# Naturalness-Panel discussion

Roberto Contino (CERN/EPFL)
Nathaniel Craig (Santa Barbara)
Csaba Csáki (Cornell)
Michele Redi (Florence INFN)
Witold Skiba (Yale)

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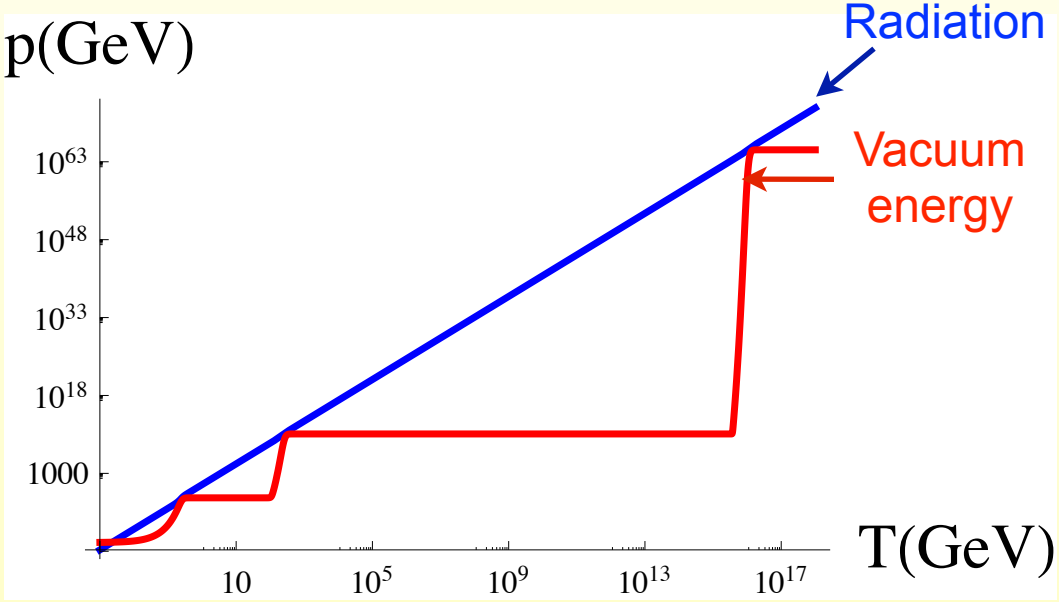
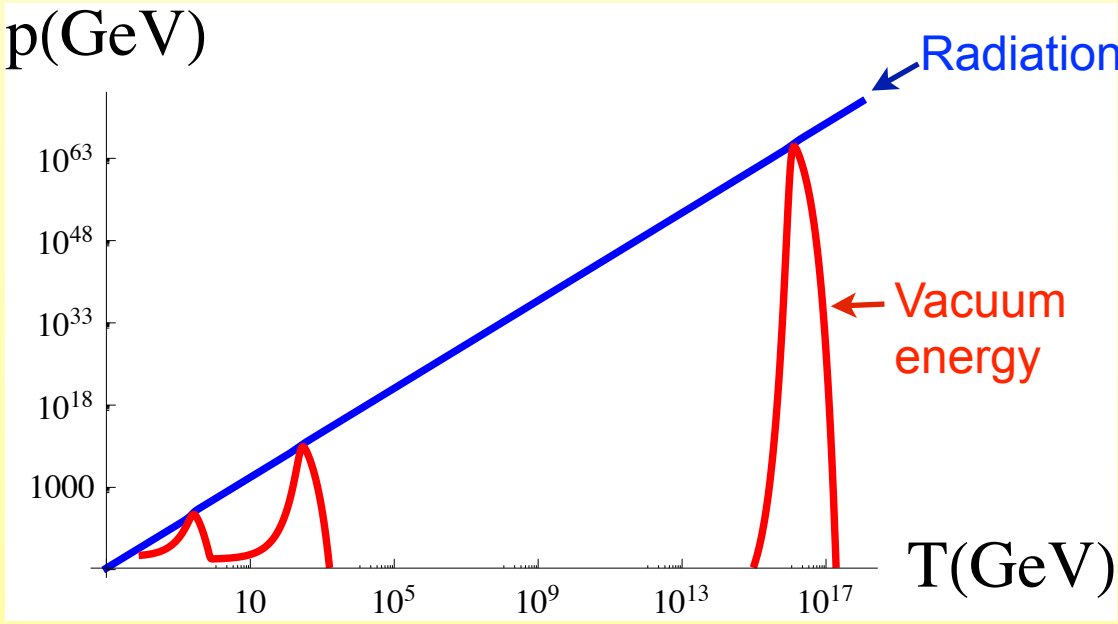
# The Evolution of vacuum energy




