The Standard Model and (some of) its extensions

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Zuoz, August 14-20, 2016

I. The SM and its status, as of 2016

II. Problems of (questions for) the SM

III. Mirror Twin Higg World

IV. Anomalies in B-decays

V. Axion searches by way of their coupling to the spin

The Standard Model
and its status summarized

The SM Lagrangian
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} \not{D} \psi \qquad (\sim 1975\text{-}2000)$$

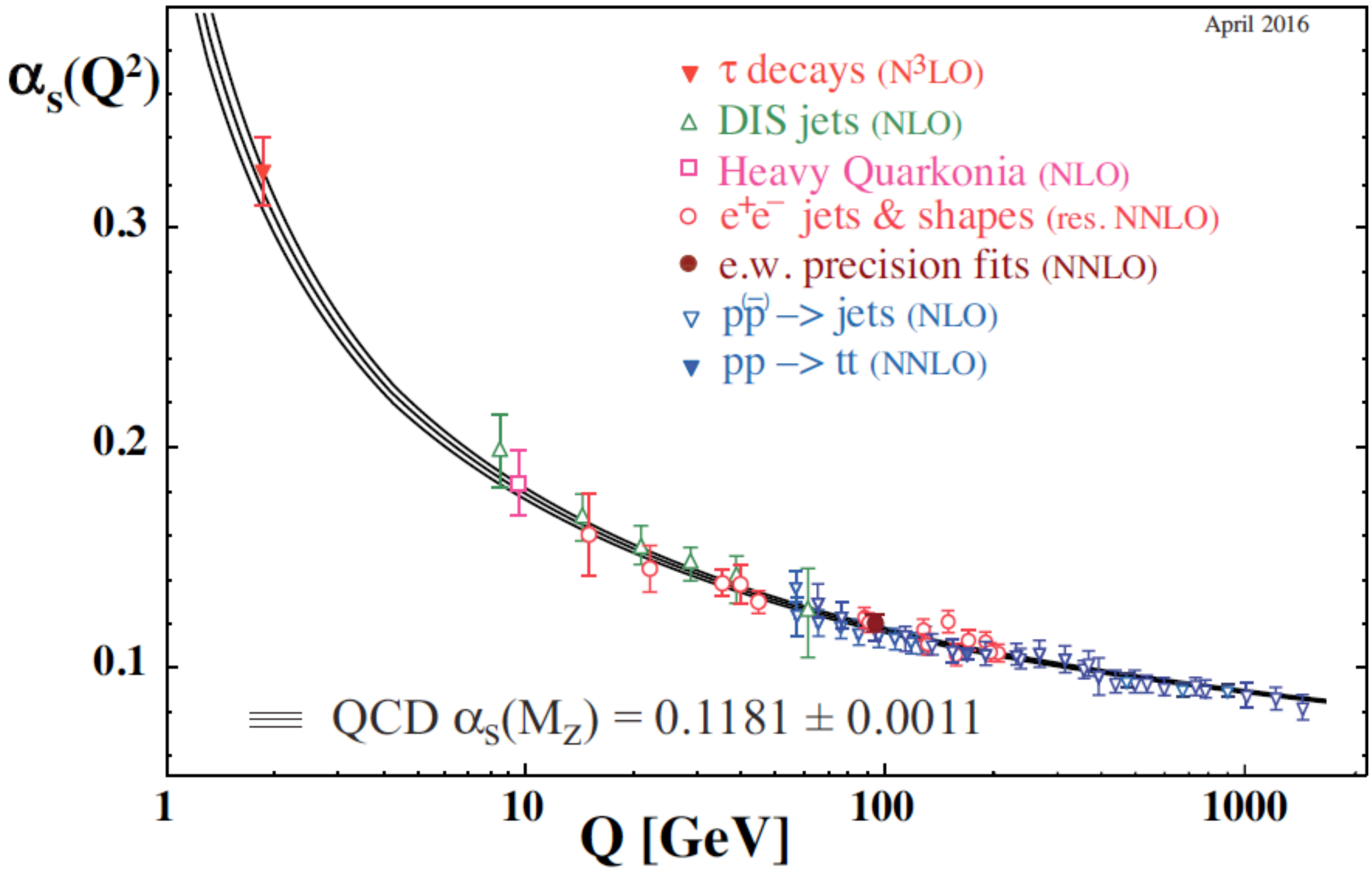
$$+ |D_\mu h|^2 - V(h) \qquad (\sim 1990\text{- } 2012)$$

$$+ \psi_i \lambda_{ij} \psi_j h + h.c. \qquad (\sim 2000\text{- now})$$

In () the approximate dates of the experimental shining of the various lines (at different levels)

The synthetic nature of PP exhibited

QCD in full strength



G. Dissertori 2016

even though in the strong coupling regime...

The observables at the Z-pole

Assuming quark-lepton and flavour universality,

3 effective observables only

$$V_\mu(Z\to f\bar f)=(\sqrt{2}G_F m_Z^2)^{1/2}\gamma_\mu(g_V^f-g_A^f\gamma_5)$$

$$g_A^f = T_{3L}^f(1+\frac{\epsilon_1}{2}) \qquad \frac{g_V^f}{g_A^f} = 1-4|Q_f|s^2(1+\frac{\epsilon_3-c^2\epsilon_1}{c^2-s^2})$$

$$\frac{\sqrt{2}G_F M_W^2}{\pi\alpha}(1-\frac{M_W^2}{M_Z^2})\equiv 1+\Delta r$$

$$\Delta r=\frac{1}{s^2}(-c^2\epsilon_1+(c^2-s^2)\epsilon_2+2s^2\epsilon_3) \qquad s^2c^2=\frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$$

+1 including flavour breaking in $Z\to b\bar b$

$$g_A^b = -\frac{1}{2}(1+\frac{\epsilon_1}{2})(1+\epsilon_b) \qquad \frac{g_V^b}{g_A^b} = \frac{1}{1+\epsilon_b}(1-\frac{4}{3}s^2(1+\frac{\epsilon_3-c^2\epsilon_1}{c^2-s^2})+\epsilon_b)$$

Altarelli, B 1990 Altarelli, B, Jadach 1991

The relation with S and T

(Peskin, Takeuchi 1990)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{2g^2}{M_W^2}[c_H \mathcal{O}_H + c_{WB}\mathcal{O}_{WB}]$$

Adimensional form factors	operators
$\widehat{S} = \Pi'_{W_3B}(0)$	$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$
$M_W^2 \widehat{T} = \Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\mathcal{O}_H = \lvert H^\dagger D_\mu H \rvert^2$

$$\delta\epsilon_1 \approx \hat{T} = -c_H \qquad \delta\epsilon_3 \approx \frac{c_W}{s_W}\hat{S} = 2\frac{c_W}{s_W}c_{WB}$$

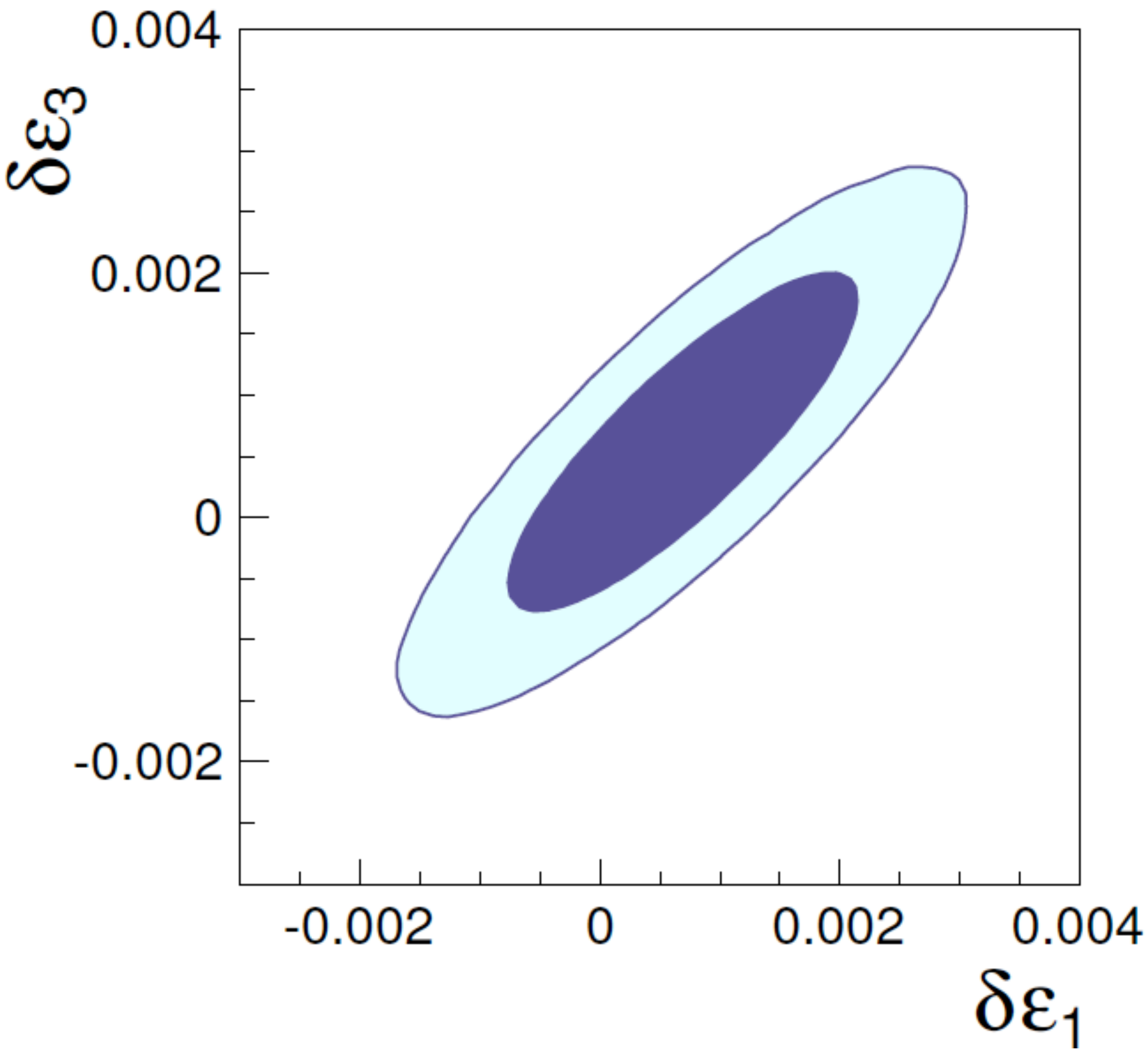
if no other operator contributes

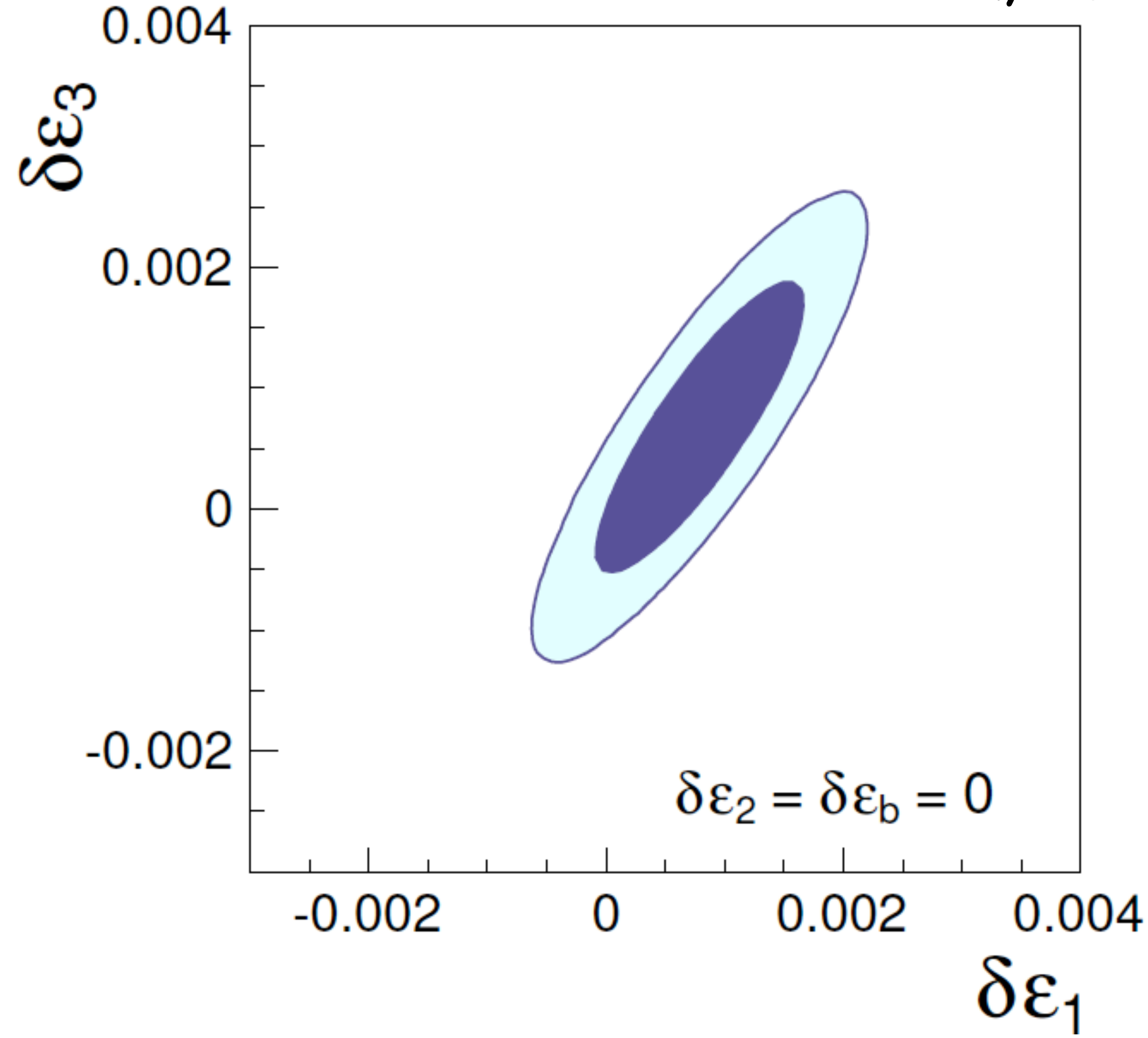
Currently

$$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}, \;\; \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$$

