Conformality: SM & Beyond

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CP[3]-Origins, Danish IAS, Univ. Southern Denmark

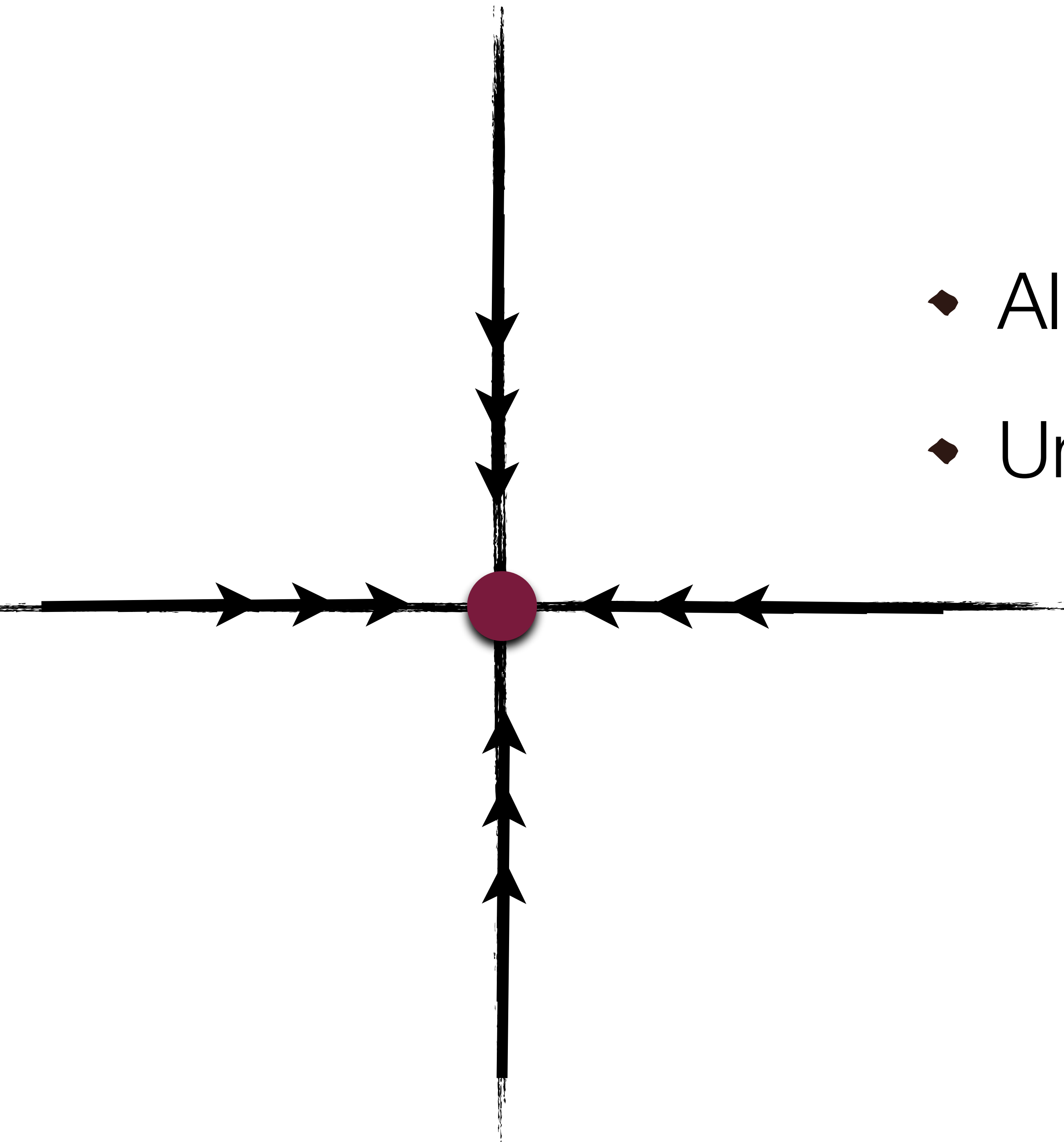
Scalars 2013 - Warsaw

CP3 Origins
Cosmology & Particle Physics

Points

- Degrees of naturality
- CF organizes PT (SM App)
- Composite EW is viable

RG (un)naturality



- All stable directions = Fixed point
- Unstable direction = Fine-tuned FP

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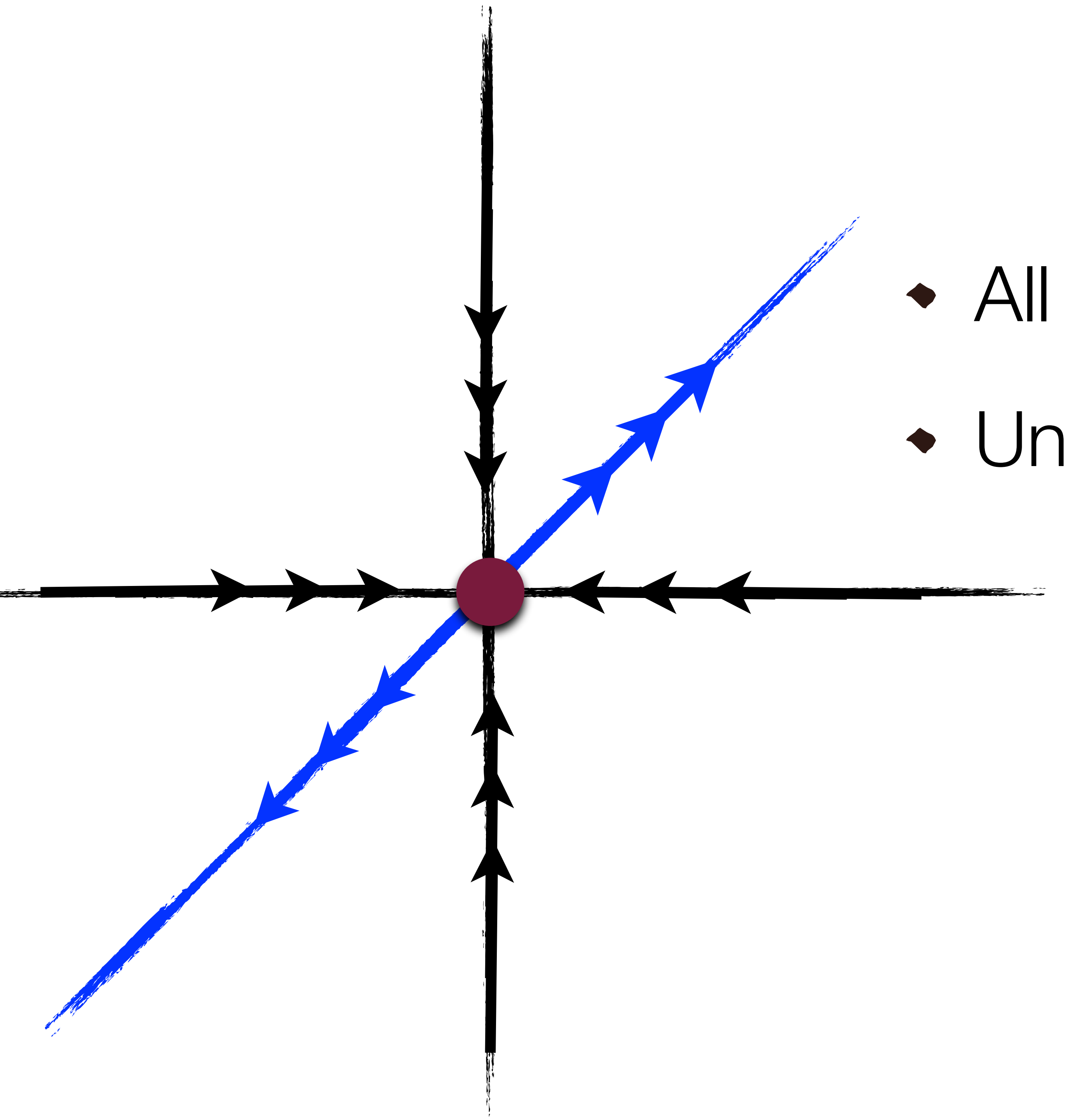

