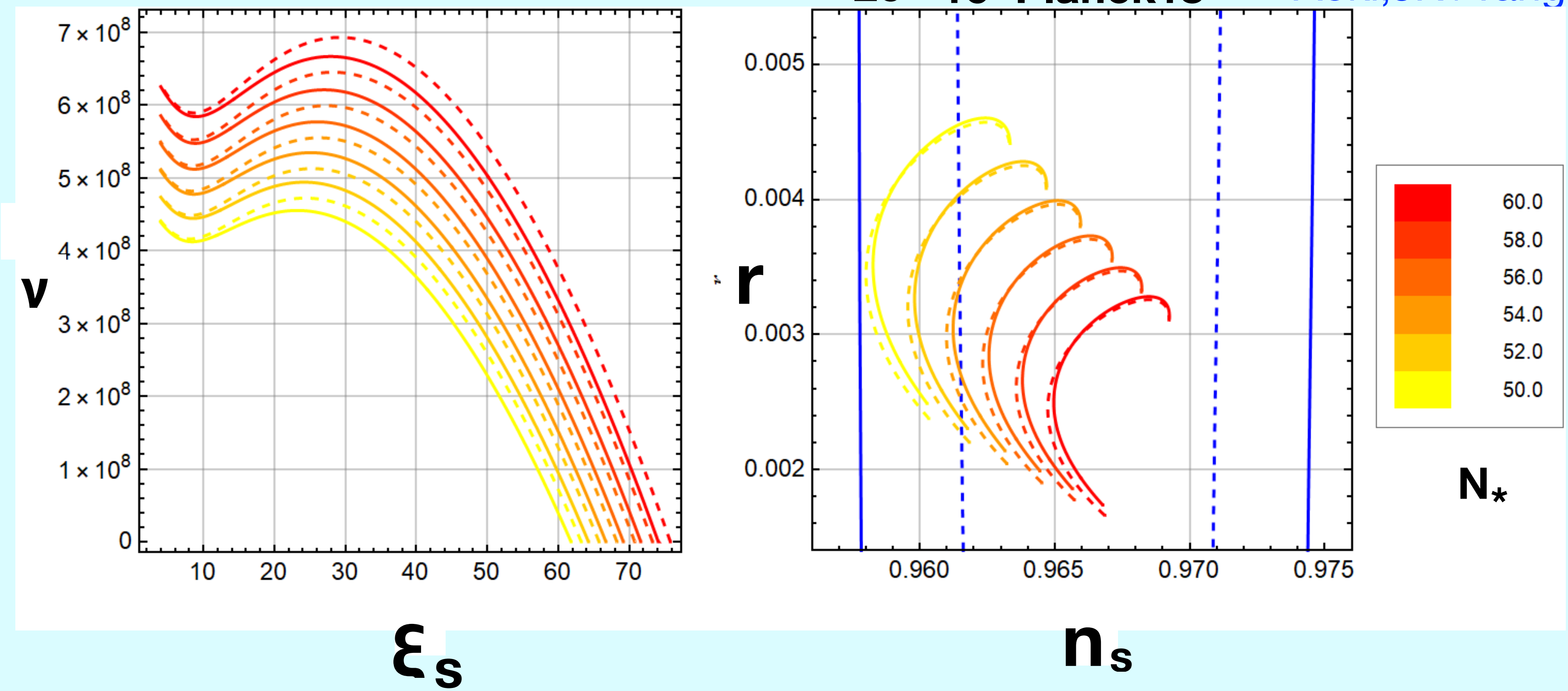
triggers SSB of scale invariance

JK,Kuntz,Rezacek+Saake, to appear

Scale invariant extension of the Starobinsky model

Salvio+Strumia,’14; Kannike et al,’15; Rinaldi et al,’14; Farzinnia+Kouwn,’15;
Ghilenea +H.M.Lee,’18; Karam+Pappas+Tamvakis,’18;JK,Lindner,Schmitz+Yamada,’18;
JK,Kuntz,Lindner,Rezacek,Saake+Trautner,’20; Ghoshal+Mukhejee+Rinaldi,’22;…
see e.g. Gialamas et al, 2104.04550 for more references (talk by Rezacek)

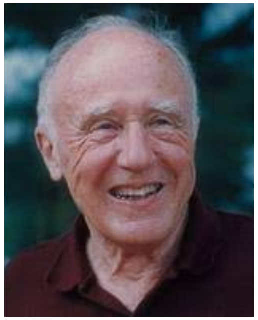
Aoki,JK+Yang,’22



Naturalness => $(\xi_H \lesssim 10^{-14}$ and $\kappa \gtrsim 10^{8})$ OR $(\xi_H \simeq -1/6$ and $\kappa \gtrsim 10^{19})$

Theoretical aspect:

Summary



1. E_{EW} and $M_{\mathbf{Pl}}$ can be spontaneously generated, both perturbatively and non-perturbatively

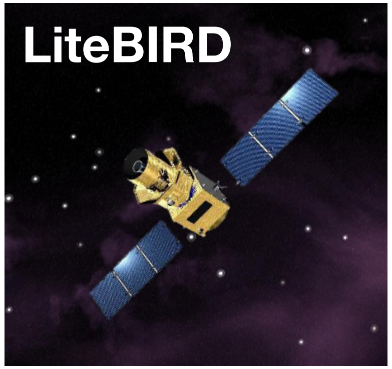
2. Naturalness of m_H $\Rightarrow$ naturalness of λ_{HS} $\Rightarrow$ multiplicative solution

3. The desert $\Rightarrow$ the SM and Planck scale physics are directly related Naturalnessof λ_{HS} $\Leftrightarrow$ Inflationary parameters

Phenomenological aspect:

1. For CW breaking: Supercooling $\Rightarrow$ new history of the Universe, strong GW

2. For non-perturbative scale symmetry breaking: Short duration of PT$\Rightarrow$ suppression of GW should be confirmed by 1st principle calculations



3. Scale invariant extensions of the R^2 model of Starobinsky $\Rightarrow r \gtrsim r_{R^2} \sim O(10^{-3})$ and more than two scalars during inflation

Is it possible to distinguish these models by measuring small r and also non-Gaussianity in the CMB anisotropy and large scale structure by future experiments such as LiteBIRD, CMB-S4, Simons Observatory DESI, Euclid, LSST, etc ?