$$\delta\epsilon_i = \epsilon_i - \epsilon_i^{SM}$$

Ciuchini et al, 2013

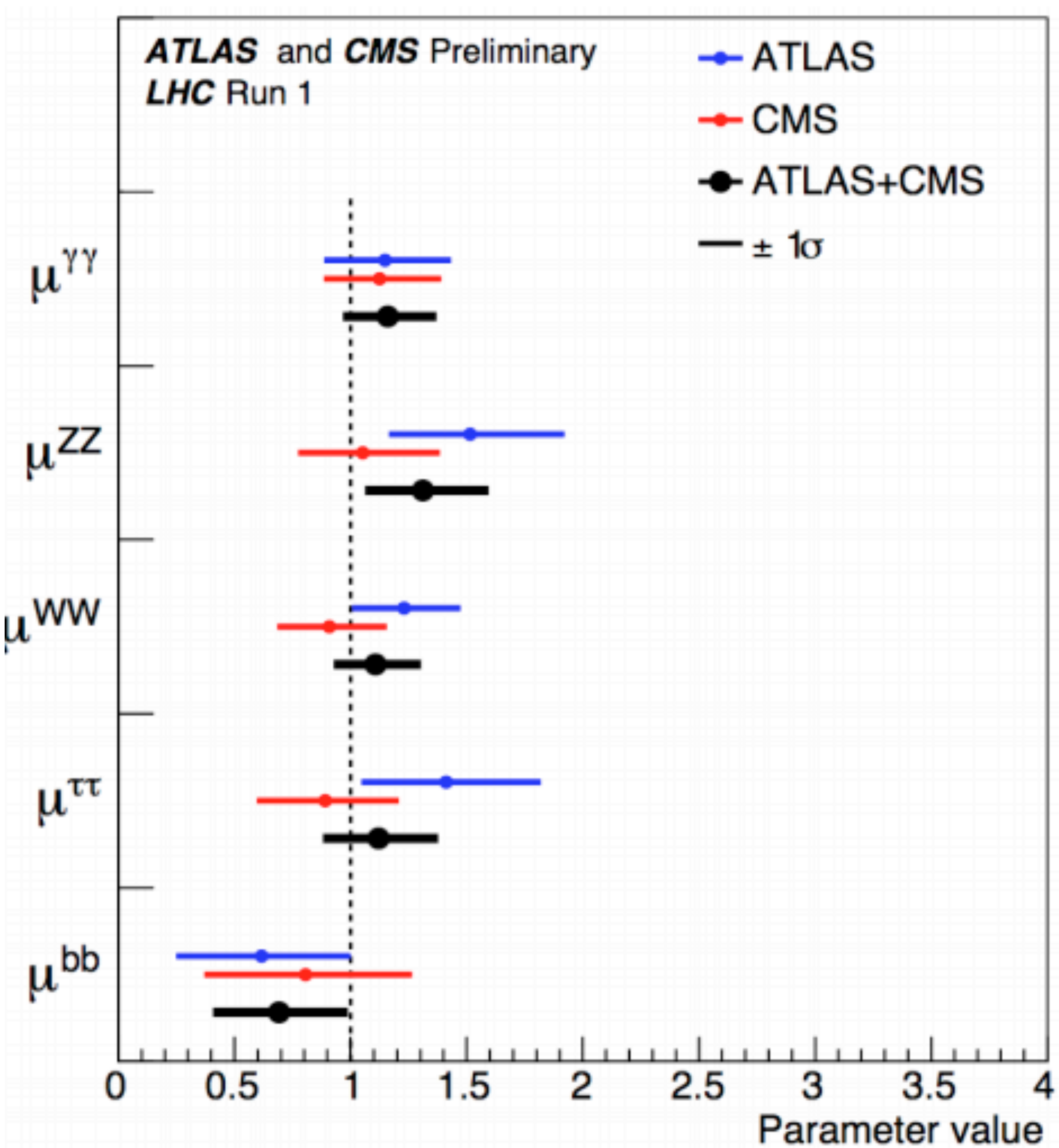


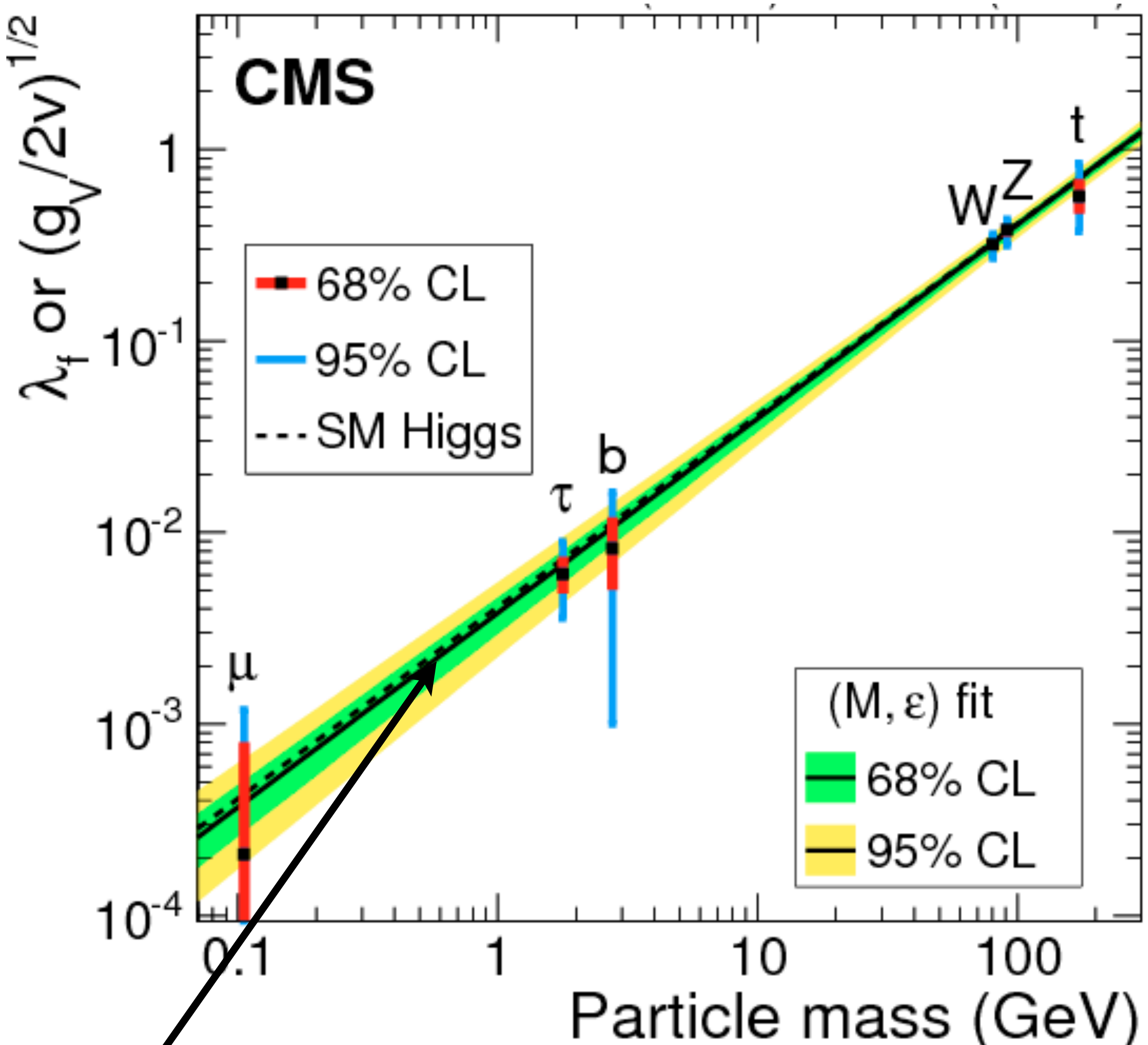


the "EW loops" measured at about 20% level

The Higgs boson triumph

SM production σ assumed





the slope of the line is the only parameter (v)

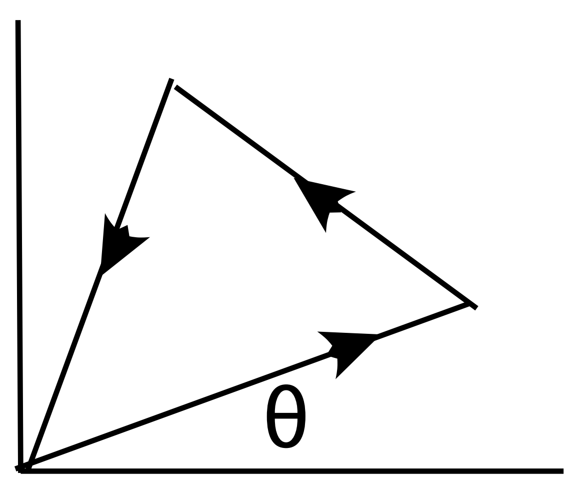
The single prediction of the SM in quark flavour physics

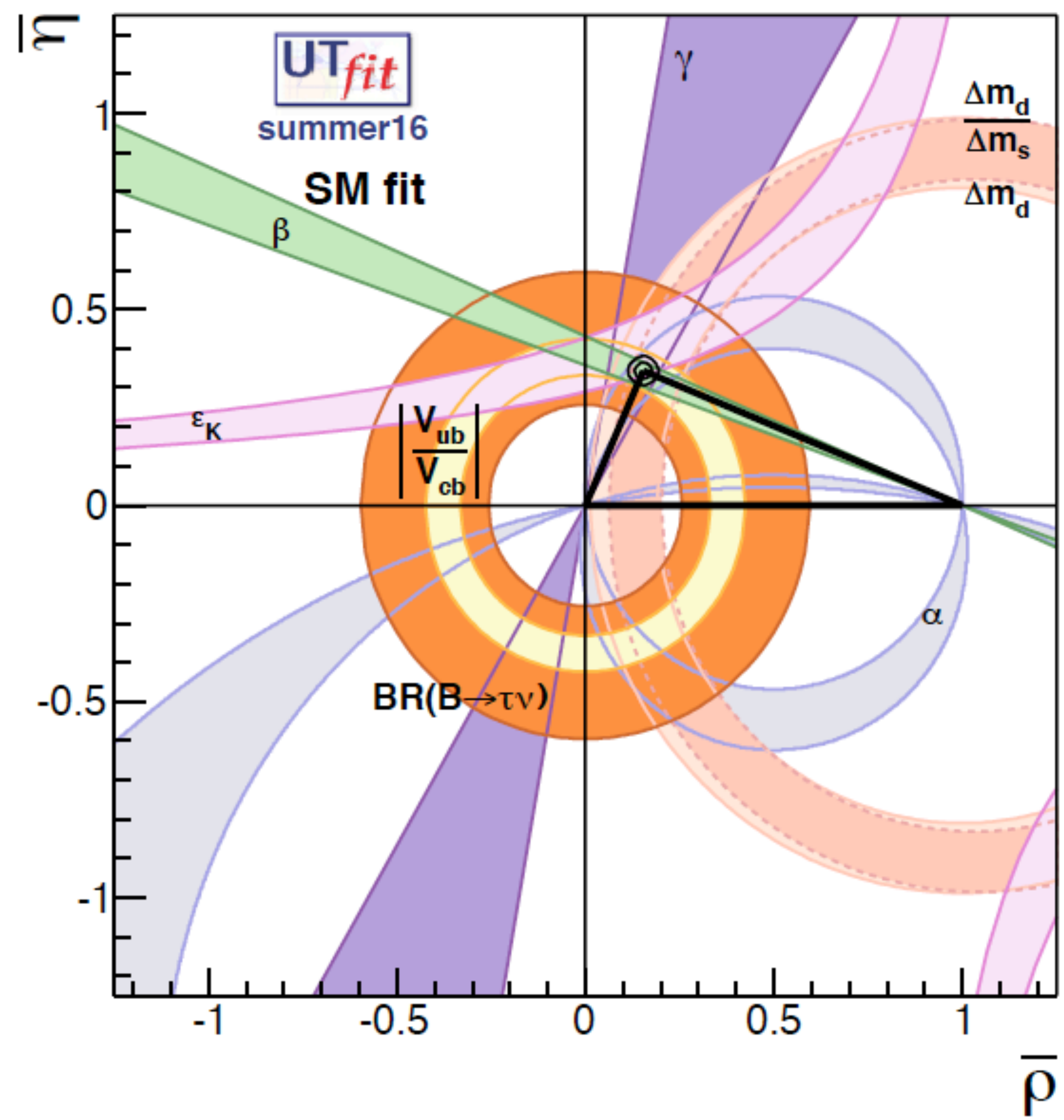
$$J^\mu_W|_{\text{quarks}} = \bar{u}^i_L \gamma^\mu d^i_L \quad \xrightarrow{u,d\ \text{mass}-\text{basis}} \quad \bar{u}^i_L V_{ij} \gamma^\mu d^j_L$$

$$VV^+ = 1$$

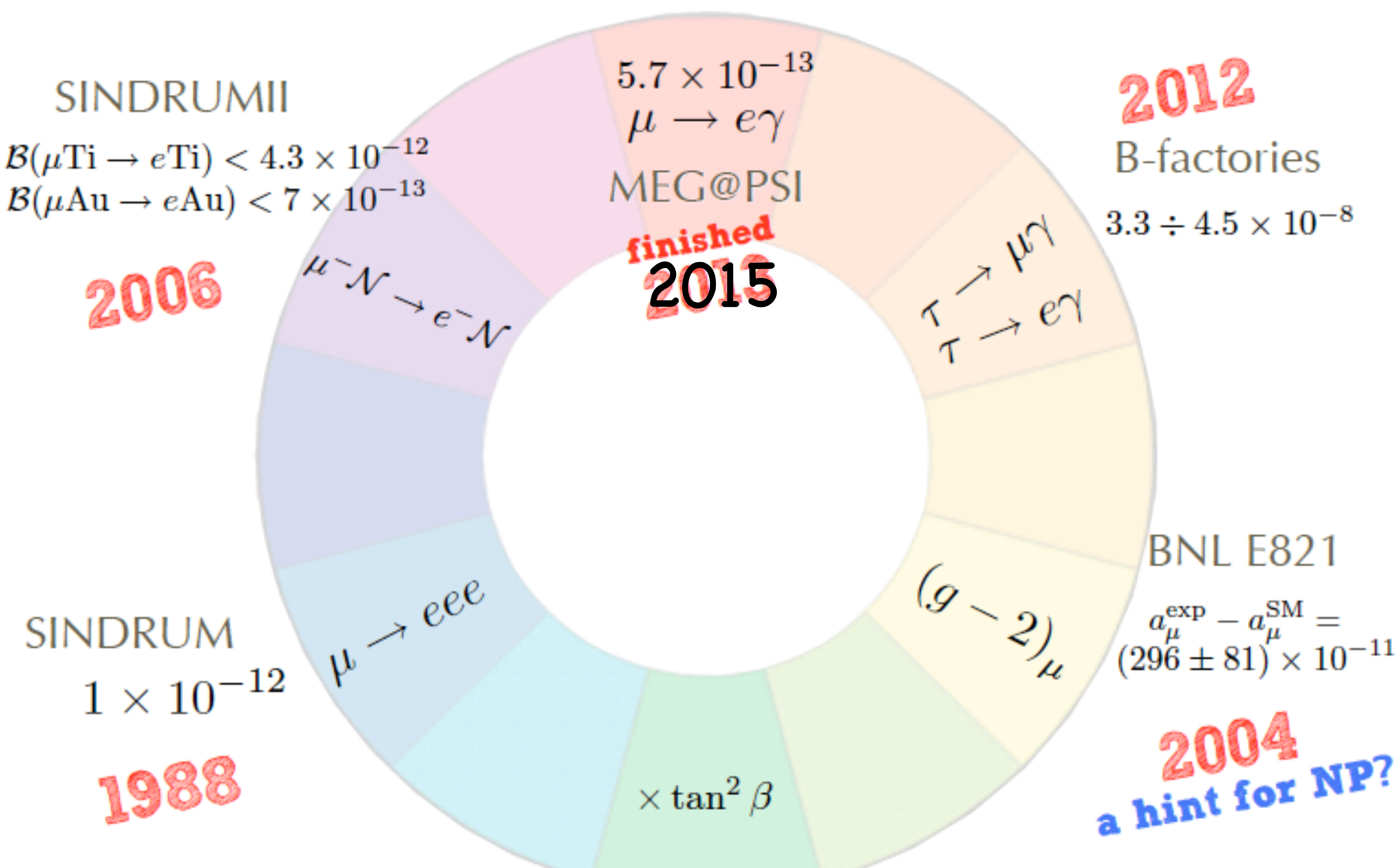
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$





Lepton Flavour Violation is absent in the SM



An alternative definition of the SM (equally precise!)