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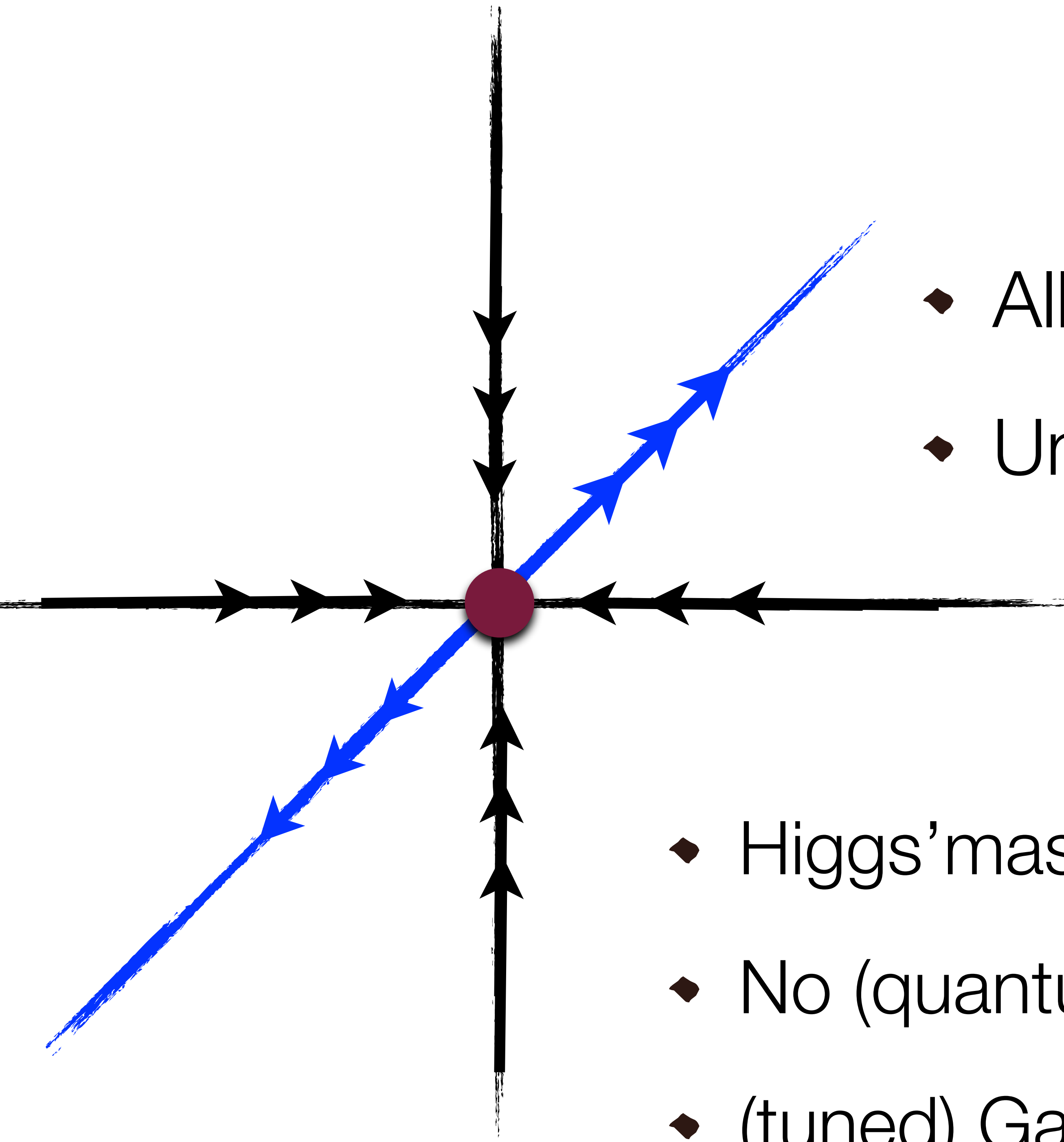


- All stable directions = Fixed point
- Unstable direction = Fine-tuned FP

- Higgs'mass = unstable direction
- No (quantum) symmetry = No protection
- (tuned) Gauge - Yukawa are interesting FTs

Degrees of naturality

SM

Space of 4d theories

Degrees of naturality

SM

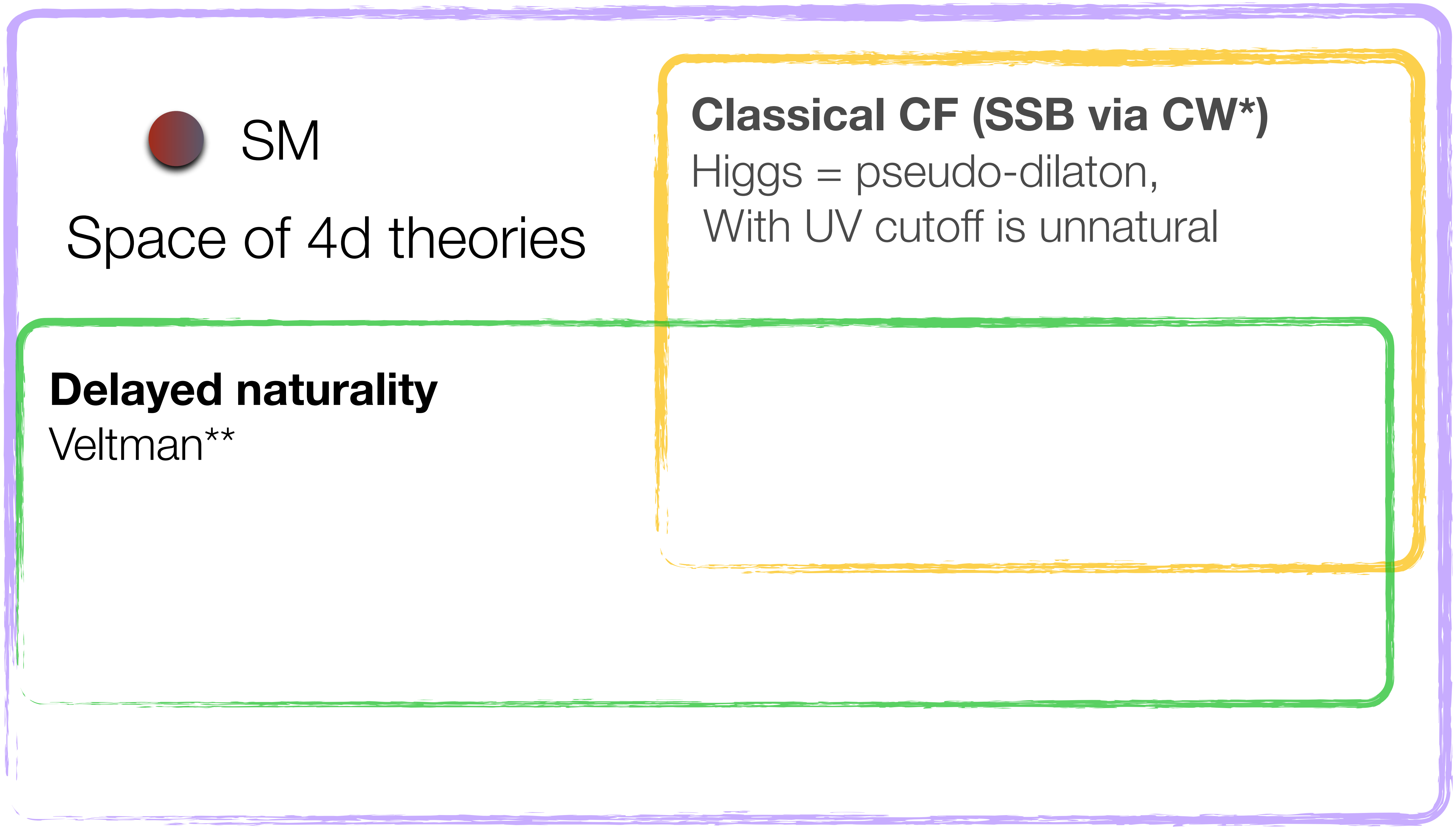
Space of 4d theories

Classical CF (SSB via CW*)