- Series of jumps at every PT
- $\Delta\Lambda_i \propto T_{c,i}^4$
- CC after PT should be of order of $T_c$ of next PT
- CC much bigger in previous history
- CC is always subleading except now
- Alternative picture: for some reason CC always small (adjustment?)
- How should we distinguish?
- Difficult experimentally since QCDPT at very high cosmological T

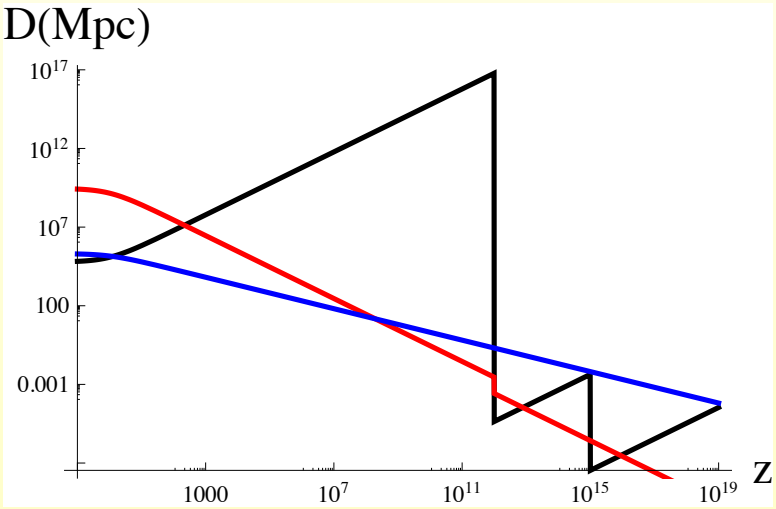
- Look for effects where leading contribution suppressed
- Propagation of primordial GW's
- Look for systems where CC is sizable fraction of total energy
- Neutron stars

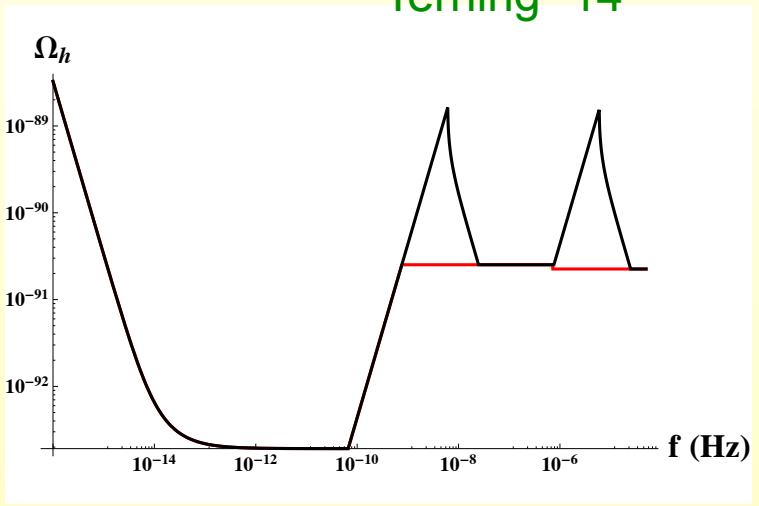


# Experimental Tests of Vacuum Energy

Propagation of GW's: $$\chi_k'' + \left[k^2 - \frac{4\pi G}{3} a^2 T_\mu^\mu\right] \chi_k = 0 .$$