1. Symmetry group $\mathcal{L} \times \mathcal{G}$

$\mathcal{L}$ = Lorentz (rigid, exact)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local, spontaneously broken)

2. Particle content (rep.s of $\mathcal{L} \times \mathcal{G}$) - See below

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4 with a single exception $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

$$\hbar = c = 1 \Rightarrow [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4$$

The particles of the Standard Model (SM)

$J=0$

$h(2012)$

$J=1/2$

$\Psi_i =$

				$i=$
$u(1968)$	$d(1968)$	$e(1897)$	$\nu_e(1956)$	$\leftarrow 1$
$c(1974)$	$s(1968)$	$\mu(1937)$	$\nu_\mu(1962)$	$\leftarrow 2$
$t(1994)$ *	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$ *	$\leftarrow 3$

$H=(pe)$ $p=(uud)$ $n=(udd)$

$J=1$

$G^a_\mu(1978)$ *	$A_\mu(1905)$	$W_\mu(1984)$	$Z_\mu(1984)$

A complete story? A single scalar?

Representation content and accidental symmetries

$$\Psi = Q(3,2)_{1/6} \;\; u(\bar{3},1)_{-2/3} \;\; d(\bar{3},1)_{1/3} \;\; L(1,2)_{-1/2} \;\; e(1,1)_1$$

(the key to the non-observation of any new particle so far?)

(An important hint for "algebraic" Unification?)

From $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$

$$\Rightarrow B,\;\; L_e, L_\mu, L_\tau$$

and $U(3)^3 \equiv U(2)_Q \times U(3)_u \times U(3)_d$ only broken by Y_u, Y_d

An interesting story about symmetries

∞'s $\Rightarrow$ renormalizable th.s $\mathcal{O}_d(\Phi, \partial_\mu \Phi)\ d \leq 4$ $\Rightarrow d > 4$

30's 40's - 50's 70's

$\Downarrow$

Accidental symmetries (approximate)

Parity in the electromagnetic interactions

Isospin, $SU(3)$, chiral symmetry in strong interactions

Barion (B) and Lepton (L) numbers in the full SM

$\boxed{B = N_q - N_{\bar{q}}}$ $\boxed{L = N_l - N_{\bar{l}}}$

$\cancel{p \to e^+ + \pi^0}$

The problems of the Standard Model

Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

$$|Q_p + Q_e| < 10^{-21} e$$

1. Phenomena unaccounted for

neutrino masses
Dark matter

matter-antimatter asymmetry
inflation?

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

Axions

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses
Gravity

Are the protons forever?

4. Lack of calculability (a euphemism)

the hierarchy problem
the flavour paradox

Why $|Q_p + Q_e| < 10^{-21} e$?

(recall Einstein's lesson from $m_a = m_p$)

$$\Psi = Q(3,2)_{1/6} \;\; u(\bar{3},1)_{-2/3} \;\; d(\bar{3},1)_{1/3} \;\; L(1,2)_{-1/2} \;\; e(1,1)_1$$

Ψ = next-to-simplest rep of $\mathcal{G}$:

chiral, anomaly-free, vector-like under $SU(3) \times U(1)_{em}$

However:

1. A simpler rep: $\Xi = (3,2)_0 \;\; (\bar{3},1)_{1/2} \;\; (\bar{3},1)_{-1/2}$

2. What if ν_R are added?

$$\tilde{\Psi} = Q(3,2)_y \;\; u(\bar{3},1)_{-y-1/2} \;\; d(\bar{3},1)_{-y+1/2} \;\; L(1,2)_{-3y} \;\; e(1,1)_{5y+1/2} \;\; \nu^c(1,1)_{3y-1/2}$$

(An important hint for "algebraic" Unification?)

The unification way: $SU(5)$

A unique "embedding" of $SU_{3,2,1}$ into SU_5

$$\left(\begin{array}{c|c} \frac{1}{2}\lambda^i_{3\times 3} & \\ \hline & \frac{1}{2}\sigma^a_{2\times 2} \end{array}\right) \qquad Y \propto \left(\begin{array}{c|c} 1_{3\times 3} & \\ \hline & -\frac{3}{2}1_{2\times 2} \end{array}\right)$$

The particle content follows in the simplest reps

$$\bar{5} = \begin{pmatrix} d^c{}_1 \\ d^c{}_2 \\ d^c{}_3 \\ e^- \\ -\nu_e \end{pmatrix} \qquad 10 = \begin{pmatrix} 0 & u^c{}_3 & -u^c{}_2 & -u_1 & -d_1 \\ & 0 & u^c{}_1 & -u_2 & -d_2 \\ & & 0 & -u_3 & -d_3 \\ & & & 0 & -e^c \\ & & & & 0 \end{pmatrix}$$

with all quantum numbers fixed (including hypercharge)

Neutrino masses

Known to be nonzero since about 1990

Yet vanishing in the SM because of an accidental symmetry: L-conservation

$$(A, Z) \to (A, Z+1) + e + \bar{\nu}$$

Accidental symmetries are not exact

$$\Downarrow$$

$$\Delta\mathcal{L} = \frac{(LH)(LH)}{M}$$

Neutrinos are massive and of Majorana type ($\nu = \bar{\nu}$)

Should observe: $(A, Z) \to (A, Z+2) + 2e$

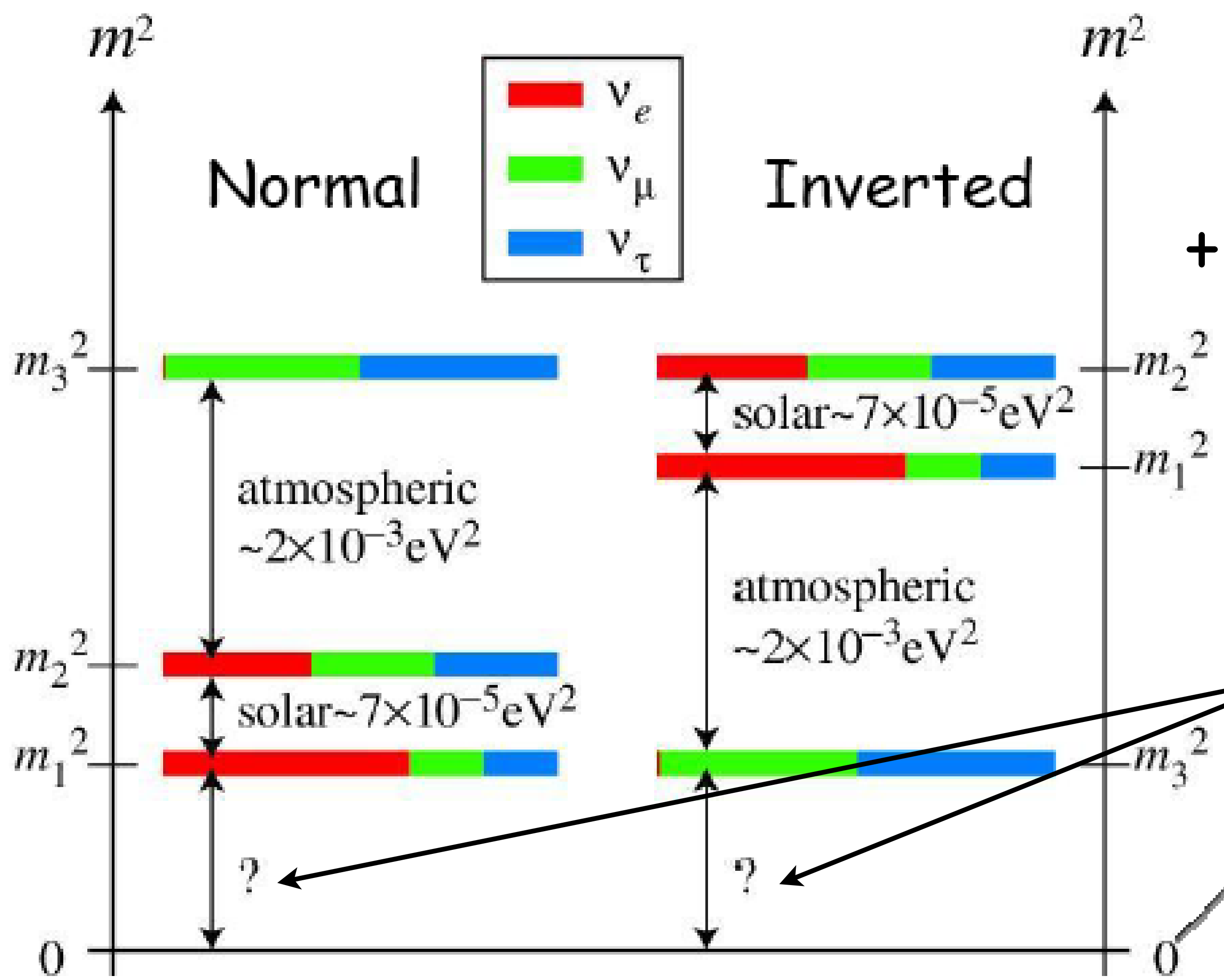
So far $\tau(2\beta^{0\nu}) \gtrsim 10^{25}\ years$

Neutrino oscillations
(in the standard 3-neutrino framework)

$$|\nu_{l_\alpha}> \quad t=0 \quad R=ct \quad t \quad |\nu_{l_\beta}> \qquad l_{\alpha,\beta} = e,\mu,\tau$$

$$|\nu_i> = V_{i\alpha}|\nu_\alpha> \qquad <\nu_\beta|\nu_\alpha, t> = \sum_{i=1,2,3} V^*_{i\beta} V_{i\alpha} e^{-i\frac{m_i^2 t}{2p}}$$

$$\alpha = e,\mu,\tau$$



$$V(\theta_{12}, \theta_{23}, \theta_{13}, \phi)$$

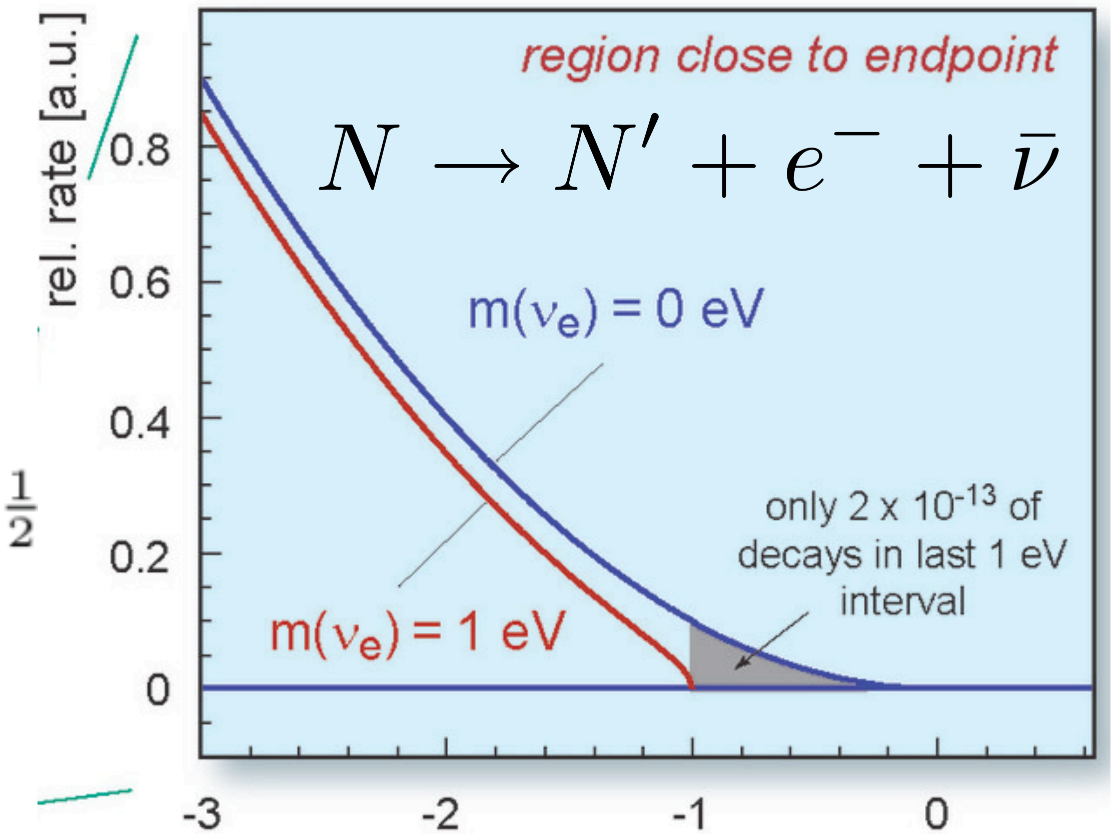
+ 2 more phases if ν's are Majorana, not affecting oscillations