Higgs = pseudo-dilaton,
With UV cutoff is unnatural

* CW = Coleman-Weinberg

Degrees of naturality



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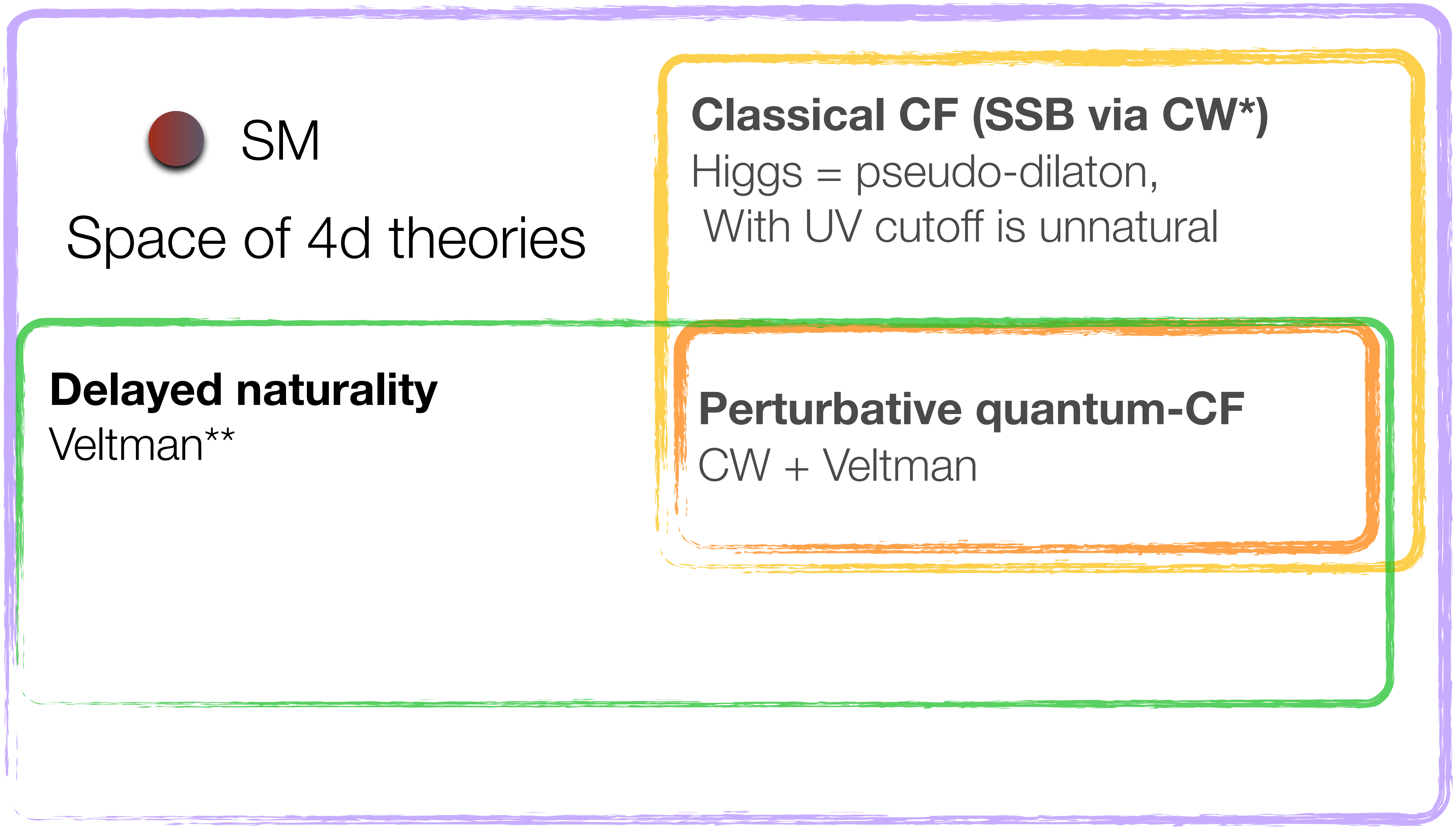
**Perturbative cancellation of quadratic divergences

Degrees of naturality



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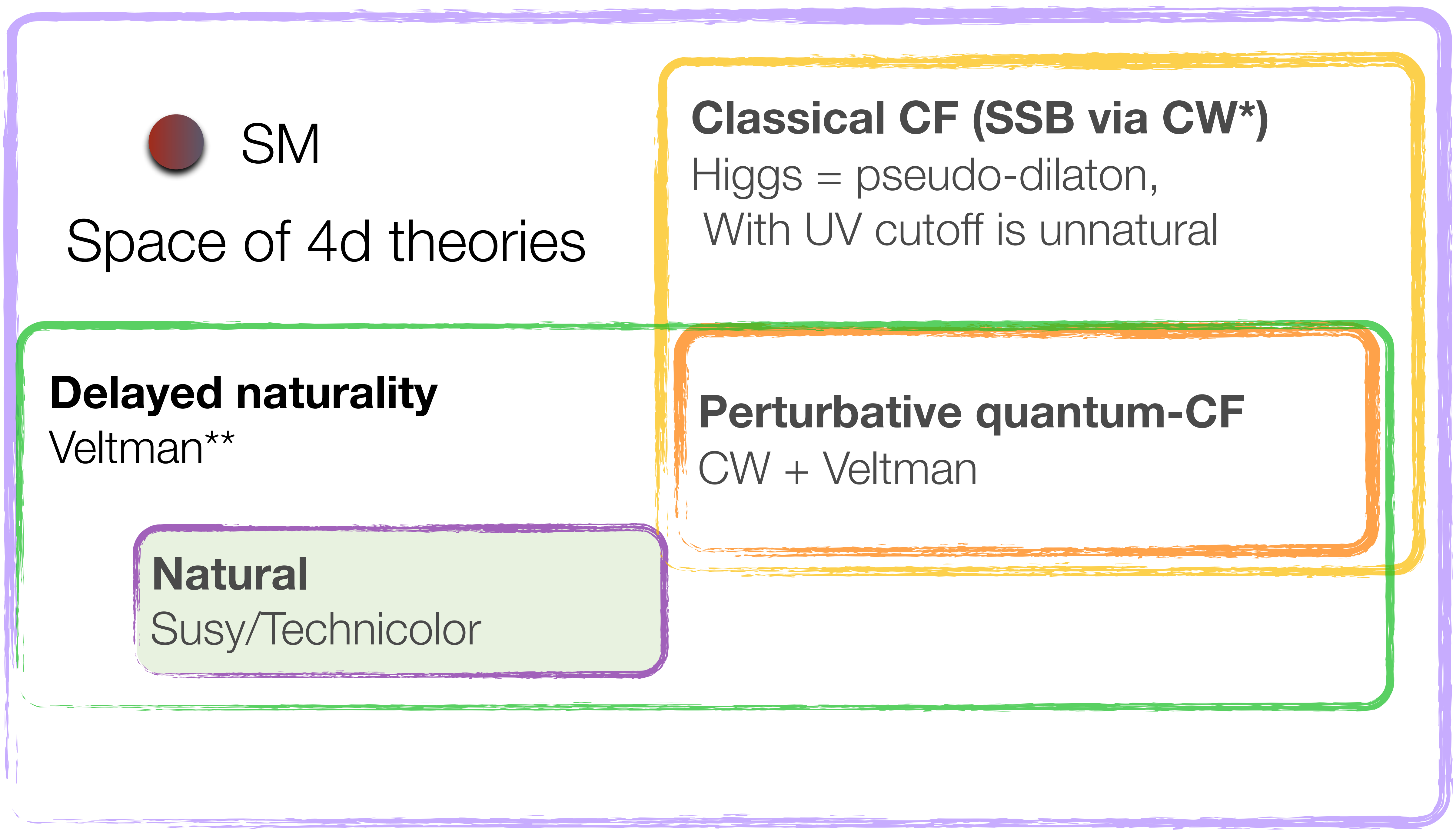