Bellazzini, CC, Hubisz, Serra, Terning `14



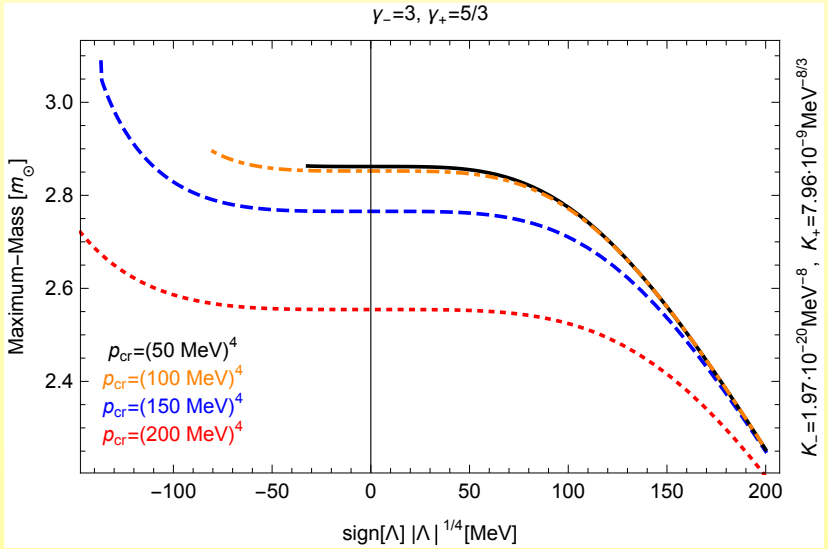

## The structure of neutron stars:

Assume core has different phase of QCD

Use simple two-phase model with EoS

$$p_{(-)}(\rho) = p_f(\rho) - \Lambda = K_- \rho_f^{\gamma_-} - \Lambda$$
$$\rho_{(-)} = \rho_f + \Lambda$$

Compare case with and w/o Λ



# Scale Invariance and Higgs Naturalness

- SM embedded in a CFT has new thresholds that Higgs mass is sensitive to
- Need to modify, or ignore, gravity if the Planck scale is not to break scale invariance
- Classical scale invariance not sufficient, symmetries of the quantum theory needed
- A UV-complete with natural Higgs mass seems to require an interacting UV fixed point

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- Are there "precision Higgs" observables that are relevant/crucial for naturalness ?

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- Question: Are there any more major questions worth asking of weak scale supersymmetry?

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- Questions: Are there other unexplored means of symmetry reduction? Are there more types of exotic natural theories based on symmetries?

## Estimate of Higgs mass in CH theories

$$V(h) = \frac{m_*^4}{g_*^2}\frac{N_c}{8\pi^2}\left[\lambda^2 \sum_i A_i(h/f) + \frac{\lambda^4}{g_*^2}\sum_i B_i(h/f) + \dots\right]$$

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or EWSB at $O(\lambda^4)$, $\lambda_L \sim \lambda_R \sim \sqrt{g_* y_t}$ ➡ $m_h^2 \sim \frac{N_c}{4\pi^2} g_*^2 y_t^2\, v^2 = \left(175\,\text{GeV} \times \left(\frac{g_*}{3}\right)\right)^2$

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- Super-Soft theories $\quad m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} m_*^2 \qquad \delta c \sim O\left(\frac{m_t^2}{m_h^2} \times \frac{g_*^2}{16\pi^2}\right)$

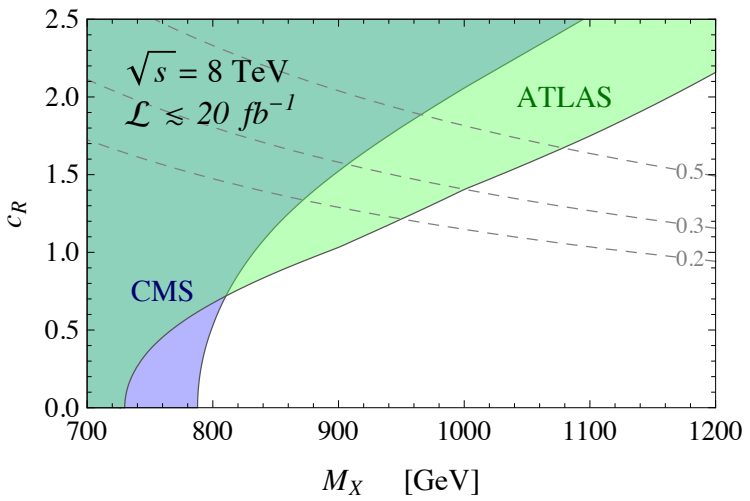
- Soft theories $\quad m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} \log\left(\frac{\Lambda}{m_*}\right) m_*^2 \simeq m_*^2 \qquad \delta c \sim O\left(\frac{m_t^2}{m_*^2}\right) = O(1)$