the absolute scale yet unknown

3 ways to be sensitive to the absolute ν-mass scale

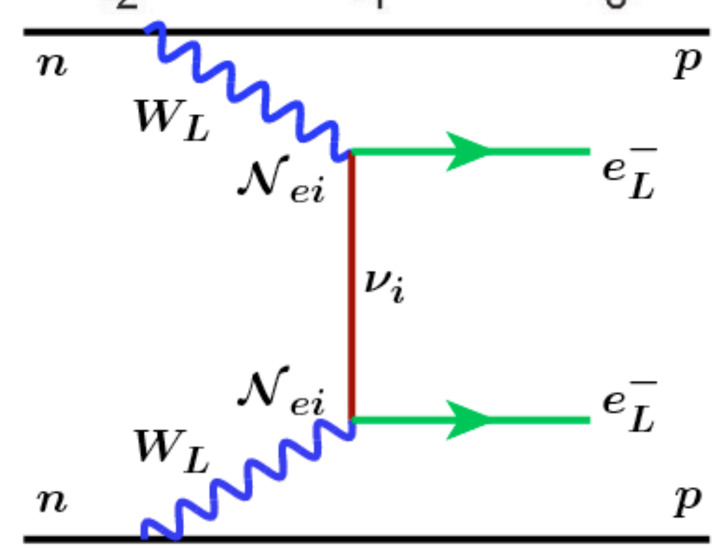
1- beta-decay endpoint

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



2- neutrino-less ββ-decay

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

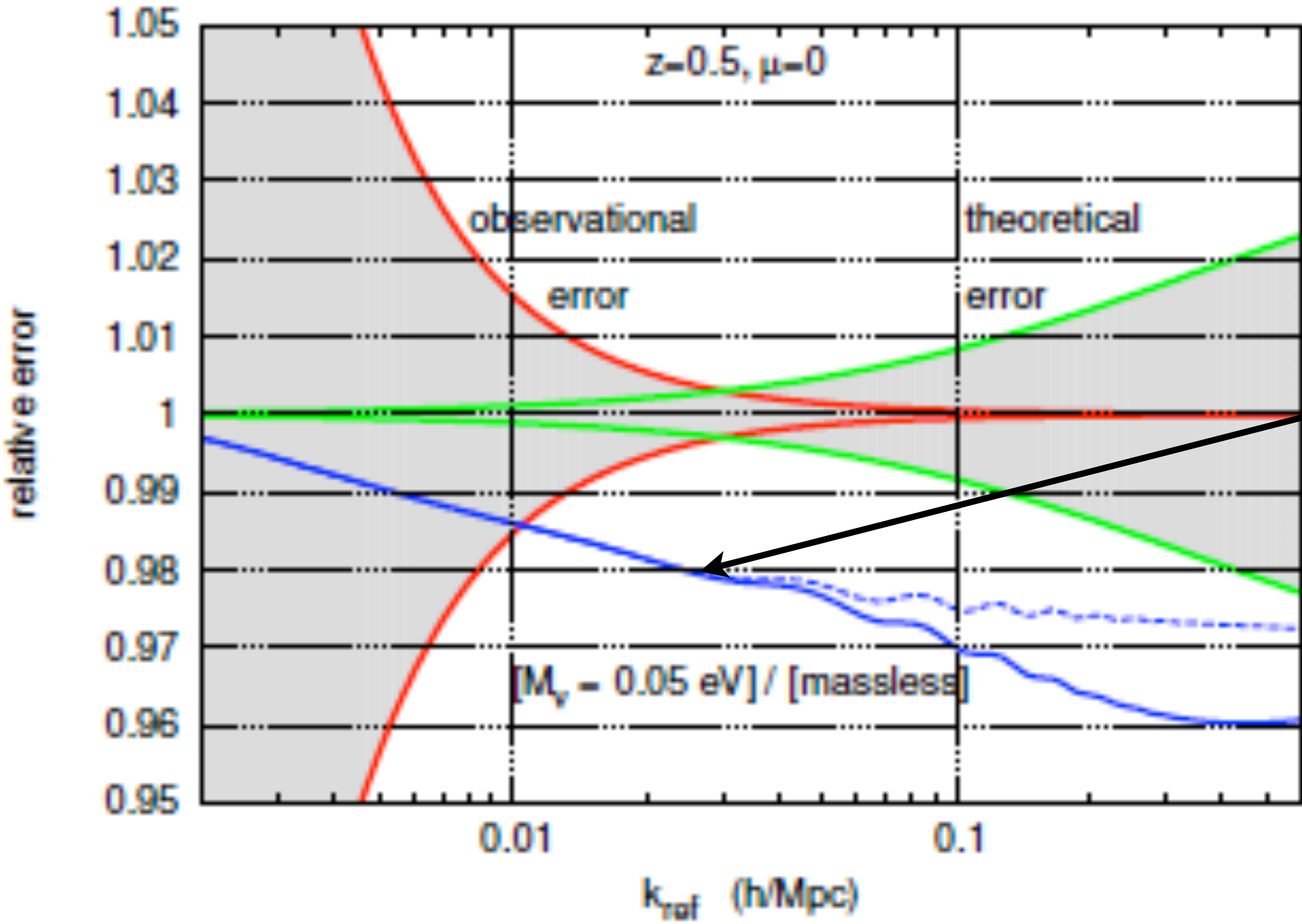


3 - cosmology (large scale structures)

$$\Sigma = m_1 + m_2 + m_3$$

Power spectrum of large scale structures

Power spectrum $P(k)/P_{massless\ \nu}(k)$



ratio between
with (ν massive) and
without (ν massless)
"free streaming"

Lesgourgues et al, 2103

- Determination with future large-scale structure observations (Euclid) at $2-5\sigma$ depending on control of (mildy) non-linear physics

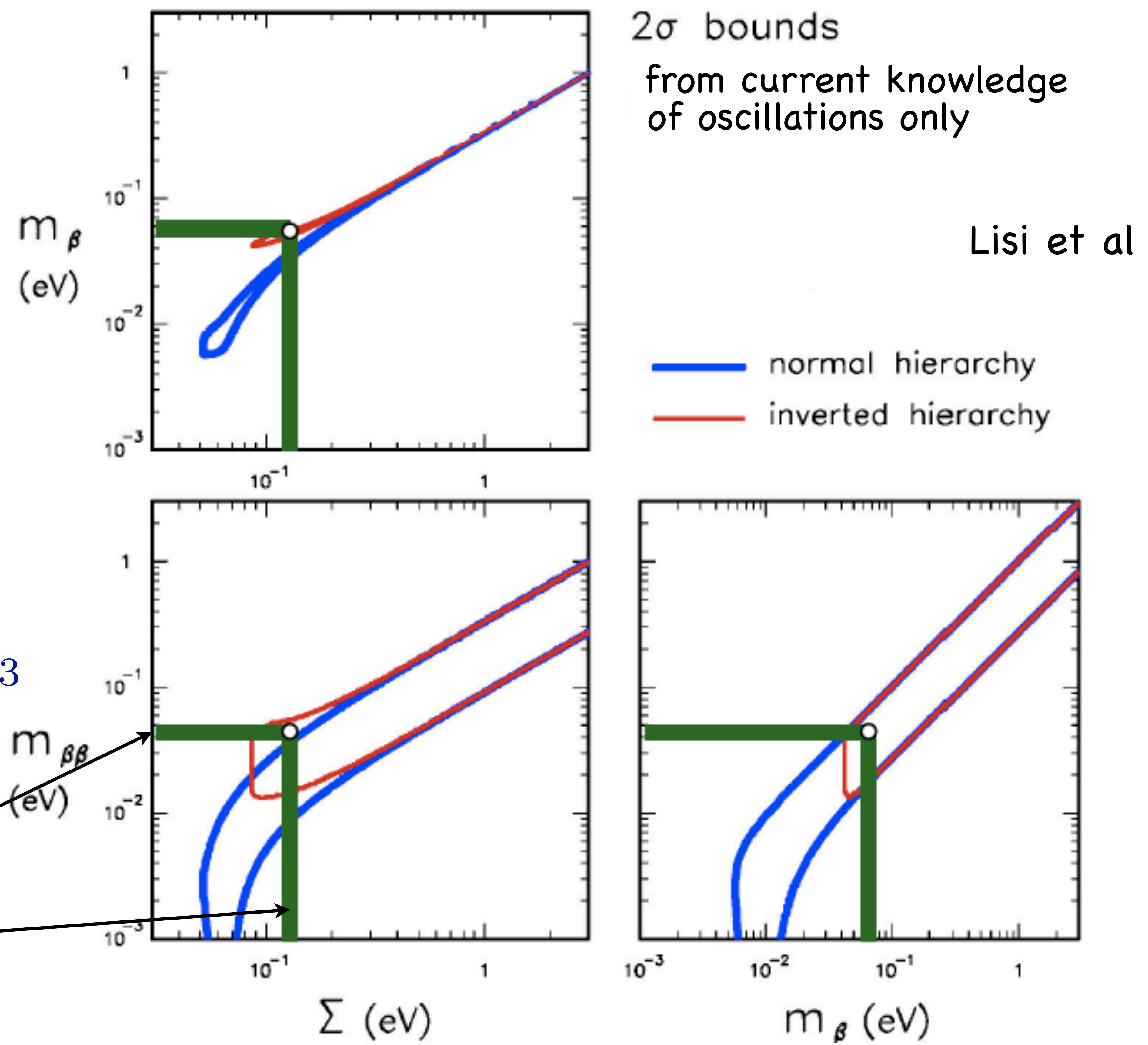
▶ Not independent on "priors" but still highly significant

Key neutrino measurements

m_β
beta-decay endpoint

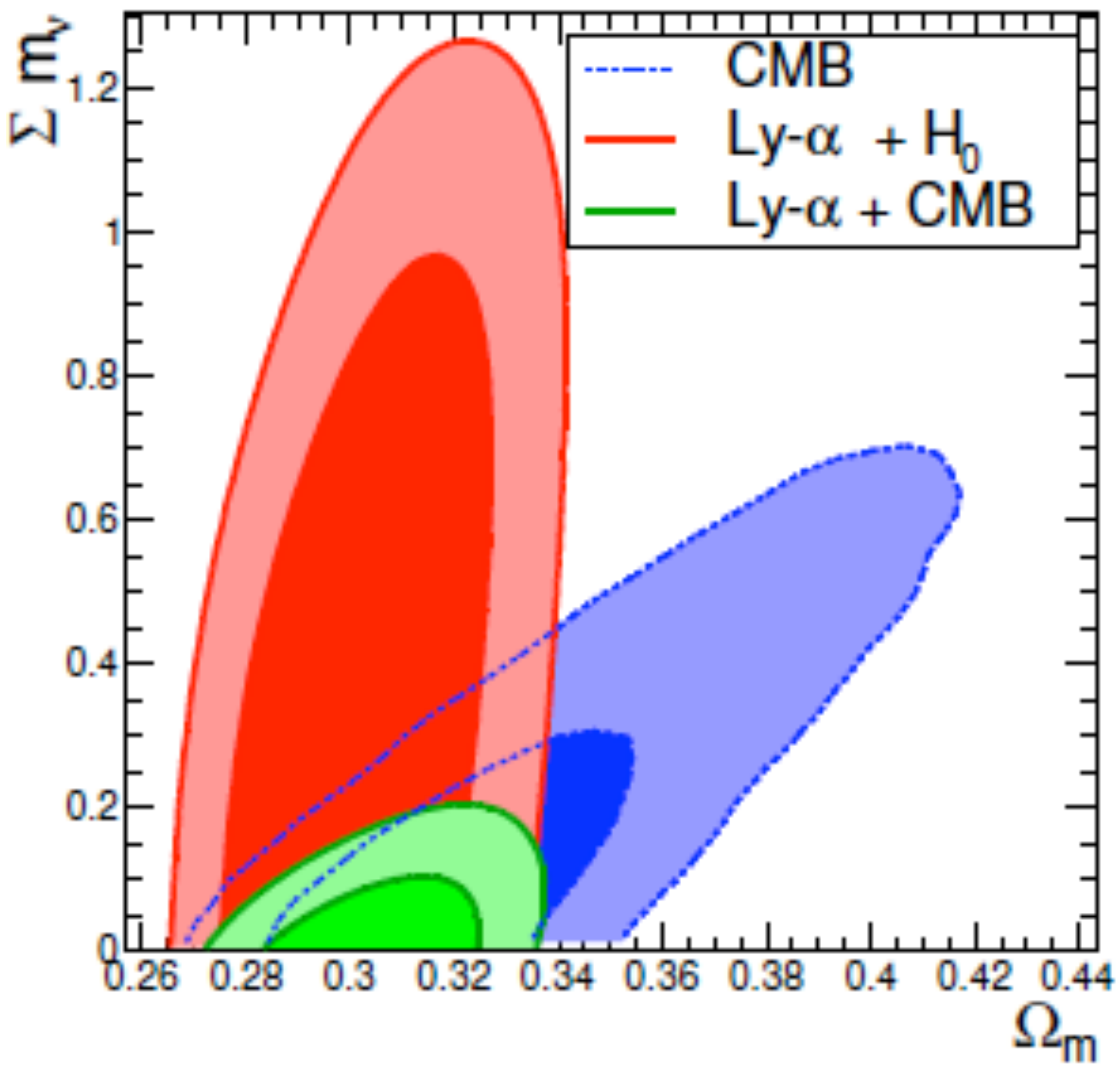
$m_{\beta\beta}$
neutrino-less $\beta\beta$ decay