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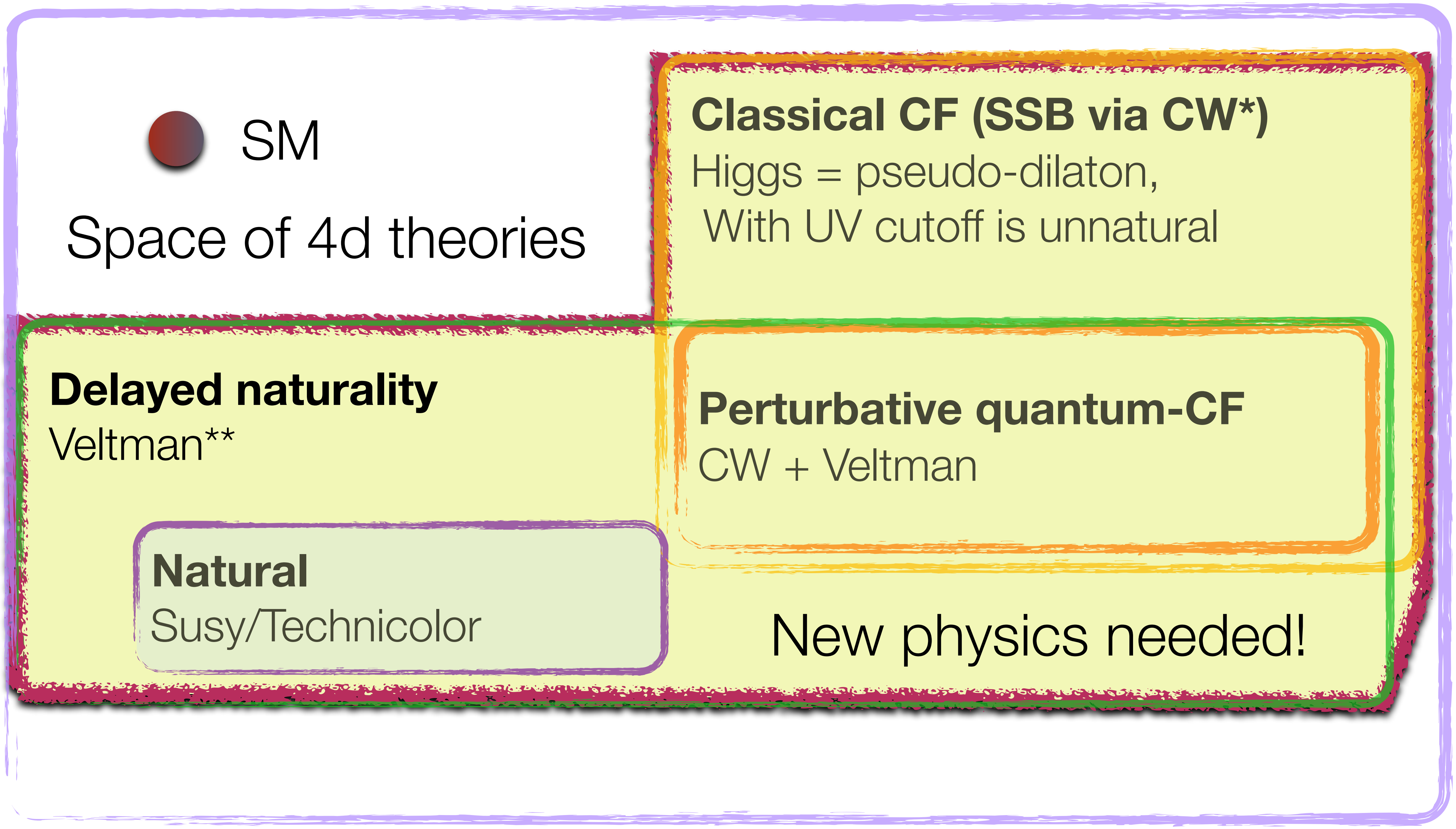

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**Perturbative cancellation of quadratic divergences

Gauge - Yukawa theories

CF Organizes PT

Power of conformality

$$\mathcal{L} = \mathcal{L}_{CFT} + g_i \mathcal{O}^i$$

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Conformal transformation

$$g_i(\mu) \to g_i(e^{-\sigma(x)}\mu)$$

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$$W = \log \left[\int \mathcal{D}\Phi e^{i \int d^4x \mathcal{L}} \right]$$ Variation of the generating functional

Weyl (anomaly) relations

$$\Delta_\sigma W \equiv \int d^4x\, \sigma(x) \left(2\gamma_{\mu\nu} \frac{\delta W}{\delta \gamma_{\mu\nu}} - \beta_i \frac{\delta W}{\delta g_i} \right) = \sigma \left(aE(\gamma) + \chi^{ij} \partial_\mu g_i \partial_\nu g_j G^{\mu\nu} \right) + \partial_\mu \sigma w^i \, \partial_\nu g_i G^{\mu\nu} + \ldots$$

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$$E(\gamma) = R^{\mu\nu\rho\sigma} R_{\mu\nu\rho\sigma} - 4R^{\mu\nu} R_{\mu\nu} + R^2$$

Euler density

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2}\gamma^{\mu\nu} R$$

Einstein tensor

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$$\beta_i$$

Beta functions

$$a, \quad \chi^{ij}, \quad \omega^i$$

Functions of couplings

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β_i Beta functions

$a, \quad \chi^{ij}, \quad \omega^i$ Functions of couplings

Weyl relations from abelian nature of Weyl anomaly

$$\Delta_\sigma \Delta_\tau W = \Delta_\tau \Delta_\sigma W$$

Relation to the a-theorem

$$\tilde{a} \equiv a - w^i \beta_i \qquad\qquad \frac{\partial \tilde{a}}{\partial g_i} = \left(-\chi^{ij} + \frac{\partial w^i}{\partial g_j} - \frac{\partial w^j}{\partial g_i} \right) \beta_j$$

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True in lowest order PT

Osborn 89 & 91, Jack & Osborn 90

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True in lowest order PT — Osborn 89 & 91, Jack & Osborn 90

Analyticity: a-tilde bigger in UV — Komargodski & Schwimmer 11, Komargodski 12

Gauge - Yukawa theories

Antipin, Gillioz, Mølgaard, Sannino 13

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omega is an exact form

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Gradient flow fundamental relation

$$\frac{\partial \beta^j}{\partial g_i} = \frac{\partial \beta^i}{\partial g_j} \,,$$

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Relations among the modified β of different couplings

It is **inconsistent** to expand to the same order in all couplings

Antipin, Gillioz, Mølgaard, Sannino 13

SM & Weyl relations

$$\alpha_1 = \frac{g_1^2}{(4\pi)^2}, \quad \alpha_2 = \frac{g_2^2}{(4\pi)^2}, \quad \alpha_3 = \frac{g_3^2}{(4\pi)^2}, \quad \alpha_t = \frac{y_t^2}{(4\pi)^2}, \quad \alpha_\lambda = \frac{\lambda}{(4\pi)^2}$$

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- 3 (gauge) - 2(yukawa) - 1(Higgs' coupling) preserves WR