- Searches for top partners can be highly improved by including single production

☞ jet substructure, 1lepton final states

Azatov, Salvarezza, Son, Spannowsky arXiv:1308.6601
Ortiz, Ferrando, Kar, Spannowsky arXiv:1403.7490

Matsedonskyi, Panico, Wulzer arXiv:1409.0100



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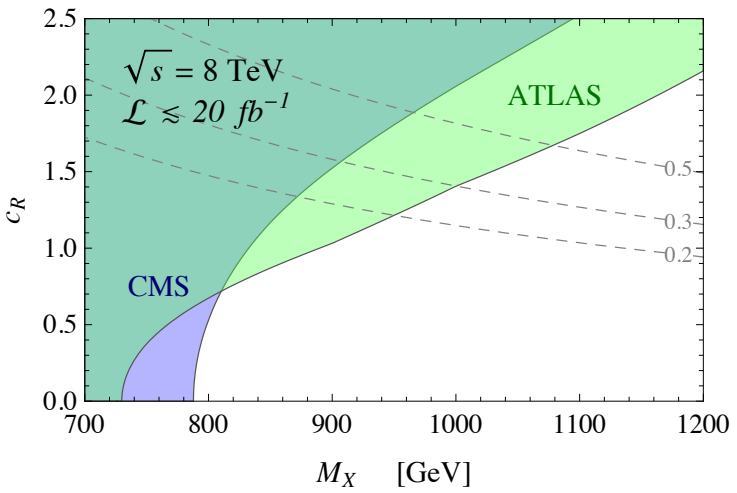



- direct searches vs Higgs couplings

— precision on Higgs couplings scales with *luminosity*, though limited by systematics

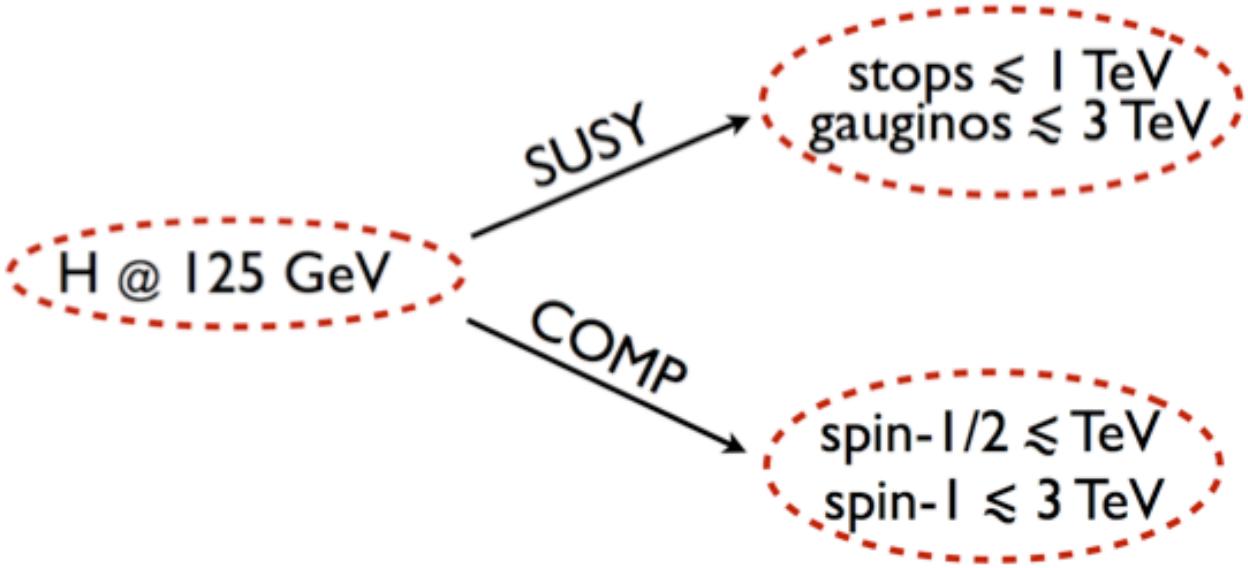
— direct searches mainly driven by *energy* through PDF luminosity