$\Sigma = m_1 + m_2 + m_3$
large scale structures

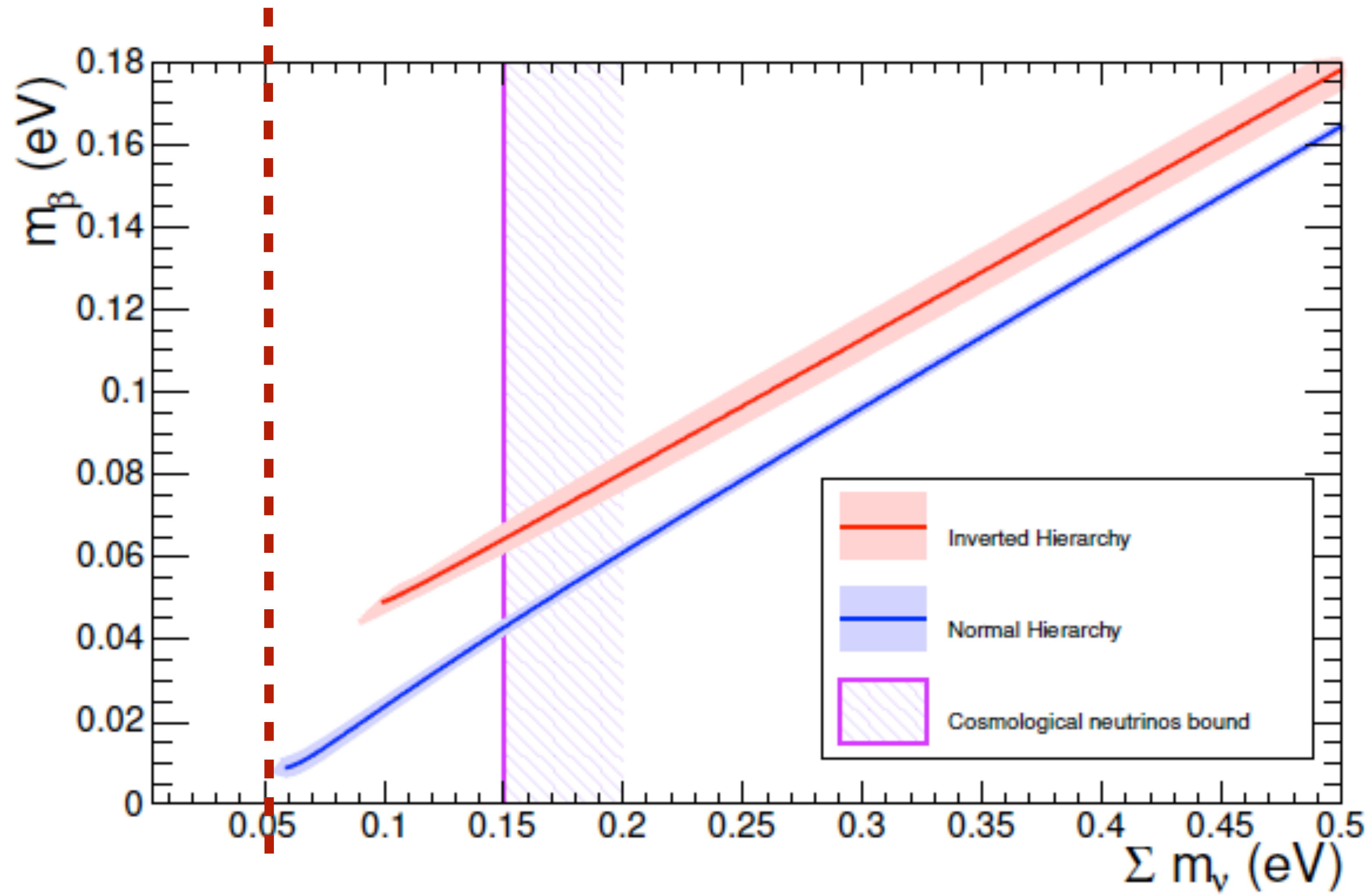


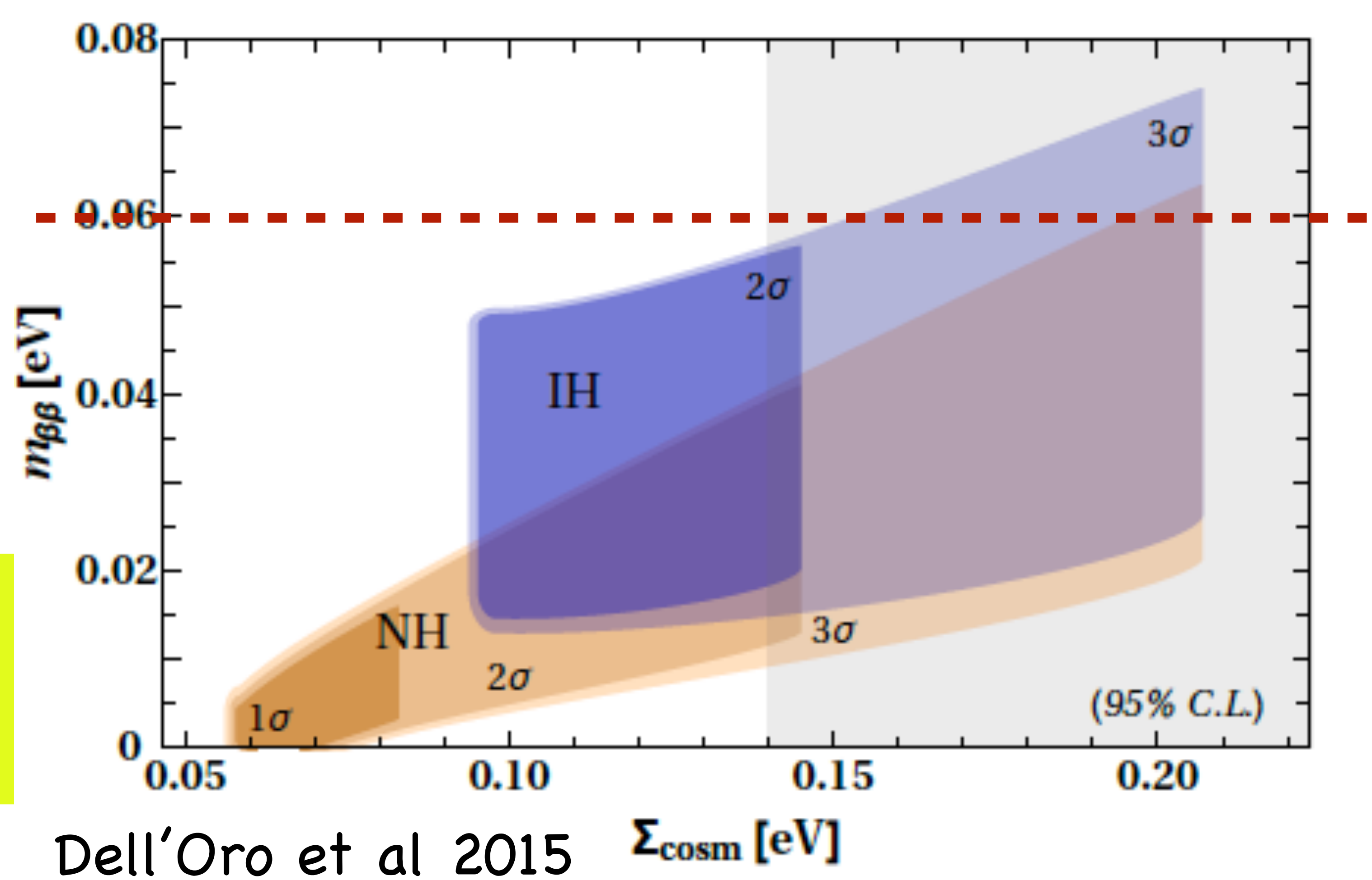
hypothetical measurements

Σm_ν determination



Palanque-Delabroullle et al 2015





Dell'Oro et al 2015

(a recent result from KamLAND)

$$m_{\beta\beta} < 0.06 \div 0.16\ eV$$

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

How do we know that $\theta \lesssim 10^{-10}$?

$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ is T-odd and (almost) the only source of T-violation in the SM

	$\vec{\mu} \cdot \vec{B}$	$\vec{d} \cdot \vec{E}$
T	$+$	$-$

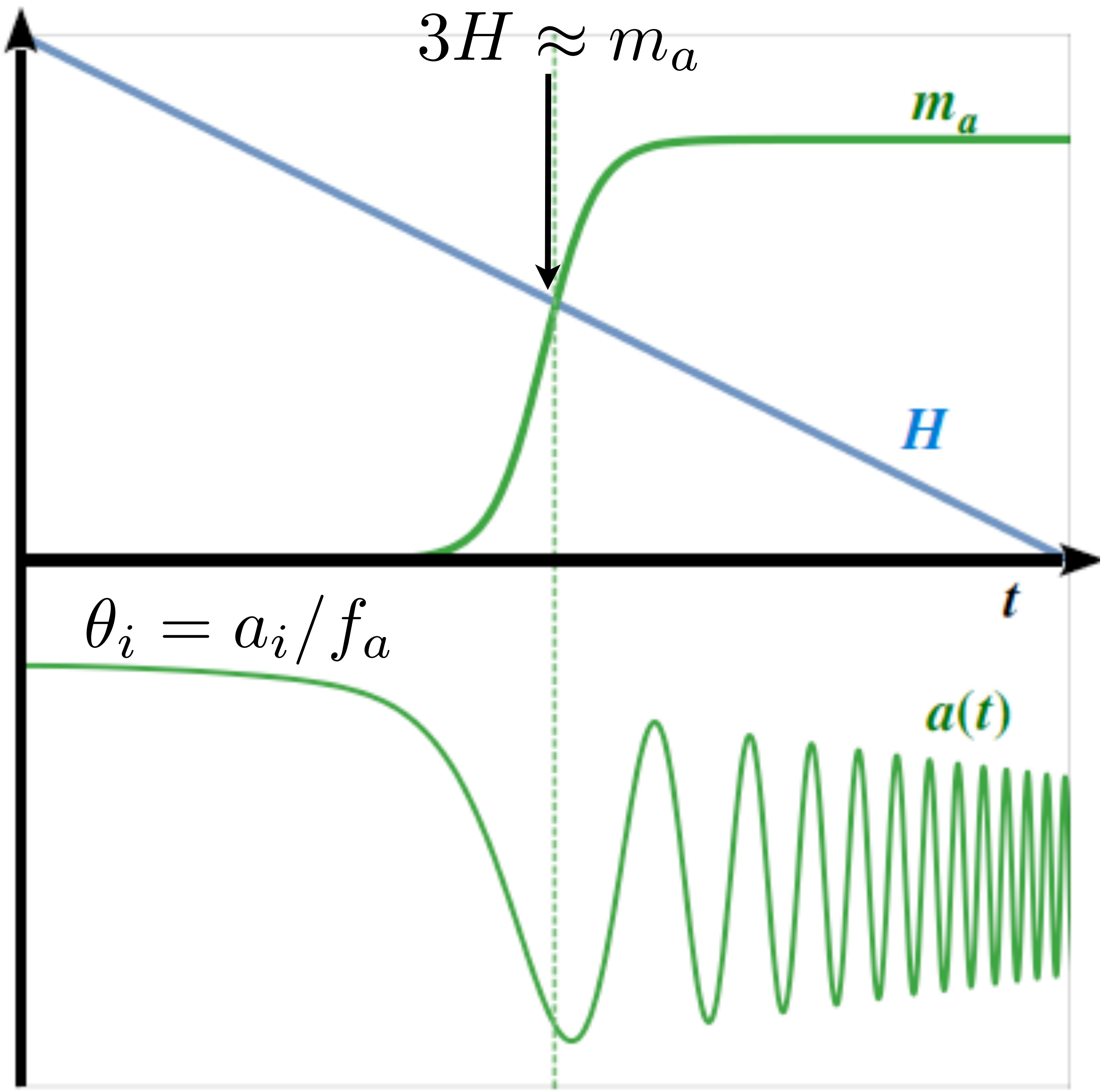
$$|\vec{\mu_N}| = 2 \cdot 10^{-14} e \cdot cm$$

$$|\vec{d_N}| \approx \theta \cdot 10^{-15} e \cdot cm$$

$$|\vec{d_N}|_{exp} < 3 \cdot 10^{-26} e \cdot cm$$

$\Rightarrow$ Make θ a dynamical field forced in its cosmological history to relax to 0 (almost) and (possibly) appear as DM

Relic abundance of the QCD axion



$$H = T^2/M_{Pl}$$

m_a

$T > \Lambda_{QCD}$: $\frac{m_\pi}{f_a}(\frac{\Lambda_{QCD}}{T})^4$

$T < \Lambda_{QCD}$: $\frac{m_\pi}{f_a}$

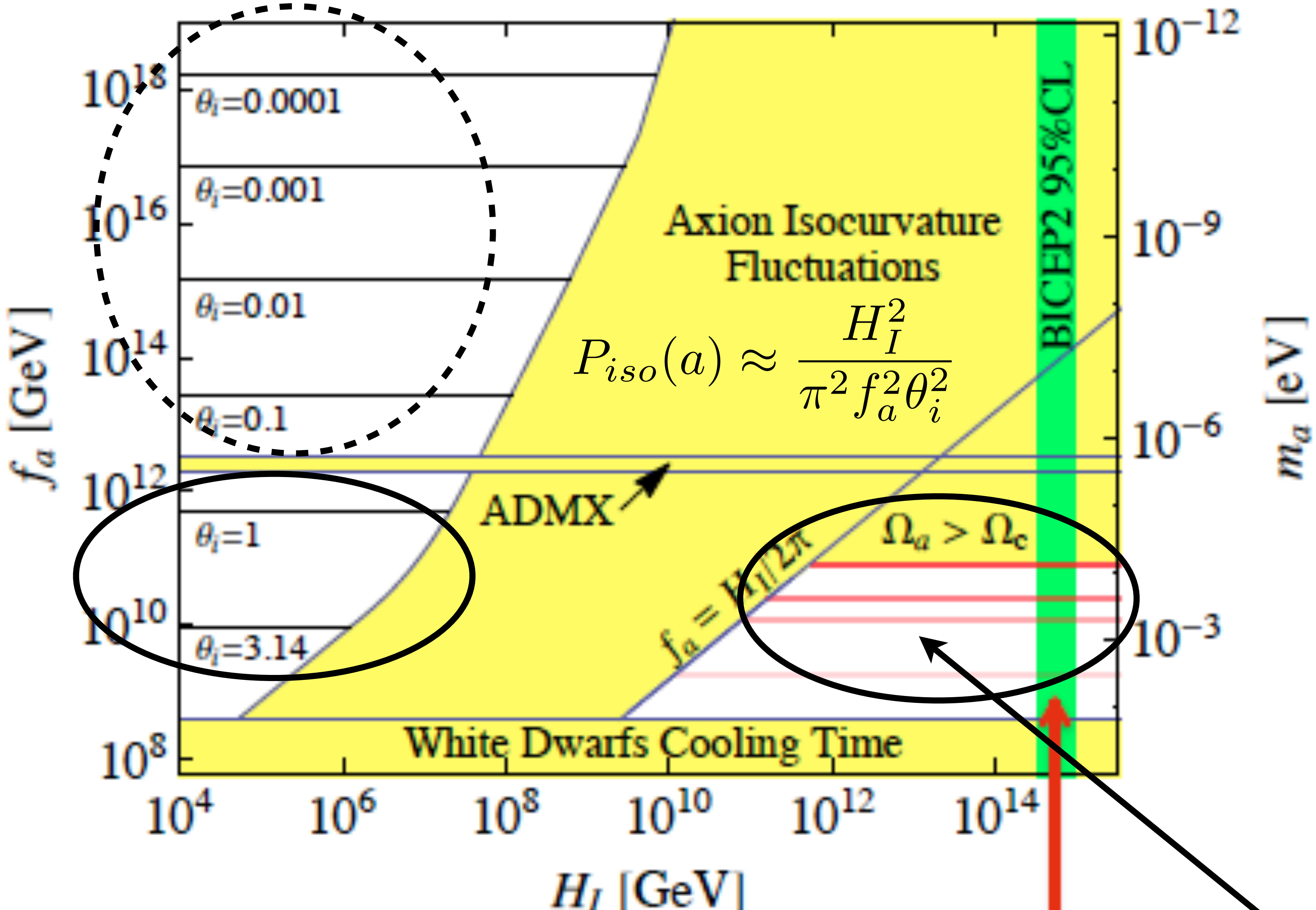
$$\rho_a = m_a^2 a^2 \propto T^3 \propto 1/R^3$$