- 3 - 3 - 3 violates WR

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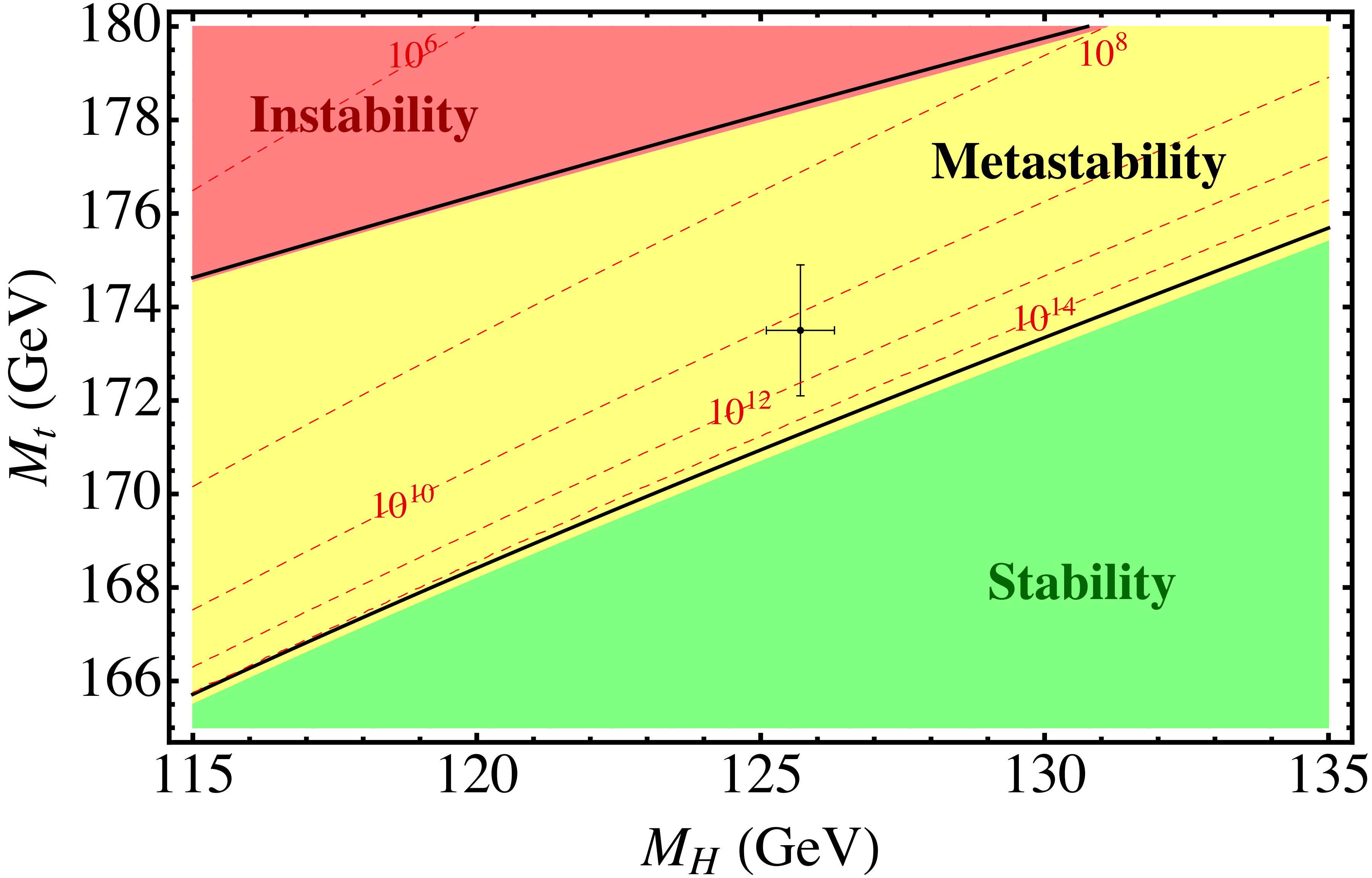
Weyl consistent Vacuum Stability

3-3-3 Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia 2012 (2-black lines).
WR inconsistent

3-2-1 Antipin, Gillioz, Krog, Mølgaard, Sannino 2013. WR consistent



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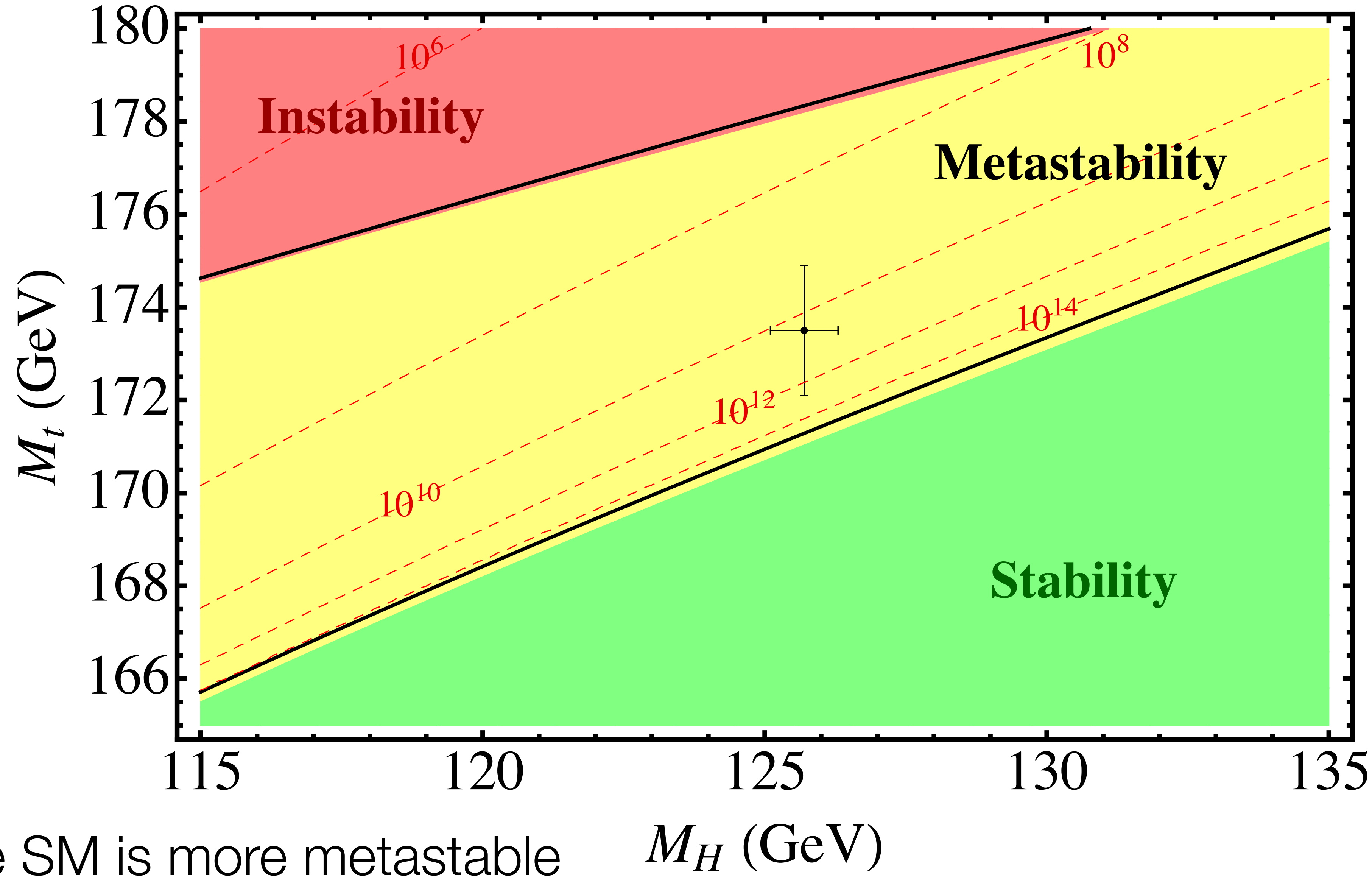
- Smaller top mass
- To do: 4 - 3 - 2
- Only 4 is not known
- Reorganize PT
- At the 3 - 2 - 1 level the SM is more metastable



Hold on, fundamental?

- Would be the first time
- Spinors are building blocks
- Scalar theories are fine-tuned

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How to get a non-GB light Higgs in composite dynamics?