ILC: 250fb$^{-1}$ @ 250GeV + 500fb$^{-1}$ @ 500GeV
TLEP: 10ab$^{-1}$ @ 240GeV + 2.6ab$^{-1}$ @ 350GeV

| | LHC 8TeV 20fb$^{-1}$ | LHC 14TeV 300fb$^{-1}$ | HL-LHC 14TeV 3ab$^{-1}$ | 100TeV 3ab$^{-1}$ | ILC | TLEP |
|---|---|---|---|---|---|---|
| Higgs couplings ( $\xi$ ) | 0.2-0.3 | 0.1 (0.054) | 0.09 (0.02) | | 0.6-1.2 x 10$^{-2}$ | 1.5 x 10$^{-3}$ |
| → $m_*$ [TeV] (for $g_* = 2$ ) | 0.9-1.1 | 1.6 (2.1) | 1.6 (3.5) | | 4.5-6.4 | 12.7 |
| Direct searches $m_*$ [TeV] | | | | | | |
| $T_{5/3}$ | 0.8-1.2 | 1.5-2.6 | 2.2-? | 9.6-? | | |
| $T_{2/3}$ | 0.7-? | 1.5-? | 1.8-? | 7.5-? | | |

using: G. Salam, A. Weiler, cern.ch/collider-reach/

# NATURALNESS 2.0



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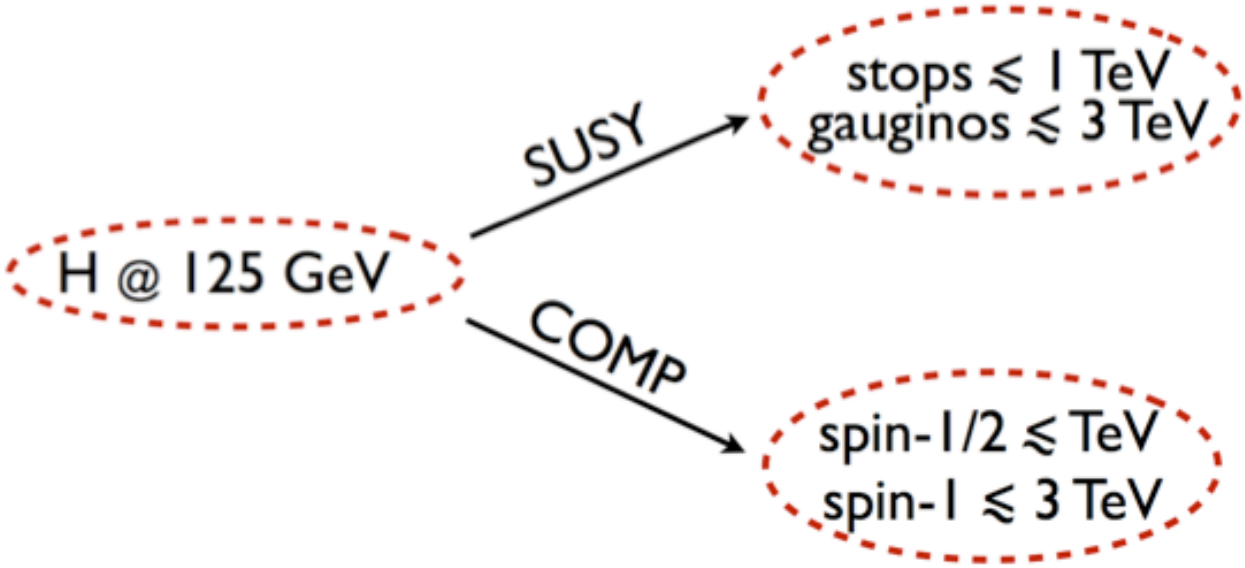


- Field driven by the hierarchy problem for too long

- Need to consider alternatives: A-gravity?

# PHYSICS 2045

**#1 If not naturalness what should be our guide?**

- Are global symmetries natural?

- Where do you think new progress will come from?