i.e. cold Dark Matter

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

QCD Axions in cosmology

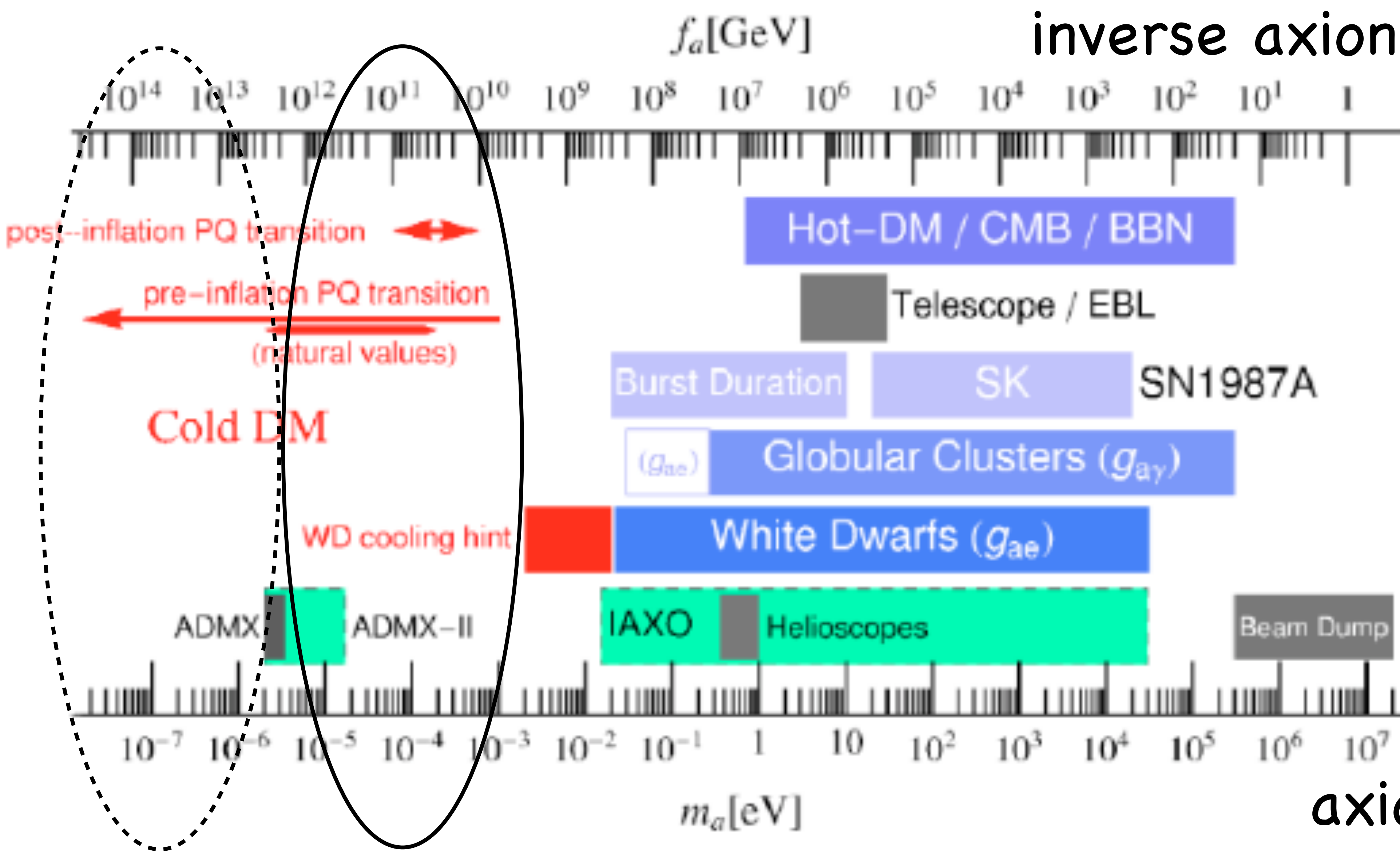
$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$



$$\Omega_a h^2 \approx 0.16\left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

(Axion Like Particles: m and f unrelated)

The dynamical field, a, is the "axion"



inverse axion coupling

axion mass

Olive et al, 2104

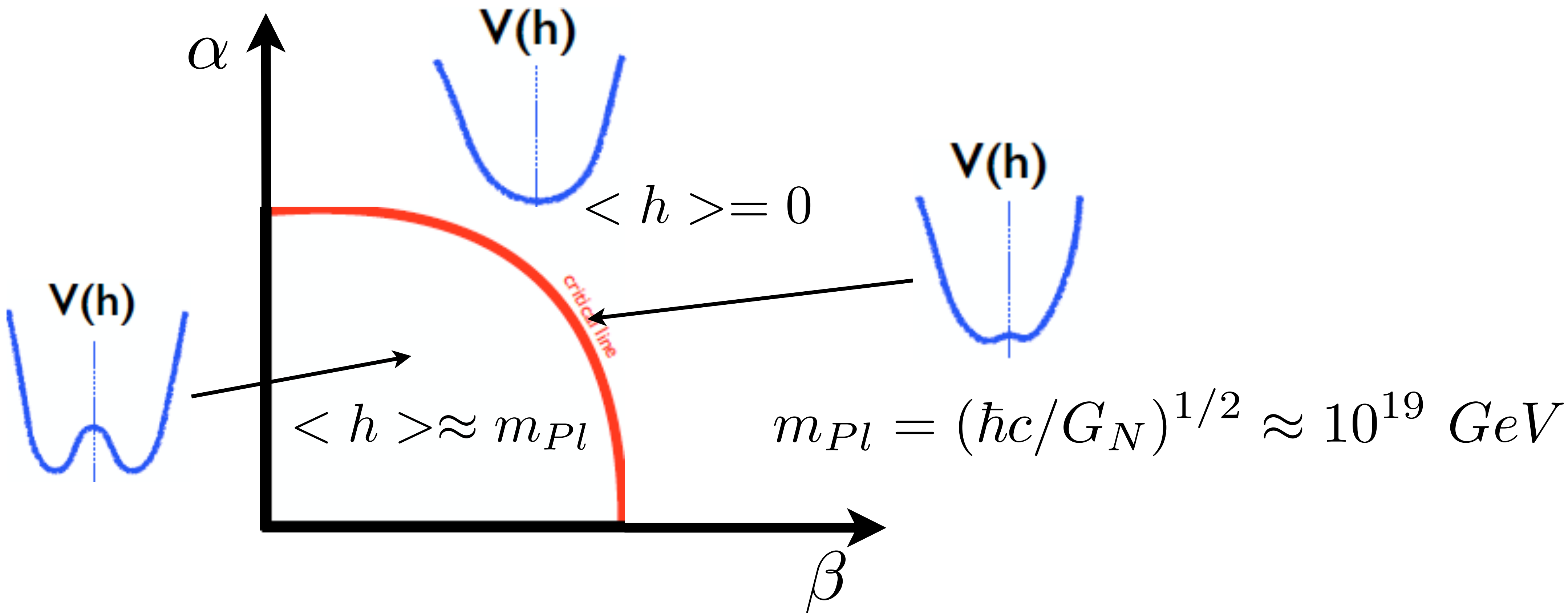
and is very intensively searched for

(with the most interesting region still unaccessible)

The "hierarchy" problem

Can we calculate the Higgs mass? NOT in the SM

If we try: $V(h) = m^2(\alpha, \beta)|h|^2 + \lambda|h|^4$



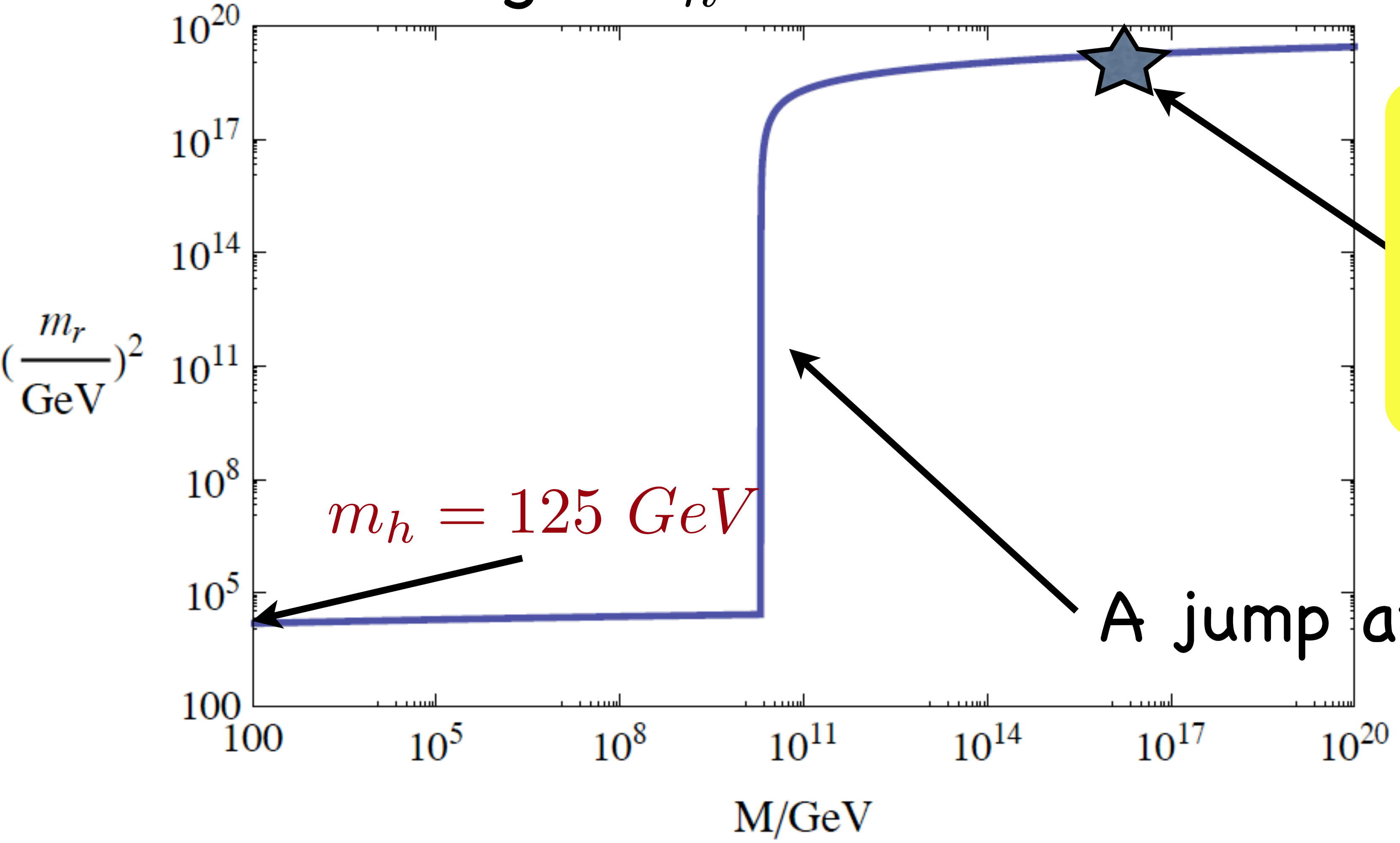
To get <h> = 175 GeV, as observed, we have to live very very close to the critical line

But we don't have knobs!

The Higgs naturalness problem illustrated in another way

Take the SM + a particle of mass $M_H = 10^{10}\ GeV$
and coupling λ_H to the Higgs boson

The running m_h^2 versus the scale M



"fine tuning"

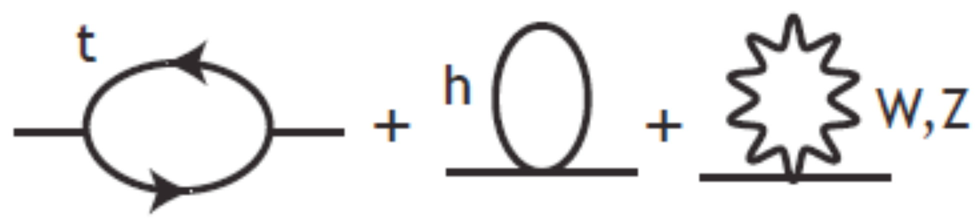
m_h depends on a very precise initial condition of order $O(m_h^2/m_H^2)$ at some short distance

A jump at M_H of size $\dfrac{(\lambda_H M_H)^2}{16\pi^2}$

The hierarchy problem, once again

Can we compute the Higgs mass/vev in terms of some fundamental dynamics?