Composite Higgs dynamics

$$DH^\dagger DH - V(H) + \overline{\Psi}_L H \psi_R$$

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$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

Composite Higgs dynamics

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$$m_\psi \overline{\Psi}_L \psi_R$$

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TC

Composite Higgs dynamics

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TC

Extended TC

Composite Higgs dynamics

$$DH^\dagger DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW \qquad\qquad m_\psi \overline{\psi}_L \psi_R$$

TC ⟷ Extended TC

TC Higgs

TC - Higgs is the lightest spin-0 scalar made of TC-fermions

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$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}Q\bar{Q}Q + \cdots$$

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Will contain also a TC-glue component

TC Higgs

TC - Higgs is the lightest spin-0 scalar made of TC-fermions

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Will contain also a TC-glue component

QCD lightest scalar is $f_0(500)$ with mass ~ 400-550 MeV

Sannino & Schechter 95 PRD [‘t Hooft 1/N, crossing, chiral, pole mass]
Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL
Pelaez - Confinement X - lecture

Narrow state in strong dynamics?

Example $f_0(980)$

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Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL [Large N apparent violation]

S. Weinberg 2013

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$$\mathcal{L}_H \supset \frac{2\ m_W^2\ r_\pi}{v}\ H\ W_\mu^+\ W^{-\mu} + \frac{m_Z^2\ r_\pi}{v}\ H\ Z_\mu\ Z^\mu - \frac{m_t\ r_t}{v}\ H\ \bar{t}\ t$$

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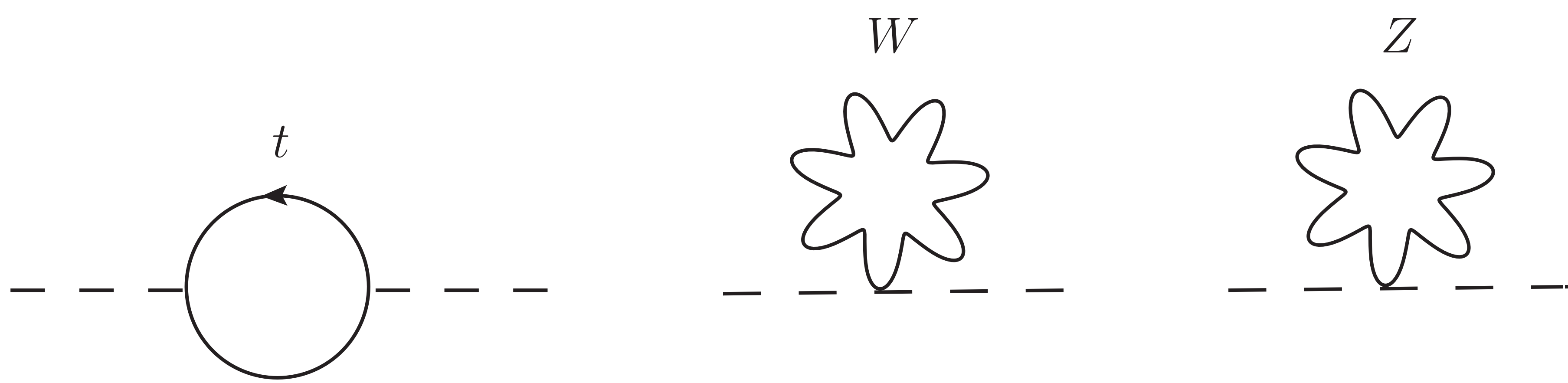

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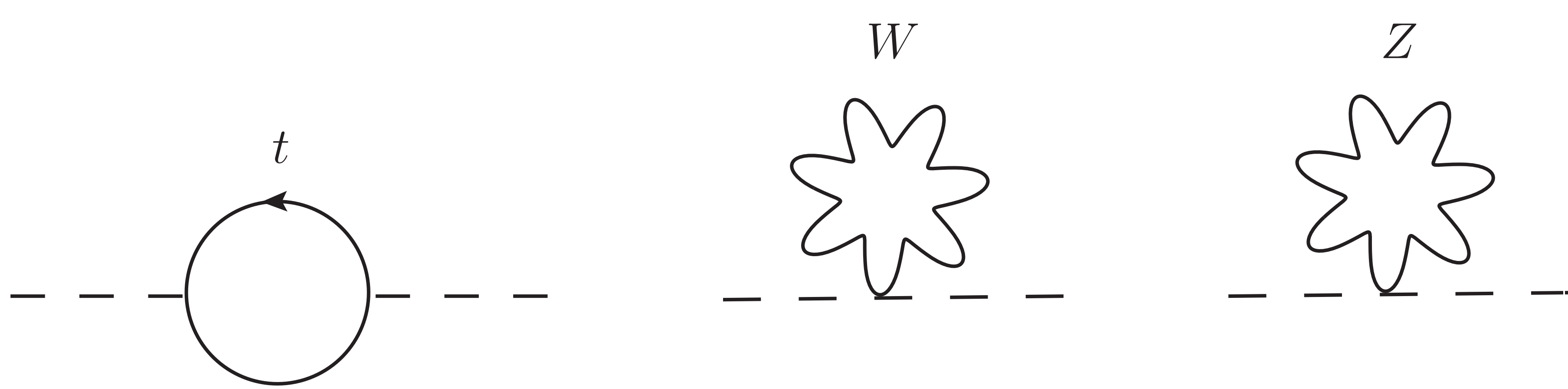

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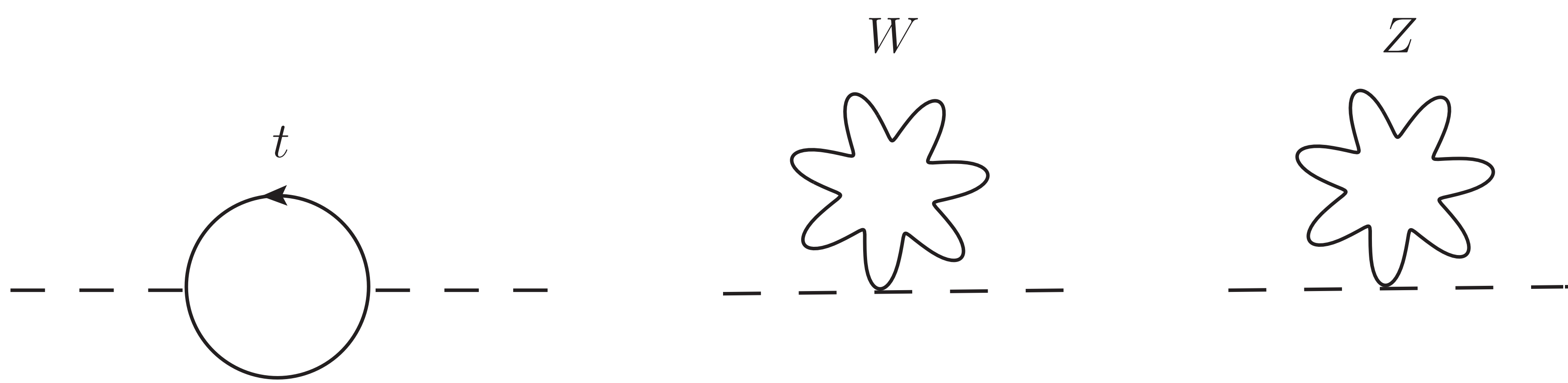

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Foadi, Frandsen, Sannino, 1211.1083