NOT in the SM



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 + \ldots$$

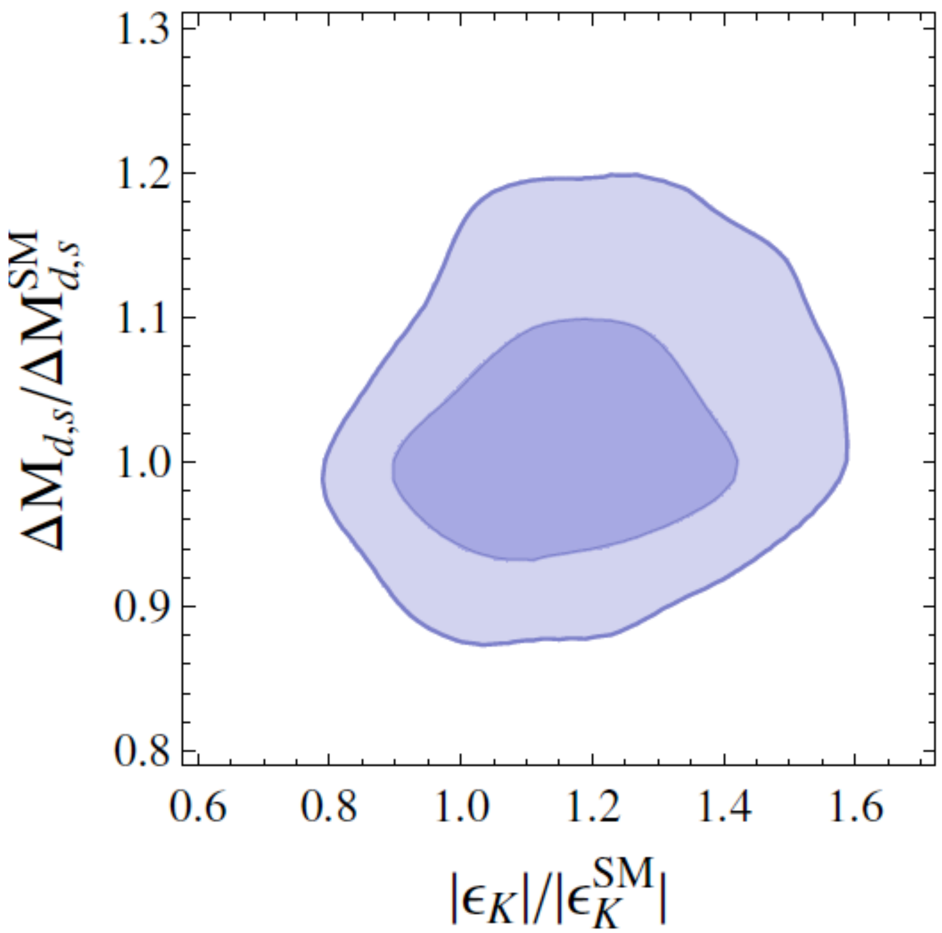
$\Lambda_t \lesssim 0.4\sqrt{\Delta}\ TeV$ $\Lambda_g \lesssim 1.1\sqrt{\Delta}\ TeV$ $\Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$

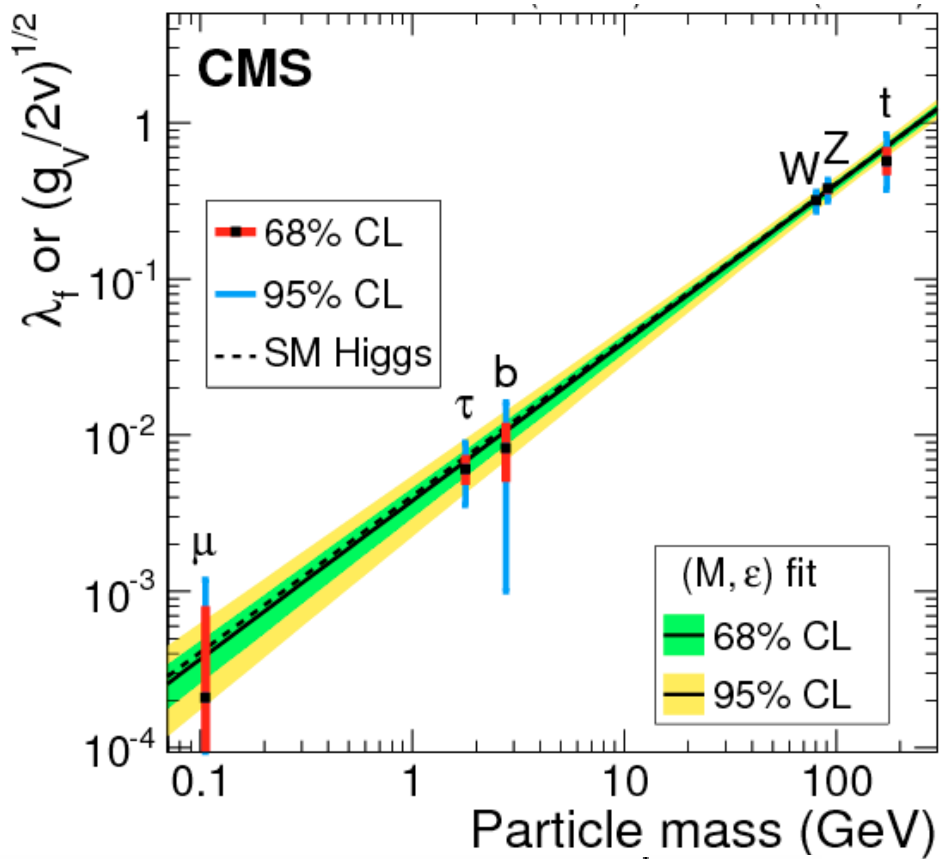
$1/\Delta$ = amount of tuning

⇒ Look for a top "partner" (coloured, S=0 or 1/2) with a mass not far from 1 TeV

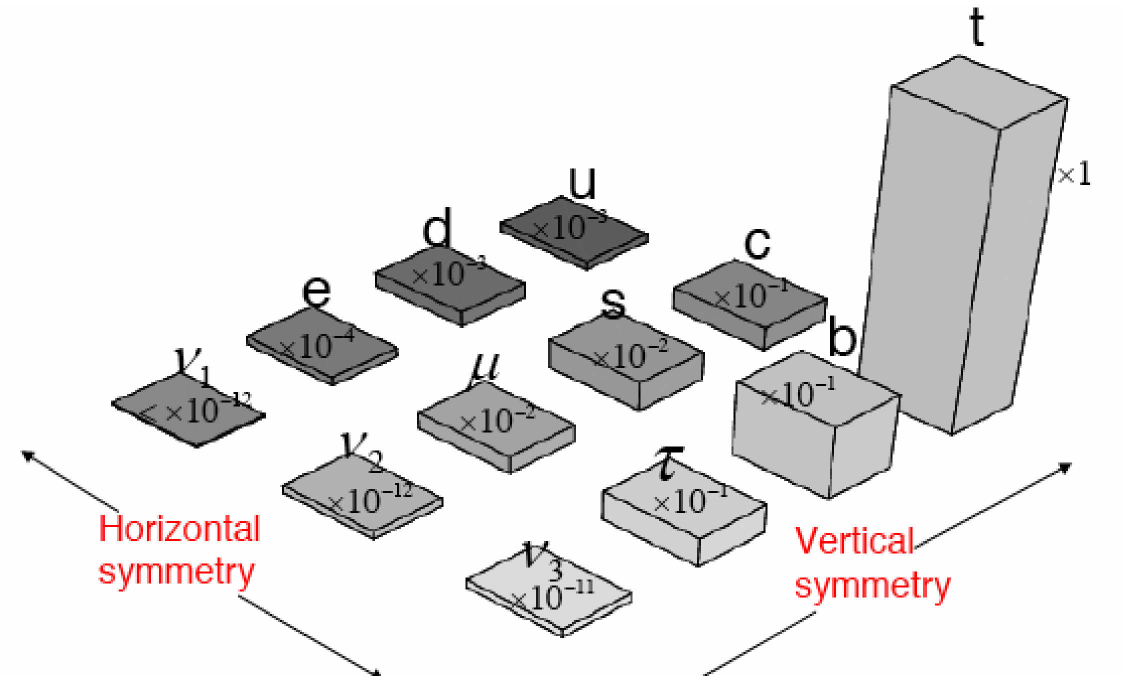
The flavour paradox

Yukawa couplings: a piece of physical reality





as opposed to:



?!?!?

Summary

The Standard Model is NOT a complete story

Pictures that go Beyond the SM are not lacking,
but - fair to say - we don't know which one is right

The very nature of Particle Physics and the current
uncertain situation REQUIRE
highly diverse frontiers of research

(Not in contradiction with above) the SM is going
TO STAY as an accurate and very economic
description/explanation of fundamental physics
at short scales

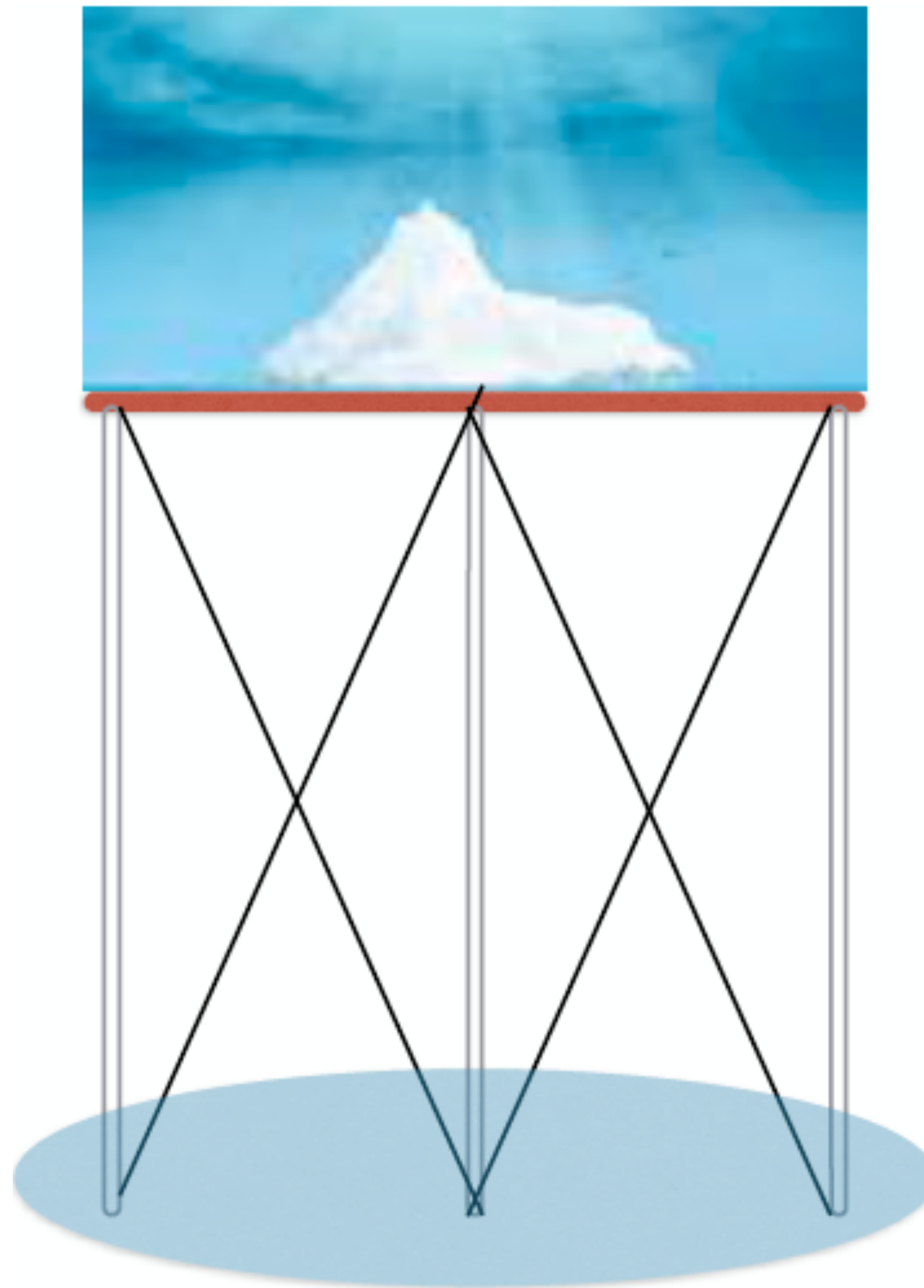
The SM as an emerging iceberg

What there is under the water?

(out of a conversation with Lawrence Hall)

BSM in the multi TeV region...

BSM in the multi TeV region...



... or the SM extended up to E >> TeVs?

For question time

vacuum stability

$$V(\varphi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

$$\frac{d\lambda}{d\log Q} = \frac{3}{2\pi^2}\left[\lambda^2 + \frac{1}{2}\lambda y_t^2 - \frac{1}{4}y_t^4 + \cdots\right]$$

$$m_W = gv/\sqrt{2}$$

$$m_H = 2\sqrt{\lambda}v$$

$$m_t = y_t v$$

With current values of $m_H,\ m_t,\ \alpha_S, \ldots$

$$\lambda(\approx 10^{11}\ GeV) < 0$$

$\Rightarrow$ A second minimum of V at $\phi \gtrsim 10^{11}\ GeV$
to which v should tunnel in a very long time (>> t_{Univ})

- Is there a real meta-stability at $\phi < M_{Pl}$?
- Any experimental implication?
- Connection to inflation?
- Is it a problem?

Landau poles

$$\frac{dg_1^2}{dt} = \frac{41}{40} g_1^4 \quad \Rightarrow \text{ a Landau pole at } \Lambda_1$$

- the problem not cured by including other couplings
- can it be cured by gravity? Yes, since $\Lambda_1 > M_{Pl}$, if gravity important at $E \lesssim M_{Pl}$
- what if gravity softened enough, so that it becomes irrelevant? (How is hard to tell, but...)

- need $SU(3) \times SU(2) \times U(1)$ fully immersed in a non-abelian group

$$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

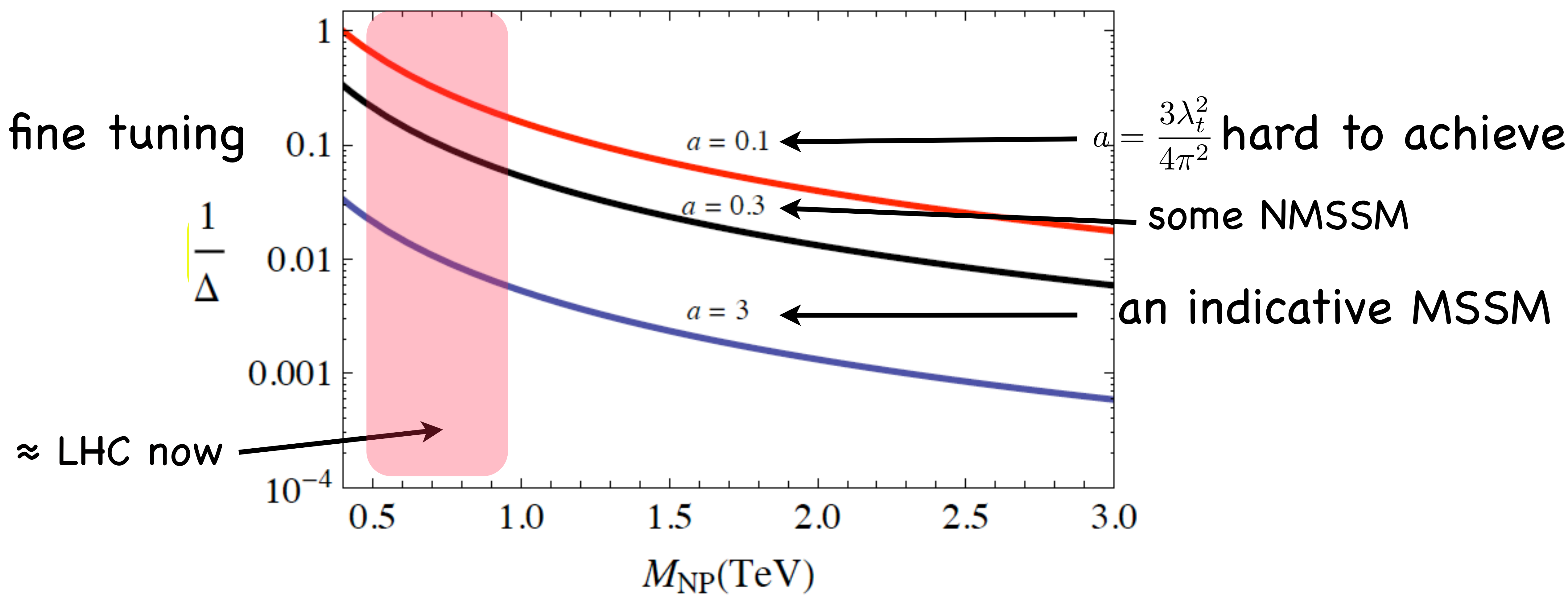
$$SU(3)_c \times SU(3)_L \times SU(3)_R$$

which requires heavier scales than v

How dramatic is the "little hierarchy problem"?

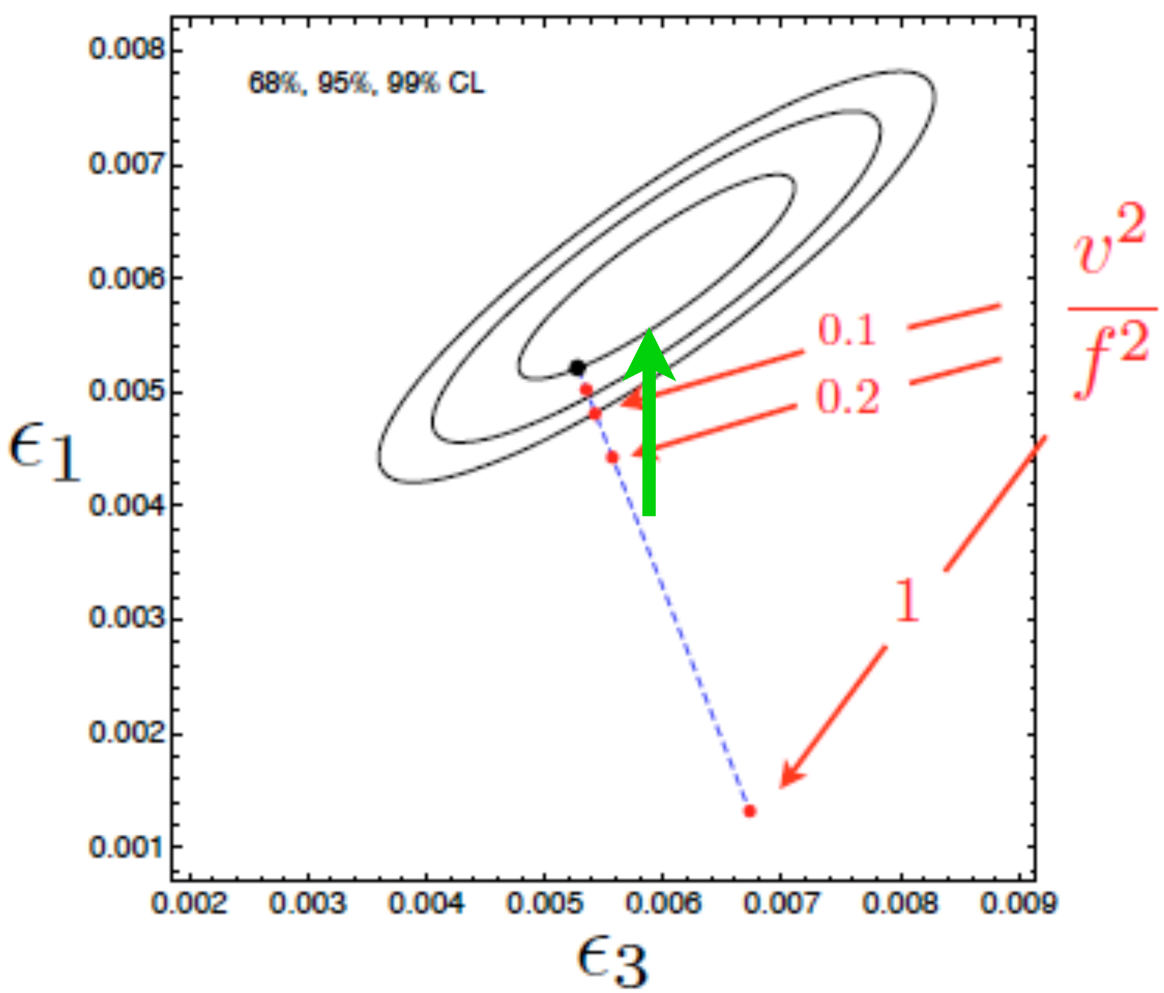
$$\Delta \equiv \frac{\delta m_h^2}{m_h^2} \approx a \frac{M_{NP}^2}{m_h^2}$$

model dependent

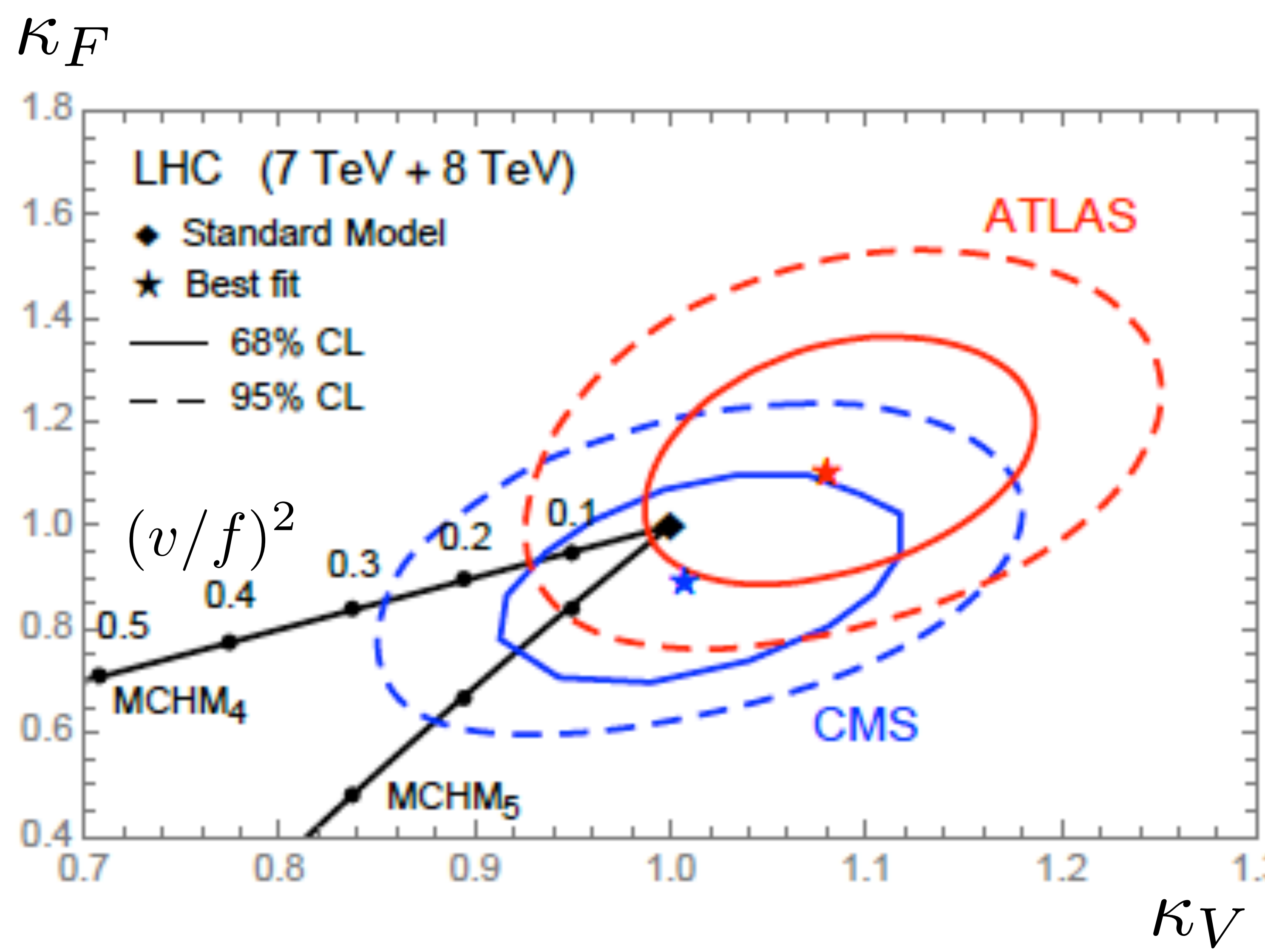


- Things do not work the way they were originally thought
- Not a serious problem at a fundamental level LHC-13 TeV

The epsilon-parameters constraining the scale f of a composite Higgs boson picture



EWPT



Higgs precision

(from a stop-sbottom $\delta\epsilon_1 = \frac{G_F m_t^4}{\sqrt{2}\, 8\pi^2 m_{\tilde{Q}_3}^2} \approx 10^{-3}(\frac{300GeV}{m_{\tilde{Q}_3}})^2$)

A self-critical Higgs vev

1. A Goldstone boson ϕ of a U(1) broken at a scale f
2. A U(1)-breaking coupling of ϕ to H (that keeps $\phi \to \phi + 2n\pi f$)
3. A breaking of $\phi \to \phi + 2n\pi f$ controlled by a small mass parameter m entering the Higgs mass term

$$V = -f^2|S|^2 + |S|^4 + \rho(H)\frac{S+S^+}{f} + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$S = se^{-i\phi/f}$

Λ = UV cutoff

V is a natural potential

Minimizing $V(H,\phi)$

$$V = \rho(H)\cos\phi/f + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$$\rho(H) = \cancel{\rho_0} + \rho_1\frac{H}{v_F} + \rho_2(\frac{H}{v_F})^2 + \ldots \qquad v_F^4 > \rho_{1,2}$$

(non trivial)

$$\frac{\partial V}{\partial h} = 0 \;\Rightarrow h^2 \approx \frac{\Lambda^2 - m\phi}{\lambda} > 0$$

$$\frac{\partial V}{\partial \phi} = 0 \;\Rightarrow h \approx v_F\frac{\Lambda^2 m f}{\rho_1}$$

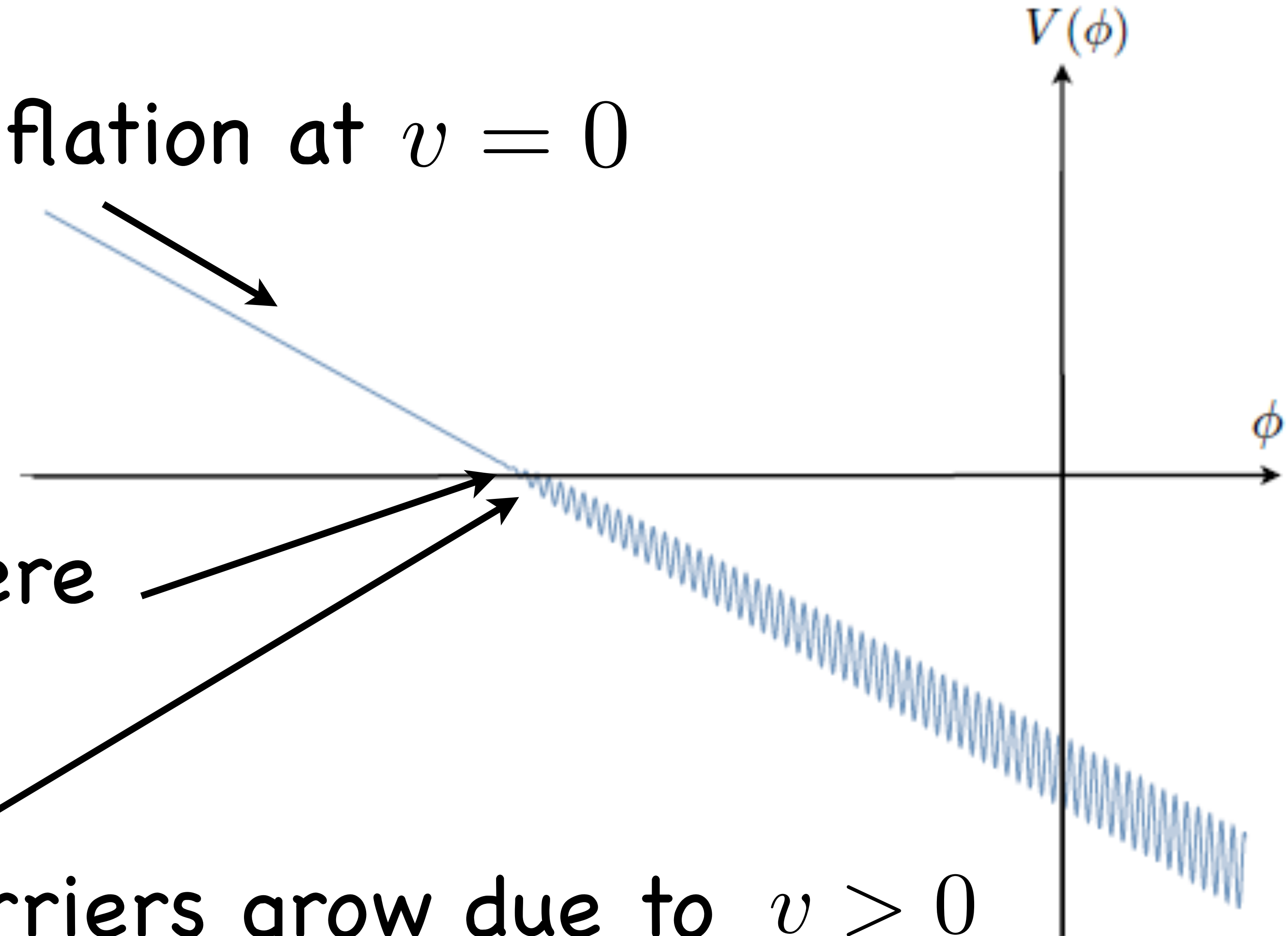
$h = v_F$ natural = moving Λ, m, f, ρ_1 by O(1)
h changes by O(1)

$$m = \frac{\rho_1}{\Lambda^2 f} \lesssim \frac{v_F^4}{\Lambda^2 f} \qquad \phi \approx \frac{\Lambda^2}{m} \gtrsim \frac{\Lambda^4 f}{v_F^4}$$

historical evolution of ϕ (and of v)

(under suitable conditions: e.g. a very very long inflation period)

ϕ slow-rolls during inflation at $v = 0$



until it hits value where m_h^2 crosses zero

rolling stops when barriers grow due to $v > 0$

experimental consequences:??