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$\kappa\ r_t$ ~ TC x ETC

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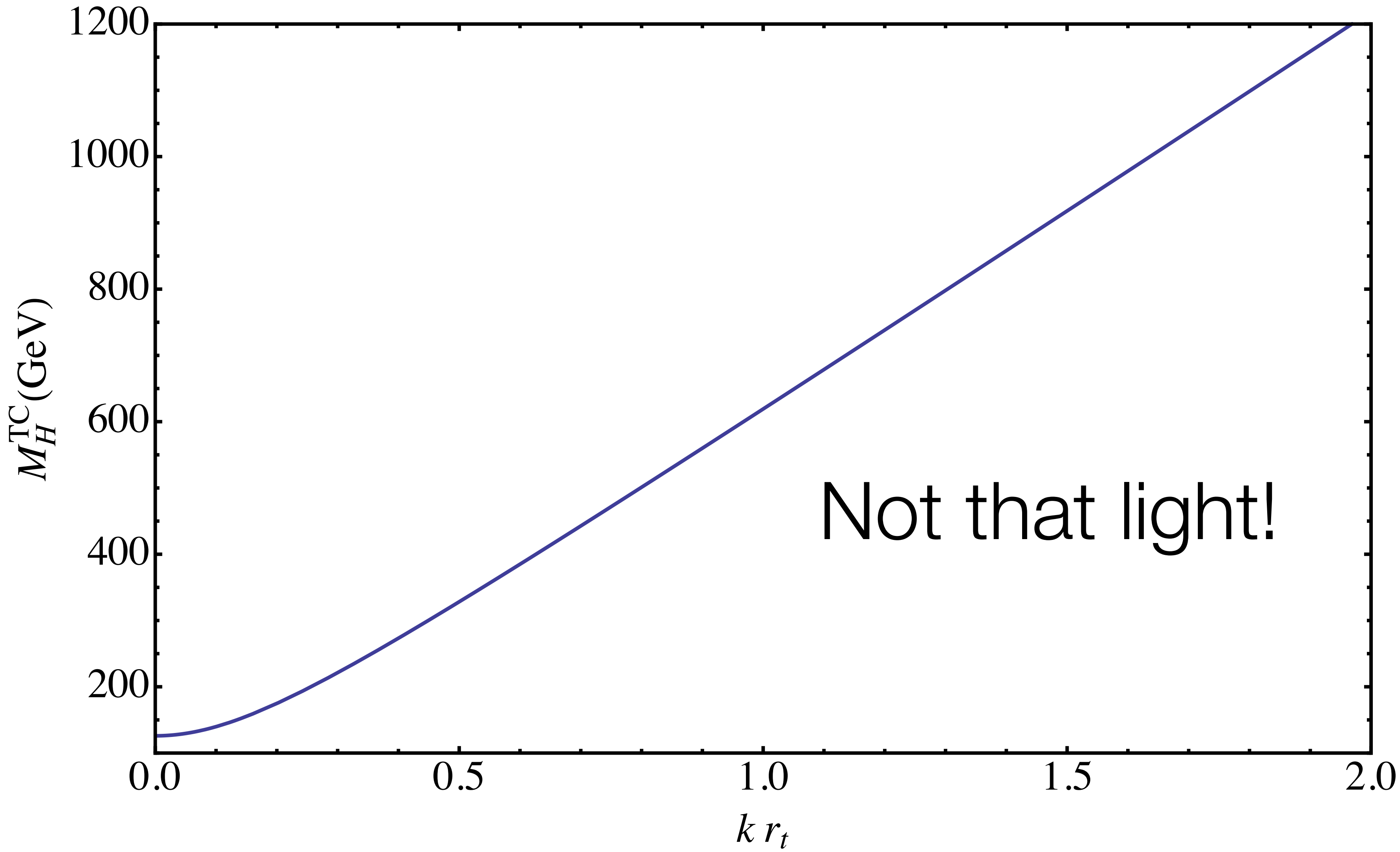

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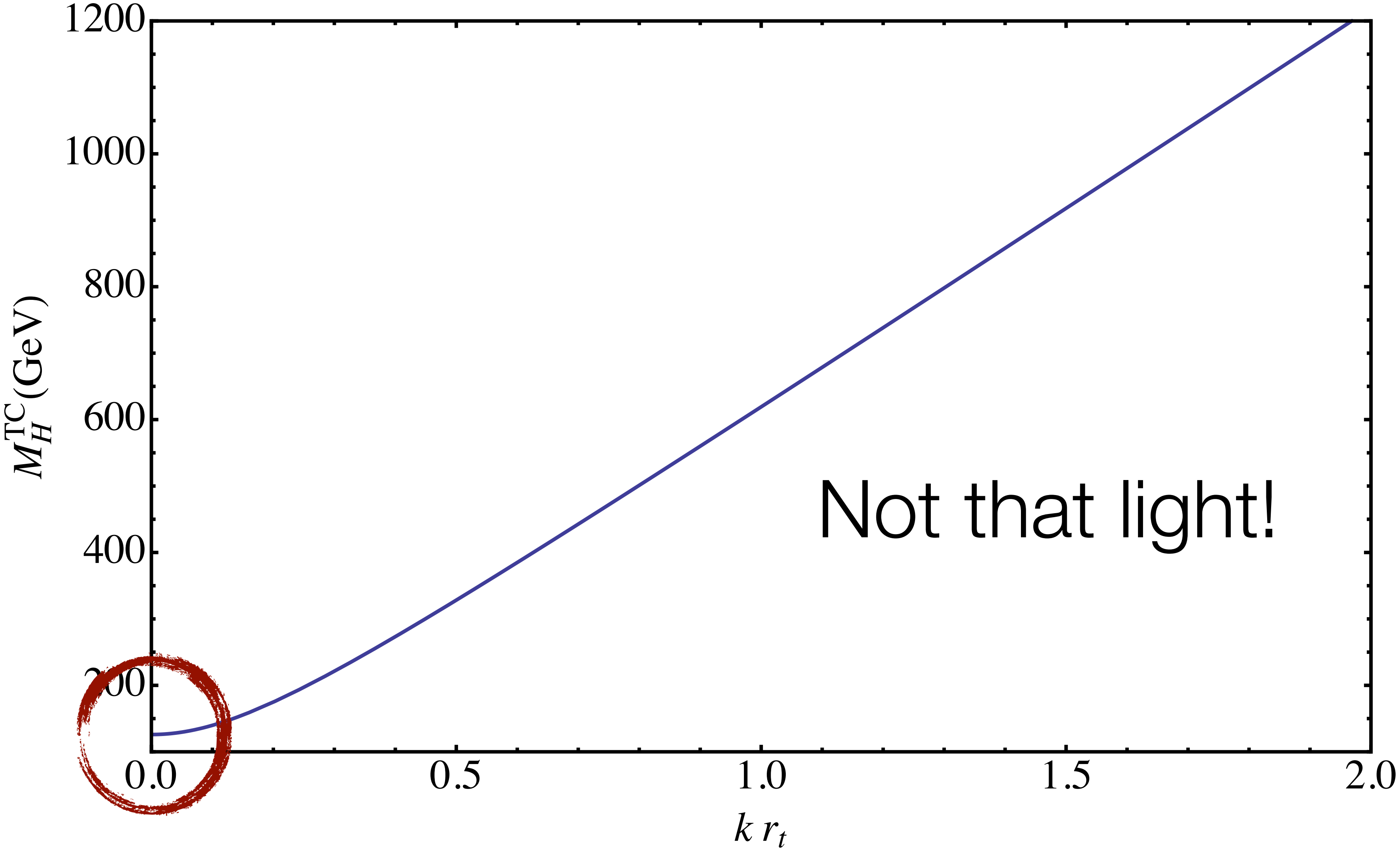

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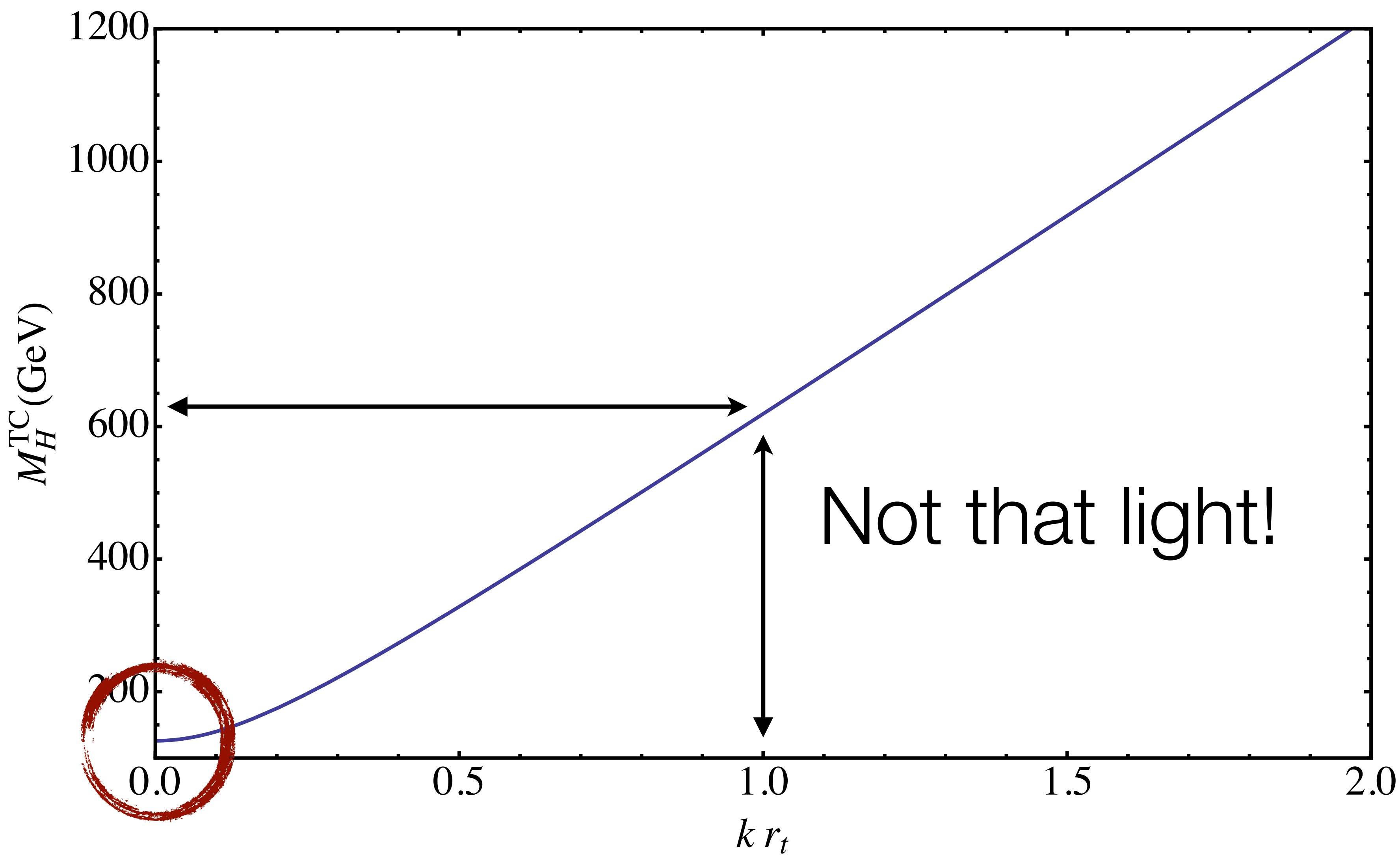

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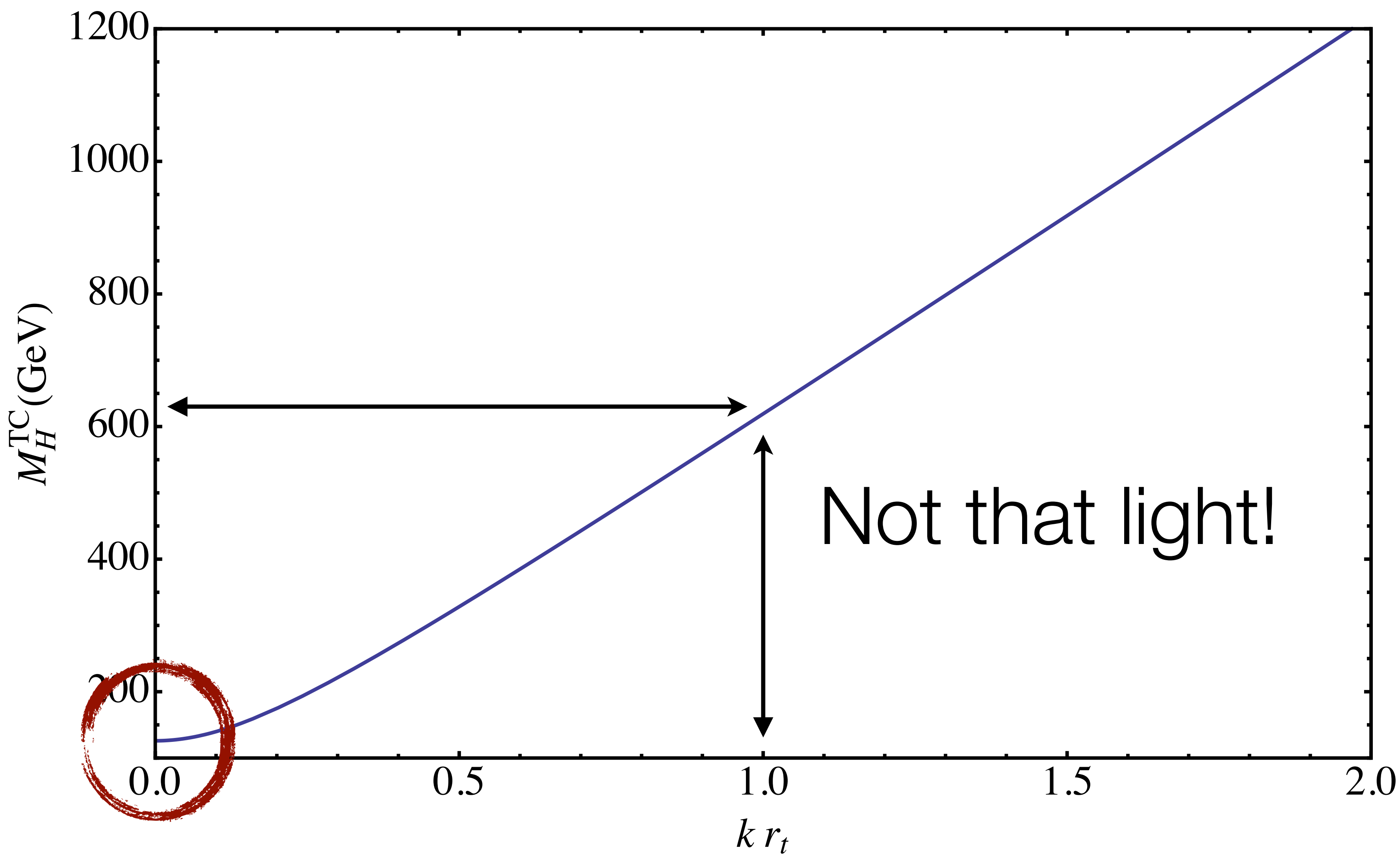

Narrow due to kinematics [Similar to f_0(980) in QCD]

Minimal Walking Theories

- SU(2) + 2 Dirac Adjoint — $SU(2)_A$ - MWT
- SU(3) + 2 Dirac Symmetric — $SU(3)_S$ - MWT
- SU(2) +2 Dirac Fund. + .. (U - MWT) — $SU(2)_F$ - MWT
- SO(4) + 2 Dirac Vector — $SO(4)_V$ - MWT
- SU(3) + 2 Dirac Fund. + Ungauged — $SU(3)_F$ - pMWT

Only one N_D gauged: Small S

Realistic SU(3)$_S$ MWT

$N_D = 1 \quad d(\mathrm{Symmetric}) = 6$

Sannino & Tuominen hep-ph/0405209

$M_H^{TC} \simeq 735\ \mathrm{GeV}$

Large N scaling

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Model agrees with LHC data @ 95% CL

Belyaev, Brown, Foadi, Frandsen 2013

Summary

RG (un)naturality

Conformality & consistent Gauge - Yukawa PT

A natural avenue: Compositeness

A 125 Higgs via a not-to-light TC Higgs

Promising lattice & pheno studies of Minimal TC

New particles naturally in the (multi)-TeV region